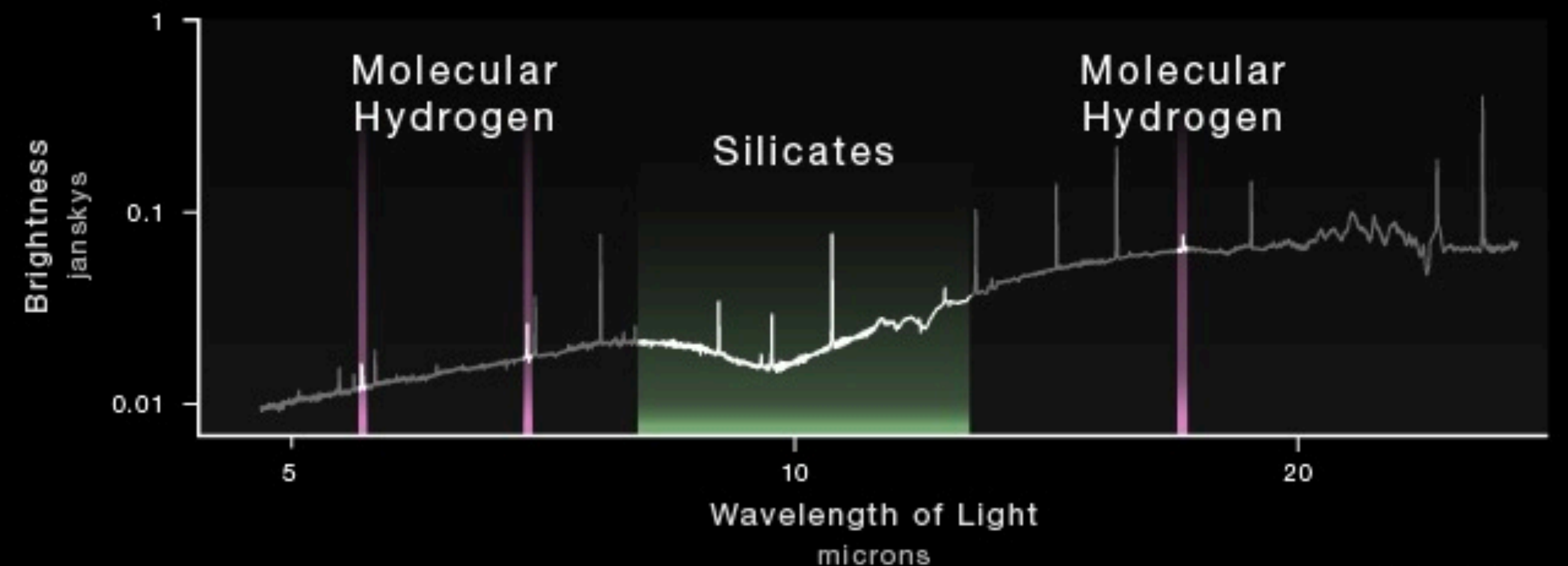
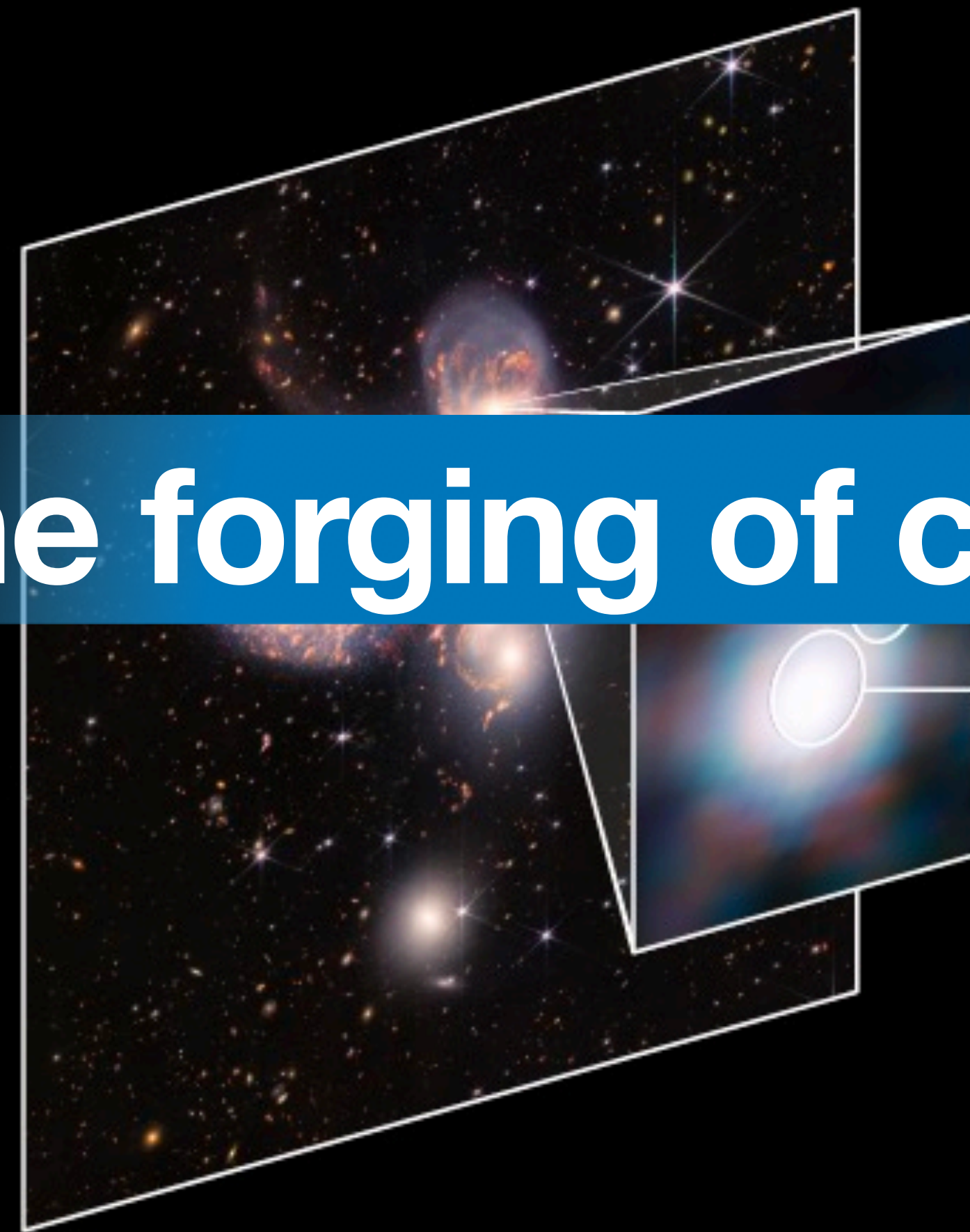


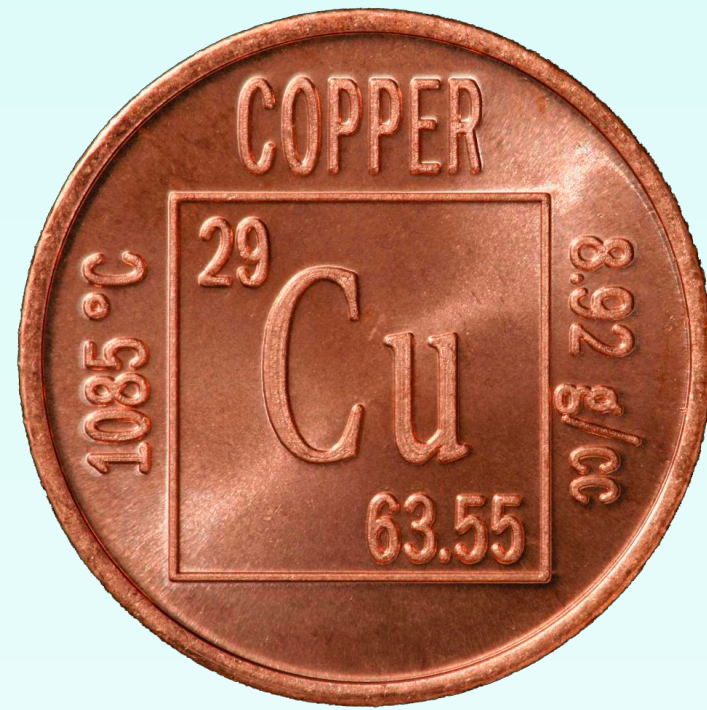
NIRCam and MIRI Imaging

MIRI IFU Medium Resolution Spectroscopy

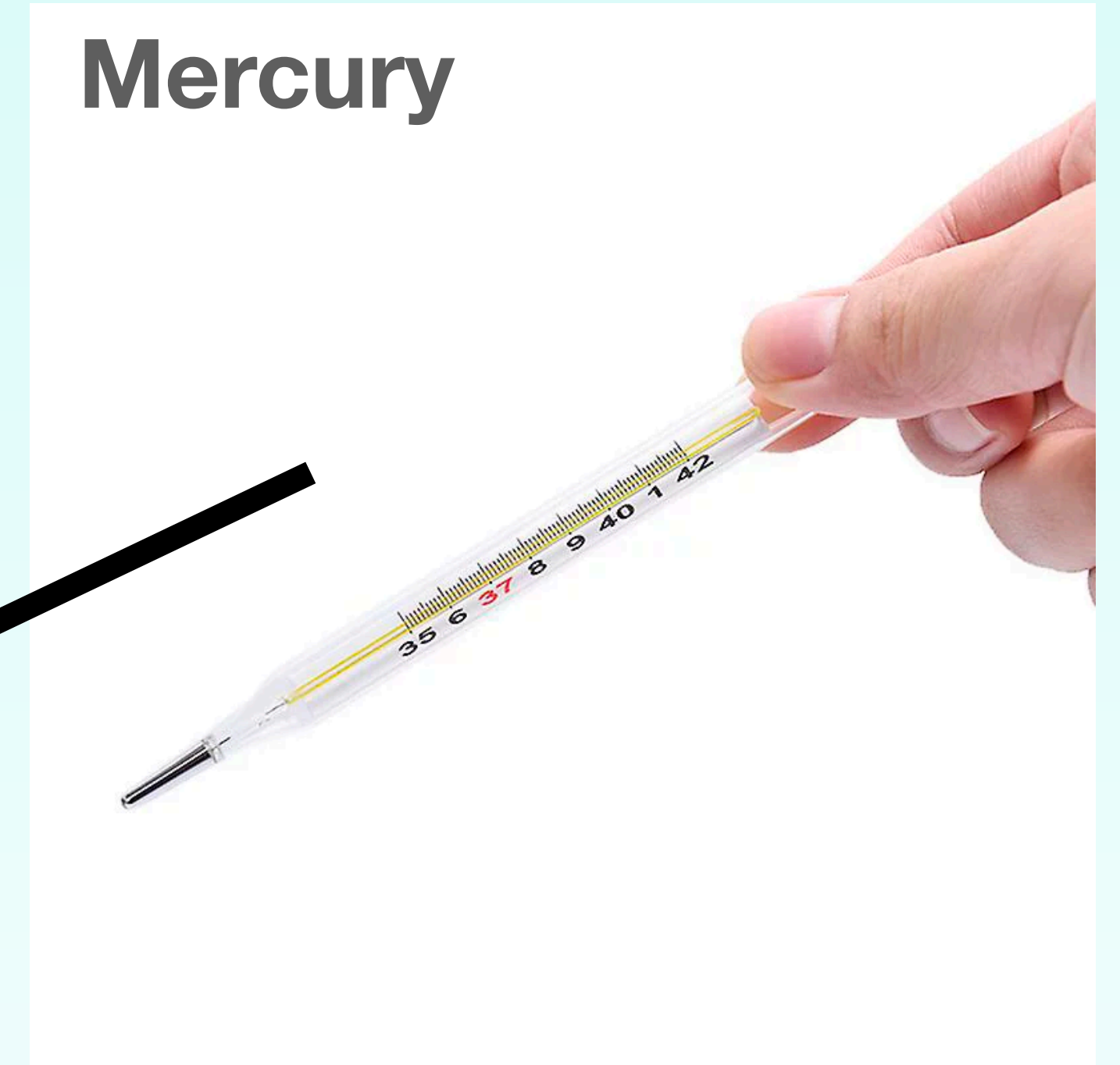
The forging of chemical elements in galaxies



Copper



Mercury



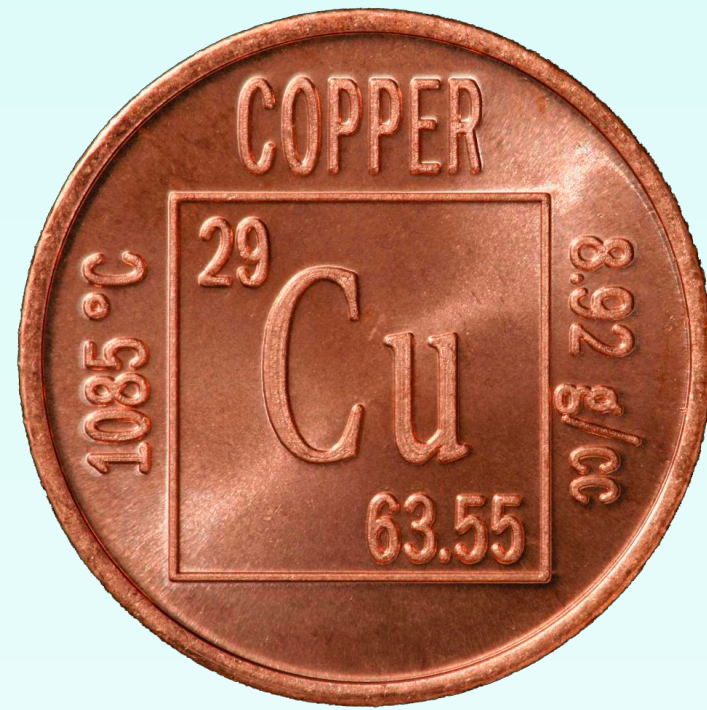
Phosphorous



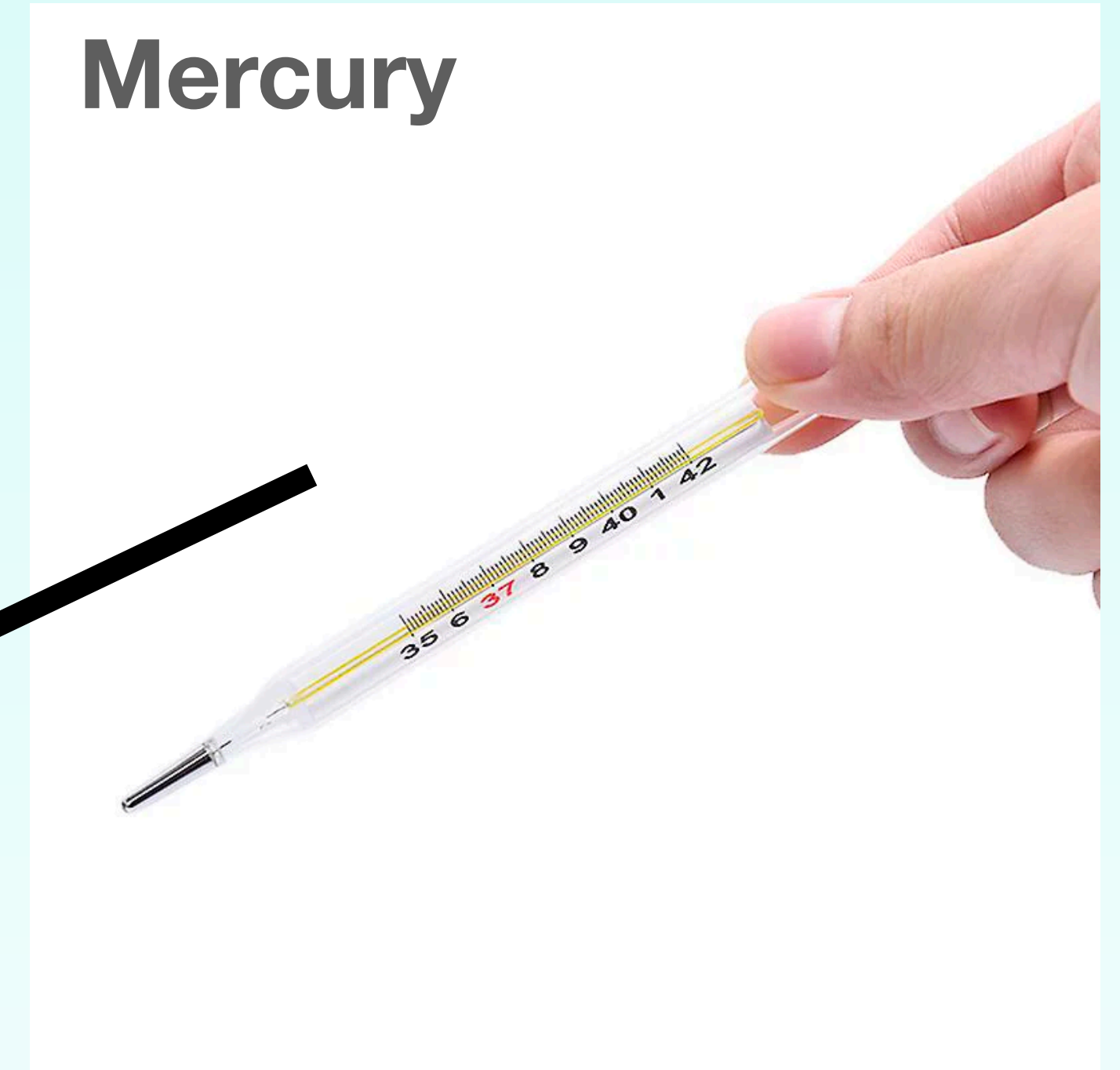
Uranium



Copper



Mercury

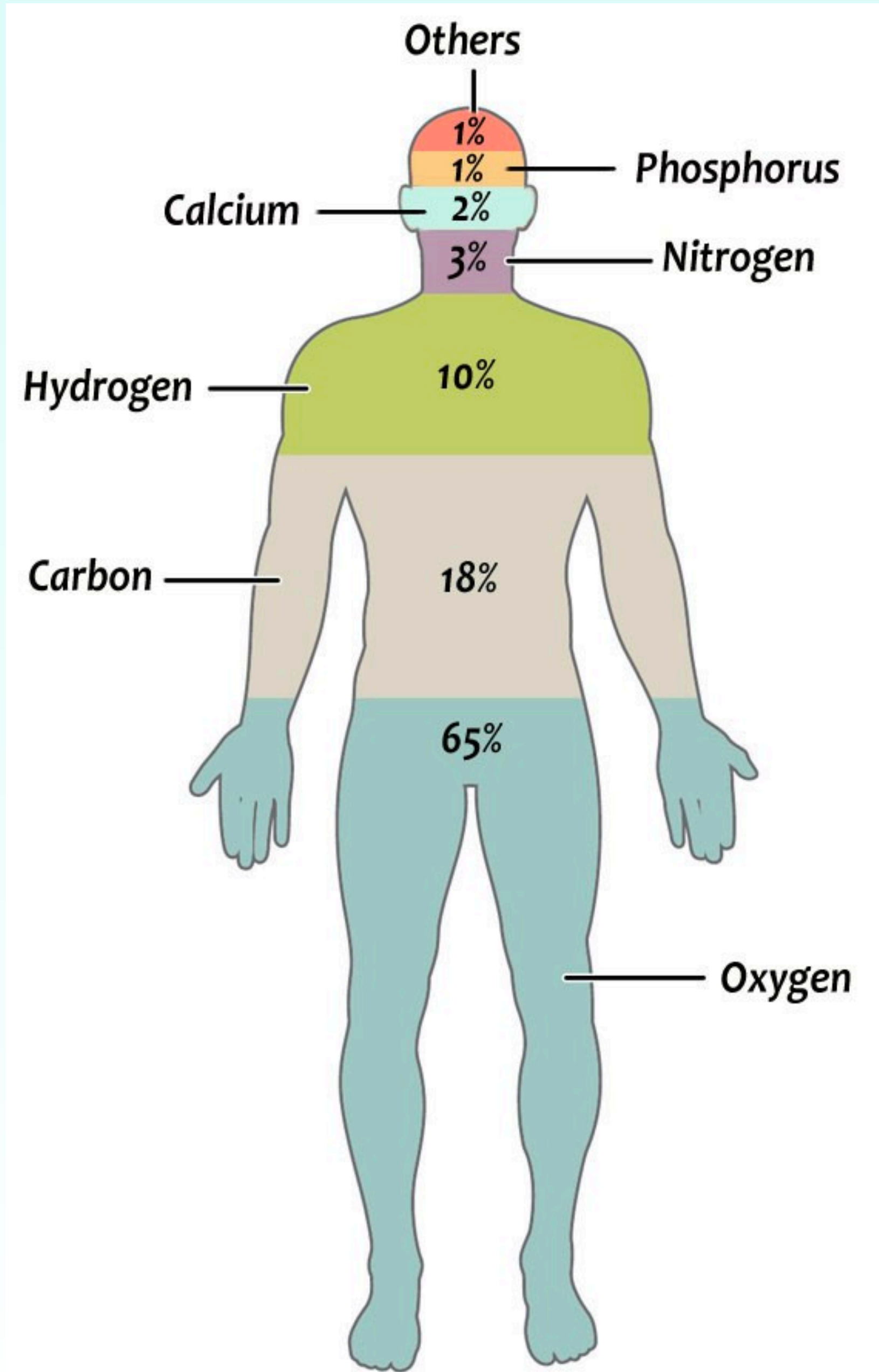


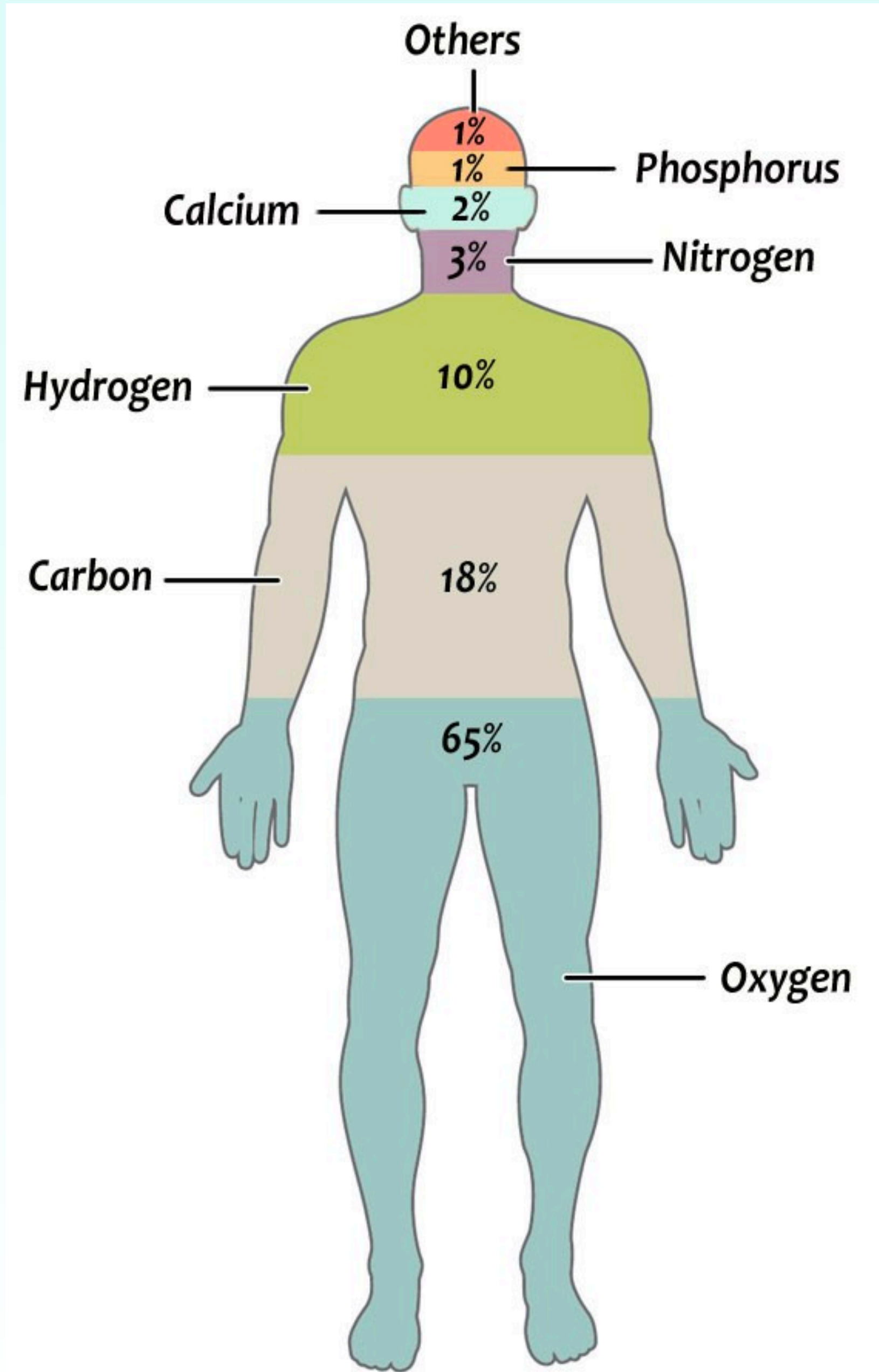
Phosphorous



Uranium







Others

THE PERIODIC TABLE OF ELEMENTS

1

H

HYDROGEN

1.008

3

Li

LITHIUM

6.941

4

Be

BERYLLIUM

9.012

11

Na

SODIUM

22.990

12

Mg

MAGNESIUM

24.305

19

K

POTASSIUM

39.098

20

Ca

CALCIUM

40.078

21

Sc

SCANDIUM

44.956

22

Ti

TITANIUM

47.867

23

V

VANADIUM

50.942

24

Cr

CHROMIUM

51.996

25

Mn

MANGANESE

54.938

26

Fe

IRON

55.845

27

Co

COBALT

58.933

28

Ni

NICKEL

58.693

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

37

Rb

RUBIDIUM

85.468

38

Sr

STRONTIUM

87.620

39

Y

YTTRIUM

88.906

40

Zr

ZIRCONIUM

91.224

41

Nb

NIOBIUM

92.906

42

Mo

MOLYBDENUM

95.951

43

Tc

TECHNETIUM

(97.907)

44

Ru

RUTHENIUM

101.072

45

Rh

RHODIUM

102.906

46

Pd

PALLADIUM

106.421

47

Ag

SILVER

107.868

48

Cd

CADMIUM

112.414

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

55

Cs

CAESIUM

132.905

56

Ba

BARIUM

137.328

57-71

72

Hf

HAFNIUM

178.492

73

Ta

TANTALUM

180.948

74

W

TUNGSTEN

183.841

75

Re

RHENIUM

186.207

76

Os

OSMIUM

190.233

77

Ir

IRIDIUM

192.217

78

Pt

PLATINUM

195.084

79

Au

GOLD

196.967

80

Hg

MERCURY

200.592

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.210

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(208.982)

85

At

ASTATINE

(209.987)

86

Rn

RADON

(222.018)

87

Fr

FRANCIUM

(223.020)

88

Ra

RADIUM

(226.025)

89-103

104

Rf

RUTHERFORDIUM

(261.109)

105

Db

DUBNIUM

(262.114)

106

Sg

SEABORGIUM

(266.122)

107

Bh

BOHRIUM

(264.120)

108

Hs

HASSIUM

(277.000)

109

Mt

MEITNERIUM

(268.139)

110

Ds

DARMSTADIUM

(281.000)

111

Rg

ROENTGENIUM

(280.000)

112

Cn

COPECNICIUM

(285.000)

113

Nh

NIHONIUM

(286.000)

114

Fl

FLEROVIUM

(289.000)

115

Mc

MOSCOWIUM

(289.000)

116

Lv

LIVERMORIUM

(293.000)

117

Ts

TENNESSINE

(294.000)

118

Og

OGANESSON

(294.000)

Symbol Key

Atomic number

Element symbol

Element name

Relative atomic mass

Block

Colour Key

s block elements

p block elements

d block elements

f block elements

2

He

HELIUM

4.003

5

B

BORON

10.811

6

C

CARBON

12.011

7

N

NITROGEN

14.007

8

O

OXYGEN

15.999

9

F

FLUORINE

18.998

10

Ne

NEON

20.180

13

Al

ALUMINIUM

26.982

14

Si

SILICON

28.086

15

P

PHOSPHORUS

30.974

16

S

SULFUR

32.065

17

Cl

CHLORINE

35.453

18

Ar

ARGON

39.948

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

47

Ag

SILVER

107.868

48

Cd

CADMIUM

112.414

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.210

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(208.982)

85

At

ASTATINE

(209.987)

86

Rn

RADON

(222.018)

111

Rg

ROENTGENIUM

(280.000)

112

Cn

COPECNICIUM

(285.000)

113

Nh

NIHONIUM

(286.000)

114

Fl

FLEROVIUM

(289.000)

115

Mc

MOSCOWIUM

(289.000)

116

Lv

LIVERMORIUM

(293.000)

117

Ts

TENNESSINE

(294.000)

118

Og

OGANESSON

(294.000)

57

La

LANTHANUM

138.905

58

Ce

CERIUM

140.116

59

Pr

PRASEODYMIUM

140.908

60

Nd

NEODYMIUM

144.242

61

Pm

PROMETHIUM

(144.000)

62

Sm

SAMARIUM

150.362

63

Eu

EUROPIUM

151.964

64

Gd

GADOLINIUM

157.253

65

Tb

TERBIUM

158.925

66

Dy

DYSPROSIUM

162.500

67

Ho

HOLMIUM

164.930

68

Er

ERBIUM

167.259

69

Tm

THULIUM

168.934

70

Yb

YTBRIUM

173.054

71

Lu

LUTETIUM

174.967

89

Ac

ACTINIUM

(227.028)

90

Th

THORIUM

(232.038)

91

Pa

PROTACTINIUM

(231.036)

92

U

URANIUM

(238.029)

93

Np

NEPTUNIUM

(237.048)

94

Pu

PLUTONIUM

(244.064)

95

Am

AMERICIUM

(243.061)

96

Cm

CURIUM

(247.070)

97

Bk

BERKELIUM

(247.070)

98

Cf

CALIFORNIUM

(251.080)

99

Es

EINSTEINIUM

(252.083)

100

Fm

FERMIUM

(257.095)

101

Md

MENDELEVIUM

(258.098)

102

No

NOBELIUM

(259.101)

103

Lr

LAWRENCIUM

(262.110)



© Andy Brunning/Compound Interest 2017 – www.compoundchem.com | Facebook: facebook.com/compoundchem | Twitter: [@compoundchem](https://twitter.com/compoundchem)
This graphic is shared under a Creative Commons 4.0 Attribution-NoDerivatives-NonCommercial licence.



Others

THE PERIODIC TABLE OF ELEMENTS

1

H

HYDROGEN

1.008

3

Li

LITHIUM

6.941

4

Be

BERYLLIUM

9.012

11

Na

SODIUM

22.990

12

Mg

MAGNESIUM

24.305

19

K

POTASSIUM

39.098

20

Ca

CALCIUM

40.078

21

Sc

SCANDIUM

44.956

22

Ti

TITANIUM

47.867

23

V

VANADIUM

50.942

24

Cr

CHROMIUM

51.996

25

Mn

MANGANESE

54.938

26

Fe

IRON

55.845

27

Co

COBALT

58.933

28

Ni

NICKEL

58.693

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

37

Rb

RUBIDIUM

85.468

38

Sr

STRONTIUM

87.620

39

Y

YTTRIUM

88.906

40

Zr

ZIRCONIUM

91.224

41

Nb

NIOBIUM

92.906

42

Mo

MOLYBDENUM

95.951

43

Tc

TECHNETIUM

(97.907)

44

Ru

RUTHENIUM

101.072

45

Rh

RHODIUM

102.906

46

Pd

PALLADIUM

106.421

47

Ag

SILVER

107.868

48

Cd

CADMIUM

112.414

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

55

Cs

CAESIUM

132.905

56

Ba

BARIUM

137.328

57-71

72

Hf

HAFNIUM

178.492

73

Ta

TANTALUM

180.948

74

W

TUNGSTEN

183.841

75

Re

RHENIUM

186.207

76

Os

OSMIUM

190.233

77

Ir

IRIDIUM

192.217

78

Pt

PLATINUM

195.084

79

Au

GOLD

196.967

80

Hg

MERCURY

200.592

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.210

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(208.982)

85

At

ASTATINE

(209.987)

86

Rn

RADON

(222.018)

87

Fr

FRANCIUM

(223.020)

88

Ra

RADIUM

(226.025)

E89-103

104

Rf

RUTHERFORDIUM

(261.109)

105

Db

DUBNIUM

(262.114)

106

Sg

SEABORGIUM

(266.122)

107

Bh

BOHRIUM

(264.120)

108

Hs

HASSIUM

(277.000)

109

Mt

MEITNERIUM

(268.139)

110

Ds

DARMSTADIUM

(281.000)

111

Rg

ROENTGIUM

(280.000)

112

Cn

COPECNICIUM

(285.000)

113

Nh

NIHONIUM

(286.000)

114

Fl

FLEROVIUM

(289.000)

115

Mc

MOSCOWIUM

(289.000)

116

Lv

LIVERMORIUM

(293.000)

117

Ts

TENNESSINE

(294.000)

118

Og

OGANESSON

(294.000)

Symbol Key

Atomic number

Element symbol

Element name

Relative atomic mass

Block

Colour Key

s block elements

p block elements

d block elements

f block elements

2

He

HELIUM

4.003

5

B

BORON

10.811

6

C

CARBON

12.011

7

N

NITROGEN

14.007

8

O

OXYGEN

15.999

9

F

FLUORINE

18.998

10

Ne

NEON

20.180

13

Al

ALUMINIUM

26.982

14

Si

SILICON

28.086

15

P

PHOSPHORUS

30.974

16

S

SULFUR

32.065

17

Cl

CHLORINE

35.453

18

Ar

ARGON

39.948

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.210

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(208.982)

85

At

ASTATINE

(209.987)

86

Rn

RADON

(222.018)

113

Nh

NIHONIUM

(286.000)

114

Fl

FLEROVIUM

(289.000)

115

Mc

MOSCOWIUM

(289.000)

116

Lv

LIVERMORIUM

(293.000)

117

Ts

TENNESSINE

(294.000)

118

Og

OGANESSON

(294.000)

57

La

LANTHANUM

138.905

58

Ce

CERIUM

140.116

59

Pr

PRASEODYMIUM

140.908

60

Nd

NEODYMIUM

144.242

61

Pm

PROMETHIUM

(144.000)

62

Sm

SAMARIUM

150.362

63

Eu

EUROPIUM

151.964

64

Gd

GADOLINIUM

157.253

65

Tb

TERBIUM

158.925

66

Dy

DYSPROSIUM

162.500

67

Ho

HOLMIUM

164.930

68

Er

ERBIUM

167.259

69

Tm

THULIUM

168.934

70

Yb

YTBRIUM

173.054

71

Lu

LUTETIUM

174.967

89

Ac

ACTINIUM

(227.028)

90

Th

THORIUM

(232.038)

91

Pa

PROTACTINIUM

(231.036)

92

U

URANIUM

(238.029)

93

Np

NEPTUNIUM

(237.048)

94

Pu

PLUTONIUM

(244.064)

95

Am

AMERICIUM

(243.061)

96

Cm

CURIUM

(247.070)

97

Bk

BERKELIUM

(247.070)

98

Cf

CALIFORNIUM

(251.080)

99

Es

EINSTEINIUM

(252.083)

100

Fm

FERMIUM

(257.095)

101

Md

MENDELEVIUM

(258.098)

102

No

NOBELIUM

(259.101)

103

Lr

LAWRENCIUM

(262.110)



© Andy Brunning/Compound Interest 2017 – www.compoundchem.com | Facebook: facebook.com/compoundchem | Twitter: @compoundchem
This graphic is shared under a Creative Commons 4.0 Attribution-NoDerivatives-NonCommercial licence.



Others

THE PERIODIC TABLE OF ELEMENTS

1
H
HYDROGEN
1.008

3
Li
LITHIUM
6.941

11
Na
SODIUM
22.990

19
K
POTASSIUM
39.098

37
Rb
RUBIDIUM
85.468

55
Cs
CAESIUM
132.905

87
Fr
FRANCIUM
(223.020)

4
Be
BERYLLIUM
9.012

12
Mg
MAGNESIUM
24.305

20
Ca
CALCIUM
40.078

38
Sr
STRONTIUM
87.620

56
Ba
BARIUM
137.328

88
Ra
RADIUM
(226.025)

21
Sc
SCANDIUM
44.956

39
Y
YTTRIUM
88.906

57-71
E57-71

89-103
E89-103

2
He
HELIUM
4.003

10
Ne
NEON
20.180

18
Ar
ARGON
39.948

36
Kr
KRYPTON
83.798

54
Xe
XENON
131.294

86
Rn
RADON
(222.018)

5
B
BORON
10.811

13
Al
ALUMINIUM
26.982

31
Ga
GALLIUM
69.723

49
In
INDIUM
114.818

81
Tl
THALLIUM
204.383

113
Nh
NIHONIUM
(286.000)

6
C
CARBON
12.011

14
Si
SILICON
28.086

32
Ge
GERMANIUM
72.640

50
Sn
TIN
118.711

82
Pb
LEAD
207.210

114
Fl
FLEROVIUM
(289.000)

7
N
NITROGEN
14.007

15
P
PHOSPHORUS
30.974

33
As
ARSENIC
74.922

51
Sb
ANTIMONY
121.760

83
Bi
BISMUTH
208.980

115
Mc
MOSCOWIUM
(289.000)

8
O
OXYGEN
15.999

16
S
SULFUR
32.065

34
Se
SELENIUM
78.971

52
Te
TELLURIUM
127.603

84
Po
POLONIUM
(209.982)

116
Lv
LIVERMORIUM
(293.000)

9
F
FLUORINE
18.998

17
Cl
CHLORINE
35.453

35
Br
BROMINE
79.904

53
I
IODINE
126.904

85
At
ASTATINE
(209.987)

117
Ts
TENNESSINE
(294.000)

26
Fe
IRON
55.845

27
Co
COBALT
58.933

28
Ni
NICKEL
58.693

29
Cu
COPPER
63.546

30
Zn
ZINC
65.382

40
Zr
ZIRCONIUM
91.224

41
Nb
NIOBIUM
92.906

42
Mo
MOLYBDENUM
95.951

43
Tc
TECHNETIUM
(97.907)

44
Ru
RUTHENIUM
101.072

45
Rh
RHODIUM
102.906

46
Pd
PALLADIUM
106.421

47
Ag
SILVER
107.868

48
Cd
CADMIUM
112.414

72
Hf
HAFNIUM
178.492

73
Ta
TANTALUM
180.948

74
W
TUNGSTEN
183.841

75
Re
RHENIUM
186.207

76
Os
OSMIUM
190.233

77
Ir
IRIDIUM
192.217

78
Pt
PLATINUM
195.084

79
Au
GOLD
196.967

80
Hg
MERCURY
200.592

104
Rf
RUTHERFORDIUM
(261.109)

105
Db
DUBNIUM
(262.114)

106
Sg
SEABORGIUM
(266.122)

107
Bh
BOHRIUM
(264.120)

108
Hs
HASSIUM
(277.000)

109
Mt
MEITNERIUM
(268.139)

110
Ds
DARMSTADIUM
(281.000)

111
Rg
ROENTGIUM
(280.000)

112
Cn
COPECNICIUM
(285.000)

118
Og
OGANESSON
(284.000)

57
La
LANTHANUM
138.905

58
Ce
CERIUM
140.116

59
Pr
PRASEODYMIUM
140.908

60
Nd
NEODYMIUM
144.242

61
Pm
PROMETHIUM
(144.000)

62
Sm
SAMARIUM
150.362

63
Eu
EUROPIUM
151.964

64
Gd
GADOLINIUM
157.253

65
Tb
TERBIUM
158.925

66
Dy
DYSPROSIUM
162.500

67
Ho
HOLMIUM
164.930

68
Er
ERBIUM
167.259

69
Tm
THULIUM
168.934

70
Yb
YTTERIUM
173.054

71
Lu
LUTETIUM
174.967

89
Ac
ACTINIUM
(227.028)

90
Th
THORIUM
(232.038)

91
Pa
PROTACTINIUM
(231.036)

92
U
URANIUM
(238.029)

93
Np
NEPTUNIUM
(237.048)

94
Pu
PLUTONIUM
(244.064)

95
Am
AMERICIUM
(243.061)

96
Cm
CURIUM
(247.070)

97
Bk
BERKELIUM
(247.070)

98
Cf
CALIFORNIUM
(251.080)

99
Es
EINSTEINIUM
(252.083)

100
Fm
FERMIUM
(257.095)

101
Md
MENDELEVIUM
(258.098)

102
No
NOBELIUM
(259.101)

103
Lr
LAWRENCIUM
(262.110)

Atomic number

Element symbol

Element name

Relative atomic mass

Block

1
H
HYDROGEN
1.008

s block elements

p block elements

d block elements

f block elements

Groups of elements

© Andy Brunning/Compound Interest 2017 – www.compoundchem.com | Facebook: facebook.com/compoundchem | Twitter: [@compoundchem](https://twitter.com/compoundchem)
This graphic is shared under a Creative Commons 4.0 Attribution-NoDerivatives-NonCommercial licence.

3

Others

THE PERIODIC TABLE OF ELEMENTS

1

H

HYDROGEN

1.008

3

Li

LITHIUM

6.941

4

Be

BERYLLIUM

9.012

11

Na

SODIUM

22.990

12

Mg

MAGNESIUM

24.305

19

K

POTASSIUM

39.098

20

Ca

CALCIUM

40.078

21

Sc

SCANDIUM

44.956

22

Ti

TITANIUM

47.867

23

V

VANADIUM

50.942

24

Cr

CHROMIUM

51.996

25

Mn

MANGANESE

54.938

26

Fe

IRON

55.845

27

Co

COBALT

58.933

28

Ni

NICKEL

58.693

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

37

Rb

RUBIDIUM

85.468

38

Sr

STRONTIUM

87.620

39

Y

YTTRIUM

88.906

40

Zr

ZIRCONIUM

91.224

41

Nb

NIOBIUM

92.906

42

Mo

MOLYBDENUM

95.951

43

Tc

TECHNETIUM

(97.907)

44

Ru

RUTHENIUM

101.072

45

Rh

RHODIUM

102.906

46

Pd

PALLADIUM

106.421

47

Ag

SILVER

107.868

48

Cd

CADMIUM

112.414

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

55

Cs

CAESIUM

132.905

56

Ba

BARIUM

137.328

57-71

72

Hf

HAFNIUM

178.492

73

Ta

TANTALUM

180.948

74

W

TUNGSTEN

183.841

75

Re

RHENIUM

186.207

76

Os

OSMIUM

190.233

77

Ir

IRIDIUM

192.217

78

Pt

PLATINUM

195.084

79

Au

GOLD

196.967

80

Hg

MERCURY

200.592

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.210

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(208.982)

85

At

ASTATINE

(209.987)

86

Rn

RADON

(222.018)

87

Fr

FRANCIUM

(223.020)

88

Ra

RADIUM

(226.025)

E89-103

104

Rf

RUTHERFORDIUM

(261.109)

105

Db

DUBNIUM

(262.114)

106

Sg

SEABORGIUM

(266.122)

107

Bh

BOHRIUM

(264.120)

108

Hs

HASSIUM

(277.000)

109

Mt

MEITNERIUM

(268.139)

110

Ds

DARMSTADIUM

(281.000)

111

Rg

ROENTGIUM

(280.000)

112

Cn

COPECNICIUM

(285.000)

113

Nh

NIHONIUM

(286.000)

114

Fl

FLEROVIUM

(289.000)

115

Mc

MOSCOWIUM

(289.000)

116

Lv

LIVERMORIUM

(293.000)

117

Ts

TENNESSINE

(294.000)

118

Og

OGANESSON

(294.000)

Symbol Key

Atomic number

Element symbol

Element name

Relative atomic mass

Block

Colour Key

s block elements

p block elements

d block elements

f block elements

Groups of elements

s block elements

p block elements

d block elements

f block elements

2

He

HELIUM

4.003

5

B

BORON

10.811

6

C

CARBON

12.011

7

N

NITROGEN

14.007

8

O

OXYGEN

15.999

9

F

FLUORINE

18.998

10

Ne

NEON

20.180

13

Al

ALUMINIUM

26.982

14

Si

SILICON

28.086

15

P

PHOSPHORUS

30.974

16

S

SULFUR

32.065

17

Cl

CHLORINE

35.453

18

Ar

ARGON

39.948

26

Fe

IRON

55.845

27

Co

COBALT

58.933

28

Ni

NICKEL

58.693

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

44

Ru

RUTHENIUM

101.072

45

Rh

RHODIUM

102.906

46

Pd

PALLADIUM

106.421

47

Ag

SILVER

107.868

48

Cd

CADMIUM

112.414

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

62

Sm

SAMARIUM

150.362

63

Eu

EUROPIUM

151.964

64

Gd

GADOLINIUM

157.253

65

Tb

TERBIUM

158.925

66

Dy

DYSPROSIUM

162.500

67

Ho

HOLMIUM

164.930

68

Er

ERBIUM

167.259

69

Tm

THULIUM

168.934

70

Yb

YTTERBIUM

173.054

71

Lu

LUTETIUM

174.967

89

Ac

ACTINIUM

(227.028)

90

Th

THORIUM

(232.038)

91

Pa

PROTACTINIUM

(231.036)

92

U

URANIUM

(238.029)

93

Np

NEPTUNIUM

(237.048)

94

Pu

PLUTONIUM

(244.064)

95

Am

AMERICIUM

(243.061)

96

Cm

CURIUM

(247.070)

97

Bk

BERKELIUM

(247.070)

98

Cf

CALIFORNIUM

(251.080)

99

Es

EINSTEINIUM

(252.083)

100

Fm

FERMIUM

(257.095)

101

Md

MENDELEVIUM

(258.098)

102

No

NOBELIUM

(259.101)

103

Lr

LAWRENCIUM

(262.110)



© Andy Brunning/Compound Interest 2017 – www.compoundchem.com | Facebook: facebook.com/compoundchem | Twitter: @compoundchem
This graphic is shared under a Creative Commons 4.0 Attribution-NoDerivatives-NonCommercial licence.



Others

THE PERIODIC TABLE OF ELEMENTS

1

H

HYDROGEN

1.008

3

Li

LITHIUM

6.941

4

Be

BERYLLIUM

9.012

11

Na

SODIUM

22.990

12

Mg

MAGNESIUM

24.305

19

K

POTASSIUM

39.098

20

Ca

CALCIUM

40.078

21

Sc

SCANDIUM

44.956

22

Ti

TITANIUM

47.867

23

V

VANADIUM

50.942

24

Cr

CHROMIUM

51.996

25

Mn

MANGANESE

54.938

26

Fe

IRON

55.845

27

Co

COBALT

58.933

28

Ni

NICKEL

58.693

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

37

Rb

RUBIDIUM

85.468

38

Sr

STRONTIUM

87.620

39

Y

YTTRIUM

88.906

40

Zr

ZIRCONIUM

91.224

41

Nb

NIOBIUM

92.906

42

Mo

MOLYBDENUM

95.951

43

Tc

TECHNETIUM

(97.907)

44

Ru

RUTHENIUM

101.072

45

Rh

RHODIUM

102.906

46

Pd

PALLADIUM

106.421

47

Ag

SILVER

107.868

48

Cd

CADMIUM

112.414

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

55

Cs

CAESIUM

132.905

56

Ba

BARIUM

137.328

57-71

72

Hf

HAFNIUM

178.492

73

Ta

TANTALUM

180.948

74

W

TUNGSTEN

183.841

75

Re

RHENIUM

186.207

76

Os

OSMIUM

190.233

77

Ir

IRIDIUM

192.217

78

Pt

PLATINUM

195.084

79

Au

GOLD

196.967

80

Hg

MERCURY

200.592

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.210

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(208.982)

85

At

ASTATINE

(209.987)

86

Rn

RADON

(222.018)

87

Fr

FRANCIUM

(223.020)

88

Ra

RADIUM

(226.025)

E89-103

104

Rf

RUTHERFORDIUM

(261.109)

105

Db

DUBNIUM

(262.114)

106

Sg

SEABORGIUM

(266.122)

107

Bh

BOHRIUM

(264.120)

108

Hs

HASSIUM

(277.000)

109

Mt

MEITNERIUM

(268.139)

110

Ds

DARMSTADIUM

(281.000)

111

Rg

ROENTGENIUM

(280.000)

112

Cn

COPECNICIUM

(285.000)

113

Nh

NIHONIUM

(286.000)

114

Fl

FLEROVIUM

(289.000)

115

Mc

MOSCOWIUM

(289.000)

116

Lv

LIVERMORIUM

(293.000)

117

Ts

TENNESSINE

(294.000)

118

Og

OGANESSON

(294.000)

Symbol Key

Atomic number

Element symbol

Element name

Relative atomic mass

Block

Colour Key

s block elements

p block elements

d block elements

f block elements

2

He

HELIUM

4.003

5

B

BORON

10.811

6

C

CARBON

12.011

7

N

NITROGEN

14.007

8

O

OXYGEN

15.999

9

F

FLUORINE

18.998

10

Ne

NEON

20.180

13

Al

ALUMINIUM

26.982

14

Si

SILICON

28.086

15

P

PHOSPHORUS

30.974

16

S

SULFUR

32.065

17

Cl

CHLORINE

35.453

18

Ar

ARGON

39.948

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.210

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(208.982)

85

At

ASTATINE

(209.987)

86

Rn

RADON

(222.018)

113

Nh

NIHONIUM

(286.000)

114

Fl

FLEROVIUM

(289.000)

115

Mc

MOSCOWIUM

(289.000)

116

Lv

LIVERMORIUM

(293.000)

117

Ts

TENNESSINE

(294.000)

118

Og

OGANESSON

(294.000)

57

La

LANTHANUM

138.905

58

Ce

CERIUM

140.116

59

Pr

PRASEODYMIUM

140.908

60

Nd

NEODYMIUM

144.242

61

Pm

PROMETHIUM

(144.000)

62

Sm

SAMARIUM

150.362

63

Eu

EUROPIUM

151.964

64

Gd

GADOLINIUM

157.253

65

Tb

TERBIUM

158.925

66

Dy

DYSPROSIUM

162.500

67

Ho

HOLMIUM

164.930

68

Er

ERBIUM

167.259

69

Tm

THULIUM

168.934

70

Yb

YTTERBIUM

173.054

71

Lu

LUTETIUM

174.967

89

Ac

ACTINIUM

(227.028)

90

Th

THORIUM

(232.038)

91

Pa

PROTACTINIUM

(231.036)

92

U

URANIUM

(238.029)

93

Np

NEPTUNIUM

(237.048)

94

Pu

PLUTONIUM

(244.064)

95

Am

AMERICIUM

(243.061)

96

Cm

CURIUM

(247.070)

97

Bk

BERKELIUM

(247.070)

98

Cf

CALIFORNIUM

(251.080)

99

Es

EINSTEINIUM

(252.083)

100

Fm

FERMIUM

(257.095)

101

Md

MENDELEVIUM

(258.098)

102

No

NOBELIUM

(259.101)

103

Lr

LAWRENCIUM

(262.110)



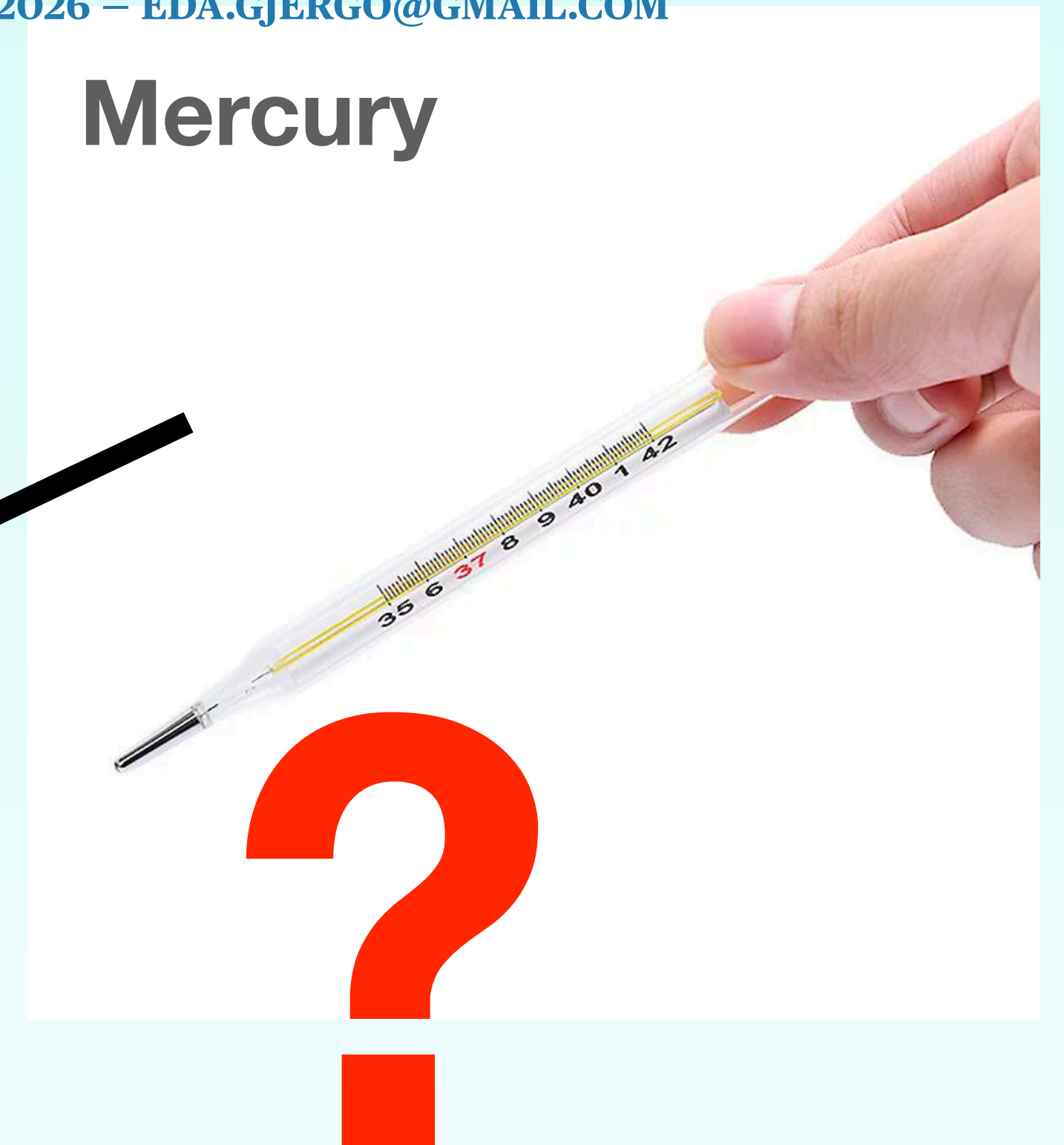
© Andy Brunning/Compound Interest 2017 – www.compoundchem.com | Facebook: facebook.com/compoundchem | Twitter: @compoundchem
This graphic is shared under a Creative Commons 4.0 Attribution-NoDerivatives-NonCommercial licence.



Copper



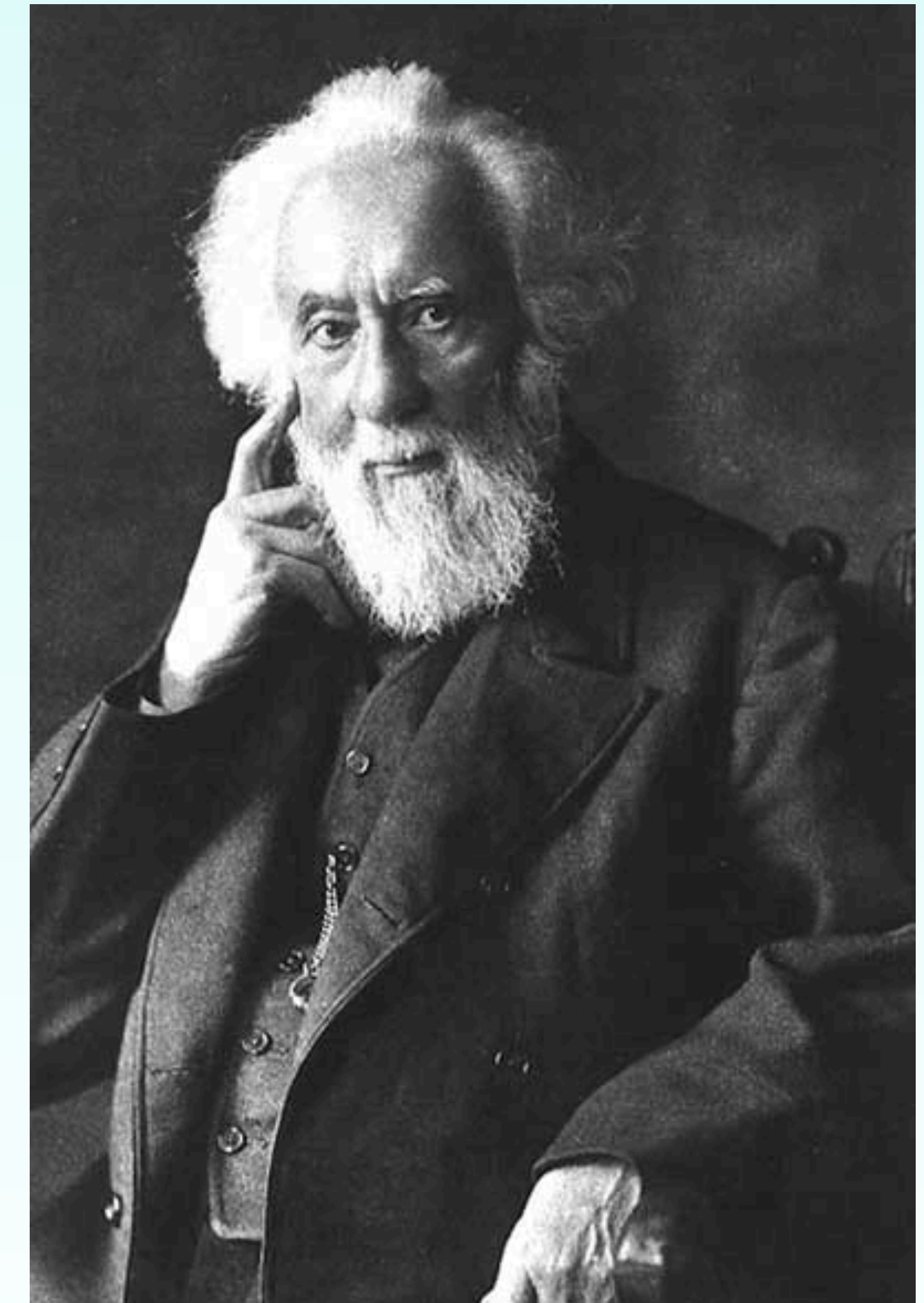
Mercury



Phosphorous

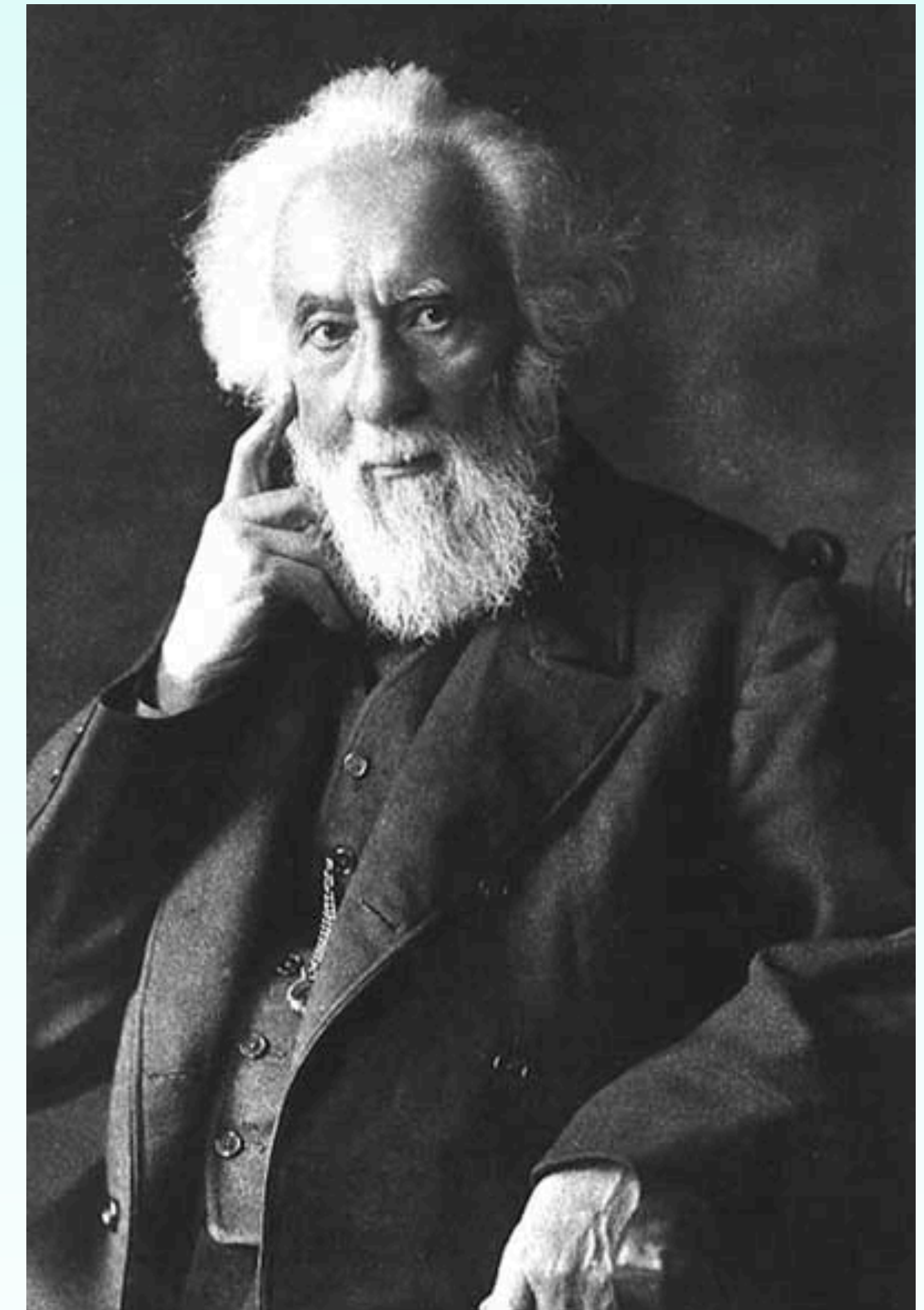
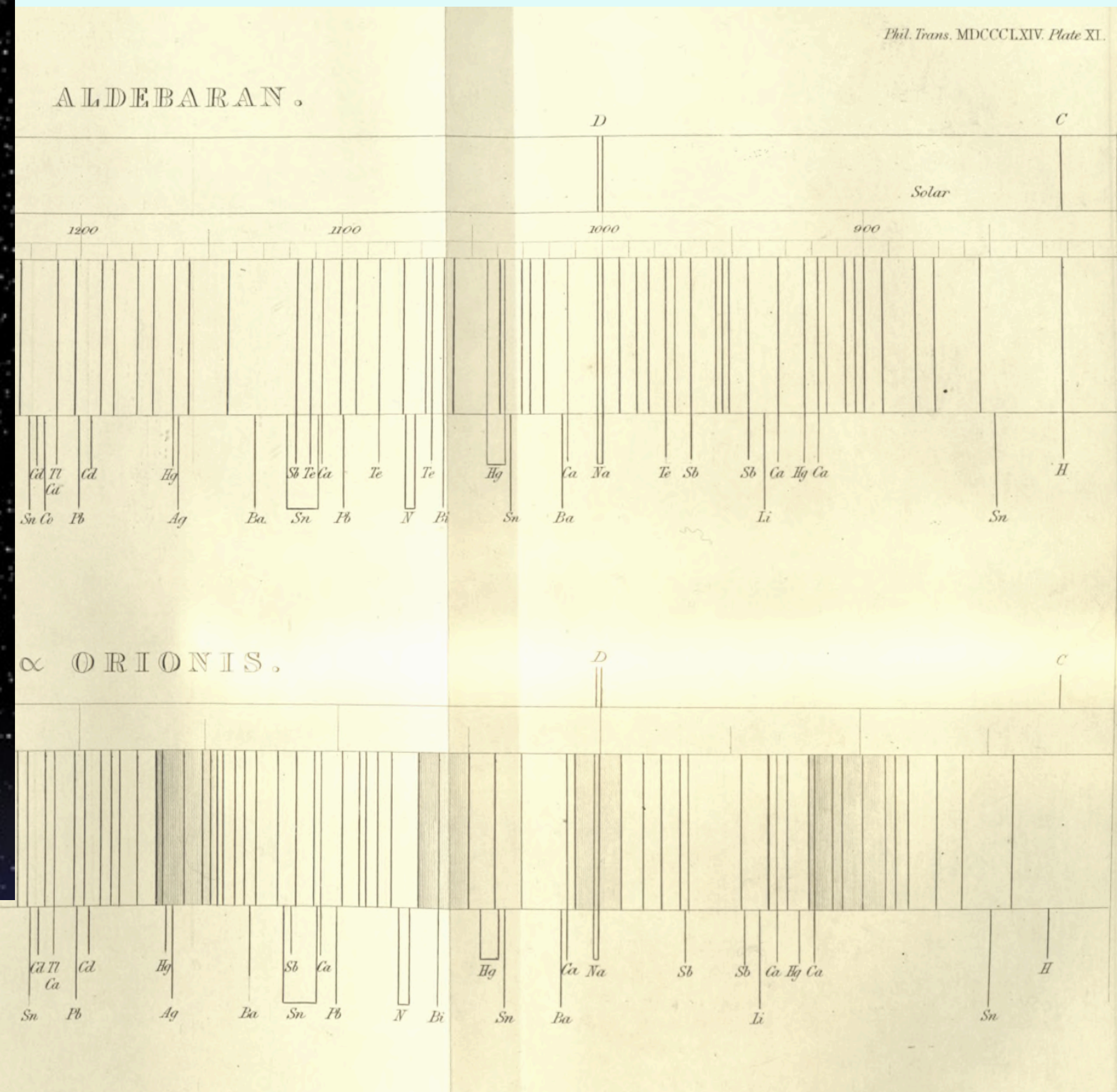


Uranium



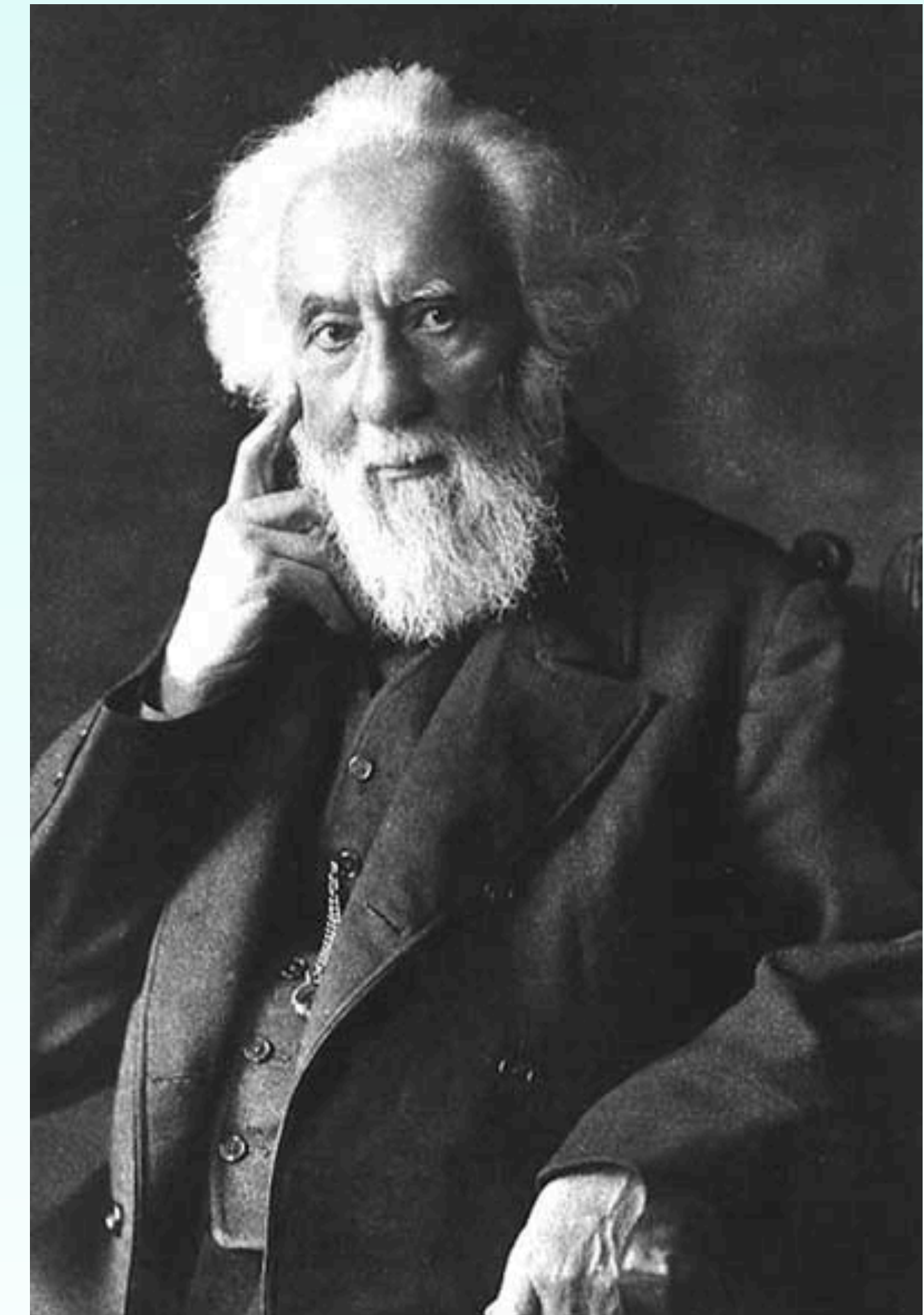
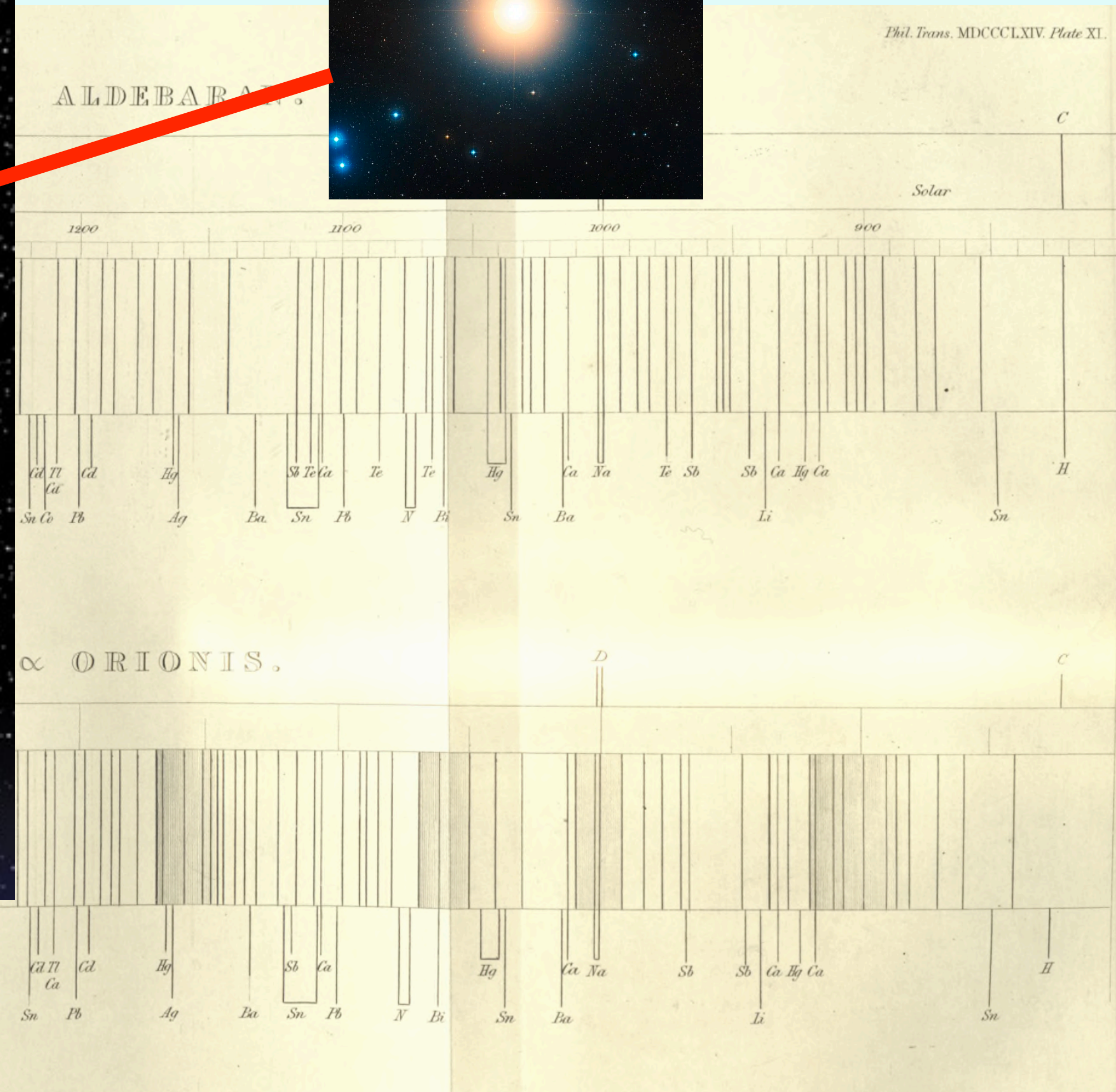
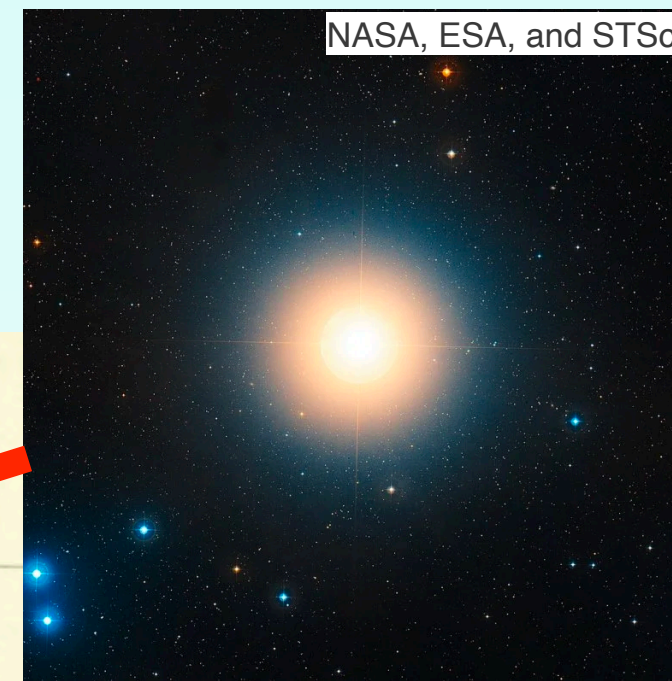
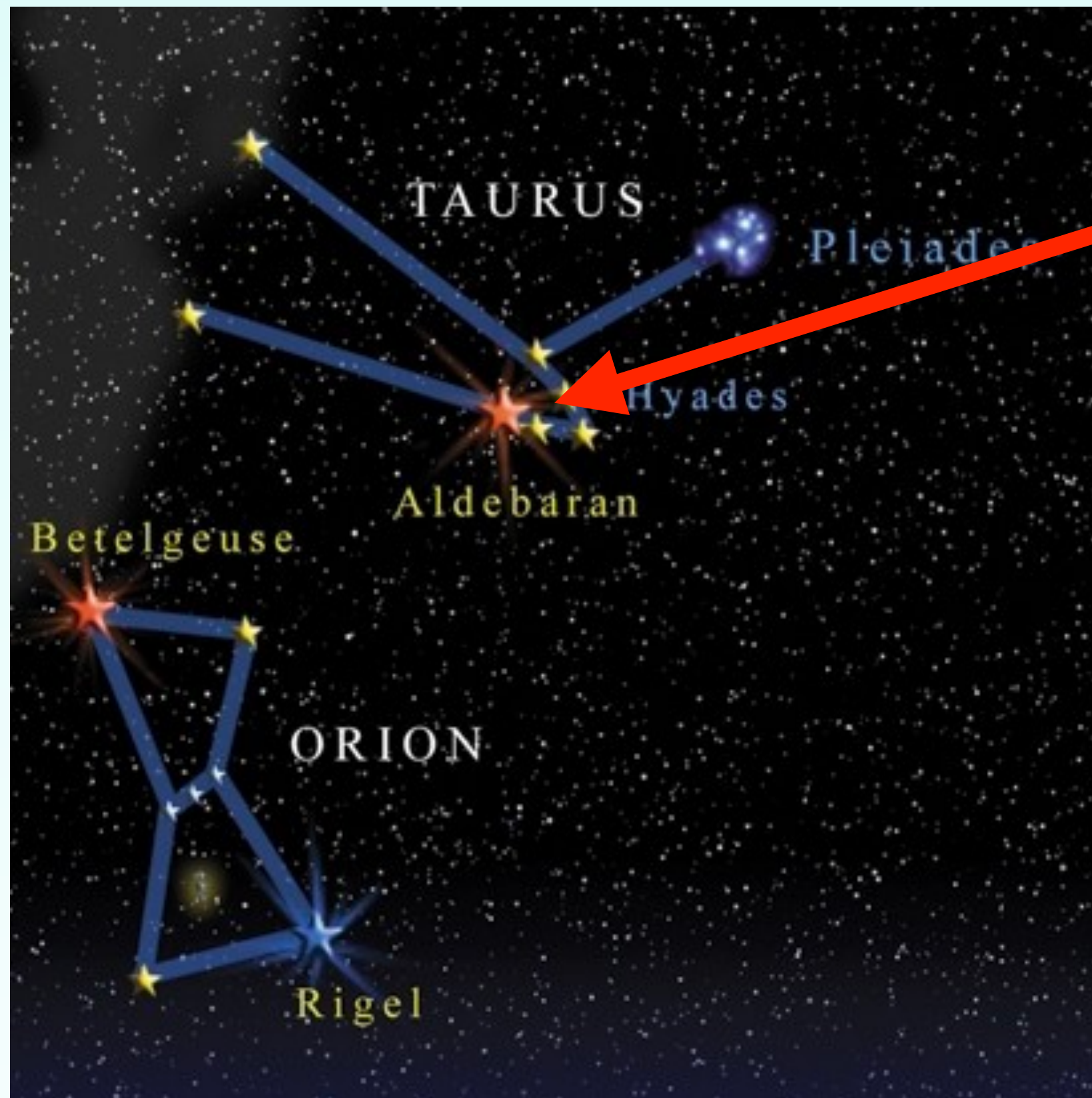
Sir William Huggins
(7 February 1824 – 12 May 1910)

XIII. On the spectra of some of the nebulæ.



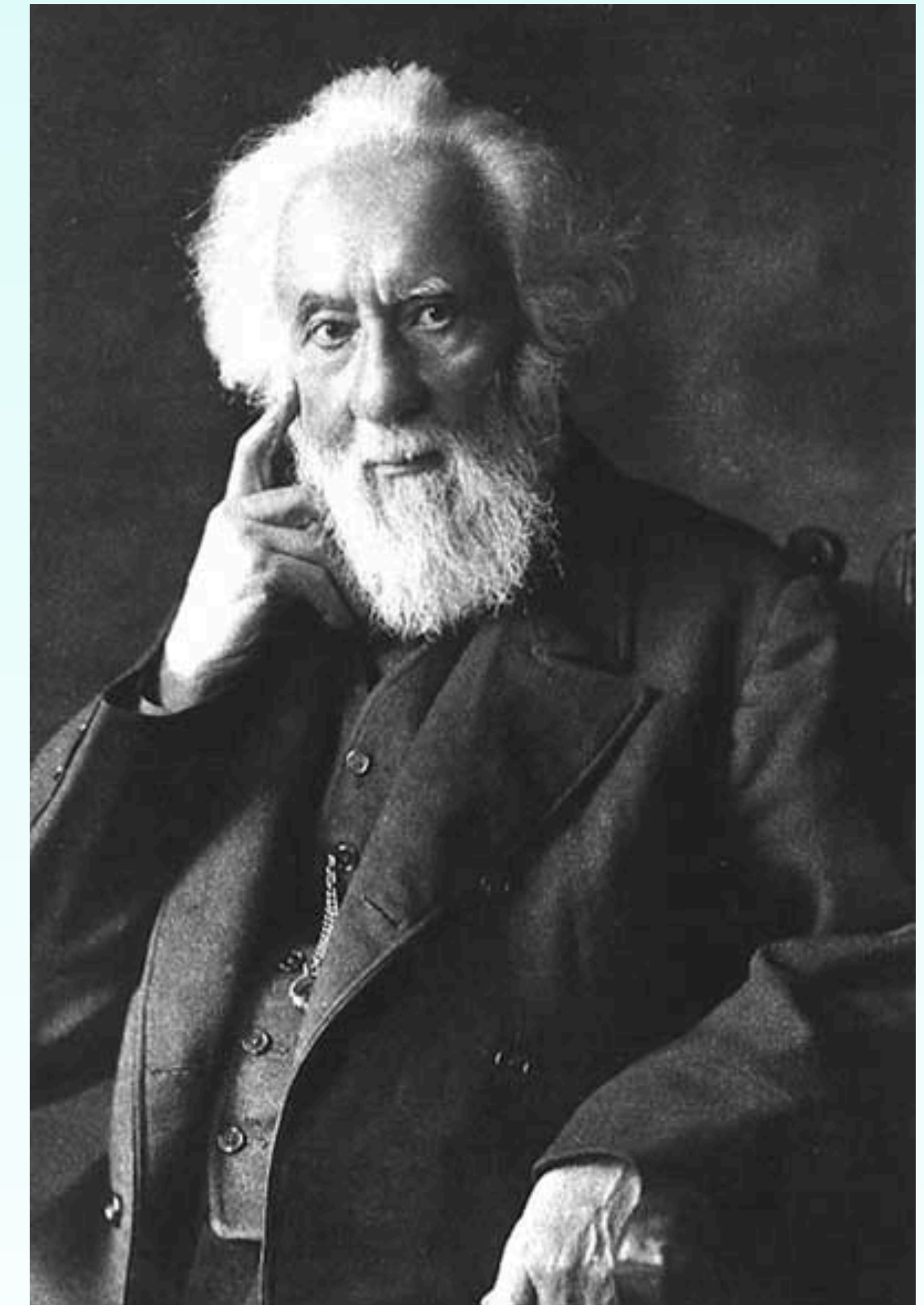
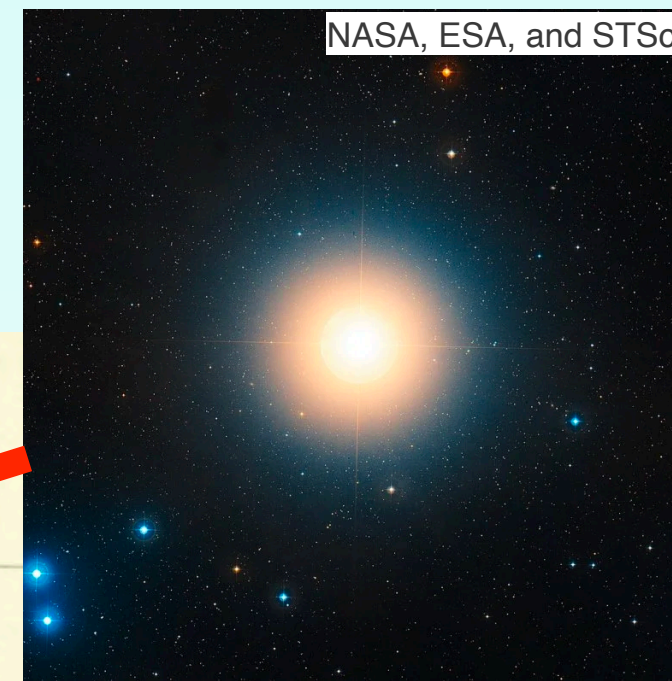
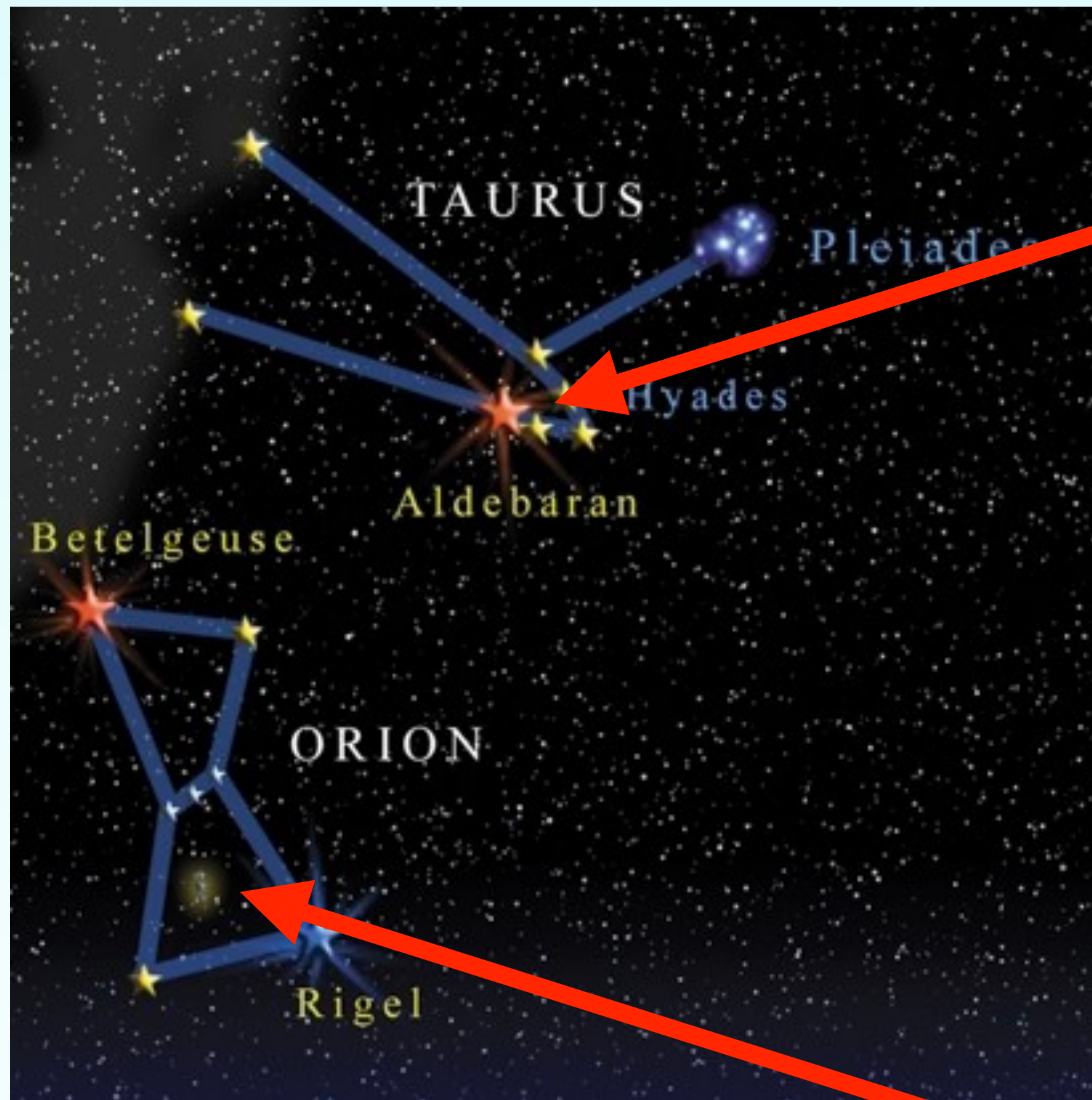
Sir William Huggins
(7 February 1824 – 12 May 1910)

XIII. On the spectra of some of the nebulae.



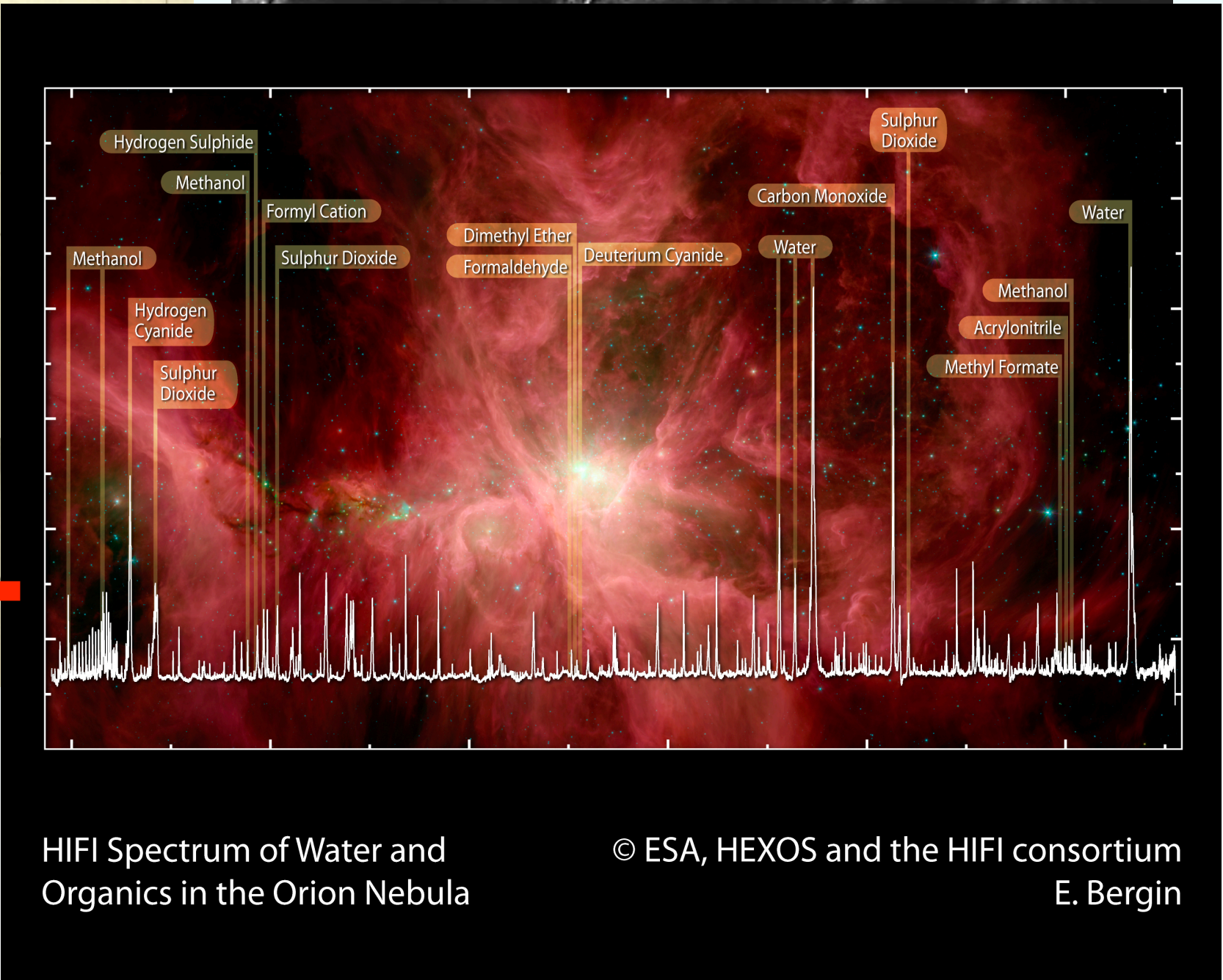
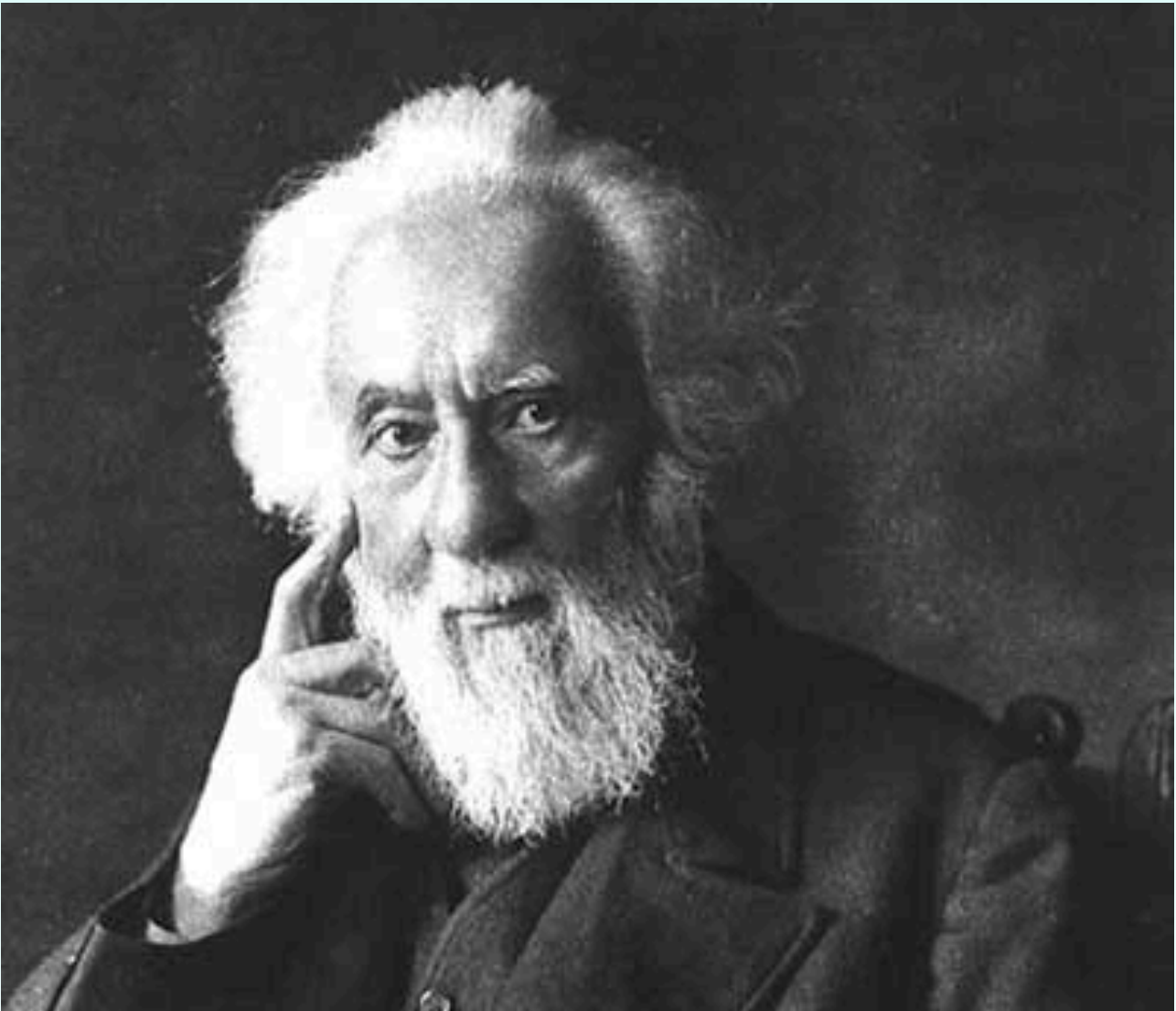
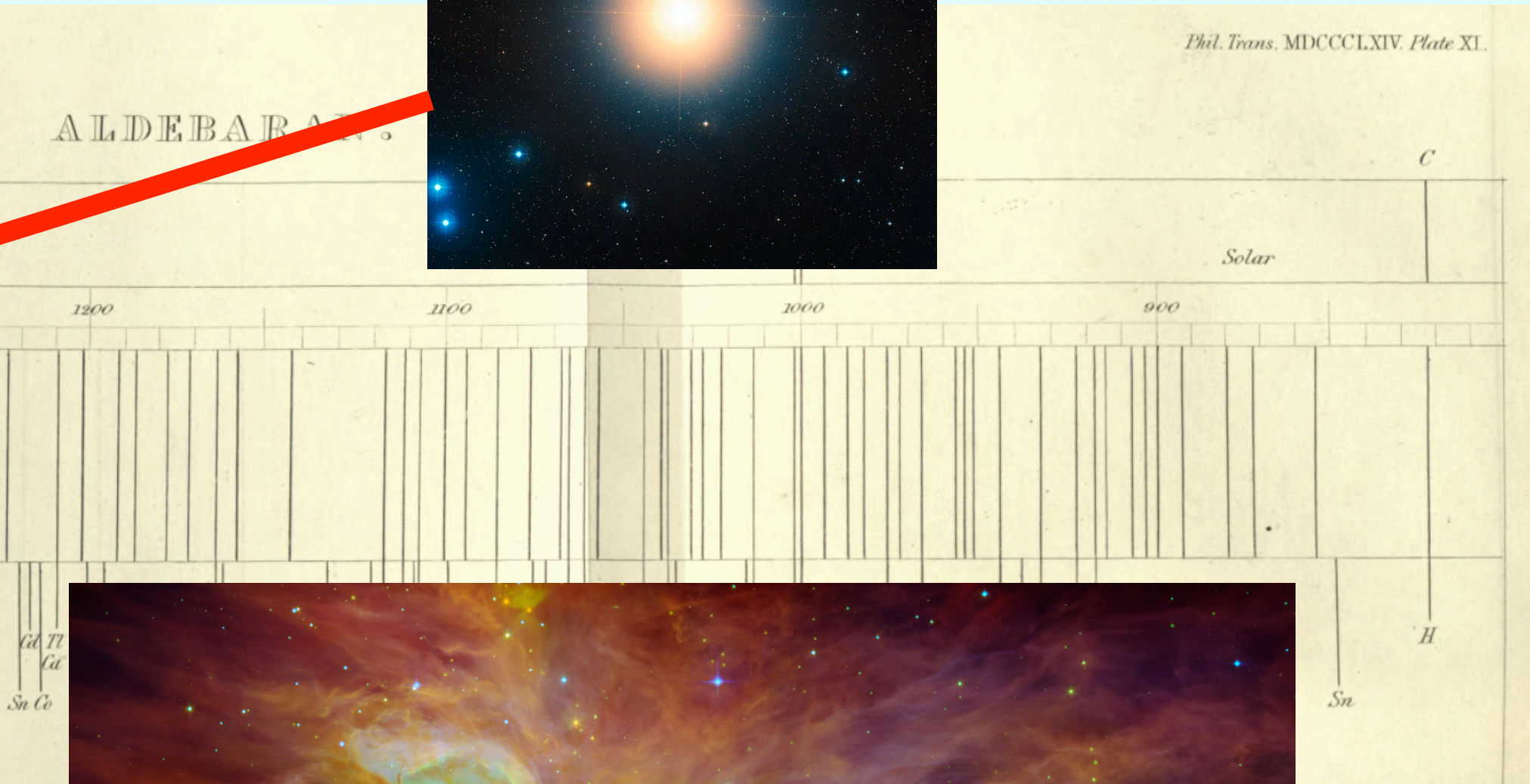
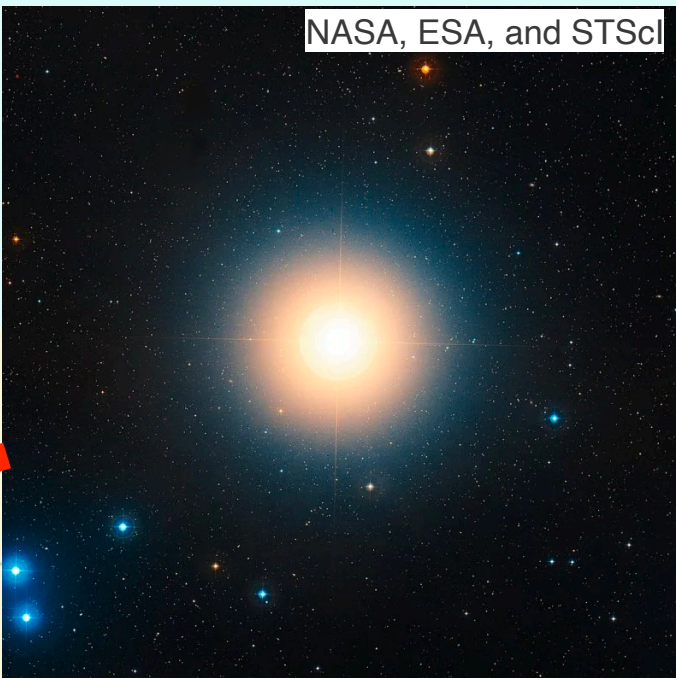
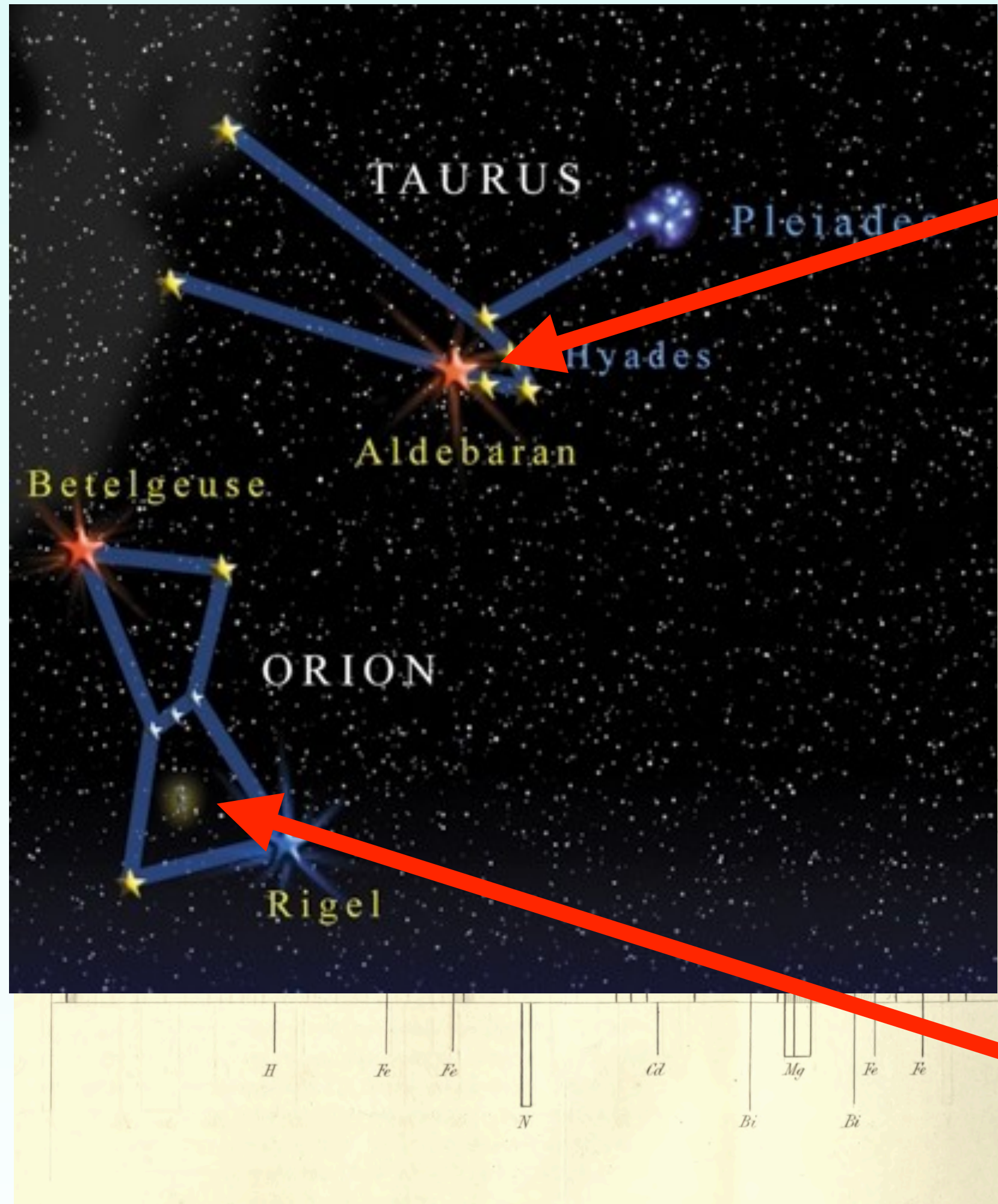
Sir William Huggins
(7 February 1824 – 12 May 1910)

XIII. On the spectra of some of the nebulae.

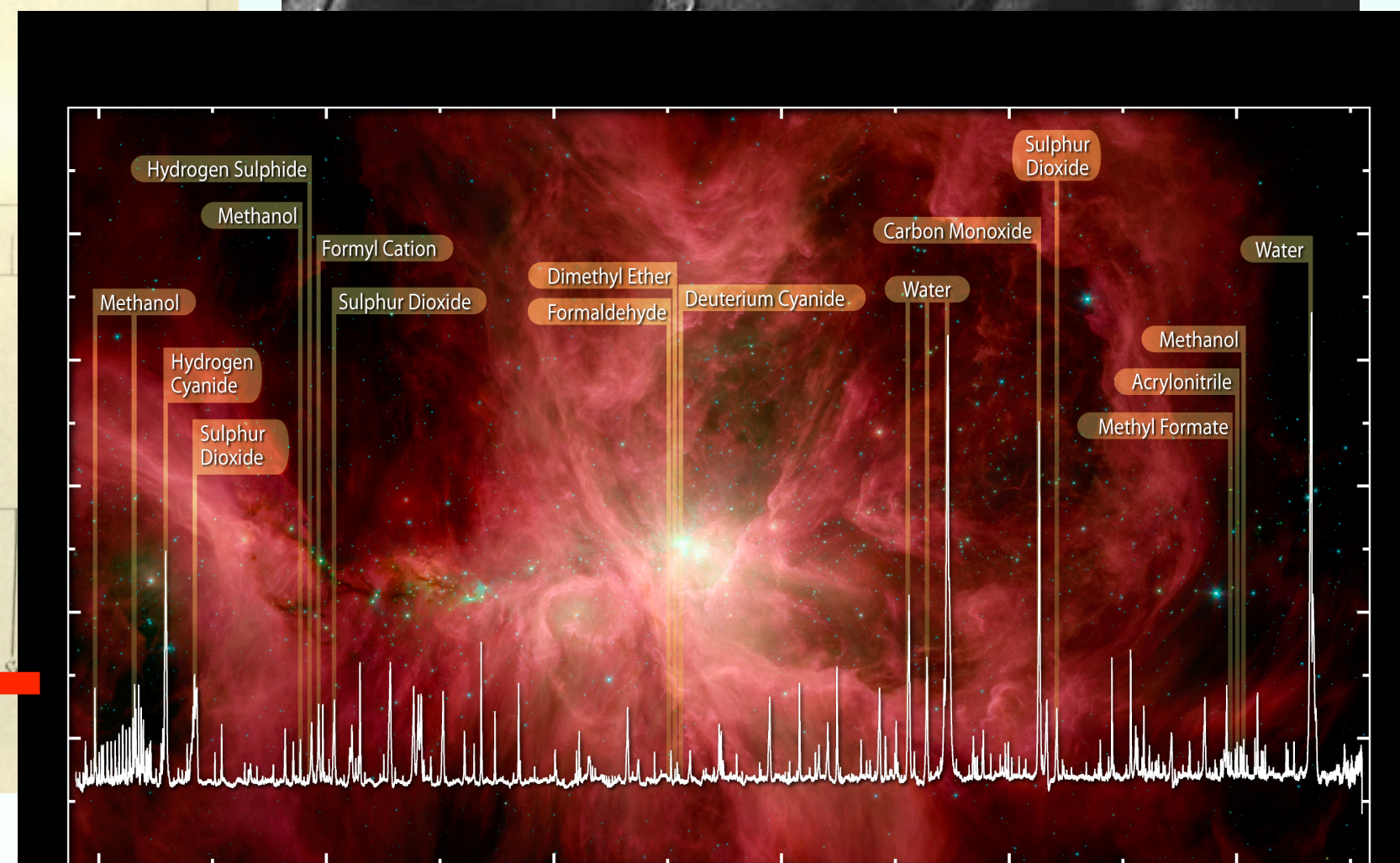
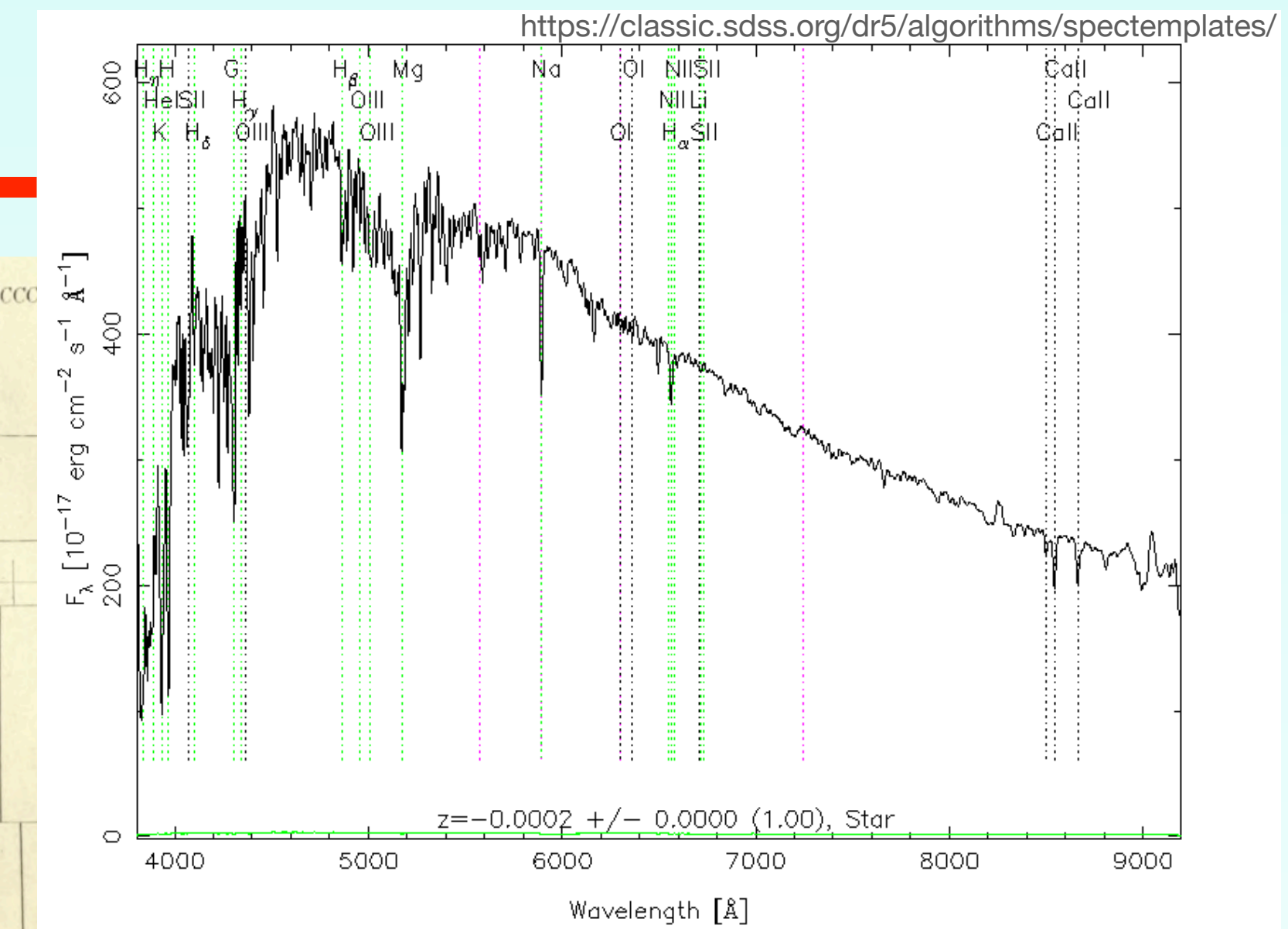
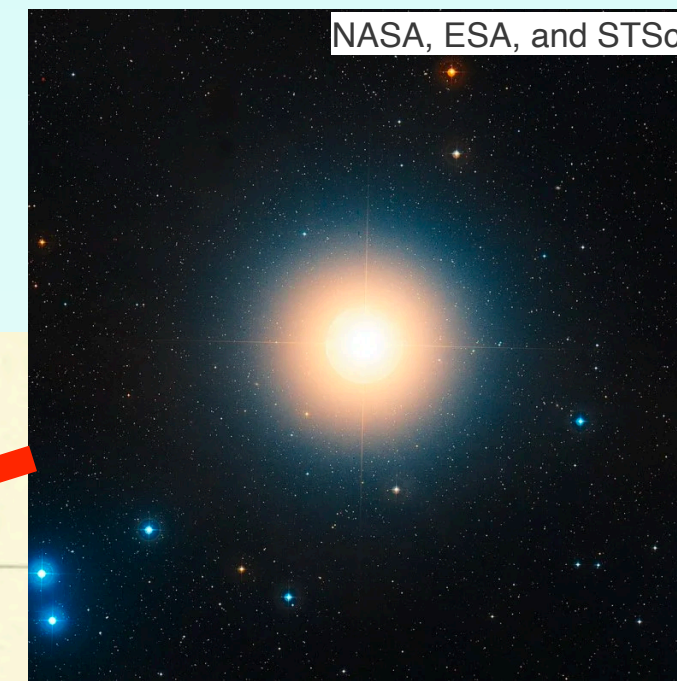
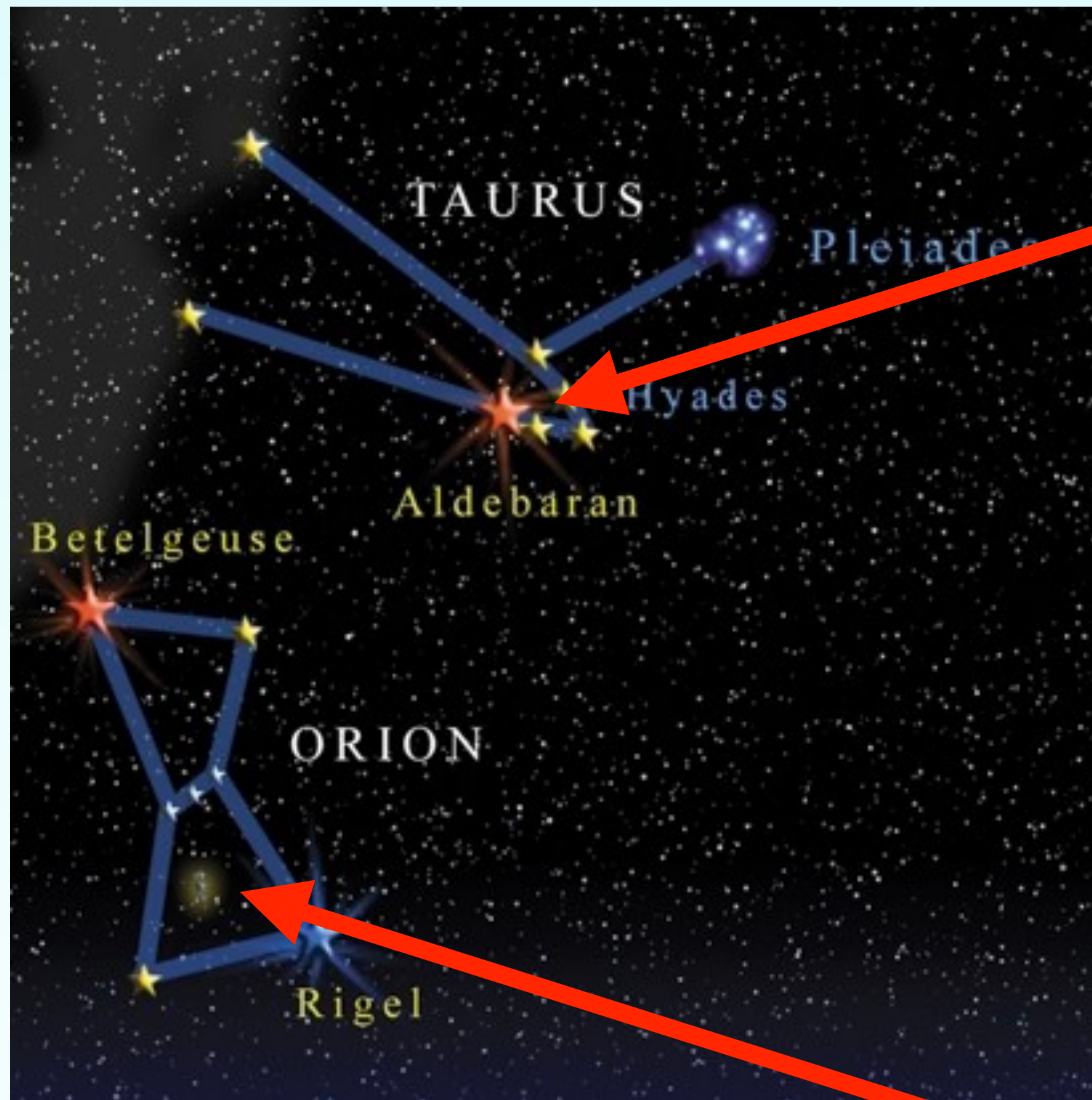


Sir William Huggins
(7 February 1824 – 12 May 1910)

XIII. On the spectra of



XIII. On the spectra of



HIFI Spectrum of Water and Organics in the Orion Nebula

© ESA, HEXOS and the HIFI consortium
E. Bergin

XIII. On the spectra of

Sir William Huggins is also responsible for
Discovering the following element.

Sir William Huggins is also responsible for
Discovering the following element.

Nebulium

云 yún (cloud) + 气 qì (gas)

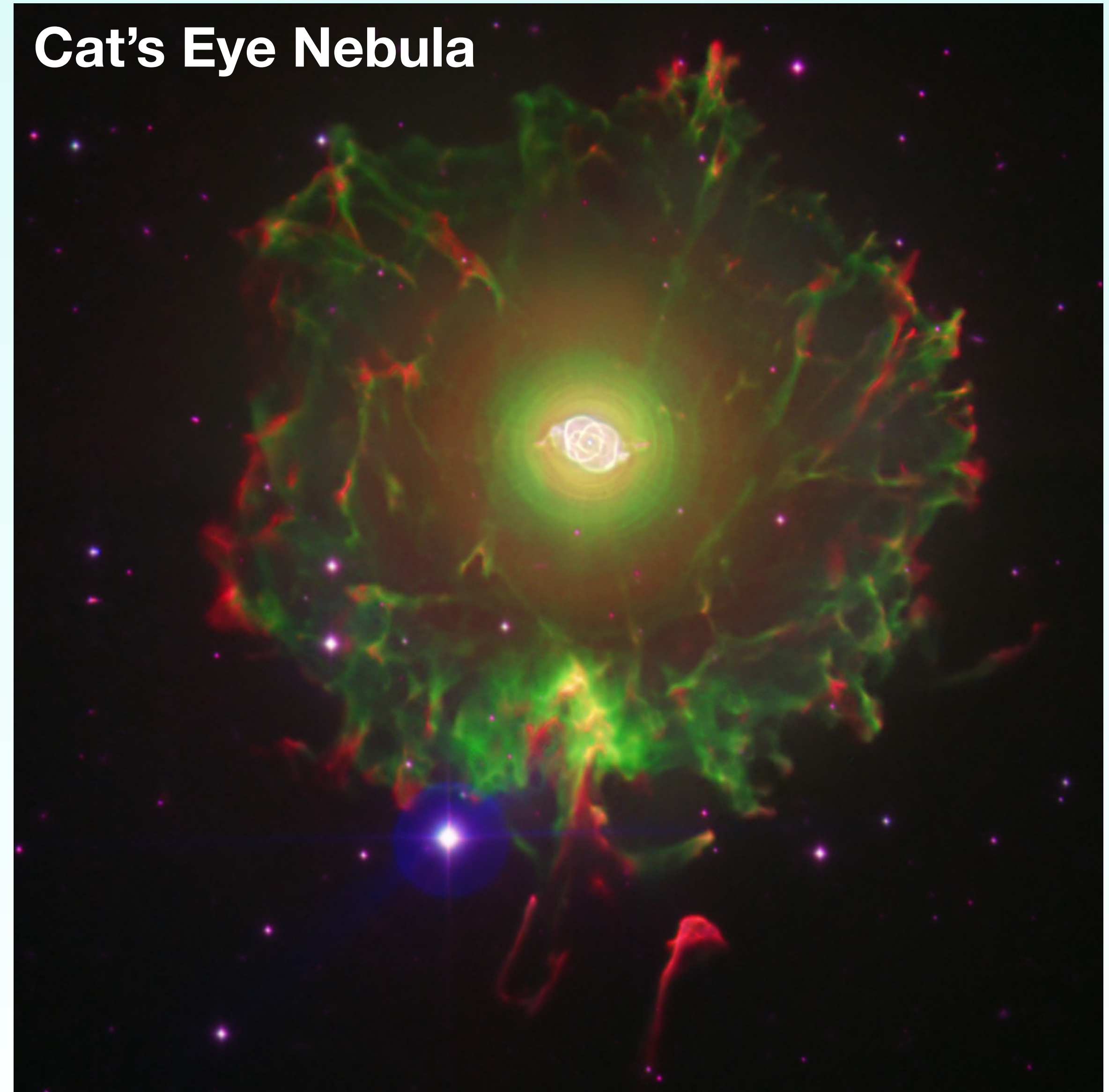


氮

Nebulium

It would be a convenience if a name were chosen for the as yet undiscovered gas, which is suggested by the typical bright nebular lines, as a principal constituent of the nebulae. Sir William Huggins has used occasionally the term *nebulium*. MARGARET. L. HUGGINS.

Cat's Eye Nebula



Wide Field Camera on the Isaac Newton Telescope
D. López and R. Barrena (IAC)

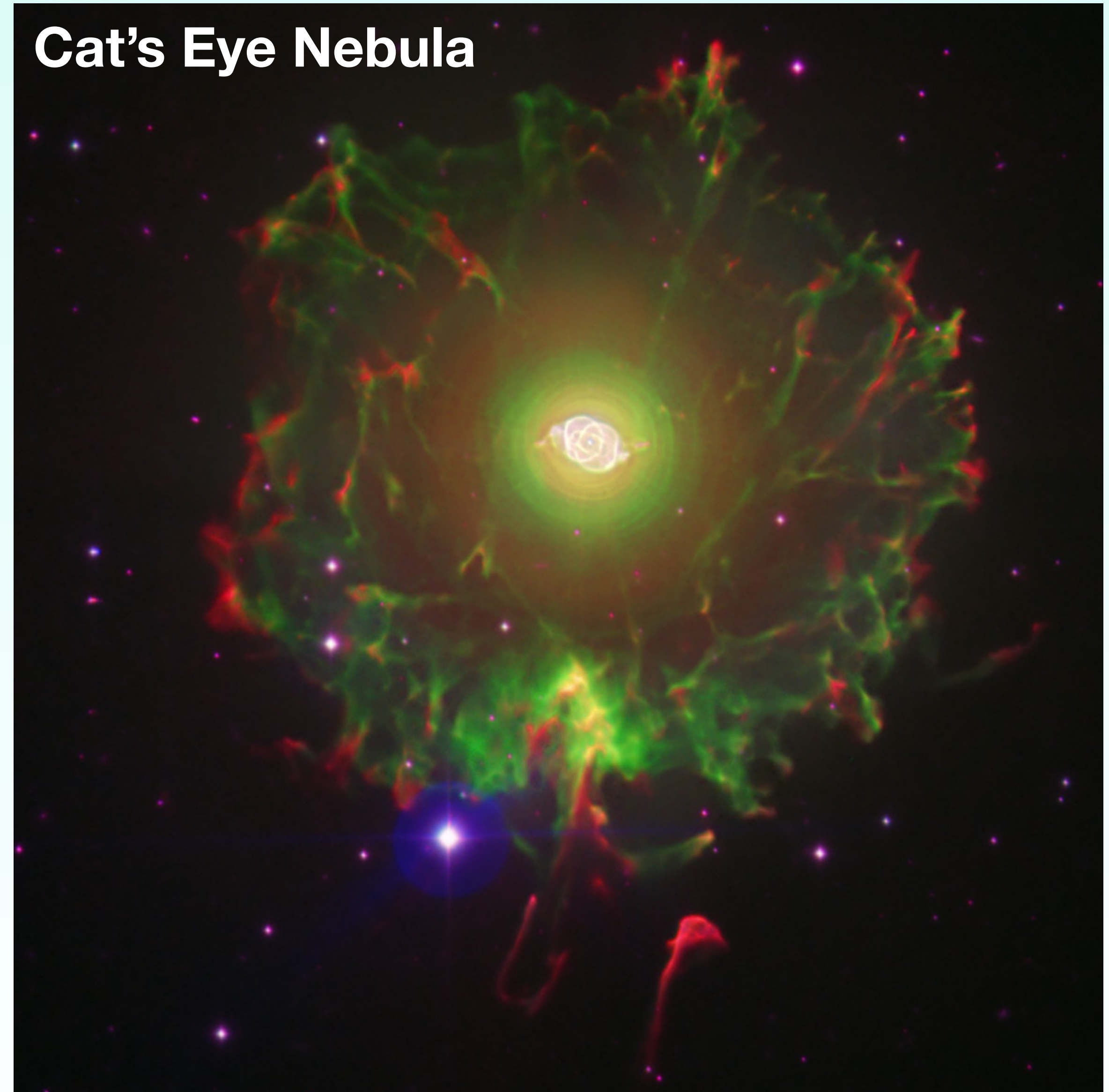
氦

Nebulium

It would be a convenience if a name were chosen for the as yet undiscovered gas, which is suggested by the typical bright nebular lines, as a principal constituent of the nebulae. Sir William Huggins has used occasionally the term *nebulium*. MARGARET. L. HUGGINS.

What was known of elements at this time?

Cat's Eye Nebula



Wide Field Camera on the Isaac Newton Telescope
D. López and R. Barrena (IAC)

Periodic table at Dmitri Mendeleev's time



1870

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

	Ti = 50	Zr = 90	? = 180.
	V = 51	Nb = 94	Ta = 182.
	Cr = 52	Mo = 96	W = 186.
	Mn = 55	Rh = 104,4	Pt = 197,1.
	Fe = 56	Ru = 104,4	Ir = 198.
	Ni = 59	Pd = 106,8	Os = 199.
H = 1	Cu = 63,4	Ag = 108	Hg = 200.
Be = 9,1	Mg = 24	Zn = 65,2	Cd = 112
B = 11	Al = 27,1	? = 68	U = 116 Au = 197?
C = 12	Si = 28	? = 70	Sn = 118
N = 14	P = 31	As = 75	Sb = 122 Bi = 210?
O = 16	S = 32	Se = 79,4	Te = 128?
F = 19	Cl = 35,5	Br = 80	I = 127
Li = 7	Na = 23	K = 39	Rb = 85,4 Cs = 133 Tl = 204.
		Ca = 40	Sr = 87,6 Ba = 137 Pb = 207.
		? = 45	Ce = 92
		?Er = 56	La = 94
		?Yt = 60	Di = 95
		?In = 75,6	Th = 118?

Д. Менделѣевъ

Periodic table at Dmitri Mendeleev's time

THE PERIODIC TABLE OF ELEMENTS

1

H

HYDROGEN

1.008

3

Li

LITHIUM

6.941

4

Be

BERYLLIUM

9.012

11

Na

SODIUM

22.990

12

Mg

MAGNESIUM

24.305

19

K

POTASSIUM

39.098

20

Ca

CALCIUM

40.078

21

Sc

SCANDIUM

44.956

22

Ti

TITANIUM

47.867

23

V

VANADIUM

50.942

24

Cr

CHROMIUM

51.996

25

Mn

MANGANESE

54.938

26

Fe

IRON

55.845

27

Co

COBALT

58.933

28

Ni

NICKEL

58.693

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.971

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

37

Rb

RUBIDIUM

85.468

38

Sr

STRONTIUM

87.620

39

Y

YTRIUM

88.906

40

Zr

ZIRCONIUM

91.224

41

Nb

NIOBIUM

92.906

42

Mo

MOLYBDENUM

95.951

43

Tc

TECHNETIUM

(97.907)

44

Ru

RUTHENIUM

101.072

45

Rh

RHODIUM

102.906

46

Pd

PALLADIUM

106.421

47

Ag

SILVER

107.868

48

Cd

CADMIUM

112.414

49

In

INDIUM

114.818

50

Sn

TIN

118.711

51

Sb

ANTIMONY

121.760

52

Te

TELLURIUM

127.603

53

I

IODINE

126.904

54

Xe

XENON

131.294

55

Cs

CAESIUM

132.905

56

Ba

BARIUM

137.328

E57-71

72

Hf

HAFNIUM

178.492

73

Ta

TANTALUM

180.948

74

W

TUNGSTEN

183.841

75

Re

RHENIUM

186.207

76

Os

OSMIUM

190.233

77

Ir

IRIDIUM

192.217

78

Pt

PLATINUM

195.084

79

Au

GOLD

196.967

80

Hg

MERCURY

200.592

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.210

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(209.982)

85

At

ASTATINE

(209.987)

86

Rn

RADON

(222.018)

87

Fr

FRANCIUM

(223.020)

88

Ra

RADIUM

(226.025)

E89-103

104

Rf

RUTHERFORDIUM

(261.109)

105

Db

DUBNIUM

(262.114)

106

Sg

SEABORGIUM

(266.122)

107

Bh

BOHRIUM

(264.120)

108

Hs

HASSIUM

(277.000)

109

Mt

MEITNERIUM

(268.139)

110

Ds

DARMSTADIUM

(281.000)

111

Rg

ROENTGIUM

(280.000)

112

Cn

COPECNICIUM

(285.000)

113

Nh

NIHONIUM

(286.000)

114

Fl

FLEROVIUM

(289.000)

115

Mc

MOSCOWIUM

(289.000)

116

Lv

LIVERMORIUM

(293.000)

117

Ts

TENNESSINE

(294.000)

118

Og

OGANESSON

(294.000)

Symbol Key

Atomic number

Element symbol

Element name

Relative atomic mass

Block

Colour Key

s block elements

p block elements

d block elements

f block elements

2

He

HELIUM

4.005

10

Ne

NEON

20.180

18

Ar

ARGON

39.948

36

Kr

KRYPTON

83.798

54

Xe

XENON

131.294

86

Rn

RADON

(222.018)

118

Og

OGANESSON

(294.000)

57

La

LANTHANUM

138.905

58

Ce

CERIUM

140.116

59

Pr

PRASEODYMIUM

140.908

60

Nd

NEODYMIUM

144.242

61

Pm

PROMETHIUM

(144.000)

62

Sm

SAMARIUM

150.362

63

Eu

EUROPIUM

151.964

64

Gd

GADOLINIUM

157.253

65

Tb

TERBIUM

158.925

66

Dy

DYSPROSIUM

162.500

67

Ho

HOLMIUM

164.930

68

Er

ERBIUM

167.259

69

Tm

THULIUM

168.934

70

Yb

YTTERBIUM

173.054

71

Lu

LUTECIUM

174.967

89

Ac

ACTINIUM

(227.028)

90

Th

THORIUM

(232.038)

91

Pa

PROTACTINIUM

(231.036)

92

U

URANIUM

(238.029)

93

Np

NEPTUNIUM

(237.048)

94

Pu

PLUTONIUM

(244.064)

95

Am

AMERICIUM

(243.061)

96

Cm

CURIUM

(247.070)

97

Bk

BERKELIUM

(247.070)

98

Cf

CALIFORNIUM

(251.080)

99

Es

EINSTEINIUM

(252.083)

100

Fm

FERMIUM

(257.095)

101

Md

MENDELEVIVM

(258.096)

102

No

NOBELIUM

(259.101)

103

Lr

LAWRENCIUM

(262.110)

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

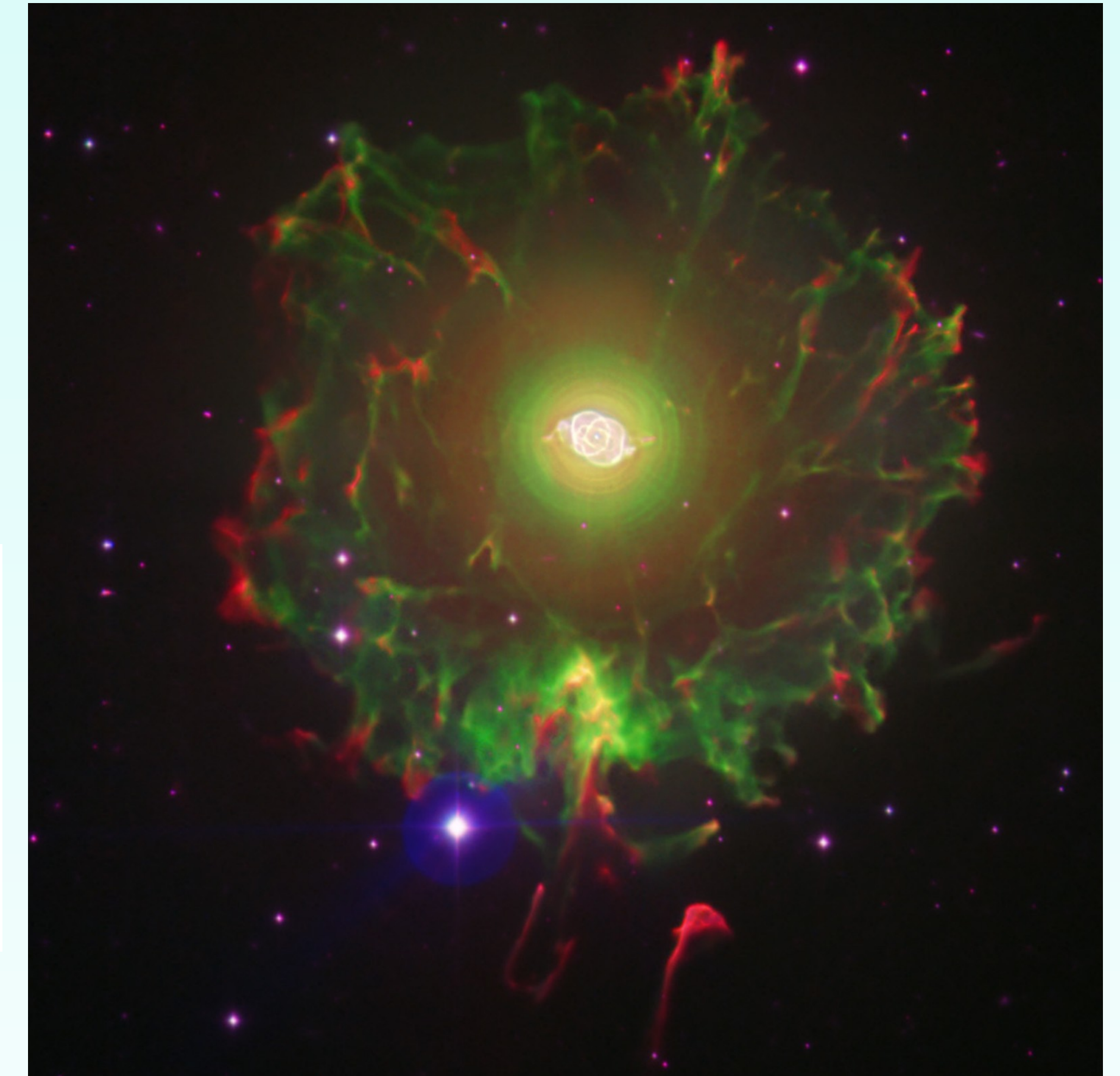
ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

H = 1

Ti = 50	Zr = 90	? = 180.
V = 51	Nb = 94	Ta = 182.
Cr = 52	Mo = 96	W = 186.
Mn = 55	Rh = 104,4	Pt = 197,1.
Fe = 56	Ru = 104,4	Ir = 198.
Ni = Co = 59	Pd = 106,8	Os = 199.
Cu = 63,4	Ag = 108	Hg = 200.
Be = 9,1	Mg = 24	Zn = 65,2
B = 11	Al = 27,1	? = 68
C = 12	Si = 28	? = 70
N = 14	P = 31	As = 75
O = 16	S = 32	Se = 79,1
F = 19	Cl = 35,5	Br = 80
Li = 7	Na = 23	K = 39
		Rb = 85,4
		Cs = 133
		Ca = 40
		Sr = 87,6
		Ba = 137
		? = 45
		Ce = 92
		?Er = 56
		La = 94
		?Yt = 60
		Di = 95
		?In = 75,6
		Th = 118?

Nature,
v. 120, p. 473 (1927)

λ .	Source.	Series Designation.
7325.0	O _{II}	$^2D - ^2P$
6583.6	N _{II}	$^3P_2 - ^1D$
6548.1	N _{II}	$^3P_1 - ^1D$
5006.84	O _{III}	$^3P_2 - ^1D$
4958.91	O _{III}	$^3P_1 - ^1D$
4363.21	O _{III}	$^1D - ^1S$
3728.91	O _{II}	$^4S - ^2D_3$
3726.16	O _{II}	$^4S - ^2D_2$



namely, $^1D - ^1S$ of O_{III} and $^2D - ^2P$ of O_{II}. The calculated frequencies, if unresolved, are 22916 and 13646, which correspond to wave-lengths of 4362.54 Å.U. and 7326.2 Å.U. respectively. Two of the strongest nebular lines are found at 4363.21 Å.U. and 7325 Å.U. These deviations are well within the rather large experimental errors arising from the fact that the

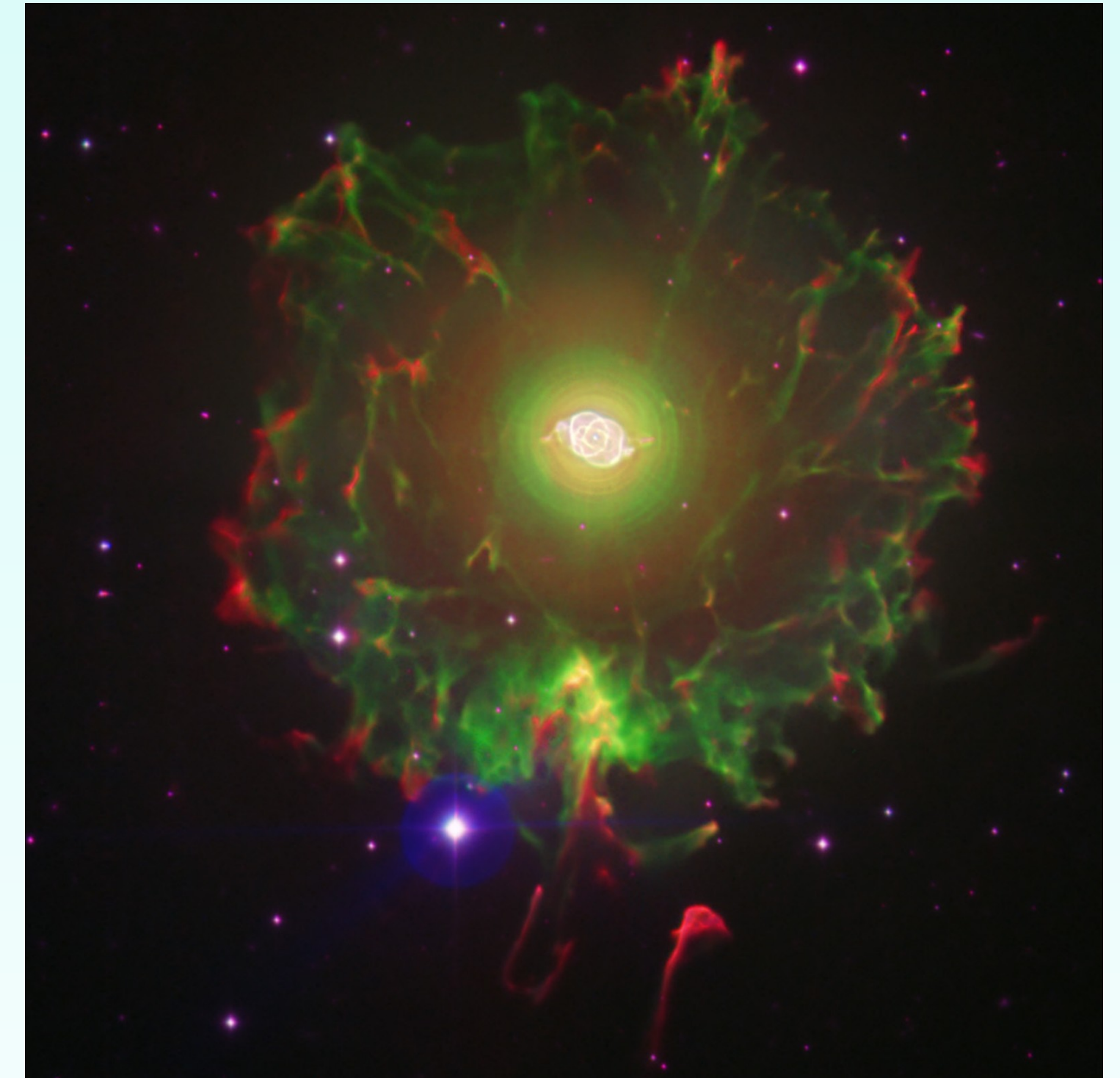
Ira Sprague Bowen

Nature,
v. 120, p. 473 (1927)

TABLE I.

λ .	Source.	Series Designation.
7325.0	O _{II}	$^2D - ^2P$
6583.6	N _{II}	$^3P_2 - ^1D$
6548.1	N _{II}	$^3P_1 - ^1D$
5006.84	O _{III}	$^3P_2 - ^1D$
4958.91	O _{III}	$^3P_1 - ^1D$
4363.21	O _{III}	$^1D - ^1S$
3728.91	O _{II}	$^4S - ^2D_3$
3726.16	O _{II}	$^4S - ^2D_2$

namely, $^1D - ^1S$ of O_{III} and $^2D - ^2P$ of O_{II}. The calculated frequencies, if unresolved, are 22916 and 13646, which correspond to wave-lengths of 4362.54 Å.U. and 7326.2 Å.U. respectively. Two of the strongest nebular lines are found at 4363.21 Å.U. and 7325 Å.U. These deviations are well within the rather large experimental errors arising from the fact that the



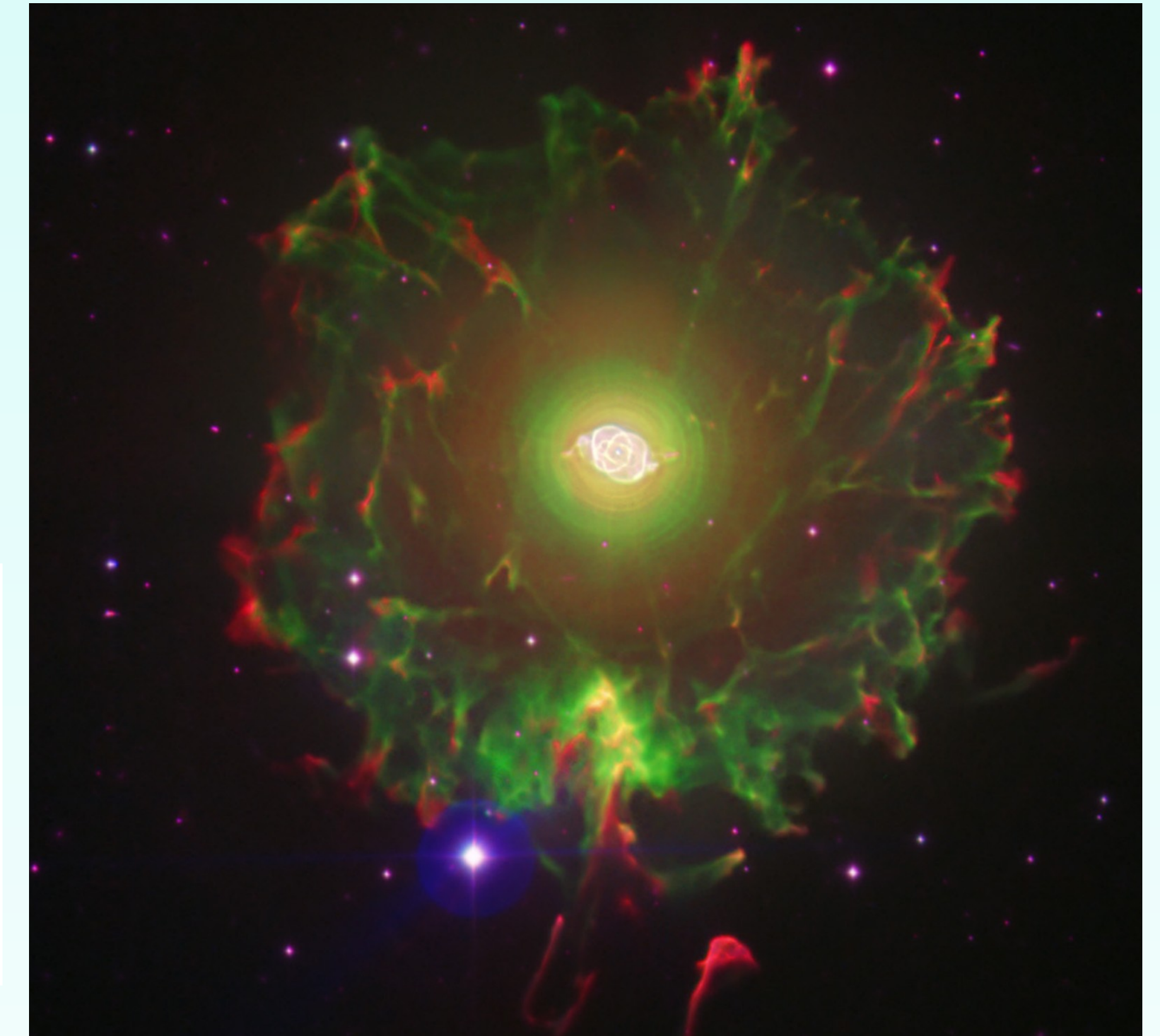
Ira Sprague Bowen

Nature,
v. 120, p. 473 (1927)

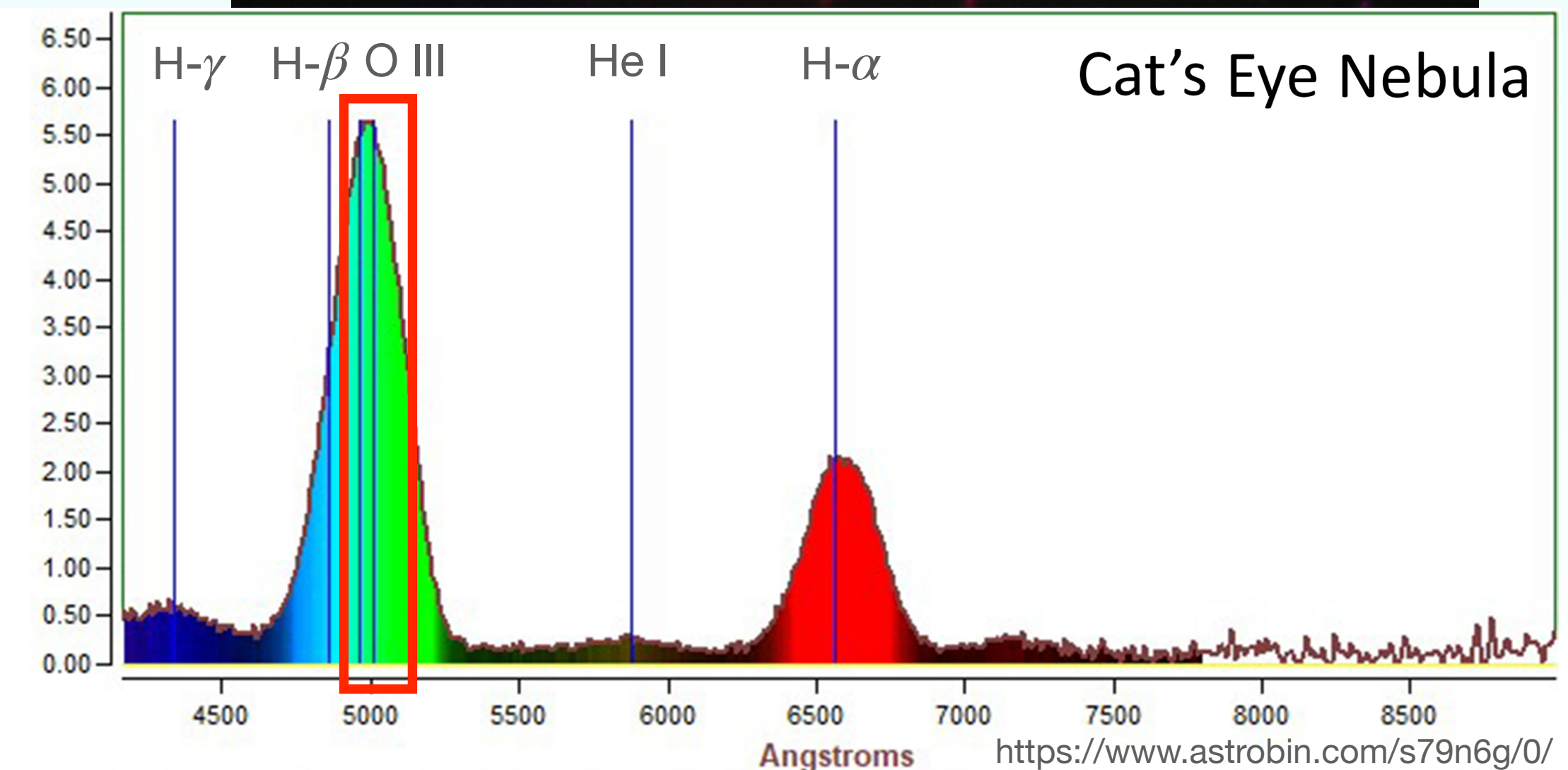
hydrogen alpha (H-alpha)
doubly ionised oxygen (OIII)
ionised sulfur (SII)

TABLE I.

λ .	Source.	Series Designation.
7325.0	OII	$^2D - ^2P$
6583.6	NII	$^3P_2 - ^1D$
6548.1	NII	$^3P_1 - ^1D$
5006.84	OIII	$^3P_2 - ^1D$
4958.91	OIII	$^3P_1 - ^1D$
4363.21	OIII	$^1D - ^1S$
3728.91	OII	$^4S - ^2D_3$
3726.16	OII	$^4S - ^2D_2$

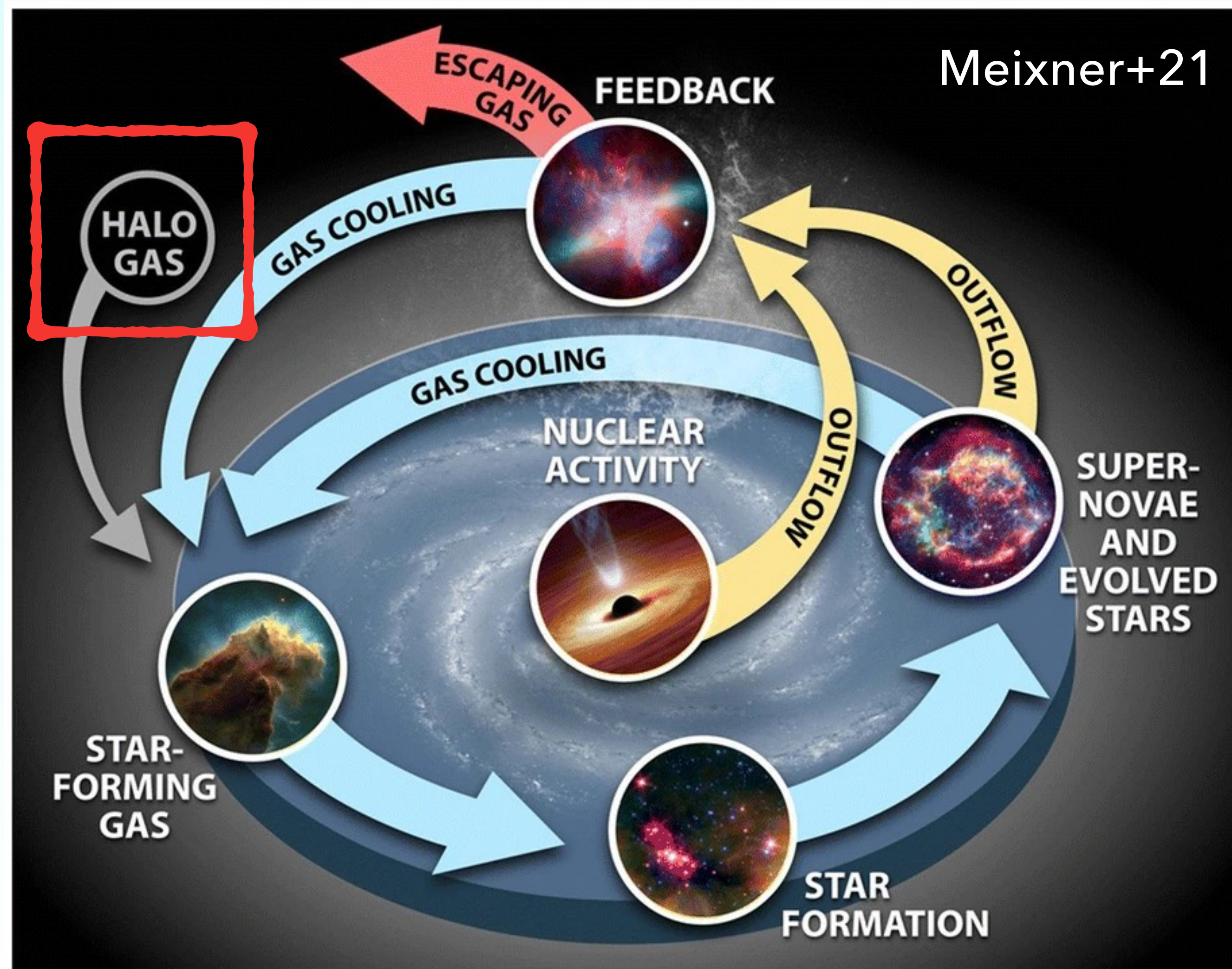


namely, $^1D - ^1S$ of OIII and $^2D - ^2P$ of OII. The calculated frequencies, if unresolved, are 22916 and 13646, which correspond to wave-lengths of 4362.54 Å.U. and 7326.2 Å.U. respectively. Two of the strongest nebular lines are found at 4363.21 Å.U. and 7325 Å.U. These deviations are well within the rather large experimental errors arising from the fact that the

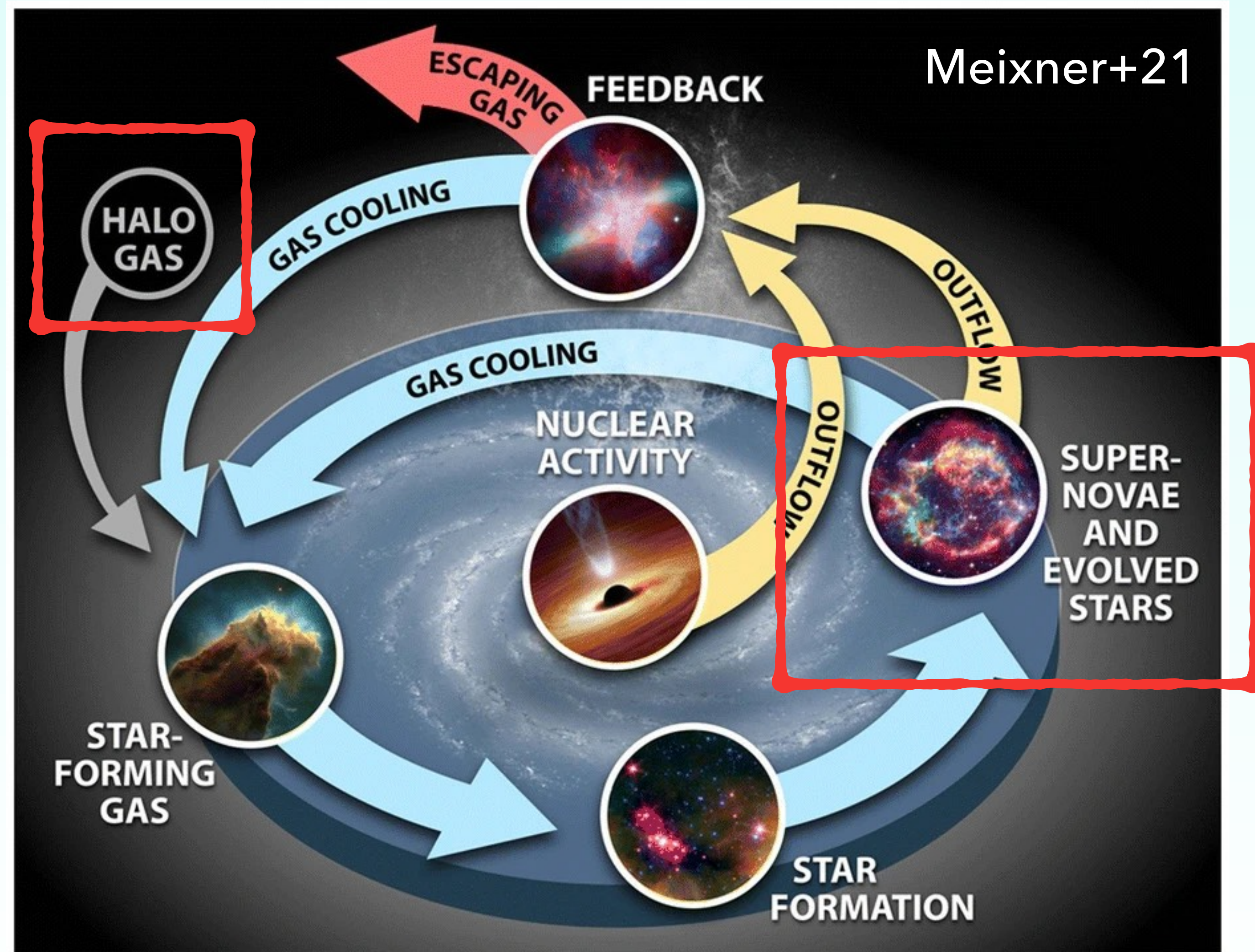


But where does this oxygen come from?

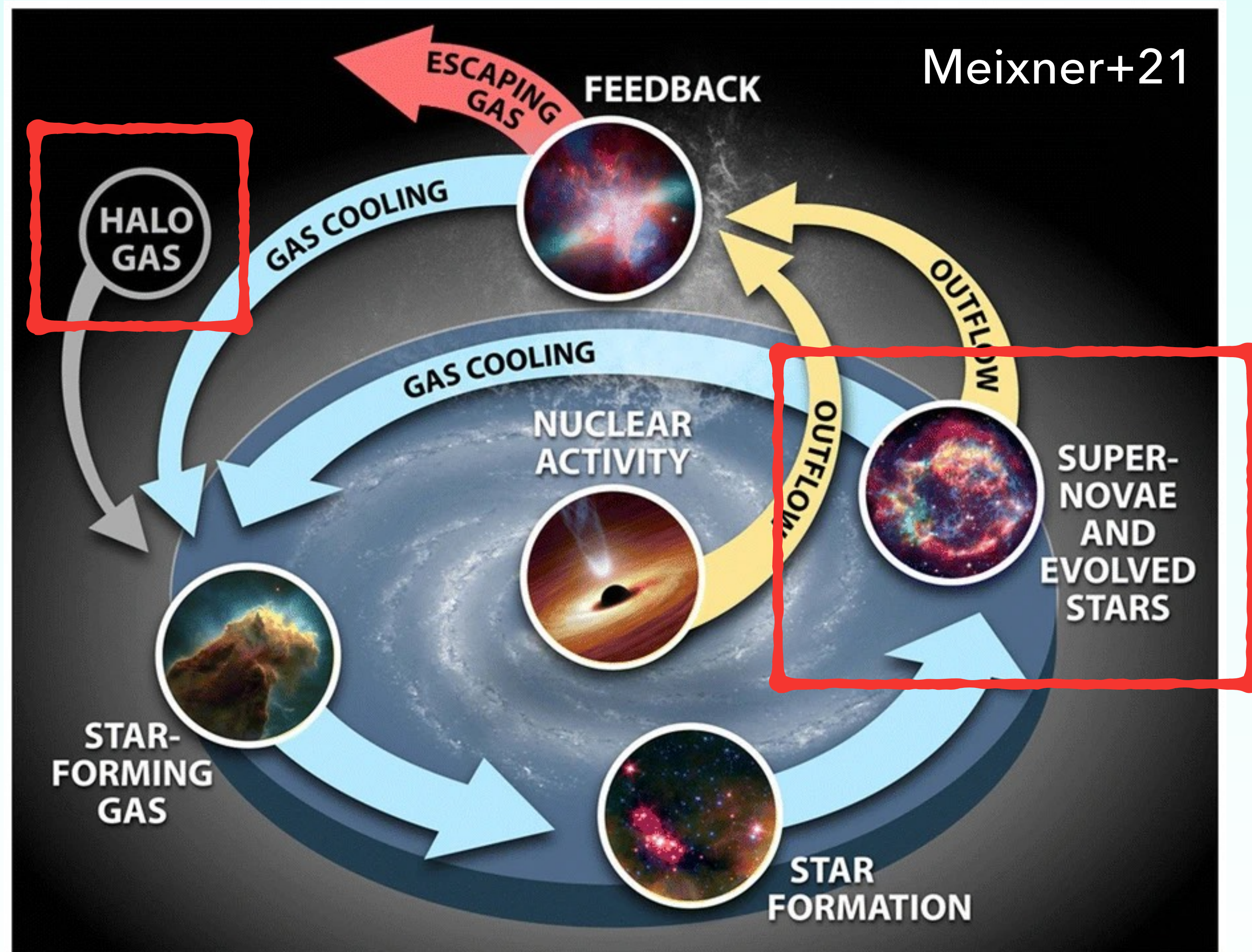
Astrophysical sites where nucleosynthesis occurs



Astrophysical sites where nucleosynthesis occurs



Astrophysical sites where nucleosynthesis occurs



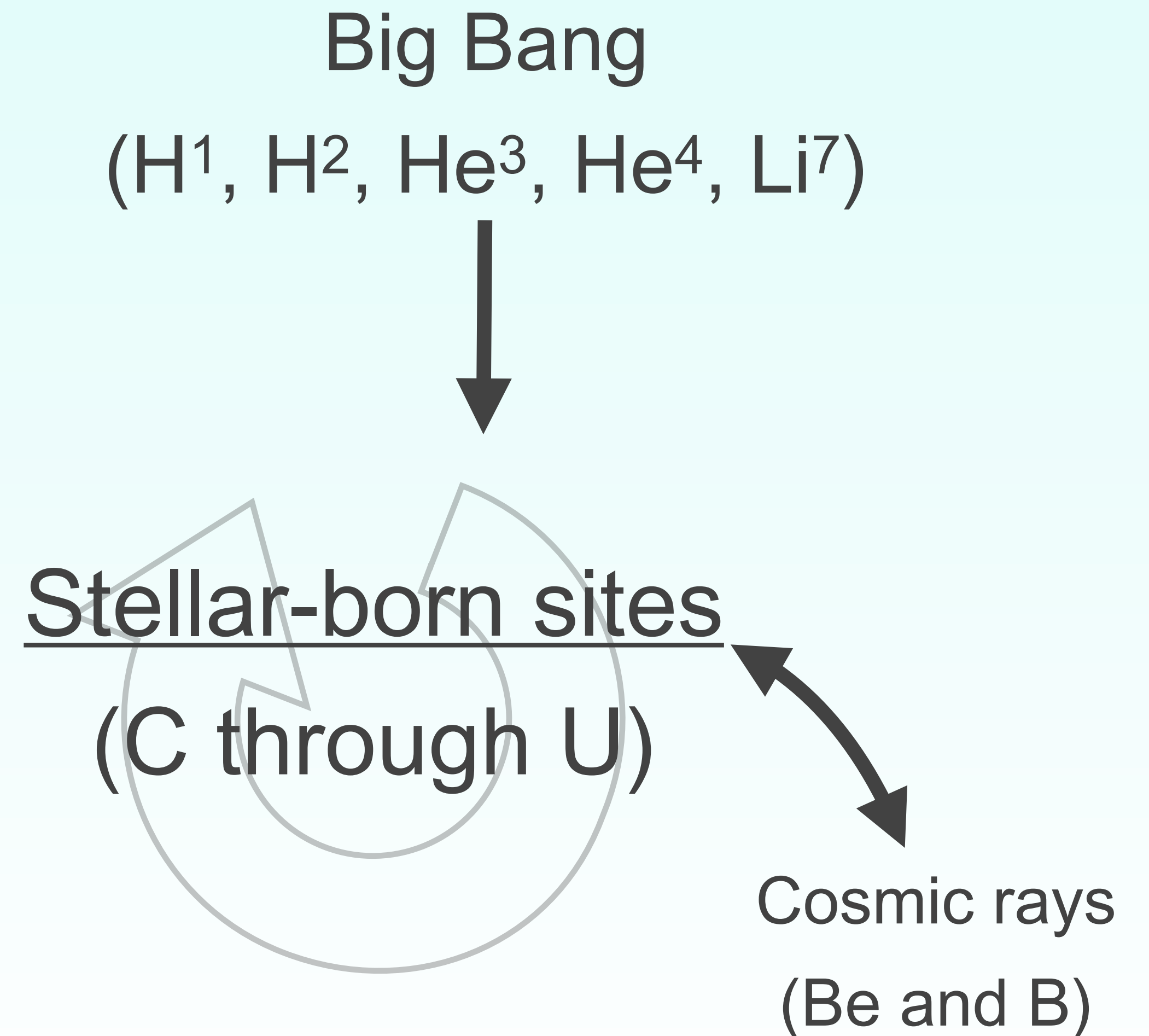
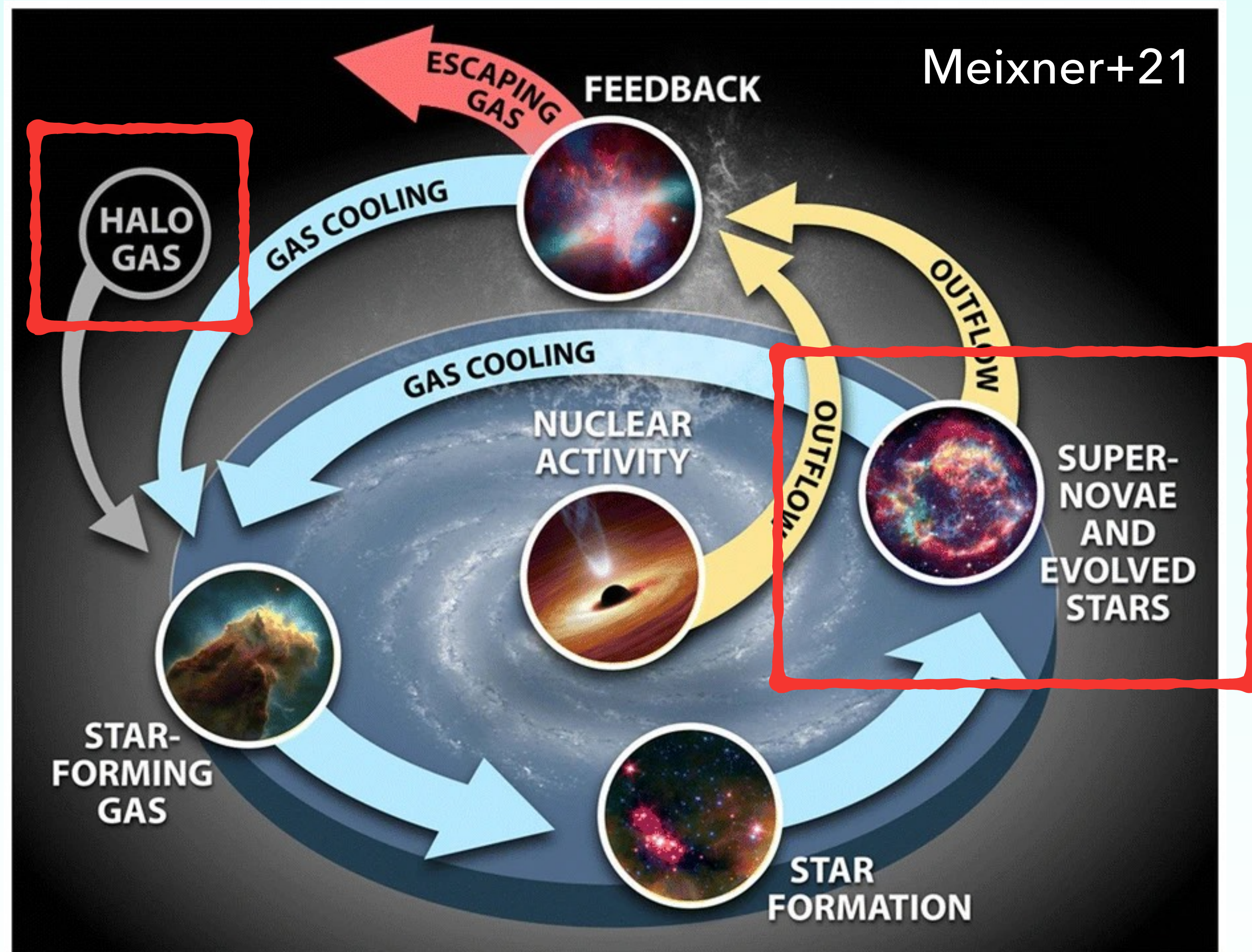
Big Bang
(H^1 , H^2 , He^3 , He^4 , Li^7)



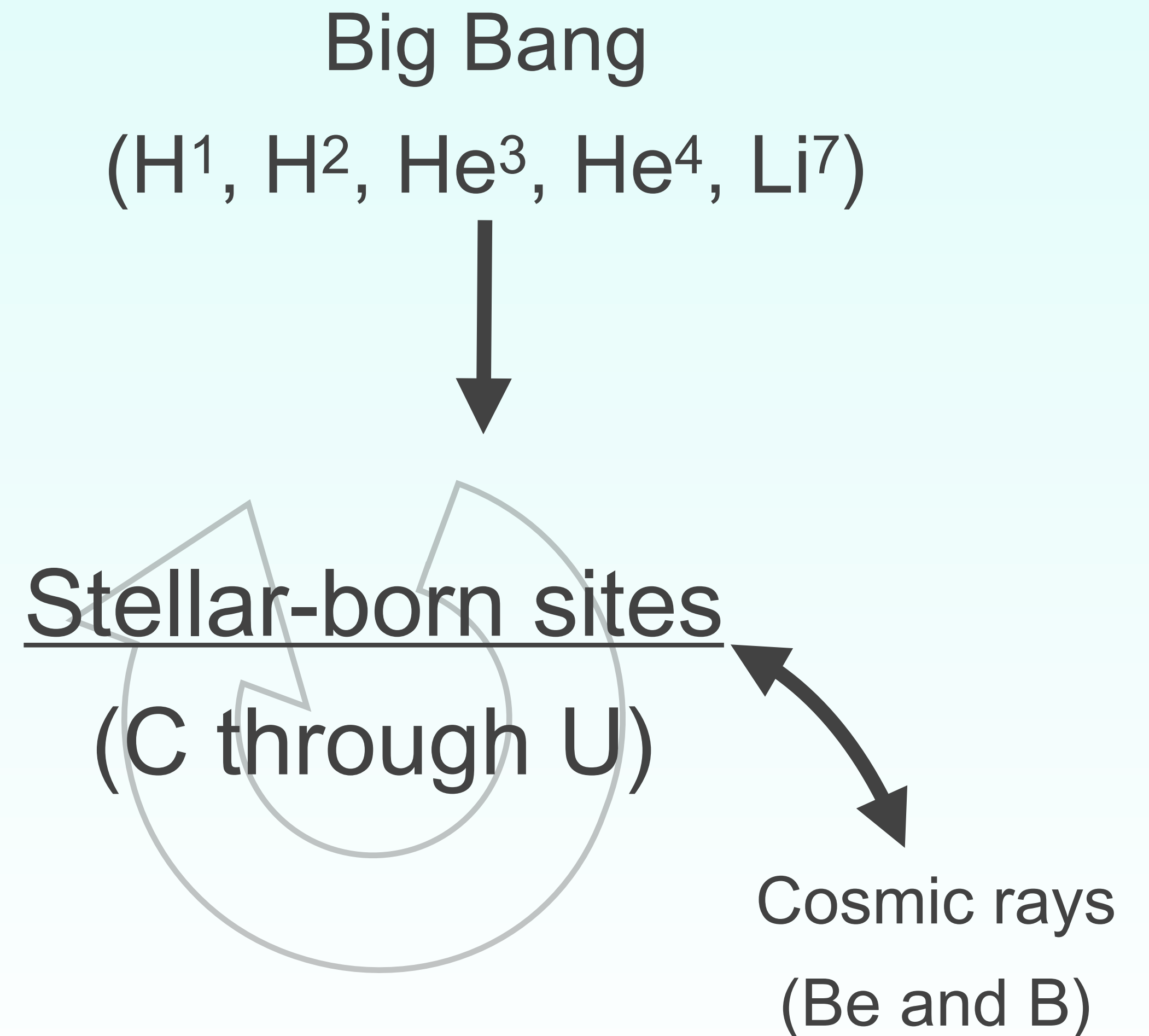
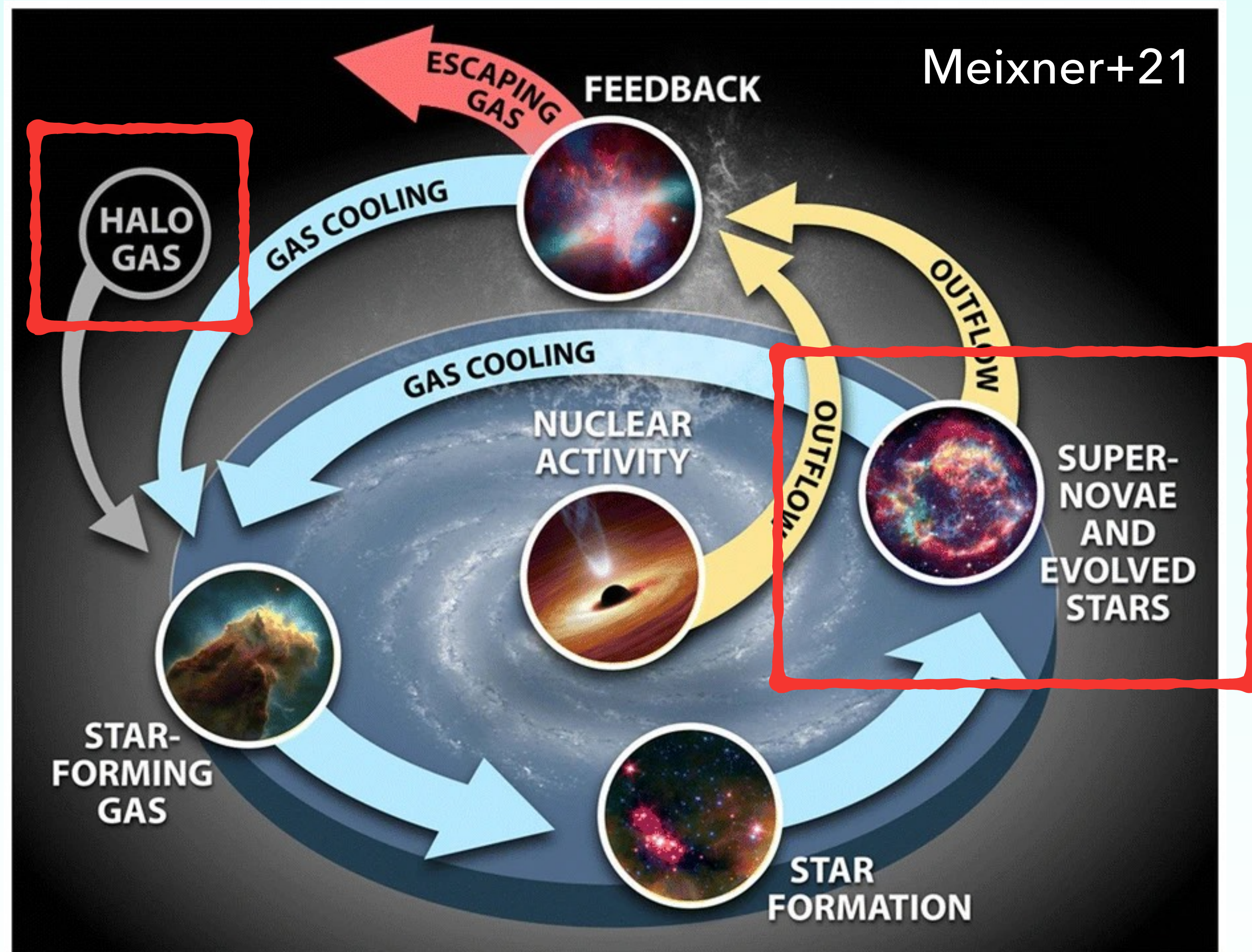
Stellar-born sites
(C through U)

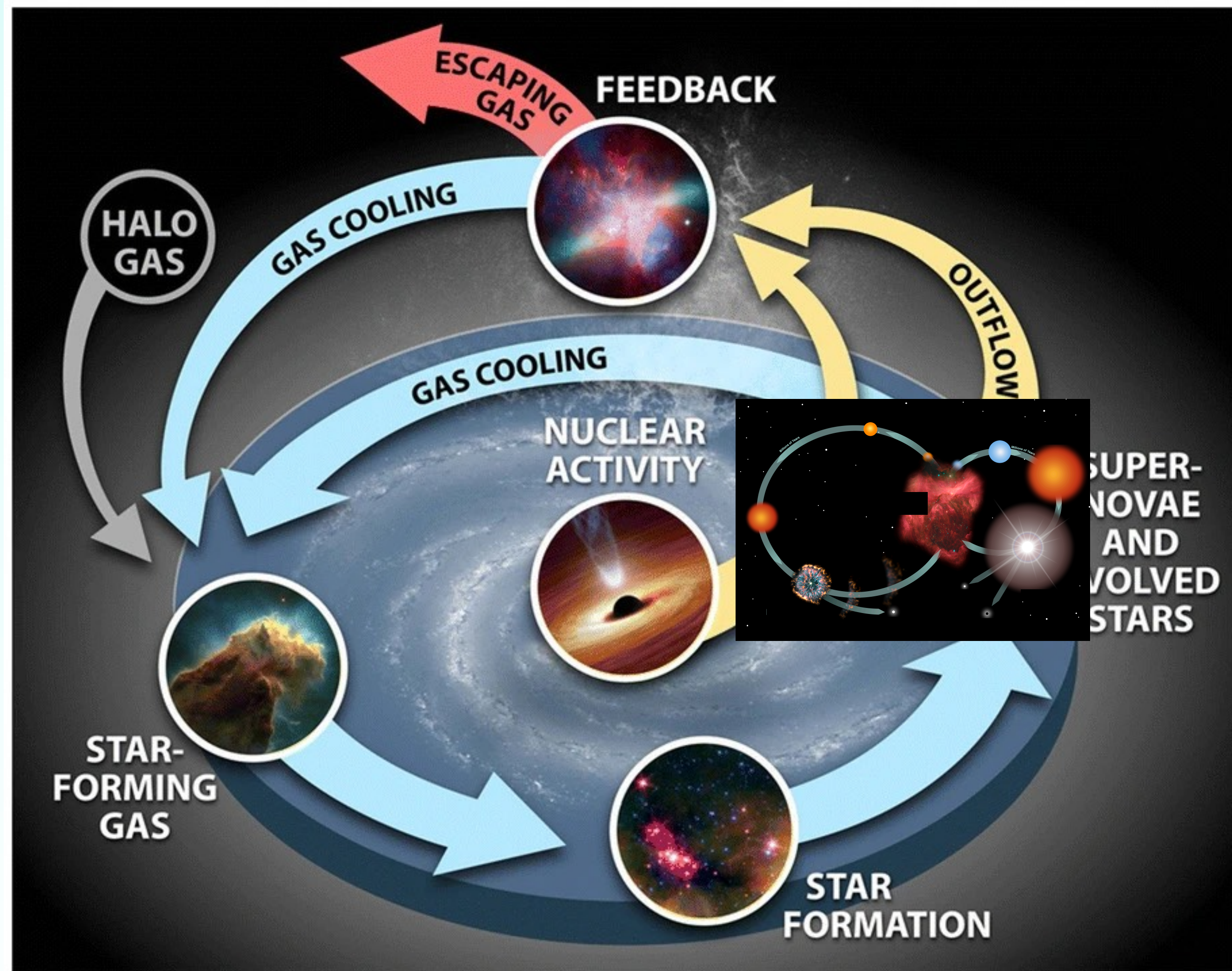
Cosmic rays
(Be and B)

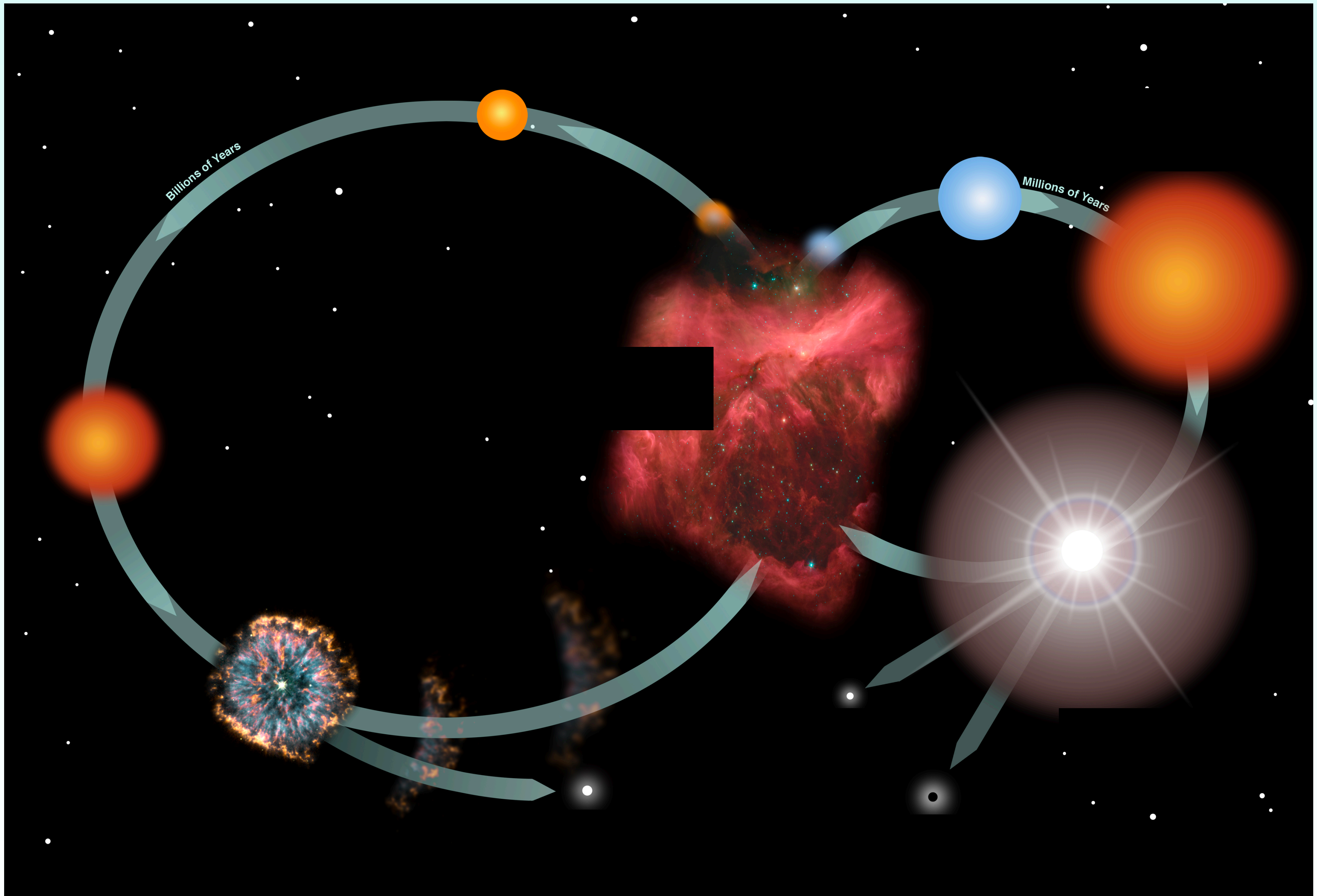
Astrophysical sites where nucleosynthesis occurs

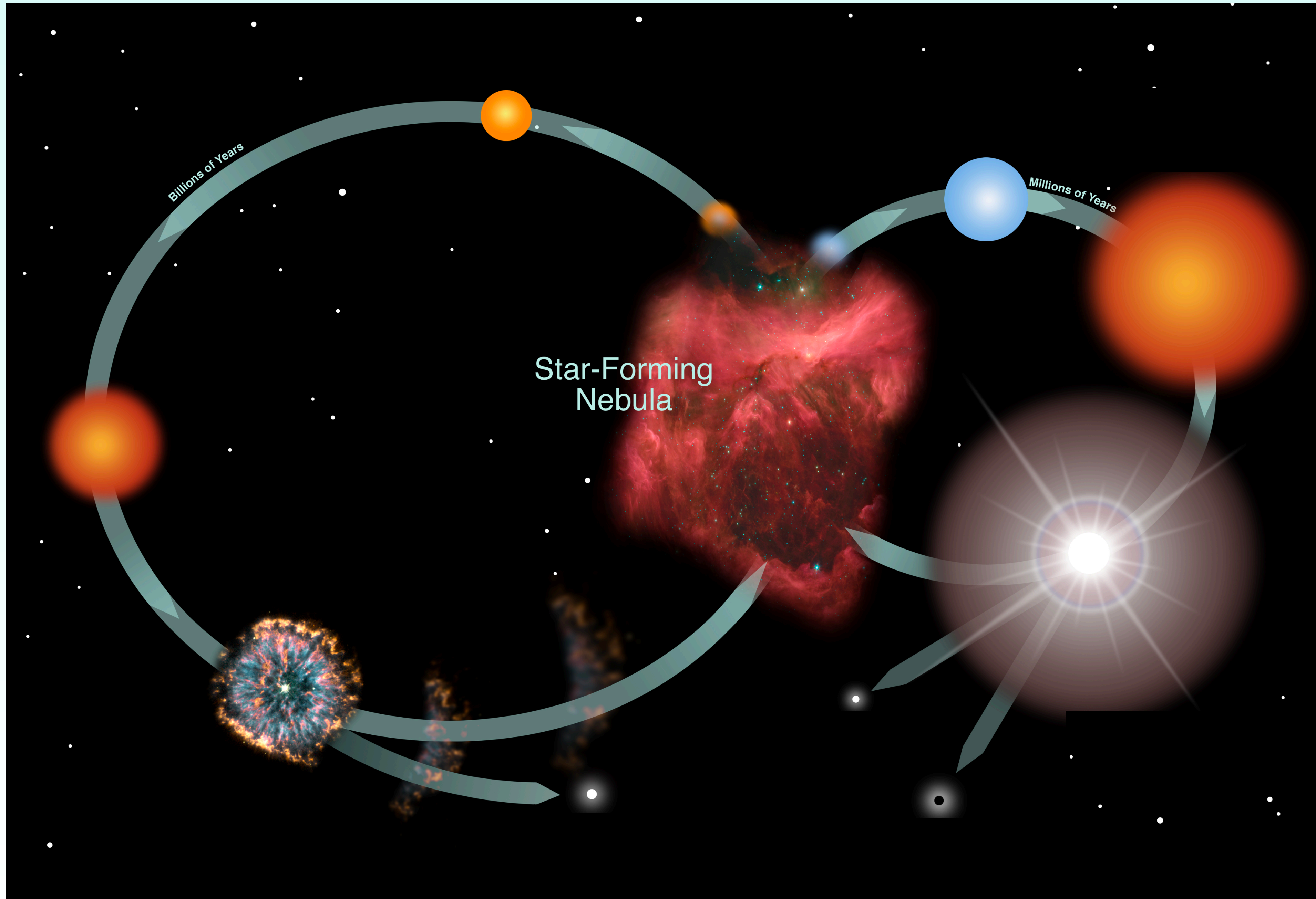


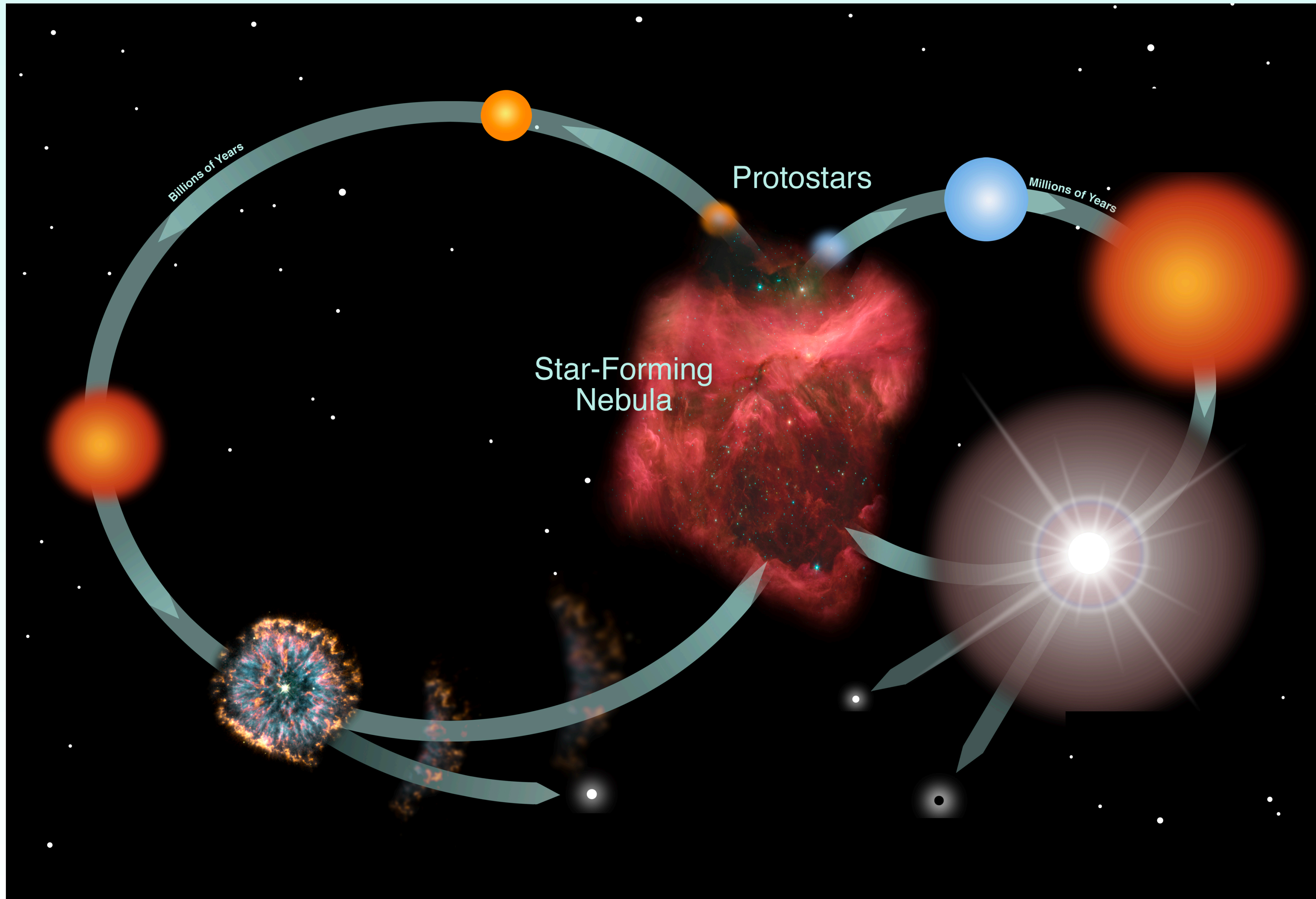
Astrophysical sites where nucleosynthesis occurs

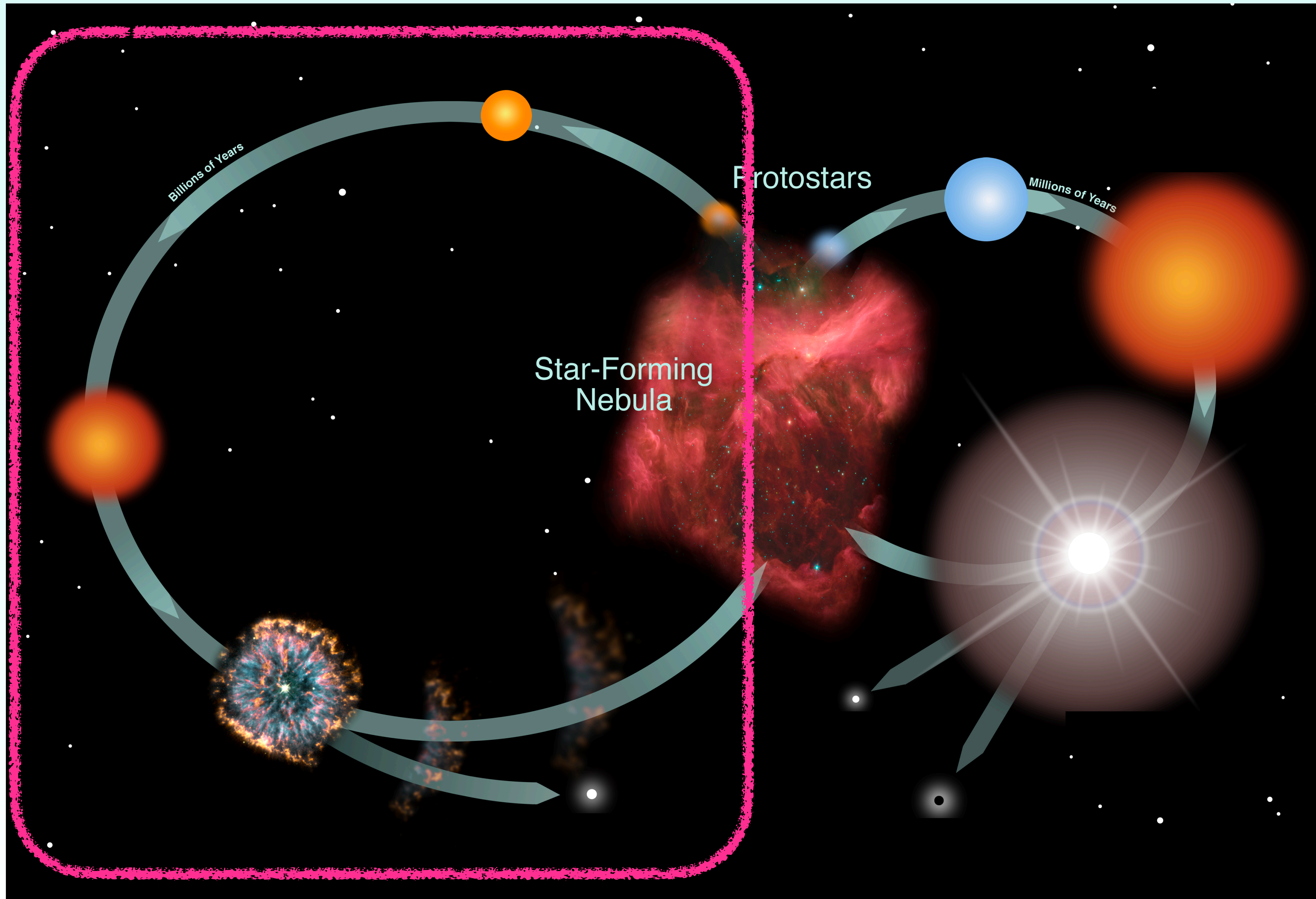


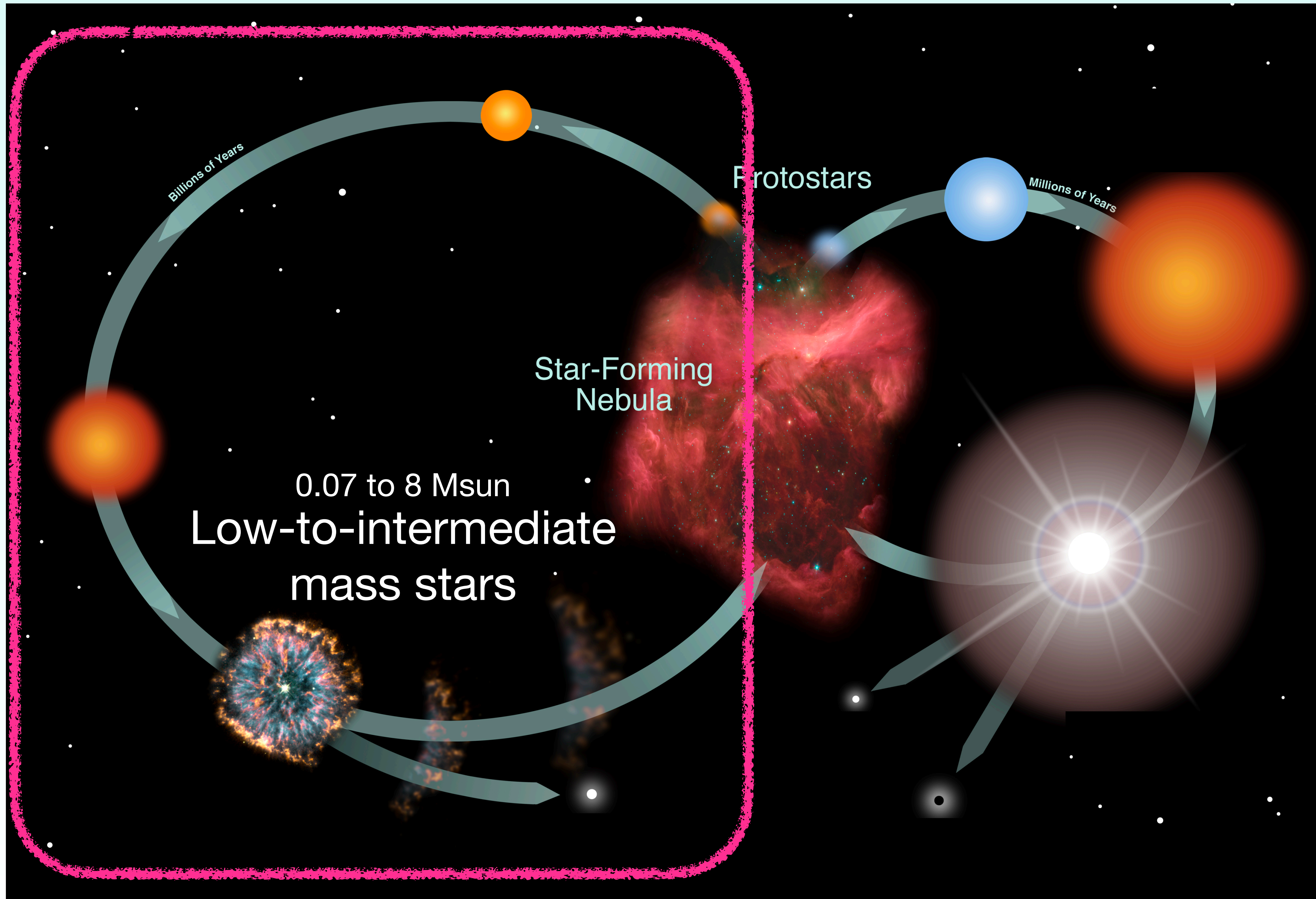


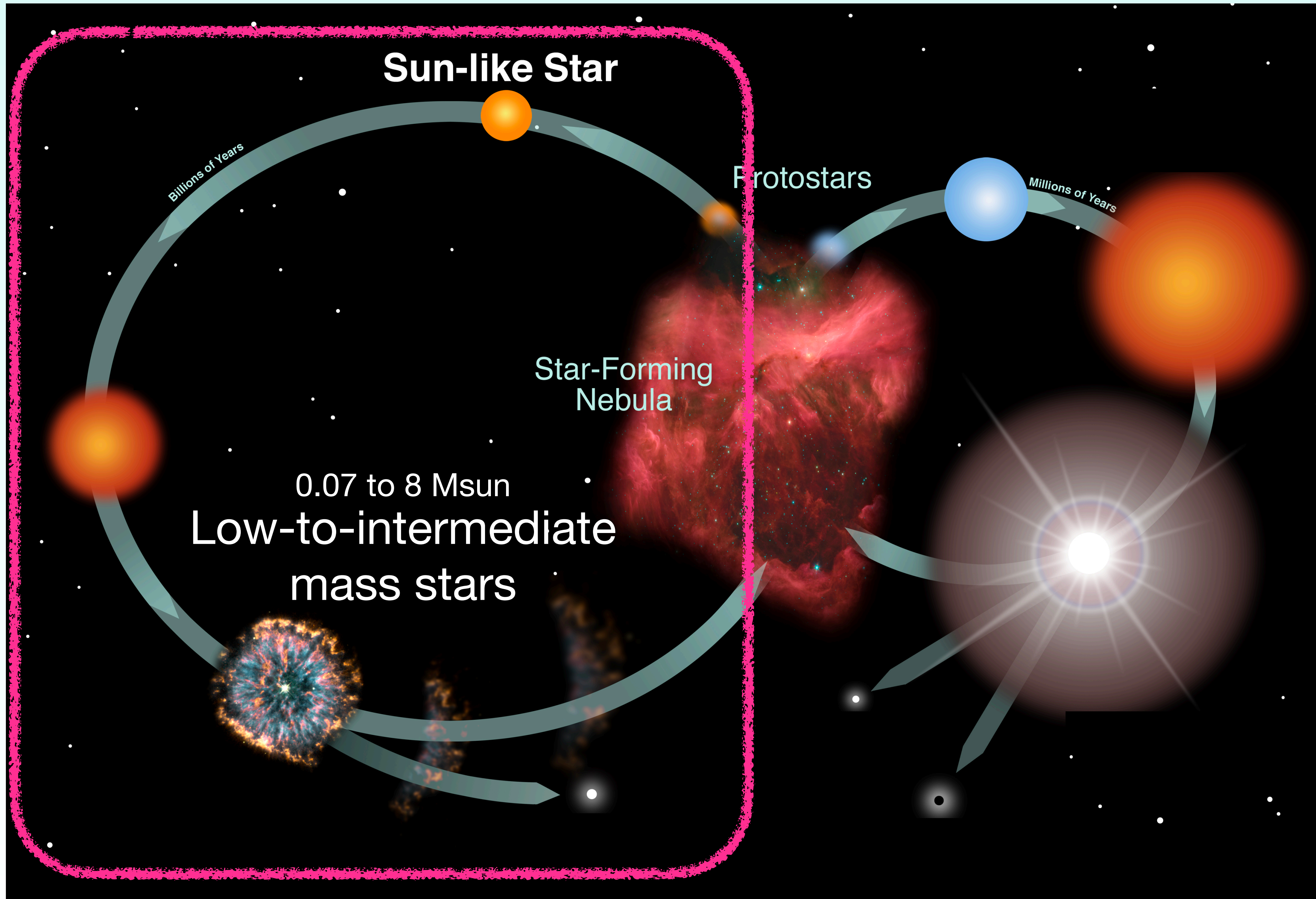


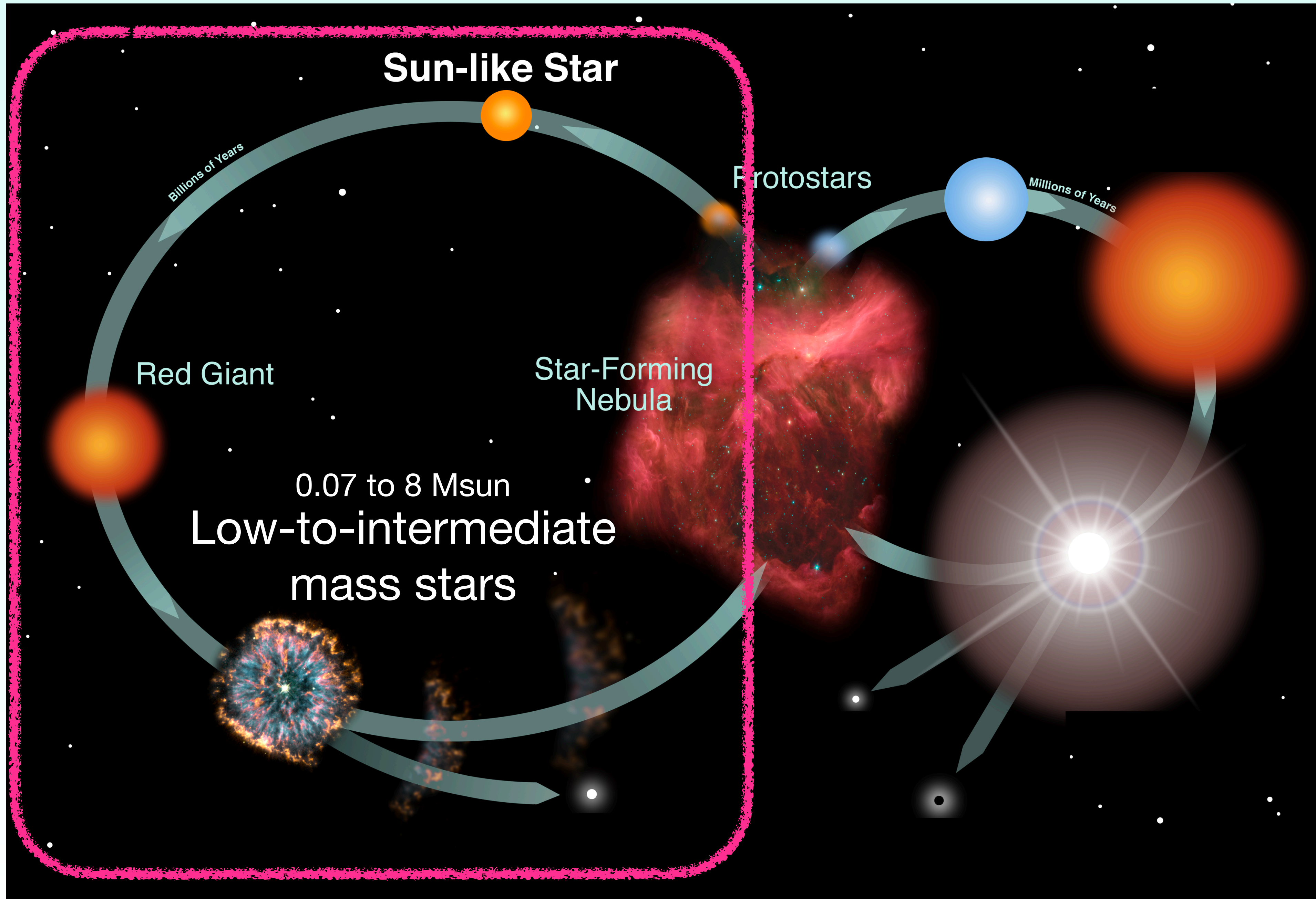


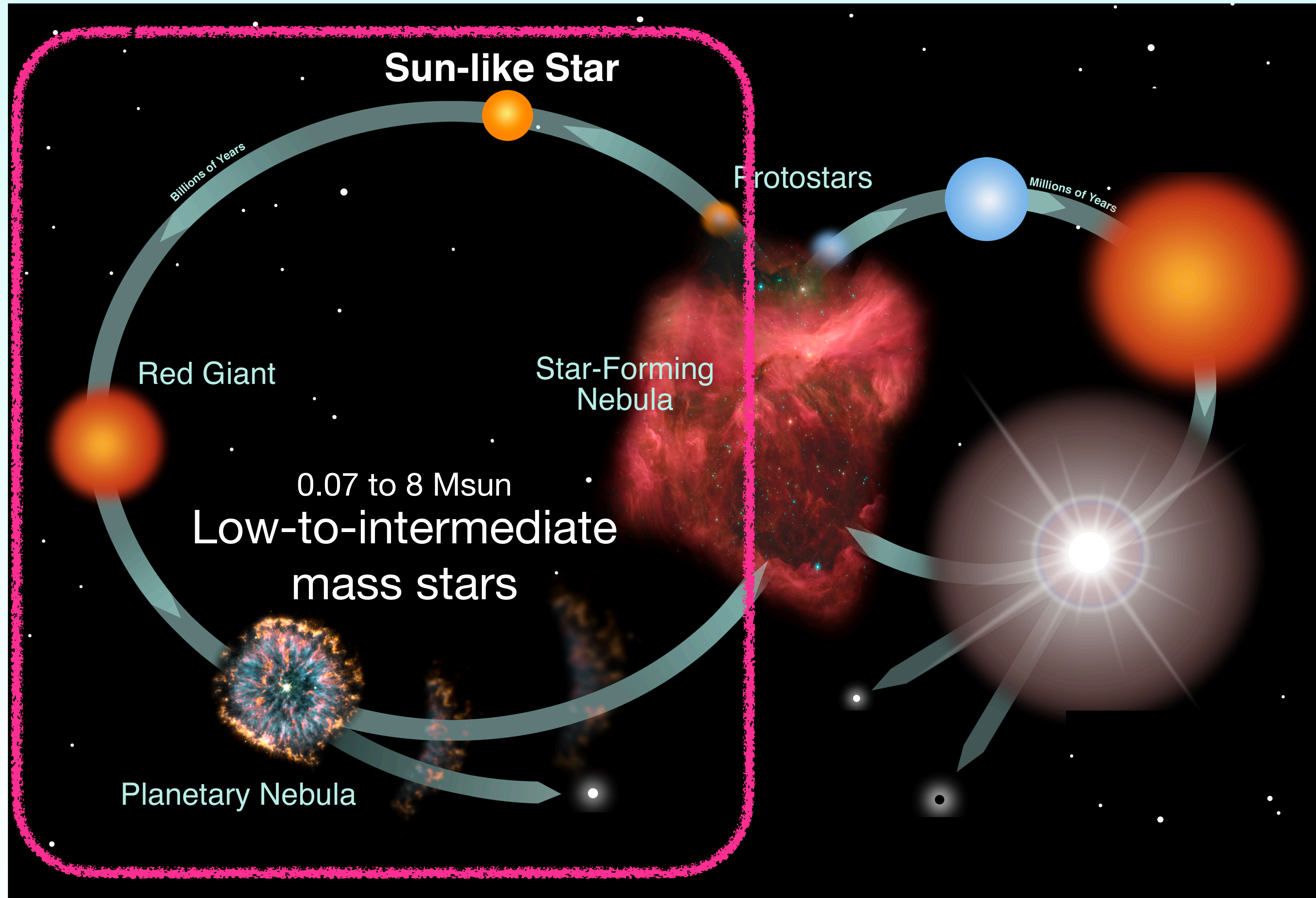


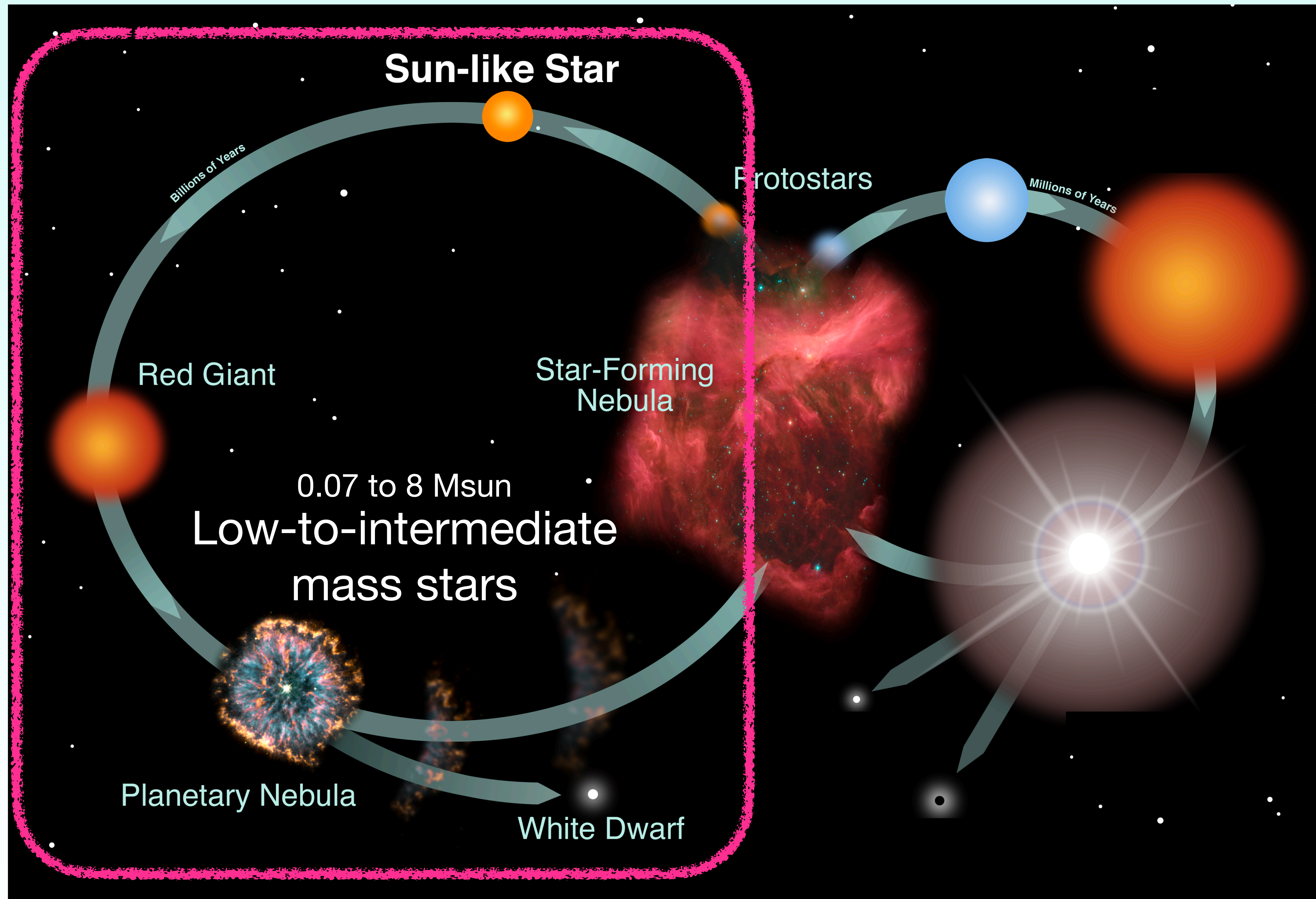


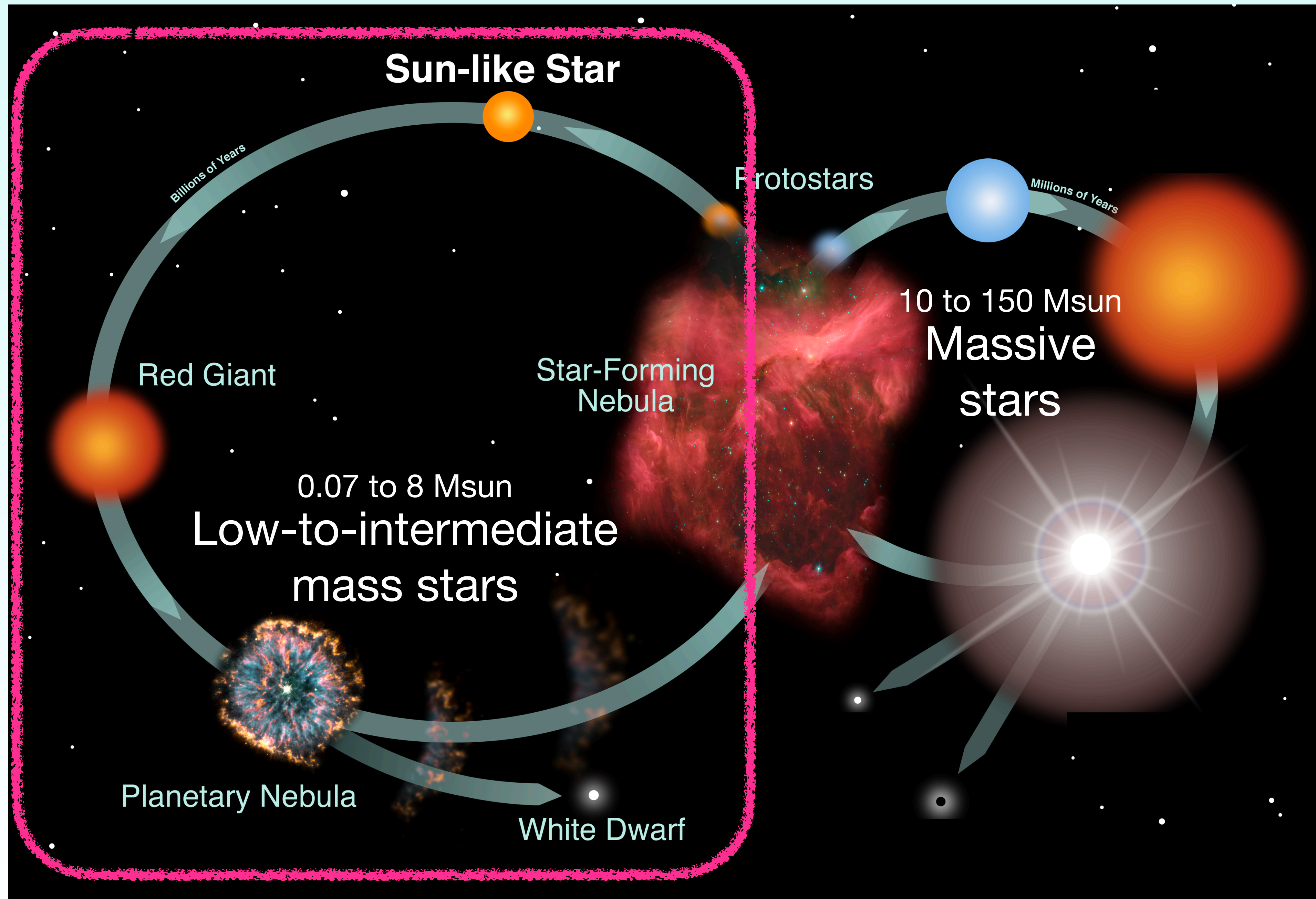


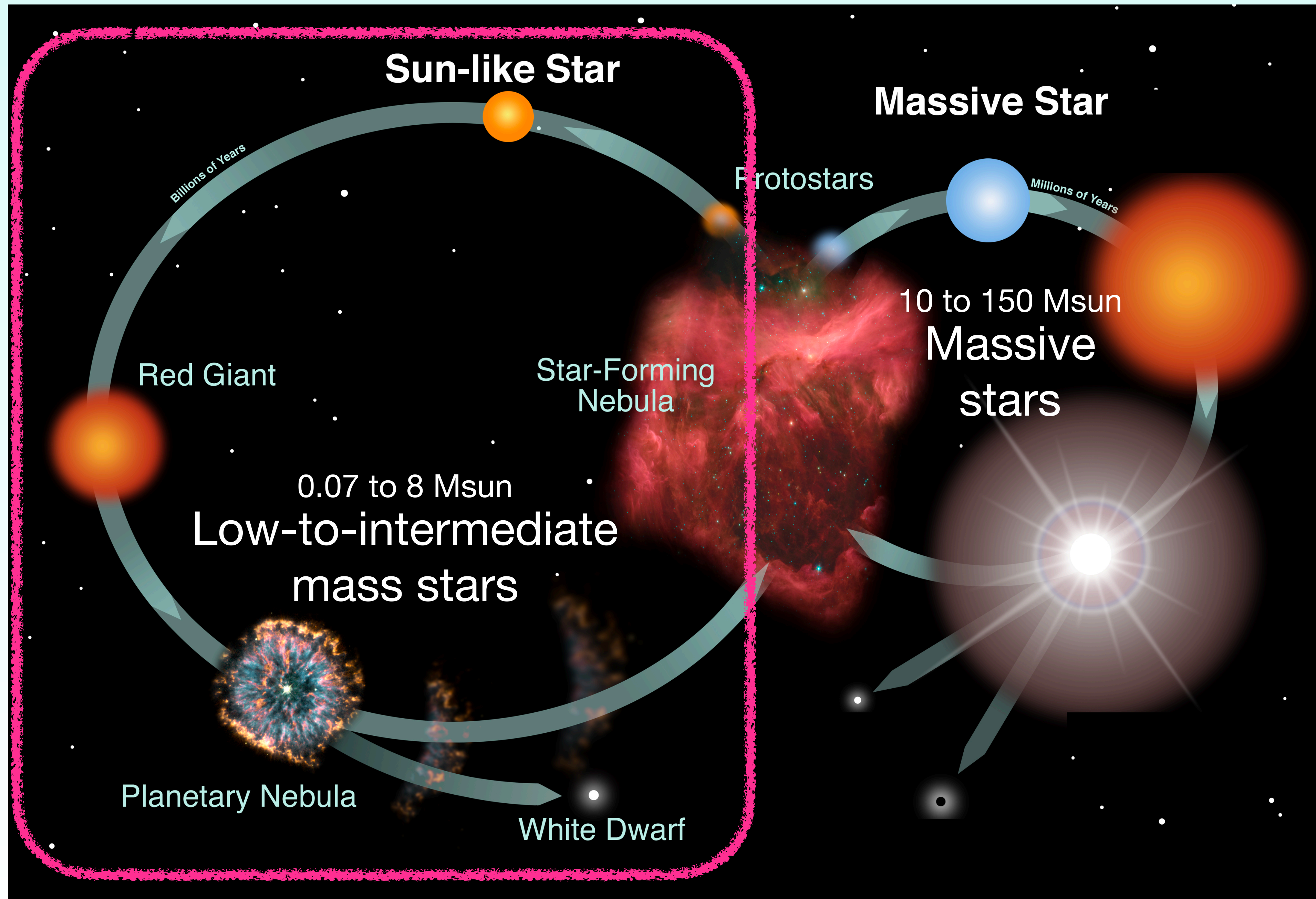


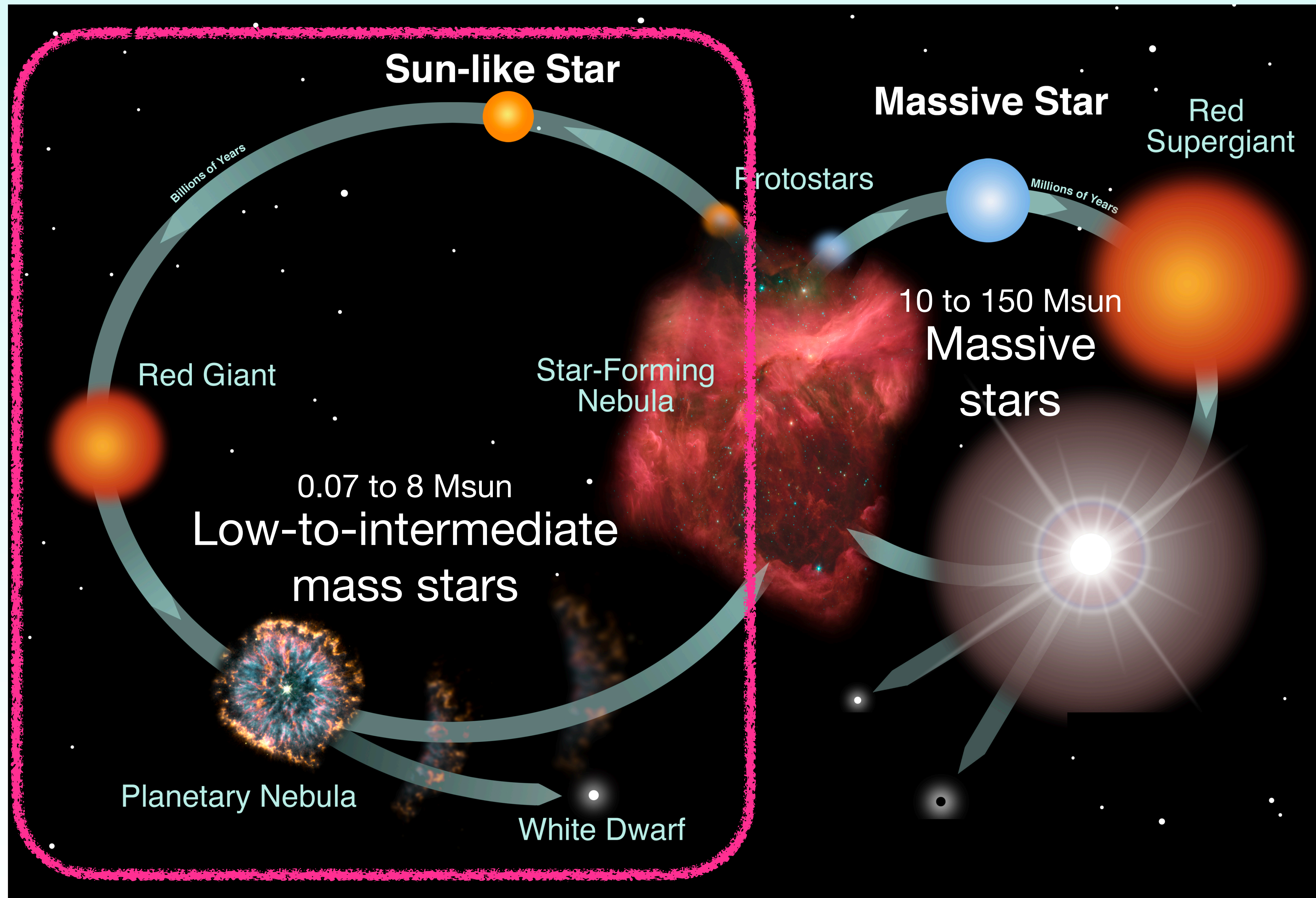


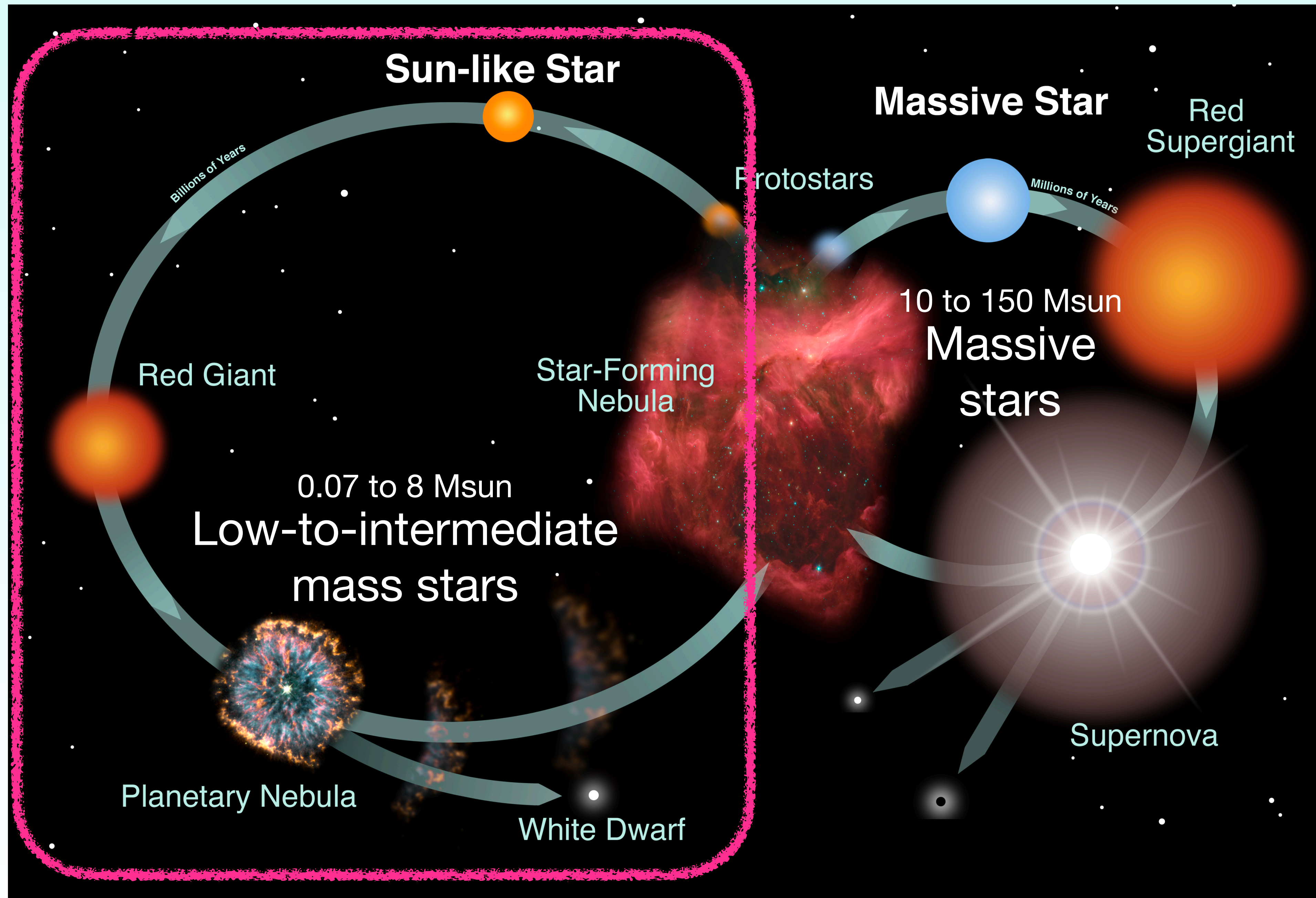


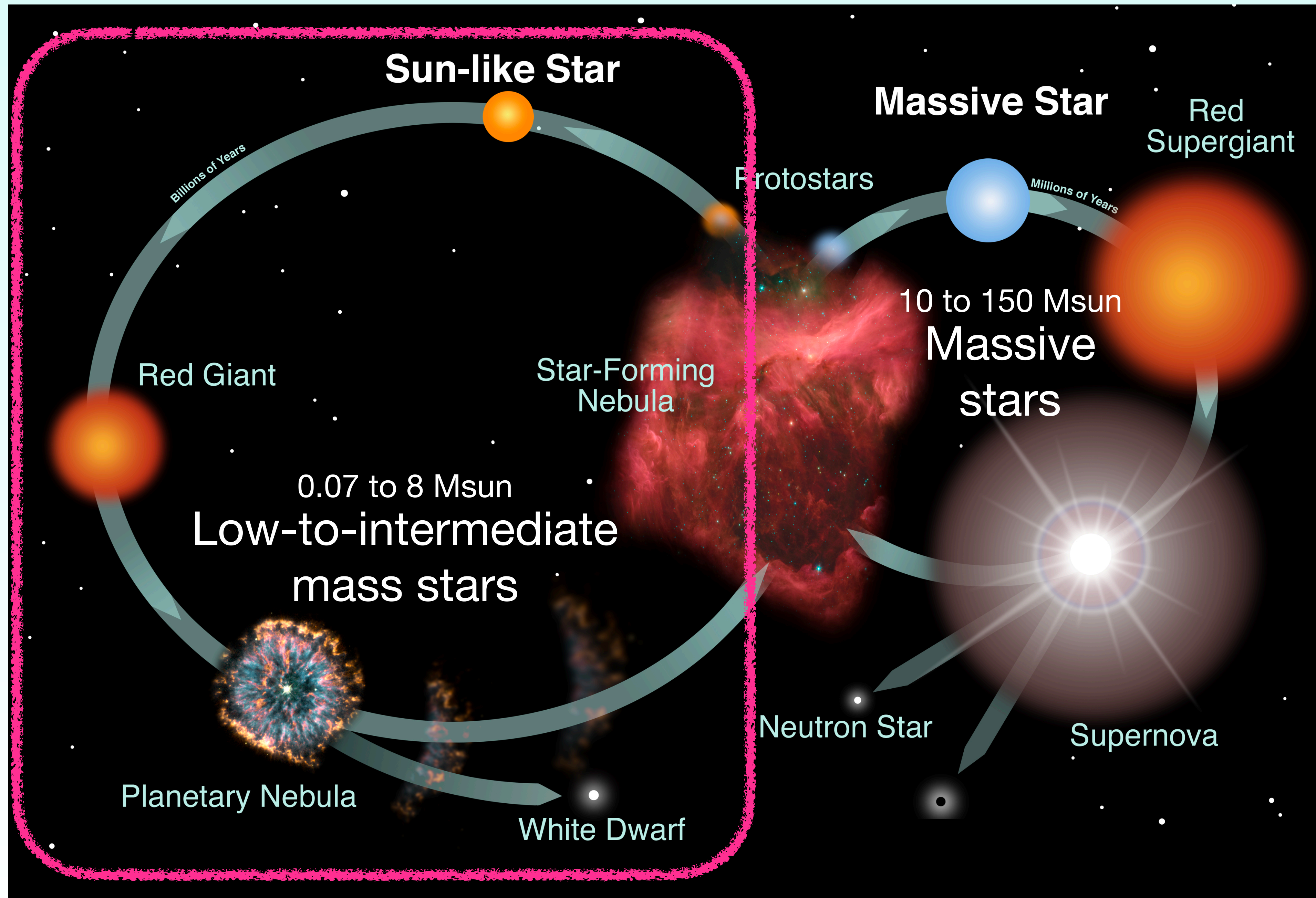


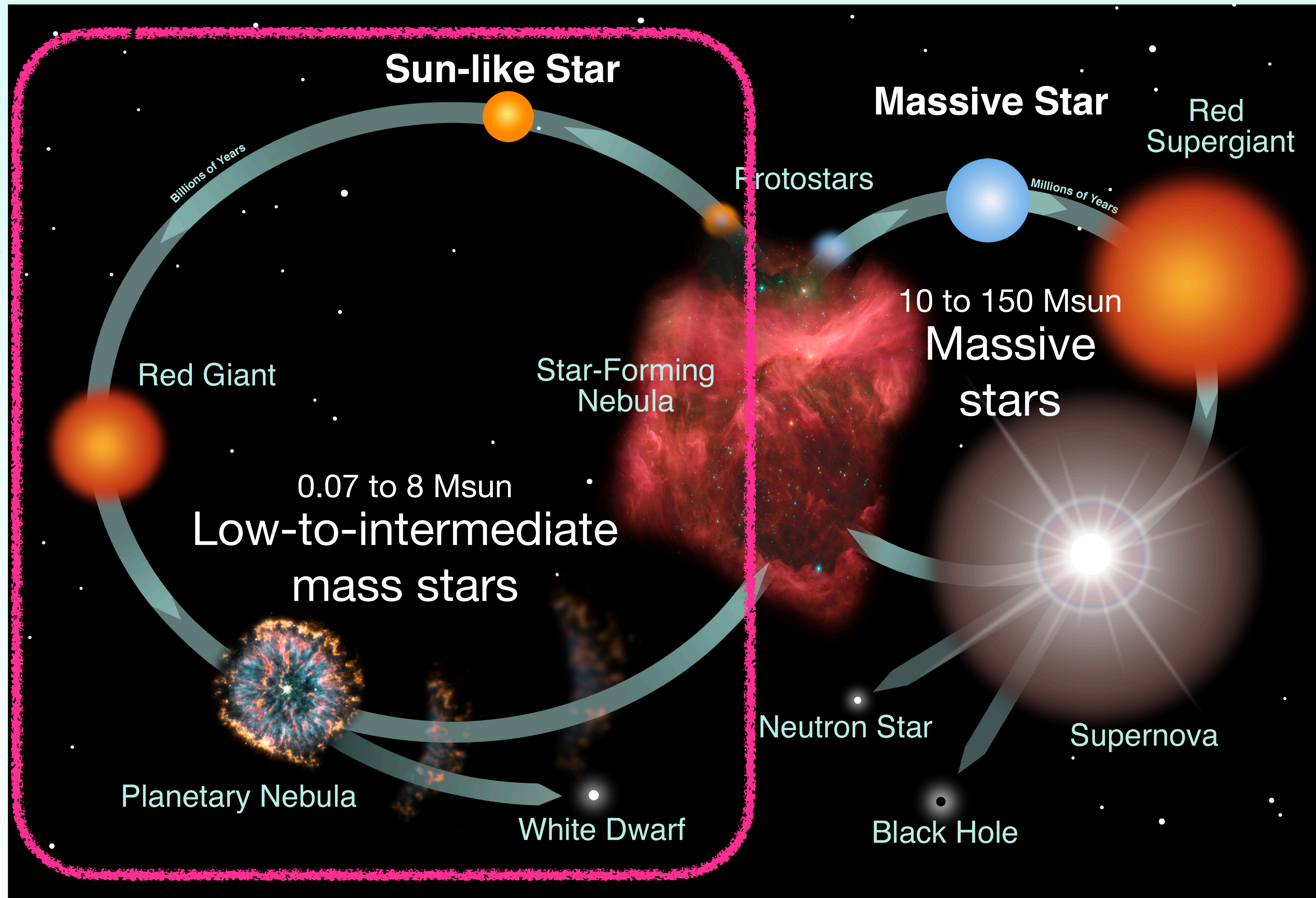


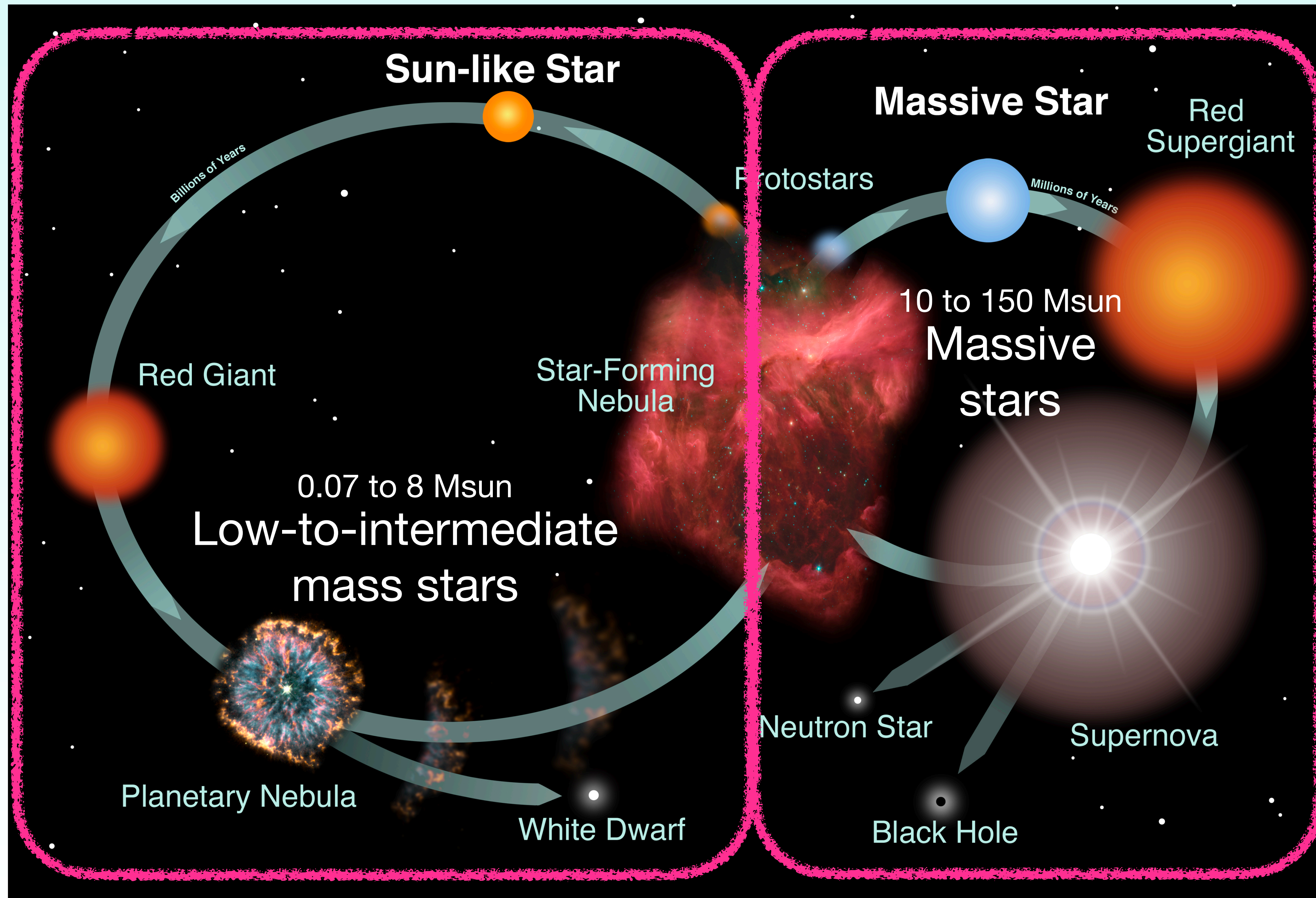


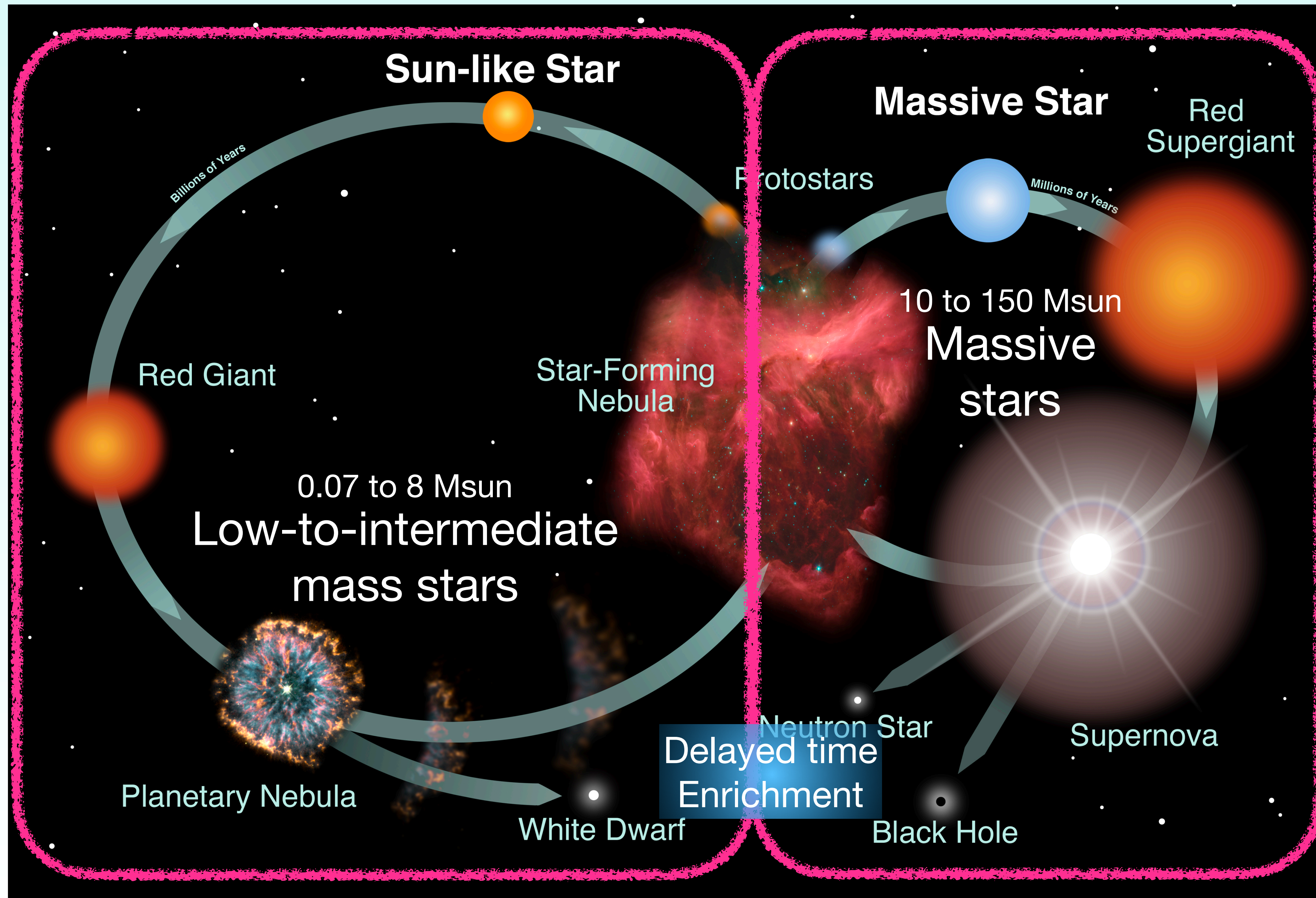


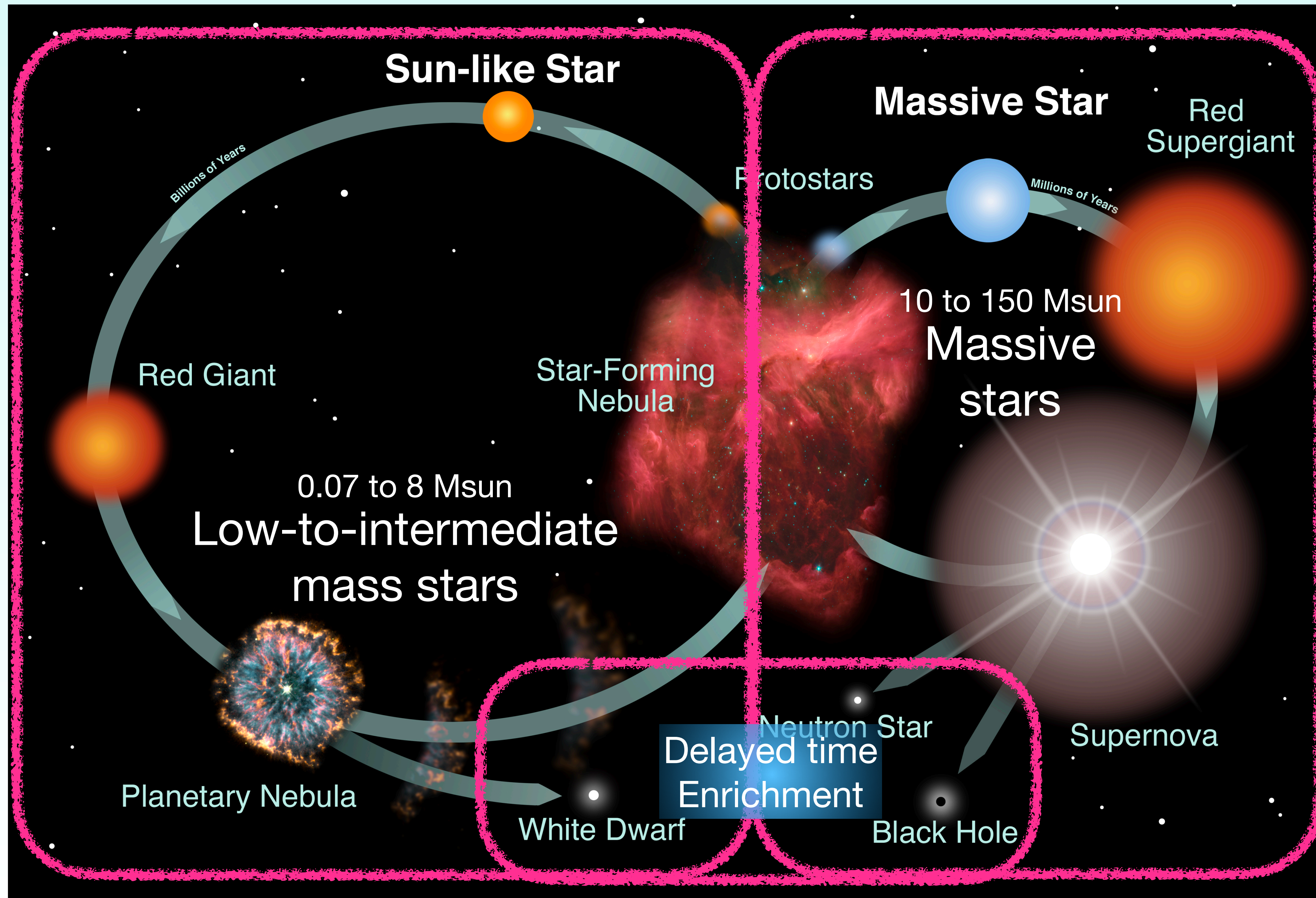


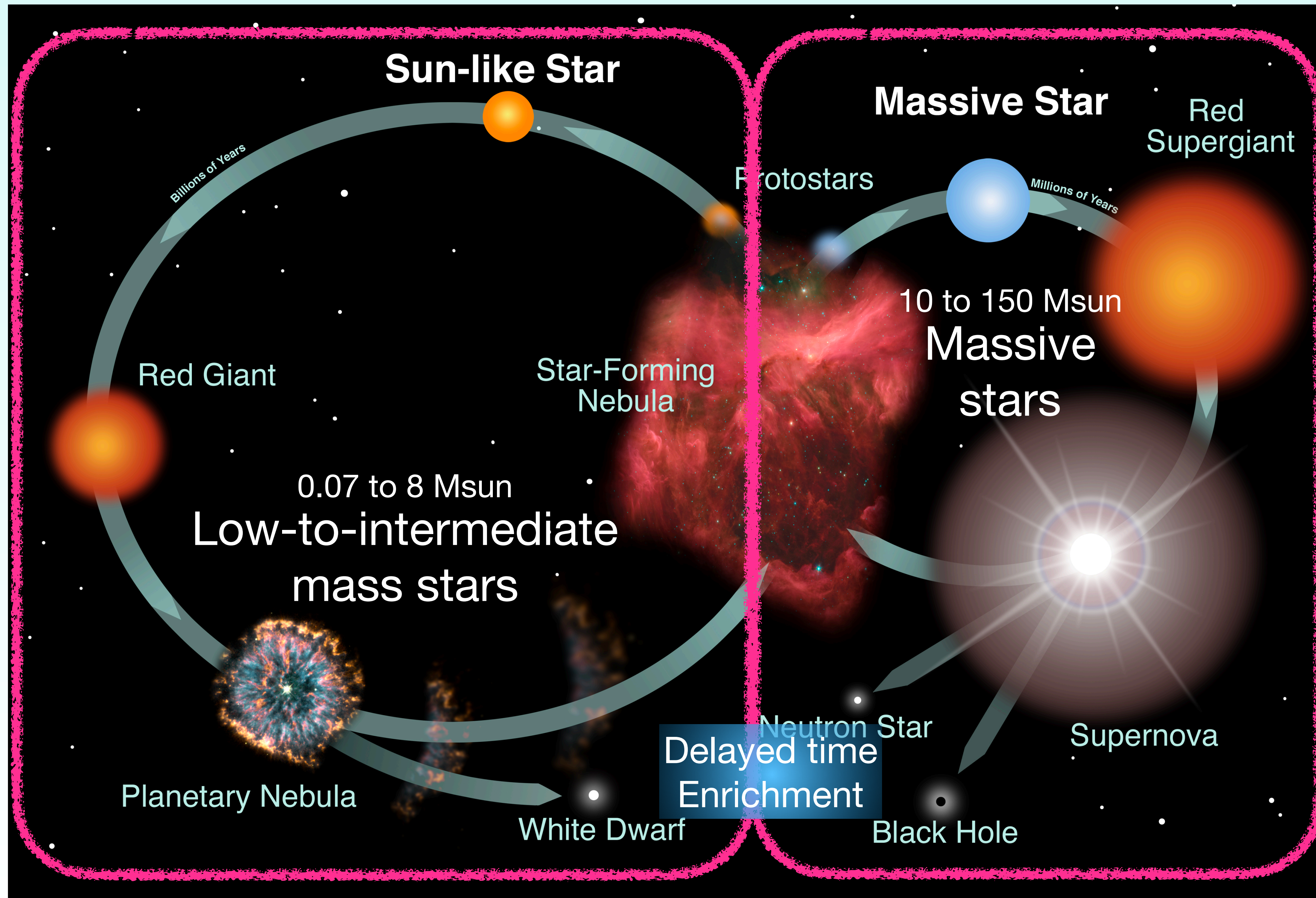












How are elements produced

Big Bang

(H¹, H², He³, He⁴, Li⁷)

1 IA																										18 VIIIA									
1 H Hydrogen 1.008																										2 He Helium 4.002602									
3 Li Lithium 6.94		4 Be Beryllium 9.0121831																																	
11 Na Sodium 22.98976928		12 Mg Magnesium 24.305																																	
		3 IIIB		4 IVB		5 VB		6 VIB		7 VIIB		8 VIIIB		9 VIIIB		10 VIIIB		11 IB		12 IIB															
19 K Potassium 39.0983		20 Ca Calcium 40.078		21 Sc Scandium 44.955908		22 Ti Titanium 47.887		23 V Vanadium 50.9415		24 Cr Chromium 51.9961		25 Mn Manganese 54.938044		26 Fe Iron 55.845		27 Co Cobalt 58.933194		28 Ni Nickel 58.6934		29 Cu Copper 63.546		30 Zn Zinc 65.38		31 Ga Gallium 69.723		32 Ge Germanium 72.630		33 As Arsenic 74.921595		34 Se Selenium 78.971		35 Br Bromine 79.904		36 Kr Krypton 83.798	
37 Rb Rubidium 85.4678		38 Sr Strontium 87.62		39 Y Yttrium 88.90584		40 Zr Zirconium 91.224		41 Nb Niobium 92.90637		42 Mo Molybdenum 95.95		43 Tc Technetium [98]		44 Ru Ruthenium 101.07		45 Rh Rhodium 102.90550		46 Pd Palladium 106.42		47 Ag Silver 107.8682		48 Cd Cadmium 112.414		49 In Indium 114.818		50 Sn Tin 118.710		51 Sb Antimony 121.760		52 Te Tellurium 127.60		53 I Iodine 126.90447		54 Xe Xenon 131.293	
55 Cs Caesium 132.90545196		56 Ba Barium 137.327		57 - 71 Lanthanoids		72 Hf Hafnium 178.49		73 Ta Tantalum 180.94788		74 W Tungsten 183.84		75 Re Rhenium 186.207		76 Os Osmium 190.23		77 Ir Iridium 192.217		78 Pt Platinum 195.084		79 Au Gold 196.966569		80 Hg Mercury 200.597		81 Tl Thallium 204.38		82 Pb Lead 207.2		83 Bi Bismuth 208.98040		84 Po Polonium [209]		85 At Astatine [210]		86 Rn Radon [222]	
87 Fr Francium [223]		88 Ra Radium [226]		89 - 103 Actinoids		104 Rf Rutherfordium [261]		105 Db Dubnium [268]		106 Sg Seaborgium [286]		107 Bh Bohrium [270]		108 Hs Hassium [285]		109 Mt Meitnerium [278]		110 Ds Darmstadtium [281]		111 Rg Roentgenium [282]		112 Cn Copernicium [289]		113 Nh Nihonium [286]		114 Fl Flerovium [289]		115 Mc Moscovium [289]		116 Lv Livermorium [293]		117 Ts Tennessine [294]		118 Og Oganesson [294]	

57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
89 Ac Actinium 227	90 Th Thorium 232.0377	91 Pa Protactinium 231.03689	92 U Uranium 238.02891	93 Np Neptunium 237.04697	94 Pu Plutonium 244.0642	95 Am Americium 243.06137	96 Cm Curium 247.07035	97 Bk Berkelium 247.07035	98 Cf Californium 251.0833	99 Es Einsteinium 252.0833	100 Fm Fermium 257.1035	101 Md Mendelevium 258.1035	102 No Nobelium 259.1035	103 Lr Lawrencium 262.1035

Stellar-born sites

(C through U)

Cosmic rays

(Be and B)

How are elements produced

Big Bang

(H¹, H², He³, He⁴, Li⁷)

I IA																				VIII 2															
1 H Hydrogen 1.008										2 He Helium 4.002602																									
3 Li Lithium 6.94		4 Be Beryllium 9.0121831												13 B Boron 10.81		14 C Carbon 12.011		15 N Nitrogen 14.007		16 O Oxygen 15.999		17 F Fluorine 18.998403163		18 Ne Neon 20.1797											
11 Na Sodium 22.98976928		12 Mg Magnesium 24.305												13 Al Aluminium 26.9815385		14 Si Silicon 28.085		15 P Phosphorus 30.973761998		16 S Sulfur 32.06		17 Cl Chlorine 35.45		18 Ar Argon 39.948											
19 K Potassium 39.0983		20 Ca Calcium 40.078		21 Sc Scandium 44.955908		22 Ti Titanium 47.887		23 V Vanadium 50.9415		24 Cr Chromium 51.9961		25 Mn Manganese 54.938044		26 Fe Iron 55.845		27 Co Cobalt 58.933194		28 Ni Nickel 58.6934		29 Cu Copper 63.546		30 Zn Zinc 65.38		31 Ga Gallium 69.723		32 Ge Germanium 72.630		33 As Arsenic 74.921595		34 Se Selenium 78.971		35 Br Bromine 79.904		36 Kr Krypton 83.798	
37 Rb Rubidium 85.4678		38 Sr Strontium 87.62		39 Y Yttrium 88.90584		40 Zr Zirconium 91.224		41 Nb Niobium 92.90637		42 Mo Molybdenum 95.95		43 Tc Technetium (98)		44 Ru Ruthenium 101.07		45 Rh Rhodium 102.90550		46 Pd Palladium 106.42		47 Ag Silver 107.8682		48 Cd Cadmium 112.414		49 In Indium 114.818		50 Sn Tin 118.710		51 Sb Antimony 121.760		52 Te Tellurium 127.60		53 I Iodine 126.90447		54 Xe Xenon 131.293	
55 Cs Caesium 132.90545196		56 Ba Barium 137.327		57 - 71 Lanthanoids		72 Hf Hafnium 178.49		73 Ta Tantalum 180.94788		74 W Tungsten 183.84		75 Re Rhenium 186.207		76 Os Osmium 190.23		77 Ir Iridium 192.217		78 Pt Platinum 195.084		79 Au Gold 196.966569		80 Hg Mercury 200.597		81 Tl Thallium 204.38		82 Pb Lead 207.2		83 Bi Bismuth 208.98040		84 Po Polonium (209)		85 At Astatine (210)		86 Rn Radon (222)	
87 Fr Francium (223)		88 Ra Radium (226)		89 - 103 Actinoids		104 Rf Rutherfordium (261)		105 Db Dubnium (268)		106 Sg Seaborgium (266)		107 Bh Bohrium (264)		108 Hs Hassium (277)		109 Mt Meitnerium (268)		110 Ds Darmstadtium (281)		111 Rg Roentgenium (282)		112 Cn Copernicium (285)		113 Nh Nihonium (286)		114 Fl Flerovium (289)		115 Mc Moscovium (288)		116 Lv Livermorium (293)		117 Ts Tennessine (294)		118 Og Oganesson (294)	

57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
89 Ac Actinium 227	90 Th Thorium 232.0377	91 Pa Protactinium 231.03689	92 U Uranium 238.02891	93 Np Neptunium 237.04817	94 Pu Plutonium 244.0642	95 Am Americium 243.06138	96 Cm Curium 247.07035	97 Bk Berkelium 247.07035	98 Cf Californium 251.0833	99 Es Einsteinium 252.0833	100 Fm Fermium 257.10528	101 Md Mendelevium 258.10528	102 No Nobelium 259.10528	103 Lr Lawrencium 262.10528

Stellar-born sites

(C through U)

Cosmic rays

(Be and B)

How are elements produced

Big Bang

(H¹, H², He³, He⁴, Li⁷)

1 IA																				18 VIIIA															
1 H Hydrogen 1.008										2 He Helium 4.002602																									
3 Li Lithium 6.94		4 Be Beryllium 9.0121831												5 B Boron 10.81		6 C Carbon 12.011		7 N Nitrogen 14.007		8 O Oxygen 15.999		9 F Fluorine 18.998403163		10 Ne Neon 20.1797											
11 Na Sodium 22.98976928		12 Mg Magnesium 24.305												13 Al Aluminium 26.9815385		14 Si Silicon 28.085		15 P Phosphorus 30.973761998		16 S Sulfur 32.06		17 Cl Chlorine 35.45		18 Ar Argon 39.948											
19 K Potassium 39.0983		20 Ca Calcium 40.078												28 Ni Nickel 58.6934		29 Cu Copper 63.546		30 Zn Zinc 65.36		31 Ga Gallium 69.723		32 Ge Germanium 72.830		33 As Arsenic 74.921595		34 Se Selenium 78.971		35 Br Bromine 79.904		36 Kr Krypton 83.798					
37 Rb Rubidium 85.4678		38 Sr Strontium 87.62		39 Y Yttrium 88.90584		40 Zr Zirconium 91.224		41 Nb Niobium 92.90637		42 Mo Molybdenum 95.95		43 Tc Technetium (98)		44 Ru Ruthenium 101.07		45 Rh Rhodium 102.90550		46 Pd Palladium 106.42		47 Ag Silver 107.8682		48 Cd Cadmium 112.414		49 In Indium 114.818		50 Sn Tin 118.710		51 Sb Antimony 121.760		52 Te Tellurium 127.60		53 I Iodine 126.90447		54 Xe Xenon 131.293	
55 Cs Caesium 132.90545196		56 Ba Barium 137.327		57 - 71 Lanthanoids		72 Hf Hafnium 178.49		73 Ta Tantalum 180.94788		74 W Tungsten 183.84		75 Re Rhenium 186.207		76 Os Osmium 190.23		77 Ir Iridium 192.217		78 Pt Platinum 195.084		79 Au Gold 196.966569		80 Hg Mercury 200.597		81 Tl Thallium 204.38		82 Pb Lead 207.2		83 Bi Bismuth 208.98040		84 Po Polonium (209)		85 At Astatine (210)		86 Rn Radon (222)	
87 Fr Francium (223)		88 Ra Radium (226)		89 - 103 Actinoids		104 Rf Rutherfordium (261)		105 Db Dubnium (268)		106 Sg Seaborgium (266)		107 Bh Bohrium (264)		108 Hs Hassium (277)		109 Mt Meitnerium (276)		110 Ds Darmstadtium (281)		111 Rg Roentgenium (282)		112 Cn Copernicium (285)		113 Nh Nihonium (286)		114 Fl Flerovium (289)		115 Mc Moscovium (293)		116 Lv Livermorium (293)		117 Ts Tennessine (294)		118 Og Oganesson (294)	

57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
89 Ac Actinium 227	90 Th Thorium 232.03806	91 Pa Protactinium 231.03689	92 U Uranium 238.02891	93 Np Neptunium 237.04817	94 Pu Plutonium 244.06422	95 Am Americium 243.06138	96 Cm Curium 247.07035	97 Bk Berkelium 247.07035	98 Cf Californium 251.0833	99 Es Einsteinium 252.0833	100 Fm Fermium 257.1035	101 Md Mendelevium 258.1035	102 No Nobelium 259.1035	103 Lr Lawrencium 262.1035

Stellar-born sites (C through U)

Cosmic rays (Be and B)

How are elements produced

Big Bang

(H¹, H², He³, He⁴, Li⁷)

Galactic Chemical Evolution (GCE)
Deals with these successive enrichments

Stellar-born sites (C through U)

Cosmic rays (Be and B)

I IA																				18 VIIIA									
1 H Hydrogen 1.008																			2 He Helium 4.002602										
3 Li Lithium 6.94	4 Be Beryllium 9.0121831																	5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998403163	10 Ne Neon 20.1797						
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305																	13 Al Aluminum 26.9815385	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948						
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.887	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798												
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybdenum 95.95	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293												
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.597	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)												
87 Fr Francium (223)	88 Ra Radium (226)	89 - 103 Actinoids	104 Rf Rutherfordium (261)	105 Db Dubnium (268)	106 Sg Seaborgium (266)	107 Bh Bohrium (270)	108 Hs Hassium (277)	109 Mt Meitnerium (276)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (288)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)												

57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
89 Ac Actinium 227	90 Th Thorium 232.0377	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium 237.04817	94 Pu Plutonium 244.0642	95 Am Americium 243.0613	96 Cm Curium 247.07035	97 Bk Berkelium 247.07035	98 Cf Californium 251.0832	99 Es Einsteinium 252.0832	100 Fm Fermium 257.1035	101 Md Mendelevium 258.1035	102 No Nobelium 259.1035	103 Lr Lawrencium 262.1035

How are elements produced

Big Bang

(H¹, H², He³, He⁴, Li⁷)

Galactic Chemical Evolution (GCE)
Deals with these successive enrichments

Stellar-born sites (C through U)

Cosmic rays (Be and B)

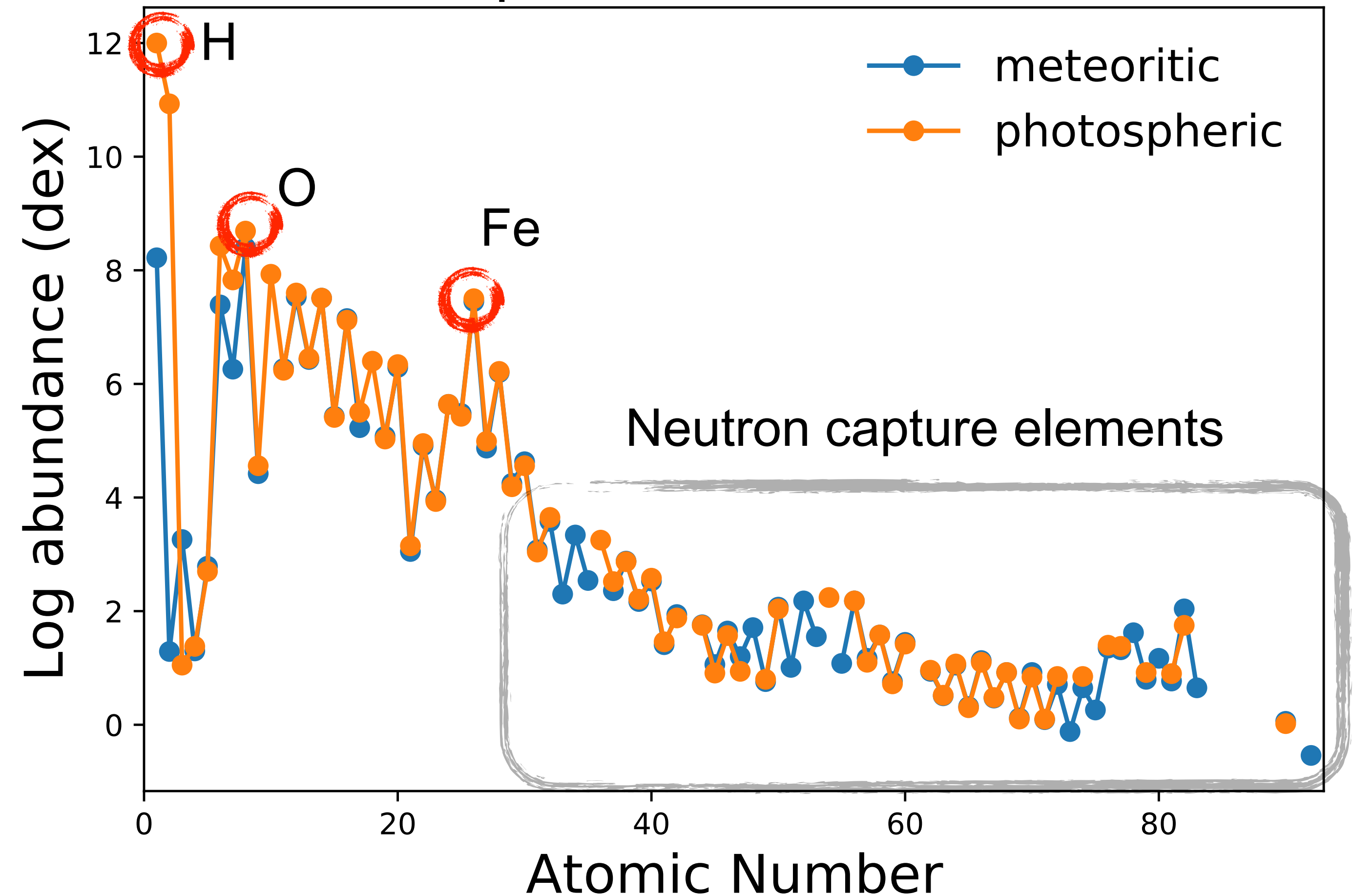
1 IA																2 IIA										13 IIIA										14 IVA										15 VA										16 VIA										17 VIIA										18 VIIIA																																																																																																					
3 H Hydrogen 1.008																4 Li Lithium 6.94										5 Be Beryllium 9.0121831																																																												6 He Helium 4.002602																																																																																											
11 Na Sodium 22.98976928																12 Mg Magnesium 24.305										3 IIIB										4 IVB										5 VB										6 VIB										7 VIIB										8 VIII B										9 VIII B										10 VIII B										11 IB										12 IIB										13 Al Aluminium 26.9815385										14 Si Silicon 28.085										15 P Phosphorus 30.973761998										16 S Sulfur 32.06										17 Cl Chlorine 35.45										18 Ar Argon 39.948	
19 K Potassium 39.0983																20 Ca Calcium 40.078										21 Sc Scandium 44.955908										22 Ti Titanium 47.887										23 V Vanadium 50.9415										24 Cr Chromium 51.9961										25 Mn Manganese 54.938044										26 Fe Iron 55.845										27 Co Cobalt 58.933194										28 Ni Nickel 58.6934										29 Cu Copper 63.546										30 Zn Zinc 65.36										31 Ga Gallium 69.723										32 Ge Germanium 72.630										33 As Arsenic 74.921595										34 Se Selenium 78.971										35 Br Bromine 79.904										36 Kr Krypton 83.798	
37 Rb Rubidium 85.4678																38 Sr Strontium 87.62										39 Y Yttrium 88.90584										40 Zr Zirconium 91.224										41 Nb Niobium 92.90637										42 Mo Molybdenum 95.95										43 Tc Technetium (98)										44 Ru Ruthenium 101.07										45 Rh Rhodium 102.90550										46 Pd Palladium 106.42										47 Ag Silver 107.8682										48 Cd Cadmium 112.414										49 In Indium 114.818										50 Sn Tin 118.710										51 Sb Antimony 121.760										52 Te Tellurium 127.60										53 I Iodine 126.90447										54 Xe Xenon 131.293	
55 Cs Caesium 132.90545196																56 Ba Barium 137.327										57 - 71 Lanthanoids										72 Hf Hafnium 178.49										73 Ta Tantalum 180.94788										74 W Tungsten 183.84										75 Re Rhenium 186.207										76 Os Osmium 190.23										77 Ir Iridium 192.217										78 Pt Platinum 195.084										79 Au Gold 196.966569										80 Hg Mercury 200.597										81 Tl Thallium 204.38										82 Pb Lead 207.2										83 Bi Bismuth 208.98040										84 Po Polonium (209)										85 At Astatine (210)										86 Rn Radon (222)	
87 Fr Francium (223)																88 Ra Radium (226)										89 - 103 Actinoids										104 Rf Rutherfordium (261)										105 Db Dubnium (268)										106 Sg Seaborgium (269)										107 Bh Bohrium (270)										108 Hs Hassium (269)										109 Mt Meitnerium (278)										110 Ds Darmstadtium (281)										111 Rg Roentgenium (282)										112 Cn Copernicium (285)										113 Nh Nihonium (286)										114 Fl Flerovium (289)										115 Mc Moscovium (289)										116 Lv Livermorium (293)										117 Ts Tennessine (294)										118 Og Oganesson (294)	
57 La Lanthanum 138.90547																58 Ce Cerium 140.16										59 Pr Praseodymium 140.90766										60 Nd Neodymium 144.242										61 Pm Promethium (145)										62 Sm Samarium 150.36										63 Eu Europium 151.964										64 Gd Gadolinium 157.25										65 Tb Terbium 158.92535										66 Dy Dysprosium 162.500										67 Ho Holmium 164.93033										68 Er Erbium 167.259										69 Tm Thulium 168.93422										70 Yb Ytterbium 173.045										71 Lu Lutetium 174.9668																															
89 Ac Actinium (227)																90 Th Thorium 232.03772										91 Pa Protactinium 231.03688										92 U Uranium 238.02891										93 Np Neptunium (237)										94 Pu Plutonium (244)										95 Am Americium (243)										96 Cm Curium (247)										97 Bk Berkelium (247)										98 Cf Californium (251)										99 Es Einsteinium (252)										100 Fm Fermium (257)										101 Md Mendelevium (261)										102 No Nobelium (259)										103 Lr Lawrencium (260)																															

Since when did we start learning where elements come from?

Chemical abundances in the Sun

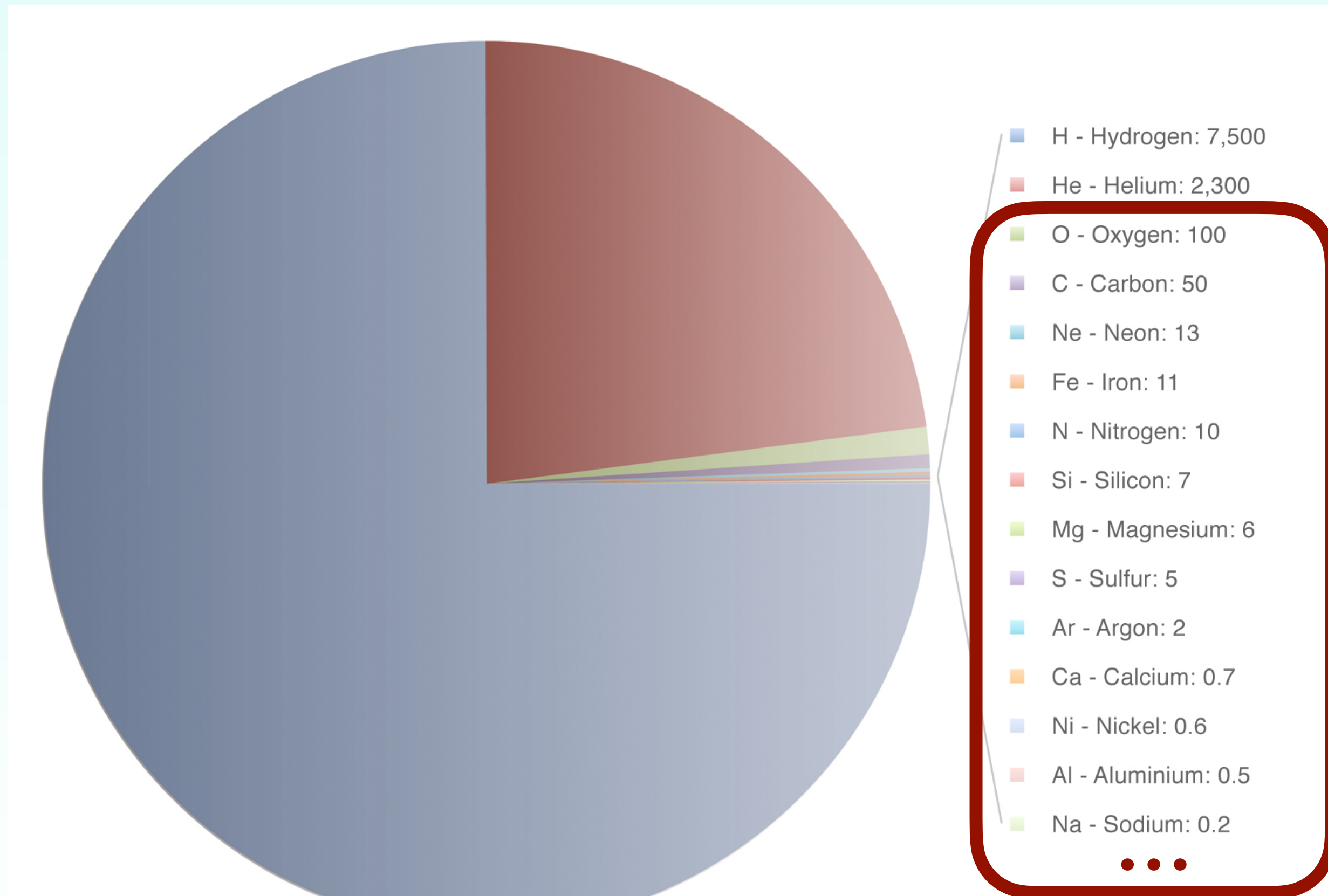
- Relevant notations:
 - dex is $\log \epsilon_X = \log (N_X/N_H) + 12$
 - Where H is defined as: $\log \epsilon_H = 12$
 - Later, abundance notation:
 - $[X/H] = \log_{10} (X/H)_* - \log_{10} (X/H)_\odot$
- Neutron-capture elements are among the least abundant elements in nature
 - ~6 dex lower than Oxygen, ~10 dex lower than H

With data from: Asplund et al. (2009)



Why astrophysical metals (Z) are all elements but H and He?

Cosmic Gas Abundances as measured by the CHANDRA X-ray Observatory



- GCE studies the production of **elements** and **isotopes** over the lifetime of a galaxy.
- Questions we want to answer:
 - *What history may have lead to present-day observed abundances?*
 - *How do these abundances change with environment?*

Metallicity (Z), Only 2% of the ISM

(Credit: NASA/CXC/M.Weiss)

THE PERIODIC TABLE OF ELEMENTS

1

H

HYDROGEN

1.008

H

Symbol Key

Atomic number

1

Element symbol

H

Element name

HYDROGEN

Relative atomic mass

1.008

Block

Colour Key

s block elements

p block elements

d block elements

f block elements

He

2

He

HELIUM

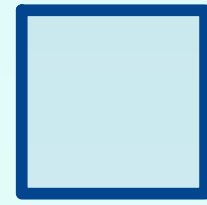
4.003

Li LITHIUM 6.941	Be BERYLLIUM 9.012									B BORON 10.811	C CARBON 12.011	N NITROGEN 14.007	O OXYGEN 15.999	F FLUORINE 18.998	Ne NEON 20.180		
11 Na SODIUM 22.990	12 Mg MAGNESIUM 24.305									13 Al ALUMINUM 26.982	14 Si SILICON 28.086	15 P PHOSPHORUS 30.974	16 S SULFUR 32.065	17 Cl CHLORINE 35.453	18 Ar ARGON 39.948		
19 K POTASSIUM 39.098	20 Ca CALCIUM 40.078	21 Sc SCANDIUM 44.956	22 Ti TITANIUM 47.867	23 V VANADIUM 50.942	24 Cr CHROMIUM 51.996	25 Mn MANGANESE 54.938	26 Fe IRON 55.845	27 Co COBALT 58.933	28 Ni NICKEL 58.693	29 Cu COPPER 63.546	30 Zn ZINC 65.382	31 Ga GALLIUM 69.723	32 Ge GERMANIUM 72.640	33 As ARSENIC 74.922	34 Se SELENIUM 78.971	35 Br BROMINE 79.904	36 Kr KRYPTON 83.798
37 Rb RUBIDIUM 85.468	38 Sr STRONTIUM 87.620	39 Y YTTRIUM 88.906	40 Zr ZIRCONIUM 91.224	41 Nb NIOBIUM 92.906	42 Mo MOLYBDENUM 95.951	43 Tc TECHNETIUM (97.907)	44 Ru RUTHENIUM 101.072	45 Rh RHODIUM 102.905	46 Pd PALLADIUM 106.421	47 Ag SILVER 107.868	48 Cd CADMIUM 112.414	49 In INDIUM 114.818	50 Sn TIN 118.710	51 Sb ANTIMONY 121.760	52 Te TELLURIUM 127.603	53 I IODINE 126.904	54 Xe XENON 131.294
55 Cs CAESIUM 132.905	56 Ba BARIUM 137.328	E57-71	72 Hf HAFNIUM 178.492	73 Ta TANTALUM 180.948	74 W TUNGSTEN 183.841	75 Re RHENIUM 186.207	76 Os OSMIUM 190.234	77 Ir IRIDIUM 192.222	78 Pt PLATINUM 195.084	79 Au GOLD 196.967	80 Hg MERCURY 200.592	81 Tl THALLIUM 204.383	82 Pb LEAD 207.210	83 Bi BISMUTH 208.980	84 Po POLONIUM (209.982)	85 At ASTATINE (209.987)	86 Rn RADON (222.018)
87 Fr FRANCIUM (223.020)	88 Ra RADIUM (226.025)	E89-103	104 Rf RUTHERFORDIUM (261.109)	105 Db DUBNIUM (262.114)	106 Sg SEABORGIUM (266.122)	107 Bh BOHRIUM (264.120)	108 Hs HASSIUM (277.103)	109 Mt MEITNERIUM (288.106)	110 Ds DARMSTADTIUM (285.108)	111 Rg ROENTGENIUM (280.000)	112 Cn COPERNICIUM (285.000)	113 Nh NIHONIUM (286.000)	114 Fl FLEROVIUM (289.000)	115 Mc MOSCOWIUM (289.000)	116 Lv LIVERMORIUM (293.000)	117 Ts TENNESSINE (294.000)	118 Og OGANESSON (294.000)
			57 La LANTHANUM 138.905	58 Ce CERIUM 140.116	59 Pr PRASEODYMIUM 140.908	60 Nd NEODYMIUM 144.242	61 Pm PROMETHIUM (144.000)	62 Sm SAMARIUM 150.362	63 Eu EUROPIUM 151.964	64 Gd GADOLINIUM 157.253	65 Tb TERBIUM 158.925	66 Dy DYSPROSIUM 162.500	67 Ho HOLMIUM 164.930	68 Er ERBIUM 167.259	69 Tm THULIUM 168.934	70 Yb YTTERBIUM 173.054	71 Lu LUTECIUM 174.967
			89 Ac ACTINIUM (227.028)	90 Th THORIUM (232.038)	91 Pa PROTACTINIUM (231.036)	92 U URANIUM (238.029)	93 Np NEPTUNIUM (237.048)	94 Pu PLUTONIUM (244.064)	95 Am AMERICIUM (243.061)	96 Cm CURIUM (247.070)	97 Bk BERKELIUM (247.070)	98 Cf CALIFORNIUM (251.080)	99 Es EINSTEINIUM (252.083)	100 Fm FERMIUM (257.095)	101 Md MENDELEVIUM (258.098)	102 No NOBELIUM (259.101)	103 Lr LAWRENCIUM (262.110)



© Andy Brunning/Compound Interest 2017 – www.compoundchem.com | Facebook: facebook.com/compoundchem | Twitter: [@compoundchem](https://twitter.com/compoundchem)
 This graphic is shared under a Creative Commons 4.0 Attribution-NoDerivatives-NonCommercial licence.



 H

He 

Z

Missing in B2FH: Galactic Chemical Evolution (GCE)

In short, GCE is the field that integrates YIELDS from nucleosynthesis sites over the evolutionary history of galaxies.

Nucleosynthesis sites

Thermo
nuclear
fusionneutron-rich
mediaNovae and
SNe

BBN

cosmic
rays

dust

Outflows

SFR

stellar
migr.

AGN

IMF

Infall

assembly

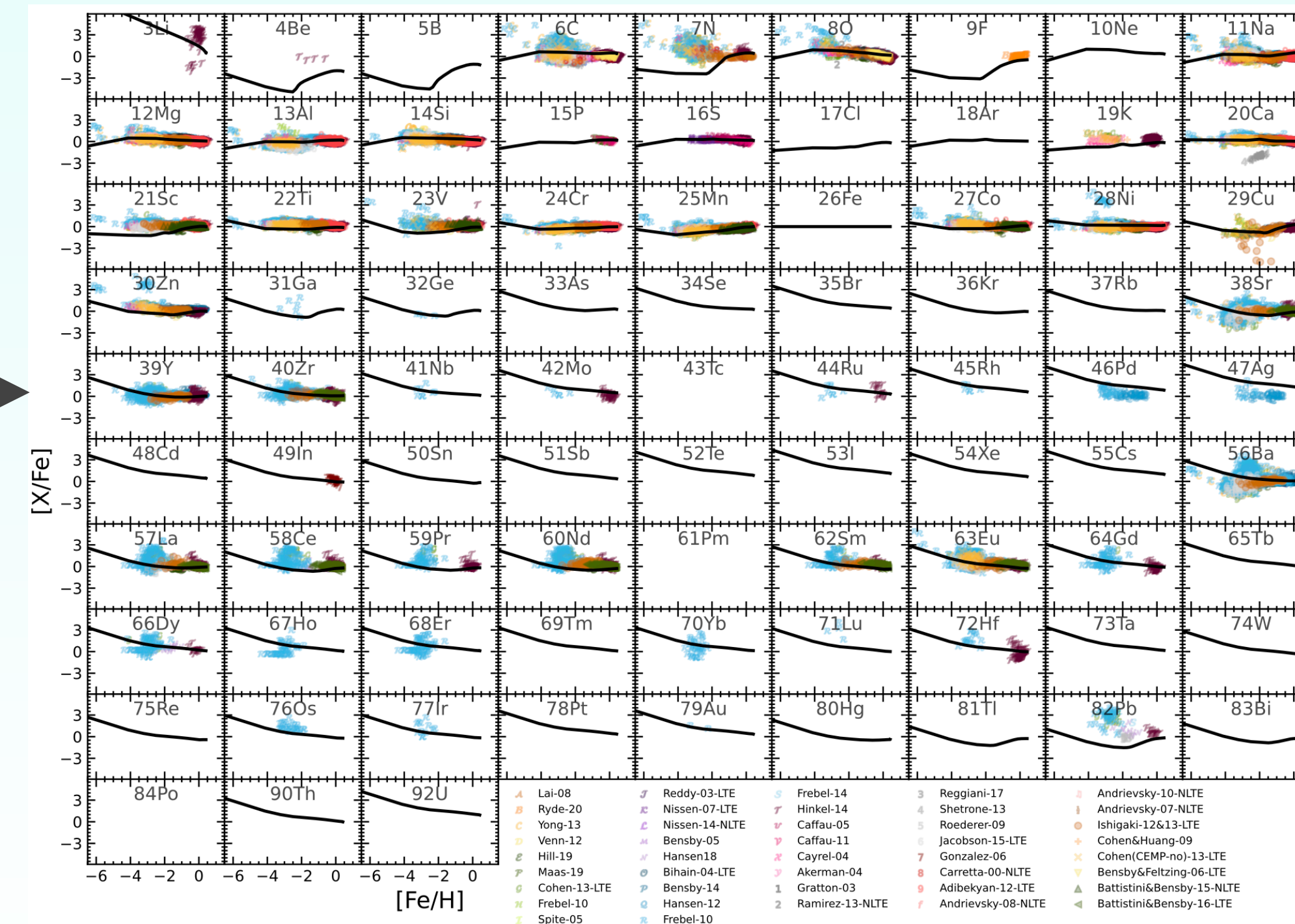
Galaxy properties



GCE

e.g.:

Gjergo+23



Missing in B2FH: Galactic Chemical Evolution (GCE)

In short, GCE is the field that integrates YIELDS from nucleosynthesis sites over the evolutionary history of galaxies.

Nucleosynthesis sites

Thermo
nuclear
fusion

neutron-rich
media

Novae and
SNe

BBN

cosmic
rays

dust

Outflows

SFR

AGN

stellar
migr.

IMF

Infall

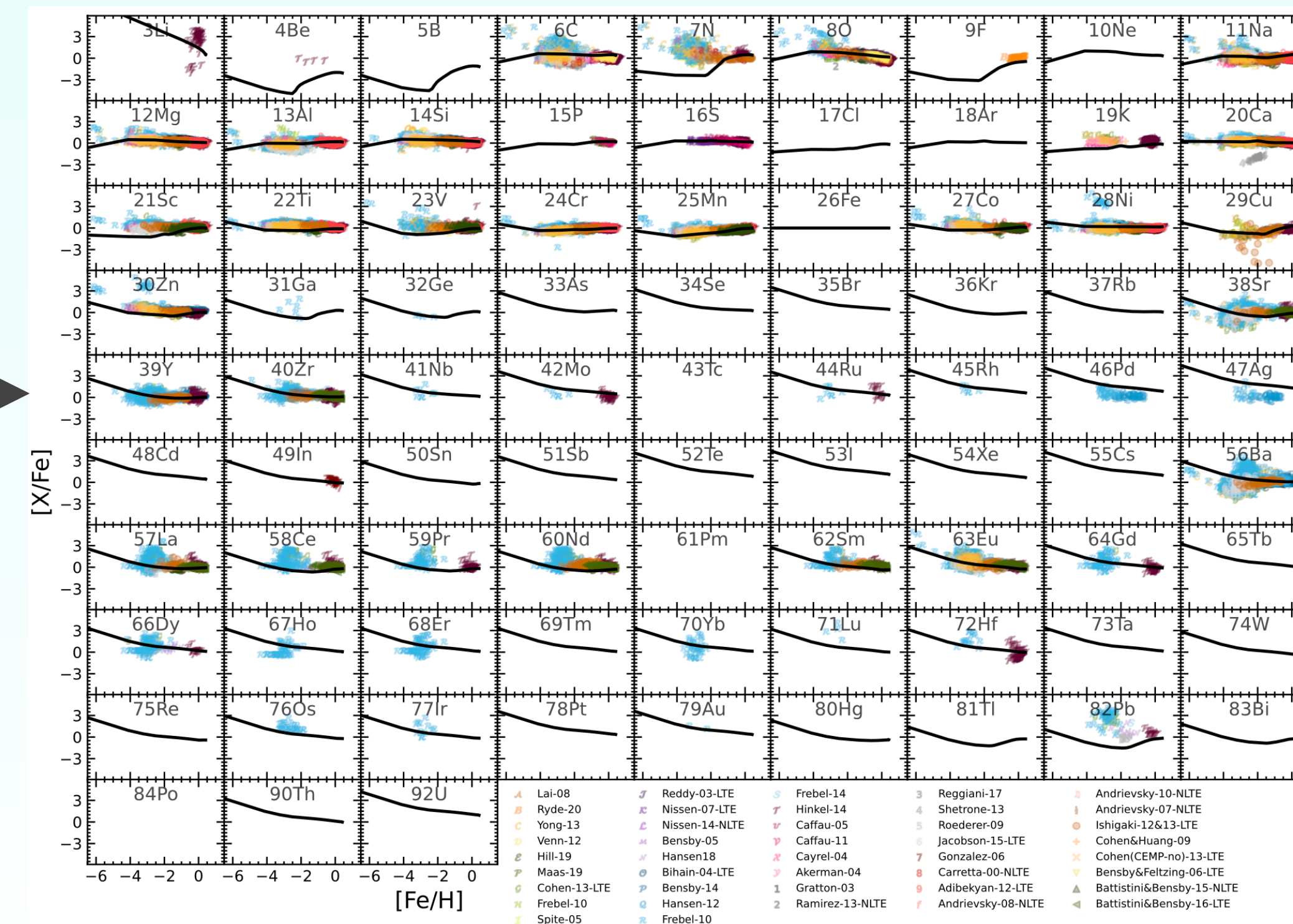
assembly

Galaxy properties

GCE

e.g.:

Gjergo+23



Missing in B2FH: Galactic Chemical Evolution (GCE)

In short, GCE is the field that integrates YIELDS from nucleosynthesis sites over the evolutionary history of galaxies.

Nucleosynthesis sites

Thermo
nuclear
fusion

neutron-rich
media

Novae and SNe

BBN

cosmic
rays

Infall

IMF

Outflows

dust

AGN

SFR

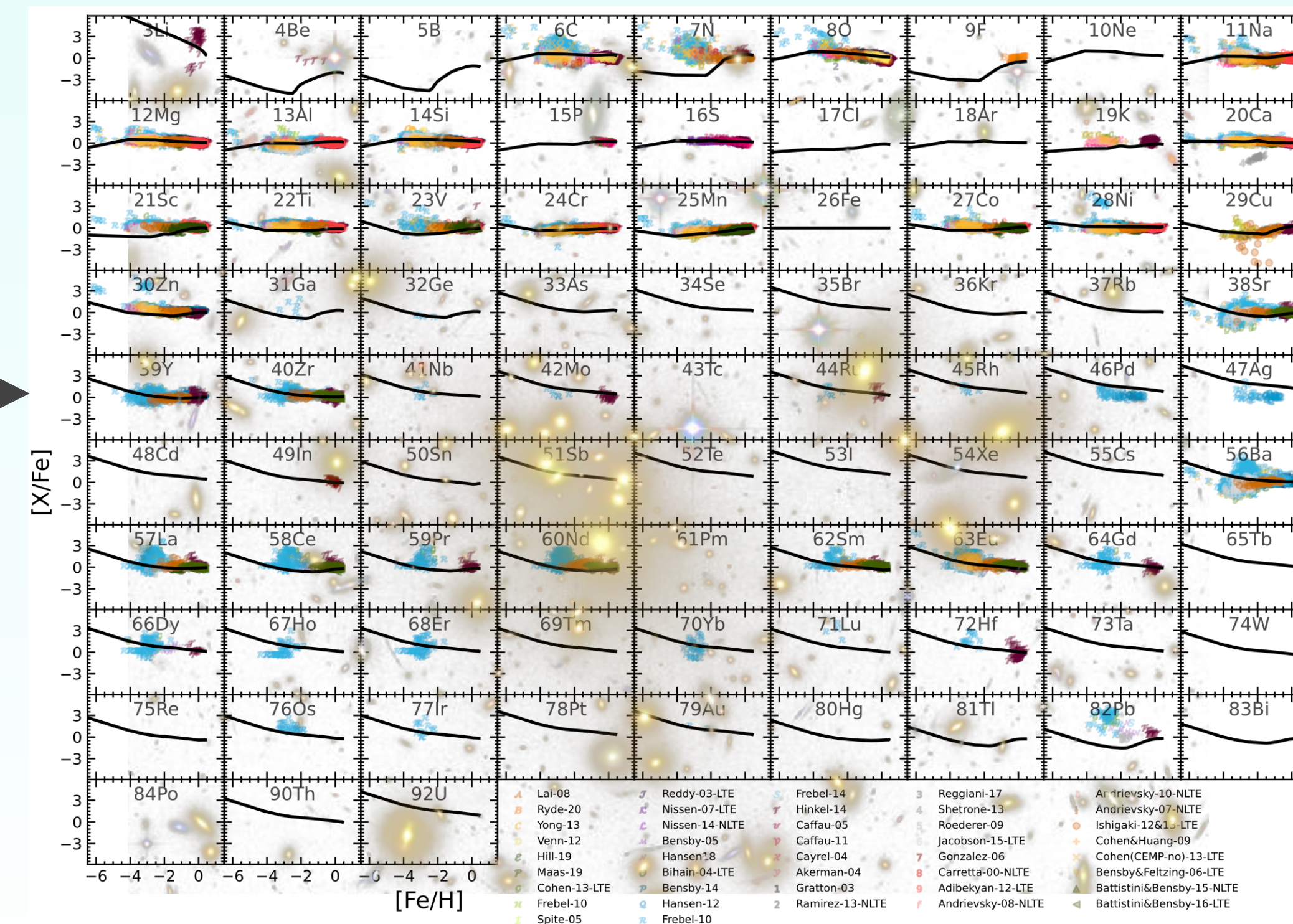
stellar
migr.

assembly

Galaxy properties

e.g.:

Gjergo+23



How does GCE reconstruct stellar populations?

We need to know which stars form at which times.

total stellar mass
produced
per unit time

$$\frac{dM_*}{dt}$$

SFR and IMF
are crucial

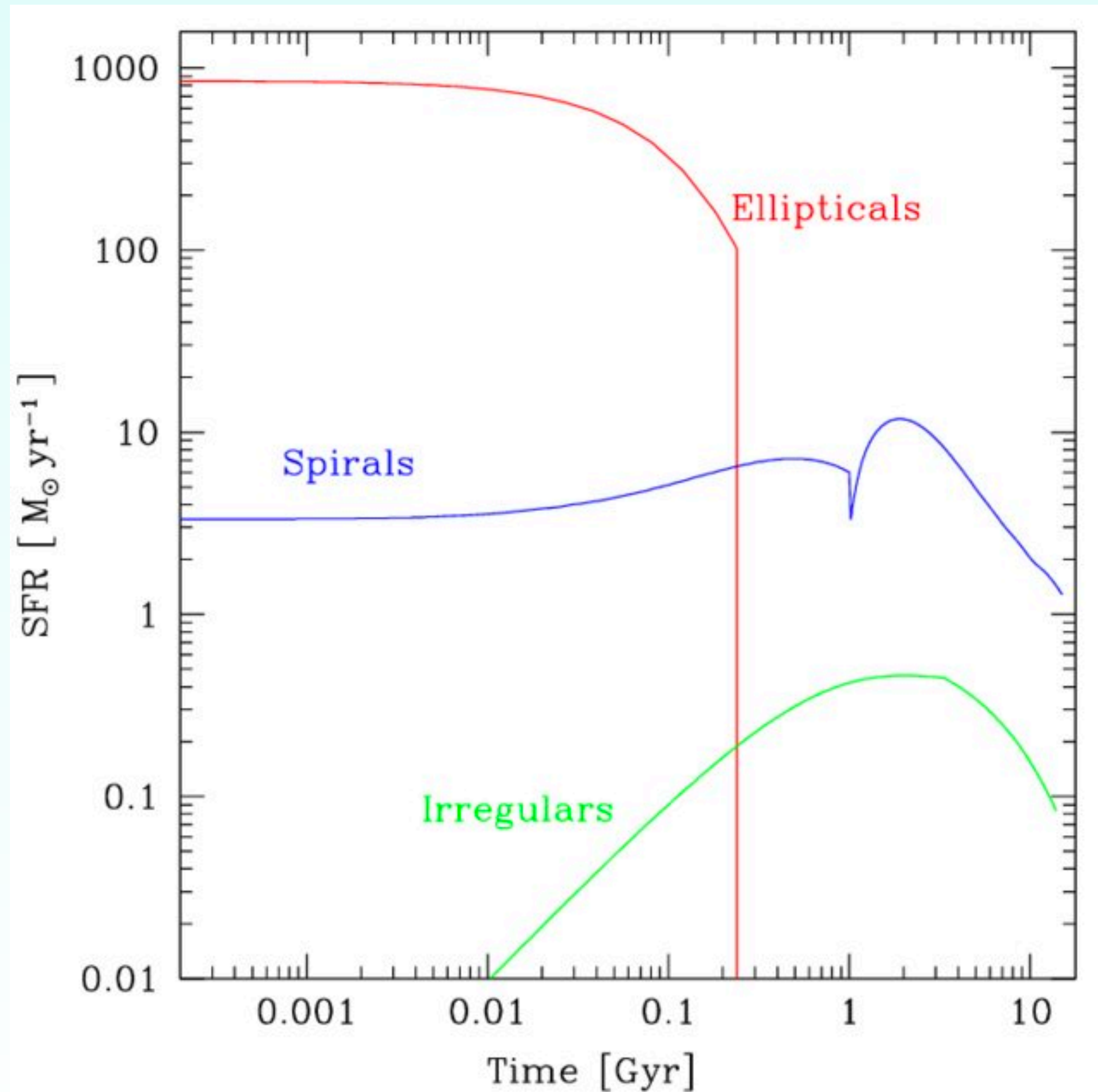
distribution of
newborn stars as a
function of mass

$$\frac{dN_*}{dm}$$

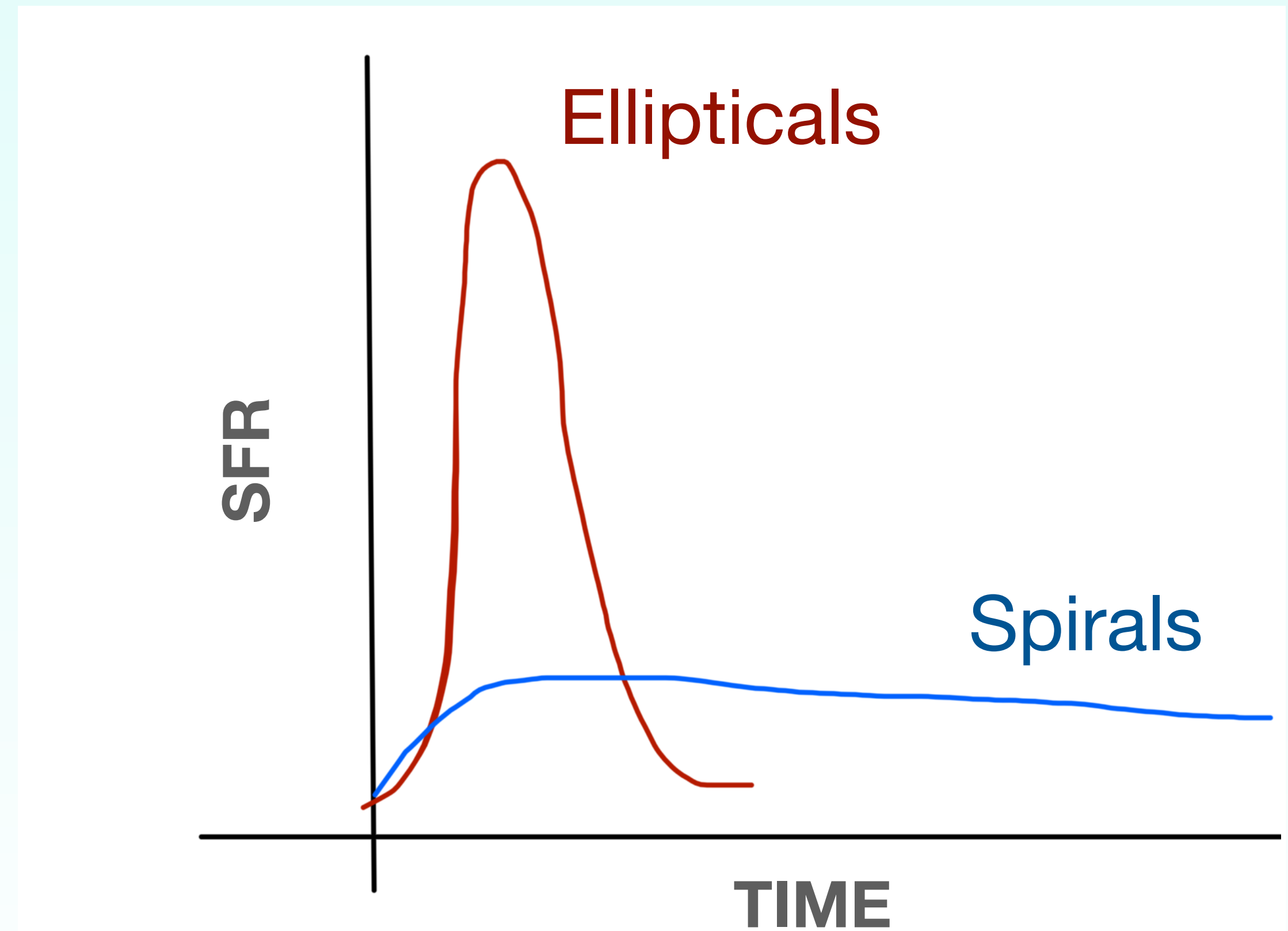
in reconstructing the
Birthrate function $\mathcal{B}$

$$\mathcal{B}(m, t) = \text{SFR}(t) \times \text{IMF}(m)$$

The other core ingredient: Star formation in galaxies

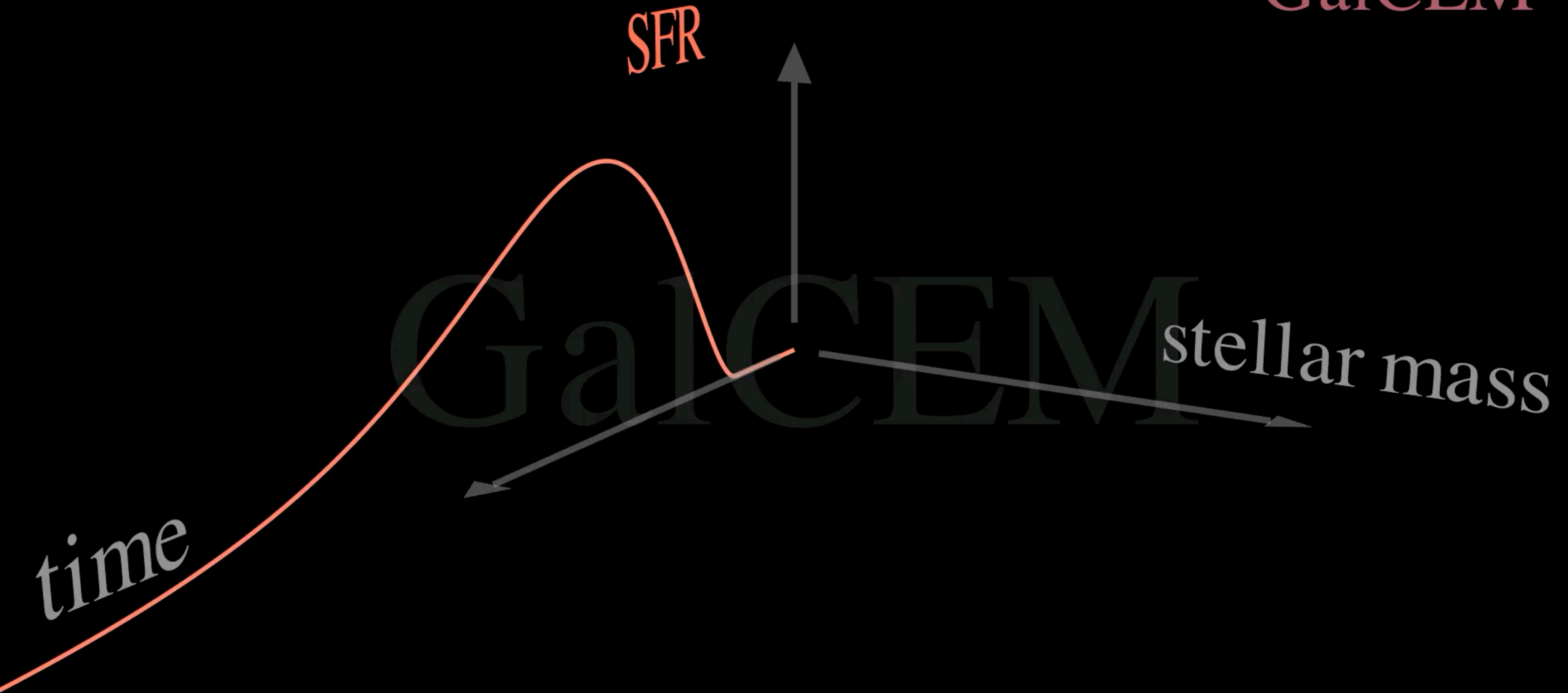


Bissaldi et al. (2007)

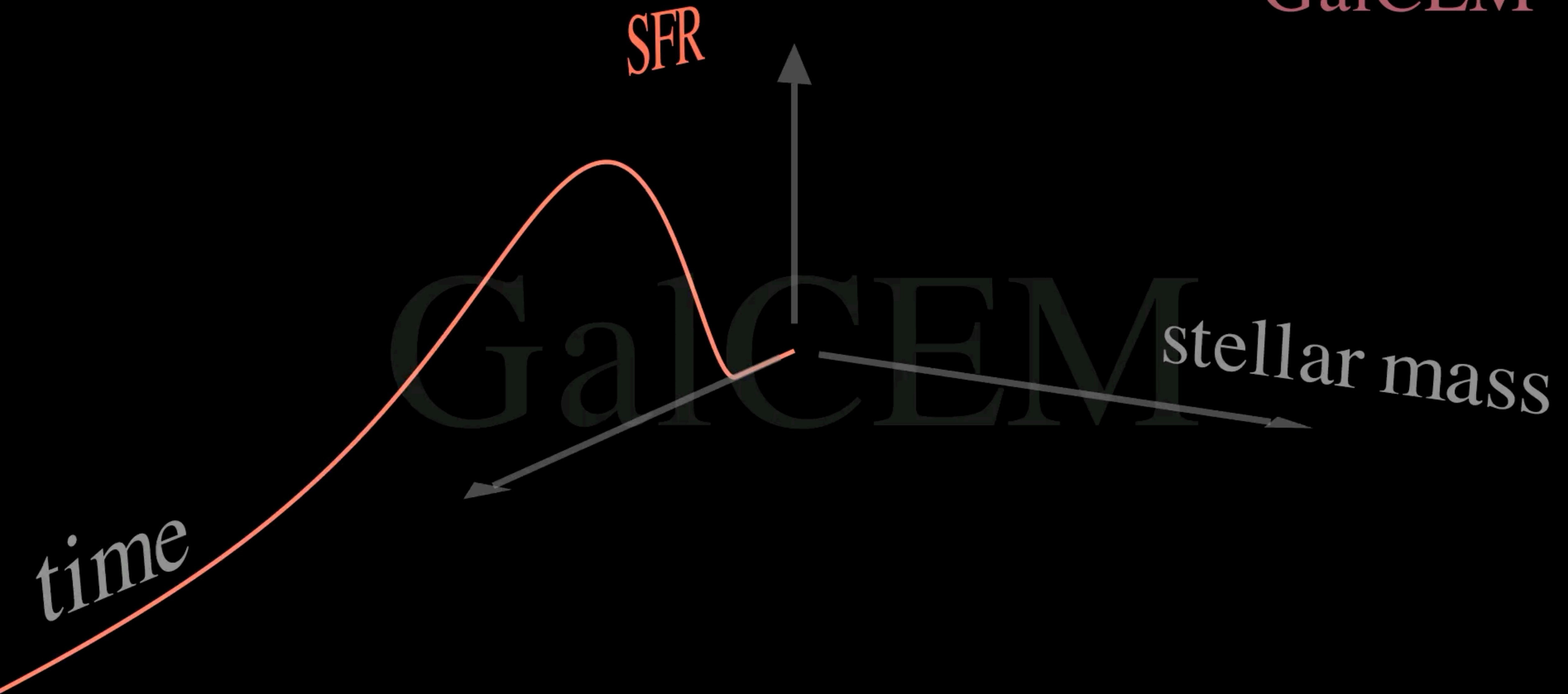


Conceptually...

GalCEM



GalCEM



GalCEM



GalCEM



GalCEM

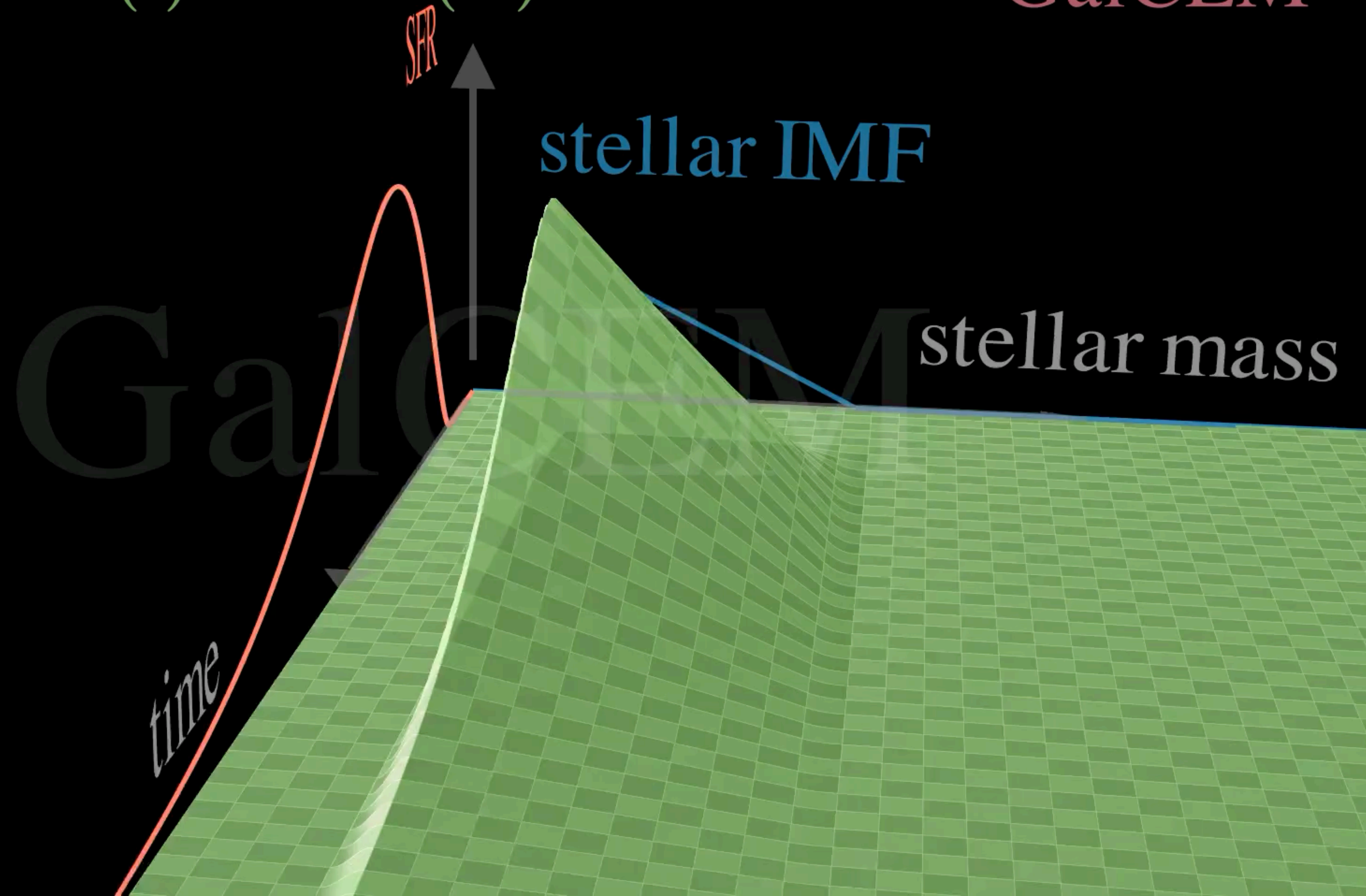


GalCEM



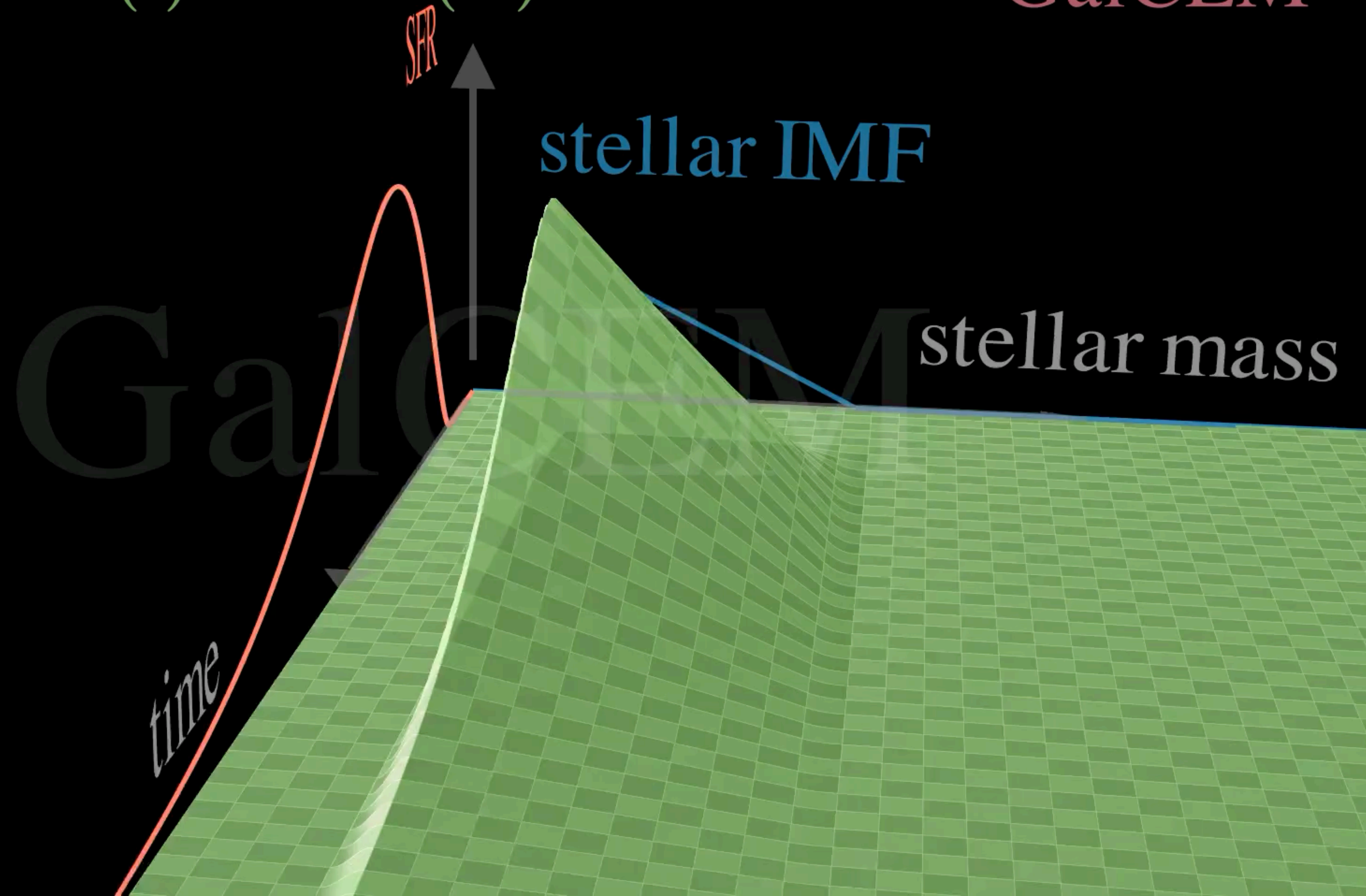
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



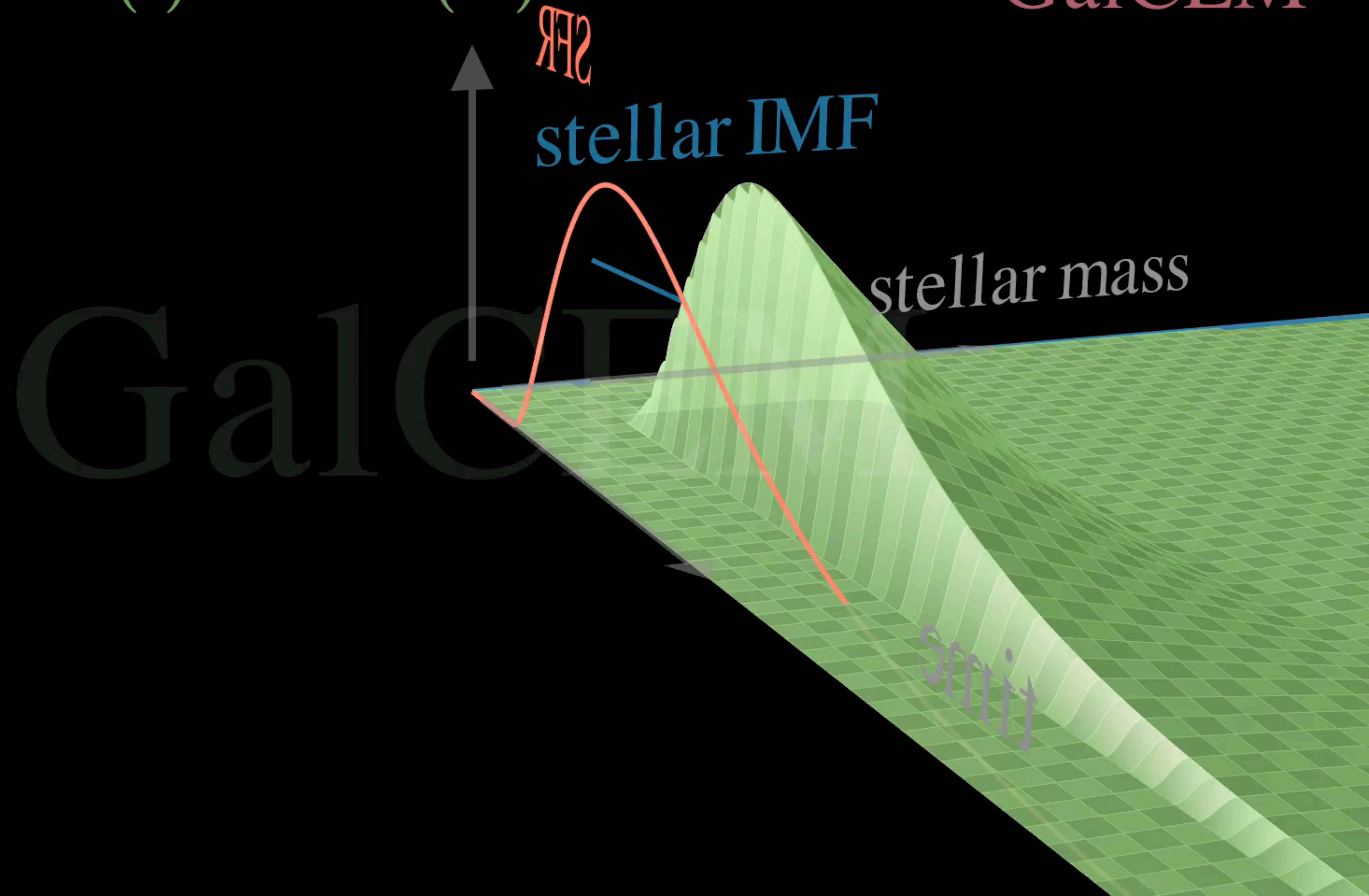
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



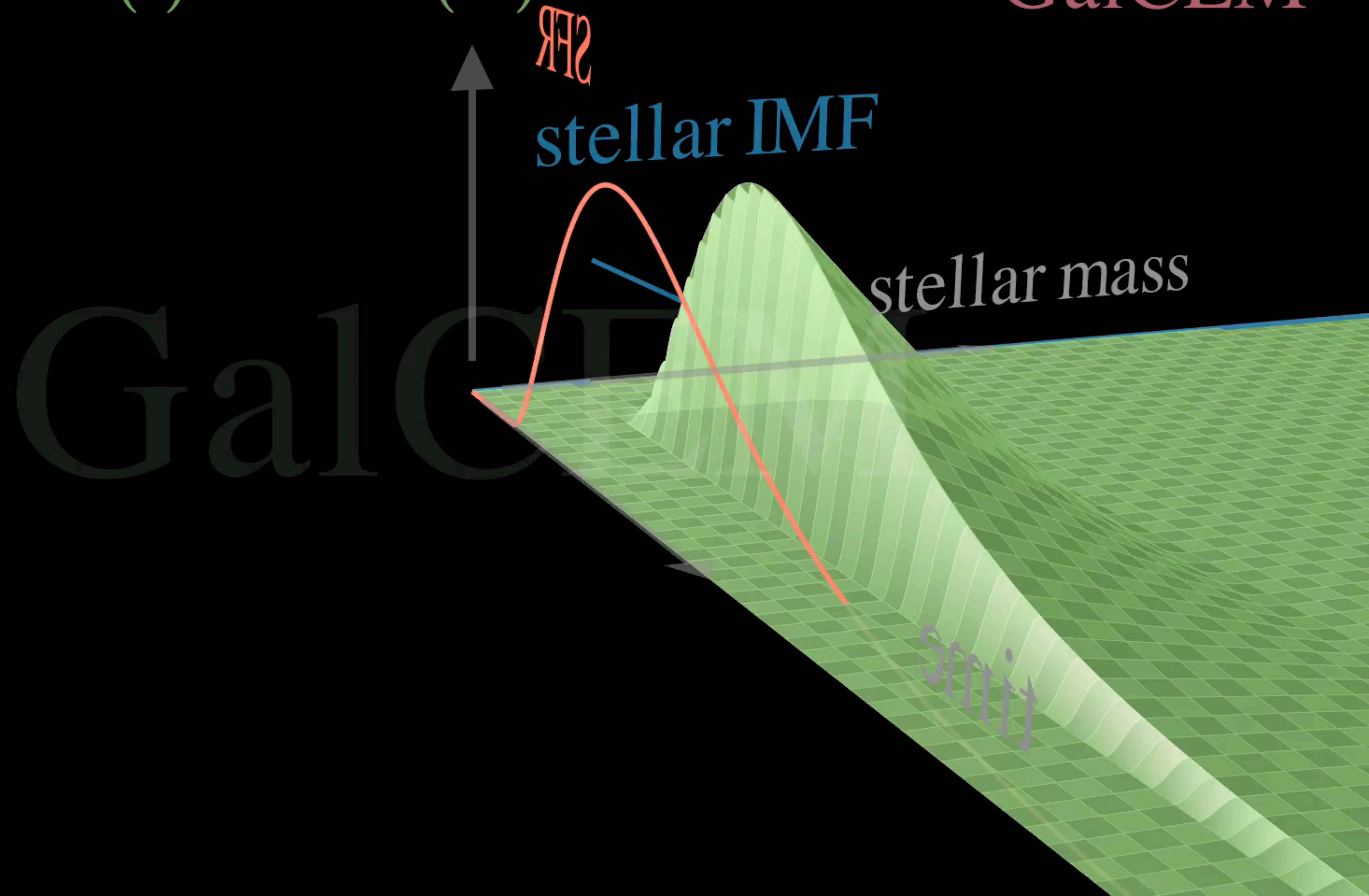
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



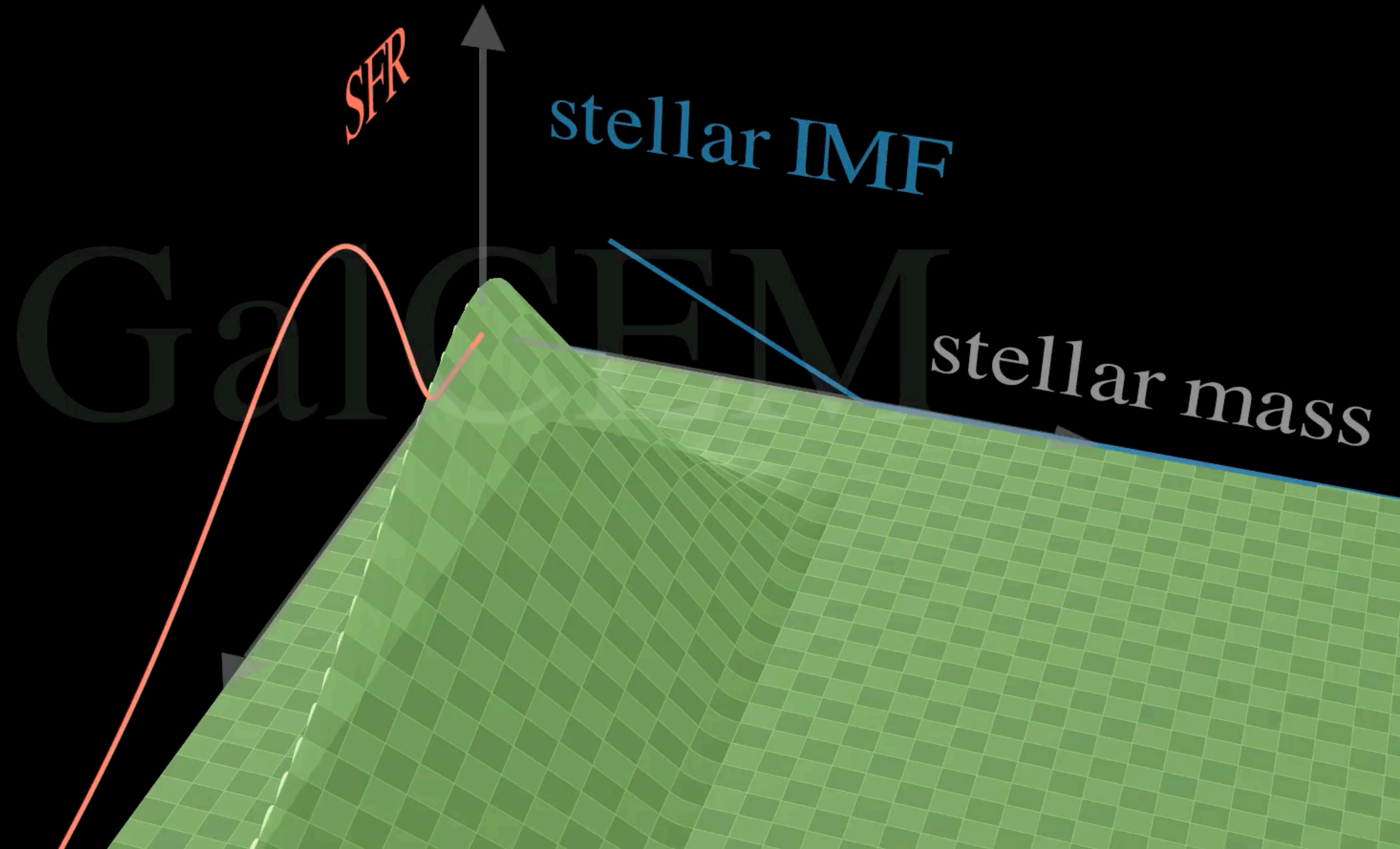
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



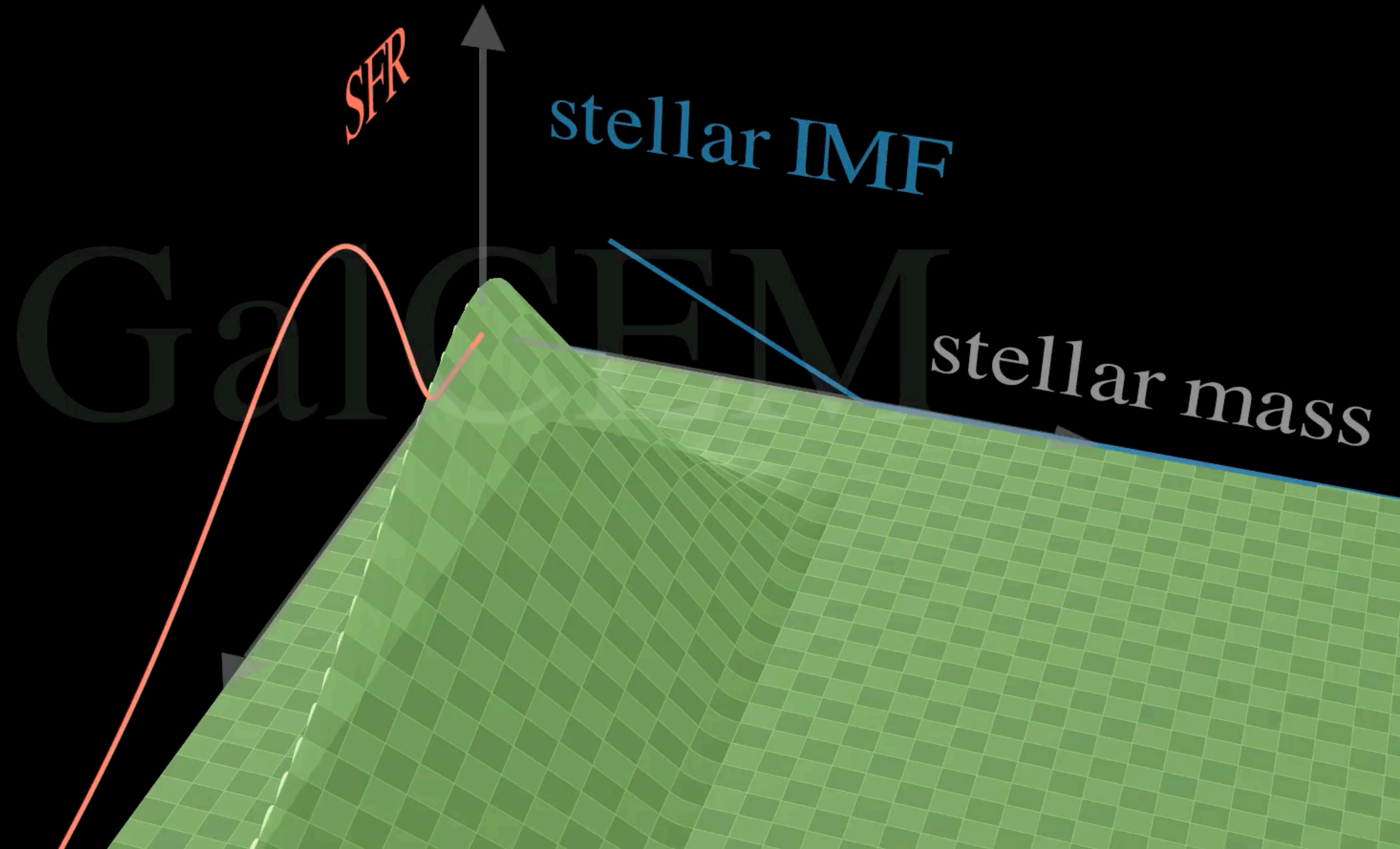
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



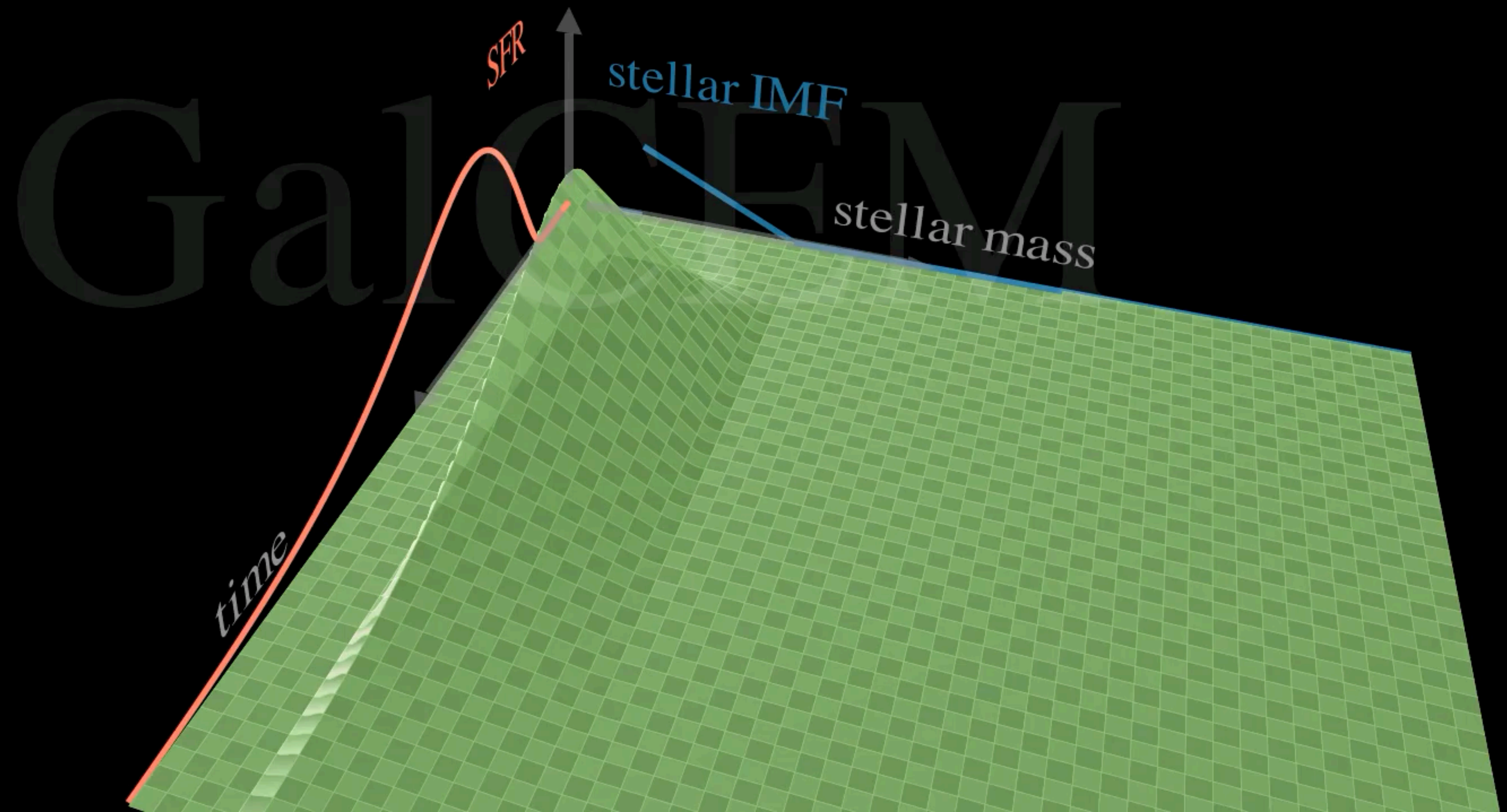
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



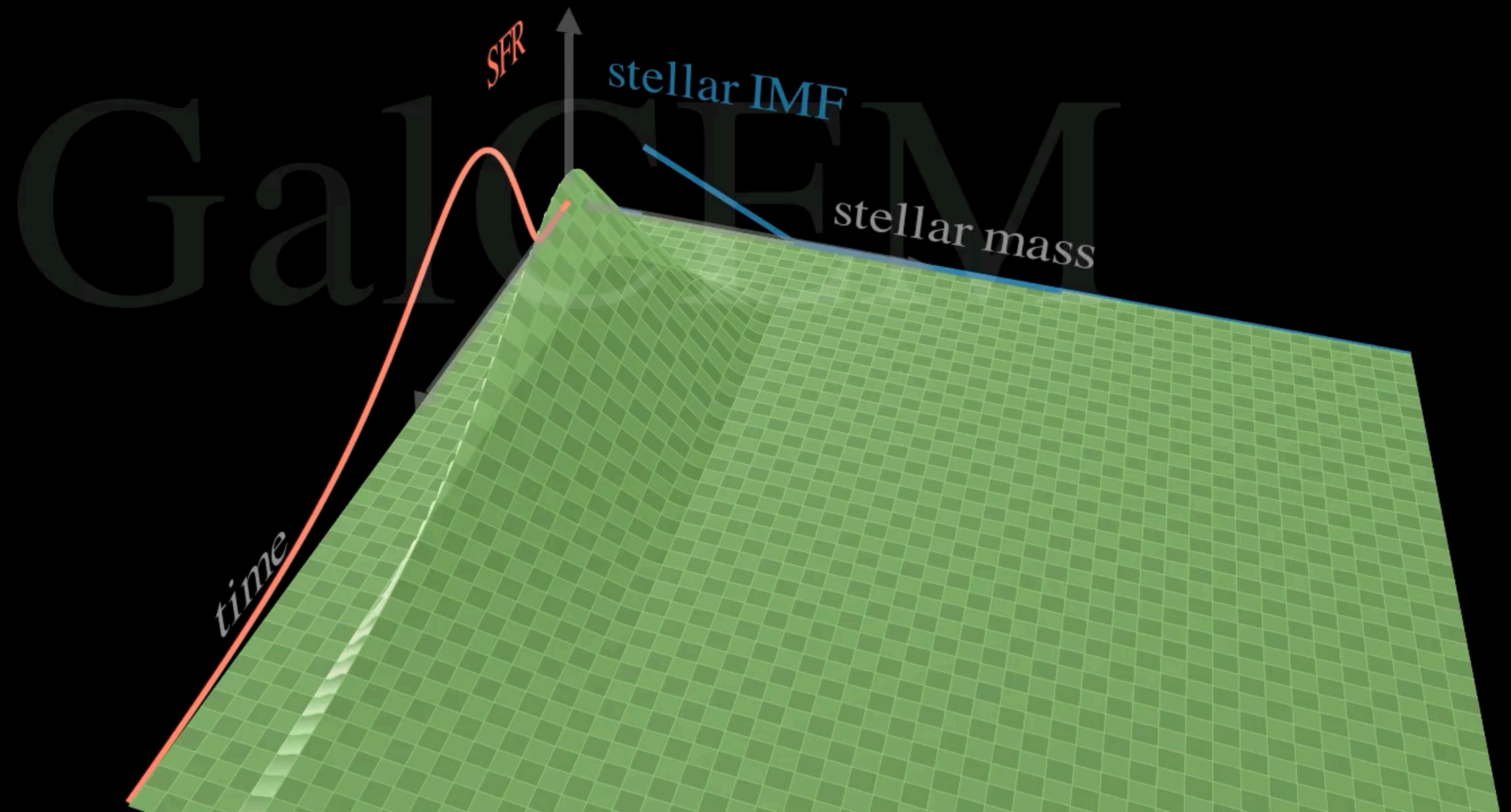
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



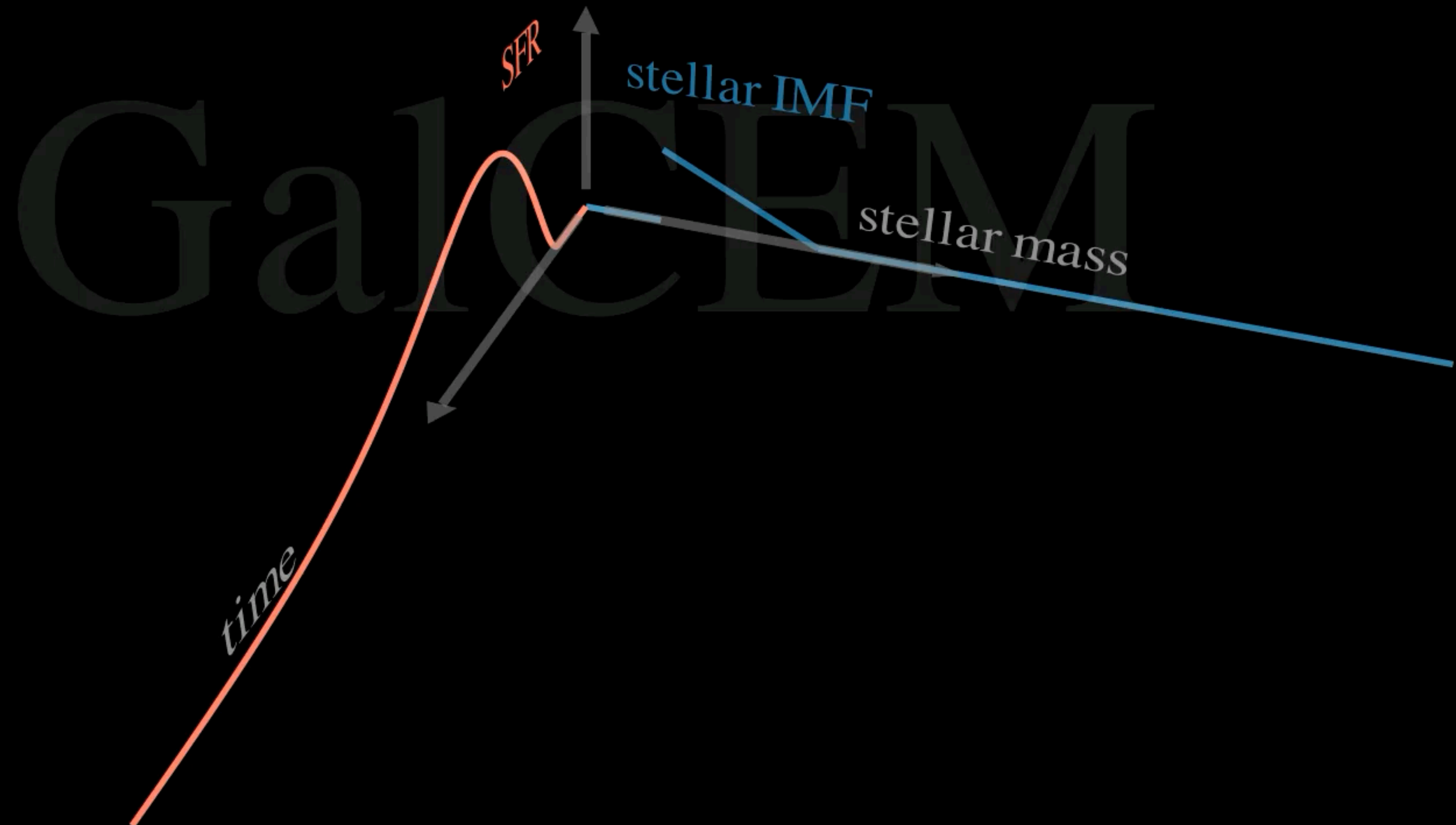
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



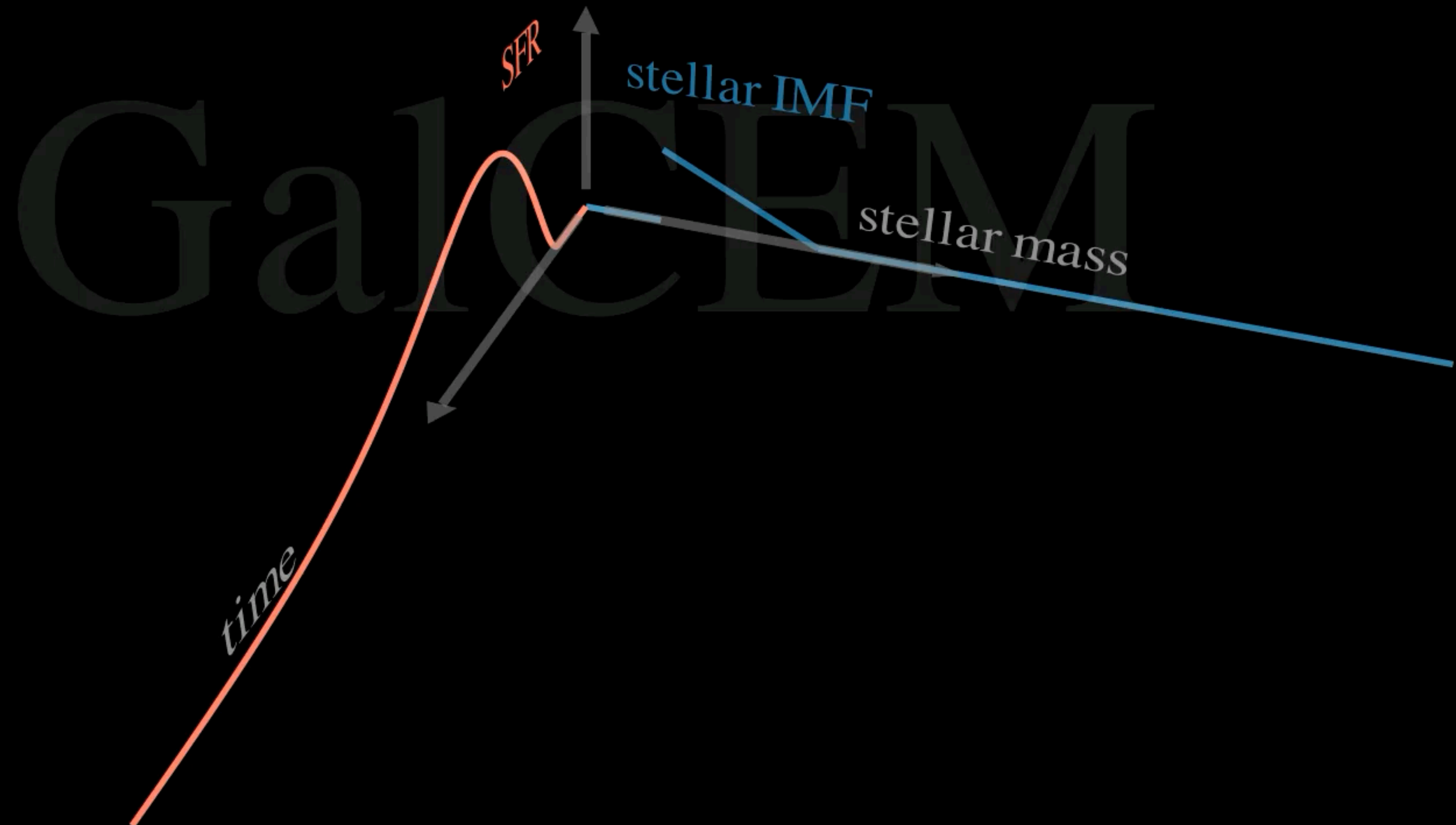
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



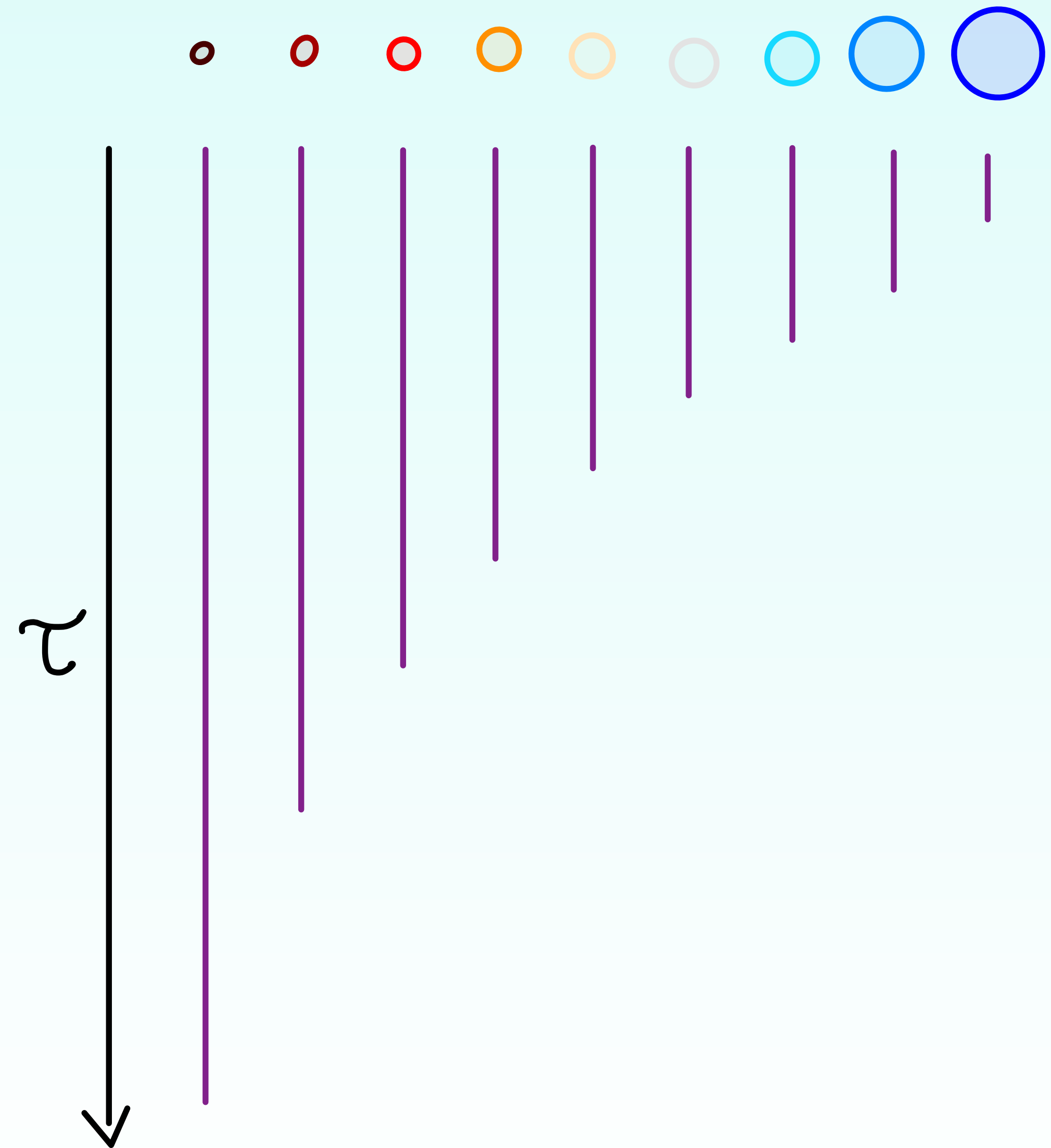
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

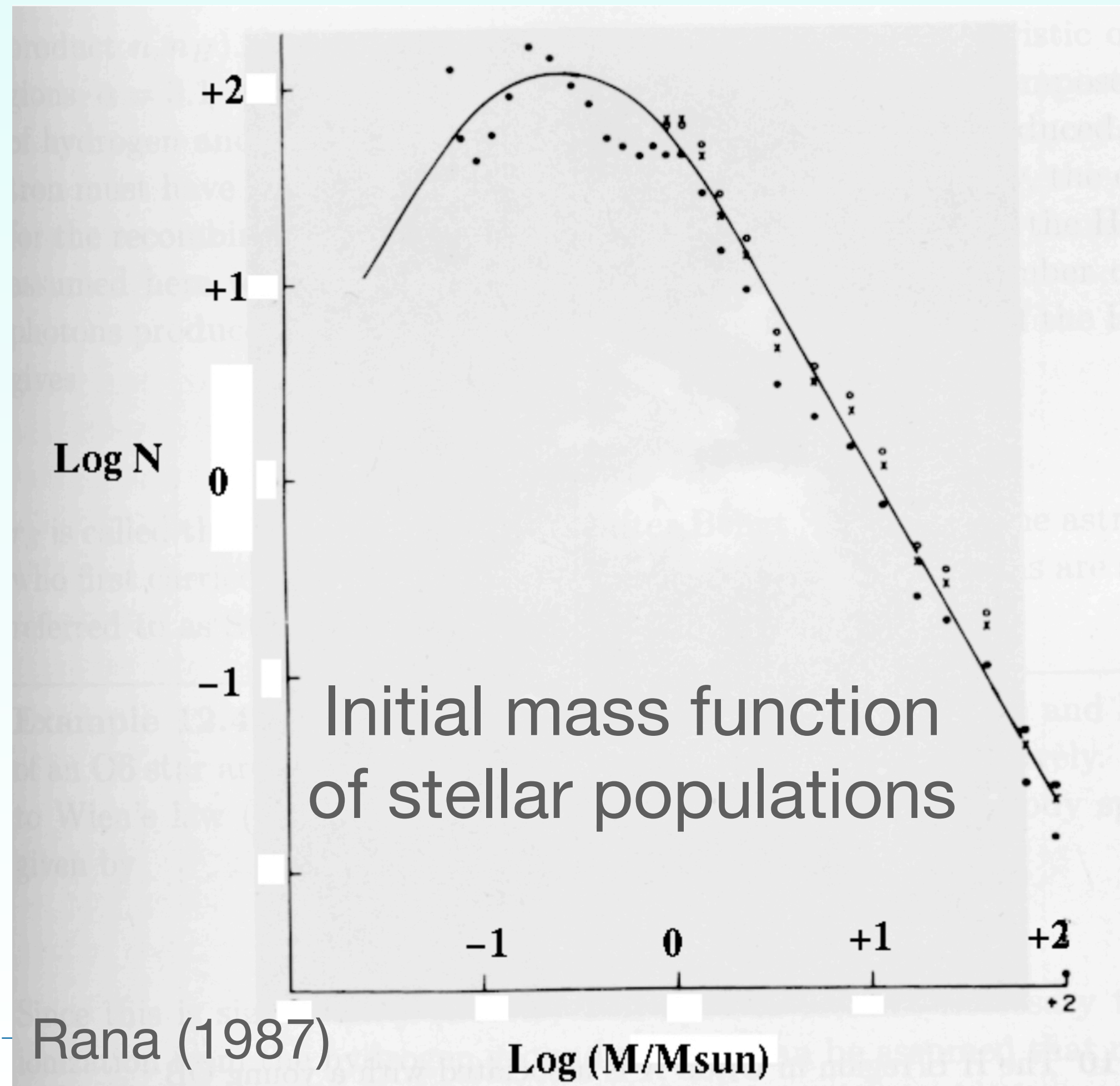


Stellar lifetimes of single stellar populations

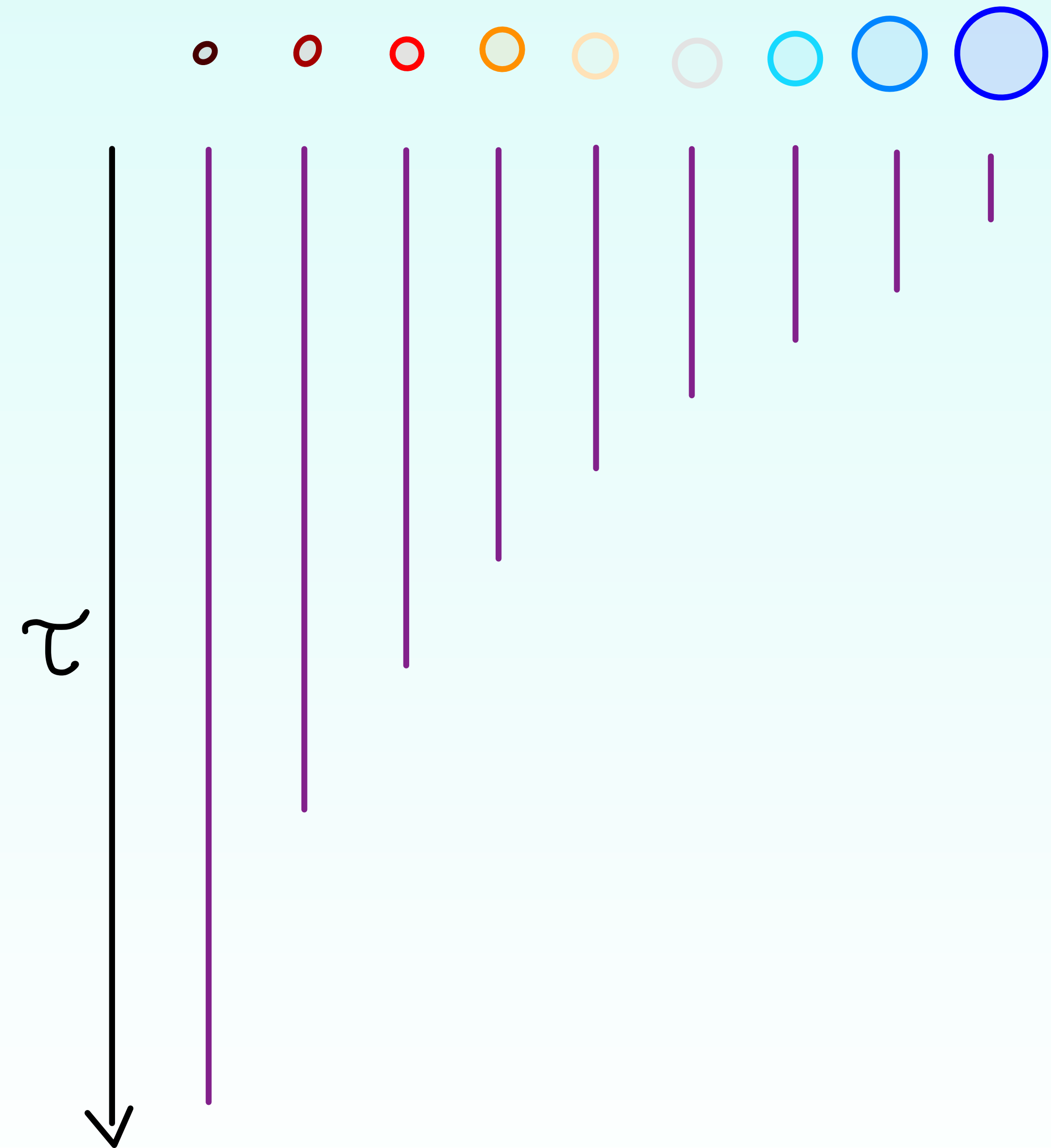
Let's consider stars
born in a single stellar population



Let's consider stars
born in a single stellar population

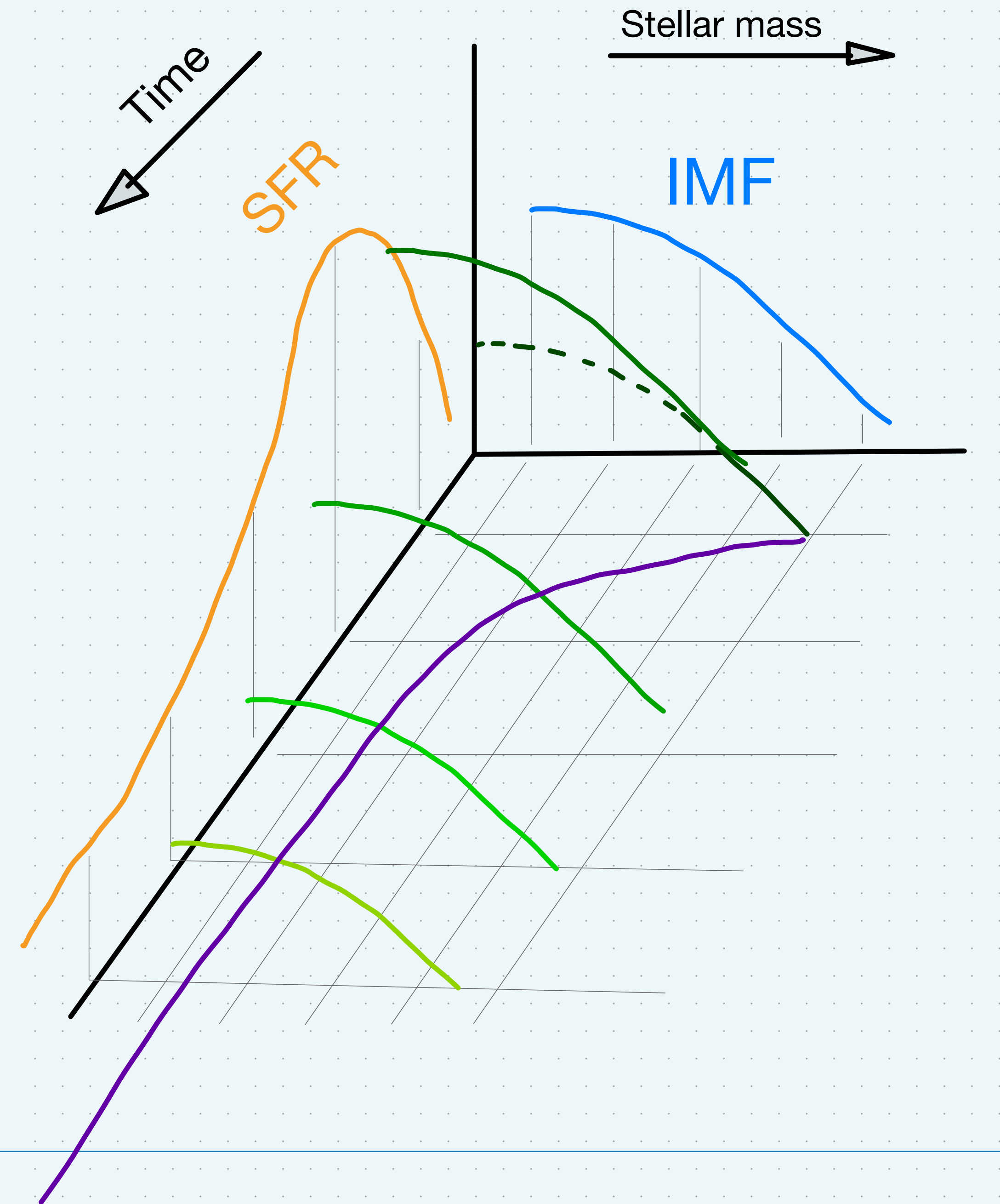


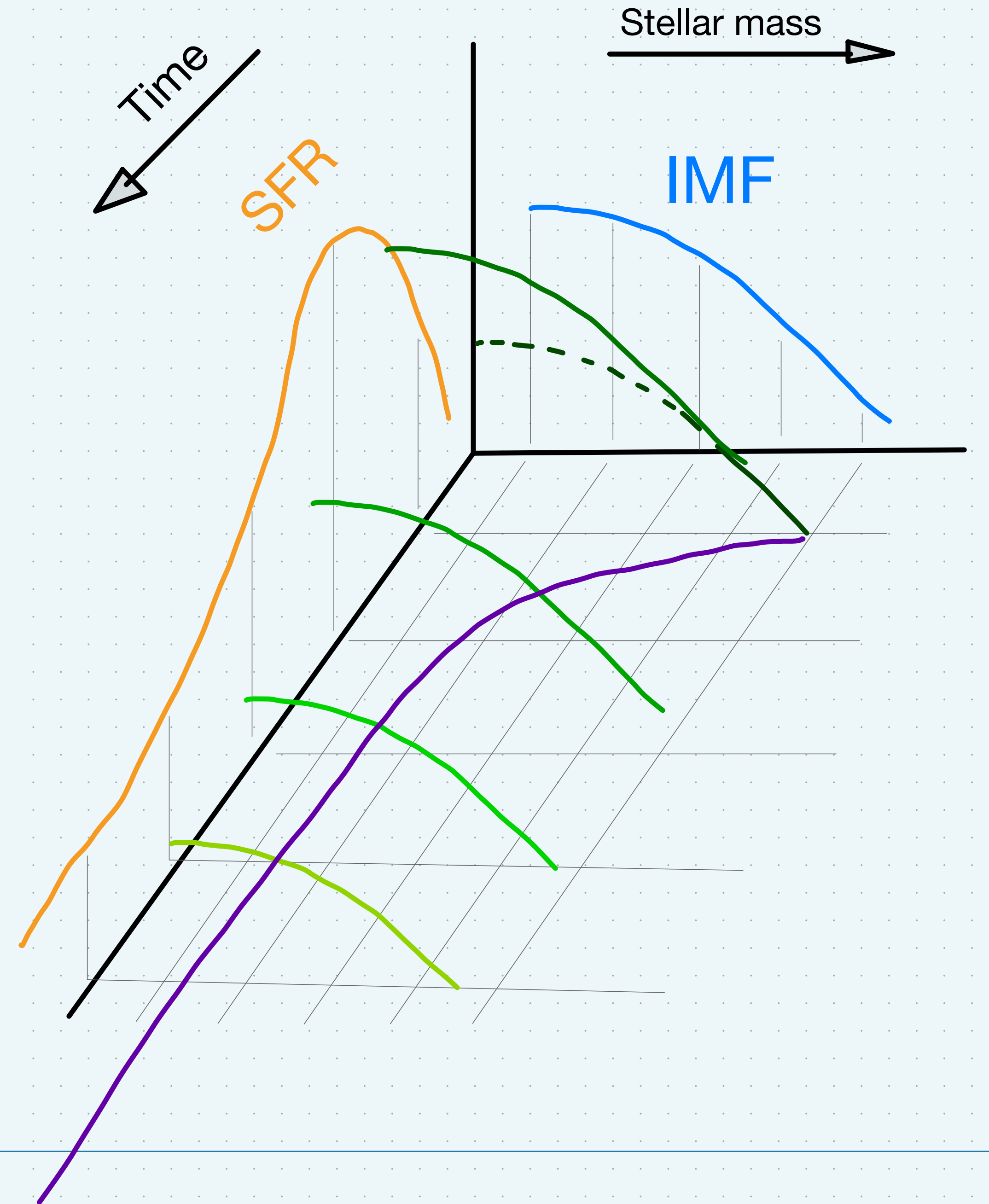
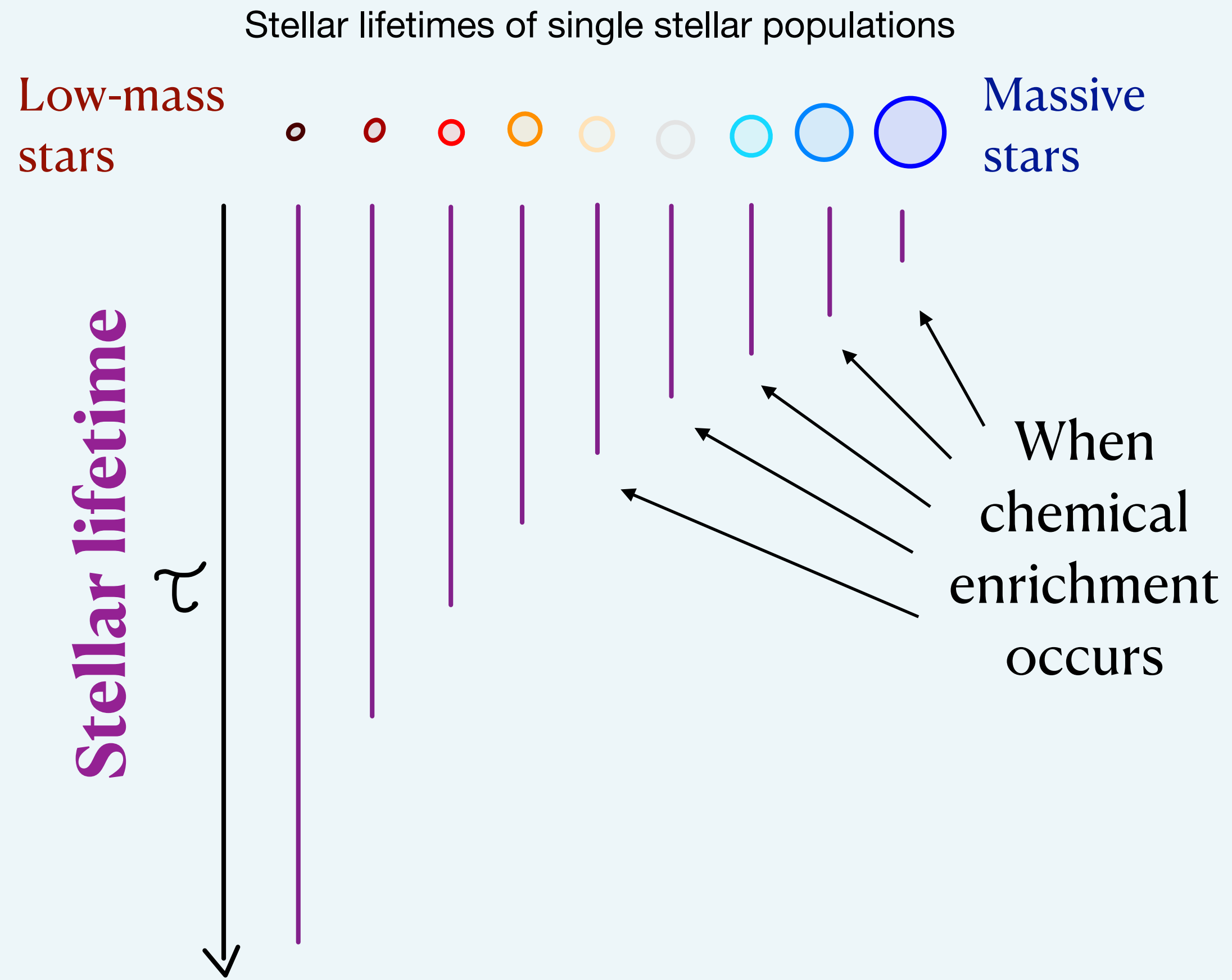
Stellar lifetimes of single stellar populations

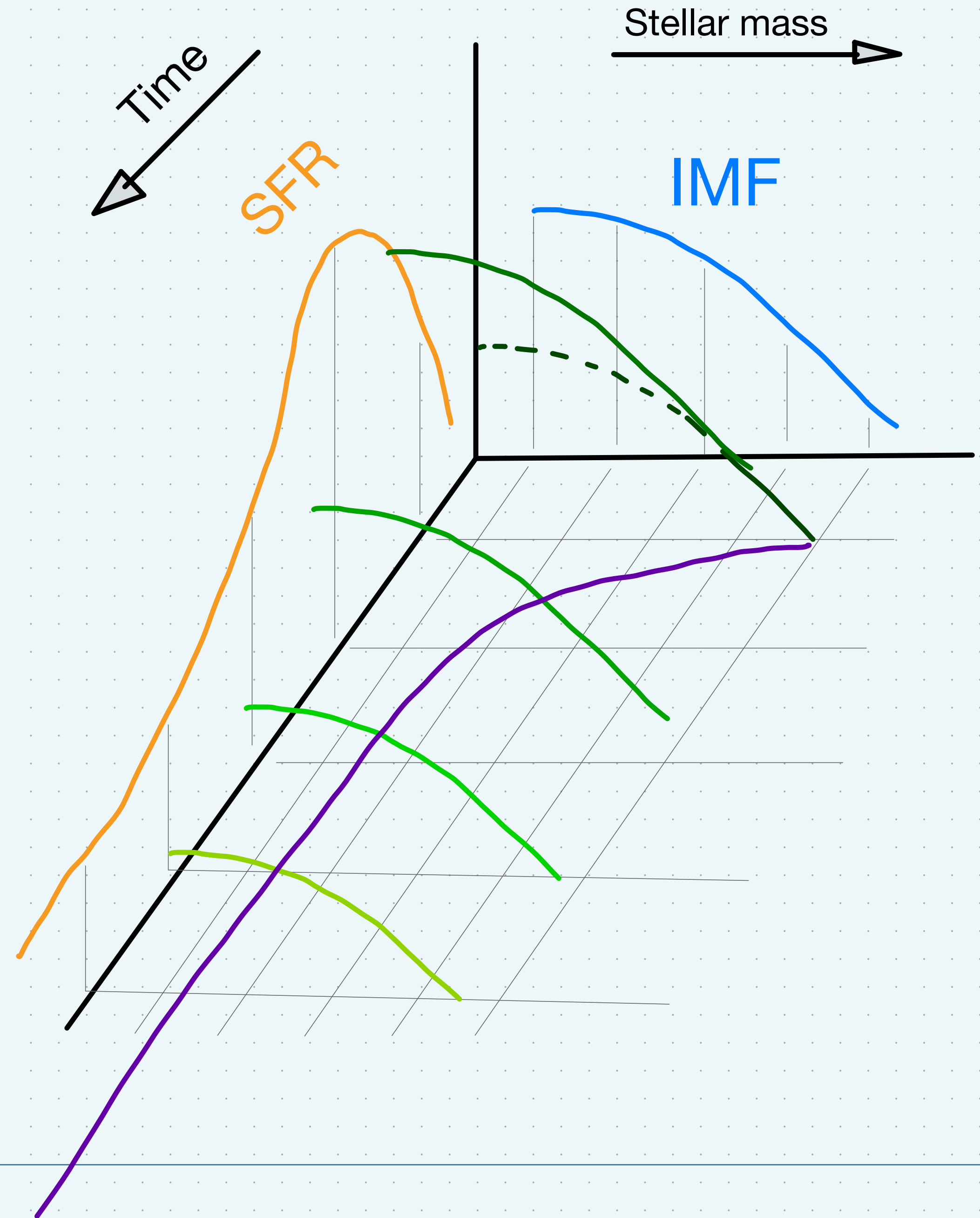
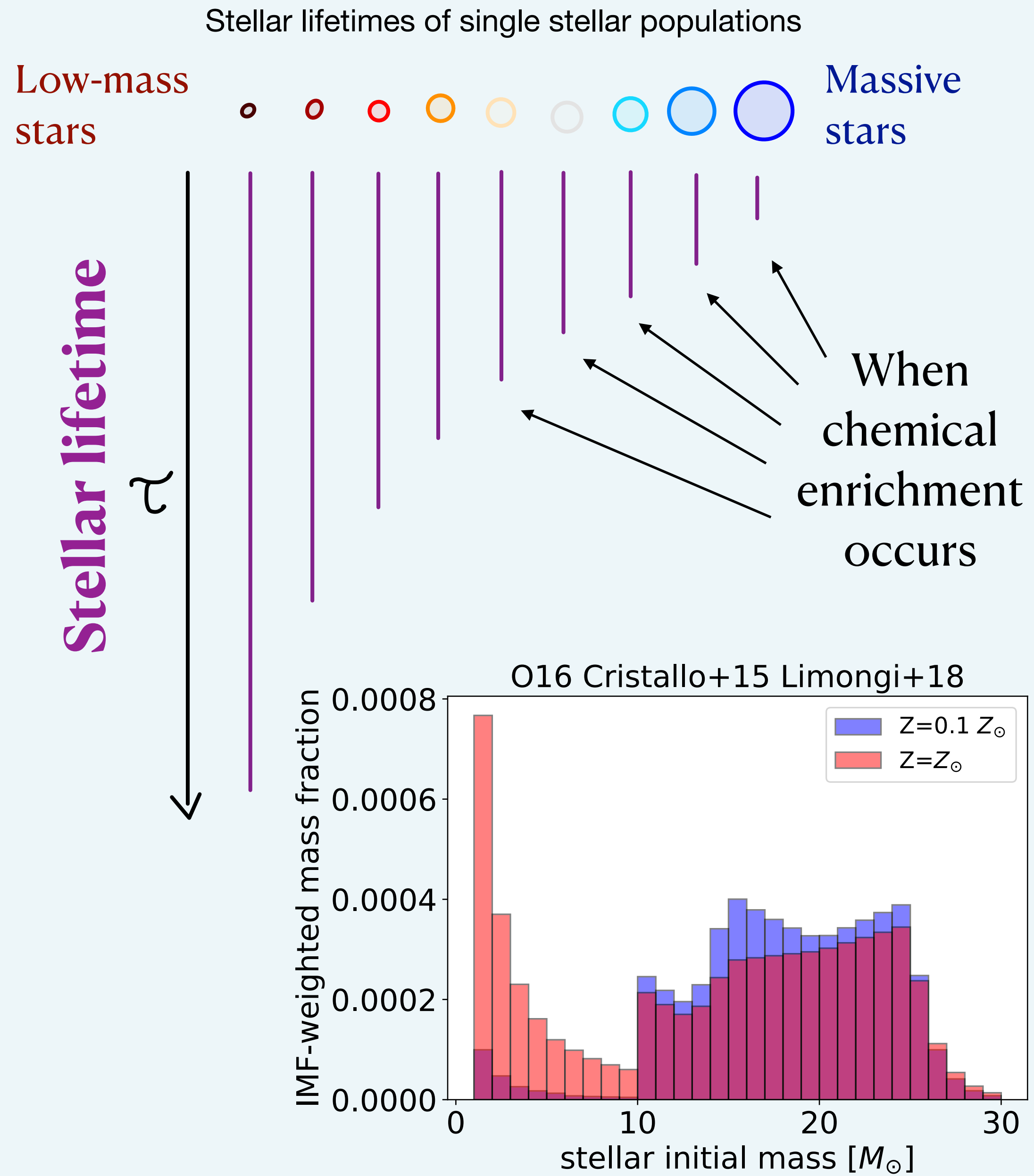


Low-mass
stars

Massive
stars





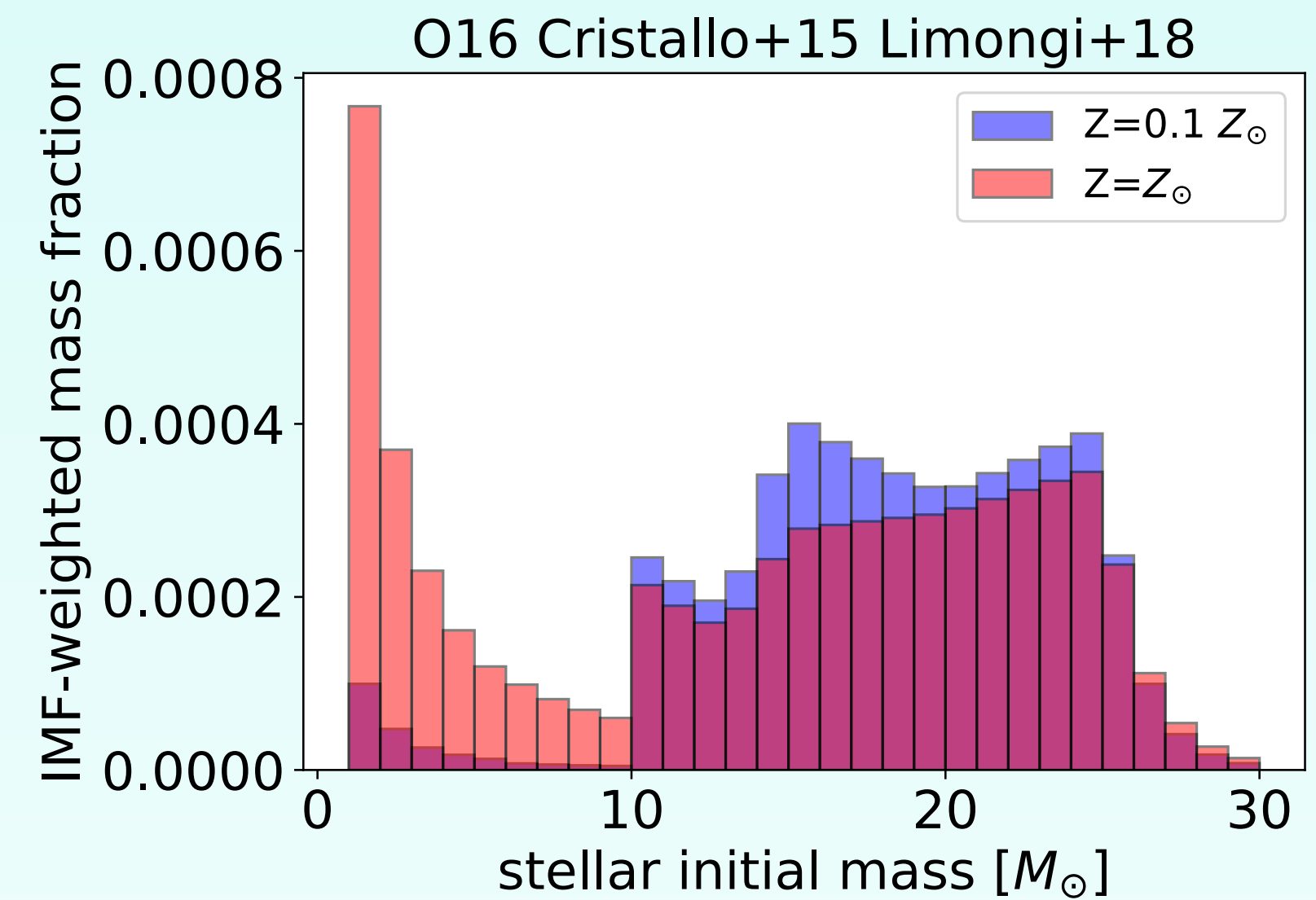
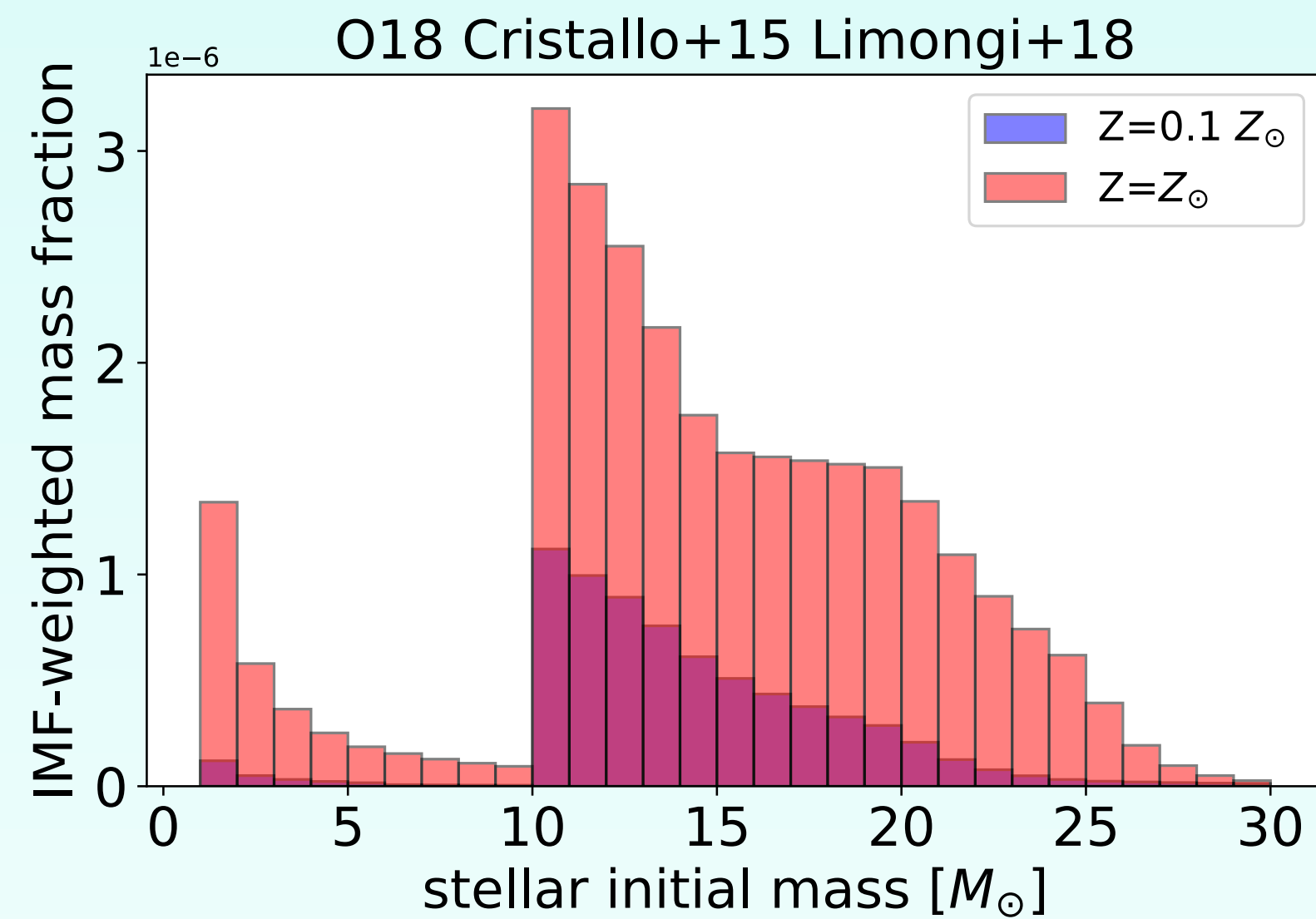
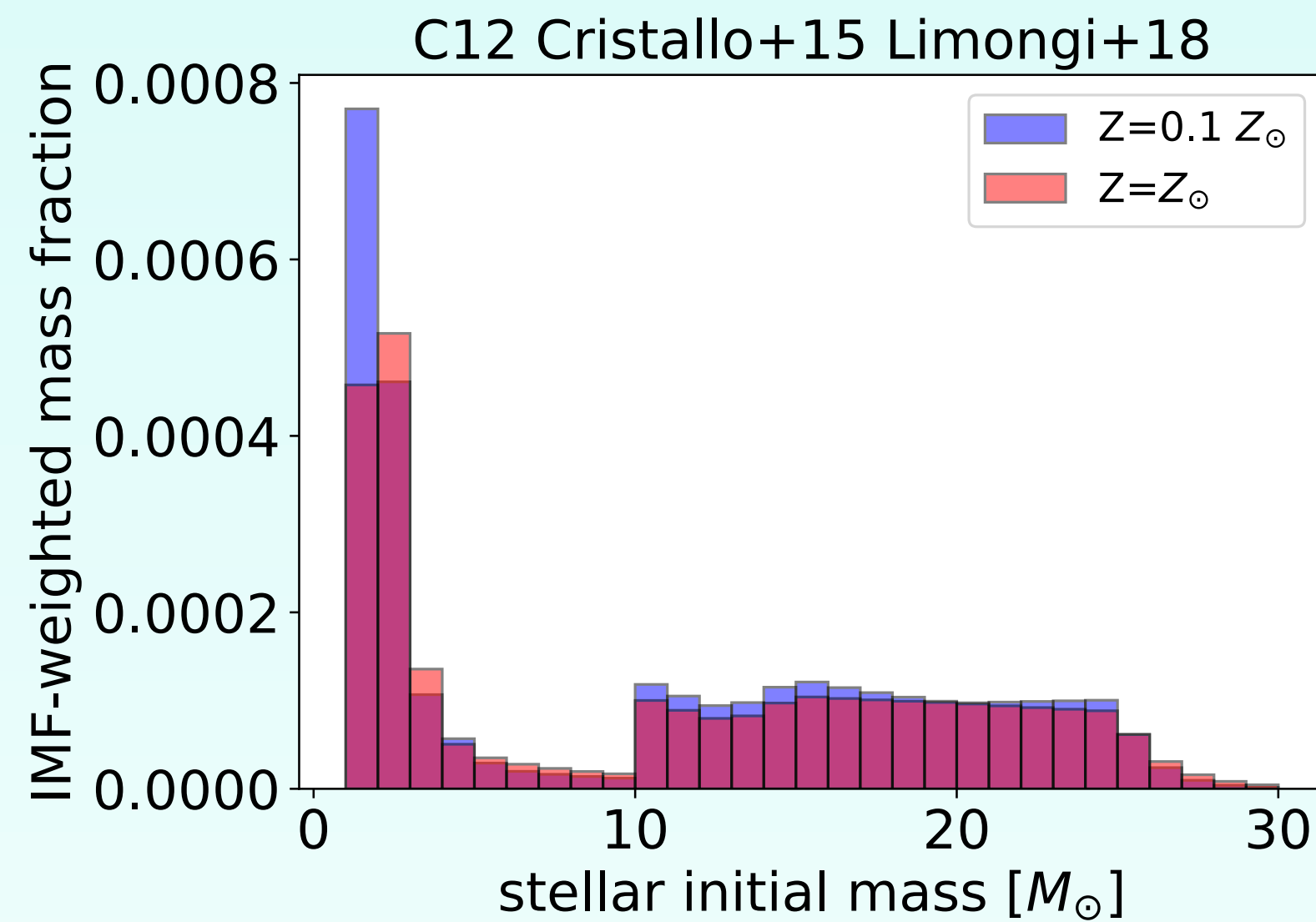


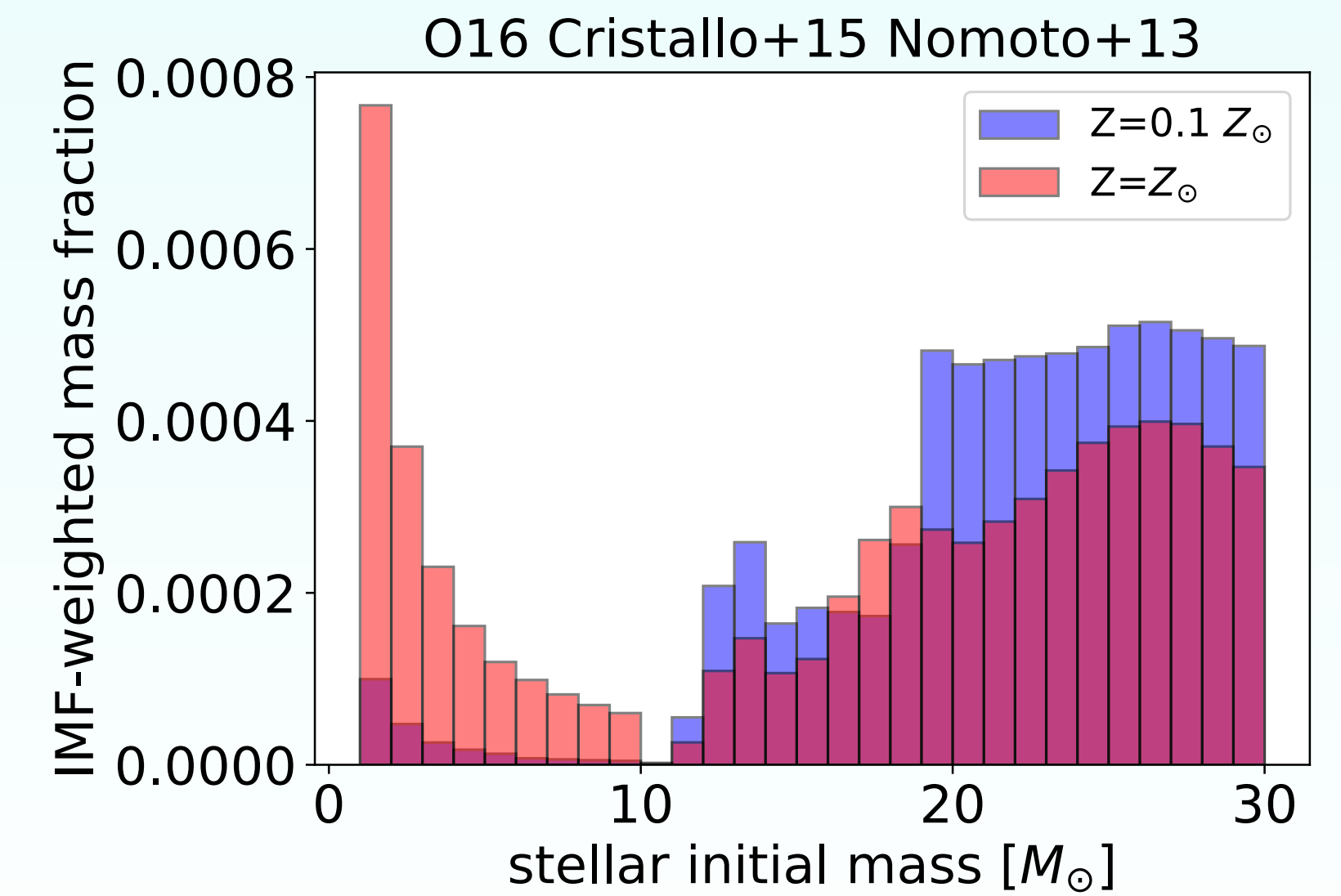
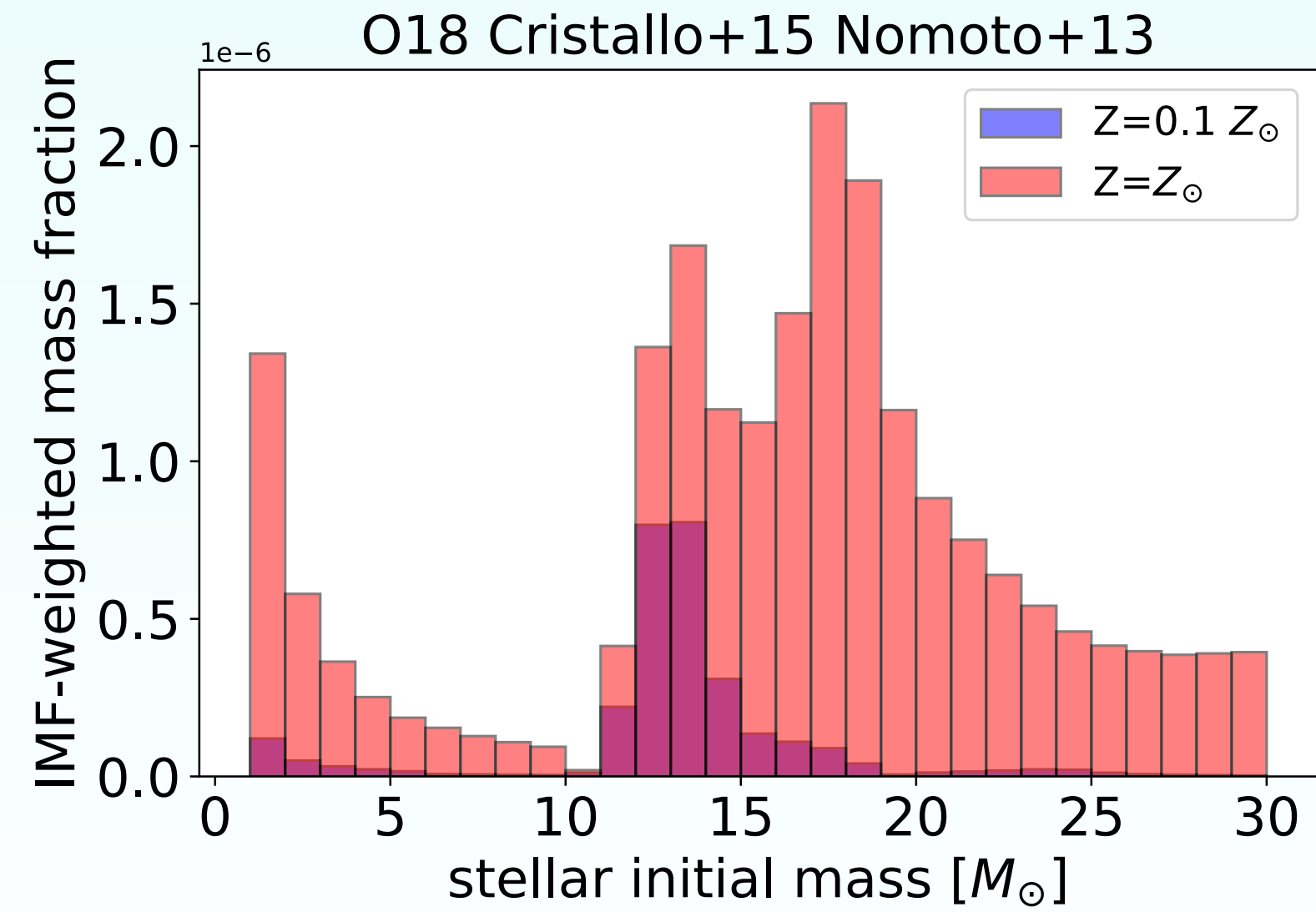
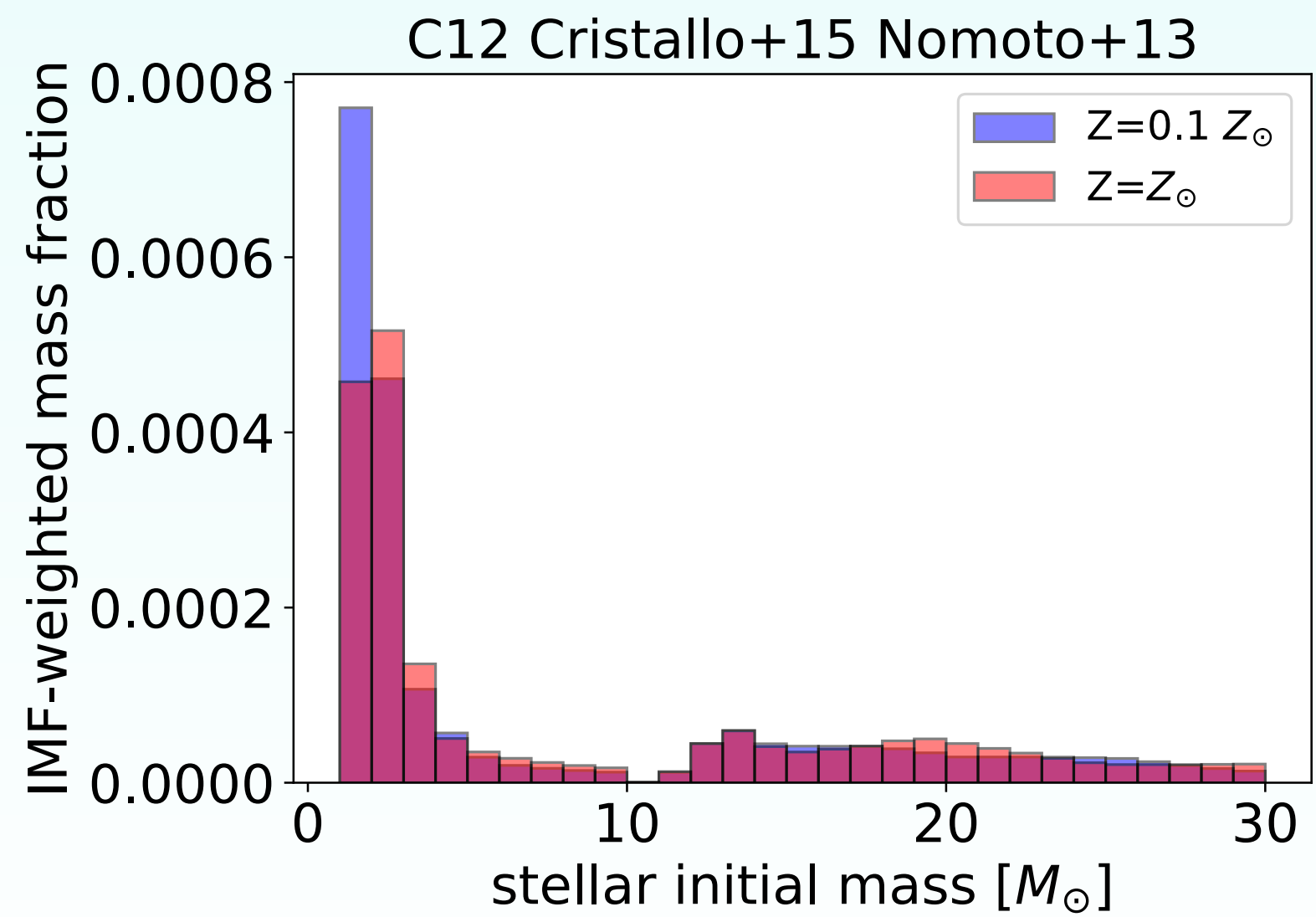
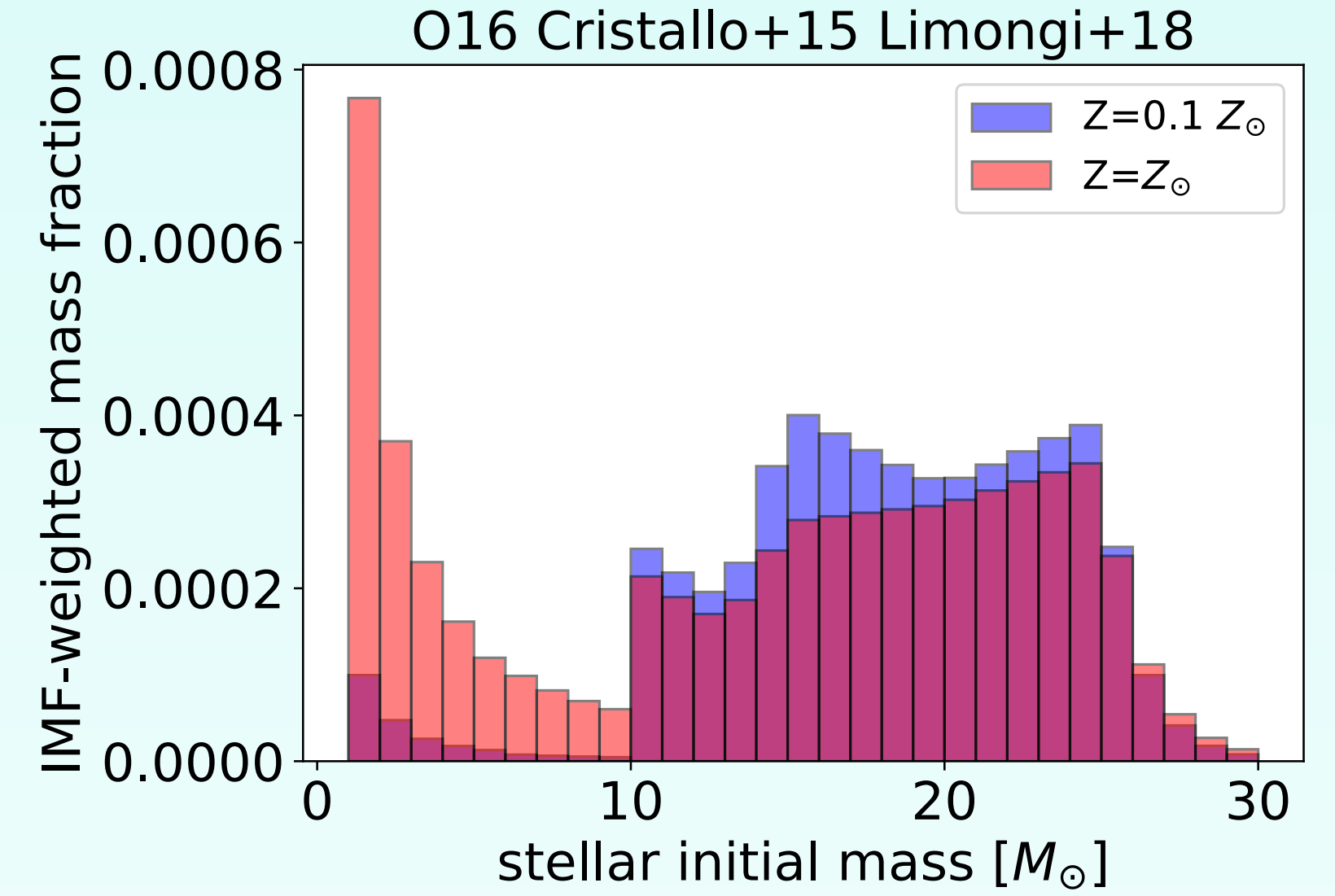
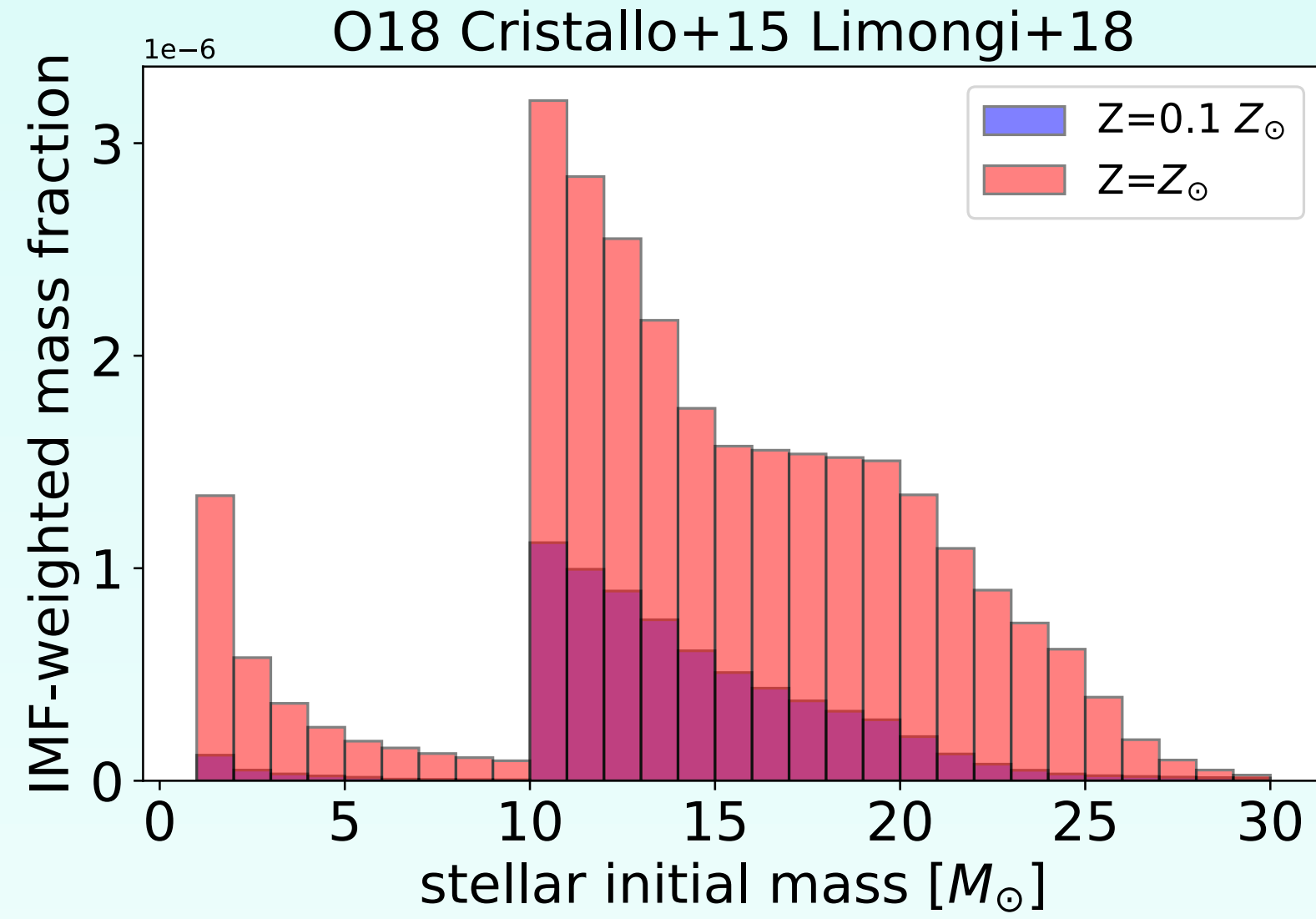
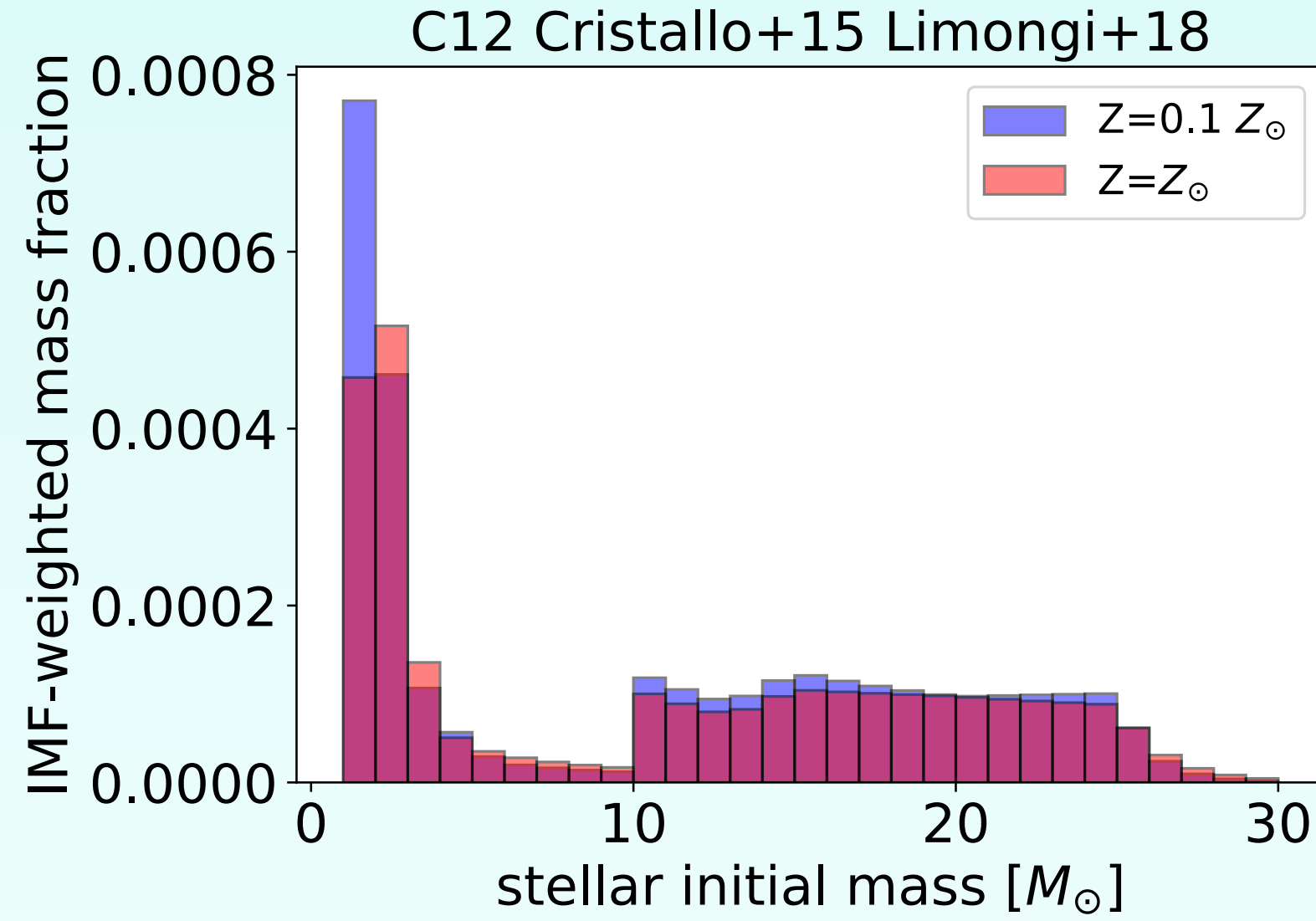
How do stars contribute to GCE?

How do stars contribute to GCE?

Through yields:

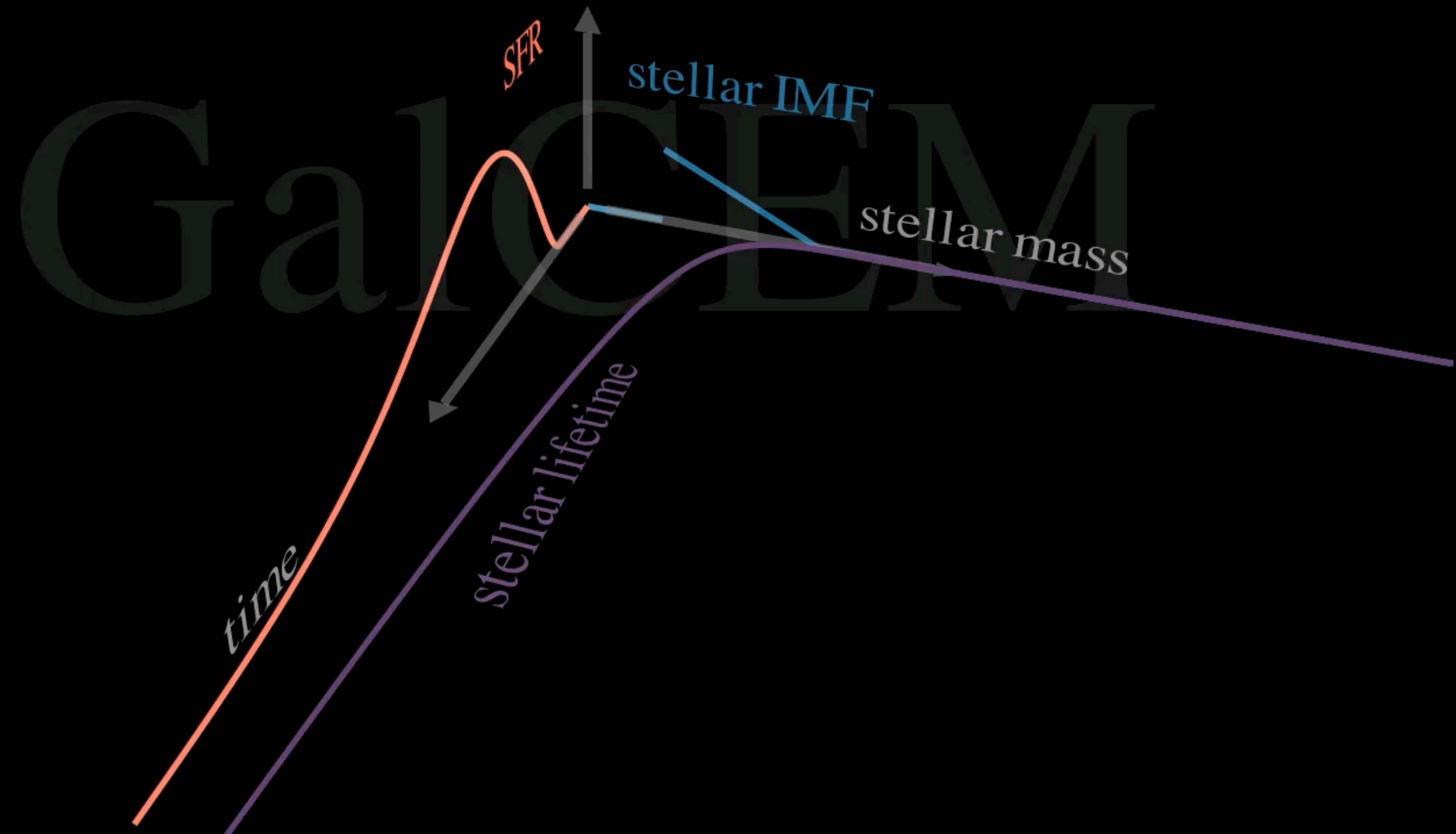
yields are star ejecta, in solar masses, broken down by isotope





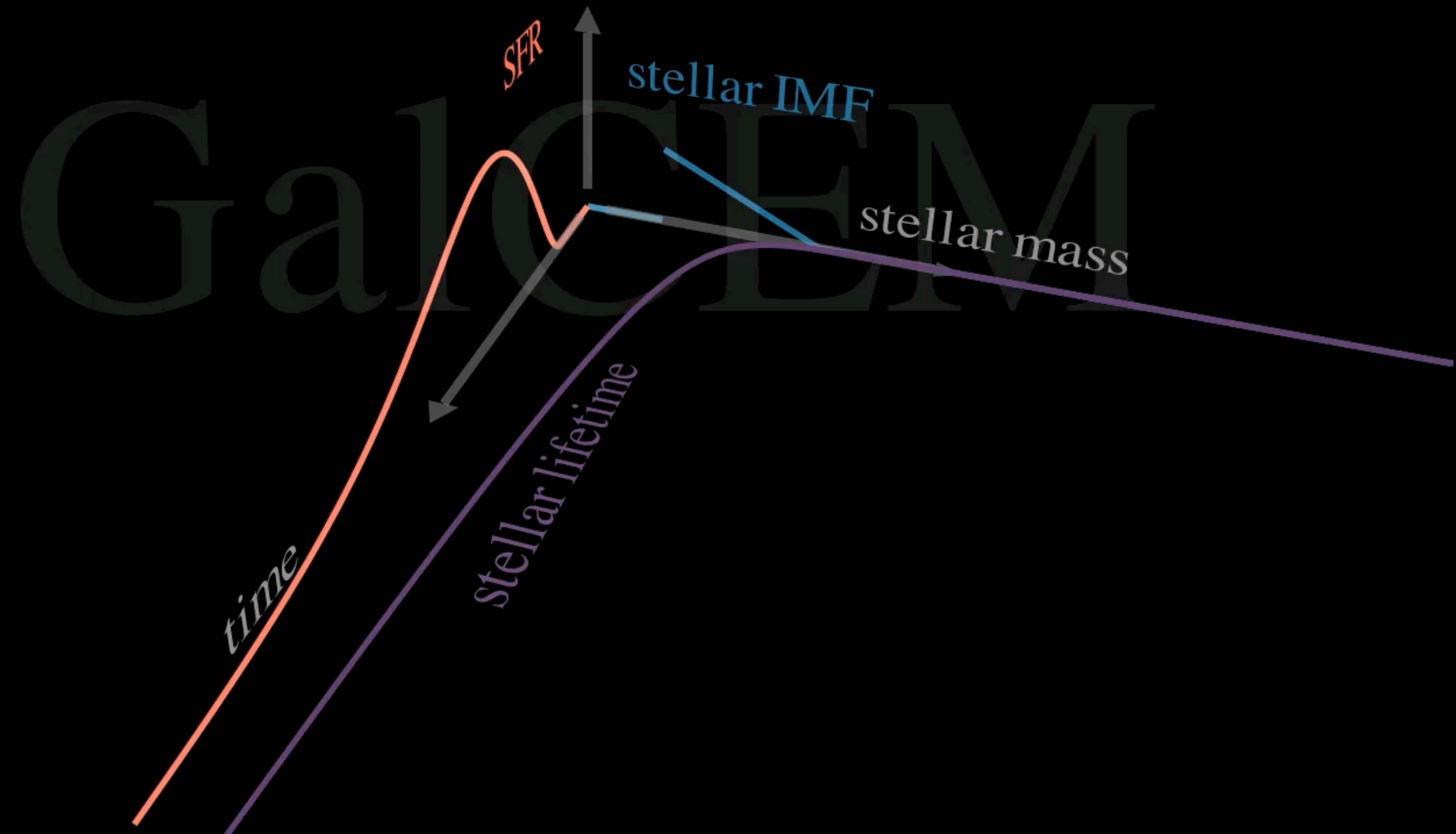
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



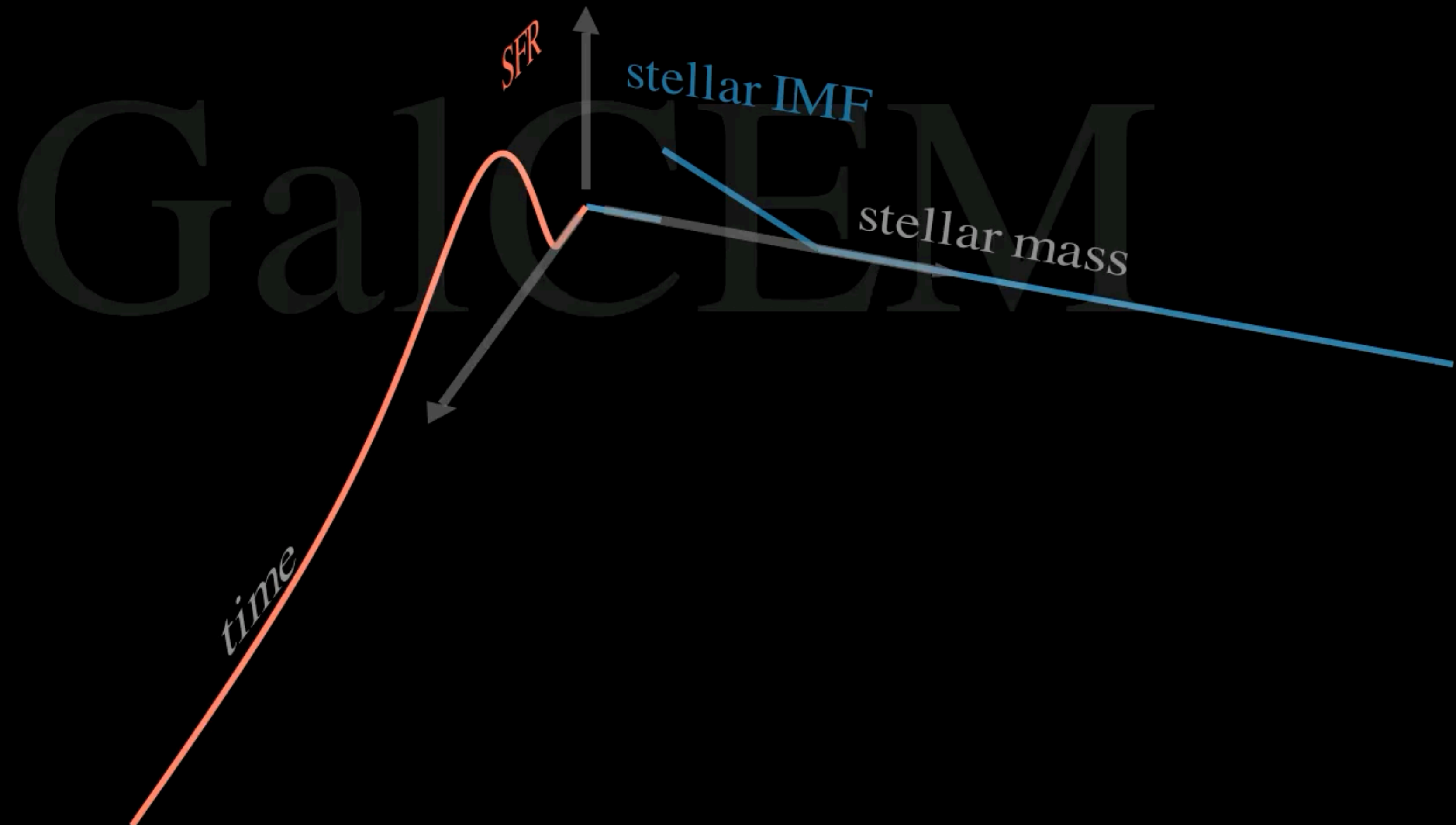
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



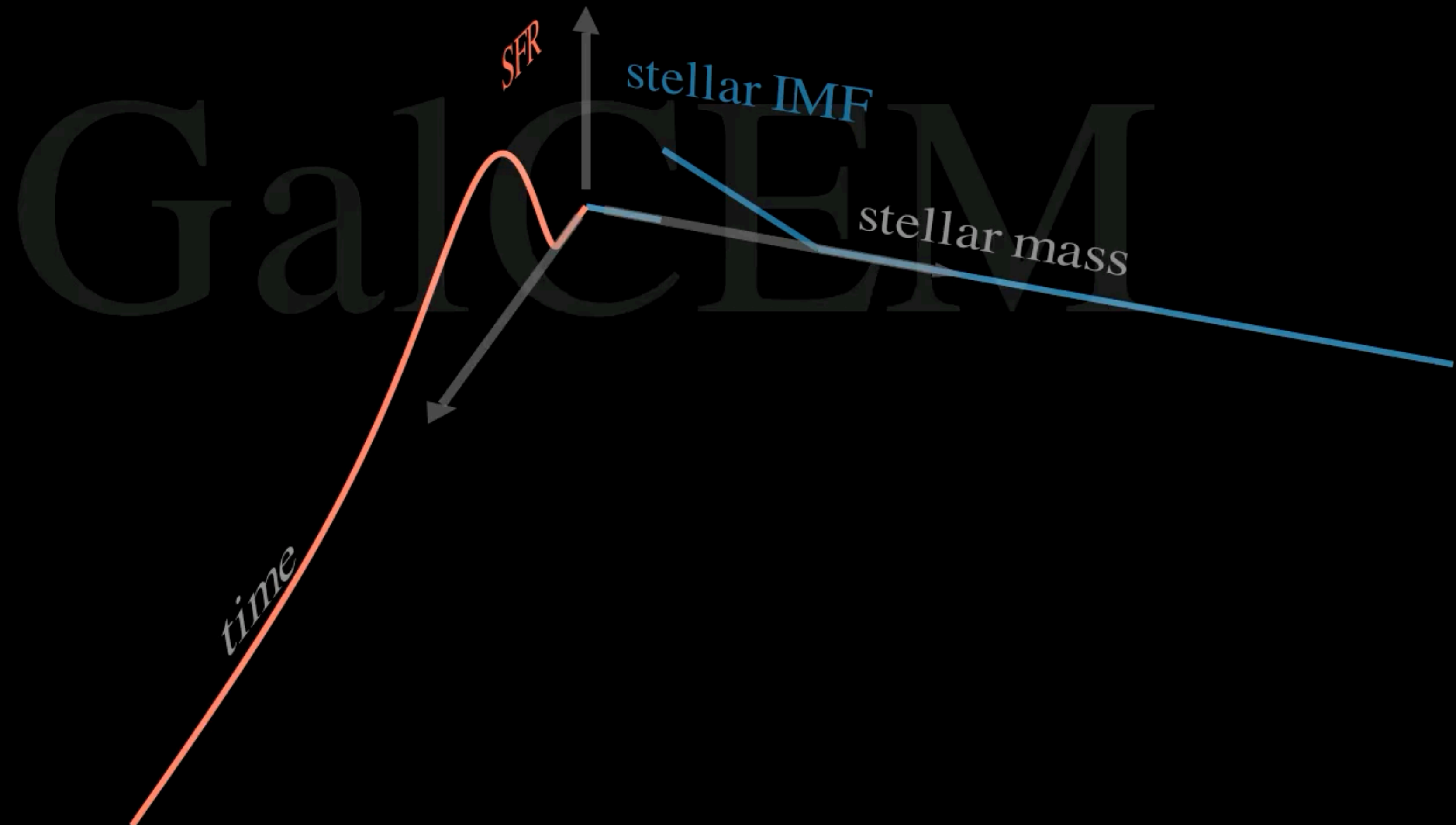
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



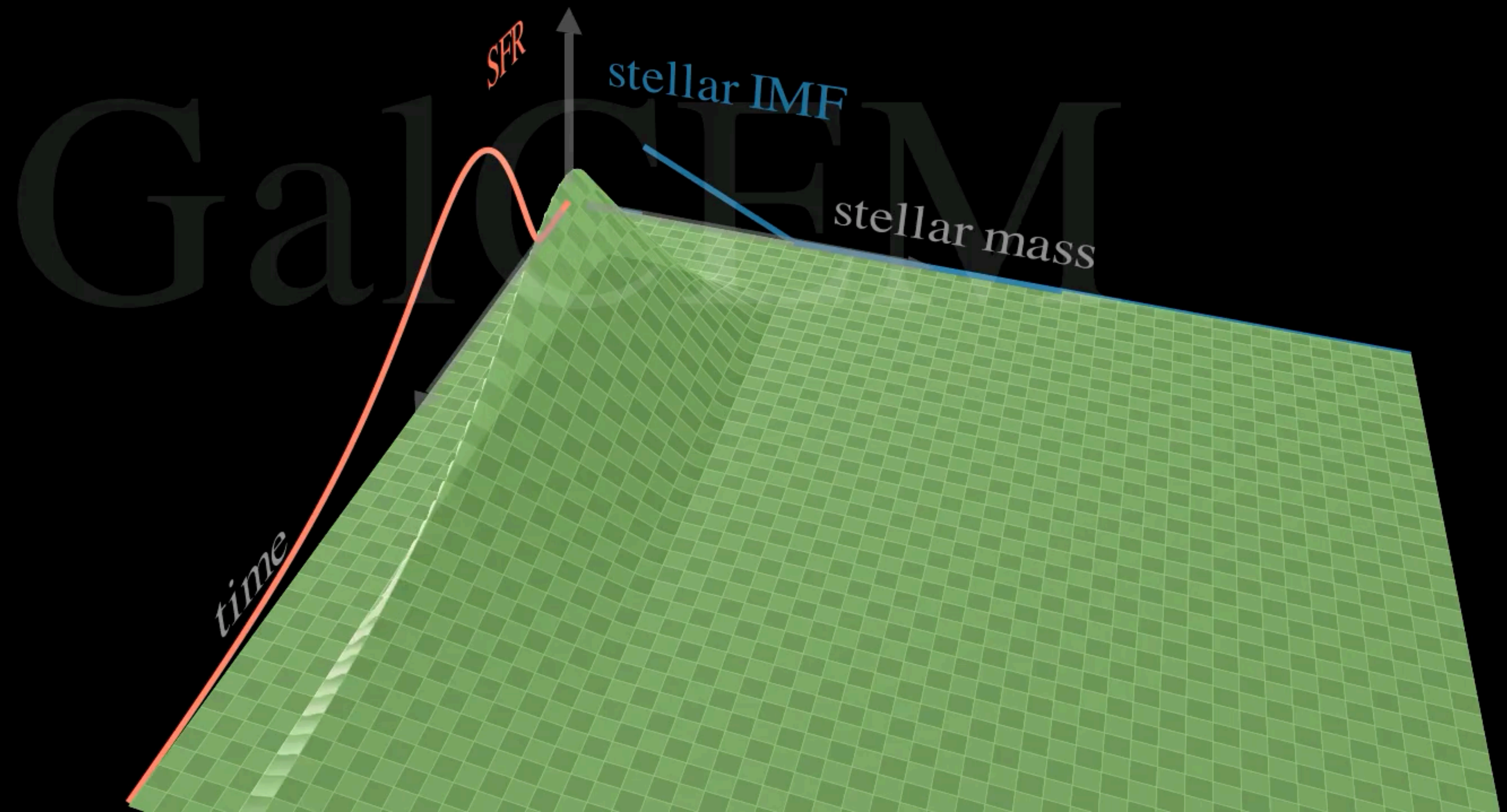
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



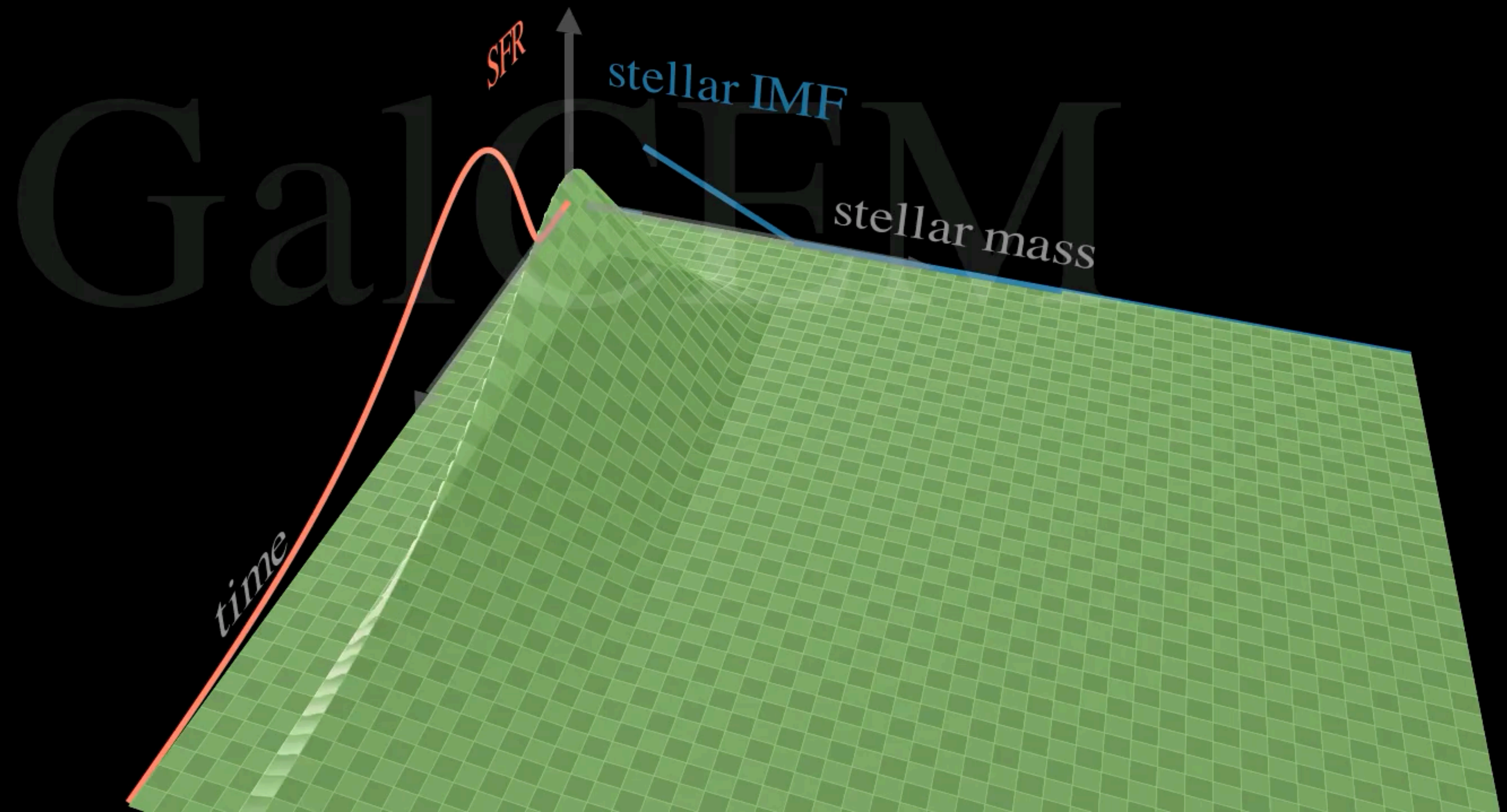
birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

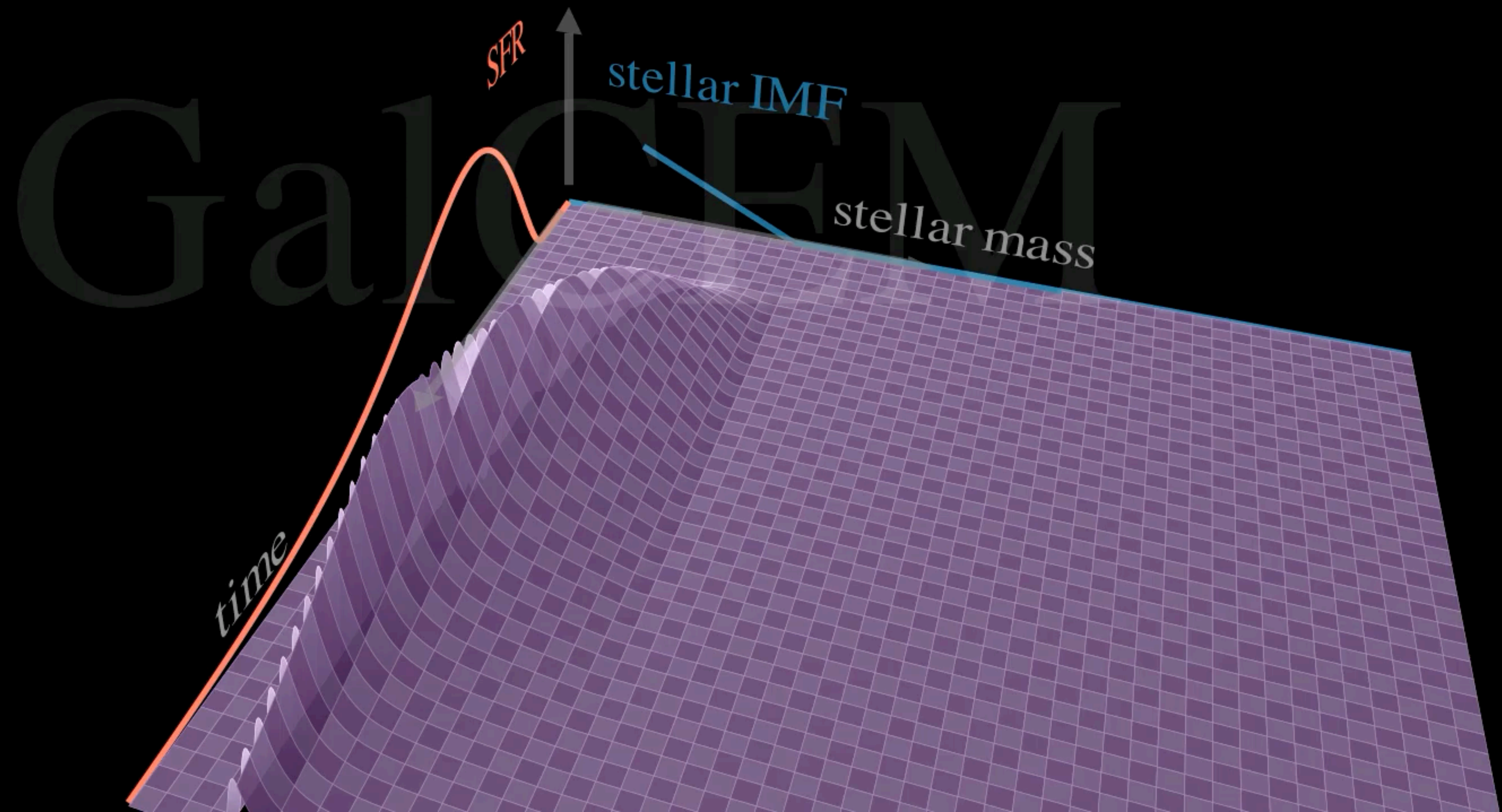
GalCEM



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

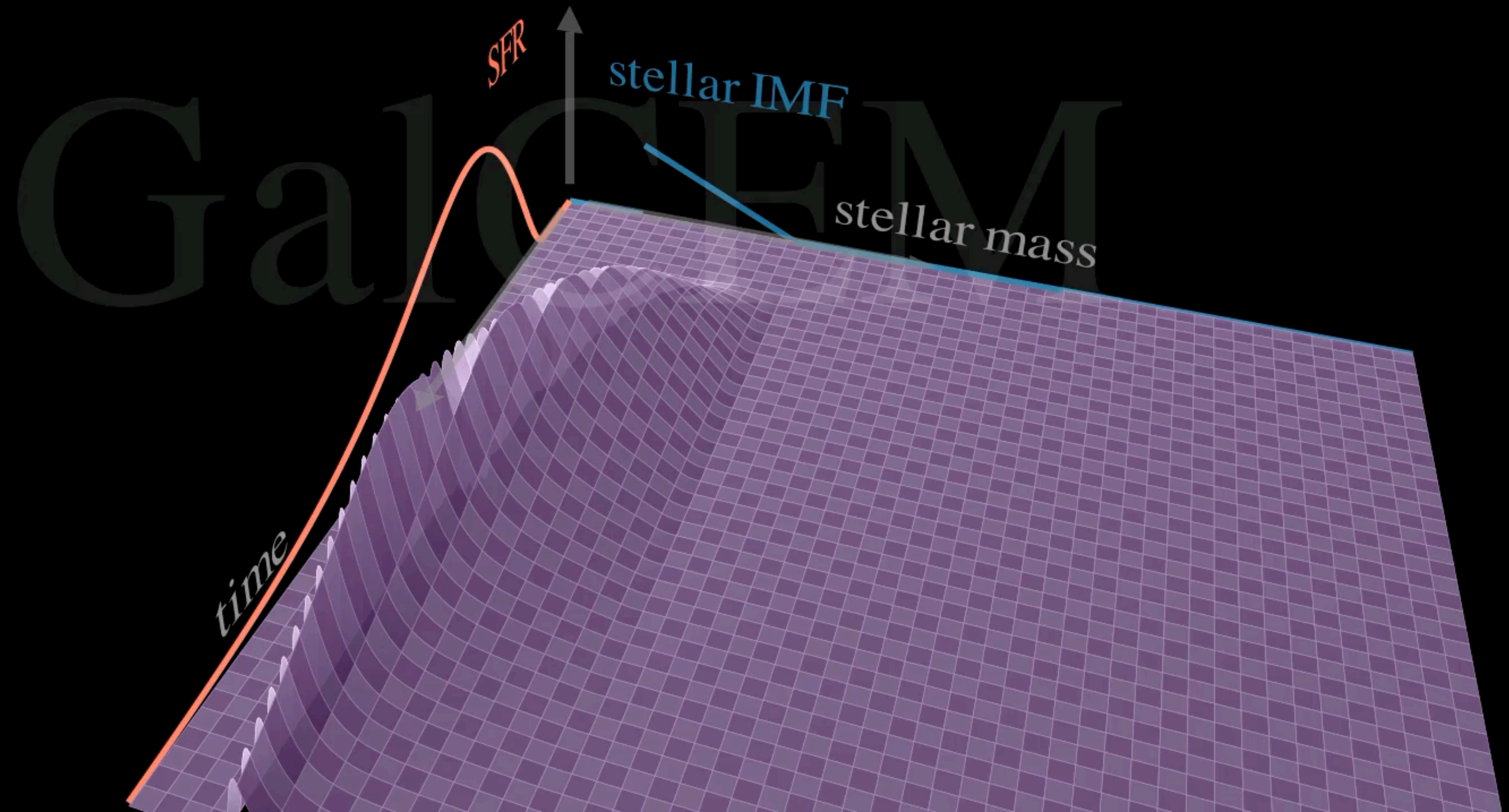
deathrate: $\text{SFR}(t - \tau(m)) \times \text{IMF}(m)$



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

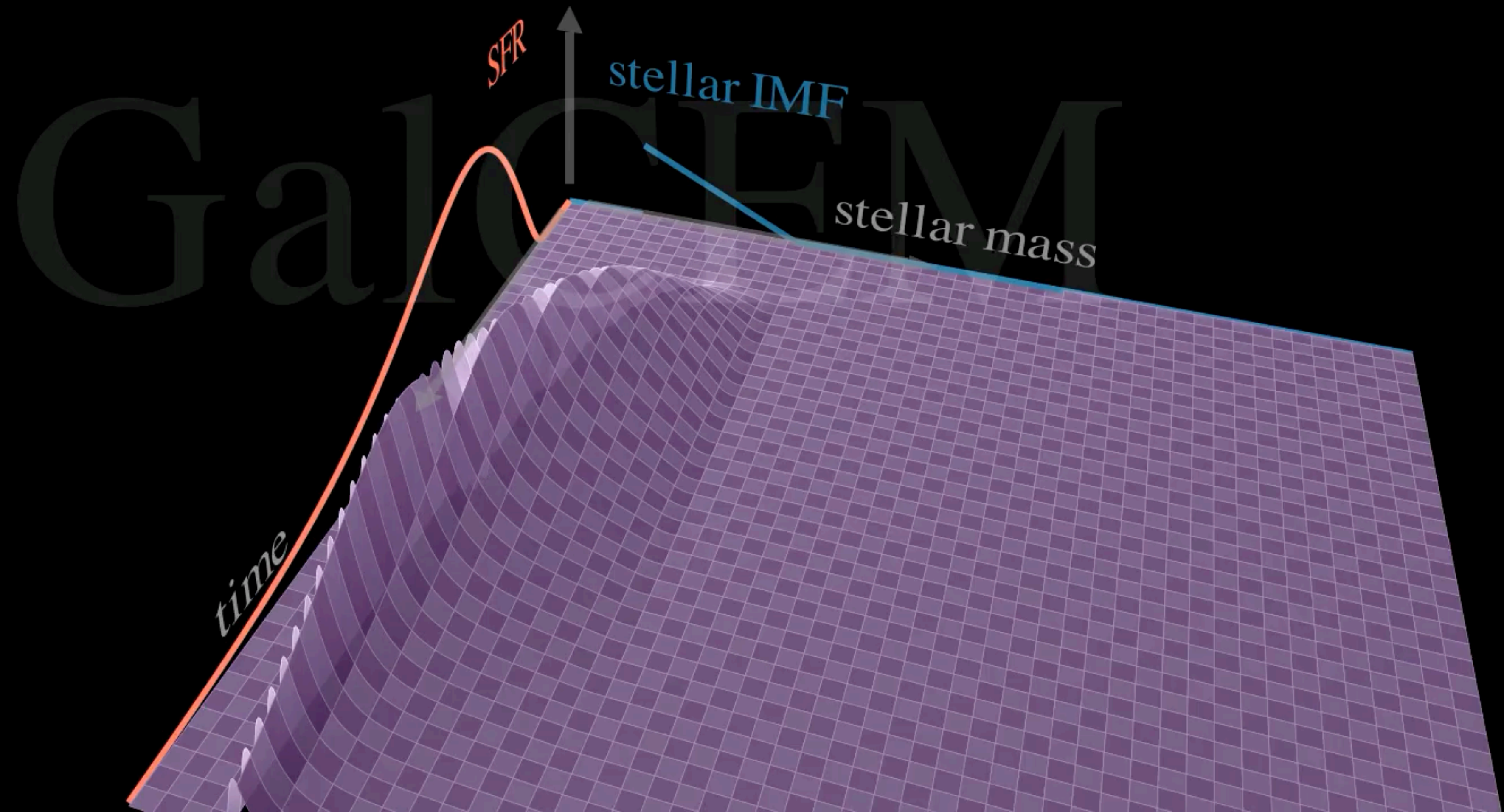
deathrate: $\text{SFR}(t - \tau(m)) \times \text{IMF}(m)$



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

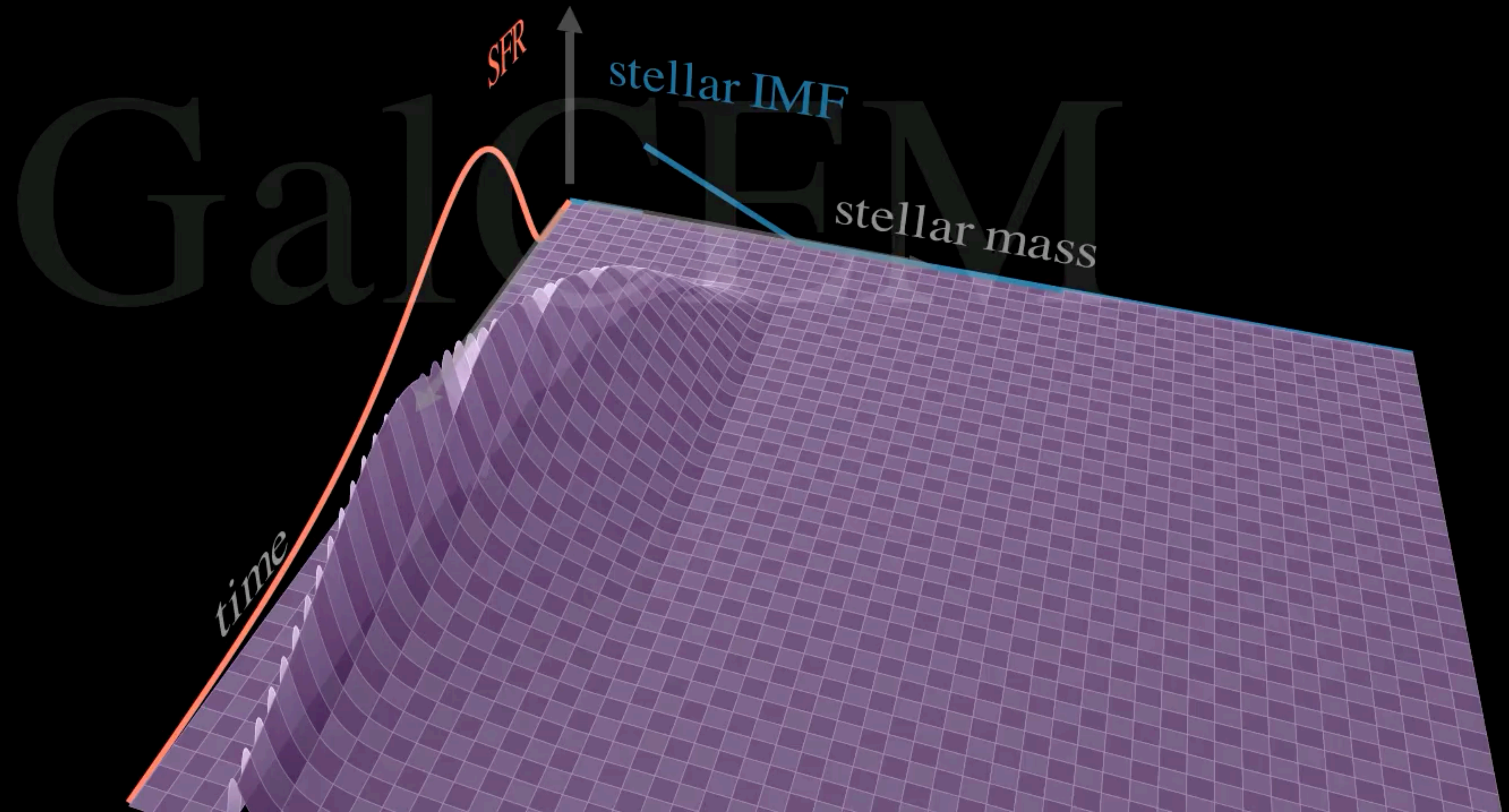
deathrate: $\text{SFR}(t - \tau(m)) \times \text{IMF}(m)$



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

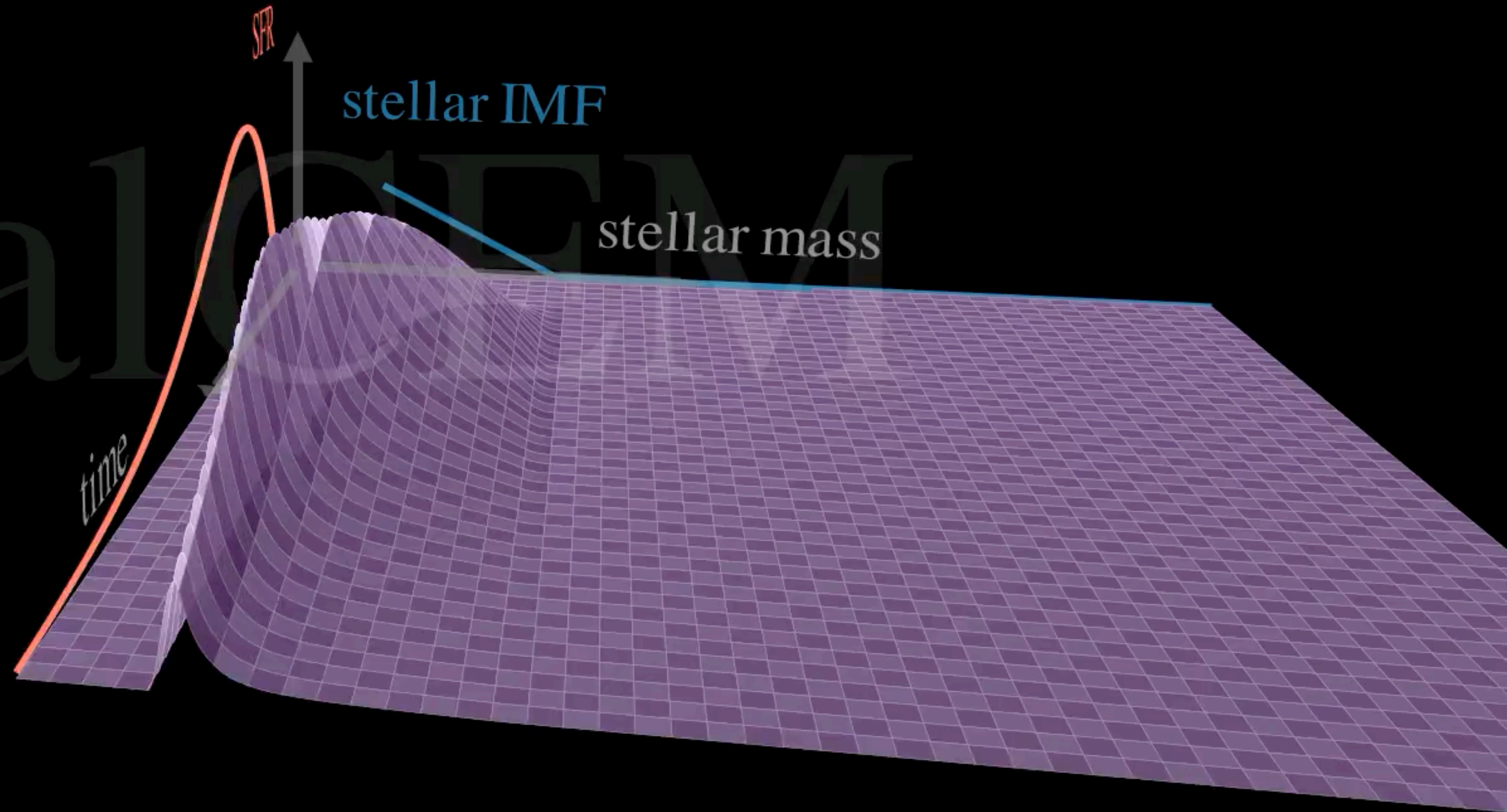
deathrate: $\text{SFR}(t - \tau(m)) \times \text{IMF}(m)$



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

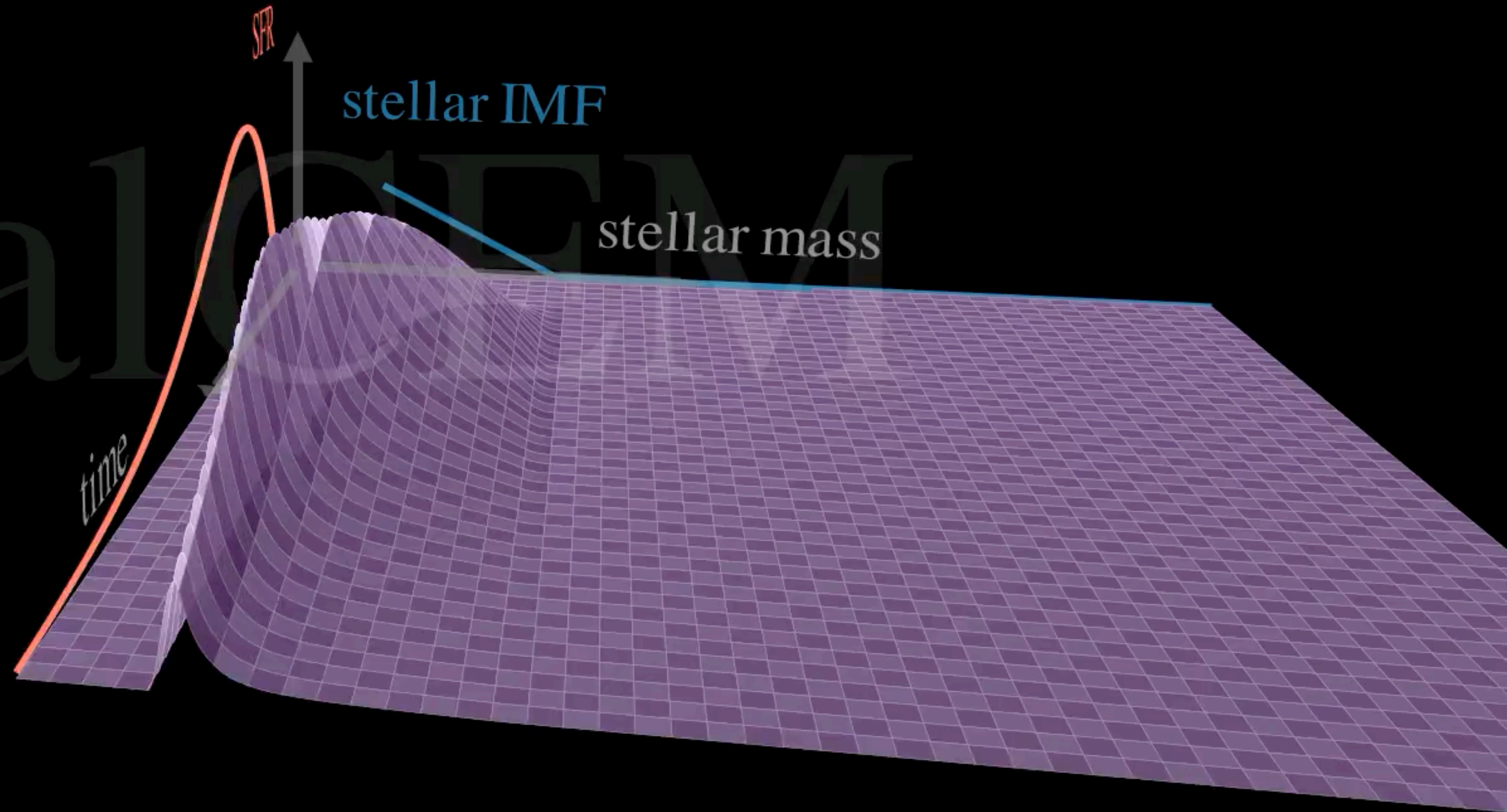
deathrate: $\text{SFR}(t - \tau(m)) \times \text{IMF}(m)$



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

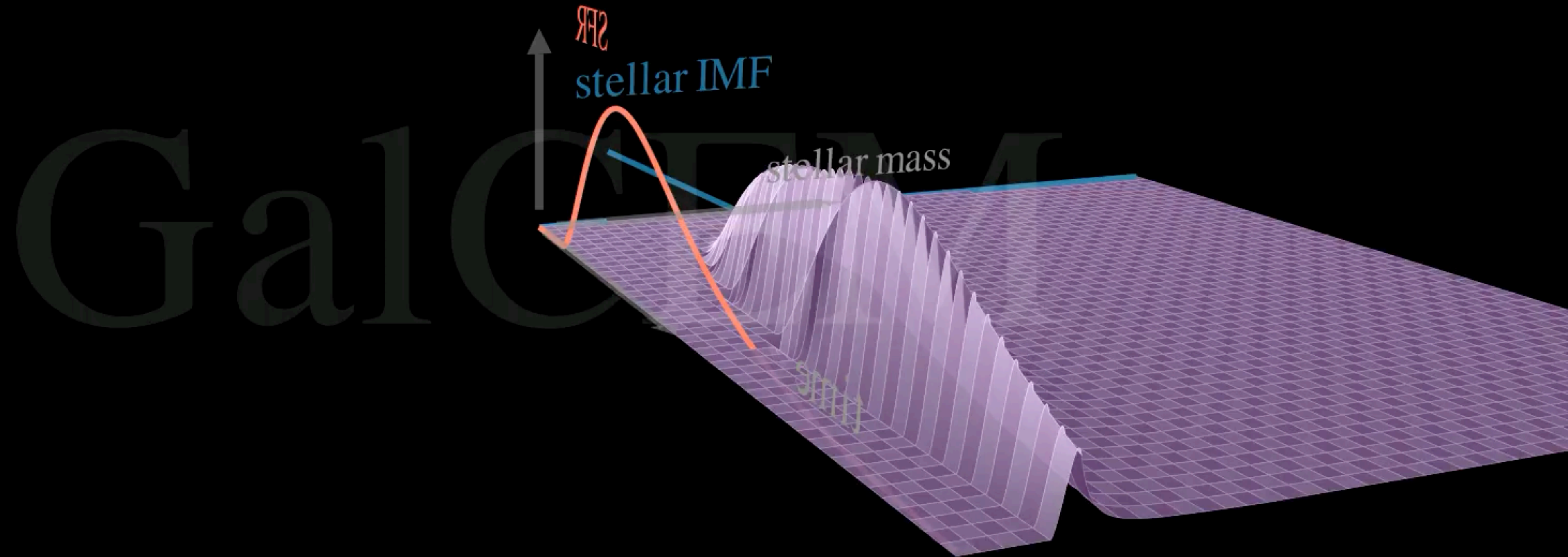
deathrate: $\text{SFR}(t - \tau(m)) \times \text{IMF}(m)$



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

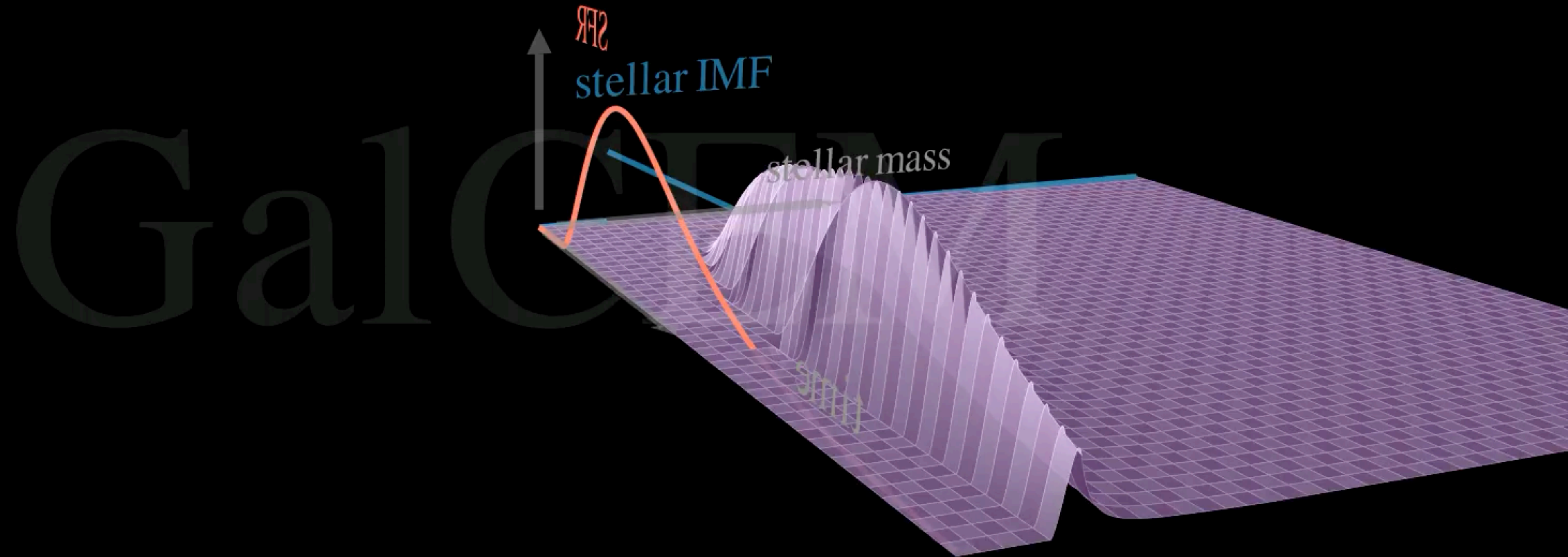
deathrate: $\text{SFR}(t - \tau(m)) \times \text{IMF}(m)$



birthrate: $\text{SFR}(t) \times \text{IMF}(m)$

GalCEM

deathrate: $\text{SFR}(t - \tau(m)) \times \text{IMF}(m)$



Can we truly separate SFR and IMF?

$$\mathcal{B}(m, t) = \text{SFR}(t) \times \text{IMF}(m)$$

Can we truly separate SFR and IMF?

$$\mathcal{B}(m, t) = \text{SFR}(t) \times \text{IMF}(m)$$

(Spoiler alert: no)

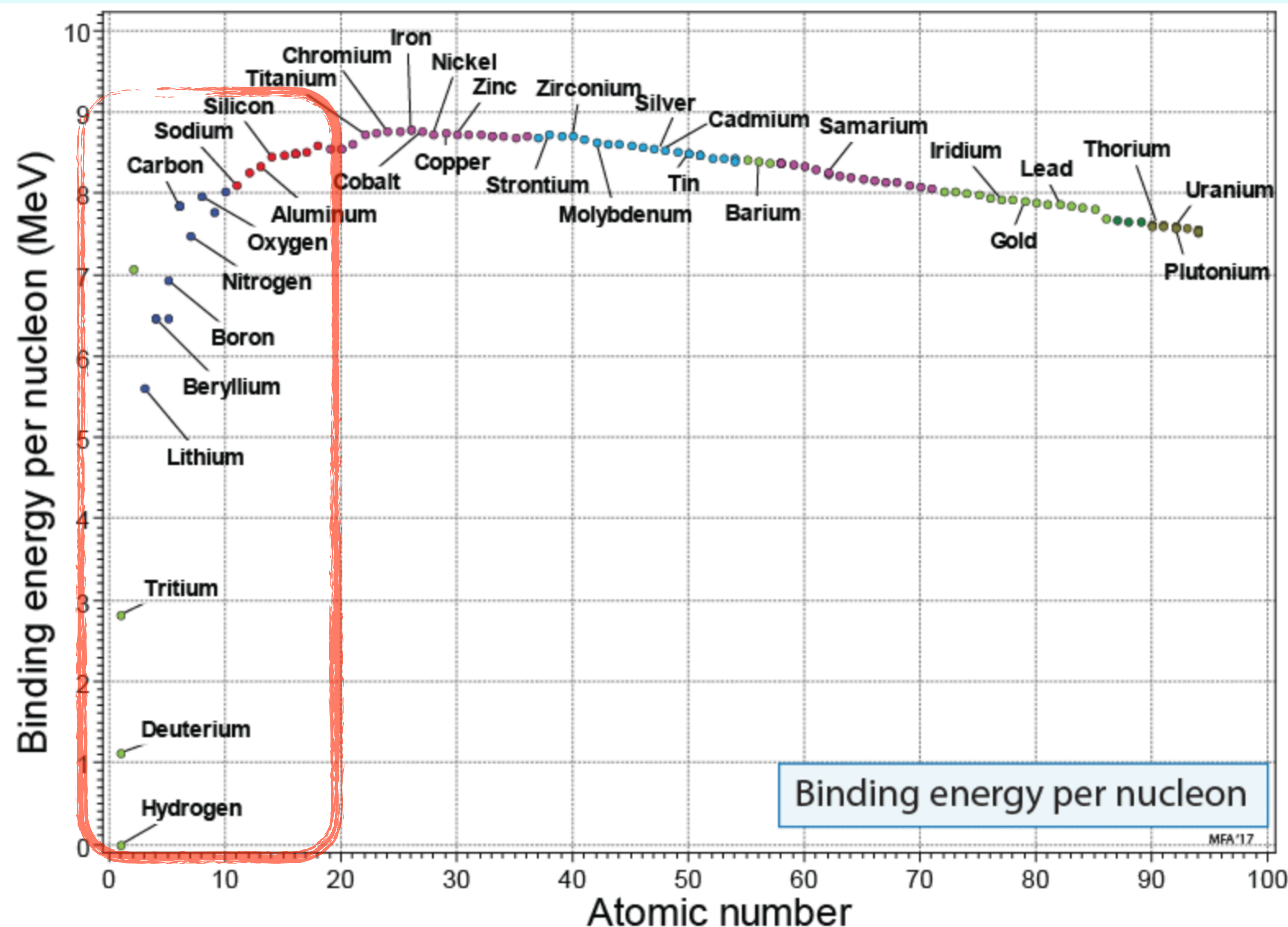
Can we truly separate SFR and IMF?

$$\mathcal{B}(m, t) = \text{SFR}(t) \times \text{IMF}(m)$$

(Spoiler alert: no)

Let us have a closer look at how stars form

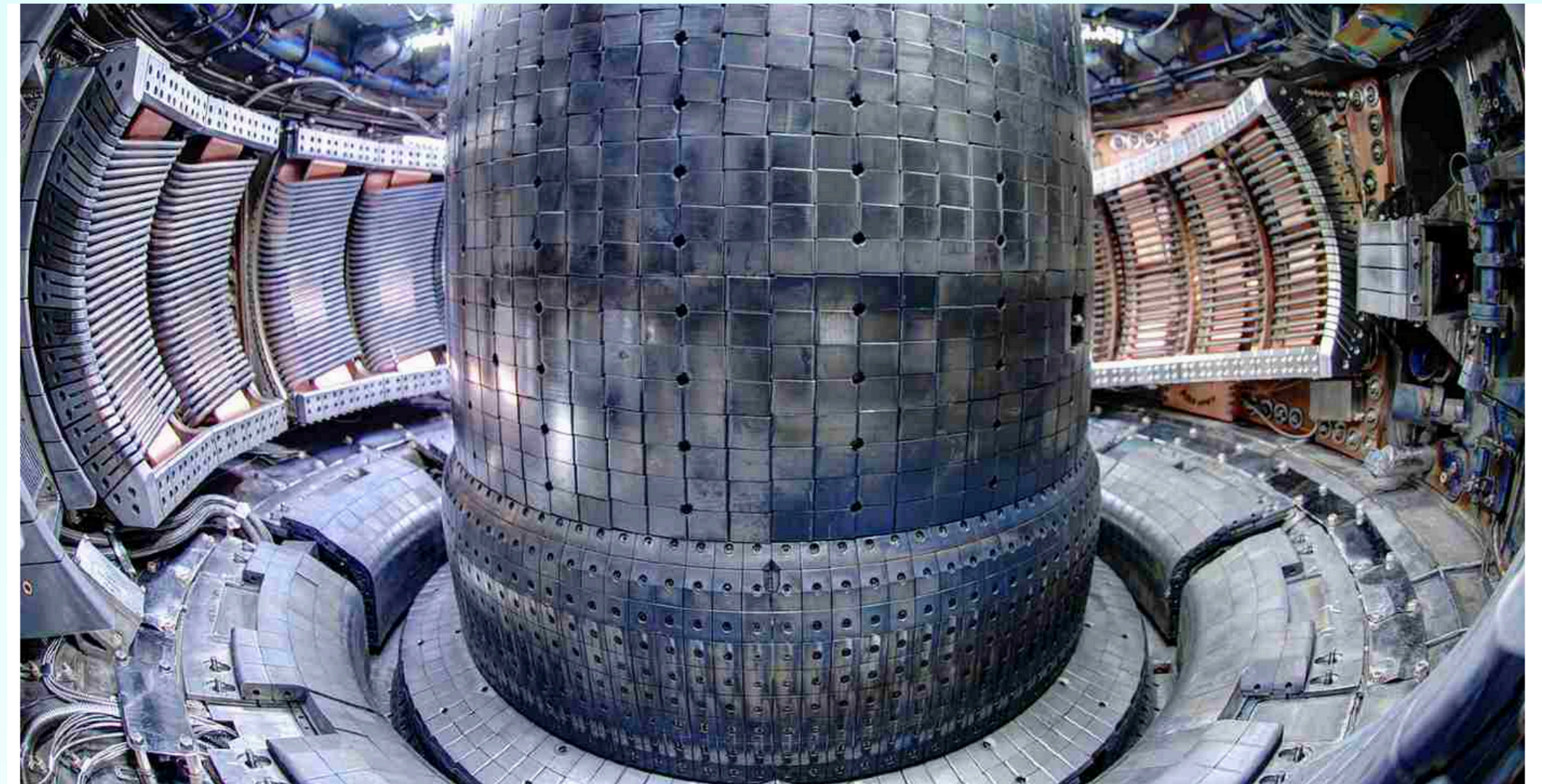
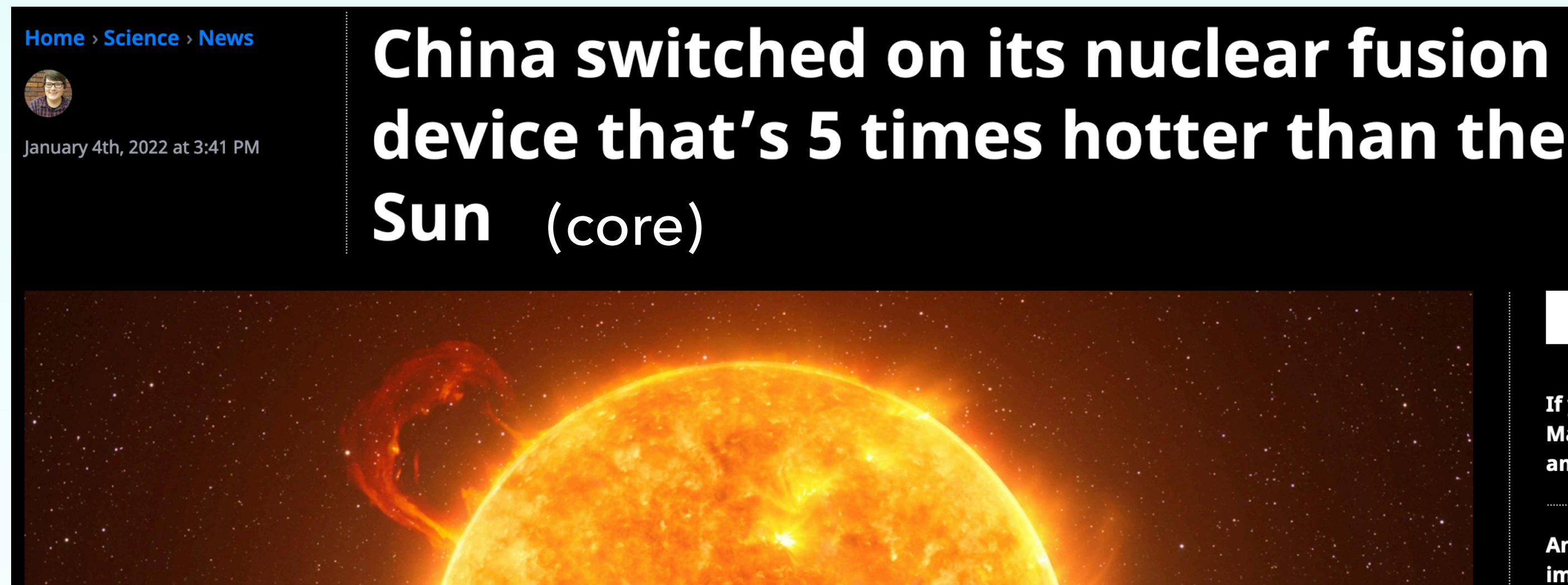
Thermonuclear processes...



Thermonuclear reactions:

- Are exothermic
- Involve the collision between two nuclides
- Don't occur for isotopes heavier than $^{56}\text{Fe}/^{56}\text{Ni}$
- Don't involve weak processes (preserve the number of p and n)

Thermonuclear Fusion



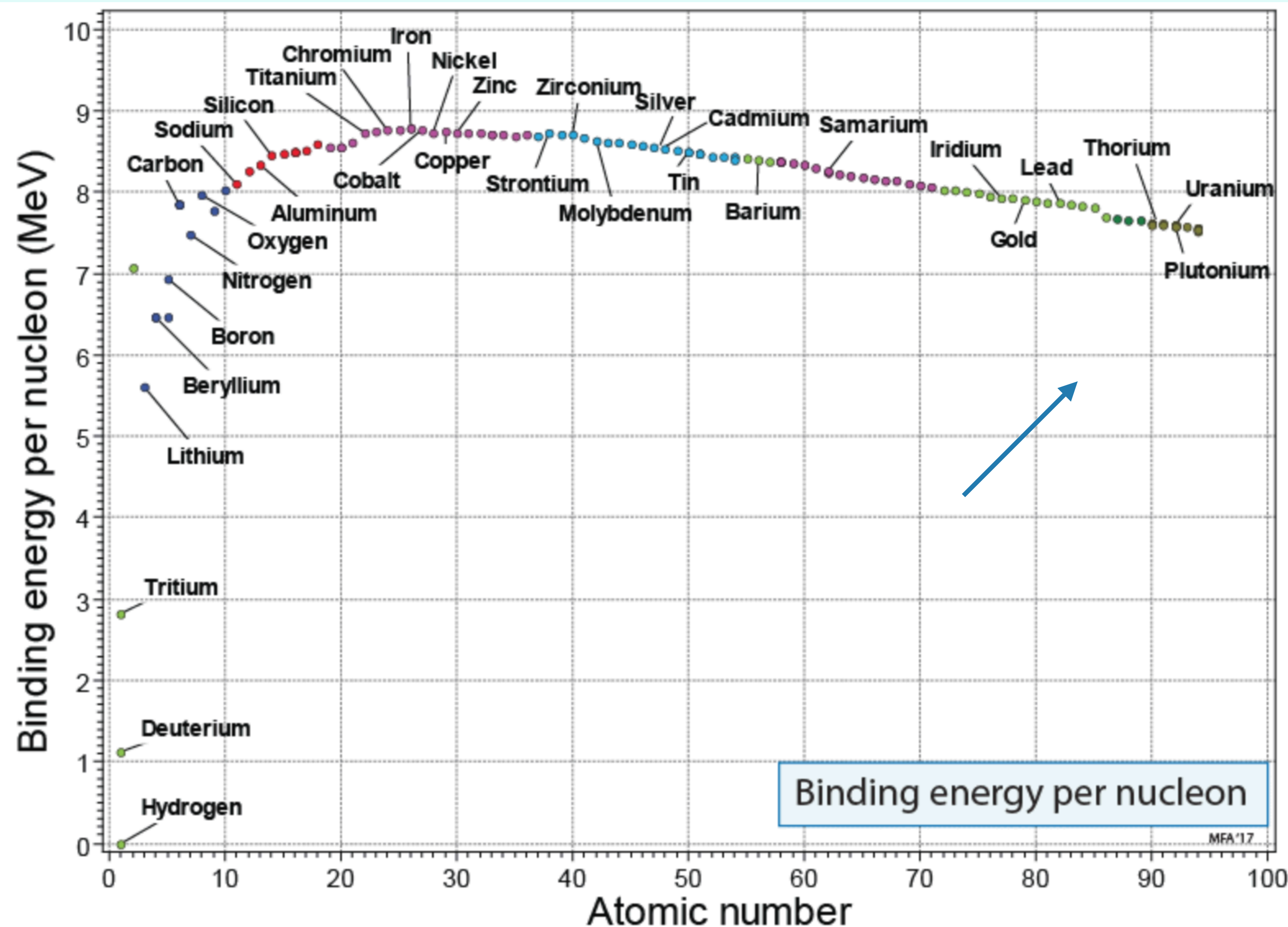
Chris Bolan, CC license

It's time to wake up and smell the plasma, as thermonuclear fusion energy inches closer and closer to reality.

In its quest to develop unlimited green energy, the EAST Fusion Facility in Heifei, China recently created a plasma gas that was heated to 120° million Celsius—that's three-times hotter than the sun—and kept it there for 101 seconds before it dissipated, setting a new world record both for heat and duration.

"The breakthrough is significant progress, and the ultimate goal should be keeping the temperature at a stable level for a long time," said Li Mao, director of physics at Southern University of Sci-Tech in Shenzhen.

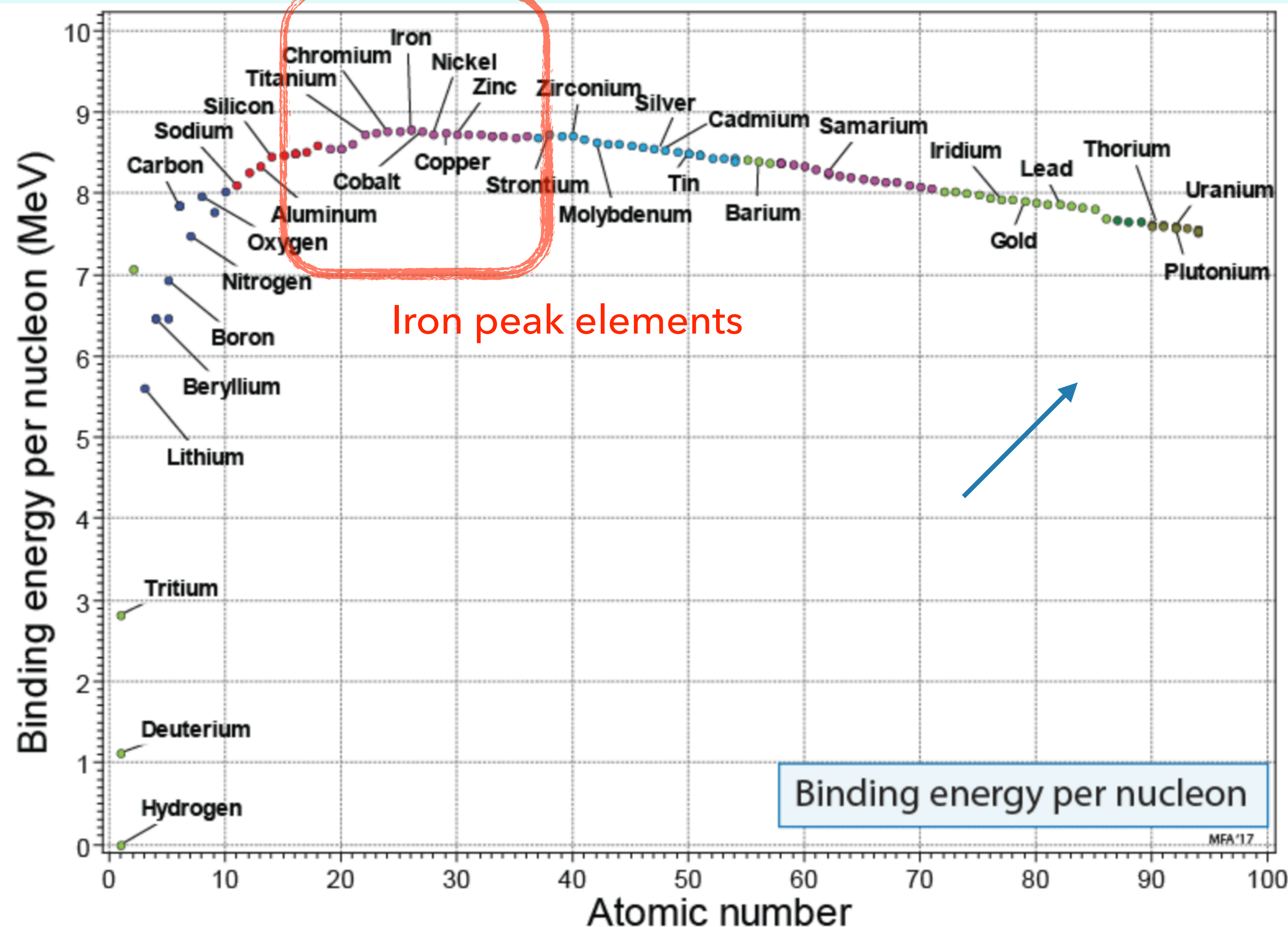
How are heavy elements different from lighter ones?



Elements up until the iron-nickel peak ($A \sim 56$, $Z \sim 26$) may form via thermonuclear reactions

Beyond, an increasing **Coulomb barrier** prevents nuclides from undergoing fusion

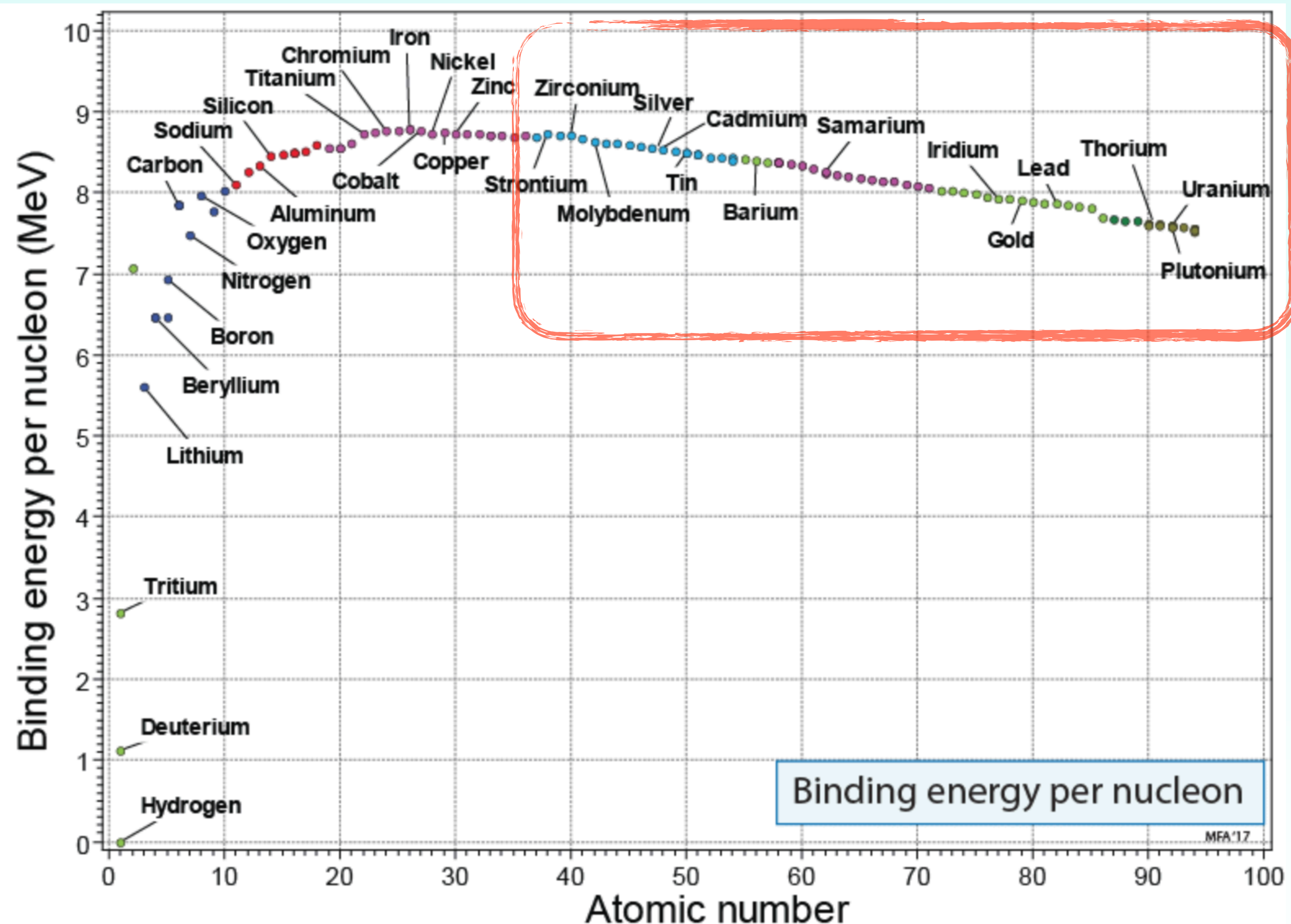
How are heavy elements different from lighter ones?



Elements up until the iron-nickel peak ($A \sim 56$, $Z \sim 26$) may form via thermonuclear reactions

Beyond, an increasing **Coulomb barrier** prevents nuclides from undergoing fusion

While heavier elements...



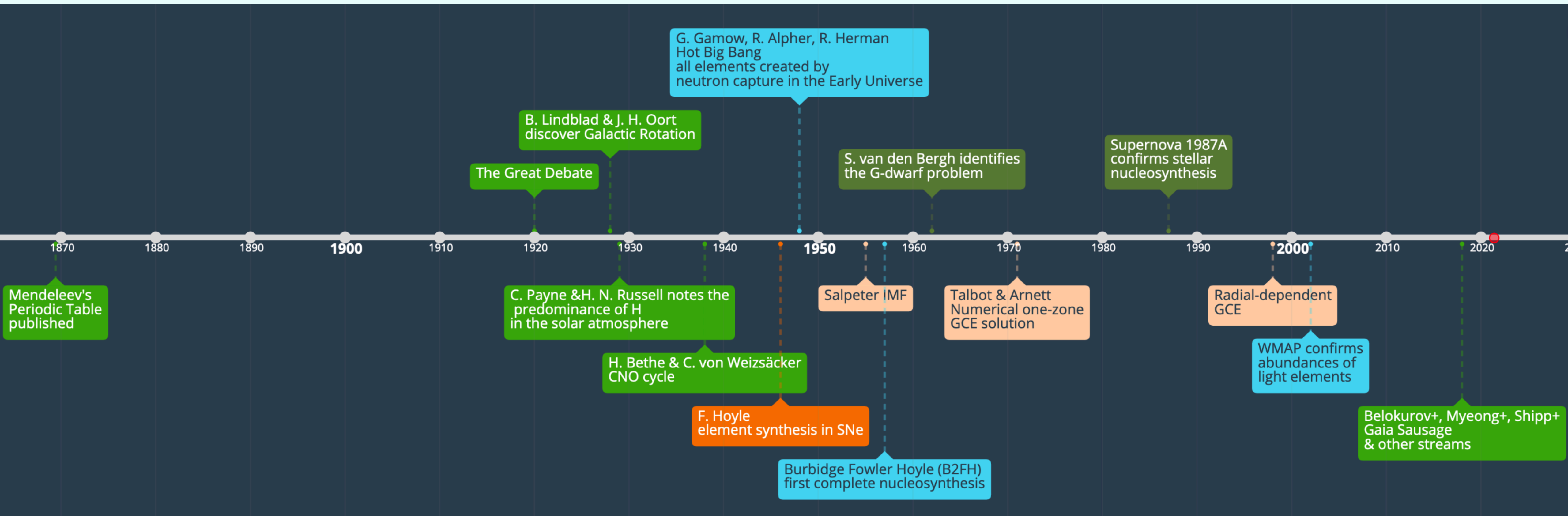
Other mechanisms are at work.
Mainly:

NEUTRON CAPTURE

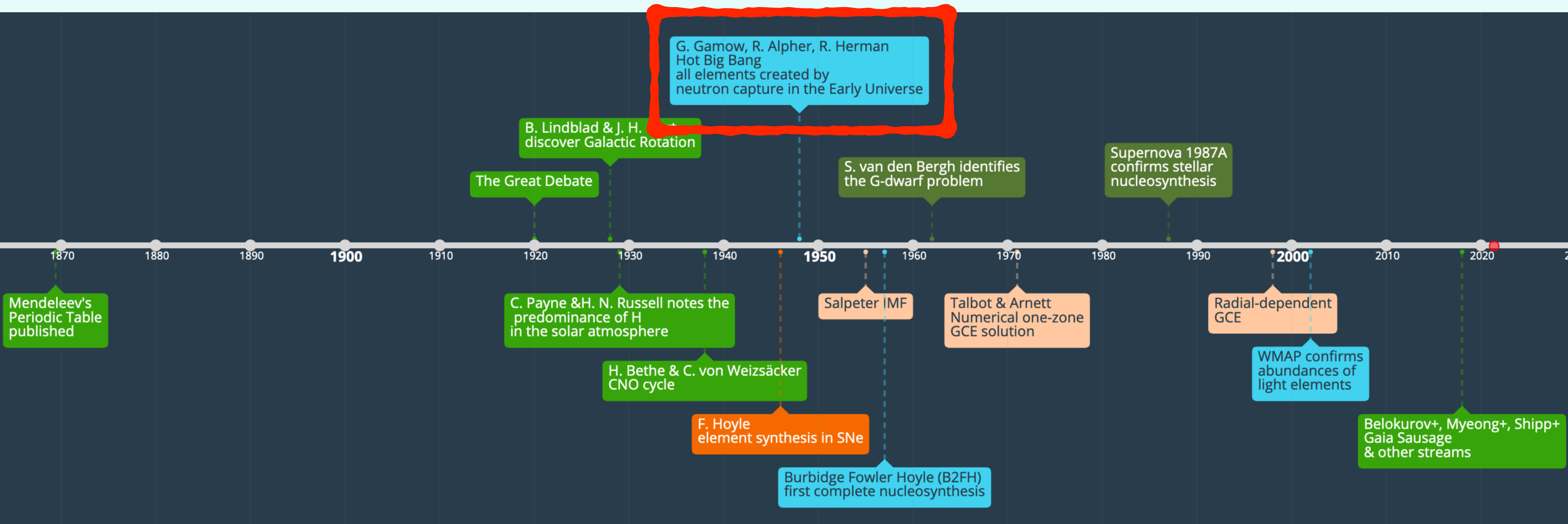
The capture of neutrons onto nuclides
in neutron-rich environments
(s-process and r-process)

(Omitted from this talk are p-
processes, i-processes, and ν p-
processes)

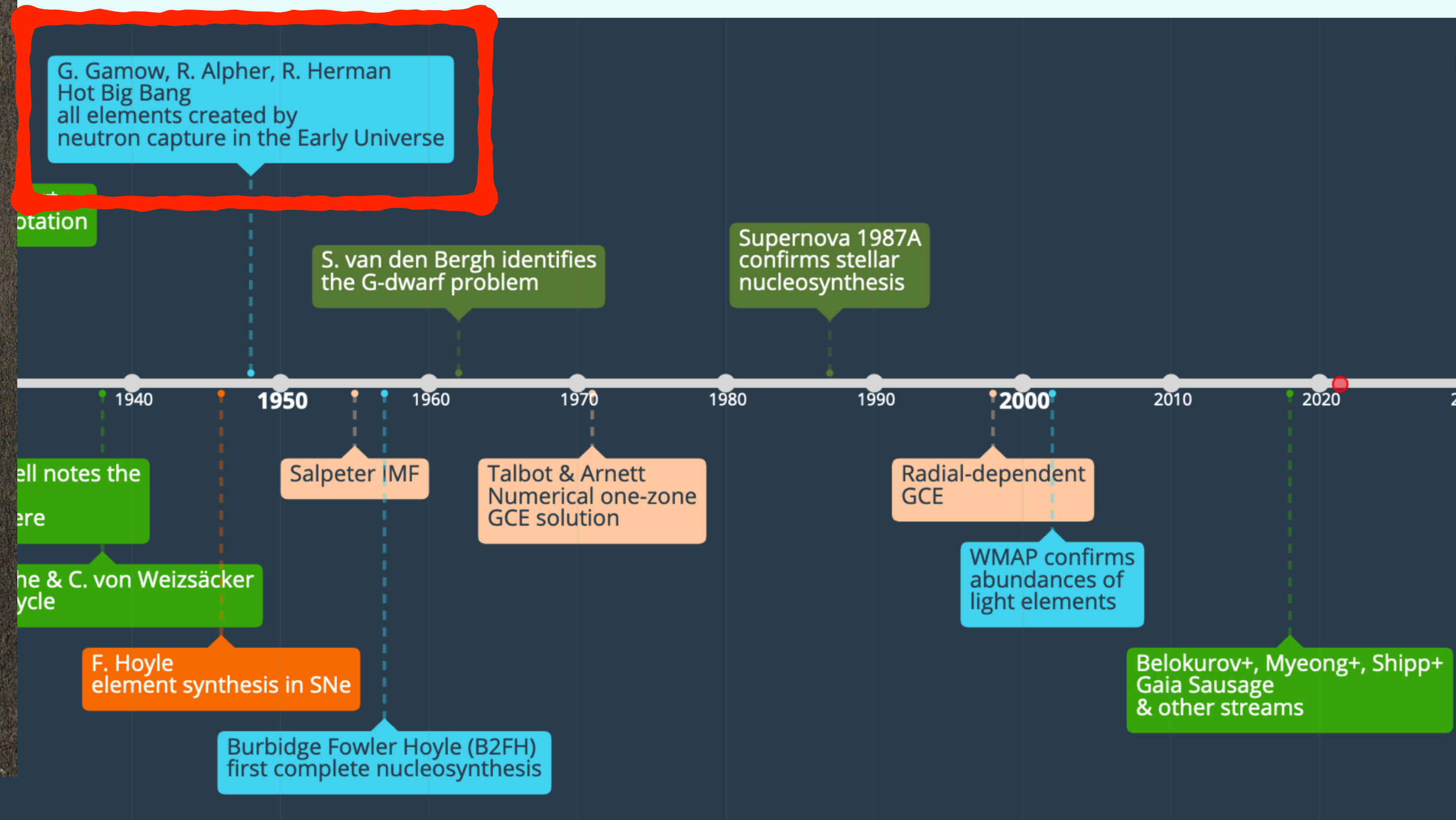
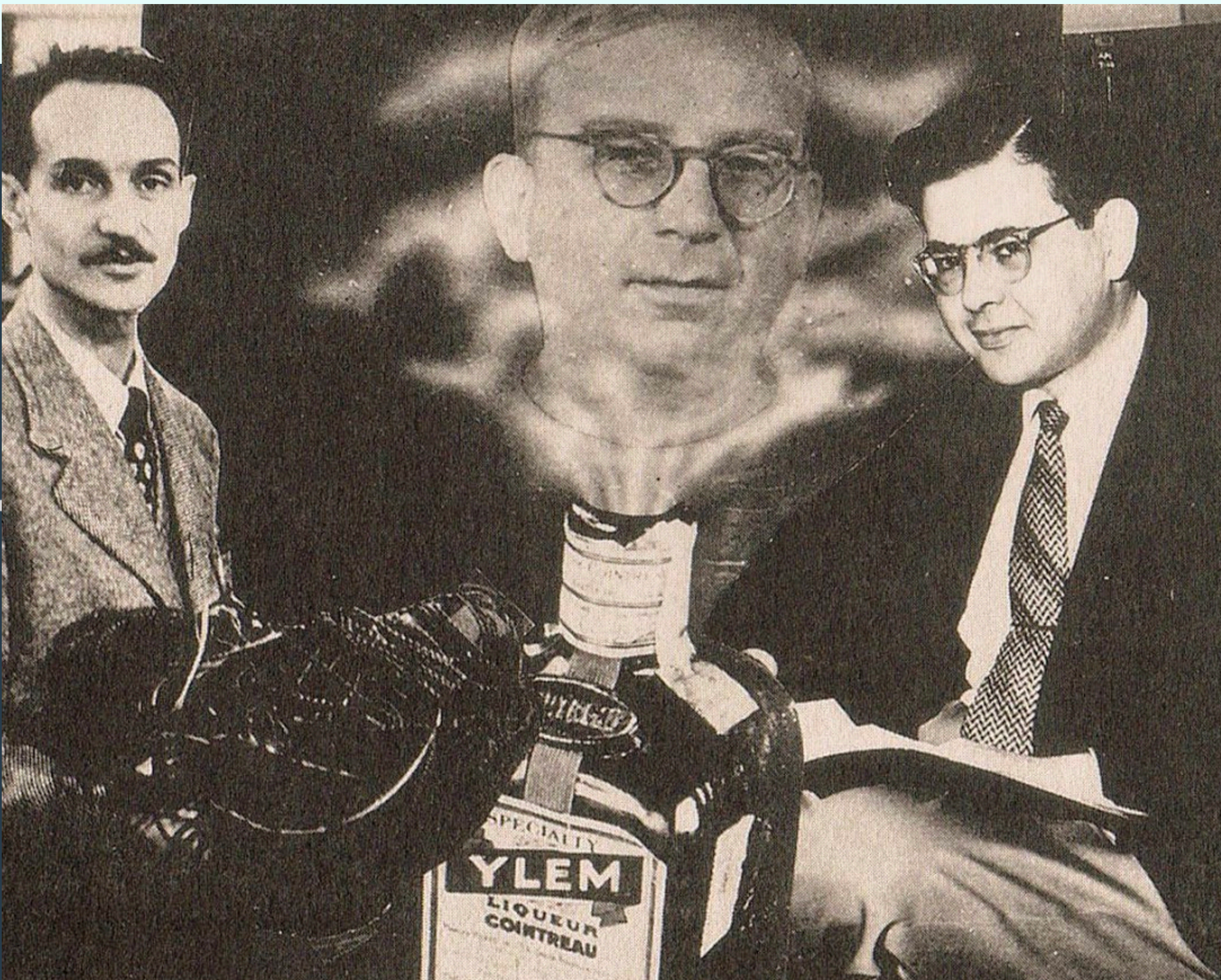
Since when did we start learning where elements come from?



Since when did we start learning where elements come from?



Since when did we start learning where elements come from?

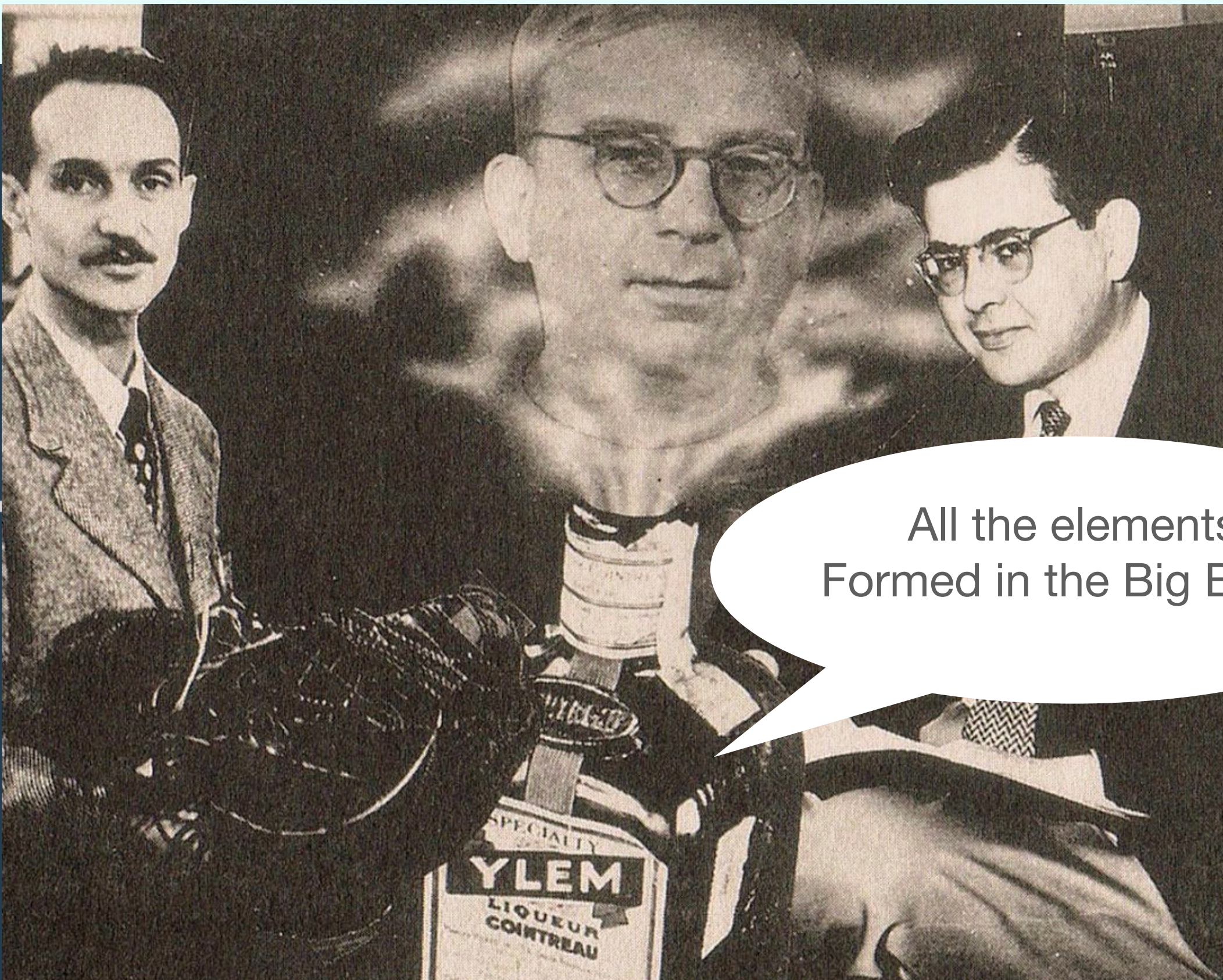


Since when did we start learning where elements come from?

Herman

Gamov

Alpher



G. Gamow, R. Alpher, R. Herman
Hot Big Bang
all elements created by
neutron capture in the Early Universe

otation

S. van den Bergh identifies
the G-dwarf problem

Supernova 1987A
confirms stellar
nucleosynthesis

All the elements
Formed in the Big Bang!

1950

1960

1970

1980

1990

2000

2010

2020

Salpeter IMF

Talbot & Arnett
Numerical one-zone
GCE solution

Radial-dependent
GCE

WMAP confirms
abundances of
light elements

Belokurov+, Myeong+, Shipp+
Gaia Sausage
& other streams

F. Hoyle
element synthesis in SNe

Burbidge Fowler Hoyle (B2FH)
first complete nucleosynthesis

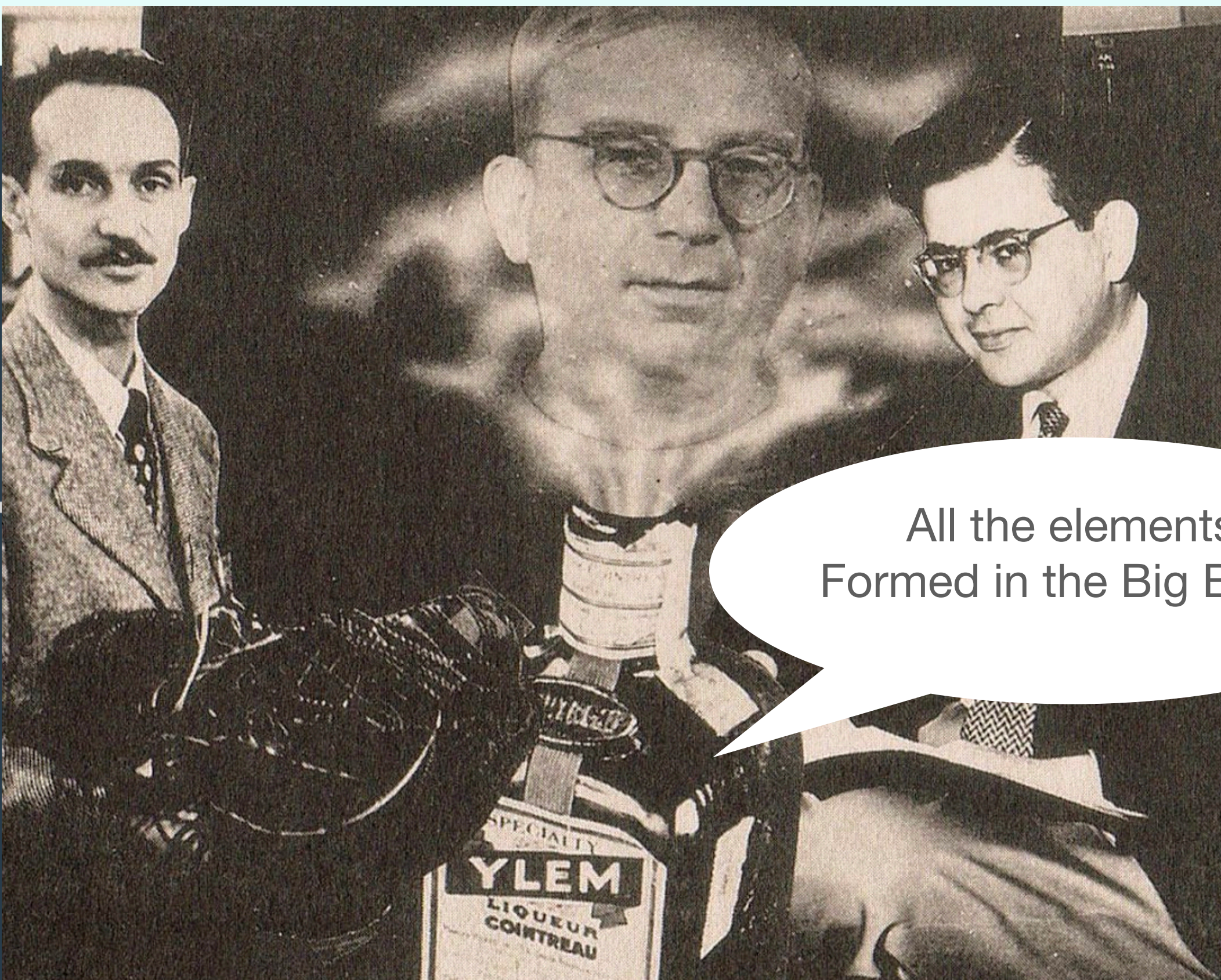
he & C. von Weizsäcker
cycle

Since when did we start learning where elements come from?

Herman

Gamov

Alpher



G. Gamow, R. Alpher, R. Herman
Hot Big Bang
all elements created by
neutron capture in the Early Universe

S. van den Bergh identifies
the G-dwarf problem

Supernova 1987A
confirms stellar
nucleosynthesis

1950

1960

1970

1980

1990

2000

2010

2020

Salpeter IMF

Talbot & Arnett
Numerical one-zone
GCE solution

Radial-dependent
GCE

WMAP confirms
abundances of
light elements

Belokurov+, Myeong+, Shipp+
Gaia Sausage
& other streams

F. Hoyle
element synthesis in SNe

Burbidge Fowler Hoyle (B2FH)
first complete nucleosynthesis

otation

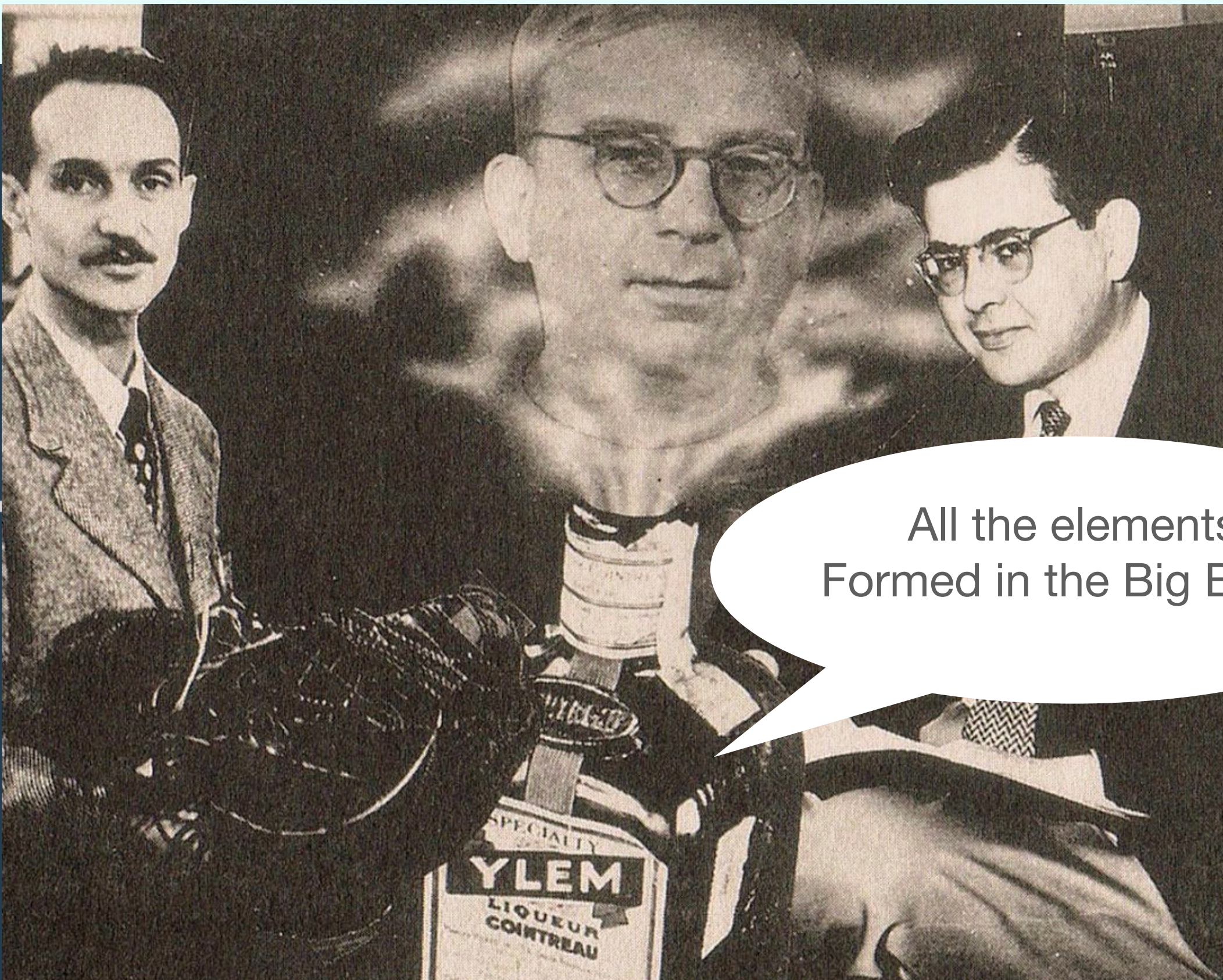
he & C. von Weizsäcker
ycle

Since when did we start learning where elements come from?

Herman

Gamov

Alpher



G. Gamow, R. Alpher, R. Herman
Hot Big Bang
all elements created by
neutron capture in the Early Universe

S. van den Bergh
the G-dwarf problem

1950

1960

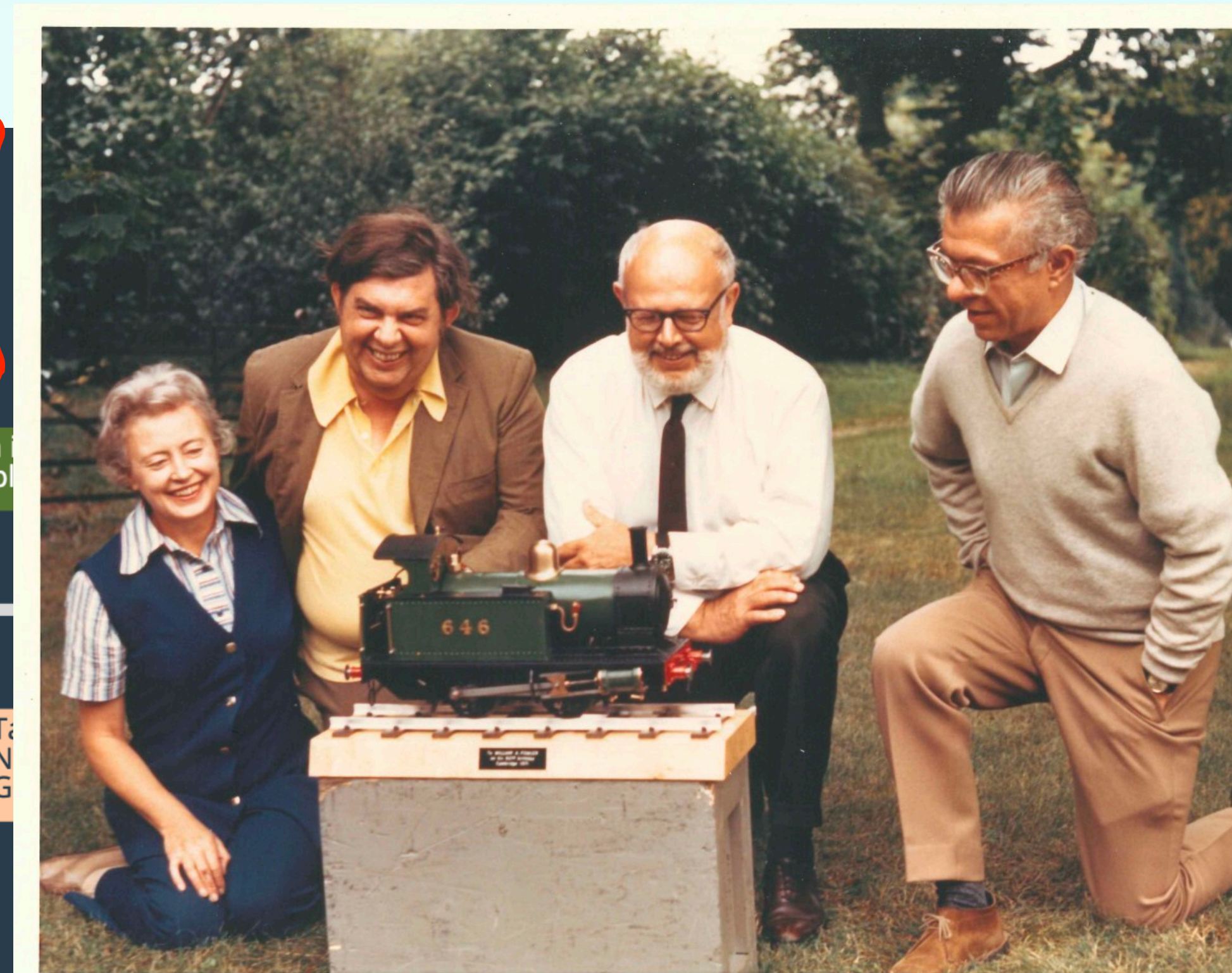
Salpeter IMF

He & C. von Weizsäcker
cycle

F. Hoyle
element synthesis in SNe

Burbidge Fowler Hoyle (B2FH)
first complete nucleosynthesis

Galaxy Sausage
& other streams

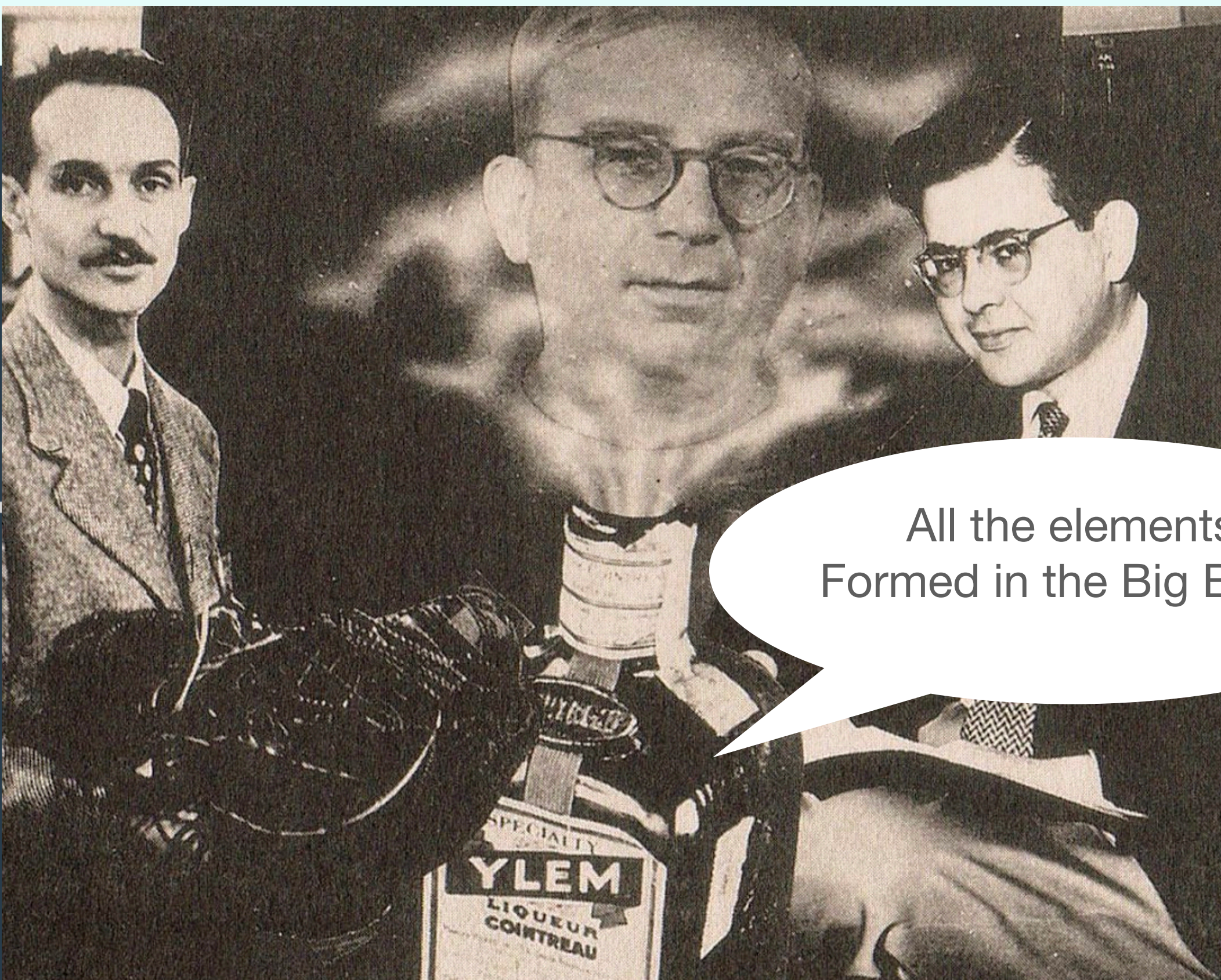


Since when did we start learning where elements come from?

Herman

Gamov

Alpher



G. Gamow, R. Alpher, R. Herman
Hot Big Bang
all elements created by
neutron capture in the Early Universe

All the elements
Formed in the Big Bang!

otation

S. van den Bergh
the G-dwarf prob

1950

1960

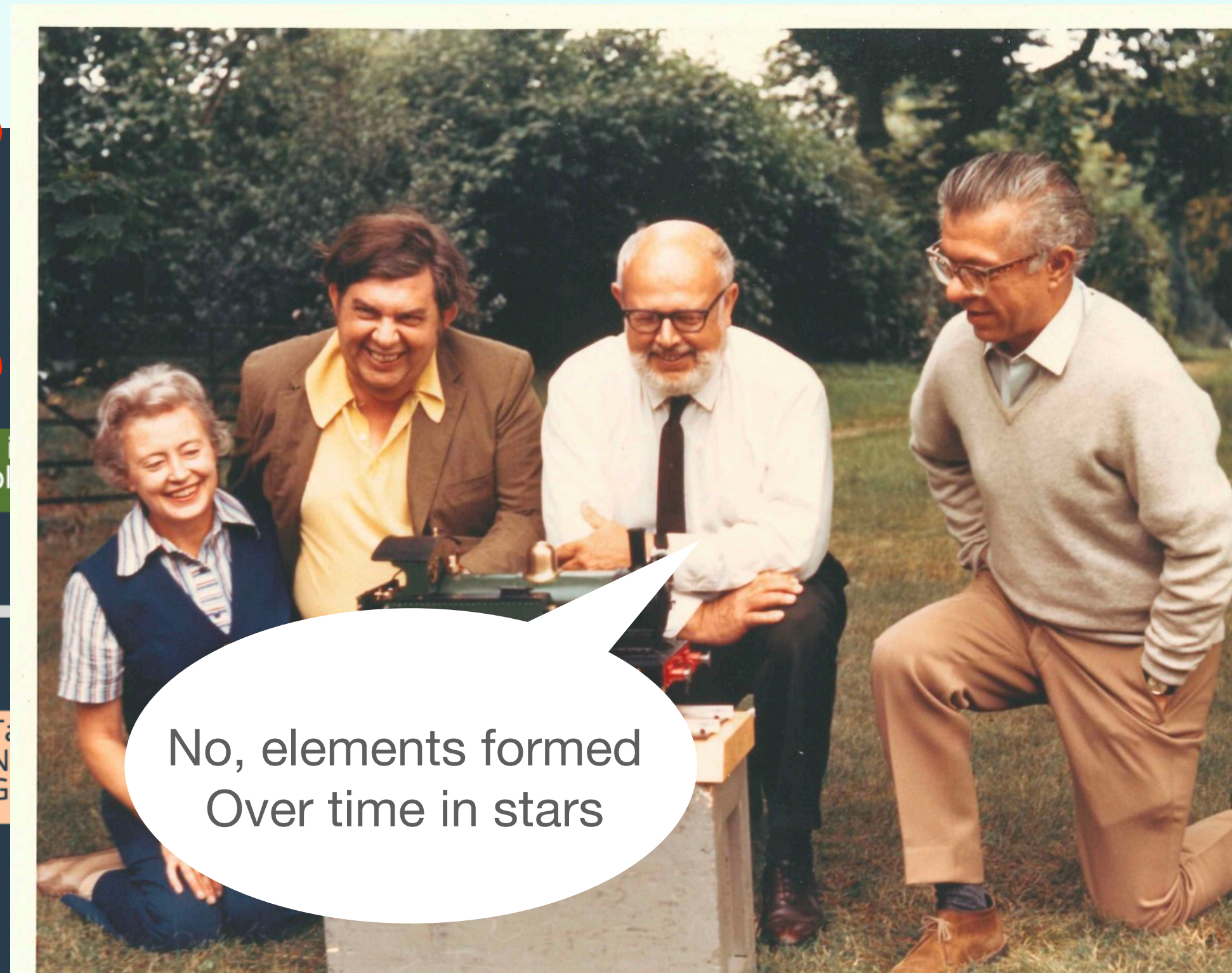
Salpeter IMF

he & C. von Weizsäcker
ycle

F. Hoyle
element synthesis in SNe

Burbidge Fowler Hoyle (B2FH)
first complete nucleosynthesis

Galaxy Sausage
& other streams



No, elements formed
Over time in stars

“B2FH”: the seminal paper

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4

OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

*Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California*

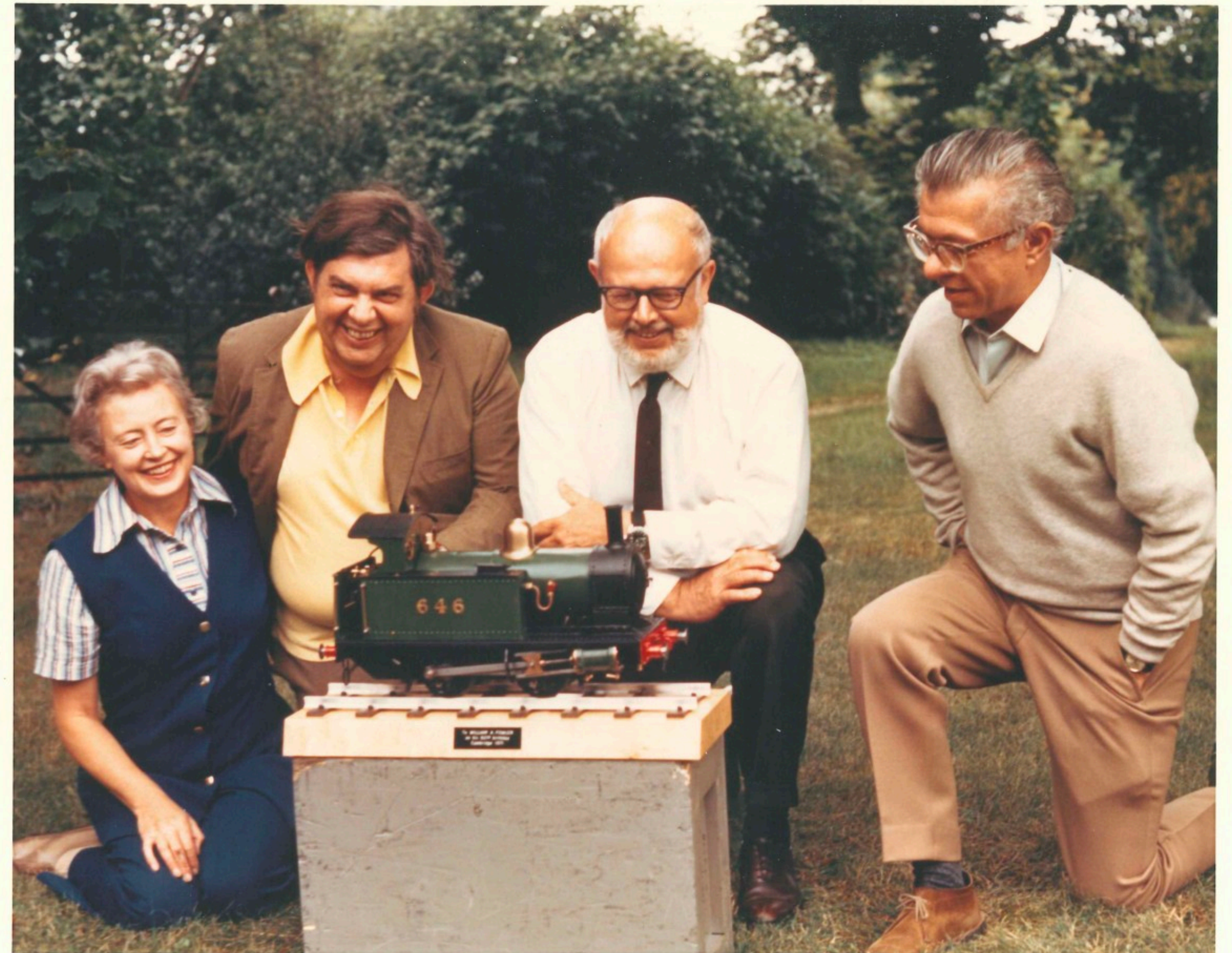
“It is the stars, The stars above us, govern our conditions”;
(*King Lear*, Act IV, Scene 3)

but perhaps

“The fault, dear Brutus, is not in our stars, But in ourselves,”
(*Julius Caesar*, Act I, Scene 2)

G.R. Burbidge

W. A. Fowler



E.M. Burbidge

F. Hoyle

“B2FH”: the seminal paper

TABLE OF CONTENTS

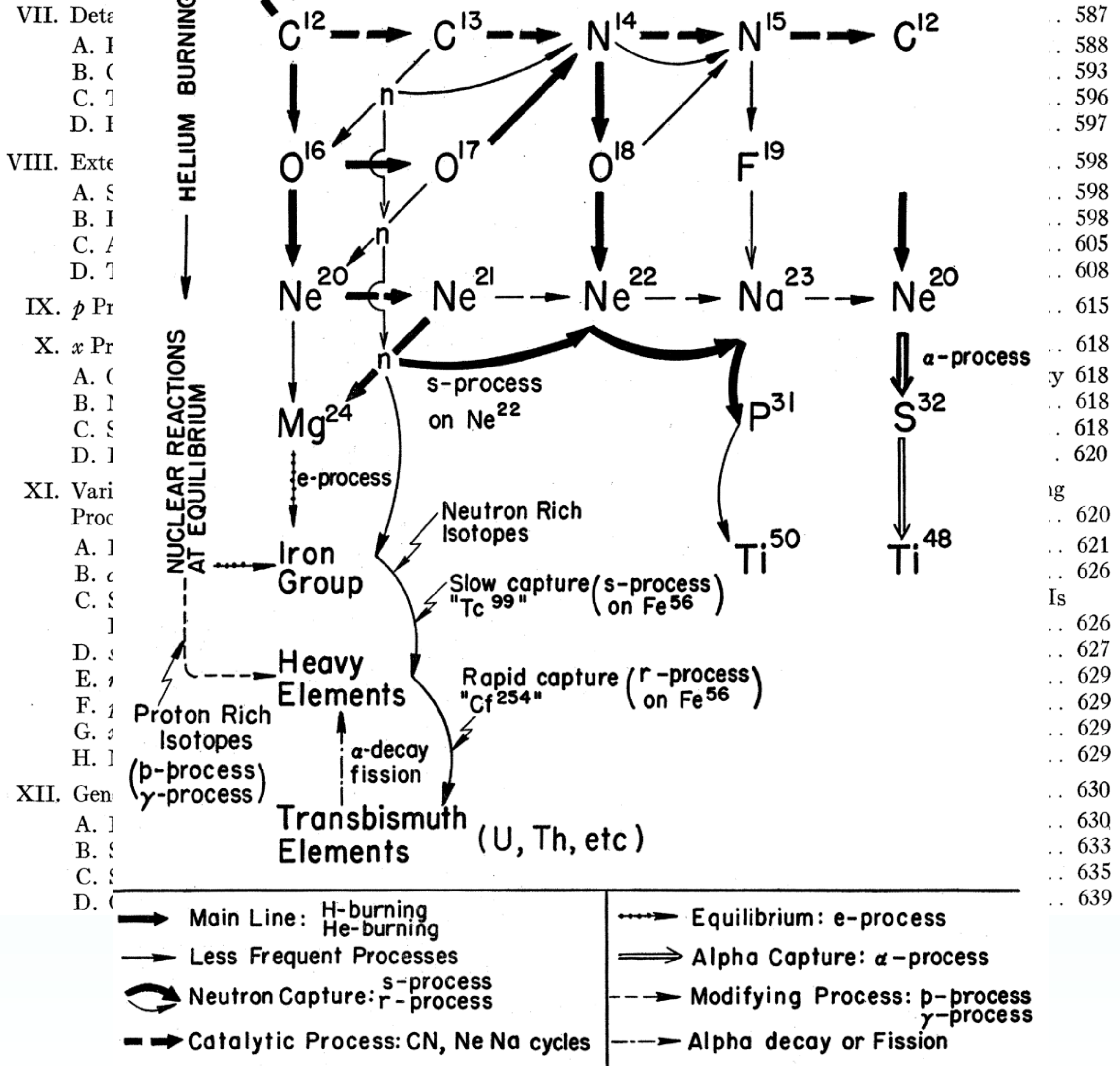
	Page
I. Introduction.....	548
A. Element Abundances and Nuclear Structure.....	548
B. Four Theories of the Origin of the Elements.....	550
C. General Features of Stellar Synthesis.....	550
II. Physical Processes Involved in Stellar Synthesis, Their Place of Occurrence, and the Time-Scales Associated with Them.....	551
A. Modes of Element Synthesis.....	551
B. Method of Assignment of Isotopes among Processes (i) to (viii).....	553
C. Abundances and Synthesis Assignments Given in the Appendix.....	555
D. Time Scales for Different Modes of Synthesis.....	556
III. Hydrogen Burning, Helium Burning, the α Process, and Neutron Production.....	559
A. Cross-Section Factor and Reaction Rates.....	559
B. Pure Hydrogen Burning.....	562
C. Pure Helium Burning.....	565
D. α Process.....	567
E. Succession of Nuclear Fuels in an Evolving Star.....	568
F. Burning of Hydrogen and Helium with Mixtures of Other Elements; Stellar Neutron Sources....	569
IV. e Process.....	577
V. s and r Processes: General Considerations.....	580
A. “Shielded” and “Shielding” Isobars and the s , r , p Processes.....	580
B. Neutron-Capture Cross Sections.....	581
C. General Dynamics of the s and r Processes.....	583
VI. Details of the s Process.....	583

VII. Details of the r Process.....	587
A. Path of the r Process.....	588
B. Calculation of the r -Process Abundances.....	593
C. Time for the r Process: Steady Flow and Cycling.....	596
D. Freezing of the r -Process Abundances.....	597
VIII. Extension and Termination of the r Process and s Process.....	598
A. Synthesis of the Naturally Radioactive Elements.....	598
B. Extension and Termination of the r Process.....	598
C. Age of the Elements and of the Galaxy.....	605
D. Termination of the s Process; the Abundances of Lead, Bismuth, Thorium, and Uranium.....	608
IX. p Process.....	615
X. x Process.....	618
A. Observational Evidence for Presence of Deuterium, Lithium, Beryllium, and Boron in our Galaxy.....	618
B. Nuclear Reactions which Destroy Deuterium, Lithium, Beryllium, and Boron.....	618
C. Synthesis of Deuterium, Lithium, Beryllium, and Boron.....	618
D. Preservation of Lithium in Stars.....	620
XI. Variations in Chemical Composition among Stars, and Their Bearing on the Various Synthesizing Processes.....	620
A. Hydrogen Burning and Helium Burning.....	621
B. α Process.....	626
C. Synthesis of Elements in the Iron Peak of the Abundance Curve, and the Aging Effect as It Is Related to This and Other Types of Element Synthesis.....	626
D. s Process.....	627
E. r Process.....	629
F. p Process.....	629
G. x Process.....	629
H. Nuclear Reactions and Element Synthesis in Surfaces of Stars.....	629
XII. General Astrophysics.....	630
A. Ejection of Material from Stars and the Enrichment of the Galaxy in Heavy Elements.....	630
B. Supernova Outbursts.....	633
C. Supernova Light Curves.....	635
D. Origin of the r -Process Isotopes in the Solar System.....	639

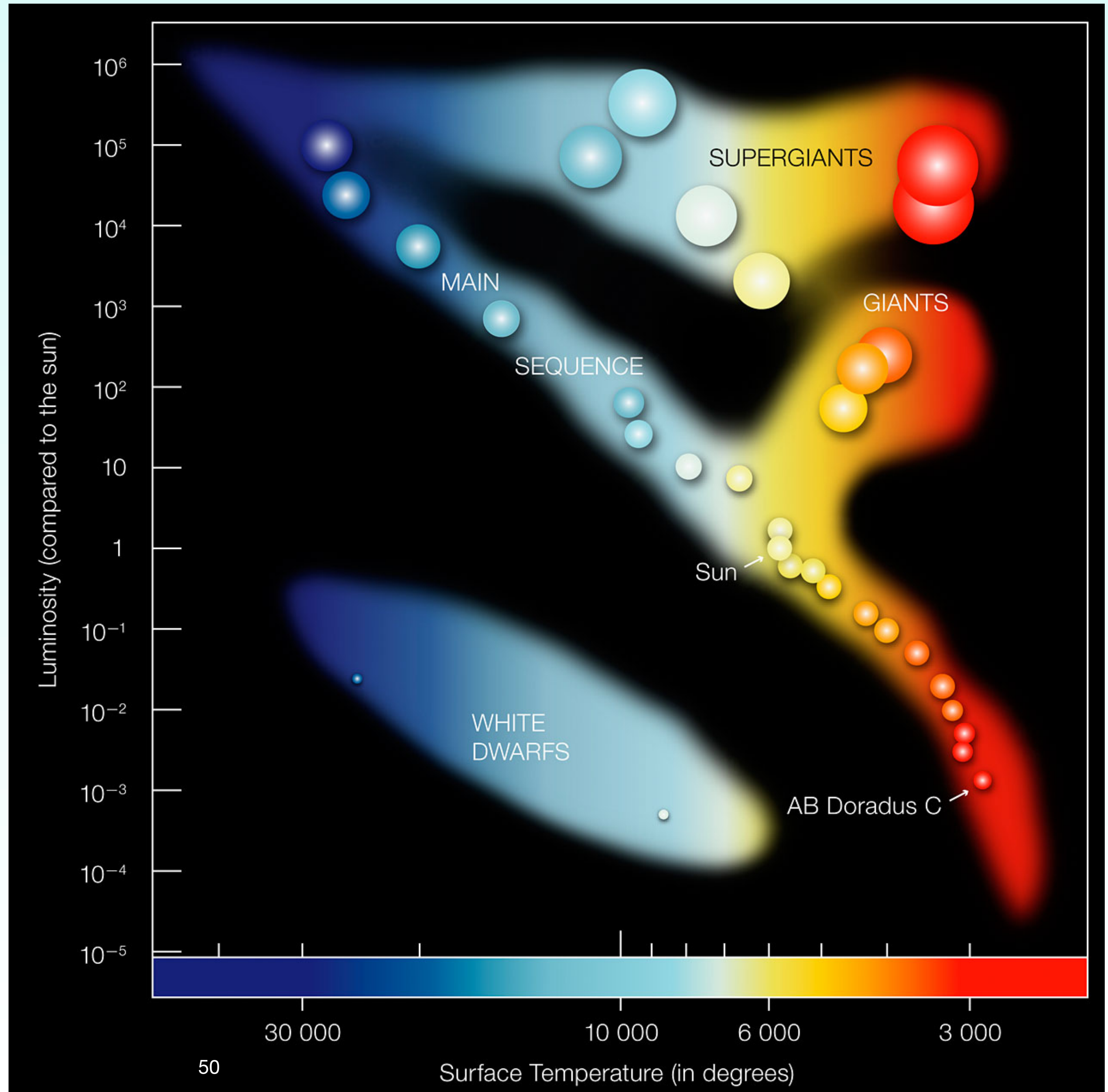
“B2FH”: the seminal paper

TABLE OF CONTENTS

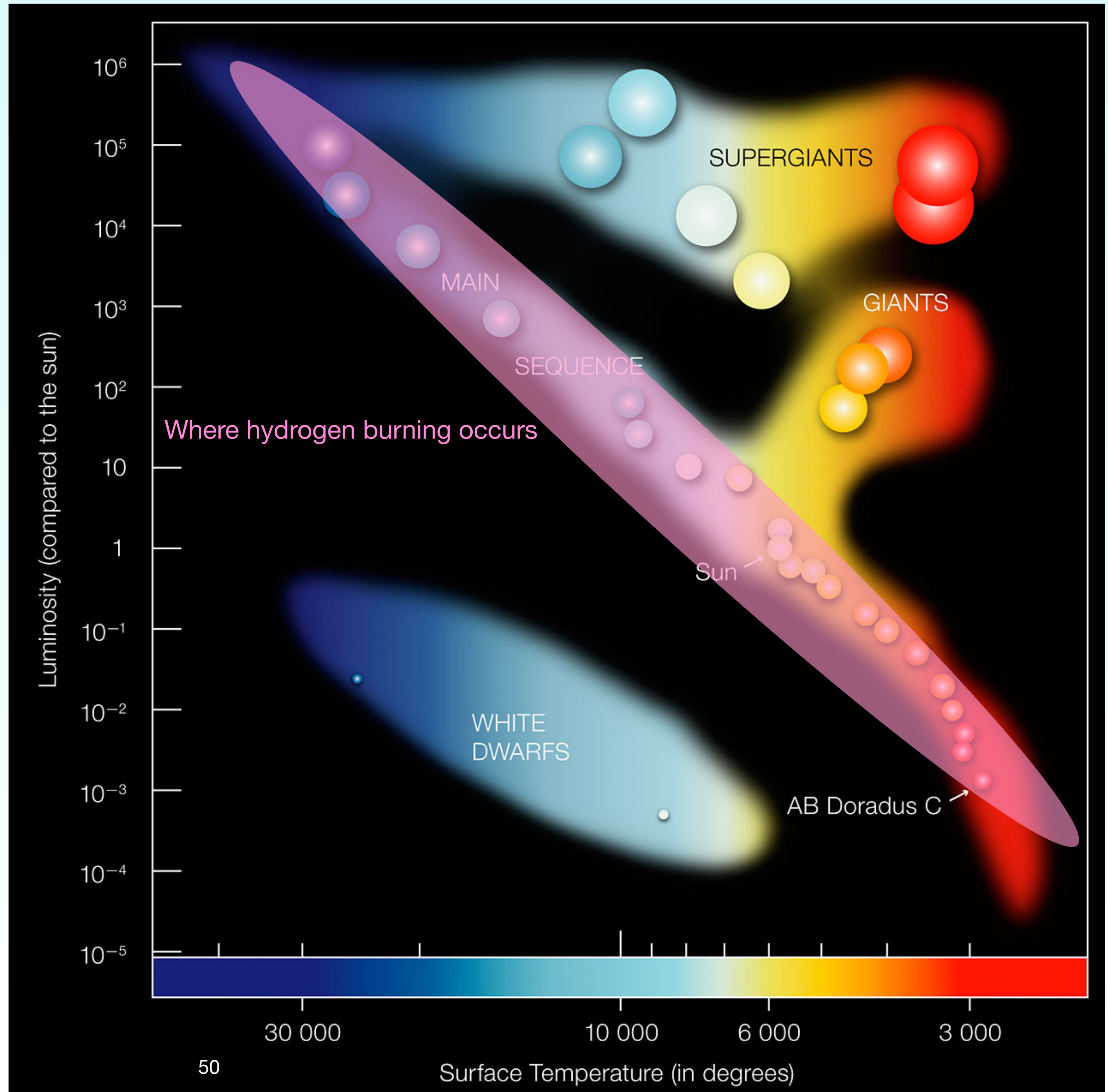
	Page
I. Introduction.....	548
A. Element Abundances and Nuclear Structure.....	548
B. Four Theories of the Origin of the Elements.....	550
C. General Features of Stellar Synthesis.....	550
II. Physical Processes Involved in Stellar Synthesis, Their Place of Occurrence, and the Time-Scales Associated with Them.....	551
A. Modes of Element Synthesis.....	551
B. Method of Assignment of Isotopes among Processes (i) to (viii).....	553
C. Abundances and Synthesis Assignments Given in the Appendix.....	555
D. Time Scales for Different Modes of Synthesis.....	556
III. Hydrogen Burning, Helium Burning, the α Process, and Neutron Production.....	559
A. Cross-Section Factor and Reaction Rates.....	559
B. Pure Hydrogen Burning.....	562
C. Pure Helium Burning.....	565
D. α Process.....	567
E. Succession of Nuclear Fuels in an Evolving Star.....	568
F. Burning of Hydrogen and Helium with Mixtures of Other Elements; Stellar Neutron Sources....	569
IV. e Process.....	577
V. s and r Processes: General Considerations.....	580
A. “Shielded” and “Shielding” Isobars and the s , r , p Processes.....	580
B. Neutron-Capture Cross Sections.....	581
C. General Dynamics of the s and r Processes.....	583
VI. Details of the s Process.....	583



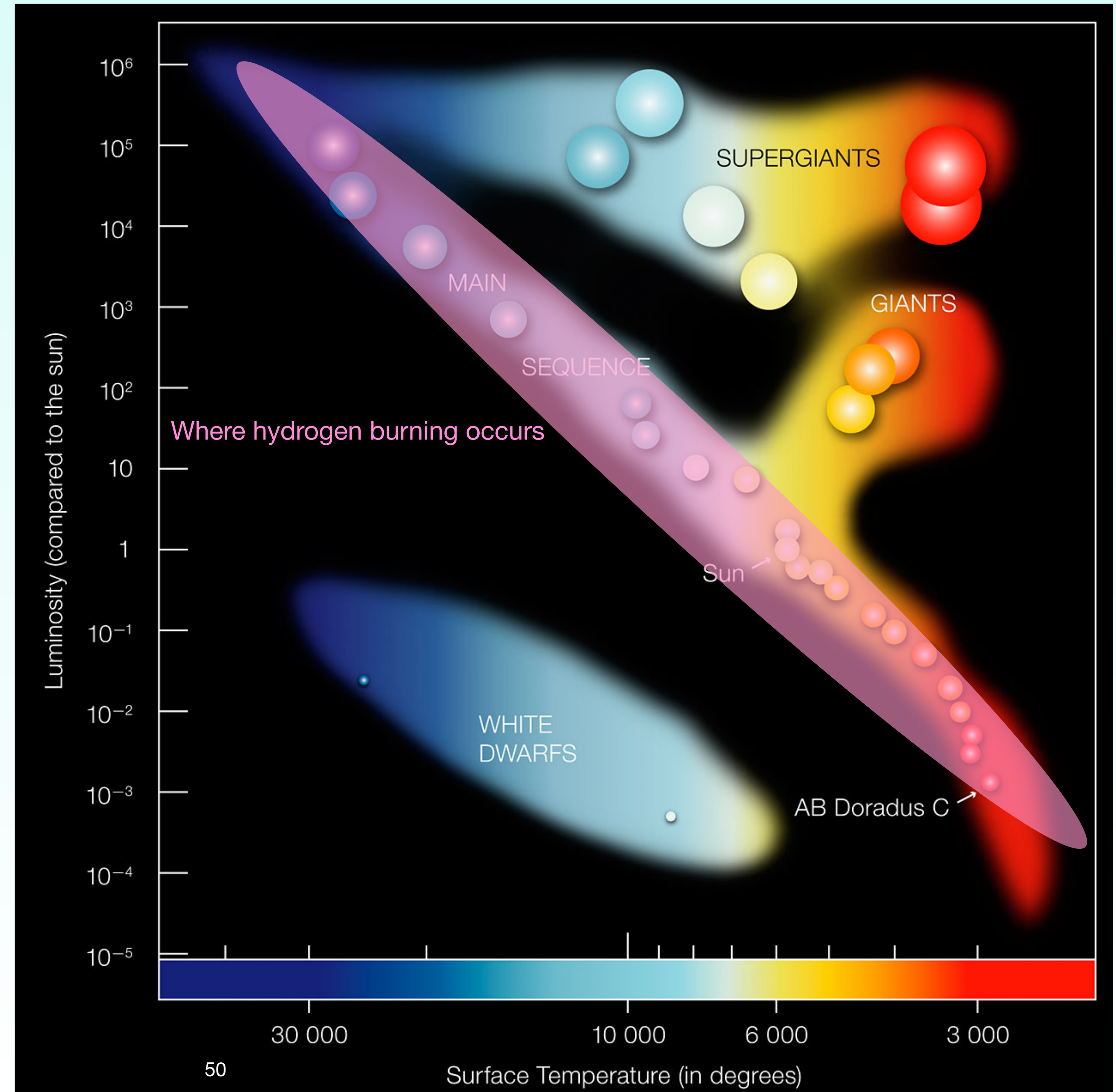
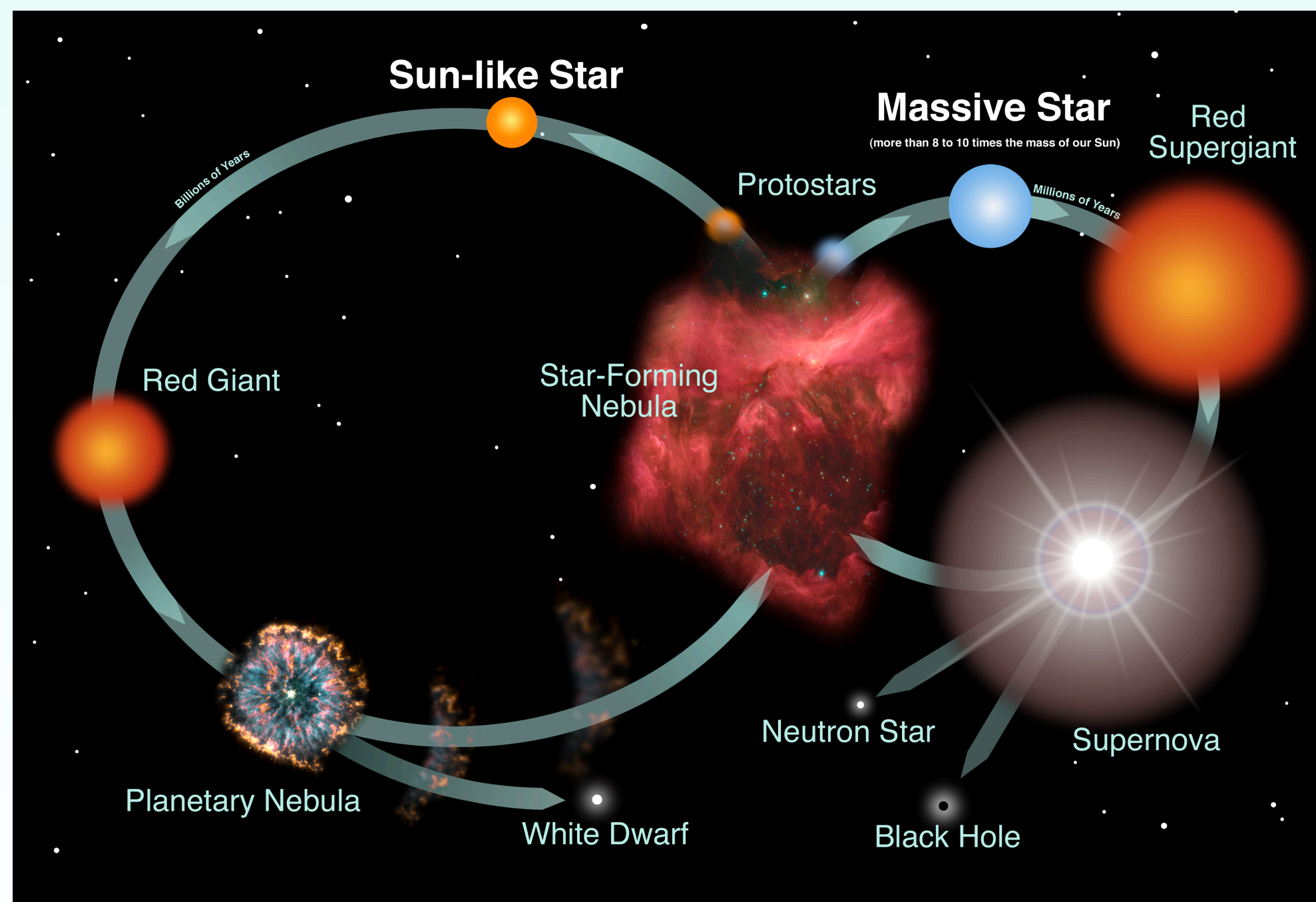
The Hertzsprung–Russell diagram



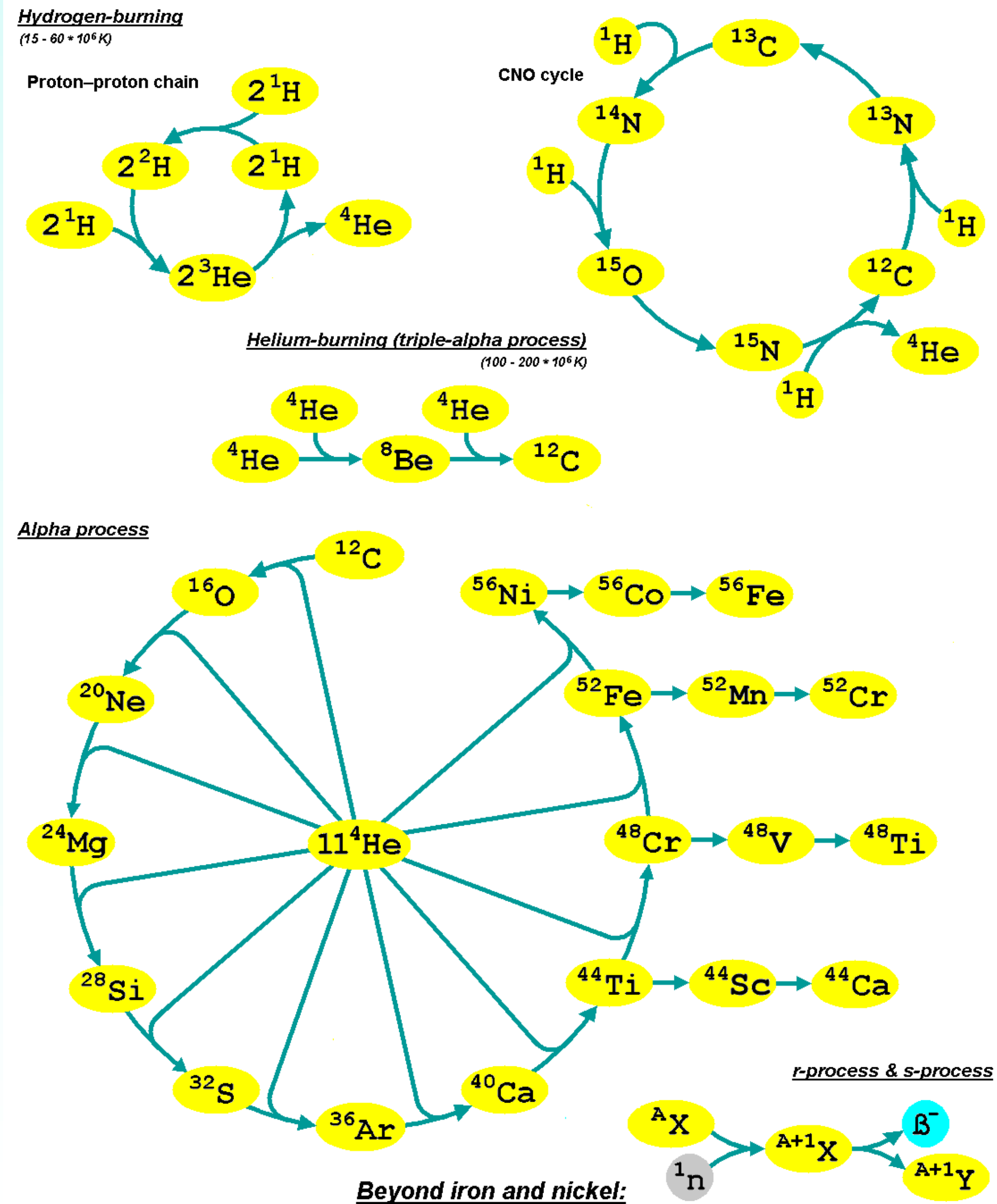
The Hertzsprung–Russell diagram

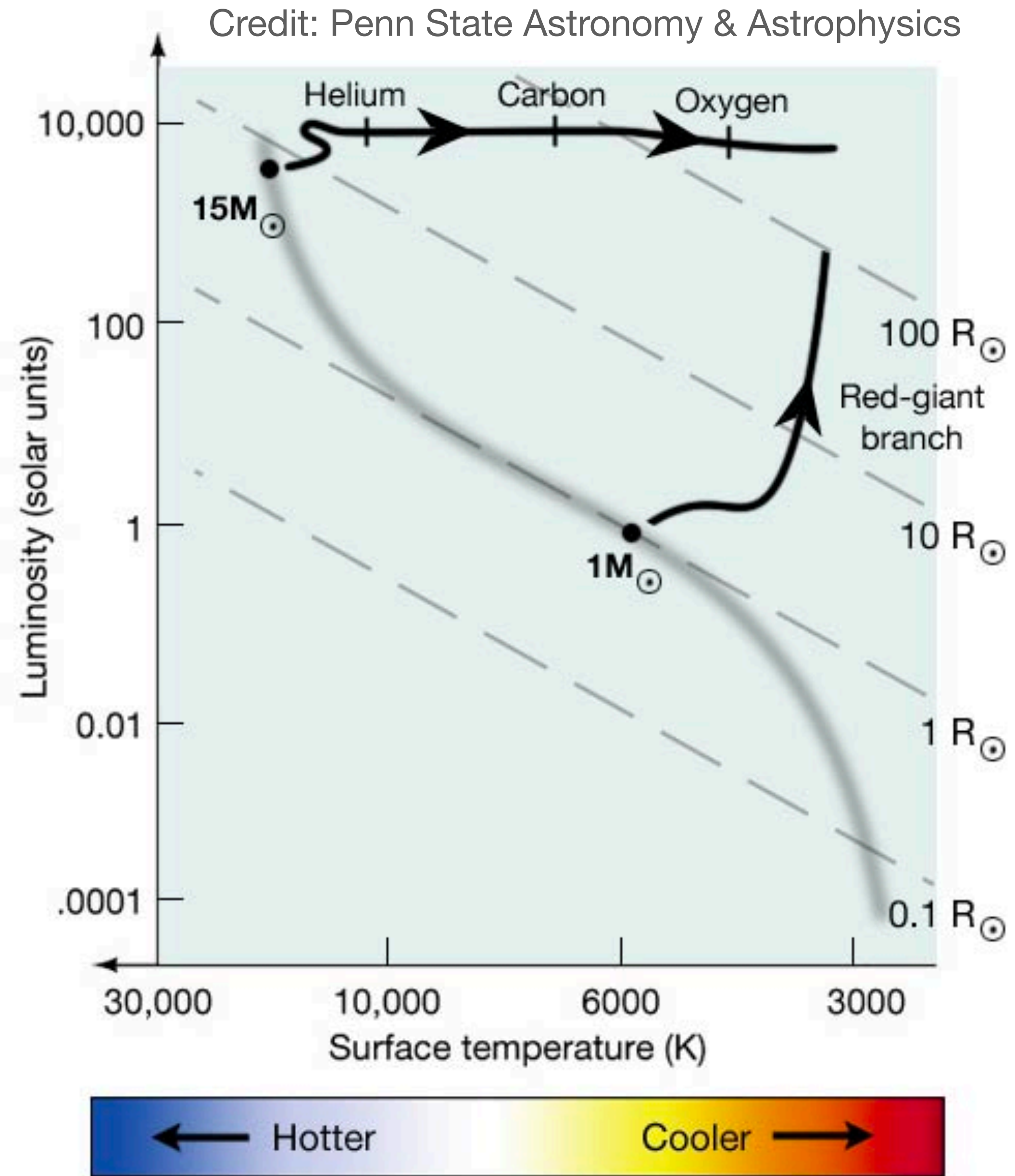


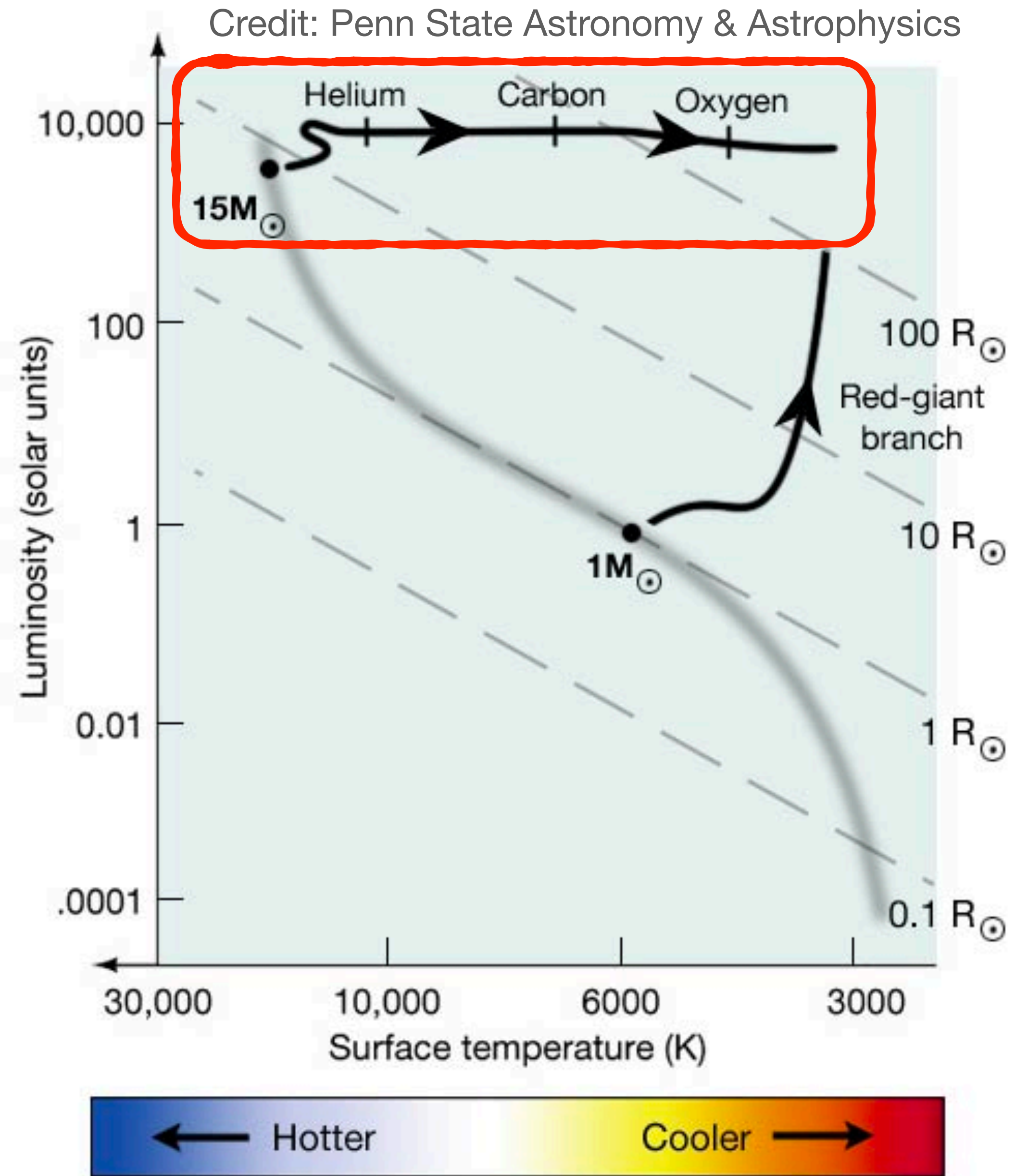
The Hertzsprung–Russell diagram



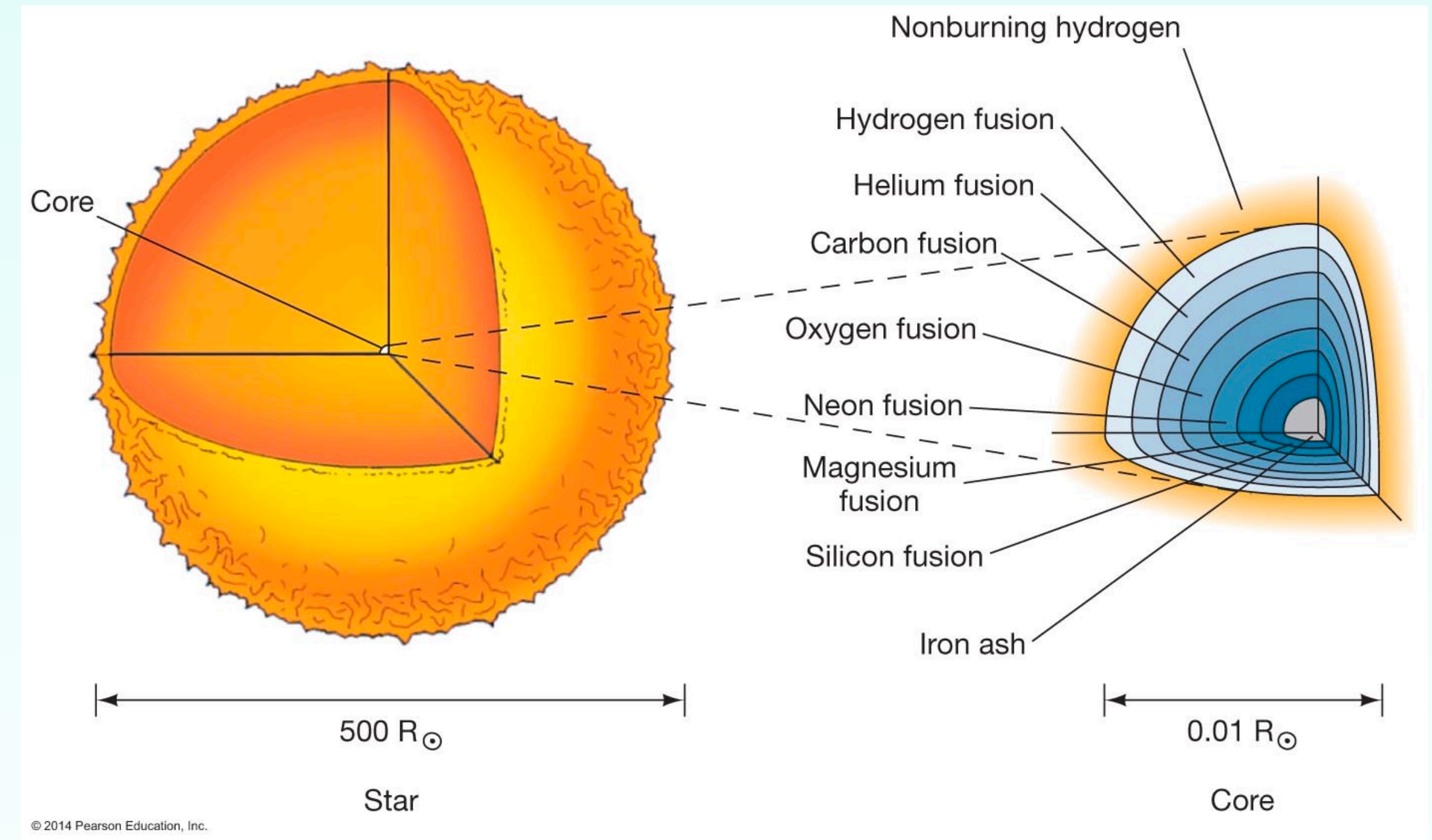
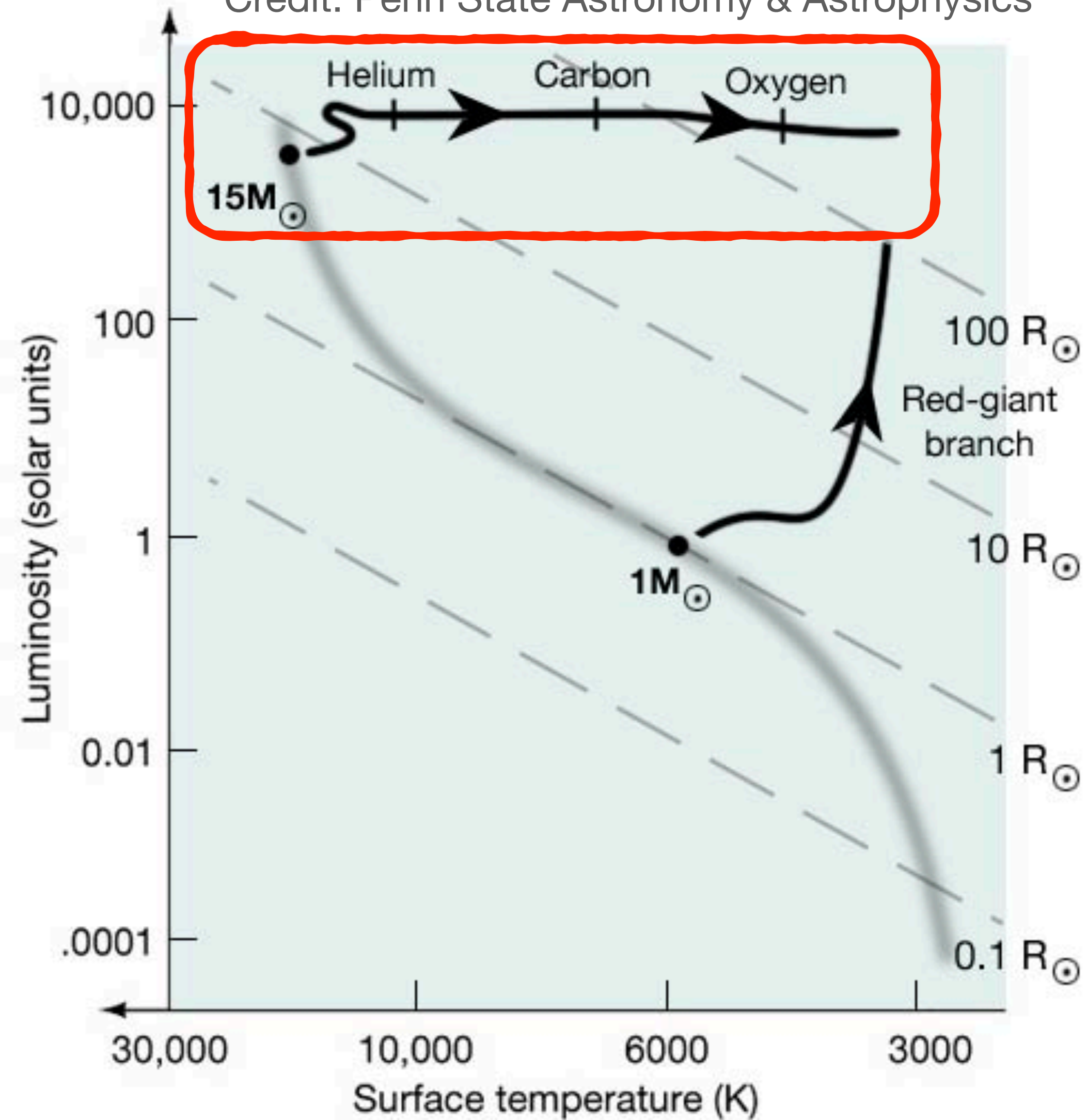
Dominant stellar nucleosynthesis routes

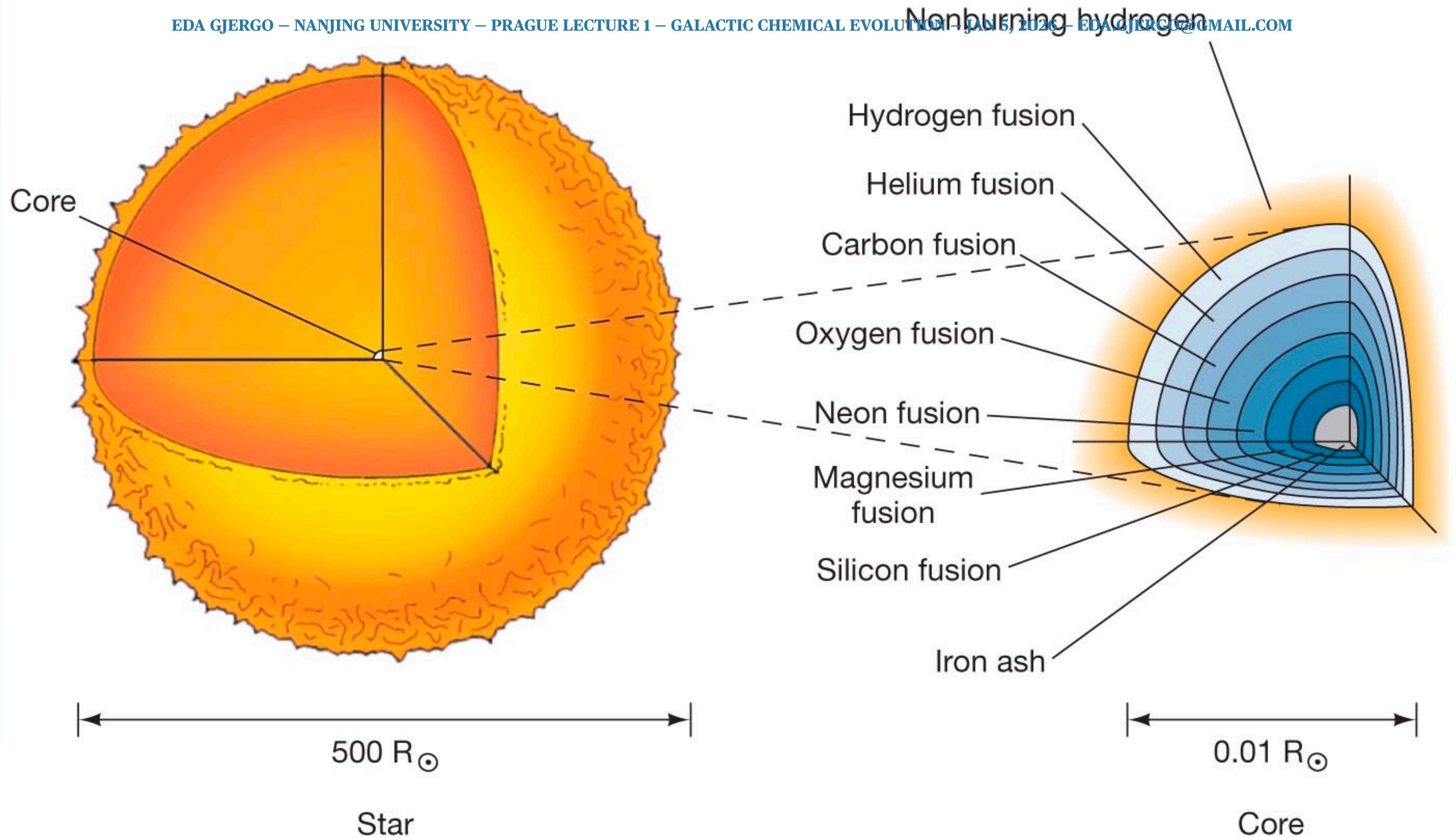


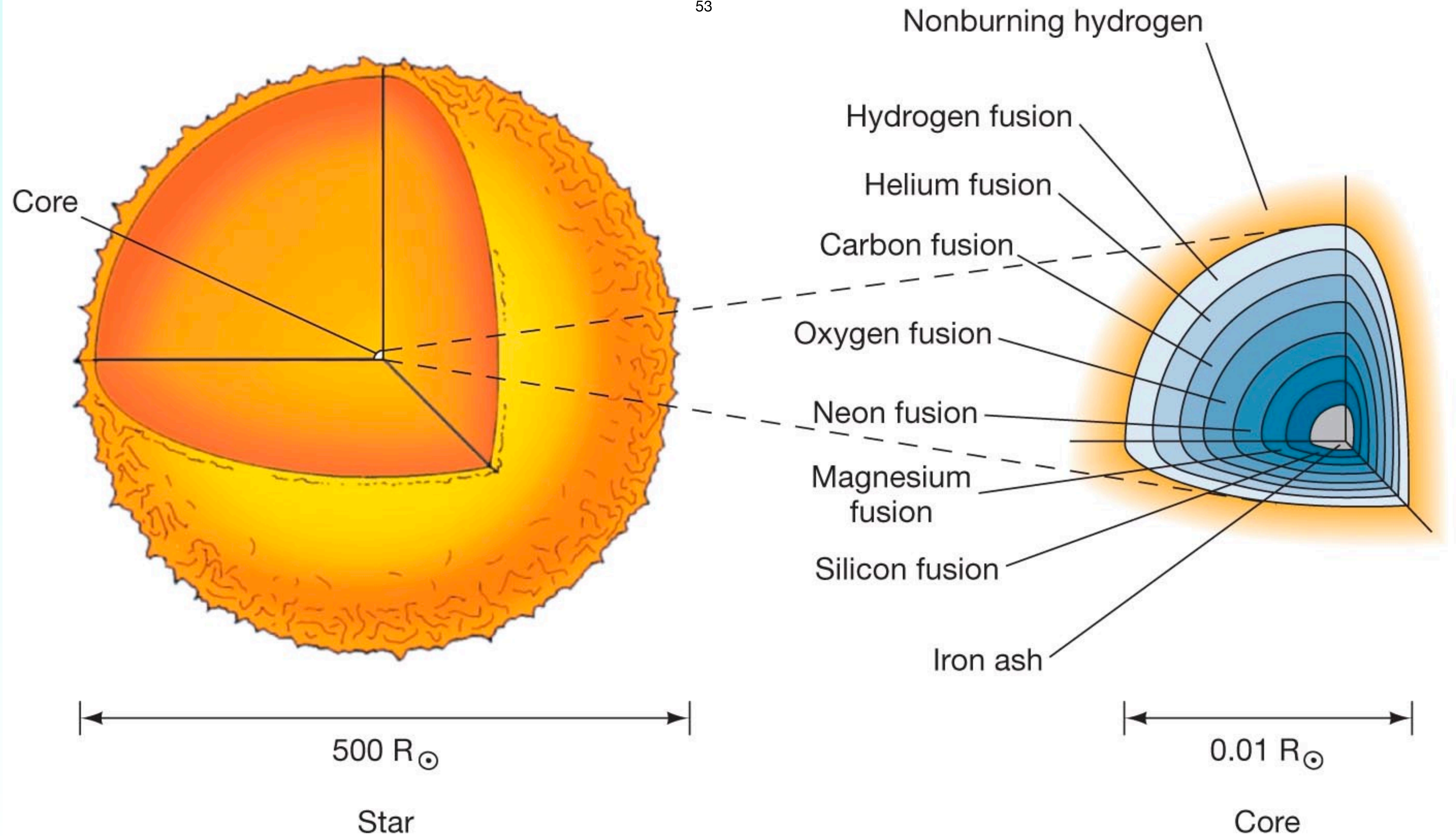




Credit: Penn State Astronomy & Astrophysics

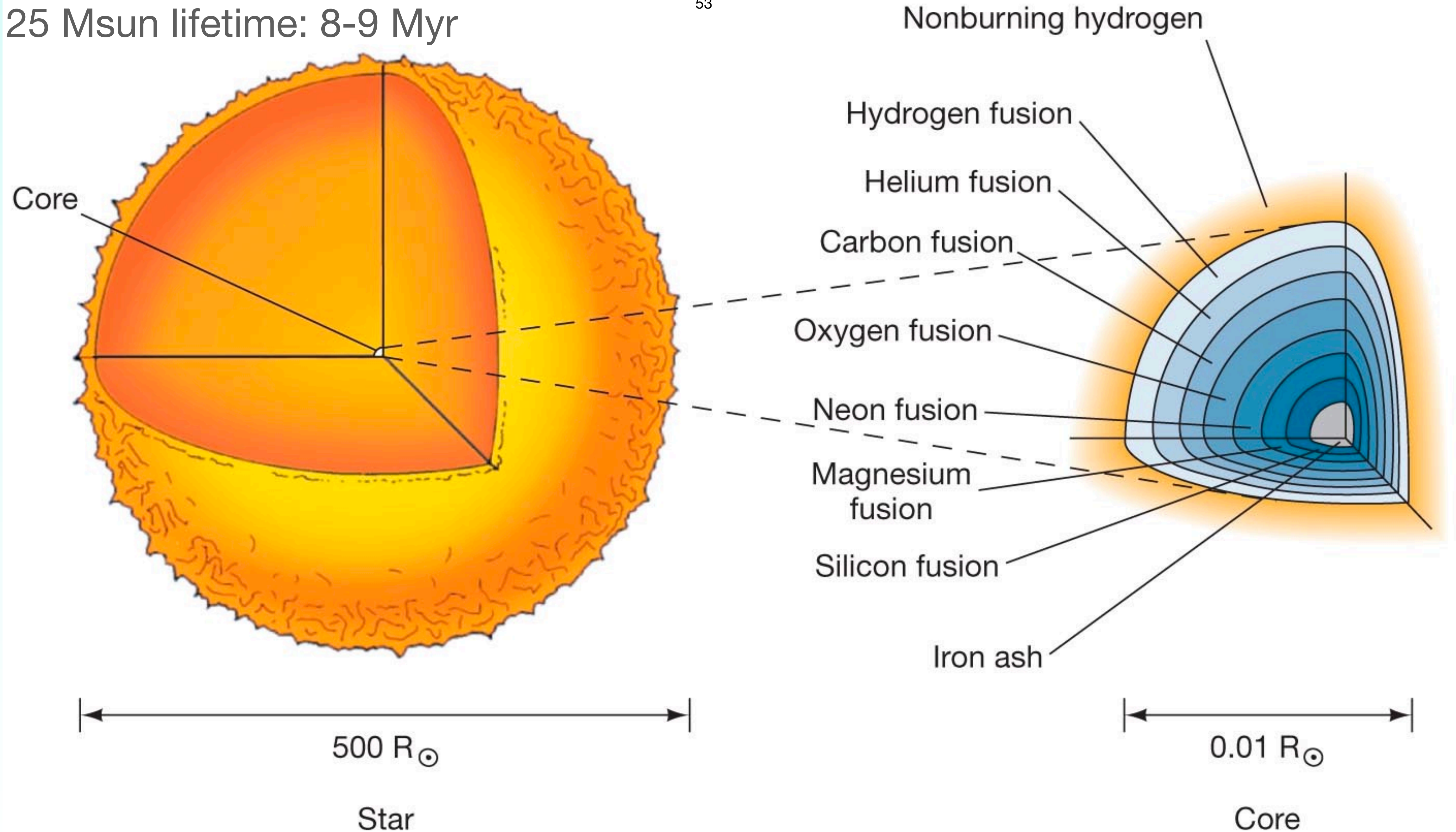






25 Msun lifetime: 8-9 Myr

53



25 Msun lifetime: 8-9 Myr

53

Core

10.000 years

Nonburning hydrogen

Hydrogen fusion

Helium fusion

Carbon fusion

Oxygen fusion

Neon fusion

Magnesium
fusion

Silicon fusion

Iron ash

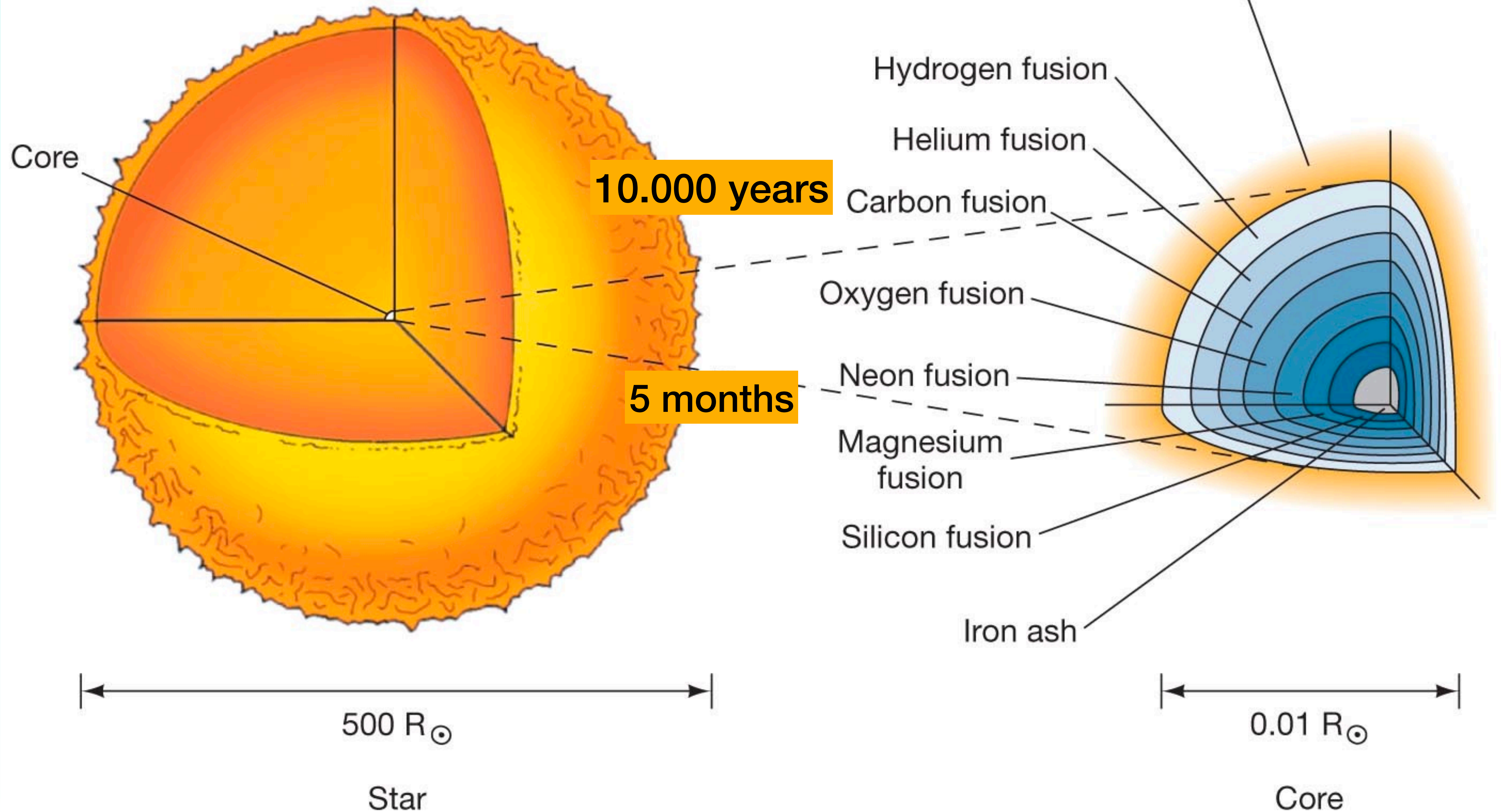
500 $R_{\odot}$

Star

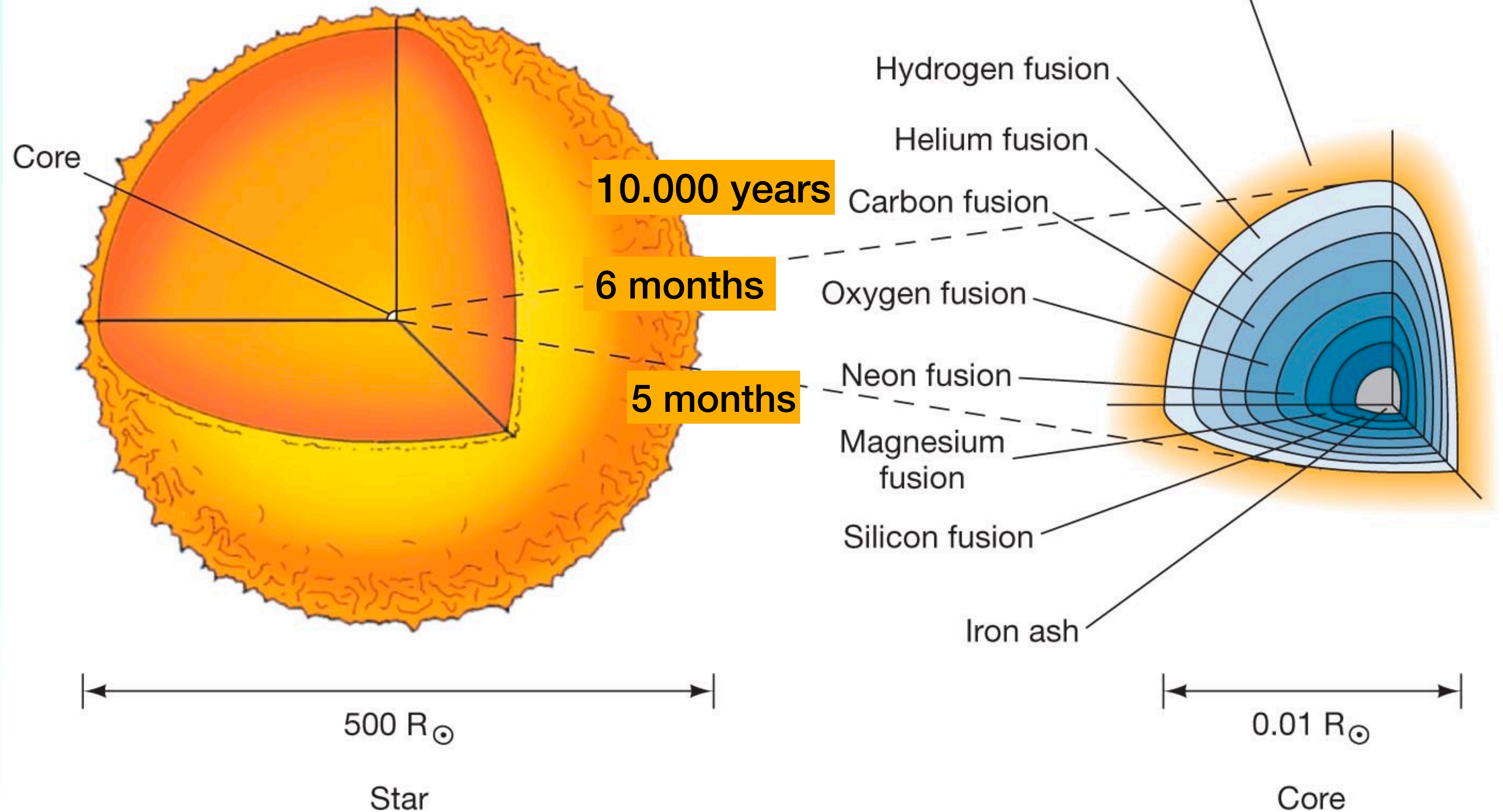
0.01 $R_{\odot}$

Core

25 Msun lifetime: 8-9 Myr



25 Msun lifetime: 8-9 Myr



25 Msun lifetime: 8-9 Myr

Core

10.000 years

6 months

5 months

3 days

Nonburning hydrogen

Hydrogen fusion

Helium fusion

Carbon fusion

Oxygen fusion

Neon fusion

Magnesium
fusion

Silicon fusion

Iron ash

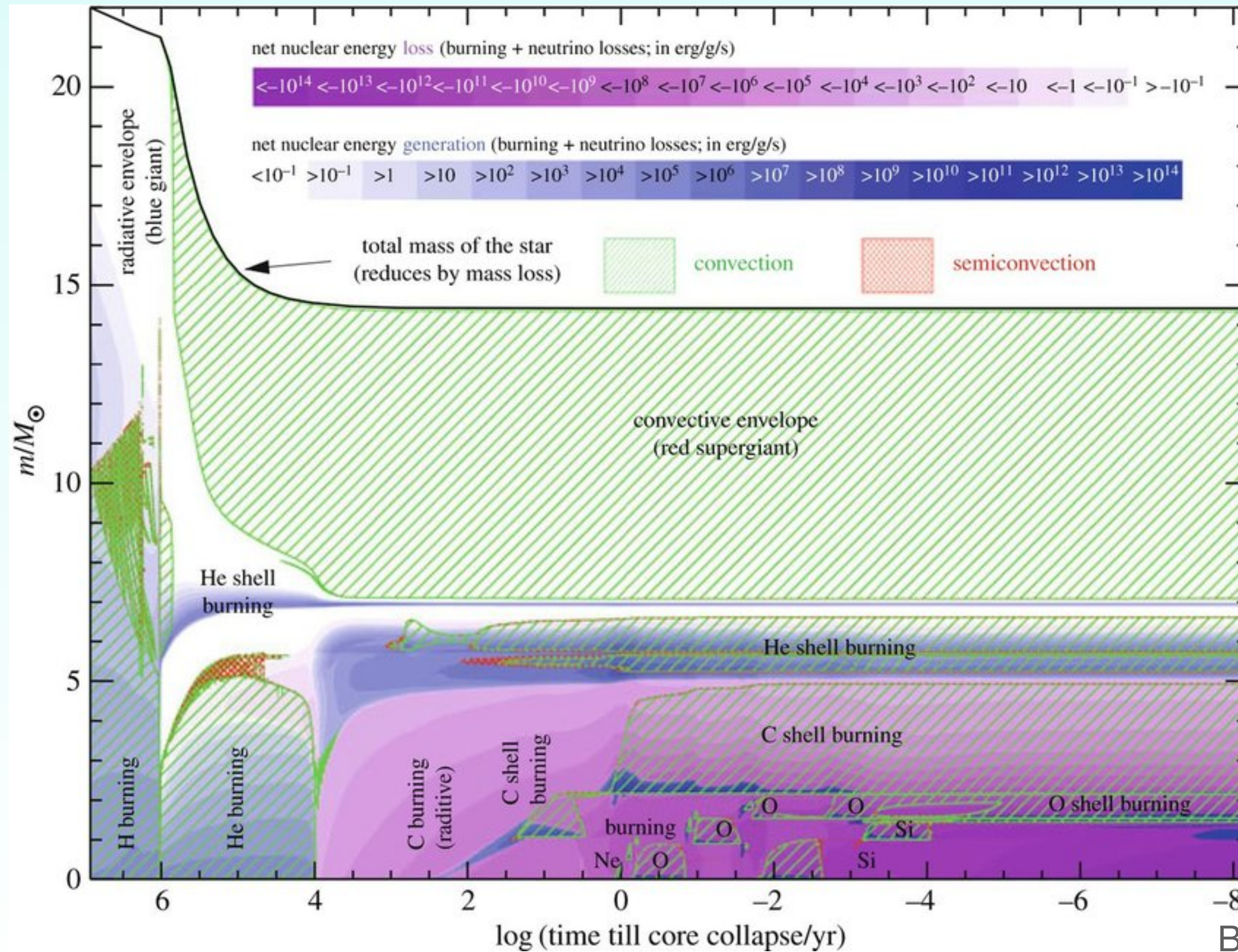
500 $R_{\odot}$

Star

0.01 $R_{\odot}$

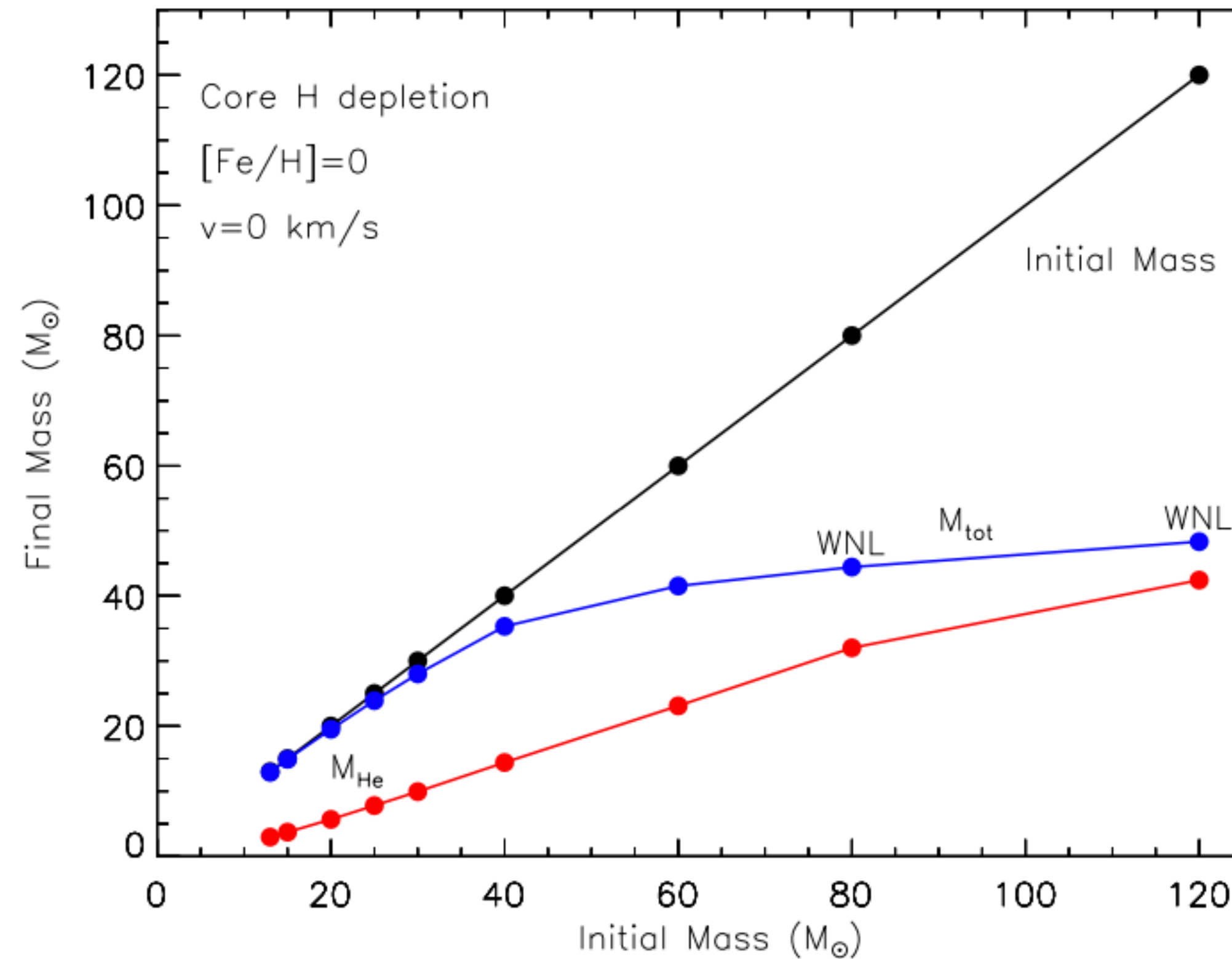
Core

The Kippenhahn diagram (Kippenhahn, Weigert, Weiss, 2012)



Braithwaite & Spruit (2017)

Mass loss for massive stars



Limongi & Chieffi (2018)

Figure 5. Total mass (blue solid line) and He core mass (red solid line) at core H exhaustion as a function of the initial mass, for non rotating solar metallicity models. The label 'WNL' marks the models entering the Wolf-Rayet stage.

Fred Hoyle



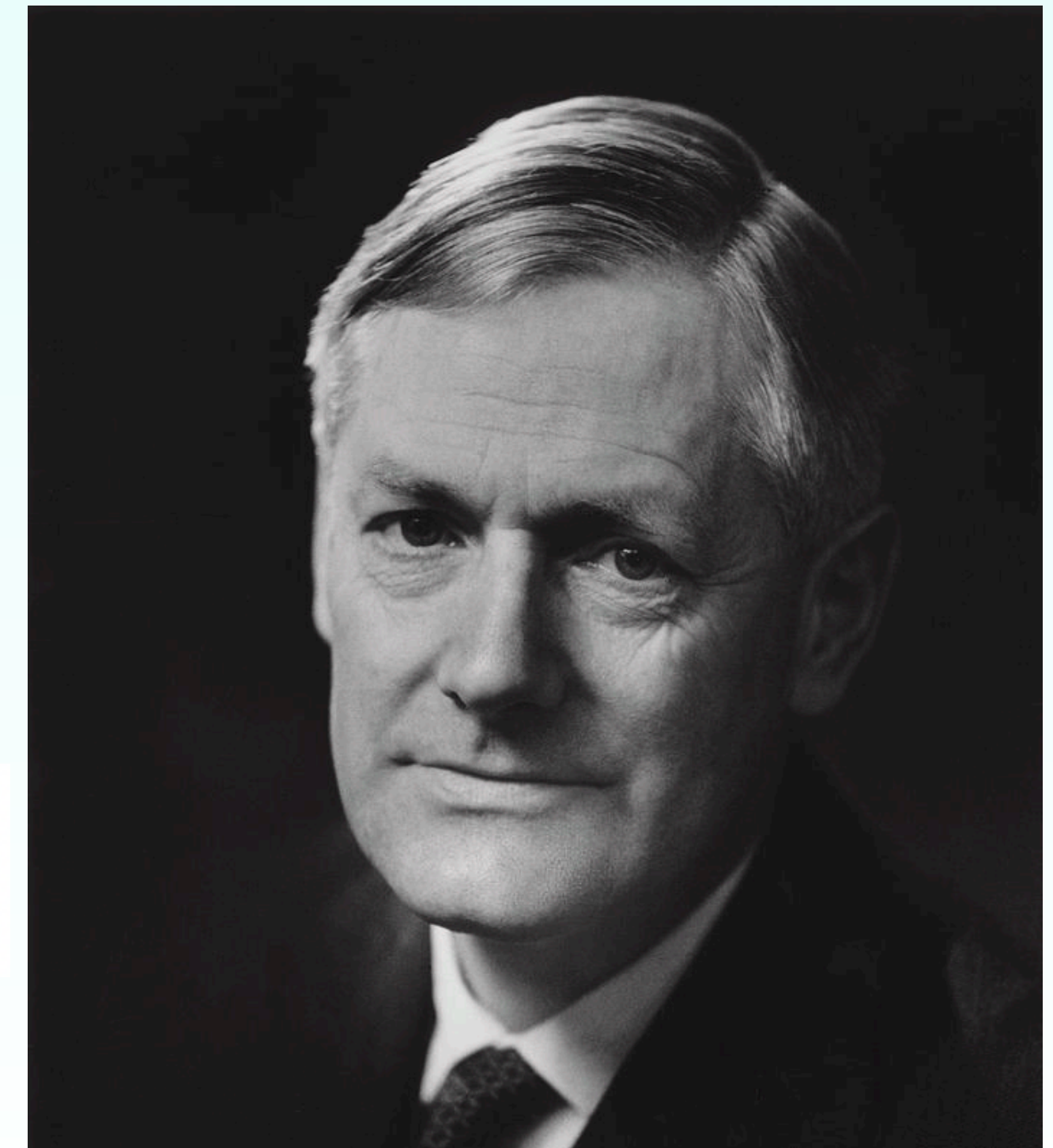
Fred Hoyle: Basically speaking a star is a pretty simple structure.

Fred Hoyle



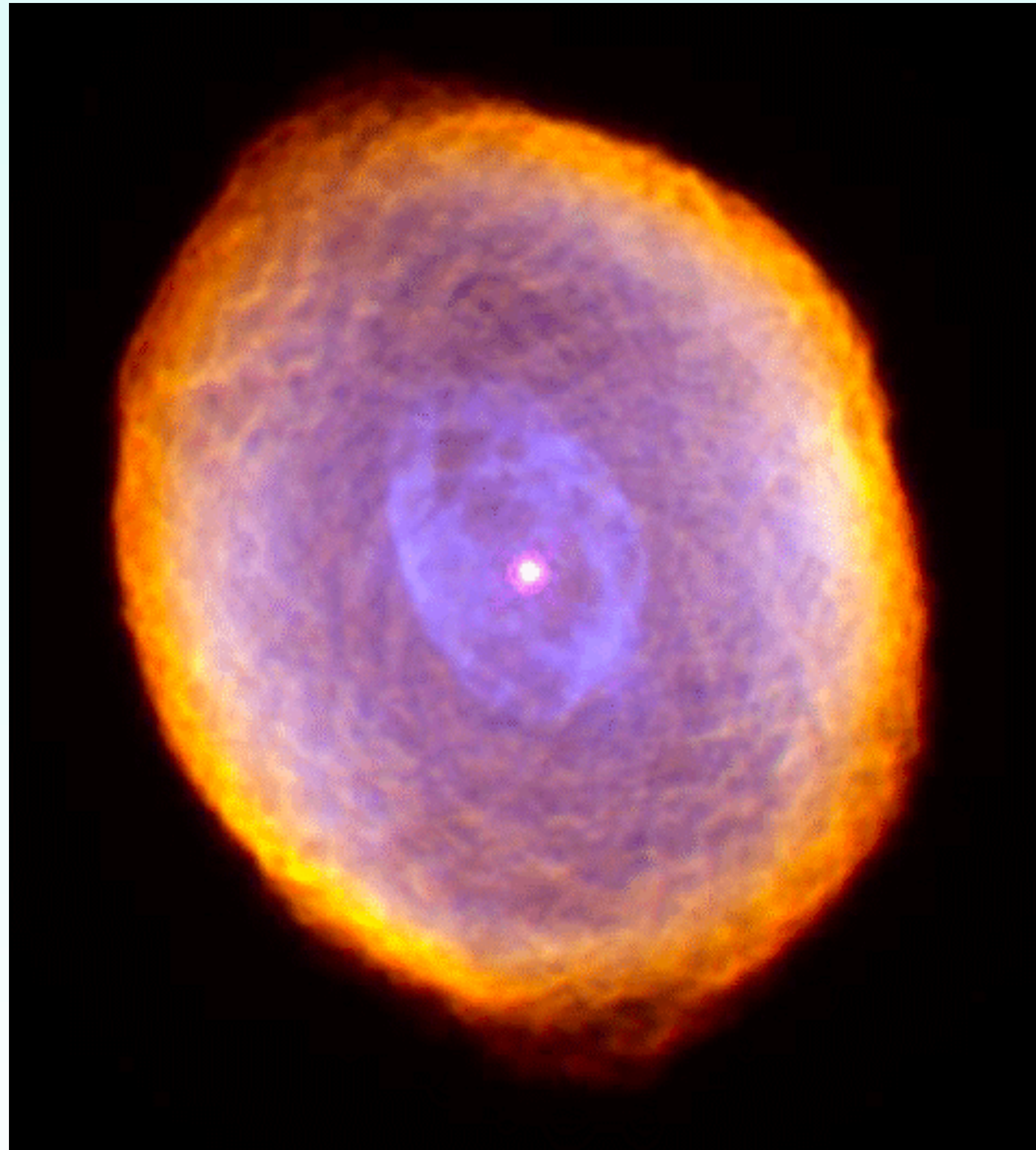
Fred Hoyle: Basically speaking a star is a pretty simple structure.

R. O. Redman: Fred, *you'd* look pretty simple at a distance of 10 parsecs!
Overheard at Cambridge Observatory Club *c.* 1954.

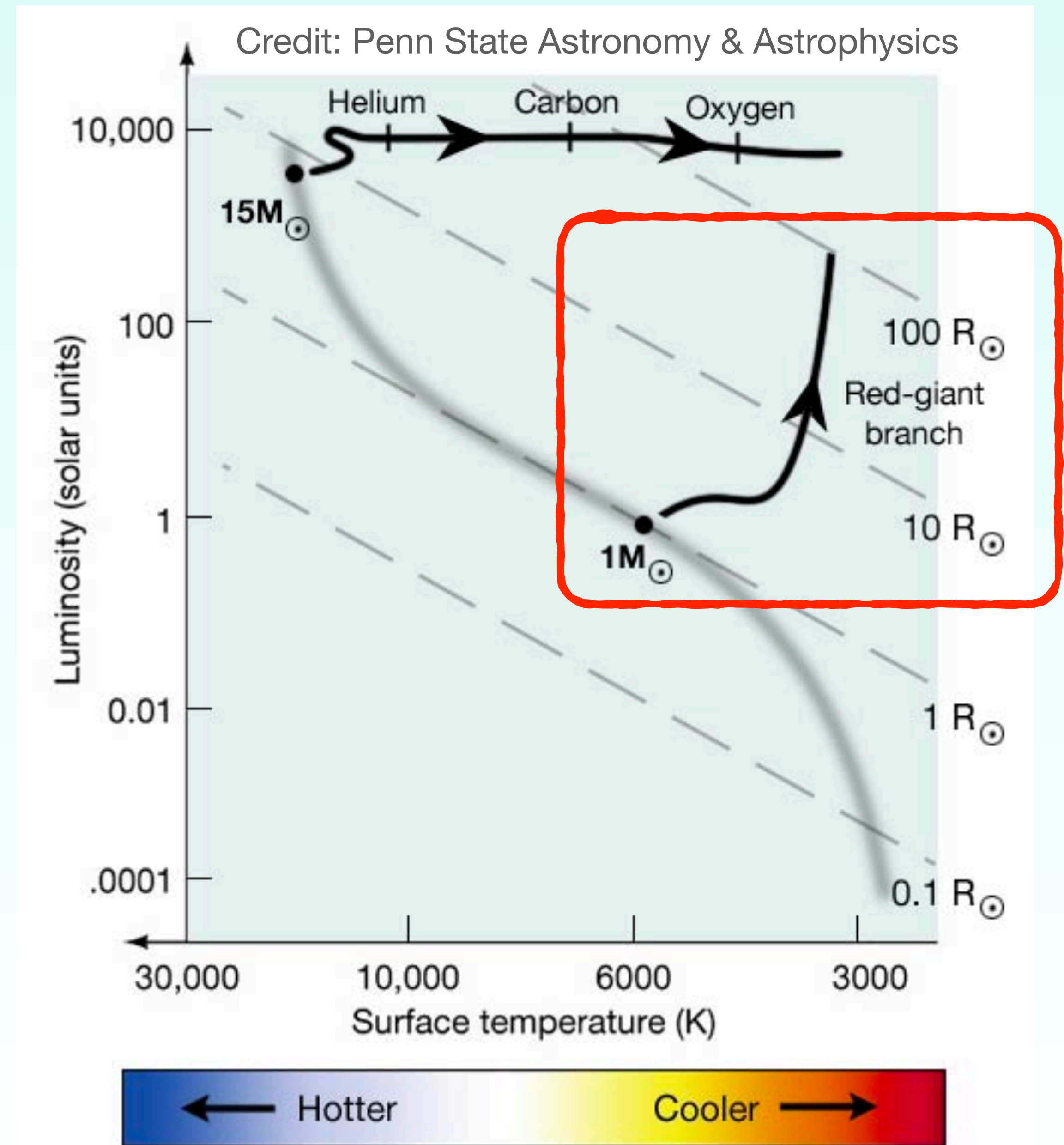


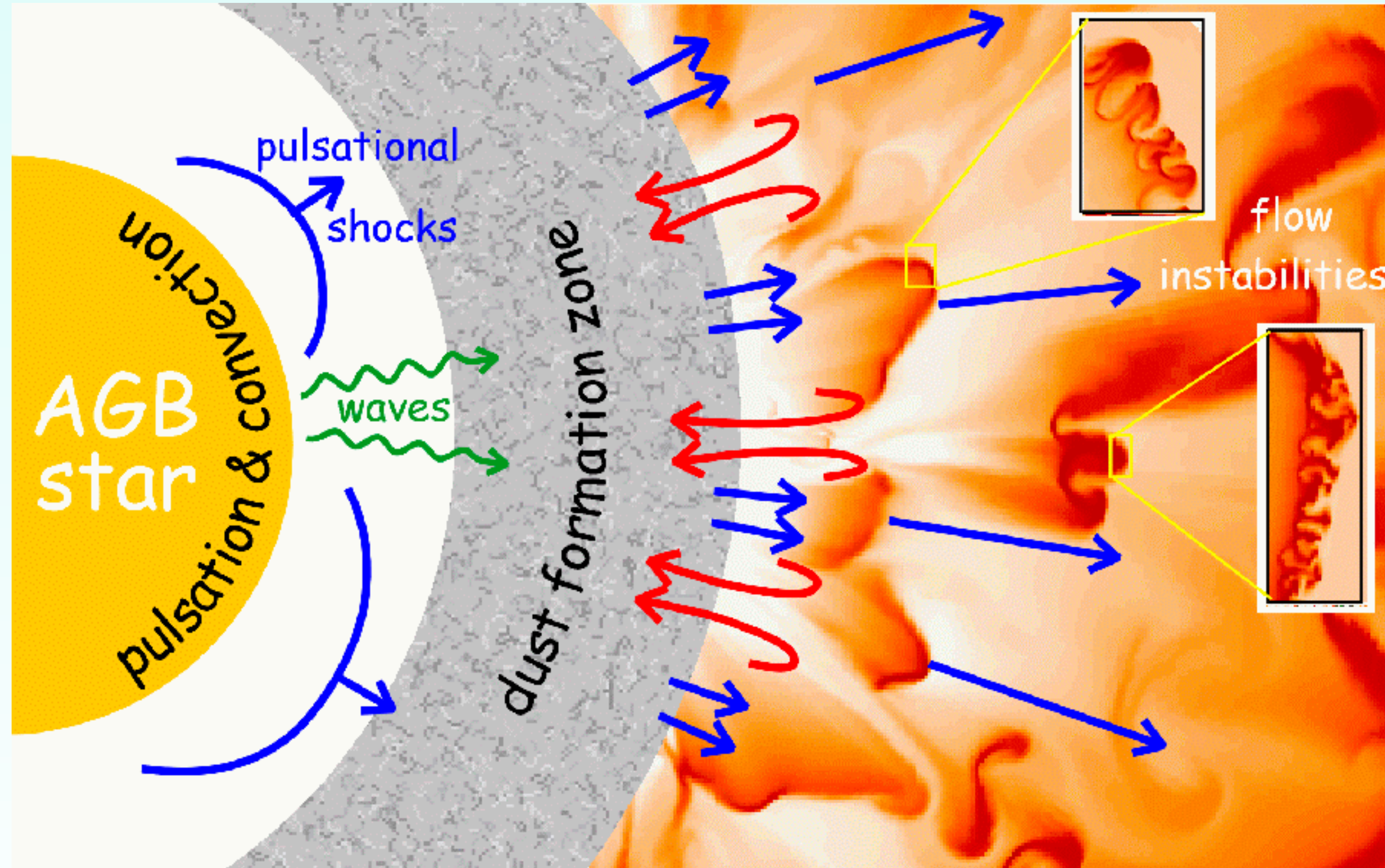
Roderick Oliver Redman

Meanwhile, lower mass stars...

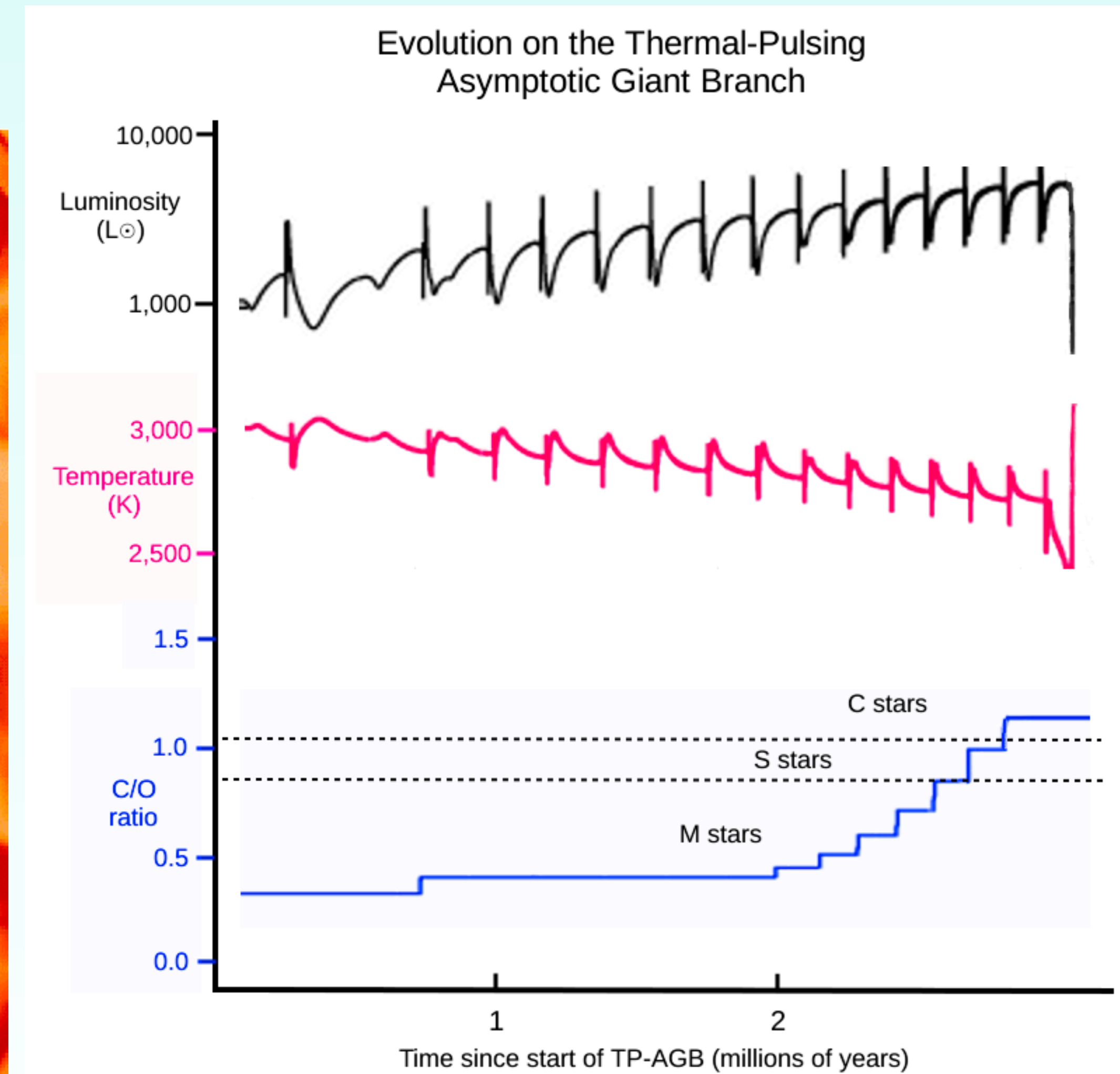


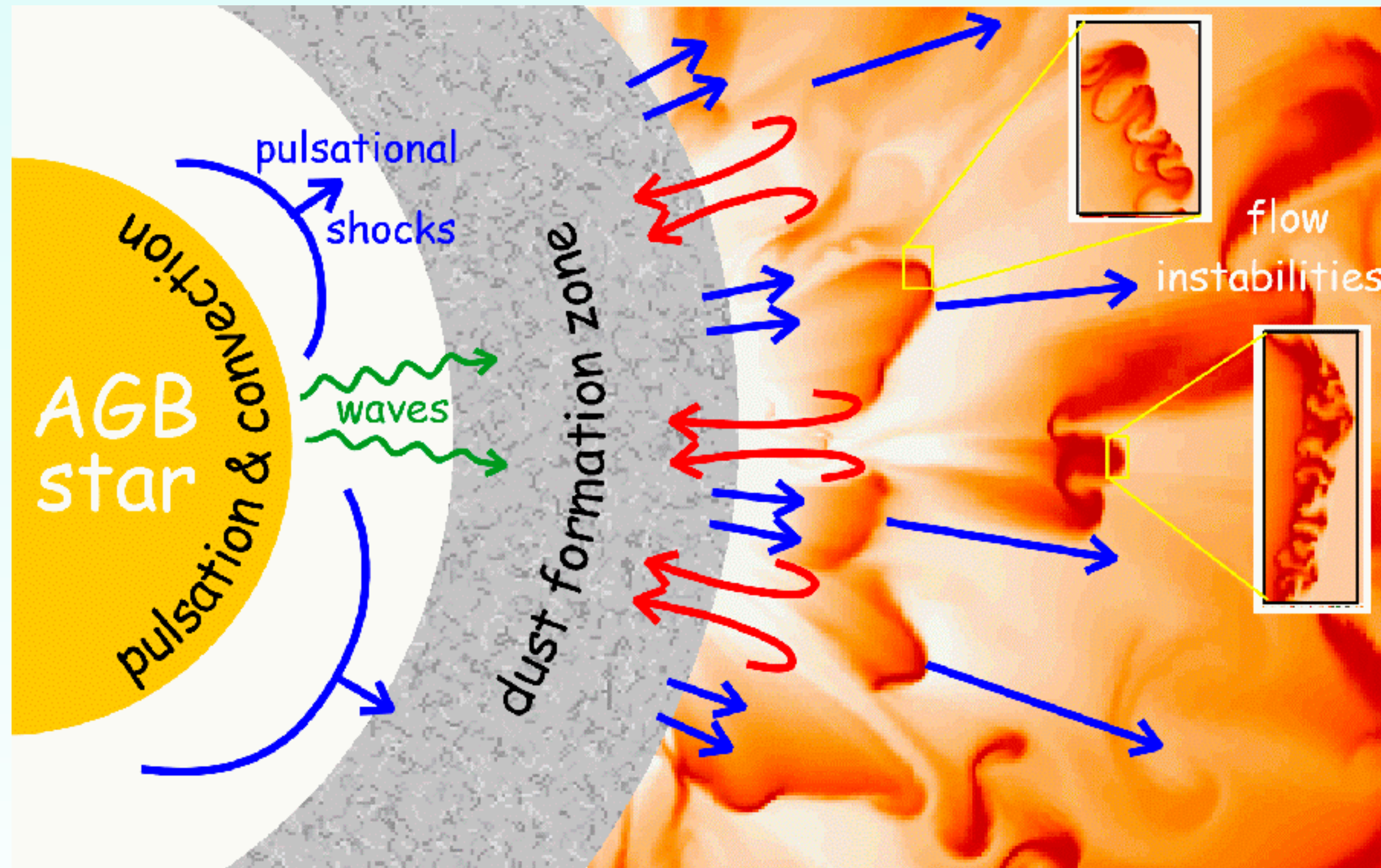
IC 418 planetary nebula (the Spirograph Nebula, © HST)



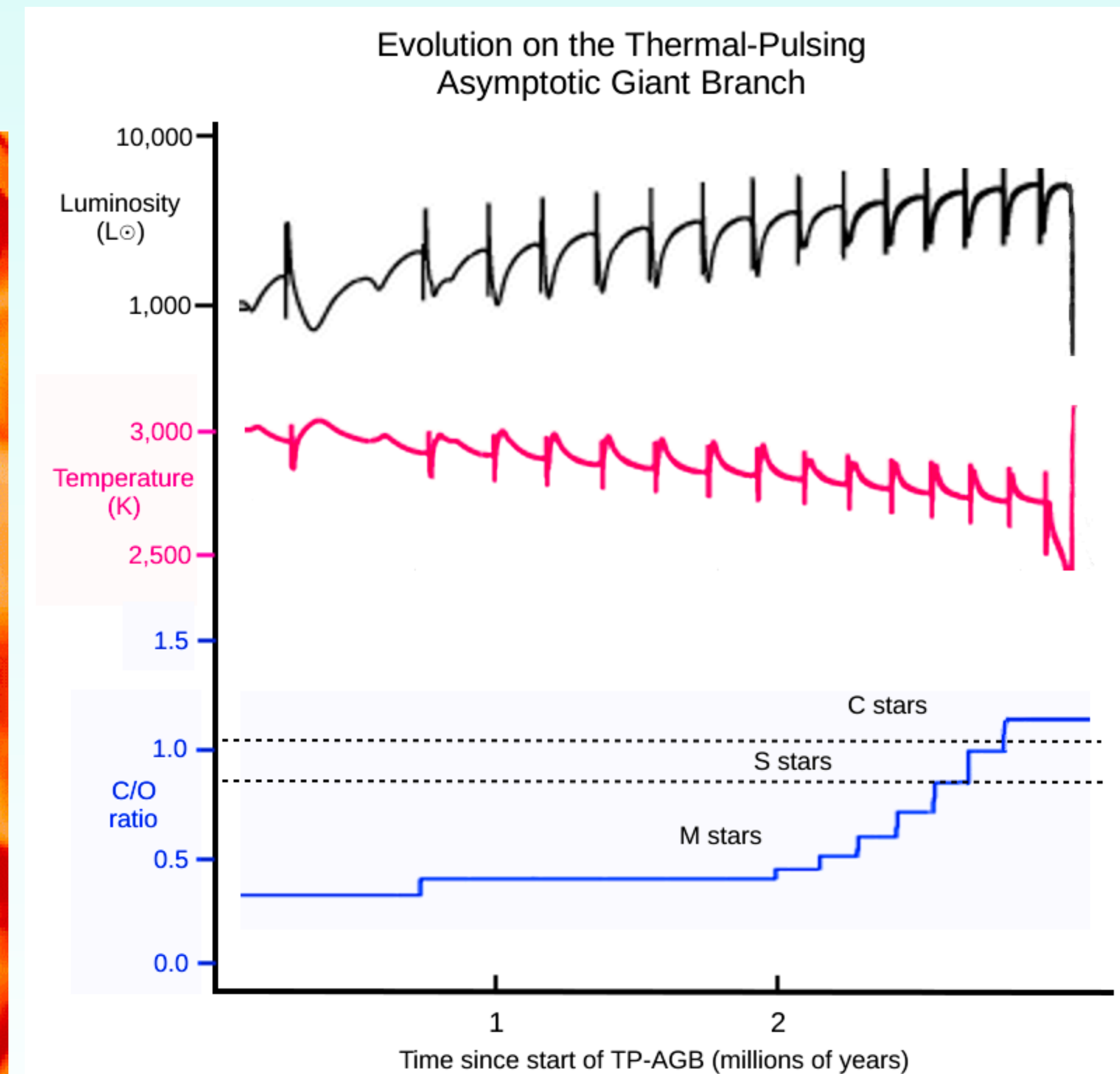


© Peter Woitke



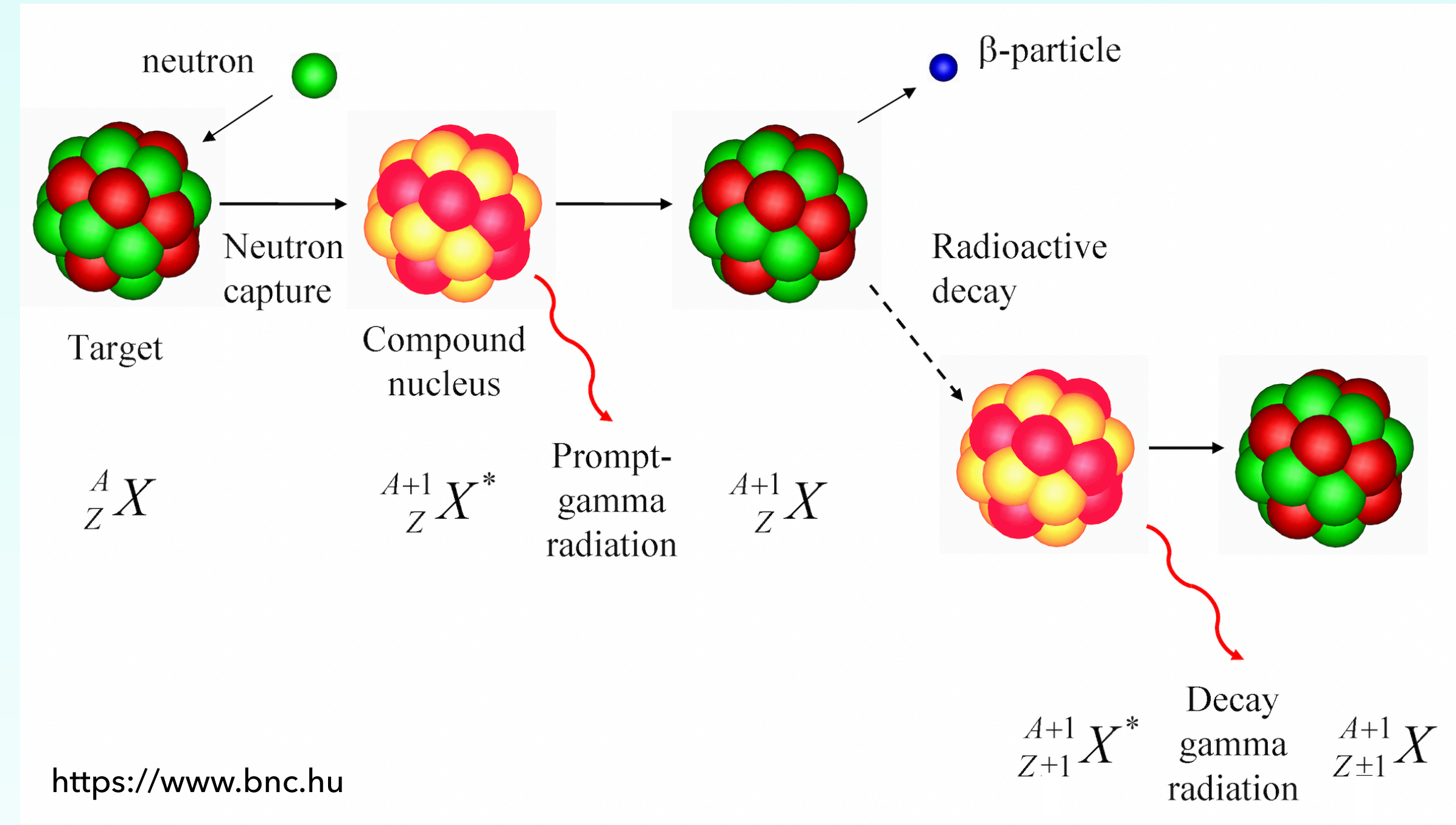


© Peter Woitke



Surprisingly, these low-to-intermediate mass stars produce about half of the present-day heavy (relative to iron) elements

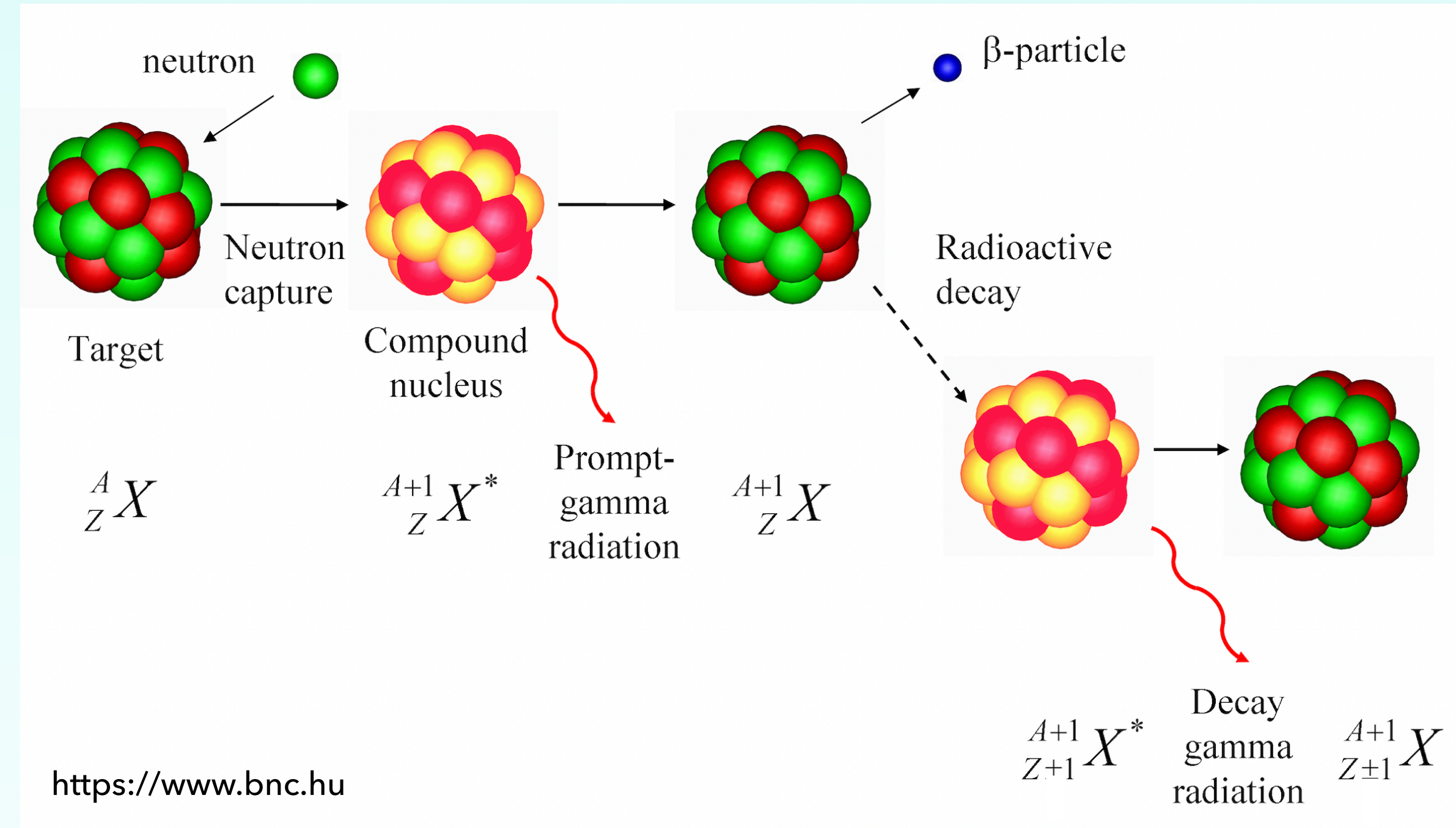
Neutron-capture elements



Neutron-capture elements

- Most heavy ($A > 56$) elements are produced by neutron capture
- **Slow process (s-processes)**

$$n_n \sim 10^{8-13} \text{cm}^{-3}, \quad t_\beta \ll t_n \simeq 10^9 \text{s (100-1000 years)}$$



Neutron-capture elements

- Most heavy ($A > 56$) elements are produced by neutron capture

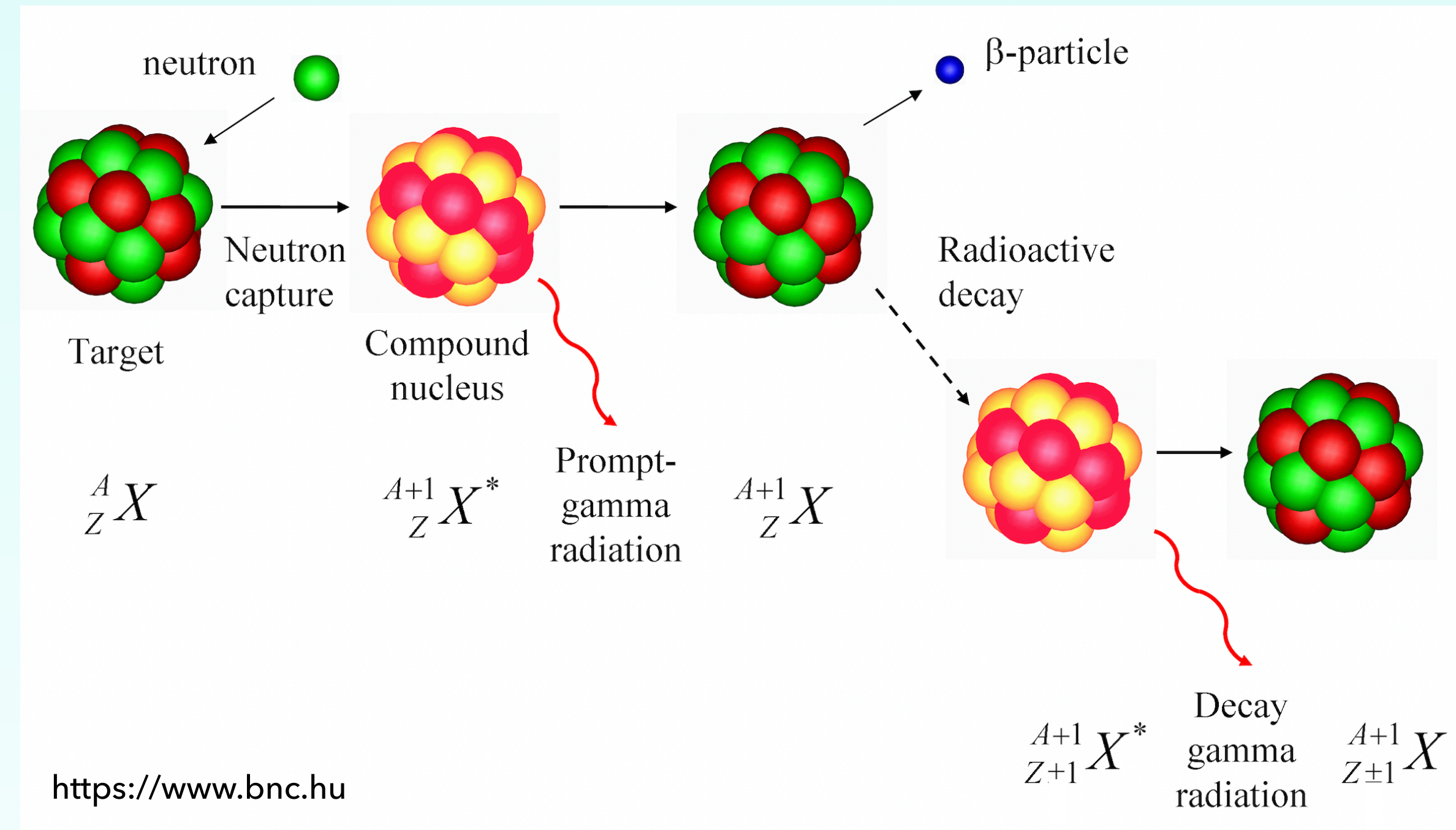
- **Slow process (s-processes)**

$$n_n \sim 10^8-10^{13} \text{cm}^{-3}, \quad t_\beta \ll t_n \simeq 10^9 \text{s (100-1000 years)}$$

- **Rapid process (r-processes)**

$$n_n > 10^{19-34} \text{cm}^{-3}, \quad t_\beta \gg t_n \simeq 1 \text{s}$$

(Pagel, 2009, Chapter 6)



Neutron-capture elements

- Most heavy ($A > 56$) elements are produced by neutron capture

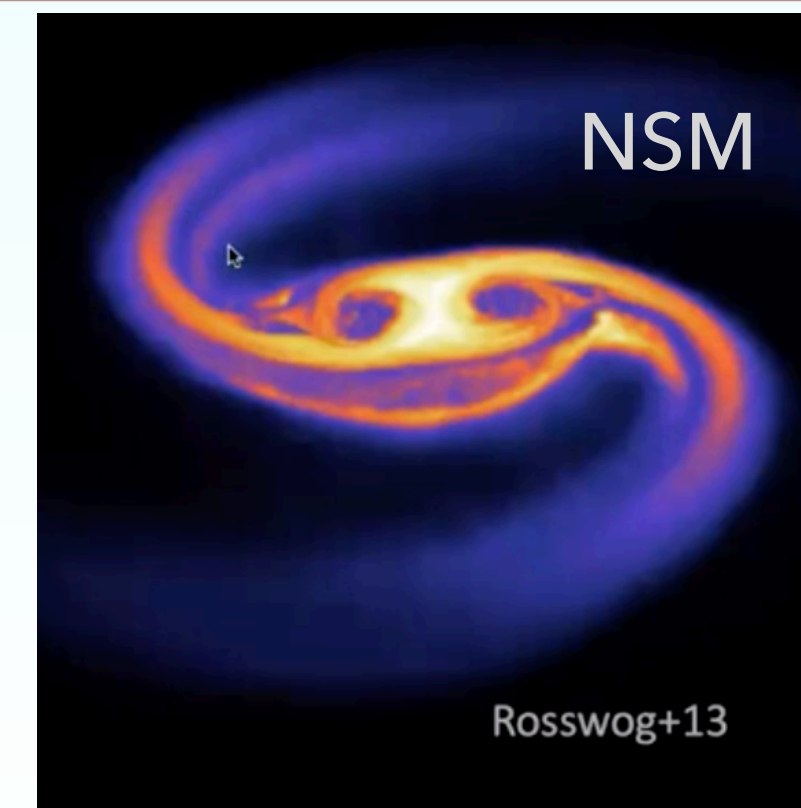
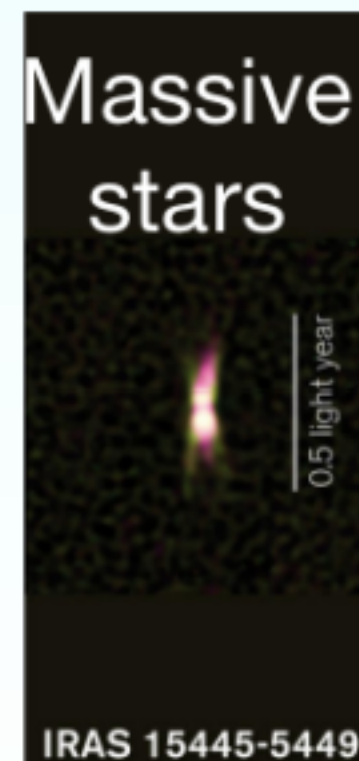
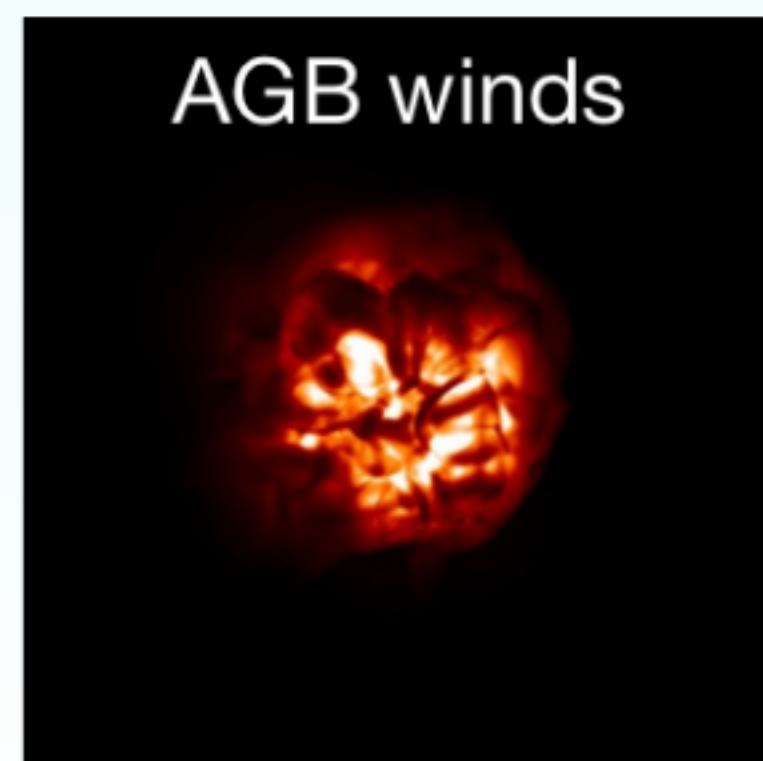
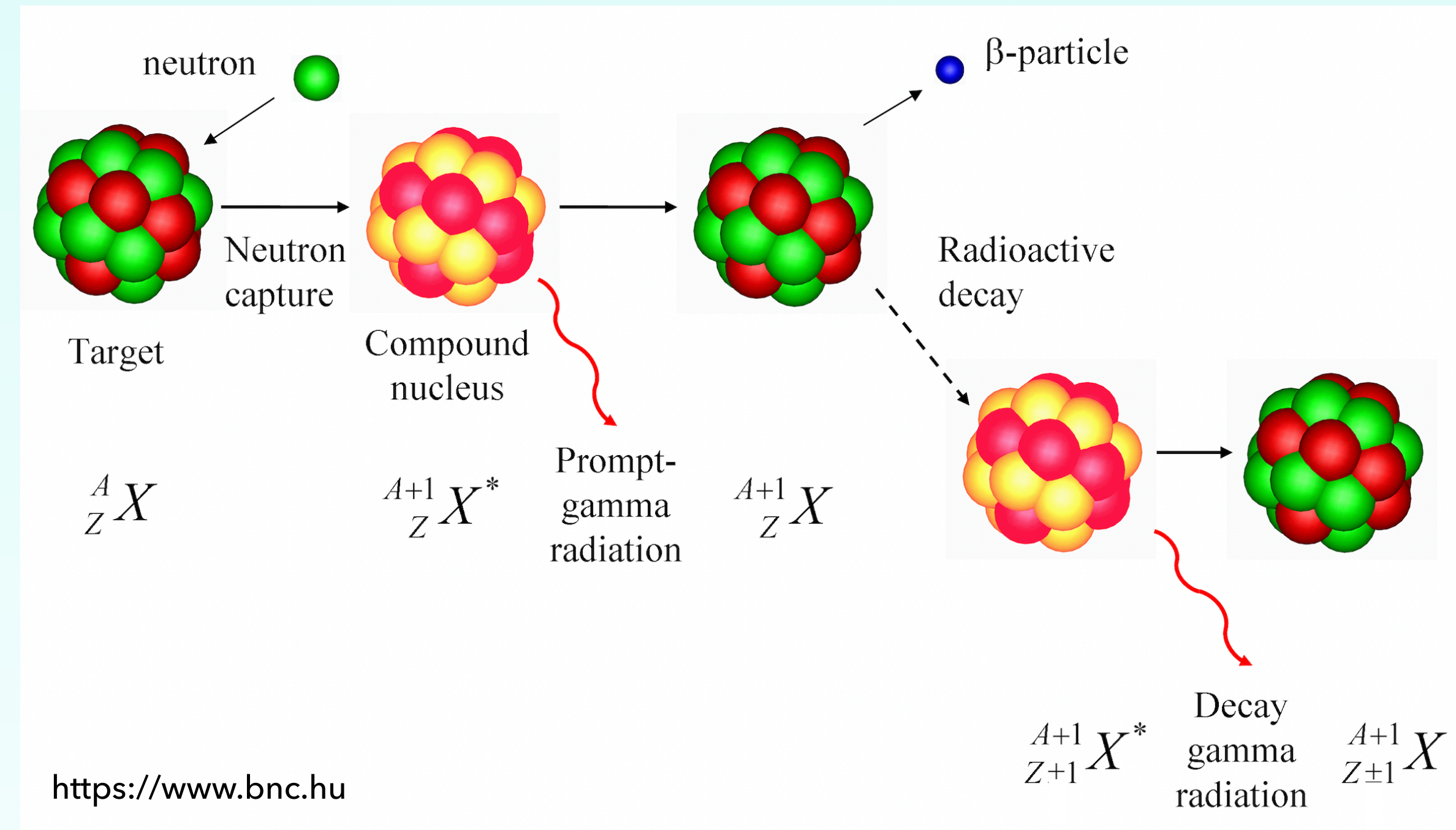
- **Slow process (s-processes)**

$$n_n \sim 10^8-10^{13} \text{cm}^{-3}, \quad t_\beta \ll t_n \simeq 10^9 \text{s (100-1000 years)}$$

- **Rapid process (r-processes)**

$$n_n > 10^{19-34} \text{cm}^{-3}, \quad t_\beta \gg t_n \simeq 1 \text{s}$$

(Pagel, 2009, Chapter 6)

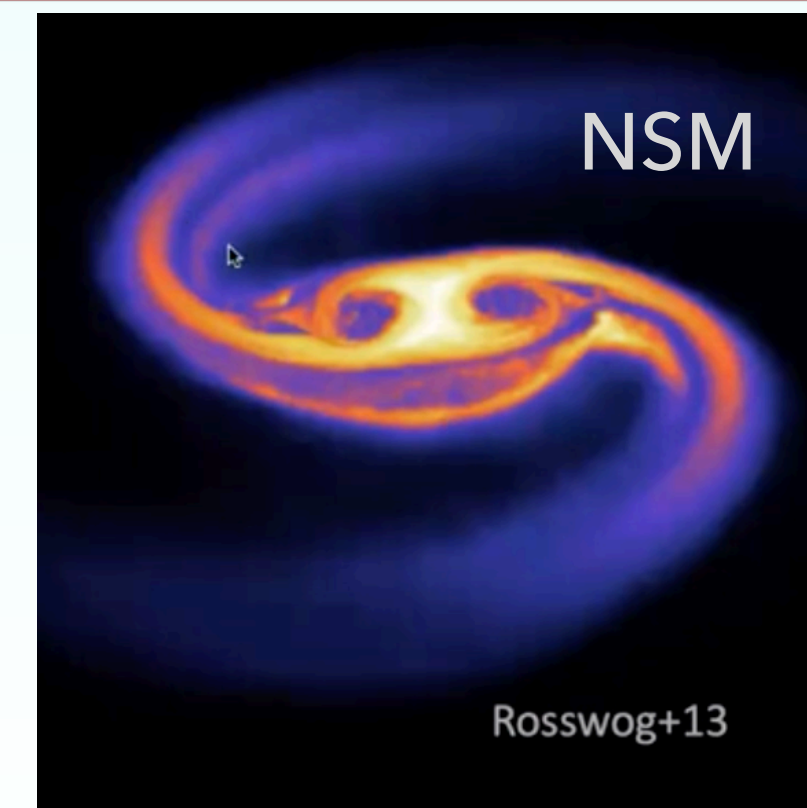
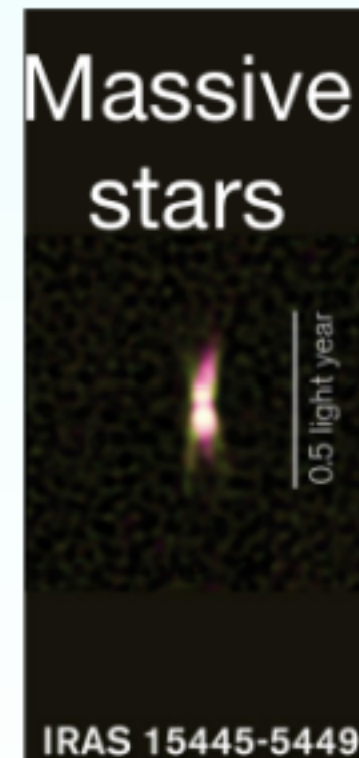
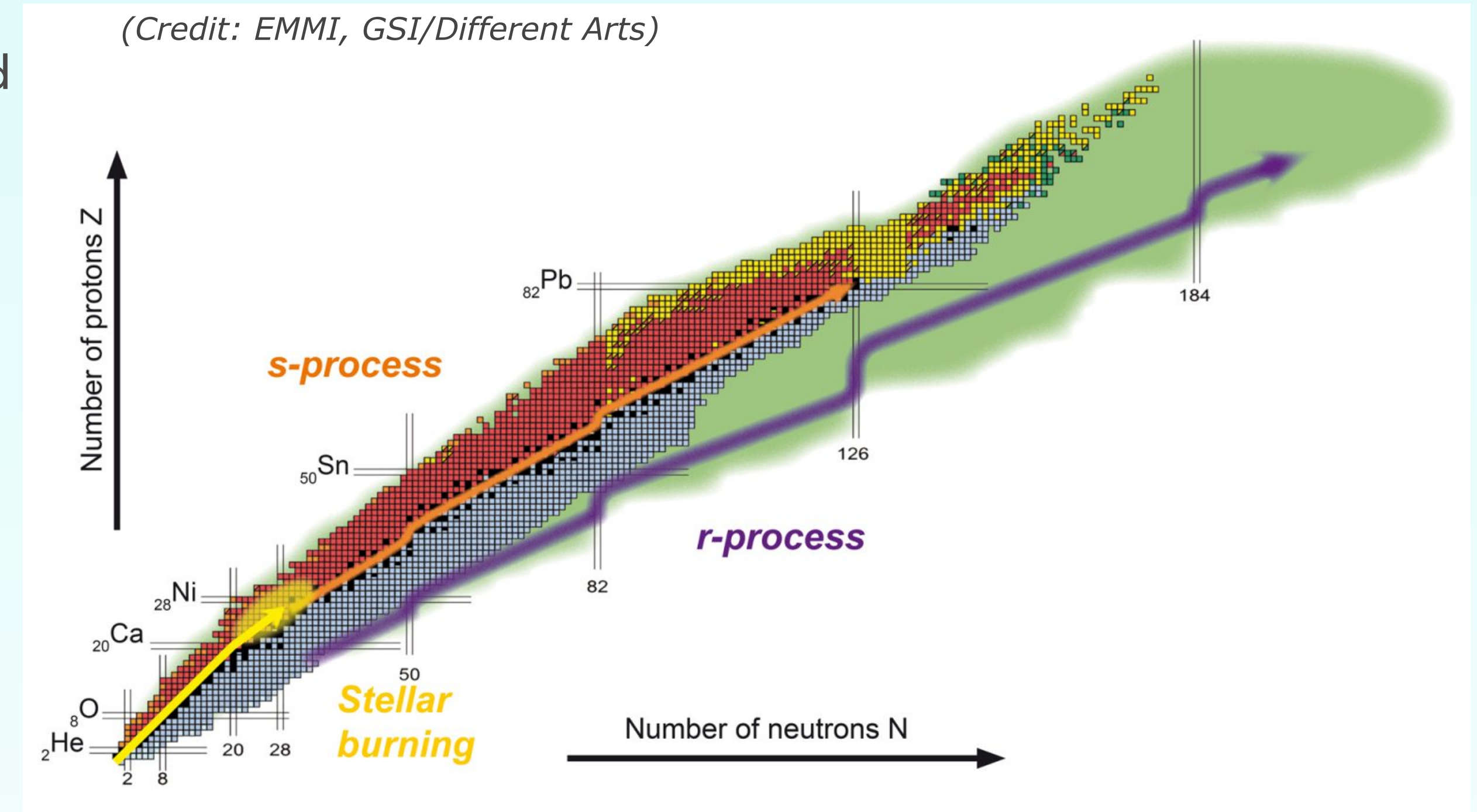


r-processes

s-processes

Neutron-capture elements

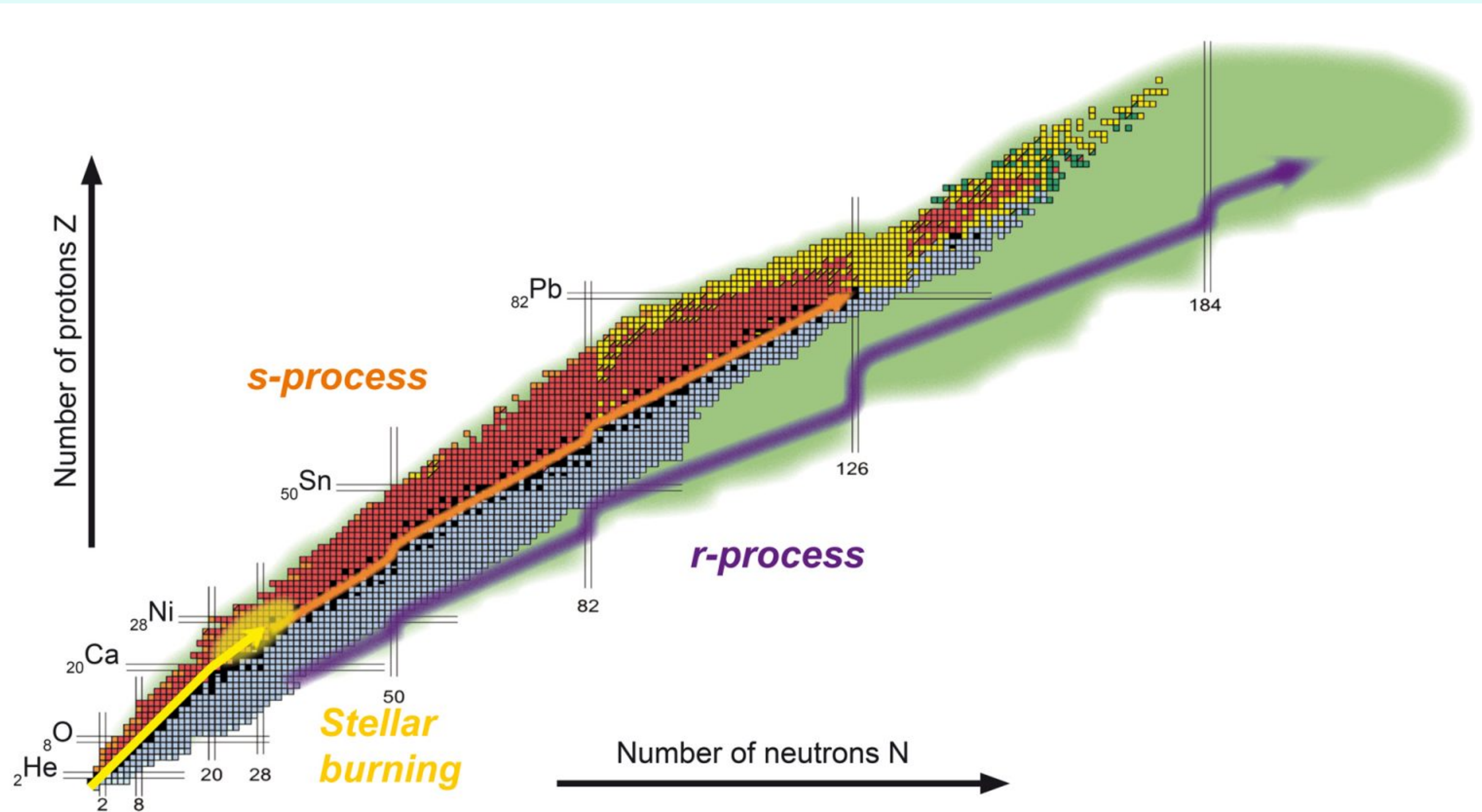
- Relative to the β -decay, $\sim 1/2$ of the elements are produced slowly (s-process), the other $1/2$ rapidly (r-process)
- **s-processes** result from successive thermal pulses of AGB stars (e.g., Cristallo+15) & massive stars (e.g., Limongi & Chieffi, 2018)
- **r-processes** sites are still uncertain, but candidates include:
 - NS-NS coalescence (verified! Watson+19)
 - MHDJs? (Winteler+12)
 - Neutrino-driven winds? (mainly SNe, Shibagaki+16)



r-processes

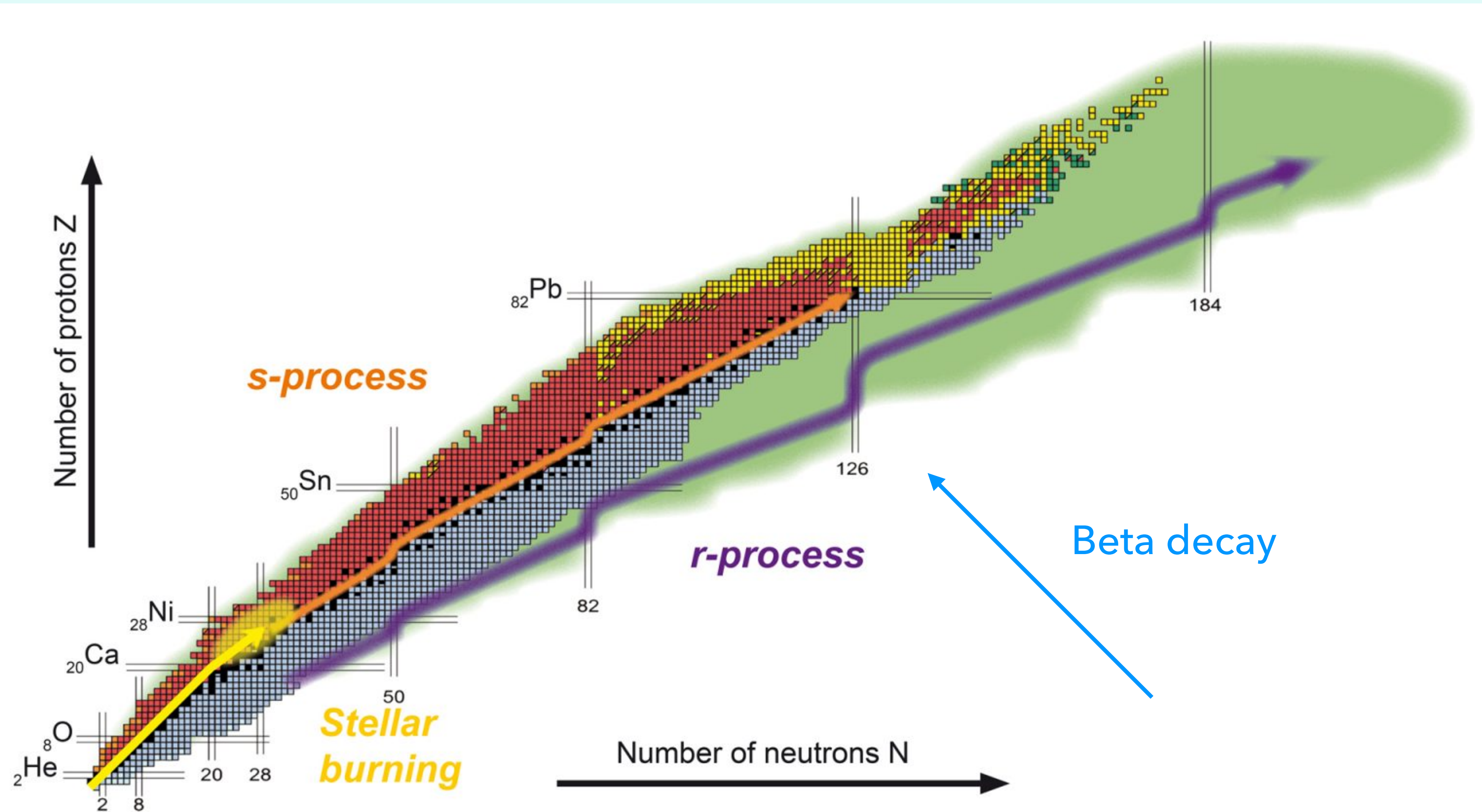
s-processes

A nuclear physicist's (isotopic) periodic table



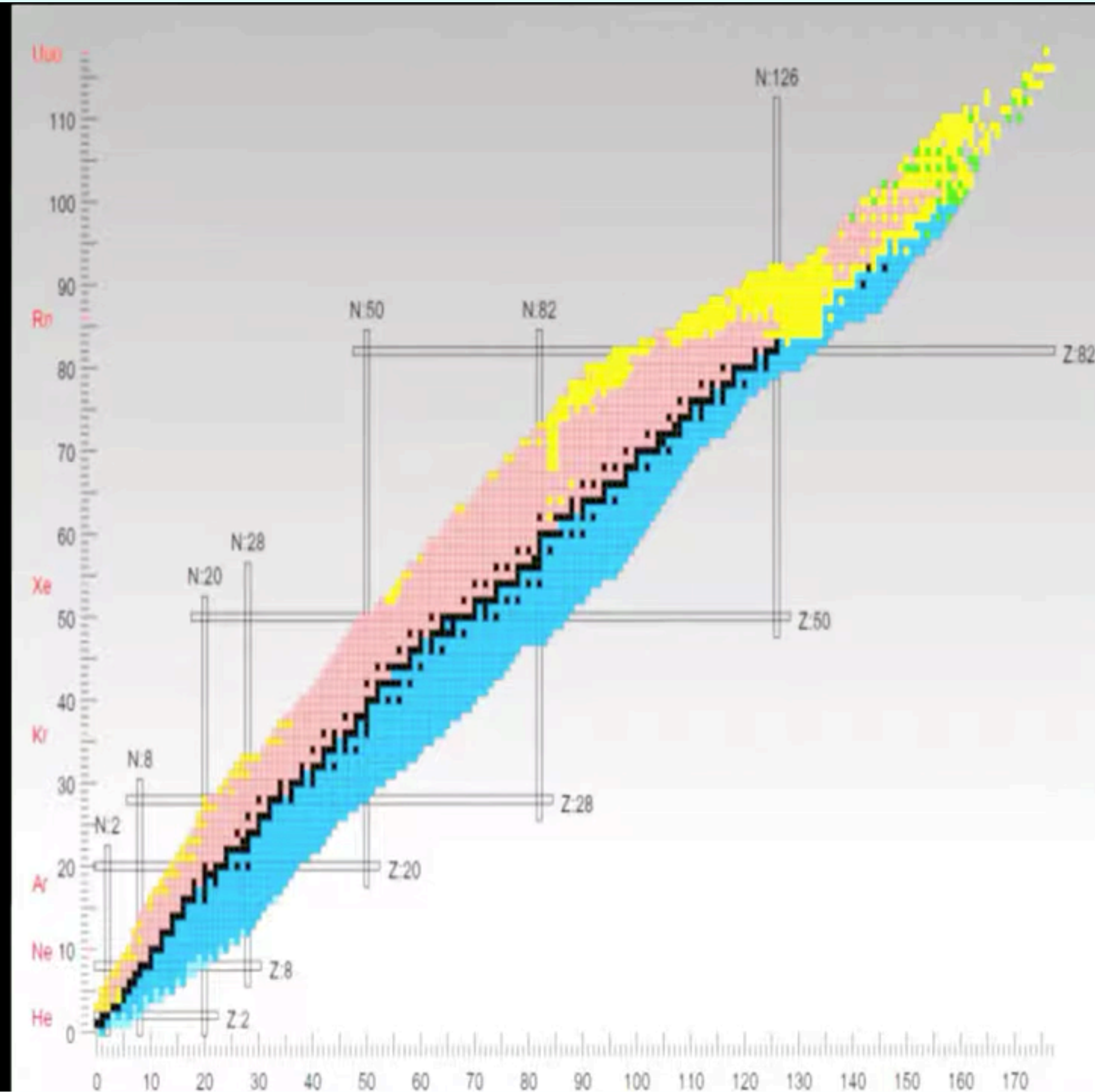
(Credit: EMMI, GSI/Different Arts)

A nuclear physicist's (isotopic) periodic table

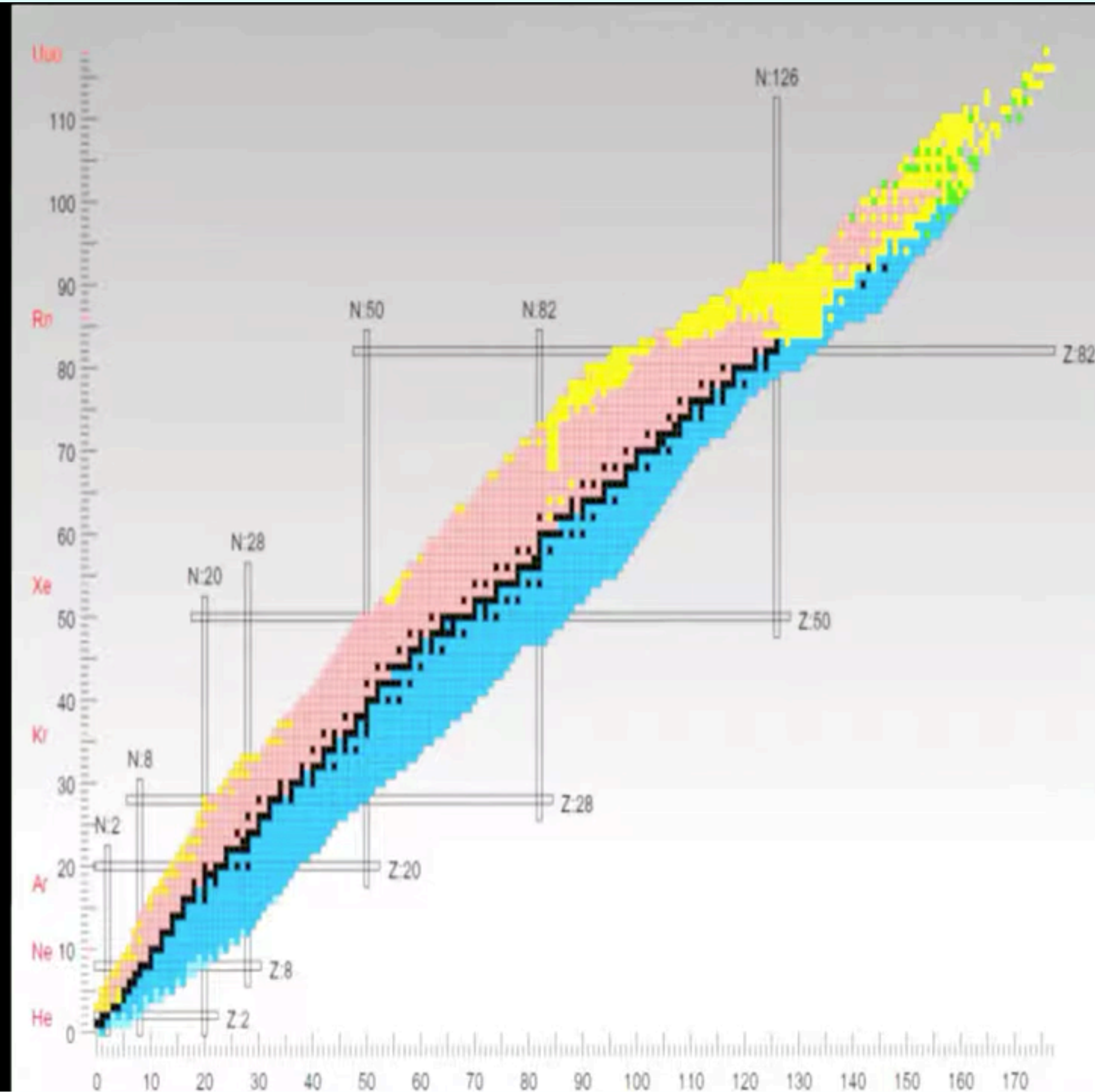


(Credit: EMMI, GSI/Different Arts)

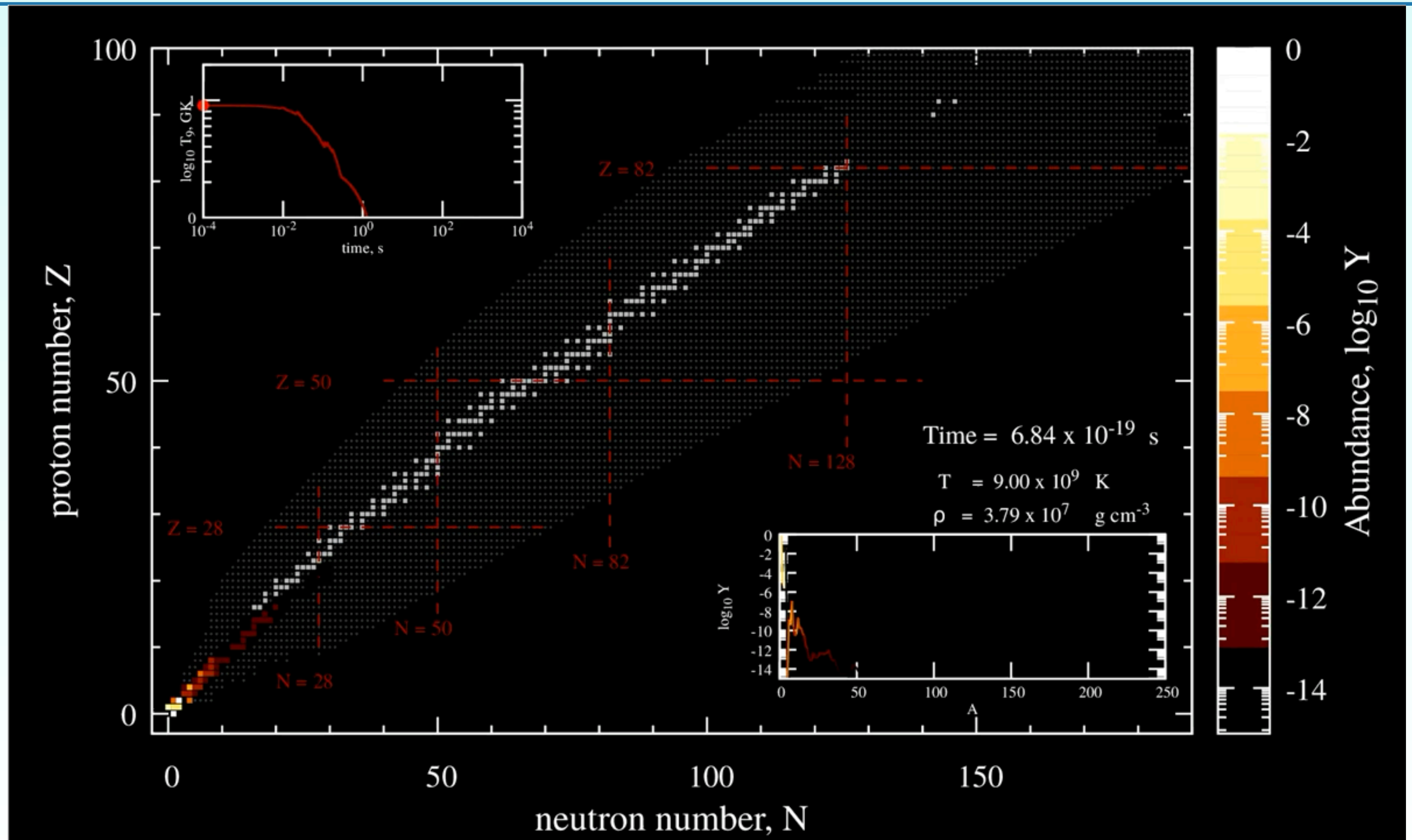
s-process



s-process

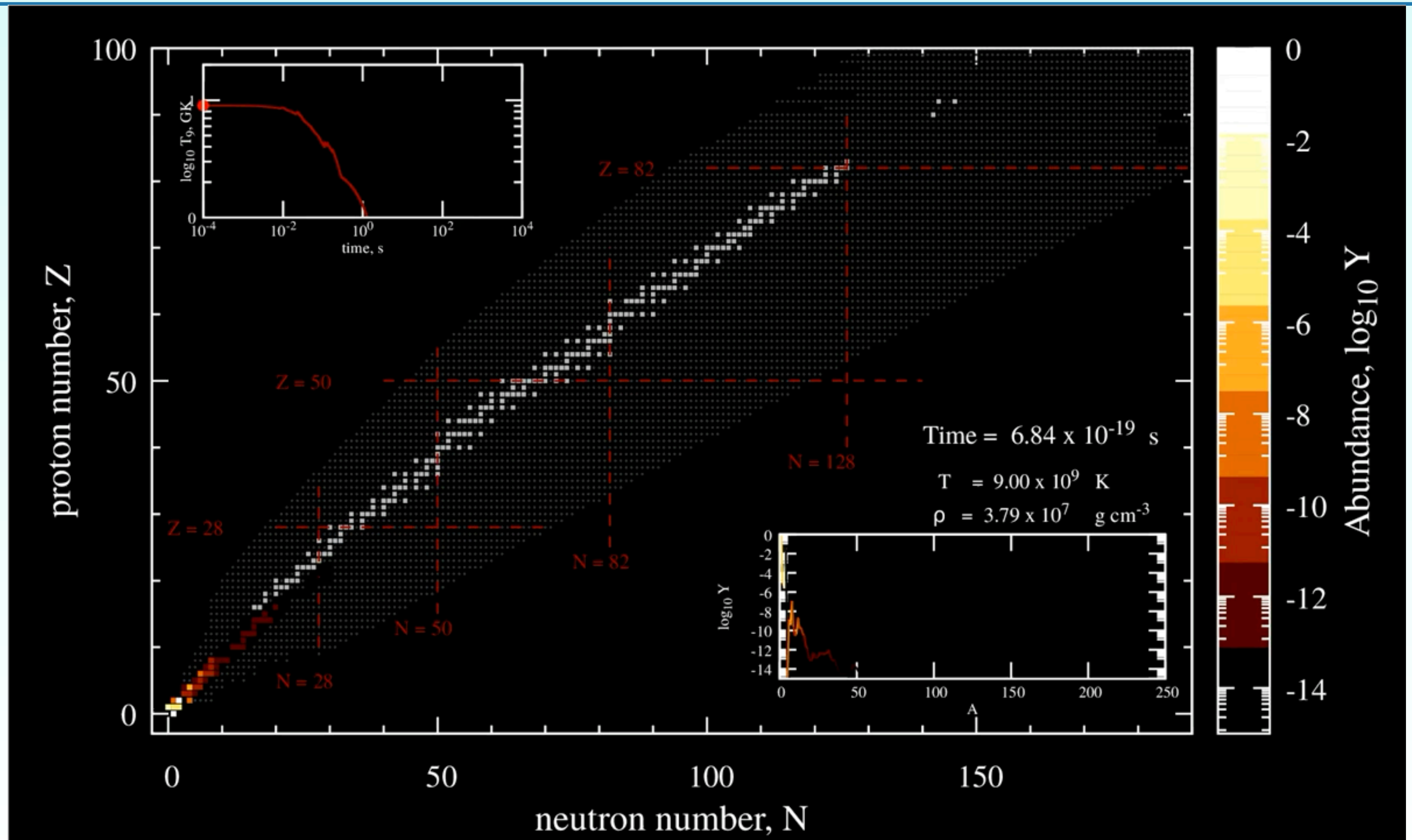


r-process



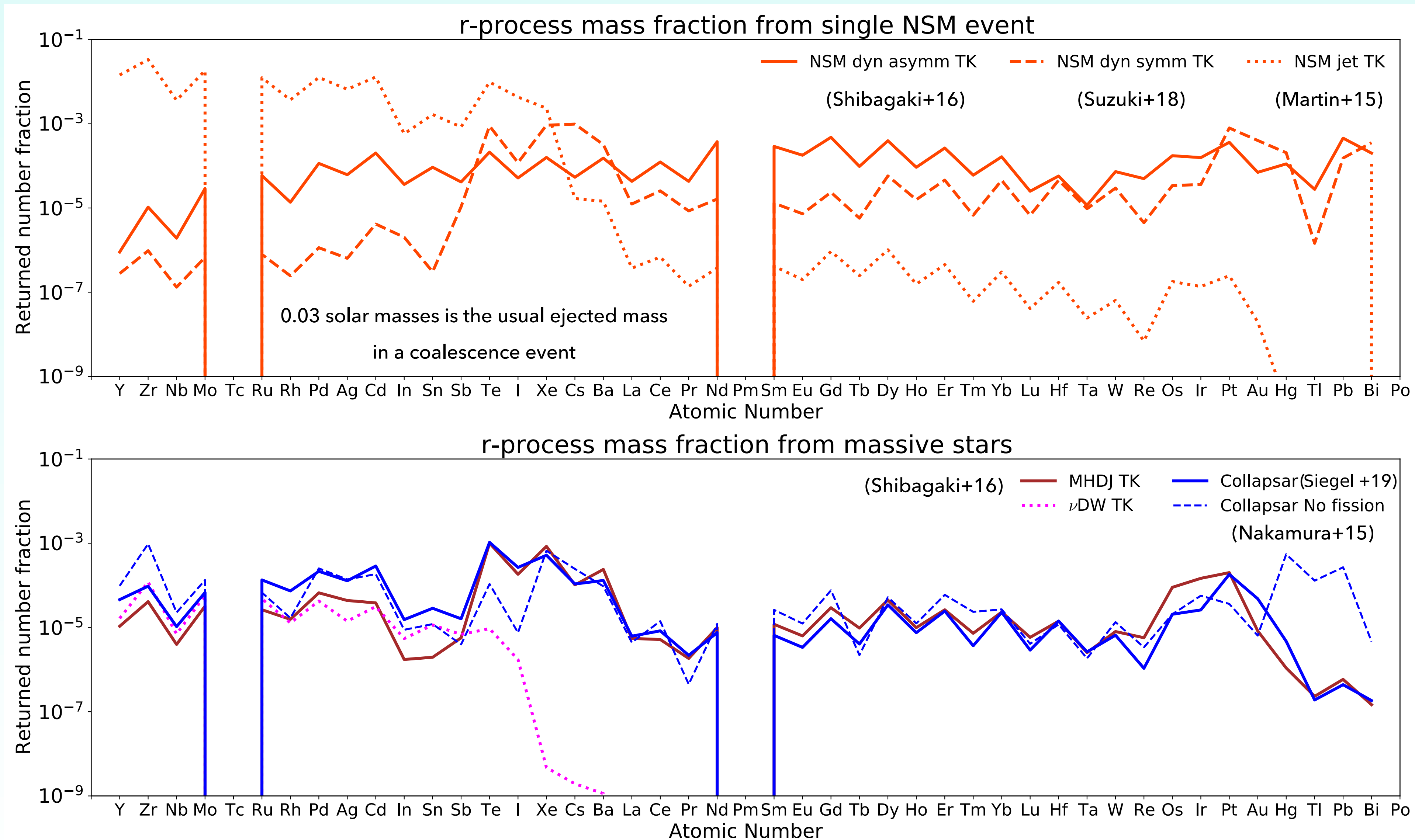
r-process in the jet-like explosions of magneto-rotational core-collapse SNe (Nishimura+15)

r-process



r-process in the jet-like explosions of magneto-rotational core-collapse SNe (Nishimura+15)

R-process yields (Gjergo+26b)



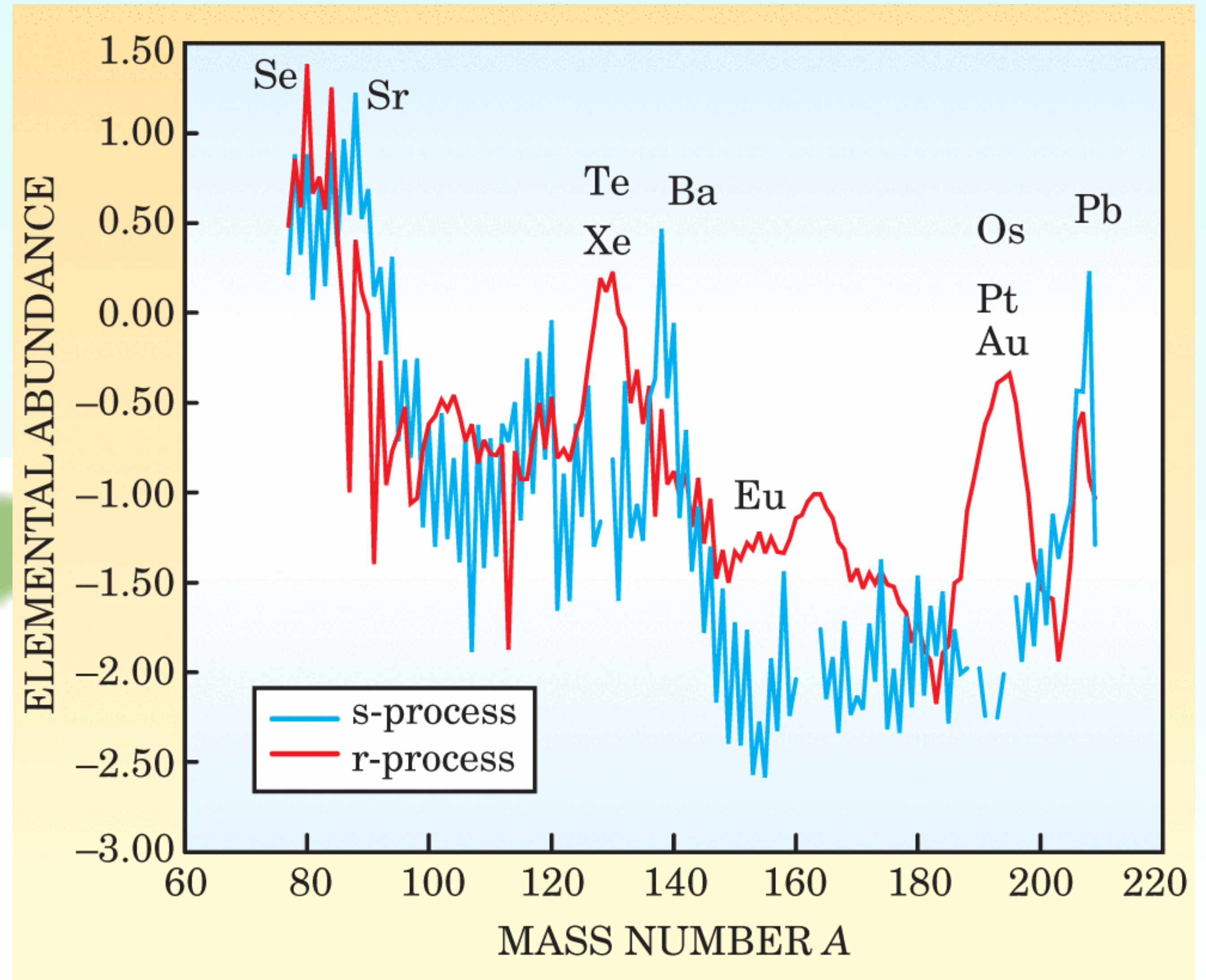
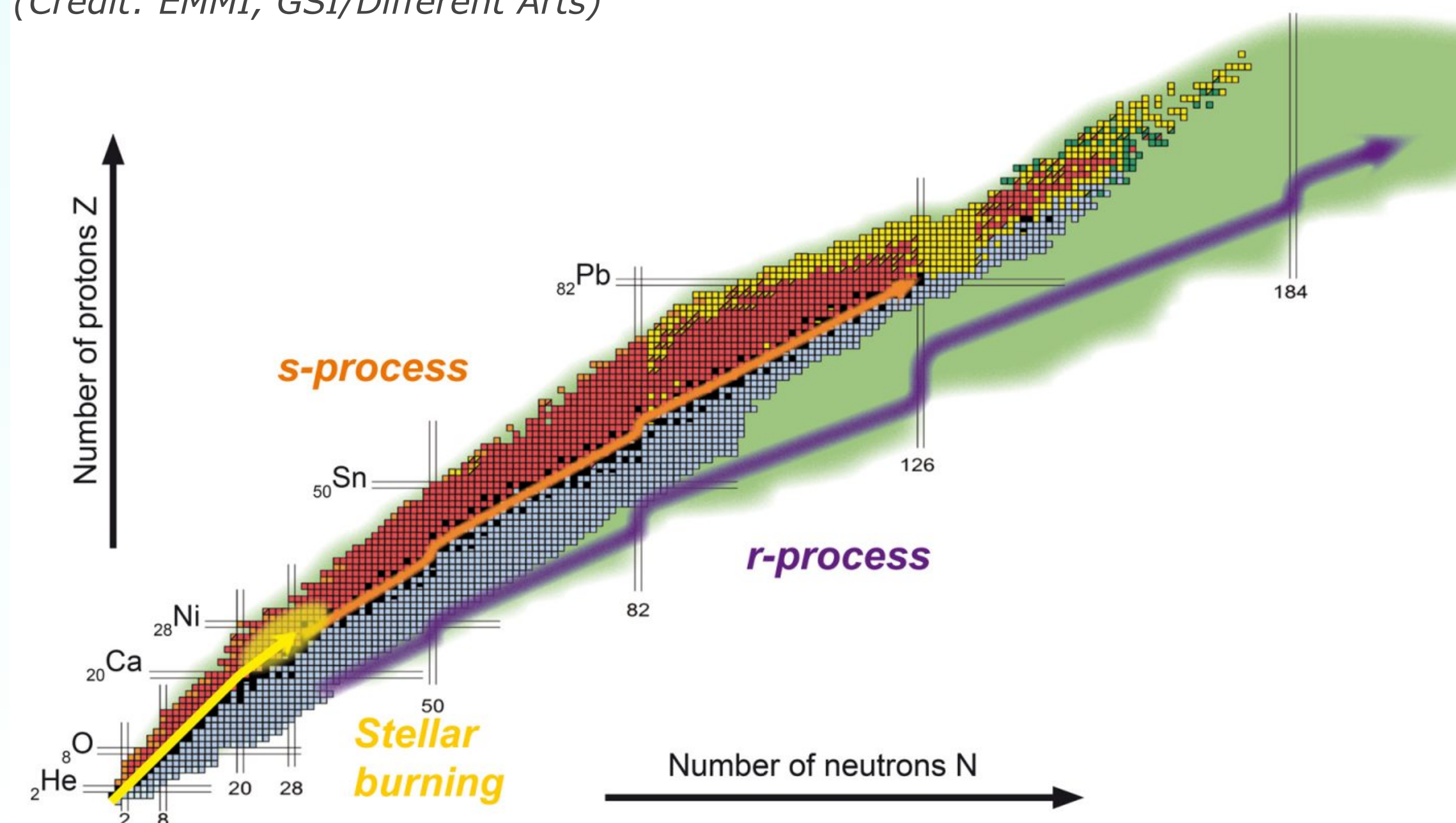
- dynamical occur pre-coalescence:
 - driven by tidal forces
 - can reach heavy nuclei like U
- jet ejecta occur post-coalescence
 - Weaker, cannot reach heaviest nuclei

The yields of s- and r-processes

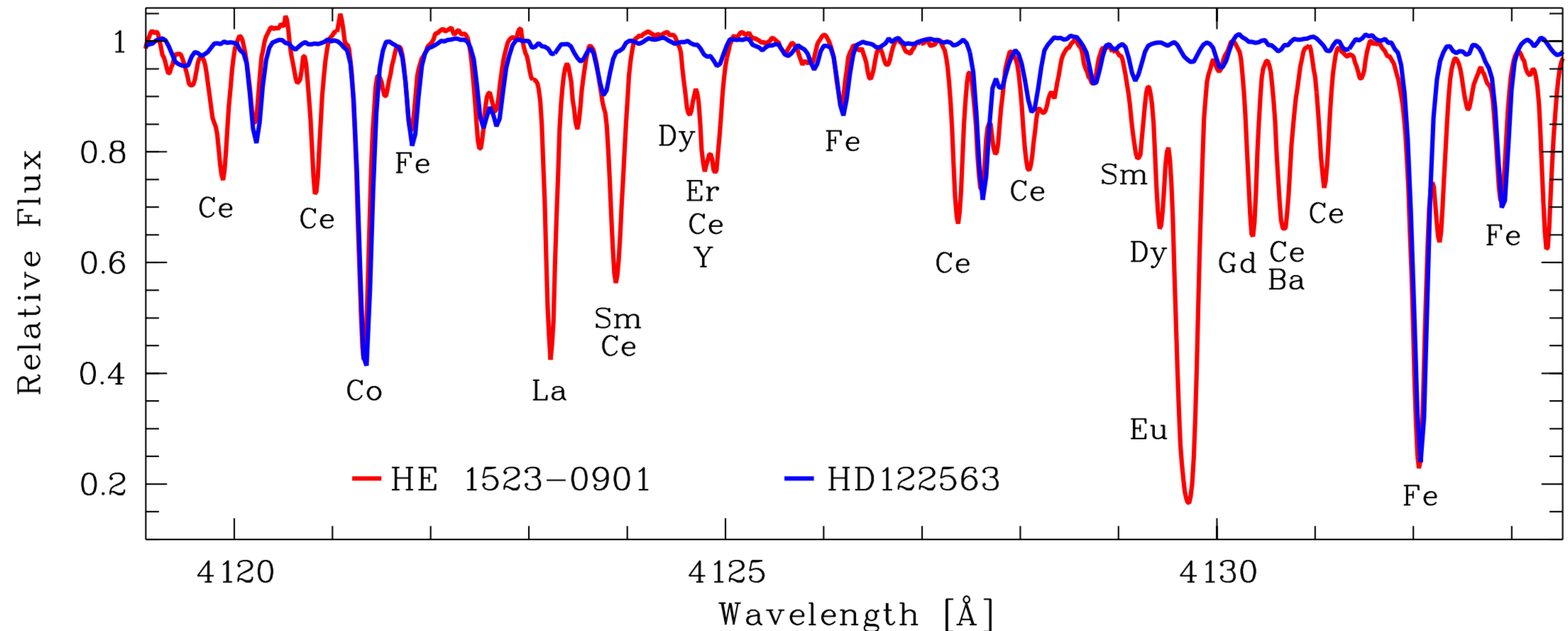
The magic neutron numbers 82, 126, 184 where the yields peak

- **s-processes** are closer to the valley of stability, so $Z+N=A$ will be larger for a given N
- **r-processes** they have to decay several times before reaching the valley of stability, $Z+N=A$ will be smaller for a given N

(Credit: EMMI, GSI/Different Arts)



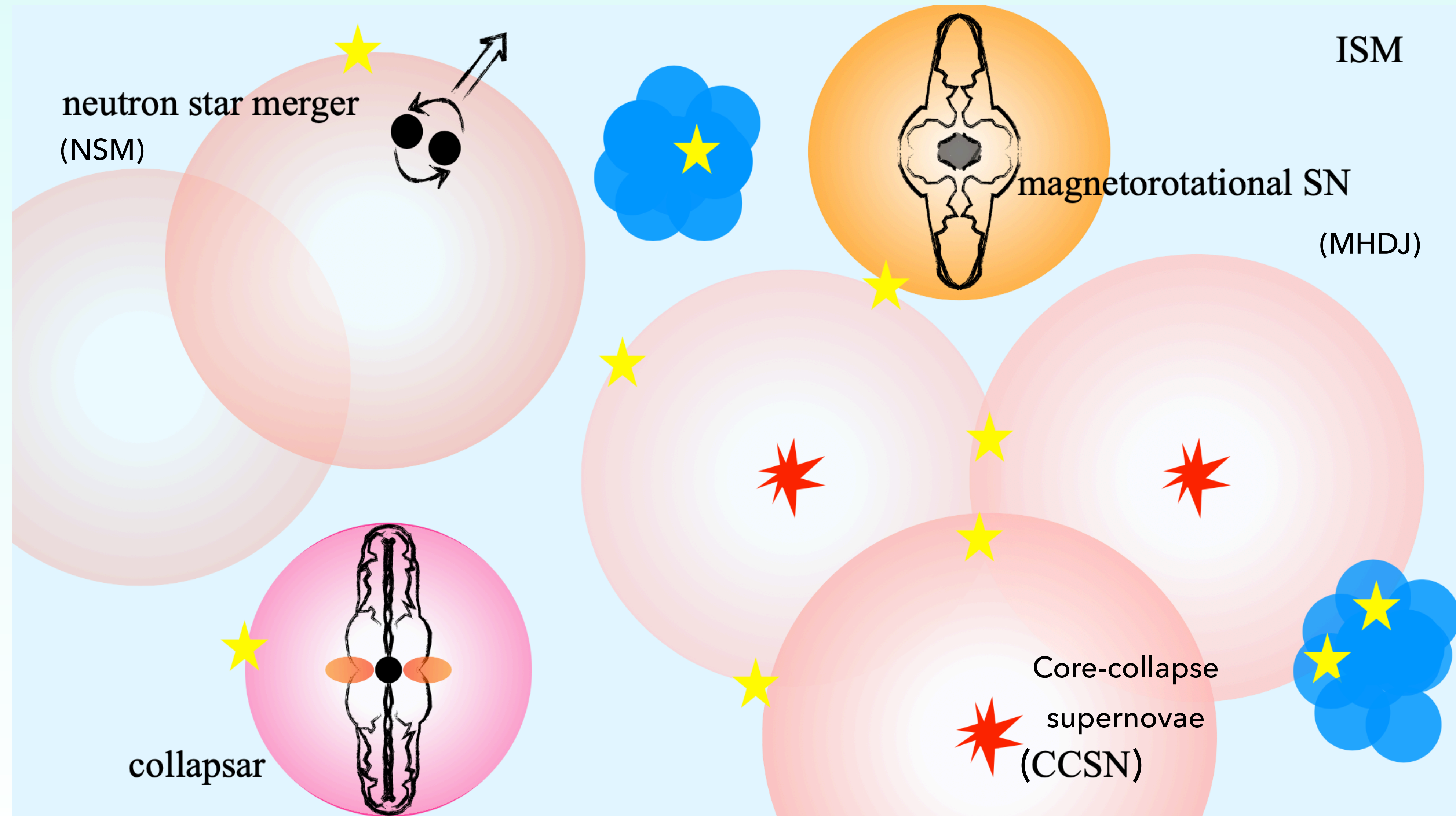
Elemental abundances in individual stars



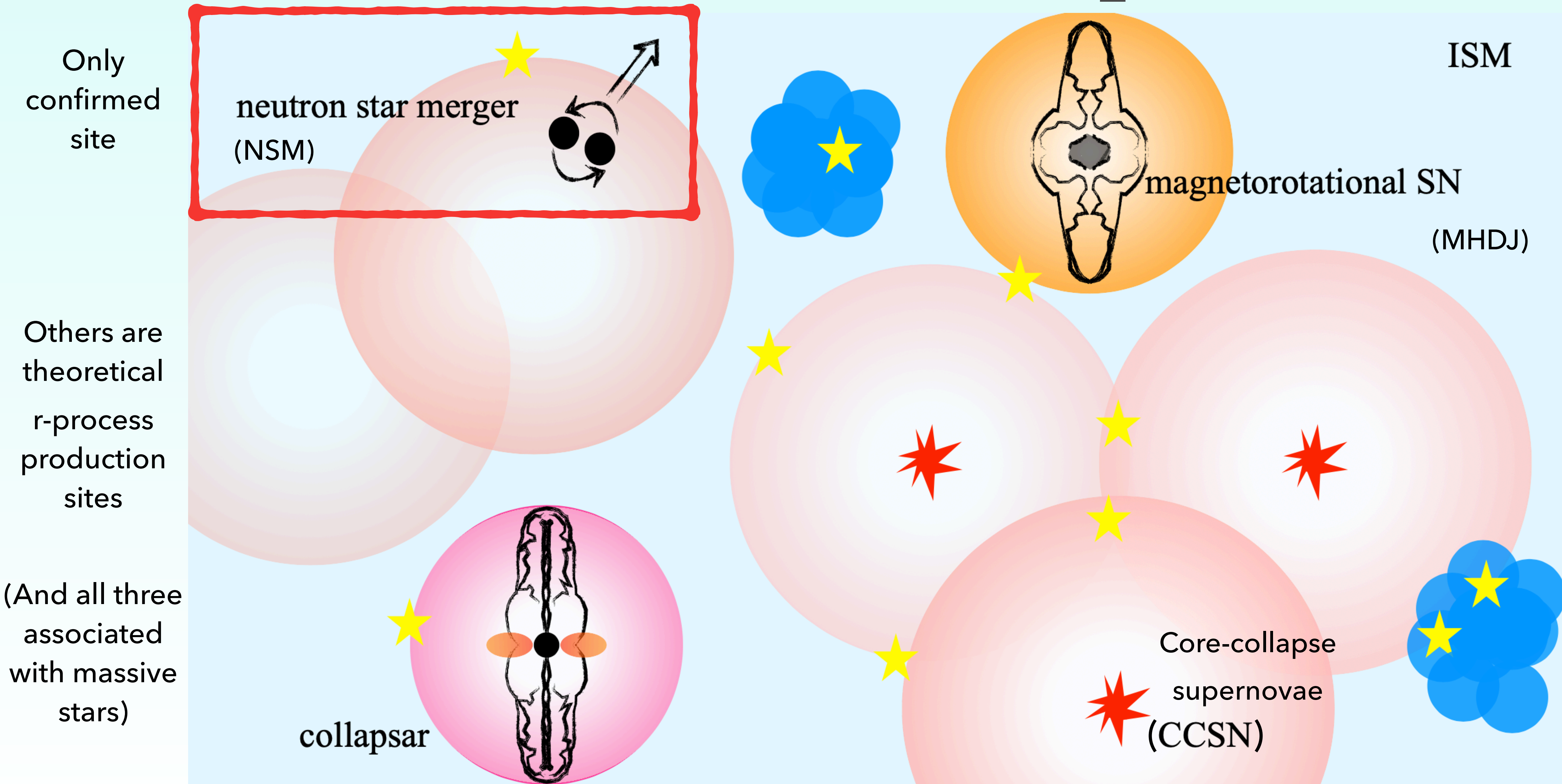
Frebel+18: Spectra of two stars of similar temperature and metallicity.

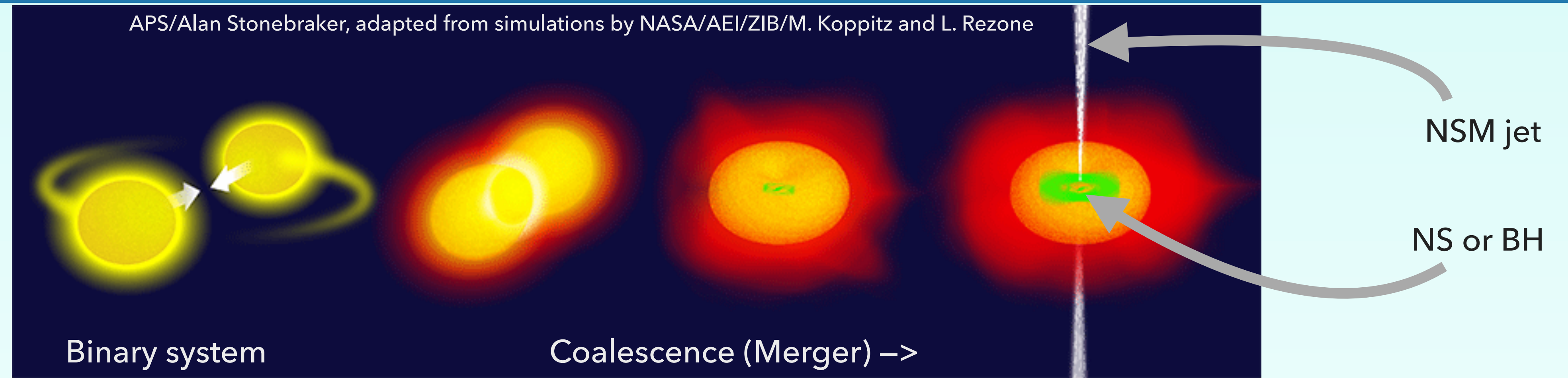
HD 122563 is an r-process deficient star. HE 1523-0901 is an r-process-enhanced star.

What are the candidate r-process sites?

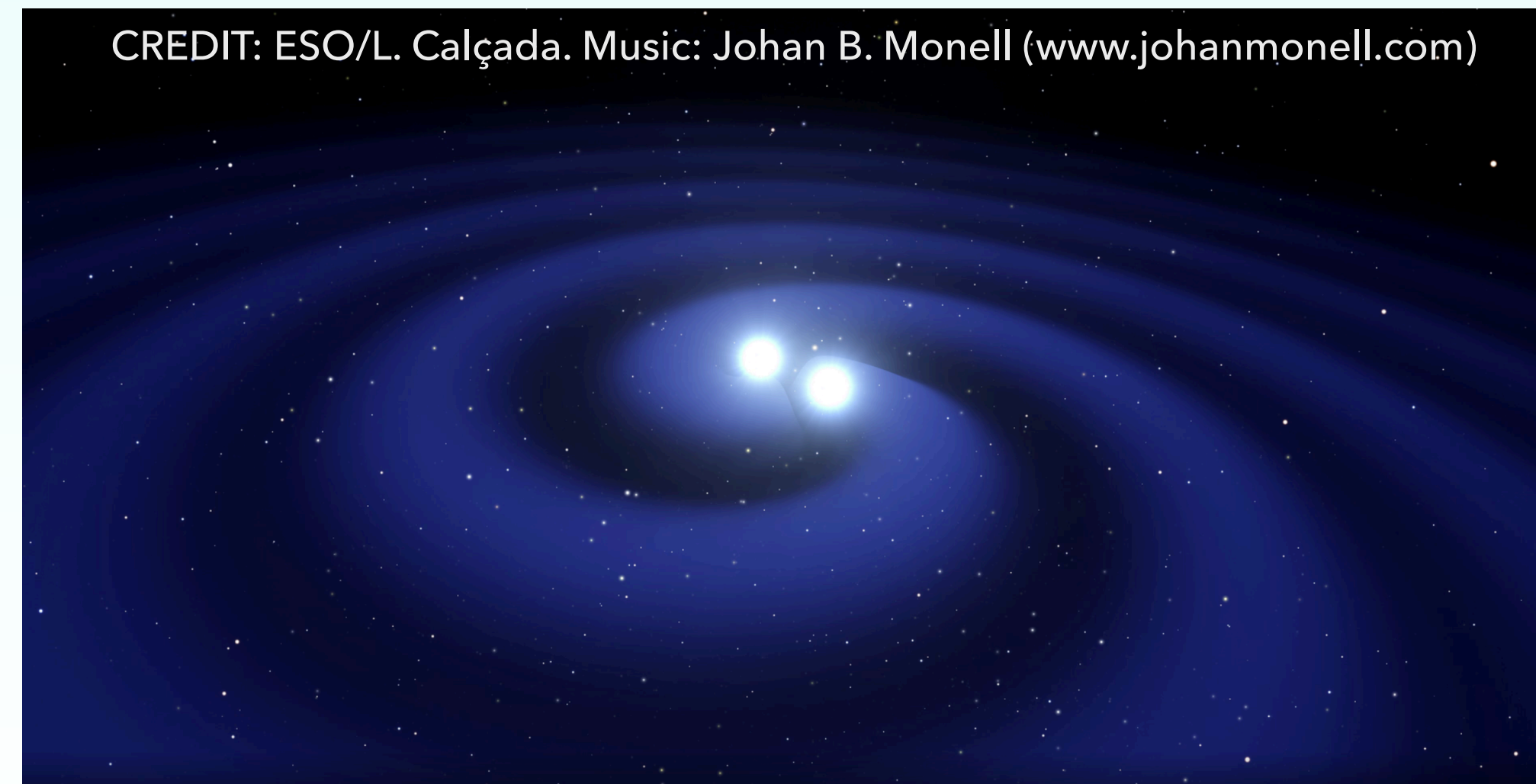


What are the candidate r-process sites?

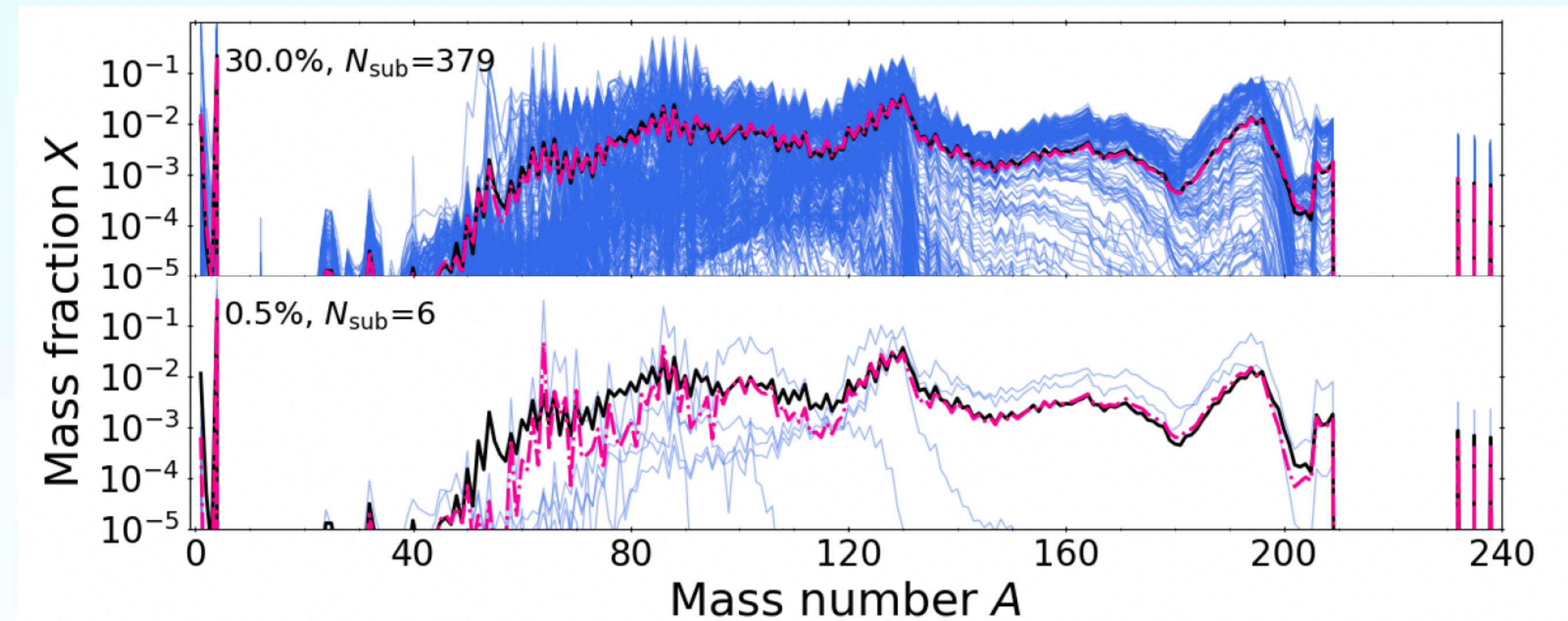
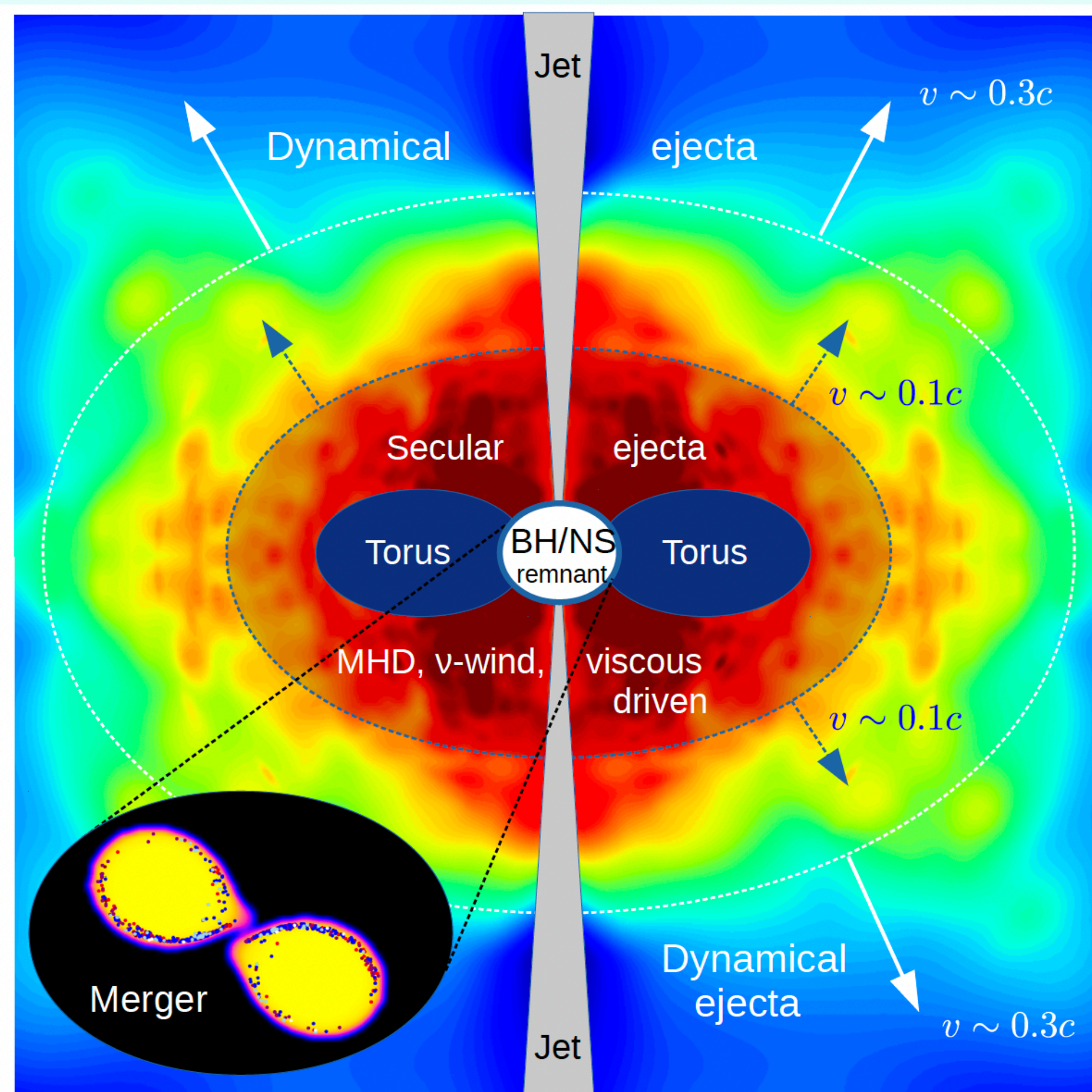




Let's focus on NSM



The r-process enrichment of neutron star mergers



The delayed time distribution for NSM

- The delayed time distribution (DTD, or $f(\tau)$) is the distribution across time of NS-NS coalescence episodes generated from one instantaneous burst of star formation (in unitary mass)

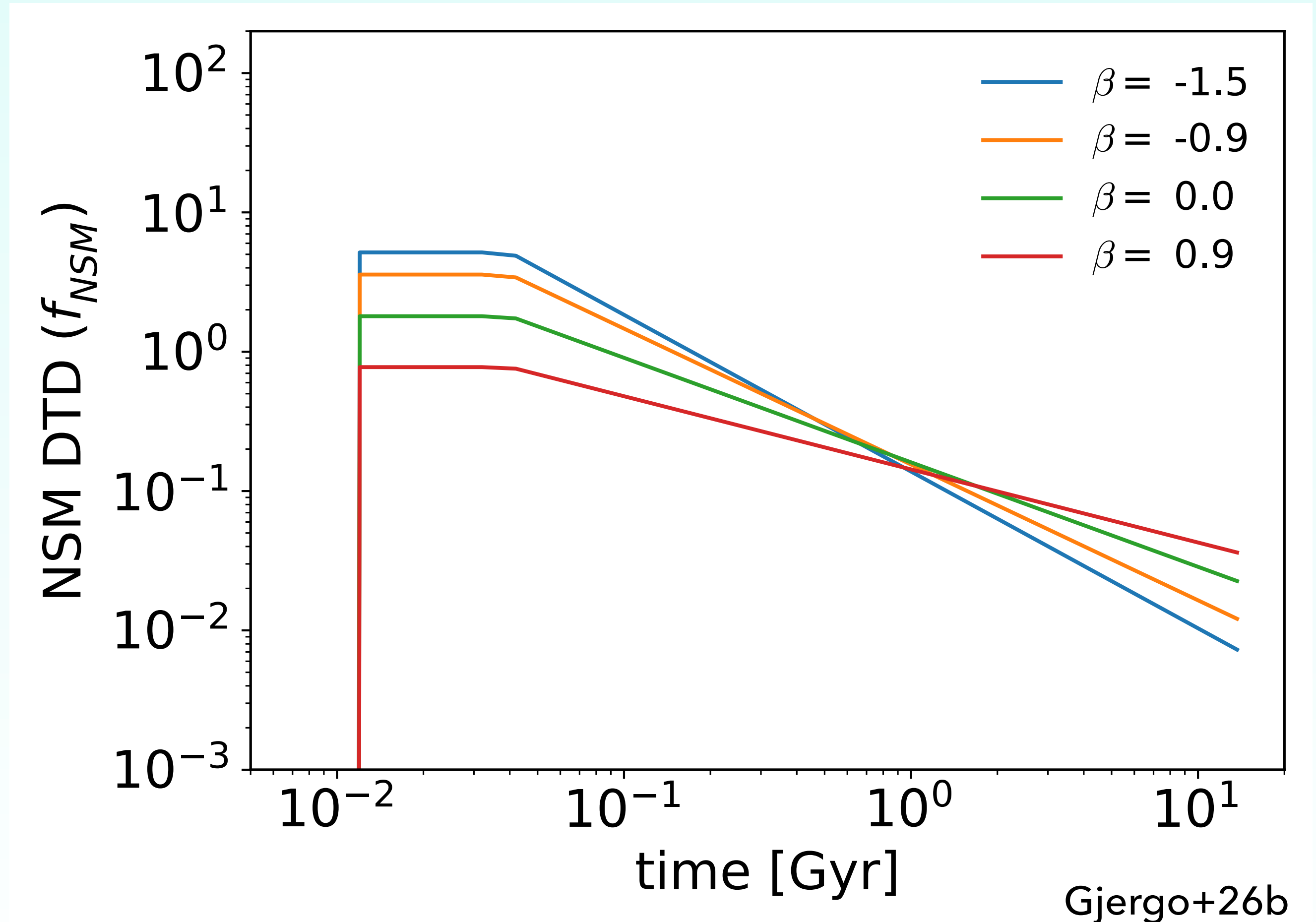
- Equivalent to power law, but motivated by GR
- It is normalized across cosmic time as:

$$\int_{\tau_{ini}=10\text{Myr}}^{\tau_{Hubble}} f(\tau) d\tau = 1$$

- (30 Myr for $9 M_{\odot}$ and 4 Myr for $50 M_{\odot}$)

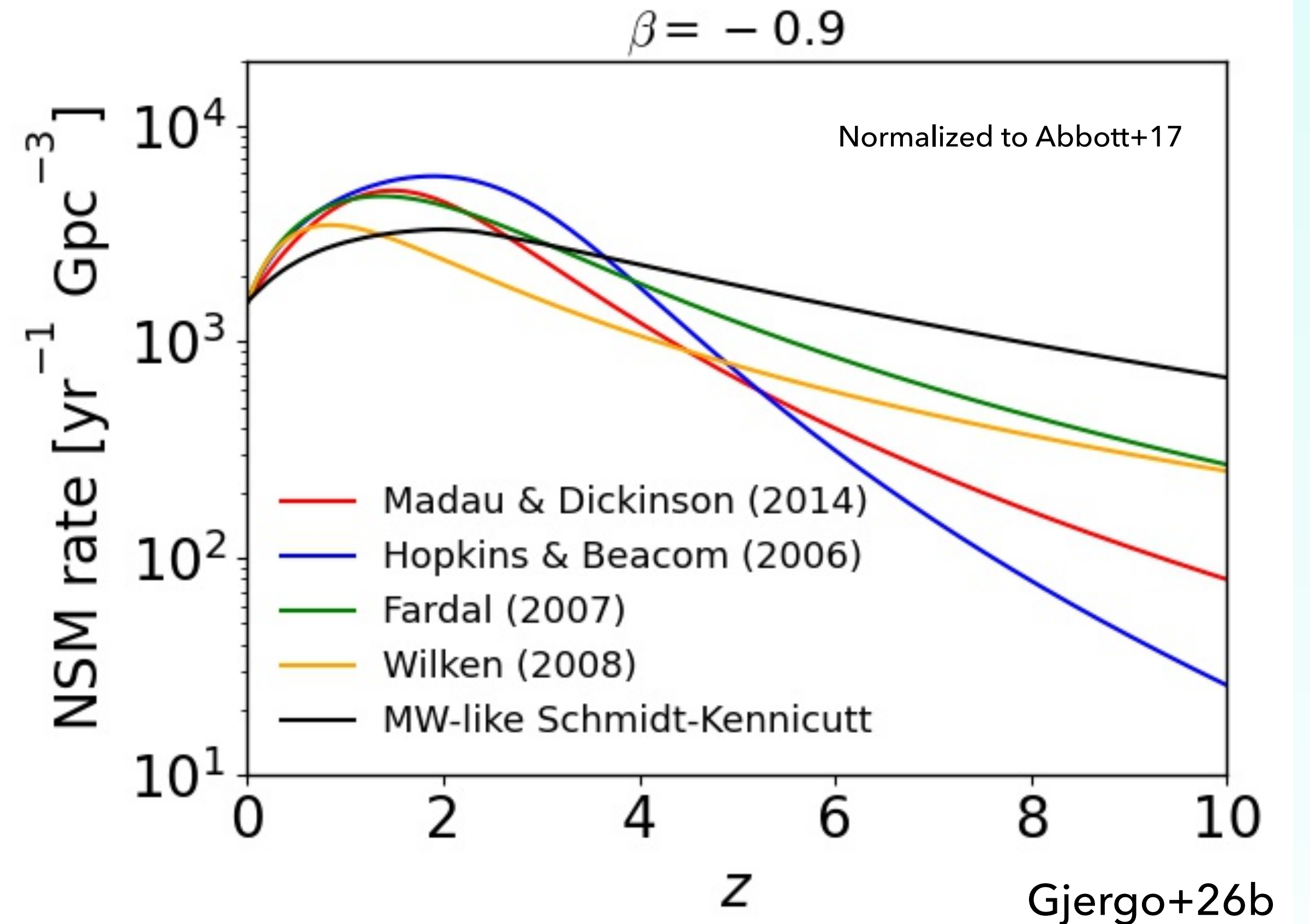
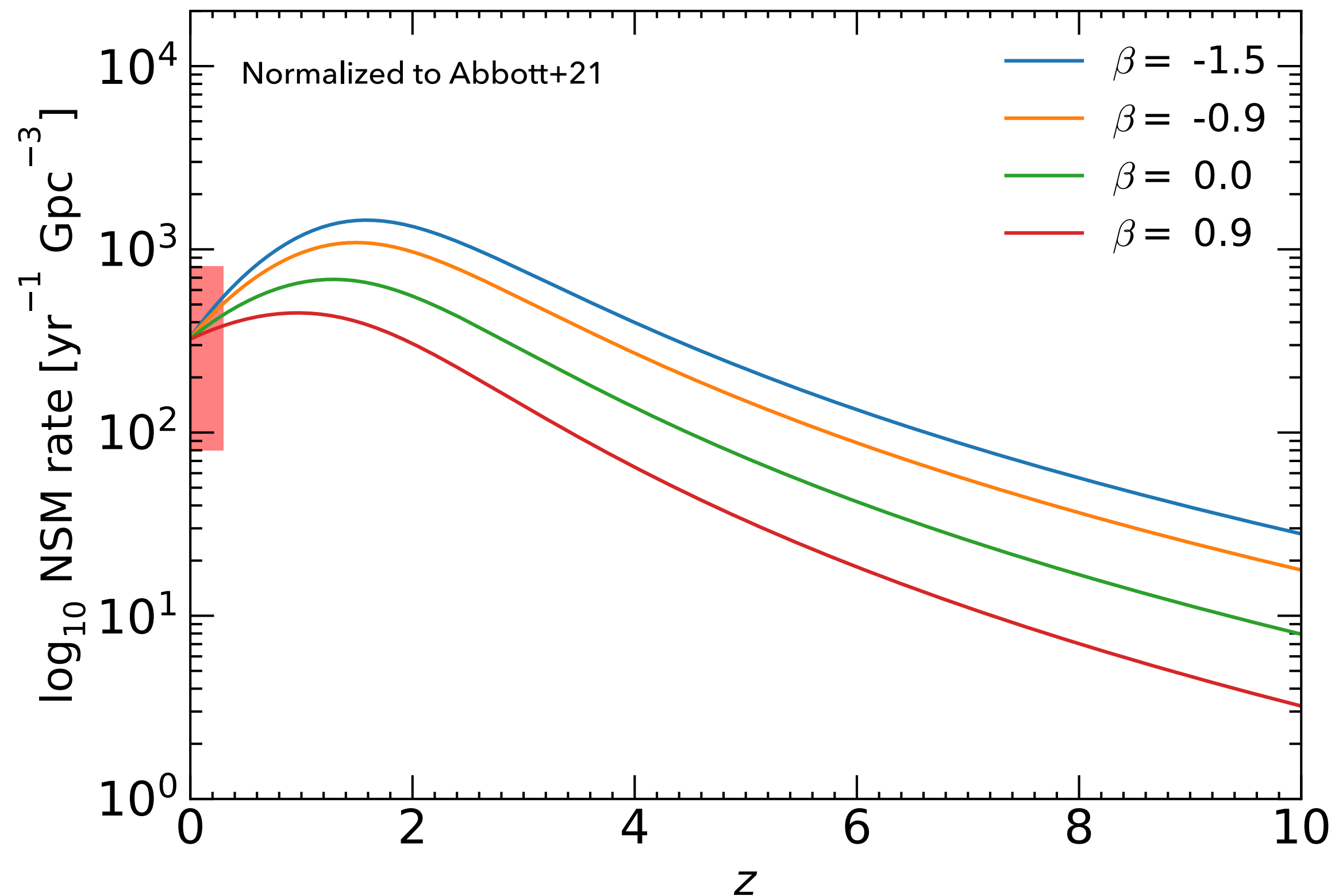
$$f(\tau) \propto \begin{cases} 0 & \text{if } \tau < 10 \text{ Myr} \\ p_1 & \text{if } 10 < \tau < 40 \text{ Myr} \\ p_2 \tau^{0.25\beta-0.75} \left(M_{\text{DN},s}^{0.75(\beta+2.33)} - M_{\text{DN},l}^{0.75(\beta+2.33)} \right) & \text{if } 40 \text{ Myr} < \tau < 13.7 \text{ Gyr} \end{cases}$$

Simonetti+19, full derivation of p_1 in Greggio+05



Variations of the NSM rate

CSFR prescription: Madau & Dickinson (2014)



(IMF integral)

$k_a = 5.97 \times 10^{-3}$ is the fraction of total star-forming gas mass which will produce NS

$$R_{NSM}(t) = k_a \alpha_{NSM} \int_{\tau_{ini}}^{\min(t, \tau_{Hubble})} \Psi(t - \tau) f_{NSM}(\tau) d\tau$$

$\alpha_{NSM} = 1.02 \times 10^{-2}$ is the fraction of NS that will undergo a merger event at a given instant τ . Taken to be time-independent

Other enrichment processes

Initial conditions (Primordial gas)

- Most GCE models assume primordial gas as IC
- The red vertical estimate for Ω_m comes from WMAP
- Circles represent observed abundances (oversimplification + Lithium problem)

THE PERIODIC TABLE OF ELEMENTS

1

H

HYDROGEN

1.008

3

Li

LITHIUM

6.941

4

Be

BERYLLIUM

9.012

11

Na

SODIUM

22.990

12

Mg

MAGNESIUM

24.305

19

K

POTASSIUM

39.098

20

Ca

CALCIUM

40.078

21

Sc

SCANDIUM

44.956

22

Ti

TITANIUM

47.867

23

V

VANADIUM

50.942

24

Cr

CHROMIUM

51.996

25

Mn

MANGANESE

54.938

26

Fe

IRON

55.845

27

Co

COBALT

58.933

28

Ni

NICKEL

58.693

29

Cu

COPPER

63.546

30

Zn

ZINC

65.382

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.960

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

37

Rb

RUBIDIUM

85.468

38

Sr

STRONTIUM

87.62

39

Y

YTTRIUM

88.906

40

Zr

ZIRCONIUM

91.224

41

Nb

NIOBIUM

92.906

42

Mo

MOLYBDENUM

95.94

43

Tc

TECHNETIUM

(97.907)

44

Ru

RUTHENIUM

101.072

45

Rh

RHODIUM

102.905

46

Pd

PALLADIUM

106.42

47

Ag

SILVER

107.868

48

Cd

CADMIUM

112.414

49

In

INDIUM

114.818

50

Sn

TIN

118.710

51

Sb

ANTIMONY

121.757

52

Te

TELLURIUM

127.603

53

I

IODINE

126.905

54

Xe

XENON

131.29

55

Cs

CAESIUM

132.905

56

Ba

BARIUM

137.327

57-71

72

Hf

HAFNIUM

178.492

73

Ta

TANTALUM

180.948

74

W

TUNGSTEN

183.841

75

Re

RHENIUM

186.207

76

Os

OSMIUM

190.233

77

Ir

IRIDIUM

192.222

78

Pt

PLATINUM

195.084

79

Au

GOLD

196.967

80

Hg

MERCURY

200.592

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.2

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(209)

85

At

ASTATINE

(221)

86

Rn

RADON

(222)

87

Fr

FRANCIUM

(223)

88

Ra

RADIUM

(226)

89-103

104

Rf

RUTHERFORDIUM

(261)

105

Db

DUBNIUM

(262)

106

Sg

SEABORGIUM

(266)

107

Bh

BOHRHIUM

(264)

108

Hs

HASSENIUM

(277)

109

Mt

MEITNERIUM

(268)

110

Ds

DARMSTADTIUM

(271)

111

Rg

ROSGOLDIUM

(272)

112

Cn

CARNEGIEMIUM

(285)

113

Nh

NIHONIUM

(286)

114

Fl

FLEROVIUM

(289)

115

Mc

MOSCOWIUM

(288)

116

Lv

LIVERMORIUM

(293)

117

Ts

TENNESSIUM

(294)

118

Og

OGANESSON

(294)

Symbol Key

Atomic number

Element symbol

Element name

Relative atomic mass

Block

Groups of elements

s block elements

p block elements

d block elements

f block elements

Colour Key

5

B

BORON

10.811

6

C

CARBON

12.011

7

N

NITROGEN

14.007

8

O

OXYGEN

15.999

9

F

FLUORINE

18.998

10

Ne

NEON

20.180

13

Al

ALUMINIUM

26.982

14

Si

SILICON

28.086

15

P

PHOSPHORUS

30.974

16

S

SULFUR

32.065

17

Cl

CHLORINE

35.453

18

Ar

ARGON

39.948

31

Ga

GALLIUM

69.723

32

Ge

GERMANIUM

72.640

33

As

ARSENIC

74.922

34

Se

SELENIUM

78.960

35

Br

BROMINE

79.904

36

Kr

KRYPTON

83.798

49

In

INDIUM

114.818

50

Sn

TIN

118.710

51

Sb

ANTIMONY

121.757

52

Te

TELLURIUM

127.603

53

I

IODINE

126.905

54

Xe

XENON

131.29

81

Tl

THALLIUM

204.383

82

Pb

LEAD

207.2

83

Bi

BISMUTH

208.980

84

Po

POLONIUM

(209)

85

At

ASTATINE

(221)

86

Rn

RADON

(222)

113

Nh

NIHONIUM

(286.100)

114

Fl

FLEROVIUM

(289.100)

115

Mc

MOSCOWIUM

(288.100)

116

Lv

LIVERMORIUM

(293.100)

117

Ts

TENNESSIUM

(294.100)

118

Og

OGANESSON

(294.100)

57

La

LANTHANUM

138.905

58

Ce

CELESIUM

140.116

59

Pr

PRASEODYMIUM

140.908

60

Nd

NEODYMIUM

144.242

61

Pm

PROMETHIUM

(144.000)

62

Sm

SAMARIUM

150.362

63

Eu

EUROPEUM

151.964

64

Gd

GADOLINIUM

157.253

65

Tb

TERBIUM

158.925

66

Dy

DYSPROSIUM

162.500

67

Ho

HOLMIUM

164.930

68

Er

ERBIUM

167.259

69

Tm

THULIUM

168.934

70

Yb

YTERBIUM

173.054

71

Lu

LUTETIUM

174.967

89

Ac

ACTINIUM

(227.028)

90

Th

THORIUM

(232.038)

91

Pa

PROTACTINIUM

(231.036)

92

U

URANIUM

(238.029)

93

Np

NEPTUNIUM

(237.048)

94

Pu

PLUTONIUM

(244.064)

95

Am

AMERICIUM

(243.063)

96

Cm

CURIUM

(247.070)

97

Bk

BERKELIUM

(247.070)

98

Cf

CALIFORNIUM

(251.080)

99

Es

EINSTEINIUM

(252.083)

100

Fm

FERMIUM

(257.095)

101

Md

Mendelevium

(258.108)

102

No

Nobelium

(259.105)

103

Lr

Lawrencium

(262.100)

Ci

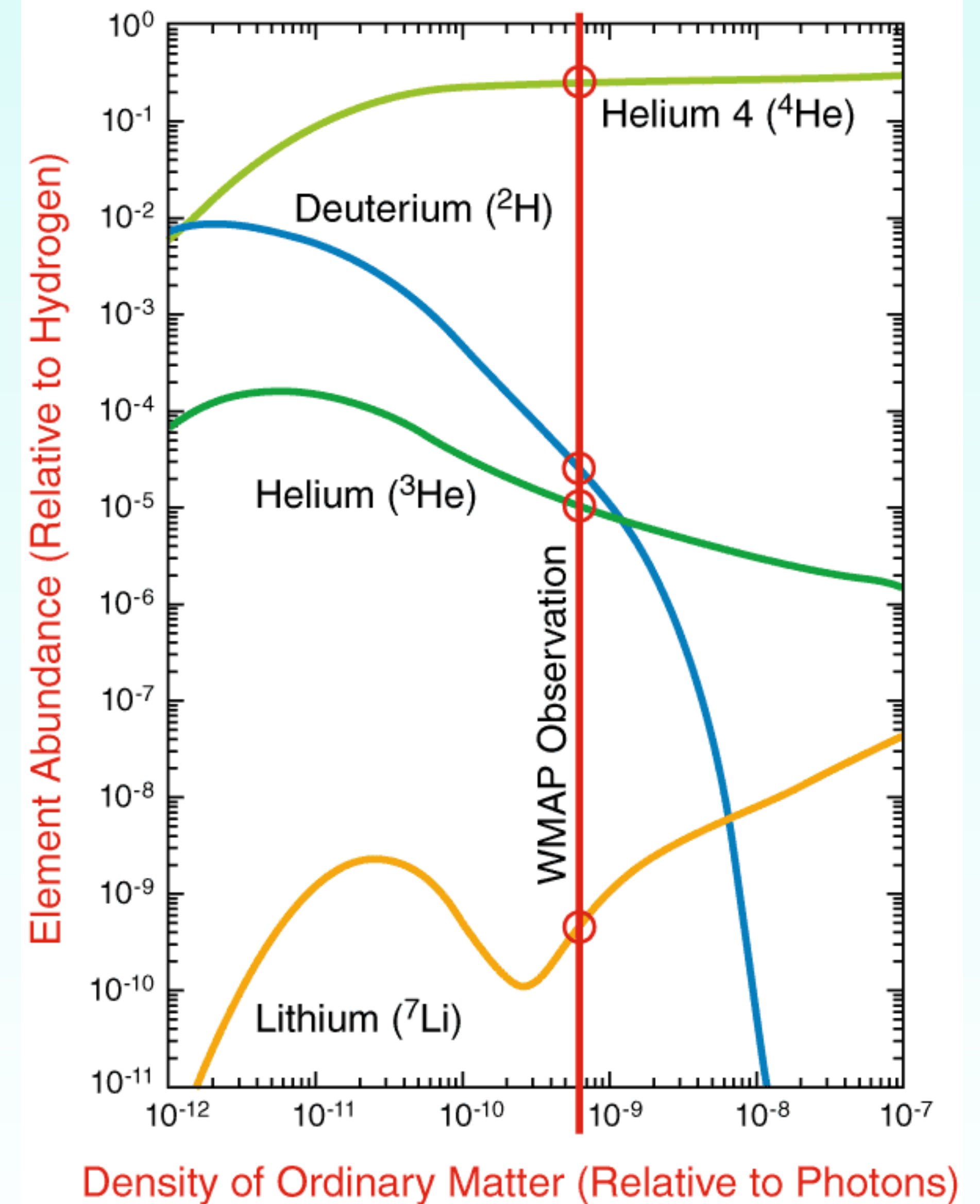
© Andy Brunning/Compound Interest 2017 – www.compoundchem.com | Facebook: facebook.com/compoundchem | Twitter: [@compoundchem](https://twitter.com/compoundchem)
This graphic is shared under a Creative Commons 4.0 Attribution-NoDerivatives-NonCommercial licence.

CC

BY

NC

ND

NASA/WMAP Science Team
WMAP101087

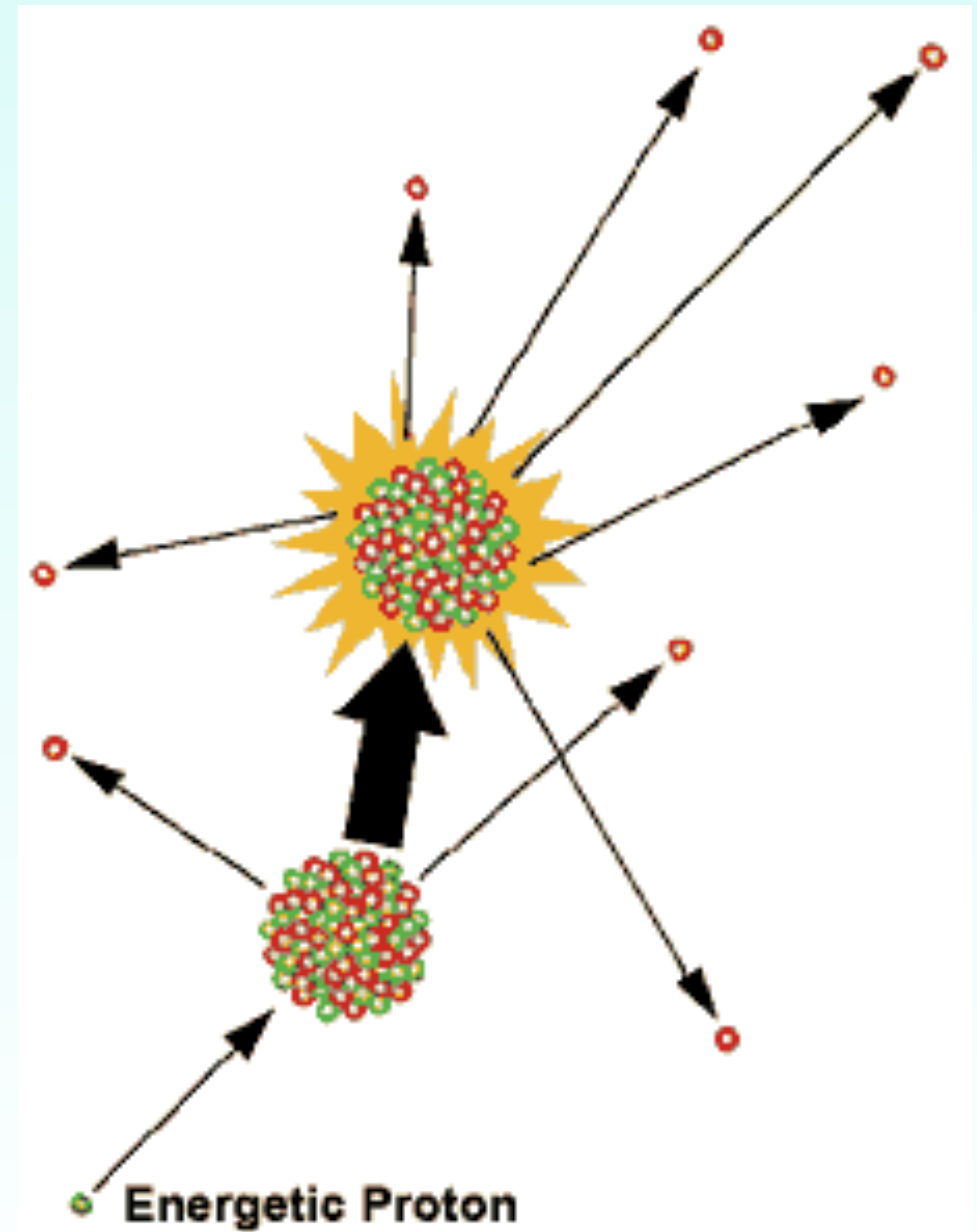
NASA/WMAP

Element Abundance graphs: Steigman, Encyclopedia of Astronomy
and Astrophysics (Institute of Physics) December, 2000

Steigman (2000)

Spallation (Cosmic rays)

- Spallation is the fission caused by cosmic rays impinging onto heavier nuclides.
- Forms isotopes with atomic mass 9, 10, 11
- i.e., isotopes of boron and beryllium
- Spallation also produces ^6Li and some ^7Li



THE PERIODIC TABLE OF ELEMENTS

Symbol Key Atomic number Element symbol Element name Relative atomic mass Block 1 H HYDROGEN 1.008 1																		Groups of elements s block elements p block elements d block elements f block elements																	
1 H HYDROGEN 1.008 1																		2 He HELIUM 4.003 2																	
3 Li LITHIUM 6.941 3																		4 Be BERYLLIUM 9.012 4																	
11 Na SODIUM 22.990 11																		12 Mg MAGNESIUM 24.305 12																	
19 K POTASSIUM 39.098 19																		20 Ca CALCIUM 40.078 20																	
27 Rb RUBIDIUM 85.468 27																		28 Sr STRONTIUM 87.62 28																	
35 Cs CAESIUM 132.905 35																		36 Ba BARIUM 137.327 36																	
87 Fr FRANCIUM (223.02) 87																		88 Ra RADIUM (226.025) 88																	
57 La LANTHANUM 138.905 57																		58 Ce CERIUM 140.12 58																	
67 Dy DYSPROSIUM 162.50 67																		68 Ho HOLMIUM 164.93 68																	
77 Ir IRIDIUM 192.22 77																		78 Pt PLATINUM 195.084 78																	
87 Fr FRANCIUM (223.02) 87																		88 Ra RADIUM (226.025) 88																	
97 Bk BERKELIUM (247.07) 97																		98 Cf CALIFORNIUM (251.08) 98																	
107 Ts TENNESSIUM (294.00) 107																		108 Og OGANESSON (294.00) 108																	

HOW MANY GENERATIONS OF STARS DO THE VARIOUS ELEMENTS OF THE SOLAR SYSTEM (SUCH AS OUR BODY) NEED TO GO THROUGH?

Courtesy of Zhiyu Zhang

CCSN: Core Collapse Supernova Explosions - From Massive Stars

R_{CCSN}

$\sim (30 \text{ years})^{-1}$

M_{gas}

$\sim 10^{10} \text{ Msun}$

t_{OBstar}

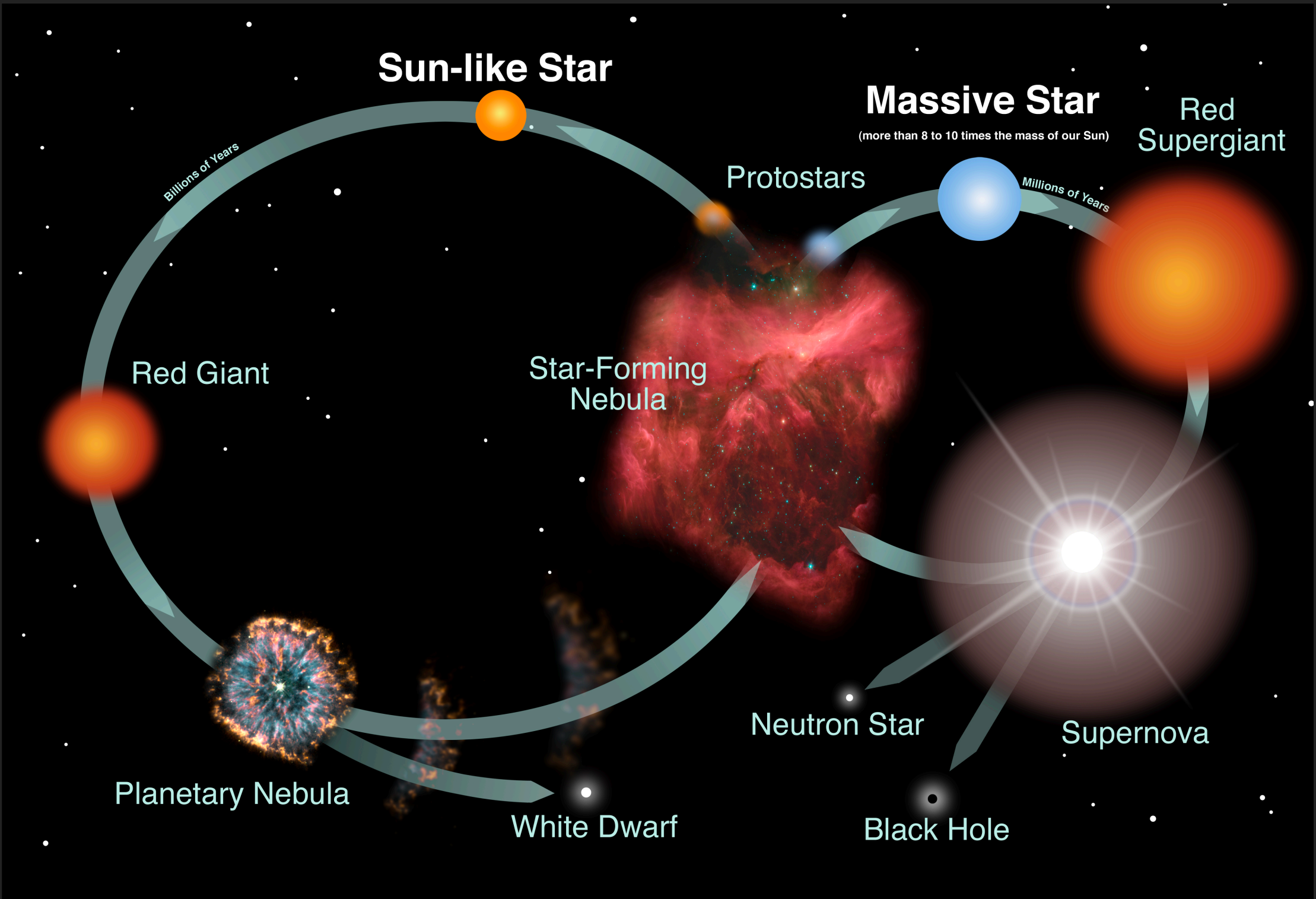
$\sim 10^7 \text{ years}$

M_{mix}

$\sim 3 \times 10^4 \text{ Msun}$

R_{mix}

$\sim R_{\text{CCSN}} * t_{\text{OBstar}} * (M_{\text{mix}} / M_{\text{gas}})$



HOW MANY GENERATIONS OF STARS DO THE VARIOUS ELEMENTS OF THE SOLAR SYSTEM (SUCH AS OUR BODY) NEED TO GO THROUGH?

Courtesy of Zhiyu

CCSN: Core Collapse Supernova Explosions - From Massive Stars

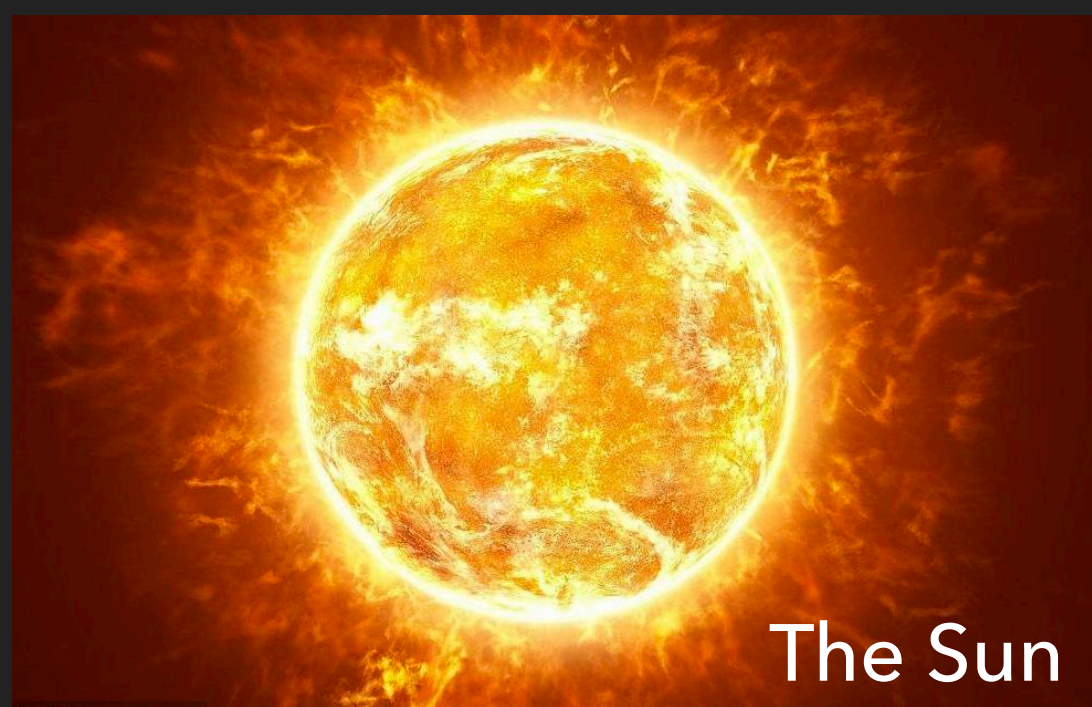
$R_{CCSN} \sim (30 \text{ years})^{-1}$

$M_{gas} \sim 10^{10} \text{ Msun}$

$t_{OBstar} \sim 10^7 \text{ years}$

$M_{mix} \sim 3 \times 10^4 \text{ Msun}$

$R_{mix} \sim R_{CCSN} * t_{OBstar} * (M_{mix} / M_{gas})$

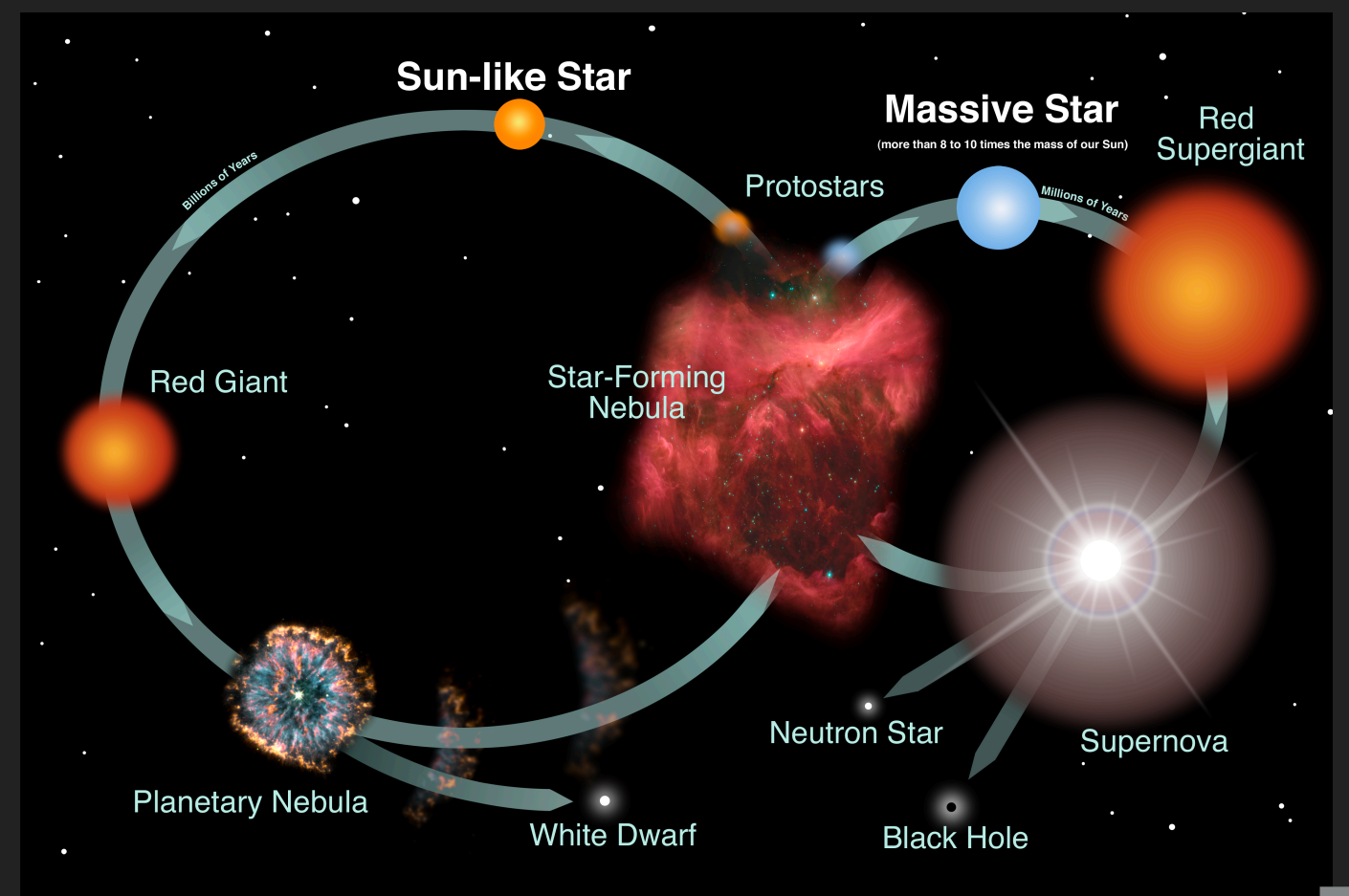


Assuming the Milky Way evolved for 9 billion years before the Sun:

$t_{MW}=9 \text{ Gyr, so } N_{CCSN} \sim R_{mix} * t_{MW} \sim 900$

It means it took 900 supernova explosions to enrich the sun

- 罗马 不是一天 建成的



HOW MANY GENERATIONS OF STARS DO THE VARIOUS ELEMENTS OF THE SOLAR SYSTEM (SUCH AS OUR BODY) NEED TO GO THROUGH?

Courtesy of Zhiyu

CCSN: Core Collapse Supernova Explosions - From Massive Stars

$R_{CCSN} \sim (30 \text{ years})^{-1}$

$M_{gas} \sim 10^{10} \text{ Msun}$

$t_{OBstar} \sim 10^7 \text{ years}$

$M_{mix} \sim 3 \times 10^4 \text{ Msun}$

$R_{mix} \sim R_{CCSN} * t_{OBstar} * (M_{mix} / M_{gas})$

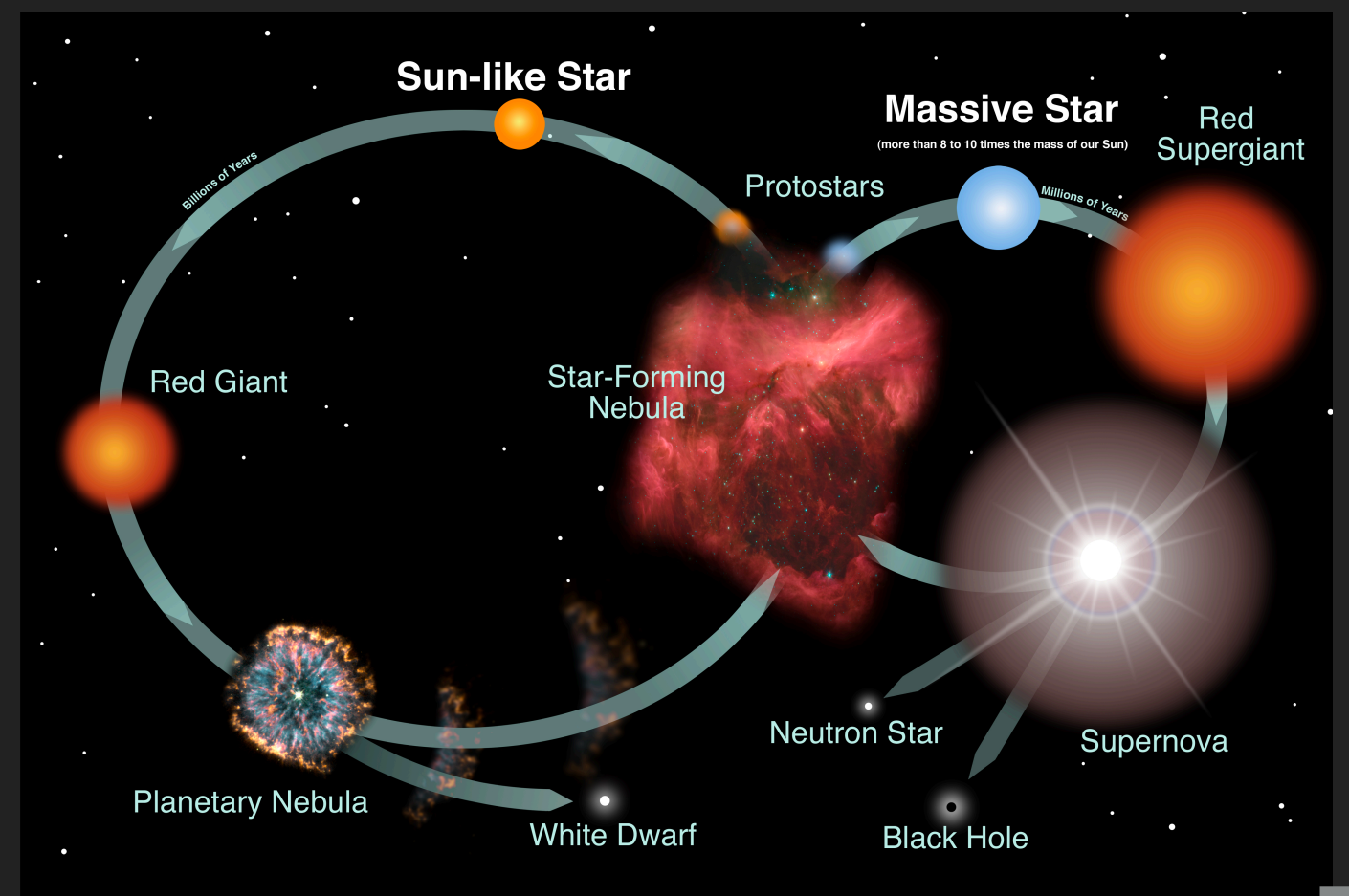


Assuming the Milky Way evolved for 9 billion years before the Sun:

$t_{MW}=9 \text{ Gyr, so } N_{CCSN} \sim R_{mix} * t_{MW} \sim 900$

It means it took 900 supernova explosions to enrich the sun

- 罗马不是一天建成的



HOW MANY GENERATIONS OF STARS DO THE VARIOUS ELEMENTS OF THE SOLAR SYSTEM (SUCH AS OUR BODY) NEED TO GO THROUGH?

Courtesy of Zhiyu

CCSN: Core Collapse Supernova Explosions - From Massive Stars

- $R_{CCSN} \sim (30 \text{ years})^{-1}$
- $M_{gas} \sim 10^{10} \text{ Msun}$
- $t_{OBstar} \sim 10^7 \text{ years}$
- $M_{mix} \sim 3 \times 10^4 \text{ Msun}$
- $R_{mix} \sim R_{CCSN} * t_{OBstar} * (M_{mix} / M_{gas})$



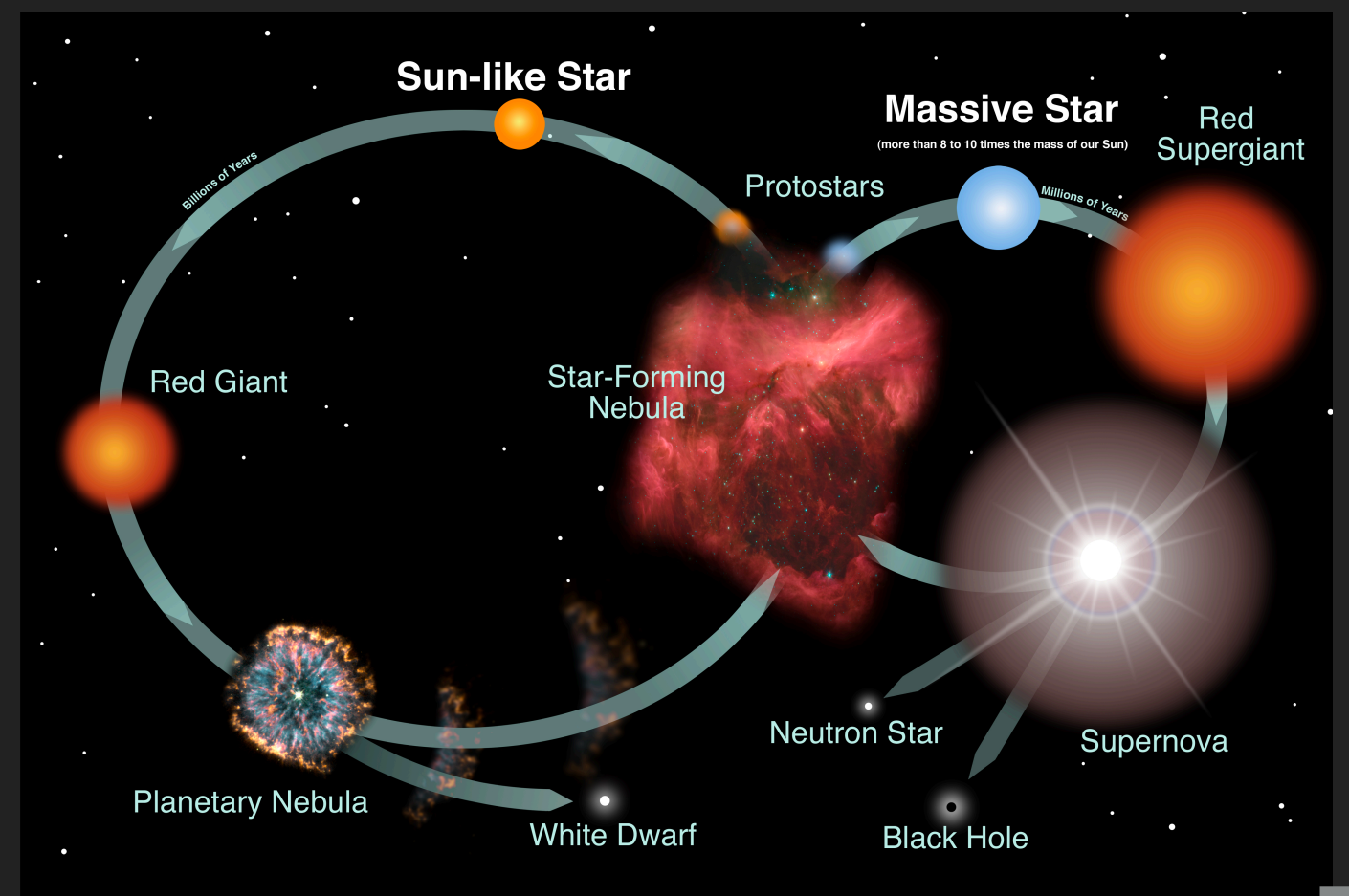
- The devil knows what I've been through

Assuming the Milky Way evolved for 9 billion years before the Sun:

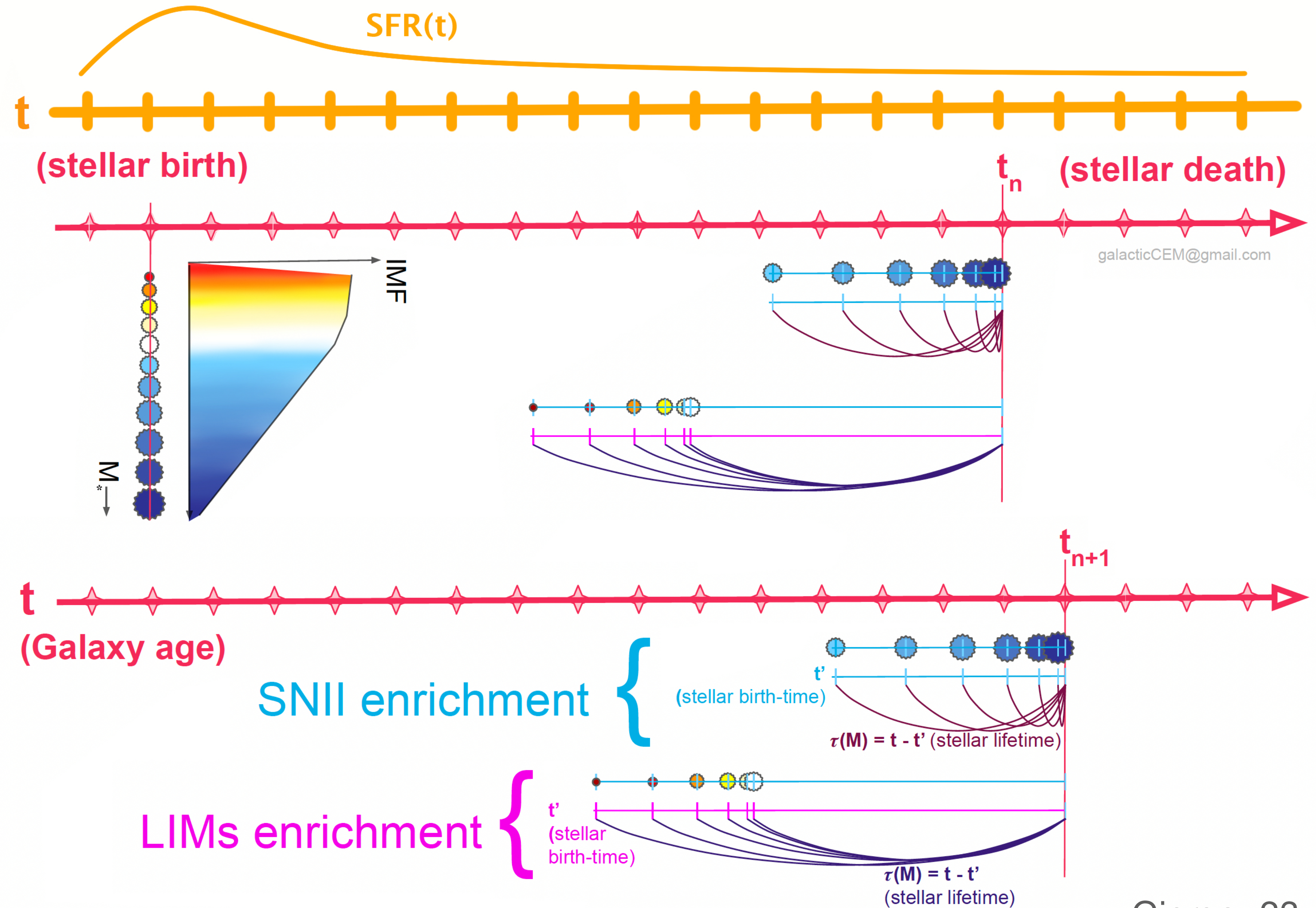
$t_{MW}=9 \text{ Gyr}, \text{ so } N_{CCSN} \sim R_{mix} * t_{MW} \sim 900$

It means it took 900 supernova explosions to enrich the sun

- 罗马不是一天建成的



GCE rationale



The full chemical evolution equations

Matteucci & Greggio (1986)

- Here i is the tracked isotope:
- $\frac{dM_{gas,i}(t)}{dt} = + I_i(t) - X_i(t)SFR(t) + R_i(t) - O_i(t)$
- $I_i(t) = X_{BBN,i}e^{-t/\tau_{eff}}$
- $SFR(t) \propto M_{gas,tot}^k(t)$
- $O_i(t) = X_i(t)[\omega SFR(t)]$
- $R_i(t) = \sum_{C}^{all-channels} R_{C,i}(t)$
- Where C are AGB, CCSN, SNIa, magnetohydrodynamic SN jets (MHDJ), NSM, Collapsars, etc.

The full chemical evolution equations

Matteucci & Greggio (1986)

- Here i is the tracked isotope:
- $\frac{dM_{gas,i}(t)}{dt} = +I_i(t) - X_i(t)SFR(t) + R_i(t) - O_i(t)$
- $I_i(t) = X_{BBN,i}e^{-t/\tau_{eff}}$
- $SFR(t) \propto M_{gas,tot}^k(t)$
- $O_i(t) = X_i(t)[\omega SFR(t)]$
- $R_i(t) = \sum_C^{all-channels} R_{C,i}(t)$
- Where C are AGB, CCSN, SNIa, magnetohydrodynamic SN jets (MHDJ), NSM, Collapsars, etc.

$$\sim R_{AGB,i}(t) = \int_{M_L}^{M_{Bm}} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{SNIa,i}(t) = A \int_{M_{Bm}}^{M_{BM}} \left[\int_{\mu_{min}}^{0.5} f(\mu) Q_{mi}(t - \tau_{m_2}) \psi(t - \tau_{m_2}) d\mu \right] \times \phi(m) dm$$

$$\sim R_{LIMS,i}(t) = (1 - A) \int_{M_{Bm}}^{M_{BM}} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{SNCC,i}(t) = \int_{M_{BM}}^{M_U} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{MHDJ,i}(t) = 0.01 \times Q_i \int_{M_{BM}}^{M_U} \psi(t - \tau_m) \phi(m) dm$$

$$\sim R_{NSM,i}(t) = \alpha k Q_i \int_{\tau_i}^{\min(t, \tau_H)} f_{NSM}(\tau) \Psi(t - \tau) d\tau$$

The full chemical evolution equations

Matteucci & Greggio (1986)

- Here i is the tracked isotope:
- $\frac{dM_{gas,i}(t)}{dt} = +I_i(t) - X_i(t)SFR(t) + R_i(t) - O_i(t)$
- $I_i(t) = X_{BBN,i}e^{-t/\tau_{eff}}$
- $SFR(t) \propto M_{gas,tot}^k(t)$
- $O_i(t) = X_i(t)[\omega SFR(t)]$
- $R_i(t) = \sum_C^{all-channels} R_{C,i}(t)$
- Where C are AGB, CCSN, SNIa, magnetohydrodynamic SN jets (MHDJ), NSM, Collapsars, etc.

$$\sim R_{AGB,i}(t) = \int_{M_L}^{M_{Bm}} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{SNIa,i}(t) = A \int_{M_{Bm}}^{M_{BM}} \left[\int_{\mu_{min}}^{0.5} f(\mu) Q_{mi}(t - \tau_{m_2}) \psi(t - \tau_{m_2}) d\mu \right] \times \phi(m) dm$$

$$\sim R_{LIMS,i}(t) = (1 - A) \int_{M_{Bm}}^{M_{BM}} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{SNCC,i}(t) = \int_{M_{BM}}^{M_U} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{MHDJ,i}(t) = 0.01 \times Q_i \int_{M_{BM}}^{M_U} \psi(t - \tau_m) \phi(m) dm$$

$$\sim R_{NSM,i}(t) = \alpha k Q_i \int_{\tau_i}^{\min(t, \tau_H)} f_{NSM}(\tau) \Psi(t - \tau) d\tau$$

The full chemical evolution equations

Matteucci & Greggio (1986)

- Here i is the tracked isotope:
- $\frac{dM_{gas,i}(t)}{dt} = +I_i(t) - X_i(t)SFR(t) + R_i(t) - O_i(t)$
- $I_i(t) = X_{BBN,i}e^{-t/\tau_{eff}}$
- $SFR(t) \propto M_{gas,tot}^k(t)$
- $O_i(t) = X_i(t)[\omega SFR(t)]$
- $R_i(t) = \sum_{C}^{all-channels} R_{C,i}(t)$
- Where C are AGB, CCSN, SNIa, magnetohydrodynamic SN jets (MHDJ), NSM, Collapsars, etc.

$$\sim R_{AGB,i}(t) = \int_{M_L}^{M_{Bm}} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{SNIa,i}(t) = A \int_{M_{Bm}}^{M_{BM}} \left[\int_{\mu_{min}}^{0.5} f(\mu) Q_{mi}(t - \tau_{m_2}) \psi(t - \tau_{m_2}) d\mu \right] \times \phi(m) dm$$

$$\sim R_{LIMS,i}(t) = (1 - A) \int_{M_{Bm}}^{M_{BM}} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{SNCC,i}(t) = \int_{M_{BM}}^{M_U} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{MHDJ,i}(t) = 0.01 \times Q_i \int_{M_{BM}}^{M_U} \psi(t - \tau_m) \phi(m) dm$$

$$\sim R_{NSM,i}(t) = \alpha k Q_i \int_{\tau_i}^{\min(t, \tau_H)} f_{NSM}(\tau) \Psi(t - \tau) d\tau$$

NSMs in single stellar populations
follow a delayed time distribution

The full chemical evolution equations

Matteucci & Greggio (1986)

- Here i is the tracked isotope:
- $\frac{dM_{gas,i}(t)}{dt} = +I_i(t) - X_i(t)SFR(t) + R_i(t) - O_i(t)$
- $I_i(t) = X_{BBN,i}e^{-t/\tau_{eff}}$
- $SFR(t) \propto M_{gas,tot}^k(t)$
- $O_i(t) = X_i(t)[\omega SFR(t)]$
- $R_i(t) = \sum_{C}^{all-channels} R_{C,i}(t)$
- Where C are AGB, CCSN, SNIa, magnetohydrodynamic SN jets (MHDJ), NSM, Collapsars, etc.

$$\sim R_{AGB,i}(t) = \int_{M_L}^{M_{Bm}} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{SNIa,i}(t) = A \int_{M_{Bm}}^{M_{BM}} \left[\int_{\mu_{min}}^{0.5} f(\mu) Q_{mi}(t - \tau_{m_2}) \psi(t - \tau_{m_2}) d\mu \right] \times \phi(m) dm$$

$$\sim R_{LIMS,i}(t) = (1 - A) \int_{M_{Bm}}^{M_{BM}} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{SNCC,i}(t) = \int_{M_{BM}}^{M_U} \psi(t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm$$

$$\sim R_{MHDJ,i}(t) = 0.01 \times Q_i \int_{M_{BM}}^{M_U} \psi(t - \tau_m) \phi(m) dm$$

$$\sim R_{NSM,i}(t) = \alpha k Q_i \int_{\tau_i}^{\min(t, \tau_H)} f_{NSM}(\tau) \Psi(t - \tau) d\tau$$

Only ~1% of massive stars may have Strong enough magnetic fields For MHDJs

NSMs in single stellar populations follow a delayed time distribution