PTA gravitational waves and JWST early galaxies: from Primordial Black Holes to Axion Clusters

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2023 was a great year for cosmo!

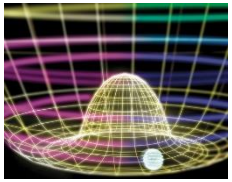
[Gouttenoire, ST, Valogiannis, Vanvlasselaer]
2307.01457

Spoiler Alert: HST has restricted New Physics!

Outline

I. Observations

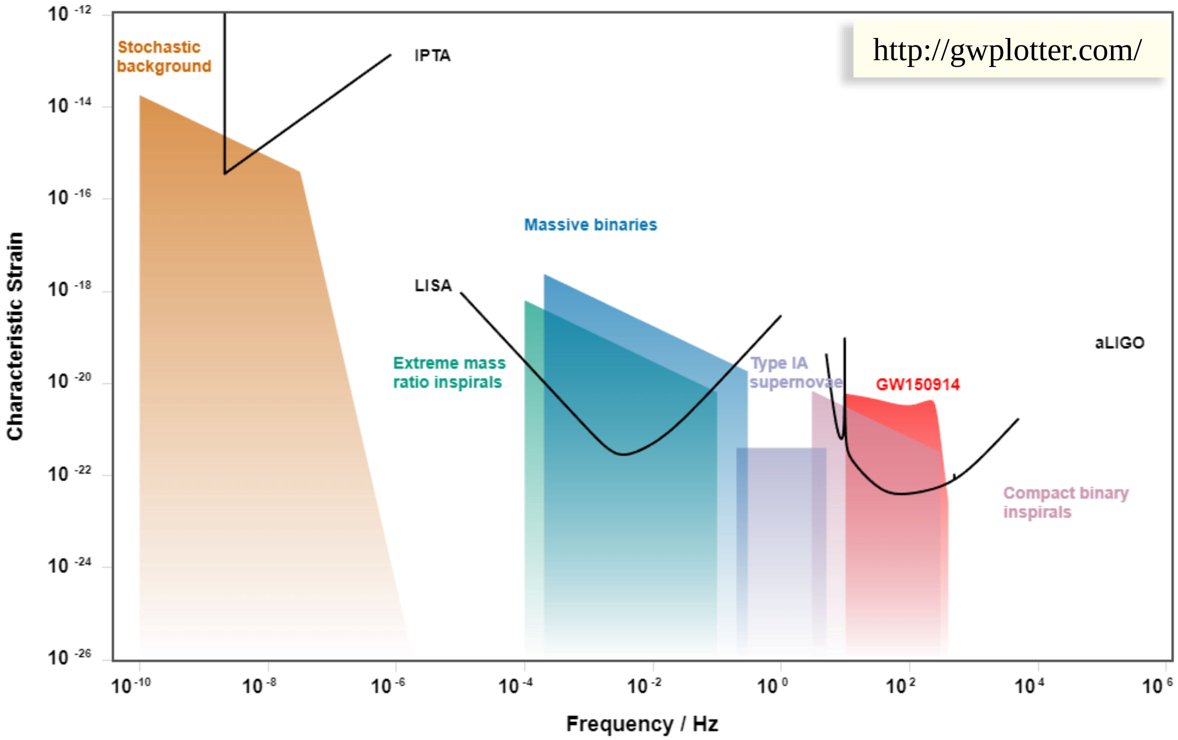
II. Primordial Black Holes



III. Axion Clusters

Observations of Gravitational Waves (GWs)

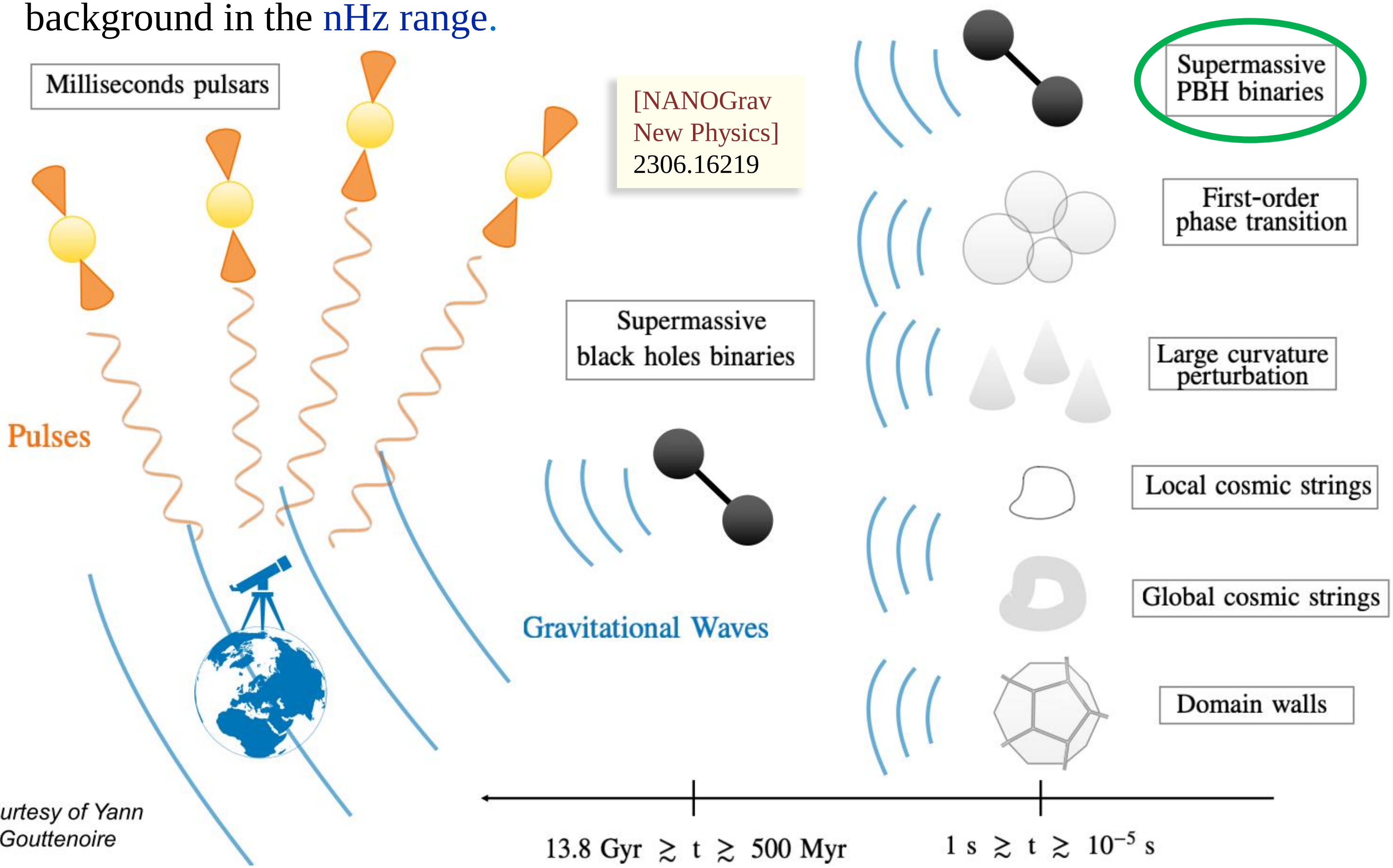
- GWs offer a new lens into the dynamics of the early universe.



http://gwplotter.com/

Pulsar Timing Arrays (PTAs)

- The NANOGrav combined with 4 PTA collaborations have recently released evidence for the existence of a stochastic Gravitational Wave (GW) background in the nHz range.

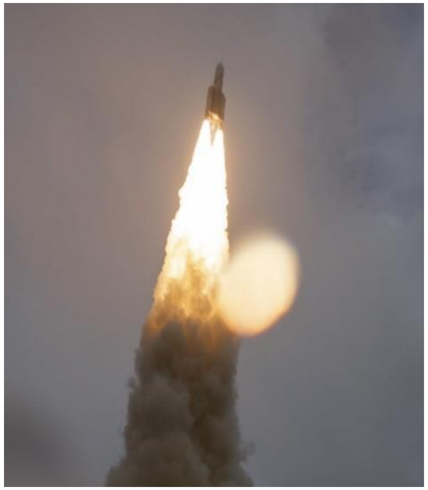


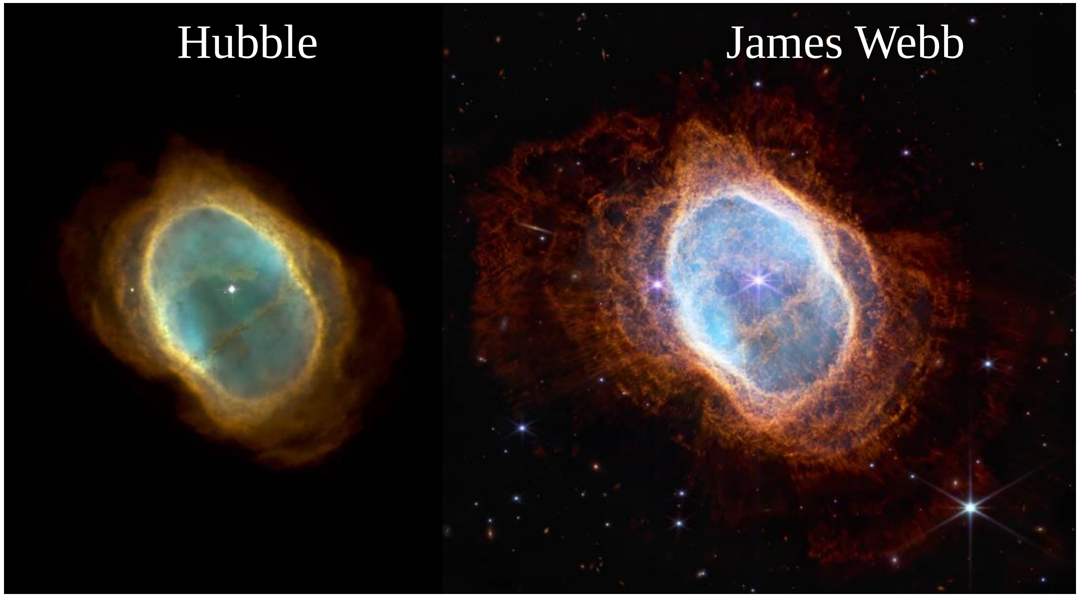
[NANOGrav New Physics] 2306.16219

Courtesy of Yann Gouttenoire

James Webb Space Telescope

- JWST launched and it is already collecting data!

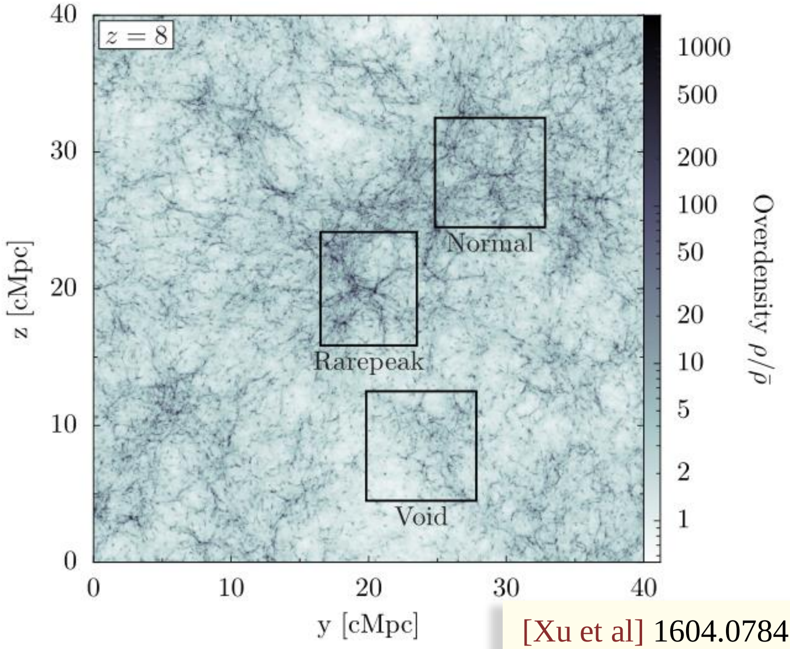




[STSI/NASA, ESA, CSA, STScI, Webb ERO] Southern Ring Nebula

JWST Early Massive Galaxies

- Initial observations (e.g. JADES & CEERs surveys) have reported photometric evidence of massive galaxies at unexpectedly high redshifts $7 < z < 12$. A large subset of them has been recently spectroscopically confirmed.



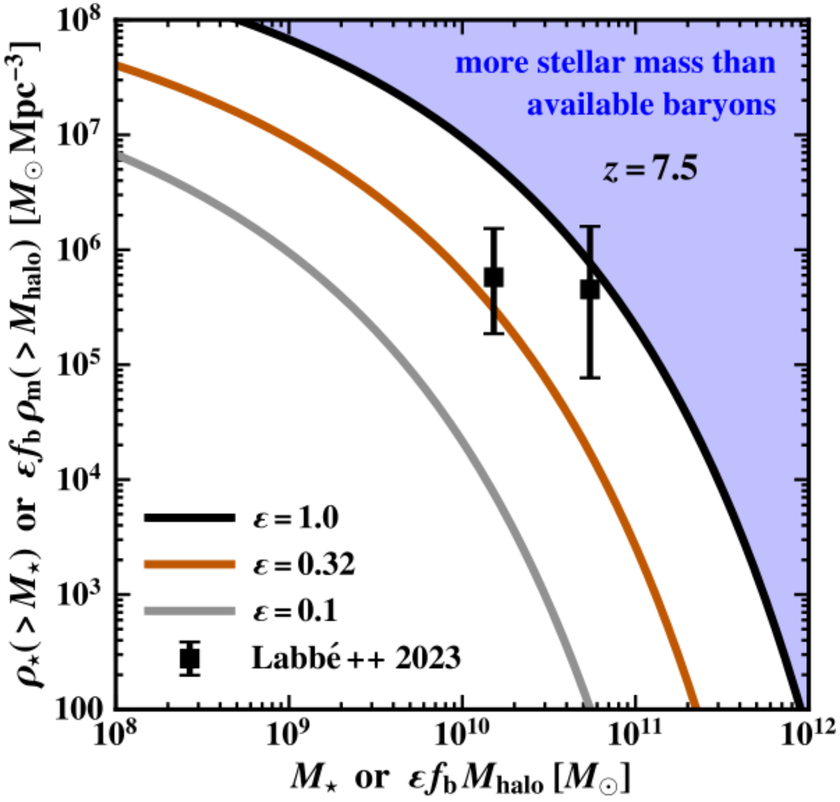
[Xu et al] 1604.07842

[Adams et al] 2207.11217, [Finkelstein et al] 2211.05792, [Naidu et al] 2207.09434

- Large cosmological hydrodynamical simulation demonstrated compatibility with existing models of galaxy formation.

[Keller et al] 2212.12804
[McCaffrey et al] 2304.13755

JWST Early Massive Galaxies: ΛCDM tension?



- ➢ The status of extreme galaxy candidates with stellar mass as high as 10^{11} $M_\odot$ still remains under investigation.

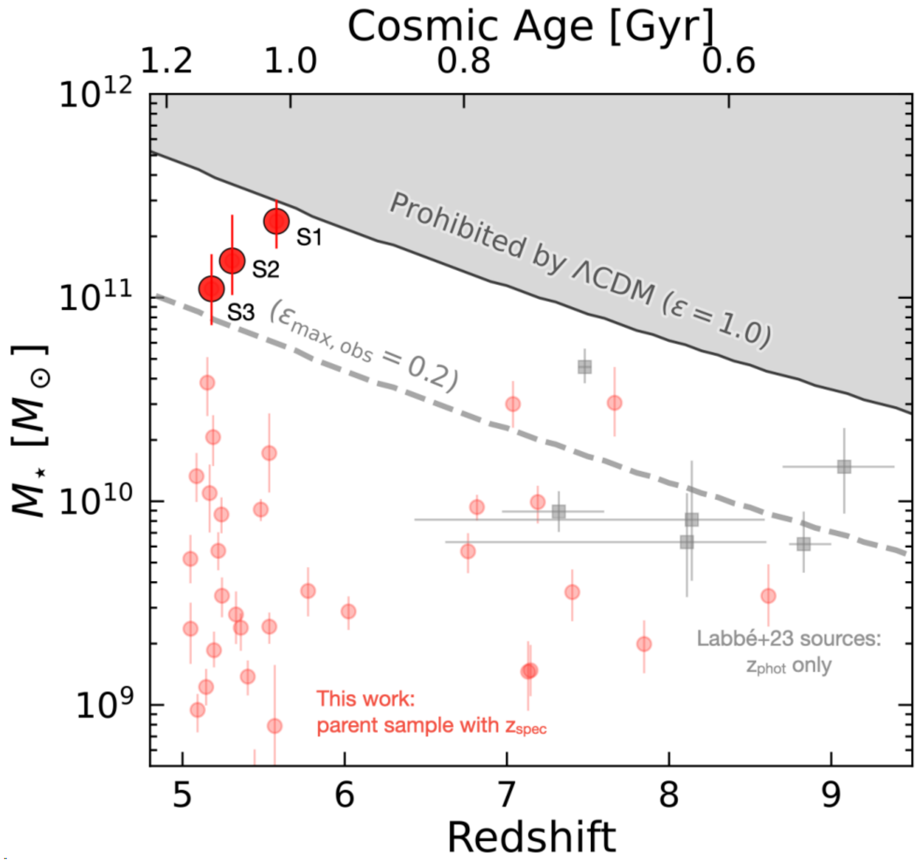
[Labbe et al] 2207.12446

- ➢ If those results hold under spectroscopic scrutiny, they would pose a challenge to ΛCDM itself. For $\varepsilon = 0.1$, the current tension amounts to **2.5-3σ** confidence level.

[Boylan-Kolchin] 2208.01611 [Lovell et al] 208.10479 [Wang, Liu,Lu] 2311.02866

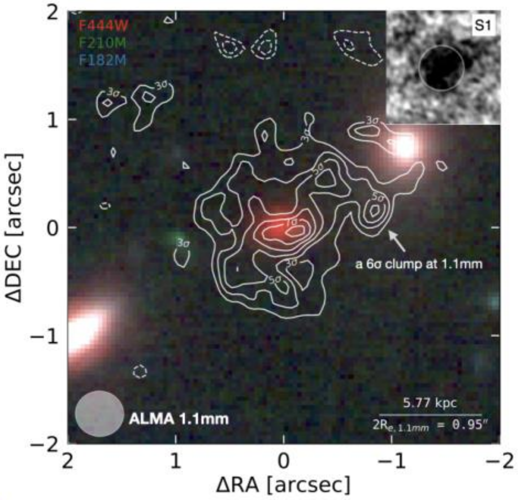
Sokratis Trifinopoulos

JWST Early Massive Galaxies: ΛCDM tension?



- ➢ A sample of 36 galaxies with robust spectroscopic redshifts at z~5-9 was announced by FRESCO survey.

[Xiao et al] 2309.02492



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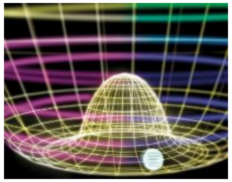
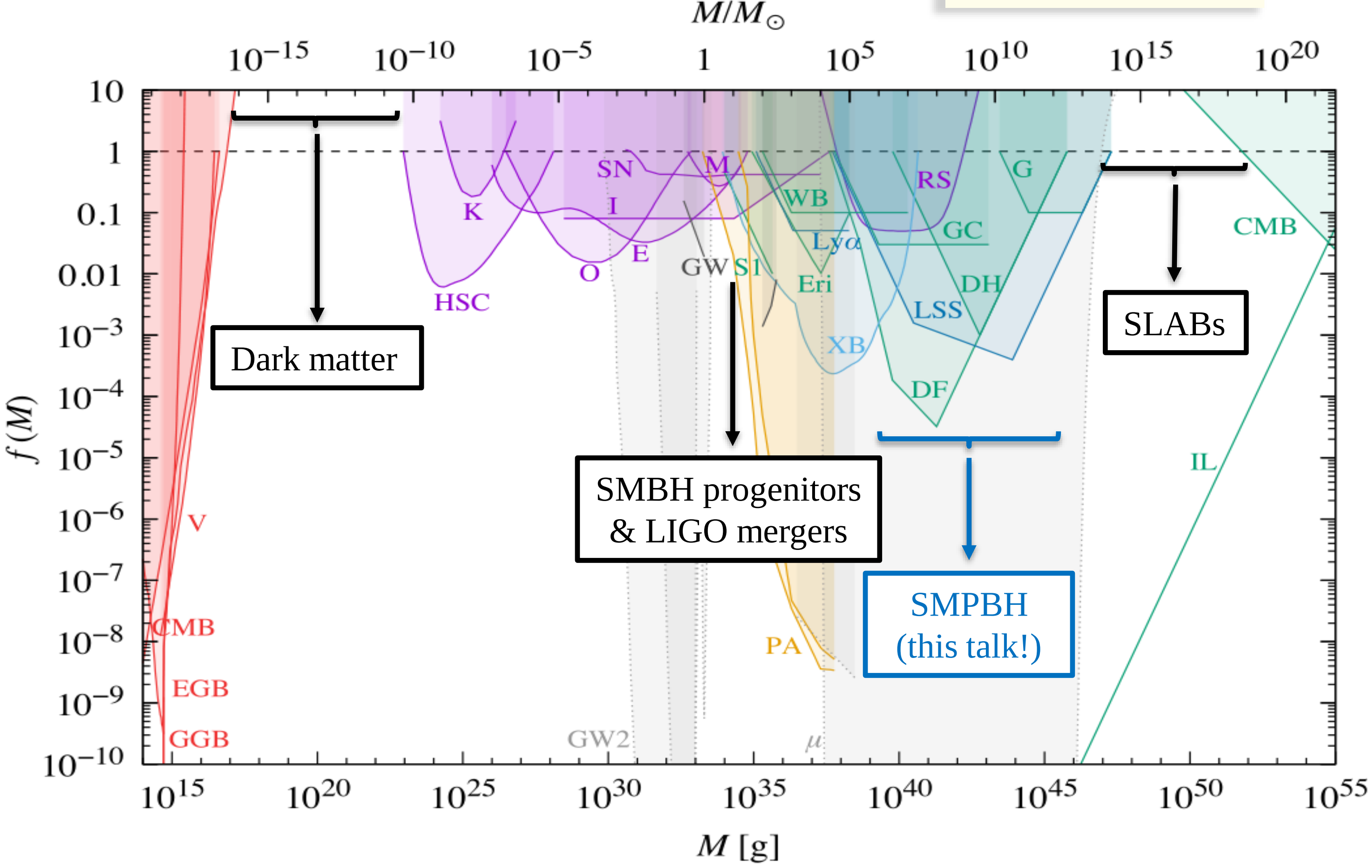


III. Axion Clusters

Primordial Black Holes (PBHs)

- PBHs emerge as one of the most long-studied scenarios, capable of leaving distinctive imprints on cosmic history.

[Carr et al] 2002.12778



Dark matter

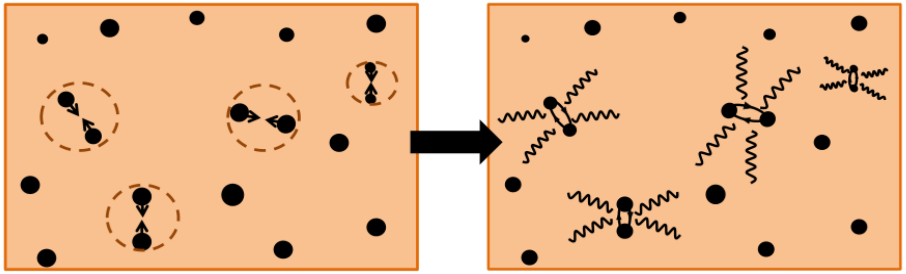
SMBH progenitors & LIGO mergers

SMPBH (this talk!)

SLABs

Early-Universe PBH binaries formation

- Immediately after their formation, PBHs are sparsely distributed in space.
- The mean separation between PBHs, $\bar{l}_{\mathrm{PBH}}\,(t) \propto t^{1/2}$, falls below the Hubble distance $H^{-1} \propto t$ before matter-radiation equality.
- A pair of PBH decouples from the expansion of the Universe and becomes gravitationally bound when $M_{\mathrm{PBH}} R^{-3} > \rho(z_{\mathrm{dec}})$.



[Sasaki et al]
[1801.05235]

- The two PBHs will orbit around each other and gradually shrink by gravitational radiation (***inspiral***). At later times when they are close enough they ***merge*** and eventually settle down to a stable form (***ring-down***).

Gravitational Waves from PBH Mergers

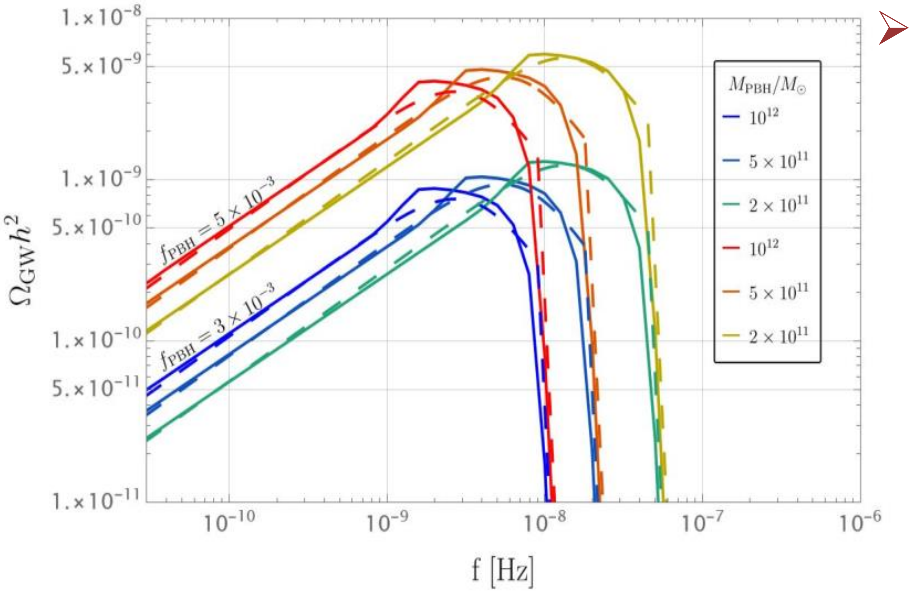
- The energy density of the stochastic GWs from PBH binaries reads

$$\Omega_{\rm GW}h^2 = \frac{f}{\rho_c/h^2}\int_0^\infty dz \frac{\mathcal{R}(z)}{(1+z)H(z)}\frac{dE_{\rm GW}(f')}{df'}\bigg|_{f'=(1+z)f}$$

[LIGO] 1602.03847

- We perform a full Bayesian analysis of the PTA signals.

[PTArcade] 2306.16377



- We include as priors:
  1) Environmental effects: At low frequencies, the assumption of GW-driven energy loss breaks down due to interactions with the environment.
  2) Continuous signal: At high frequencies, the number of sources per frequency bins can become $N(f,\Delta f) < 1$, and the assumption of a smooth distribution of sources breaks down.

Isocurvuture Perturbations: Poisson vs Seed

- On large scales, we expect $\rho_{\rm PBH}$ to follow the adiabatic perturbations $\delta_{\rm ad}$. However, on small enough scales, due to the discrete nature of PBHs an isocurvuture component $\delta^0_{\rm PBH}$ is generated. For a Poissonian gas of PBH the variance is $\left\langle \left| \delta^0_{\rm PBH}(k) \right|^2 \right\rangle = (\bar{n}_{\rm PBH})^{-1} = \frac{M_{\rm PBH}}{f_{\rm PBH}\rho_{\rm DM}}$.
- PBH bind gravitationally regions of mass $\widetilde{M}$ via two mechanisms:

[Carr, Silk] 1801.00672

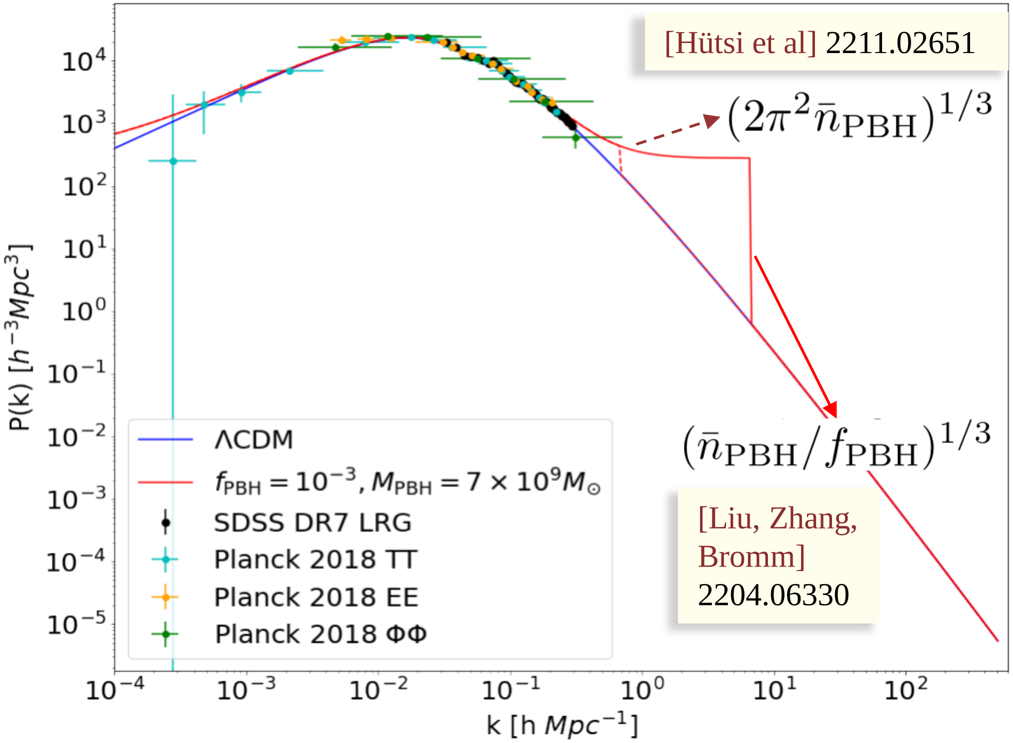
1. **Poisson Effect**: If $f_{\rm PBH} > \frac{M_{\rm PBH}}{\widetilde{M}}$ then the Poisson-distributed locations of the PBH introduce a shot noise in $\rho_{\rm DM}$, i.e.

$$\delta^0_{\rm DM} = \delta^0_{\rm ad} + f_{\rm PBH}\delta^0_{\rm PBH} \approx \sqrt{\frac{f_{\rm PBH}M_{\rm PBH}}{\widetilde{M}}}\,.$$

[Afshordi, McDonald, Spergel] astro-ph/0302035
[Inma, Ali-Haimoud] 1907.08129

2. **Seed Effect**: If $f_{PBH} < \frac{M_{\rm PBH}}{\widetilde{M}}$, evolve in isolation . They generate $\delta^0_{\rm PBH} = \frac{M_{\rm PBH}}{\widetilde{M}}$, which grow linearly and thus $\widetilde{M} \approx \frac{z}{z_{\rm eq}} M_{PBH}$.

Matter Power Spectrum (Poisson effect)



[Hütsi et al] 2211.02651

$(2\pi^2 \bar{n}_{\rm PBH})^{1/3}$

$(\bar{n}_{\rm PBH}/f_{\rm PBH})^{1/3}$

[Liu, Zhang, Bromm] 2204.06330

- The isocurvature perturbations induce modification of the <u>matter-power spectrum</u>:

$$P(k) = P_{\rm ad}(k) + P_{\rm iso}(k) \ ,$$

$$P_{\rm iso}(k) \simeq \begin{cases} \frac{(f_{\rm PBH} D(0))^2}{\bar{n}_{\rm PBH}} \ , & \text{if } k \leq k_{\rm cut} \\ 0 \ , & \text{otherwise} \end{cases}$$

where D(0) $\approx a/a_{\rm eq}$(at late times) is the growth factor.

Accelerated Galaxy Formation and JWST

1. **Poisson Effect:** We use modified Press-Schechter (PS) formalism to compute the halo mass function $n(M_h, z)$. Then the expected number density of galaxies is given by

$$n_{\rm gal}(M_\star \geq M_\star^{\rm obs}) = \int_{M_h^{\rm cut}}^{\infty} \frac{dn(z_{\rm obs}, M_h)}{dM_h} dM_h \ .$$

[Sheth & Tormen]
[astro-ph/9901122]

The JWST signature can be expressed as $n_{\rm gal}(M_* \geq 10^{10.8} M_\odot) \simeq 10^{-5}{\rm Mpc}^{-3}$ at $z_{\rm obs} \sim 8$.

2. **Seed Effect:** Due to its highly non-linear nature, this effect can be examined properly only using simulations. We can still determine the part of the parameter space compatible with JWST by requiring: i) $f_{\rm PBH} < M_{\rm PBH}/\widetilde{M}$, ii) $\bar{n}_{\rm PBH} \geq 10^{-5}{\rm Mpc}^{-3}$, iii) $\widetilde{M}(M_{\rm PBH}, z_{\rm obs}) \geq M_h\left(M_* \sim 10^{11} M_\odot\right)$.

[Liu, Zhang, Bromm] 2204.06330

Observational Constraints

- **CMB μ distortion:** The PBH formation from large-amplitude Gaussian primordial fluctuations leaves imprints in the CMB, strictly constraint by COBE/FIRAS.

[Nakama et al] 1609.02245

Large non-Gaussianities (NGs) :

$p = 2$: Gaussian

$$P(\zeta) = \frac{1}{2\sqrt{2}\tilde{\sigma}\Gamma\left(1+1/p\right)} \exp\left[-\left(\frac{|\zeta|}{\sqrt{2}\tilde{\sigma}}\right)^{p}\right]$$

- **Large-scale structure (LSS):** The non-observation of different types of cosmic structures can be used to constrain population of PBHs.

$$\widetilde{M} < \begin{cases} 10^{10} M_{\odot} \text{ at } z \sim 7 \text{ (dwarf galaxies)} \\ 10^{12} M_{\odot} \text{ at } z \sim 3 \text{ (MW-type galaxies)} \\ 10^{14} M_{\odot} \text{ at } z \sim 1 \text{ (galaxy clusters)} \end{cases}$$

[Carr et al] 1801.00672

- **Lyman-α forest:** sensitive to modifications to the PS at scales $0.1 < k$ Mpc < 10. The most recent bounds yield $f_{PBH} M_{\mathrm{PBH}} < 170 M_{\odot}$ ($M_{\mathrm{PBH}} < 10^{5} M_{\odot}$).

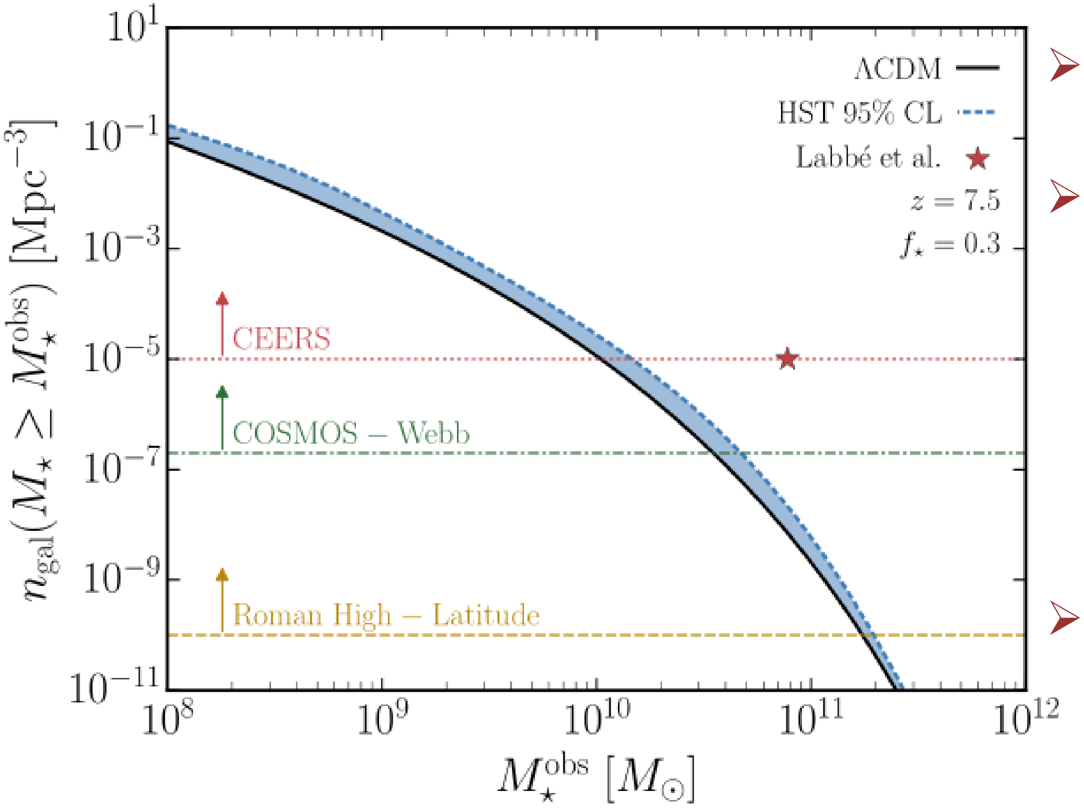
[Murgia et al] 1903.10509

[Ivanov, Toomey, ST] TBA

improve the Ly-α bound!

Ultraviolet Luminosity Function (UV LF)

Novel!



- Young massive stars emit in the ultraviolet.
- The Hubble Space Telescope (HST) has already probed the range $7 < z < 10$ via the UV LF:

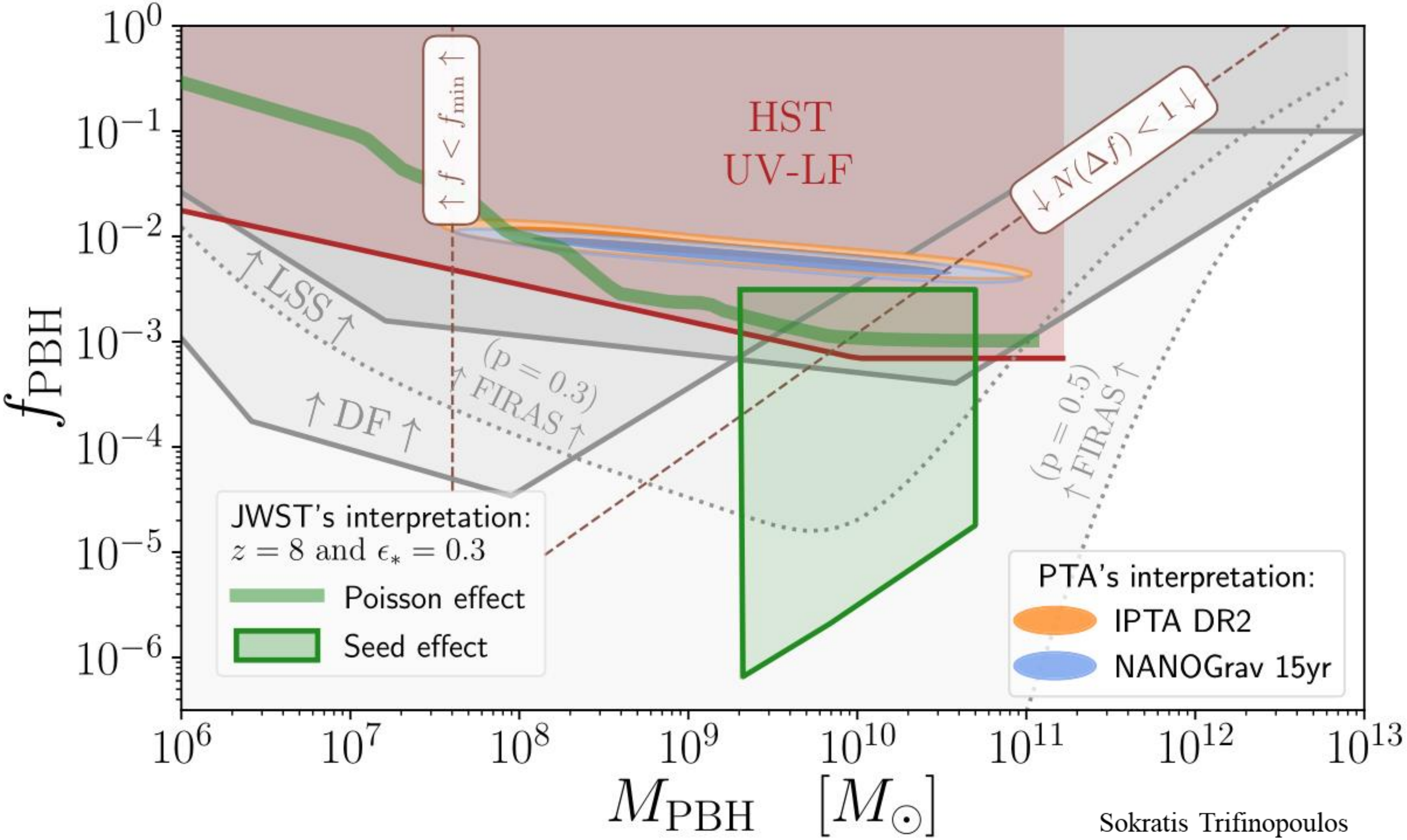
$$\Phi_{\rm UV} = \underbrace{\frac{\mathrm{d}n}{\mathrm{d}M_{\rm h}}}_{\text{cosmology}} \times \underbrace{\frac{\mathrm{d}M_{\rm h}}{\mathrm{d}M_{\rm UV}}}_{\text{astrophysics}}$$

- A cosmological solution to the JWST anomaly is disfavored.

[Sabti, Munoz, Kamionkowski] 2305.07049,
[Sabti, Munoz, Blas] 2110.13161

PBH parameter space

[Gouttenoire, ST, Valogiannis, Vanvlasselaer] 2307.01457



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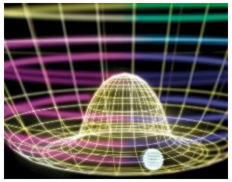
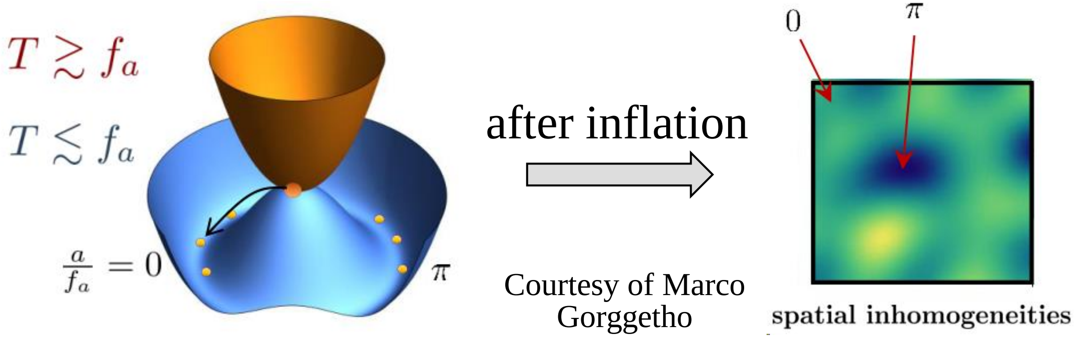


III. Axion Clusters

[Gorghetto, Foster ST, Valogiannis] TBA

Post-inflationary axions

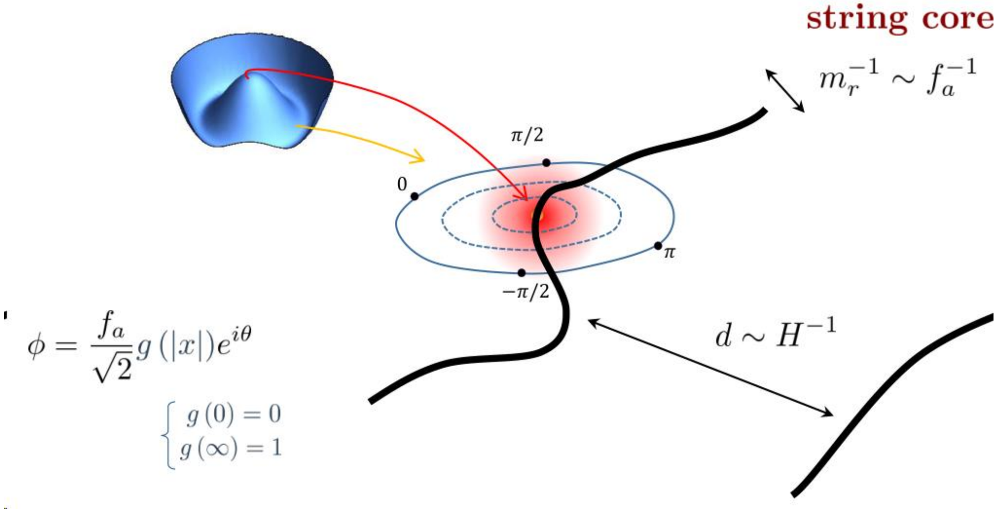
- **Axion**: Goldstone boson of a spontaneously broken global $U(1)_{\mathrm{PQ}}$ symmetry at scale f_a: $\varphi = \frac{1}{\sqrt{2}}(r + f_a)e^{i\frac{a}{f_a}}$.
- $U(1)_{\mathrm{PQ}}$ is also explicitly broken at scale $\Lambda \ll f_a$ by non-perturbative effects that generate a periodic potential and the axion mass $m_a \approx \Lambda^2/f_a$.
- The initial conditions for the axion field are inhomogeneous if $T_{\mathrm{RH}} > f_a$ (thermal fluctuations) or $H_I > f_a$ (quantum inflationary fluctuations):



Courtesy of Marco Gorggetho

Axion Strings

- The e.o.m. of φ admit in this case non-trivial solutions: **axion strings.**

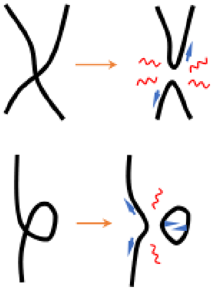


[Gorghetto, Hardy, Nicolaescu] 2101.11007

- The strings contain energy which is proportional to

$$\mu = \pi f_a^2 \log \frac{m_r}{H}.$$

- When they interact with other strings they can release energy in the form of axion radiation.



- The string network reaches an attractor solution (scaling regime), in which the number of strings per Hubble patch remains constant.

Isocurvature perturbations: Axion Clusters

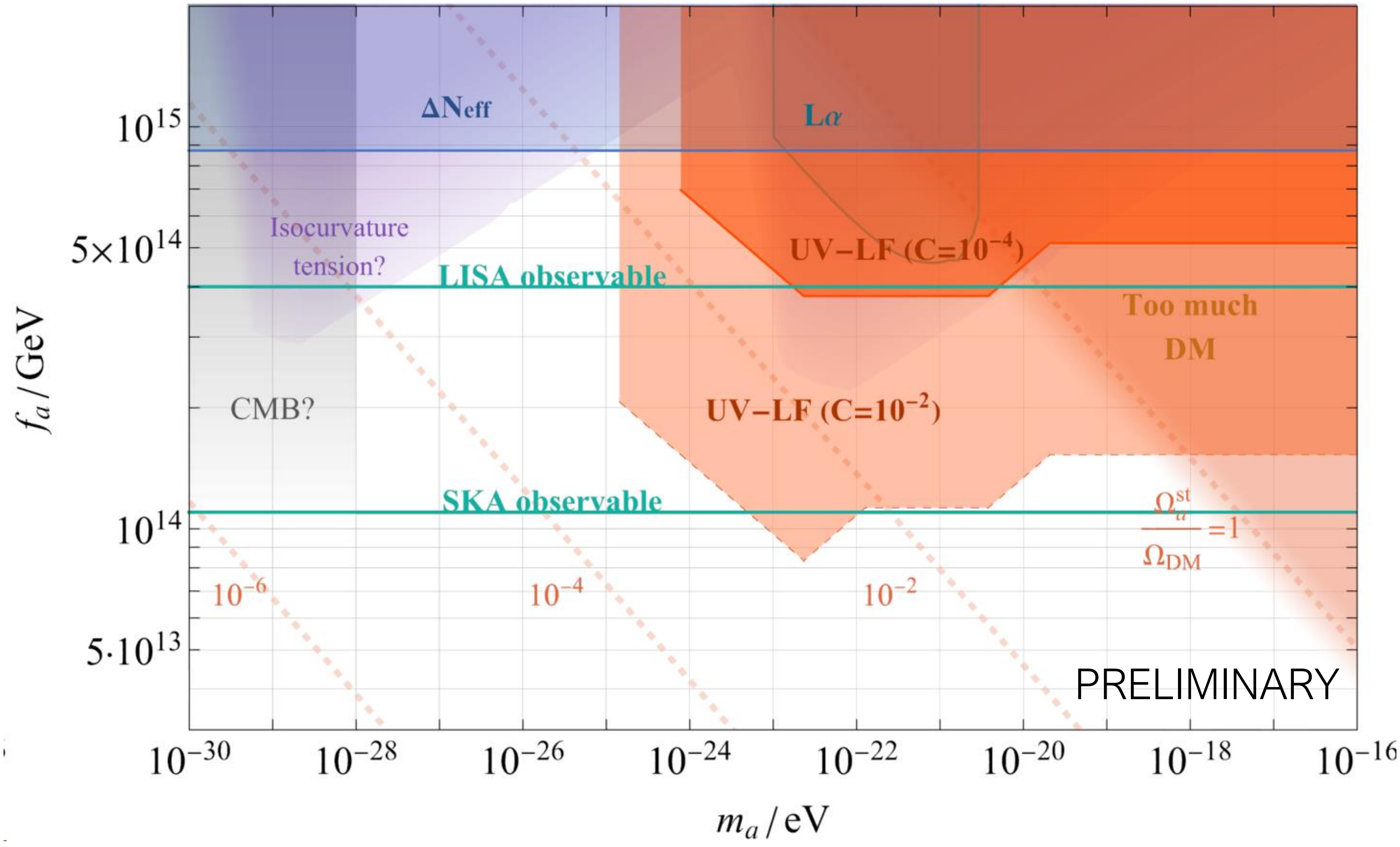
- The scaling regime is maintained by axion radiation and GW energy emission.
- When the Hubble scale is $H_* \sim m_a$, **domain walls** bounded by the strings form and subsequently annihilate rendering the network unstable.
- Inhomogeneities in the axion field develop during this period that lead to the formation of ACs of mass $M_{\mathrm{AC}} \propto \rho_a k_*^{-3}$, where $k_* \propto f_{\mathrm{AC}}^{1/4} m_a^{1/2}$.
- They correspond to isocurvature perturbations of the form:

$$P_{\mathrm{iso}}(k) \simeq \begin{cases} 2\pi^2 C (f_{\mathrm{AC}} D(0))^2 / k_*^3 \,, & \text{if } k \leq k_* \\ 0 \,, & \text{otherwise} \end{cases}$$

[Buschmann, Foster, Safdi] 1906.00967
[O;Hare, Perobon, Redondo,Wong] 2112.05117

- Similarly to PBH, LSS constraints are imposed due to the accelerated structure formation induced by the AC seeds.

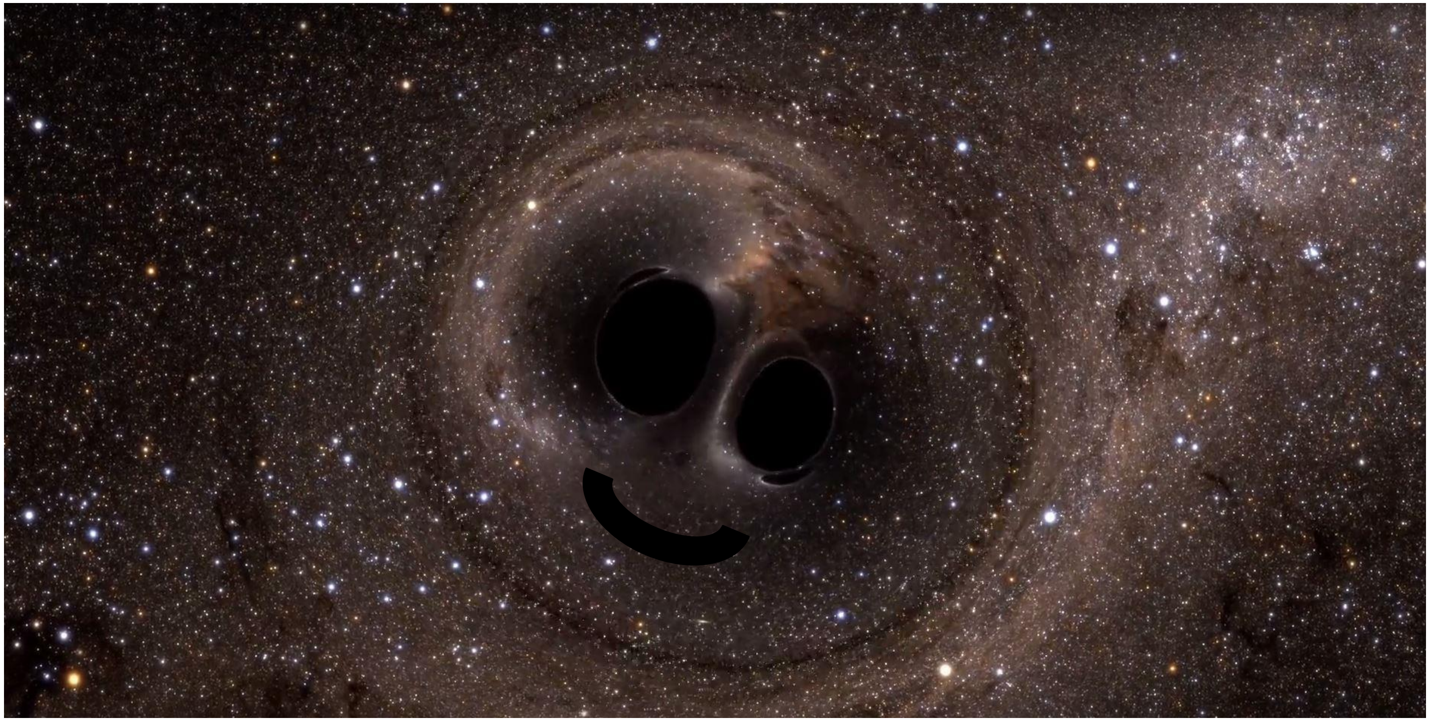
Ultra-light axion parameter space



Conclusions & Future Outlook

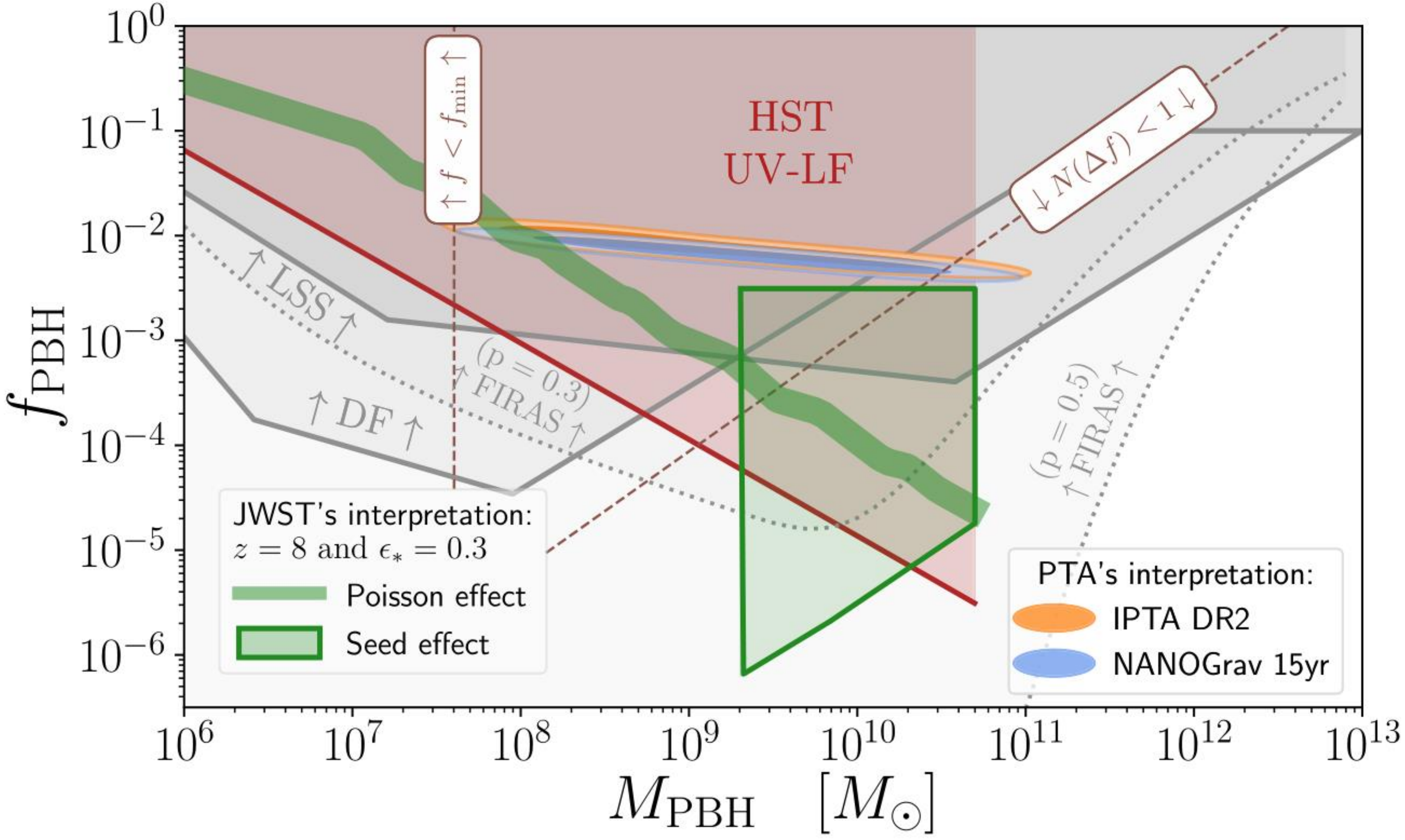
- We explore for the first time a common explanation of the PTA gravitational waves signal and the JWST early galaxies observations.
- The PBH populations needed to source the PTA GW signal are partly excluded by LSS and decisively excluded by the UV LF constraint.
- The PBH and ACs interpretations of the JWST extreme galaxies with the **Poisson** effect is excluded due to UV LF, while the one based on PBH **seed** effect is in principle still viable for $f_{\mathrm{PBH}} < 10^{-3}$ (needs very large NGs).
- A spectroscopic analysis will provide the final verdict on whether the JWST observations constitute a ΛCDM anomaly.
- Future increase in observation time of PTAs and in number of detected pulsars might facilitate the resolution of individual sources at larger frequencies and thus enable the more careful examination of NP scenarios.

Thank you!!!!



Backup slides

PBH parameter space



Spectroscopy vs Photometry

Method	Advantages	Disantvantages
Spectroscopy: record the intensity of dispersed light vs wavelength.	✓ excellent discrimination between wavelengths ✓ individual spectral features	✗ difficult to obtain multiple spectra due to wide range of speading over the detector
Photometry: record images of the source light after allowing it to pass through colored filters.	✓ better signal-to-noise ratios (fainter objects reachable) ✓ examine thousands of sources simultaneously	✗ effective wavelength resolution is limited by the filter bandpass ✗ no individual spectral features

GW Energy Density Spectrum

- We employ a power broken-law and we truncate the frequency at the end of the ring-down phase:

$$\Omega_{\rm GW}h^2 \simeq \Omega_{\rm peak}S(f)\Theta(2f_{\rm peak}-f)\ ,\quad S(f)=\frac{f_{\rm peak}^b f^a}{\left(bf^{\frac{a+b}{c}}+af_{\rm peak}^{\frac{a+b}{c}}\right)^c}$$

- The peak amplitude and frequencies are:

$$\Omega_{\rm peak}\simeq 0.05 f_{\rm PBH}^3\left(1.5\frac{M_{\rm PBH}}{10^{12}M_\odot}\right)^{-0.3}\ ,\ f_{\rm peak}\simeq 5000M_\odot/M_{\rm PBH}$$

- Due to environmental effects, we discard frequencies below:

$$f_{\rm min}=\left(\frac{T_{\rm max}}{\delta_2}\right)^{-\frac{3}{8}},$$

and to ensure that the signal is stochastic, high frequencies that yield

$$N(f,\Delta f)=\int_{f_0-\Delta f/2}^{f_0+\Delta f/2}\frac{df}{f}\int_0^\infty dz\,\frac{4\pi d_c^2(z)}{H(z)}R(z)\tau_r < 1$$

CMB μ distortion

- PBH form when large-amplitude primordial fluctuations ζ undergo spherical gravitational collapse upon horizon reentry. We may parametrize the ζ PDF as:

$p = 2$: Gaussian

$$P(\zeta) = \frac{1}{2\sqrt{2}\tilde{\sigma}\Gamma\left(1+1/p\right)} \exp\left[-\left(\frac{|\zeta|}{\sqrt{2}\tilde{\sigma}}\right)^{p}\right]$$

[Nakama Suyama, Yokoyama] 1609.02245
[Hooper, Ireland, Krnjaic, Stebbins] 2308.00756

- Fluctuations that dissipate via Silk damping during the photon diffusion scale, $5 \times 10^4 < z < 2 \times 10^6$, inject energy in the photon bath and modify the number of photons w.r.t. the black-body equilibrium.

- Let us consider a sharp feature $\Delta\mathcal{P}_\zeta = 2\pi^2\sigma^2 k^{-2}\delta(k - k_\delta)$, the weighted total energy release μ is strictly constrained by COBE/FIRAS:

$$\mu \simeq 2.2\sigma^2\left[\exp\left(-\frac{\hat{k}_\delta}{5400}\right) - \exp\left(-\left[\frac{\hat{k}_\delta}{31.6}\right]^2\right)\right] < 4.7\times10^{-5}$$

Solution: Large NGs $p < 0.3$

[Chubla, Erickcek,Ben-Dayan] 1203.2681