Gabriele Franciolini

Searching for primordial black holes at current and future GW detectors

Outline

- *Overview on Primordial Black Holes (PBHs)*

- *GW signatures of PBH mergers:*

  - *The predictions of PBH model*
  - *Individual events*
  - *Population analyses*

  } *current vs future GW detectors*

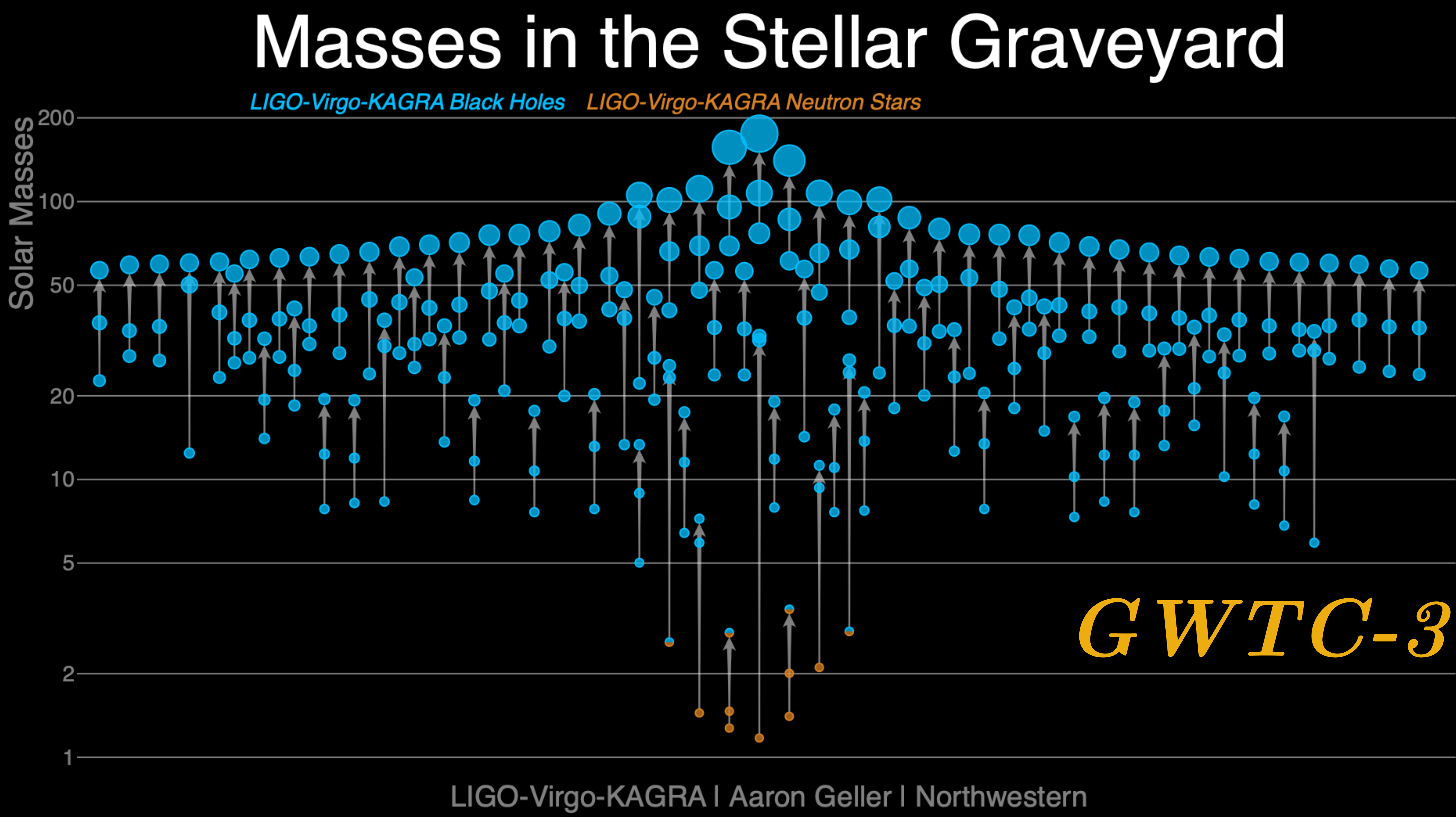
Based on [... , 2105.03349, 2112.10660] and refs. therein

In collaboration with:

V. Baibhav, E. Berti, R. Cotesta, V. De Luca, N. Loutrel, K. Ng, P. Pani, A. Riotto, S. Vitale, K. Wong

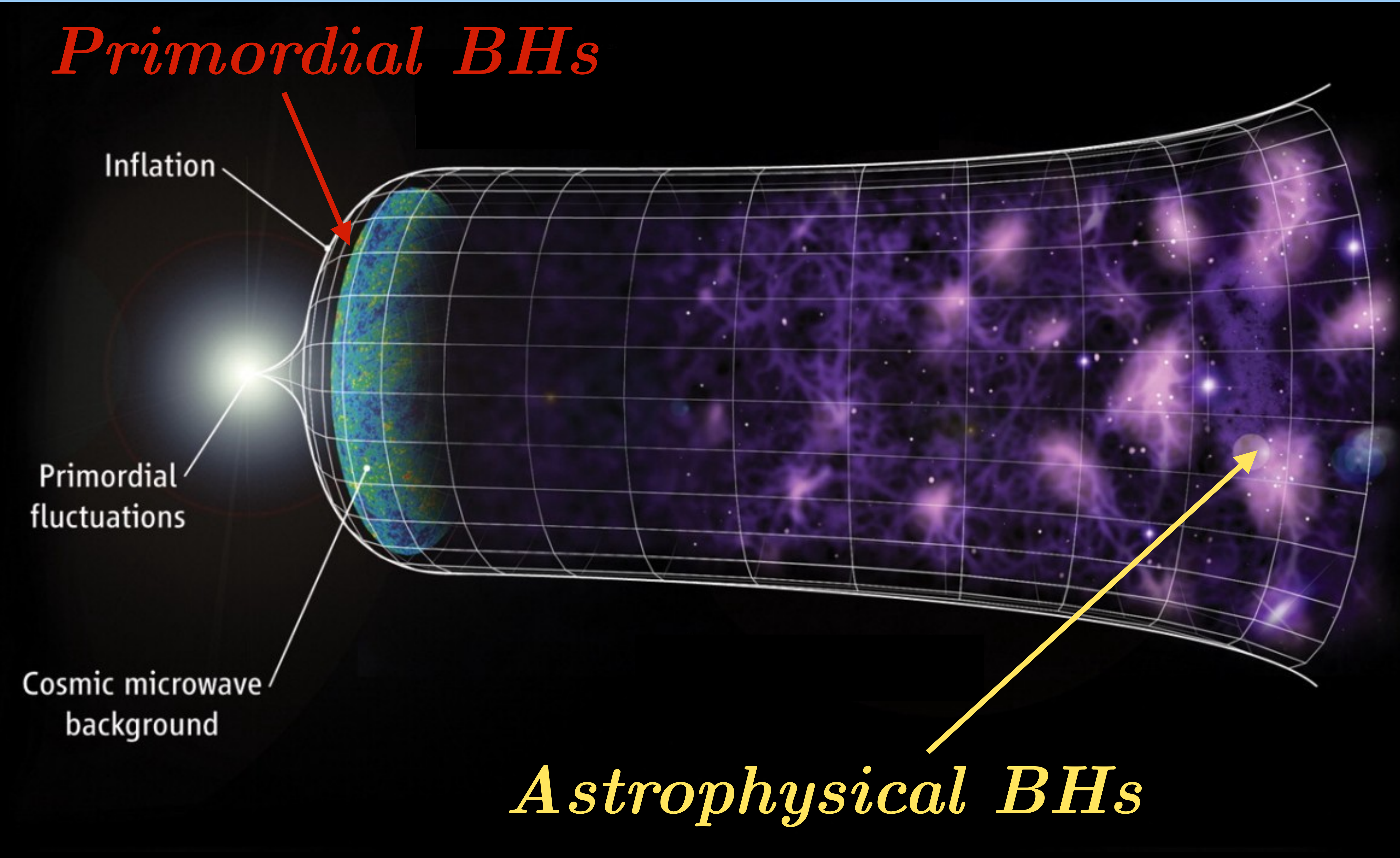
Introduction

Our universe is full of Black Holes

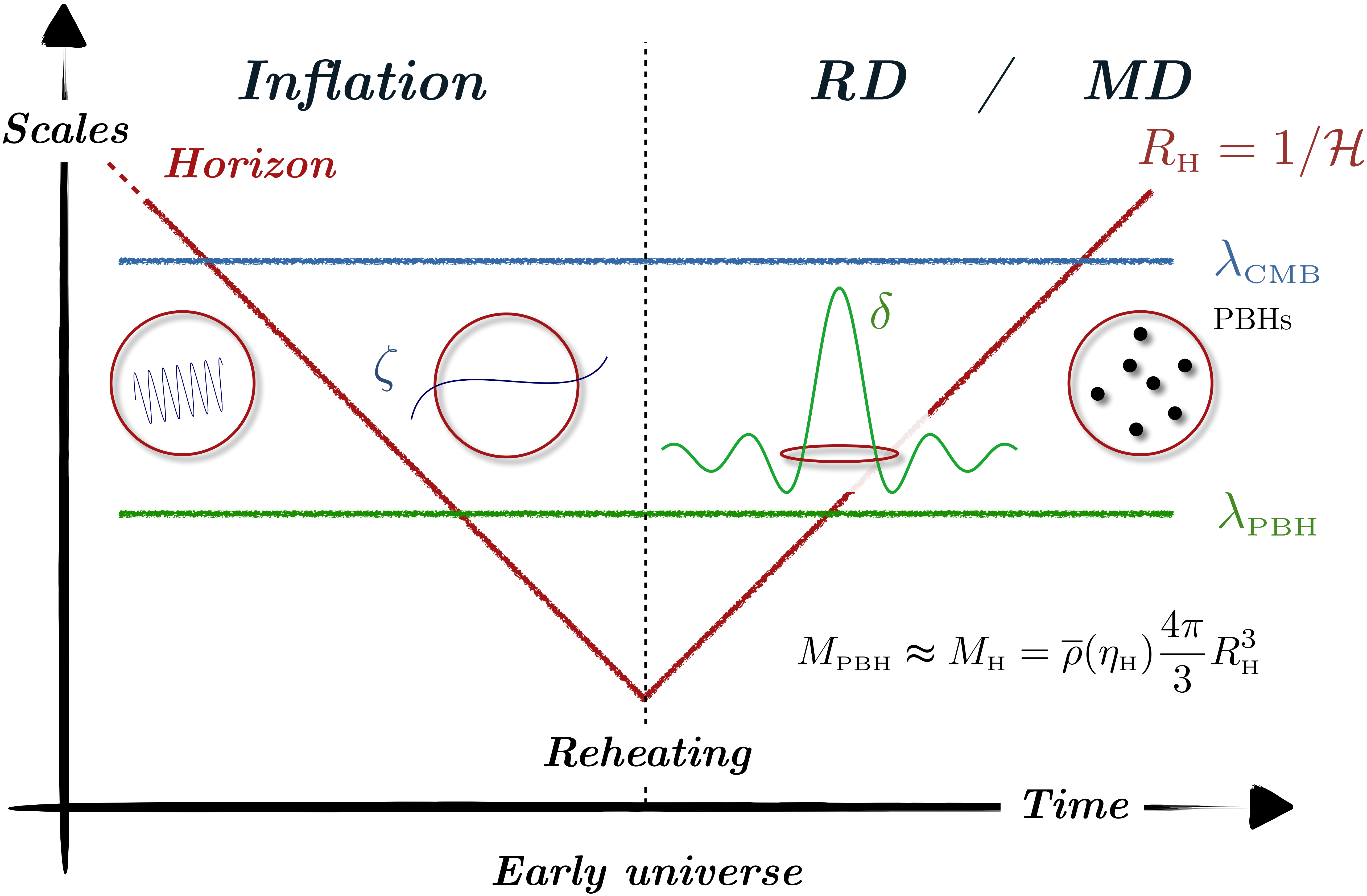


- *90 events (and counting), O(0.1-1) millions in the 3G era!*
- *How many formation channels? All of astrophysical origin?*

Where do they come from?

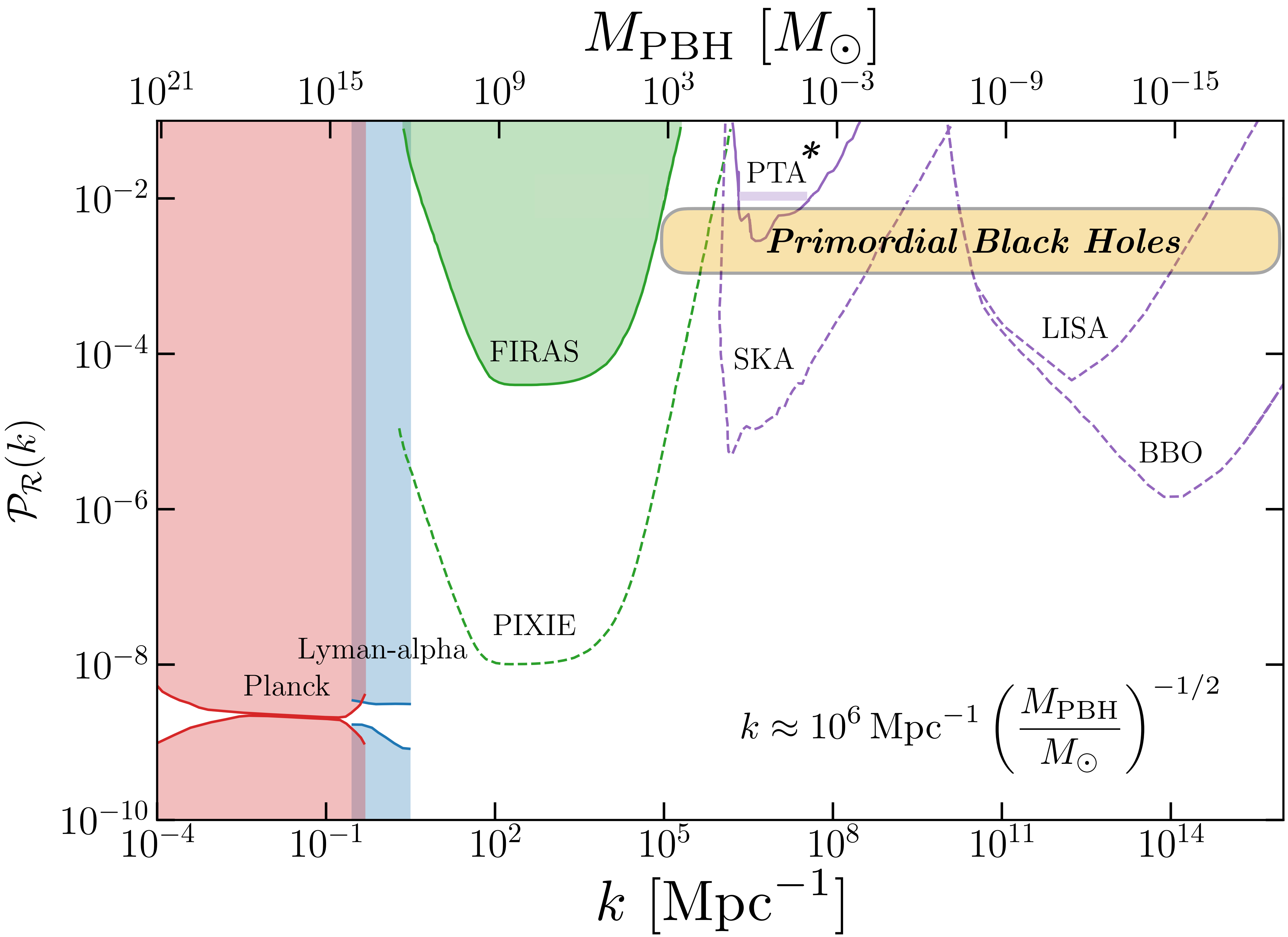


PBH formation timeline



(review: Sasaki+[1801.05235])

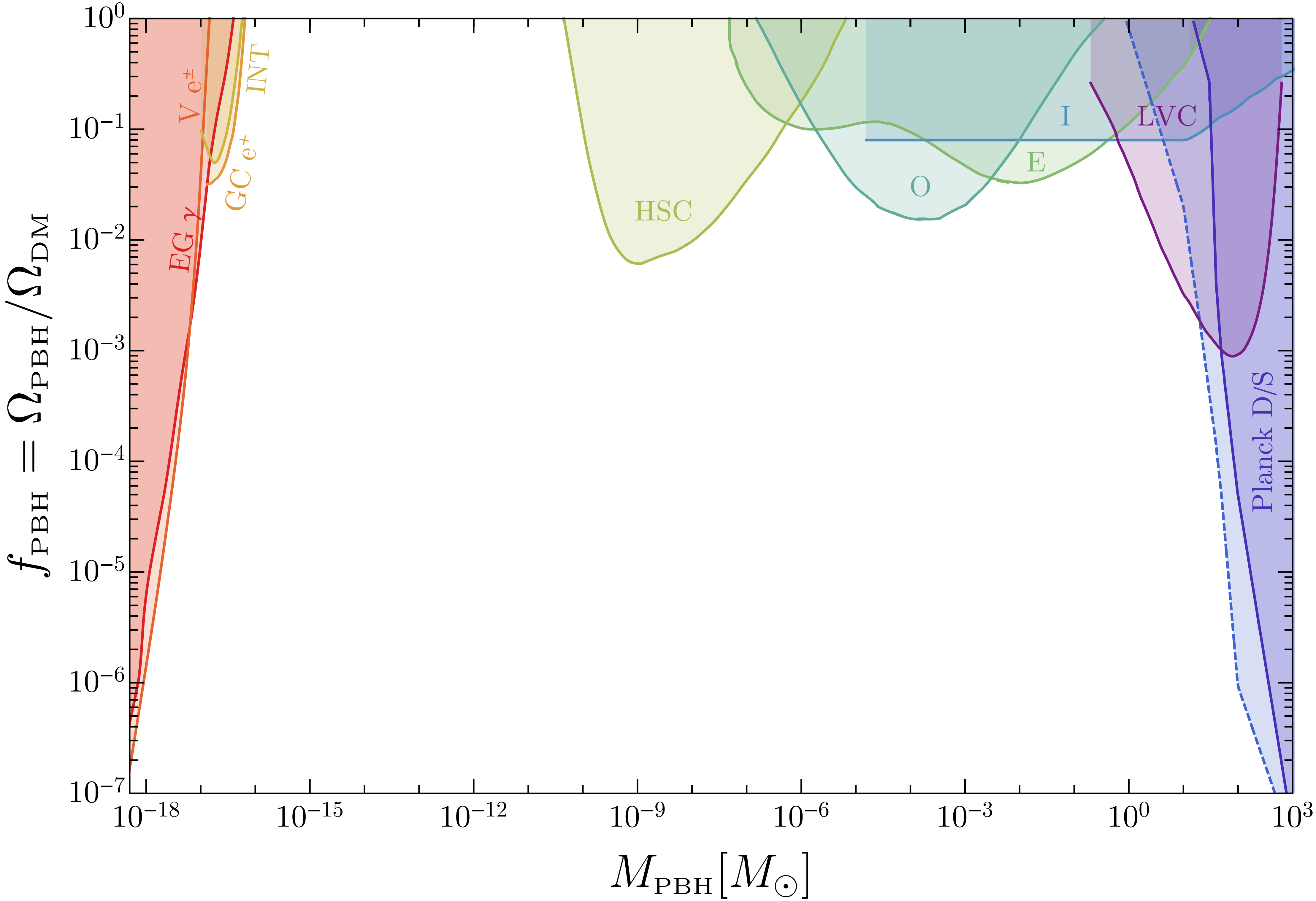
Small scales - large amplitudes



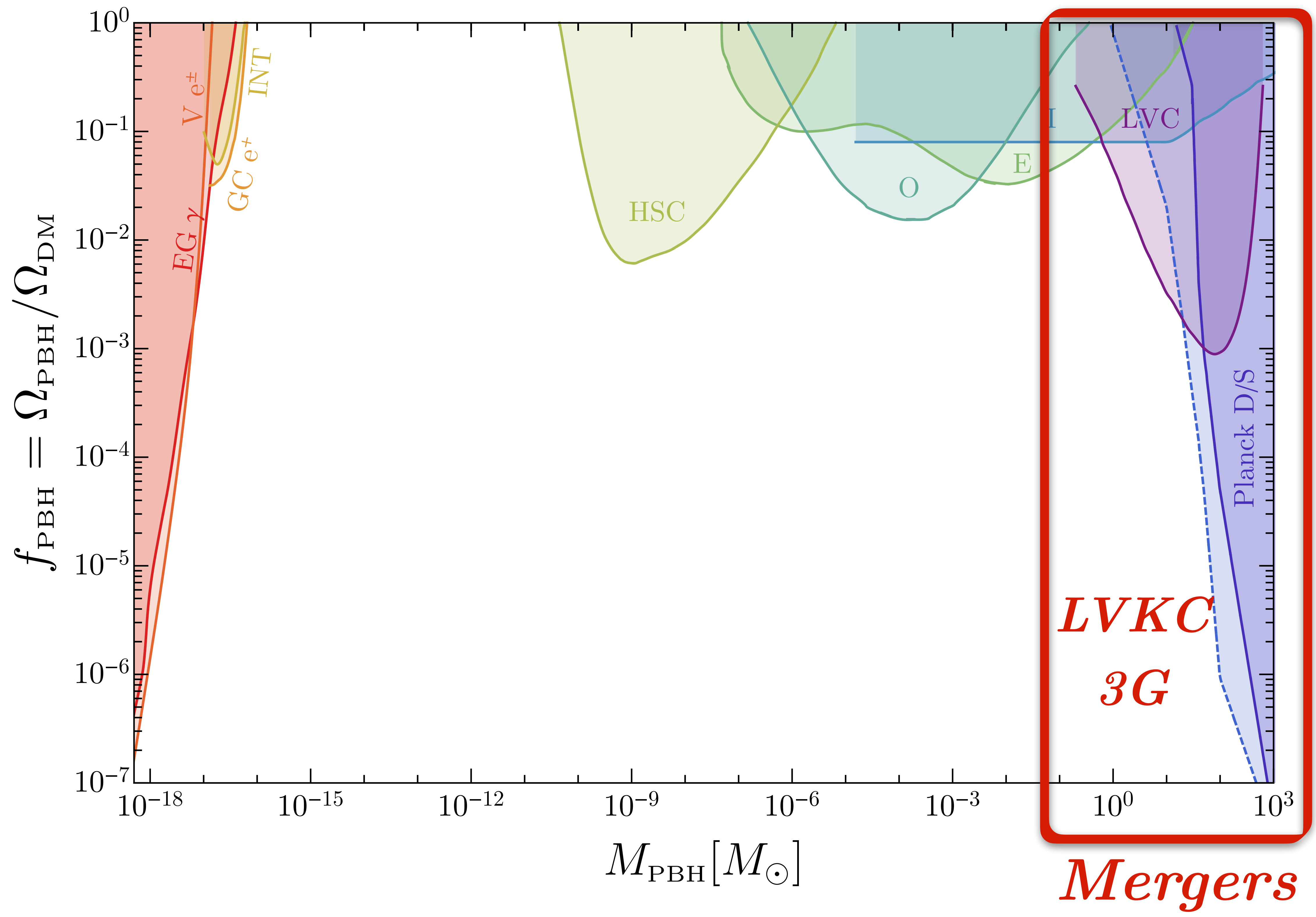
Green-Kavanagh [2007.10722]

Constraints on the PBH abundance

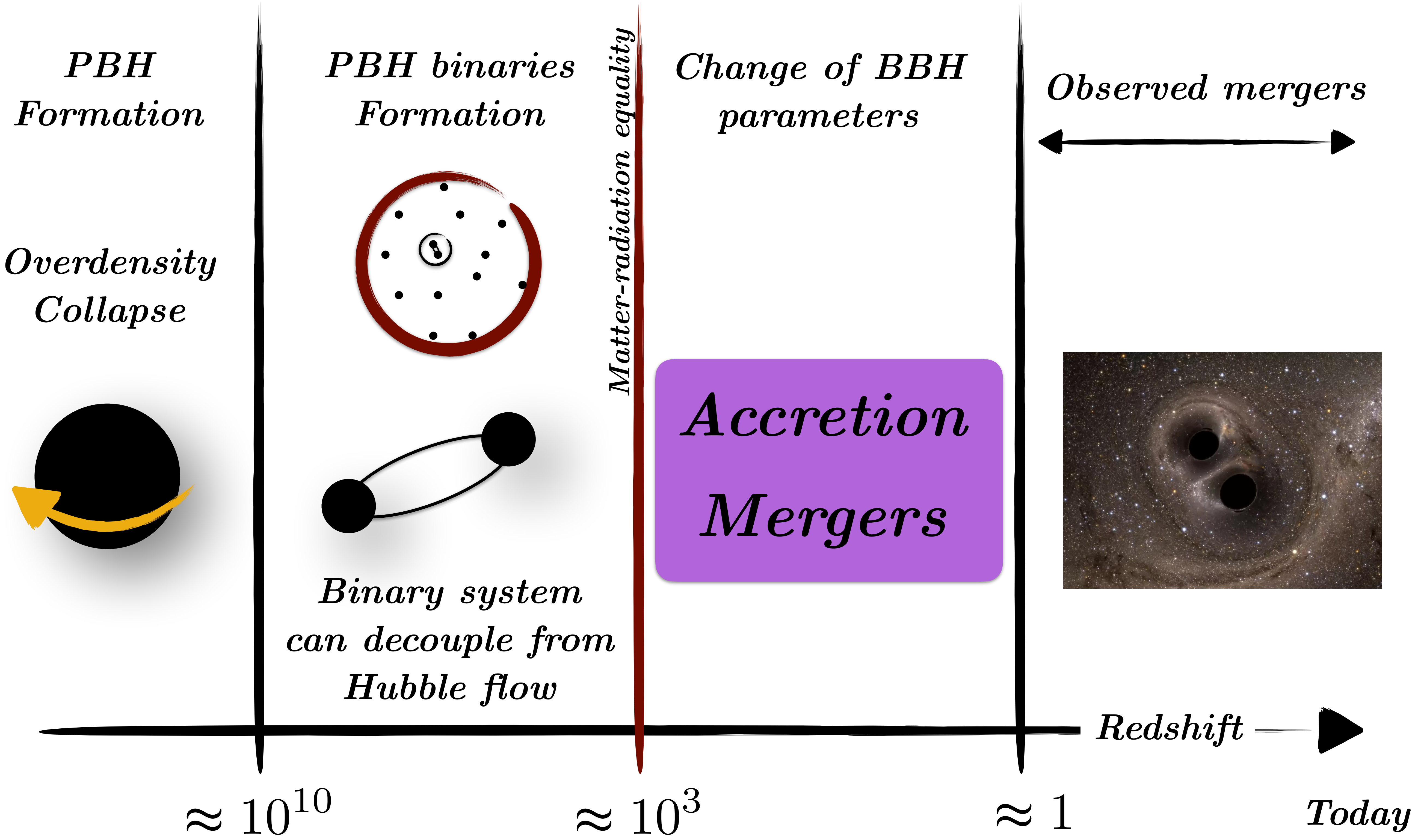
e.g. review: Carr et al [2002.12778]



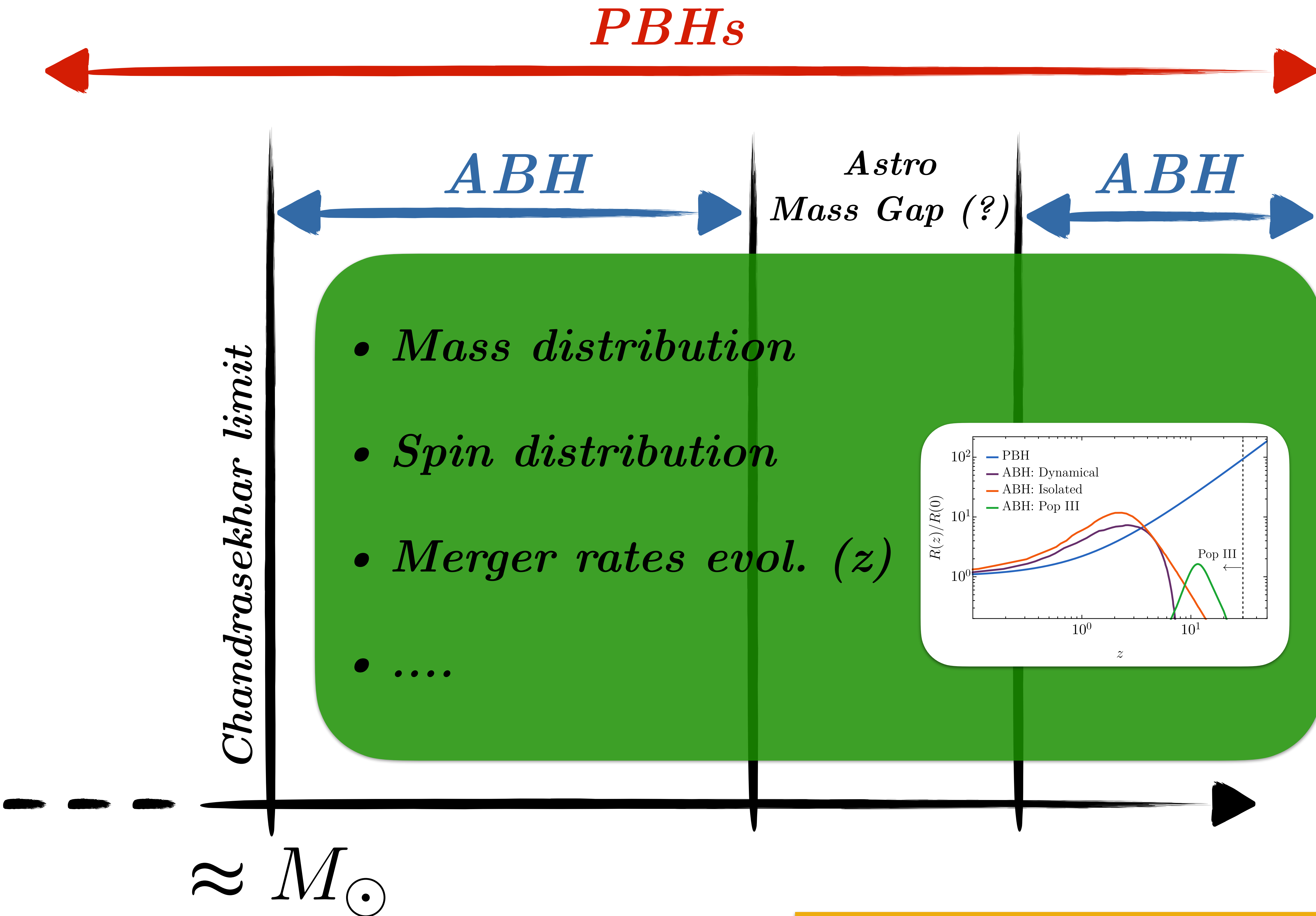
Constraints on the PBH abundance



The PBH timeline



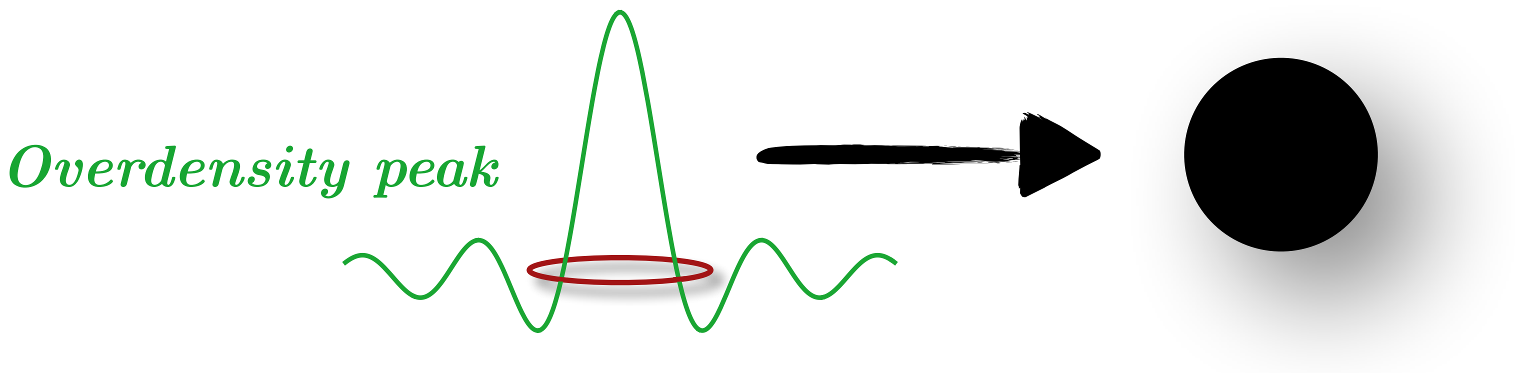
Astro vs Primordial origin



Properties of PBH mergers

PBH Mass distribution

(review: Sasaki+[1801.05235])



- *Mass distribution depends spectrum and statistical properties of curvature perturbations:*

  - *No observational constraints*

  - *Theoretical expectations:*

  i) No gaps in the mass distribution

  ii) Minimum width due to critical collapse

- *General parametrisation (recovering a large class of models):*

$$\psi(m) = \frac{1}{m\sigma\sqrt{2\pi}} \exp\left[-\frac{\log^2(m/M_c)}{2\sigma^2}\right]$$

M_c : *central mass*

σ : *width*

(There may be interesting exceptions: QCD epoch reduces the threshold and boost formation of solar mass PBHs...)

Jedamzik+ (1998), Byrnes (2018), ...

May be relevant for light events at LIGO/Virgo

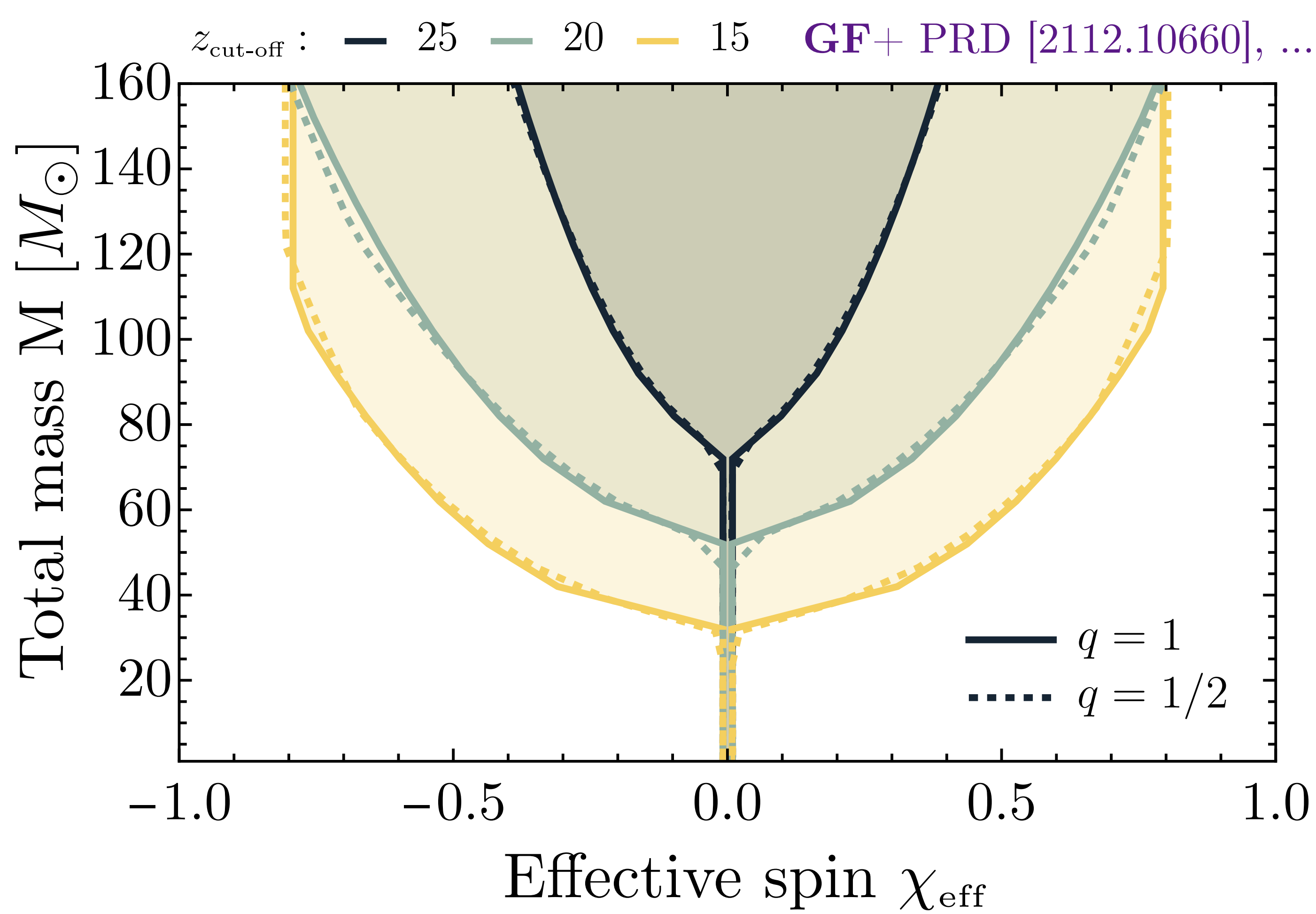
GF, Musco, Urbano, Pani, to appear

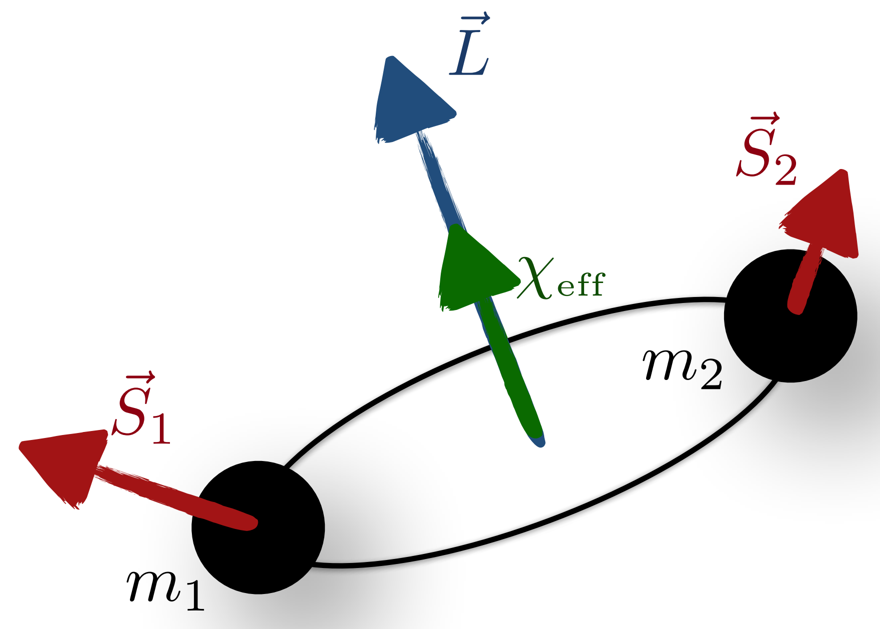
PBH spins and accretion

- *Small spins at formation* — De Luca, **G.F.**, Desjaques, Malhotra, Riotto JCAP(2019)
- *Baryonic disk accretion can spin-up PBHs*
  (leading to uncorrelated spin orientations in binaries)
- *Large uncertainties over the efficiency and when it becomes negligible (around the reionization epoch)*

$$z_{\text{cut-off}} \approx 10 \div 30$$

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





PBH abundance

- ***PBH abundance expressed in terms of the dark matter***

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

(can be thought as a proxy for the average PBH number density)

- ***The abundance sets the merger rate:*** $R \propto f^2_{\rm PBH}$ Raidal et al. JCAP (2019)

- ***A PBH merger rate in the ballpark of LIGO/Virgo implies:***

$$f_{\rm PBH} \approx 10^{-3}$$

Wong, **G.F.** et al. PRD (2021),
Hutsi et al. JCAP(2021),
...

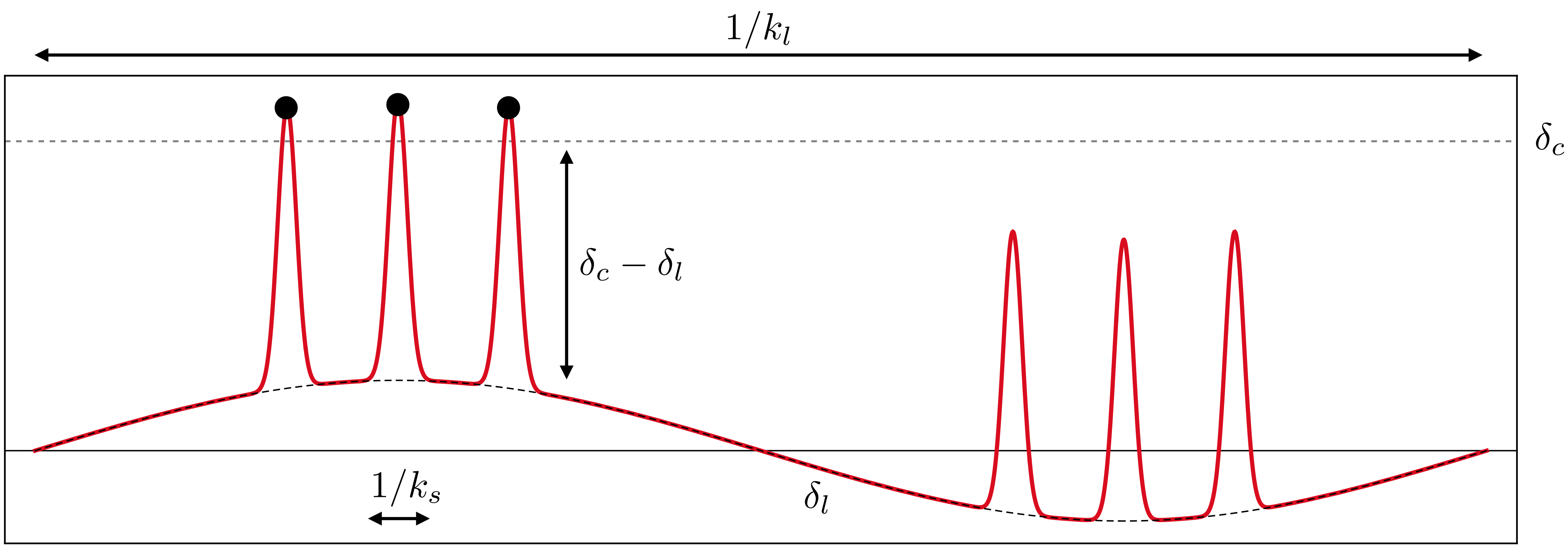
$f_{\rm PBH}$ ***: determines the PBH merger rate***

PBH initial clustering

Tada-Yokoyama (2015), Young-Byrnes (2015), Desjacques-Riotto (2018), Ali-Haimoud (2018), ...

In the standard scenario, PBHs are not clustered at formation

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

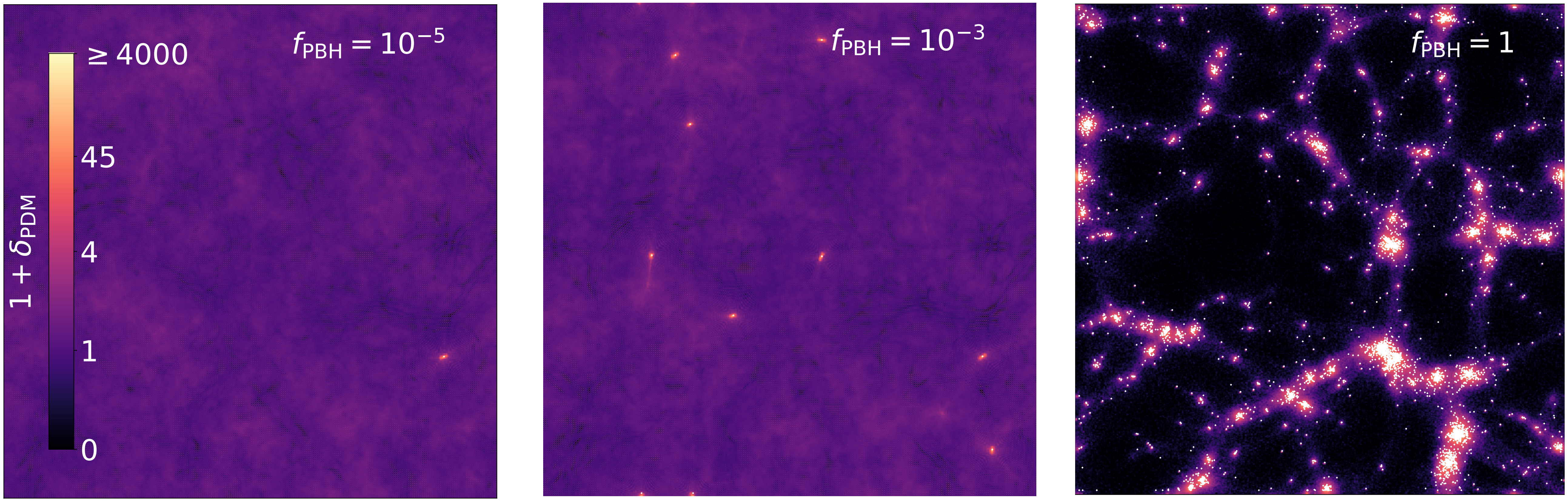


Bias induced by long modes suppressed for gaussian perturbations

$$\delta_l \simeq \nu/\sigma (R_{\rm PBH}/R_{\rm cl})^2 \zeta(k_{\rm cl}) \ll 1$$

PBH Clustering evolution

$z \approx 100$ ***Cosmological N-body simulation*** Inman, Ali-Haïmoud PRD (2019)



- ***Shot noise induce early small structures depending on*** $f_{\rm PBH}$
- ***PBHs isolated for:*** $f_{\rm PBH} \lesssim z \cdot 10^{-4}$

See (De Luca, Desjacques, **GF**, Riotto, JCAP [2009.04731]***) for an analytic description***

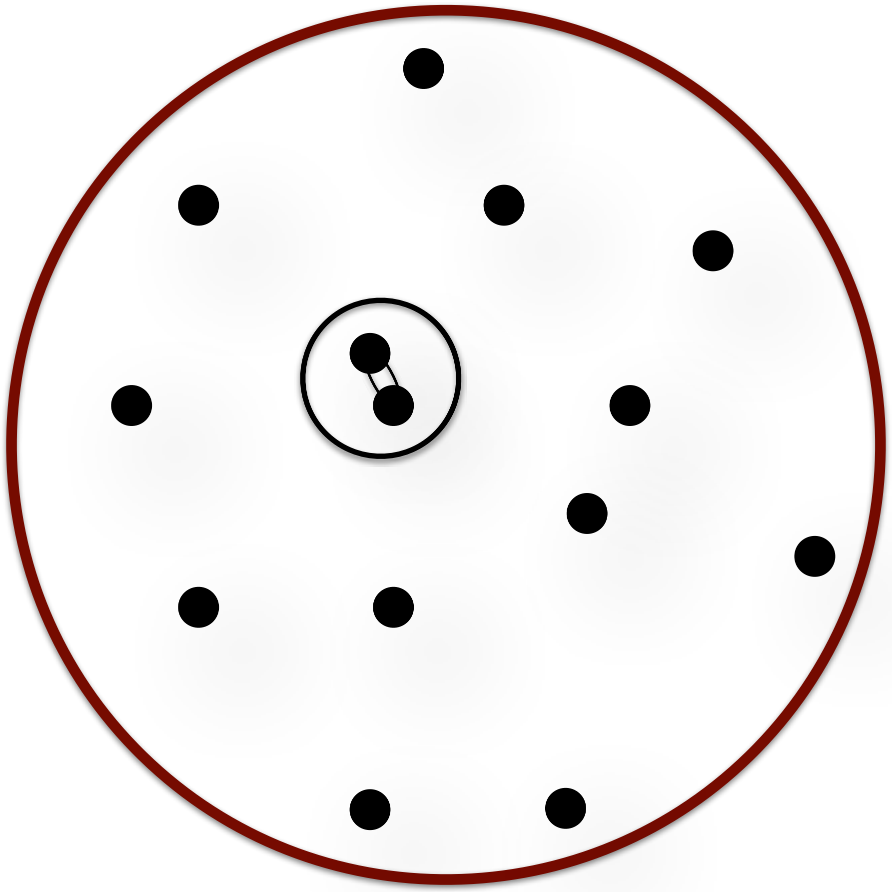
Merger rate

- ***Initial spatial Poisson distribution***
- ***Random decoupling of binary systems from the Hubble flow*** Nakamura+ (1997), ...

↓

- ***Binary formation happening before matter-radiation equality***
- ***The distribution of initial semi-major axis and eccentricity determines the merger rate***

(Peters' time-scale $t_{\rm GW} \propto a^4(1-e^2)^{7/2}$ ***)***



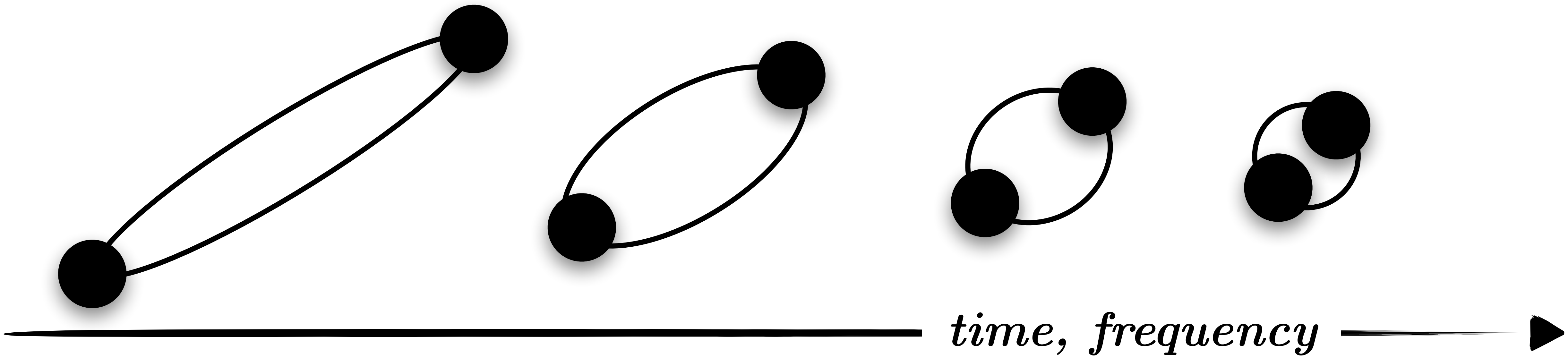
↓

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

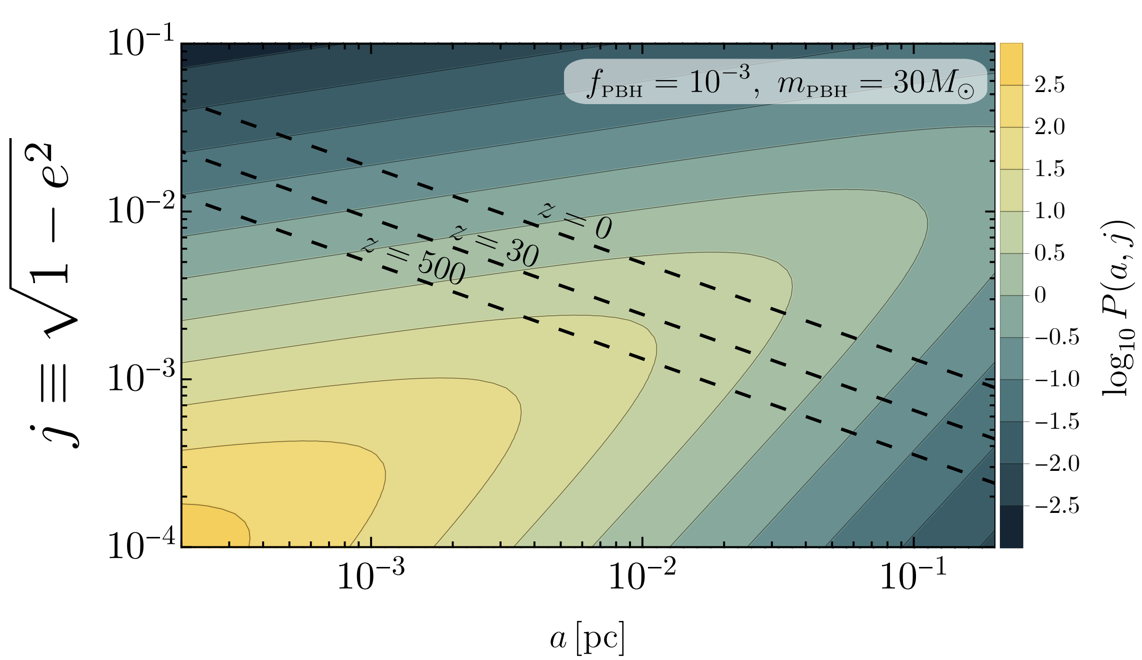
Ali-Haïmoud+(2017), Raidal+ (2018), De Luca, **GF+** (2020), ...

PBH binary properties

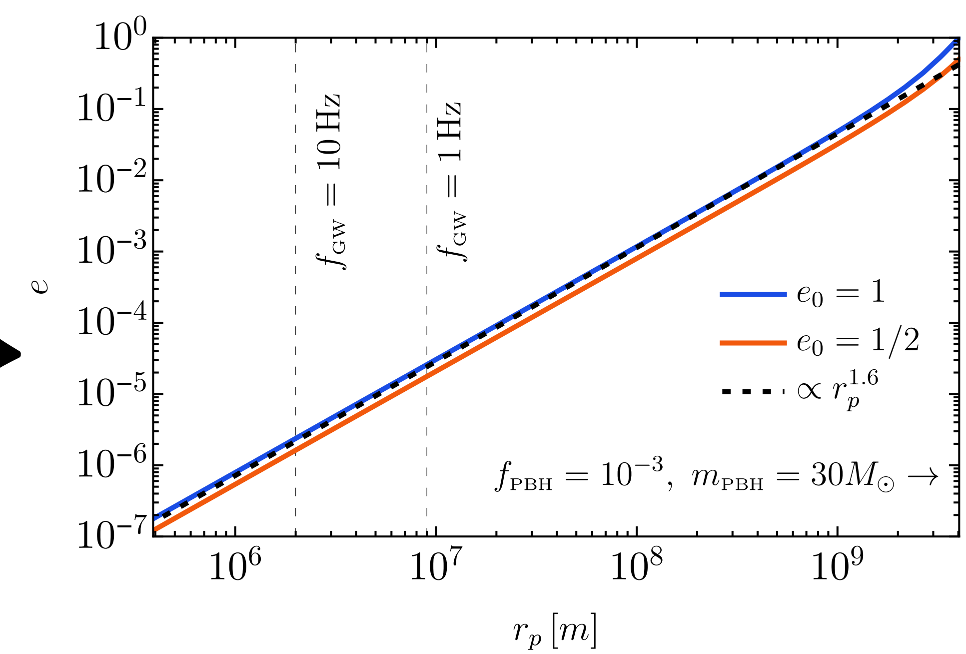
GW emission circularises the orbit



Initial large eccentricity… *…lost before entering LVK band*



$$e \propto f_{\rm GW}^{-19/18}$$

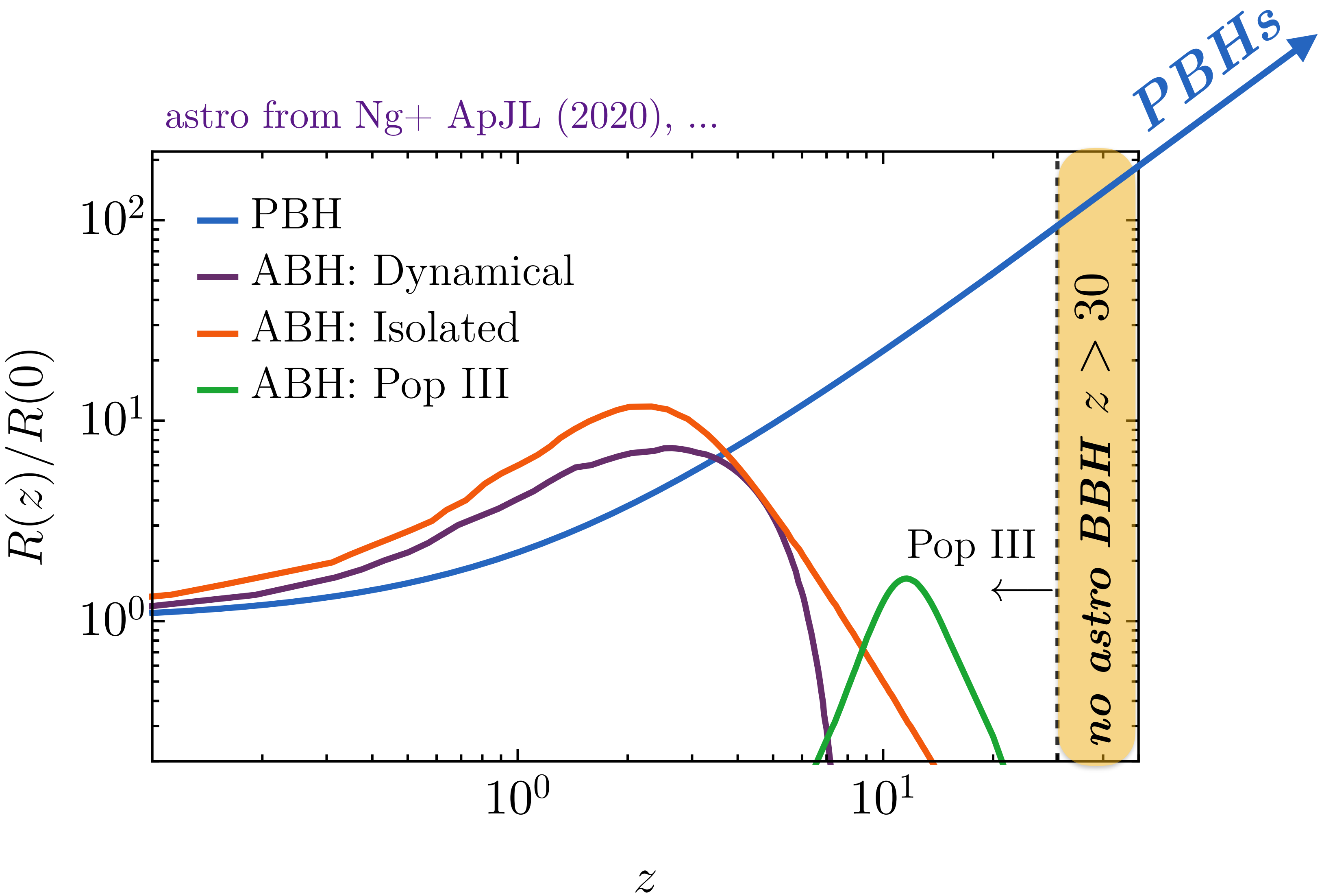


Merger rate evolution

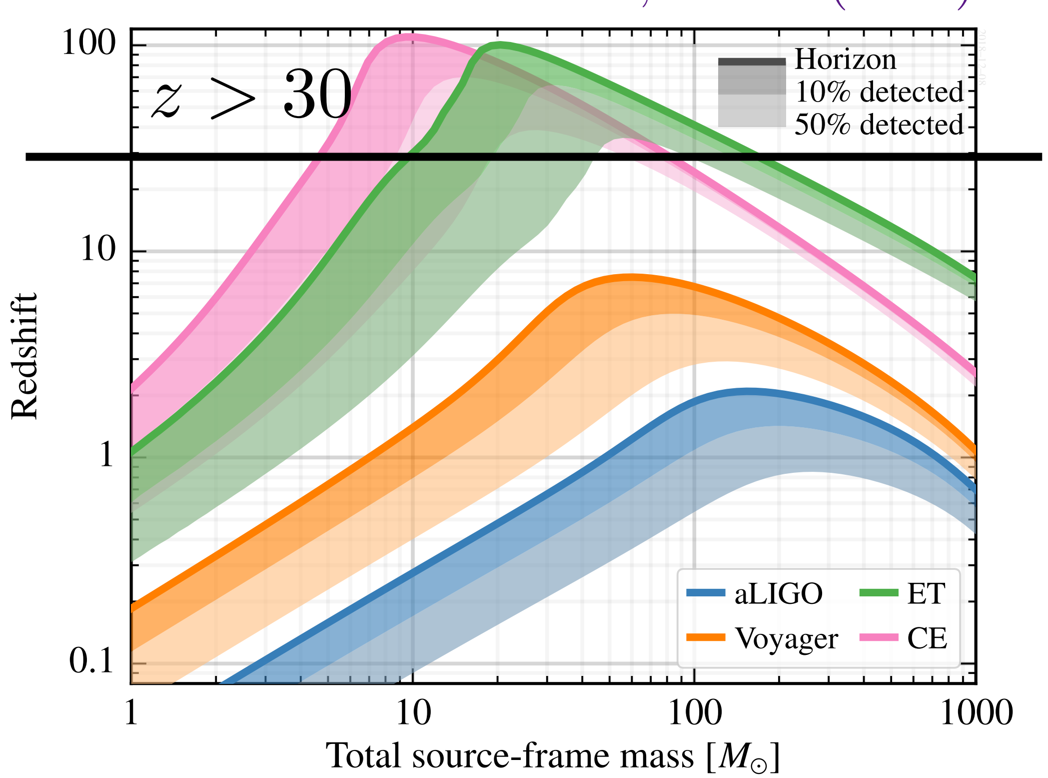
Monotonic growth up to $z \gtrsim 10^3$

$$R \approx t^{-34/37}$$

astro from Ng+ ApJL (2020), ...



Hall, Evans (2019)



- ***No astro contamination above redshift*** $z \approx 30$

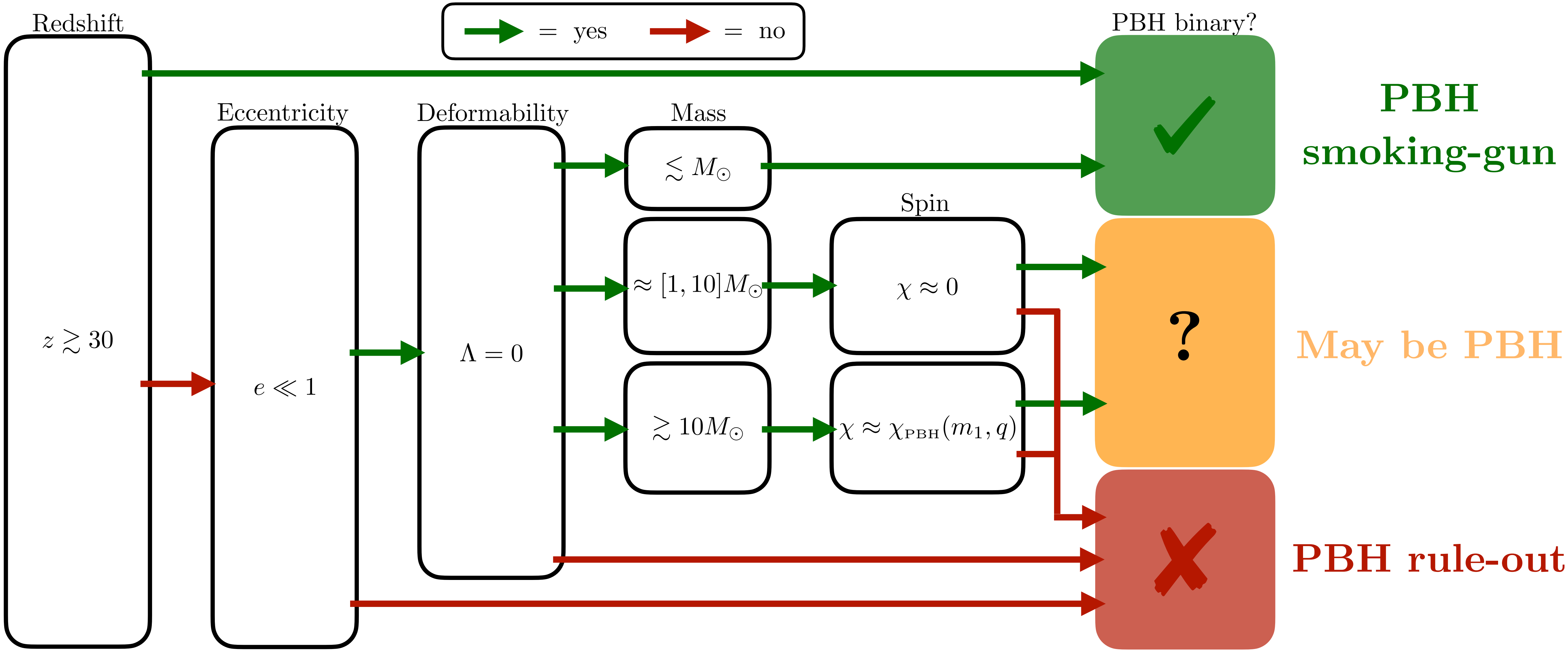
  Nakamura et al (2016), Koushiappas, Loeb (2017), ...

- ***3G detectors could observe these sources!***

PBHs vs individual events

Individual BH binary assessment

GF+, PRD [2112.10660]



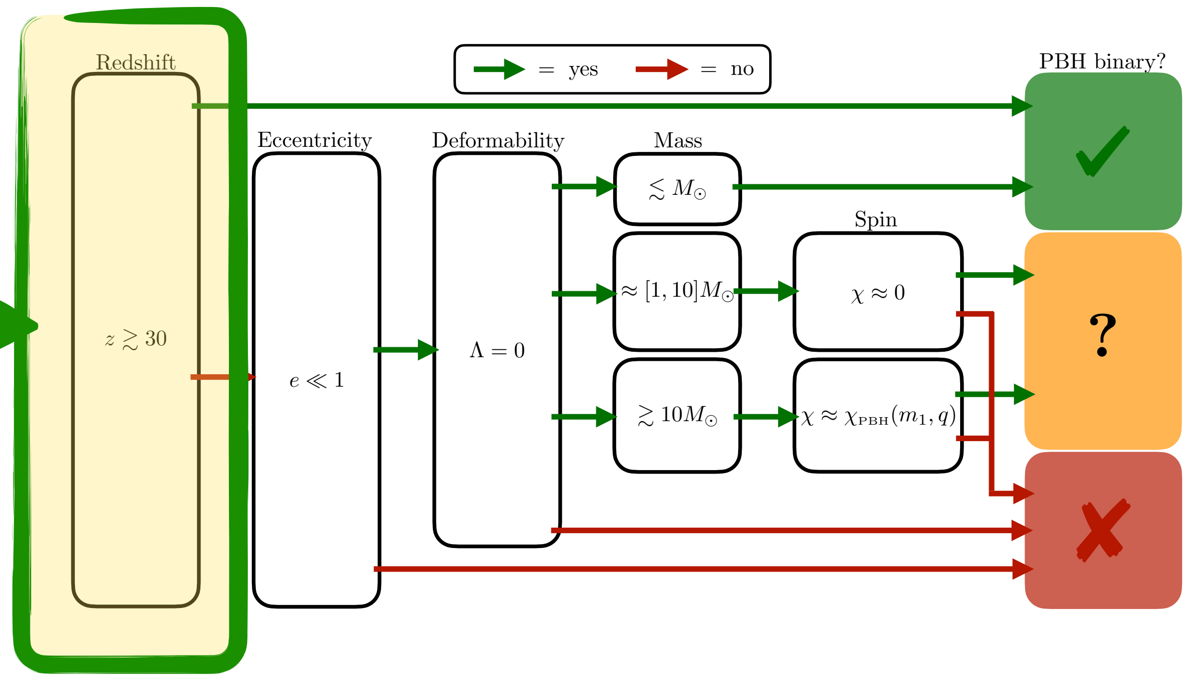
GWTC-3

~~unobserved~~ **Poorly measured** **≈ inconclusive**

Large precision improvements with 3G detectors!

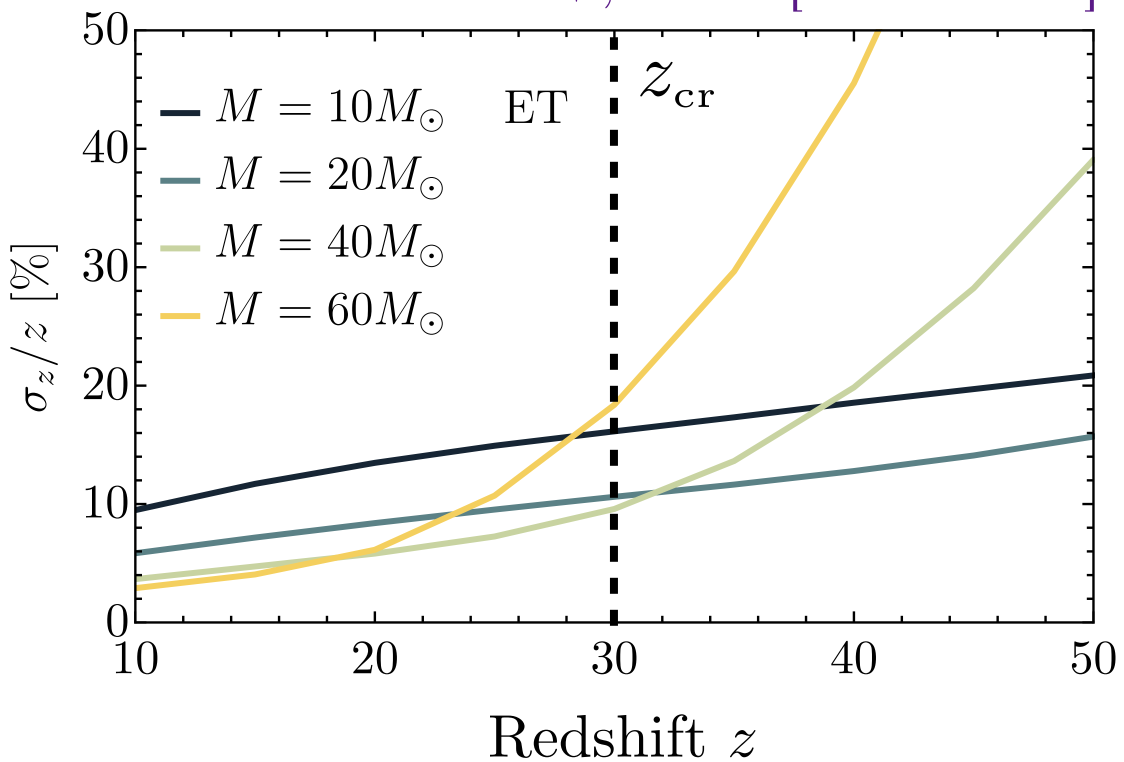
High-z smoking gun at 3G detectors

High redshift
PBH smoking gun

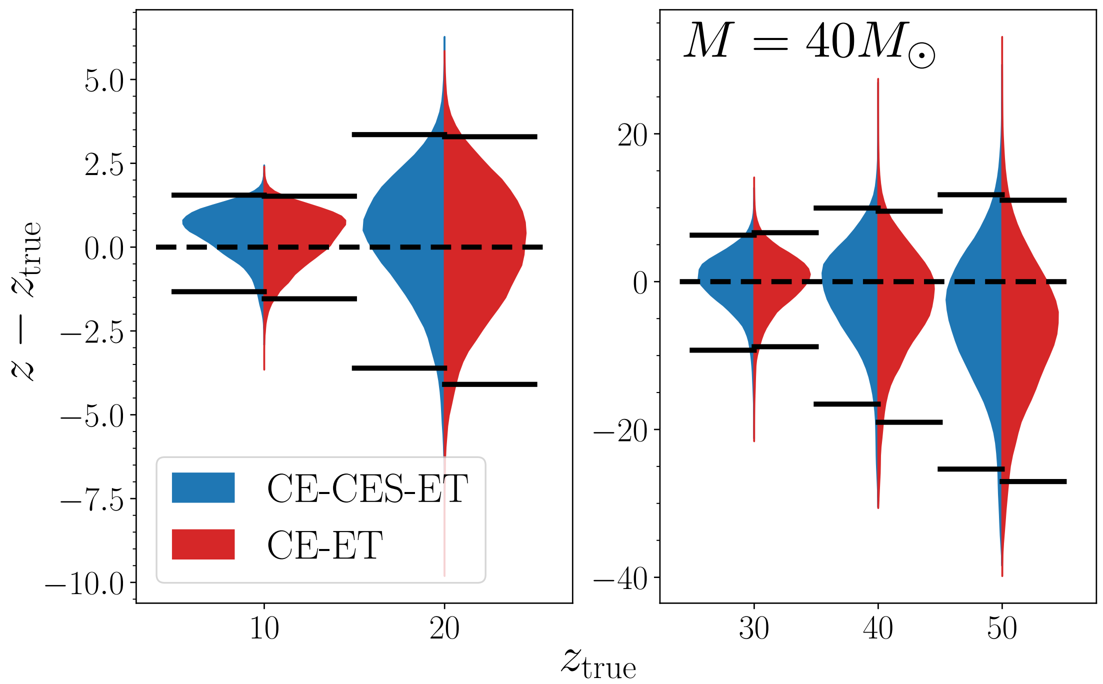


- *High redshift uncertainties and systematics*

GF+, PRD [2112.10660]



Ng+, ApJL [2108.07276]

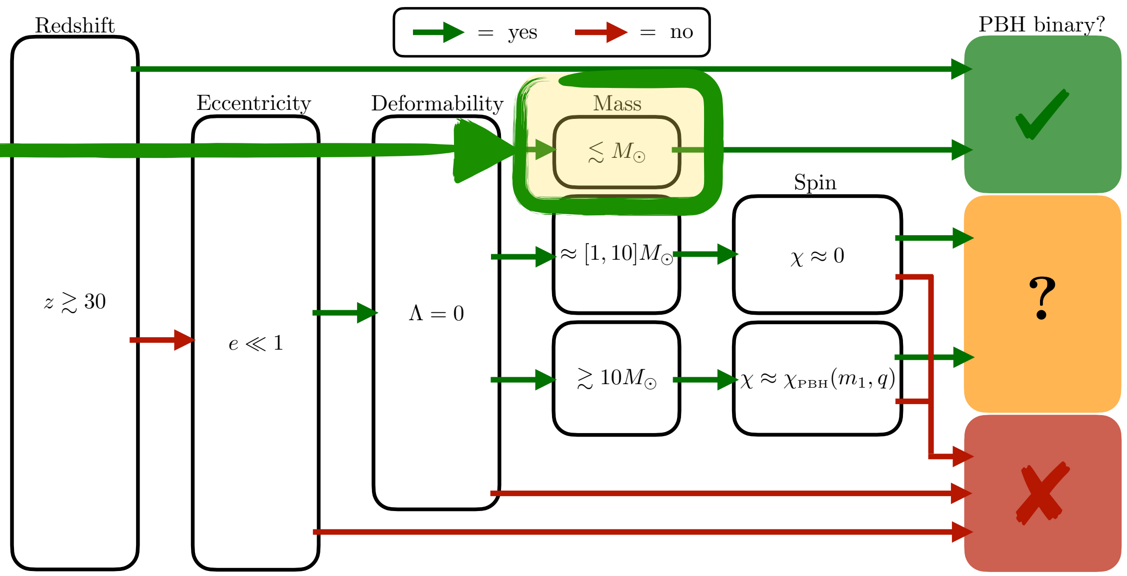


Subsolar smoking gun at 3G detectors

Subsolar mass
PBH smoking gun

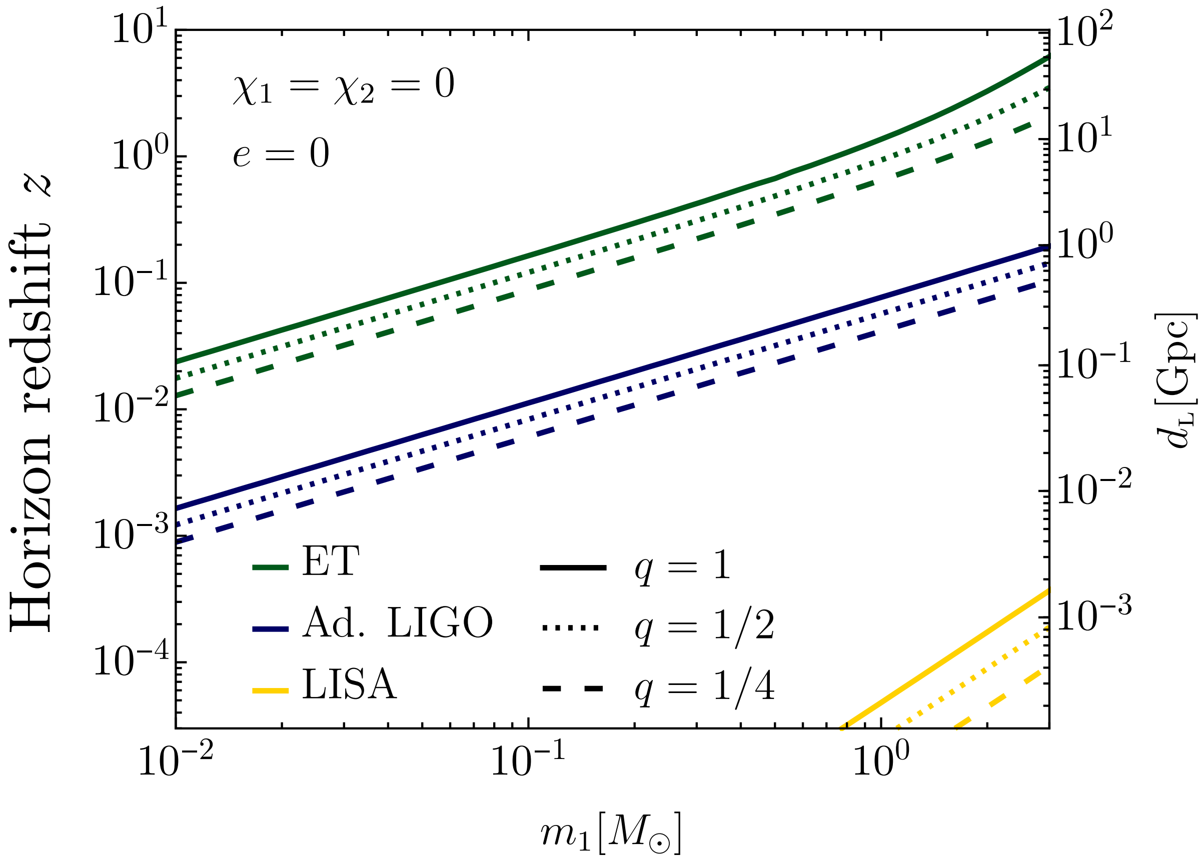
- ***Current searches limited by LVKC horizon***

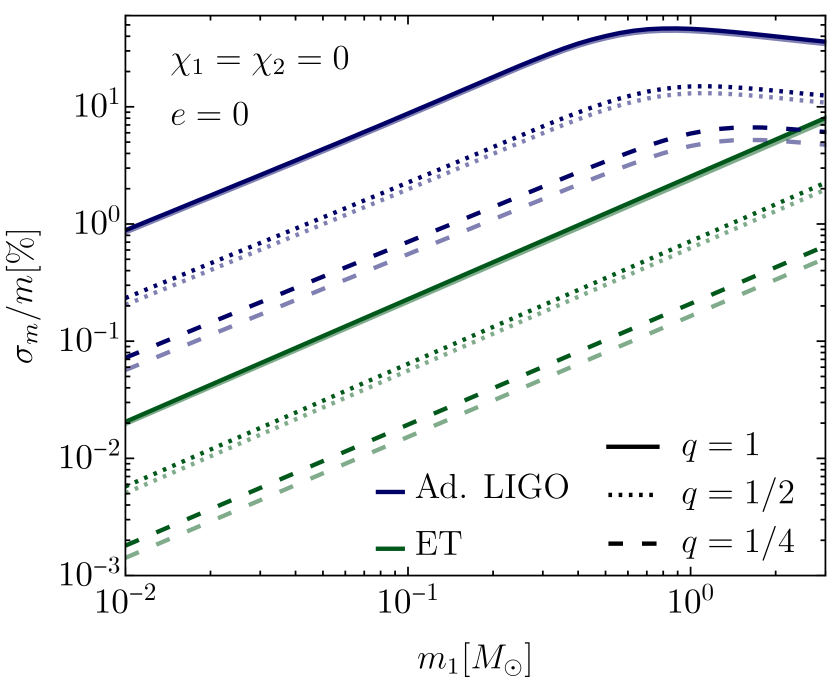
LVKC 2021, Nitz-Wang ApJ 2021



- ***3G: up to redshift $z \approx 1$ and sub-percent precision on mass***

GF+, PRD [2112.10660]

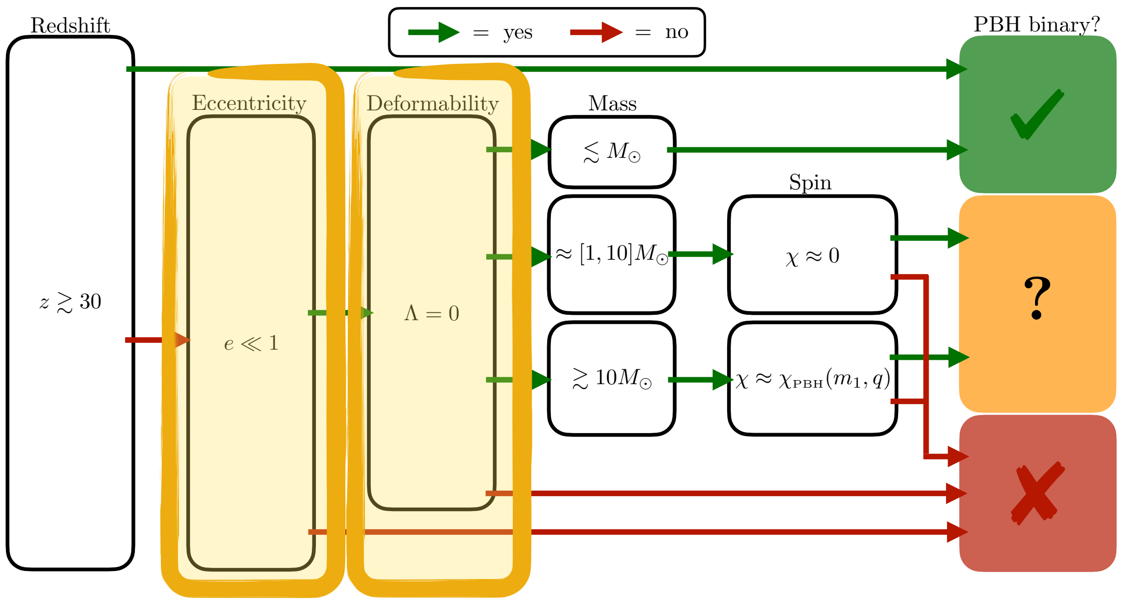




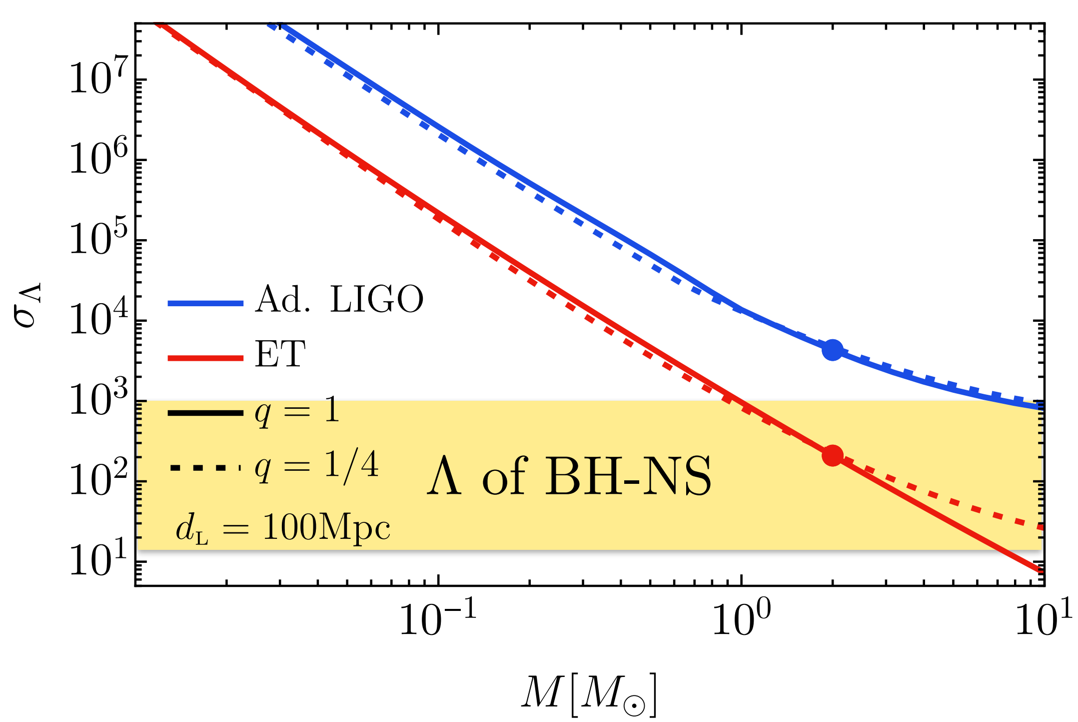
Individual BH binary assessment

GF+, PRD [2112.10660]

Large precision improvements with 3G detectors!

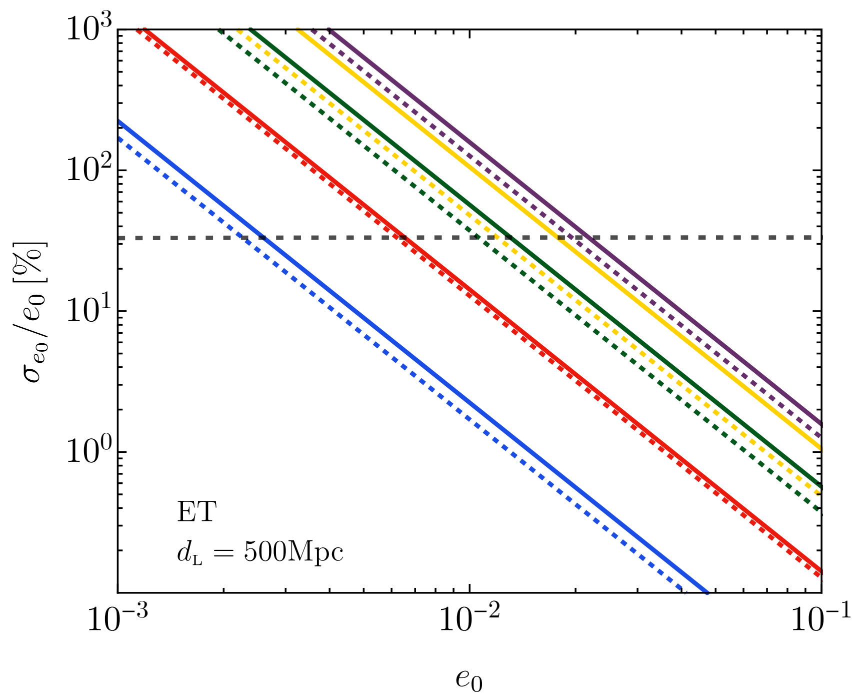


Tidal deformability



(help disentangle PBHs from NS)

Eccentricity



(help disentangle PBHs from ABHs dynamical)

(+ mass-spin relation ...)

Population analyses

Searching for mass-spin correlations

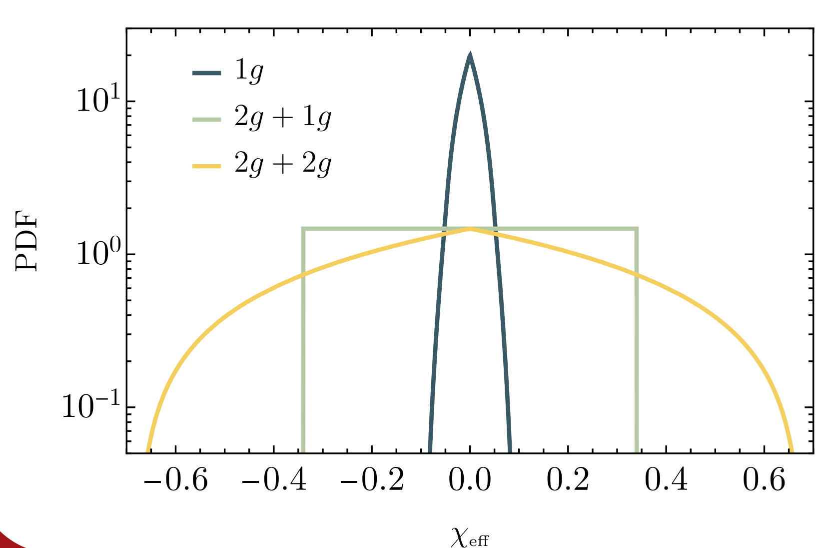
GF&Pani, PRD [2201.13098]

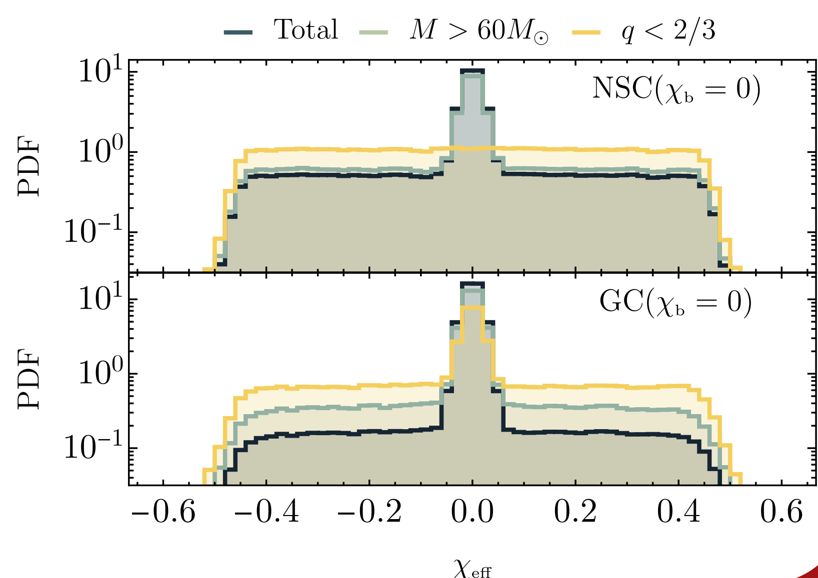
- ***Robust feature of various channels: spin distribution***

$$\chi_{\rm eff} = \frac{\chi_1^z + q\chi_2^z}{1+q}$$

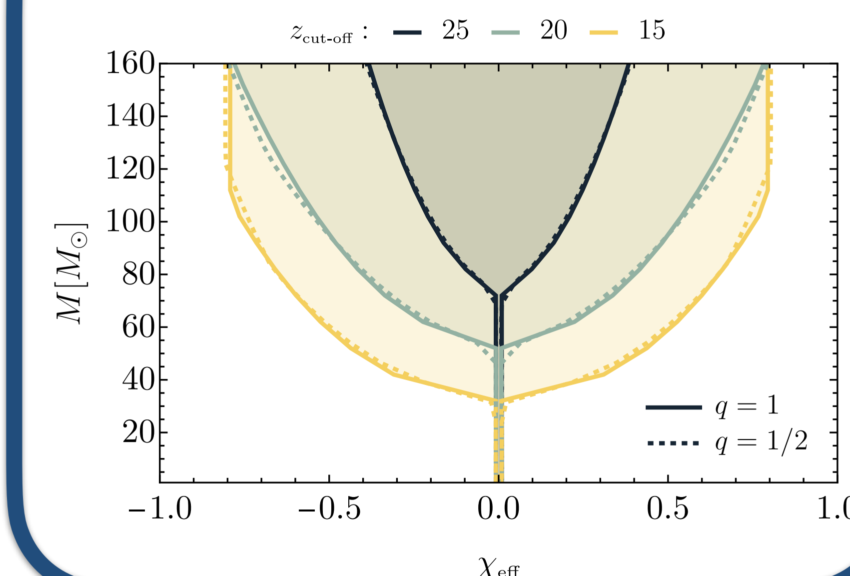
  - ***Isolated channel:*** $\chi_{\rm eff} \geq 0$
  - ***Dynamical channel:*** symmetric $\chi_{\rm eff}(M, q)$
  - ***Primordial (PBH) channel:*** symmetric $\chi_{\rm eff}(M)$

Dynamical channel





PBHs



Searching for mass-spin correlations

GF&Pani, PRD [2201.13098]

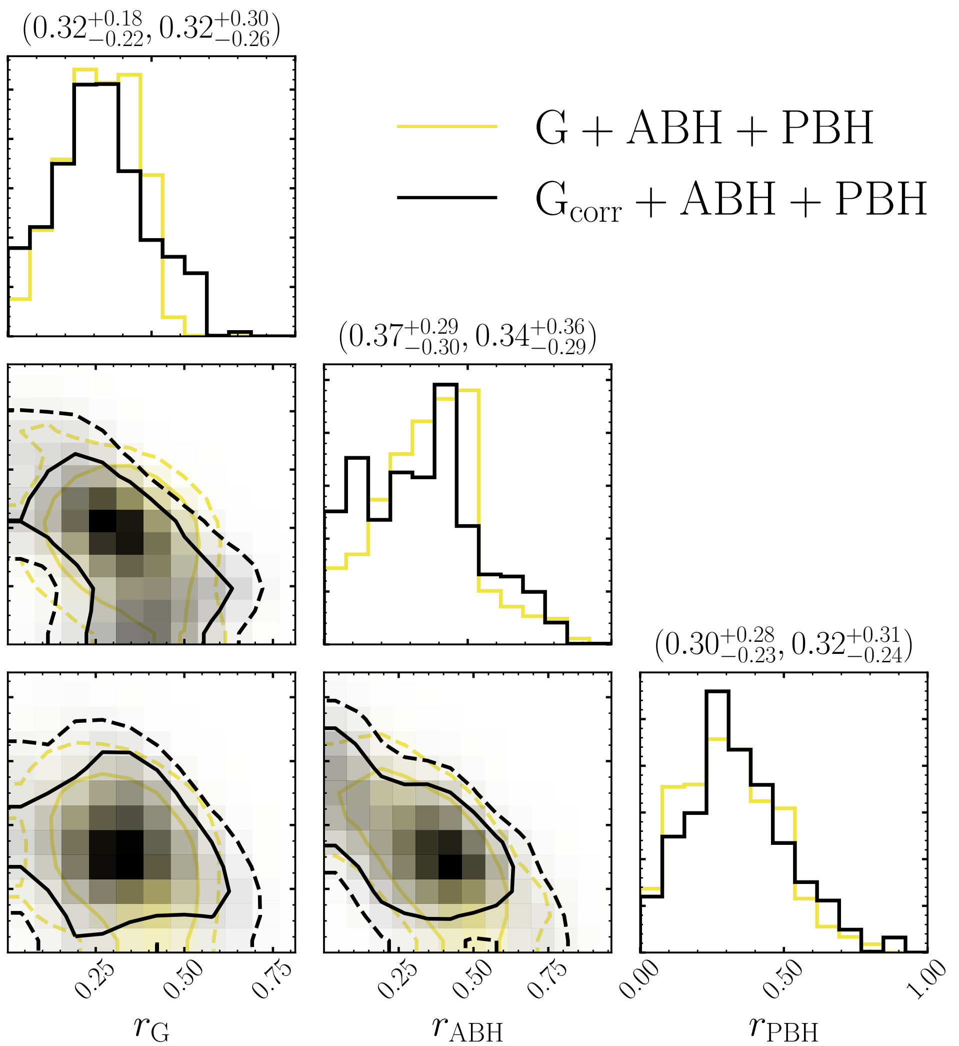
$$p_{\rm pop}(\chi_{\rm eff}) = r_{\rm G} p^{\rm G}_{\rm pop} + r_{\rm ABH} p^{\rm ABH}_{\rm pop} + r_{\rm PBH} p^{\rm PBH}_{\rm pop}$$

- ***Bayes factors mildly favour inclusion of mass-spin correlations compared to LVKC gaussian model***

$$\log_{10} \mathcal{B}_{\rm G}^{\rm G+ABH+PBH} \approx 1.4$$

- ***Degeneracy between ABH-PBH***
- ***Need larger statistics and smaller errors***

GWTC-3



Gaussian LVKC | **ABHs dynamical** | **PBHs**

Multi pop. analysis: using the full information

Major caveat: having to deal with theory uncertainties

both for PBH and the ASTRO population models

We took the astrophysical models from Zevin+ ApJ (2021)

- ***Isolated formation channels:***

  COSMIC Breivik et al. (2019)
  MESA Paxton et al. (2019)
  POSYDON Bavera et al. (2020)
  Fragos et al. (2021) in prep.

  - **Common envelope** (CE)
  - **Stable Mass transfer** (SMT)

- ***Dynamical formation channels:***
  - **Globular Clusters** (GC)

    Rodriguez et al. (2019)
  - **Nuclear Star Clusters** (NSC)

    Antonini et al. (2019)

Hyperparameters:

CE efficiency

$\alpha_{\rm CE} \subset [0.2, 0.5, 1, 2, 5]$

Natal spin

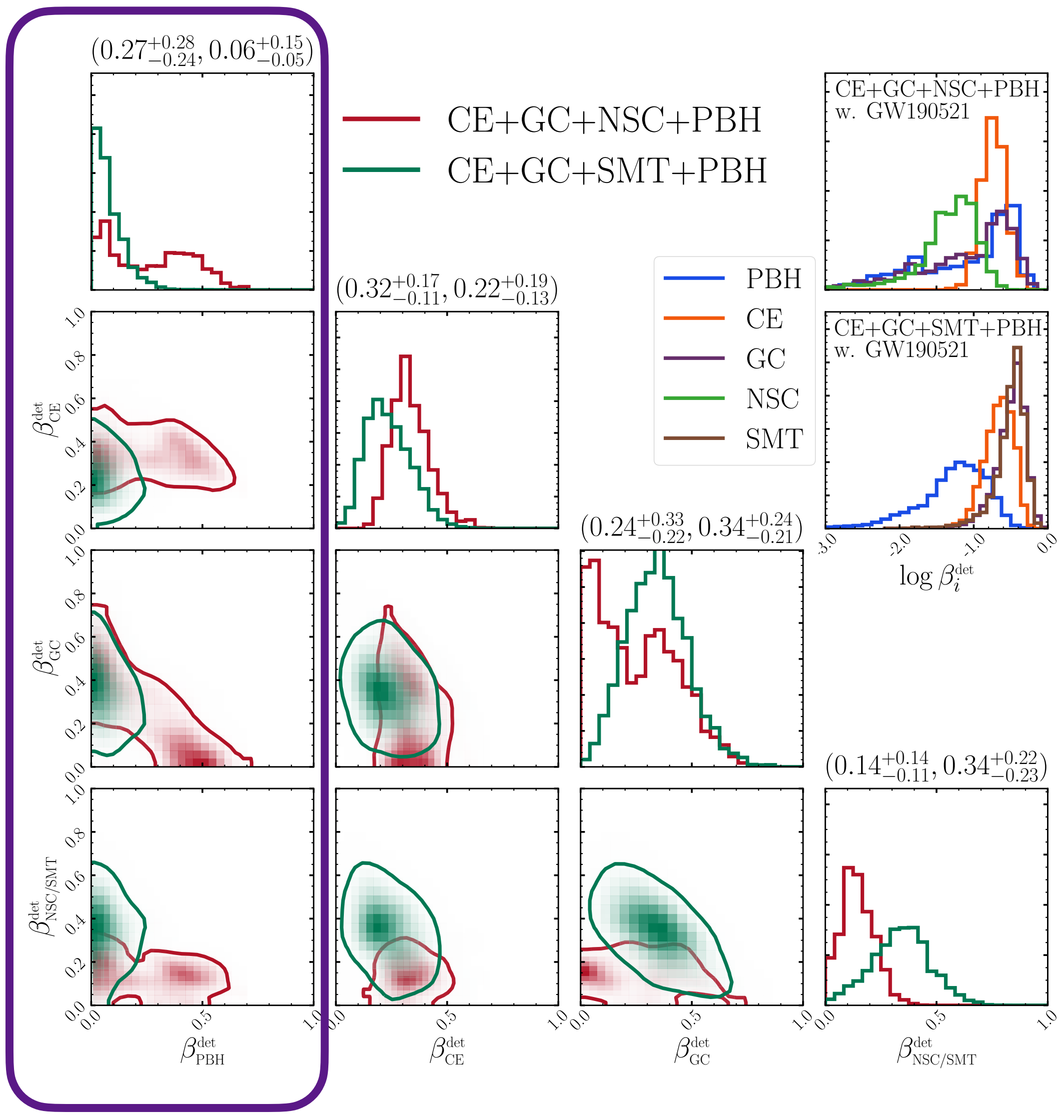
$\chi_{\rm b} \subset [0, 0.1, 0.2, 0.5]$

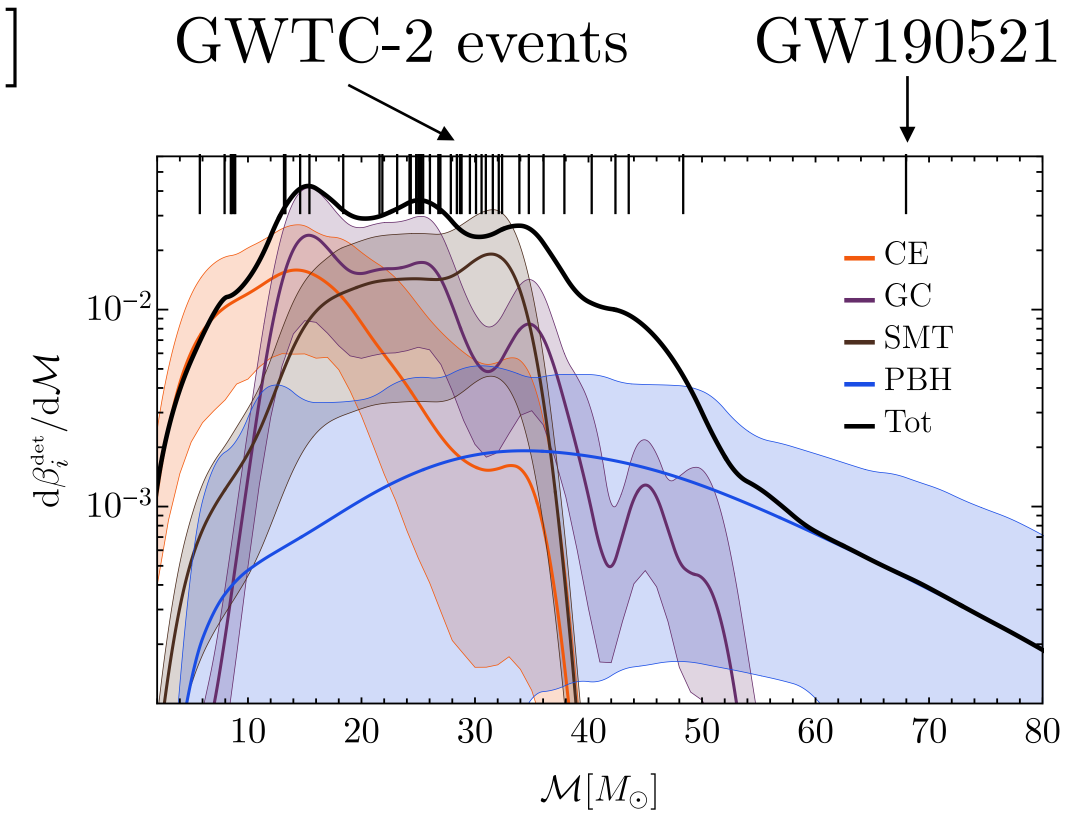
We tested various combinations of the astrophysical channels...

Multi-channel population inference with PBHs

GF+, PRD [2105.03349]

Detectable fractions $[\beta_i^{\rm det} = N_i^{\rm det} / \sum_j N_j^{\rm det}]$





PBH population

$M_c \simeq 35 M_\odot$ $\sigma \simeq 0.4$

$f_{\rm PBH} \simeq 10^{-3.5}$ $z_{\rm cut\text{-}off} \simeq 23$

- Bayes factors favour the inclusion of PBHs (mostly from GW190521)
- Need to extend the analysis with additional astro channels, more extensive treatment of astro/PBH uncertainties, more data...

GF+, PRD [2105.03349]

Most conservative reading:

The astrophysical models we tested are not able to explain all the features observed in the data (need to be extended)

Less conservative reading:

It is possible we have already observed the peak of the iceberg of a PBH subpopulation.

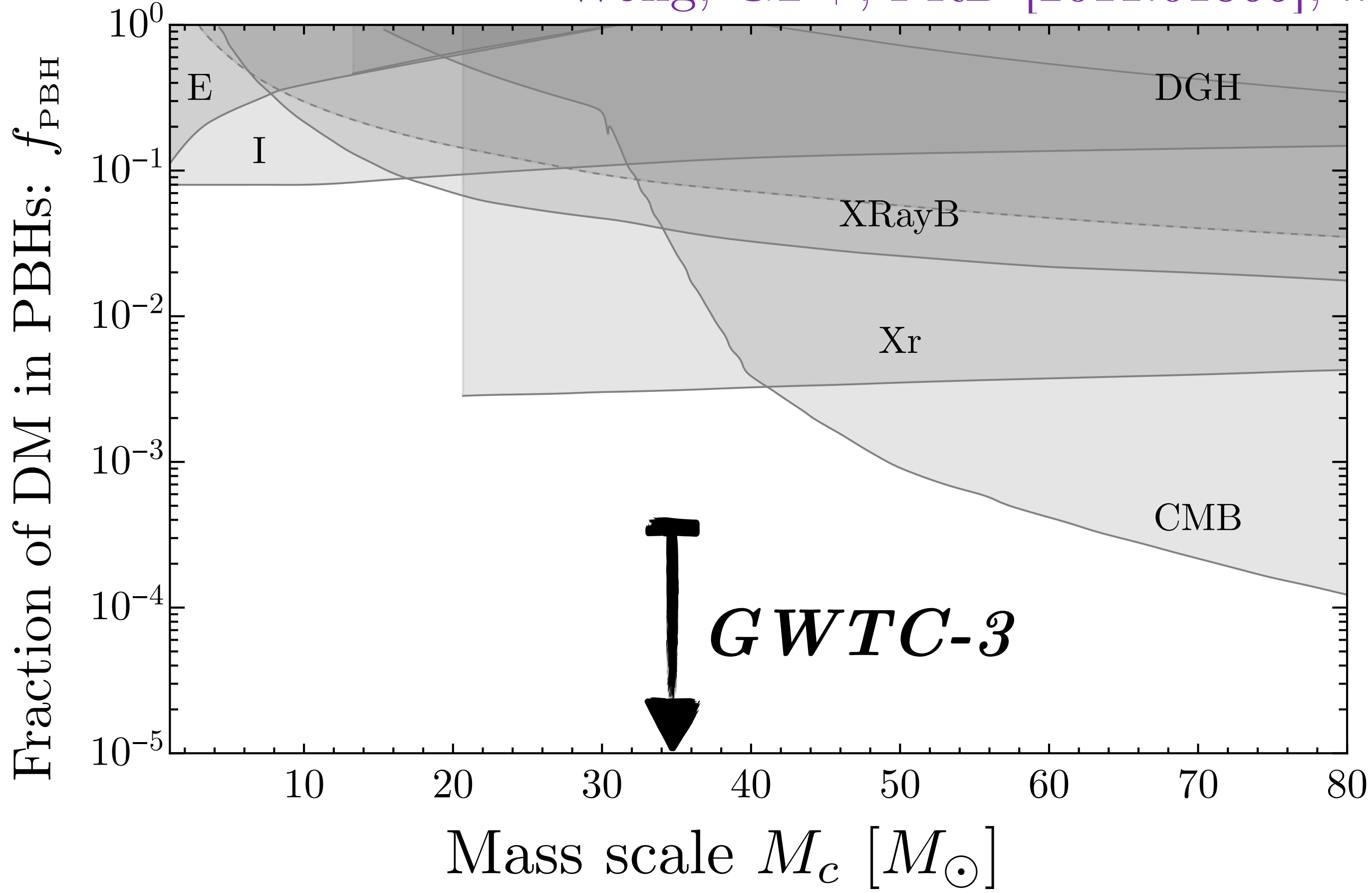
We need to devise robust tests to confirm!

Take home message and outlook for 3Gs

PBH constraints

No tension with the constraints on the PBH abundance

Wong, **GF**+, PRD [2011.01865], ...



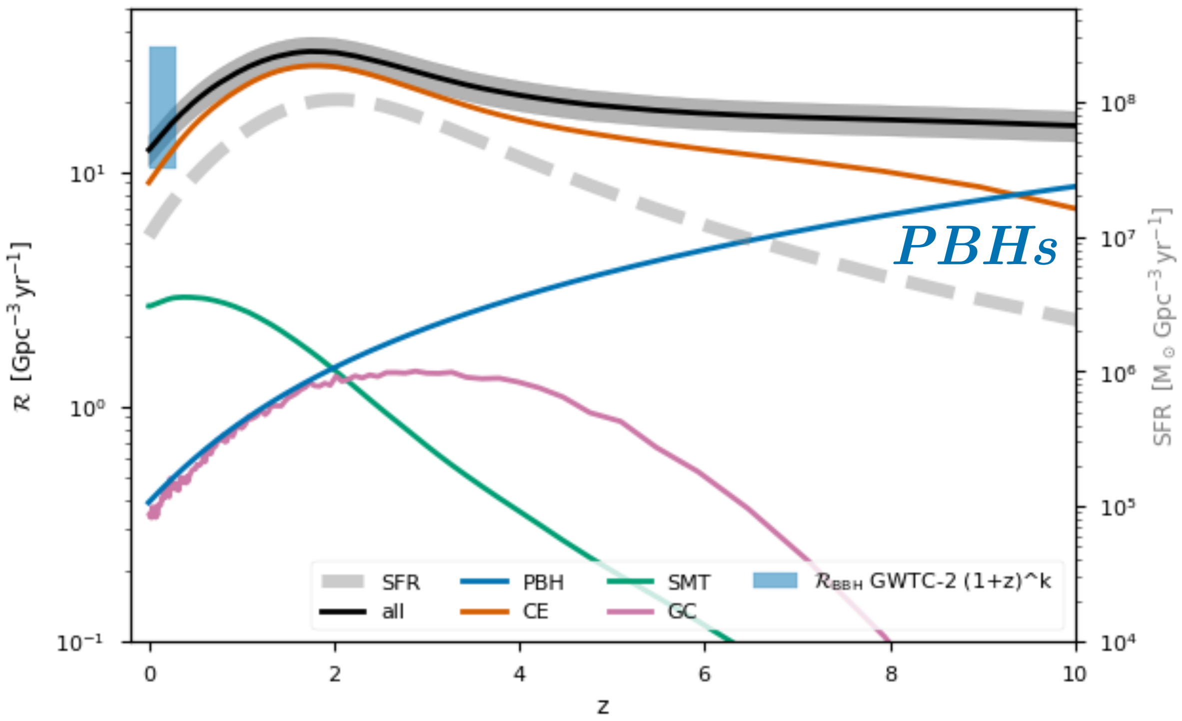
- *Also when QCD boosting formation of light LVK events* **GF**, Musco, Urbano, Pani, in preparation

- *PBH are not all the dark matter in this mass range*

(stringent bounds even if allowing for more exotic (clustered) initial conditions...)

De Luca, **GF**, Riotto, Veermae [2208.01683]

Larger SGWB from PBHs

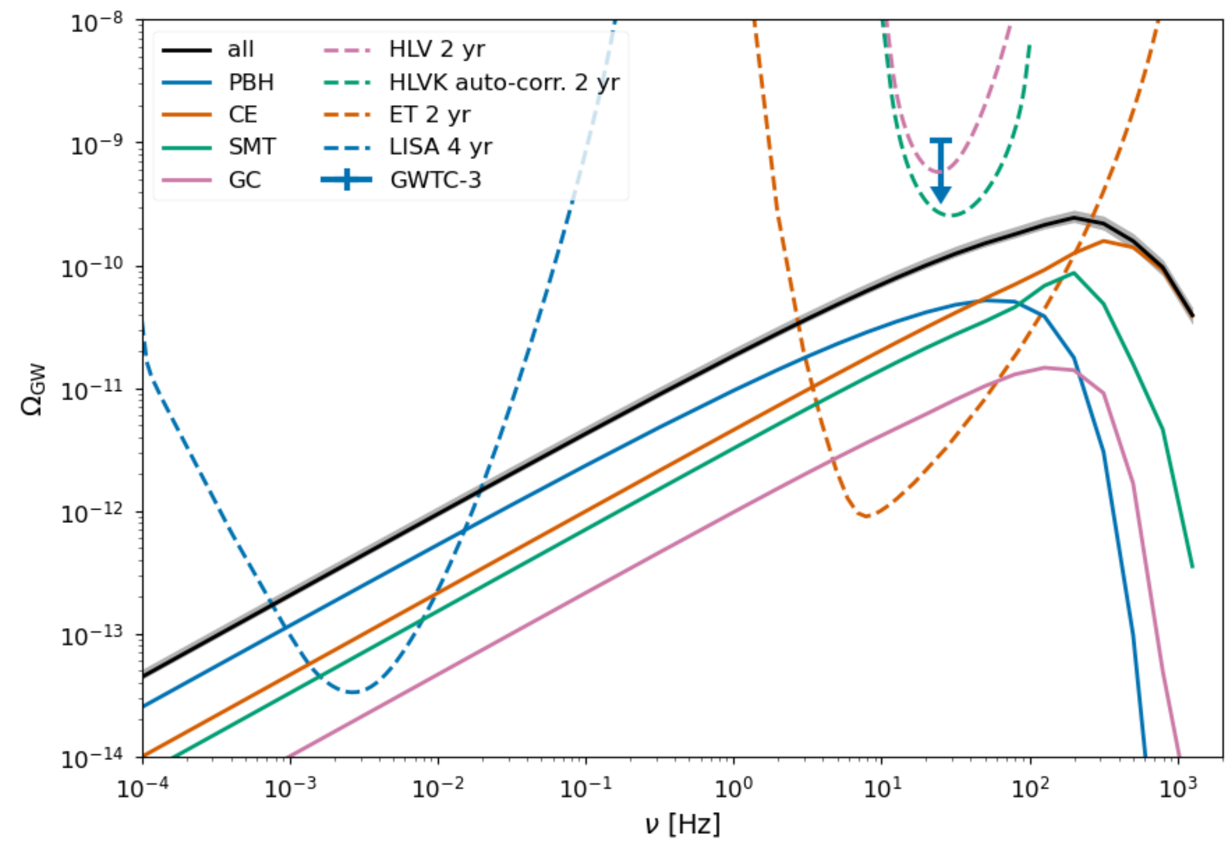


Different merger rate evolution leads to different SGWB amplitude

Additional constraint on Pop inference

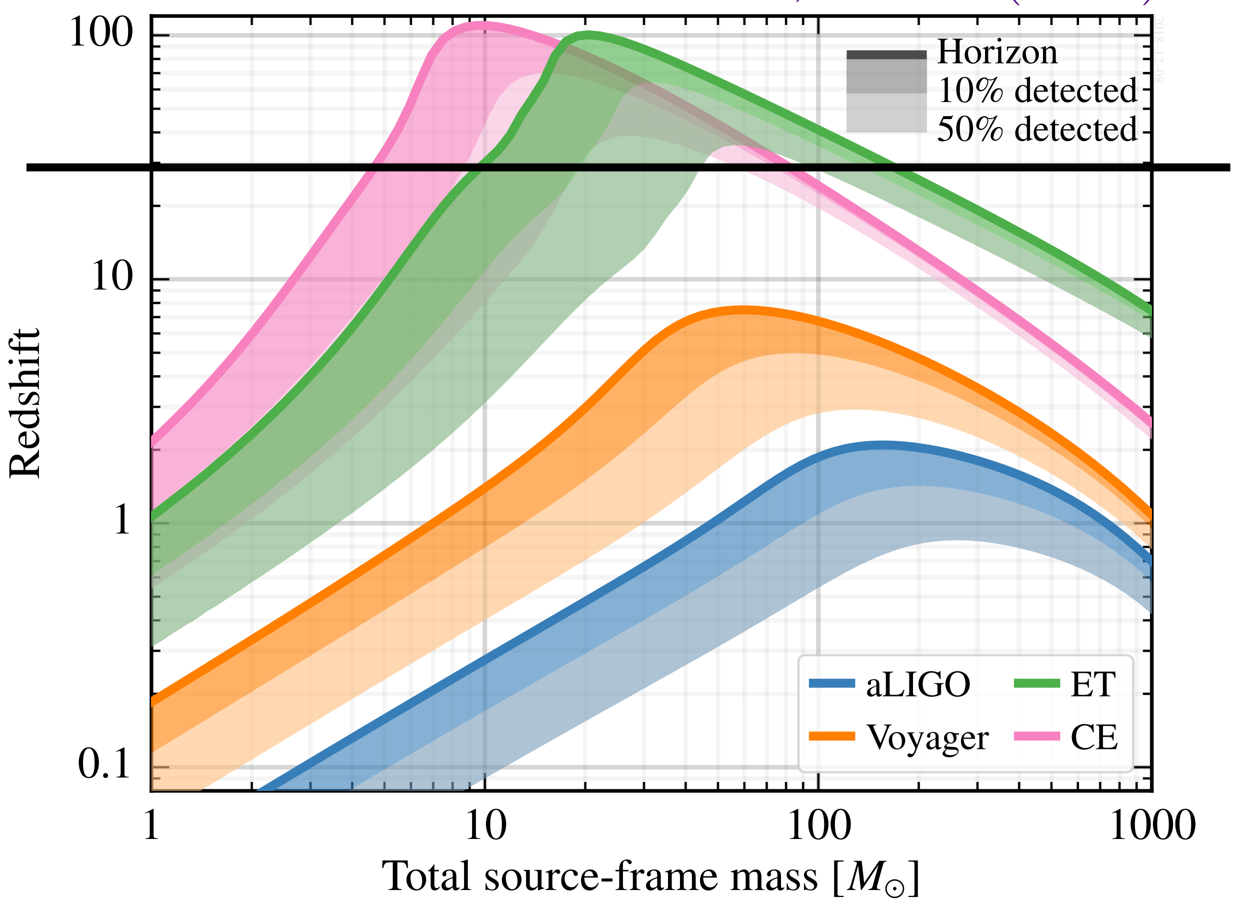
Could be probed at 3G and LISA

Bavera, **GF**+, A&A [2109.05836]



High redshift sources at 3G detectors

Hall, Evans (2019)

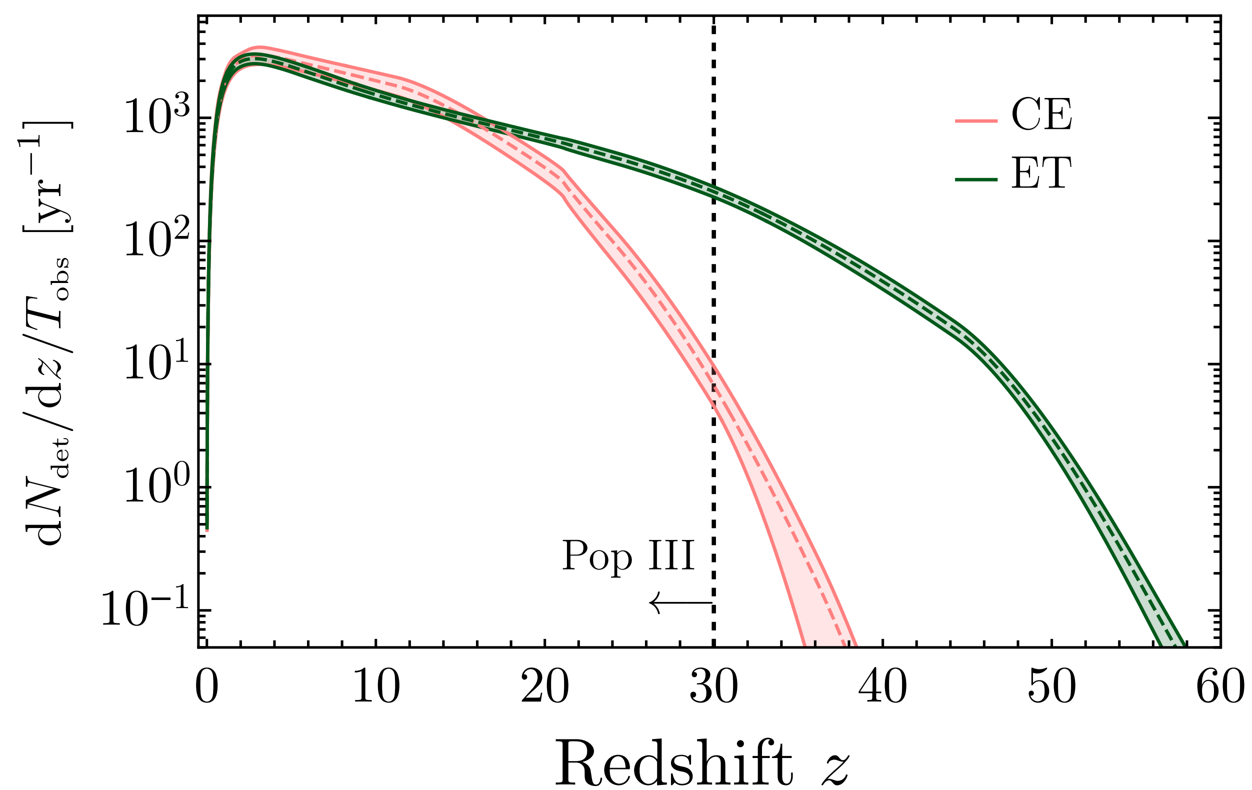


- ***No astrophysical contamination above redshift***

  Koushiappas, Loeb PRL (2017)

- ***3G detectors can reach much larger redshift***

De Luca, **G.F.**, Pani, Riotto JCAP (2021)

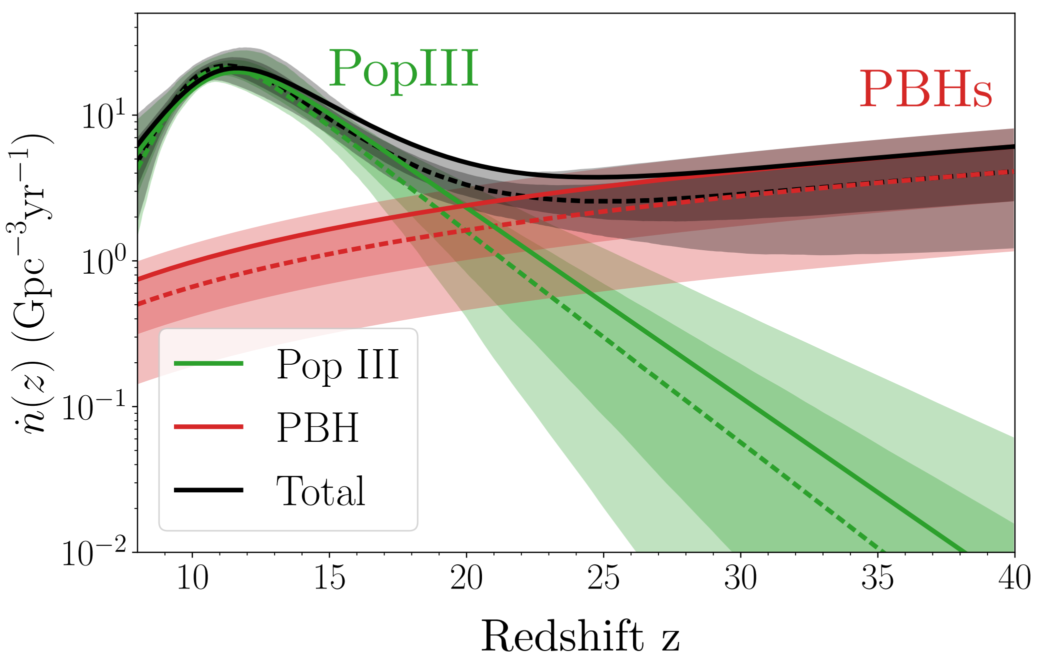


PBH sub-population compatible with GWTC-3 would give:

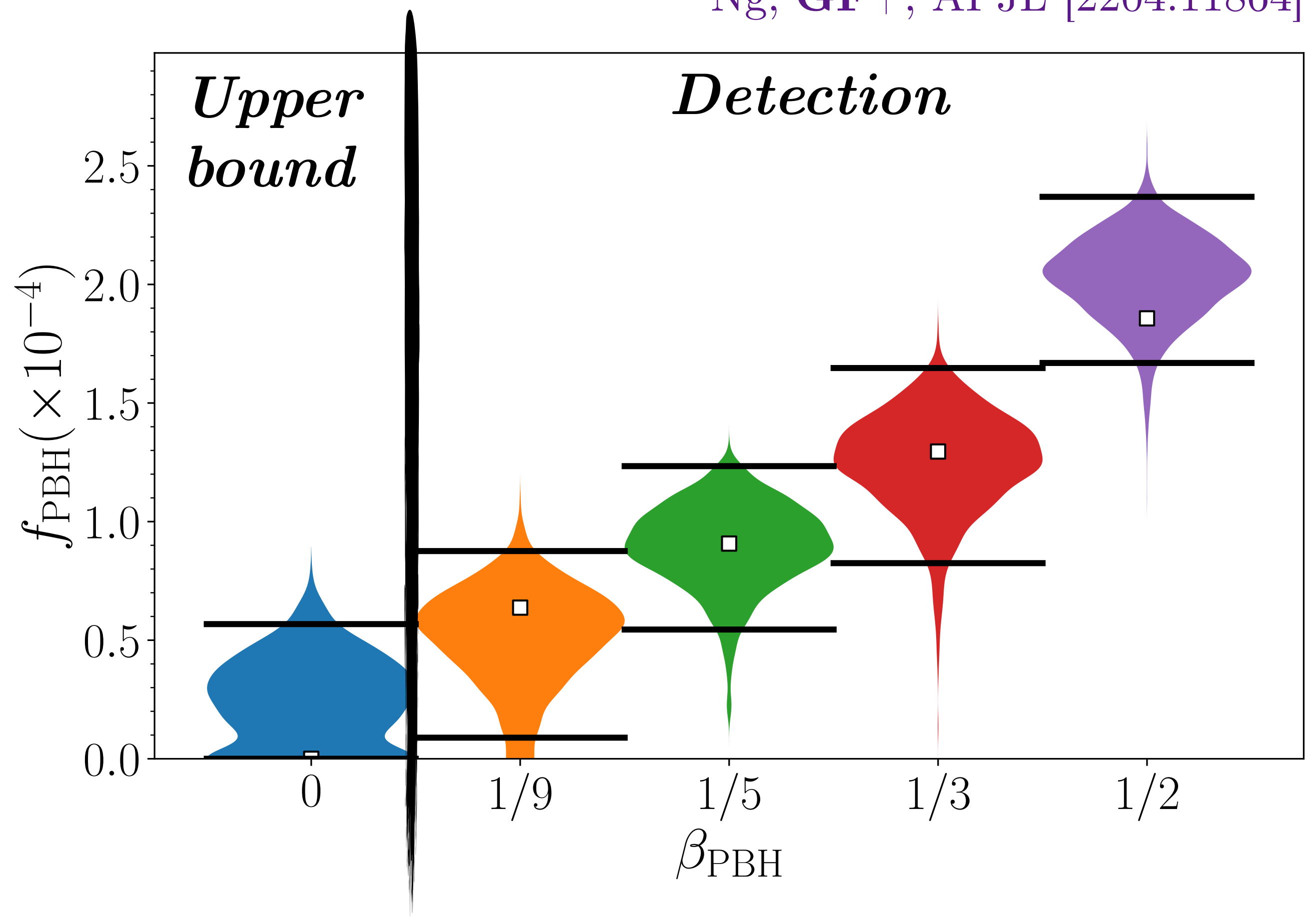
$$N^{\rm ET}_{\rm det}(z > 30) \simeq 10^3/{\rm yr}$$

High-z population study

- ***Reconstructing the merger rate*** $z \gtrsim 10$
- ***Conservative assumptions on PopIII rate***
  PopIII Belczynski+ [1612.01524]
- ***simulated 4 months of data at CE-ET***



Ng, **GF**+, APJL [2204.11864]



Within the mass range

$$M_{\rm PBH} \approx [10, 50] M_\odot$$

Conclusions

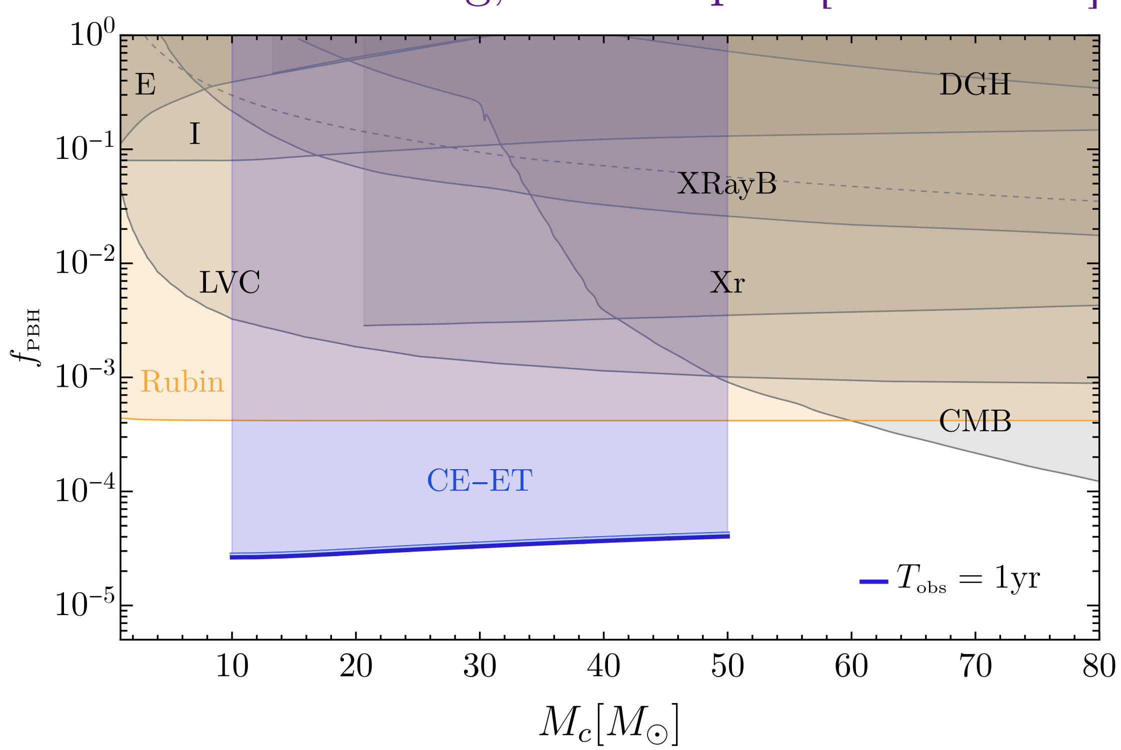
- ***Searching for PBHs in GW data is a difficult task***
- ***Robust criteria to distinguish from ABHs are needed***
- ***LVKC data and constraints allow for a PBH contribution***
- ***3G detectors needed to fully exploit smoking guns!***

3G detectors have the potential to discover a PBH population

or

set the most stringent constraint on the PBH dark matter with this mass

Ng, **GF**+ ApJL [2204.11864]



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Thanks!