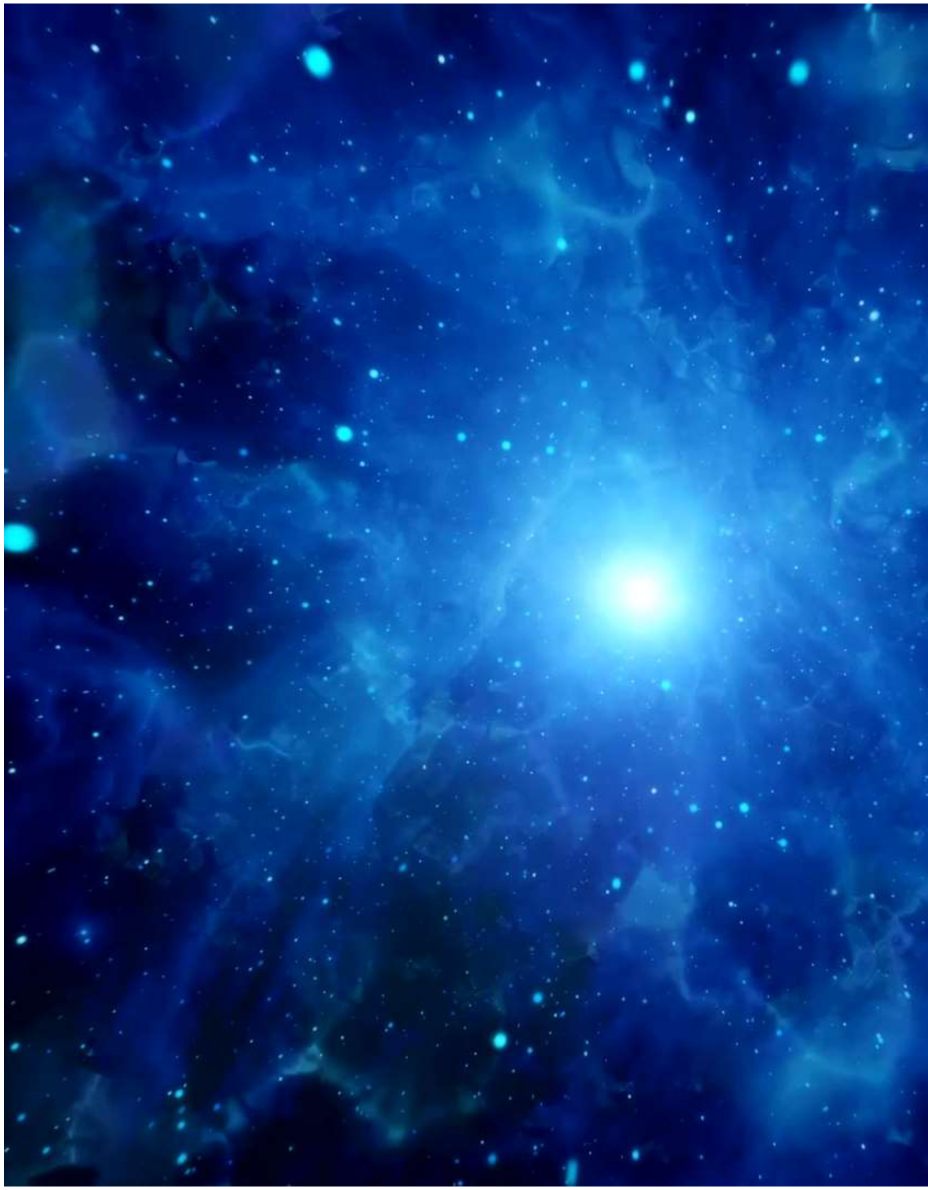
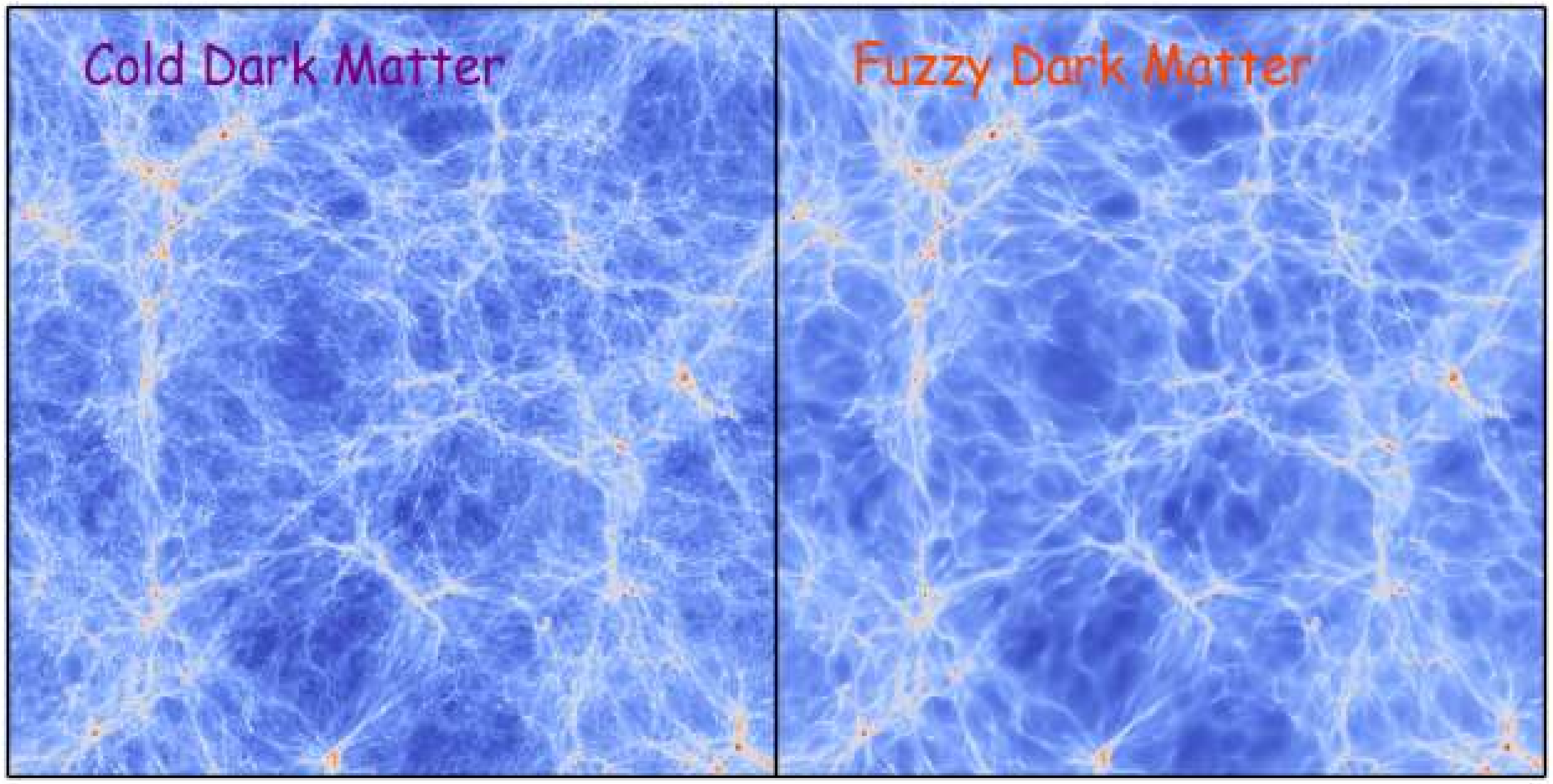
Galaxies, Axions, Gravitational Waves, Black Holes and more Galaxies

Malcolm Fairbairn
King's College London

Plan

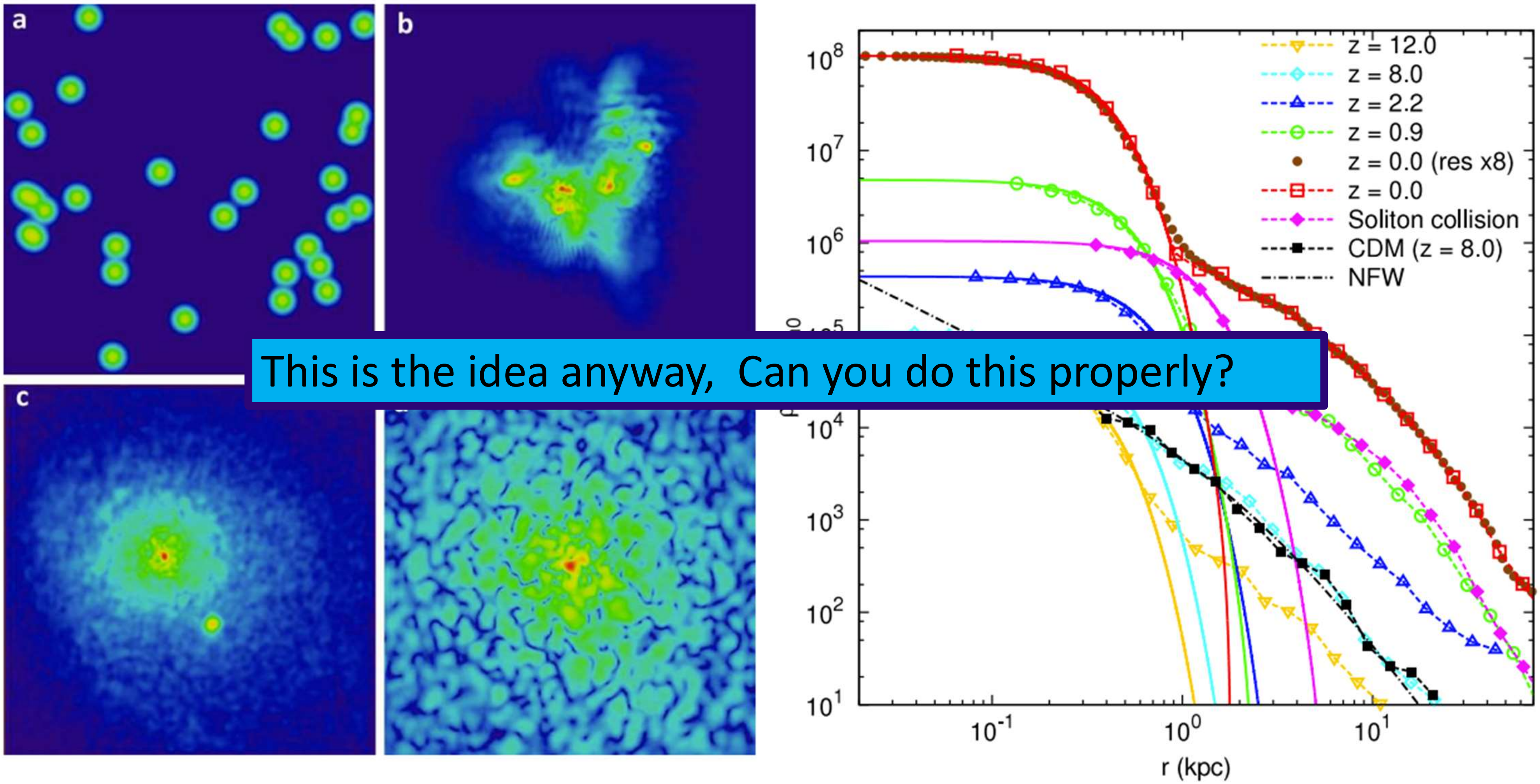
- Ultra Light Dark Matter and Dwarf Galaxies
- Ultra Light axionic Dark Matter and exploding DM halos
- Audible axions and other sources of Grav Waves
- Pulsar Timing Array
- Super Massive Black Holes and the PTA data
    - Environmental effects
    - Comparison with JWST data
    - Trying to fit more data with better models
- Conclusions and Future Work





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

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



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

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

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

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.

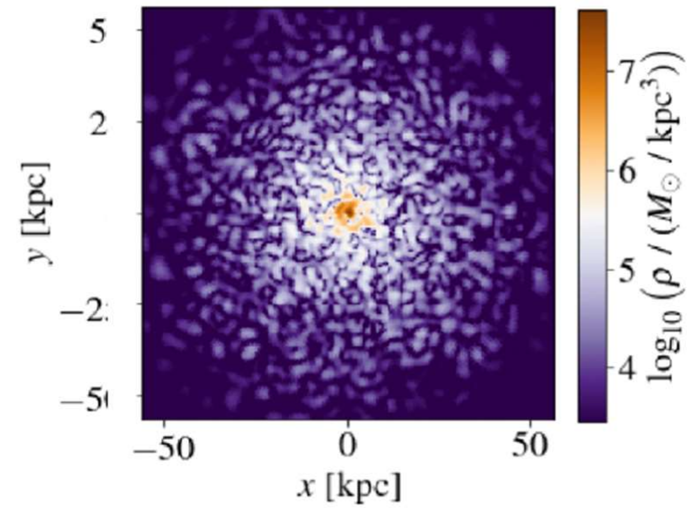
Wave Function Reconstruction

Expand in eigen states

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

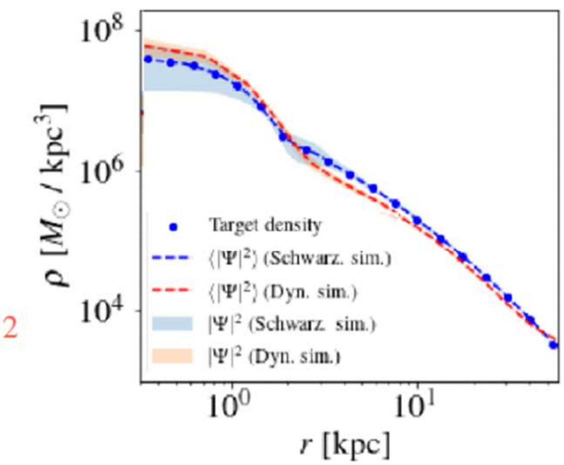
Density contributions

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



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

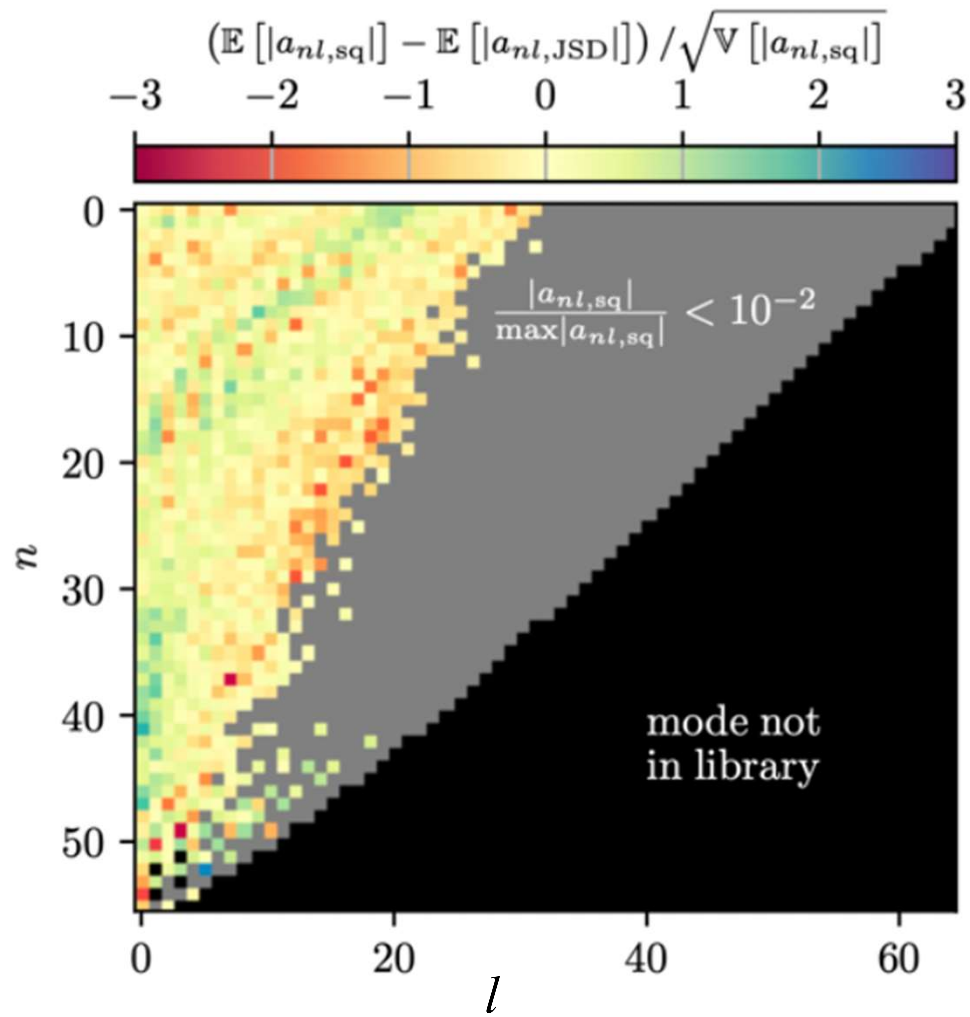
$$\chi(r,\phi,\theta) = \sum_{(n,l,m)\neq(n',l',m')} a_{nlm} a^*_{n'l'm'} u_{nl} u^*_{n'l'} Y_l^m Y_l^m * e^{i(E_{nl}-E_{n'l'})t/\hbar}$$



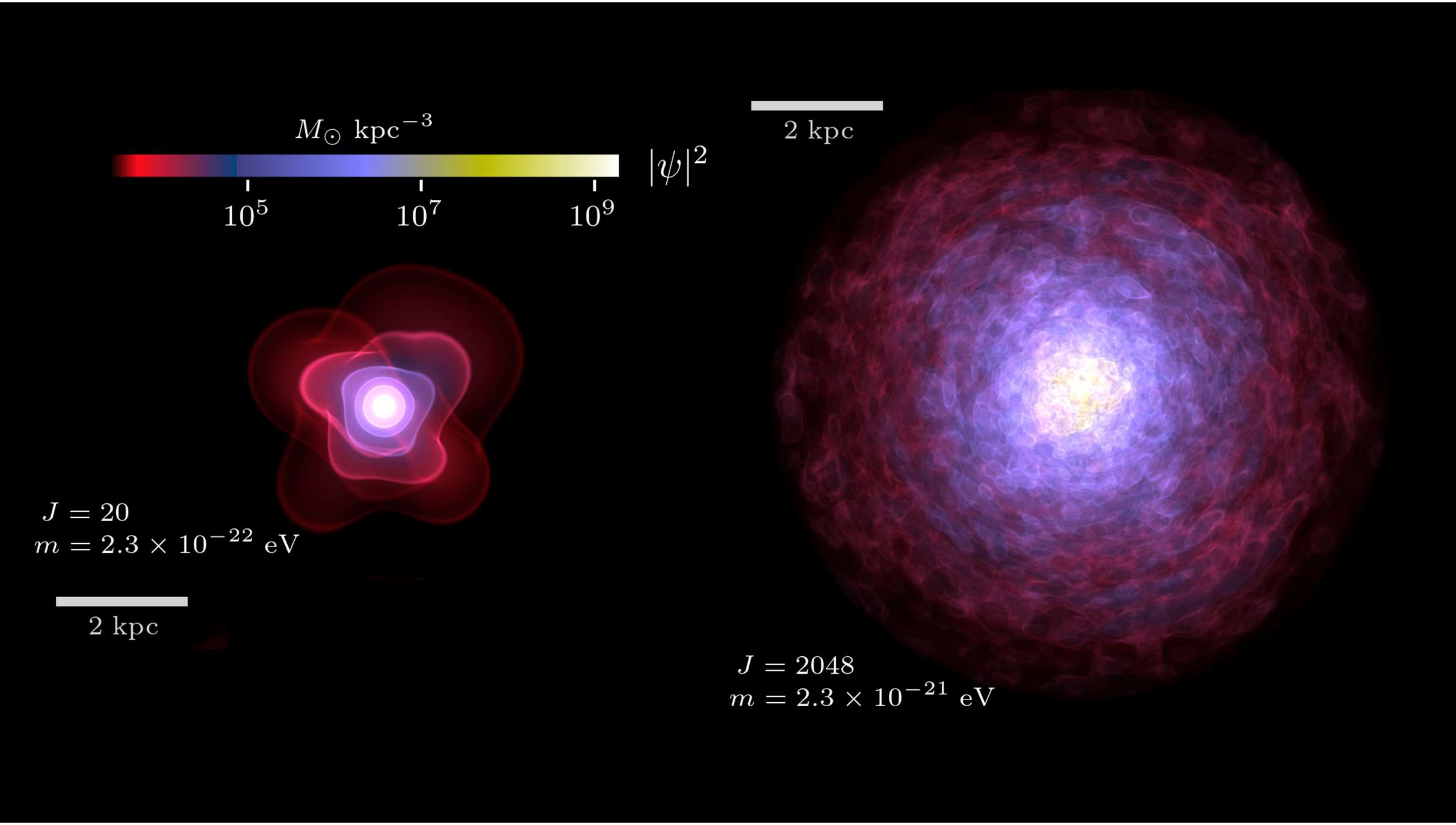
$$\langle |\psi|^2 \rangle = \mathbb{E}_{a_{nlm}}\left[|\psi|^2\right] = \lim_{T\to\infty}\frac{1}{T}\int_0^T \mathrm{d}t\, |\psi|^2 \approx \frac{1}{4\pi r^2}\int_{\mathbb{S}^2} \mathrm{d}\Omega(r)\, |\psi|^2$$

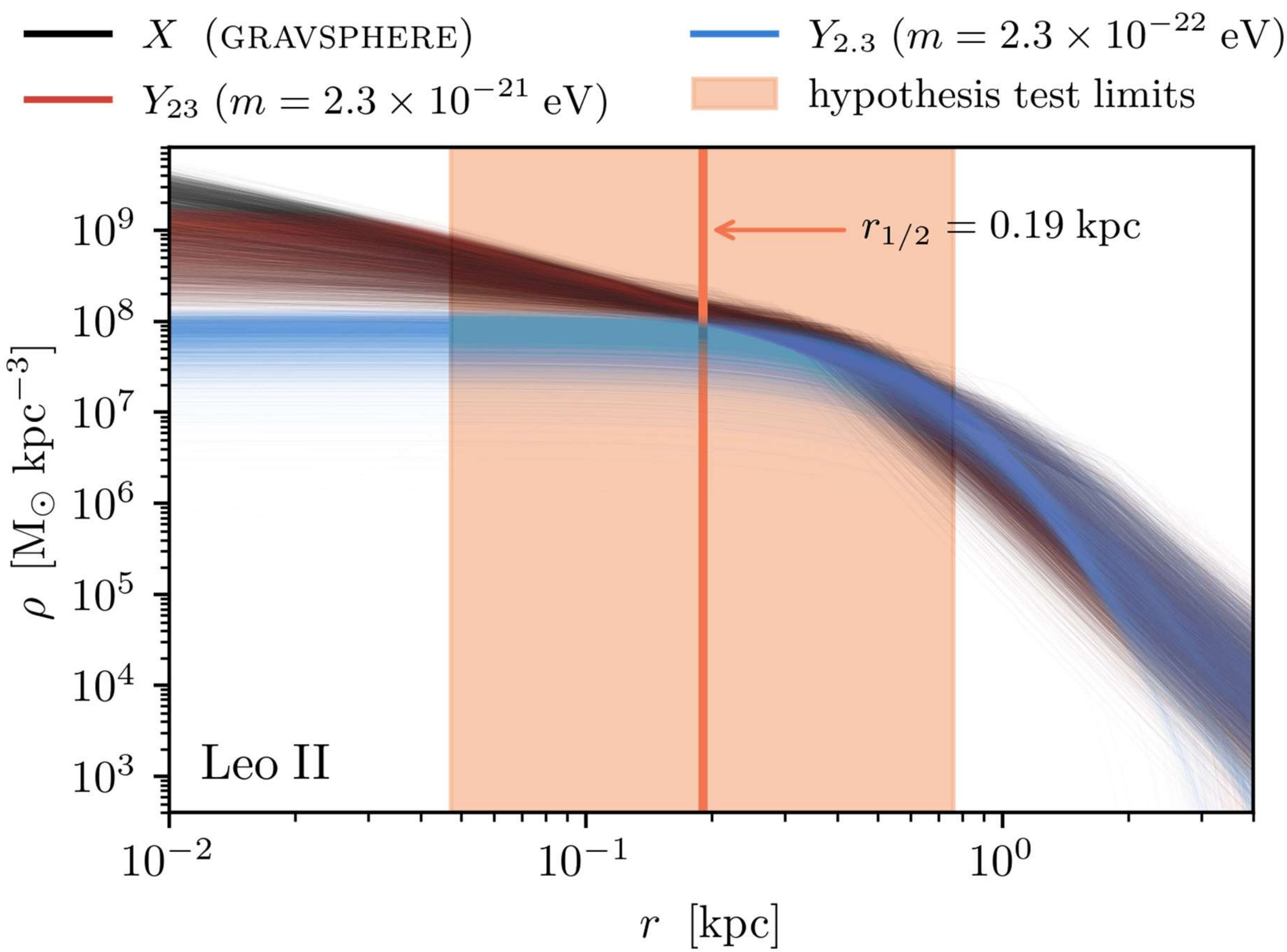
spherically symmetric steady-state configuration

Yavetz+ (2022)

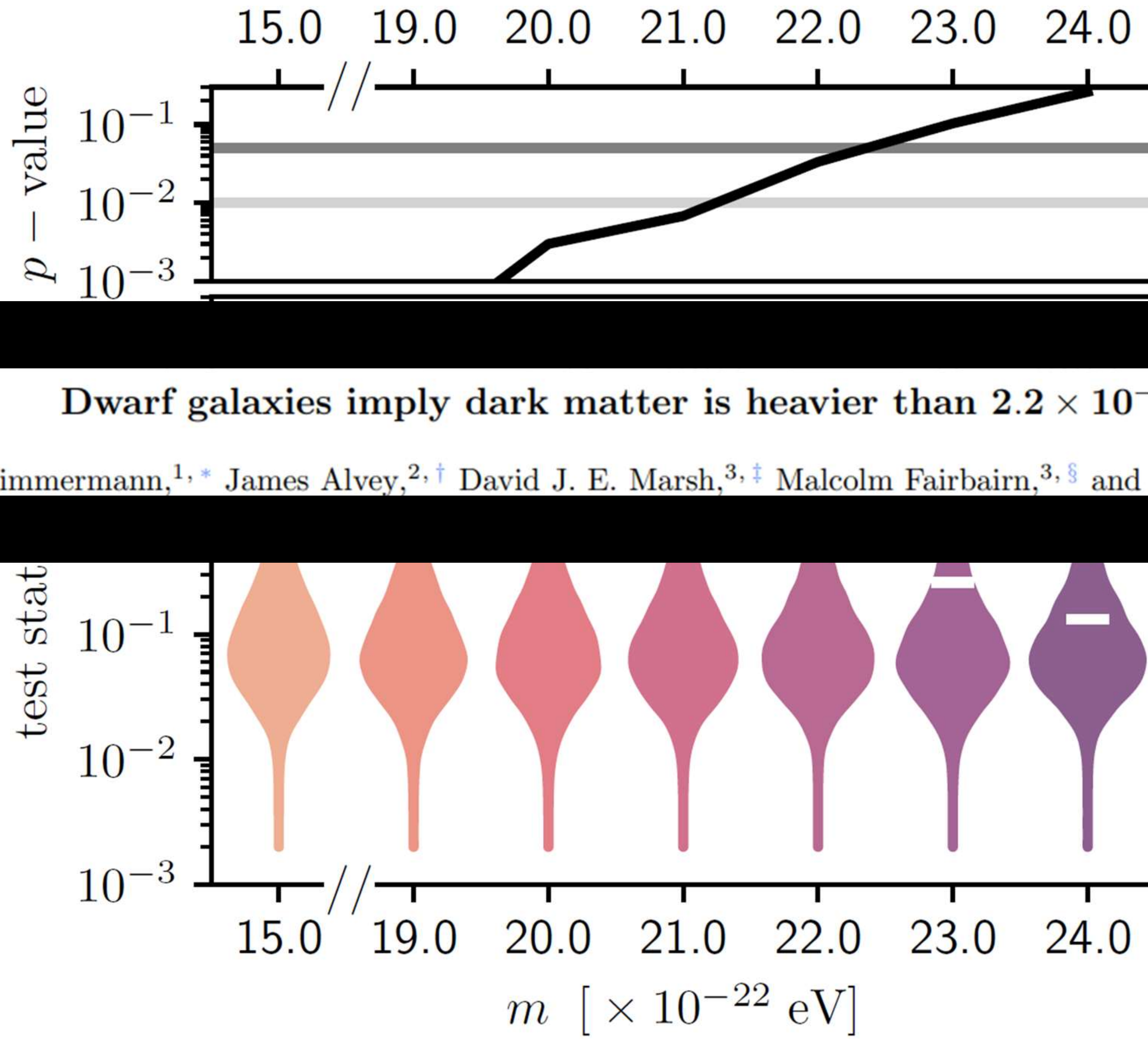


An example of the heat map of weights applied to different solutions to reconstruct the potential of Leo II


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



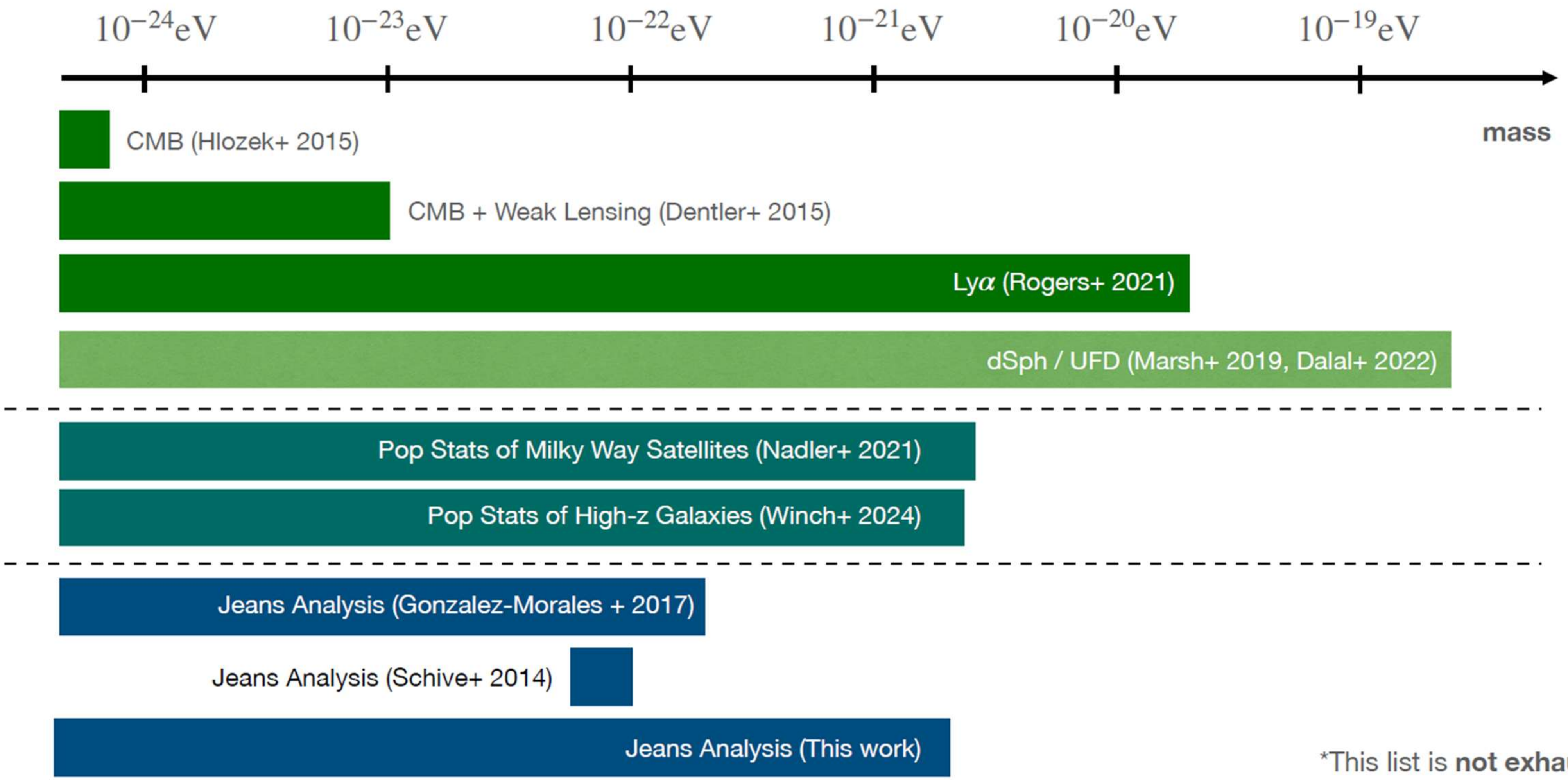
X (GRAVSPHERE)
Y_{23} ($m = 2.3 \times 10^{-21}$ eV)
$Y_{2.3}$ ($m = 2.3 \times 10^{-22}$ eV)
hypothesis test limits
$r_{1/2} = 0.19$ kpc
Leo II
ρ [$M_\odot$ kpc^{-3}]
r [kpc]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^{-2}
10^{-1}
10^0



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,¶]

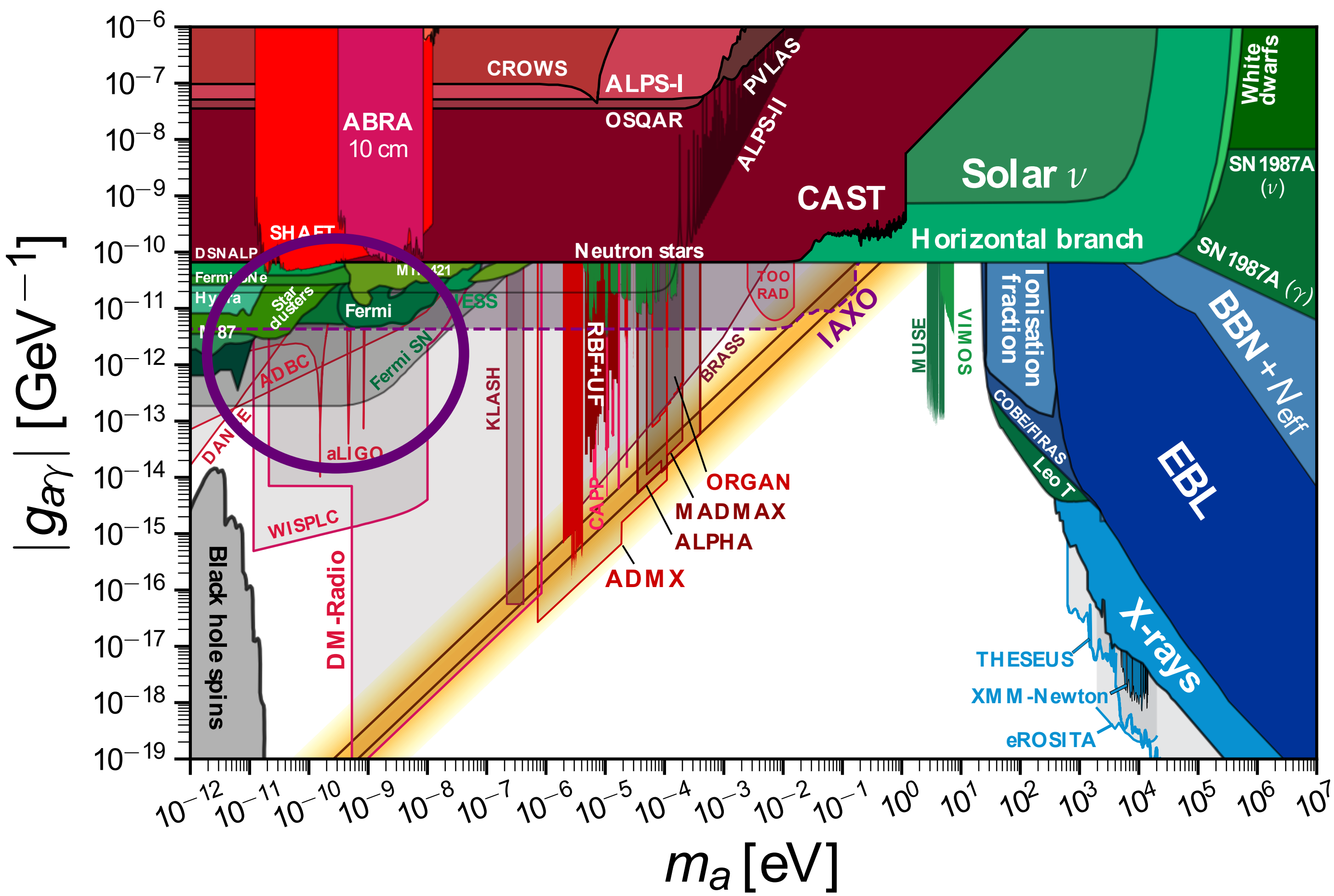
How does this compare with other constraints?



*This list is **not exhaustive**

Axion Limits

Fig: Ciaran O'Hare



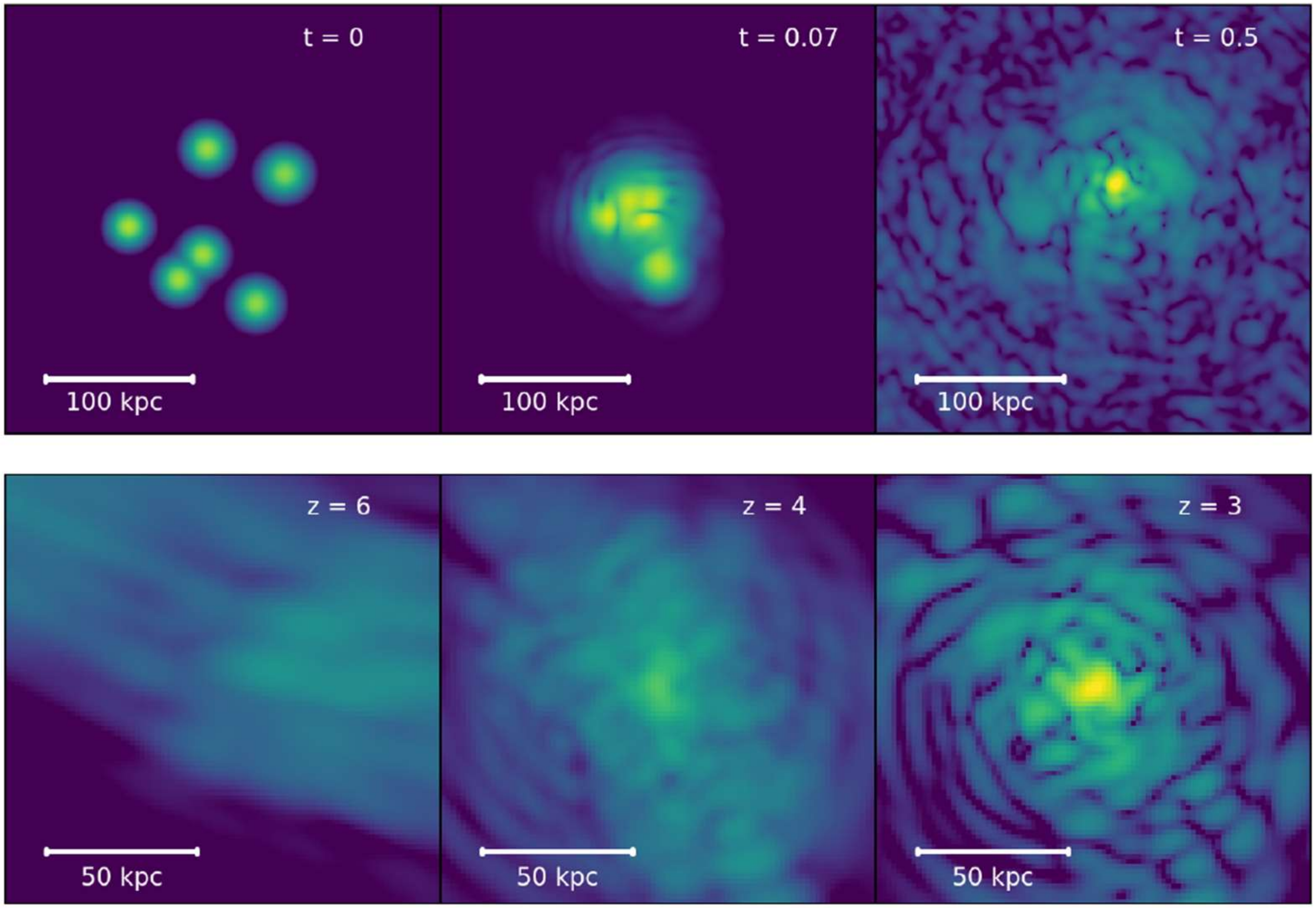
This talk: new & best limits on axion DM here.

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

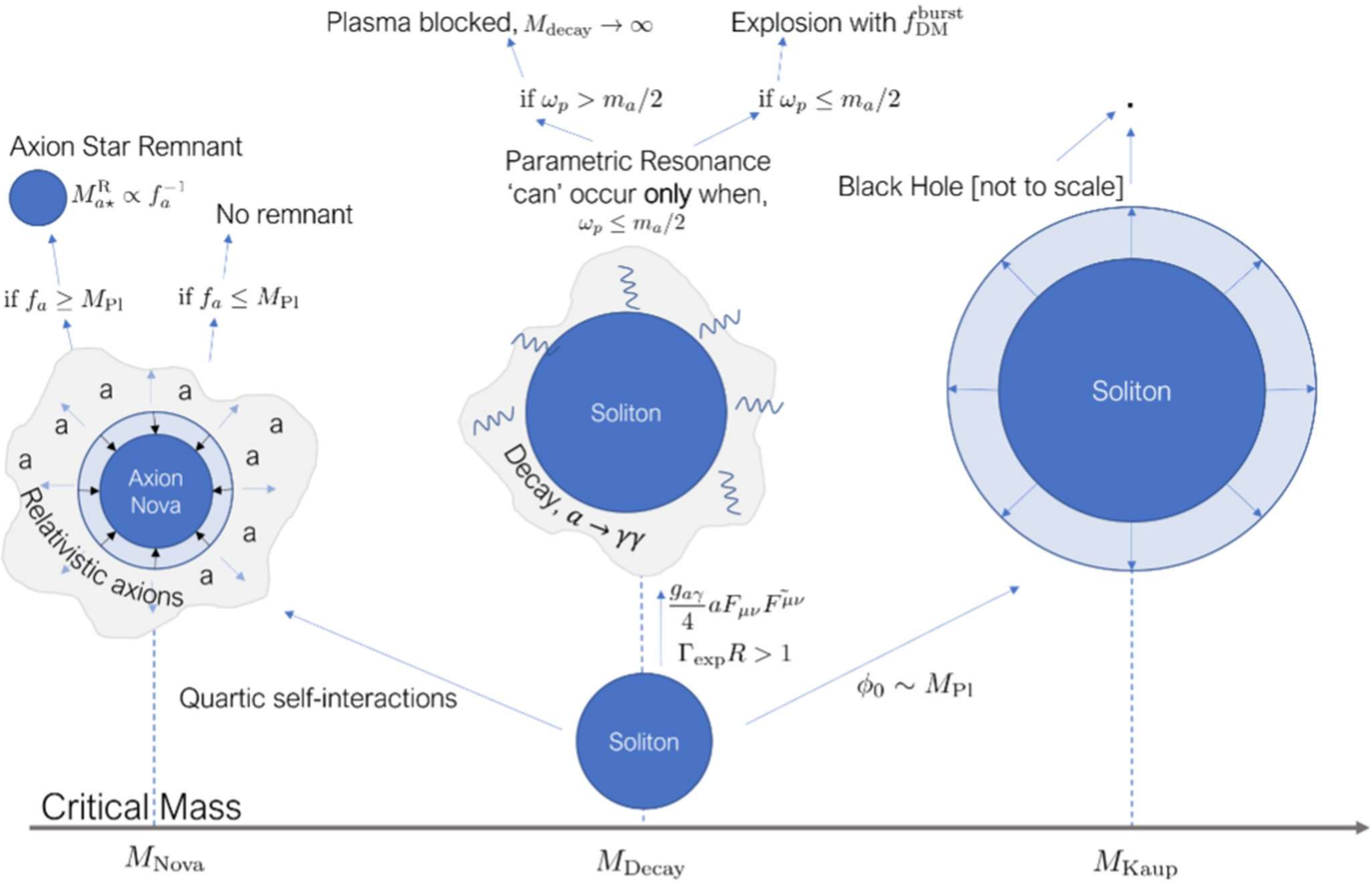
Hei Yin Jowett Chan,[1★] Elisa G. M. Ferreira,[2,3,4] Simon May,[2★] Kohei Hayashi,[5,6] Masashi Chiba[1]

Coalesence of halos to form bigger halo

Formation of a single halo from smaller halos

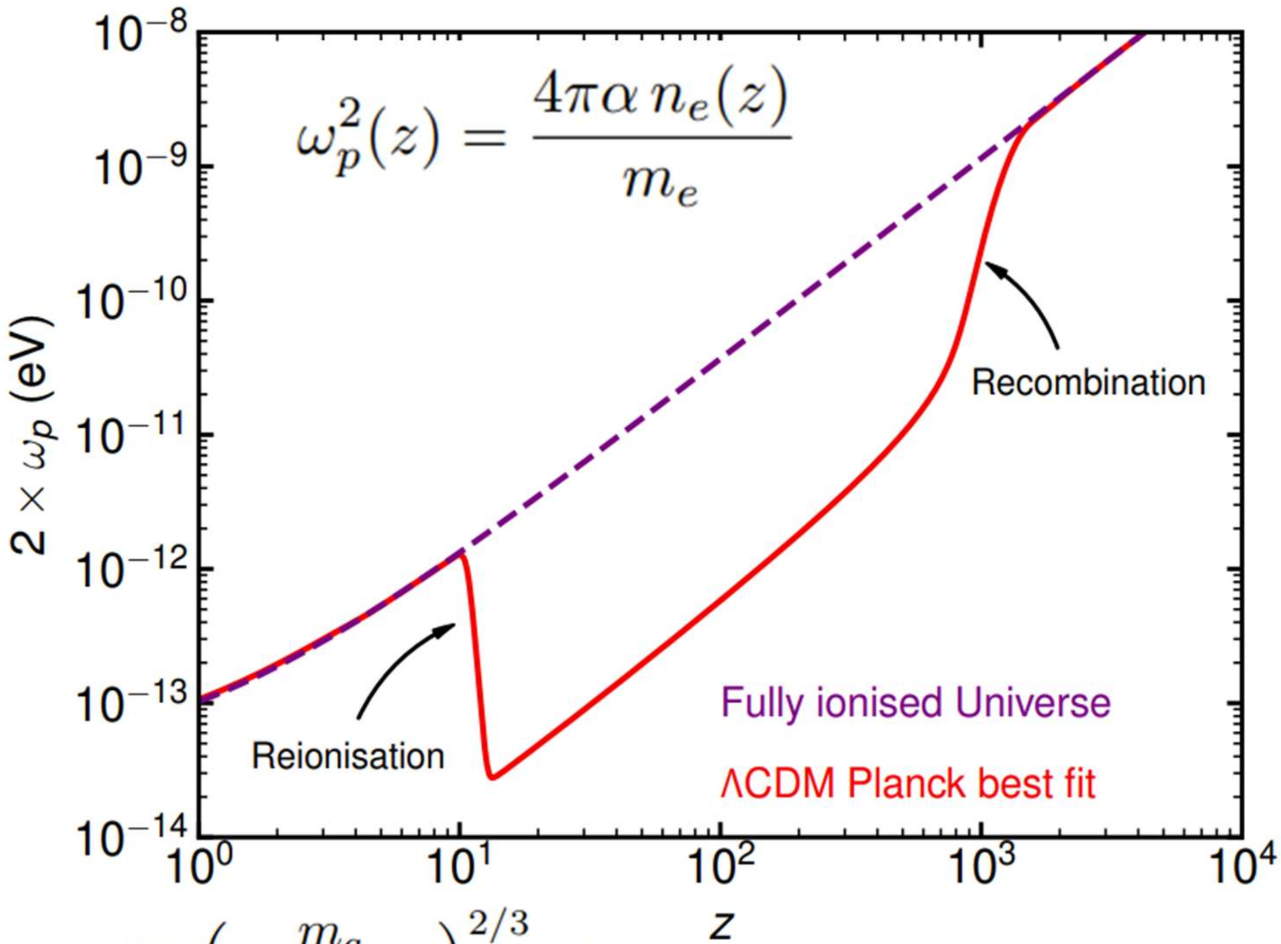


- As Theorists, we can contemplate many possible deaths for these dense cores…



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 $f_a \leq M_{\rm Pl}$
Axion Nova
Relativistic axions
Soliton
Decay, $a \to \gamma\gamma$
$\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F^{\mu\nu}}$
$\Gamma_{\rm exp} R > 1$
Quartic self-interactions
$\phi_0 \sim M_{\rm Pl}$
Critical Mass
$M_{\rm Nova}$
$M_{\rm Decay}$
$M_{\rm Kaup}$

Photon Effective Mass can prevent Decay!



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

Exploding Axion Stars Heat IGM

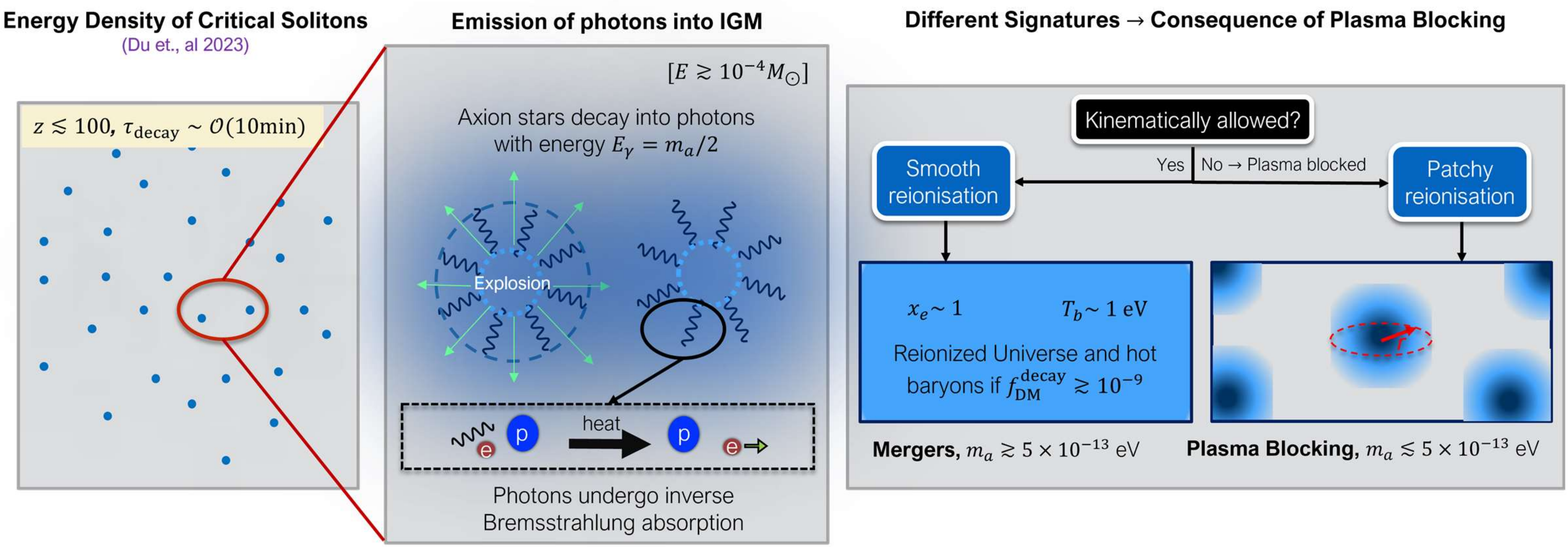
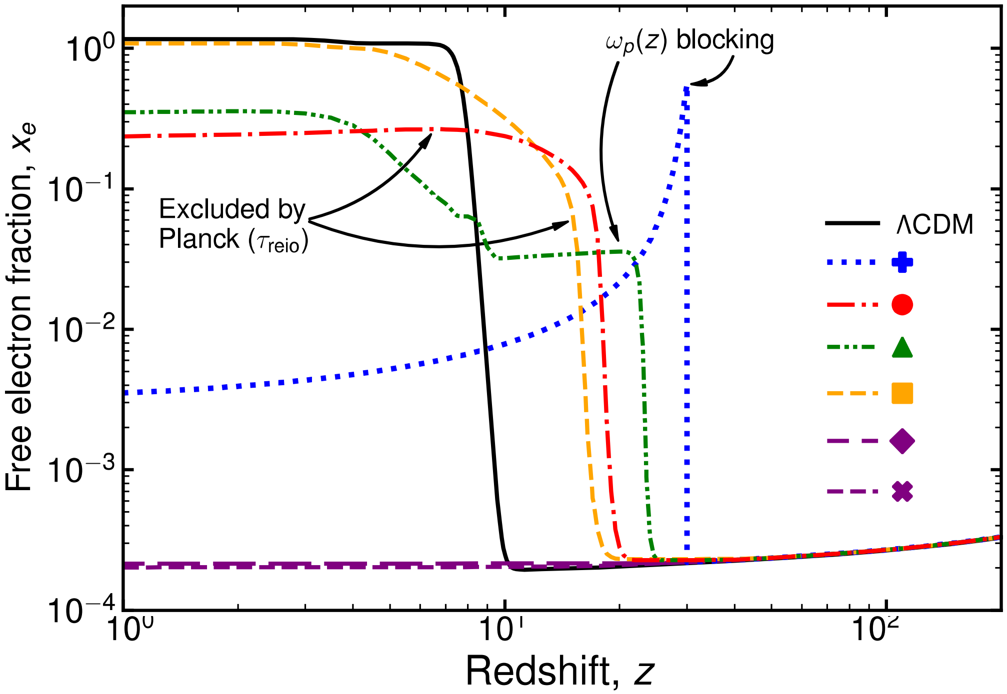
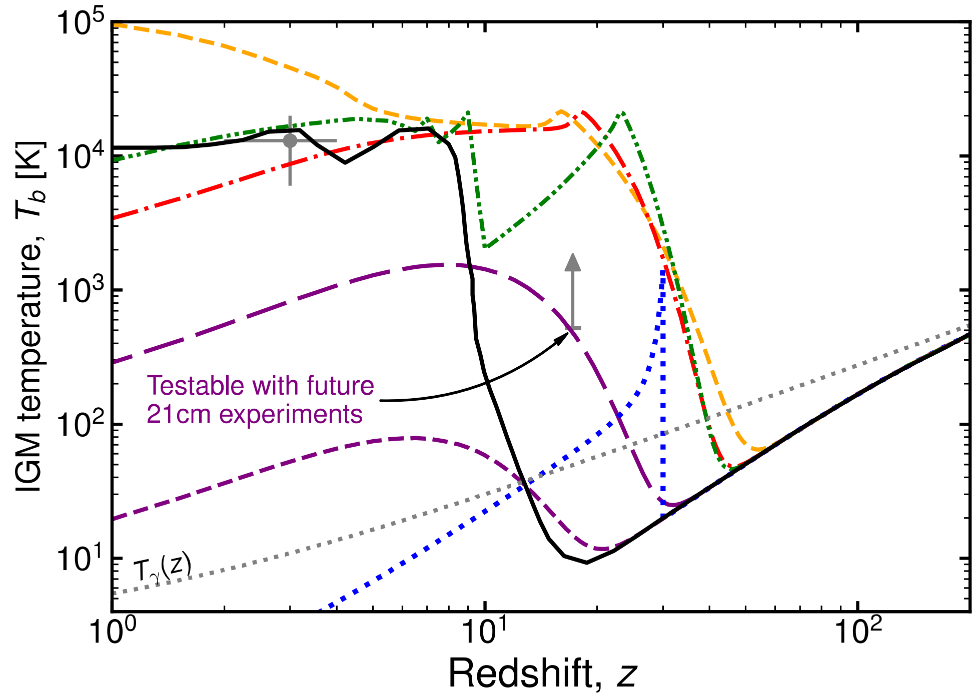


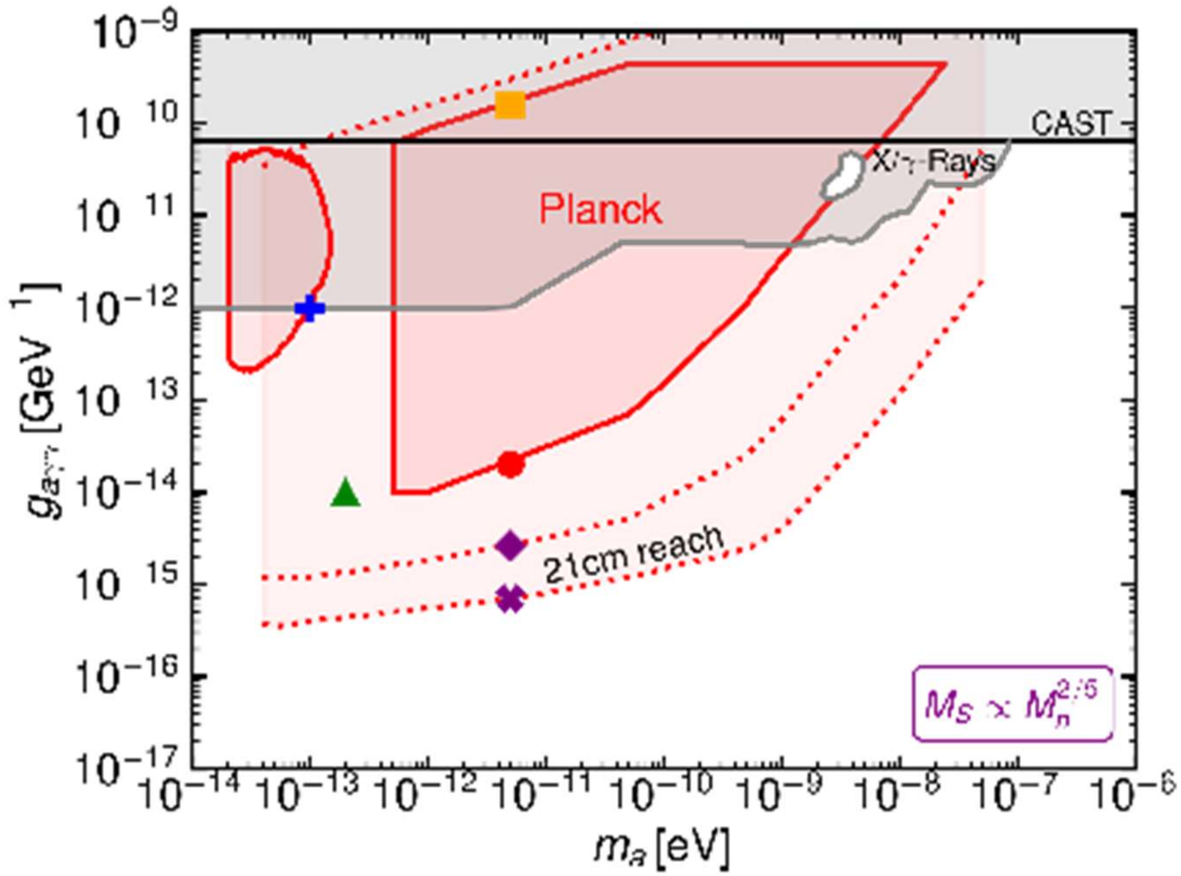
Fig by Charis Pooni

Reionization Histories





New Constraints on Axions



Audible Axions

$$\mathcal{S} = \int d^4x \sqrt{-g}\left[\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi)\right.$$
$$\left. -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}\right],$$

$$V(\phi) = m^2 f^2\left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

Coupling of axions to SM photons tightly constrained.
What if axions couple to dark sector photons?

$$\left(\frac{\partial^2}{\partial\tau^2} - \nabla^2 - \alpha\frac{\phi'}{f}\vec{\nabla}\times\right)\vec{X} = 0$$

$$\hat{X}^i(\mathbf{x},\tau) = \int\frac{d^3k}{(2\pi)^3}\hat{X}^i(\mathbf{k},\tau)e^{i\mathbf{k}\cdot\mathbf{x}}$$
$$= \sum_{\lambda=\pm}\int\frac{d^3k}{(2\pi)^3}v_\lambda(k,\tau)\,\varepsilon^i_\lambda(\mathbf{k})\,\hat{a}_\lambda(\mathbf{k})\,e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}$$

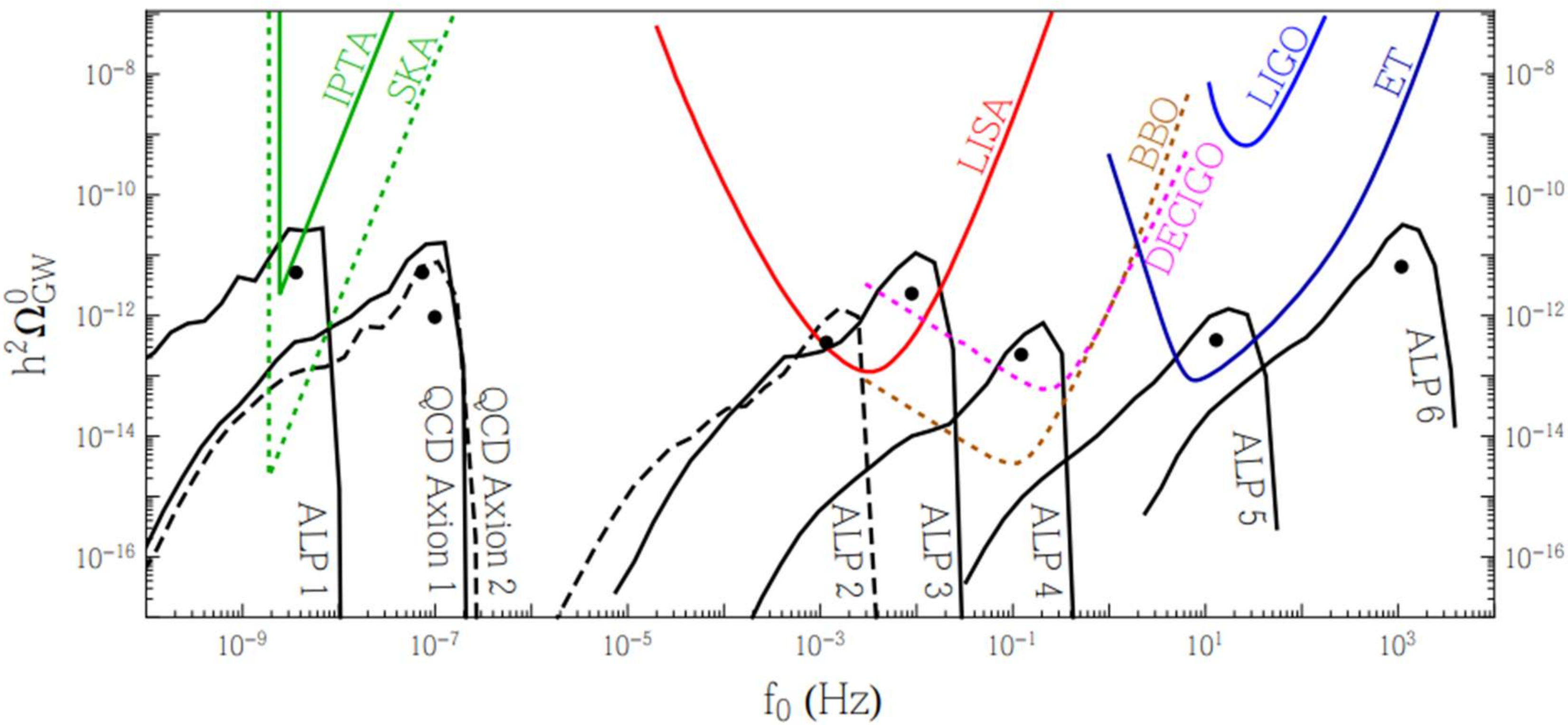
$$v''_\pm(k,\tau) + \omega^2_\pm(k,\tau)\,v_\pm(k,\tau) = 0$$

$$\omega^2_\pm(k,\tau) = k^2 \mp k\frac{\alpha}{f}\phi'$$

Machado,Ratzinger,Schwaller and Stefanek 1811.01950

Audible Axions

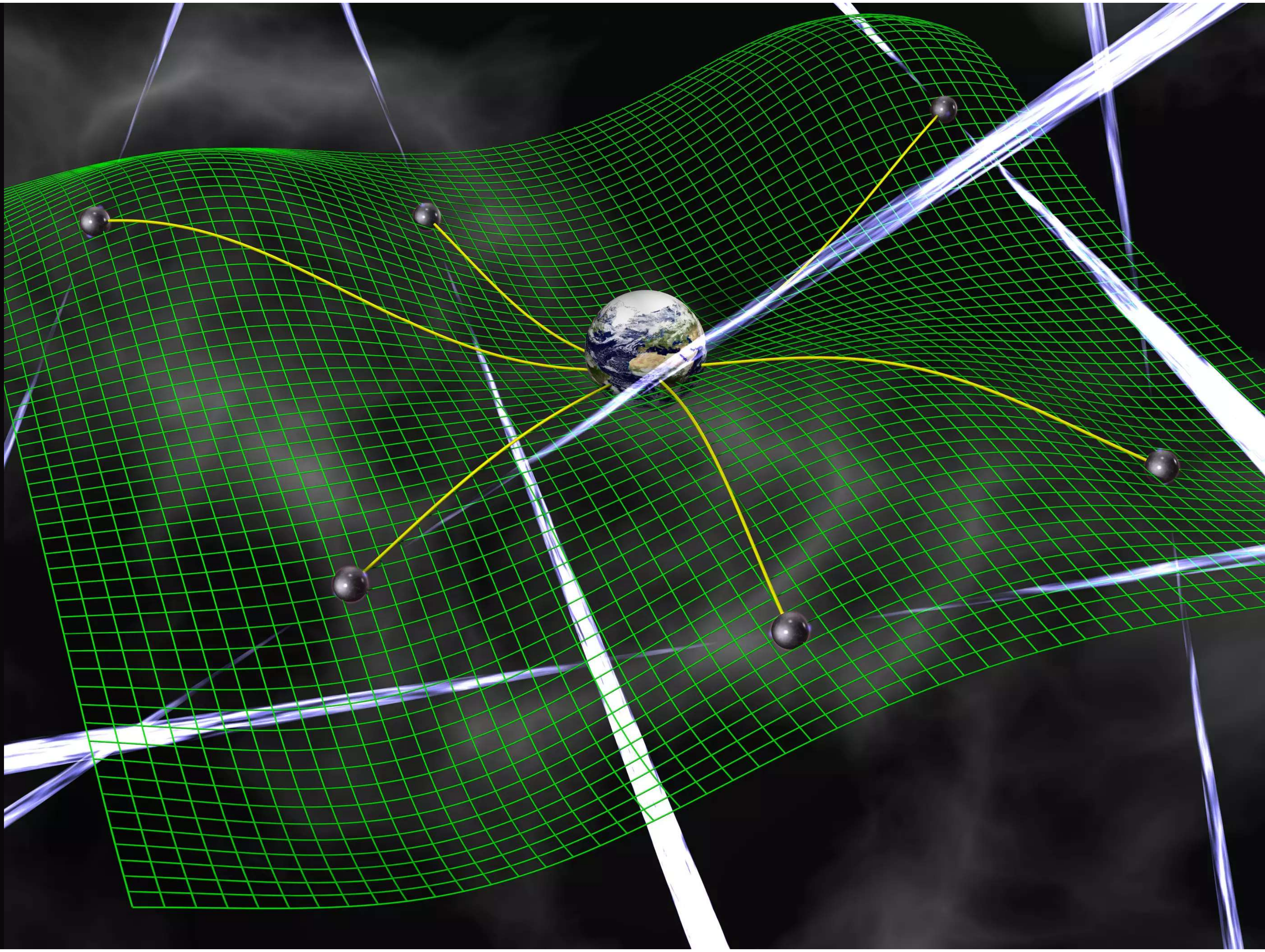
Explosive production of dark photons can lead to gravitational waves

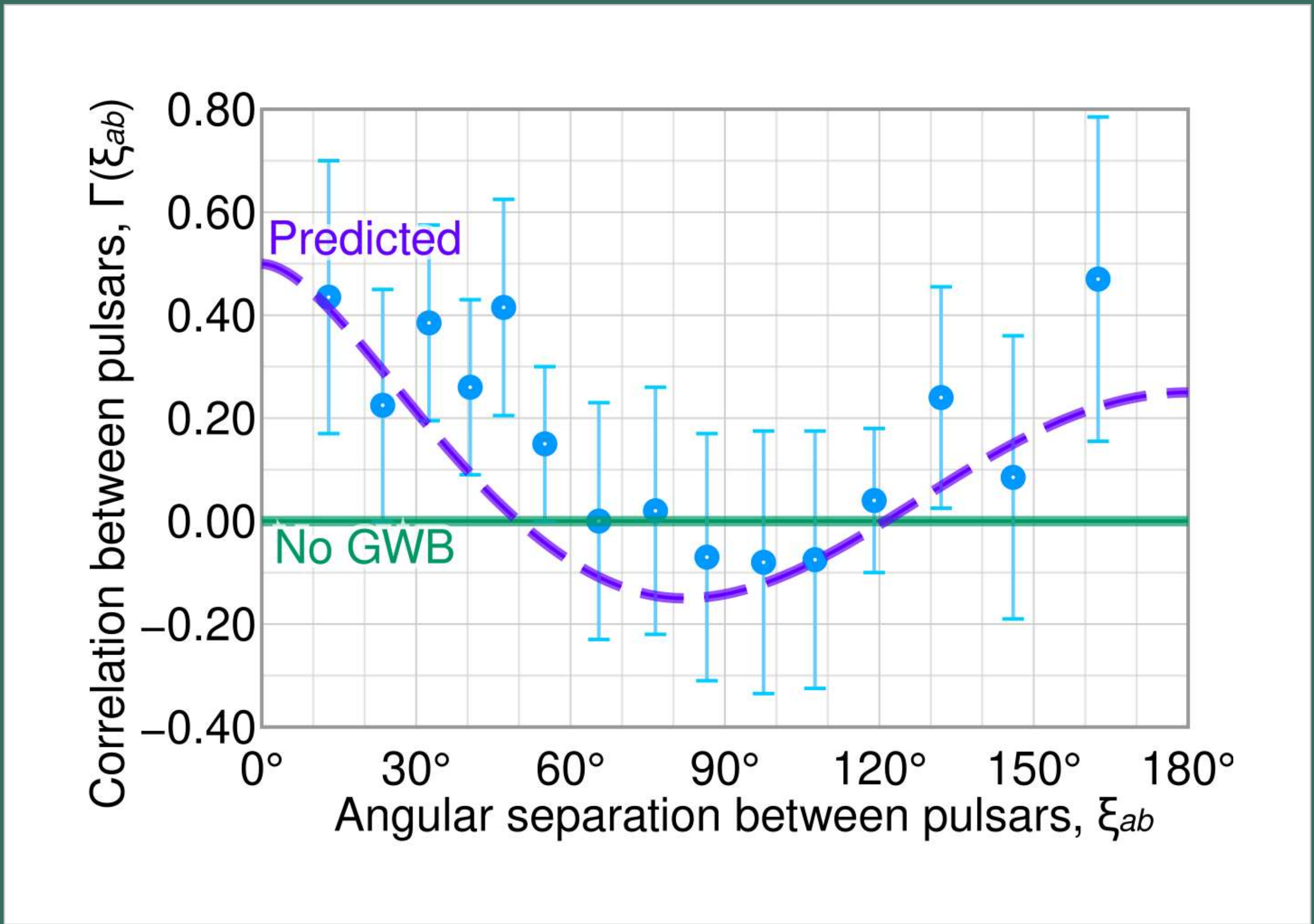


Machado,Ratzinger,Schwaller and Stefanek 1811.01950

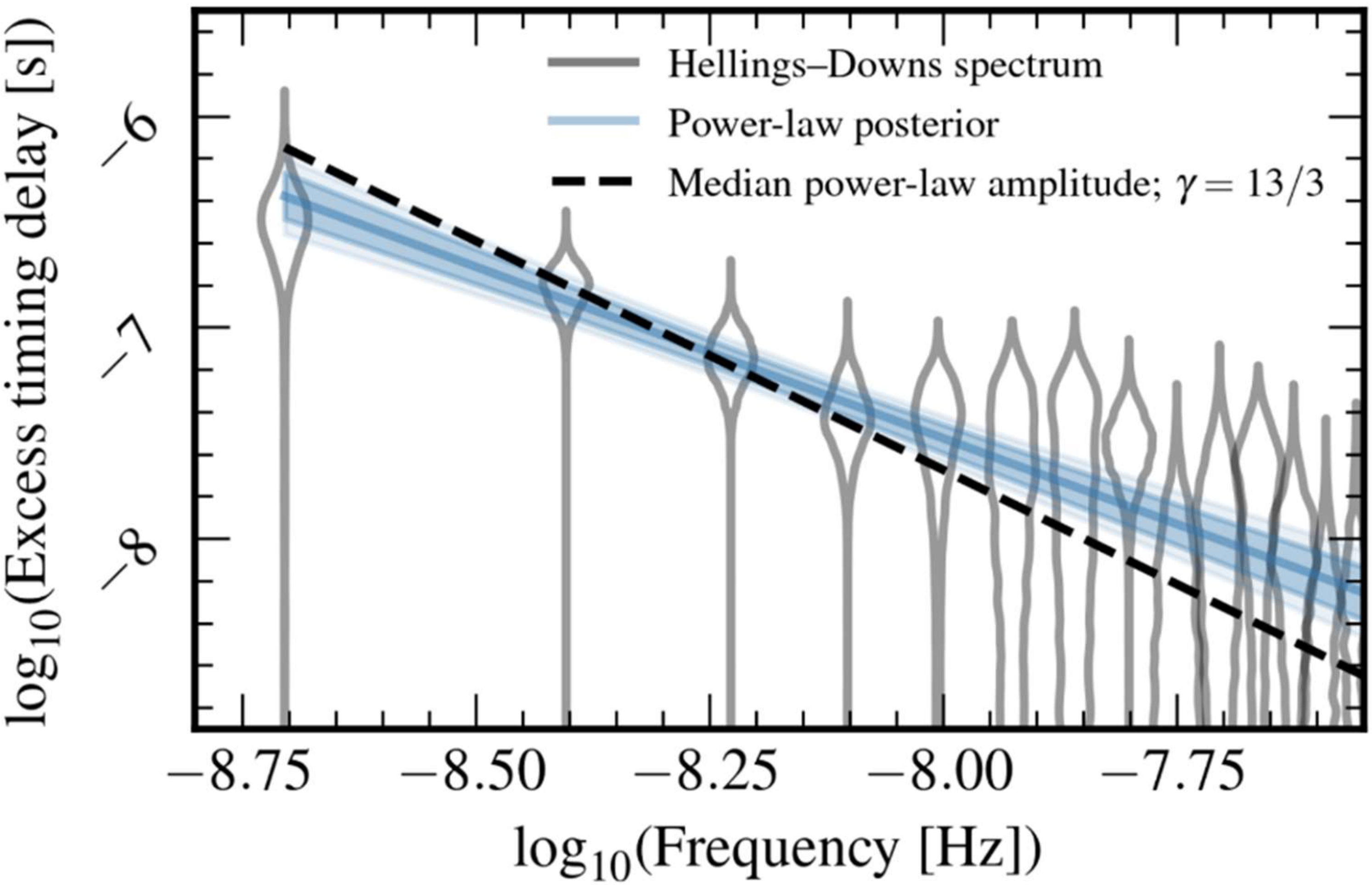
Pulsar Timing Array (PTA)

Gravitational Waves create arrival delay across the sky with characteristic pattern

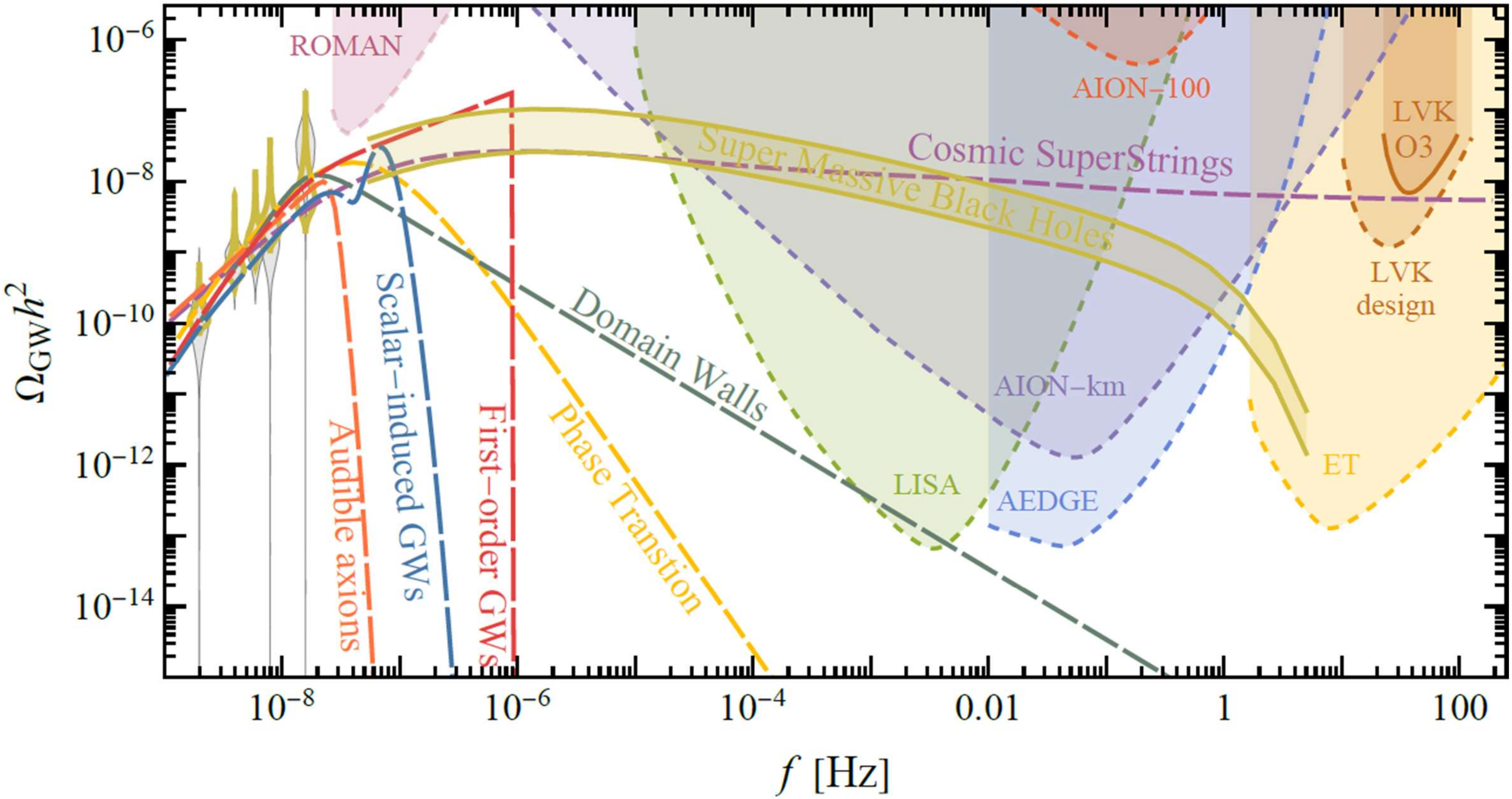




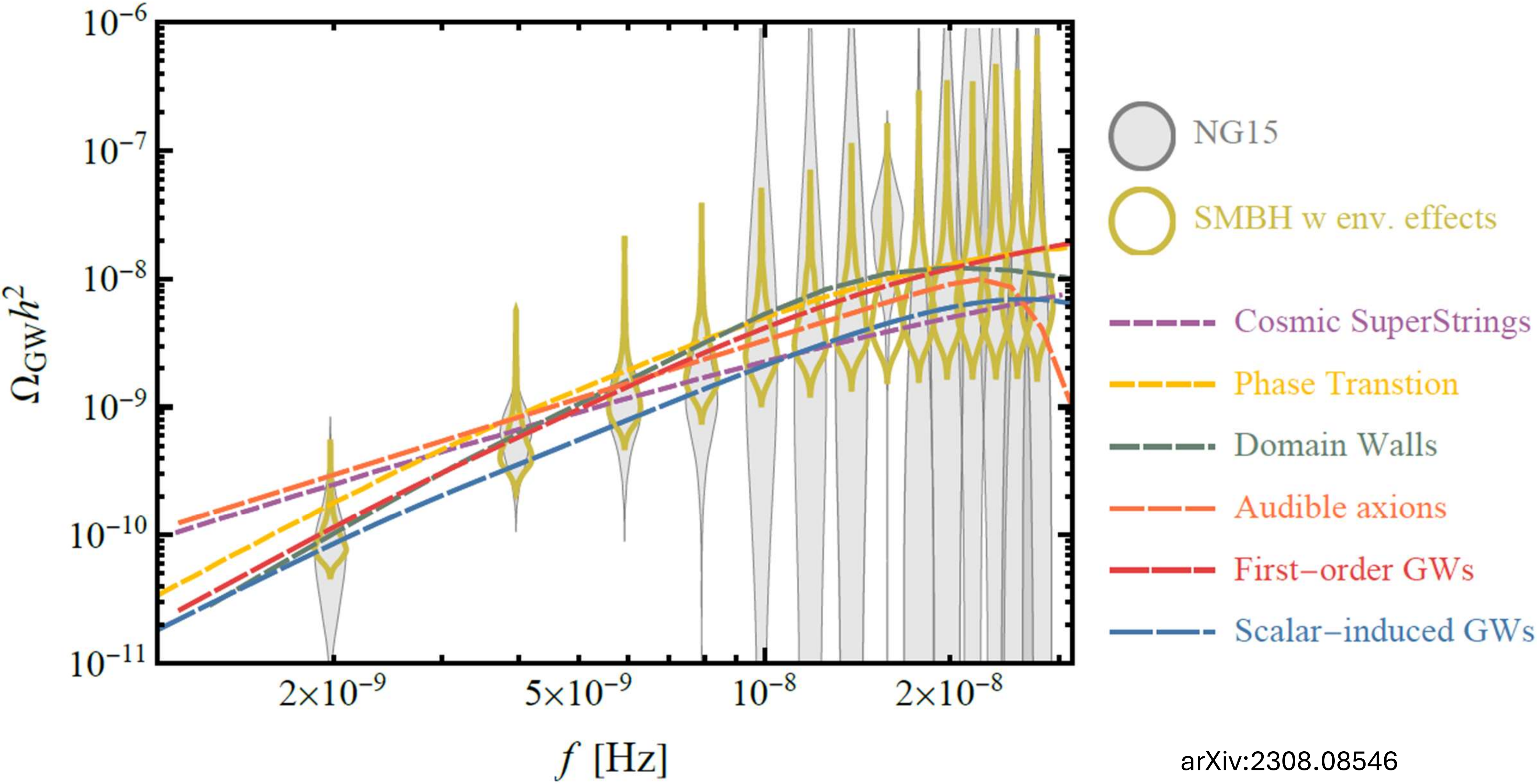
Look for Timing Residuals from Pairs of Pulsars around the sky



June 2023 - Nanograv collaboration detected such an effect 2306.16213



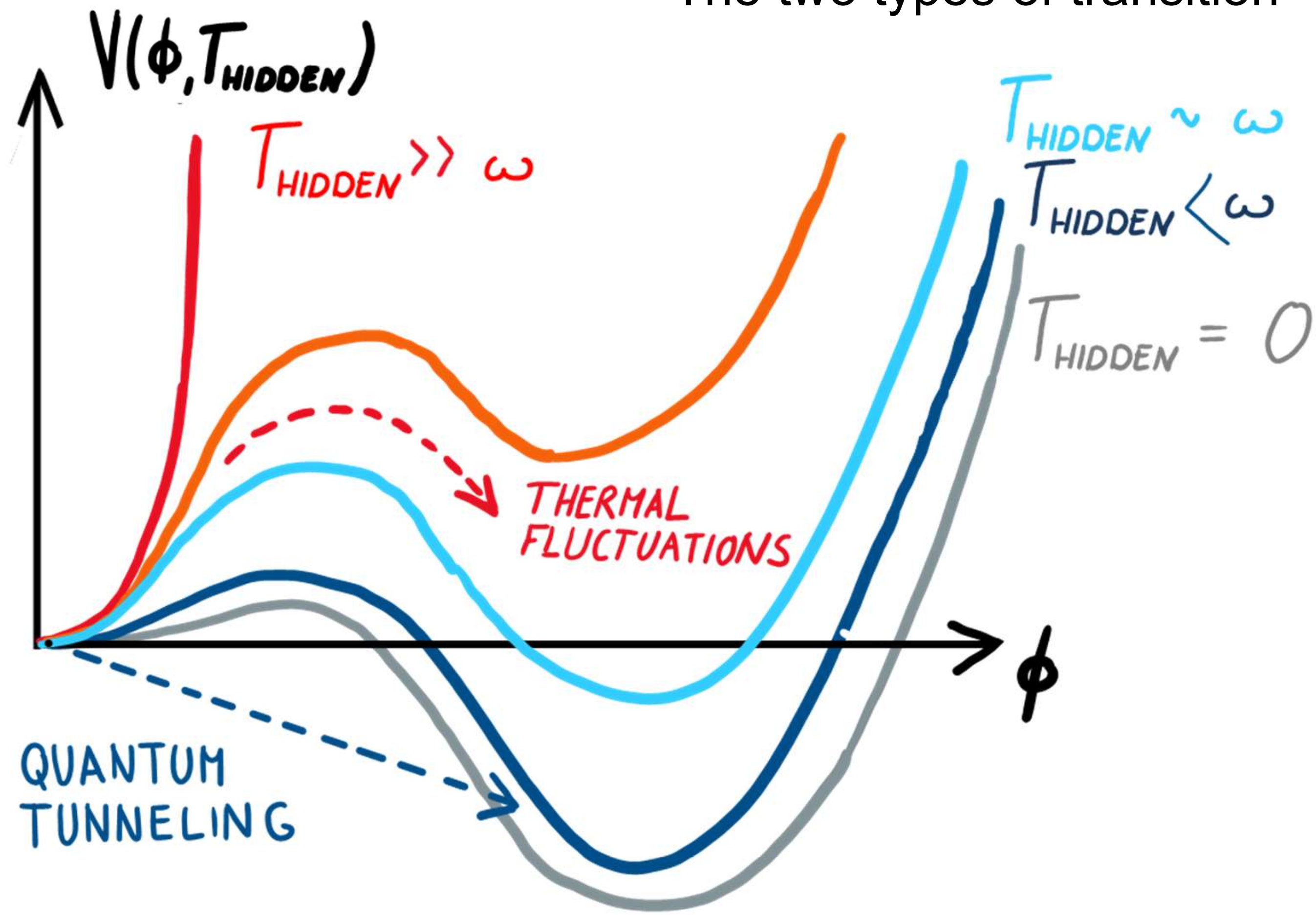
ROMAN
AION−100
LVK
O3
Cosmic SuperStrings
Super Massive Black Holes
LVK
design
Domain Walls
AION−km
Scalar−induced GWs
First−order GWs
Phase Transtion
Audible axions
LISA
AEDGE
ET
$\Omega_{\mathrm{GW}}h^2$
f [Hz]



arXiv:2308.08546

Cold hidden sectors

The two types of transition



Tunneling Transition / Thermal transition

- Happens when $\Gamma_{tunnel}(t)^{\frac{1}{4}} > H(t)$ / $\Gamma_{thermal}(t)^{\frac{1}{4}} > H(t)$

Cold hidden sectors

The two types of transition

Thermal phase transition

$$\Gamma_3 \simeq T_{\rm h}^4 \left(\frac{S_3}{2\pi T_{\rm h}}\right)^{3/2} e^{-S_3/T_{\rm h}}$$

Tunneling Phase transition

$$\Gamma_4 \simeq w^4 \left(\frac{S_4}{2\pi}\right)^2 e^{-S_4}$$

Both temperature dependent

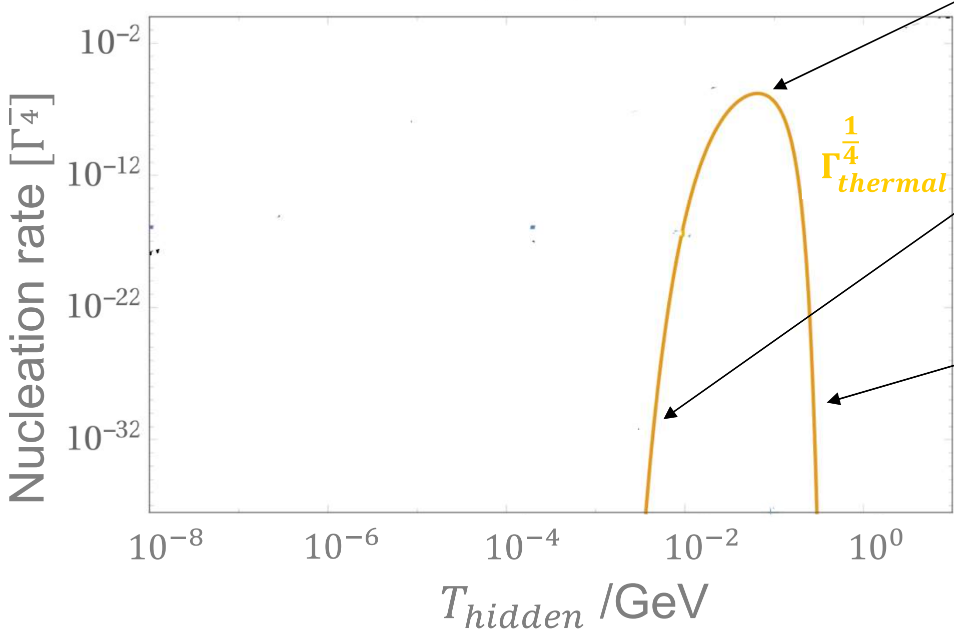
Thermal phase transition

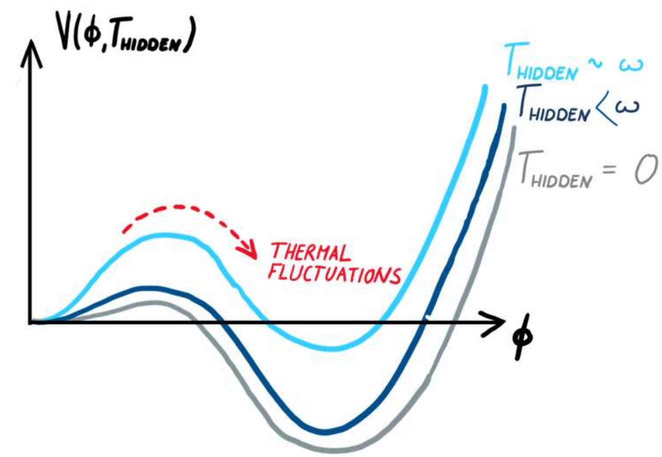
The two types of transition: concrete example

Optimal point for thermal transition

Thermal fluctuations are very small

Barrier is very high

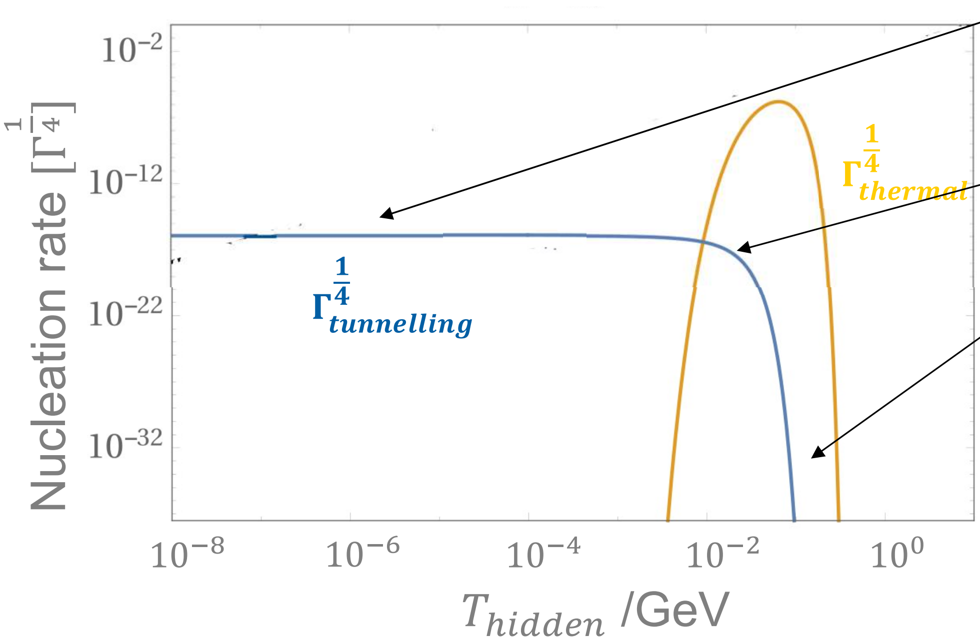




Tunnelling phase transition

The two types of transition: concrete example

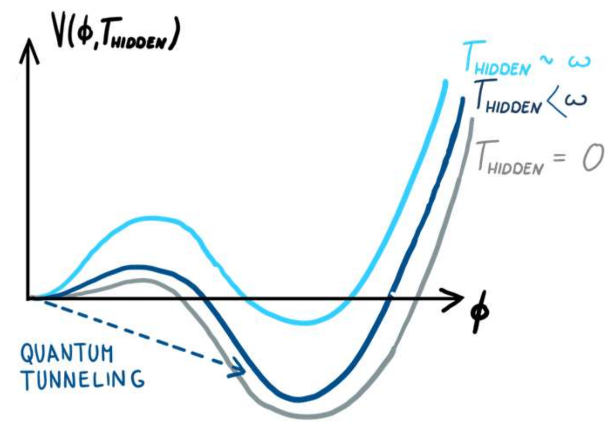
Case 1: $\epsilon = \frac{T_{hidden}}{T_{visible}} \approx 1$



Tunnelling nucleation rate stays constant

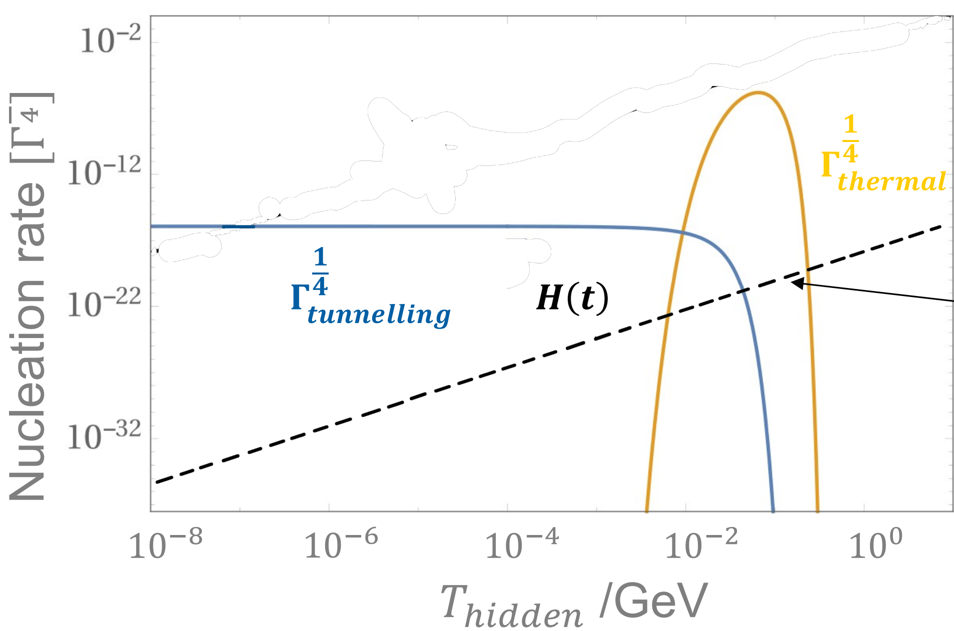
Barrier close to $T_{hidden} = 0$ form

Barrier height very high



Phase transitions

Case 1: $\epsilon = \frac{T_{hidden}}{T_{visible}} \approx 1$

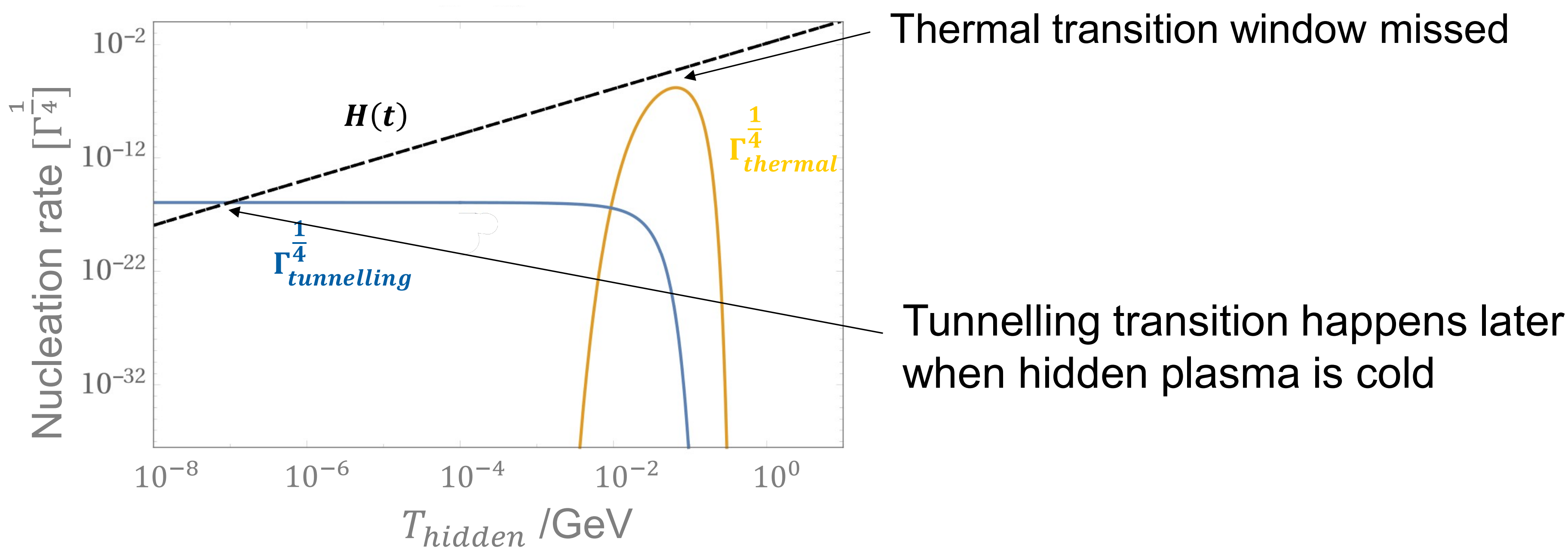


Thermal transition takes place when hidden plasma is hot

Hot plasma → High friction→ Sound wave signal

Phase transitions

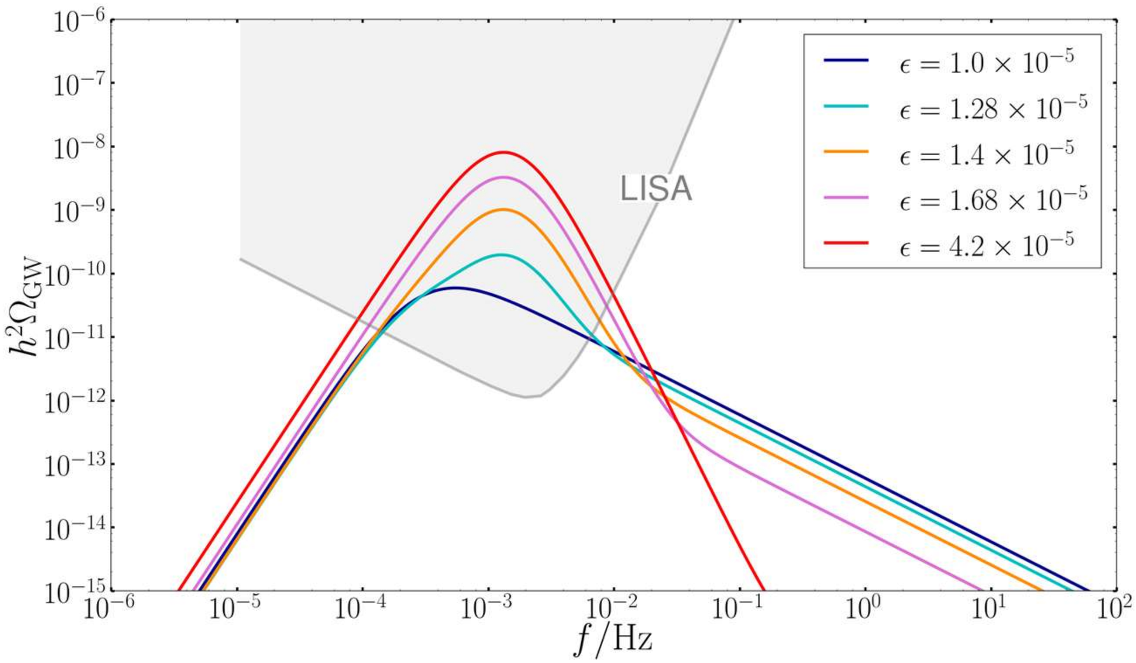
Case 2: $\epsilon = \frac{T_{hidden}}{T_{visible}} \ll 1$



Cold plasma → Low wall friction → Bubble collision signal?

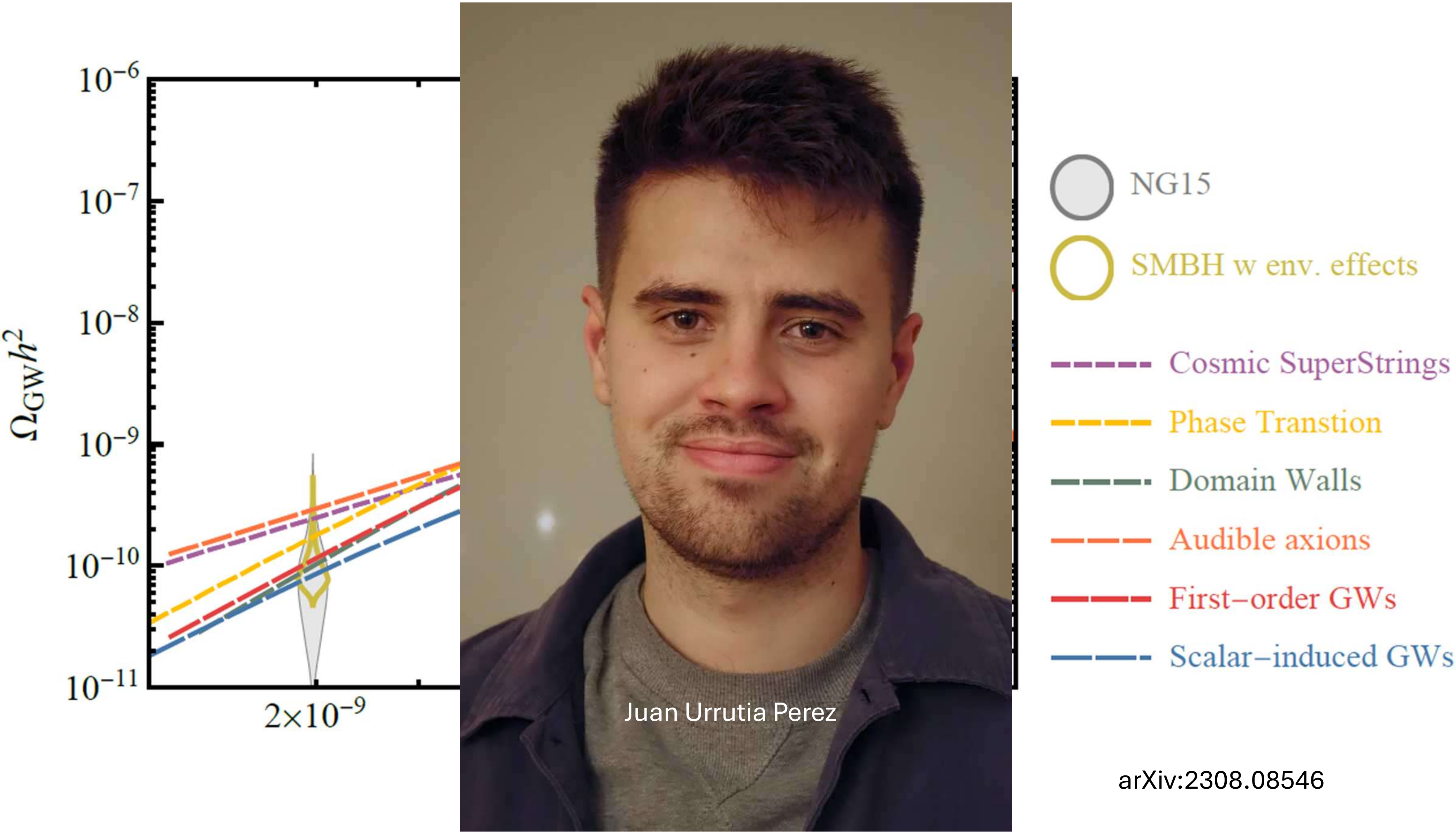
Gravitational Waves

here **visible** temperature at transition is around TeV
Hidden sector temperature different



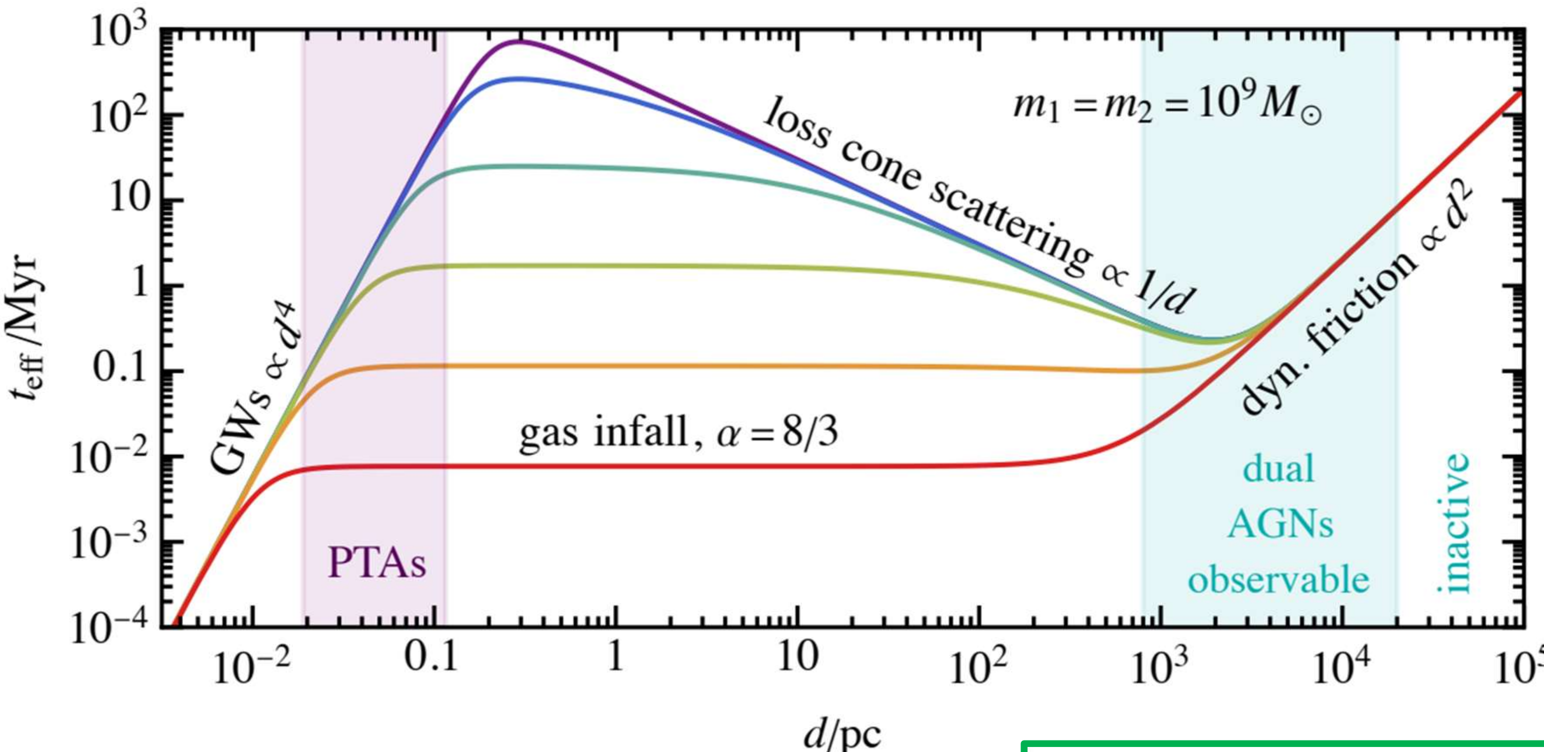
- Decreasing $\epsilon = \frac{T_{hidden}}{T_{visible}}$ decreases friction on bubble wall
- Sound wave → bubble collision
- Changes the shape of the gravitational wave signal

A tunnelling transition where a sound wave is expected could be a signal of a hidden cold sector



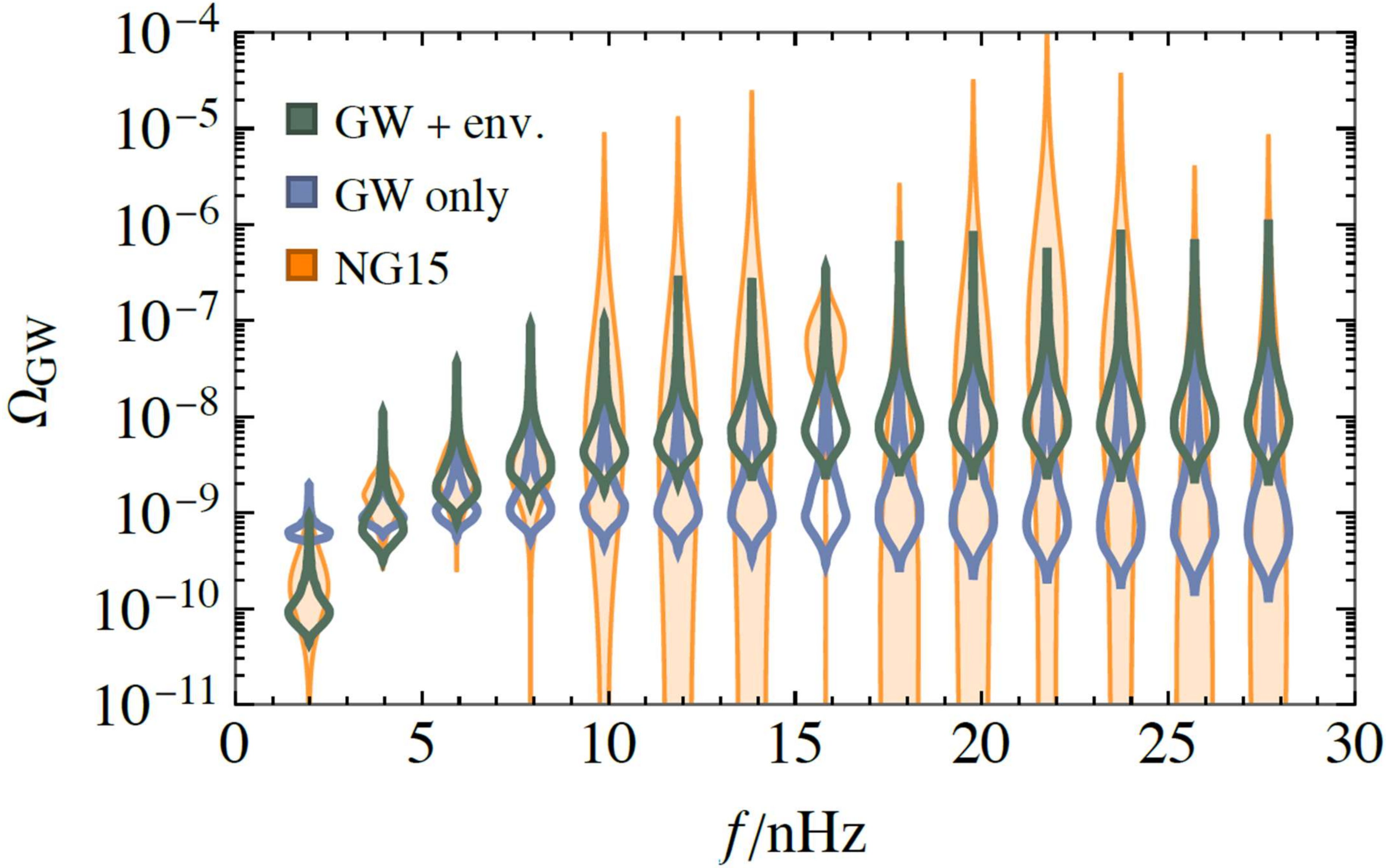
arXiv:2308.08546

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

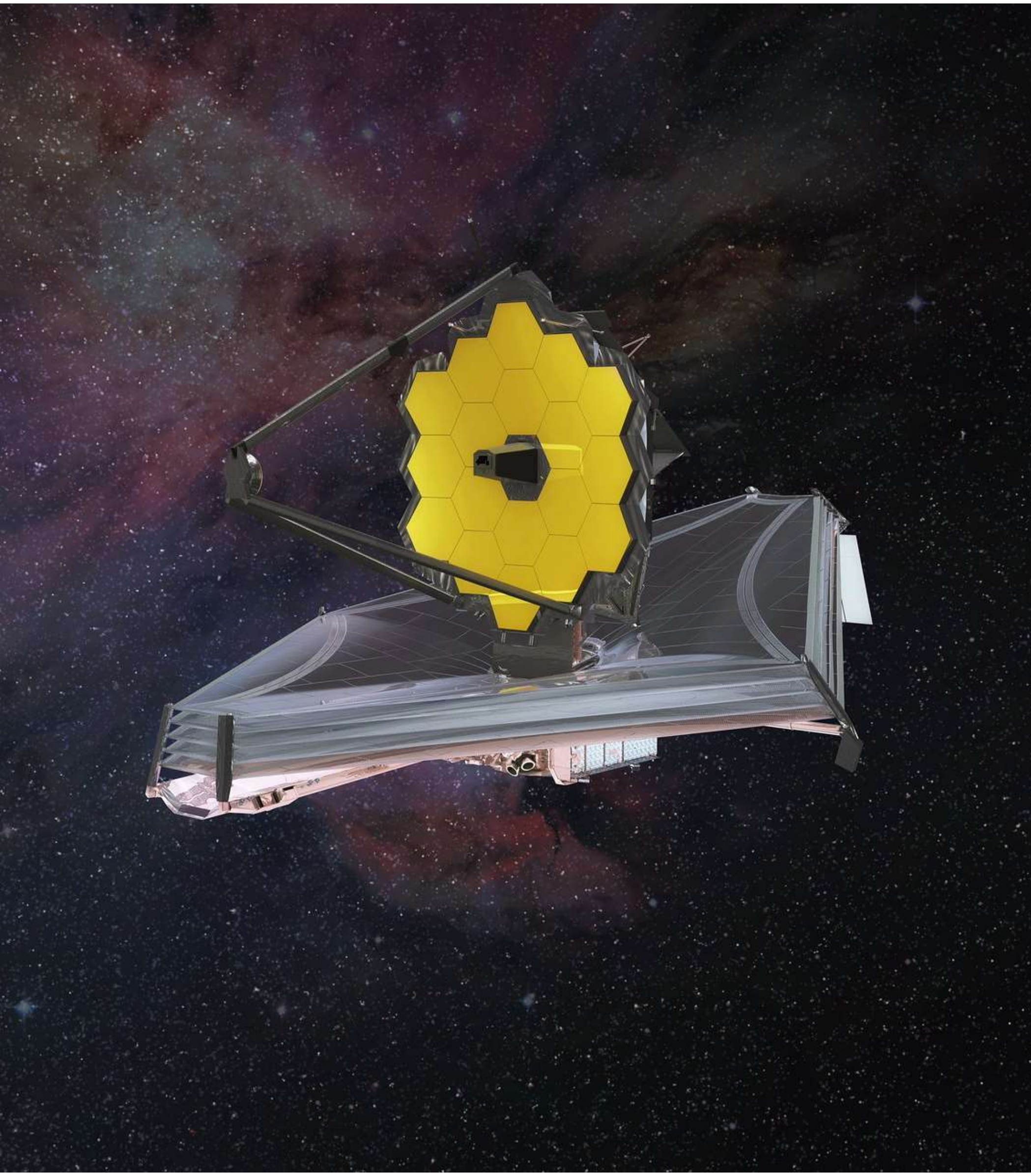


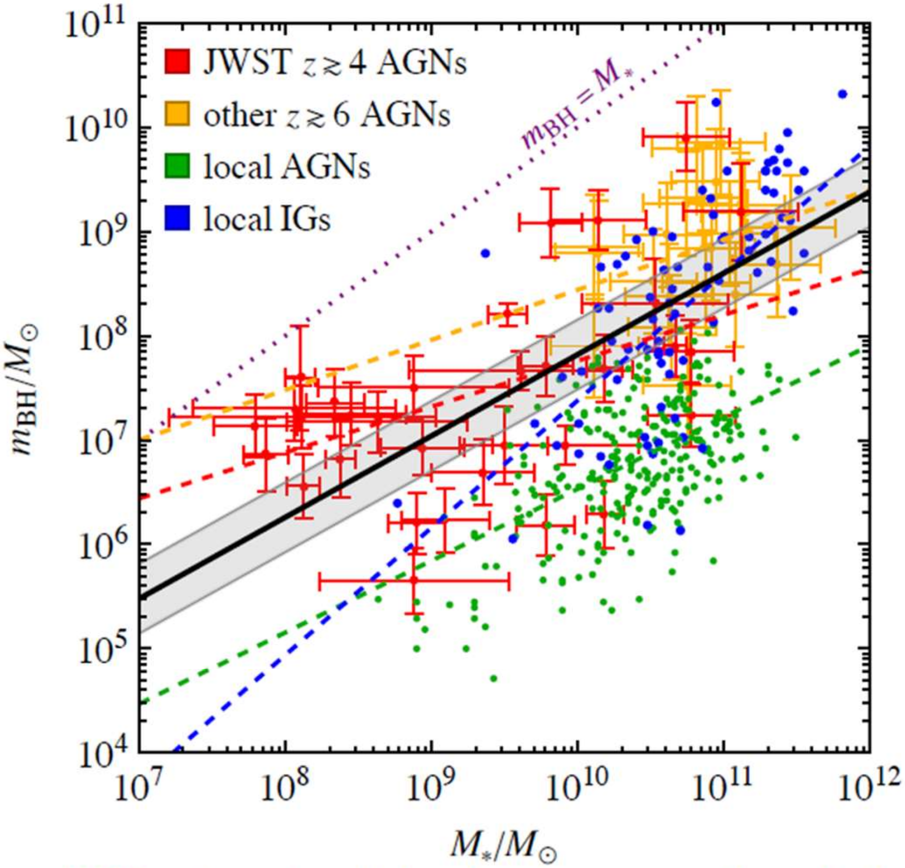
"The Final Parsec Problem"

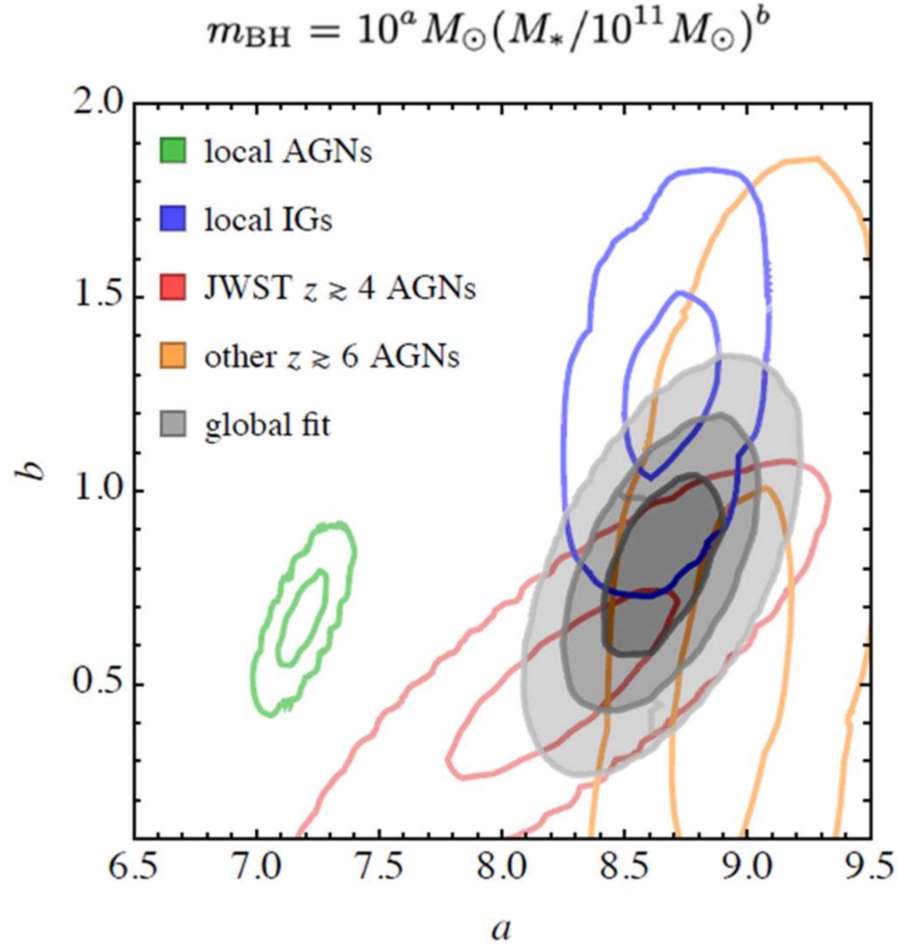
$$t_{\rm dyn} \simeq \frac{20\,{\rm Myr}}{\ln\Lambda}\frac{\sigma}{200\,{\rm km/s}}\left[\frac{M}{10^9 M_\odot}\right]^{-1}\left[\frac{d}{\rm kpc}\right]^2$$



GW + env.
GW only
NG15
Ω_{GW}
f/nHz
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0
5
10
15
20
25
30





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

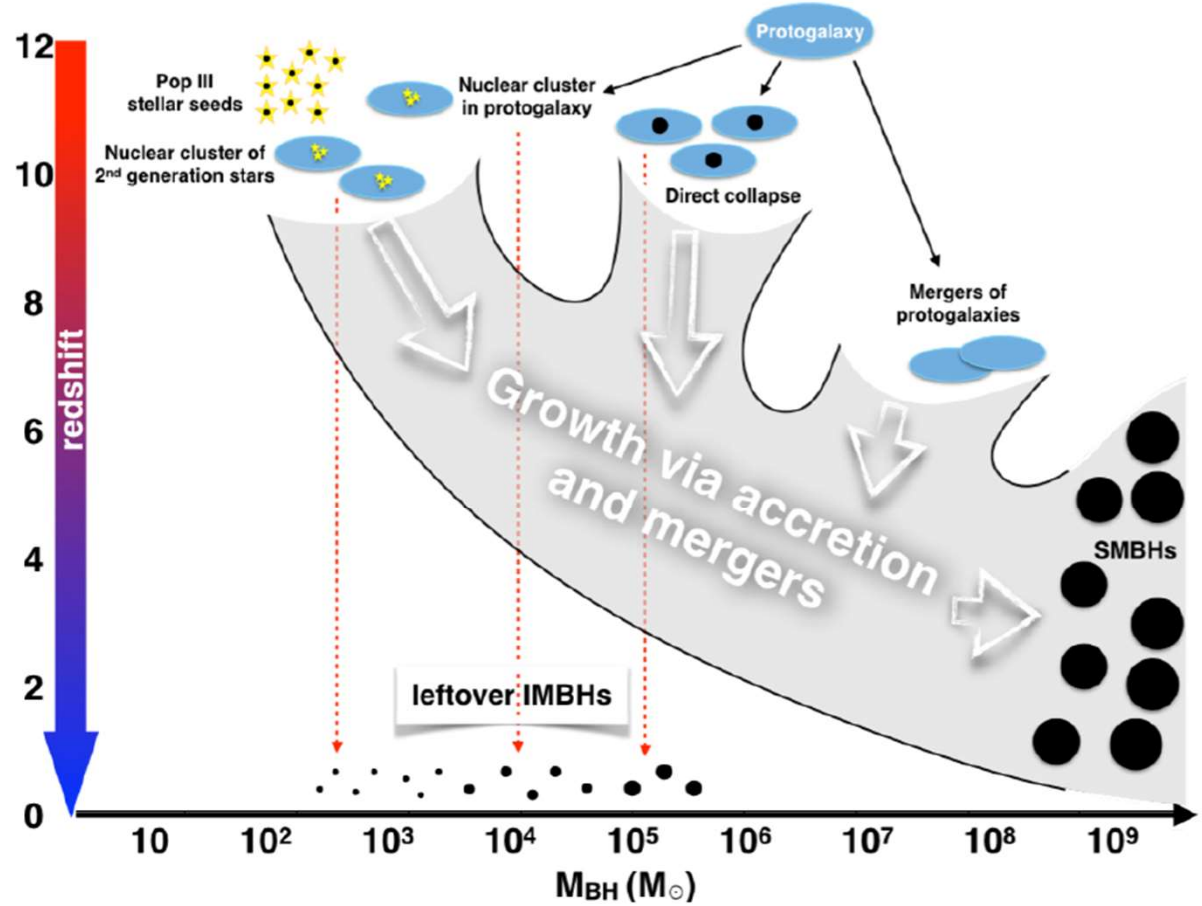
Low-z active galactic nuclei (AGNs) and inactive galaxies

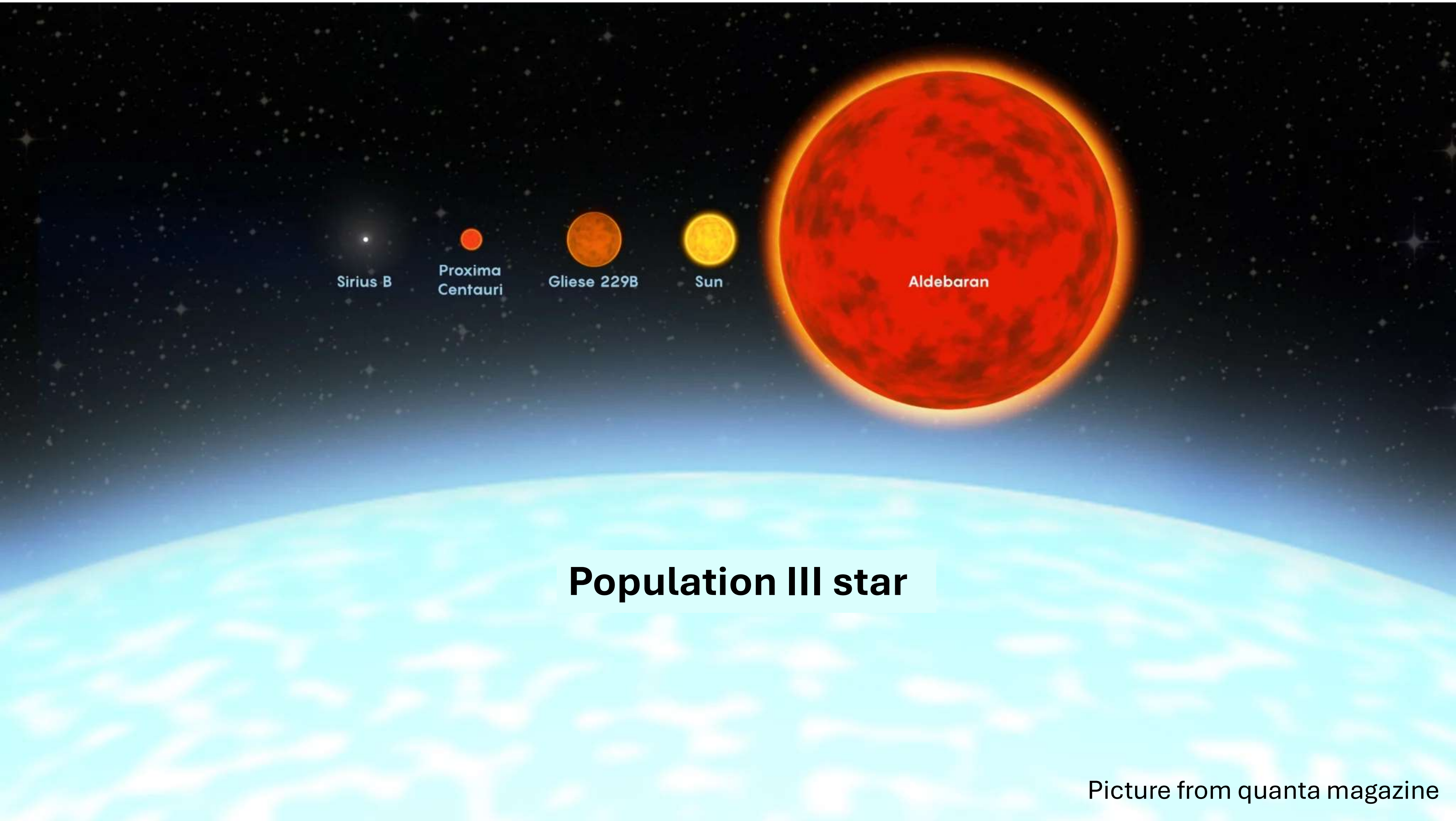
Dashed lines: power-law fits to subsets of data

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

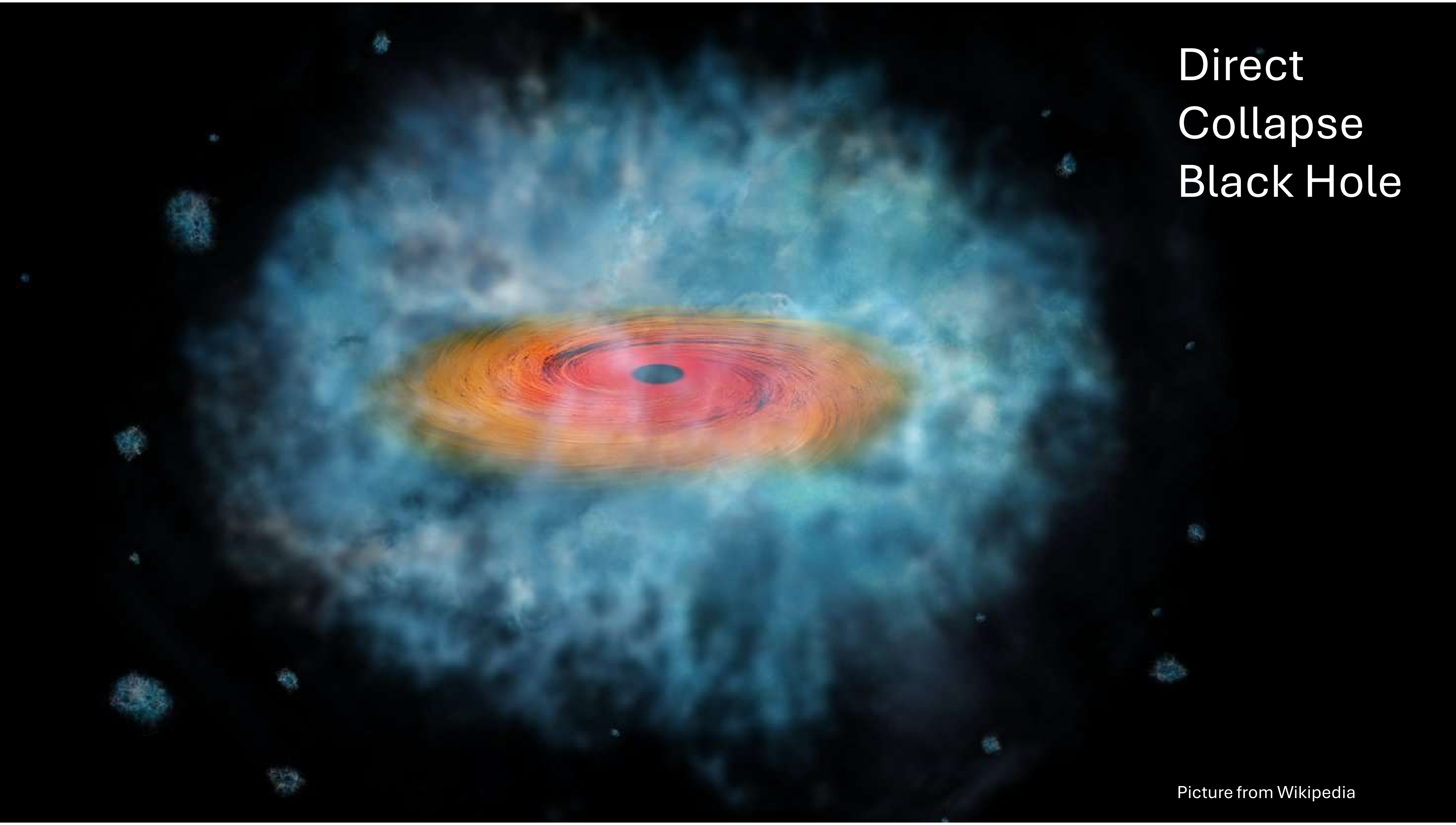
How to Make a Supermassive BH?

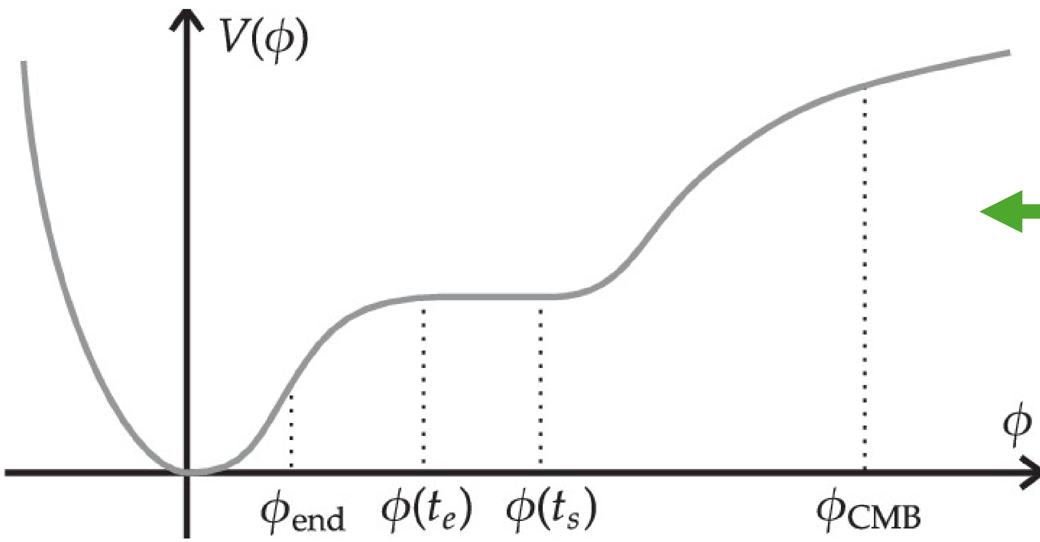
SMBHs from mergers of intermediate-mass BHs (IMBHs)?





Picture from quanta magazine

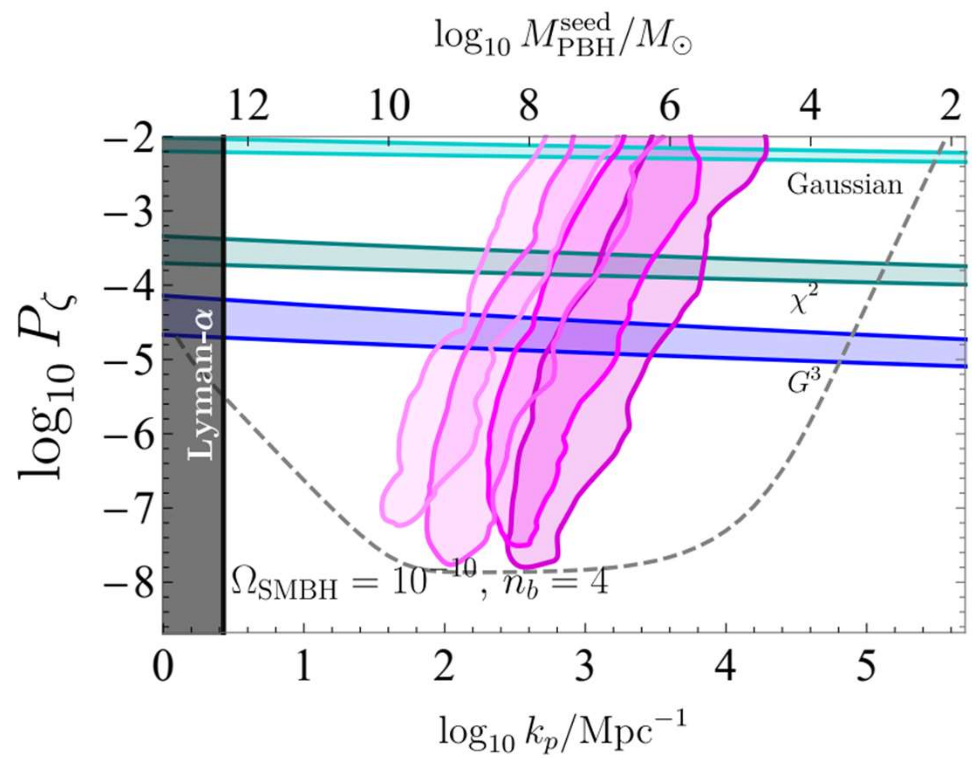

Direct
Collapse
Black Hole
Picture from Wikipedia



Kristiano and Yokoyama arXiv:2405.12149

Big black holes could also be produced conceivably during inflation

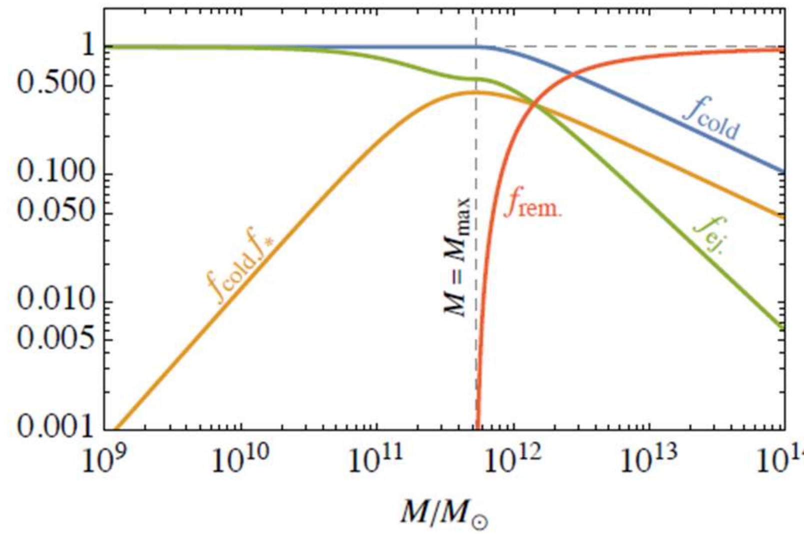
Strong constraints from things like the CMB and structure formation



Our paper 2408.11098

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



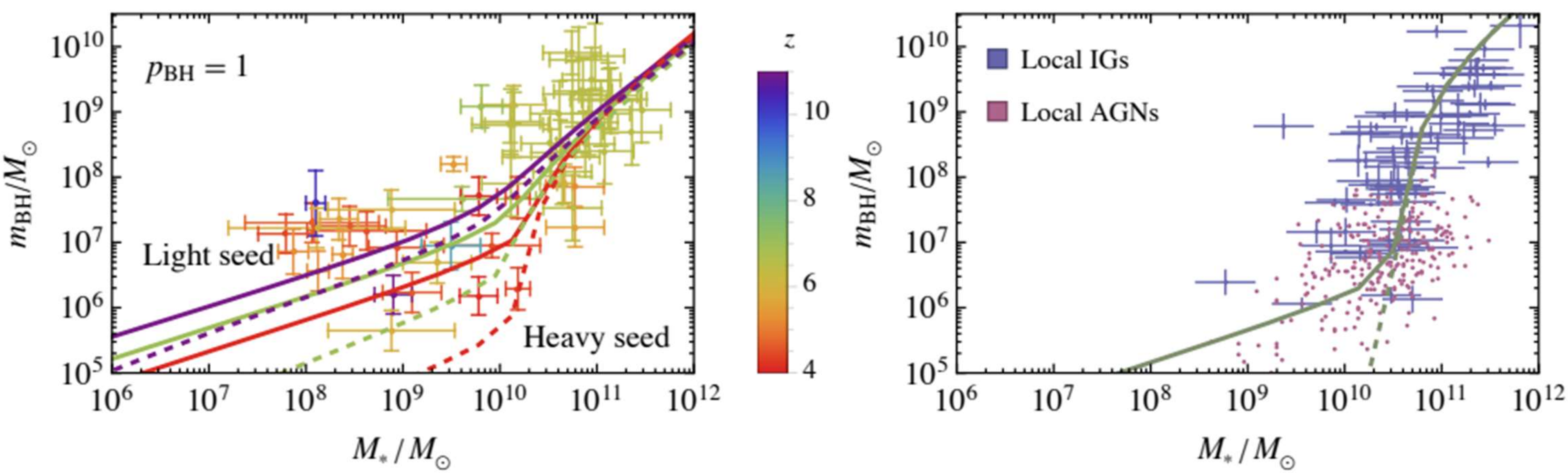
$f_{ej.}$ = cold gas fraction ejected from halo by SNe

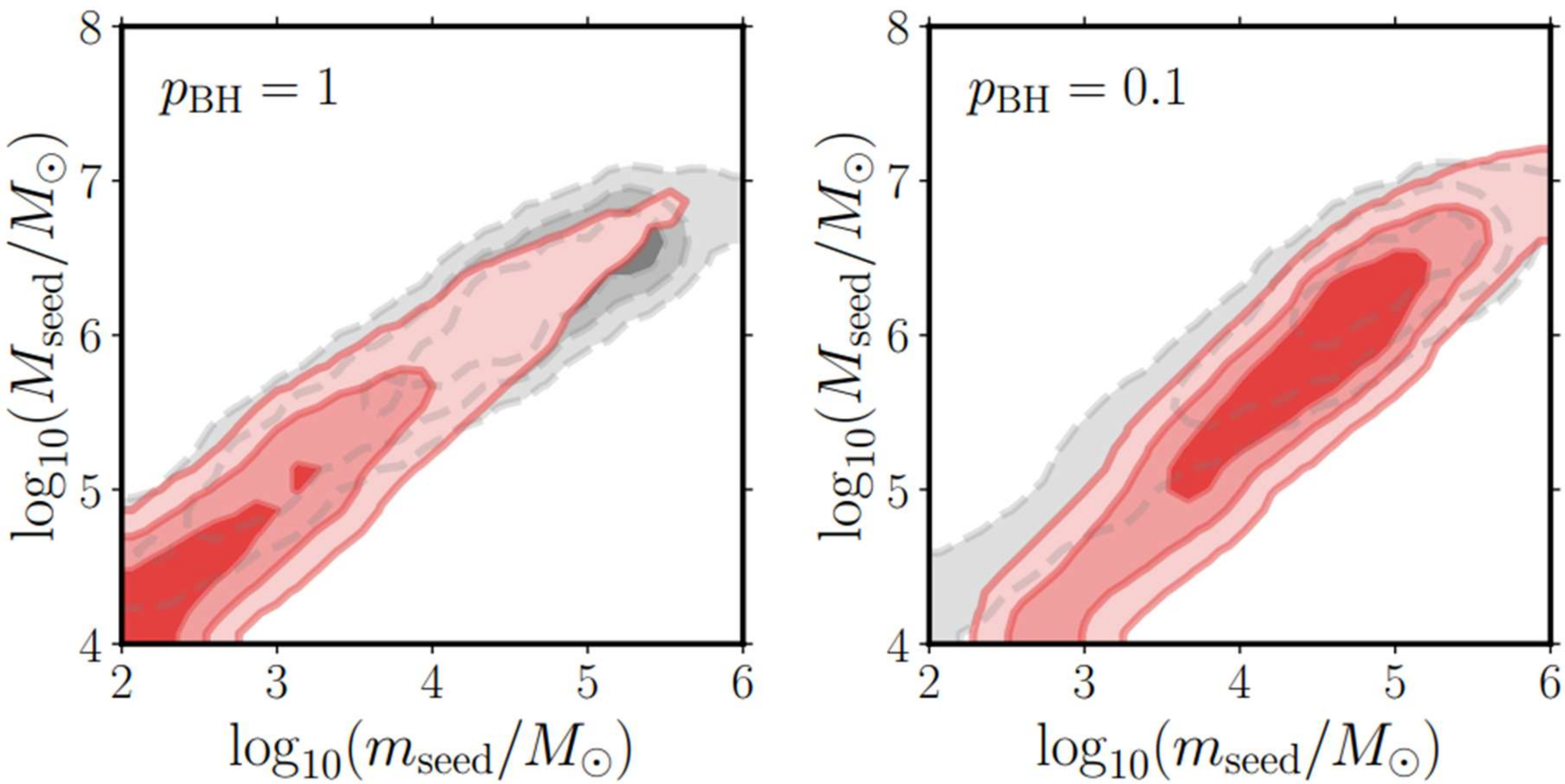
f_{cold} = fraction of remaining gas that is cold

$f_{rem.}$ = 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

- Search for dark matter goes on, including tests only sensitive to its gravitational effects.
- Gravitational waves can help us learn about BSM physics.
- Gravitational waves can also help us learn about black holes and Galaxies.
- New Data which is arriving all the time is amazing!


THANKS FOR LISTENING!
Have a fun and restful solstice and a happy, healthy and productive 2025!!!