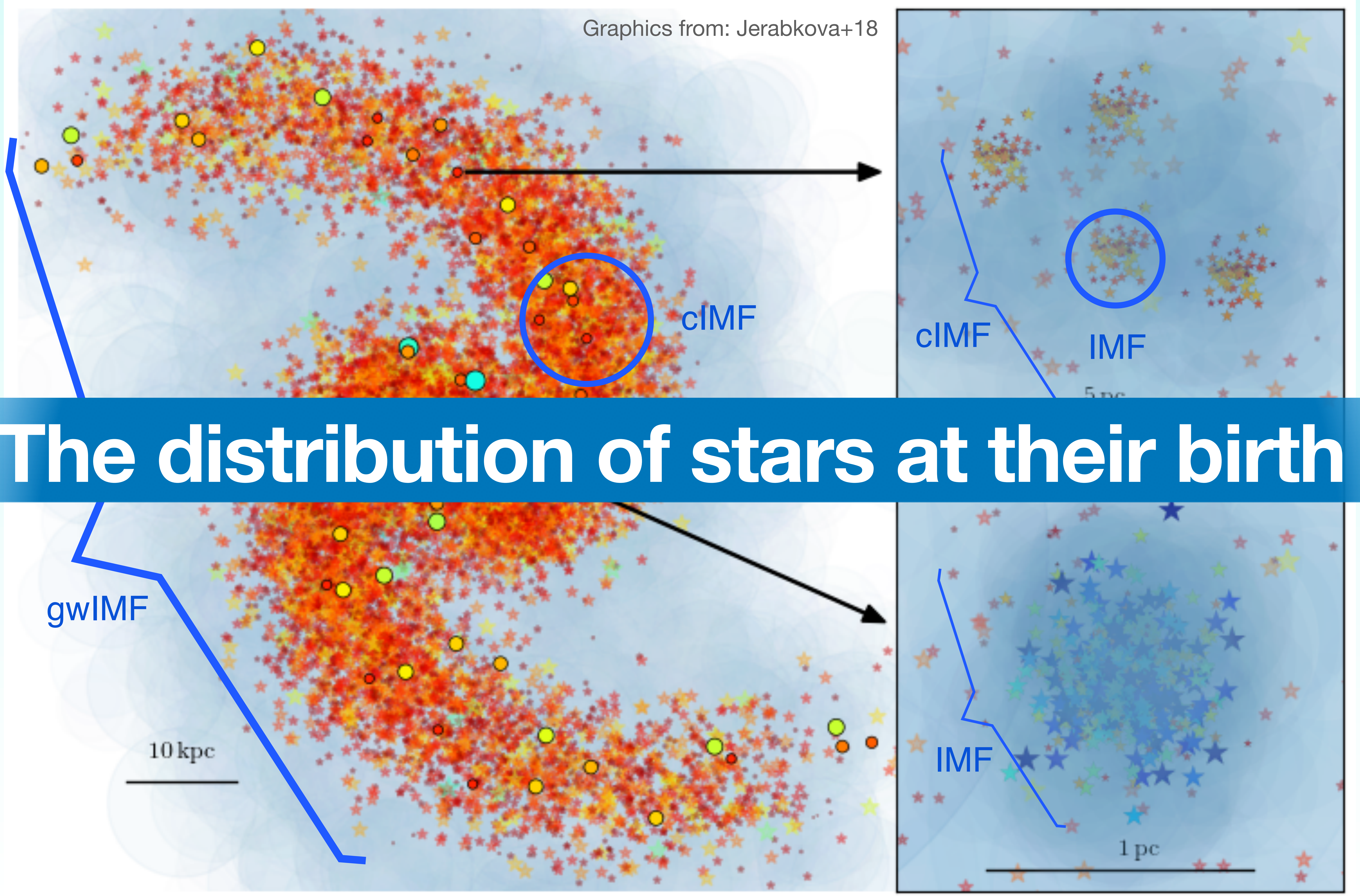
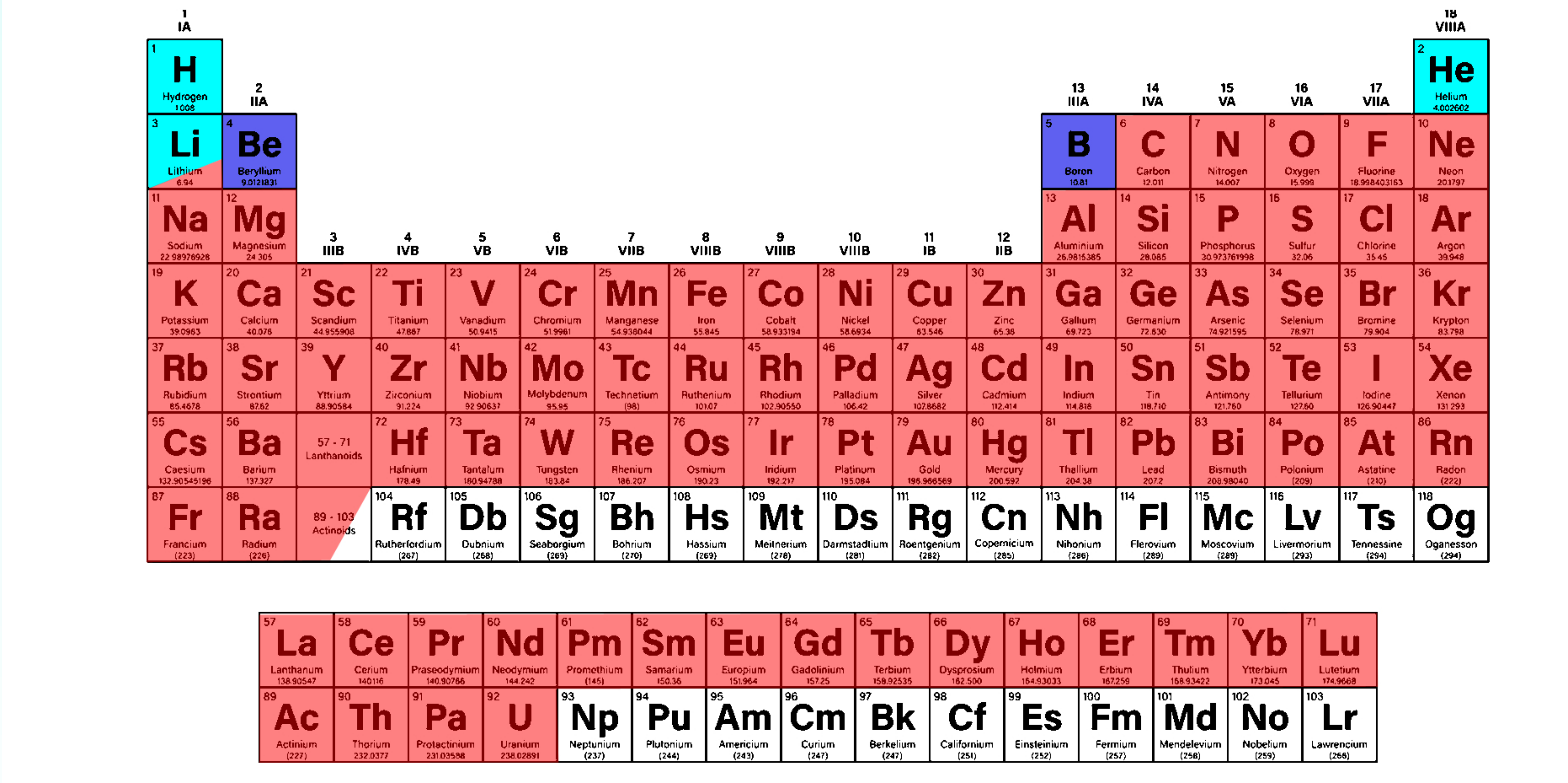


The distribution of stars at their birth

Brief GCE recap

How are elements produced
Galactic Chemical Evolution (GCE)



Big Bang

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

Stellar-born sites

(C through U)

Cosmic rays

(Be and B)

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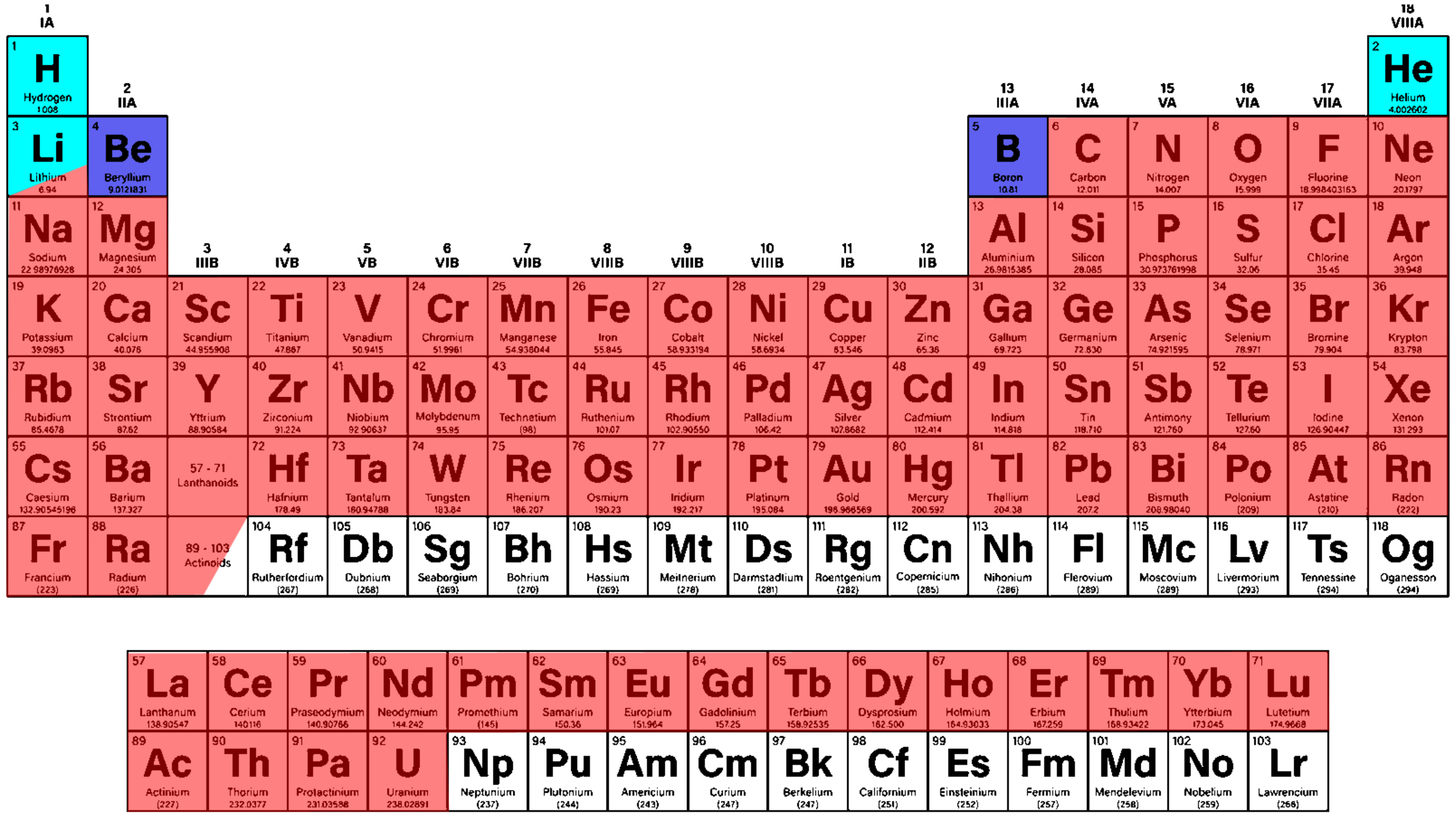

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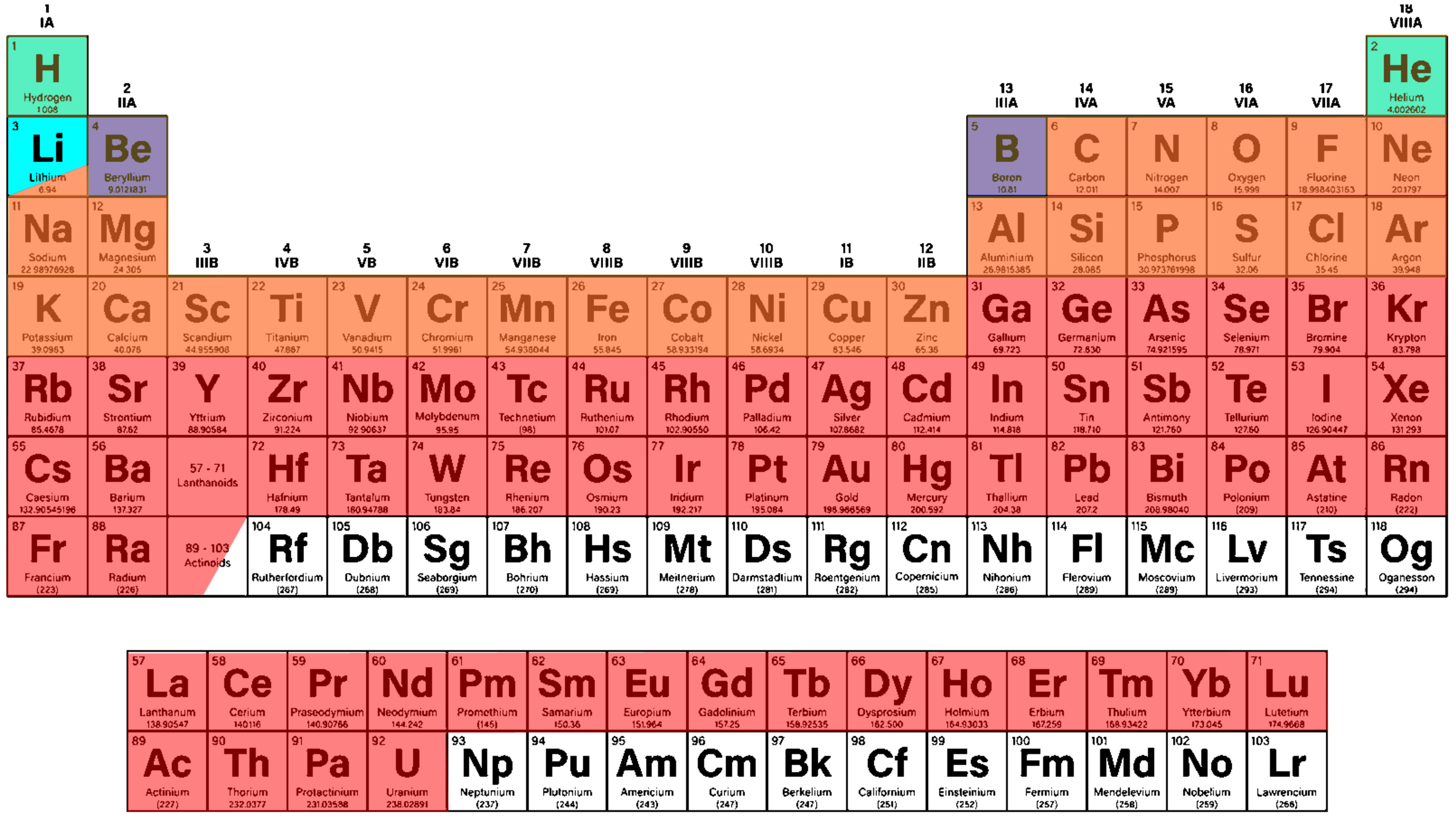

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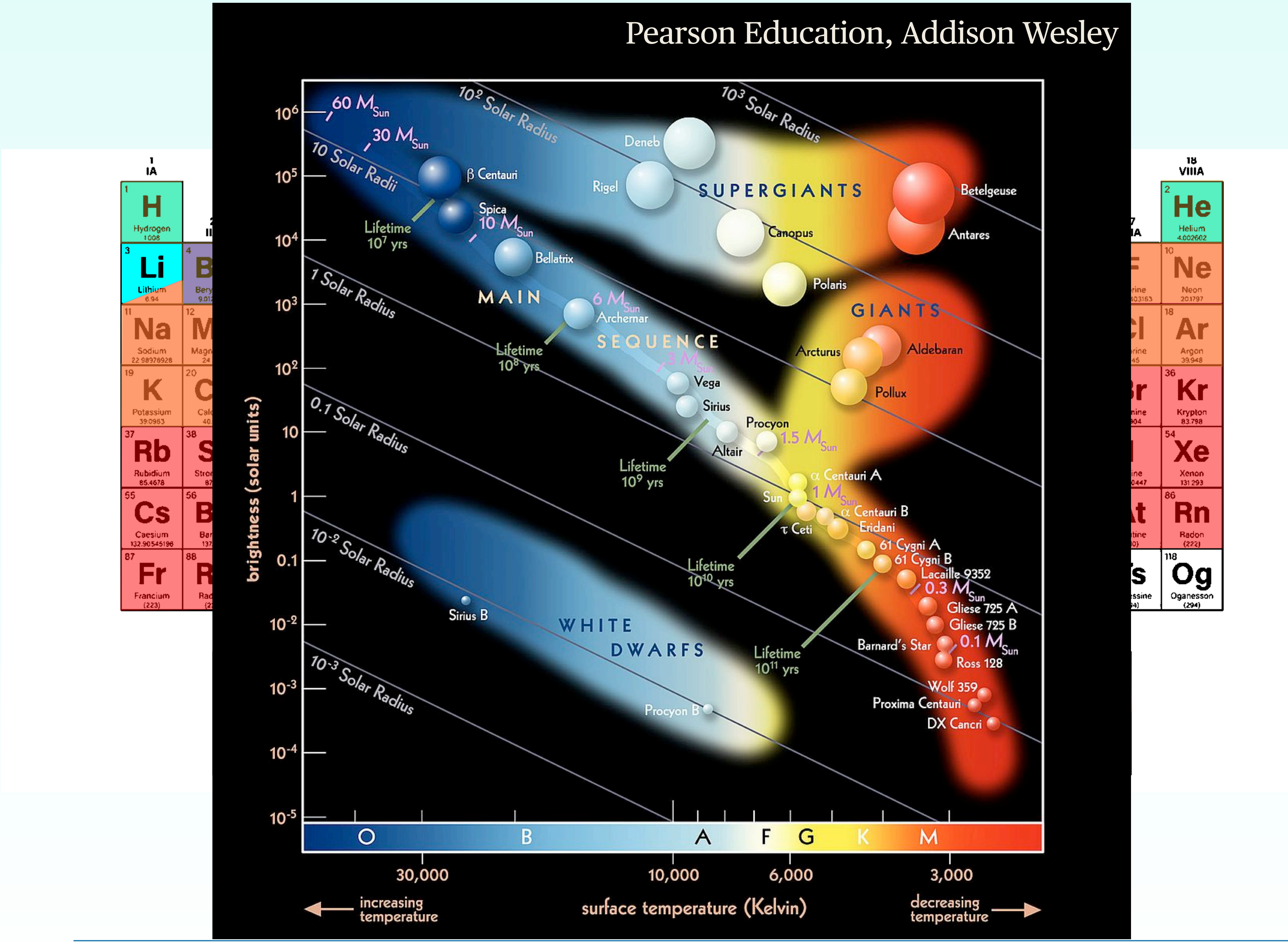

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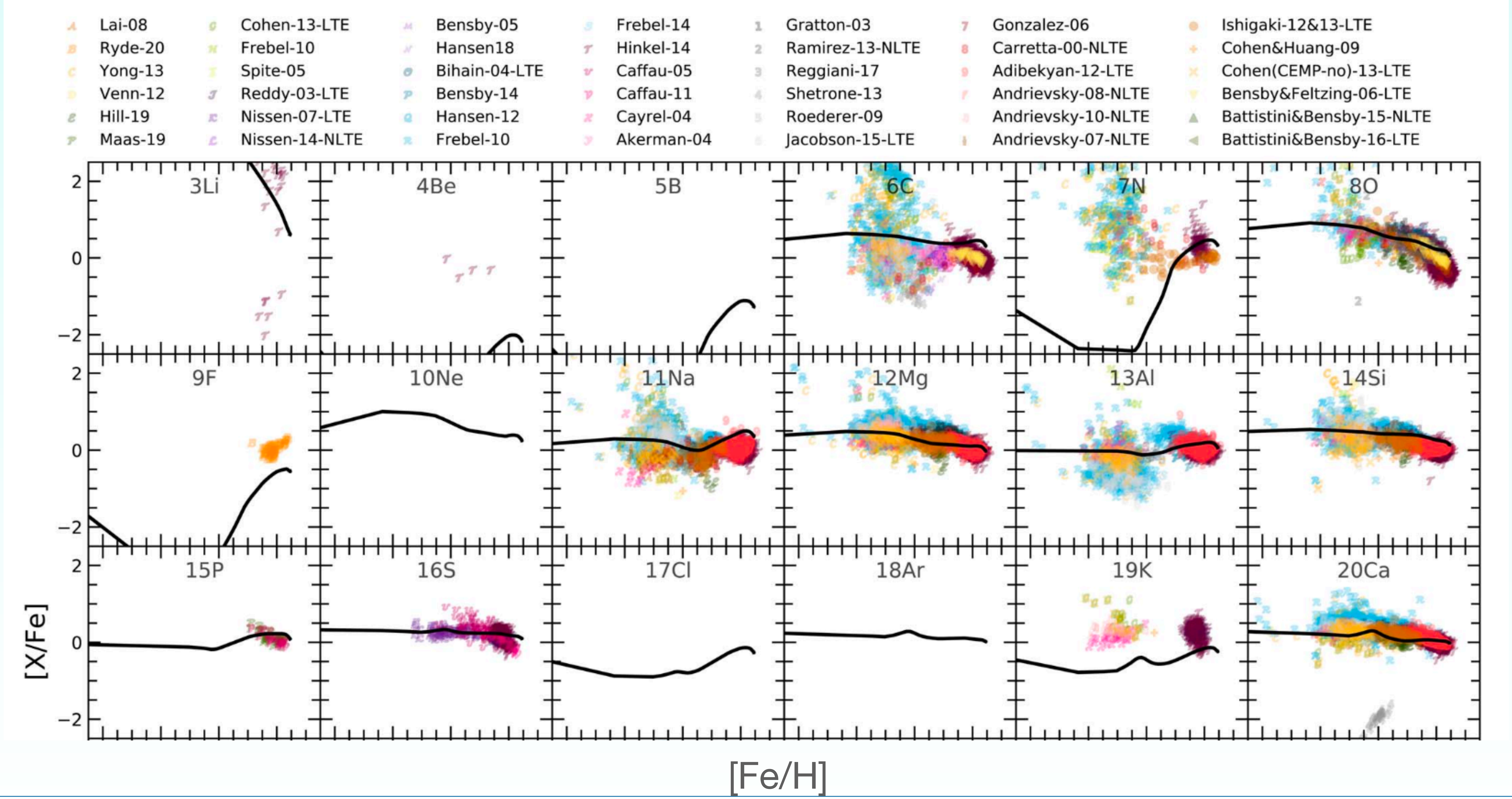
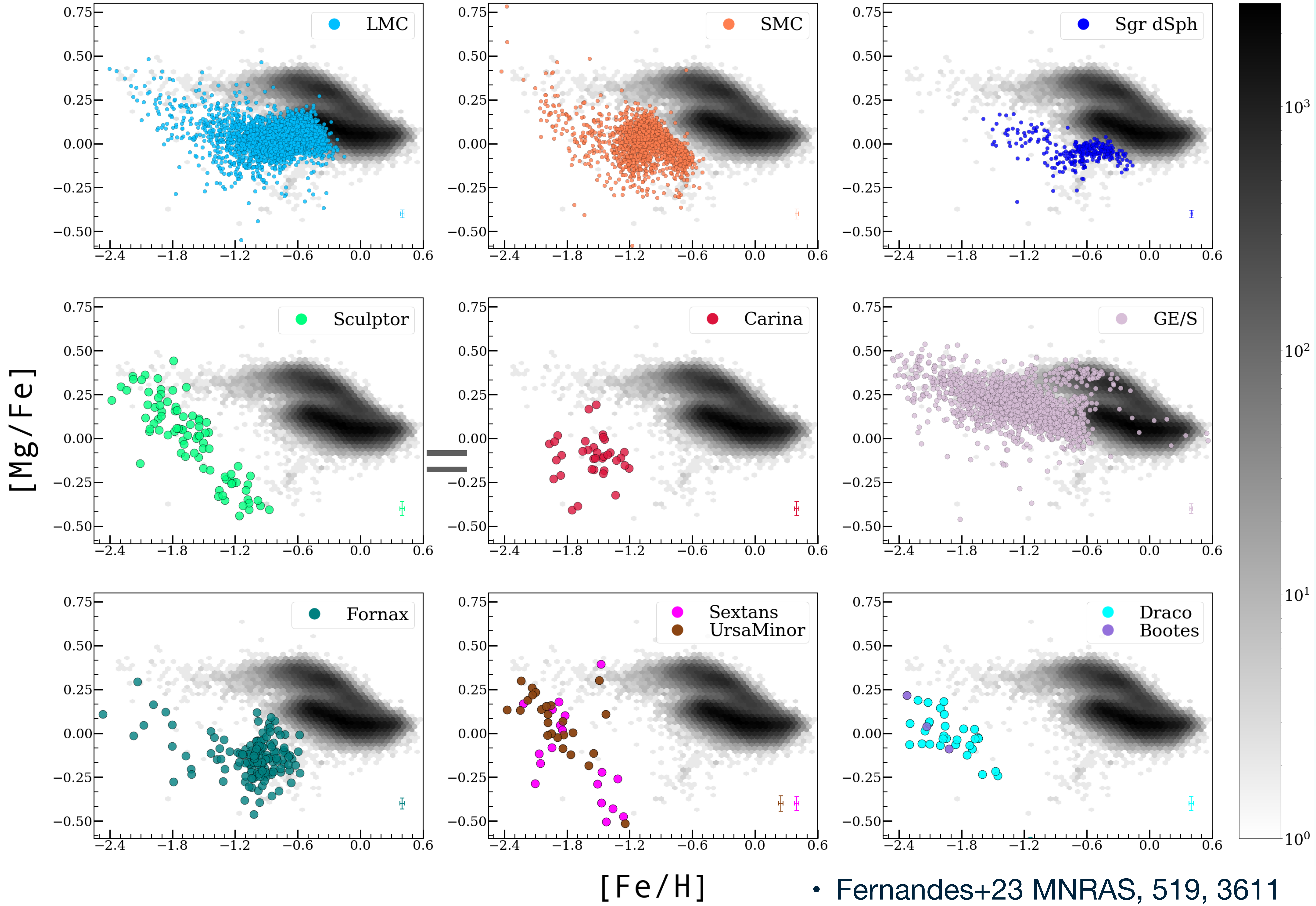
Closed box models are already remarkably powerful



Gjergo+23 benchmark

Alpha-element enrichment in the Milky Way satellites



- Fernandes+23 MNRAS, 519, 3611

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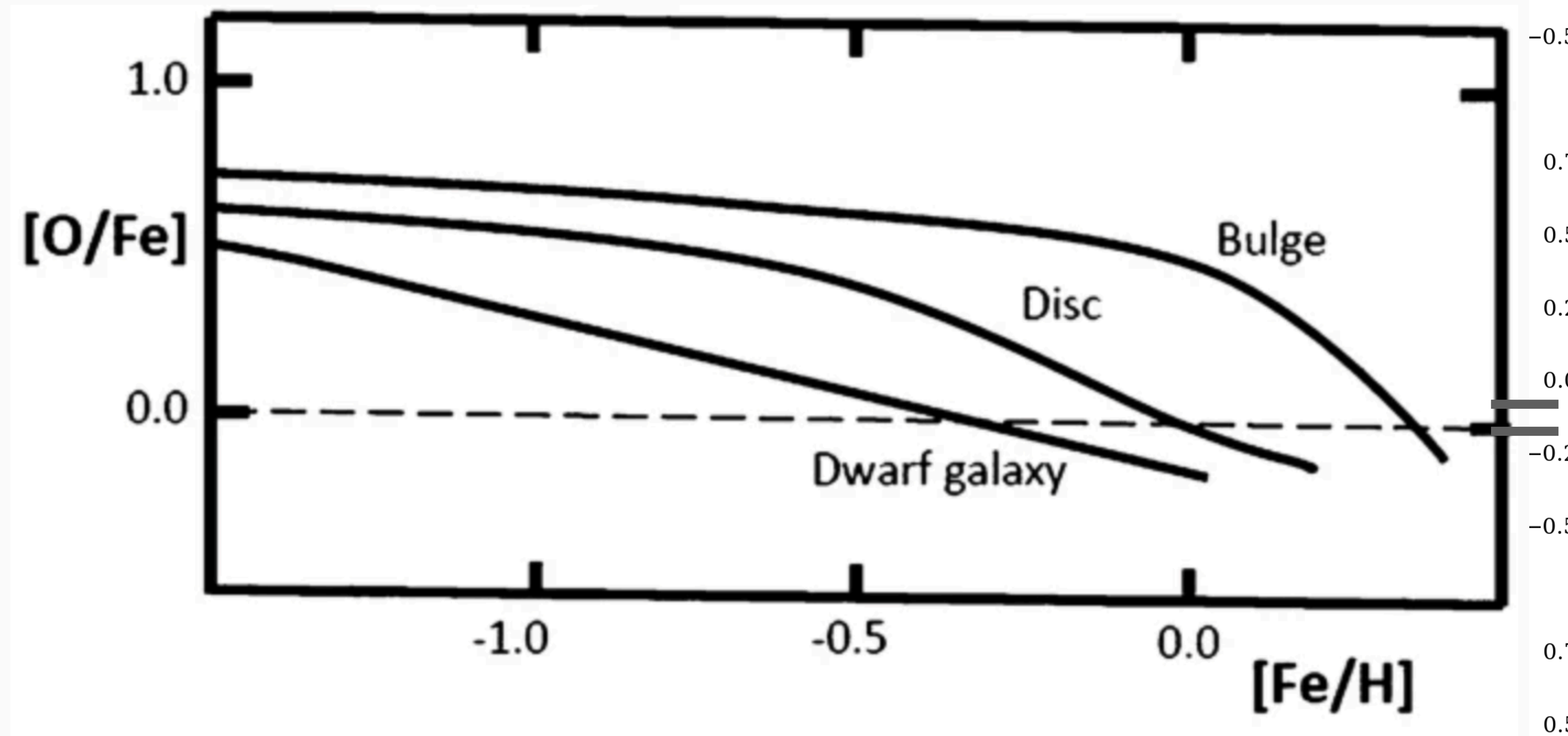
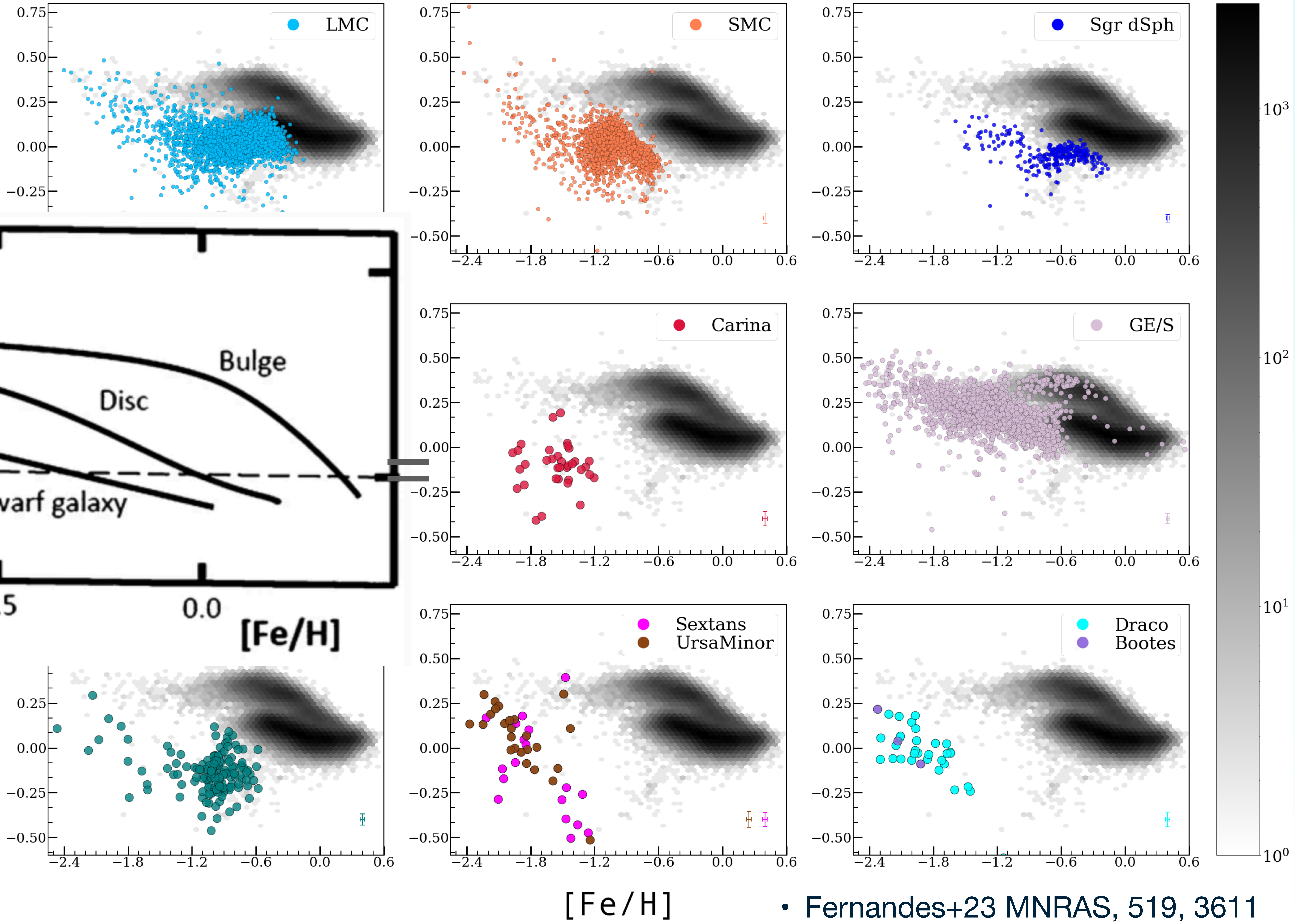


Matteucci & Brocato (1990)
Yan, Jerabkova, Kroupa (2020)



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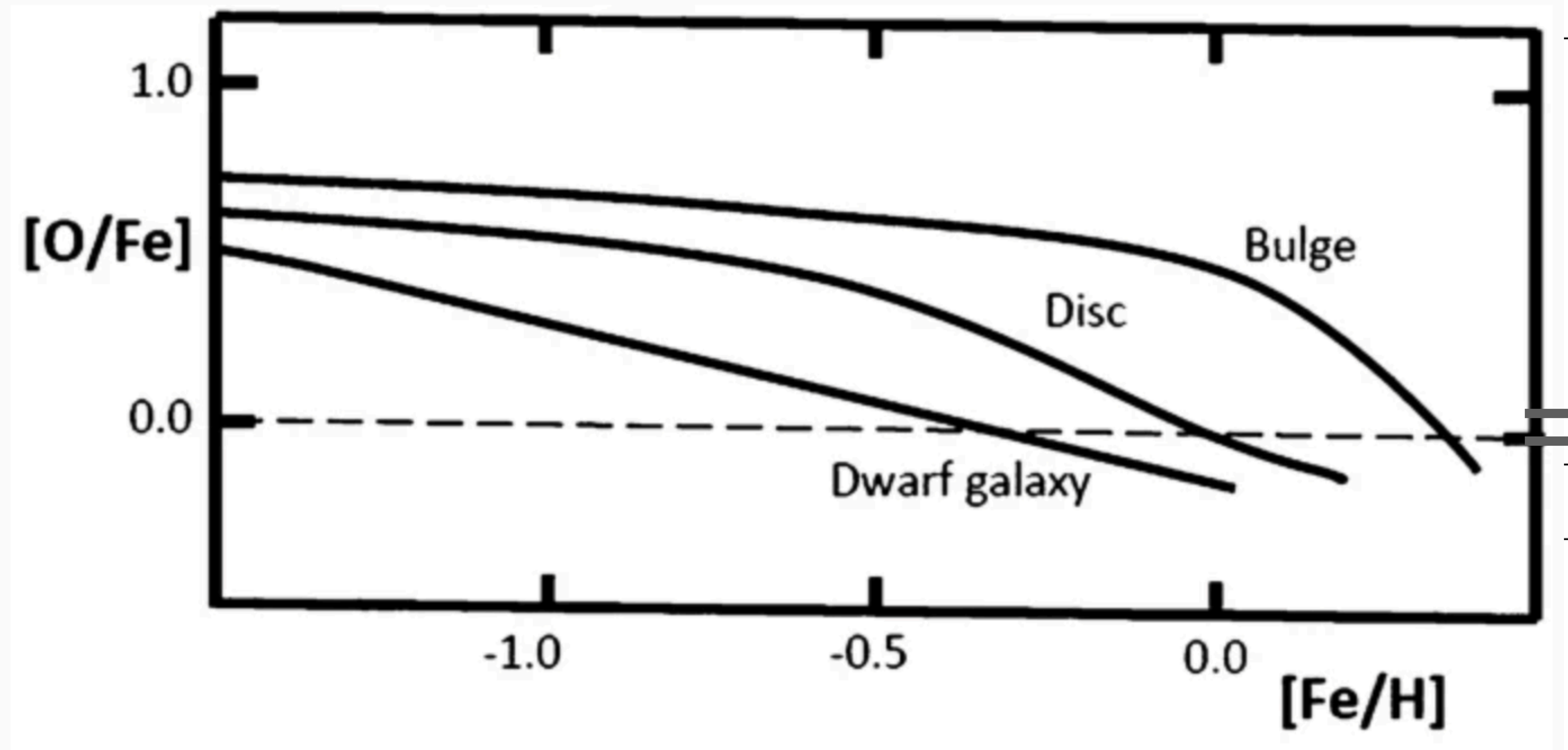

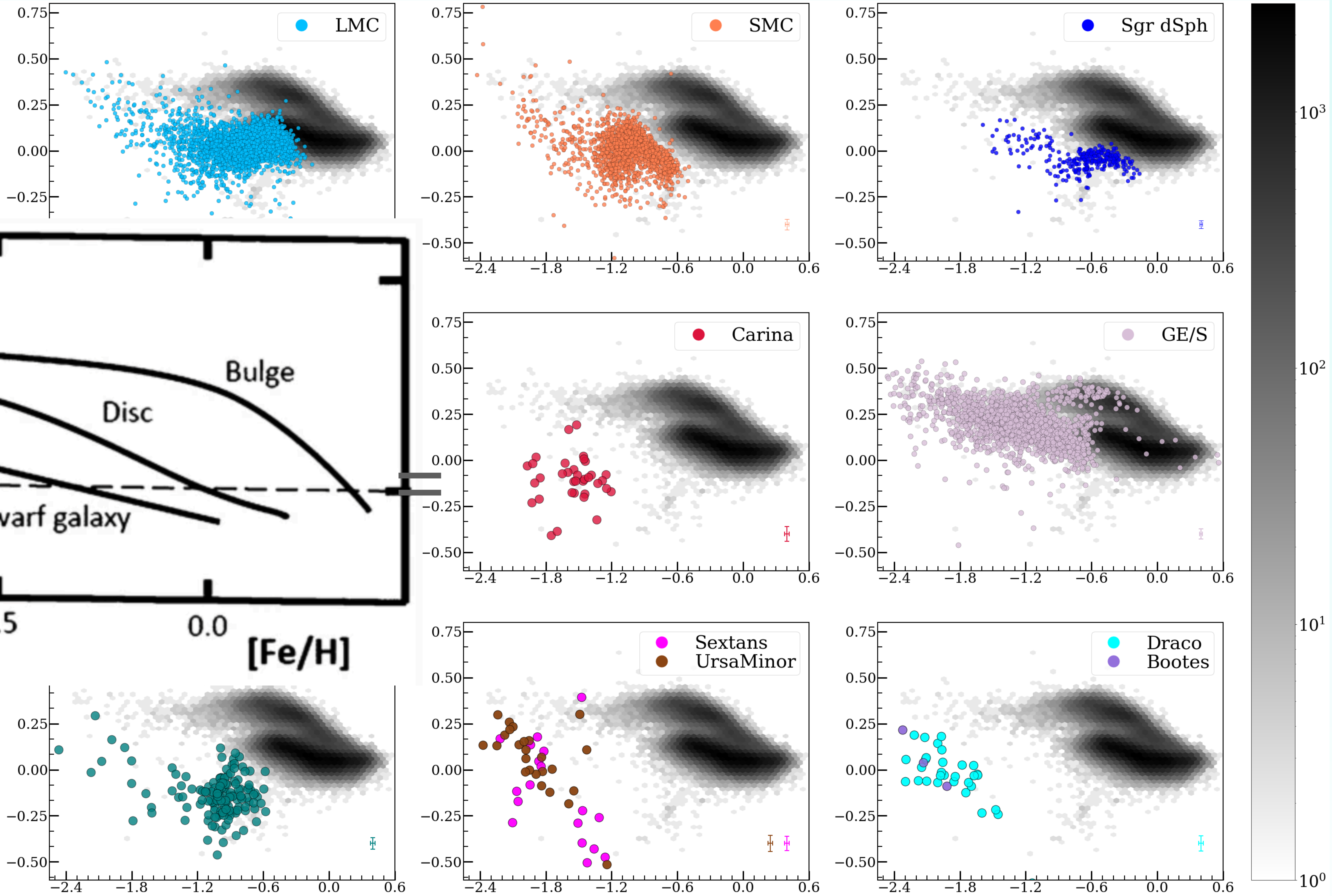

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Monolithic models capture average evolutionary trends in galaxies: Remarkably accurate!

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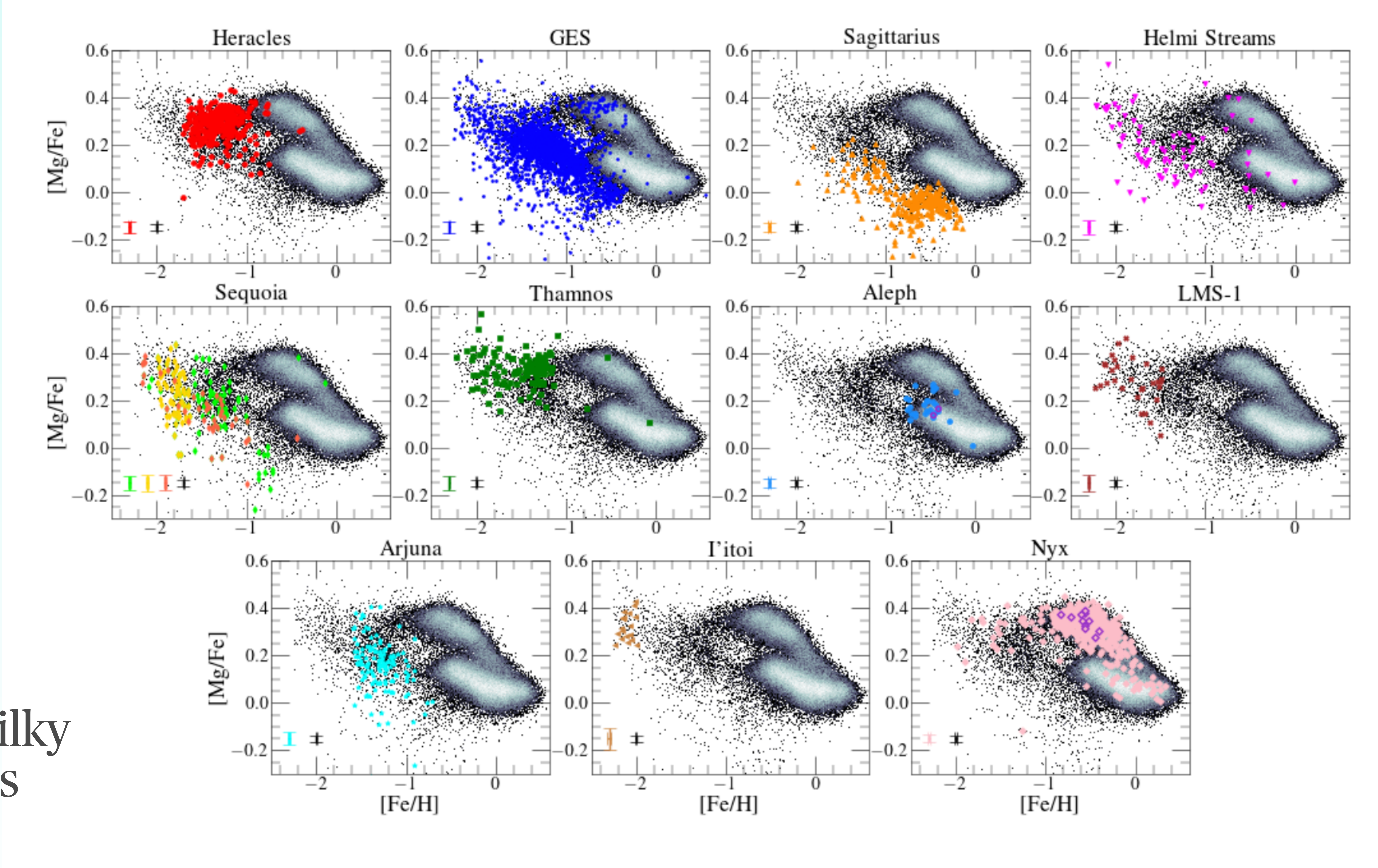
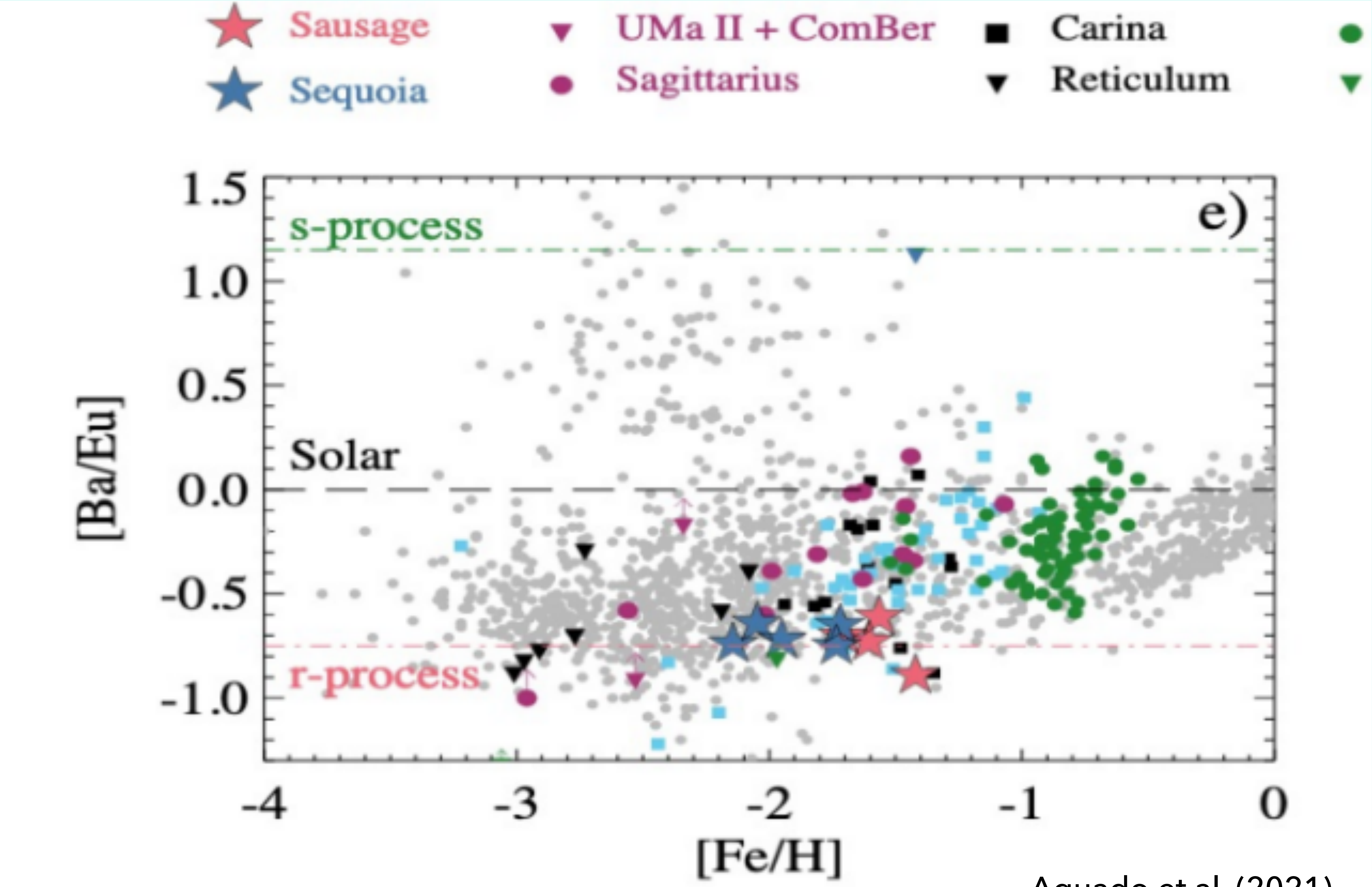


- Horta+22 APOGEE

Alpha-element enrichment in the Milky Way halo and disks

Observational Evidence



Aguado et al. (2021)

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.

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?
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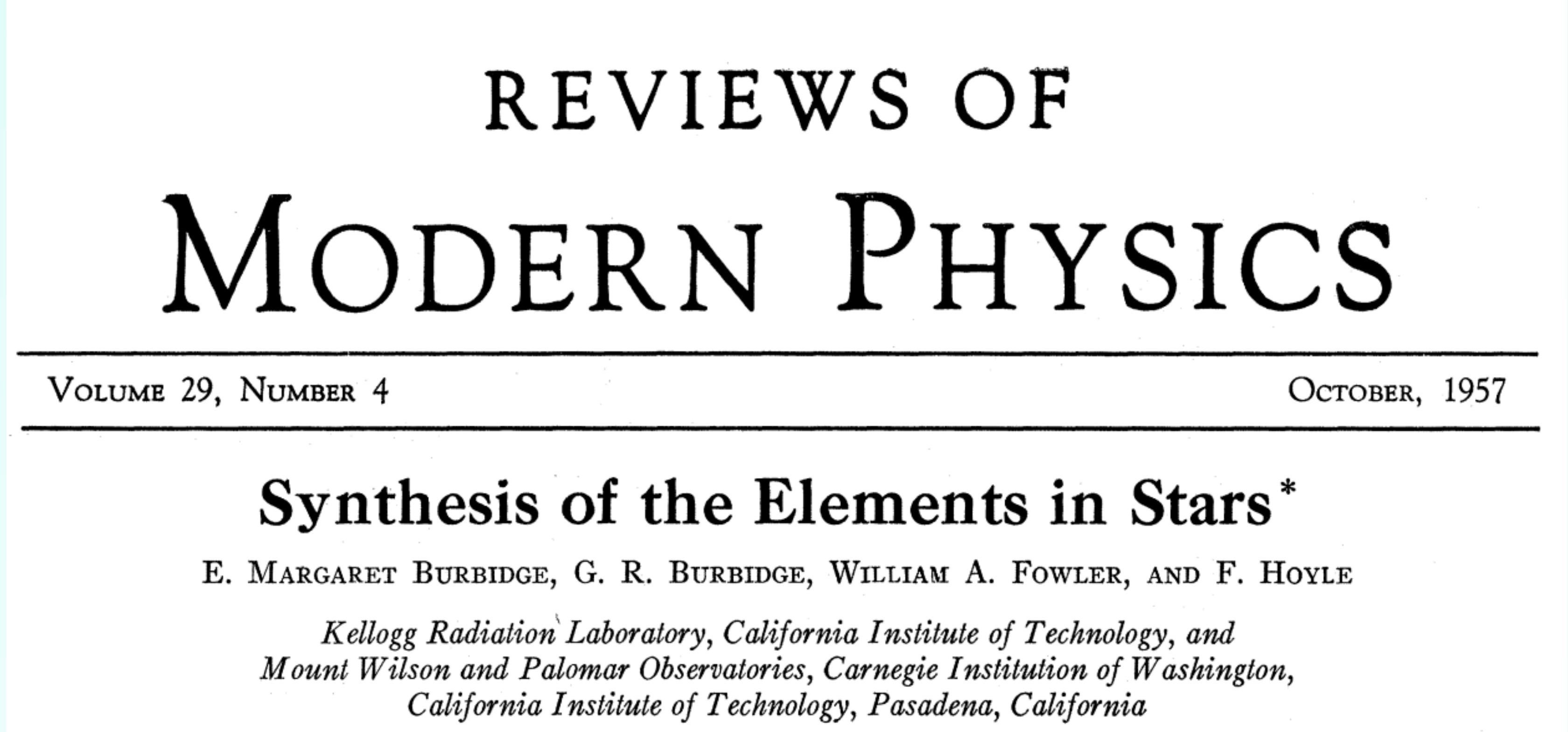
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VOLUME 29, NUMBER 4 OCTOBER, 1957

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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

Burbidge+57 (B2FH)

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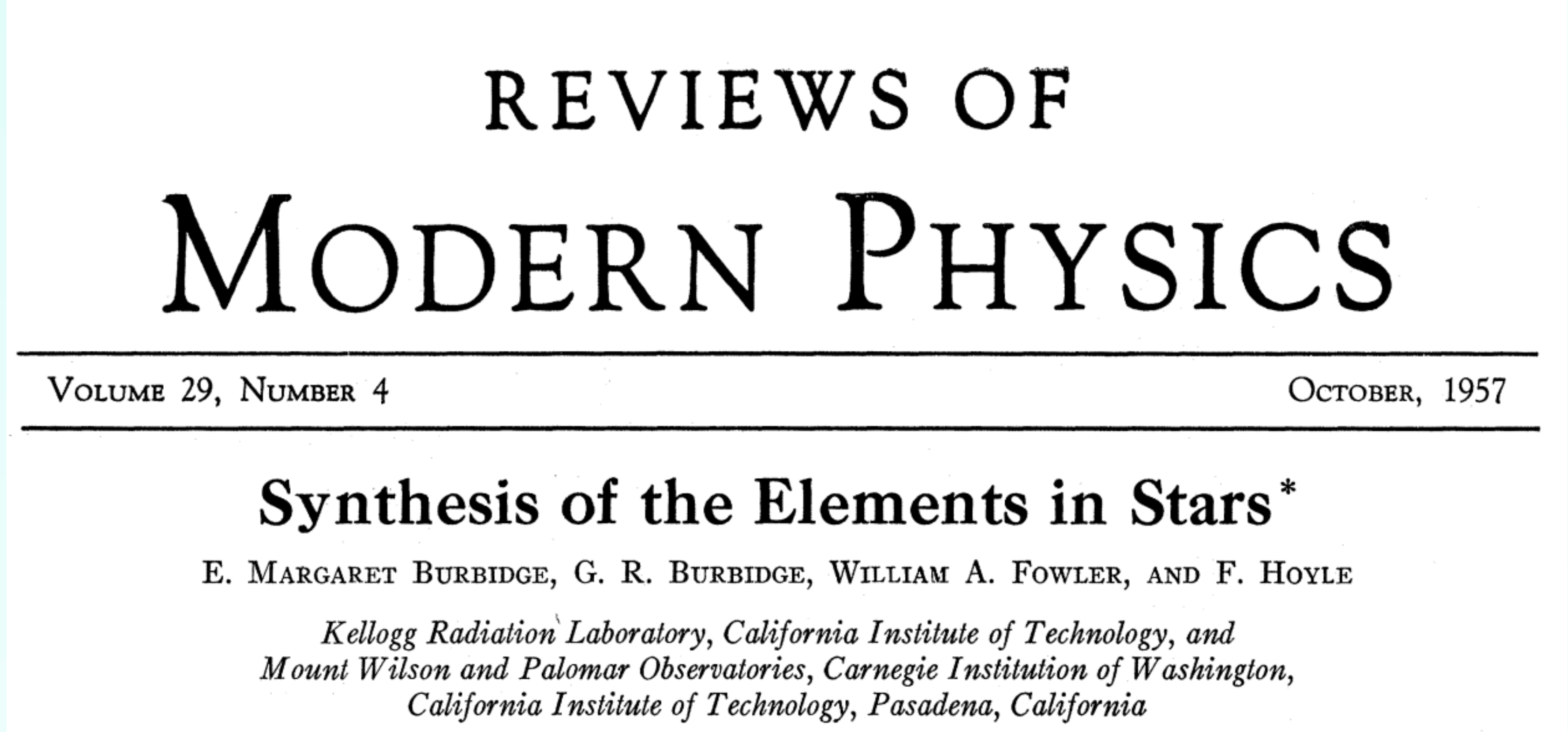
Neutron Star Mergers (NSM):

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



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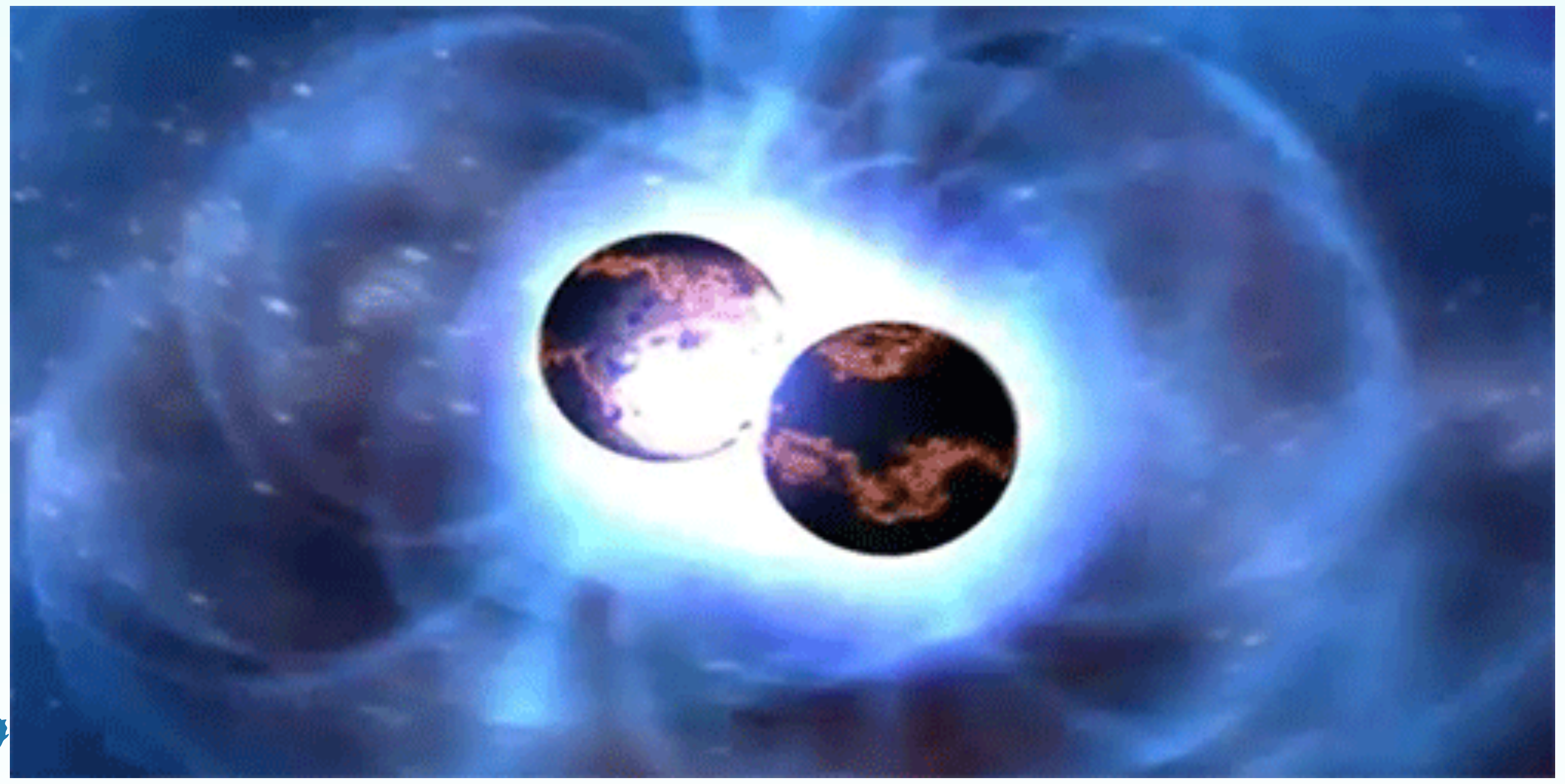
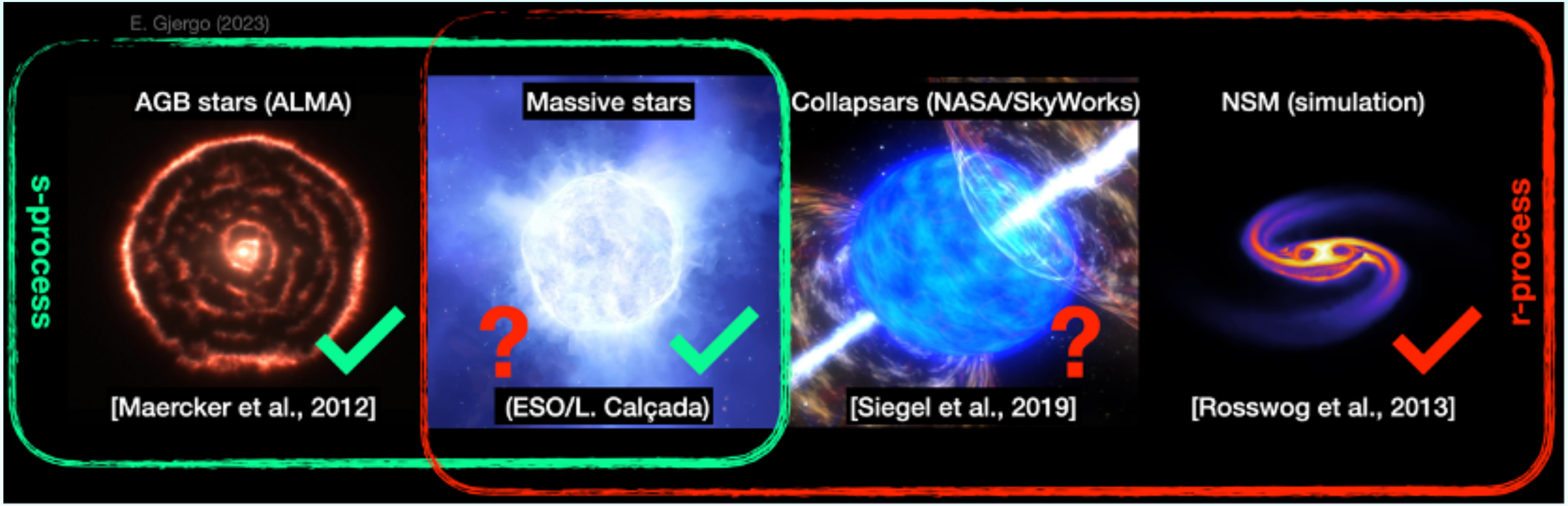


CREDIT: NASA/Goddard Space Flight Center

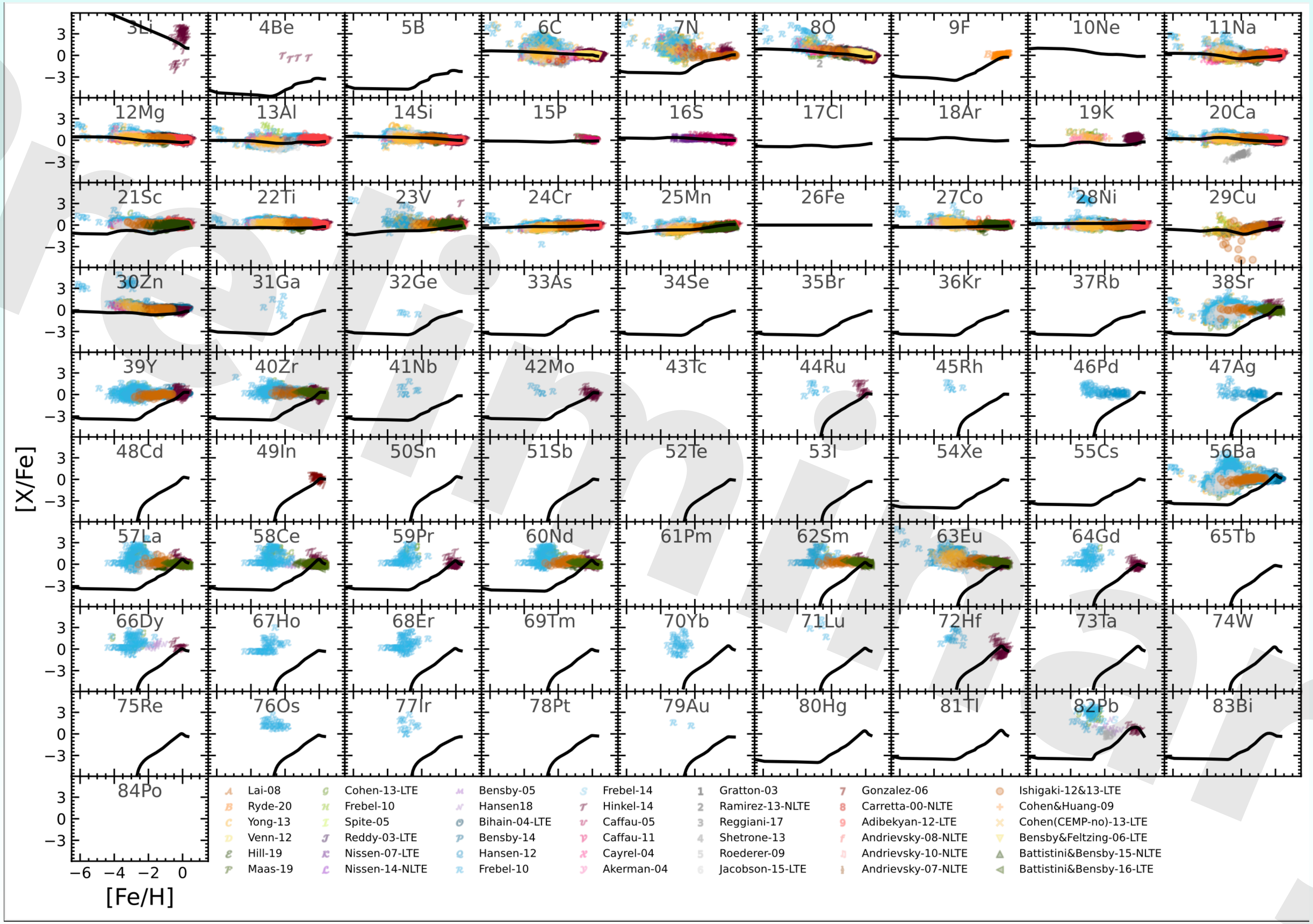
Neutron-capture astrophysical sites: Associated with stellar progenitors of different masses



- **s-processes** result from successive
  - thermal pulses of AGB stars (e.g., Cristallo+15)
  - Core-collapse SNae (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

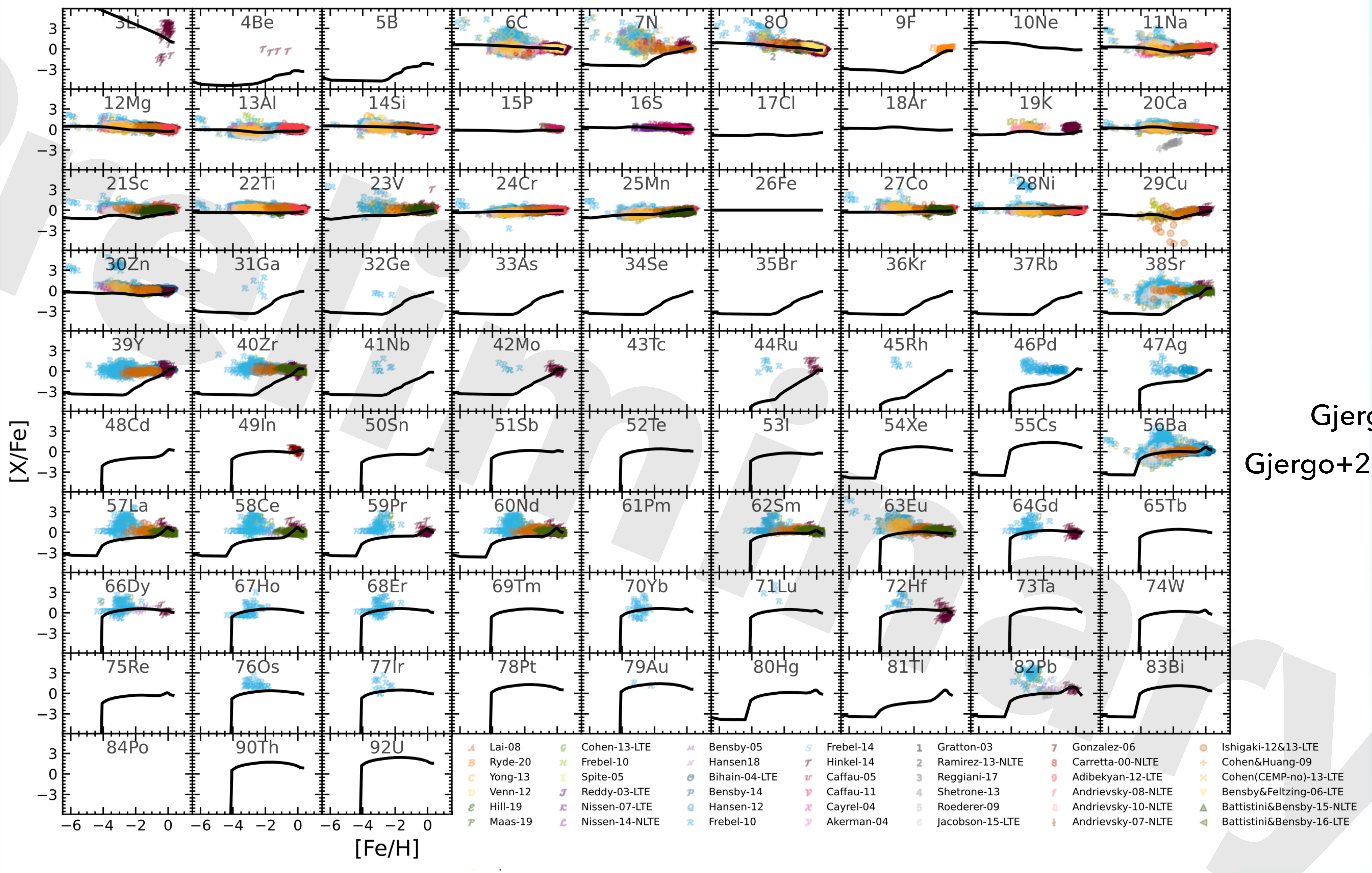


Gjergo+23

Gjergo+26b, in prep.

In the Milky Way

With NSM



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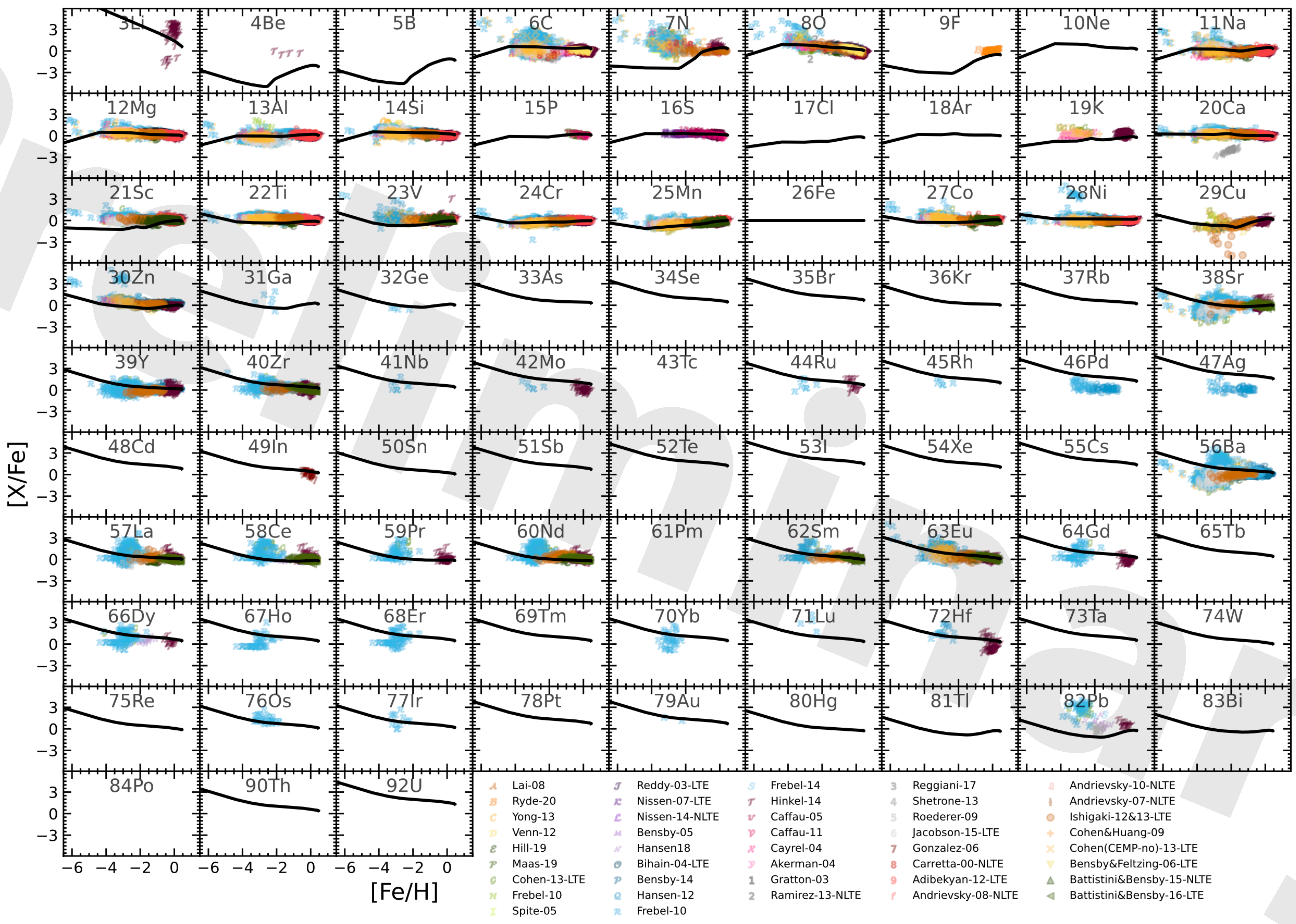
In the Milky Way

With collapsars and/or magneto-rotational SNae



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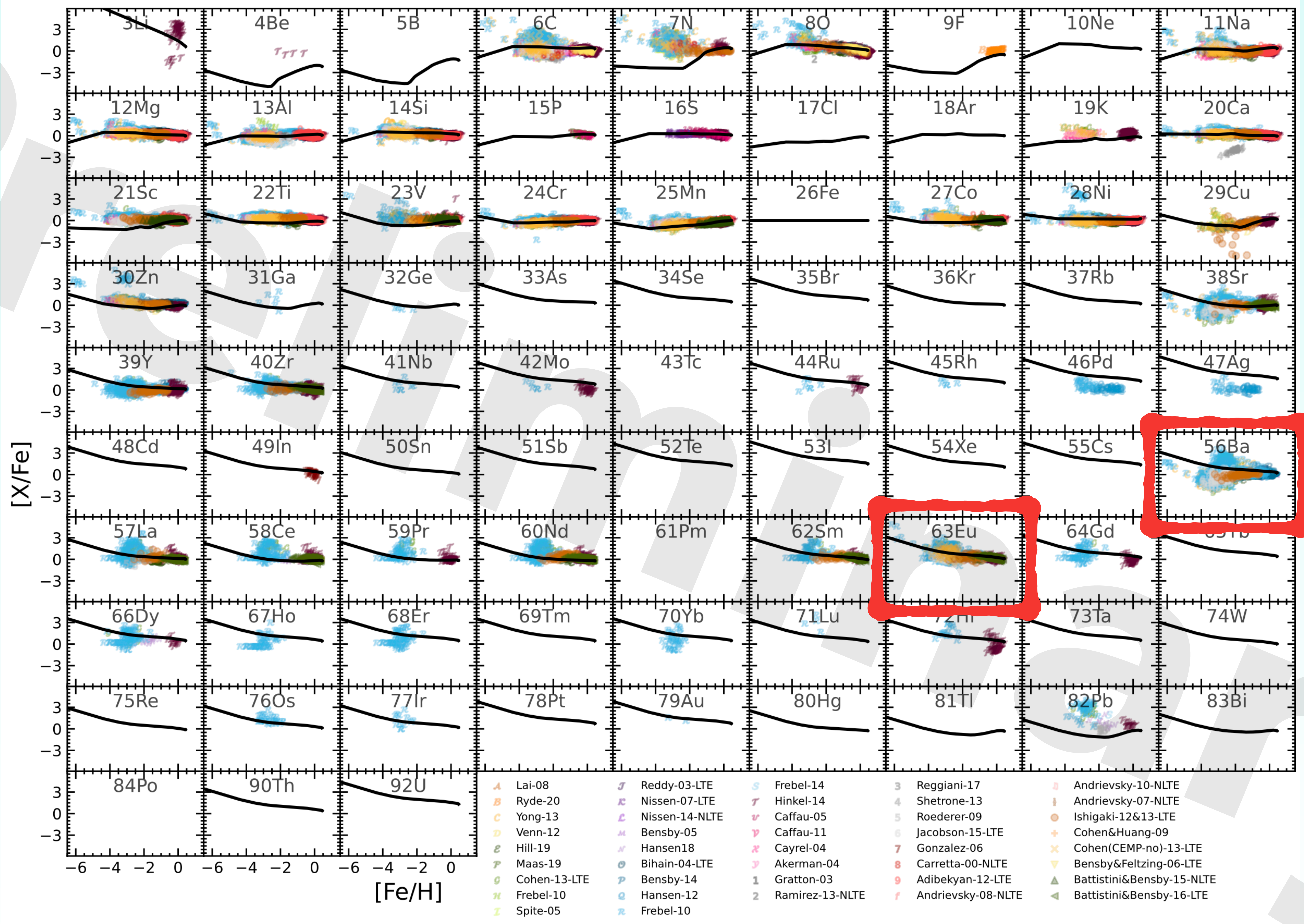

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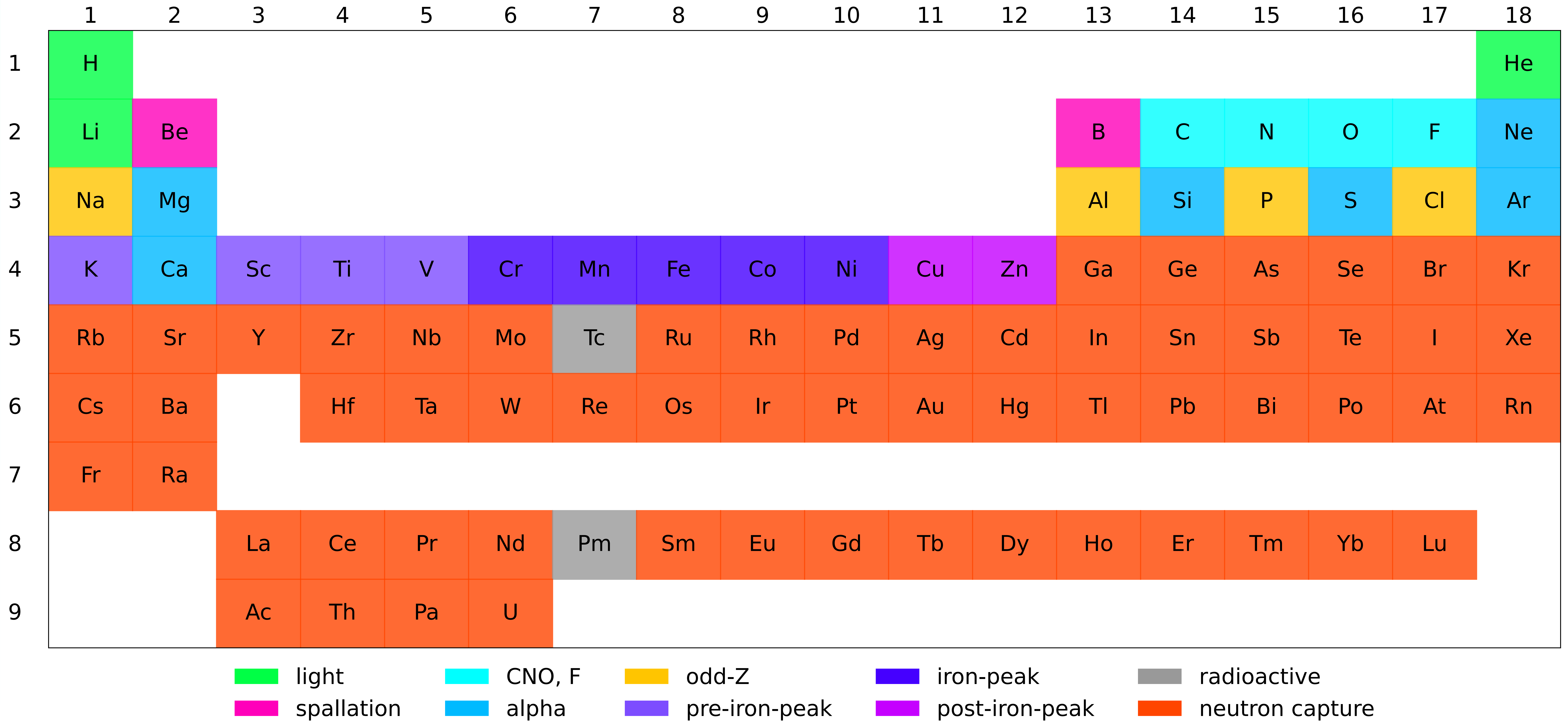
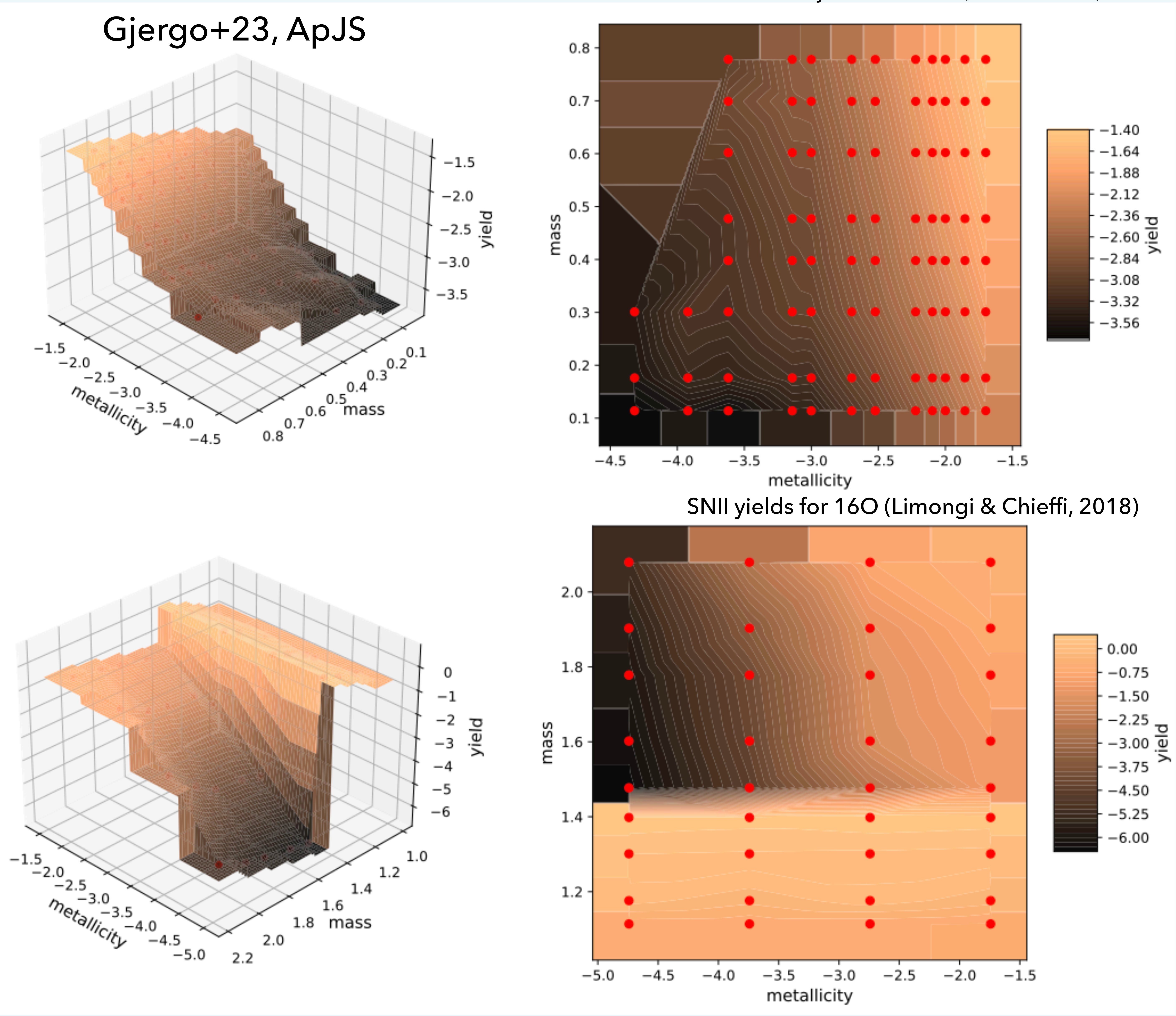
GCE of the Periodic Table of Elements in GalCEM



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

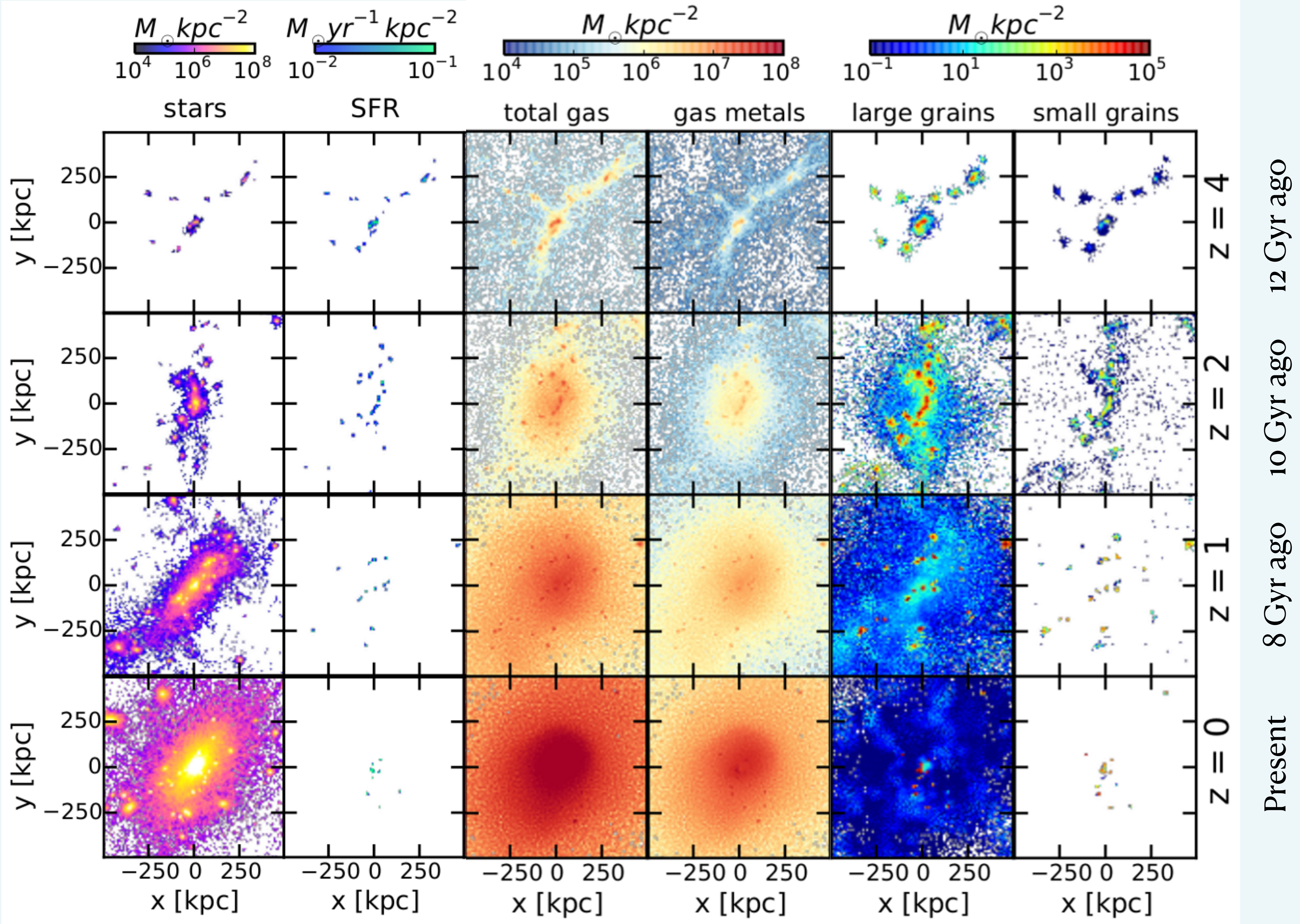
AGB yields for 12C (Cristallo+15)



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

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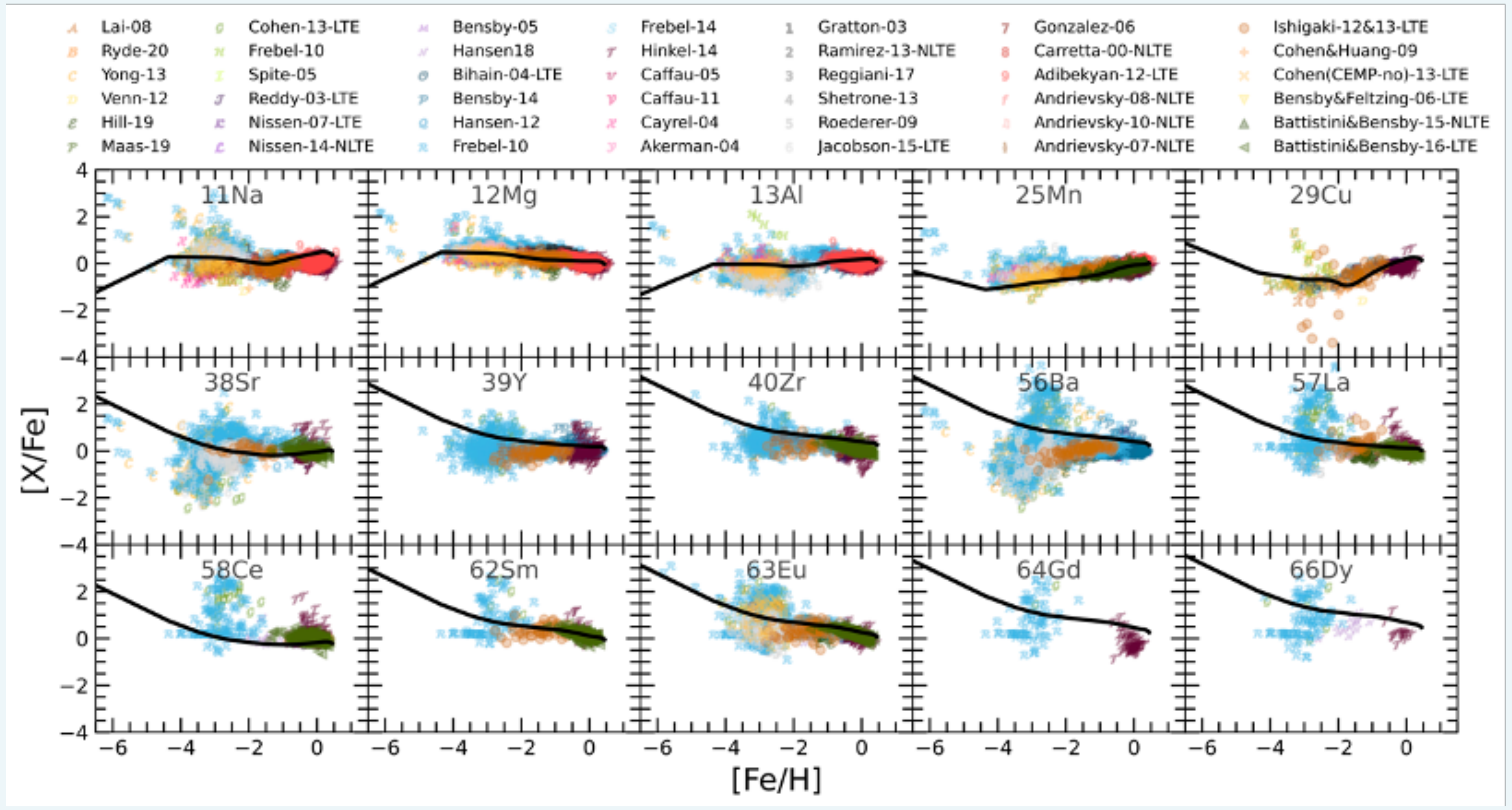
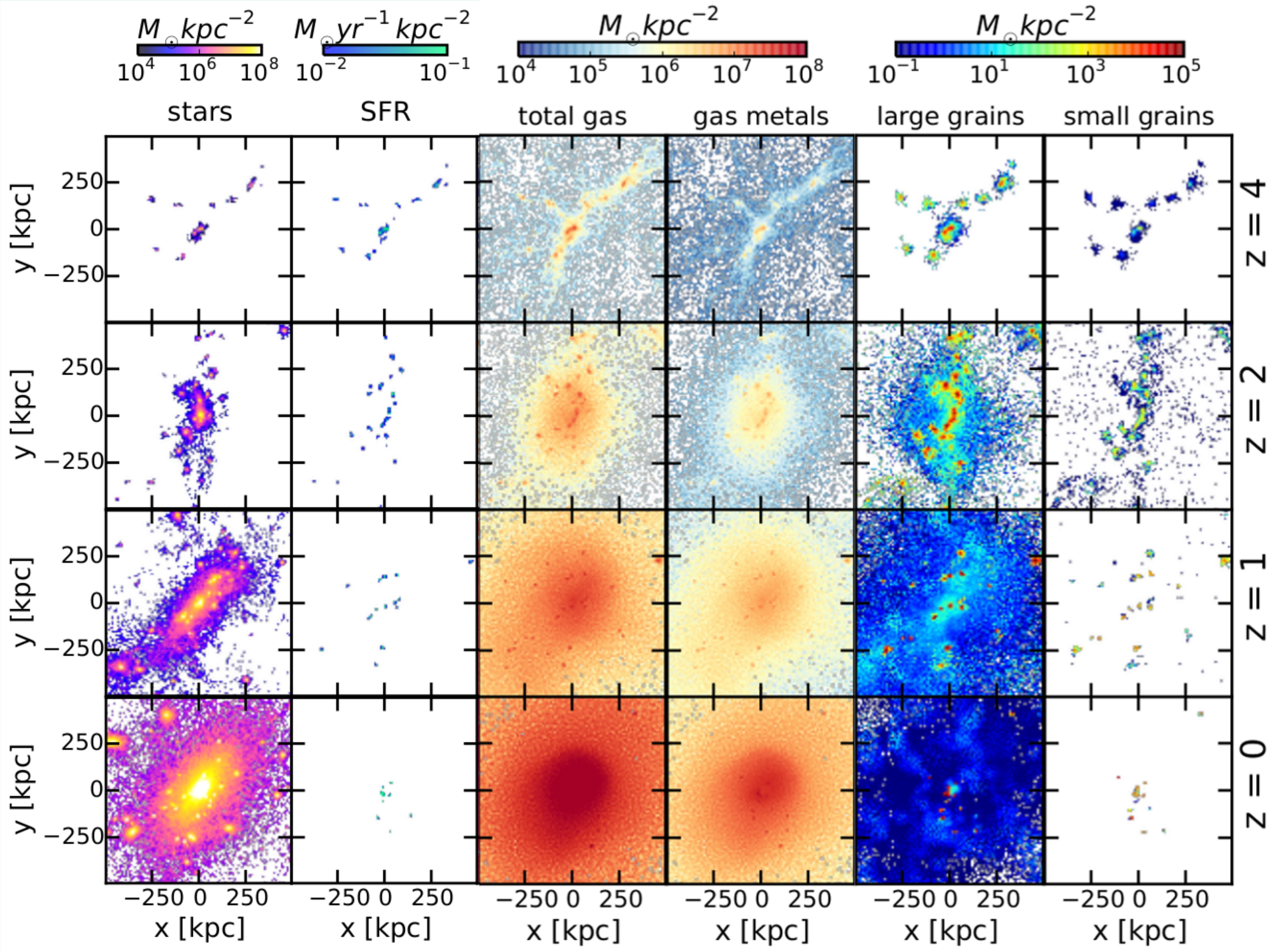


Gjergo+23a, ApJS

+

Gjergo et al., in prep.

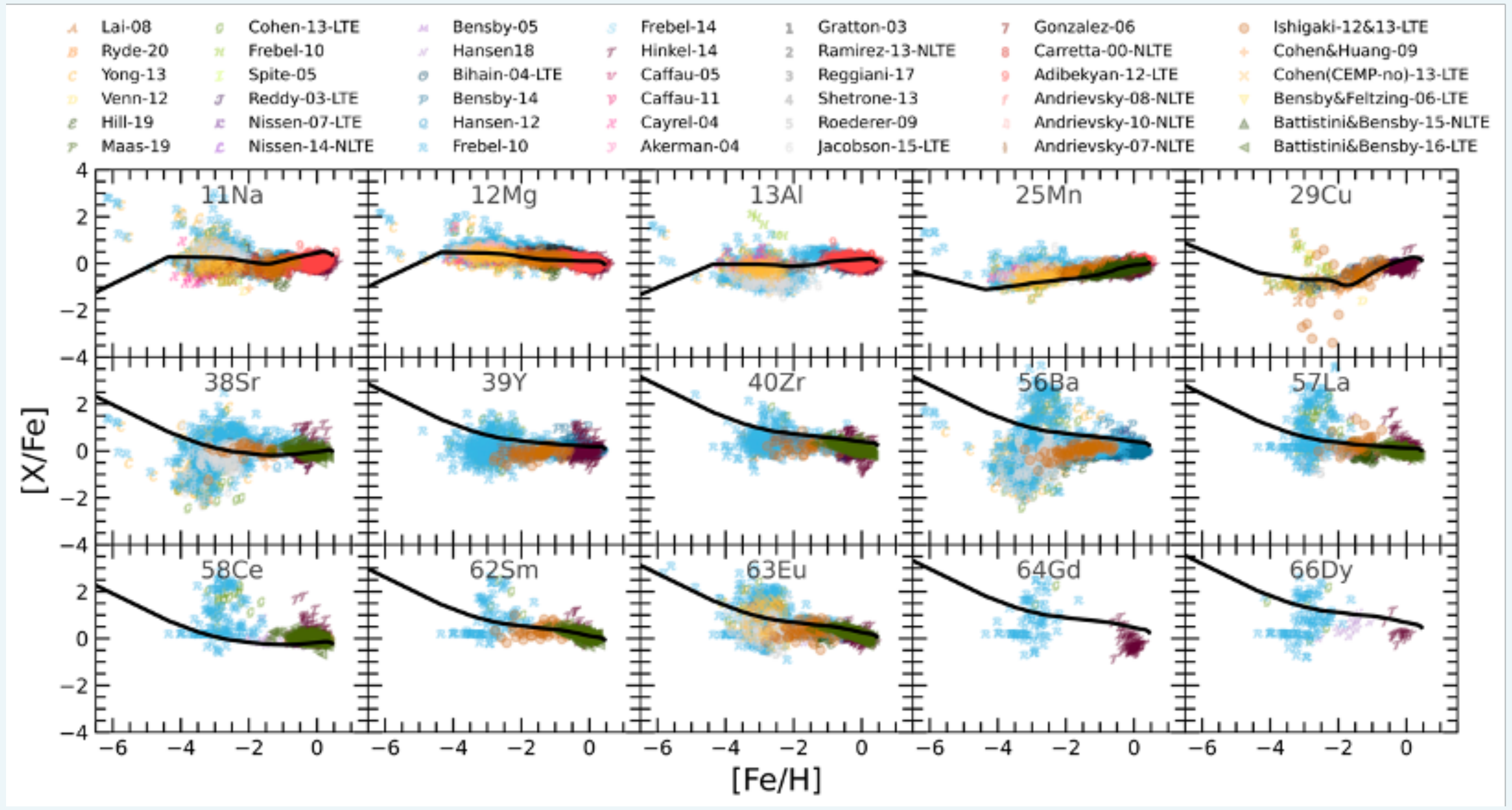


Gjergo+18

One-zone GCE vs Cosmo Sim

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

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



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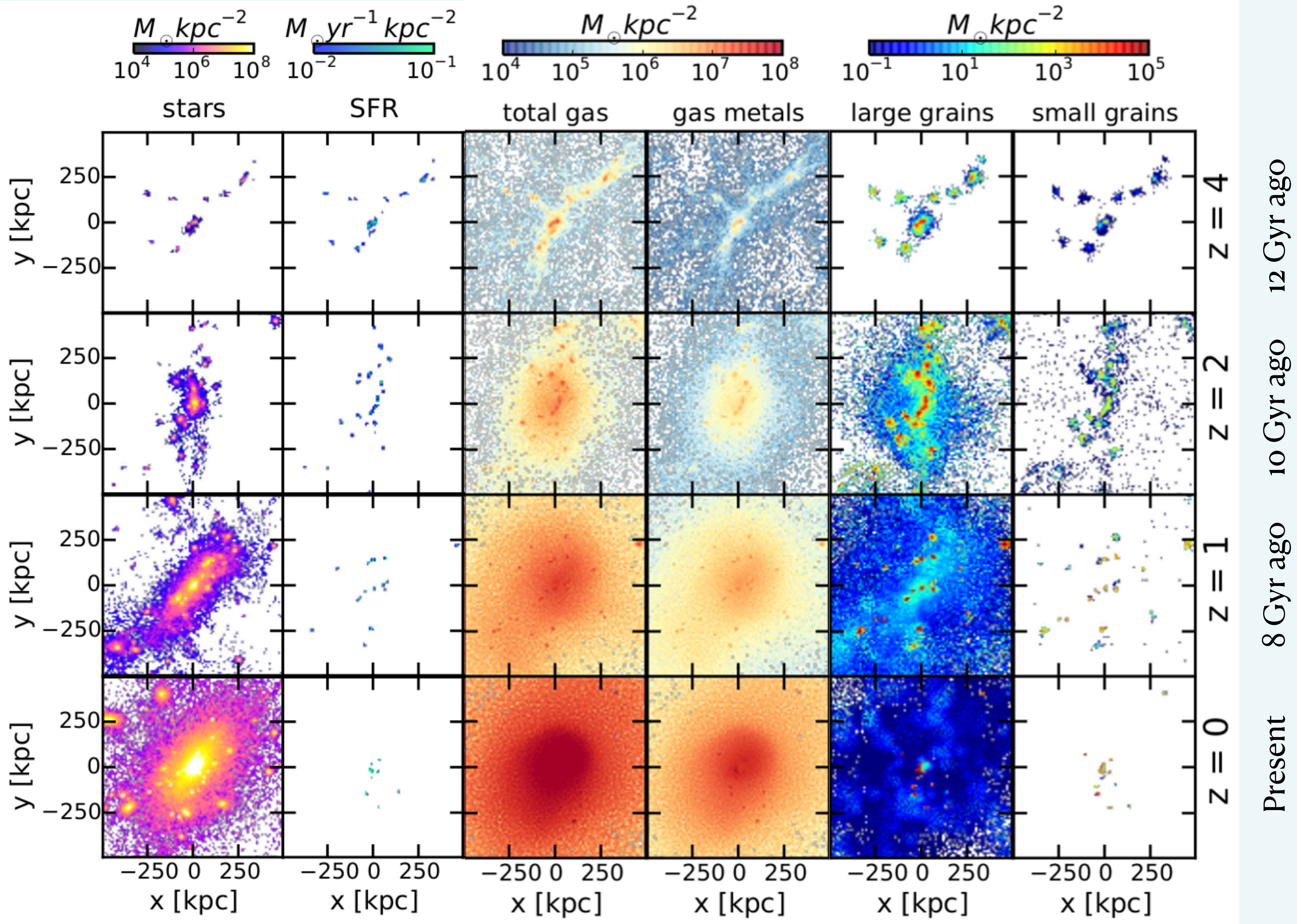

Gjergo+18

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

$$\frac{\mathrm{d}M_*}{\mathrm{d}t}$$

← SFR and IMF are crucial →

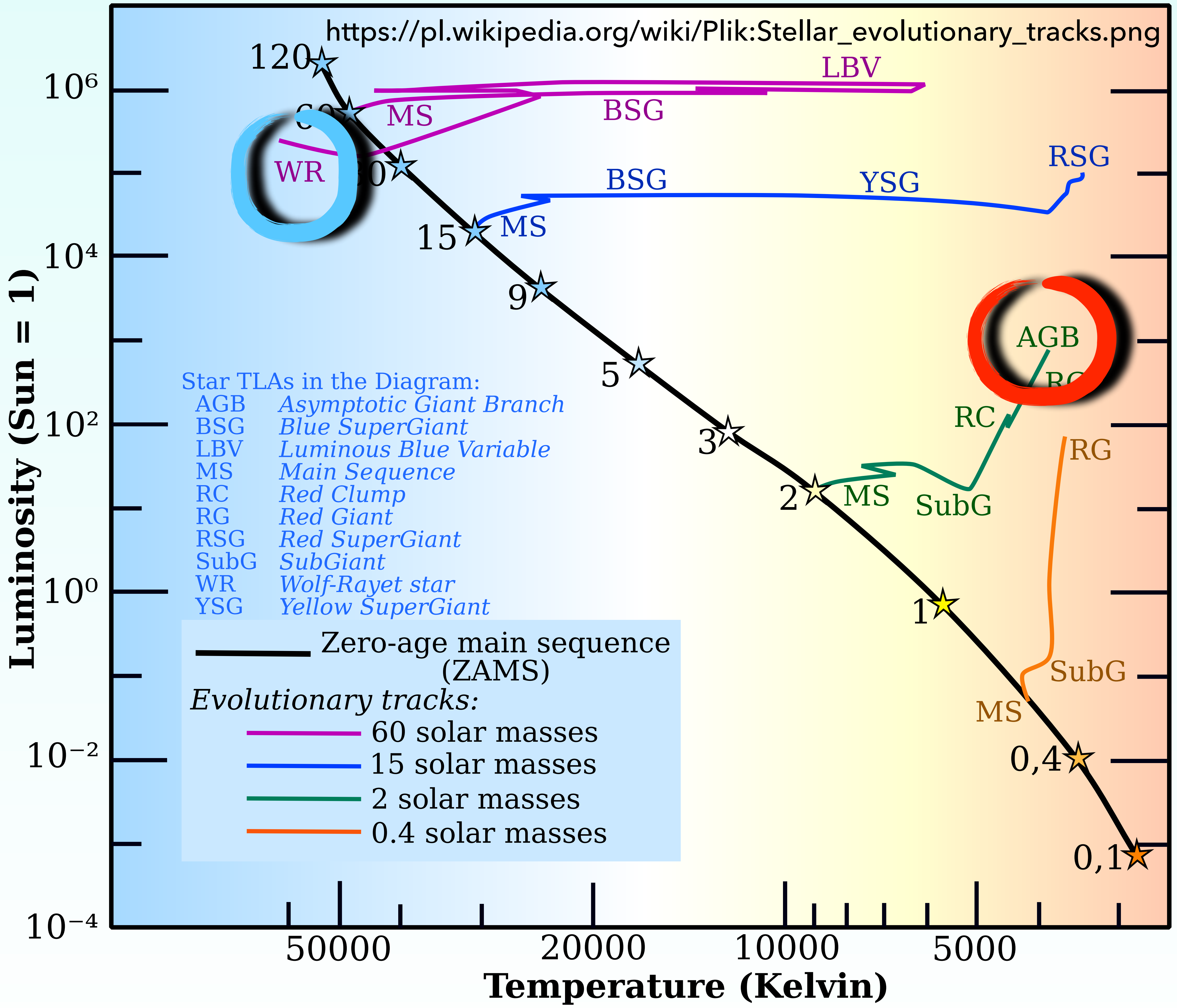
distribution of newborn stars as a function of mass

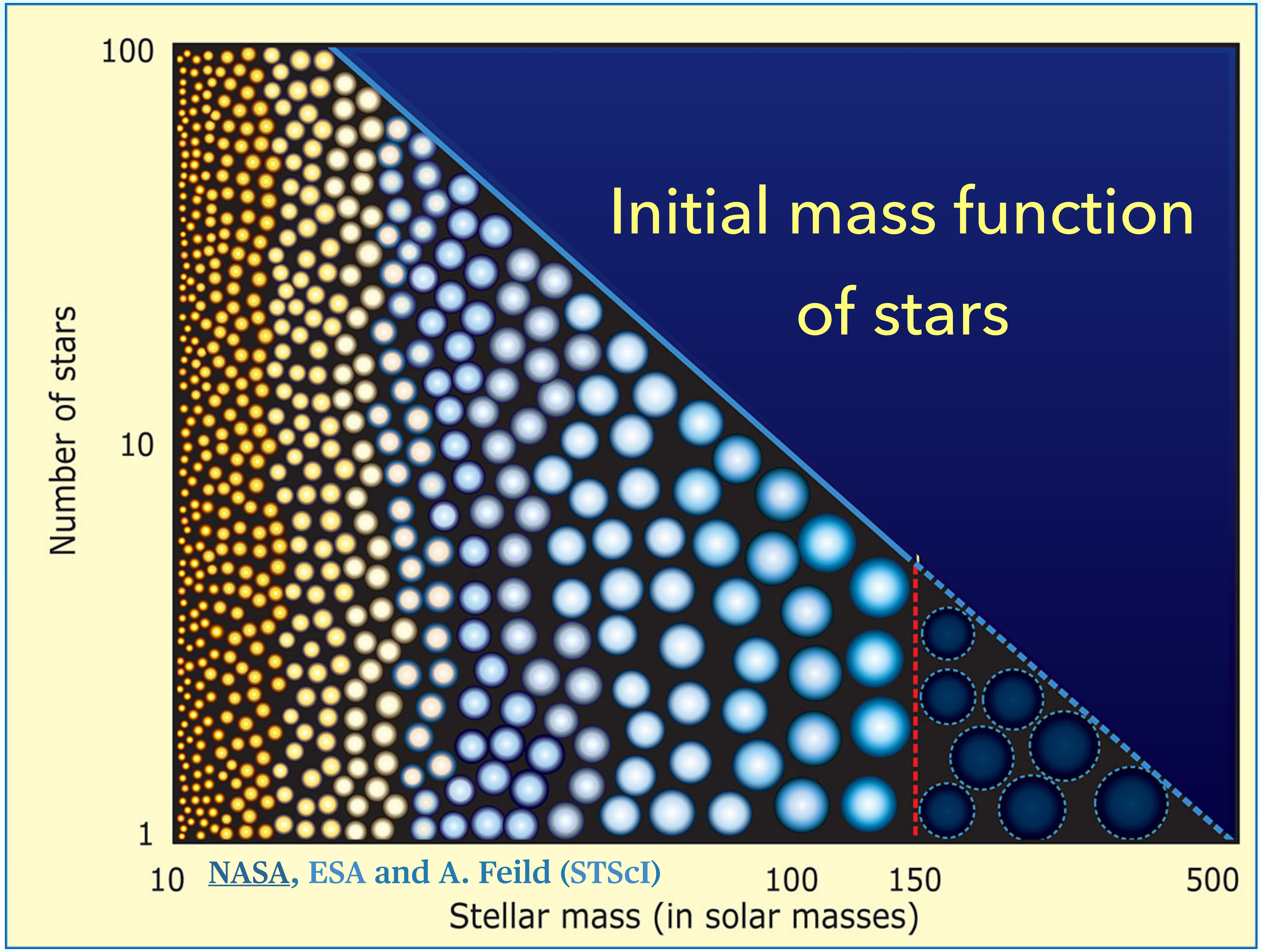
$$\frac{\mathrm{d}N_*}{\mathrm{d}m}$$

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

$$\mathscr{B}(m, t) = \mathrm{SFR}(t) \times \mathrm{IMF}(m)$$

How are elements produced Galactic Chemical Evolution (GCE)





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

Reviews: Kroupa01, Kroupa+13,

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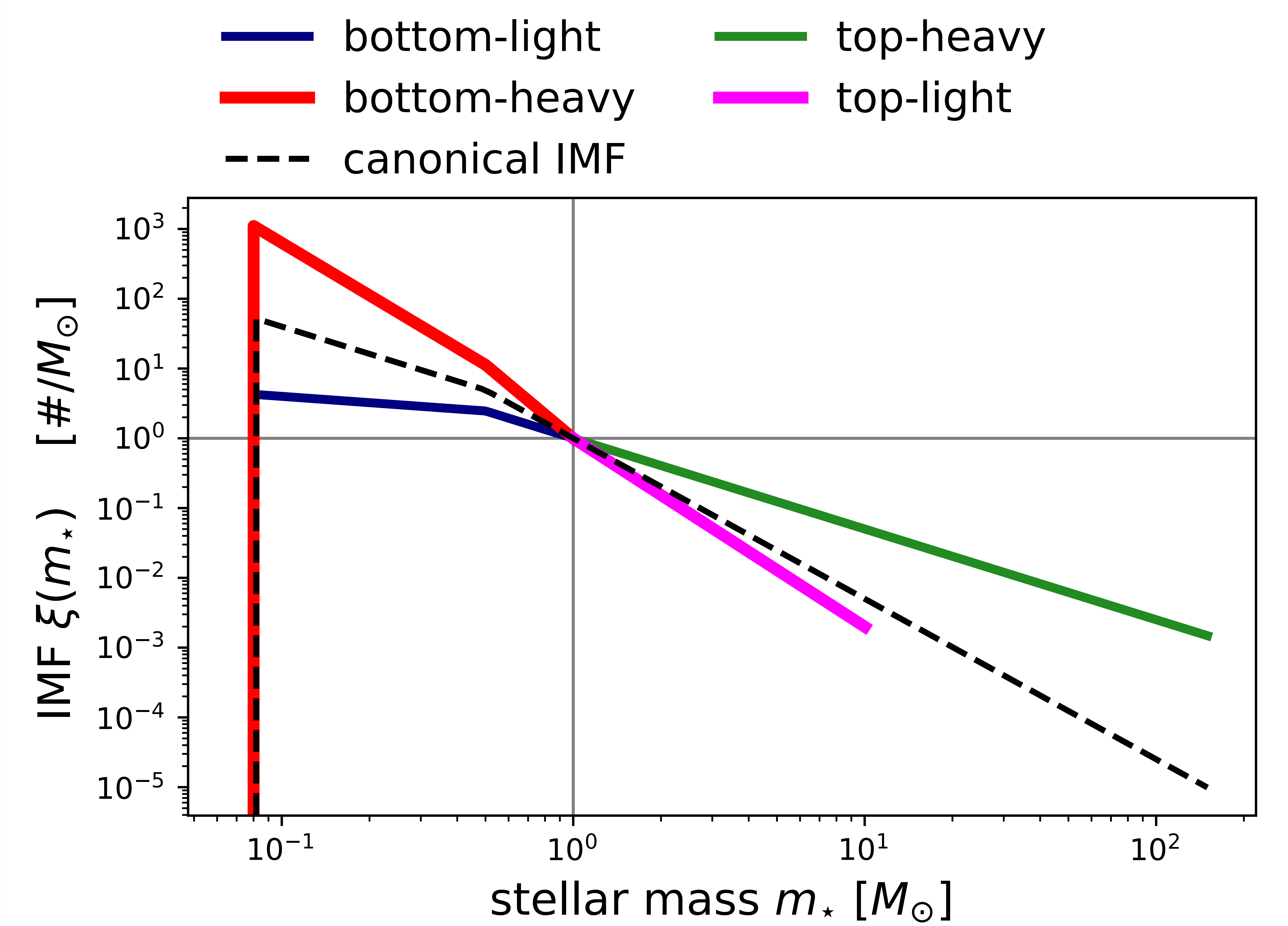

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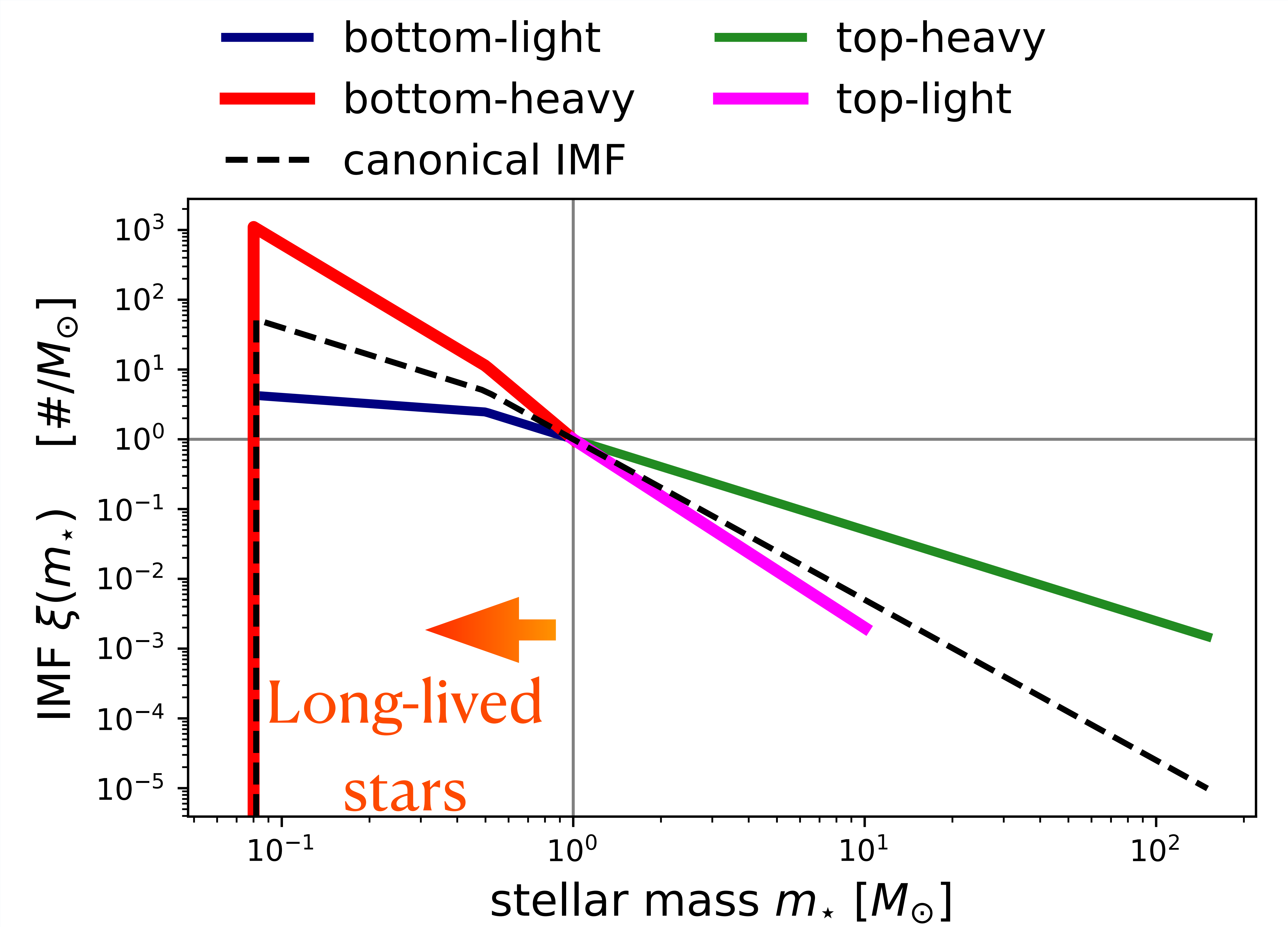

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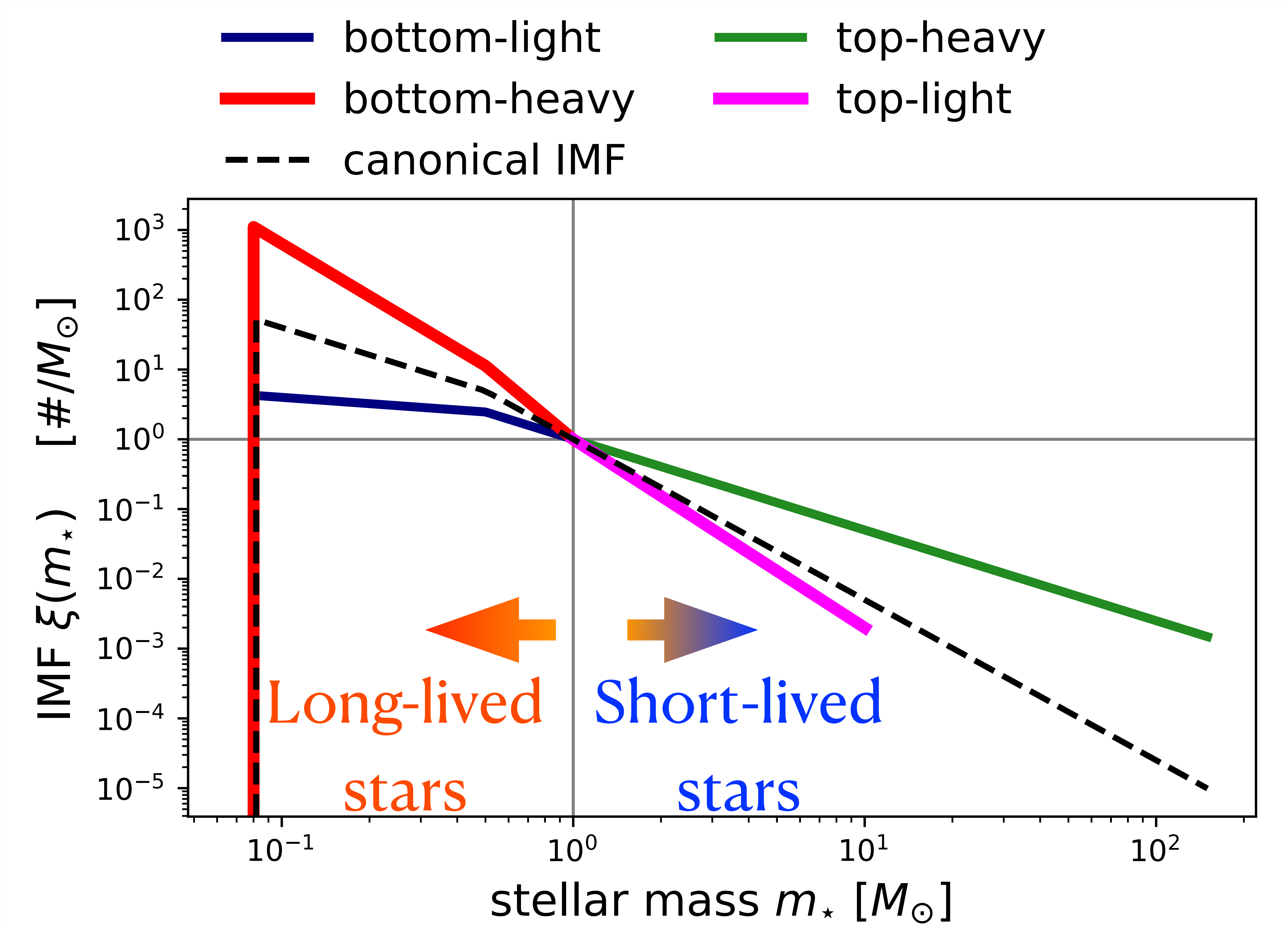

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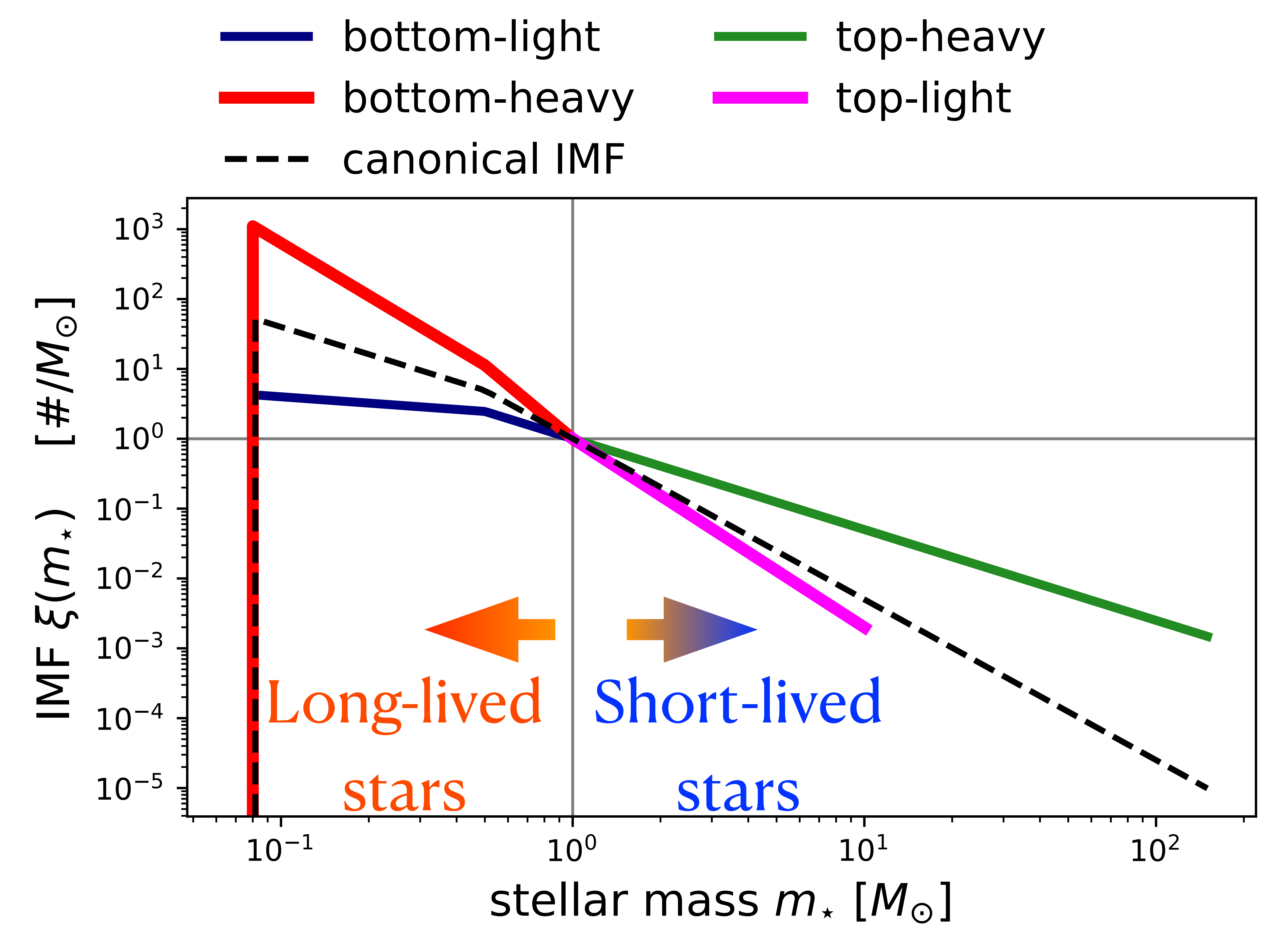
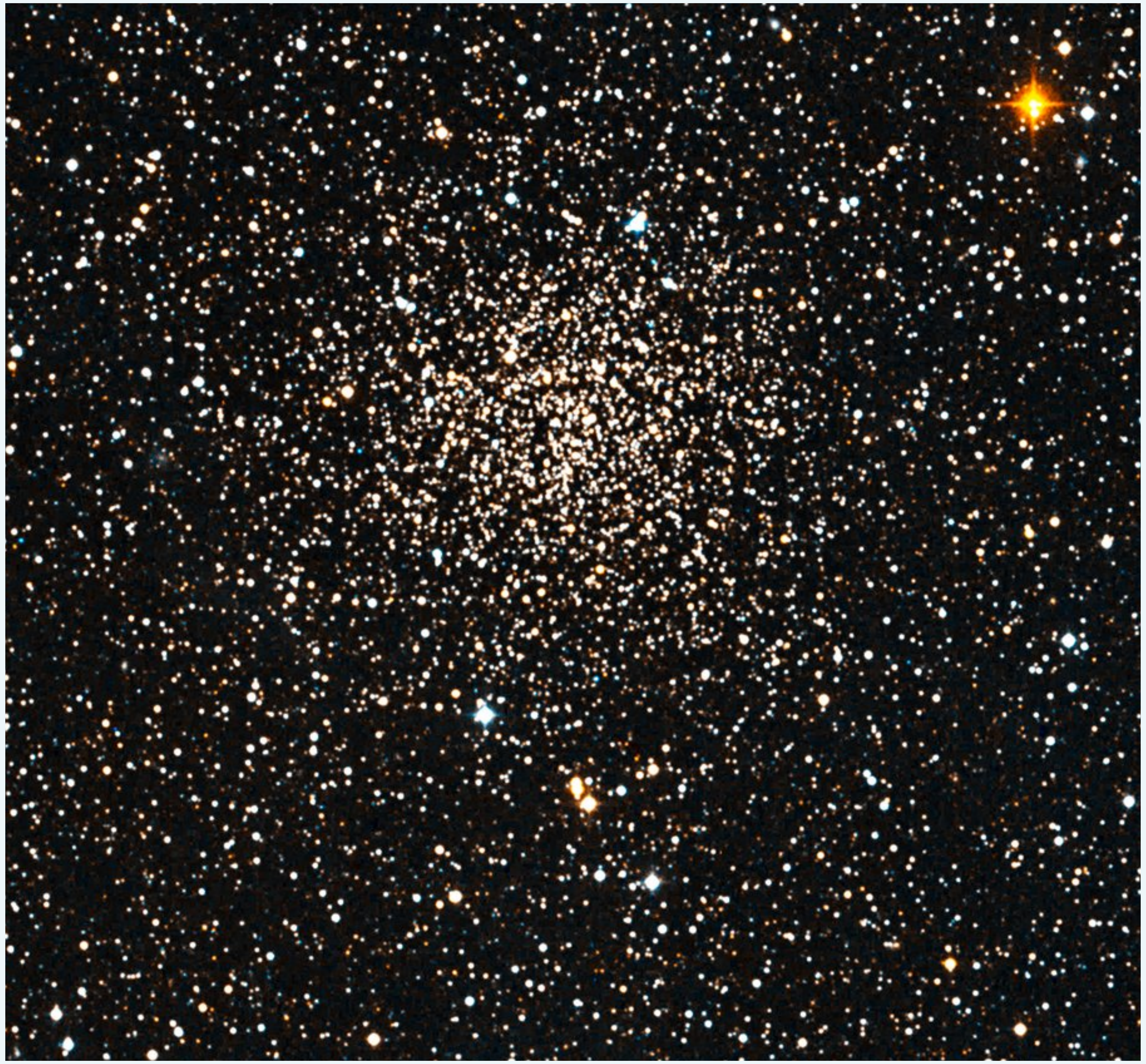
NGC 6791- old open cluster





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

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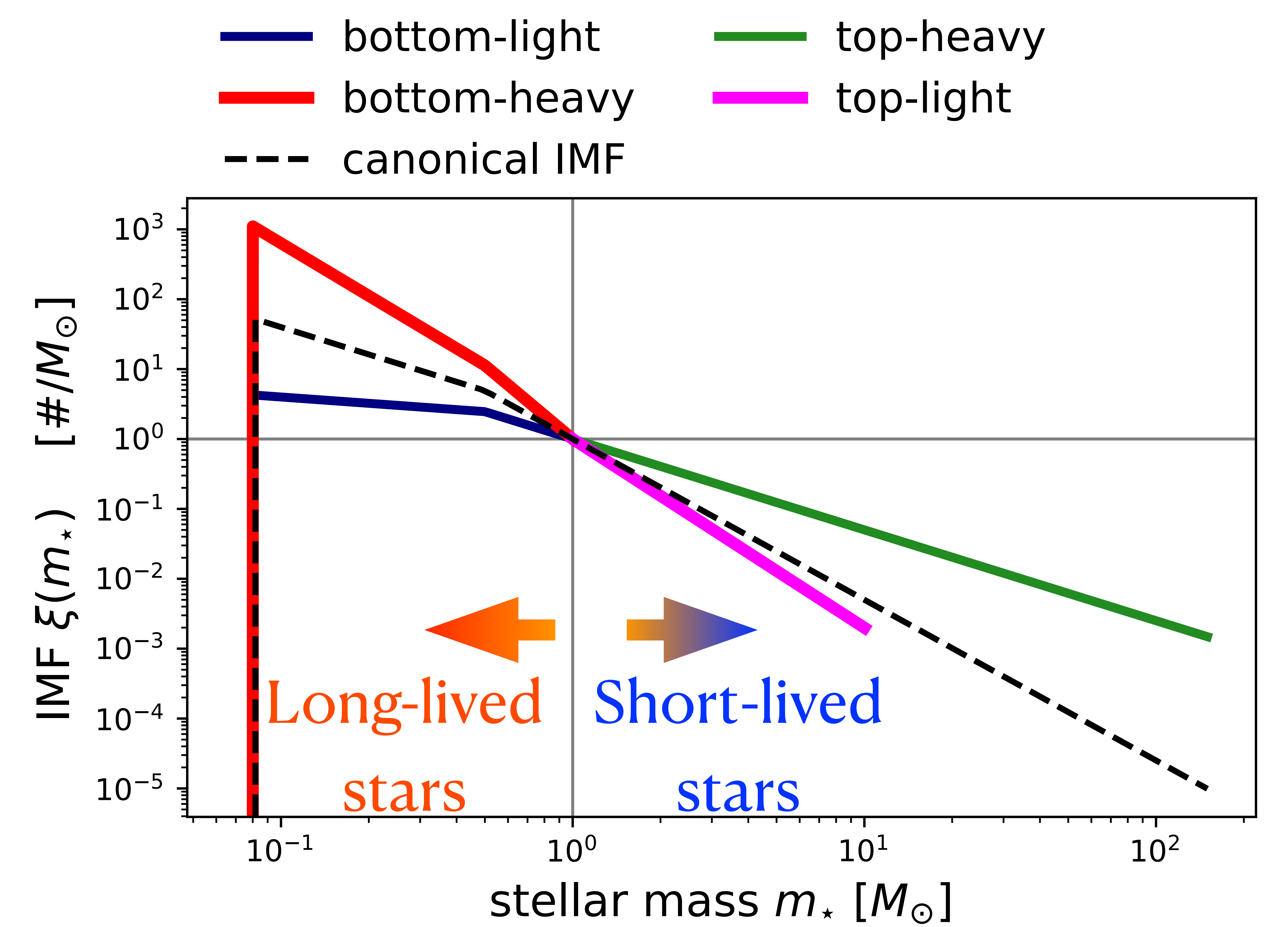

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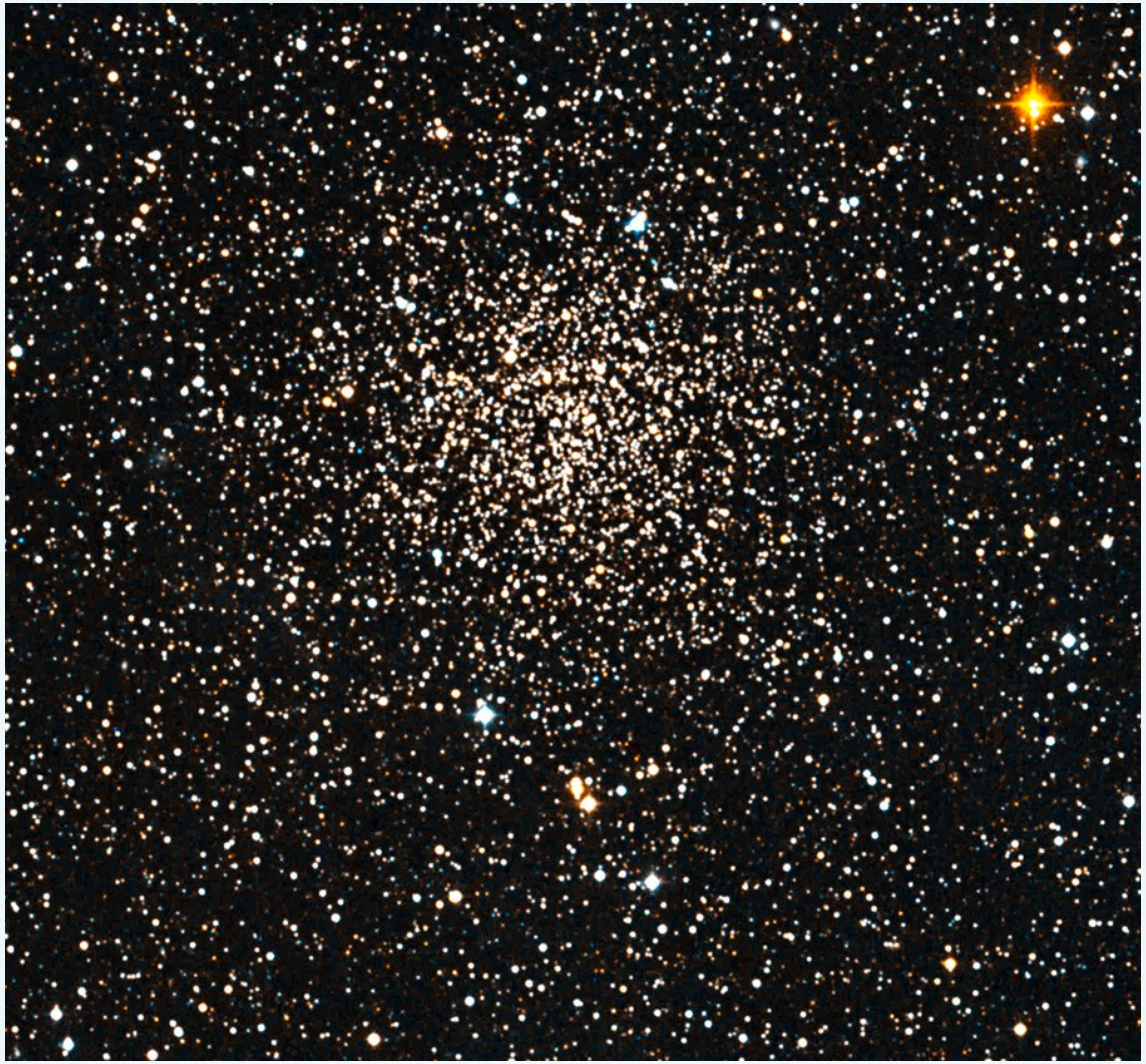

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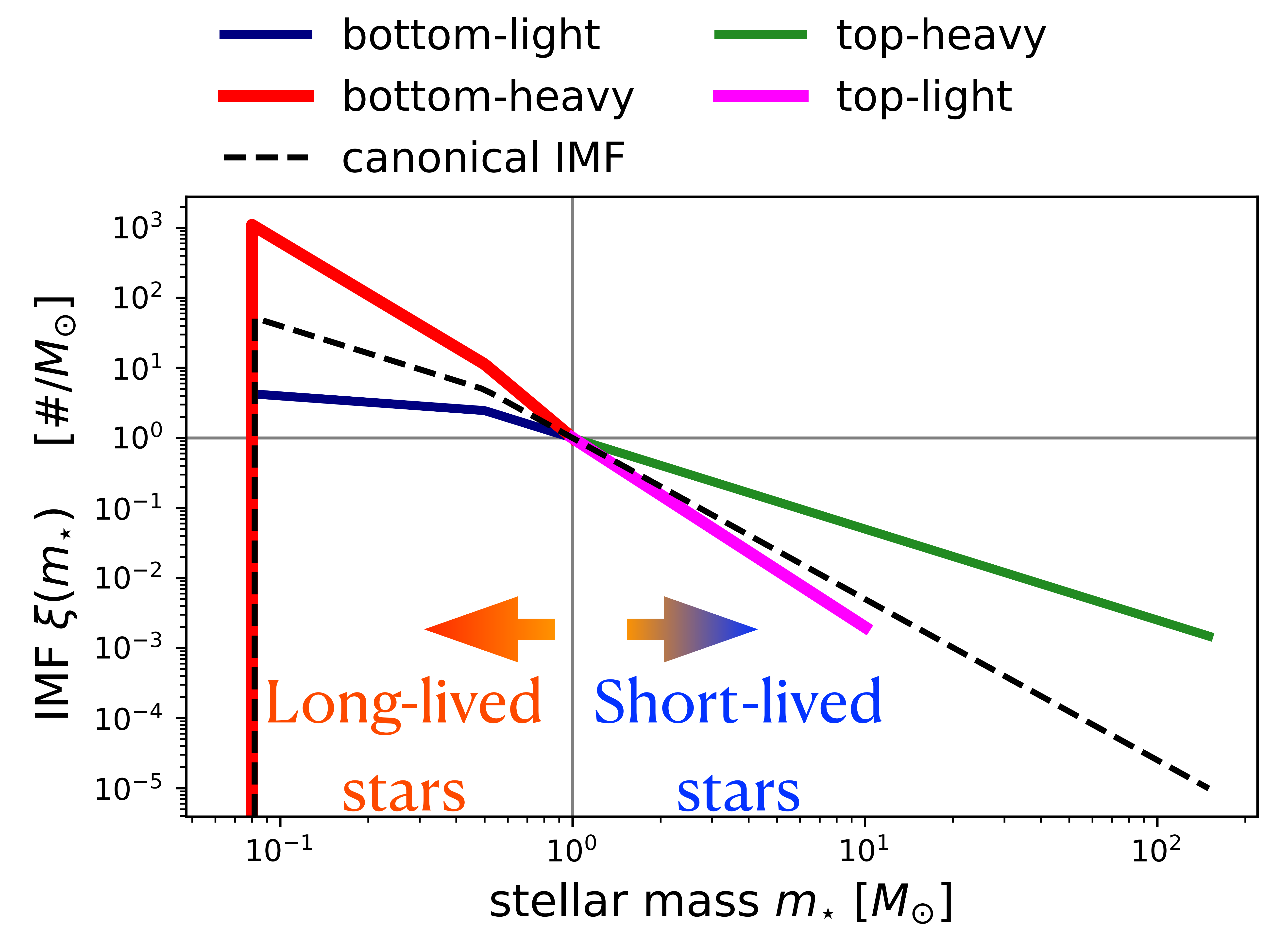
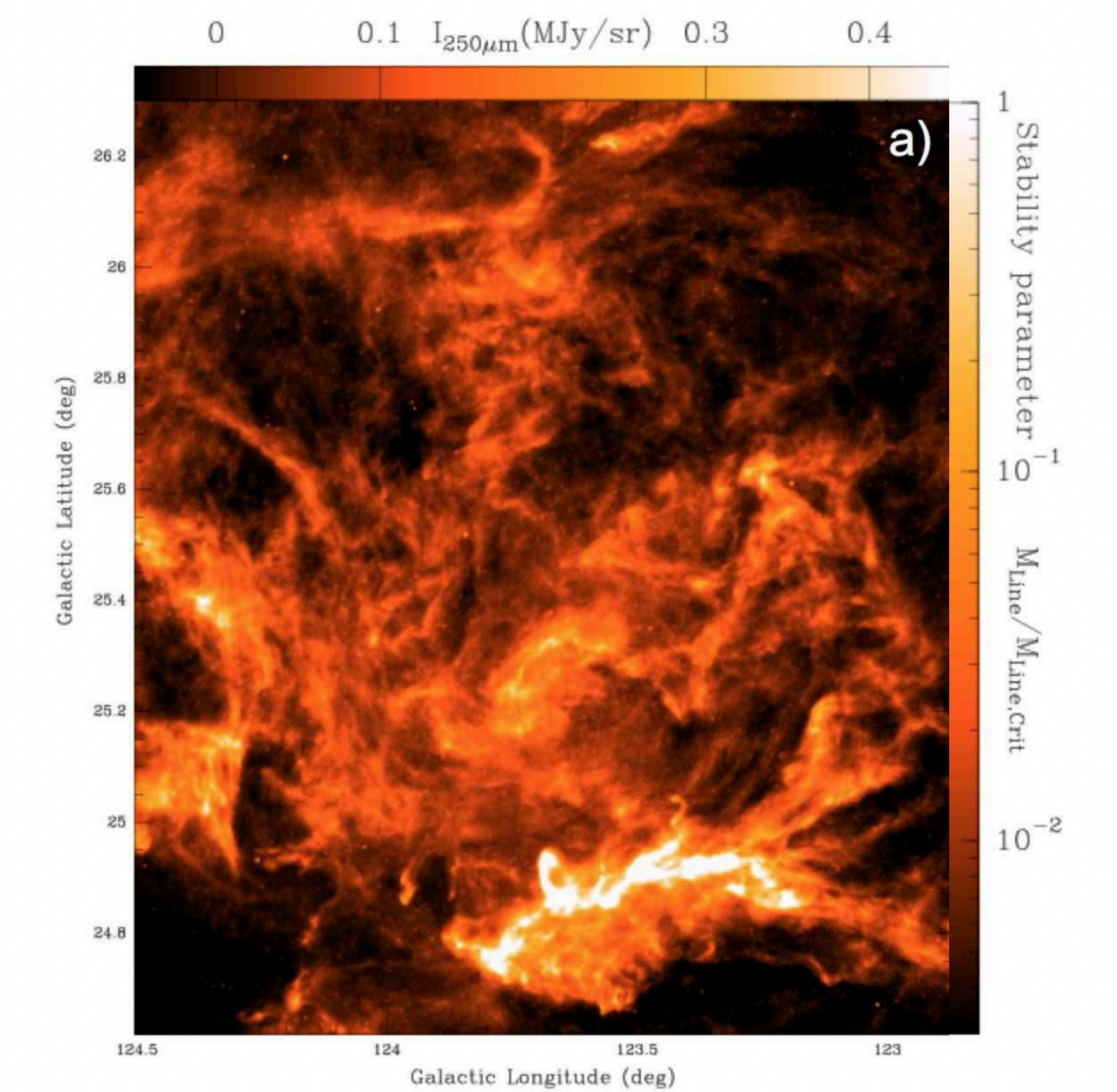


Young, star-forming Polaris flare

(Herschel, Andre Ph. et al. 2014)



Dust continuum (and H2 col. dens) in molecular clouds

 Star formation constrained in 0.1pc-sized cold and dense filaments

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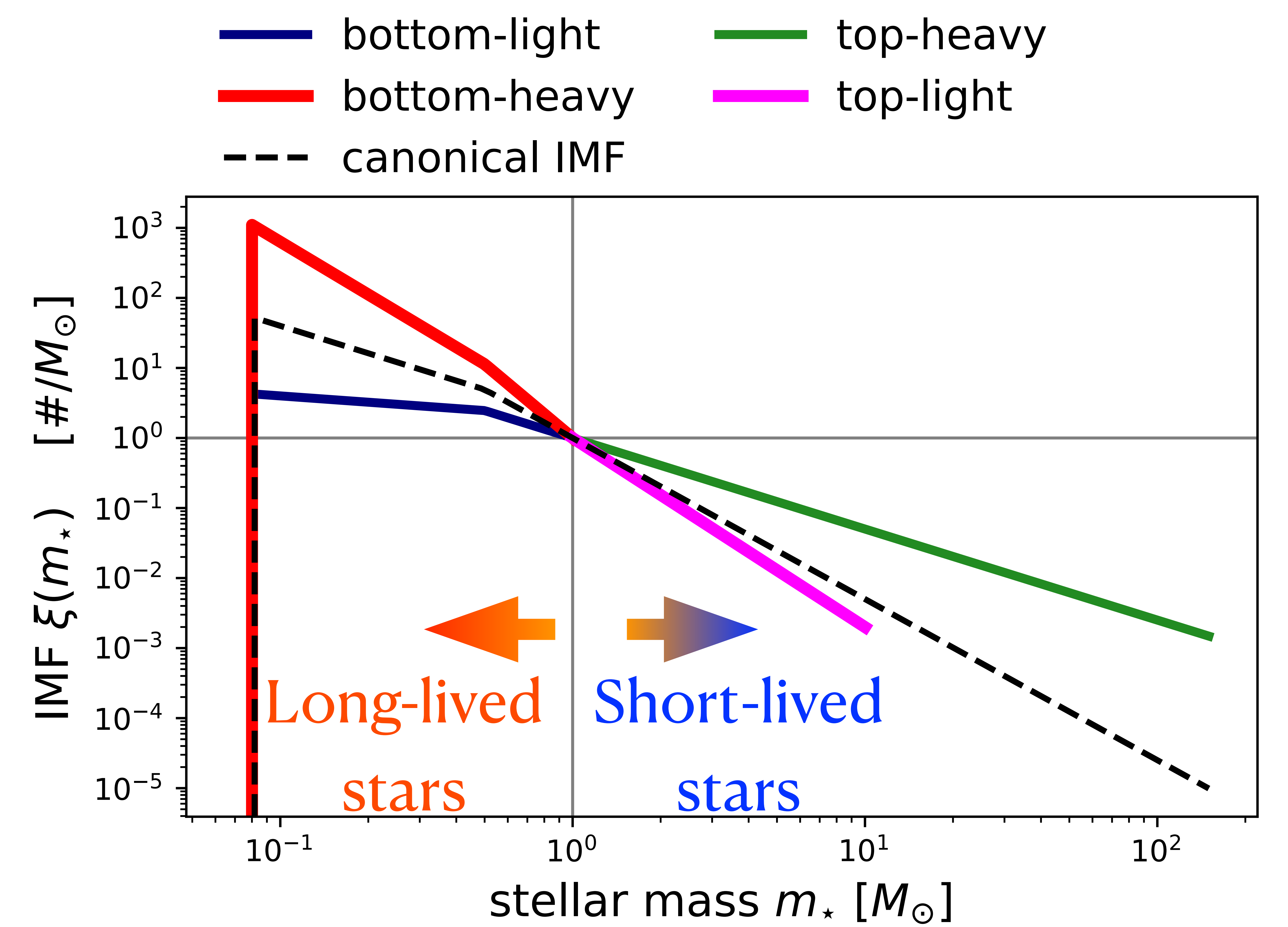

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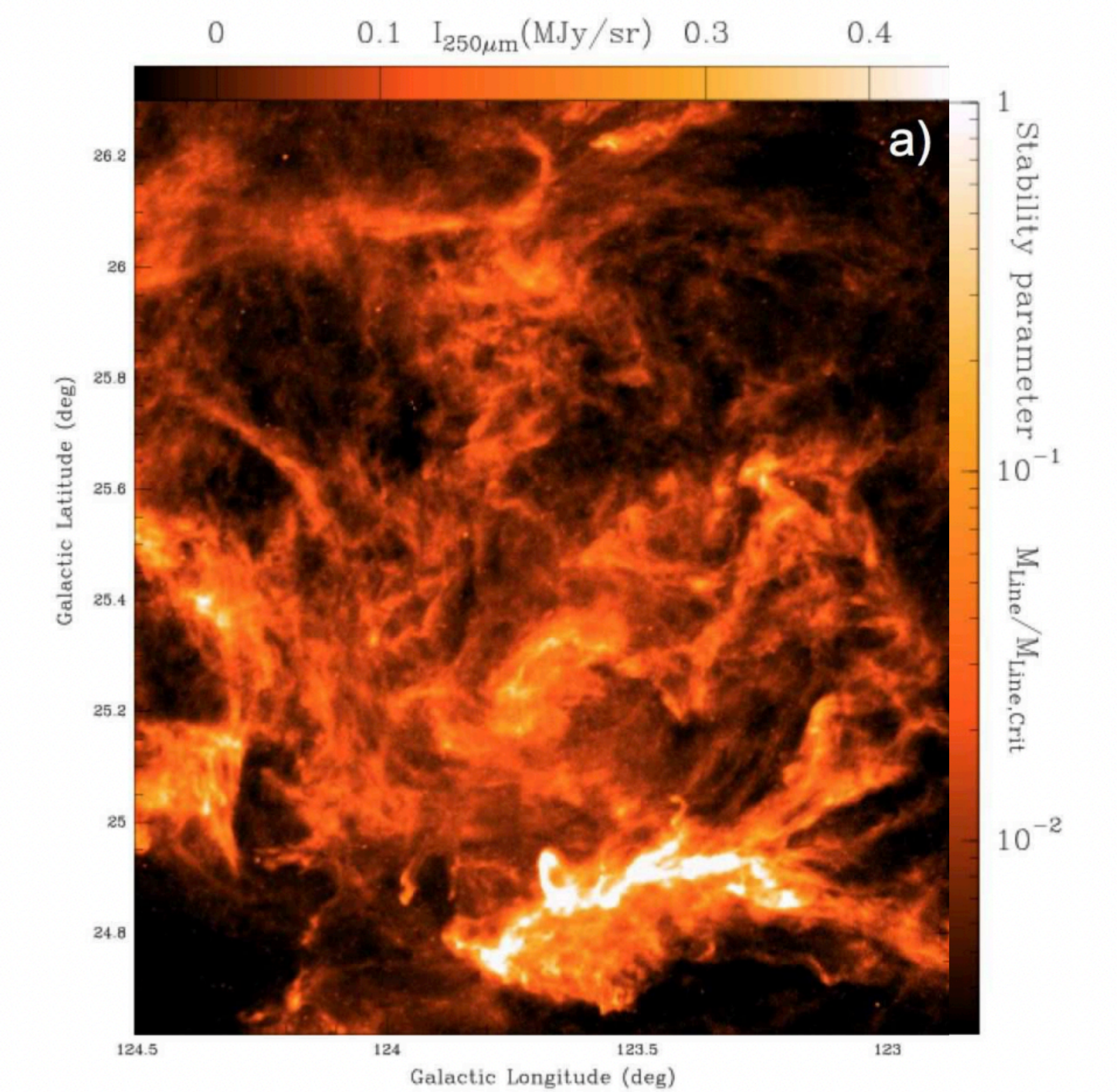

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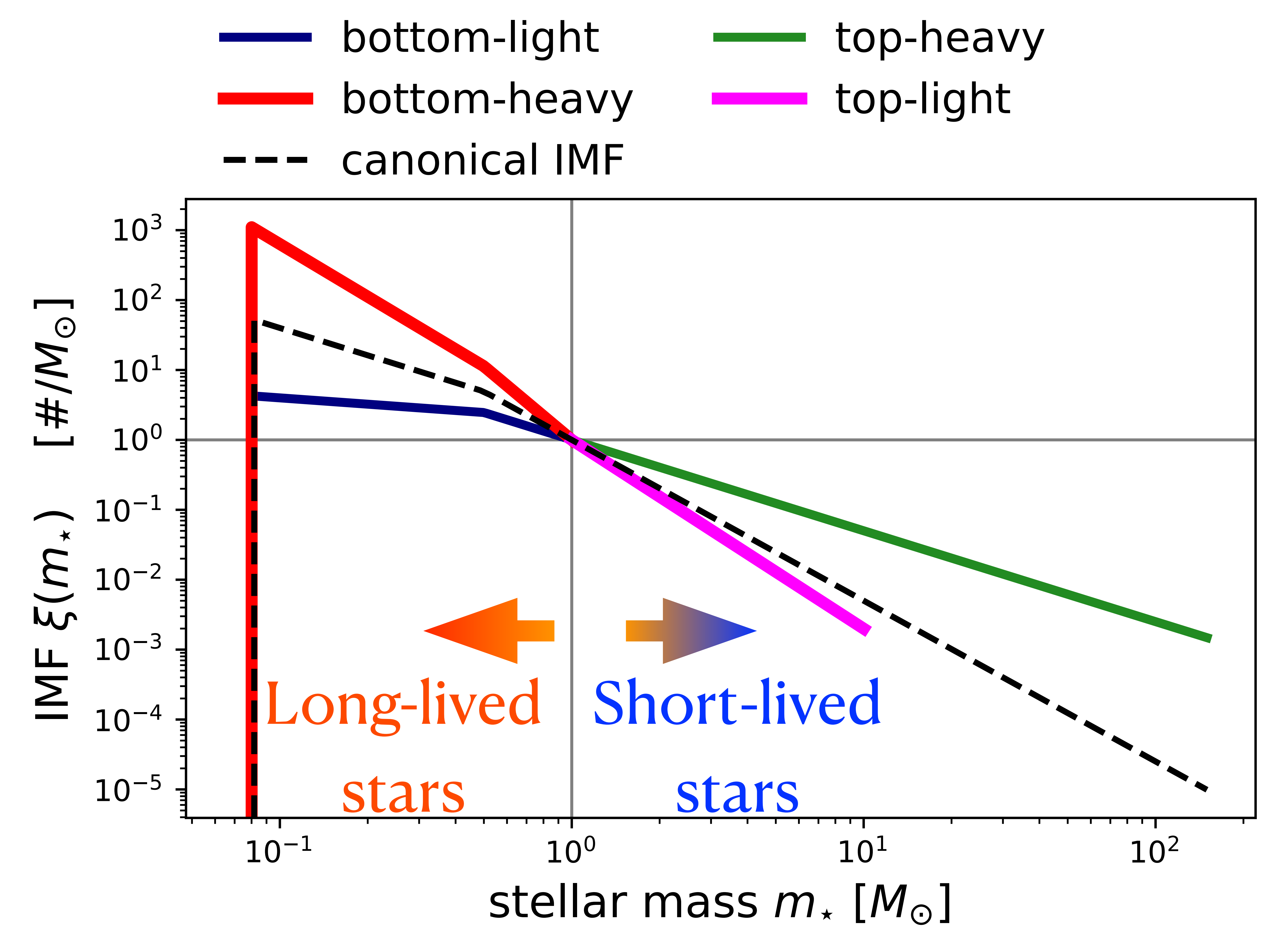

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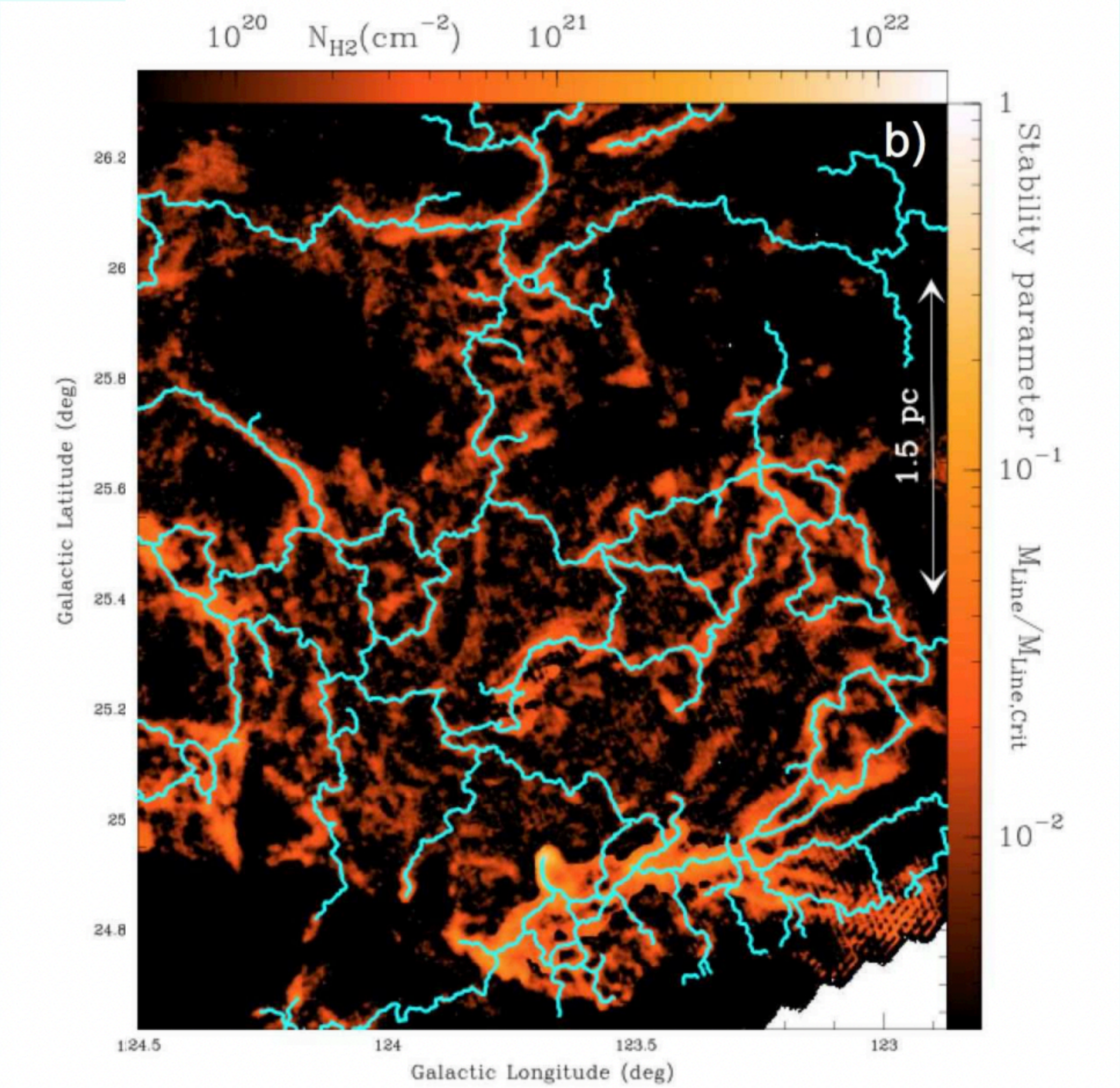
(Herschel, Andre Ph. et al. 2014)



Dust continuum (and H2 col. dens) in molecular clouds

 Star formation constrained in 0.1pc-sized cold and dense filaments

Stars form in 0.1pc thin fragmenting filaments
and
not in a super-sonic gravo-turbulent gas medium :

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See review by Philippe Andre et al. 2014
based on results from the Herschel space

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(see also the pioneering work of *Phil Myers* on star formation in filaments
(e.g. Myers, 2009, ApJ 700, 1609)

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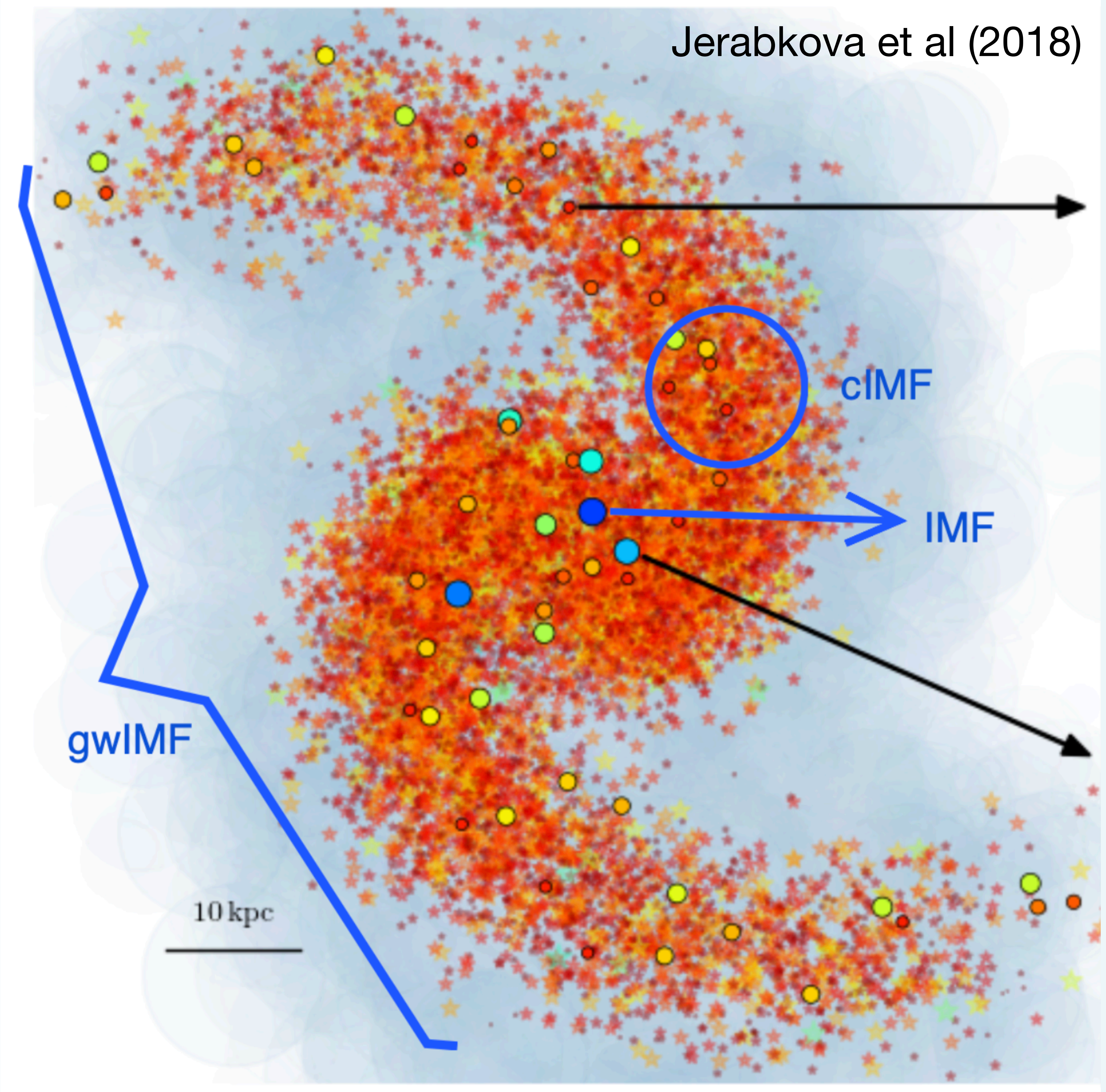
Thus: the ISM, where dense enough to cool sufficiently rapidly, molecularises and forms long thin filaments. Density fluctuations along these cause potential fluctuations and the molecular gas falls towards potential minima. There, proto-stars grow and regulate their accretion from the in-falling filament.

Integrated Galaxy-wide Initial Mass Function (IGIMF)



Red: older stellar populations

Blue: younger stars

Integrated Galaxy-wide Initial Mass Function (IGIMF)

Formulation from

Kroupa & Weidner (2003)
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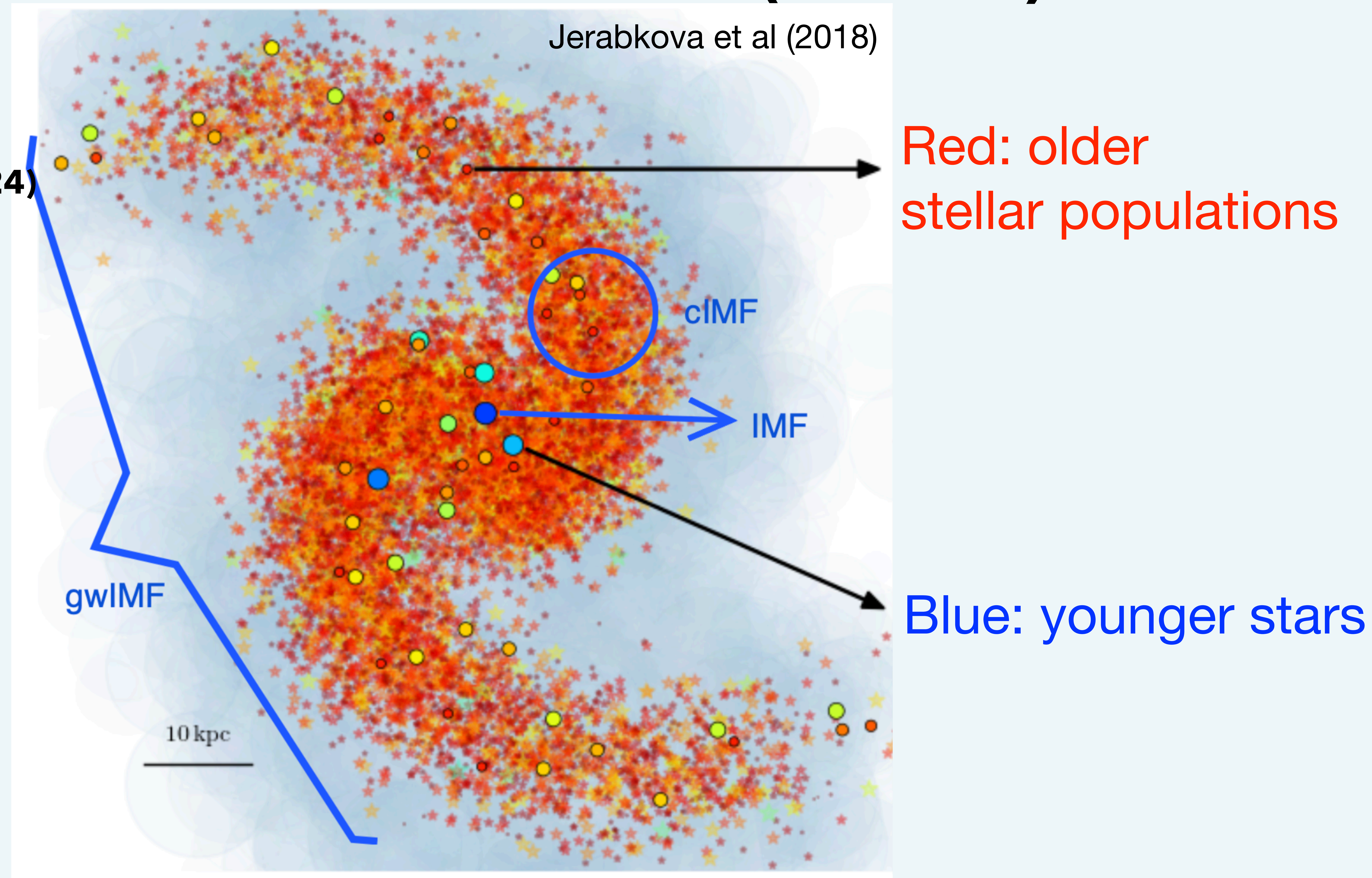

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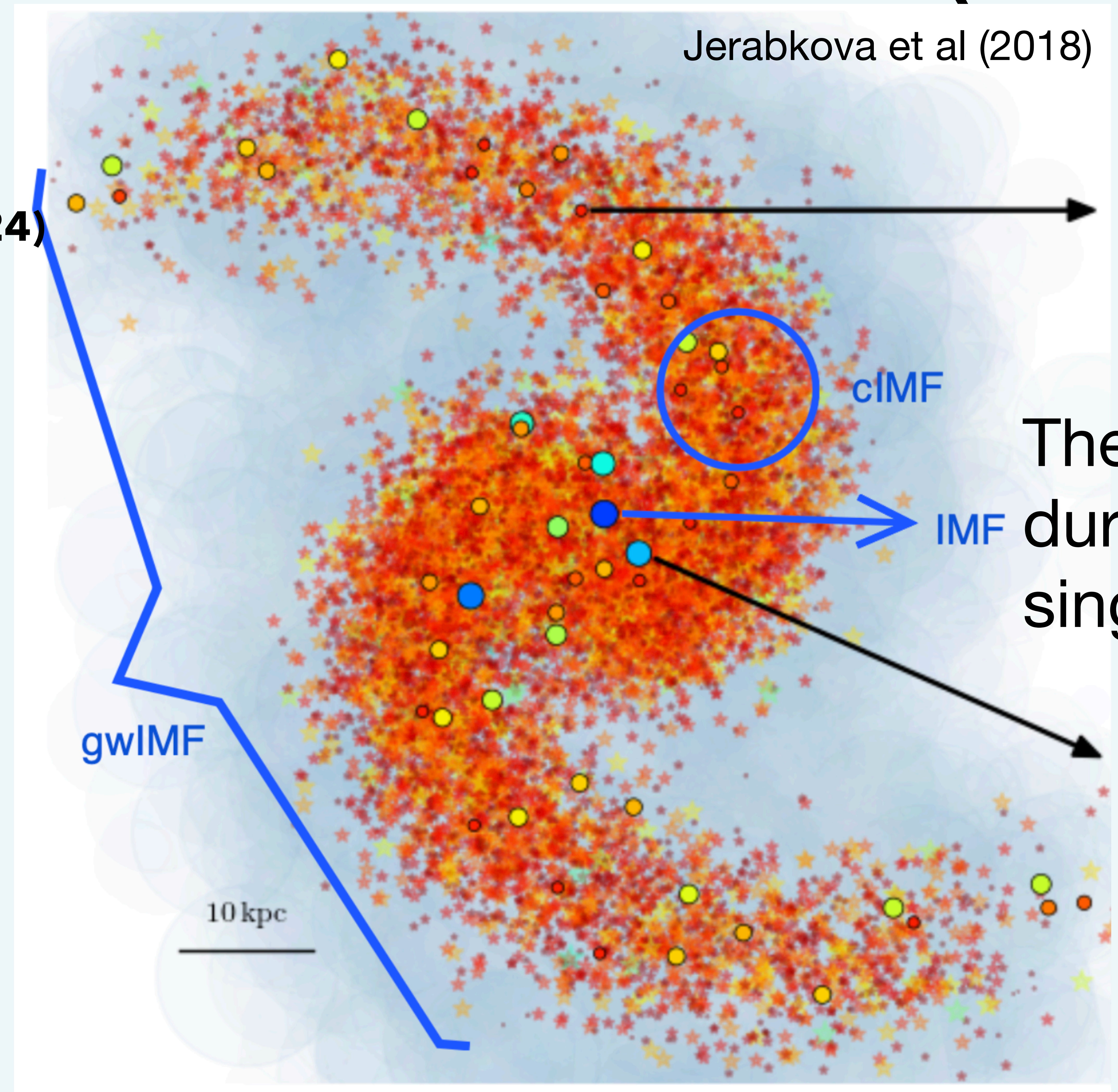

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The stellar IMF emerges only during the formation of single stellar populations

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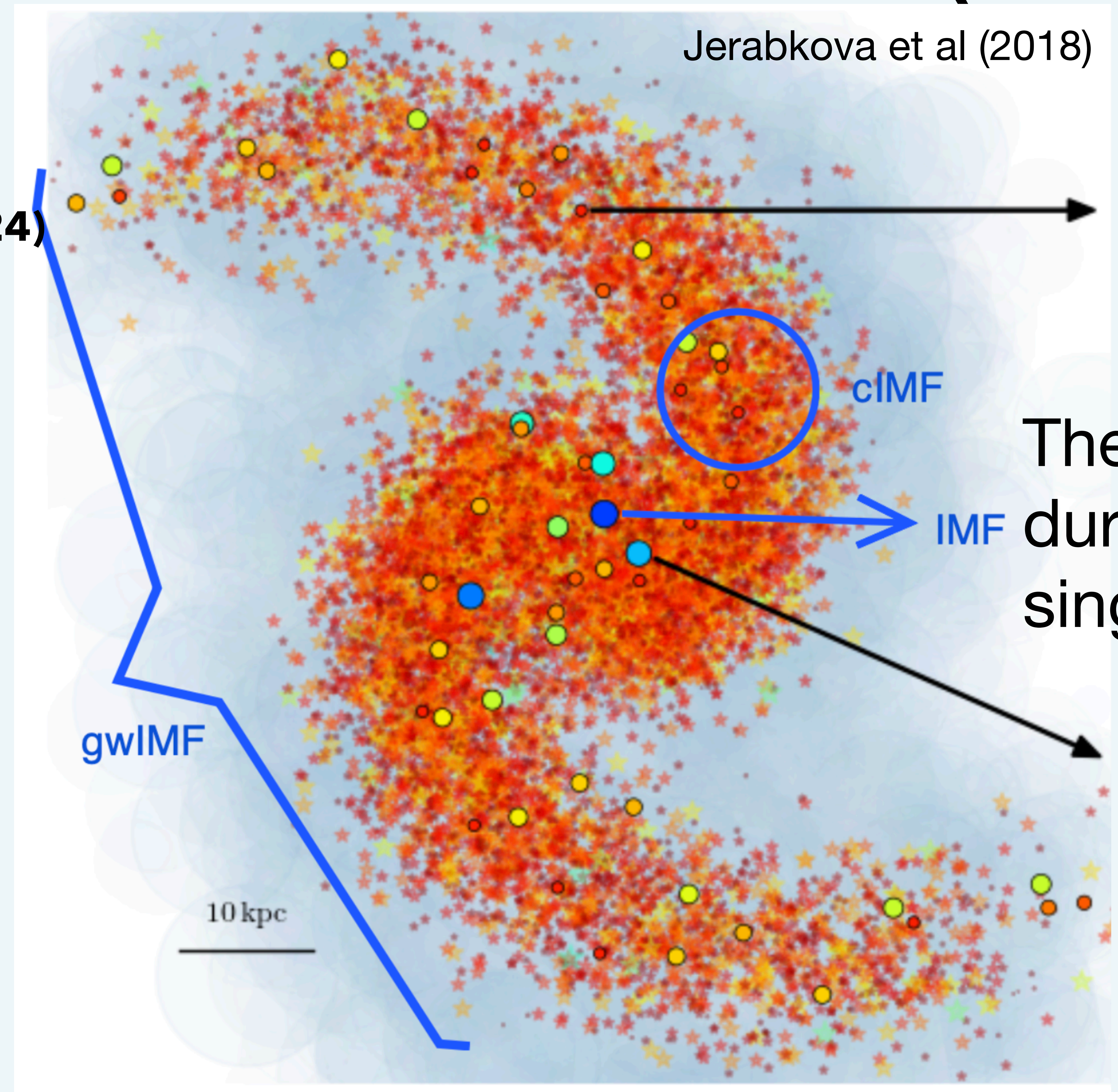

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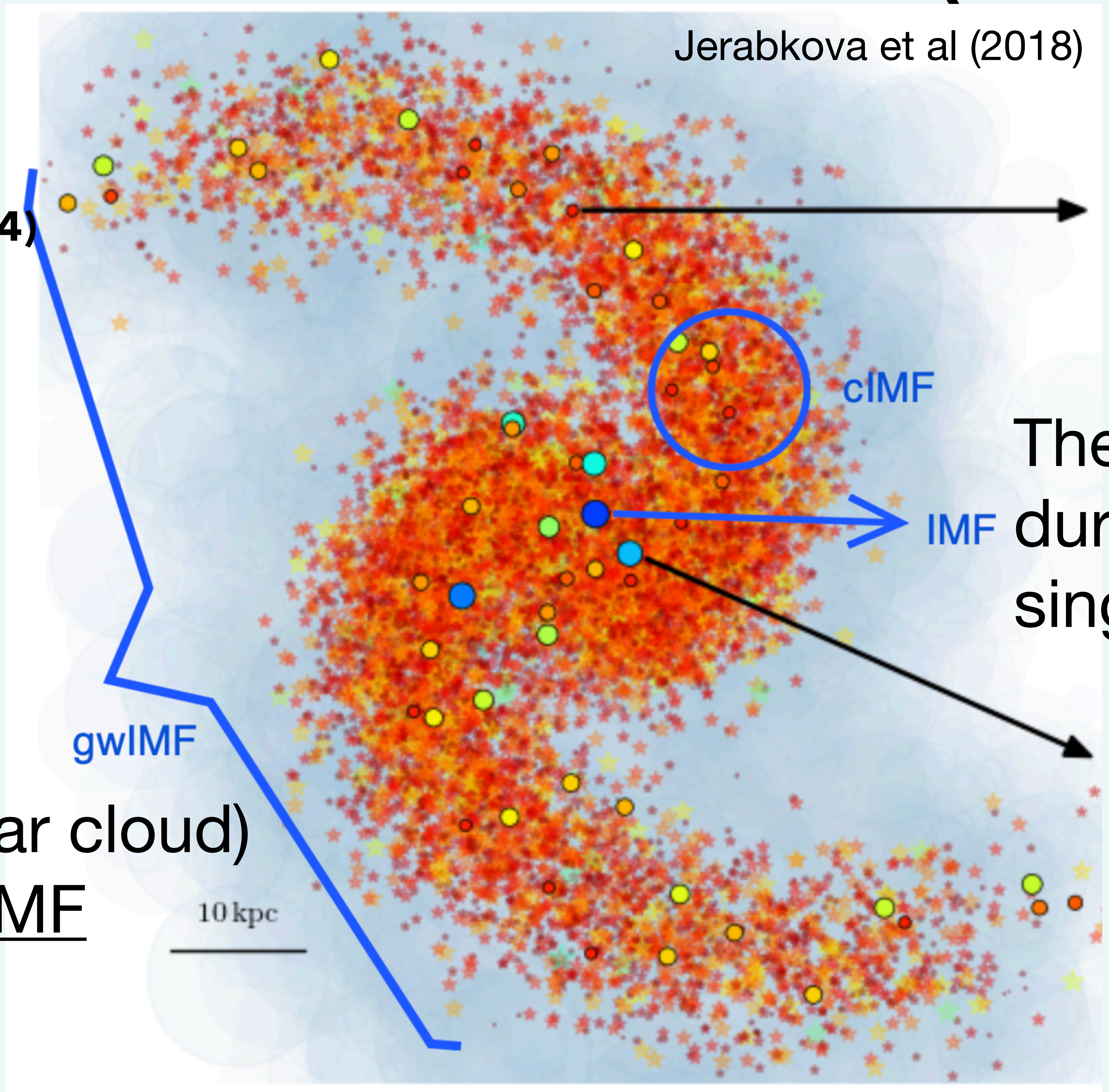

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The <u>stellar IMF</u> emerges only during the formation of single stellar populations

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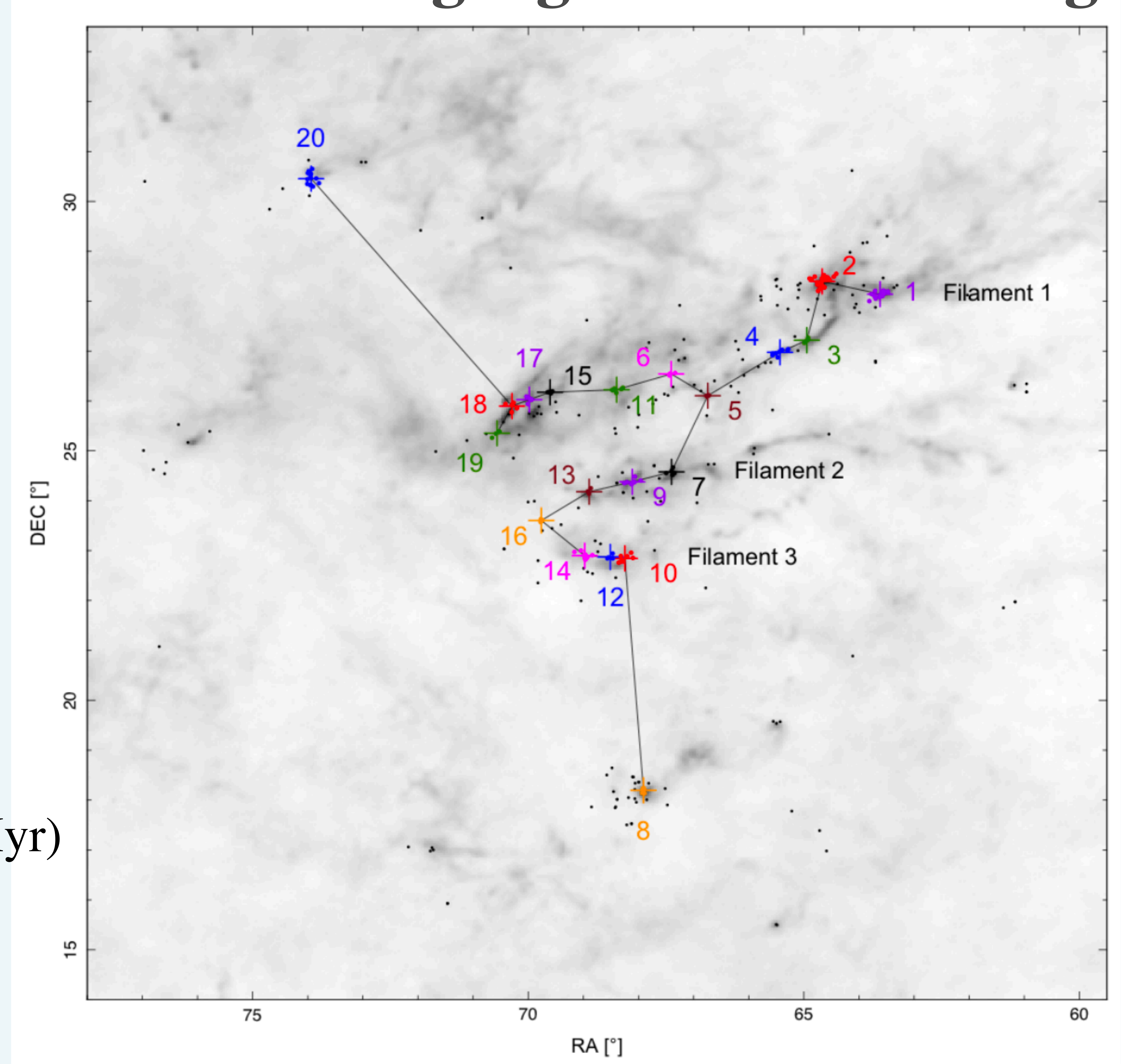
$$\text{IMF} = \frac{\Delta N \text{ of stars}}{\Delta \text{ mass of stars}}$$

The **cumulative sum** of all stellar IMFs formed in past 10 Myr (The lifetime of a molecular cloud) defines the <u>galaxy-wide IMF</u> (gwIMF)

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

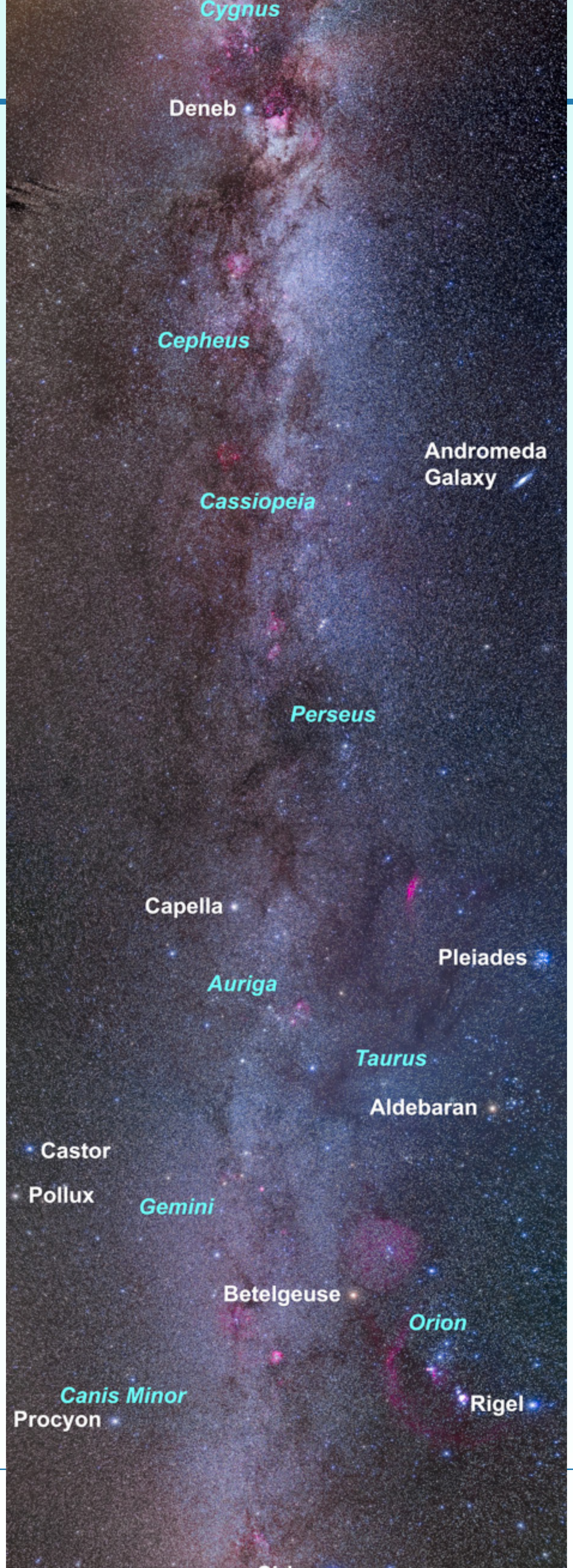
Astrophotographer: © 2015 Alan Dyer

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


Altair
Vega
Cygnus
Deneb
Cepheus
Andromeda Galaxy
Cassiopeia
Perseus
Capella
Pleiades
Auriga
Taurus
Aldebaran
Castor
Pollux
Gemini
Betelgeuse
Orion
Rigel
Canis Minor
Procyon
Sirius
Canis Major
Puppis
Canopus
© 2015 Alan Dyer/AmazingSky.com



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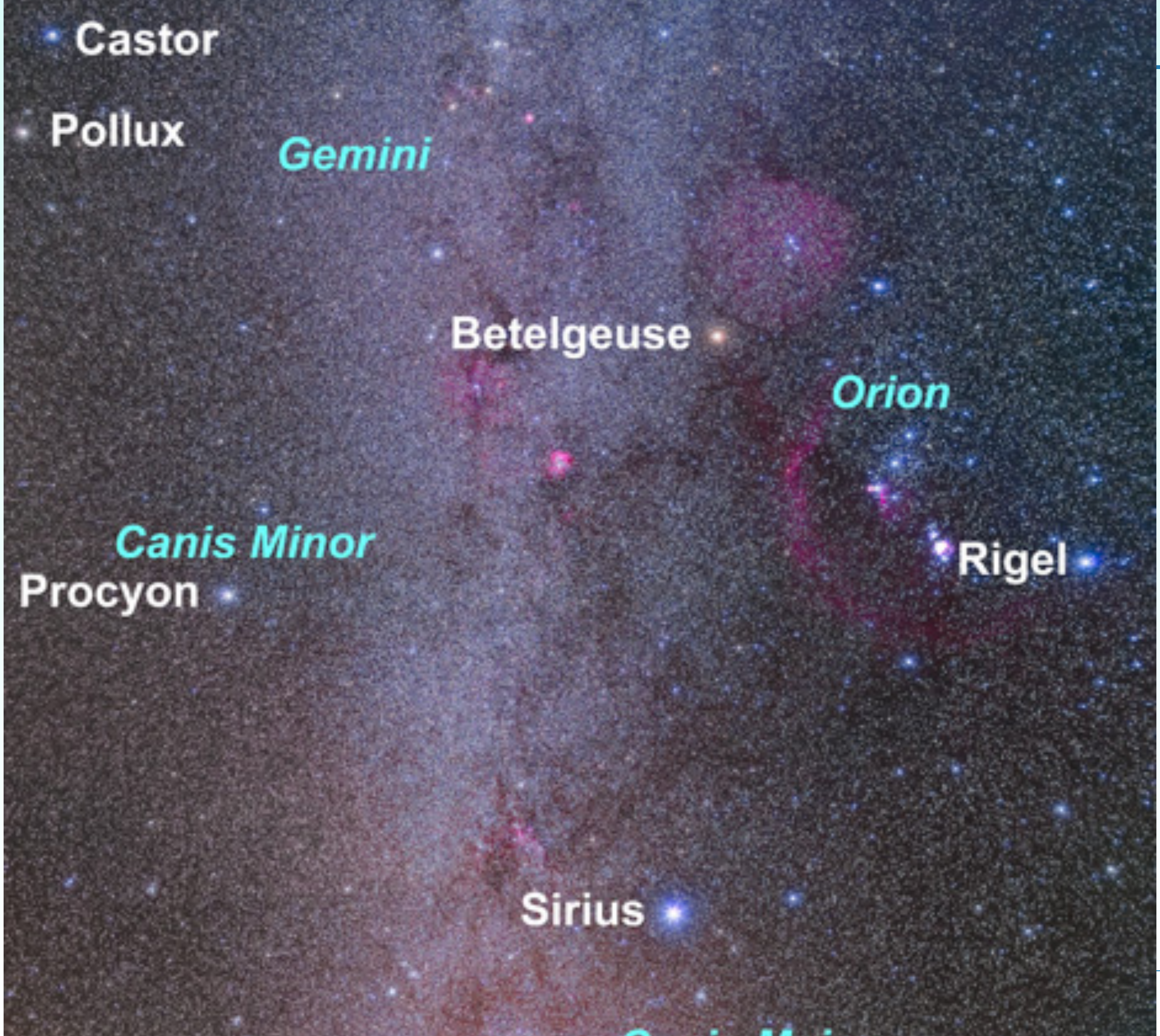
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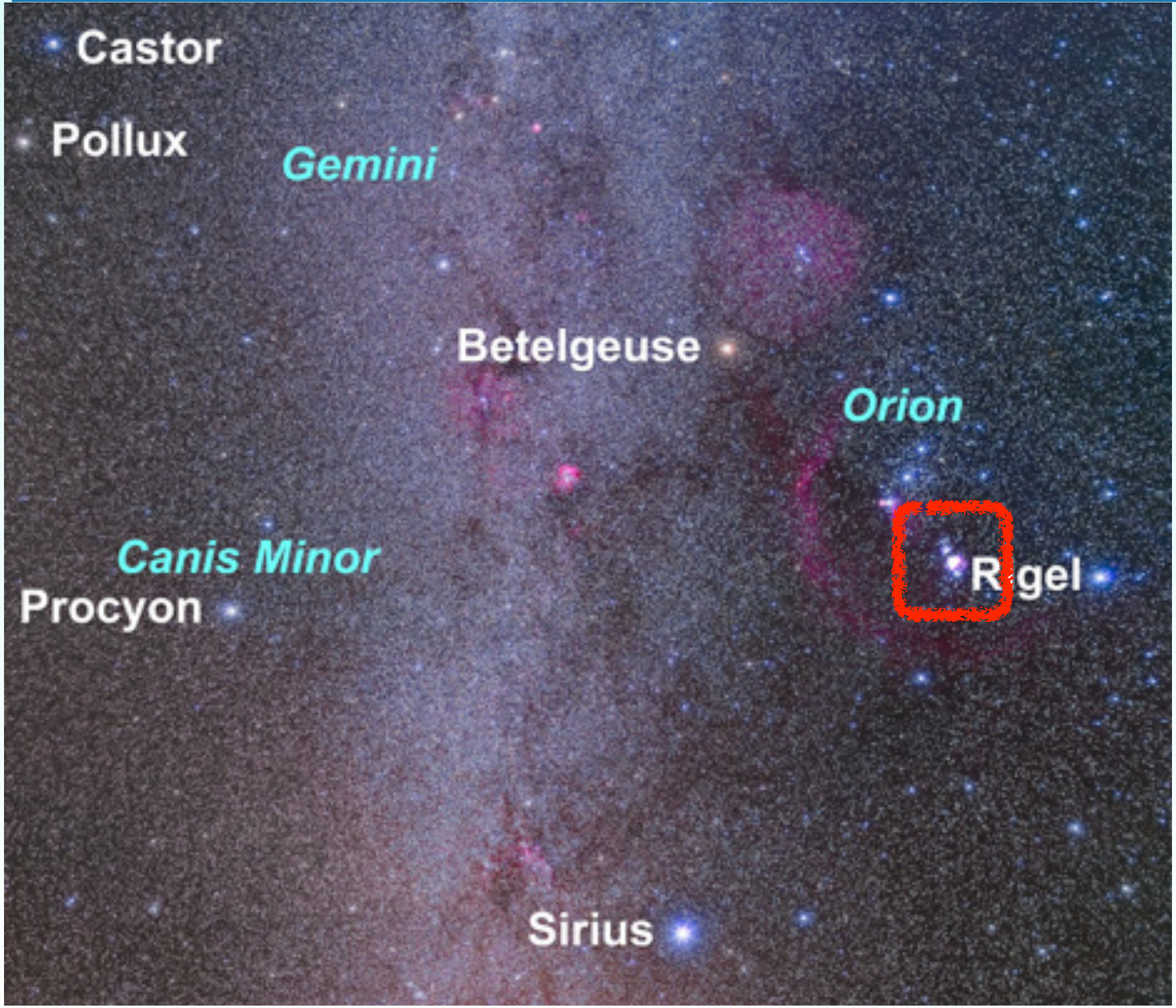
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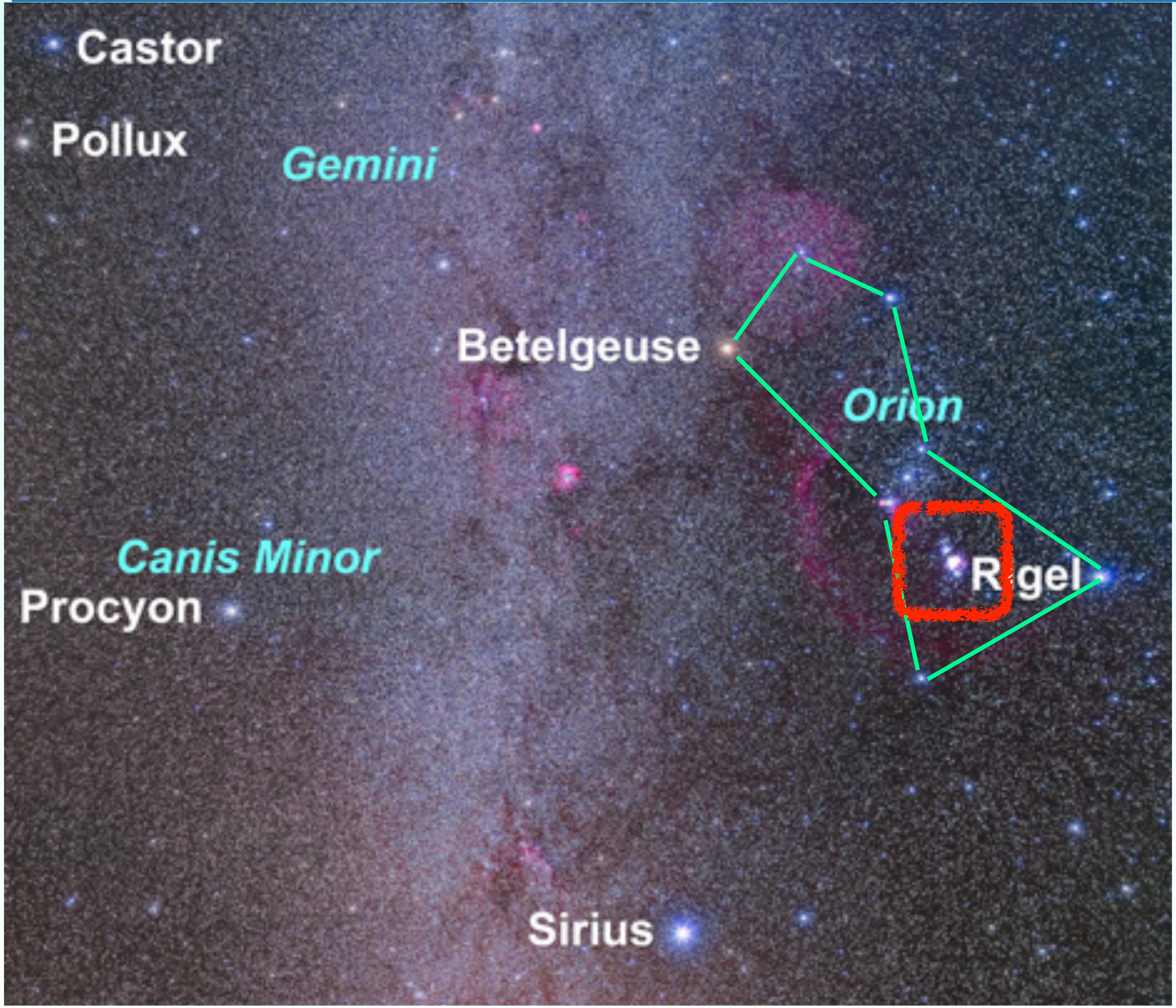
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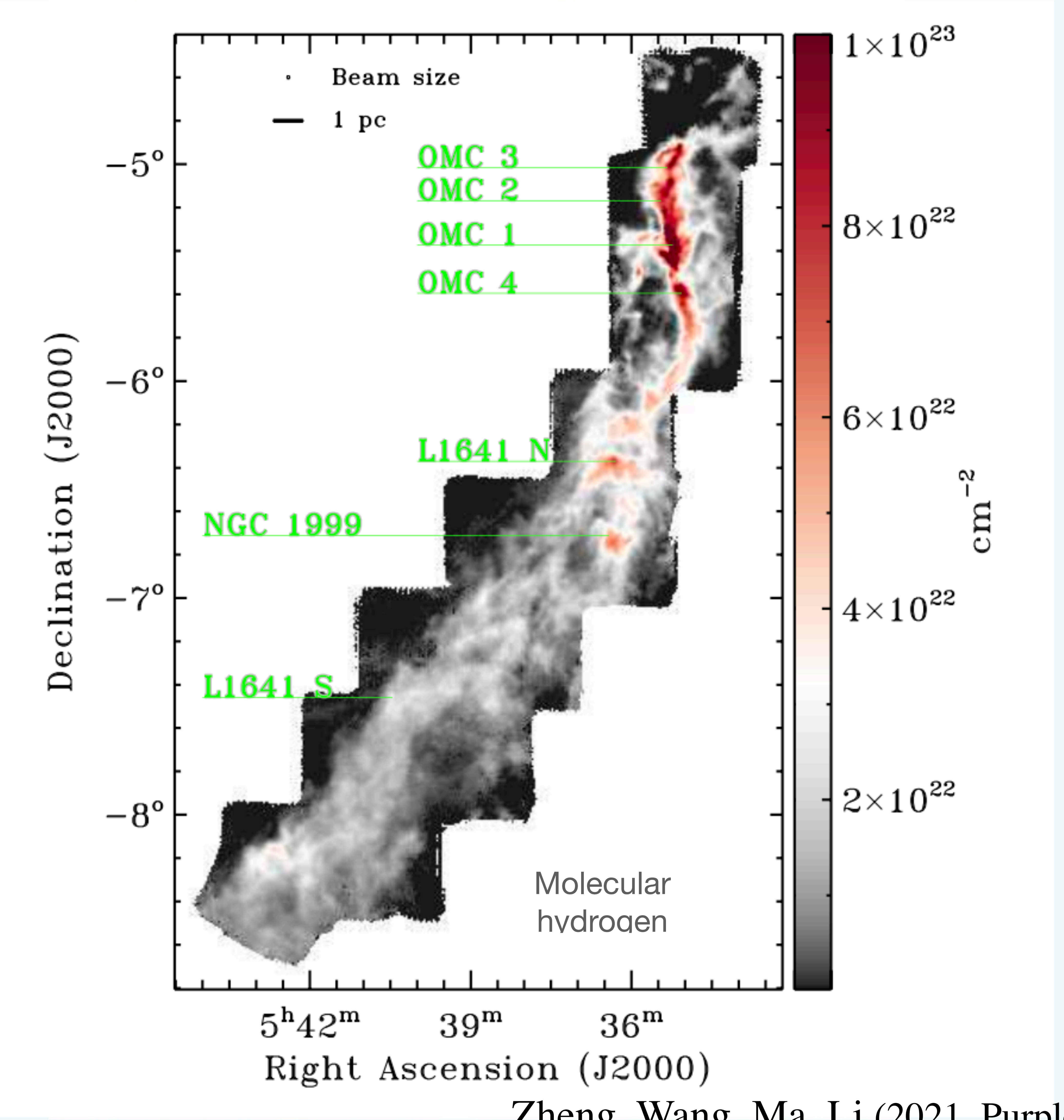
Southern cloud in Orion A: a SF region with no massive stars



400 pc away from us, same age across

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

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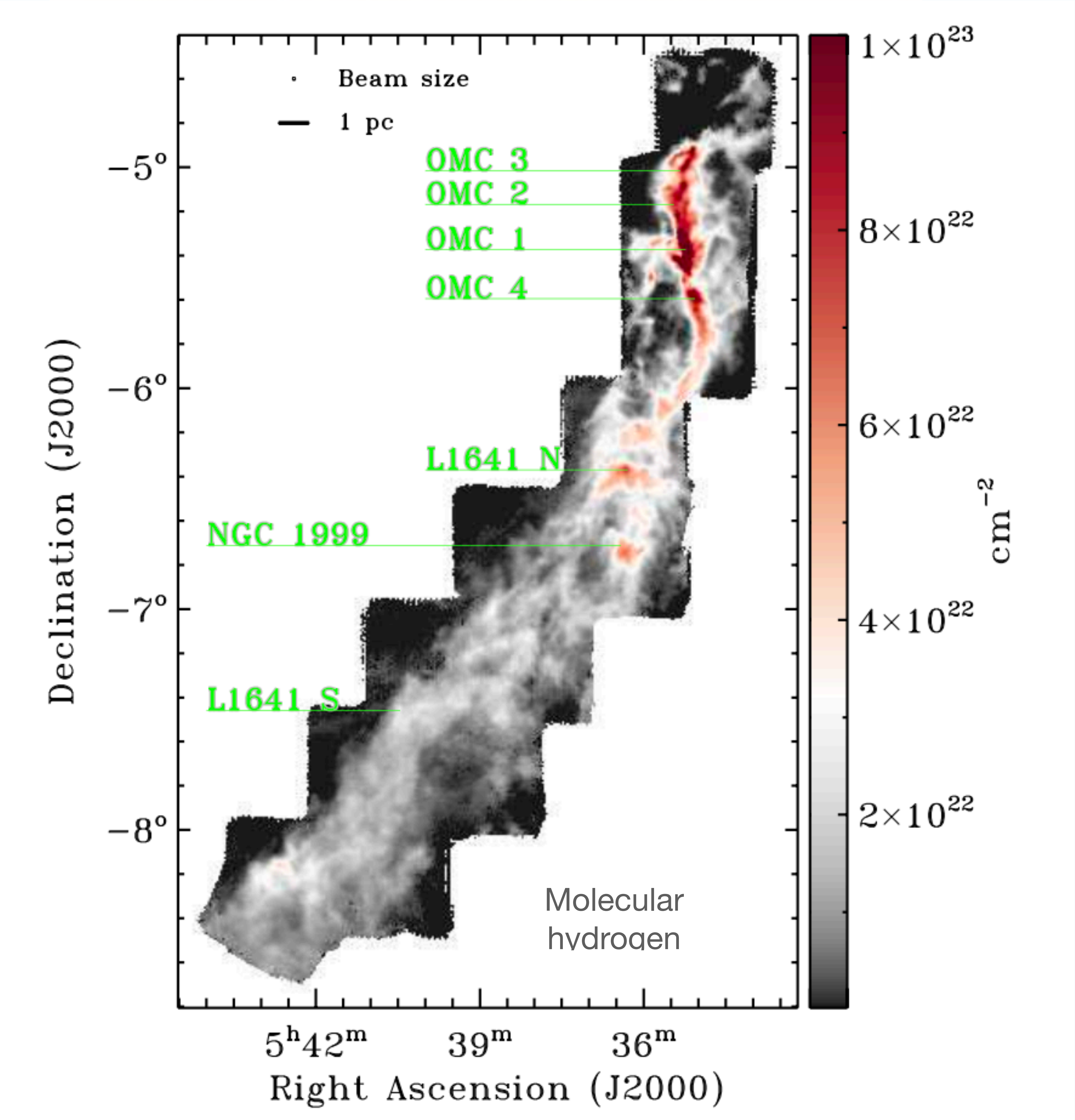

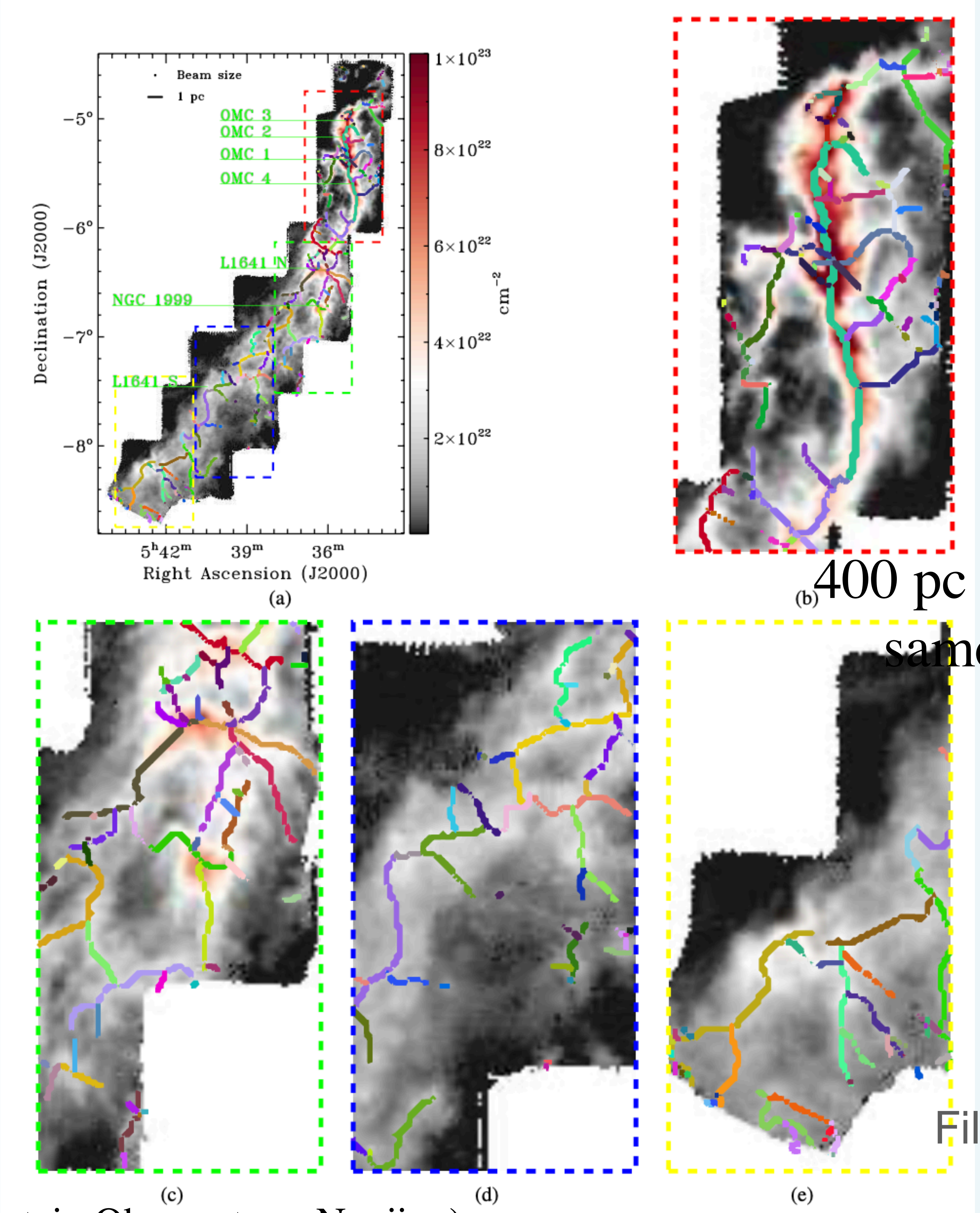

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Filamentary star formation

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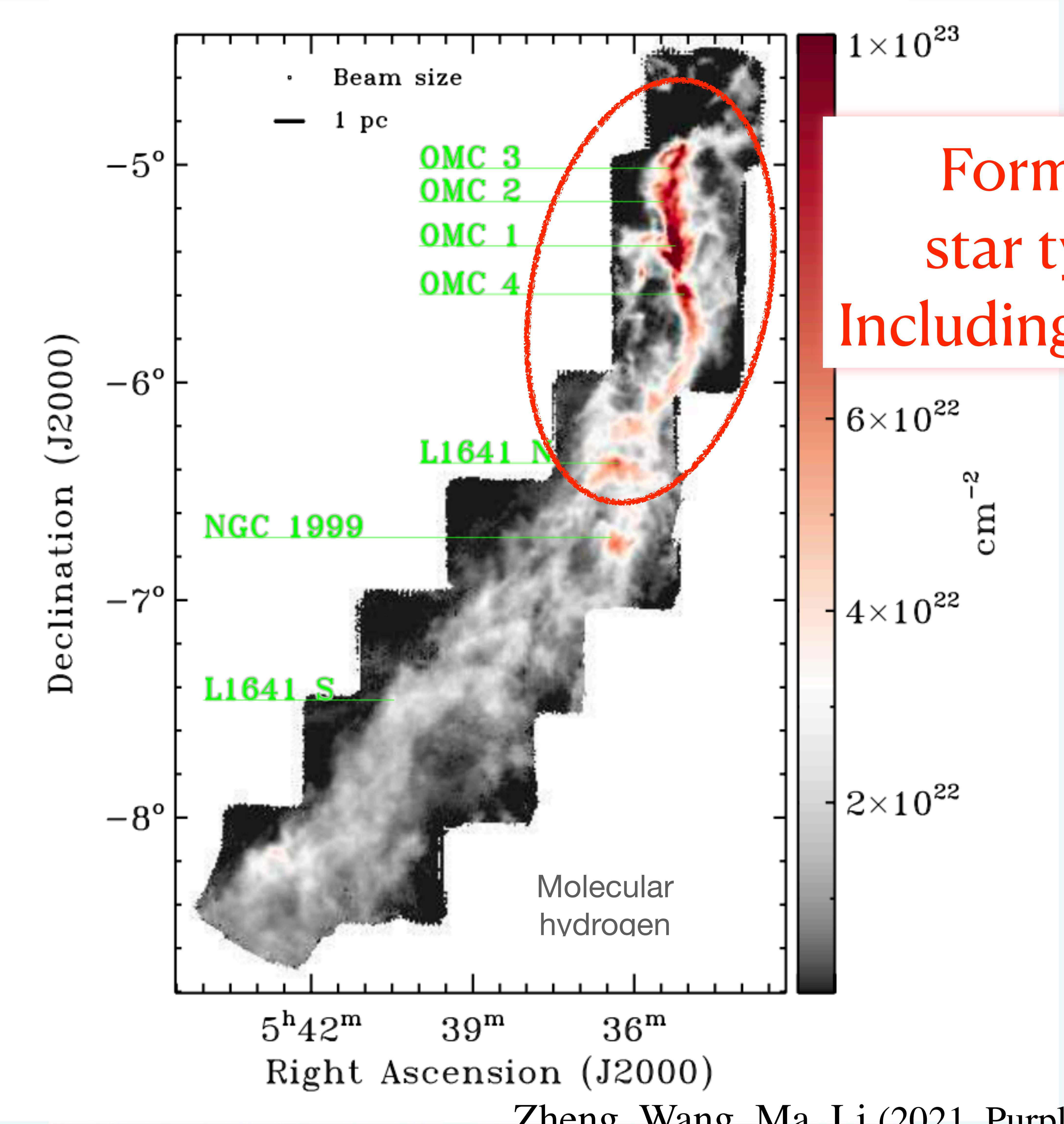
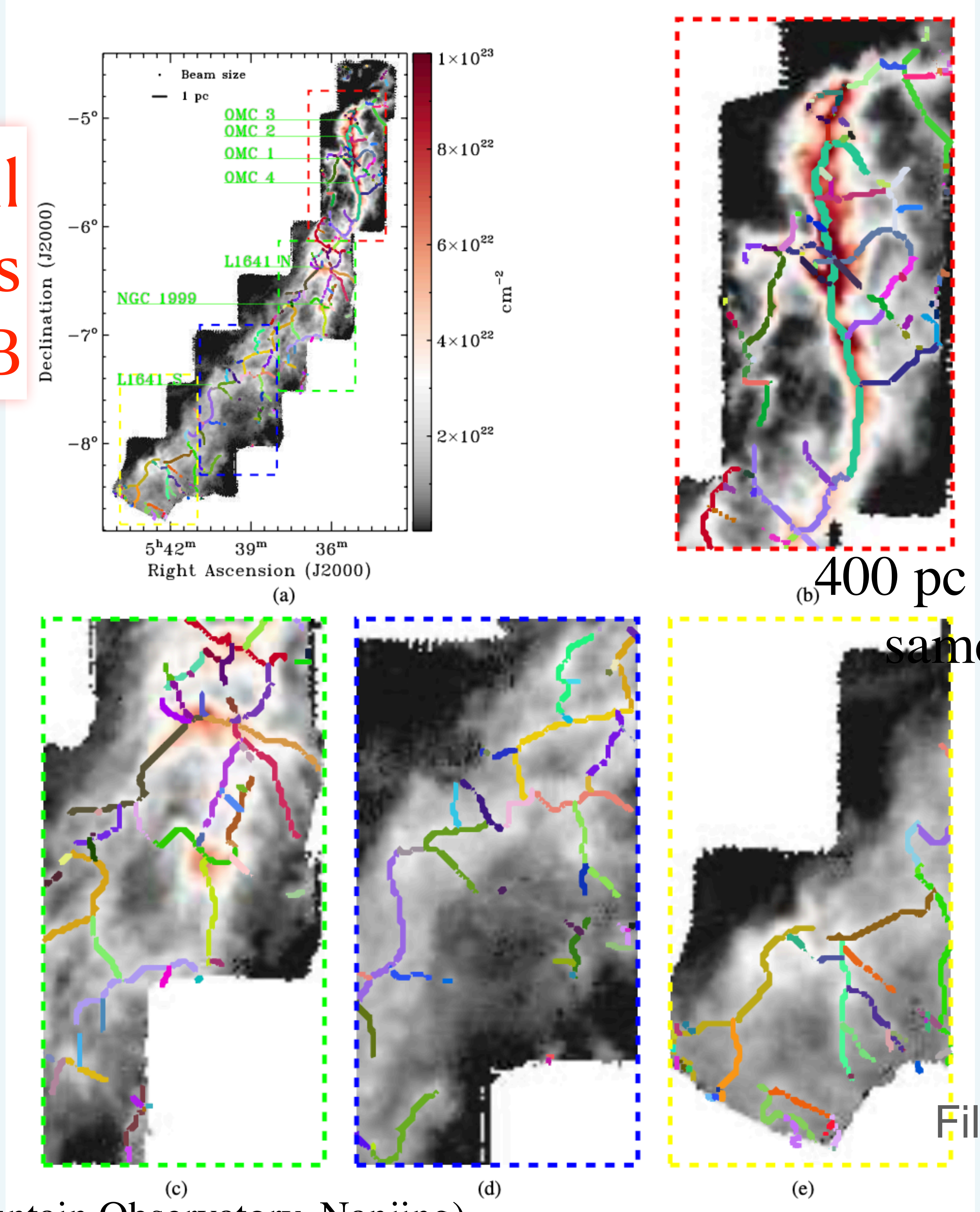


Forms all star types Including OB



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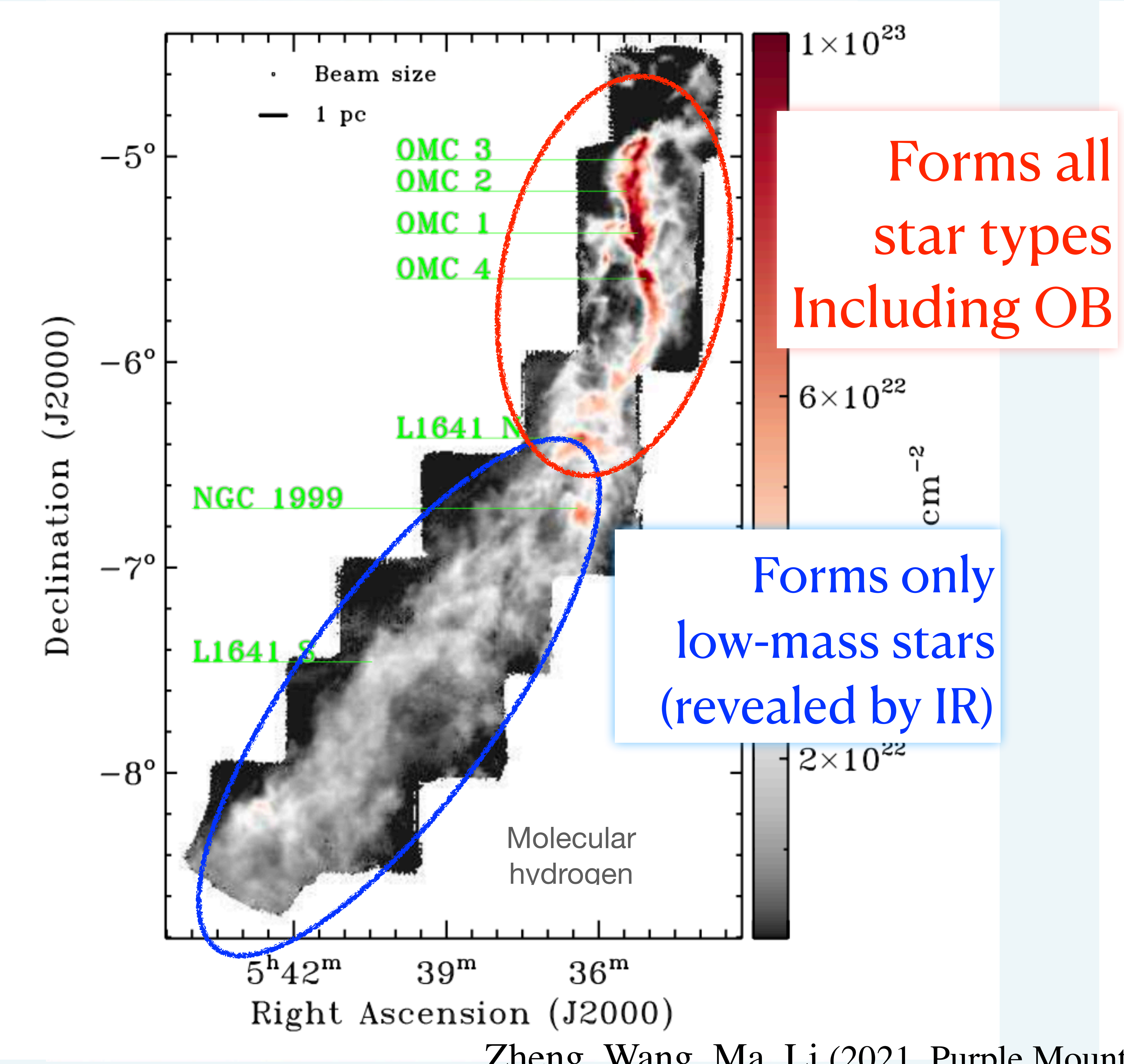

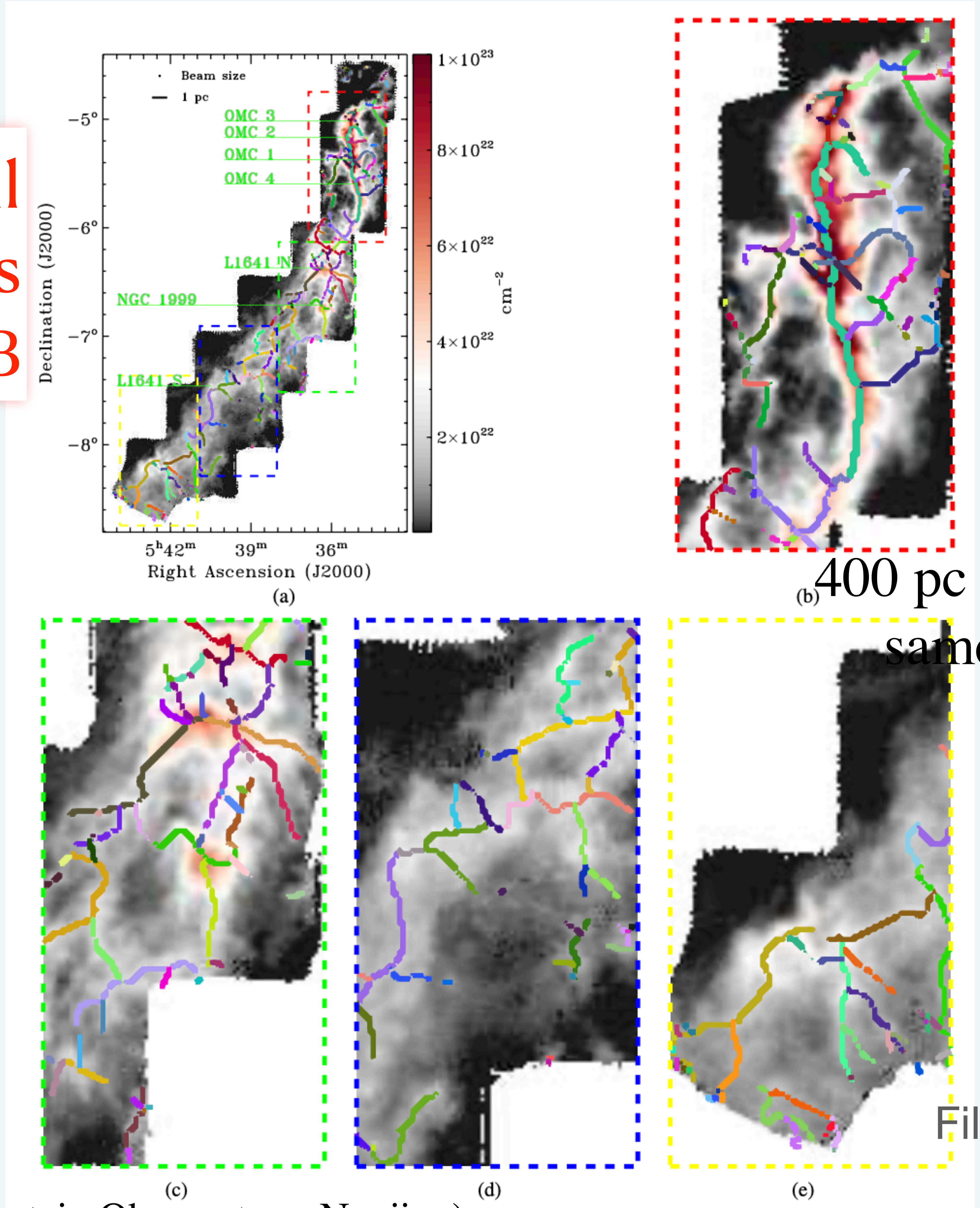

400 pc away from us,
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Filamentary star
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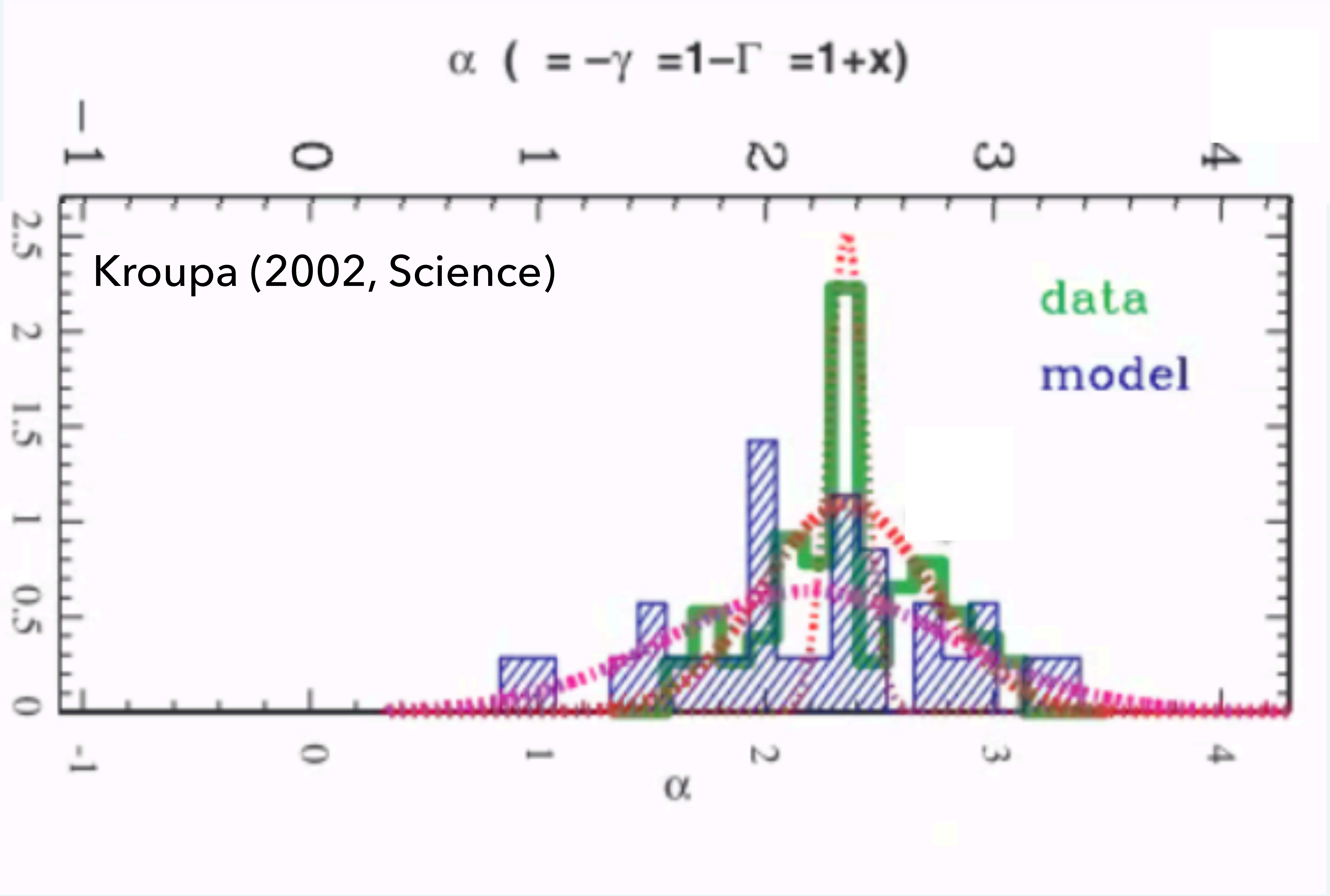
Sharp α peak



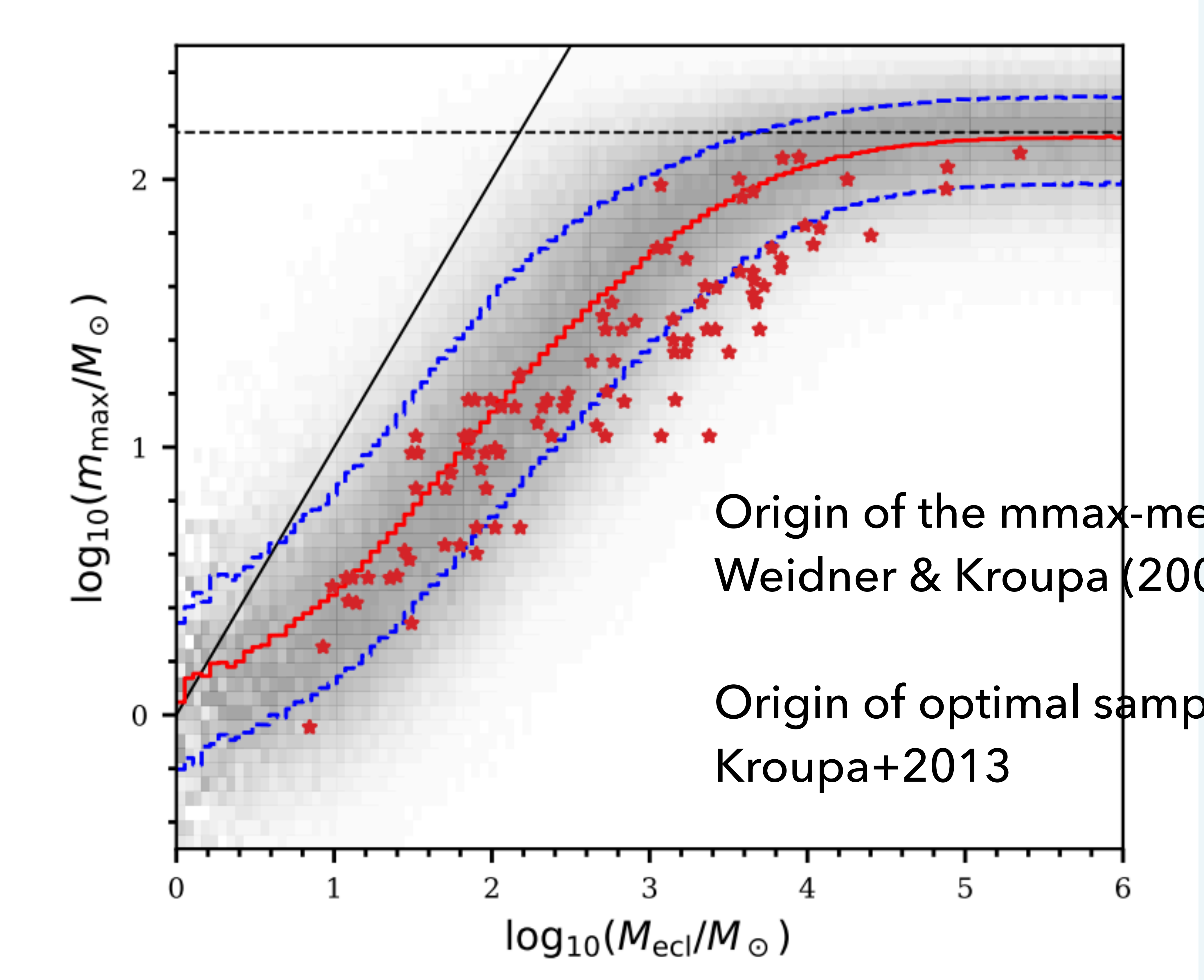
Observations spike narrowly around α = 2.3
With symmetric wings

The model with stochastic sampling predicts a much wider, asymmetric distribution for α

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

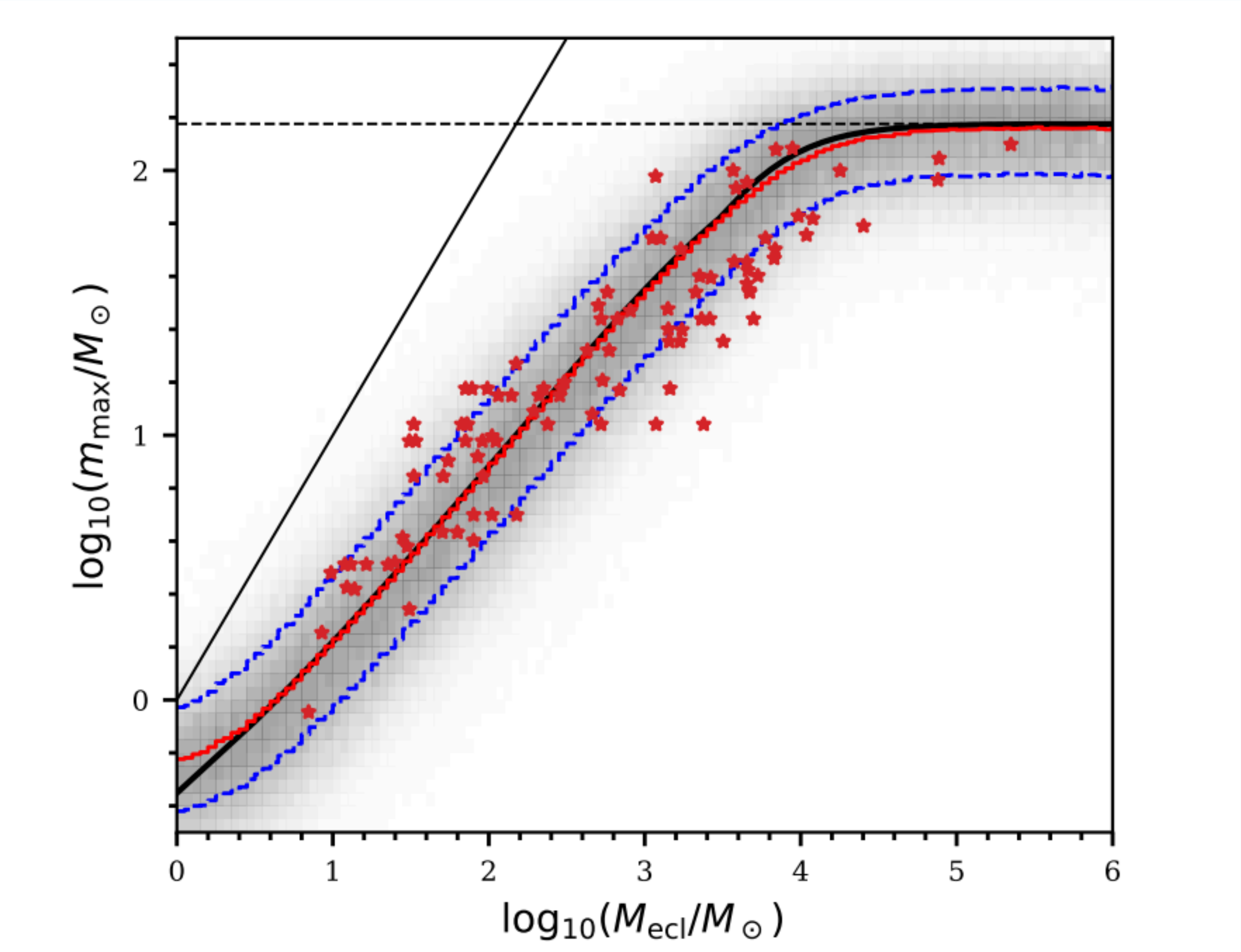
No evidence for intrinsic dispersion:

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



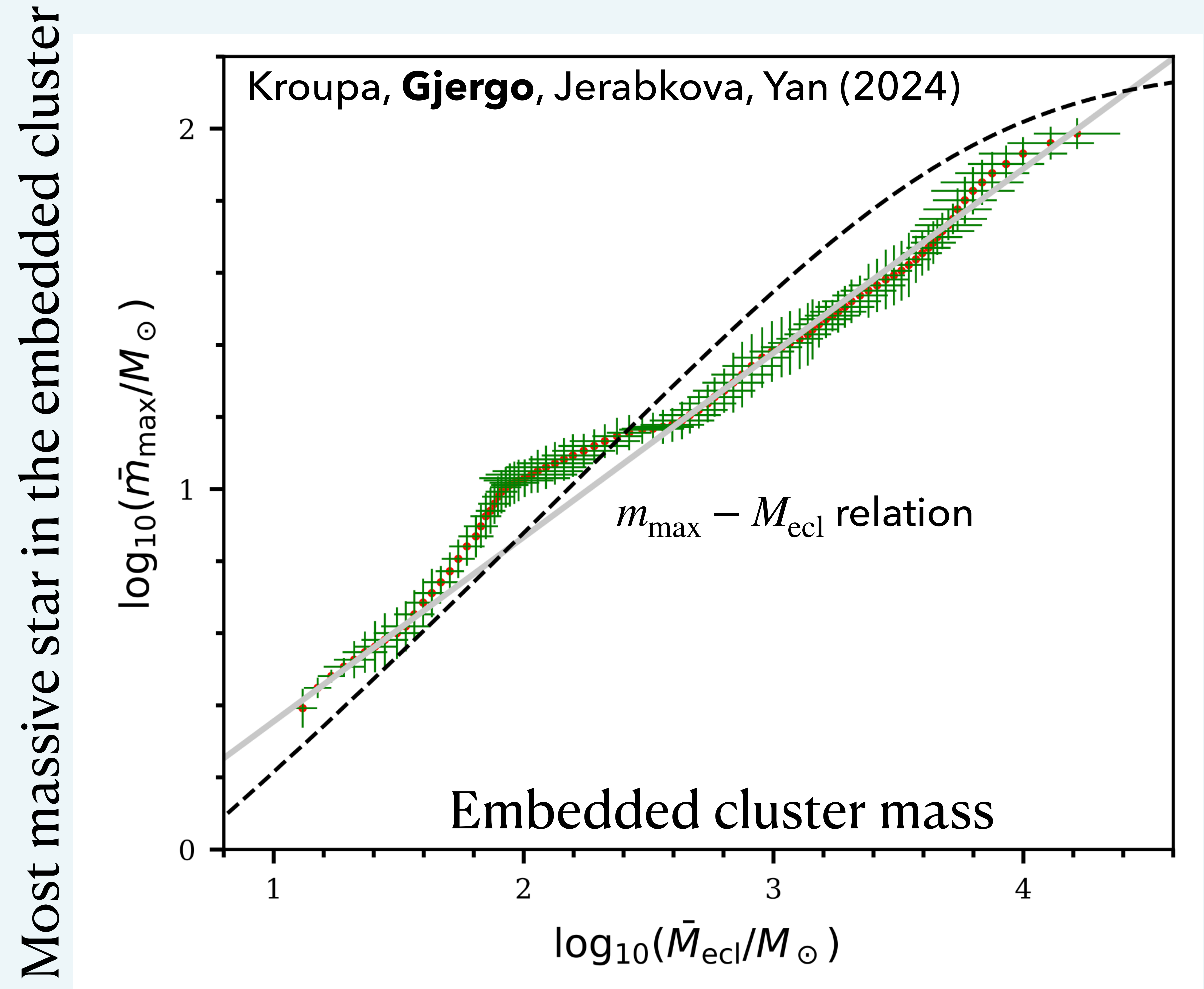
Origin of the mmax-mecl relation
Weidner & Kroupa (2006, 10,13)

Origin of optimal sampling
Kroupa+2013



Model name	α_3	m_{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:

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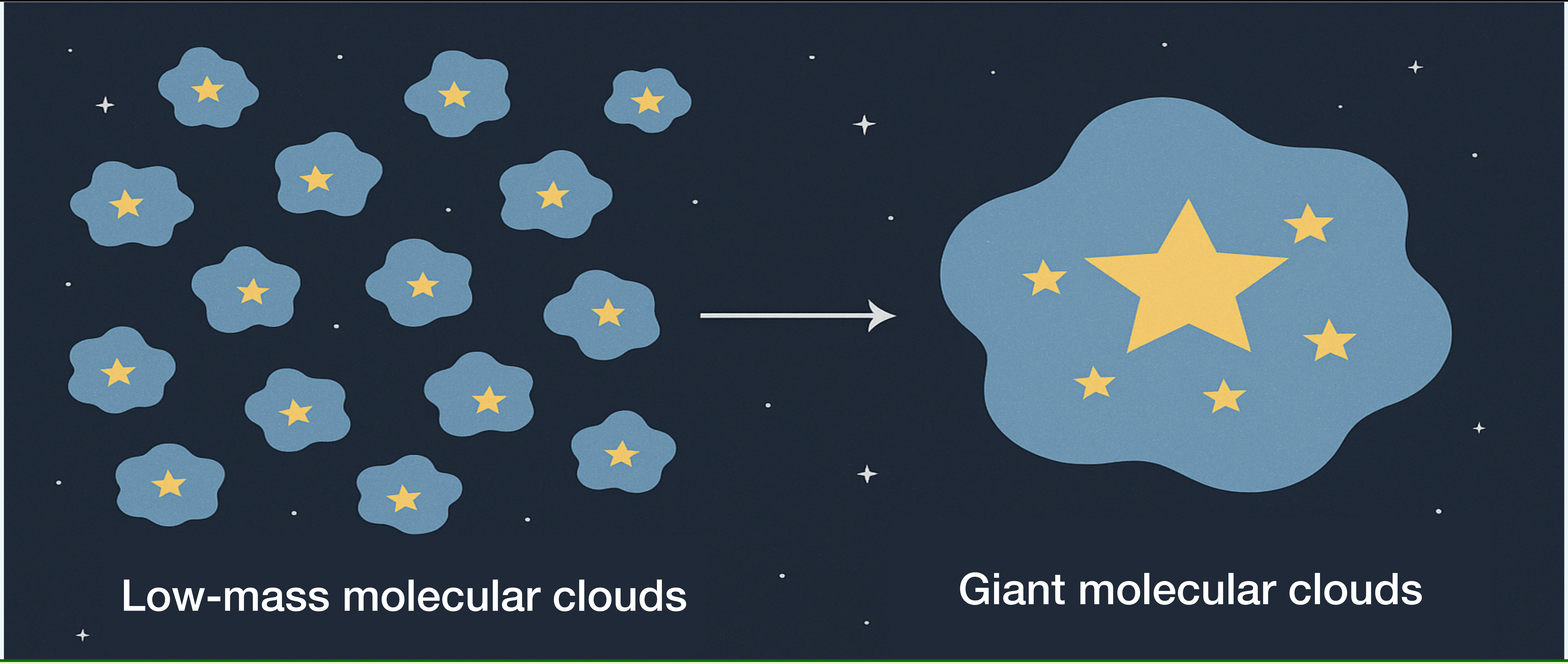
The IGIMF solution is shown with the black-dashed line

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?



Are 1000 x 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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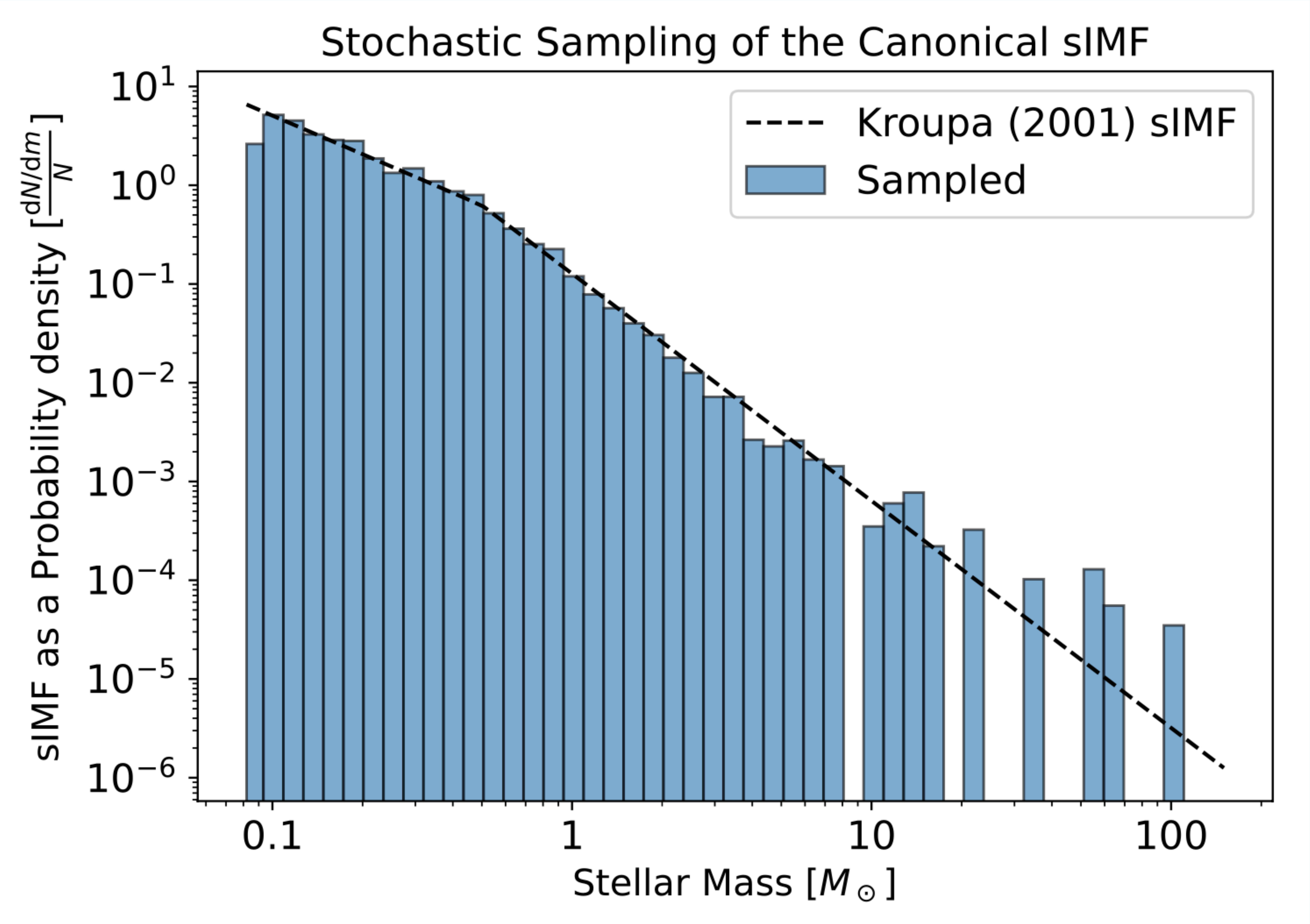

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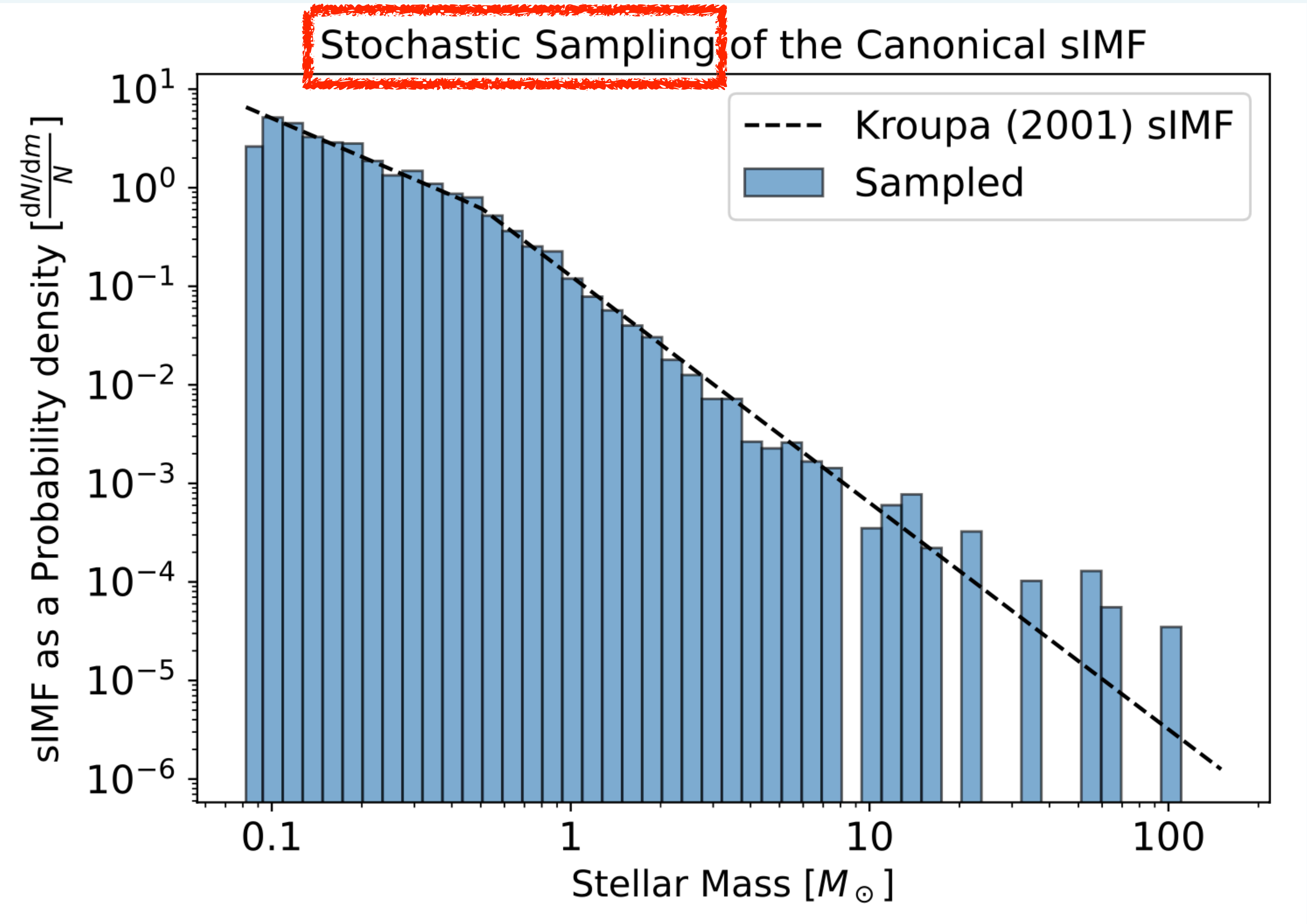

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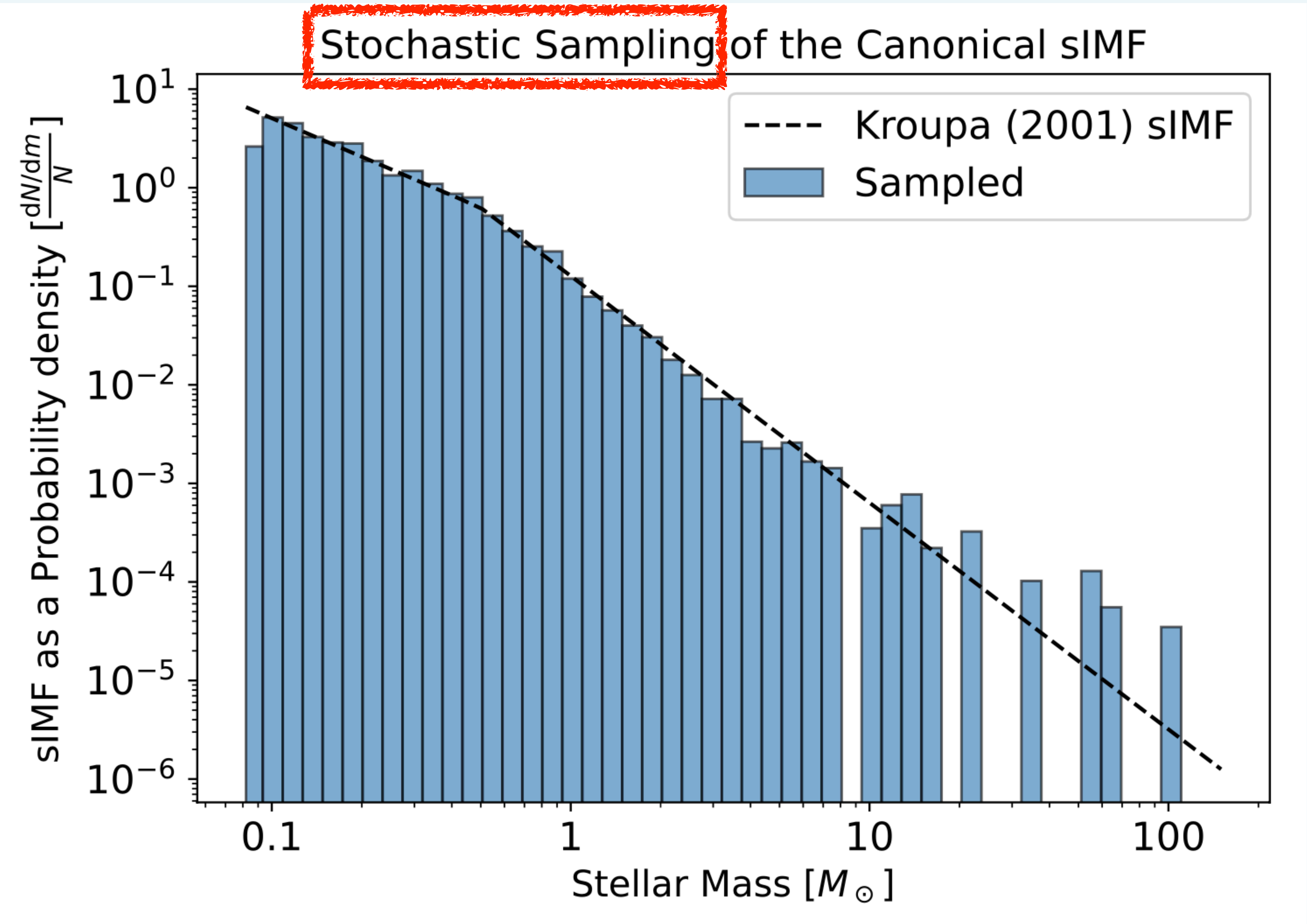

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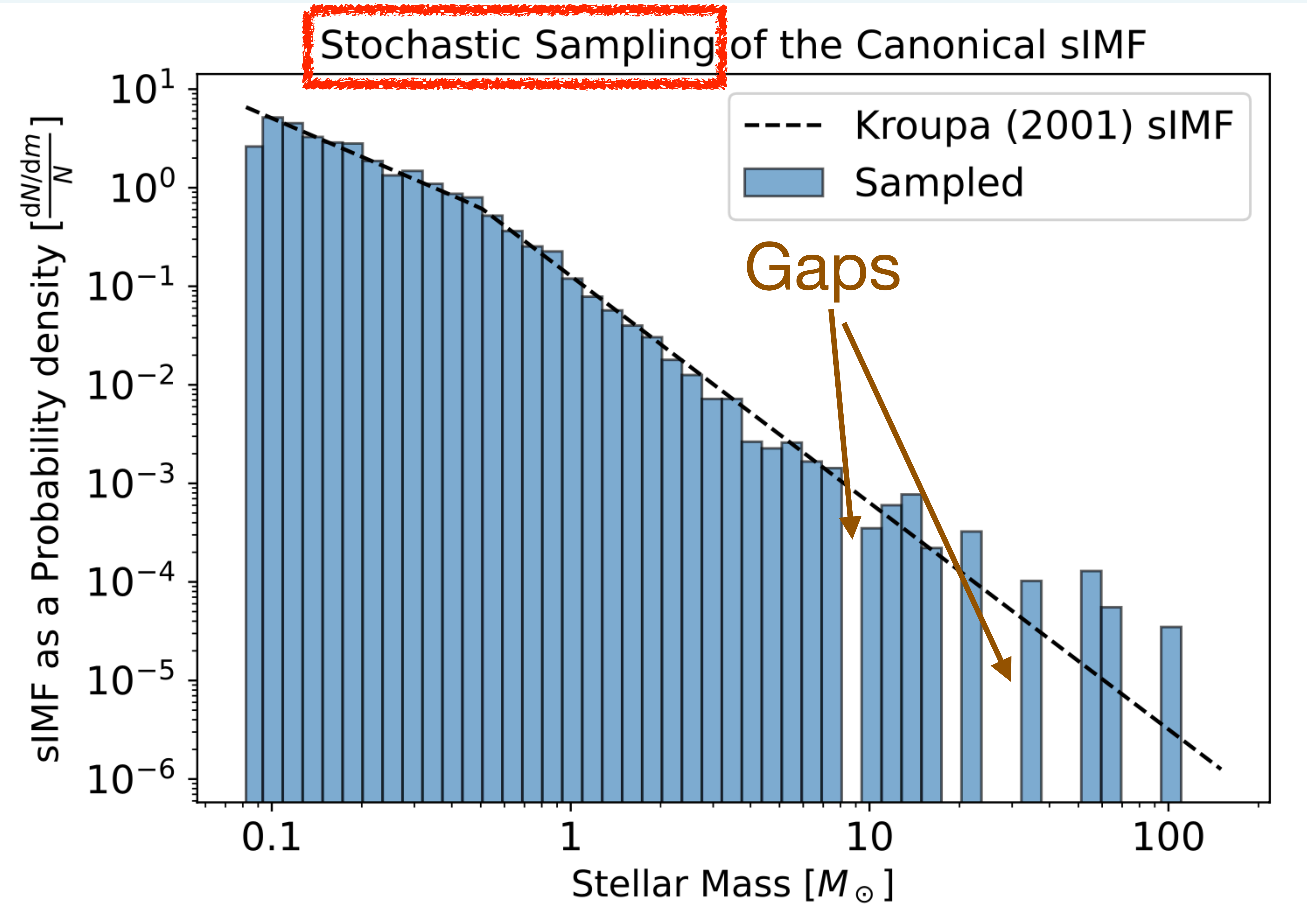

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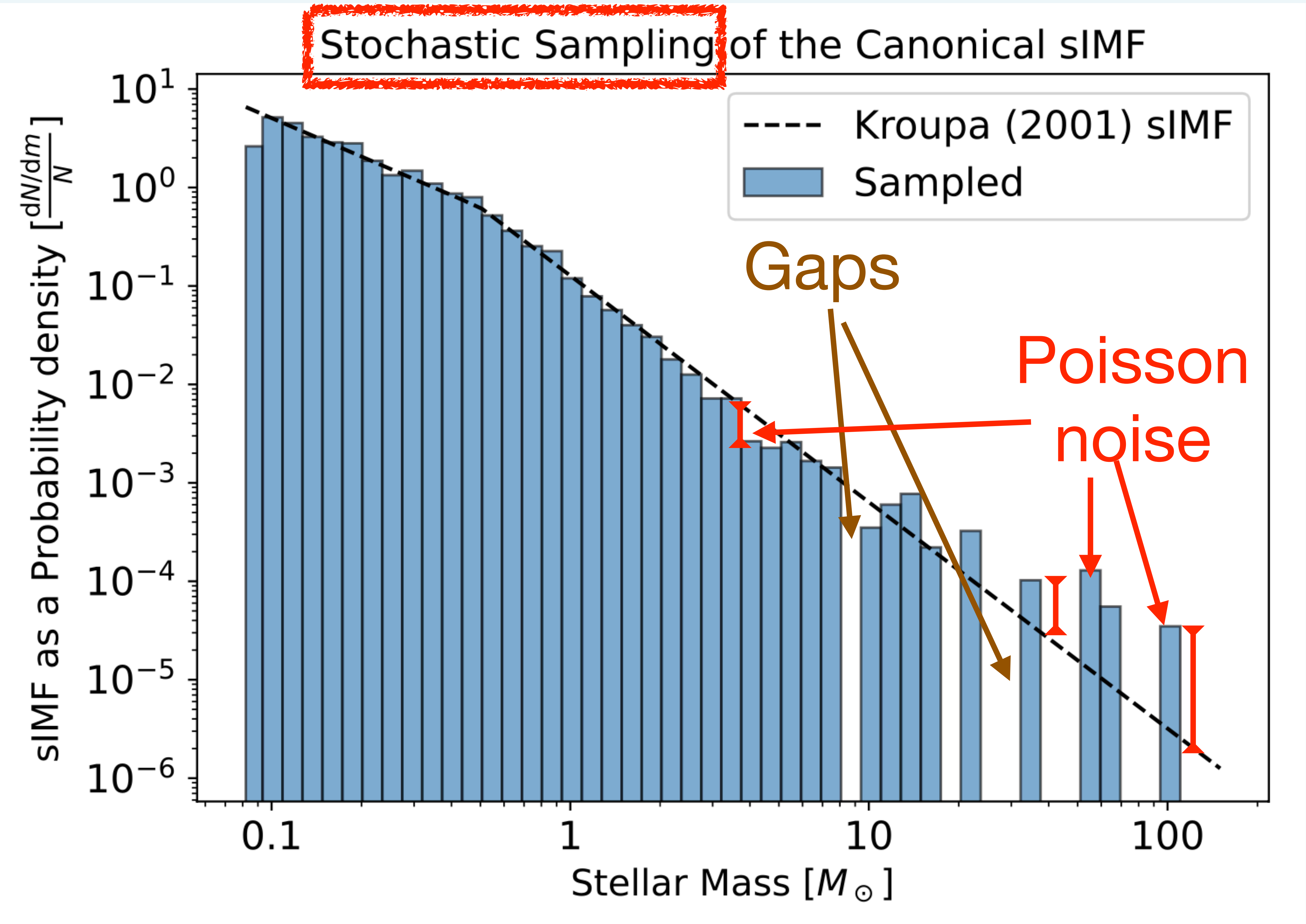

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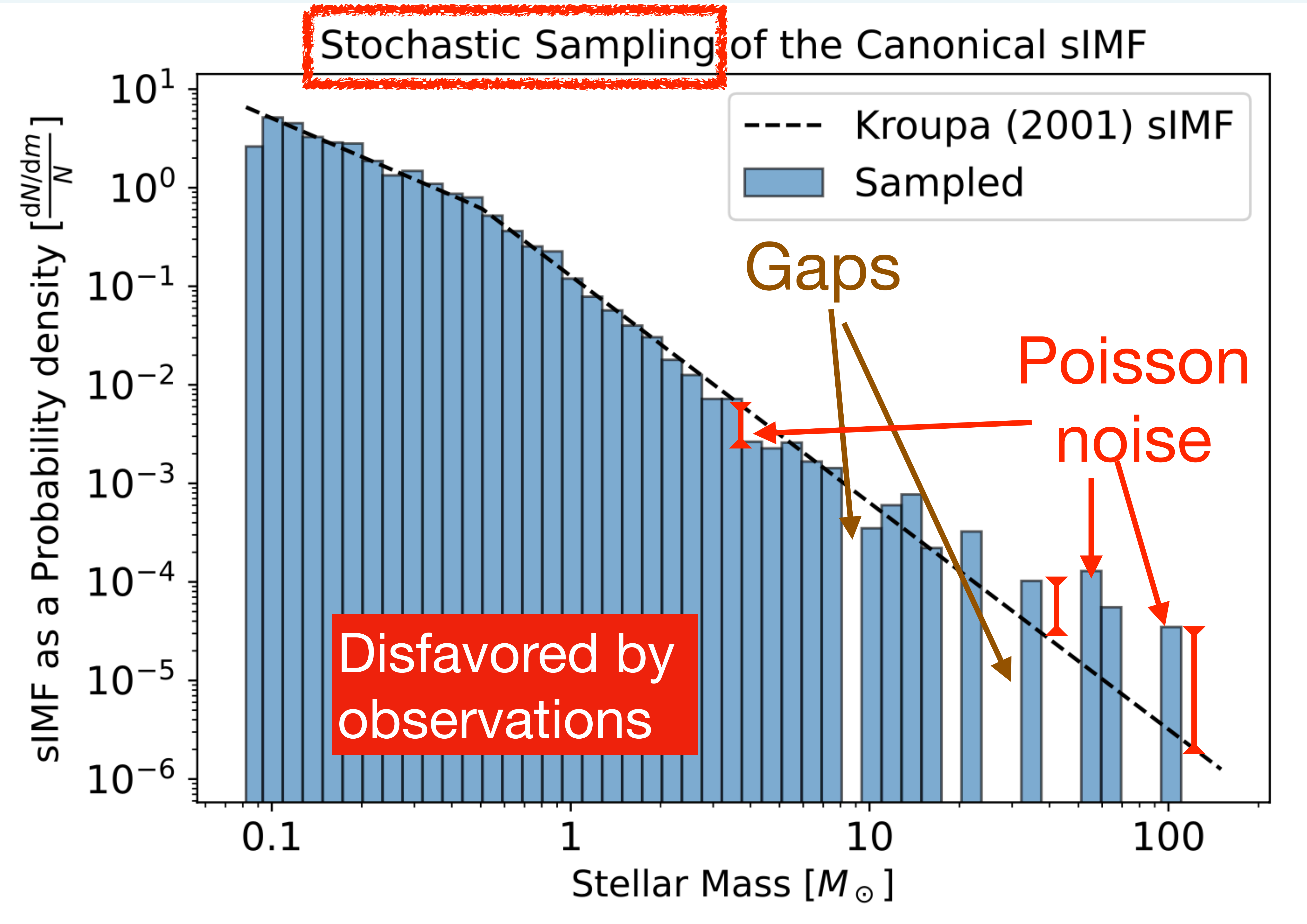

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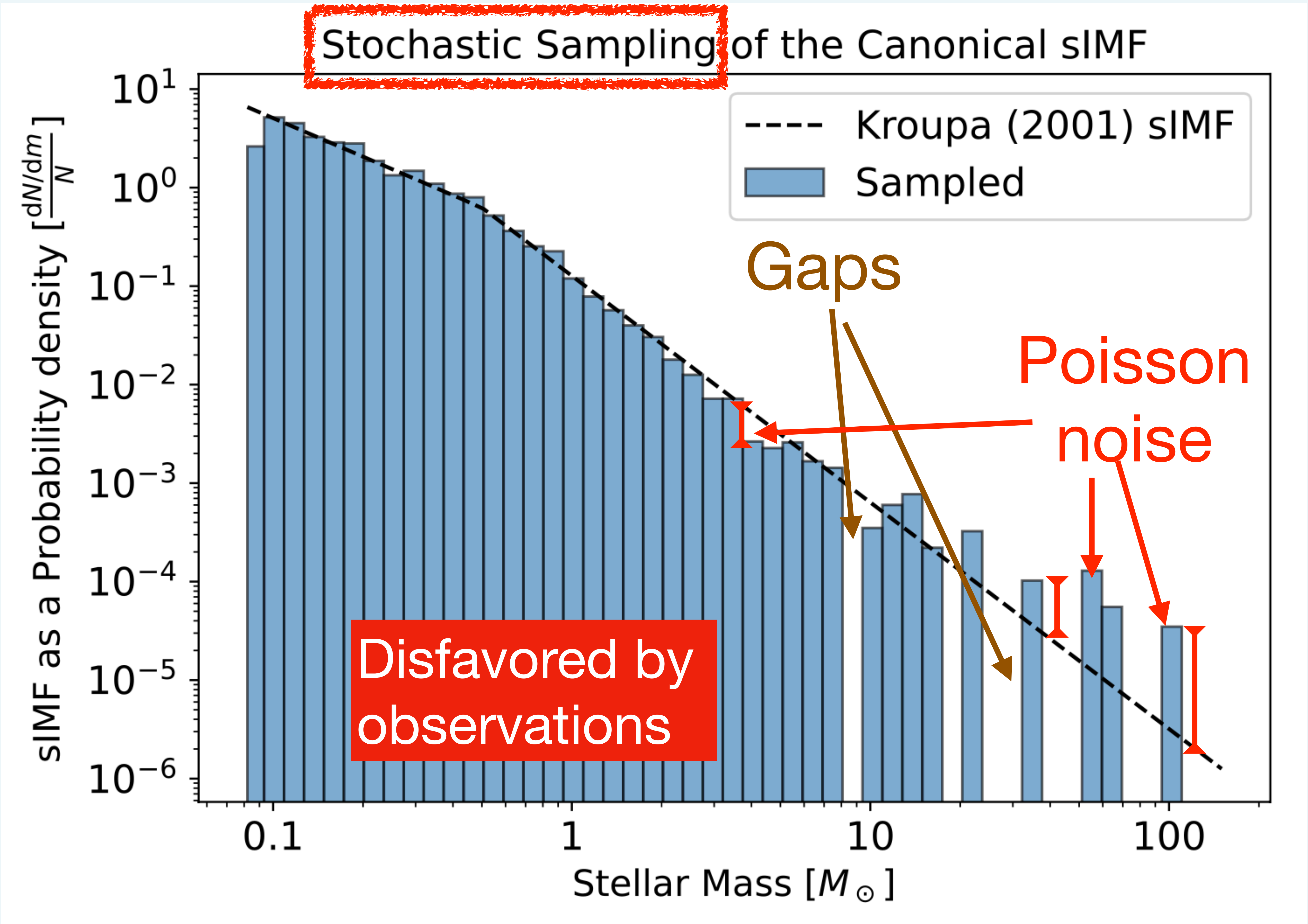

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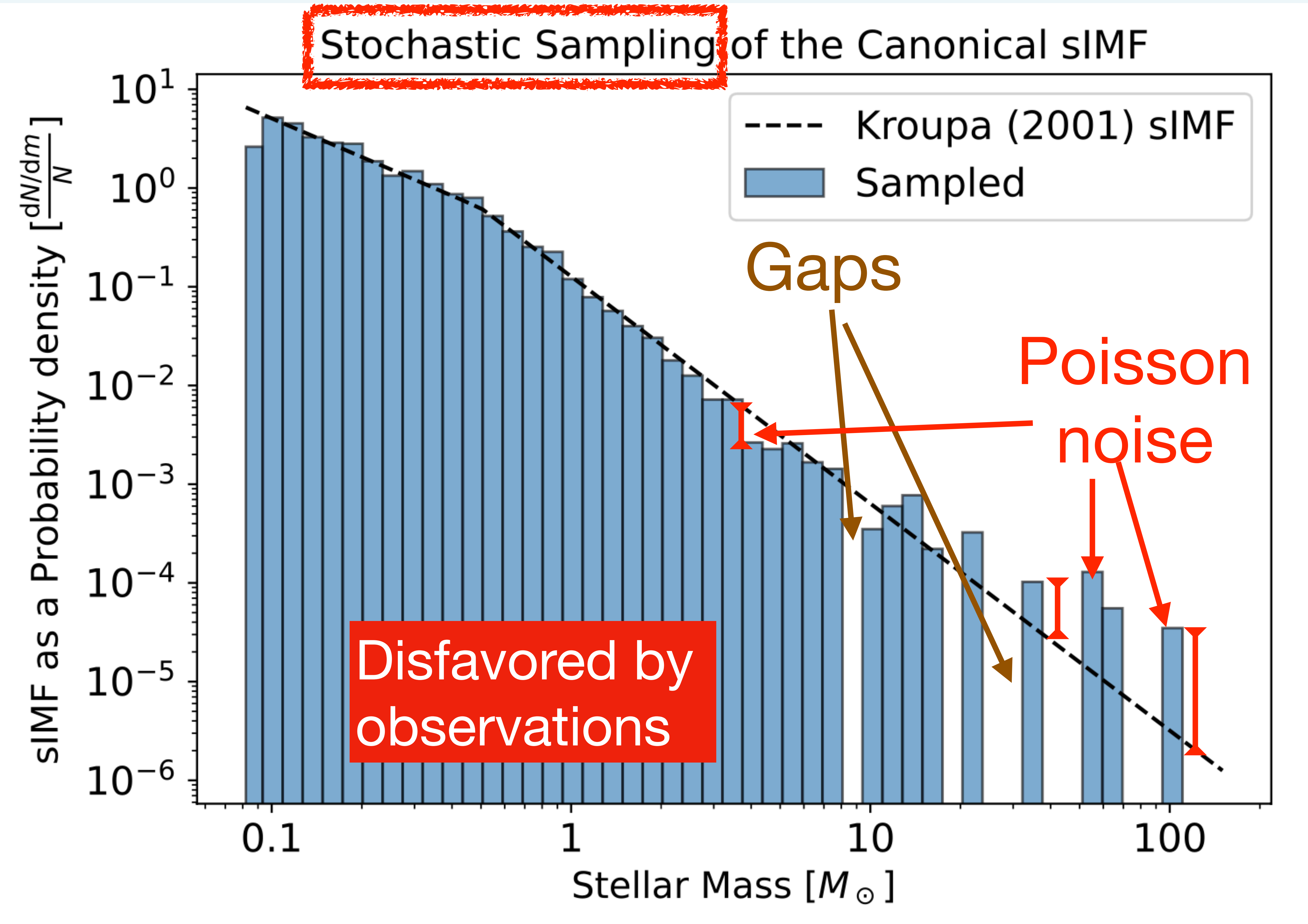

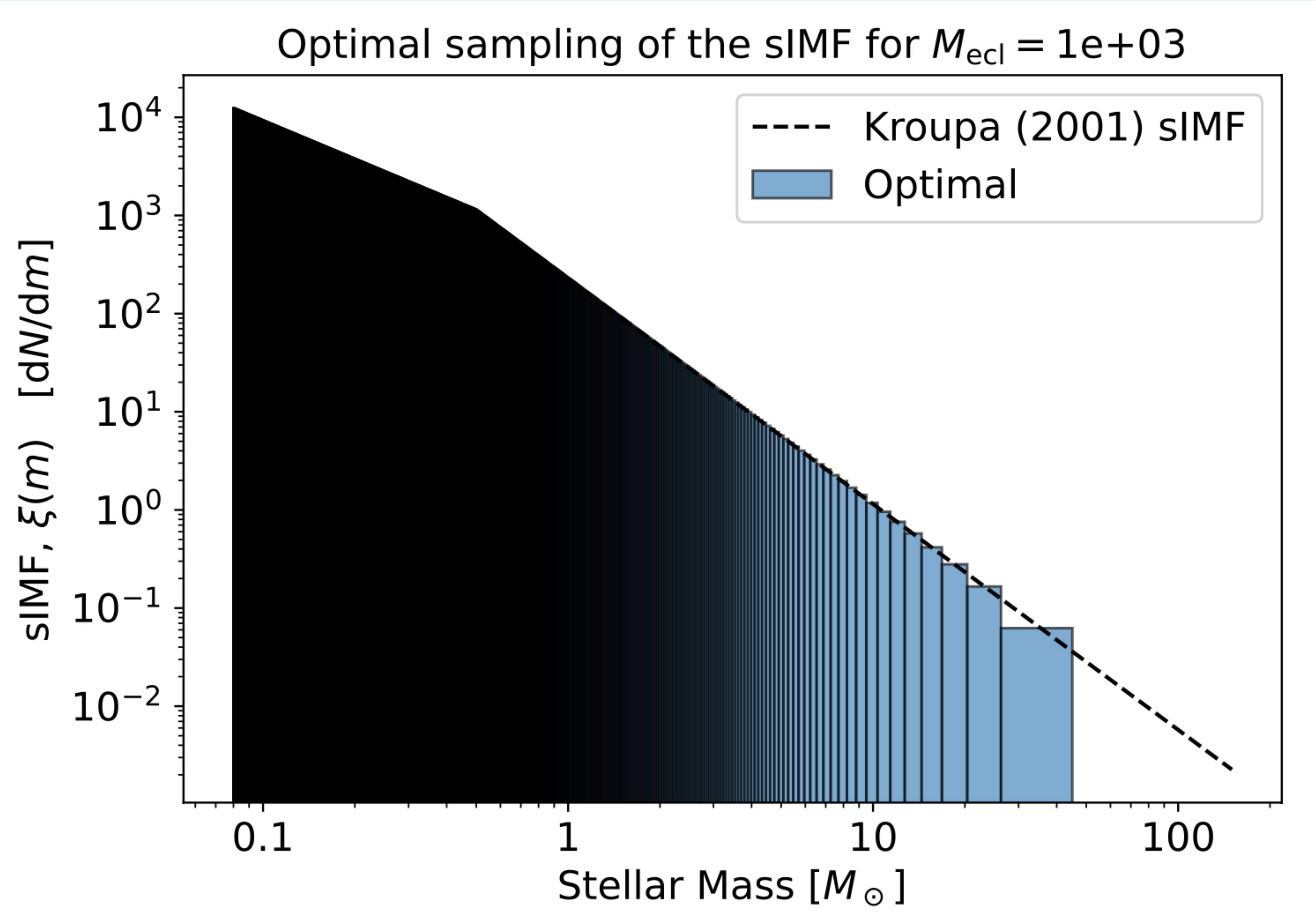

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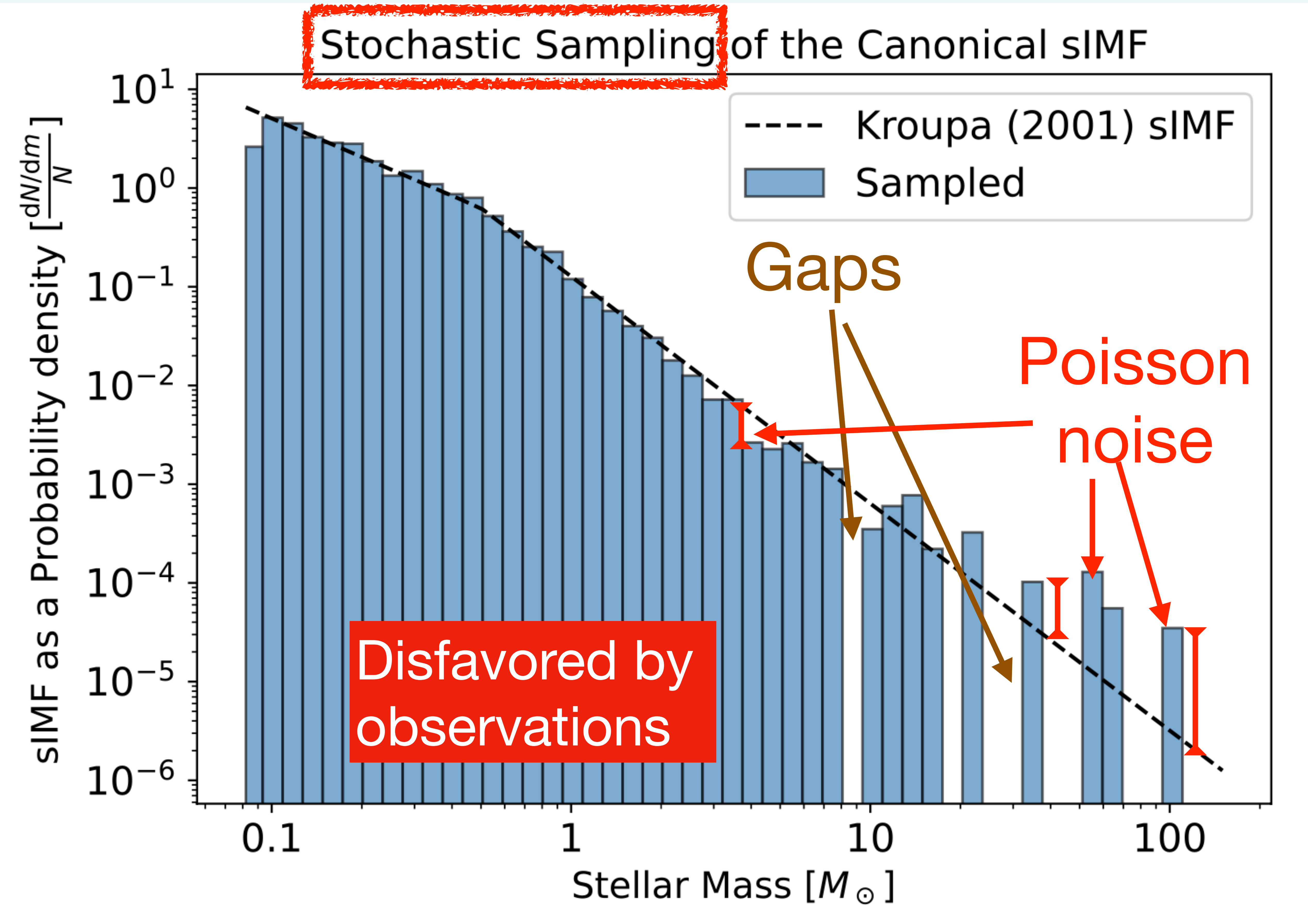
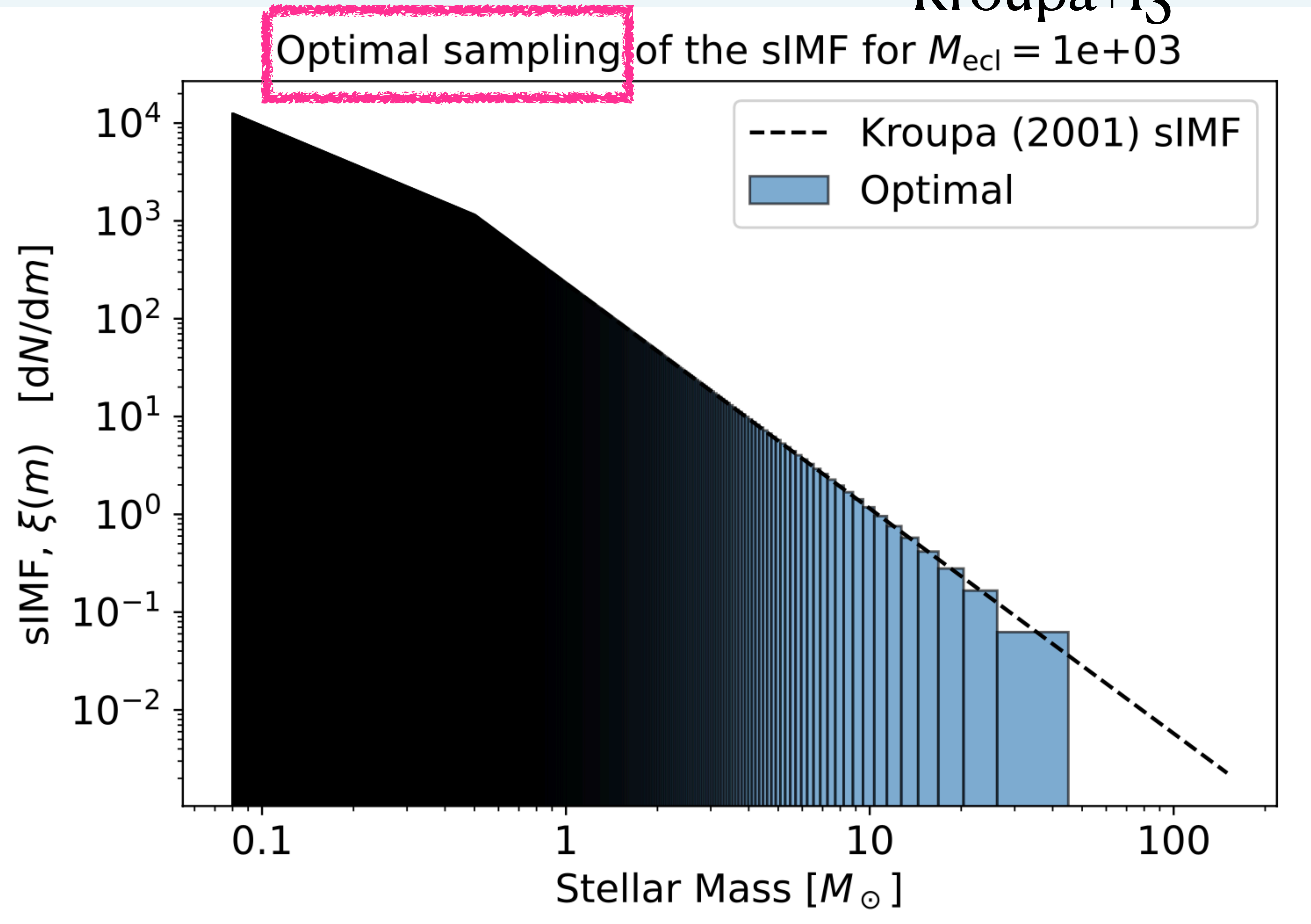
Building an SSP: How Should We Sample the IMF?

First introduced in Kroupa+13





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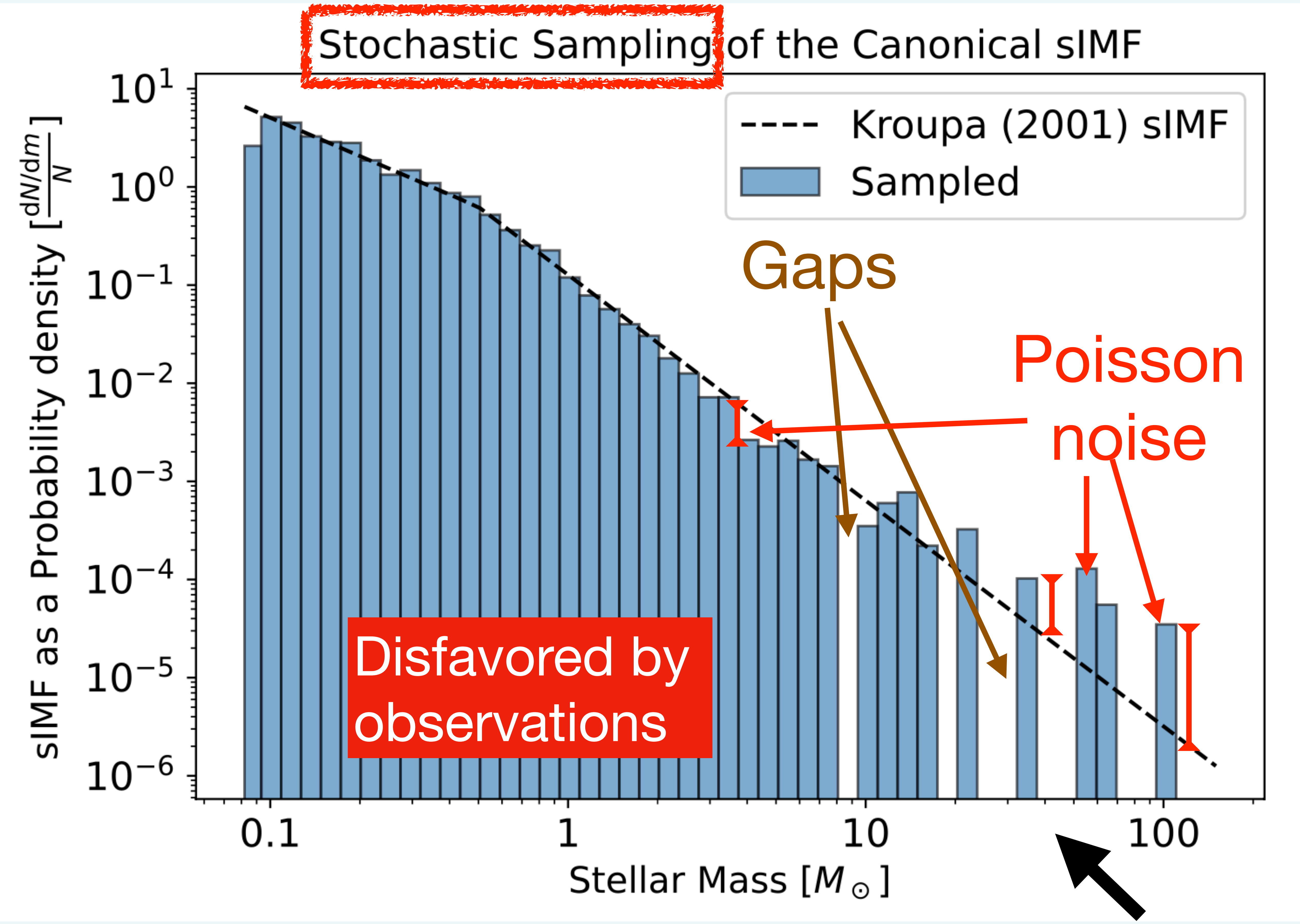

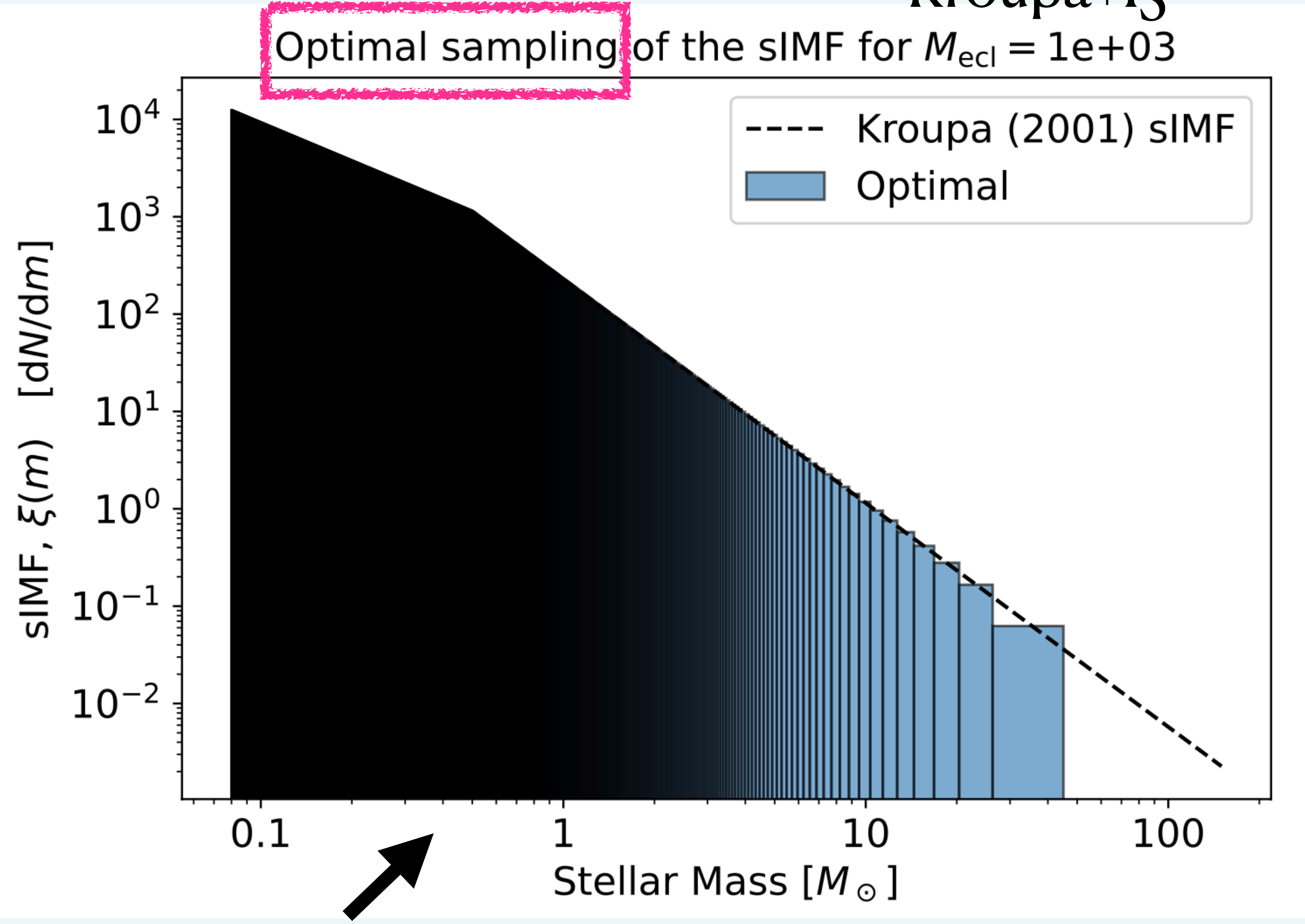

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Same total stellar mass (Mecl)
At solar metallicities

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Gjergo, Zhang & Kroupa (2025, subm.)

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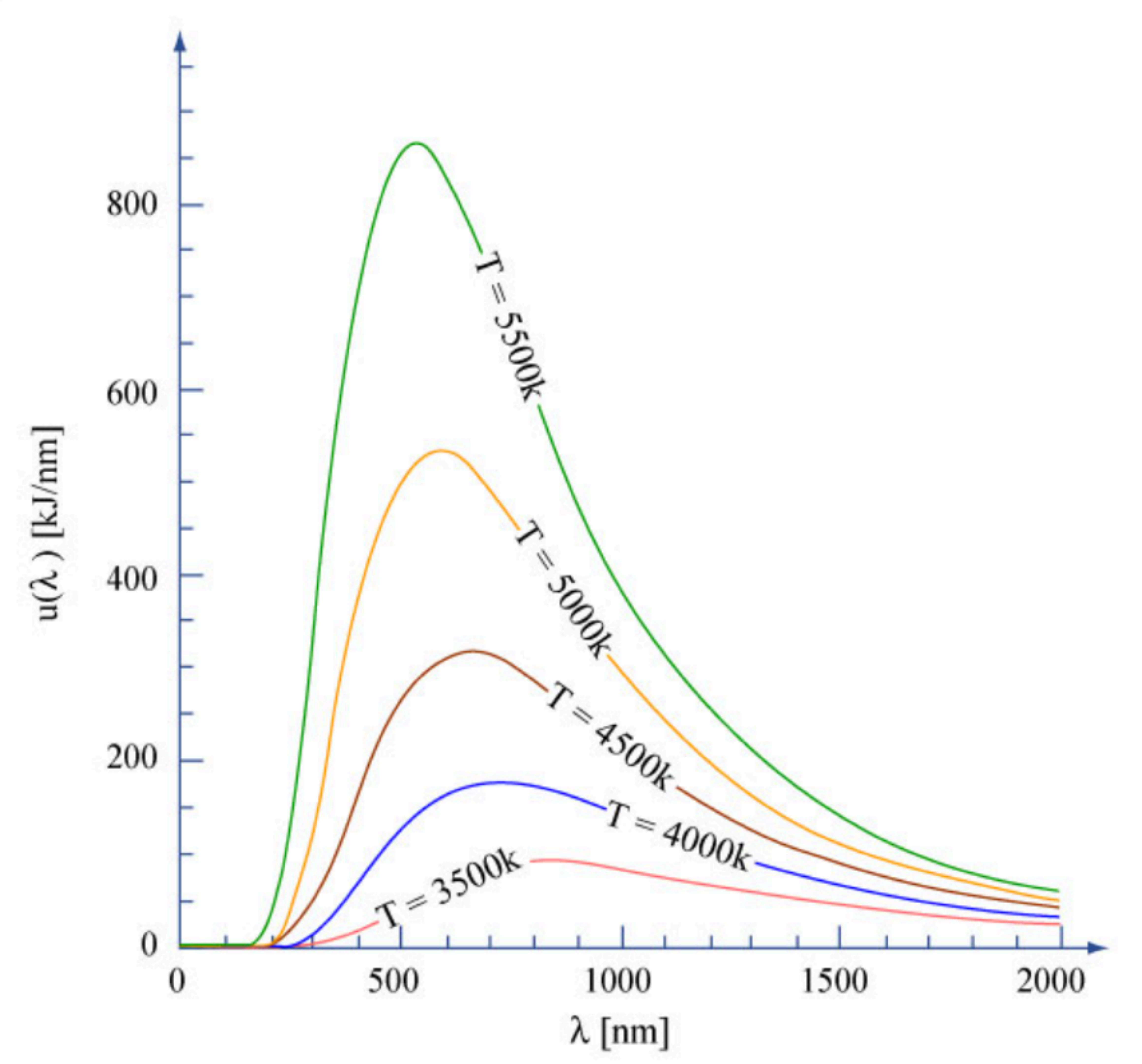
Analogy with Planck's Law:

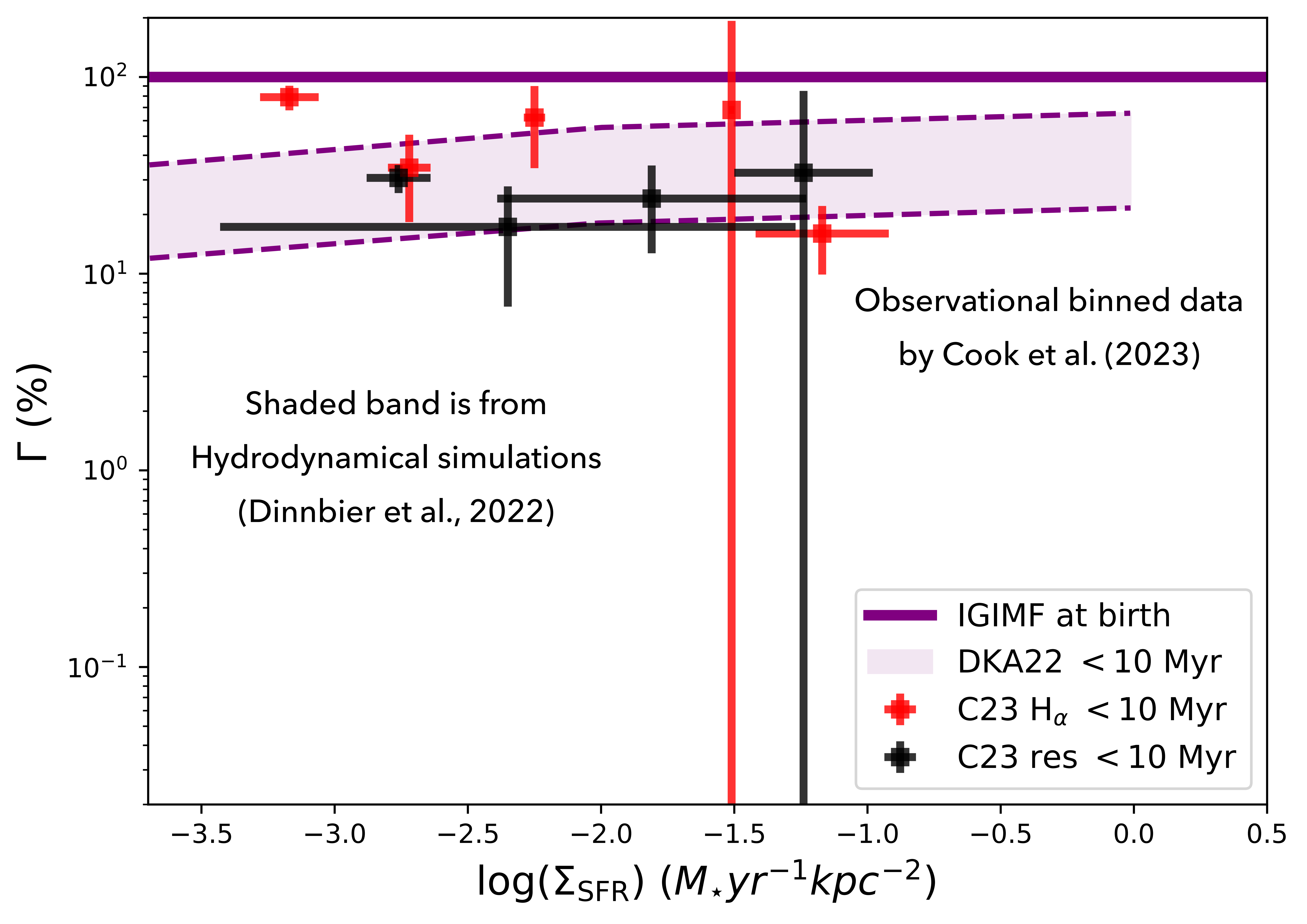
Gjergo, Zhang & Kroupa (2025, subm.)



- 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?

Γ is the percentage of stars born in embedded clusters

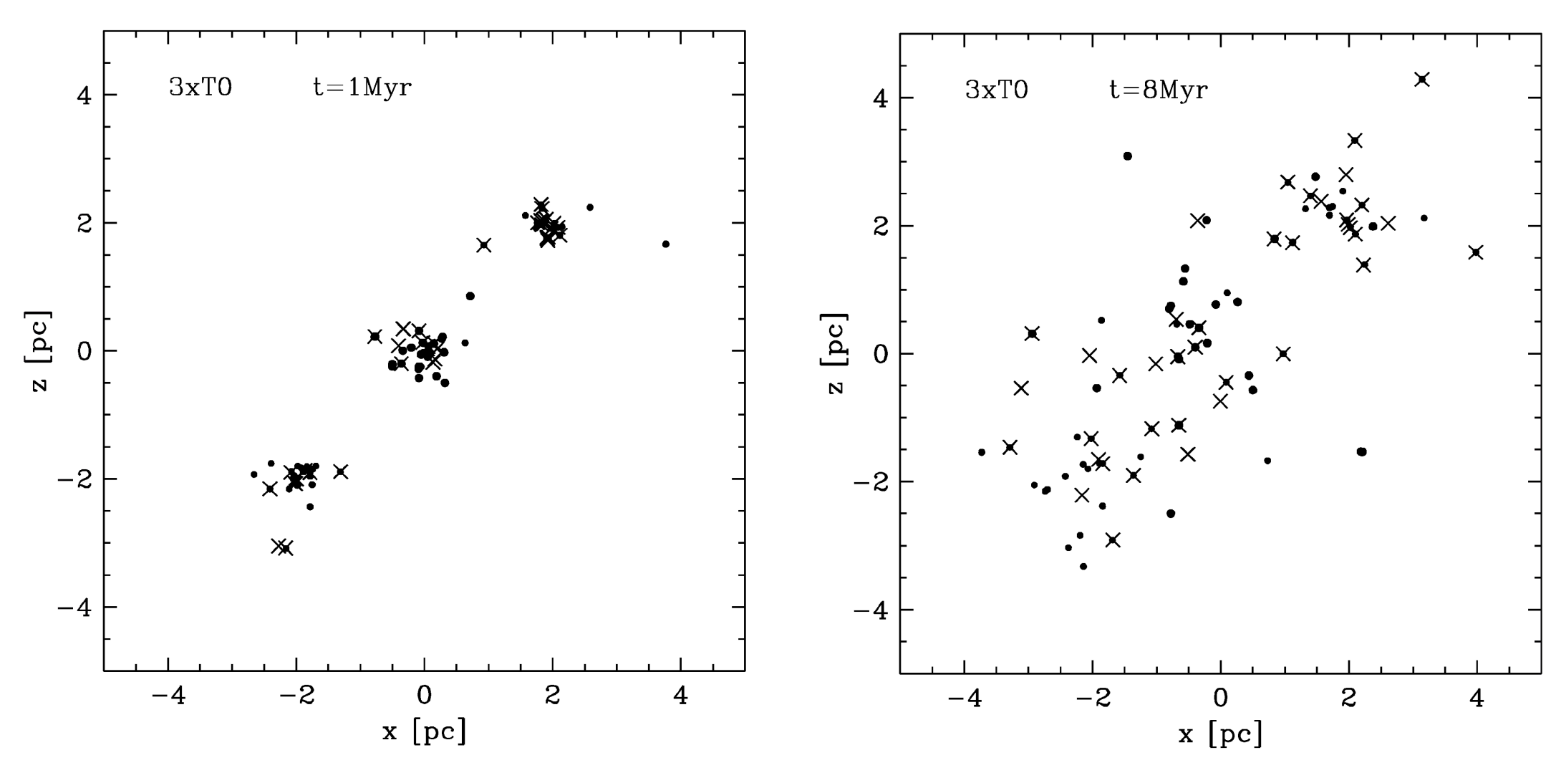


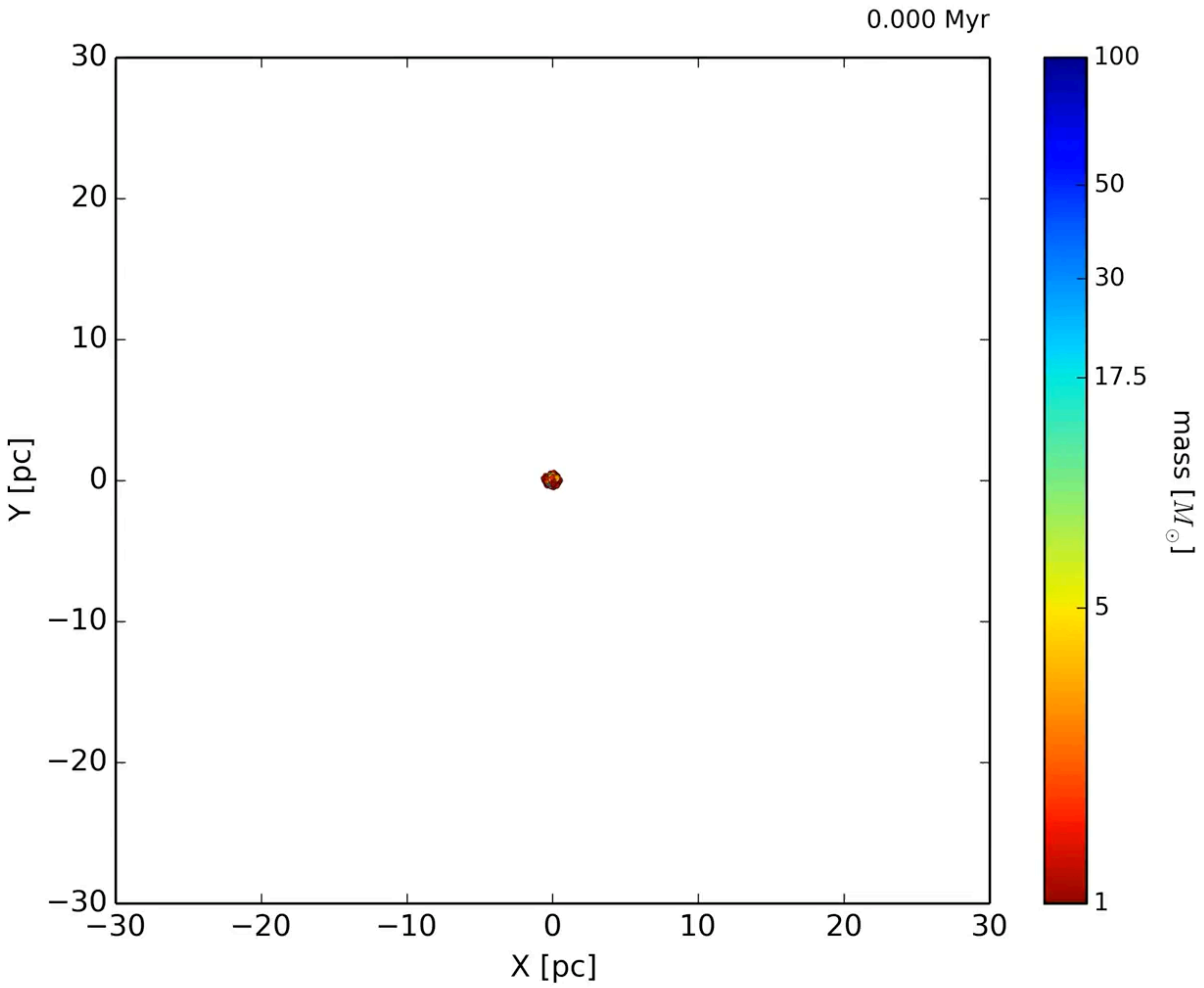
Gjergo et al. (2025a) subm.

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 Msun.

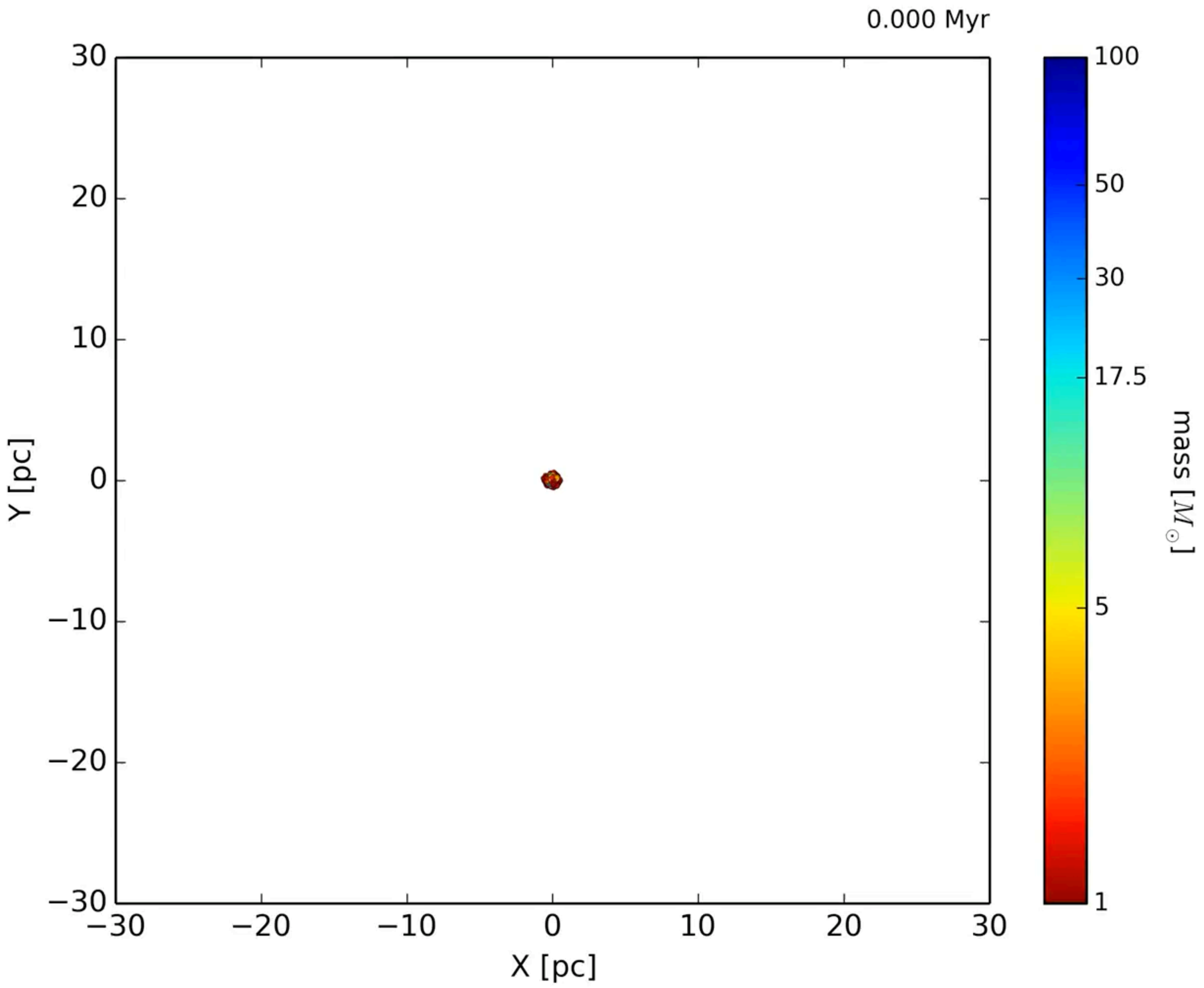
The cluster is initially mass-segregated and binary-rich (100% binary fraction).

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 ~60 + 5 + 14 + 35 Msun stars) is dynamically ejected from the cluster,



Movie of a direct N-body calculation (with NBODY6) for a cluster with a mass of 3000 Msun.

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 ~60 + 5 + 14 + 35 Msun stars) is dynamically ejected from the cluster,