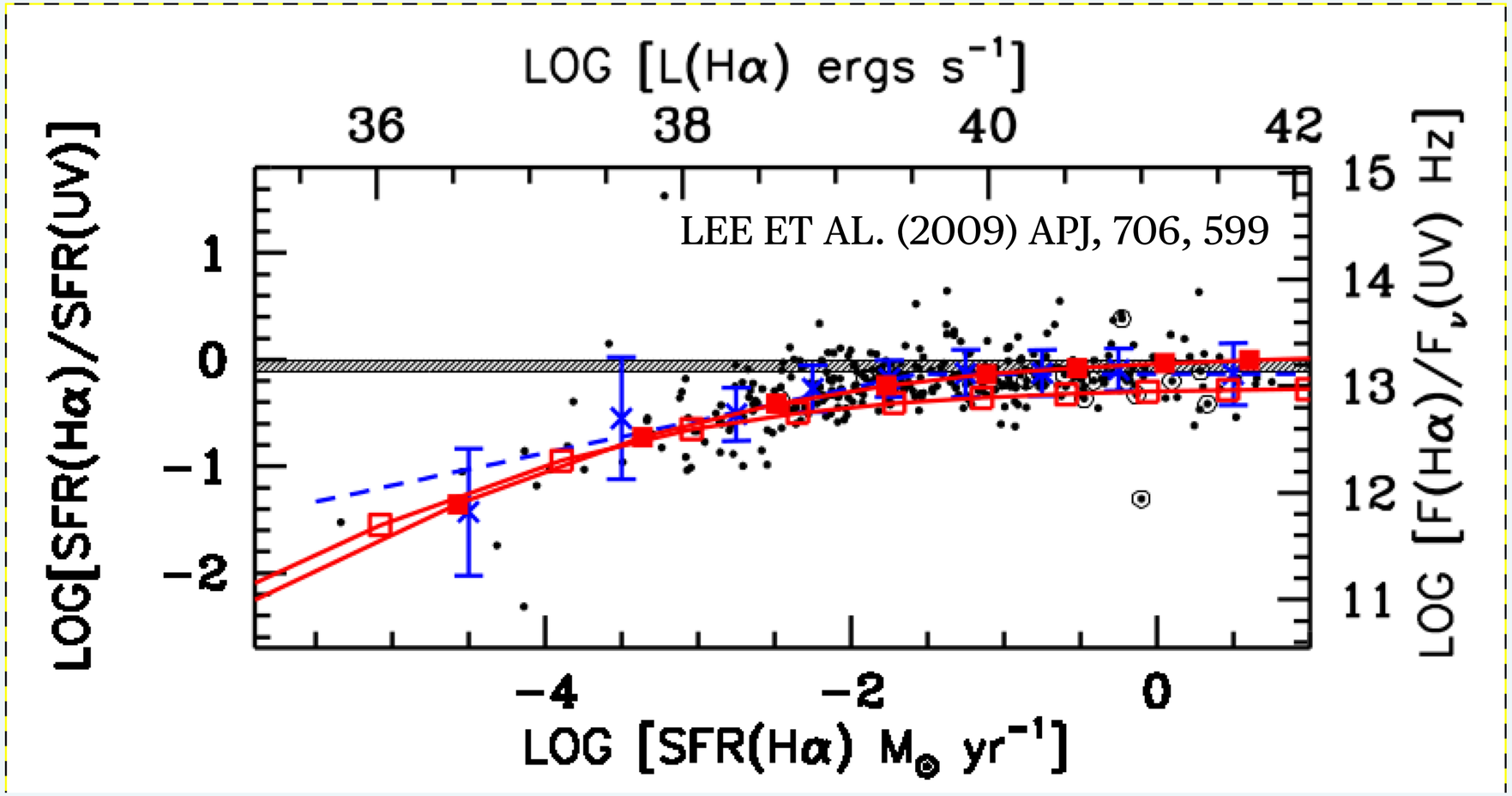
The IMF and chemical evolution in context

The variability of the IMF

THE IMF DEPENDS ON SFR

Massive stars

Most massive stars



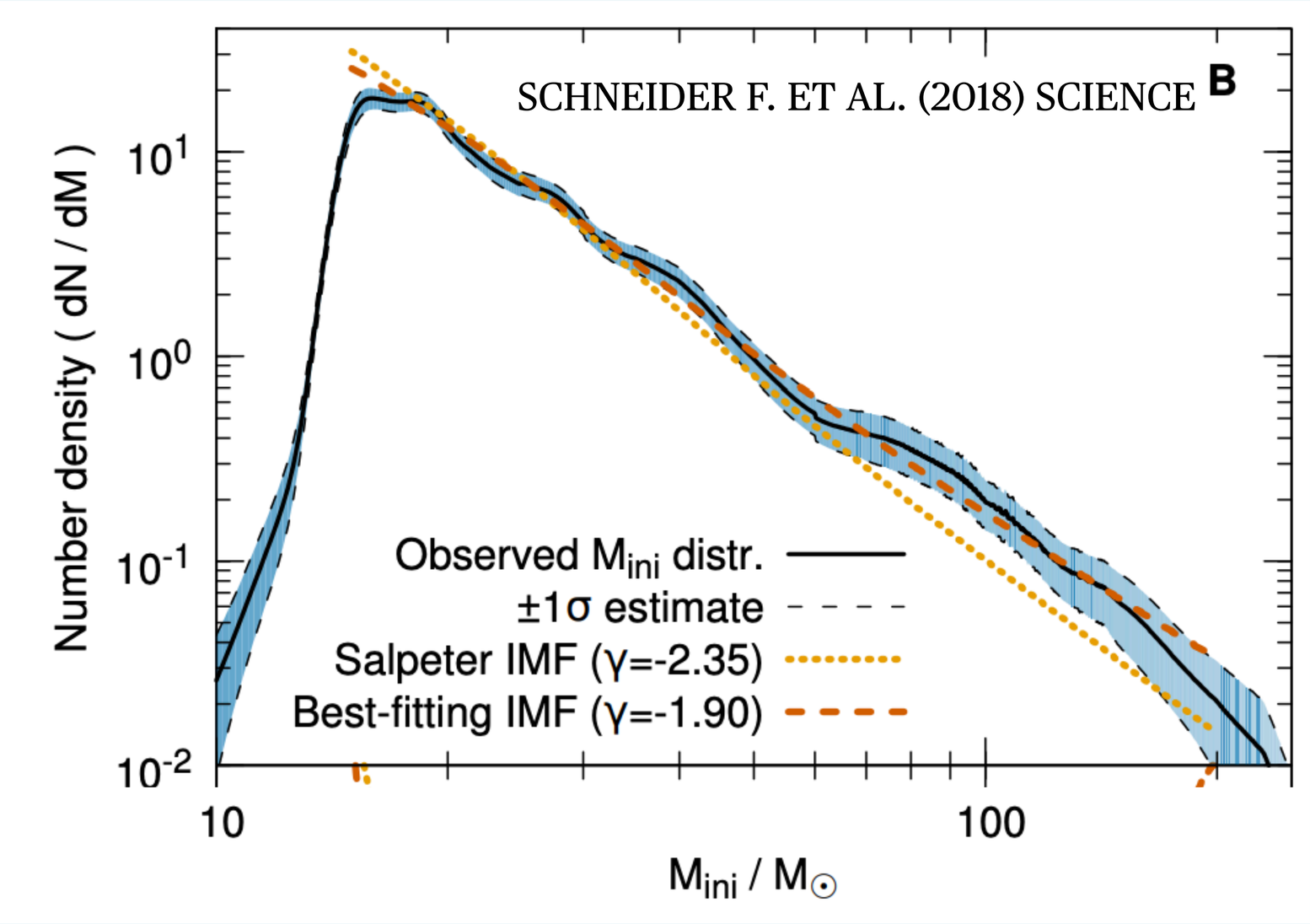
Black scatter points dwarf galaxies in the local volume

In the **blue data bins**, dwarf galaxies have been corrected for attenuation by ISM dust

The open and filled **red squares** represent the variable IMF models by Weidner+04.

A case study: the starburst region 30 Dorados in the LMC

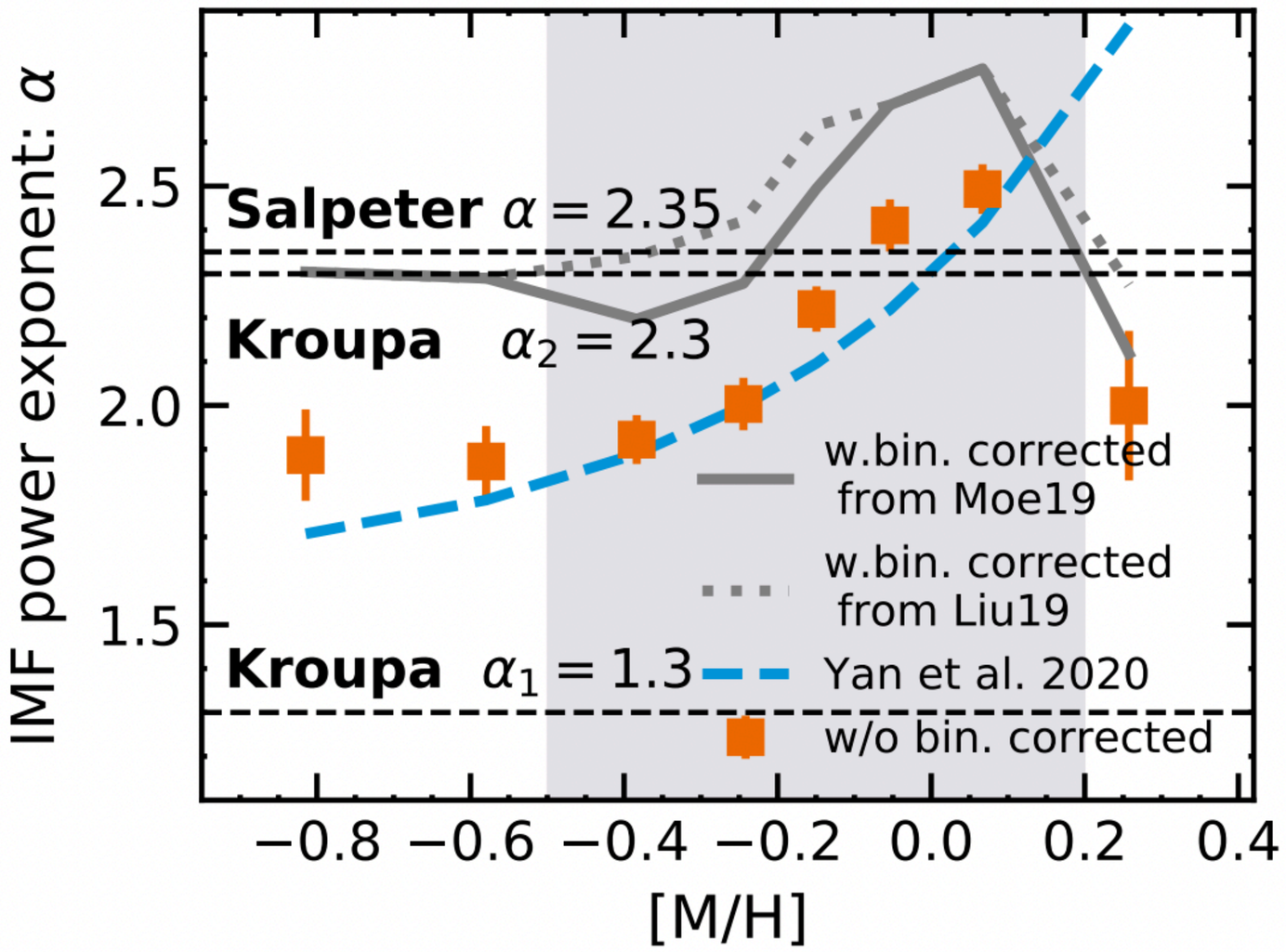
IMF



- a young (4–6 Myr) starburst region,
- Too many massive stars compared to the **Salpeter IMF slope of 2.35**.
- This suggests that 30 Doradus is inconsistent with a universal IMF

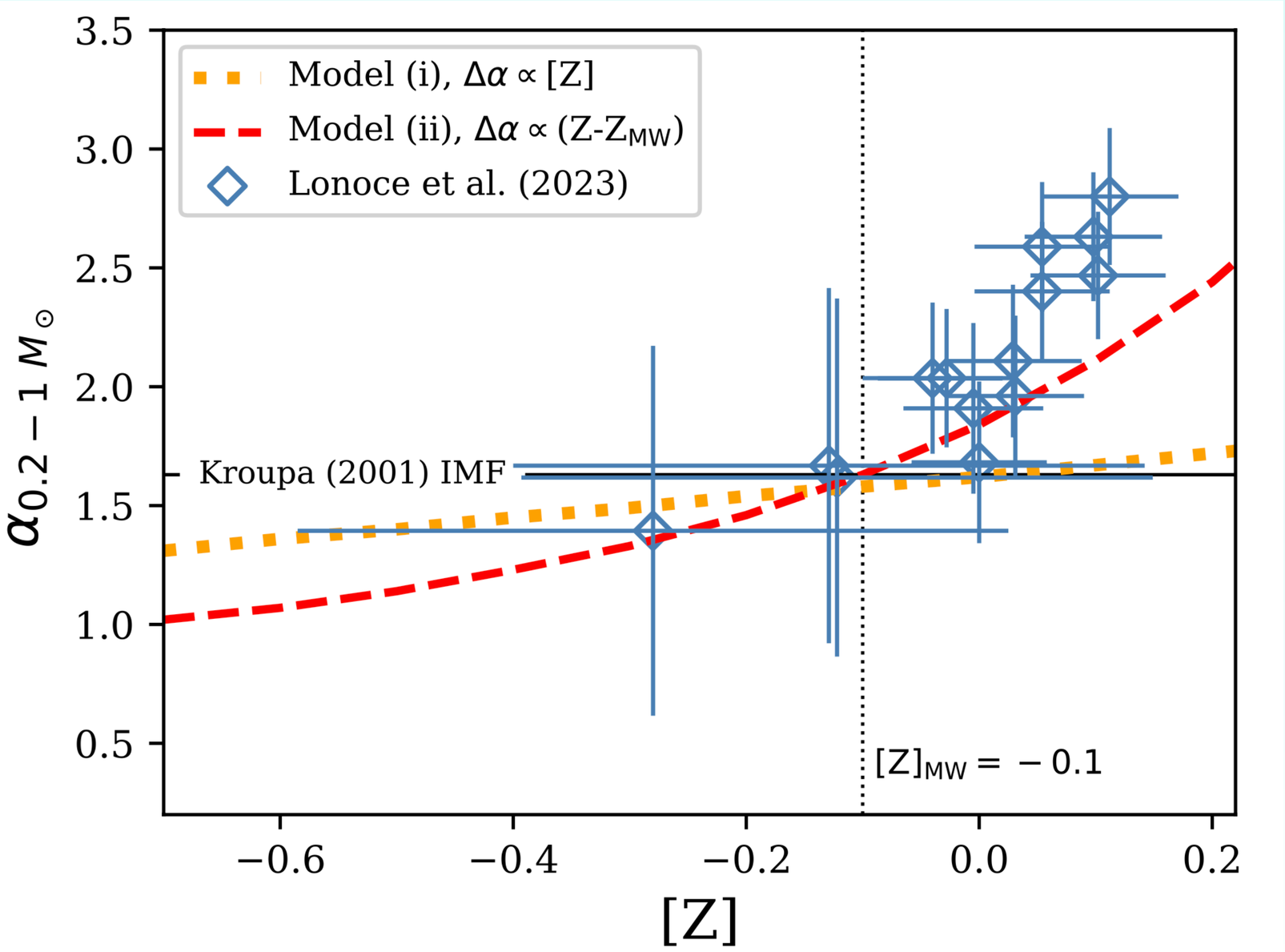
THE IMF DEPENDS ON METALLICITY

LI, 2023; NATURE, VOLUME 613, ISSUE 7944, P.460-462



- 93,000 spectroscopically observed **M-dwarf stars** (low-mass) in the 100–300 parsec (pc) Solar neighborhood.
- They find unambiguous evidence of a **variable IMF** that depends on both metallicity and stellar age.

The stellar populations formed at early times contain fewer low-mass stars compared to the canonical IMF, independent of stellar metallicities.

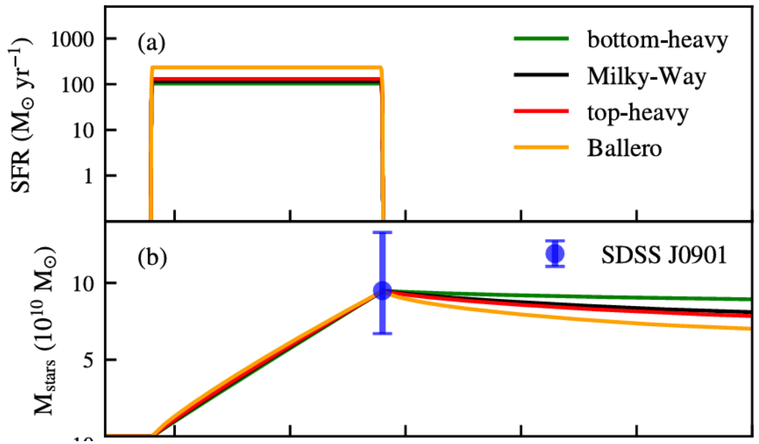


IGIMF FOR LOW MASS STARS
IN HIGH-Z ELLIPTICAL GALAXIES

NGC3309

YAN ET AL.,
INCL. **GJERGO**
(2024, APJ)

POSTDOC AT
NANJING UNIVERSITY

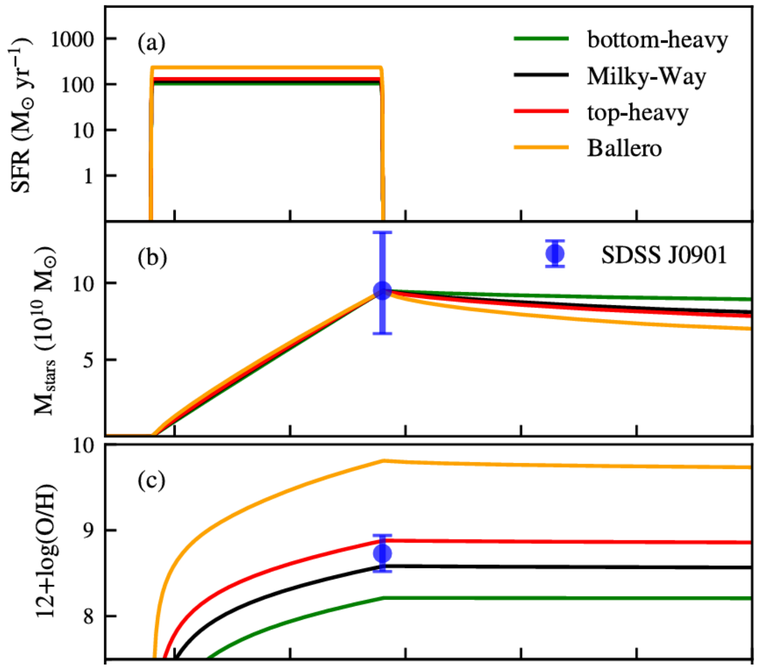


CO ISOTOPOLOGUE STUDY

GUO ET AL.,
INCL. **GJERGO**
(2024, MNRAS)

PHD STUDENT AT
NANJING UNIVERSITY

THE IMF SLOPE FOR MASSIVE STARS IN HIGH REDSHIFT STARBURSTS IS TOP-HEAVY



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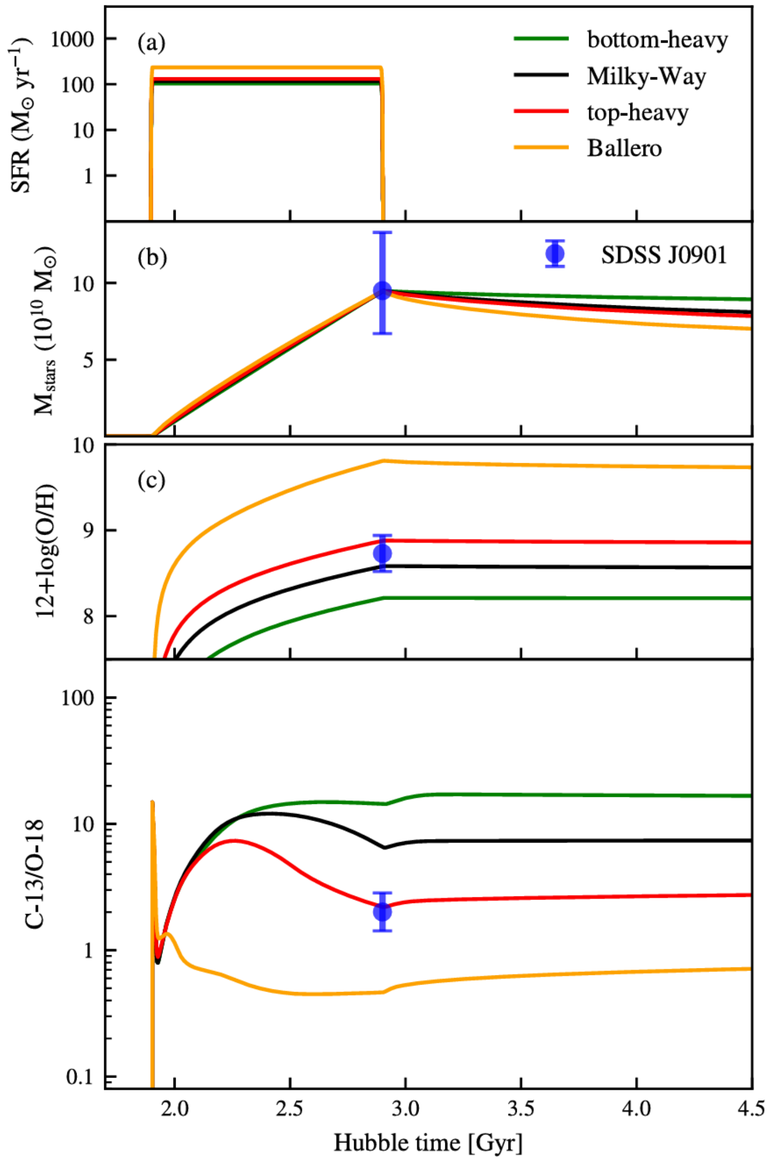

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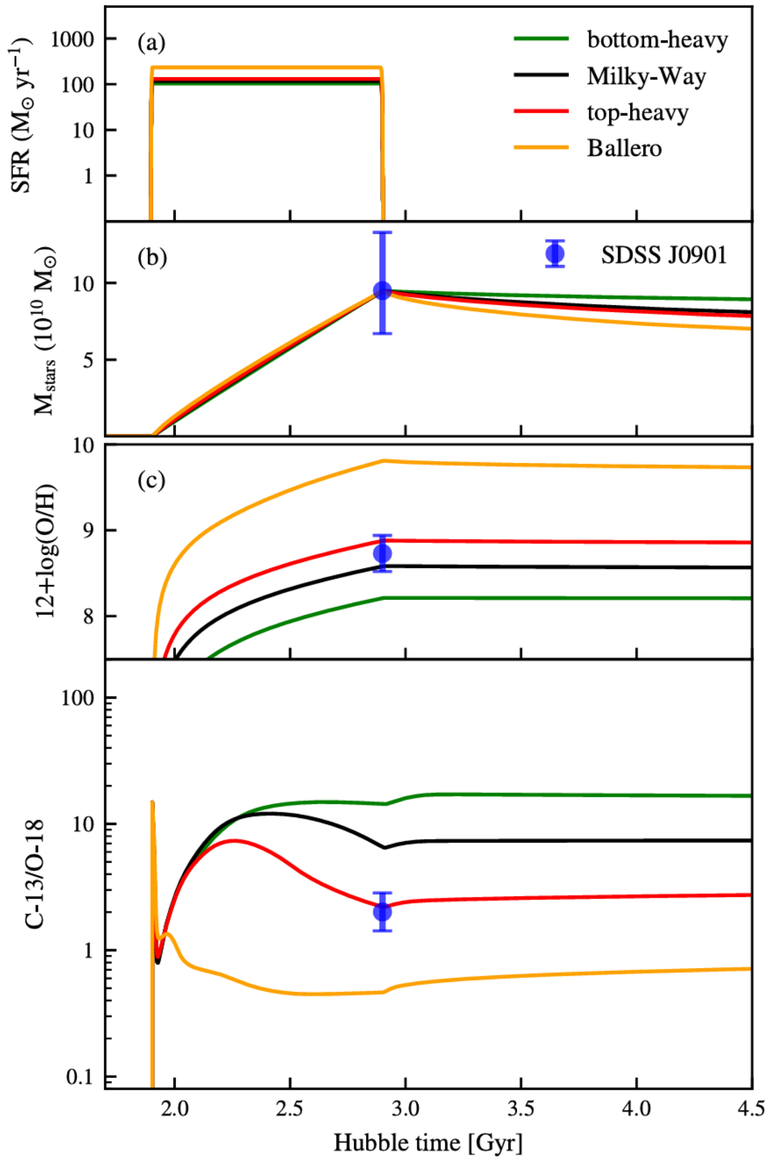

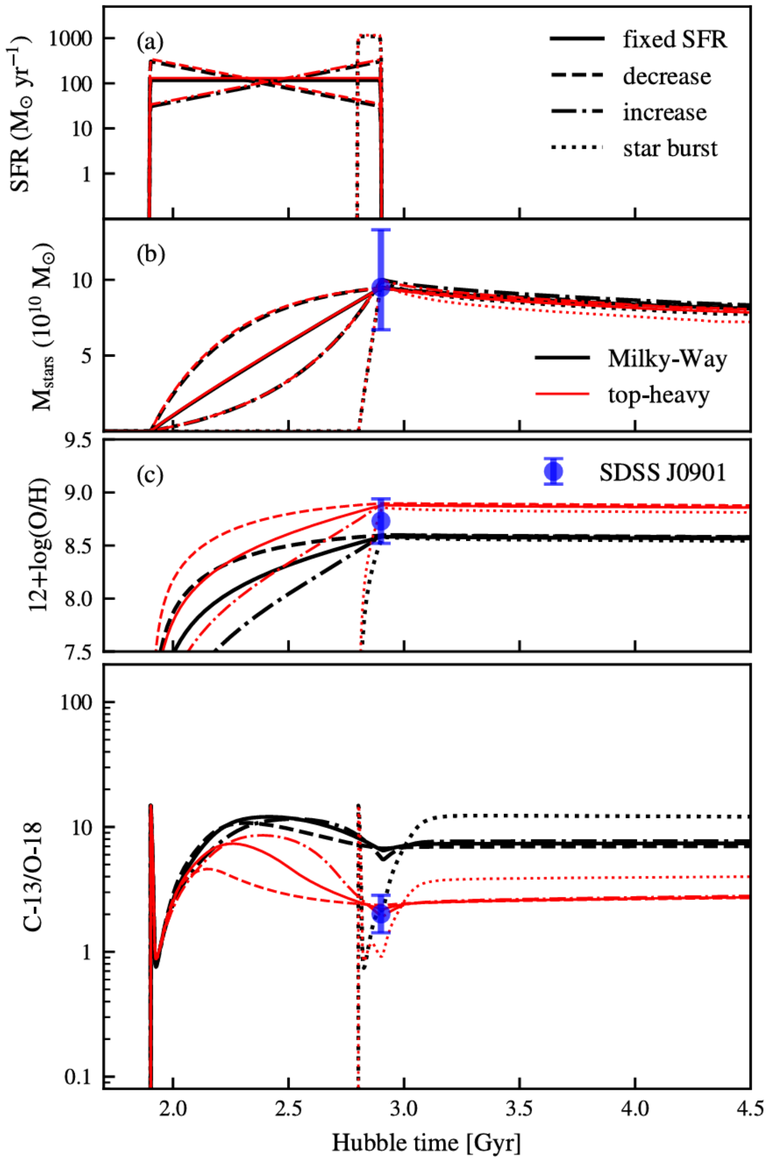

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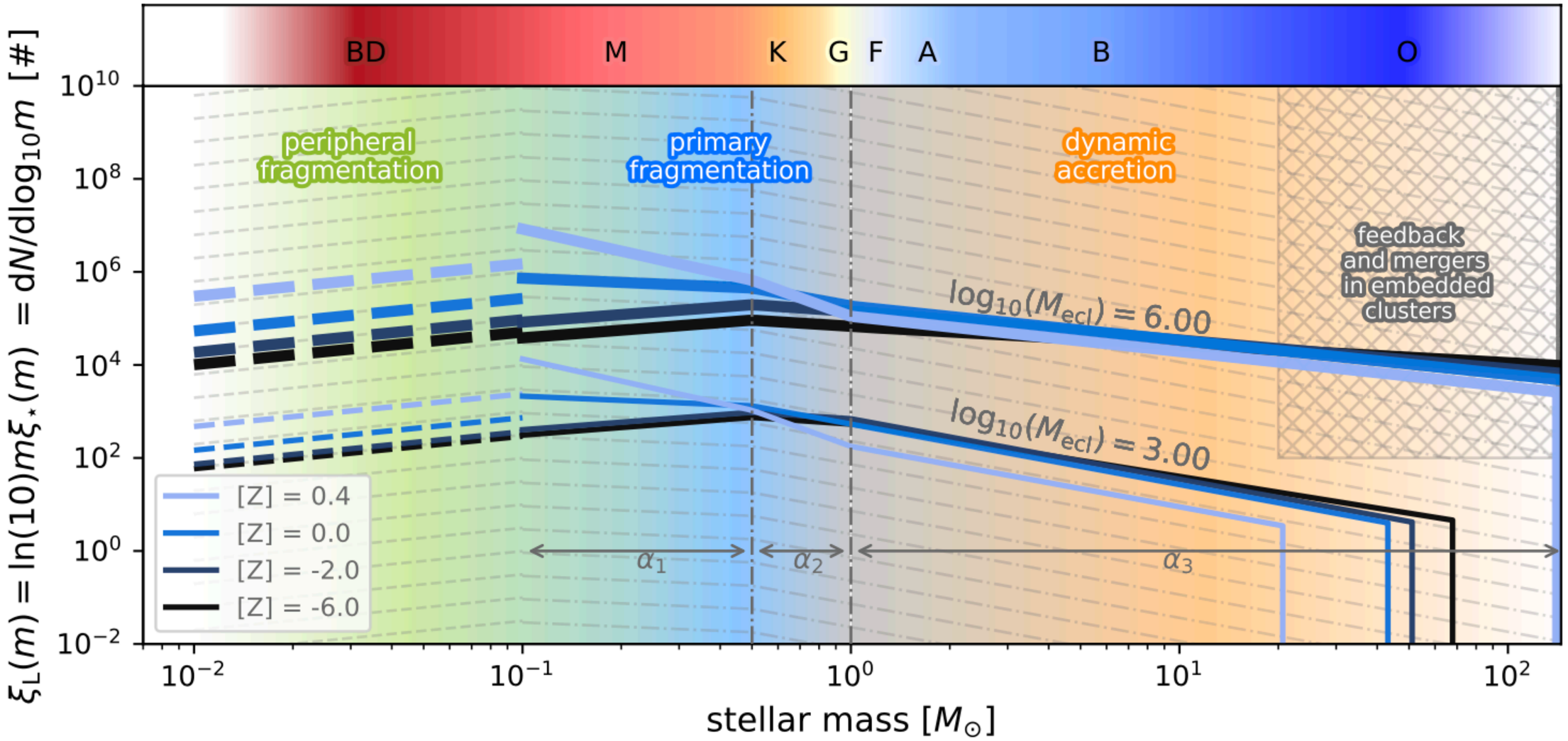
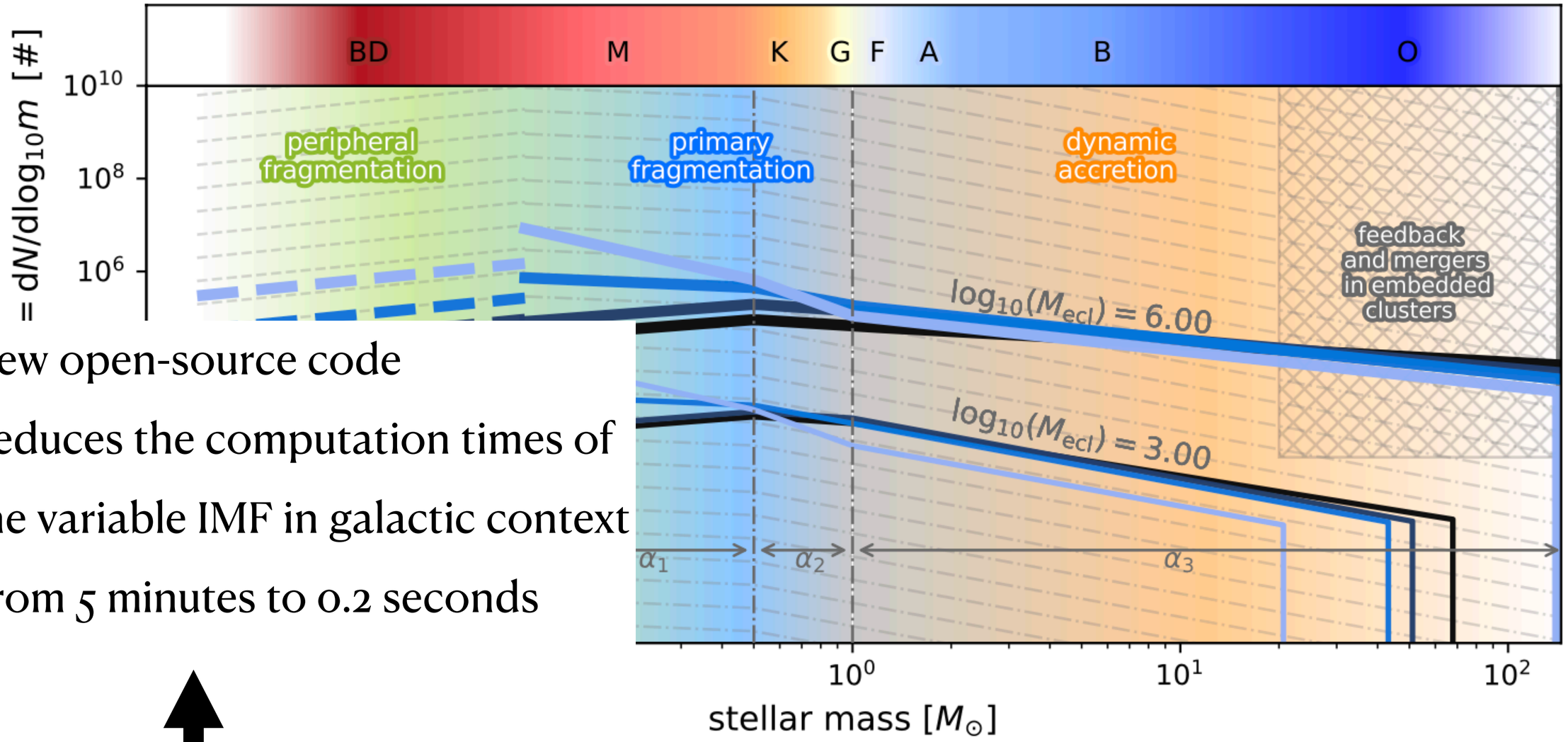
THE IMF SLOPE FOR MASSIVE STARS IN HIGH REDSHIFT STARBURSTS IS TOP-HEAVY

Overview of the variable stellar IMF



Using pyIGIMF (Gjergo et al., 2025, RAA) Kroupa, **Gjergo**, Jerabkova, Yan (2024)

Overview of the variable stellar IMF



New open-source code

Reduces the computation times of the variable IMF in galactic context

From 5 minutes to 0.2 seconds

Using pyIGIMF (Gjergo et al., 2025, RAA) Kroupa, **Gjergo**, Jerabkova, Yan (2024)

Embedded cluster mass function

Dependence on the SFR

Parameter to compute the ECMF

$$\beta = -0.106 \log_{10} \bar{\psi}_{\delta t} + 2. \tag{10}$$

Embedded cluster mass function

$$\xi_{\rm ecl} = {\rm d}N_{\rm ecl}/{\rm d}M_{\rm ecl} = k_{\rm ecl} M_{\rm ecl}^{-\beta}, \qquad 5M_\odot \leqslant M_{\rm ecl} < M_{\rm ecl,max}. \tag{11}$$

extract $k_{\rm ecl}$ and $M_{\rm ecl,max}$

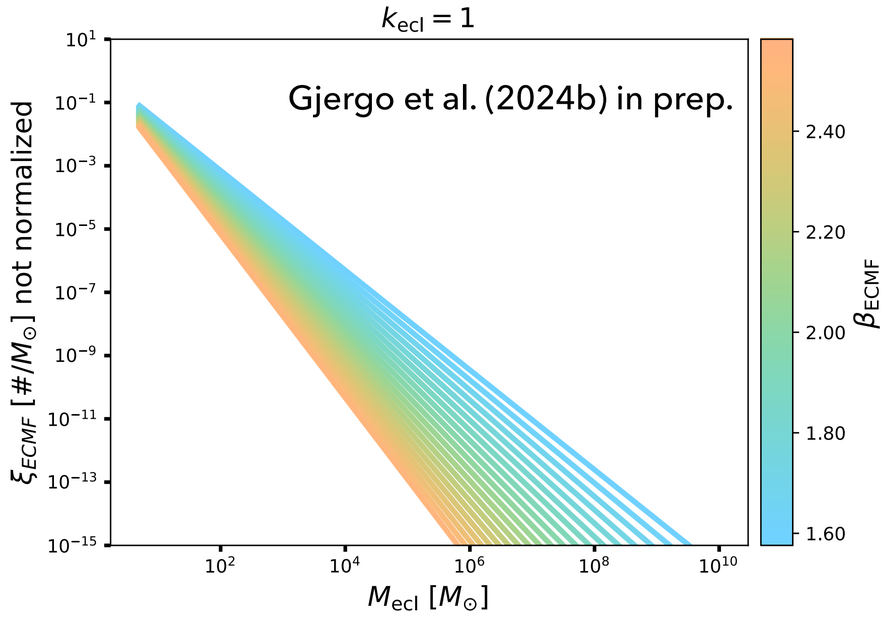
$$1 = \int_{M_{\rm ecl,max}}^{M_{\rm ecl,max*}} k_{\rm ecl} M_{\rm ecl}^{-\beta} \, {\rm d}M_{\rm ecl} \tag{12}$$

$$M_{\rm tot} = \bar{\psi}_{\delta t} \, \delta t = \int_{M_{\rm ecl,min}}^{M_{\rm ecl,max}} M_{\rm ecl} \, \xi_{\rm ecl}(M_{\rm ecl}) \, {\rm d}M_{\rm ecl} \tag{13}$$

IGIMF parameters

δt	$= 10^7 {\rm yr}$
$Z_\odot$	$= 0.0142$
$\Delta\alpha$	$= 63$
$m_{\rm max*}$	$= 150 M_\odot$
$m_{\rm min}$	$= 0.08 M_\odot$
$M_{\rm ecl,max*}$	$= 10^{10} M_\odot$
$M_{\rm ecl,min}$	$= 5 M_\odot$

Table 1: Parameters



Formulation from

Kroupa & Weidner (2003)

Kroupa & Weidner (2005)

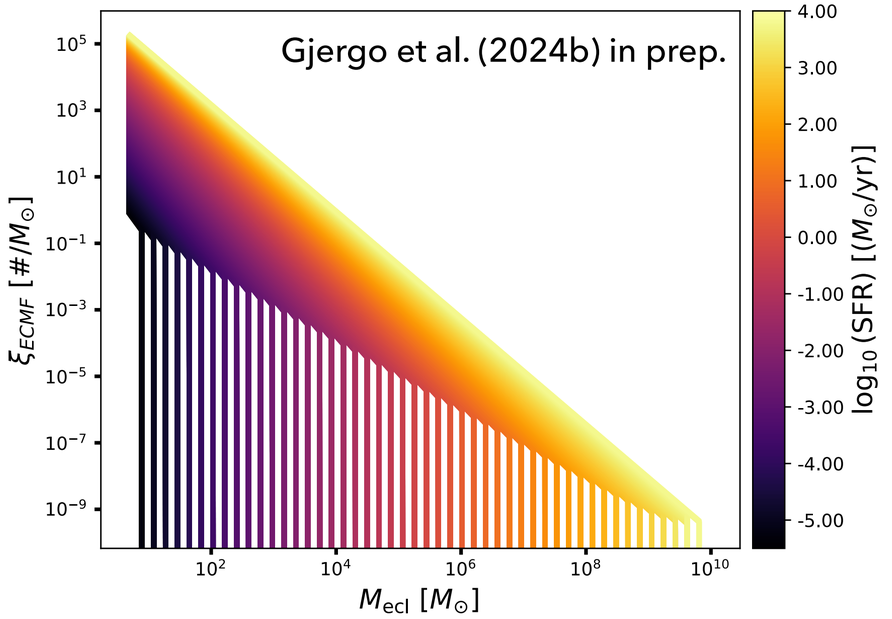
Marks & Kroupa (2012)

Kroupa (2013)

[...]

Jerabkova et al. (2018)

Yan et al. (2019,2020, 2021)



Stellar Initial Mass Function

Dependence on the embedded cluster stellar mass and metallicity

Gjergo et al. (2024b) in prep.

Formulation from

Kroupa & Weidner (2003)

Kroupa & Weidner (2005)

Marks & Kroupa (2012)

Kroupa (2013)

[...]

Jerabkova et al. (2018)

Yan et al. (2019,2020, 2021)

Parameters to compute the stellar IMF

$$\alpha_1 = 1.3 + \Delta\alpha \cdot (Z - Z_\odot),$$
$$\alpha_2 = 2.3 + \Delta\alpha \cdot (Z - Z_\odot), \tag{3}$$

$M_{\rm ecl}$-dependent exponent

$$\alpha_3 = \begin{cases} 2.3, & x < -0.87, \\ -0.41x + 1.94, & x > -0.87. \end{cases} \tag{4}$$

$$x = -0.14[\mathrm{Z}] + 0.99 \log_{10}(\rho_{\rm cl}/10^6) \tag{5}$$

$$\log_{10} \rho_{\rm cl} = 0.61 \log_{10} M_{\rm ecl} + 2.85, \tag{6}$$

Stellar IMF for individual embedded clusters

$$\xi_\star(m, M_{\rm ecl}, Z) = \mathrm{d}N_\star/\mathrm{d}m = \begin{cases} 2k_\star m^{-\alpha_1(Z)}, & 0.08 \leq m/M_\odot < 0.50\,, \\ k_\star m^{-\alpha_2(Z)}, & 0.50 \leq m/M_\odot < 1.00\,, \\ k_\star m^{-\alpha_3(Z, M_{\rm ecl})}, & 1.00 \leq m/M_\odot < m_{\rm max}\,, \end{cases} \tag{7}$$

extract $k_\star$ and $m_{\rm max}$

$$M_{\rm ecl} = \int_{0.08\ \mathrm{M}_\odot}^{m_{\rm max}} m\ \xi_\star(m)\,\mathrm{d}m, \tag{8}$$

$$1 = \int_{m_{\rm max}}^{m_{\rm max*}} \xi_\star(m)\,\mathrm{d}m, \tag{9}$$

IGIMF parameters

δt	$= 10^7$yr
$Z_\odot$	$= 0.0142$
$\Delta\alpha$	$= 63$
$m_{\rm max*}$	$= 150 M_\odot$
$m_{\rm min}$	$= 0.08 M_\odot$
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Table 1: Parameters

Stellar Initial Mass Function

Dependence on the embedded cluster stellar mass and metallicity

Gjergo et al. (2024b) in prep.

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Jerabkova et al. (2018)

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Stellar IMF for ind

$\xi_\star(m$ (7)

extract $k_\star$ and $m_{\rm ma}$

(8)

(9)

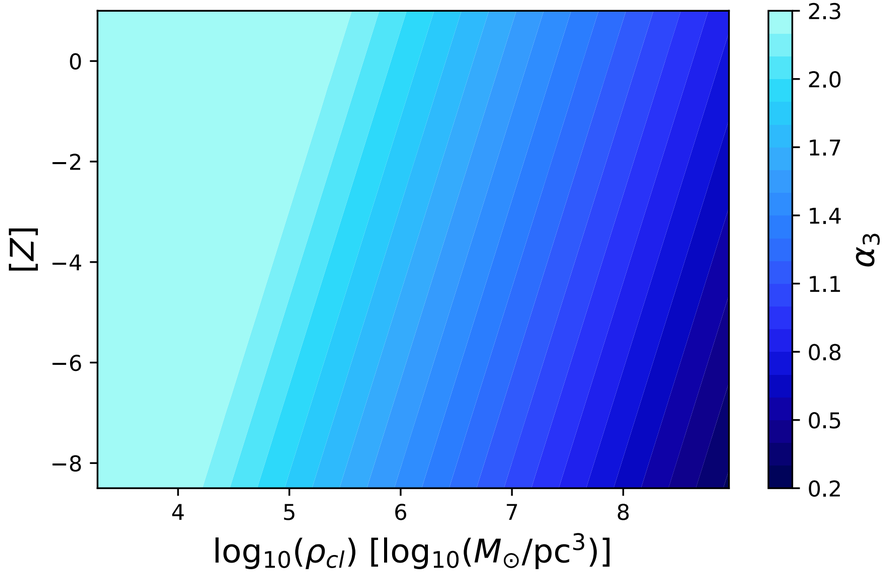

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Table 1: Parameters

Actual galaxy-wide IMF **Dependence on SFR and metallicity (both functions of time)**

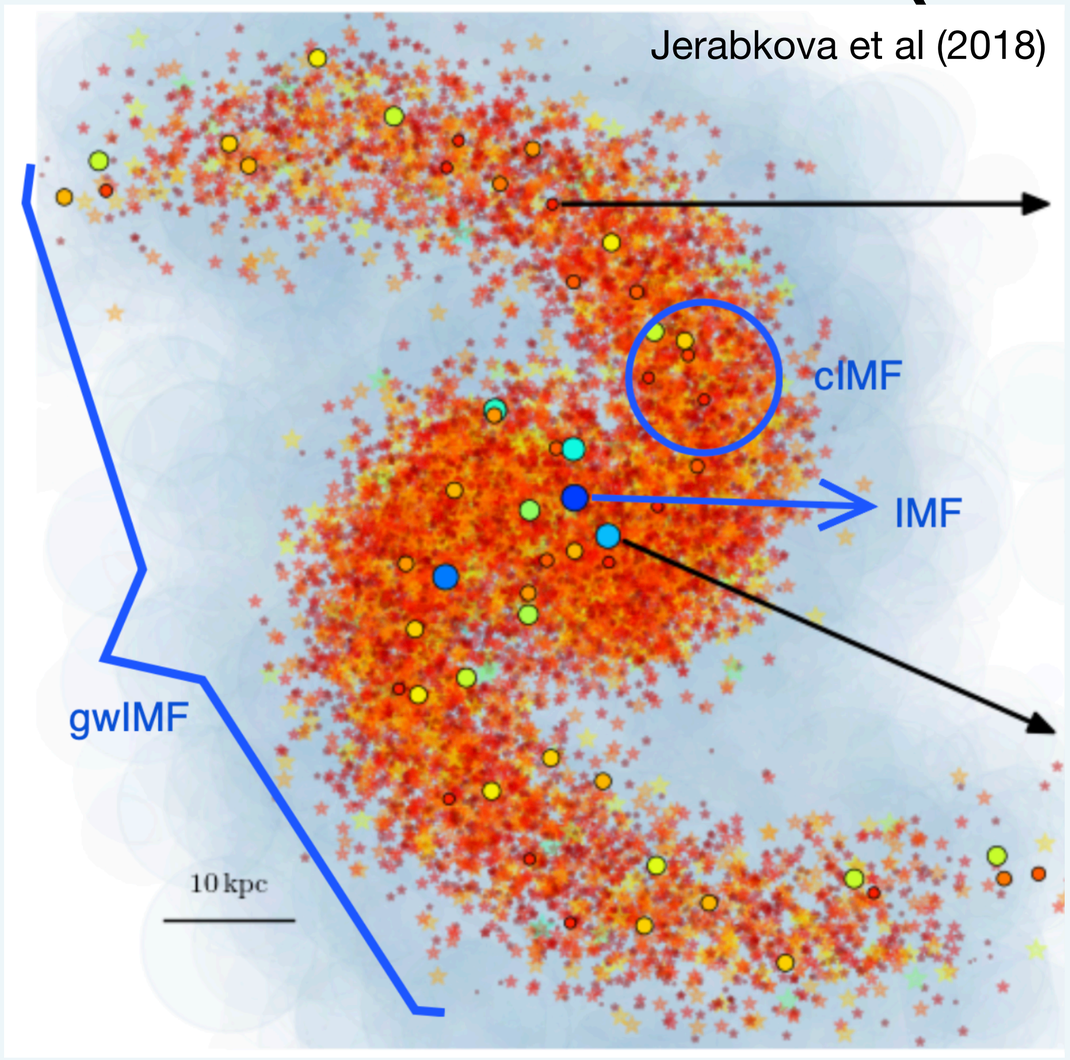
IGIMF (or equivalently, gwIMF)

$$\xi_{\rm IGIMF}(m;t) = ({\rm d}N_\star/{\rm d}m)(t) = \int_{5M_\odot}^{M_{\rm ecl,max}} \xi_{\rm ecl}(M_{\rm ecl}, \bar{\psi}_{\delta t}(t))\, \xi_\star(m, M_{\rm ecl}, [Z](t))\, {\rm d}M_{\rm ecl}. \quad (22)$$

Effectively,

$$IN(Z, SFR) = OUT(m) \quad (23)$$

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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Kroupa, Gjergo, Jerabkova, Yan (2024)
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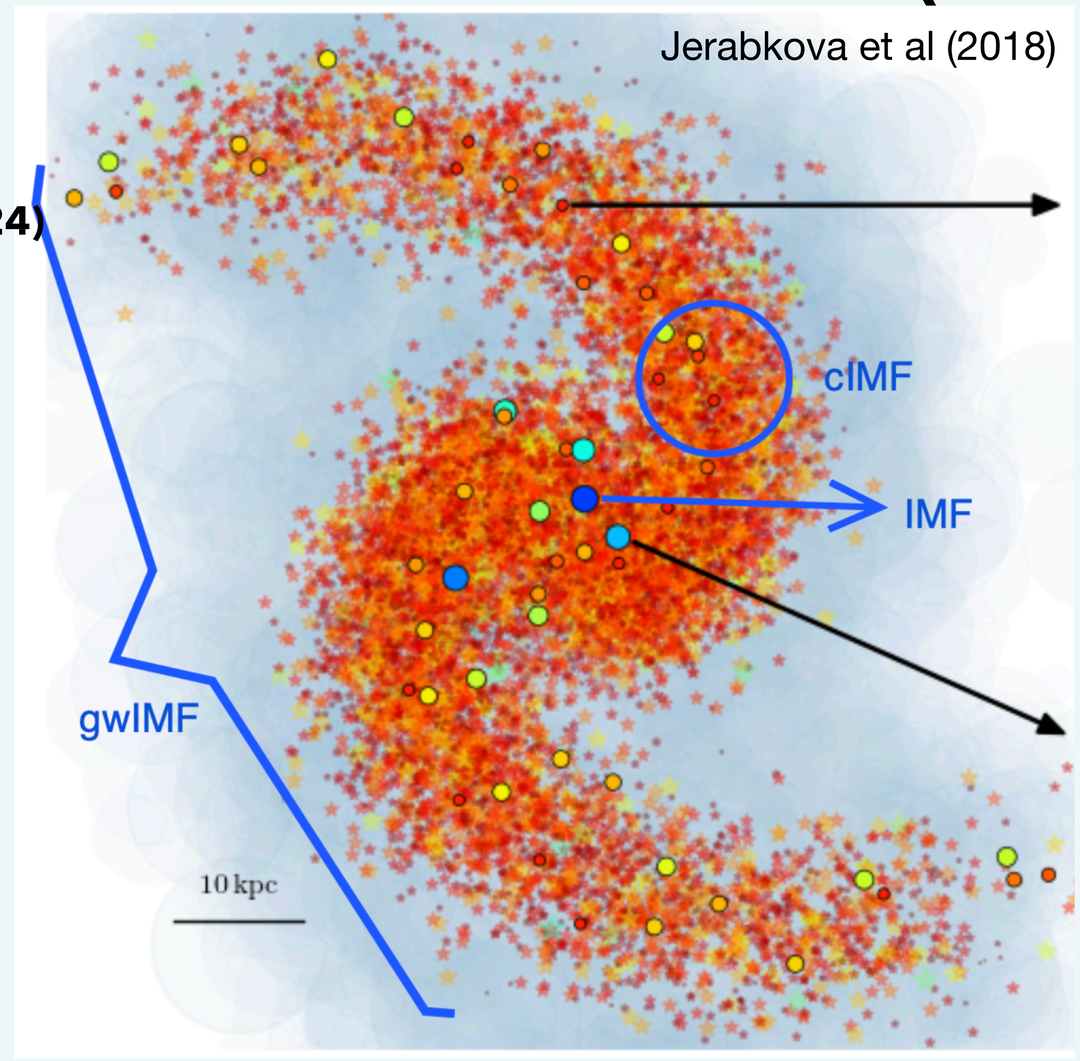
Gjergo, Zhang, Kroupa (subm.)



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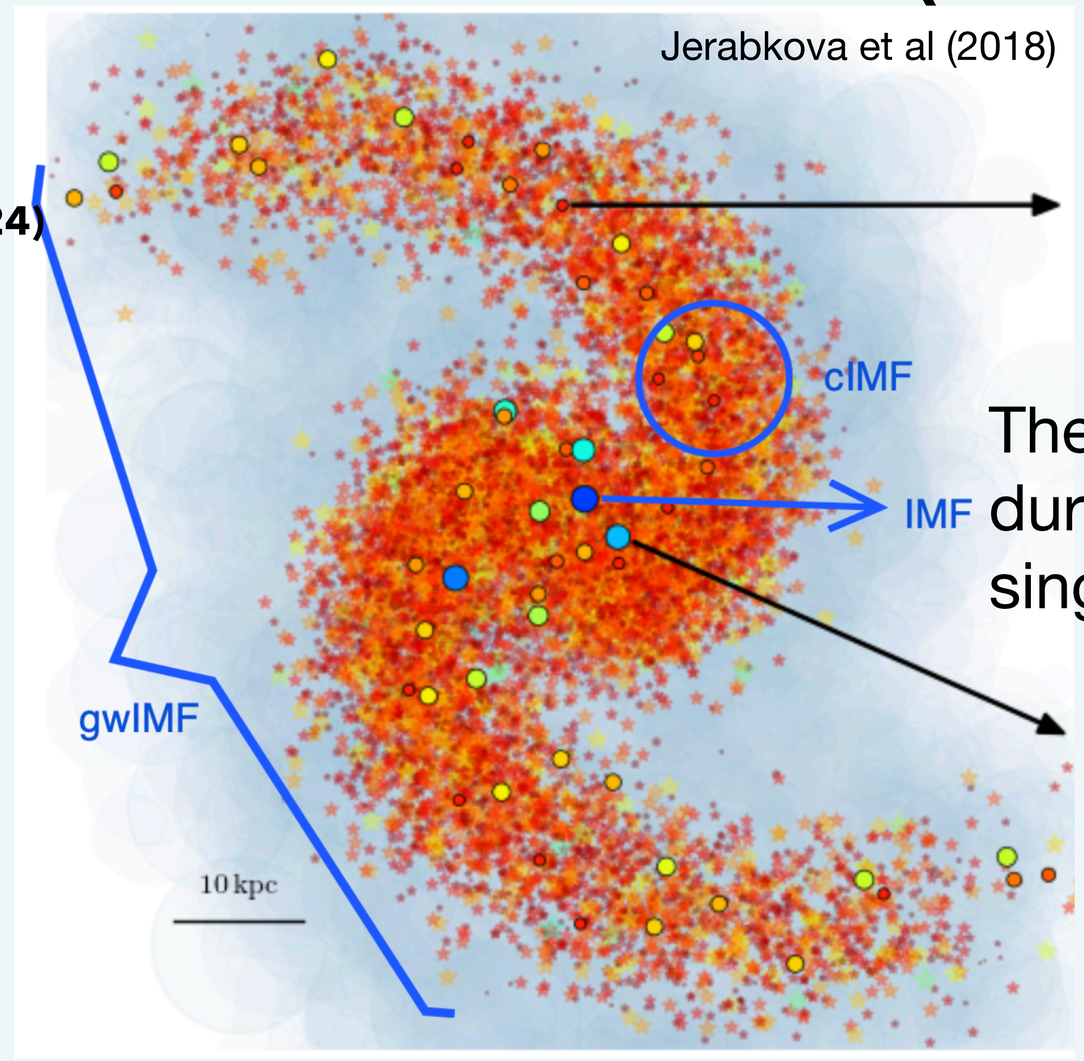

Red: older stellar populations

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

Blue: younger stars

Integrated Galaxy-wide Initial Mass Function (IGIMF)

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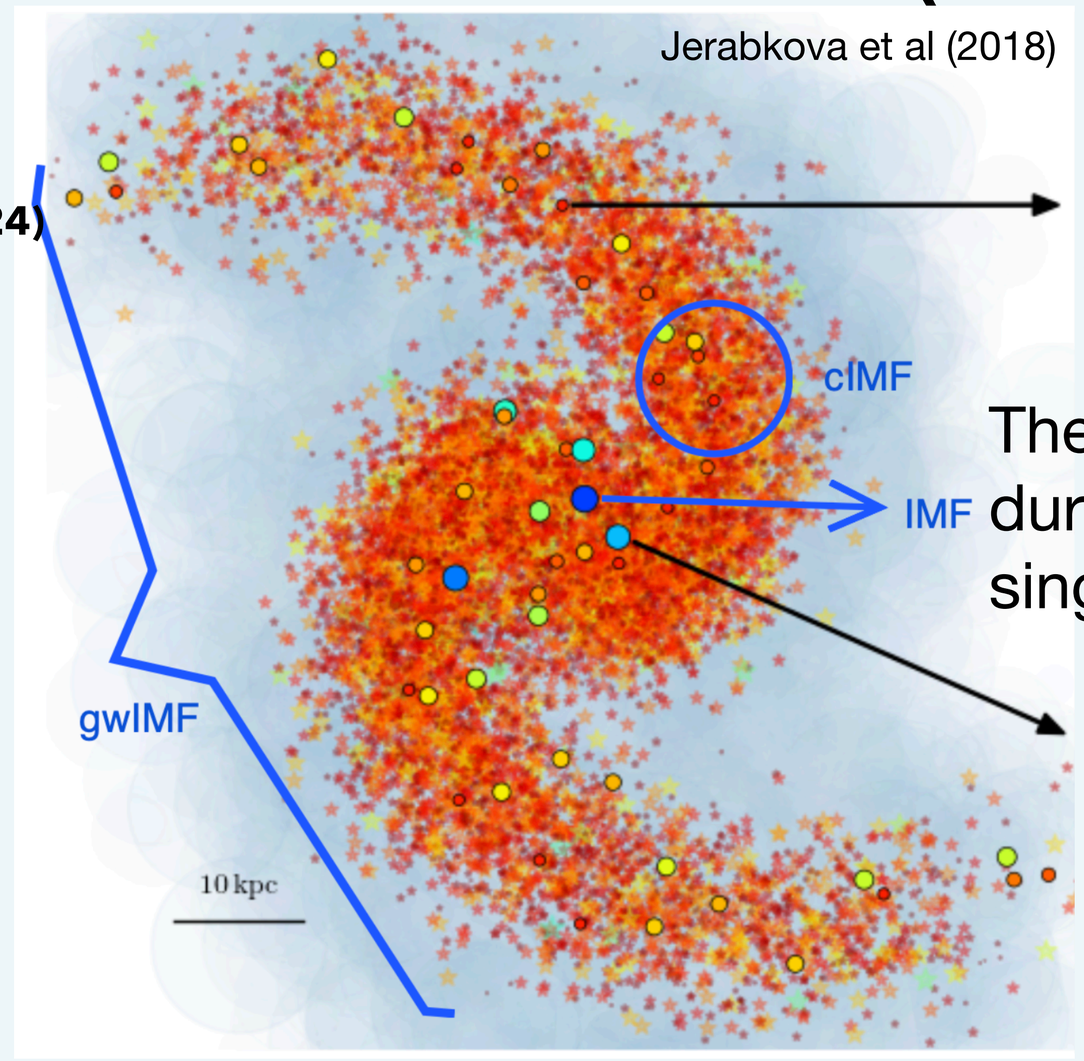

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$$\text{IMF} = \frac{\Delta N \text{ of stars}}{\Delta \text{ mass of stars}}$$

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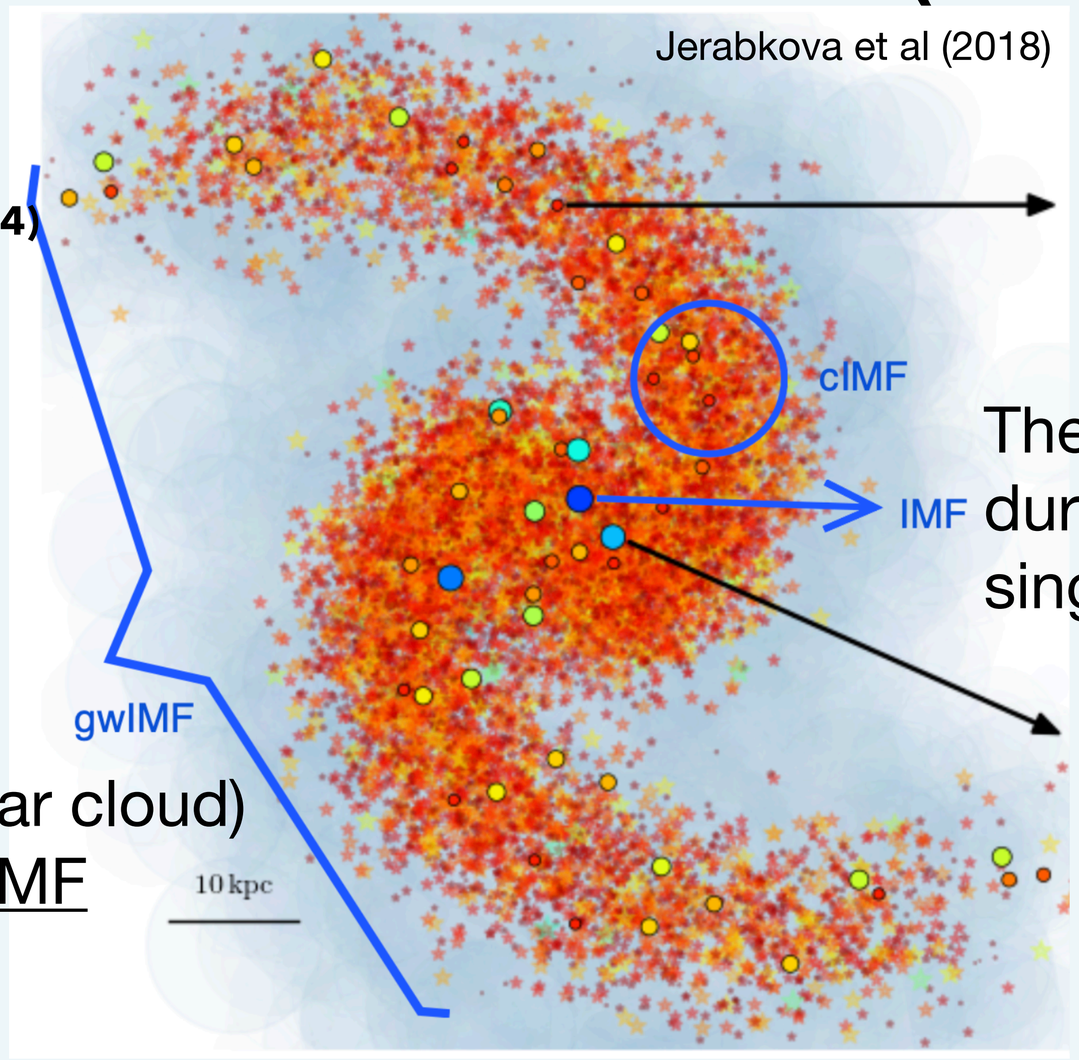


Red: older stellar populations

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

Blue: younger stars

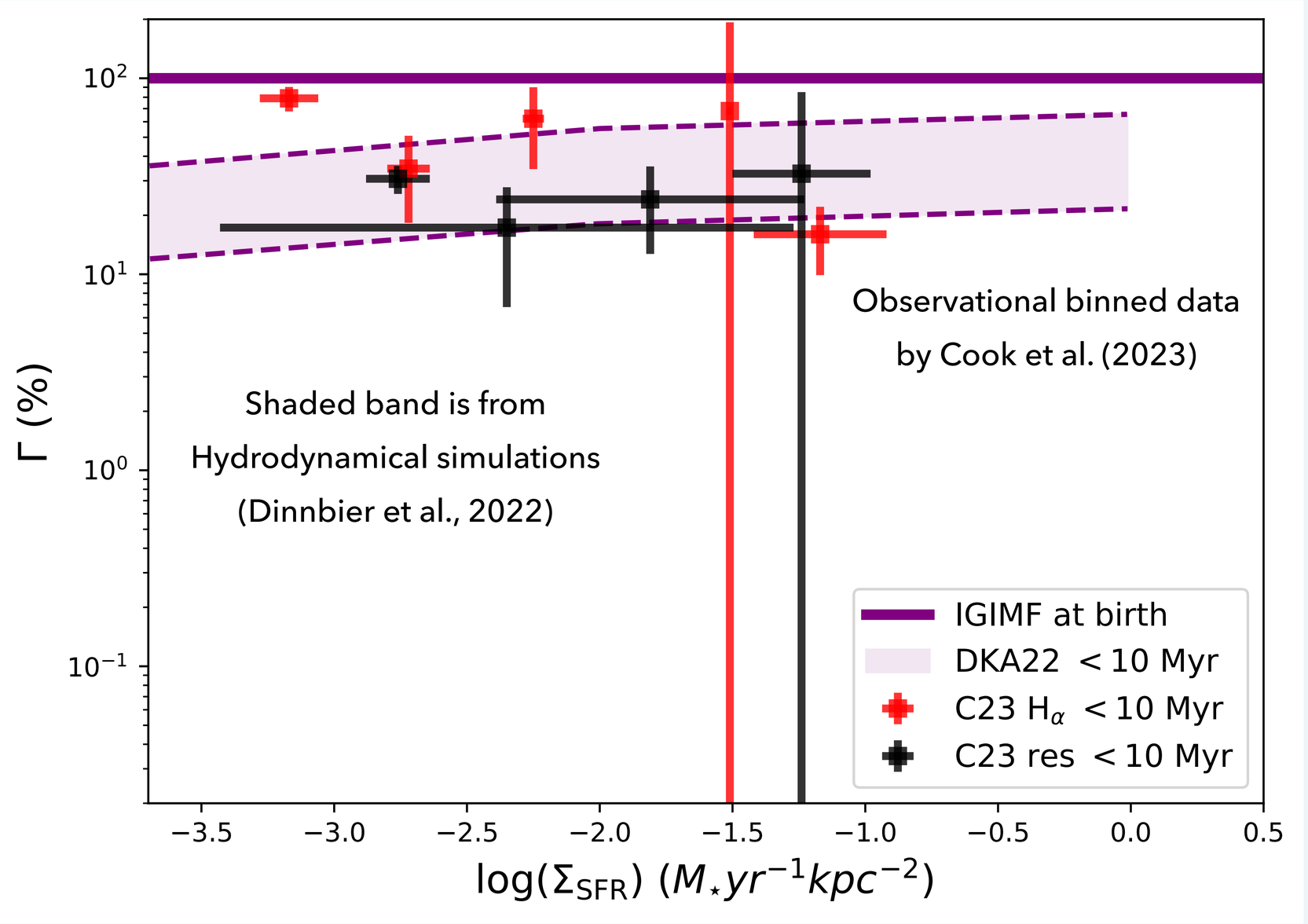
The **cumulative sum** of all stellar IMFs formed in past 10 Myr (The lifetime of a molecular cloud) defines the galaxy-wide IMF (gwIMF)

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

Where do stars form?

Γ is the percentage of stars born in embedded clusters

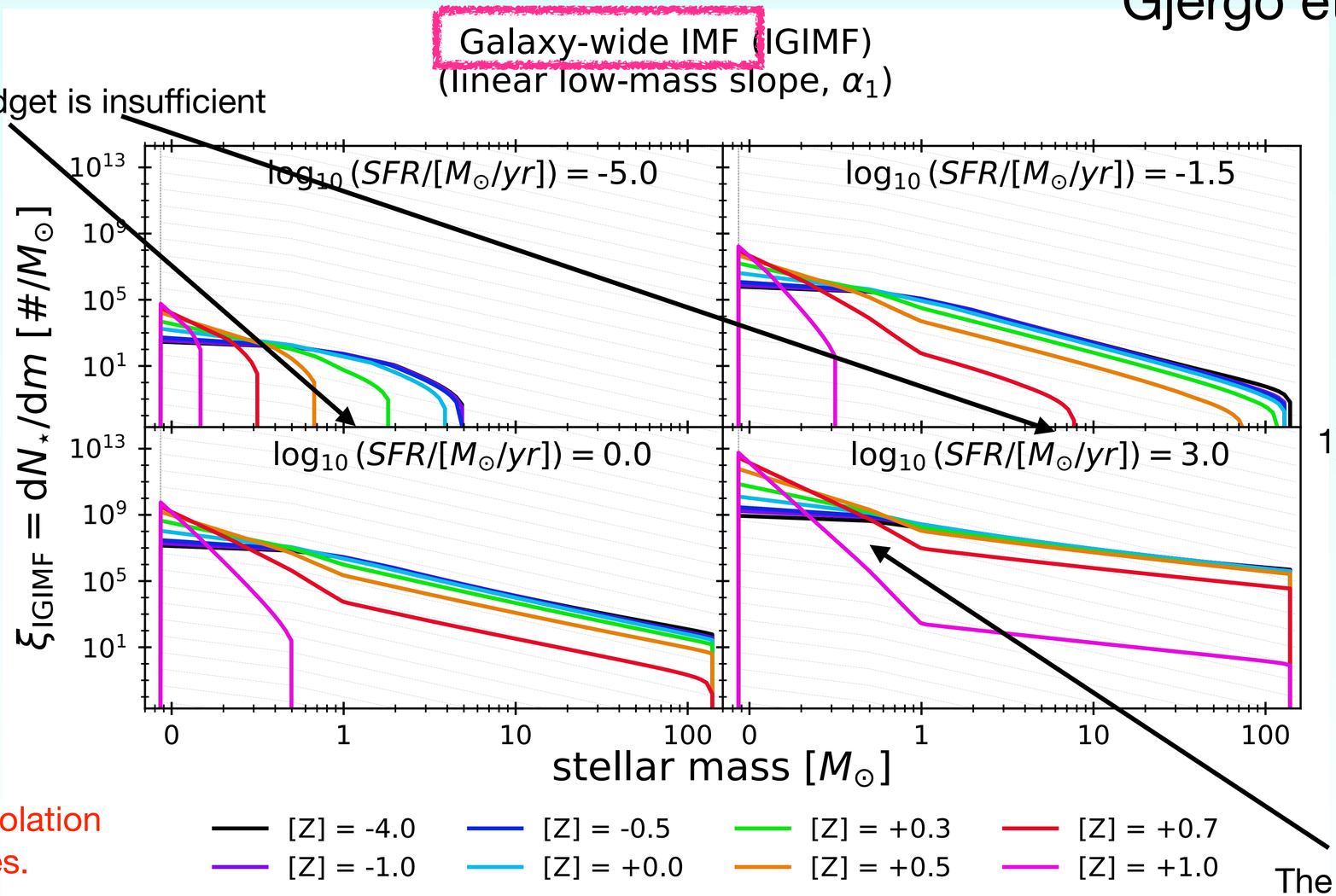
Gjergo et al. (2025, RAA)



IGIMF in practice

Gjergo et al. (2025, RAA)

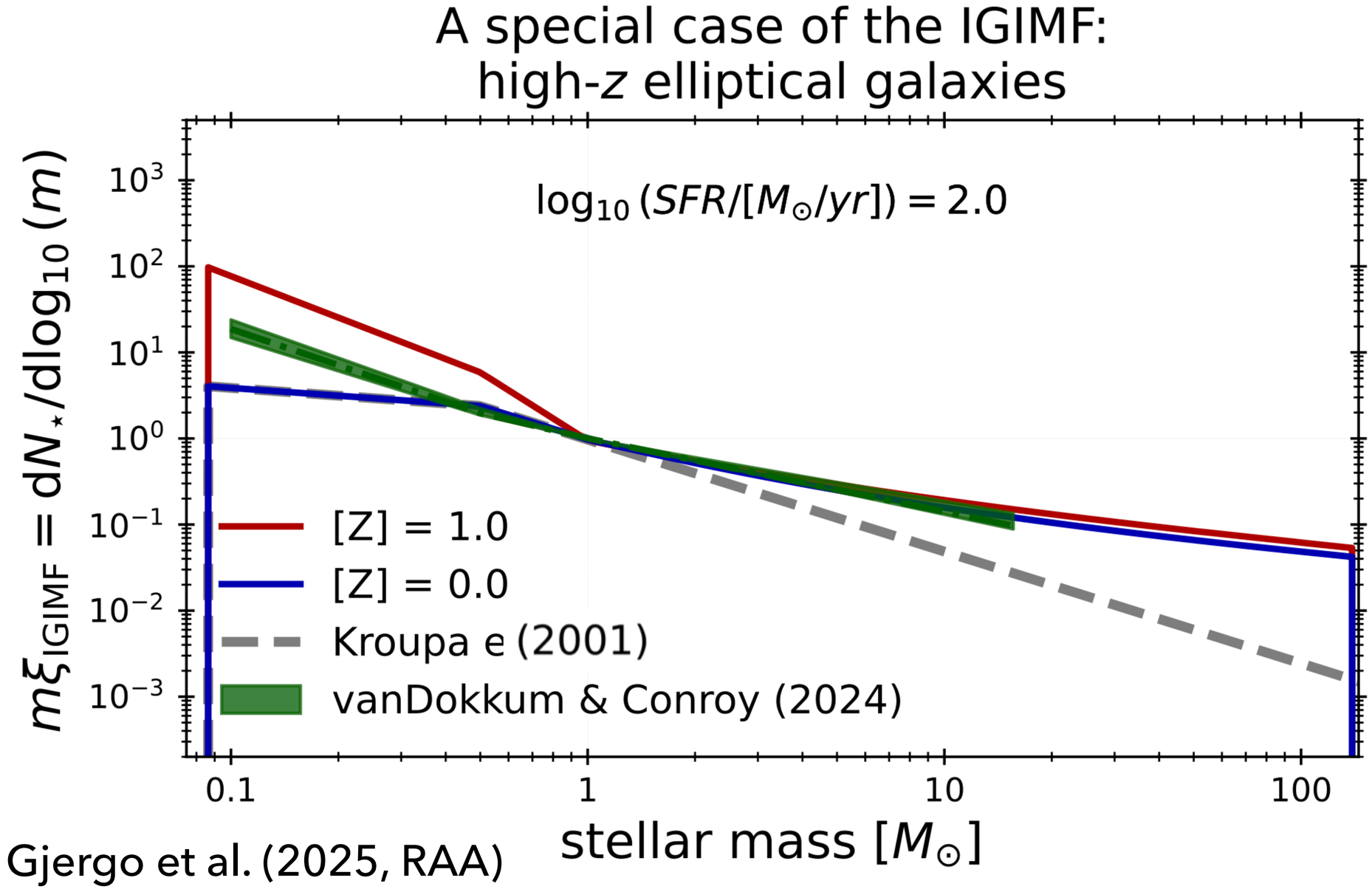
Optimal sampling:
If the star-forming mass budget is insufficient
Massive stars cannot form



Higher SFR:
1) Raises the entire gwIMF
2) Makes it top-heavy (if the mass budget is sufficient)

The higher the metallicity, [Z]
The steepr the low-mass slope

Disclaimer: untested extrapolation for high [Z] > 0.3 metallicities. Alternative proposed in Gjergo et al. (2025)



Gjergo et al. (2025, RAA)

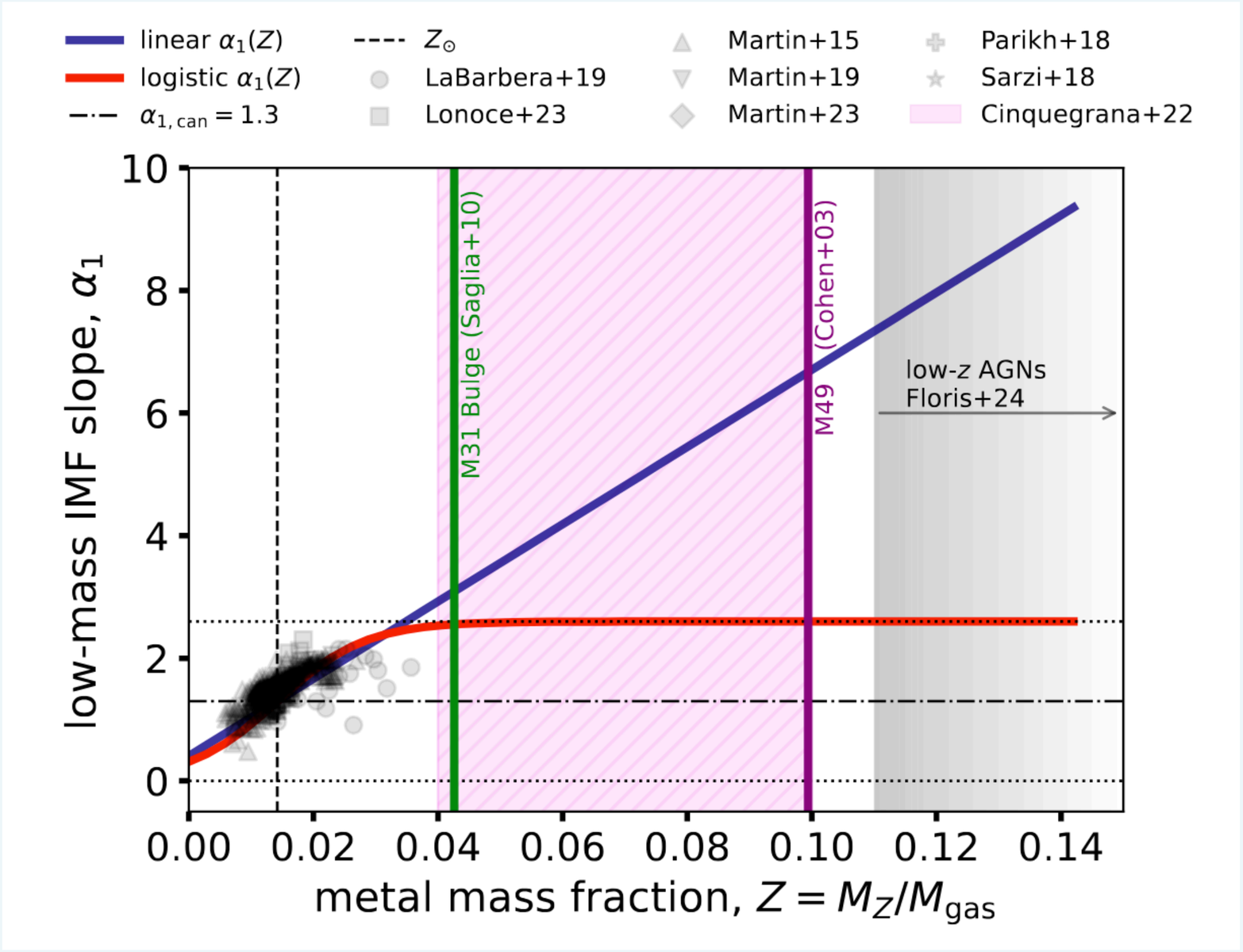
While the average IMF of most spiral galaxies looks like Kroupa (2001) (**Dashed-gray line**)

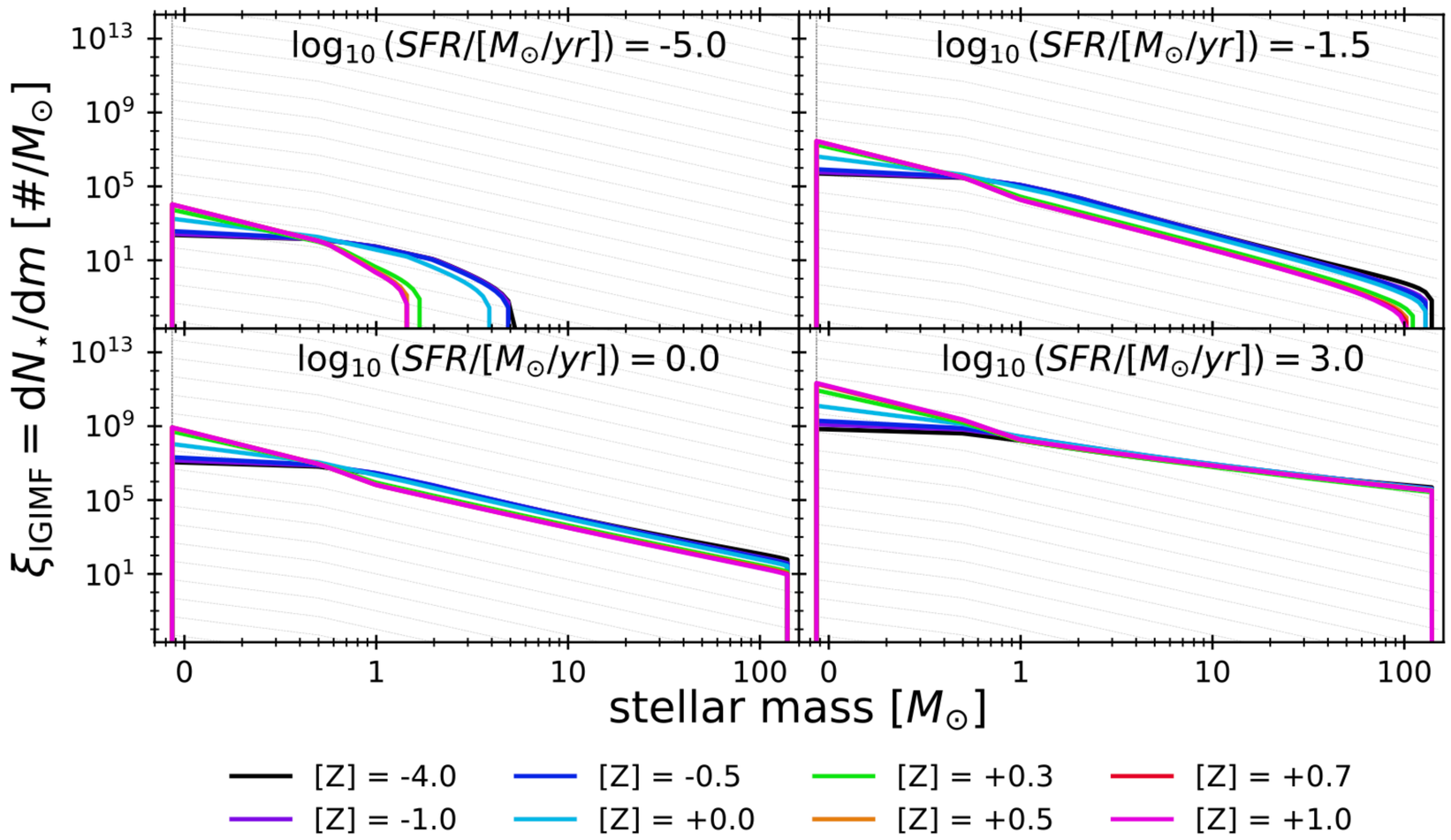
Distant elliptical galaxies have an average IMF like the **shaded green curve**.

It happens to be a special case of our galaxy-wide variable IMF model (IGIMF theory) for metal-rich starburst galaxies (**red** and **blue curves**)

Dependence of α_1 (the low-mass slope) on metal content

Gjergo et al. (2025, RAA)

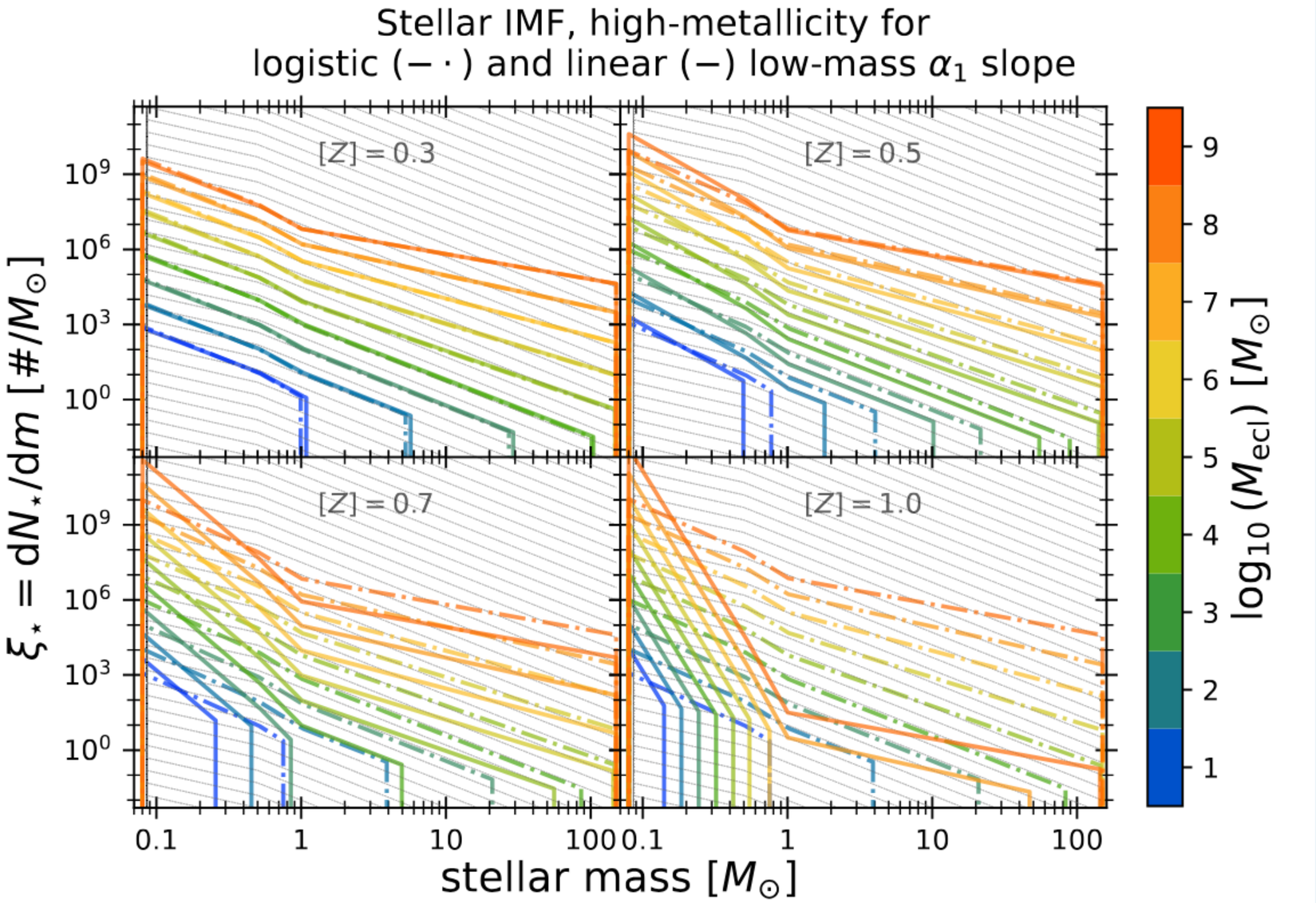




Gjergo et al. (2025, RAA)

Variation of the stellar IMF at extreme supersolar metallicities

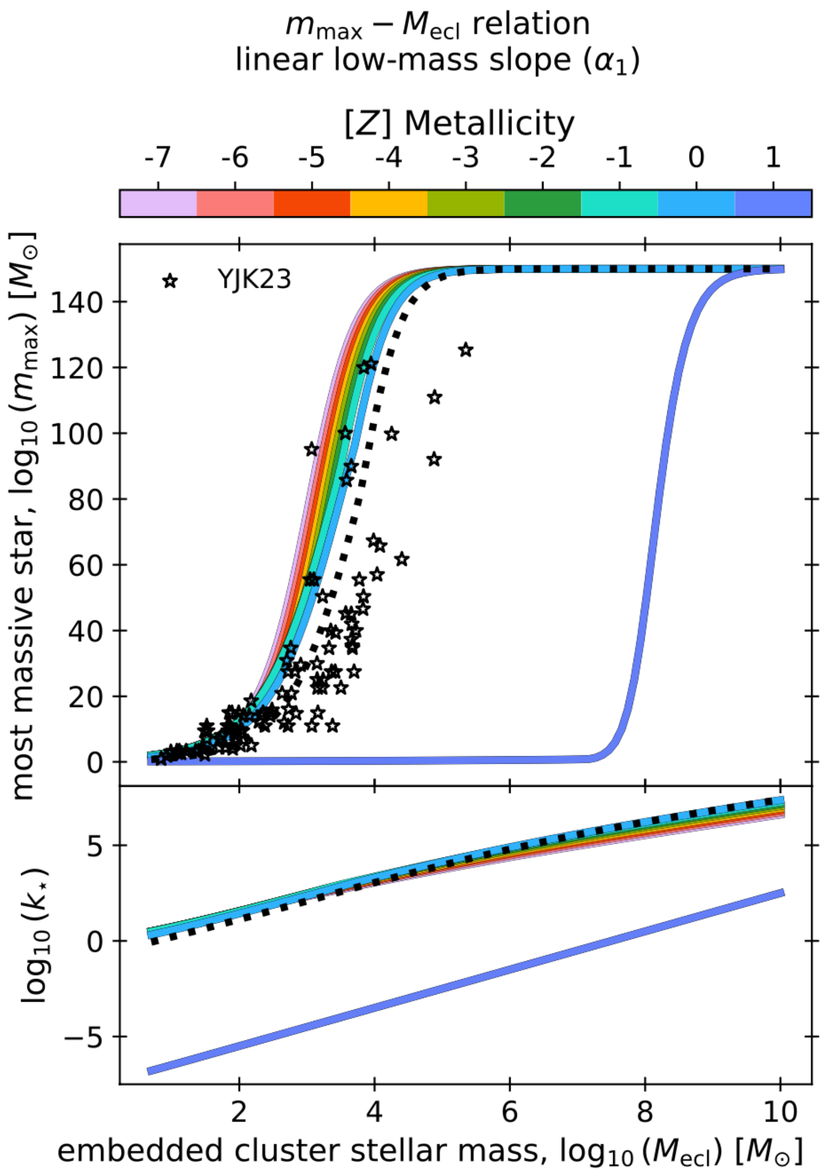
Gjergo et al. (2025, RAA)



Extrapolation of the m-max-Mecl relation

At high metallicities

Gjergo et al. (2025, RAA)



Extrapolation of the m-max-Mecl relation

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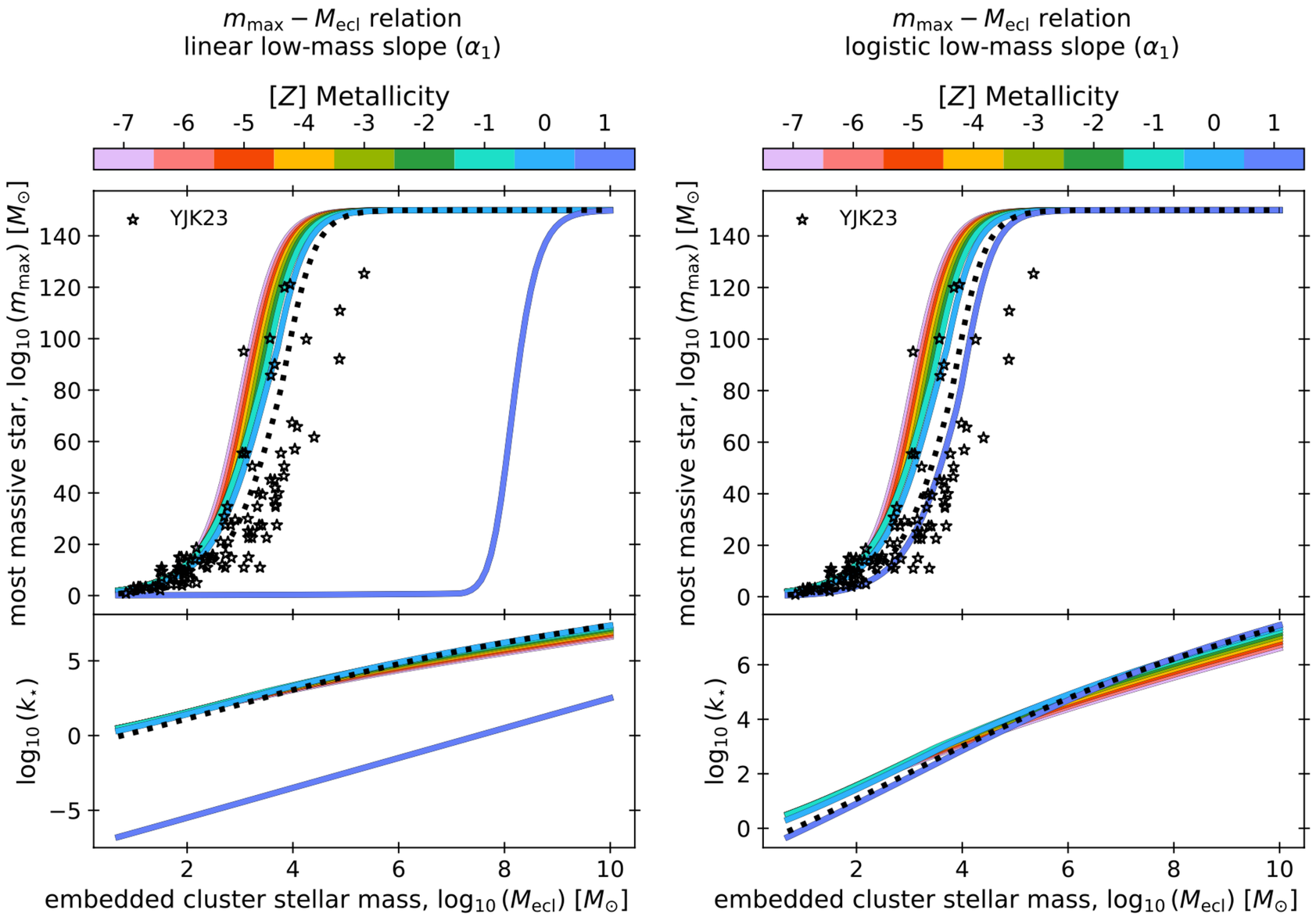
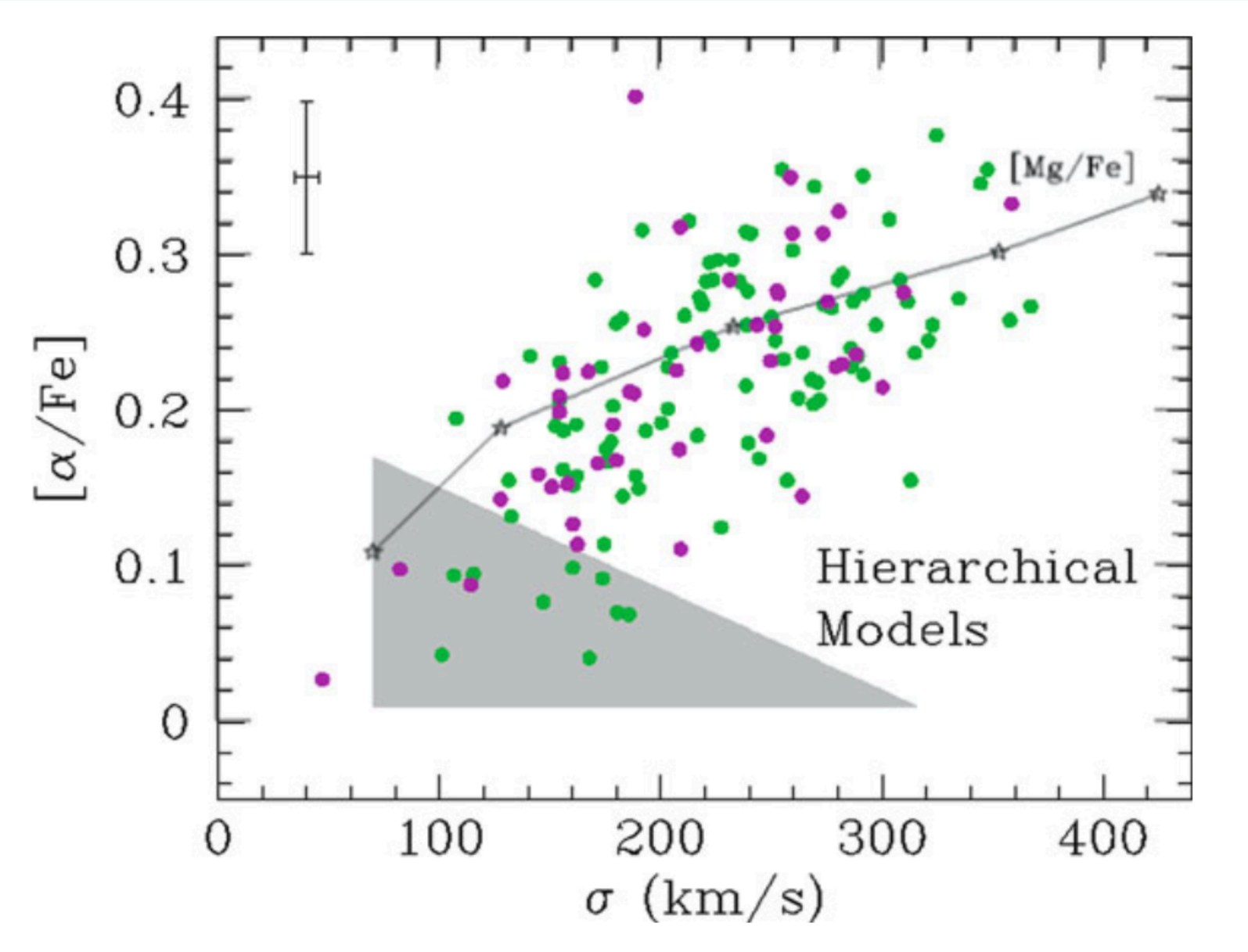
Gjergo et al. (2025, RAA)



Chemical Evolution



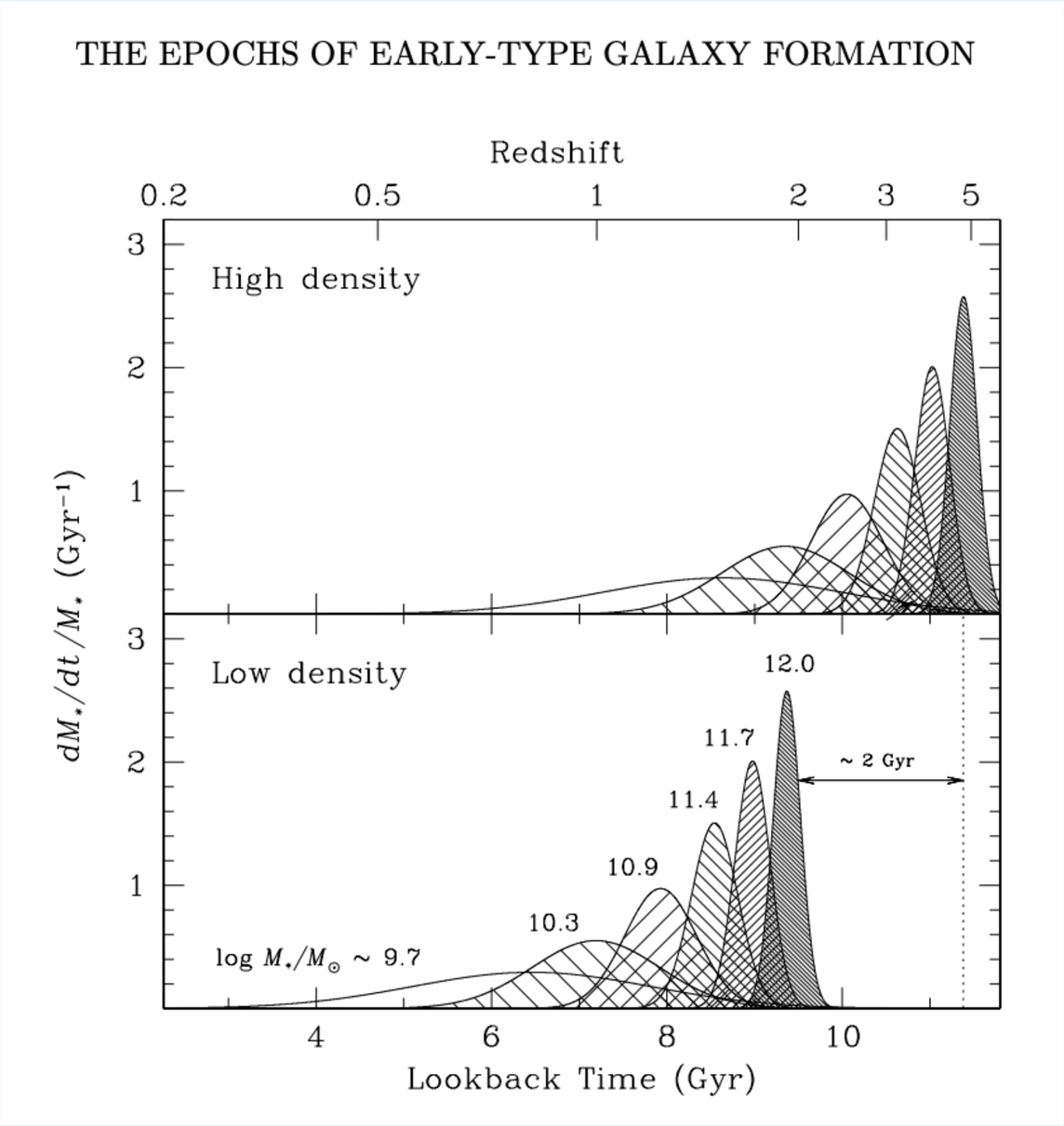
Matteucci (2012)

Figure adapted from

Thomas et al. (2002)

Curve from Matteucci & Pipino (2004)

Thomas et al. (2005)



The CMB's meaning for cosmological models and the role elliptical galaxies have on this matter

Pavel Kroupa

Helmholtz-Institut für Strahlungs- und Kernphysik (HISKP)
University of Bonn
c/o Argelander-Institut für Astronomie
University of Bonn

Astronomical Institut,
Charles University in Praha

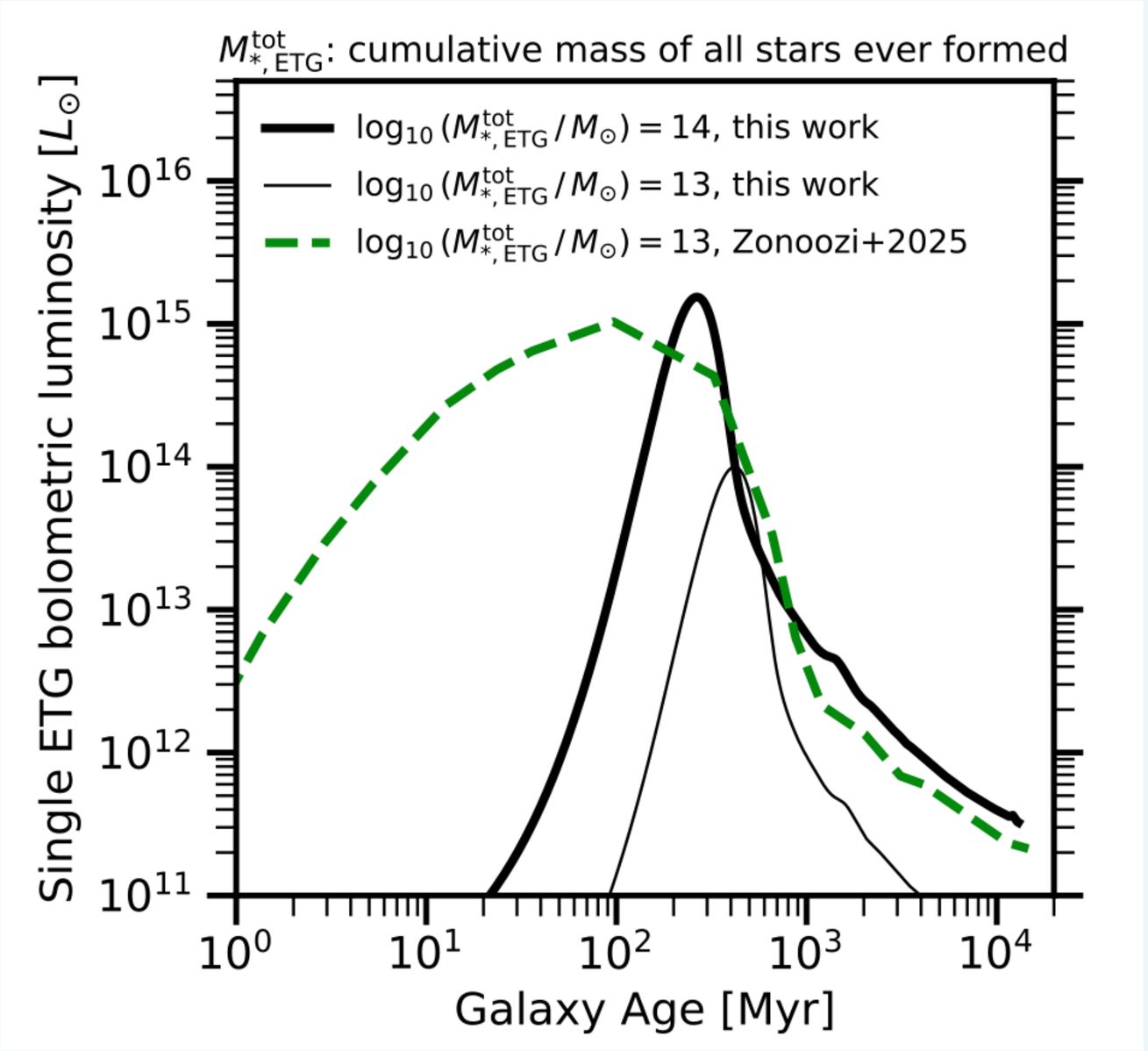
AUUK, Praha

December 10th, 2025

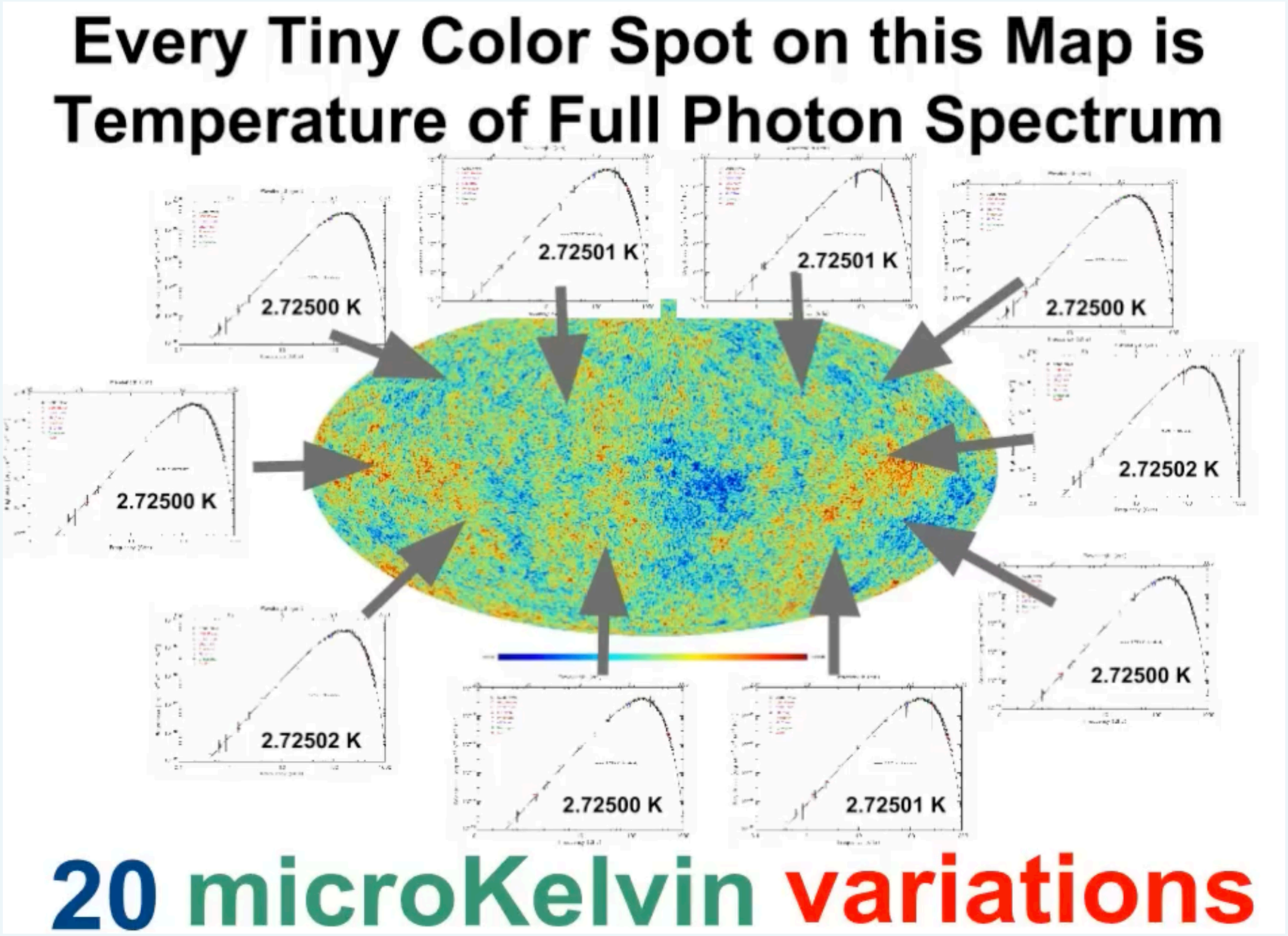
With
Eda Gjergo
and
Nikolaos Samaras

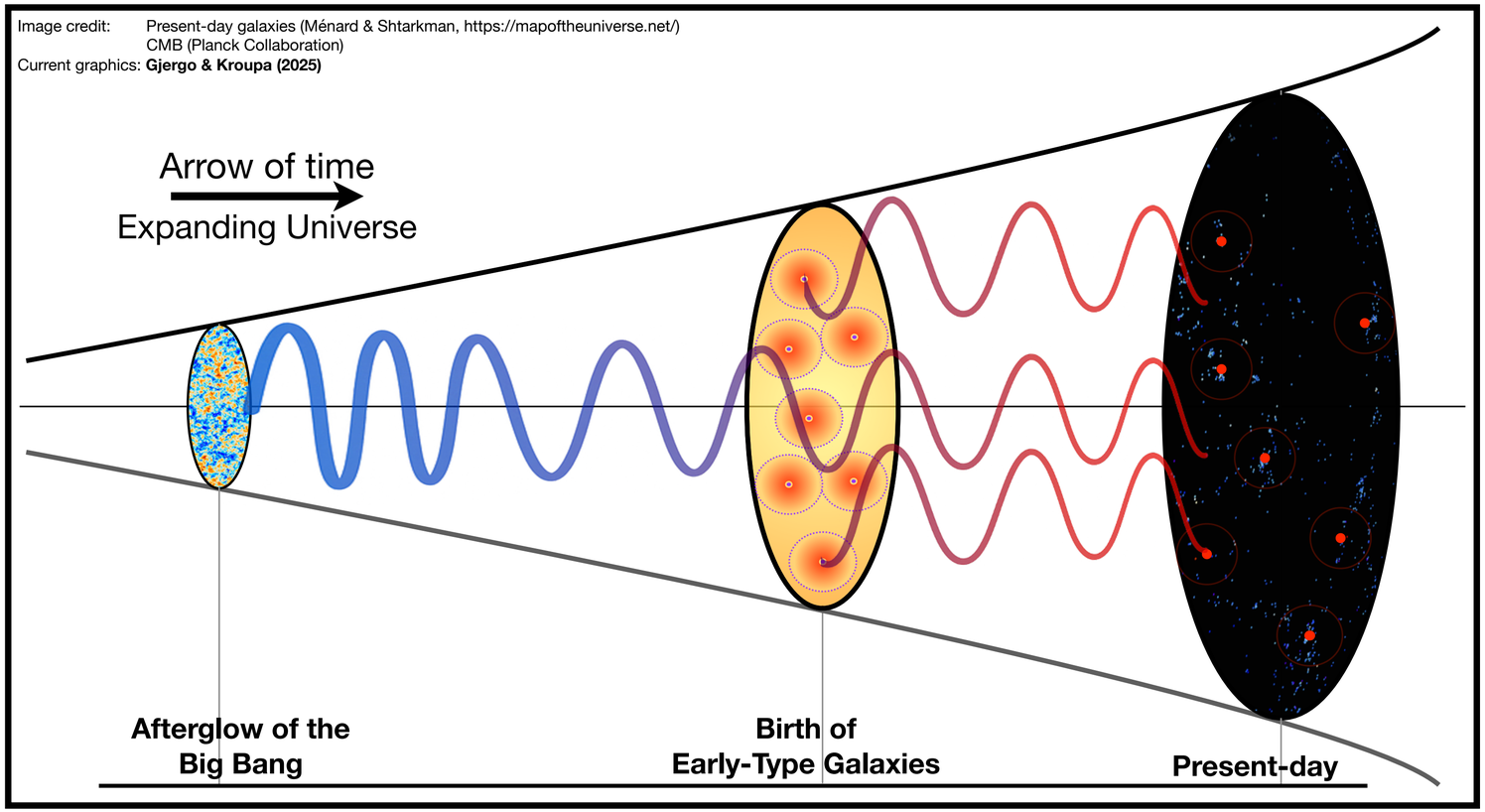
Pavel Kroupa: University of Bonn / Charles University

https://www.youtube.com/watch?v=zIUyg6KtKbs

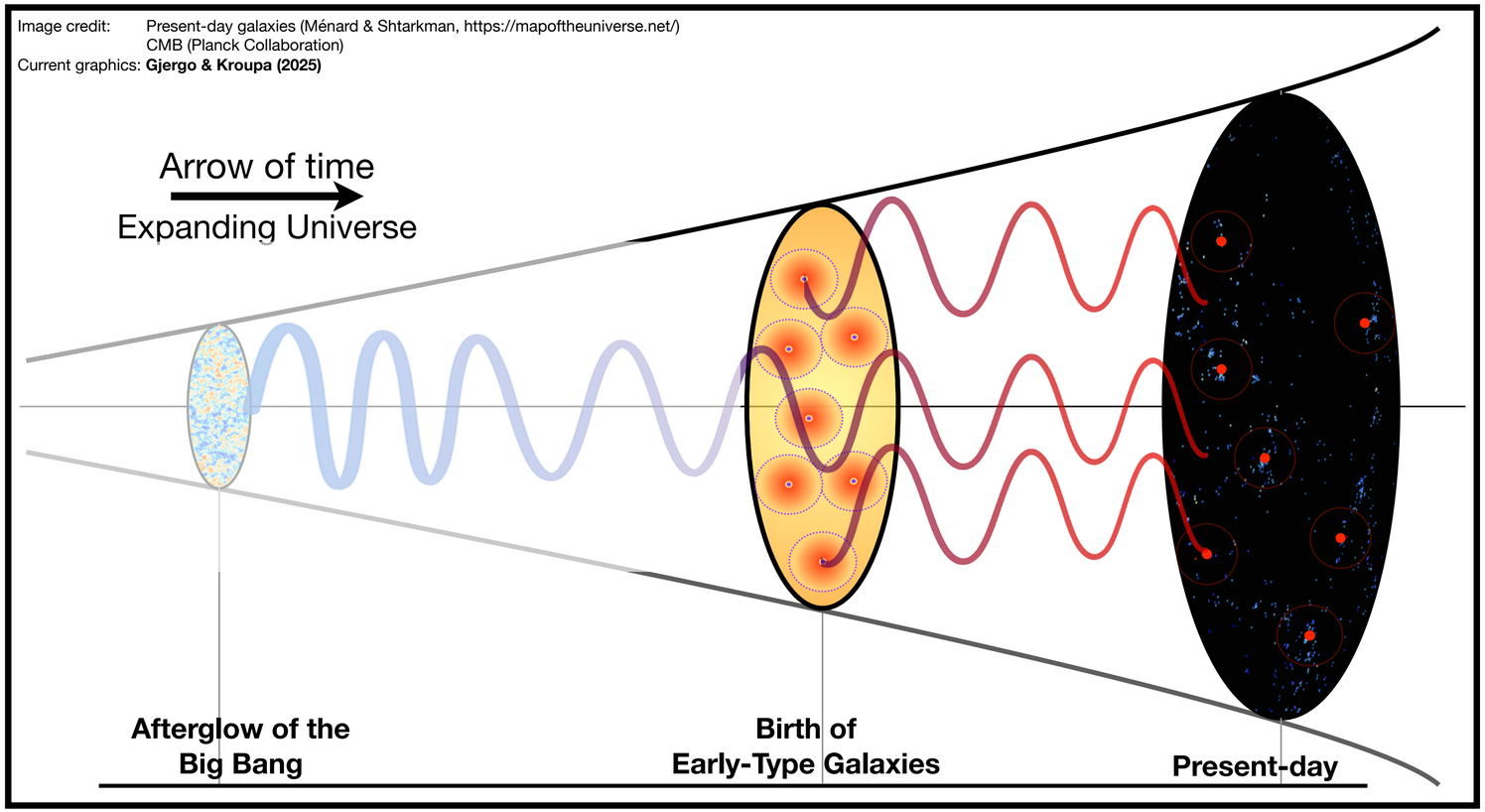


Gjergo & Kroupa (2025)


Every Tiny Color Spot on this Map is Temperature of Full Photon Spectrum
2.72500 K
2.72501 K
2.72501 K
2.72500 K
2.72500 K
2.72502 K
2.72502 K
2.72500 K
2.72500 K
2.72500 K
2.72501 K
20 microKelvin variations



Gjergo & Kroupa (2025)



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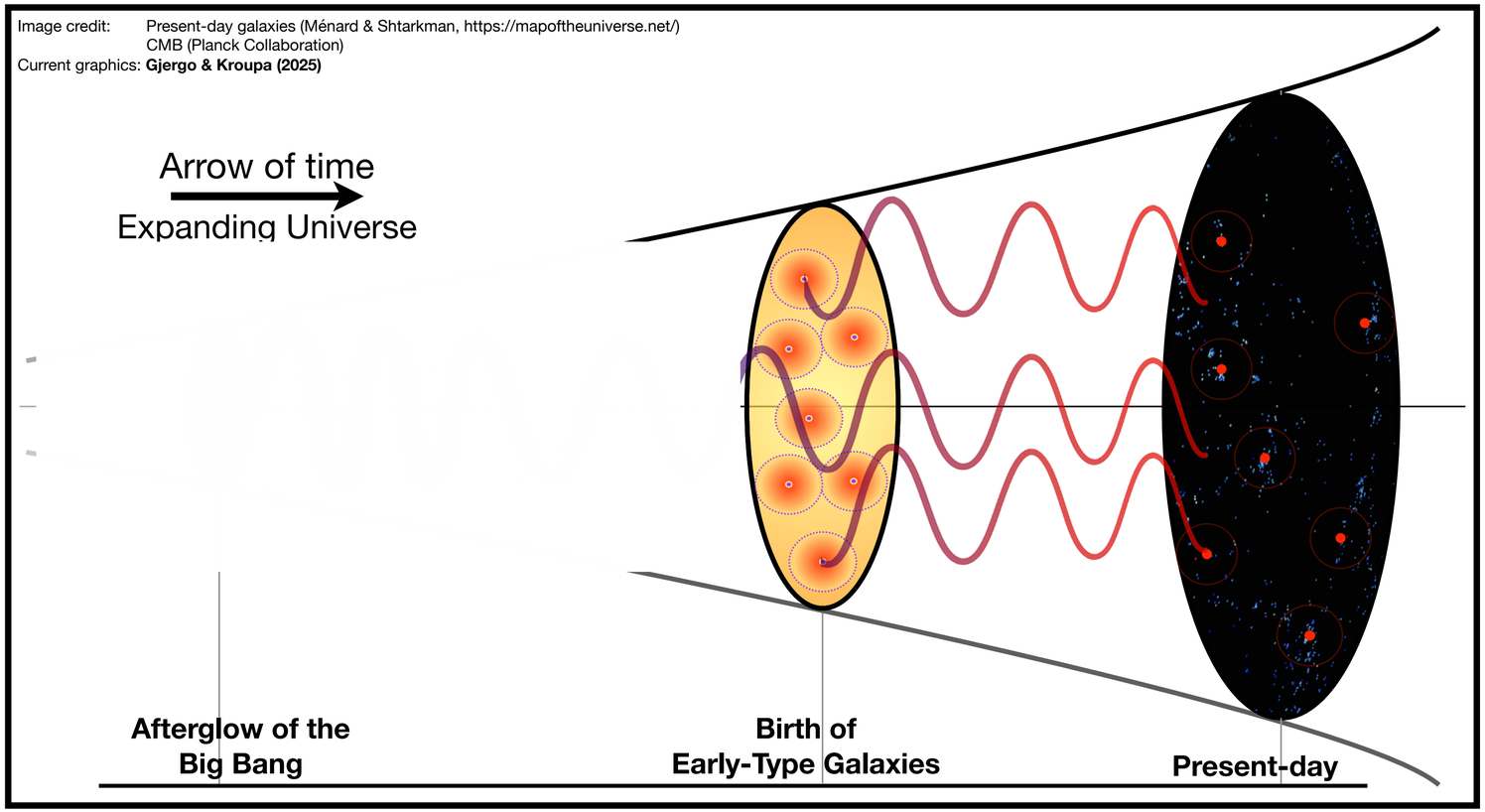

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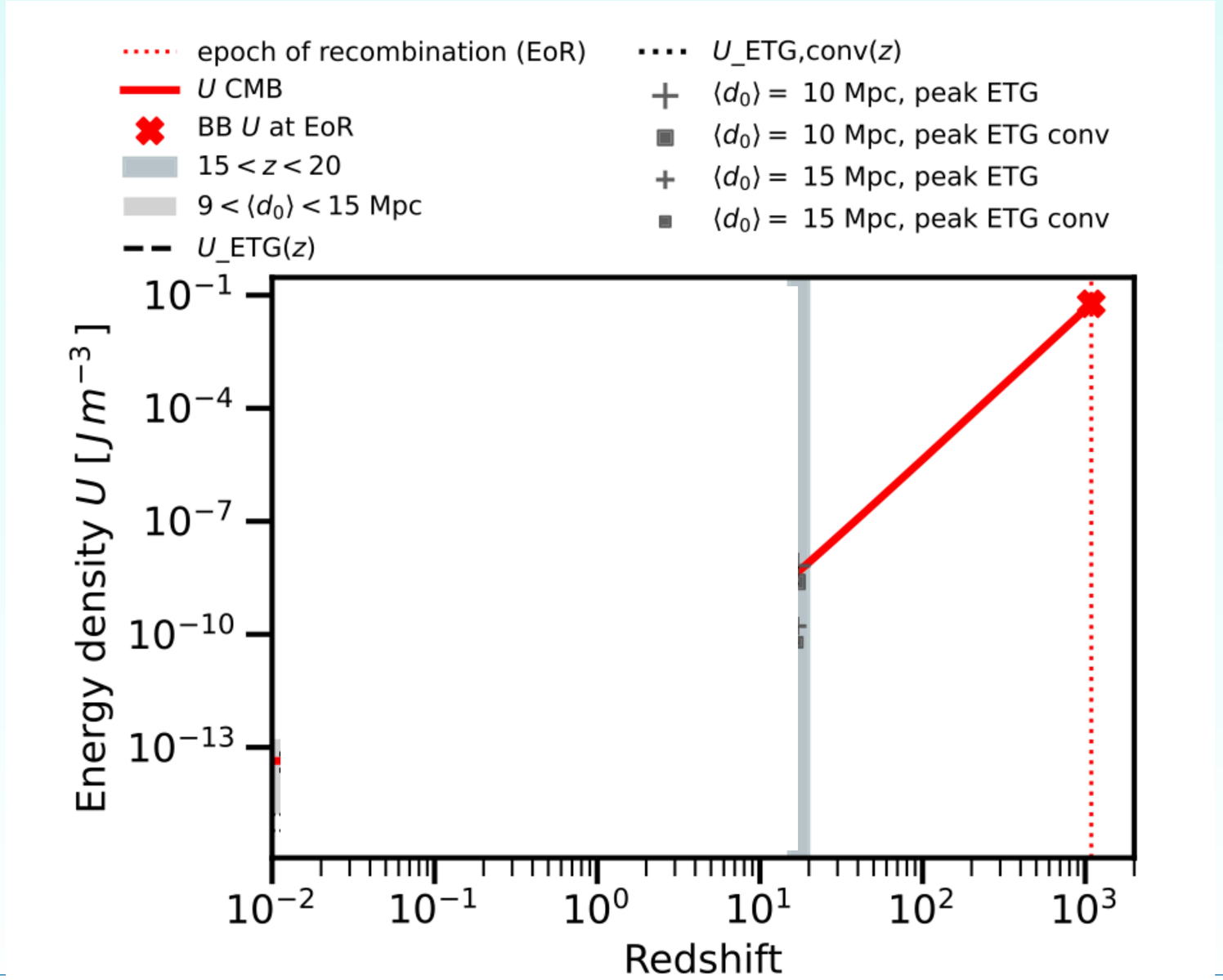
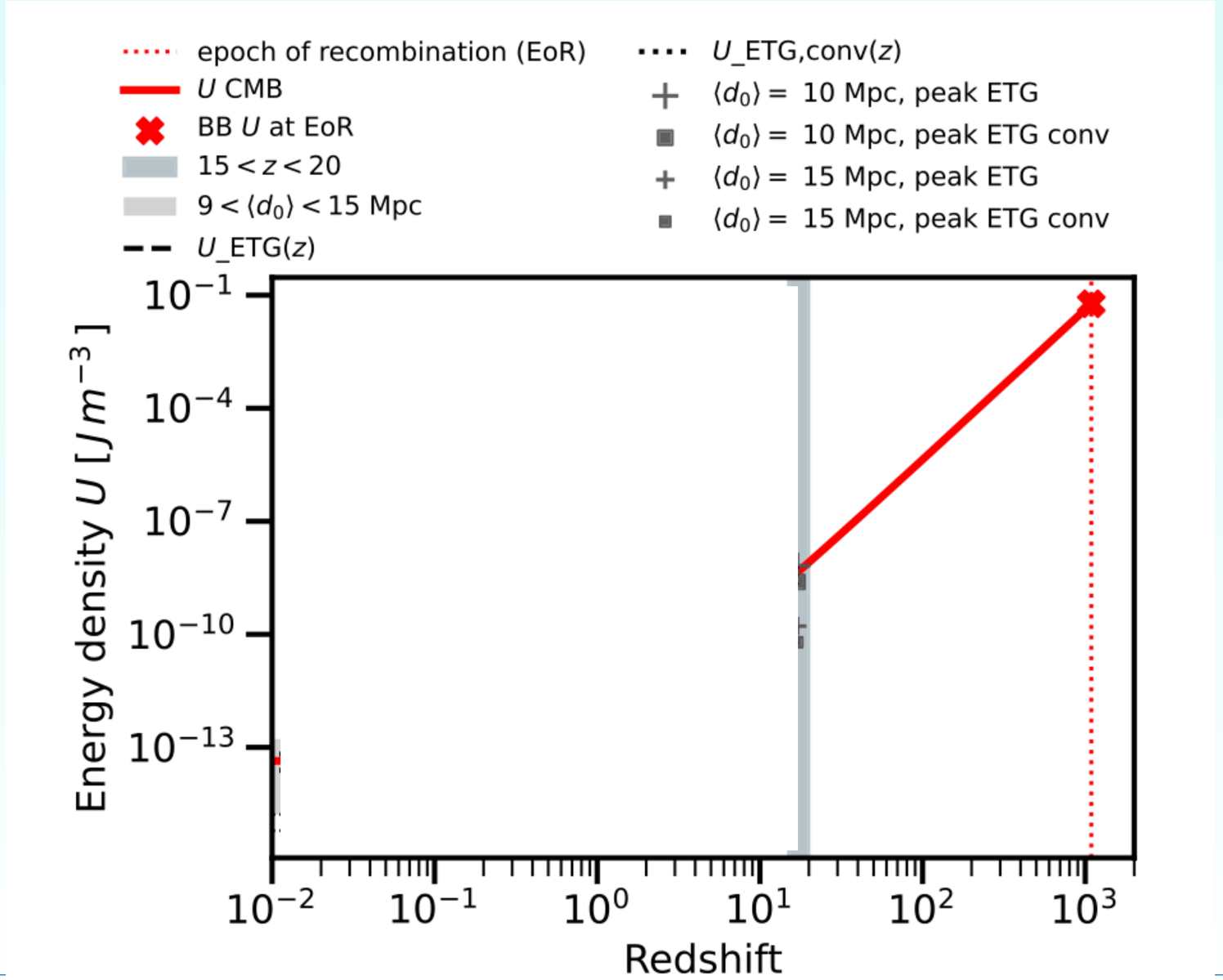


Gjergo & Kroupa (2025)

x Photosphere
of
Hot Big Bang



Gjergo & Kroupa (2025)

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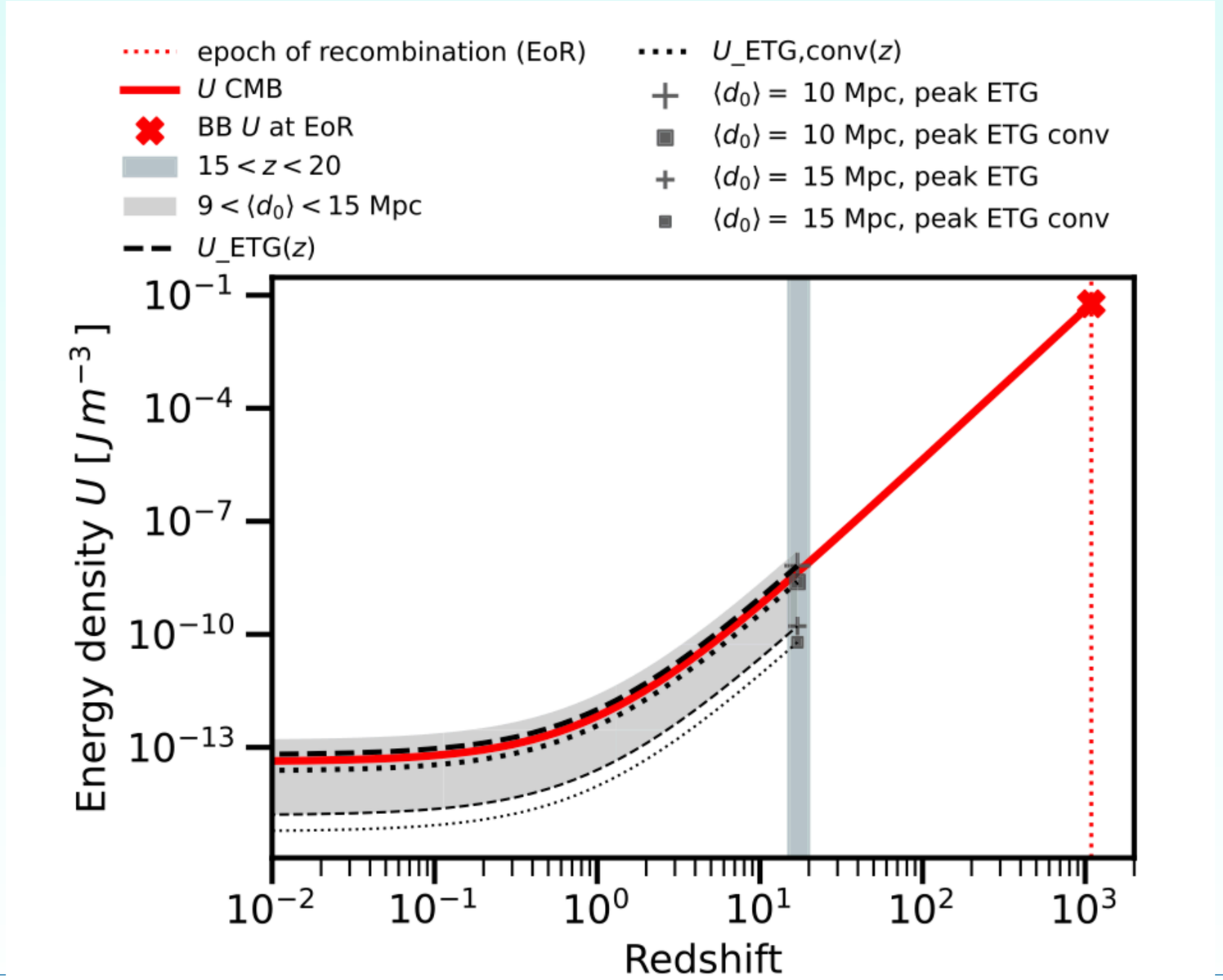
+ Elliptical galaxies form



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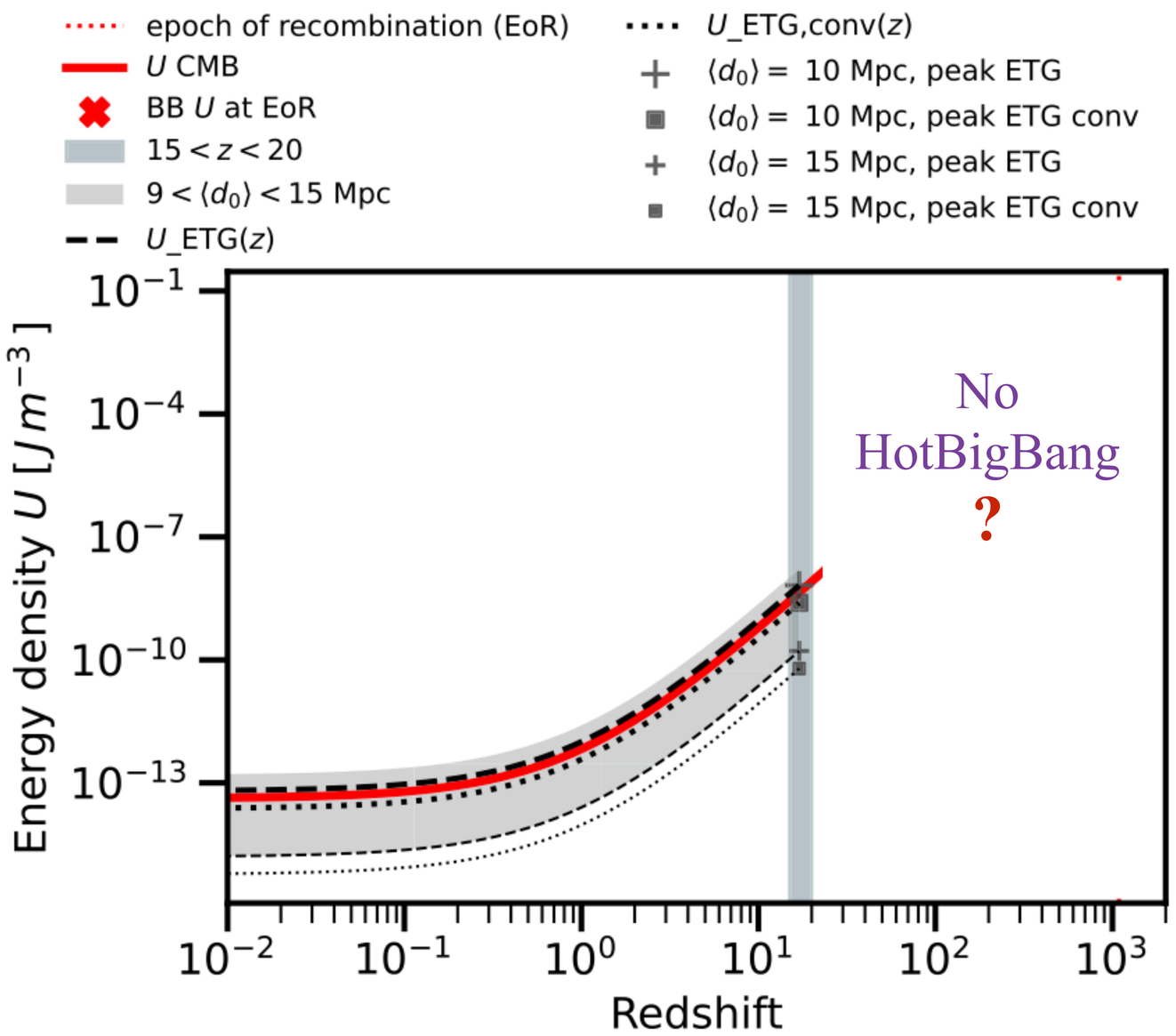

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