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

[Gouttenoire, ST, Valogiannis, Vanvlasselaer] 2307.01457

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Invisibles, Göttingen
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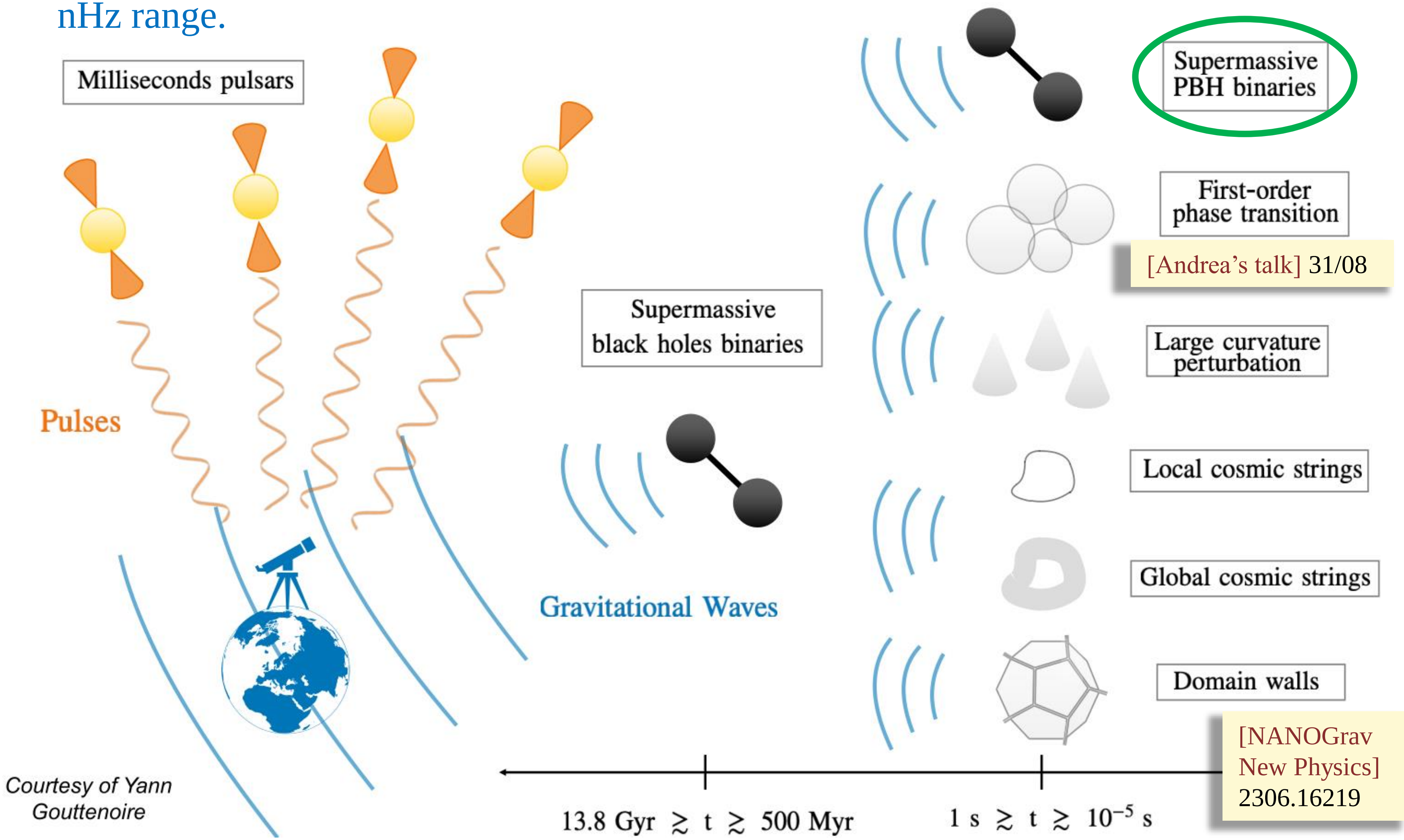
[Gorghetto, ST, Valogiannis] TBA

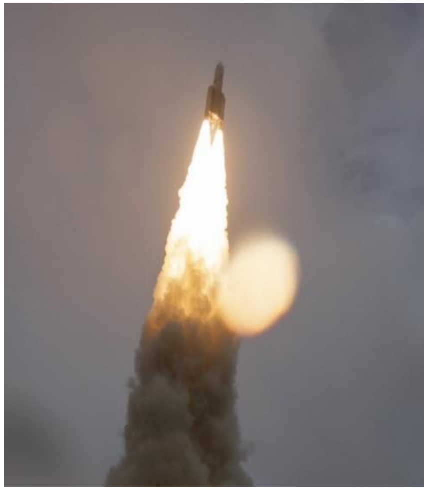
Pulsar Timing Arrays (PTAs)

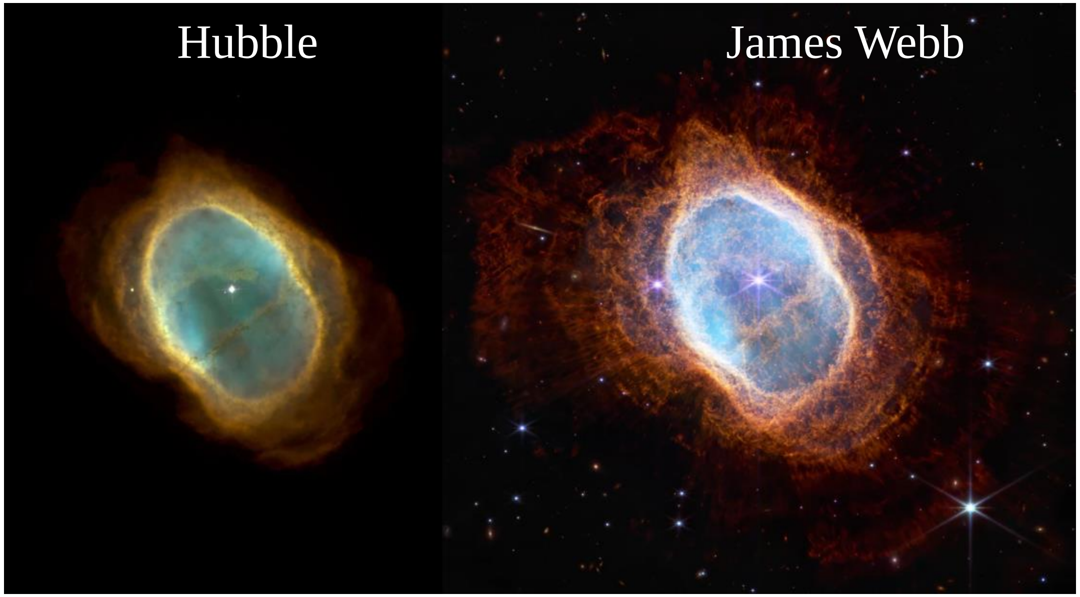
- The NANOGrav combined with PTAs have recently released evidence for the existence of a Gravitational Wave (GW) stochastic background in the nHz range.



James Webb Space Telescope

- JWST launched and it is already collecting data!



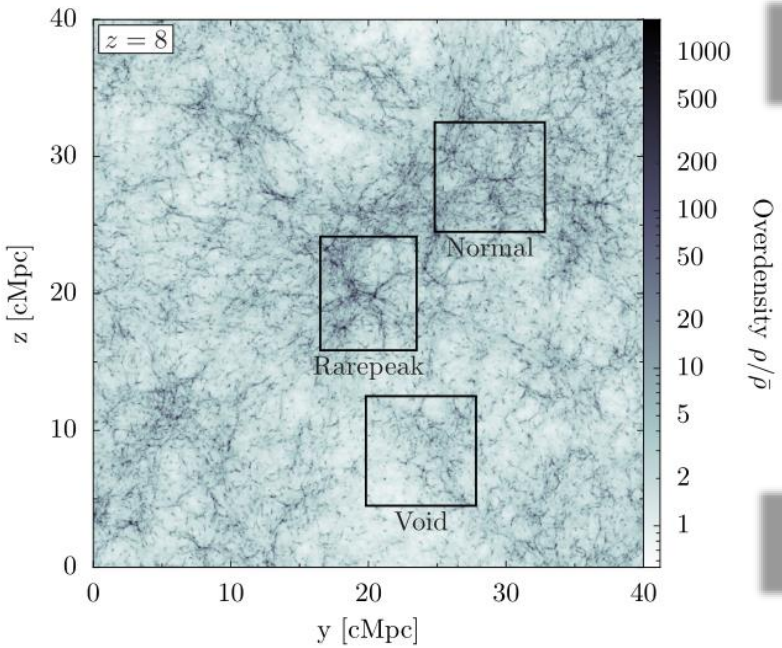


[STSI/NASA, ESA, CSA, STScI, Webb ERO] Southern Ring Nebula

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.

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



[Xu et al] 1604.07842

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

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

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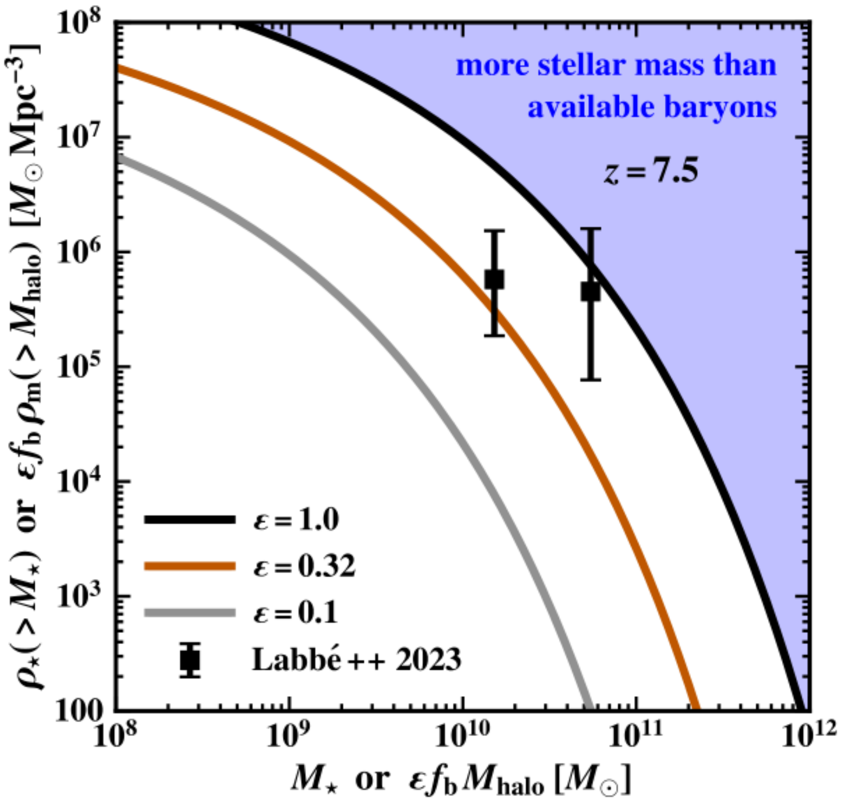
JWST Early Massive Galaxies: ΛCDM tension?



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

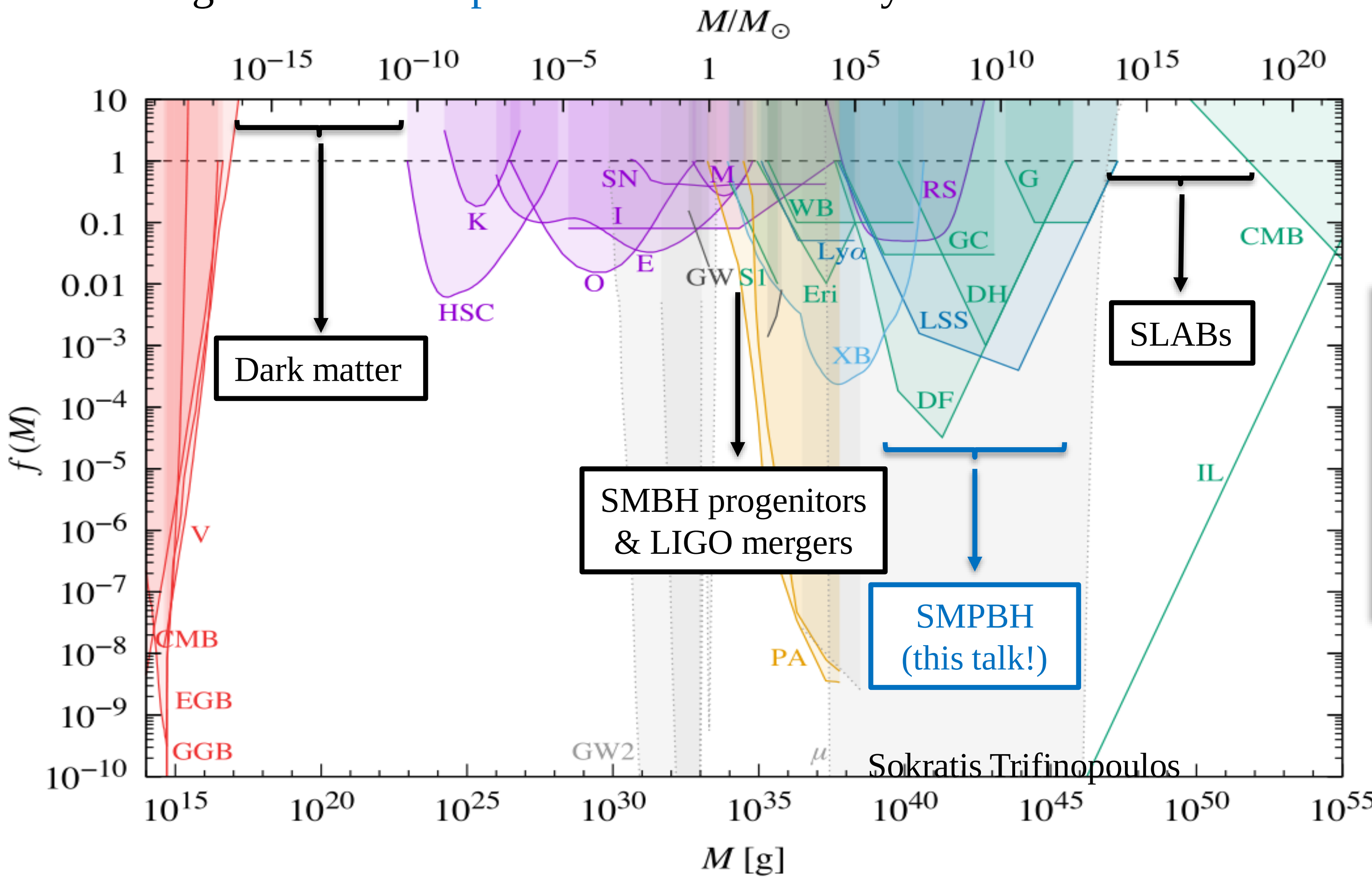
  [Labbe et al] 2207.12446

- If those results hold under spectroscopic scrutiny, they would pose a major challenge to ΛCDM itself.

  [Boylan-Kolchin] 2208.01611
  [Lovell et al] 2208.01611

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

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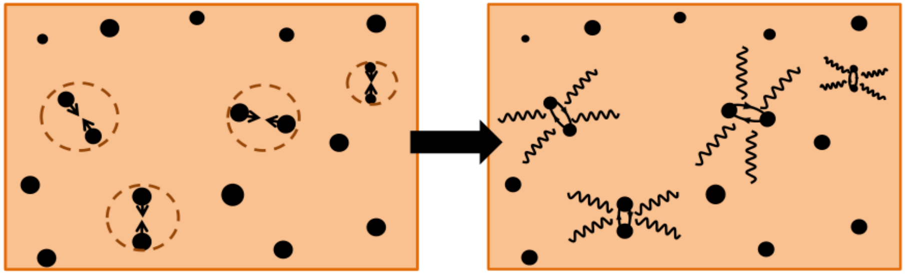
Early-Universe PBH binaries formation

- 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***).

Graviational Waves from PBH Mergers

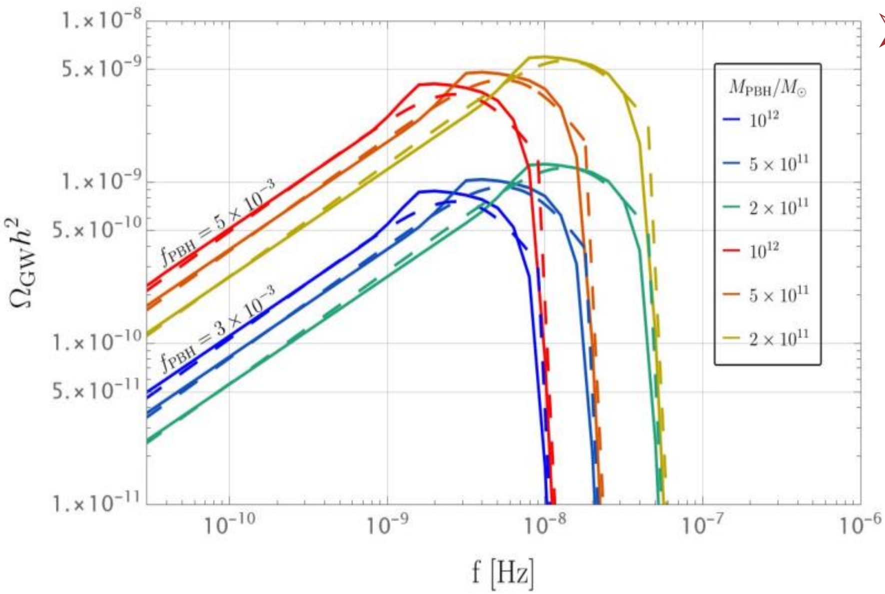
- The energy density of the stochastic GWs from PBH binaries reads

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

[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.

PBH isocurvature perturbations

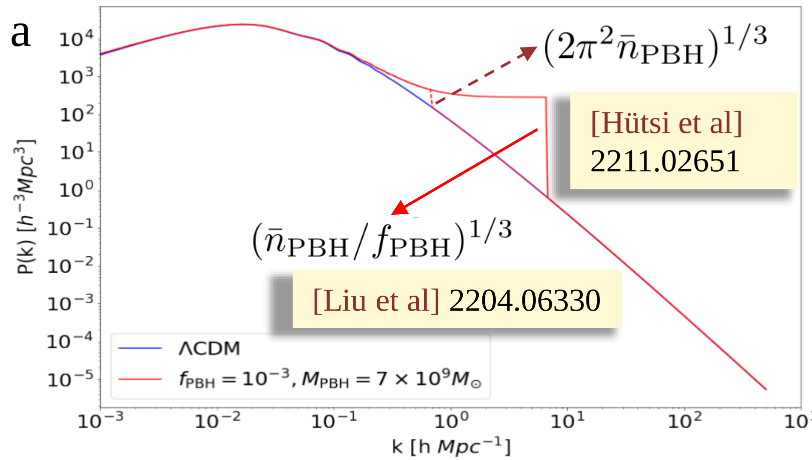
There are two different effects that can influence structure formation.

[Carr et al] 1801.00672

1. **Poisson Effect:** If $f_{\rm PBH} > M_{\rm PBH}/\widetilde{M}$, then PBHs generate the isocurvature perturbations $\delta_{{\rm PBH},i} = \left(f_{\rm PBH} M_{\rm PBH}/\widetilde{M}\right)^{1/2}$. The evolve linearly right after matter-radiation equality and result in a modification of the matter-power spectrum:

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

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



2. **Seed Effect:** PBH evolve in isolation ($f_{\rm PBH} < M_{\rm PBH}/\widetilde{M}$) and generate $\delta_{{\rm PBH},i} = M_{\rm PBH}/\widetilde{M}$. The mass of the bound region is then $\widetilde{M} \approx \frac{z+1}{z_{\rm eq}+1} M_{\rm PBH}$.

Enhanced Structure Formation

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) $\widetilde{M}(M_{\rm PBH}, z_{\rm obs}) \geq M_h(M_* \sim 10^{11} M_\odot)$.

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

$p = 2$: Gaussian

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

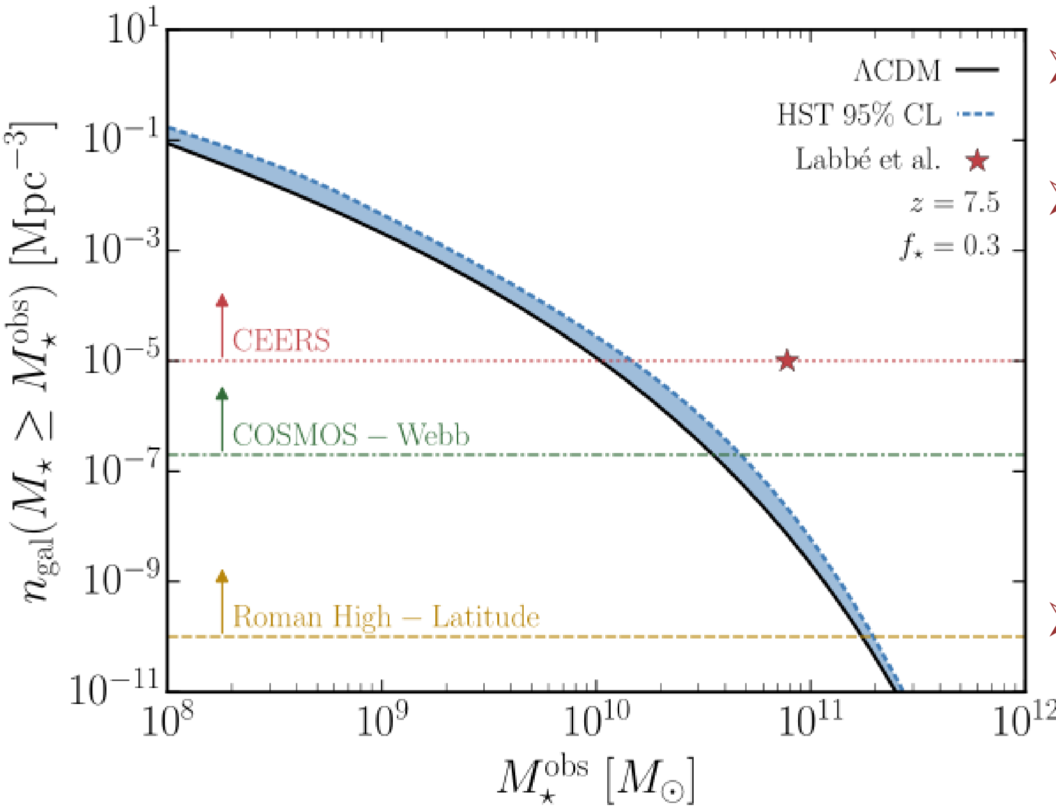
$$\widetilde{M} < \begin{cases} 10^{10} M_\odot \text{ at } z \sim 7 \text{ (dwarf galaxies)} \\ 10^{12} M_\odot \text{ at } z \sim 3 \text{ (MW-type galaxies)} \\ 10^{14} M_\odot \text{ at } z \sim 1 \text{ (galaxy clusters)} \end{cases}$$

[Carr et al] 1801.00672

- **Dynamical Friction (DF):** BHs accumulate in the center of galactic nuclei and thus if superheavy and populous they would merge to form too heavy BHs.

[Carr & Sakellariadou] A. J. 516(1999) 195–220

Ultraviolet Luminosity Function (UV LF)



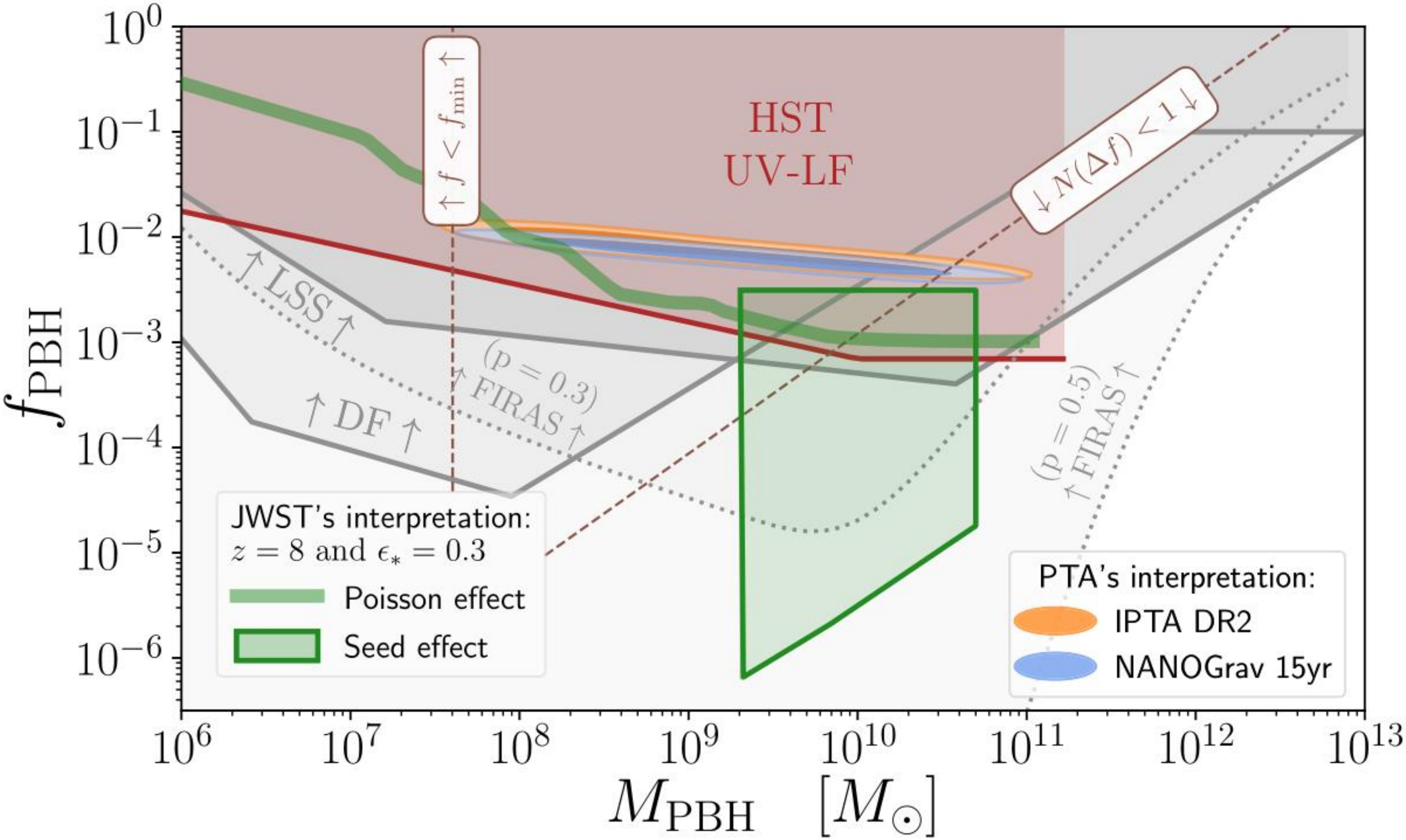
- Young massive stars emit in the ultraviolet.
- The Hubble Space Telescope (HST) has already probed the range $7 < z < 10$ via the UV LF:

$$\Phi_{\rm UV} = \underbrace{\frac{dn}{dM_{\rm h}}}_{\text{cosmology}} \times \underbrace{\frac{dM_{\rm h}}{dM_{\rm UV}}}_{\text{astrophysics}}$$

- A cosmological solution to the JWST anomaly is disfavored.

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

PBH parameter space



Axion Clusters (ACs)

- In the *postinflationary scenario*, axions can be produced from both misalignment mechanisms and the decay of axion topological defects.
- After the spontaneous breaking of the PQ symmetry a network of cosmic strings forms. 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. They correspond to isocurvature perturbations of the form:

$$P_{\rm iso}(k) = C\frac{(f_{\rm AC}D(0))^2}{k_{\rm cut}^3}\Theta(k-k_{\rm cut})\ ,\quad k_{\rm cut} = 300{\rm Mpc}^{-1}\sqrt{\frac{\rm m_a}{10^{-18}{\rm eV}}}$$

simulations of the string system suggests $C \approx 10^{-5}$

[Buschmann et al] 1906.00967
[Gorghetto et al] 2101.11007

- Similarly to PBH, LSS constraints must be imposed giving $m_a < 10^{-20}$eV.

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 interpretation of the JWST extreme galaxies with the Poisson effect is excluded due to UV LF, while the one based on **seed** effect is in principle still viable for $f_{\rm PBH} < 10^{-3}$ (needs verly 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.

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Thank you!!!!