Primordial Black Holes ...or else?

Based on work in collaboration with:

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MIT: K. Ng, S. Vitale

Sapienza: F. Crescimbeni, G. Franciolini, N. Loutrel, I. Musco, A. Urbano

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AMALDI RESEARCH CENTER

Istituto Nazionale di Fisica Nucleare
TeonGrav

Outline

PBH physics

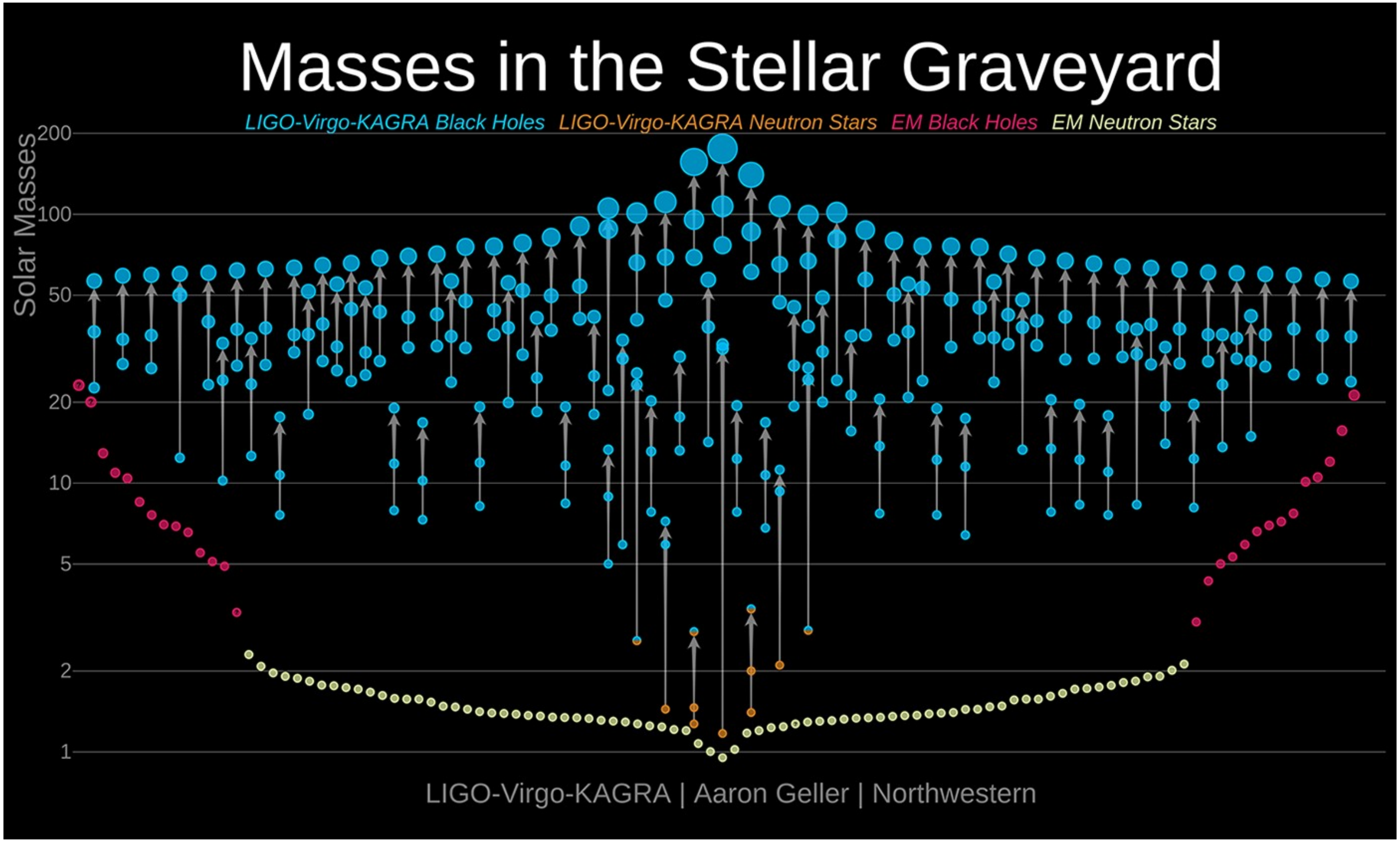
=

gravity + cosmology + particle physics + GW data

1. Primordial black holes (PBHs): motivation, formation, and constraints
2. PBHs as GW sources #1: single-event studies
3. PBH as GW sources #2: population studies

(items 2–3:) Current/future detectors, confusion with other sources

Black Hole (BH) zoology



- ~90 events (and counting...), O(0.1) million in the 3G era!

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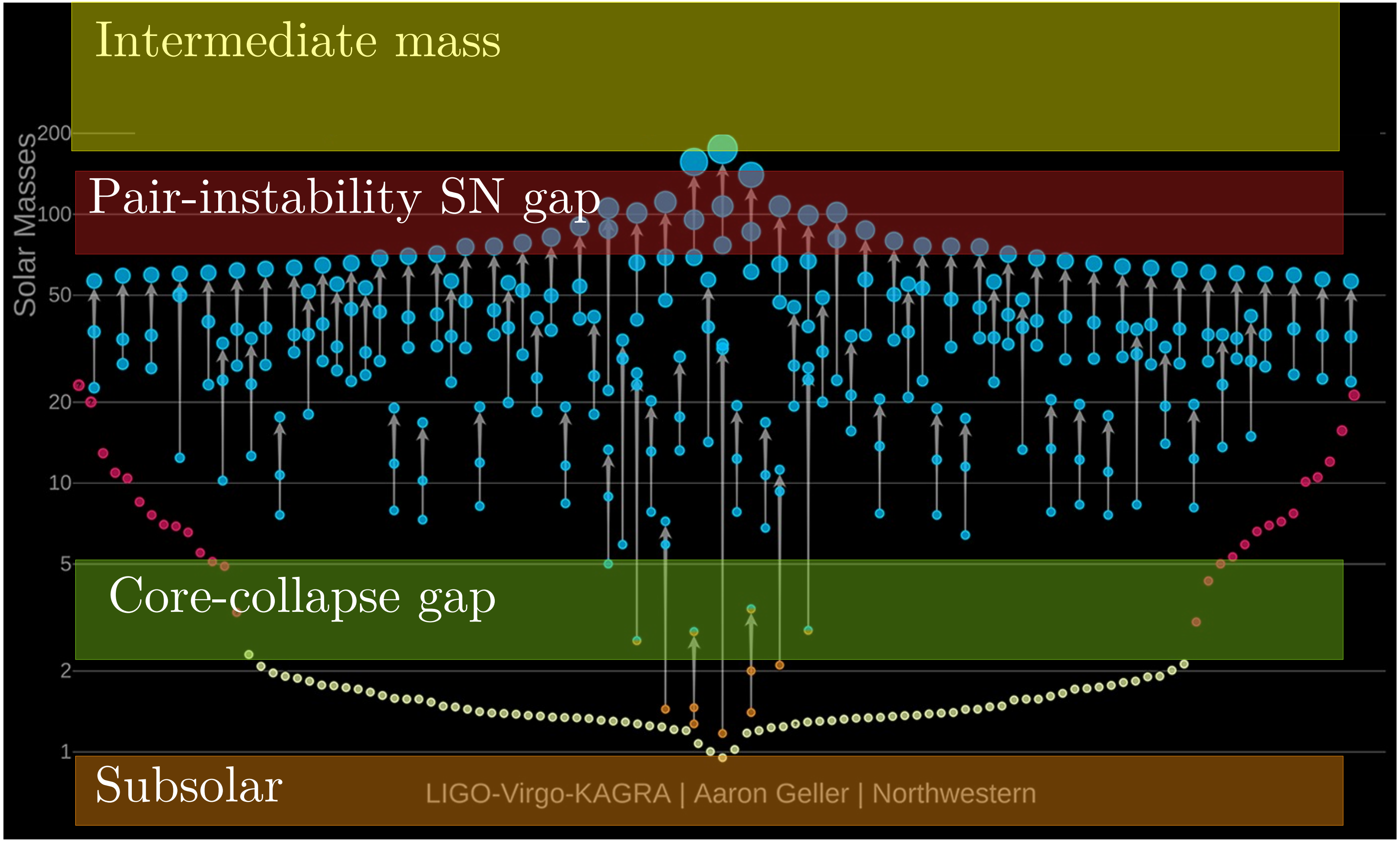
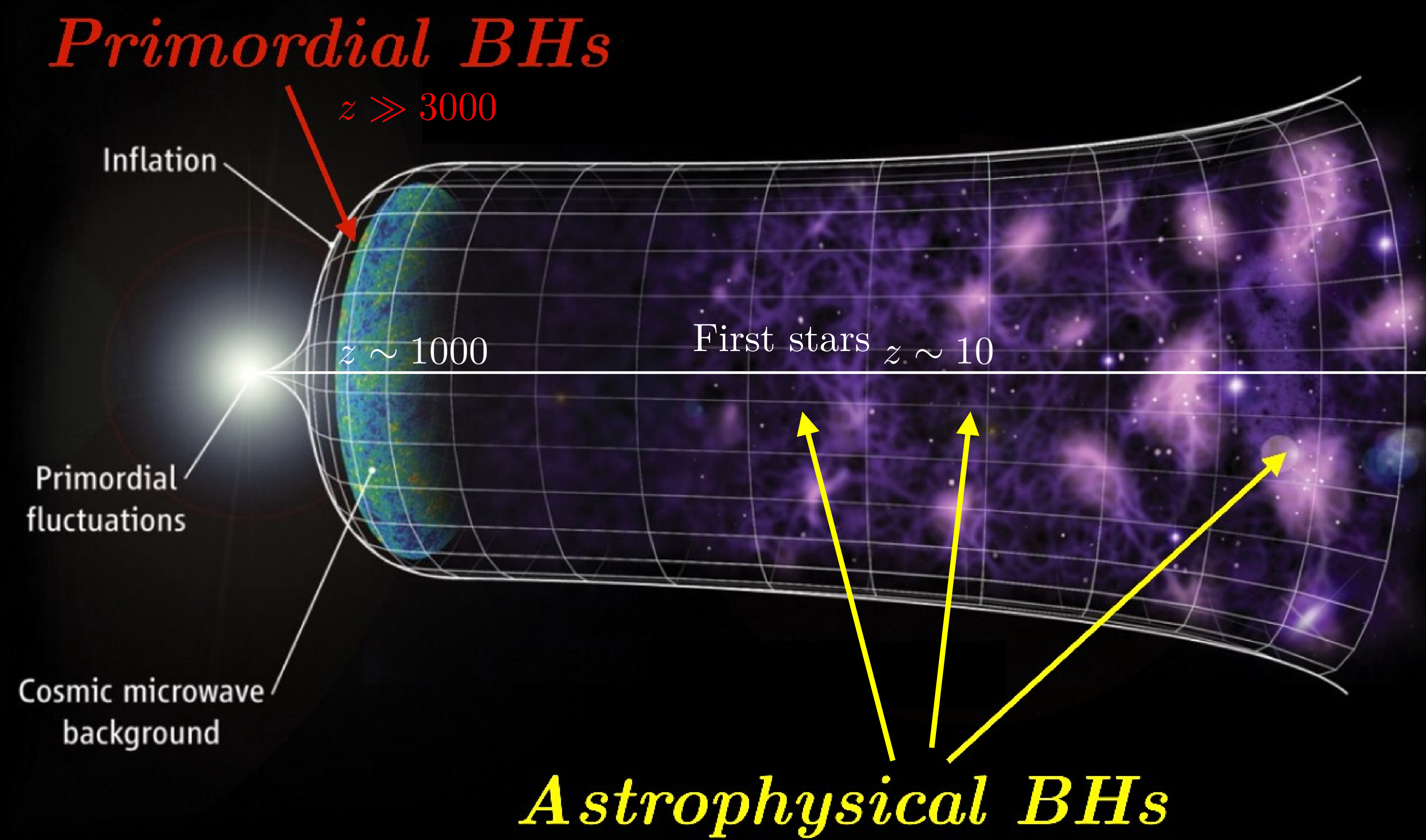
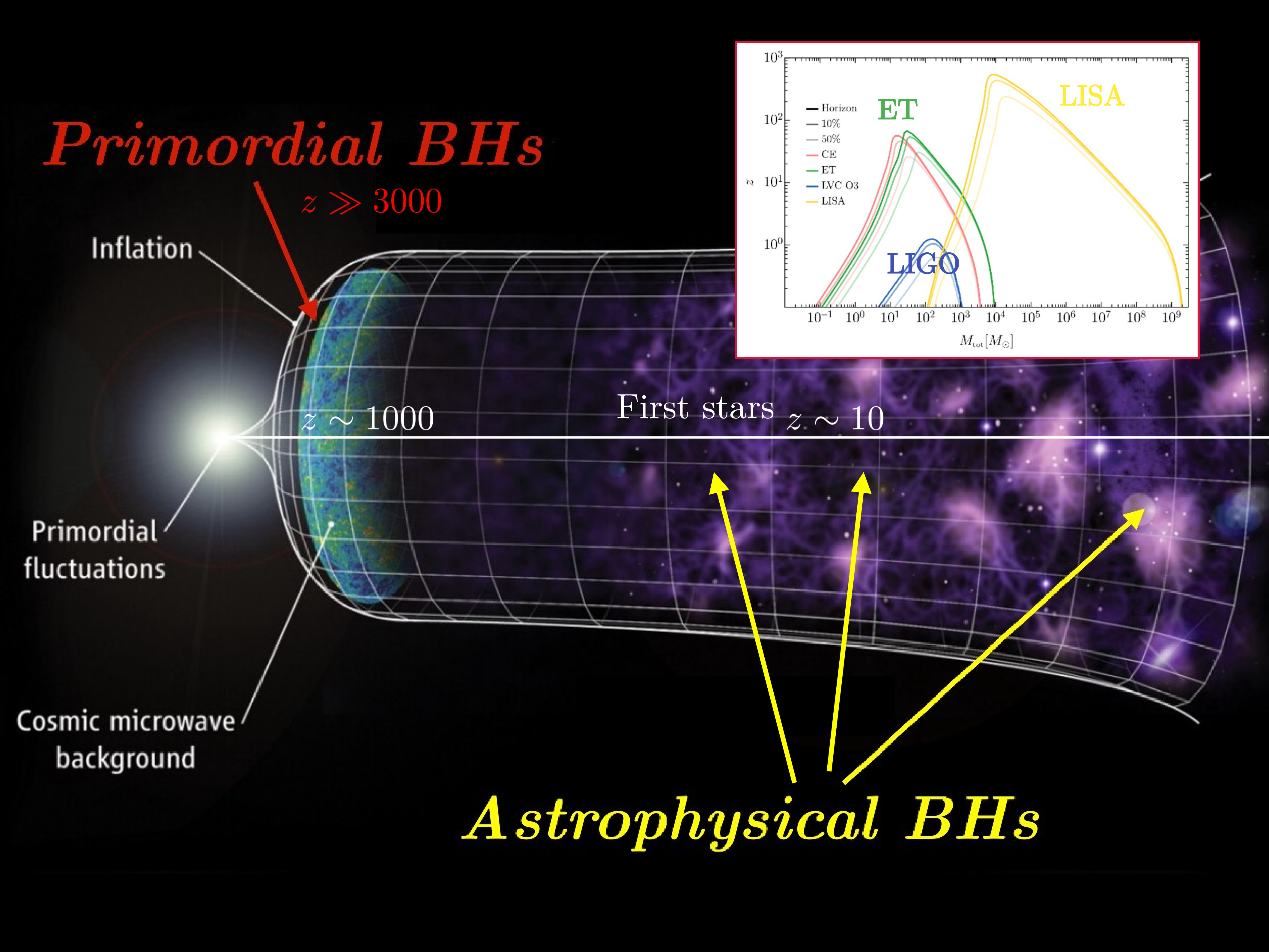


- ~90 events (and counting...), O(0.1) million in the 3G era!
- Outstanding events: Mass gap(s)? Intermediate mass? Subsolar?
- How many formation channels? Are they *all* of astrophysical origin(s)?



Primordial BHs
$z \gg 3000$
Inflation
Primordial fluctuations
Cosmic microwave background
$z \sim 1000$
First stars
$z \sim 10$
Astrophysical BHs



Primordial BHs
$z \gg 3000$
Inflation
Primordial fluctuations
Cosmic microwave background
$z \sim 1000$
First stars
$z \sim 10$
Astrophysical BHs
ET
LISA
LIGO
Horizon
10%
50%
CE
ET
LVC O3
LISA
z
$M_{tot} [M_\odot]$

Primordial BHs

Zeldovich-Novikov, Hawking, Chaplin, Carr, ...

- Unique probe of inflation and of beyond SM/GR physics
- Could comprise (at least a fraction of) the dark matter (DM)
- Supermassive BH seeds at high z?
- Could contribute (at least a fraction of) the GW signals [Bird+ 2016, Sasaki+ 2016...]
- GW events in mass gap? [Clesse-Garcia Bellido 2020, De Luca+ 2021]
- Subsolar? [Prunier+ 2023, Crescimbeni+ 2024]
- Most conservative view: exotic channel to confront with astro

Primordial BHs

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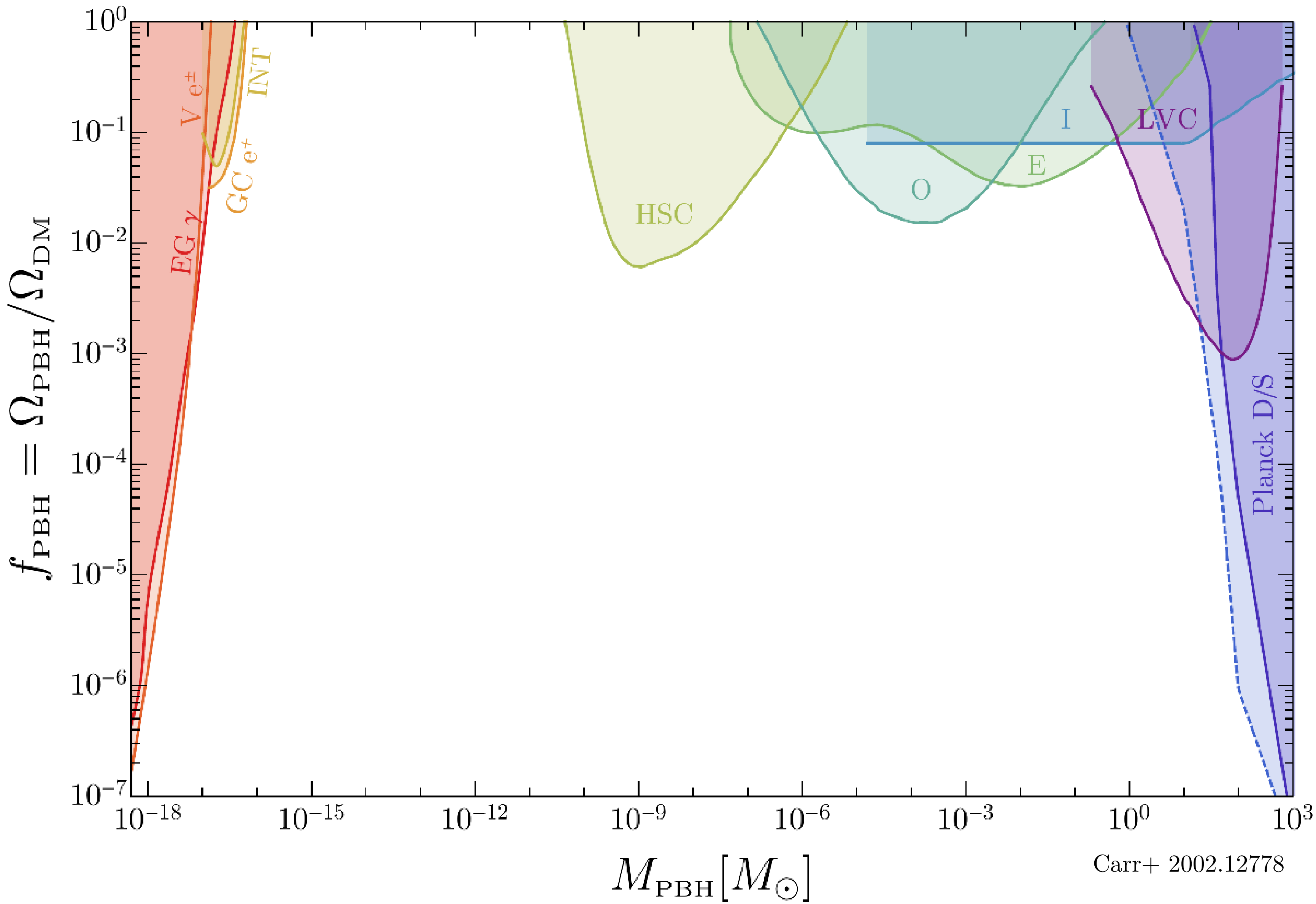
Will focus on PBHs from collapse of large overdensities in radiation domination, but also attempt to identify universal features

Recent review by LISA Cosmo WG: **2310.19857**

Constraints on PBHs as DM



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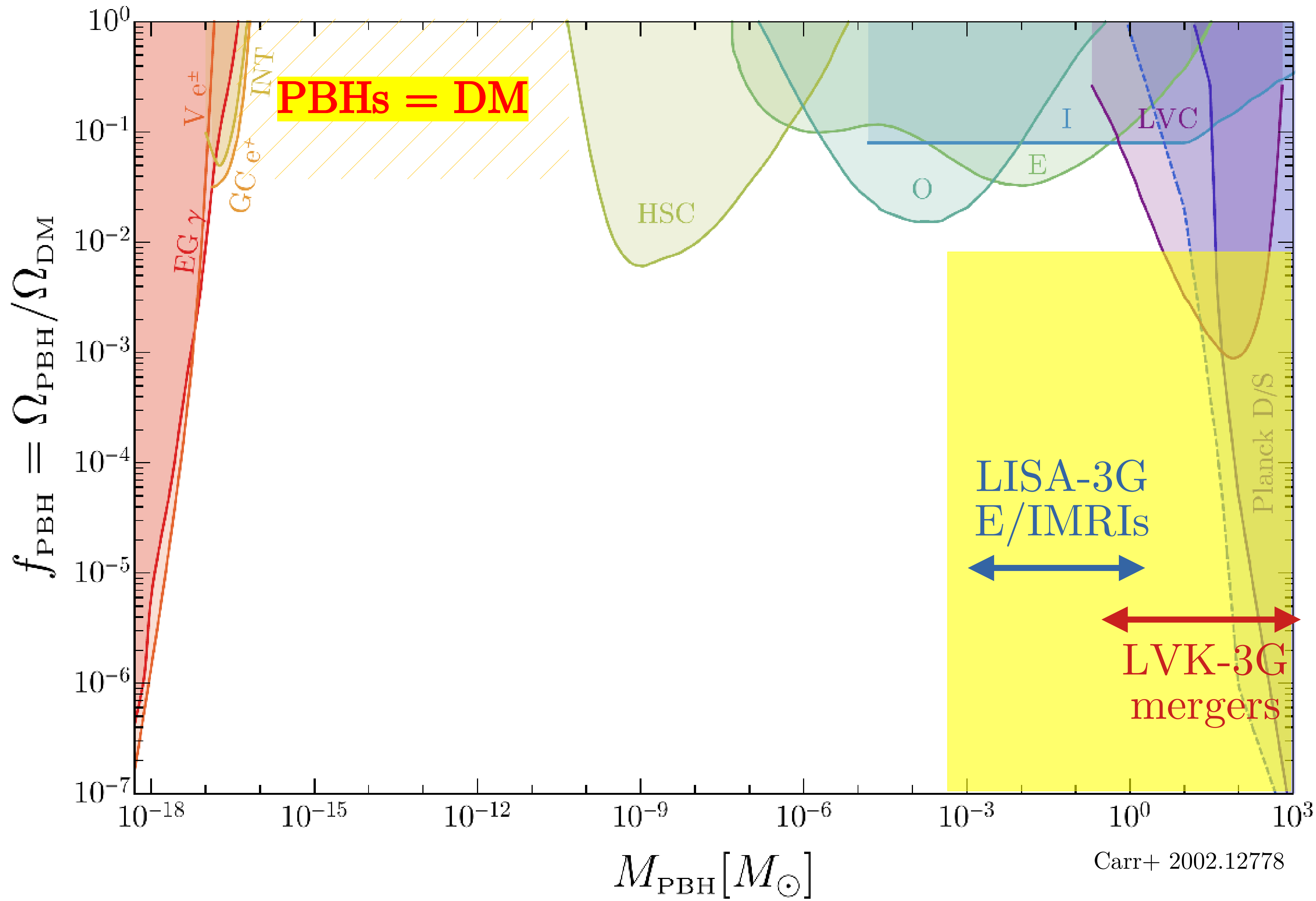
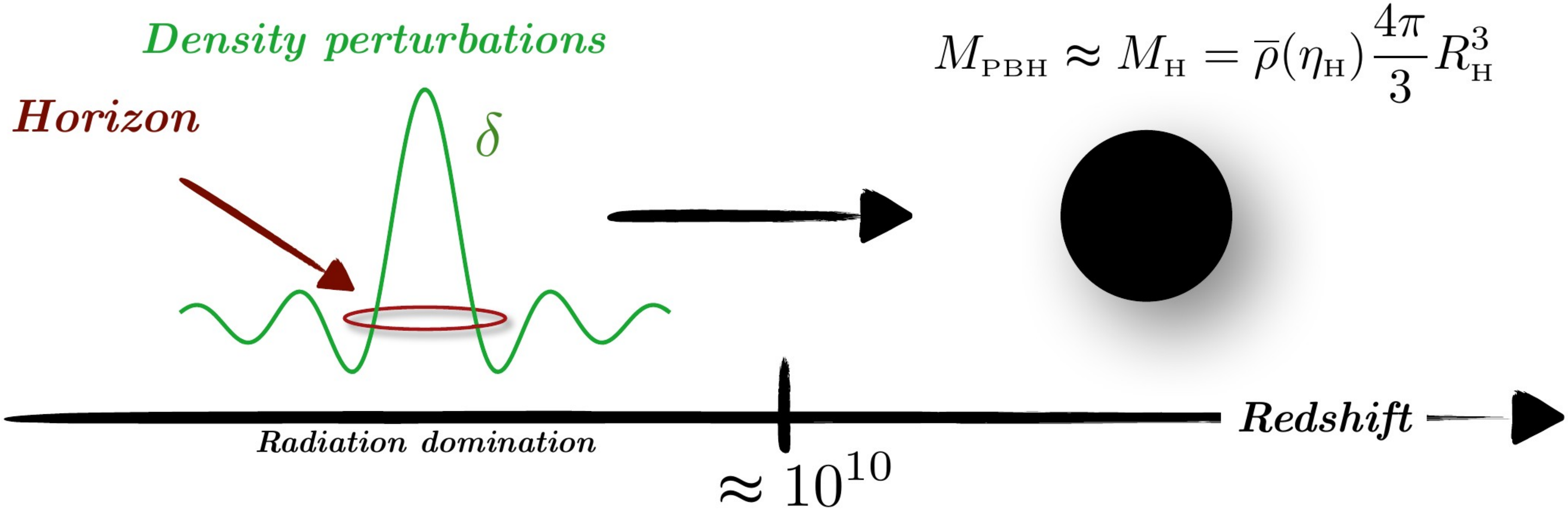
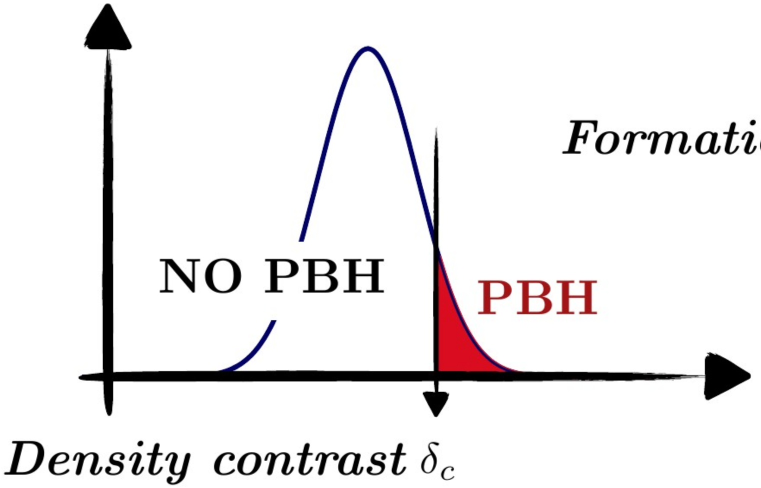


PBH formation

Credits: G. Franciolini

$$M_{\rm PBH} \approx M_{\rm H} = \bar{\rho}(\eta_{\rm H}) \frac{4\pi}{3} R_{\rm H}^3$$





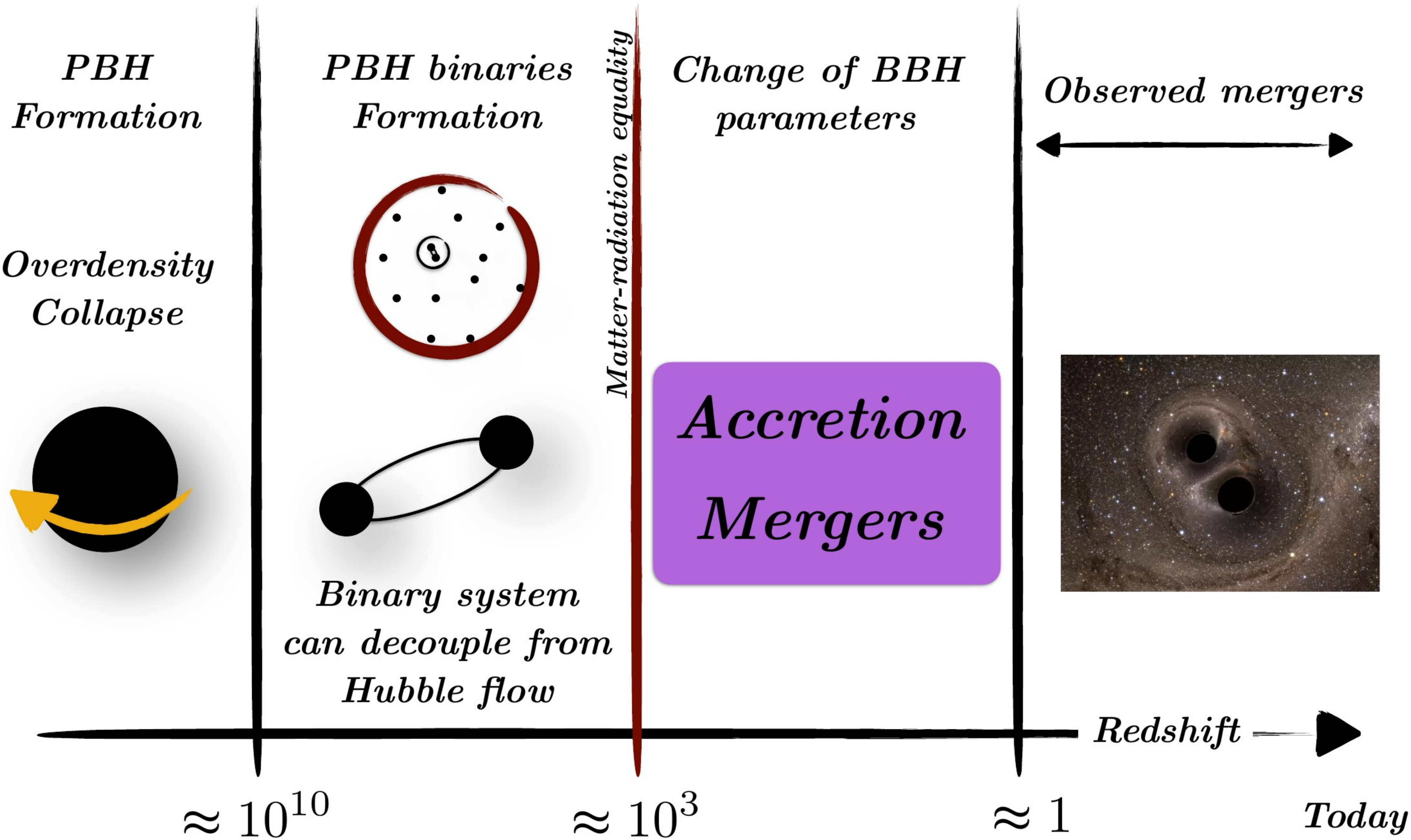
Formation criterion for horizon-crossing perturbations:

$$\delta \geq \delta_c \; (\approx 0.5)$$

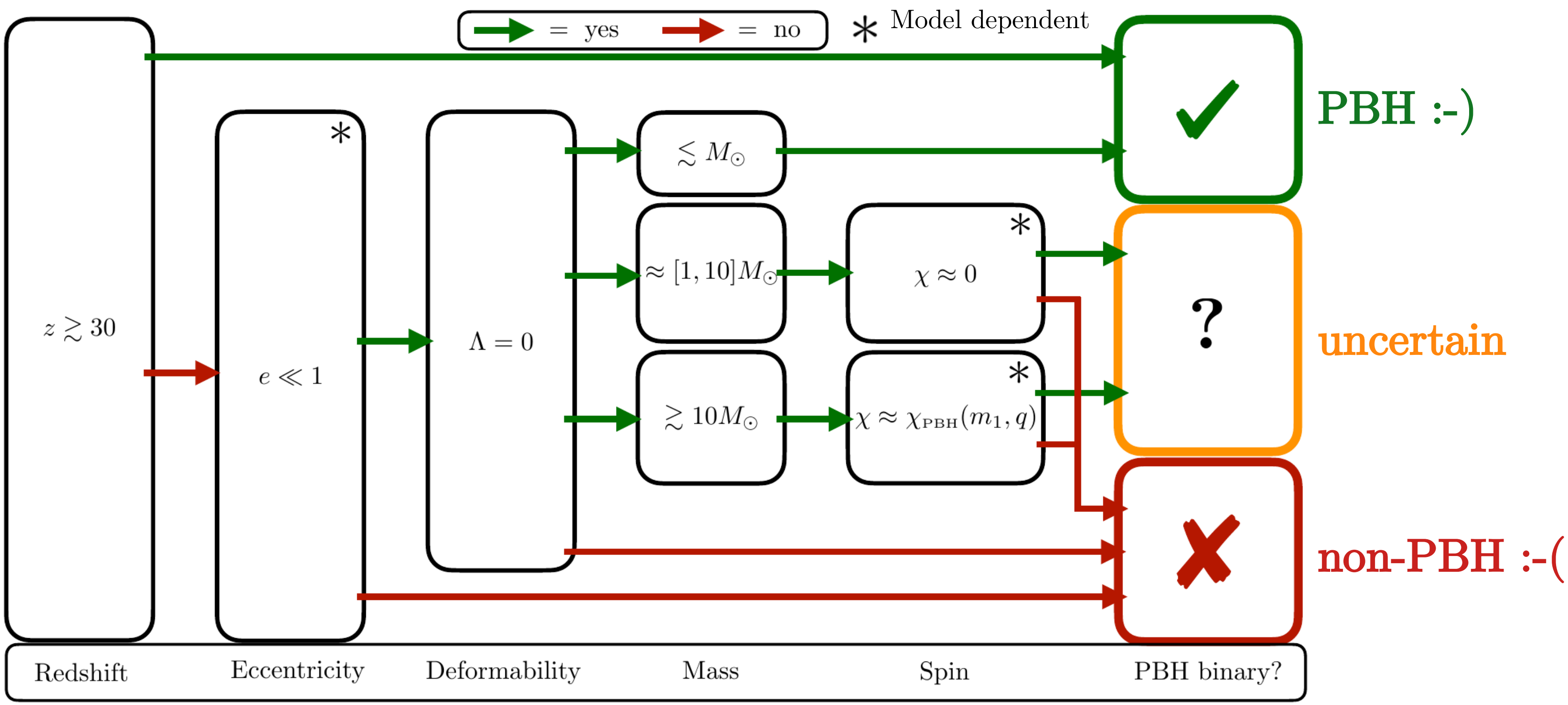
Shibata+ (1999), Musco (2018), ...

PBH merger timeline

Credits: G. Franciolini



Key predictions for PBHs

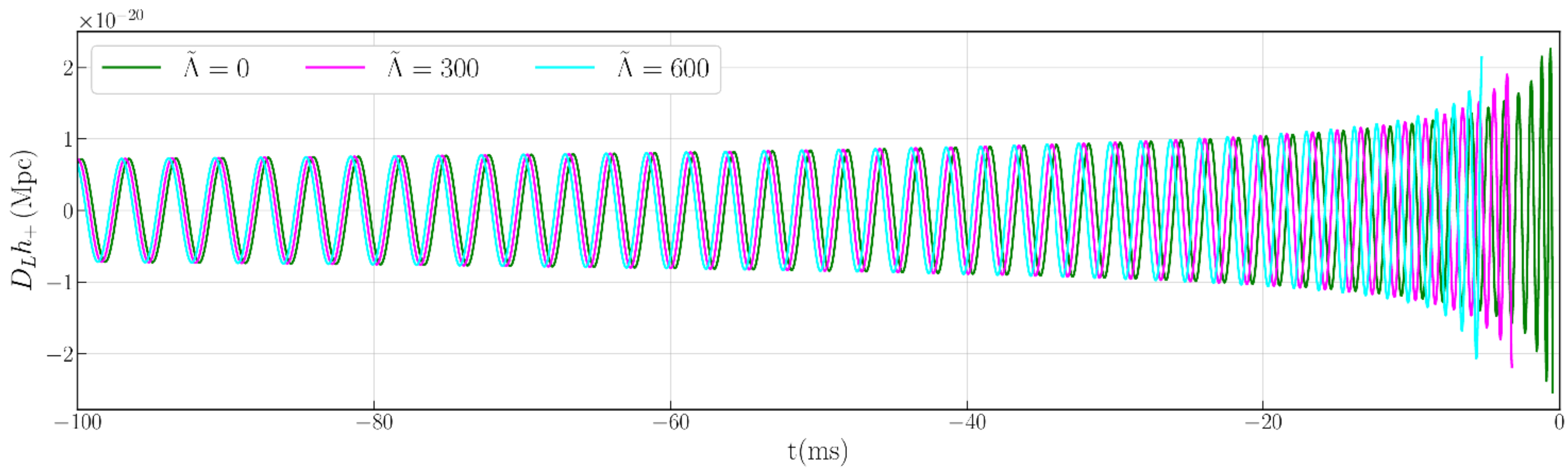


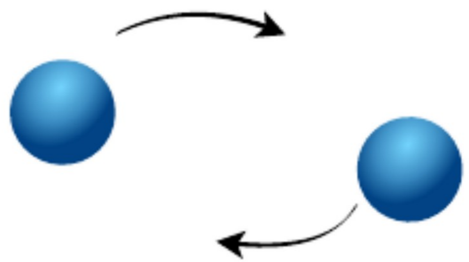
Franciolini, Loutrel, Cotesta, Berti, PP, Riotto PRD 2022

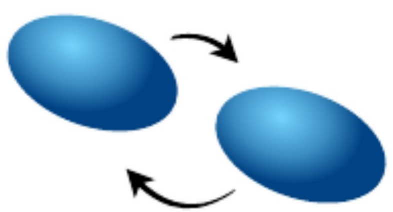
- **Redshift:** merger rates grows with z, only channel to predict mergers at z>30
[Nakamura+ 2016; Koushiappas-Loeb 2017]
- **Eccentricity:** binary formed highly eccentric, ~e=0 in the LIGO/Virgo band
- **Tidal:** all BHs (in vacuum GR) have zero Love numbers
- **Masses:** no mass gaps, no Chandra limit
- **Spins:** zero at formation in many scenarios; accretion? Mass-spin relation?

+ many cross correlations!

Extracting info from GW signals







Point masses
+ spins (1.5PN)
+ distance

... eccentricity,
precession...

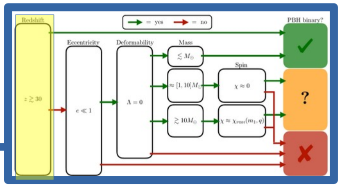
Tidal deformability
(5PN)

$$\tilde{h}(f) = \mathcal{A}(f) e^{i(\psi_{\rm PP} + \psi_{\rm TH} + \psi_{\rm TD})}$$

$$1\text{PN} = \frac{v^2}{c^2}$$

Blanchet, Living Rev. Relativity 17, 2 (2014)

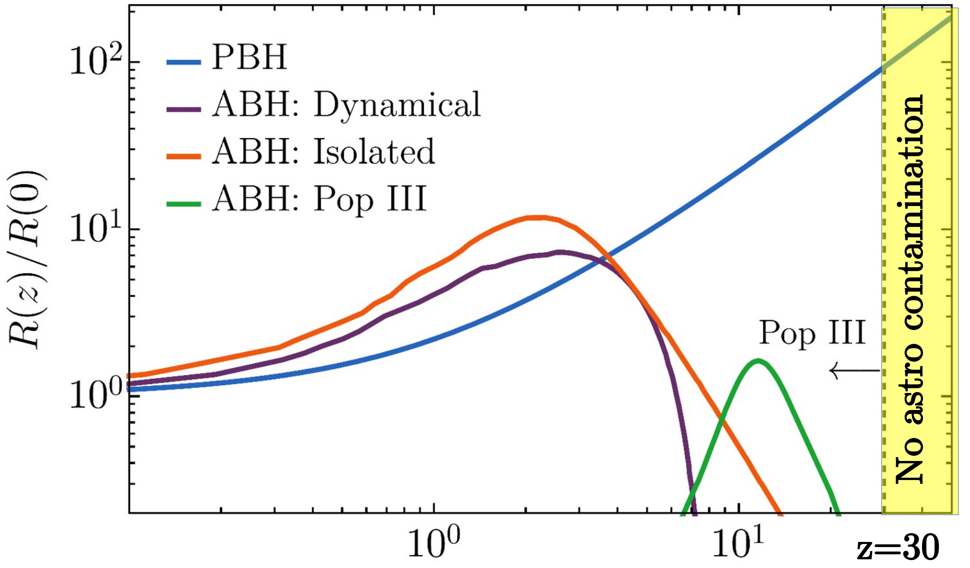
High redshift events?



- Events at z>O(10) → Pop III or PBHs

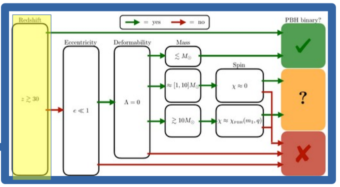
$$\dot{n}_{\rm PBH} \propto \left(\frac{t(z)}{t_0}\right)^{-34/37}$$

[Raidal+ 2018]



- How *accurately* can we measure high z? (requires 3G)

High redshift events?



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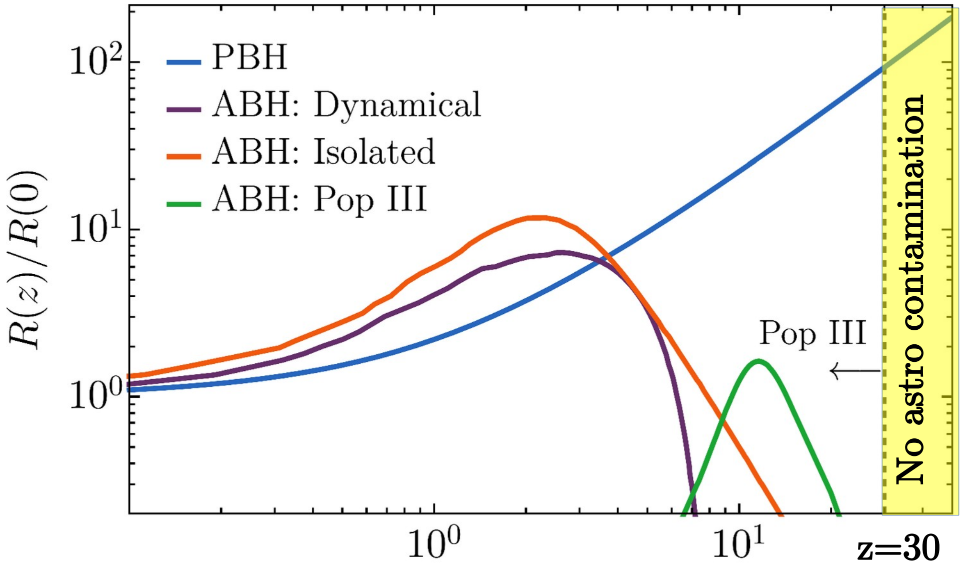
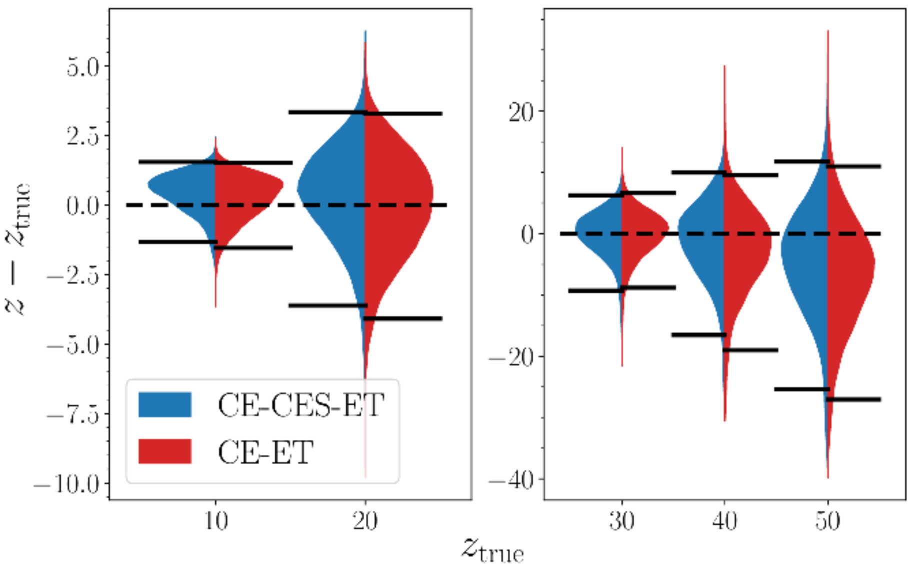
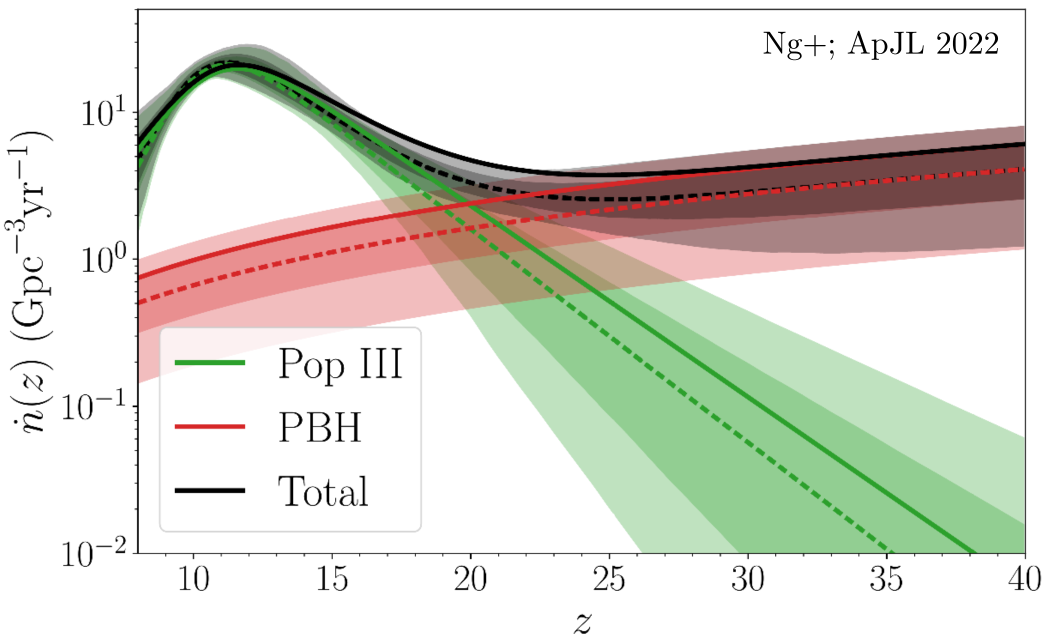


Ng+ ApJL 931 (2022)

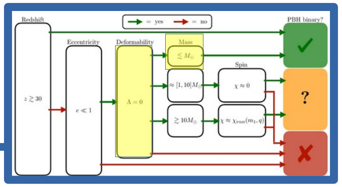




Careful with *systematics* at high z and with *higher-order* modes!

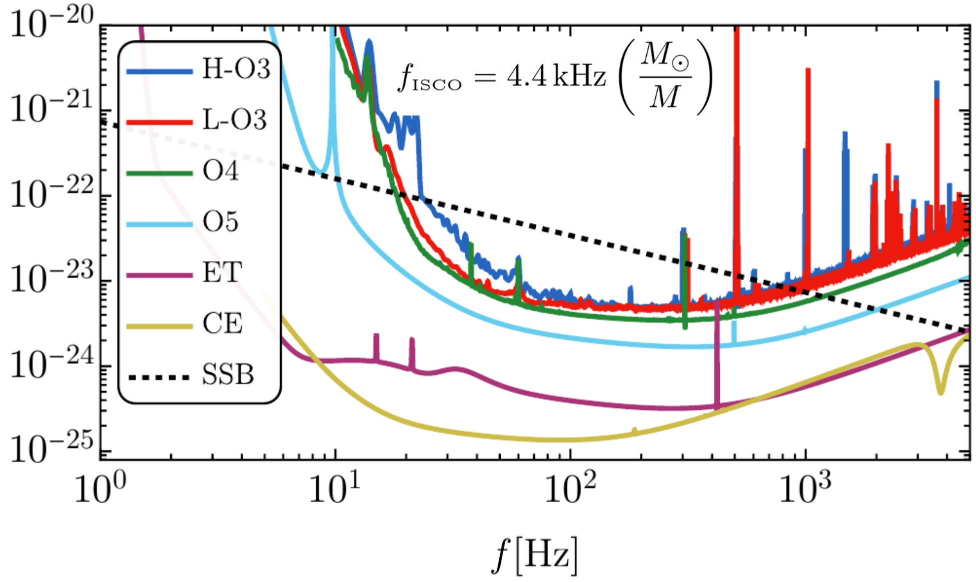
Ng+ PRD 2023

Subsolar PBHs or else?



Crescimbeni, Franciolini, Pani, Riotto, PRD 2024
Golomb+ 2403.07697

- Subsolar mass (SSM): possible confusion with NSs or exotic objects?
- Only BHs: i) never get tidally disrupted, ii) have zero Love number
- Common lore: only early inspiral detectable in LVK $\rightarrow$ tidal effects negligible



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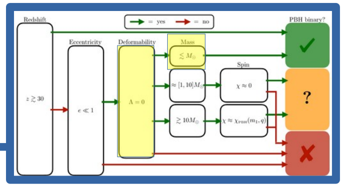

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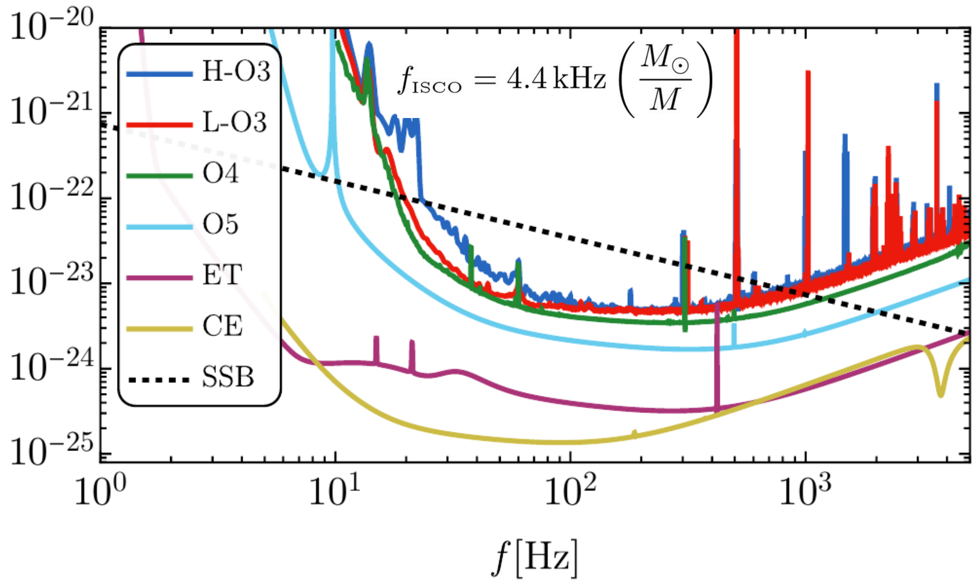
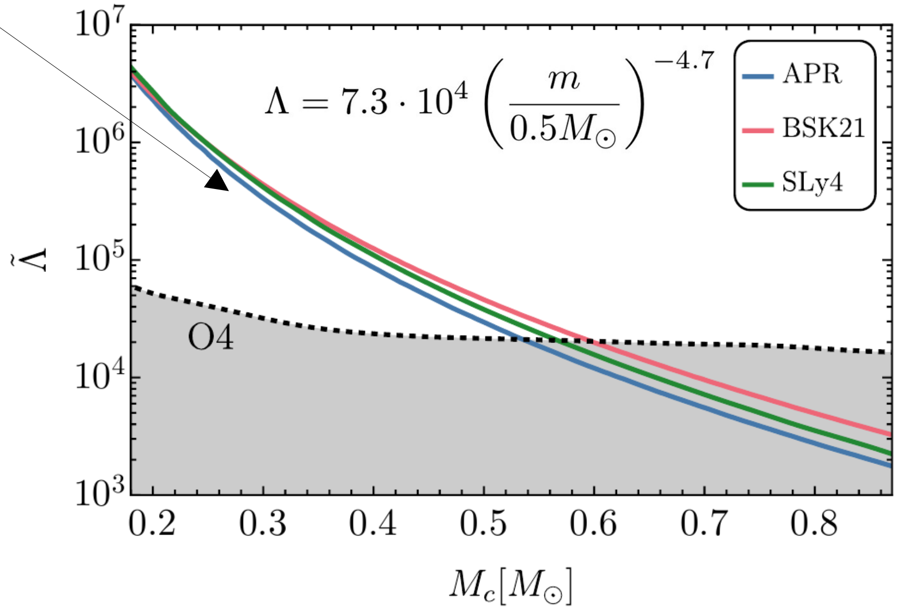
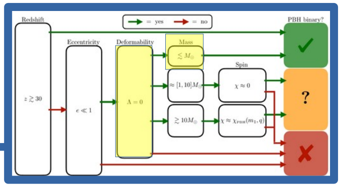
- Subsolar mass (SSM): possible confusion with NSs or exotic objects?
- Only BHs: i) never get tidally disrupted, ii) have zero Love number
- Common lore: only early inspiral detectable in LVK → tidal effects negligible
- However: SSM NSs have huge tidal deformability





Mass & tidal deformability measurements
can allow identification of putative SSM binaries

Subsolar PBHs or else?



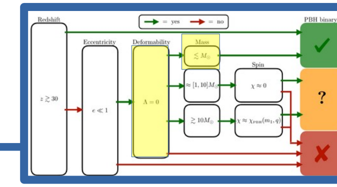
Crescimbeni, Franciolini, Pani, Riotto, PRD 2024

- TaylorF2 waveform + tidal deformability + tidal disruption

$$\psi(x) = \psi_{\rm pp}(x) + \delta\psi_{\rm tidal}(x)$$

$$\delta\psi_{\rm tidal} = \frac{3}{128\eta x^{5/2}}\left[\left(-\frac{39}{2}\tilde{\Lambda}\right)x^5 + \left(-\frac{3115}{64}\tilde{\Lambda} + \frac{6595}{364}\sqrt{1-4\eta}\,\delta\tilde{\Lambda}\right)x^6\right]$$

Subsolar PBHs or else?



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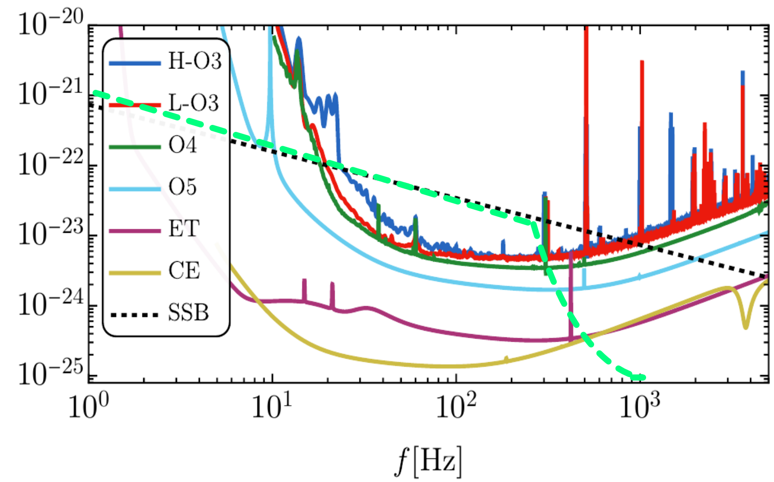
$$f_{\rm max}^{\rm NS} \approx 1.4\,{\rm kHz}\left(\frac{m_{\rm NS}}{0.5 M_\odot}\right)^{1/2}\left(\frac{15\,{\rm km}}{r_{\rm NS}}\right)^{3/2} < f_{\rm ISCO}$$

$$\tilde{h}(f) = A\, f^{-7/6}\left[\frac{1+e^{-\tilde{\lambda}_f/\delta\tilde{\lambda}_f}}{1+e^{(f/f_{\rm ISCO}-\tilde{\lambda}_f)/\delta\tilde{\lambda}_f}}\right]\exp\left[i\psi(f)\right]$$

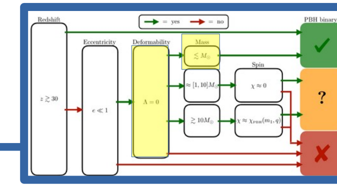


Waveform parameters

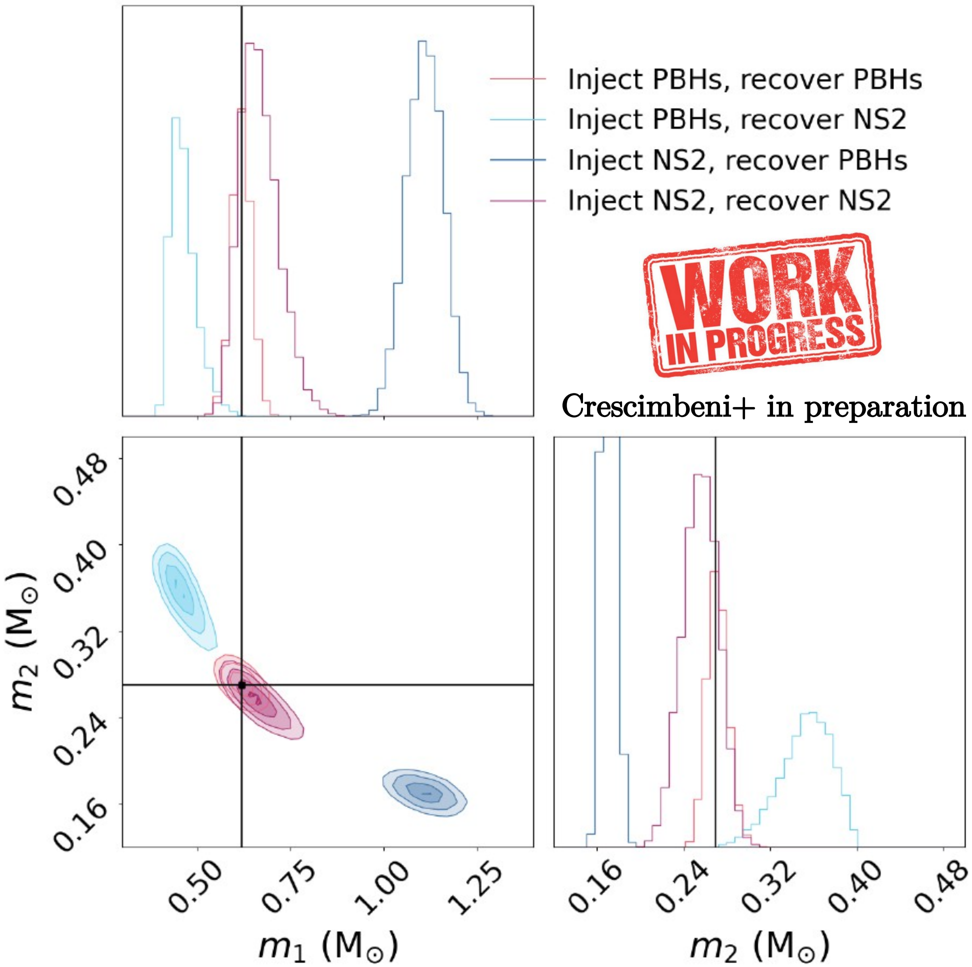
$$\boldsymbol{\theta} = \{m_1, m_2, d_L, \theta, \phi, \iota, \psi, t_c, \Phi_c, \chi_1, \chi_2\}$$

$$\boldsymbol{\theta}_T = \{\tilde{\Lambda}, \delta\tilde{\Lambda}, \tilde{\lambda}_f, \delta\tilde{\lambda}_f\}$$

Subsolar PBHs or else?



Crescimbeni, Franciolini, Pani, Riotto, PRD 2024



Crescimbeni+ in preparation

Injections+recovery Bayes Factors		
Detectors	BH2 → NS2	NS2 → BH2
O3	-0.1	1.5
O4	-3.5	-10.0

Network	LVK O3	LVK O4	LVK O5	ET+2CE
BNS SSM200308 ($\tilde{\Lambda} = 1.5 \cdot 10^5, \delta\tilde{\Lambda} = 4.9 \cdot 10^4, \tilde{\lambda}_f = 0.36$)				
SNR	7.90	12.8	22.4	398
$\Delta m_1/m_1$	0.47	0.22	0.082	0.0017
$\Delta m_2/m_2$	0.39	0.19	0.070	0.0015
$\Delta\tilde{\Lambda}/\tilde{\Lambda}$	0.86	0.66	0.55	0.047
$\Delta\tilde{\lambda}_f/\tilde{\lambda}_f$	0.38	0.24	0.13	0.015
BPBH SSM200308 ($\tilde{\Lambda} = \delta\tilde{\Lambda} = 0, \tilde{\lambda}_f = 1$)				
SNR	8.38	13.4	23.9	403
$\Delta m_1/m_1$	0.20	0.13	0.044	$6.6 \cdot 10^{-3}$
$\Delta m_2/m_2$	0.17	0.11	0.037	$5.6 \cdot 10^{-3}$
$\Delta\tilde{\Lambda}$	$9.1 \cdot 10^3$	$5.8 \cdot 10^3$	$3.0 \cdot 10^3$	$7.5 \cdot 10^2$

TABLE I: Fisher parameter estimation uncertainties with current and future GW experiments. We inject a system with similar properties to the sub-threshold event SSM200308 with $m_1 = 0.62 M_\odot$ and $m_2 = 0.27 M_\odot$, assuming the object was either a BNS (top rows) or a BPBH (bottom rows).

- Well measured masses
- Disruption better than deformability
- Constraining power already in O4!

Population studies

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

Lognormal mass function, 2 hyperparameters + $f_{\rm PBH}$ and $z_{\rm cuf\text{-}off}$

Searching for a subpopulation of primordial black holes in LIGO/Virgo gravitational-wave data

Gabriele Franciolini,[1,2,*] Vishal Baibhav,[3] Valerio De Luca,[1,2] Ken K. Y. Ng,[4,5] Kaze W. K. Wong,[3] Emanuele Berti,[3] Paolo Pani,[2,6] Antonio Riotto,[1] and Salvatore Vitale[4,5]

[1] *Département de Physique Théorique and Centre for Astroparticle Physics (CAP), Université de Genève, 24 quai E. Ansermet, CH-1211 Geneva, Switzerland*
[2] *Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, 00185, Roma, Italy*
[3] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA*
[4] *LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
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[6] *INFN, Sezione di Roma, Piazzale Aldo Moro 2, 00185, Roma, Italy,*

Hall, Gow, Byrnes, PRD 2020
Hutsi+, JCAP 2021
De Luca+ JCAP 2021
Franciolini+ PRD 2022
Chen, Yuan, Huang, PLB 2022
+ many more....

PBH merger rate

- PBHs formed at high z with small natal spin and not clustered
- Gravitational decoupling from Hubble flow before matter-radiation equality

[Nakamura+ ApJL 1997; Ioka+ PRD 1998]

$$\frac{d\mathcal{R}_{\rm PBH}}{dm_1 m_2} = \frac{1.6\times 10^6}{\rm Gpc^3\, yr} f_{\rm PBH}^{\frac{53}{37}} \left(\frac{t(z)}{t_0}\right)^{-\frac{34}{37}} \eta^{-\frac{34}{37}} \left(\frac{M}{M_\odot}\right)^{-\frac{32}{37}} S_{\rm early}(M,f,\psi) S_{\rm late}(f,z)\psi(m_1)\psi(m_2)$$

suppression factors

Ali-Haimoud, Kovetz, Kamionkowski, PRD 2017
Raidal+ JCAP 2018
De Luca+ JCAP 2020

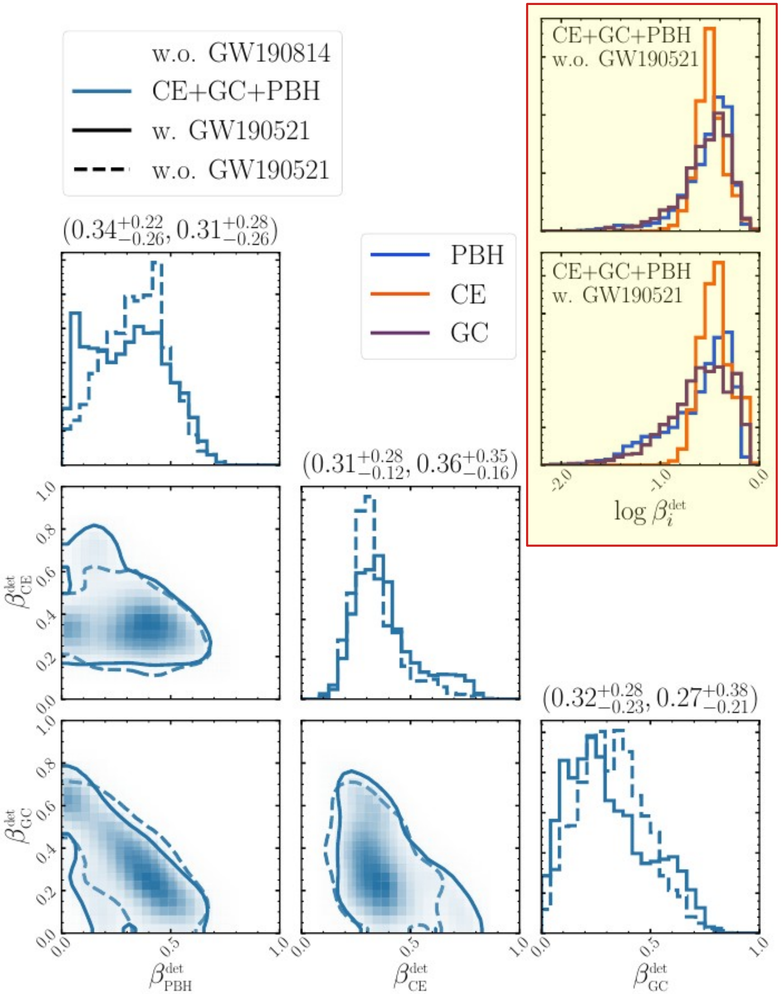
- Suppression due to:
  - **Early:** PBH and dark-matter perturbations surrounding binaries
  - **Late:** multiple PBH encounters in small clusters

(negligible if $f_{\rm PBH}<O(1e\text{-}3)$), in agreement with N-body simulations [Inman-Ali-Haïmoud, PRD 2019])

Quantifying the evidence for PBHs in GWTC-X

- Astro models from Zevin+ ApJ 2021
- Bayesian inference on hyperpar & fractions

[Franciolini+ PRD 2022]



$\log_{10} \mathcal{B}^{\mathcal{M}}_{\rm CE+GC}$	CE+GC+PBH
w.o. GW190521	1.22
w. GW190521	2.38

Quantifying the evidence for PBHs in GWTC-X

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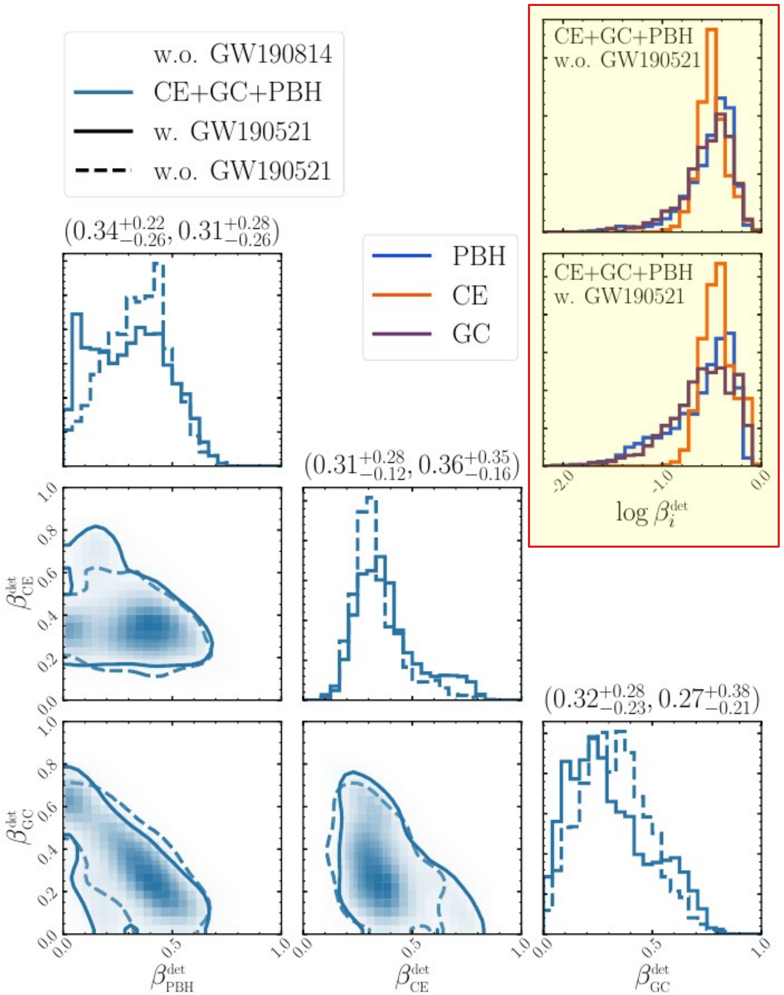
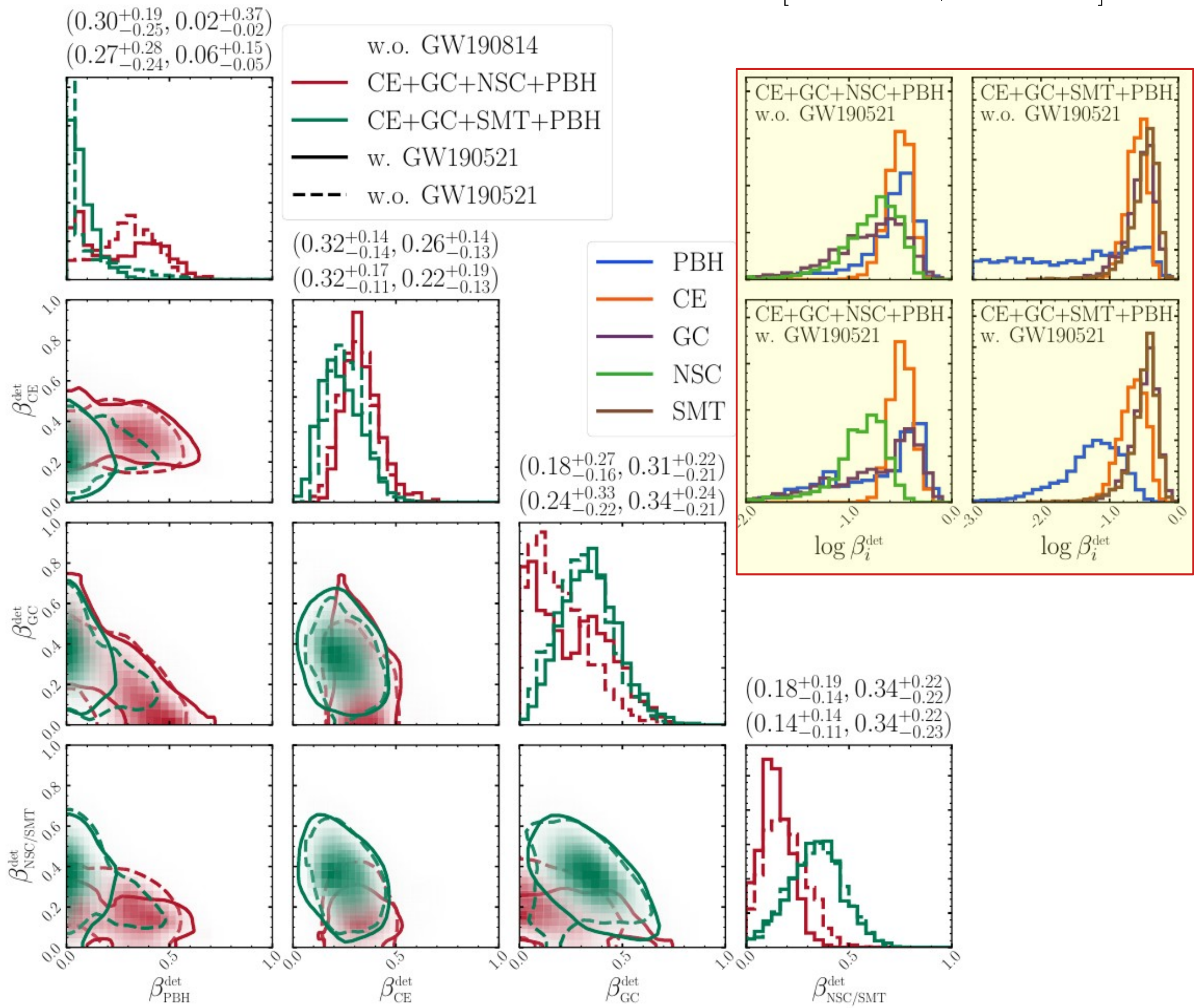
[Franciolini+ PRD 2022]

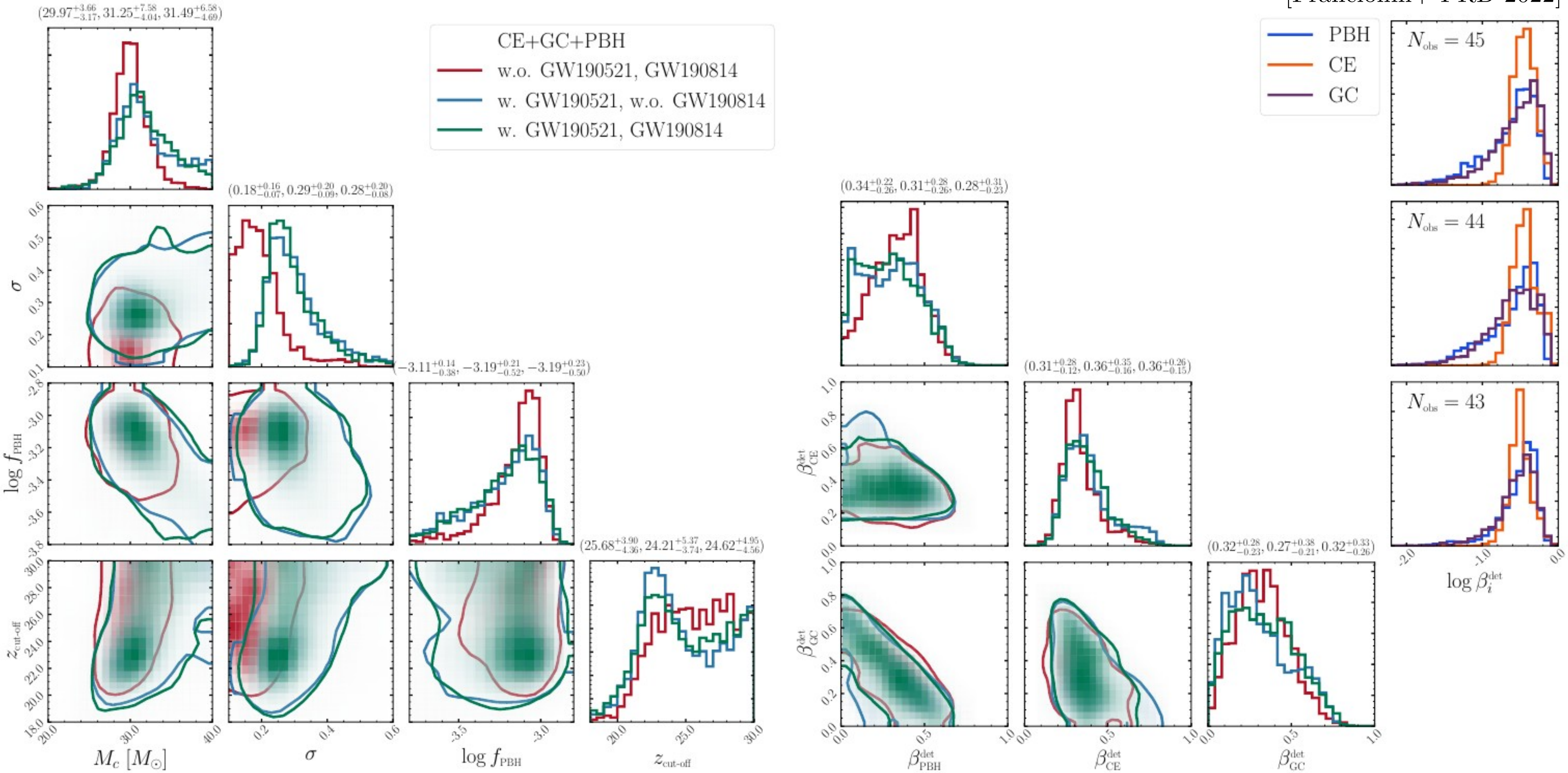




$\log_{10} \mathcal{B}^{\mathcal{M}}_{\rm CE+GC}$	CE+GC+PBH	CE+GC+NSC	CE+GC+SMT	CE+GC+NSC+PBH	CE+GC+SMT+PBH
w.o. GW190521	1.22	0.52	1.39	1.43	1.31
w. GW190521	2.38	-0.15	0.72	2.30	2.58

Quantifying the evidence for PBHs in GWTC-X

[Franciolini+ PRD 2022]



- Most conservative view: data explained by <u>at least 3 different channels</u>
- PBH statistically favored against competitive channels (eg. GC, NSC), **f_{PBH}~$10^{-3.5}$**
- Neglecting GW190521, the constraining power of current catalogs is insufficient
- To avoid PBHs, SMT should be the dominant channel (~34%)!

Population studies #2

An ab-initio model across the QCD epoch

From inflation to black hole mergers and back again: Gravitational-wave data-driven constraints on inflationary scenarios with a first-principle model of primordial black holes across the QCD epoch

Gabriele Franciolini,[1,2] Ilia Musco,[2] Paolo Pani,[1,2] and Alfredo Urbano[1,2]

[1] *Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, 00185, Roma, Italy*
[2] *INFN, Sezione di Roma, Piazzale Aldo Moro 2, 00185, Roma, Italy*

PRD106 (2022) 12, 123526

Nearly scale-invariant power spectrum (with 4 hyperparams)

$$\mathcal{P}_\zeta(k) = A\left(\frac{k}{k_{\rm min}}\right)^{n_s-1}\Theta(k-k_{\rm min})\Theta(k_{\rm max}-k).$$

→ PBH mass function

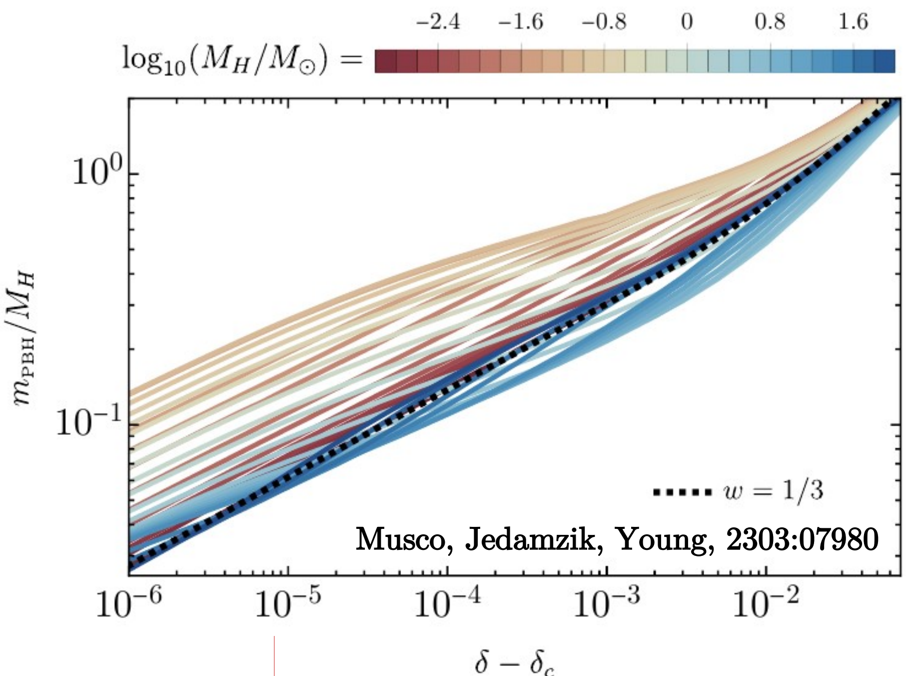
$$\psi(m_{\rm PBH})$$

Critical collapse & QCD phase

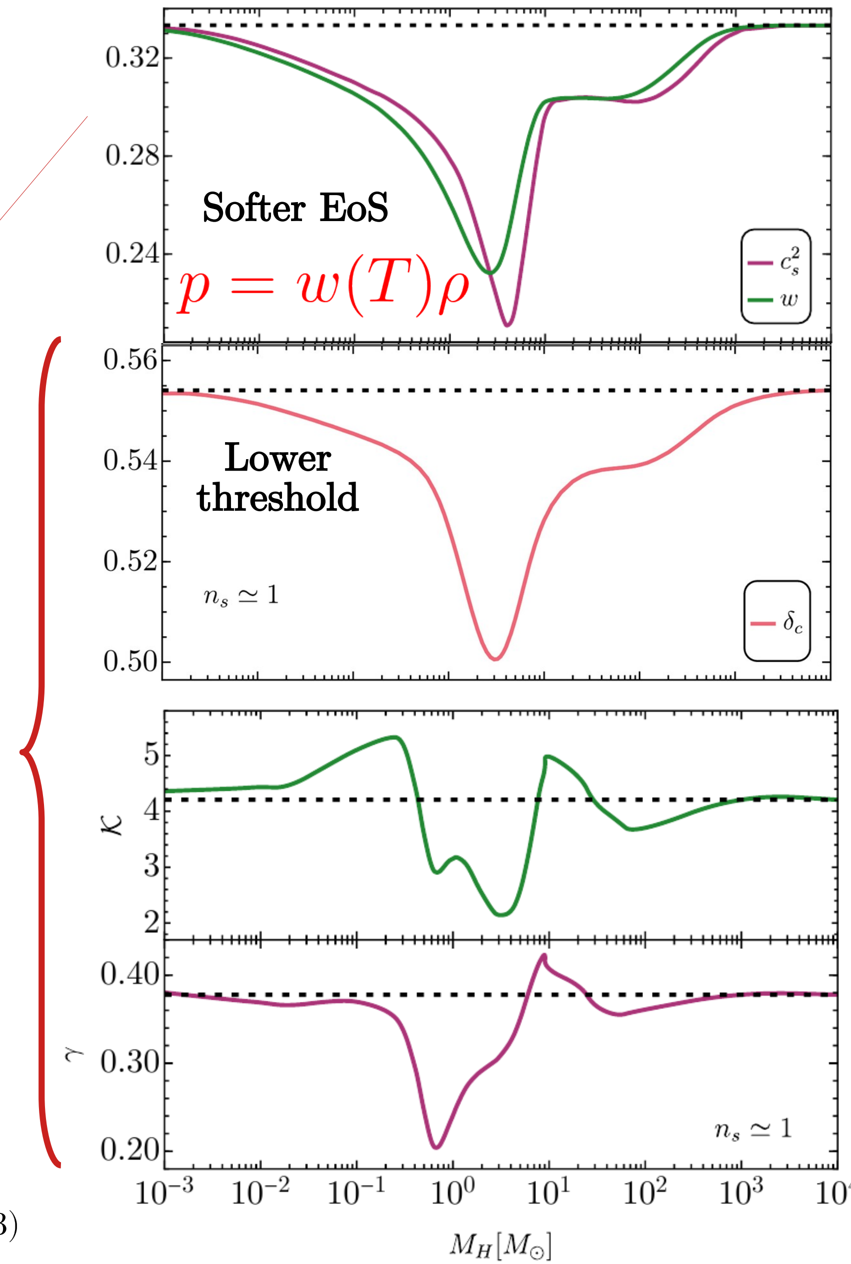
Jedamzik, Phys. Rept. 1998; Jedamzik-Niemeyer, PRD 1999; Byrnes+ JCAP 2018; Carr+ Phys. Dark Univ. (2021); Jedamzik PRL 2021

$$K(r) = \mathcal{A} \exp\left[-\frac{1}{\alpha}\left(\frac{r}{r_m}\right)^{2\alpha}\right]$$

Curvature initial perturbation



$$m_{\rm PBH}(\delta) = \mathcal{K} M_H (\delta - \delta_c)^\gamma$$



Details on simulations:
Musco, Jedamzik, Young, 2303:07980 (see also Escrivà-Bagui-Clesse JCAP 2023)

Role of the power spectrum

Young, Musco, Byrnes, JCAP 2021

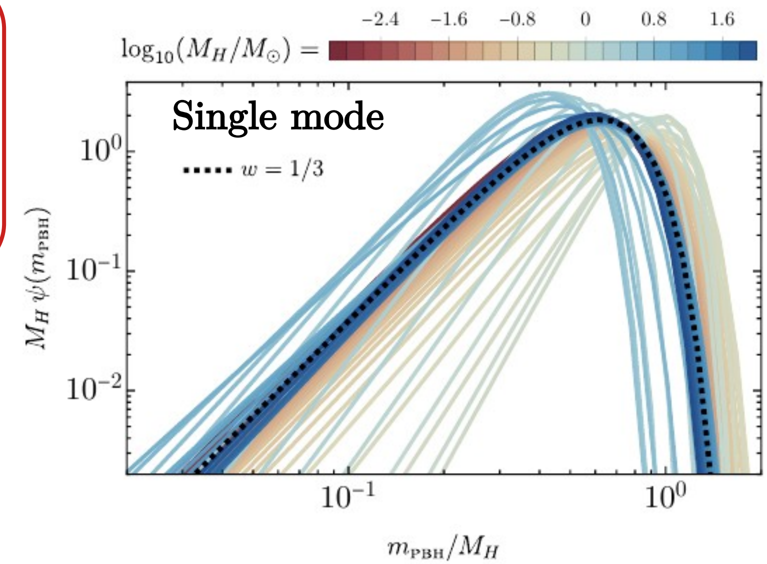
Nearly scale-invariant power spectrum (with 4 hyperparams)

$$\mathcal{P}_\zeta(k) = A\left(\frac{k}{k_{\rm min}}\right)^{n_s-1}\Theta(k-k_{\rm min})\Theta(k_{\rm max}-k).$$

Threshold for critical collapse

$$\beta(M_H) \approx \exp\left[-\frac{\delta_c^2(M_H)}{2\sigma_\delta^2(M_H)}\right]$$

Variance of density perturbations



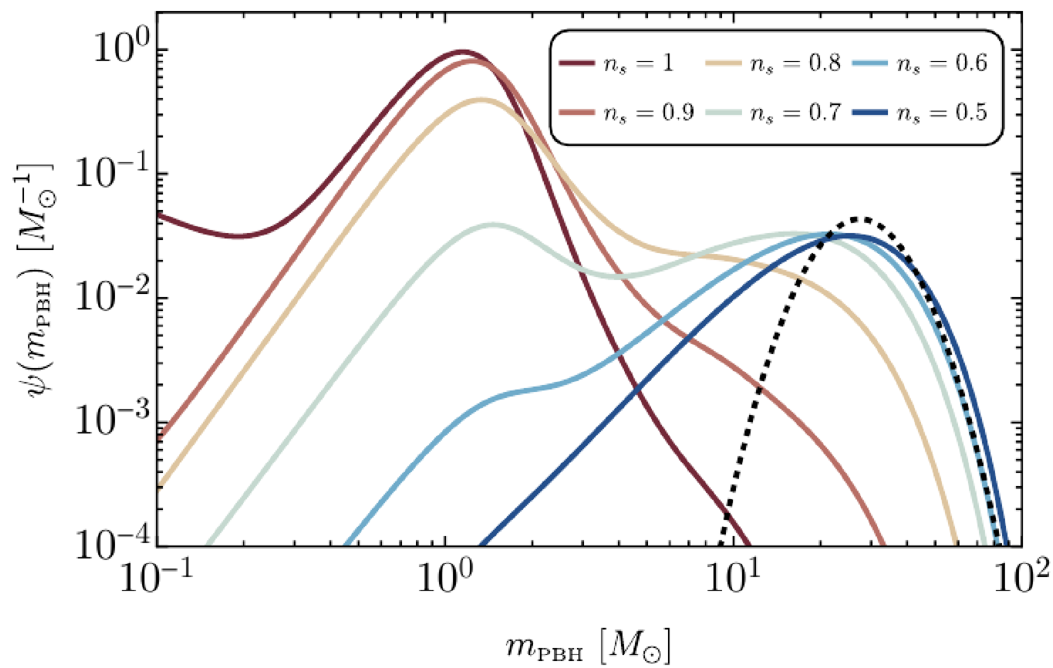
Total energy fraction in PBHs:

$$\Omega_{\rm PBH} = \int_{M_{\rm S}}^{M_{\rm L}} {\rm d}\ln M_H \left(\frac{M_{\rm eq}}{M_H}\right)^{1/2}\beta(M_H)$$

Mass function:

$$\psi(m_{\rm PBH}) = \frac{1}{\Omega_{\rm PBH}}\frac{{\rm d}\Omega_{\rm PBH}}{{\rm d}m_{\rm PBH}}$$

Full mass function (convolution)



Role of the power spectrum

Young, Musco, Byrnes, JCAP 2021

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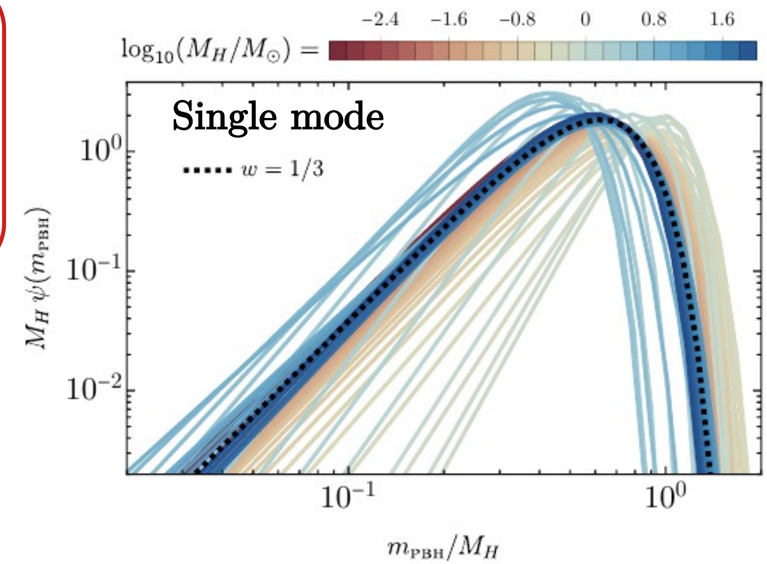
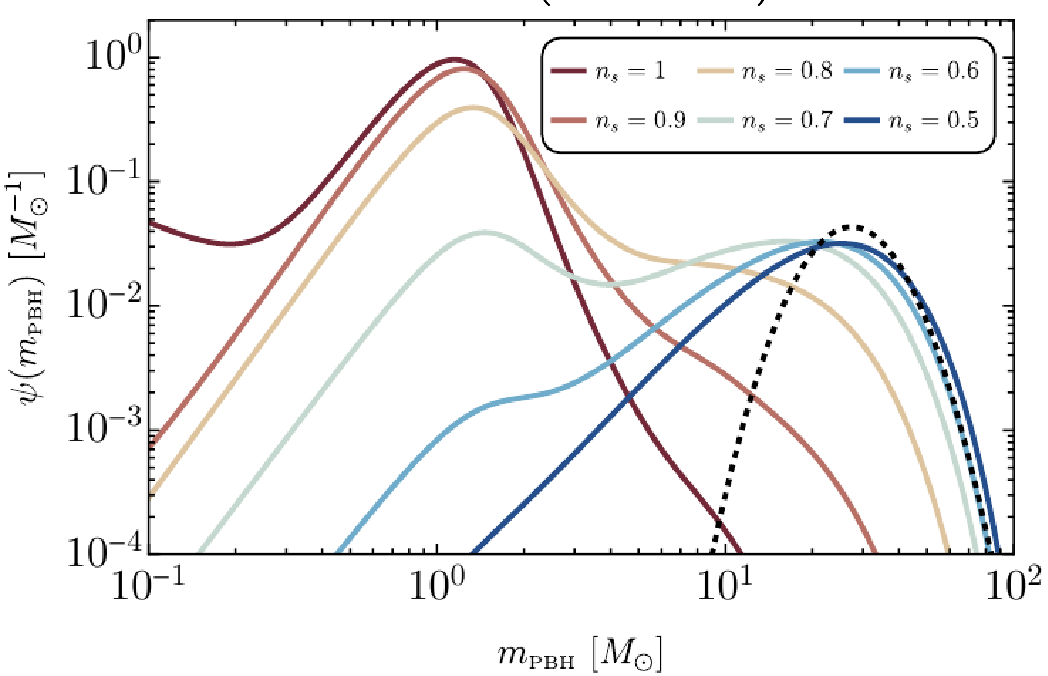


- Power spectrum is crucial!
- Strong dependence on tilt n_s
- QCD enhancement + shoulder
- More features than lognormal!

Full mass function (convolution)



Recipe: From inflation to GWTC-3

Franciolini+; 2209.05959

1. assume power spectrum

$$\mathcal{P}_\zeta(k) = A\left(\frac{k}{k_{\rm min}}\right)^{n_s-1}\Theta(k-k_{\rm min})\Theta(k_{\rm max}-k),$$

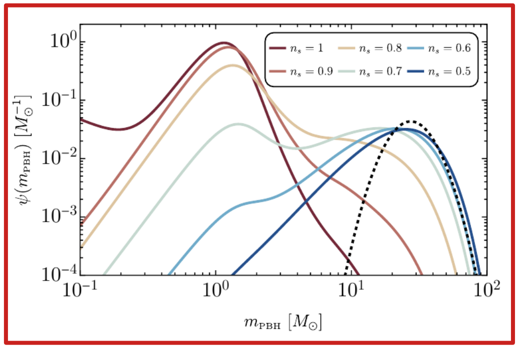
Recipe: From inflation to GWTC-3

Franciolini+; 2209.05959

1. assume power spectrum

$$\mathcal{P}_\zeta(k) = A\left(\frac{k}{k_{\rm min}}\right)^{n_s-1}\Theta(k-k_{\rm min})\Theta(k_{\rm max}-k),$$

2. compute PBH mass function across QCD phase



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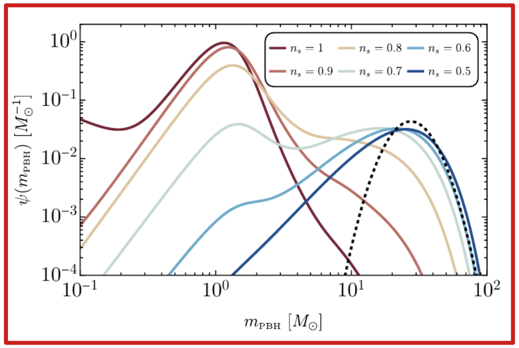

3. Merger rate

$$\frac{d\mathcal{R}_{\rm PBH}}{dm_1 m_2} = \frac{1.6\times10^6}{\rm Gpc^3\,yr} f_{\rm PBH}^{\frac{53}{37}}\left(\frac{t(z)}{t_0}\right)^{-\frac{34}{37}}\eta^{-\frac{34}{37}}\left(\frac{M}{M_\odot}\right)^{-\frac{32}{37}} S(M, f_{\rm PBH}, \psi)\psi(m_1)\psi(m_2)$$

Recipe: From inflation to GWTC-3

Franciolini+; 2209.05959

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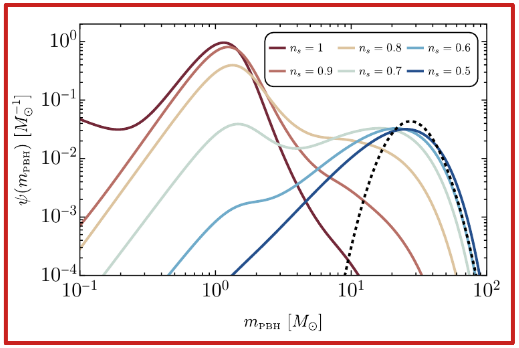

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4. Dataset of GW events (eg. GWTC-3) + intepretation models

Recipe: From inflation to GWTC-3

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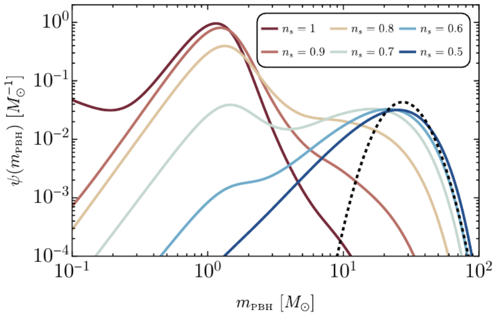

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4. Dataset of GW events (eg. GWTC-3) + intepretation models

5. Posterior distribution

$$\frac{p(\boldsymbol{\lambda}|\boldsymbol{d})}{\pi(\boldsymbol{\lambda})} \propto e^{-N_{\rm det}(\boldsymbol{\lambda})} N(\boldsymbol{\lambda})^{N_{\rm obs}} \prod_{i=1}^{N_{\rm obs}} \int {\rm d}\boldsymbol{\theta}_i \frac{p(\boldsymbol{\theta}_i|\boldsymbol{d}) p_{\rm pop}(\boldsymbol{\theta}_i|\boldsymbol{\lambda})}{\pi(\boldsymbol{\theta}_i)}$$

6. Multi-population Bayesian inference

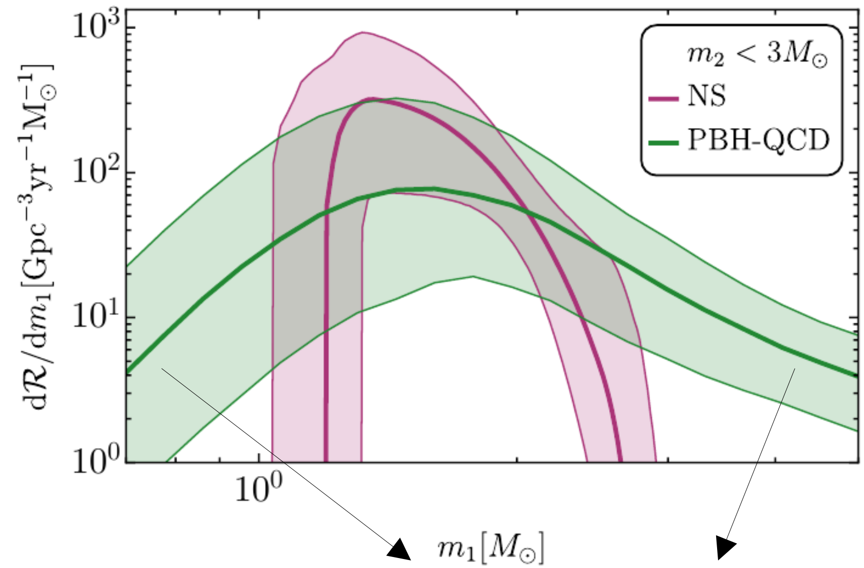
Let the data speak #1

Conservative approach:

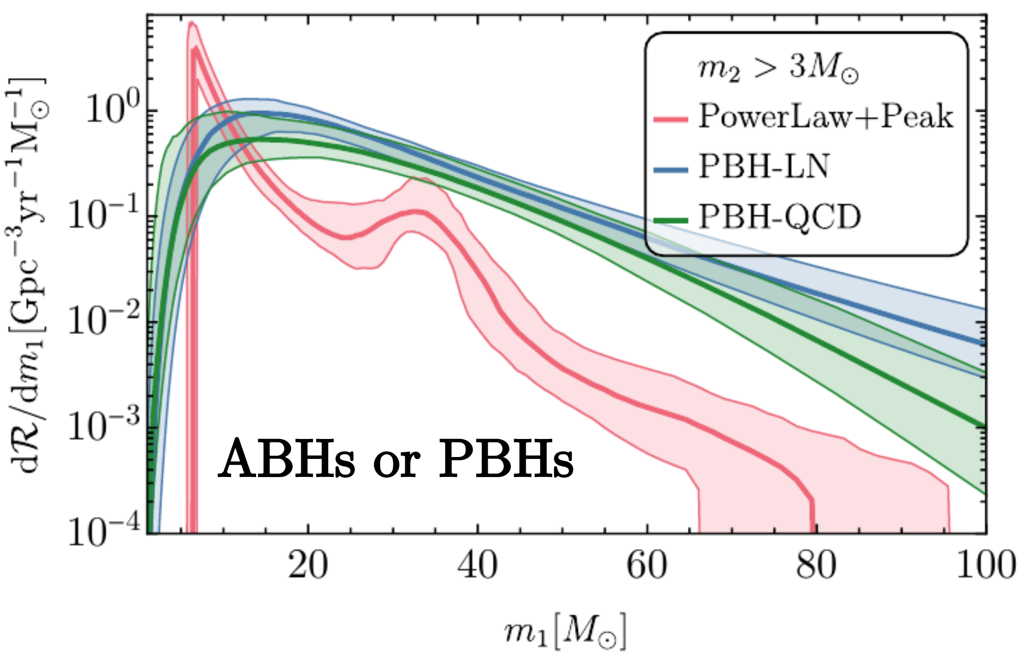
- LVK pheno BH/NS models (tuned to data!)
- + ab-initio PBH channel

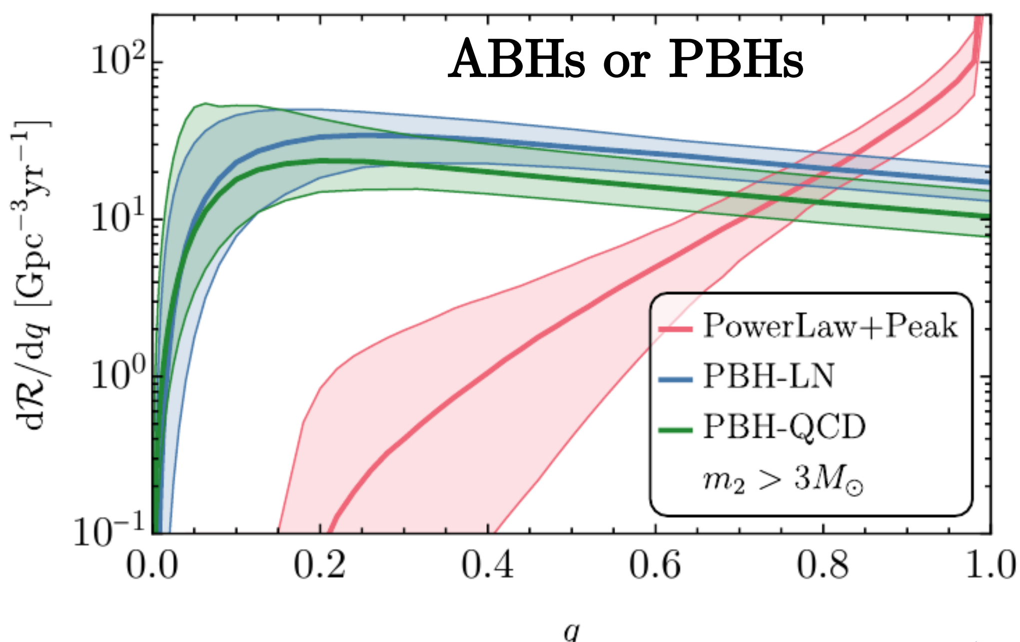
Model	PBH			
$\boldsymbol{\lambda}$	$\log_{10} f_{\rm PBH}$	n_s	$\log_{10} M_{\rm S}$	$\log_{10} M_{\rm L}$
Prior	$[-6, 0]$	$[0, 1.5]$	$[-2.5, \log_{10} M_{\rm L}]$	$[\log_{10} M_{\rm S}, 4]$
	Abundance	Tilt	Lightest mass	Heaviest mass

NSs or PBHs

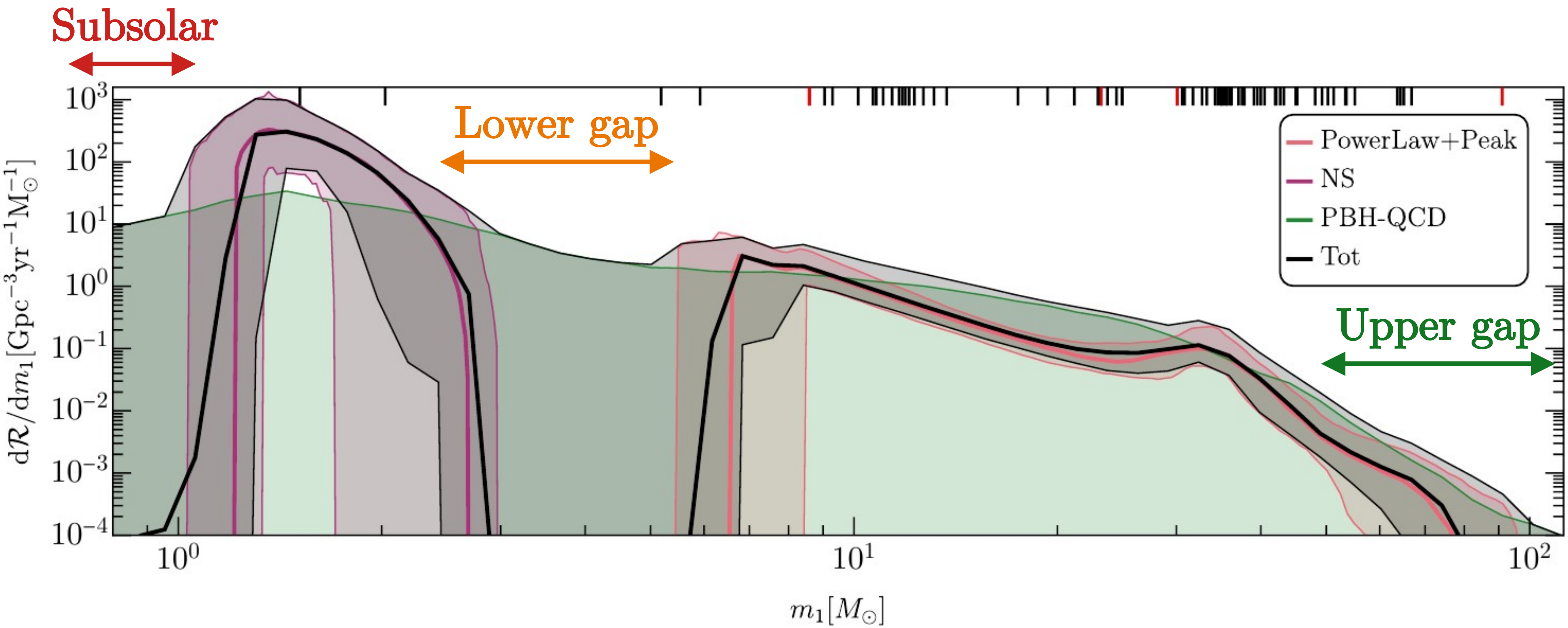


Support both for subsolar and lower gap





Let the data speak #2



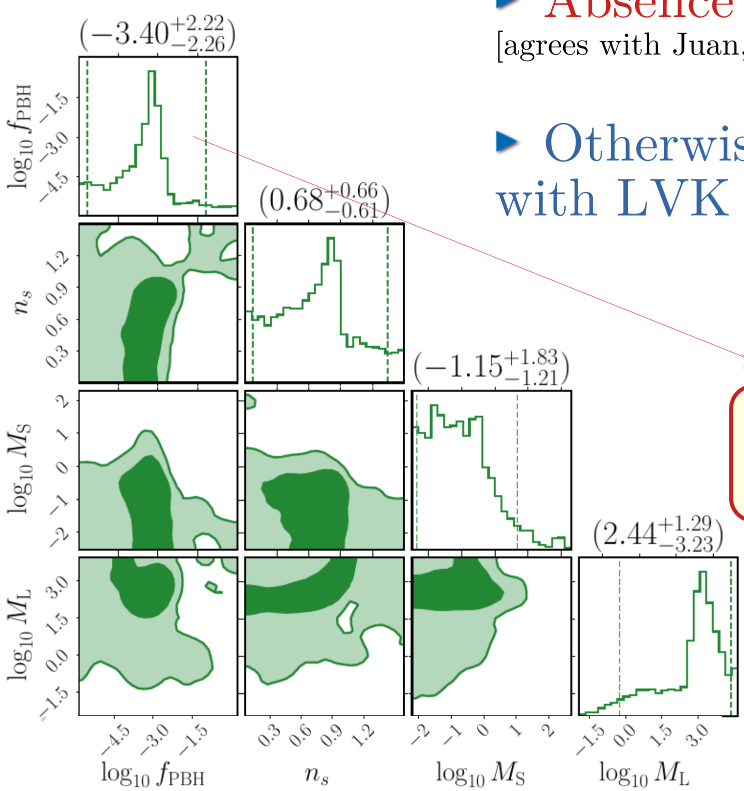
GW event	PBH prob. [%]	$m_1[M_\odot]$	$m_2[M_\odot]$
GW190412	25.4	$30.1^{+4.7}_{-5.1}$	$8.3^{+1.6}_{-0.9}$
GW190521	7.2	$95.3^{+28.7}_{-18.9}$	$69.0^{+22.7}_{-23.1}$
GW190924_021846	40.3	$8.9^{+7.0}_{-2.0}$	$5.0^{+1.4}_{-1.9}$
GW190814	29.1	$23.2^{+1.1}_{-1.0}$	$2.59^{+0.08}_{-0.09}$

Constraints from no subsolar detection up to O3 automatically included

Mass-gap events naturally standing out

(even if using LVK pheno models!)

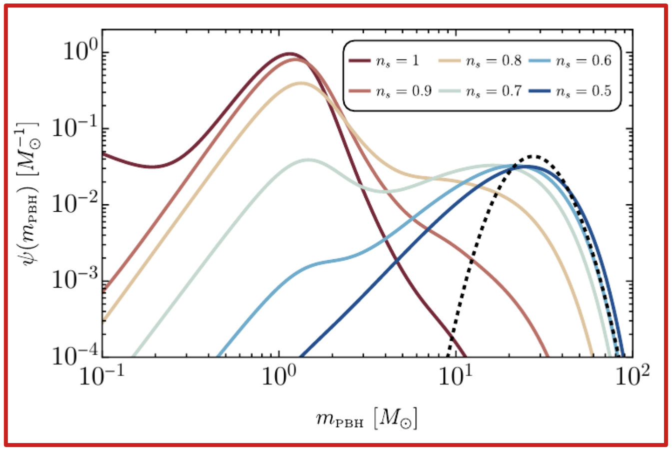
Can LIGO detect the dark matter?



- Absence of subsolar events in O3 excludes f_{PBH}~1 with n_s~0.97
[agrees with Juan, Serpico, Abellan JCAP 2022, disagrees with Escrivà-Bagui-Clesse 2209.06196]

- Otherwise ~30 subsolar and ~100 solar events → incompatible with LVK null searches [LVKC 2212.01477]

$$\log_{10} f_{\rm PBH} = -3.4^{+2.2}_{-2.3}$$

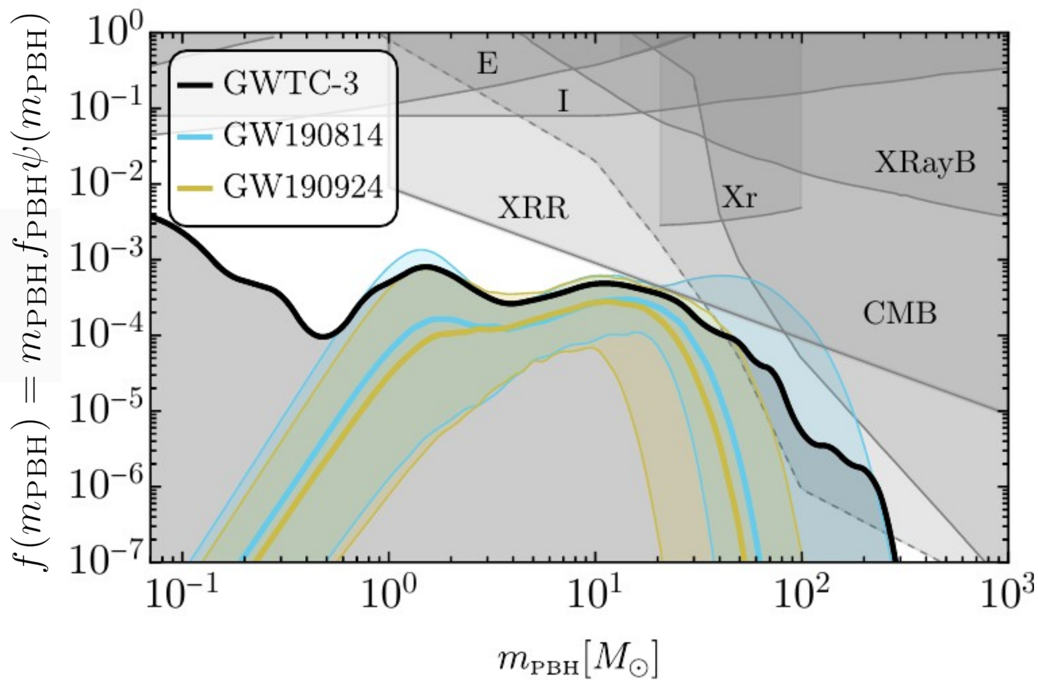


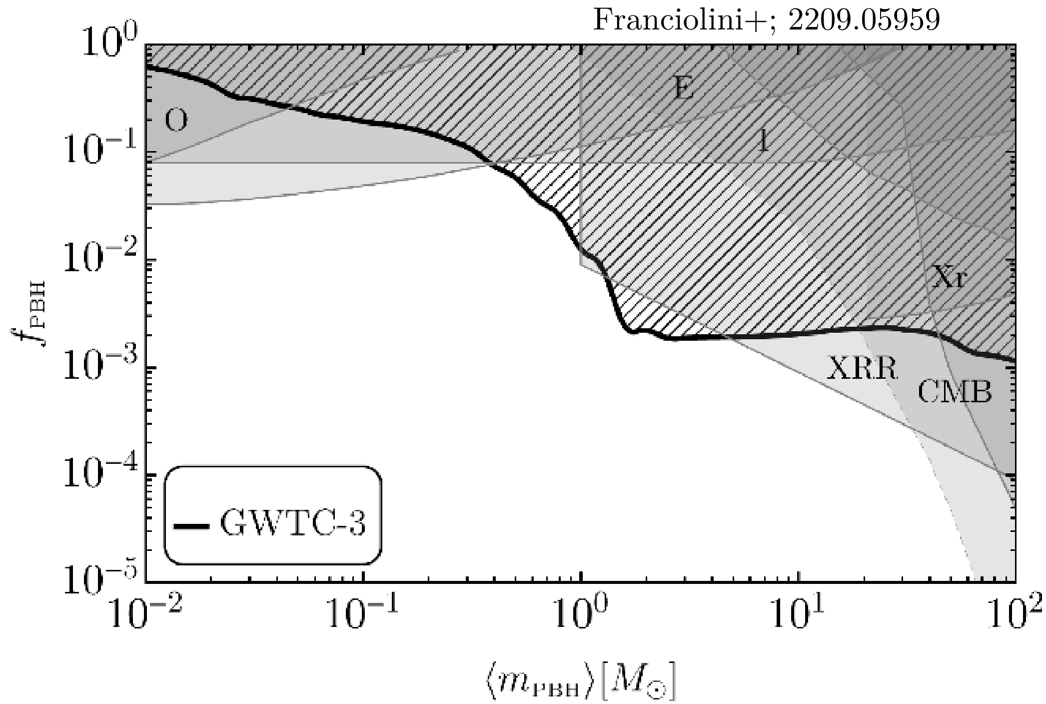
- f_{PBH}~1 only for blue spectrum (n_s>1) → PBH mass peaks outside LVK

- However, some GWTC-3 events can be PBHs

- Inferred red tilt is key: reduces hierarchy between QCD peak and O(10) M_{sun}

PBH constraints & predictions





If lower-mass-gap event GW190814 (~25% probability) is primordial, then:

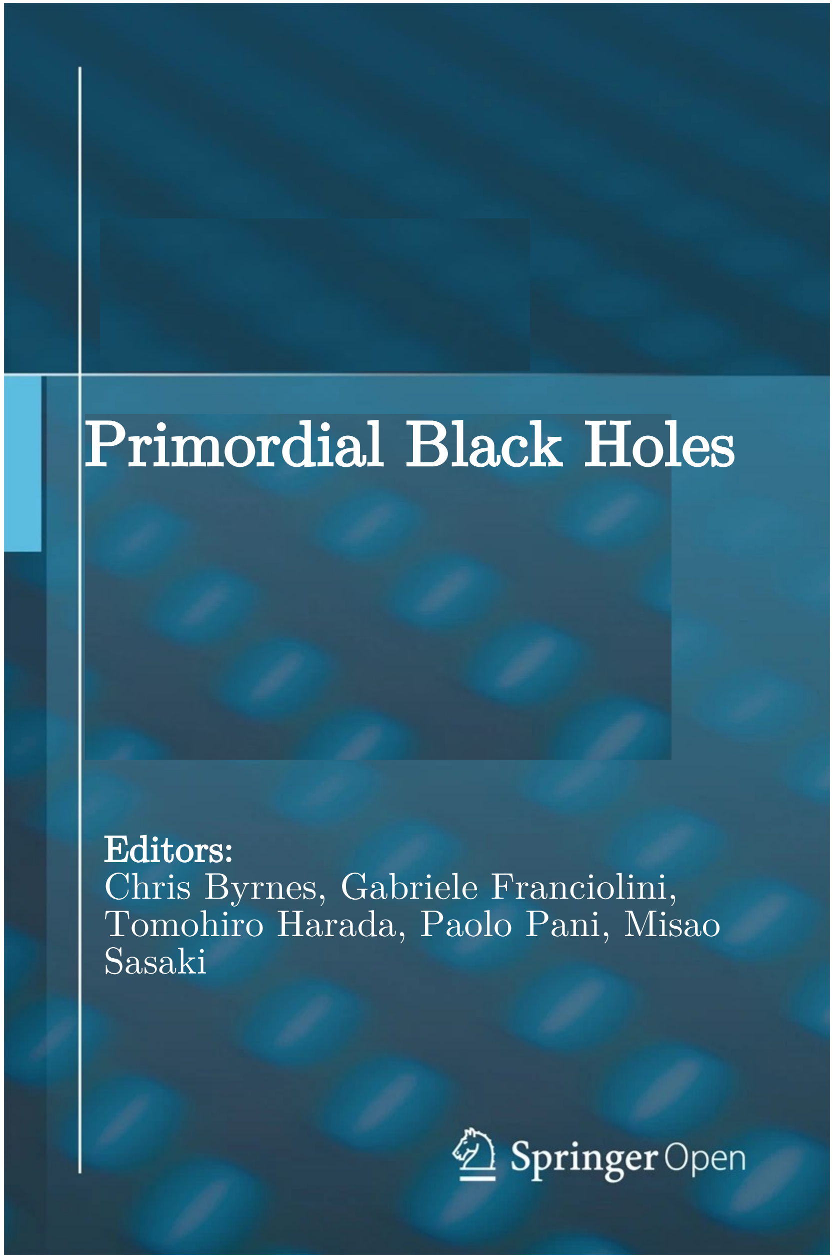
	N_{PBH}^{det}	$N_{PBH}^{det}(SS)$	$N_{PBH}^{det}(LMG)$	$N_{PBH}^{det}(UMG)$
O1-O3	$[0.8, 22.4]$	$[0.0, 0.6]$	$[0.1, 2.3]$	$[0.0, 6.1]$
O4	$[1.9, 43.7]$	$[0.0, 1.3]$	$[0.3, 13.0]$	$[0.0, 13.1]$
O5	$[10.3, 216.7]$	$[0.0, 8.6]$	$[0.8, 25.2]$	$[0.0, 47.3]$
		subsolar	lower gap	upper gap

Conclusion

PBH physics
=
gravity + cosmology + particle physics + GW data

- **Searching for PBHs with precision GW astronomy**
  - Golden single events with peculiar properties + population studies
  - More than meets the eye already in GWTC-3, looking forward to O4
- Various ways to rule out the primordial hypothesis, harder to firmly rule it in
- ET/LISA will be a game changers for many tests
- The Optimistic: *great opportunity to find a subpop of PBHs in GW data*
- The Pessimistic: *hypothetical PBH subpop can benchmark astro uncertainties*

PBH textbook



With contributions from:

Bellomo, Bromm, Carr, Chen, Chulmoon, Cole, Colpi, De Luca, Domenech, Green, Hall, Iacovelli, Jedamzik, Kohri, Kovetz, Kuehnel, Kuroyanagi, Kusenko, Lupi, Maggiore, Miller, Musco, Pi, Profumo, Raidal, Riotto, Romero-Rodriguez, Serpico, Silk, Suyama, Tiniakov, Vaskonen, Veermae, Vennin, Wands, Yokoyama, Young...

and others!

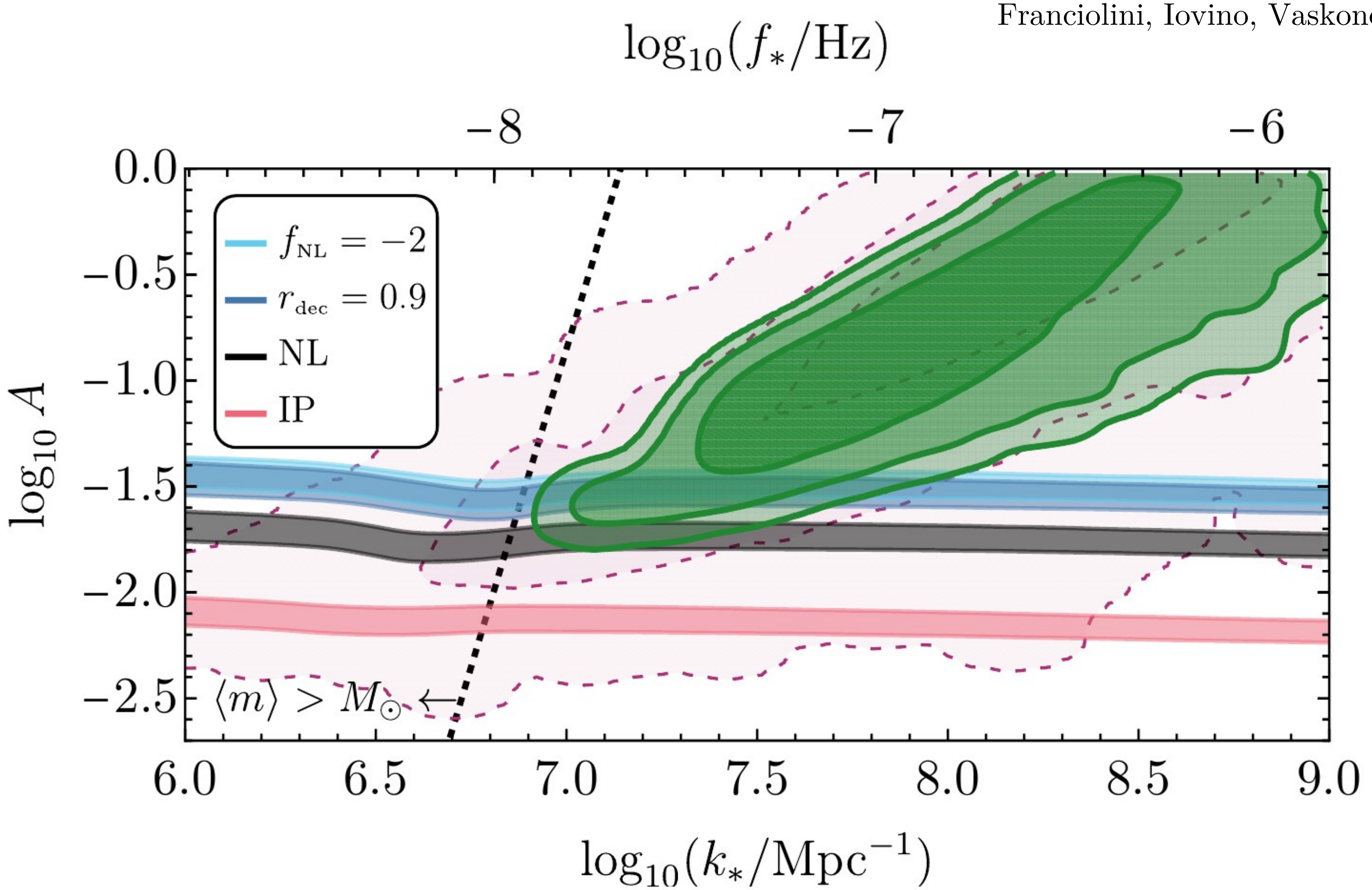
Out in Fall 2024!

Backup slides

"Nothing is More Necessary than the Unnecessary" [cit.]

PBHs & detected SGWB

Franciolini, Iovino, Vaskonen, Veermae, 2306.17149



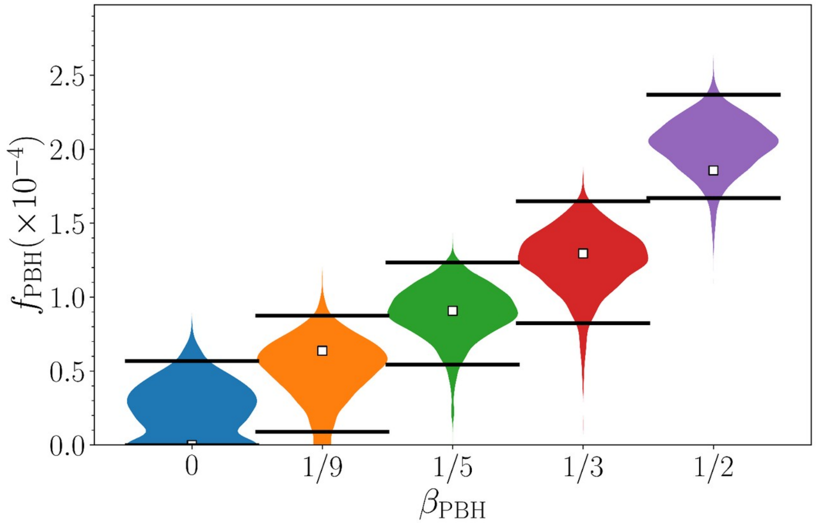
- If SGWB induced by 2nd order perturbations → overproduction of PBHs unless non-Gaussianities suppress PBH formation
- PTA data do not constrain directly the PBH abundance, but can indirect probe it

Population studies in the 3G era

- Focus on z>10 → Pop III vs PBHs
- 4-month data with CE-ET network

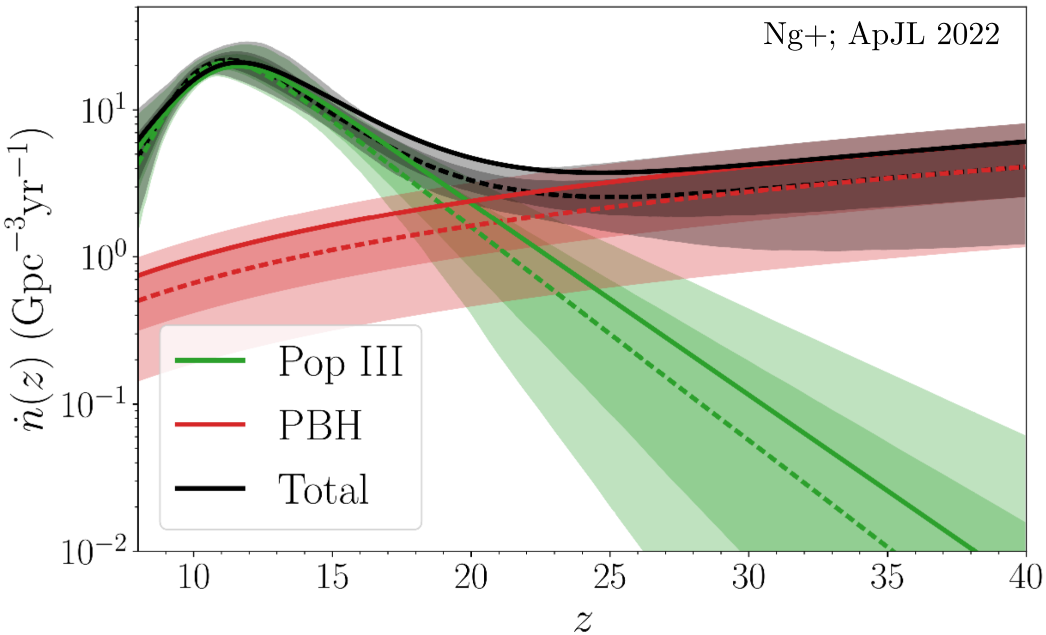
$$\frac{dR}{dz} = R\left[\beta_{\rm PBH} p_{\rm PBH}(z) + (1-\beta_{\rm PBH}) p_{\rm III}(z)\right]$$

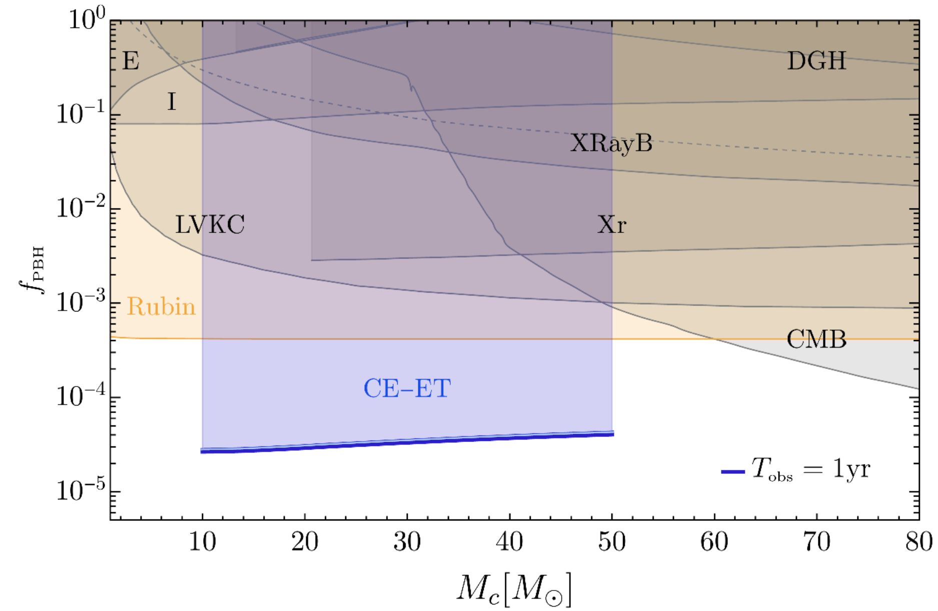
differential merger rate



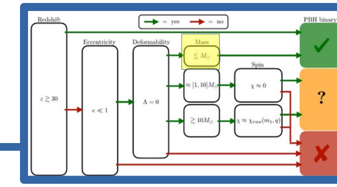
Most conservative assumptions:

- Same mass function, only redshift info
- No PBH accretion
- Optimistic Pop III merger rate

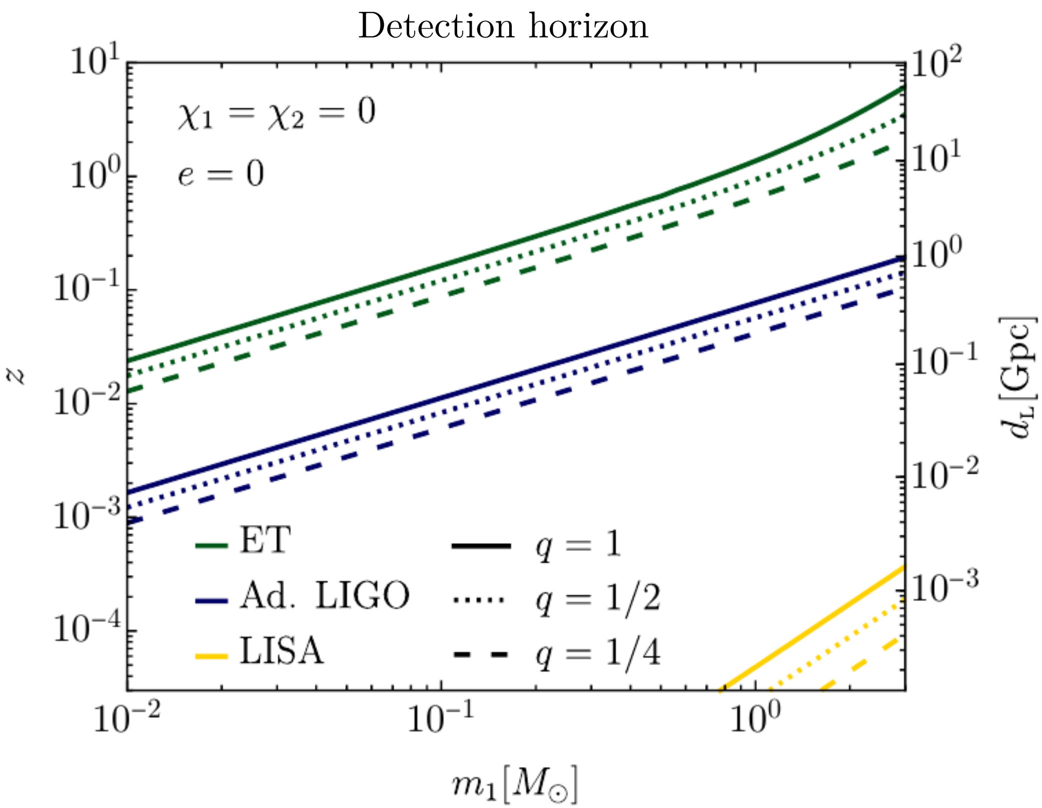


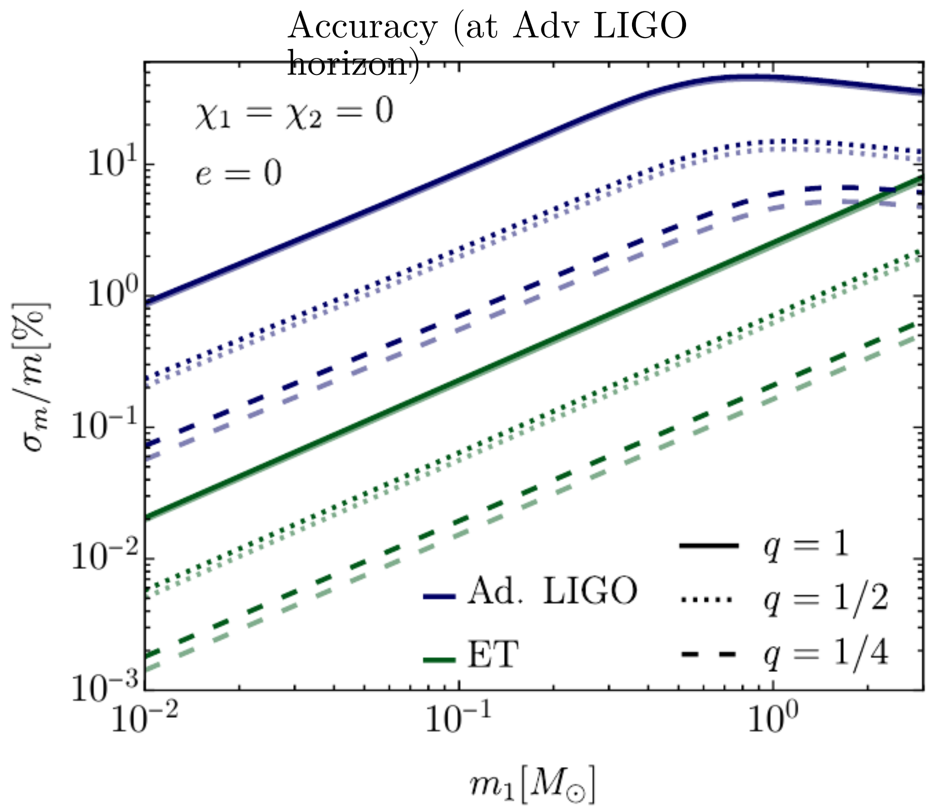


Subsolar masses?



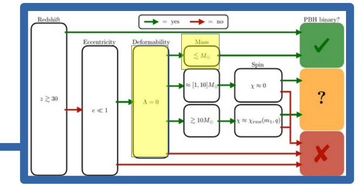
- How accurately can we measure subsolar masses?





- Current searches limited in horizon [Phukon+ 2021; Nitz-Wang PRL 2021, ApJ 2021, LVKC MNRAS 2023]
- Mass measurements typically accurate already for O4
- 3G: up to z~1 and subpercent accuracy [Franciolini+ PRD 2022]
- E/IMRIs detected by LISA/ET → astonishing accuracy [Barsanti+ PRL 2022]

Subsolar PBHs or else?

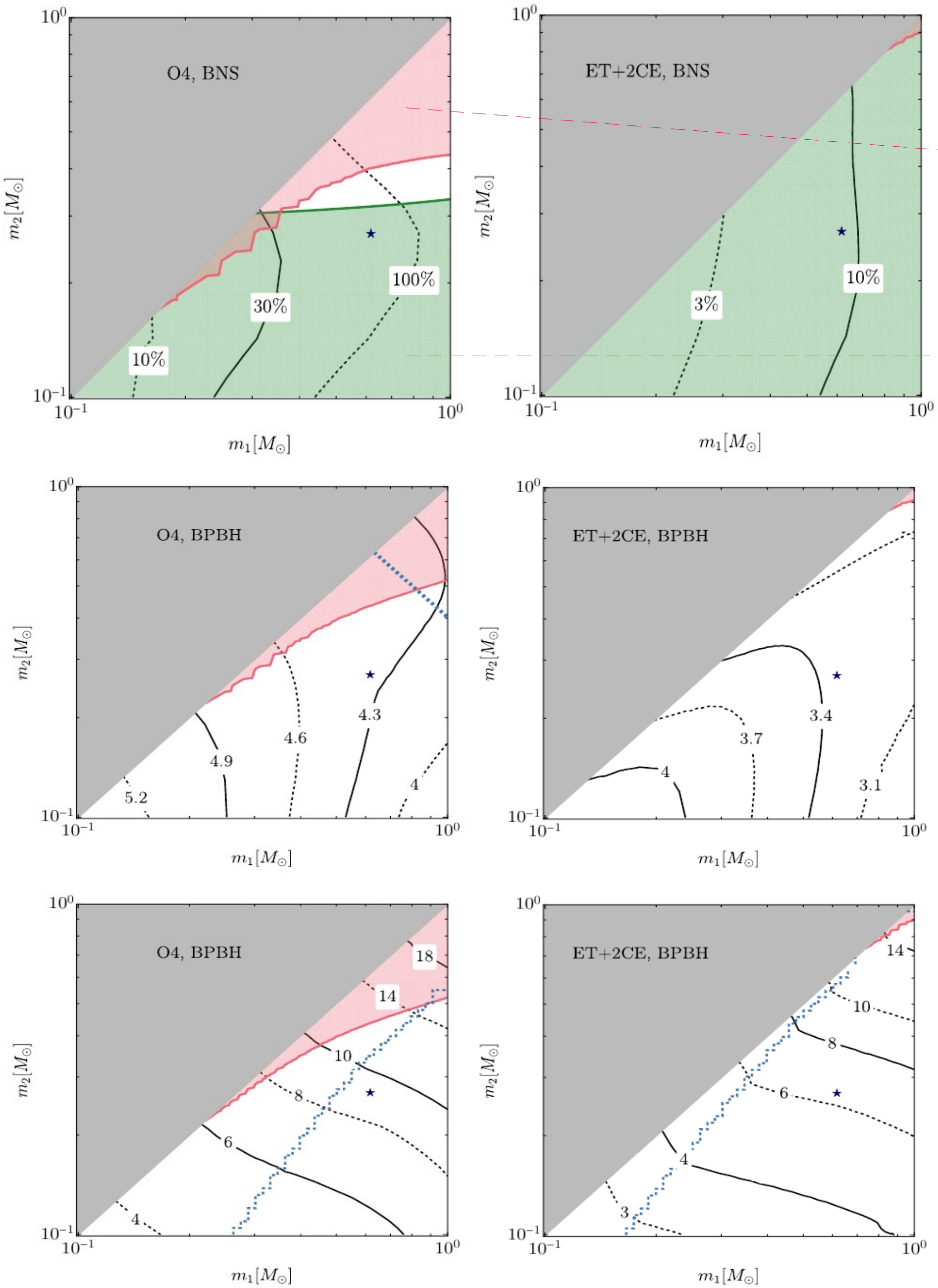


Crescimbeni, Franciolini, Pani, Riotto, 2402.18656

NS vs BH

BH vs NS

BH vs boson star



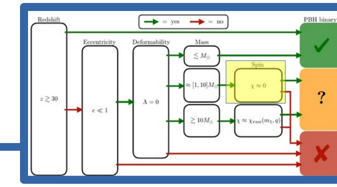
$$m_i + 3\Delta m_i > M_\odot$$

$$\tilde{\Lambda} - 3\Delta\tilde{\Lambda} > 0$$

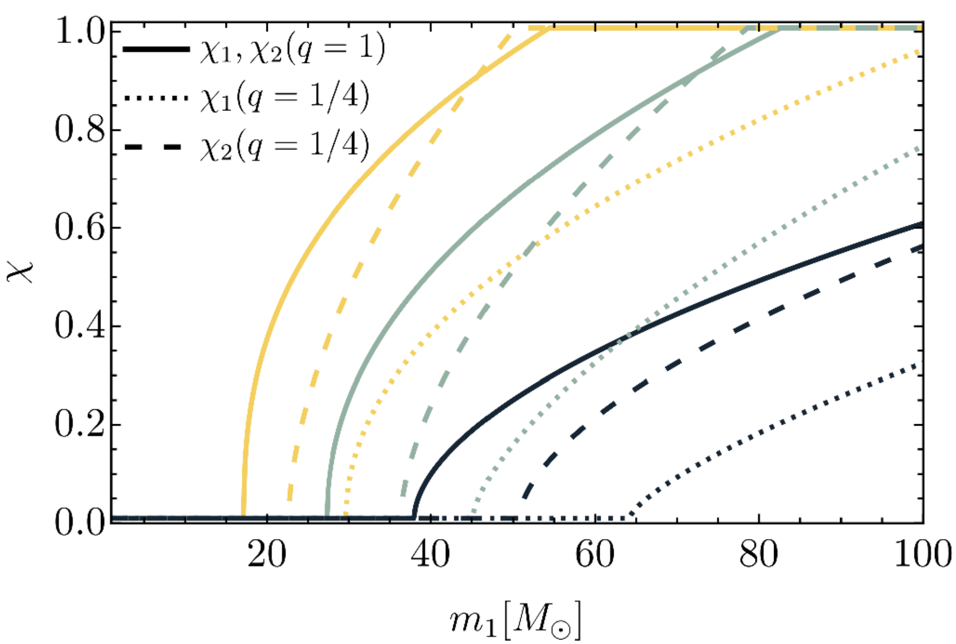
$$\tilde{\lambda}_f + 3\Delta\tilde{\lambda}_f < 1$$

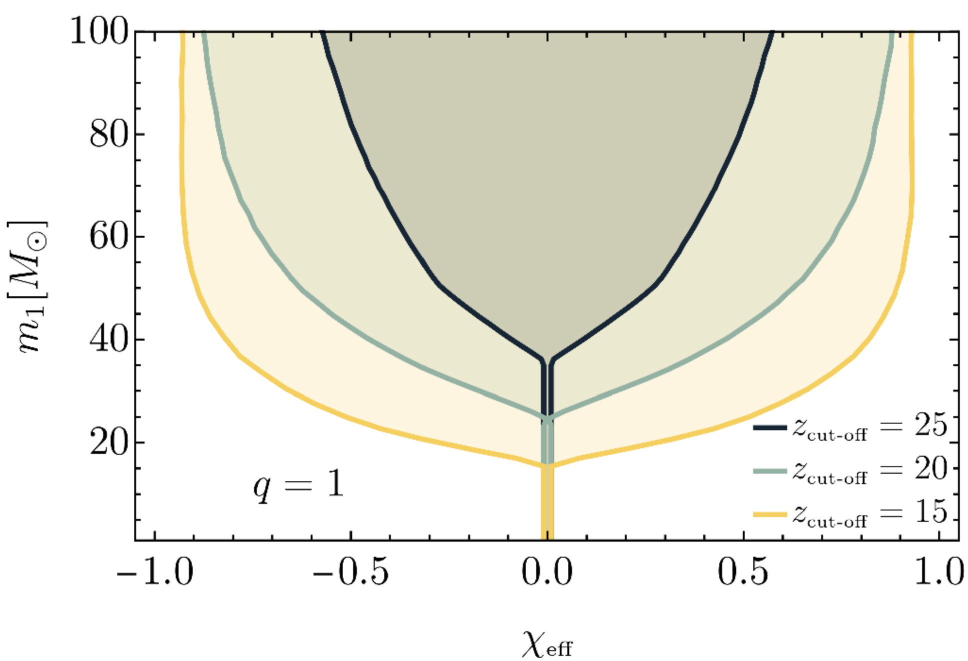
- Constraining power already in O4
- ET will cover the entire param space
- Can exclude NS and more exotic objects

Spin



- PBHs formed with spin χ~O(0.01) in various scenarios [Mirbabayi+ 2019, De Luca+ 2019]
- Accretion before rionization? [Ricotti+ 2008, Ali-Haïmoud 2018, De Luca+ 2020]
  - Not efficient for mass < 10 M_{sun}, very efficient otherwise (SMBHs?)
  - Suppressed at some z (feedback, structure formation, X-ray pre-heating) $\rightarrow$ $z_{cut\text{-}off}$
  - Accretion flow not spherical $\rightarrow$ ang. mom. accretion $\rightarrow$ BH spin up
- Model uncertainties but one robust prediction: mass-spin correlation

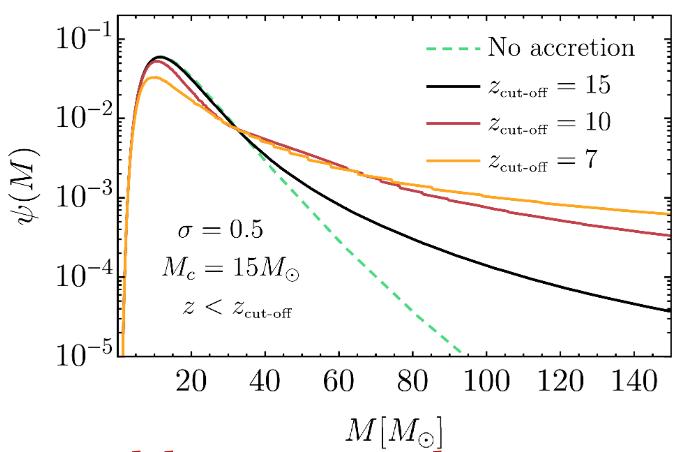


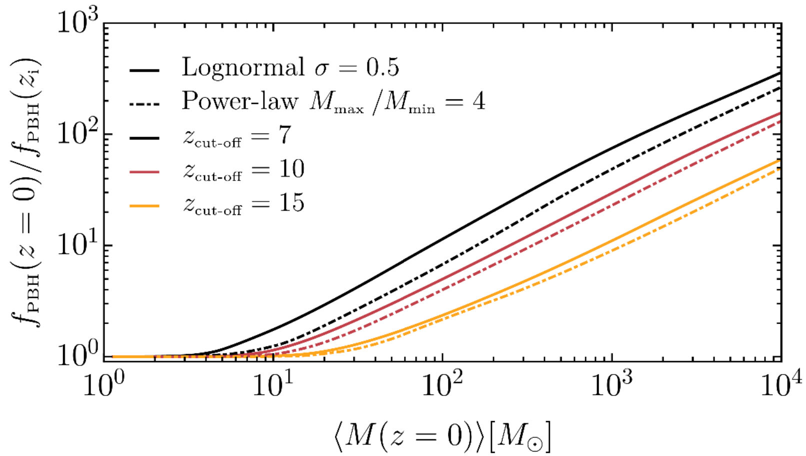


Role of accretion: the case of GW190521

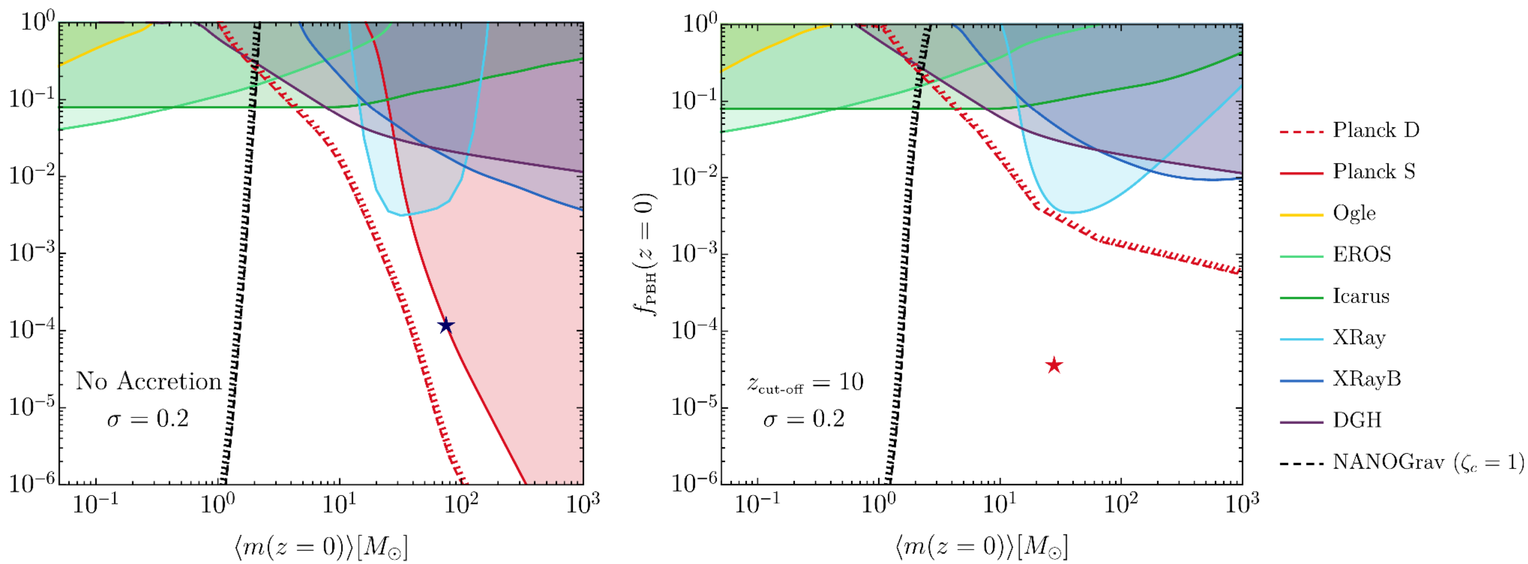
[De Luca+ PRL 2021]

- Accretion affects: [De Luca+ PLB 2020]
  - Mass function, PBH abundance, merger rate, masses and spin





- Accretion could remove observational tension for GW190521 as primordial:



Mass-spin correlations

Franciolini-Pani 2201.13098; Franciolini+ (in prep)

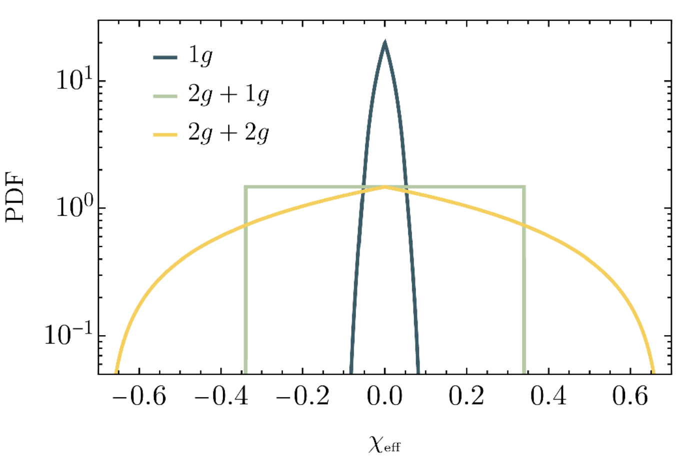
- High z is out of reach until 3G, formation models & mass distribution uncertain
- Can we identify robust features to be searched for in 2G?
  - BHs born in isolation → $\chi_{\rm eff}>0$
  - BHs assembled dynamically → $\chi_{\rm eff}$ distributed symmetrically around zero
  - PBHs → mass-spin correlation

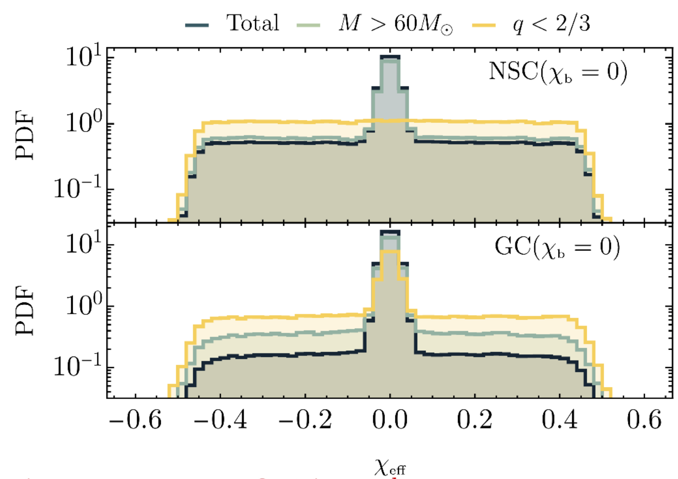
$$\chi_{\rm eff} \equiv \frac{\chi_1 \cos\alpha_1 + q\chi_2\cos\alpha_2}{1+q}$$

1) LVKC phenomenological model: $p^{\rm G}_{\rm pop}(\chi_{\rm eff}|\mu,\sigma) = \mathcal{N}(\mu,\sigma)\exp\left(-(\chi_{\rm eff}-\mu)^2/2\sigma^2\right)$

(parameters can be q-dependent [Callister+ ApJL 2021])

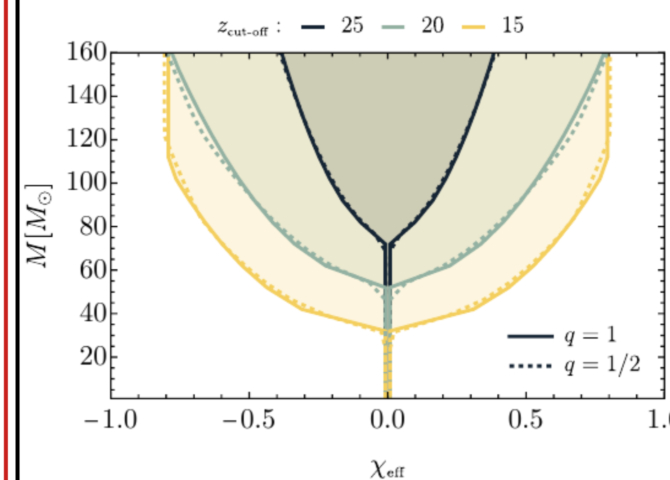
2) Dynamical channel [Baibhav+ PRD 2020]





$$p^{\rm ABH}_{\rm pop}(\chi_{\rm eff}) = (1-f_g)p^{1g}_{\rm pop}(\chi_{\rm eff}) + f_g\, p^{2g+1g\,{\rm mod}}_{\rm pop}(\chi_{\rm eff})$$

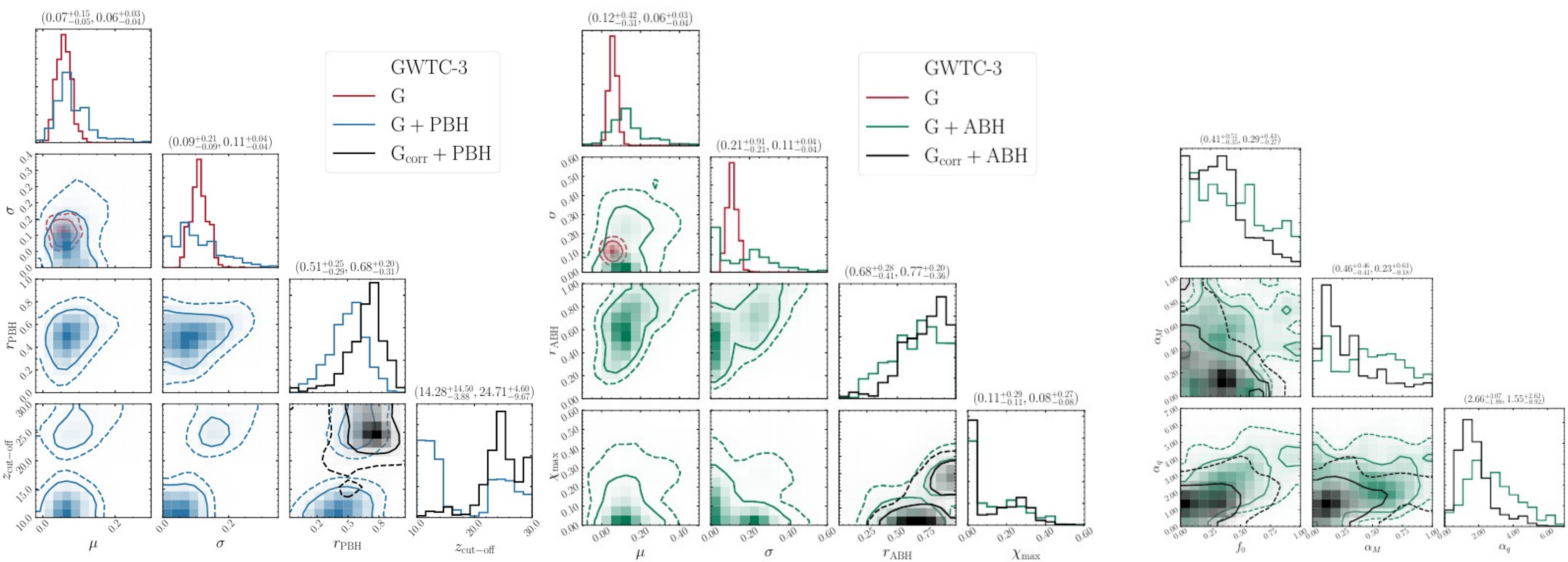
3) PBHs



Mass-spin correlations in GWTC-3

Franciolini-Pani PRD 2022

$$p_{\rm pop}(\chi_{\rm eff}) = (1 - r_{\mathcal{M}})p^{\rm G}_{\rm pop} + r_{\mathcal{M}} p^{\mathcal{M}}_{\rm pop}$$



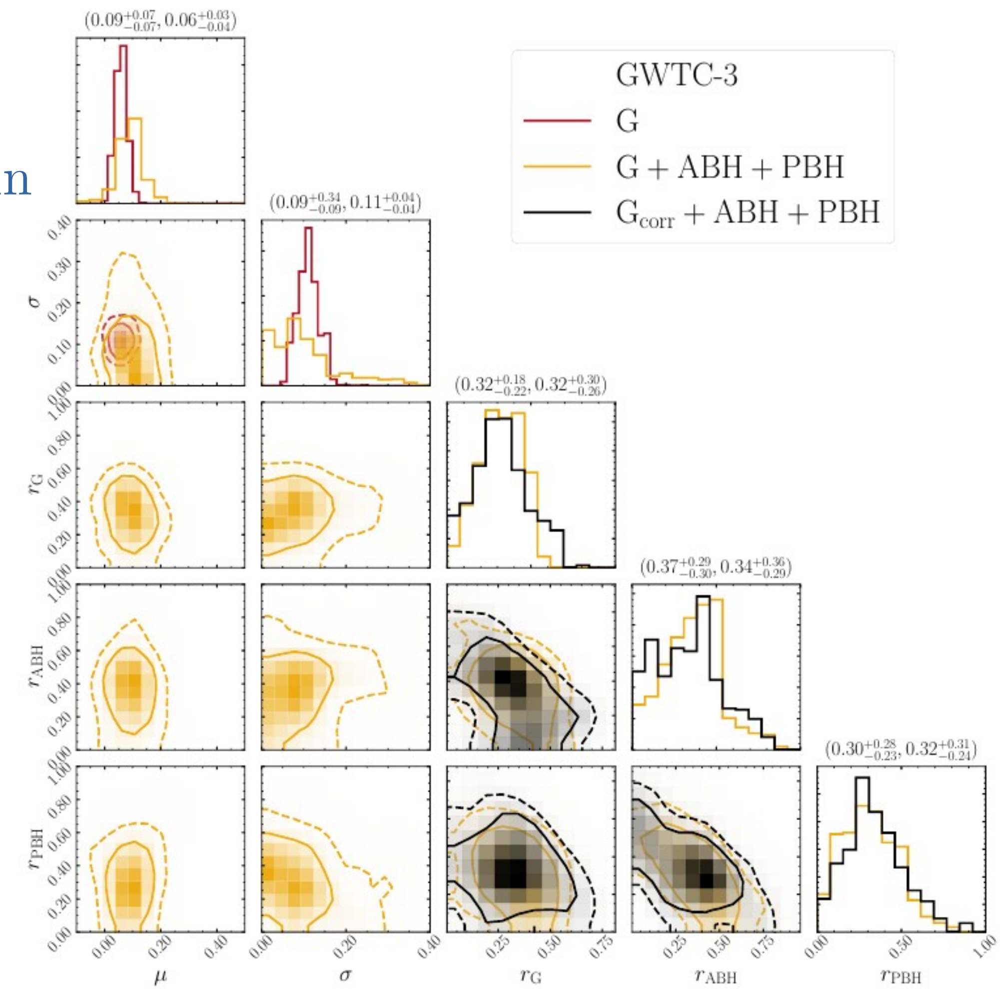
Model $\mathcal{M}$	G+ABH	G+PBH	G+ABH+PBH	G$_{\rm corr}$	G$_{\rm corr}$+ABH	G$_{\rm corr}$+PBH	G$_{\rm corr}$+ABH+PBH
Fraction $r_{\mathcal{M}}$	$0.68^{+0.28}_{-0.41}$	$0.51^{+0.25}_{-0.29}$	$(0.37^{+0.29}_{-0.30}, 0.30^{+0.28}_{-0.23})$	-	$0.77^{+0.20}_{-0.36}$	$0.68^{+0.20}_{-0.31}$	$(0.34^{+0.36}_{-0.29}, 0.32^{+0.31}_{-0.24})$
$\log_{10} \mathcal{B}^{\mathcal{M}}_{\rm G}$	0.94	0.88	1.33	1.06	2.15	1.72	2.40

Mass-spin correlations in GWTC-3

Franciolini-Pani PRD 2022

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

- More than just (extended) Gaussian model in GWTC-3 data
- Features of astro dynam. formation / PBH
- Degeneracy between ABHs & PBHs
- Need larger statistics and smaller errors
- More realistic isolated channels?

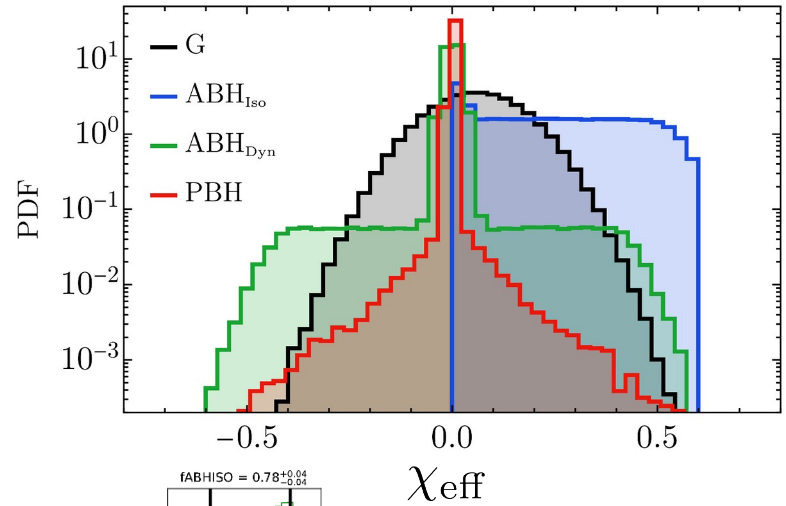


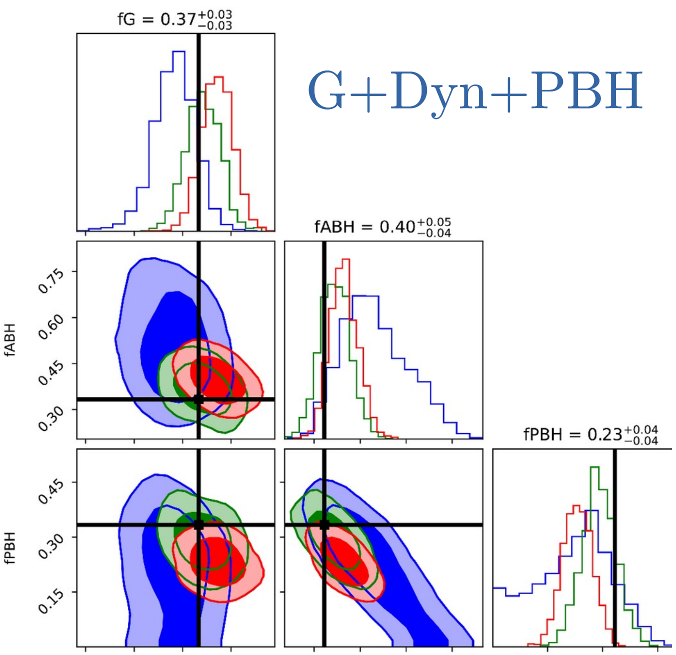
Model $\mathcal{M}$	G+ABH	G+PBH	G+ABH+PBH	$G_{\rm corr}$	$G_{\rm corr}$+ABH	$G_{\rm corr}$+PBH	$G_{\rm corr}$+ABH+PBH
Fraction $r_{\mathcal{M}}$	$0.68^{+0.28}_{-0.41}$	$0.51^{+0.25}_{-0.29}$	$(0.37^{+0.29}_{-0.30}, 0.30^{+0.28}_{-0.23})$	-	$0.77^{+0.20}_{-0.36}$	$0.68^{+0.20}_{-0.31}$	$(0.34^{+0.36}_{-0.29}, 0.32^{+0.31}_{-0.24})$
$\log_{10} \mathcal{B}_{\rm G}^{\mathcal{M}}$	0.94	0.88	1.33	1.06	2.15	1.72	2.40

Mass-spin correlations: prospects

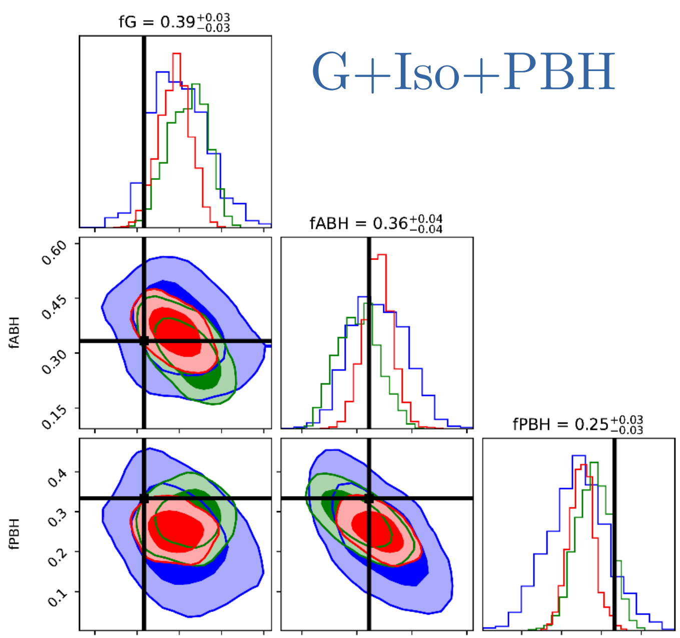
Bavera, Berti, Franciolini, Pani; in preparation

- Gaussian + Isolated + Dynamical + PBH
- Same mass/redshift distributions
- 500 events @ Ad. LIGO

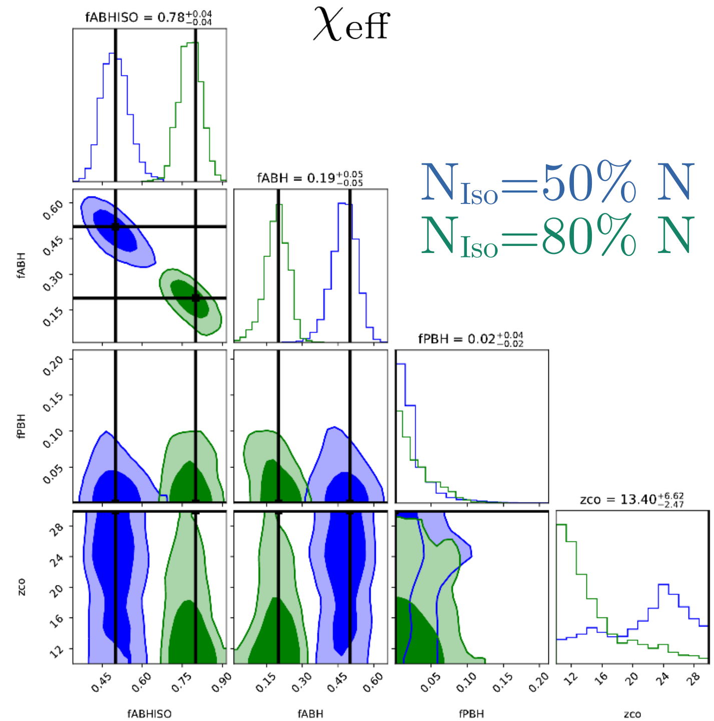




G+Dyn+PBH



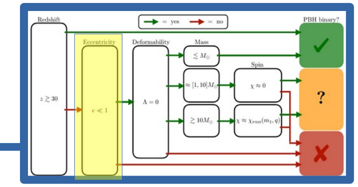
G+Iso+PBH



N_{Iso}=50% N

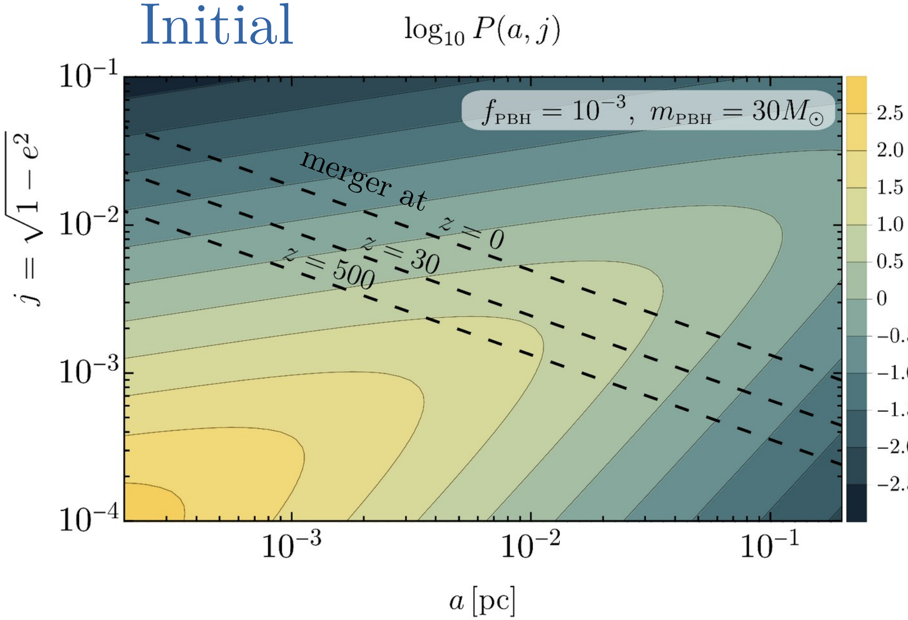
N_{Iso}=80% N

Eccentricity

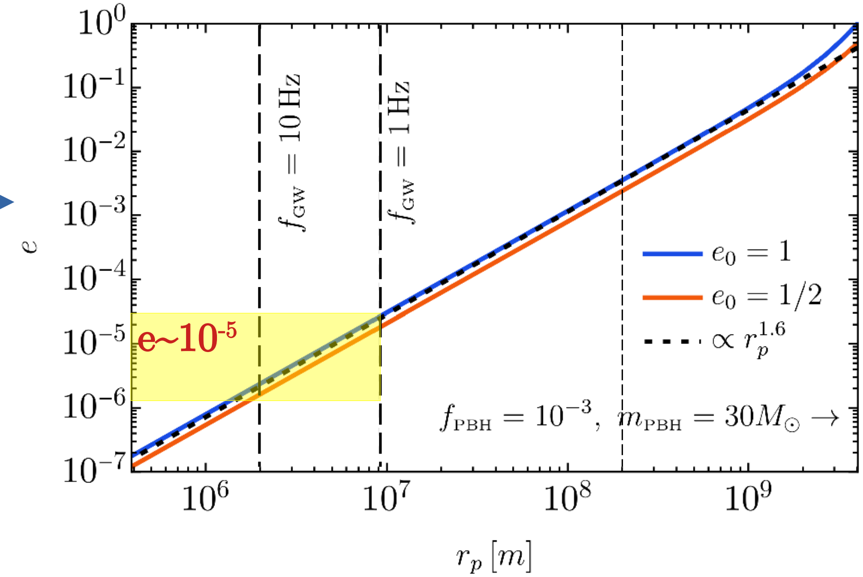


- PBH binary formed with e~1, but e~0 when detected (other channels subdominant)

Initial

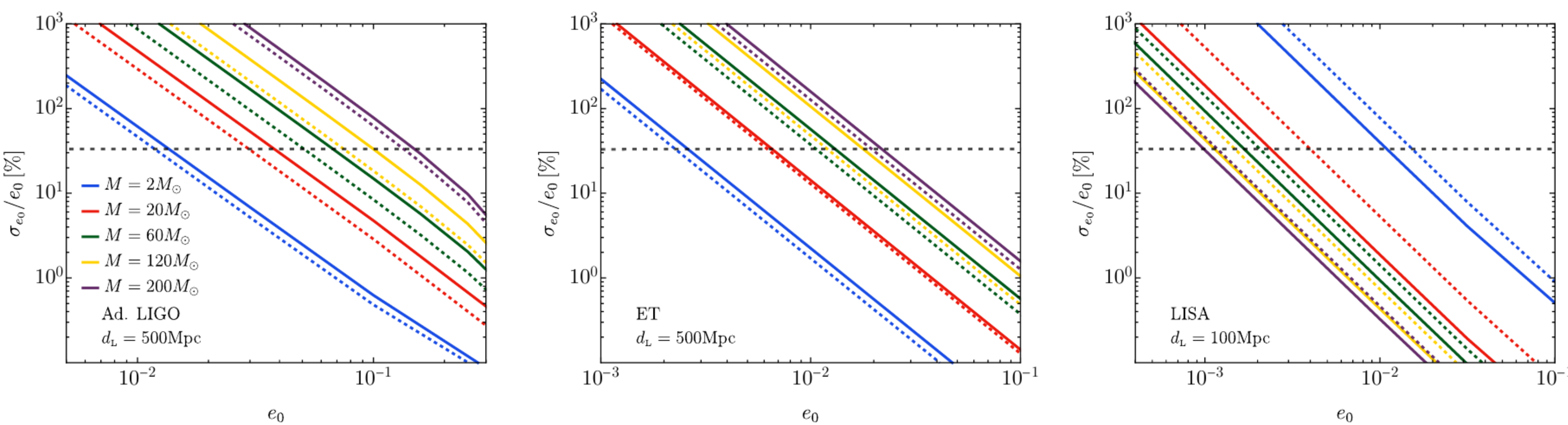


Evolution



- How well can we exclude e=0?

[Franciolini+ PRD 2022, see also Favata+ PRD 2022]



From GWTC-3 back to inflation

Franciolini-Urbano, PRD 2022

- Engineering a single-field inflationary potential

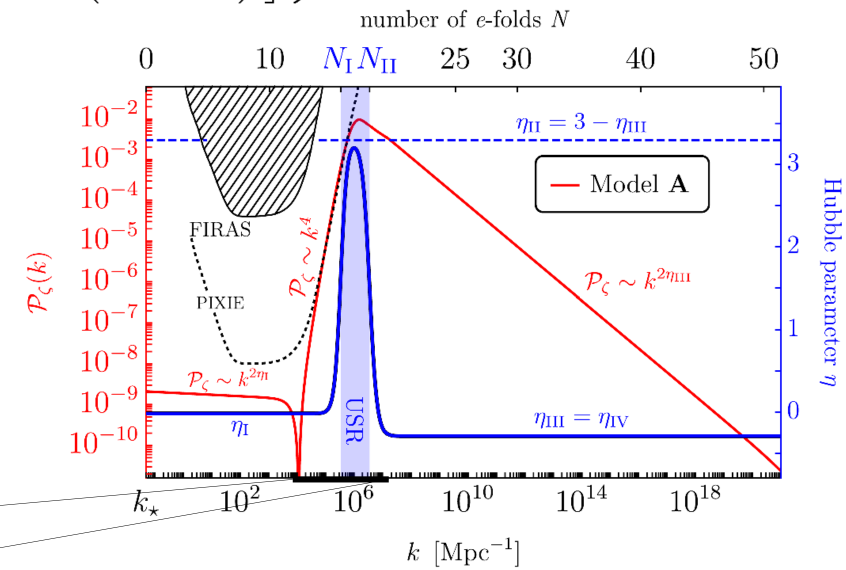
$$\eta(N) = \frac{1}{2}\left\{ \left[\eta_{\rm I} - \eta_{\rm II} + (\eta_{\rm II} - \eta_{\rm I}) \tanh\left(\frac{N - N_{\rm I}}{\delta N_{\rm I}}\right)\right] + \left[\eta_{\rm II} + \eta_{\rm III} + (\eta_{\rm III} - \eta_{\rm II}) \tanh\left(\frac{N - N_{\rm II}}{\delta N_{\rm II}}\right)\right]\right\}$$

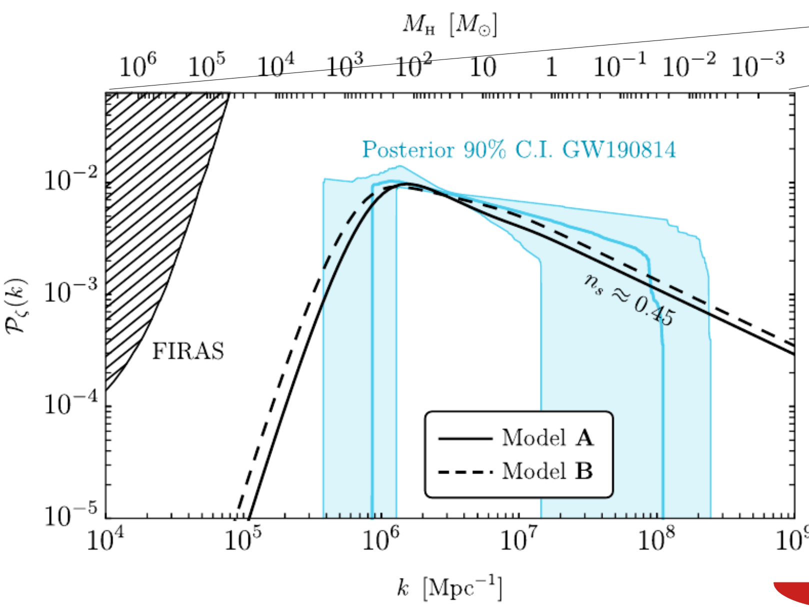
$$\eta = -\ddot{H}/(2H\dot{H})$$

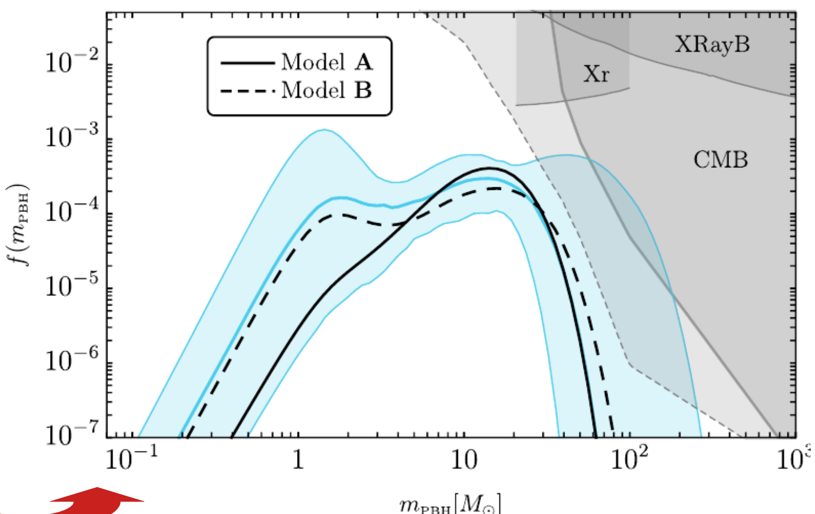
- Power spectrum from Mukhanov-Sasaki eq.

[Sasaki PTP 1986; Mukhanov JETP 1988]

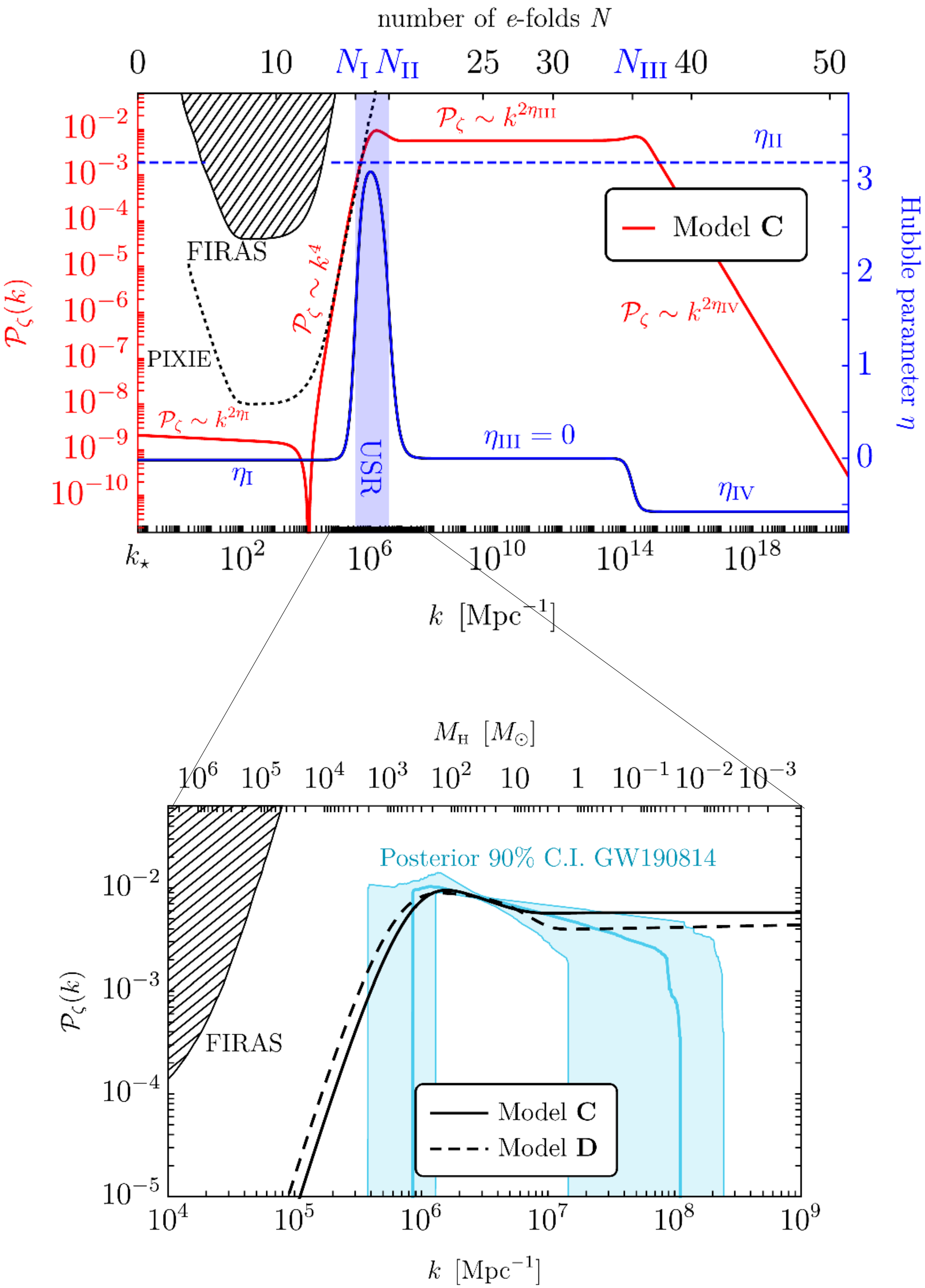
- Fix inflationary model to match GW data



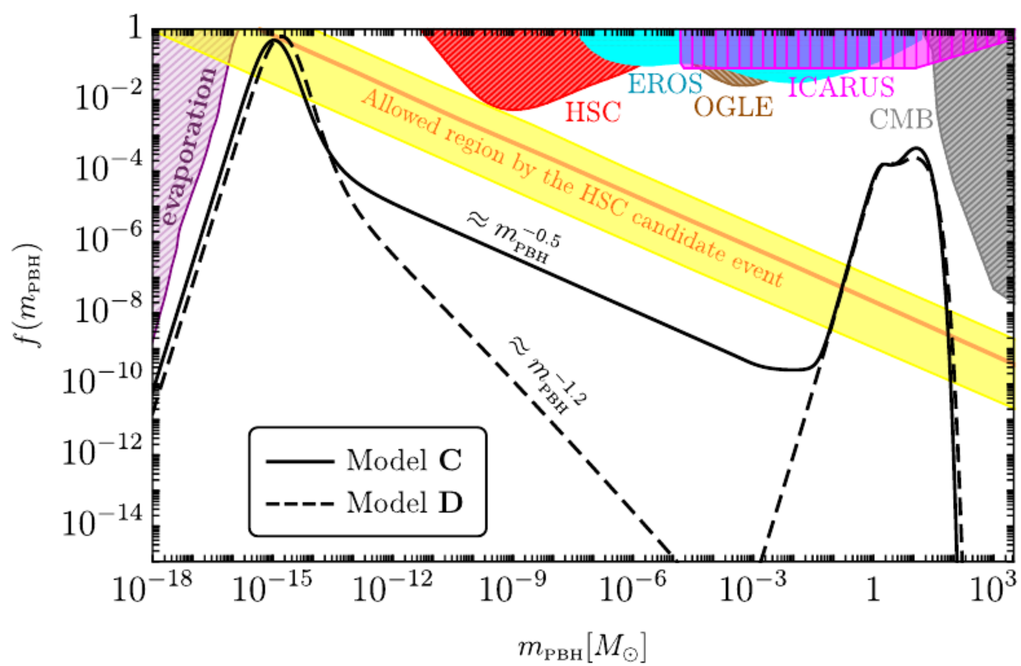




Four birds with one stone?

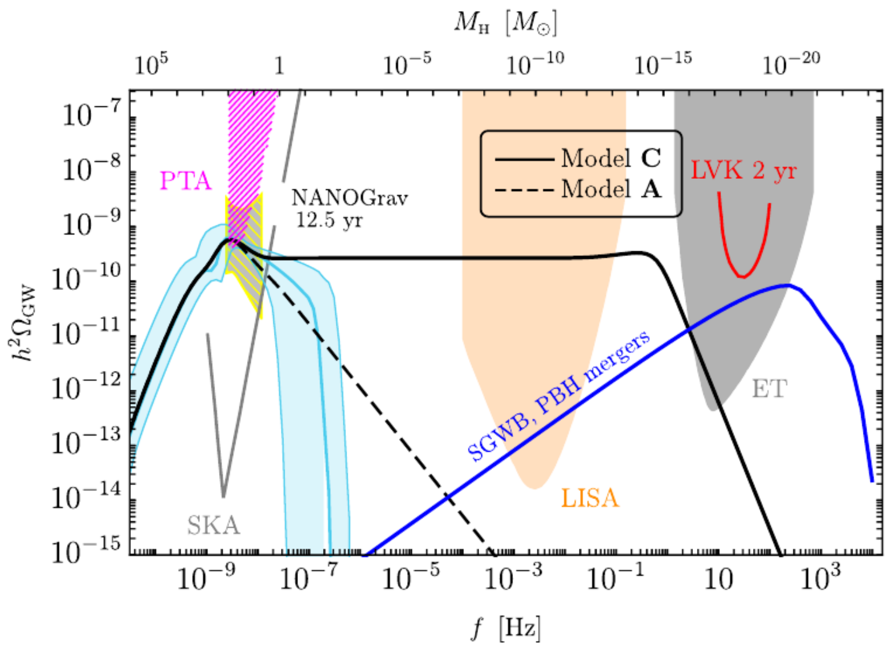


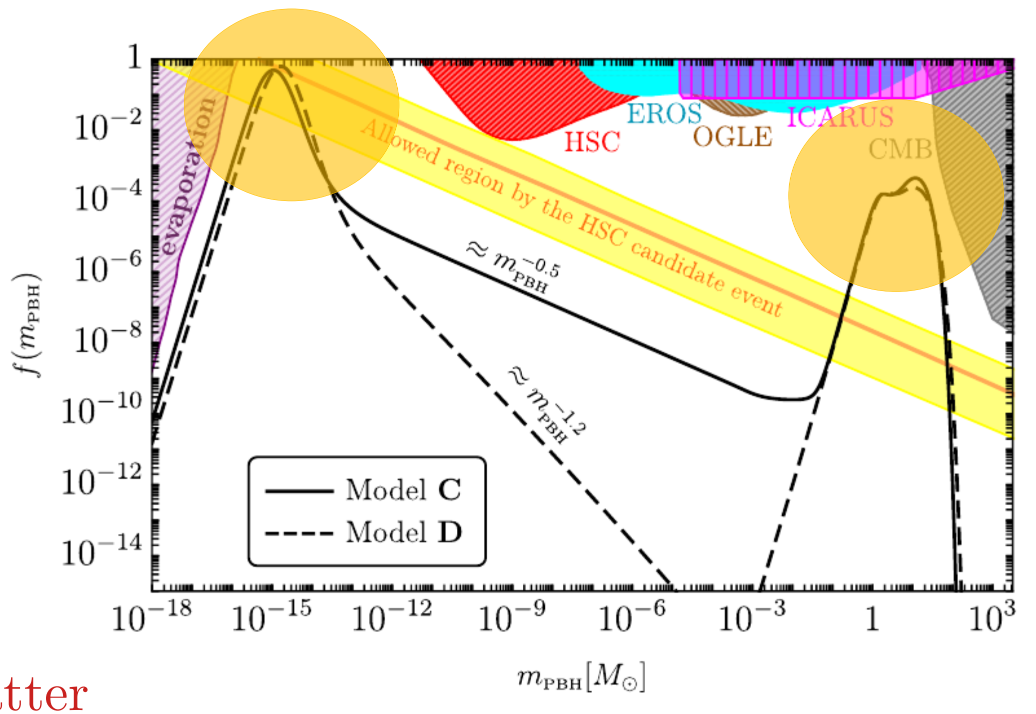
- Step power spectrum connects vastly different scales [De Luca, Franciolini, Riotto PLB 2020, PRL 2021; Sugiyama PLB 2021]
- Can be built out of inflationary dynamics [Franciolini-Urbano, 2207.10056, PRD 2022]
- Can be made compatible with GW data [Franciolini+ 2209.05959, PRD 2022]



Four birds with one stone?

De Luca, Franciolini, Riotto PRL 2021; Sugiyama+ PLB 2021
Franciolini+; 2209.05959





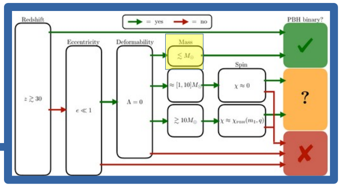
1. Asteroid-mass peak gives PBH dark matter

2. Stellar-mass secondary peak compatible with bounds and with events in LVK band

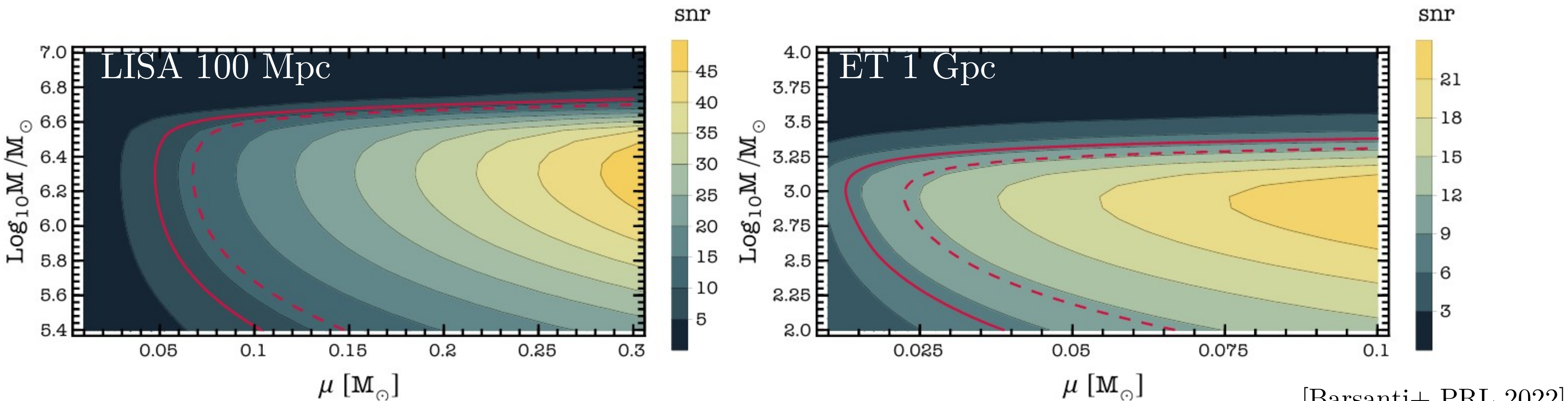
3. SGWB induced at second order detectable by PTAs and LISA

4. SGWB from PBH mergers detectable by ET

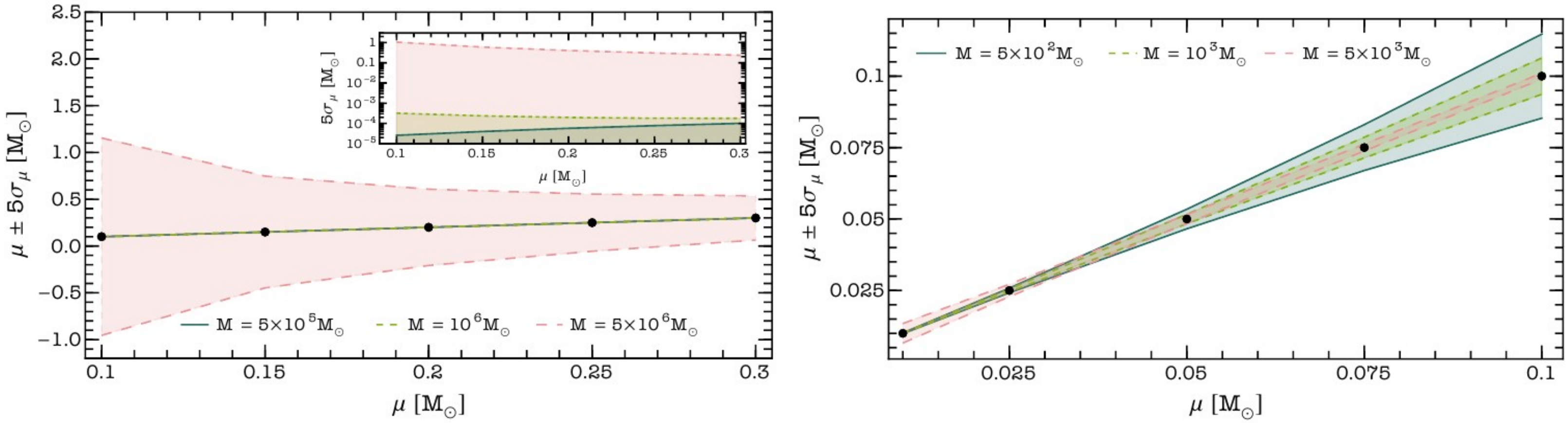
Subsolar masses?



- How accurately can we measure subsolar masses?
- If EMRIs/IMRIs detected by LISA (and ET!) → astonishing measurements!



[Barsanti+ PRL 2022]

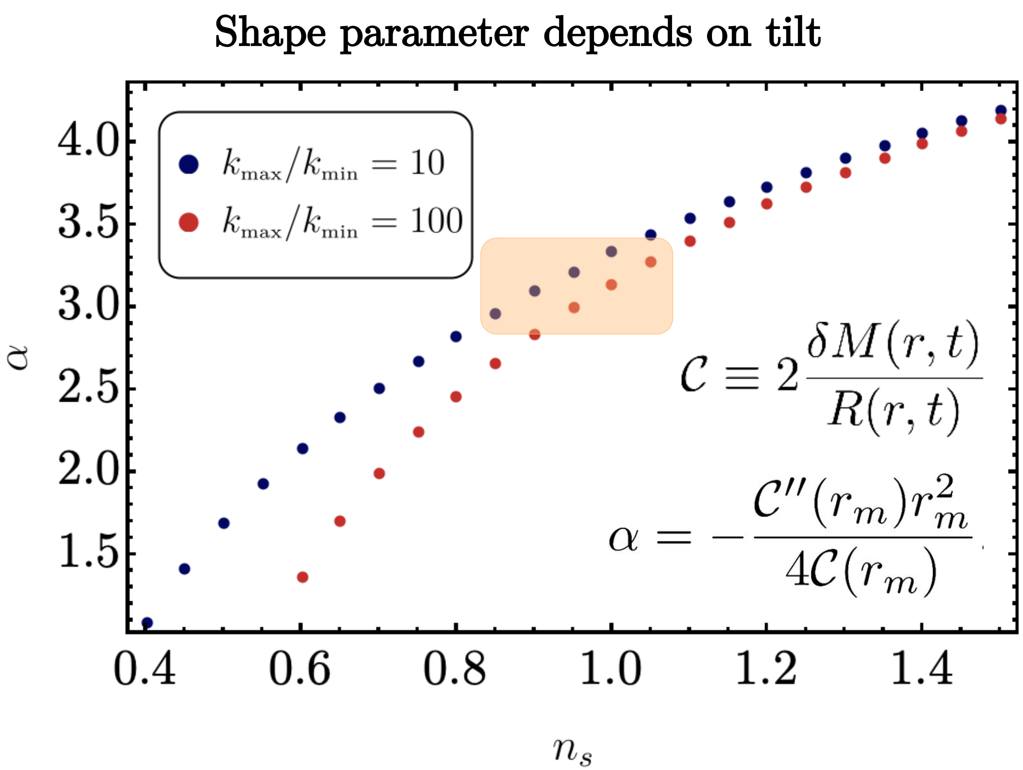


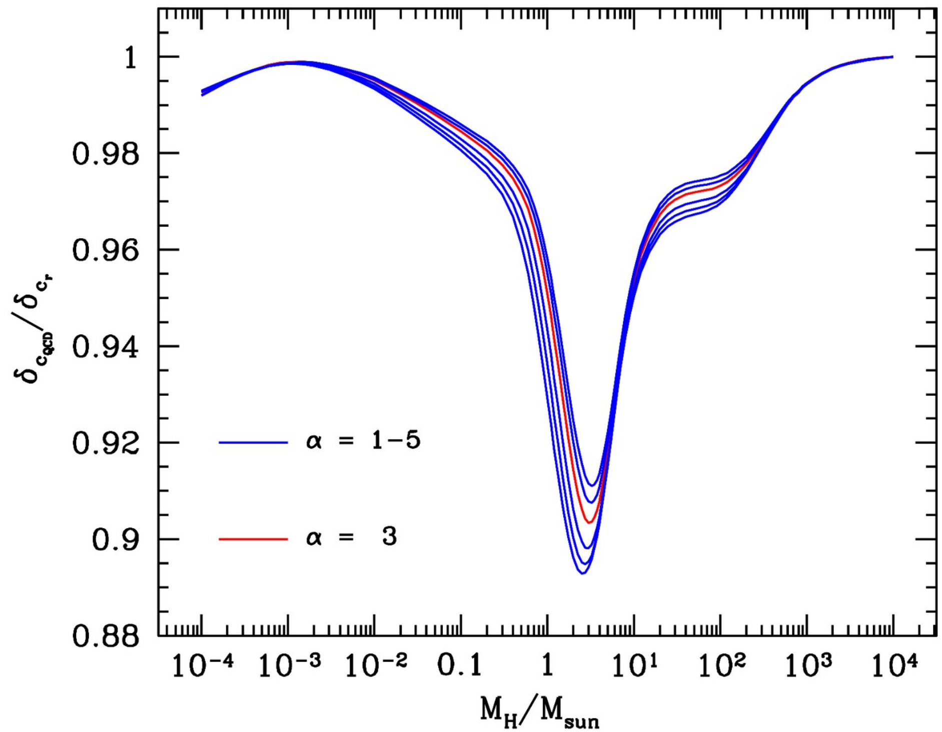
How about (primordial) EMRI/IMRI rates? [Guo+ PRD 20219]

Critical collapse & QCD phase

Approximation: we assume α~3 from peak theory for n_s~O(1)

[Musco, De Luca, Franciolini, Riotto PRD 2021]





Courtesy of Ilia Musco

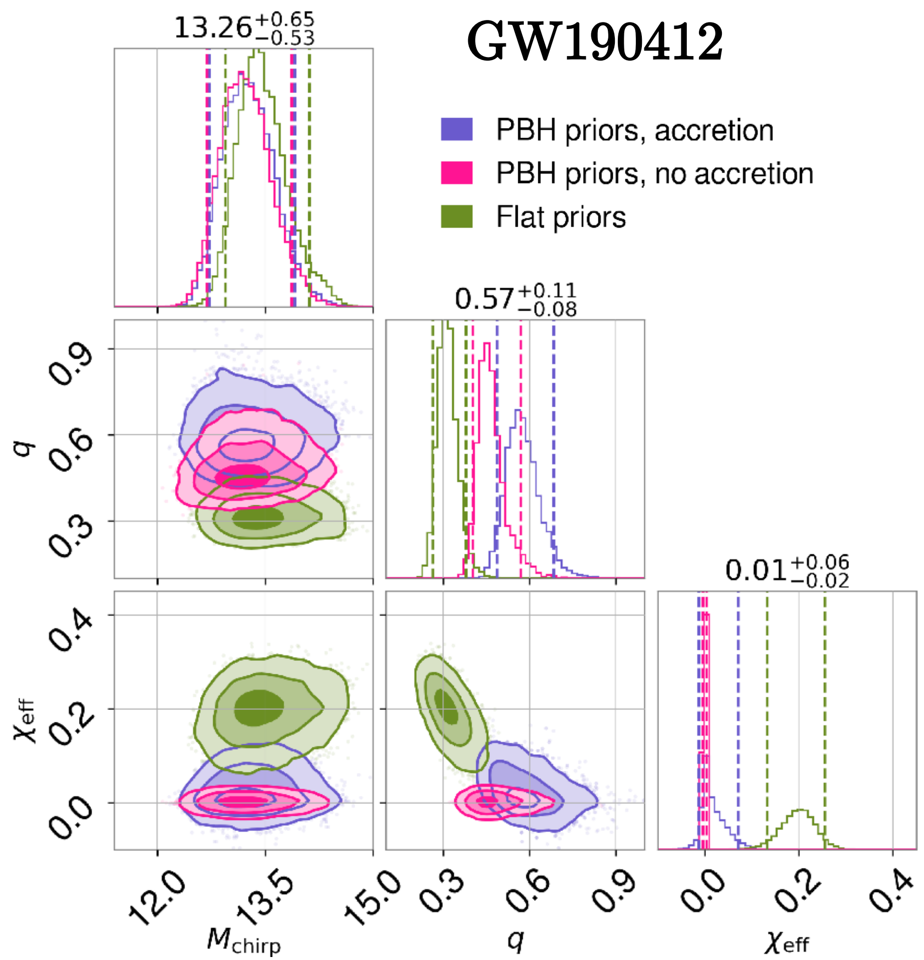
Musco, Jedamzik, Young, 2303:07980

Final Caveat: role of priors

[Bhagwat+ JCAP 2021]

We have always assumed the posteriors on params as measured by LVKC

- Are "agnostic" priors motivated in searches for PBHs?
- Can PBH-motivated priors change the properties of certain events?



- Chirp mass insensitive to prior
- q-χ correlation
- Agnostic priors mildly favored
- Careful with spinning, asymmetric binaries (with LVKC priors)!

TABLE V: Posterior 90% C.I. for PBH population parameters assuming GW190814 is primordial (similar results are found by assuming that GW190924 is primordial).

Parameter	All	GW190814	GW190924
$\log_{10} A$	$-1.9^{+0.4}_{-0.6}$	$-1.93^{+0.10}_{-0.05}$	$-1.9^{+0.1}_{-0.1}$
n_s	$0.68^{+0.66}_{-0.61}$	$0.68^{+0.18}_{-0.40}$	$0.64^{+0.29}_{-0.56}$
$\log_{10}(k_{\rm min}/{\rm Mpc}^{-1})$	$6.0^{+1.6}_{-0.6}$	$5.9^{+0.2}_{-0.4}$	$6.0^{+0.3}_{-0.2}$
$\log_{10}(k_{\rm max}/{\rm Mpc}^{-1})$	$7.8^{+0.6}_{-0.9}$	$8.1^{+0.3}_{-0.9}$	$8.0^{+0.4}_{-1.2}$
$\log_{10} f_{\rm PBH}$	$-3.4^{+2.2}_{-2.3}$	$-3.1^{+0.5}_{-0.4}$	$-3.2^{+0.3}_{-0.5}$
$\log_{10}(M_{\rm S}/M_\odot)$	$-1.2^{+1.8}_{-1.2}$	$-1.6^{+1.7}_{-0.7}$	$-1.6^{+2.5}_{-0.9}$
$\log_{10}(M_{\rm L}/M_\odot)$	$2.4^{+1.3}_{-3.2}$	$2.6^{+0.7}_{-0.3}$	$2.5^{+0.5}_{-0.5}$