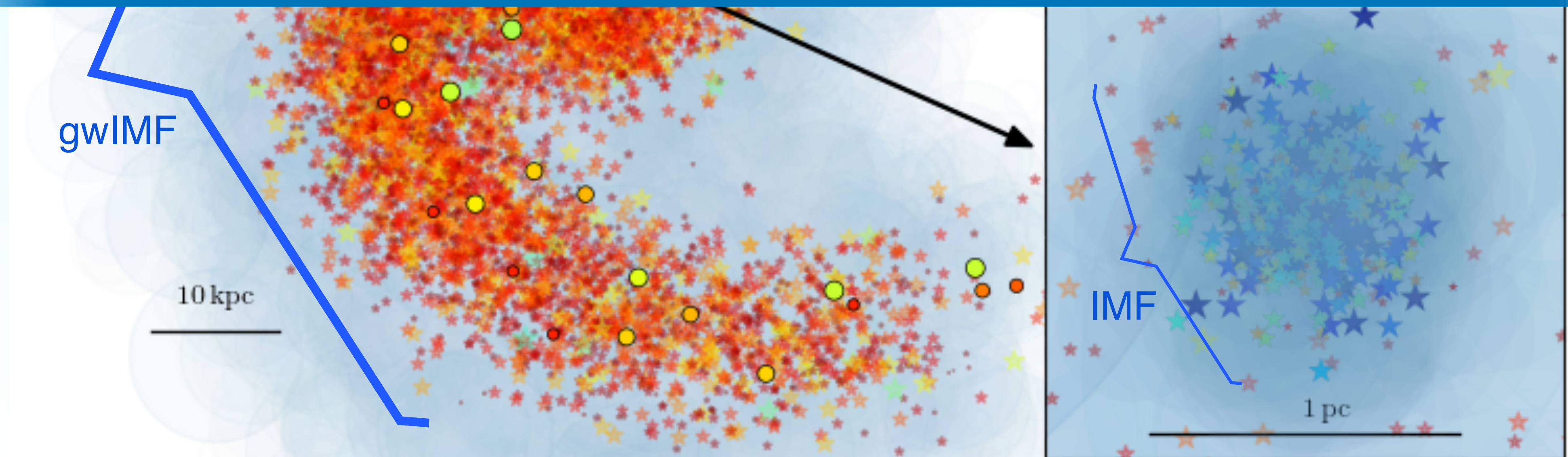


# The distribution of stars at their birth





# Brief GCE recap



# How are elements produced

## Galactic Chemical Evolution (GCE)

# Big Bang

(H<sup>1</sup>, H<sup>2</sup>, He<sup>3</sup>, He<sup>4</sup>, Li<sup>7</sup>)

1 IA																										18 VIIIA																					
1 H Hydrogen 1.008																2 IIA										2 He Helium 4.002602																					
3 Li Lithium 6.94		4 Be Beryllium 9.0121831																														13 IIIA		14 IVA		15 VA		16 VIA		17 VIIA							
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		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 (276)		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 <b>La</b> Lanthanum 138.90547	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.90766	60 <b>Nd</b> Neodymium 144.242	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92535	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93033	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.93422	70 <b>Yb</b> Ytterbium 173.045	71 <b>Lu</b> Lutetium 174.9668
89 <b>Ac</b> Actinium 227	90 <b>Th</b> Thorium 232.0377	91 <b>Pa</b> Protactinium 231.03688	92 <b>U</b> Uranium 238.02891	93 <b>Np</b> Neptunium 237.04817	94 <b>Pu</b> Plutonium 244.0642	95 <b>Am</b> Americium 243.06138	96 <b>Cm</b> Curium 247.07035	97 <b>Bk</b> Berkelium 247.07035	98 <b>Cf</b> Californium 251.0833	99 <b>Es</b> Einsteinium 252.0833	100 <b>Fm</b> Fermium 257.10528	101 <b>Md</b> Mendelevium 258.10528	102 <b>No</b> Nobelium 259.10528	103 <b>Lr</b> Lawrencium 262.10528

# Stellar-born sites (C through U)

# Cosmic rays (Be and B)



# How are elements produced

## Galactic Chemical Evolution (GCE)

# Big Bang

(H<sup>1</sup>, H<sup>2</sup>, He<sup>3</sup>, He<sup>4</sup>, Li<sup>7</sup>)

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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					
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37 Rb Rubidium 85.4678		38 Sr Strontium 87.62												47 Ag Silver 107.8682		48 Cd Cadmium 112.414		49 In Indium 114.818		50 Sn Tin 118.710		51 Sb Antimony 121.757		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										63 Bi Bismuth 208.98040		64 Po Polonium (209)		65 At Astatine (210)		66 Rn Radon (222)									
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# Stellar-born sites (C through U)

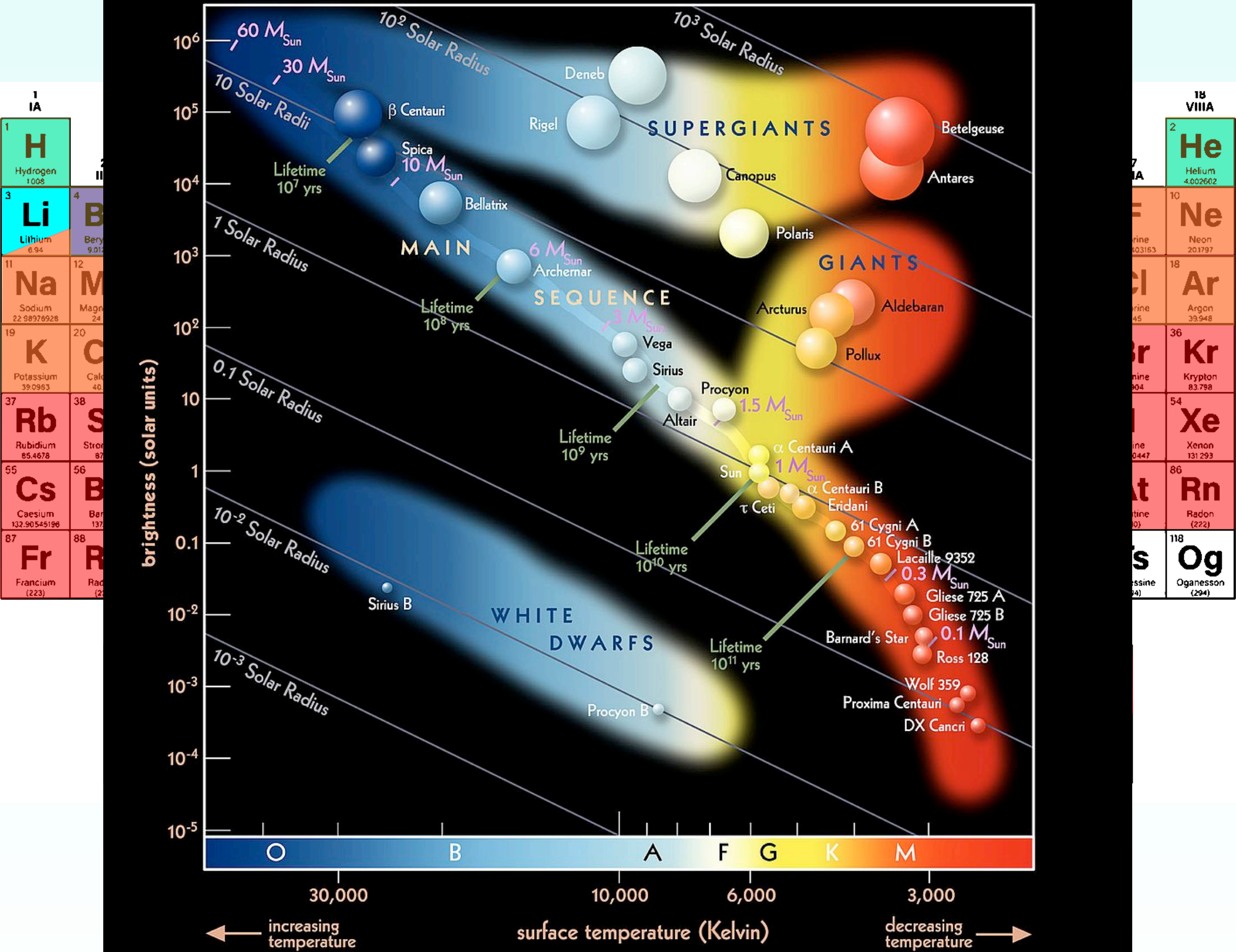
# Cosmic rays (Be and B)



# How are elements produced

## Galactic Chemical Evolution (GCE)

Pearson Education, Addison Wesley



Big Bang

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



Stellar-born sites

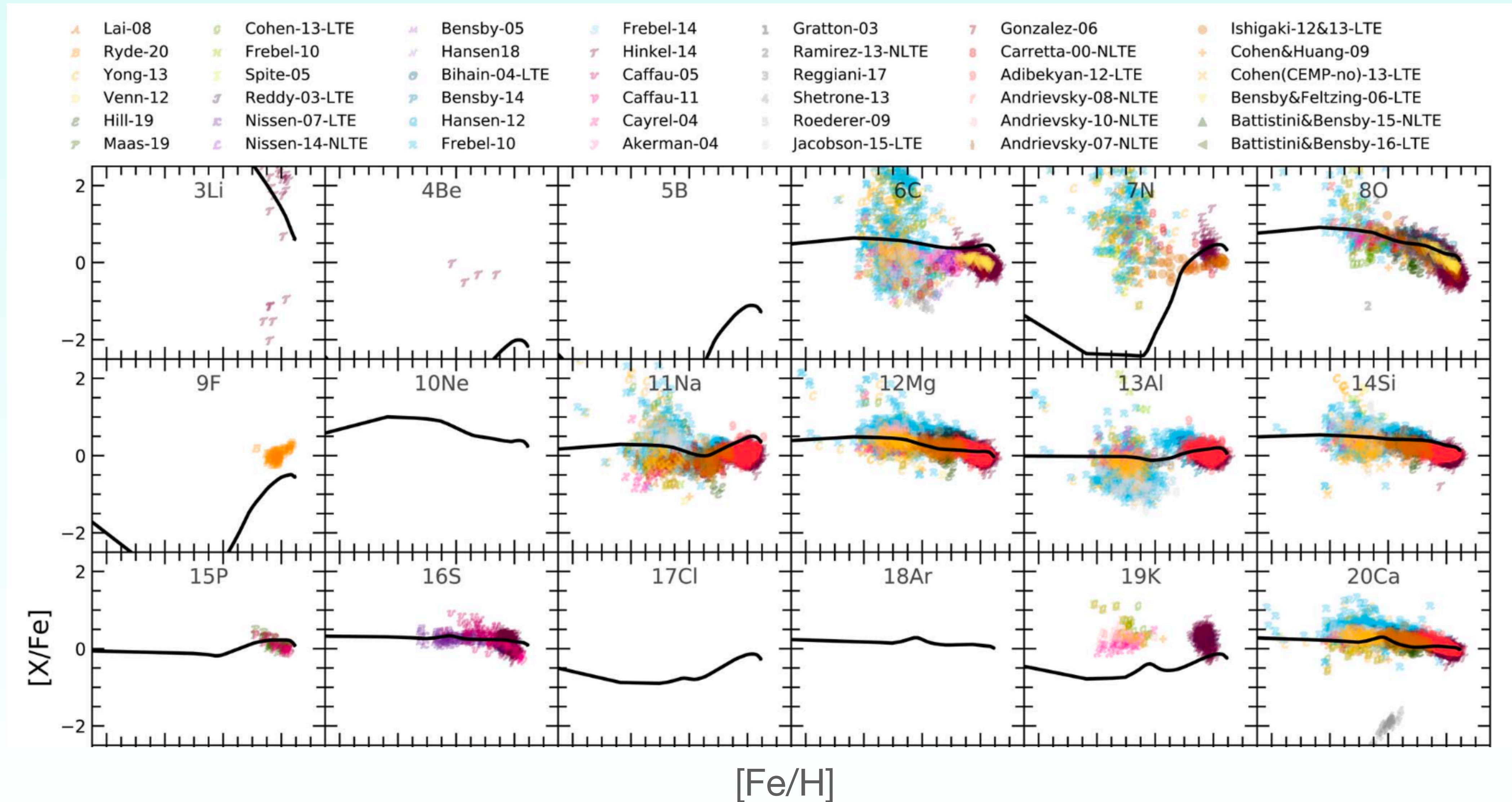
(C through U)

Cosmic rays

(Be and B)

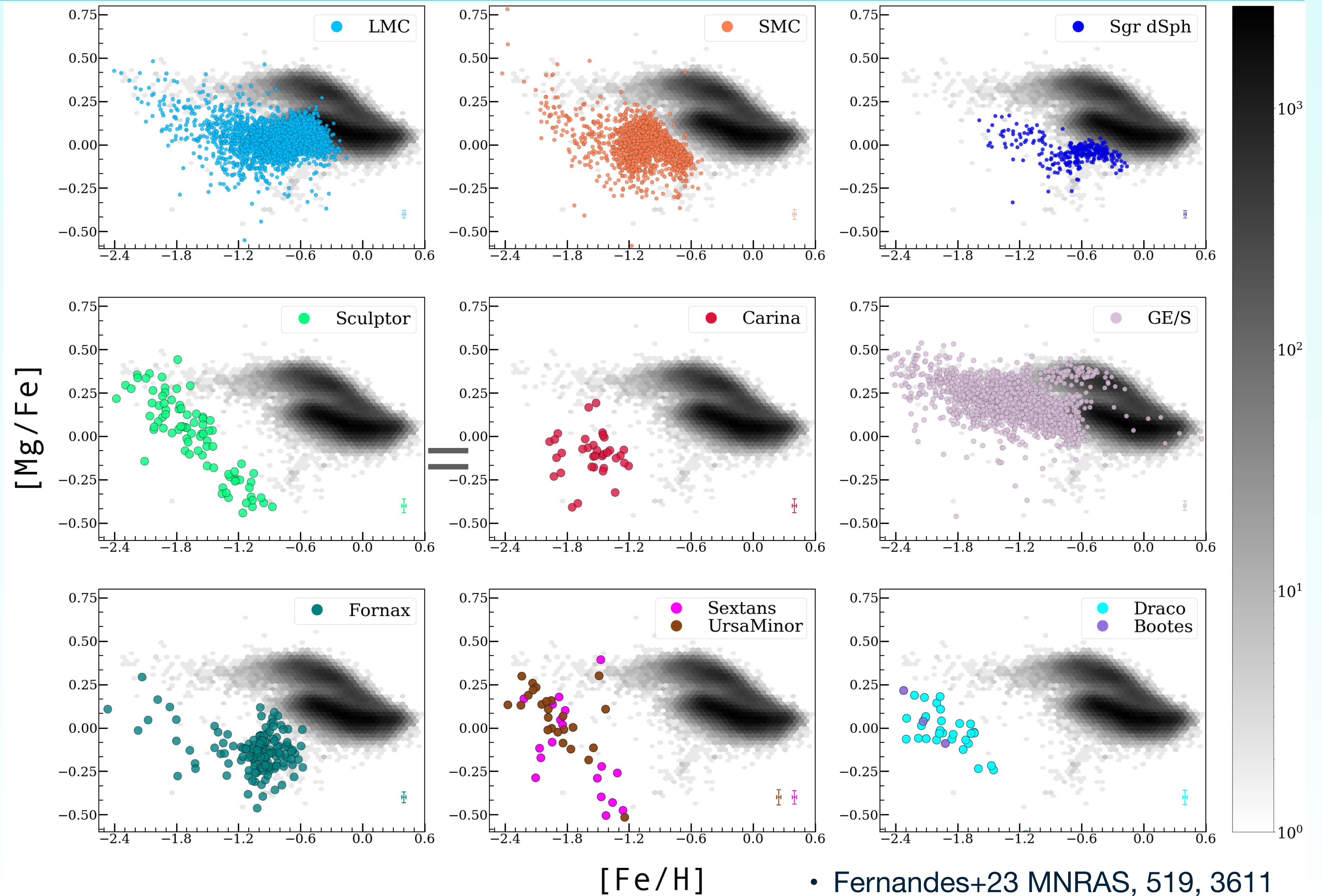


# Closed box models are already remarkably powerful





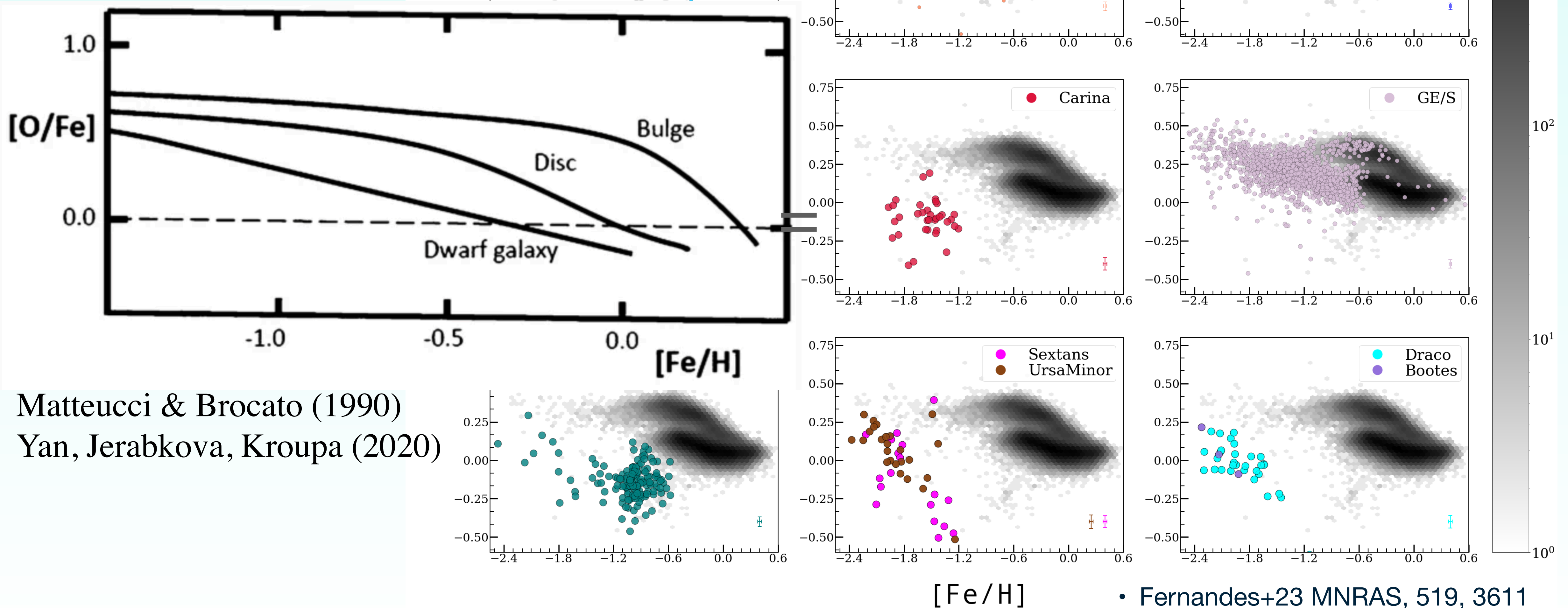
# Alpha-element enrichment in the Milky Way satellites



• Fernandes+23 MNRAS, 519, 3611



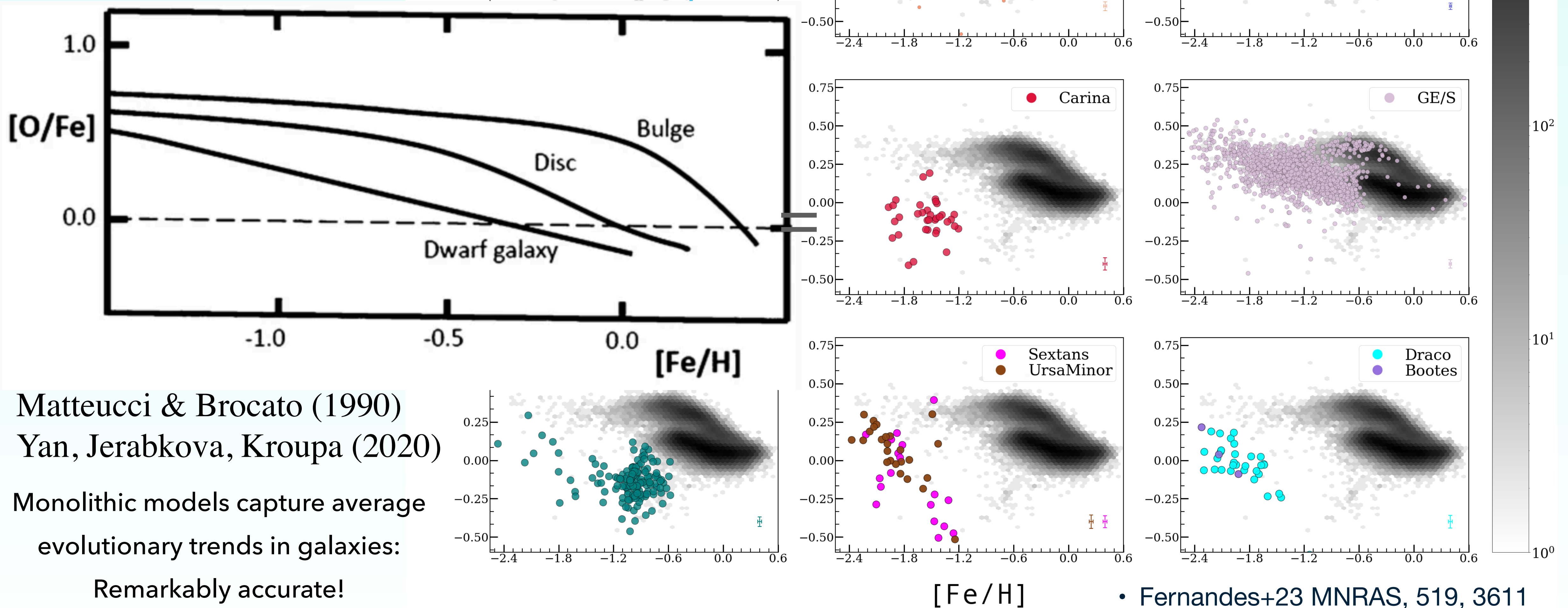
# Alpha-element enrichment in the Milky Way satellites



Matteucci & Brocato (1990)  
Yan, Jerabkova, Kroupa (2020)



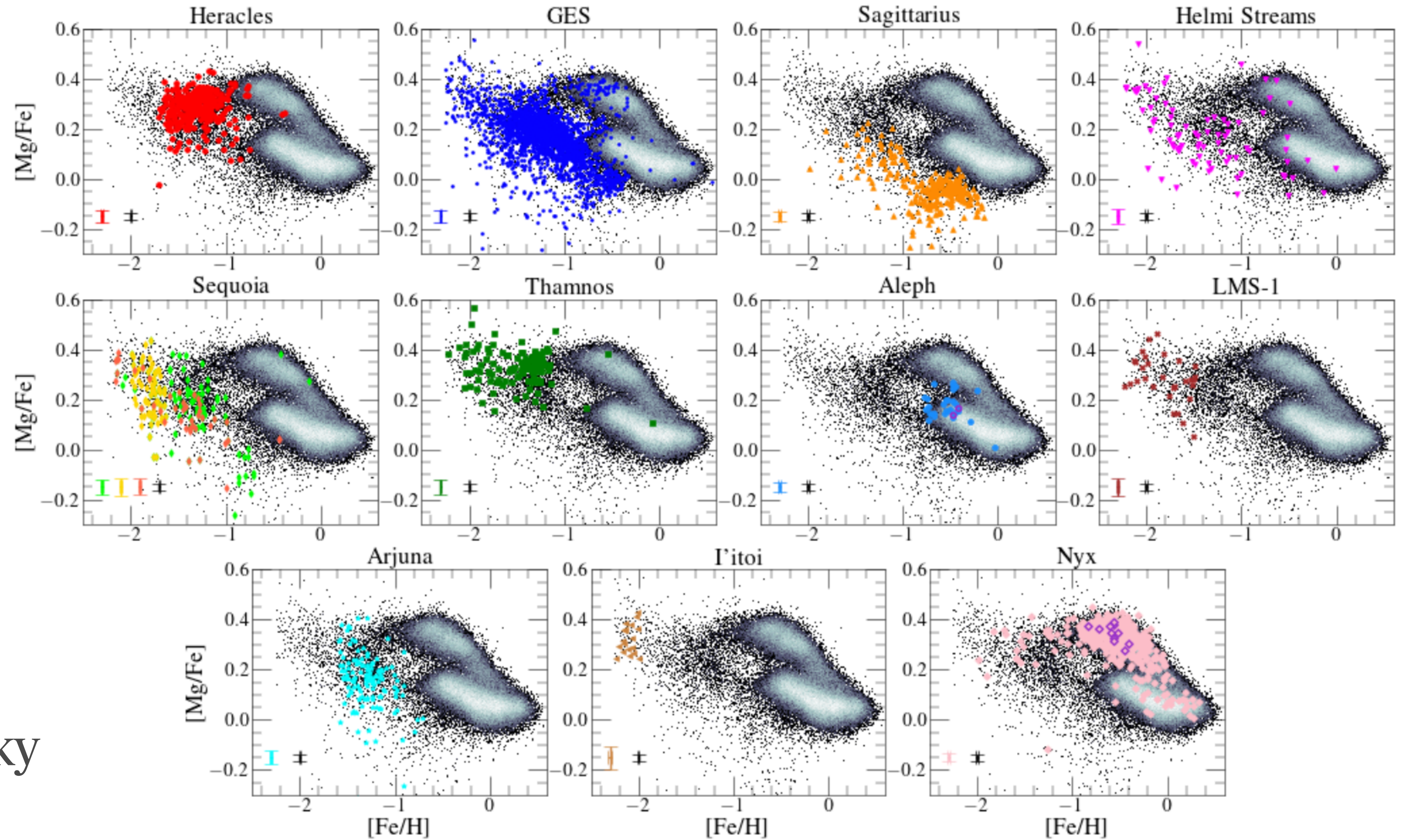
# Alpha-element enrichment in the Milky Way satellites





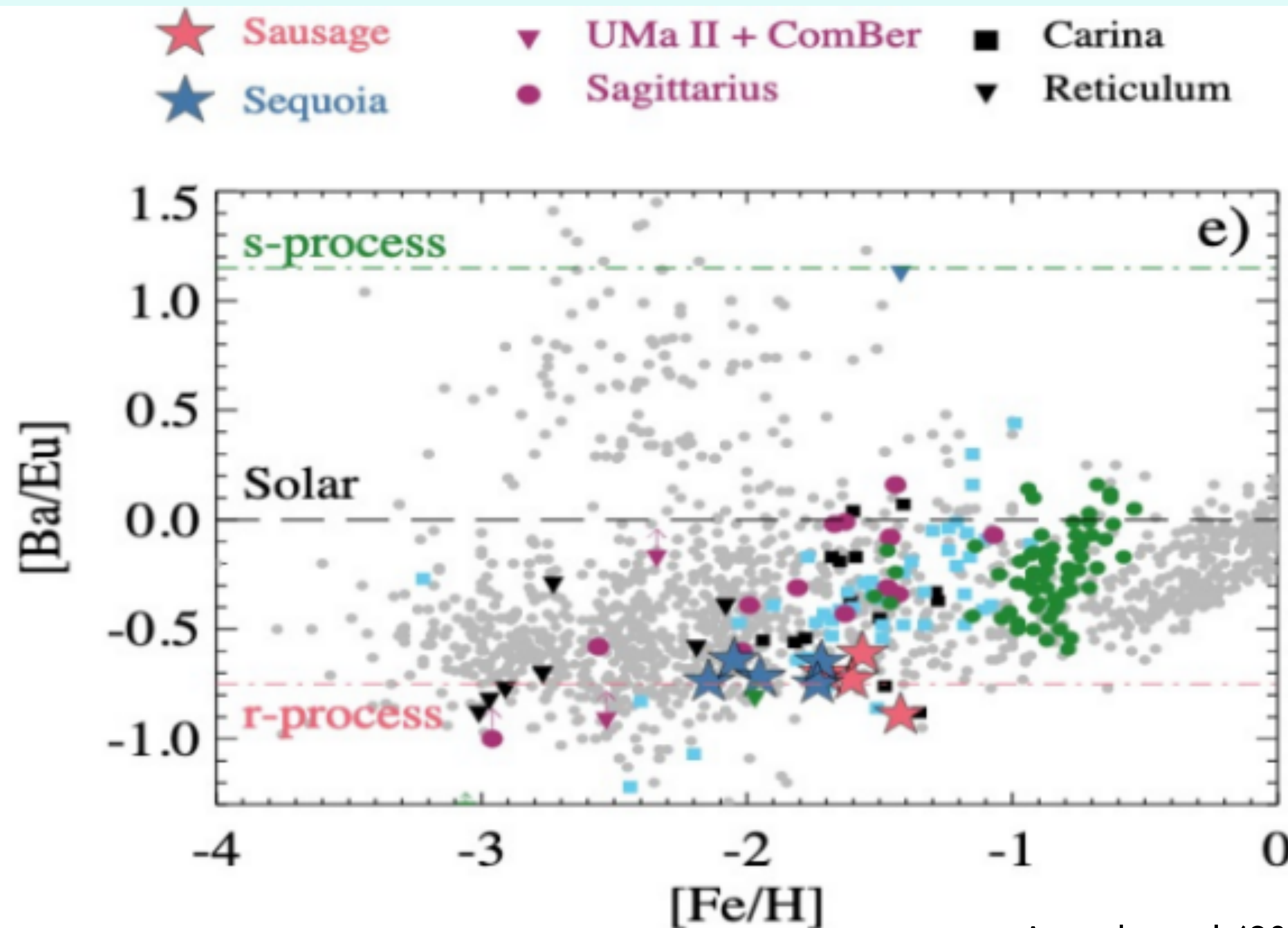
- Horta+22 APOGEE

Alpha-element  
enrichment in the Milky  
Way halo and disks





# Observational Evidence



Different colors represent different galaxies (or streams, etc.) and consequently different morphologies in galaxy modeling.

The ratio of s-process elements vs Eu (r-process element) informs on whether a dwarf galaxy or substructure is s-process or r-process enhanced.

Aguado et al. (2021)



# Big questions

CONNECTING QUARKS WITH THE COSMOS: 11 SCIENCE QUESTIONS FOR THE NEW CENTURY, NATIONAL ACADEMIES PRESS (2003)

1. What is Dark Matter?
2. What is the Nature of Dark Energy?
3. How did the Universe begin?
4. Did Einstein have the last word on Gravity?
5. What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
6. How do cosmic accelerators work and what are they accelerating?
7. Are protons unstable?
8. What are the new states of matter at exceedingly high Density and Temperature?
9. Are there additional space-time dimensions?
- 10. How were the elements from Iron to Uranium made?**
11. Is a new theory of matter needed at the highest energies?

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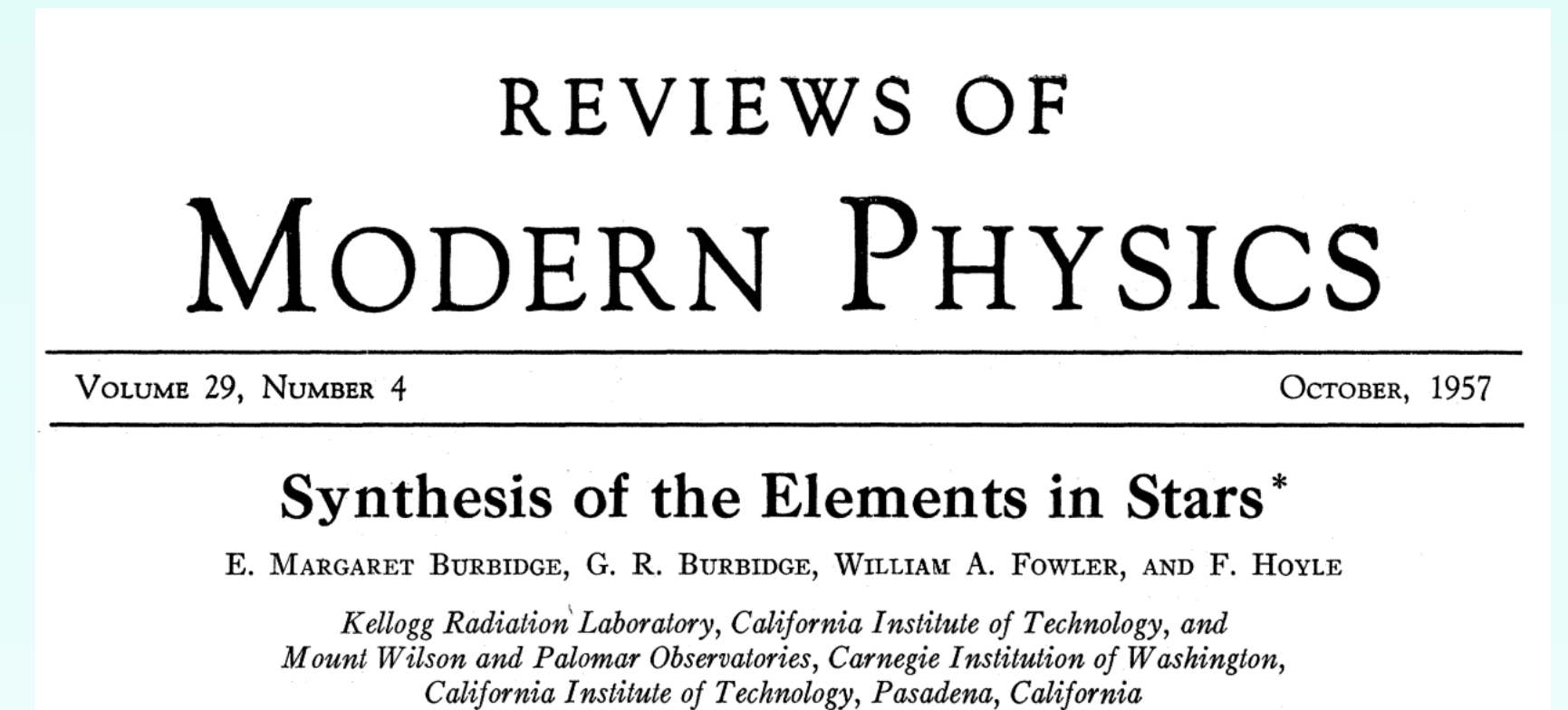
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**Burbidge+57 (B2FH)**

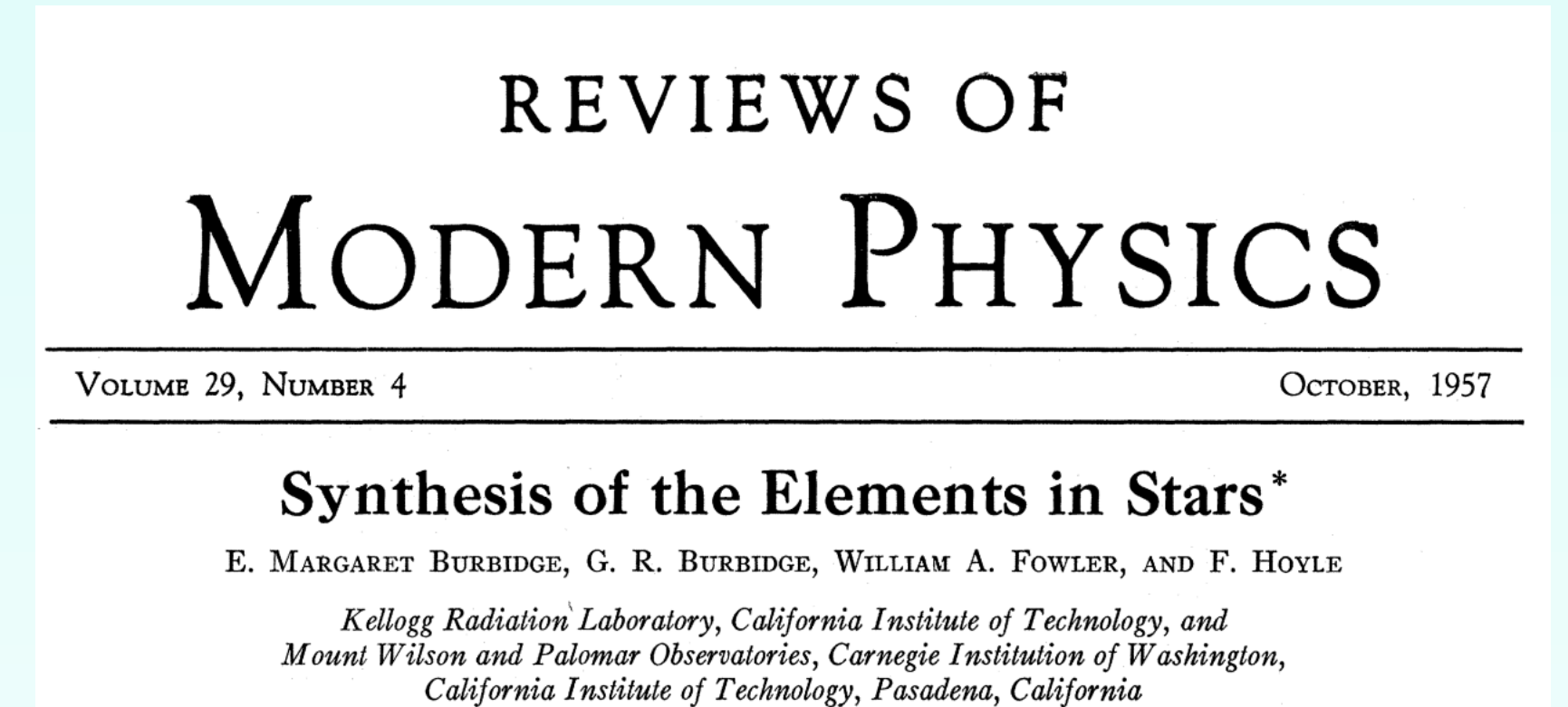
# Big questions

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Neutron Star Mergers (NSM):

Very hot topic since the first NS-NS merger event  
observed in 2017 by LIGO



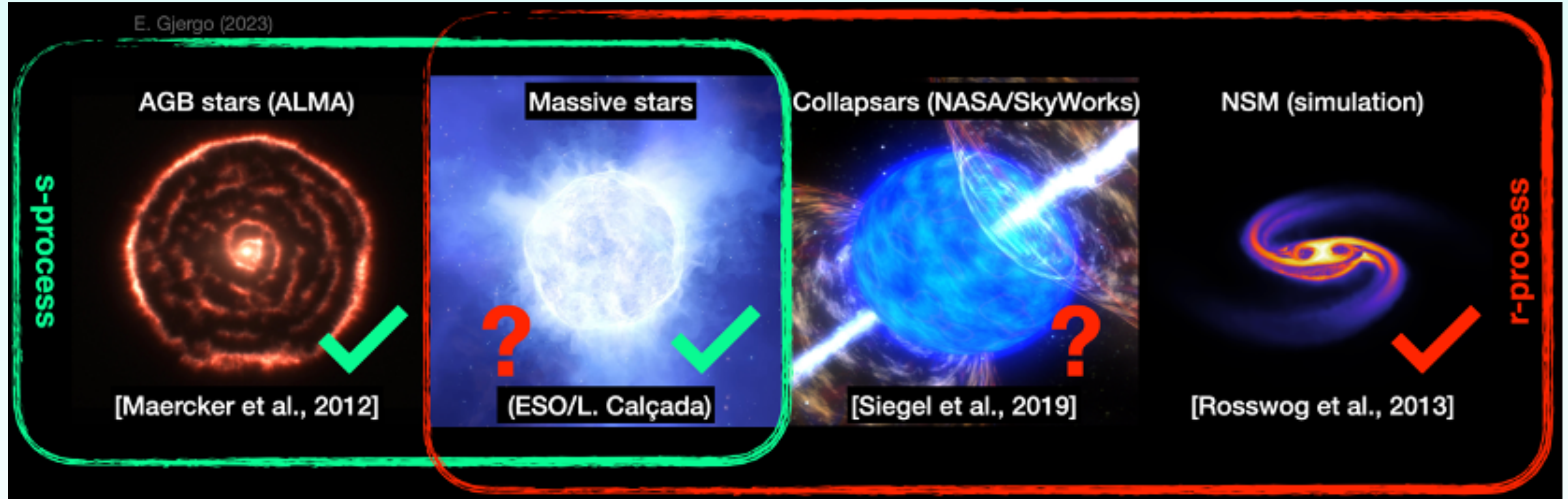
## Burbidge+57 (B2FH)



CREDIT: NASA/Goddard Space Flight Center



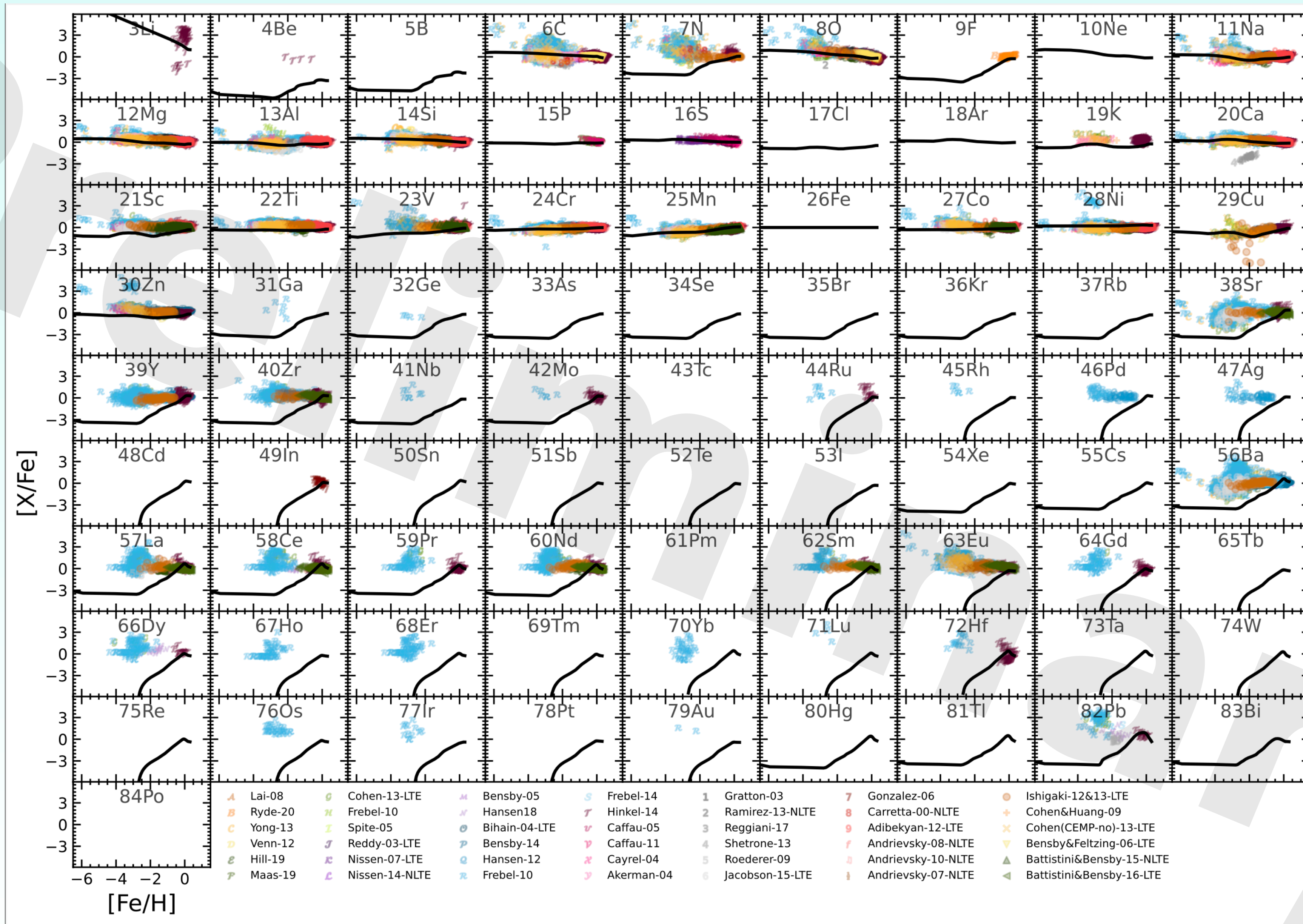
# Neutron-capture astrophysical sites: Associated with stellar progenitors of different masses



- **s-processes** result from successive
  - thermal pulses of AGB stars (e.g., Cristallo+15)
  - Core-collapse SNa (e.g., Limongi & Chieffi, 2018)
- **r-processes** sites are still uncertain:
  - Neutron star mergers (verified! Watson+19)
  - Magnetohydrodynamic jets ? (Winteler+12)
  - Collapsars ? (e.g., Shibagaki+16, Siegel+19)



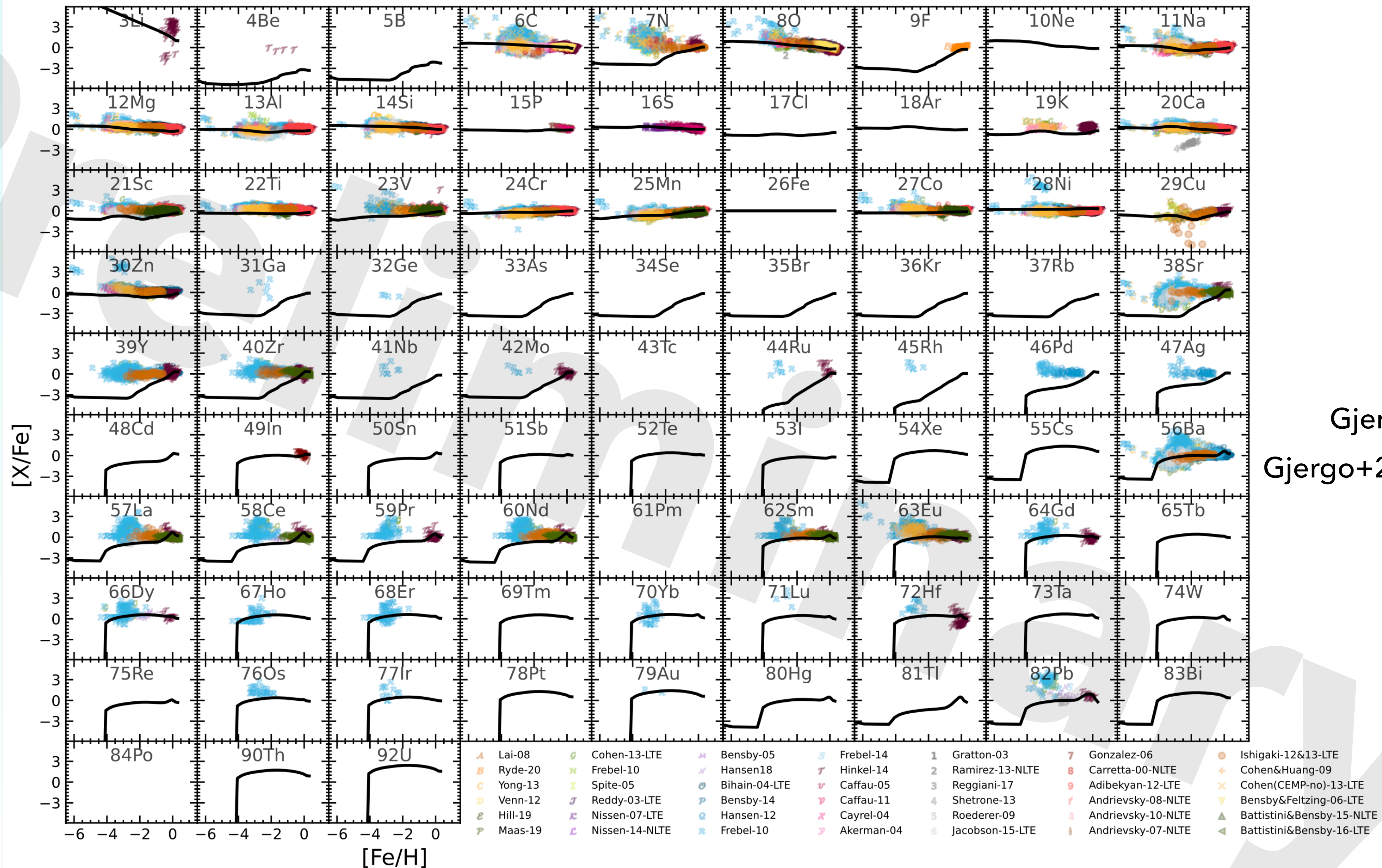
In the Milky Way  
With s-processes



Gjergo+23  
Gjergo+26b, in prep.



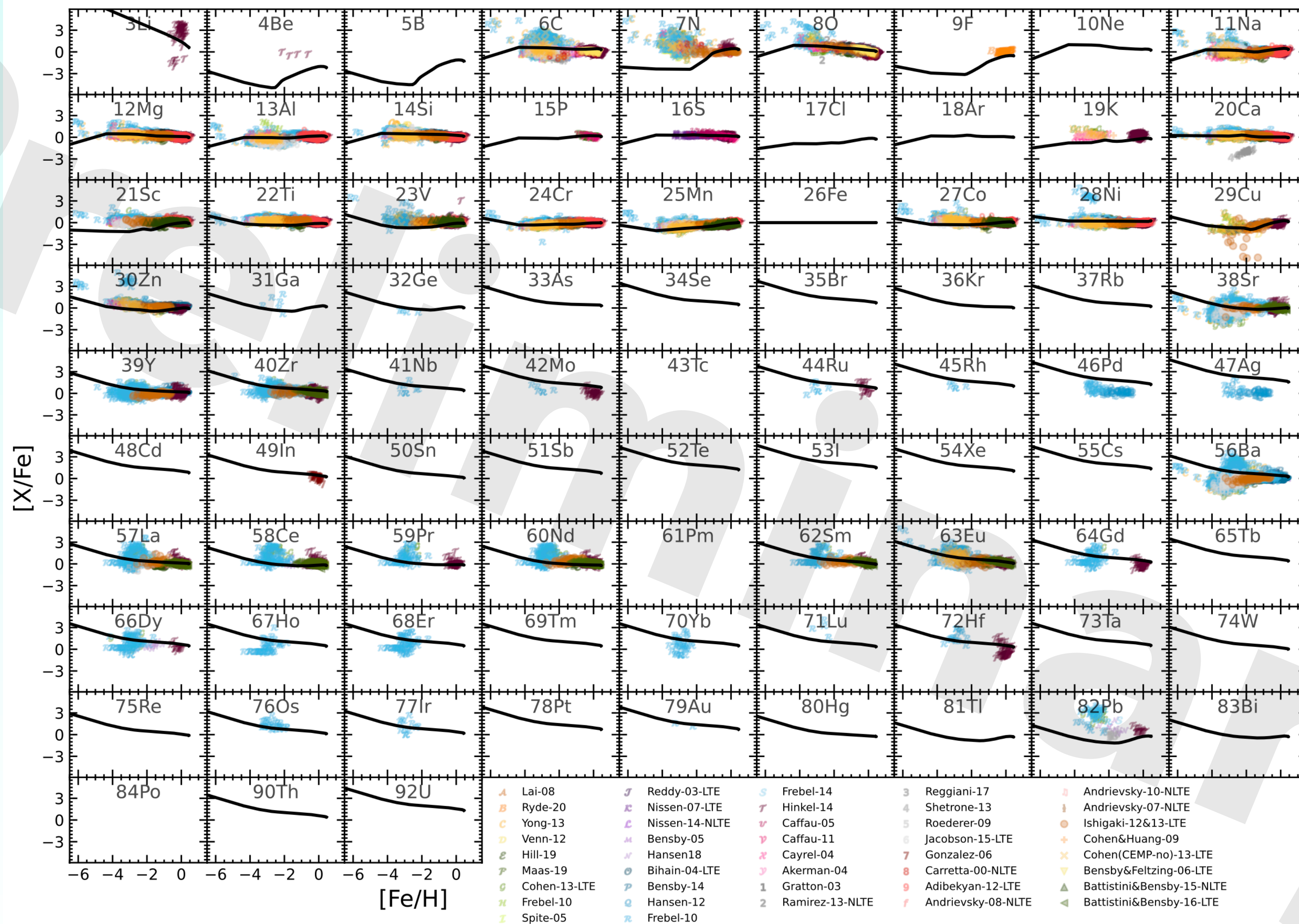
In the Milky Way  
With NSM



Gjergo+23  
Gjergo+26b, in prep.



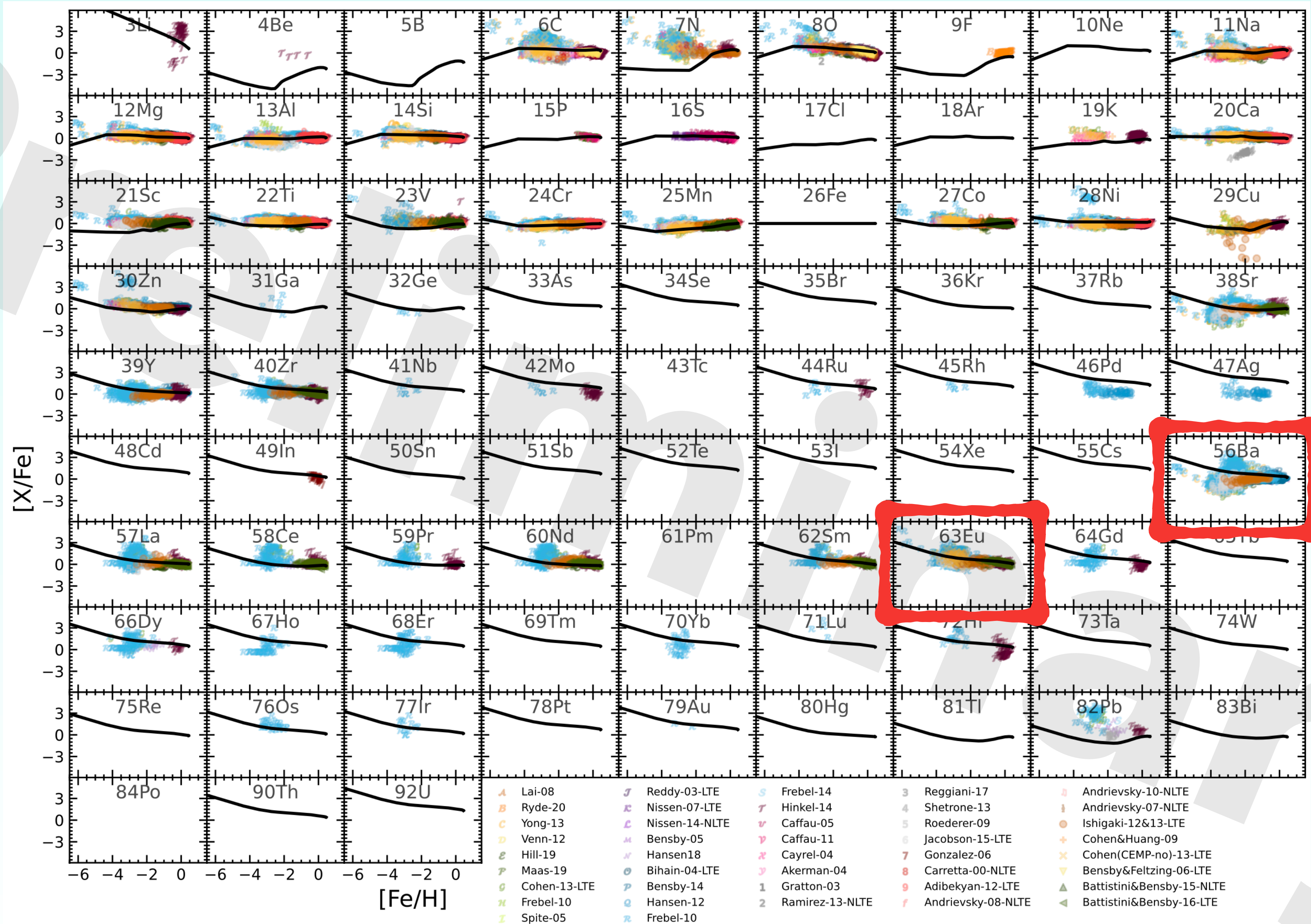
In the Milky Way  
With collapsars  
and/or magneto-  
rotational SNaE



Gjergo+23  
Gjergo+26b, in prep.



In the Milky Way  
With collapsars  
and/or magneto-  
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Gjergo+23  
Gjergo+26b, in prep.

GCE of the Periodic Table of Elements in GalCEM

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
1	H																	He		
2	Li	Be											B	C	N	O	F	Ne		
3	Na	Mg											Al	Si	P	S	Cl	Ar		
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe		
6	Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		
7	Fr	Ra																		
8			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu			
9			Ac	Th	Pa	U														

light

spallation

CNO, F

alpha

odd-Z

pre-iron-peak

iron-peak

post-iron-peak

radioactive

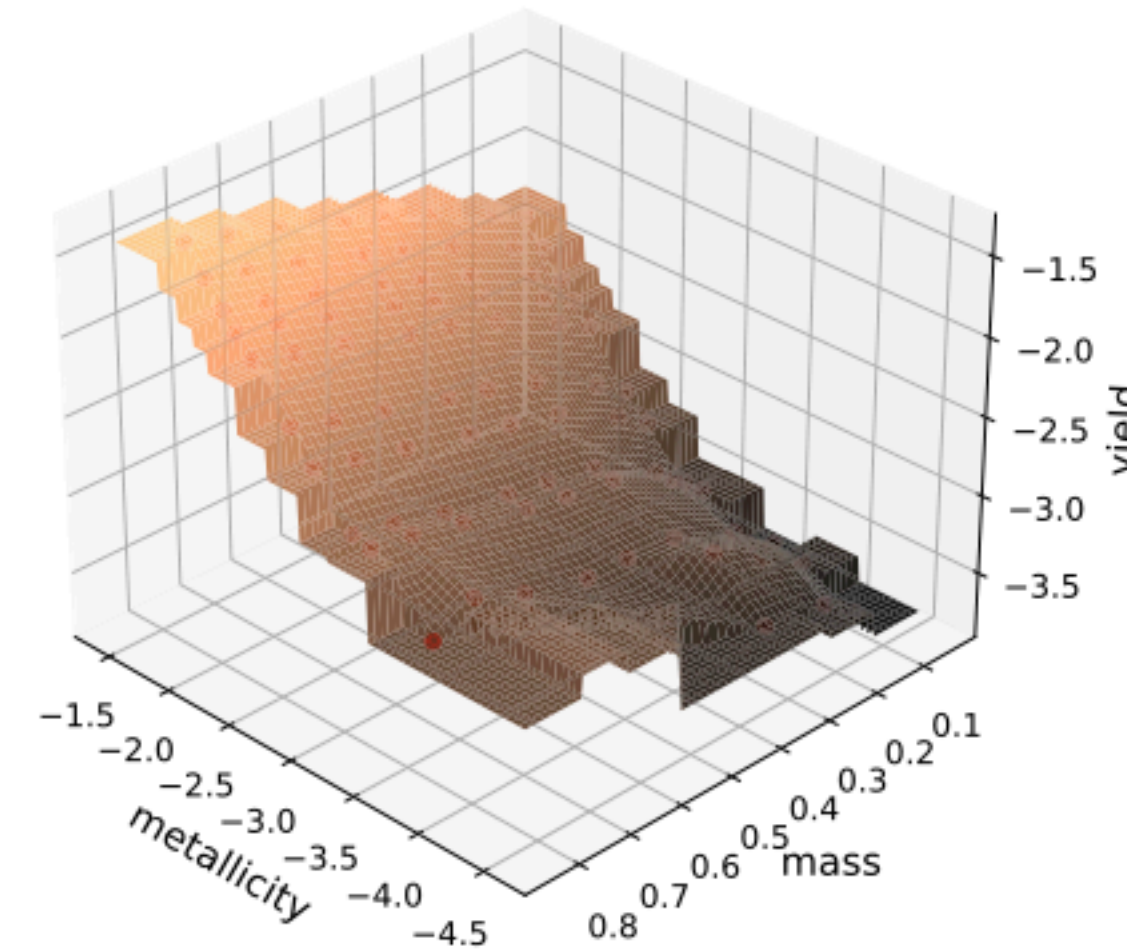
neutron capture



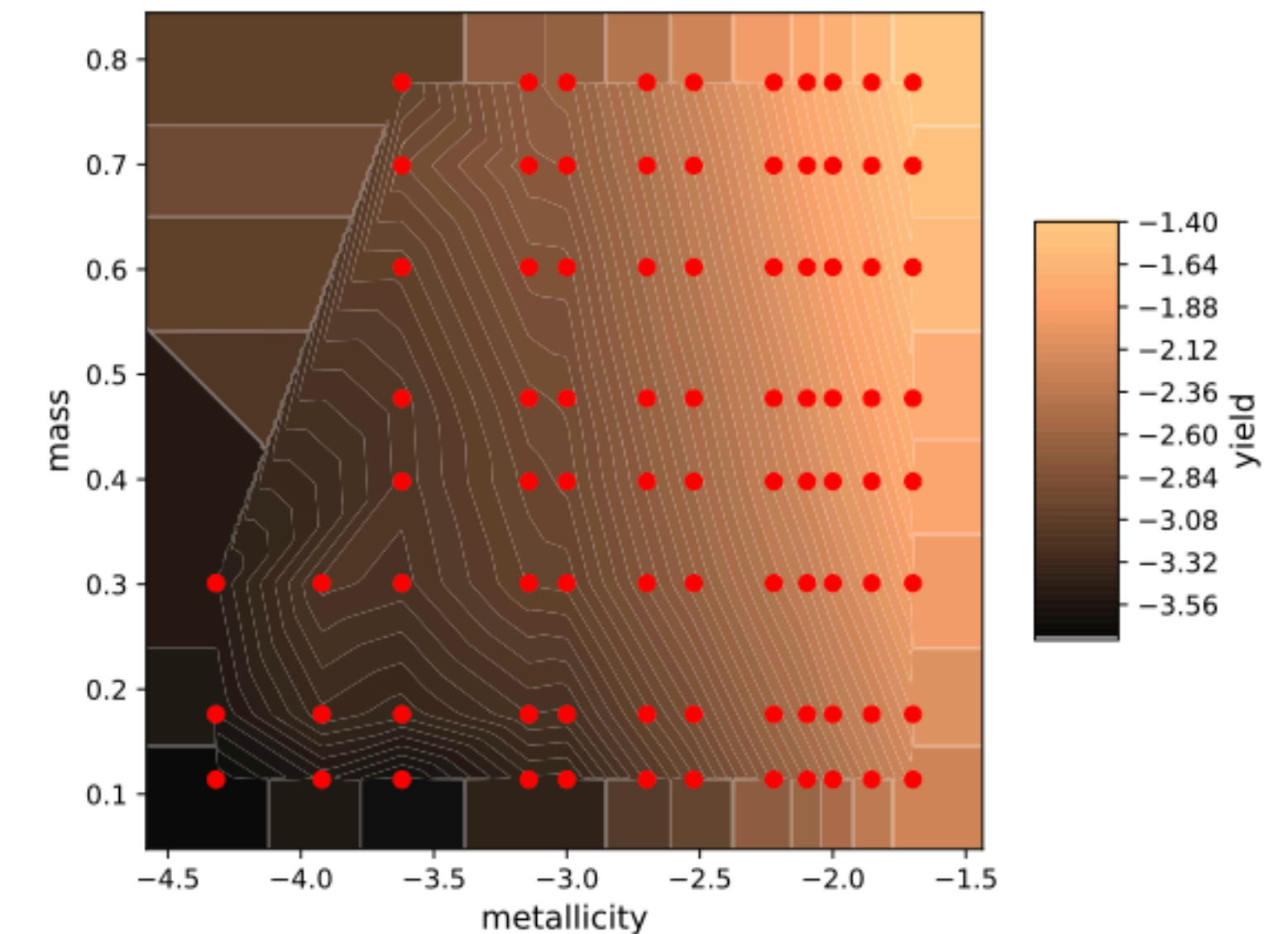
# GCE isotope evolution with GalCEM

- It adapts to the # of isotopes included in all the selected yield tables.
- Unlike other public codes (VICE, ChemPy, NuPyCEE), it uses full yield tabulations and does not average over the IMF
- It is a fast code (x50 then equivalent private code) because:
  - It computes the yield interpolation in pre-processing
  - It uses efficient integration and differentiation methods
- <https://github.com/egjergo/GalCEM>

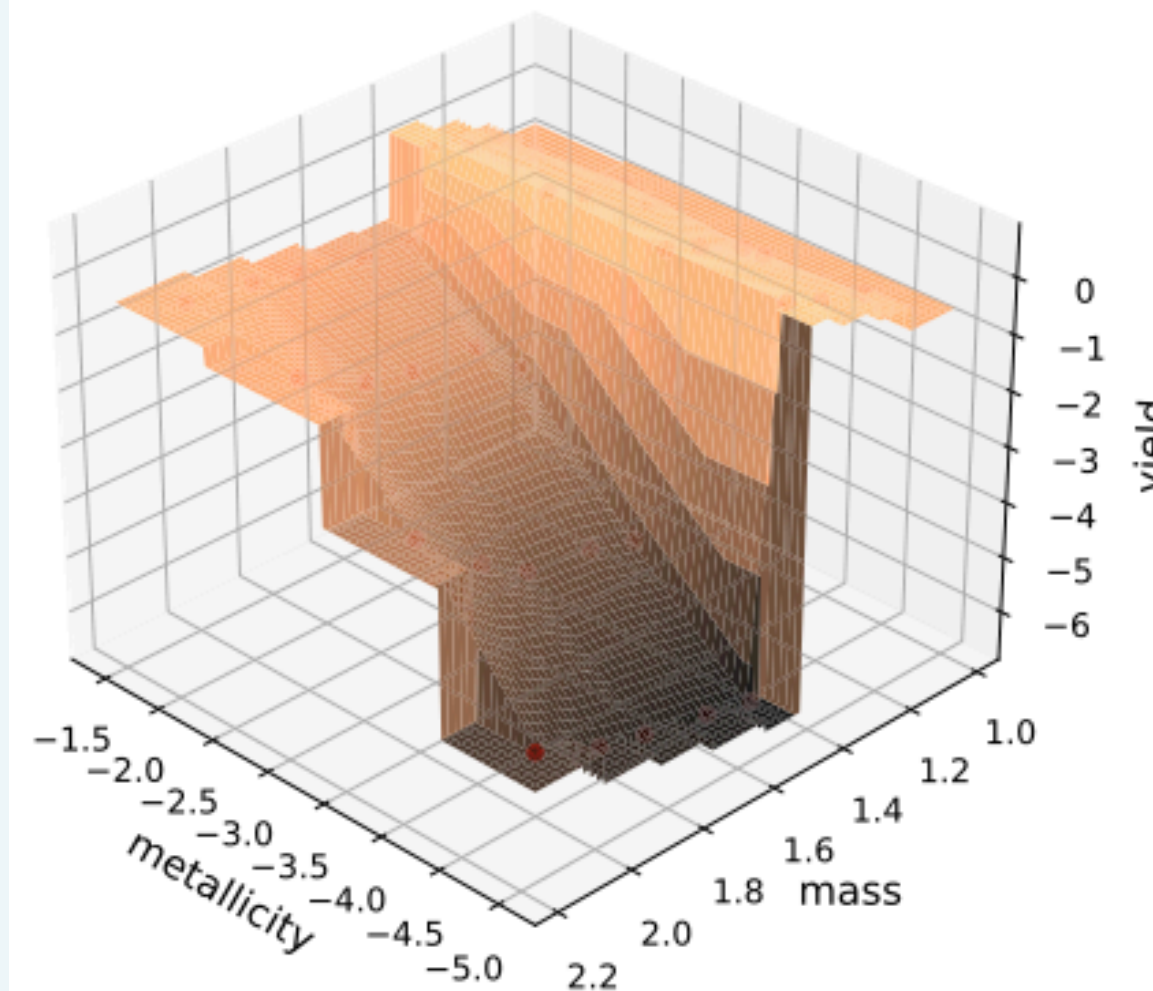
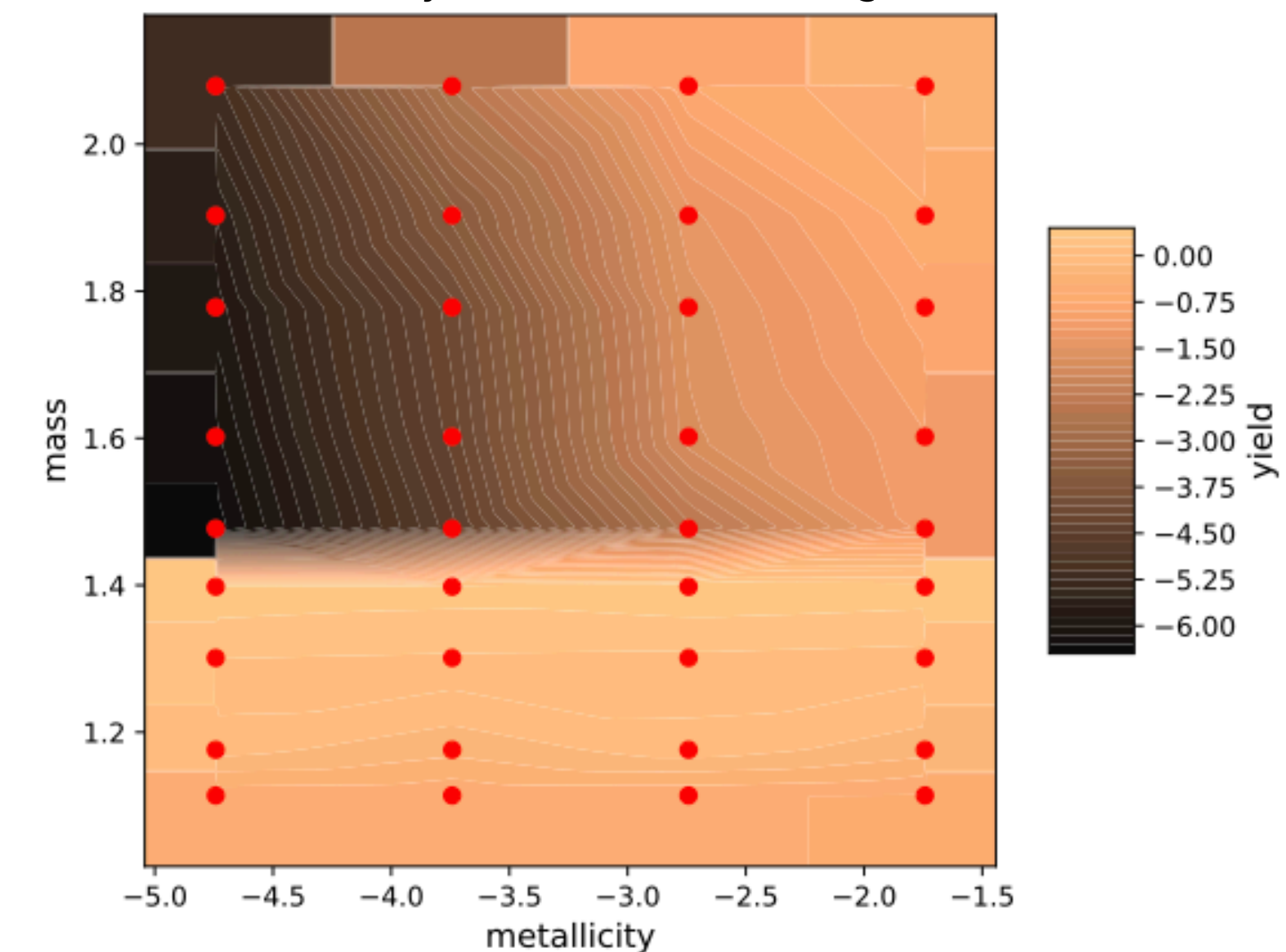
Gjergo+23, ApJS



AGB yields for 12C (Cristallo+15)



SNII yields for 16O (Limongi & Chieffi, 2018)

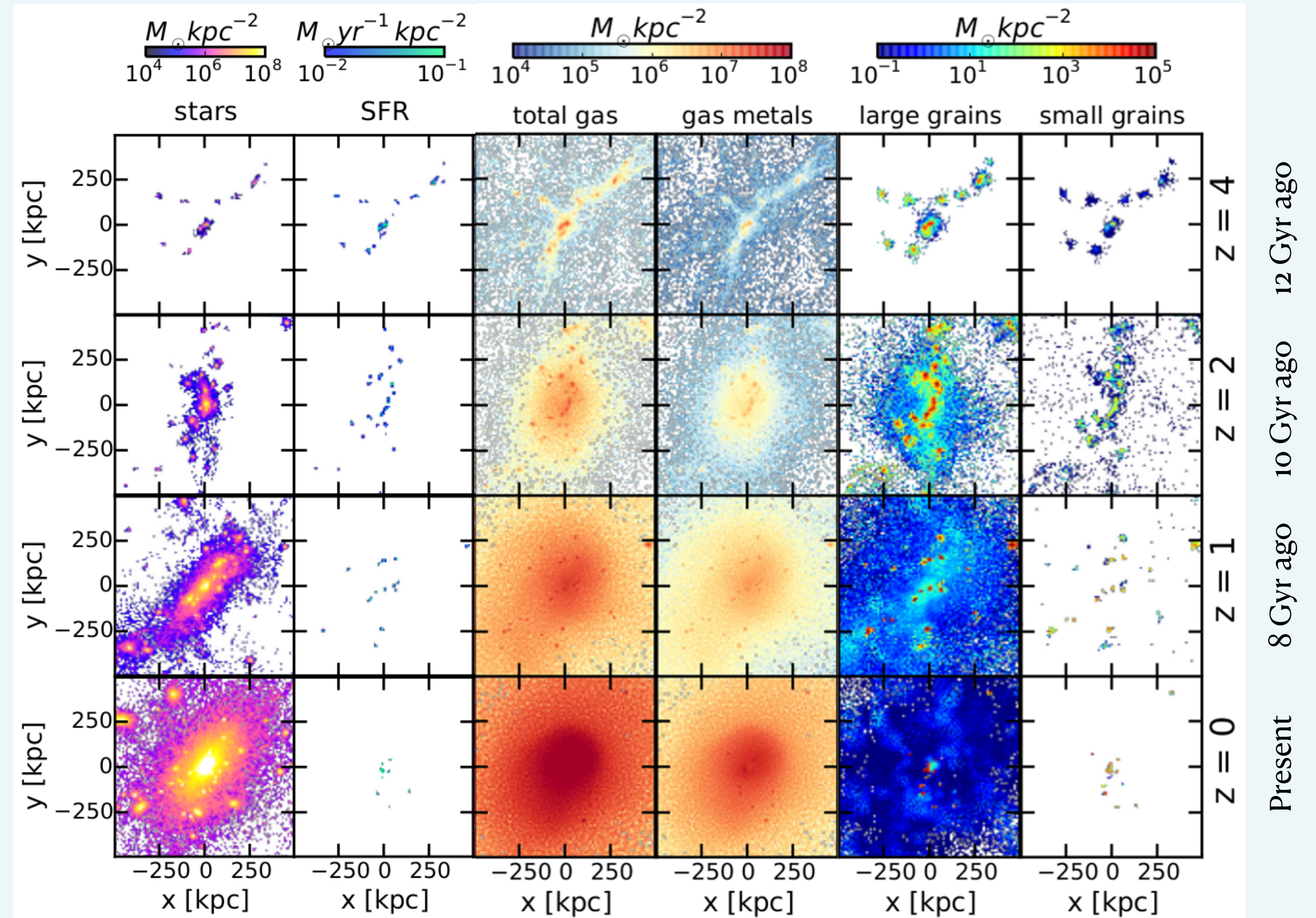


# One-zone GCE vs Cosmo Sim



# One-zone GCE vs Cosmo Sim

- 10-15 isotopes
- 12-24 hours for low/mid resolution
- Coarse stellar population grid
- Full dynamics

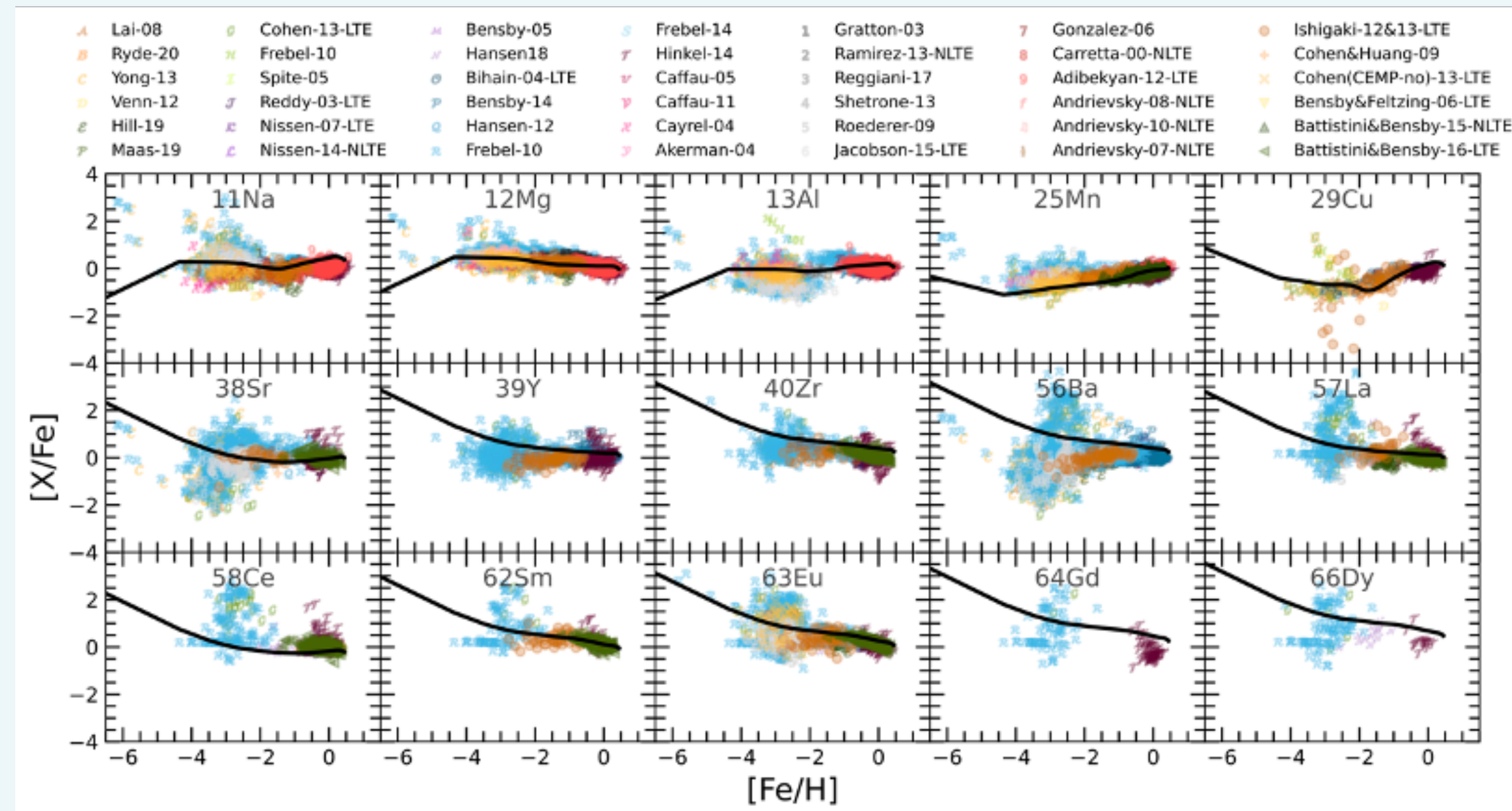


Gjergo+18



# One-zone GCE vs Cosmo Sim

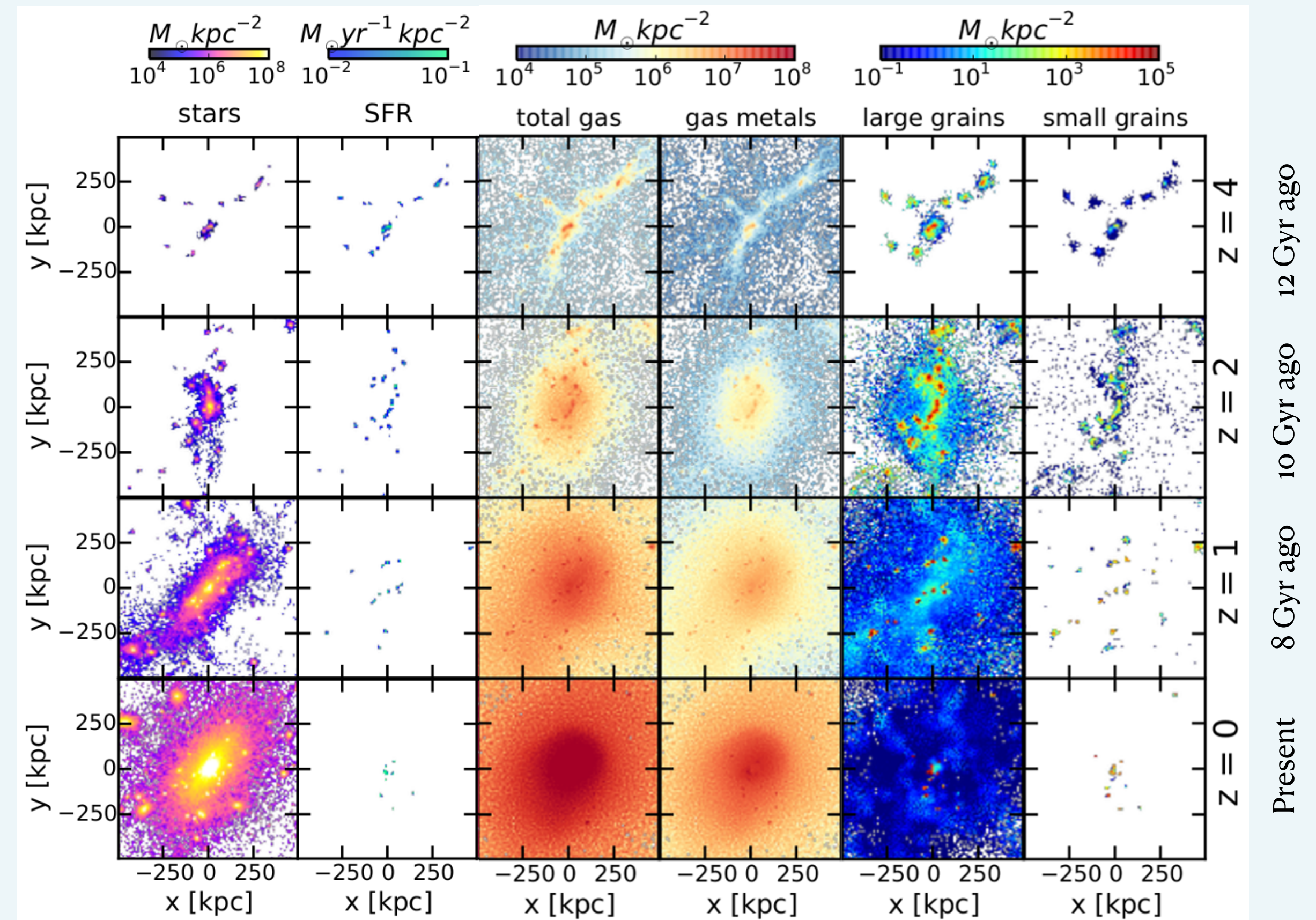
- 10-15 isotopes
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Gjergo+23a, ApJS

+

Gjergo et al., in prep.



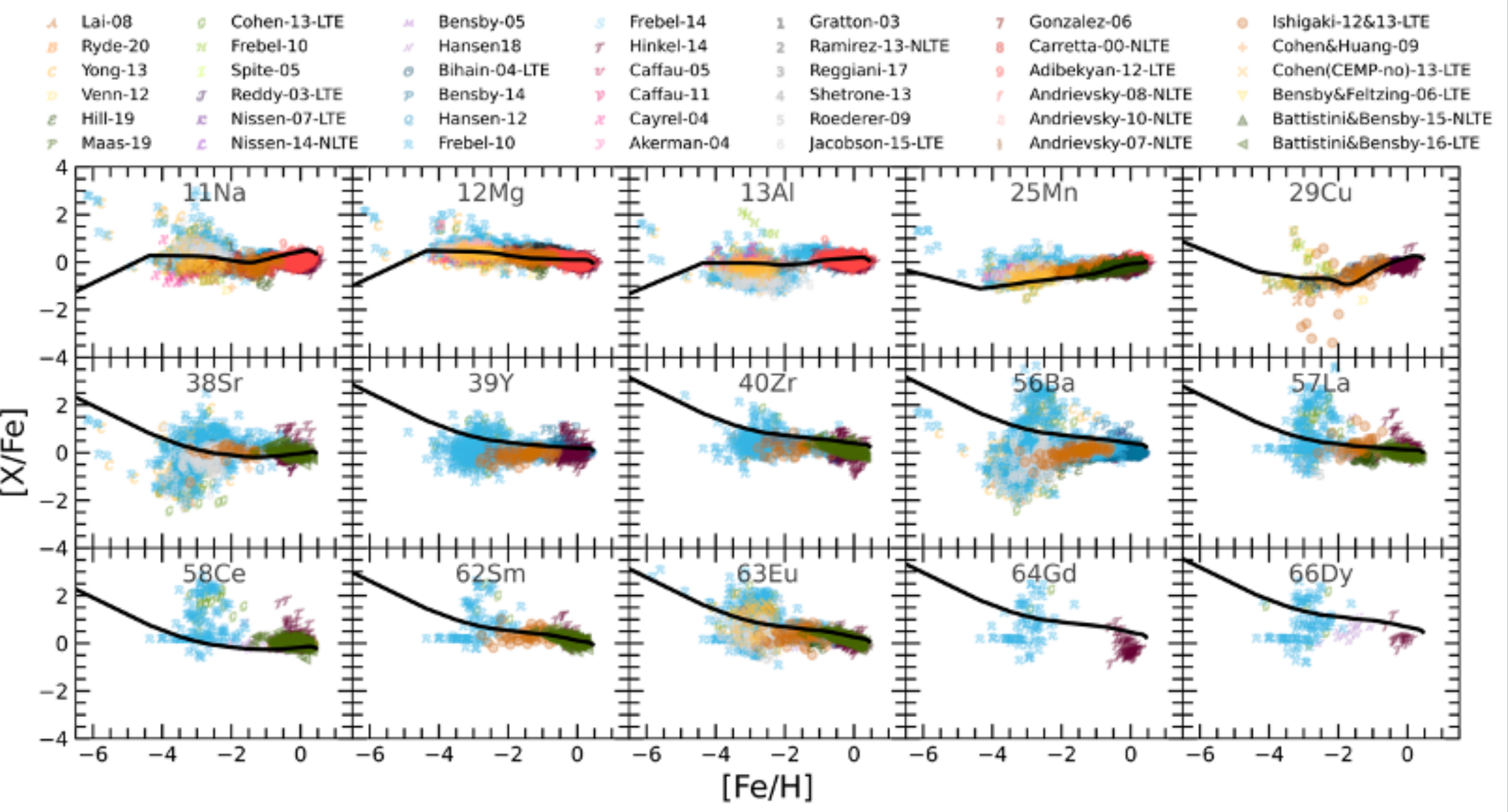
Gjergo+18



# One-zone GCE vs Cosmo Sim

- 252 stable isotopes - approx 500 radioactive isotopes
- A few minutes
- Fine stellar population grid
- Analytical galaxy formation

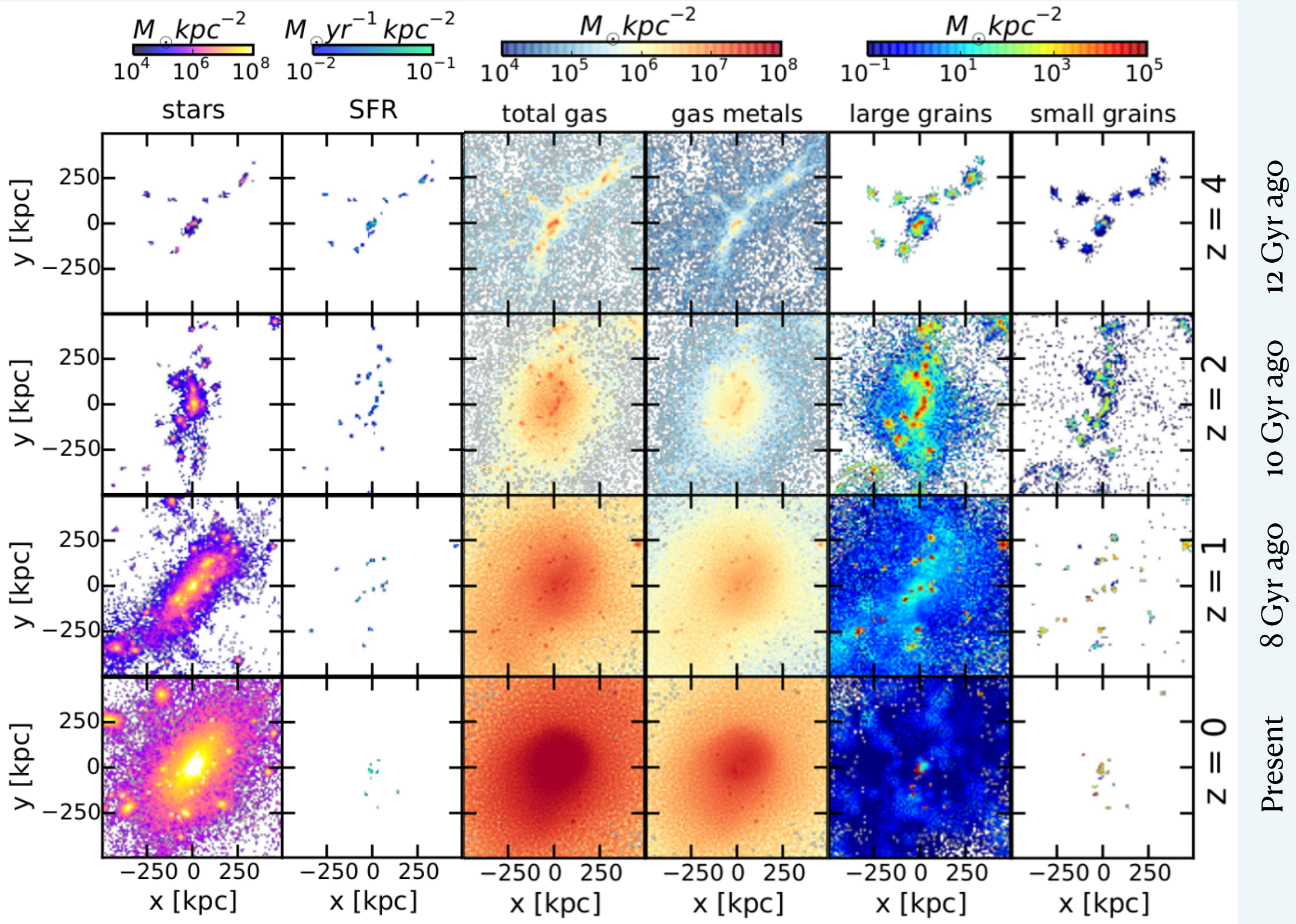
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Gjergo+18



# Take-home messages



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- **Where it is incomplete:** Key uncertainties and open questions remain (Lecture 3)

# 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

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

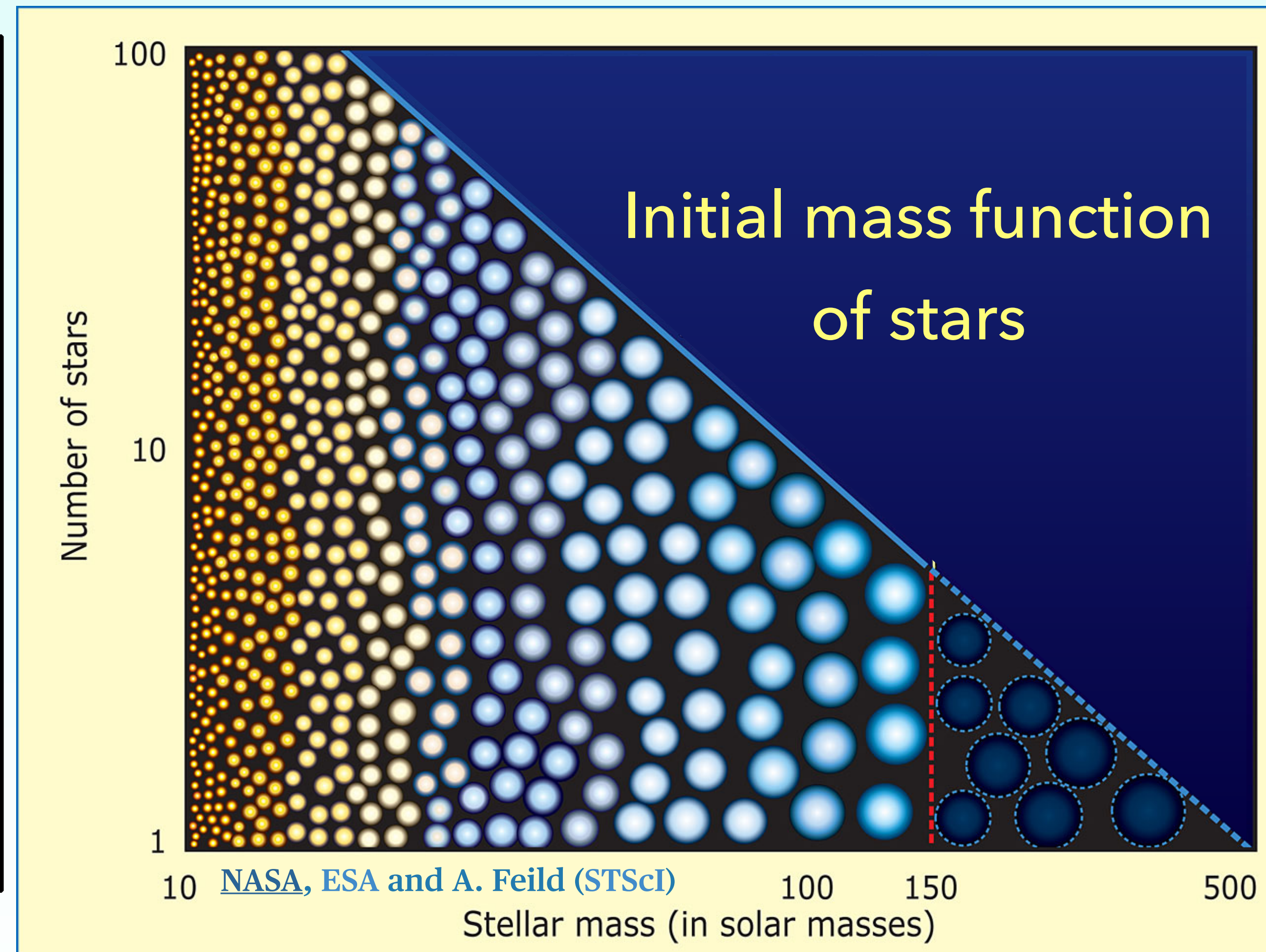
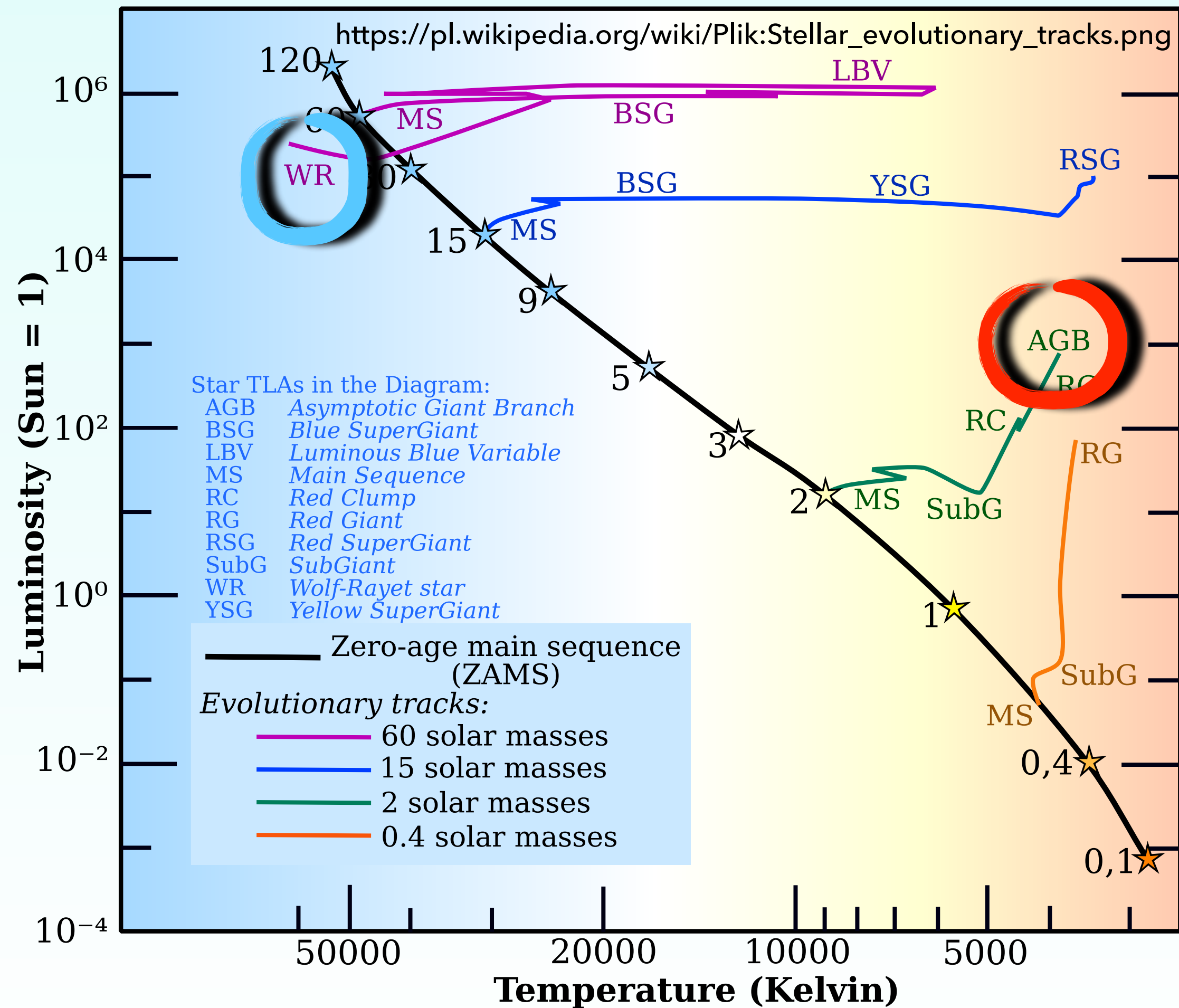
in reconstructing the  
Birthrate function  $\mathcal{B}$

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



# How are elements produced

## Galactic Chemical Evolution (GCE)

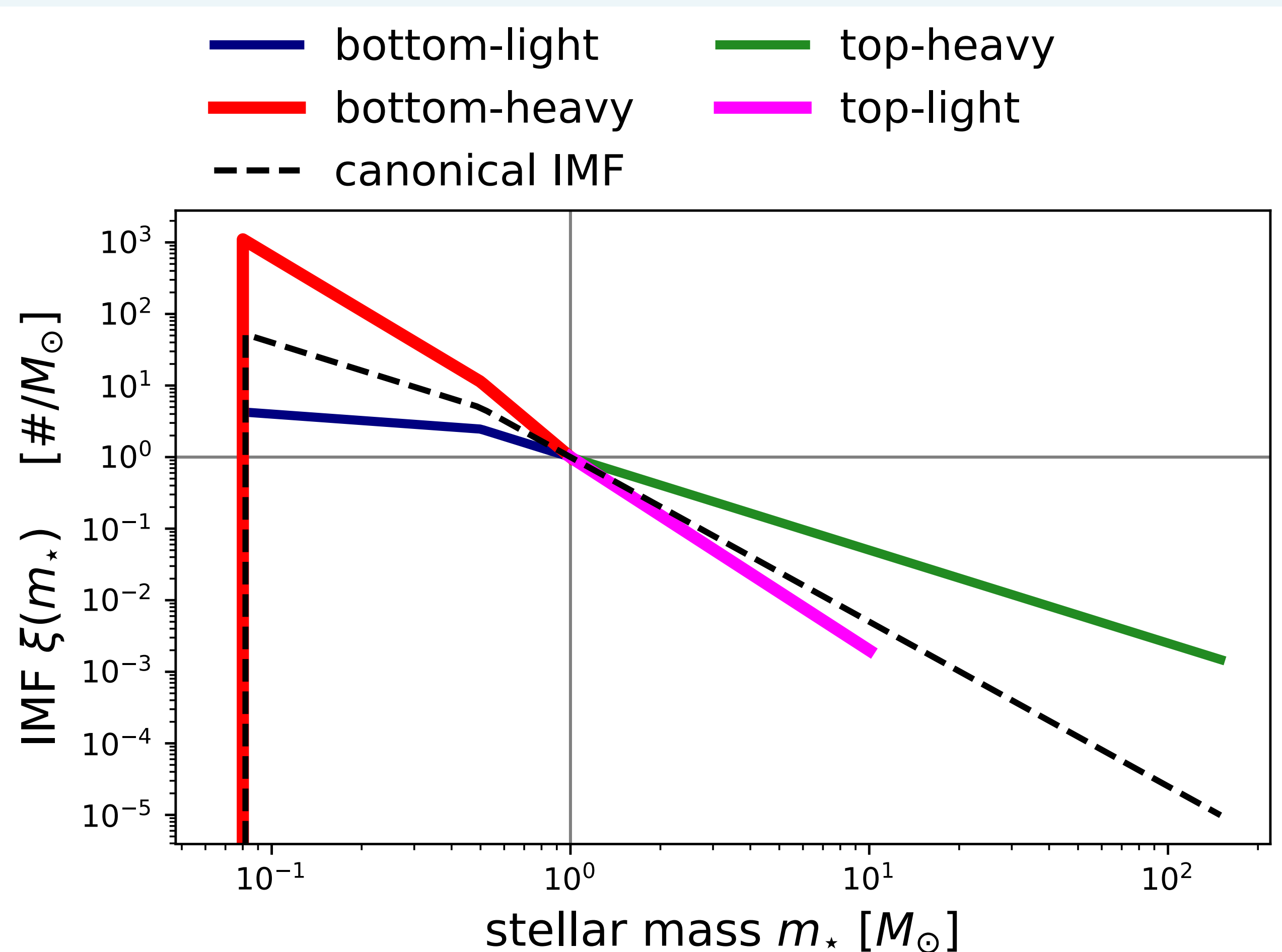




# Stellar IMF: stellar mass distribution of a single star-forming event

Reviews: Kroupa01, Kroupa+13,

Kroupa, **Gjergo**, et al. (2024)

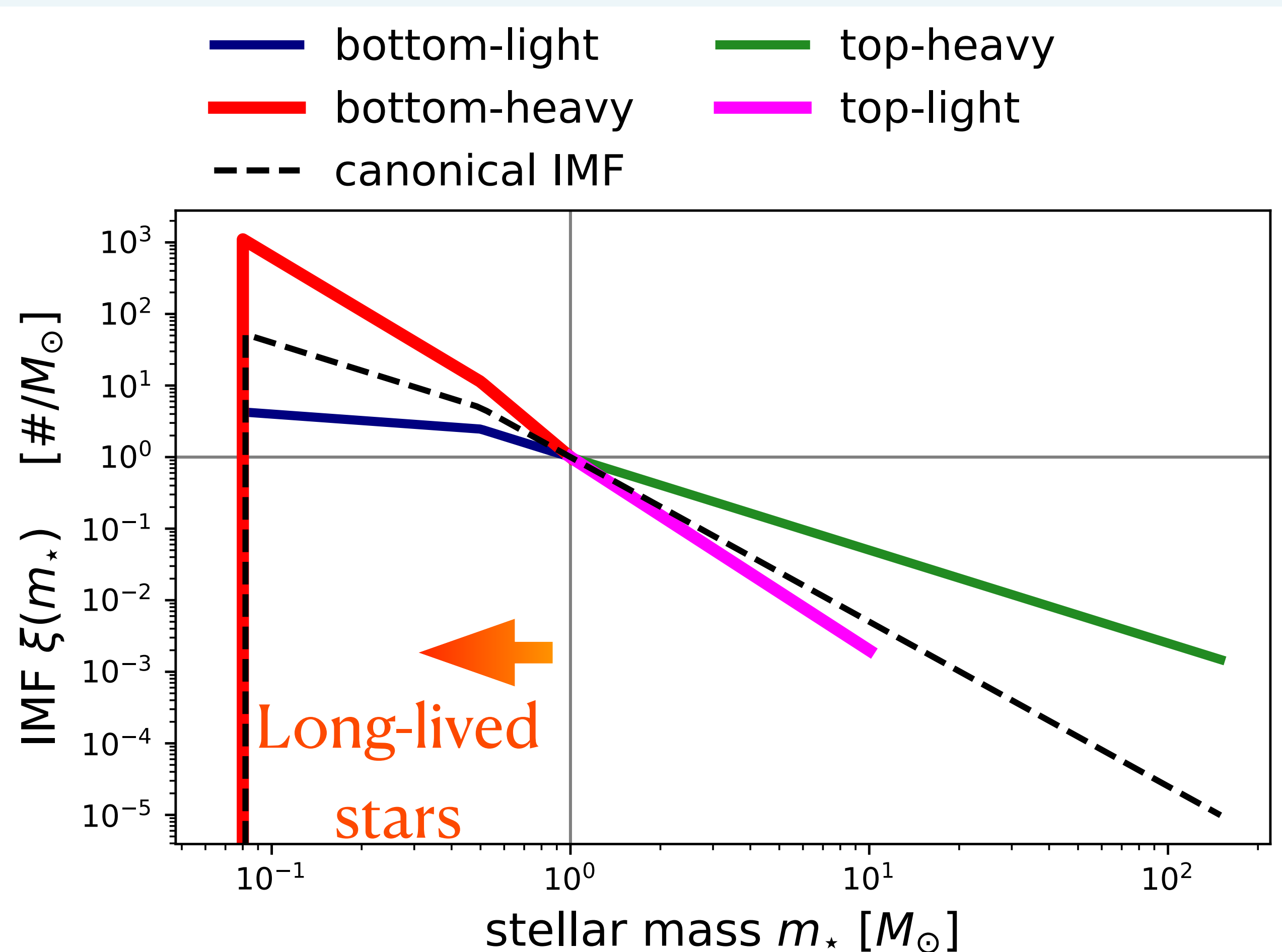




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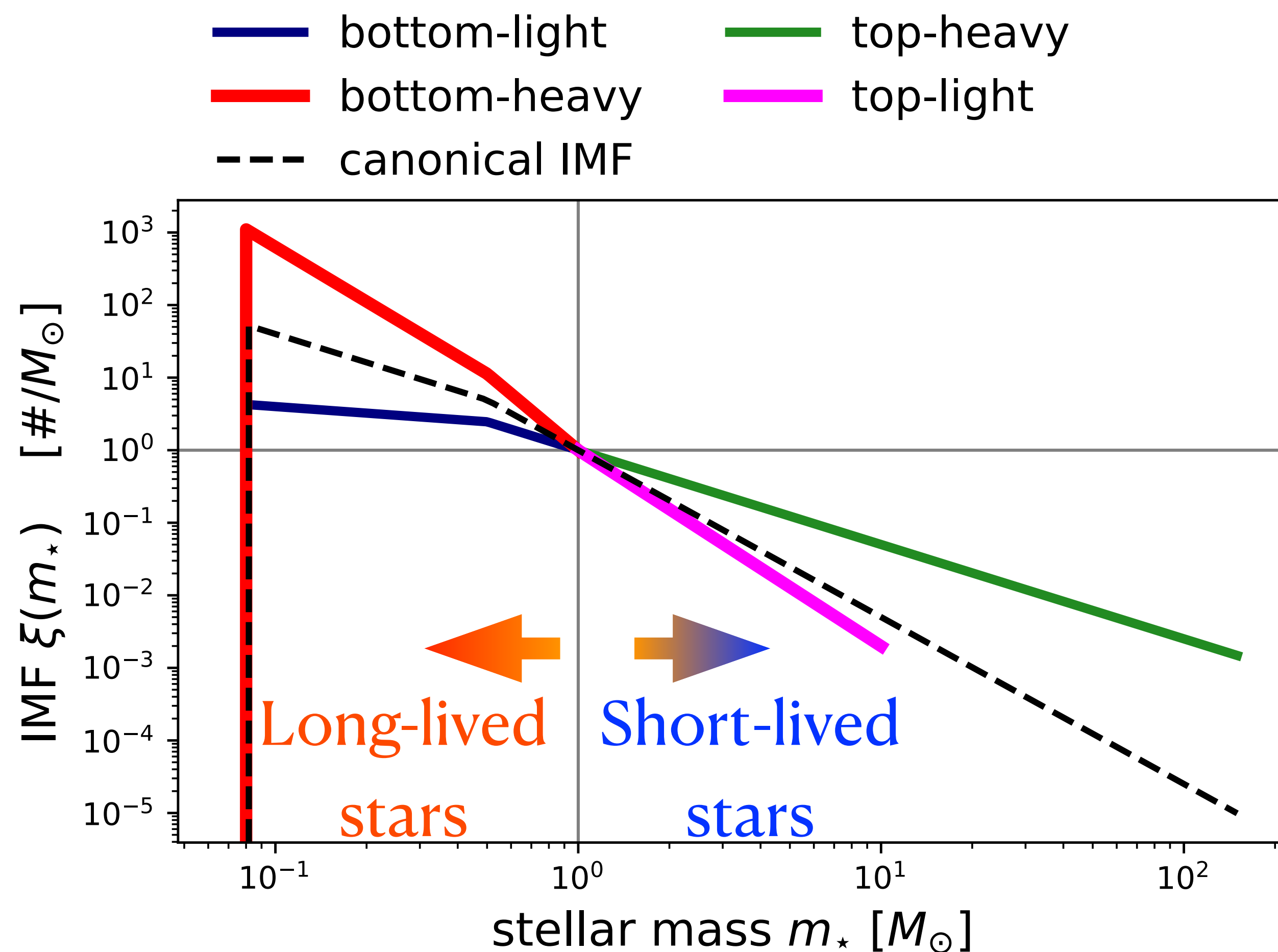
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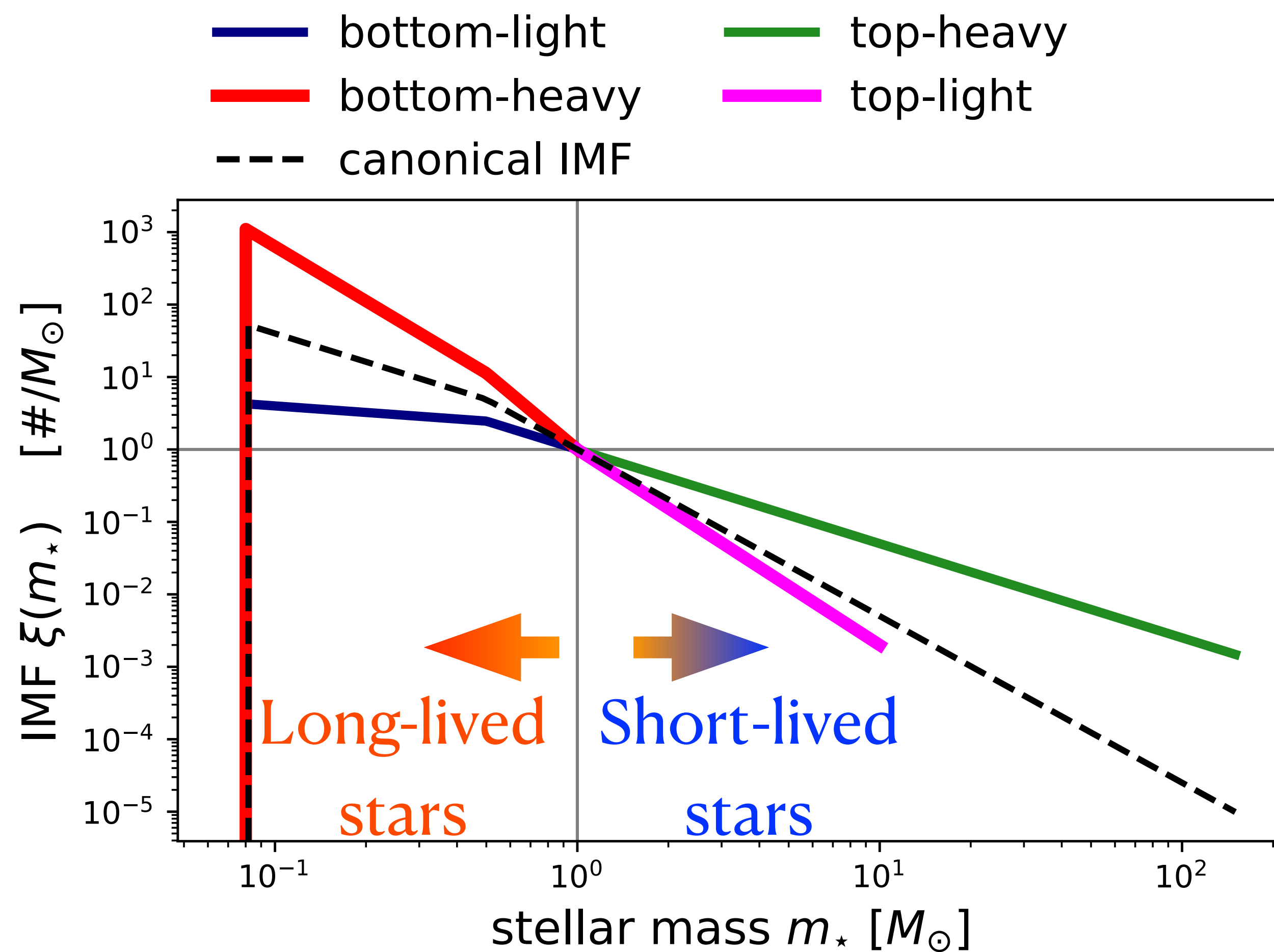


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Credit: NASA, ESA, DSS, and L. Bedin (STScI)

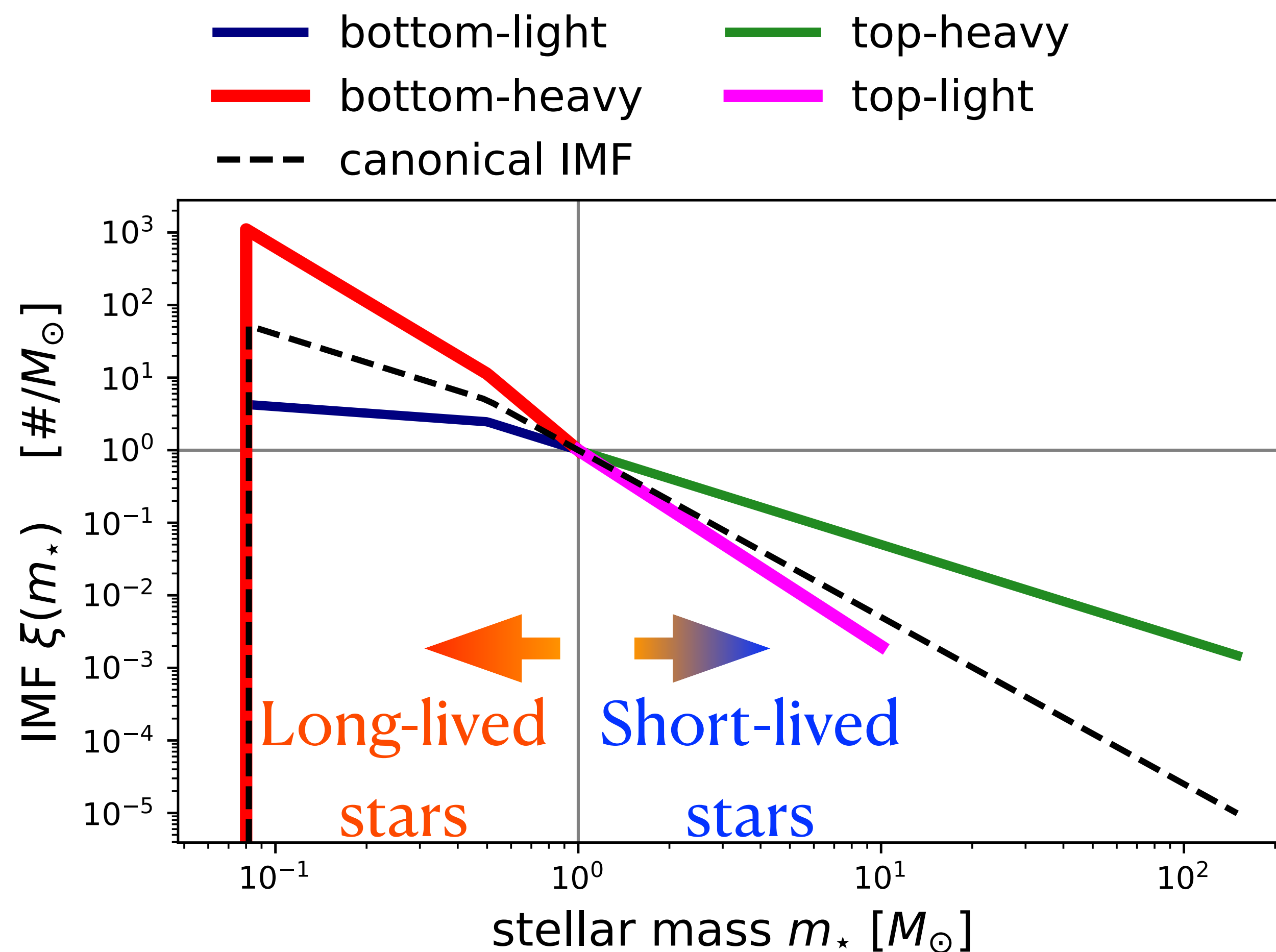


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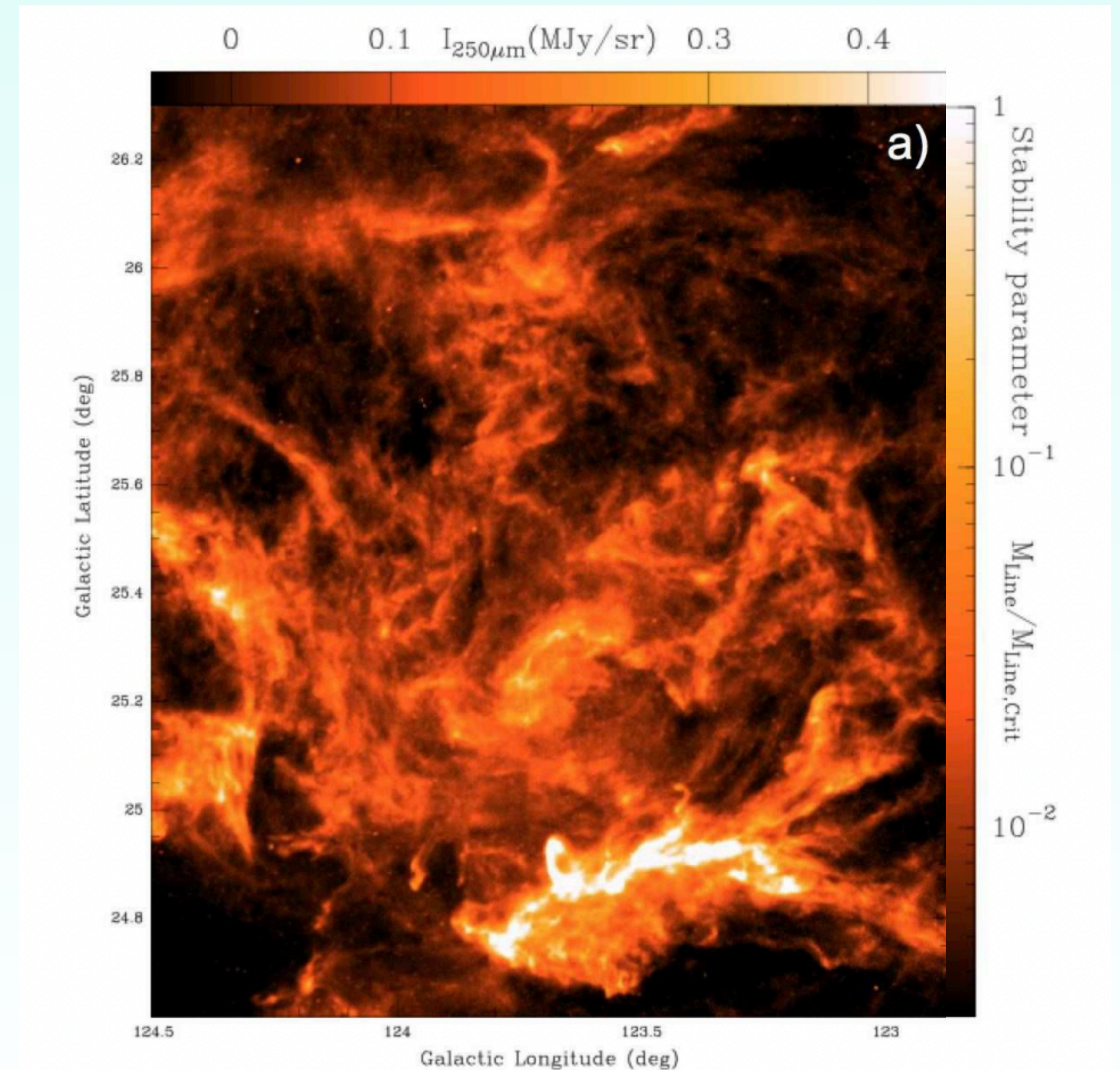
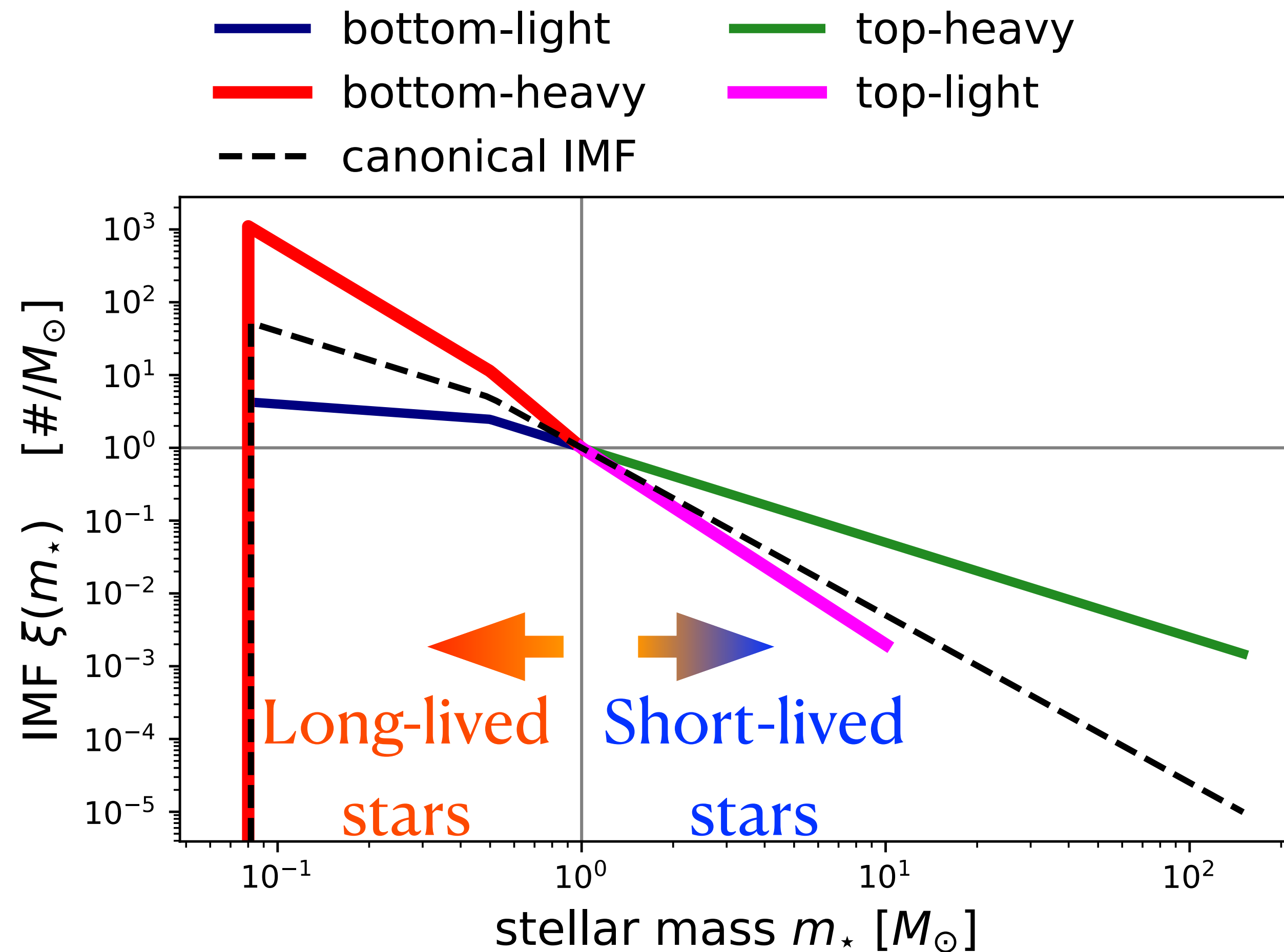


# Stellar IMF: how do stars form?

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Young, star-forming Polaris flare  
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Dust continuum (and H<sub>2</sub> col. dens) in molecular clouds

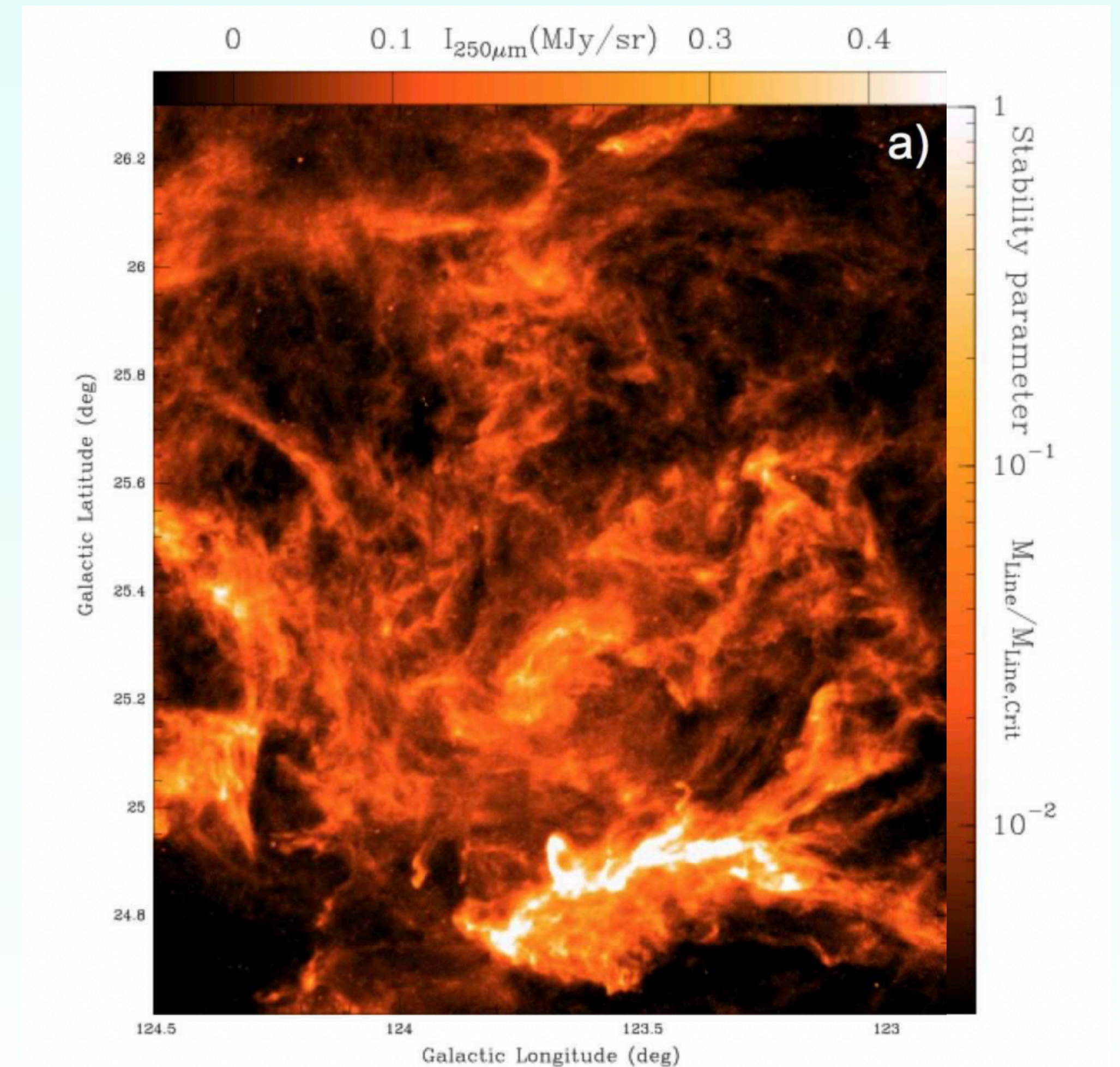
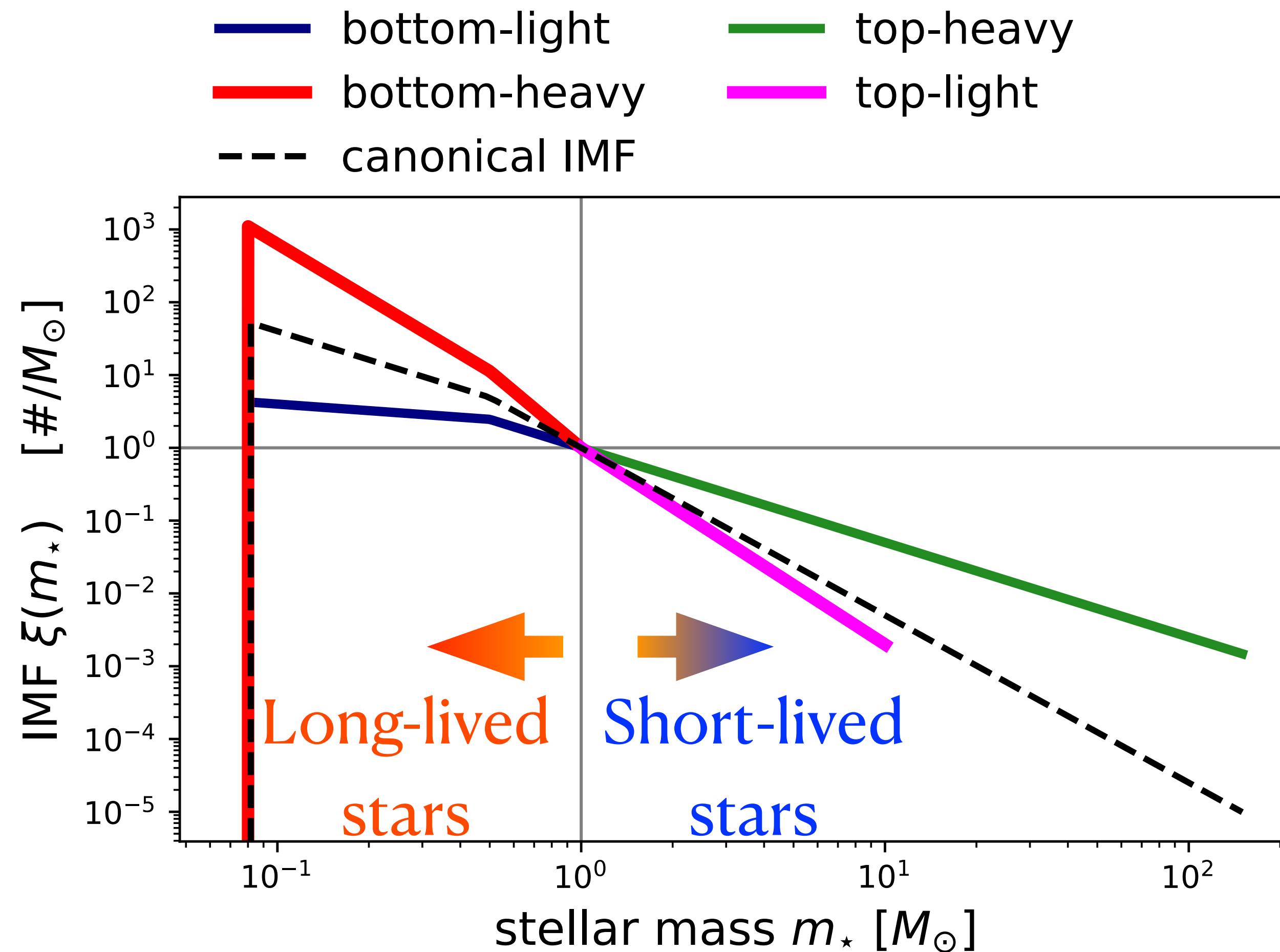


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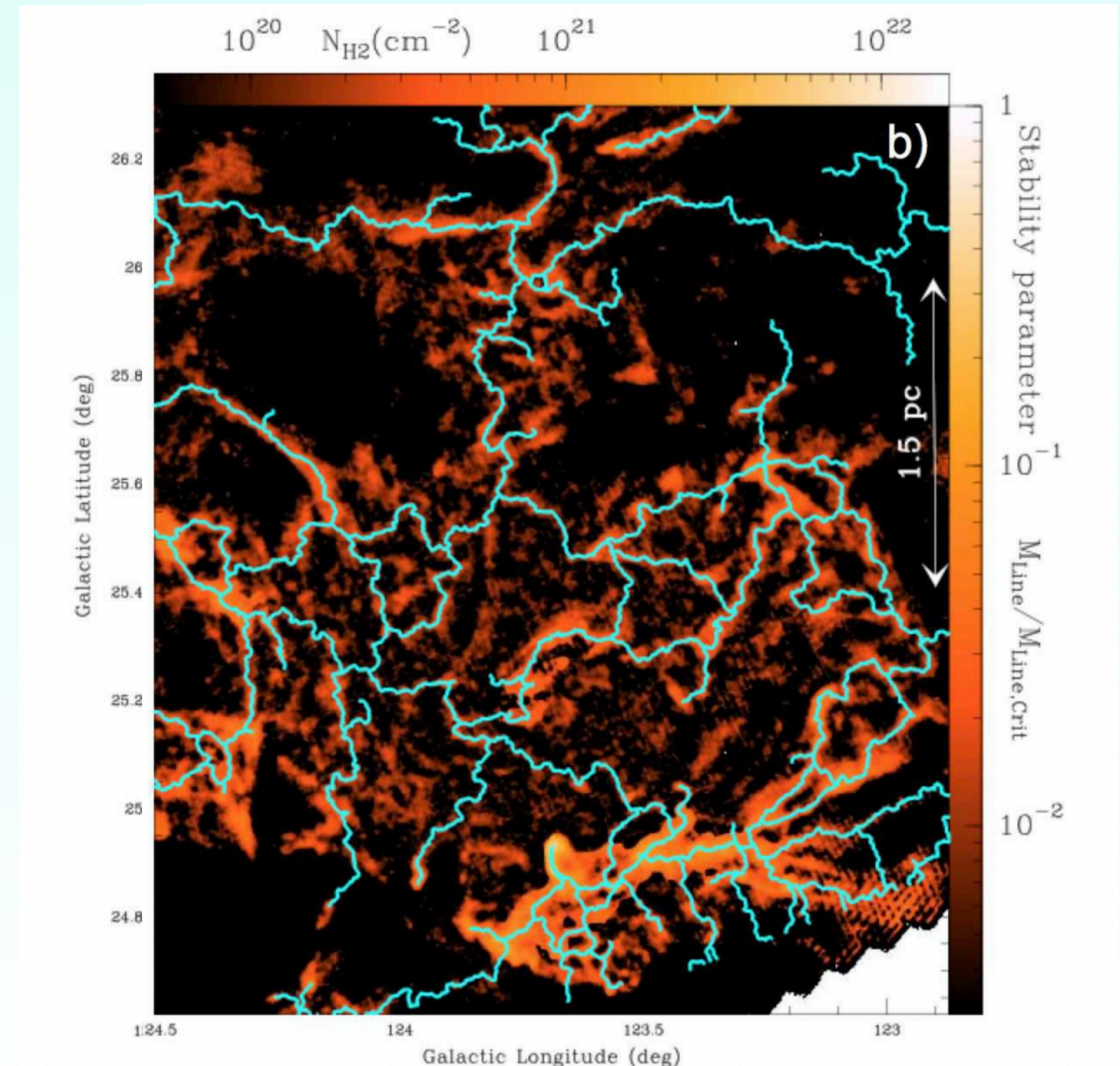
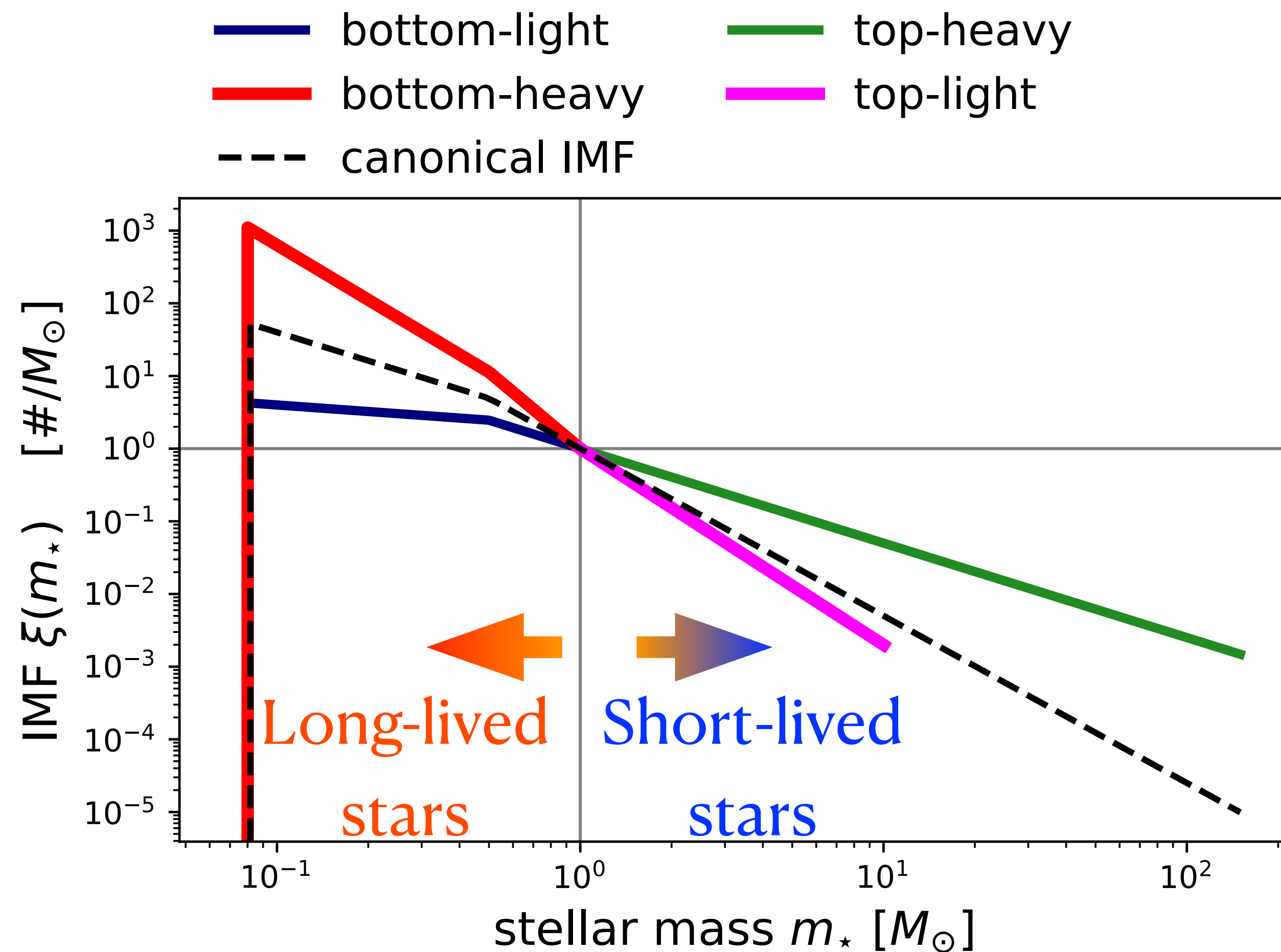


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and  
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Recent studies of the nearest star-forming clouds of the Galaxy at submillimeter wavelengths with the Herschel Space Observatory have provided us with unprecedented images of the initial and boundary conditions of the star-formation process. The Herschel results emphasize the role of interstellar filaments in the star-formation process and connect remarkably well with nearly a decade's worth of numerical simulations and theory that have consistently shown that the interstellar medium (ISM) should be highly filamentary on all scales, and star formation is intimately related to self-gravitating filaments. In this review, we trace how the apparent complexity of cloud structure and star formation is governed by relatively simple universal processes — from filamentary clumps to galactic scales. We emphasize two crucial and complementary aspects: (1) the key observational results obtained with Herschel over the past three years,



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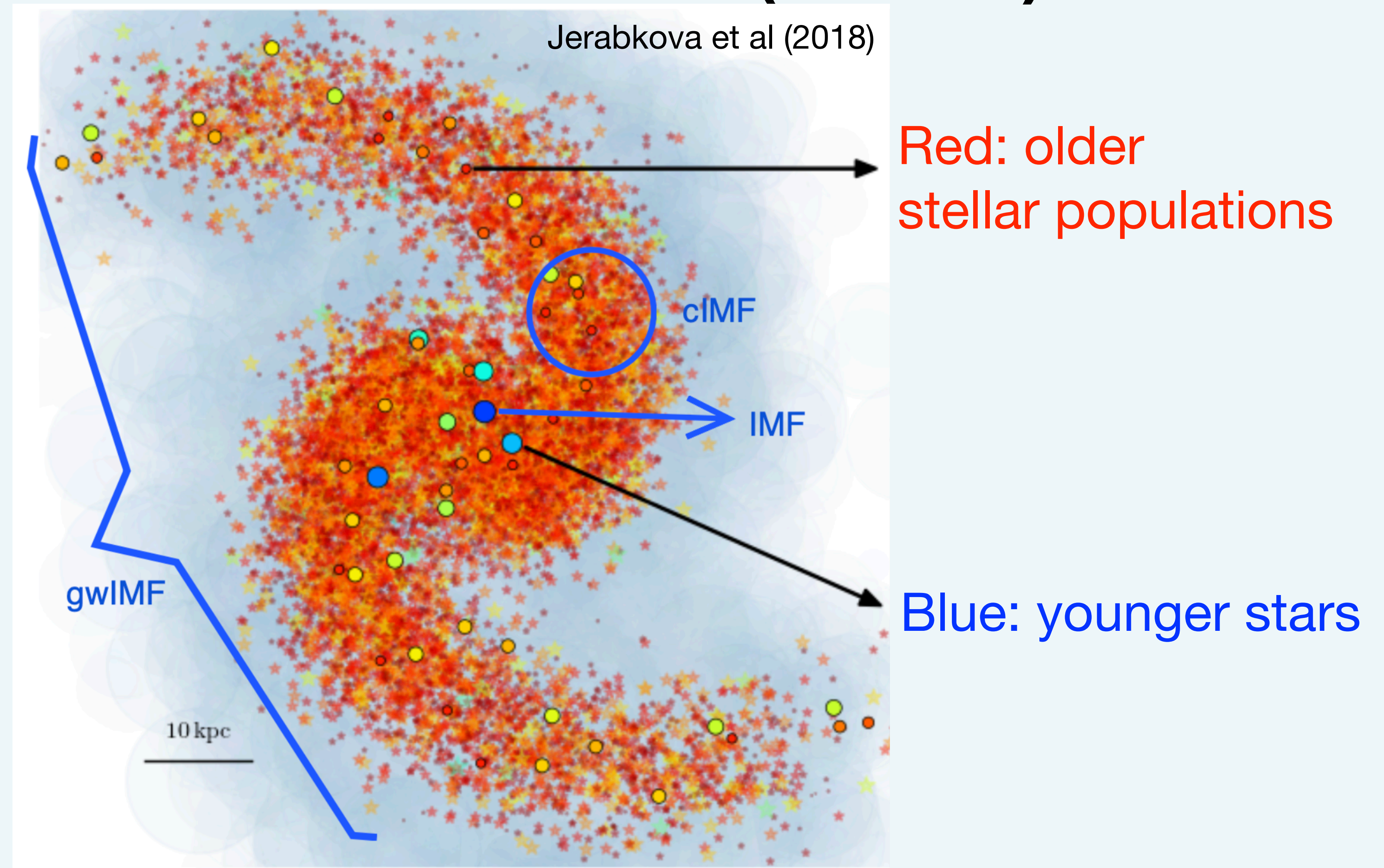
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Thus: the ISM, where dense enough to cool sufficiently rapidly, molecularises and forms long thin filaments. Density fluctuations along these cause potential fluctuations and the molecular gas falls towards potential minima. There, proto-stars grow and regulate their accretion from the in-falling filament.



# Integrated Galaxy-wide Initial Mass Function (IGIMF)





**Formulation from**

Kroupa & Weidner (2003)

Weidner & Kroupa (2005, 06, 10, 13)

Marks & Kroupa (2012)

Kroupa et al. (2013)

[...]

Jerabkova et al. (2018)

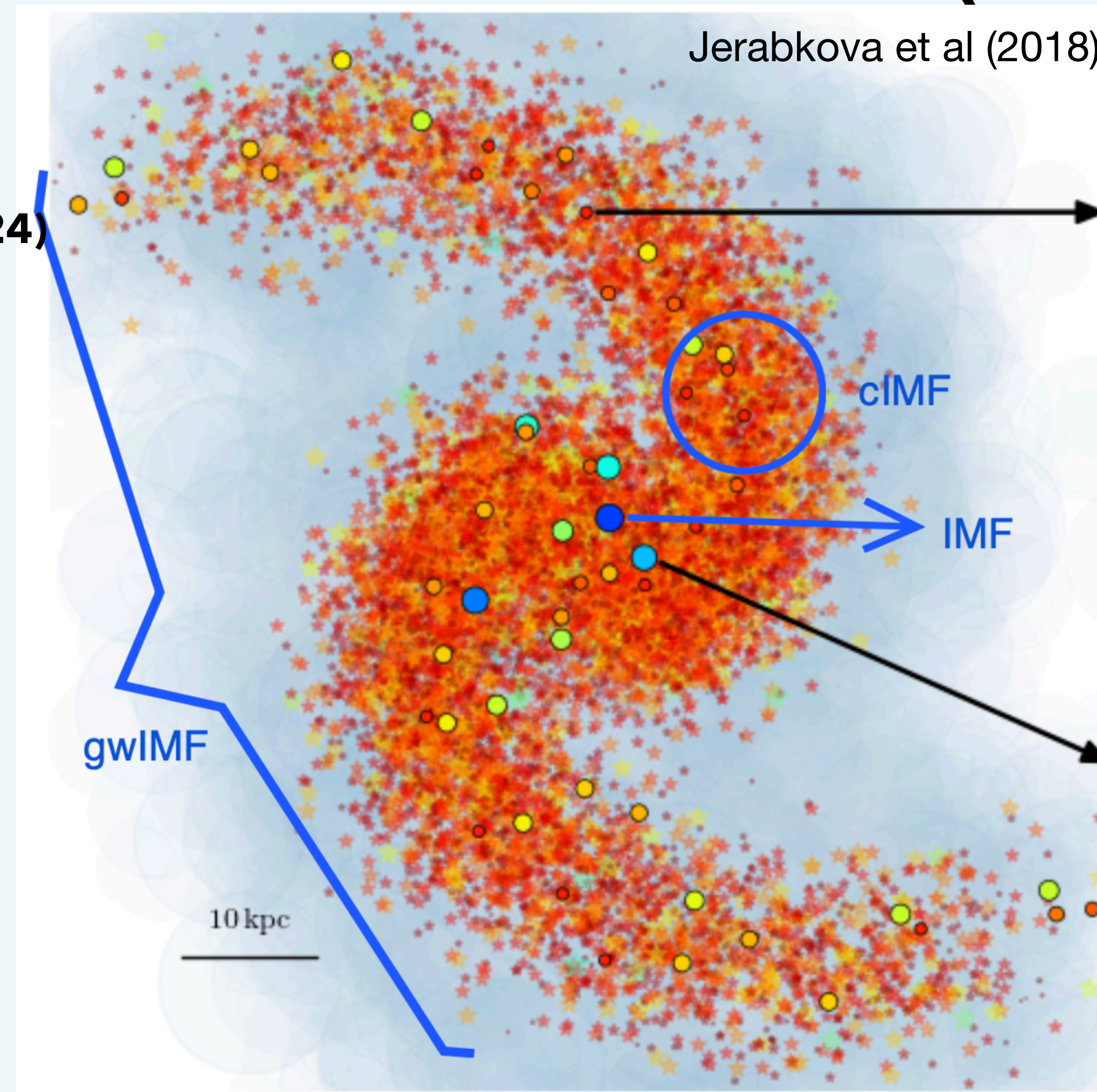
Yan et al. (2017, 2021, 2023)

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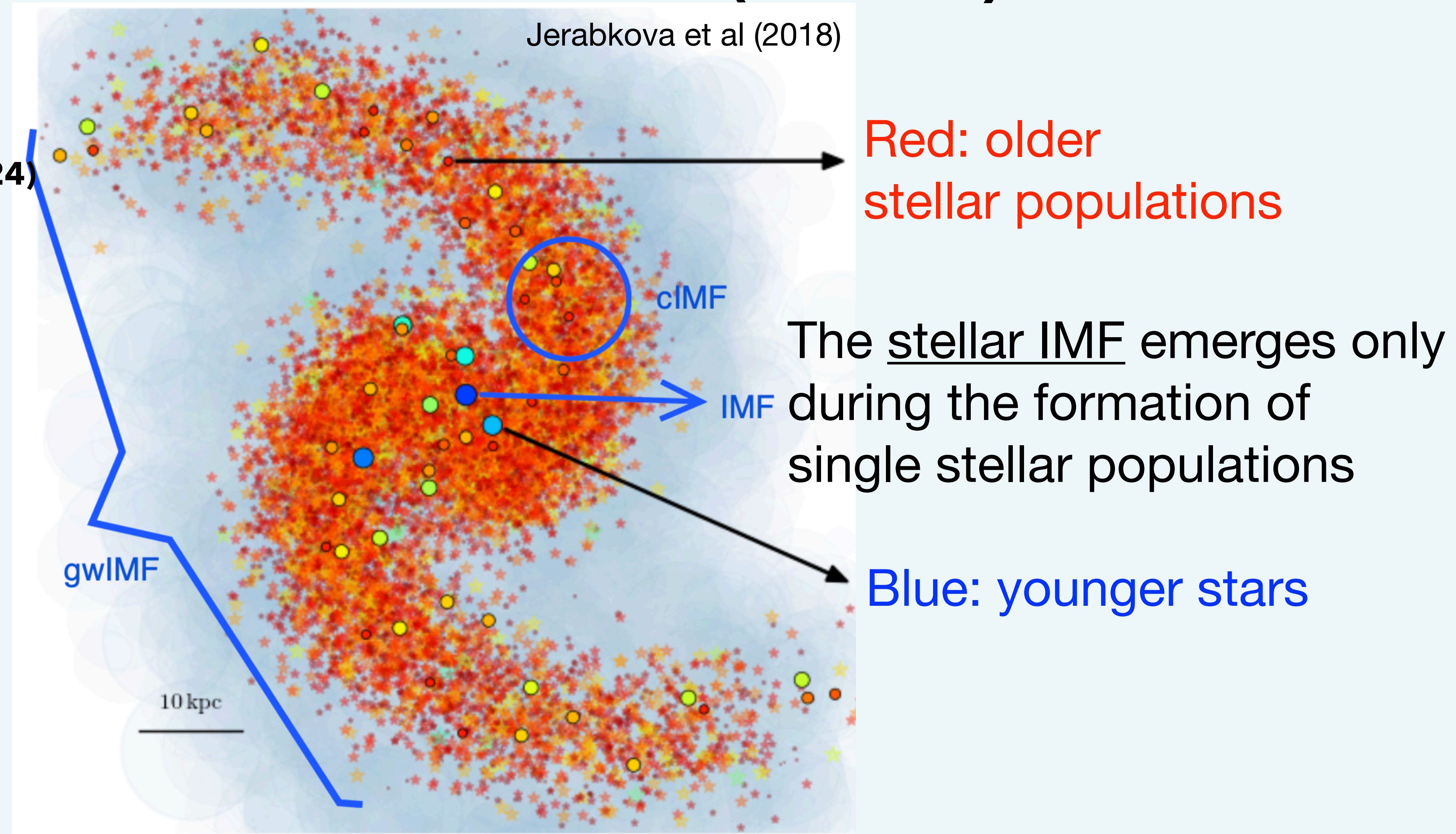
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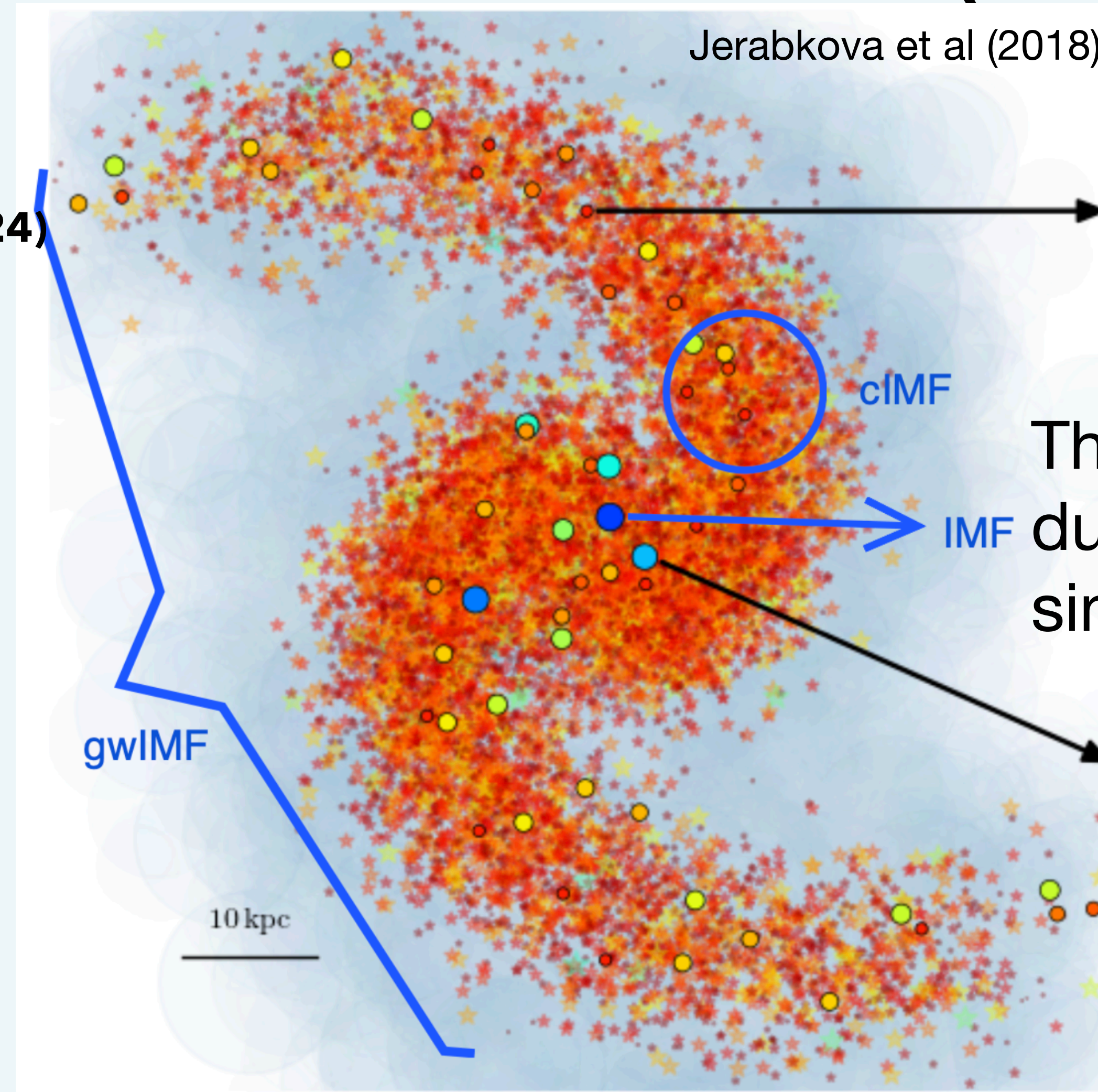
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Red: older  
stellar populations

The stellar IMF emerges only  
during the formation of  
single stellar populations

Blue: younger stars

$$\text{IMF} = \frac{\Delta N \text{ of stars}}{\Delta \text{ mass of stars}}$$



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The **cumulative sum**

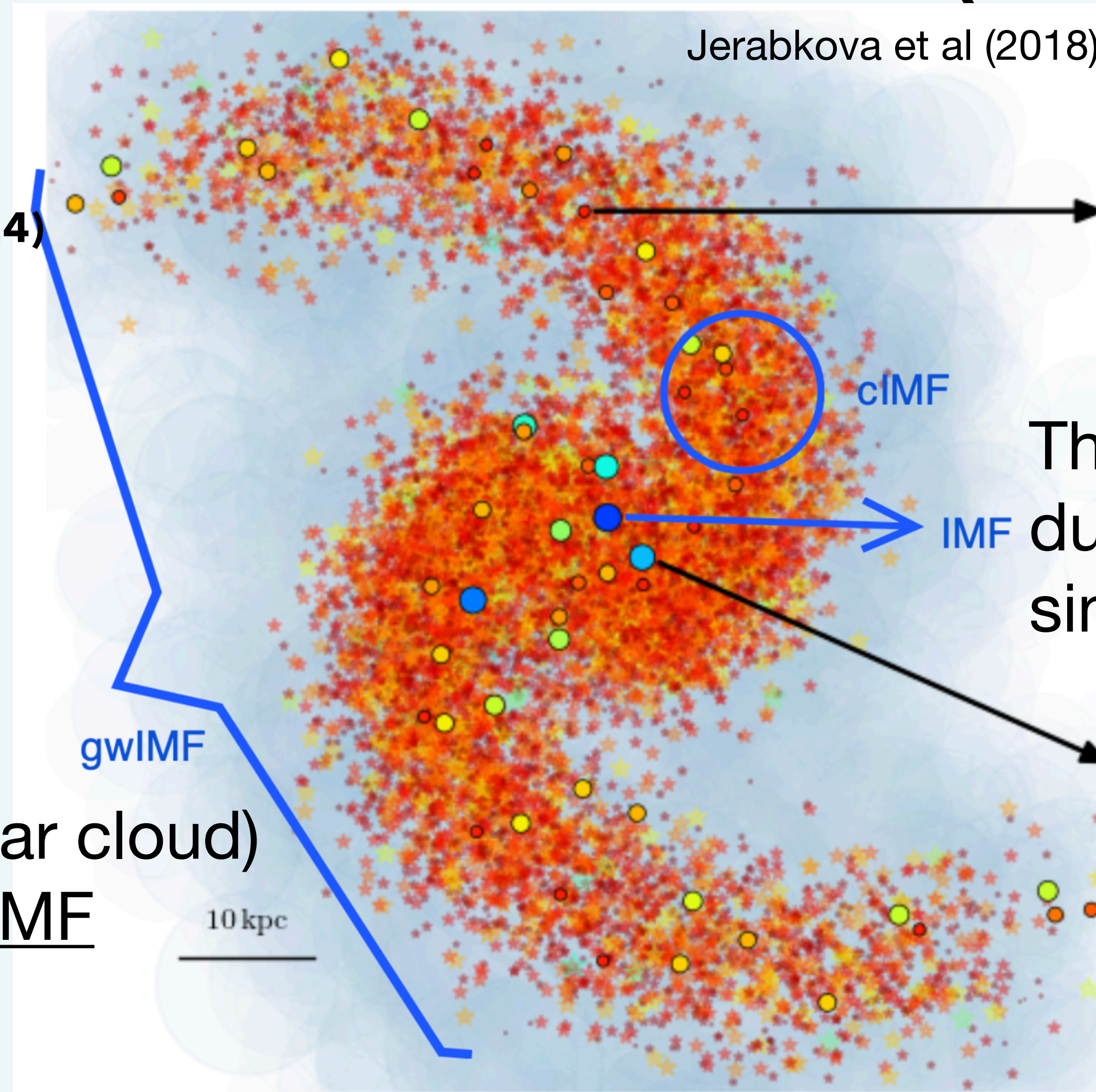
of all stellar IMFs

formed in past 10 Myr

(The lifetime of a molecular cloud)

defines the galaxy-wide IMF

(gwIMF)



Jerabkova et al (2018)

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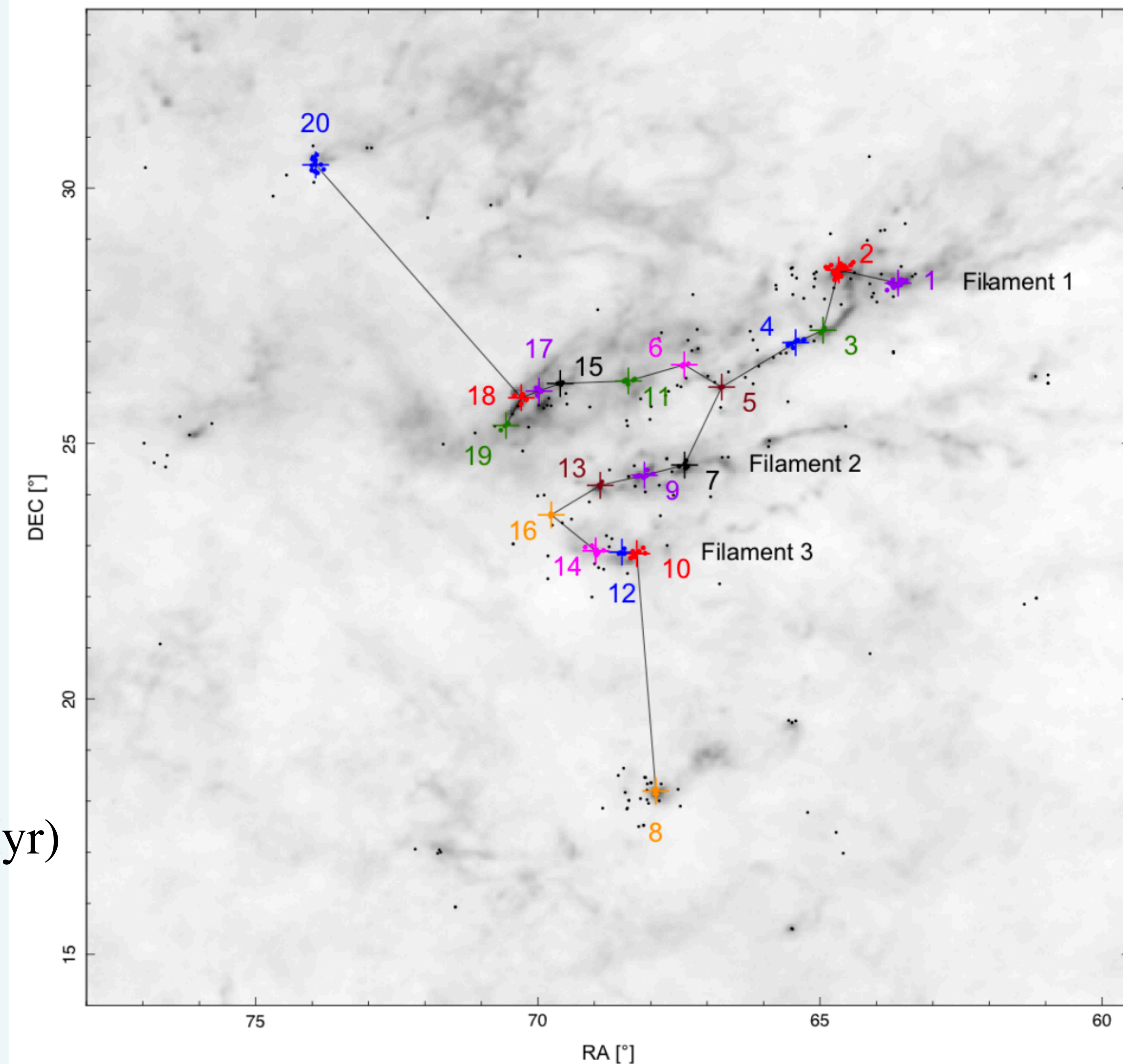
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# Taurus star-forming region: closest SF-neighbor



- Closest SF region to us
- Very young stars (1-5 Myr)
- No star above  $3 M_{\odot}$
- No OB stars

Joncour+18



Astrophotographer: © 2015 Alan Dyer



The Milky Way panorama: 14 composite optical images  
Each image is obtained by stacks of 5 x 2.5 minute exposures.

The long exposure reveals the deep red H-alpha emissions from star-forming regions









Cygnus

Deneb

Cepheus

Cassiopeia

Andromeda  
Galaxy

Perseus

Capella

Auriga

Pleiades

Taurus

Aldebaran

Gemini

Castor

Pollux

Betelgeuse

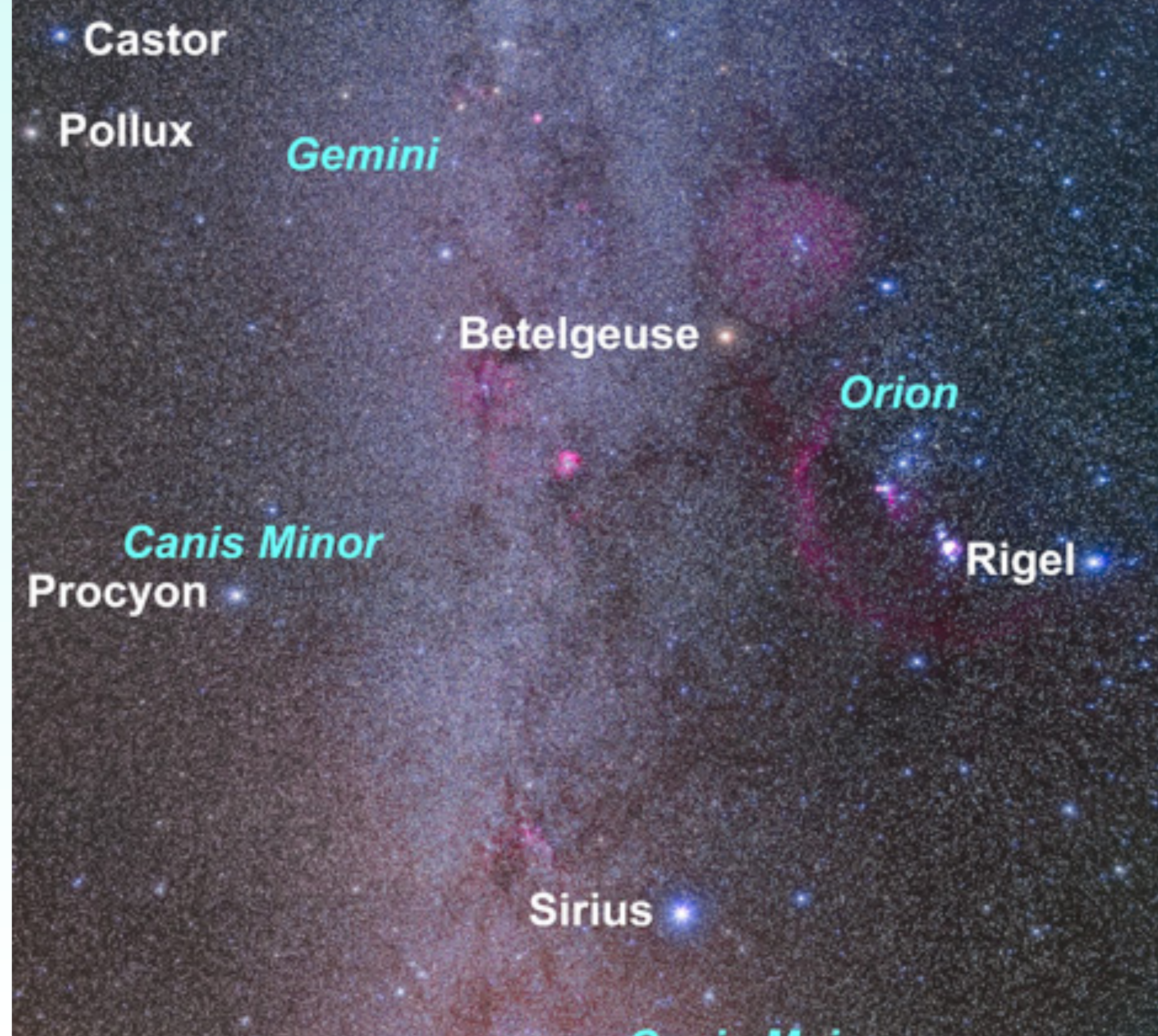
Orion

Rigel

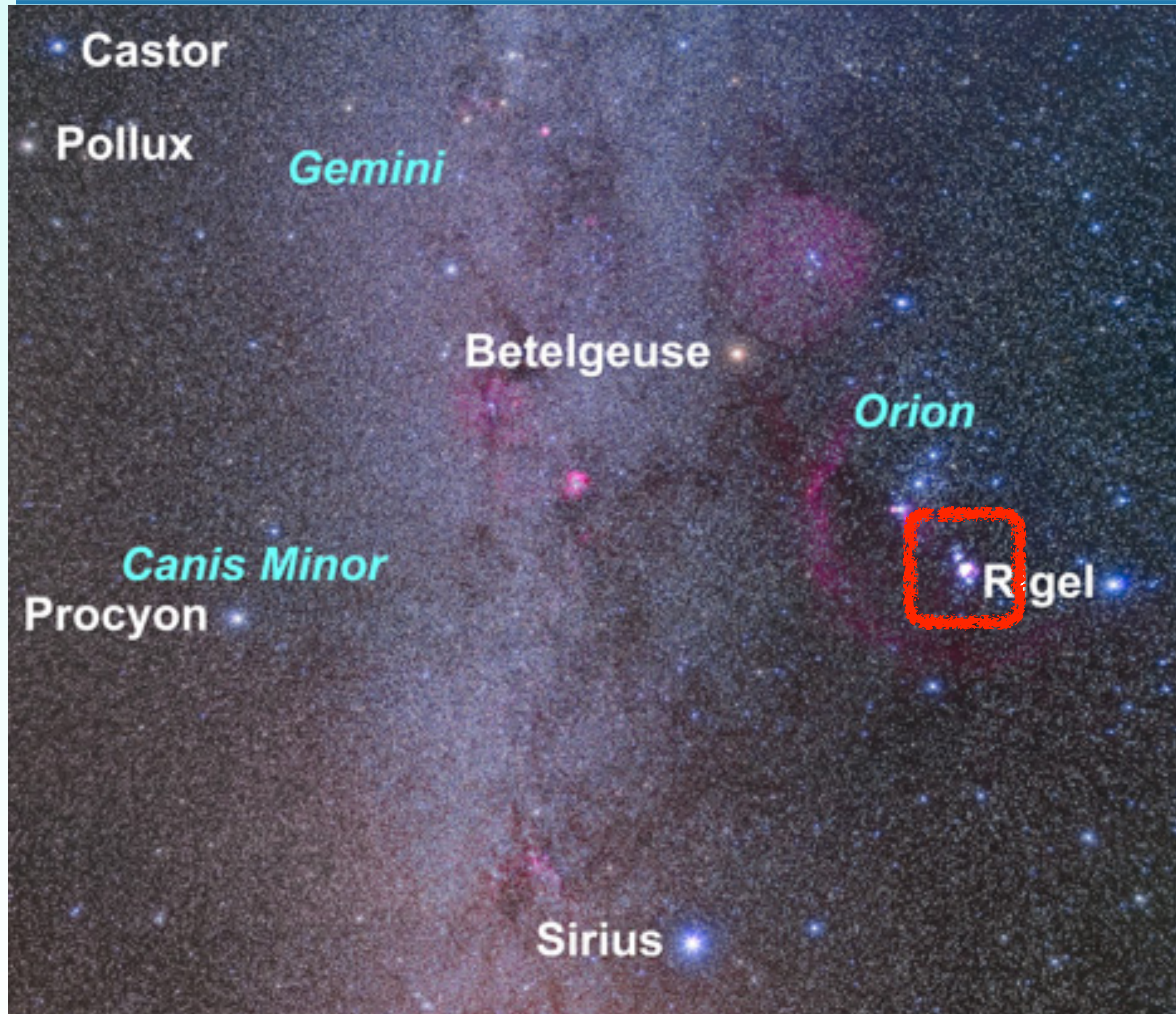
Canis Minor

Procyon

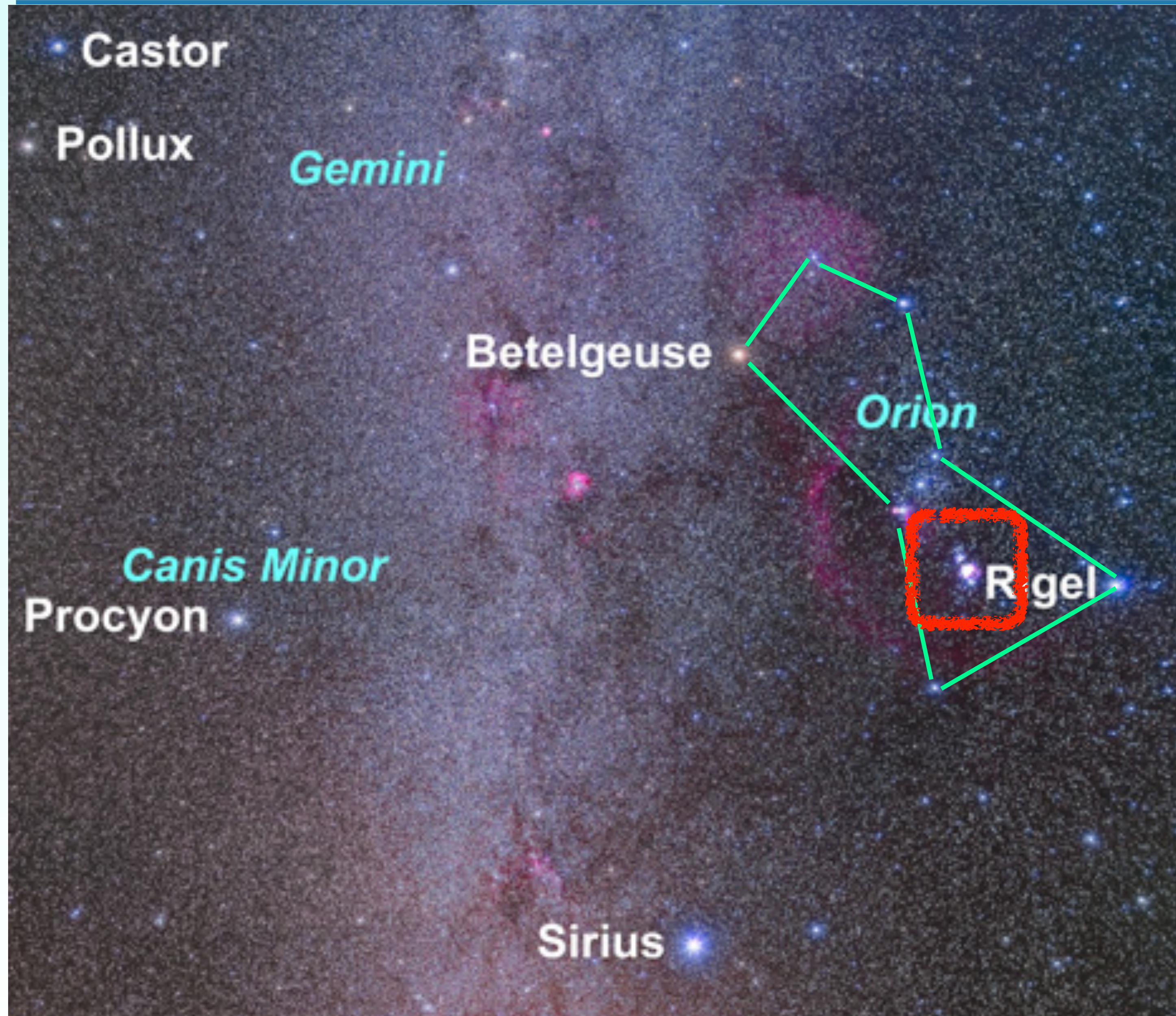






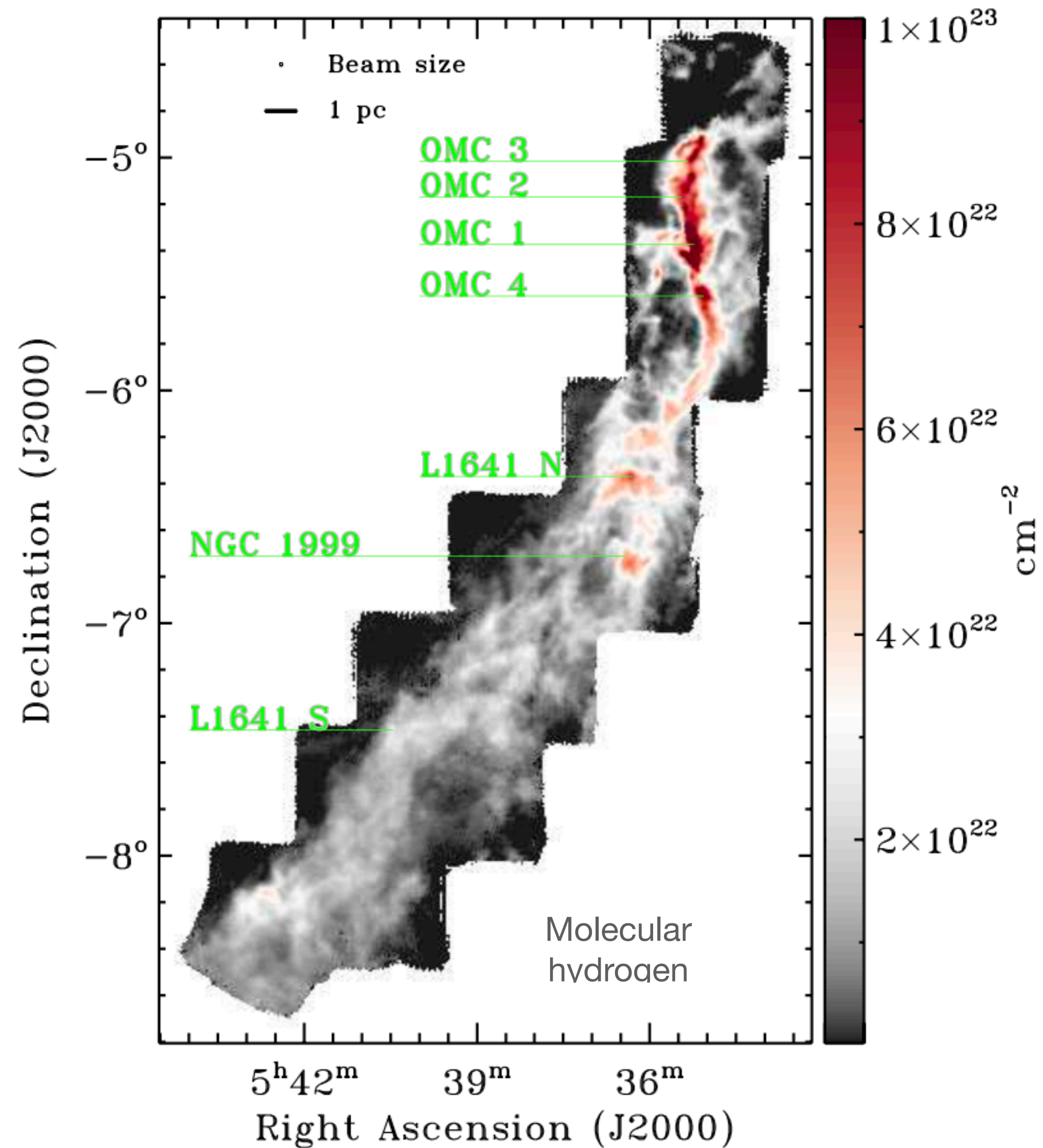








# Southern cloud in Orion A: a SF region with no massive stars

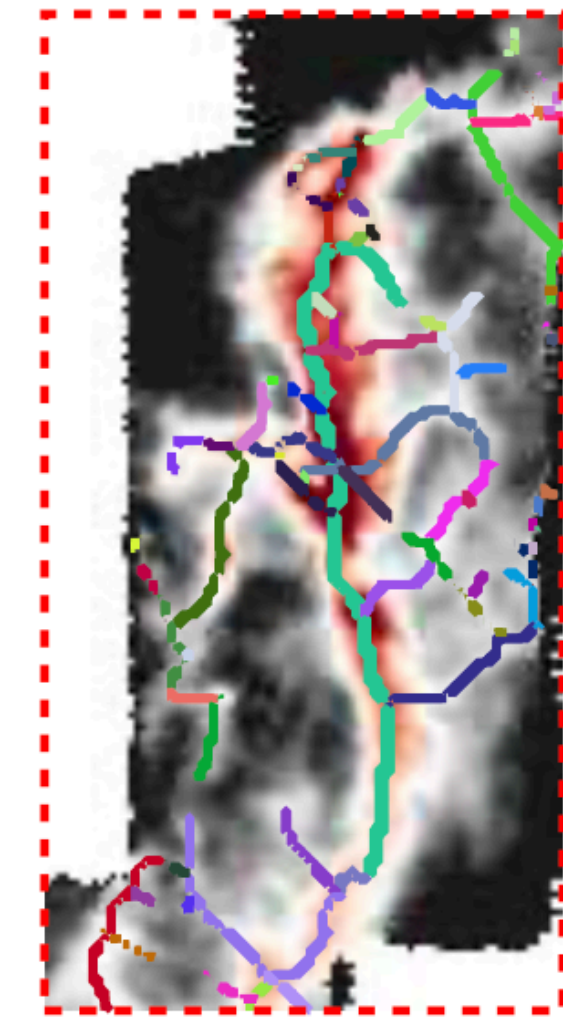
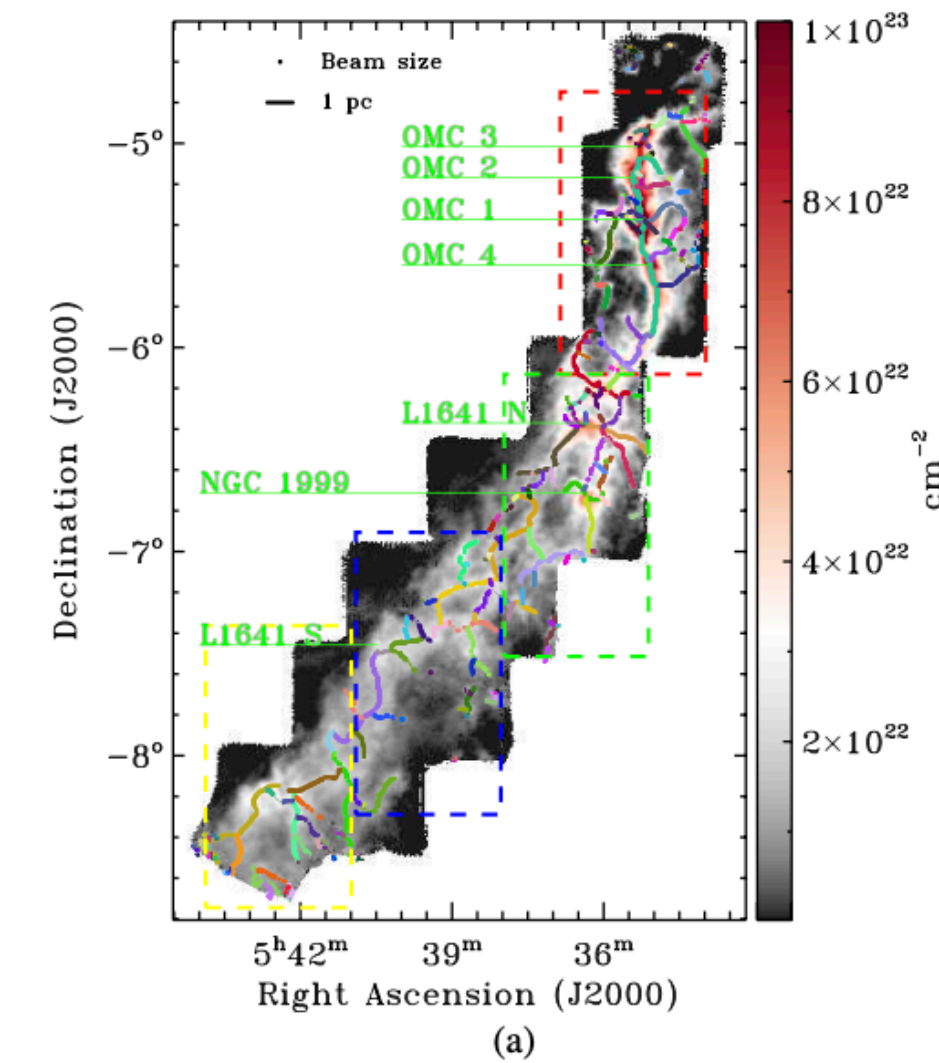
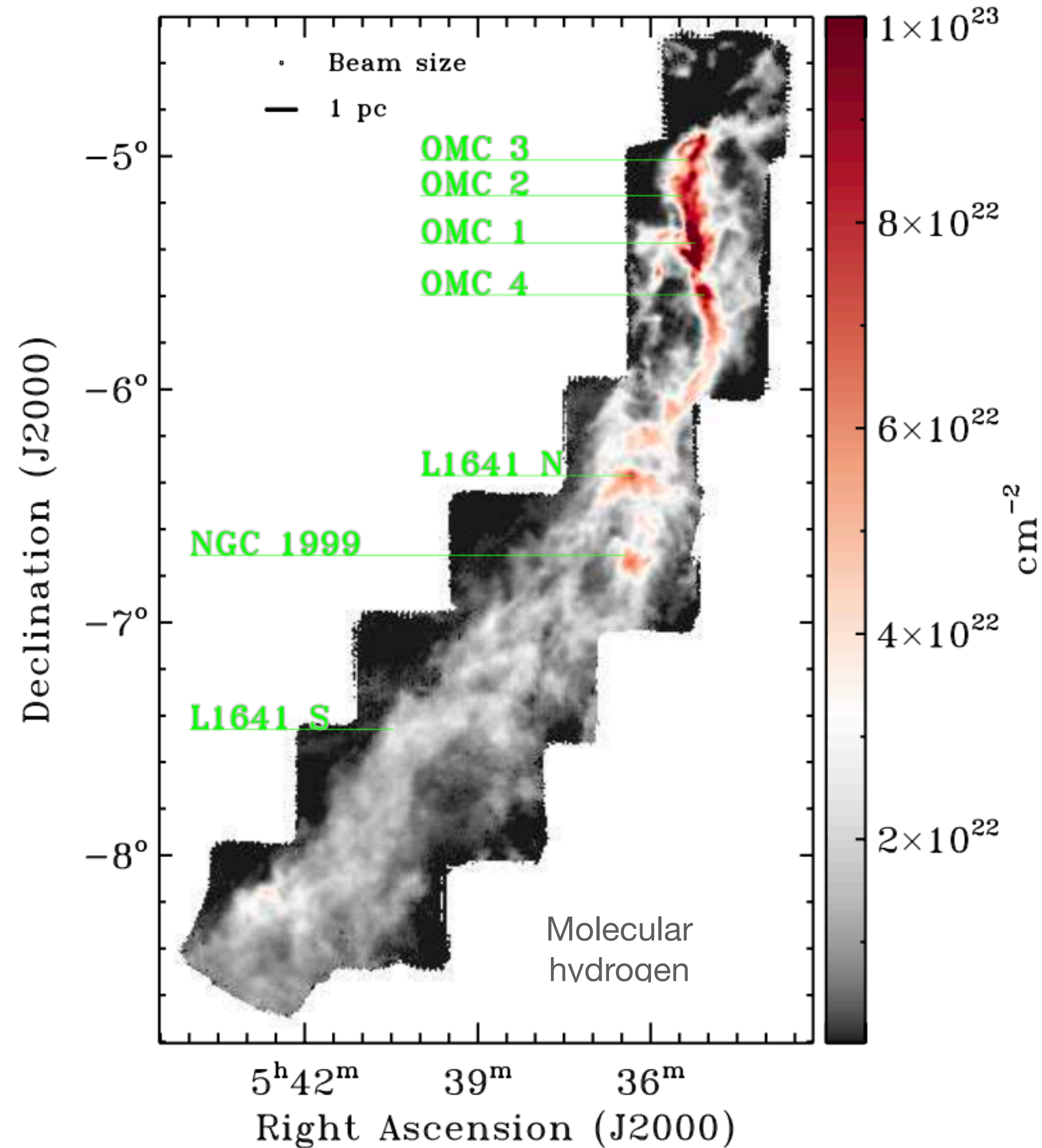


400 pc away from us,  
same age across

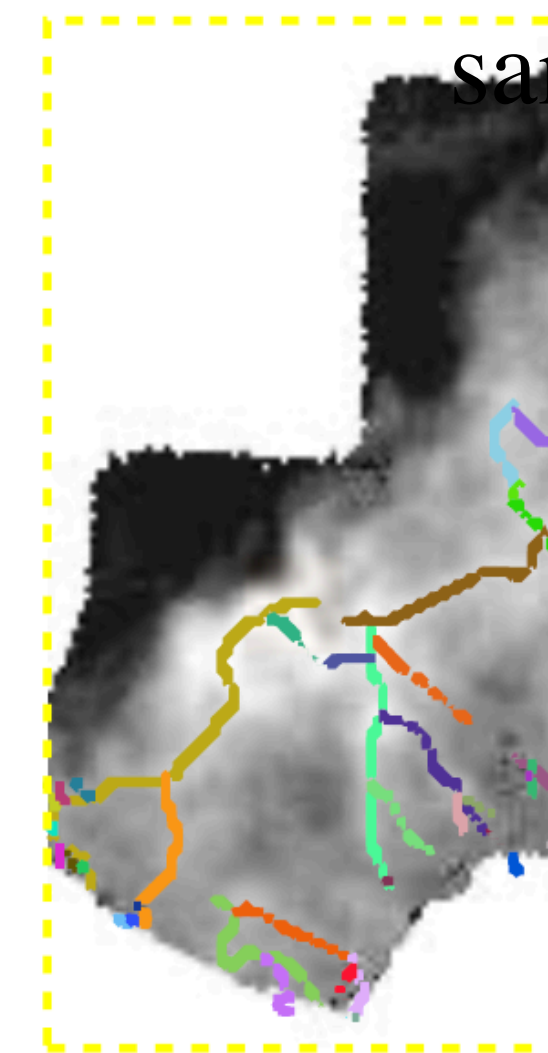
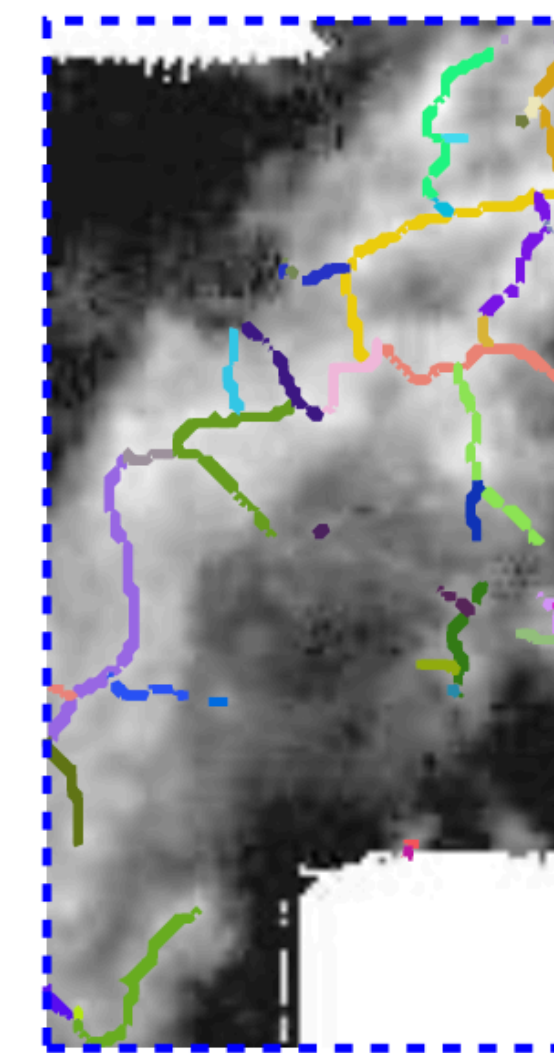
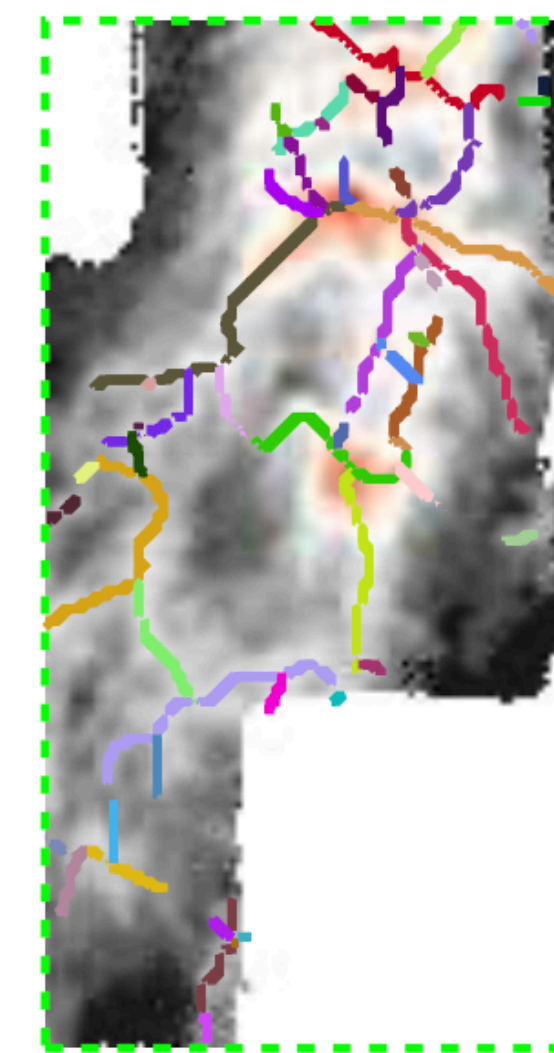
Zheng, Wang, Ma, Li (2021, Purple Mountain Observatory, Nanjing)



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(b) 400 pc away from us,  
same age across

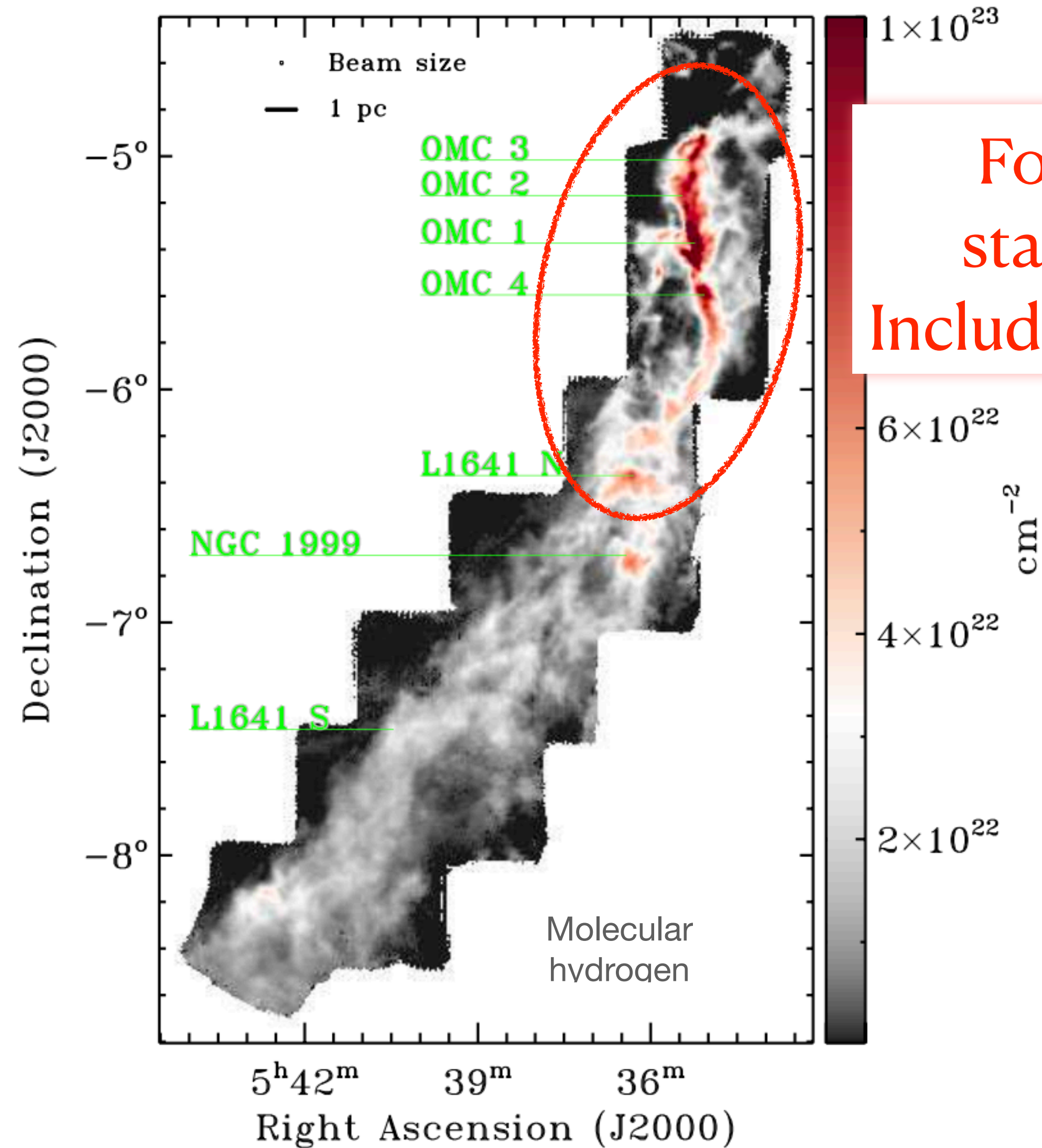


Filamentary star  
formation

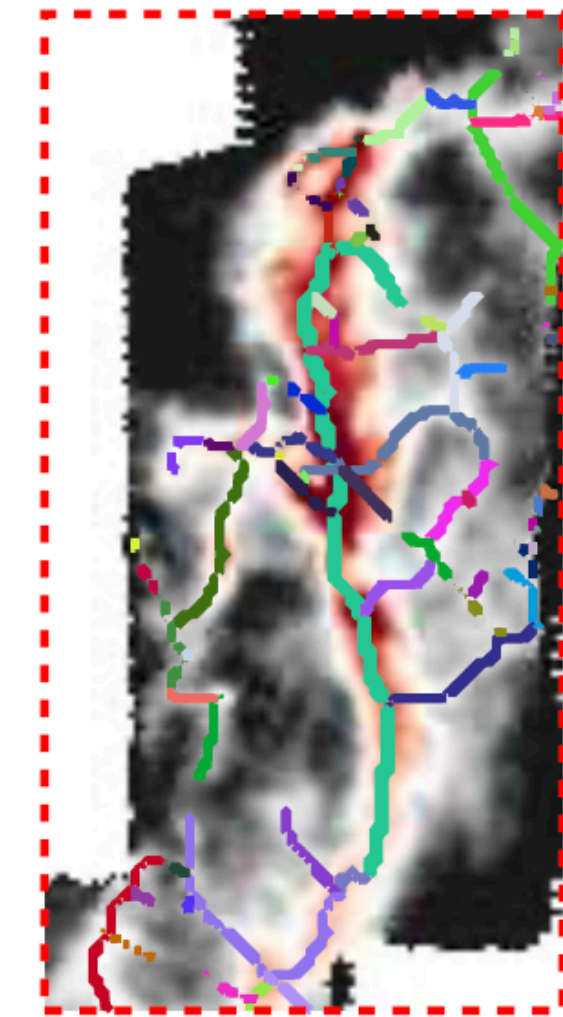
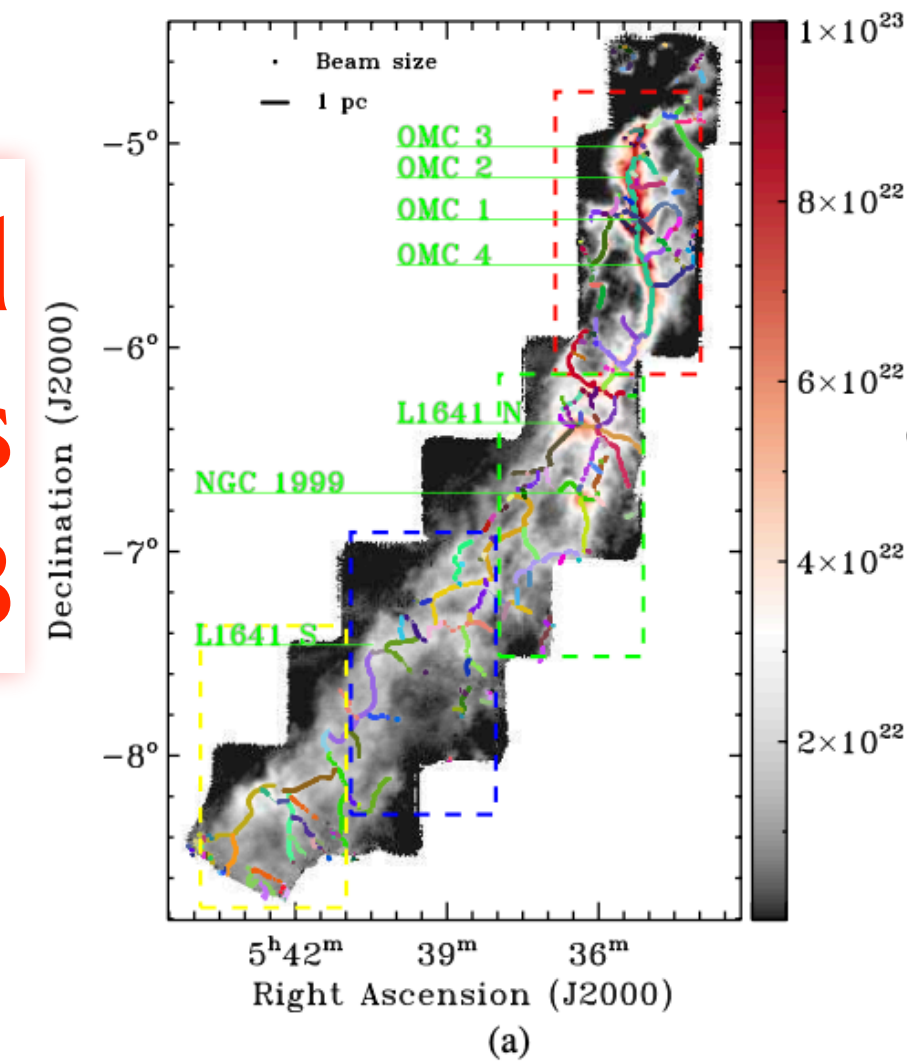
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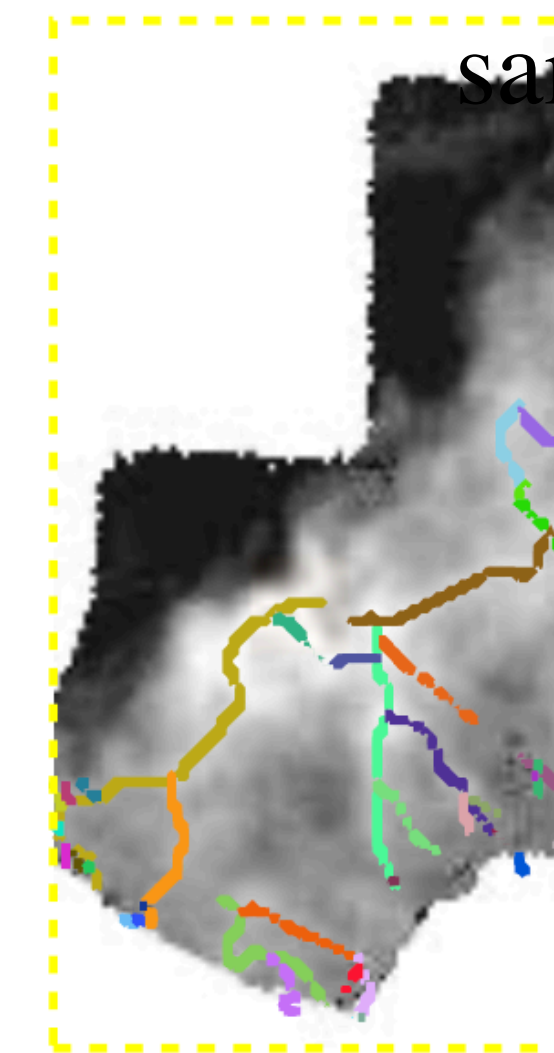
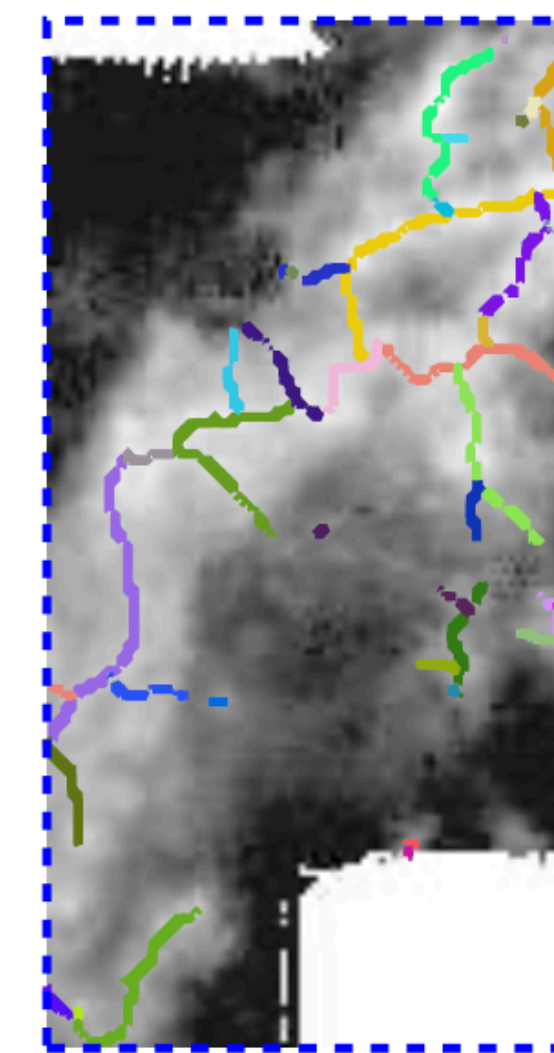
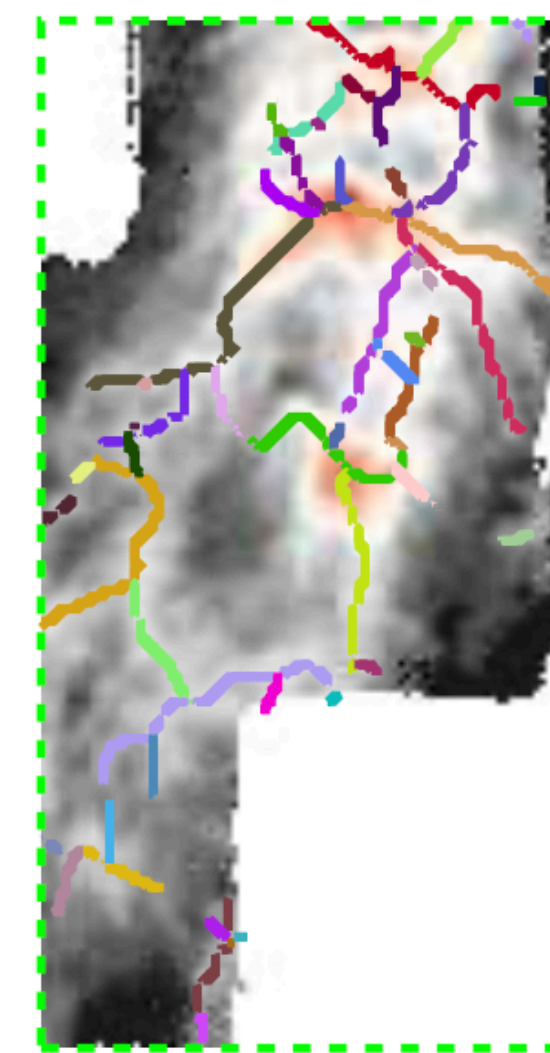
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Forms all  
star types  
Including OB



400 pc away from us,  
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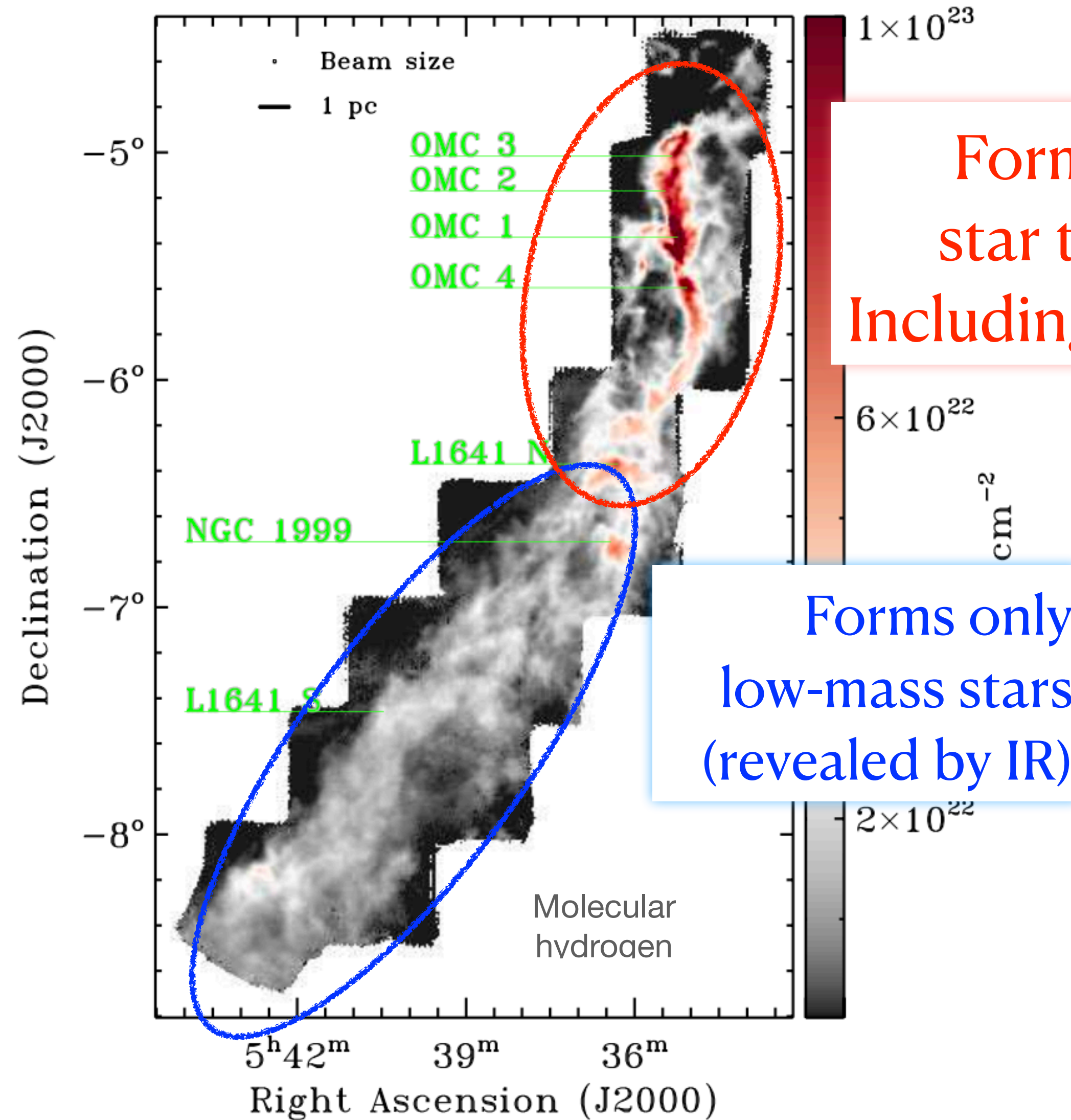


Filamentary star  
formation

Zheng, Wang, Ma, Li (2021, Purple Mountain Observatory, Nanjing)

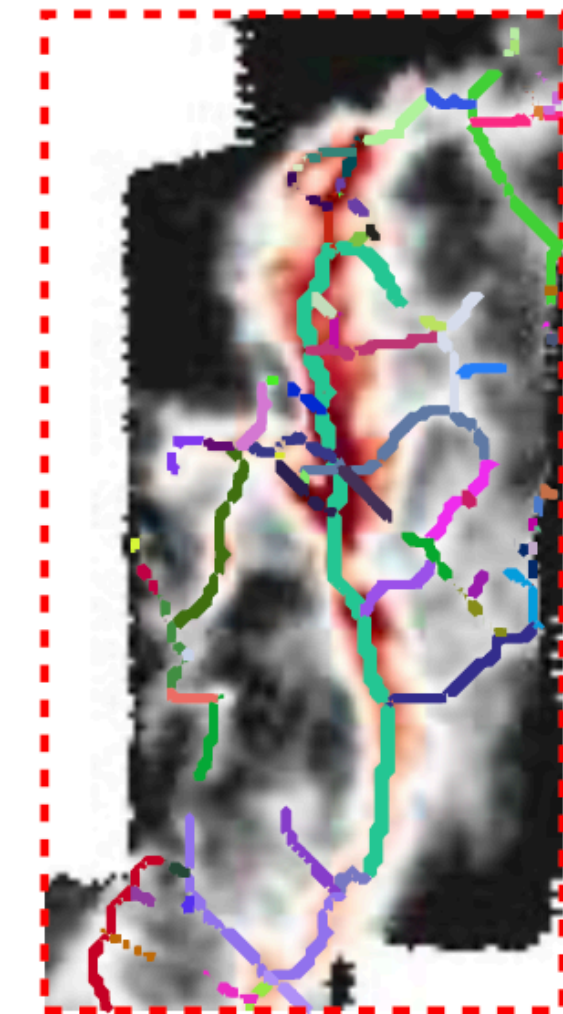
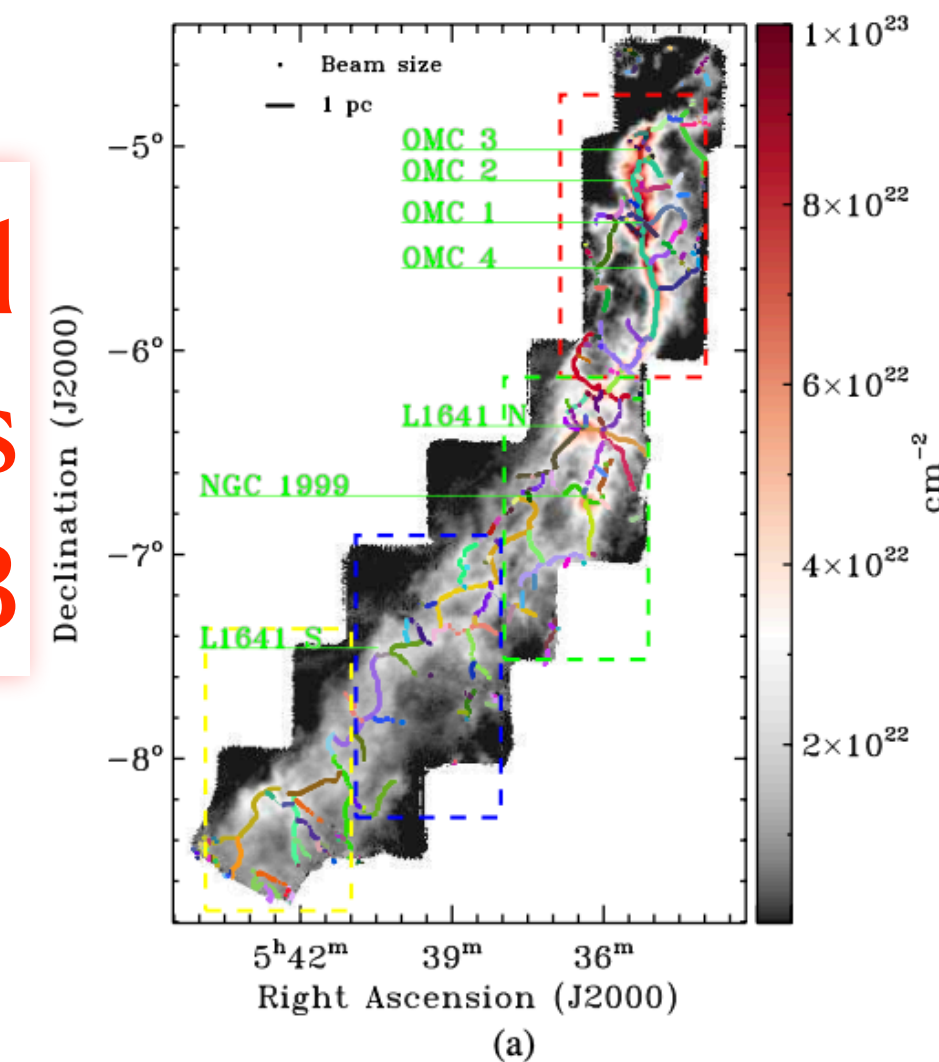


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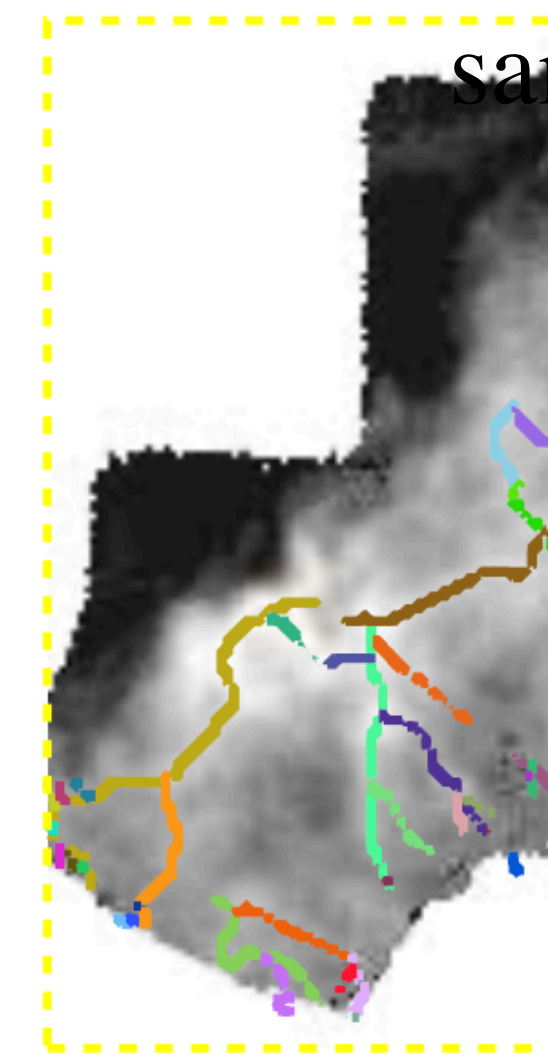
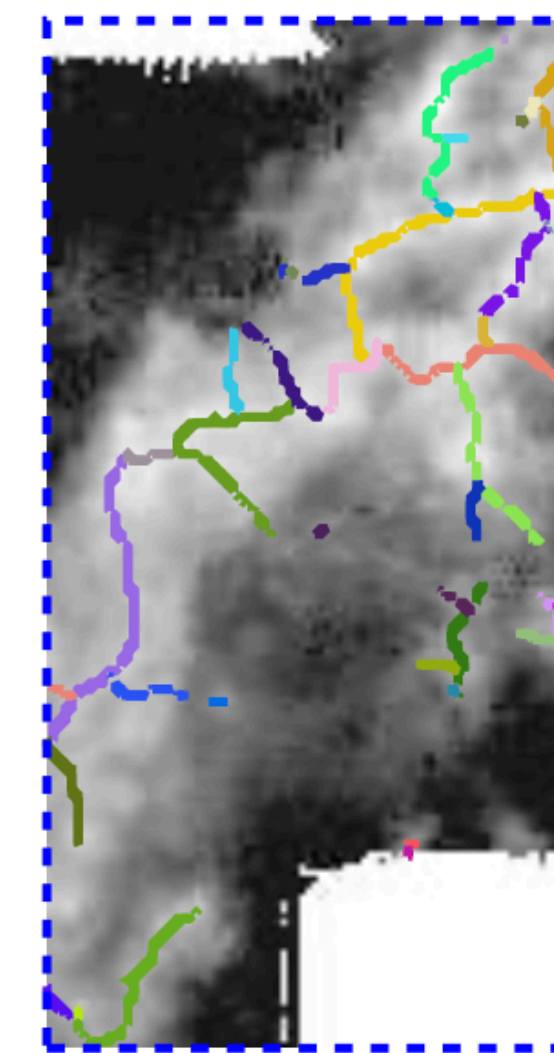
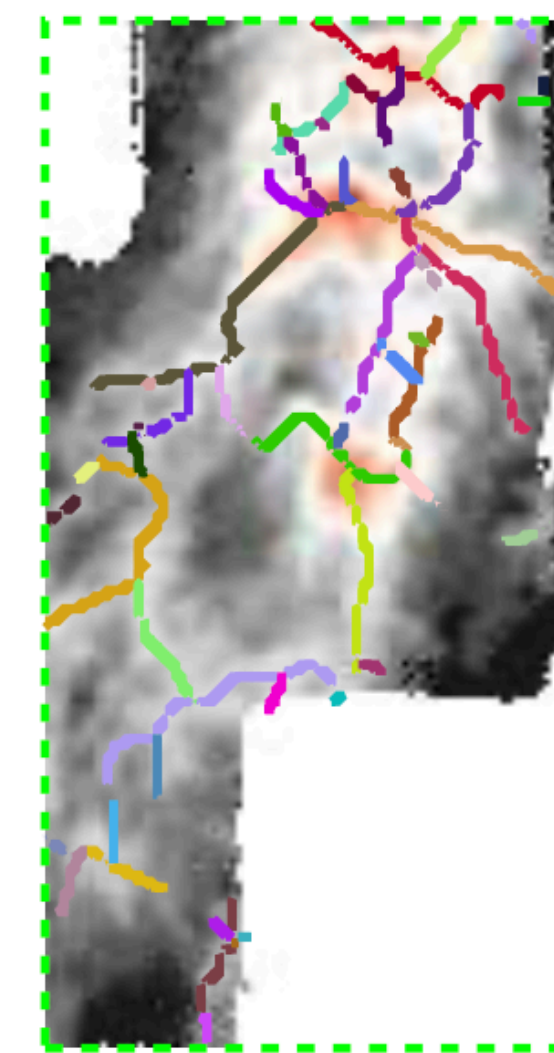


Forms all  
star types  
Including OB

Forms only  
low-mass stars  
(revealed by IR)



(b) 400 pc away from us,  
same age across

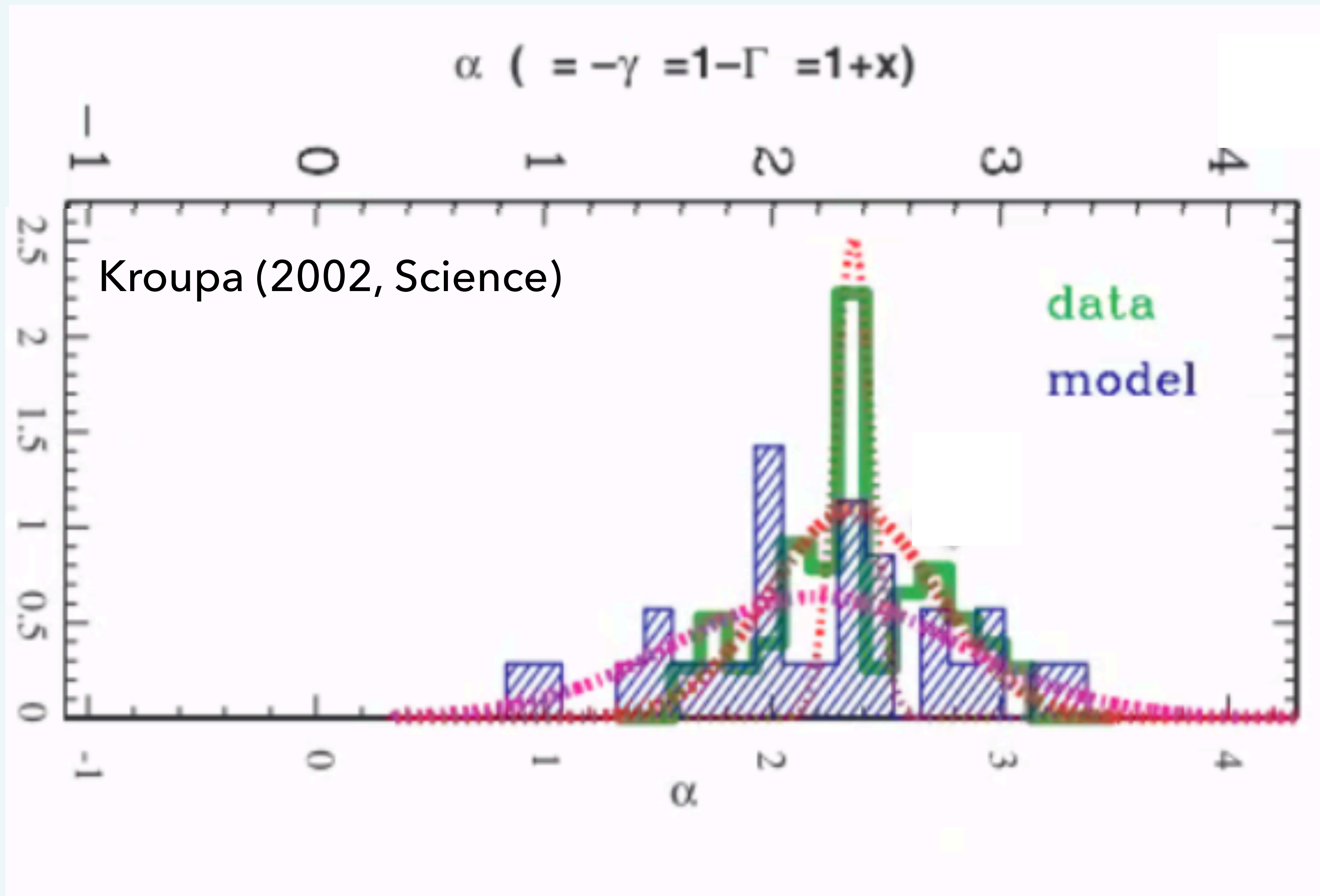


Filamentary star  
formation

Zheng, Wang, Ma, Li (2021, Purple Mountain Observatory, Nanjing)



## Sharp $\alpha$ peak



Observations spike narrowly around  $\alpha = 2.3$   
With symmetric wings

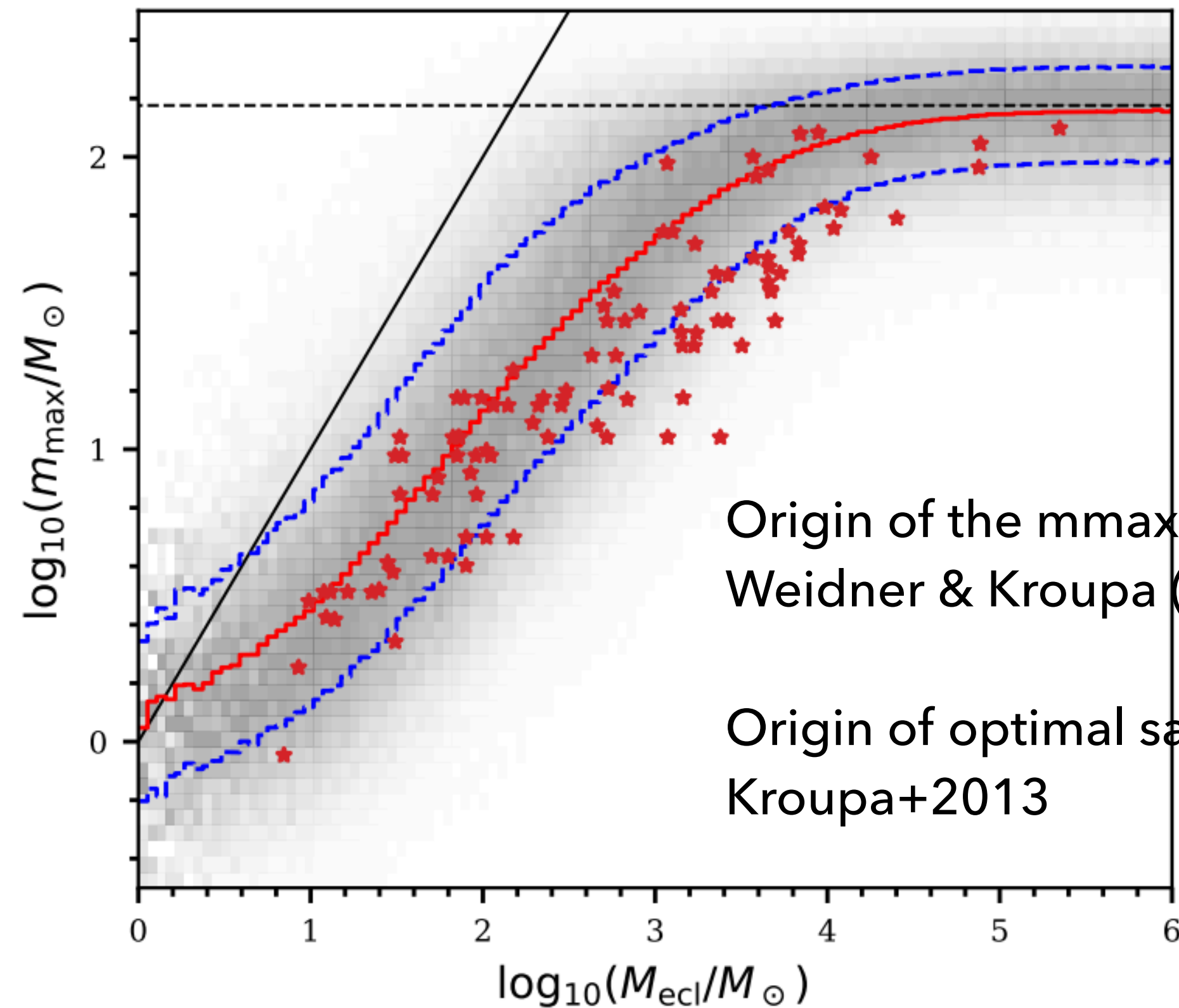
The model with stochastic sampling predicts a much wider, asymmetric distribution for  $\alpha$



$m_{\max} - M_{\text{ecl}}$  relation from Yan+23 (Nanjing University)

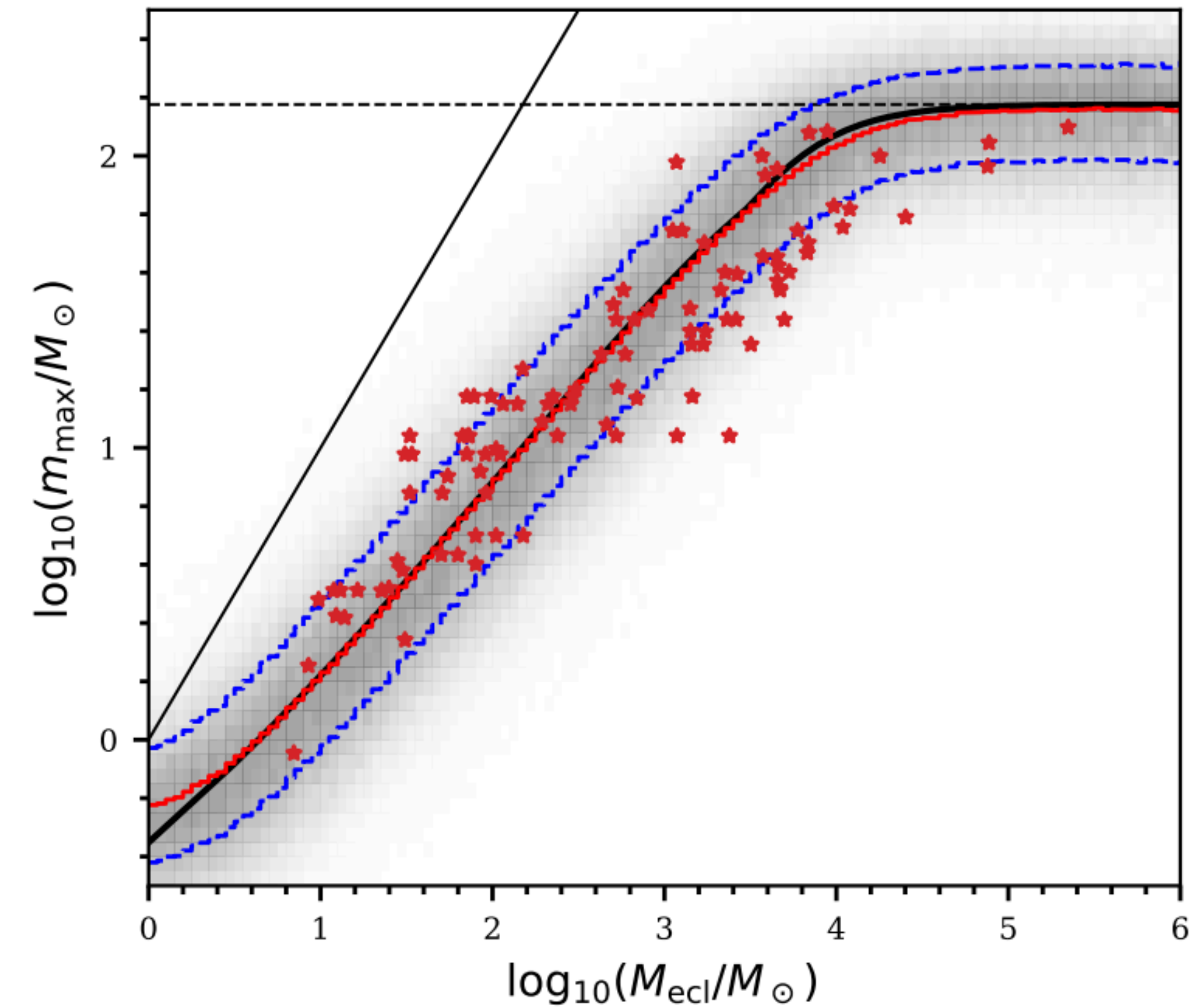
No evidence for intrinsic dispersion:

The observed dispersion is smaller than the uncertainty on the measurement errors



Origin of the  $m_{\max}$ - $m_{\text{ecl}}$  relation  
Weidner & Kroupa (2006, 10, 13)

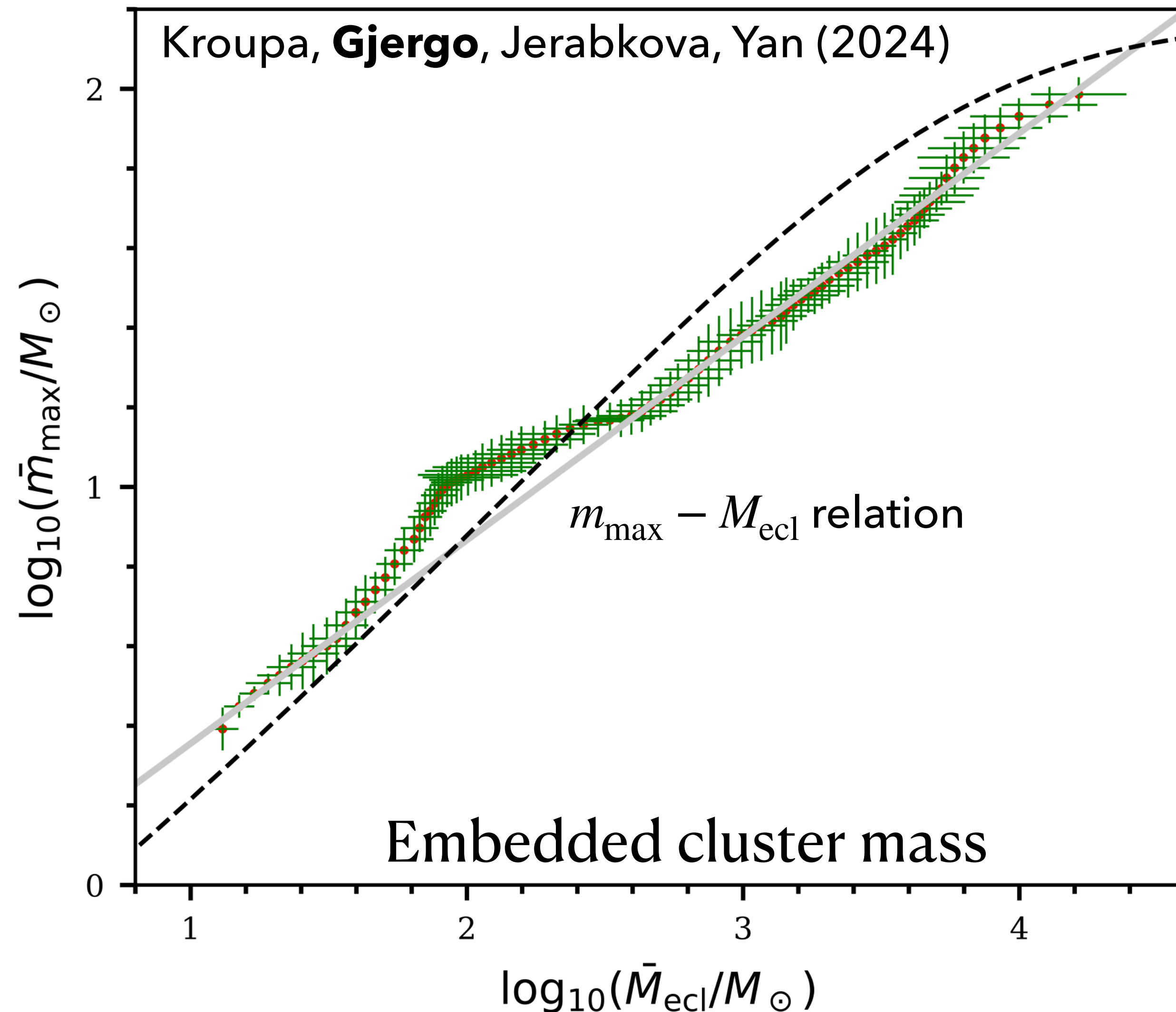
Origin of optimal sampling  
Kroupa+2013



Model name	$\alpha_3$	$m_{\text{up}}$
a23m150	2.3	150



## Relation between the total embedded cluster stellar mass and its most massive star



Red dots with green error bars are the running mean of observations, with associated uncertainty

### No evidence for intrinsic dispersion:

The observed dispersion is smaller than the uncertainty on the measurement errors

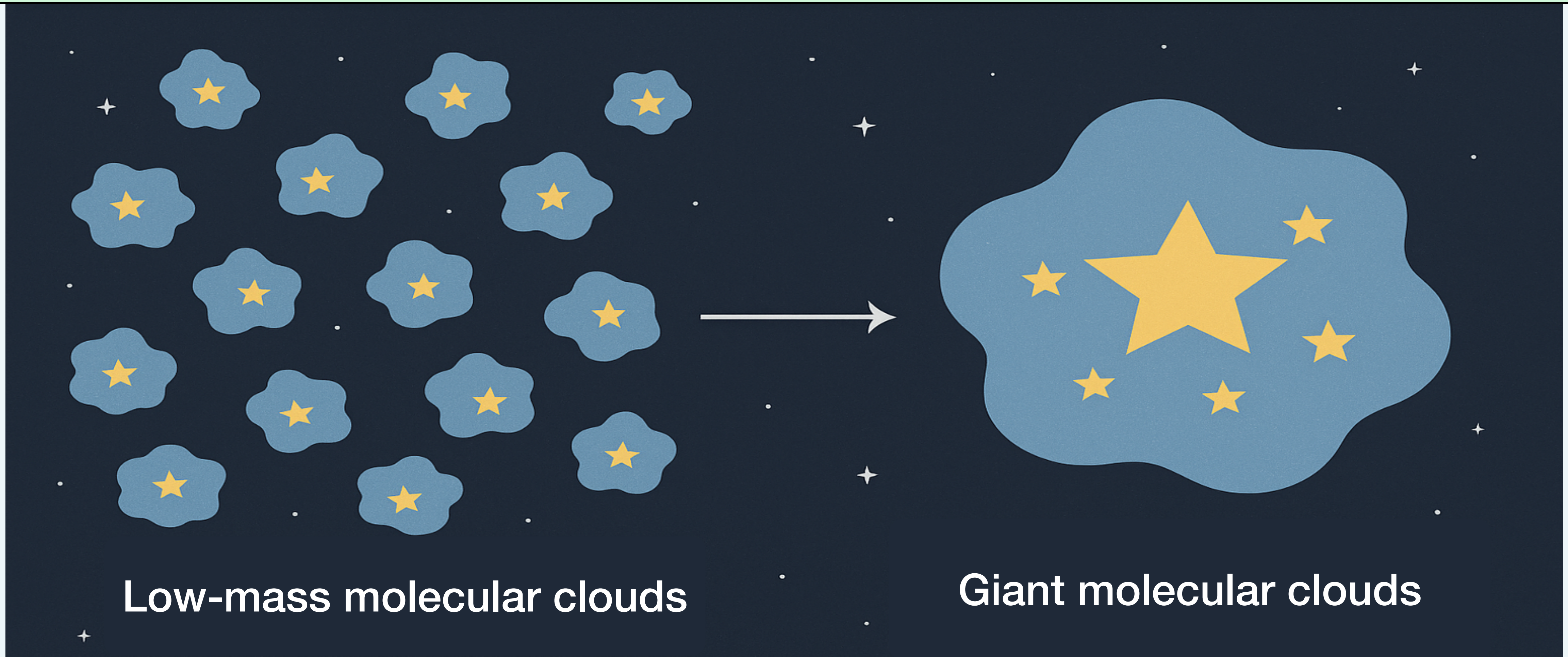
The IGIMF solution is shown with the black-dashed line

The grey line is a linear regression of the data



# Is star formation a stochastic process?

**Can a  $10^3 M_{\odot}$  cloud form a  $100 M_{\odot}$  star?**



Low-mass molecular clouds

Giant molecular clouds

**Are  $1000 \times 10^3 M_{\odot}$  clouds equivalent to a single  $10^6 M_{\odot}$  cloud?**

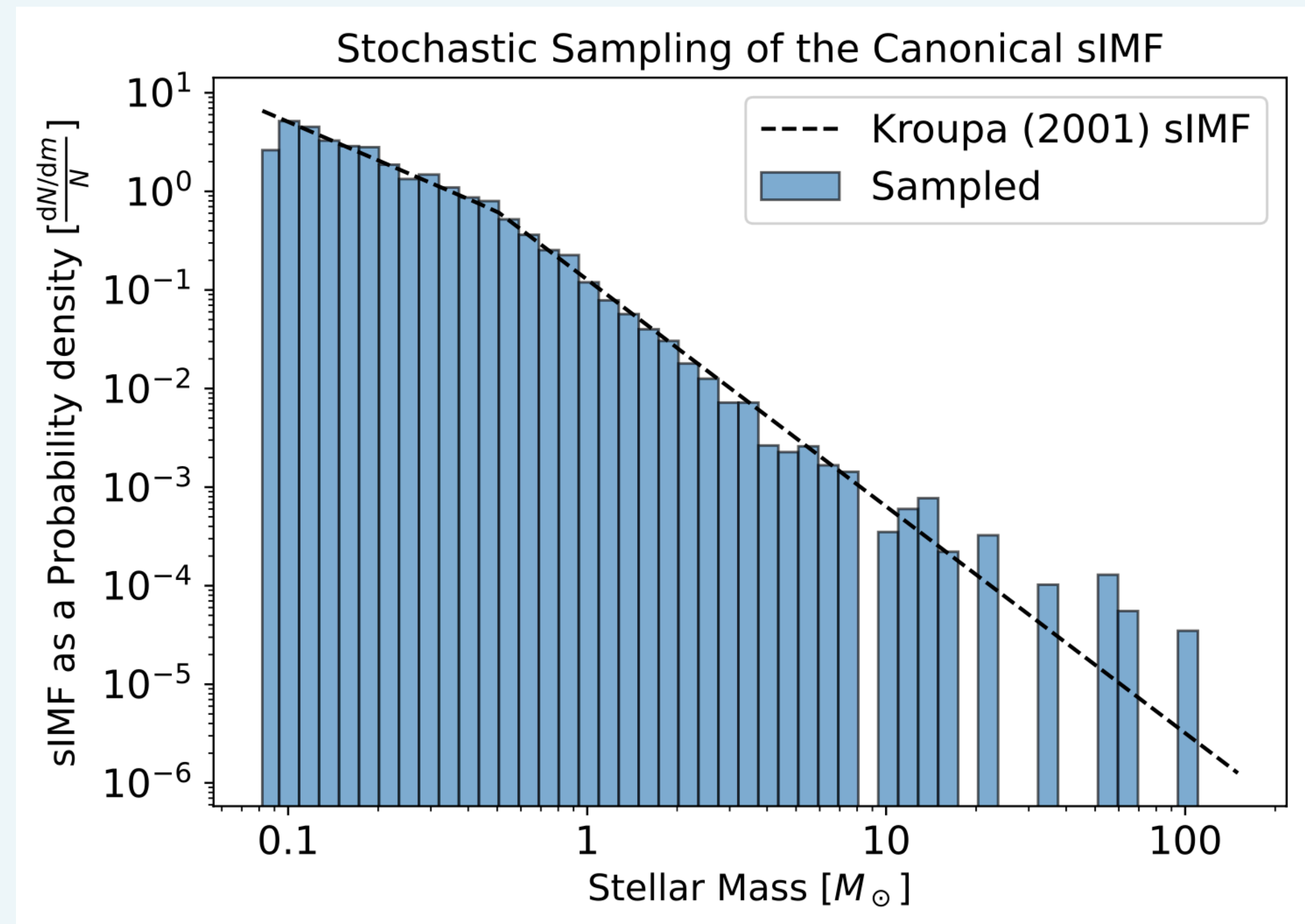


# Building an SSP: How Should We Sample the IMF?

Gjergo, Zhang & Kroupa (2025, subm.)



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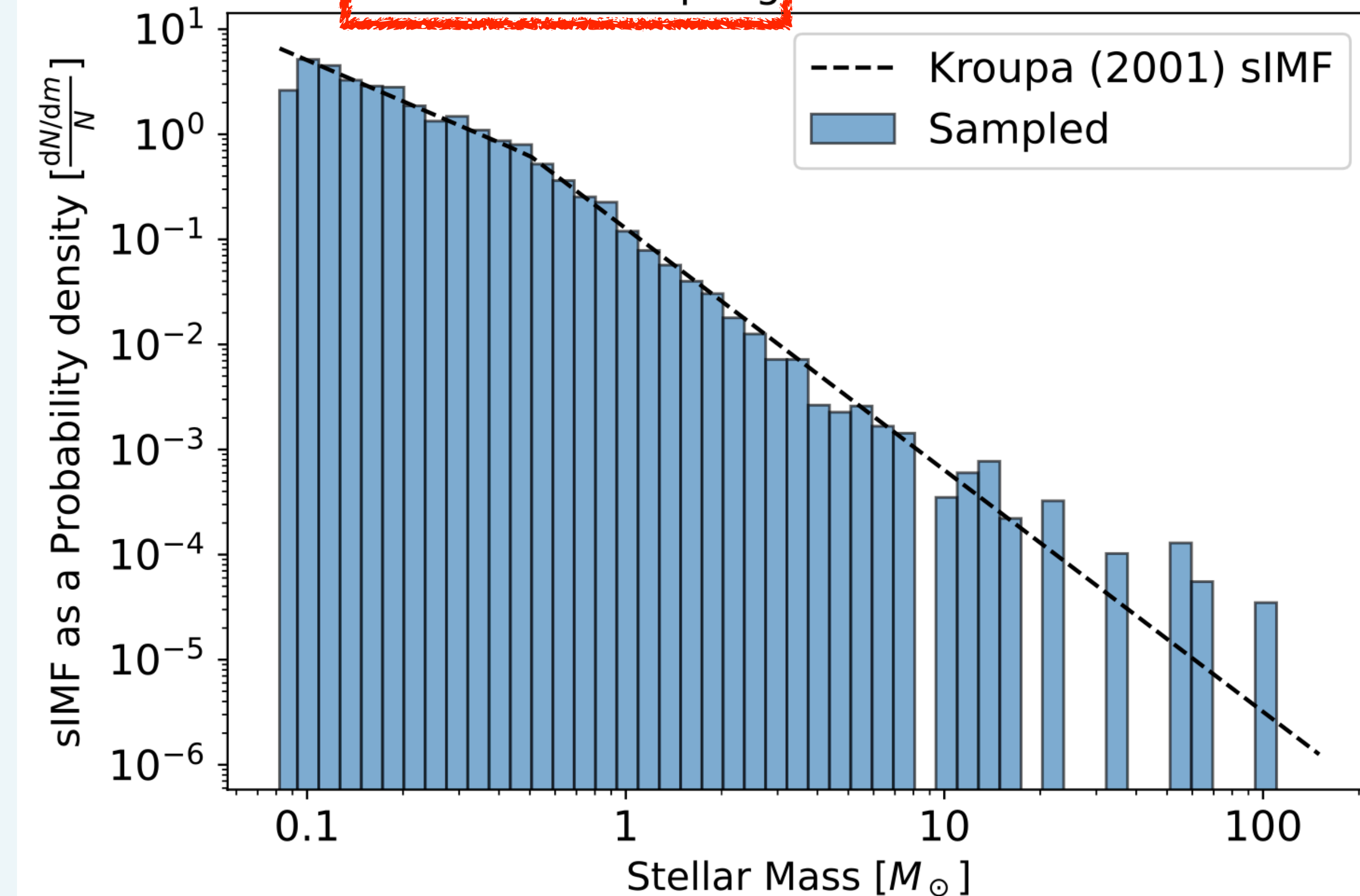


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# Building an SSP: How Should We Sample the IMF?

Stochastic Sampling of the Canonical sIMF

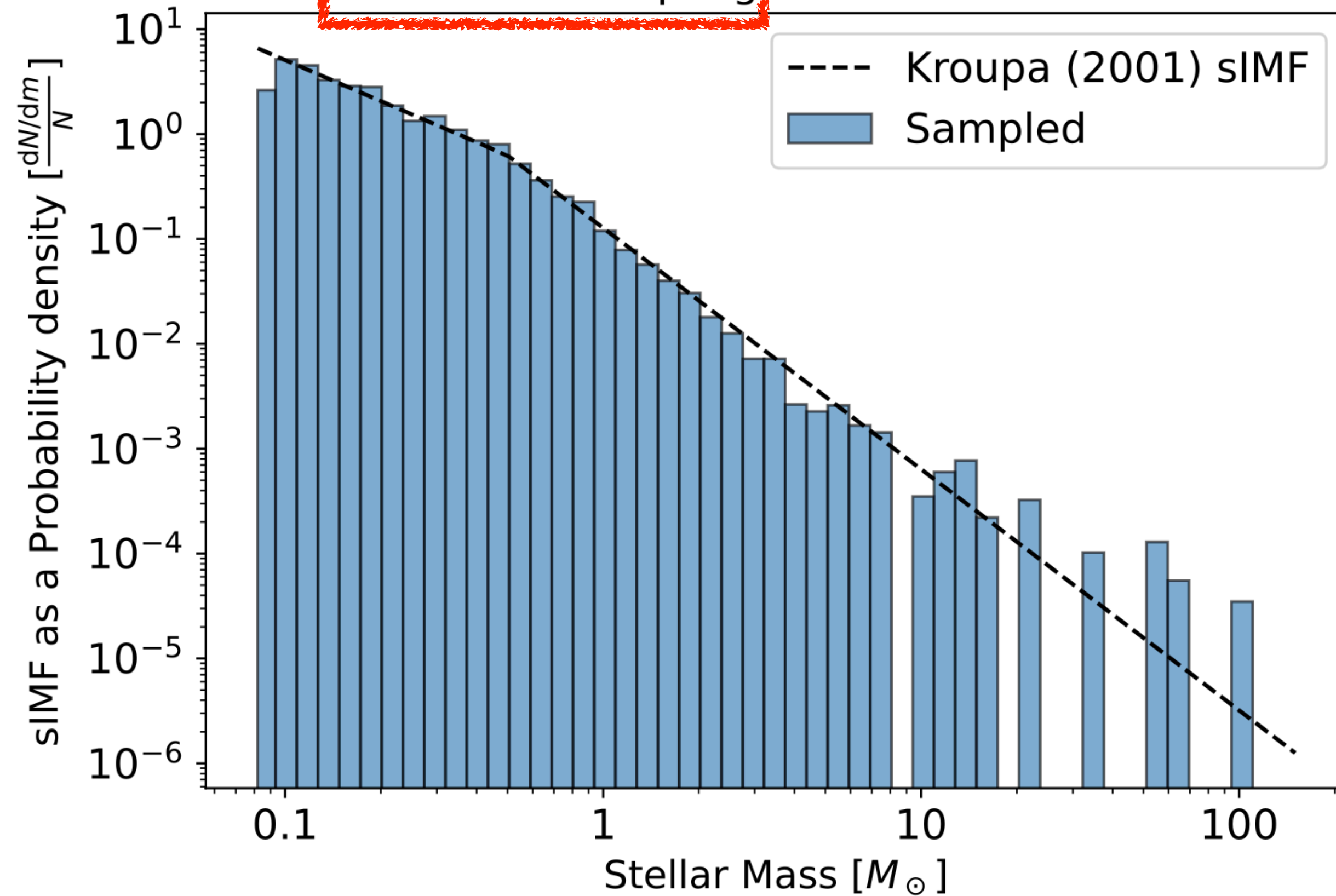


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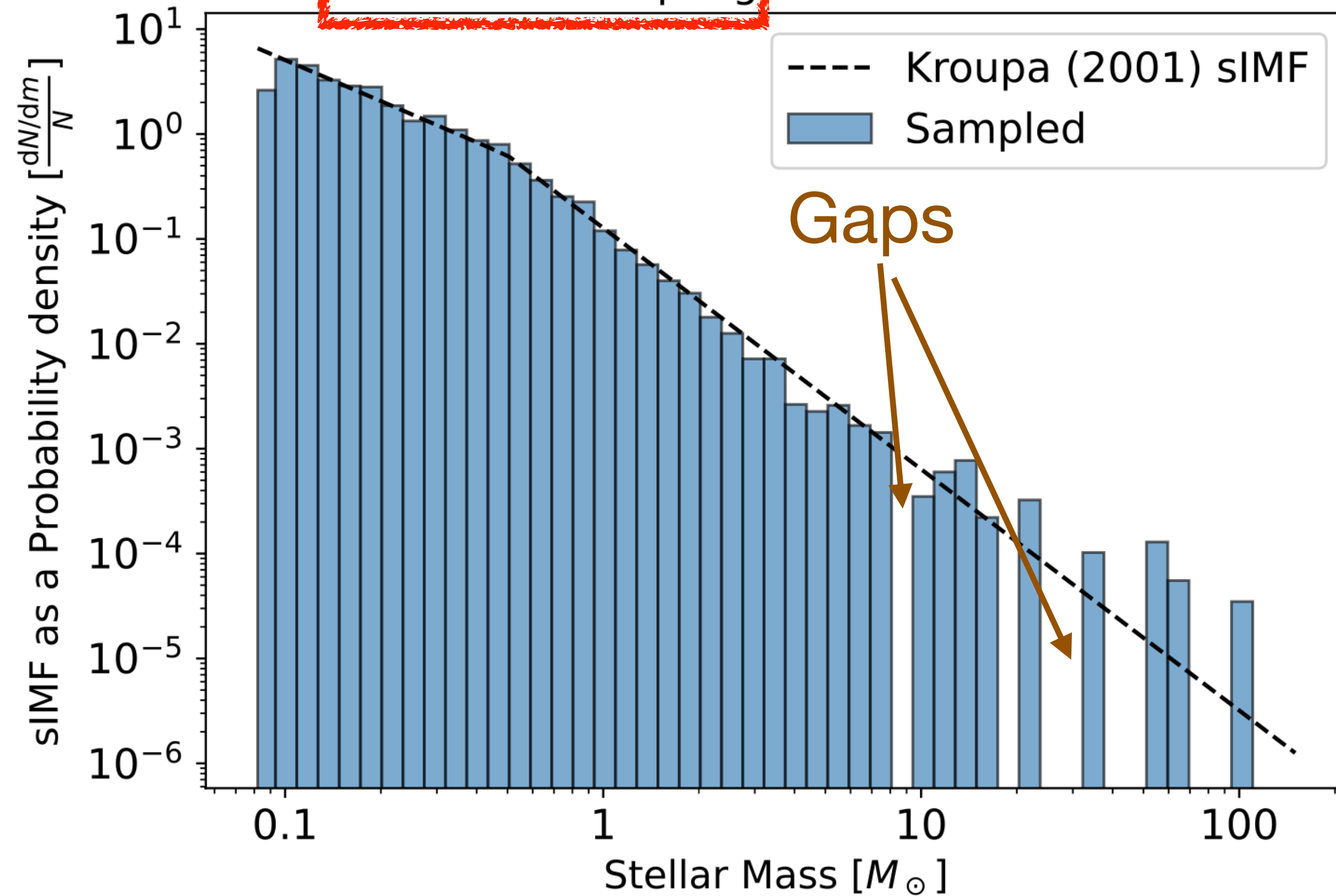
Treats the sIMF  
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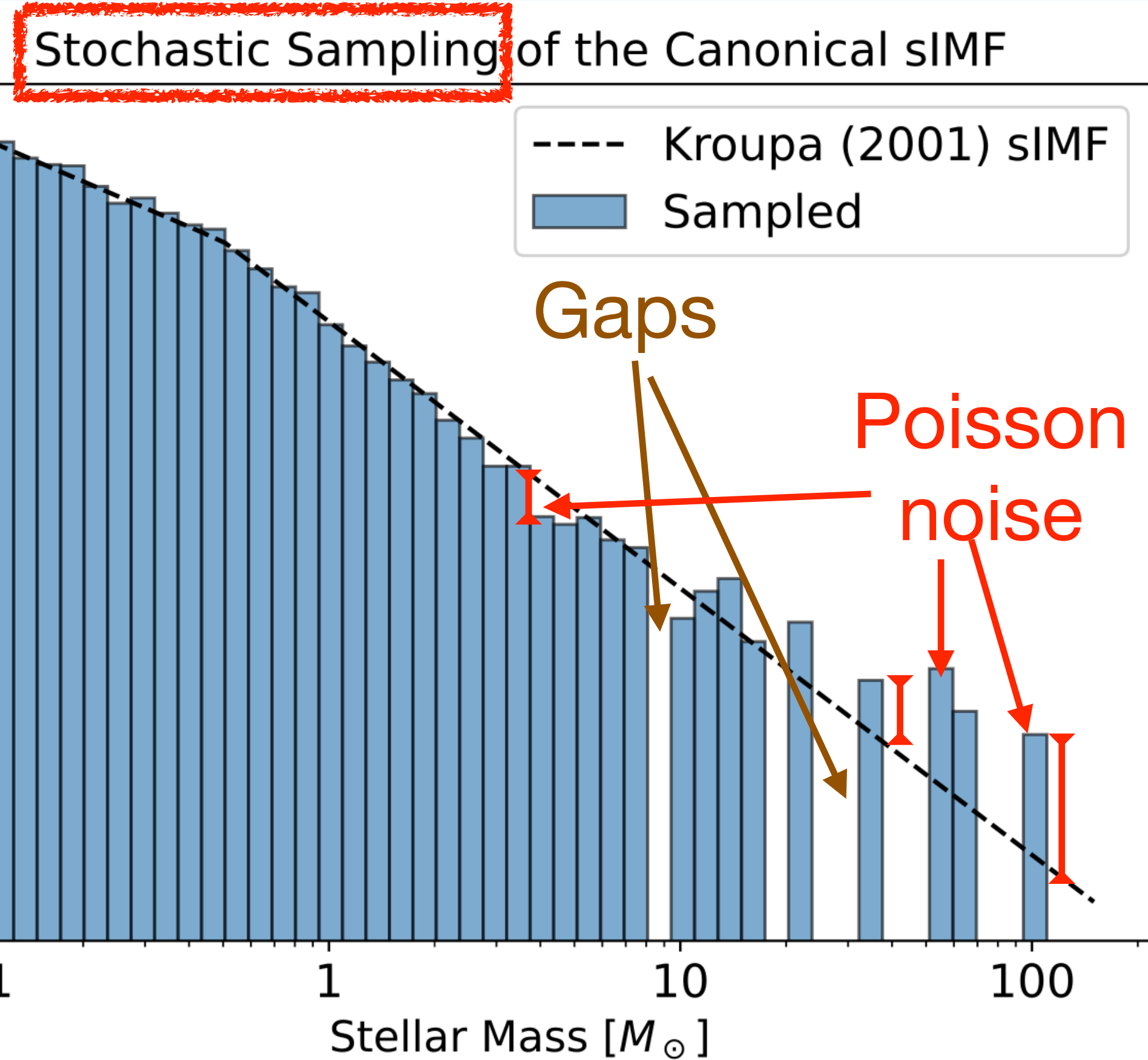


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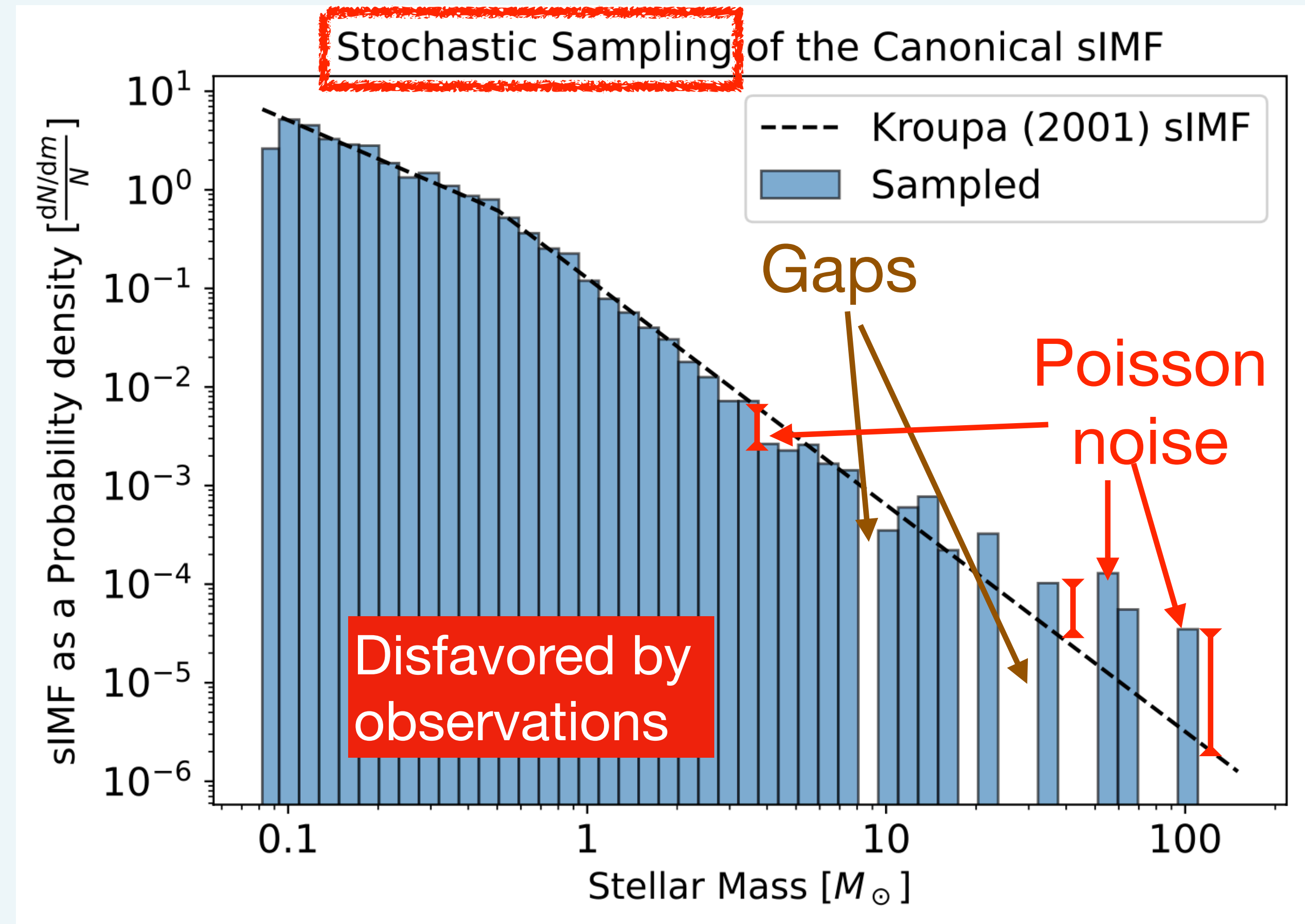


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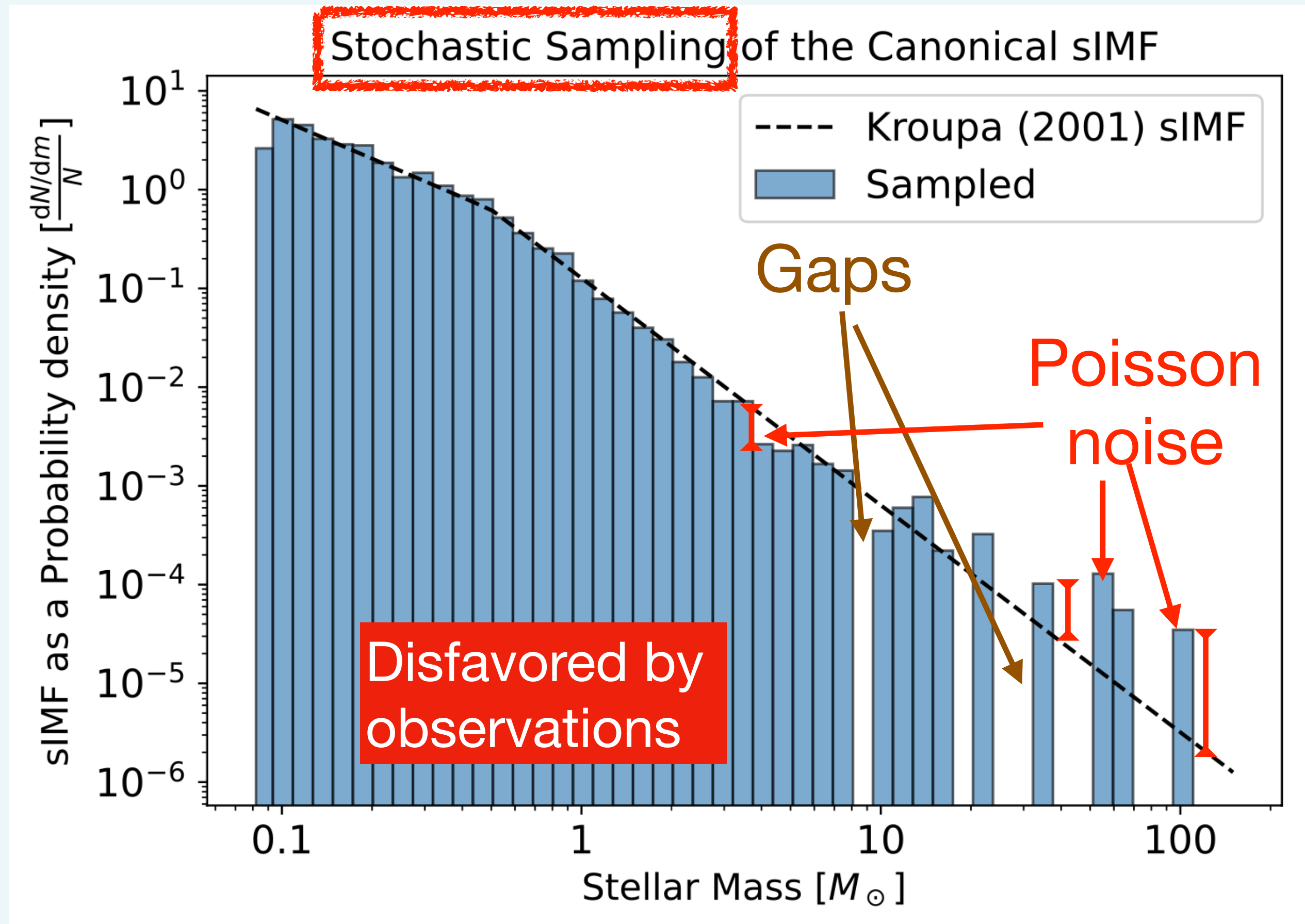


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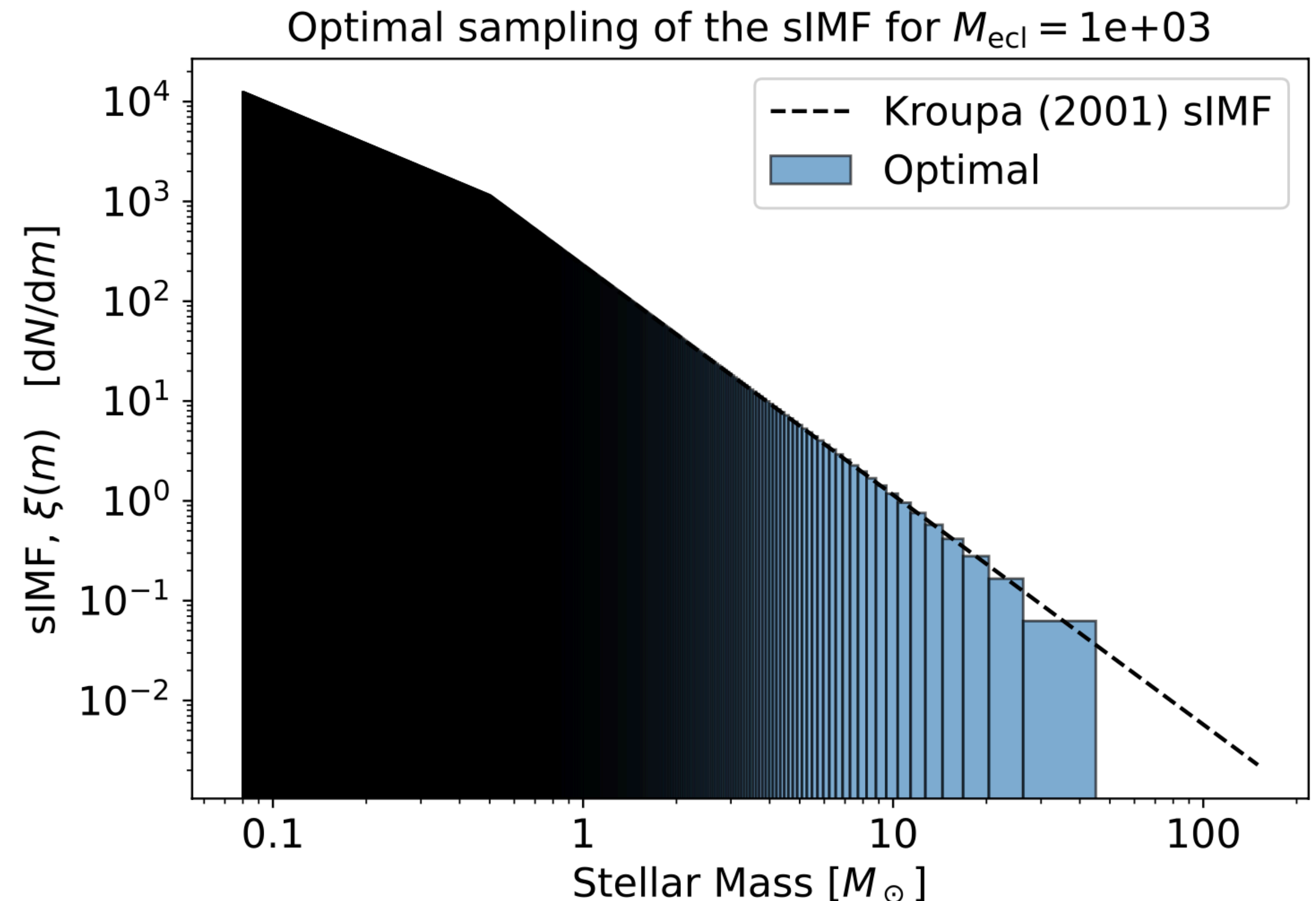
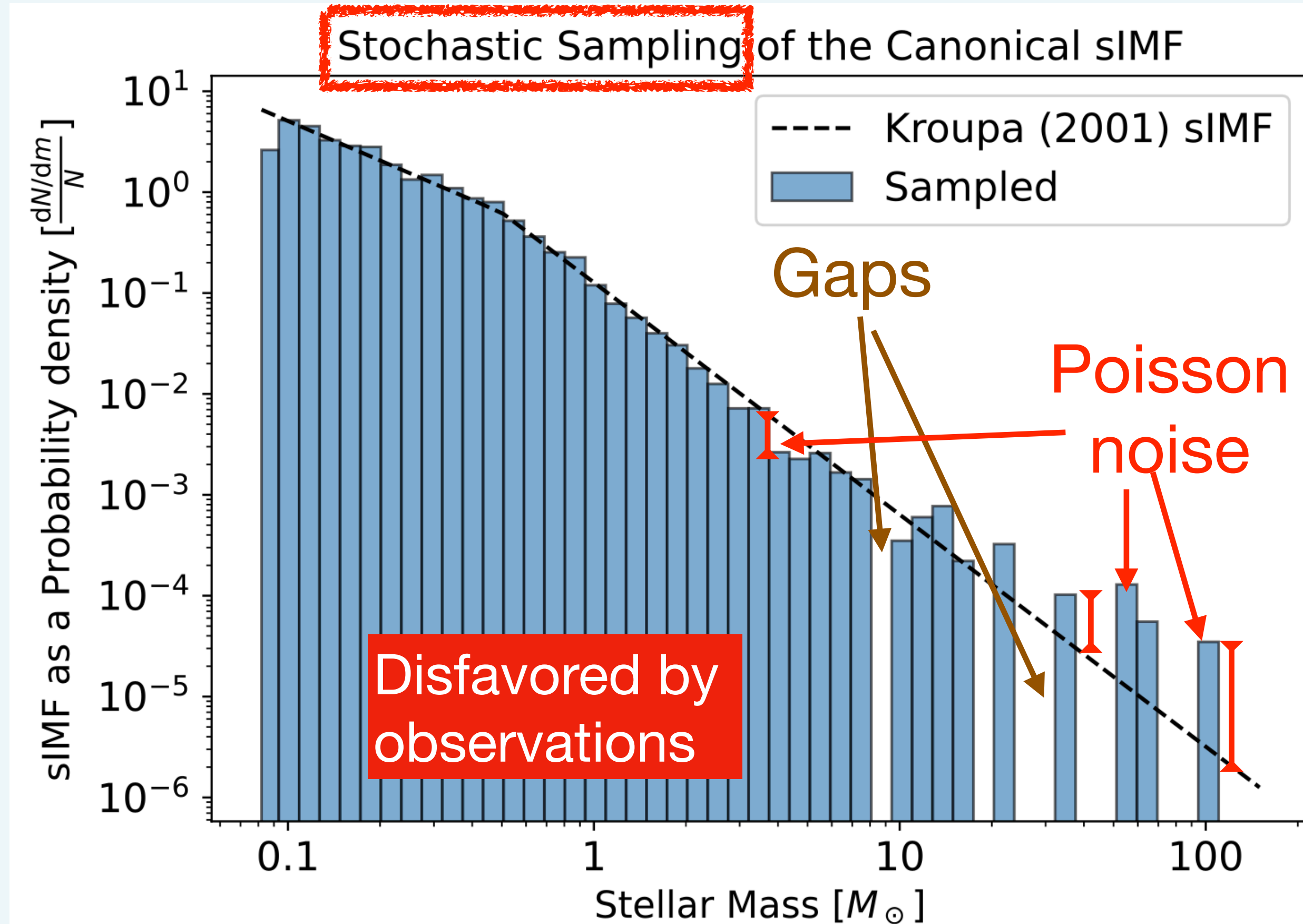


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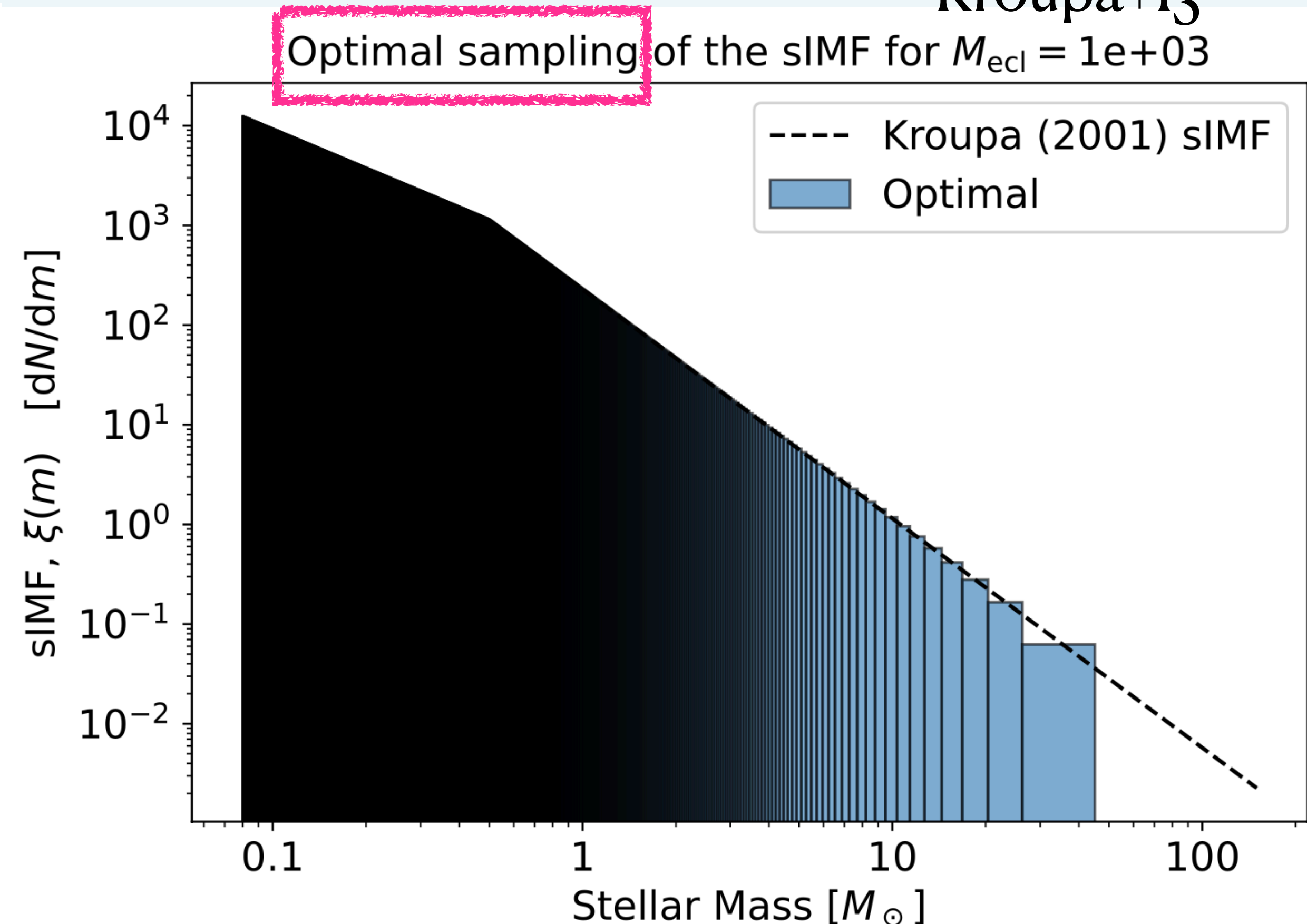
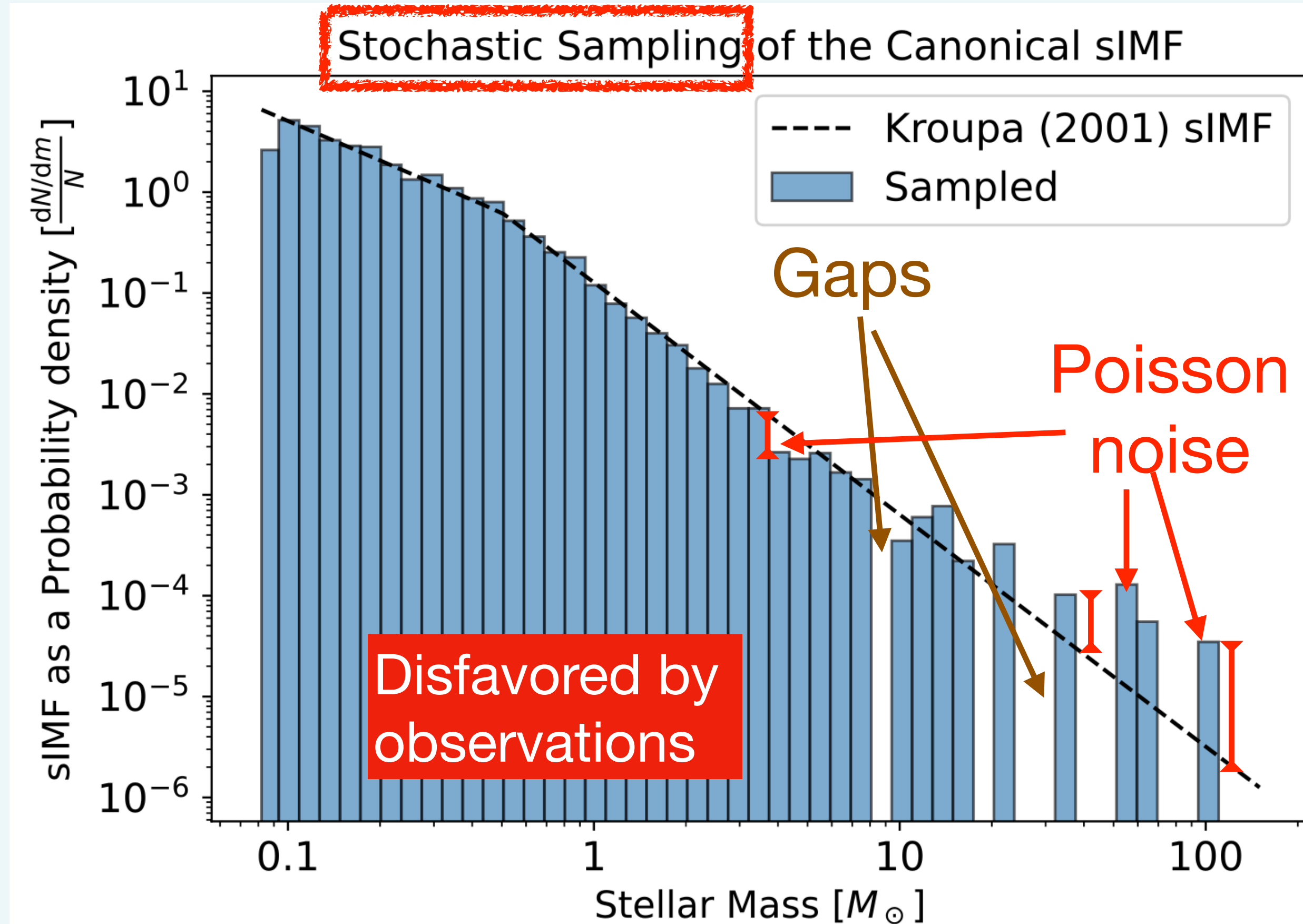
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# Building an SSP: How Should We Sample the IMF?

First introduced in  
Kroupa+13



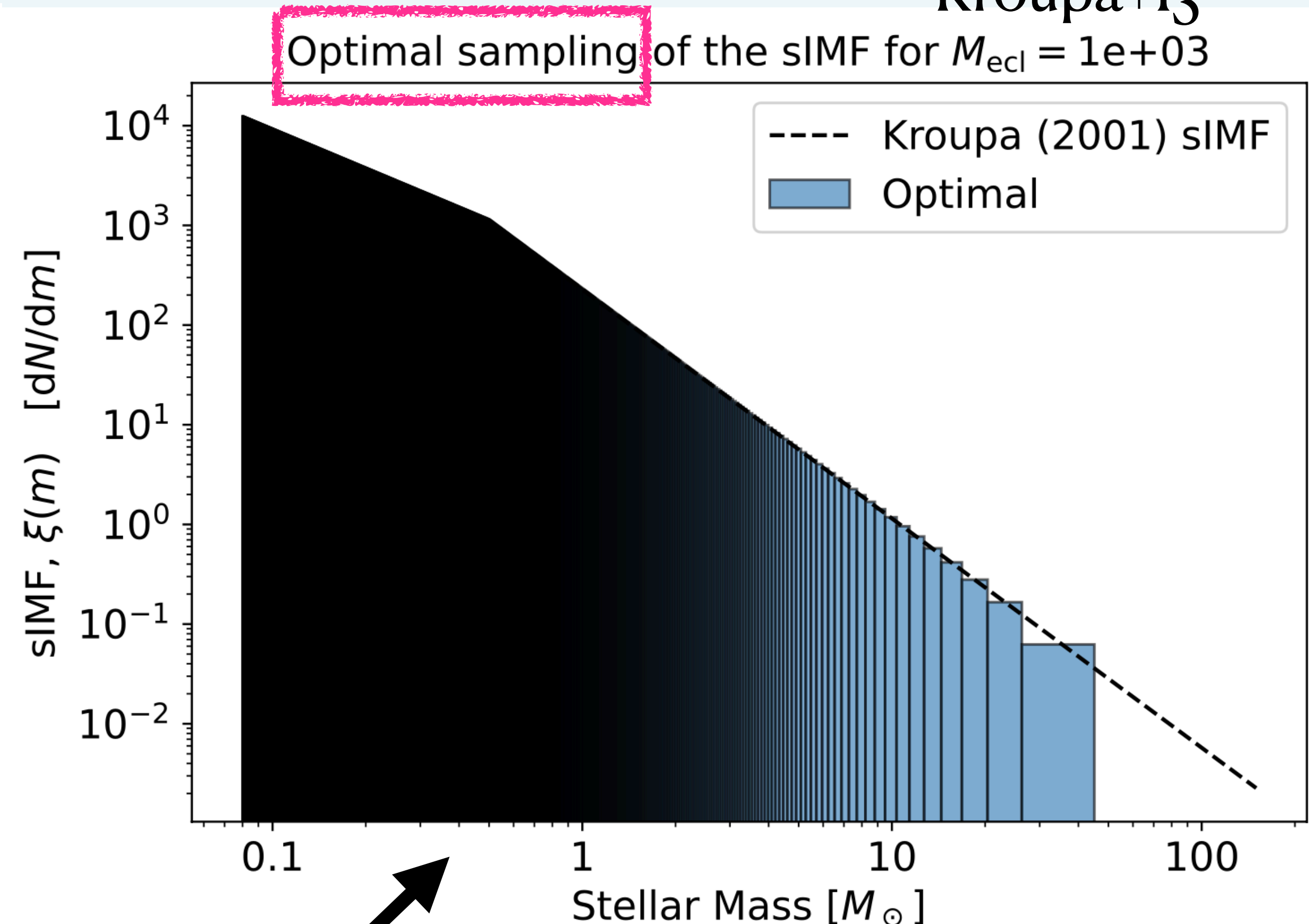
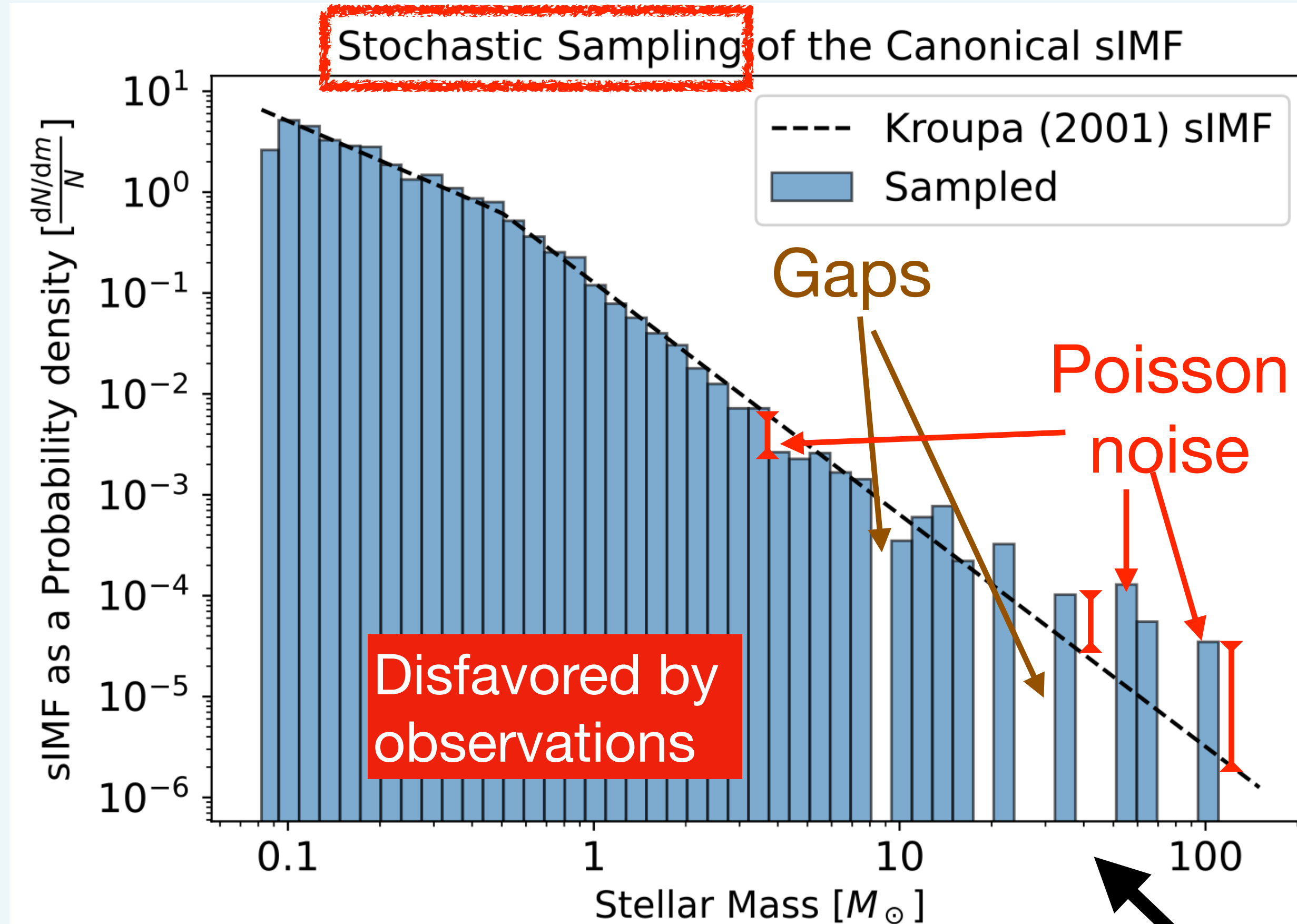
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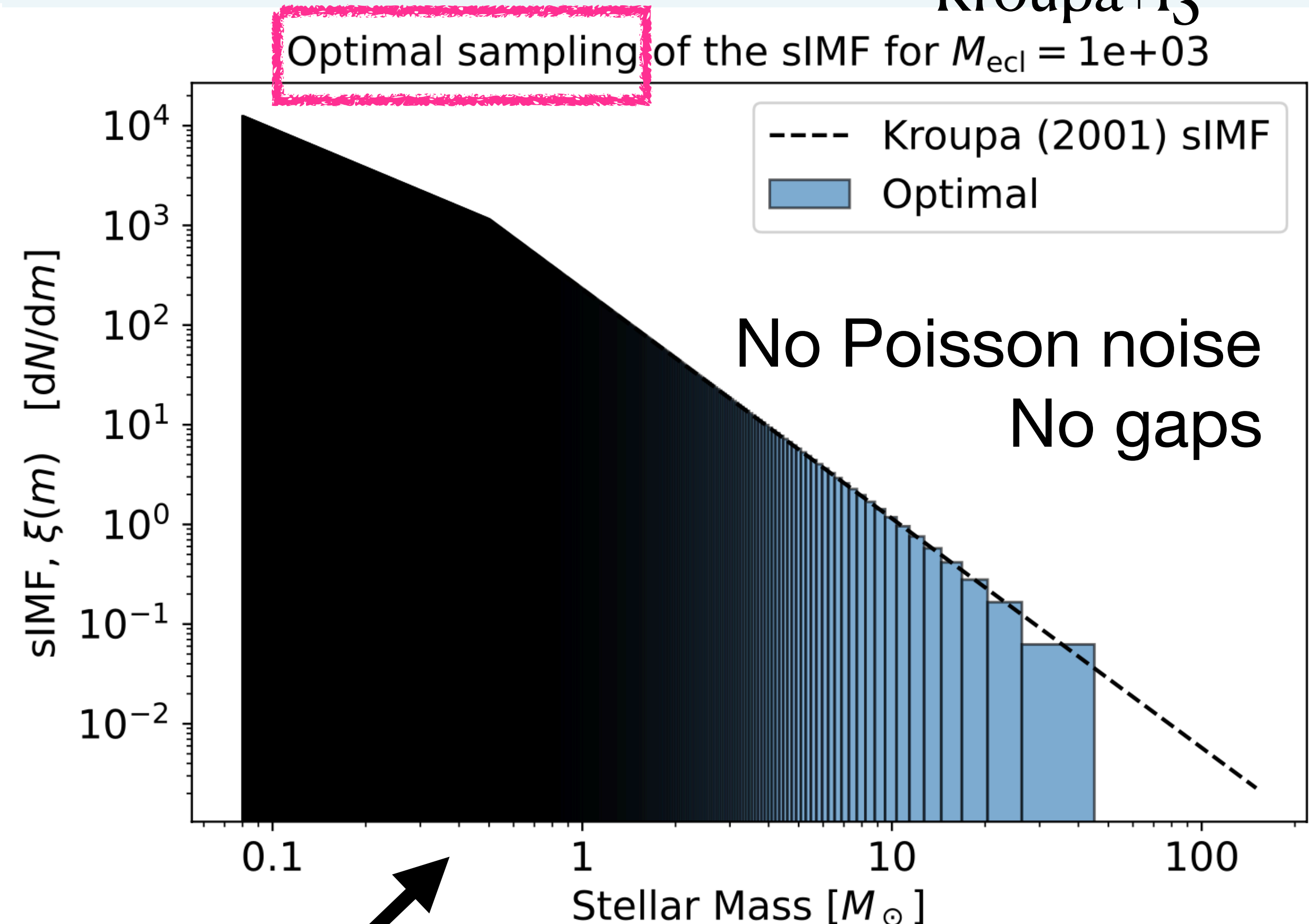
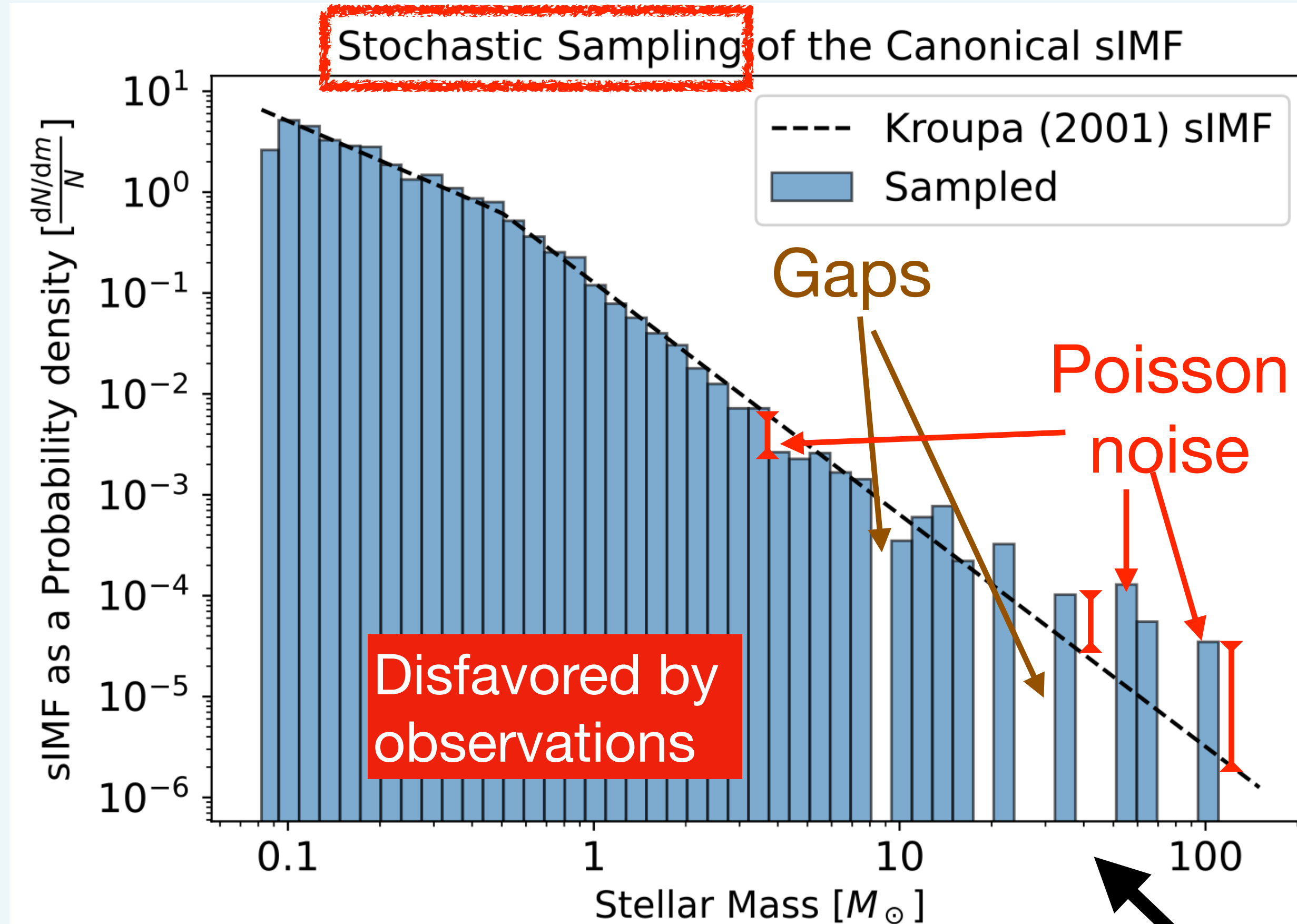
Same total stellar mass ( $M_{\text{ecl}}$ )  
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Gjergo, Zhang & Kroupa (2025, subm.)



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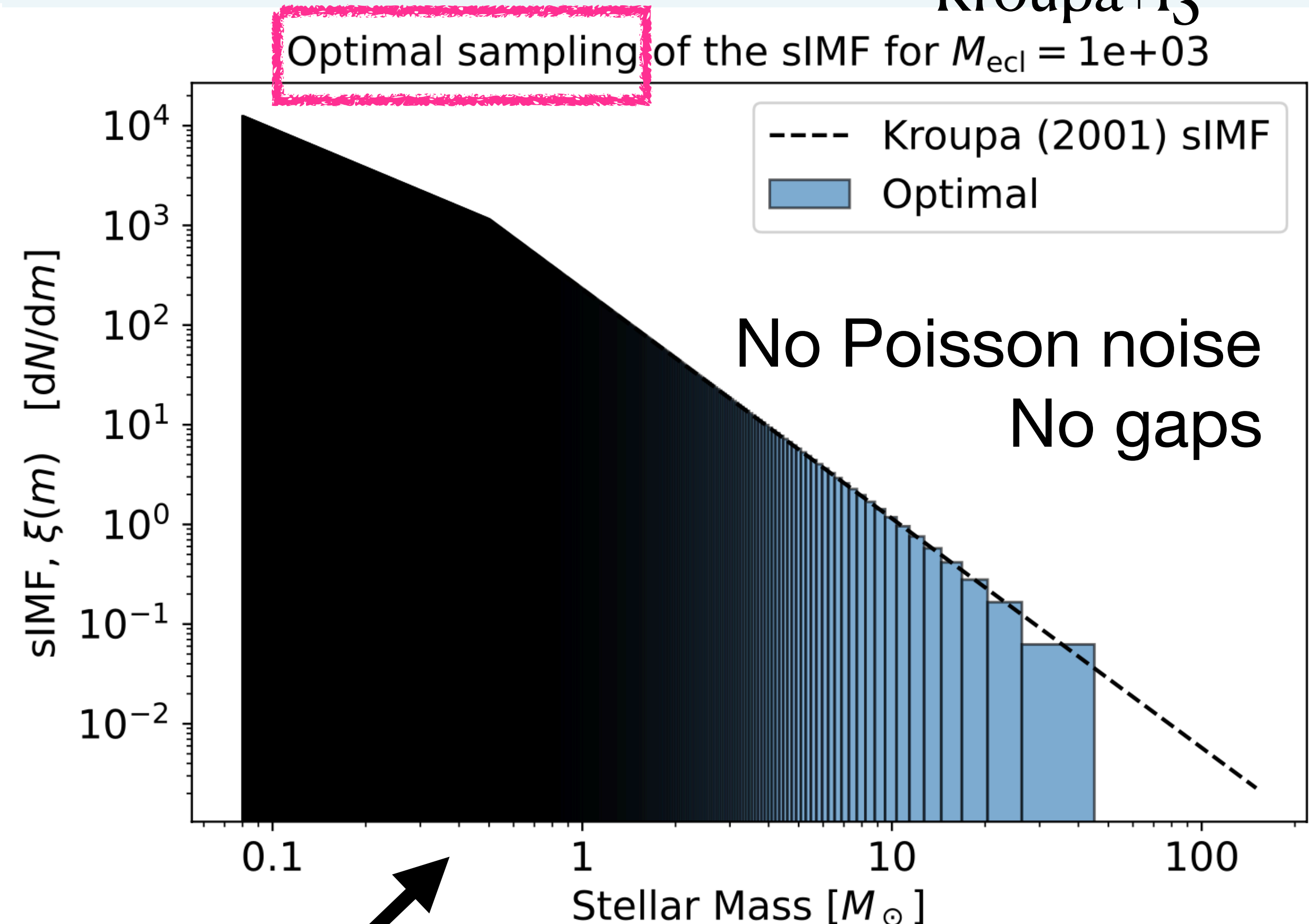
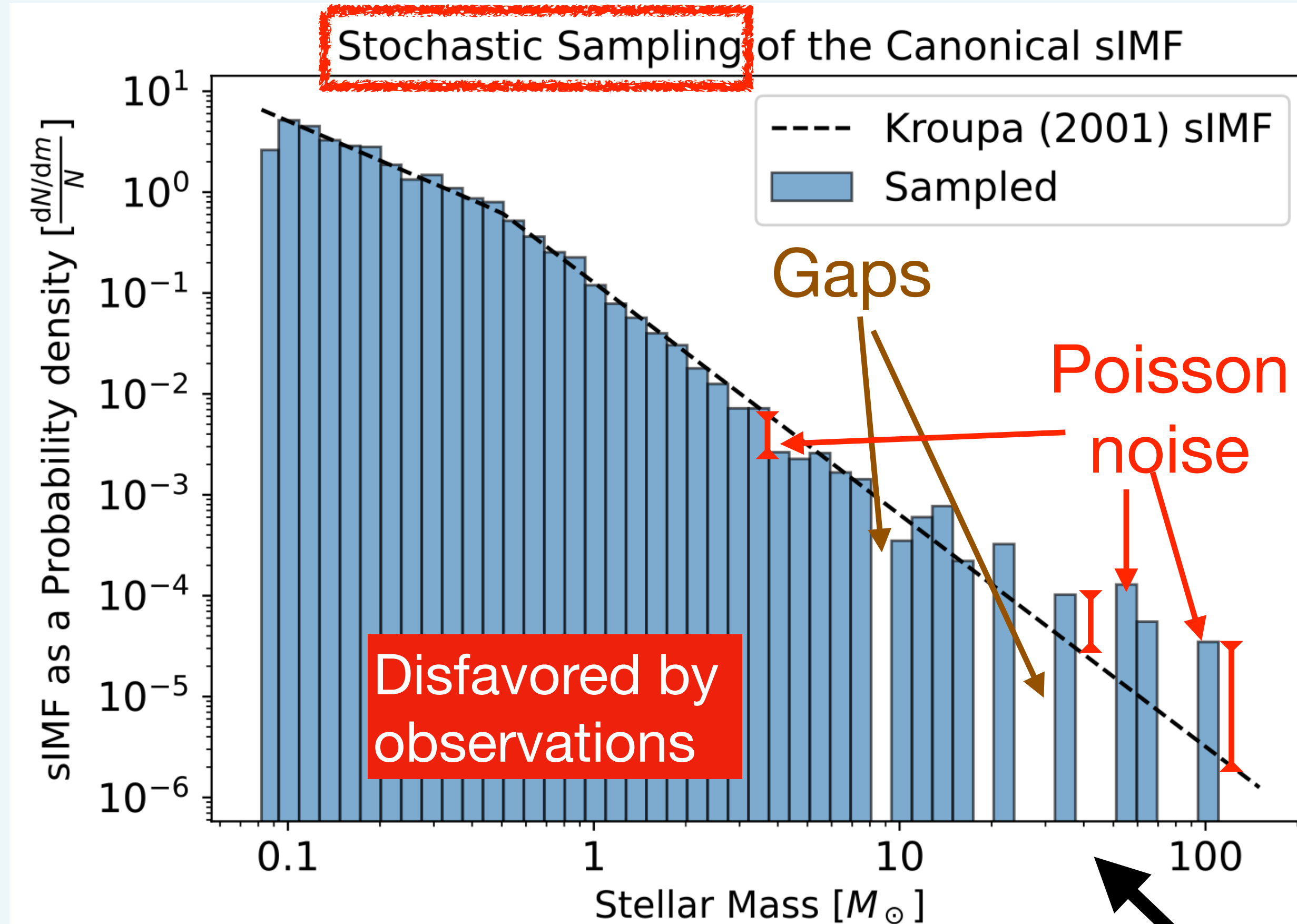
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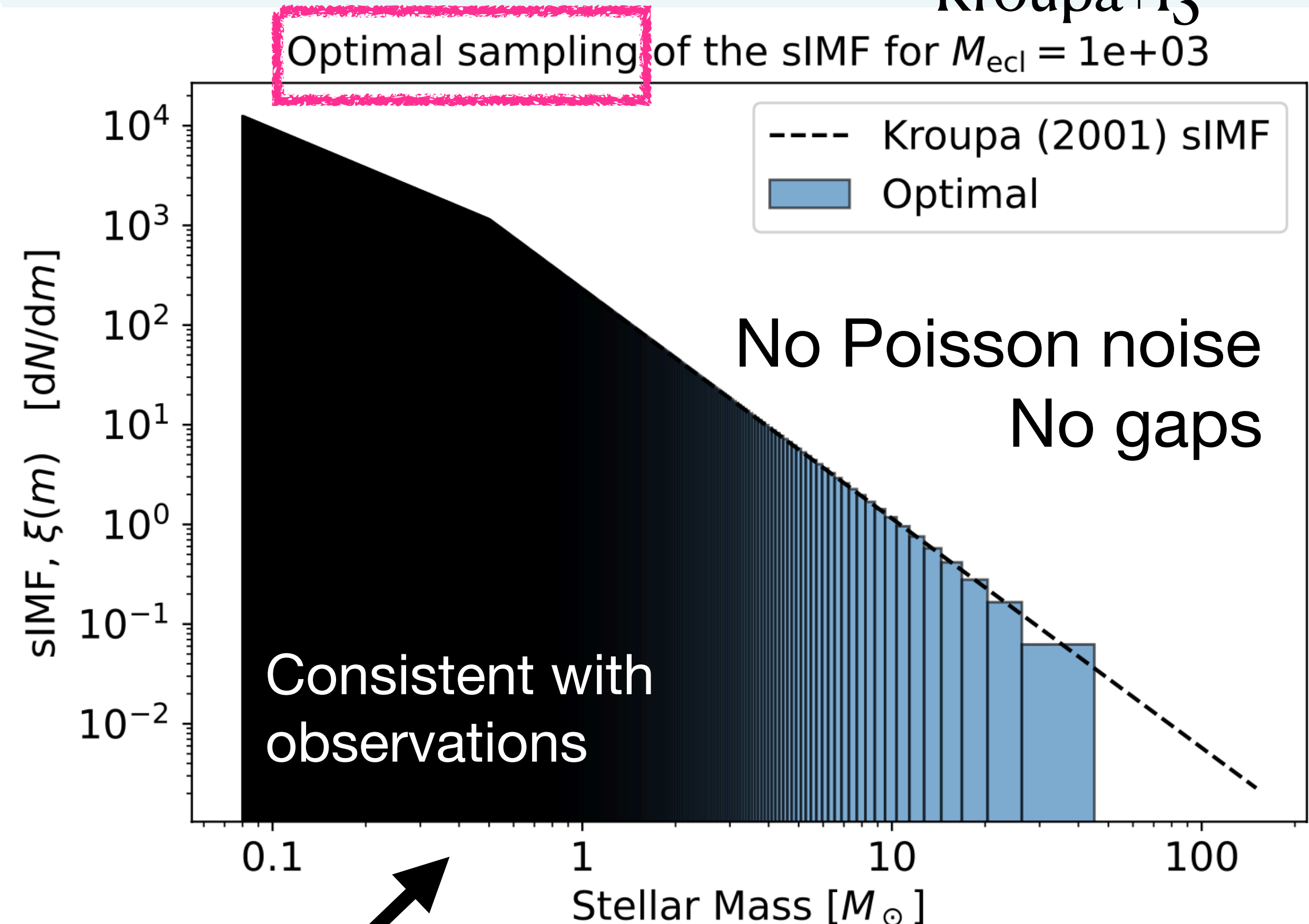
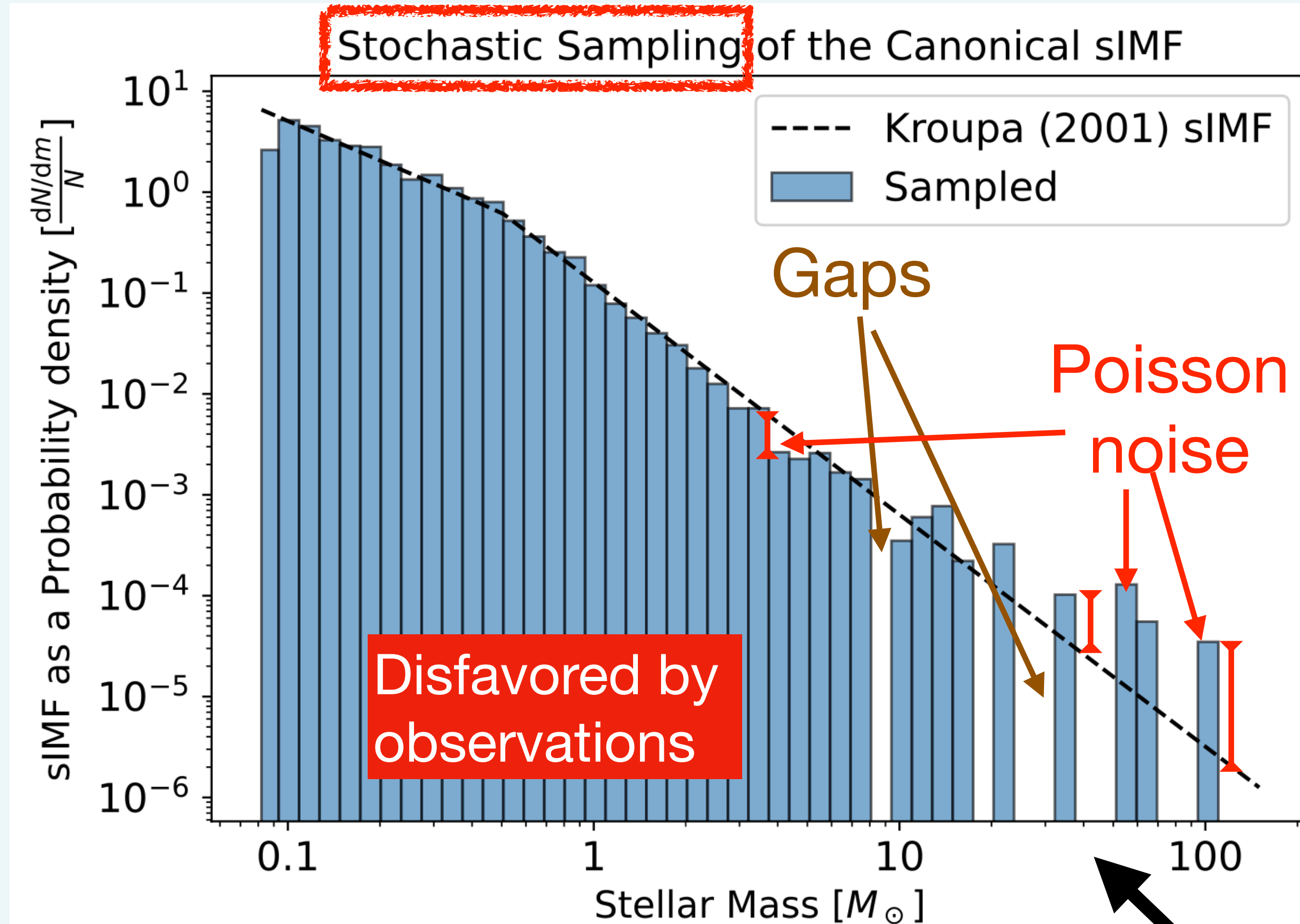
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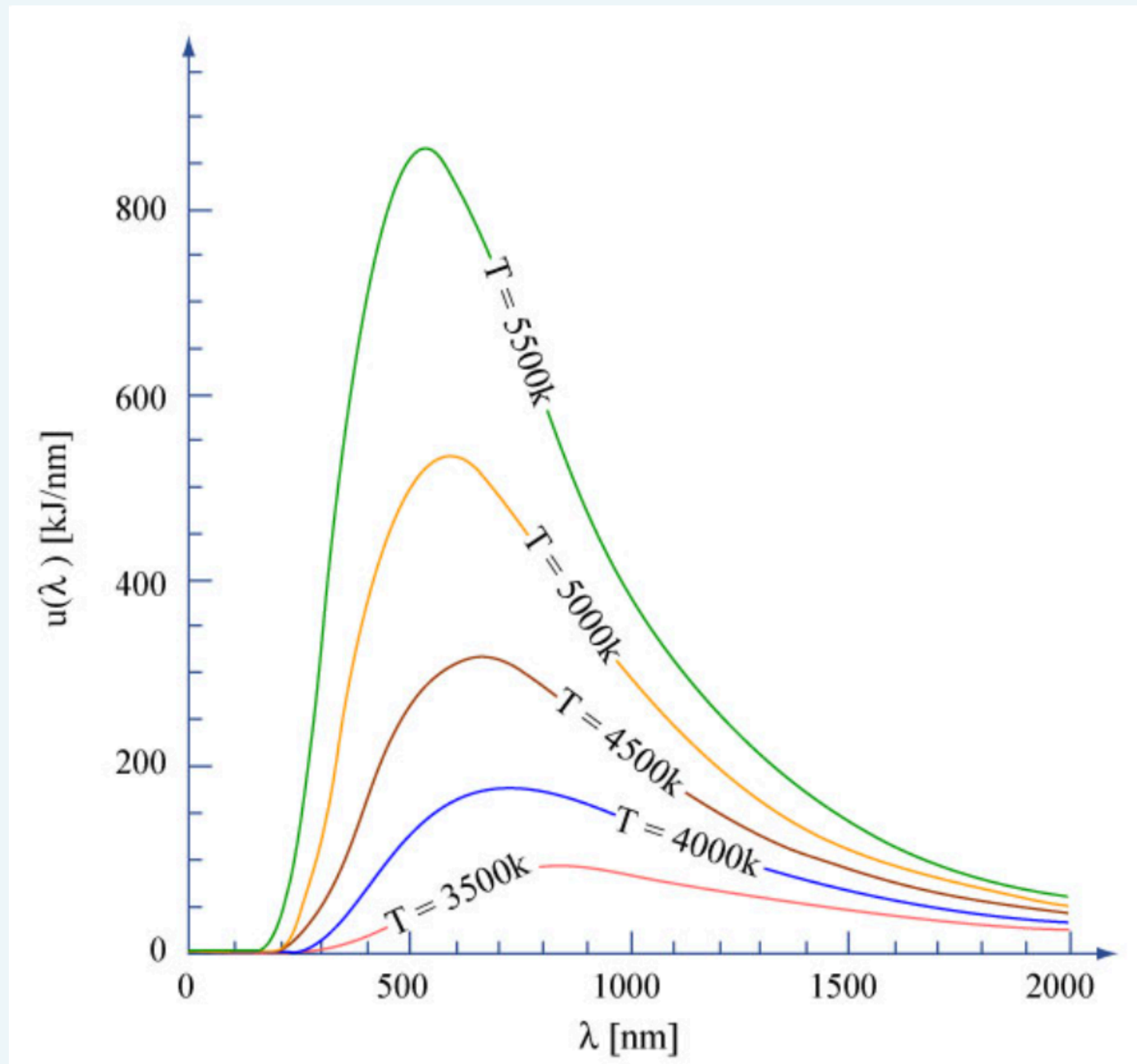
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Gjergo, Zhang & Kroupa (2025, subm.)



# Analogy with Planck's Law:

Gjergo, Zhang & Kroupa (2025, subm.)

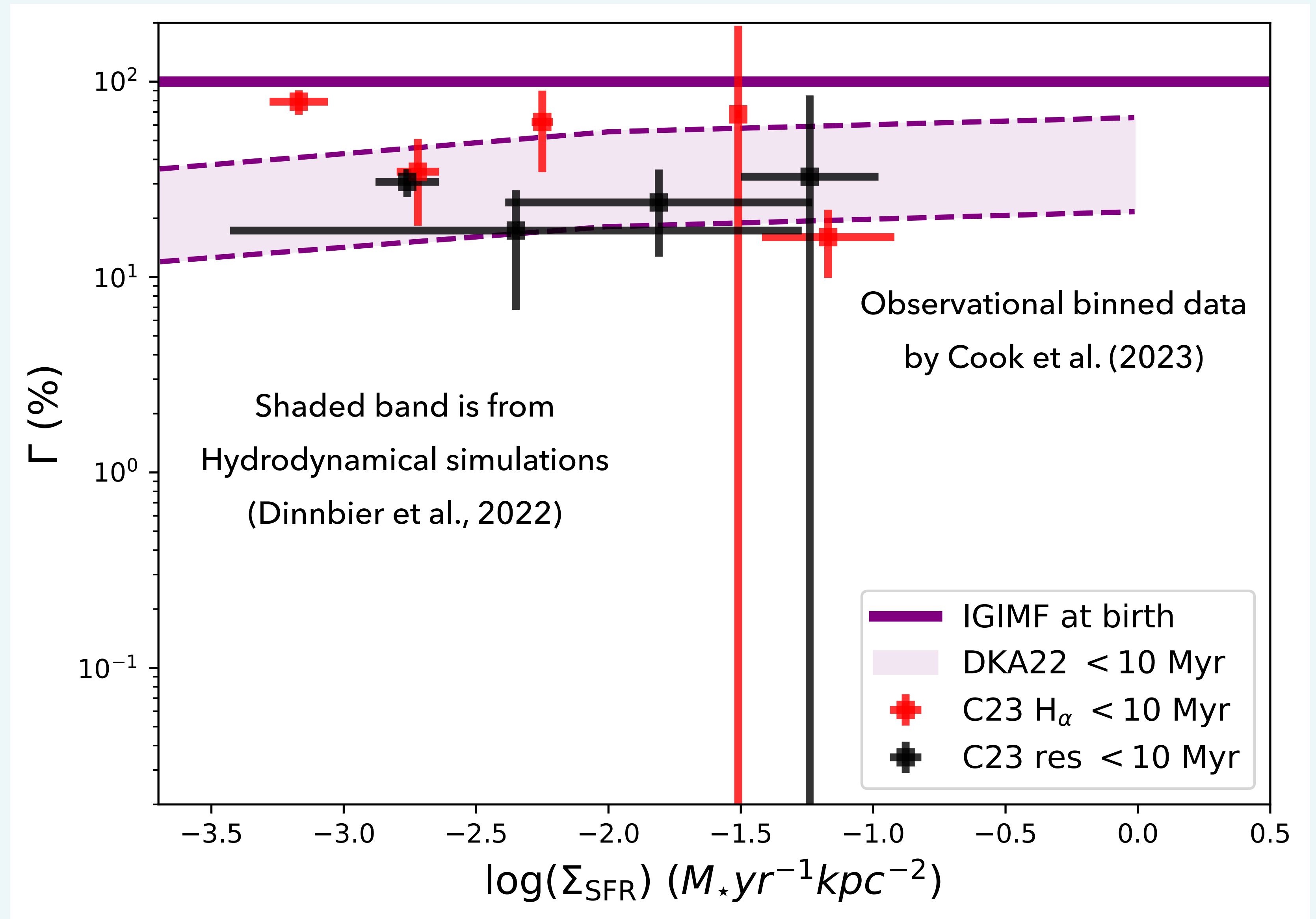


- Statistical mechanics at thermal equilibrium is self-regulated:
- A single parameter (average temperature) determines the full distribution
- The chaotic creation, annihilation, and scattering of photons reaches a steady state
- The complexity of the microstates is washed out by the equilibrium



Where do stars form?

$\Gamma$  is the percentage of stars born in embedded clusters



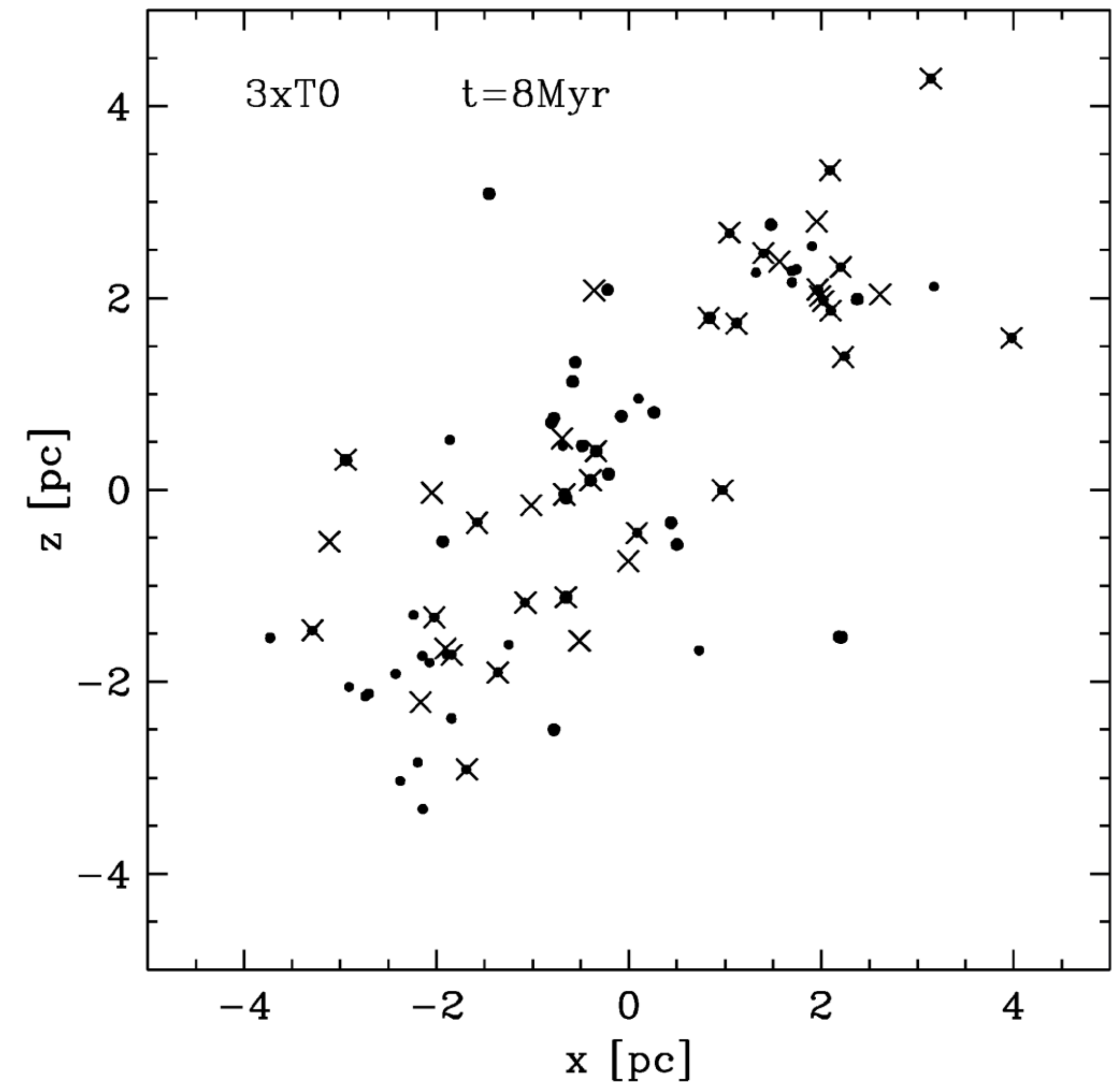
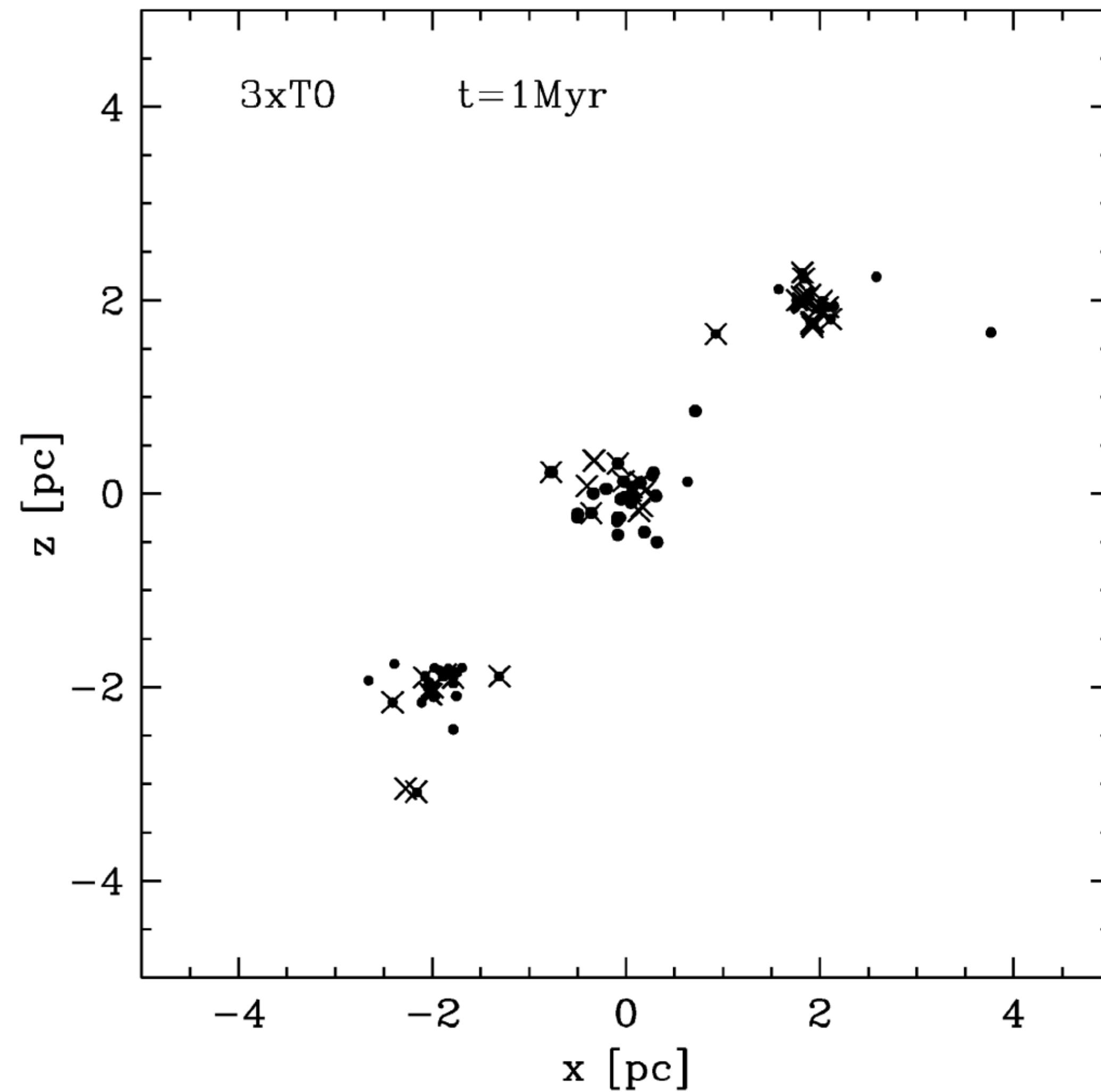
Gjergo et al. (2025a) subm.



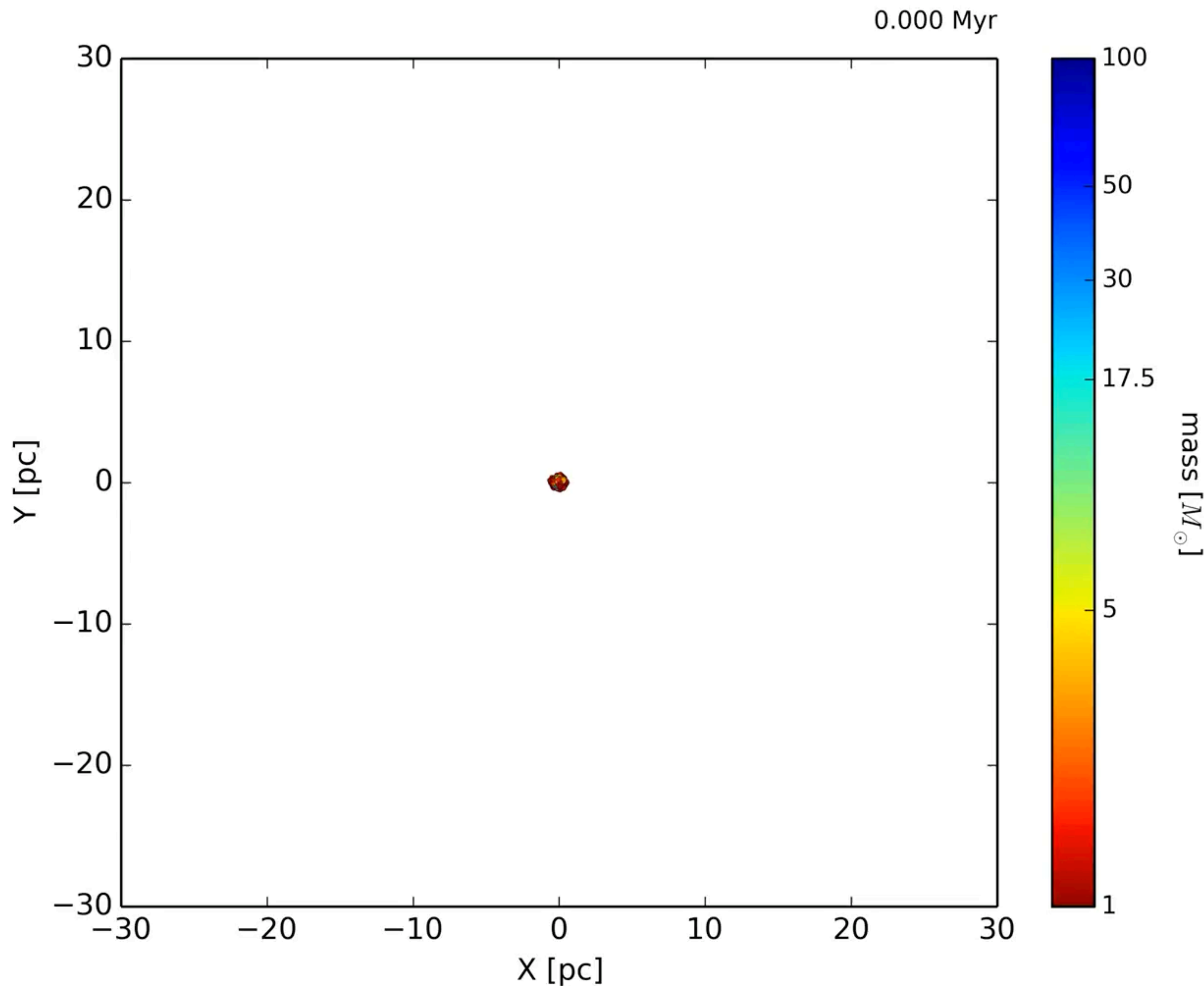
## N-body simulation of a region in Taurus Aurigae:

stars are lost through dynamic interactions, not only through feedback

Kroupa & Bouvier (2003)







Movie of a direct N-body calculation (with NBODY6) for a cluster with a mass of 3000  $M_{\text{sun}}$ .

The cluster is initially mass-segregated and binary-rich (100% binary fraction).

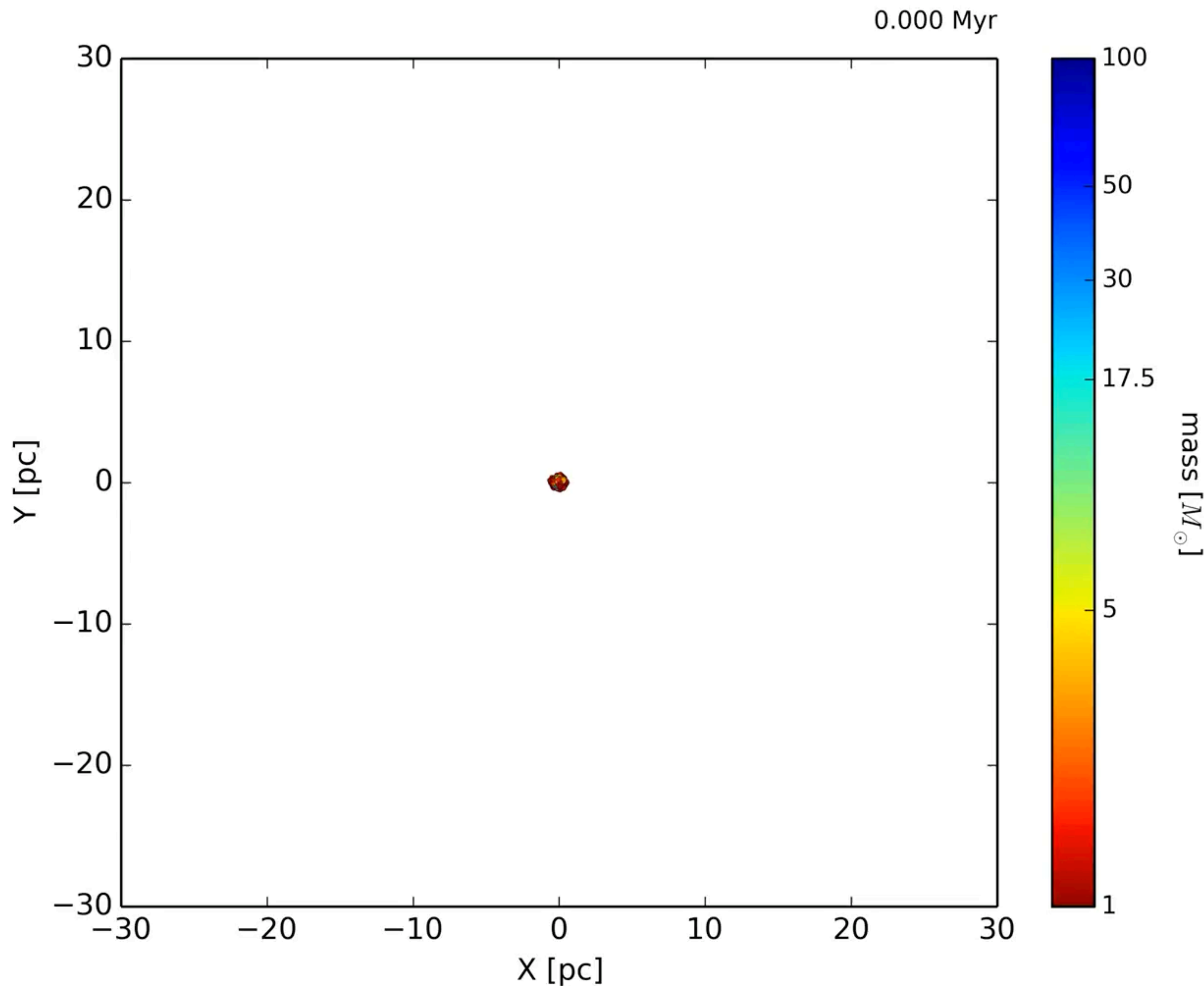
**Oh & Kroupa (2016)**

Two-step mass ejection

Masses of stars are color-coded. Black holes are marked with grey points.

The video shows a massive quadruple system (composed of  $\sim 60 + 5 + 14 + 35 M_{\text{sun}}$  stars) is dynamically ejected from the cluster,





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