Dark Recipe for the First Giants

From Population III Stars to Early Supermassive Black Holes via Dark Matter Capture

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CHEP, IISc, Bengaluru, India

Based on arXiv:2512.23789 done in collaboration with

Sulagna Bhattacharya, Prof. Basudeb Dasgupta, Jaya Doliya, Prof. Ranjan Laha

Identification of Dark Matter (IDM) 2026
2nd June, 2026

Outline:

- What are Supermassive black holes (SMBHs)?
- How are SMBHs detected?
- Astrophysical seed formation mechanisms
- Black hole seed via dark matter (DM) capture (via beyond standard model interactions)
- SMBH mass function, galaxy stellar mass
- Gravitational wave signatures
- Conclusion

What are Supermassive Black Holes (SMBHs):

- SMBHs are black holes with masses $\geq 10^6 \, M_\odot$
- Our Milky Way SMBH is Sagittarius A* (Sgr A*) $(z = 0)$
- Mass of Sgr A* is $4.297 \times 10^6 \, M_\odot \sim 10^{-6} \, M_{\rm MW}$

What are Supermassive Black Holes (SMBHs):

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Telescopes:

For high redshifts: $(z \gtrsim 5)$

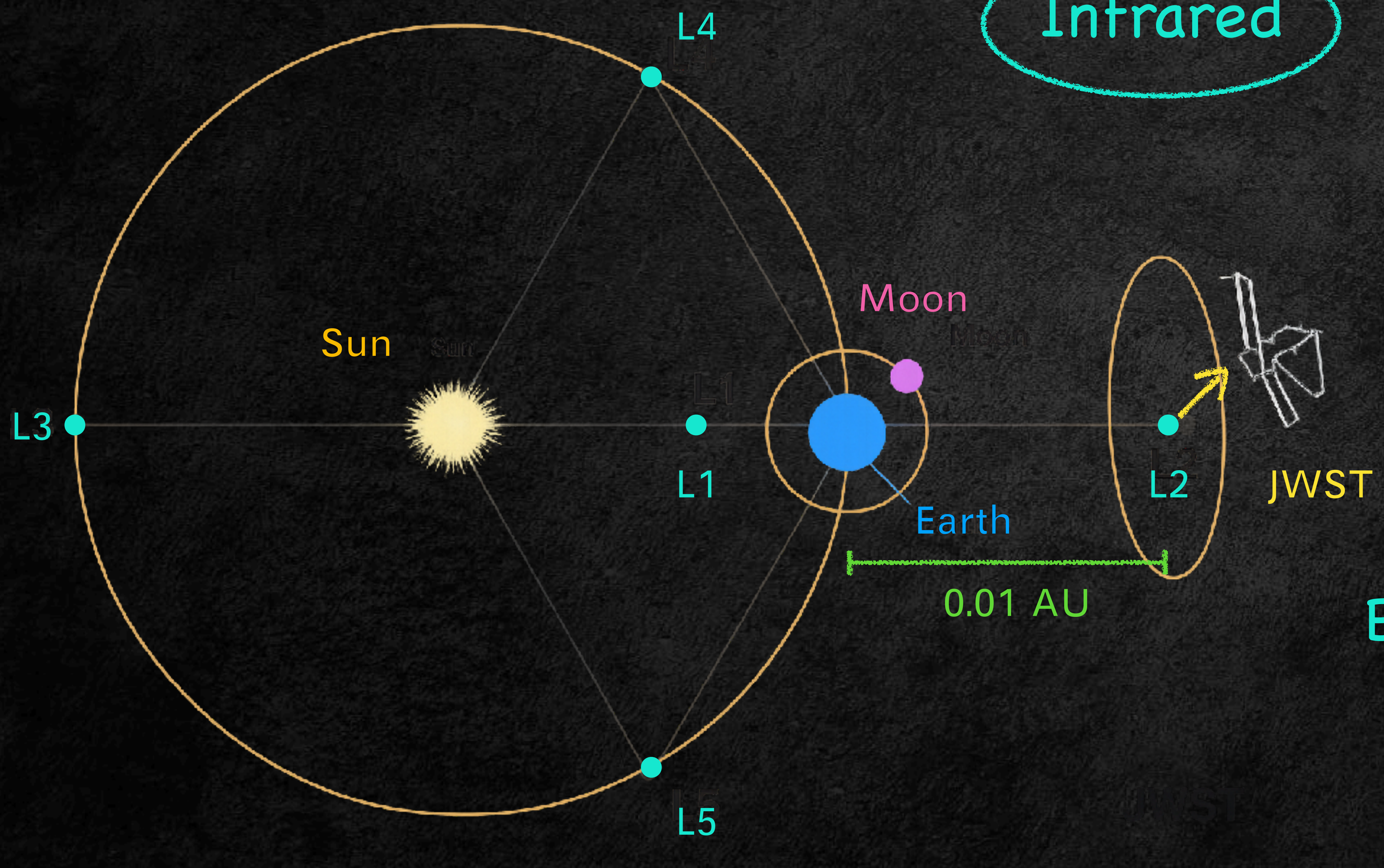
- Sloan Digital Sky Survey Telescope (SDSS) - New Mexico, USA
  Imaging: 300 - 1000 nm, Spectroscopy: 380 - 920 nm
- Subaru 8.2m Telescope - Mauna Kea, Hawaii, USA
  Imaging: 400 nm - 1000 nm, Spectroscopy: 370 nm - 1000 nm, 1 - 2.5 μm
- Very Large Telescope (VLT) - Mauna Kea, Hawaii, USA
  Imaging: 330 - 1100 nm, Spectroscopy: 0.3 - 2.5 μm , and many more..

} Ground based

Telescopes: For high redshifts: $(z \gtrsim 5)$

James Webb Space Telescope (Space based)

Infrared



JWST orbit

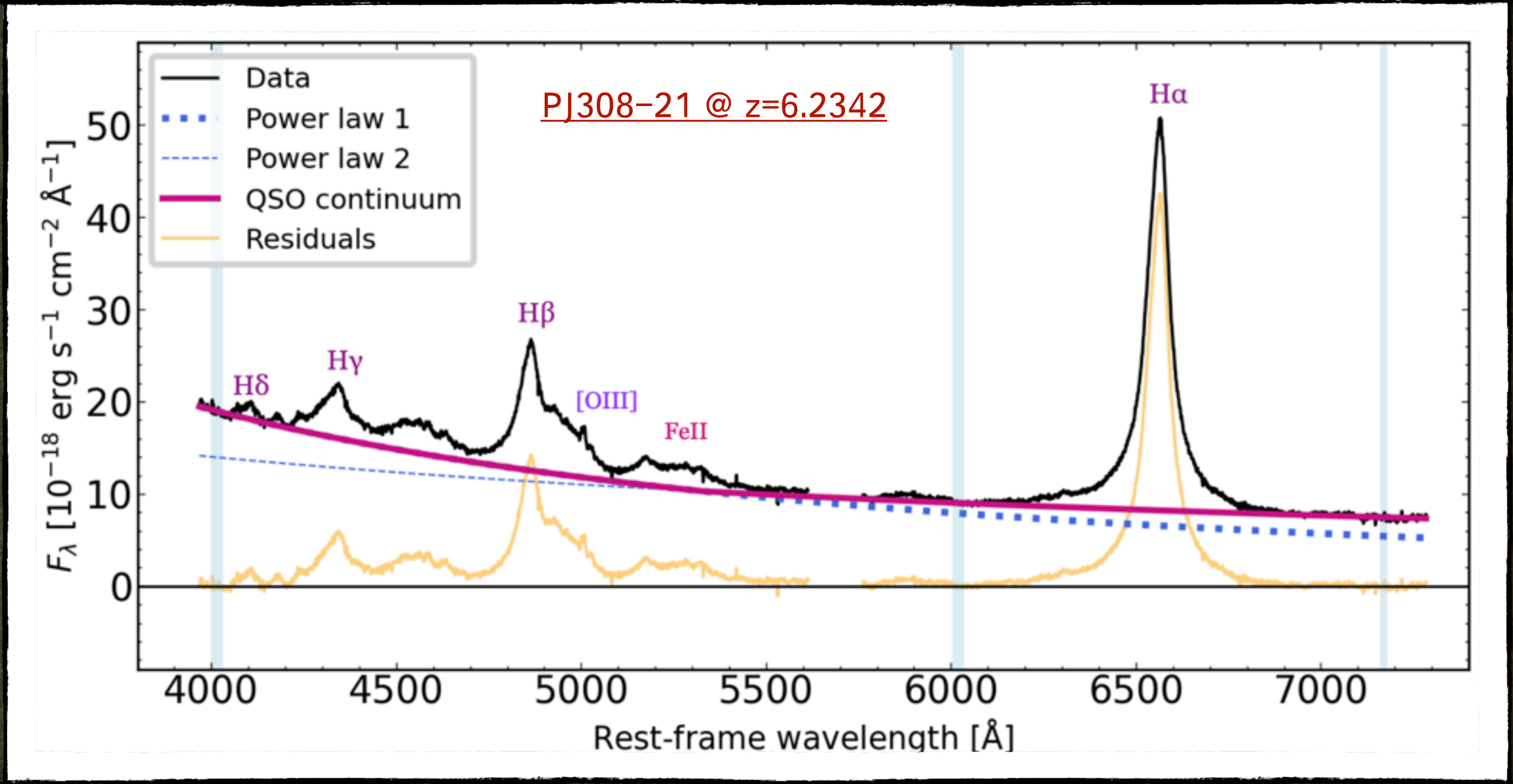
$$\lambda_{obs} = \lambda_{rest}(1+z)$$

for $z \gtrsim 5$

Emission frequency redshifts towards infrared regime!

How are SMBHs detected?

Loiacono et al. – A&A 685, A121 (2024)



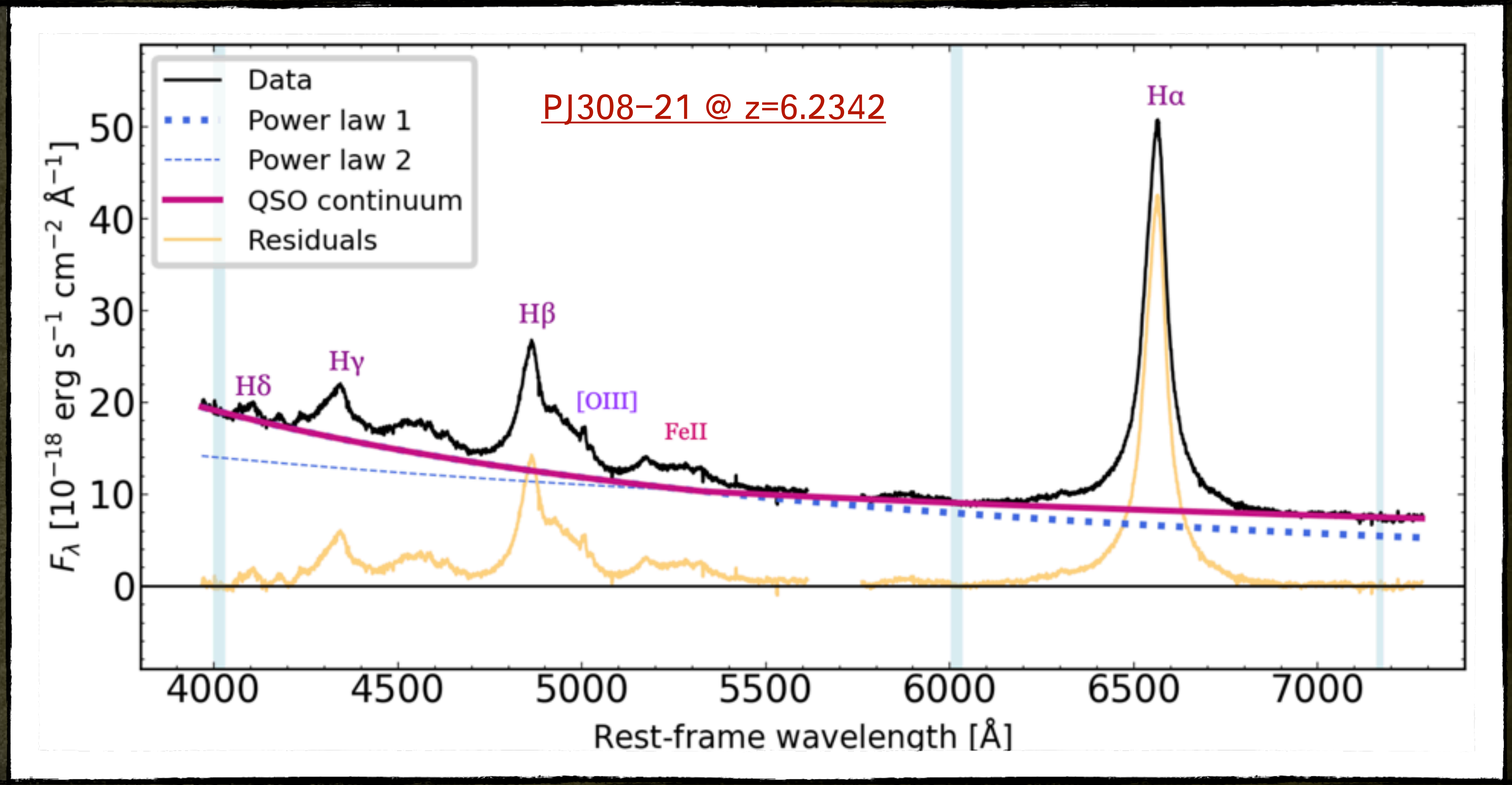
There are emission lines in the spectra due to recombination and excitation

- Precise redshift measurement:

After determining λ_{obs} for transition lines like $\mathrm{H}\alpha$, $\mathrm{H}\beta$, $\mathrm{Mg\,II}$, $\mathrm{O\,III}$, etc .

$$z = \frac{\lambda_{obs}}{\lambda_{rest}} - 1$$

How are SMBHs detected?



There are emission lines in the spectra due to recombination and excitation

- Black hole mass estimate:

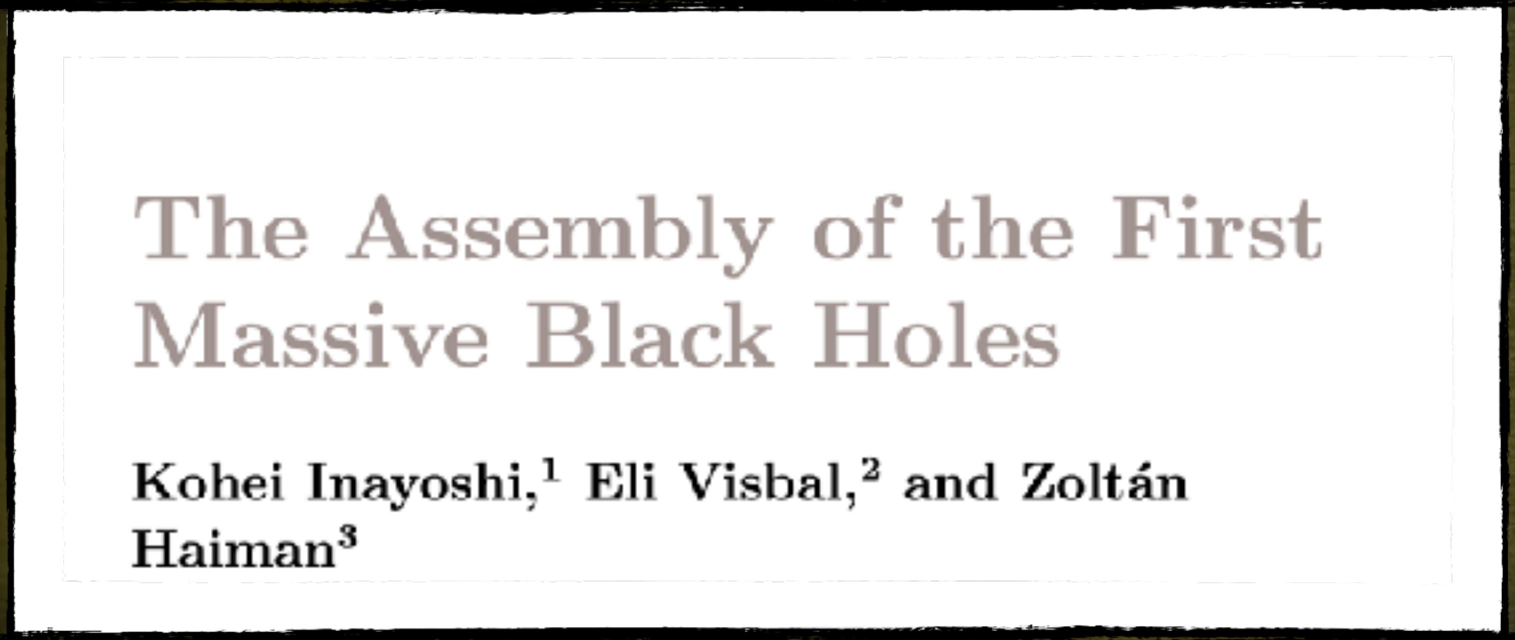
After determining $\Delta\lambda_{obs}$ for transition lines like $H\alpha$, $H\beta$, Mg II, O III, etc .

$$M_{BH} \propto (\Delta v)^2 \propto \left(\frac{\Delta\lambda}{\lambda_{rest}}\right)^2$$

Detected SMBHs at high redshifts:

Pre-JWST

(SDSS, Subaru, etc.)


The Assembly of the First Massive Black Holes

Kohei Inayoshi,[1] Eli Visbal,[2] and Zoltán Haiman[3]

JWST


THE ASTROPHYSICAL JOURNAL LETTE

OPEN ACCESS

Hidden Little Monsters: Spectroscopic Identifica
mass, Broad-line AGNs at $z > 5$ with CEERS

Dale D. Kocevski, Masafusa Onoue, Kohei Inayoshi, Jonathan R. Trump, Pa
Andrea Grazian, Mark Dickin


THE ASTROPHYSICAL JOURNAL

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Jorryt Matthee, Rohan P. Naidu, Gabriel Brammer, John Chisholm, Anna-Christina Eilers, Andy Goulding, Jenny Greene, Daichi Kashino, Ivo Labbe, Simon J. Lilly ▾ Show full author list

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The Astrophysical Journal, Volume 963, Number 2


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Jenny E. Greene, Ivo Labbe, Andy D. Goulding, Lukas J. Furtak, Iryna Chemerynska, Vasily Kokorev, Pratika Dayal, Marta Volonteri, Christina C. Williams, Bingjie Wang (王冰洁) ▾ Show full author list

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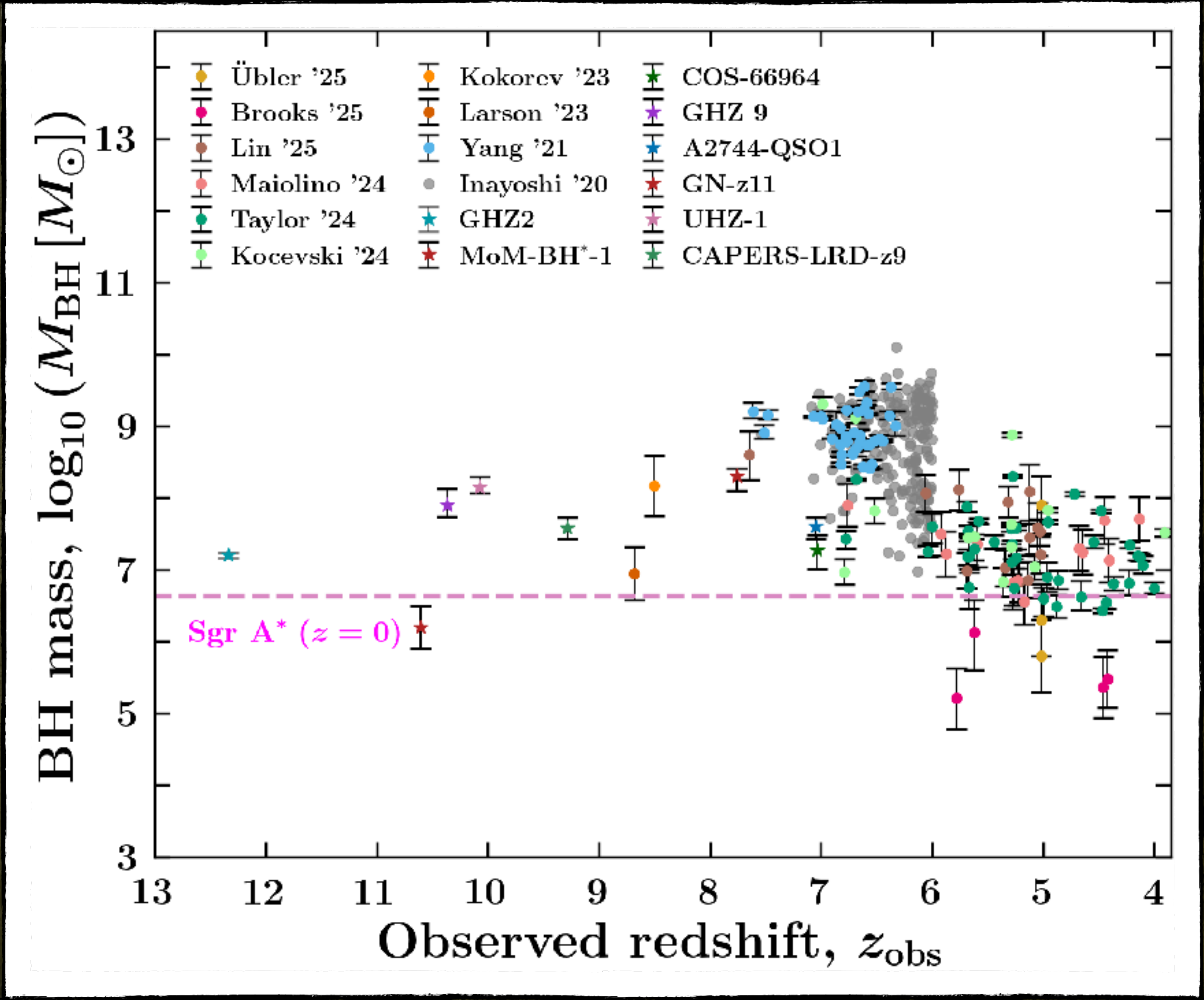
The Astrophysical Journal, Volume 964, Number 1



SMBH masses at high redshifts

Astrophysical ways of SMBH formation:

1. Pop III stars: $z_{\rm obs} \sim 15 - 30,\quad M{\rm seed} \sim \mathcal{O}(10^{1-2})\ M_\odot$

   Death of first-generation metal-free stars (lifetime ~ Myr.)

2. Nuclear Star cluster: $z_{\rm obs} \sim 15 - 20,\quad M{\rm seed} \sim \mathcal{O}(10^{2-3})\ M_\odot$

   Dense stellar clusters at galactic center undergo frequent stellar collisions and mergers

3. Direct Collapse: $z_{\rm obs} \sim 8 - 17,\quad M{\rm seed} \sim \mathcal{O}(10^{4-6})\ M_\odot$

   Pristine collapsing gas in early Universe that escapes star-formation

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Pristine collapsing gas in early Universe that escapes star-formation

Many BSM models explore 3rd possibility via photon injection

Astrophysical ways of SMBH formation:

We explore the premature death of Pop III stars via dark matter accumulation

1. Pop III stars: $z_{\rm obs} \sim 15 - 30$, $M{\rm seed} \sim \mathcal{O}(10^{1-2})\ M_\odot$

   Death of first-generation metal-free stars (lifetime ~ Myr.)

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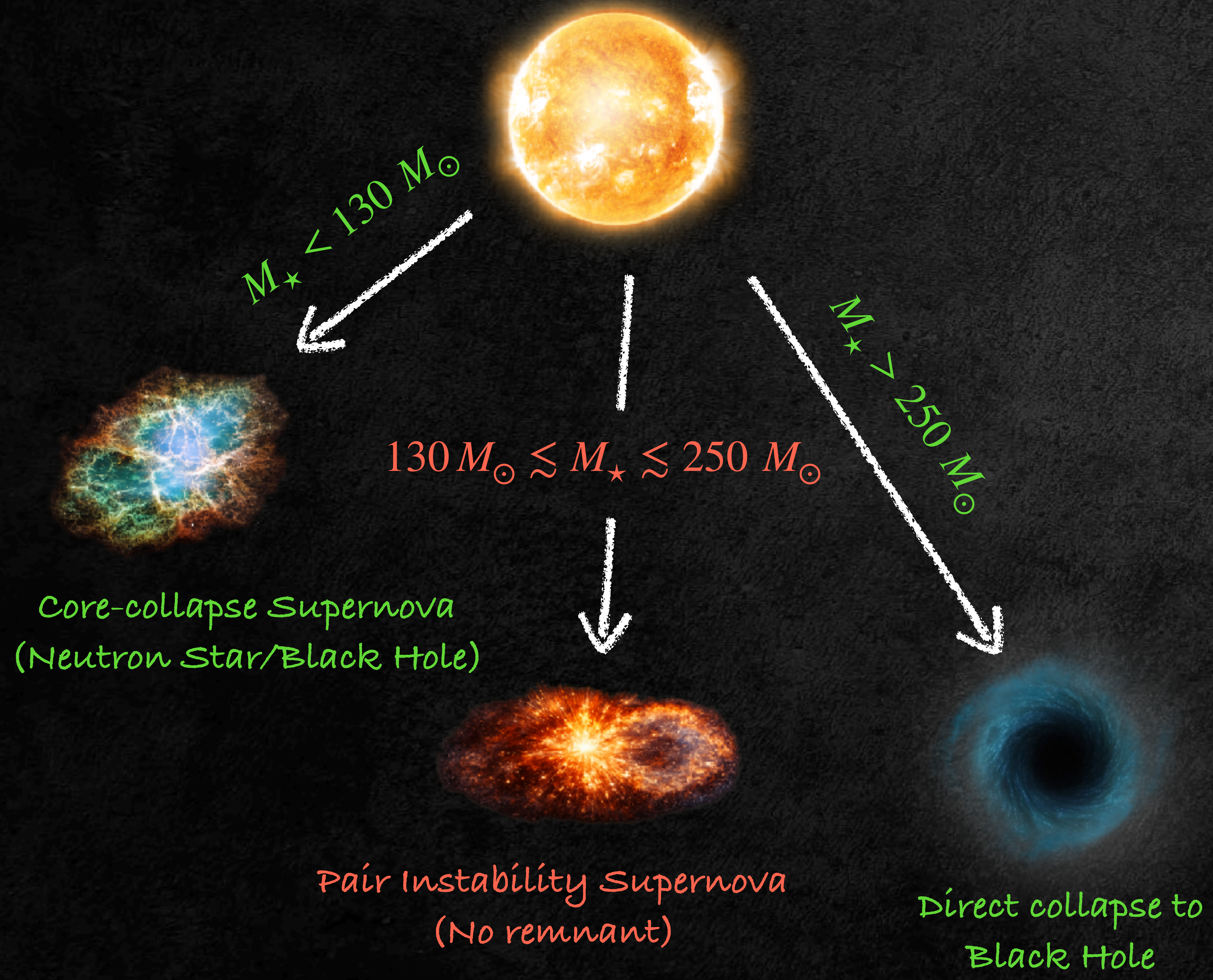
Many BSM models explore 3rd possibility via photon injection

Pop III stars:

First generation stars formed during $z \sim 15 - 30$ (Very small metallicity)

Pop III stars:

Usual Fate



Made with the help of ChatGPT

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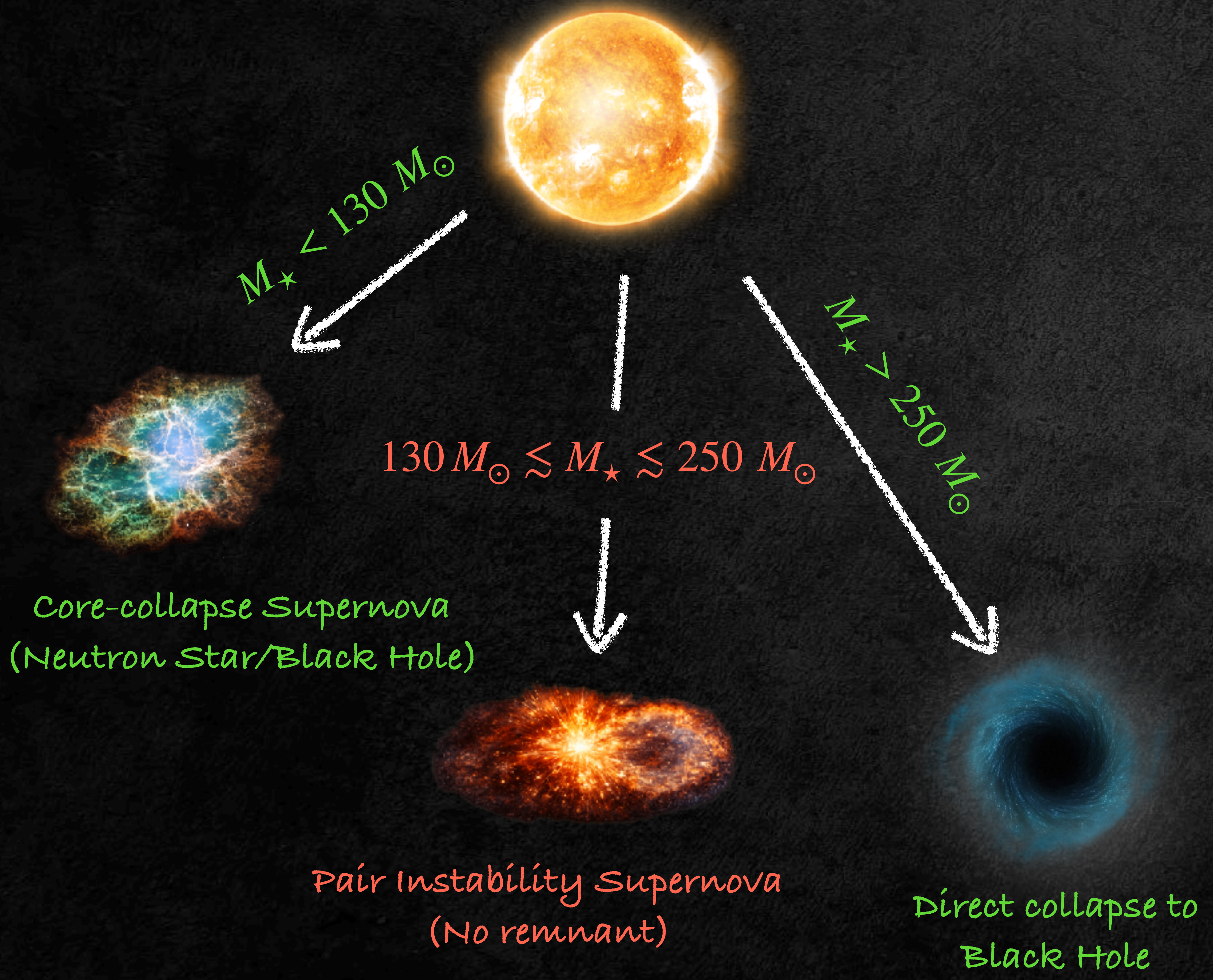
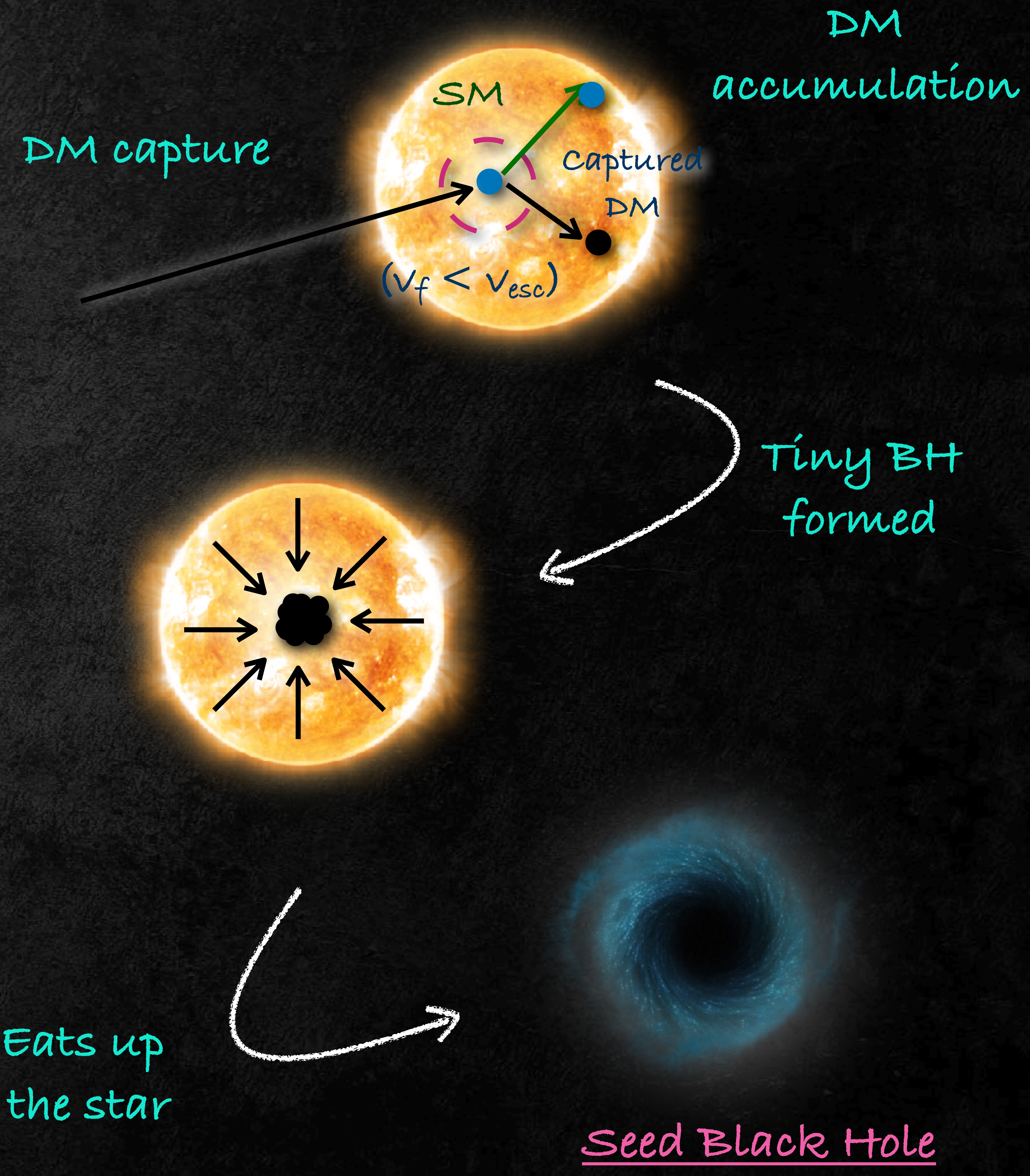


Our Scenario



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Pop III stars:

First generation stars formed during $z \sim 15 - 30$ (Very small metallicity)

Fate of stars: $\left(\text{lifetime, } \tau_{\rm age} \sim \mathcal{O}(1)\,\text{Myr}\right)$

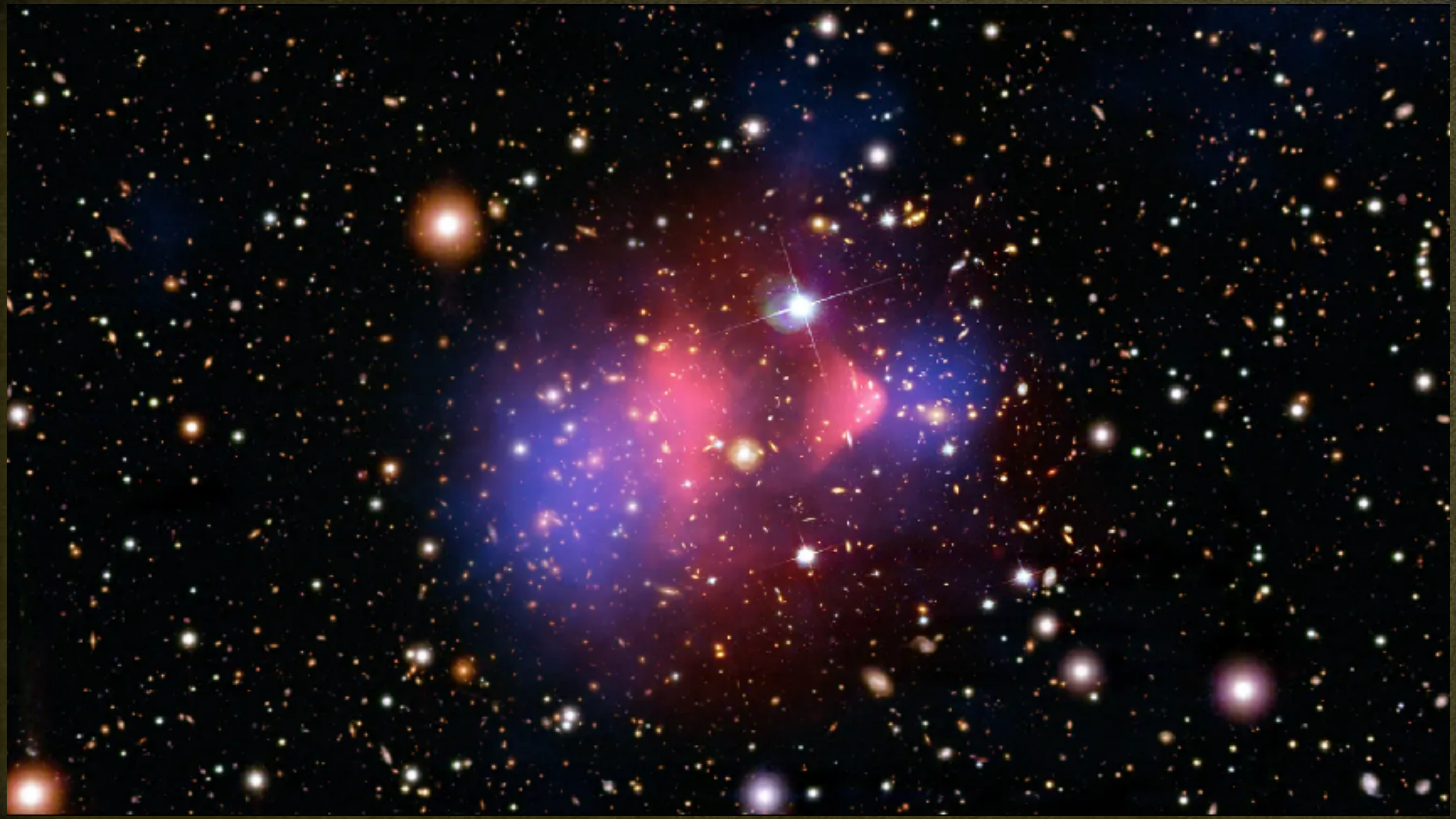
- ⋆ Type II Supernova (Core-Collapse) $\rightarrow \left(M_s < 130\, M_\odot\right)$
- ⋆ Pair-Instability Supernova (PISN) - no remnant $\rightarrow \left(130\, M_\odot \lesssim M_s \lesssim 250\, M_\odot\right)$
- ⋆ Direct collapse to black hole $\rightarrow \left(M_s > 250\, M_\odot\right)$

Advantage of dark accumulation:

- ⋆ Premature death before main-sequence end
- ⋆ All mass Pop-III stars can form black holes

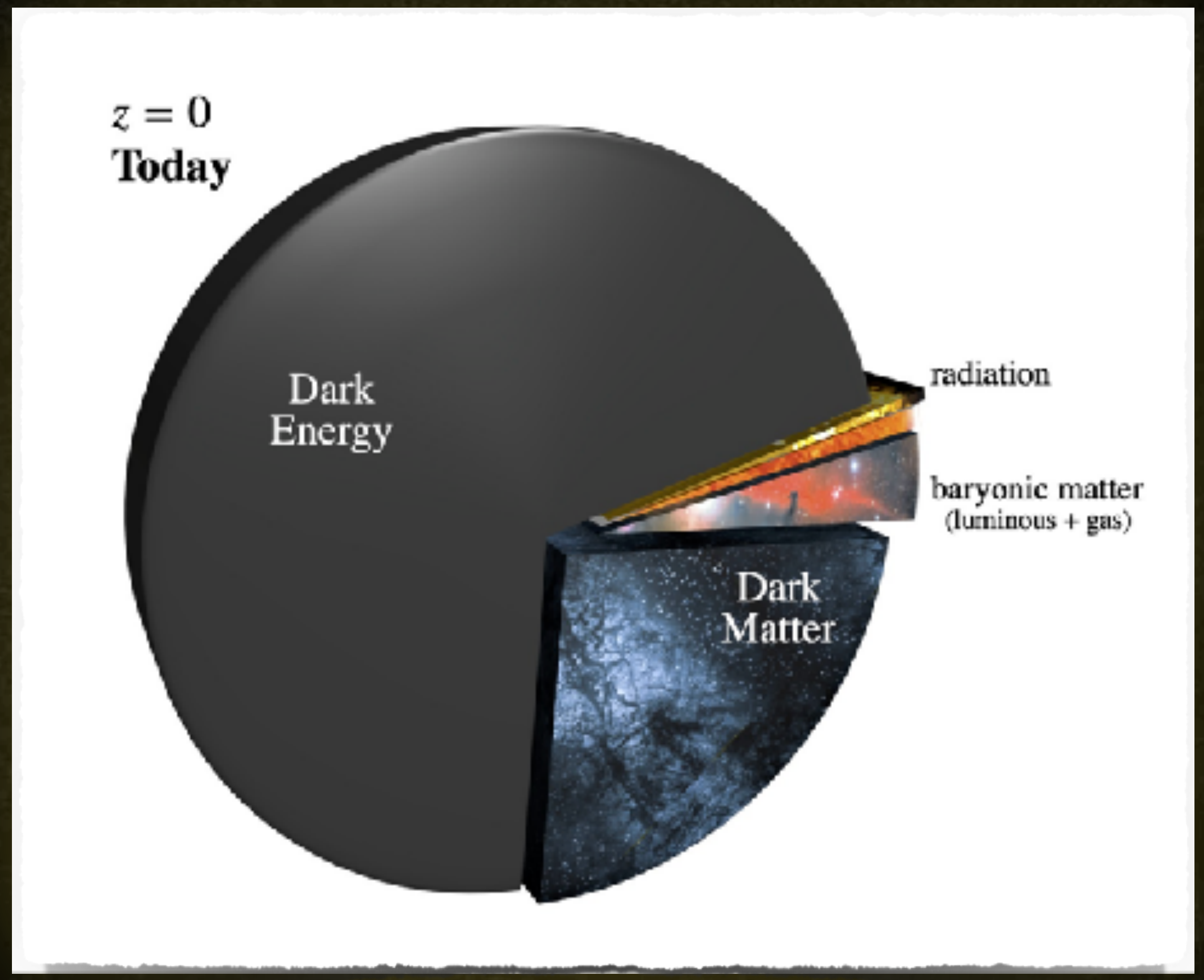
Evidences of Dark Matter:

Bullet Cluster Observation



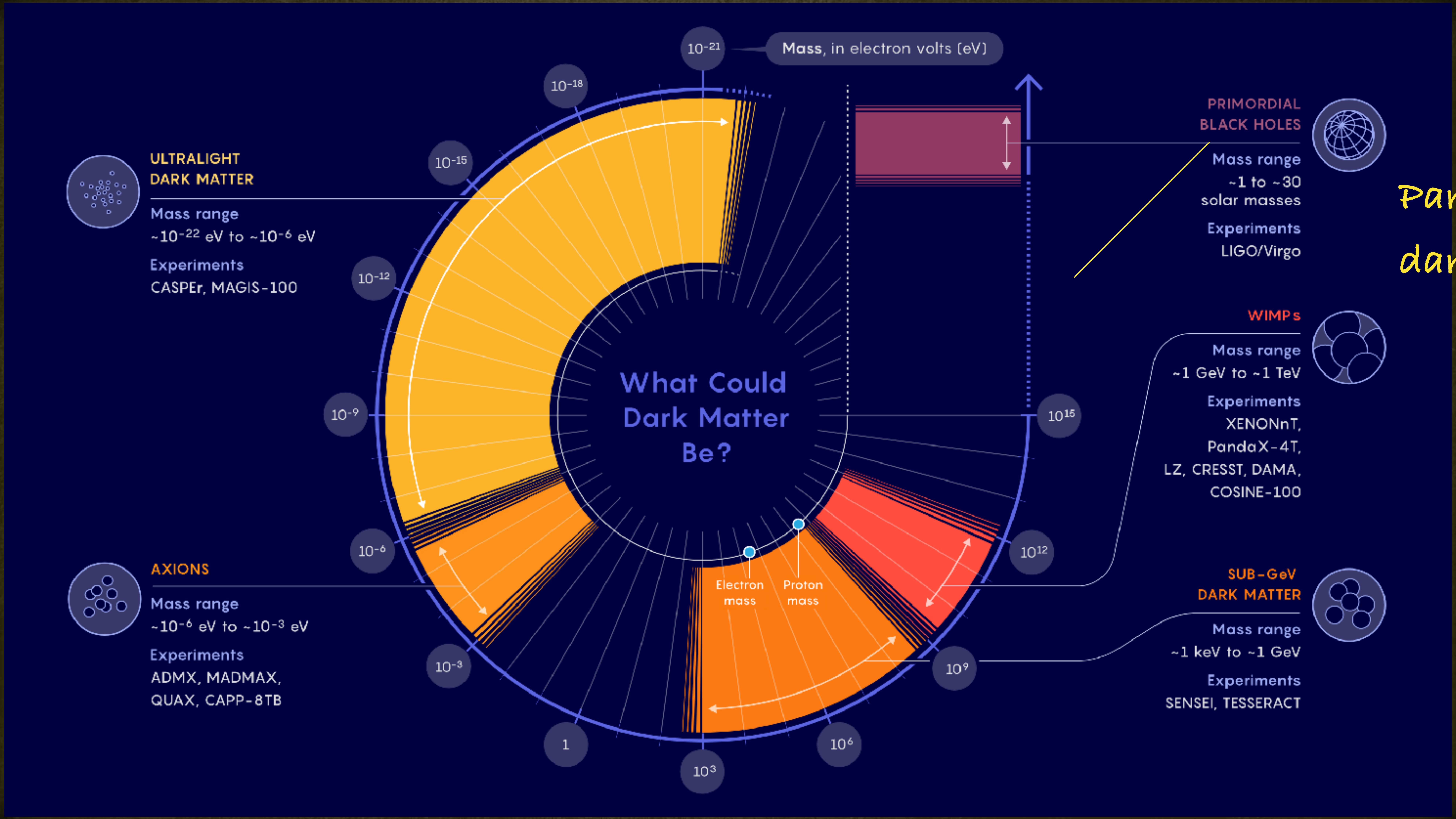
Credit: NASA/CXC/M. Weiss

- Structure formation
- Galaxy rotation curve
- Galaxy cluster dynamics
- Comic Microwave Background Radiation



https://arxiv.org/abs/2406.01705

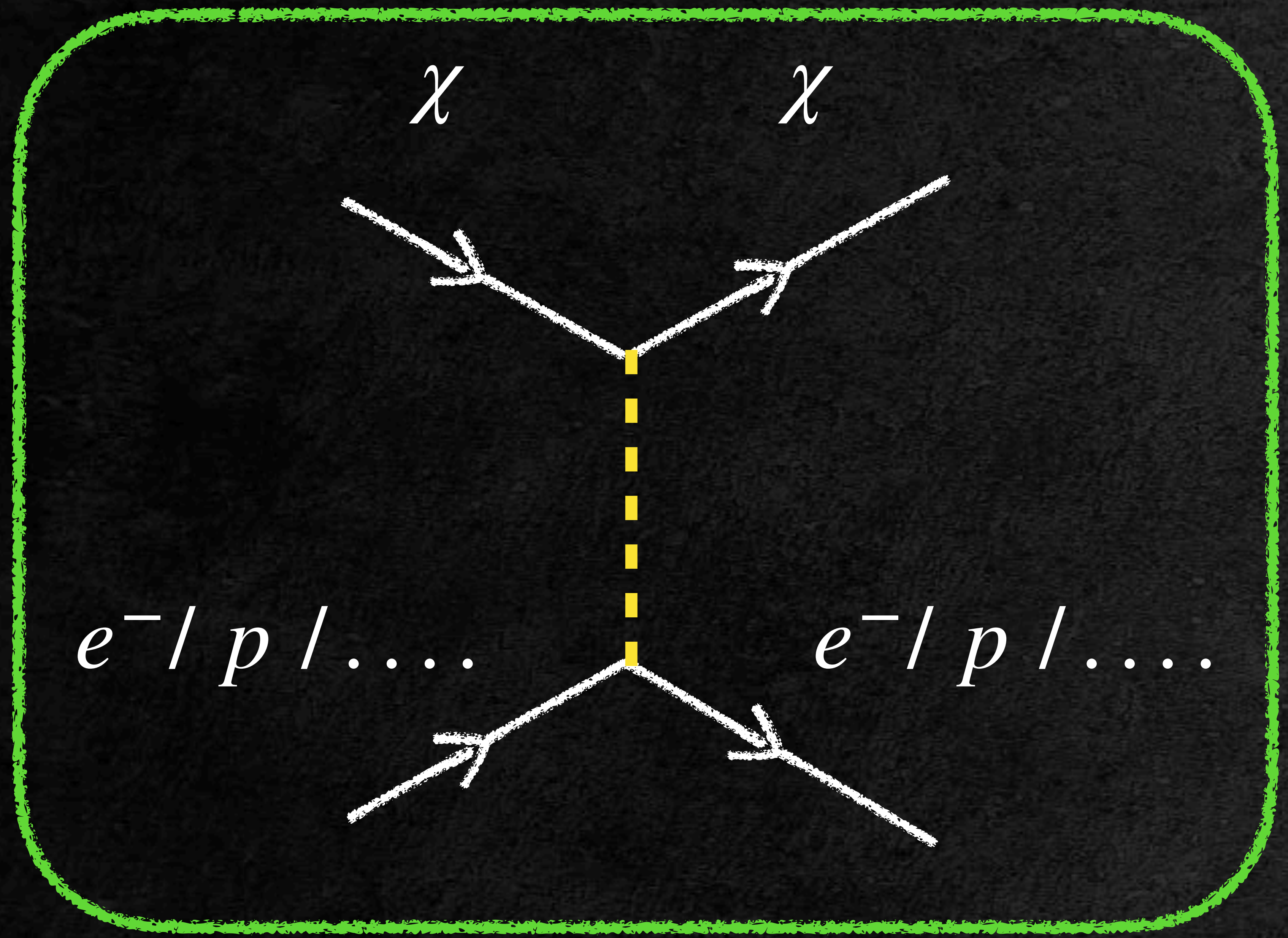
Possible candidates:



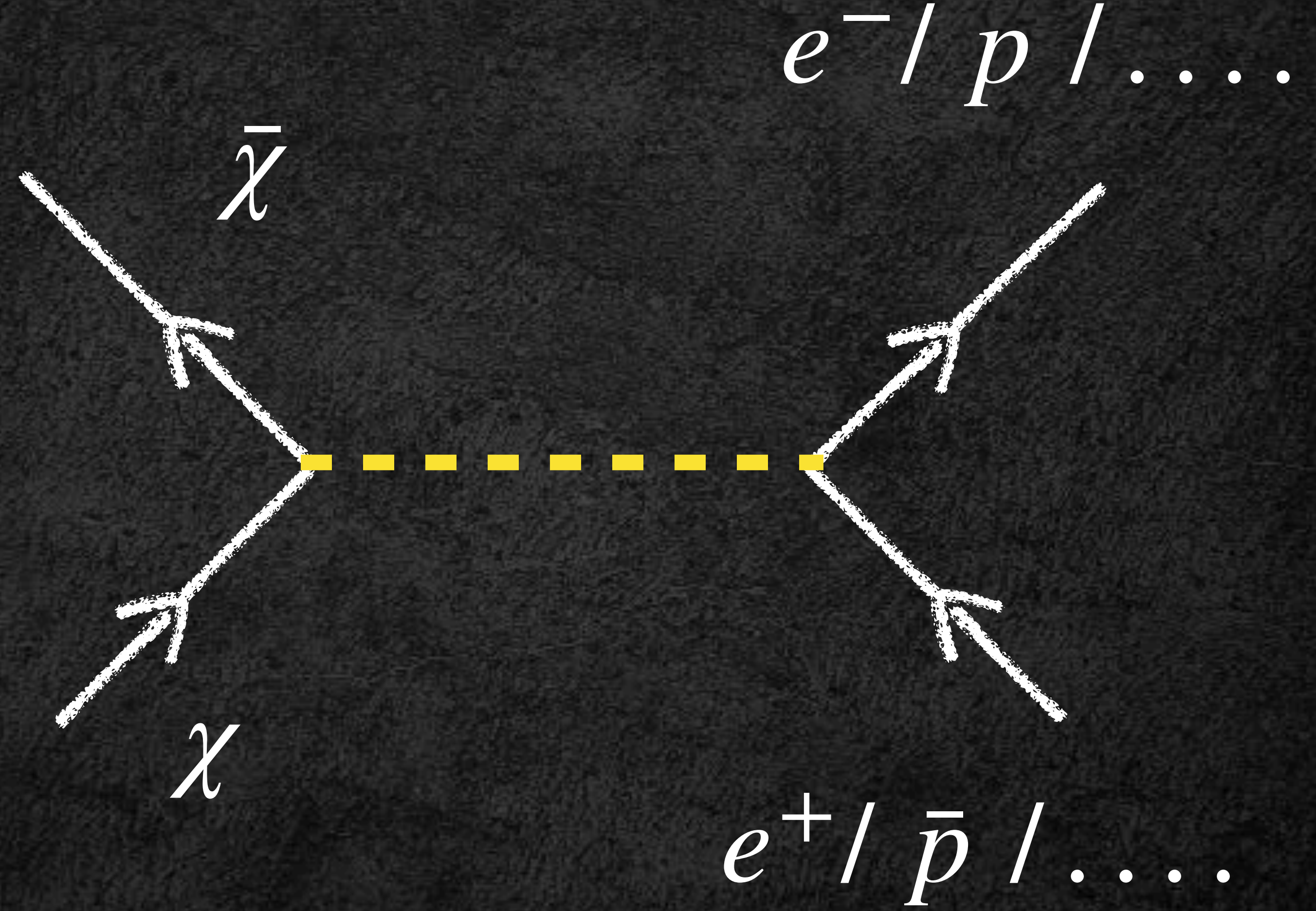
Particle dark matter

Samuel Velasco/Quanta Magazine

Particle dark matter

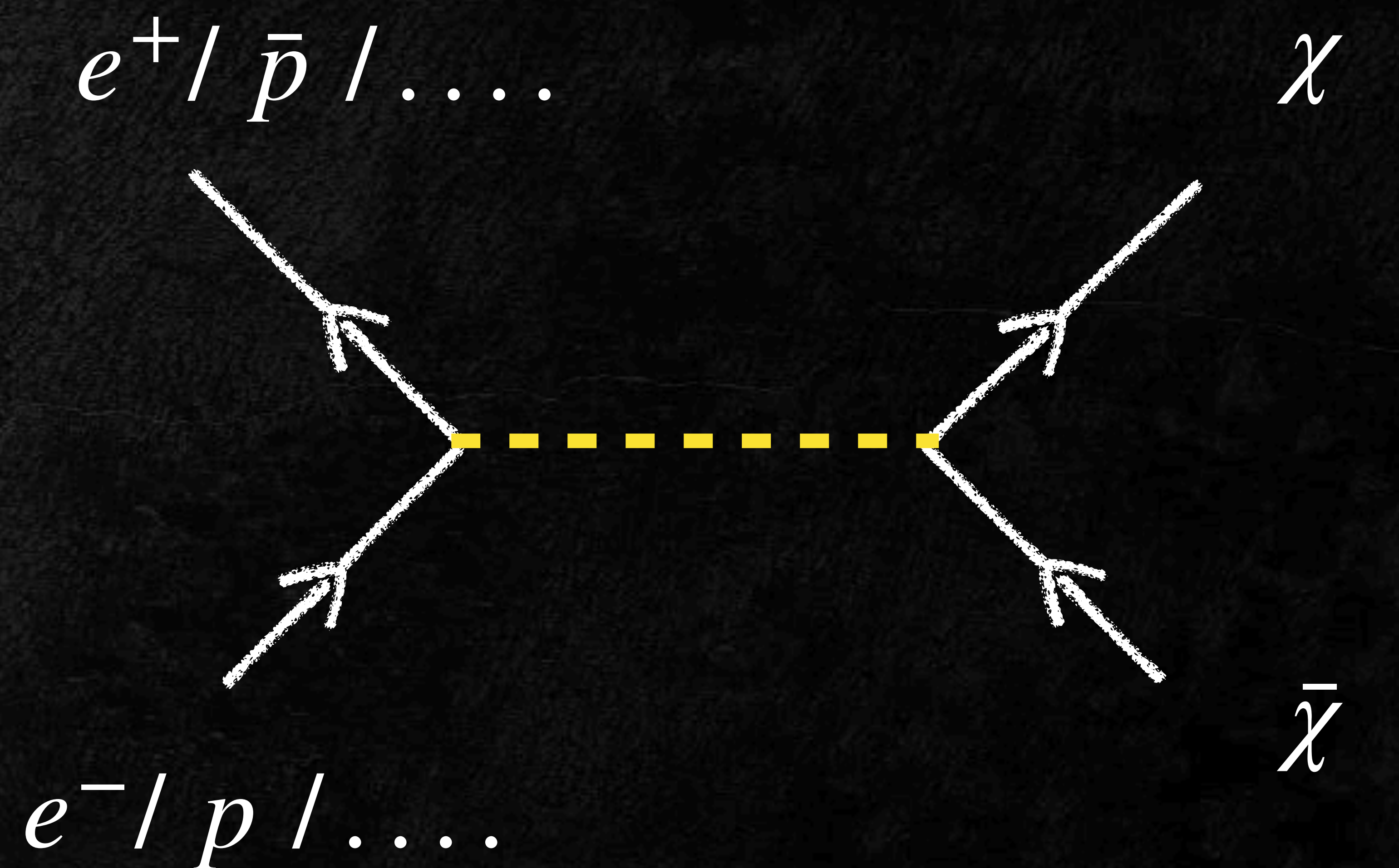


Scattering inside stars



Annihilation

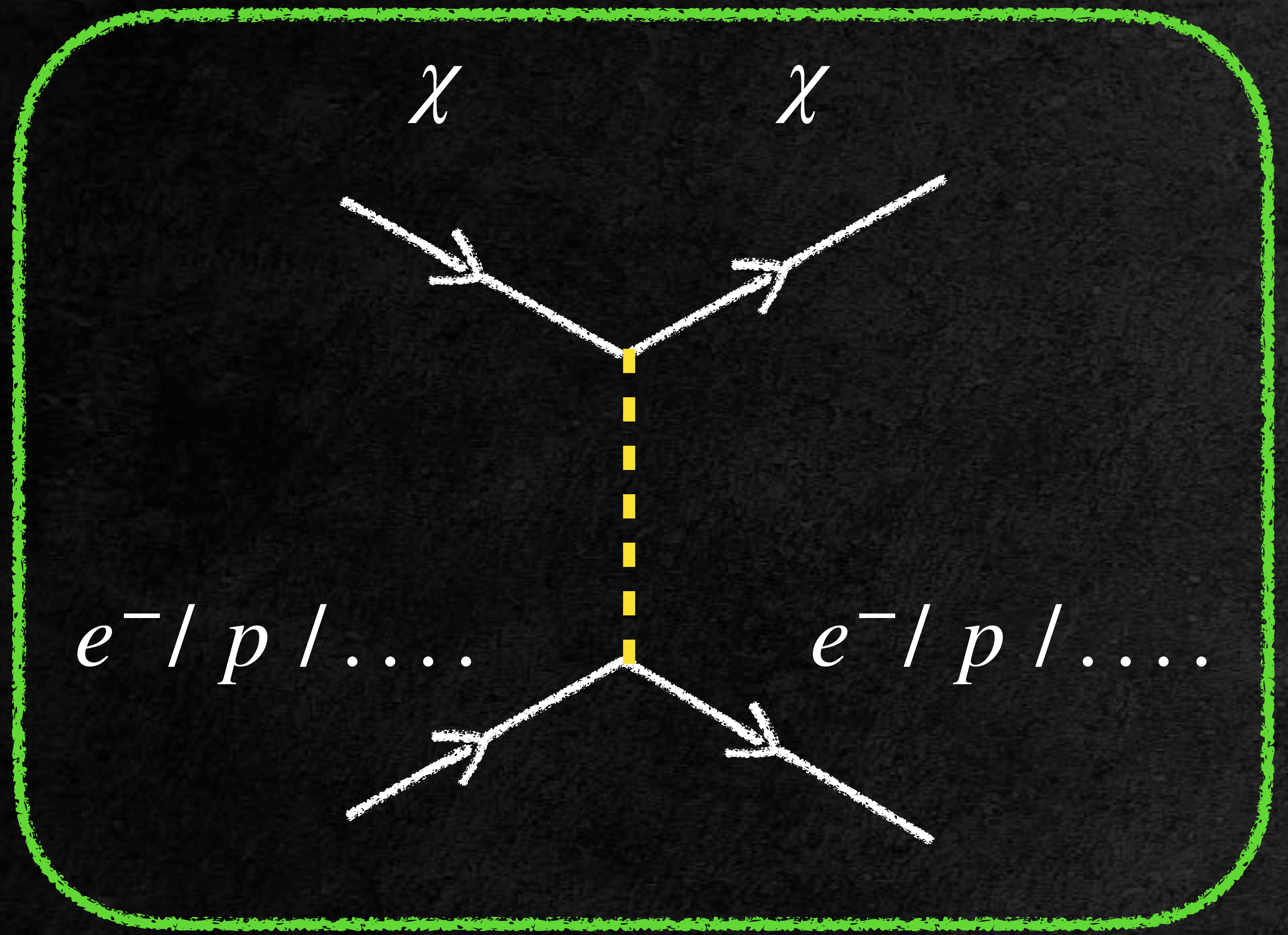
(Indirect Detection)



Production

(Collider Searches)

Particle dark matter



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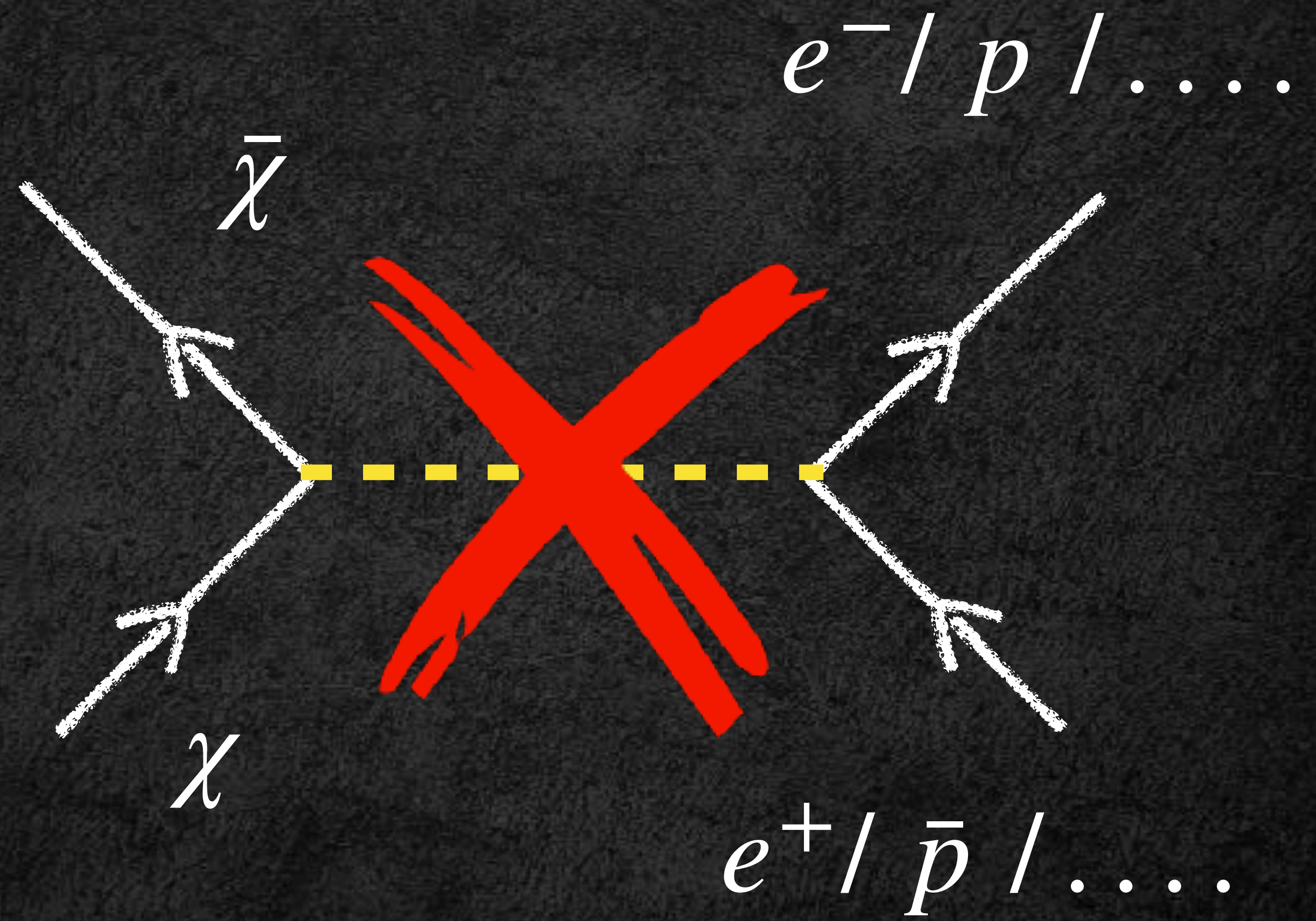
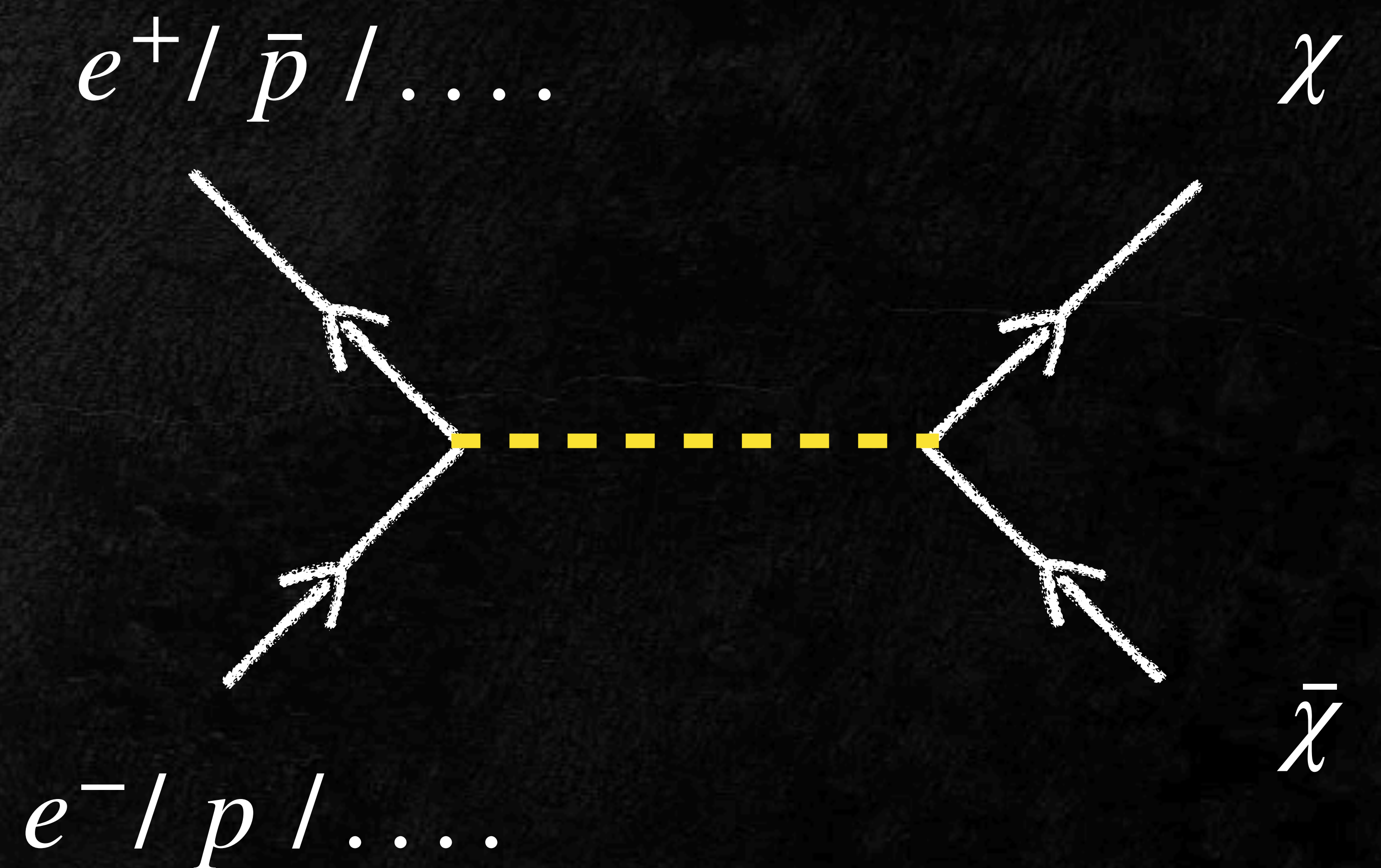
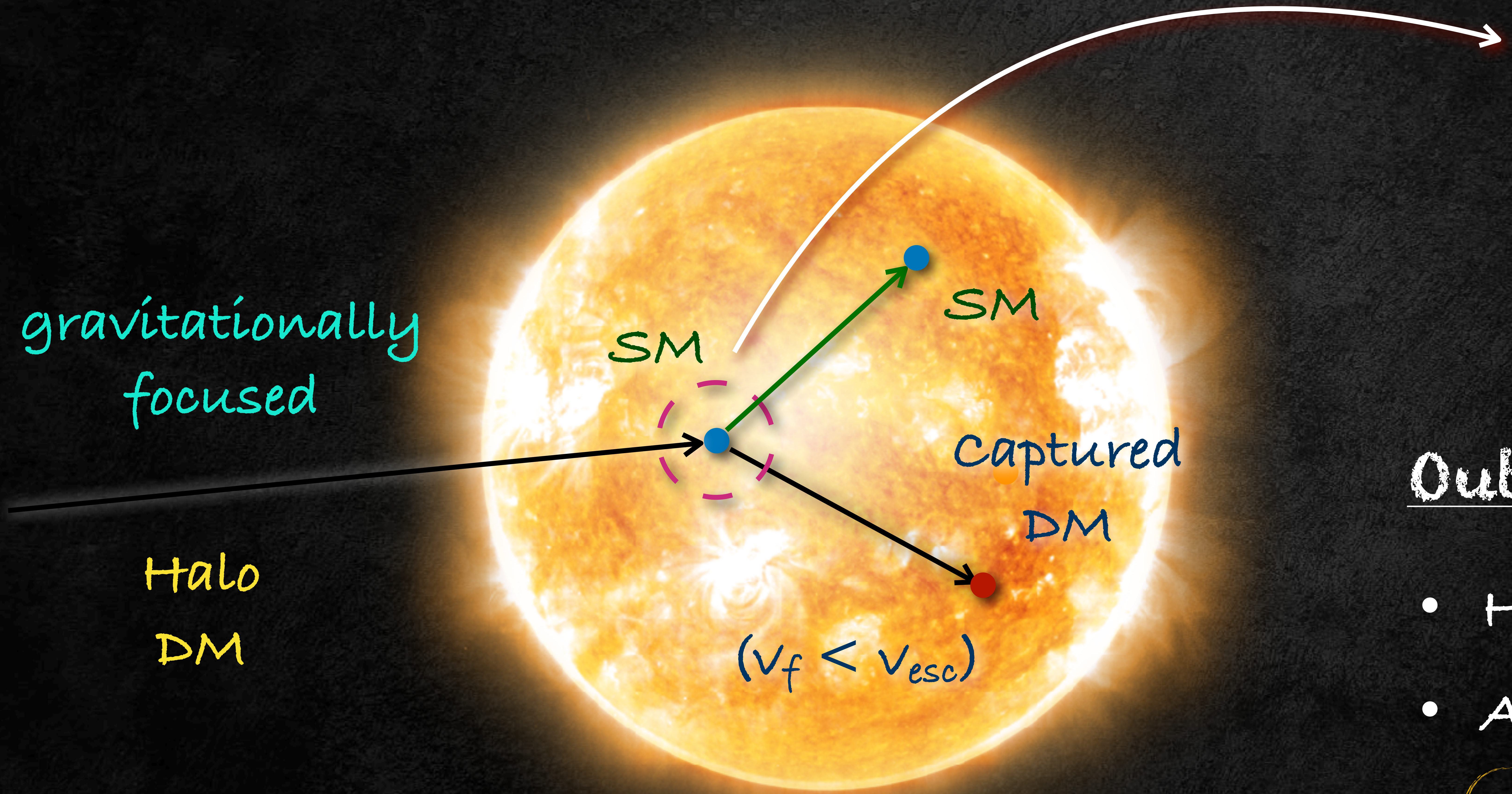


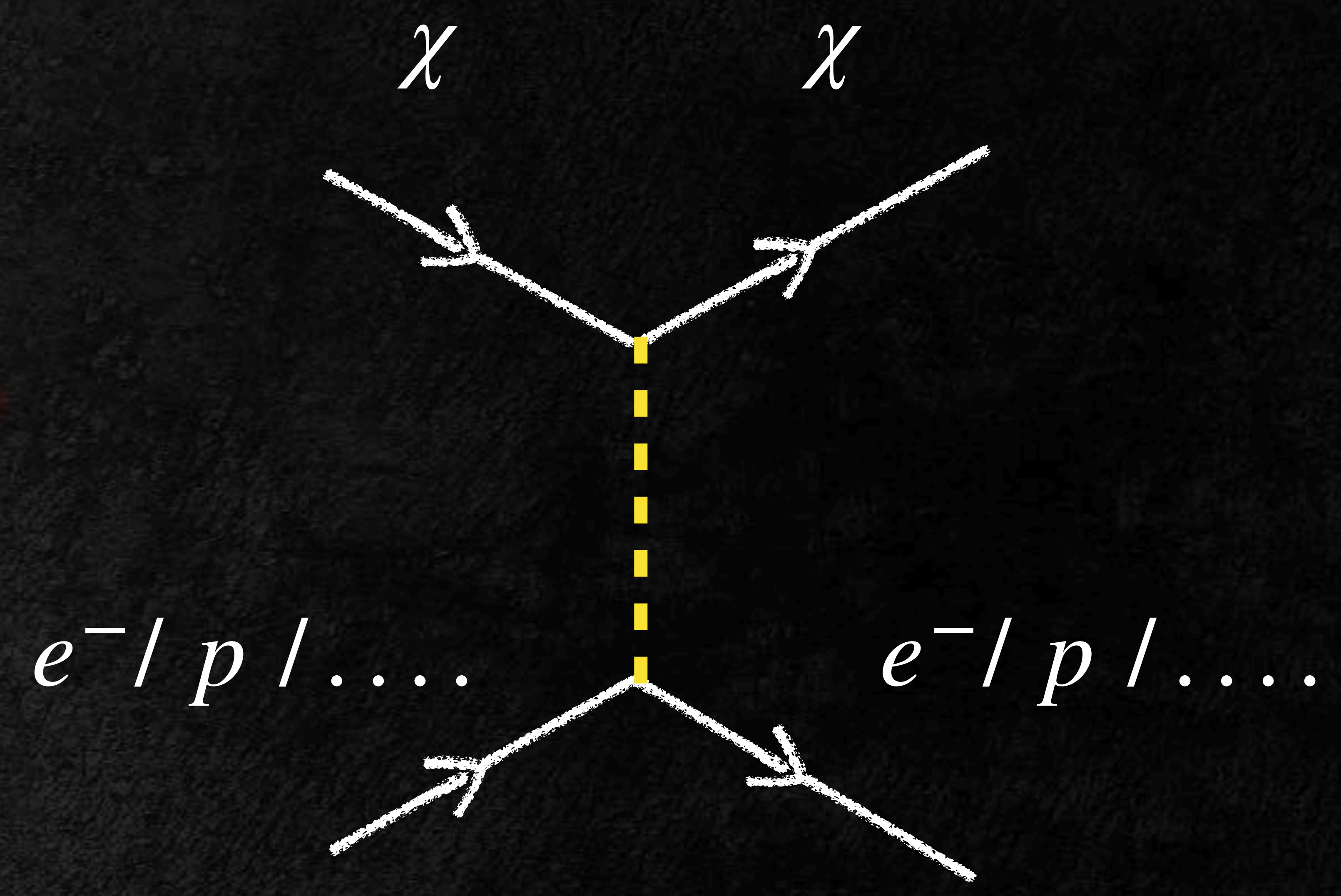
Non-annihilating
dark matter



Production
(Collider searches)

Capture Mechanism:





Outcomes :

- Heating of celestial objects
- Annihilation signatures
- Black Hole formation
- Supernova ignition, ...

Capture Rate:

Area of the object — DM flux — Capture probability

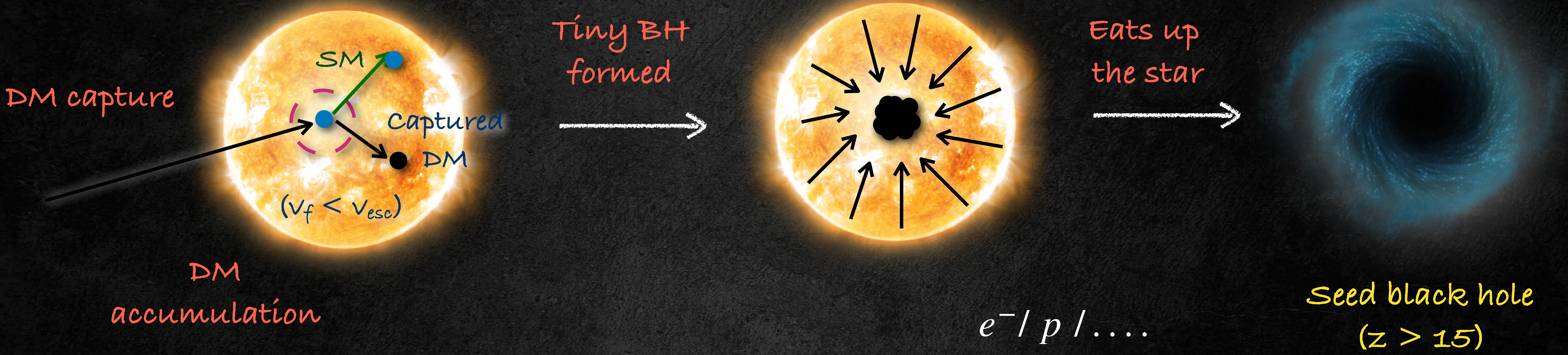
$$C = \pi R_s^2 \left(\frac{\rho_\chi}{m_\chi}\right) \int_0^{u_{esc}} du \, \frac{f(u)}{u} \left(u^2 + v_{esc}^2\right) P_{\text{cap}}(u)$$

Approximate capture rate $(M_s = 110\ M_\odot,\ \ R_s = 5\ R_\odot)$

$$m_\chi C_{\text{approx}} \approx 7.6 \times 10^{-16} \times \left(\frac{\rho_\chi}{10^{11}\,\text{GeV/cm}^3}\right) \times \left(\frac{200\,\text{GeV}}{m_\chi}\right) \times \left(\frac{\sigma_{\chi p}^{\text{SD}}}{10^{-42}\,cm^2}\right) M_\odot/\text{s}$$

$$M_{\text{captured}} \approx 2.4 \times 10^{-3}\ M_\odot \quad (0.1\ \text{Myr})$$

Black hole formation:



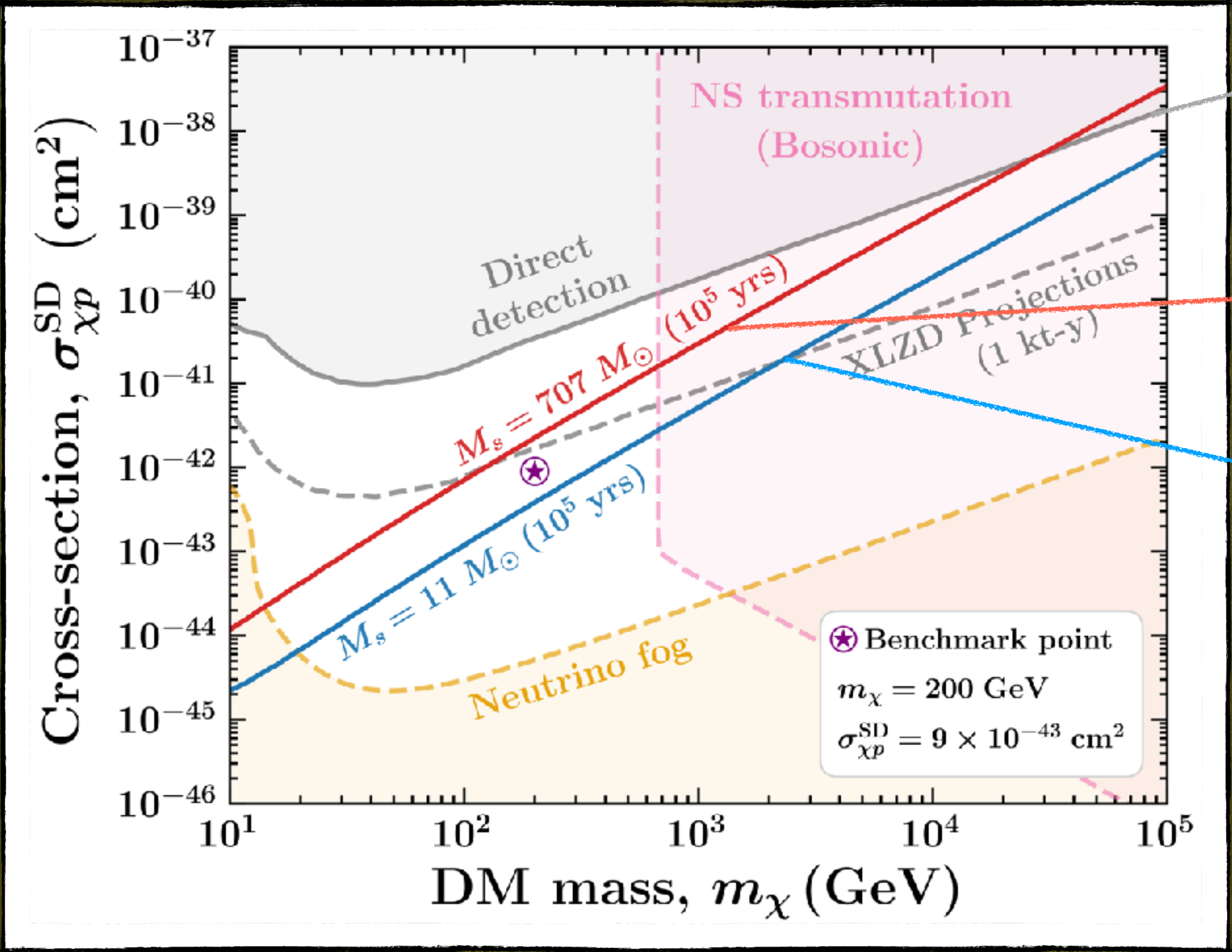
BH formation requirement:

- ⋆ DM needs to be non-annihilating
- ⋆ Sufficient dark accumulation, i.e., $m_\chi C_\chi = \text{Max}\left[\, M_{\text{Self}} \,,\, M_{\text{Quantum}} \,\right]$

Seed black hole formation isochrones:

Seed black hole formation timescale

$$t_{\rm BH-form} = \tau_{\rm accum} + \tau_{\rm therm} + \tau_{\rm col} + \tau_{\rm star-eating}$$



Direct detection (Combo of PICO-60, LUX-ZEPLIN)

High : $M_s = 707\,M_\odot$, $R_s = 16.4\,R_\odot$

Low : $M_s = 11\,M_\odot$, $R_s = 1.5\,R_\odot$

Radius, density, temperature are obtained with MESA code

Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

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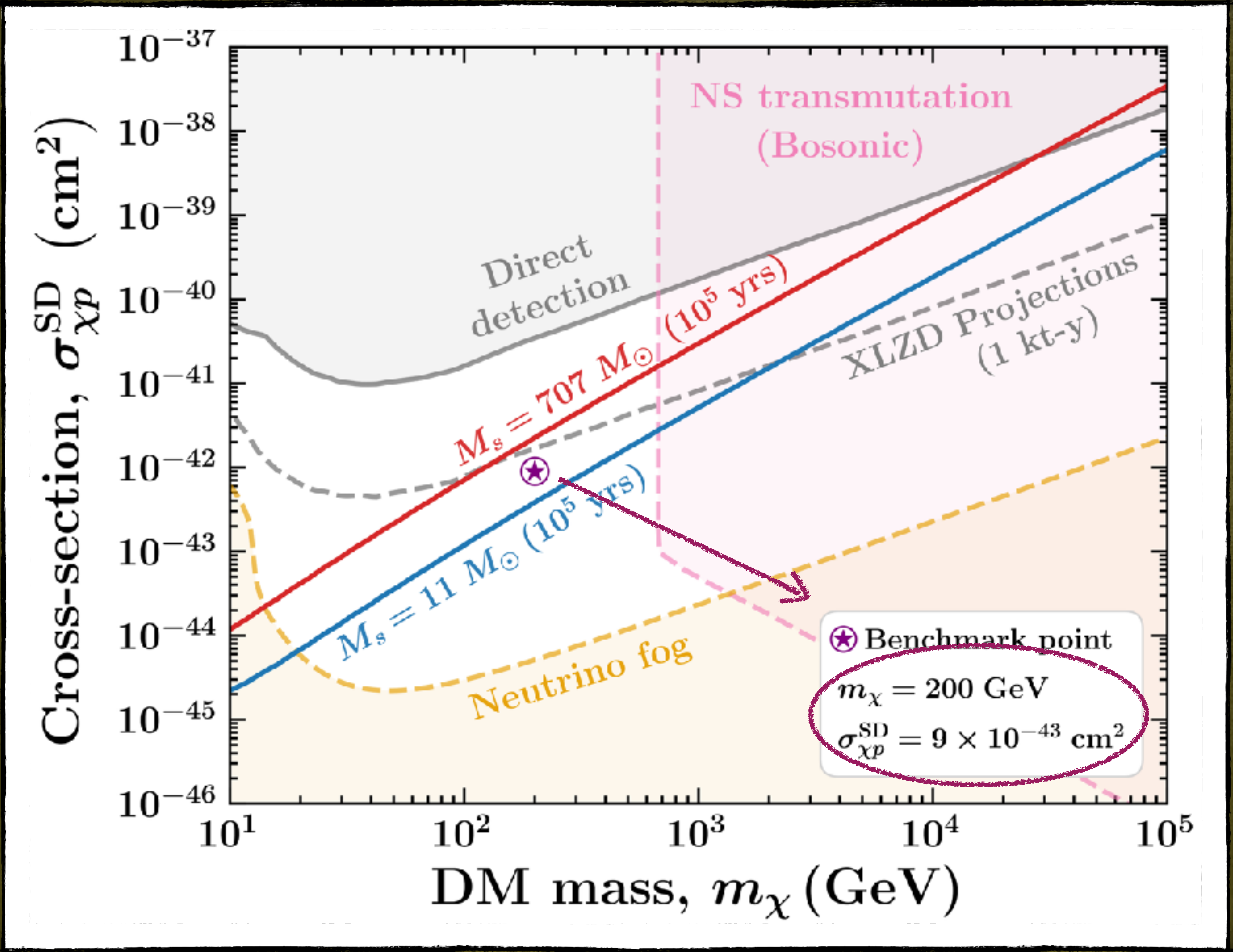

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Low : $M_s = 11\,M_\odot, \quad R_s = 1.5\,R_\odot$

This is the benchmark value we have taken for further analysis

Seed BH accretion:

~99% of the datapoints can be explained!

Final black hole mass

$$M_{\rm BH} = M_{\rm seed} \exp\left(\frac{\eta_{\rm Edd}\,(1-\epsilon_r)\,\Delta t}{t_{\rm Sal}}\right)$$

Salpter time → $t_{\rm Sal} \approx 45.1 \left(\frac{\epsilon_r}{0.1}\right)$ Myr

Radiation efficiency → $\epsilon_r = 0.1$

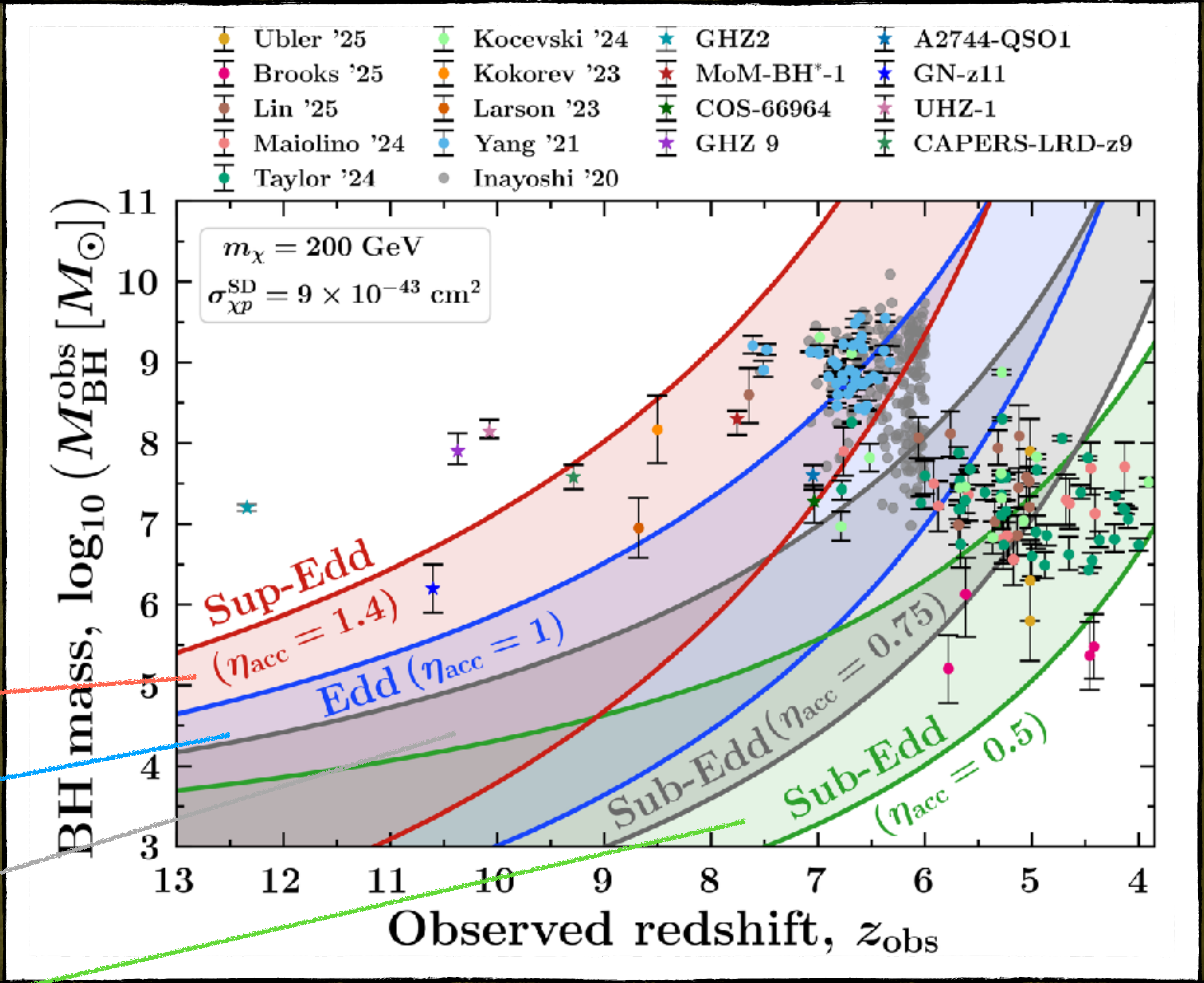
Accretion efficiency → $\eta_{\rm Edd}$ =

1.4 (Sup-Edd)

1.0 (Eddington)

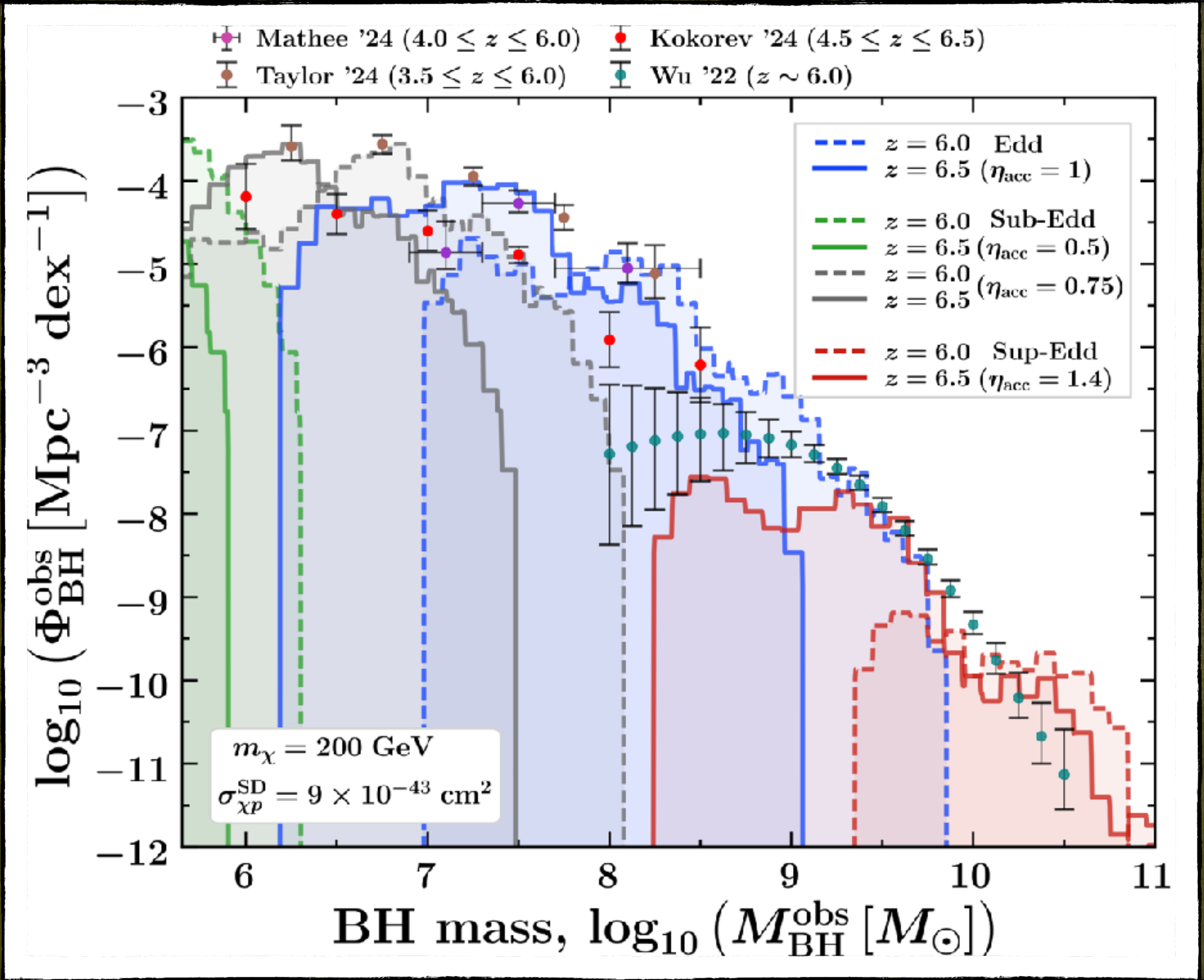
0.75 (Sub-Edd)

0.5 (Sub-Edd)



Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

SMBH mass function:



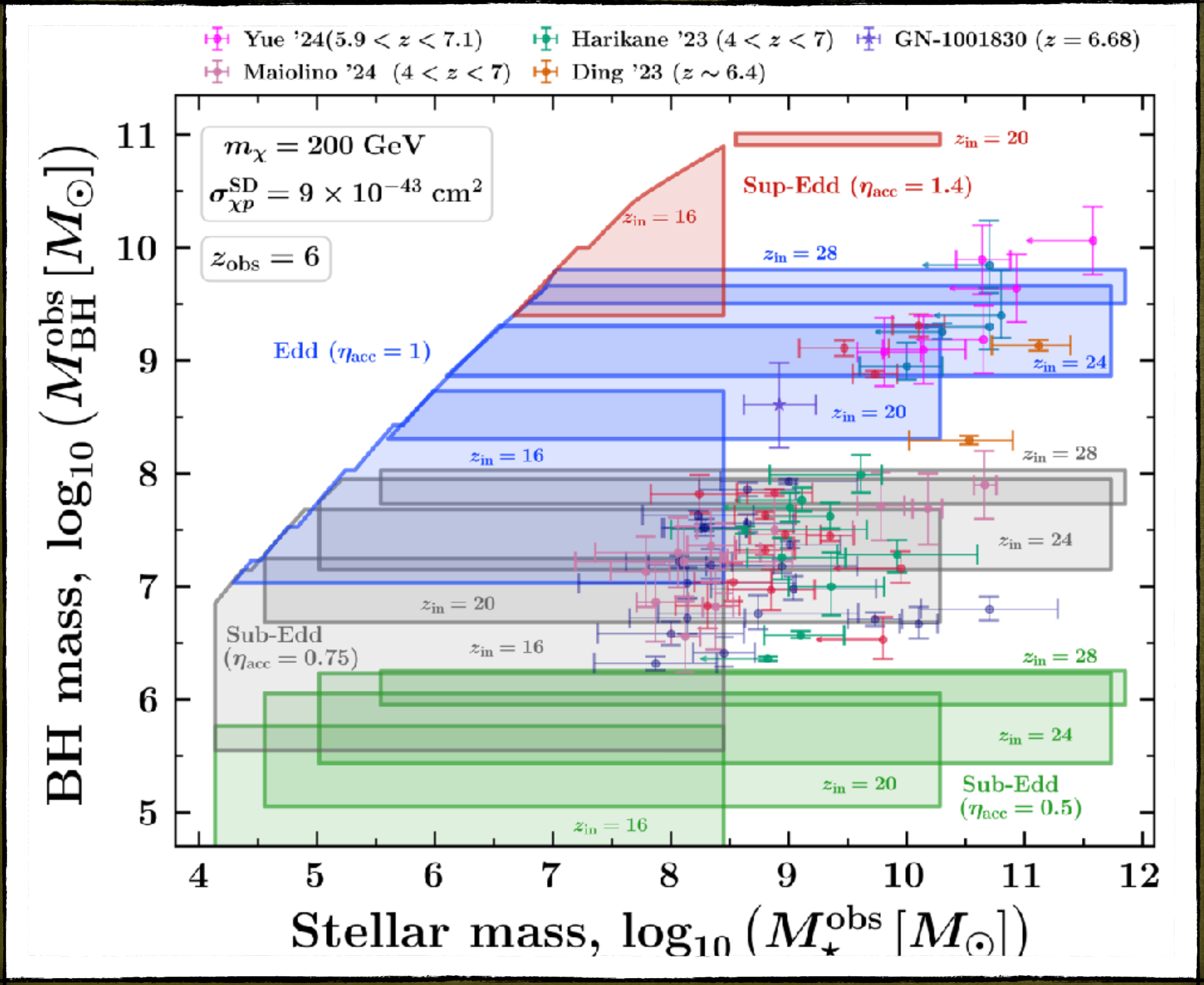
Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

- Initial redshifts $z_{in} = 16, 20, 24, 28$
- Halo mass $M_{halo} \in [10^6, 10^9]\ M_\odot$
- One Pop III star in a halo
- Pop III IMF constructed from Hirano'15
- Tracked halo growth
- Mass function

$$\Phi_{SMBH} = \frac{dn_{BH}}{d\ln M_{BH}} = n_{halo} \times \frac{\delta n_s}{\delta M_s} \times f_{norm}$$

$$M_s \to M_{BH}$$

SMBH mass vs stellar mass:



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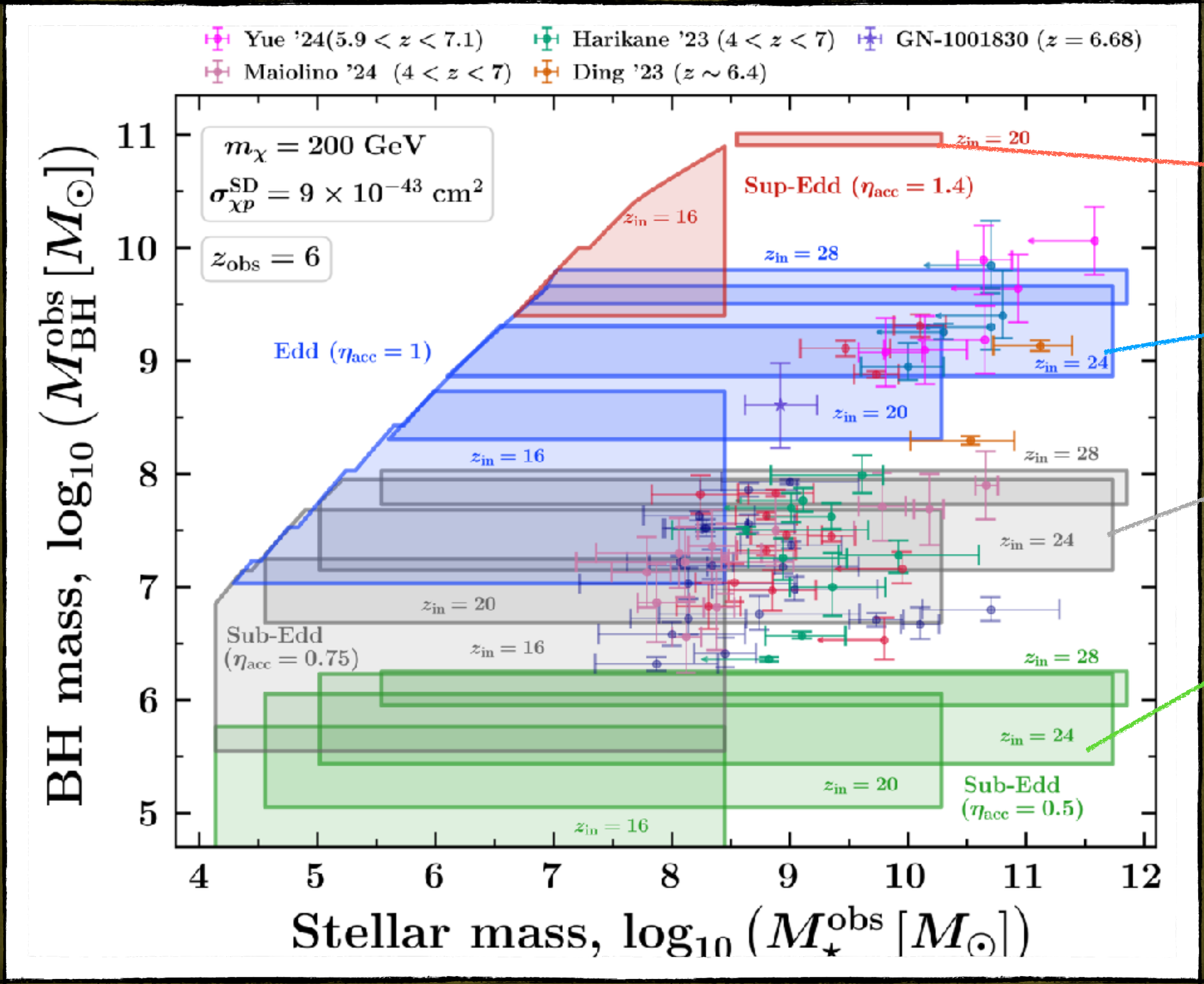
- Tracked halo growth
- Stellar mass

$$M_\star = \xi_{ratio} M_{halo}$$

Obtained from fitting of UniverseMachine-DR1

SMBH mass vs stellar mass:



Accretion efficiency → η_{Edd}

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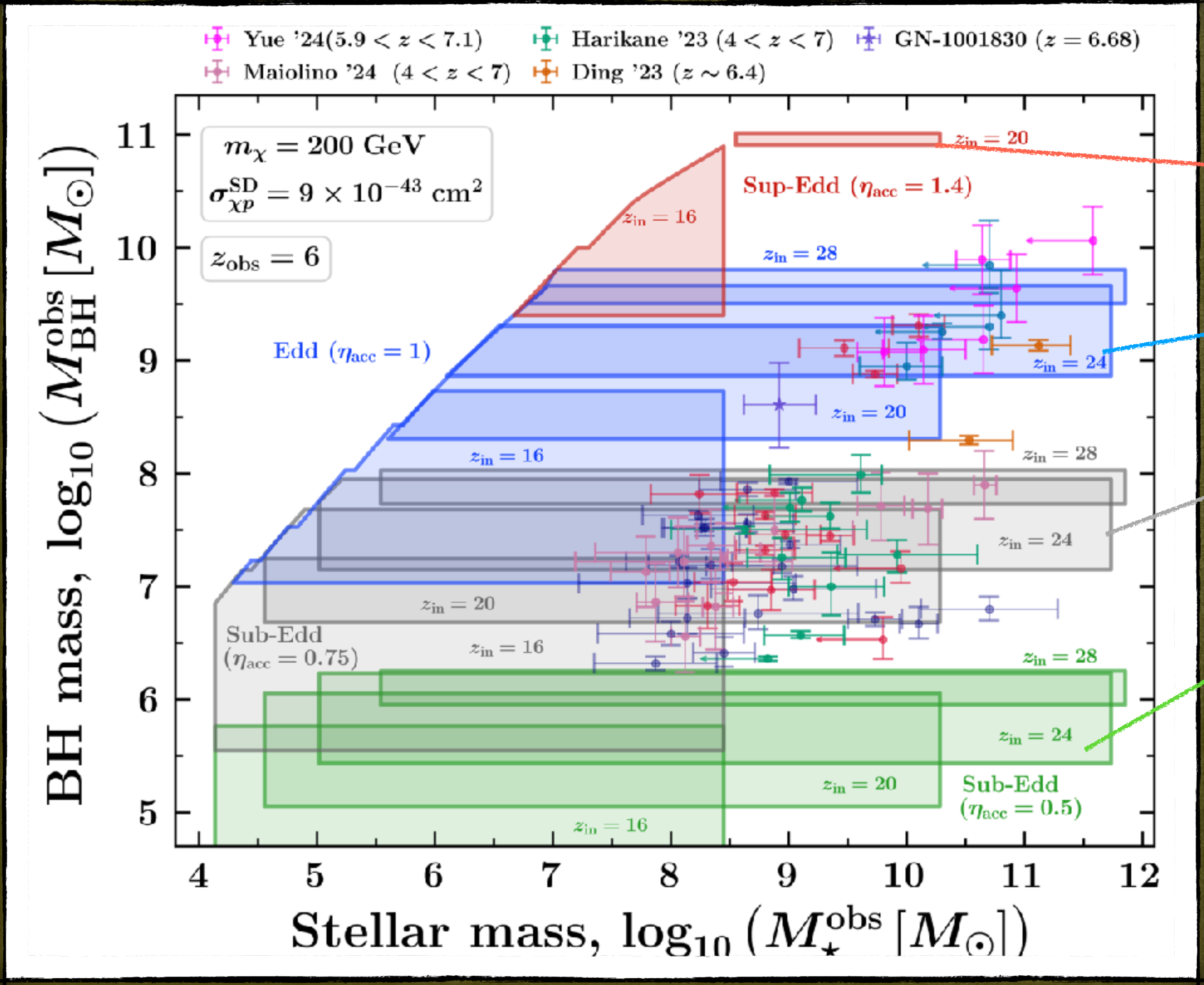
Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

SMBH mass vs stellar mass:



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Accretion efficiency → η_{Edd}

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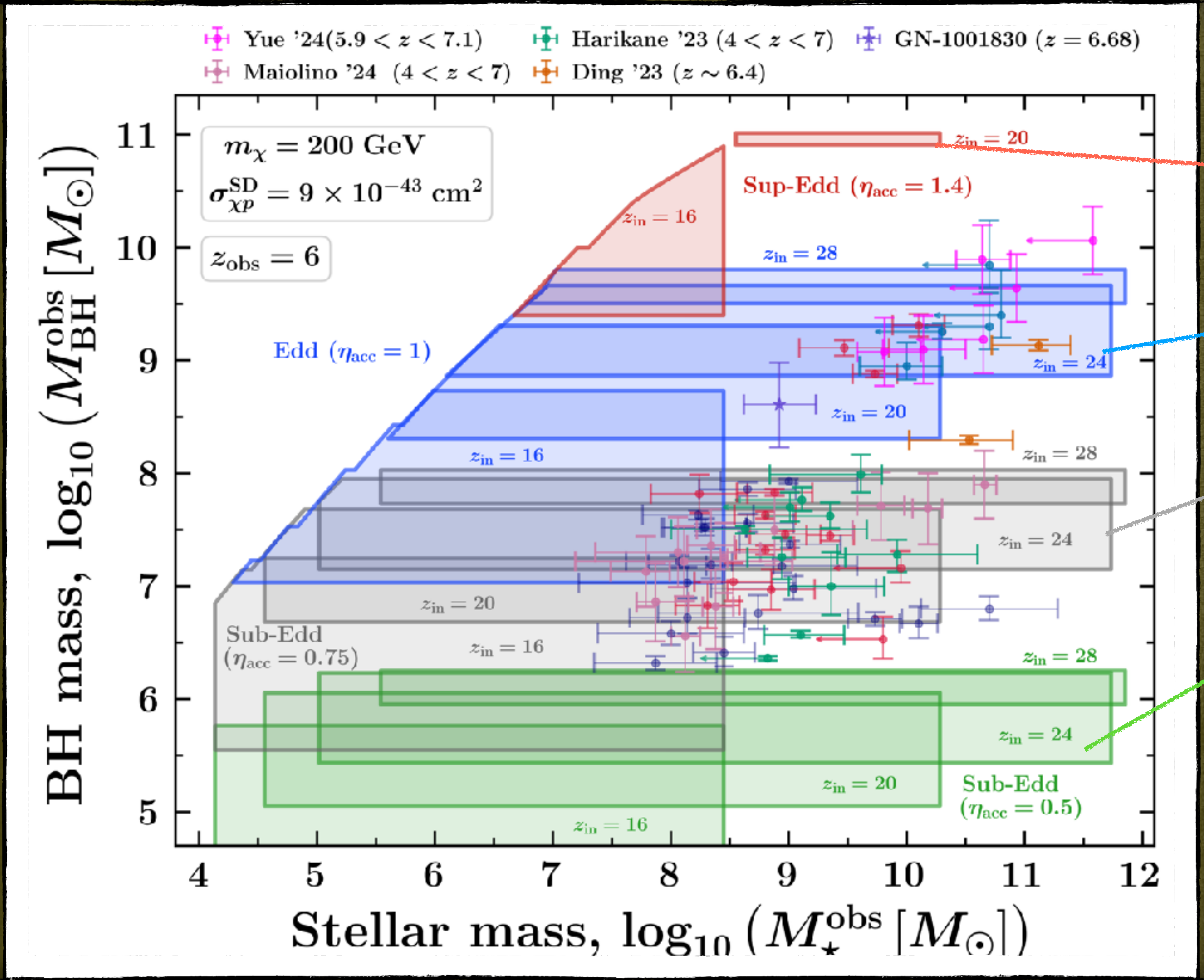
Increasing Pop III star mass

Increasing halo mass

SMBH mass vs stellar mass:



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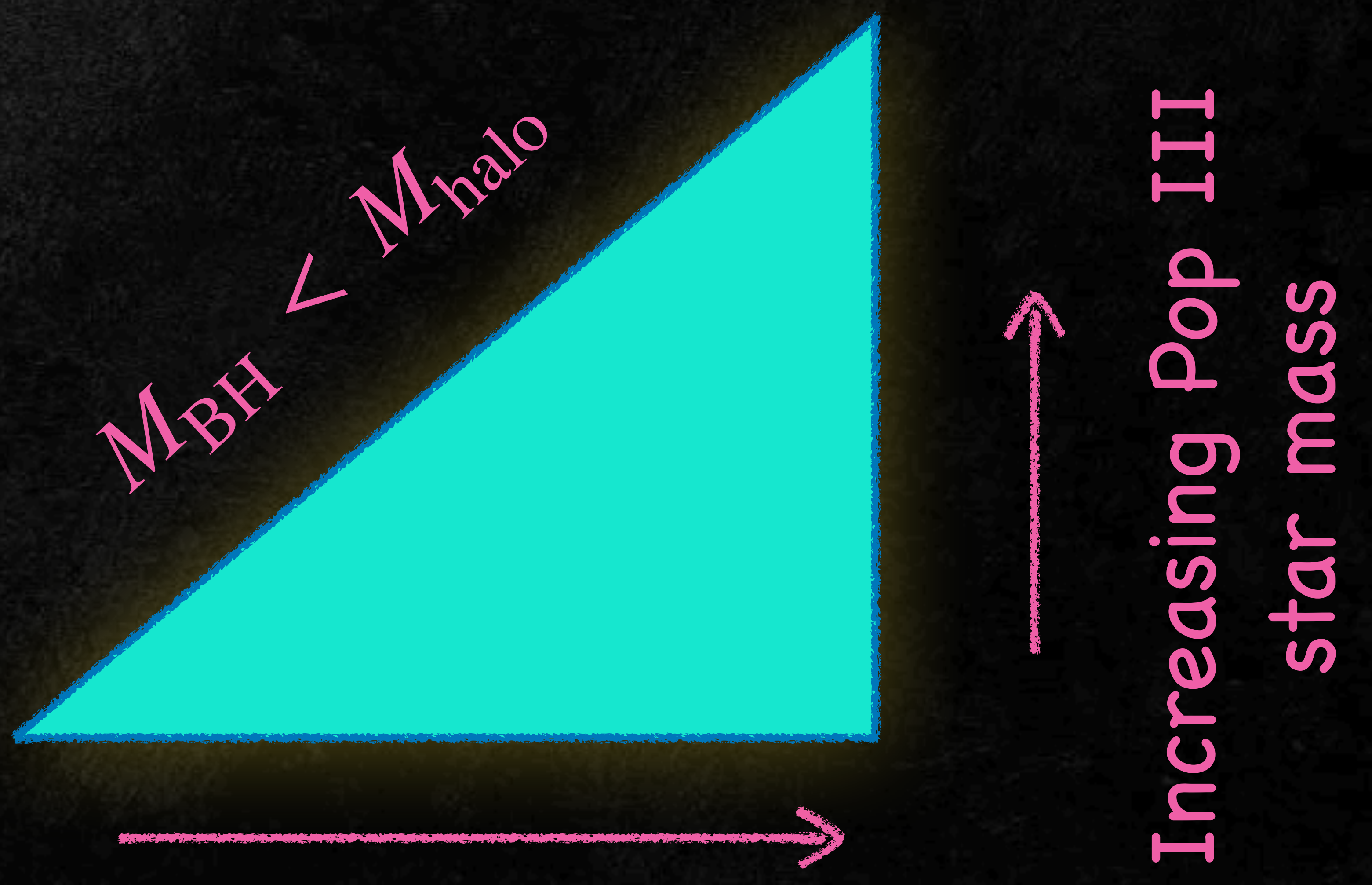
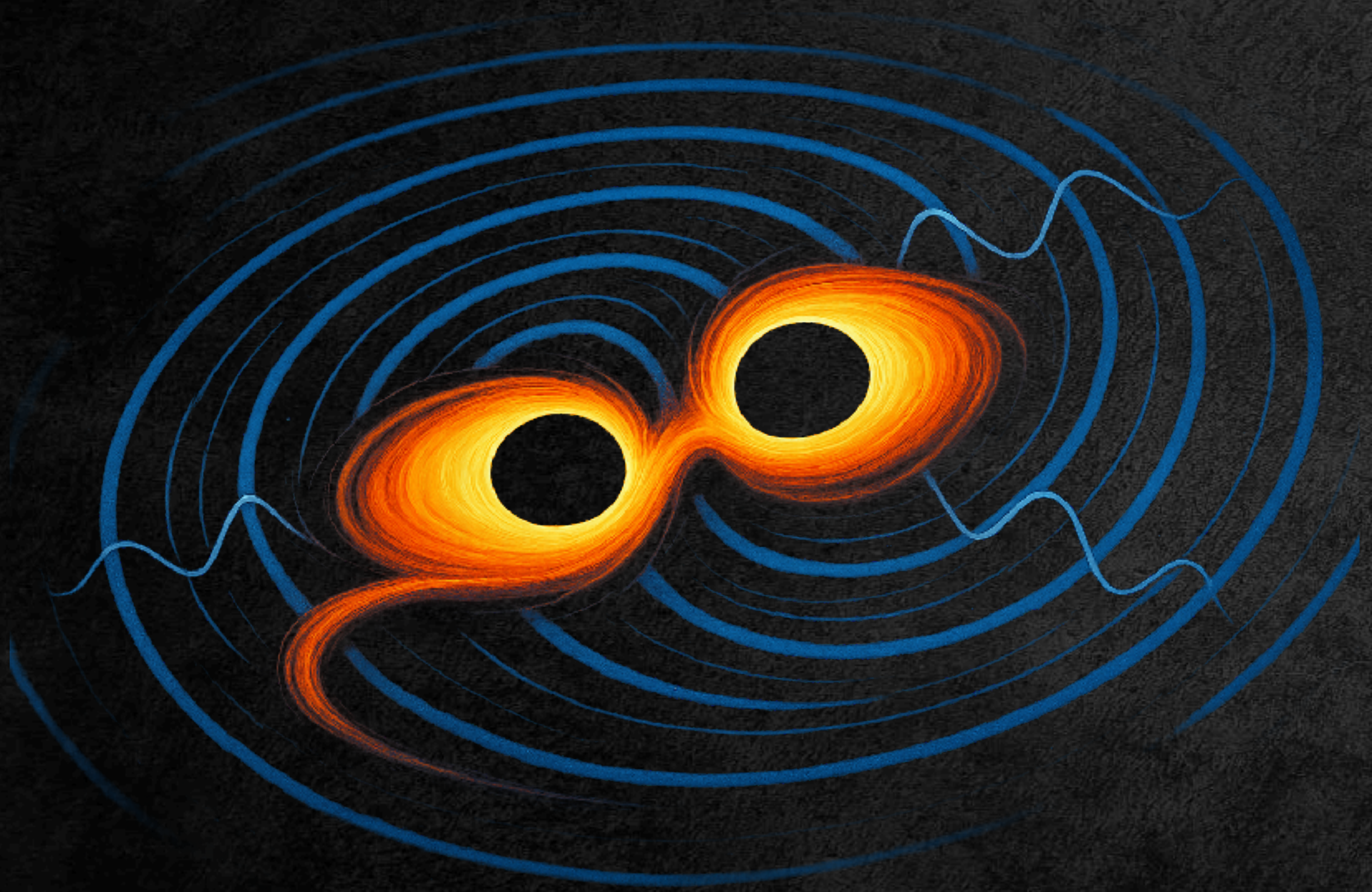


Gravitational Waves (GWs):



GW from Black hole merger (ChatGPT)

Two types of GW signatures -

- Individual mergers (detectable by LISA)

  Strain obtained with pyCBC code

- Stochastic GW background (PTA band)

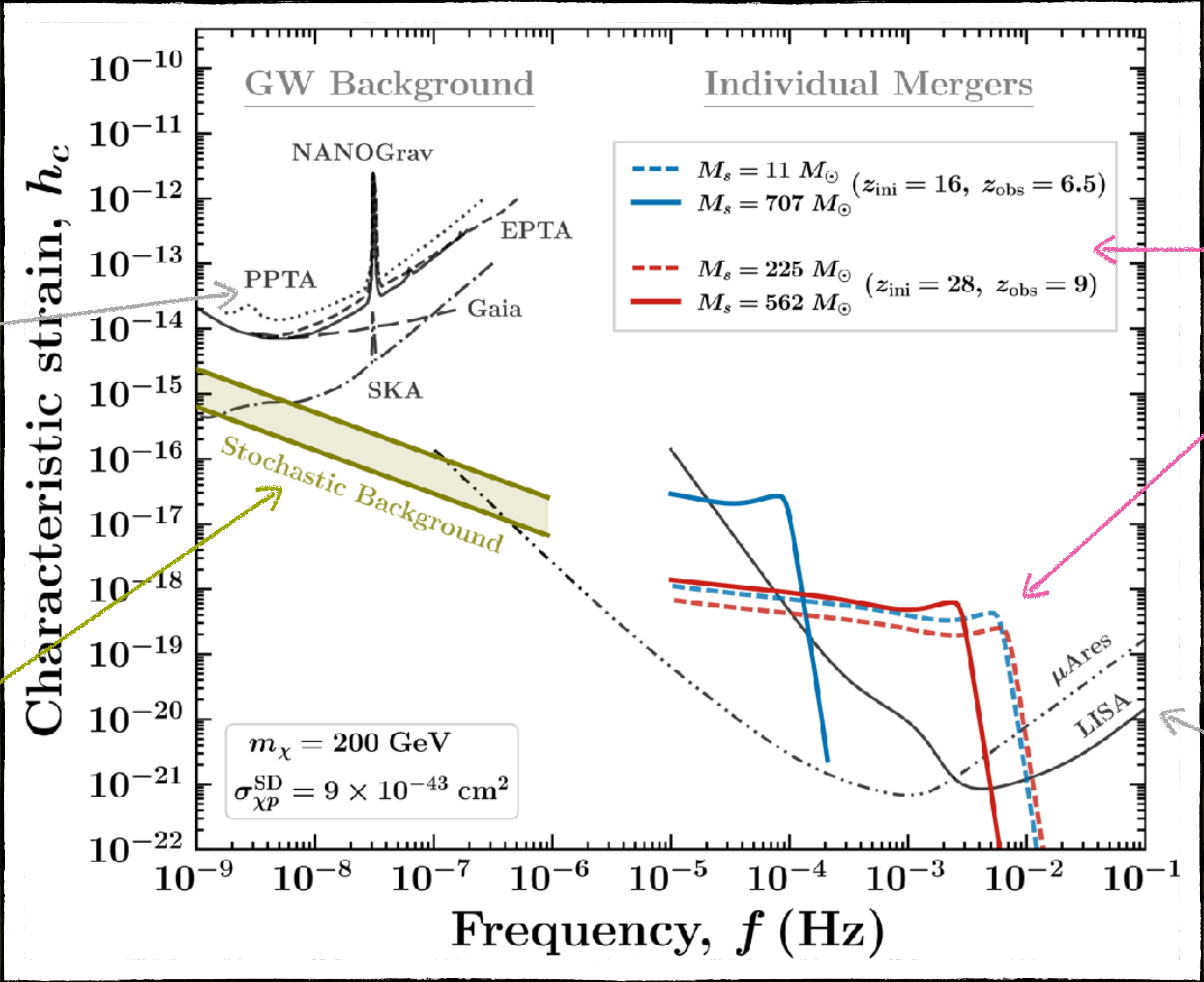
$$h_{c,\,\mathrm{back}} \approx 3\times10^{-24}\left(\frac{\mathcal{M}_c}{m_\odot}\right)^{5/6}\left(\frac{f}{1\,\mathrm{mHz}}\right)^{-2/3}\left(\frac{n_{\mathrm{SMBH}}^{\mathrm{merger}}}{\mathrm{Mpc}^{-3}}\right)^{1/2}$$

Phinney 2001

Gravitational Waves (GWs):

PTA, SKA, Gaia Sensitivities

Stochastic GW background



Individual mergers (For two extreme initial redshift)

LISA and μAres sensitivities

Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

Conclusion

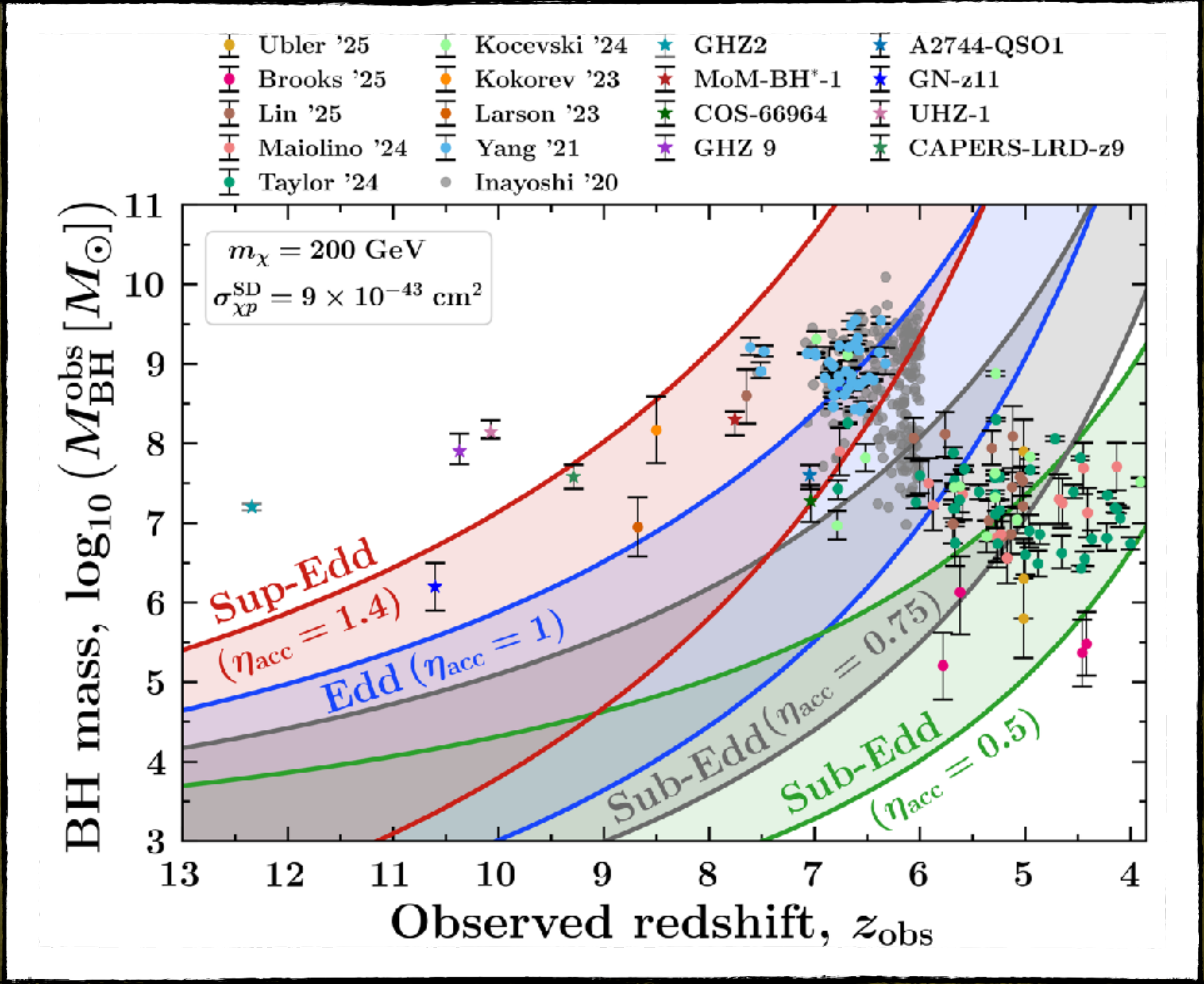
- Non-annihilating dark matter capture can lead to formation of SMBH seeds from premature death of Pop-III stars

- In this framework, we can explain

  - ★ SMBH masses at high redshifts
  - ★ SMBH mass vs galaxy stellar mass
  - ★ SMBH mass function

- Two types of GW signatures can be produced

  - ★ Individual mergers
  - ★ Stochastic GW background

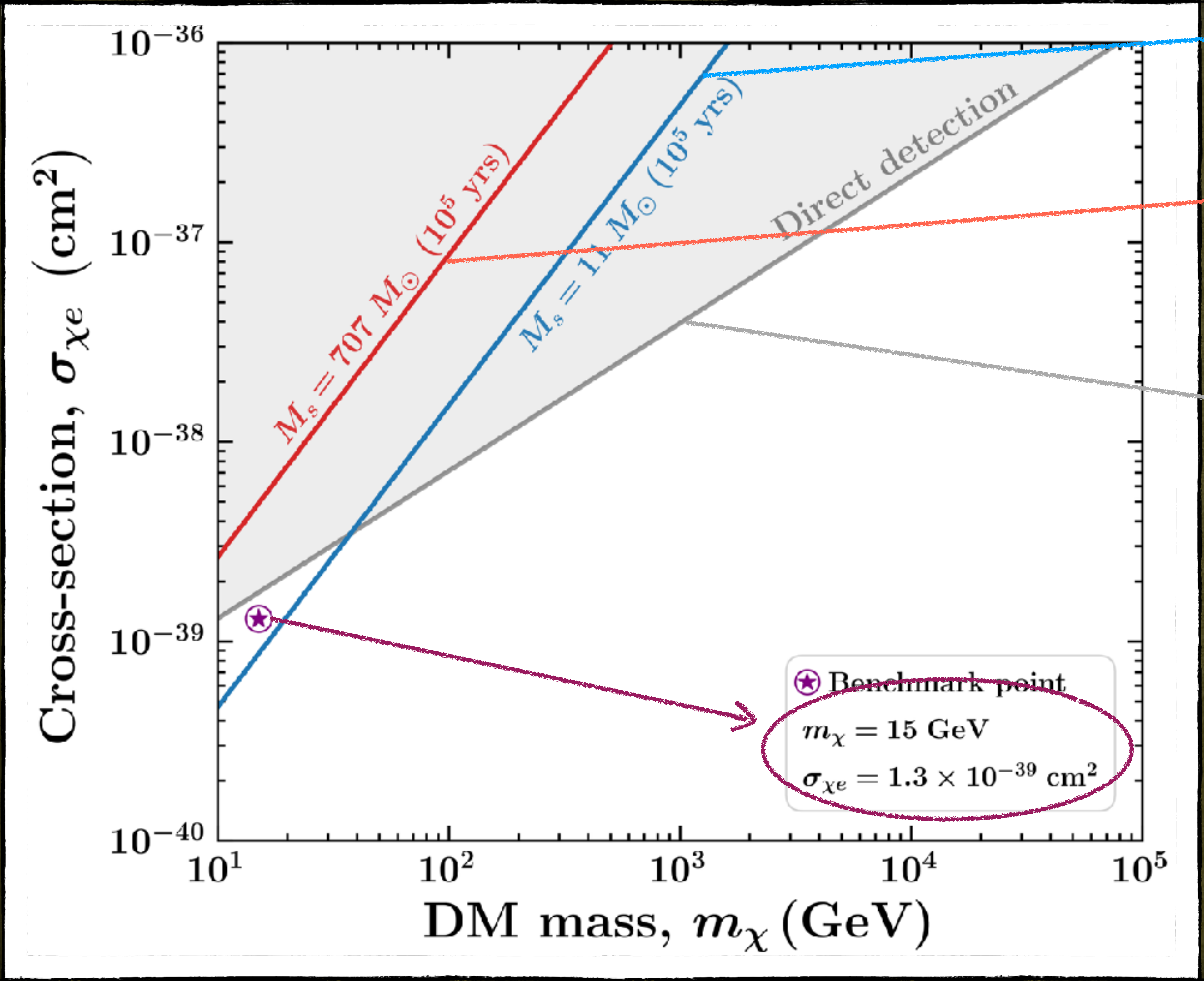


Thank You

Contact: debajitbose550@gmail.com

Backup Slides

DM-electron Scattering:



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High : $M_s = 707\, M_\odot$, $R_s = 16.4\, R_\odot$

Direct detection
(Extension of XENON1T S2-only)

Radius, density, temperature are obtained with MESA code

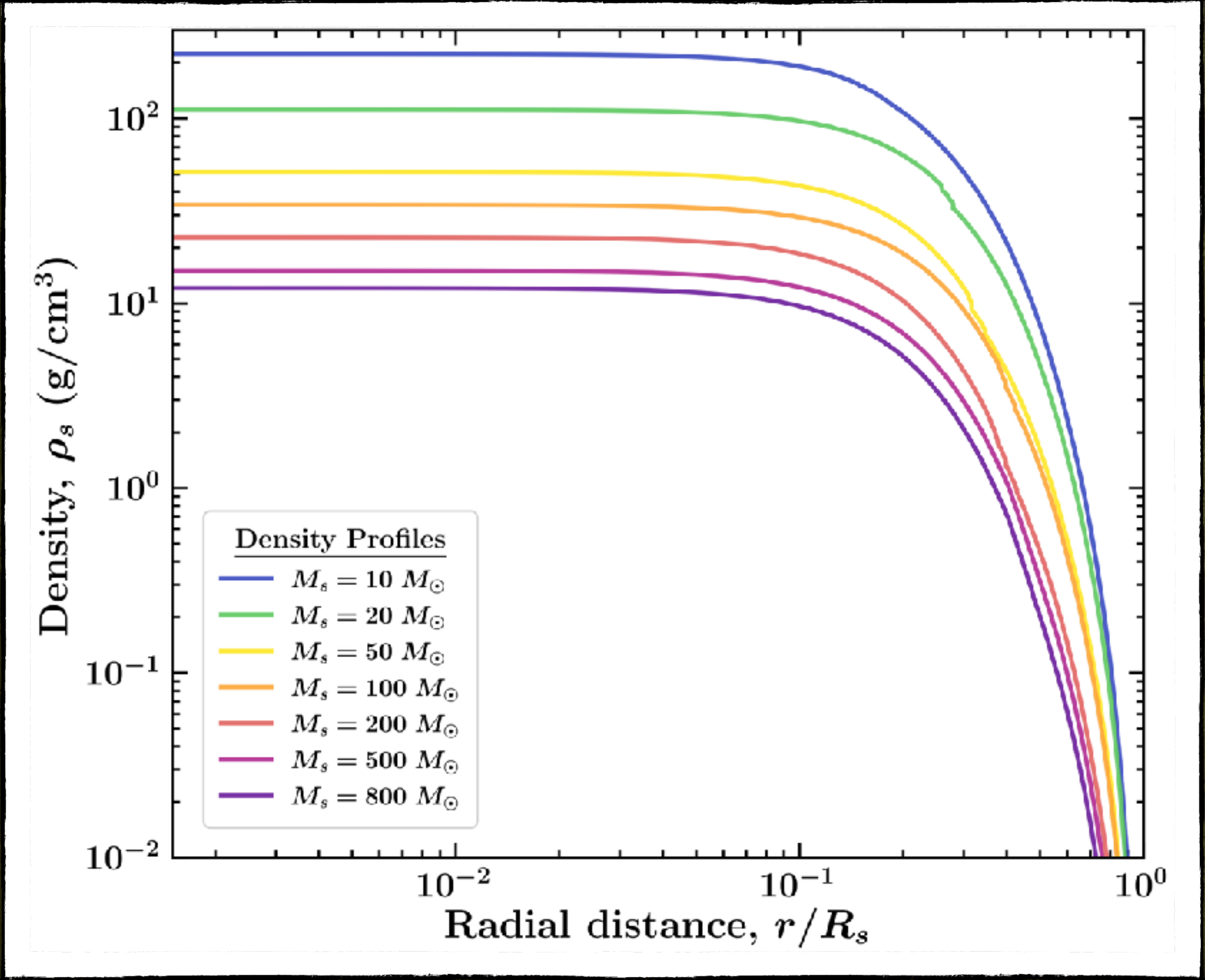
Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

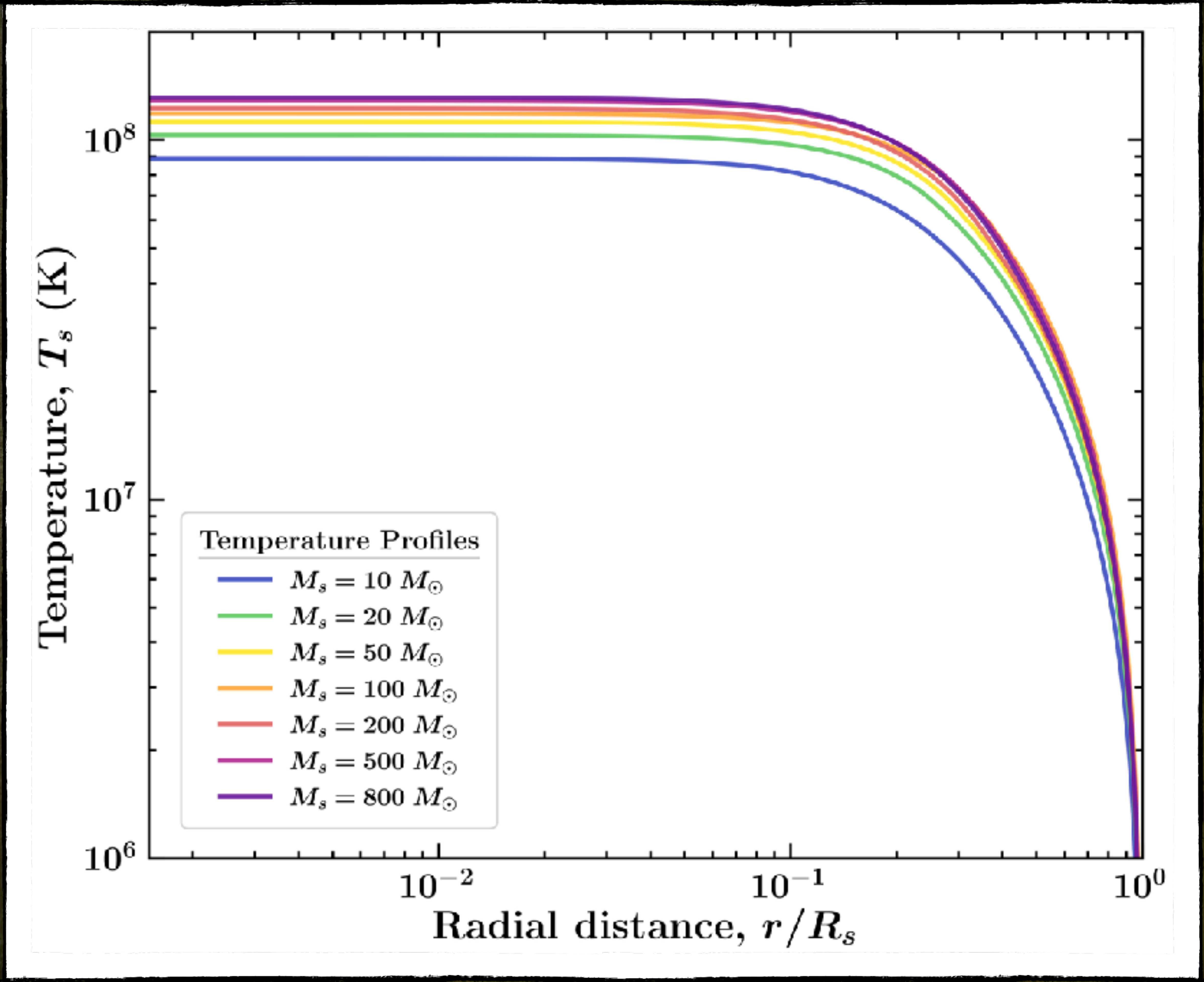
Pop-III radial profile:

Density profile

Obtained with MESA code

Temperature profile

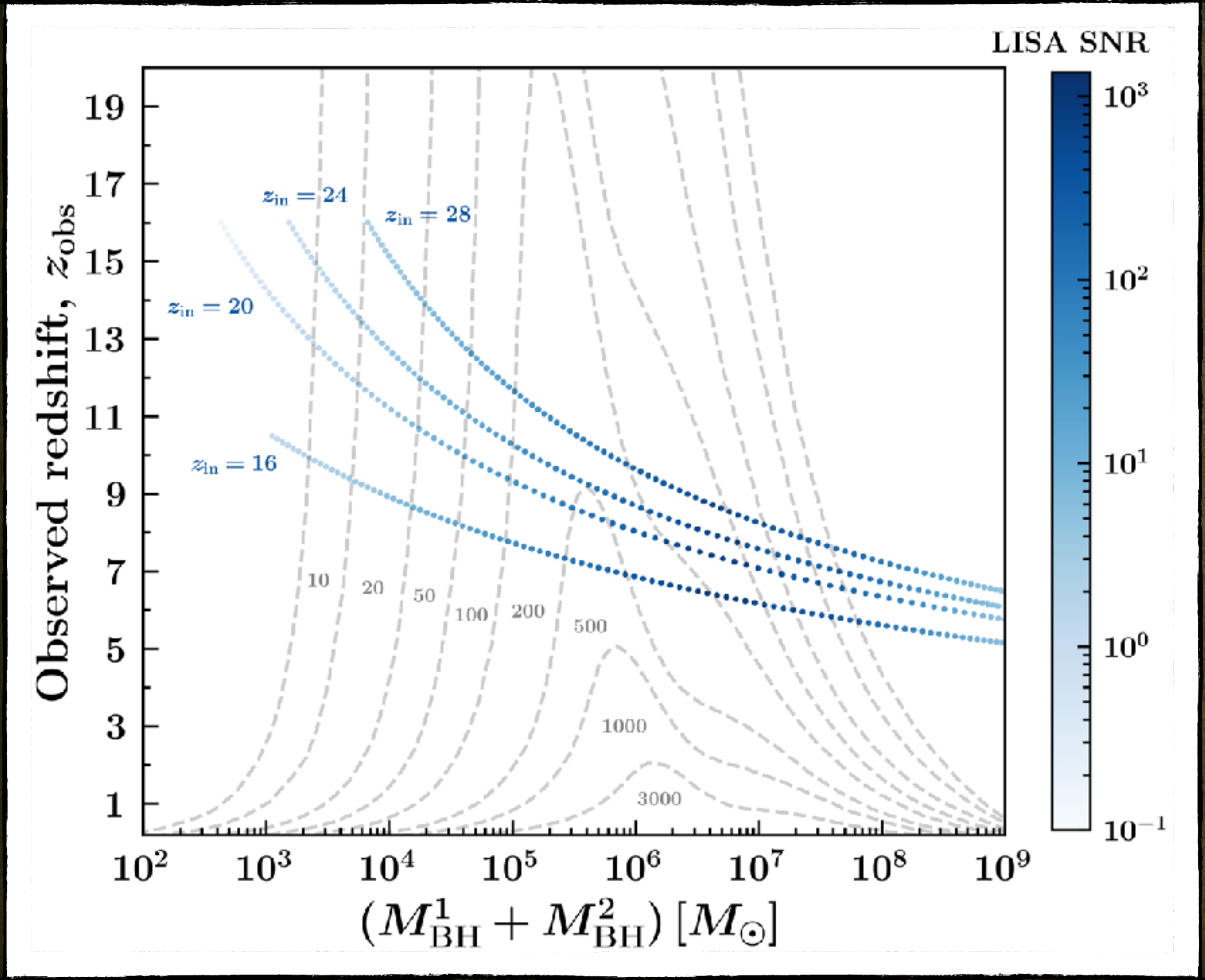


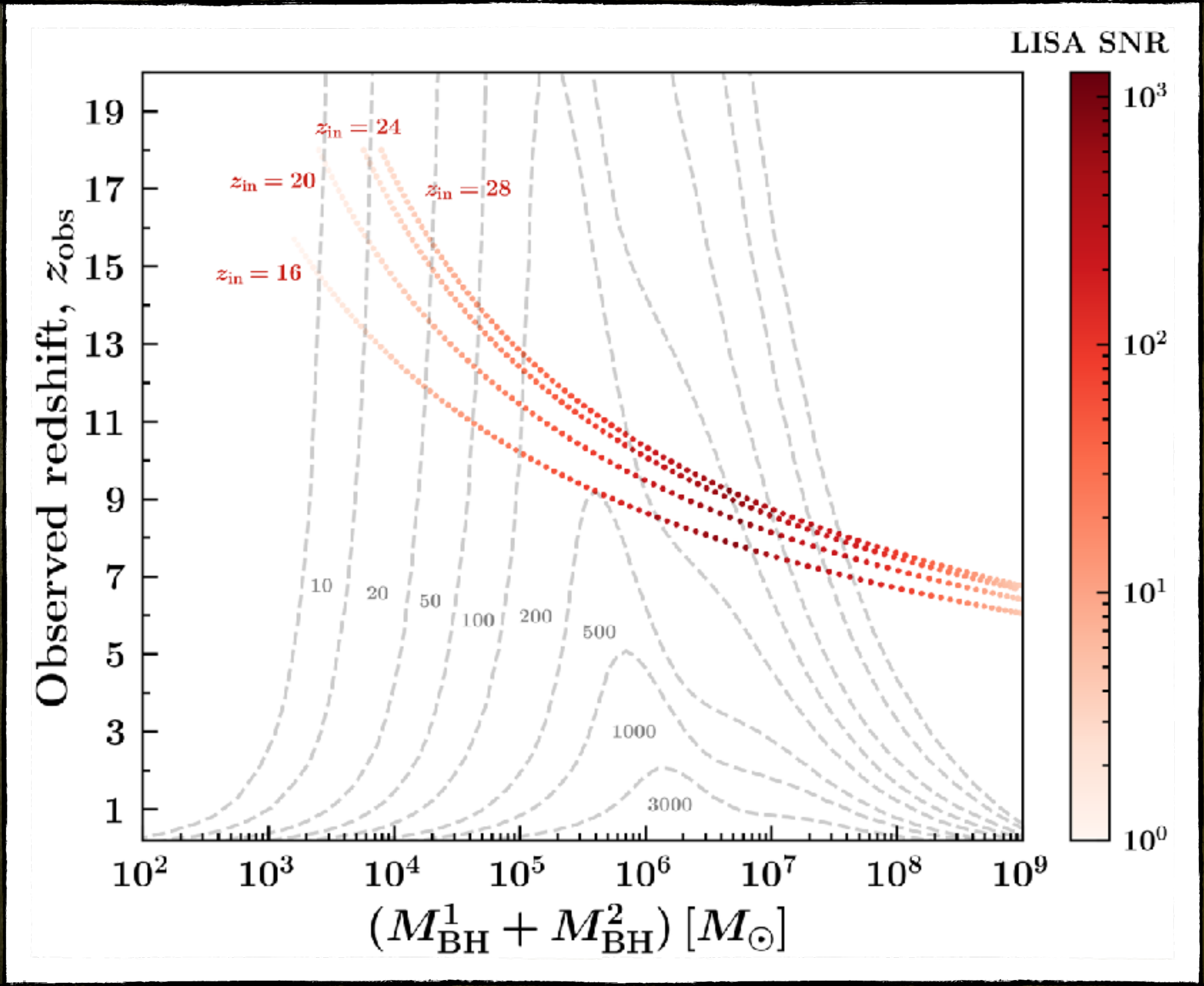


Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

LISA Signal-to-Noise Ratio:

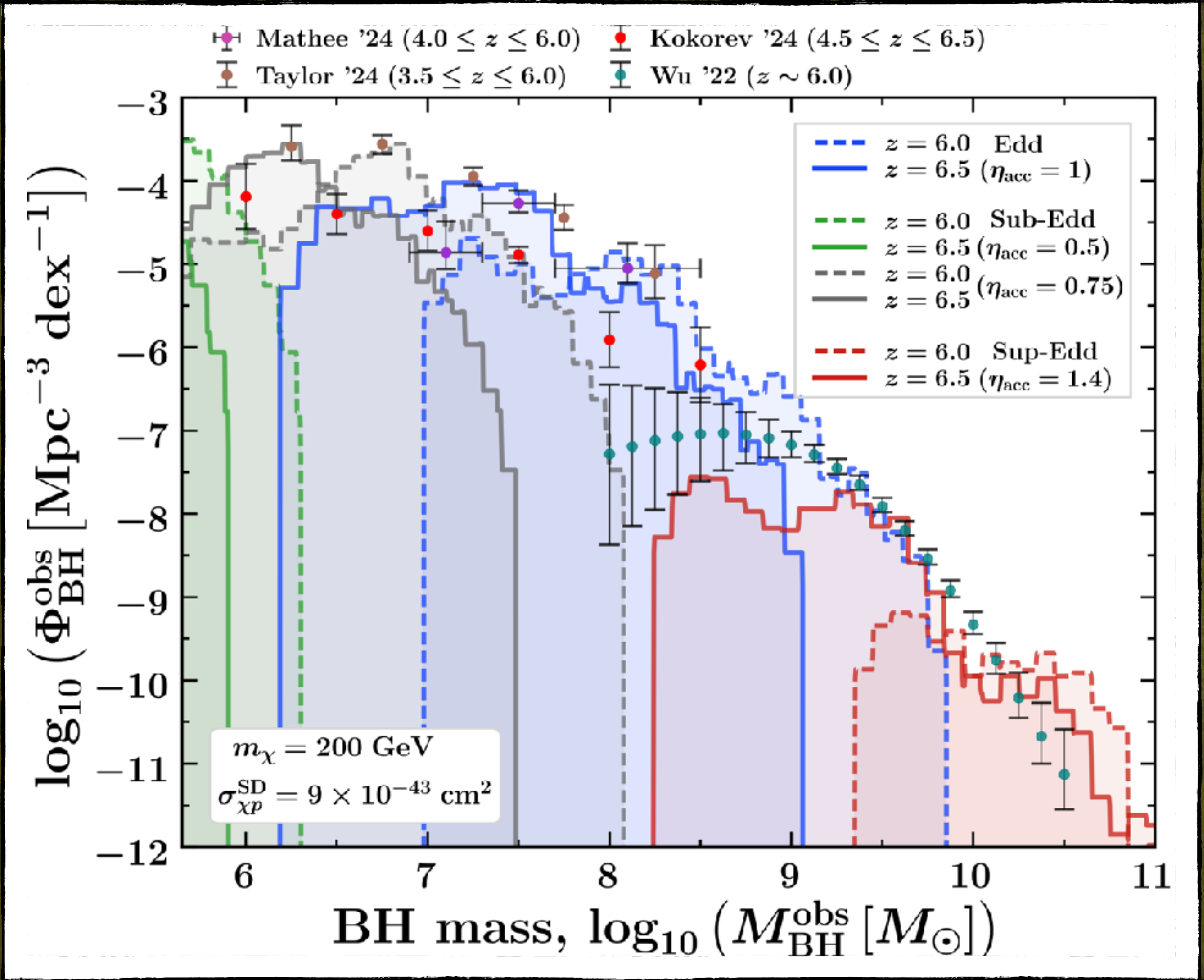
Lowest Pop III mass | Individual mergers | Highest Pop III mass





Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

SMBH mass function:



Bhattacharya, DB, Dasgupta, Doliya, Laha (arXiv:2512.23789)

$M_s \rightarrow M_{BH}$

$$\Phi_{SMBH} = \frac{dn_{BH}}{d\ln M_{BH}} = n_{halo} \times \frac{\delta n_s}{\delta M_s} \times f_{norm}$$

is a product of -

- DM halo may not be follow NFW
- Pop III star may not be at central region
- SMBH may not be in active phase
- Seed black hole may not accrete efficiently