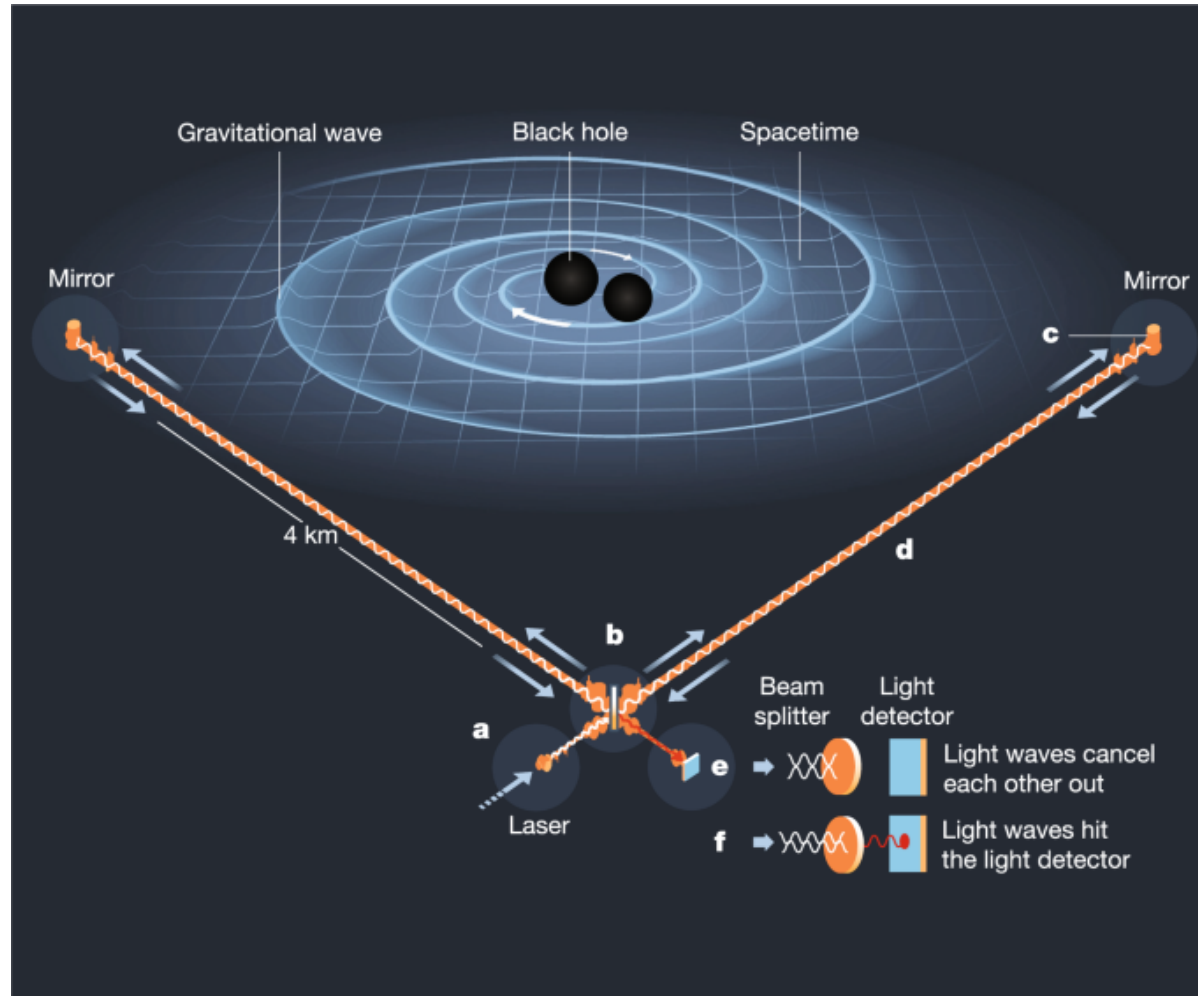


Primordial Black Holes in the era of Gravitational Wave Astronomy

Antonio Riotto
University of Geneva

in collaboration, among others, with V. De Luca and G. Franciolini

Gravitational waves and Black Holes are key predictions of General Relativity



Black Holes

- Astrophysical BHs forms from the gravitational collapse of a star. We know they exist. Their mass must be above the Chandrasekhar limit,

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

- PBHs are formed in the early universe. Their mass can be small and they can still be around as long as they do not evaporate within the age of the universe

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

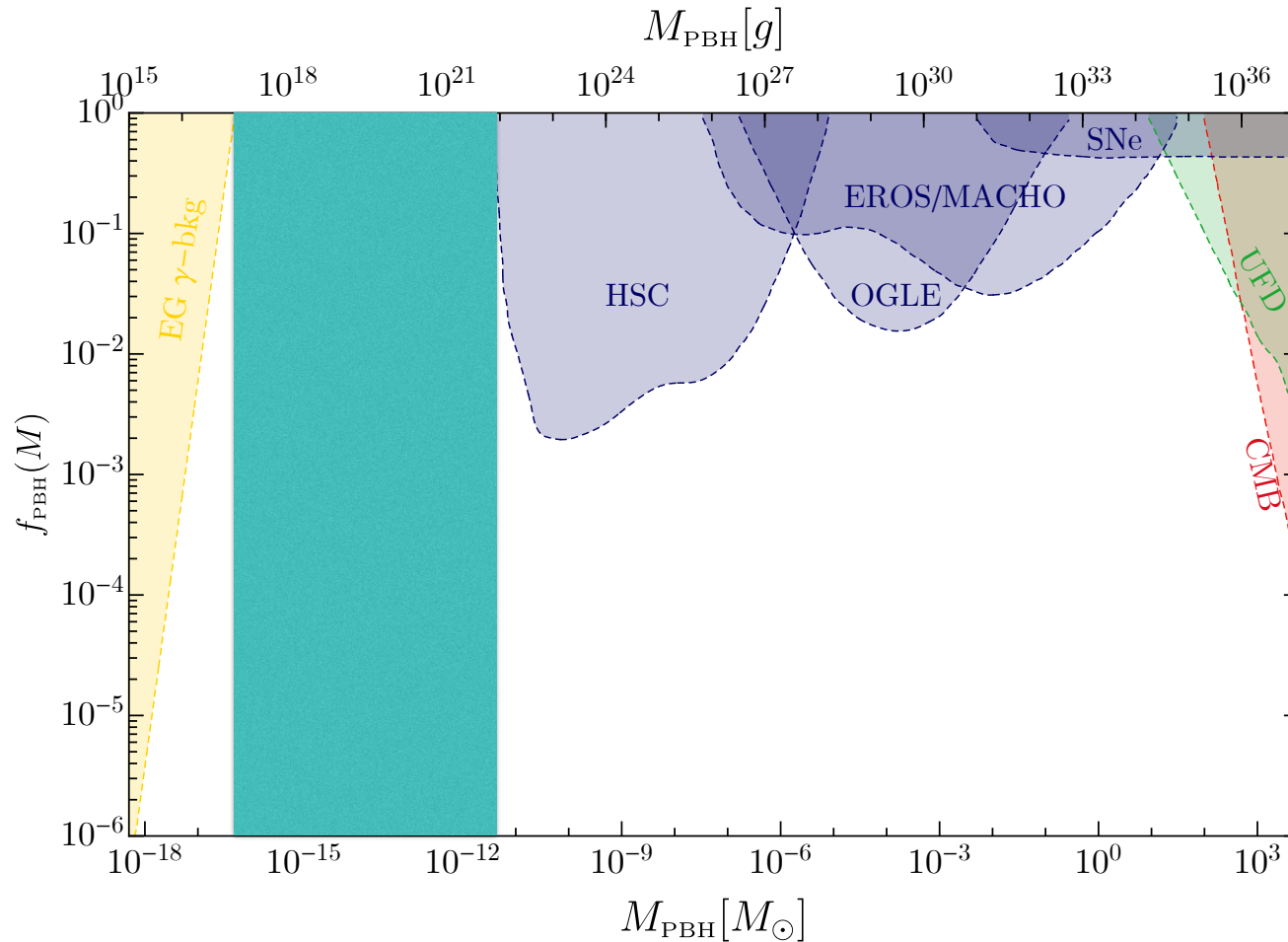
Key Questions on PBHs in the GW era

- Do (will) PBHs contribute to current (future) GW signals?
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- Can PBHs account for all the dark matter in the universe?

PBHs

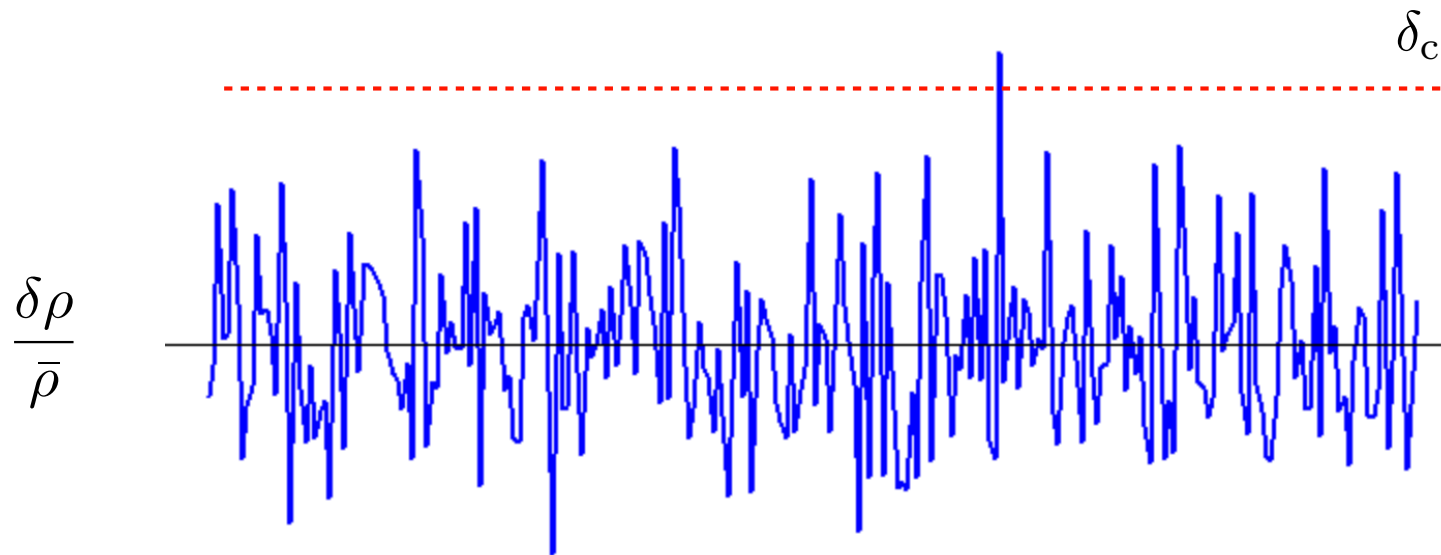
Primordial black holes can compose all the dark matter (or a fraction of it)

$$f_{\text{PBH}} = \Omega_{\text{PBH}} / \Omega_{\text{DM}}$$



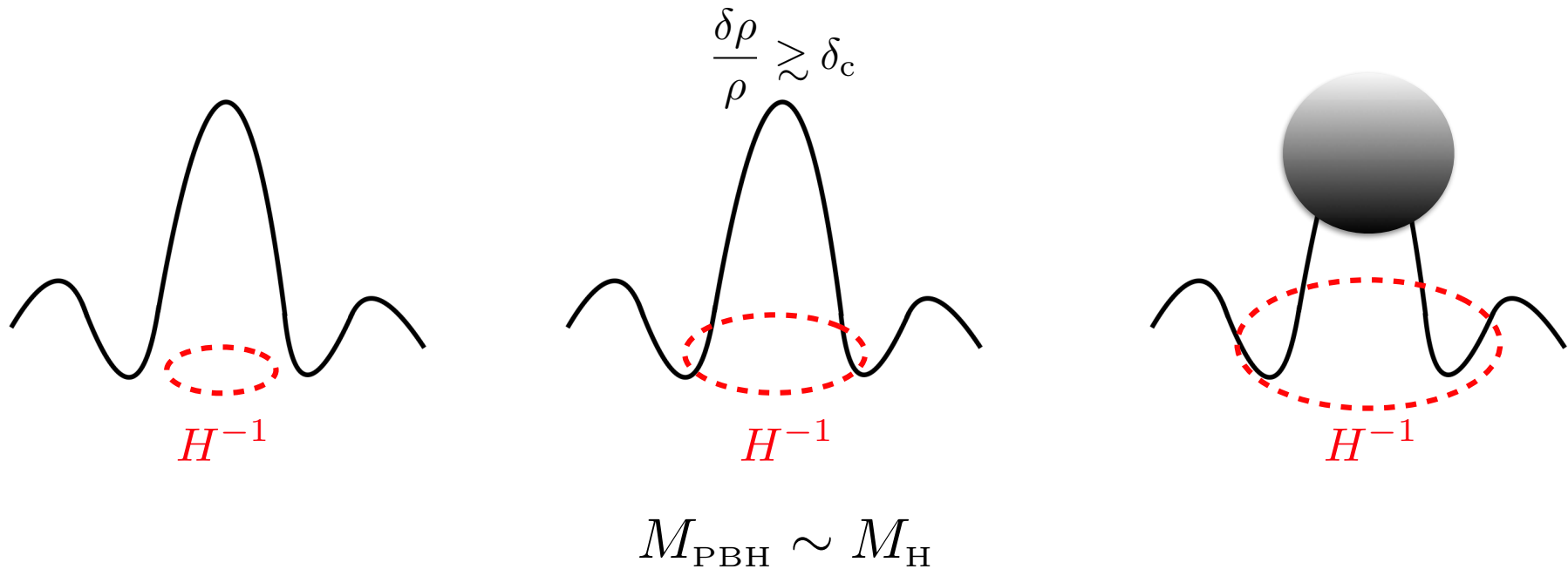
Where the PBHs may come from?

PBHs may be originated from peaks of the density perturbations generated in the early universe



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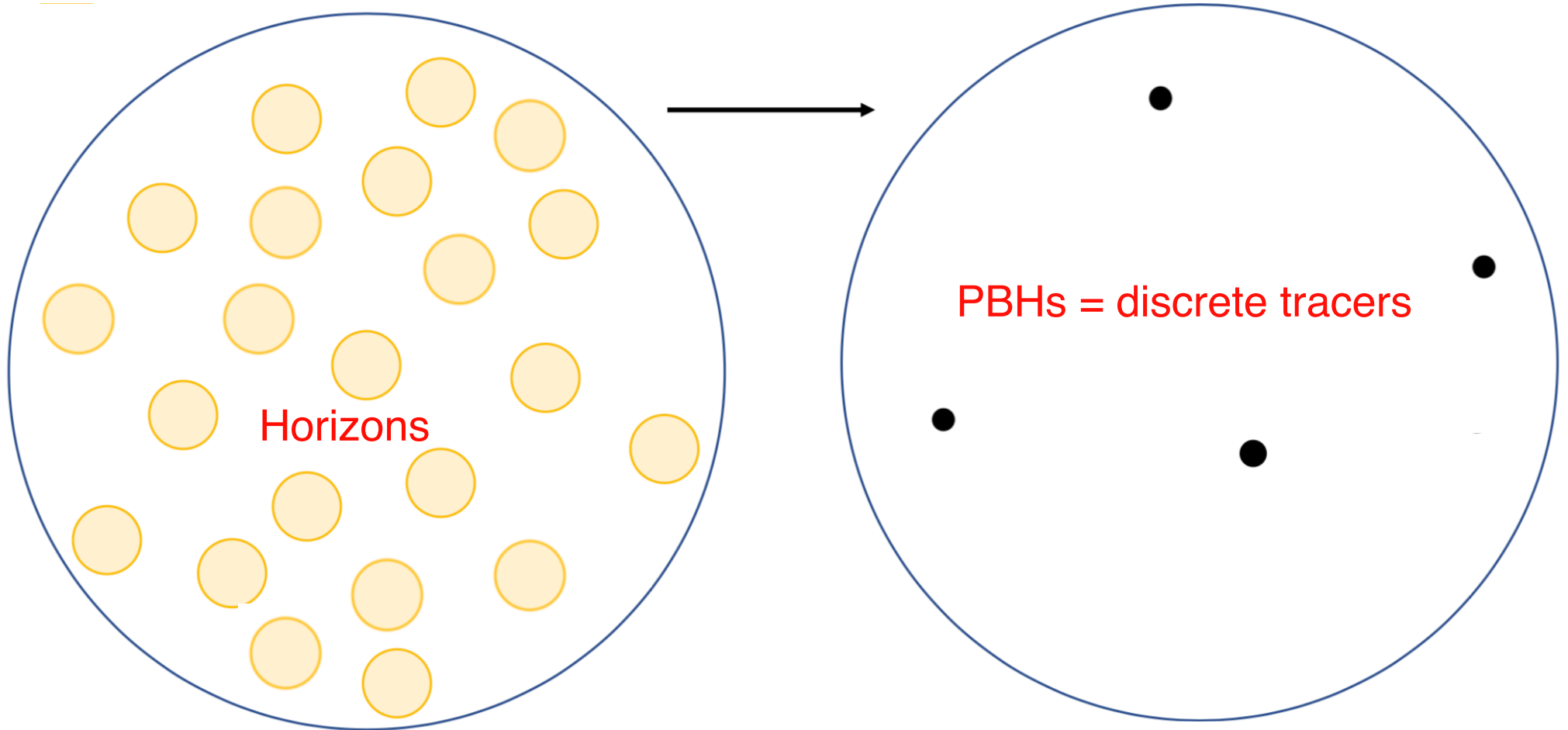


PBHs are rare events, tail of the distribution

One possible mechanism: large fluctuations from inflation

Properties of PBHs at formation

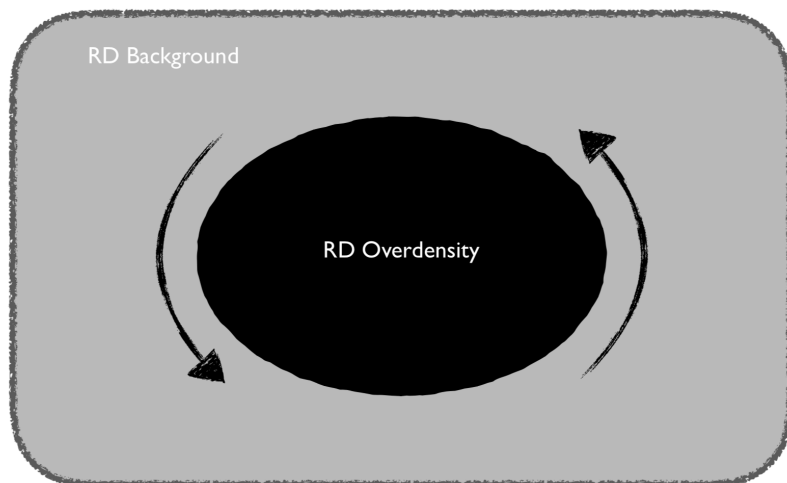
PBHs are not clustered at formation



$$\left\langle \frac{\delta\rho_{\text{PBH}}(\vec{x}, z)}{\bar{\rho}_{\text{DM}}} \frac{\delta\rho_{\text{PBH}}(0, z)}{\bar{\rho}_{\text{DM}}} \right\rangle = \frac{f_{\text{PBH}}^2}{n_{\text{PBH}}} \delta_{\text{D}}(\vec{x}) + \xi(x, z)$$

The spin of PBHs at formation is small

- PBHs originate from peaks, that is from *maxima* of the local density contrast.
- The spin results from the action of the torques generated by the gravitational tidal forces upon horizon crossing



$$\vec{\chi} = \vec{S} / G_N M_{\text{PBH}}^2$$

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

Shape of the density power spectrum

De Luca et al. (2018)

The PBH mass function at formation

Mass distribution dependent on the overdensity perturbation spectrum and statistical properties

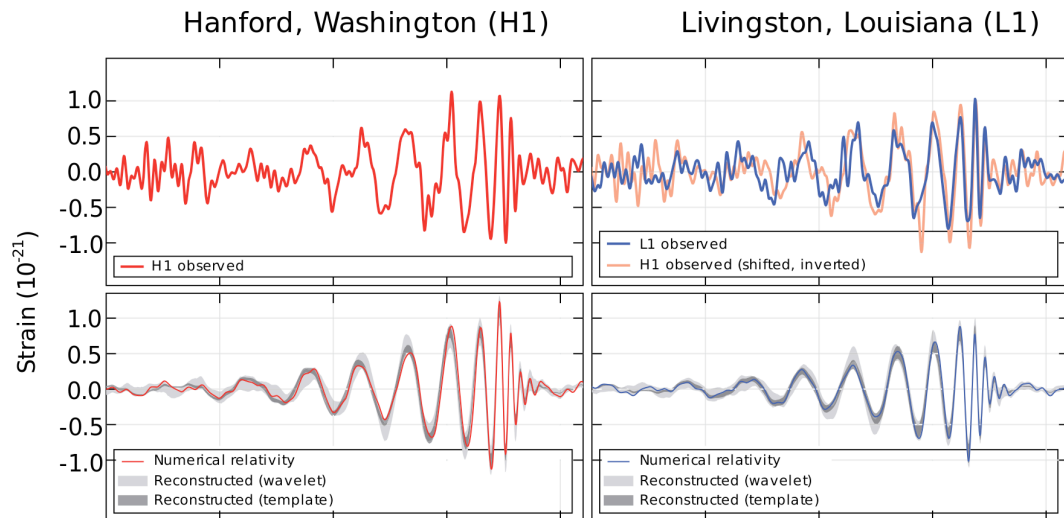
Standard parametrisation

$$\psi(M_{\text{PBH}}) = \frac{1}{\sqrt{2\pi}M_{\text{PBH}}} \exp\left(-\frac{\ln^2(M_{\text{PBH}}/M_c)}{2\sigma^2}\right)$$

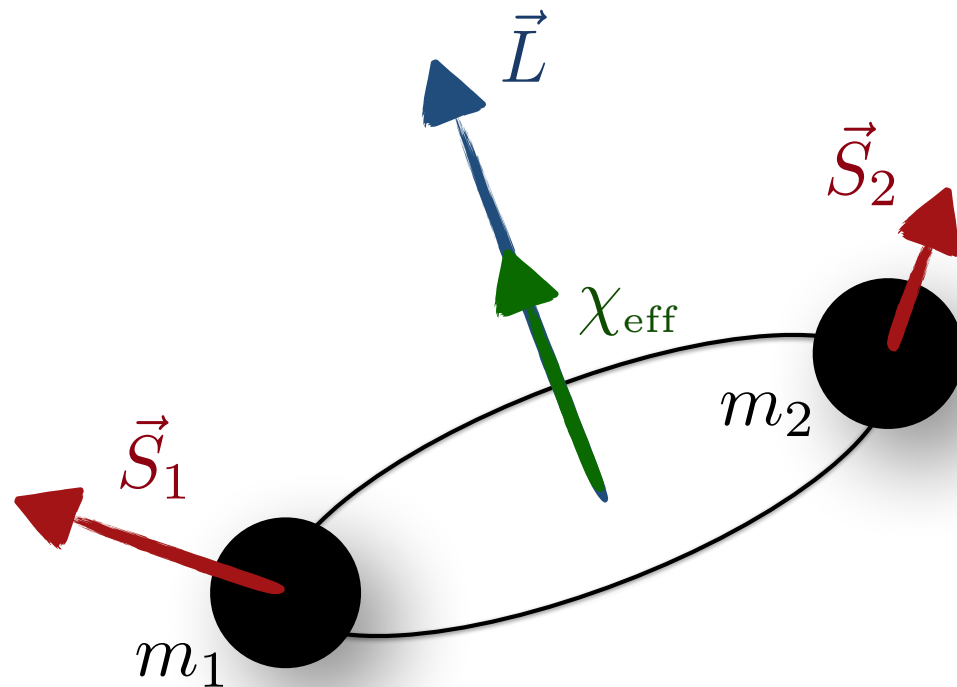
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BH binary



GW150914, LIGO (2016)



Waveforms dependent on the binary event parameters

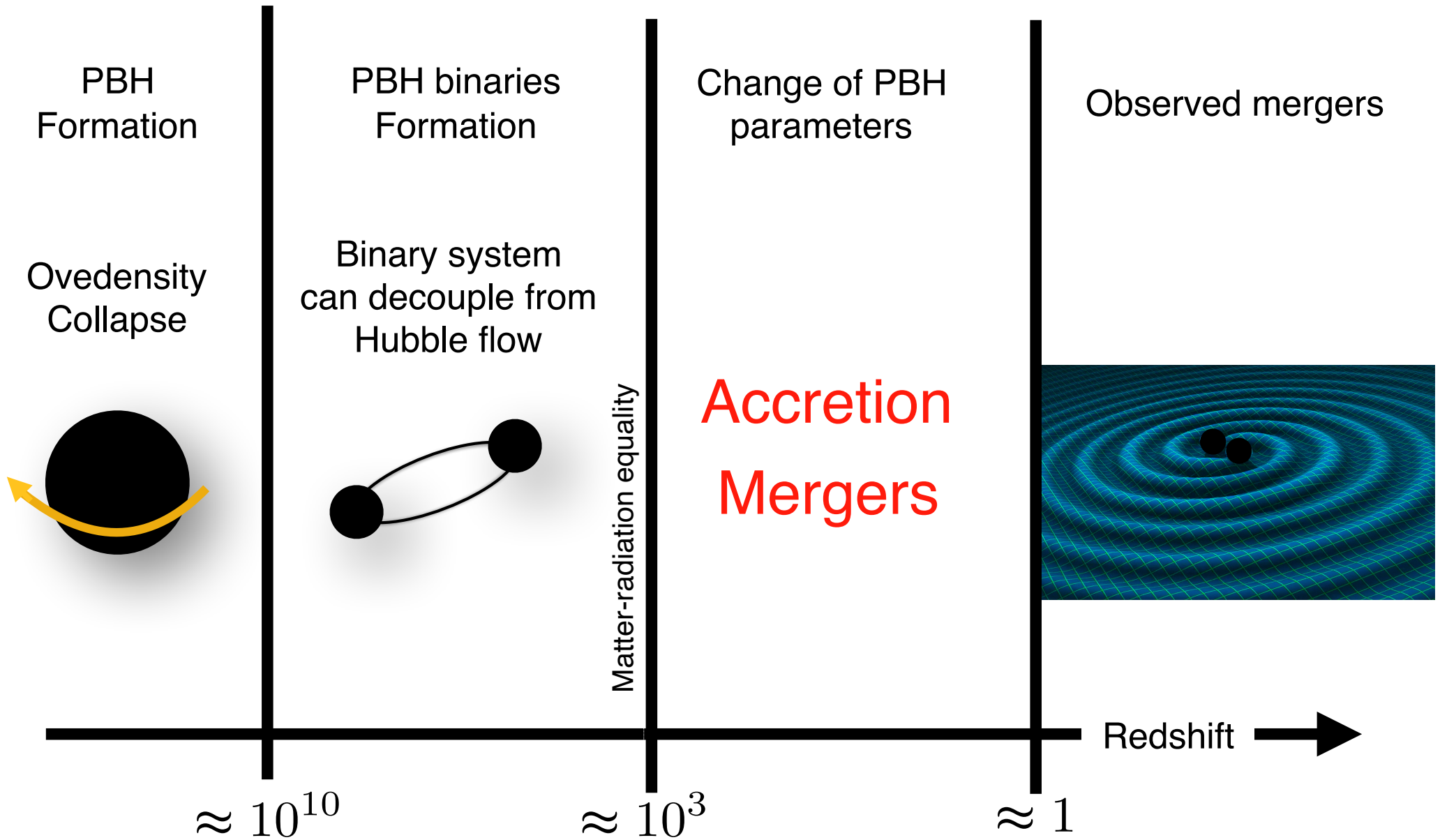
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$q = m_2 / m_1$$

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

...

PBH evolution



Accretion onto isolated PBHs

For $f_{\text{PBH}} < 1$ PBHs coexist with another DM component in the universe

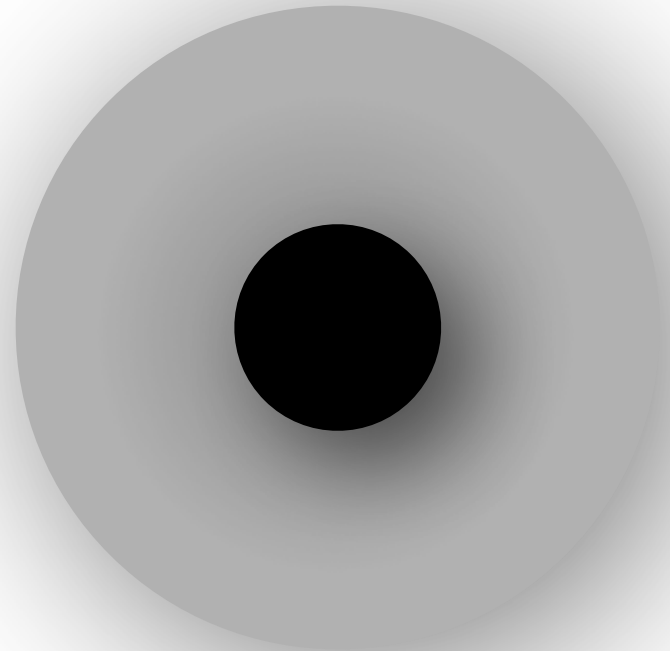
A DM halo builds up around the PBHs
enhancing accretion

(larger gravitational potential well)

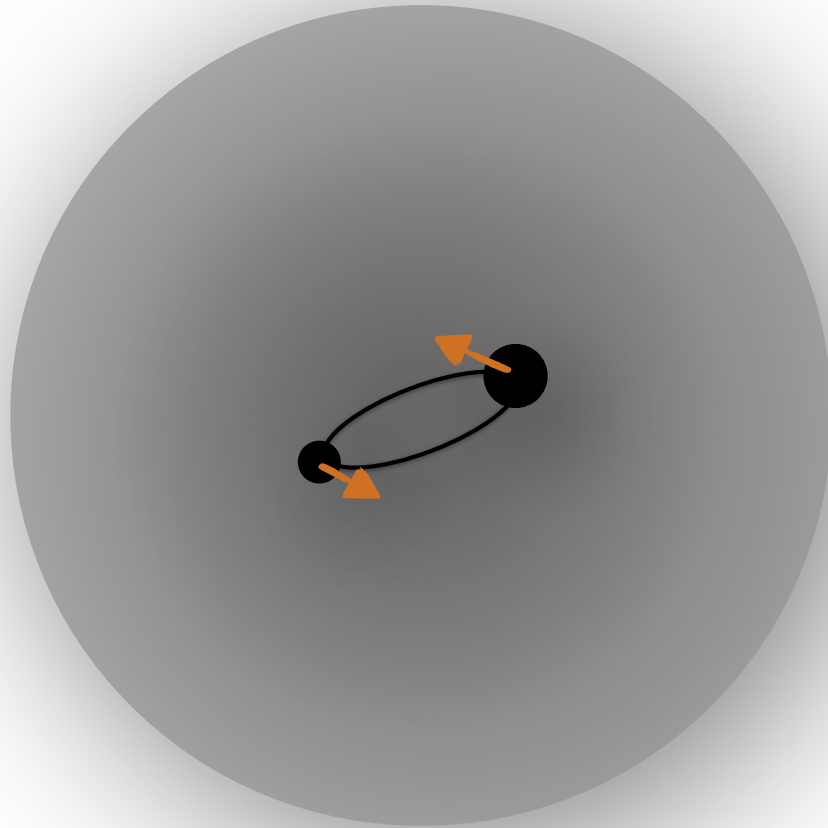
$$M_h(z) \approx 3M_{\text{PBH}} \left(\frac{1000}{1+z} \right)$$

Bondi-Hoyle accretion from the
surrounding baryonic fluid

$$\dot{M} = 4\pi\lambda m_H n_{\text{gas}} v_{\text{eff}}^{-3} M^2$$



Accretion onto PBH binaries



Accretion on the system enhances the gas density around the PBH binary

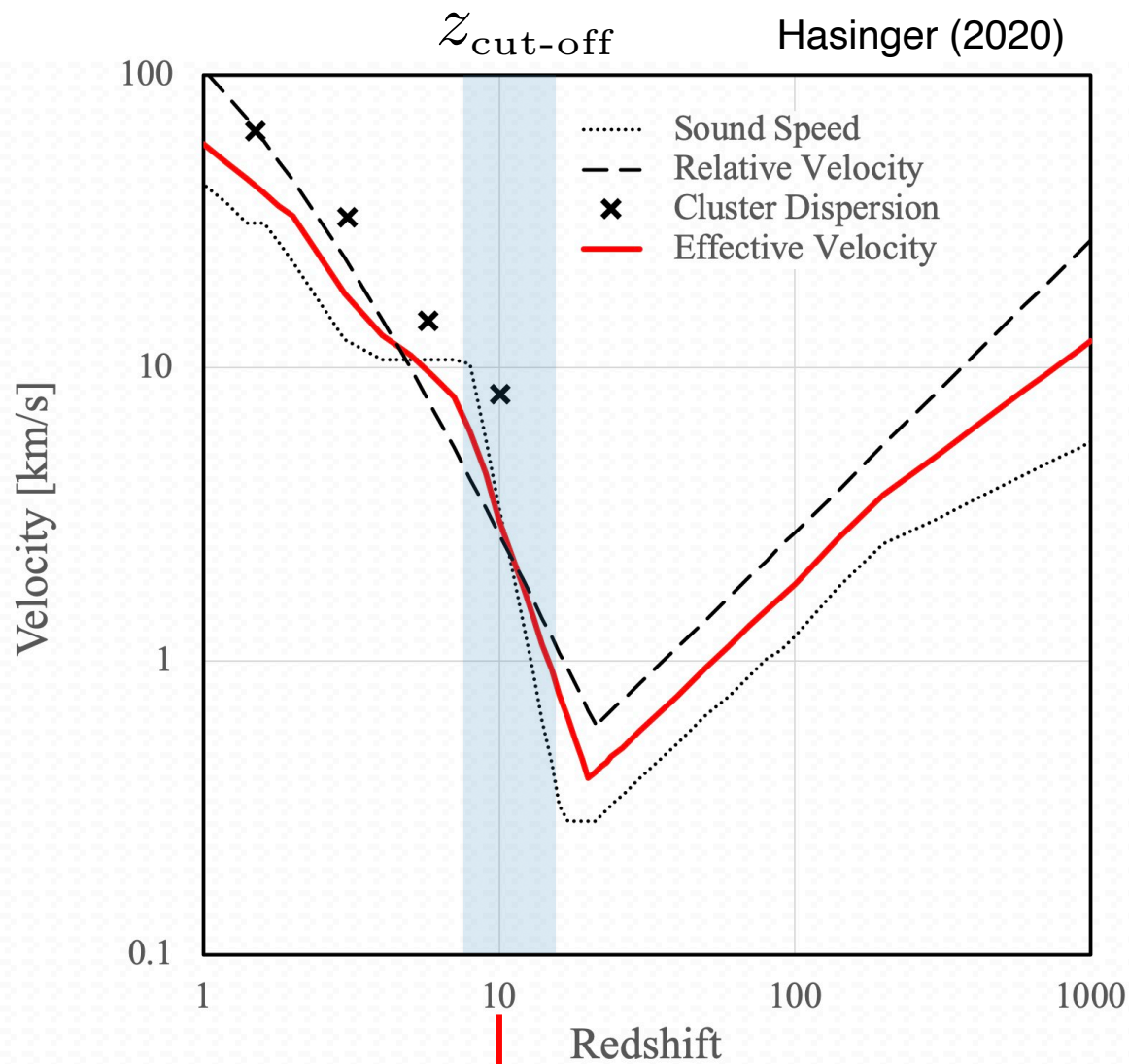
Accretion on the single PBH modulated by masses and orbital velocities

$$\dot{M}_1 = \dot{M} \frac{1}{\sqrt{2(1+q)}}$$

$$\dot{M}_2 = \dot{M} \sqrt{\frac{q}{2(1+q)}}$$

$$q = 1 \quad \text{fixed point}$$

- The smaller PBH always experiences a larger relative accretion
- PBH can experience accretion for $M \gtrsim \mathcal{O}(10)M_\odot$



Structure formation
reionization epoch

- Virialised velocities
- Higher temperatures

$$\dot{M} \approx (v_{\text{rel}}^2 + c_s^2)^{-3/2}$$

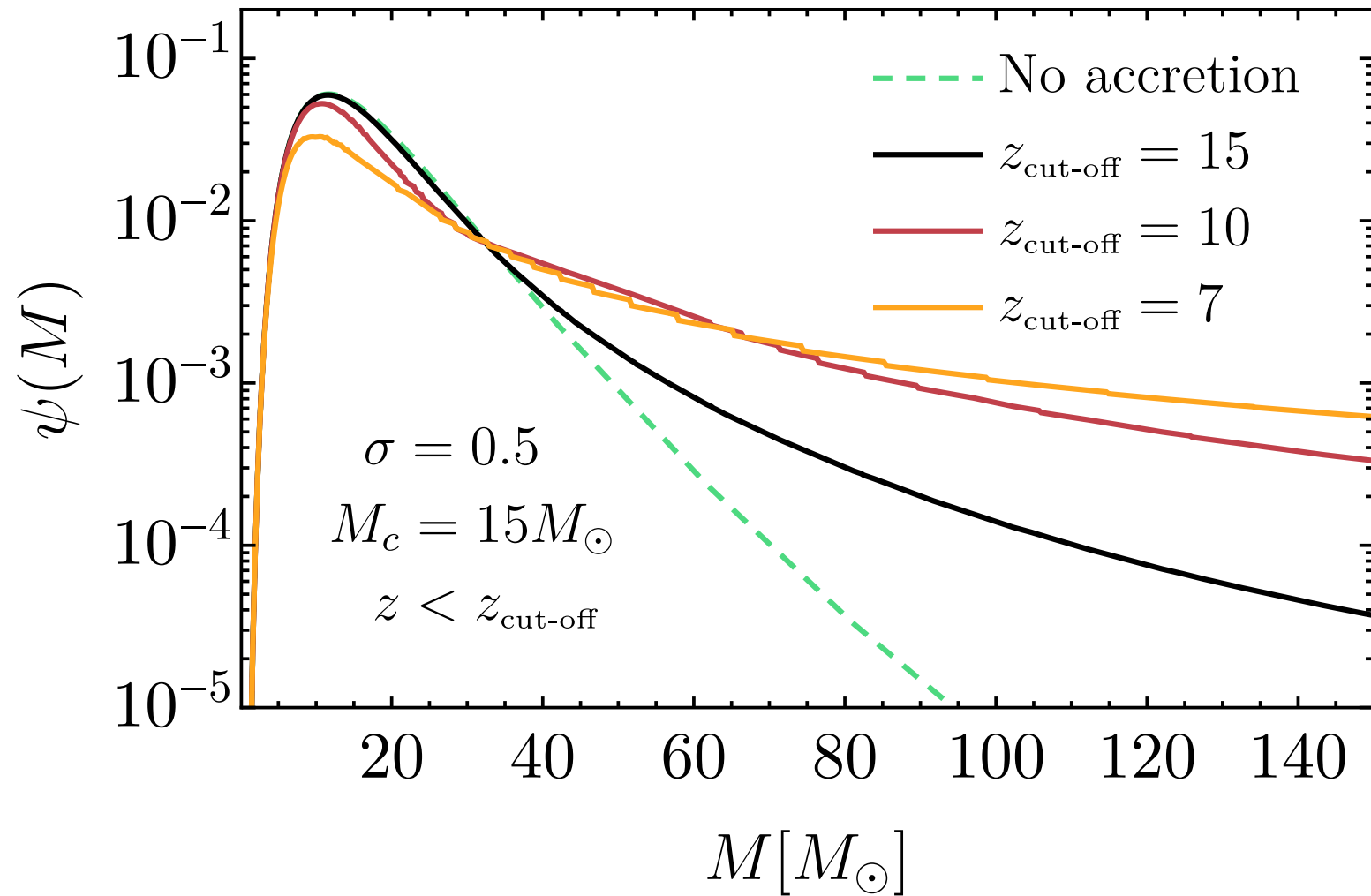


Strong suppression around

$z_{\text{cut-off}}$

Uncertainties
in the accretion model
accounted for by
varying the cut-off

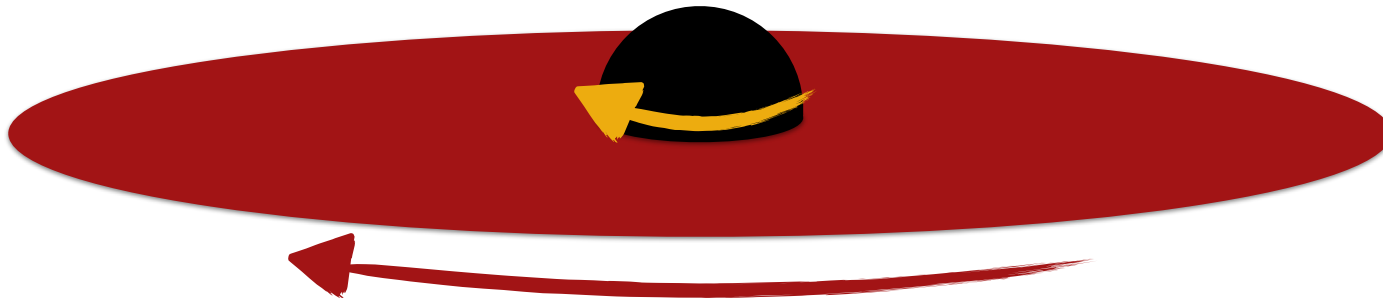
PBH mass function evolution



Non-linear mass evolution enhances large-mass tails

PBH spin evolution

If matter angular momentum is large enough, an accreting disk forms, leading to a spin growth

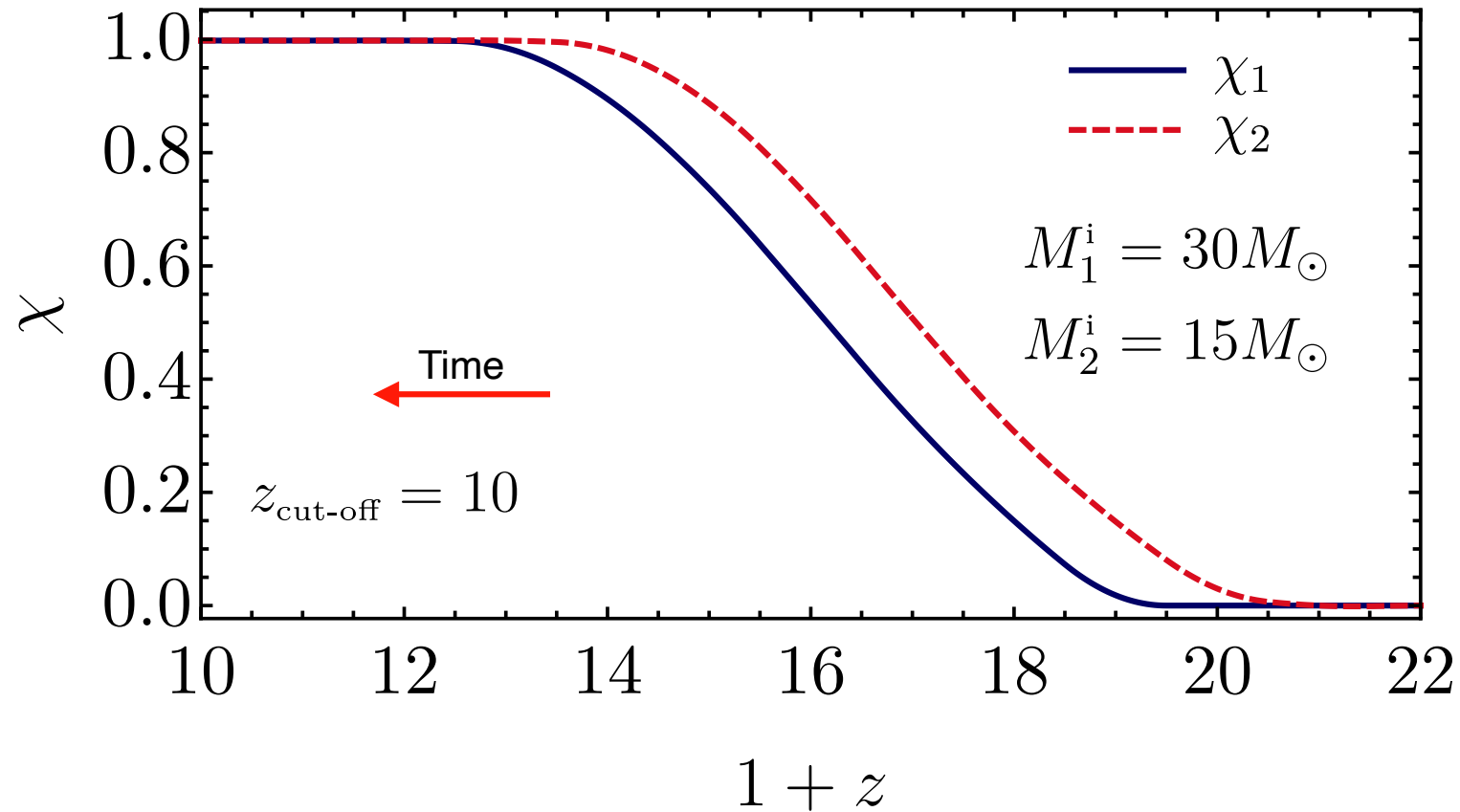


Angular momentum transfer between gas and PBH

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

by solving the geodesic model of disk accretion

Spins pushed towards extremality



- Uncorrelated spin orientation
- Effective spin spreads around zero
- Accretion: low/large mass - low/large spin correlation

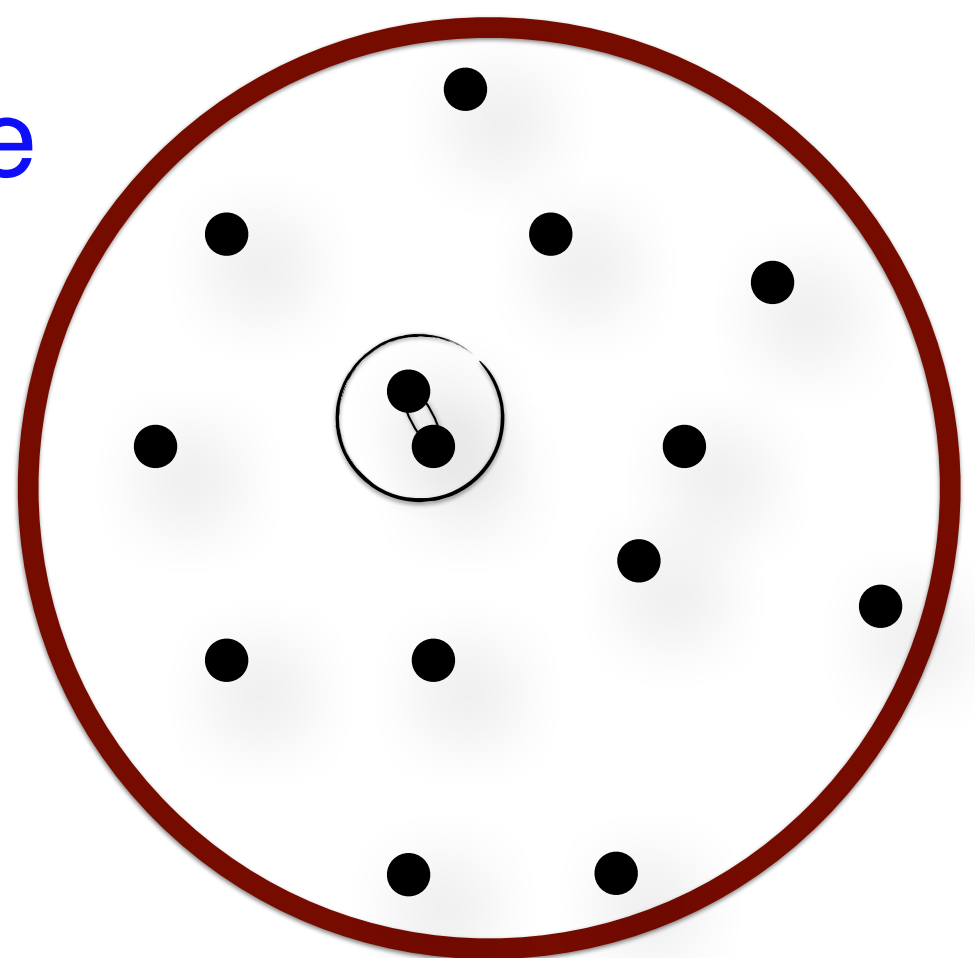
Merger rate

- Initial spatial Poisson distribution
- Random decoupling of binary systems



Compute probability of decoupling and the binary initial geometry

- Semi-major axis
- Eccentricity



Raidal et al (2018)

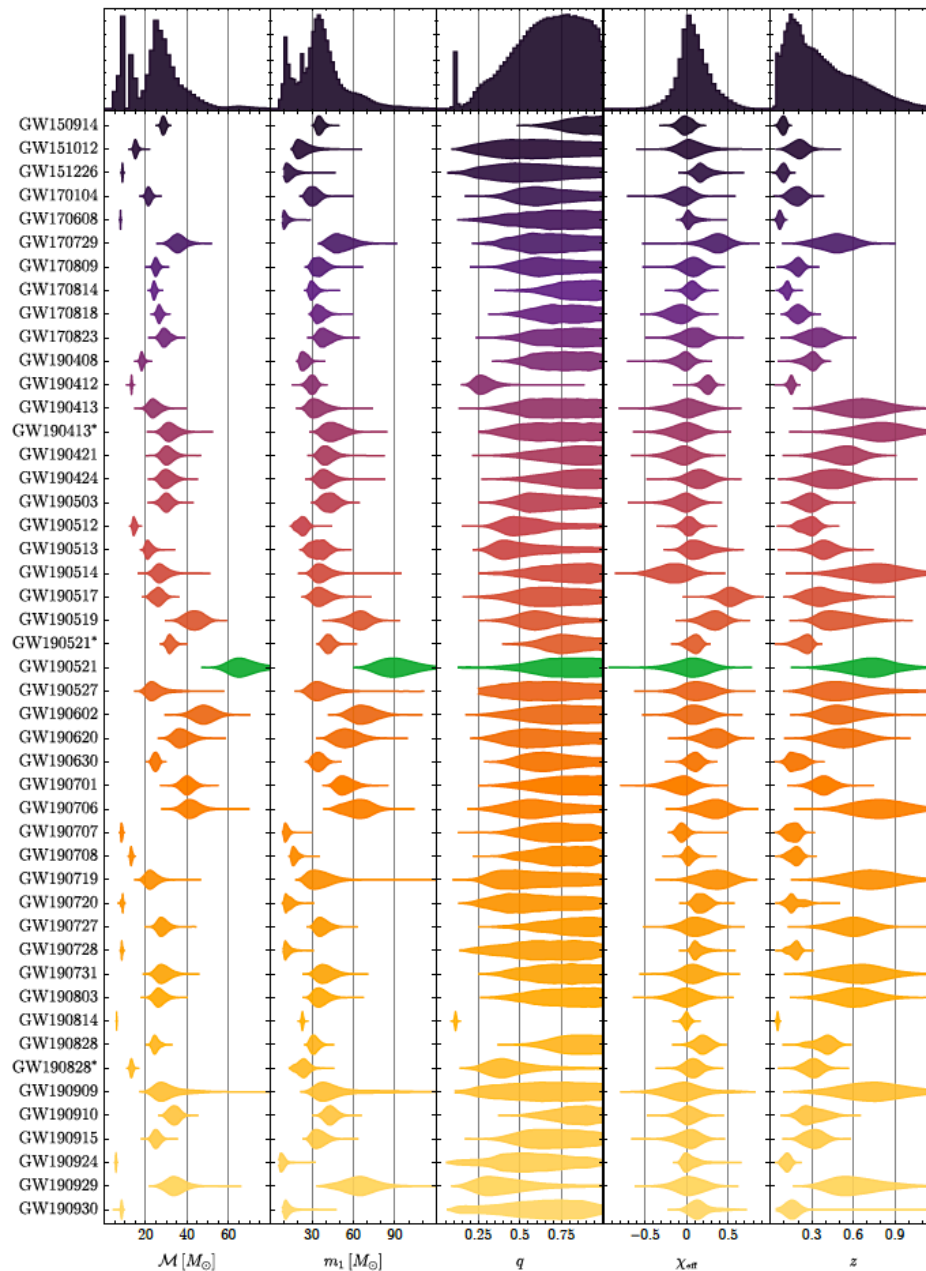
$$\frac{dR}{dm_1 dm_2} = \frac{1.6 \times 10^6}{\text{Gpc}^3 \text{ yr}} f_{\text{PBH}}^{\frac{53}{37}} \eta^{-\frac{34}{37}} \left(\frac{t}{t_0}\right)^{-\frac{34}{37}} \left(\frac{M_{\text{tot}}}{M_{\odot}}\right)^{-\frac{32}{37}} S(M_{\text{tot}}, f_{\text{PBH}}) \mathcal{A}_{\text{acc}}(m_j) \psi(m_1) \psi(m_2)$$

- Accretion hardens the binaries
- Larger masses leads to shorter mergers



De Luca et al. (2020)

GWTC-2 catalogue



Most events consistent with equal masses

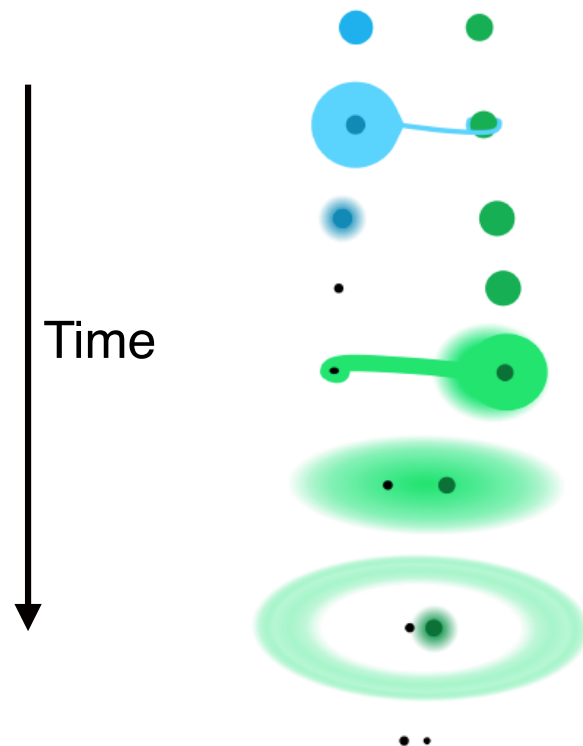
About 10 events with large spins

Astrophysical populations

Zevin et al. (2021)

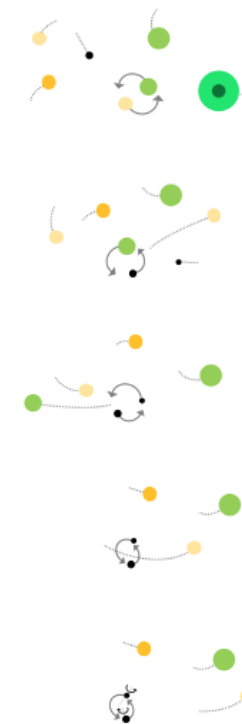
Isolated formation

Binary formation in galactic fields through a Stable Mass Transfer (SMT) or Common-Envelope (CE) phase



Dynamical formation

Binary formation in Globular Cluster (GC) or Nuclear Star Clusters (NCS) through encounters and GW captures



For a review, Mandel and Farmer (2018)

Bayesian evidence in GWTC-2

Event parameters $\vec{\theta}$

m_1 m_2 χ_{eff} z

Population Hyperparameters $\vec{\lambda}$

M_c σ f_{PBH} $z_{\text{cut-off}}$ α_{CE} χ_b N_{CE} N_{GC} N_{NSC}

$$p(\vec{\lambda}|\vec{d}) \propto p(\vec{\lambda}) \int d\vec{\theta} p(\vec{d}|\vec{\theta}) p_{\text{pop}}(\vec{\theta}|\vec{\lambda})$$

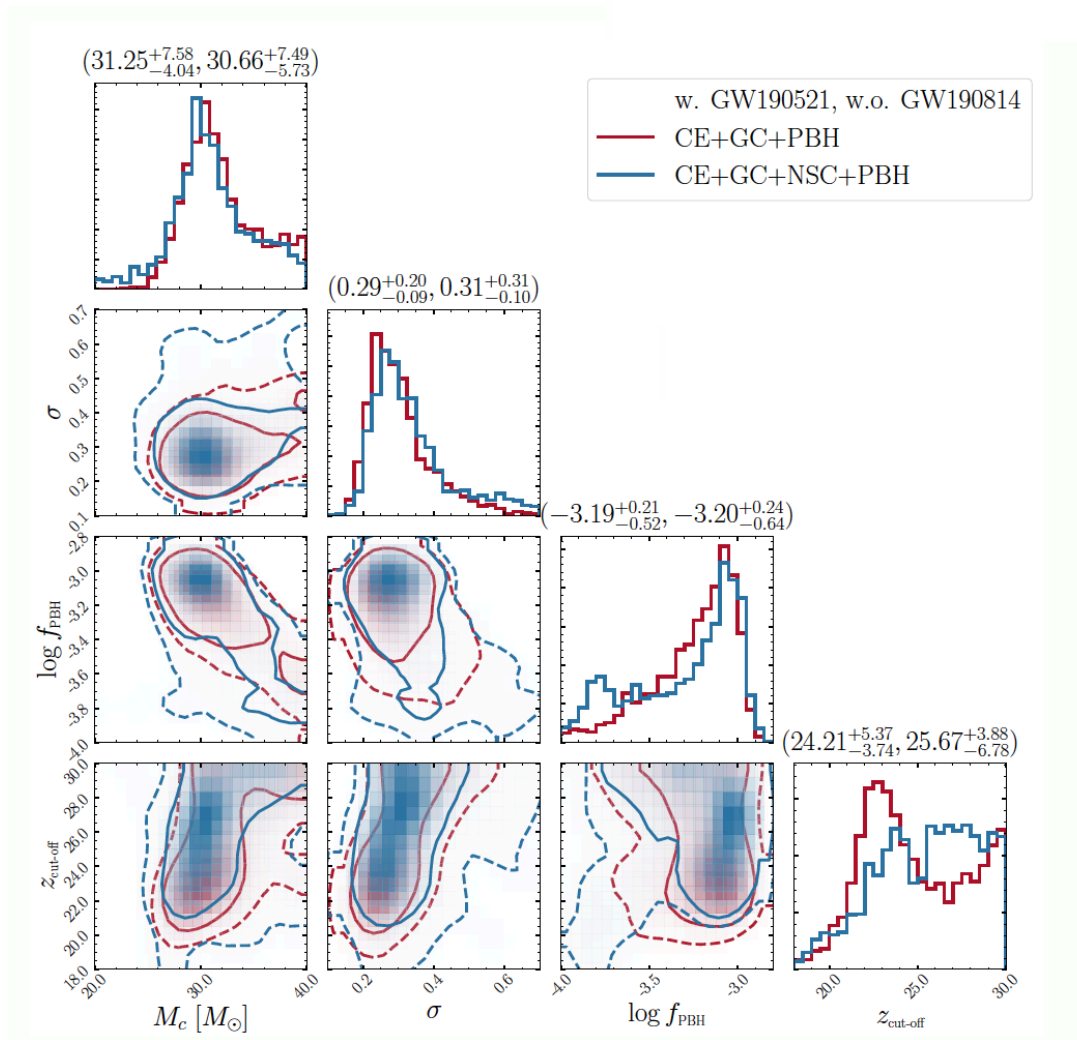
Posterior
distribution

Hyperparameter
prior

Single event
likelihood

Population
likelihood (ML)

Population posterior distributions



$$M_c \simeq 30M_\odot$$

$$\sigma \simeq 0.3$$

$$f_{\text{PBH}} \simeq 6 \cdot 10^{-4}$$

$$z_{\text{cut-off}} \simeq 25$$

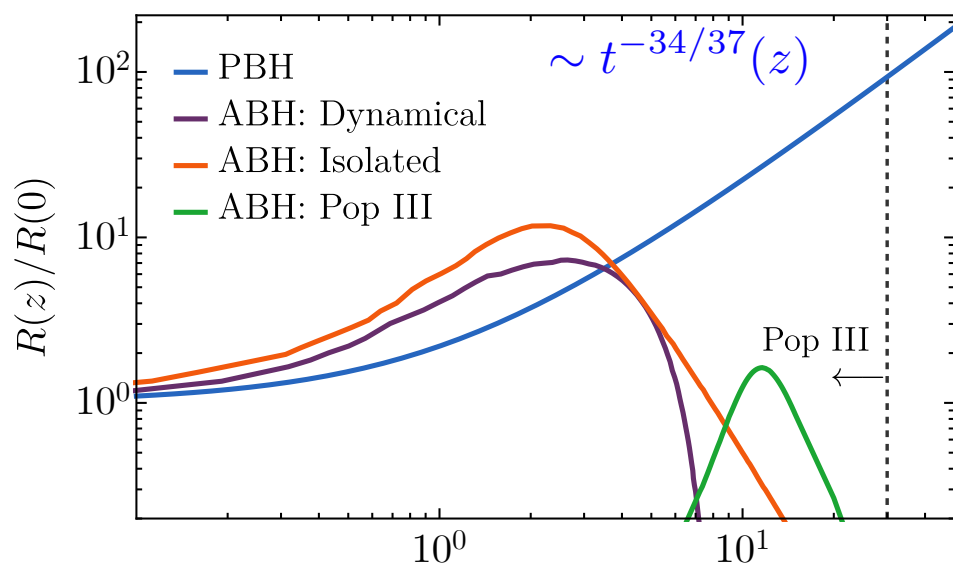
PBH not the dark matter

Moderate accretion

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K. Ng et al. (2020)

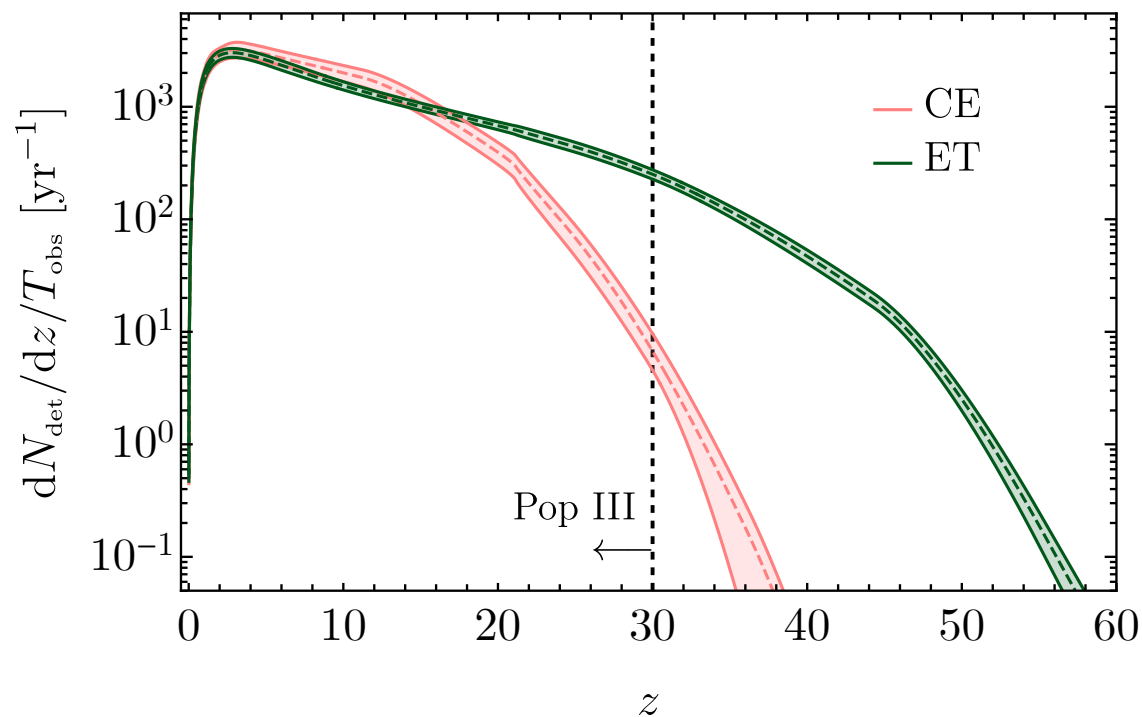
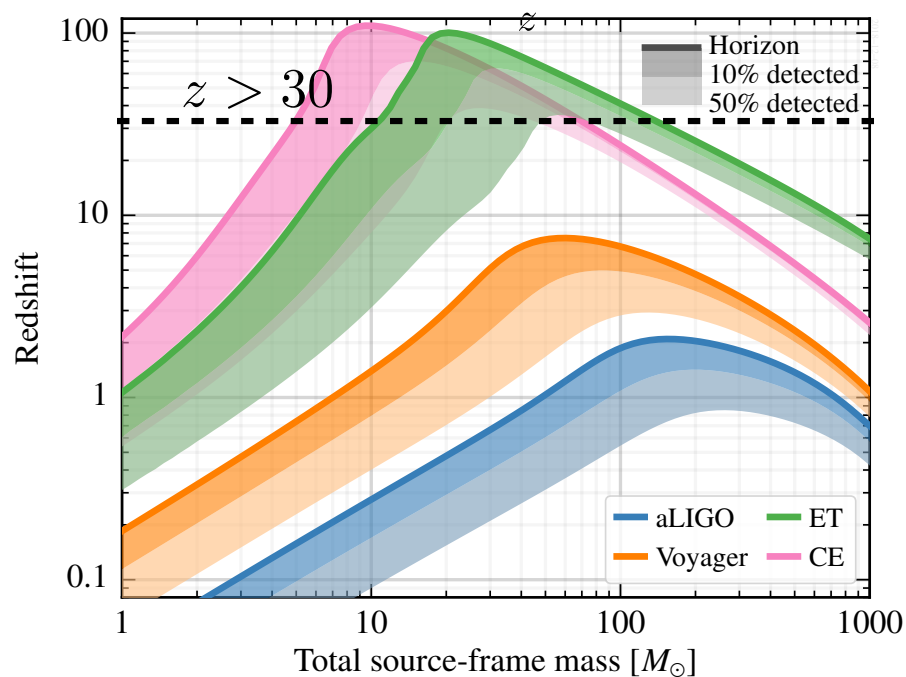


- The PBH population would imply high-redshift observations:

$$N_{\text{det}}^{\text{ET}}(z > 30) = 1315_{-168}^{+305} / \text{yr}$$

No astrophysical contamination

V. De Luca et al. (2021)



Key Questions on PBHs in the GW era

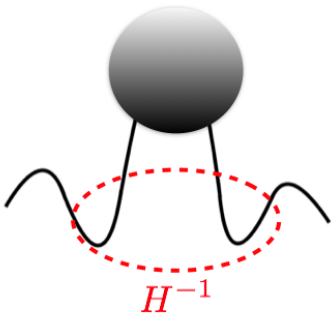
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PBHs and the stochastic background of GWs

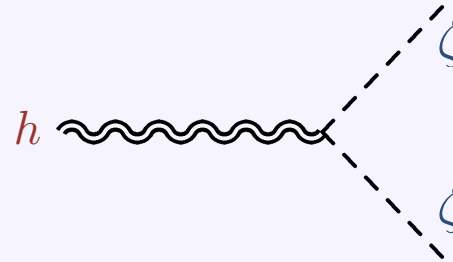
GWs from PBHs

The same curvature perturbations giving rise to PBHs are unavoidably a source for GWs at *second-order* in perturbation theory

$$\frac{\delta\rho}{\bar{\rho}} \sim \frac{\nabla^2\zeta}{a^2H^2}$$



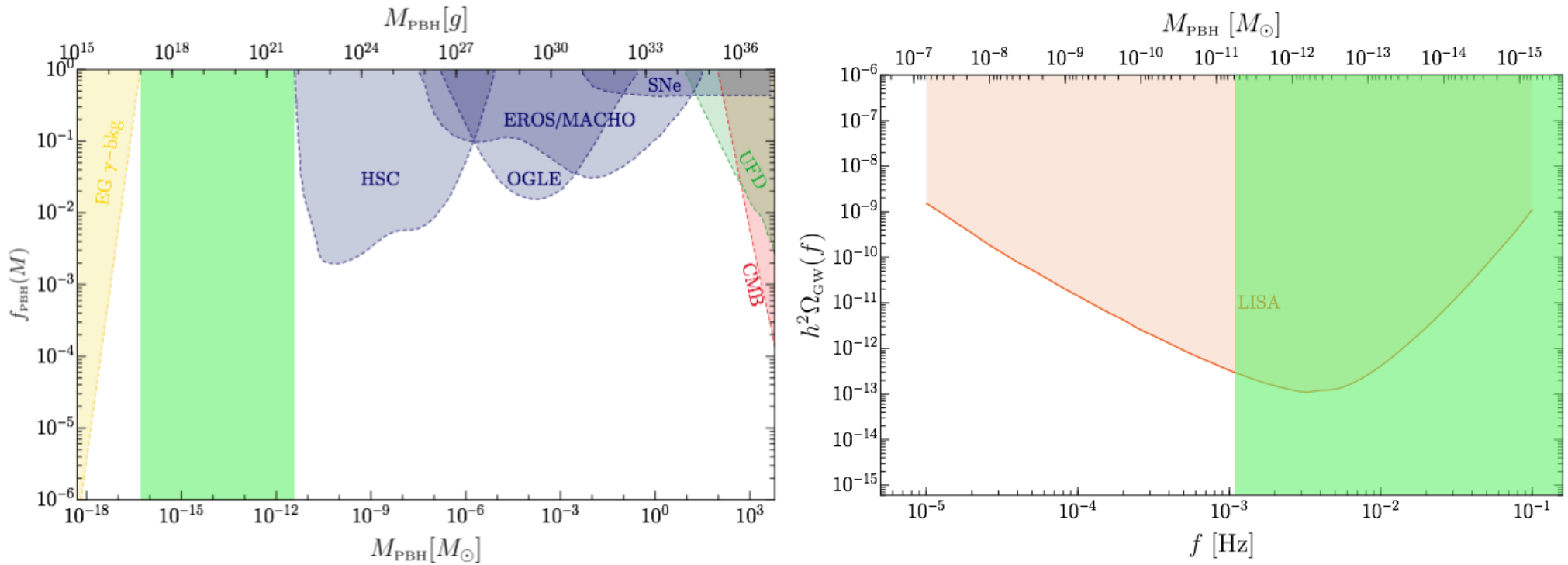
$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = \mathcal{O}(\partial_i\zeta\partial_j\zeta)$$



Potentially observable at current and future GW observatories



The PBH dark matter-LISA serendipity



$$M \simeq 10^{-12} M_{\odot} \left(\frac{f_{\text{LISA}}}{f} \right)^2$$

$$f_{\text{LISA}} = 3.4 \text{ mHz}$$

$$M \approx 10^{-12} M_{\odot}$$

Bartolo et al. PRL (2019)

Nano-Grav 12.5 year



Millisecond pulsars whose signal sensitive to the stochastic GW background

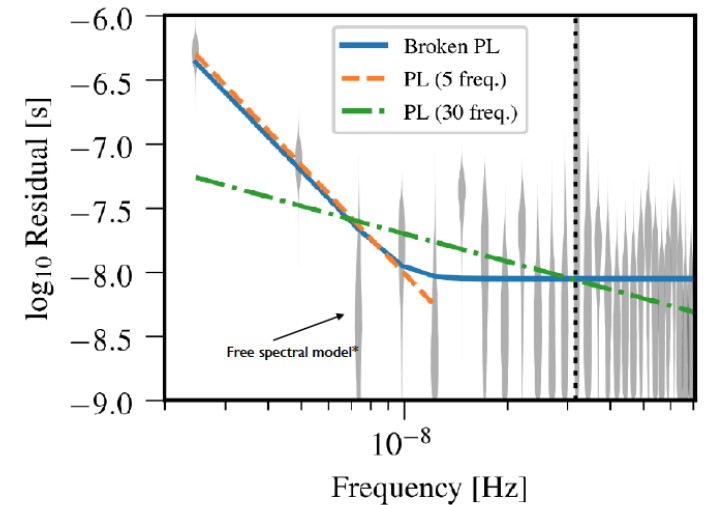
Cross-correlation of
timing residuals

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

Nano-Grav 12.5 year

Strong evidence for a stochastic common process across 45 pulsars

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



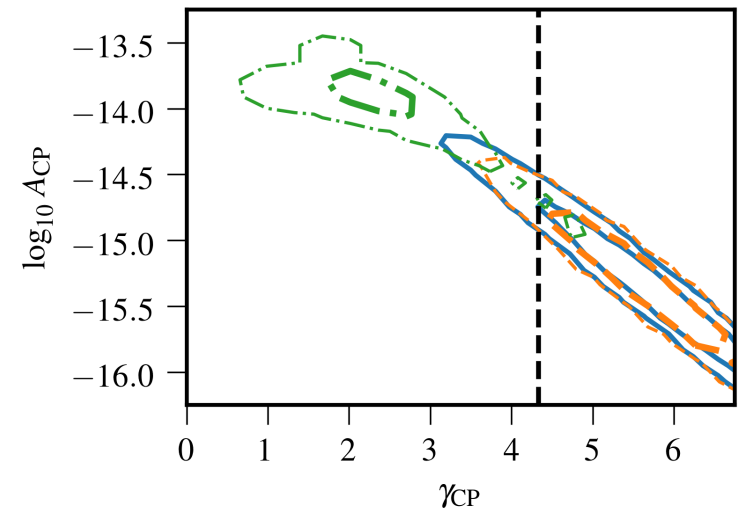
Possible flat spectrum with amplitude

$$\Omega(f) \sim 5 \cdot 10^{-10}$$

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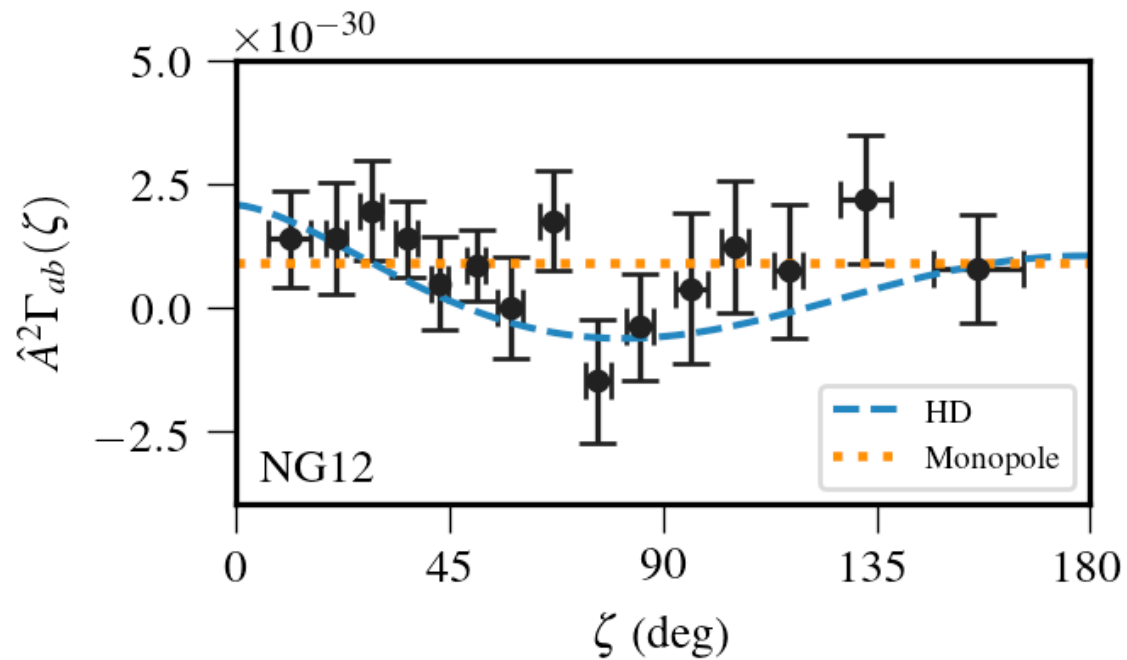


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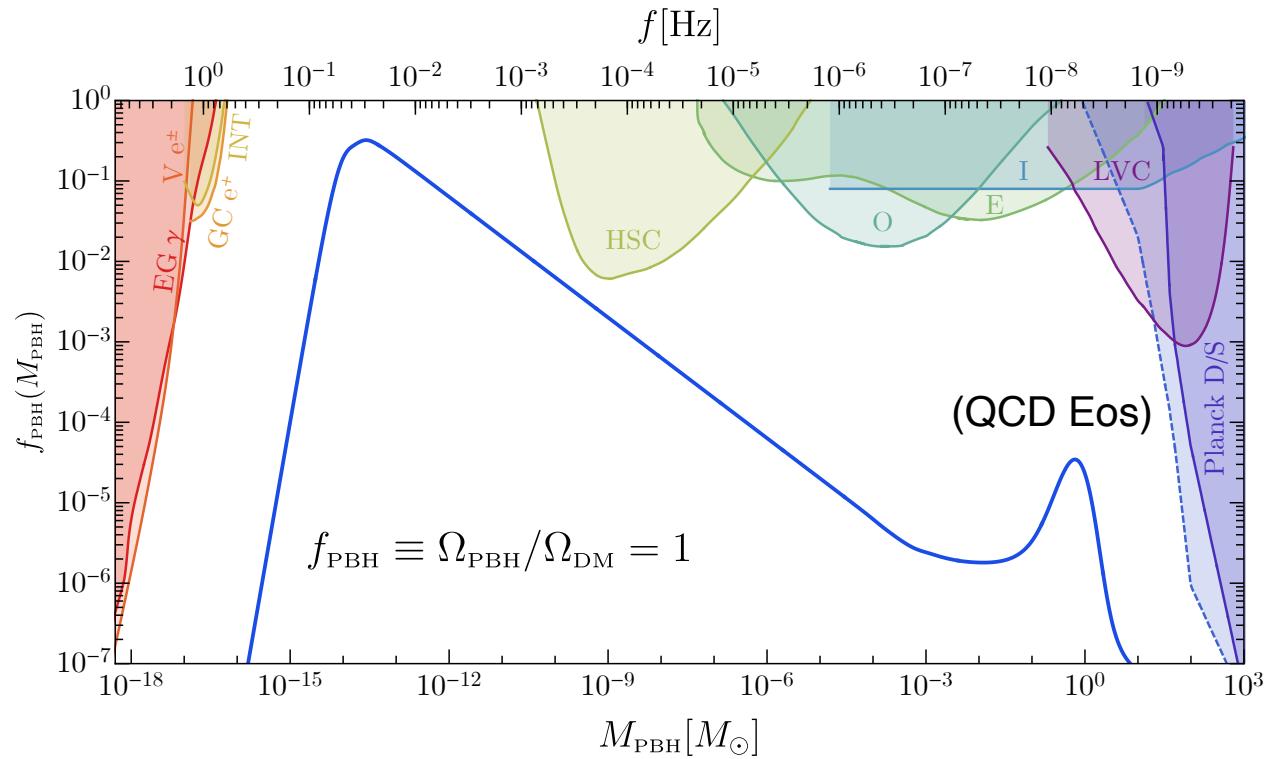
Nano-Grav 12.5 year

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



Need to wait for more data (two years on)

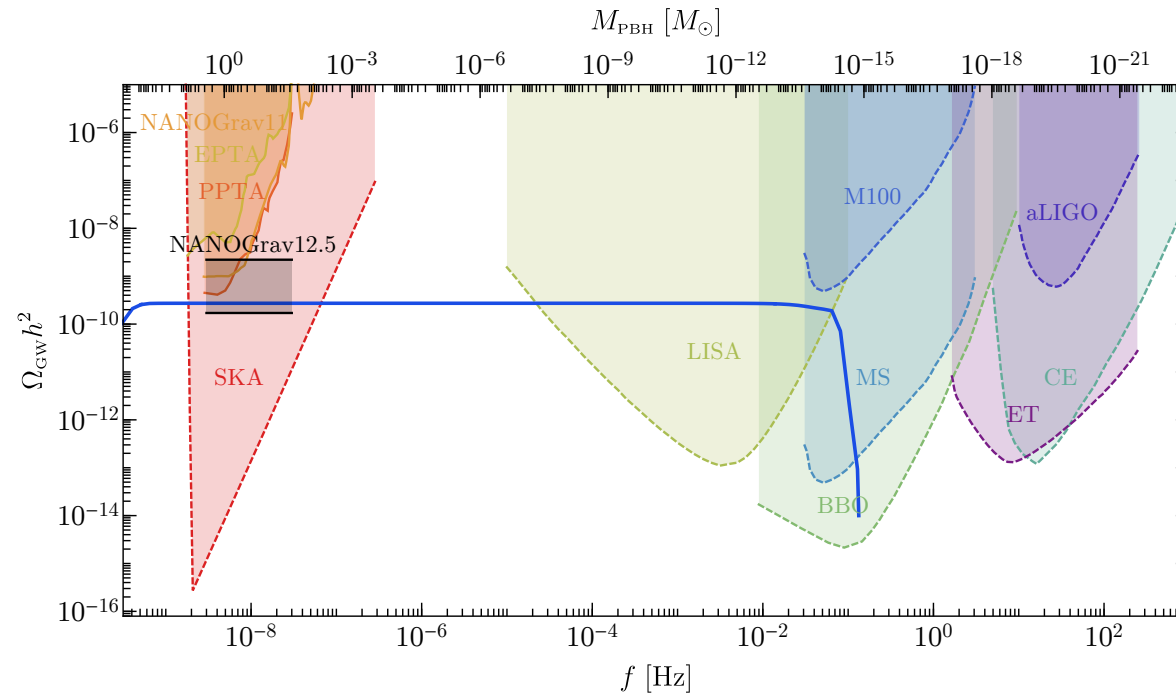
Can be consistent with a PBH = DM scenario



From flat curvature power spectrum

$$\mathcal{P}_{\zeta}(k) = A_{\zeta} \Theta(k_s - k) \Theta(k - k_l) \quad k_s \gg k_l$$

Can be consistent with a PBH = DM scenario



May be confirmed by LISA

Conclusions

- The era of gravitational wave astronomy has begun opening a new window into fundamental physics and cosmology
- PBHs may exist and comprise the totality of the dark matter, future data will tell us