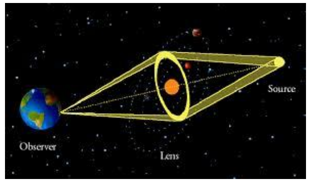
Charting the Universe with Primordial Black Holes: From Planetary to Supermassive

Sokratis Trifinopoulos

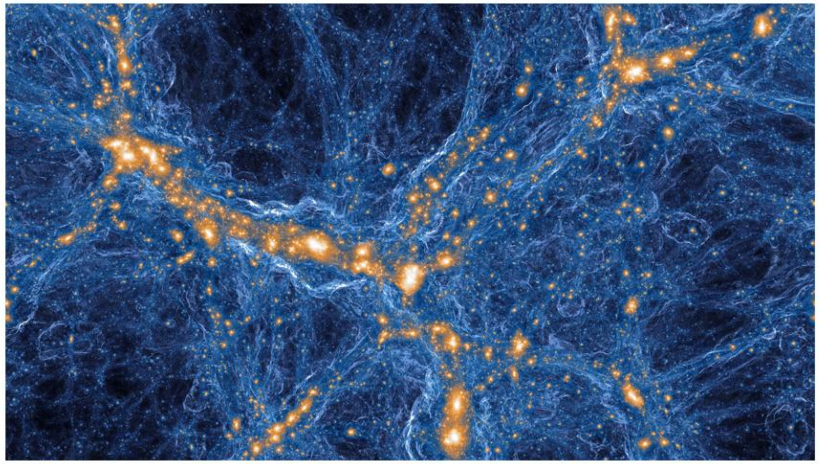
NEHOP26, CERN, 17 June 2026

This talk

1. “Would a potential discovery of planetary / subsolar PBHs discovery imply an associated effect at Gravitational Waves (GWs) experiments?

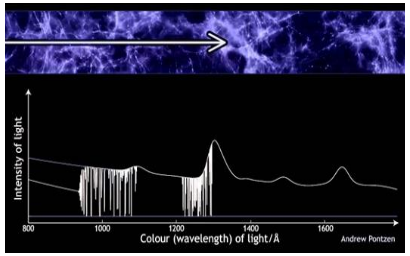


2. “What can Large Scale Structure (LSS) tell us about supermassive PBHs?”

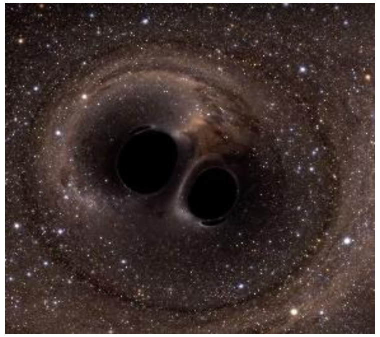


PBHs: The Usual Suspects

[Ivanov, **ST**] 2508.04767



[Vanvlasselaer, **ST**, Klipfel, Kaiser] 2603.15746 , 2603.29024



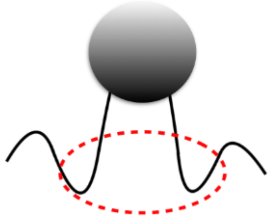
[Gouttenoire, **ST**, Vanvlasselaer] 2508.19328

[Blas, Foster, Gouttenoire, Iovinio, Musco, **ST**, Vanvlasselaer] 2602.12252

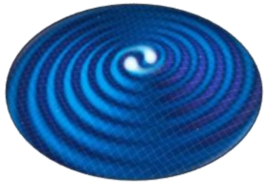
[Gouttenoire, **ST**, Valogiannis, Vanvlasselaer] 2307.01457

[Franciolini, Gouttenoire, Iovinio, **ST**, Vanvlasselaer] 26XX.XXXXX

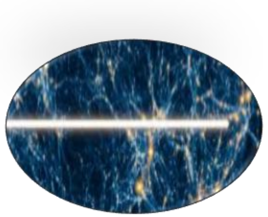
Outline



I. PBH formation



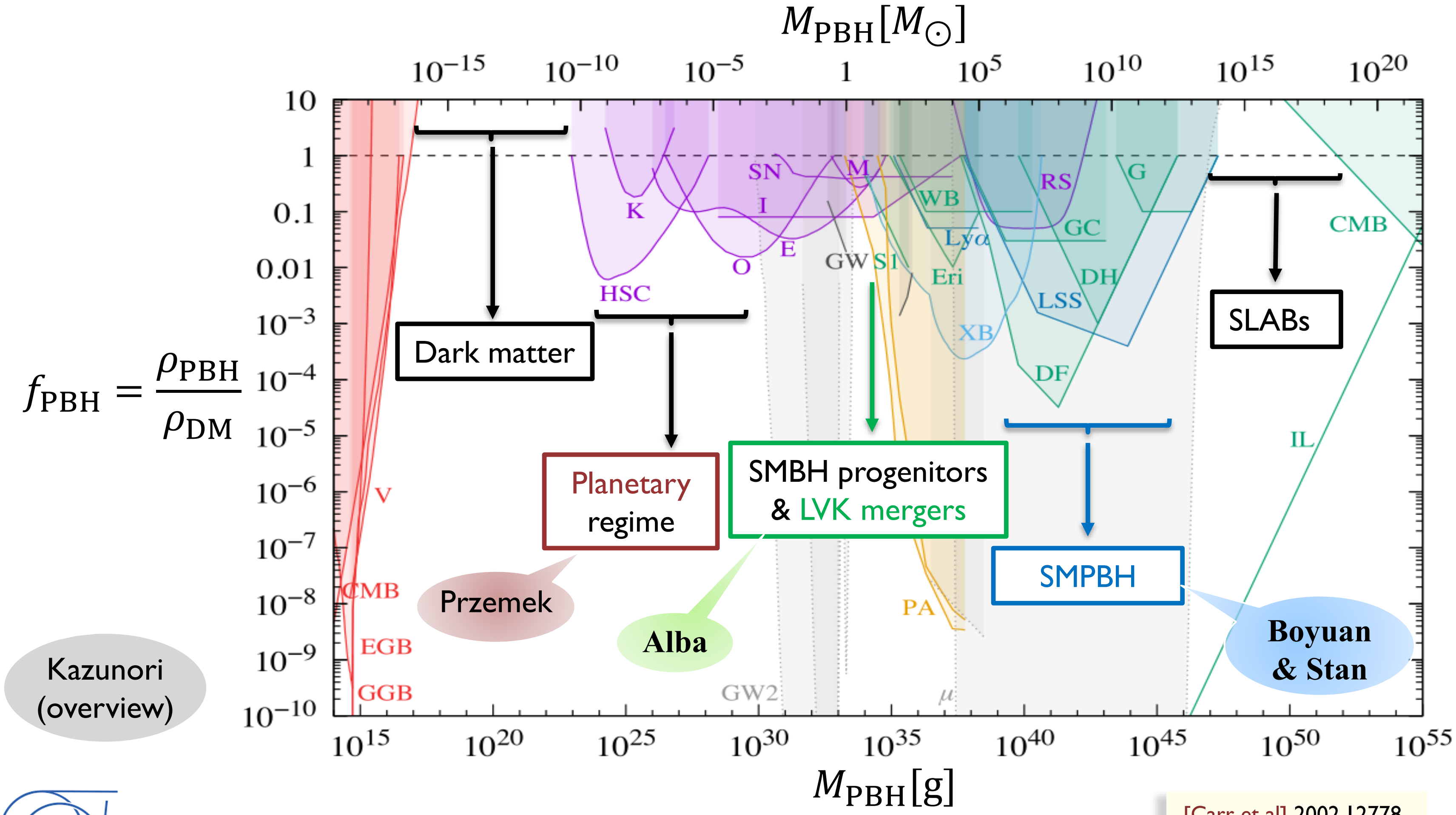
II. Gravitational Waves from PBHs



III. LSS Constrains on Supermassive PBHs

PBH Spectrum

- 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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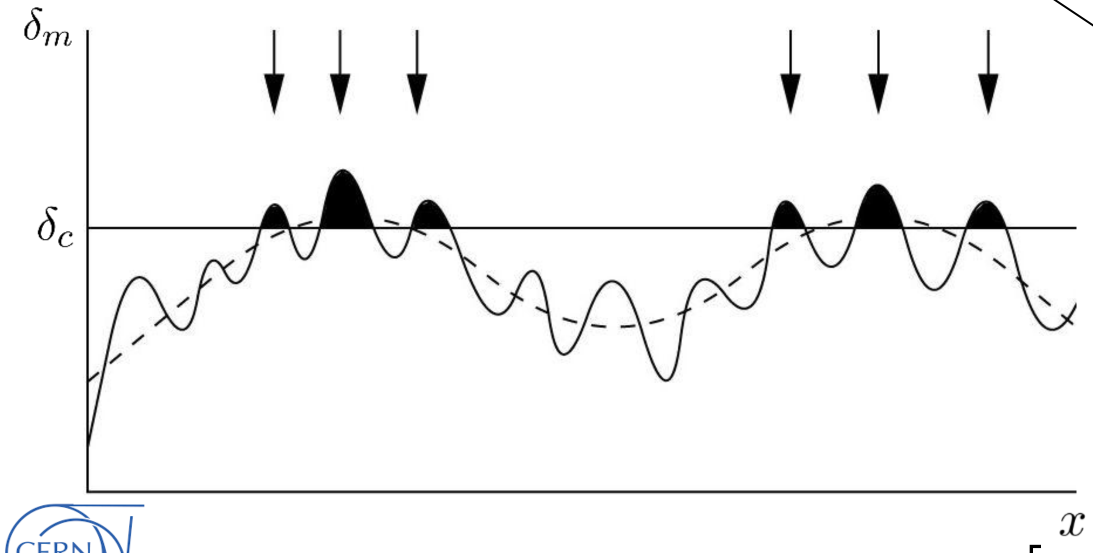
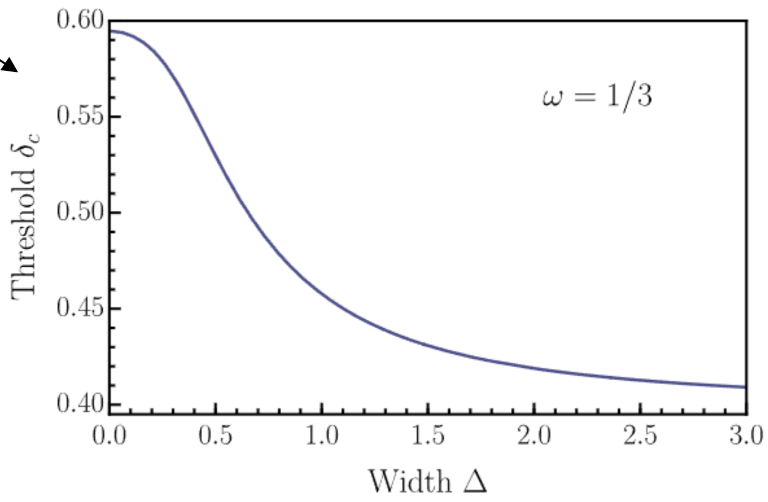
PBHs from large curvature perturbations

- Inflationary dynamics produce primordial curvature perturbations ζ.
- We parametrize the curvature power-spectrum (PS) with a log-normal: $\mathcal{P}_\zeta(k) = \frac{\mathcal{A}_\zeta}{\sqrt{2\pi}\Delta} \exp\left(-\frac{\ln^2(k/k_*)}{2\Delta^2}\right)$
- In the *long-wavelength* limit, perturbations are super-horizon and when they reenter the horizon they may collapse to form PBHs!

peak of the matter density contrast $\frac{\delta\rho}{\rho_b}$

- **PBH formation criterion:** $\delta_m \geq \delta_c$





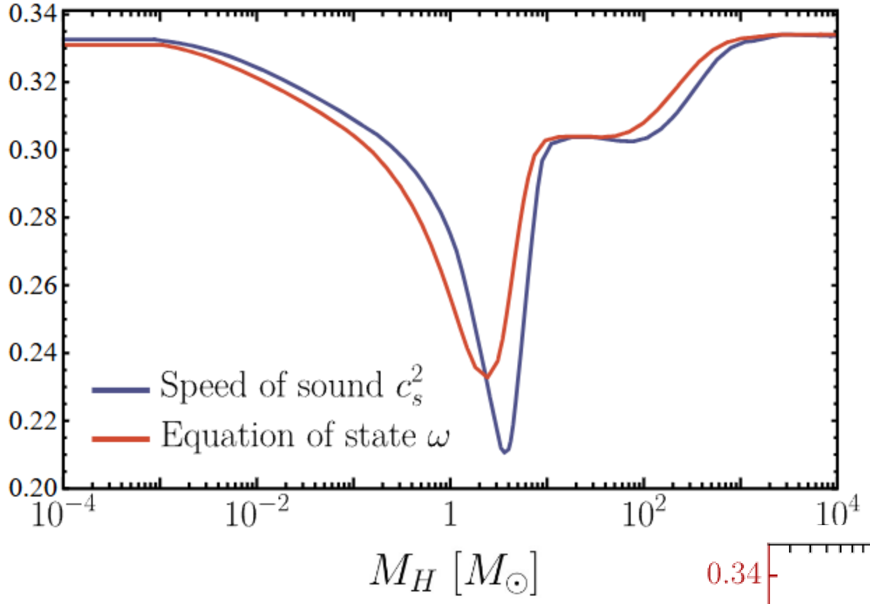
Δ

[Shibata, Sasaki] gr-qc/9905064
[Polnarev, Musco] gr-qc/0605122
[Harada, Yoo, Nakama, Koga] 1503.03934
[Musco] 1809.02127
[Young, Musco, Byrnes] 1904.00984
[De Luca et al] 1904.00970

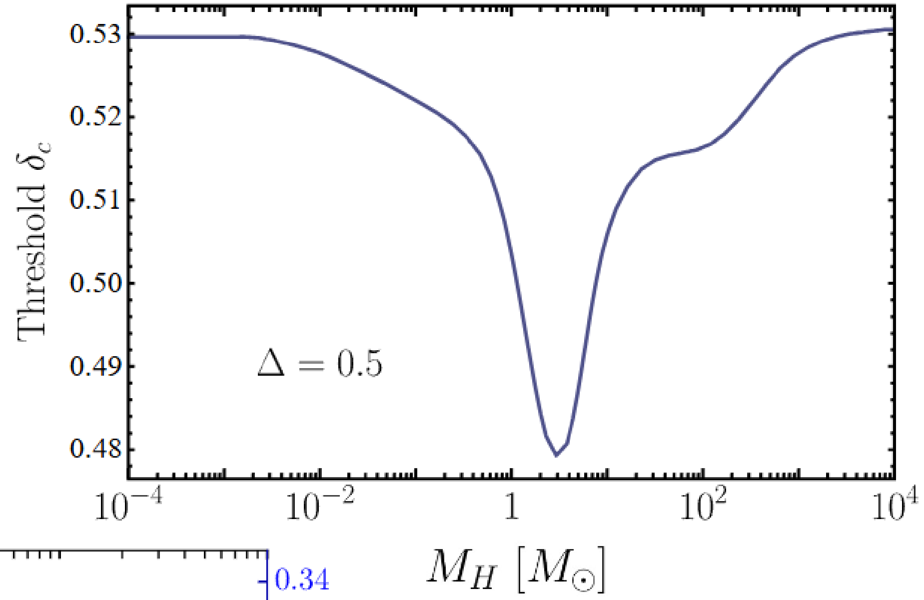
[Musco, De Luca, Franciollini, Riotto] 2002.12778

Equation of State (EoS)

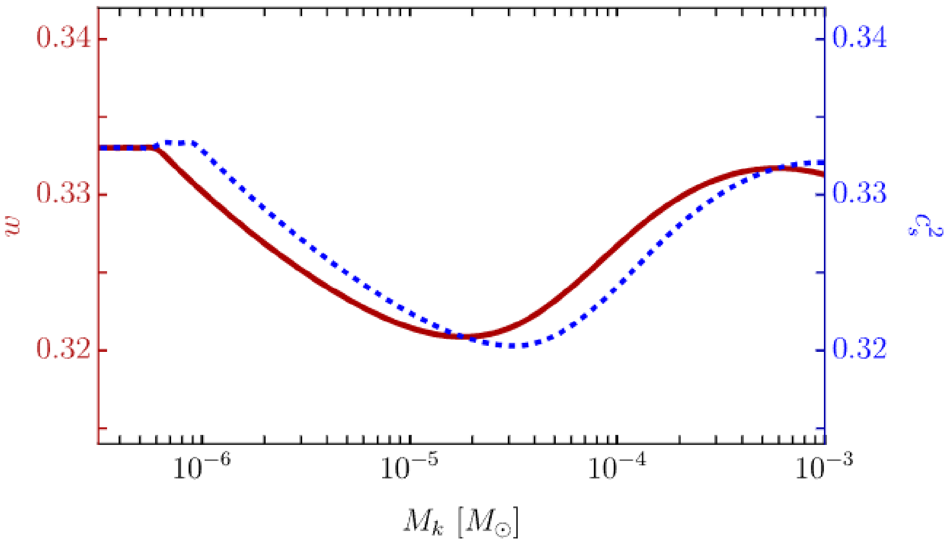
- Solar-mass PBHs form during the **QCD** phase transition (PT), and the EoS softens resulting in a lower formation threshold.



[Musco, Jedamzik, Young] 2303.07980



- During the second order **electroweak** PT, the effect is less pronounced.



[Blas, Foster, Gouttenoire, Iovinio, Musco, **ST**, Vanvlasselaer] 2602.12252

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The PBH mass function

- The collapse of large overdensities that lead to PBH formation is a highly non linear & rare event.
- For a Gaussian field δ_ℓ , the probability that a PBH will form in the Hubble patch can be calculated:

1. In *Press-Schechter* formalism: $P_{\rm f}(\delta_\ell) = \frac{1}{\sqrt{2\pi}\sigma_{\delta_\ell}} \exp\left(-\frac{\delta_\ell^2}{2\sigma_{\delta_\ell}^2}\right)$ [Press & Schechter] ApJ 187 (1974) 425-438
2. In the *theory of peaks:* $P_{\rm f}(\delta_\ell) = \frac{4\pi r_m^3}{3}\mathcal{N}_{\rm pk}(\delta_\ell)$ [Bardeen, Bond, Kaiser, Szalay,] ApJ 304 (1986) 15-61

- Let $\beta(M_{\rm PBH}; M_H) = \int_{\delta_c}^{\infty} d\delta_\ell \, \frac{M_{\rm PBH}}{M_H} P_f(\delta_\ell; M_H)\, \delta_{\rm D}\left[\ln \frac{M_{\rm PBH}}{m_{\rm PBH}(\delta_m)}\right]$ be the energy fraction of universe contained in PBHs. Then we integrate to obtain the **PBH mass function (MF)** as:

$$\frac{df_{\rm PBH}}{d\ln M_{\rm PBH}} = \frac{1}{\Omega_{\rm DM}} \int_{M_H^{\rm min}}^{\infty} d\ln M_H \left(\frac{M_{\rm eq}}{M_H}\right)^{1/2} \beta(M_{\rm PBH}; M_H)$$

- The phenomenology can be simplified by replacing extended MF with average populations:

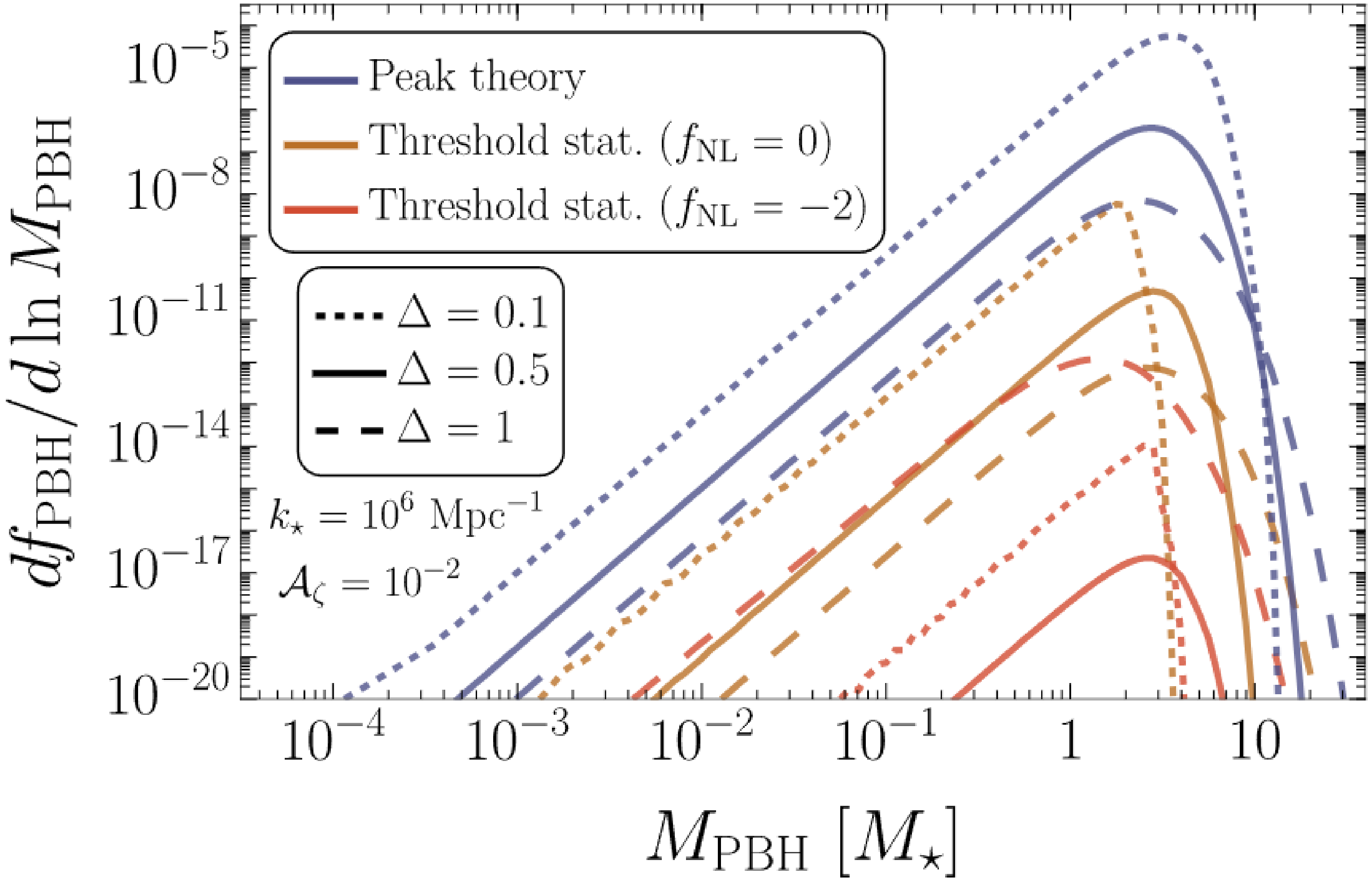
$$\langle f_{\rm PBH}\rangle = \int \frac{dM_{\rm PBH}}{M_{\rm PBH}} \frac{df_{\rm PBH}}{d\ln M_{\rm PBH}}\,, \quad \langle M_{\rm PBH}\rangle = \langle f_{\rm PBH}\rangle \left(\int \frac{dM_{\rm PBH}}{M_{\rm PBH}^2} \frac{df_{\rm PBH}}{d\ln M_{\rm PBH}}\right)^{-1}$$

The PBH mass function (non-Gaussianities)

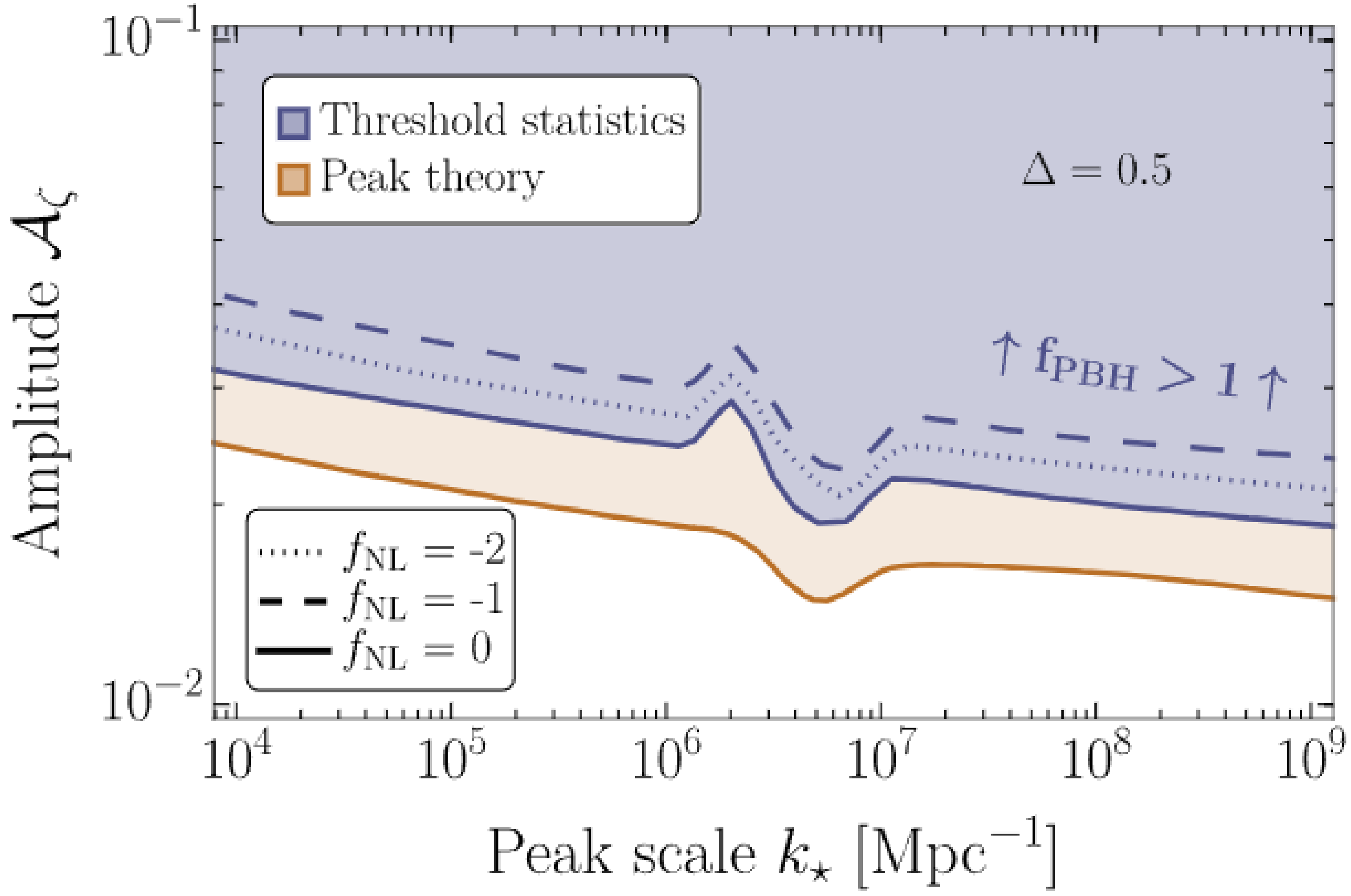
- NGs are parameterized by the power-series: $\zeta_{\rm NG} = \zeta + F_{\rm NL}(\zeta^2 - \langle\zeta^2\rangle) + G_{\rm NL}\zeta^3 + \ldots$

  The formation probability (in threshold statistics) becomes a 2D Gaussian PDF of δ_ℓ and ζ.

[Meng, Yuan, Huang] 2207.07668
[Young] 2201.13345
[Ferrante et al] 2211.01728



Bounds from Overclosure



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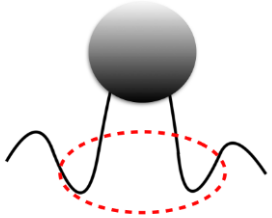
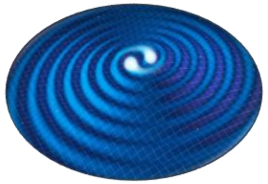
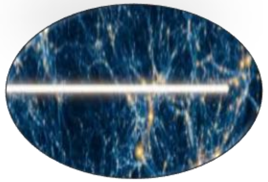
Outline



I. PBH formation

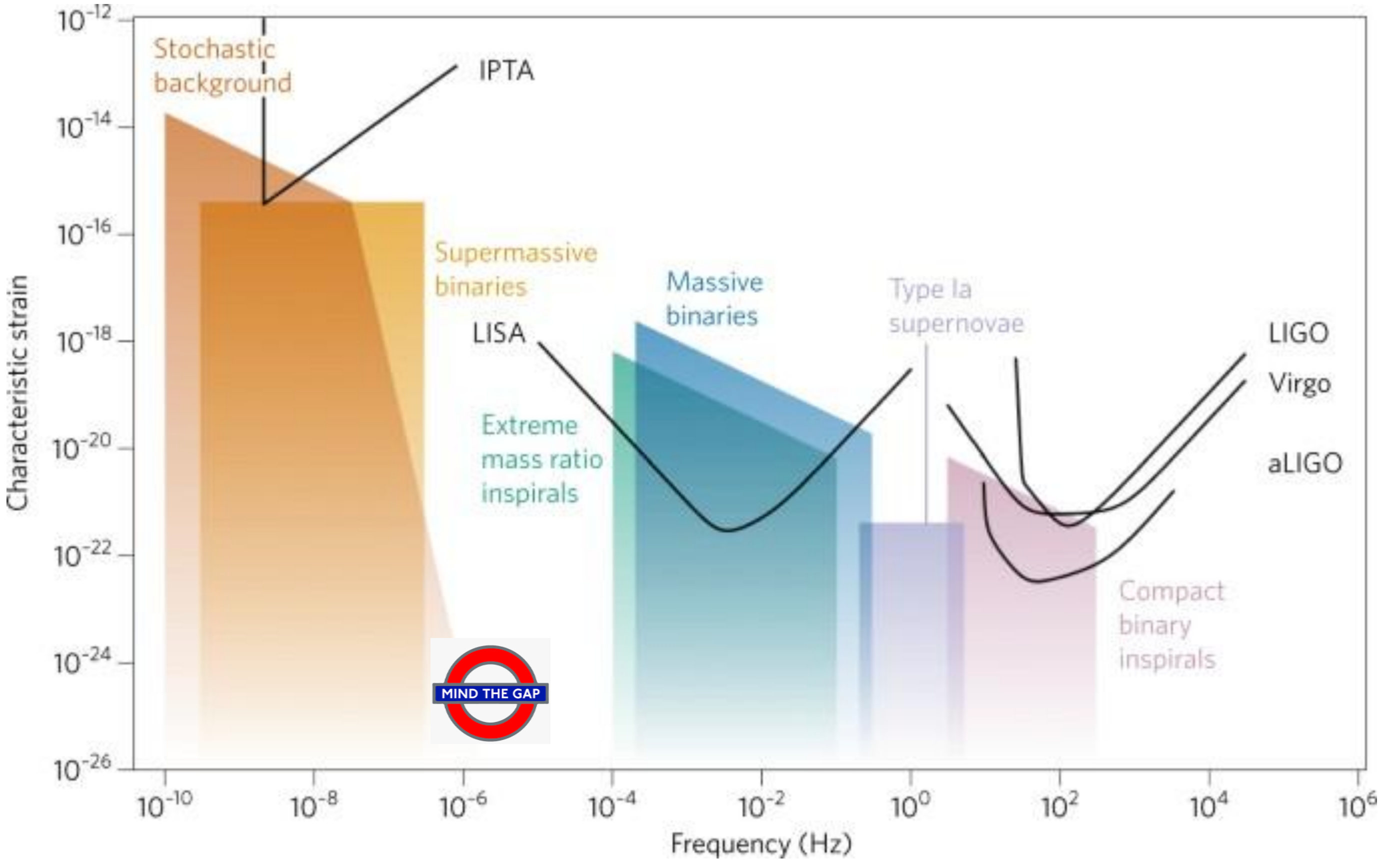


II. Gravitational Waves from PBHs

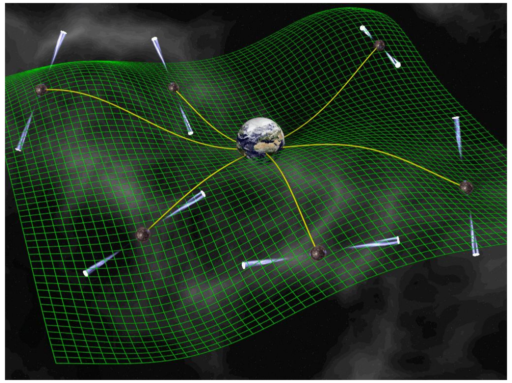


III. LSS Constrains on Supermassive PBHs

The new Golden Era for Cosmology: Gravitational Waves (GWs)



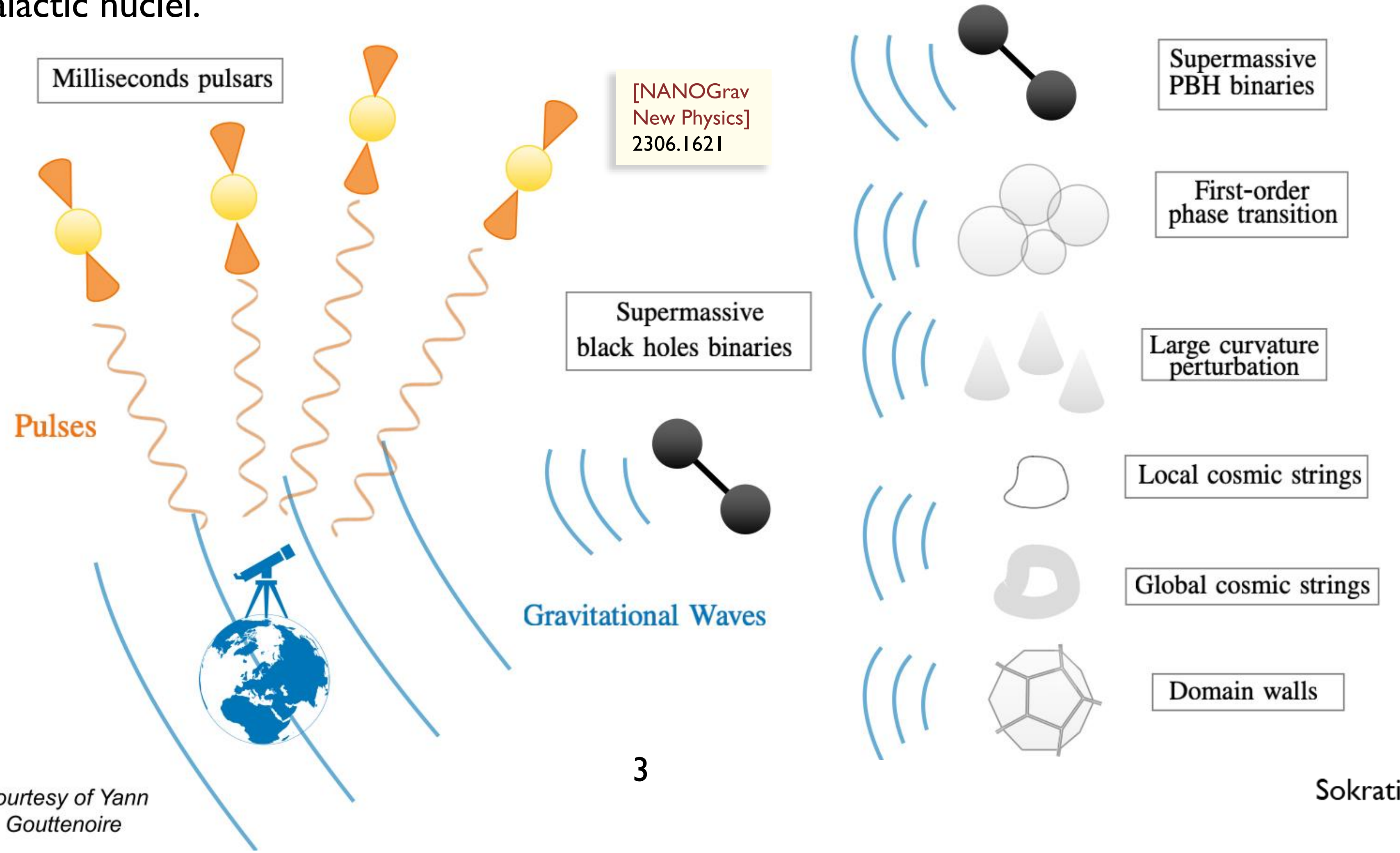
218 merger events



67 pulsars

Are Pulsar Timing Arrays (PTAs) a New Physics signal?

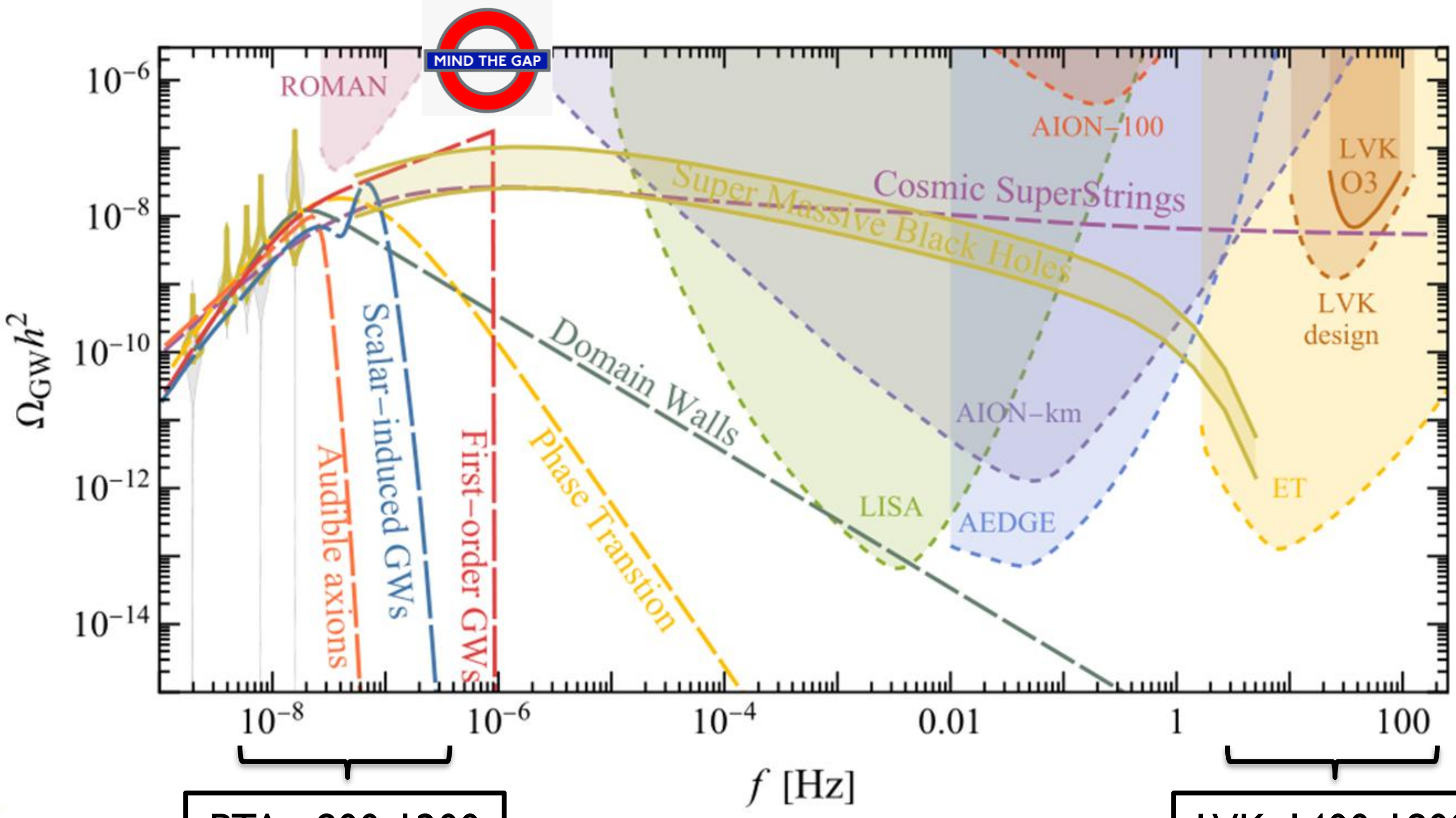
- For the PTAs, the astrophysical explanation is in terms of binaries of supermassive Black Holes (SMBHs) with masses above $10^5\ M_{\odot}$, which are well-known to reside within galactic nuclei.



[NANOGrav New Physics] 2306.1621

Courtesy of Yann Gouttenoire

Solution: Complementarity between experiments



PTAs: 800-1200 NP papers

[Ellis et al] 2308.08546

LVK: 1400-1800 NP papers

JWST early galaxies: 200-300 NP paper

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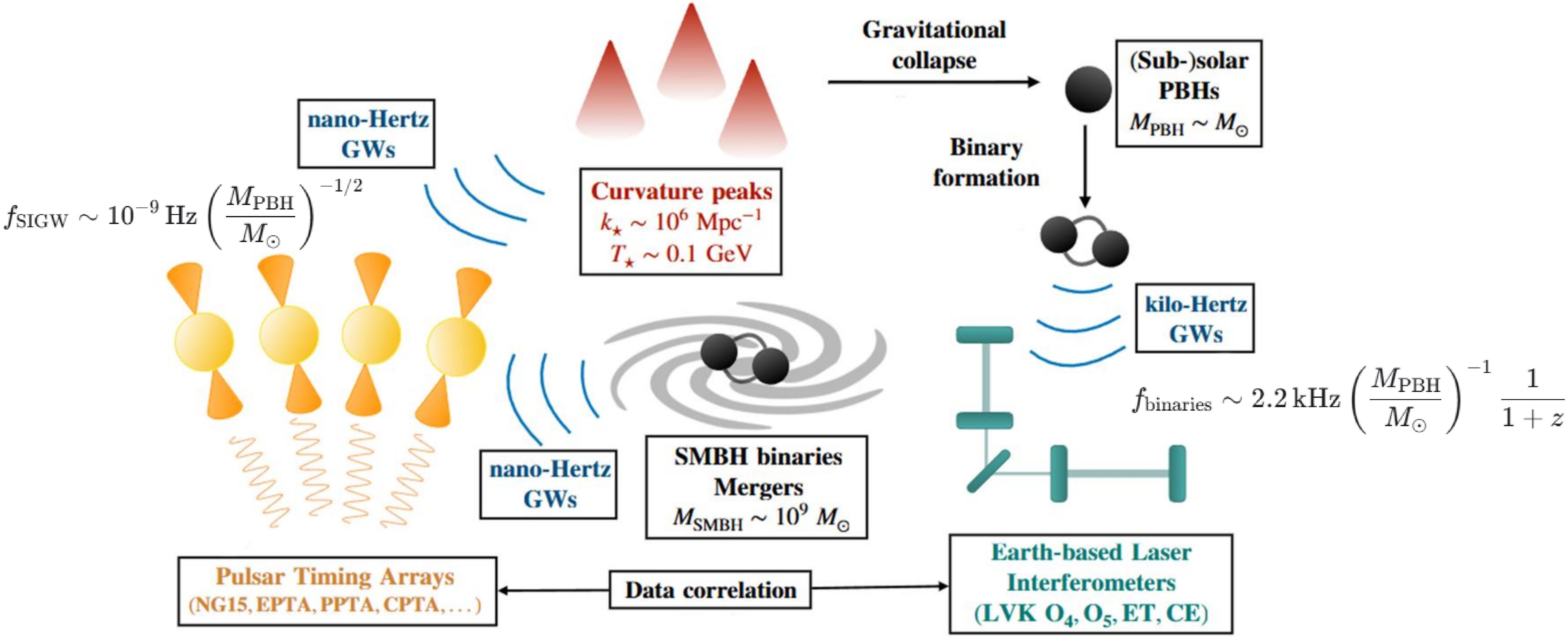
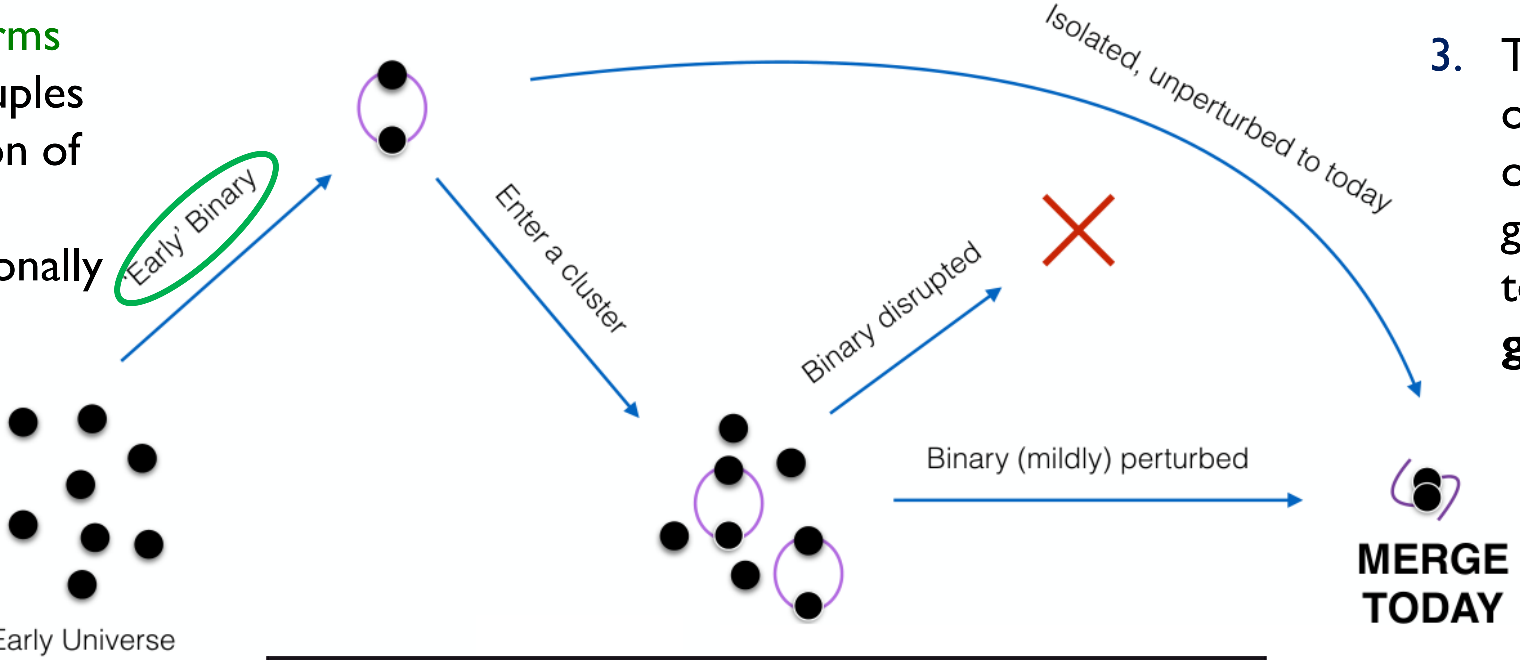
The mechanism in a nutshell



PBH binary formation and evolution

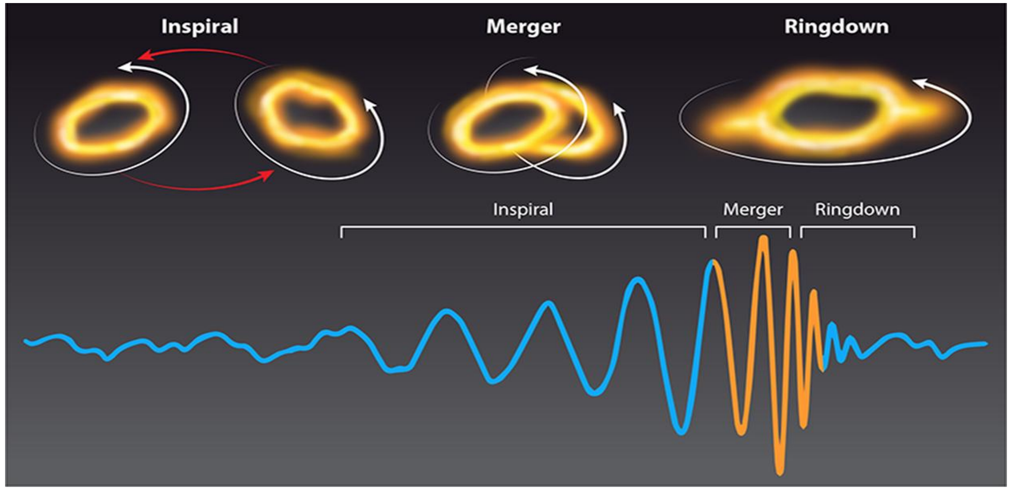
2. A PBH **binary** forms when a pair decouples from the expansion of the Universe and becomes gravitationally bound.



3. The two PBHs will orbit around each other and the radius gradually shrinks due to emittance of **gravitational waves**.

[Sasaki et al] 1801.05235

1. Immediately after their formation, PBHs are sparsely distributed.



4. When they are close enough they merge when the GW's frequency is approximately:

$$f_{\rm binaries} \sim 2.2\,{\rm kHz} \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1} \frac{1}{1+z}$$

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Transient Gravitational Waves

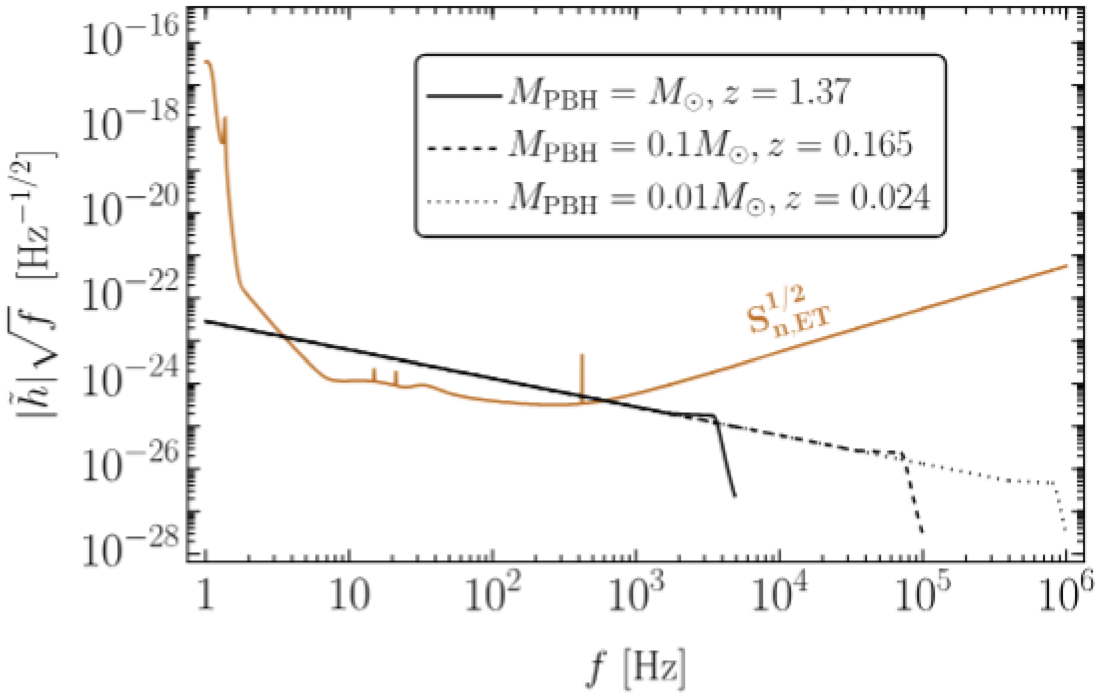
- The detectability of a merger event is quantified by the *signal-to-noise ratio:*

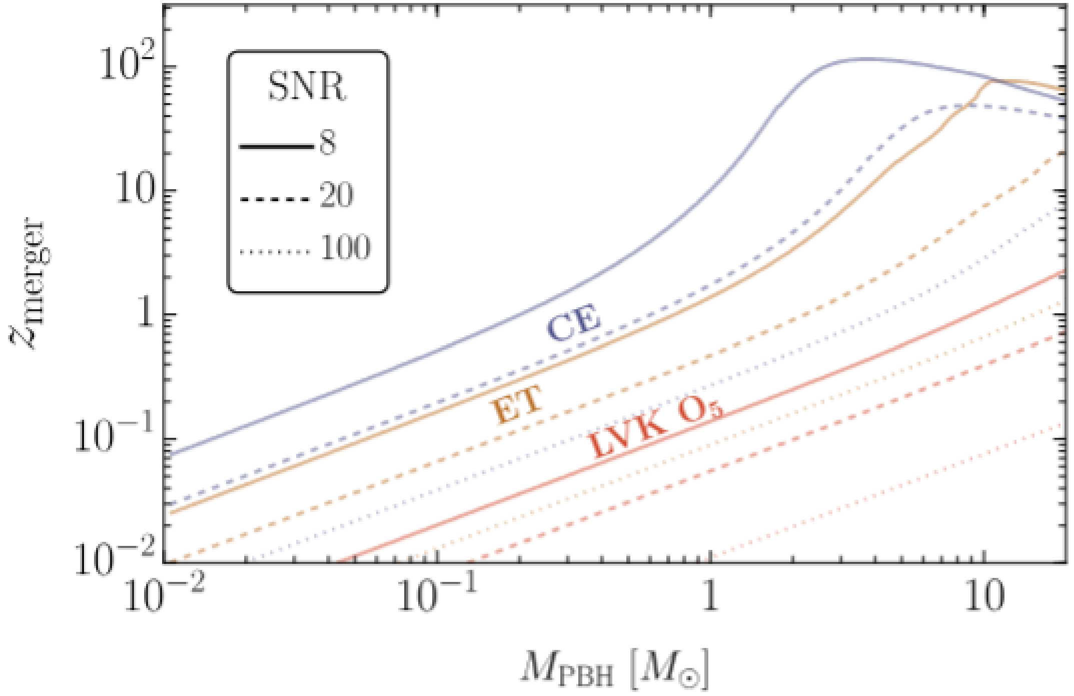
$$\mathrm{SNR}(z) \equiv 2\sqrt{\int df \frac{|\tilde{h}(f,z)|^2}{S_n(f)}}$$

merging redshift

empirical amplitude strain in Fourier domain

noise power spectrum of the GW detector





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Binary Merger Rate (Early Formation)

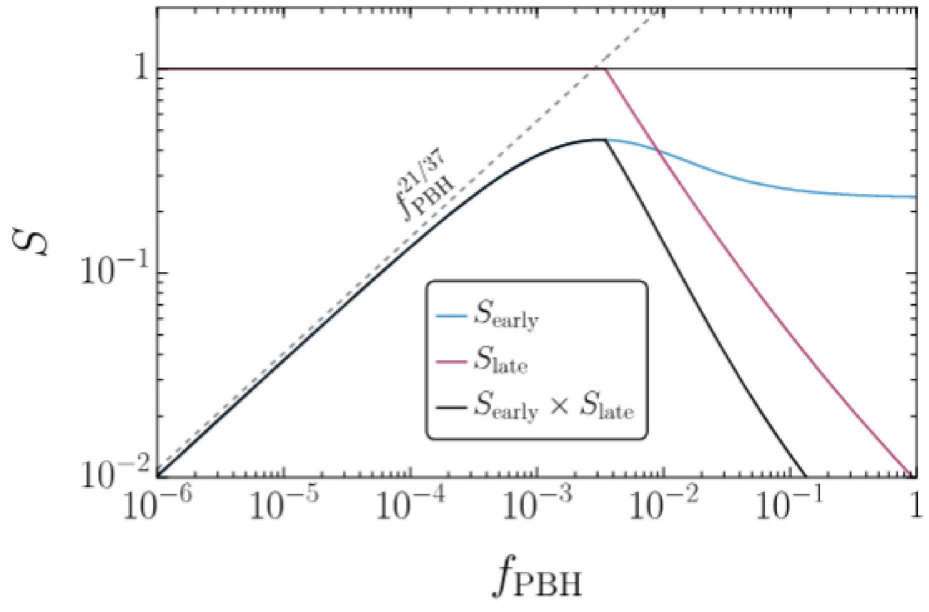
- The merger rate at time t for binaries formed in the early universe (neglecting accretion and initial clustering):

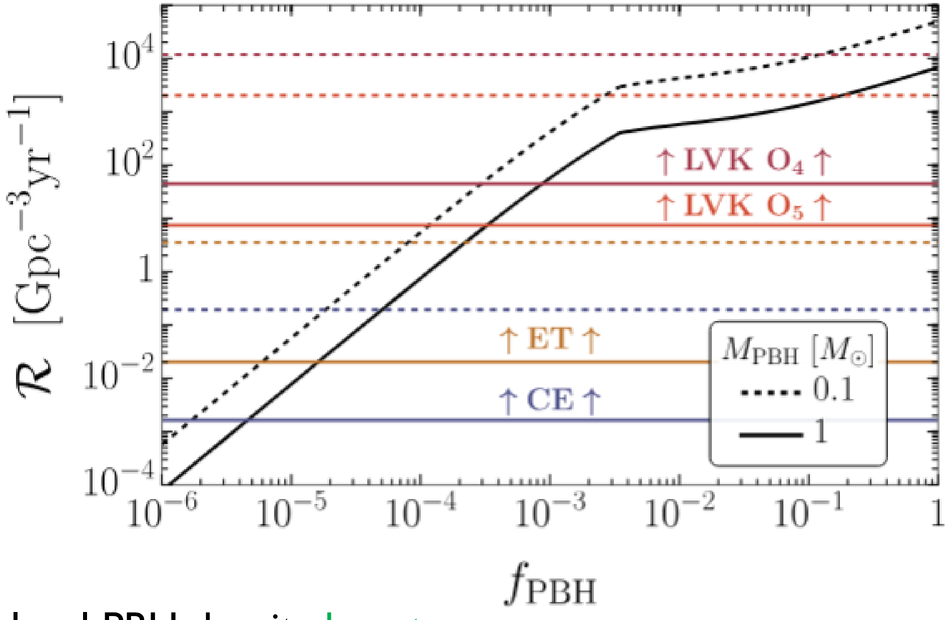
[Ajith et al] 0710.2335

$$\mathcal{R}(f_{\rm PBH}, M_{\rm PBH}, t) = \frac{3\times 10^6}{\rm Gpc^3 yr} f_{\rm PBH}^{53/37} \left(\frac{t}{t_0}\right)^{-34/37} \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-32/37} \times S(f_{\rm PBH}, t)$$

$S_{\rm early} \times S_{\rm late}$

[Raidal et al] 1812.01930]





- Number of **detected events**: $N = T \int \frac{dz}{1+z} \frac{dV_c}{dz} \mathcal{R}(t(z))\, \delta_\odot(d(z))\, p_{\rm det}({\rm SNR}_c/{\rm SNR(z)})$

comoving Hubble volume

local PBH density boost

threshold value ${\rm SNR}_c = 8$

[Pujolas, Vaskonen, Veermäe] 2107.03379

observation period

accounts for random detector orientation

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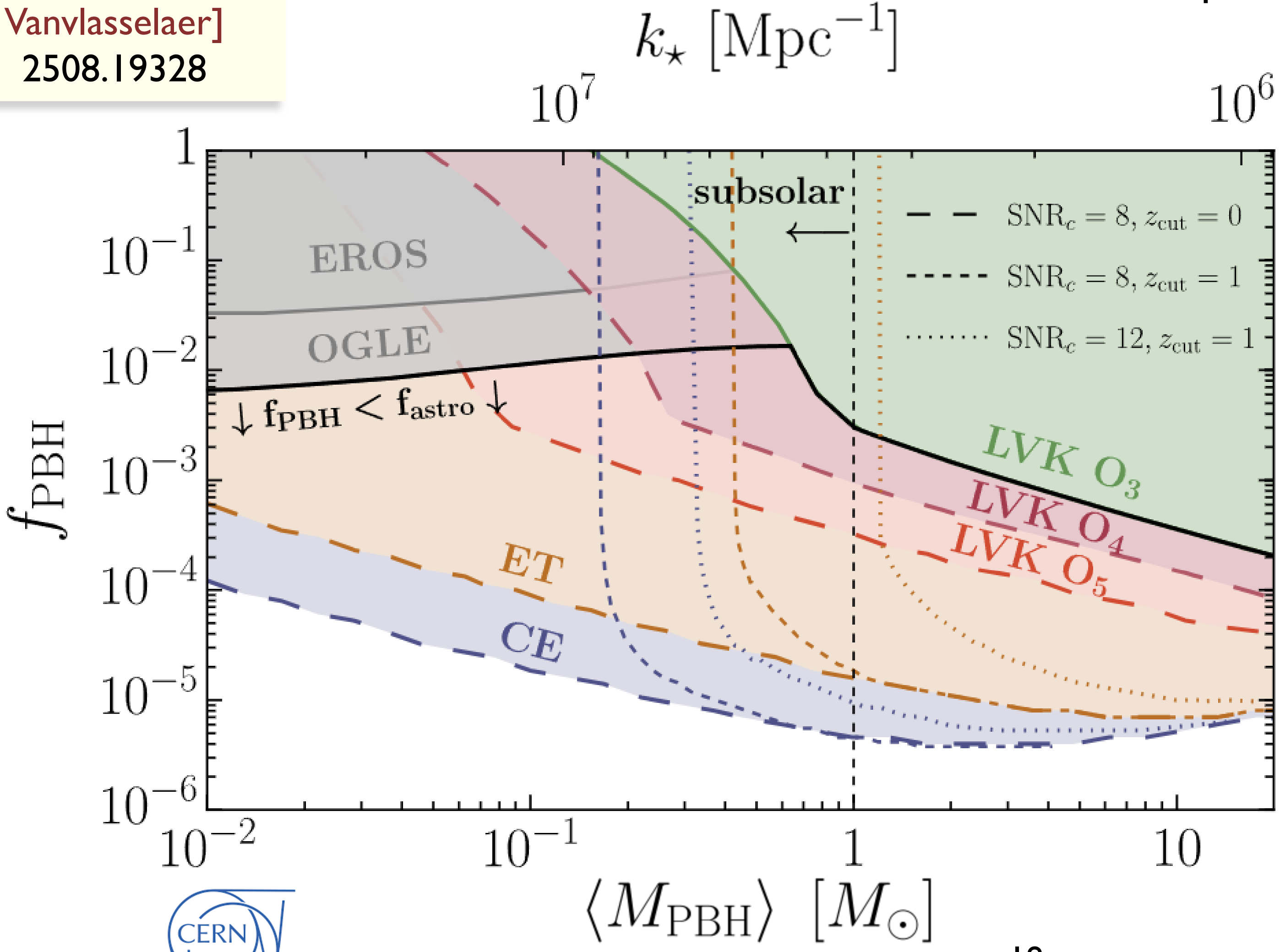
Reach of future experiments

[Gouttenoire, **ST**, Vanvlasselaer] 2508.19328

- A sub-solar PBH discovery would be a smoking gun signature of **New Physics,** since there is no standard astrophysical channel to produce them!



- There are three alternative scenarios beyond our scope:

1. Stellar transmutation: subsolar astrophysical objects, e.g. white dwarves, could accrete (certain types of) DM and convert to BHs.

   [Dasgupta, Laha, Ray] 2009.01825 [Chakraborty, Bhattacharyya] 2401.08462

   ➡ Earlier stages in stellar life cycle: $z > 1$

2. Exotic compact objects: Q-balls, boson states, fermion soliton stars can be distinguished from BHs based on their tidal deformabilities.

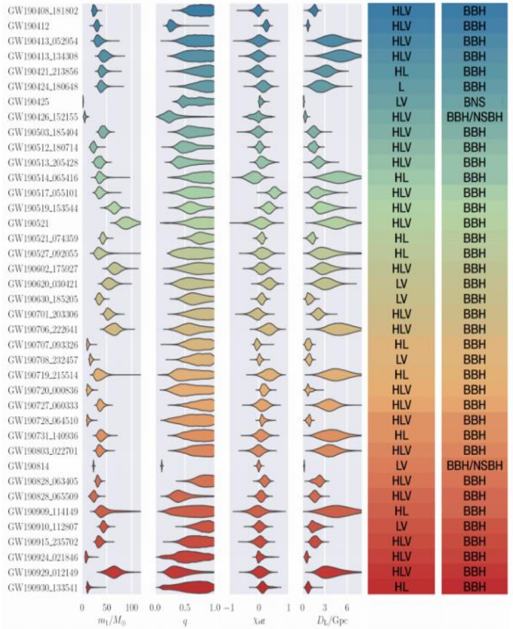
   [Crescimbeni et al] 2402.18656, 2408.14287 [De Luca et al] 2106.13769

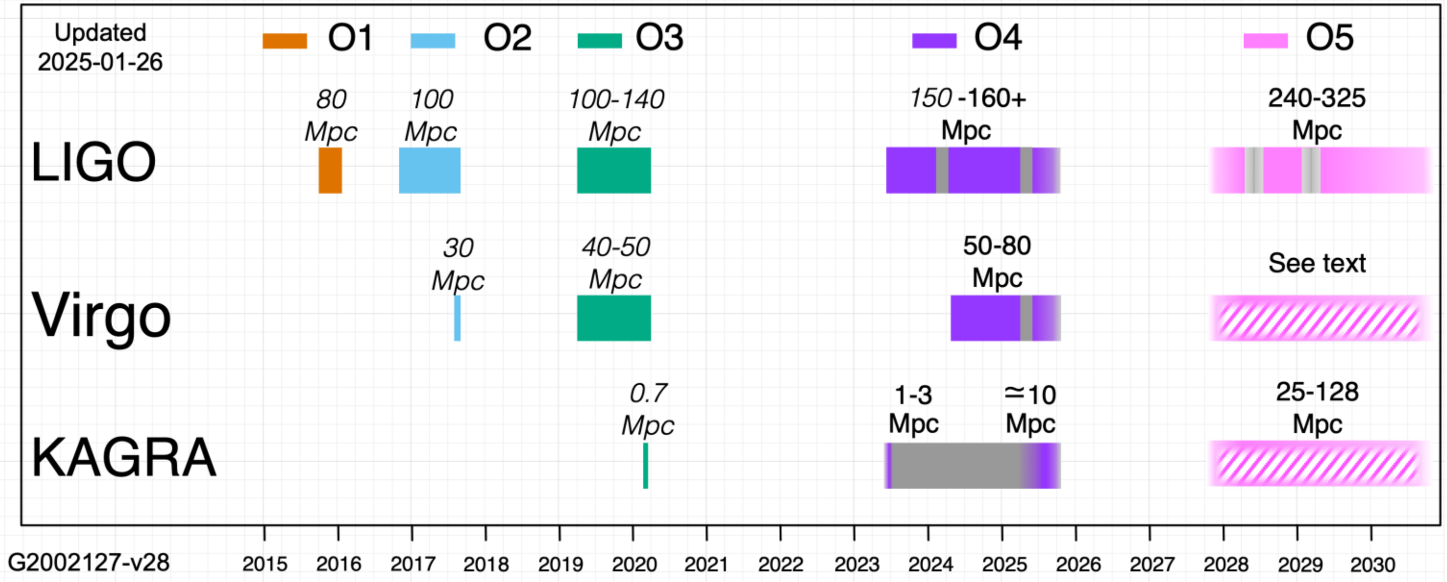
   ➡ More statistics: SNR> 12

3. PBHs of different origin than inflation.

   [Flores, Kusenko] 2404.05430

LIGO-Virgo-KAGRA Timelines & Prospects





- One candidate with sub-solar masses (SSM200308) on the cusp of detection in the O3 dataset.

[Prunier et al] 2311.16085
[Yuan, Huang] 2404.03328

Can we identify primordial black holes?
Tidal tests for subsolar-mass gravitational-wave observations

Francesco Crescimbeni,[1,2,*] Gabriele Franciolini,[3,†] Paolo Pani,[1,2,‡] and Antonio Riotto[4,5,§]

(LVK) sensitivities as well as next-generation experiments. We show that, should LVK O4 run observe subsolar neutron-star mergers, it could measure the (large) tidal effects with high significance. In particular, for subsolar neutron-star binaries, O4 and O5 projected sensitivities would allow measuring the effect of tidal disruption on the waveform in a large portion of the parameter space, also constraining the tidal deformability at $\mathcal{O}(10\%)$ level, thus excluding a primordial origin of the binary. Vice versa, for subsolar PBH binaries, model-agnostic upper bounds on the tidal deformability can rule out neutron stars or more exotic competitors. Assuming events similar to the subthreshold candidate SSM200308 reported in LVK O3b data are PBH binaries, O4 projected sensitivity would allow ruling out the presence of neutron-star tidal effects at $\approx 3\sigma$ C.L., thus strengthening the PBH hypothesis. Future experiments would lead to even stronger ($> 5\sigma$) conclusions on potential discoveries of this kind.

2402.18656

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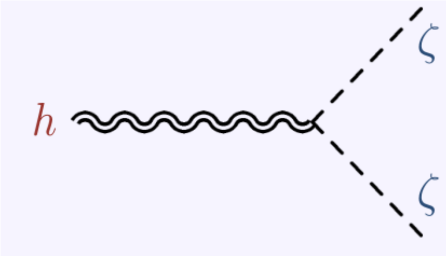
Scalar-Induced Gravitational Waves (SIGW)

- The same curvature perturbations that collapse to form PBHs, are the source of GWs at second-order in perturbation theory.



$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4\mathcal{T}^{lm}_{ij}\mathcal{S}^{ij} = \mathcal{O}(\partial_i\zeta\partial_j\zeta)$$

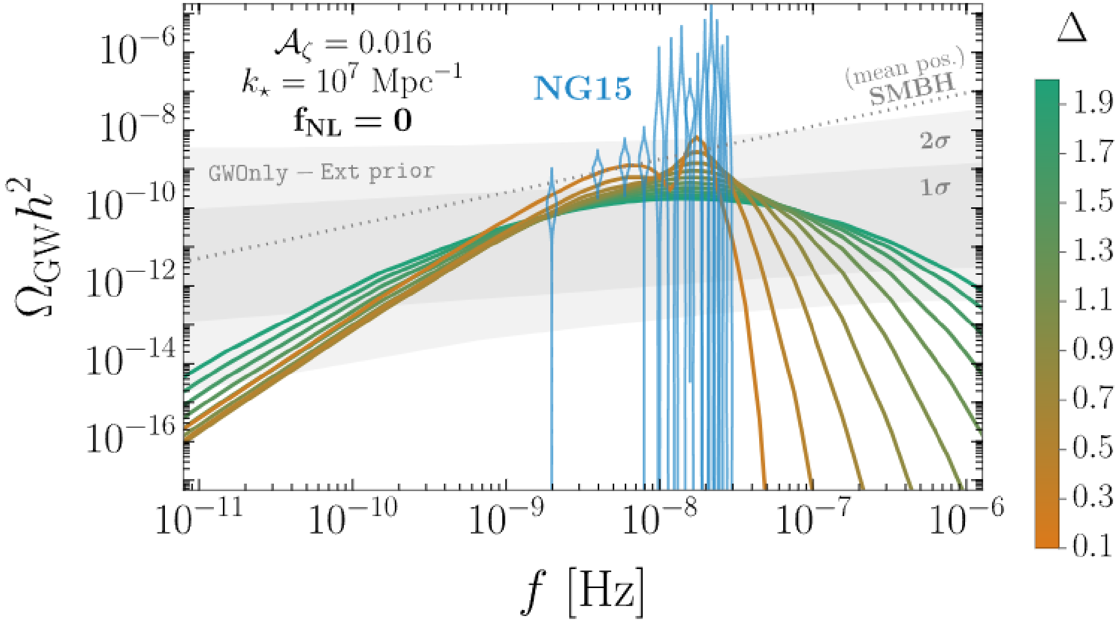
$$\mathcal{T}^{lm}_{ij}G^{(2)}_{ij} = 8\pi G\mathcal{T}^{lm}_{ij}T^{(2)}_{lm}$$

$$\langle h_{\lambda_1}(\tau,\mathbf{k}_1)h_{\lambda_2}(\tau,\mathbf{k}_2)\rangle \equiv \delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2)\delta^{\lambda_1\lambda_2}\frac{2\pi^2}{k_1^3}\Delta_{\lambda_1}(\tau,\mathbf{k}_1)$$

[Nakamura] gr-qc/0605108
[Kohri, Terada] 1804.08577

SIGW Power Spectrum:

$$\Omega_{\rm GW}(\tau,k) \equiv \frac{\rho_{\rm GW}(\tau,k)}{\rho_{\rm tot}(t)} = \frac{1}{48}\left(\frac{k}{a(\tau)H(\tau)}\right)^2 \sum_{\lambda=+,\times}\overline{\Delta_\lambda(\tau,\mathbf{k})}$$



- The Gaussian contribution in the limit $\Delta \to 0$ reads:

$$\Omega^{(0)}_{\rm GW}(k) \simeq 3\mathcal{A}^2_\zeta\left(\frac{k}{k_*}\right)^2 \ln^2\left(\frac{k_*}{k}\right)\Theta(2k_*-k)$$

[Cai, Pi, Sasaki] 1810.11000 [Unal] 1811.09151
[Adshead, Lozanov, Weiner] 2105.01659

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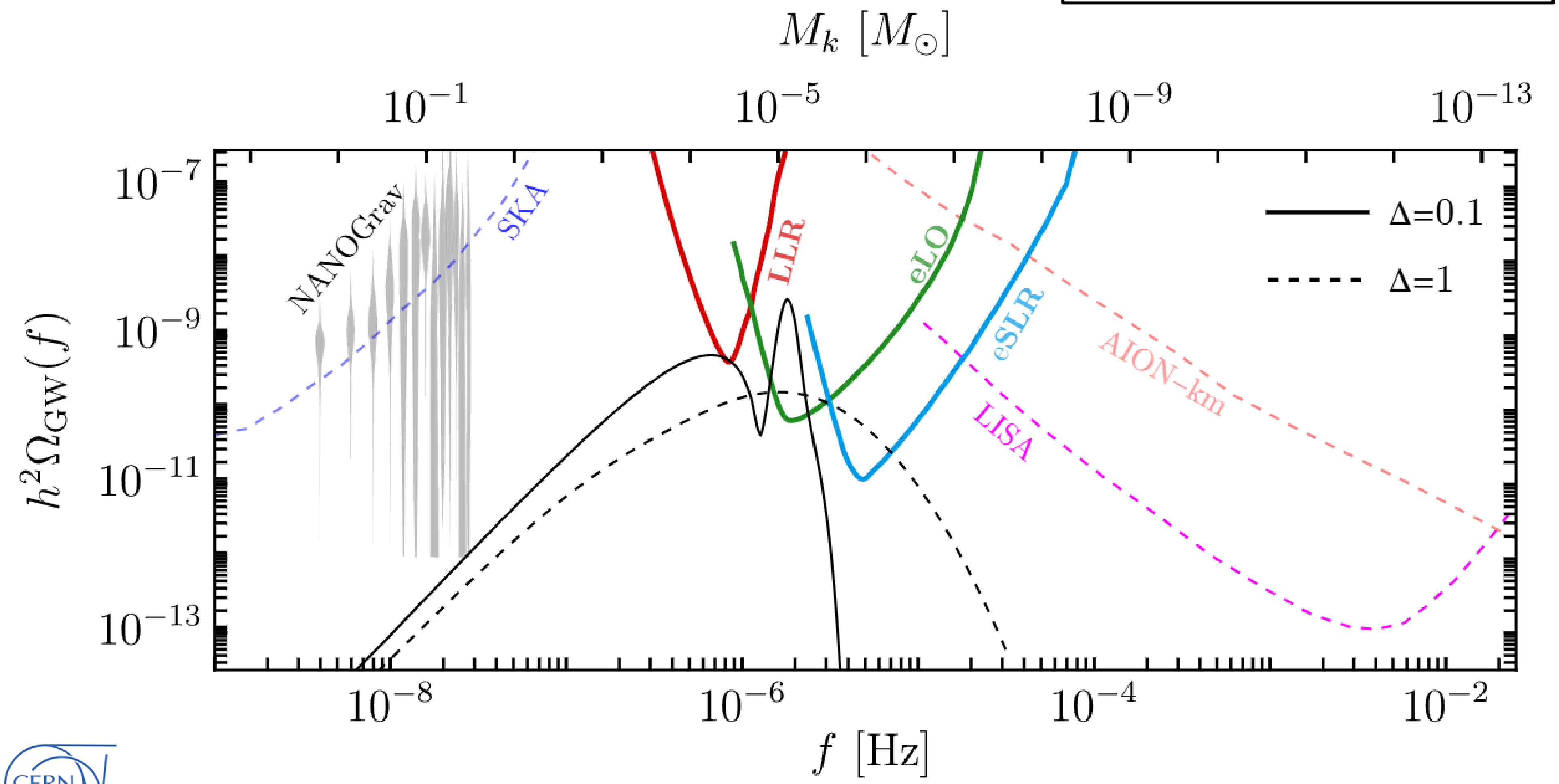
SIGW and subsolar PBHs

- The SIGW frequency is given approximately by: $f_{\rm SIGW} \sim 10^{-9}\,{\rm Hz}\left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2}$



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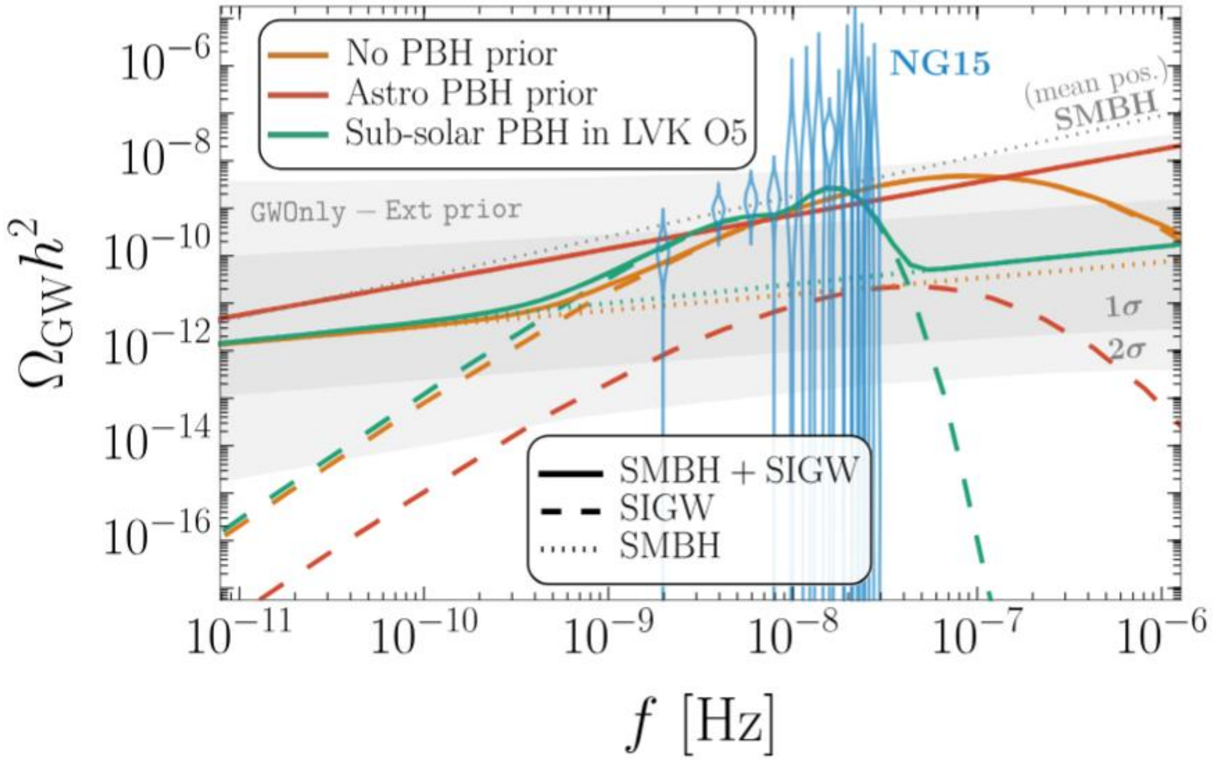
Bayesian analysis with motivated priors

➢ The (irreducible) SMBHs GW energy density is given by a blue-tilted power-law:

$$\Omega_{\rm ABH}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f), \qquad h_c(f) = A_{\rm ABH}\left(\frac{f}{1\ {\rm yr}^{-1}}\right)^{-2/3}$$

[Romero-Rodriguez et al] 2107.11660



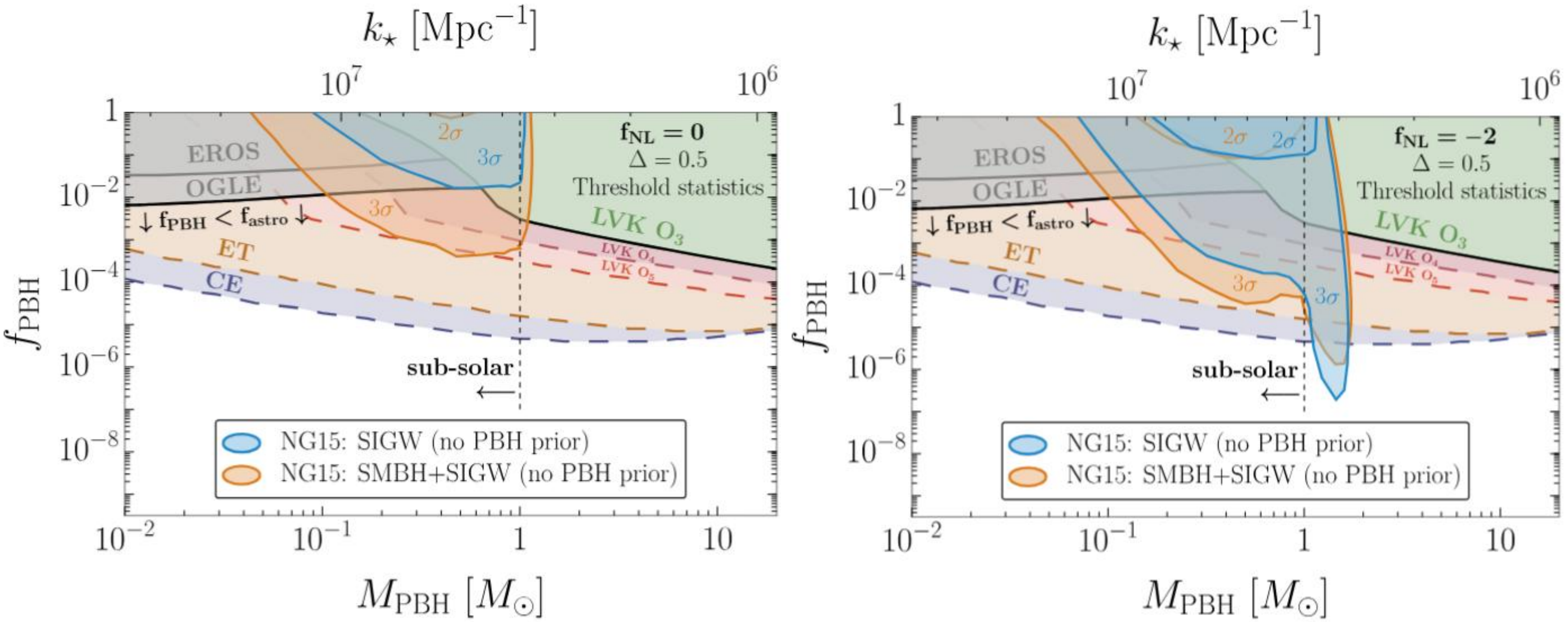
➢ We perform a full Bayesian analysis of the PTA signals in 3 scenarios: [PTArcade] 2306.16377

1. SMBHs alone
2. SIGW from PBHs alone
3. SIGW + SMBHs

➢ For scenarios 1 and 3 we use 3 different prior hypothesis on the PBH abundances:

1. No priors
2. Astrophysical priors (LVK O4 & OGLE)
3. Sub-solar PBHs discovered in LVK O5

SIGW explanation: NGs matter!



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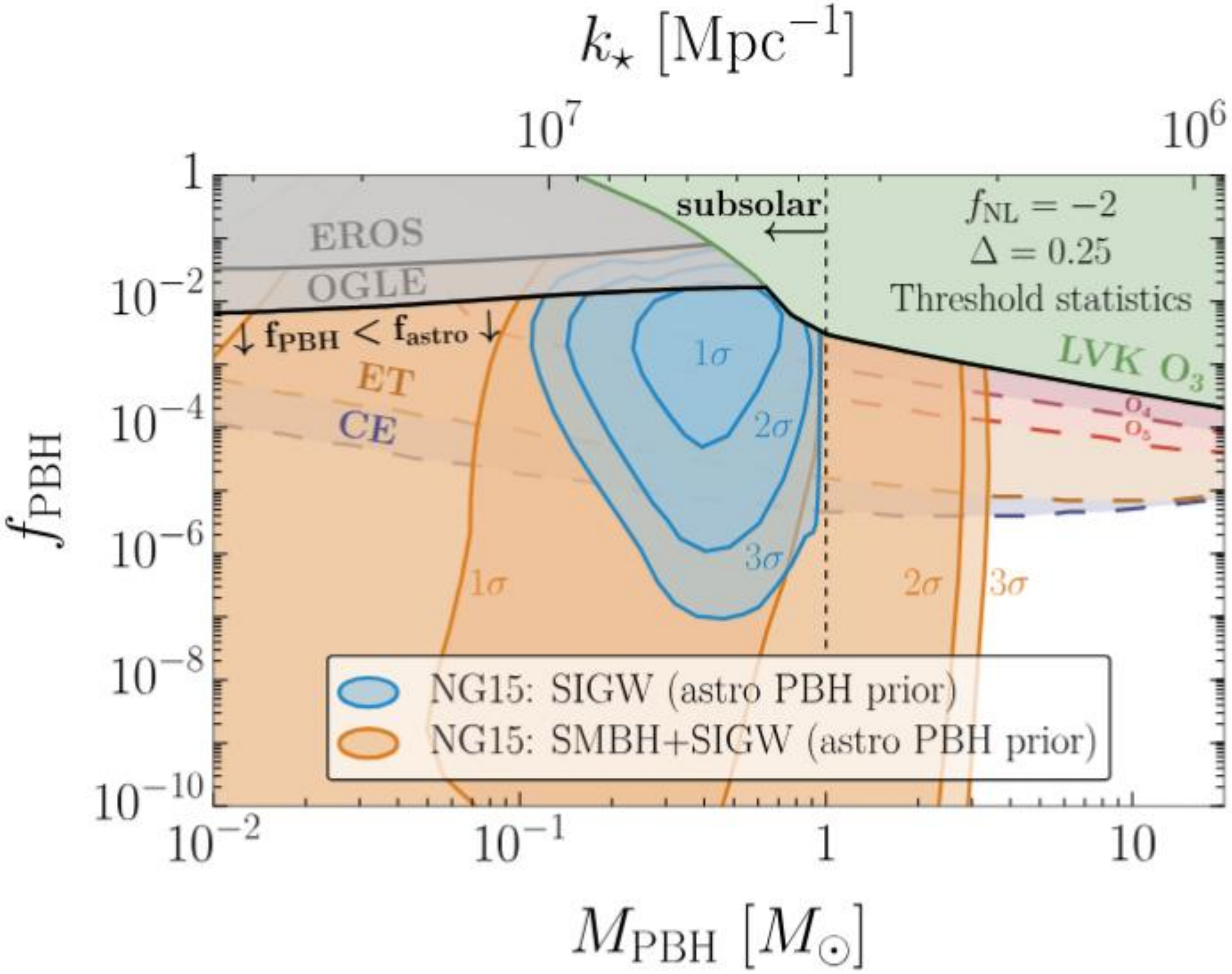
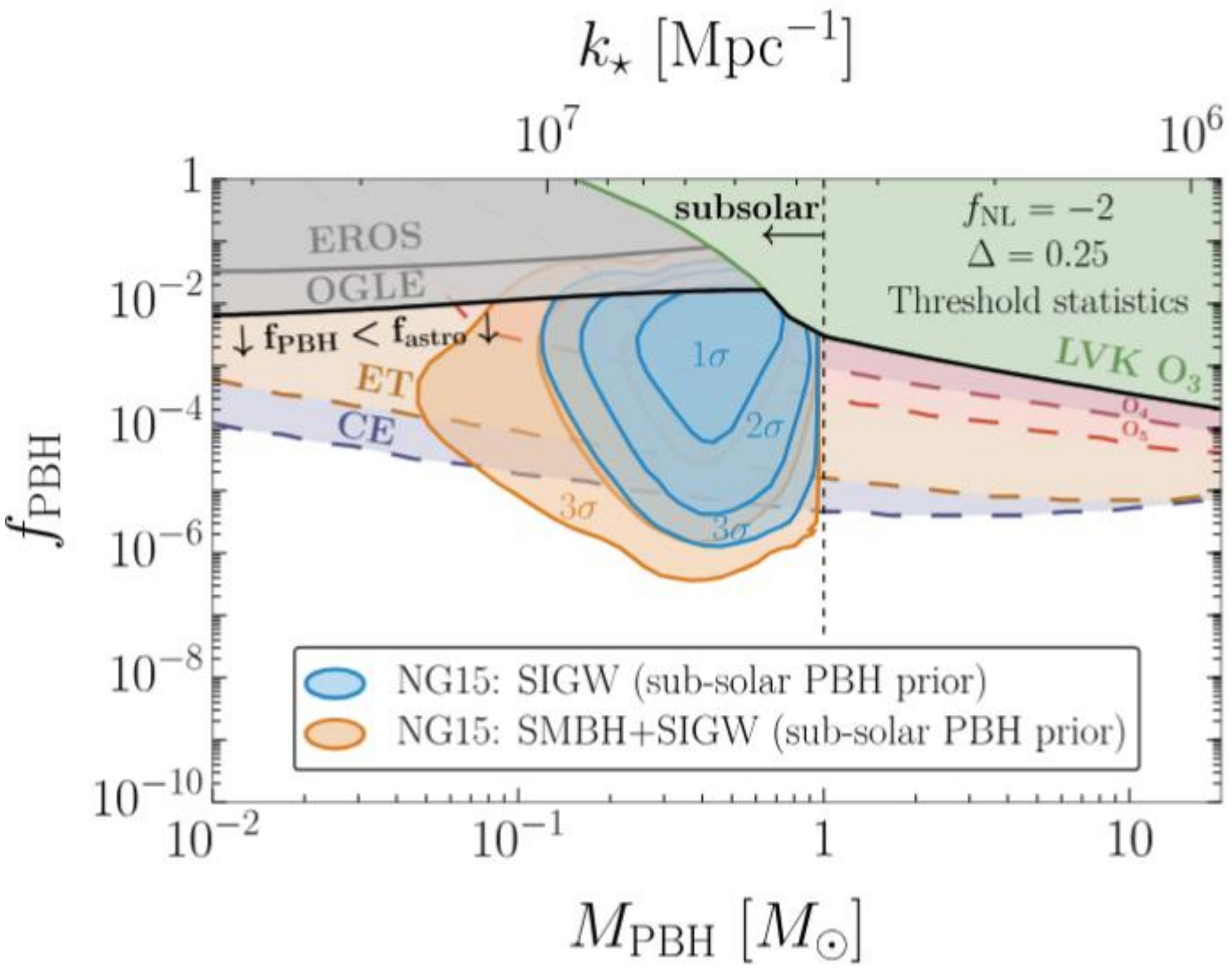
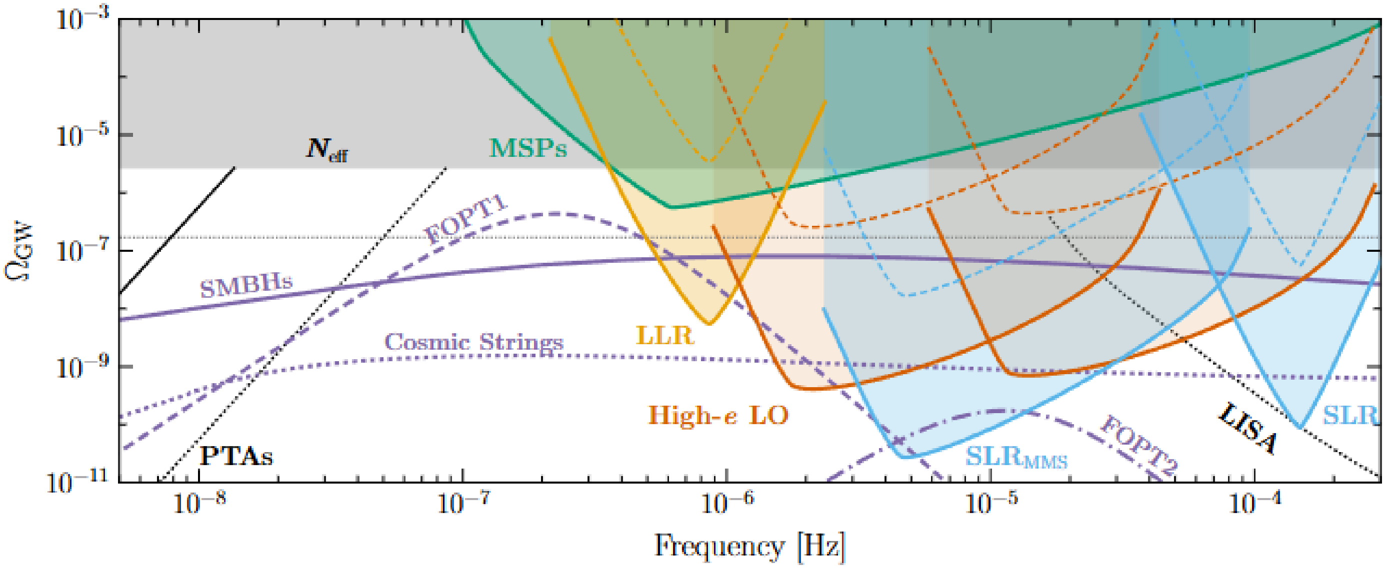
Discovery at Interferometers ⇒ Signal at PTAs





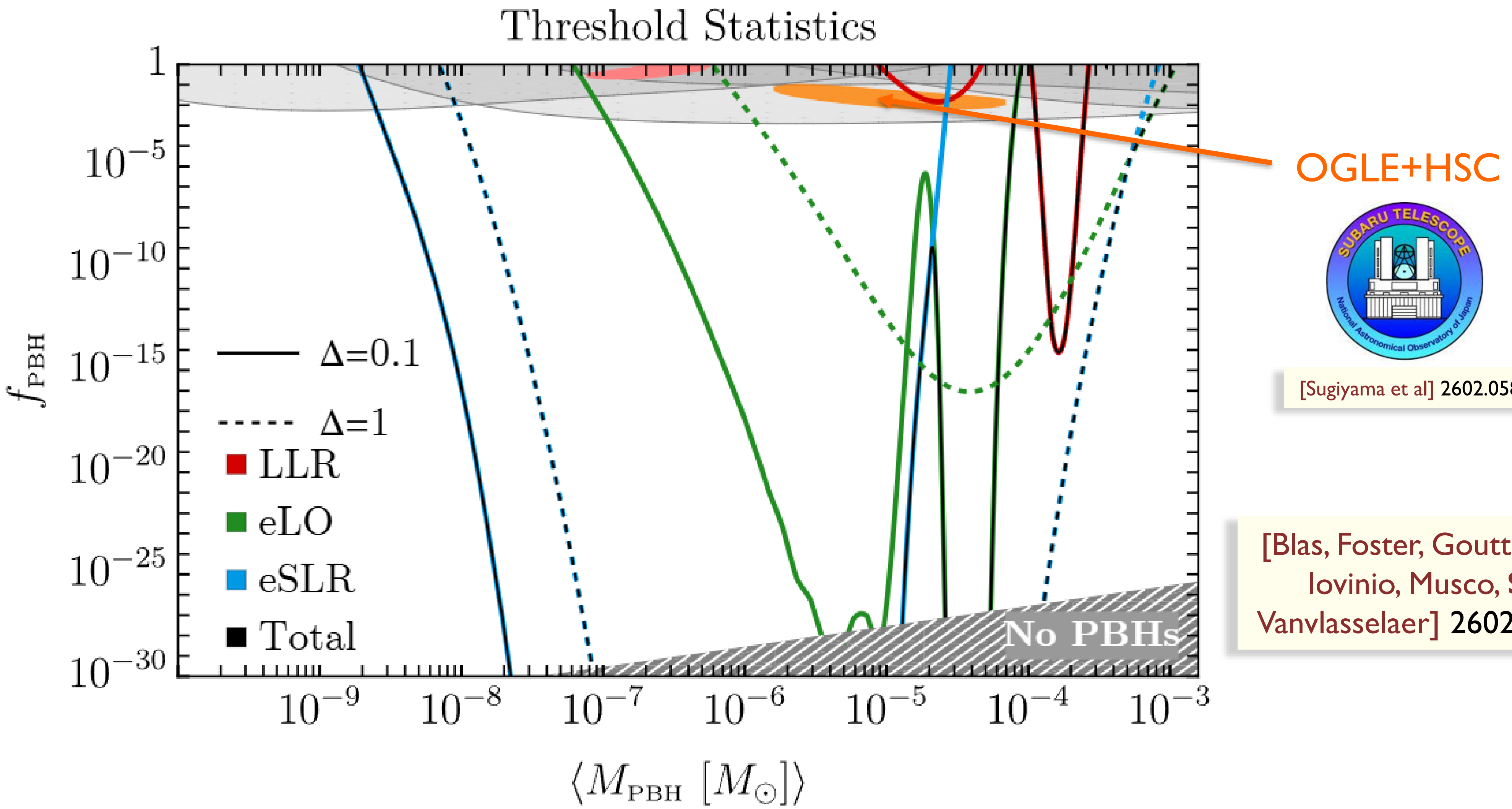
New Experiment to Close the μHz Gap: Lunar Laser Ranging (LLR)

- Exploit resonant response of gravitationally bound systems, such as the Earth-Moon (LLR) as well as Earth-satellite binaries (SLR) to a persistent GW signal: $f_{\rm GW} = \frac{n}{P_{\rm lunar}}$.
- The GW induces a tidal acceleration $a_i = \frac{1}{2}\ddot{h}_{ij}r^j$ on the Earth-Moon separation, and the observable perturbation $\delta r \propto hT_{\rm obs}^2$.



[Blas et al] 2602.12252

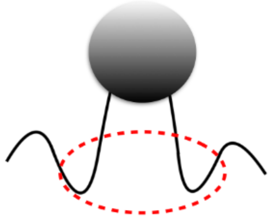
Constraints by Laser Ranging



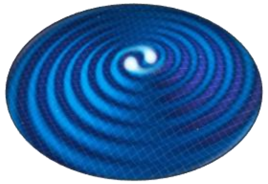
[Sugiyama et al] 2602.05840

[Blas, Foster, Gouttenoire, Iovinio, Musco, **ST**, Vanvlasselaer] 2602.12252

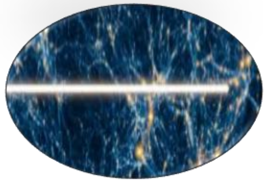
Outline



I. PBH formation

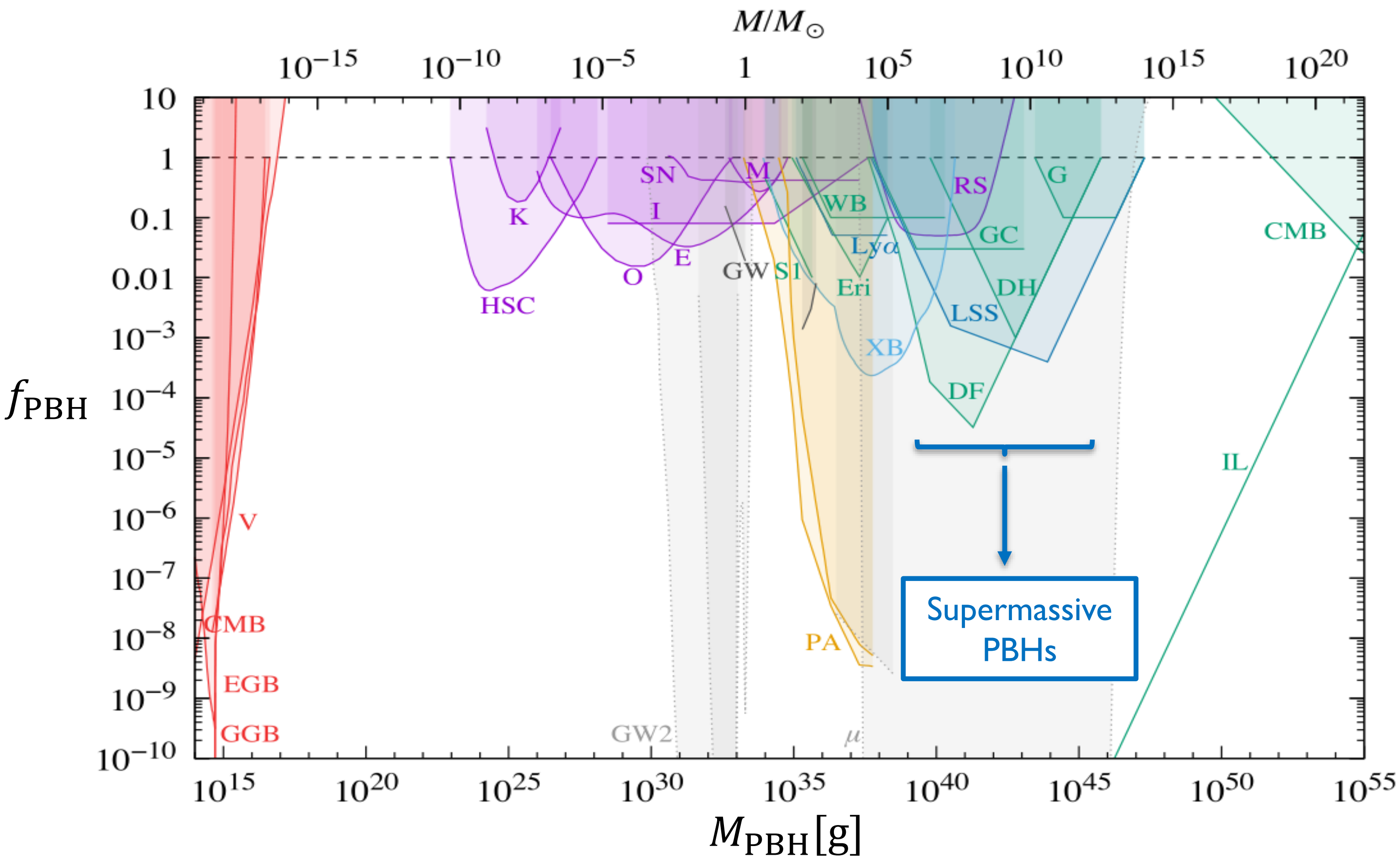


II. Gravitational Waves from PBHs

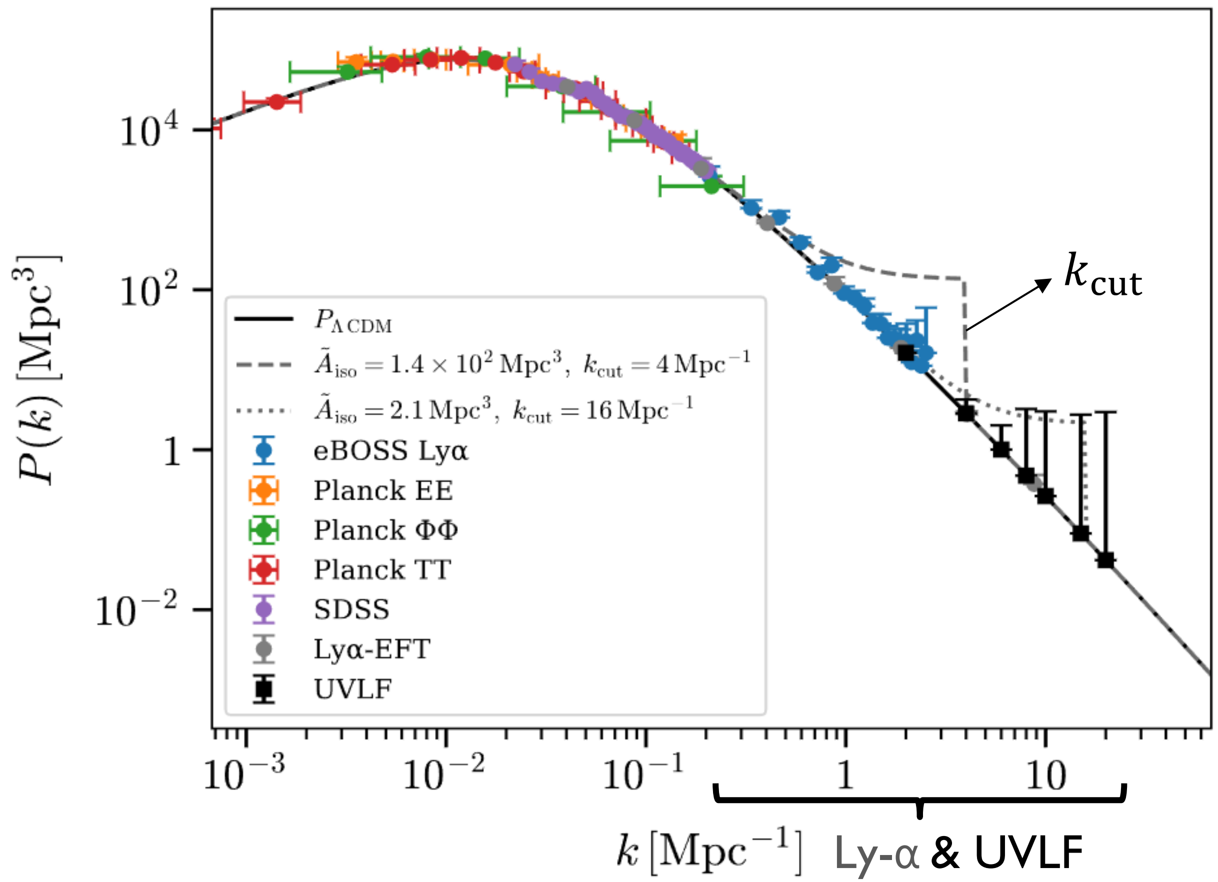


III. LSS constraints on Supermassive PBHs

Supermassive PBHs



Seeds of accelerated structure formation



[Gorghetto, **ST**, Valogiannis] 2511.04734 [Ivanov, **ST**] 2508.04767

- On large scales, we expect $\rho_{\rm PBH}$ to follow the adiabatic perturbations $\delta_{\rm ad}$.
- On small enough scales, due to the discrete nature of PBHs an *isocurvuture* component is generated.
- The **matter-power_spectrum** is enhanced:

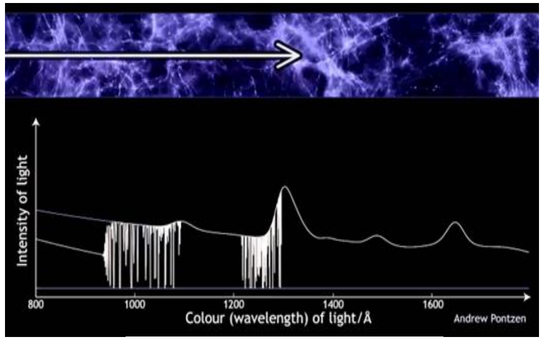
$$P(k) = P_{\rm ad}(k) + P_{\rm iso}(k)\ ,$$

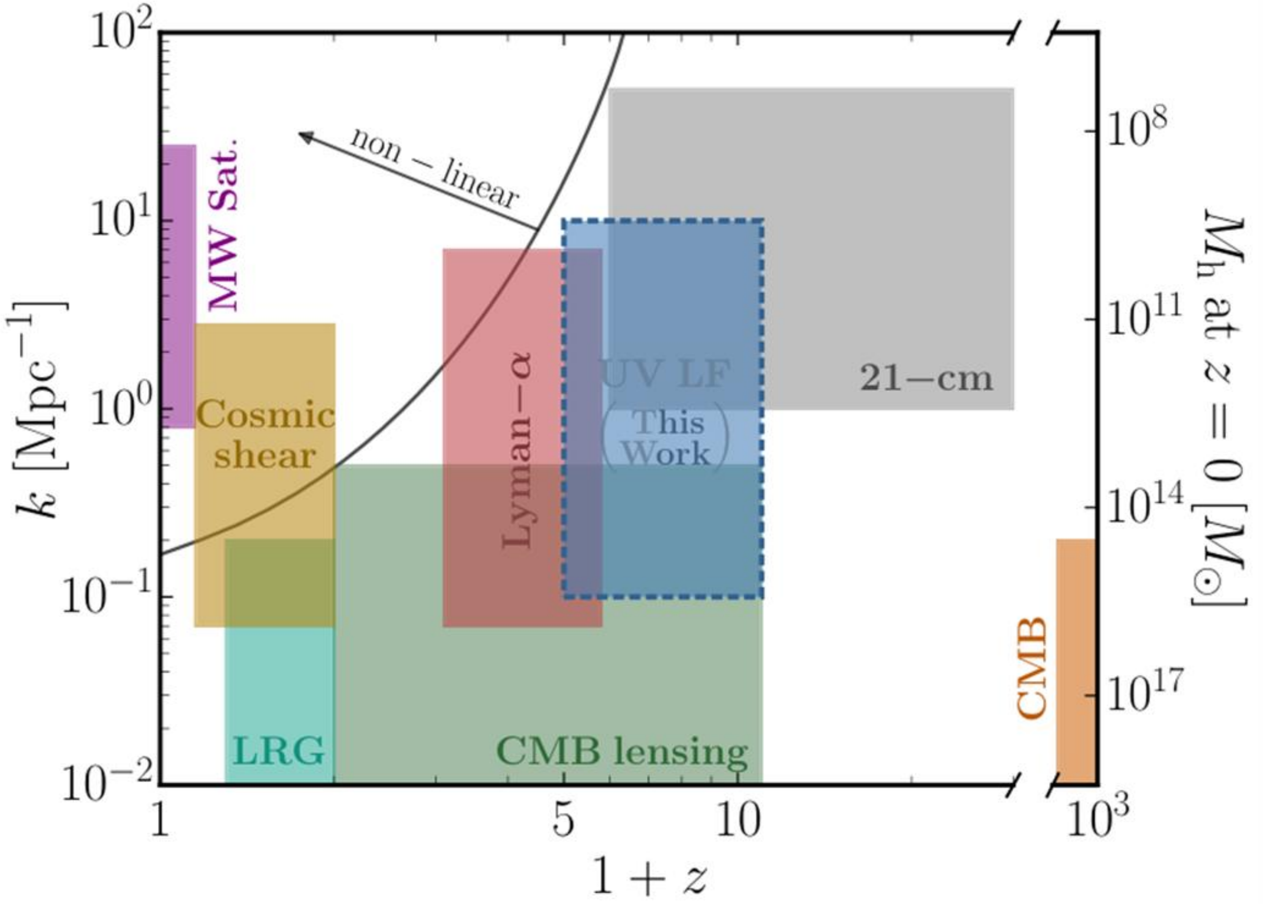
$$P_{\rm iso}(k) \simeq \begin{cases} \dfrac{(f_{\rm PBH} D(0))^2}{\bar{n}_{\rm PBH}}\ , & \text{if } k \leq k_{\rm cut} \\ 0\ , & \text{otherwise} \end{cases}$$

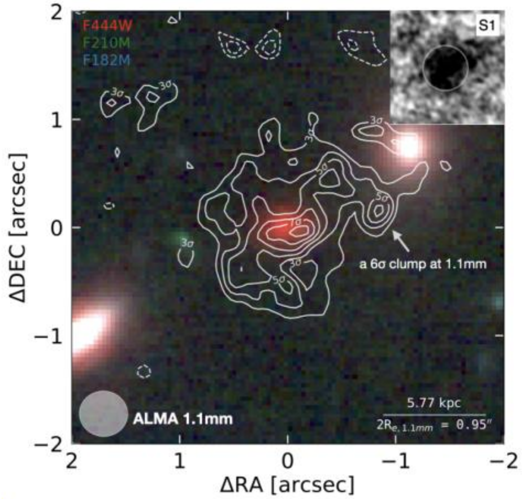
[Afshordi, McDonald, Spergel] astro-ph/0302035 [Inma, Ali-Haimoud] 1907.08129

- Could they be the seeds of massive galaxies at unexpectedly high redshifts $7 < z < 12$ observed by JWST surveys? [Hütsi et al] 2211.02651

The new Golden Era for Cosmology: Large-scale Structure (LSS)







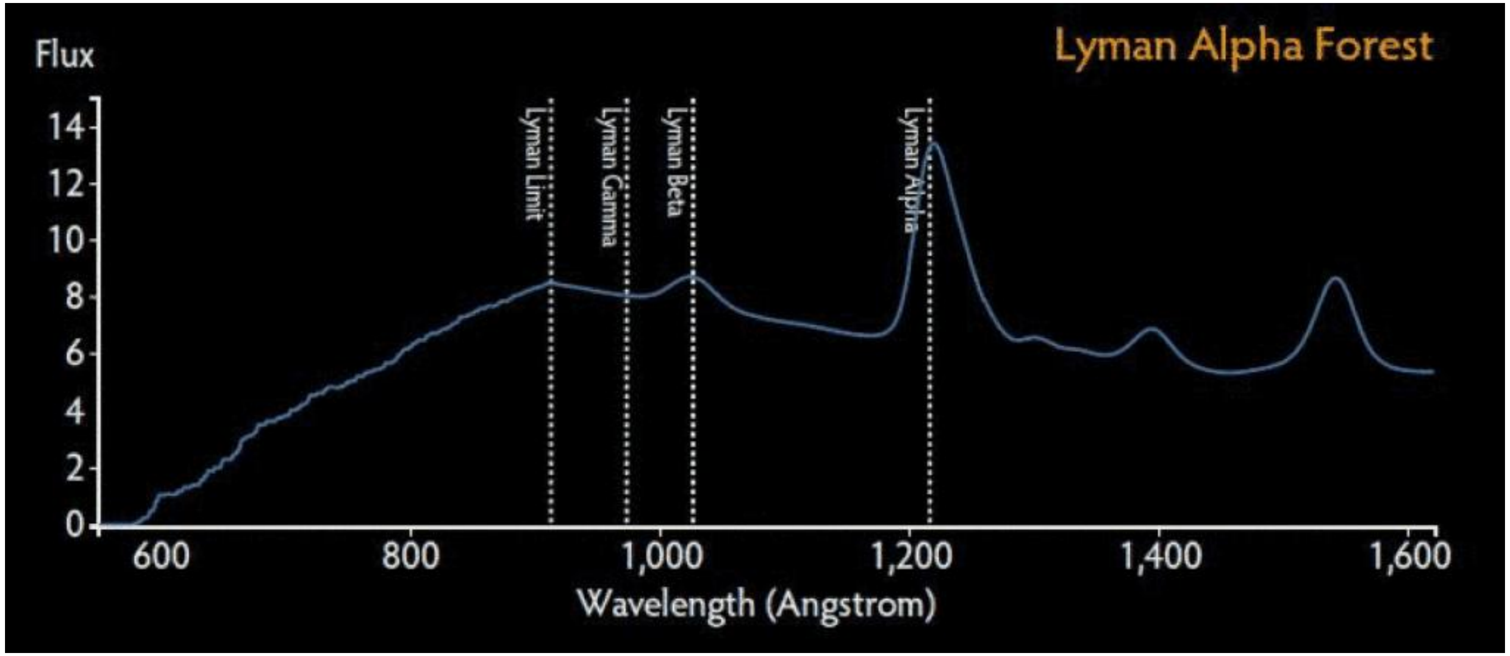
[Sabti, Munoz, Blas] 2110.13161

Sokratis Trifinopoulos

The Lyman-α forest

- The Ly-α forest arises from the $\mathrm{n} = 2 \rightarrow n = 1$ electron transition of the H-atom ($\lambda_0 = 1216$ Å) observed at a range of redshifts due to multiple absorptions inside clouds of intergalactic gas in superclusters.

- It is a powerful tool for tracing the dark matter distribution at (sub)galactic scales.

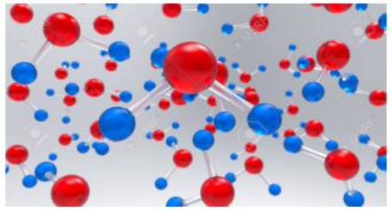


An Effective Field Theory (EFT) approach

effective fluid *full N-body + hydro simulations*

$k_{\rm NL} \sim 5$ $k_J \sim 10\ h\ {\rm Mpc}^{-1}$

[Ivanov] 2309.10133



- The EFT exploits the existing symmetries, i.e. equivalence principle and SO(2) invariance around the line-of-sight:

15 nuisance parameters for Ly-α EFT

$$\delta_F = b_1\delta + \frac{b_2}{2}\delta^2 + \ldots + b_\eta \eta \qquad \eta \equiv \frac{\partial_z v_z}{aH}$$

Perturbation Theory:

✗ limited range

✓ precision & accuracy

✓ fast/cheap BΛCDM

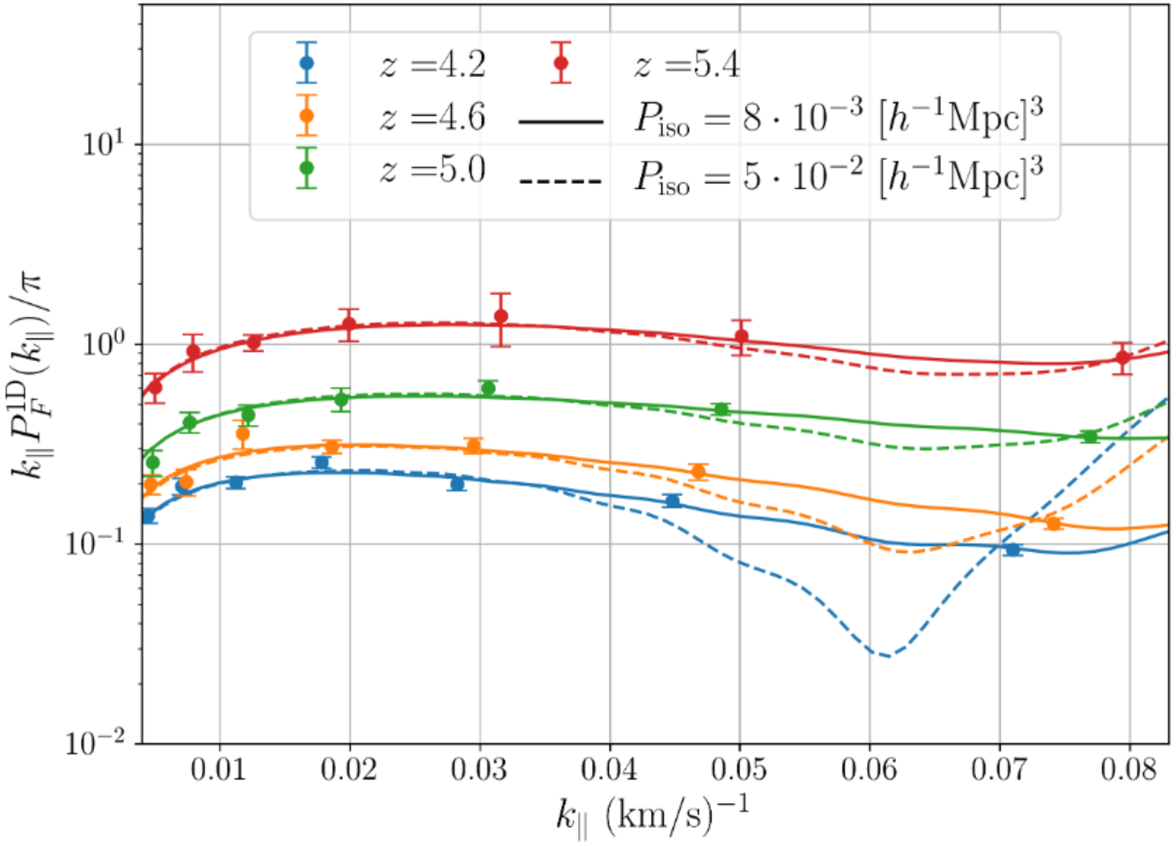
Simulations:

✓ very large range (N-body)

✗ galaxy formation

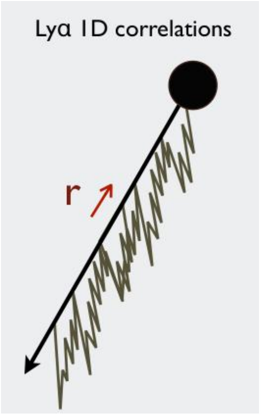
✗ resource-intense

1D spectra at small scales



[Ivanov, **Trifinopoulos**] 2508.04767

- The 1D power spectra are available from HIRES/MIKE surveys for $z \lesssim 5.4$.



- The EFT can descrive the full 3D spectrum. Then the 1D spectra are:

$$P_{\rm 1D}(k_{\parallel}) = \frac{1}{2\pi}\int_{k_{\parallel}}^{k_{\rm max}} dk\ k P_{\rm 3D}(k, k_{\parallel}) + \mathcal{C}_0 + \mathcal{C}_1 k_{\parallel}^2 + \mathcal{C}_2 k_{\parallel}^4$$

projection along the LOS

UV-sensitive contributions captured by the EFT!

- We use the `MontePython` sampler to perform likelihood analysis of the enhanced power-spectrum with a modified code of `CLASS`.

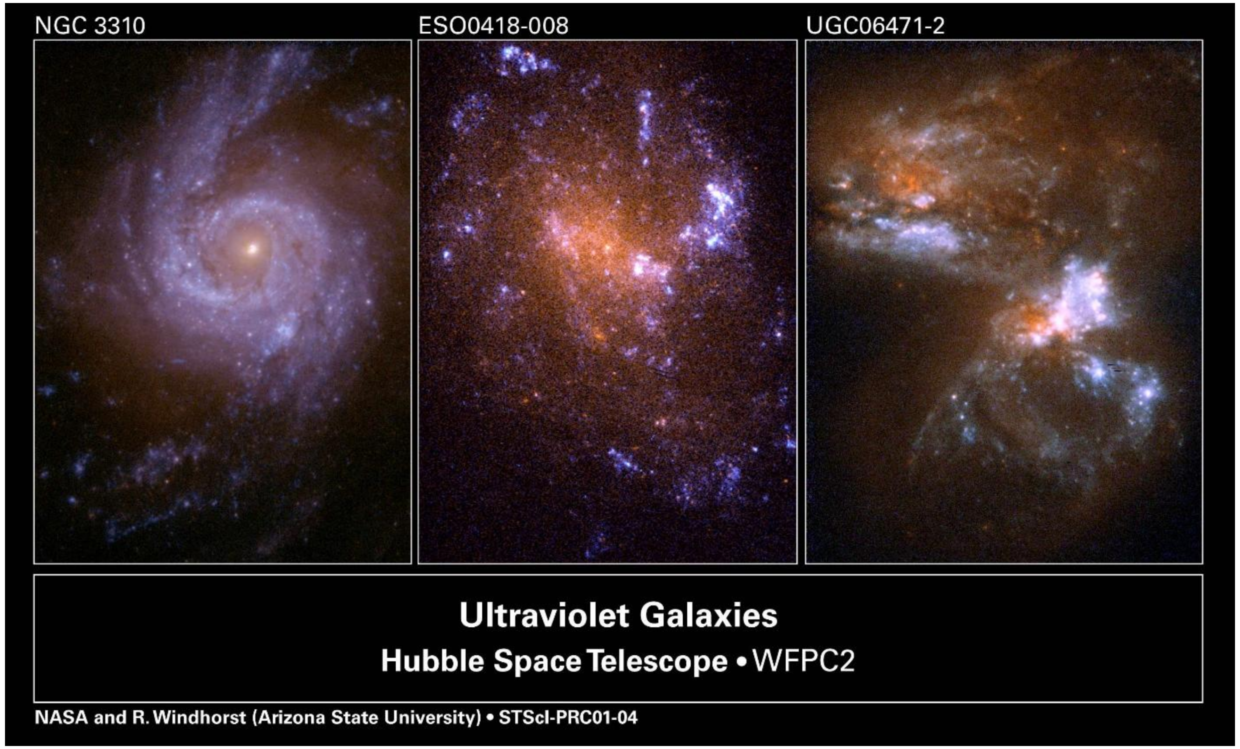
[Brinckmann, Lesgourgues] 1804.07261

[Chudaykin, Ivanov, Philcox, Simonovic] 2004.10607

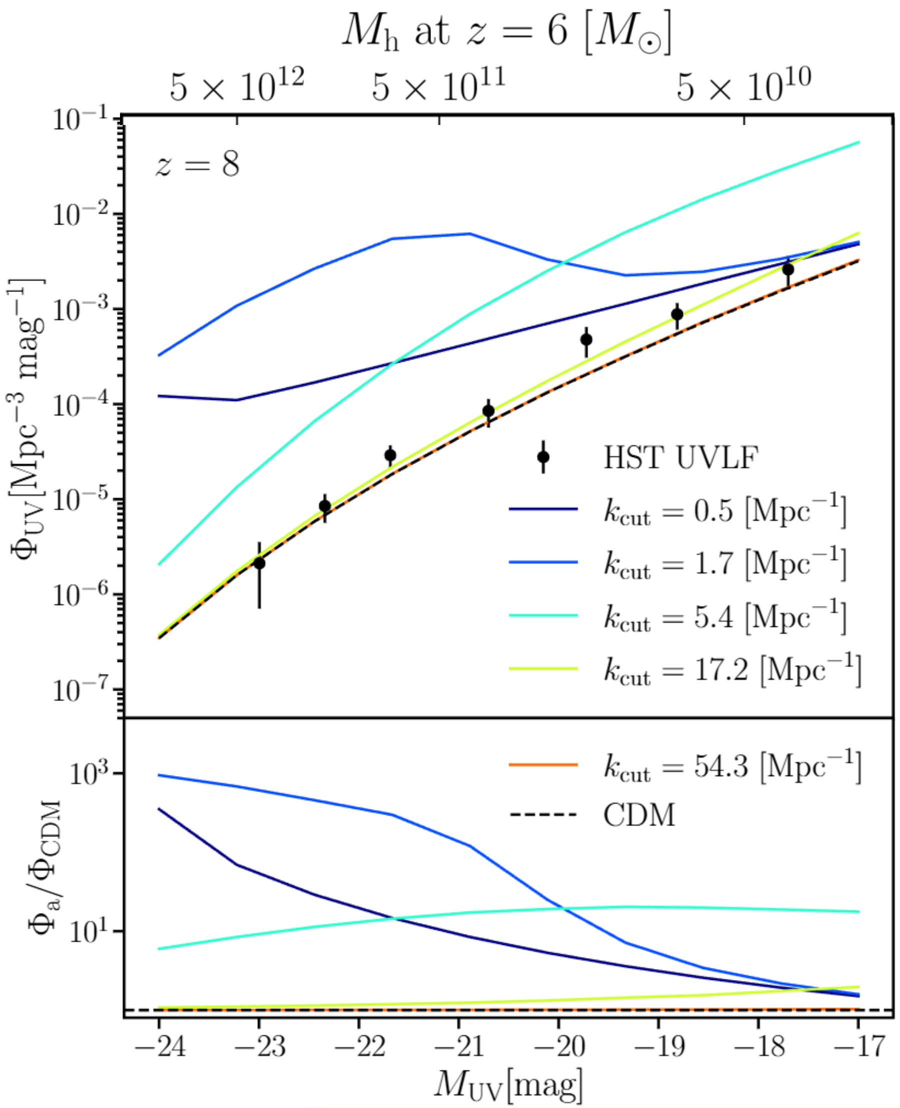
CERN

UV light from Early Stars

- Young massive stars emit primarily in the ultraviolet region.
- The Hubble Space Telescope (HST) has discovered $O(10^4)$ of UV-bright galaxies.



HST UV Luminosity Function (UV LF)



[Gorghetto, **Trifinopoulos**, Valogiannis] 2511.04734

- In Press-Schechter theory, **halos** correspond to regions where the smoothed δ exceeds a critical collapse threshold.
- Halo-Mass Function (HMF) depends on $\mathcal{P}(k)$.
- The HST catalogues probe the range $7 < z < 10$ via the UV LF:

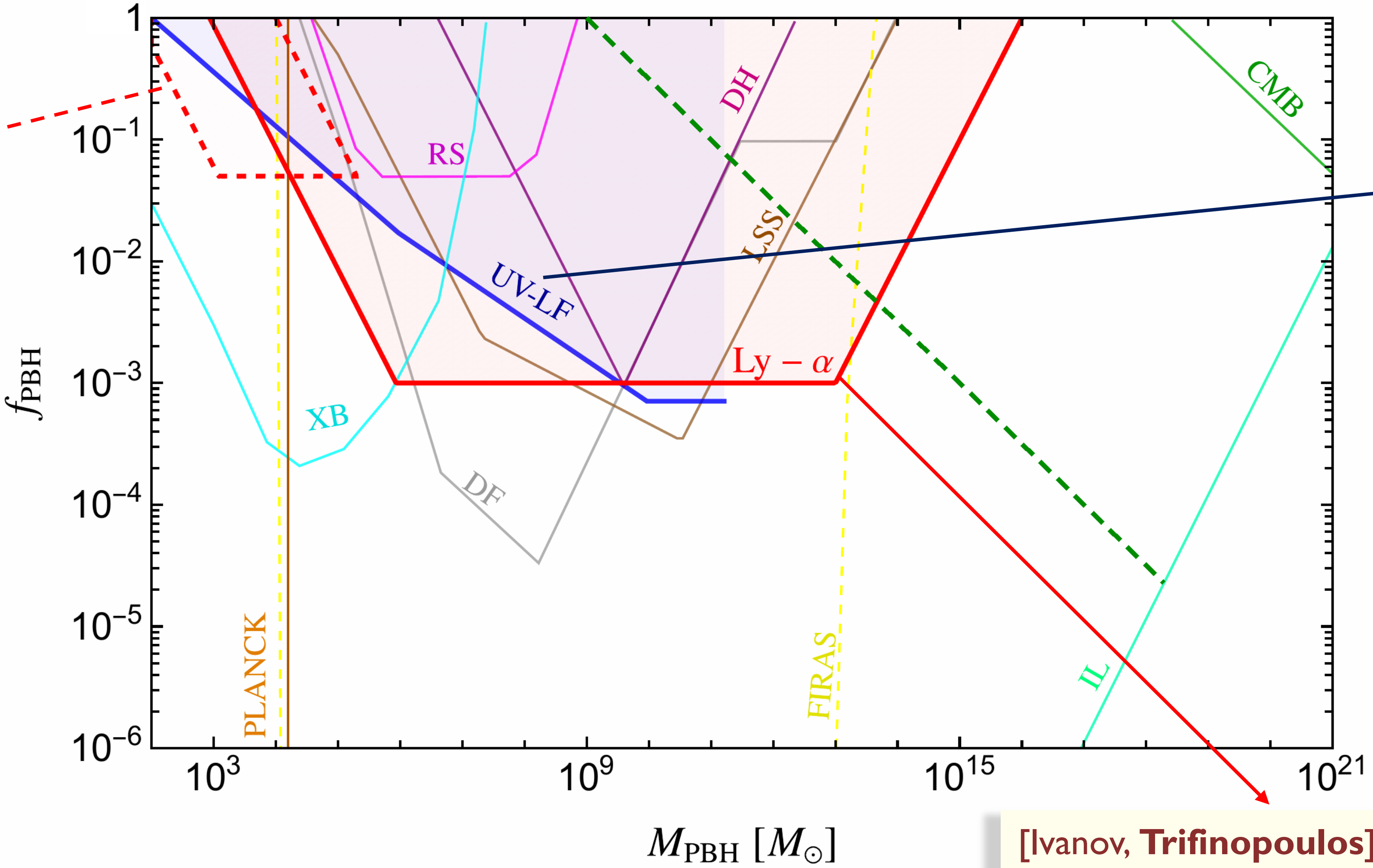
$$\Phi_{UV} = \underbrace{\frac{dn_h}{dM_h}}_{\text{cosmology (7 params)}} \times \underbrace{\frac{dM_h}{dM_{UV}}}_{\text{astrophysics (8 params)}}$$

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

- We use the likelihood code `GALLUMI` to constrain modifications to UVLF due to $\mathcal{P}_{iso}(k)$.

Curbing Supermassive PBHs with LSS

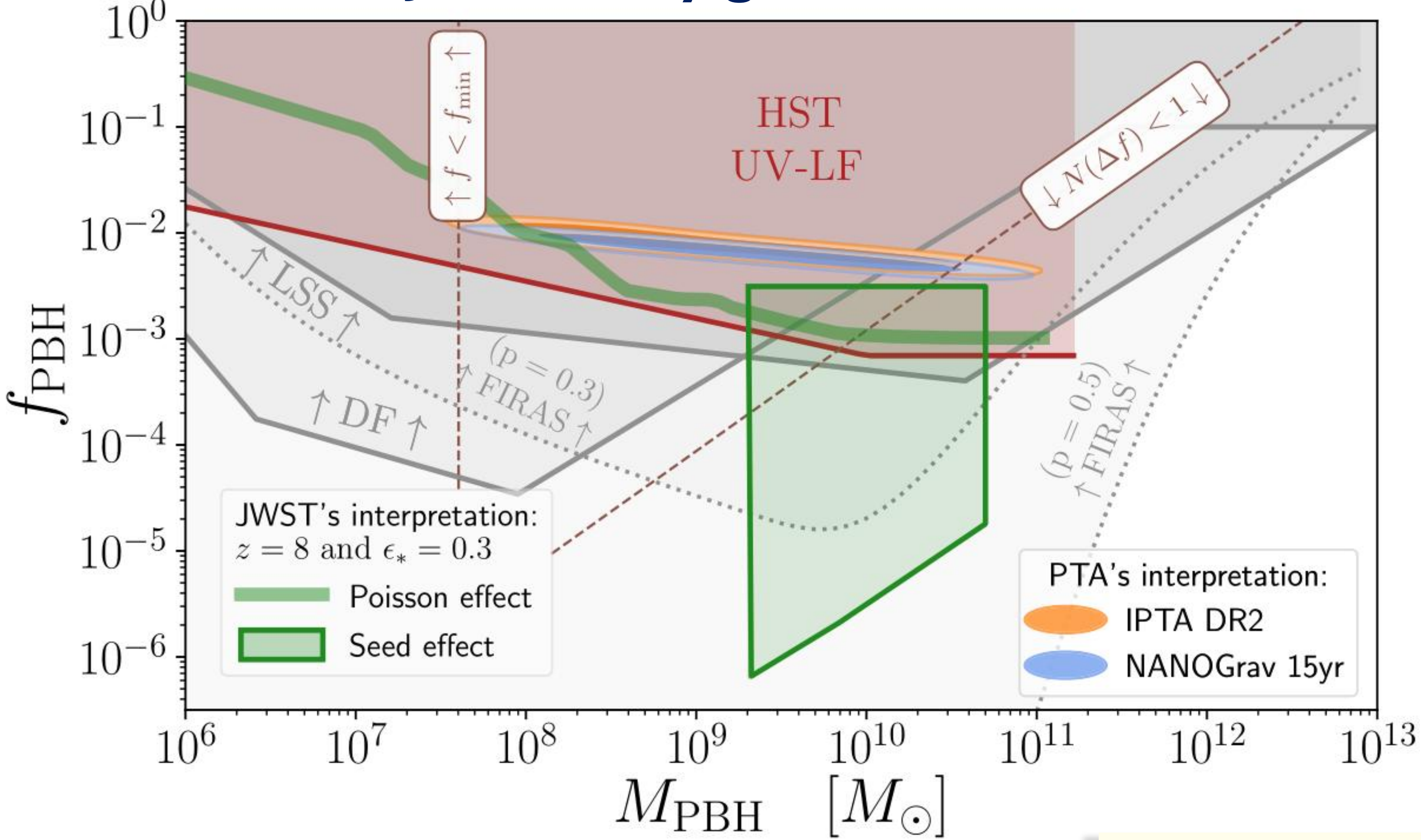
[Murgia, Scelfo, Viel, Raccanelli] 1903.10509



[Gouttenoire, **Trifinopoulos**, Valogiannis, Vanvlasselaer] 2307.01457

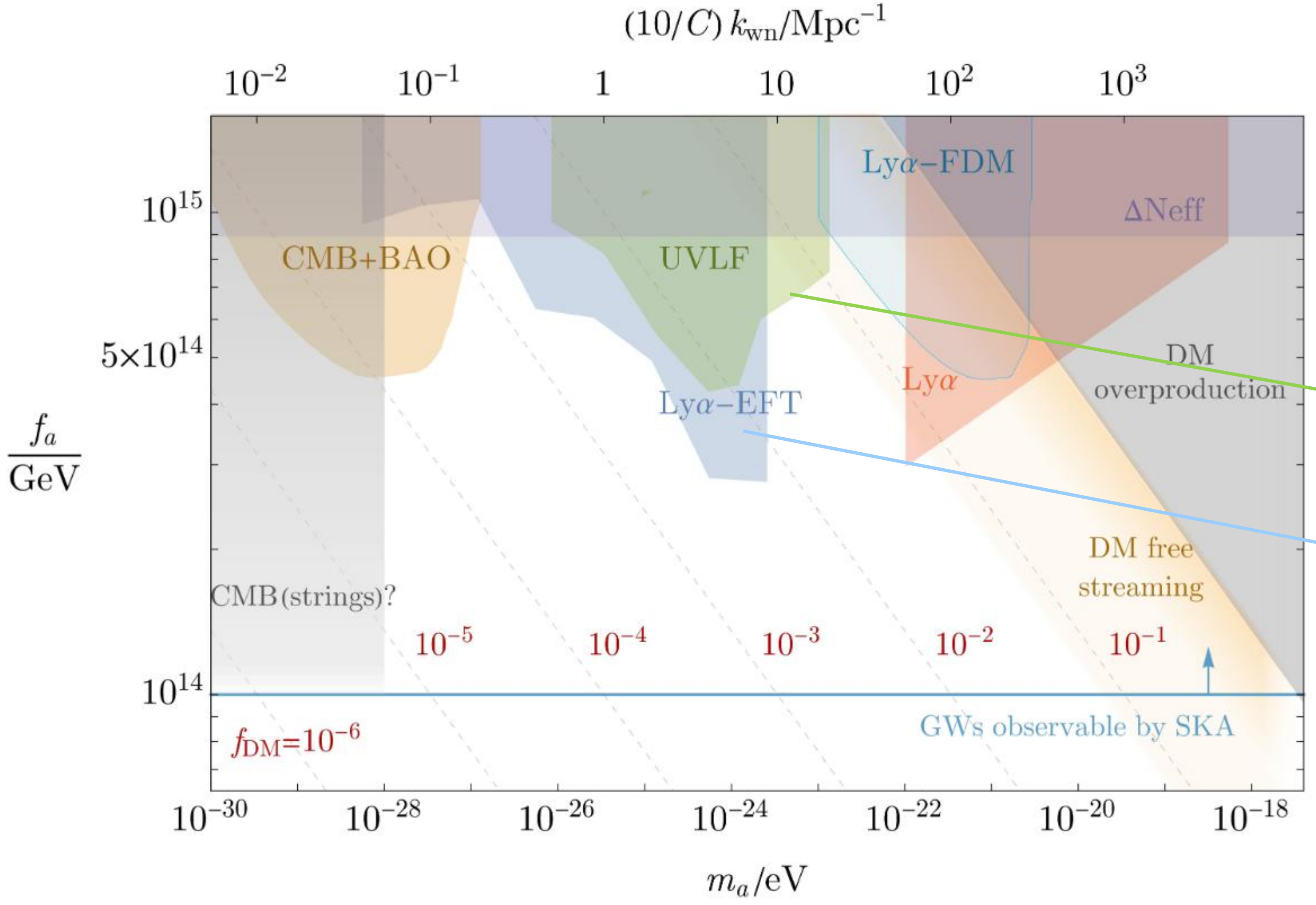
[Ivanov, **Trifinopoulos**] 2508.04767

JWST early galaxies + PTAs



[Gouttenoire, **Trifinopoulos**, Valogiannis, Vanvlasselaer] 2307.01457

Novel Constraints on Ultralight Dark Matter!

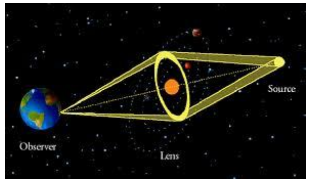


[Gorghetto, **Trifinopoulos**, Valogiannis]
2511.04734

[Ivanov, **Trifinopoulos**]
2508.04767

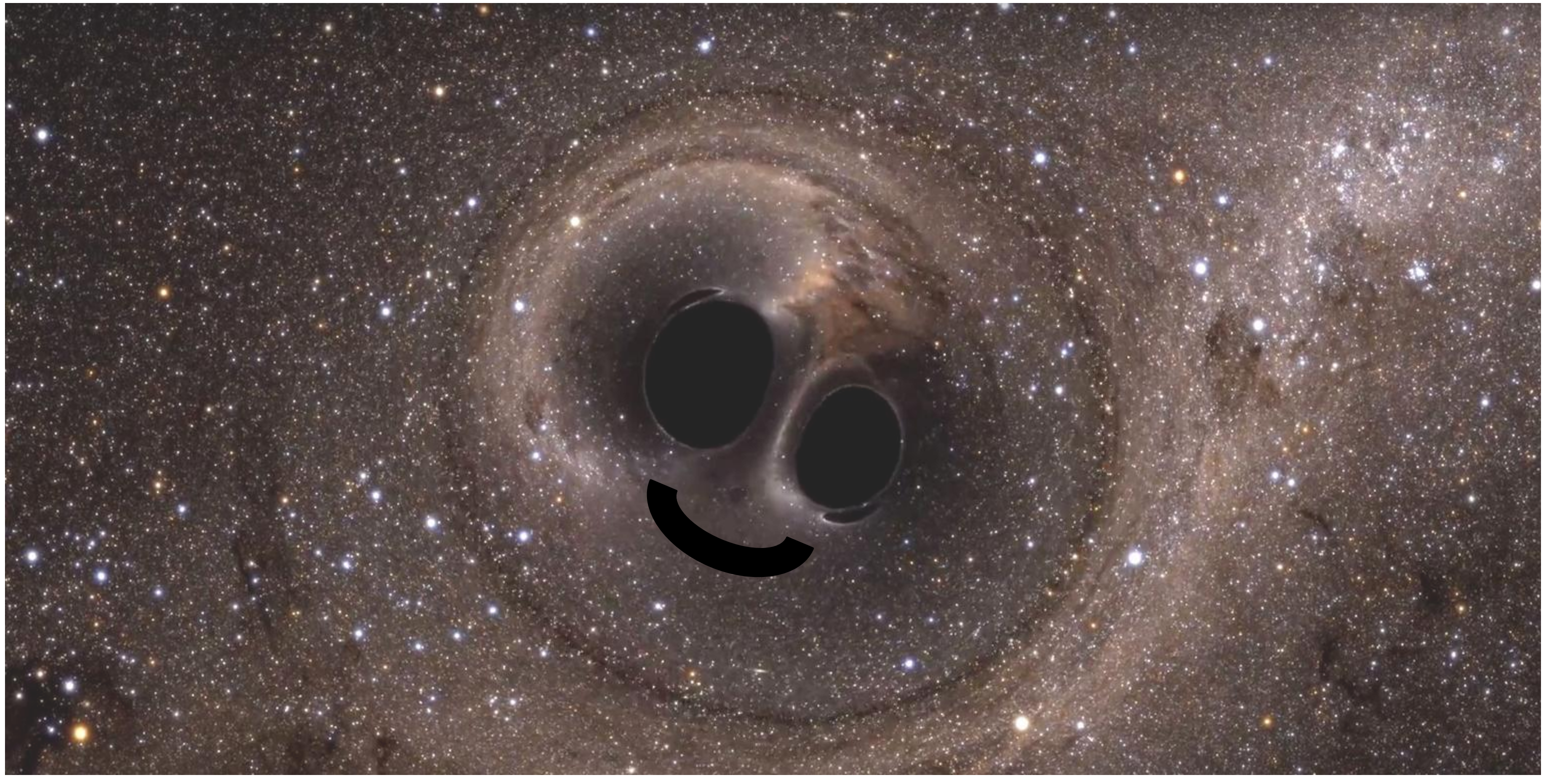
Conclusions

1. "Would a potential discovery of subsolar PBH merger event at LVK/ET/CE (or HSC) imply an associated effect at PTAs (or LLR)?" – YES! Even merger events that could appear at LVK O5 would accommodate both signals!



2. "What can the high-redshift Lyman-α forest and the UVLF tell us about supermassive PBHs?" – That they are ruled out for $f_{\rm PBH} > 10^{-3}$ and $10^5 \lesssim \frac{M_{\rm PBH}}{M_\odot} \lesssim 10^{15}$.

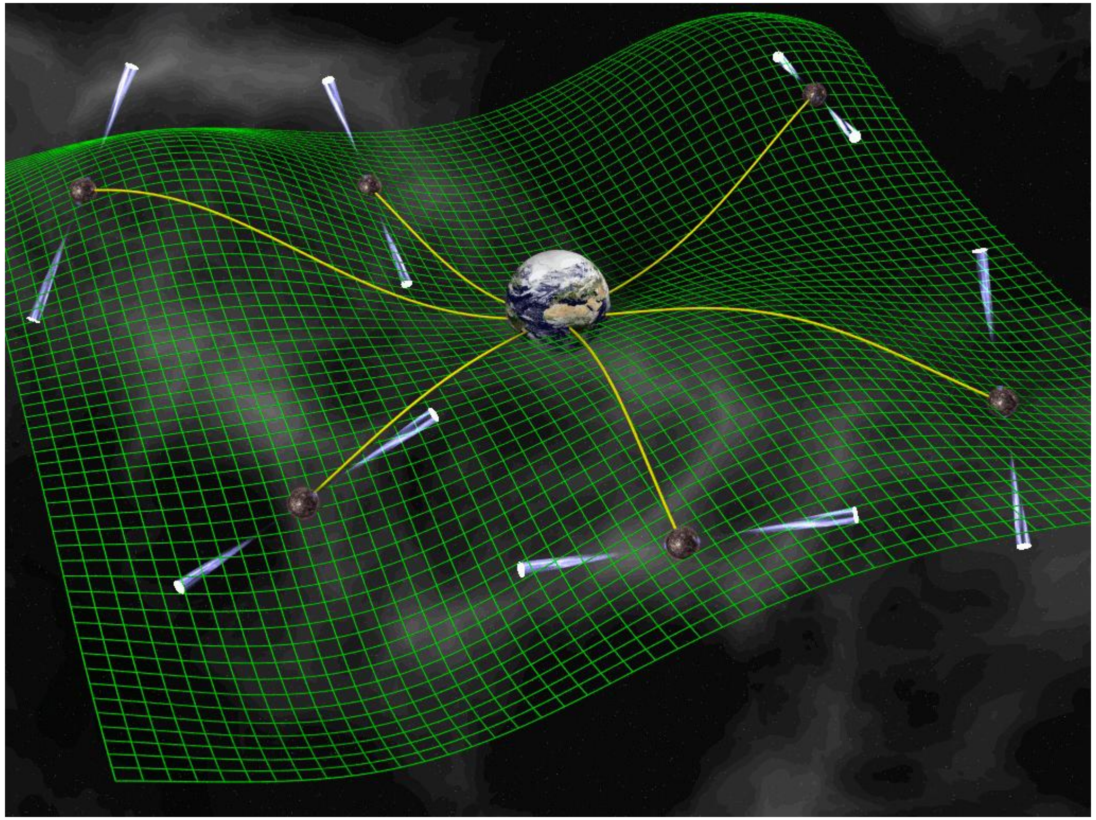
Thank you!!!!



Backup slides

Pulsar Timing Arrays

- The NANOGrav combined with 4 PTA collaborations have released strong evidence (**3.5-4σ**) for the existence of a *stochastic* **Gravitational Wave background** in the nHz range.



67 pulsars
15 years

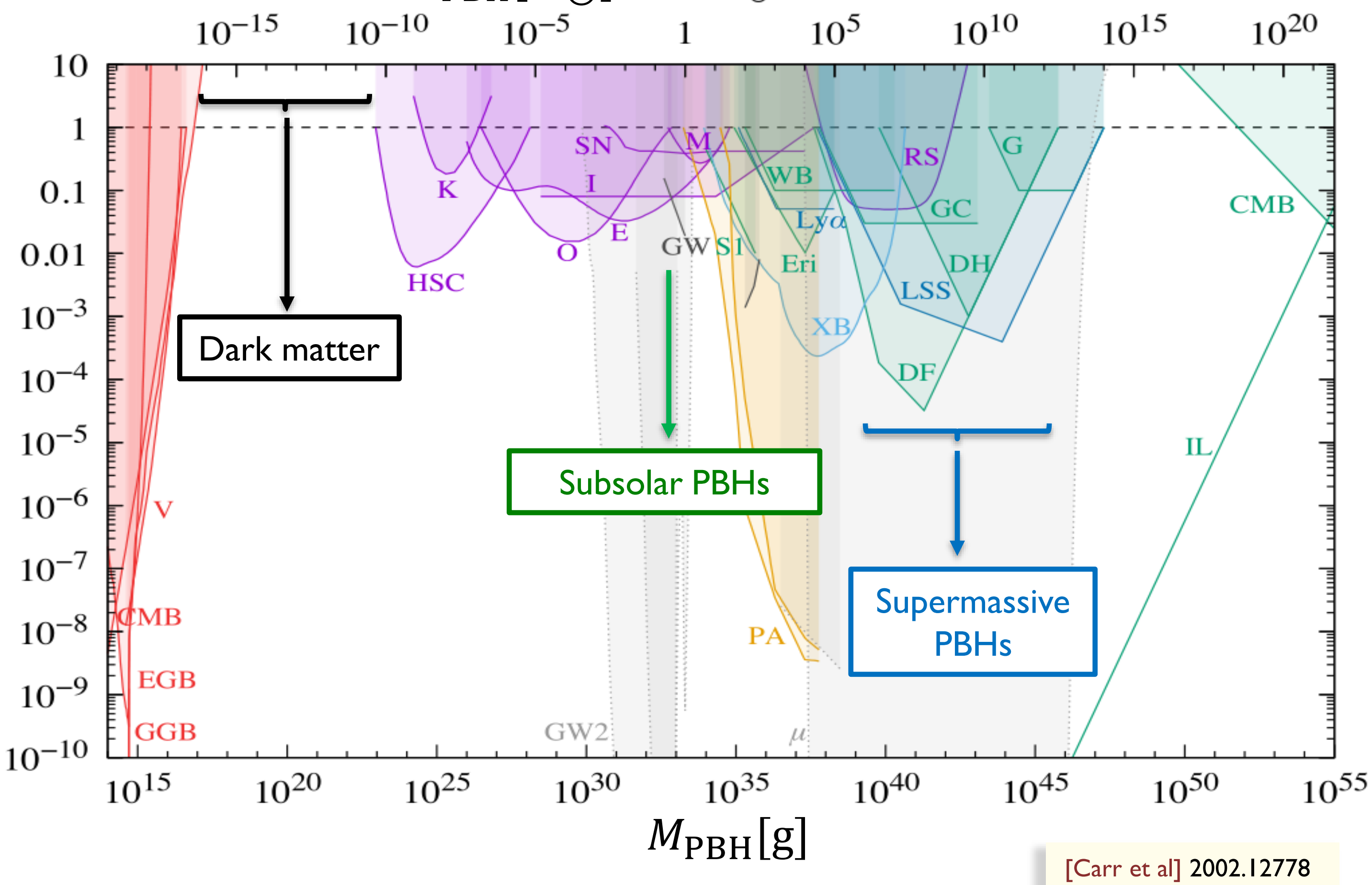
[NANOGrav] 2306.16213

CERN

PBH Spectrum

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

$$f_{\rm PBH} = \frac{\rho_{\rm PBH}}{\rho_{\rm DM}}$$



[Carr et al] 2002.12778

Sokratis Trifinopoulos

Setting the stage for PBH formation

- **Formalism**: i) In the long-wavelength approximation: $\epsilon(t) = \frac{1}{a(t)H(t)\hat{r}_k} \ll 1$, the perturbation is super-horizon, and we may assume that each patch evolves as if it is part of a separate FRLW-like universe.

$$ds^2 = -dt^2 + a^2(t)e^{2\zeta(r)}\left[dr^2 + r^2 d\Omega\right]$$

[Shibata, Sasaki] gr-qc/9905064
[Polnarev, Musco] gr-qc/0605122
[Harada, Yoo, Nakama, Koga] 1503.03934

ii) We solve the *Misner-Sharp-Hernandez* equations and obtain the density contrast:

$$\frac{\delta\rho(r,t)}{\rho_b(t)} = -\frac{4}{3}\mathcal{F} r_k^2 \epsilon(t)^2 e^{-5\zeta(r)/2}\Delta\left(e^{\zeta(r)/2}\right)$$

} unavoidable non-Gaussianities

❖ at radiation epoch $\mathcal{F} = 2/3$

iii) We define the **perturbation amplitude** as: $\bar{\delta}(\hat{r},t) \equiv \frac{1}{V}\int_0^R \frac{\delta\rho}{\rho_b}(r,t)dV = \left(\frac{1}{a(t)H(t)}\right)^2 \mathcal{F}K(\hat{r})$

❖ curvature: $K(\hat{r})\hat{r}^2 = -r\zeta'(r)(2 + r\zeta'(r))$

- The key quantity that that characterizes an overdensity in a collapsing region is the *compaction function:*

$$\mathcal{C}(\hat{r}) \equiv 2G\frac{M(\hat{r},t) - M_b(\hat{r},t)}{R(\hat{r},t)}$$

[Musco] 1809.02127
[Young, Musco, Byrnes] 1904.00984
[De Luca et al] 1904.00970

- At time of horizon crossing, i.e. $\epsilon(t_H) \equiv 1$, the scale $\hat{r}_m$ where $\mathcal{C}(\hat{r})$ is maximized defines the peak amplitude :

$$\delta_m \equiv \bar{\delta}(\hat{r}_m, t_H) = \mathcal{C}(\hat{r}_m) = \mathcal{F}K(\hat{r}_m)\hat{r}_m^2 = 3\frac{\delta\rho}{\rho_b}(\hat{r}_m, t_H)$$

The PBH mass function (detailed)

- The PBH mass at formation obeys the critical scaling law: $$m_{\rm PBH}(\delta_m) = \mathcal{K} M_H (\delta_m - \delta_c)^\gamma$$

[Choptuik] PRL 70 (1993) 9–12 [Niemeyer, Jedamzik] astroph/9709072(9901292) [Musco, Miller] 1201.2379

- To investigate PBH formation over a wide range of scales, we introduce a smoothing function W:

$$\bar{\delta}(X, t_H) = \int \frac{\delta\rho}{\rho_b}(x, t_H) W(X - x, r_m) d^3x\,, \quad W(\mathbf{x}, r_m) = \frac{\Theta(r_m - X)}{\frac{4}{3}\pi r_m^3}$$

- In Fourier space we obtain: $\delta_m = \delta_\ell - \frac{1}{4\mathcal{F}}\delta_\ell^2\,,\ \ \delta_\ell(k, r_m) = \frac{2}{3}\mathcal{F}(kr_m)^2 \tilde{W}(k, r_m)\mathcal{T}(k, r_m)\zeta(k)$

linear transfer function

Joint PDF and NG mass function

- The statistics of and ζ are described by:

$$\mathrm{P_G}(\delta_\ell,\zeta) = \frac{1}{(2\pi)\sqrt{\det\Sigma}} \exp\left(-\frac{1}{2}Y^{\mathrm{T}}\Sigma^{-1}Y\right), \quad \Sigma = \begin{pmatrix} \langle\delta_\ell^2\rangle & \langle\delta_\ell\zeta\rangle \\ \langle\delta_\ell\zeta\rangle & \langle\zeta^2\rangle \end{pmatrix}, \quad Y = \begin{pmatrix} \delta_\ell \\ \zeta \end{pmatrix}$$

- The correlators are calculated by:

$$\sigma_n^2(r_m) = \left(\frac{2f}{3}\right)^n \int_0^\infty \frac{\mathrm{dk}}{k} (kr_m)^{2n} \tilde{W}^n(k,r_m)\tilde{W}_s^{2-n}(k,r_m)\mathcal{T}^2(k,r_m)\, P_\zeta(k), \quad n = 0,1,2\,.$$

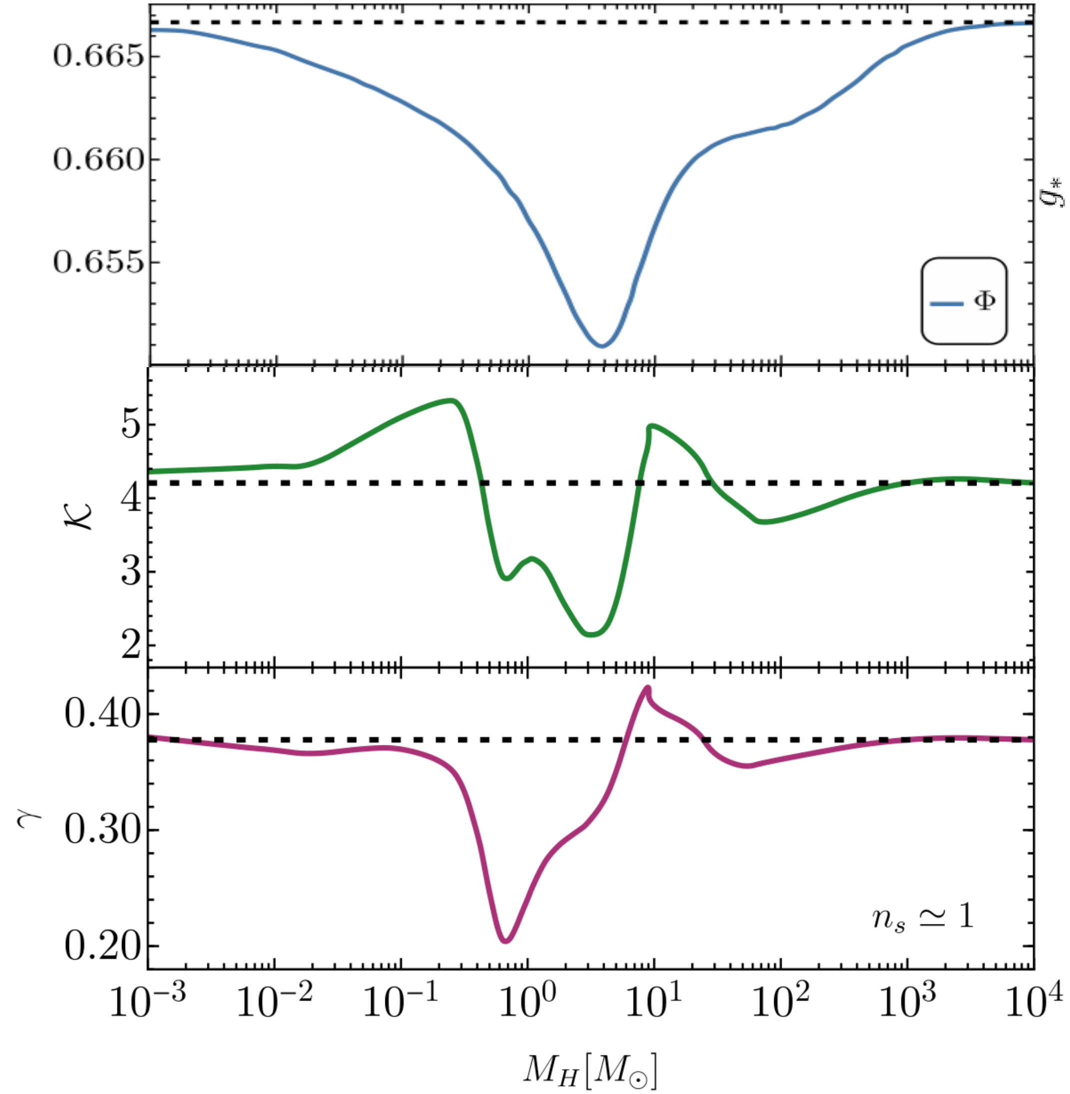
$$\tilde{W}(k,r_m) = 3\frac{\sin(kr_m) - kr_m\cos(kr_m)}{(kr_m)^3} \qquad \tilde{W}_s(k,r_m) = \frac{\sin(kr_m)}{kr_m} \qquad \mathcal{T}(k,r_m) = 3\frac{\sin(c_s kr_m) - c_s kr_m\cos(c_s kr_m)}{(c_s kr_m)^3}$$

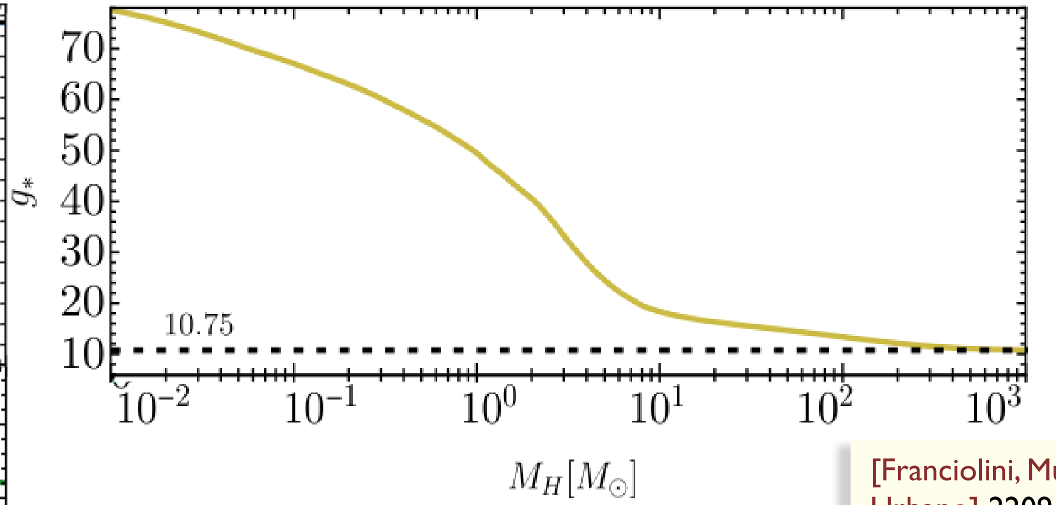
- PBH mass function (with $\delta_\ell = 2\mathcal{F}F'(\zeta)^{-1}\left(1-\sqrt{\Lambda}\right)$, $\Lambda \equiv 1 - \frac{\delta_c}{\mathcal{F}} - \frac{1}{\mathcal{F}}\left(\frac{M_{\mathrm{PBH}}}{\mathcal{K}M_H}\right)^{1/\gamma}$):

$$f_{\mathrm{PBH}}(M_{\mathrm{PBH}}) = \frac{1}{\Omega_{\mathrm{DM}}}\int_{M_H^{\mathrm{min}}}^\infty d\ln M_H \left(\frac{M_{\mathrm{eq}}}{M_H}\right)^{1/2}\left(\frac{M_{\mathrm{PBH}}}{\mathcal{K}M_{\mathrm{H}}}\right)^{\frac{1+\gamma}{\gamma}} \frac{\mathcal{K}}{\gamma\sqrt{\Lambda}}\int_{-\infty}^\infty d\zeta\,\mathrm{P_G}(\delta_\ell,\zeta)F'(\zeta)^{-1}$$

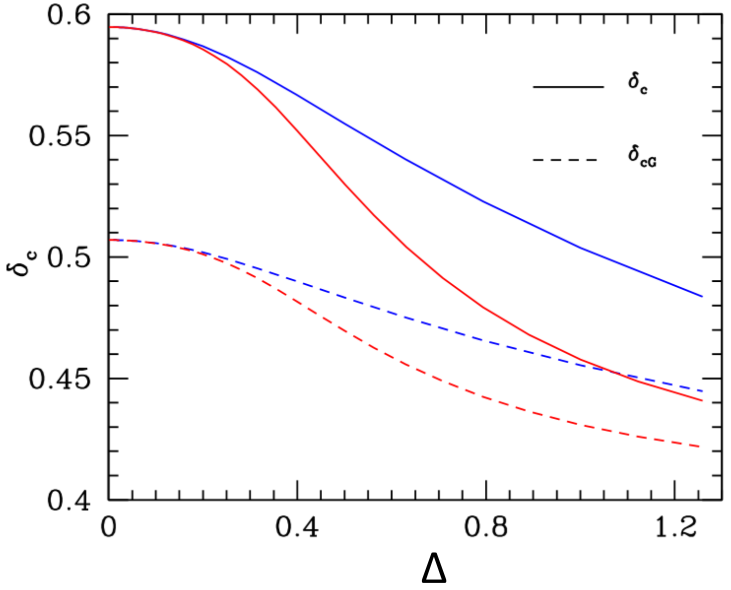
[Meng, Yuan, Huang] 2207.07668 [Young] 2201.13345 [Ferrante et al] 2211.01728

QCD Phase Transition & Threshold/Shape dependece





[Franciolini, Musco, Pani, Urbano] 2209.05959



[Musco, De Luca, Franciollini, Riotto] 2002.12778

Sokratis Trifinopoulos

GW strain (Fourier space)

- The empirical expression for the Fourier-transform of the strain amplitude reads

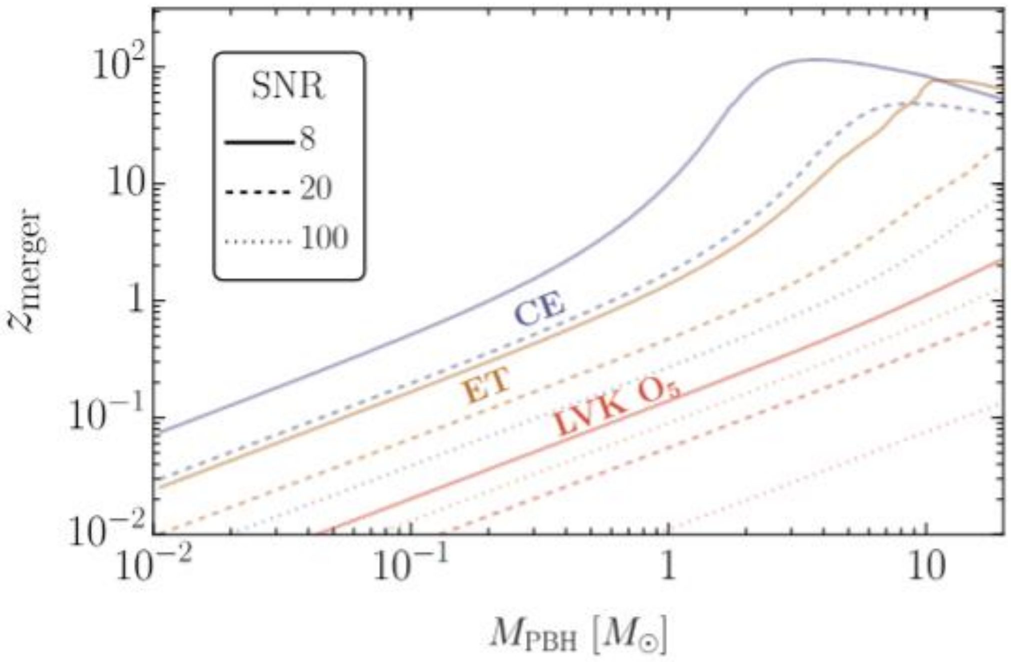
$$\tilde{h}(f,z) = \sqrt{\frac{5\eta}{24}} \frac{(G(1+z)(2M_{\rm PBH}))^{5/6}}{\pi^{2/3} d_L(z)} \times \begin{cases} f^{-7/6} \,, & f < f_{\rm merg} \\ f^{-2/3} f_{\rm merg}^{-1/2} \,, & f_{\rm merg} < f < f_{\rm ring} \\ f_{\rm ring}^{-2/3} f_{\rm merg}^{-1/2} \left(\frac{\sigma^2}{\sigma^2 + 4(f - f_{\rm ring})} \right) \,, & f_{\rm ring} < f < f_{\rm cut} \end{cases}$$

[Ajith et al] 0710.2335

$$d_L(z) = d_c(z)(1+z) = (1+z) \int_0^z \frac{dz'}{H[z]}$$

- The transition frequencies that separate the inspiral, merger and are fitted to template waveform.

Subsolar Merger Event = Susolar PBH?



- The detectability of a merger event is quantified by the *signal-to-noise ratio* **SNR.**

- There are three alternative scenarios beyond our scope:

1. Stellar transmutation: subsolar astrophysical objects, e.g. white dwarves, could accrete (certain types of) DM and convert to BHs. ➡ Earlier stages in stellar life cycle: $z > 1$

   [Dasgupta, Laha, Ray] 2009.01825 [Chakraborty, Bhattacharyya] 2401.08462

2. Exotic compact objects: Q-balls, boson states, fermion soliton stars can be distinguished from BHs based on their tidal deformabilities. ➡ More statistics: SNR> 12

   [Crescimbeni et al] 2402.18656, 2408.14287 [De Luca et al] 2106.13769

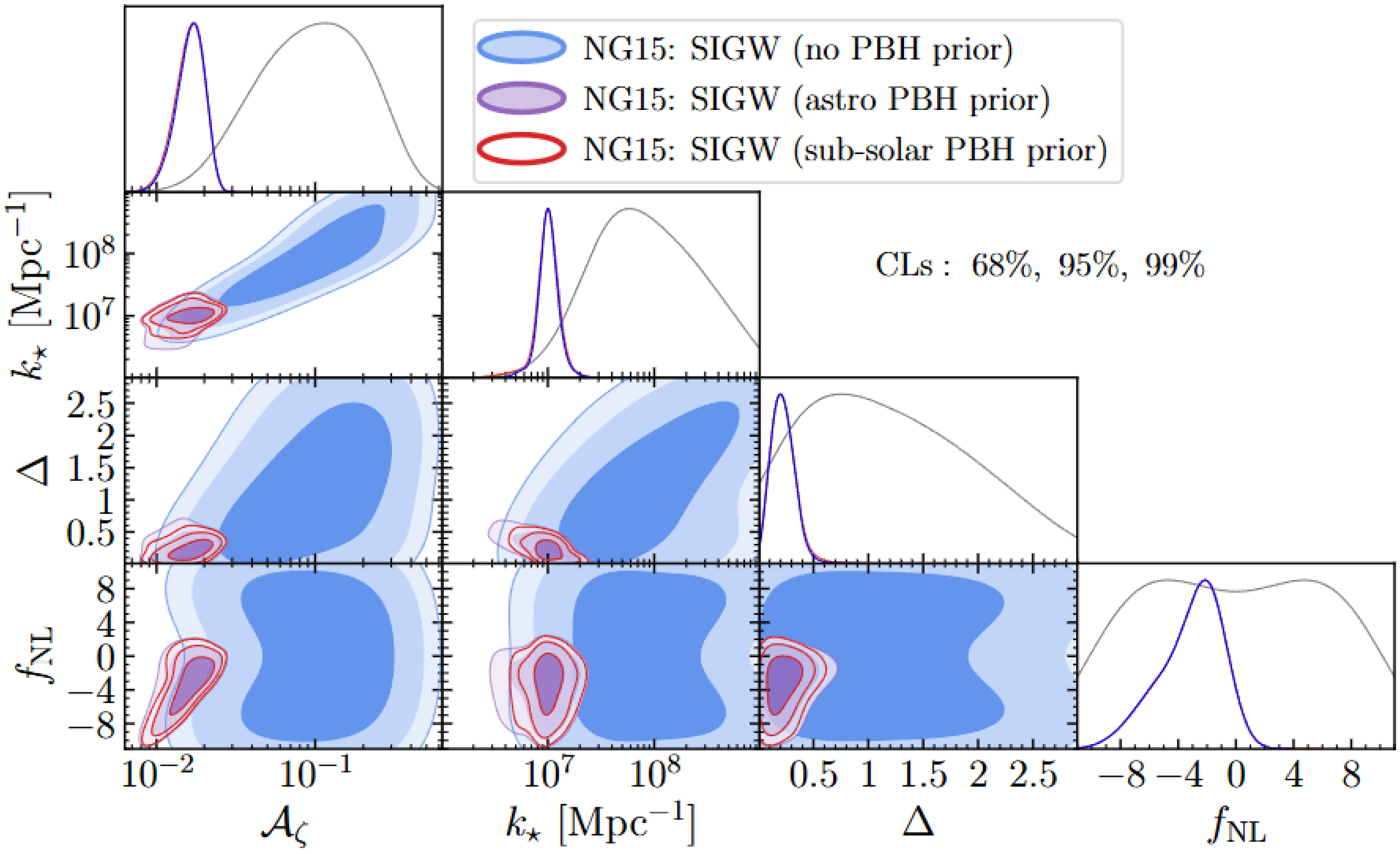
3. PBHs of different origin than inflation. 🤷‍♂️

   [Flores, Kusenko] 2404.05430

Bayes Factors

Prior on PBHs		Model X = SMBH only	Model Y	$\text{Log}_{10}\, \mathcal{B}_{\mathbf{Y},\mathbf{X}}$ (± 0.10)			
				Threshold statistics			Peak theory
				$f_{\rm NL} = 0$	$f_{\rm NL} = -2$	$\lvert f_{\rm NL}\rvert < 10$	
No prior		free amplitude	SIGW	1.67	1.74	1.74	1.67
			SIGW+SMBH	1.57	1.64	1.64	1.57
		`GWOnly-Ext`	SIGW	2.17	2.28	2.33	2.17
			SIGW+SMBH	2.05	2.16	2.22	2.05
Astrophysical		free amplitude	SIGW	−1.46	−0.70	−1.33	−3.34
			SIGW+SMBH	−0.08	−0.01	−0.11	−0.10
		`GWOnly-Ext`	SIGW	−0.90	−0.14	−0.75	−2.78
			SIGW+SMBH	0.05	0.20	0.06	−0.01
Sub-solar	CE	free amplitude	SIGW	−0.01	0.77	0.07	−2.20
			SIGW+SMBH	0.34	0.81	0.32	0.05
		`GWOnly-Ext`	SIGW	0.55	1.33	0.66	−1.64
			SIGW+SMBH	0.72	1.31	0.74	0.17
	ET	free amplitude	SIGW	0.16	0.95	0.23	−2.05
			SIGW+SMBH	0.45	0.96	0.42	0.09
		`GWOnly-Ext`	SIGW	0.72	1.51	0.82	−1.49
			SIGW+SMBH	0.86	1.48	0.87	0.23
	LVK O5	free amplitude	SIGW	0.62	1.40	0.69	−1.50
			SIGW+SMBH	0.74	1.36	0.72	0.20
		`GWOnly-Ext`	SIGW	1.18	1.96	1.28	−0.94
			SIGW+SMBH	1.21	1.90	1.25	0.37
	LVK O4	free amplitude	SIGW	0.66	1.59	0.79	−1.24
			SIGW+SMBH	0.77	1.52	0.79	0.24
		`GWOnly-Ext`	SIGW	1.22	2.15	1.37	−0.68
			SIGW+SMBH	1.27	2.06	1.33	0.40

2D Posteriors (SIGW-only)



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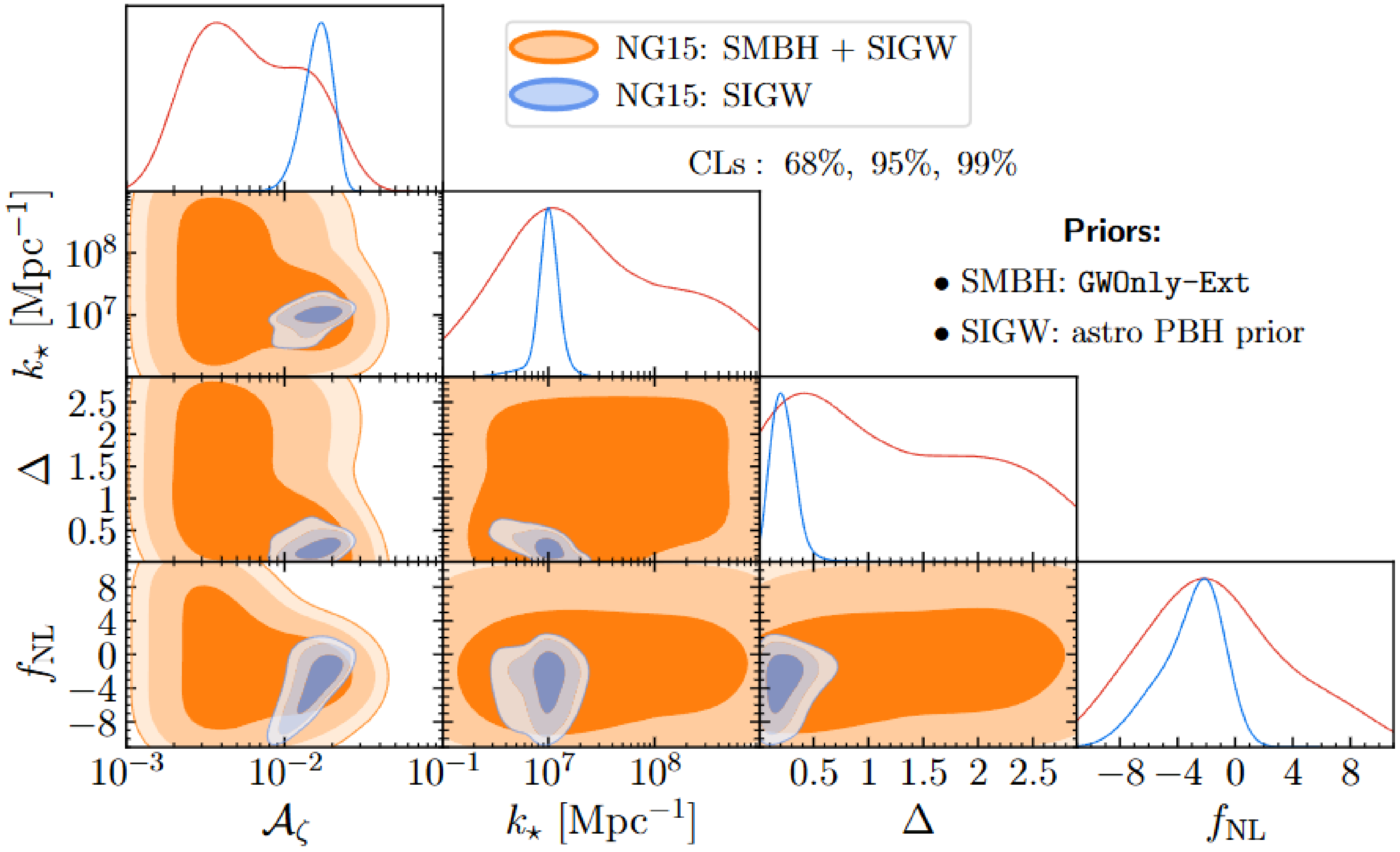
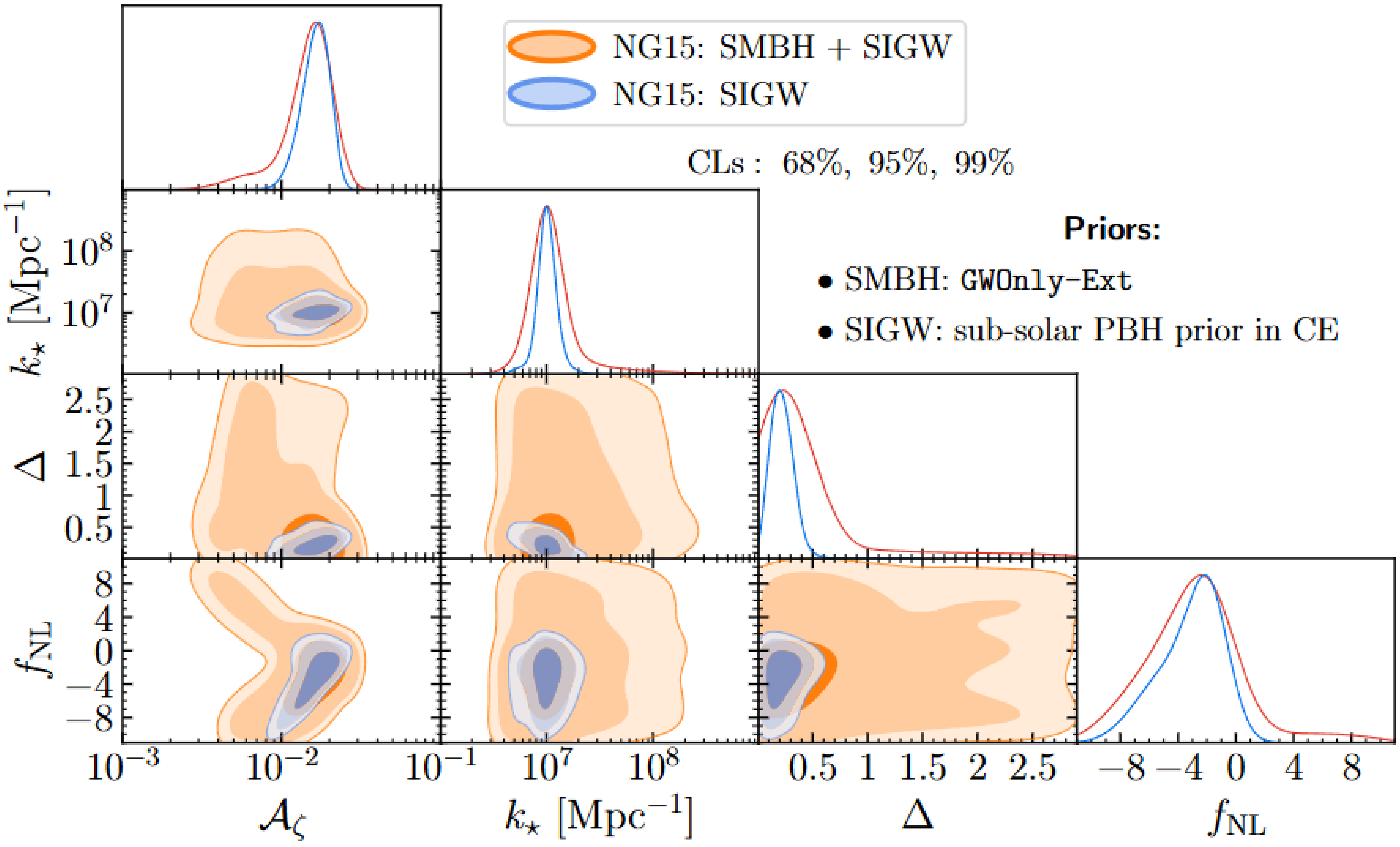
2D Posteriors (Astrophysical Prior)



Priors:

- SMBH: `GWOnly-Ext`
- SIGW: astro PBH prior

2D Posteriors (Subsolar Prior)



Priors:

- SMBH: `GWOnly-Ext`
- SIGW: sub-solar PBH prior in CE

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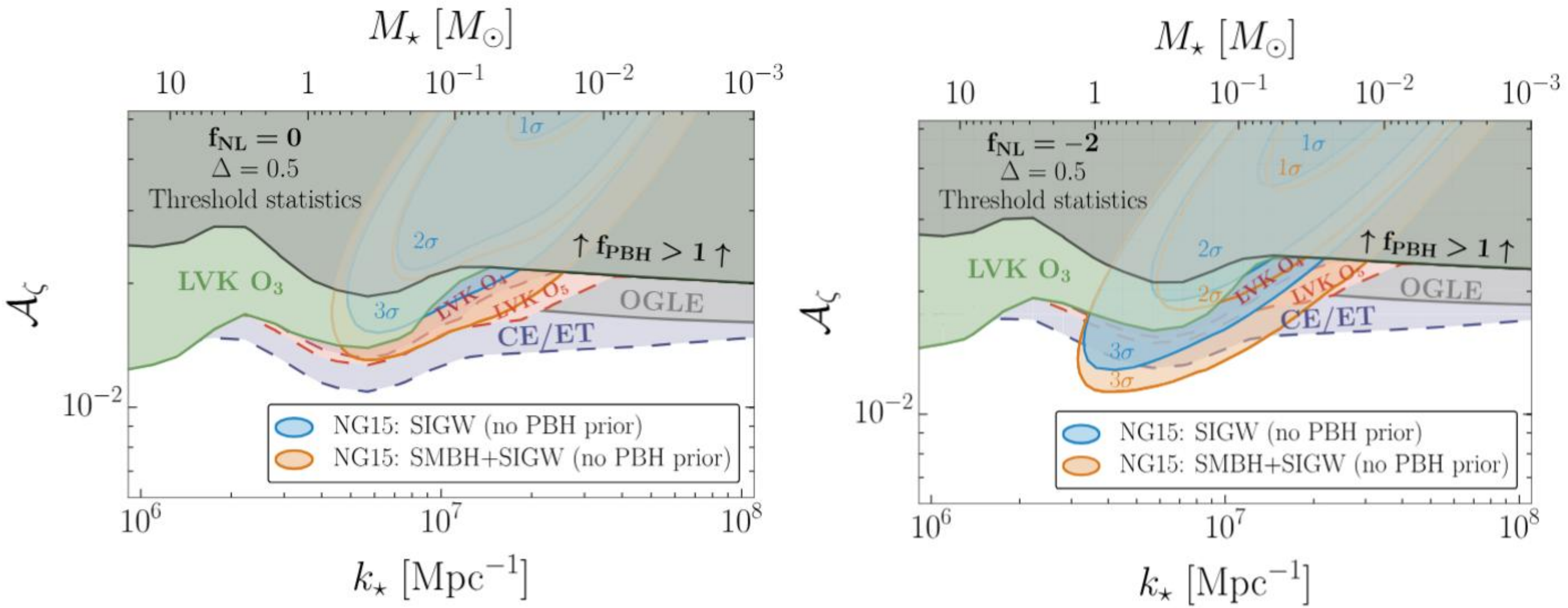
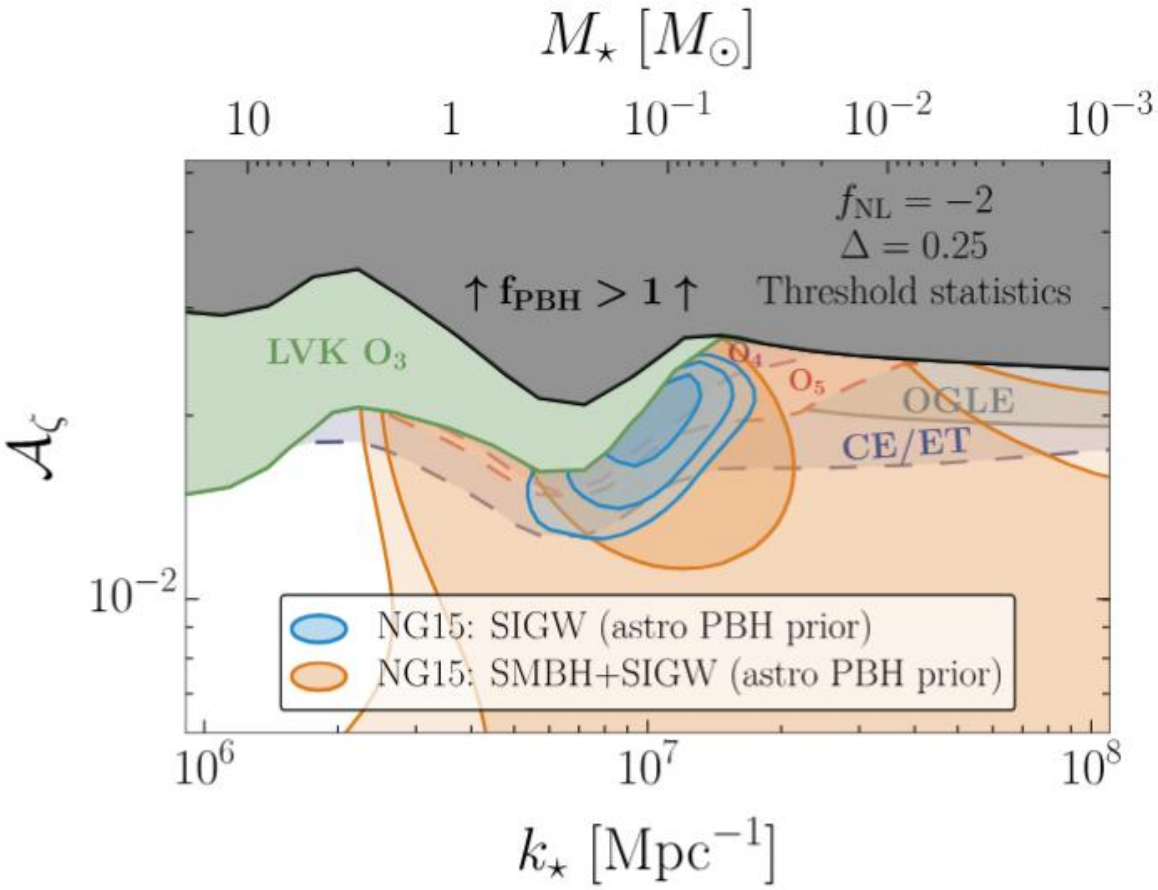
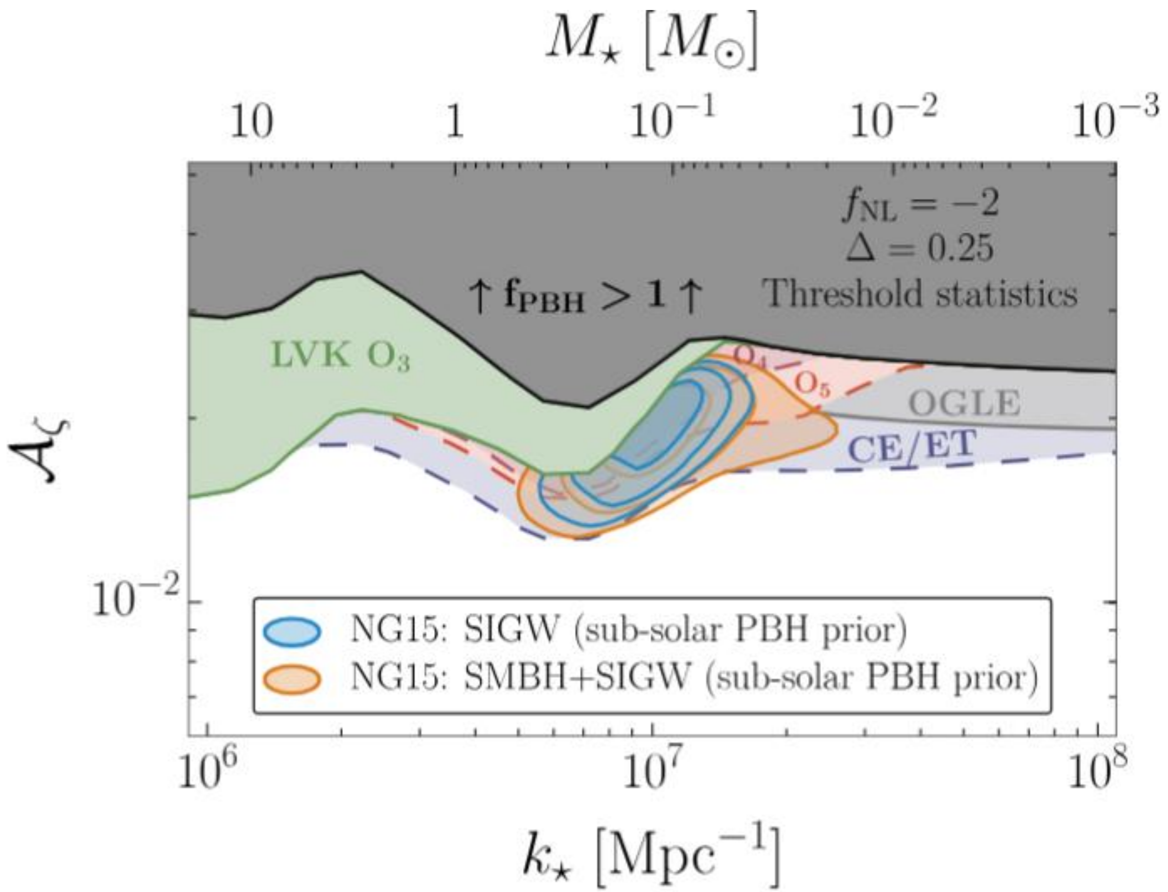
SIGW explanation (model parameters)



PBH priors (model parameters)

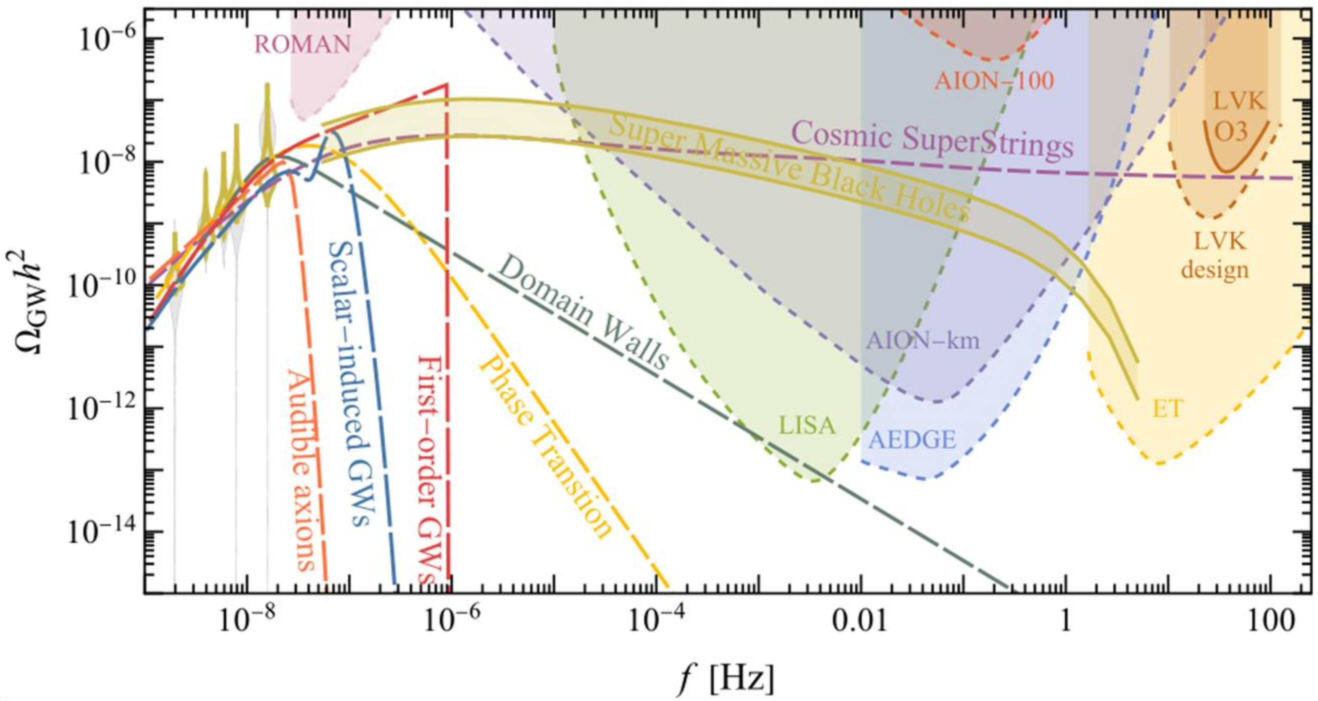




The final verdict on PTAs?

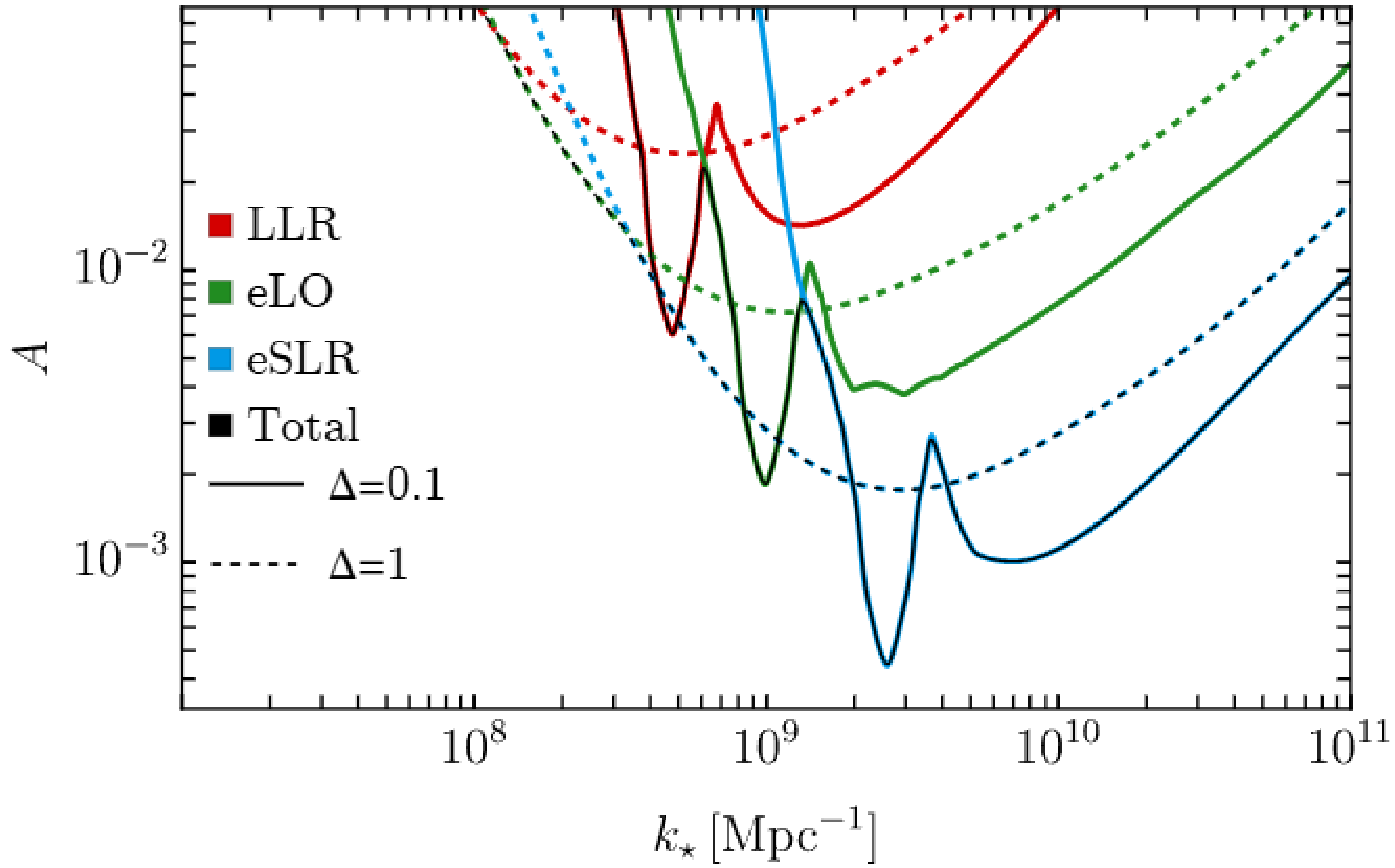
- The spectral fluctuations in the SGWB for every cosmological BSM model are expected to be negligible.
- An individual nearby SMBH binary will stand out from the background as a resolvable binary. Any deviation from the ABH spectral slope $\sim f^{-2/3}$ would offer unprecedented information about the surrounding environment (e.g. DM density).

Complementarity of Future Experiments:



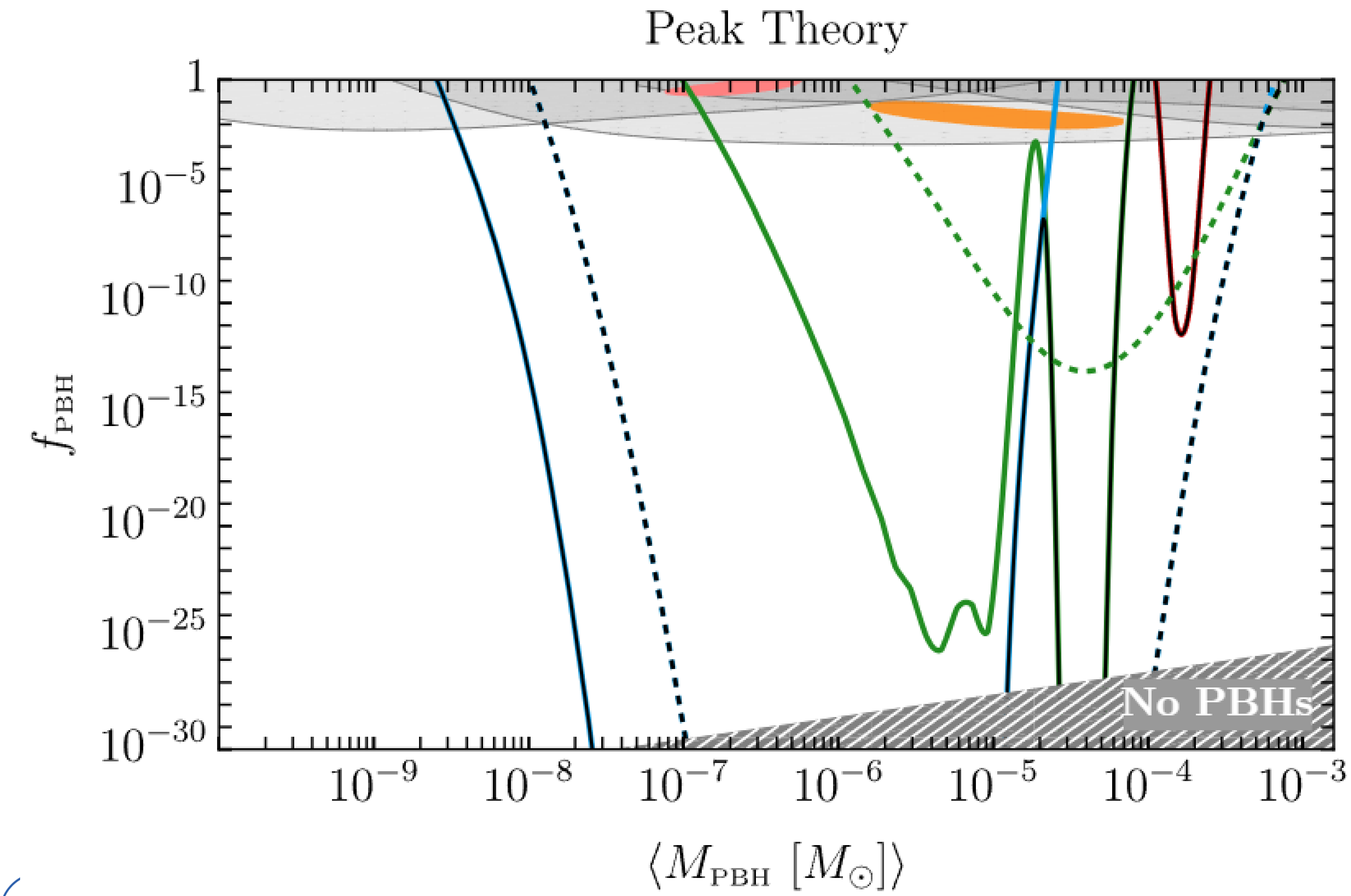
[Ellis et al] 2308.08546

Constraints by Laser Ranging (model parameters)



[Blas, Foster, Gouttenoire, Iovinio, Musco, **ST**, Vanvlasselaer] 2602.12252

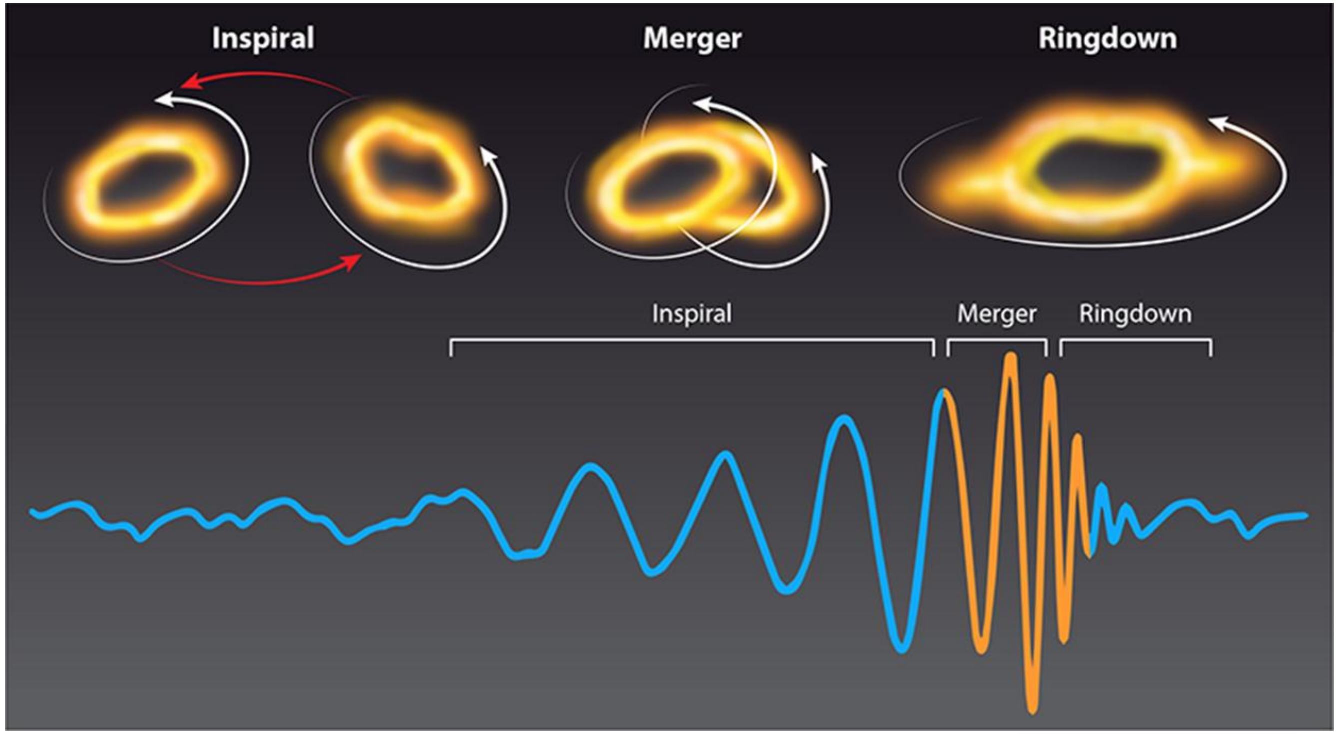
Constraints by Laser Ranging (peak theory)



[Blas, Foster, Gouttenoire, Iovinio, Musco, **ST**, Vanvlasselaer] 2602.12252

Phases of binary evolution

- The two PBHs will orbit around each other and the radius gradually shrinks due to emittance of gravitational radiation (***inspiral***). At later times when they are close enough they ***merge*** and eventually settle down to a stable form (***ring-down***). [Sasaki et al] [1801.05235]



[LIGO] 1602.03837

More EFT details

Modeling details. The full EFT model for the 3D Lyman alpha correlations reads

$$P_F^{3D}(k, k_\parallel, z) = (b_1 - b_\eta f \mu^2)^2 P(k) + P_{22} + P_{13} - 2k^2 P_{11}(c_0 + c_2\mu^2 + c_4\mu^4)\,, \tag{S2}$$

where $f = \frac{d\ln D_+}{d\ln a}$, $b_1(z), b_\eta(z)$ are linear bias parameters, c_n $(n = 0, 2, 4)$ are higher-derivative counterterms, and

$$P_{22} = \int 2\frac{d^3q}{(2\pi)^3}[K_2(\mathbf{k}-\mathbf{q},\mathbf{q})]^2 P(|\mathbf{k}-\mathbf{q}|)P(q)\ , \quad P_{13} = 6(b_1 - b_\eta f\mu^2)P(k)\int \frac{d^3q}{(2\pi)^3}K_3(\mathbf{k},-\mathbf{q},\mathbf{q})P(q)\,, \tag{S3}$$

and K_n are the Ly-α EFT kernels [44]. We ignore the 3D stochastic contributions. They will be added with the appropriate counterterms when we switch to 1D correlations. Precision measurements of EFT parameters from the ACCEL[2] simulation based on Ref. [49] carried out for the relevant redshift bins $z = 4, 5$ imply the following relations between the EFT parameters:

$$\begin{aligned}
b_\eta &= -0.46107\,b_1 + 0.22784, \quad b_{\eta^2} = -1.66391\,b_1 - 0.59993, \quad b_{\mathcal{G}_2} = -2.56067\,b_1 - 1.82742,\\
b_2 &= -10.01096\,b_1 - 3.23455, \quad b_{\delta\eta} = -5.22520\,b_1 - 1.38922, \quad b_{(KK)_\parallel} = 6.13639\,b_1 + 2.43267,\\
b_{\Pi^{(2)}_\parallel} &= -0.99037\,b_1 + 0.17342, \quad b_{\Pi^{(3)}_\parallel} = -0.35982\,b_1 + 1.32888, \quad b_{\delta\Pi^{(2)}_\parallel} = -3.19383\,b_1 - 2.81066,\\
b_{(K\Pi^{(2)})_\parallel} &= -1.35666\,b_1 - 2.60276, \quad b_{\eta\Pi^{(2)}_\parallel} = -10.61760\,b_1 - 6.93219, \quad b_{\Gamma_3} = -0.11903\,b_1 - 0.24599\,,\\
c_0 &= 0.02827\,b_1 + 0.01177, \quad c_2 = -0.01933\,b_1 - 0.01002, \quad c_4 = 0.00535\,b_1 + 0.00321\,.
\end{aligned}$$

The uncertainties in these relations are negligibly small thanks to an extended range of scales used in the fit at high redshifts, so we ignore them in what follows. We additionally multiply our 3D EFT model with a Doppler broadening kernel,

$$P_F^{3D}(k, k_\parallel, z) \to P_F^{3D}(k, k_\parallel, z)\, e^{-k_\parallel^2/k_F^2}\,. \tag{S4}$$

Even more EFT details

The sensitivity to small scales controlled by Λ is renormalized by the 1D stochastic counterterms

$$P_{1\mathrm{D},\ \mathrm{stoch}}(k_\parallel) = \mathcal{C}_0 + \mathcal{C}_1 k_\parallel^2 + \mathcal{C}_2 k_\parallel^4 + \dots \tag{S6}$$

In practice we use $\Lambda = 20\ h\mathrm{Mpc}^{-1}$ for the linear theory piece and $\Lambda = 12\ h\mathrm{Mpc}^{-1}$ for the one-loop contribution. These choices are made in order to be conservative and ensure $\Lambda \ll k_{\mathrm{NL}}$, which is especially important for the one-loop correction which is more UV-sensitive than the linear theory integrals. Within this scheme, the ACCEL^2 1D data implies the priors

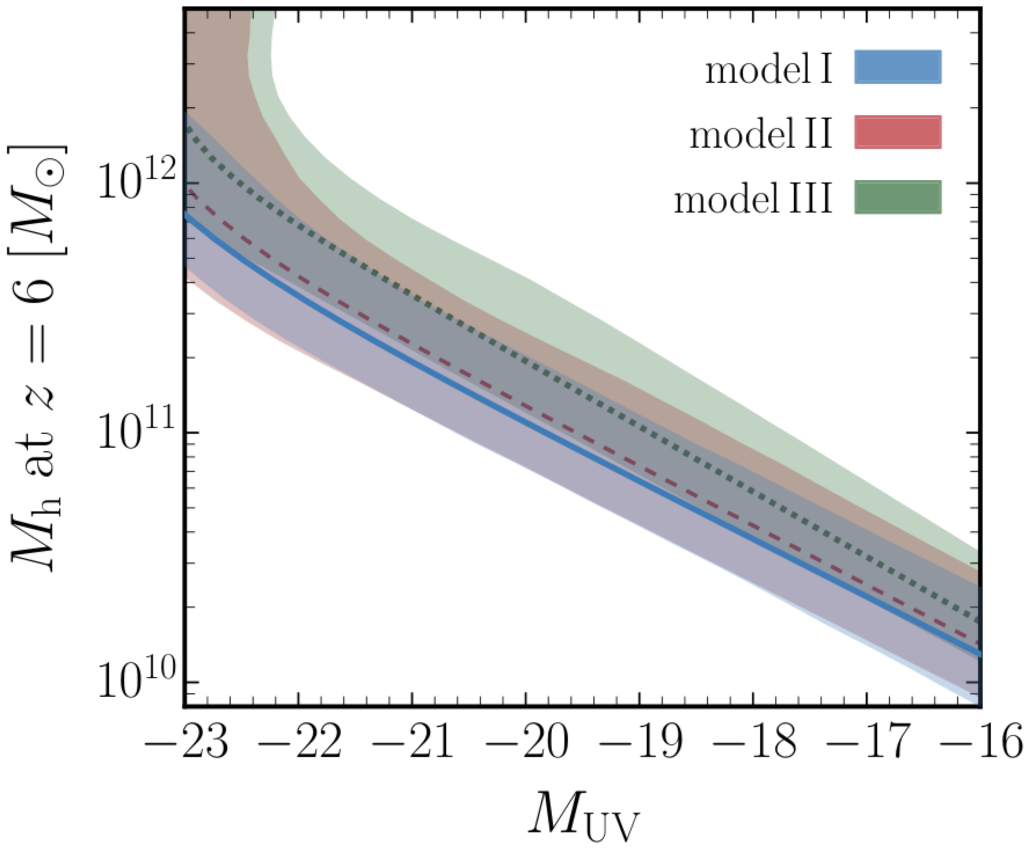
$$\mathcal{C}_0 = 0.82540\, b_1 + 0.13270\,, \quad \mathcal{C}_1 = -0.00725\, b_1 - 0.00133\,, \quad \mathcal{C}_2 = 0.0000050\, b_1 + 0.0000004\,. \tag{S7}$$

In order to be conservative, we additionally marginalize these relations over some width $\Delta\mathcal{C}_n$, estimated from the UV-sensitivity of the theory predictions. We find that increasing the cutoff Λ to $\Lambda' = 30\ h\mathrm{Mpc}^{-1}$ (and switching off the Doppler broadening) shifts $\mathcal{C}_n$ by

$$\Delta\mathcal{C}_n \simeq 0.05\ h^{-1}\mathrm{Mpc}/[20\ h\mathrm{Mpc}^{-1}]^{2n}\ , \tag{S8}$$

which we choose as a prior on $\Delta\mathcal{C}_n$ that we marginalize over independently for every redshift bin.

Halo-Galaxy Connection



- The SFR and halo-mass accretion are related via a double-power law:

$$\tilde{f}_* = \frac{\dot{M}_*}{\dot{M}_{\rm h}} = \frac{\epsilon_*}{\left(\frac{M_{\rm h}}{M_c}\right)^{\alpha_*} + \left(\frac{M_{\rm h}}{M_c}\right)^{\beta_*}}, \quad \dot{M}_* = \kappa_{\rm UV} L_{\rm UV}$$

derived from a stellar synthesis population models with IMF in $0.1 - 100\, M_\odot$ and with constant SFR.

- Within the AB magnitude system, we have:

$$\log_{10}\left(\frac{L_{\rm UV}}{\rm erg\, s^{-1}}\right) = 0.4\,(51.63 - M_{\rm UV})$$

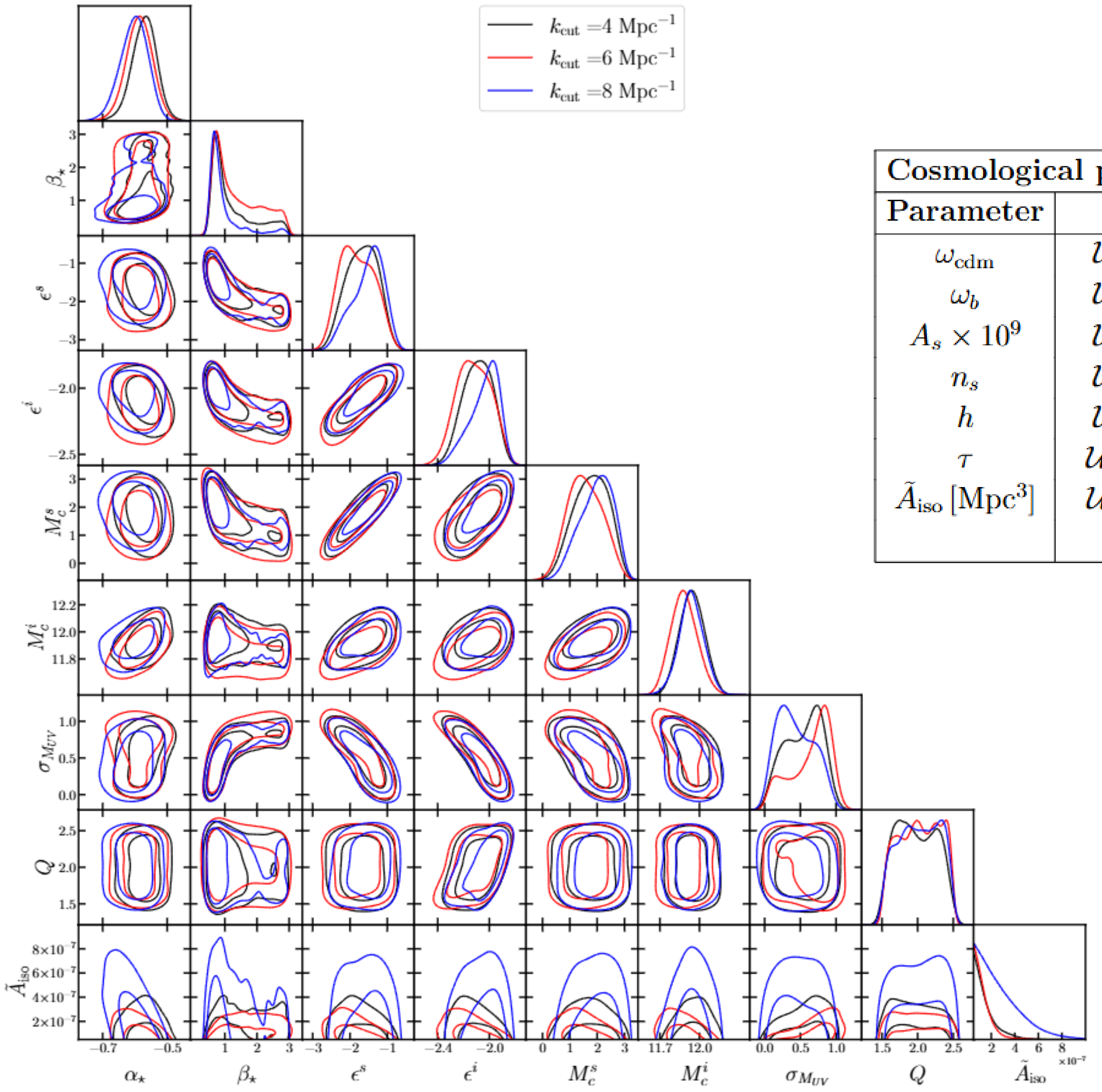
- In extended PS the accretion rate can be obtained as:

[Mandau, Dickinson] 1403.0007

$$\dot{M}_{\rm h} = -\sqrt{\frac{2}{\pi}} \frac{(1+z)H(z)M_{\rm h}}{\sqrt{\sigma^2_{M_{\rm h}}(Q) - \sigma^2_{M_{\rm h}}}} \frac{1.686}{D^2(z)} \frac{{\rm d}D(z)}{{\rm d}z}$$

fitted with the data using priors motived by simulations

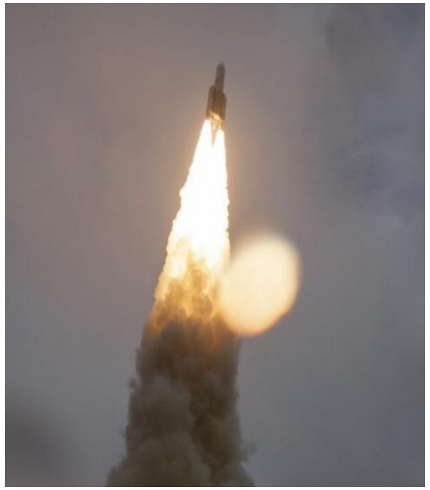
UVLF Priors and Contour Plots

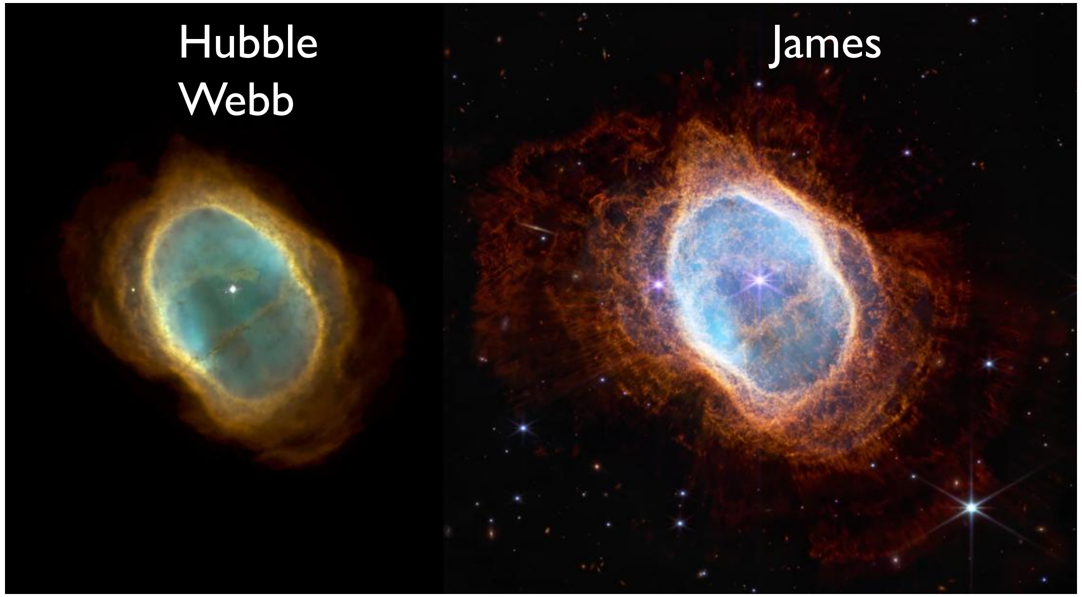


Cosmological parameters		UVLF parameters	
Parameter	Prior	Parameter	Prior
$\omega_{\rm cdm}$	$\mathcal{U}[-\infty,\ \infty]$	$\alpha_\star$	$\mathcal{N}(-0.557,\ 0.05)$
ω_b	$\mathcal{U}[-\infty,\ \infty]$	$\beta_\star$	$\mathcal{U}[0.0,\ 3.0]$
$A_s \times 10^9$	$\mathcal{U}[-\infty,\ \infty]$	$\epsilon_s^\star$	$\mathcal{U}[-3.0,\ 3.0]$
n_s	$\mathcal{U}[-\infty,\ \infty]$	$\epsilon_i^\star$	$\mathcal{U}[-3.0,\ 3.0]$
h	$\mathcal{U}[-\infty,\ \infty]$	M_c^s [$M_\odot$]	$\mathcal{U}[7.0,\ 15.0]$
τ	$\mathcal{U}[0.004,\ \infty]$	M_c^i [$M_\odot$]	$\mathcal{U}[7.0,\ 15.0]$
$\tilde{A}_{\rm iso}$ [Mpc^3]	$\mathcal{U}[0.0,\ 10^{-4}]$	$\sigma_{M_{\rm UV}}$ [mag^2]	$\mathcal{U}[0.001,\ 3.0]$
		Q	$\mathcal{U}[1.5,\ 2.5]$

James Webb Space Telescope

- JWST launched and it is already collecting data!



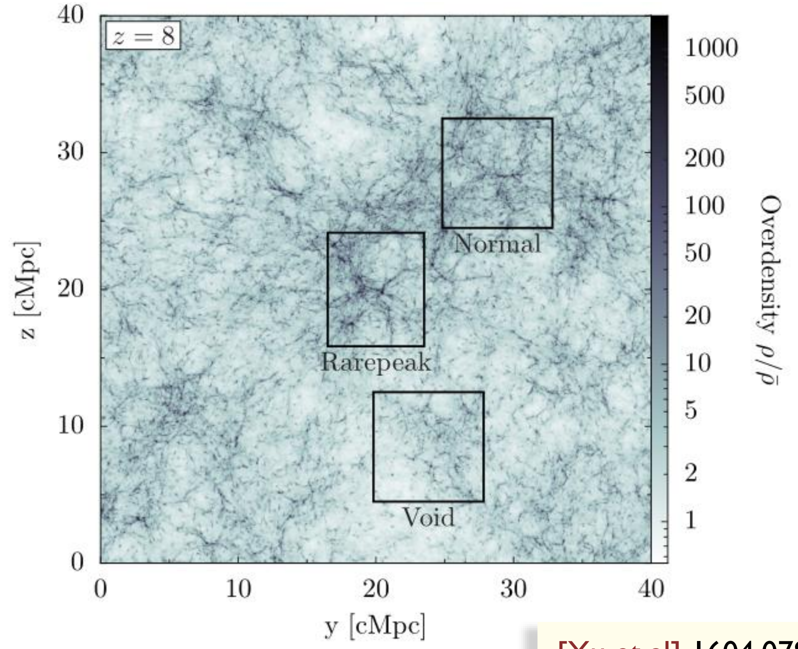


[Xu et al] [STSI/NASA, ESA, CSA, STScI, Webb ERO] Southern Ring Nebula

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

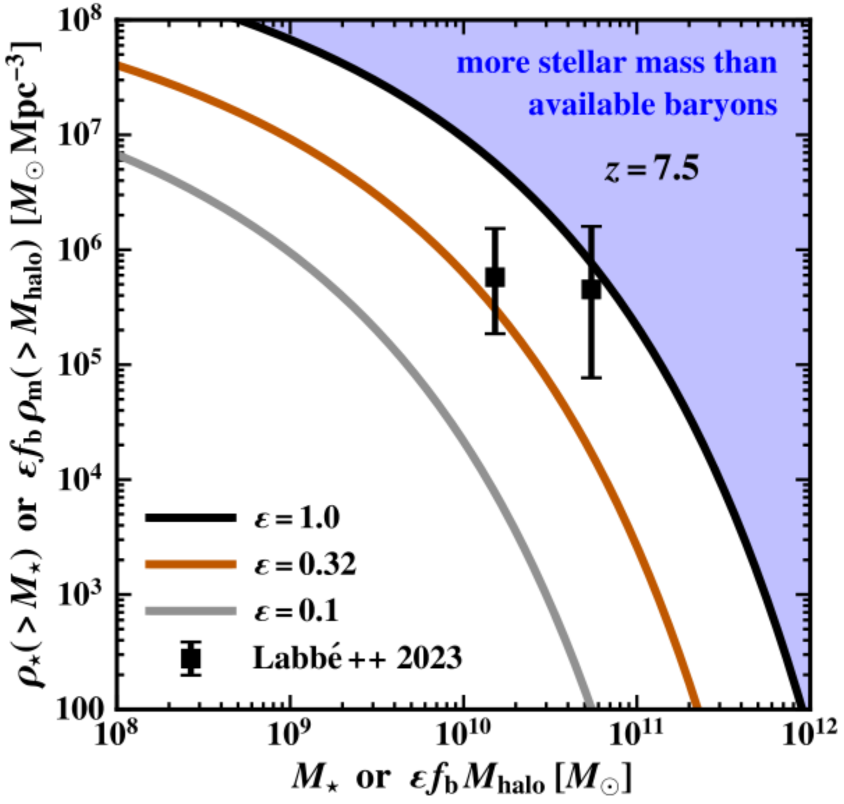


[Xu et al] 1604.07842

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

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

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

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.
- 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. $\delta^0_{\rm DM} = \delta^0_{\rm ad} + f_{\rm PBH}\delta^0_{\rm PBH}$. The isocurvature variance is $\left\langle \left|\delta^0_{\rm PBH}(k)\right|^2 \right\rangle = (\bar{n}_{\rm PBH})^{-1} = \frac{M_{\rm PBH}}{f_{\rm PBH}\rho_{\rm DM}}$.
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 $\widetilde{M} \approx \frac{z}{z_{\rm eq}} M_{PBH}$.

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

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:

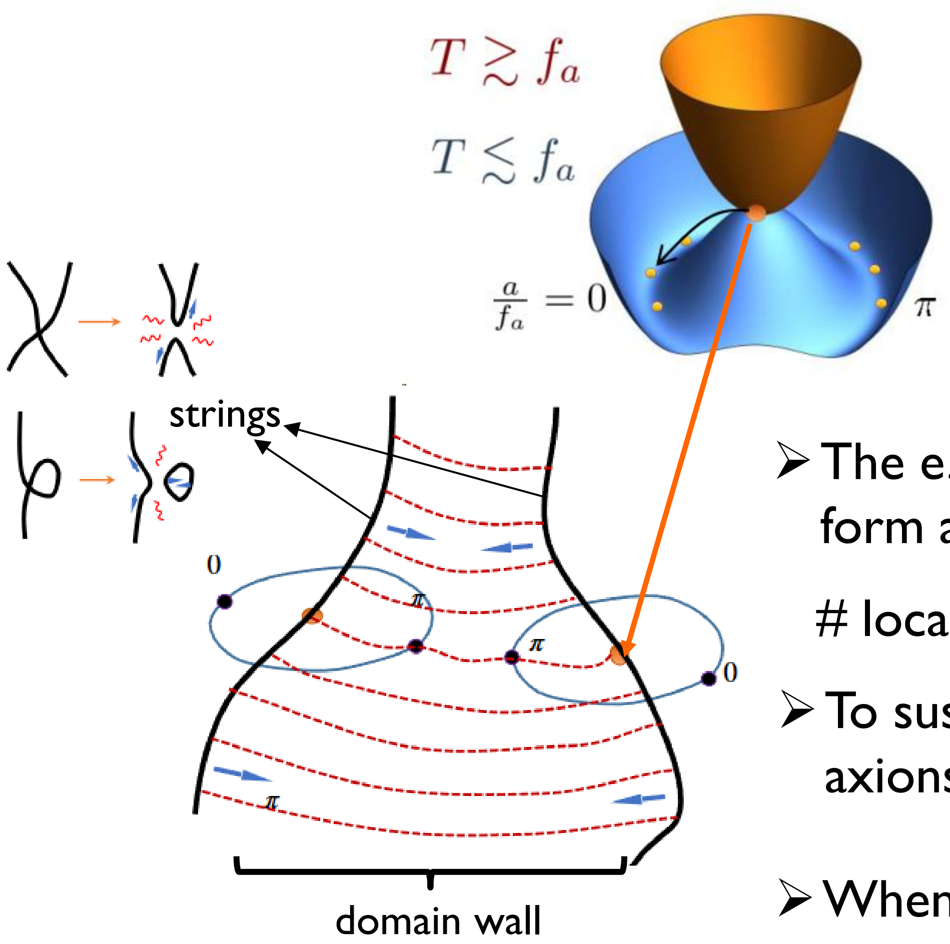
$$\mu \simeq 2.2\sigma^2 \left[\exp\left(-\frac{\hat{k}_\delta}{5400}\right) - \exp\left(-\left[\frac{\hat{k}_\delta}{31.6}\right]^2\right)\right] < 4.7\times10^{-5}$$

Solution: Large NGs $p < 0.3$

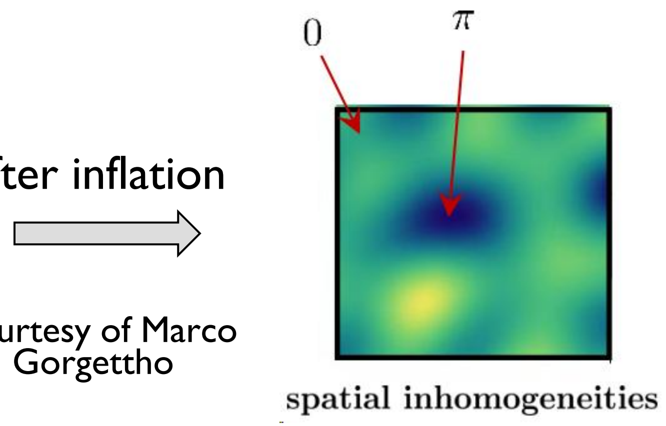
[Chubla, Erickcek,Ben-Dayan] 1203.2681

Post-inflationary Axions

- The initial conditions for the axion field are inhomogeneous if $H_{\text{inf}} > f_a$.



after inflation

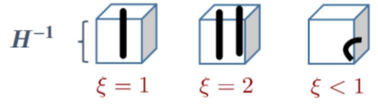


Courtesy of Marco Gorgettho

[Buschmann et al] 1906.00967 [O'Hare et al] 2112.05117 [Gorgettho et al] 2007.04990, 2101.1100

- The e.o.m. admit non-trivial solutions: **axion strings**, which form a network with an attractor solution (*scaling regime*):

  # local strings per Hubble patch $\xi \simeq 0.24 \log(f_a/H)$

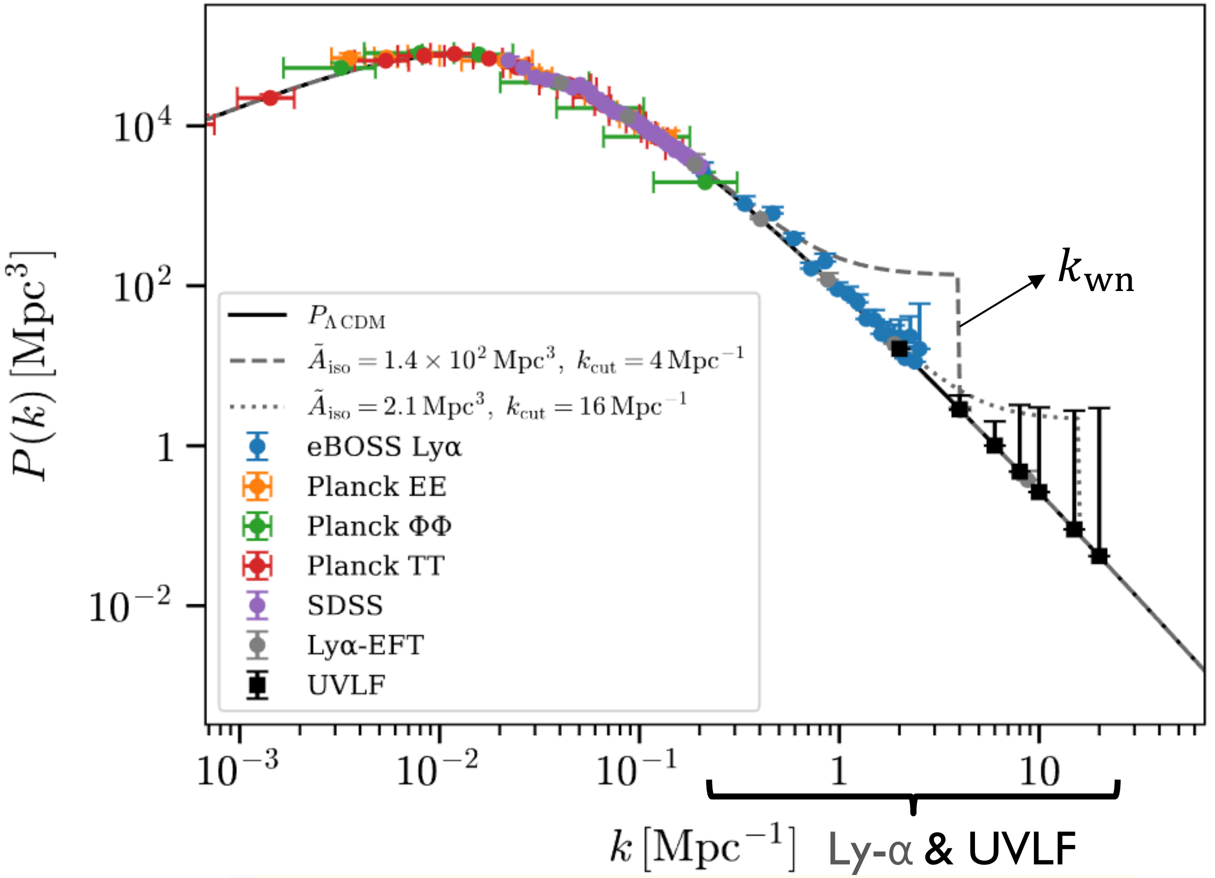


- To sustain the regime, the network radiates energy into axions at rate $\Gamma = \xi\, \mu / t^3$ and gravitational waves.

  string tension $\mu = E/L$

- When $H_* \sim m_a$, **domain walls** bounded by the strings form.

Seeds of accelerated structure formation (axions)



[Gorghetto, **Trifinopoulos**, Valogiannis] 2511.04734

- The string-wall system is unstable and collapses in one Hubble time. On length scales $\sim 1/H_*$, the axion field develops $O(1)$ isocurvature fluctuations $\delta_{\rm iso}$.
- The fluctuations in the CDM overdensity field δ define the **matter-power spectrum**:

$$\langle \delta^*(k)\,\delta(k')\rangle = \frac{2\pi^2}{k^3}(2\pi)^3\delta^3(k-k')\,\mathcal{P}(k)$$

- If axions are a sub-component of total CDM with fraction $f_{\rm DM}$, then we can write

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

$$\mathcal{P}_{\rm iso}(k) = \begin{cases} f_{\rm DM}^2 (k/k_{\rm wn})^3\,, & \text{if } k \lesssim k_{\rm wn} \\ 0\,, & \text{otherwise} \end{cases}$$

where $k_{\rm wn} \equiv C k_*$ and $k_* = H_* a_* \simeq 54\sqrt{\frac{m_a}{10^{-20}{\rm eV}}}\ {\rm Mpc}^{-1}$

$C \sim O(10)$ according to simulations

[Gorgettho, Hardy, Nicolaescu] 2101.11007