

Dark Stars in the JWST era

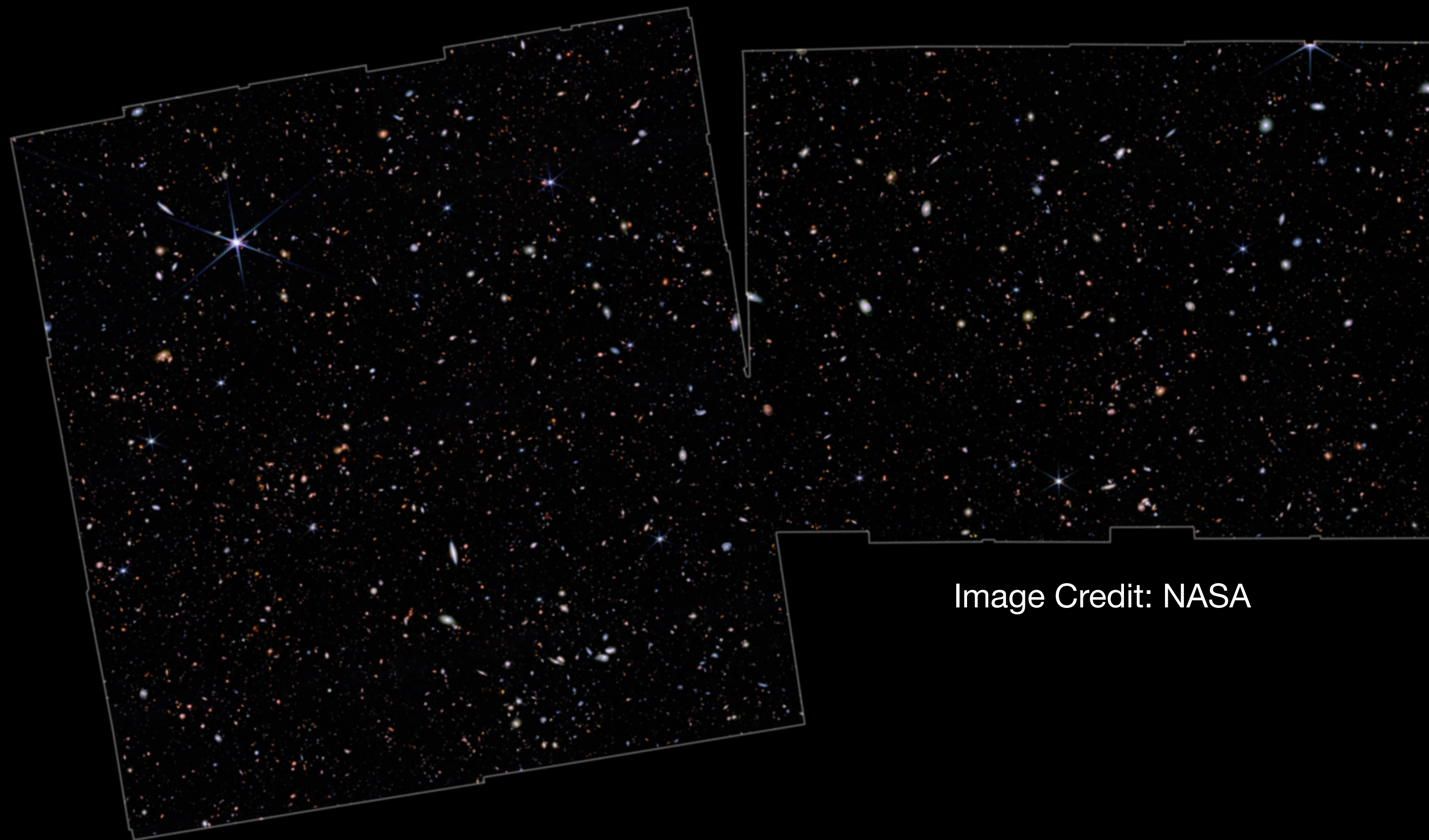
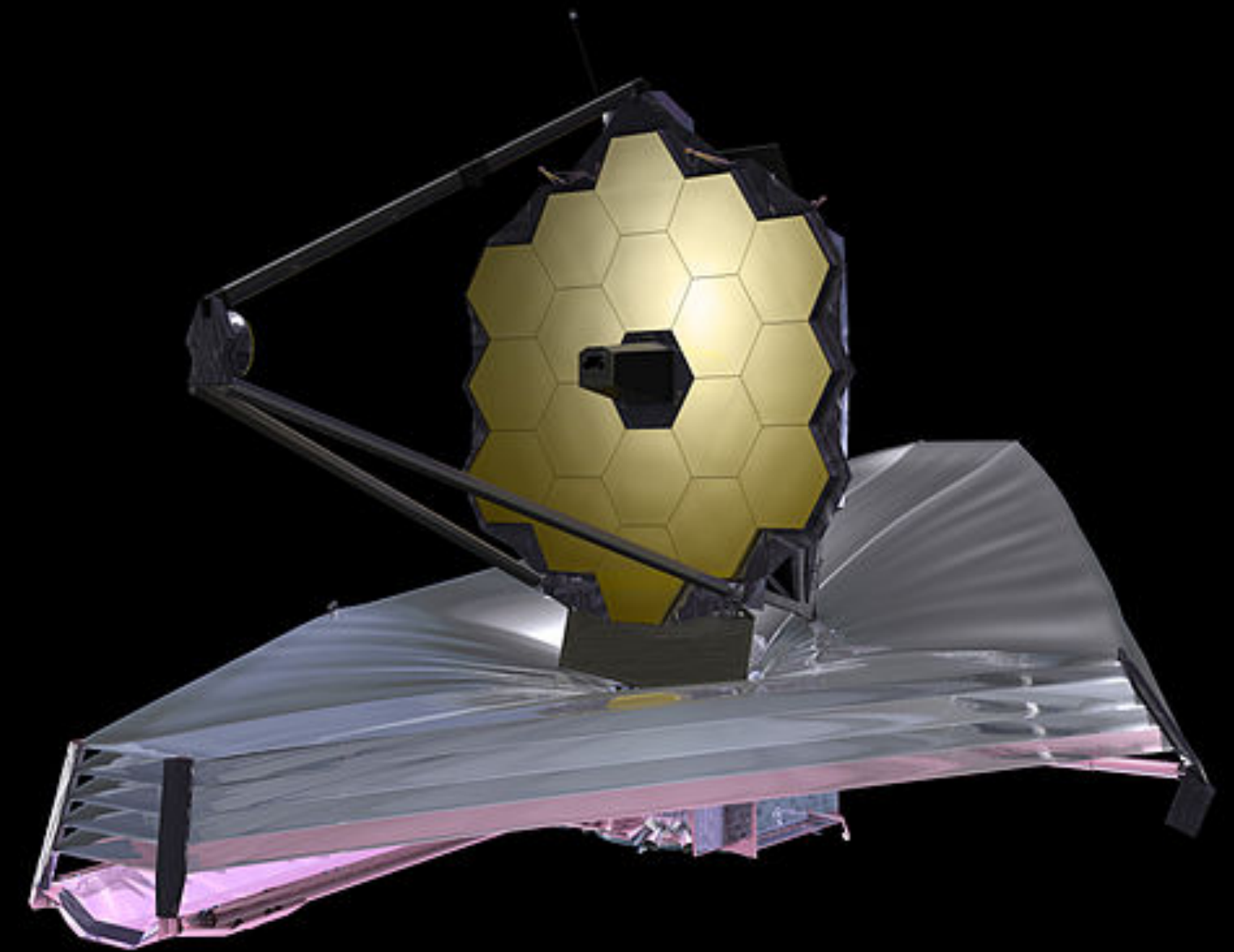


Image Credit: NASA



The first Stars, bird's-eye view

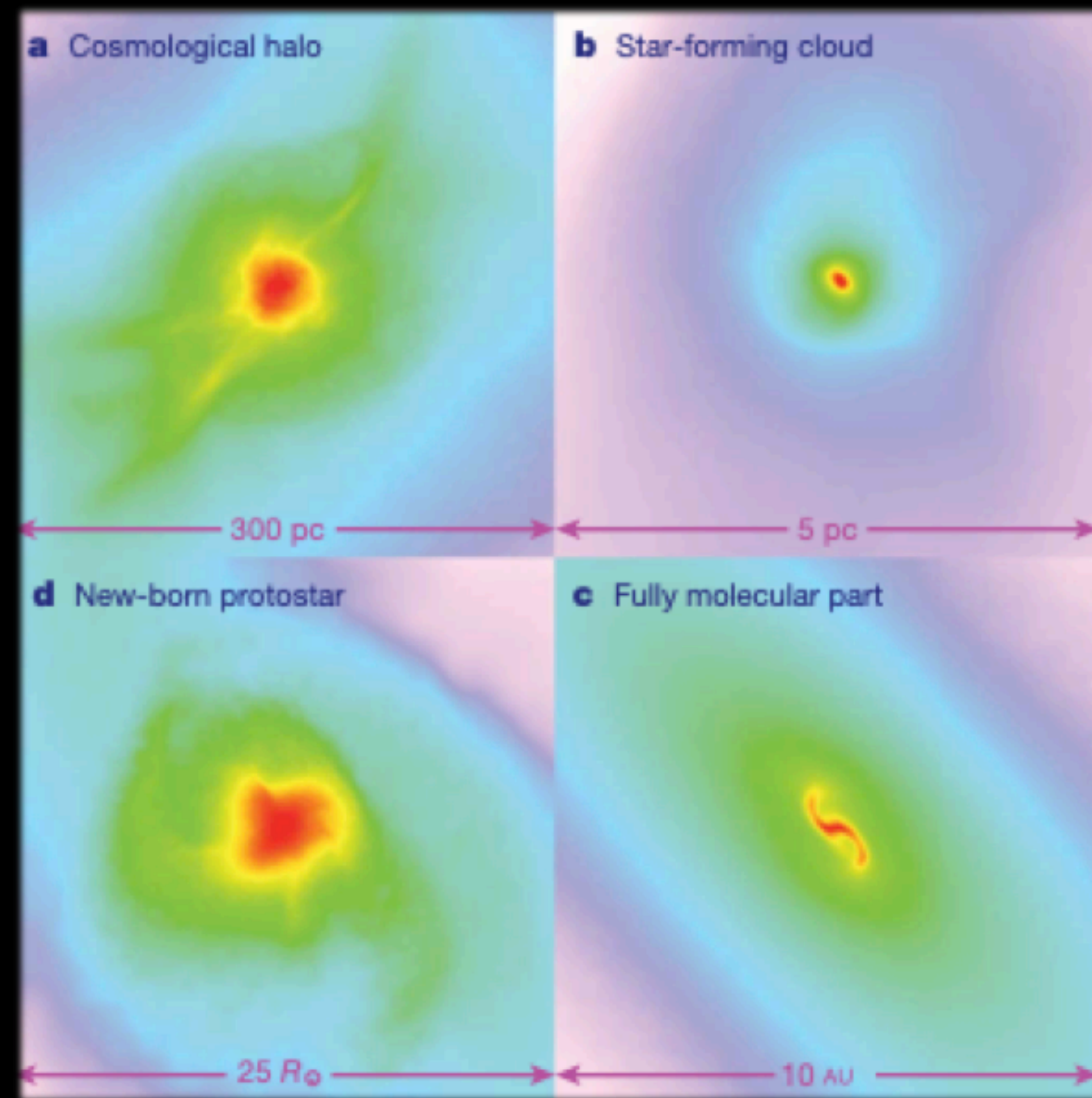


Figure From: Bromm et al. Nature 459 (2009)

- The form at high redshift ($z \sim 10-40$) from pristine BBN H and He gas
- In very DM rich environments, at the center of DM microhalos
- Usually in isolation, or with few companions

The first Stars, bird's-eye view

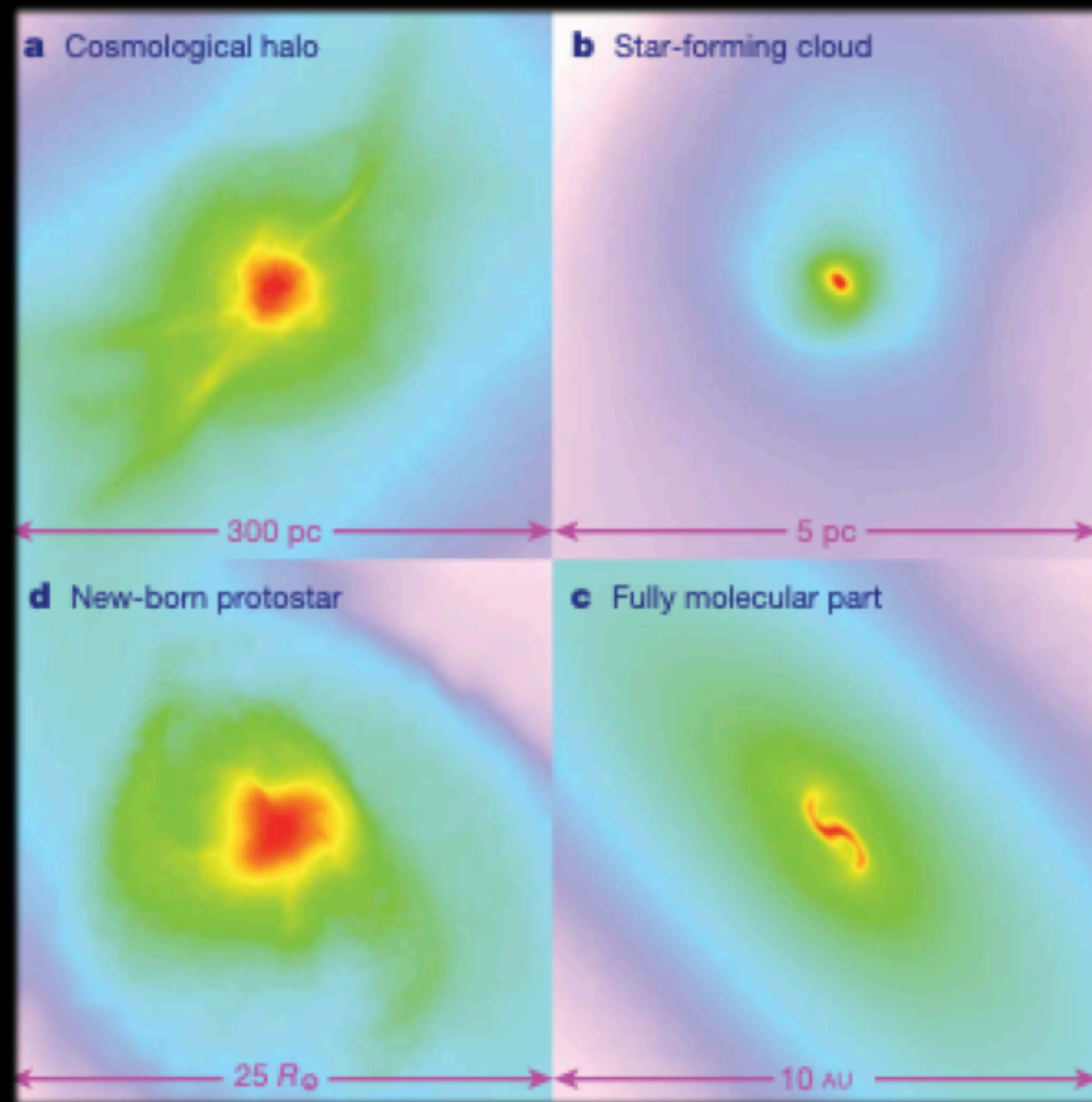
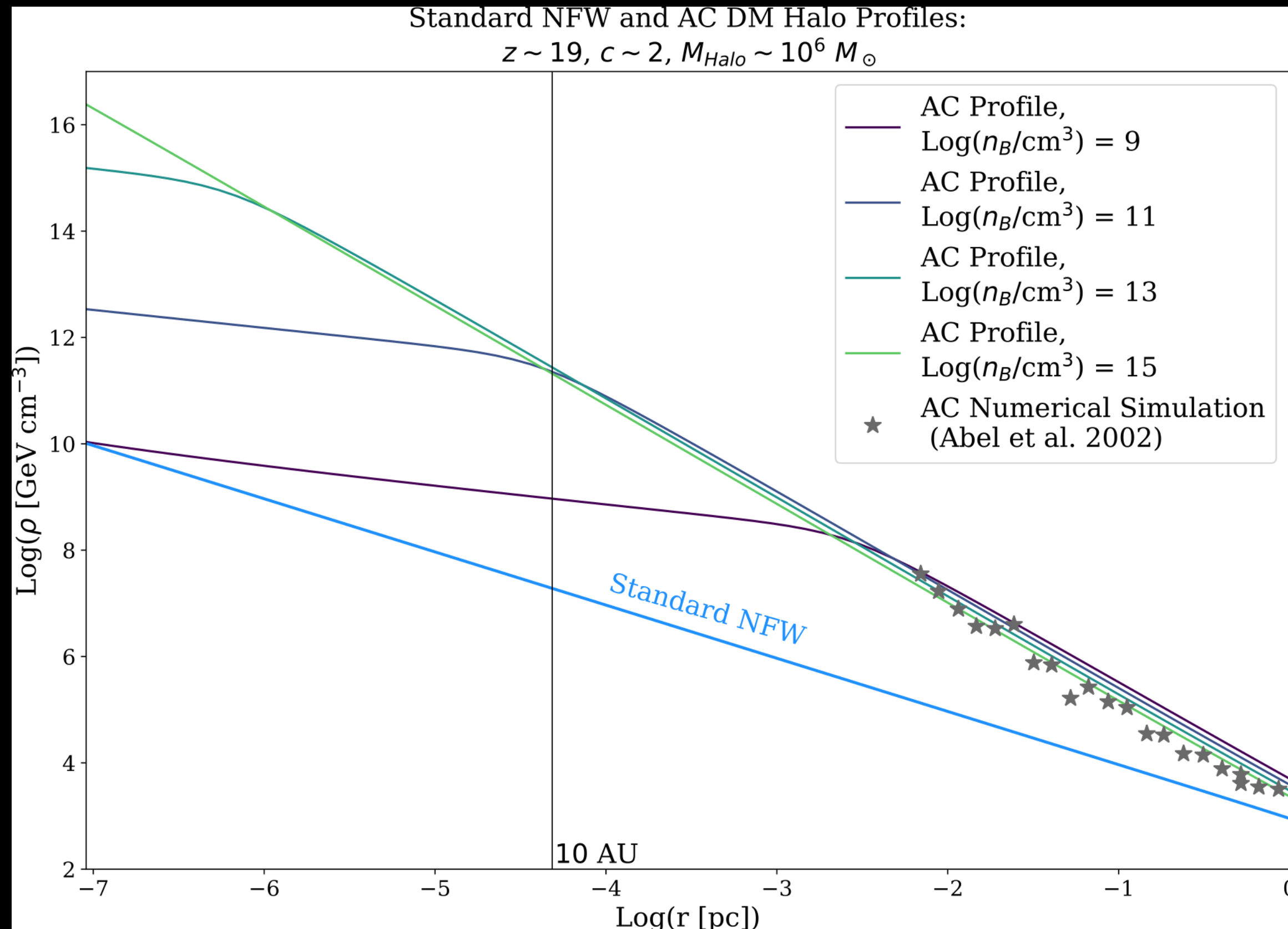


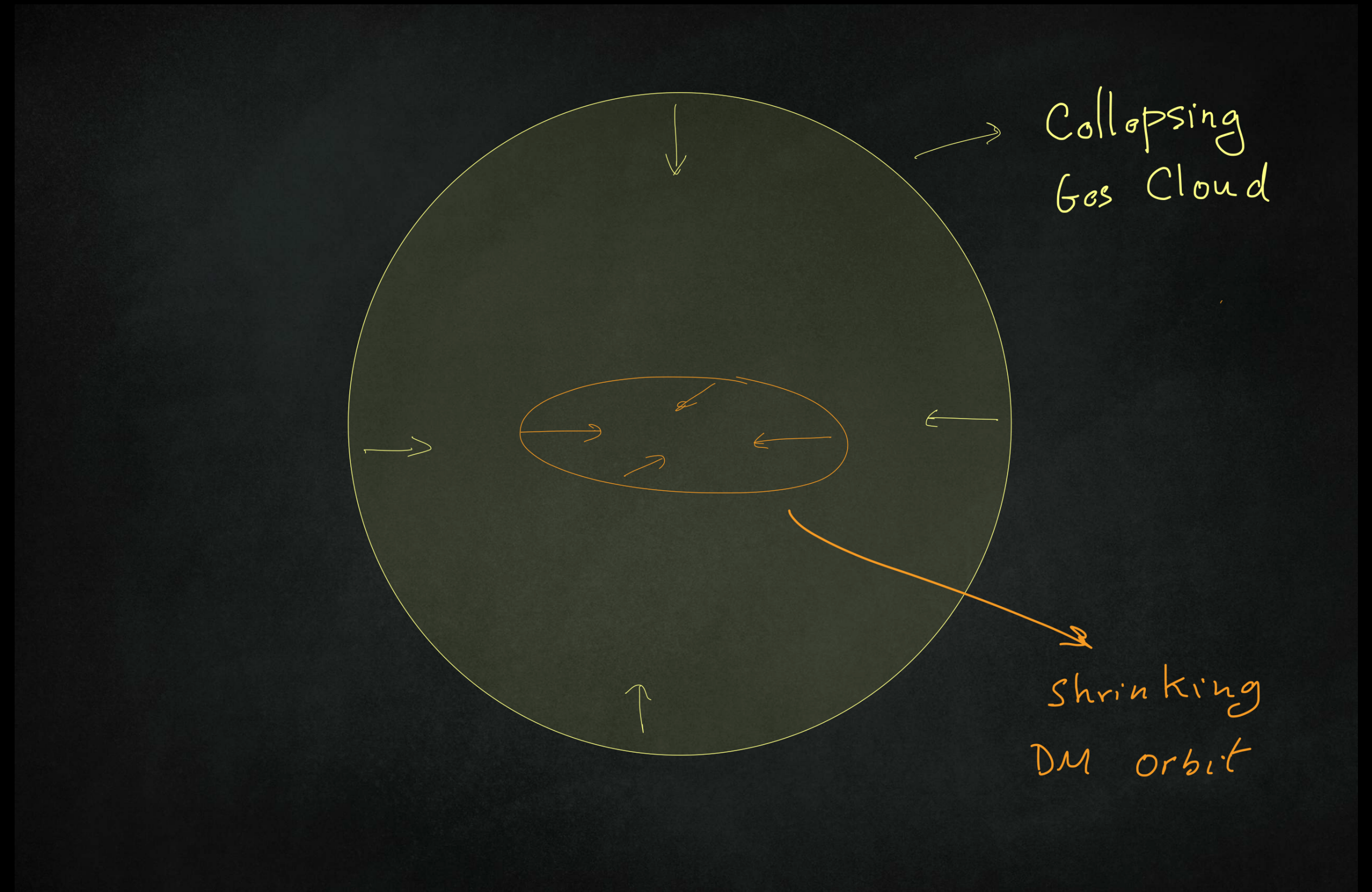
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- In very DM rich environments, at the center of DM microhalos
- Usually in isolation, or with few companions
- They can grow as massive as $1000M_{\odot}$ (Population III aka PopIII stars: zero metallicity stars powered by H fusion)

DM Densities enhancement: Adiabatic Compression



Blumenthal AC formalism vs Abel et al Science (2002) Simulation



The first Stars, bird's-eye view

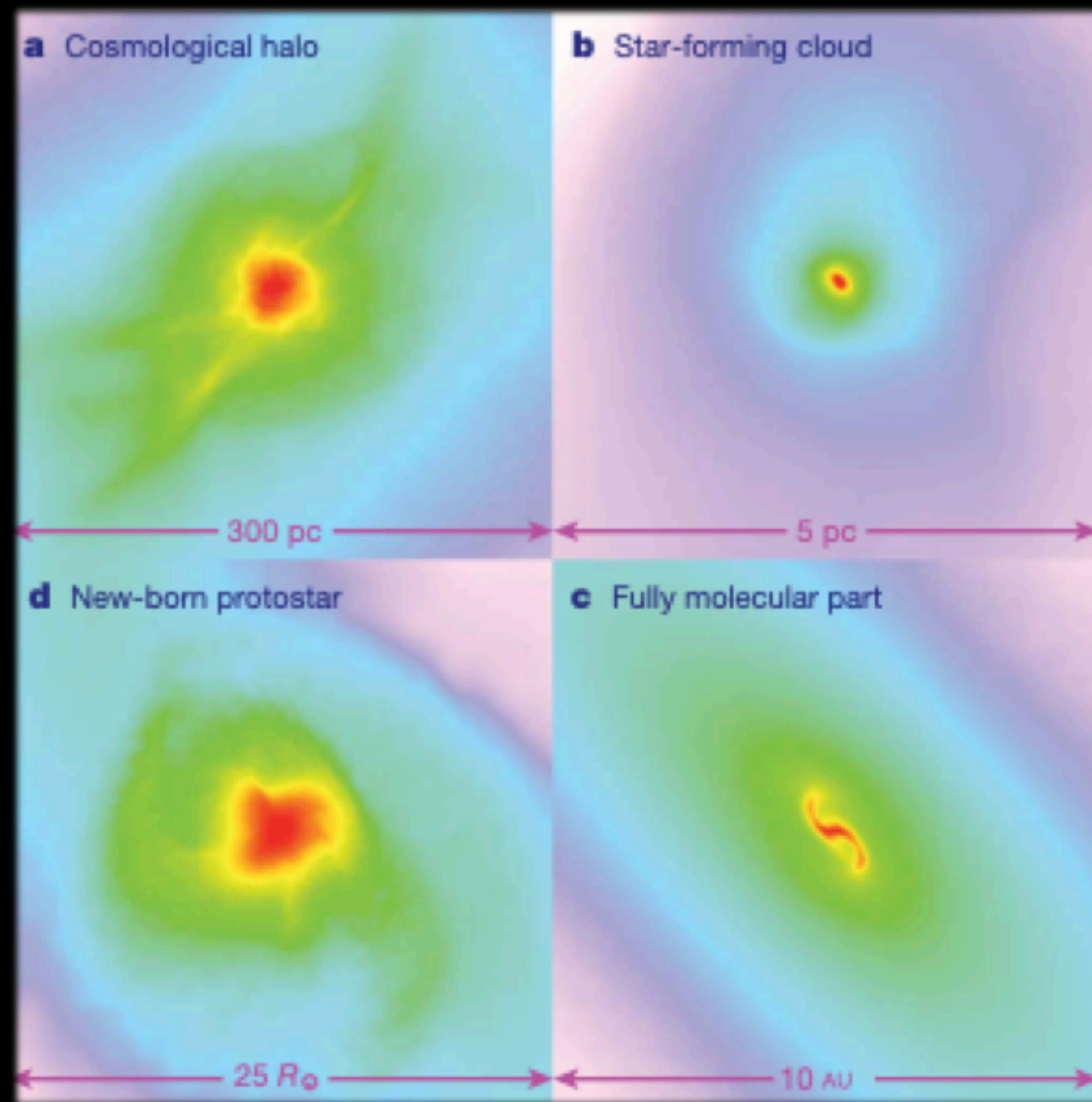


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- In very DM rich environments, at the center of DM microhalos
- Usually in isolation, or with few companions
- DM annihilations can lead to formation of **Dark Stars (DS) powered solely by DM annihilations** [Spolyar, Freese, Gondolo PRL 2007]
- Note: Dark Stars are sometimes called PopIII.1 Stars (i.e. Banik et al. 2019 etc)

The three conditions for the formation of a Dark Star

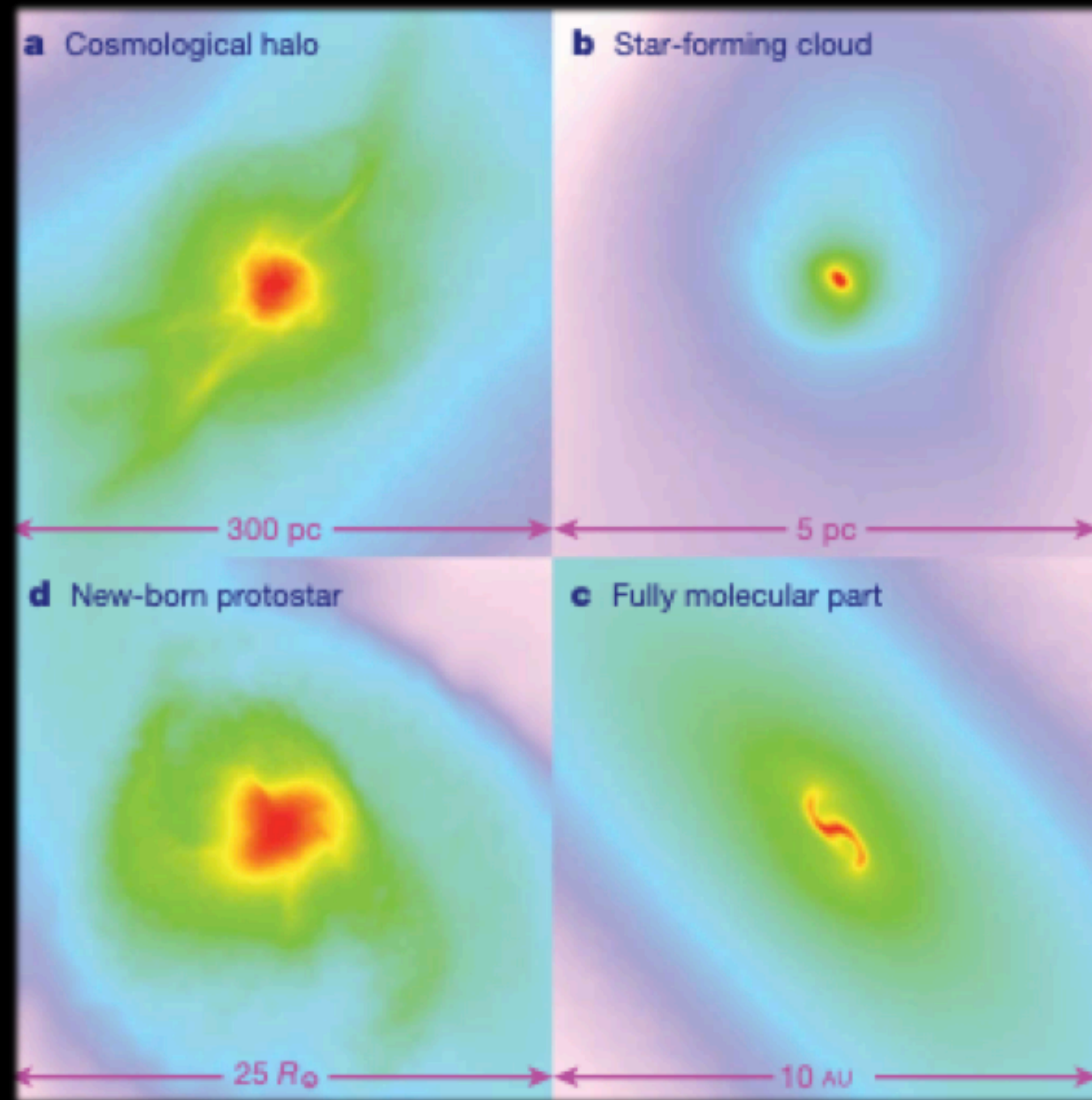
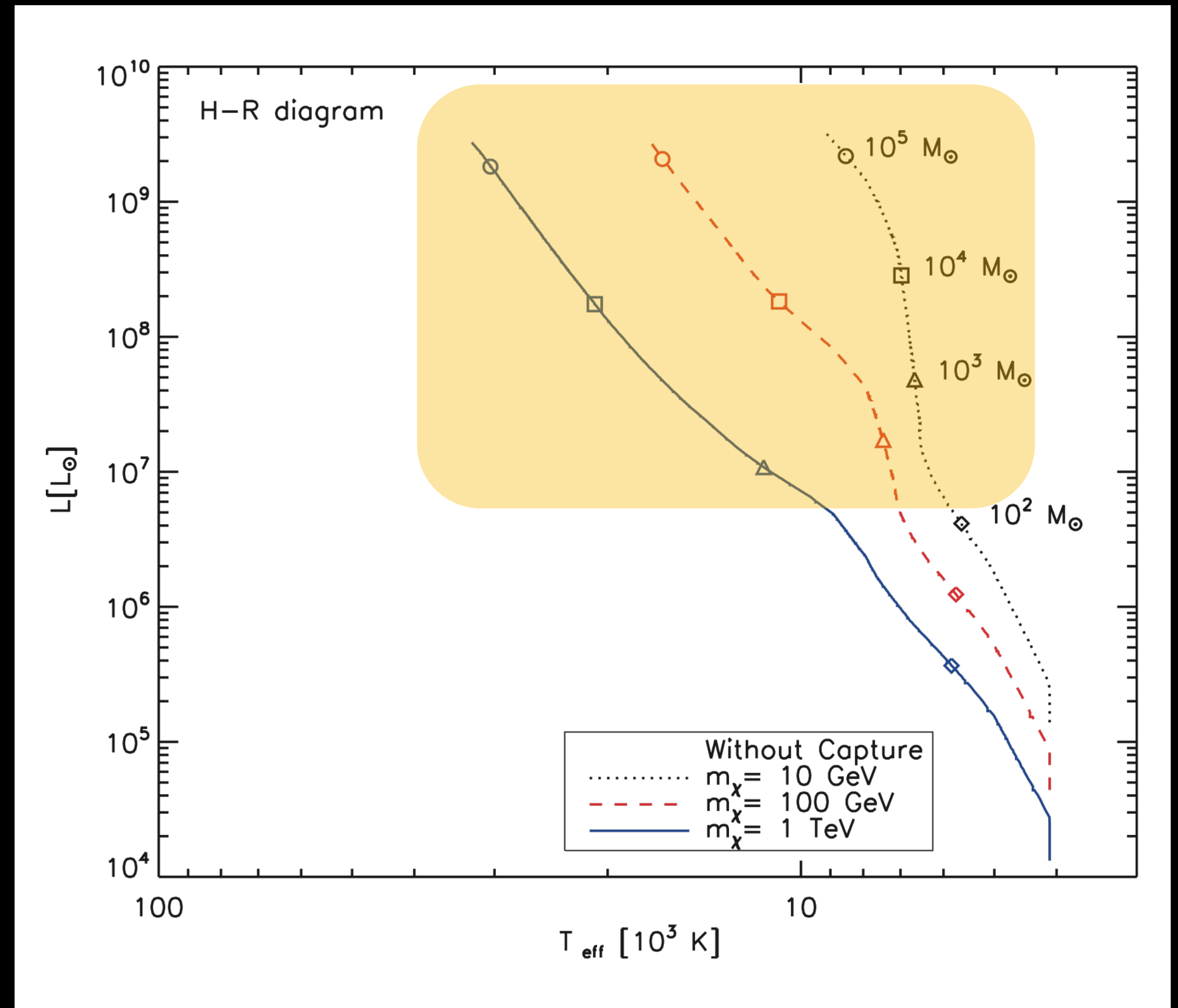


Figure From: Bromm et al. Nature 459 (2009)

- Sufficiently high DM densities
- Poor cooling mechanisms for the collapsing molecular cloud
- DM annihilation products can thermalize efficiently with the baryons in the cloud

Growth of DS to Supermassive Status: via **Extended AC**

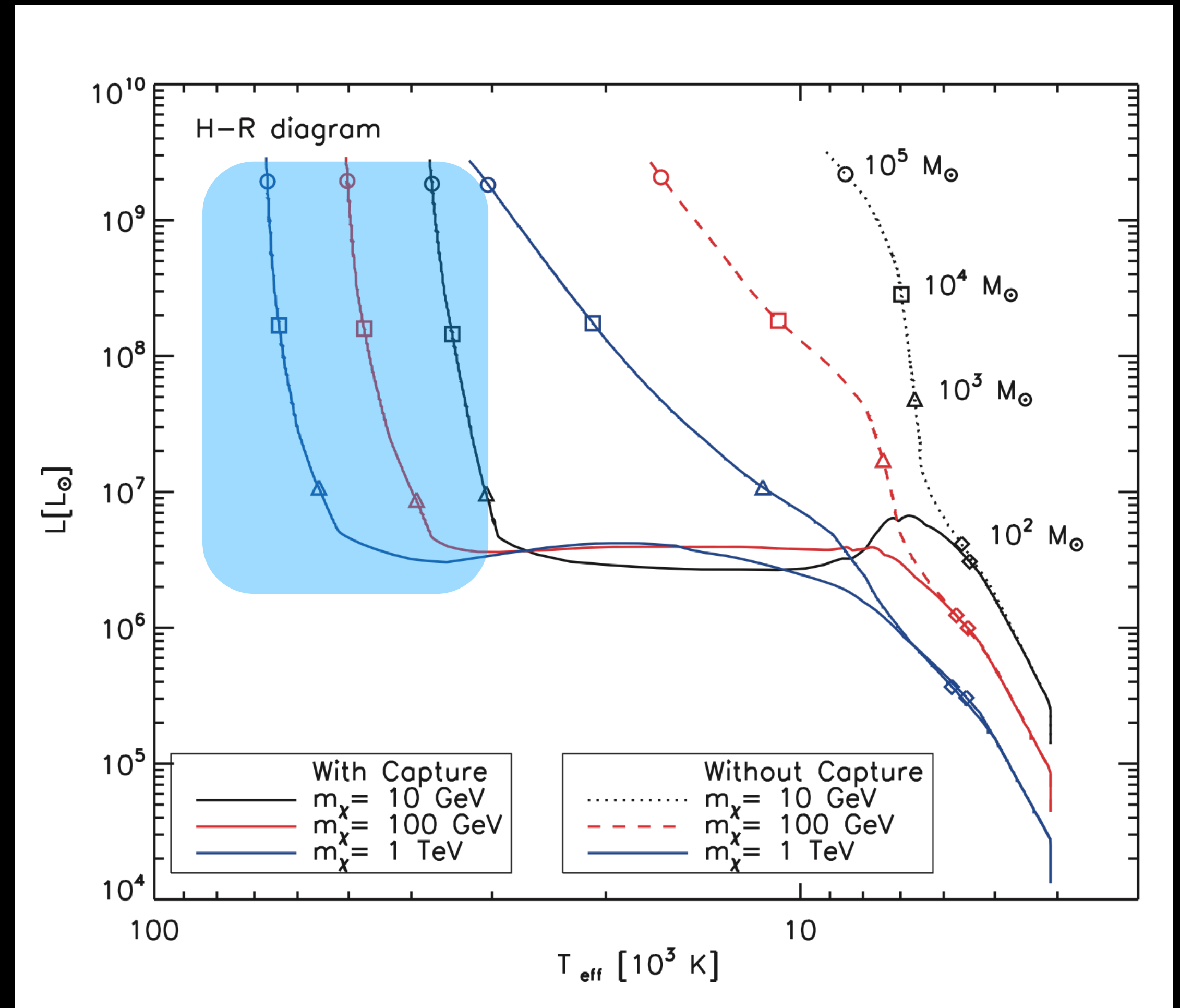
- In triaxial DM halos (expected from simulations) a large population DM orbits are centrophilic (chaotic and box orbits)
- Those orbits can continue to supply DM to provide a heat source for the DS for a prologued time
- DS growing via accretion inside a $10^6 M_\odot$ DM halo to reach $M_{SMDS} \sim 10^5 M_\odot$



Freese, CI, Spolyar, et al. 2010 ApJ

Growth of DS to Supermassive Status: via **DM capture**

- If DM interacts with baryons inside a star it can get trapped (Captured)
- Same basic physics as that exploited by Direct Detection experiments: elastic collisions of DM with nuclei
- Blue shaded region from plot on Right for the assumes:
 $\rho_\chi \sigma = 10^{14} \text{GeVcm}^{-3} \times 10^{-40} \text{cm}^2$



Freese, CI, Spolyar, et al. 2010 ApJ

The Fate of Supermassive Dark Stars

- Collapses to SMBH if the DS is dislodged (via mergers for example) from the center of the host halo
- Collapses to SMBH if central density is sufficiently high, triggering GR instabilities

$$\rho_{\text{crit}} \approx 3.98 \left(\frac{0.59}{\mu} \right)^3 \left(\frac{10^5 M_{\odot}}{M} \right)^{7/2} \text{ g cm}^{-3},$$

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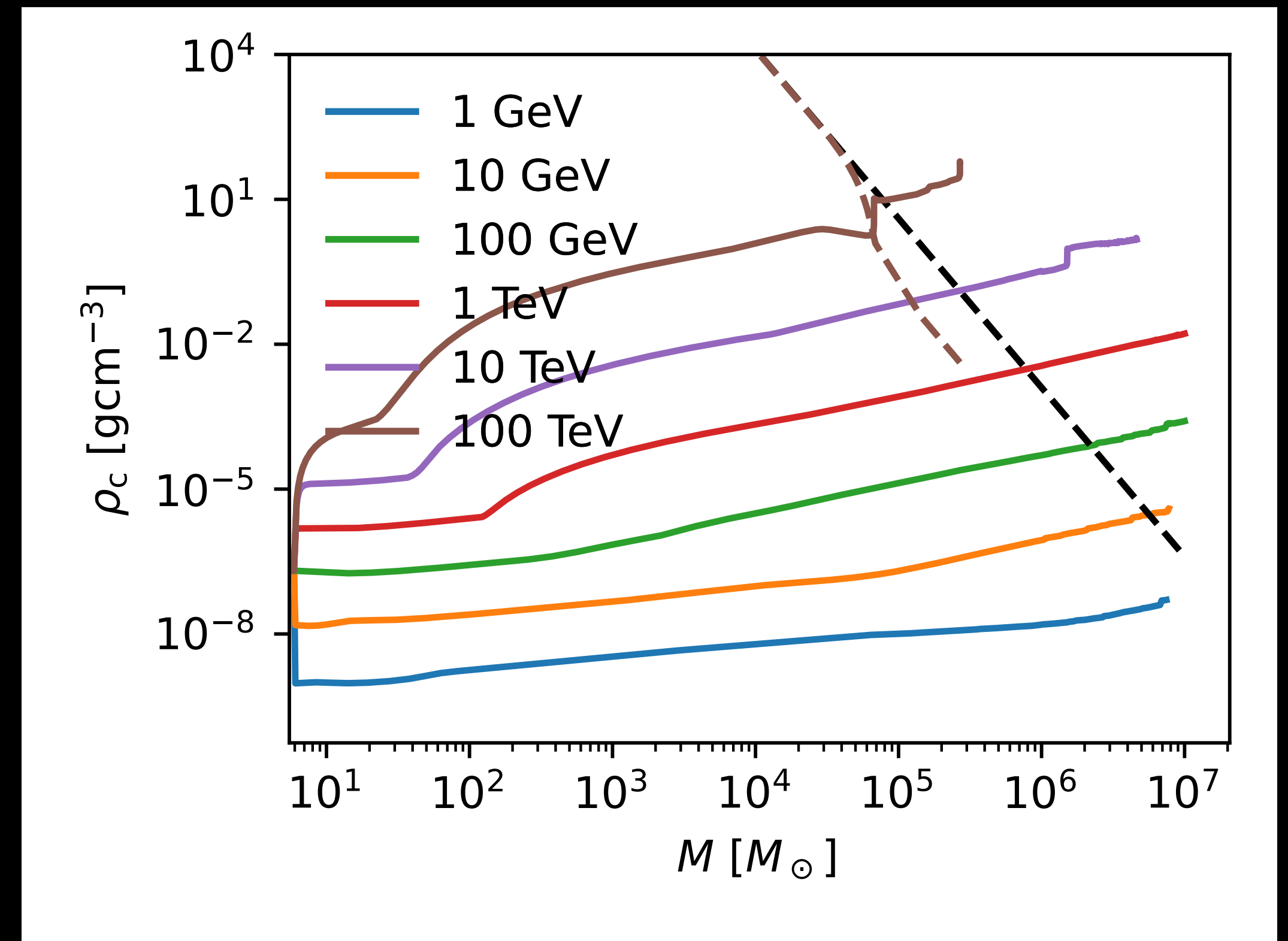


Fig from 2511.08578 Freese, Cl, +

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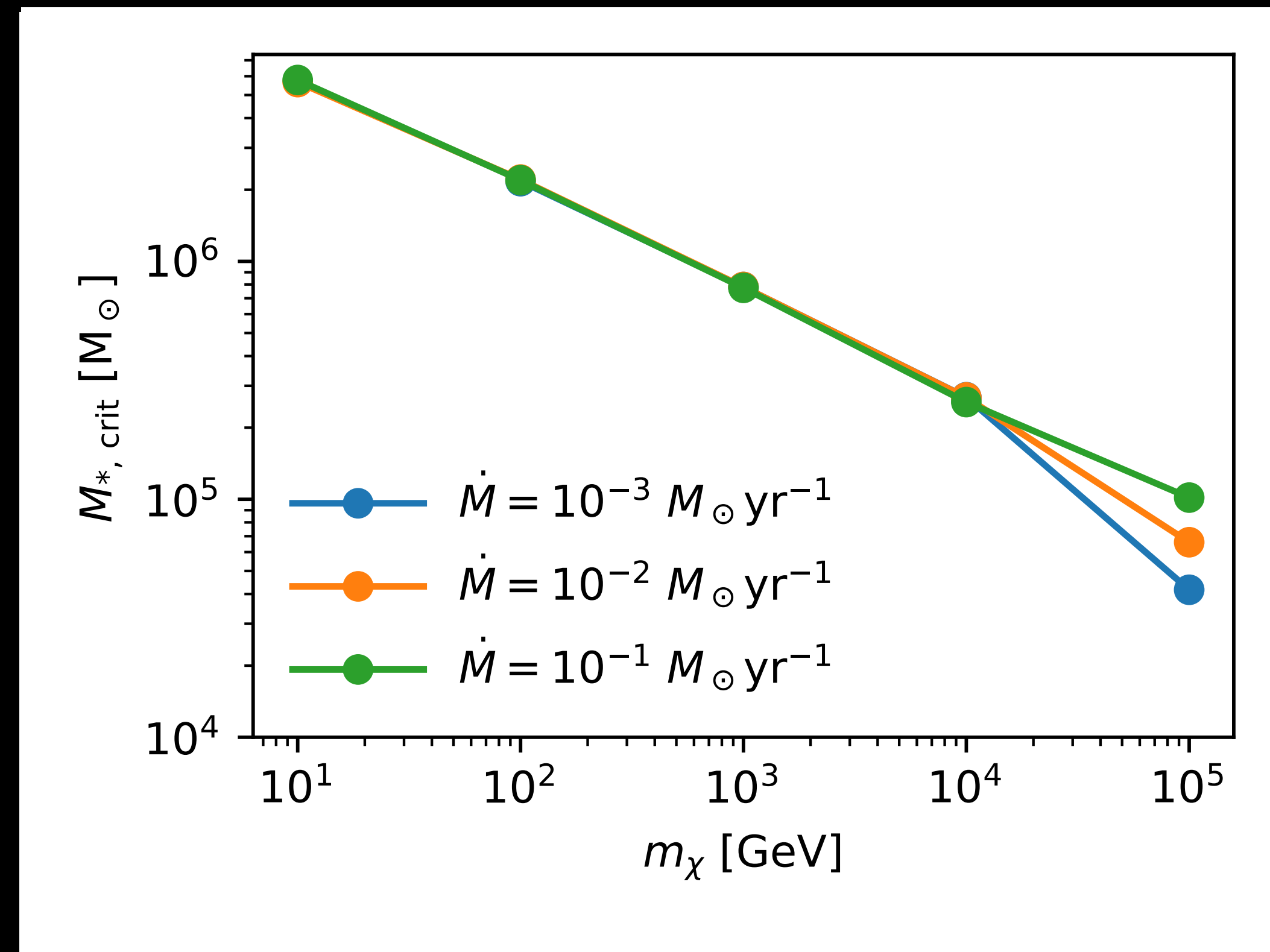
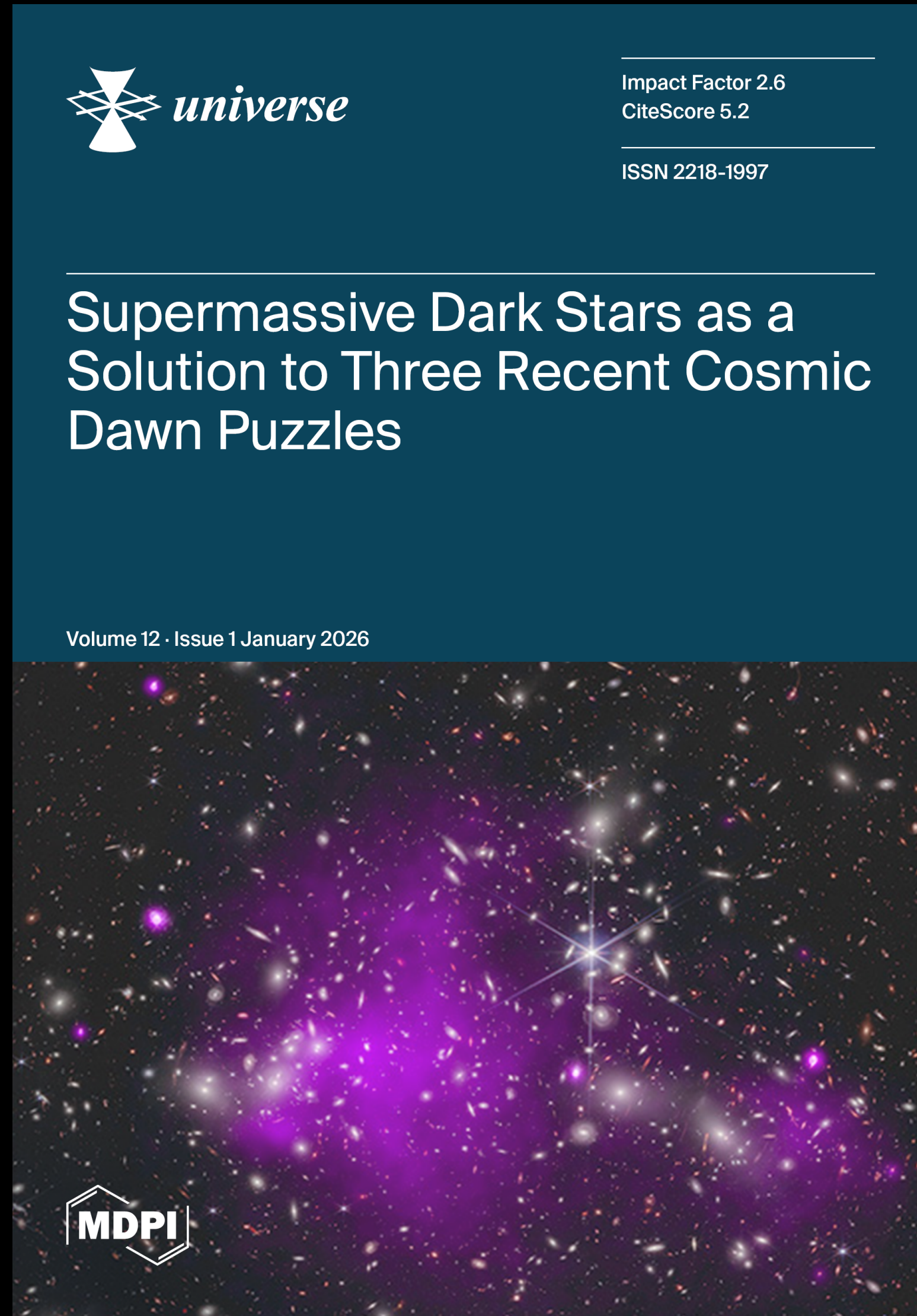


Fig from 2511.08578 Freese, Cl, +

Observational puzzles **SMDS** can solve



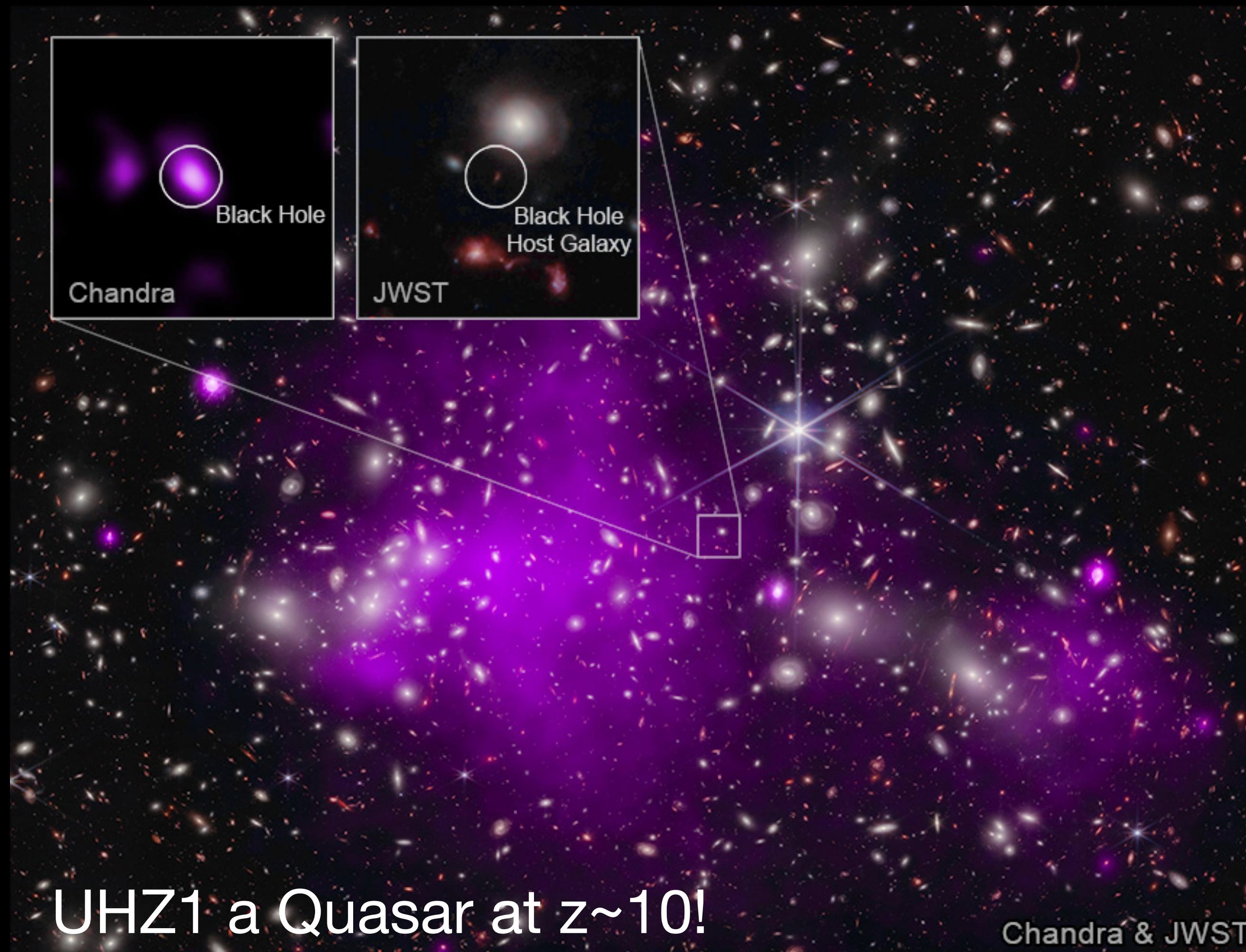
2511.08477 Cl et al. Universe 12 (1) 2026

I. Seeds for the many SMBHs observed too early in the Universe (in the first billion years after the BB)

II. Little Red Dots

III. Blue Monster Galaxies

Observational puzzle I. **SMDS** can solve: Seeds for SMBHs



- The many Supermassive Black Holes powering observed quasars at $z > 6$ for which either a **heavy seed** is necessary, or sustained Super Eddington Accretion.

Observational puzzle II. **SMDS** can solve: Little Red Dots

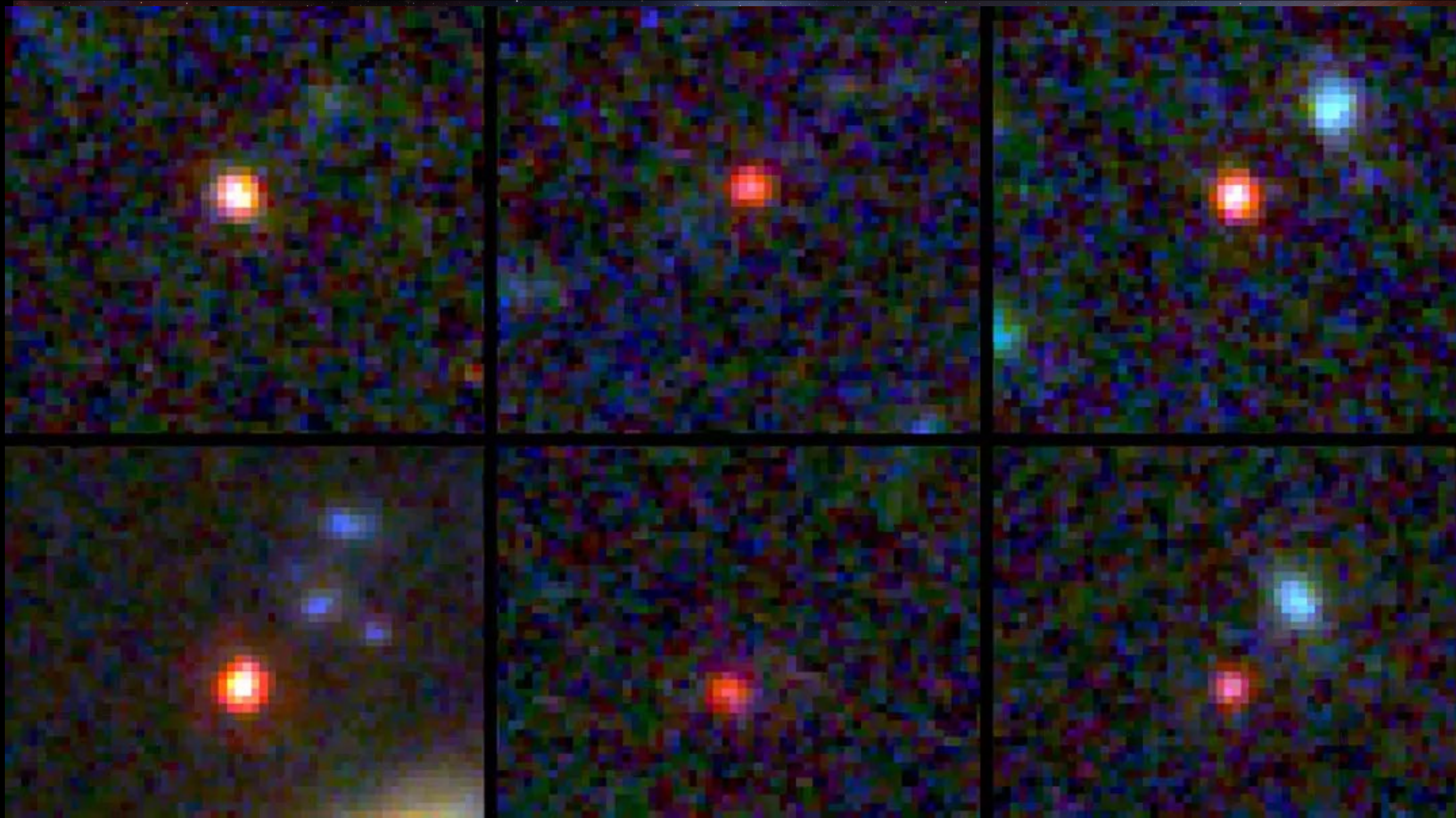


Image Credit: NASA/JWST/STScI

- A large population of JWST galaxies are very compact
- Show as red dots
- Do not have X-ray emissions
- Spectrum has a characteristic V-shape
- Spectral analysis show very little metallicity

Observational puzzle II. **SMDS** can solve: Little Red Dots

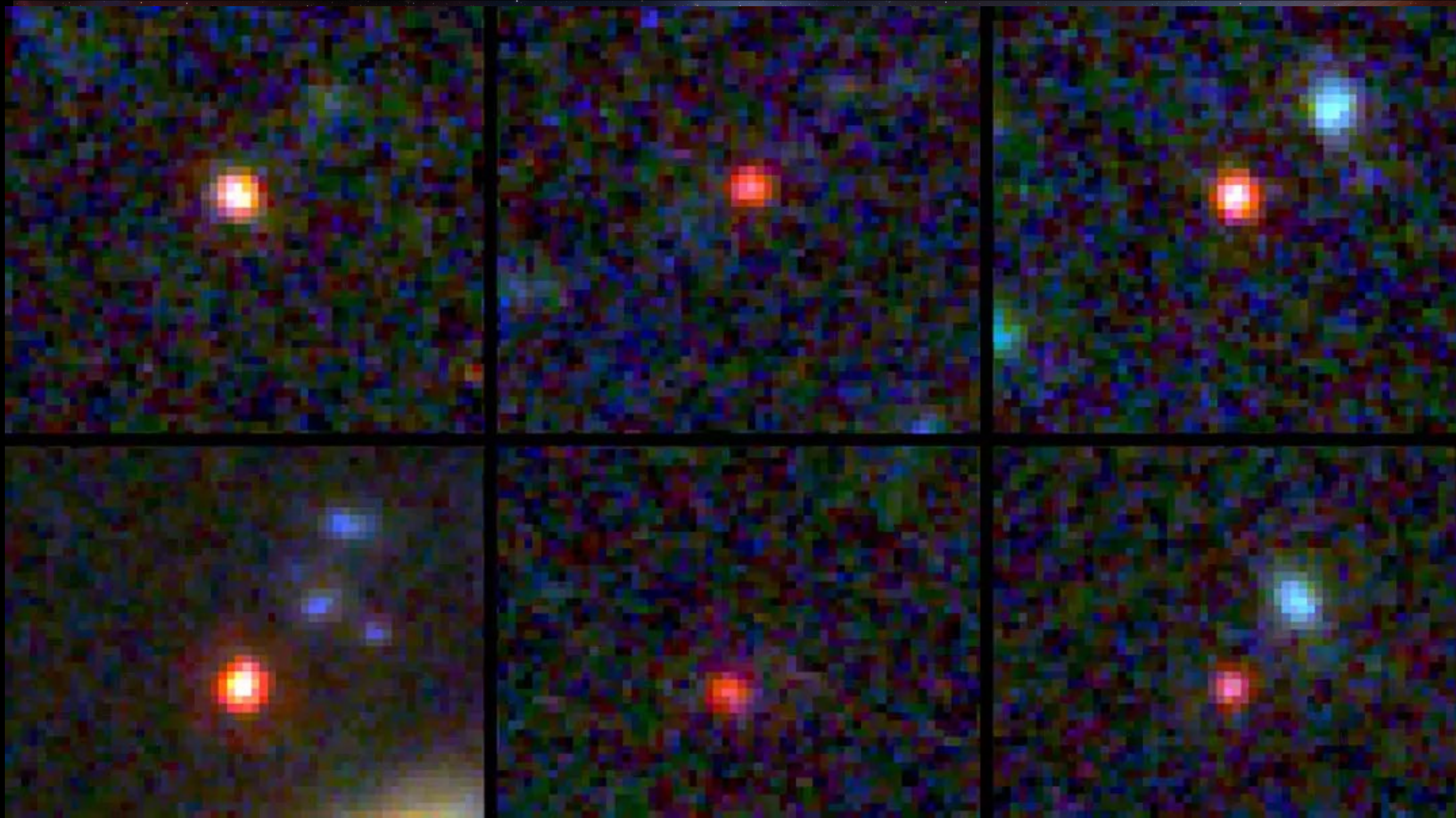
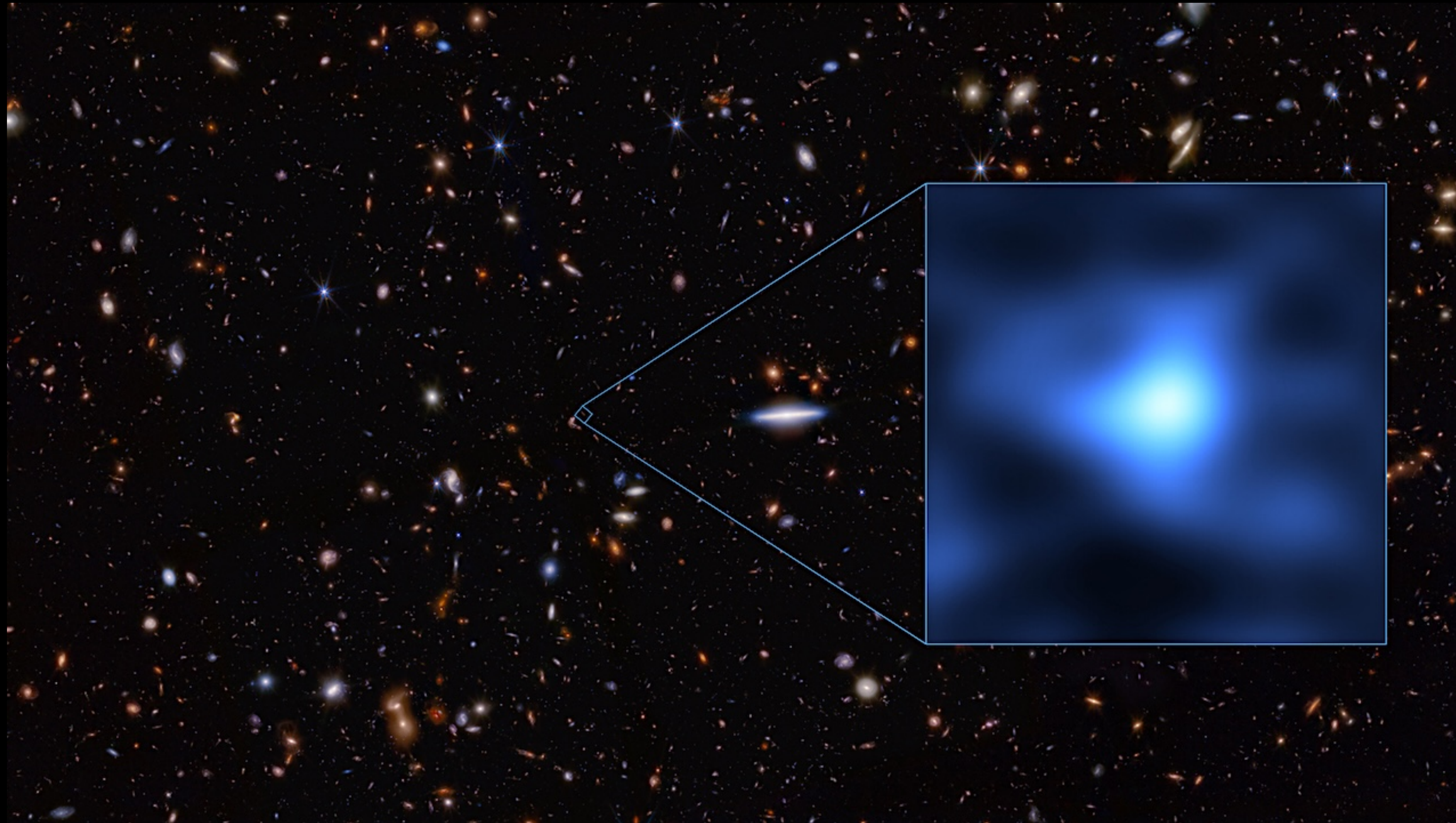


Image Credit: NASA/JWST/STScI

- LRDs could be Black Holes shrouded by cocoons of H gas a.k.a. Quasi Stars (QS)
[2503.16596](#) Naidu et al.
- Collapse of SMSs can lead to the formation of QS [0711.4078](#) Begelman et al.
- SMDS collapse can lead to formation of “late stage” QSs.
[2606.02539](#) Ilie

Observational puzzle III. **SMDS** can solve: Blue Monsters



JADES-GS-z14-0 Image Credit: NASA/JWST/STSci

- Some of the JWST high-z galaxies are compact, yet significantly brighter than expected
- They would require **extreme efficiency** of gas to star conversion. (e.g. Bolyan-Kolcin *Nat.Ast.* '23)
- They are almost devoid of dust

Supermassive Dark Stars: First Three Photometric candidates



Jillian Paulin (Colgate '23)

JADES-GS-z11-0

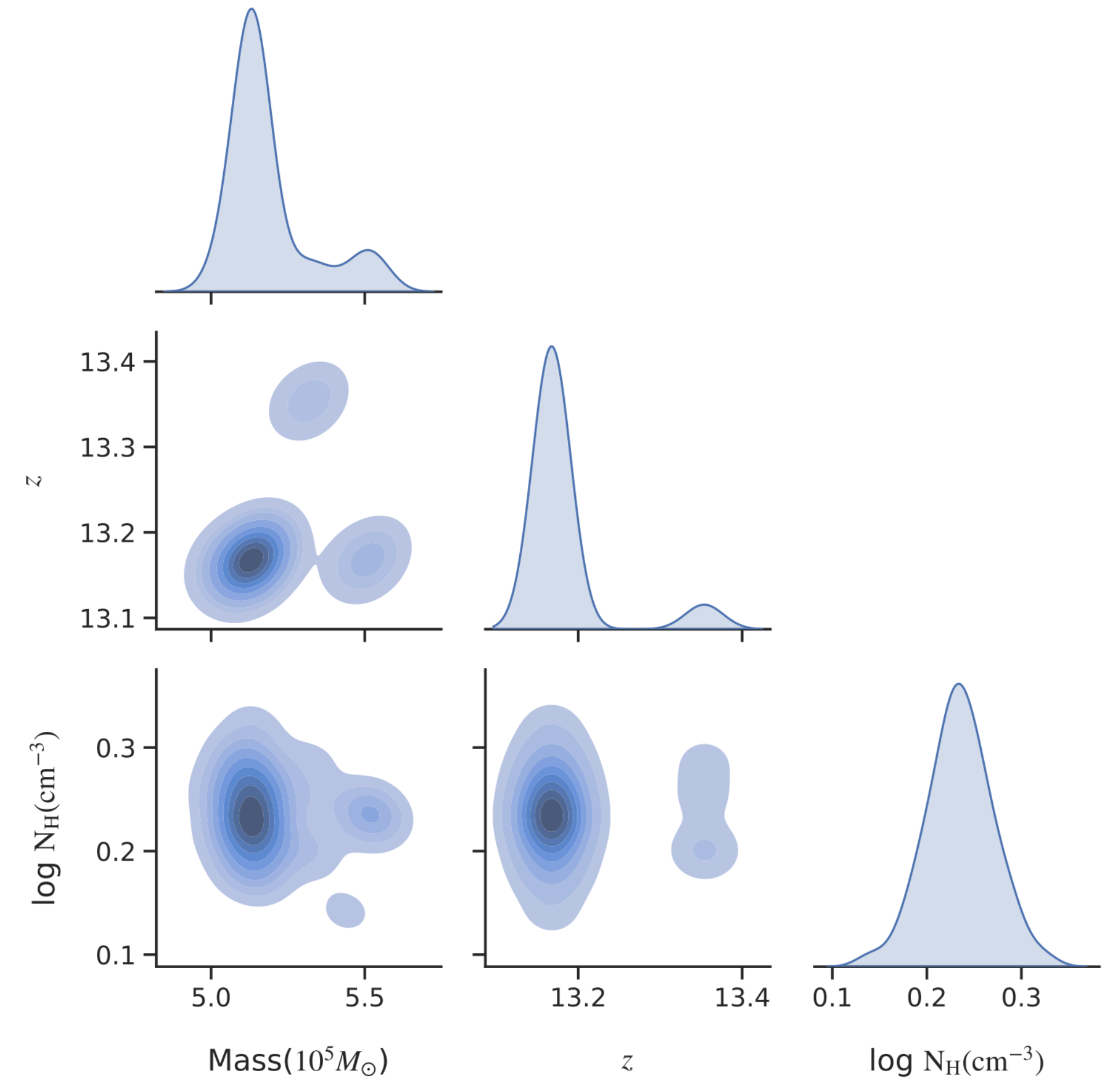
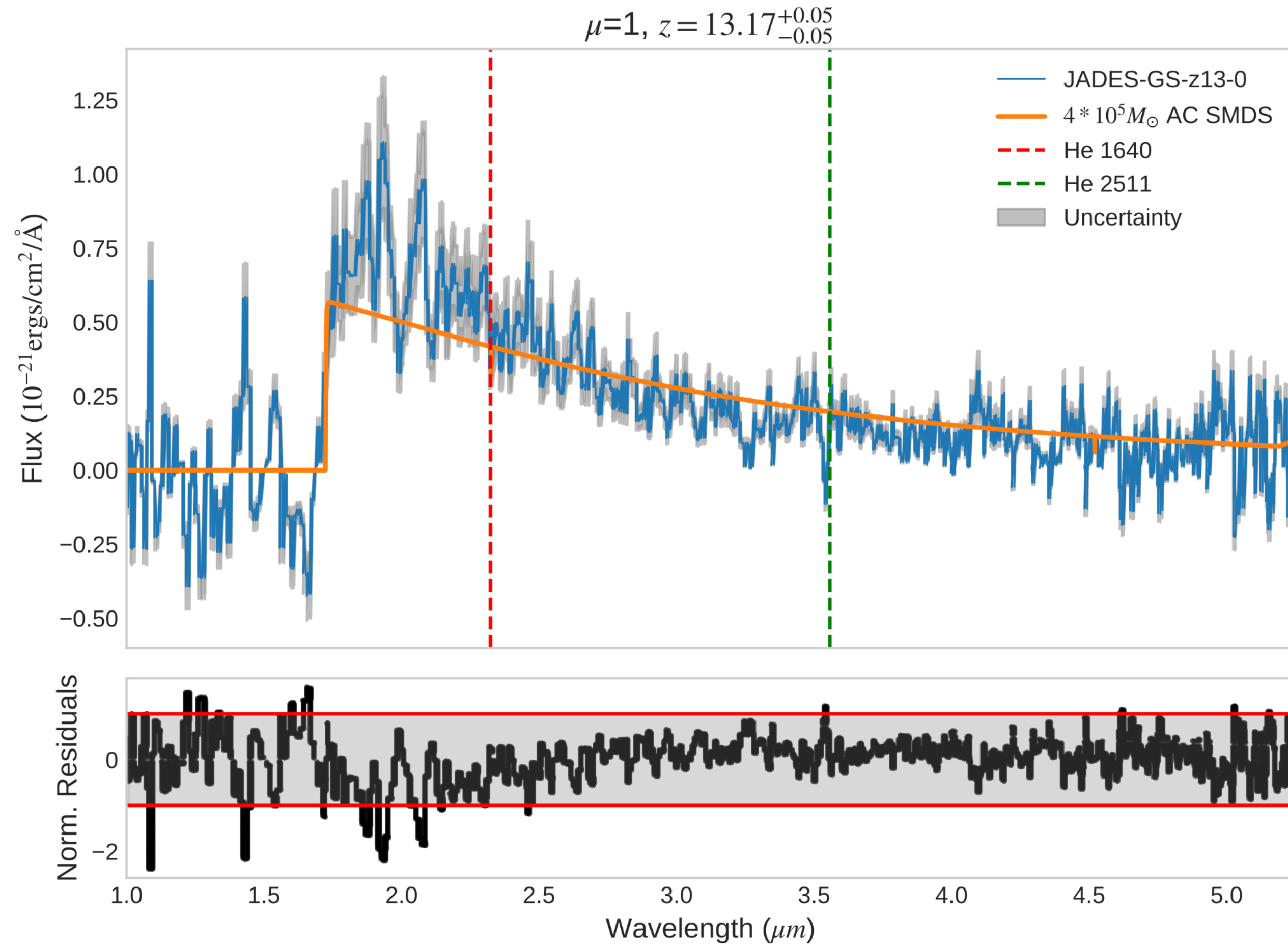
JADES-GS-z12-0

JADES-GS-z13-0

Cl, Paulin and Freese PNAS
120 (30) 2023

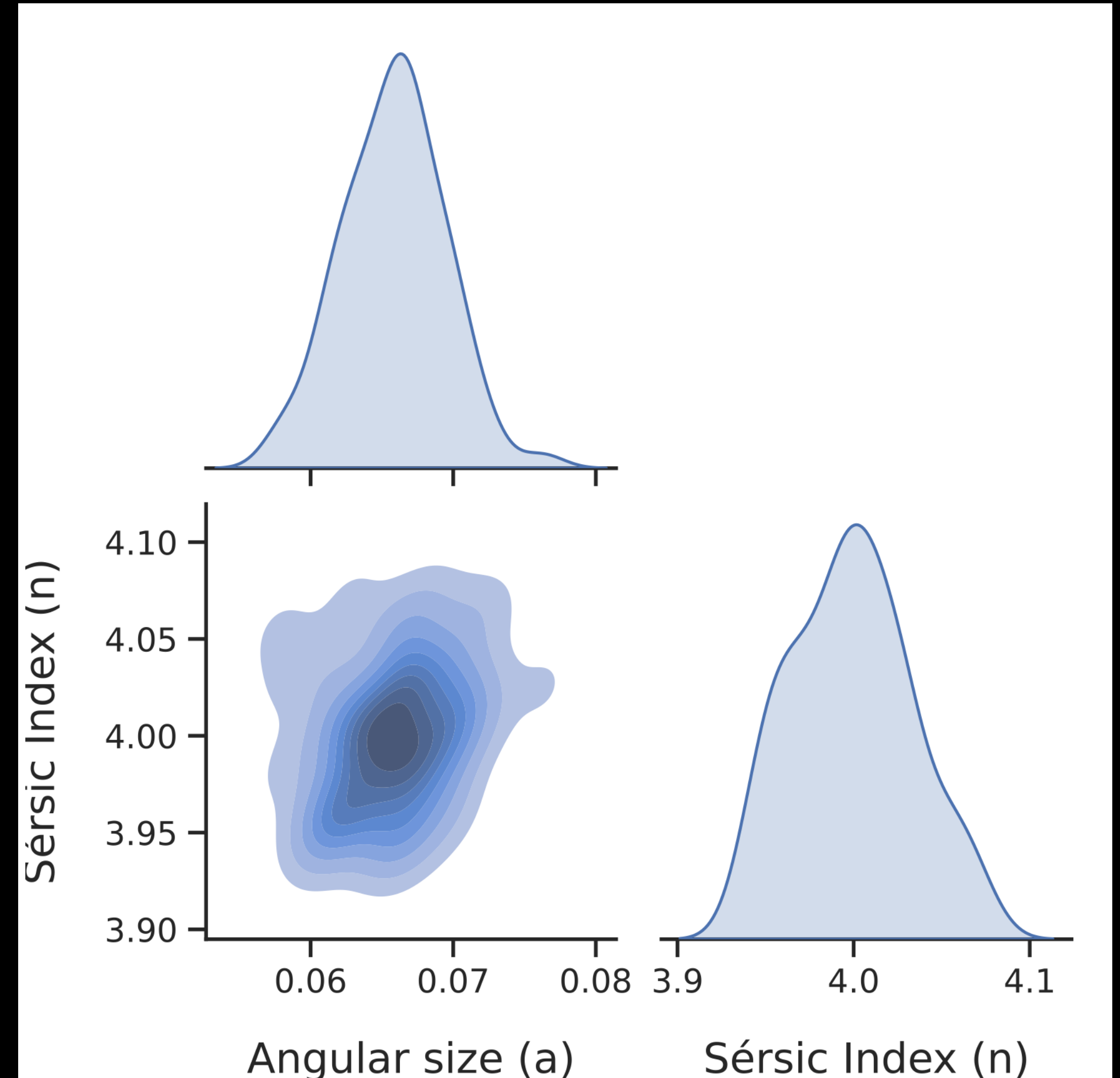
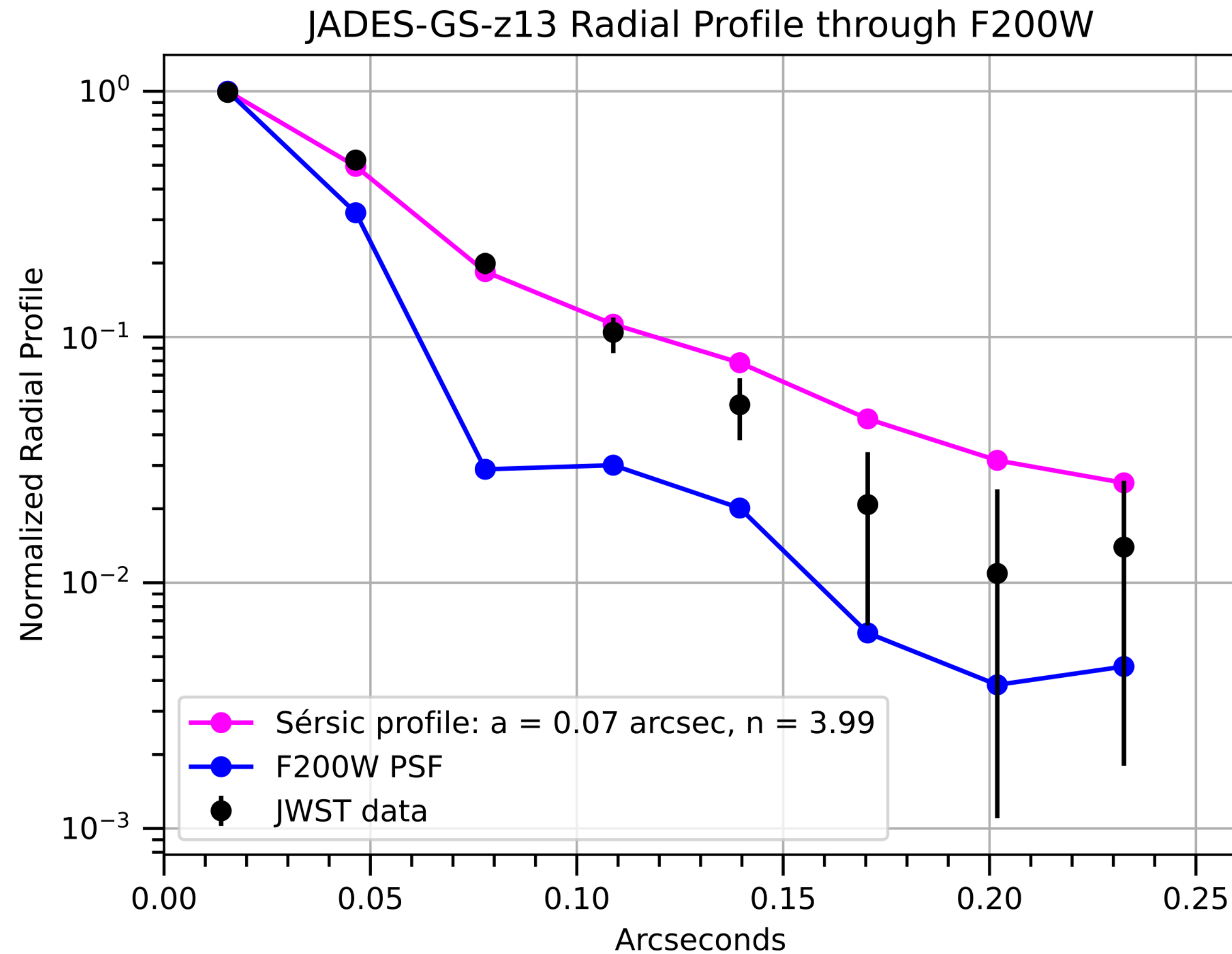


JADES-GS-z13-0 as a SMDS



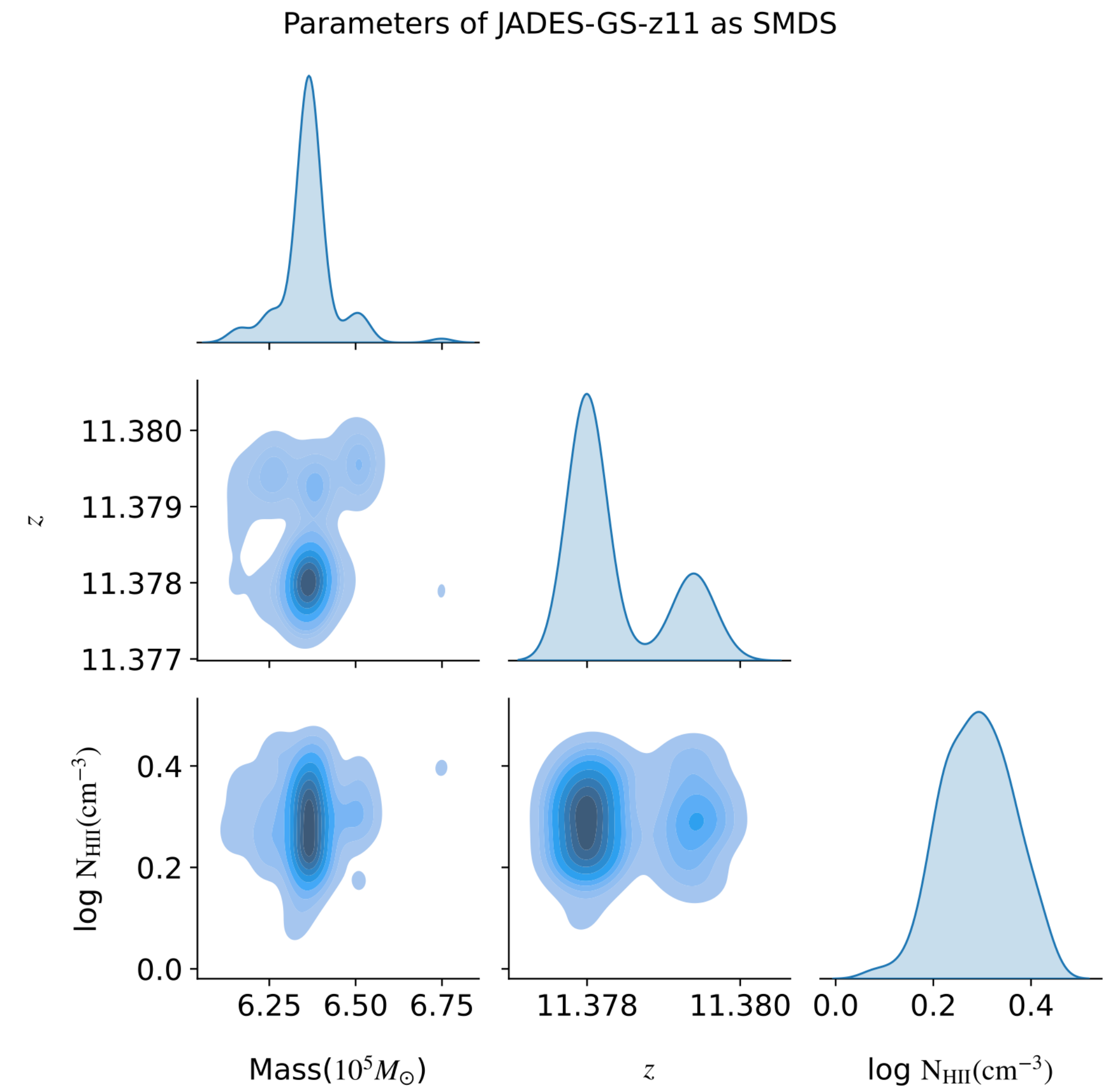
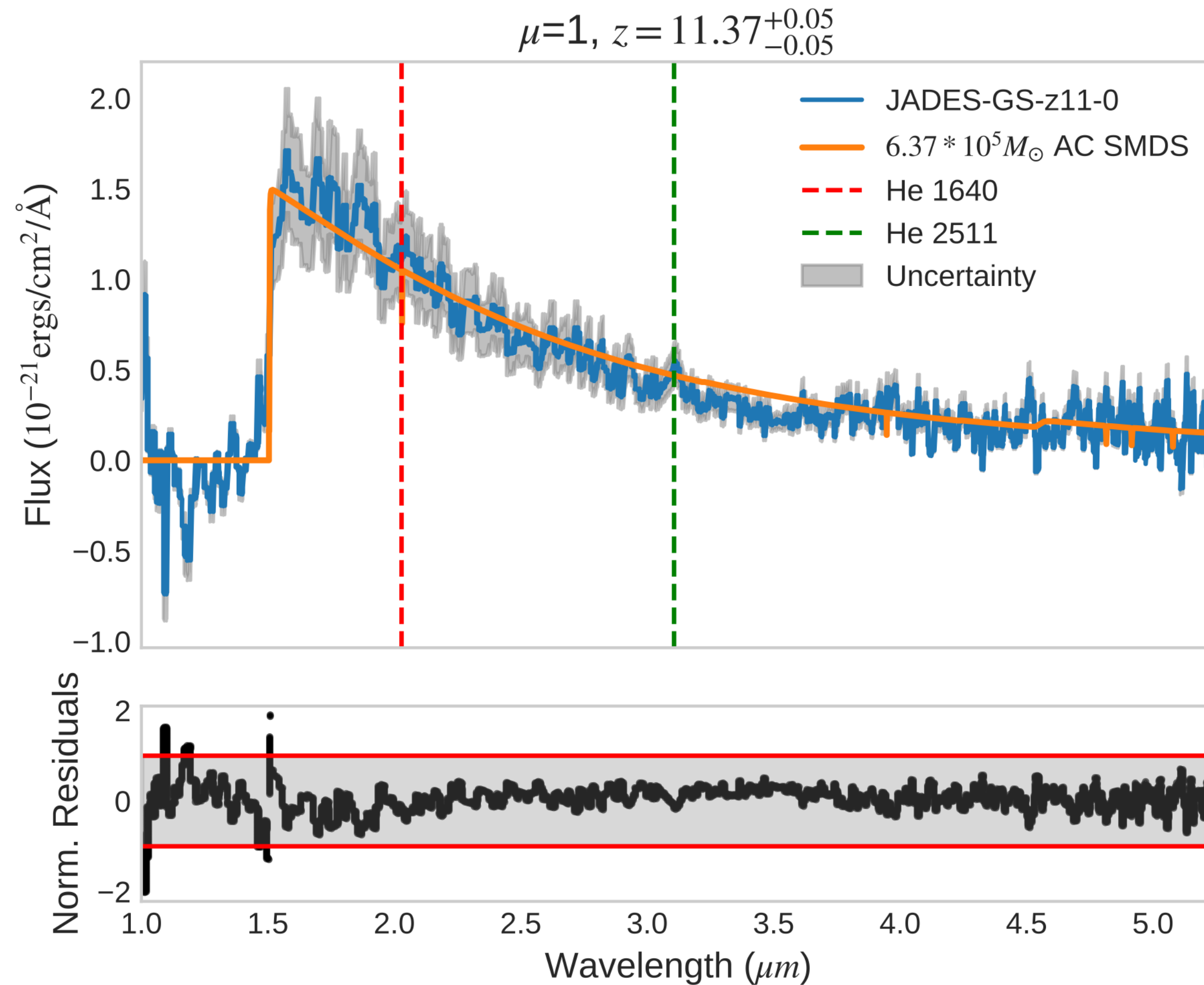
CI et al. 2505.06101 PNAS 122 (40) 2025

JADES-GS-z13-0 as a SMDS



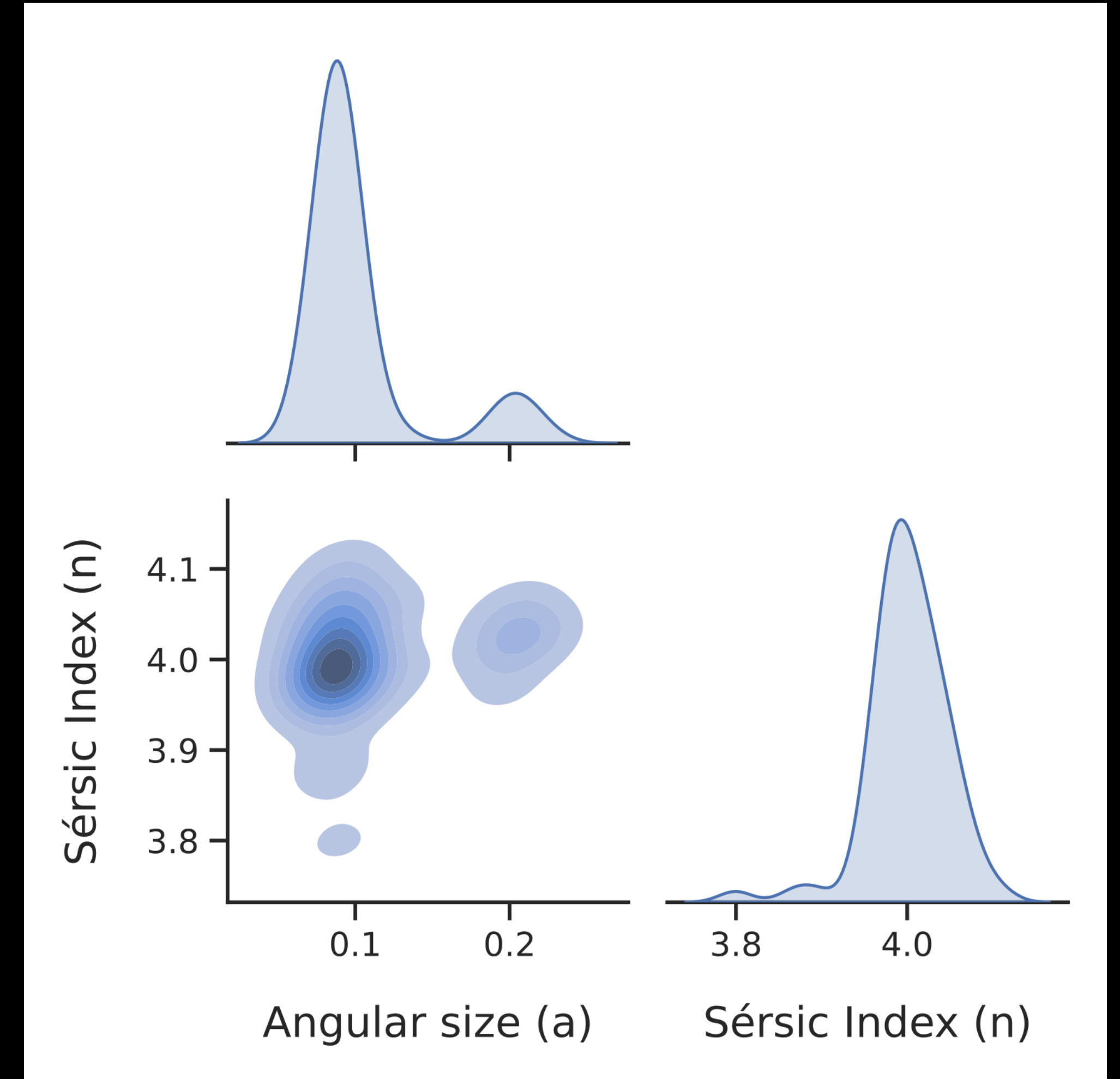
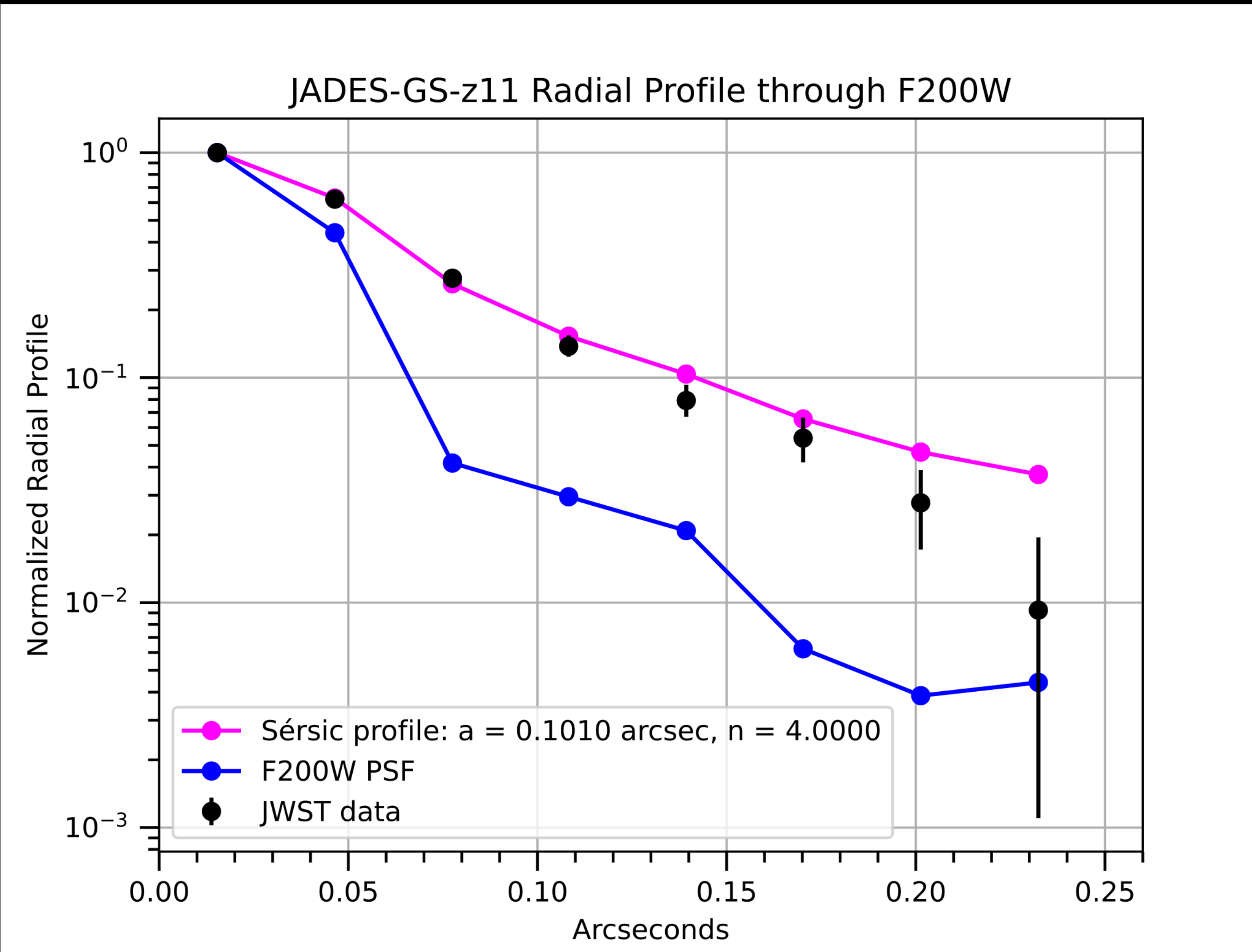
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JADES-GS-z11-0 as a SMDS



Cl et al. 2505.06101 PNAS 122 (40) 2025

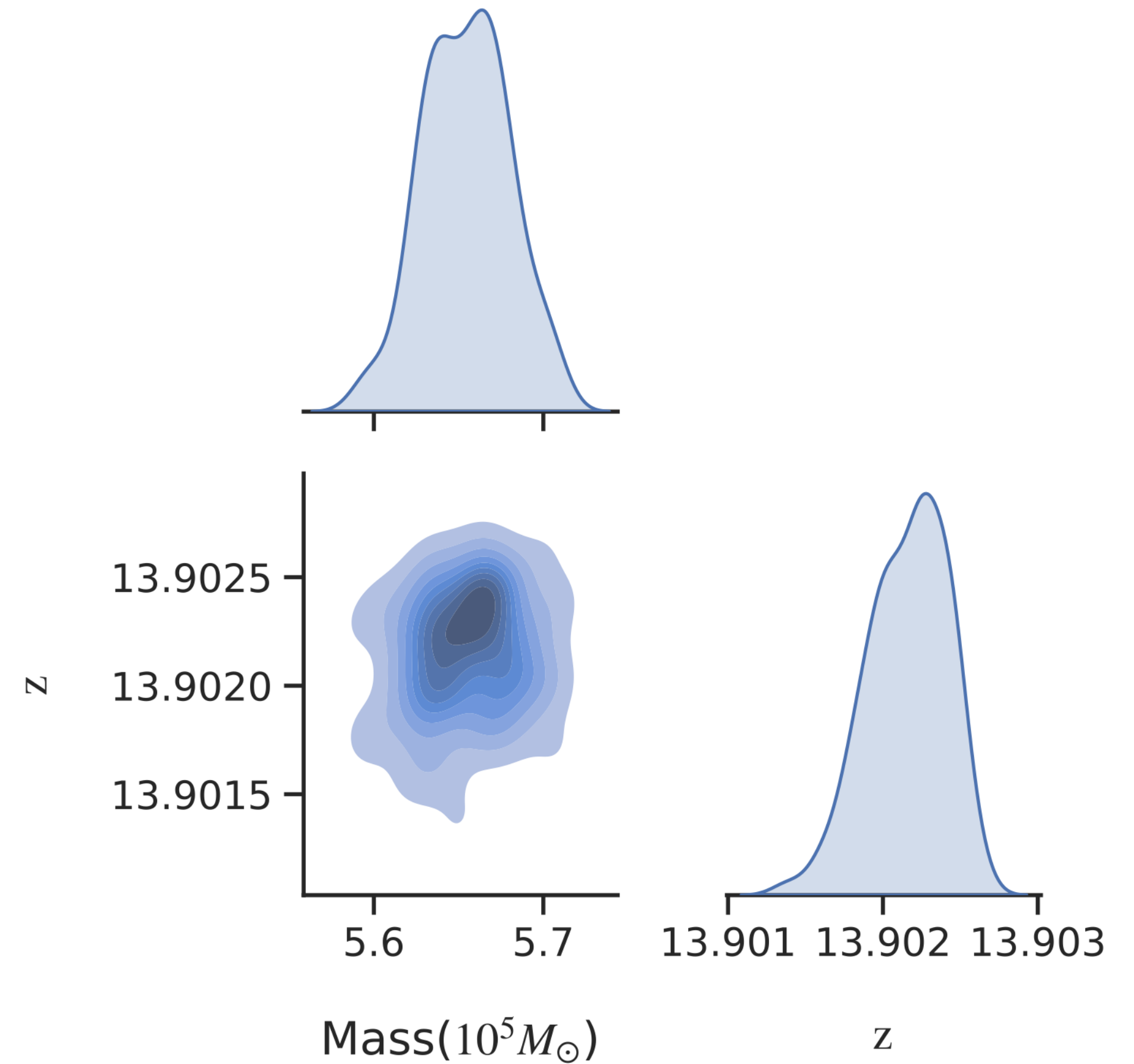
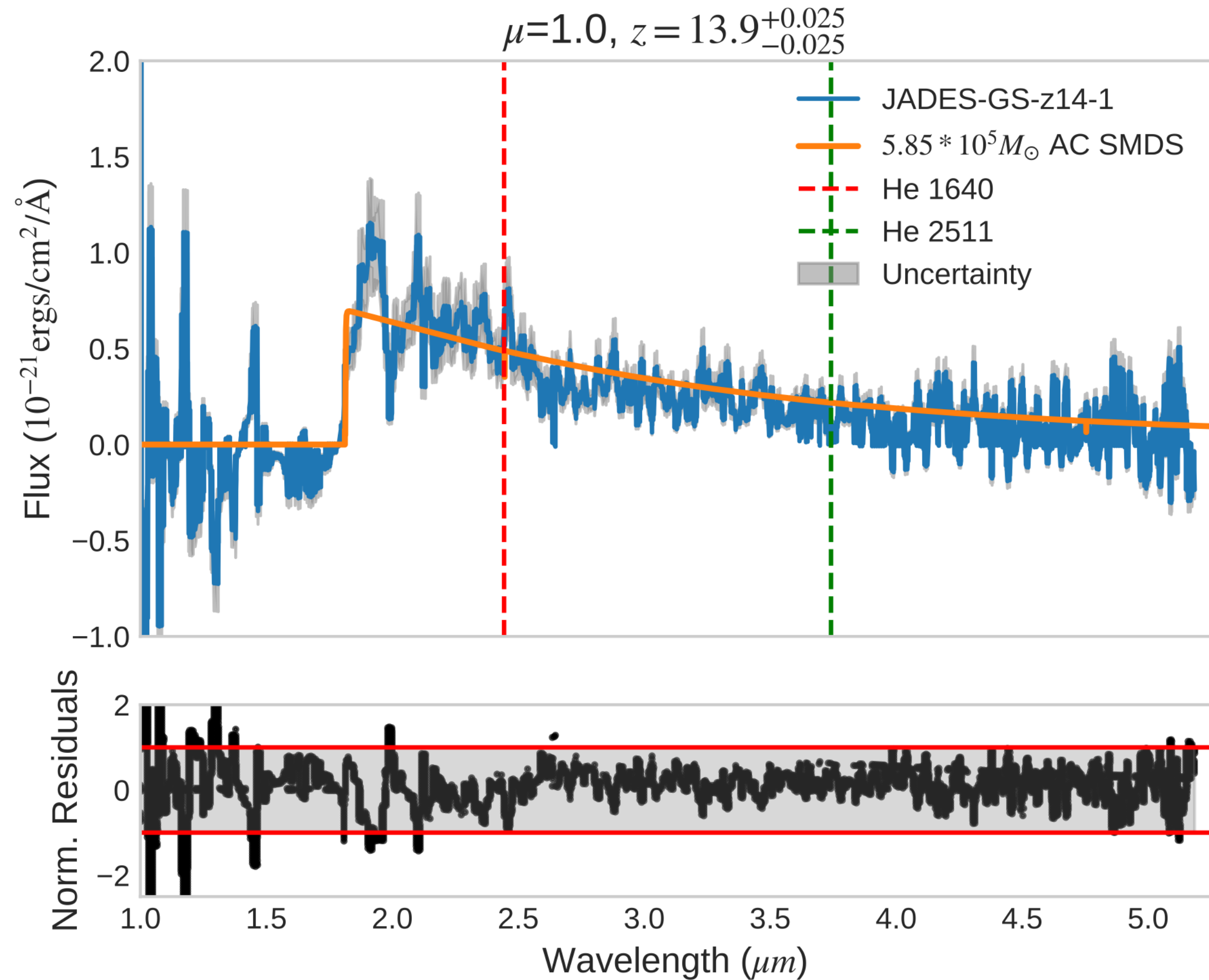
JADES-GS-z11-0 as a SMDS



Cl et al. 2505.06101 PNAS 122 (40) 2025

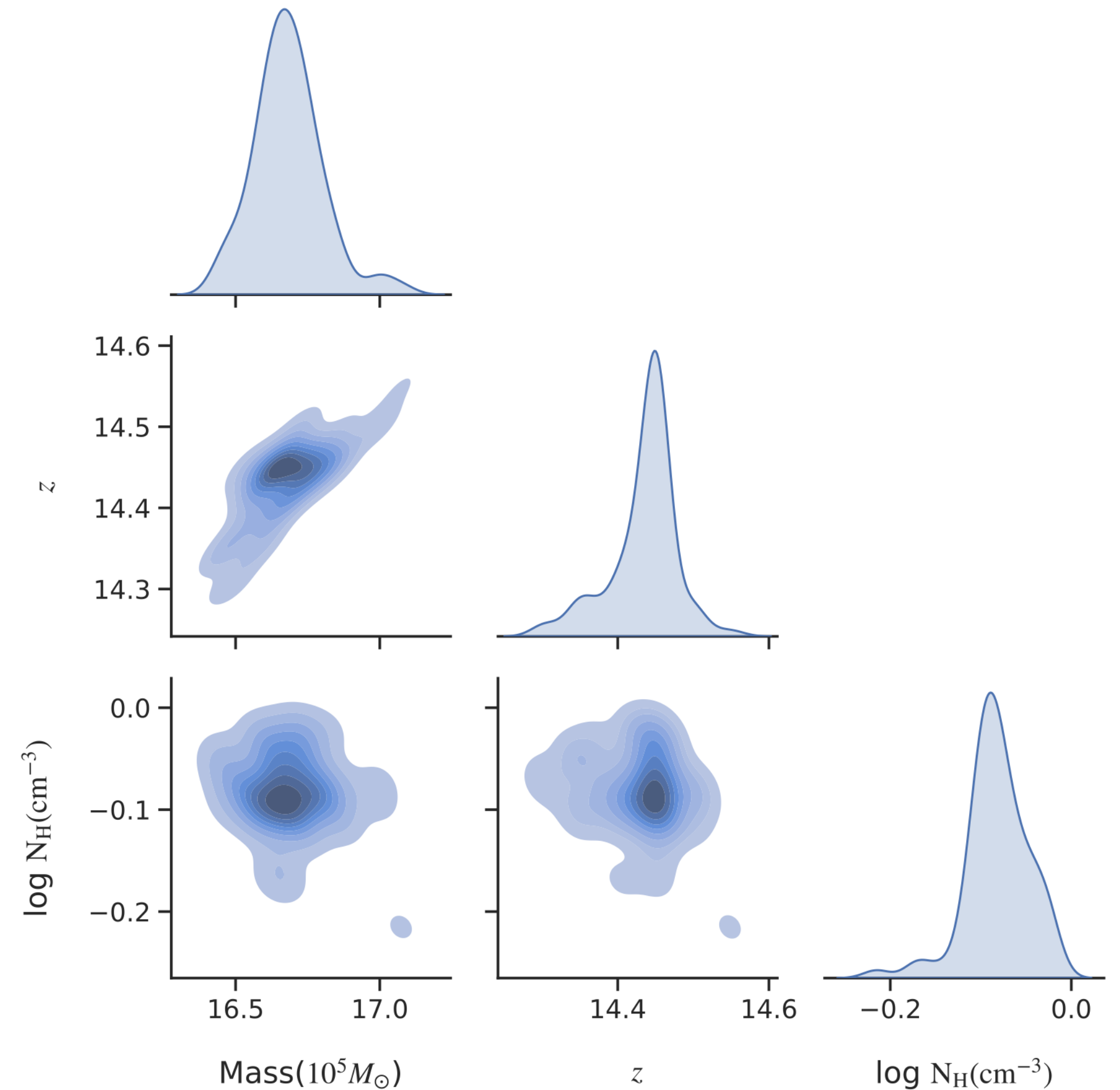
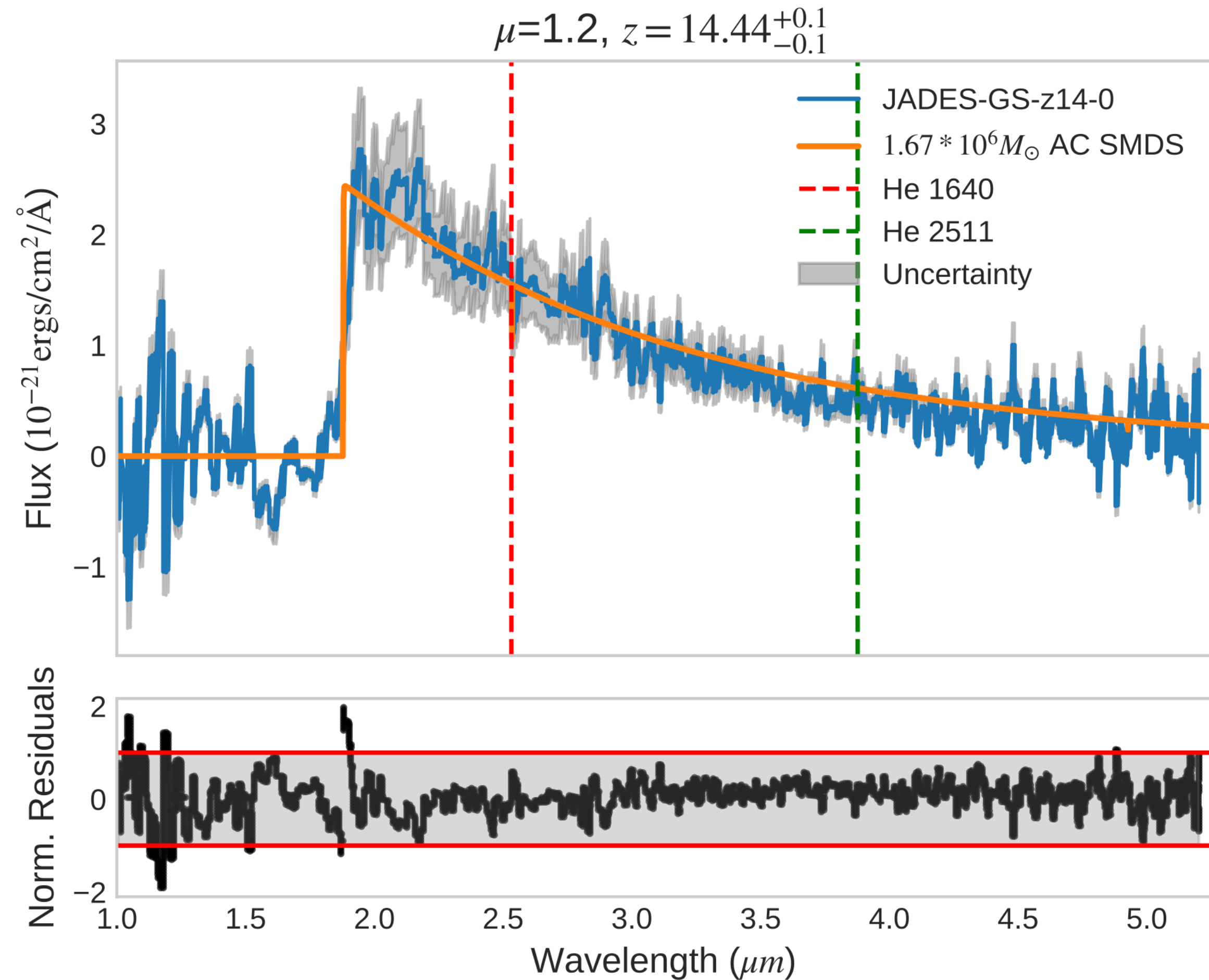
Two additional spectroscopic
Supermassive Dark Stars candidates
found using NIRSpec data:

JADES-GS-z14-1 as a SMDS



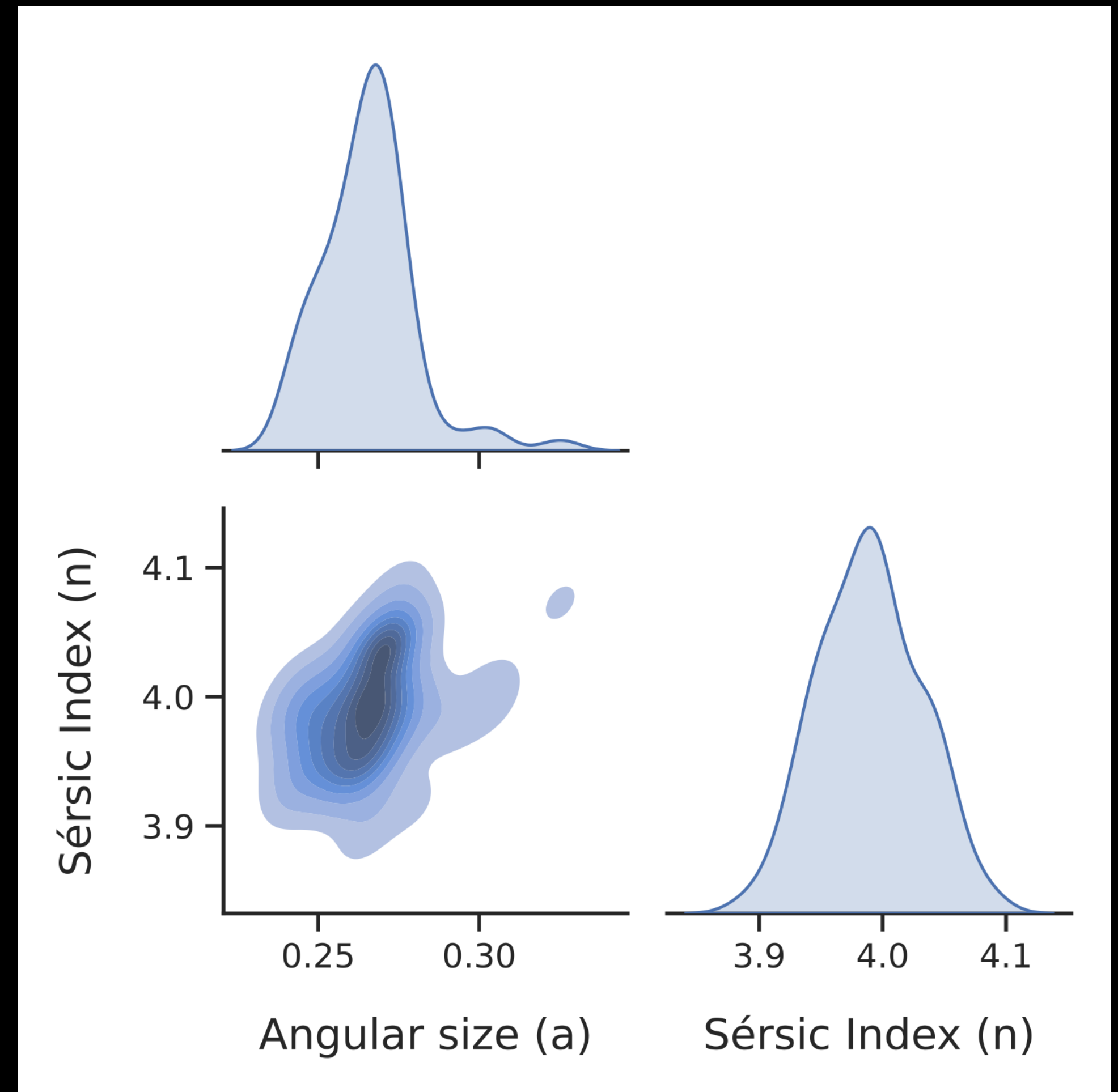
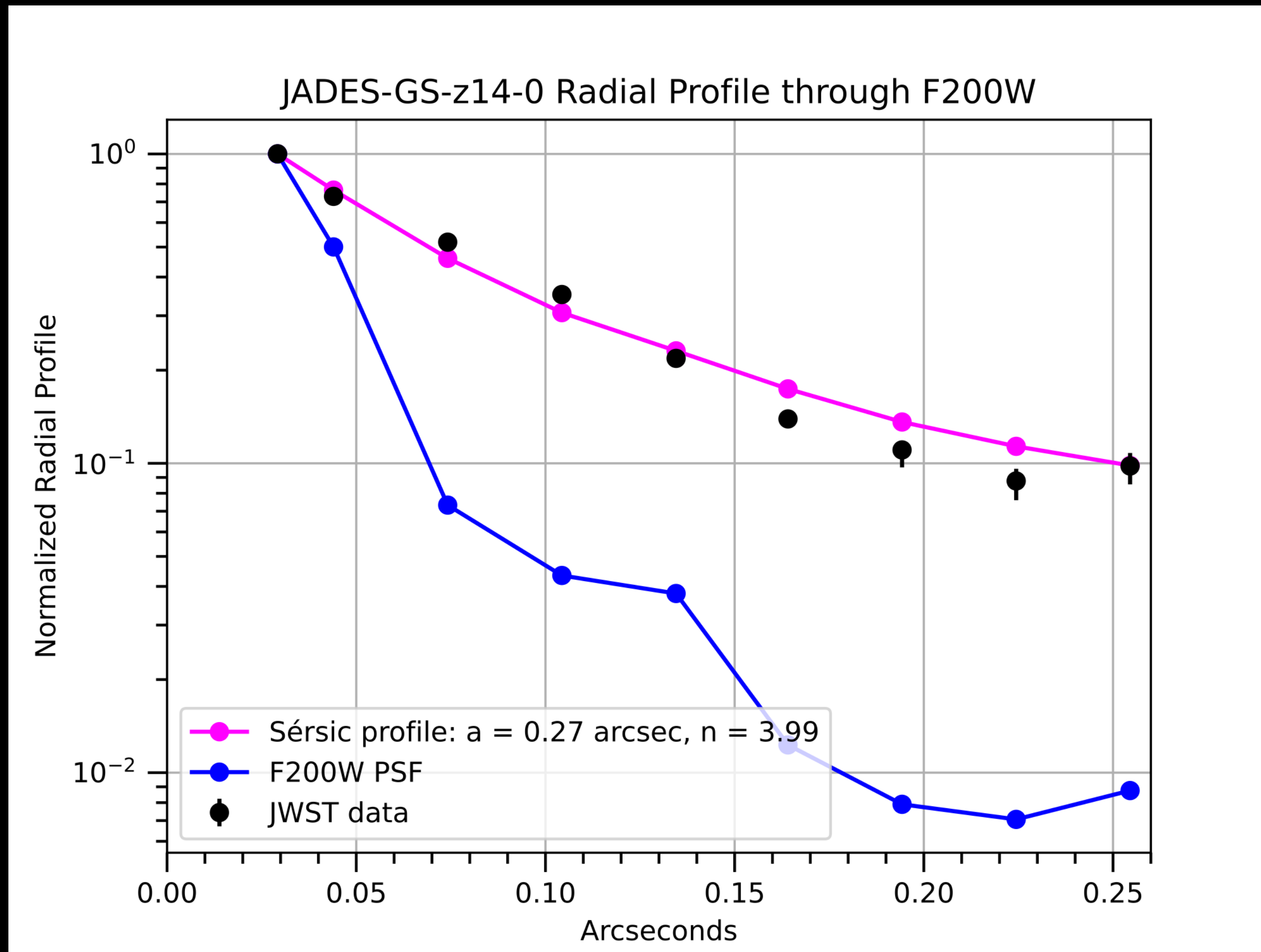
CI et al. 2505.06101 PNAS 122 (40) 2025

JADES-GS-z14-0 as a SMDS



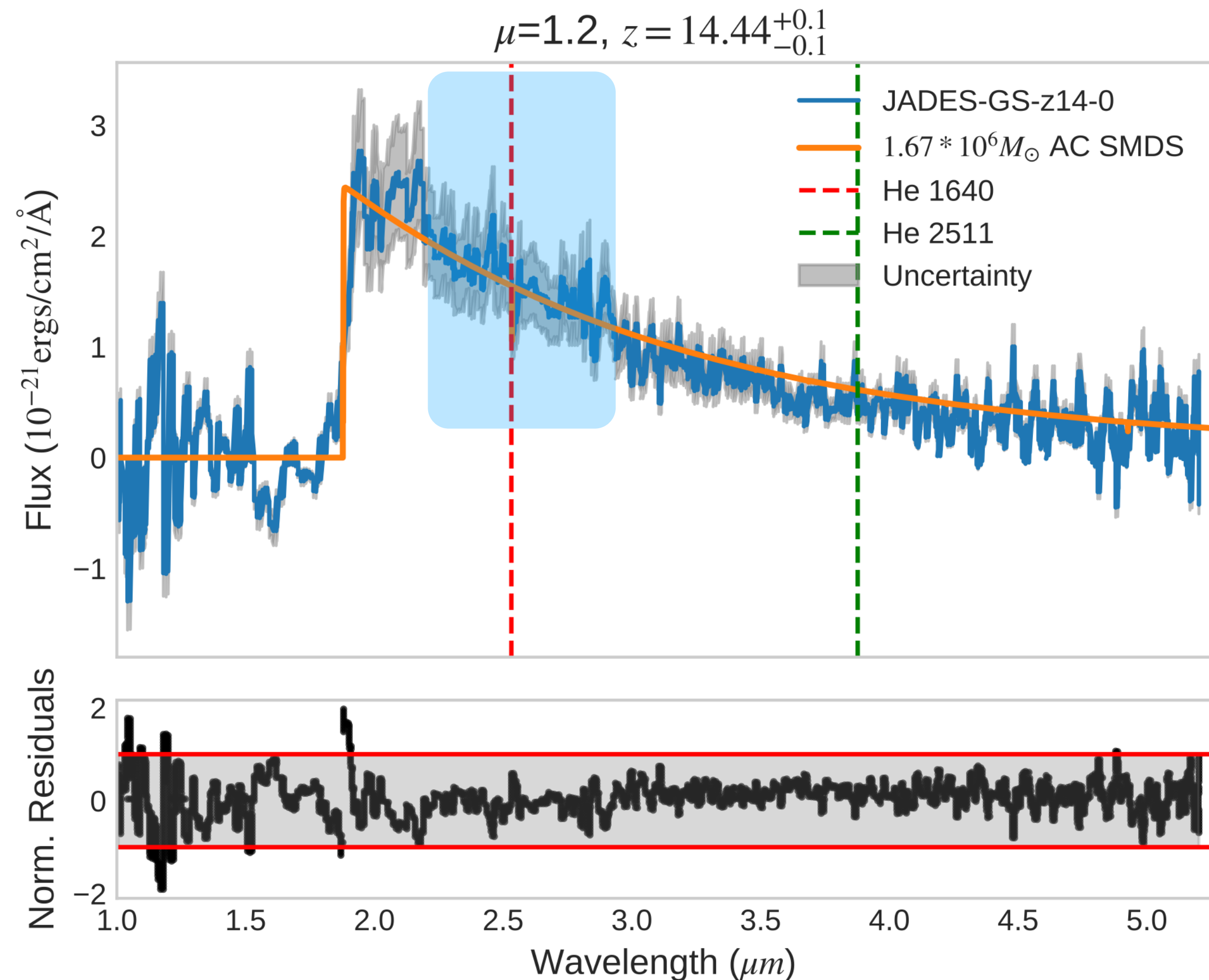
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JADES-GS-z14-0 as a SMDS



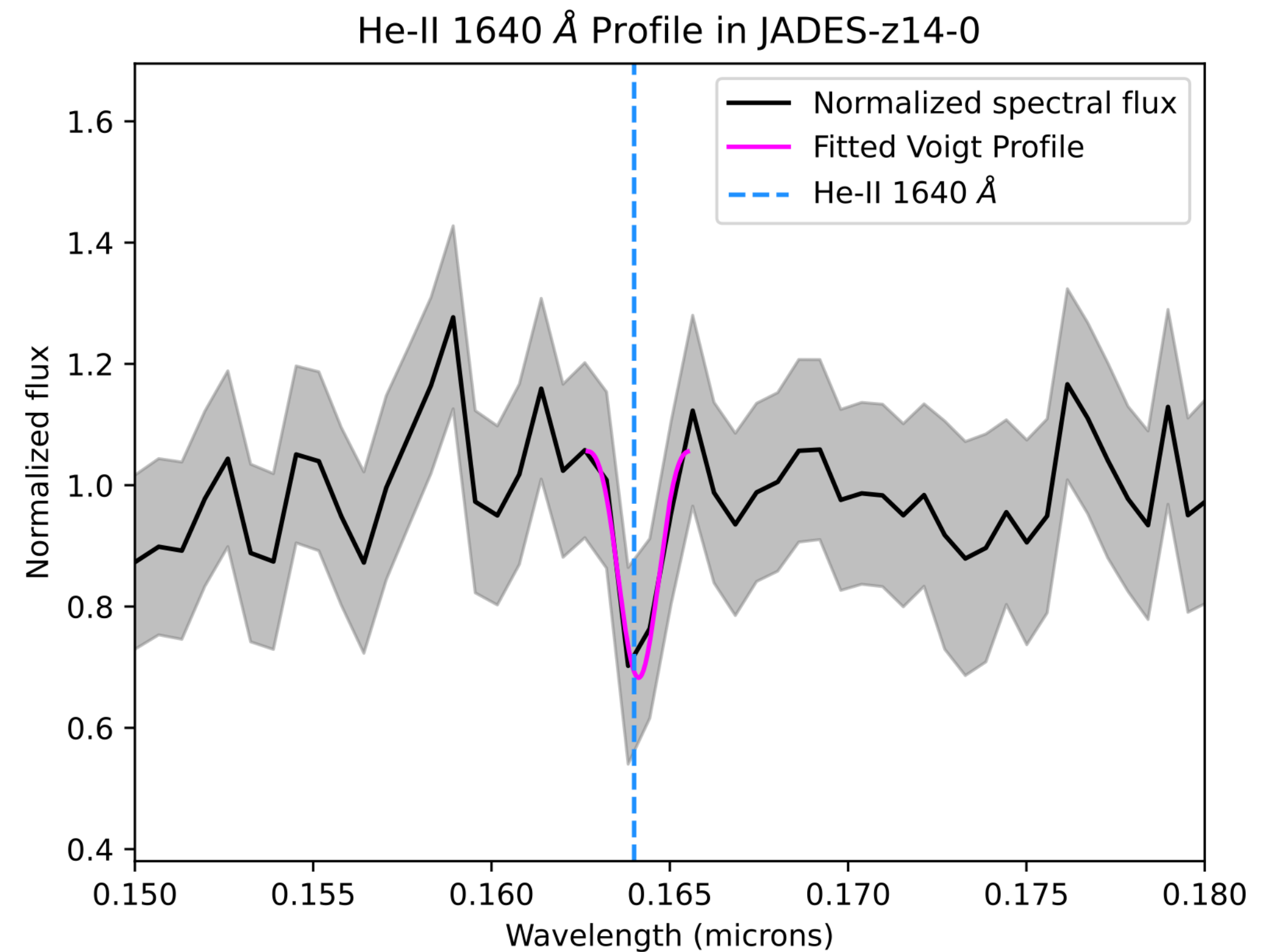
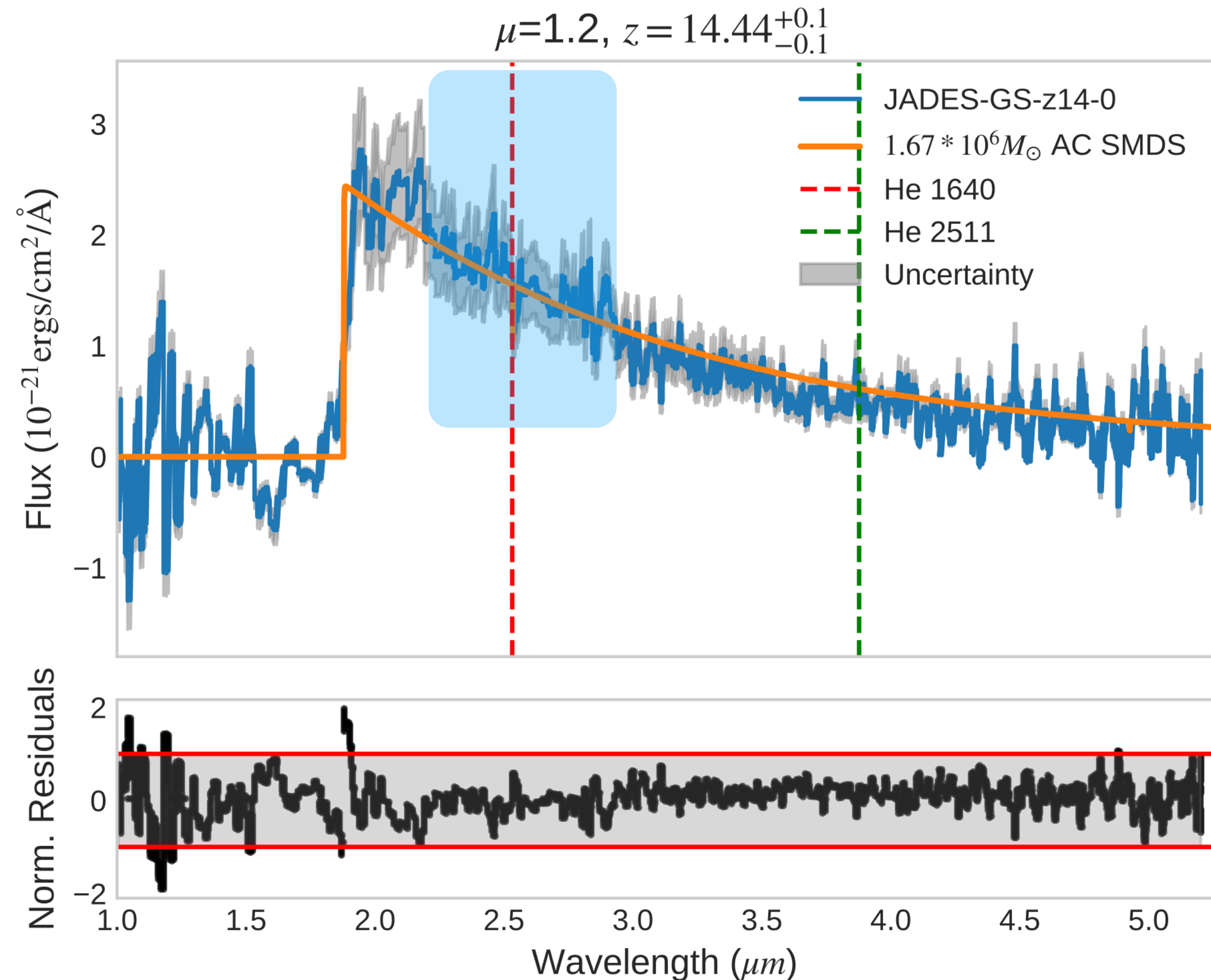
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JADES-GS-z14-0, a tentative HeII feature?



Cl et al. 2505.06101 PNAS 122 (40) 2025

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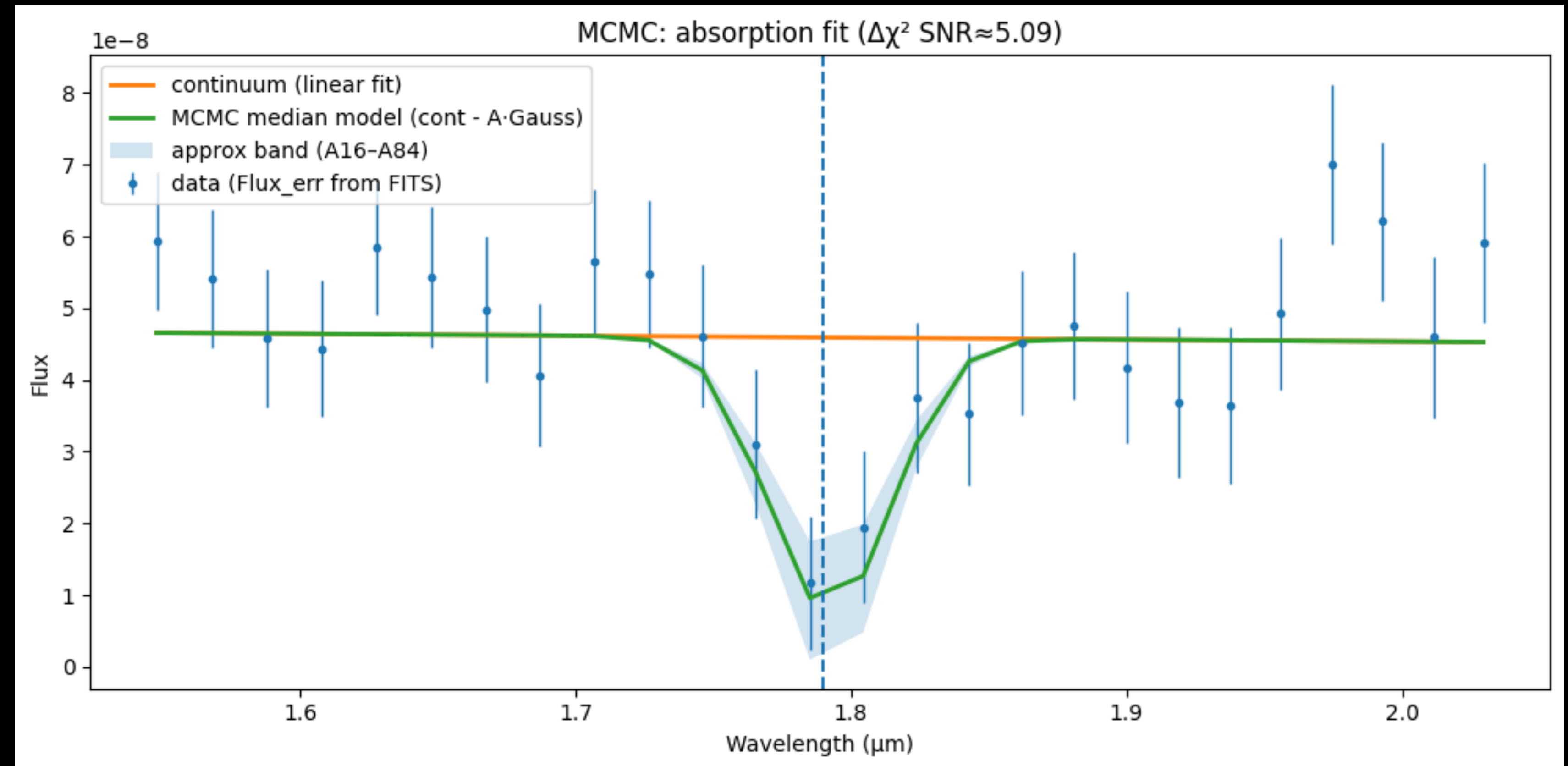
SNR ~ 2.5 for this feature

CI et al. 2505.06101 PNAS 122 (40) 2025

CEERS 99715 Best Evidence for a SMDS yet



Sayed Shafaat Mahmud (Colgate '26)



SNR $\sim$ 5 for the smoking gun Hell absorption feature

Summary

- Supermassive Dark Stars provide natural Heavy BH Seeds required by the most distant quasars data [2511.08578](#)
- Supermassive Dark Stars can be part of the solution to the too many too massive early galaxies observed by JWST ([Blue Monsters](#))
- Supermassive Dark Stars could explain [Little Red Dots](#) [2606.02539](#)
- We have identified five spectroscopic Supermassive Dark Star Candidates, two of which show H α absorption feature (a smoking gun of Dark Stars)
- Out of those five one is unresolved and four are extremely compact, with morphologies that are consistent with those of SMDSs powering a nebula.
- Dark Stars could seed the population of SMBHs whose mergers generate the PTA GW signal. [2507.06163](#)

SGWB from DS Seeded SMBHs can explain PTA data

Start our simulation at $z_{\text{start}} \approx 10$, which marks the end of the SMBH seeding halos via DCBHs or SMDSSs.



Subsequent accretion driven growth of seeds (Eq. 2) tuned to match the BH-halo mass relation.



Calculate the probability of a halo housing an SMBH seed (Eq. 8).



Halos merge and eventually the central SMBHs merge with some delay (Eq. 12).



Inspiring and merging population of SMBHs produce a SGWB (Eq. 13).



Compare predicted SGWB to PTA data (Fig. 5) & put upper limit on the number density of such seeds.

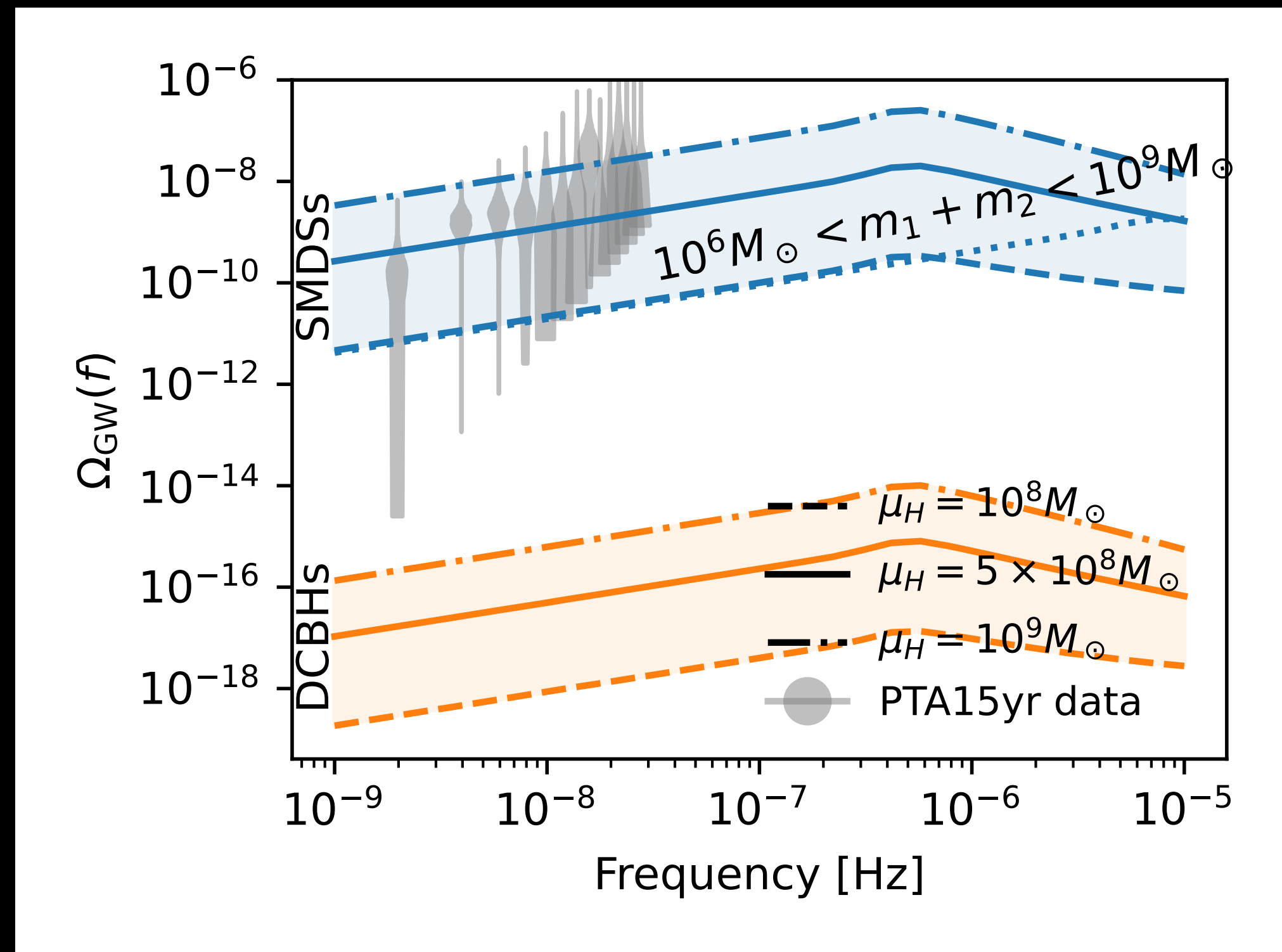
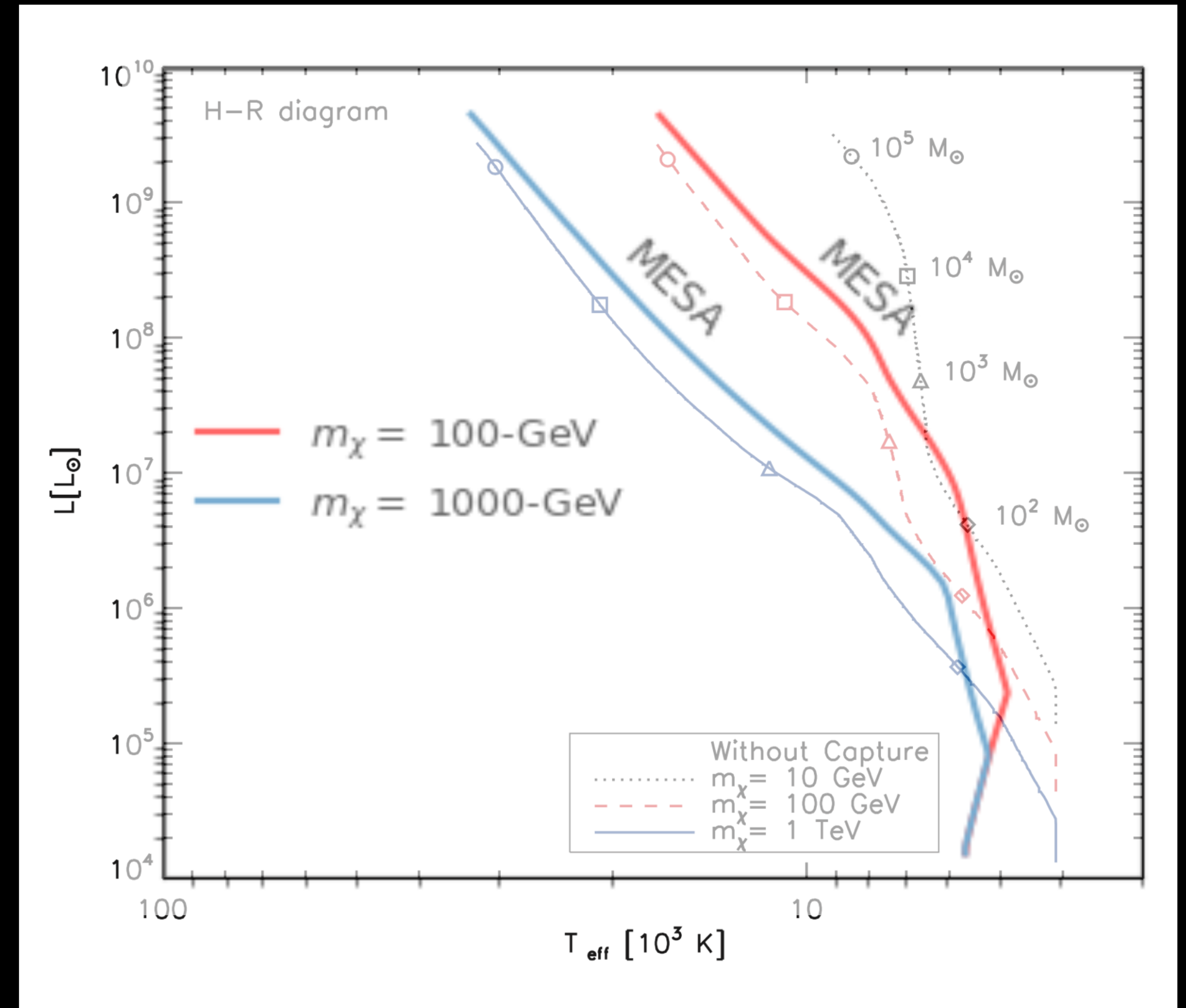


Fig from: Ghodla & Ilie 2507.06163

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From polytropes to MESA SMDS models

- 1408.2082 Models SMDS via extended AC with MESA and finds consistency with polytropic models
- **Sohan Ghodla** & CI (in progress) models SMDS via AC and Capture in MESA.



Sohan Ghodla, CI (in progress)

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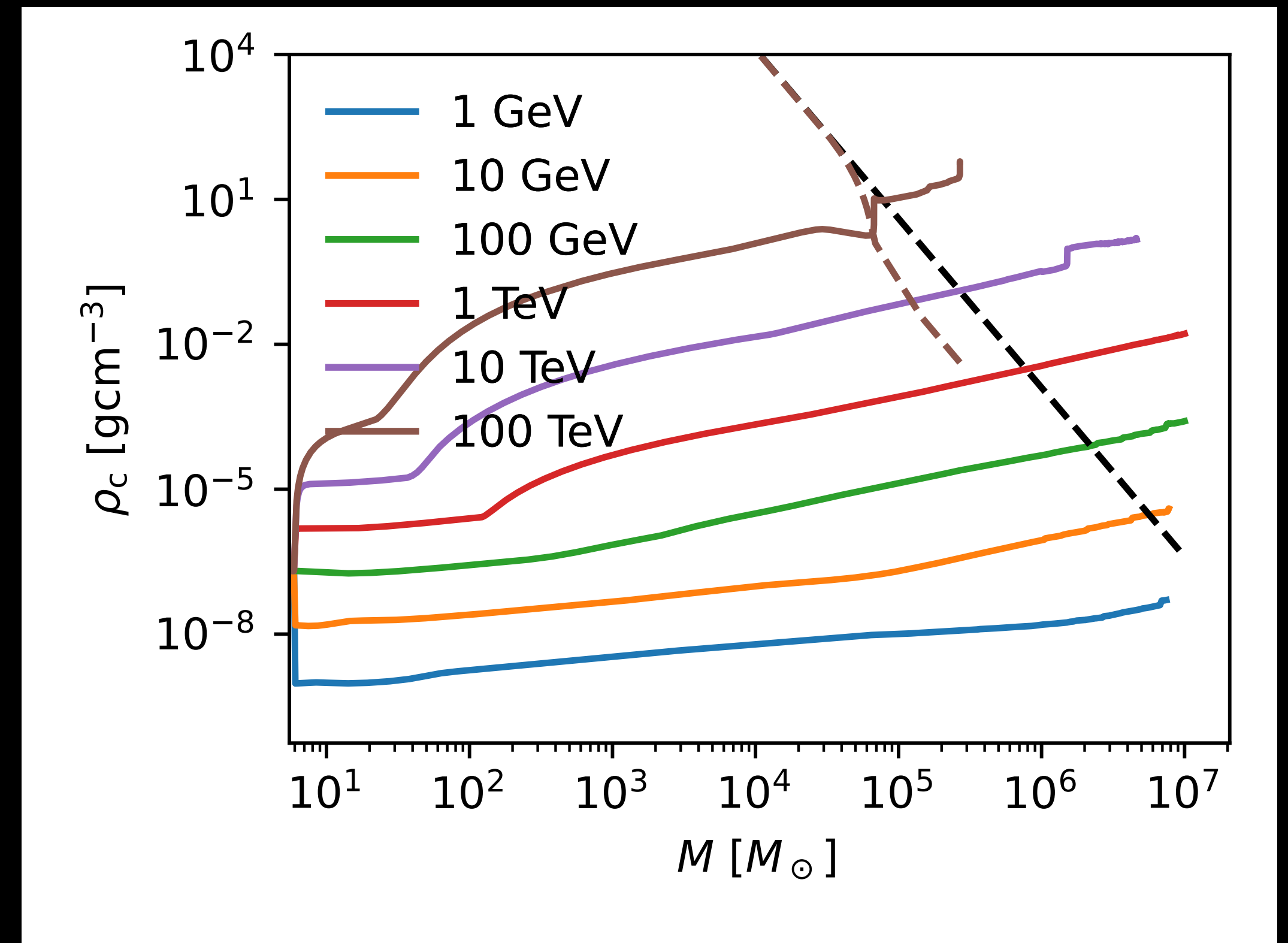
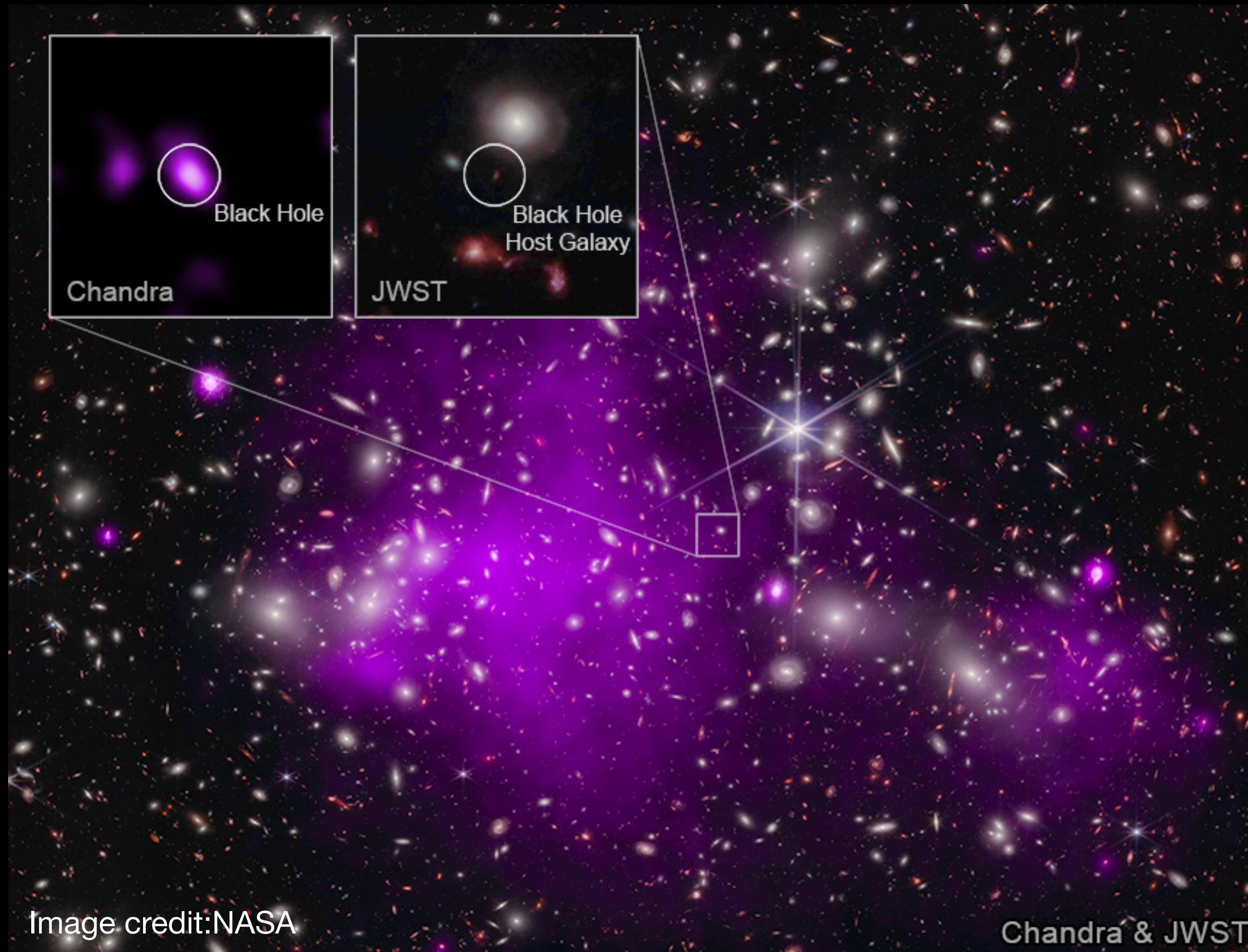


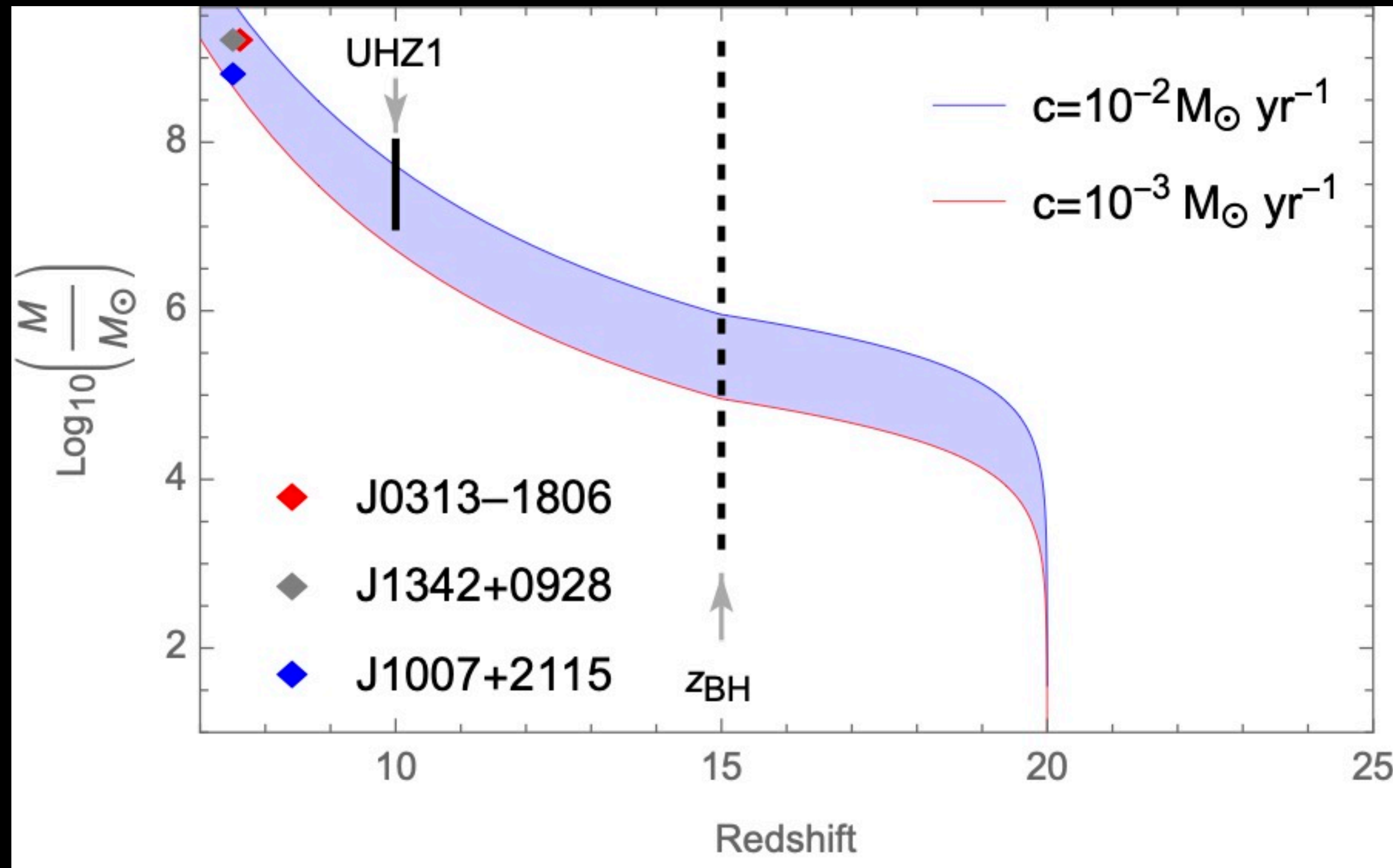
Fig from 2511.08578 Freese, Cl, +

SMDS solution to the UHZ1 puzzle



- UHZ1: a system at $z \sim 10$
- Observed with JWST/Chandra
- Contains a quasar of powered by a BH $\sim 10^7 M_{\odot}$
- Significant stellar population, $M_{\star} \sim 10^7 M_{\odot}$

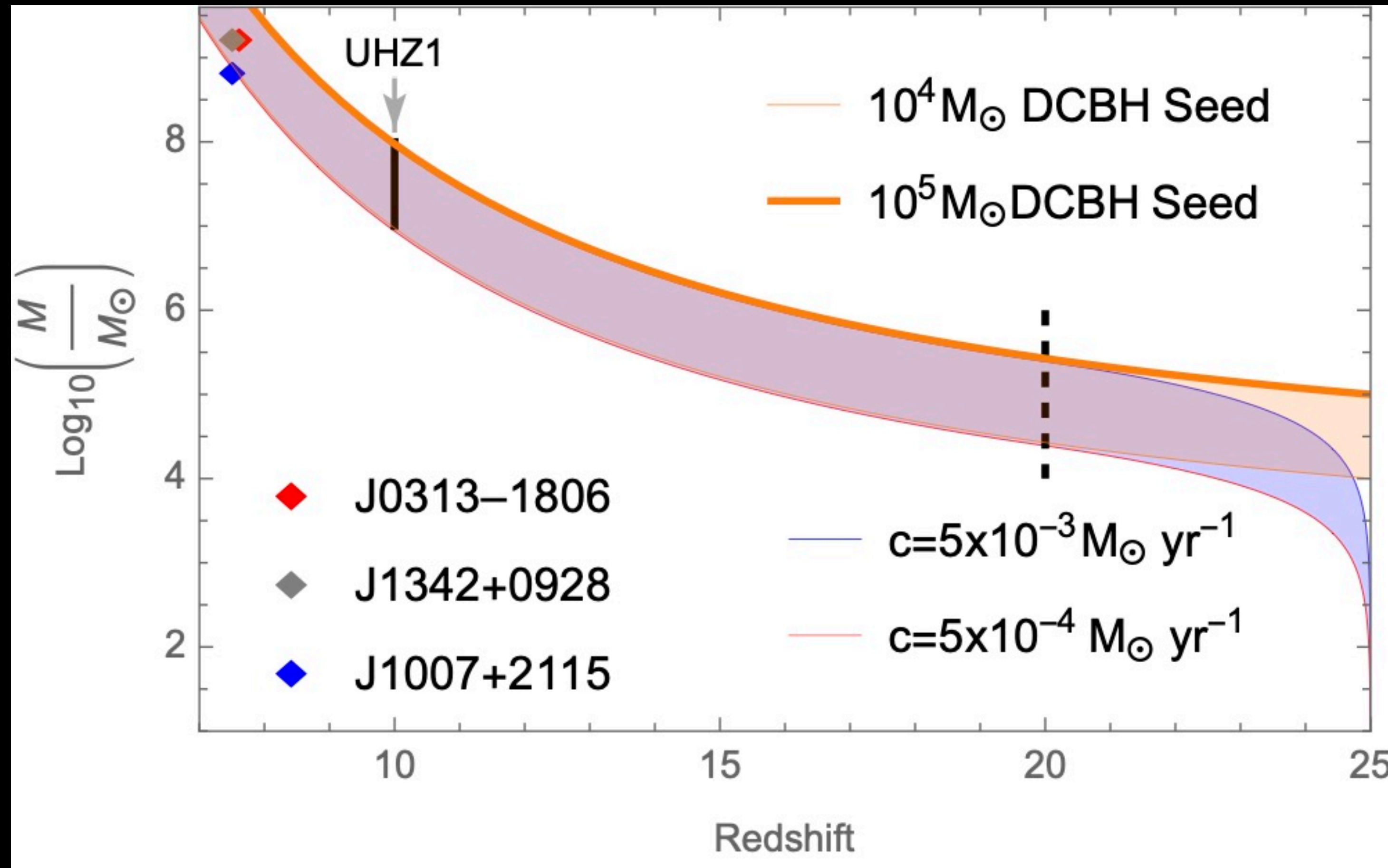
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Figure from: 2511.08477 Cl et al. Universe 12 (1) 2026

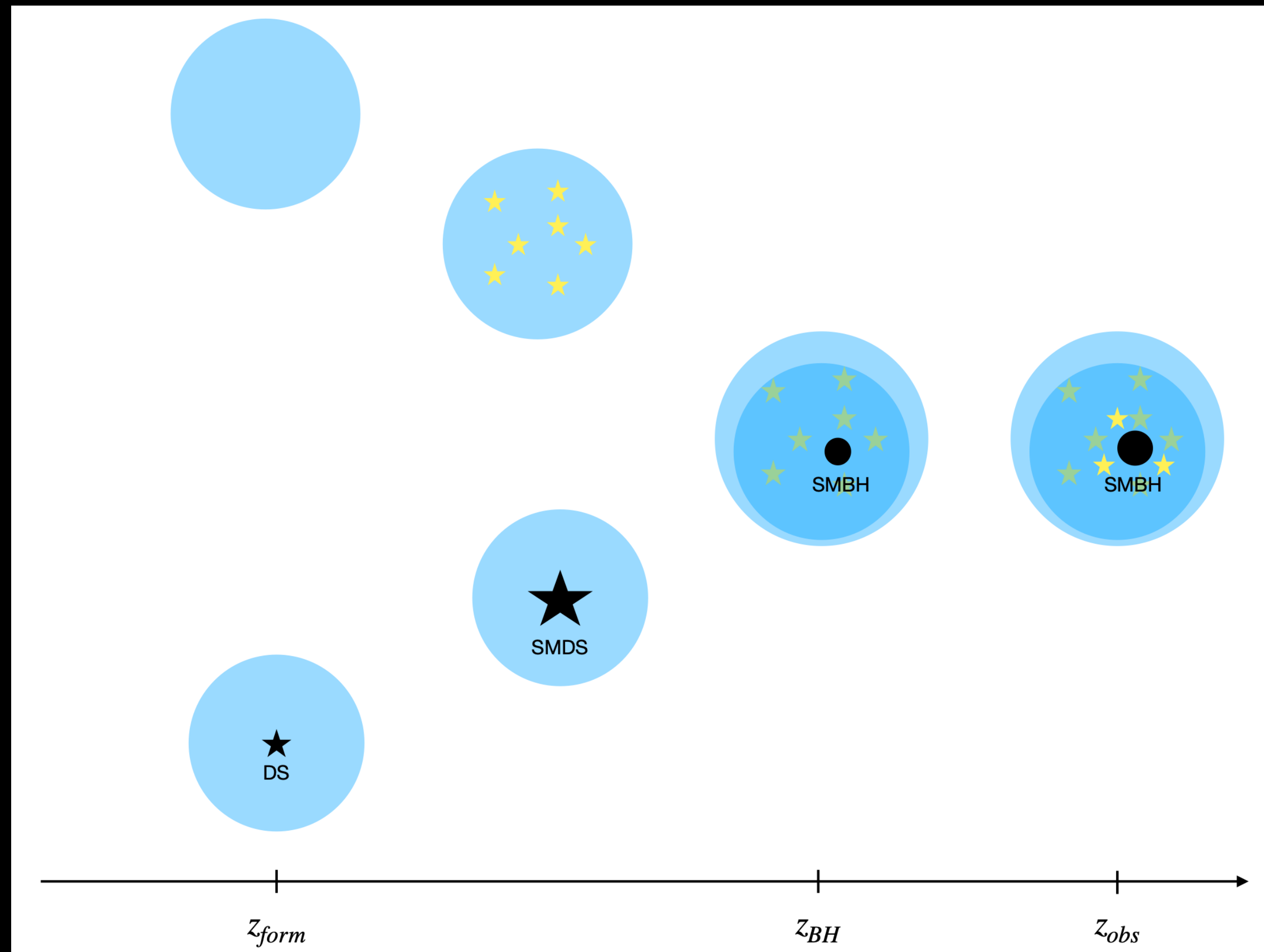
SMDS vs DCBH solution to the UHZ1 puzzle



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Figure from: 2511.08477 Cl et al. Universe 12 (1) 2026

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Figure from: 2511.08477 Cl et al. Universe 12 (1) 2026

Observational puzzle III. **SMDS** can solve: Blue Monsters

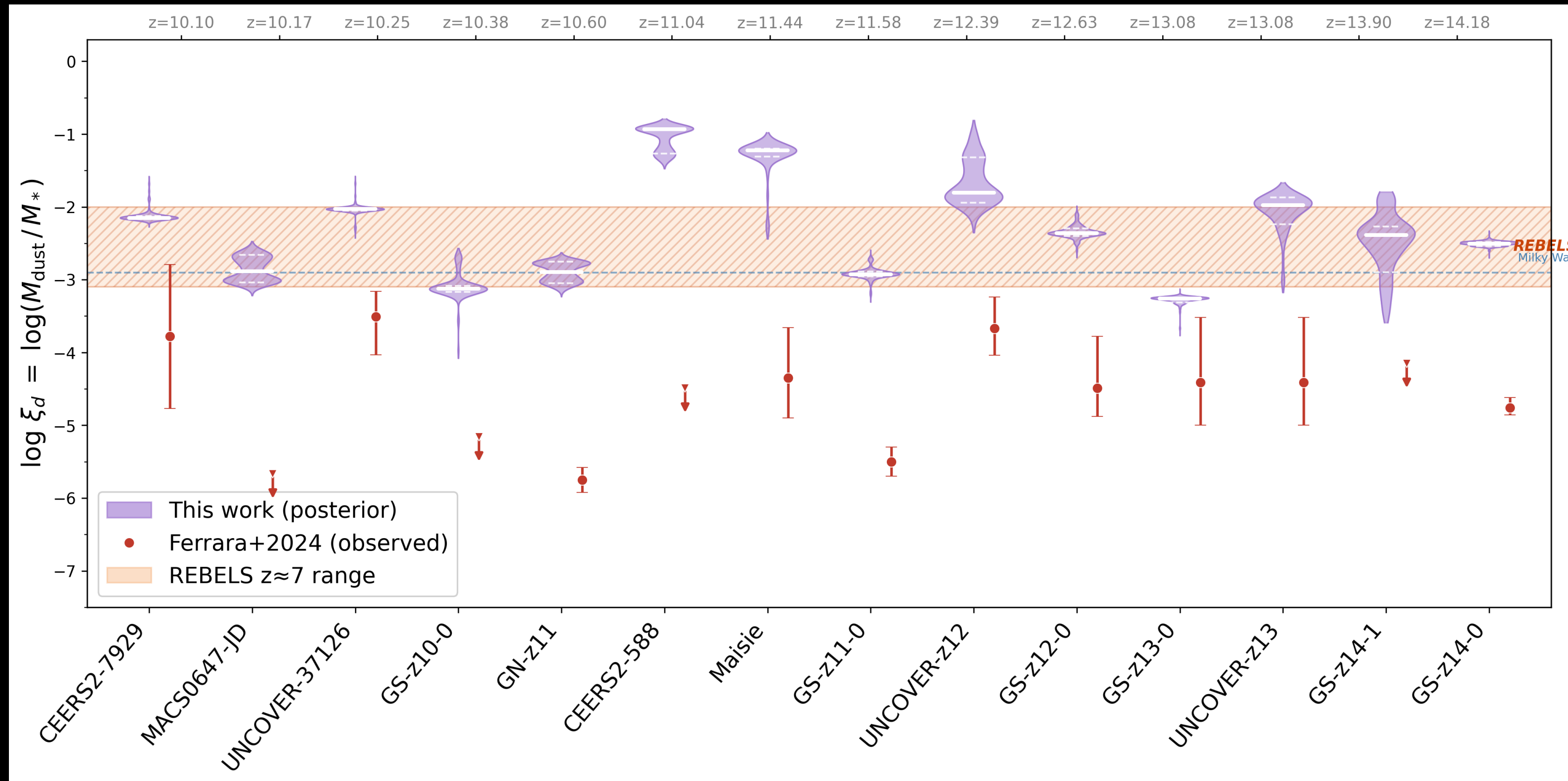
Table 1. Relevant properties of spectroscopically confirmed super-early galaxies at $z > 10$.

ID (1)	Redshift (2)	A_V [mag] (3)	$\log(Z/Z_\odot)$ (4)	r_e [pc] (5)	$\log(M_d/M_\odot)$ (6)	$\log(M_\star/M_\odot)$ (7)	$\log \xi_d$ (8)
CEERS2-7929 ^(a)	10.10	$0.14^{+0.29}_{-0.14}$	—	520^{+127}_{-127}	$5.2^{+10.9}_{-5.2} \times 10^4$	$8.50^{+0.30}_{-0.40}$	$-3.78^{+0.99}_{-0.99}$
MACS0647-JD ^(b)	10.17	<0.01	$-0.90^{+0.09}_{-0.09}$	70^{+24}_{-24}	$<6.7 \times 10^1$	$7.50^{+0.10}_{-0.10}$	<-5.67
UNCOVER-37126 ^(c)	10.25	^(*) $0.18^{+0.14}_{-0.14}$	—	426^{+40}_{-42}	$4.5^{+3.5}_{-3.5} \times 10^4$	$8.16^{+0.08}_{-0.07}$	$-3.51^{+0.35}_{-0.35}$
GS-z10-0 ^(d)	10.38	$0.05^{+0.03}_{-0.02}$	$-1.91^{+0.25}_{-0.20}$	<62	$<2.6 \times 10^2$	$7.58^{+0.19}_{-0.20}$	<-5.16
GN-z11 ^(e)	10.60	$0.17^{+0.03}_{-0.03}$	$-0.92^{+0.06}_{-0.05}$	64^{+20}_{-20}	$9.6^{+3.4}_{-3.4} \times 10^3$	$8.73^{+0.06}_{-0.06}$	$-5.75^{+0.17}_{-0.17}$
CEERS2-588 ^(a)	11.04	$0.10^{+0.11}_{-0.07}$	$-0.84^{+0.16}_{-0.12}$	<477	$<3.1 \times 10^4$	$8.99^{+0.54}_{-0.22}$	<4.49
Maisie ^(f)	11.44	$0.07^{+0.09}_{-0.05}$	—	340^{+14}_{-14}	$1.1^{+1.4}_{-1.1} \times 10^4$	$8.40^{+0.30}_{-0.40}$	$-4.35^{+0.69}_{-0.69}$
GS-z11-0 ^(d)	11.58	$0.18^{+0.06}_{-0.06}$	$-1.87^{+0.28}_{-0.18}$	^(†) 77^{+8}_{-8}	$1.5^{+0.5}_{-0.5} \times 10^3$	$8.67^{+0.08}_{-0.13}$	$-5.50^{+0.20}_{-0.20}$
GHZ2 ^(g)	12.34	$0.04^{+0.07}_{-0.03}$	$-1.40^{+0.27}_{-0.24}$	105^{+9}_{-9}	$6.1^{+10.6}_{-6.1} \times 10^2$	$9.05^{+0.10}_{-0.25}$	$-6.27^{+0.80}_{-0.80}$
UNCOVER-z12 ^(c)	12.39	$0.19^{+0.17}_{-0.10}$	$-1.34^{+0.60}_{-0.42}$	426^{+40}_{-42}	$4.7^{+4.2}_{-4.2} \times 10^4$	$8.35^{+0.14}_{-0.18}$	$-3.67^{+0.43}_{-0.43}$
GS-z12-0 ^(d)	12.63	$0.05^{+0.03}_{-0.02}$	$-1.44^{+0.23}_{-0.22}$	^(†) 144^{+15}_{-15}	$1.4^{+0.9}_{-0.9} \times 10^3$	$7.64^{+0.66}_{-0.39}$	$-4.49^{+0.71}_{-0.71}$
UNCOVER-z13 ^(c)	13.08	$0.04^{+0.08}_{-0.03}$	$-1.57^{+0.35}_{-0.28}$	309^{+110}_{-74}	$5.2^{+10.7}_{-5.2} \times 10^3$	$8.13^{+0.11}_{-0.15}$	$-4.41^{+0.89}_{-0.89}$
GS-z13-0 ^(d)	13.20	$0.05^{+0.03}_{-0.02}$	$-1.69^{+0.28}_{-0.31}$	<52	$<1.9 \times 10^2$	$7.95^{+0.19}_{-0.29}$	<-5.68
GS-z14-1 ^(h)	13.90	$0.20^{+0.11}_{-0.07}$	$-1.10^{+0.60}_{-0.50}$	<160	$<7.0 \times 10^3$	$8.00^{+0.40}_{-0.30}$	<-4.15
GS-z14-0 ^(h)	14.18	$0.31^{+0.14}_{-0.17}$	$-0.75^{+0.03}_{-0.03}$	260^{+2}_{-2}	$1.2^{+0.3}_{-0.3} \times 10^4$	$8.84^{+0.09}_{-0.10}$	$-4.76^{+0.14}_{-0.14}$

- Most of the JWST $z > 10$ galaxies are **compact**, yet significantly brighter than expected
- They would require **extreme efficiency** of gas to star conversion. (e.g. Bolyan-Kolcin *Nat.Ast.* '23)
- They are almost devoid of dust

Table from Ferrara et al. A&A, 694, A286 (2025)

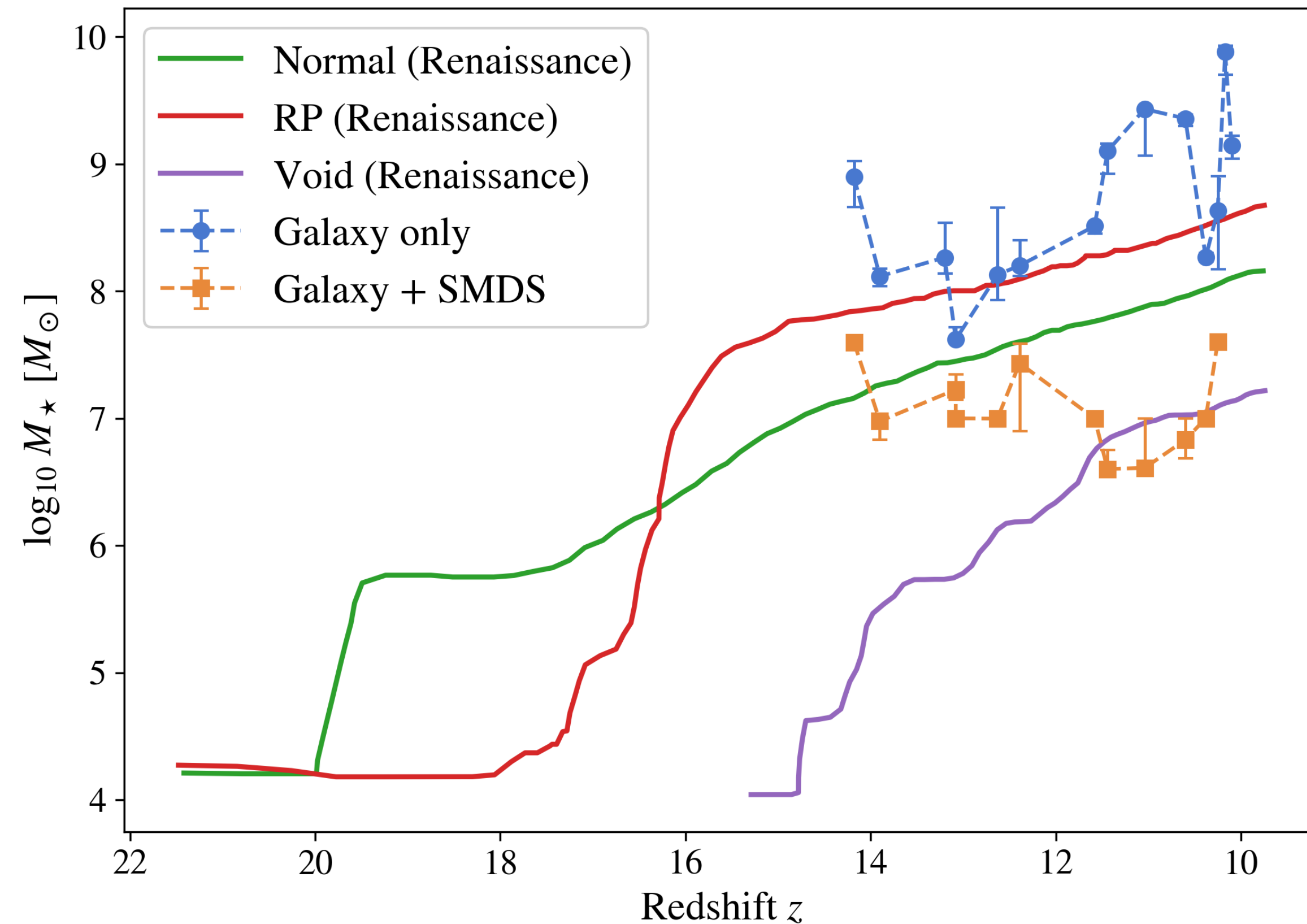
Observational puzzle III. **SMDS** can solve: Blue Monsters



CI & Shafaat Mahmud (in progress)

- Most of the JWST $z > 10$ galaxies are **compact**, yet significantly brighter than expected
- They would require **extreme efficiency** of gas to star conversion. (e.g. Bolyan-Kolcin *Nat.Ast.* '23)
- They are almost devoid of dust

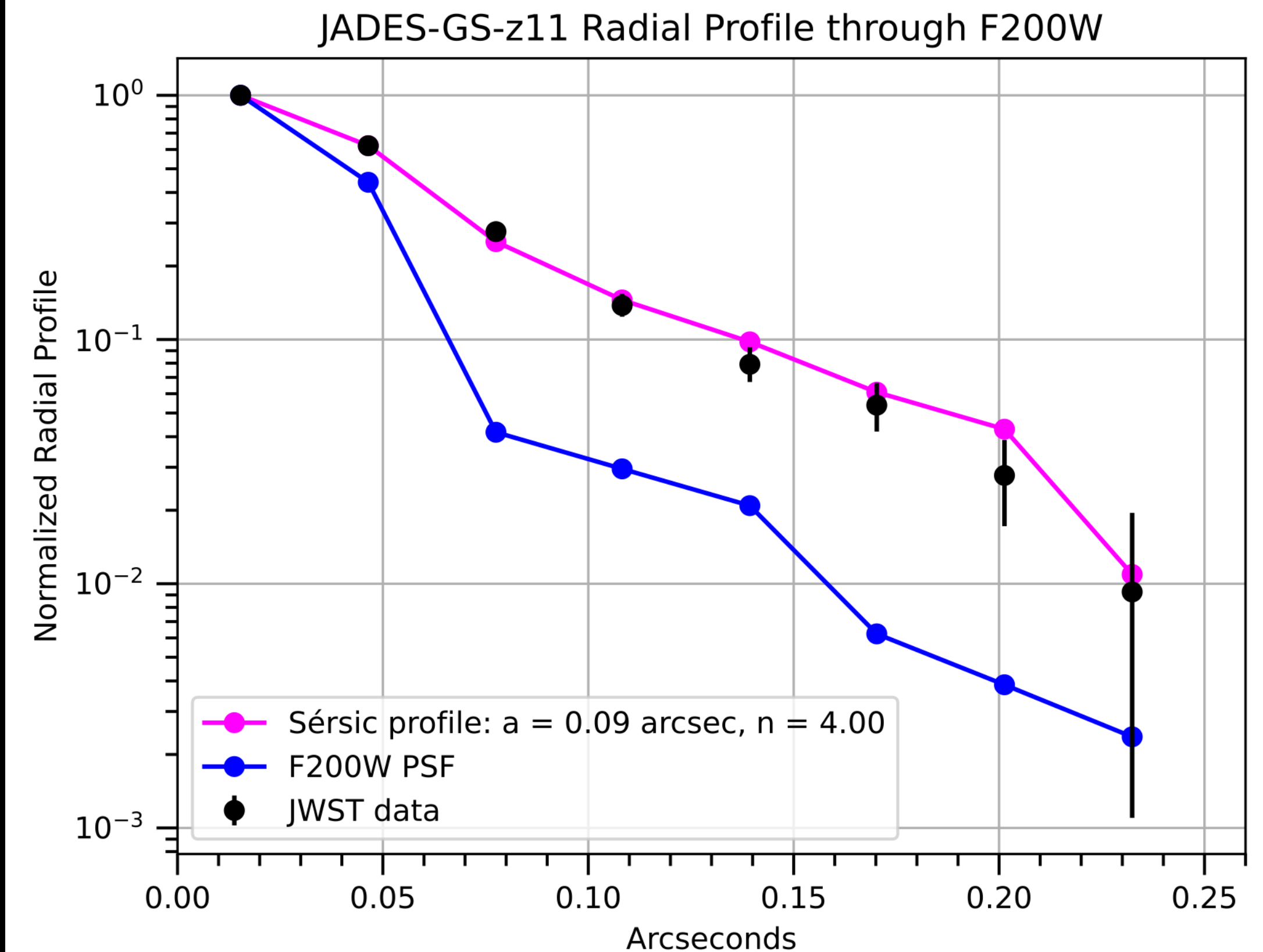
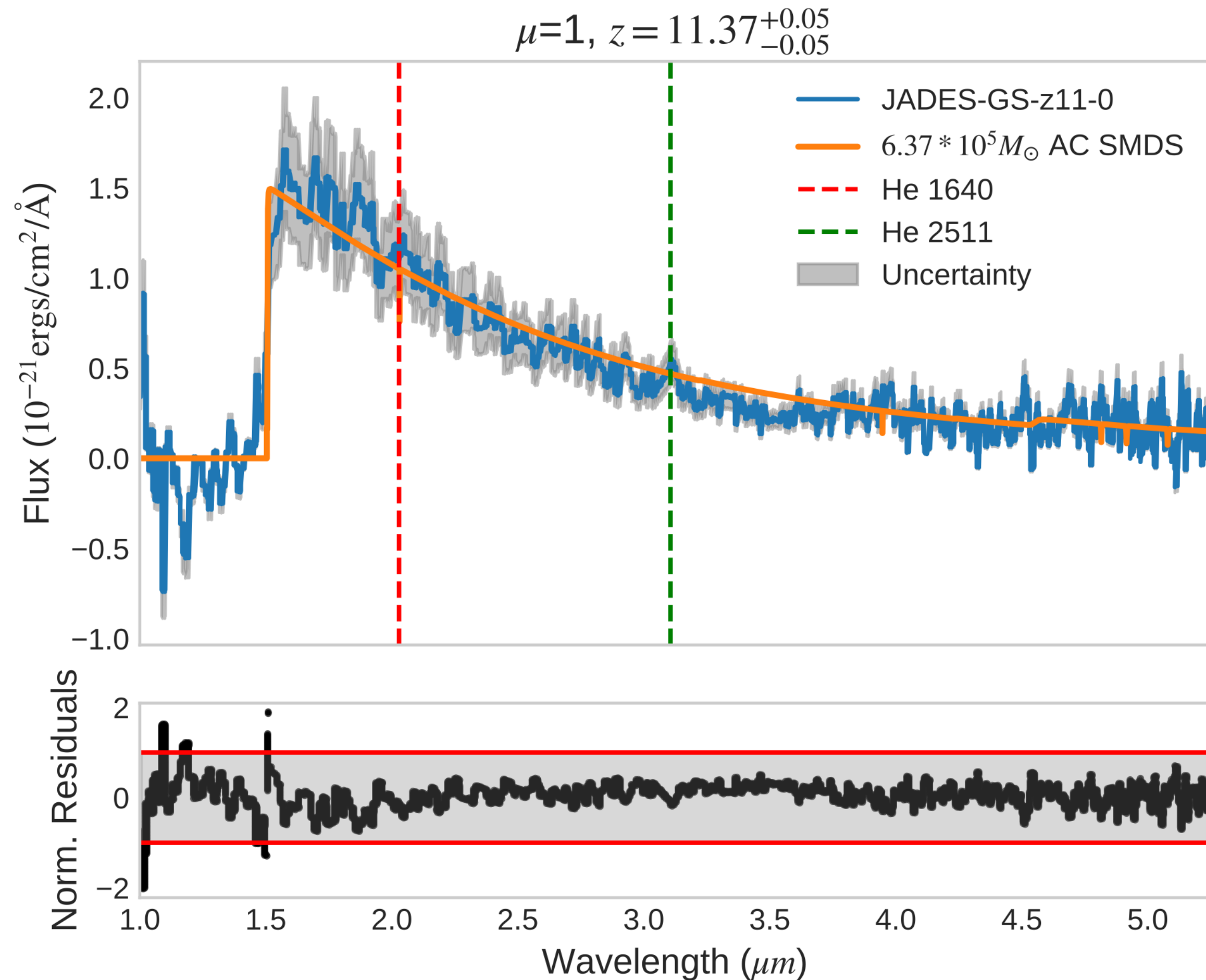
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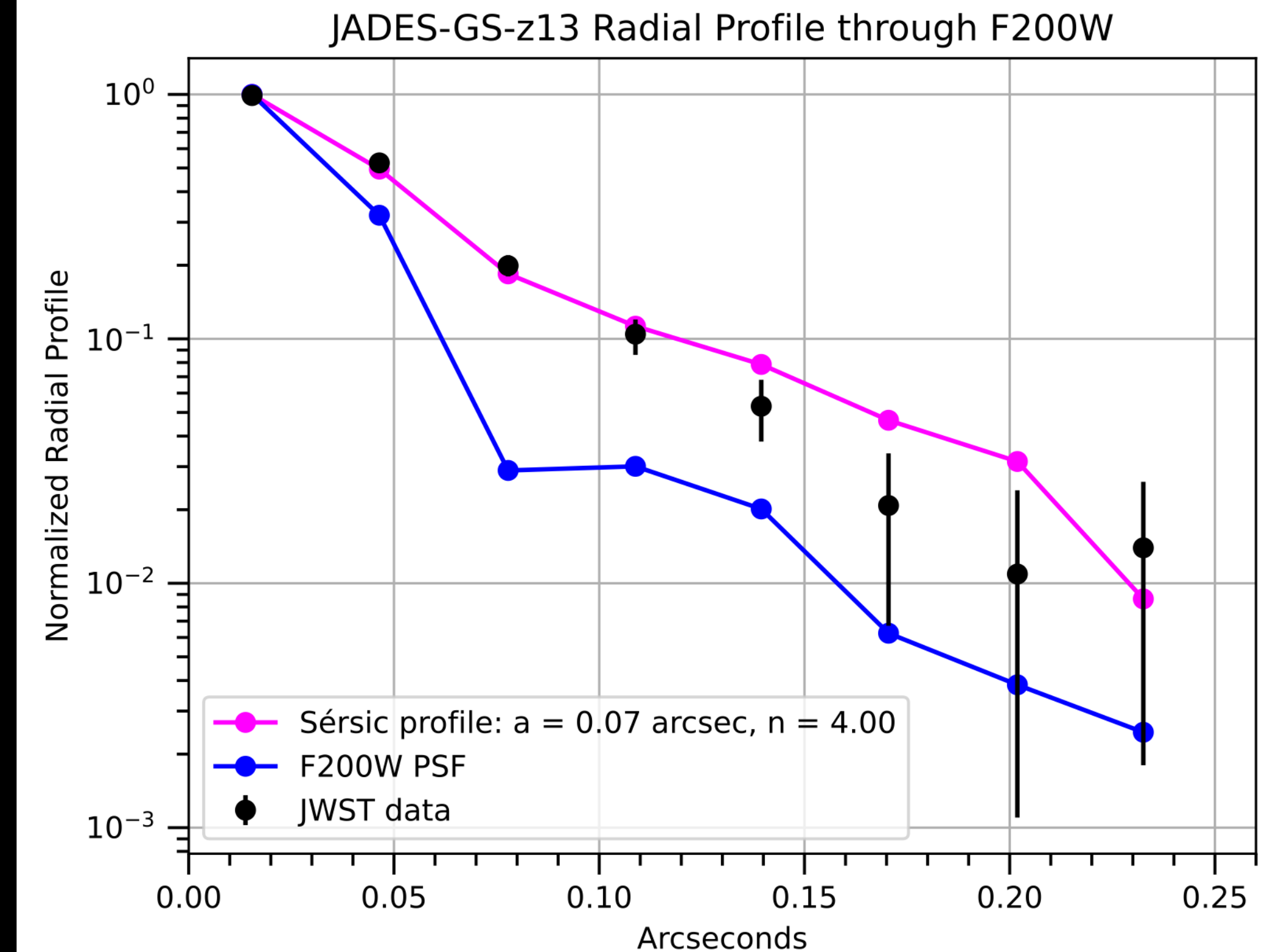
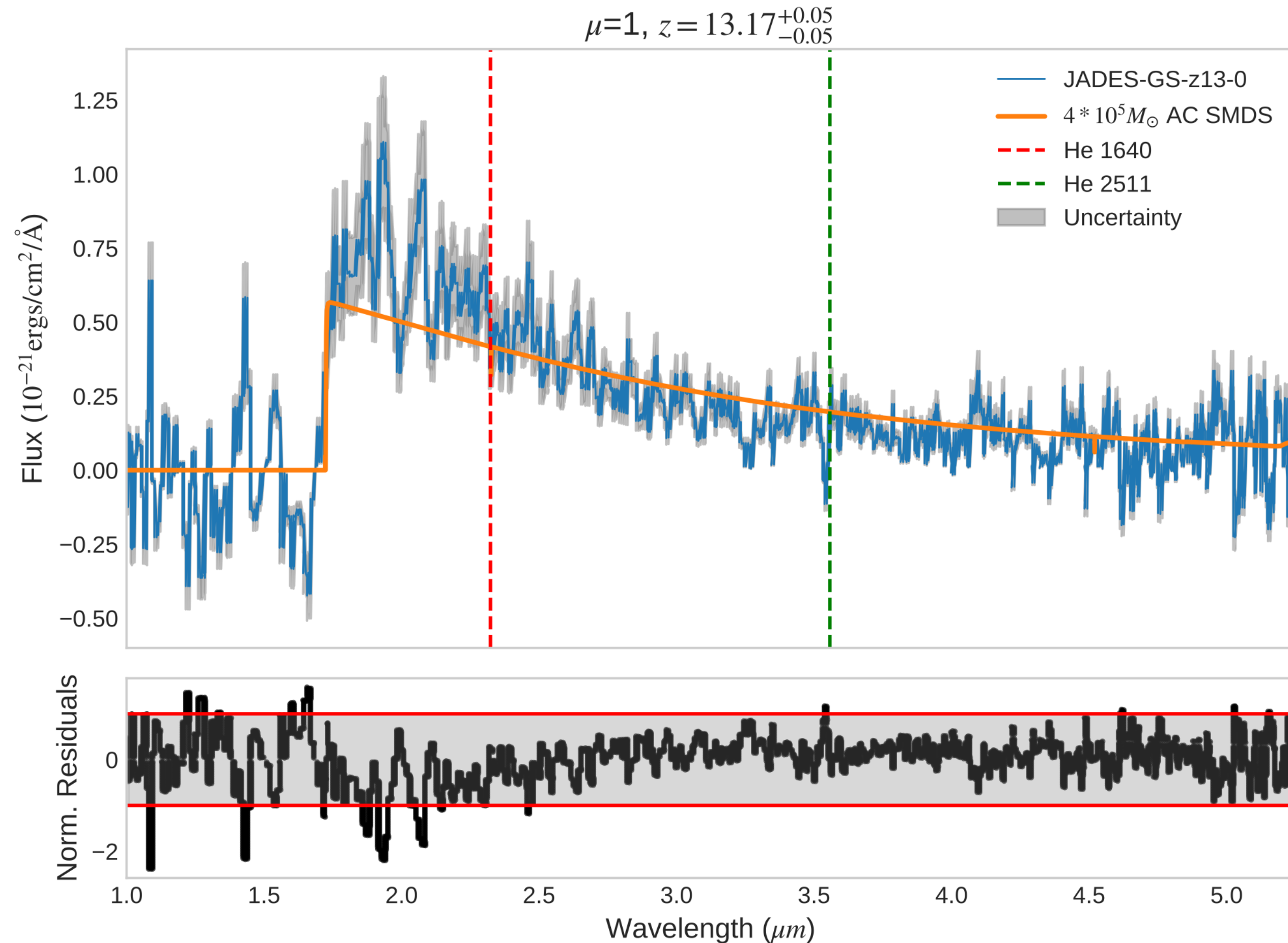
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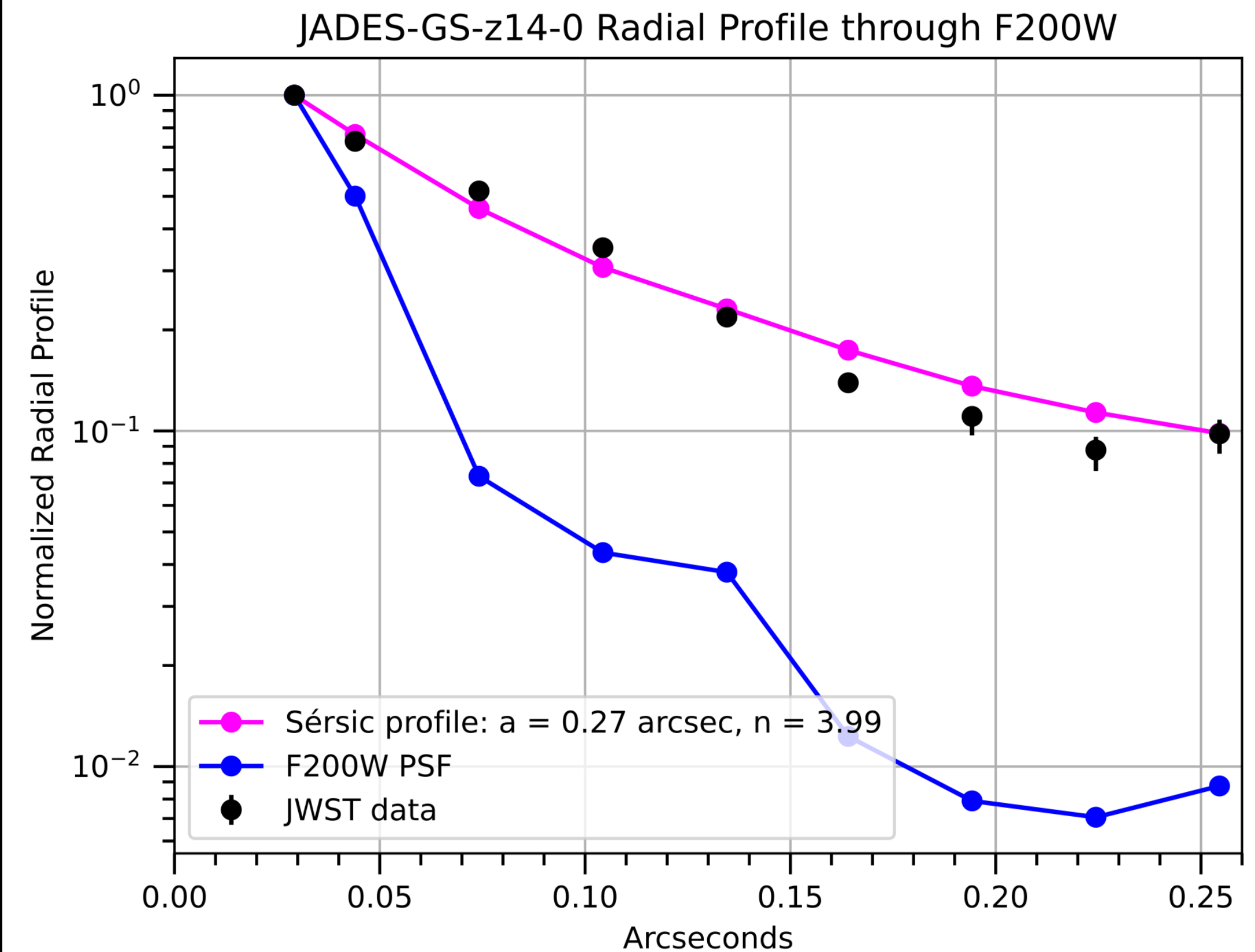
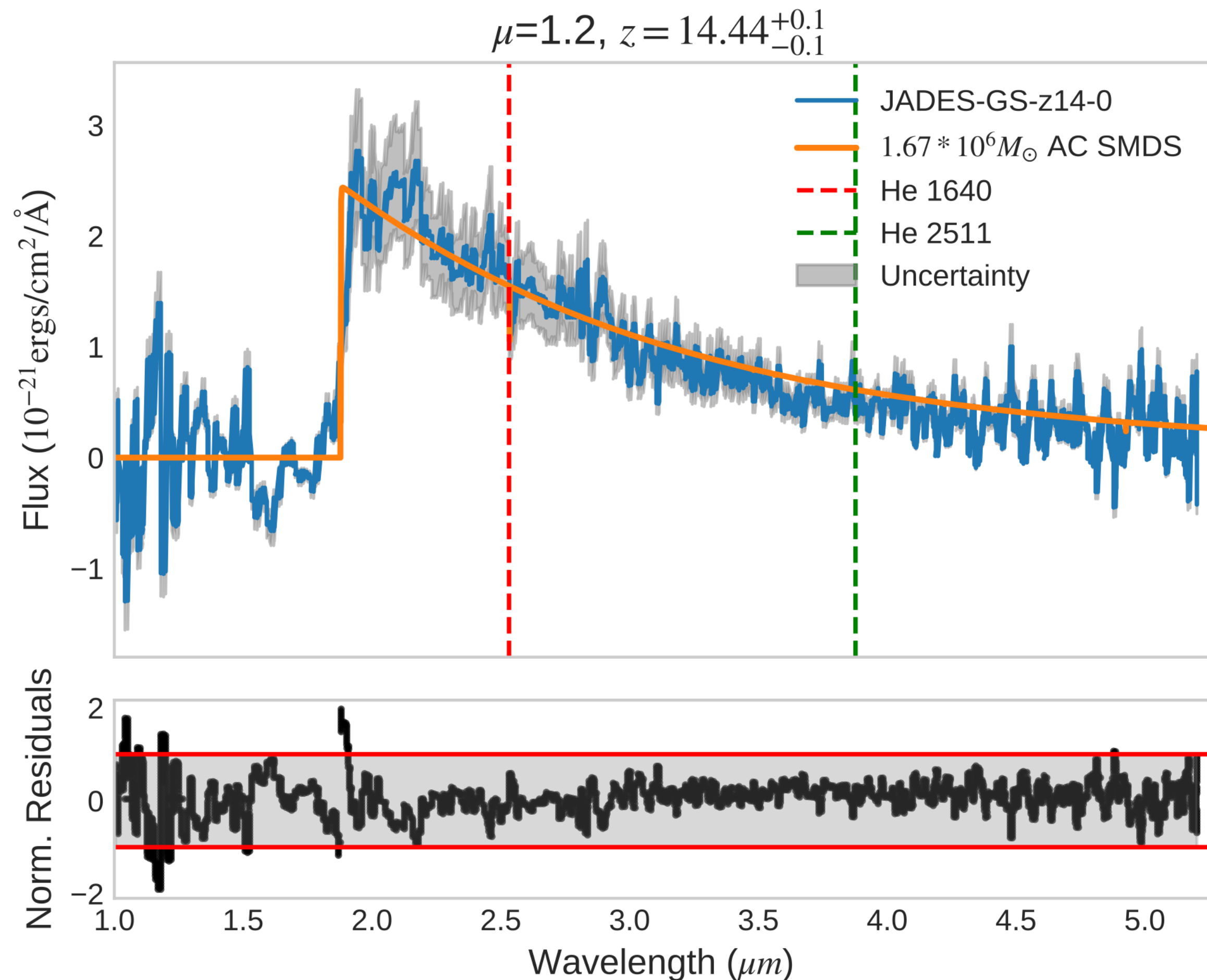
JADES-GS-z11-0 Spectra and Morphology



JADES-GS-z13-0 Spectra and Morphology



JADES-GS-z14-0 Spectra and Morphology



SGWB from DS Seeded SMBHs can explain PTA data

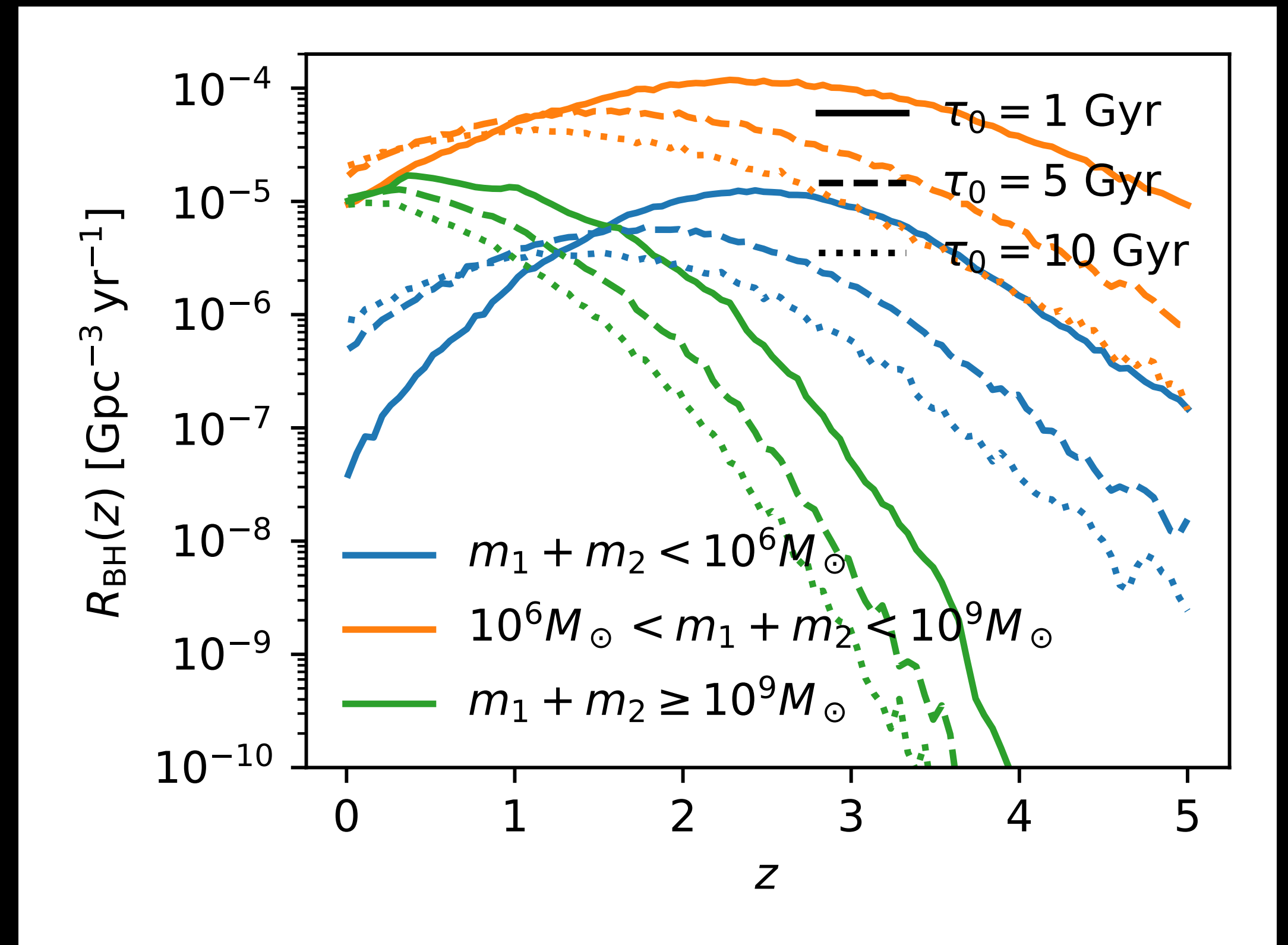
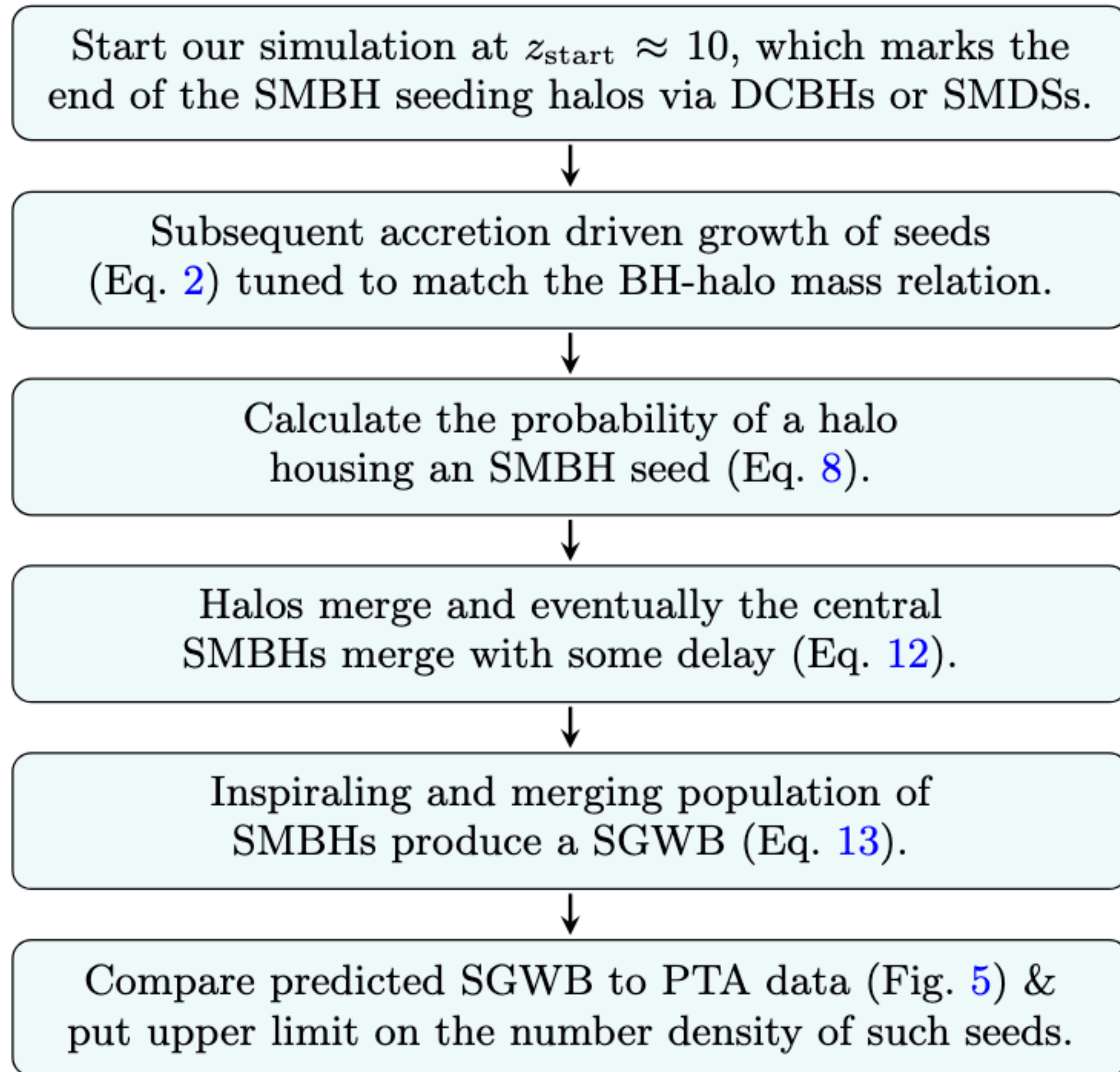


Fig from: Ghodla & Ilie 2507.06163

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CEERS 99715 Best Evidence for a SMDS yet

