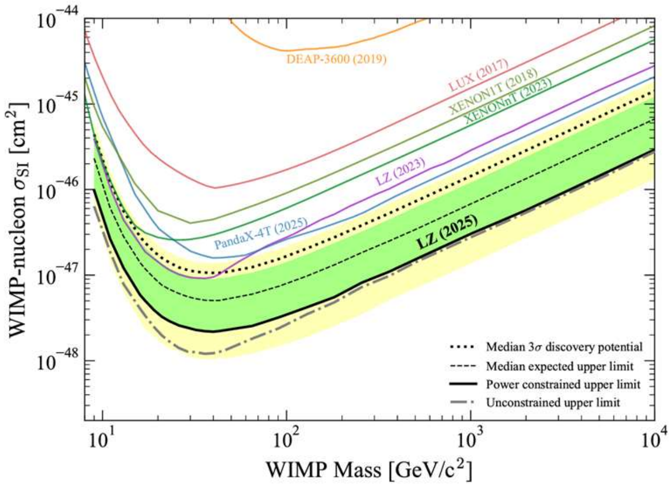
Dark Matter
where are we now?

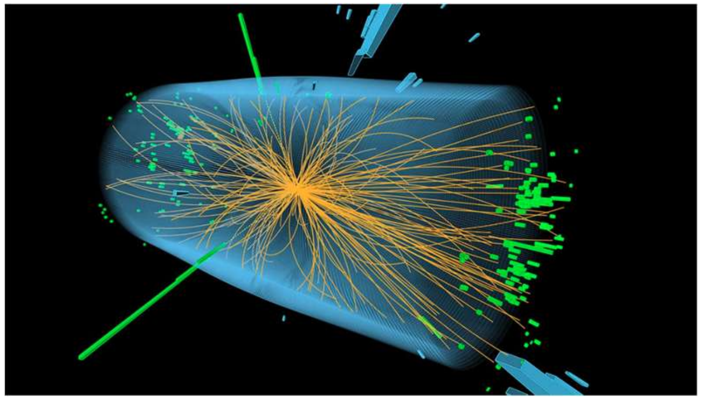
Malcolm Fairbairn
King’s College London

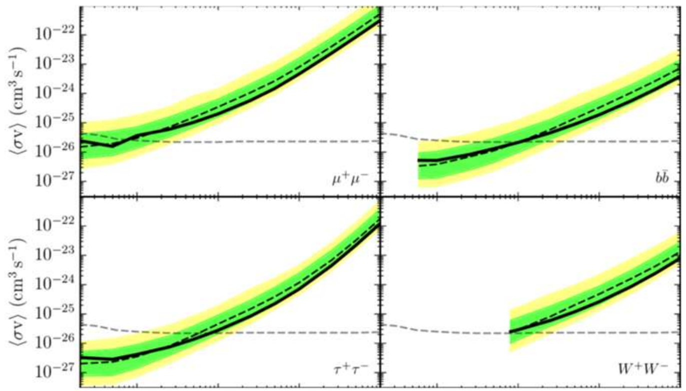
Dark Matter where am I now?

Malcolm Fairbairn
King’s College London

WIMPs / Thermal Relics Under Pressure

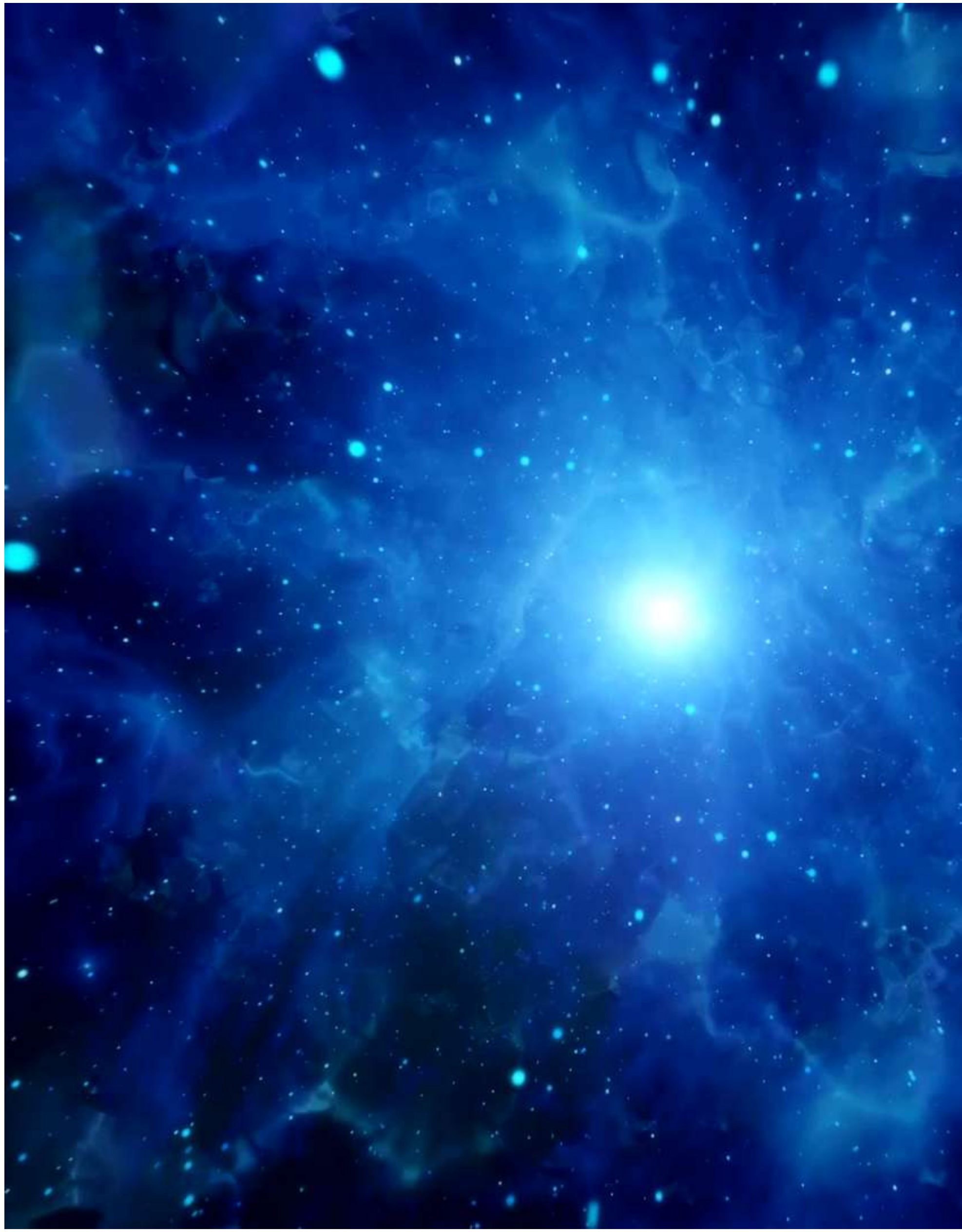


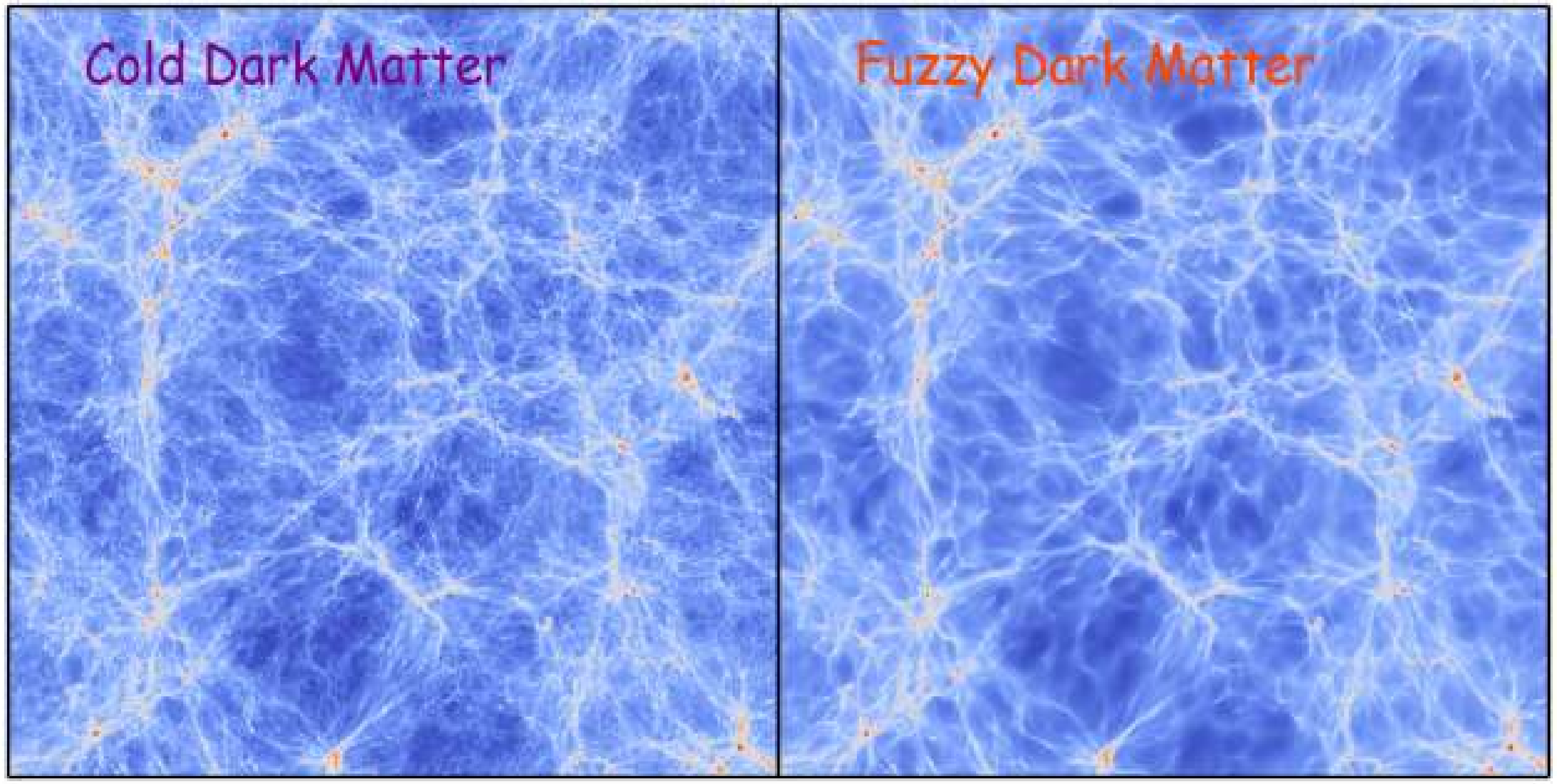




Plan

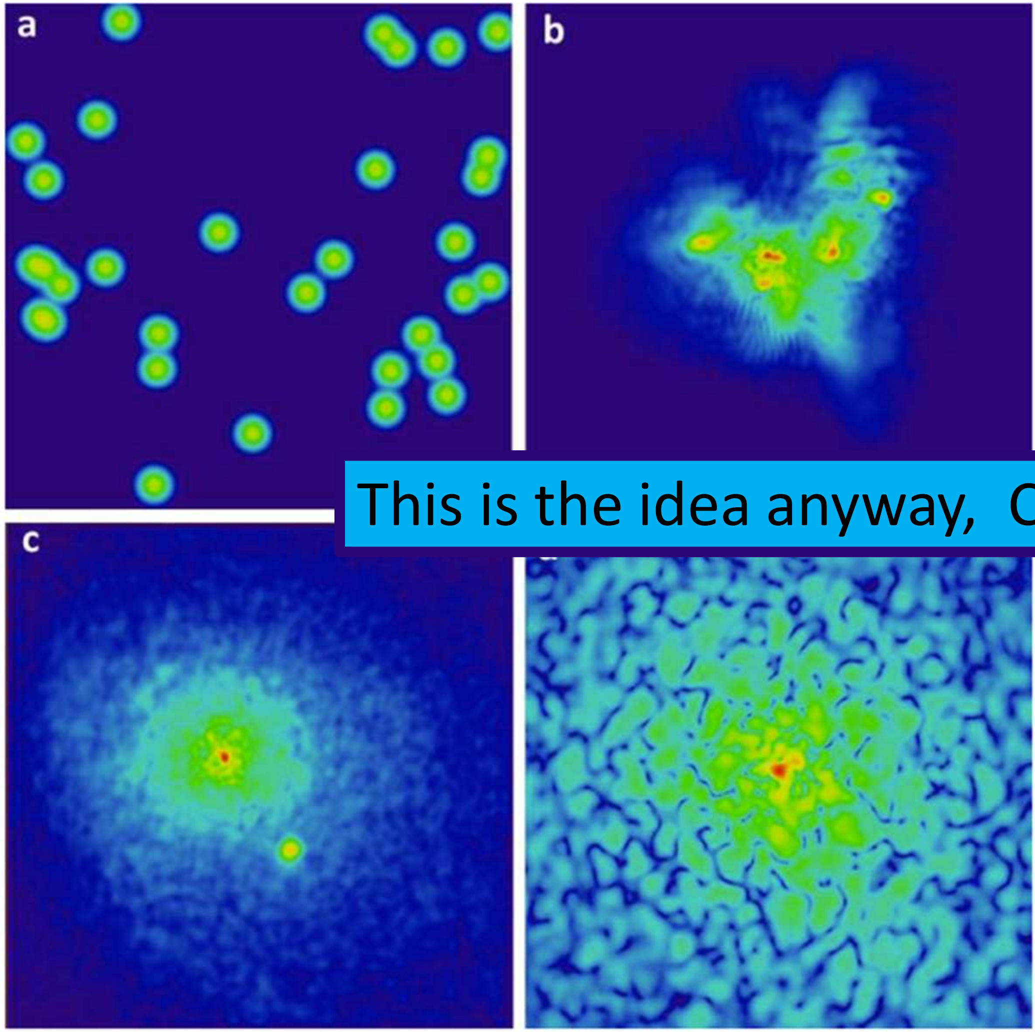
- Ultra Light Dark Matter and Dwarf Galaxies
- Ultra Light axionic Dark Matter and exploding DM halos
- Super Massive Black Holes beyond the PTA data.
  - Constraints on SMBH progenitors
  - Constraints on particle DM

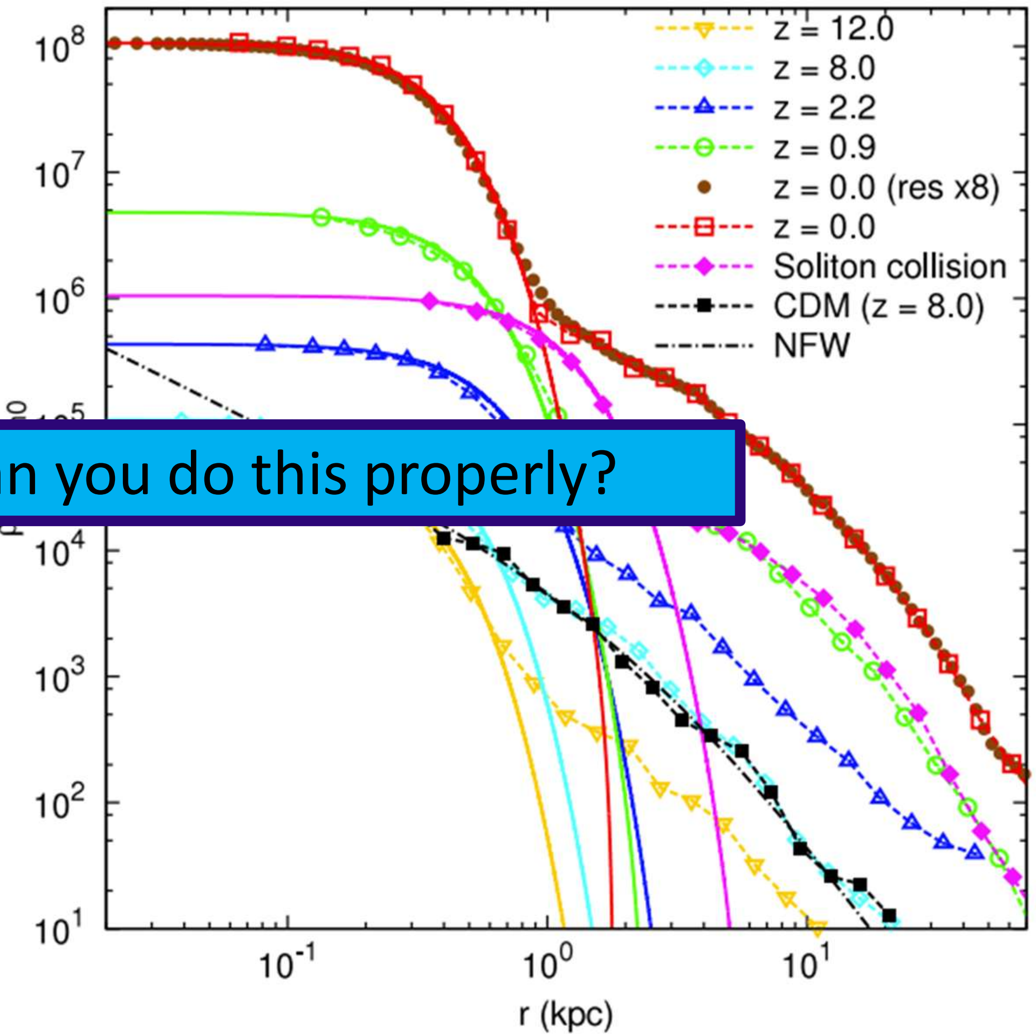




$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + \frac{m\Phi}{a}\psi$$

$$\nabla^2\Phi = 4\pi G m\left(|\psi|^2 - \langle|\psi|^2\rangle\right)$$





This is the idea anyway, Can you do this properly?

Schive et al 2014


Leo II
Ultra Faint Dwarf
Mass $2.5x10^7 M_\odot$

Jeans Analysis to get density of DM

$$\Phi(r) = \frac{4\pi G}{r}\int_0^r r^2 \rho(r) dr$$

$$\beta(r) \equiv 1 - \frac{\sigma_t^2(r)}{2\sigma_r^2(r)}$$

2nd order Jeans equation

$$\frac{d(\nu\sigma_r^2)}{dr} + \frac{2\beta}{r}\nu\sigma_r^2 + \nu\frac{d\Phi}{dr} = 0$$

$$\Sigma\sigma_{\rm los}^2(R) = 2\int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right)\frac{\nu\sigma_r^2 r}{\sqrt{r^2 - R^2}} dr$$

Jeans Analysis to get density of DM

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2nd order Jeans equation

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↓

$$\Sigma\sigma_{\rm los}^2(R) = 2\int_R^\infty (1-\beta\frac{R^2}{r^2})\frac{\nu\sigma_r^2 r}{\sqrt{r^2-R^2}}dr$$

But can also include 4th order information

$$\frac{d(\nu\overline{v_r^4})}{dr} - \frac{3}{r}\nu\overline{v_r^2v_t^2} + \frac{2}{r}\nu\overline{v_r^4} + 3\nu\sigma_r^2\frac{d\Phi}{dr} = 0$$

$$\frac{d(\nu\overline{v_r^2v_t^2})}{dr} - \frac{1}{r}\nu\overline{v_t^4} + \frac{4}{r}\nu\overline{v_r^2v_t^2} + \nu\sigma_t^2\frac{d\Phi}{dr} = 0$$

↓

$$\Sigma\overline{v_{\rm los}^4}(R) = 2\int_R^\infty \left(C_{2,0}\overline{v_r^4} + C_{2,1}\overline{v_r^2v_t^2} + C_{2,2}\overline{v_t^4}\right)\frac{\nu(r)r}{\sqrt{r^2-R^2}}dr$$

Can obtain wavefunctions of DM within the gravitational potential from that density.

$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial r^2}-\frac{l(l+1)}{r^2}\right)u_{nl}+mVu_{nl}=E_{nl}u_{nl}$$

$$\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}\right)V=4\pi G\rho\ ,$$

$$\psi_{nlm}(\boldsymbol{x},t) = r^{-1}u_{nl}(r)Y_l^m(\phi,\theta)e^{iE_{nl}t/\hbar}$$

$$\langle|\psi|^2\rangle = (4\pi r^2)^{-1}\sum_{nl}(2l+1)|a_{nl}|^2u_{nl}^2(r)$$

$$\rho(\boldsymbol{x},t)=|\psi(\boldsymbol{x},t)|^2$$

Now you check THIS density reproduces the actual density from the Jeans analysis.

Nobody ever actually does this in real life.
need to construct library of tens of thousands of wavefunctions then combine them to reconstruct your potential.

Nobody sane anyway.

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need to construct library of tens of thousands of wavefunctions then combine them to reconstruct your potential.

Nobody sane anyway.

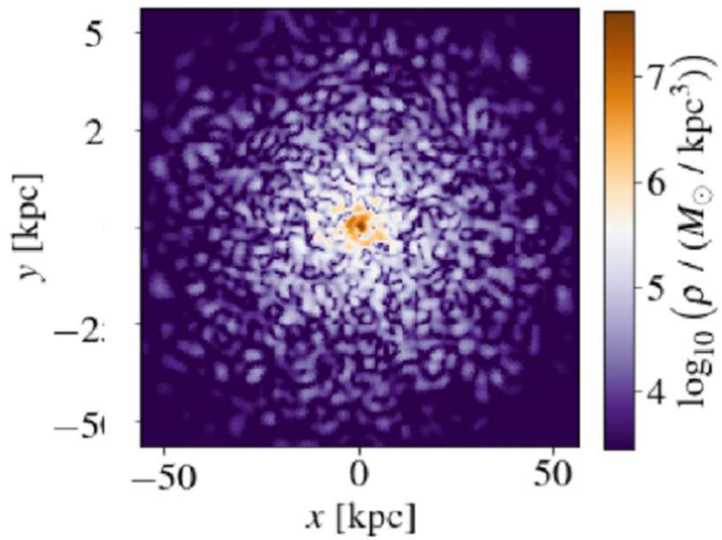
Wave Function Reconstruction

Expand in eigen states

$$\psi(r,\phi,\theta) = \sum_{nlm} a_{nlm} u_{nl}(r) Y_l^m(\phi,\theta) e^{iE_{nl}t/\hbar}$$

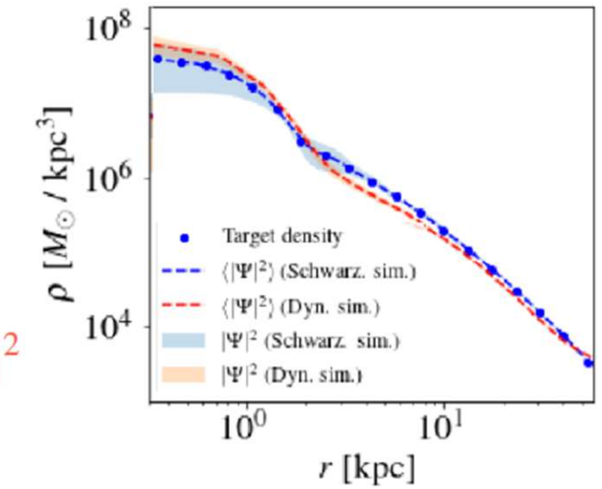
Density contributions

$$|\psi|^2 = \langle |\psi|^2 \rangle(r) + \chi(r,\phi,\theta)$$



$$\langle |\psi|^2 \rangle(r) = \frac{4\pi}{r^2} \sum_{n,l} (2l+1)\,|a_{nl}|^2 u_{nl}^2(r)$$

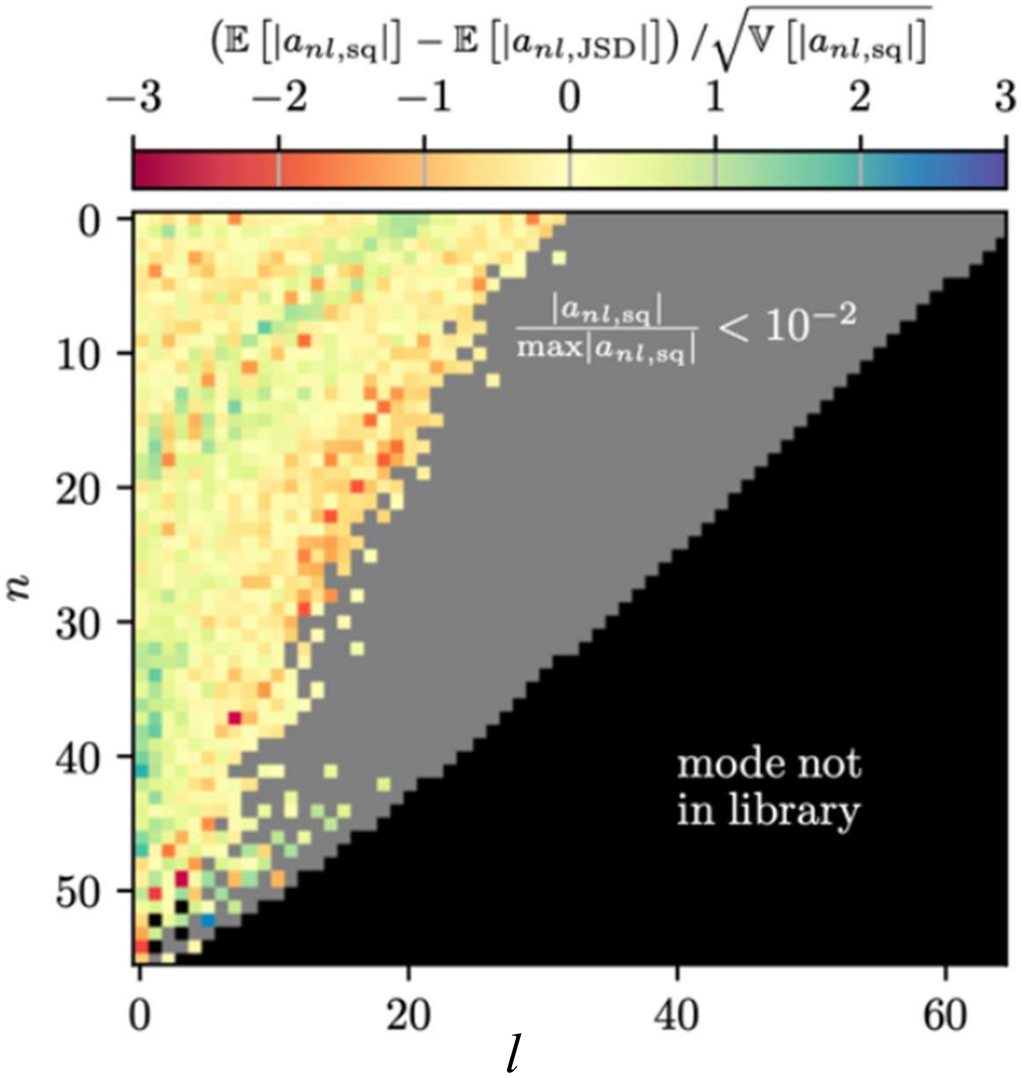
$$\chi(r,\phi,\theta) = \sum_{(n,l,m)\neq(n',l',m')} a_{nlm} a^*_{n'l'm'} u_{nl} u^*_{n'l'} Y_l^m Y_l^{m}* \, e^{i(E_{nl}-E_{n'l'})t/\hbar}$$



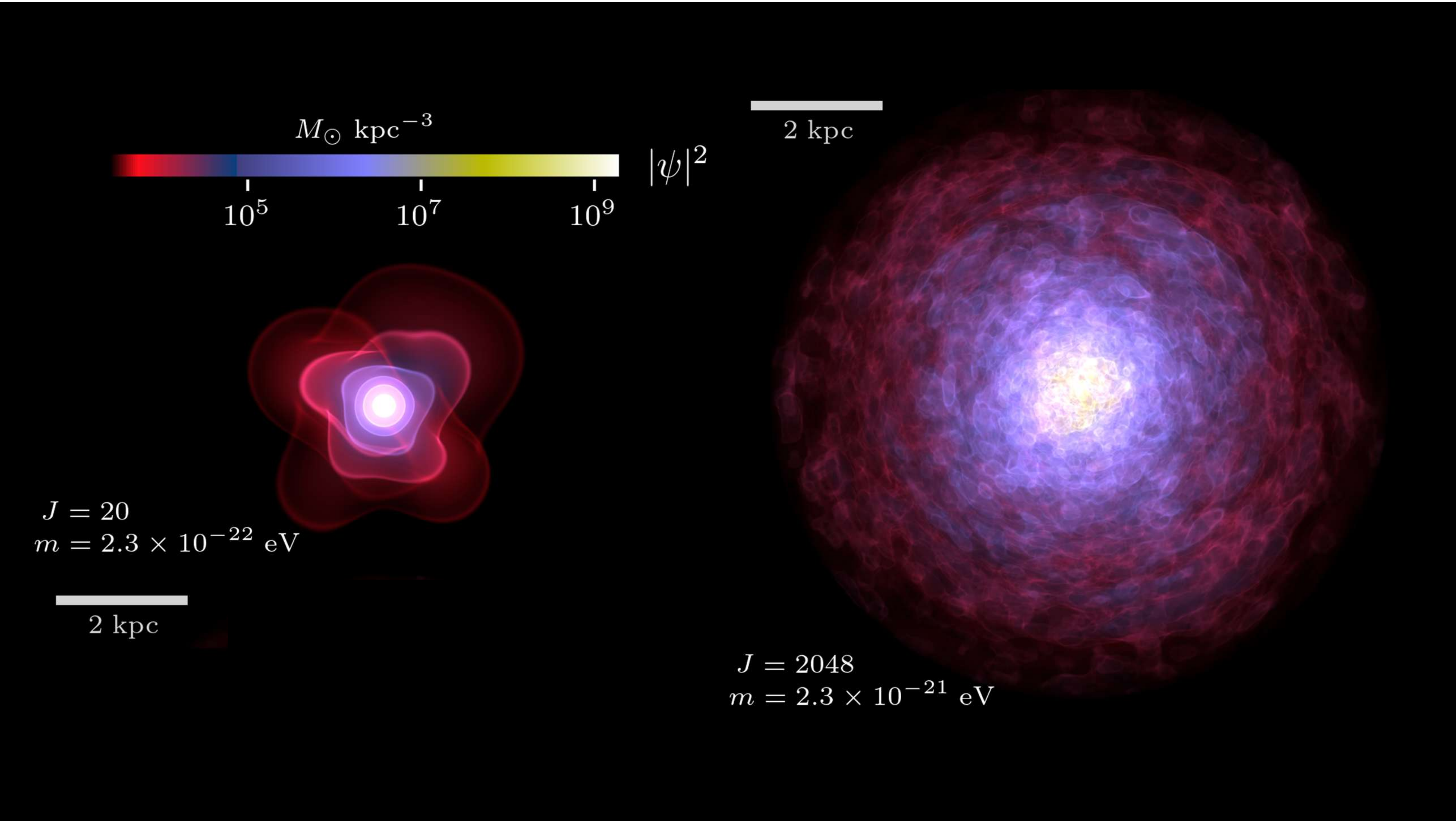
$$\langle |\psi|^2 \rangle = \mathbb{E}_{a_{nlm}}\left[|\psi|^2\right] = \lim_{T\to\infty} \frac{1}{T}\int_0^T \mathrm{d}t\,|\psi|^2 \approx \frac{1}{4\pi r^2}\int_{\mathbb{S}^2} \mathrm{d}\Omega(r)\,|\psi|^2$$

spherically symmetric steady-state configuration

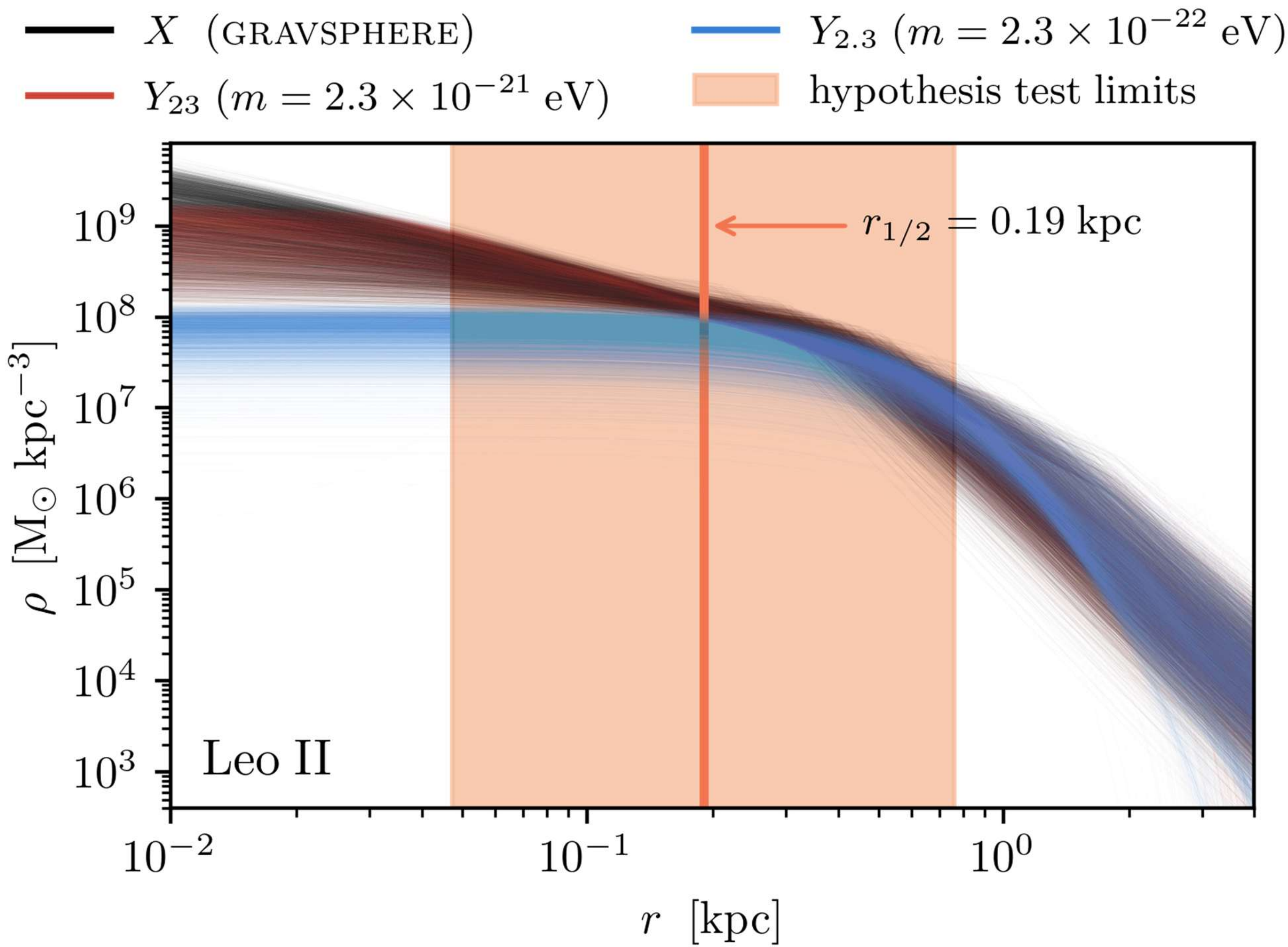
Yavetz+ (2022)



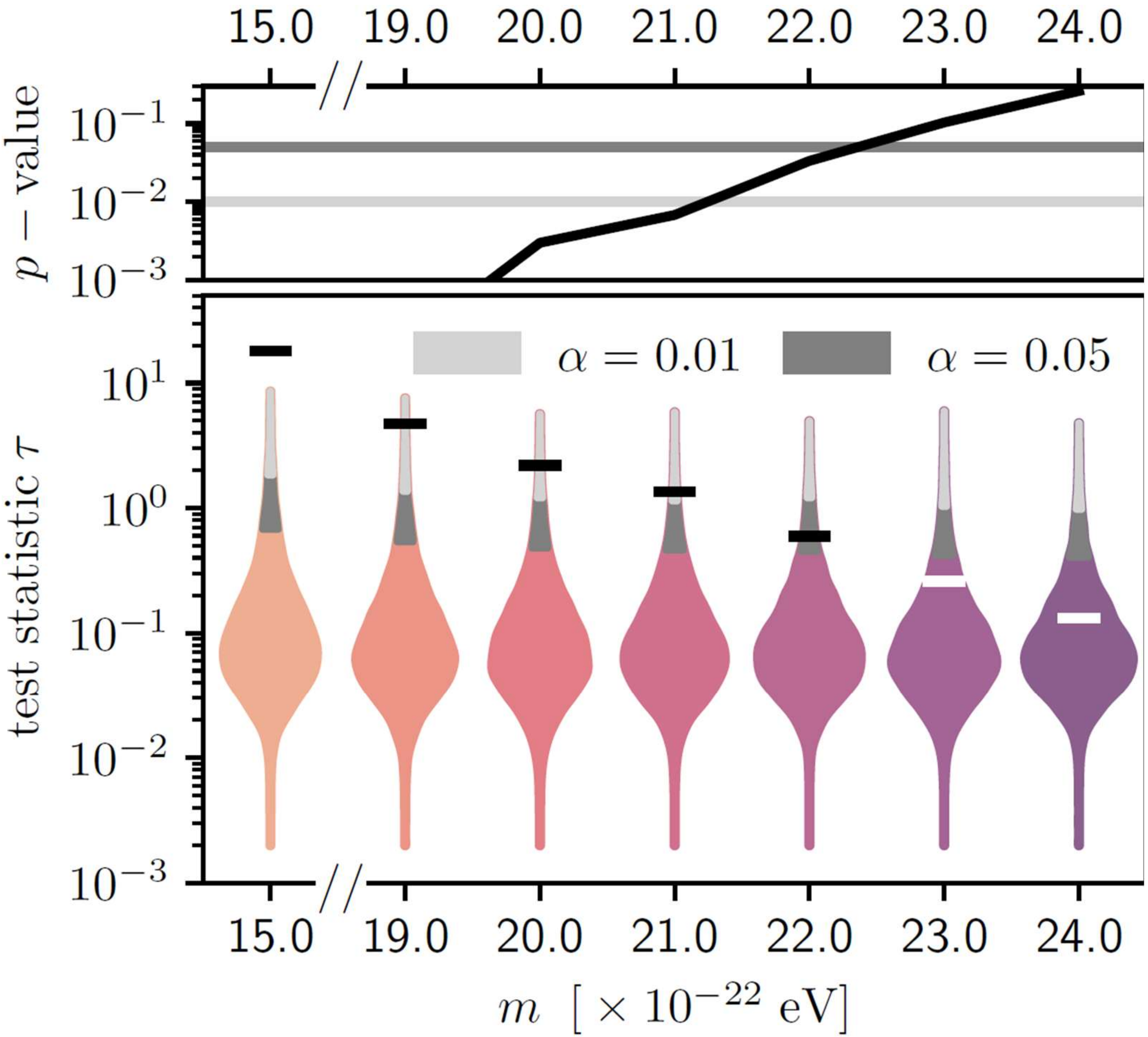
An example of the heat map of weights applied to different solutions to reconstruct the potential of Leo II



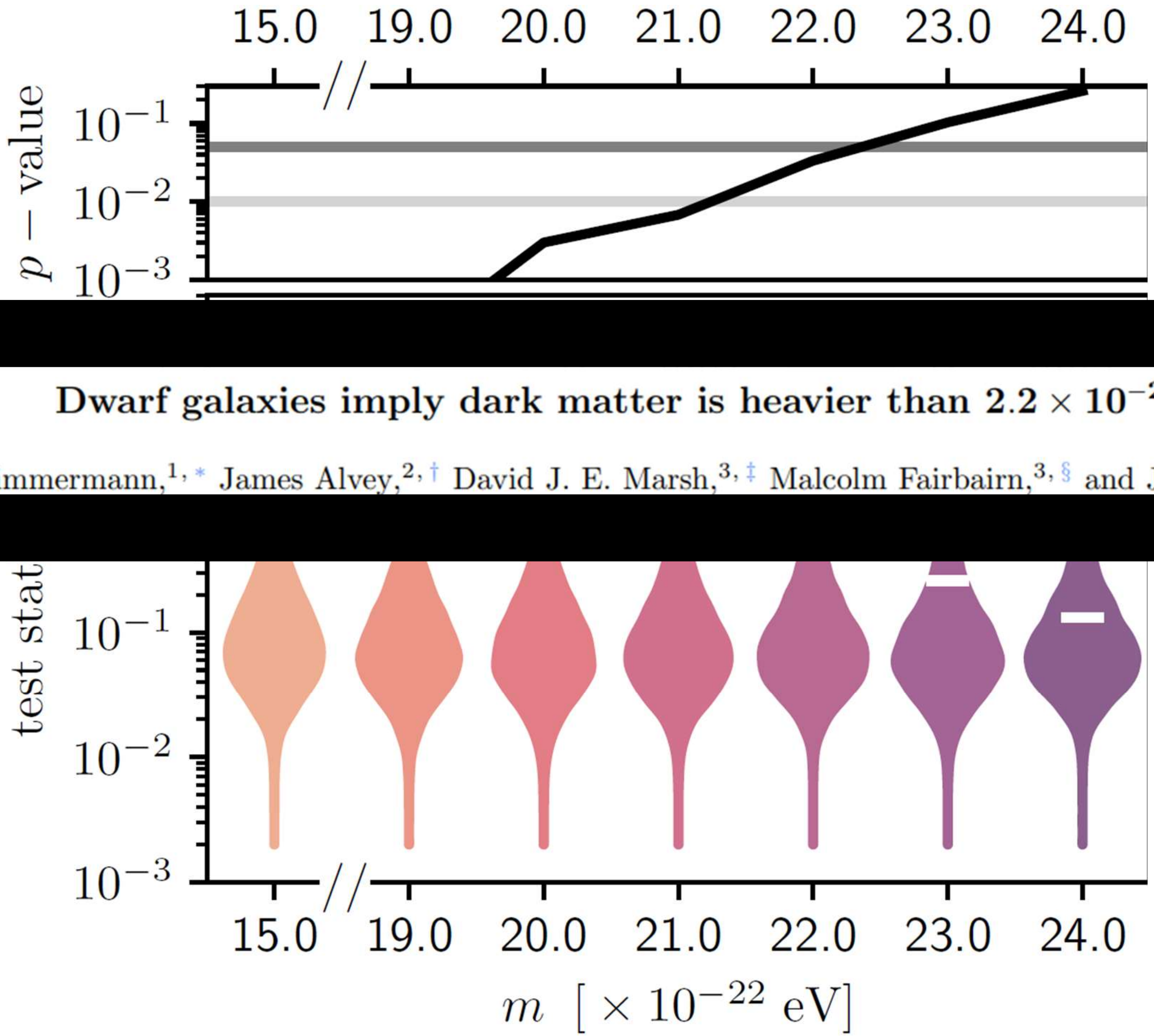
$M_\odot$ kpc^{-3}
$|\psi|^2$
10^5
10^7
10^9
2 kpc
$J = 20$
$m = 2.3 \times 10^{-22}$ eV
2 kpc
$J = 2048$
$m = 2.3 \times 10^{-21}$ eV



X (GRAVSPHERE)
Y_{23} ($m = 2.3 \times 10^{-21}$ eV)
$Y_{2.3}$ ($m = 2.3 \times 10^{-22}$ eV)
hypothesis test limits
$r_{1/2} = 0.19$ kpc
Leo II
ρ [$M_\odot$ kpc^{-3}]
r [kpc]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^{-2}
10^{-1}
10^0



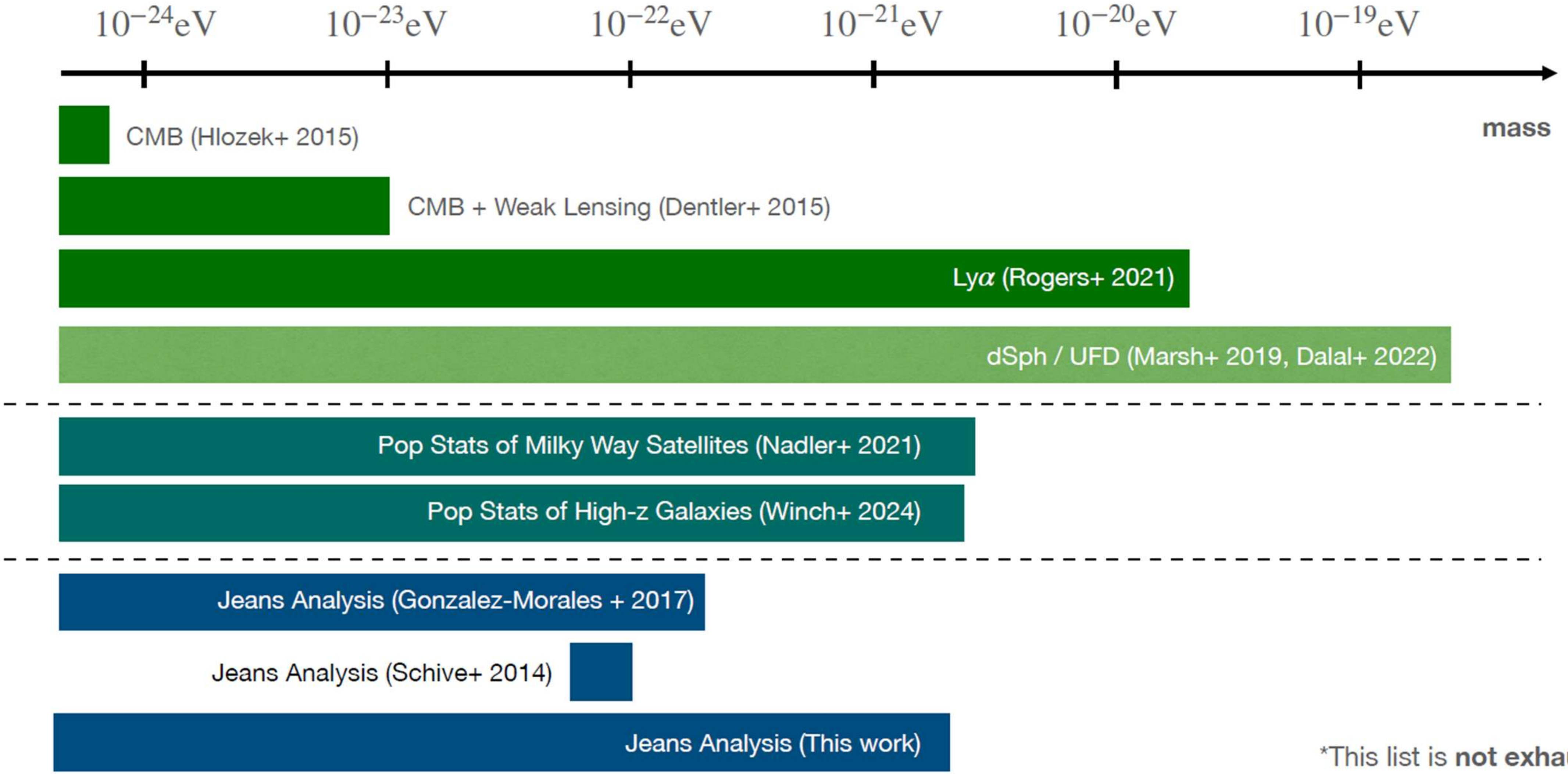
15.0
19.0
20.0
21.0
22.0
23.0
24.0
p − value
10^{-1}
10^{-2}
10^{-3}
test statistic τ
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
$\alpha = 0.01$
$\alpha = 0.05$
m [$\times 10^{-22}$ eV]



Dwarf galaxies imply dark matter is heavier than 2.2×10^{-21} eV

Tim Zimmermann,[1,*] James Alvey,[2,†] David J. E. Marsh,[3,‡] Malcolm Fairbairn,[3,§] and Justin I. Read[4,¶]

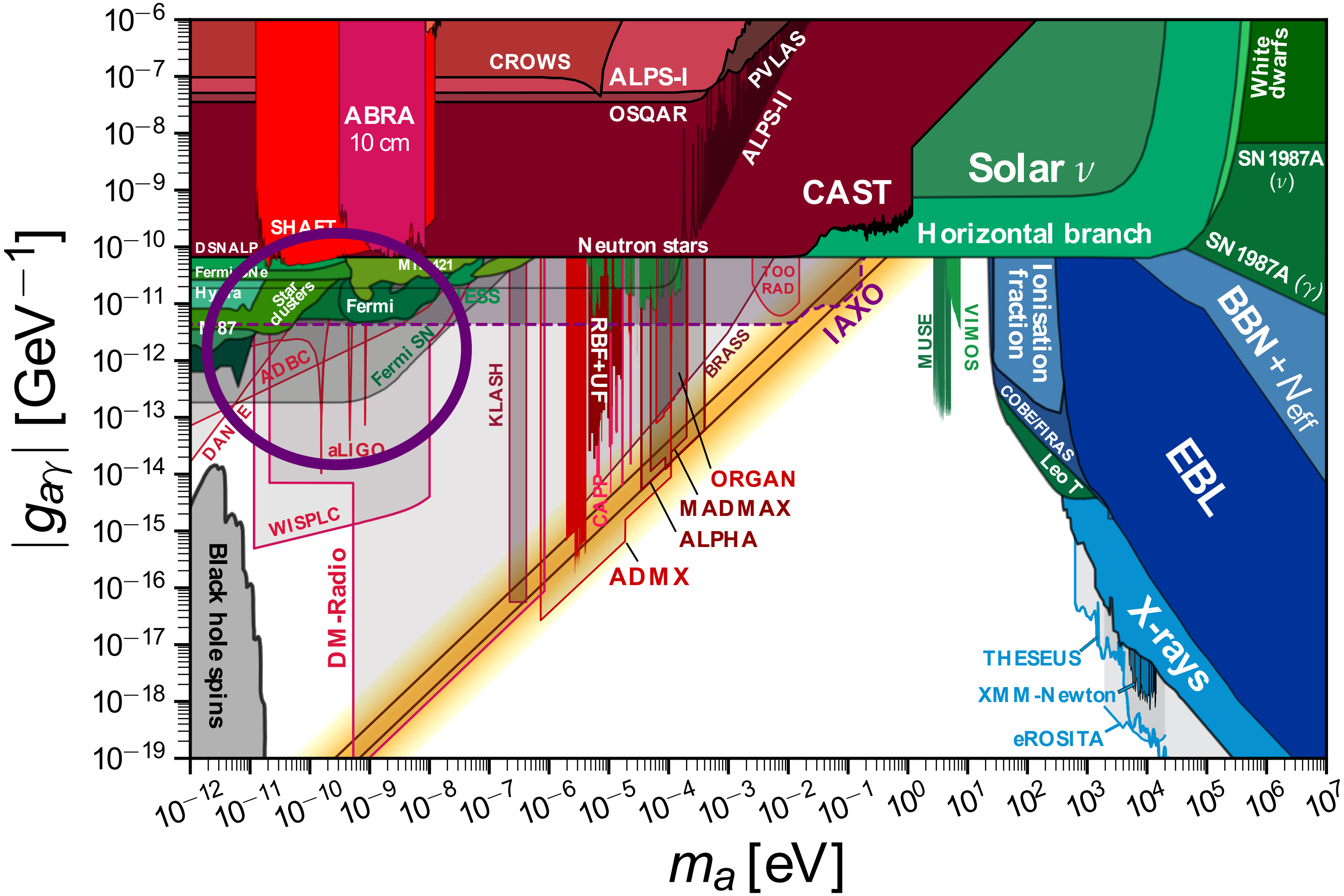
How does this compare with other constraints?



*This list is **not exhaustive**

Axion Limits

Fig: Ciaran O'Hare



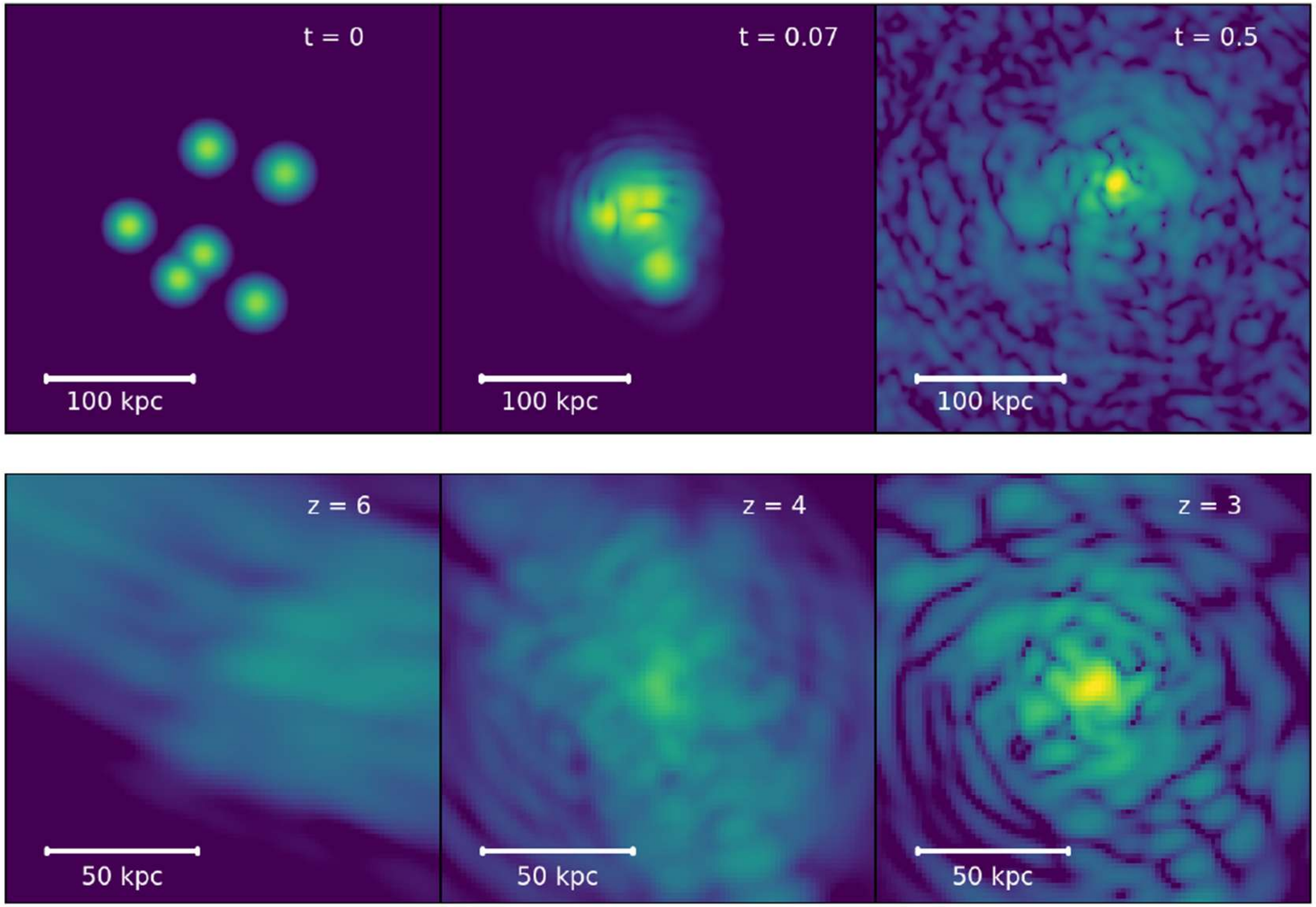
This talk: limits on axion DM here.

The Diversity of Core–Halo Structure in the Fuzzy Dark Matter Model

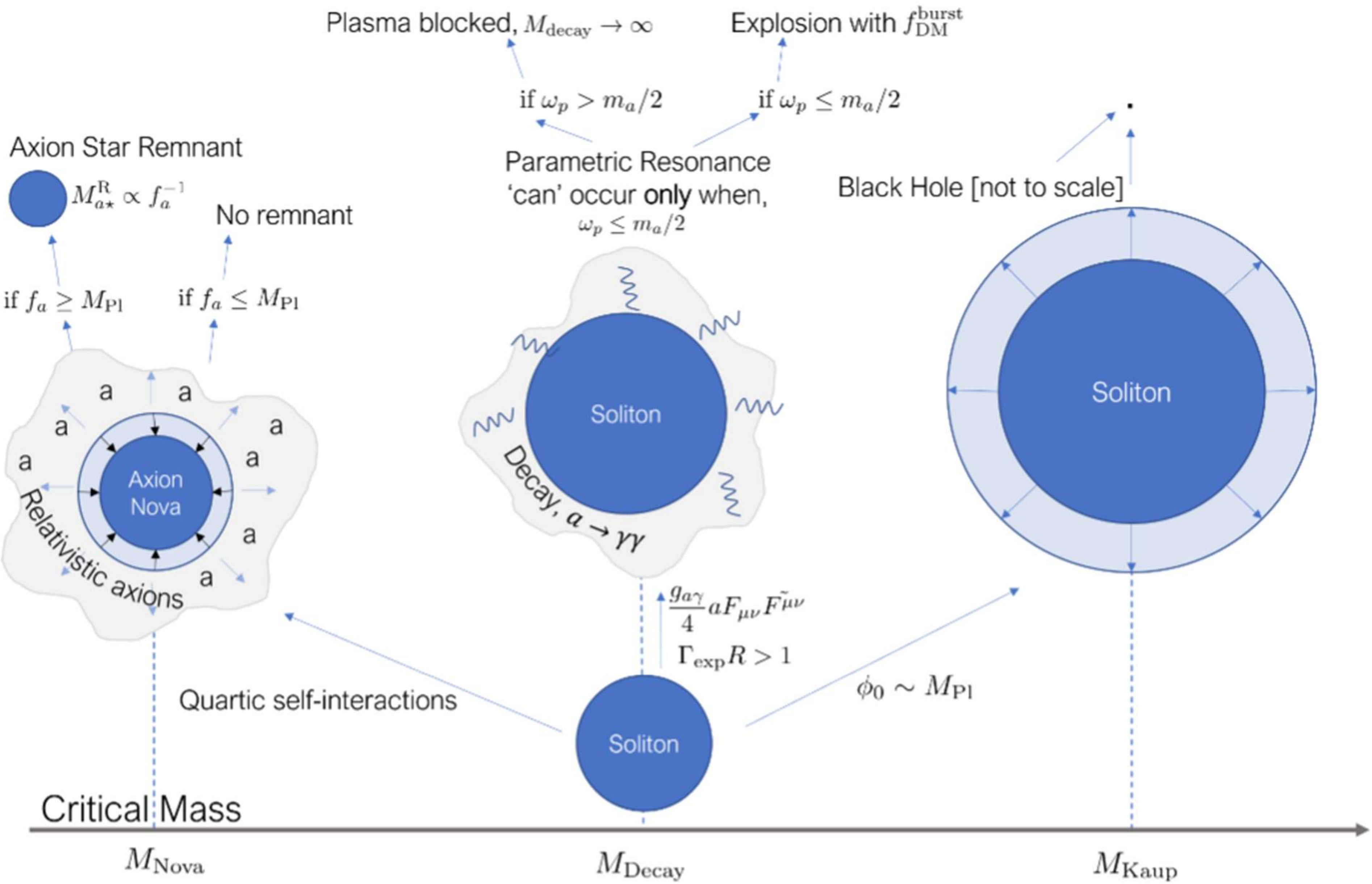
Hei Yin Jowett Chan,[1★] Elisa G. M. Ferreira,[2,3,4] Simon May,[2★] Kohei Hayashi,[5,6] Masashi Chiba[1]

Coalesence of halos to form bigger halo

Formation of a single halo from smaller halos

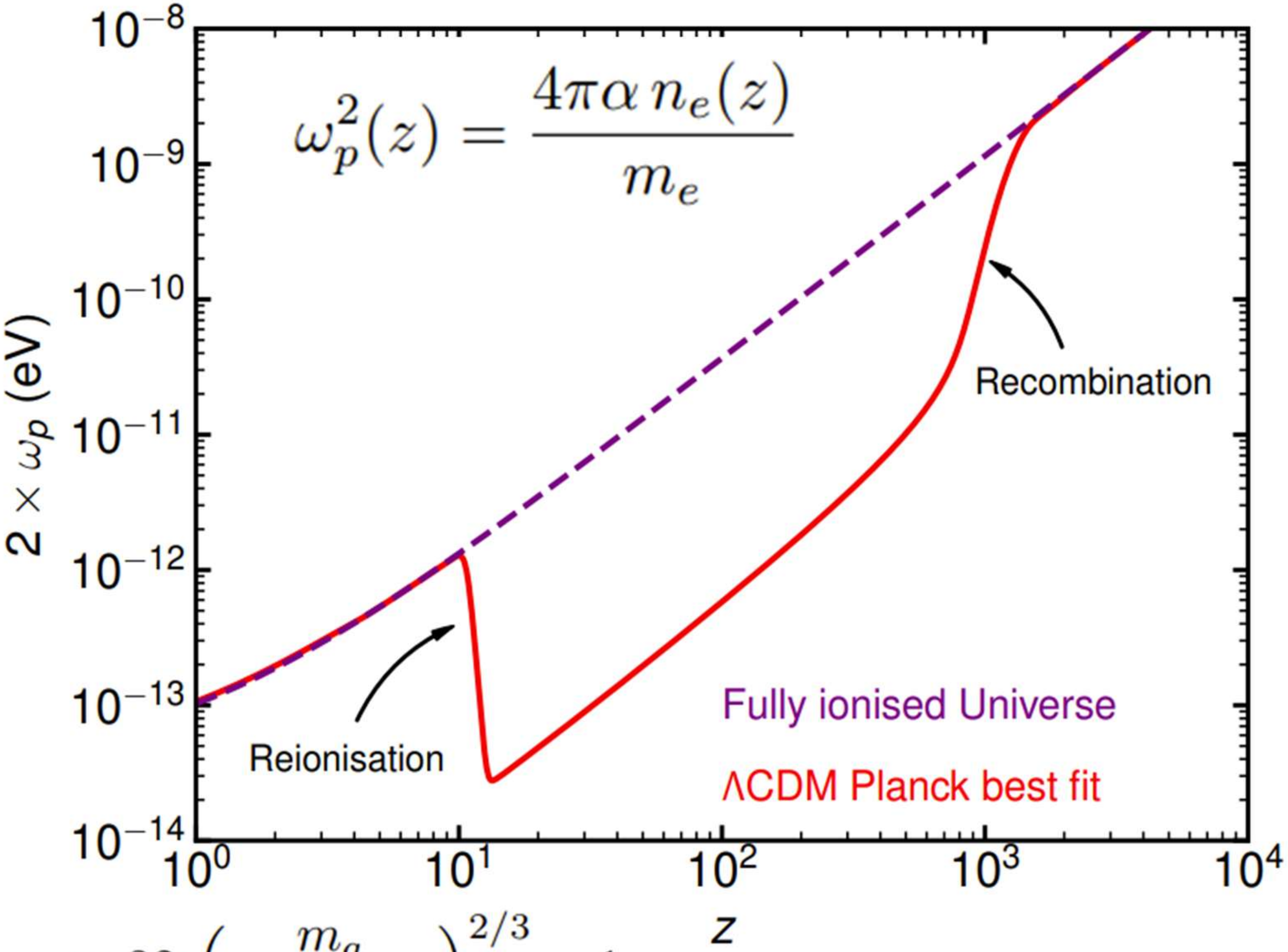


- As Theorists, we can contemplate many possible deaths for these dense cores…



Plasma blocked, $M_{\rm decay} \to \infty$
Explosion with $f_{\rm DM}^{\rm burst}$
if $\omega_p > m_a/2$
if $\omega_p \leq m_a/2$
Axion Star Remnant
$M_{a\star}^{\rm R} \propto f_a^{-1}$
No remnant
Parametric Resonance
'can' occur **only** when,
$\omega_p \leq m_a/2$
Black Hole [not to scale]
if $f_a \geq M_{\rm Pl}$
if $f_a \leq M_{\rm Pl}$
Soliton
Soliton
Axion Nova
Relativistic axions
Decay, $a \to \gamma\gamma$
$\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F^{\mu\nu}}$
$\Gamma_{\rm exp} R > 1$
$\phi_0 \sim M_{\rm Pl}$
Quartic self-interactions
Soliton
Critical Mass
$M_{\rm Nova}$
$M_{\rm Decay}$
$M_{\rm Kaup}$

Photon Effective Mass can prevent Decay!



$$z_{\rm decay} \simeq 32 \left(\frac{m_a}{10^{-13}\,{\rm eV}}\right)^{2/3} - 1$$

Exploding Axion Stars Heat IGM

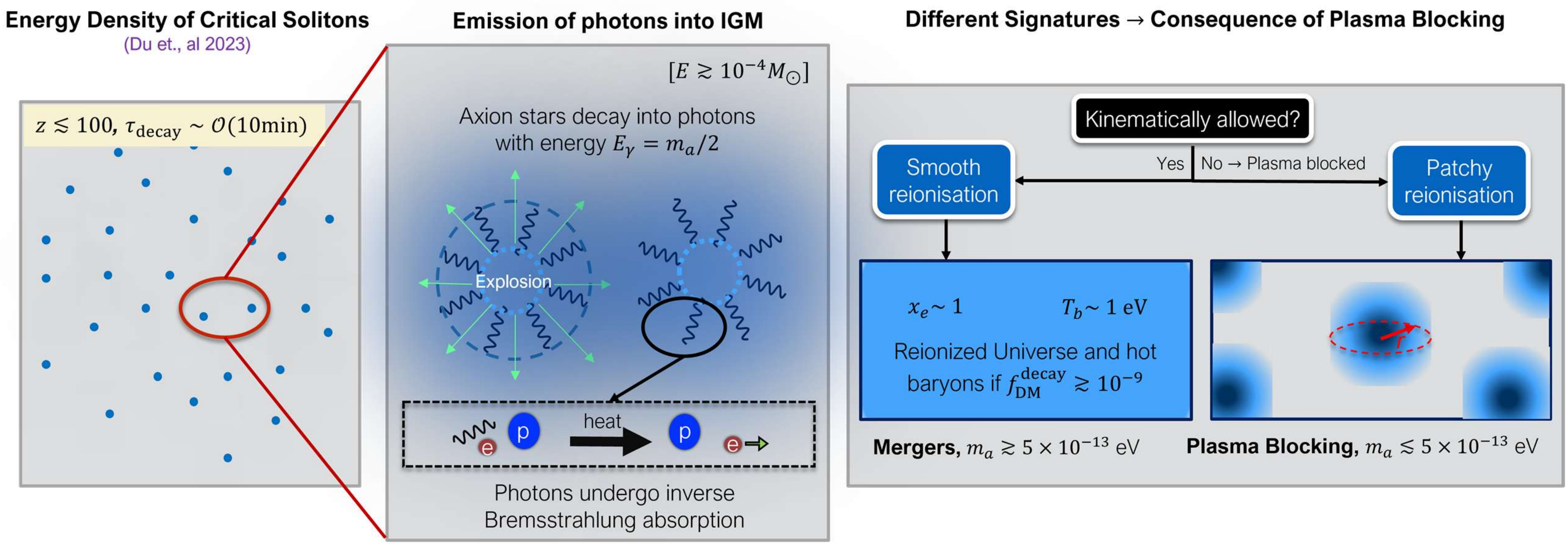
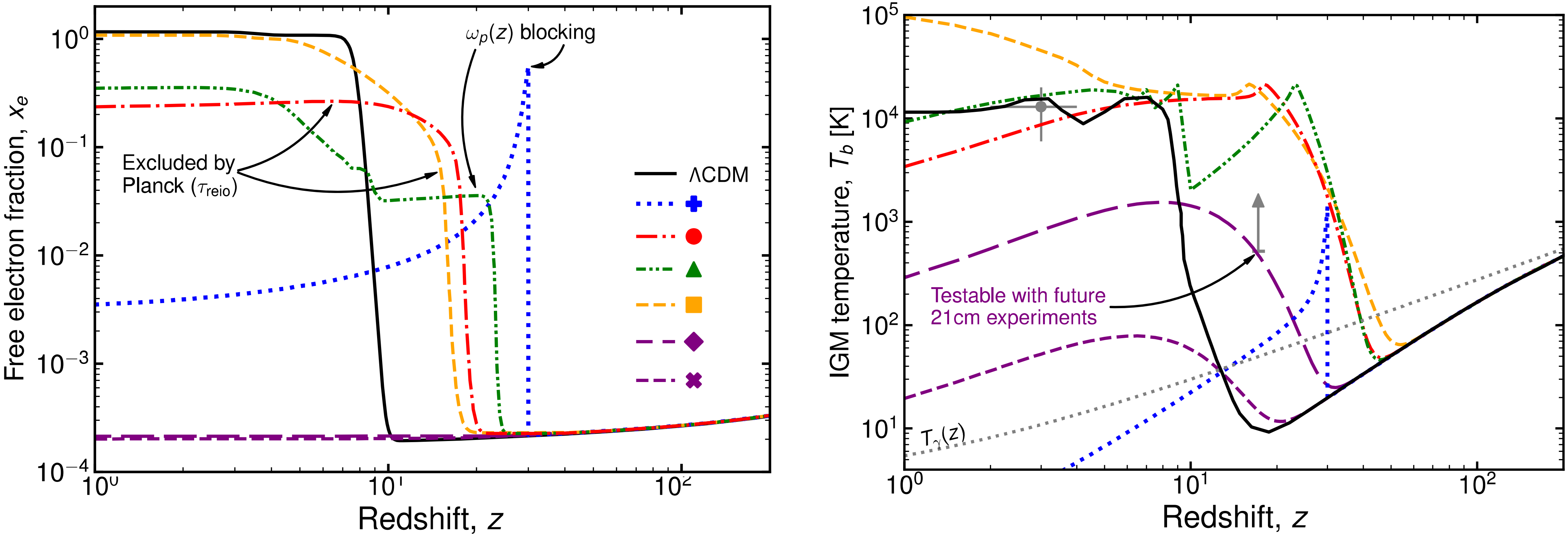
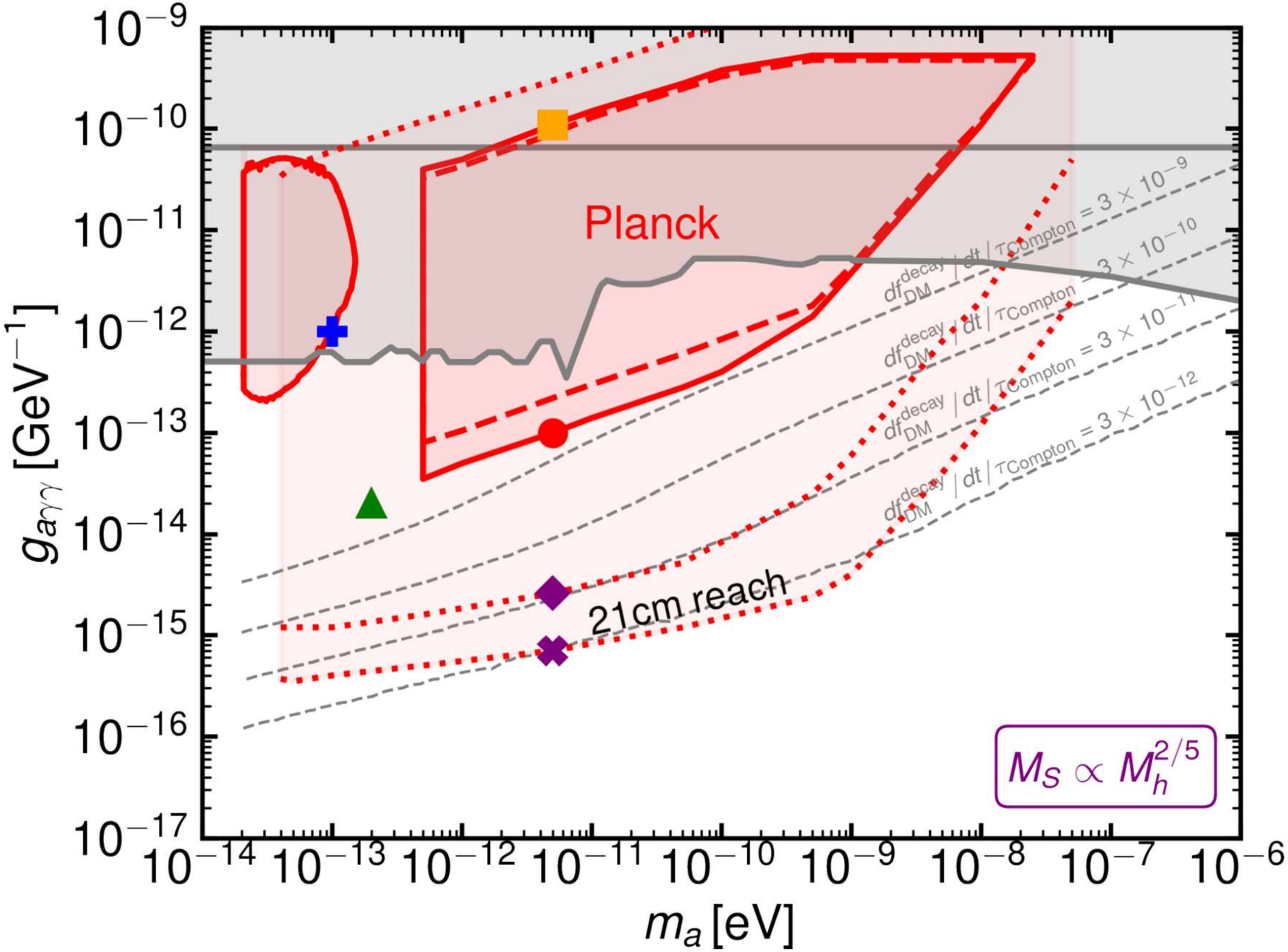


Fig by Charis Pooni

Reionization Histories

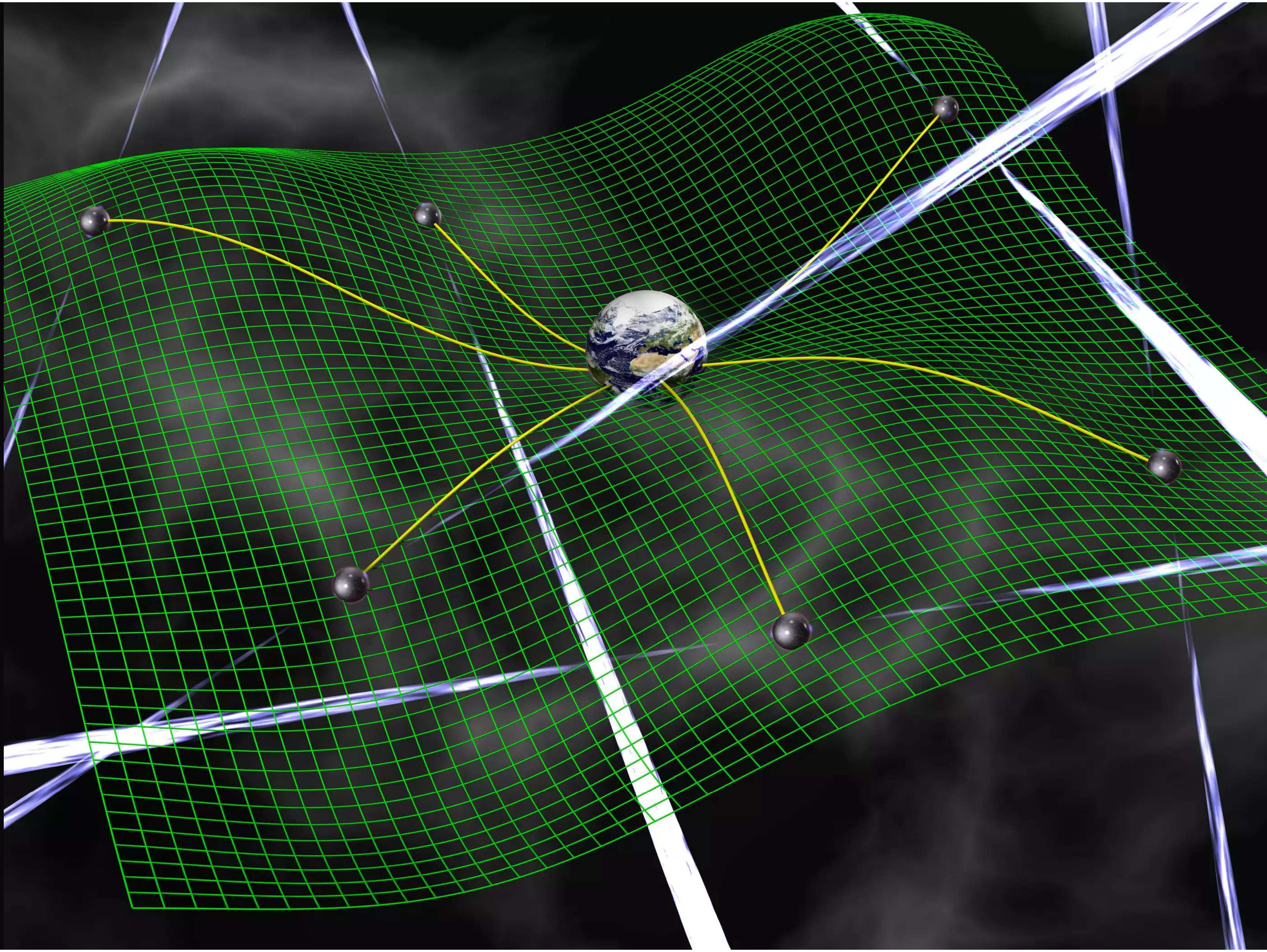


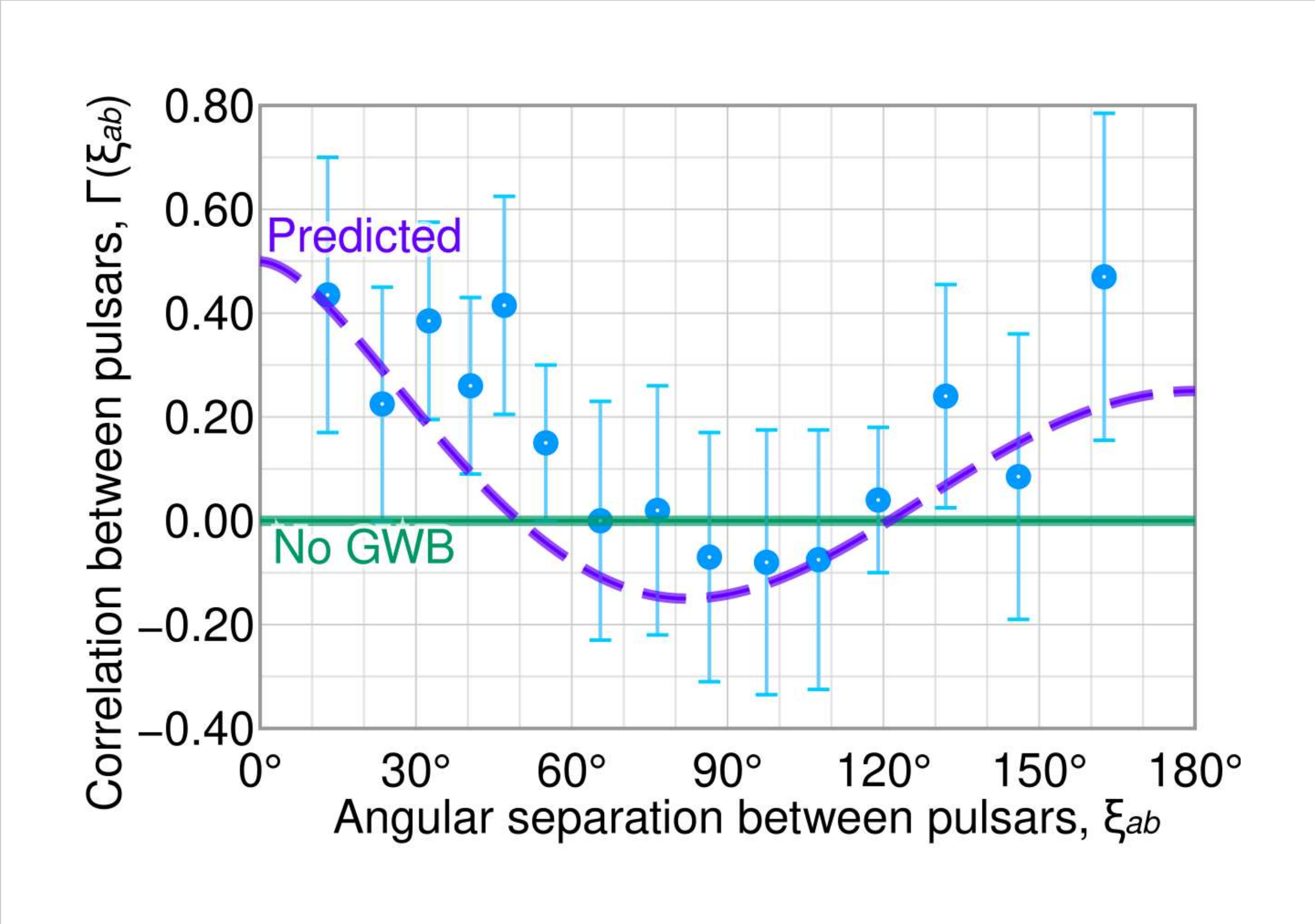
New Constraints on Axions



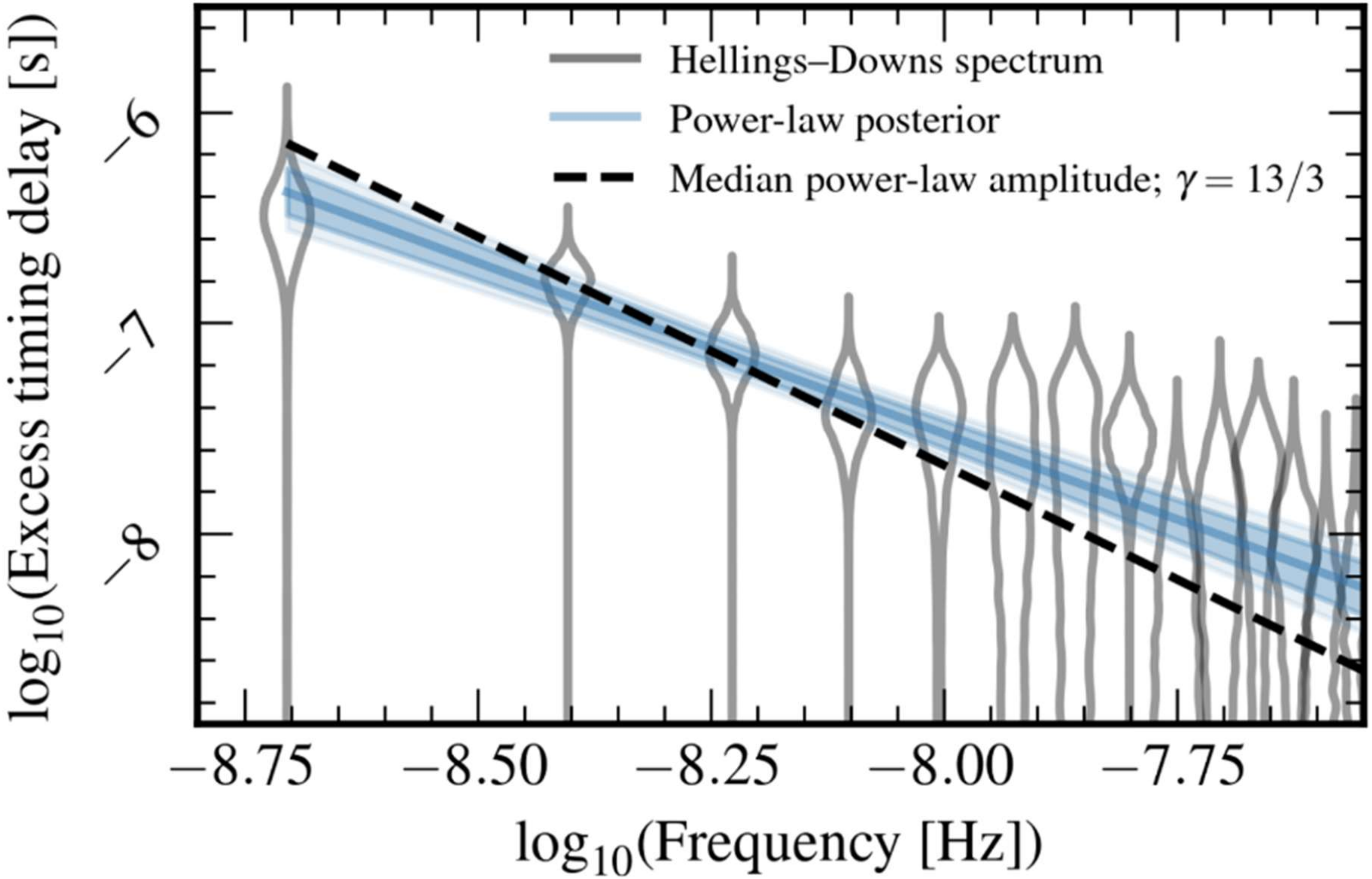
Pulsar Timing Array (PTA)

Gravitational Waves create arrival delay across the sky with characteristic pattern



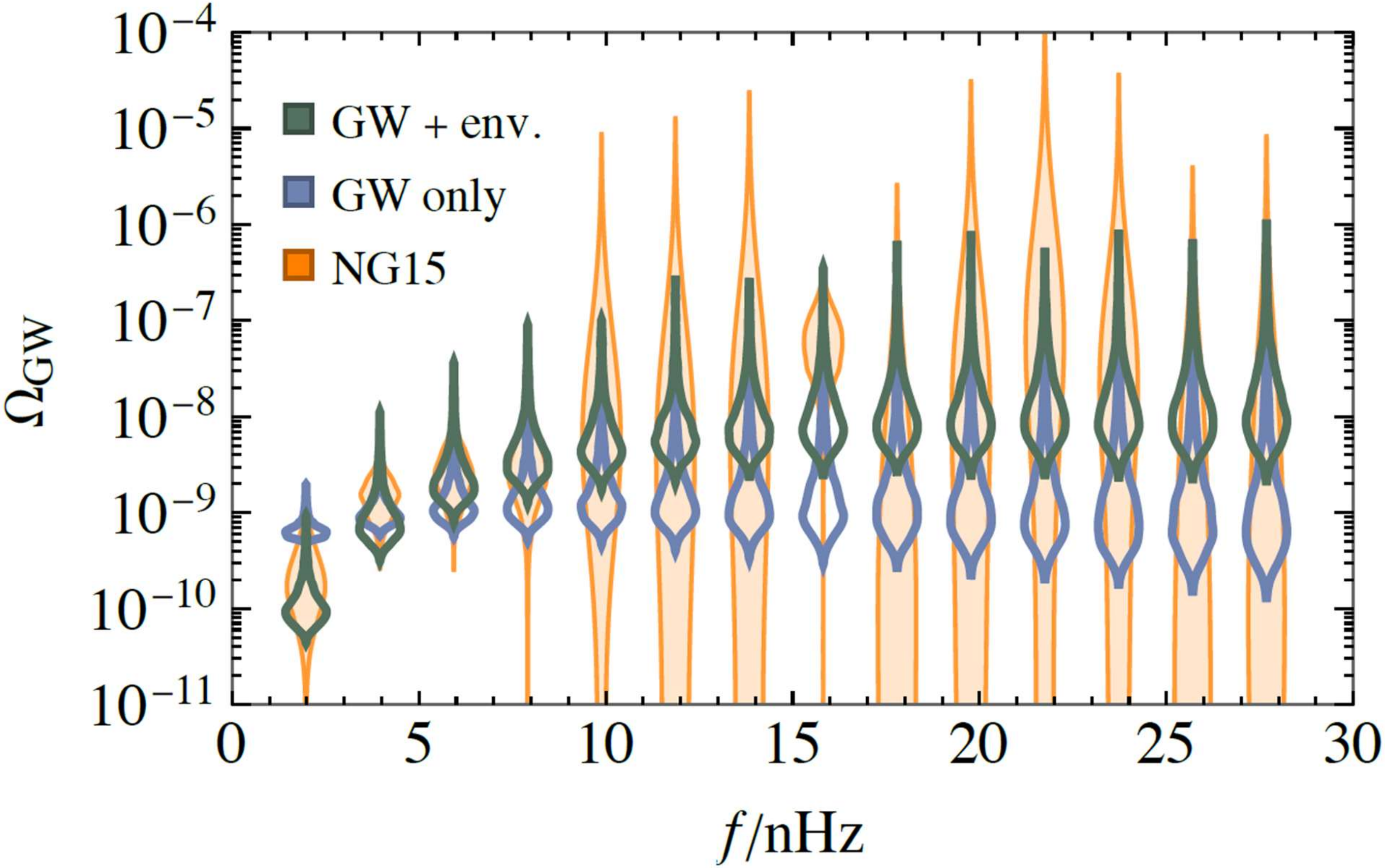


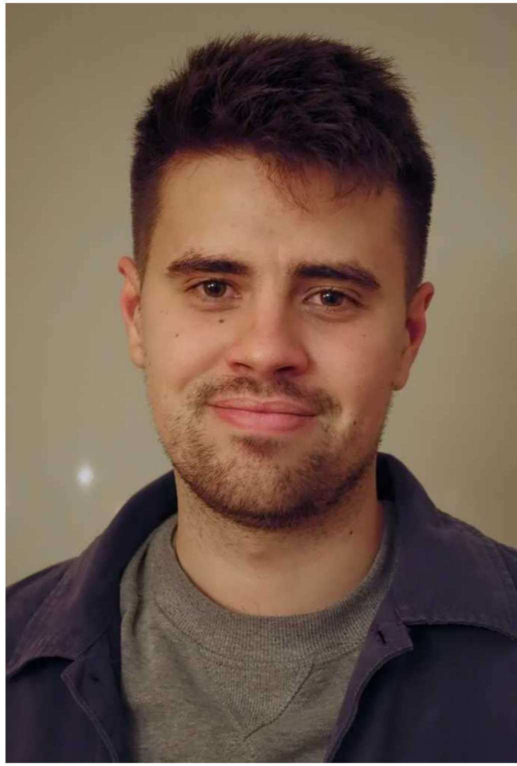
Look for Timing Residuals from Pairs of Pulsars around the sky



June 2023 - Nanograv collaboration detected such an effect 2306.16213

Simplest Interpretation is SMBH Coalescence



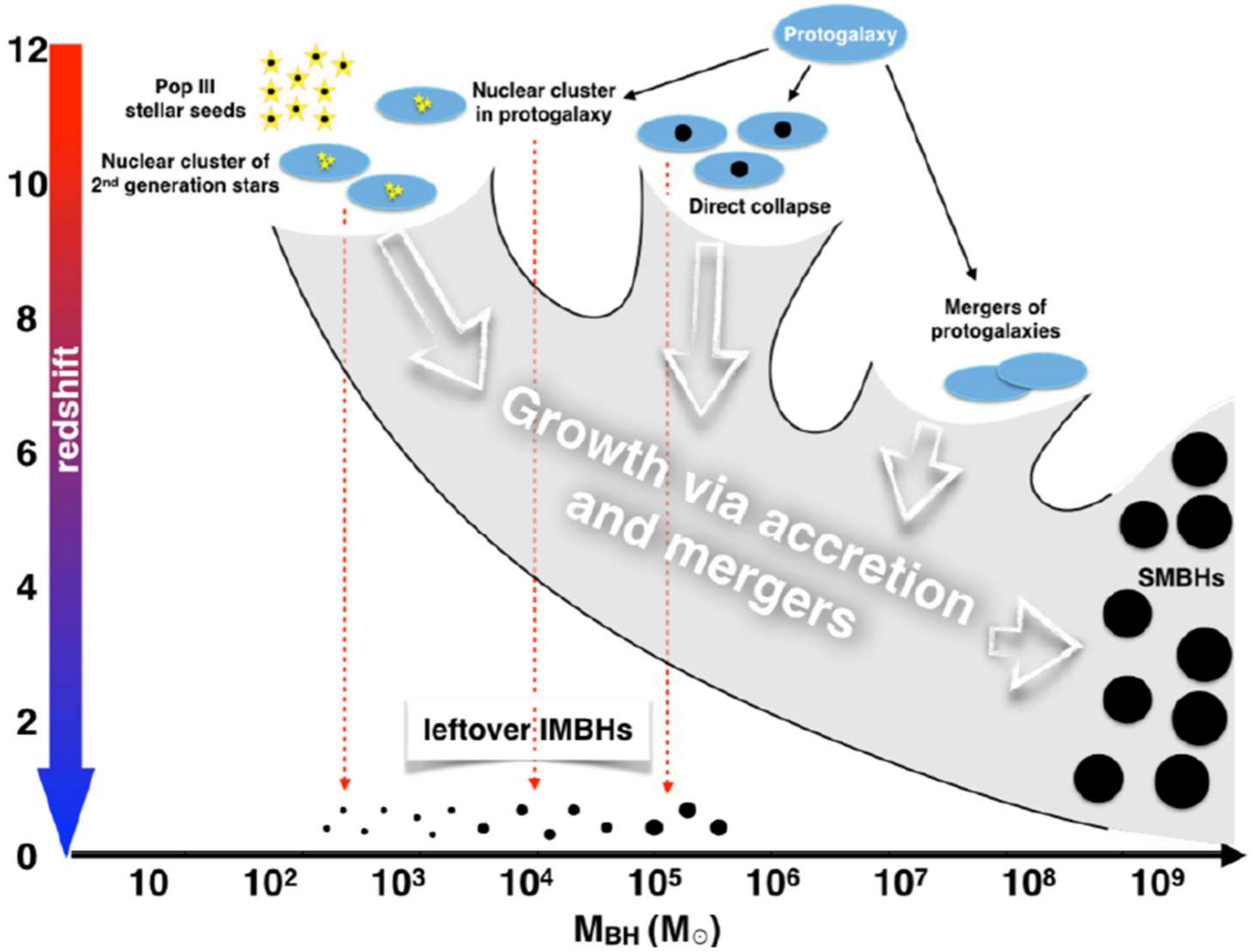


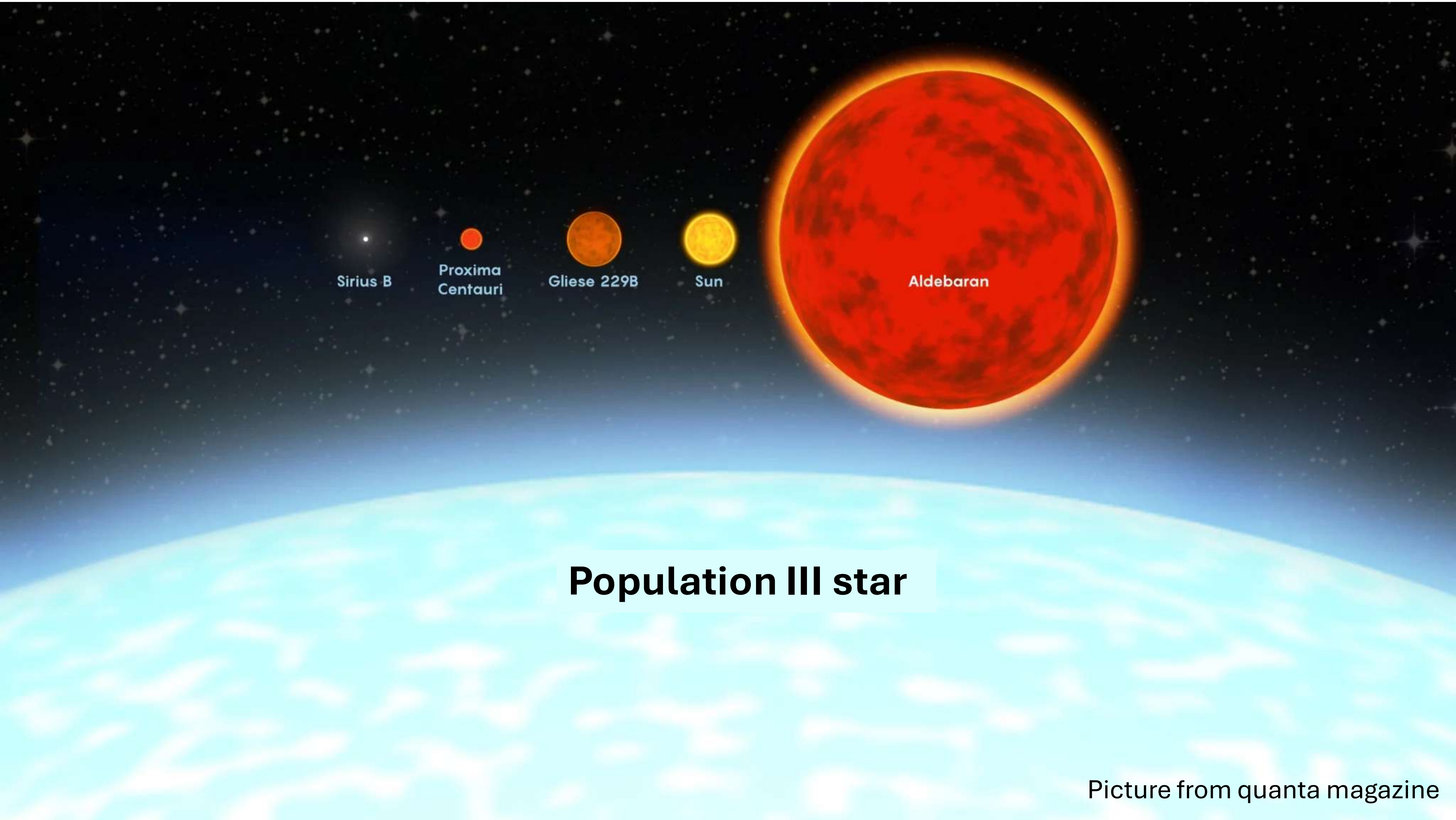
With **Juan Urrutia,** Ville Vaskonen and John Ellis, Hutsi, Raidal, Vaermae

arXiv:2306.17021

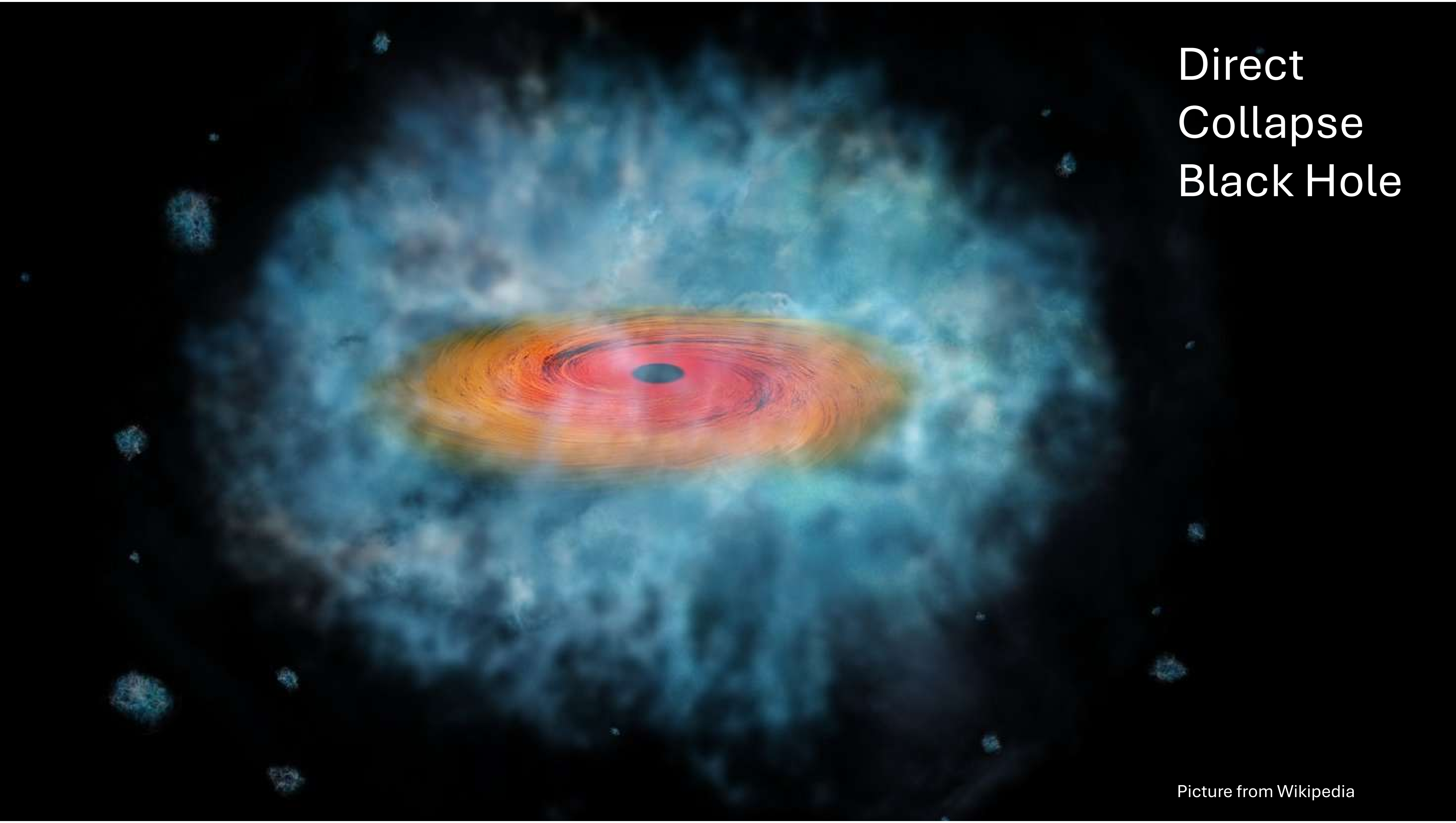
How to Make a Supermassive BH?

SMBHs from mergers of intermediate-mass BHs (IMBHs)?

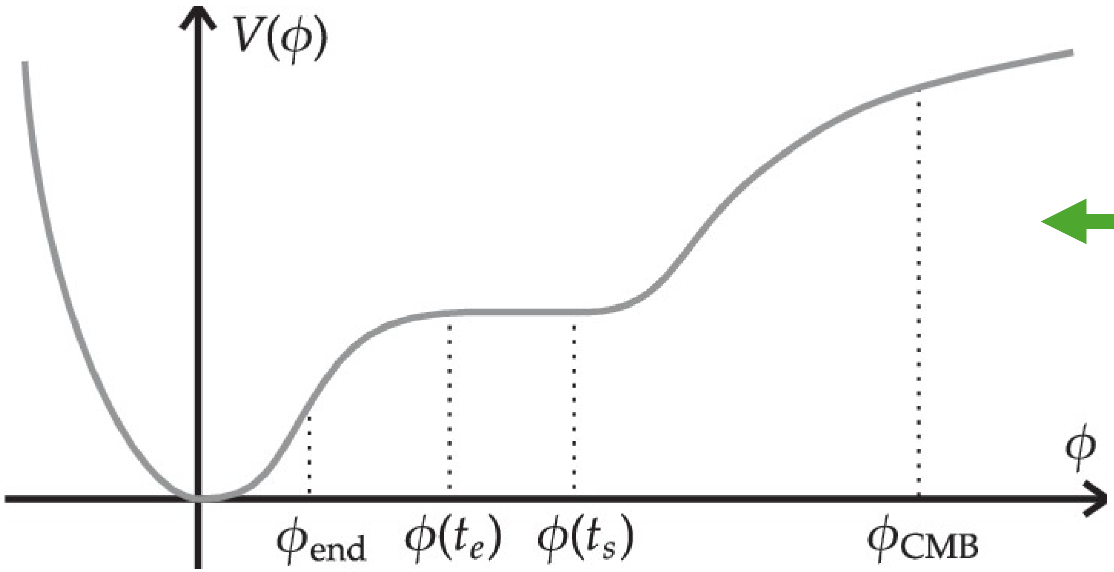




Picture from quanta magazine



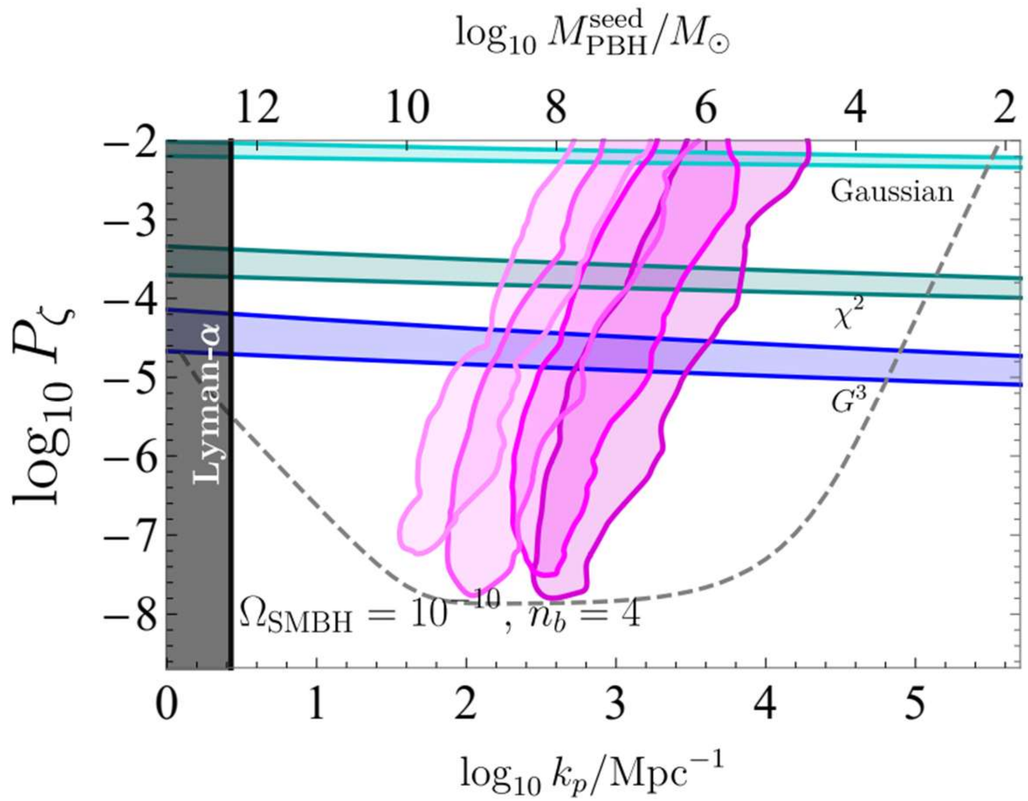
Picture from Wikipedia



Kristiano and Yokoyama arXiv:2405.12149

Big black holes could also be produced conceivably during inflation

Strong constraints from things like the CMB and structure formation



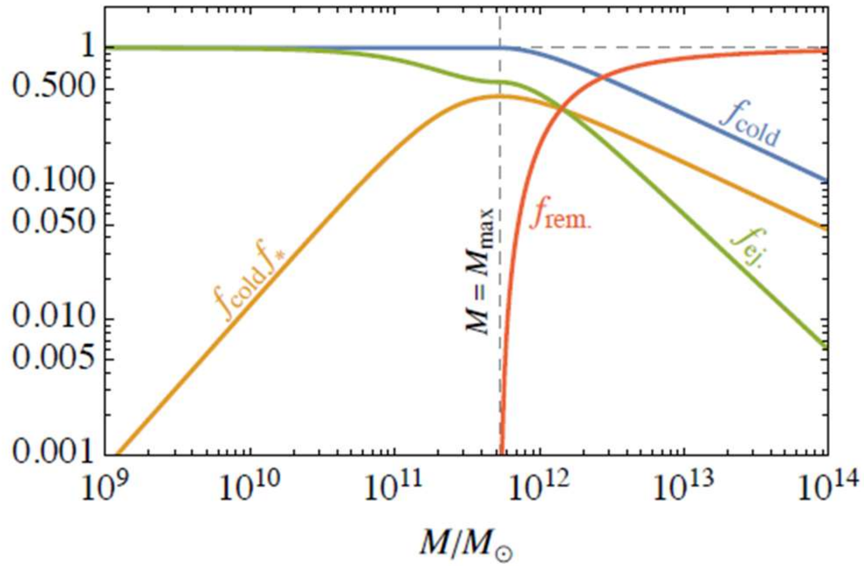
Our paper 2408.11098

Our Approach

- We use Extended Press-Schechter formalism to model merger rate of galaxies
- We assume a constant probability for BH mergers
- Can explain relationship between masses of BHs and the stellar masses of their host galaxies

Star and Black Hole Formation

- Stars form from cold gas only
- Supernovae eject cold gas
- Black holes can form from either hot or cold gas
- Peak in star formation followed by BH formation



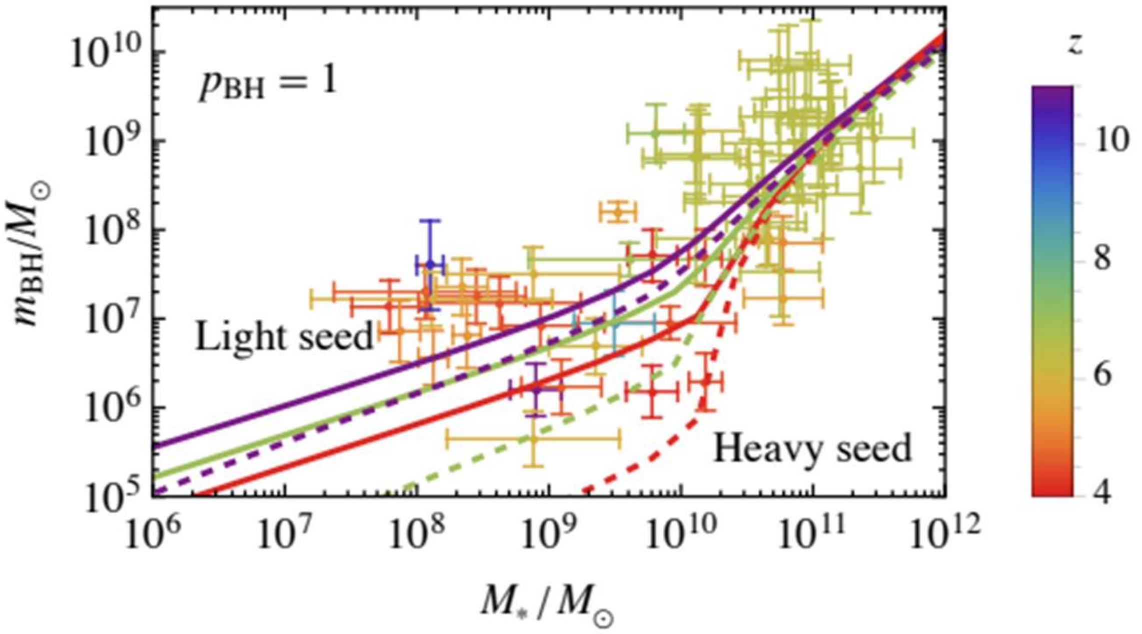
$f_{ej.}$ = cold gas fraction ejected from halo by SNe

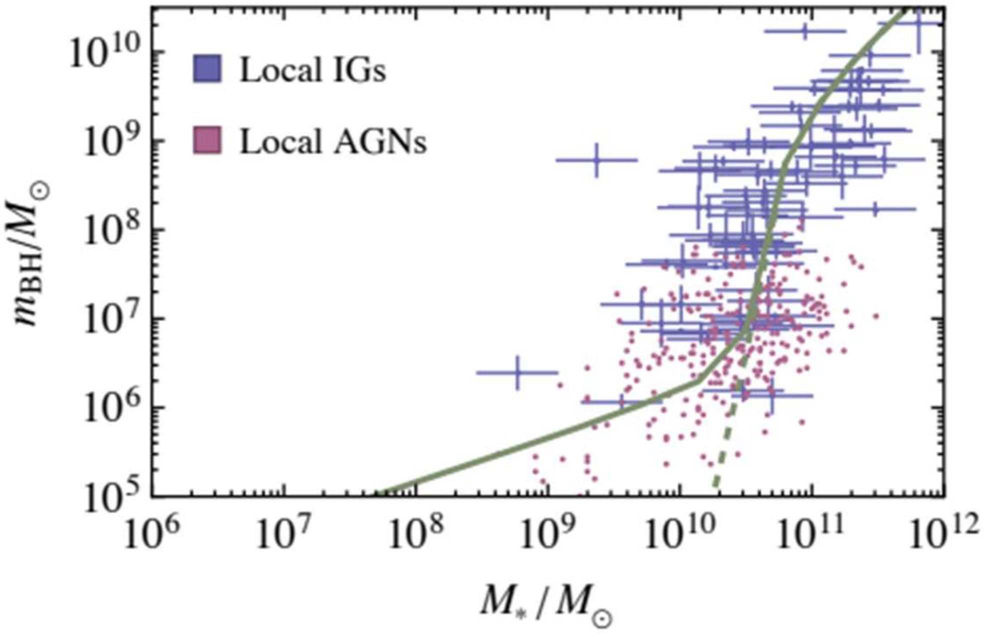
f_{cold} = fraction of remaining gas that is cold

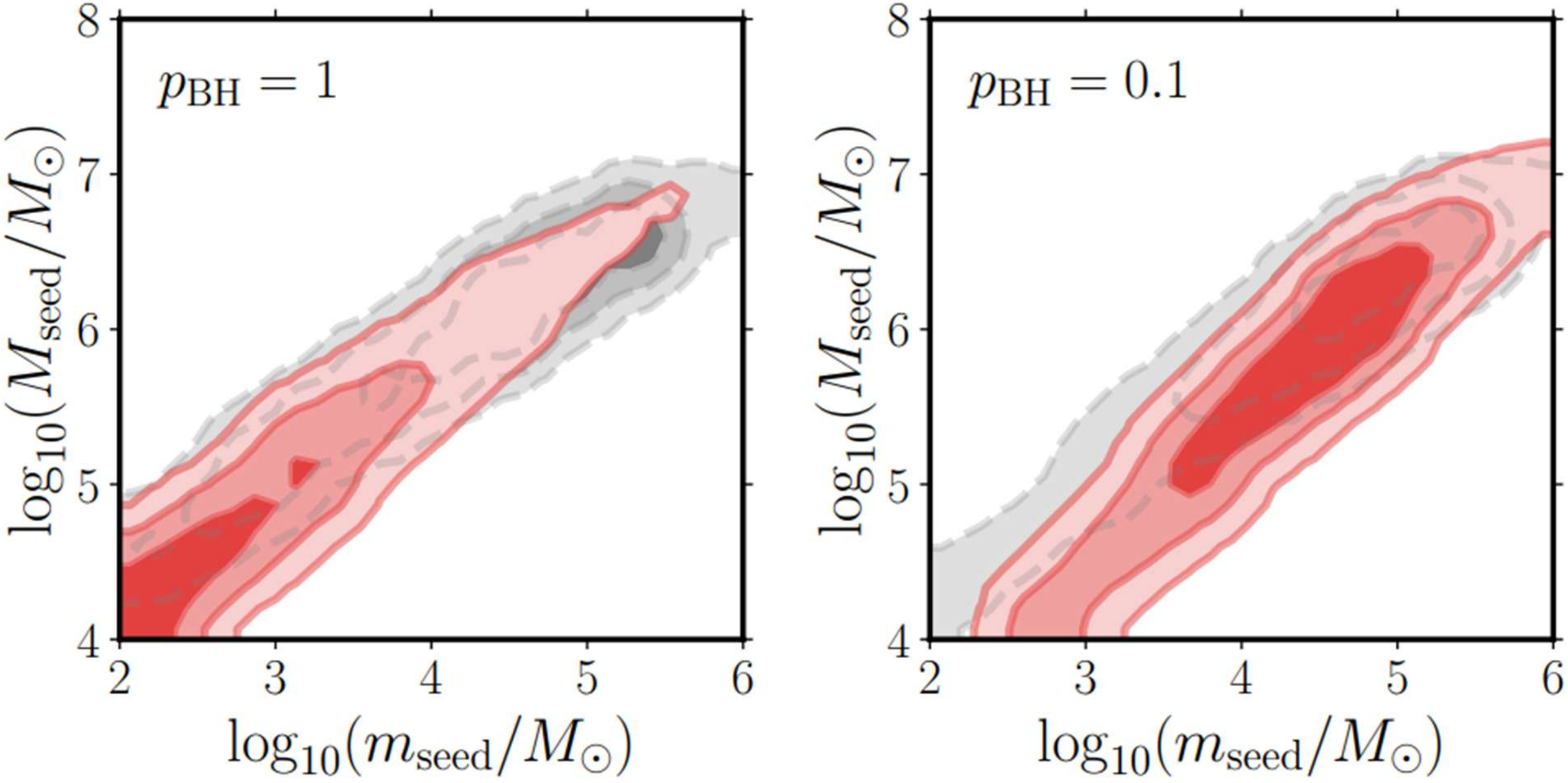
$f_{rem.}$ = fraction of gas remaining after star formation and SN feedback

f_* = fraction of cold gas used for star formation

With Better models we can model the population better….







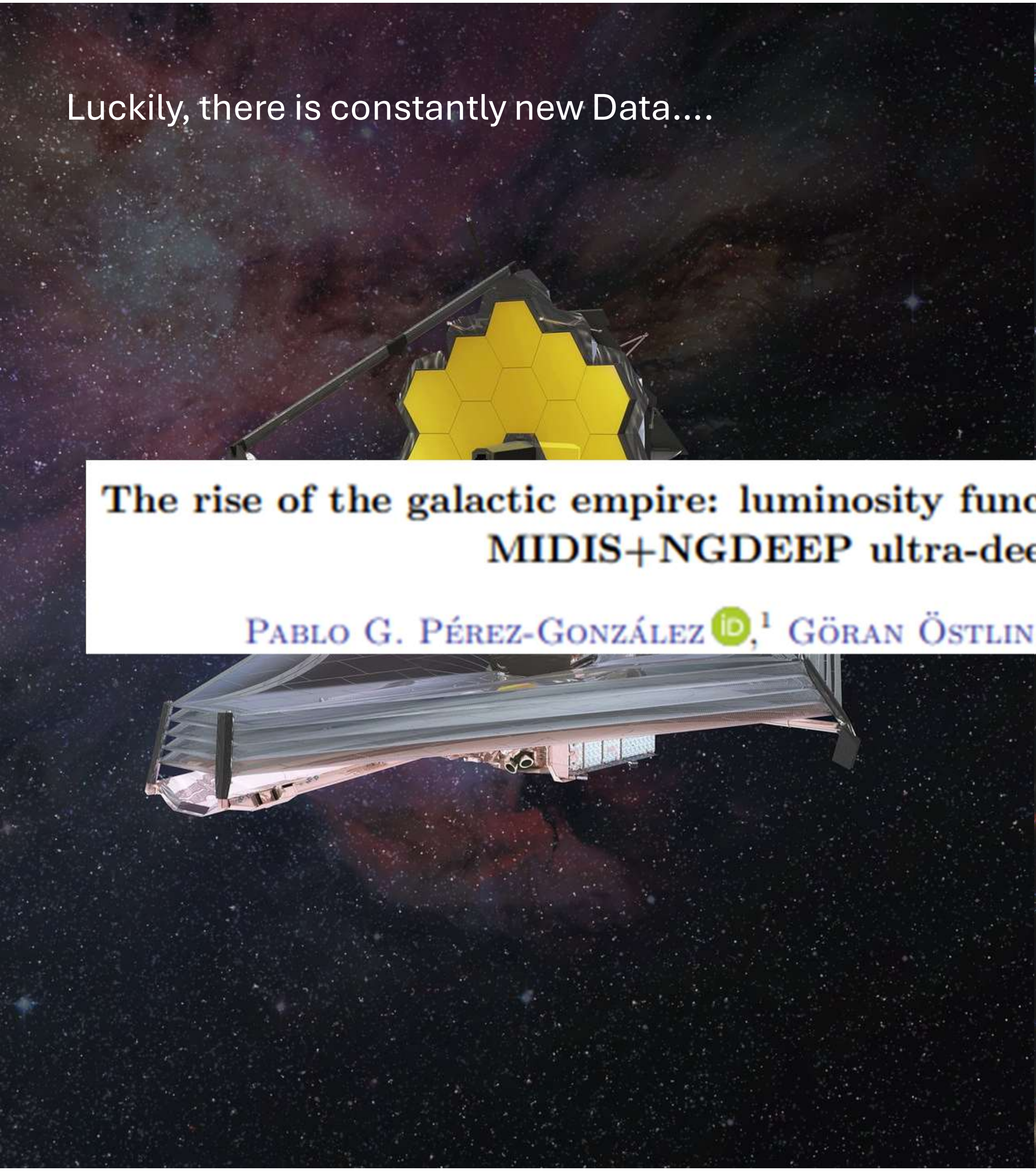
M_{seed} is the mass of the seed halo
m_{seed} is the mass of the BH in the seed halo
p_{BH} is the probability of BH merger when halos merge

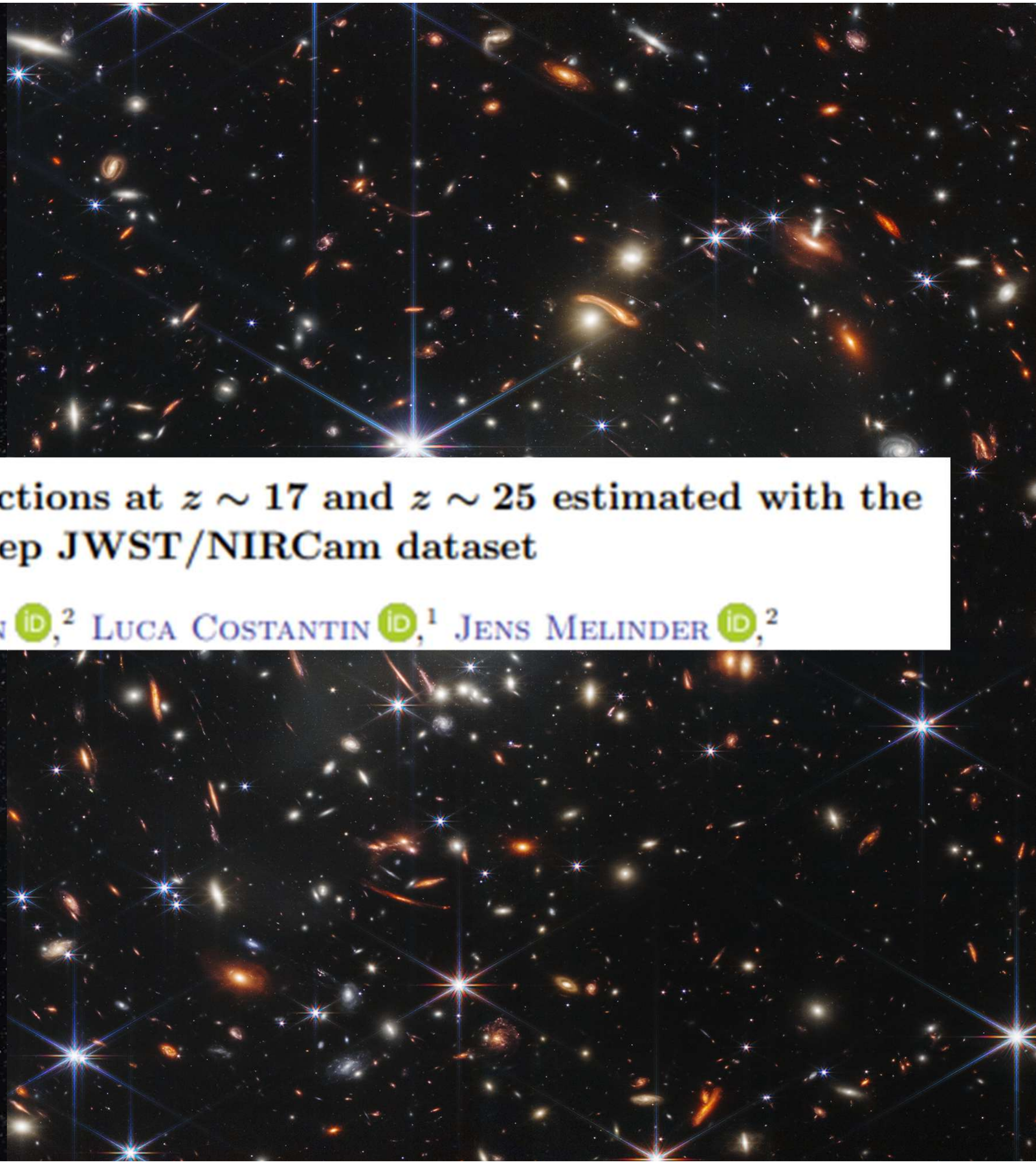
"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk."

John von Neumann

We need more data

Luckily, there is constantly new Data....

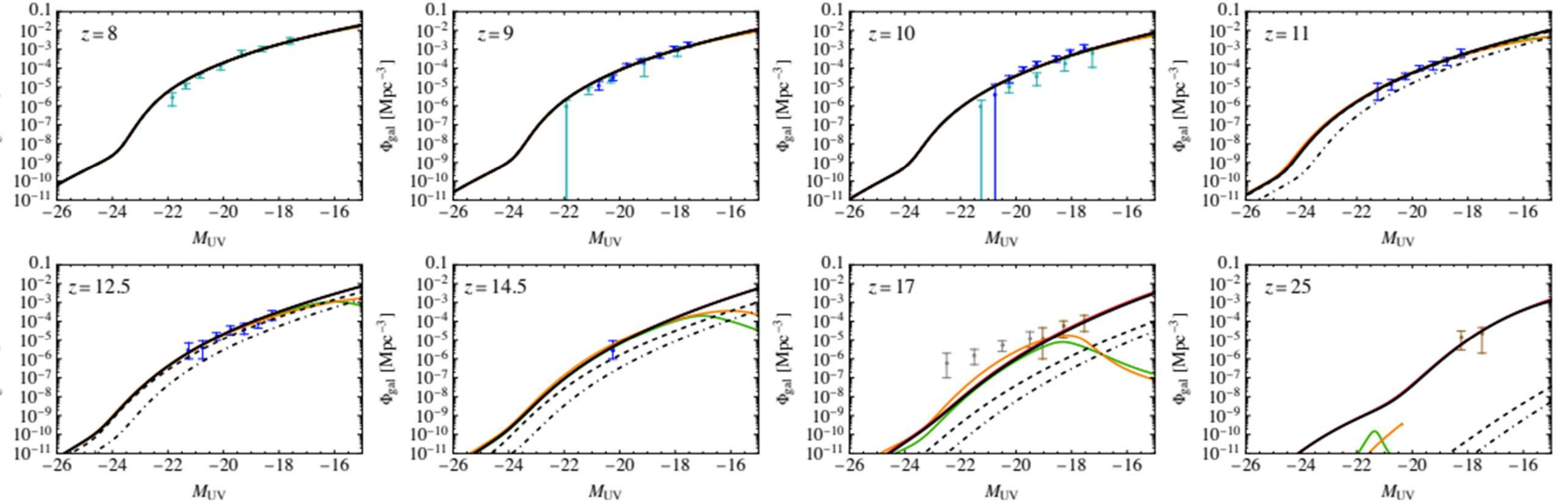




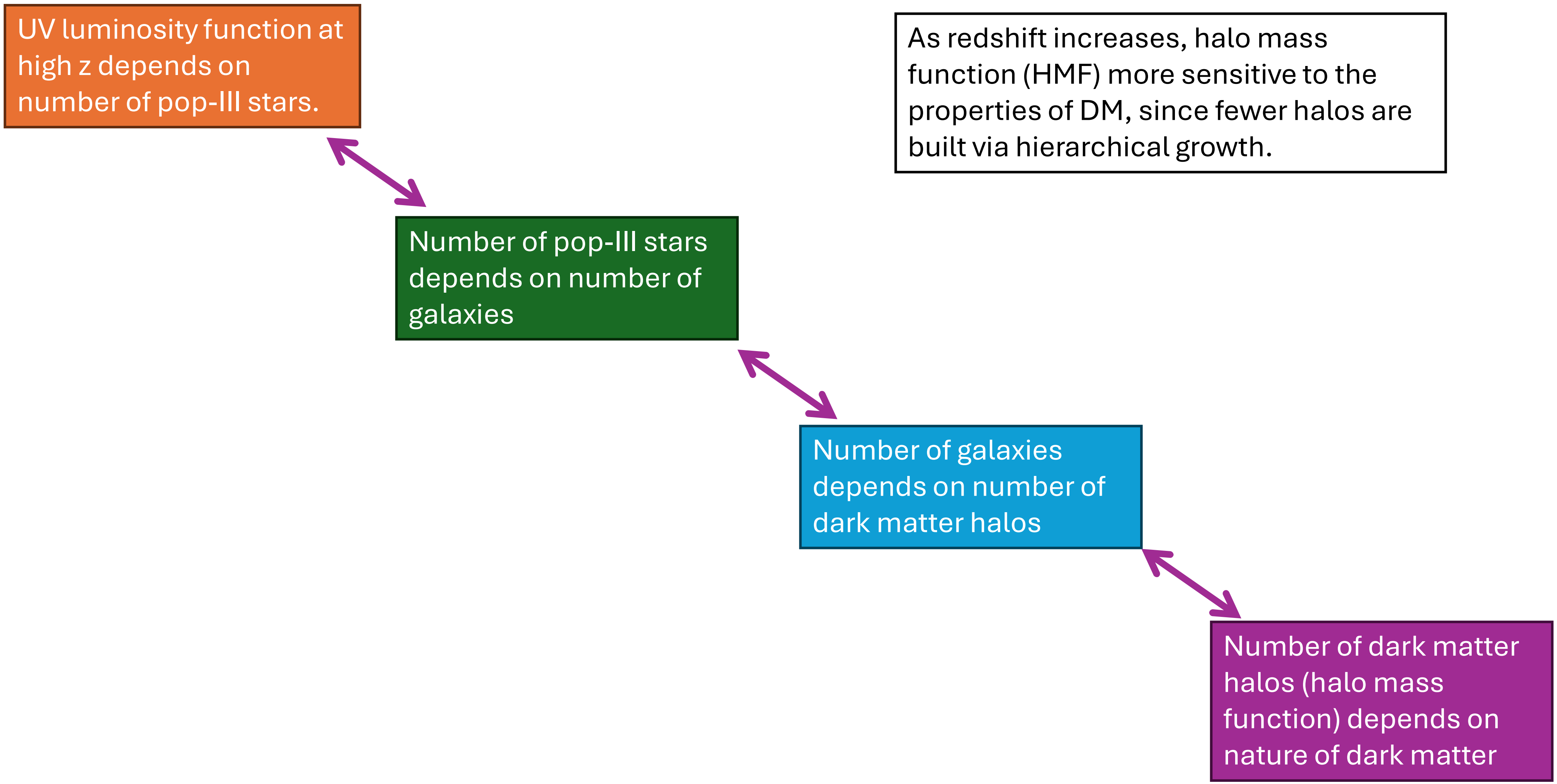
The rise of the galactic empire: luminosity functions at $z \sim 17$ and $z \sim 25$ estimated with the MIDIS+NGDEEP ultra-deep JWST/NIRCam dataset

Pablo G. Pérez-González,[1] Göran Östlin,[2] Luca Costantin,[1] Jens Melinder,[2]

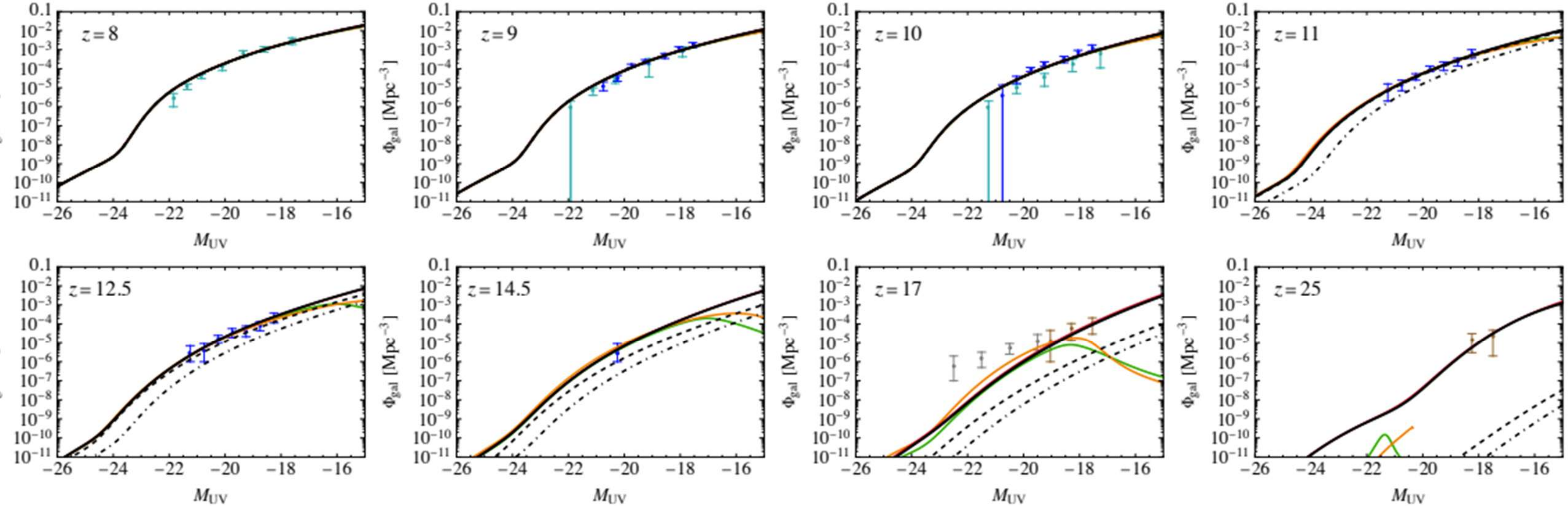
- Luminosity Function is decreasing at higher redshifts, as expected
- However, higher than expected beyond a redshift of 10.



What has this got to do with dark matter?


UV luminosity function at high z depends on number of pop-III stars.
Number of pop-III stars depends on number of galaxies
Number of galaxies depends on number of dark matter halos
Number of dark matter halos (halo mass function) depends on nature of dark matter
As redshift increases, halo mass function (HMF) more sensitive to the properties of DM, since fewer halos are built via hierarchical growth.

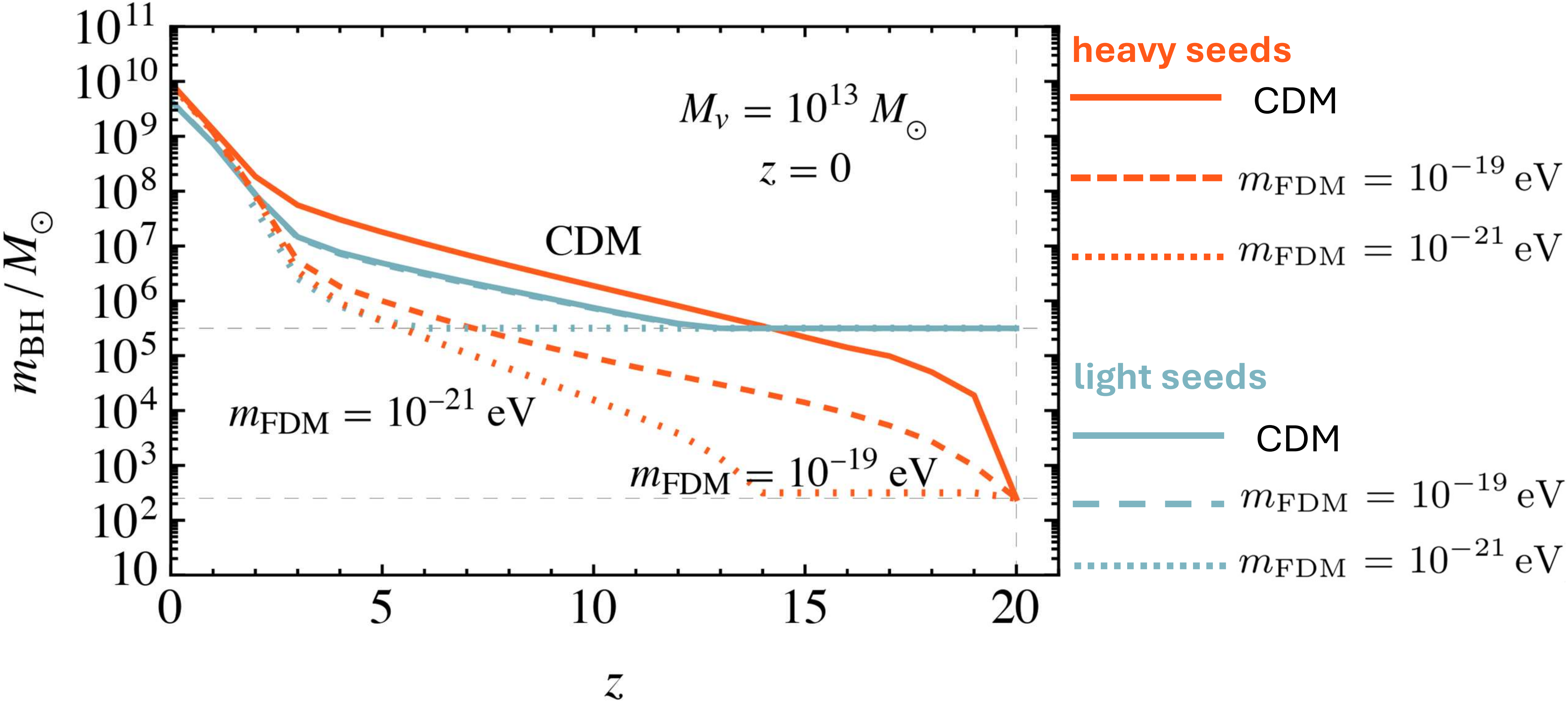
- Luminosity Function is decreasing at higher redshifts, as expected
- However, higher than expected beyond a redshift of 10.

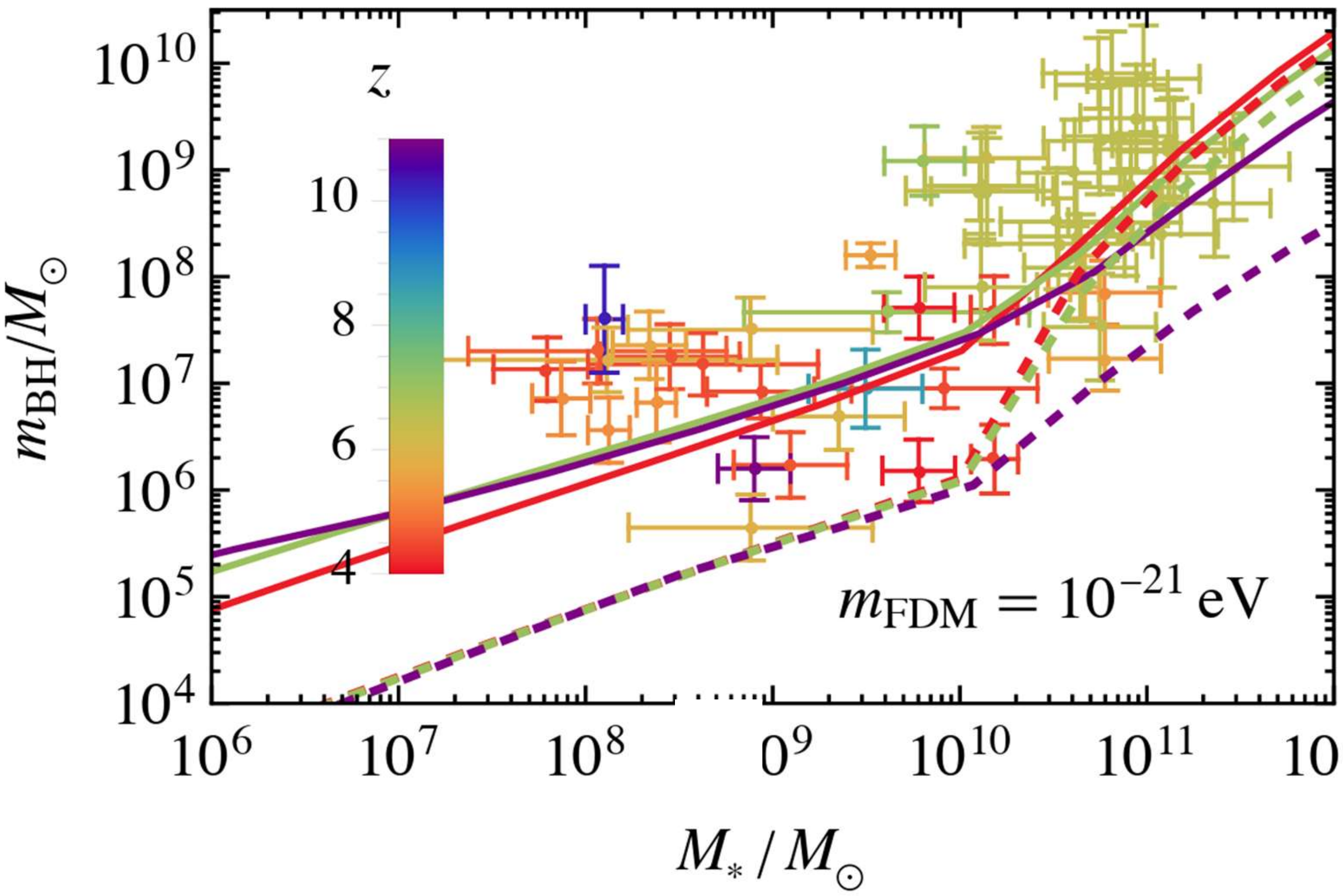


CDM **FUZZYDM** **WARMDM**

While we can use these UV luminosity functions to constrain DM, all three scenarios require same boost in population III stars above redshift 10.
Our lower bounds are 4.5×10^{-22}eV for FDM mass and 1.5 keV for WDM mass, at 95% CL

Growth of Black Holes in different scenarios





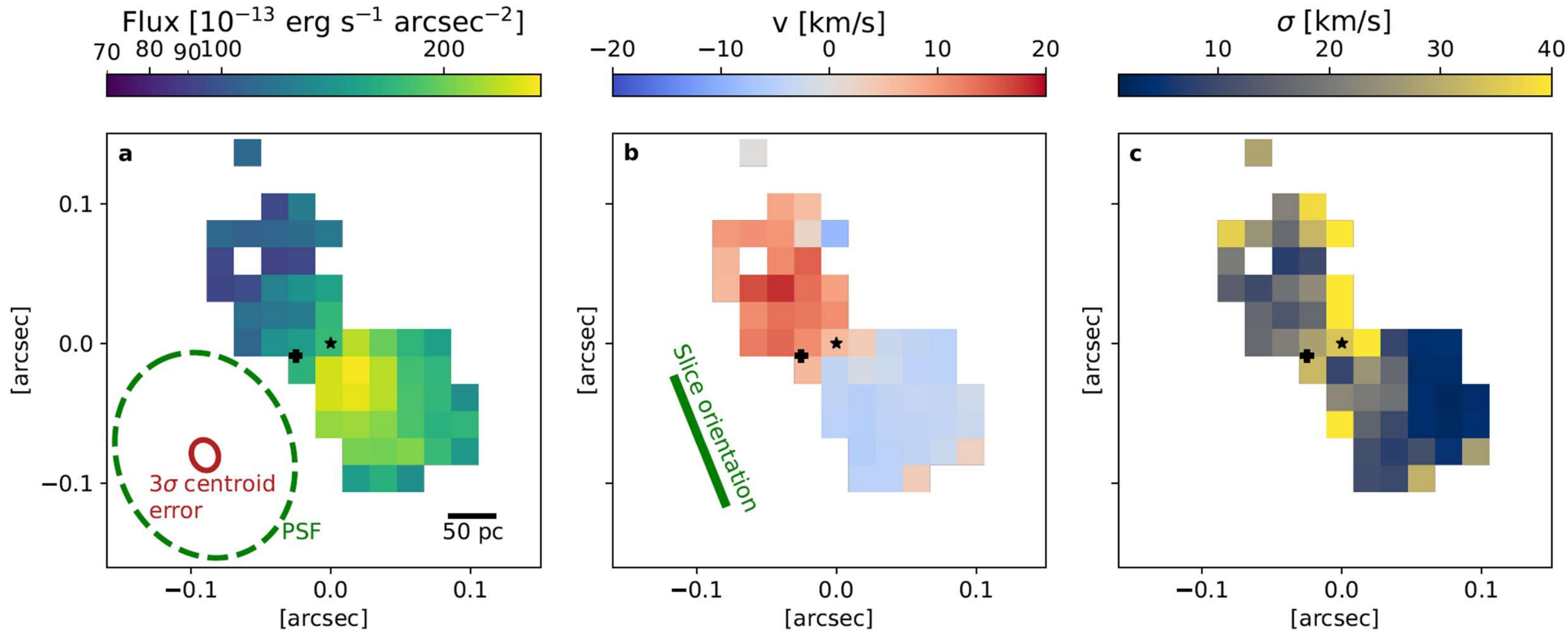
Can then use $m_{BH} - m_*$ relation to constrain dark matter.

$m_{FDM} > 2 \times 10^{-21}$ eV

$m_{WDM} > 7.2$ keV

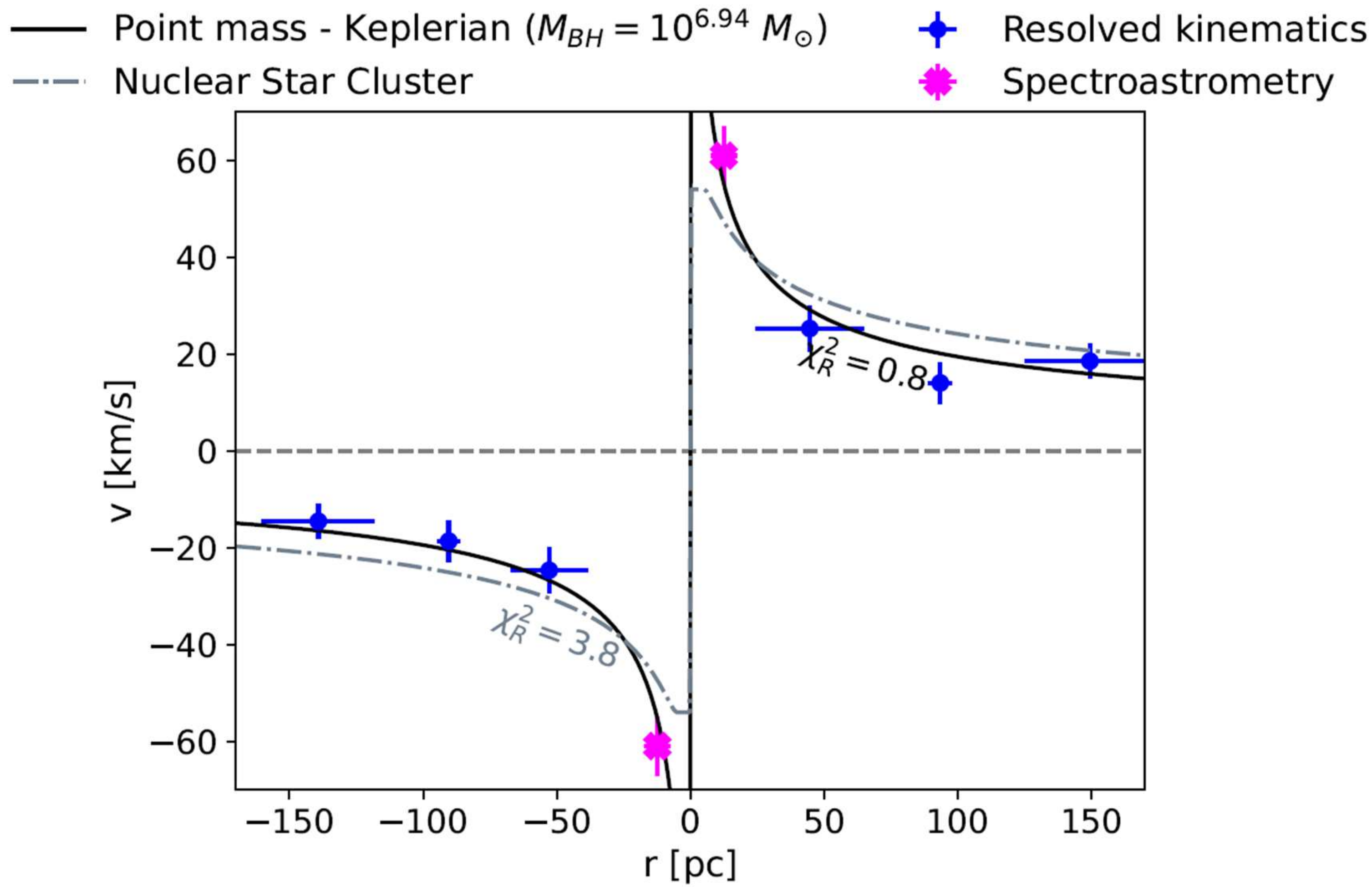
Finally, a Mystery….

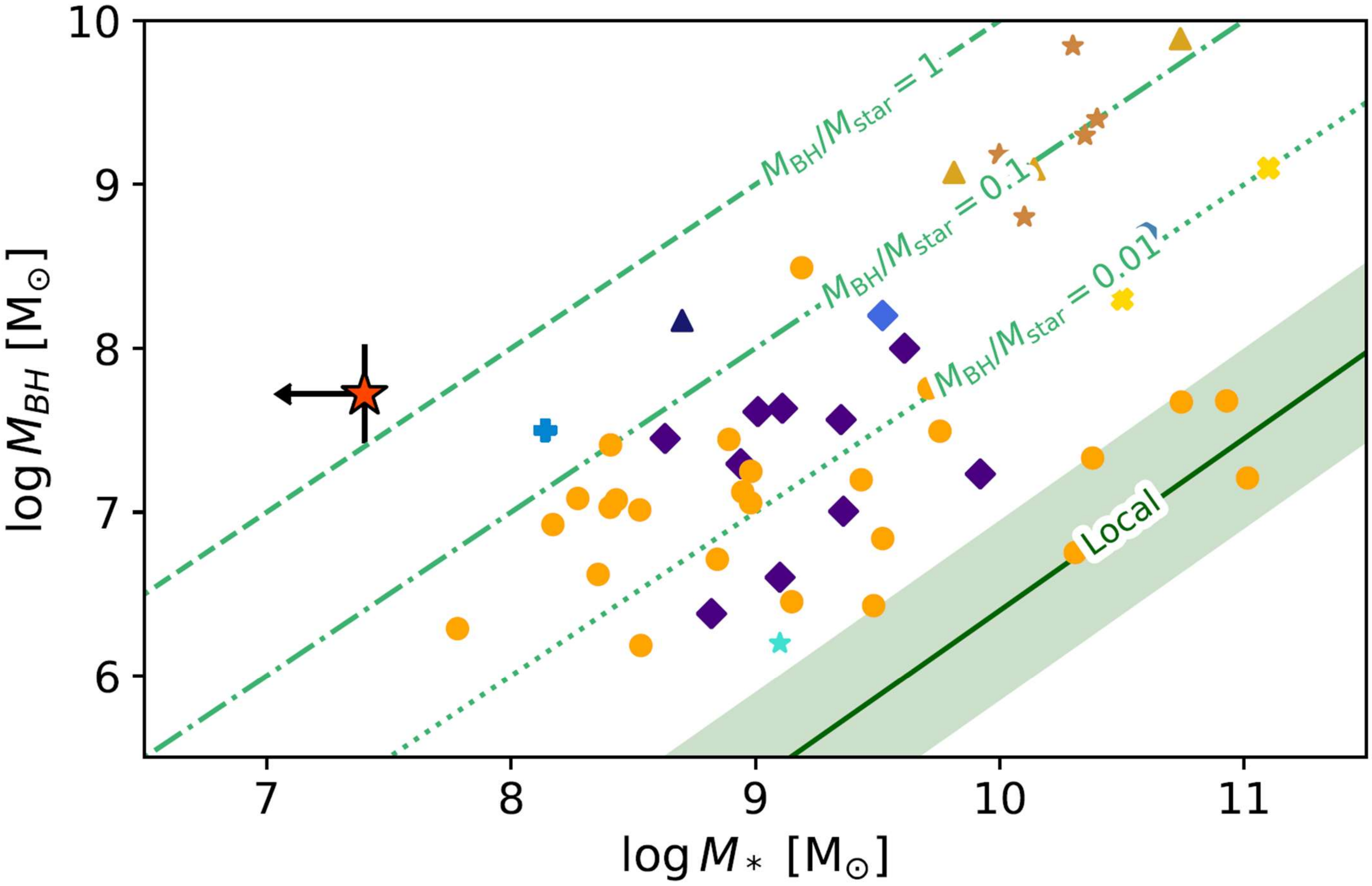
A direct black hole mass measurement in a Little Red Dot at the Epoch of Reionization



Dynamical mass measurement of SMBH at z=7.04 ?? arXiv:2508.21748

Seems to be consistent with a SMBH, with no stars around it...

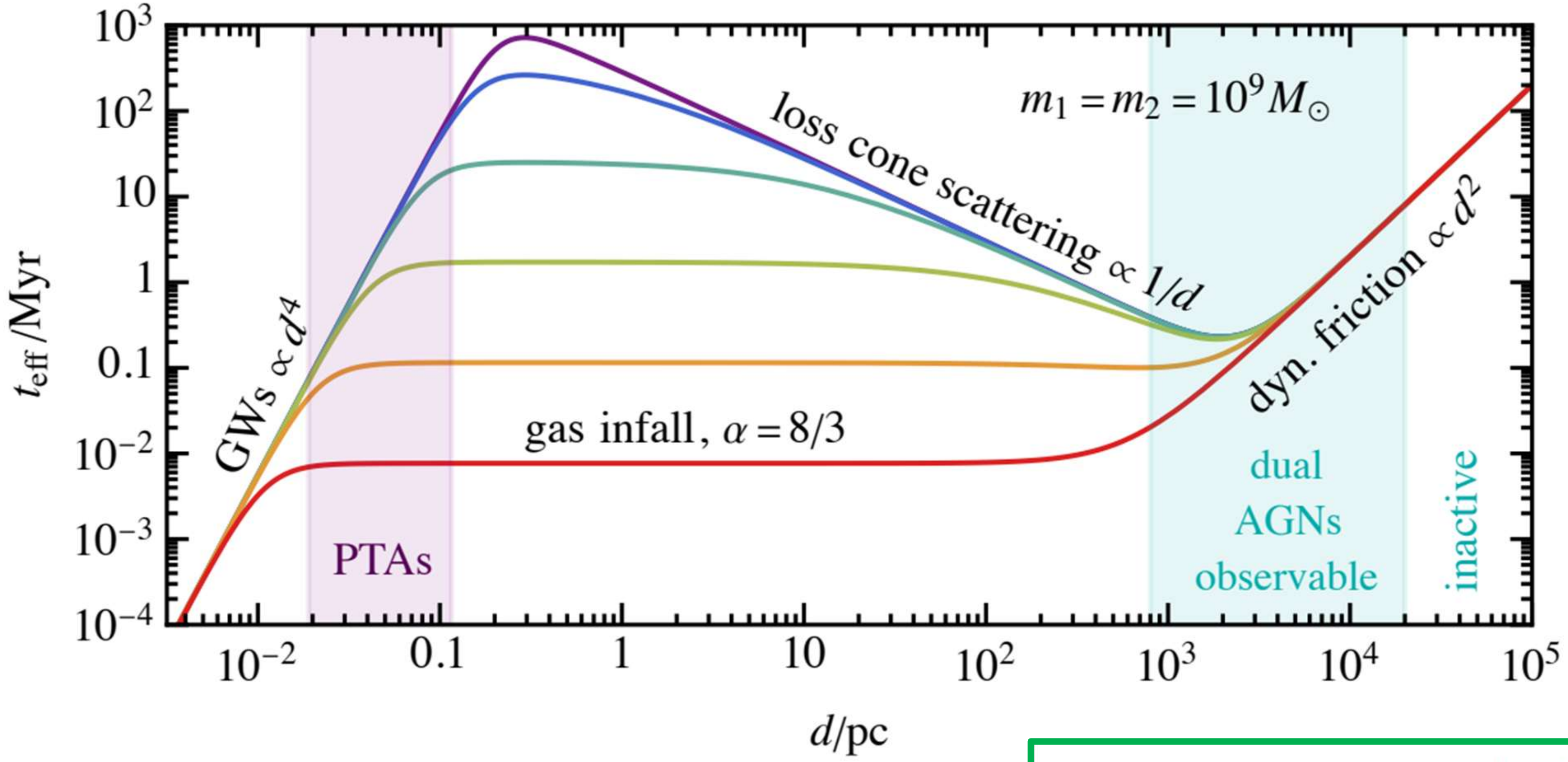




10
9
8
7
6
7
8
9
10
11
$\log M_{BH}$ [$M_\odot$]
$\log M_*$ [$M_\odot$]
$M_{BH}/M_{star} = 1$
$M_{BH}/M_{star} = 0.1$
$M_{BH}/M_{star} = 0.01$
Local

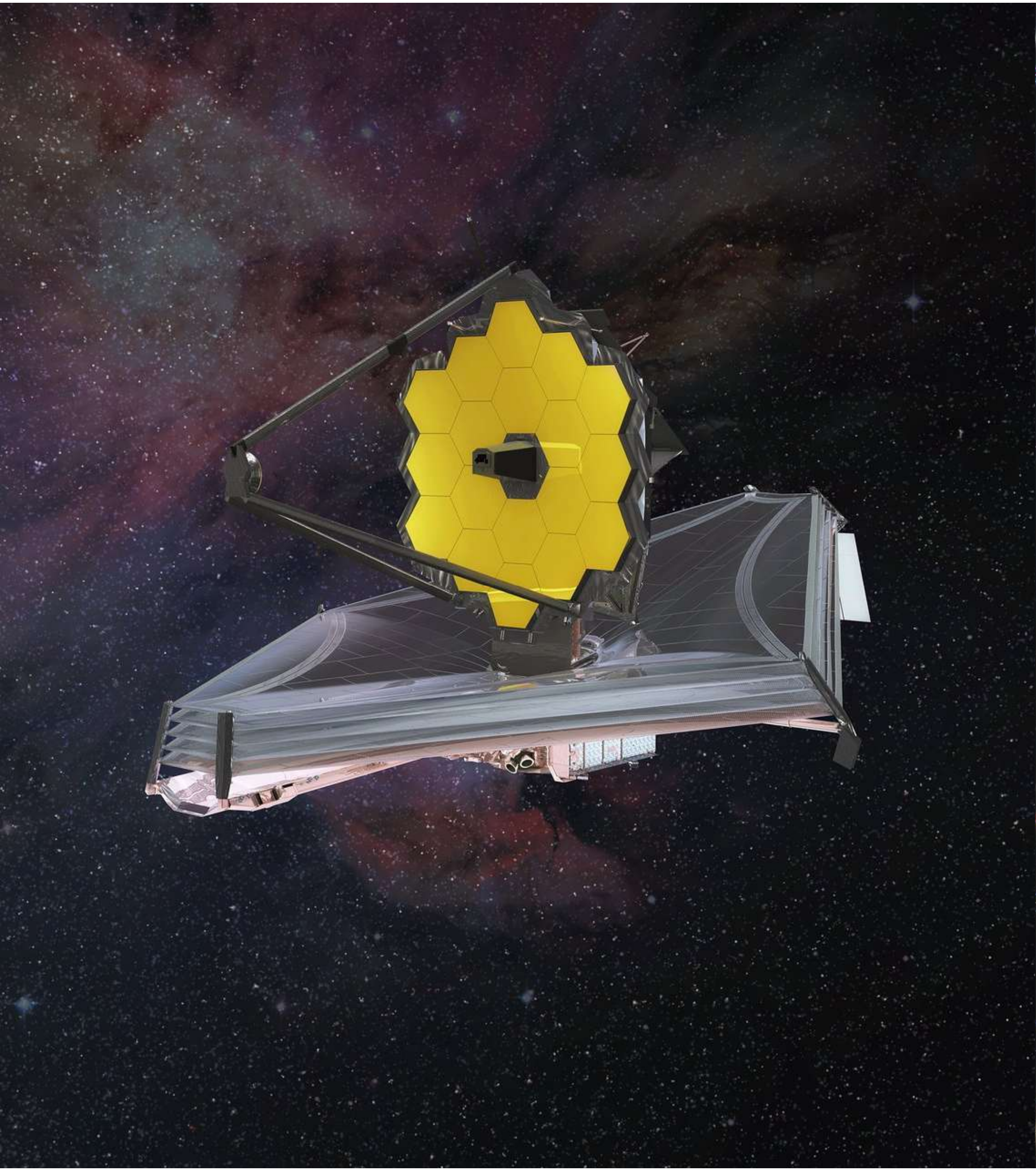
- Search for dark matter goes on, including tests only sensitive to its gravitational effects.
- Gravitational waves can also help us learn about black holes.
- New Data which is arriving all the time is amazing!
- Combination of better PTA data with JWST data will shed great light origins of SMBH, and also DM!

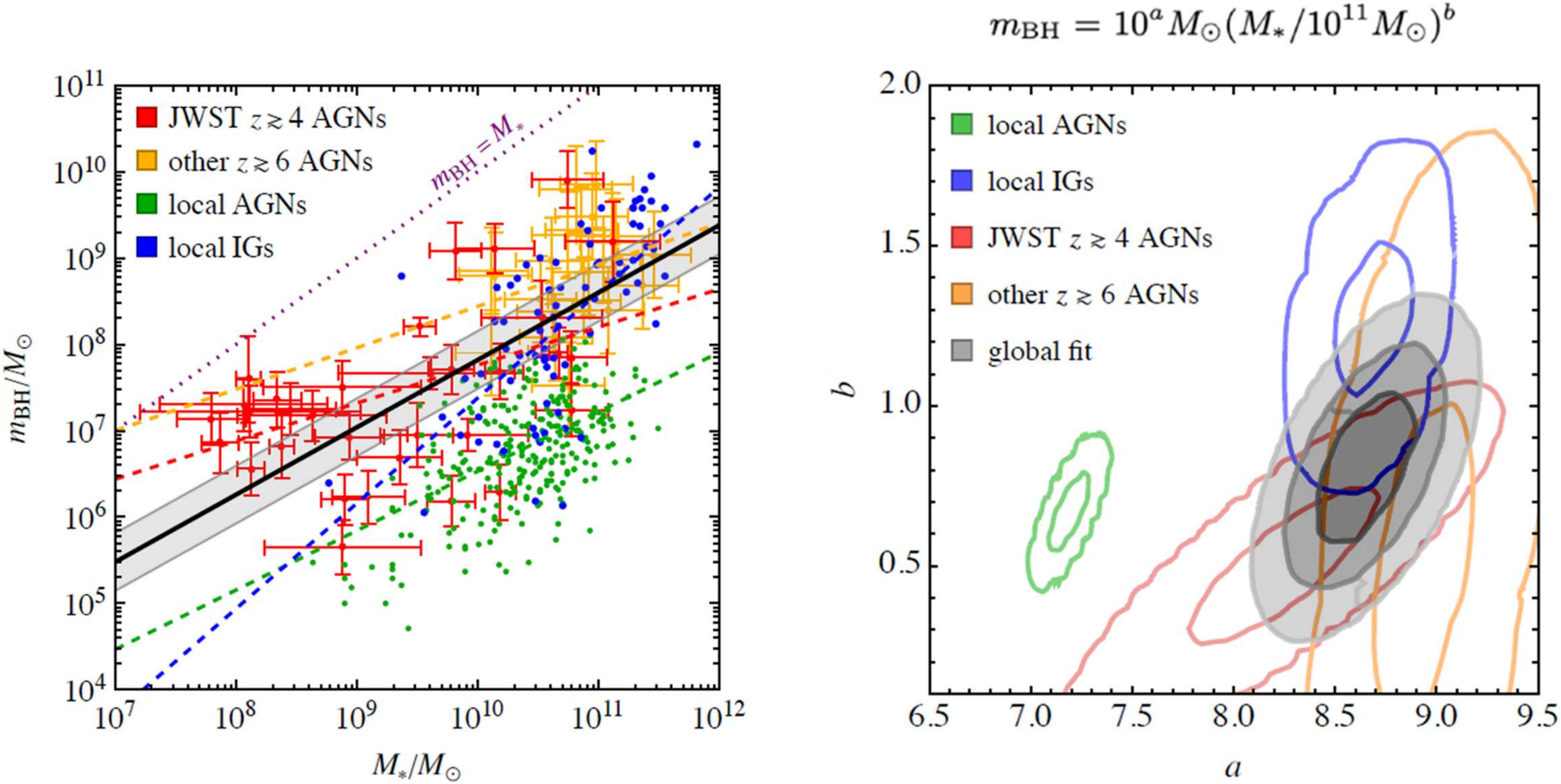
$$t_{\rm GW} = \frac{5d^4}{1024\eta M^3} \approx \frac{14\,{\rm Myr}}{\eta}\left[\frac{M}{10^9 M_\odot}\right]^{-3}\left[\frac{d}{0.1\,{\rm pc}}\right]^4$$



$$t_{\rm dyn} \simeq \frac{20\,{\rm Myr}}{\ln\Lambda}\frac{\sigma}{200\,{\rm km/s}}\left[\frac{M}{10^9 M_\odot}\right]^{-1}\left[\frac{d}{\rm kpc}\right]^2$$

"The Final Parsec Problem"



JWST and previous high-z data from ground-based telescopes

Low-z active galactic nuclei (AGNs) and inactive galaxies

Dashed lines: power-law fits to subsets of data

Solid line: global fit to all data, including NANOGrav, excluding local AGNs

$$\dot{M}_{\rm BH}(M, p_{\rm BH}) = \dot{M}_{\rm BH}^{\rm merg.}(M, p_{\rm BH}) + \dot{M}_{\rm BH}^{\rm acc.}(M_{\rm BH}, M)\,,$$

$$\dot{M}_*(M) = \dot{M}_*^{\rm merg.}(M) + \dot{M}_*^{\rm sf.}(M)\,,$$