News from the Dark 7

Clustering of Primordial Black Holes

and its implications for PBH constraints

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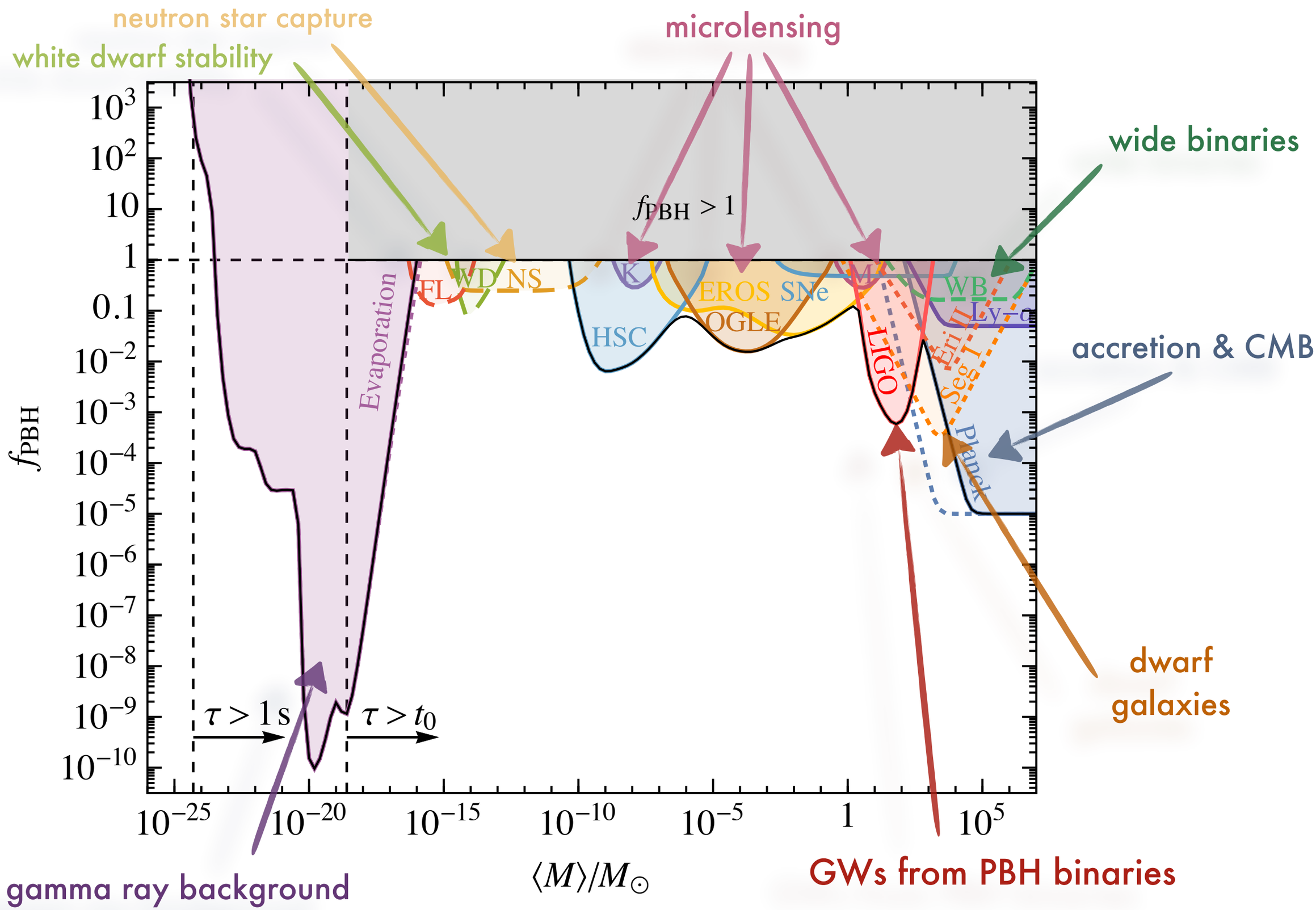
Keemilise ja Bioloogilise Füüsika Instituut
National Institute of Chemical Physics and Biophysics


neutron star capture
white dwarf stability
microlensing
wide binaries
accretion & CMB
dwarf galaxies
GWs from PBH binaries
gamma ray background
$f_{\rm PBH} > 1$
$f_{\rm PBH}$
$\langle M \rangle / M_\odot$
$\tau > 1\,{\rm s}$
$\tau > t_0$
Evaporation
FL
WD
NS
HSC
K
EROS
SNe
OGLE
M
LIGO
WB
Ly-α
Eri II
Seg I
Planck
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
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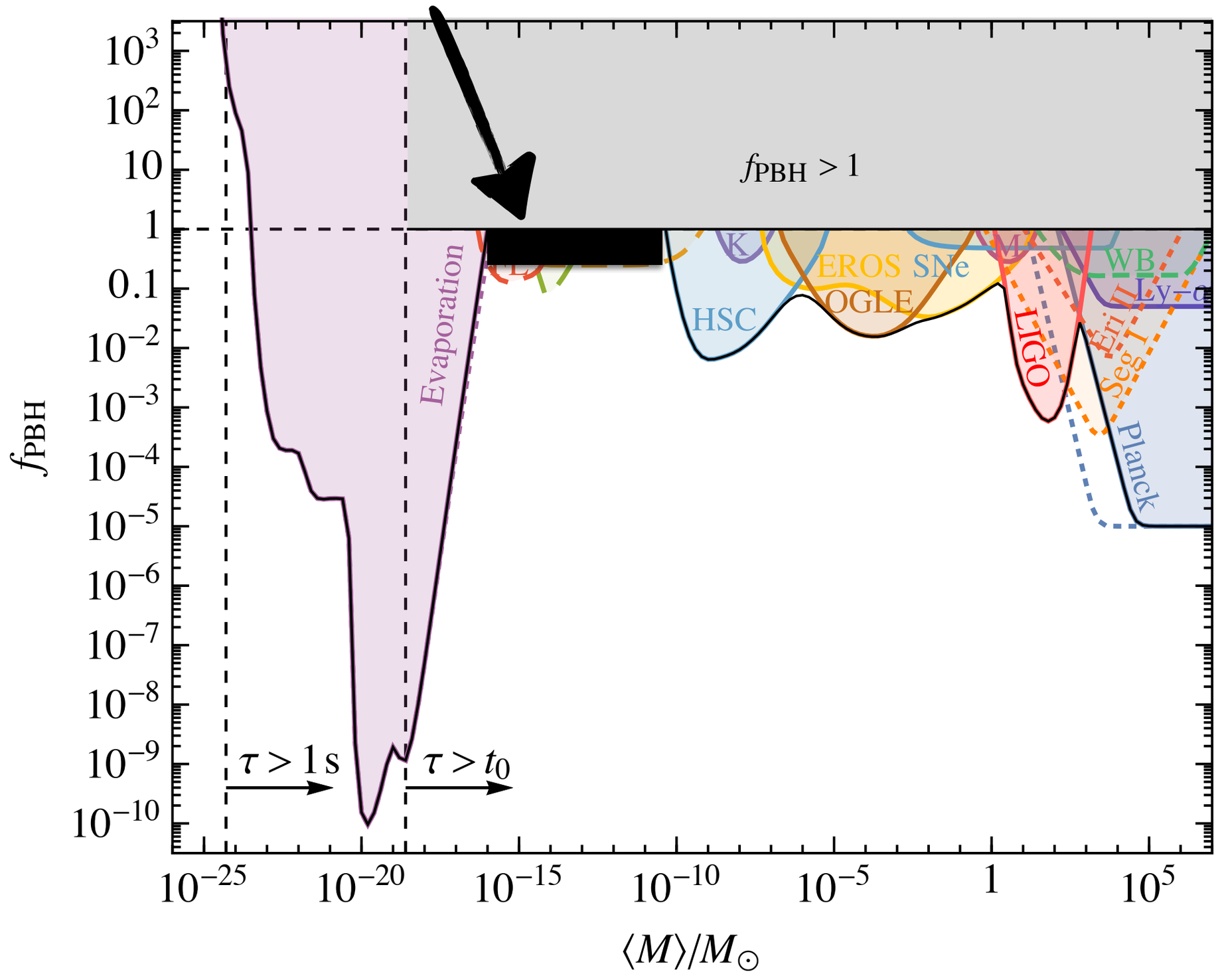
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10^5

PBHs as *all* of dark matter



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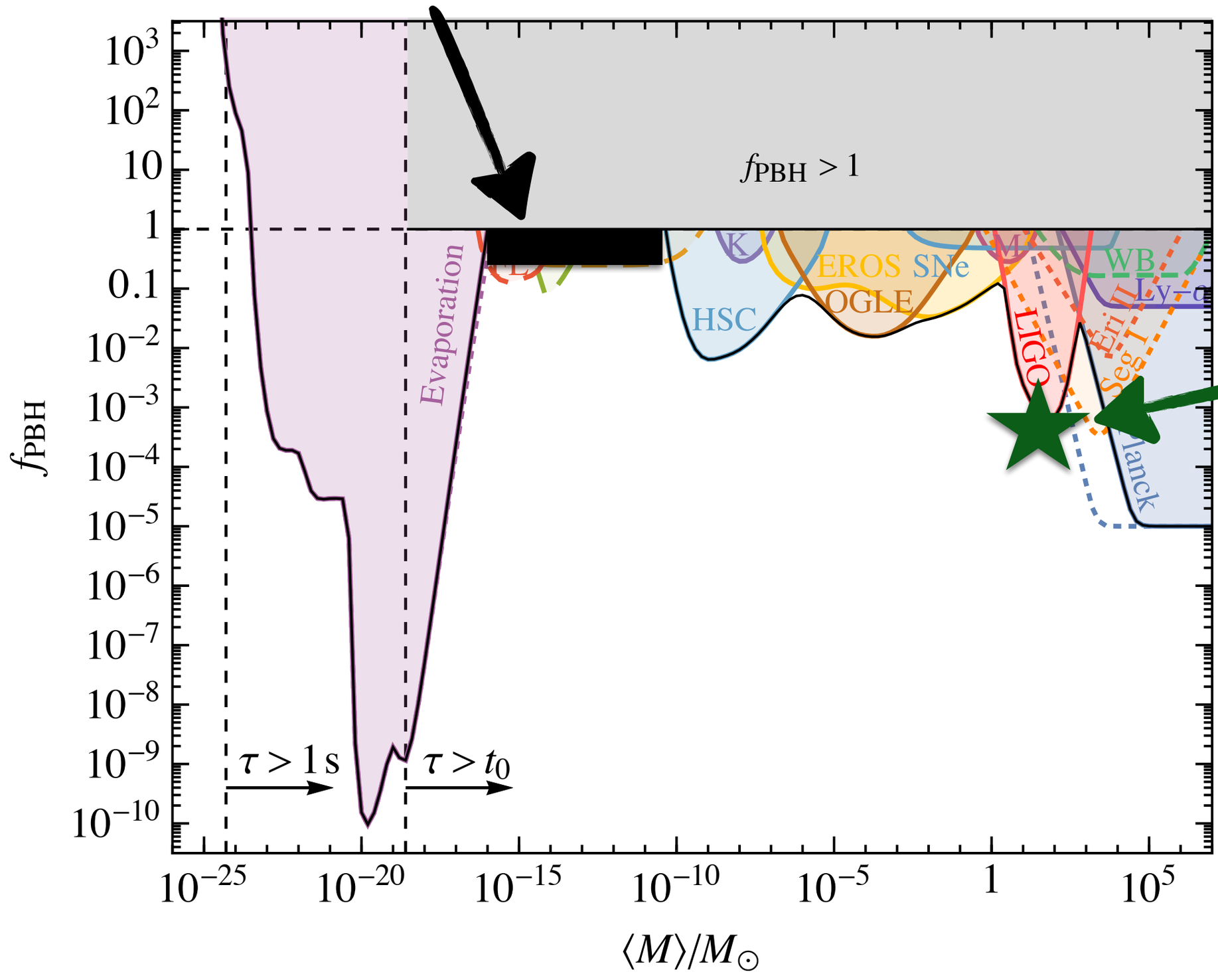
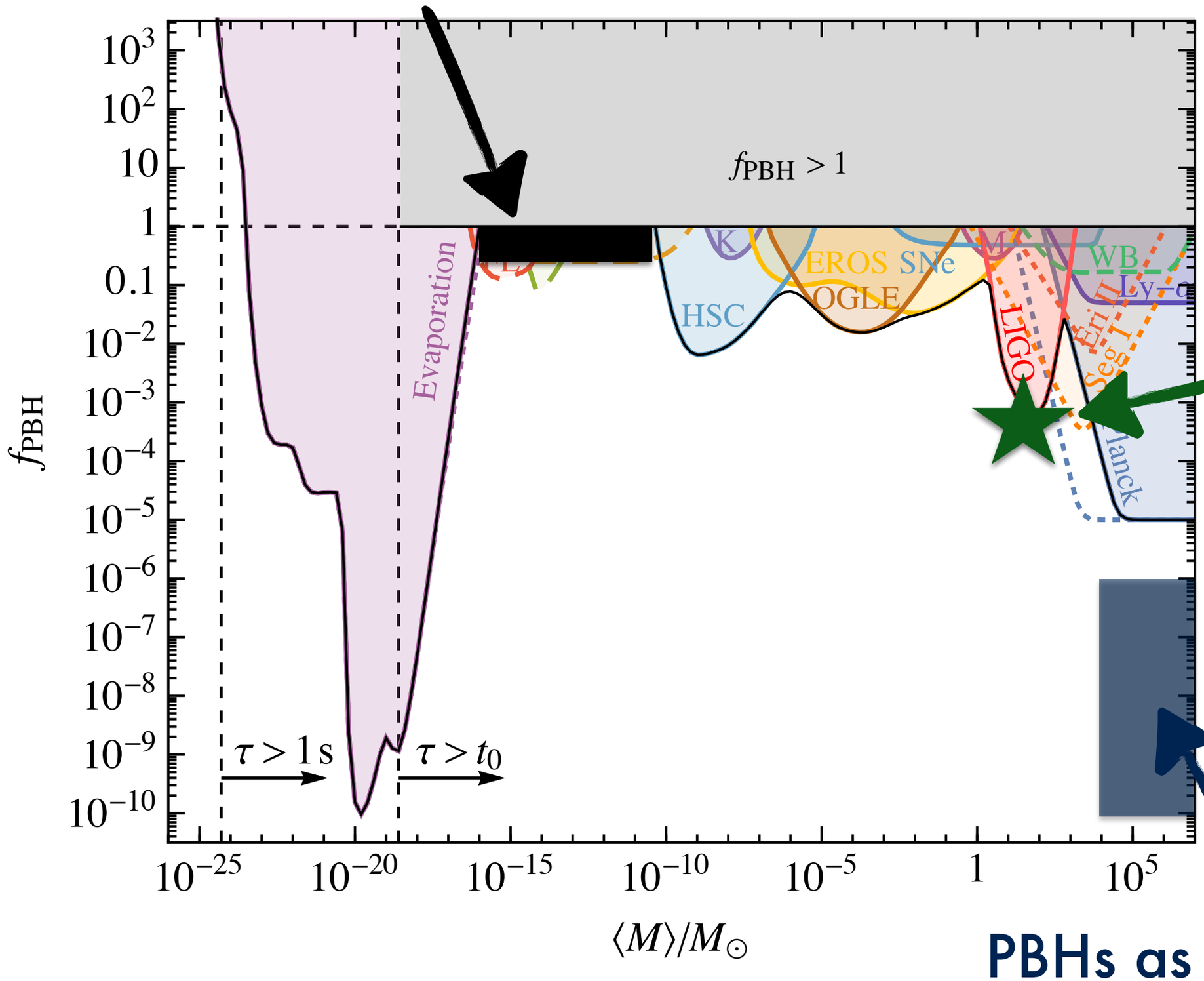


LIGO PBH binaries

PBHs as *all* of dark matter



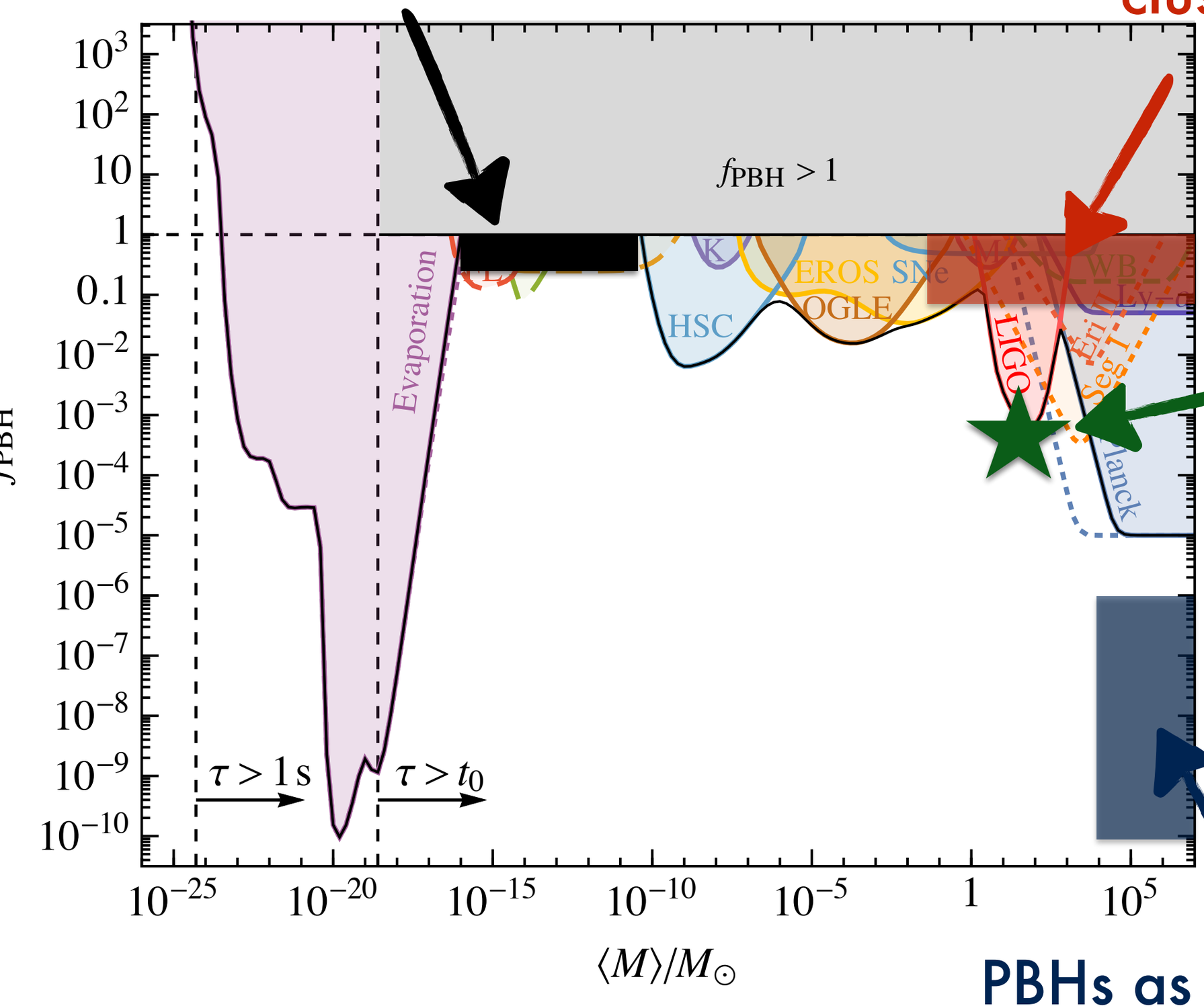
LIGO PBH binaries

PBHs as SMBH seeds

PBHs as *all* of dark matter

clustering most relevant

LIGO PBH binaries



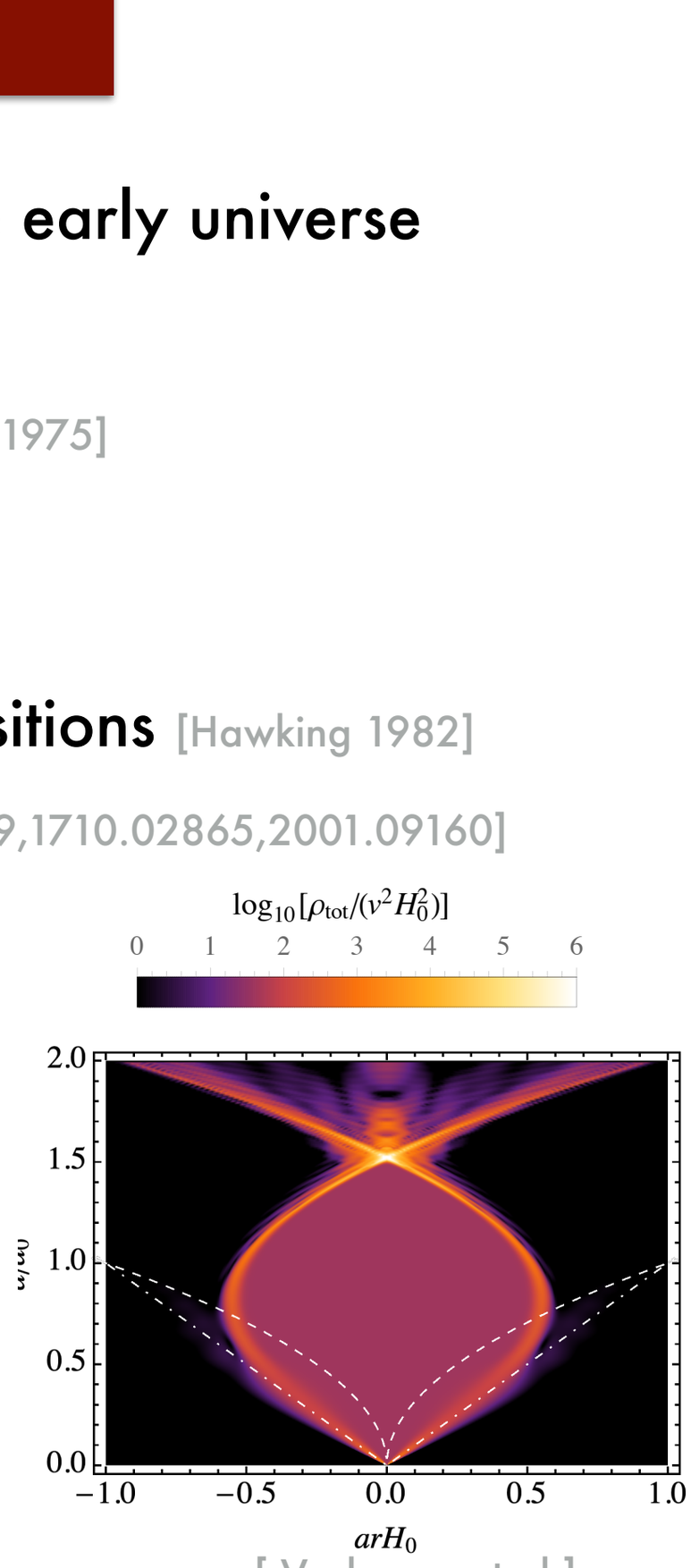
PBHs as SMBH seeds

PBH formation

general idea: collapse of large inhomogeneities in the early universe

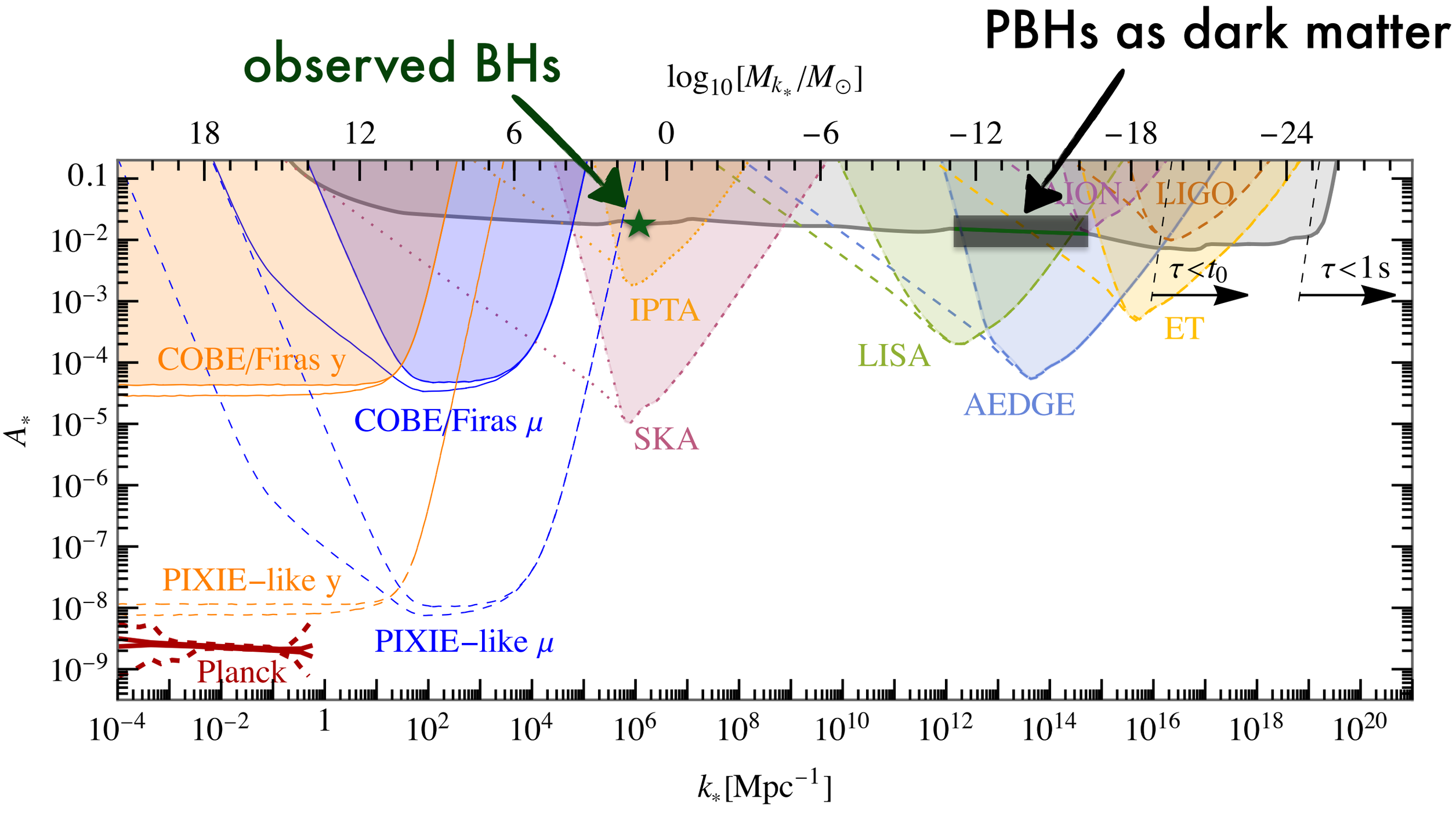
mechanisms:

- <u>inflationary perturbations</u> [Hawking, Carr 1974, Carr 1975]
- collapse of cosmic strings [Hawking 1989]
- vacuum bubbles
  - bubble collisions in first order phase transitions [Hawking 1982]
  - collapse of false vacuum bubbles [1512.01819,1710.02865,2001.09160]
- collapse of compact objects
  - *oscillons* [1801.03321]
  - *Q-balls* [1612.02529,1706.09003,1907.10613]
  - *Fermi balls* [2106.00111]
- Yukawa "fifth force" [2008.12456]
- ...



[Vaskonen et al]

Scalar induced GWs



[2205.13540 Karam et al]

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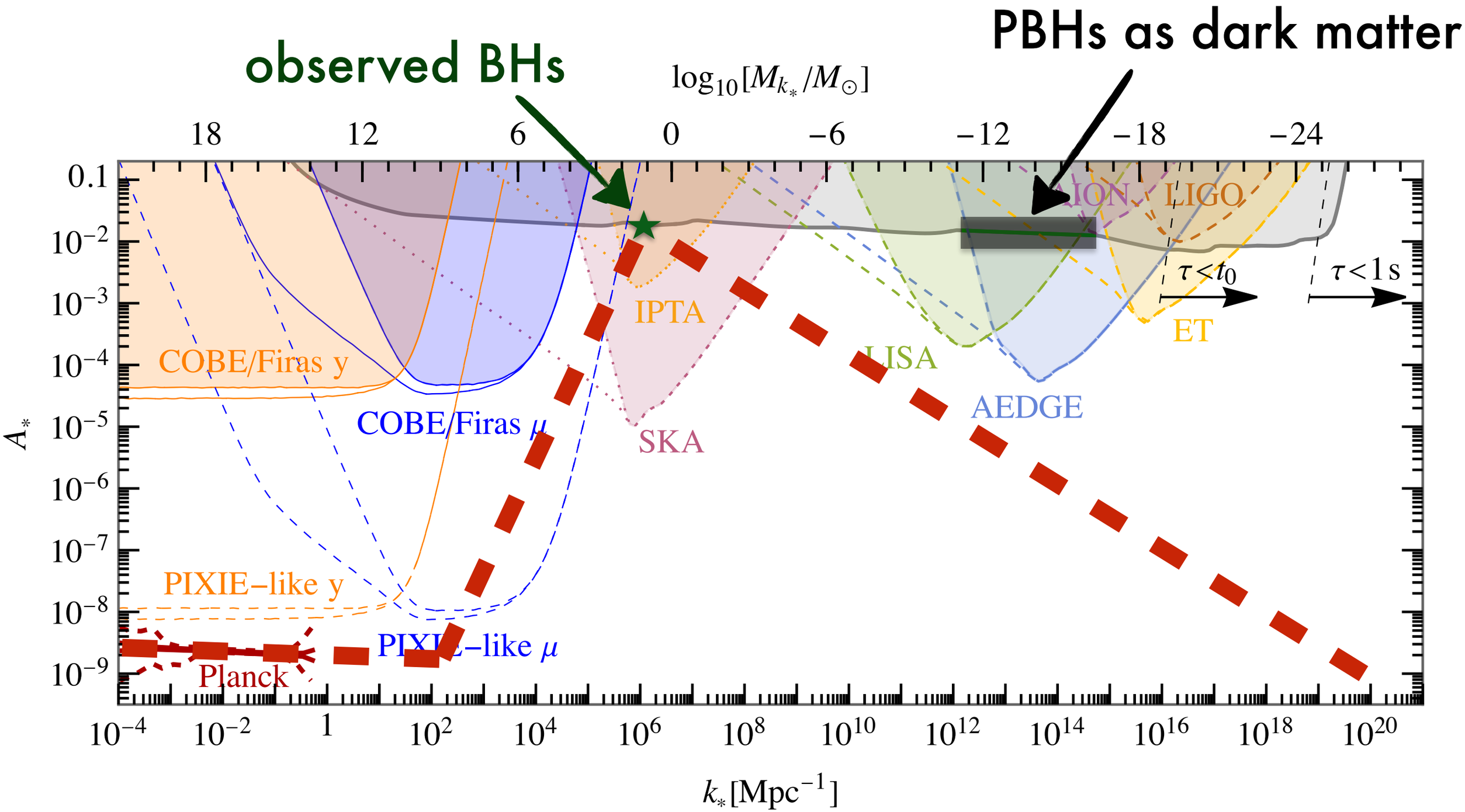
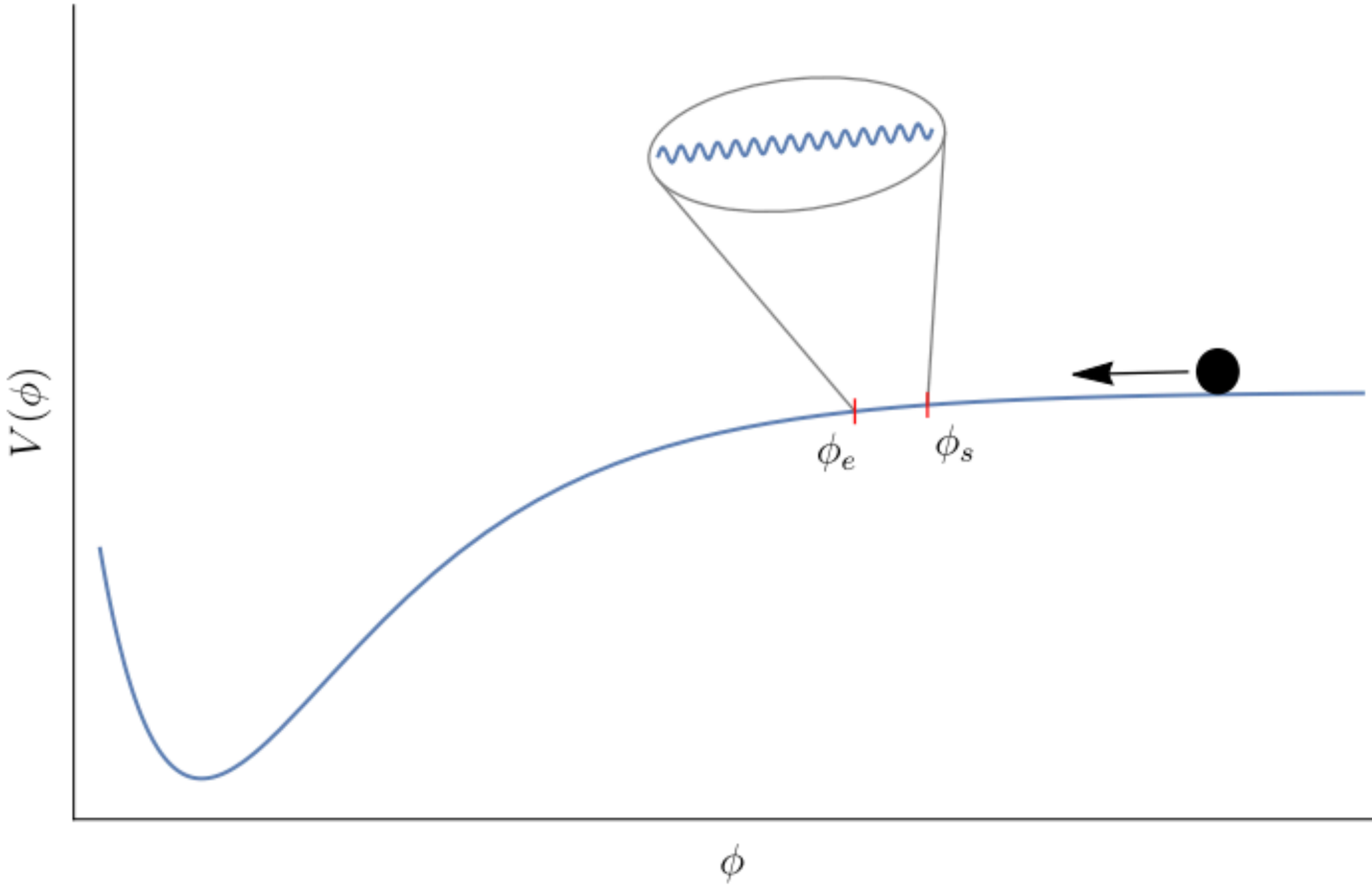
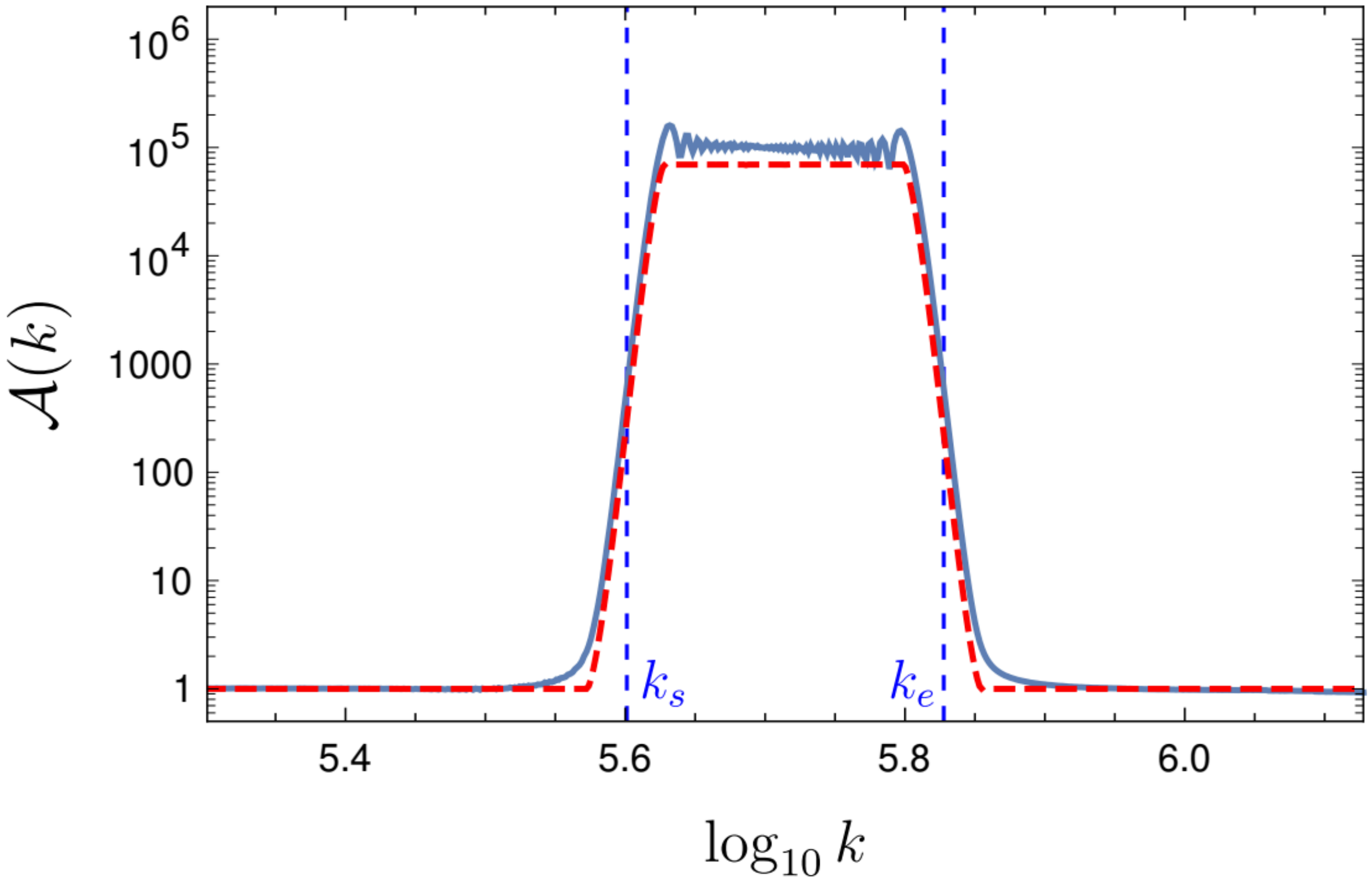


[2205.13540 Karam et al]



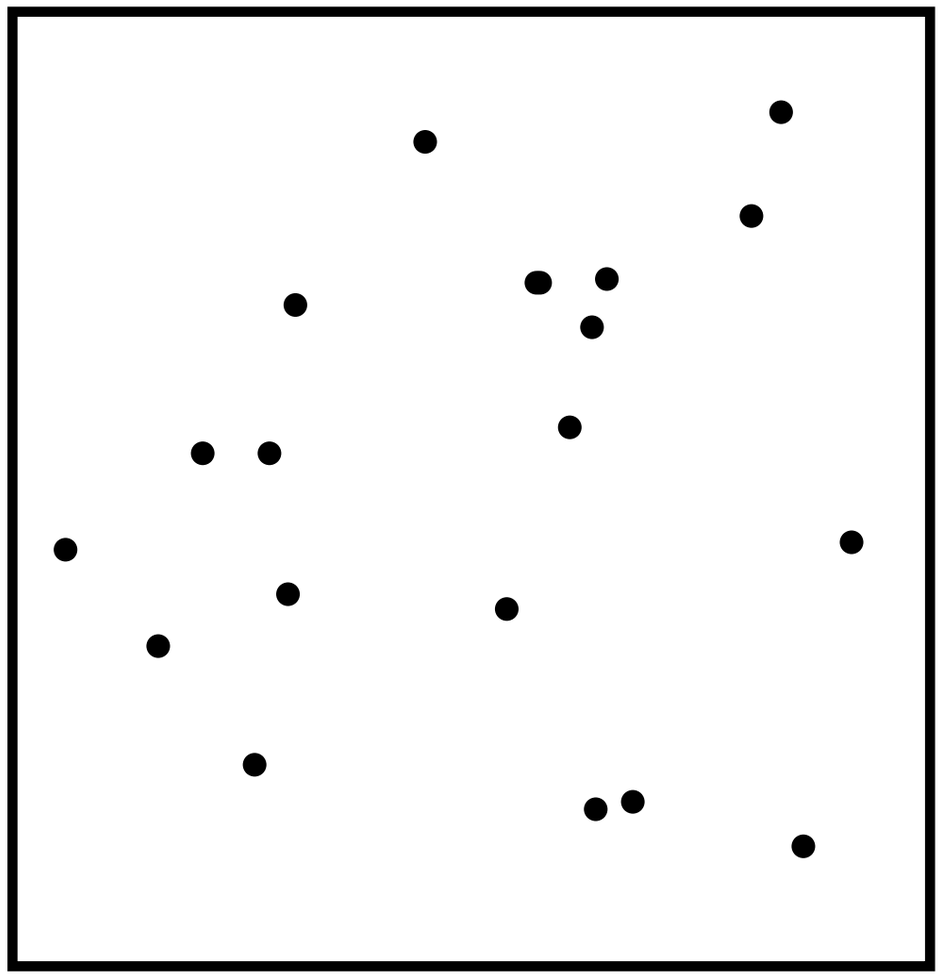
[1912.10437 Cai et al]



$$\mathcal{P}_{\mathcal{R}}(k) \approx A_s \left(\frac{k}{k_p}\right)^{n_s-1} \mathcal{A}^2(k)$$

[1912.10437 Cai et al]

NO INITAL CLUSTERING



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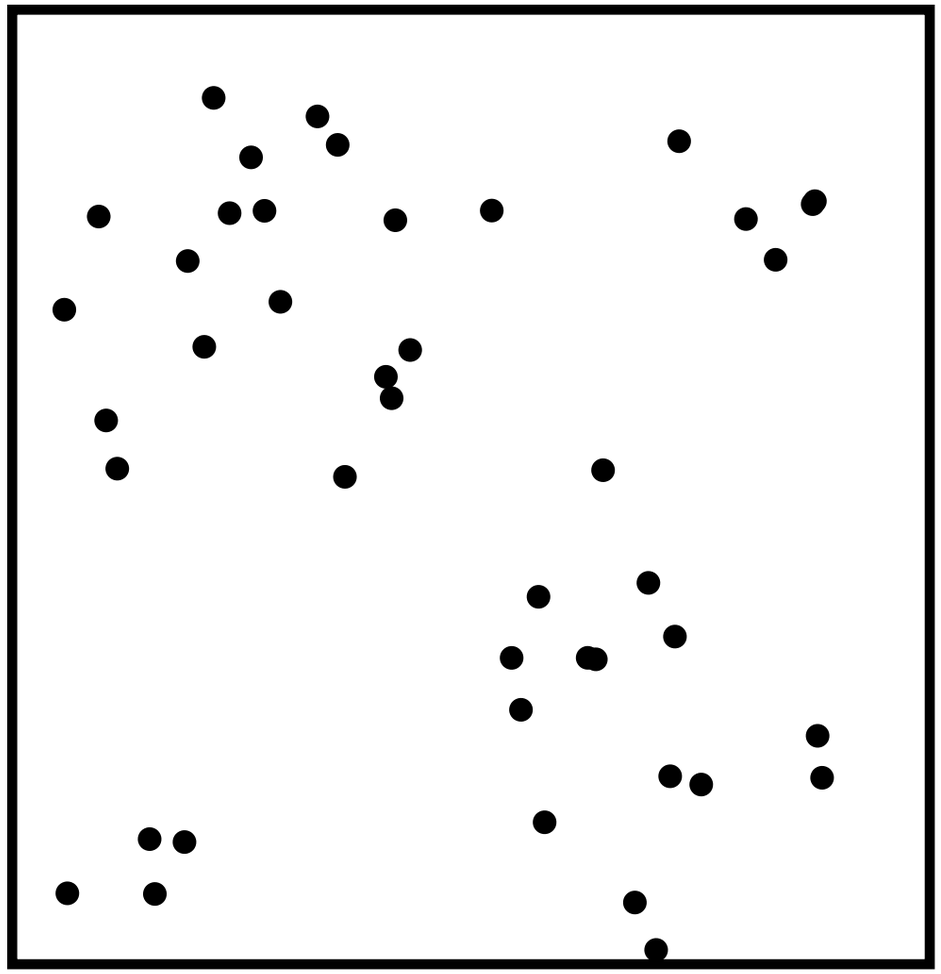

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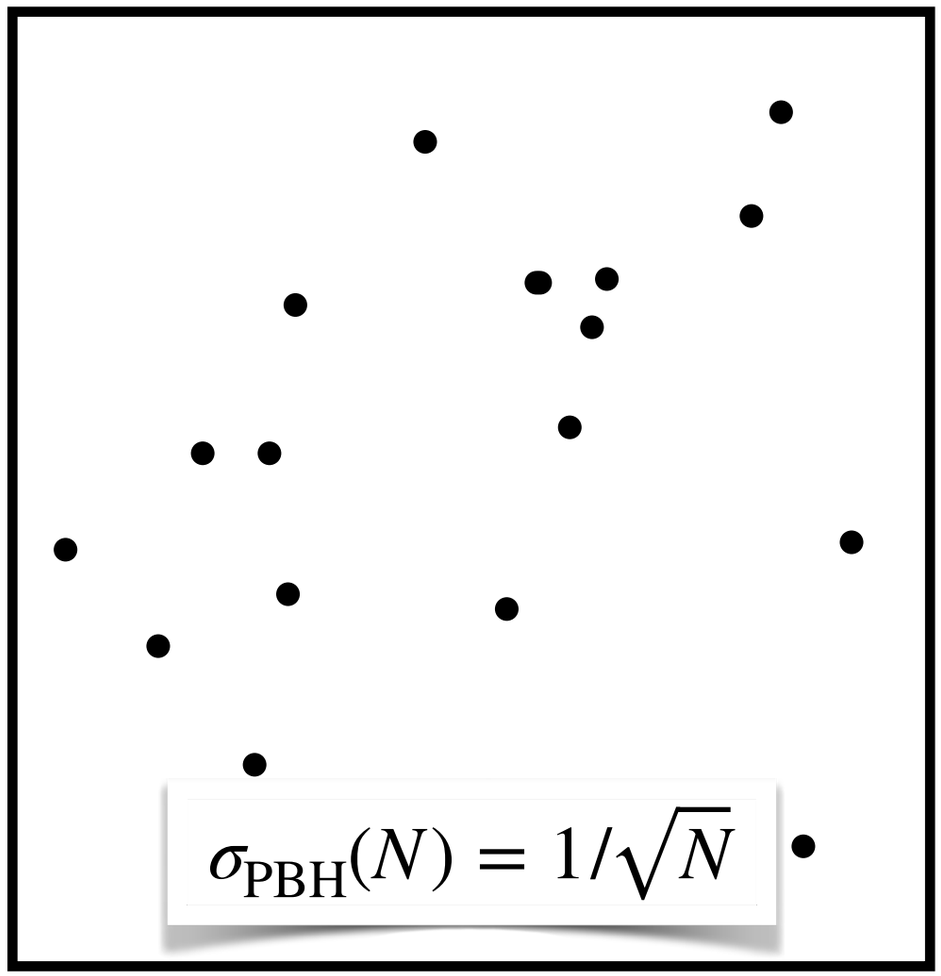

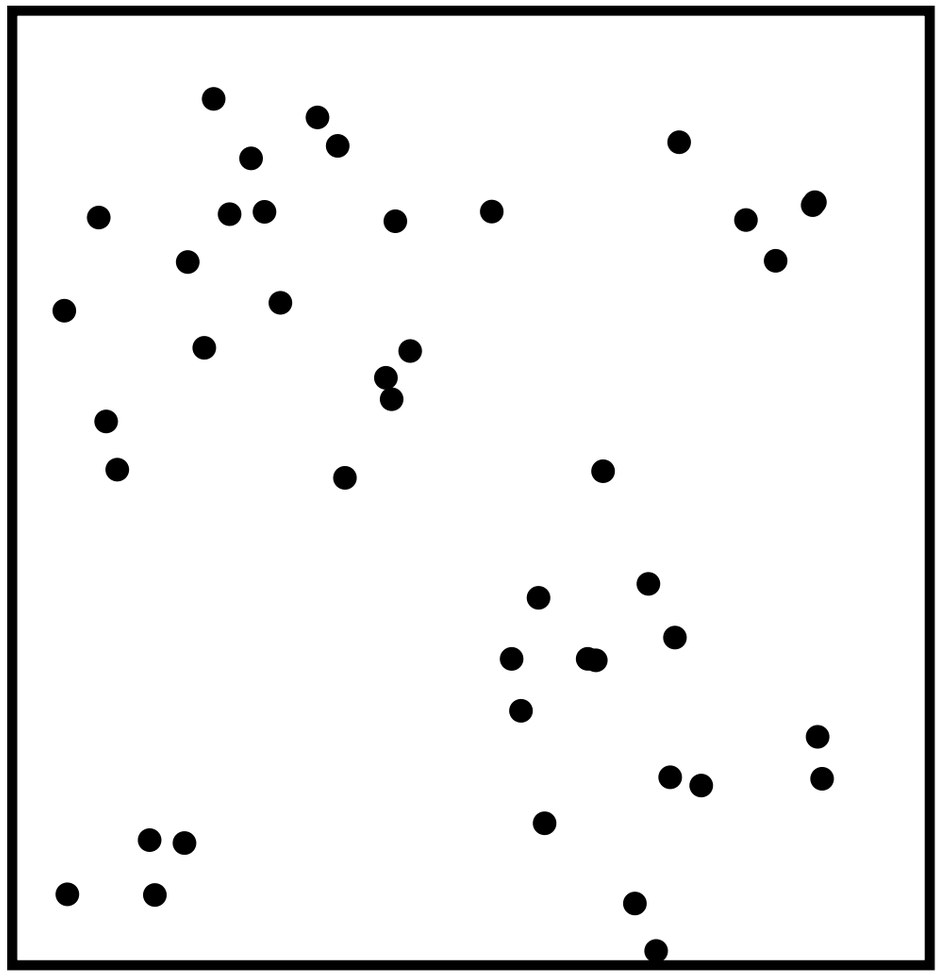

$$\left\langle \frac{\delta n}{\bar{n}}(\mathbf{x}) \frac{\delta n}{\bar{n}}(\mathbf{y}) \right\rangle = \underbrace{\frac{1}{\bar{n}}\,\delta(\mathbf{x}-\mathbf{y})}_{\text{Poisson}}$$

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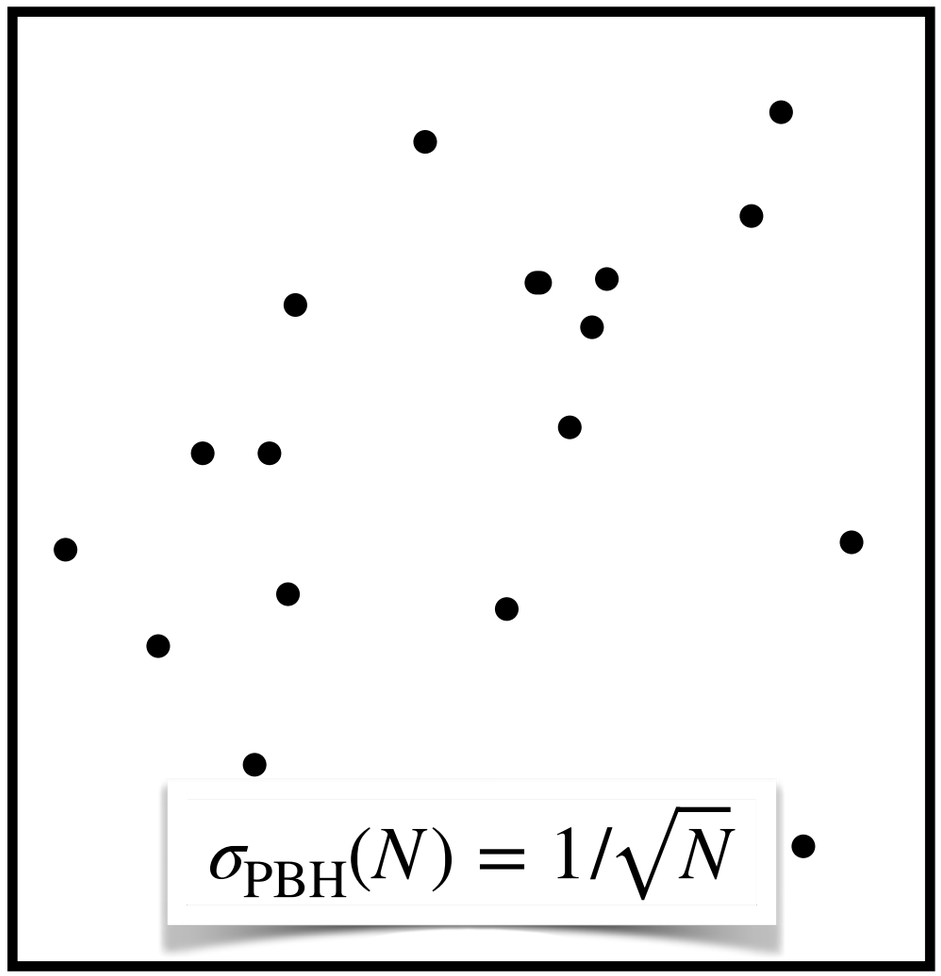

$$\sigma_{\rm PBH}(N) = 1/\sqrt{N}$$

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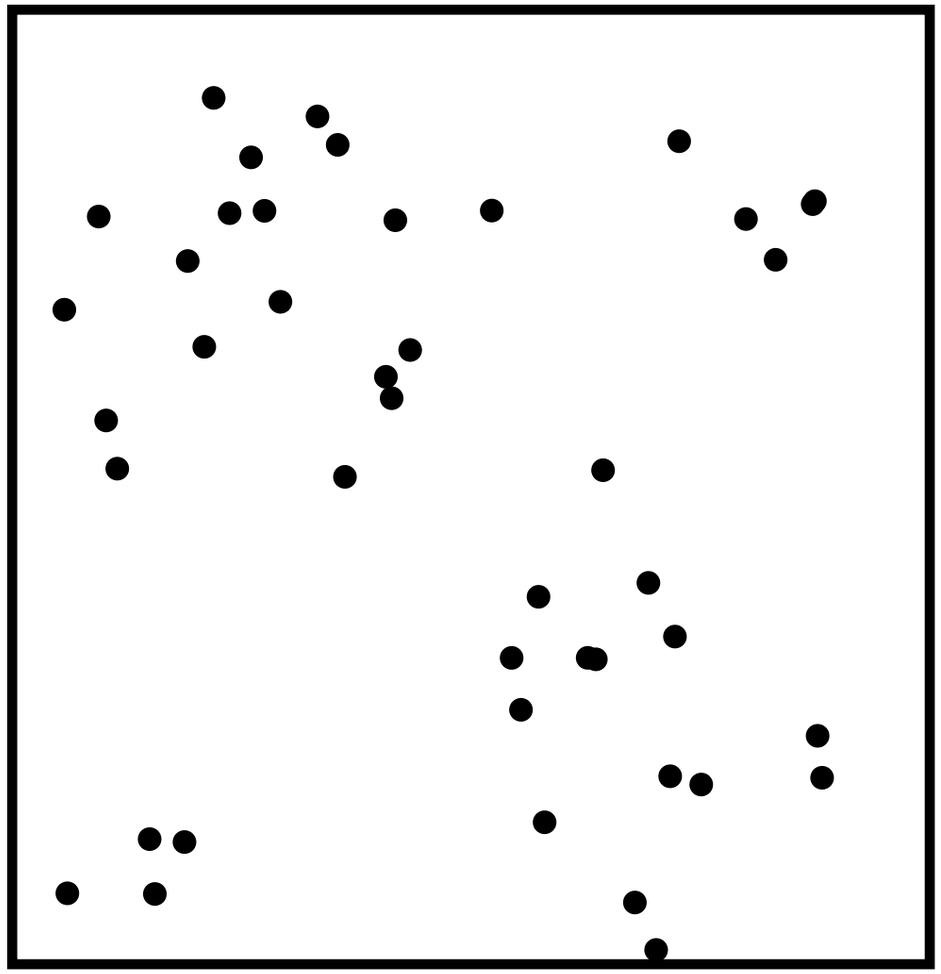
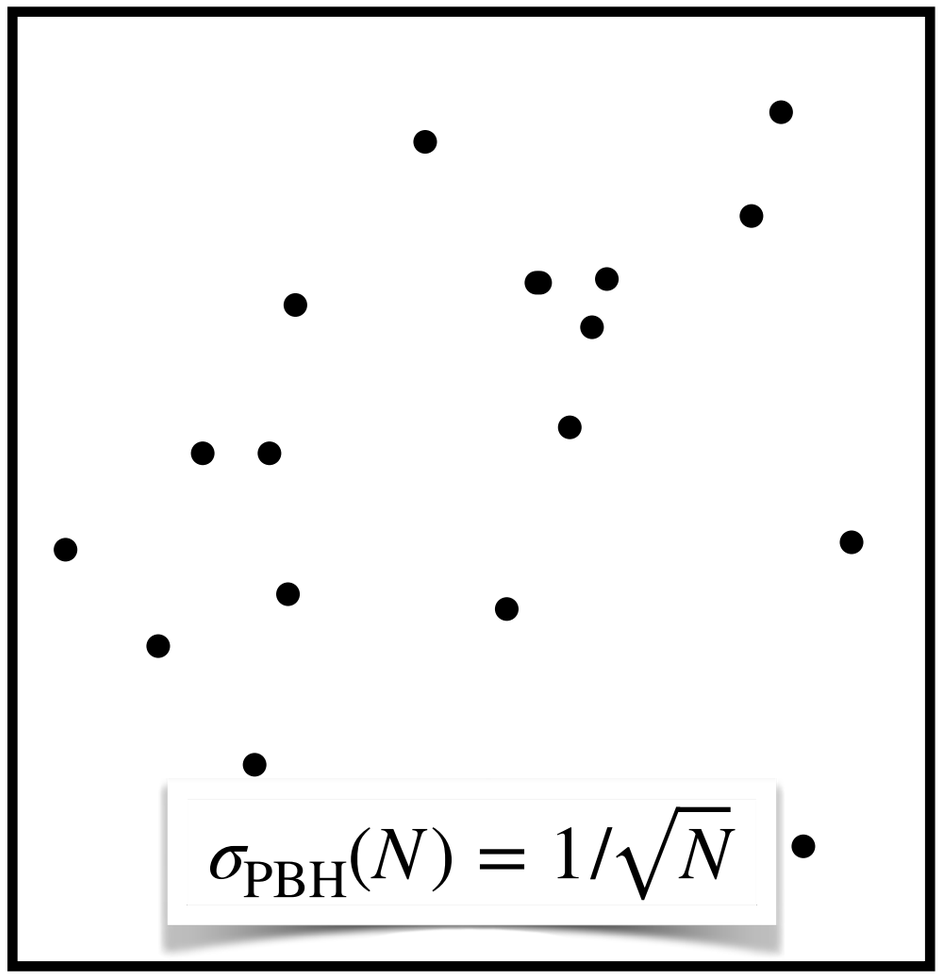


$$\langle \frac{\delta n}{\bar{n}}(\mathbf{x}) \frac{\delta n}{\bar{n}}(\mathbf{y}) \rangle = \underbrace{\frac{1}{\bar{n}}\delta(\mathbf{x}-\mathbf{y})}_{\text{Poisson}} + \underbrace{\xi_{\rm PBH}(\mathbf{x},\mathbf{y})}_{\text{non-Poisson}}$$

** non-gaussianity can be relevant*

NO INITAL CLUSTERING



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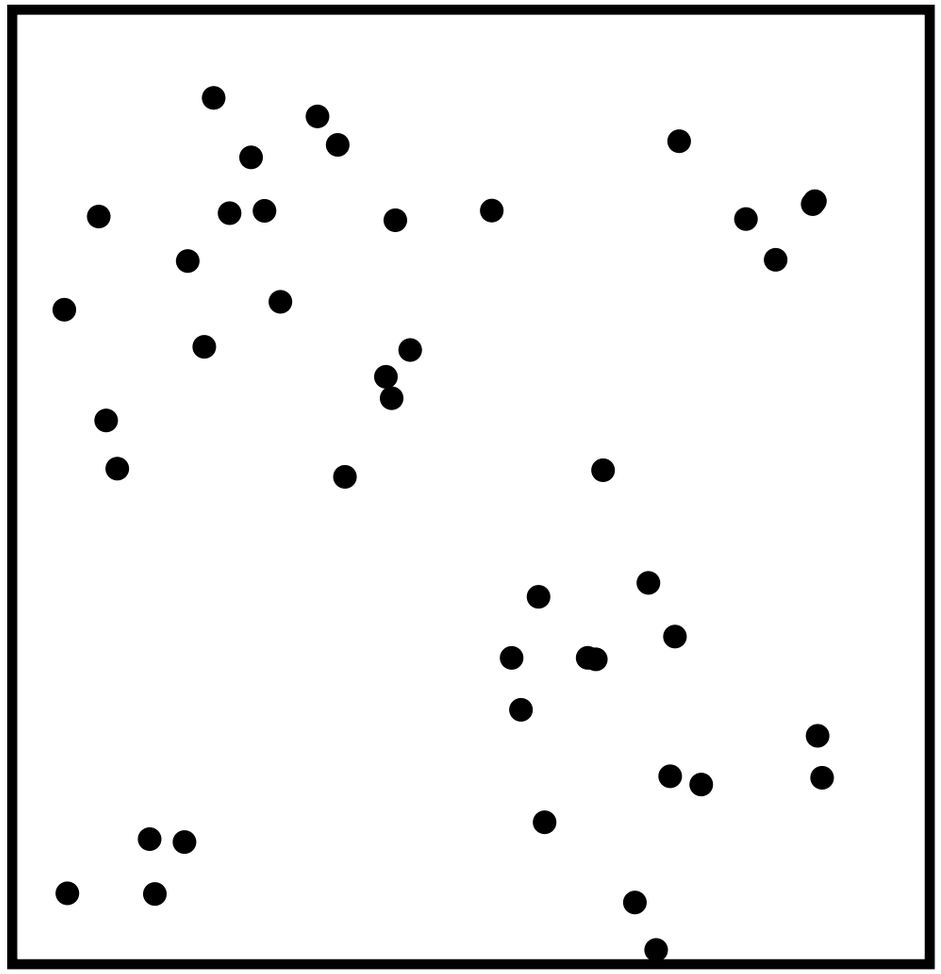

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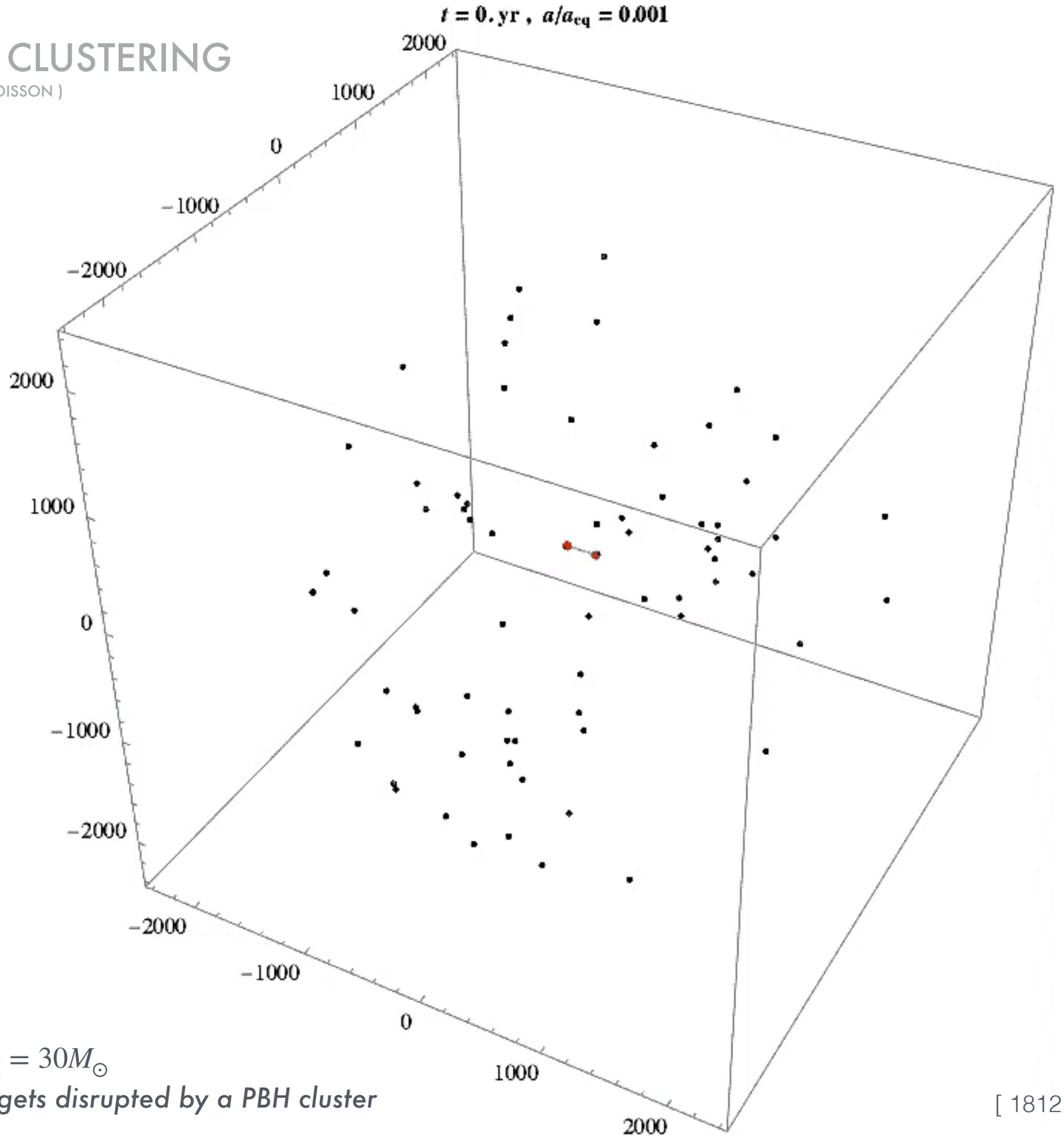
(POISSON)



* $f_{\mathrm{PBH}} = 1, M_{\mathrm{PBH}} = 30 M_{\odot}$
* *central binary gets disrupted by a PBH cluster*

[1812.01930 Raidal et al]

NO INITAL CLUSTERING

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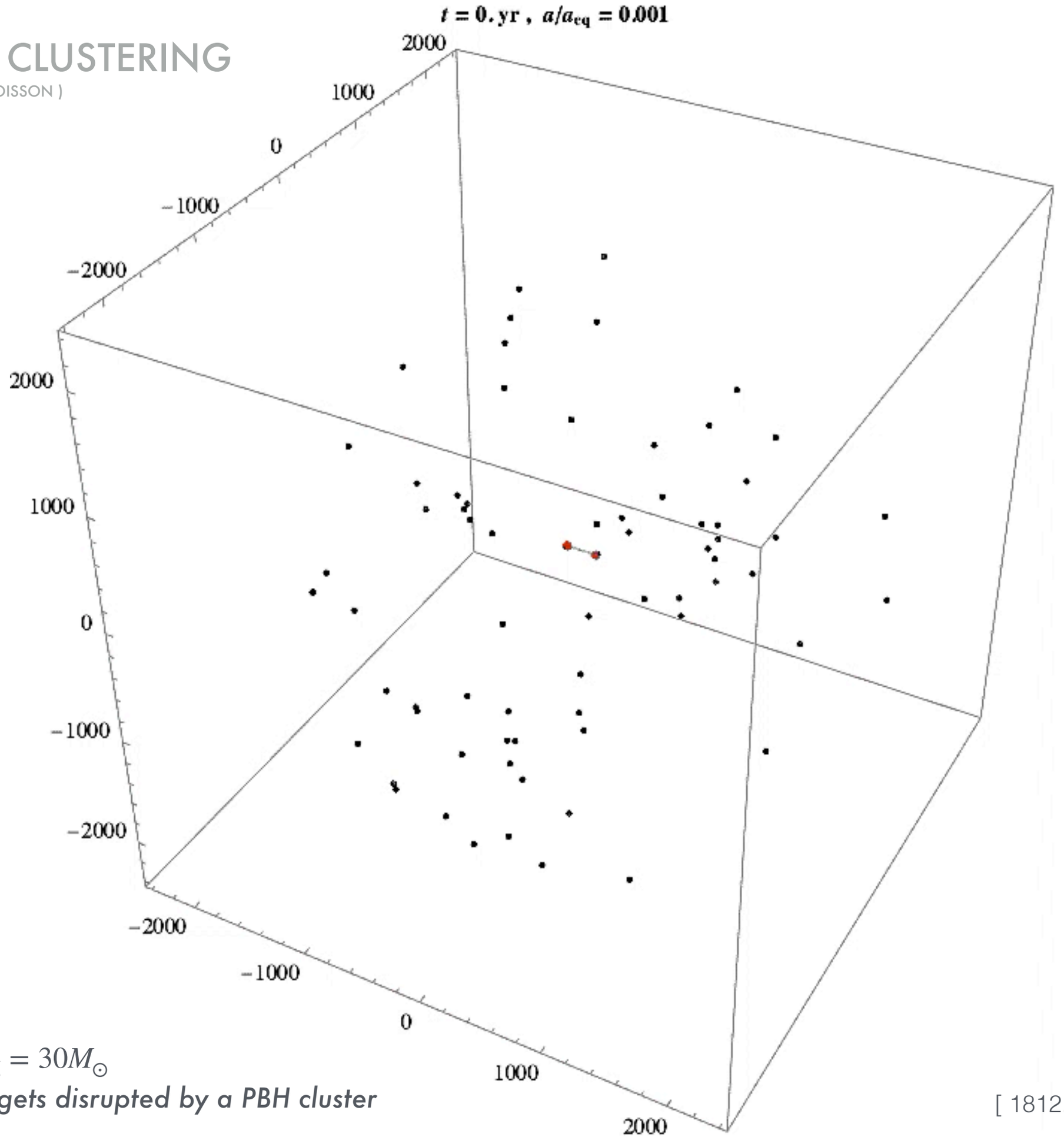

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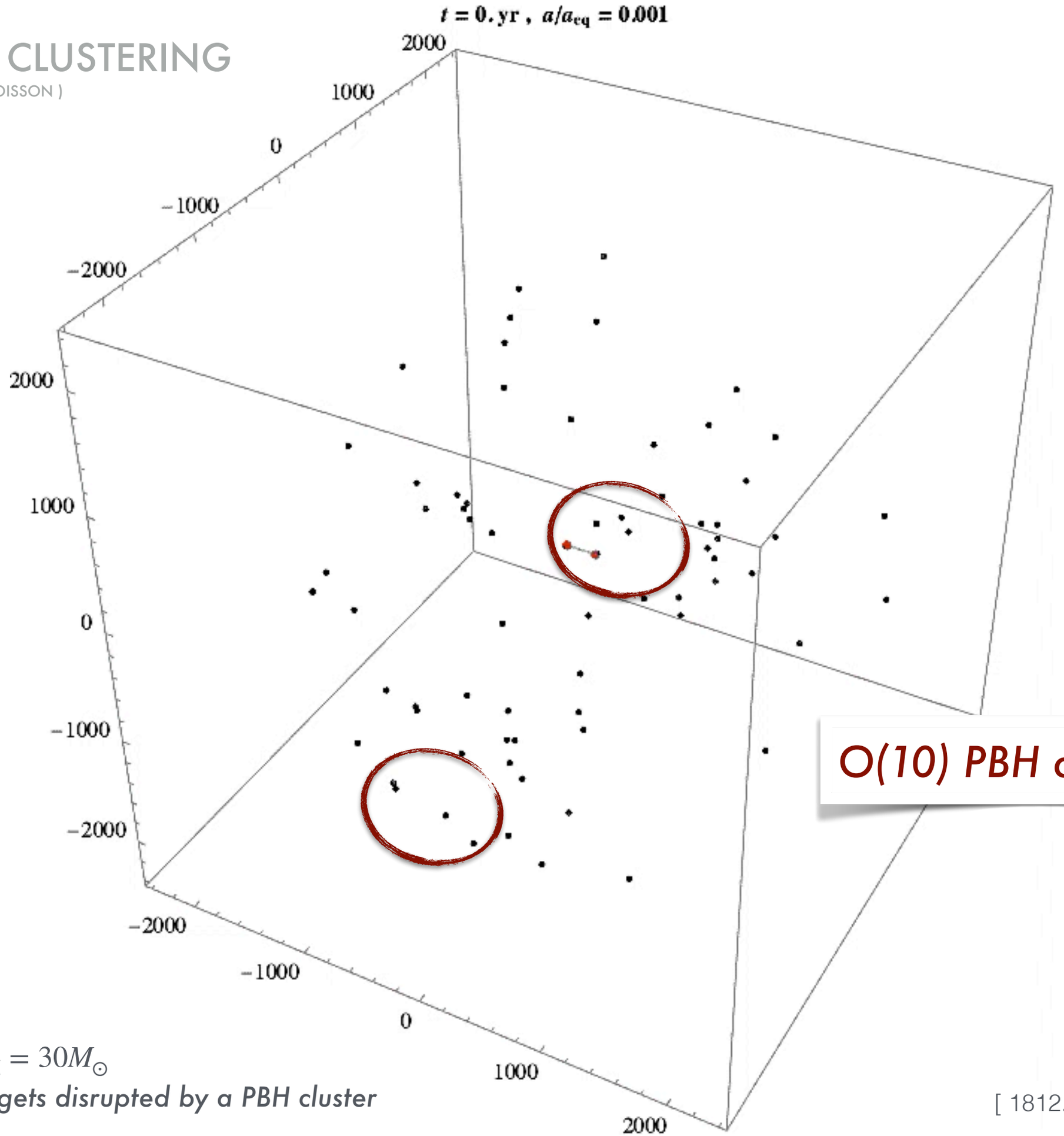

O(10) PBH clusters

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[1812.01930 Raidal et al]

Structure Formation with PBHs

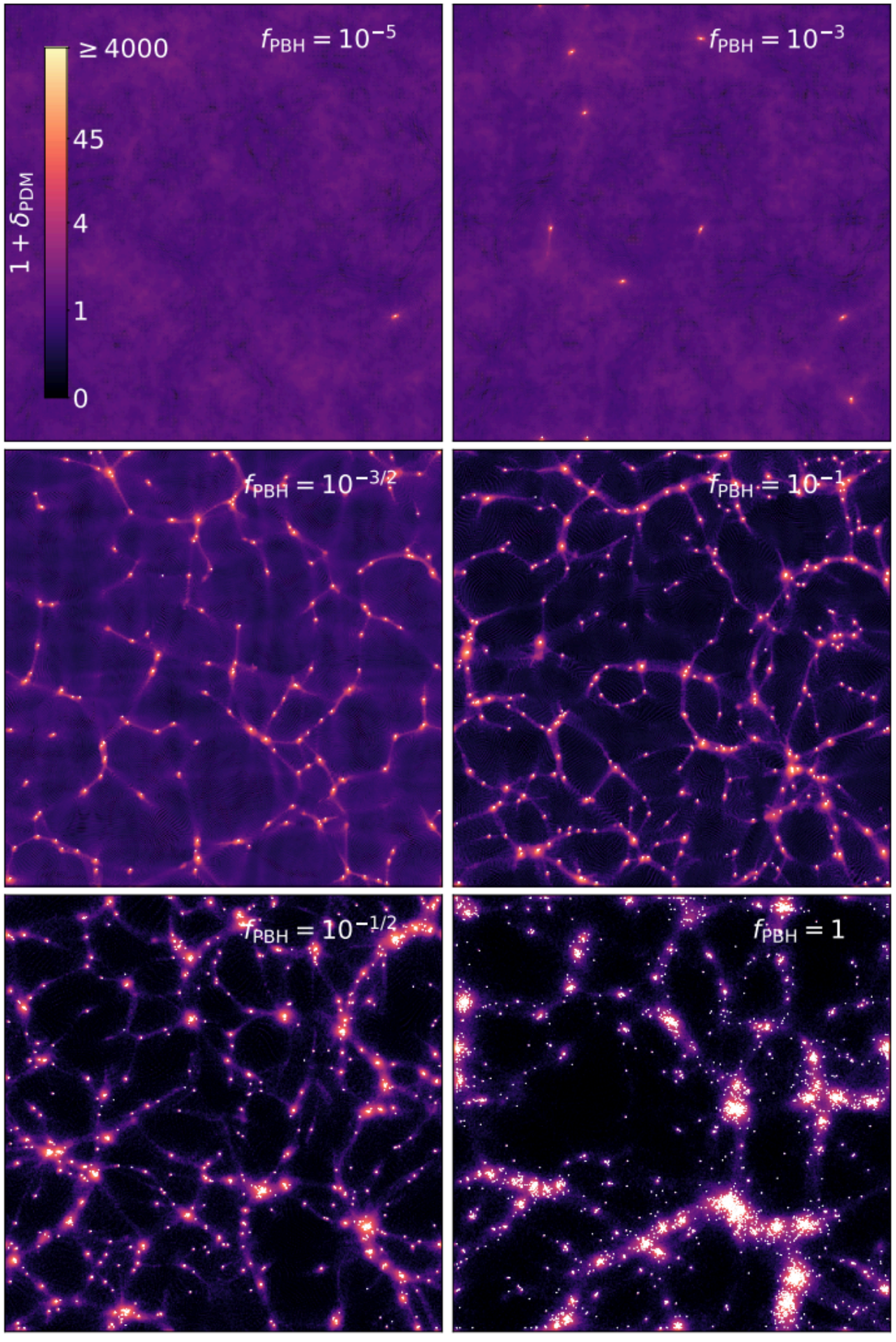
- *PBH + CDM simulation* [1907.08129 Inman et al]
- *all snapshots at* $z = 99$,
- *box size* $2\,\mathrm{kpc}/h$,
- $N_{\mathrm{PBH}} = 10^5 f_{\mathrm{PBH}}$, $M_{\mathrm{PBH}} = 20\,M_\odot/h$

scaling:

$$M \to \lambda^3 M, \quad x \to \lambda x$$

asteroid mass window:

$$M \approx 10^{-14} M_\odot, \quad d_{\mathrm{box}} \approx 10^{-2}\,\mathrm{pc}$$



Halo mass function

Probability that a PBH is in a halo of size *N*

[Epstein 1983, 1907.06533 Hütsi et al]

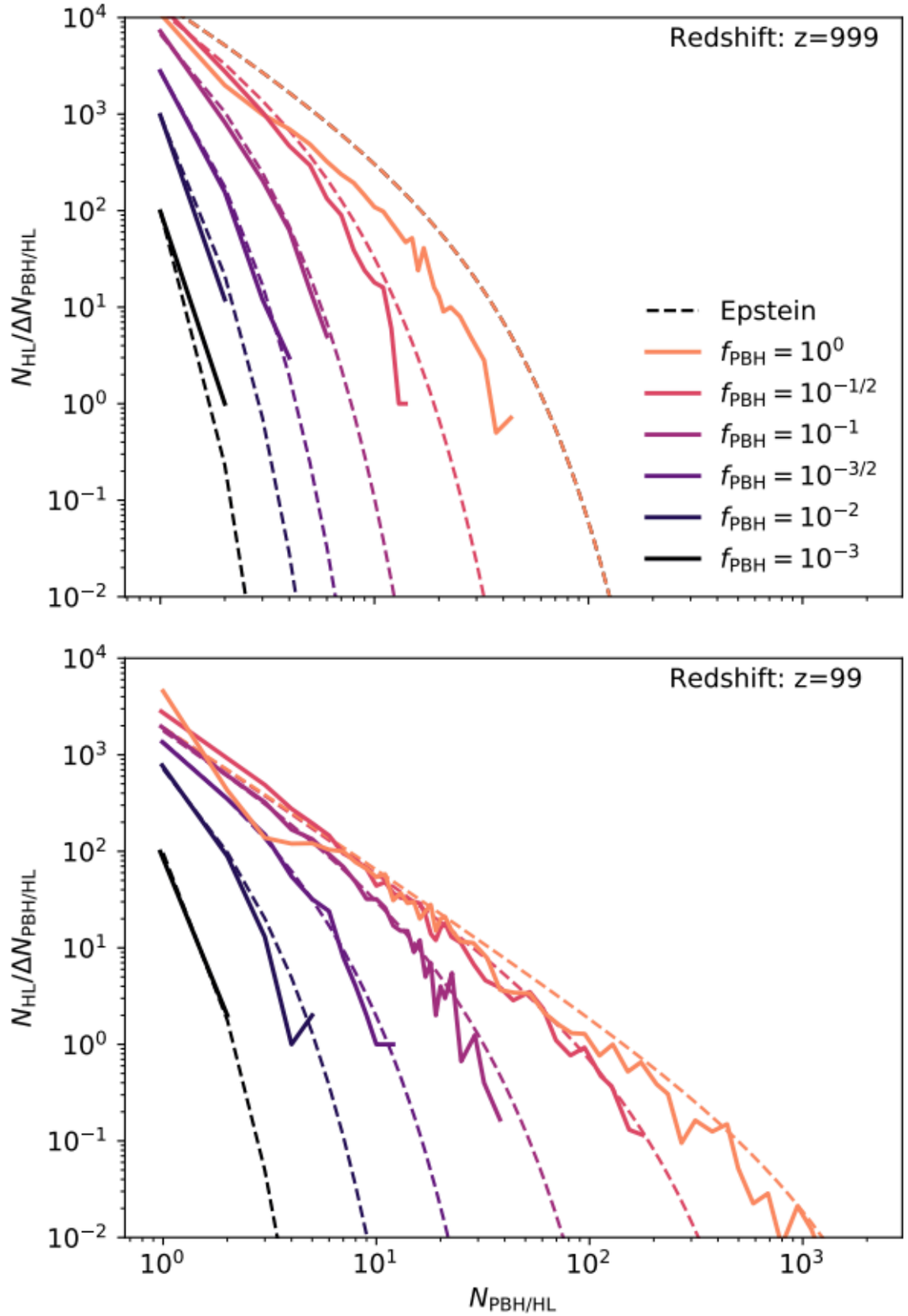
$$p_N(z) \propto N^{-1/2} e^{-N/N^*(z)},$$

where [1907.06533 Hütsi et al]

$$N^*(z) \approx \left(\frac{2600}{1+z}\right)^2 f_{\rm PBH}^2$$

Halo mass function

$$\frac{{\rm d}n_H}{{\rm d}N} \propto M_{\rm PBH}\, p_N/N$$



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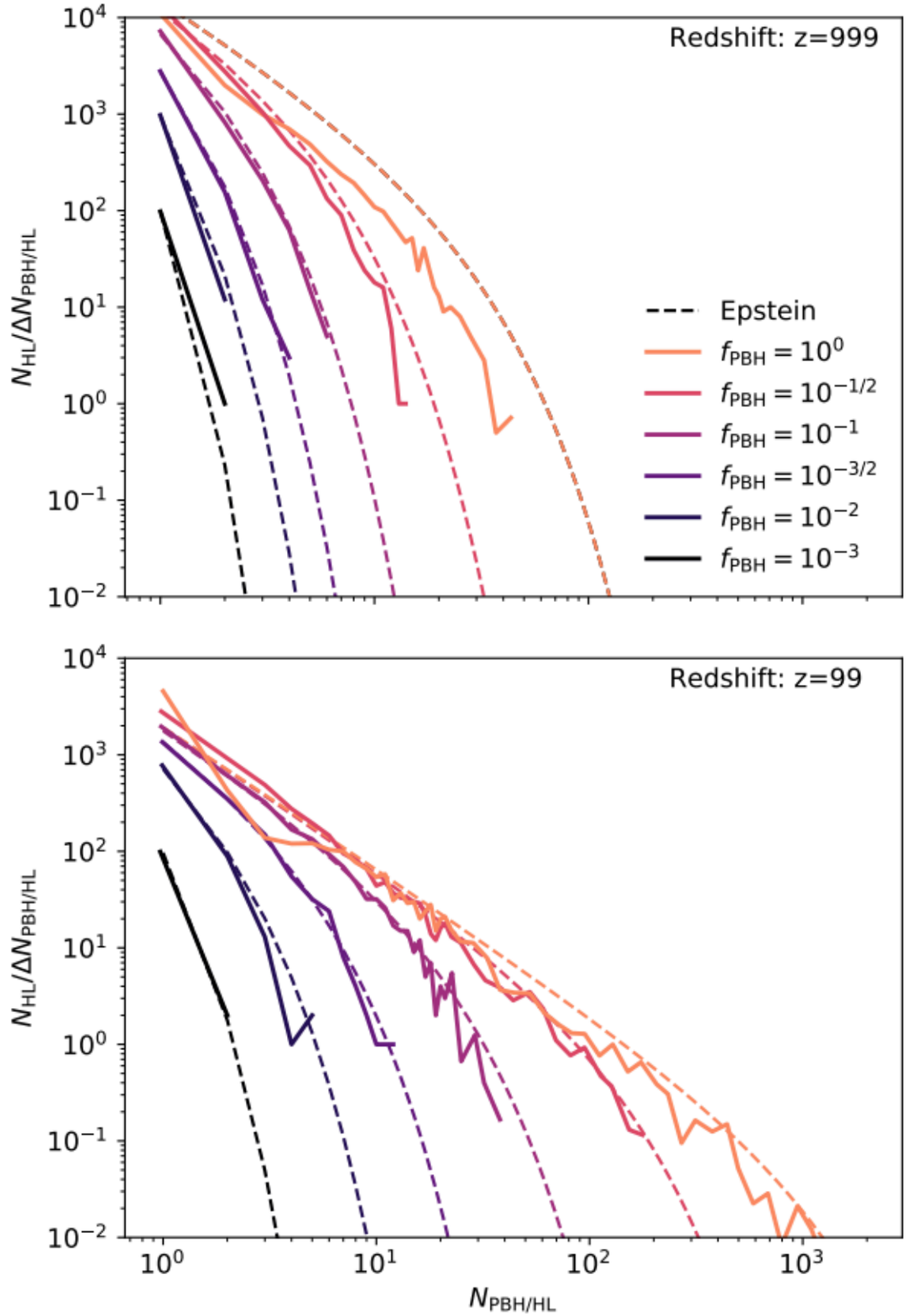
Halo mass function

$$\frac{{\rm d}n_H}{{\rm d}N} \propto M_{\rm PBH}\, p_N/N$$

First structures form early

$$z_{\rm form}(N) \approx z_{\rm eq}\, f_{\rm PBH}/\sqrt{N}$$

when $f_{\rm PBH} \approx 1$.



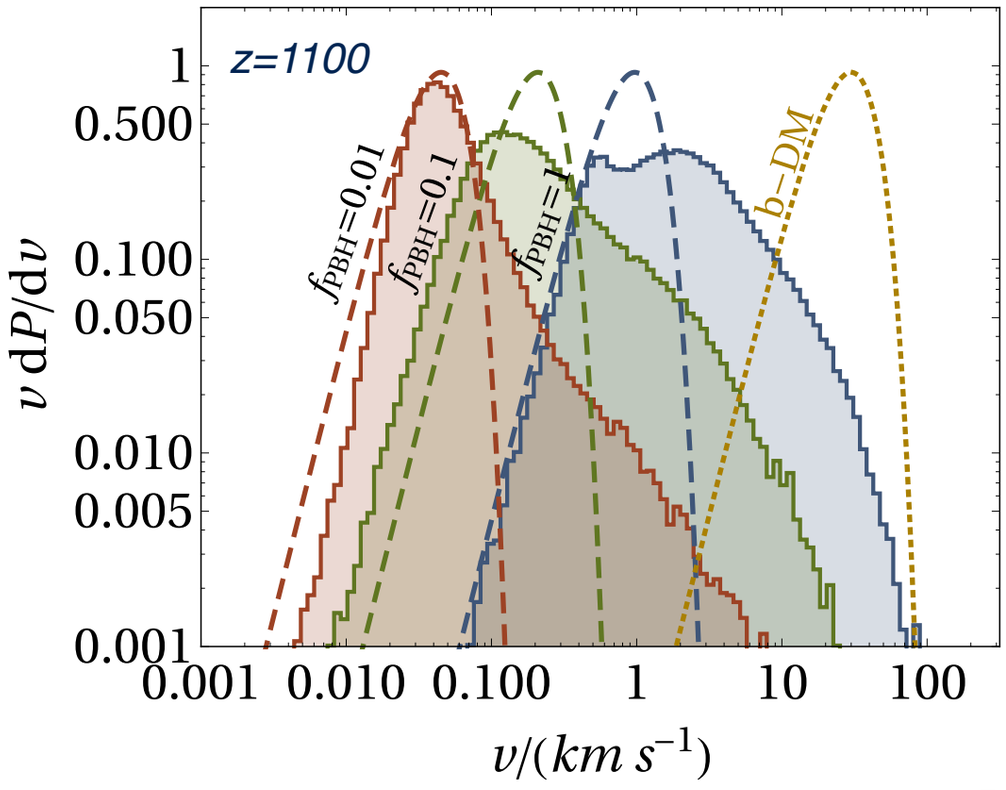
[1907.08129 Inman et al]

Velocity distribution

- *low velocity tail is Maxwell with*

  [1907.06533 Hütsi et al]

$$\sigma_{v,L}(z) \approx 6\,\mathrm{km/s}\,\frac{f_{\mathrm{PBH}}^{\frac{2}{3}}\left(M/M_\odot\right)^{\frac{1}{3}}}{\sqrt{1+z}}$$

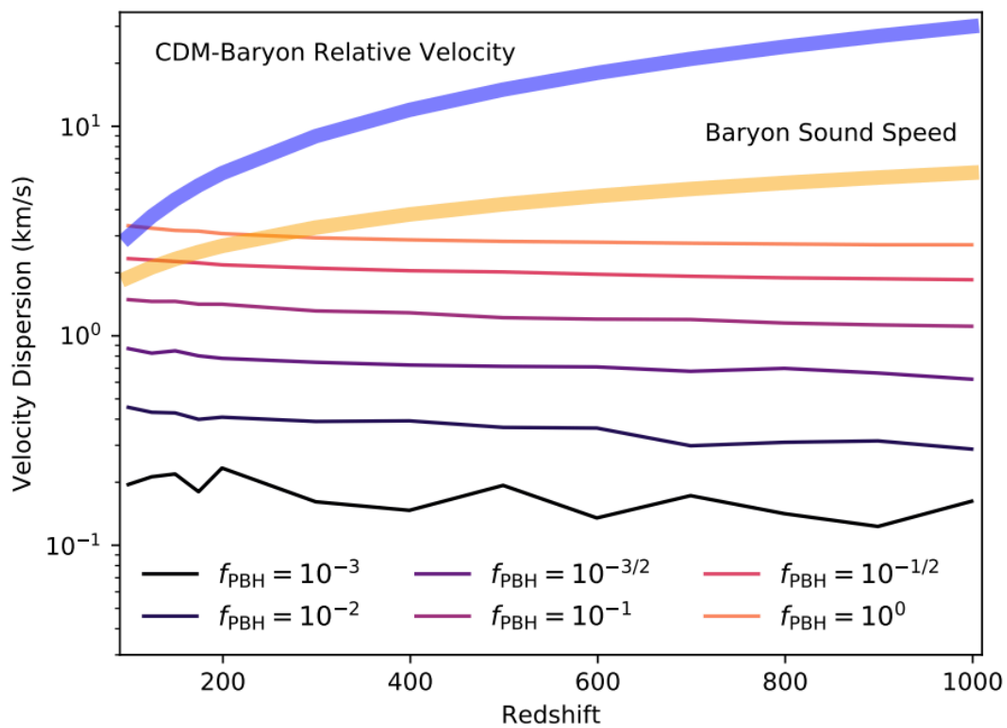


[1812.01930 Raidal et al]

- *high velocity tail dominated by binaries/small scale structure*

$$\sigma^2_{v,NL}(z) \approx \left\langle \sigma^2_{v,\mathrm{halo}}(N) \right\rangle_N$$

**assuming virialized haloes*



- *total:* $\sigma_v(z) = \sqrt{\sigma^2_{v\mathrm{L}} + \sigma^2_{v\mathrm{NL}}}$

[1907.08129 Inman et al]

timescales for PBH clusters

[astro-ph/0302035 Ashfordi et al, 1908.09752 Vaskonen et al, 2009.04731 De Luca et al]

timescales for PBH clusters

[astro-ph/0302035 Ashfordi et al, 1908.09752 Vaskonen et al, 2009.04731 De Luca et al]

- *Collisions*

$$t_{\rm p} = 90{\rm kyr}\,\frac{N^{\frac{19}{12}}}{f_{\rm PBH}^{2.8}(m/M_\odot)^{0.09}}$$

relevant N if $f_{\rm PBH} \approx 1$, $m_{\rm PBH} \approx 10 M_{\rm odot}$

→ $N < \mathcal{O}(2000)$

timescales for PBH clusters

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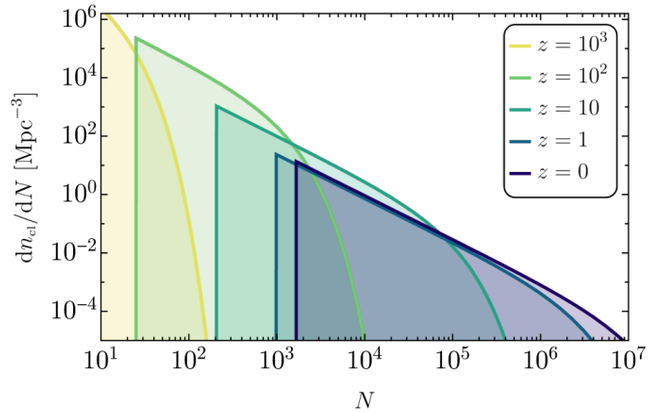

- *Evaporation*

$$t_{\rm ev} \approx 140 t_{\rm rel} = 14 \frac{N}{\ln(N/f_{\rm PBH})}\frac{R_H}{\sigma_v}$$

$$\approx 100{\rm kyr} \times \frac{N^{7/4}}{f_{\rm PBH}^{\frac{5}{2}}\ln(N/f_{\rm PBH})}$$

→ $N < \mathcal{O}(3000)$

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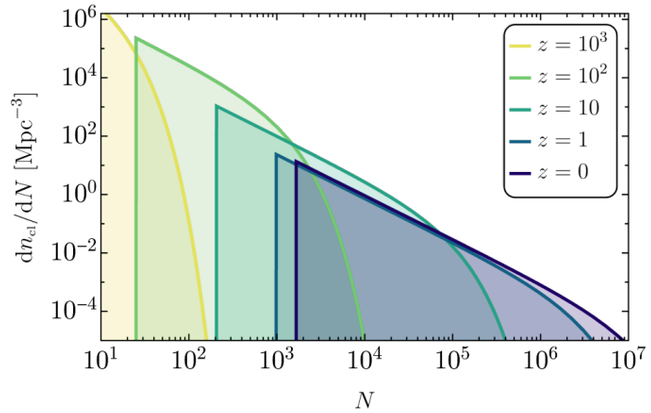

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- Core collapse

→ $N < \mathcal{O}(5000)$

timescales for PBH clusters

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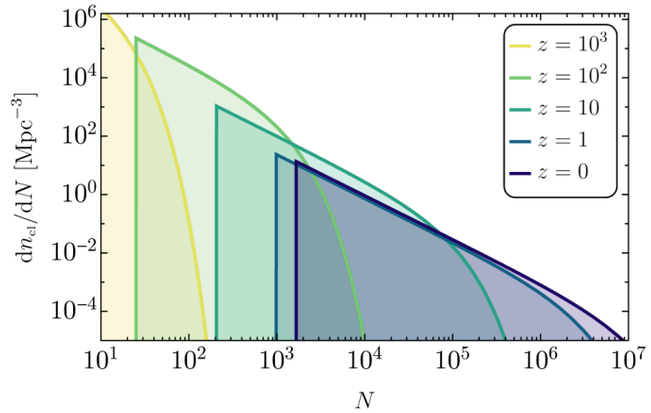

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Clusters typically absorbed in larger haloes before evaporation

[2009.04731 De Luca et al]

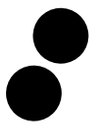
PBH BINARIES

dominates if

$f_{\rm PBH} \ll 1$

highly eccentric

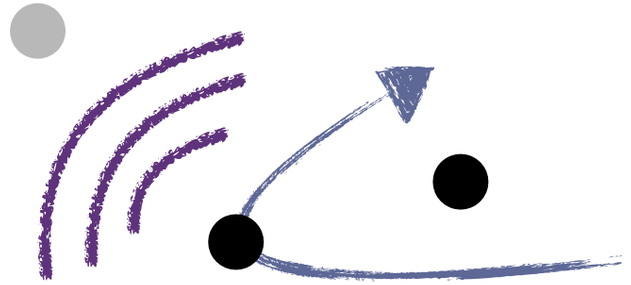
EARLY



compact pairs
(non-perturbed)

[astro-ph/9708060 Nakamura et al]

LATE



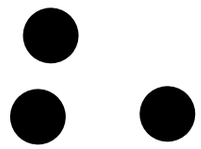
2-body capture

[1603.00464 Bird et al]

dominates if

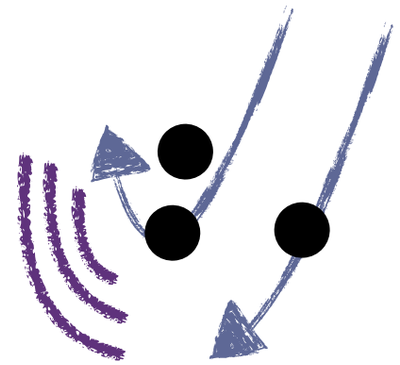
$f_{\rm PBH} \sim 1$

some evolution via BH-BBH collisions



compact 3-body systems

[1908.09752 Vaskonen, HV]



3-body interactions

[2205.15340 Franciolini et al]

PBH BINARIES

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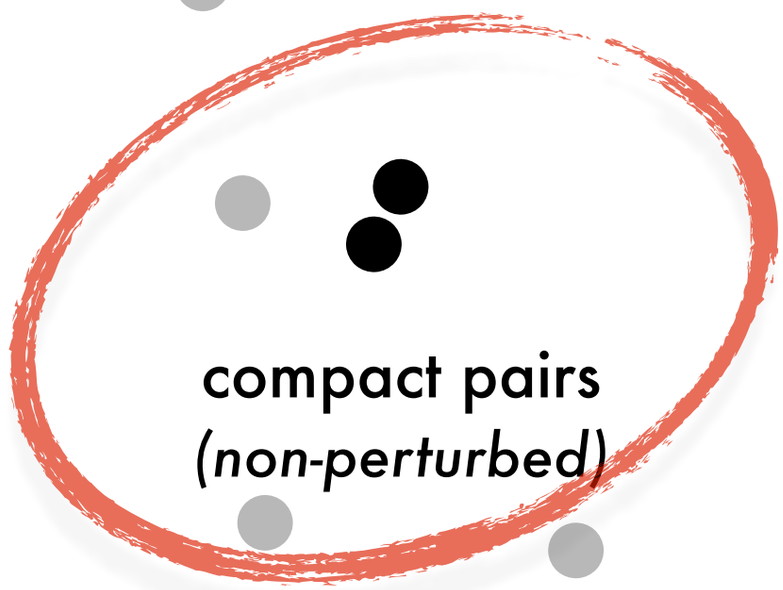
highly eccentric

EARLY



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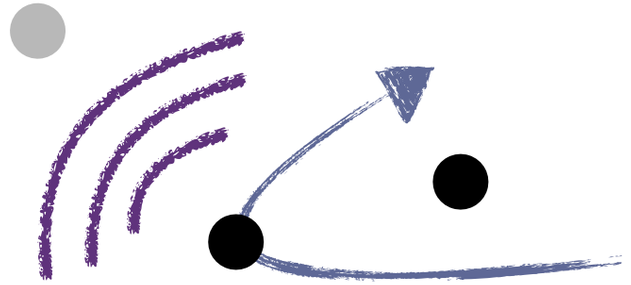

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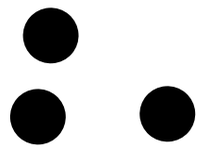

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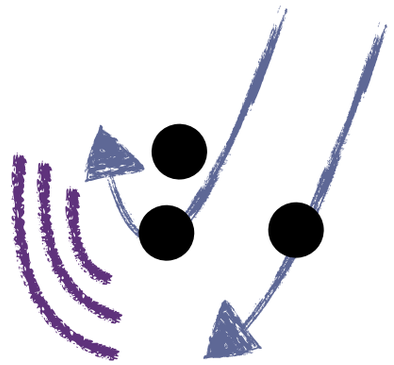
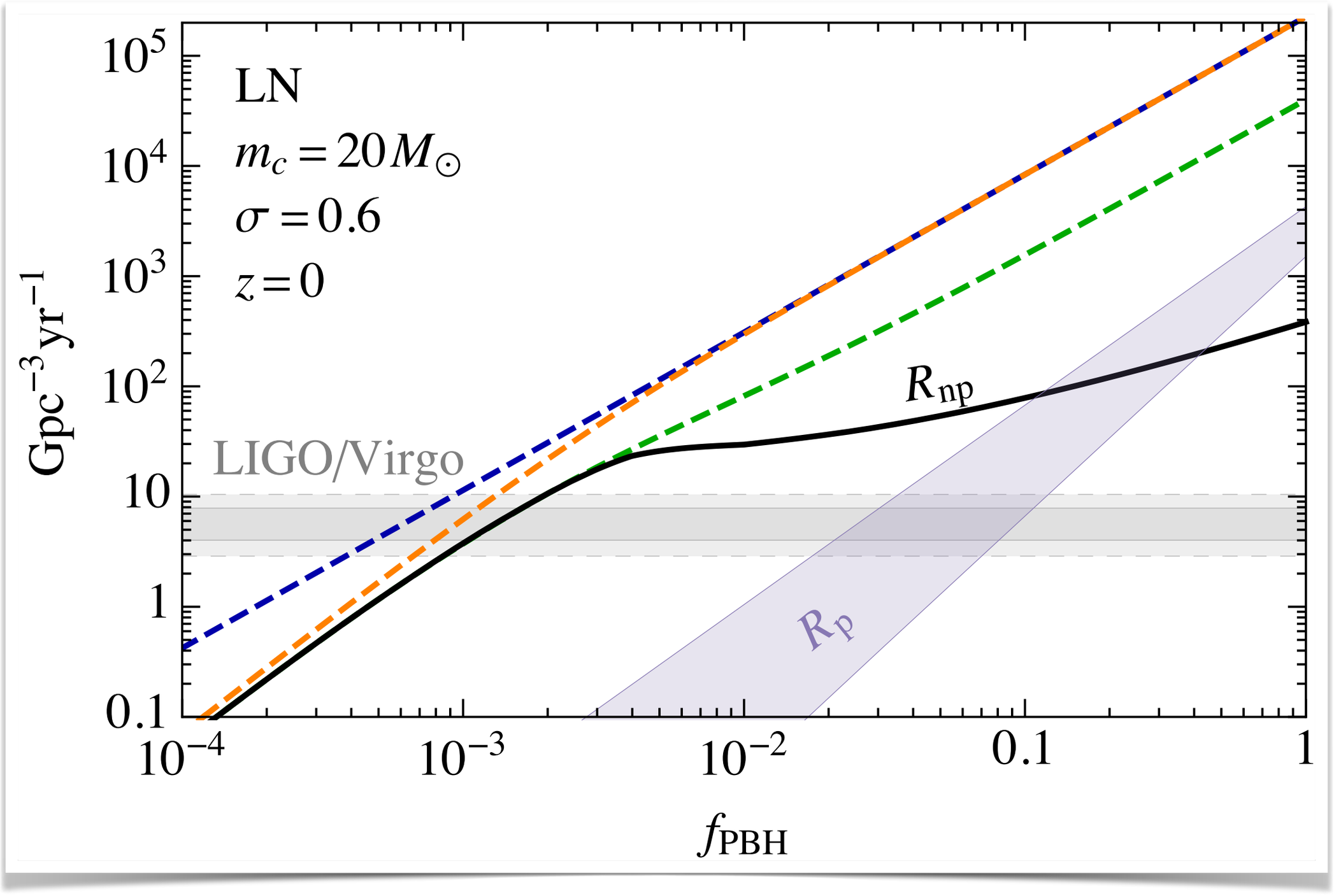


3-body interactions

[2205.15340 Franciolini et al]

$$\tau \approx \frac{3}{170} \frac{r_a^4}{M^2} j^7, \qquad j \equiv \sqrt{1 - e^2}$$

PBH binary merger rate



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

[1908.09752 Vaskonen, HV]
[2012.02786 Vaskonen et al]
[2205.15340 Franciolini et al]

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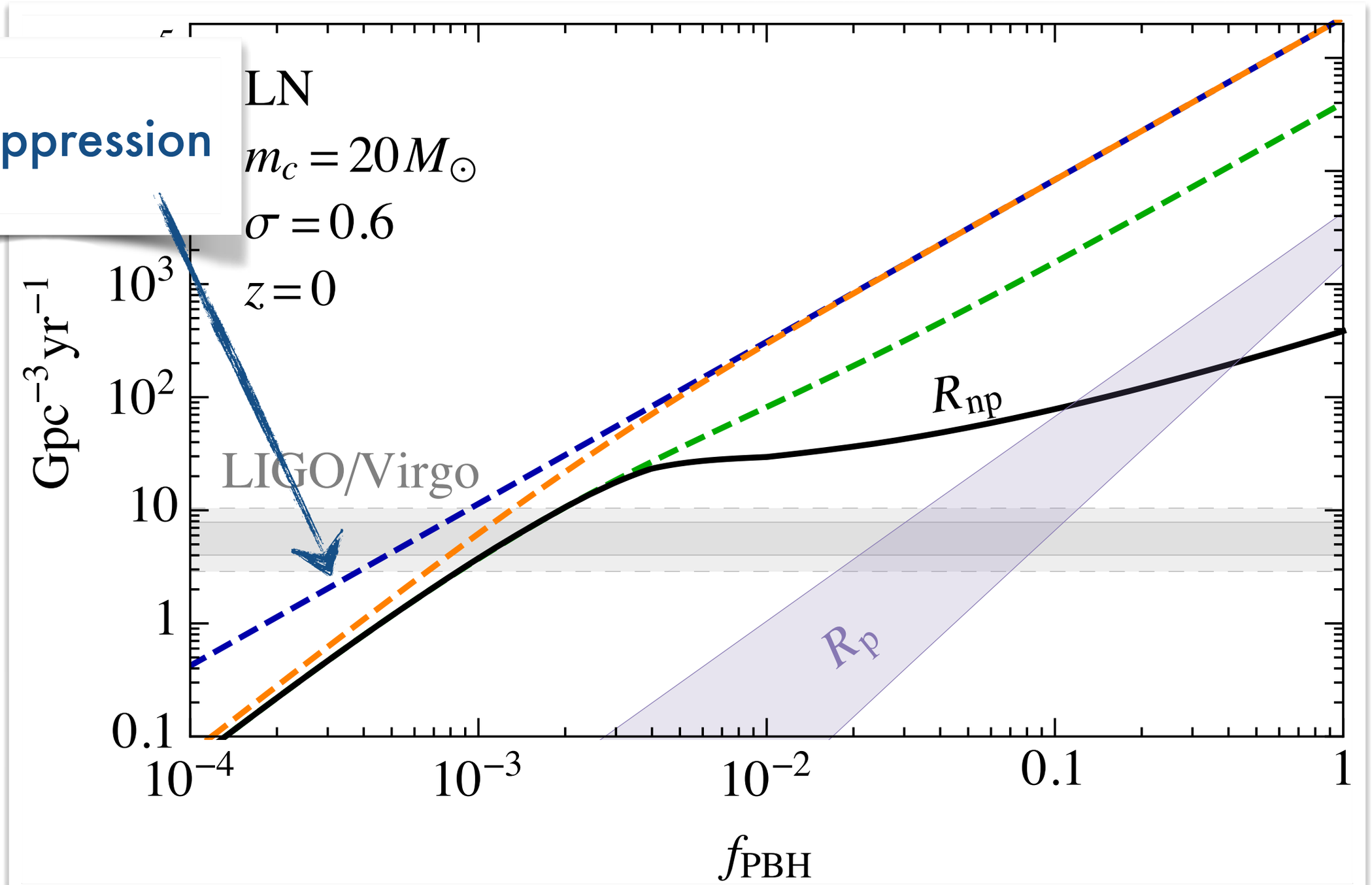
no suppression



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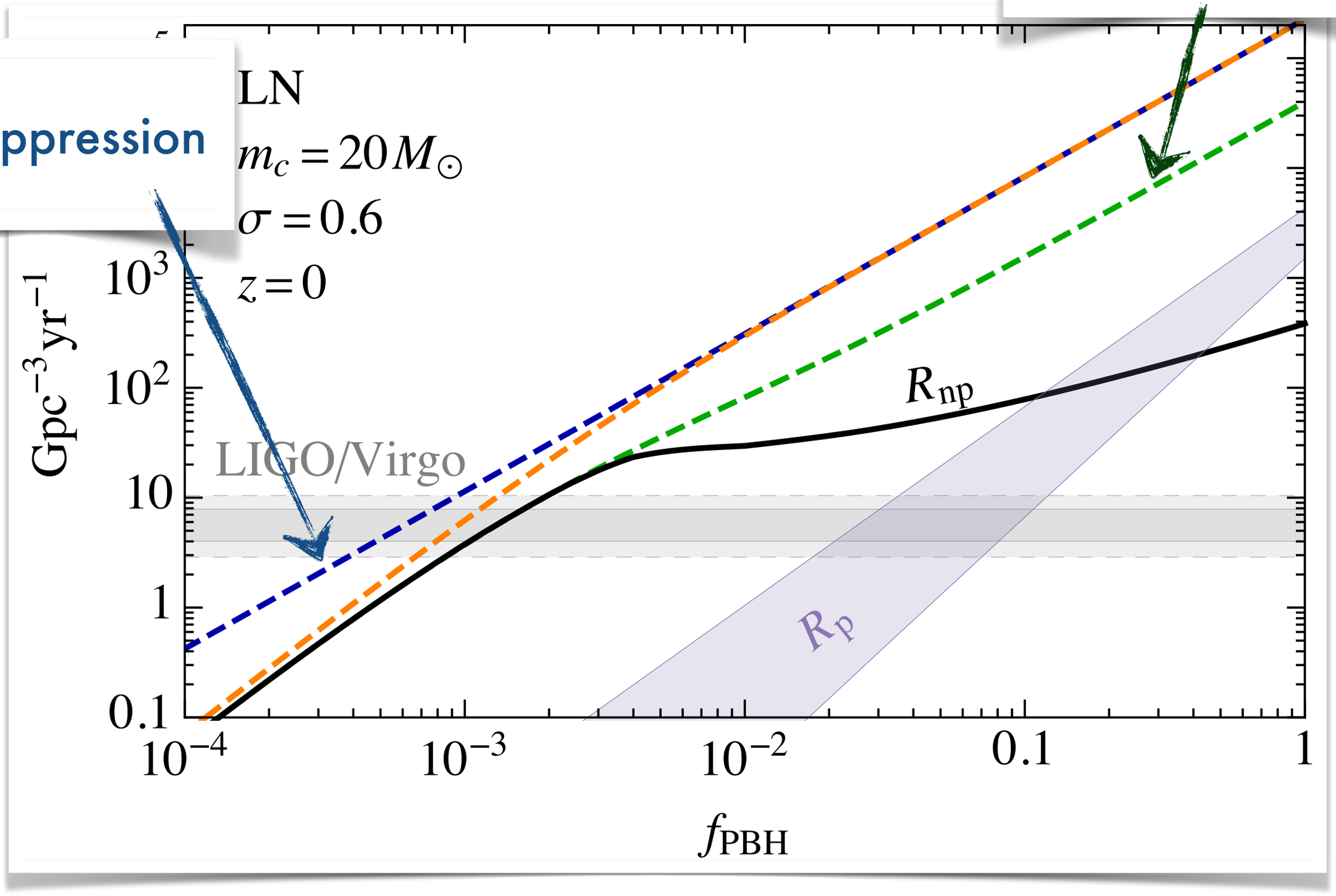

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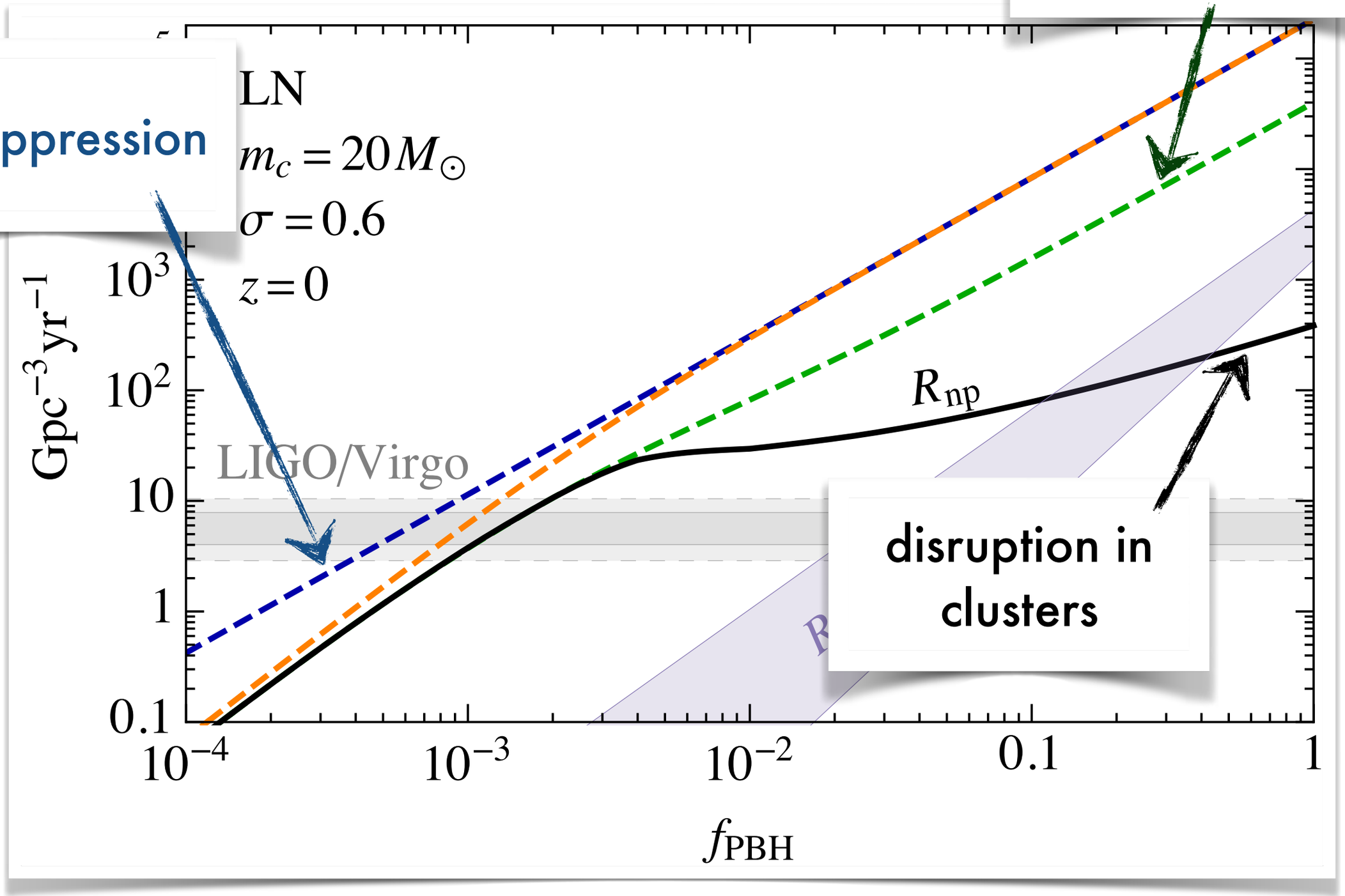

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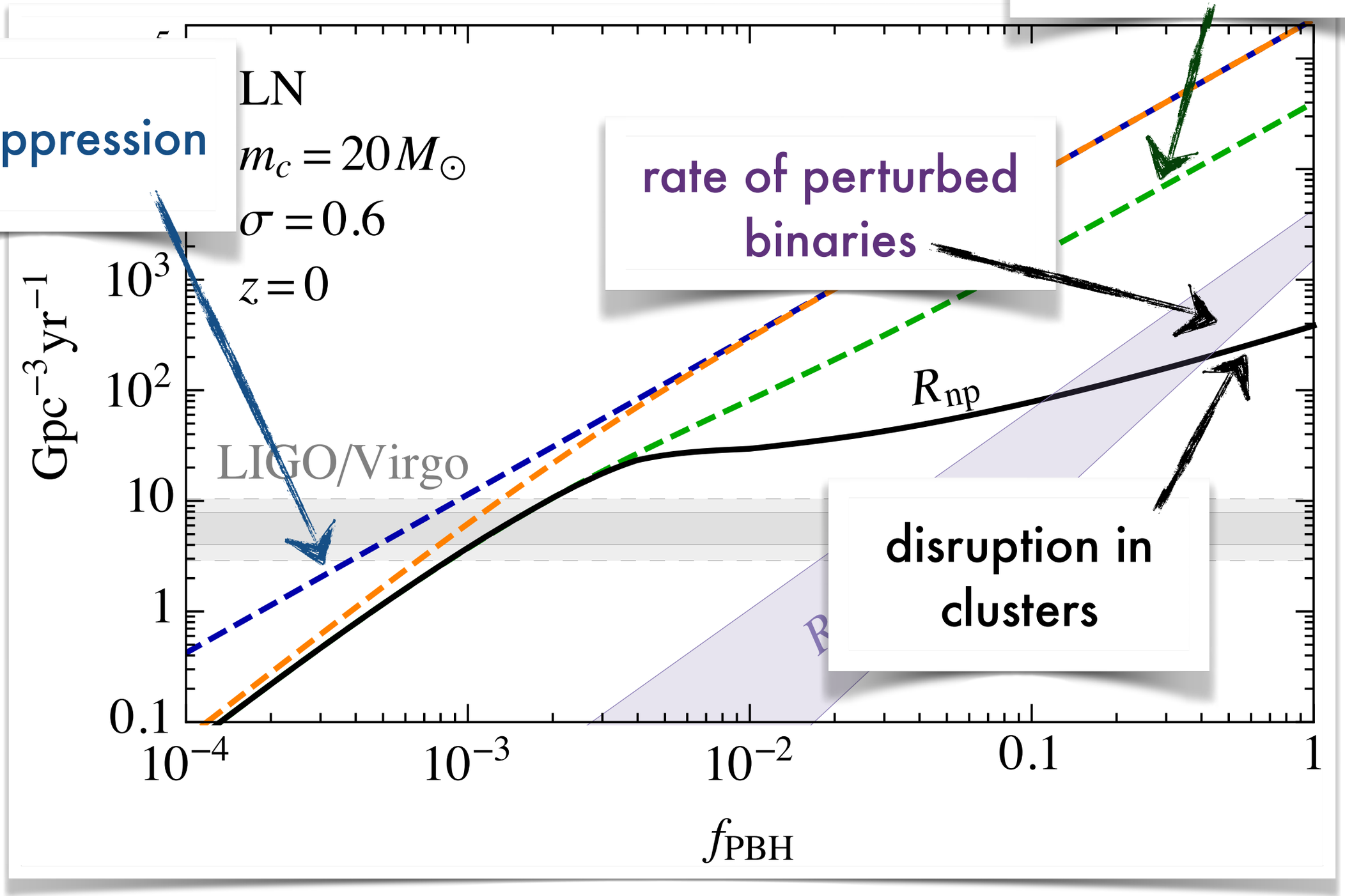

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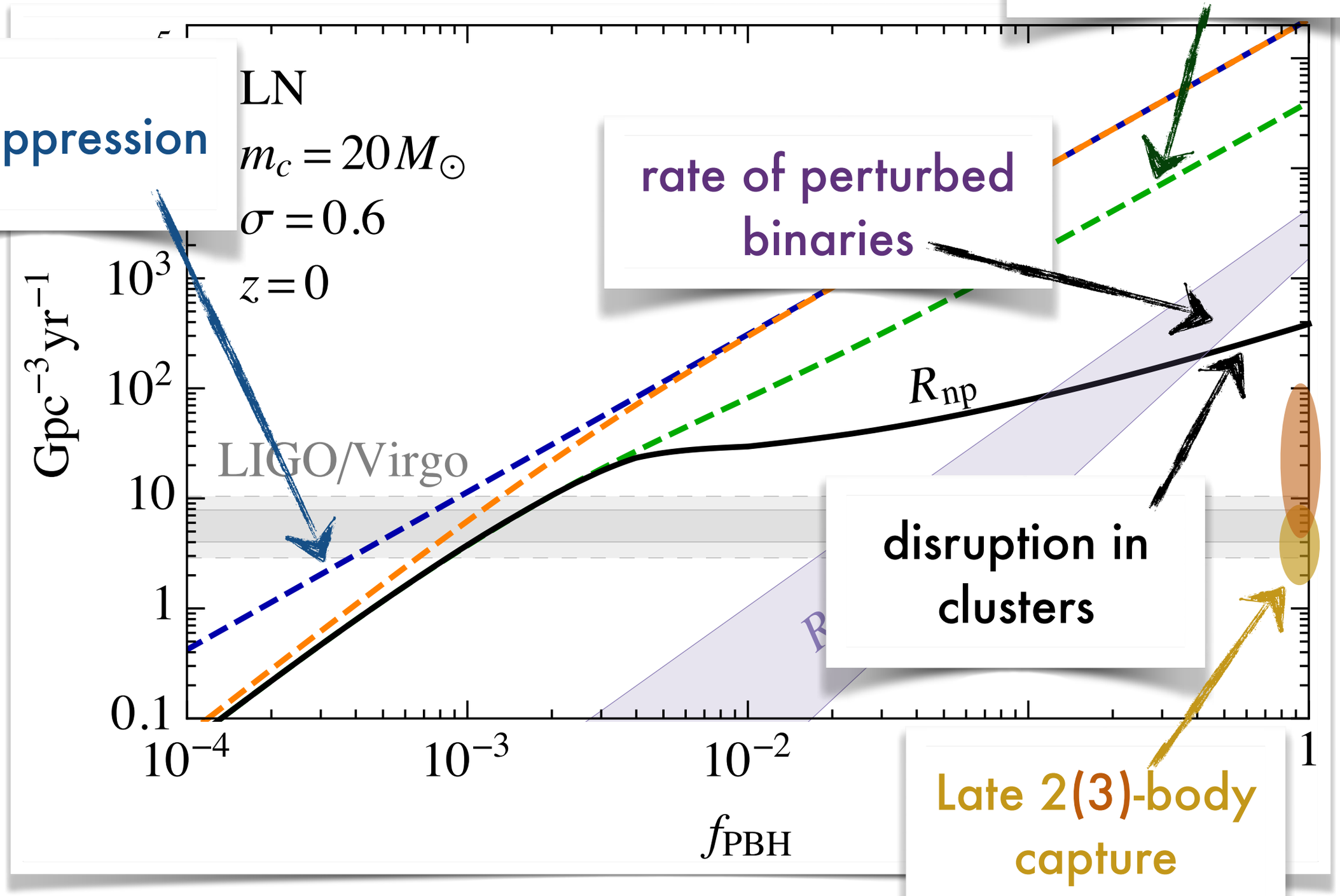

disruption in clusters

Late 2(3)-body capture

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

[1908.09752 Vaskonen, HV]
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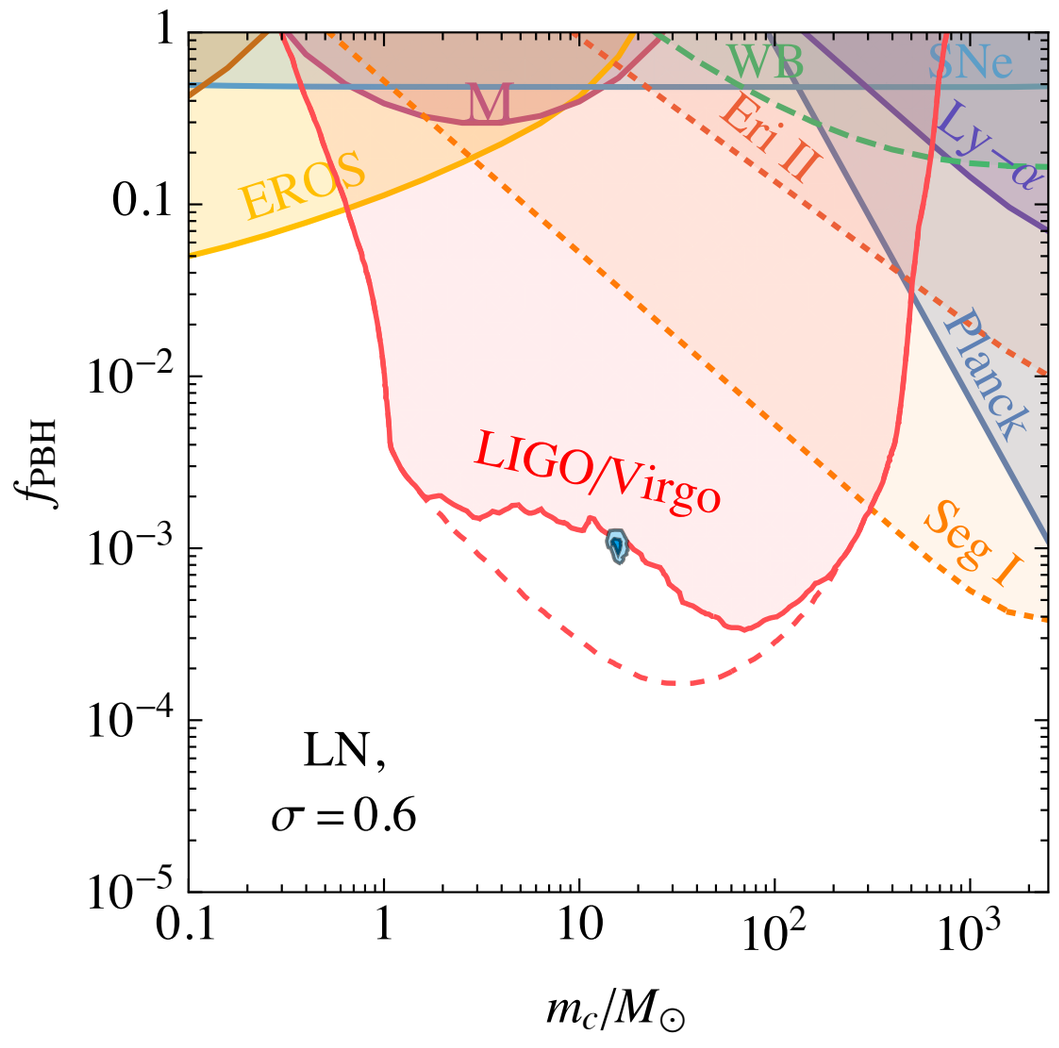
testing PBHs with LIGO-Virgo-Kagra



** non-perturbed binary formation channel only*

[2012.02786 Vaskonen et al]

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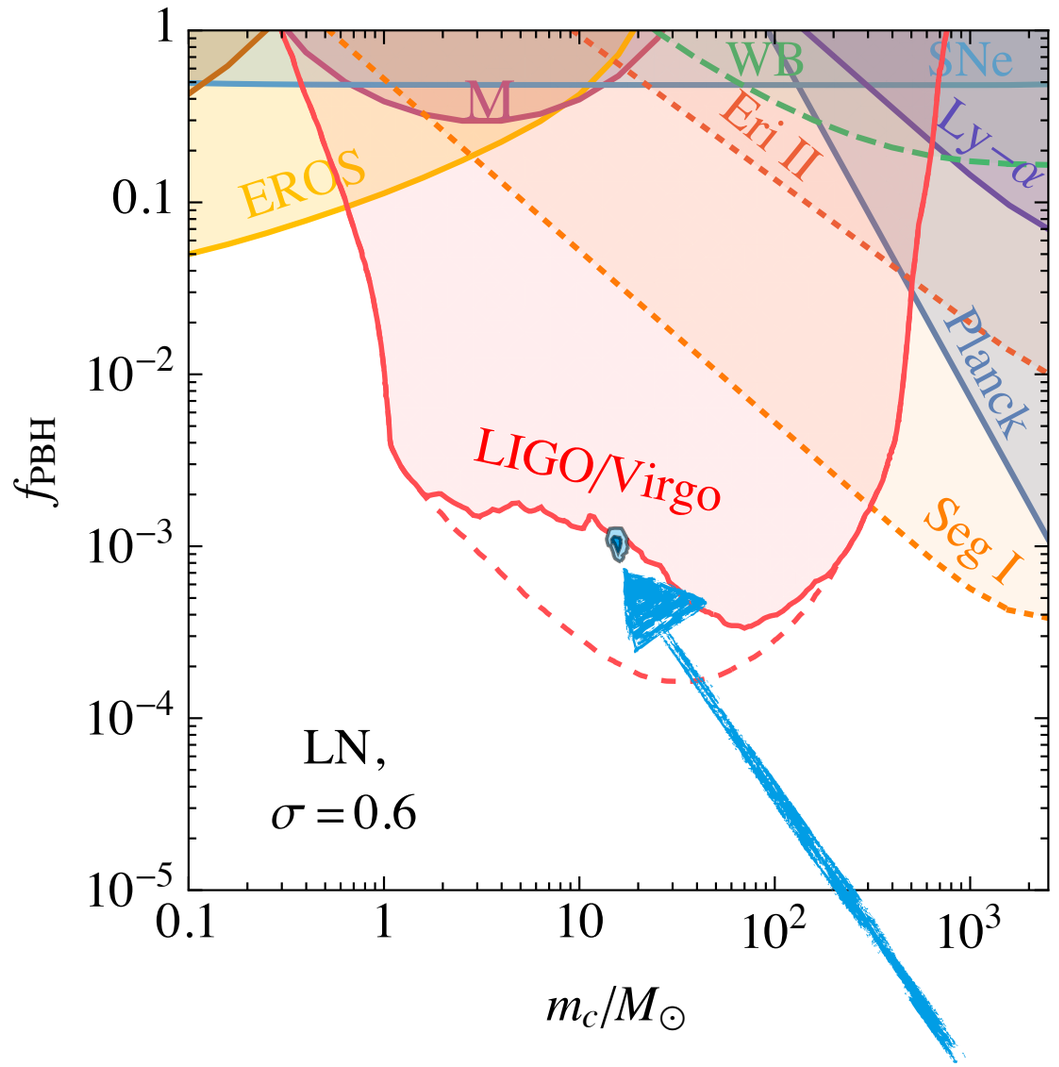

best-fit PBH only scenario

** non-perturbed binary formation channel only*

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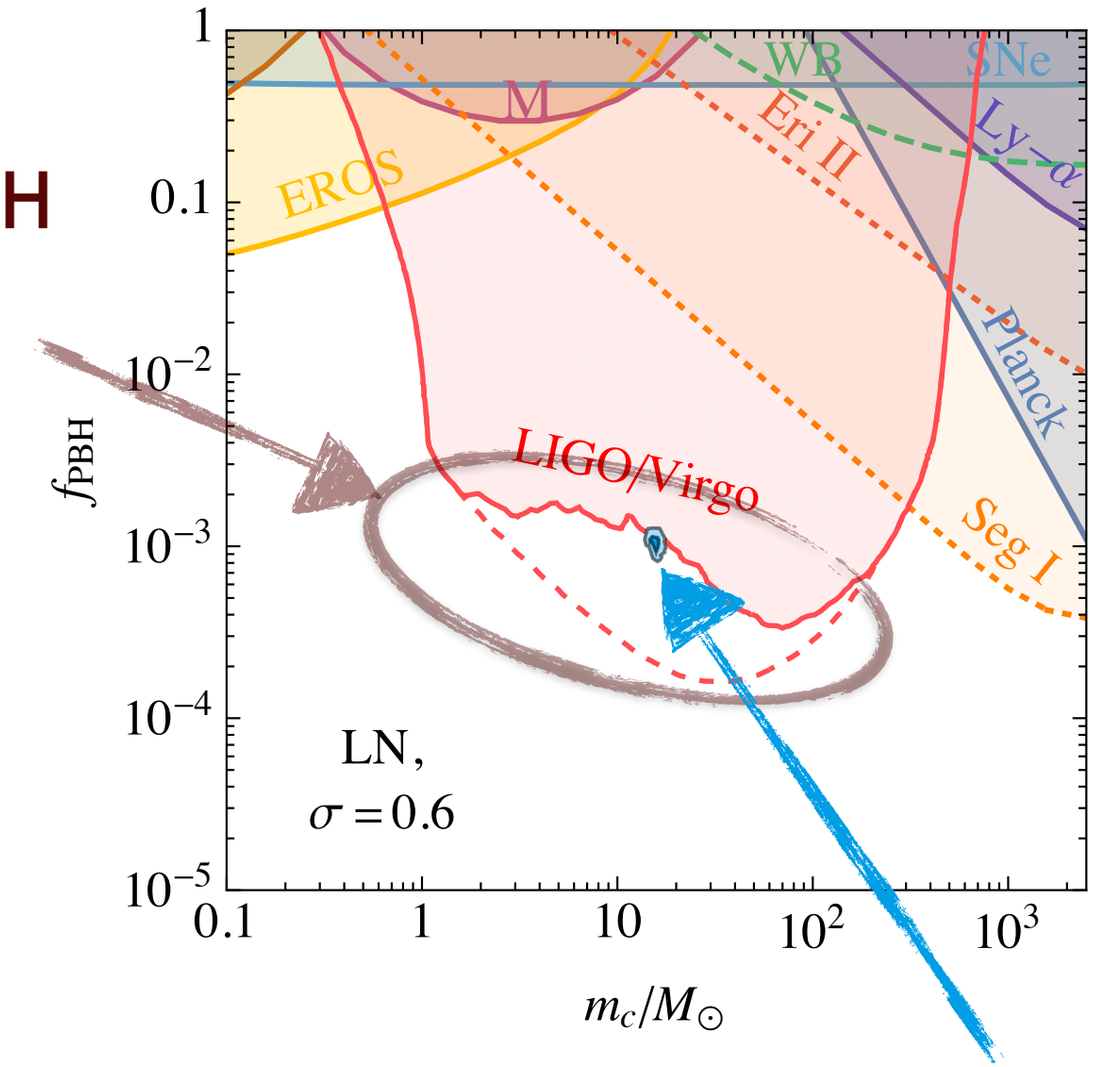
testing PBHs with LIGO-Virgo-Kagra

scenarios with PBH subpopulations



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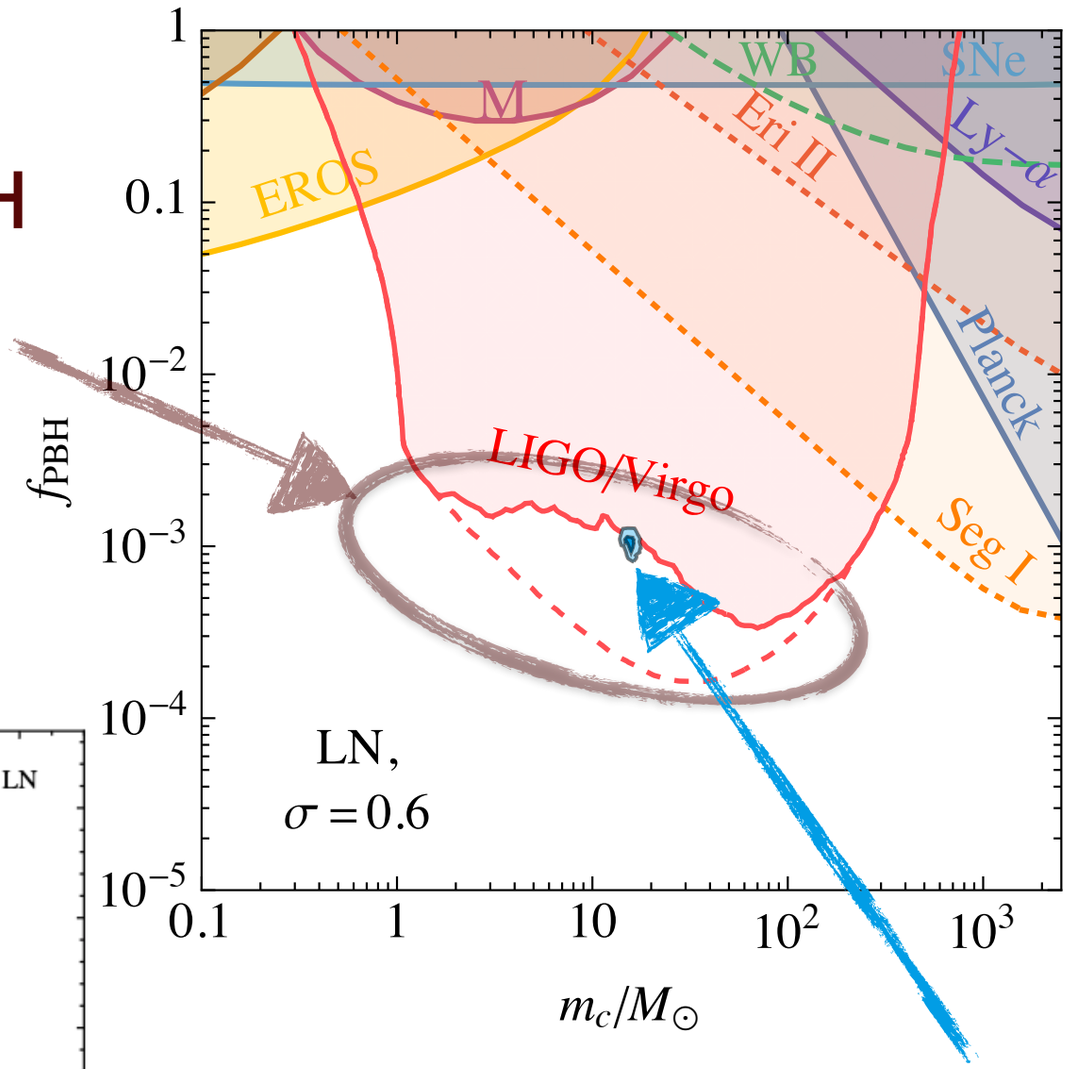
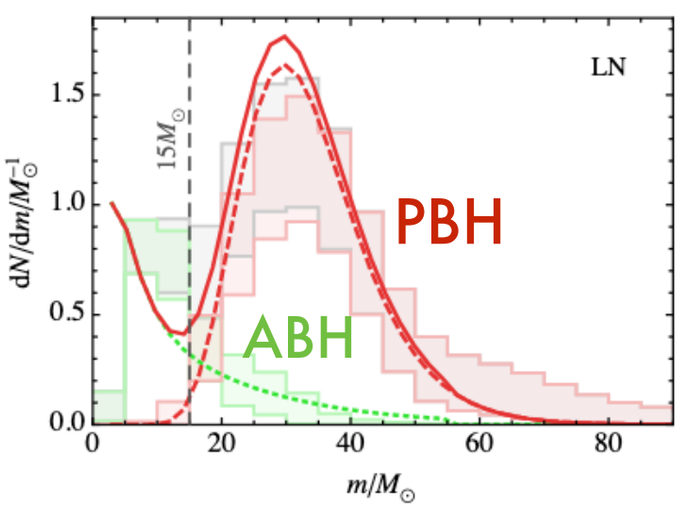


for example:



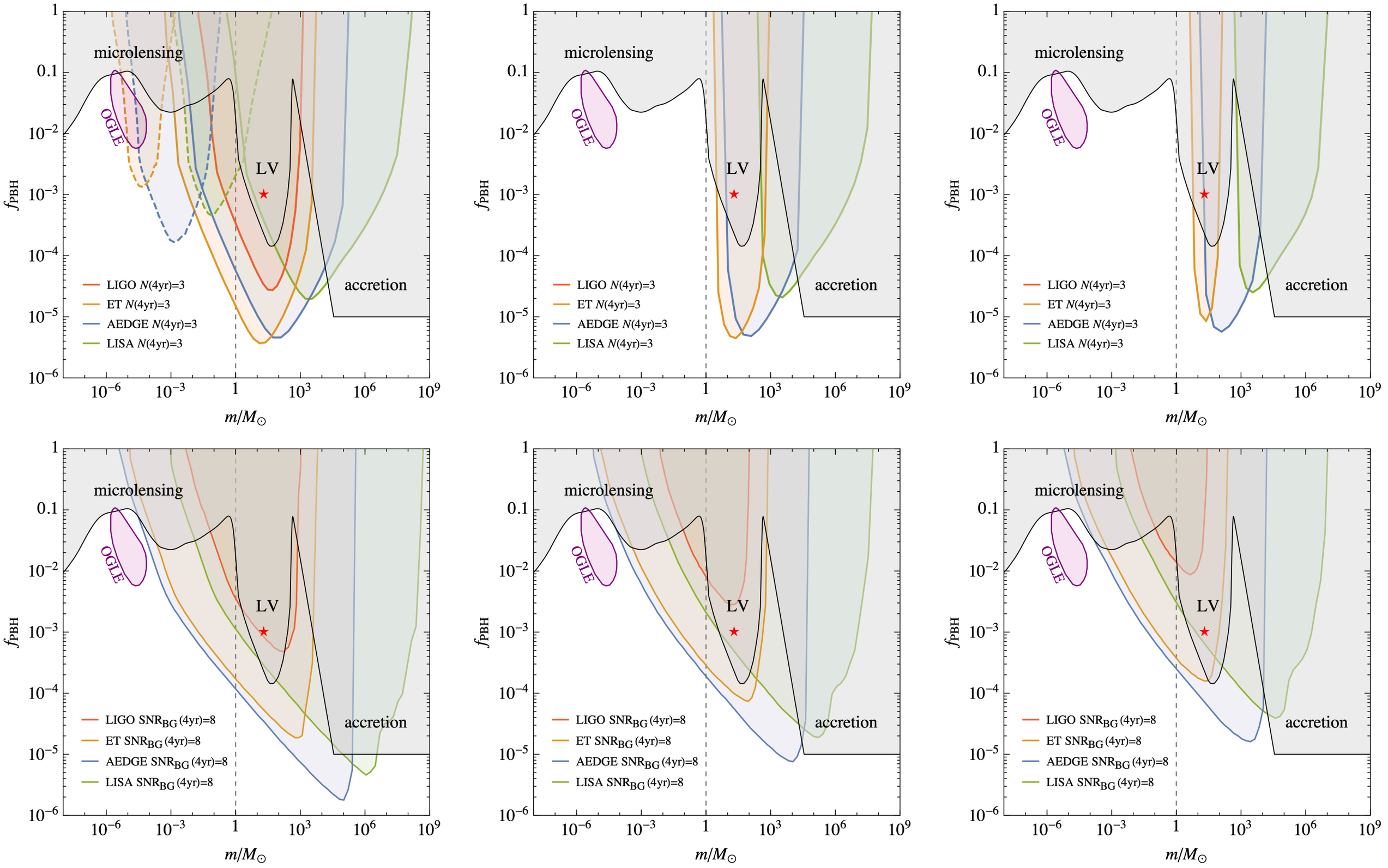
best-fit PBH only scenario

* *non-perturbed binary formation channel only*

[2012.02786 Vaskonen et al]

INDIVIDUAL MERGERS

$z_{cut} = 0$ $z_{cut} = 5$ $z_{cut} = 20$



SGWB

[2107.03379 Pujolas et al]

Initial clustering?

only including local PBH density:

$$f_{\rm PBH} \to \delta_{\rm PBH} f_{\rm PBH} \quad \rightarrow \quad R(f_{\rm PBH}) \to \delta_{\rm PBH}^{-1} R(\delta_{\rm PBH} f_{\rm PBH})$$

**negelects "non-local" effects such as structure formation*

**with primordial non-gaussianity $f_{\rm PBH} \approx 10^{-7}$ might be sufficient to explain LV* [1910.06077 Byrnes et al]

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different formation channels when $f_{\rm PBH} \gg \mathcal{O}(10^{-3})$

**assuming $M_{\rm PBH} = 20 M_\odot$*

EARLY

$$R_{2-\rm body} \approx \underbrace{f_{\rm PBH}^{1.4}}_{\text{formation}} \times \underbrace{f_{\rm PBH}^{-0.7}}_{\text{disruption}} \times \frac{530}{\rm Gpc^3 yr}$$

$$R_{3-\rm body} \approx f_{\rm PBH}^{0.9-1.8} \times \frac{\mathcal{O}(10^3)}{\rm Gpc^3 yr}$$

How much does clustering boost binary disruption?

Evolution of perturbed binaries?

LATE

$$R_{2-\rm body} \approx f_{\rm PBH}^{2.5} \times \frac{\mathcal{O}(10)}{\rm Gpc^3 yr}$$

$$R_{3-\rm body} \approx f_{\rm PBH}^{2.5-3} \times \frac{\mathcal{O}(10-100)}{\rm Gpc^3 yr}$$

Small scale structure and the halo mass function with clustrering?

Perturbing binaries in clusters

The probability for being outside of a halo or a subhalo containing less than N_c PBH.

[1908.09752 Vaskonen et al]

$$P_{\rm np}(z) \gtrsim 1 - \sum_{N=3}^{N_c(z)} \bar{p}_N(z_c) - \sum_{N'>N_c(z)} \left[\sum_{N=3}^{N_c(z)} \tilde{p}_N(z_c) \right] \bar{p}_{N'}(z_c)$$

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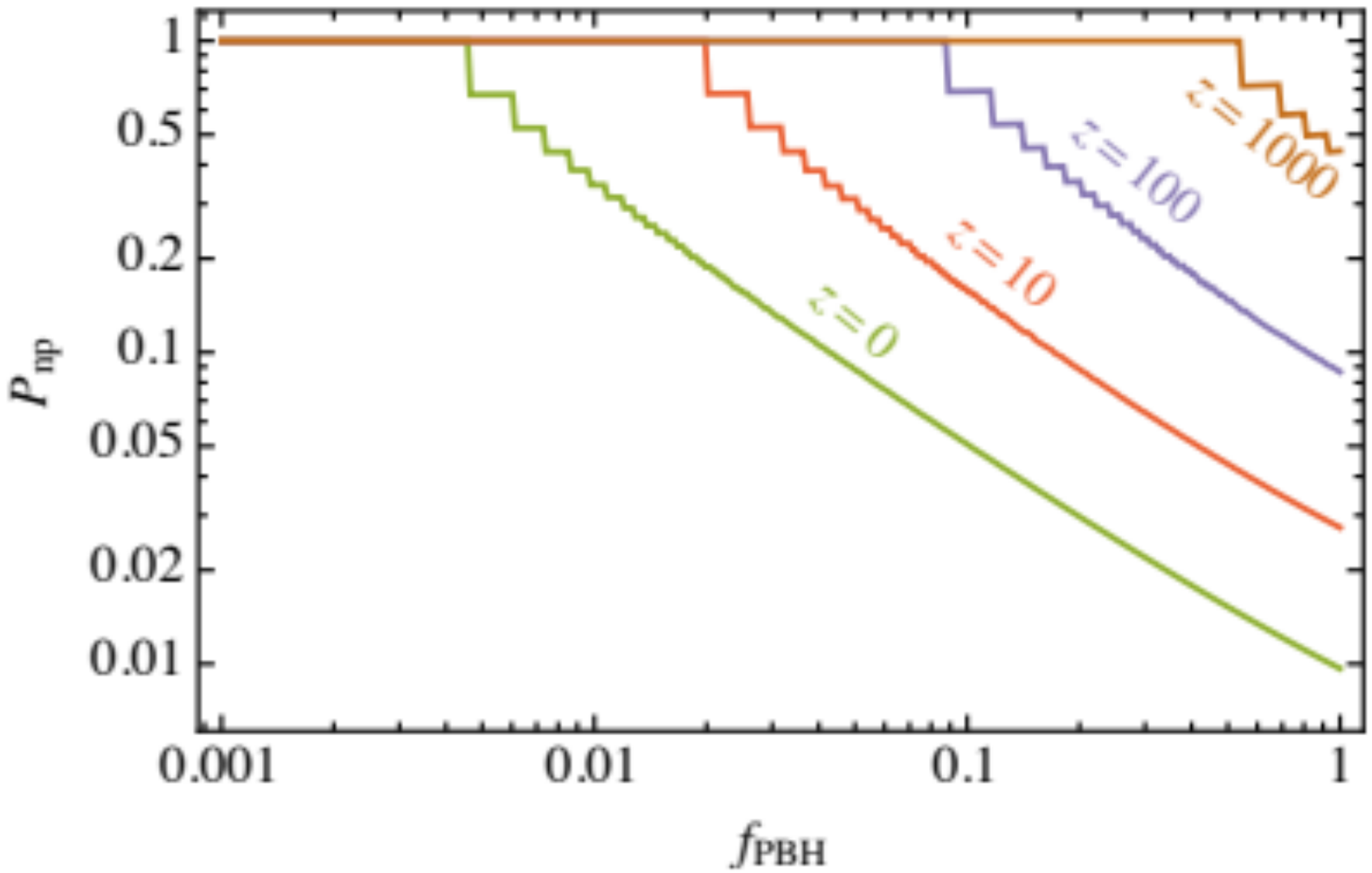

- designed to *overestimate* suppression
- consistent with simulations

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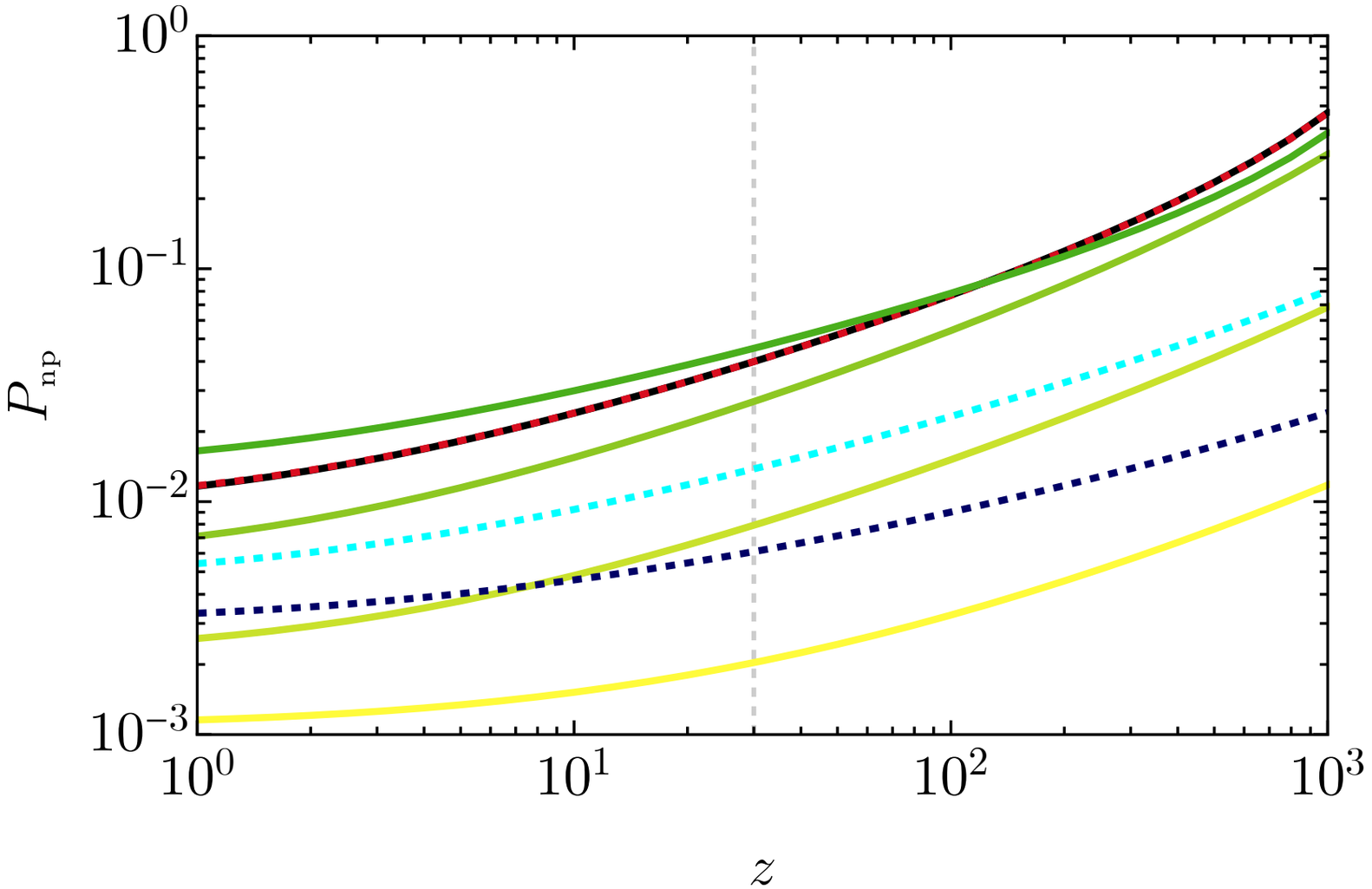
Including initial clustering



$$\Delta^2_{\rm PBH} = \Delta^2_0 \left(\frac{k}{k_*} \right)^{3+n}$$

- Poisson
- PS: $\Delta_0 = 1,\ n = 0$
- PS: $\Delta_0 = 1,\ n = -1$
- PS: $\Delta_0 = 1,\ n = 1$
- PS: $\Delta_0 = 1,\ n = 2$
- PS: $\Delta_0 = 1,\ n = 3$
- PS: $\Delta_0 = 10,\ n = 0$
- PS: $\Delta_0 = 100,\ n = 0$

[preliminary, plot by G. Franciolini]

Estimating the contribution of perturbed binaries

Strategy:

- *take a compact initial 3-PBH system - binary forms by once the 3rd PBH is ejected*
- *the binding energy is set by the closest PBH pair in the system*
- *ignore systems where the 3rd PBH couples after the close pair emits more than 10% of their binidng energy in GWs*

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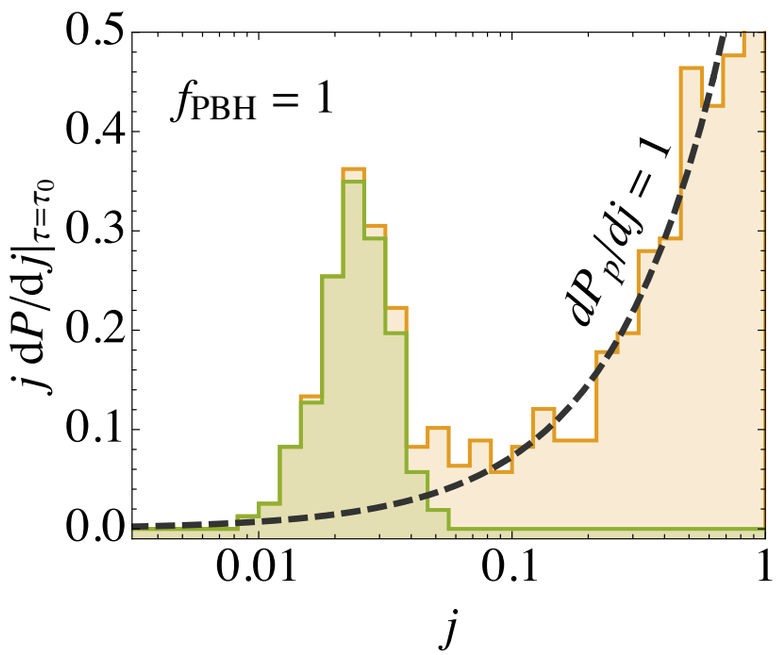
- ***Distribution of angular momenta*** $\frac{\partial P_p(j)}{\partial j} \approx \gamma j^{\gamma-1}, \qquad \gamma \in [1,2]$



"equilibrium"
$\gamma = 2$

for perturbed binaries in the simulation
$\gamma \approx 1$

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- *Merger rate*

$$R_p \propto \mathcal{O}\left(10^3\right) \mathrm{Gpc}^{-3}\mathrm{yr}^{-1} \times f_{\mathrm{PBH}}^{\frac{144\gamma}{259}+\frac{47}{37}} \left[\frac{t}{t_0}\right]^{\frac{\gamma}{7}-1} \left[\frac{M}{20M_\odot}\right]^{\frac{5\gamma-32}{37}}$$

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modified

- *time dependence*
- *eccentricity distribution*
- *mass distribution*

Can dominate when f > 0.1.

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modified
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- *mass distribution*

Can dominate when f > 0.1.

Merger rate can grow due to collisions in later PBH clusters!

ACCRETION

- injected luminocity from Bondi accretion

$$j = n_{\rm PBH}\langle L_{\rm PBH}\rangle \propto f_{\rm PBH} M_{\rm PBH}^2\, v_{\rm eff}^{-6}$$

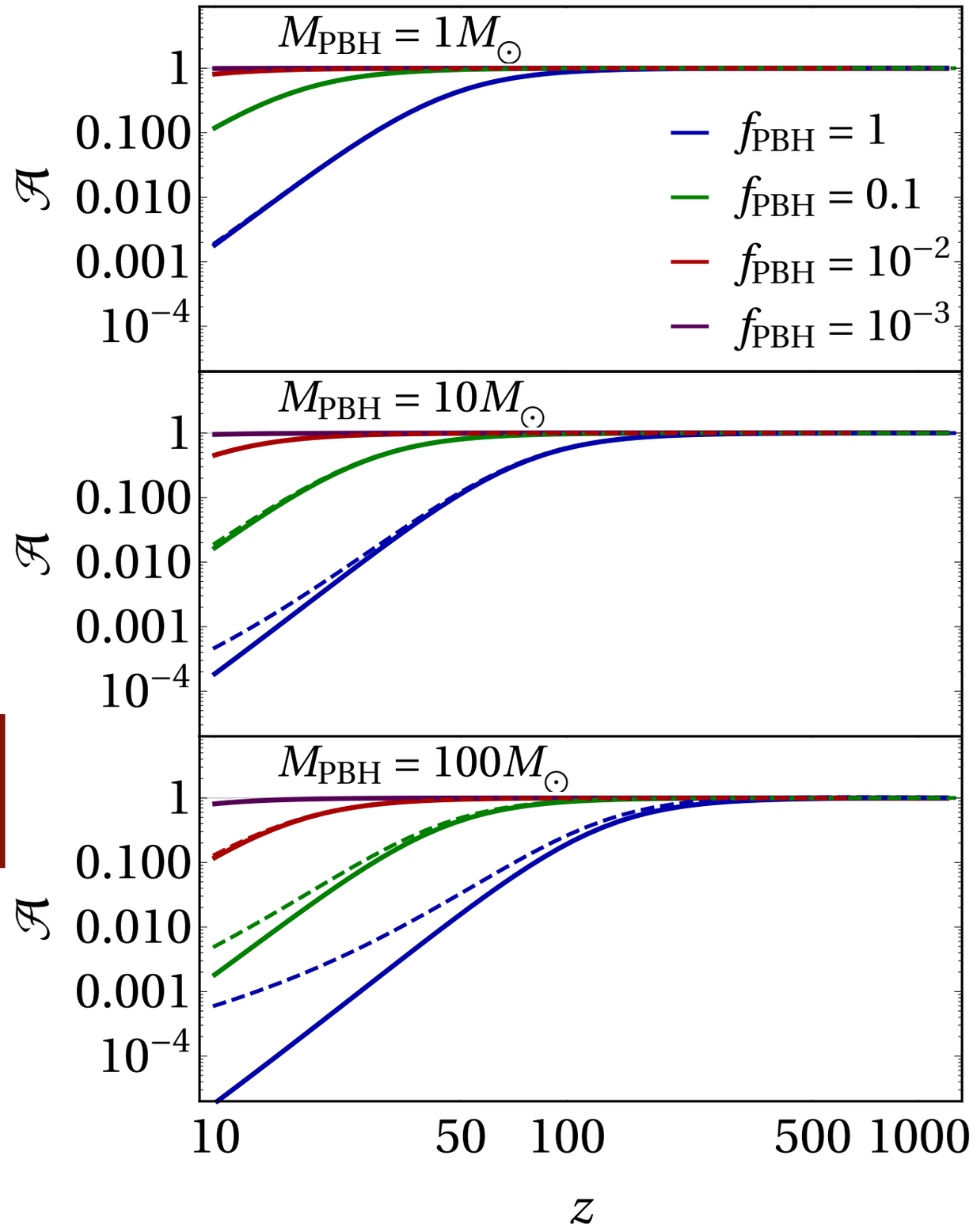
$$v_{\rm eff} \approx \left\langle (v_{\rm rel}^2 + c_s^2)^3 \right\rangle^{1/6}$$

- coherent enhancement if several objects in the Bondi radius

$$\mathscr{A} \equiv \frac{\langle L\rangle}{\langle L\rangle_{\rm std}} = \frac{\langle N^\alpha v_{\rm a}^{-6}\rangle}{\langle v_{\rm a}^{-6}\rangle_{\rm std}}$$

IRRELEVANT IN THE EARLY UNIVERSE BUT CAN BE RELEVANT IN THE LATE UNIVERSE

e.g. for 21cm constraints for PBH



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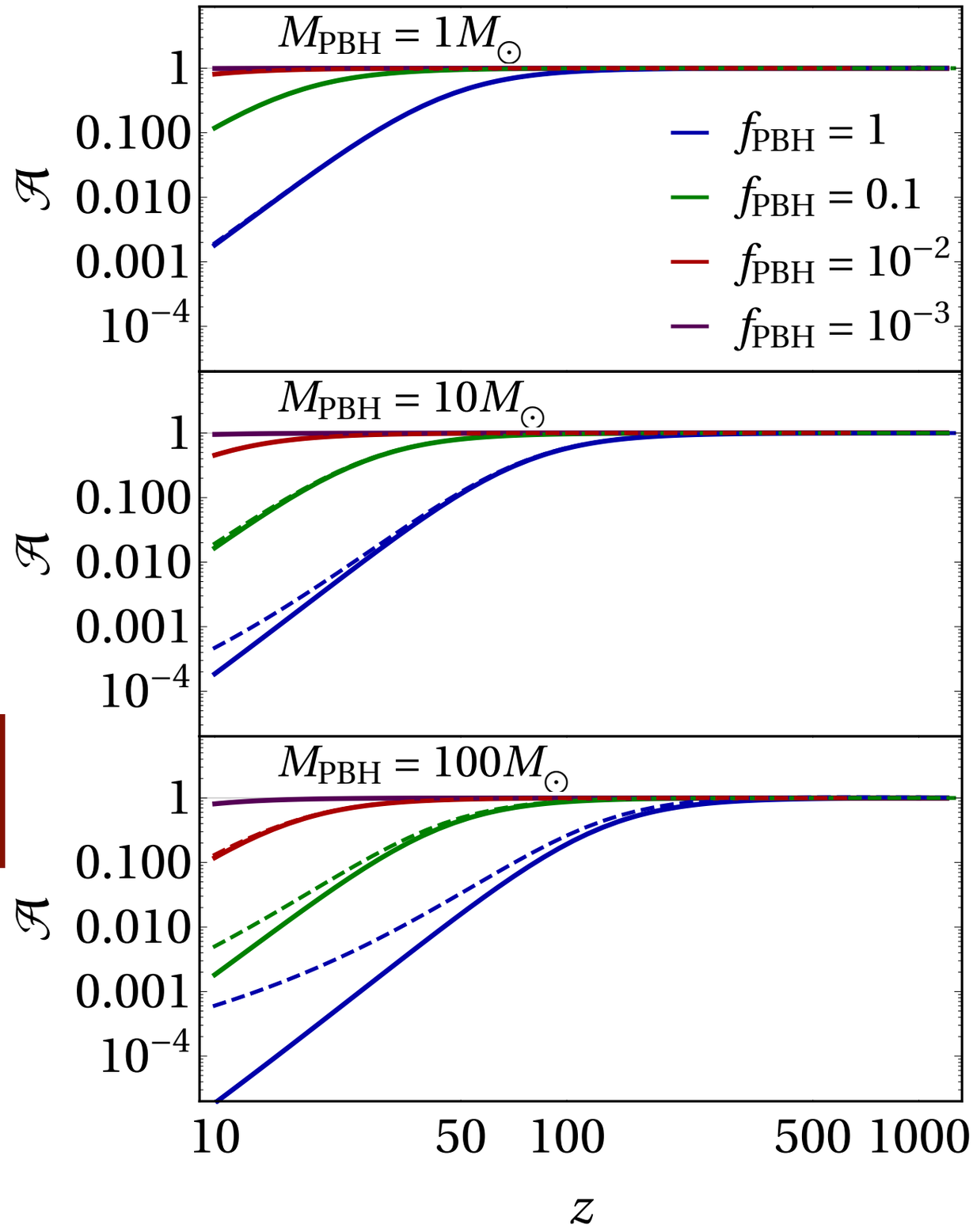

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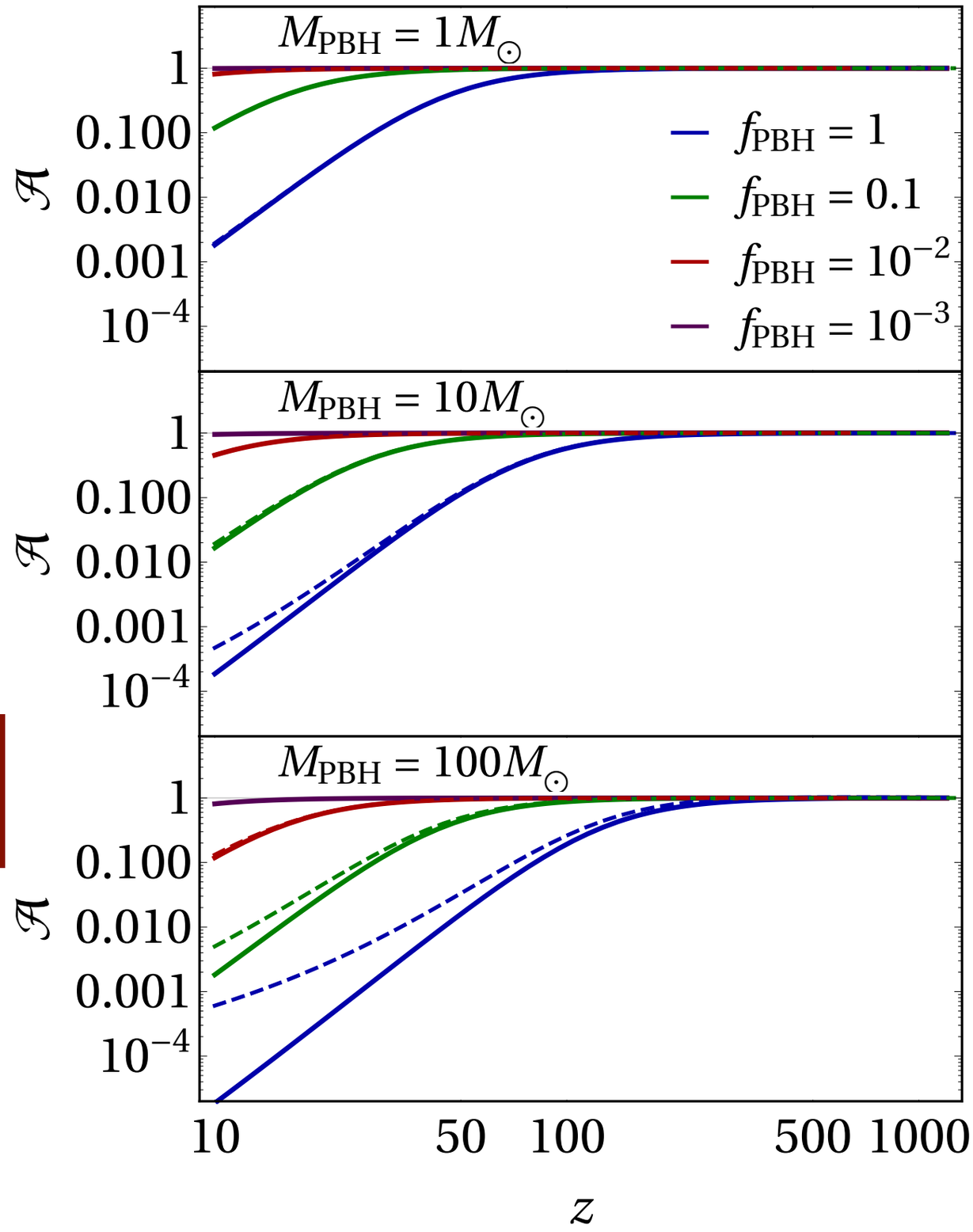


LENSING
[Sébastien's talk]

- Microlensing of the MW halo constrains PBHs up to $15 M_\odot$
  [astro-ph/0607207 EROS]

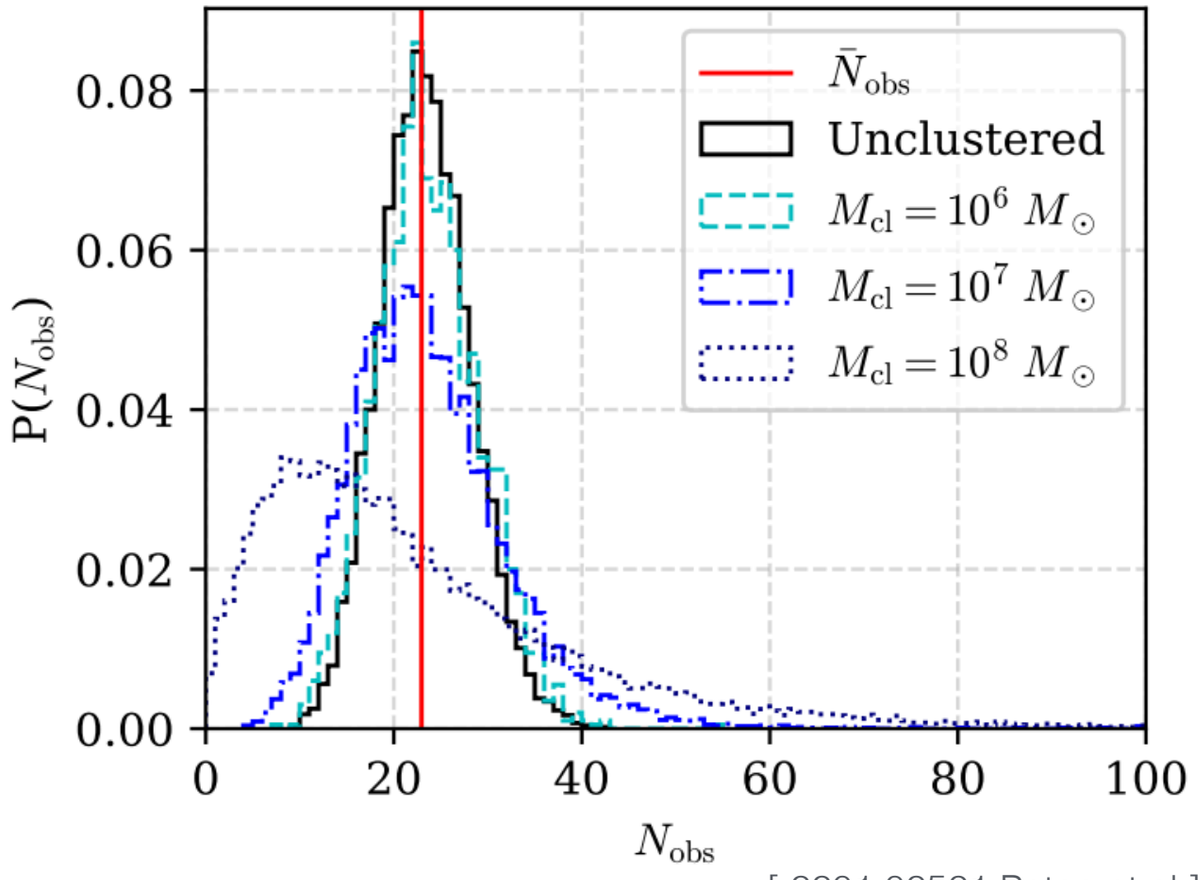
→ upper bound may be lowered by clustering

[1710.04694 García-Bellido et al]

- Microlensing constraints unaffected without significant initial clustering

→ extremely compact or massive clusters required

[2201.02521 Petac et al, 2203.04209 Gorton et al]



[2201.02521 Petac et al]

SUMMARY

Clustering form Poisson fluctuations relevant for mainly $M \approx 10^{\mathcal{O}(0)} M_\odot$ PBHs.

GWs constrain less than O(0.1%) of PBH DM in the $2 - 400\, M_\odot$ range.

- 3-body PBH binary formation channels relevant with strong clustering or $f_{\rm PBH} \approx 1$

Lensing and accretion constraints affected weakly by clustering.

Initial clustering is model dependent, but can affect constraints.