Title: The Primordial Black Holes Quest

Speakers: Valerio De Luca

Series: Particle Physics

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Abstract: Primordial black holes are a fascinating candidate for the dark matter in the universe. We discuss about their formation in the early universe and evolution across the cosmic history, and focus on their possible detectability at present and future gravitational wave experiments.

UNIVERSITÉ DE GENÈVE

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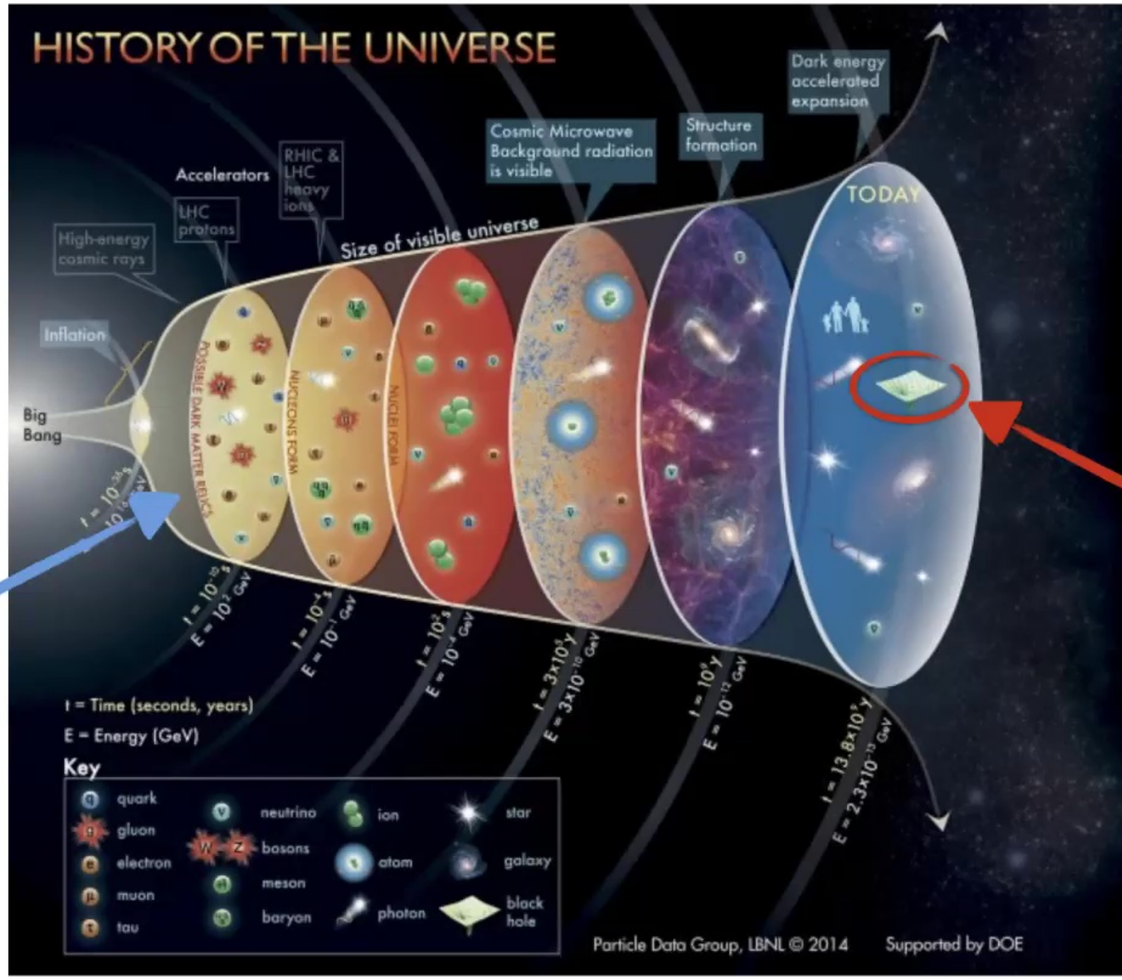
The Primordial Black Holes Quest

Valerio De Luca

March 1, 2022

Motivation



Primordial Black Holes?

Astrophysical Black Holes

Motivation

Astrophysical BHs

They form from the gravitational collapse of a star, with mass bigger than the Chandrasekhar mass,

$$M > \mathcal{O}(1) M_{\odot}$$

Primordial BHs

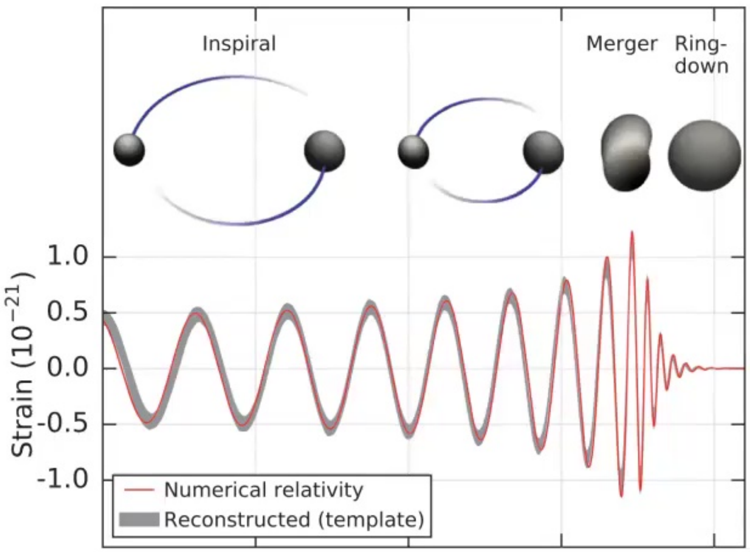
They form in the early universe from the collapse of large inhomogeneities and are not evaporated until today,

$$M > 10^{-18} M_{\odot}$$

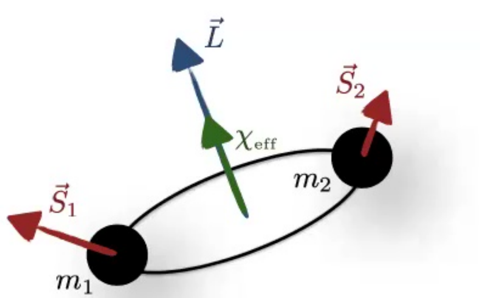
- Mass
- Spin
- Merger rate

Motivation

What do we observe at GWs experiment? → **Gravitational waveform**



Credit: LVKC



Chirp mass: $$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

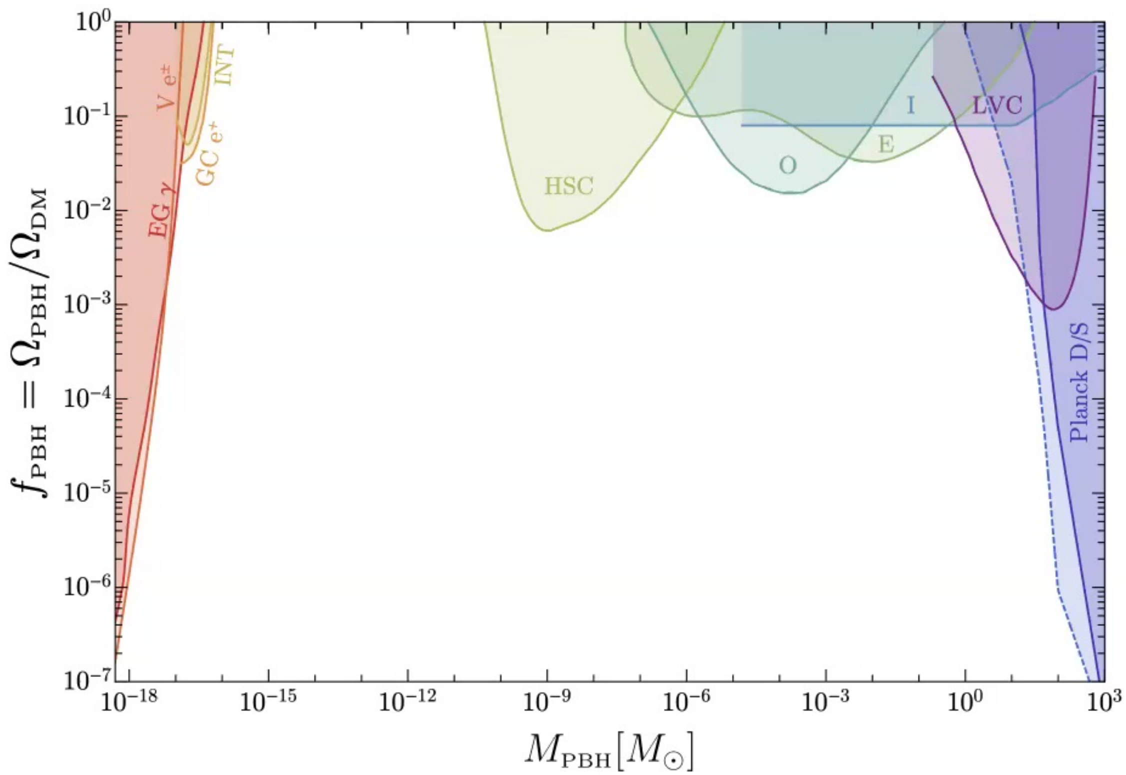
Mass ratio: $$q = m_2/m_1$$

Effective spin: $$\chi_{\rm eff} = \frac{\vec{S}_1/m_1 + \vec{S}_2/m_2}{m_1+m_2}\cdot\hat{L}$$

Love number: $$\Lambda = f(m_1, m_2) k_2^{(1,2)}$$

Motivation

PBHs on cosmological scales are a cold and collisionless fluid: they may represent a fraction of the **Dark Matter** in the universe

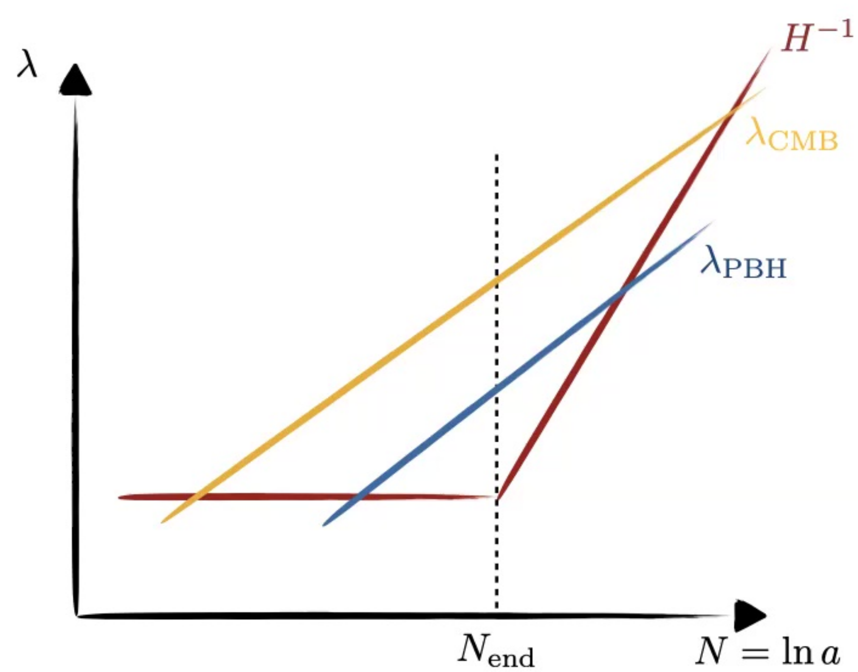


Outline

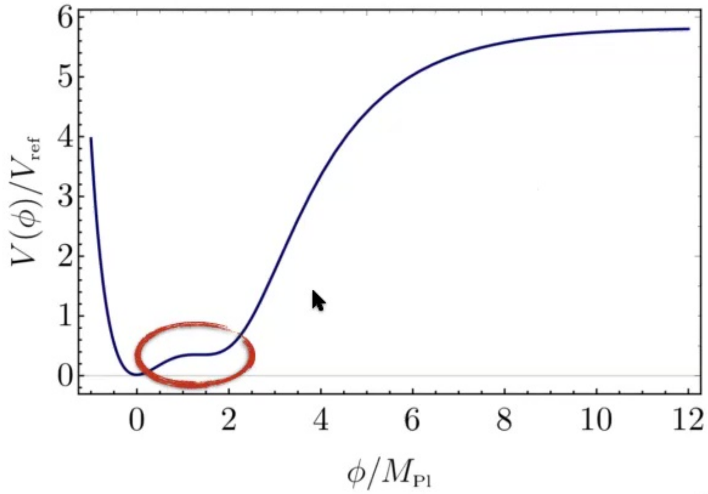
- Motivation
- PBH formation
- GWs from PBH formation
- PBH evolution
- GWs from PBH coalescence

Formation

Inflation can lead to an enhancement of the comoving curvature perturbation on small scales, which is then transferred to radiation during reheating and will collapse in PBH at horizon re-entry



Ultra-slow-roll



To get an enhancement: Slow-roll violation

↓

Ultra Slow-roll (USR)

$$\phi'' + 3\phi' = 0 \longrightarrow \begin{array}{l} \phi(N) = \phi_e + \frac{\pi_e}{3}(1 - e^{-3N}) \\ \pi(N) = \phi'(N) = \pi_e e^{-3N} \end{array}$$

Modes which exit the horizon during the USR phase experience super horizon growth

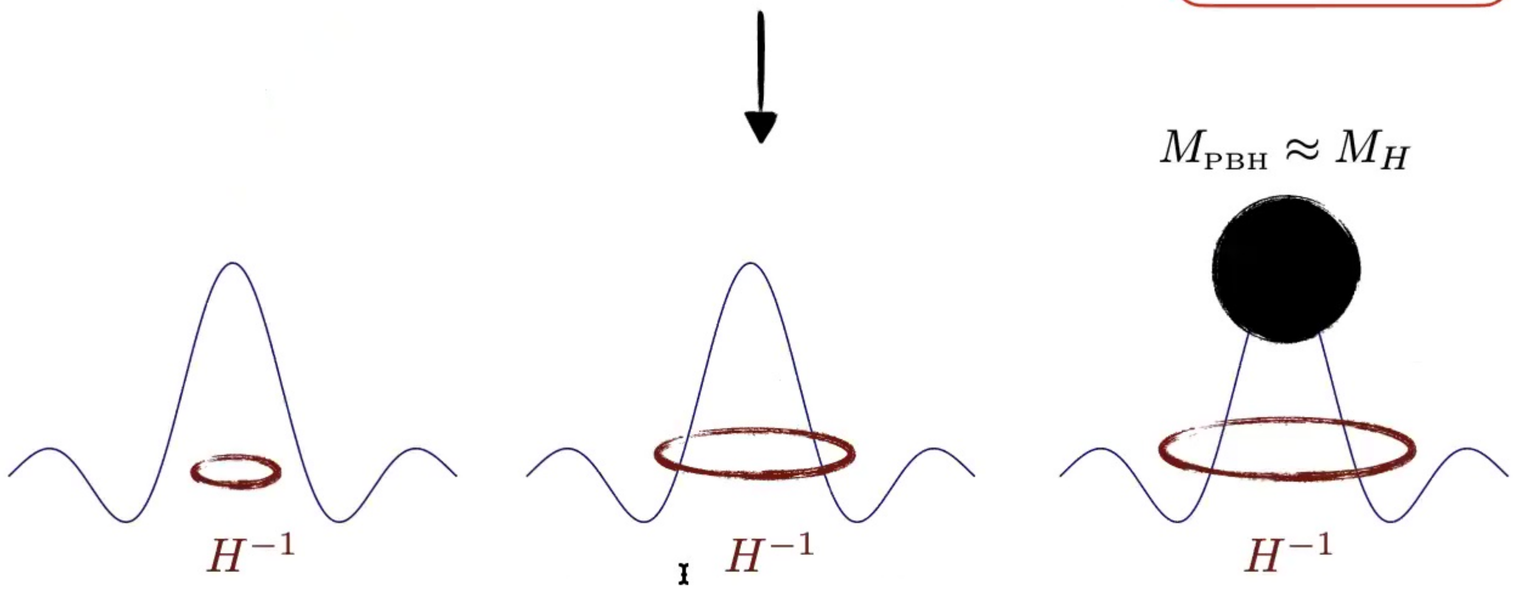
$$\zeta = \delta N = -\frac{1}{3}\ln\left(1 + \frac{\delta\phi}{\pi_e}\right)$$

Biagetti, De Luca, Franciolini, Kehagias, Riotto PLB [2105.07810]

Formation

PBHs are originated from peaks of the density contrast:

$$\delta \equiv \frac{\delta\rho}{\rho} > \delta_c$$

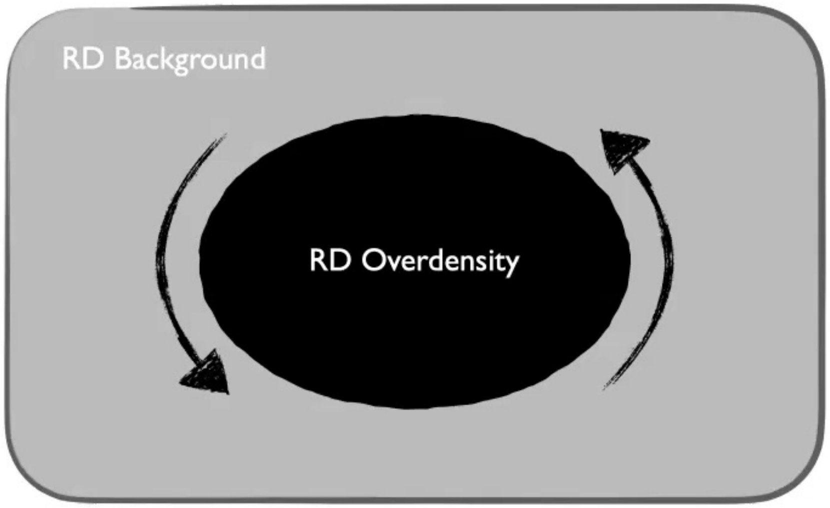


Sasaki et al. (2018)

PBH formation threshold depends on the curvature power spectrum

Musco, De Luca, Franciolini, Riotto PRD [2011.03014]

Initial spin



- PBHs originate from local maxima of the radiation overdensity field
- Spin originates from the action of torques generated by gravitational tidal forces upon horizon re-entry due to non-spherical collapse
- Action of torques limited in time due to small timescales of collapse

$$\chi_i \sim 10^{-2}\sqrt{1-\gamma^2}$$

De Luca, Desjacques, Franciolini, Malhotra, Riotto JCAP [1903.01779]

Shape of the density power spectrum

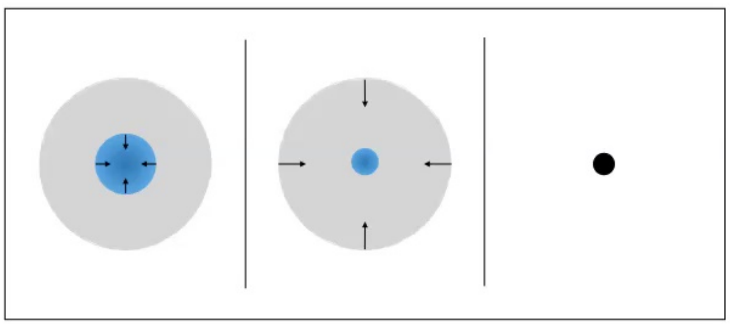
Alternative scenarios

Formation during an early matter-dominated era before reheating

↓

- Direct collapse of growing perturbations
- Post-collapse accretion onto dispersed scalar clouds or boson stars

De Luca, Franciolini, Kehagias, Pani, Riotto [2112.02534]

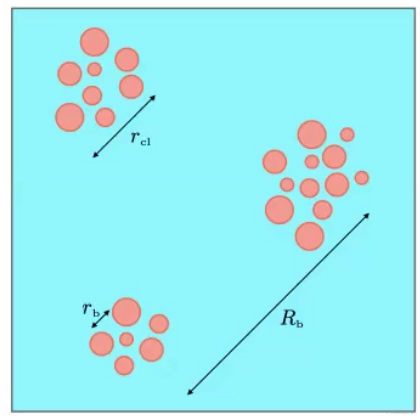


First-order phase transitions

↓

Bubble collisions may leave detectable signatures like GWs and PBHs

De Luca, Franciolini, Riotto PRD [2110.04429]



GWs from PBH formation

Second-order GWs

The same curvature perturbations giving rise to PBHs are responsible for the production of GWs at second-order in perturbation theory

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} \approx \partial_i\zeta\partial_j\zeta$$

Acquaviva et al. (2002), Mollerach et al. (2003), Ananda et al. (2006), Baumann et al. (2007)

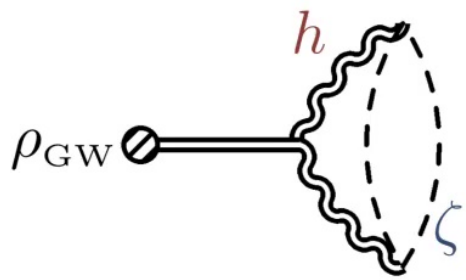
Large perturbations generate a sizable SGWB at horizon re-entry, potentially observable at current and future GW experiments

lisa

NANOGrav

Second-order GWs

The GWs energy density is given by the time average over several cycles

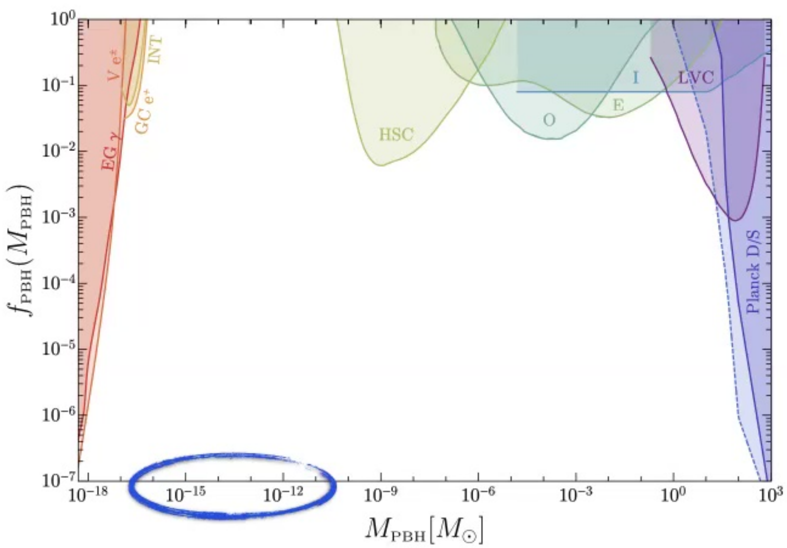


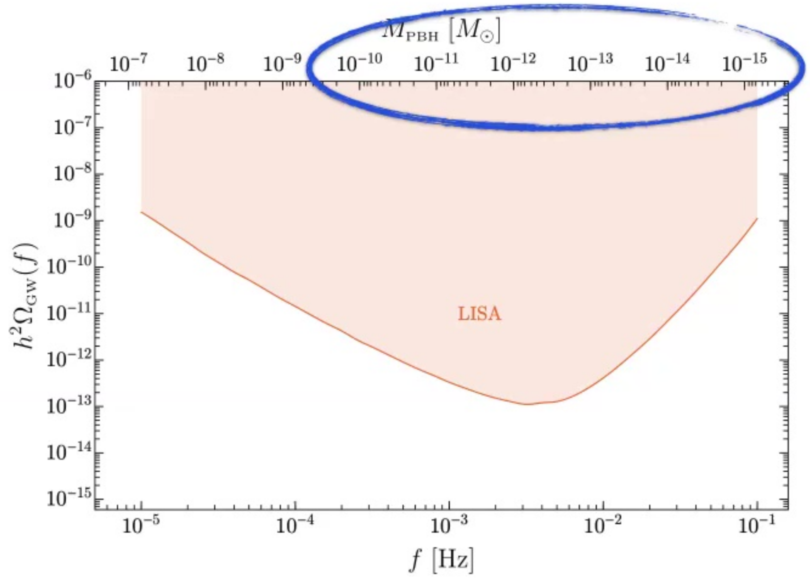
$$\Omega_{\rm GW}(\eta, \vec{x}) = \frac{\rho_{\rm GW}(\eta, \vec{x})}{\bar{\rho}(\eta)} = \frac{m_P^2}{16 a^2 \bar{\rho}(\eta)} \langle h'_{ab}(\eta, \vec{x}) h'_{ab}(\eta, \vec{x}) \rangle_{\rm t.a.}$$

The characteristic frequency of the GWs is similar to the frequency of the scalar perturbations, related to the PBH mass

$$M_{\rm PBH} \simeq 50\gamma \left(\frac{10^{-9}{\rm Hz}}{f}\right)^2 M_\odot$$

PBH-DM vs LISA





$$M_{\rm PBH} \simeq 10^{-12} M_\odot \longleftrightarrow f_{\rm LISA} \simeq 3.4 \text{ mHz}$$

LISA Serendipity

Bartolo, De Luca, Franciolini, Peloso, Racco, Riotto PRD [1810.12224]

Bartolo, De Luca, Franciolini, Lewis, Peloso, Riotto PRL [1810.12218]

NANOGrav

PTA experiment looking for delays in the arrival time of radio pulses from ms pulsars due to nHz GWs

appear as a red-noise signal

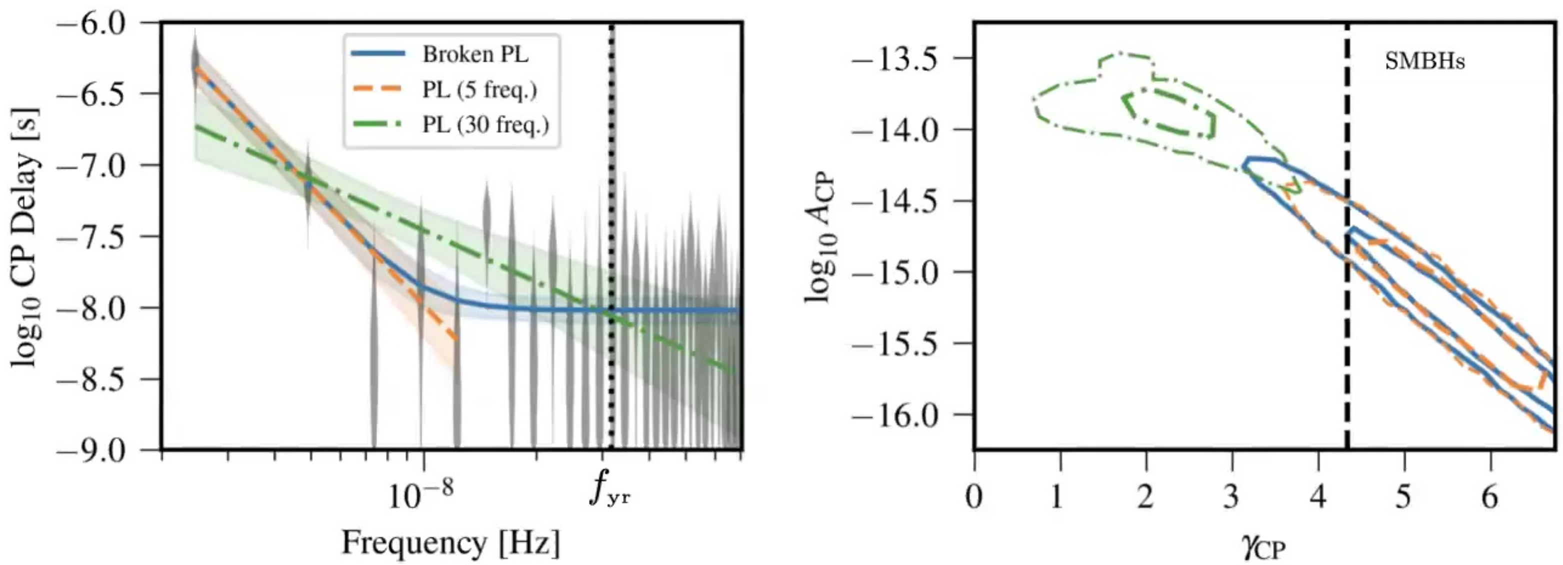
Cross correlation of timing residuals

$$S_{ab} = \Gamma_{ab} \frac{h_c^2}{12\pi^2 f^3}$$

Angular correlation

GW strain

NANOGrav 12.5 yrs



Strong evidence for a stochastic process, with common amplitude and spectral slope across 45 pulsars

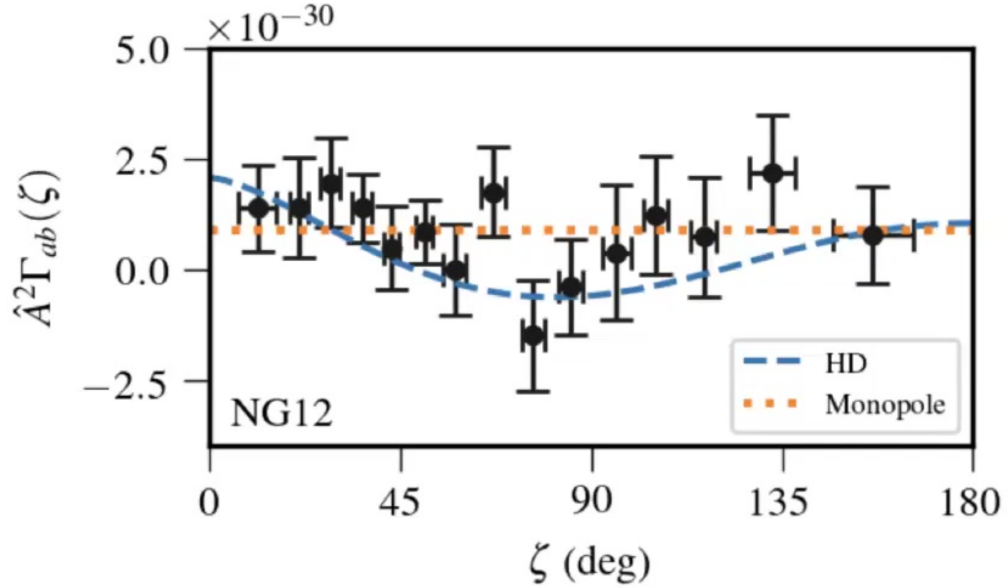
$$\Omega(f) = \frac{2\pi^2}{3H_0^2} A^2 f_{yr}^2 \left(\frac{f}{f_{yr}}\right)^{5-\gamma}$$

Possible flat GW spectrum with amplitude $\Omega(f) \sim 5 \cdot 10^{-10}$

Arzoumanian et al. (2020)

NANOGrav 12.5 yrs

Non-conclusive evidence for quadrupolar
Hellings-Downs curve (HD) correlation pattern



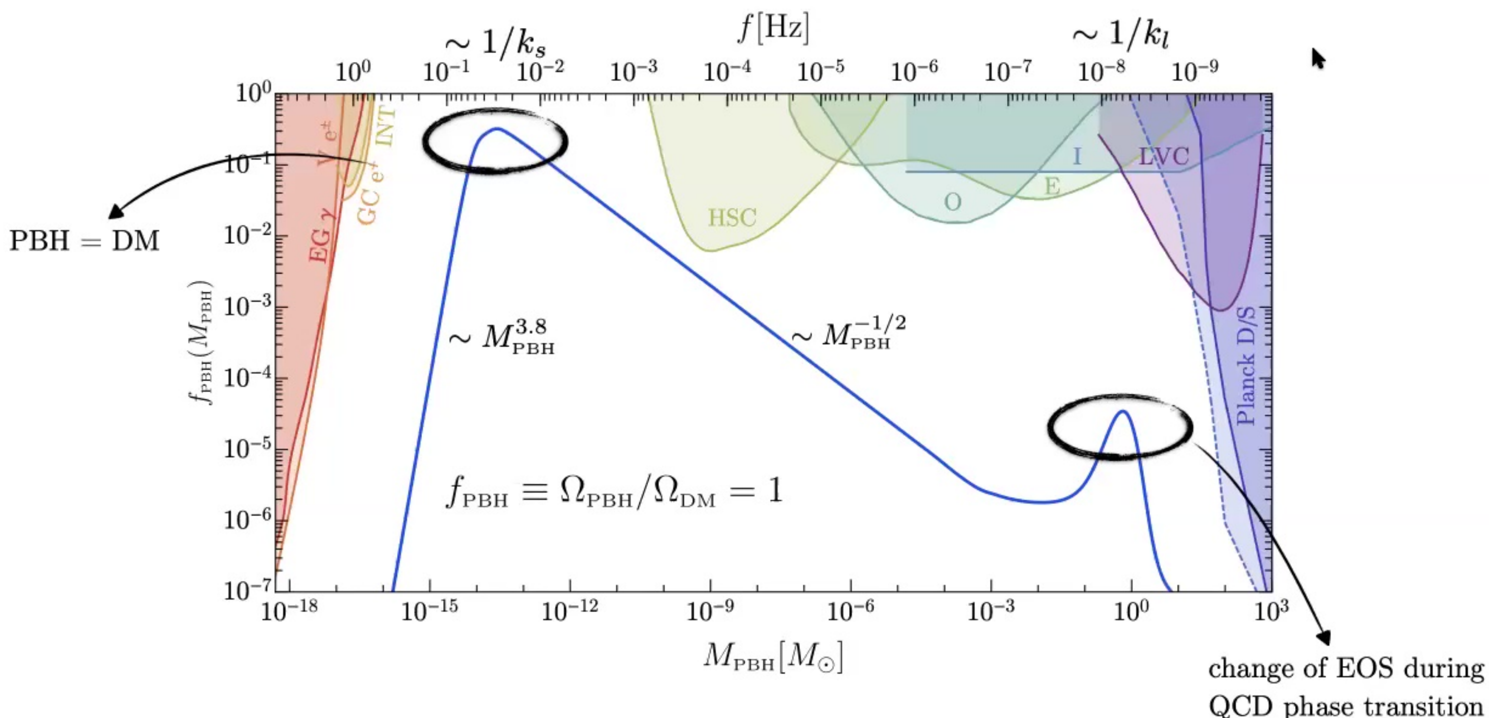
Need to wait for more data...
(2-3 more years)

Arzoumanian et al. (2020)

NANOGrav 12.5 yr : PBH-DM scenario

Broad and flat power spectrum of the curvature perturbation

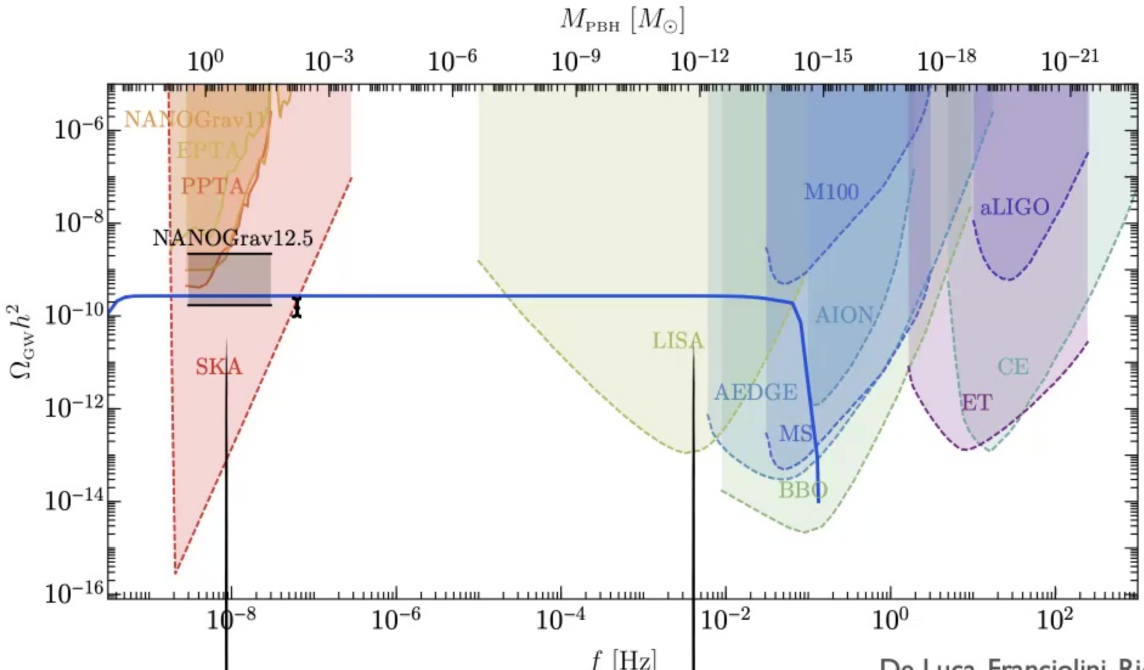
$$\mathcal{P}_\zeta(k) \approx A_\zeta\, \Theta(k_s - k)\Theta(k - k_l), \qquad k_s \gg k_l$$



De Luca, Franciolini, Riotto PRL [2009.08268]

NANOGrav 12.5 yr : PBH-DM scenario

Flat spectrum for the SGWB



De Luca, Franciolini, Riotto PRL [2009.08268]

GW abundance falls within 90% C.I.

Detectable by LISA

PBH evolution

Cosmic evolution

PBH at formation

↓

PBHs evolve through the cosmological history

- Assemble in binaries
- Accretion
- Clustering

↓

PBHs evolution affects the GW parameters measured at present and future experiments

Assemble in binaries

Initial spatial Poisson distribution

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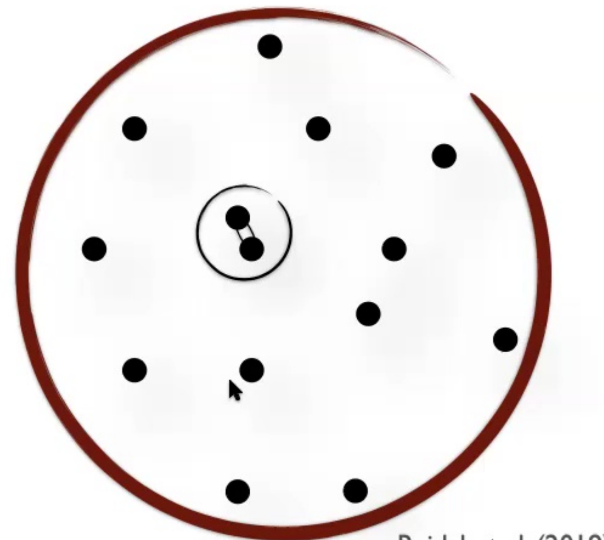
Probability of 2-body systems
to decouple from the Hubble flow before matter-radiation equality, form a binary and merge

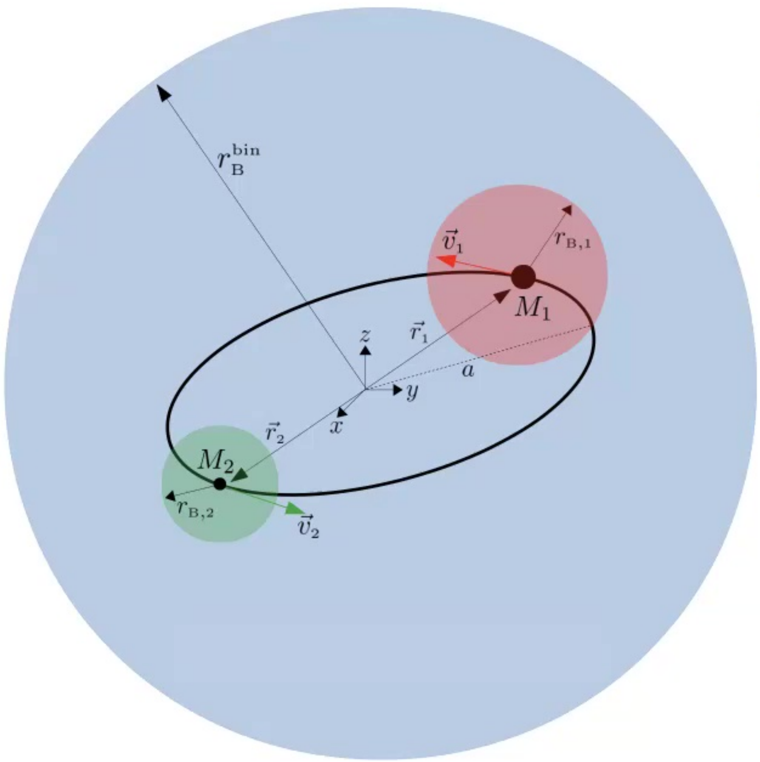


$$\mathrm{d}R = \frac{1.6\times10^6}{\mathrm{Gpc}^3\,\mathrm{yr}} f_{\mathrm{PBH}}^{\frac{53}{37}}(z_\mathrm{i}) \left(\frac{t}{t_0}\right)^{-\frac{34}{37}} \eta_\mathrm{i}^{-\frac{34}{37}} \left(\frac{M_\mathrm{tot}^\mathrm{i}}{M_\odot}\right)^{-\frac{32}{37}} S\left(M_\mathrm{tot}^\mathrm{i}, f_\mathrm{PBH}(z_\mathrm{i})\right) \psi(M_1^\mathrm{i}, z_\mathrm{i})\psi(M_2^\mathrm{i}, z_\mathrm{i})\mathrm{d}M_1^\mathrm{i}\mathrm{d}M_2^\mathrm{i}$$

PBH abundance — Time evolution — Suppression factor — Mass function

Accretion

Baryonic material from the surrounding IGM is accreted by the PBH binary



Bondi-Hoyle mass accretion rate

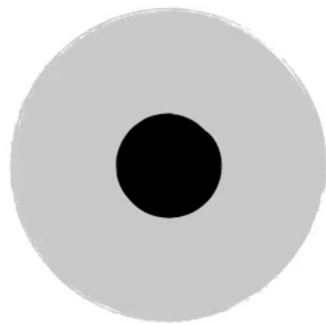
$$\dot{M}_{\rm bin} = 4\pi\lambda m_H n_{\rm gas} v_{\rm eff}^{-3} M_{\rm tot}^2$$

- Epochs of efficient accretion: $M \gtrsim \mathcal{O}(10) M_\odot$ at $z \lesssim 30$
- Smaller PBH always experiences a larger relative accretion

De Luca, Franciolini, Pani, Riotto JCAP [2005.05641]

Accretion: impact of DM halo

If PBH do not account for all the DM in the universe,
the dominant DM component can create a halo around PBH



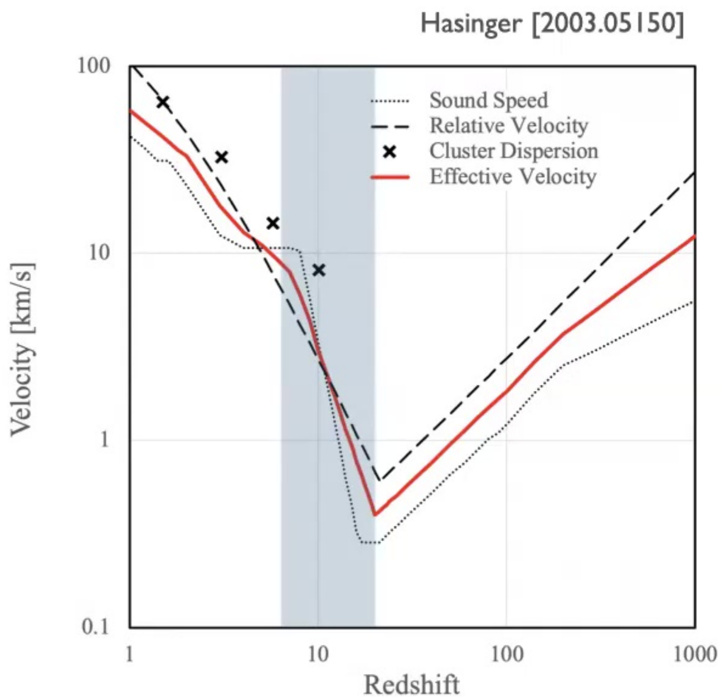
$$M_h(z) = 3M \left(\frac{1+z}{1000}\right)^{-1}, \quad r_h = 0.019\,\mathrm{pc}\left(\frac{M}{M_\odot}\right)^{1/3}\left(\frac{1+z}{1000}\right)^{-1}$$

↓

Catalyst to accrete baryonic material
from the surrounding IGM

Ricotti et al. (2005)

Accretion



Structure formation and reionization

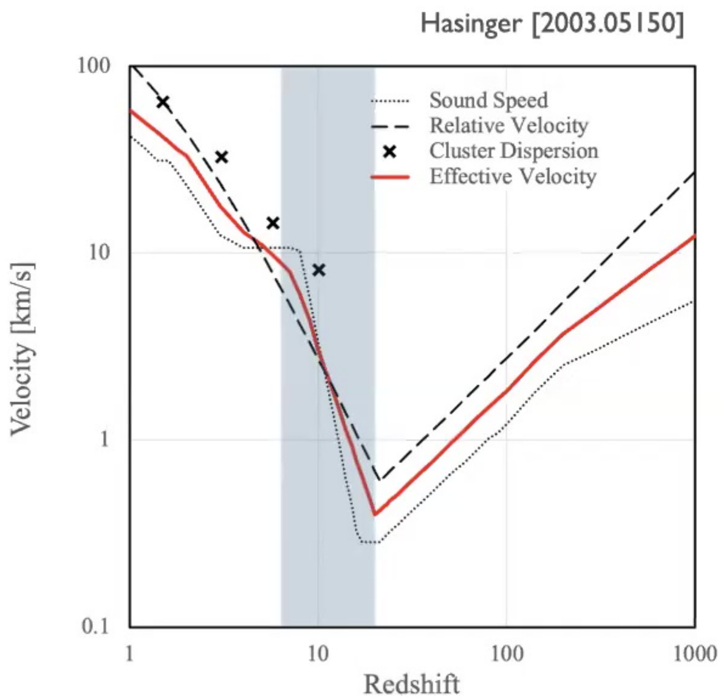
- Higher temperatures
- Virialised velocities

↓

Sharp decrease in the accretion efficiency parametrized with cut-off redshift $z_{\texttt{cut-off}}$

Uncertainties in the accretion model → We vary the cut-off redshift

Accretion



Structure formation and reionization

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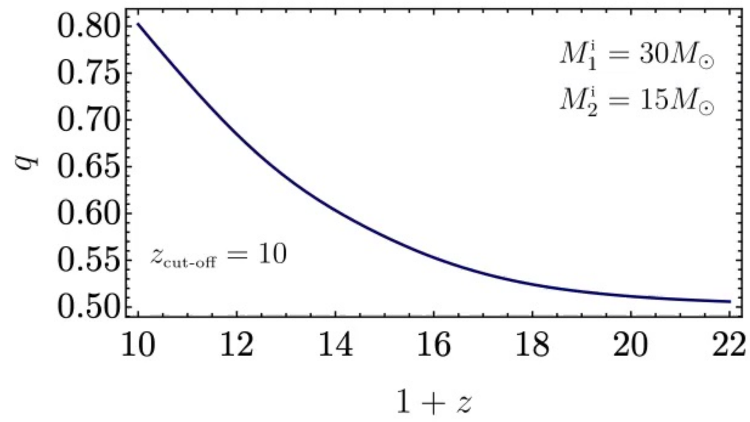
↓

Sharp decrease in the accretion efficiency parametrized with cut-off redshift $z_{\text{cut-off}}$

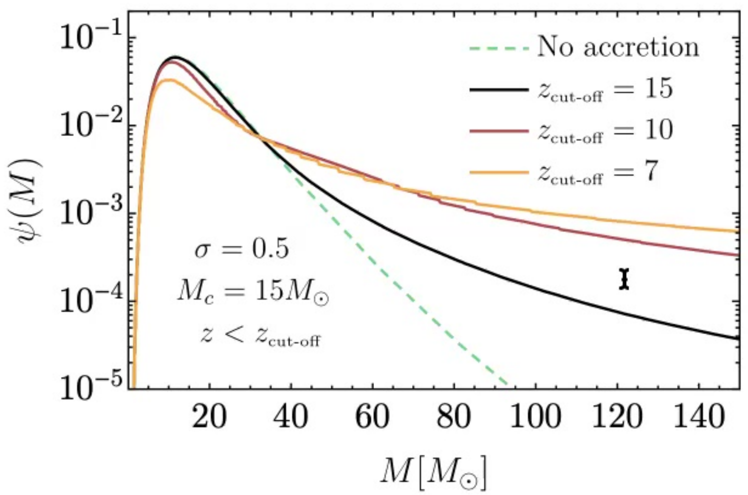
Uncertainties in the accretion model → We vary the cut-off redshift

Accretion: effects

- Asymmetrical binaries tend to become symmetrical



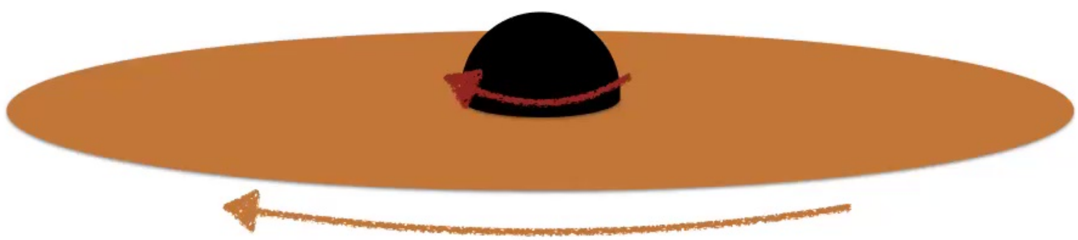
- Evolved mass function broader with high-mass tail



Disk formation

Accretion rate and geometry of the accretion flow are intertwined

The matter angular momentum can create
an accreting disk around the PBH for high accretion rate

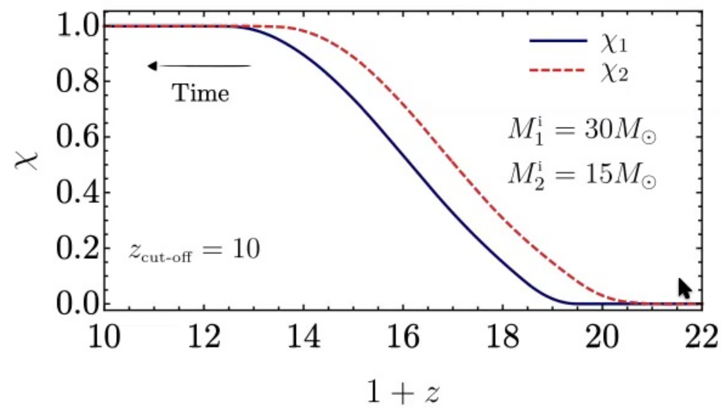


The accreting disk leads to angular momentum transfer on the PBH

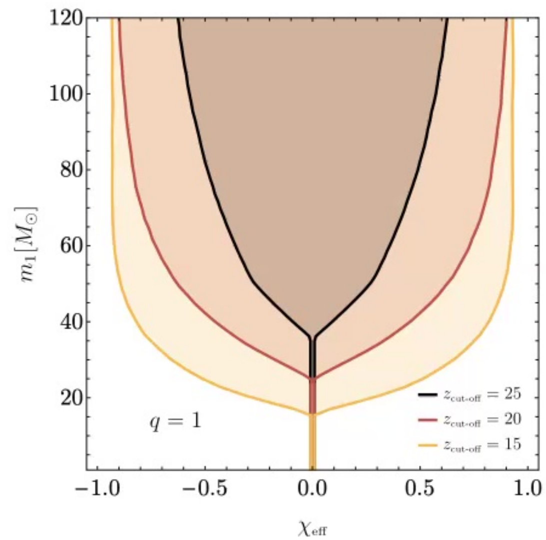
$$\dot{\chi} = g(\chi)\frac{\dot{M}}{M}$$

Bardeen et al. (1972)

Effective spin



Spins pushed towards extremality,
with secondary spin bigger than the primary



- Uncorrelated spin orientation
- Effective spin spreads around zero
- Accretion: low (high) mass - low (high) spin correlation

$$\chi_{\text{eff}} = \frac{\vec{S}_1/m_1 + \vec{S}_2/m_2}{m_1 + m_2} \cdot \hat{L}$$

Accretion

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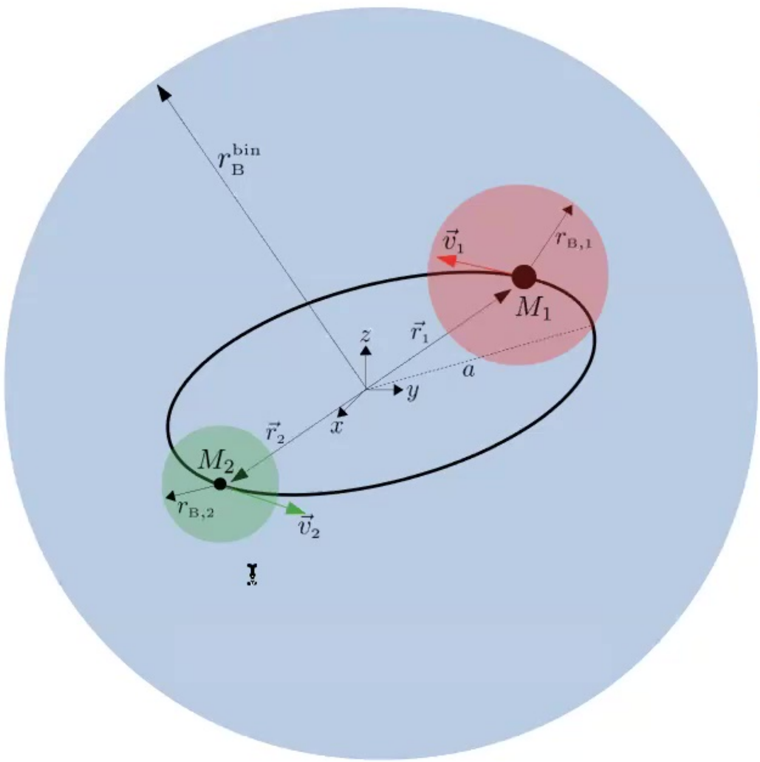

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↓

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De Luca, Franciolini, Pani, Riotto JCAP [2005.05641]

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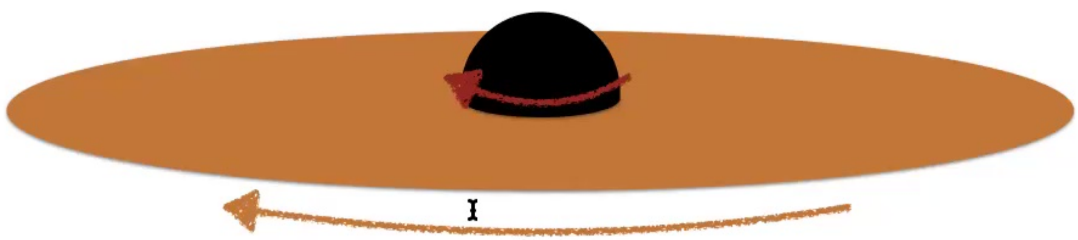

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Bardeen et al. (1972)

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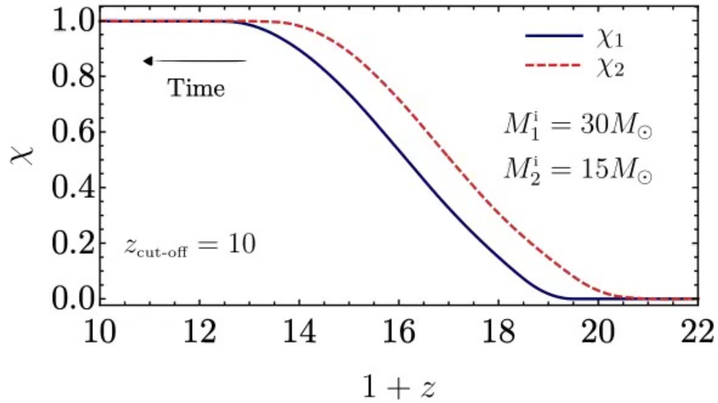

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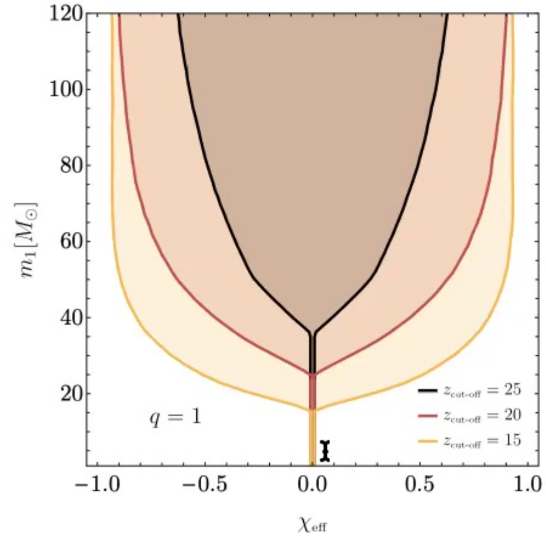
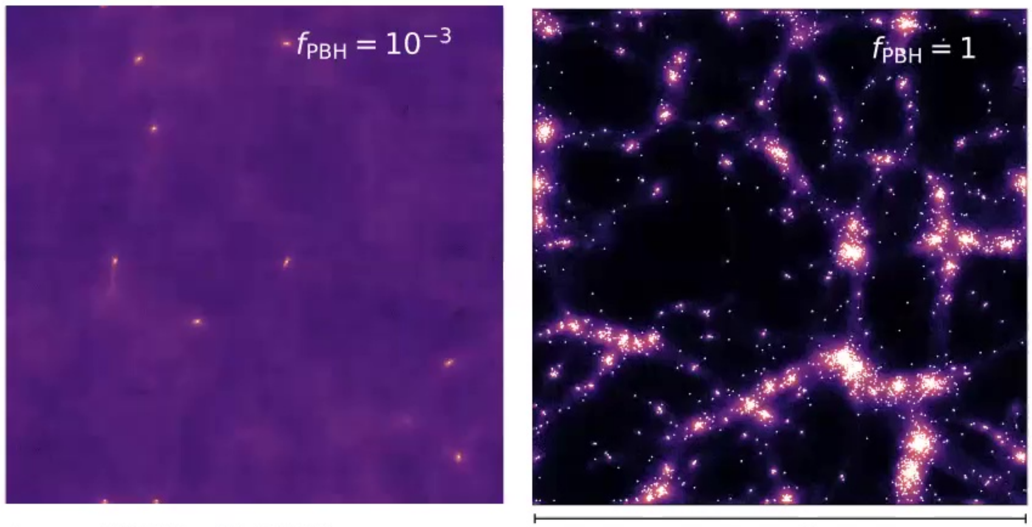


Clustering

After matter-radiation equality they may form clusters for large abundance

$z \approx 100$

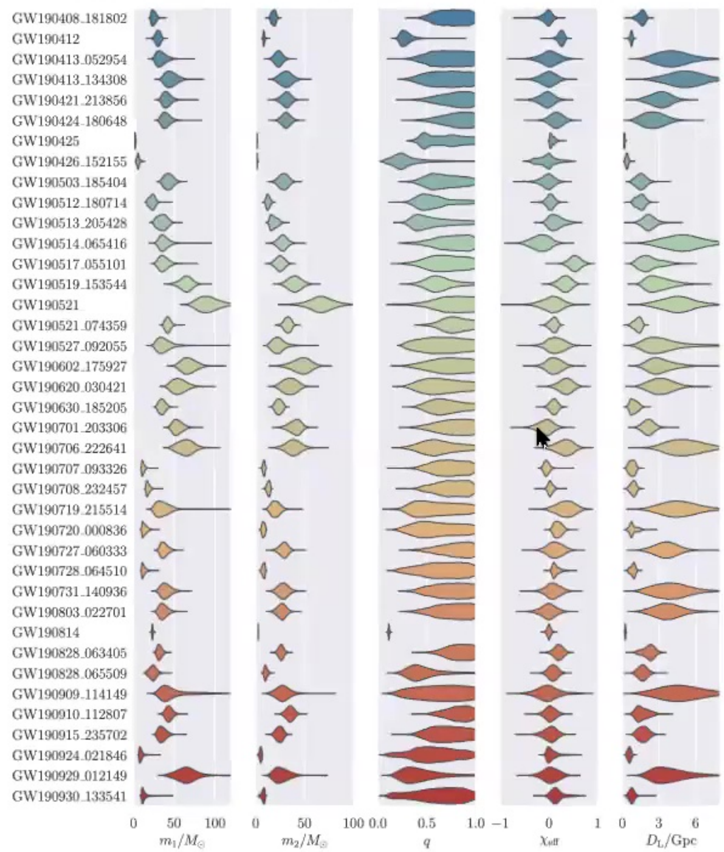


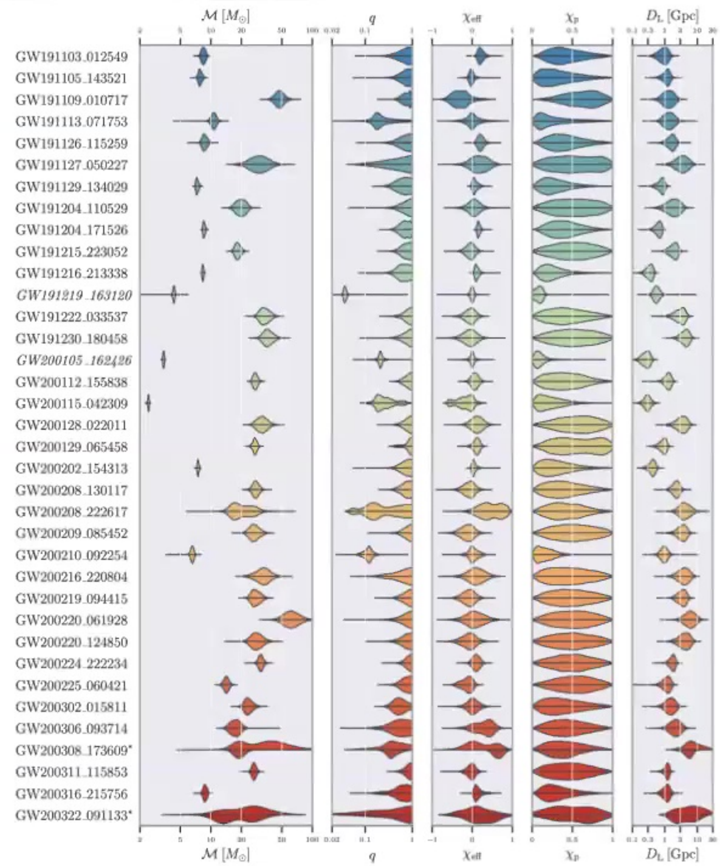
Inman, Ali-Haimoud (2019)

Early-time merger rate suppressed by binary interactions in clusters

De Luca, Desjacques, Franciolini, Riotto JCAP [2009.04731]

GWTC-2 & GWTC-3





Highlights:

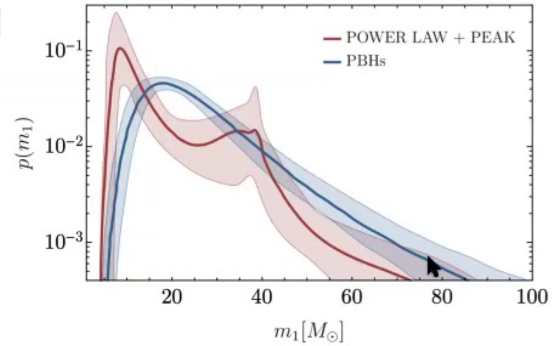
- Spinning events
- Events in the mass gap

→ Some features start to appear

Comparison with LVK (GWTC-2)

Wong, Franciolini, De Luca, Baibhav, Berti, Pani, Riotto JCAP [2011.01865]

- PBHs "alone" are not able to reproduce all the features

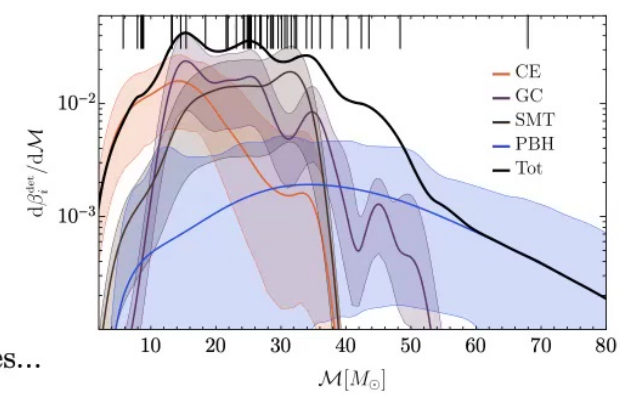


- Confront between PBH and ABH models (CE, SMT, GC, NSC)

Role of PBHs depends on considered ABH models

Constraint on the PBH abundance: $f_{\rm PBH} \lesssim 10^{-3}$

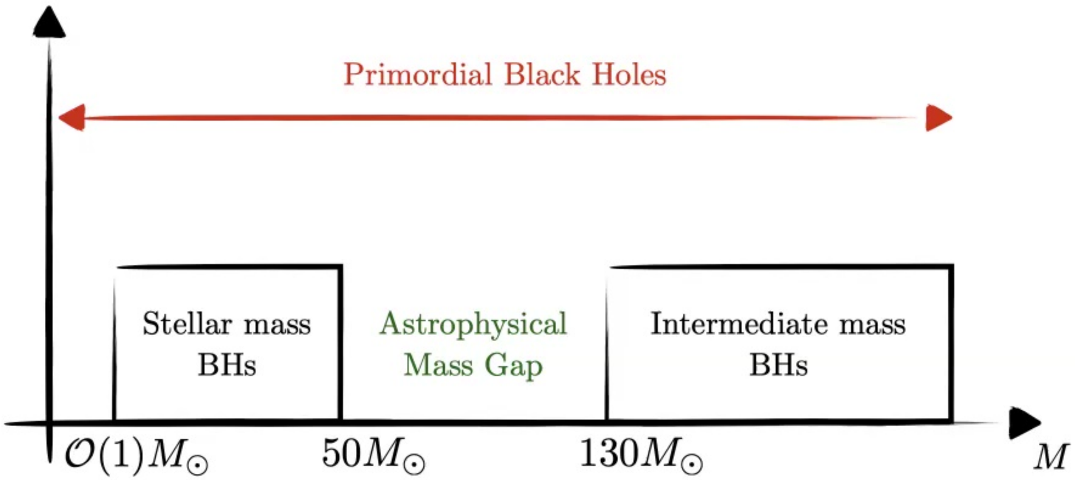
Extend the analysis with more ABH channels, uncertainties...

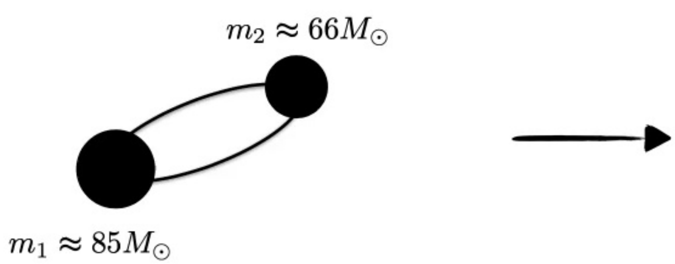


Franciolini, Baibhav, De Luca, Ng, Wong, Berti Pani, Riotto, Vitale [2105.03349]

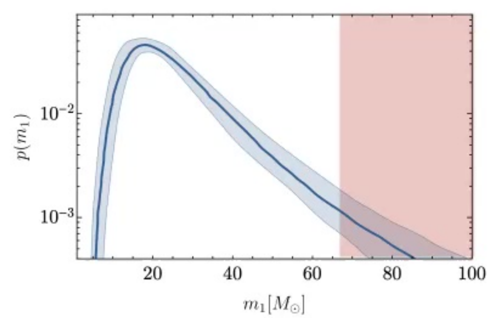
Mass Gap: GW190521

PBHs may fill the astrophysical **Mass Gap**





GW190521-like events expected from PBH population with rate compatible with observation

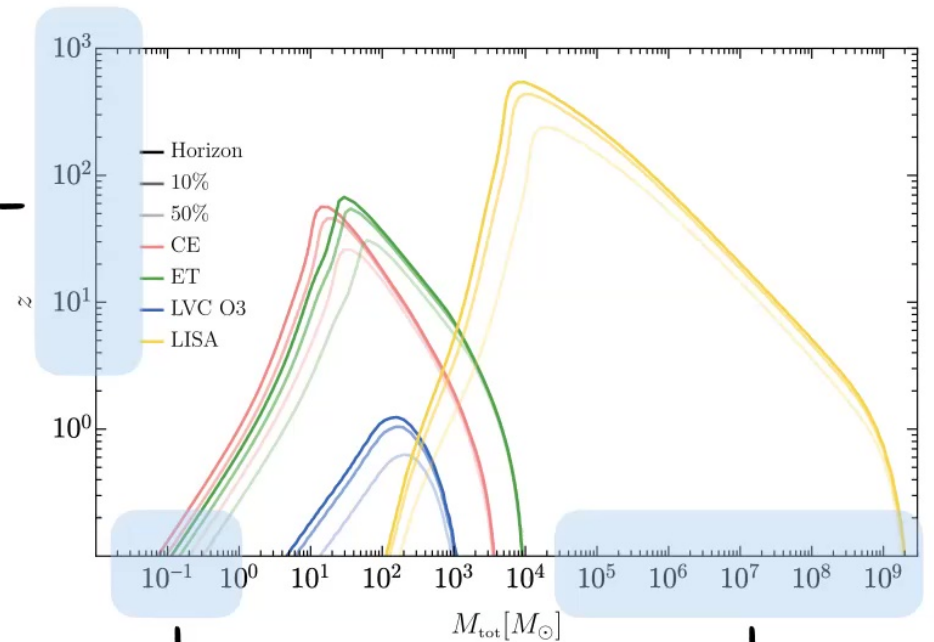


De Luca, Desjacques, Franciolini, Pani, Riotto PRL [2009.01728]

Future GW experiments

3G detectors (ET/CE) and LISA have larger horizon redshifts

Large redshift



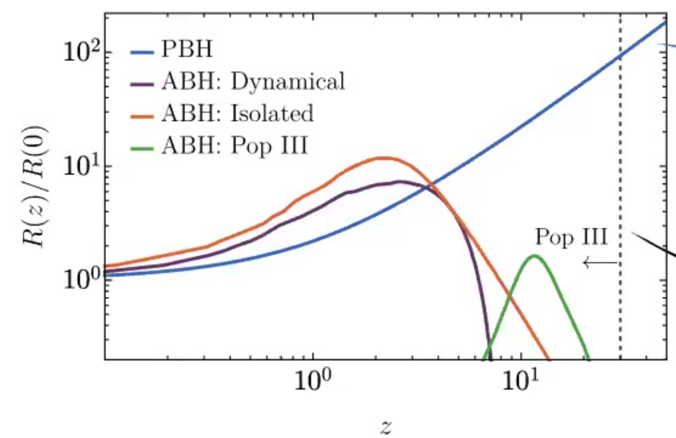
Subsolar objects

SMBHs

They may help in distinguishing PBHs from ABHs

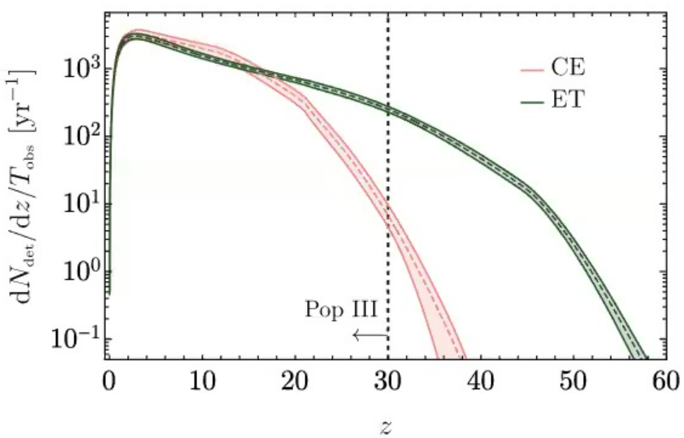
Merging at high redshift

GWs observation at high redshift with ET/CE may help in distinguish PBH from ABH



$R_{\rm PBH} \sim t(z)^{-34/37}$

No contamination from ABH (pop III)



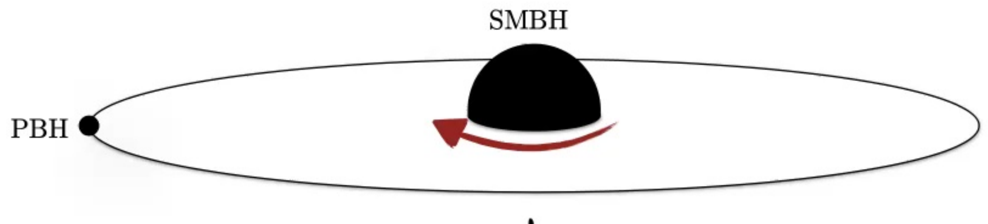
High redshift observations at ET
in PBH/ABH phenomenological scenario:

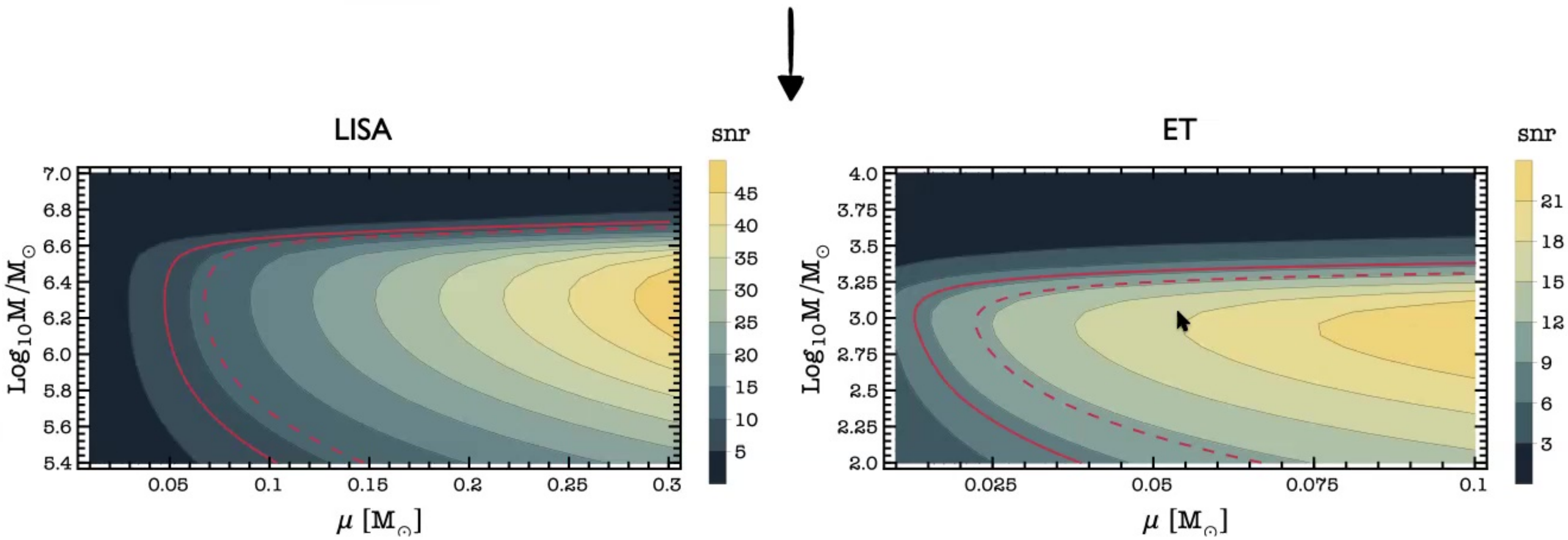
$$N^{\rm det}_{\rm PBH}(z > 30) = 1315^{+305}_{-168}/{\rm yr}$$

De Luca, Franciolini, Pani, Riotto JCAP [2102.03809]

Extreme mass-ratio inspirals (EMRI)

Detection of subsolar compact objects may point to PBH discovery



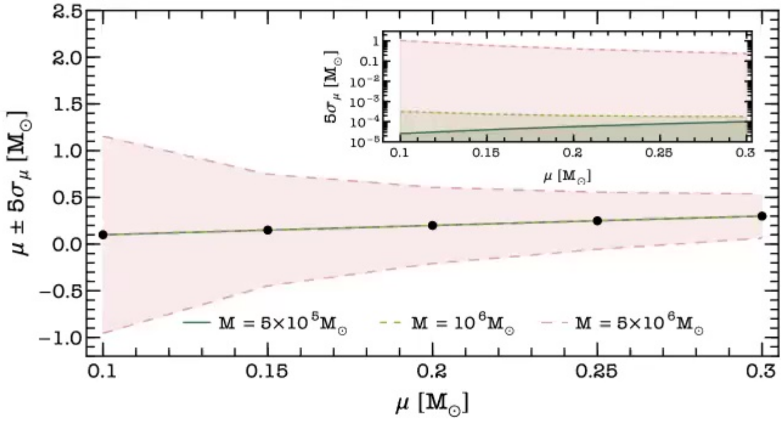


- LISA: detection of subsolar masses up to O(500) Mpc
- ET: detection of subsolar masses up to O(1) Gpc

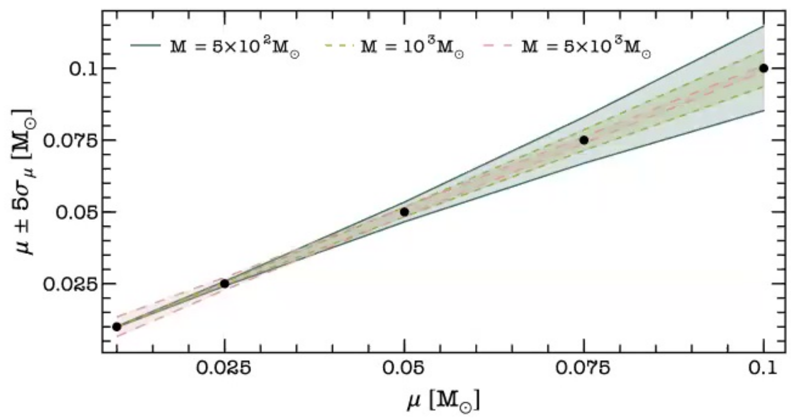
Extreme mass-ratio inspirals (EMRI)

Investigate detectability of subsolar compact objects: **Fisher analysis**

LISA



ET

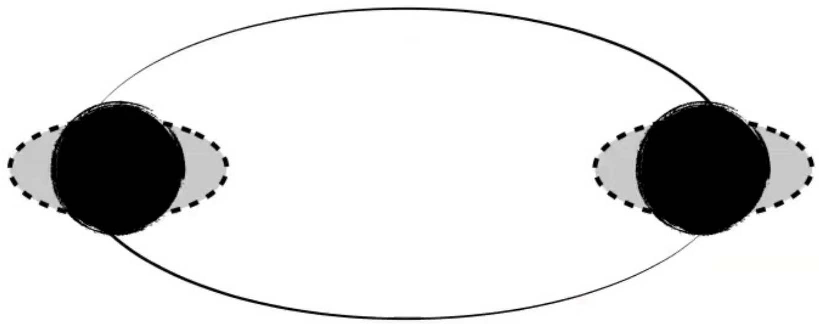


Barsanti, De Luca, Maselli, Pani PRL [2109.02170]

- Exclude super-solar mass at more than 5-sigma confidence level at both ground and space interferometers
- EMRIs at ET would provide novel GW sources (currently undetectable at LVK)

Love Number

External tidal fields may deform astrophysical objects



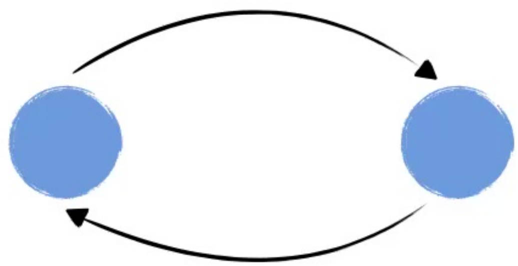
The tidal deformability of a compact object is expressed in terms of its Tidal Love Number, which depends on the internal properties of the object

↓

It leaves detectable imprints in GW signals (5PN)

Love Number

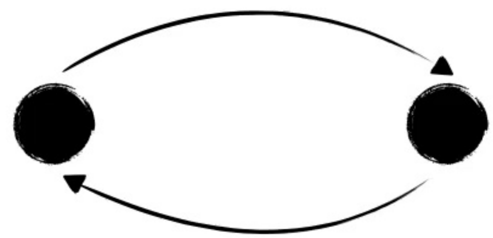
Binary NSs



Measuring TLNs provide constraints on NS equation of state

Hinderer (2008)

Binary BHs

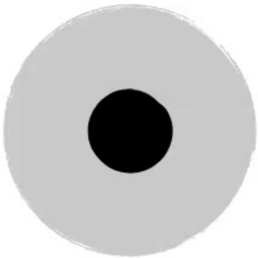


TLNs of naked BHs are zero

Binnington et al. (2009)
Damour et al. (2009)

What happens for dressed BHs, i.e. those surrounded by matter fields?

Love Number of dressed BHs



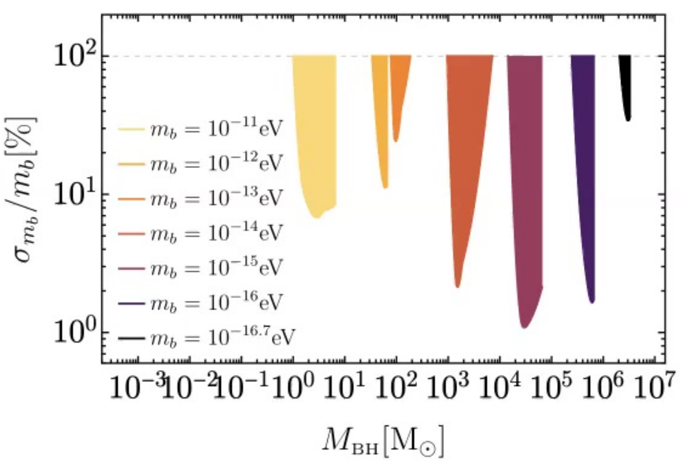
Accretion of scalar field on BH

Superradiance over spinning BH

$$\mathrm{TLN} \propto \frac{1}{(GM_{\mathrm{BH}}m_b)^8}$$

De Luca, Pani JCAP [2106.14428]

Constraints on the ultralight scalar field mass from ET and LISA



- LISA can measure the TLN of dressed BHs from the stellar-mass to the supermassive range
- Probe ultralight boson masses
- Future prospects: accretion disks?

Conclusions

- PBHs are fascinating early-universe compact objects and provide a candidate for the dark matter
- They may be produced within different formation scenarios, which could be tested at GW experiments like LISA or NANOGrav
- PBHs are competitive with ABH models and may contribute to the present GW data detected by the LVKC
- Future GW experiments like LISA or ET/CE may help in discovering PBHs and shed light on their properties