Workshop on New Trends in Dark Matter

# Gravitational Wave Probes of Primordial Black Hole Dark Matter

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December 8, 2020

Keemilise ja Bioloogilise Füüsika Instituut
National Institute of Chemical Physics and Biophysics

white dwarf stability

neutron star capture

microlensing

wide binaries

accretion and CMB

dwarf galaxies

GWs from binaries

gamma ray background

$f_{\rm PBH} > 1$

$\tau > 1\,{\rm s}$

$\tau > t_0$

Evaporation

FL

ID

NS

K

HSC

EROS

SNe

OGLE

M

LIGO

Eri II

Seg I

Planck

WB

Ly-α

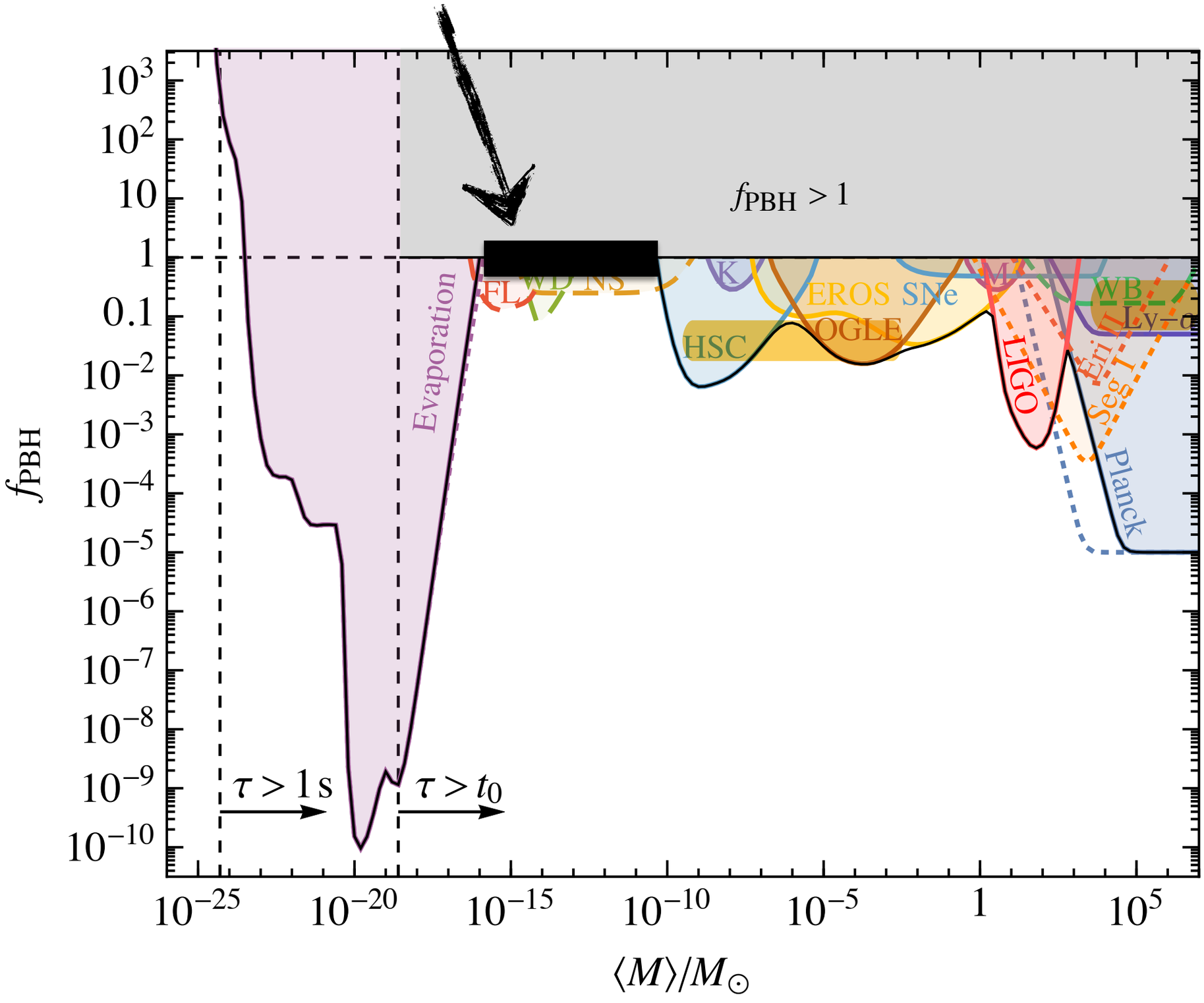
$f_{\rm PBH}$

$10^{3}$
$10^{2}$
$10$
$1$
$0.1$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$

$10^{-25}$ $10^{-20}$ $10^{-15}$ $10^{-10}$ $10^{-5}$ $1$ $10^{5}$

$\langle M \rangle / M_\odot$

# PBH as all dark matter



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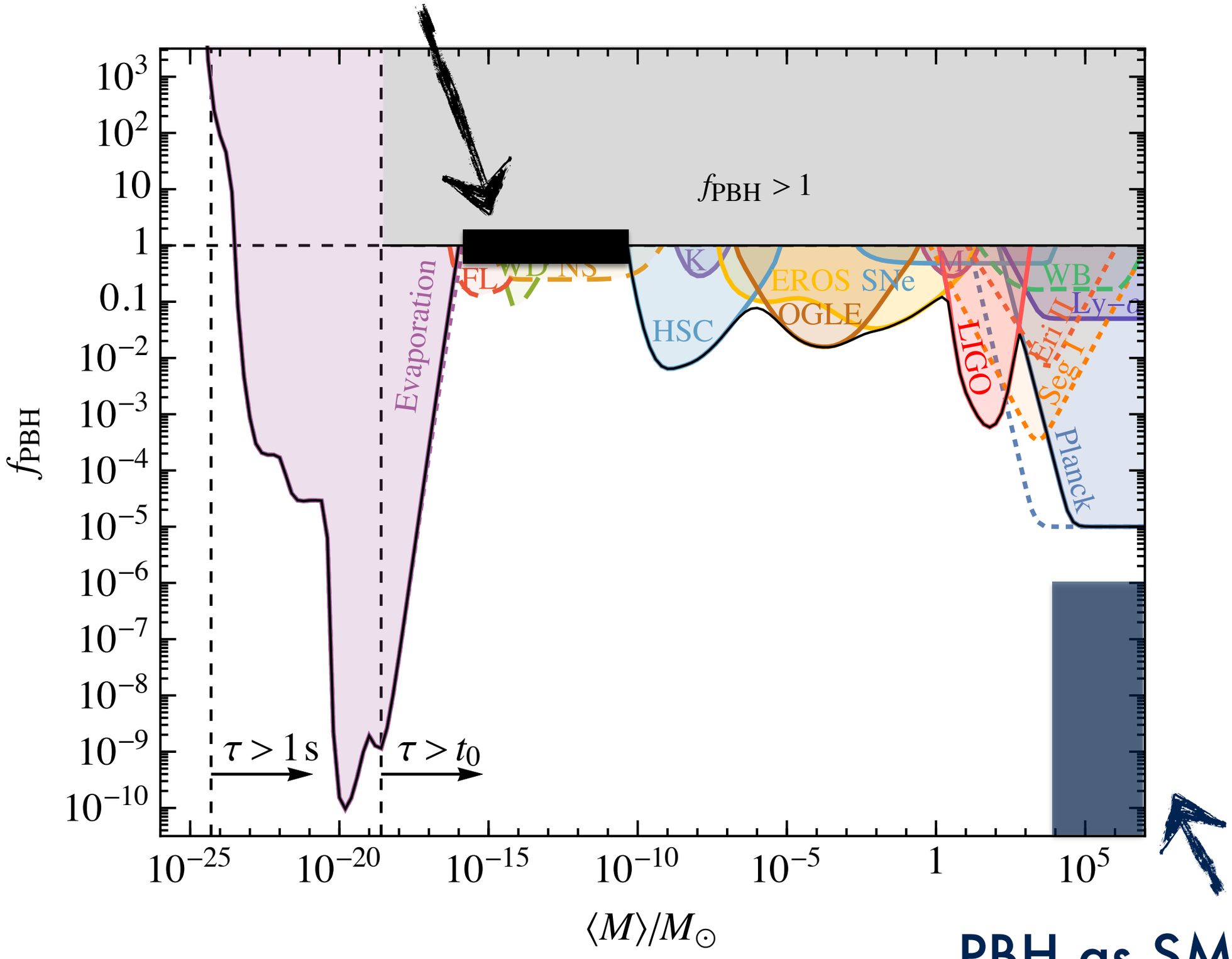
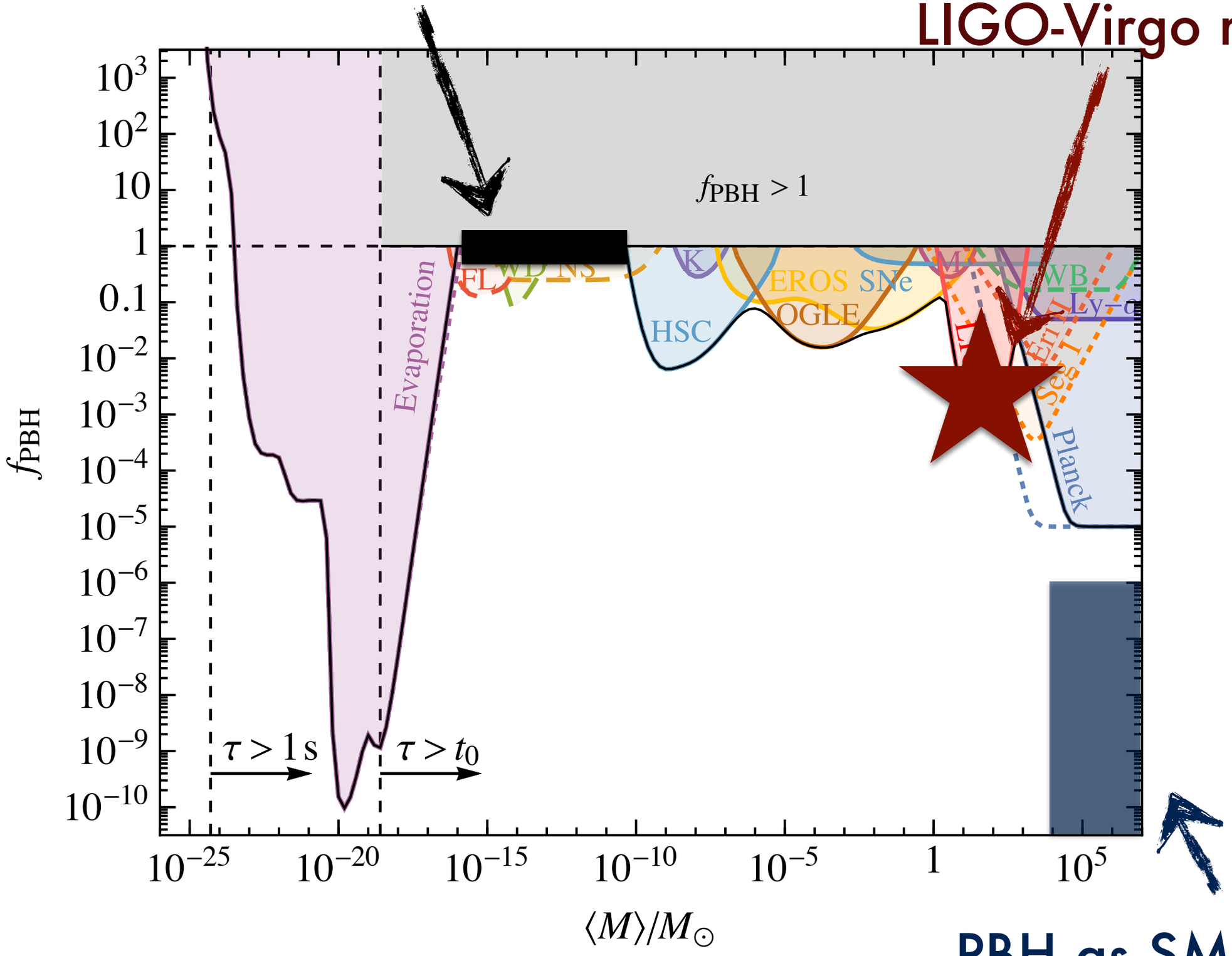



PBH as SMBH seeds

PBH as all dark matter

PBH scenario for LIGO-Virgo mergers

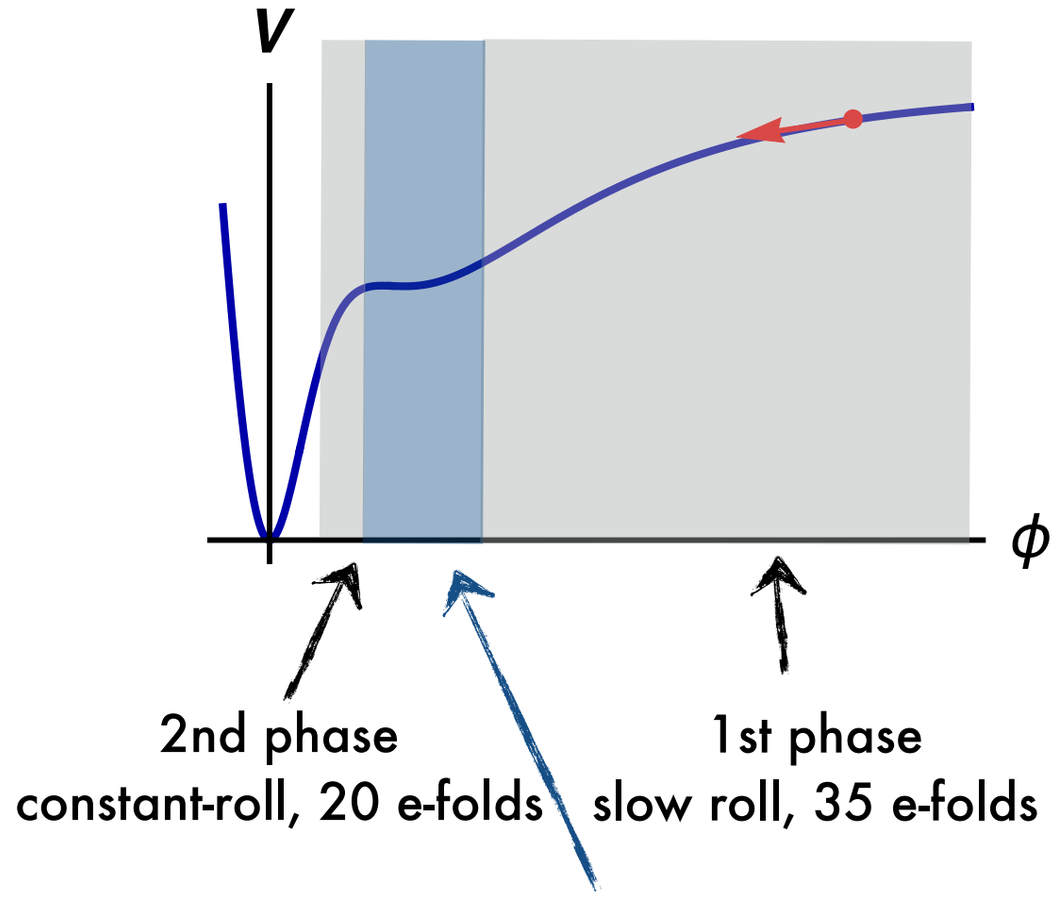



PBH as SMBH seeds

# (inflationary) PBH formation

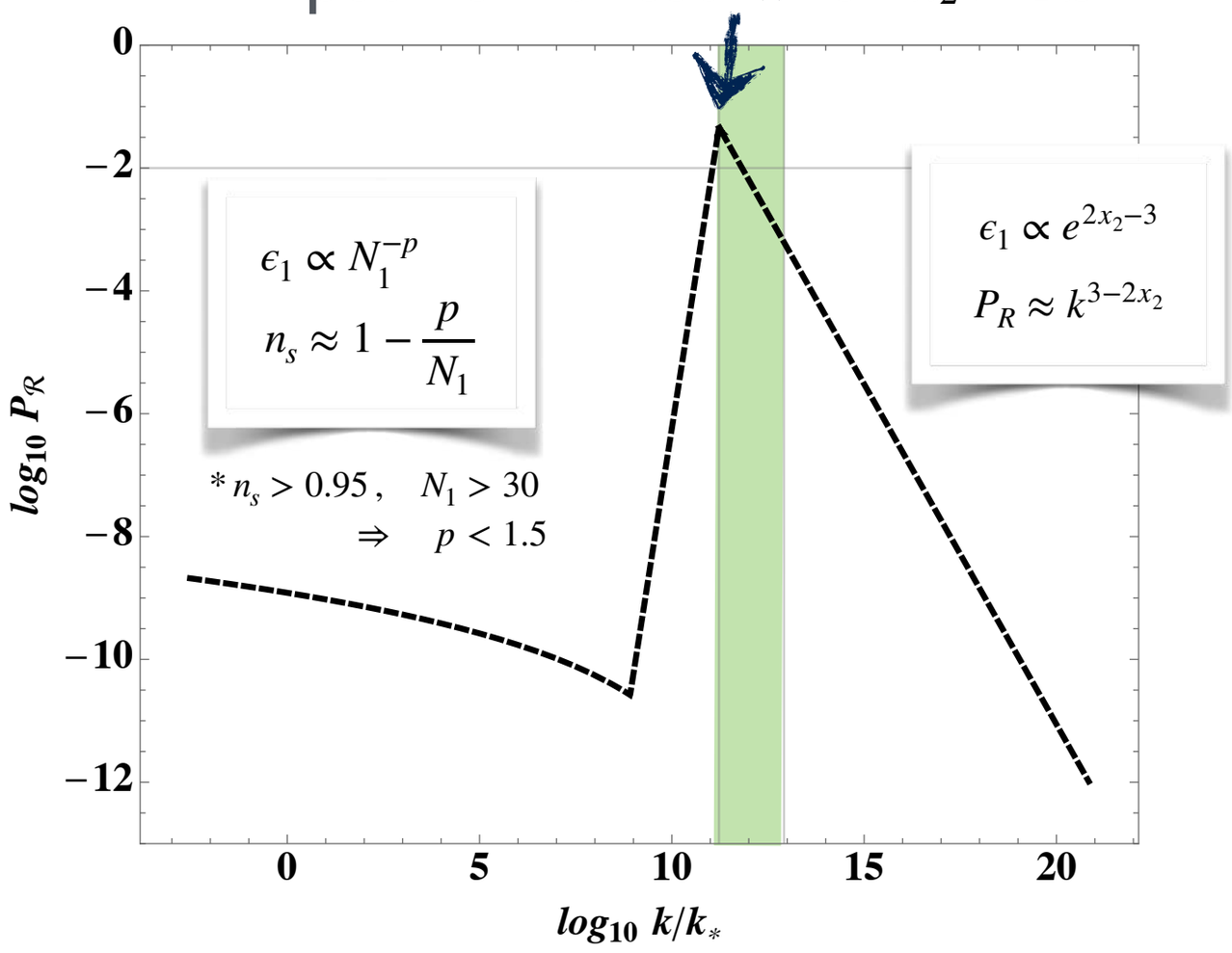
*general idea:* collapse of large inhomogeneities in the early universe

*an example:* two phase single field inflation




$$M_k \approx 30 M_\odot \left(\frac{k}{10^{-6}\mathrm{Mpc}^{-1}}\right)^2$$

peak enhanced when $x_2 > 1.5$




- *requires fine-tuning*
- *difficult to produce heavy PBHs*

[1705.06225 Kannike et al]

# PBH formation

## Critical collapse

$$m = \kappa M_k \left(\delta_m - \delta_c\right)^\gamma$$

horizon mass $M_k \approx 1.4 \times 10^{13} M_\odot \left(k/\mathrm{Mpc}^{-1}\right)^{-2}$

collapse parameters $\gamma = 0.36,\ \kappa = 4,\ \delta_c = 0.55$

*for a real-space top-hat window function [ 1904.00984 Young et al ]

non-linear relation between density contrast and curvature fluctuations $\delta_m = \delta_\zeta - (3/8)\,\delta_\zeta^2$

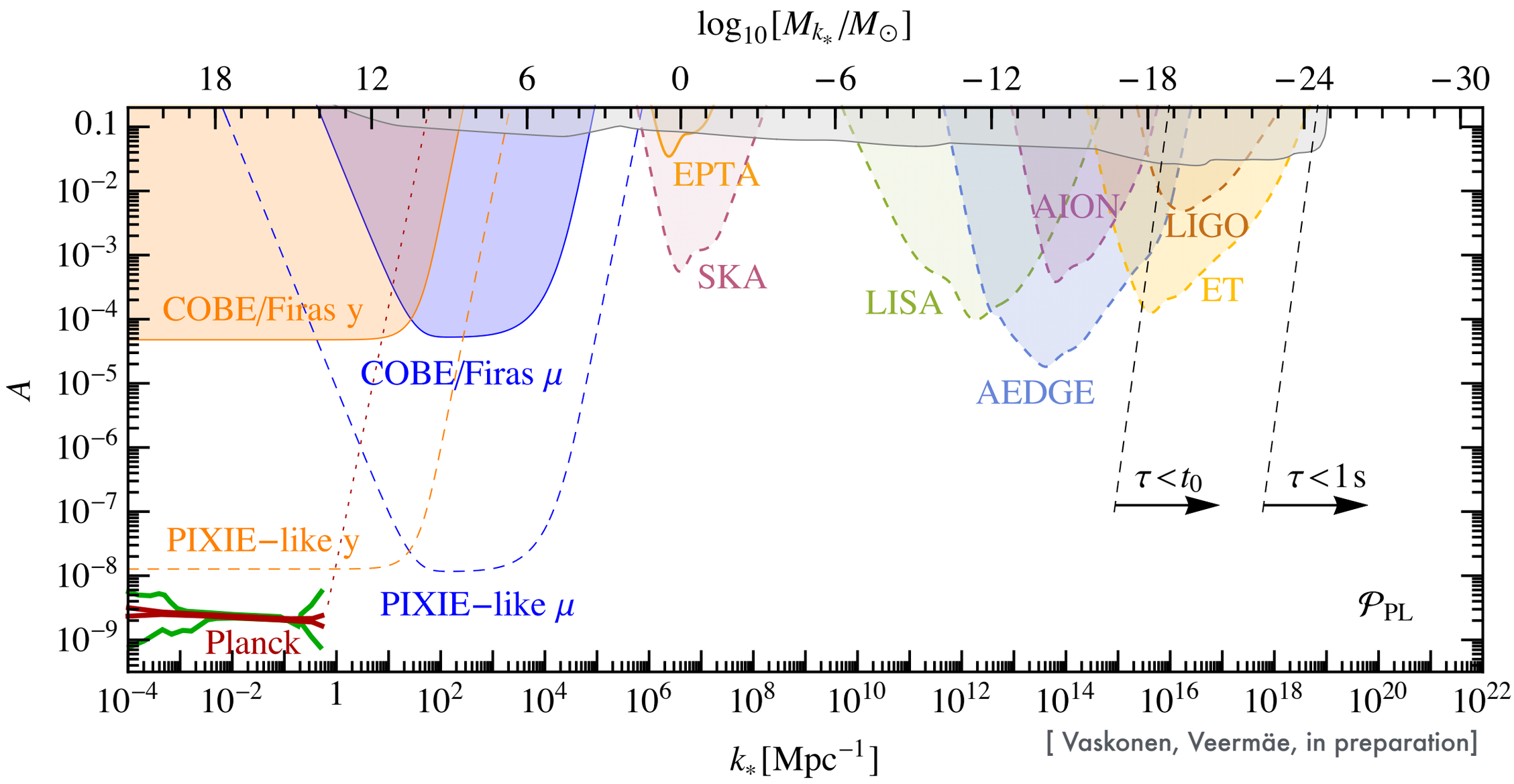
## Mass function

$$\psi(m) \propto m^{1+1/\gamma} \exp\left[-c_1 (m/\langle m \rangle)^{c_2}\right]$$

## Average PBH mass

$$\langle m \rangle \approx 3 M_k$$

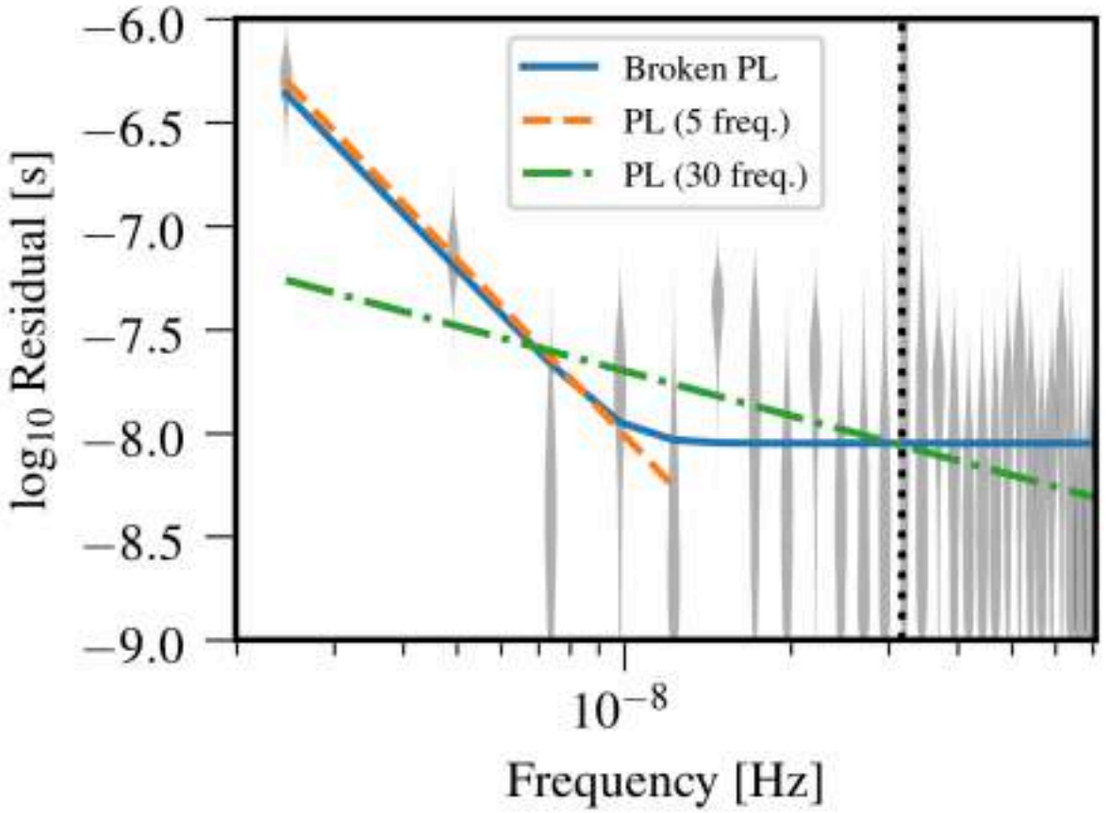
# Scalar induced GWs

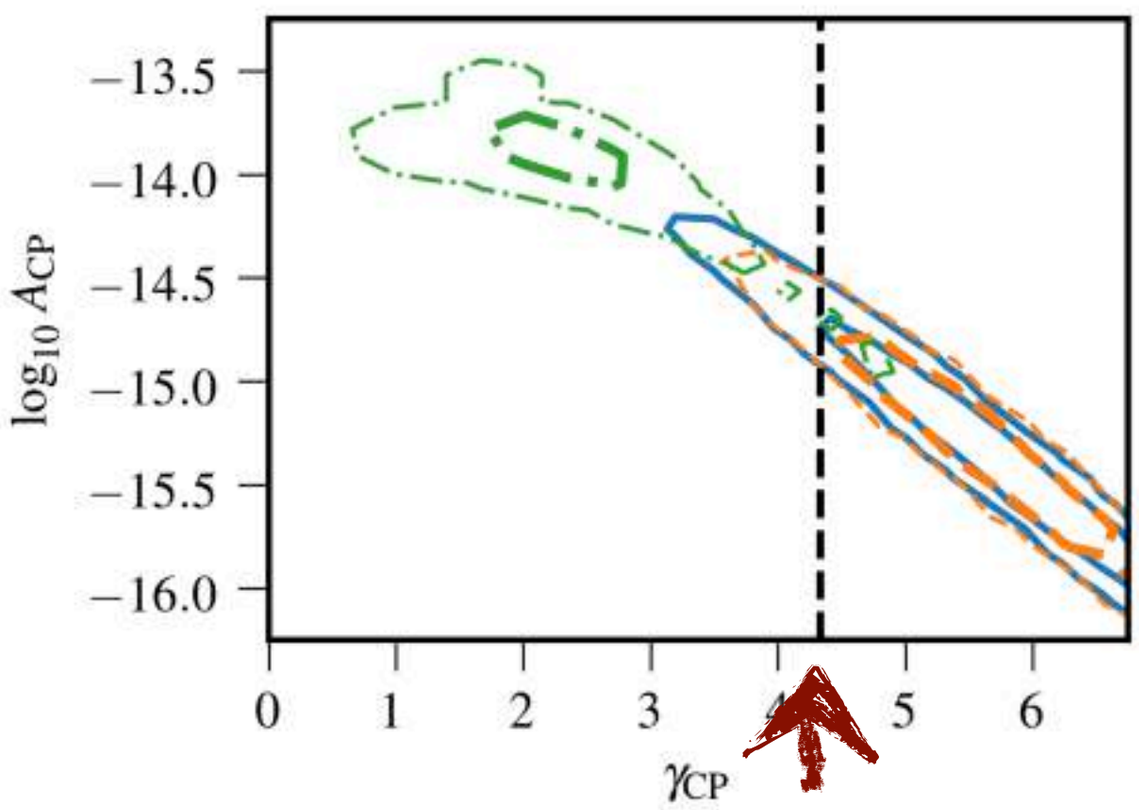



[ Vaskonen, Veermäe, in preparation]

* *Large primordial scalar perturbations source a stochastic GW background at the second order.*
* *<u>Light PBH DM scenarios testable by future GW experiments.</u>*

# the NANOGrav signal




SMBH binary inspirals

No monopolar or dipolar correlations, but also
no definite evidence for quadrupolar correlations.

→ *No definite GW detection, but we can speculate.*

[ 2009.04496 NANOGrav collaboration ]

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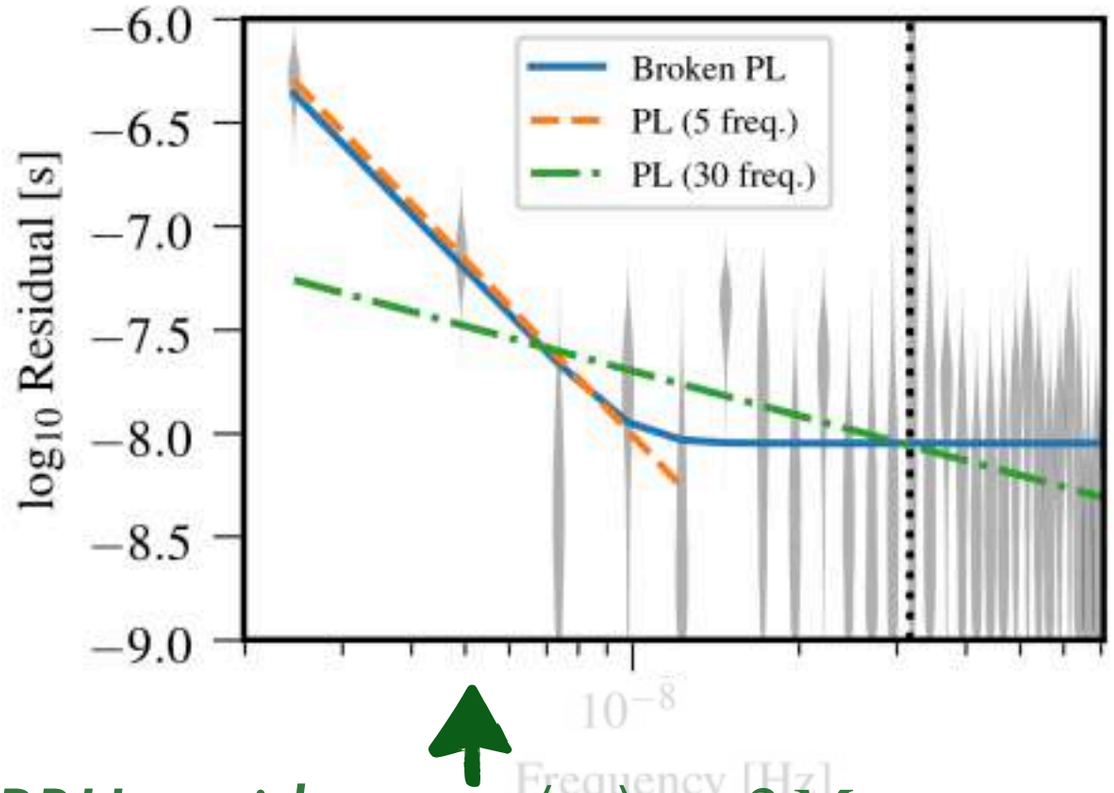
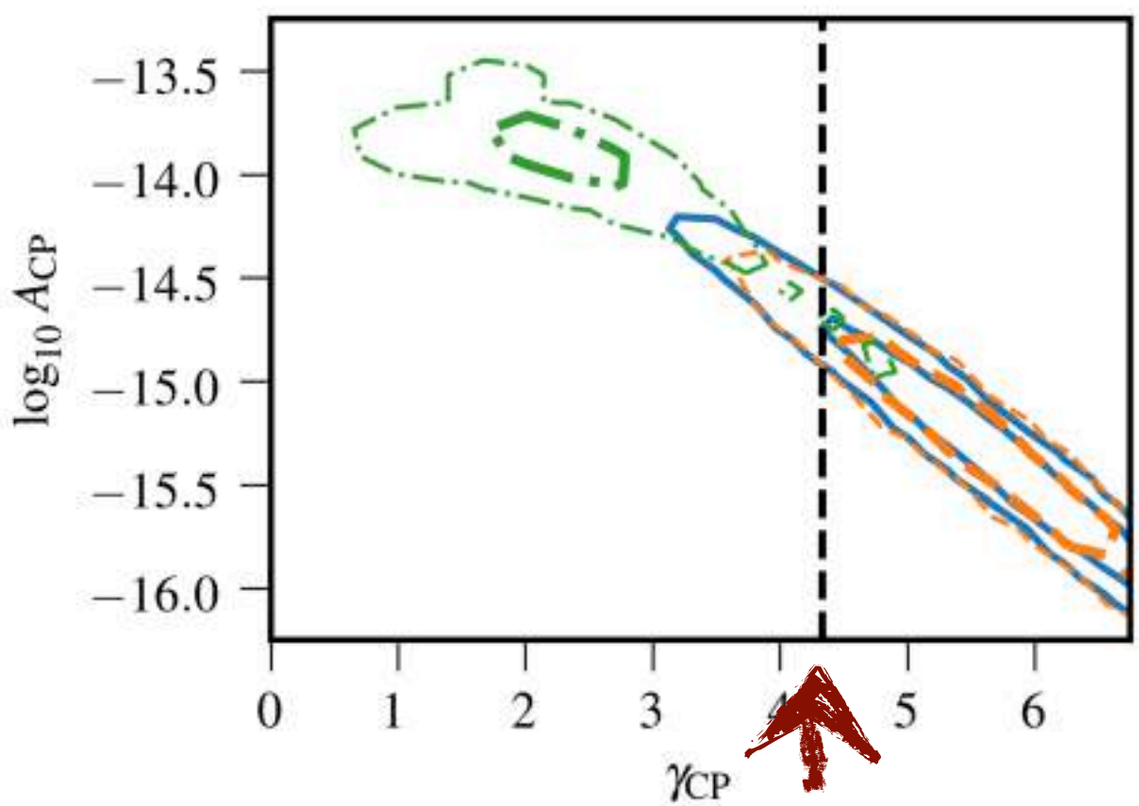



*PBHs with mass* $\langle m \rangle \approx 3M_\odot$

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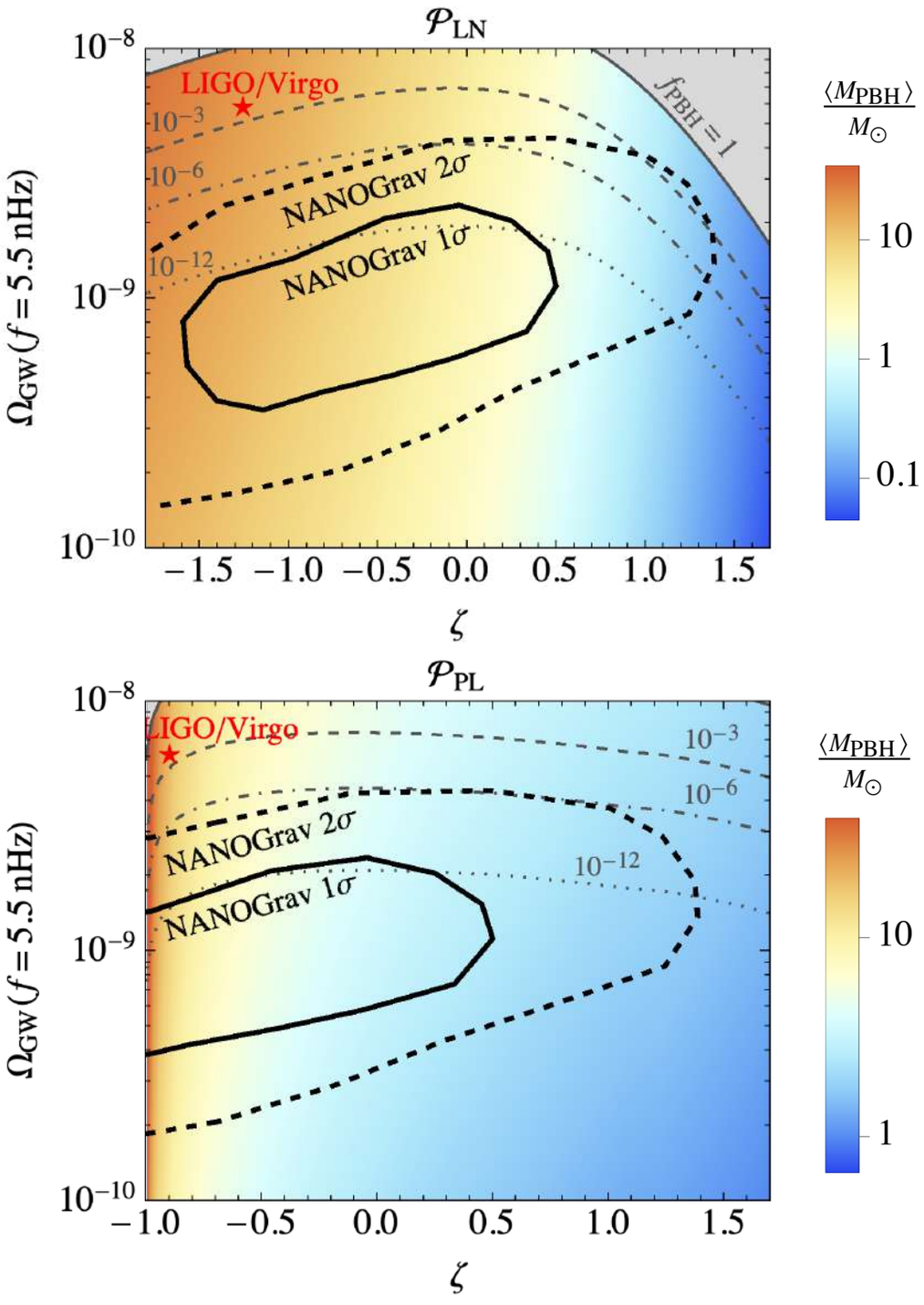
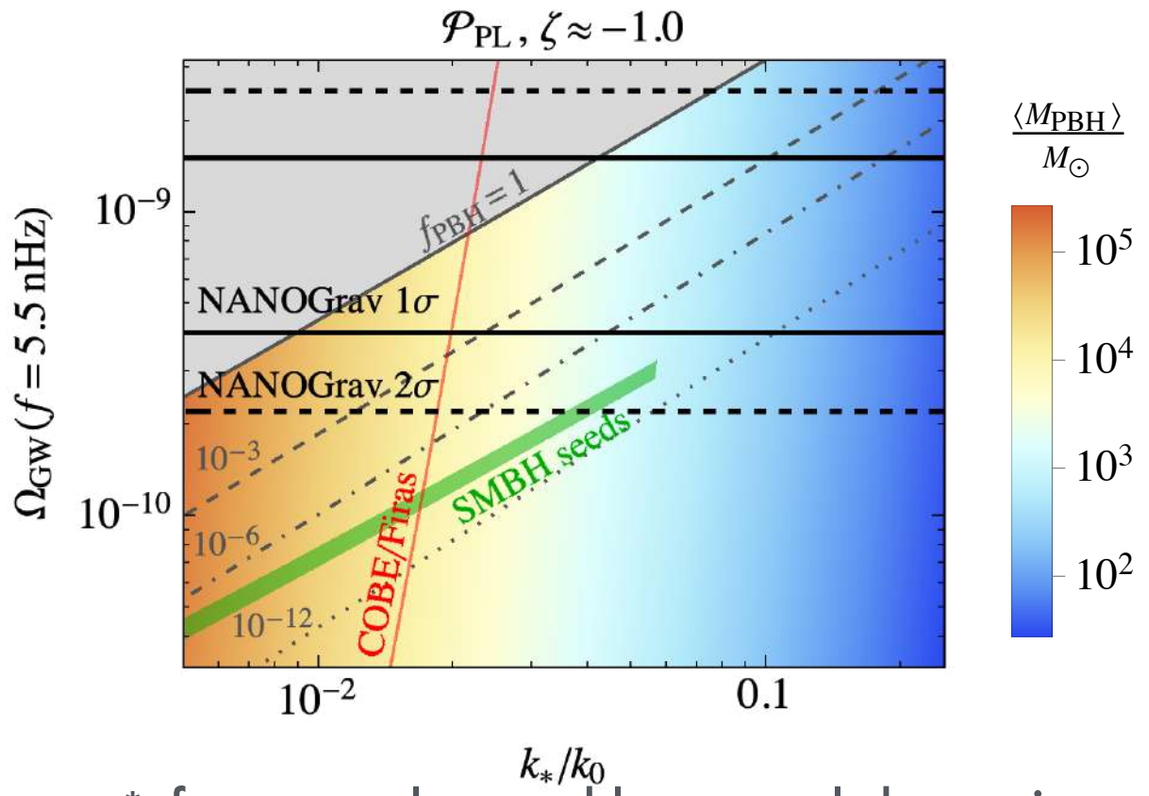
# PBH interpretations of the NANOGrav signal

## LIGO-Virgo PBH scenario

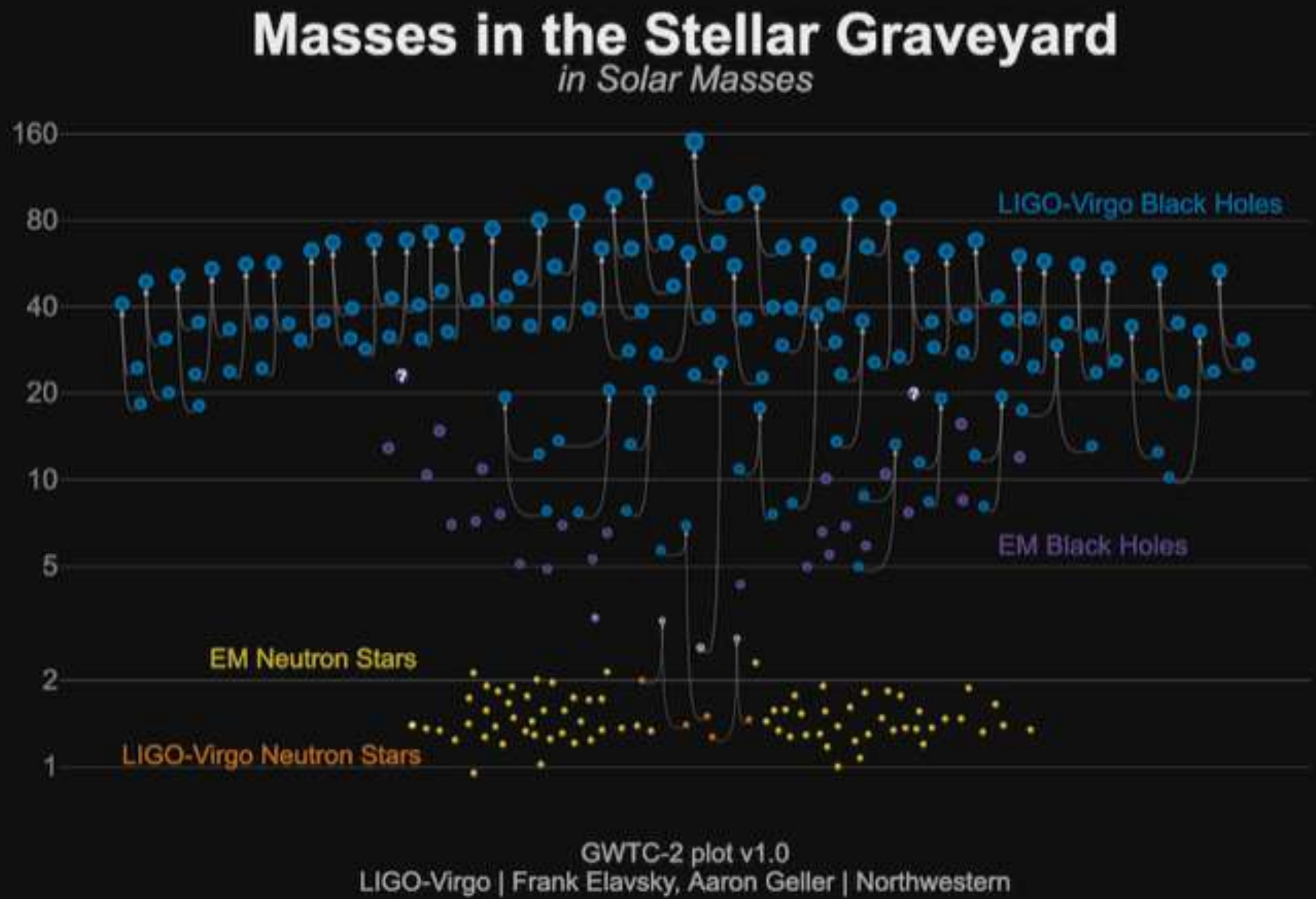



## PBH scenario for SMBH seeds




* for power law and lognormal shapes in curvature power spectra
* $k_*$ is the position of the peak and $A$ is of the peak are varied
* curvature fluctuations assumed to be gaussian
* potentially large uncertainties related to the PBH formation process

[ 2009.07832 Vaskonen et al ]




# BHs after LIGO-Virgo O3a

# discriminators of binary BH populations

- Mass distribution
  - PBHs tend to have simple peaked mass distributions
  - astrophysical BHs have a low mass cut-off around $3M_\odot$, pair-instability supernova (PISN) gap around $55 - 130M_\odot$

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  - PBHs initially non-spinning, spin aquired by accretion [ e.g. 2011.01865 Wong et al ]
  - spins of astrophysical BHs expected to be aligned , depends on the production channel

EFFECTIVE SPIN

$$\chi_{\rm eff} = \frac{m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2}{M} \cdot \hat{L}_{\rm orbital}$$

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# PBH Binary formation

*Poisson distribution of surrounding PBH*

* *does not have to be Poisson*

*Forces acting on the pair:*

$$\mathbf{F}/\mu = \underbrace{\mathbf{r}\ddot{a}/a}_{\text{Hubble flow}} - \underbrace{M\hat{\mathbf{r}}/r^2}_{\text{self-gravity}} + \underbrace{(\hat{\mathbf{r}}\cdot\mathbf{T}\cdot\mathbf{r})\hat{\mathbf{r}}}_{\text{radial tidal forces}} + \underbrace{(\mathbf{r}\times(\mathbf{T}\cdot\mathbf{r}))}_{\text{tidal torque}}\times(\hat{\mathbf{r}}/r)$$

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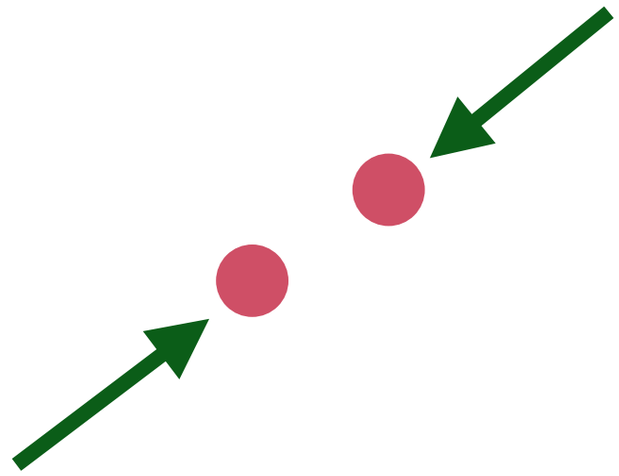

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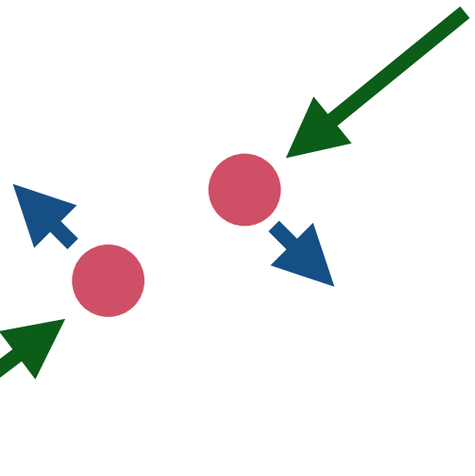

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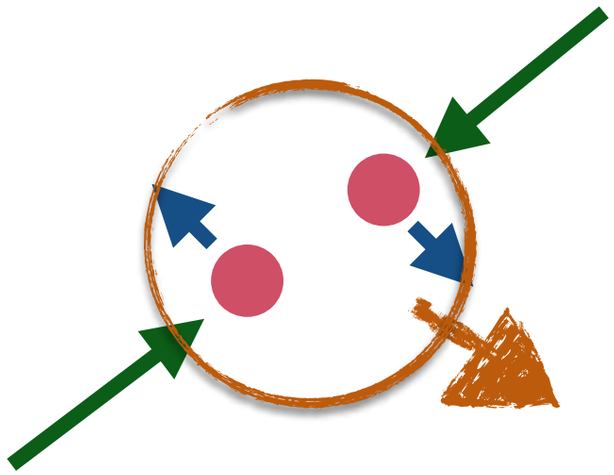

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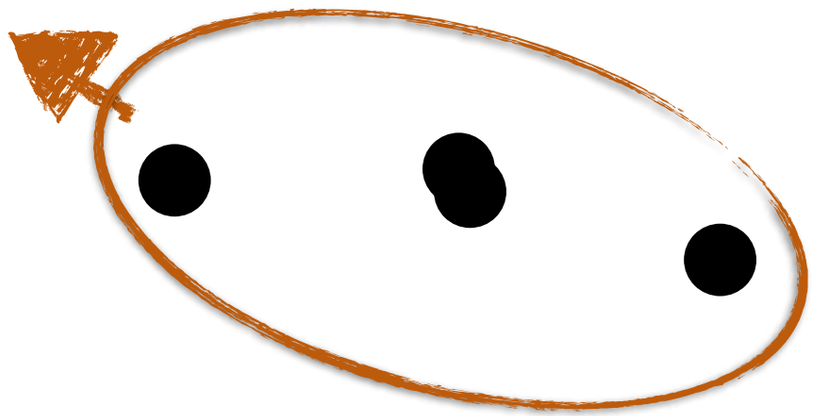

*3. interations with surrounding PBH*

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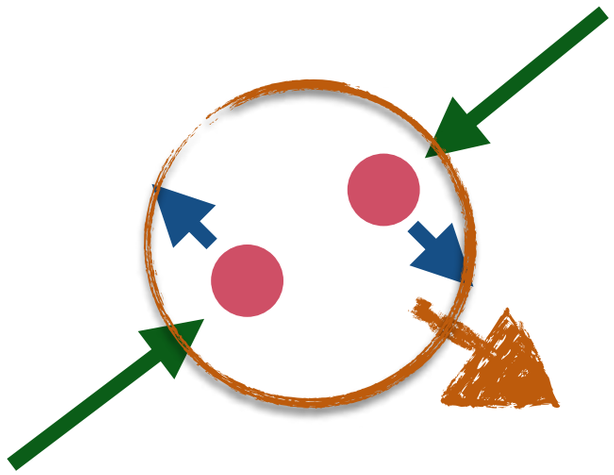

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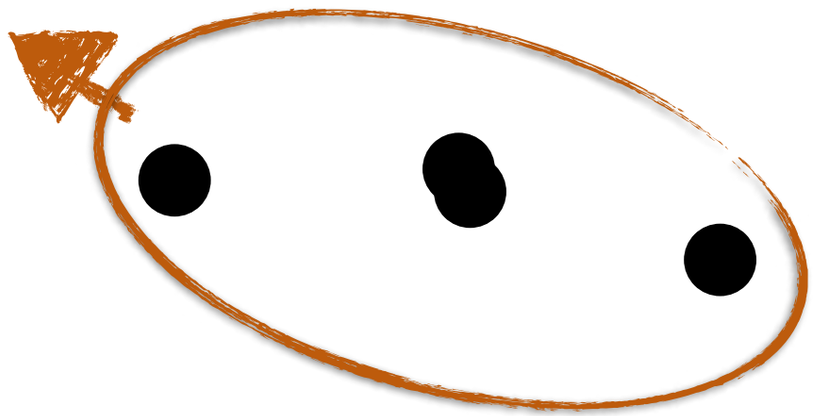

*3.1 infall of the nearest PBH*
*3.2 collisions within PBH clusters/haloes*

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# PBH binaries

## MERGER RATE

$$R_{\rm early} \approx \frac{2.8\times10^6}{\rm Gpc^3 yr} f_{\rm PBH}^{\frac{53}{37}} \left(\frac{t}{t_0}\right)^{-\frac{34}{37}} \left(\frac{m}{M_\odot}\right)^{-\frac{32}{37}} \times S_{\rm sup}$$

**PBH BINARY SUBPOPULATIONS: perturbed initial binaries, binaries formed in present DM haloes, ...*

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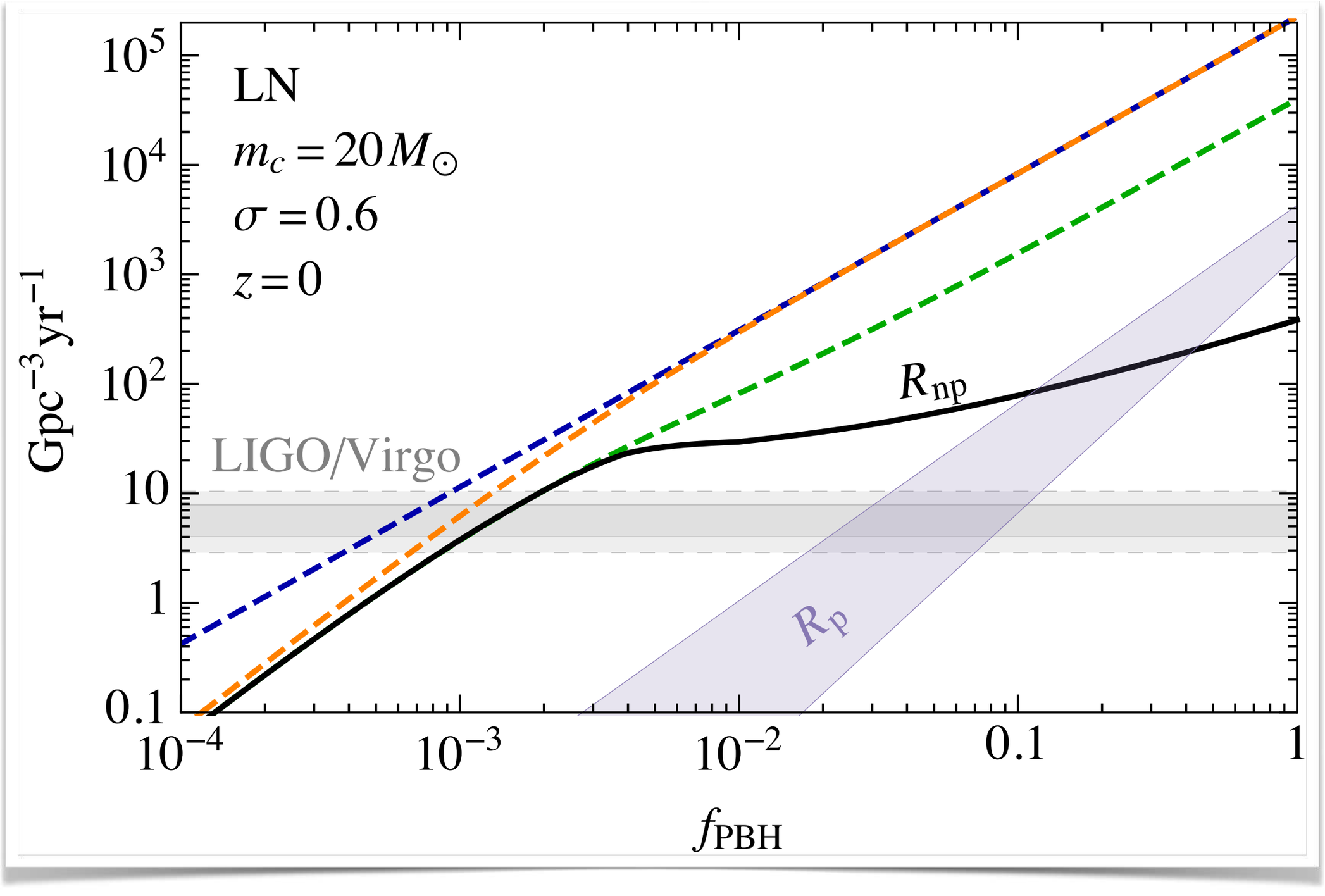
## TYPICAL CHARACTERISTICS

*These PBH binaries are...*

- Hard => collisions tend to harden them further
- Extremely eccentric => collisions tend to reduce eccentricity, increase coalescence time

**PBH BINARY SUBPOPULATIONS: perturbed initial binaries, binaries formed in present DM haloes, ...*

# PBH binary merger rate

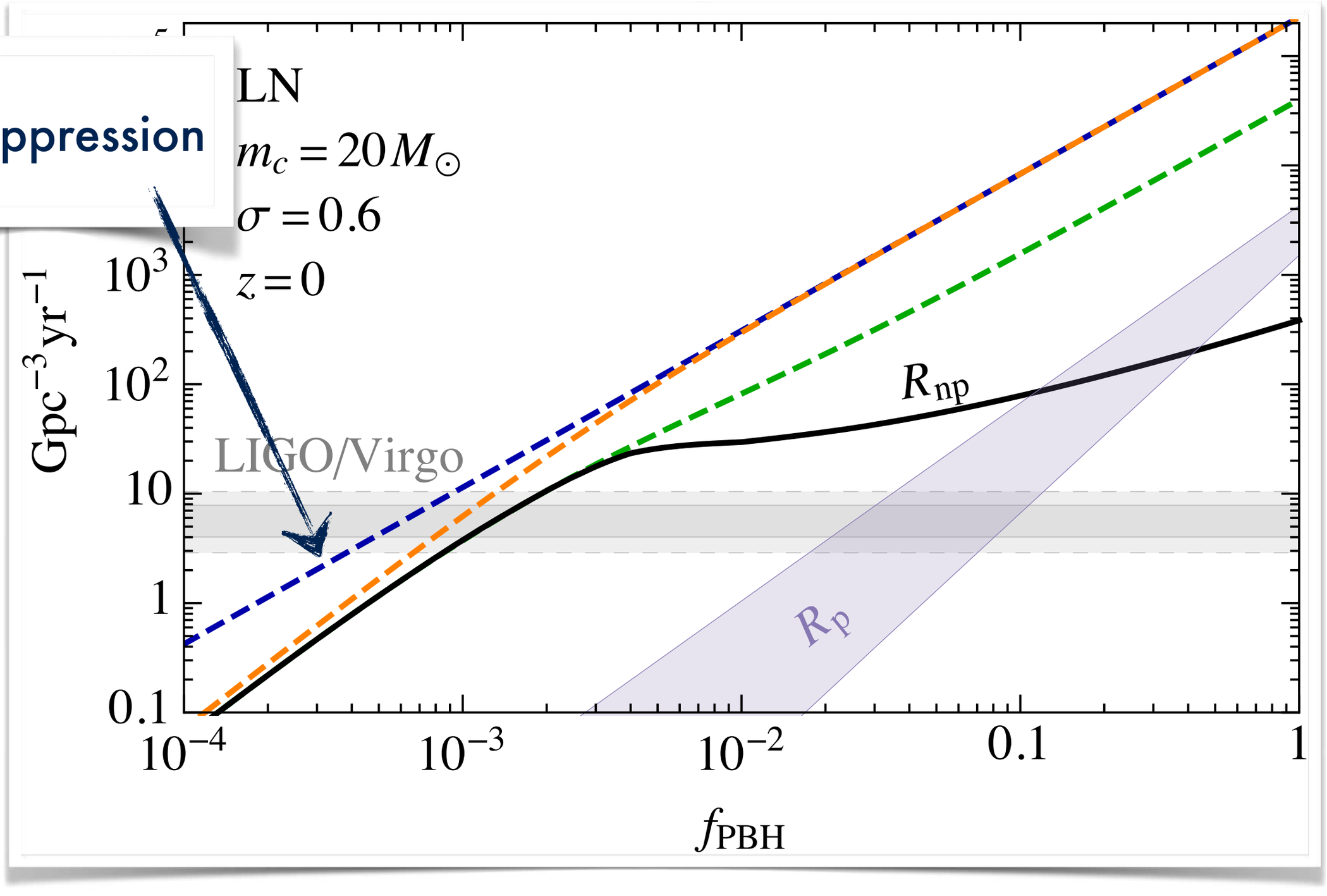



**assuming a log-normal mass function* $\psi(m) \propto \exp\left[-\ln^2(m/m_c)/(2\sigma^2)\right]$

[ 2012.02786 Vaskonen et al ]

# PBH binary merger rate

no suppression

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infall of nearest PBH

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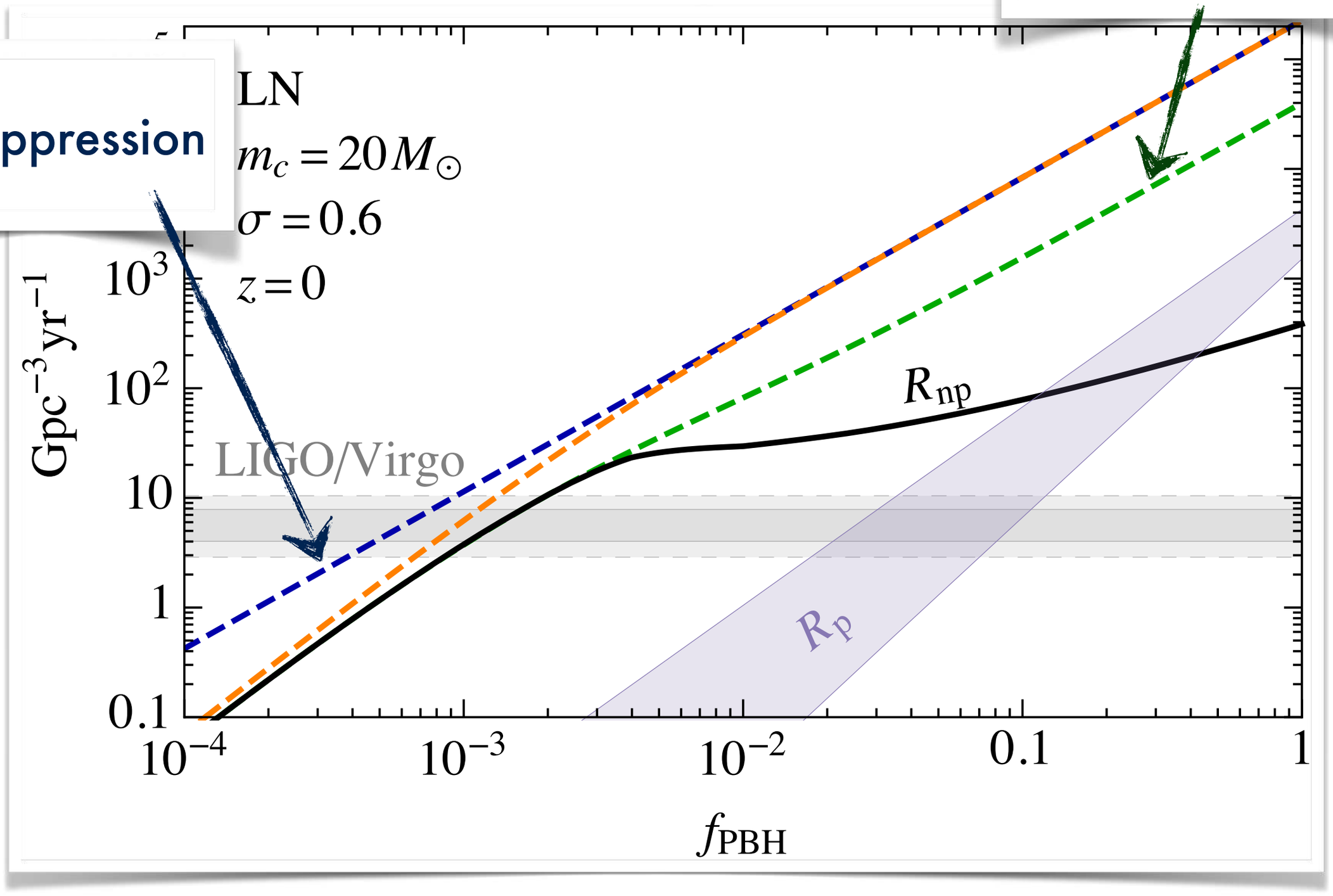


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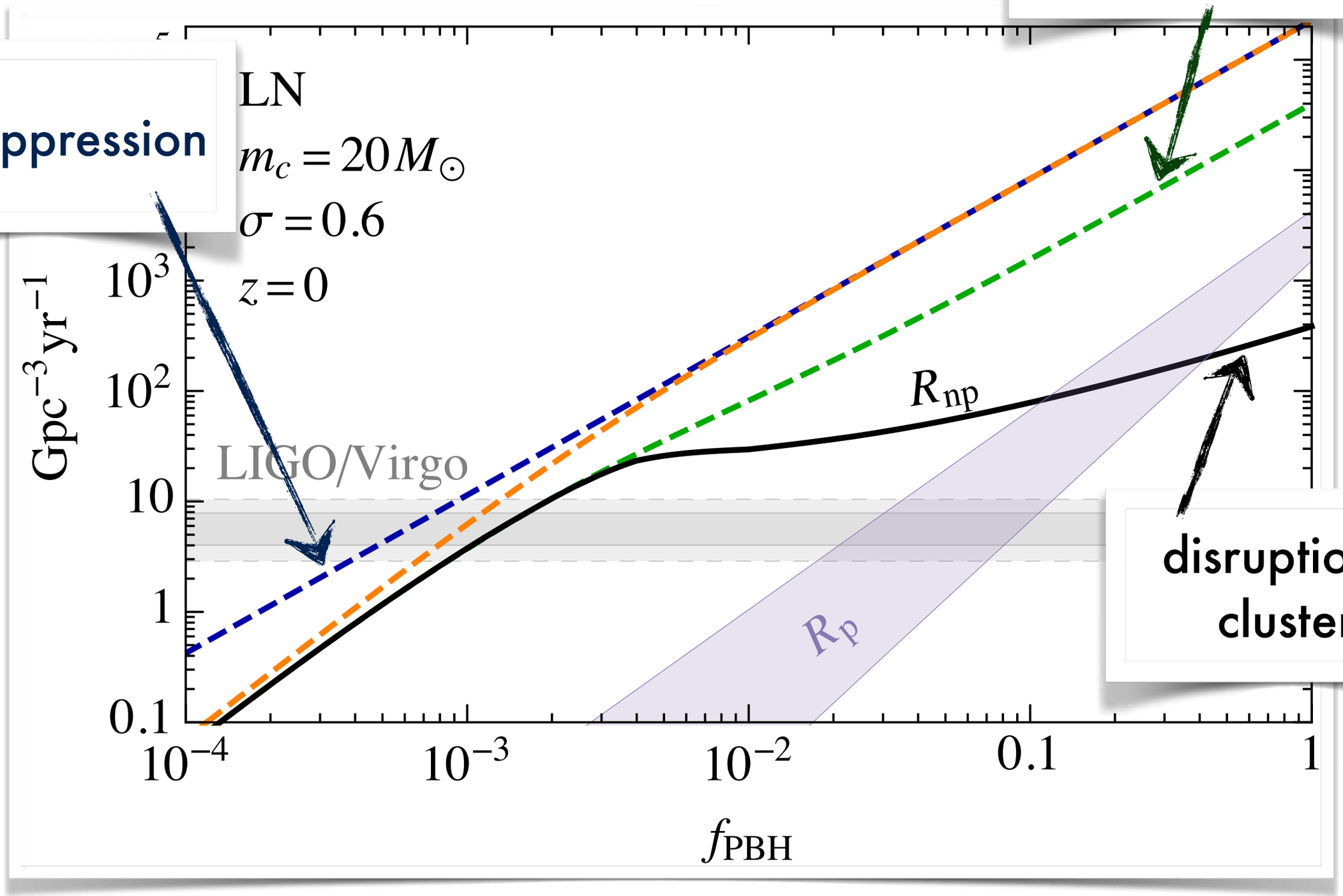


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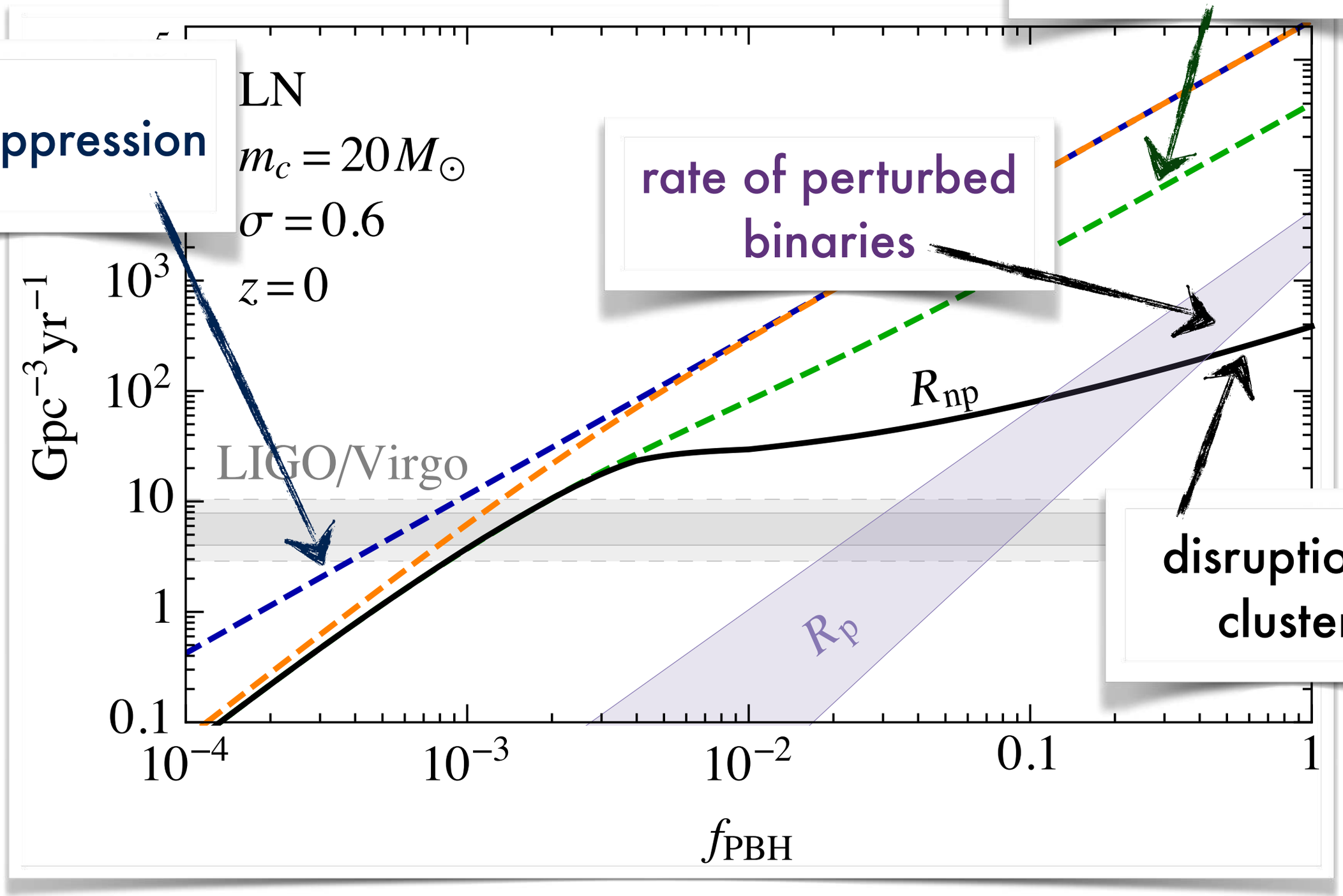
rate of perturbed binaries




disruption in clusters

**assuming a log-normal mass function* $\psi(m) \propto \exp\left[-\ln^2(m/m_c)/(2\sigma^2)\right]$

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# best-fit scenarios for the LIGO-Virgo events

*the log-normal mass function*

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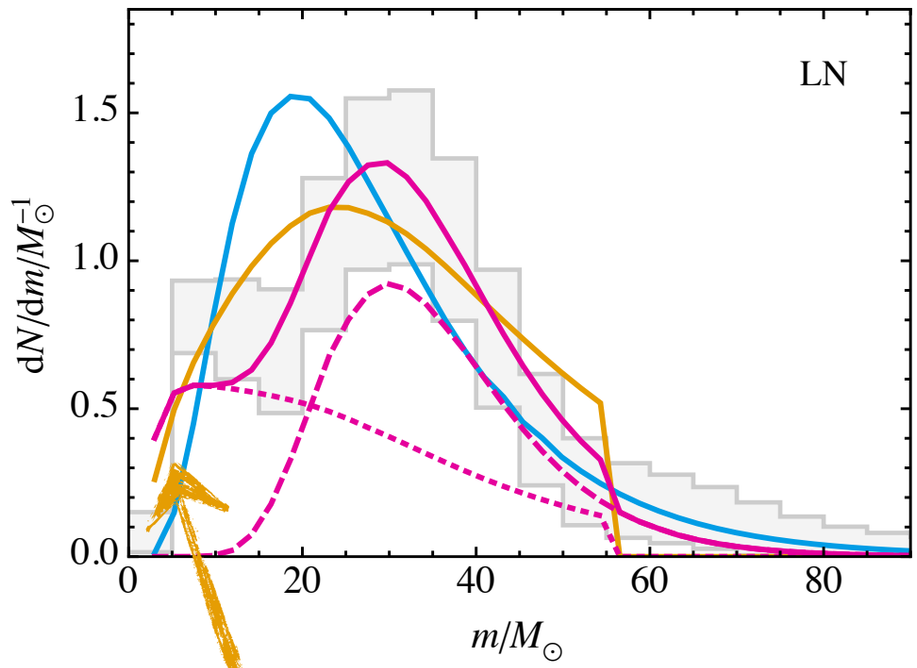
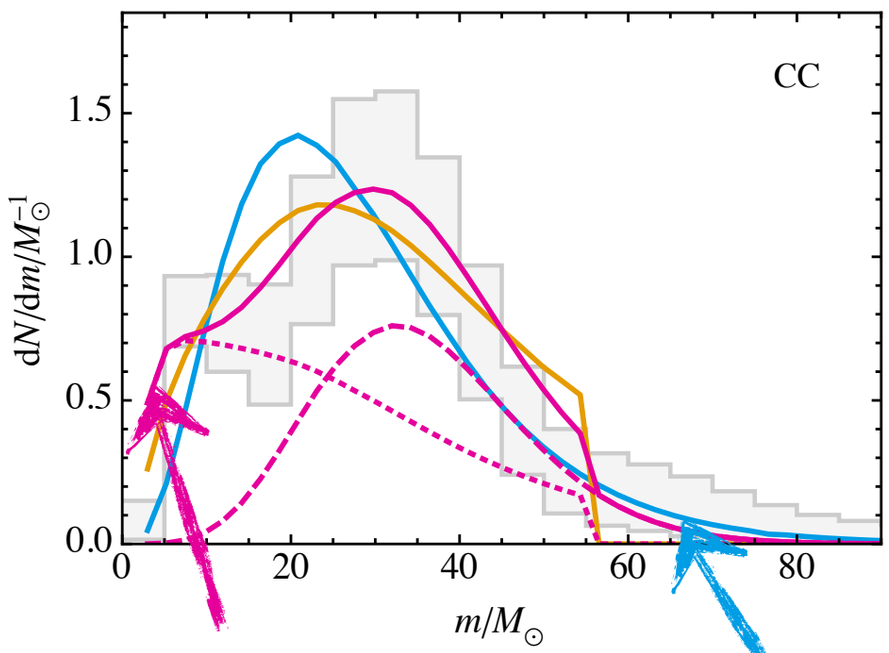



astrophysical BH only

*the critical collapse mass function*

$$\psi(m) \propto m^{1+1/\gamma} \exp\left[-c_1(m/\langle m\rangle)^{c_2}\right]$$

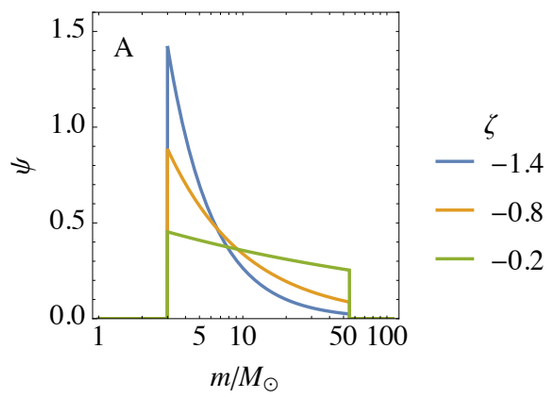



PBH + astrophysical BH

PBH only

*Our naive model for astrophysical BH:*

* *a power law mass distribution truncated at* $3M_\odot$ *and* $55M_\odot$
* *z-dependence derived from star formation*

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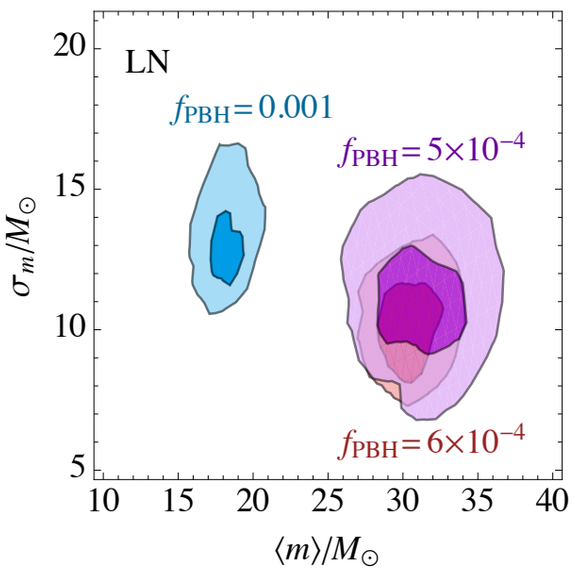
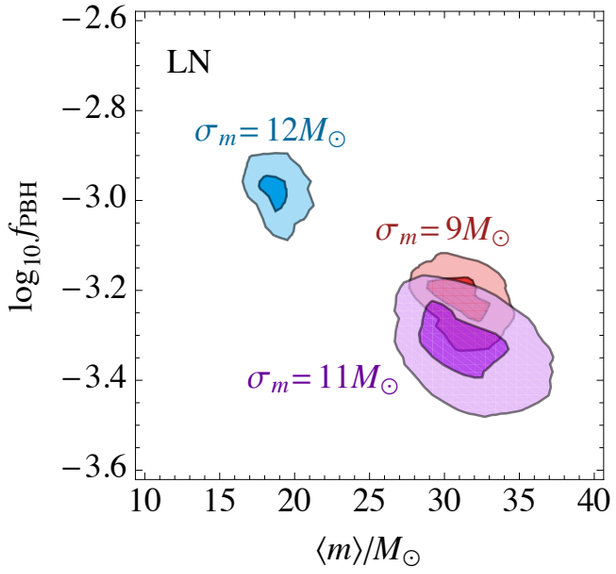
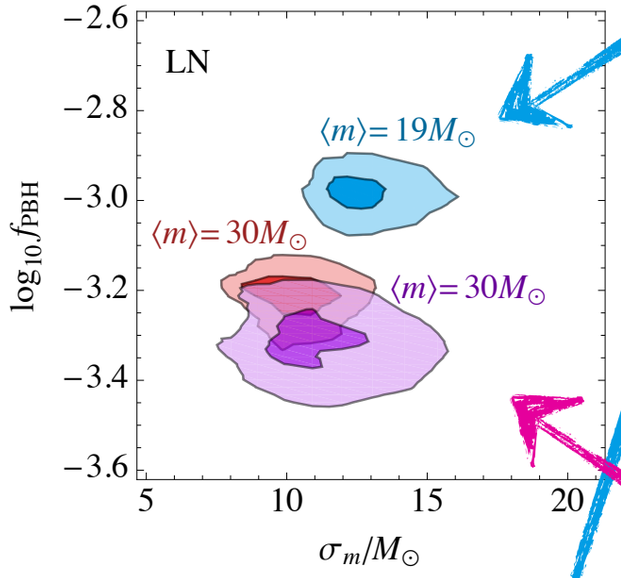
# fitting LIGO-Virgo events



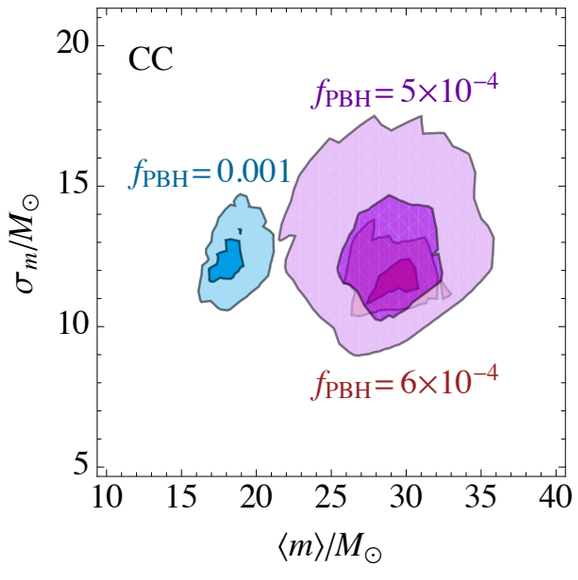



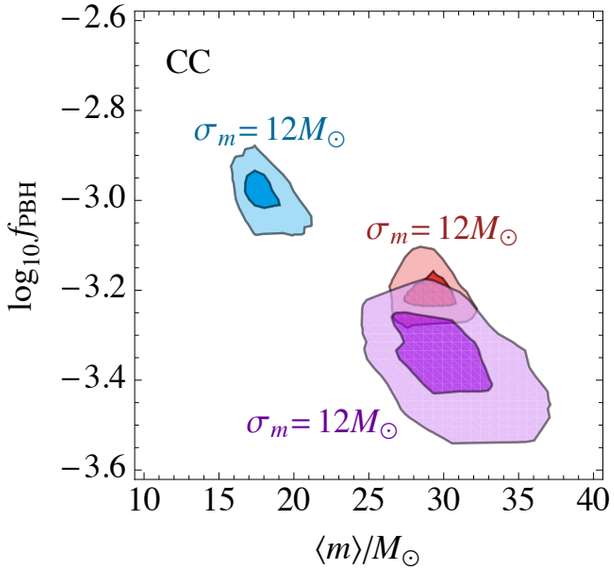



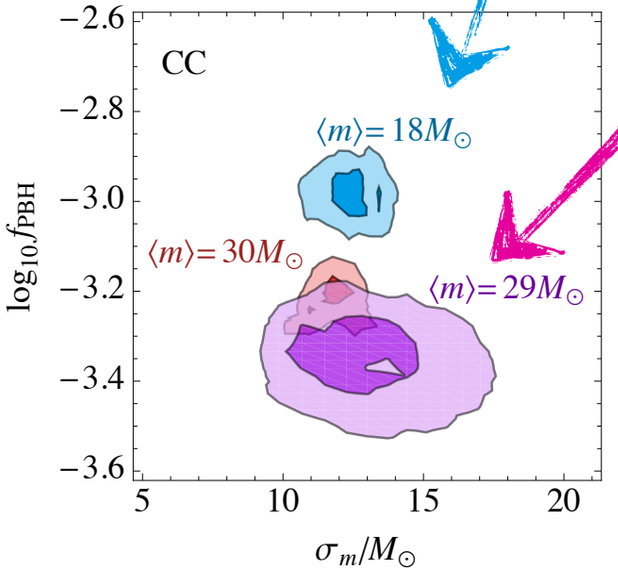

PBH only

PBH + astrophysical BH

*LN: the log-normal mass function* $\psi(m) \propto \exp\left[-\ln^2(m/m_c)/(2\sigma^2)\right]$



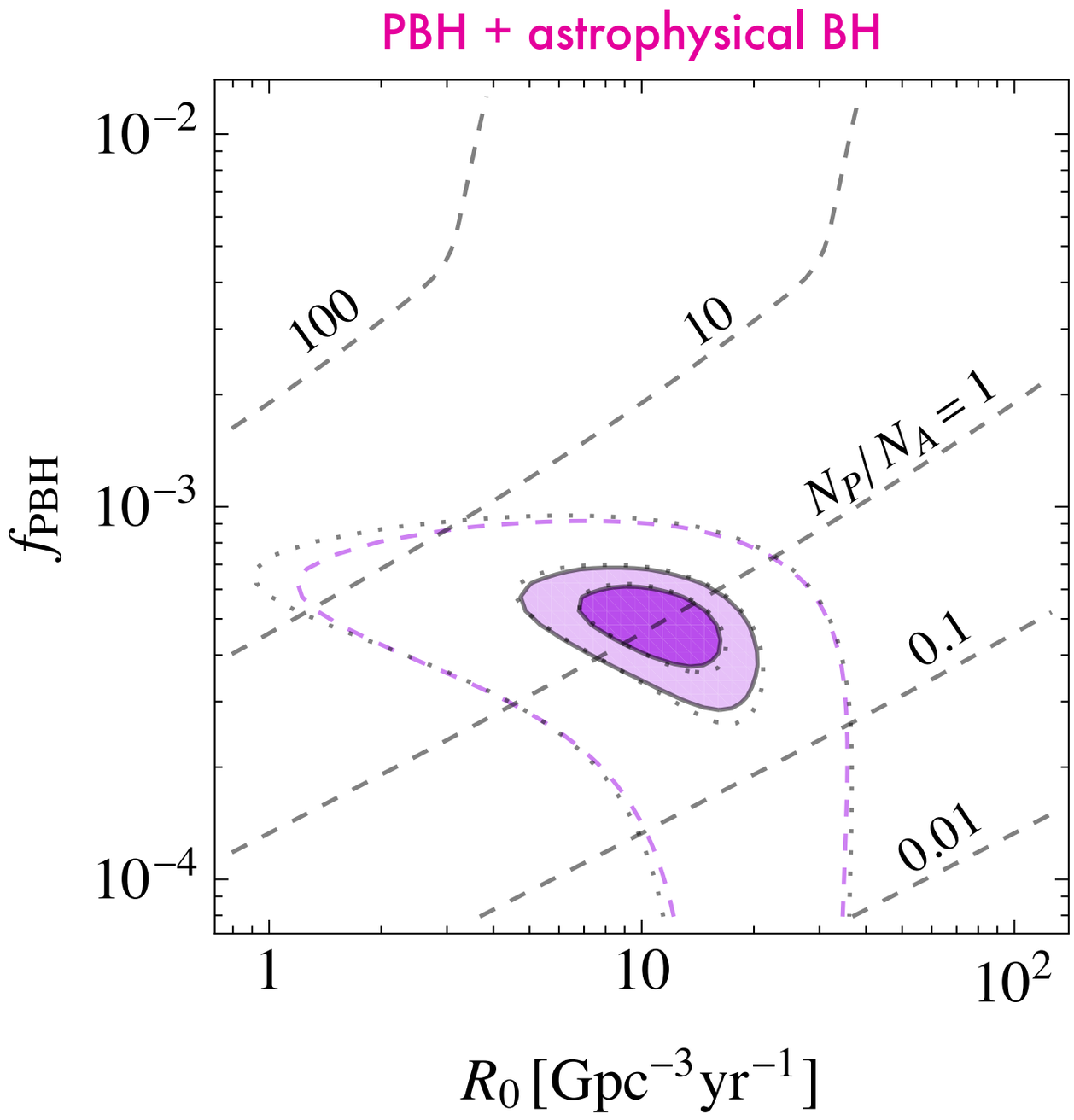




*CC: the critical collapse mass function* $\psi(m) \propto m^{1+1/\gamma}\exp\left[-c_1(m/\langle m\rangle)^{c_2}\right]$

[ 2012.02786 Vaskonen et al ]

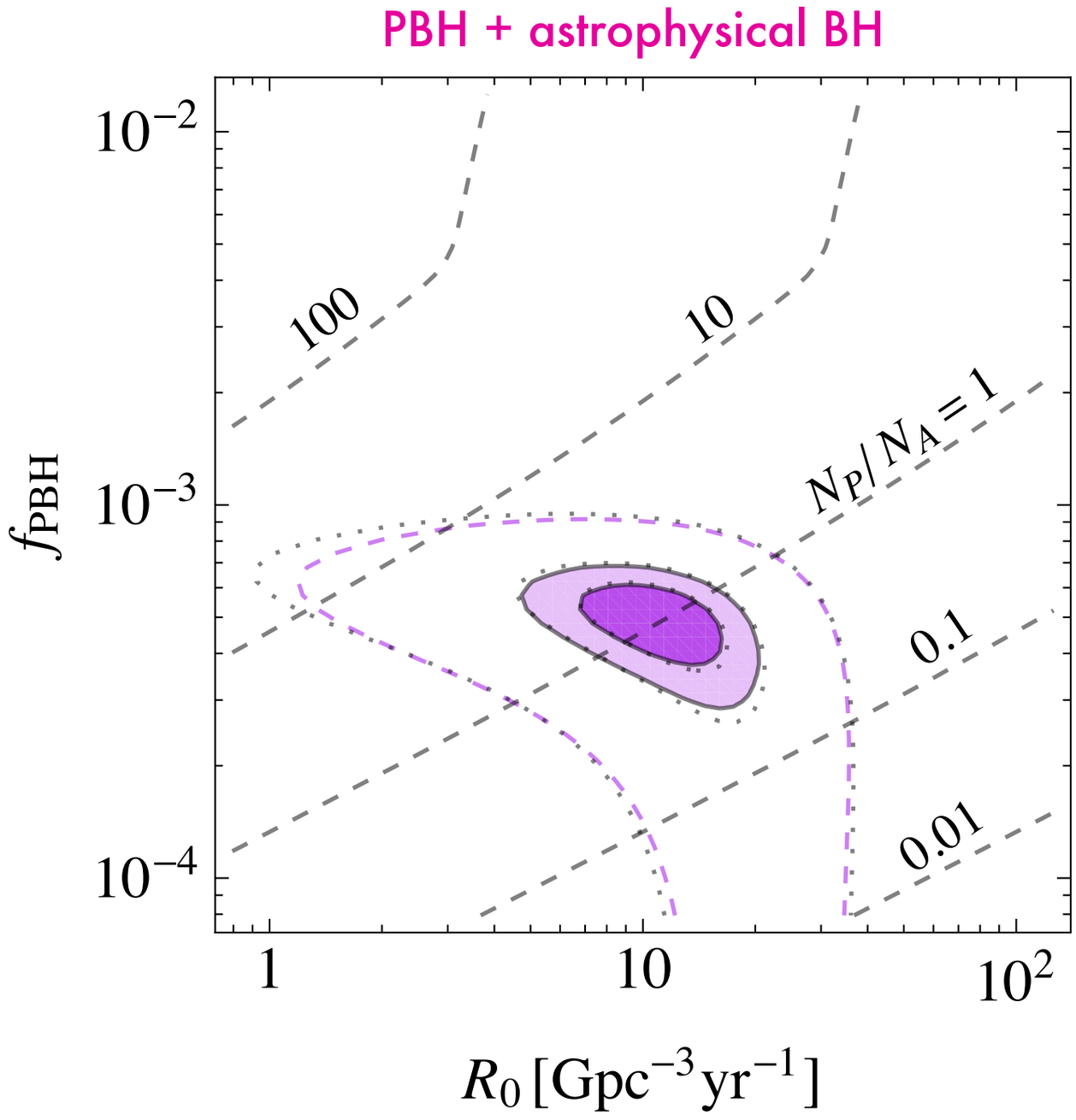
# fitting LIGO-Virgo events




*$R_0$ - present merger rate of the astrophysical component*

[ 2012.02786 Vaskonen et al ]

# fitting LIGO-Virgo events

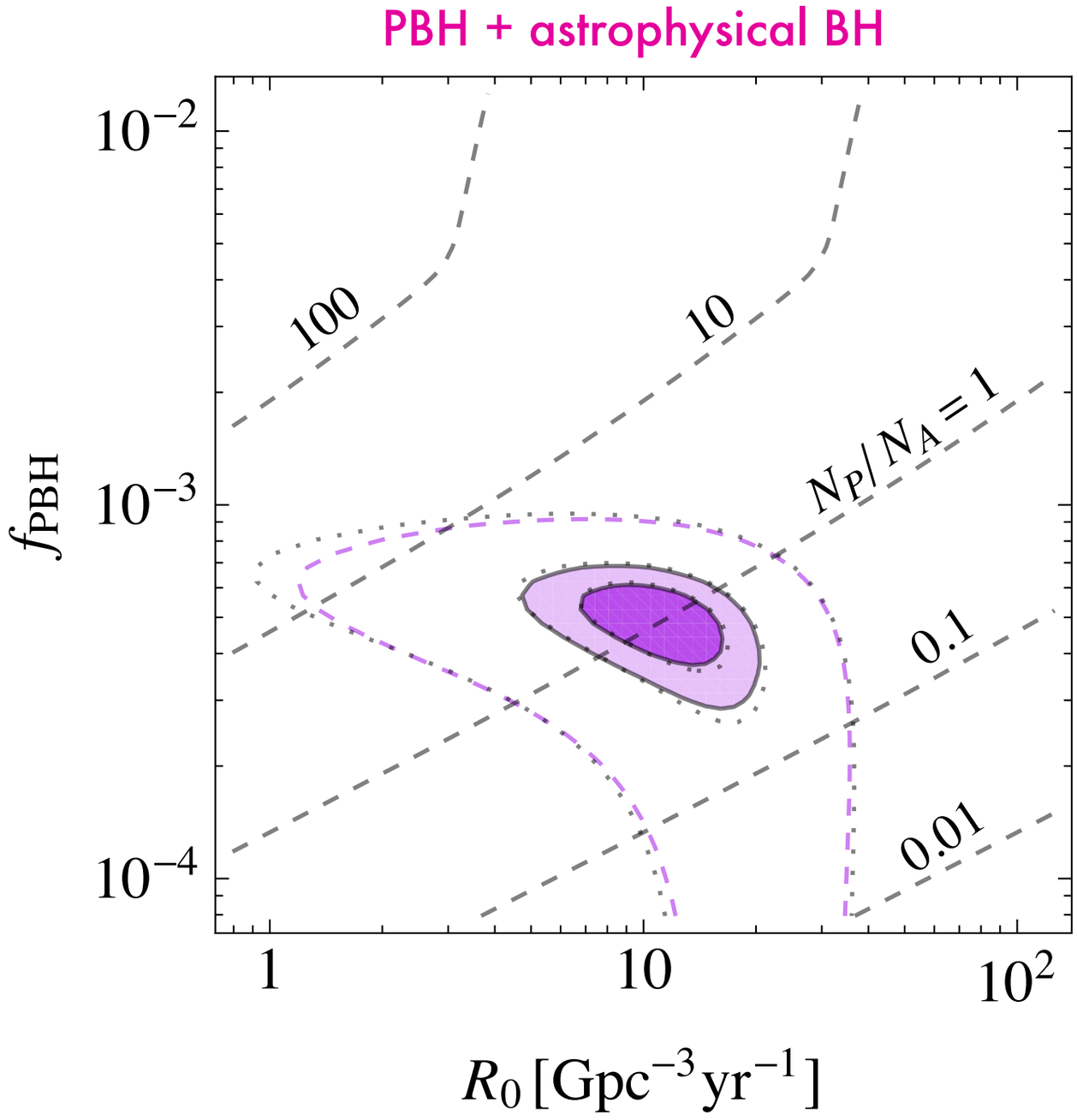



- Both populations contain a roughly equal number of events

*$R_0$ - present merger rate of the astrophysical component*

[ 2012.02786 Vaskonen et al ]

# fitting LIGO-Virgo events



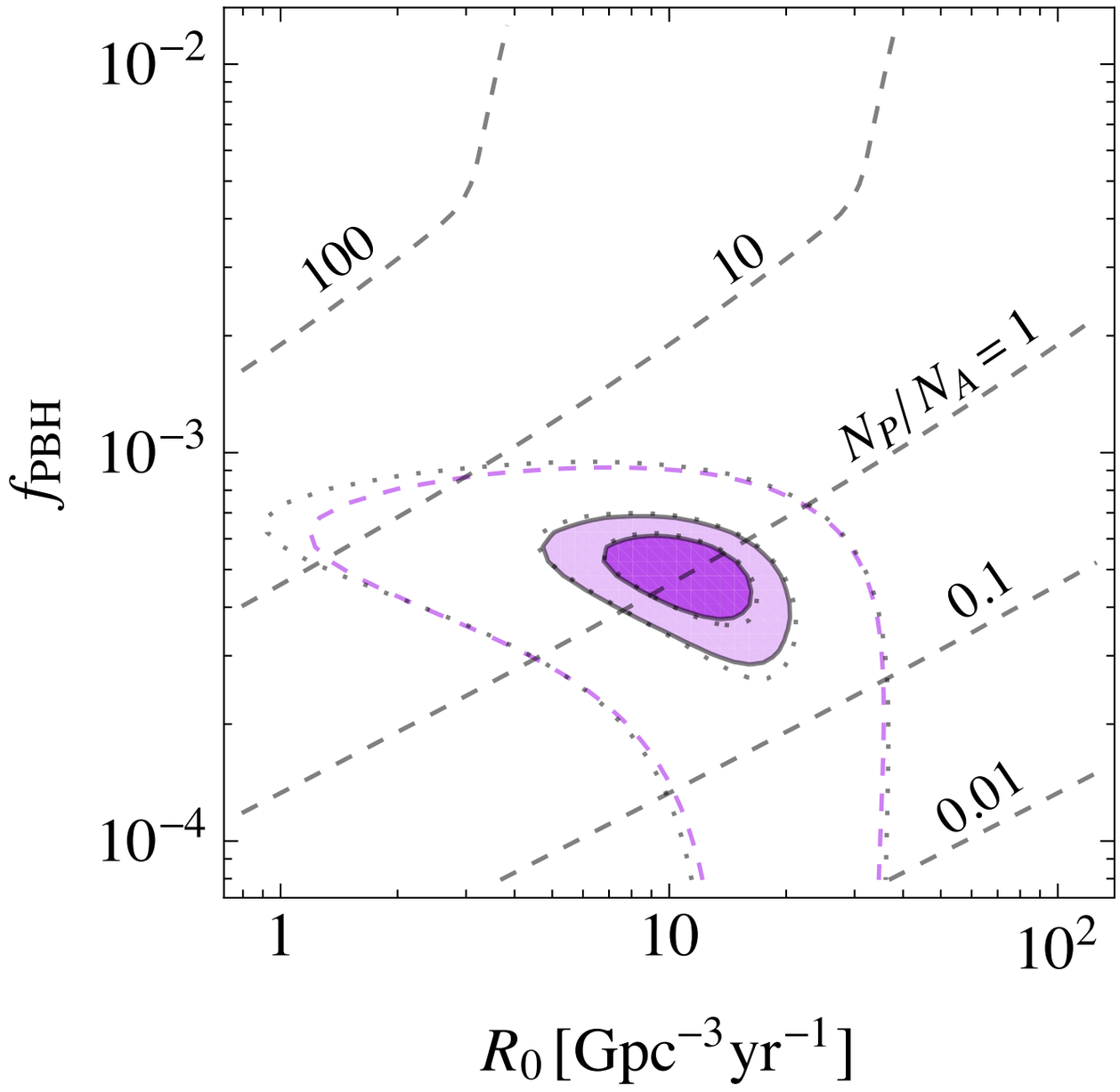

- Both populations contain a roughly equal number of events
- $R_0 = 0$, i.e., the PBH only scenario disfavoured at $4\sigma$

*$R_0$ - present merger rate of the astrophysical component*

[ 2012.02786 Vaskonen et al ]

# fitting LIGO-Virgo events

PBH + astrophysical BH



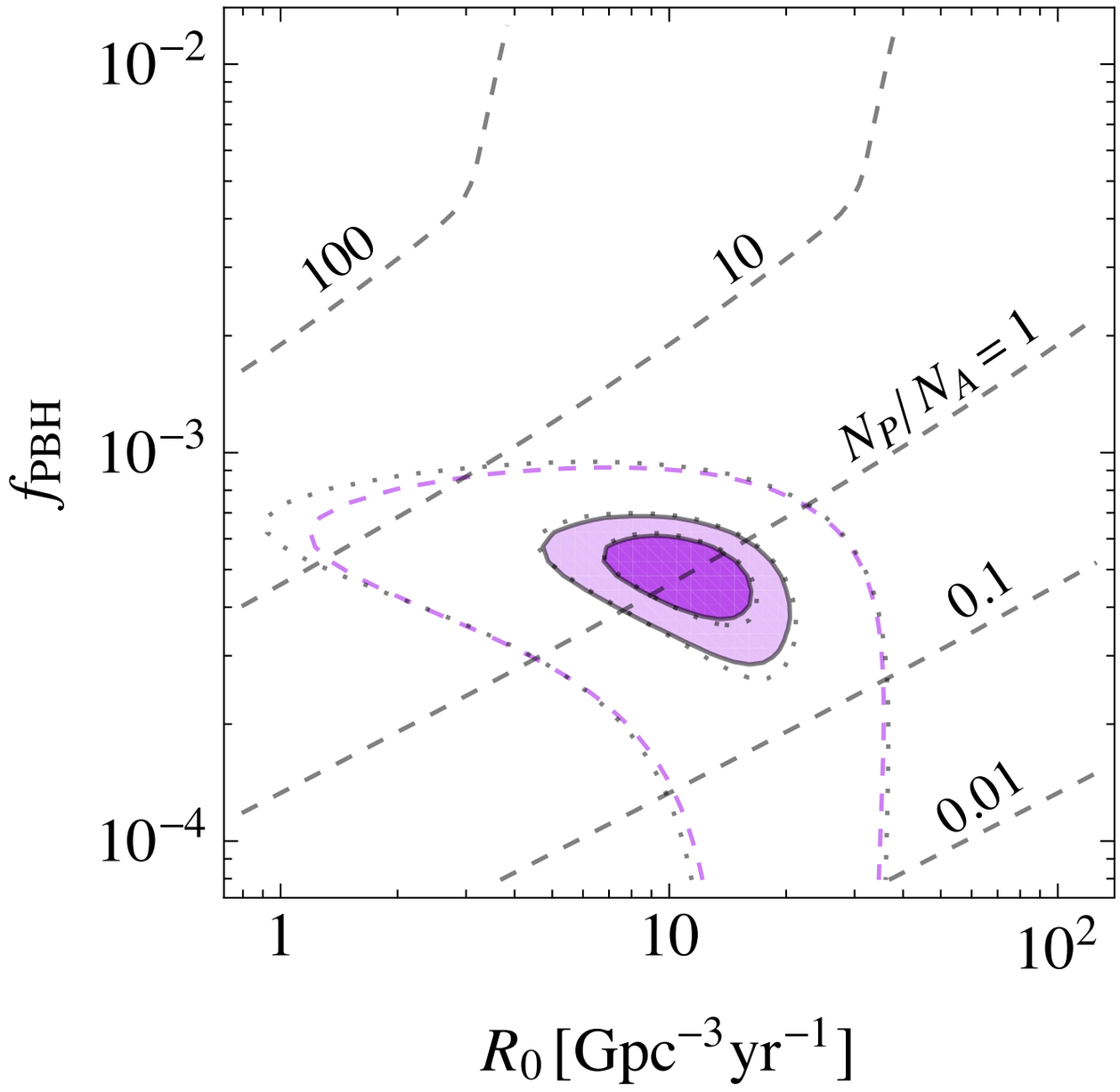

- Both populations contain a roughly equal number of events
- $R_0 = 0$, i.e., the PBH only scenario disfavoured at $4\sigma$
- a peak on top of the truncated power law favoured at $1.7\sigma$

*$R_0$ - present merger rate of the astrophysical component*

[ 2012.02786 Vaskonen et al ]

# fitting LIGO-Virgo events

PBH + astrophysical BH



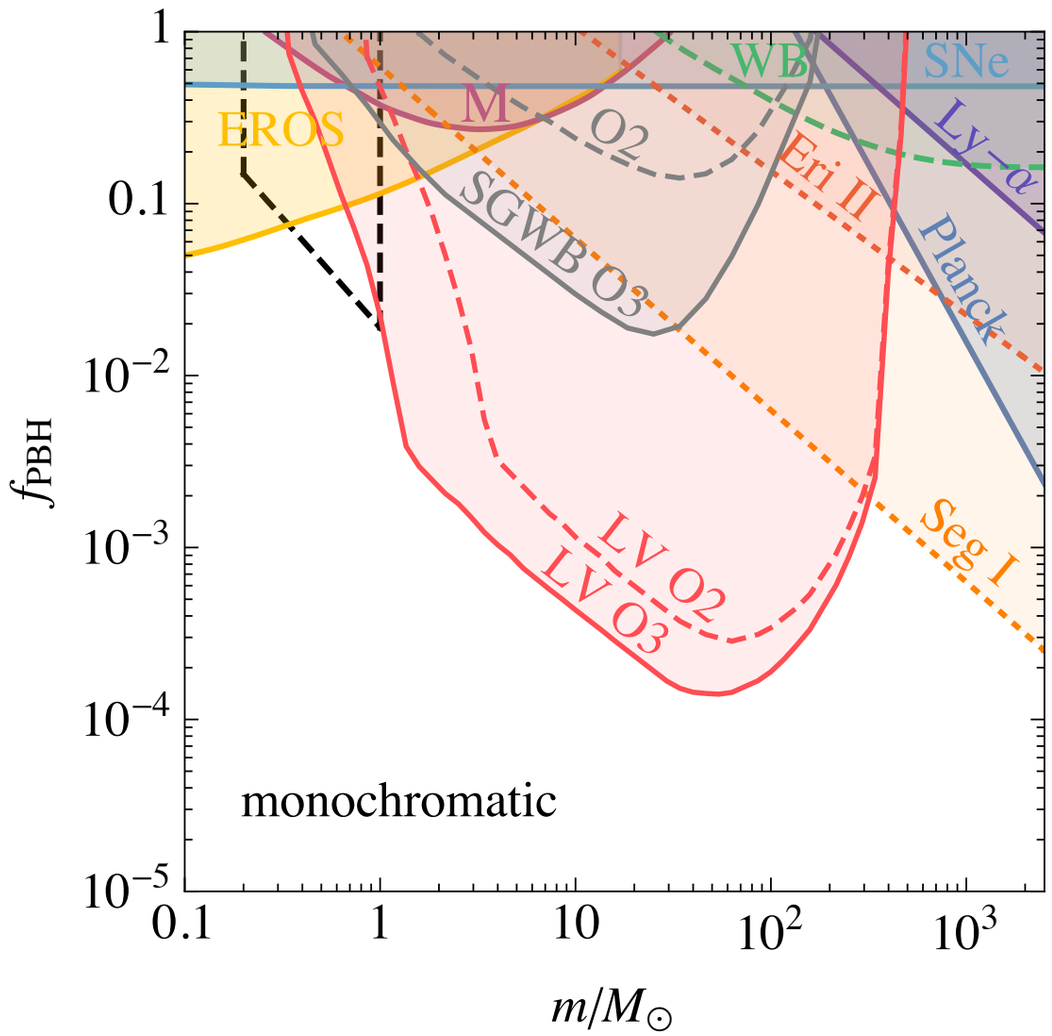

- Both populations contain a roughly equal number of events
- $R_0 = 0$, i.e., the PBH only scenario disfavoured at $4\sigma$
- a peak on top of the truncated power law favoured at $1.7\sigma$
- more complete astrophysical binary BH models may also contain peaks around $30M_\odot$

**$R_0$ - present merger rate of the astrophysical component*

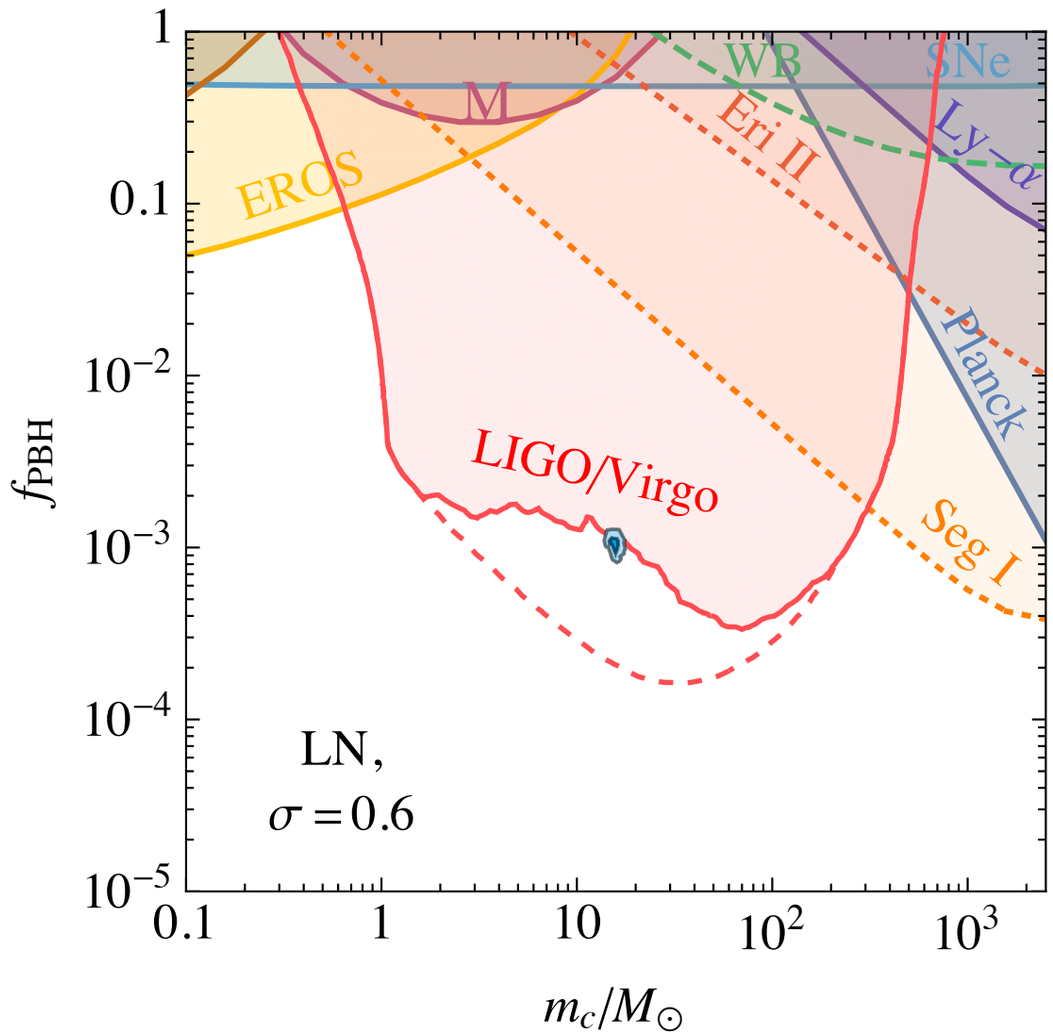
[ 2012.02786 Vaskonen et al ]

# Constraints on solar mass PBH

## MONOCHROMATIC MASS FUNCTION



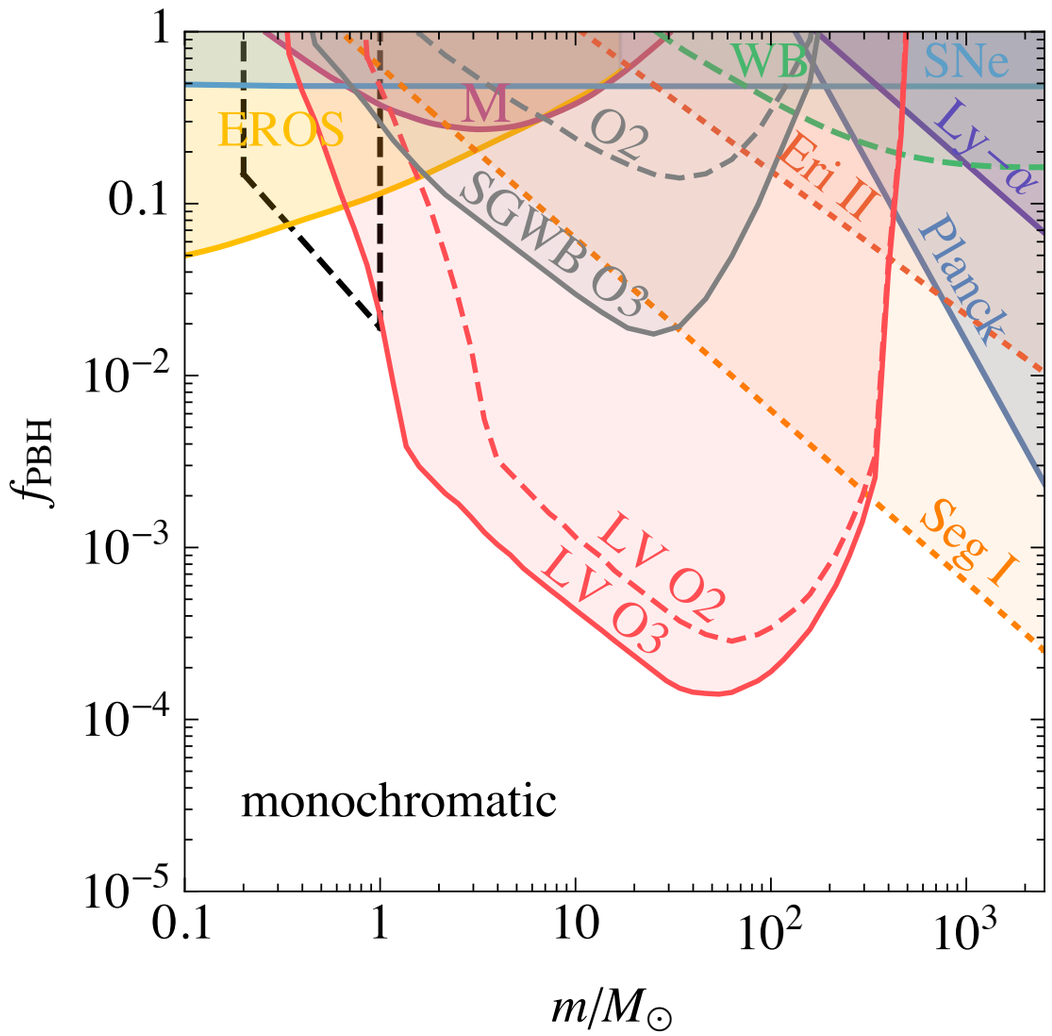

## LOG-NORMAL MASS FUNCTION



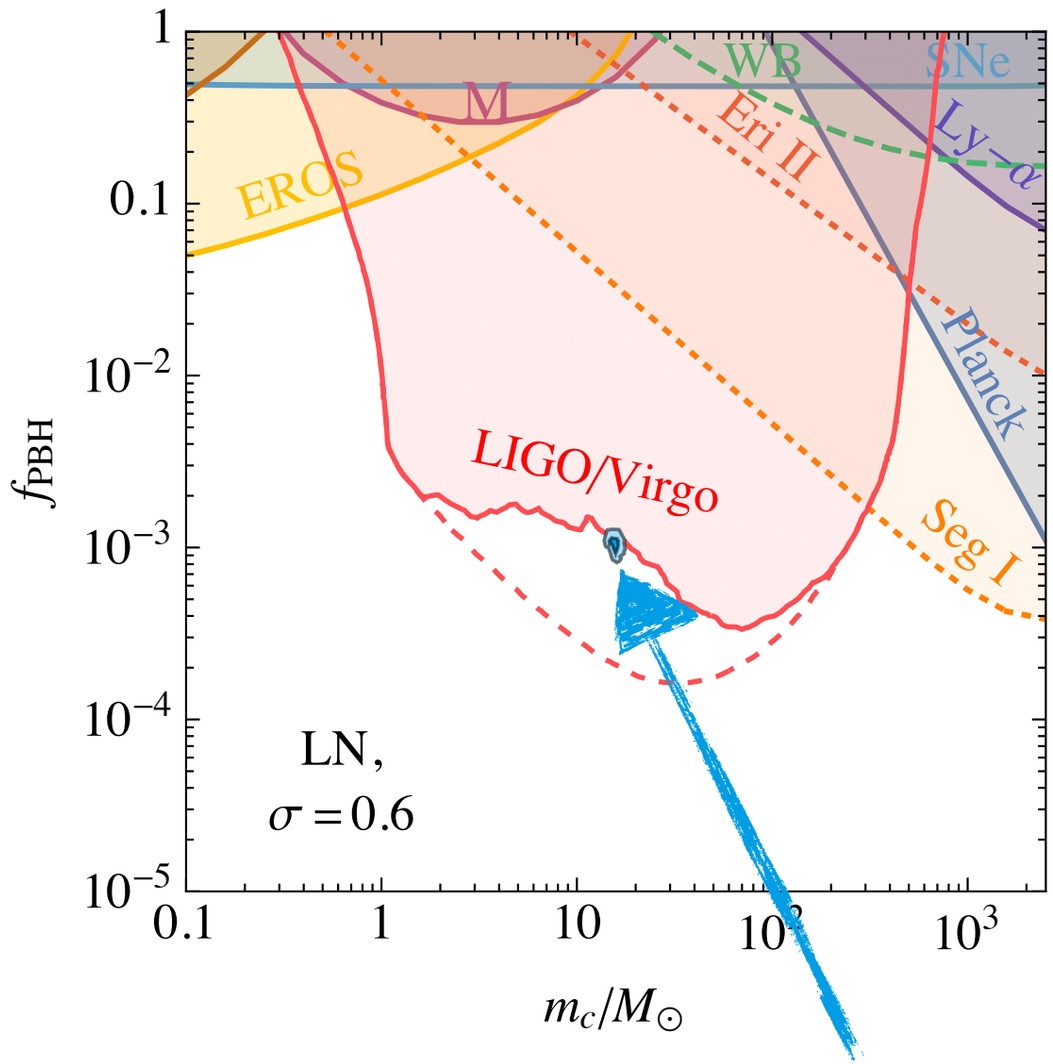

[ 2012.02786 Vaskonen et al ]

# Constraints on solar mass PBH

## MONOCHROMATIC MASS FUNCTION




## LOG-NORMAL MASS FUNCTION

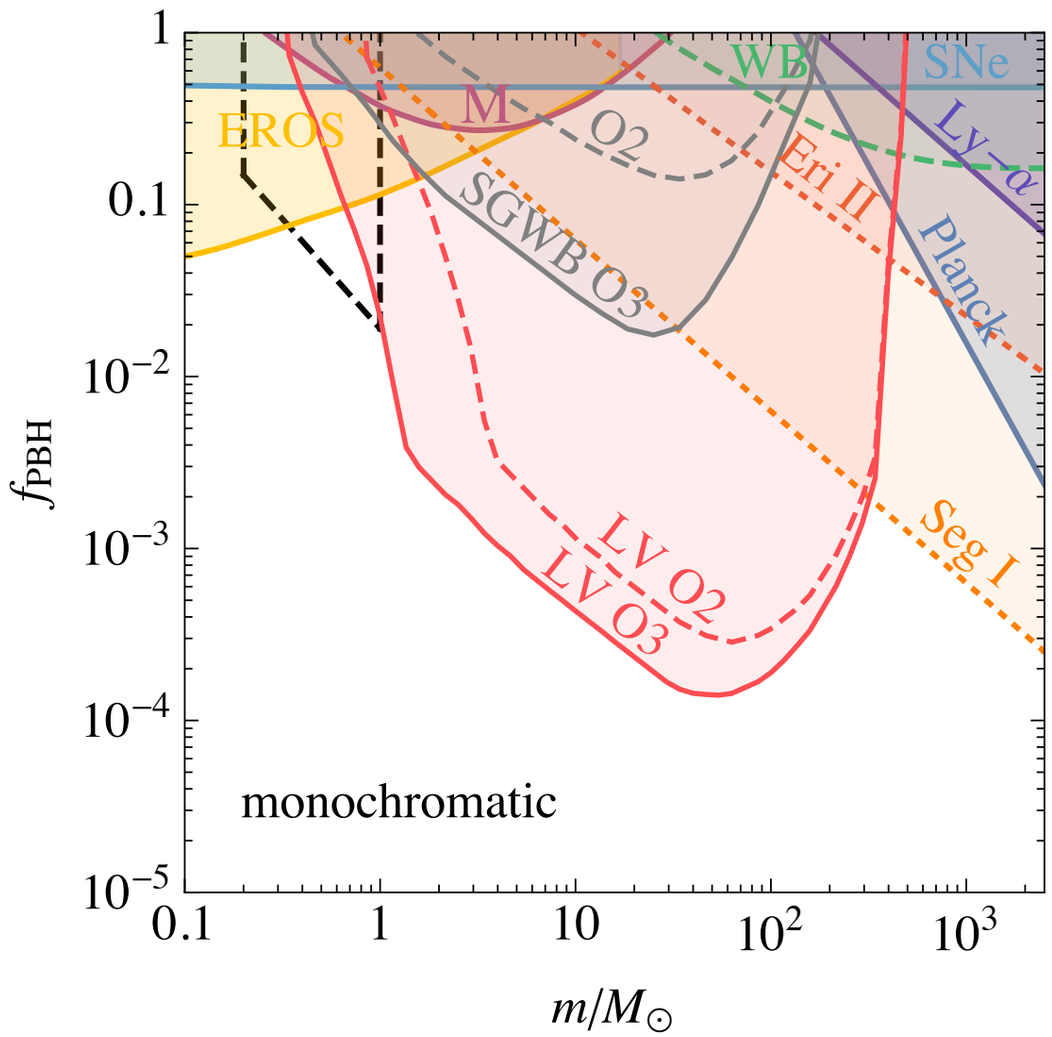



best-fit PBH only scenario

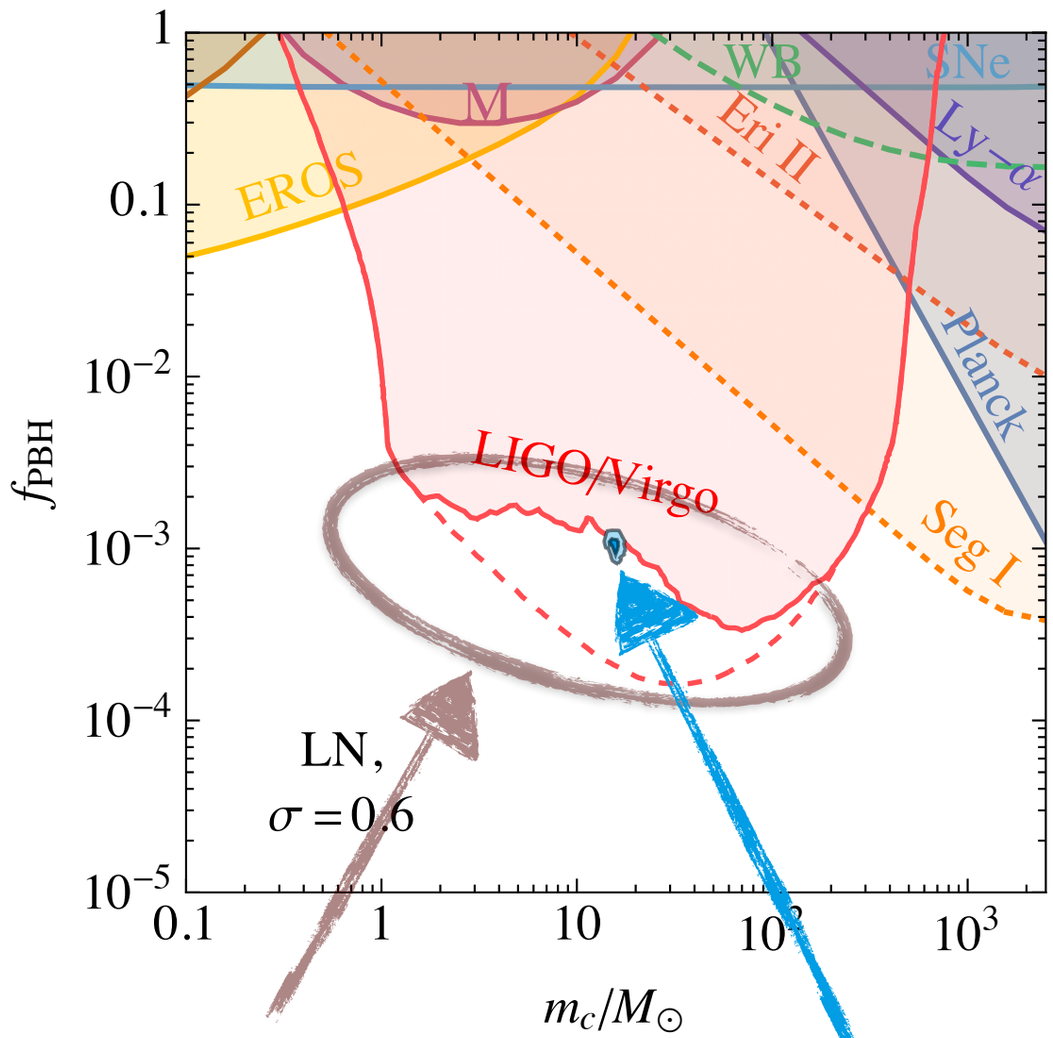
[ 2012.02786 Vaskonen et al ]

# Constraints on solar mass PBH

## MONOCHROMATIC MASS FUNCTION




## LOG-NORMAL MASS FUNCTION




scenarios with PBH subpopulations

best-fit PBH only scenario

[ 2012.02786 Vaskonen et al ]

# SUMMARY

- An astrophysical component must be included when modelling LIGO-Virgo GW events. *PBH only scenario is disfavoured.*

- Less than 0.2% of PBH DM in the $2 - 400\,M_\odot$ range

- A better understanding of *accretion* and *spins* of astrophysical and primordial BH spins needed

- NANOGrav may hint for PBH formation

- PBHs are viable DM candidates in the $10^{-16} - 10^{-11} M_\odot$ mass range