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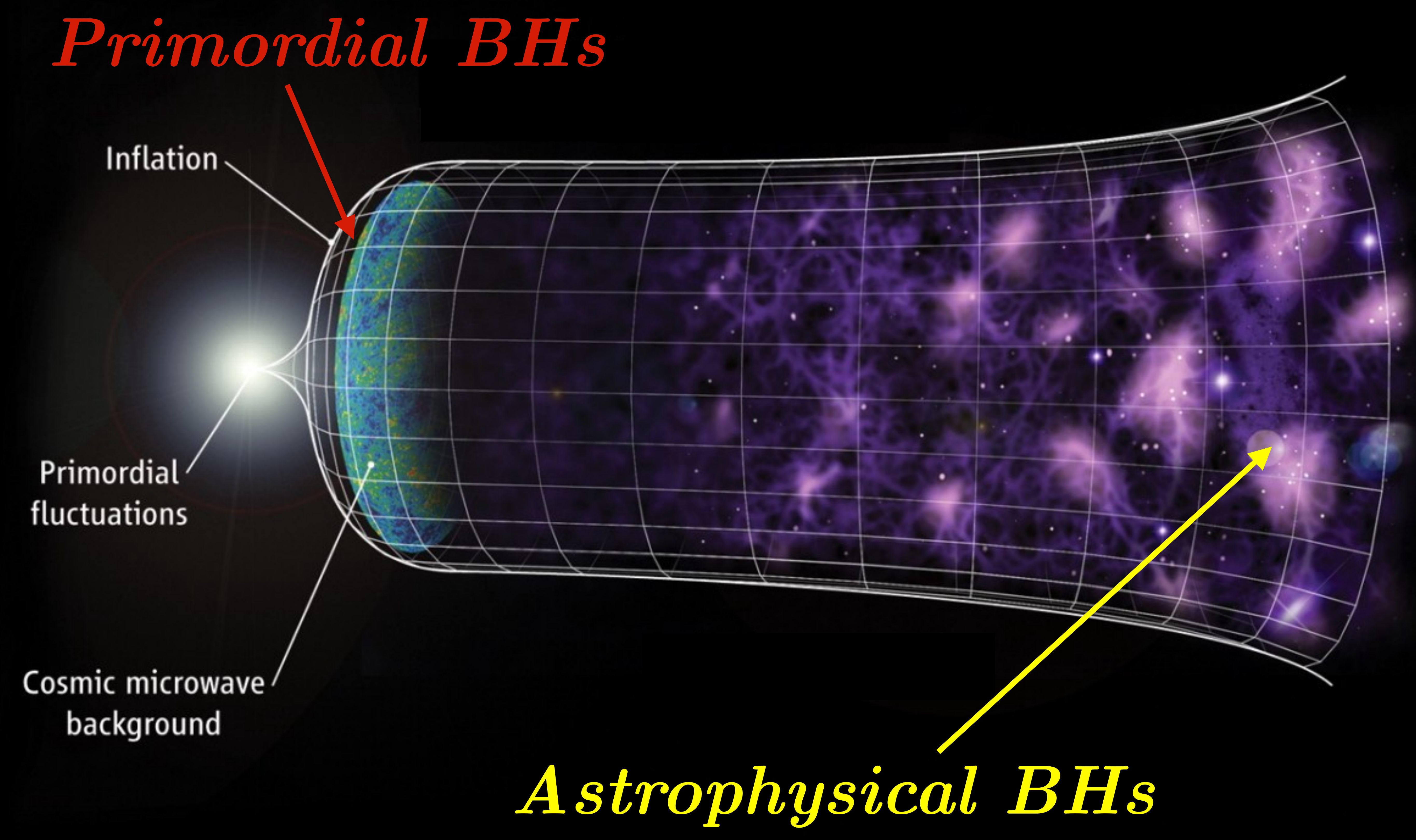
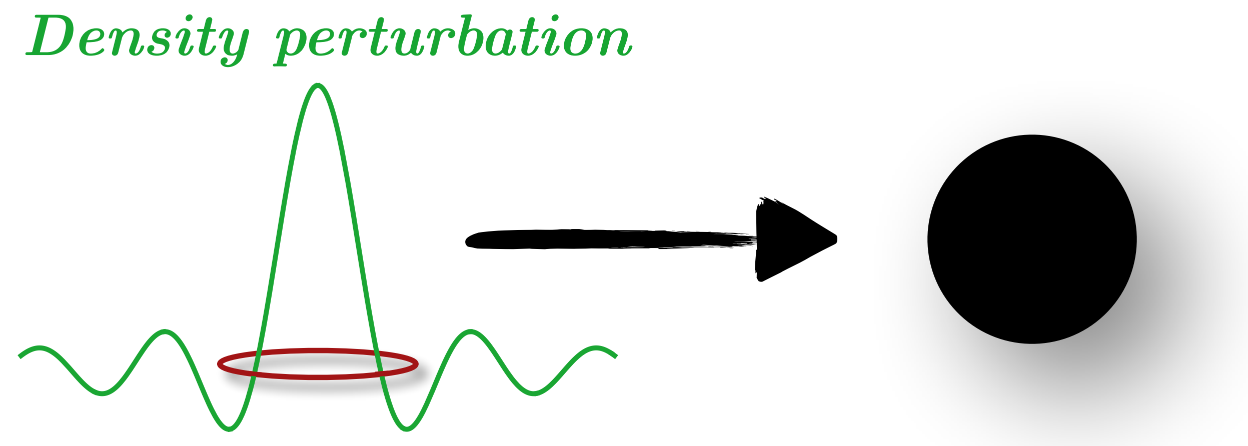
Searching for Primordial Black Holes: The Role of 3rd Generation GW Detectors

Based on recent work in collaboration with:
V. Baibhav, E. Berti, V. De Luca, K. Ng, P. Pani, A. Riotto, S. Vitale, K. Wong
arXiv: 2102.03809, 2105.03349

GWADW 2021


Primordial BHs
Inflation
Primordial
fluctuations
Cosmic microwave
background
Astrophysical BHs

PBH dictionary I: Masses



- Standard formation scenario: collapse of radiation overdensities
- PBH mass is approximately the mass of the cosmological horizon

(The mass spectrum does not possess gaps)

- Model independent parametrisation of the mass function:

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

M_c : central value of mass distribution

σ : width of PBH mass distribution

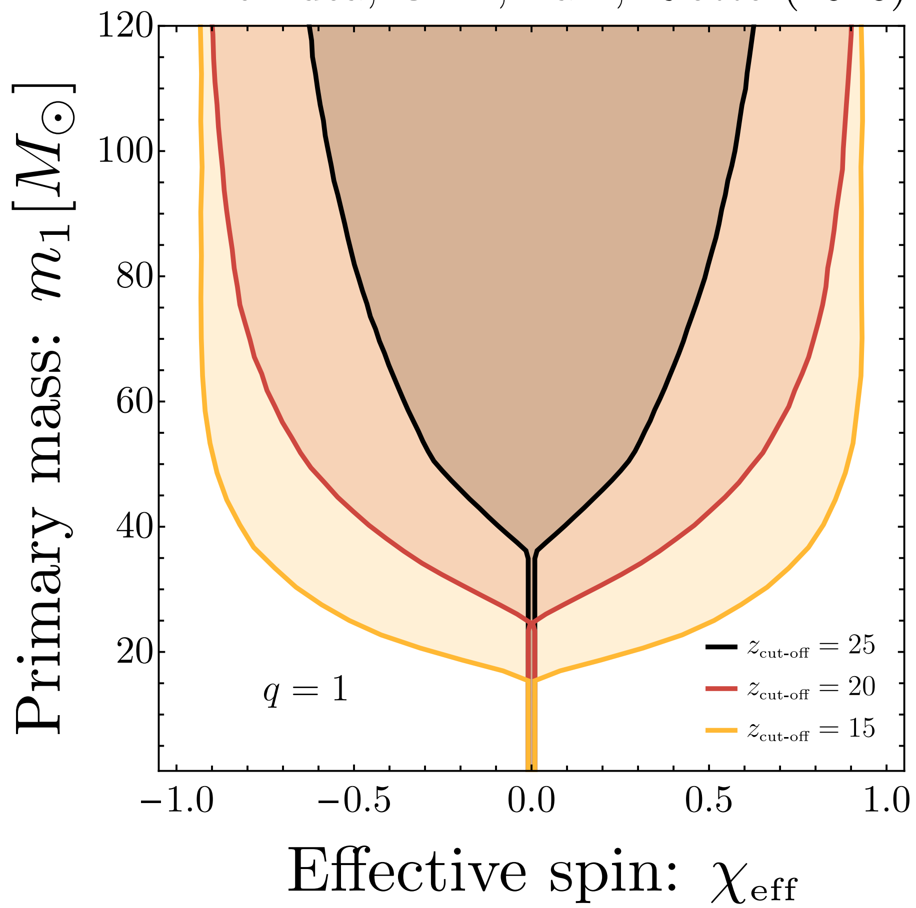
(not the chirp mass)

PBH dictionary II: Spins and accretion

- Small spins at formation $\chi \lesssim 10^{-2}$ De Luca, Desjacques, **G.F.**, Malhotra, Riotto (2019)
- Baryonic disk accretion can spin up PBHs (uncorrelated spin orientations)
- Large uncertainties over the efficiency and when it becomes negligible (around the reionization epoch)

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

De Luca, **G.F.**, Pani, Riotto (2020)



Impact on PBH spin

- Large $z_{\text{cut-off}}$:
  weak accretion, small spins

- Small $z_{\text{cut-off}}$:
  strong accretion, large spins

$z_{\text{cut-off}}$: *i)* correlated with the mass function

ii) *crucially* affects the spin distribution

PBH dictionary III: 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: $R \propto f_{\rm PBH}^2$ Raidal et al. (2019)

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

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

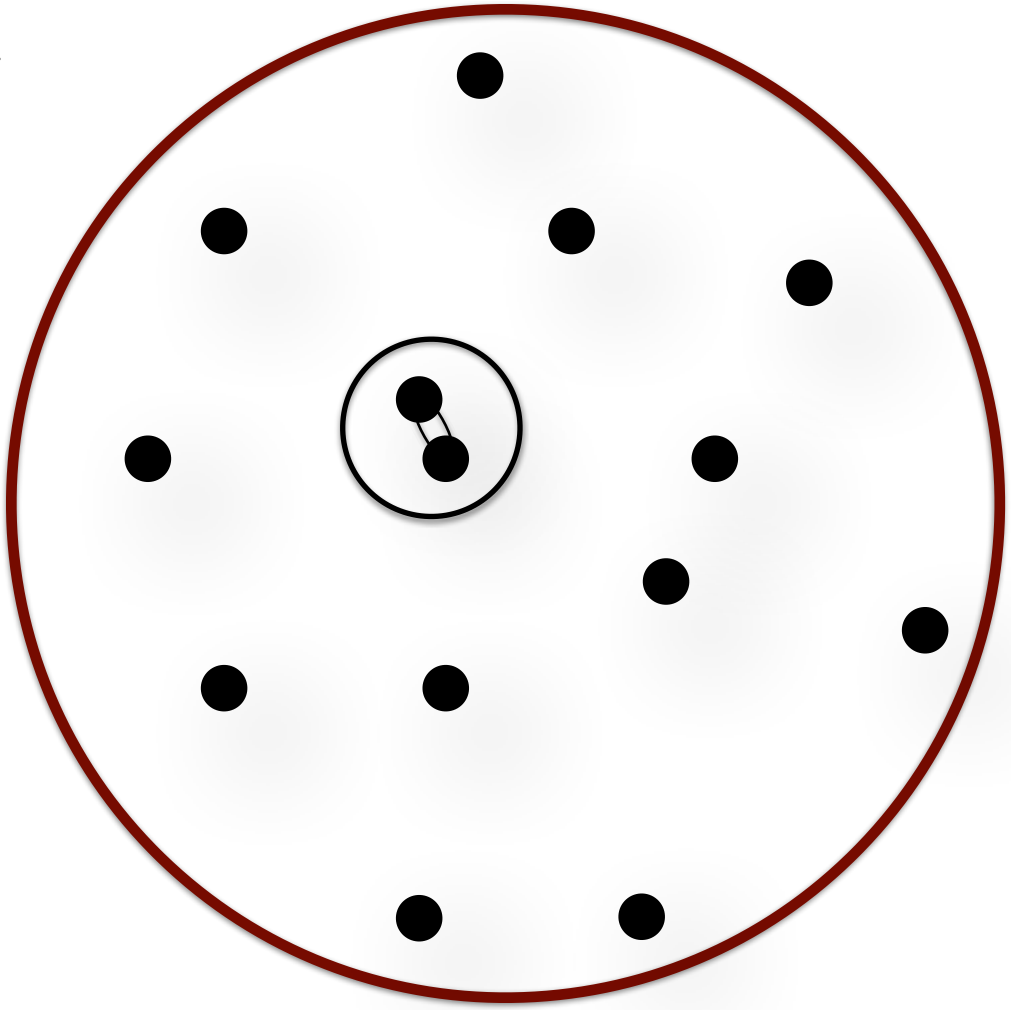
Hutsi et al. (2021), Wong et al. (2021), ...

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

PBH dictionary IV: The merger rate evolution

- Initial spatial Poisson distribution
- Random decoupling of binary systems from the Hubble flow

Nakamura (1997), ...



$\downarrow$

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

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

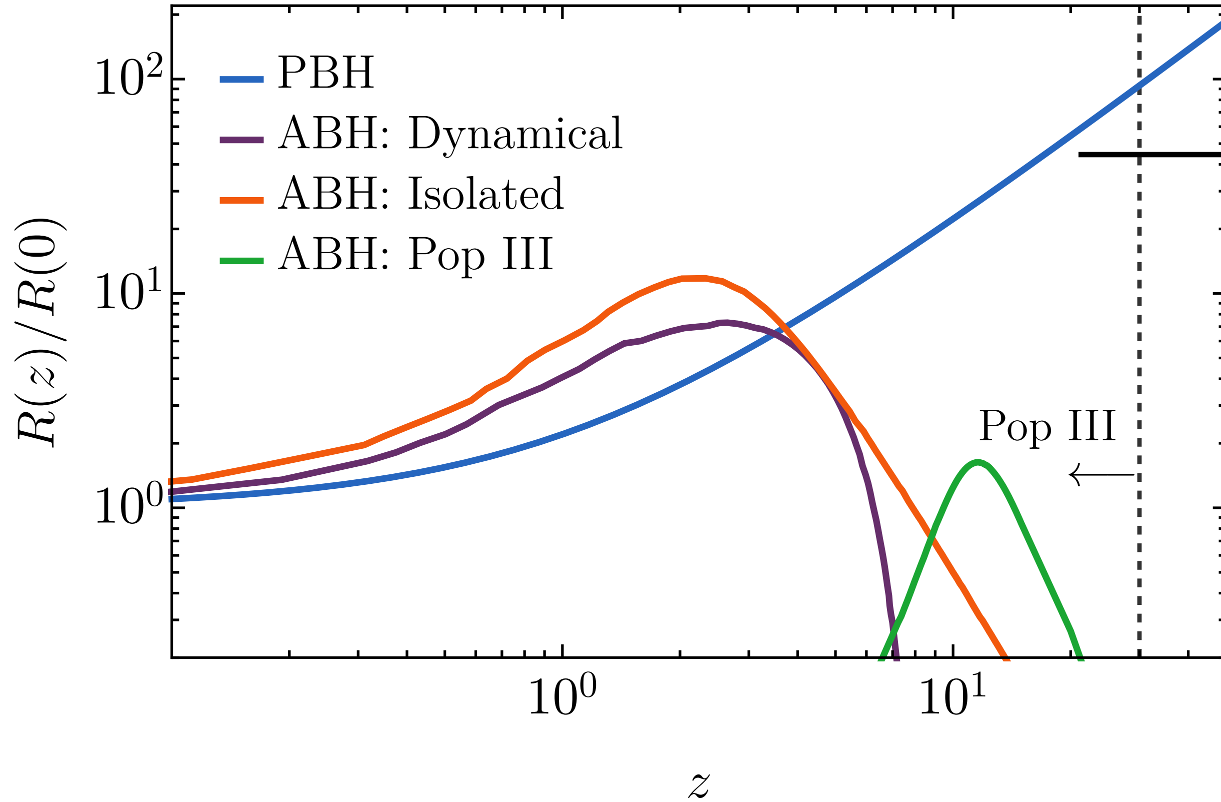
Raidal+ (2018), ...

$$\boxed{R \approx t^{-34/37}, \text{ monotonic up to redshift } z \gtrsim 10^3}$$

Redshift evolution can be used to distinguish primordial from astrophysical binaries...

Search for Primordial binaries using 3G detectors

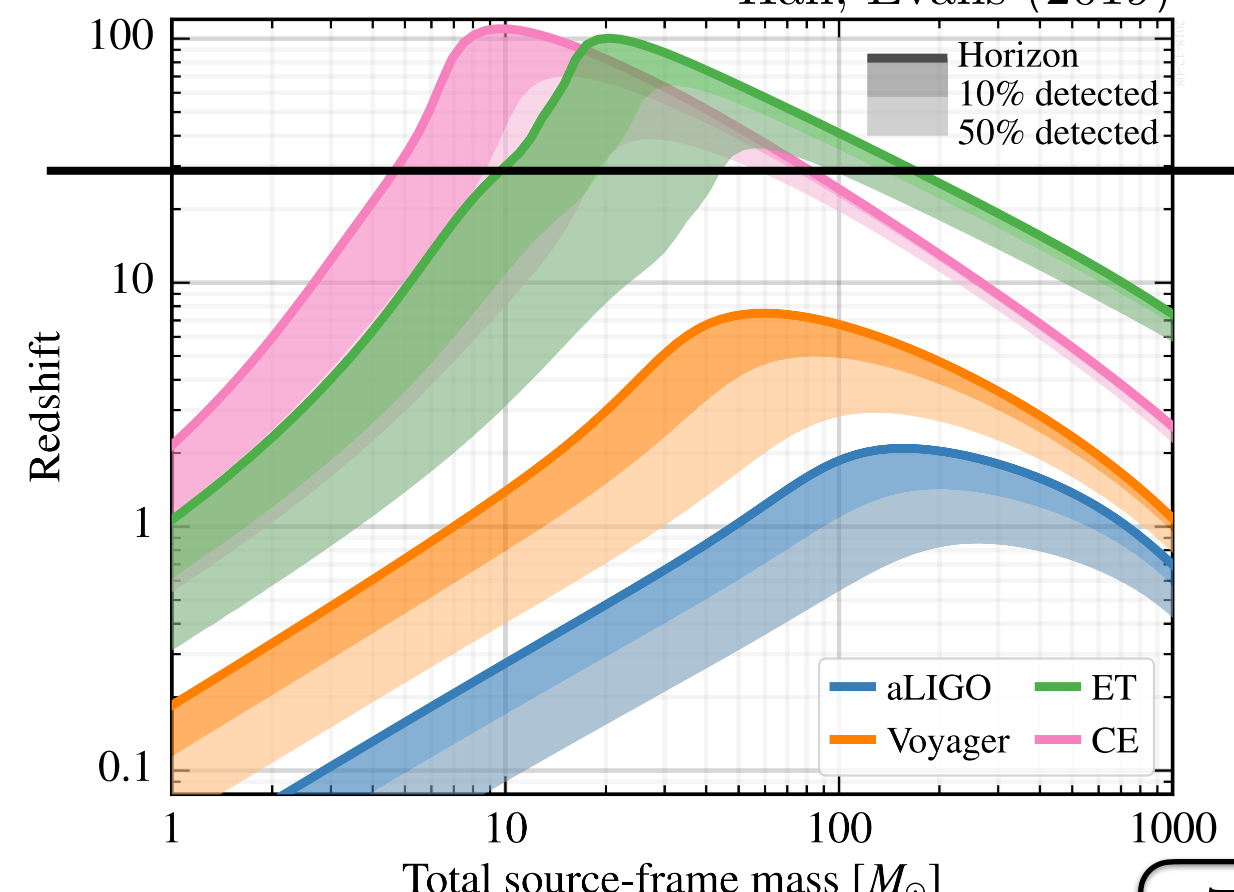
astro from Ng et al. (2020) and refs. therein



PBH merger rate evolution
with arbitrary normalisation

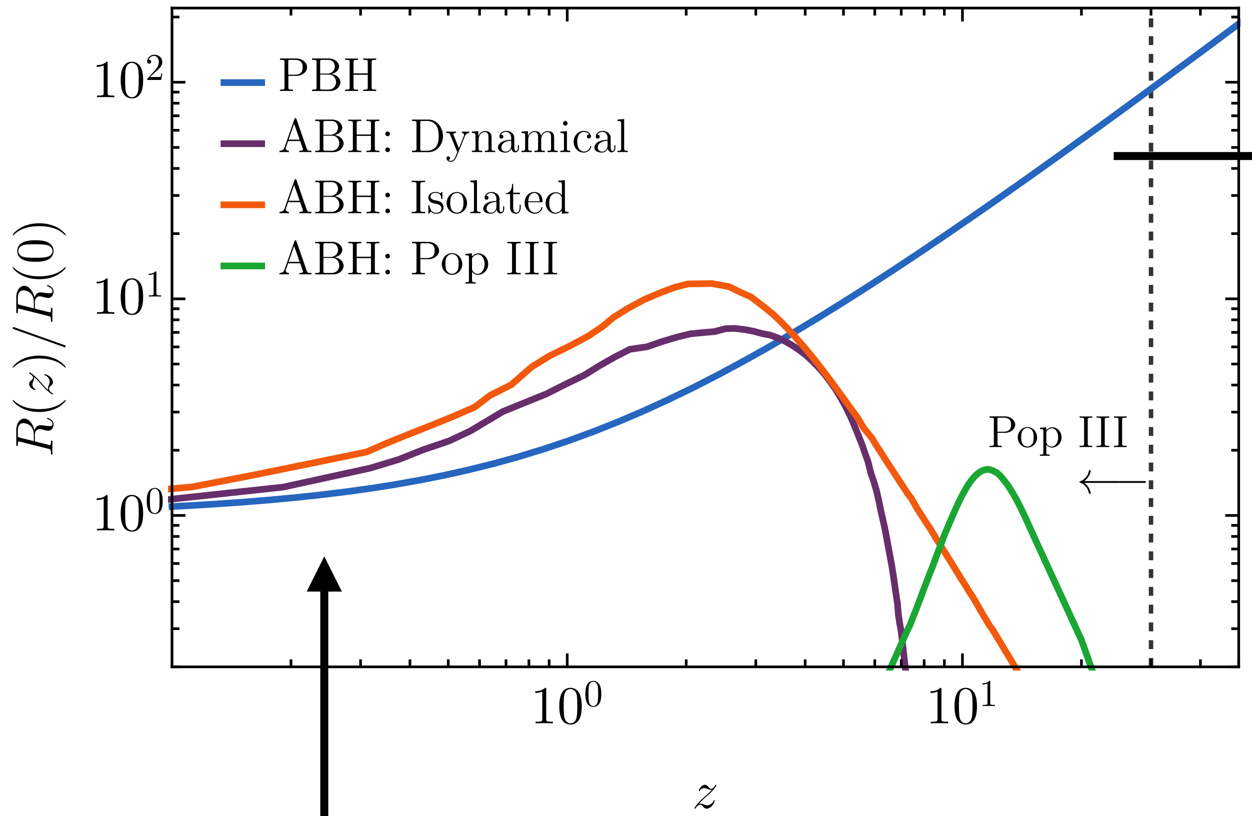
Raidal+ (2018), ...

Hall, Evans (2019)



- No astrophysical contamination above redshift $z \approx 30$
  Koushiappas, Loeb (2017)
- 3G detectors can reach much larger redshift!

We can show the potential of 3G detectors using a PBH population which is compatible with current GW data



Map the PBH population to forecast high redshift events at 3G

- We performed a population inference on current GW data (GWTC-2) mixing a PBH population with astrophysical channels

Astrophysical models adopted in our work

We take the astrophysical models from Zevin et al. (2021)

(made available at doi:10.5281/zenodo.4448170)

- Isolated formation channel:

  - **Common envelope** (CE)

    COSMIC Breivik et al. (2019)

    MESA Paxton et al. (2019)

    POSYDON Fragos et al. (2021), in prep.

- Dynamical formation channels:

  - **Globular Clusters** (GC)

    Rodriguez et al. (2019)

  - **Nuclear Star Clusters** (NSC)

    Antonini et al. (2019)

Hyperparameters:

CE efficiency

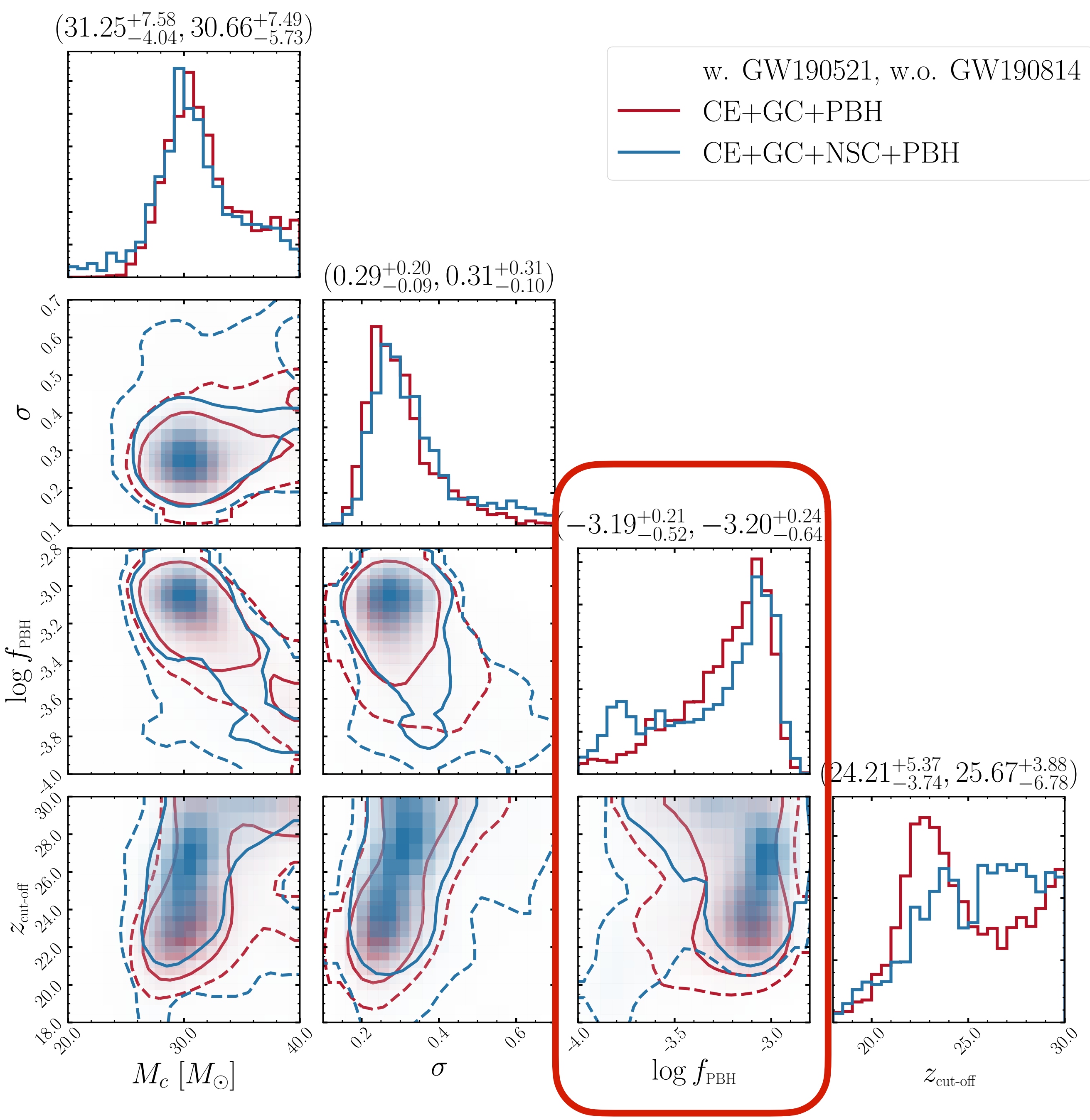
$\alpha_{\mathrm{CE}} \in [0.2, 0.5, 1.0, 2.0, 5.0]$

Natal spin

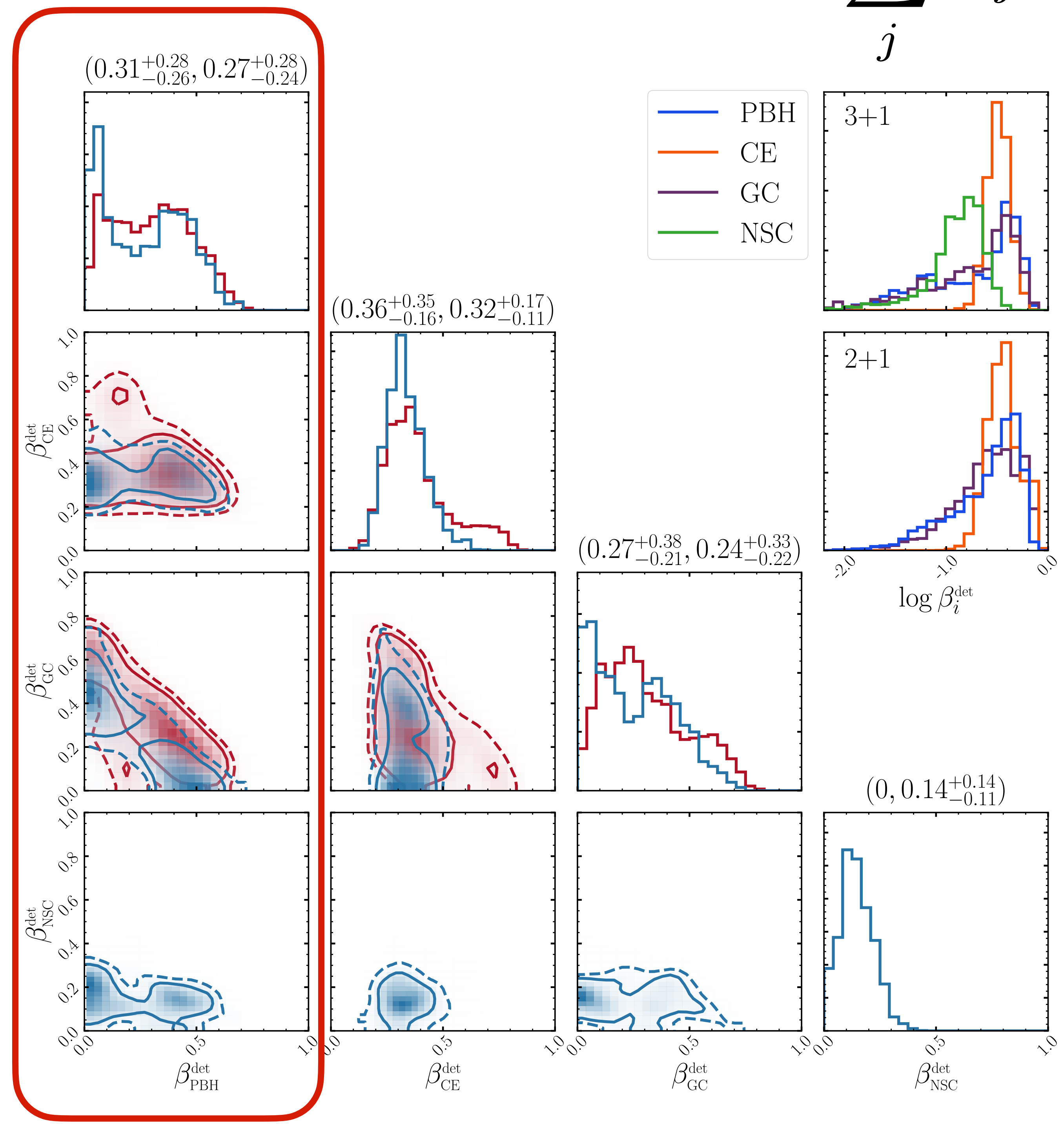
$\chi_{\mathrm{b}} \in [0, 0.1, 0.2, 0.5]$

Population inference (including GW190521)

PBH population

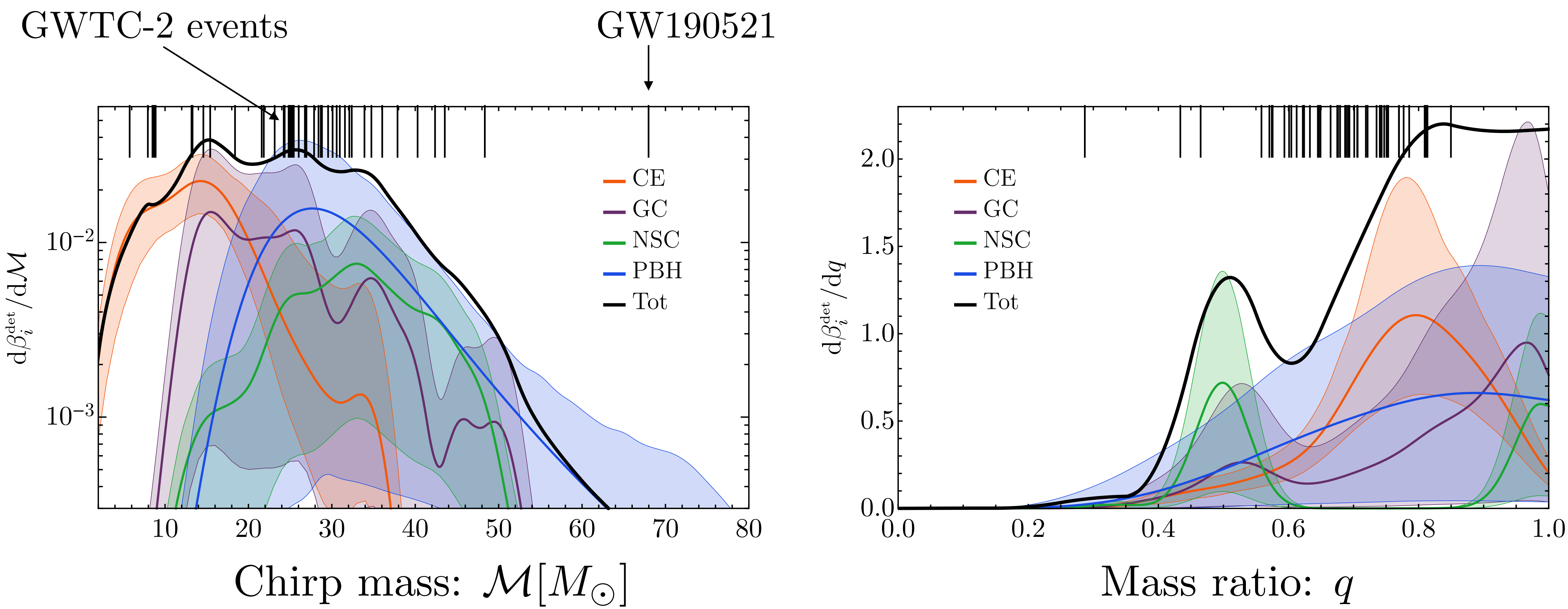


Detectable fractions $[\beta_i^{\rm det} = N_i^{\rm det} / \sum_j N_j^{\rm det}]$



Model $\mathcal{M}$	CE+GC	CE+GC+NSC	CE+GC+PBH	CE+GC+NSC+PBH
$\log_{10} \mathcal{B}^{\mathcal{M}}_{\rm CE+GC}$	0	-0.15	2.38	2.30

Population inference (including GW190521)



- PBHs can easily reach the mass gap event
- PBHs can help in explaining the "bulk" of events at $\mathcal{M} \approx 30 M_\odot$

(A similar result also found **excluding** GW190521 from the dataset)

Franciolini et al. (2021)

- Need to extend the analysis with additional astro channels, more extensive treatment of astrophysical uncertainties, more data...

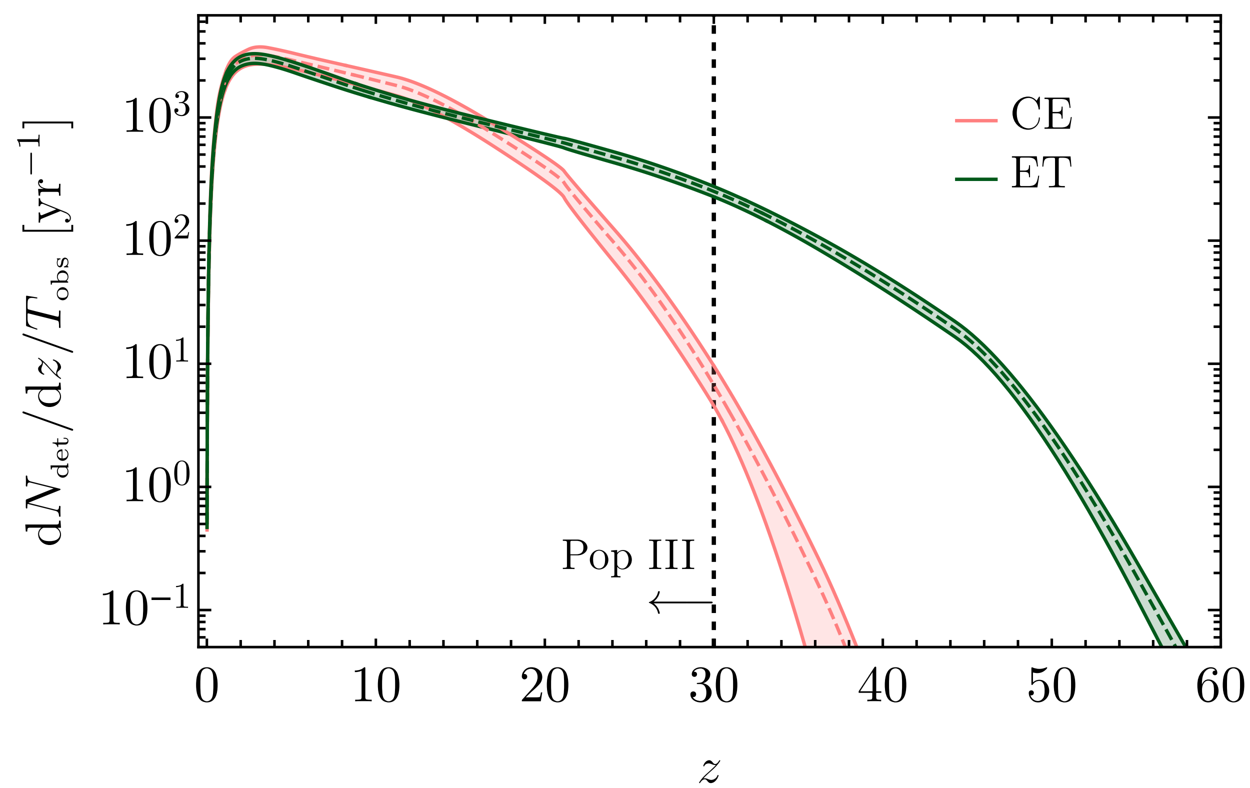
High redshift observations with 3G detectors:

- ***this*** PBH population implies high-z observations:

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

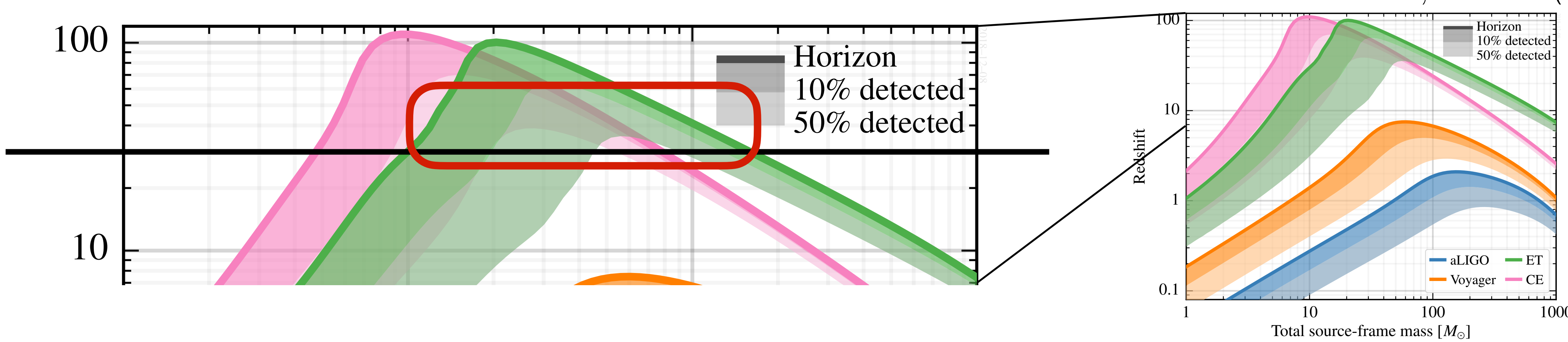
where there is no astrophysical contamination!

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



Higher performance of ET for ***this*** PBH population due to the differences between CE and ET designs

Hall, Evans (2019)



High-z at 3G detectors: Challenges and opportunities

- Problem of reconstructing the source redshift for distant events

Vitale, Evans (2017), ...

- Population studies focusing on rate evolution at high z

Ng et al. (2020), ...

- 3G detectors have the potential of discover a PBH population undetected by current GW experiments!

V. Baibhav, E. Berti, V. De Luca, **G.F.**, K. Ng, P. Pani, A. Riotto, S. Vitale, K. Wong, in preparation

Conclusions:

- PBHs may explain GW190521 as well as a fraction of massive events in the current GW catalog
- Current data accommodates the hypothesis that a sub-population of PBH binaries may have already been detected
(to be tested including more astro-model uncertainties and more data)
- PBHs are mostly degenerate with the GC channel
- Peculiar PBH merger rate evolution can be exploited using 3G detectors

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3G detectors have the unique opportunity to uncontroversially discover a PBH population of mergers!