Understanding PBH DM from N-body simulations

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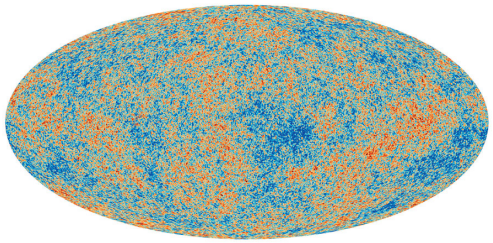
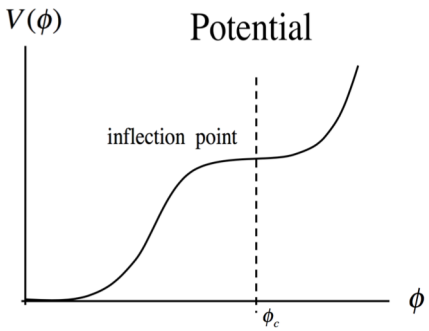
arXiv:1812.01930
arXiv:1907.06533

PBHs – the oldest DM candidate

- Hawking (1971), Carr and Hawking (1974)
  - Primordial fluctuation of order 0.1 enter Universe at radiation era and collapse to BHs



PBHs -- frozen radiation energy density



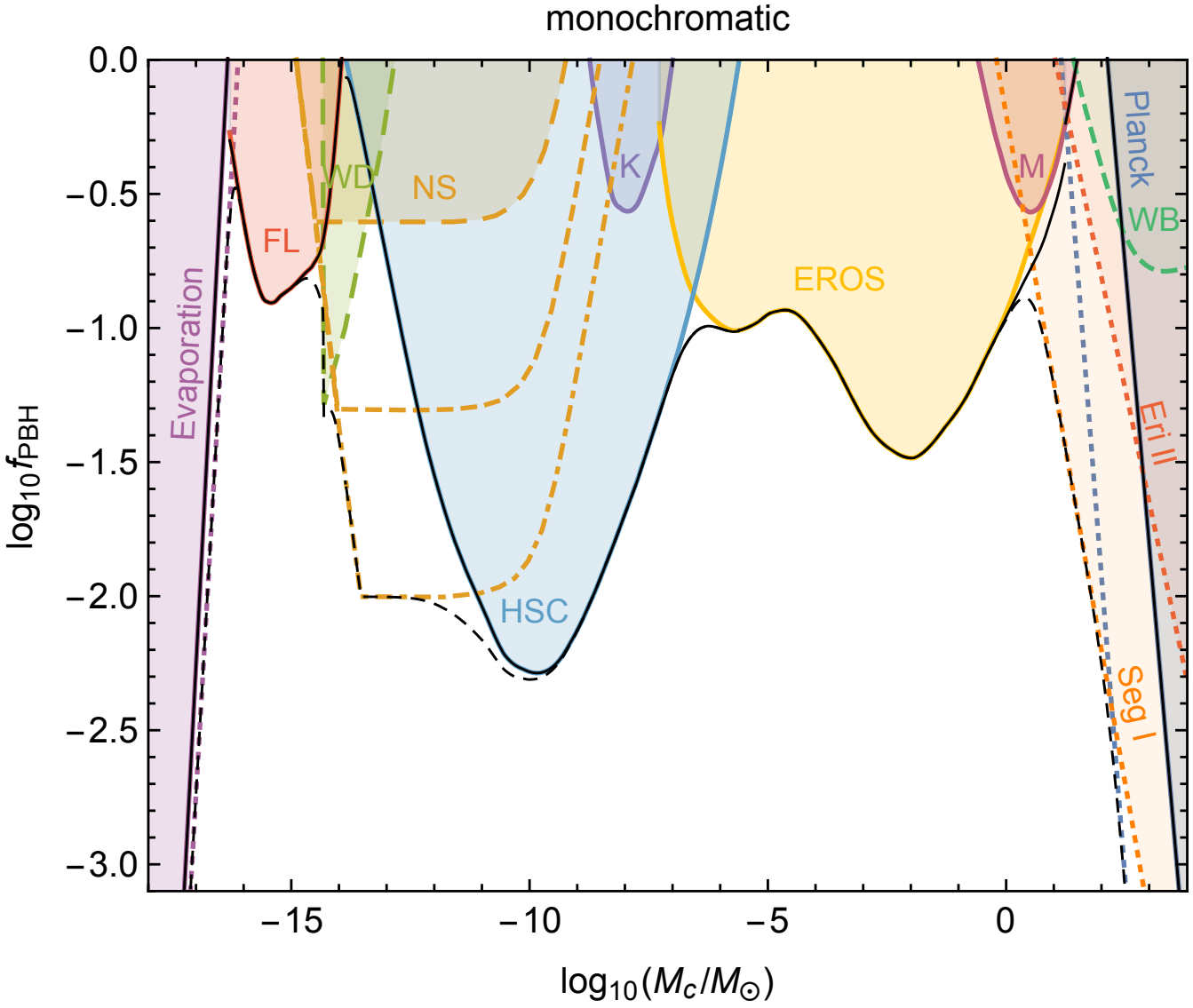
- Hawking radiation (1974) changed the picture
  - Lower bound $M > 10^{-16}\ M_{\odot}$, macroscopic objects

The PBH cosmology

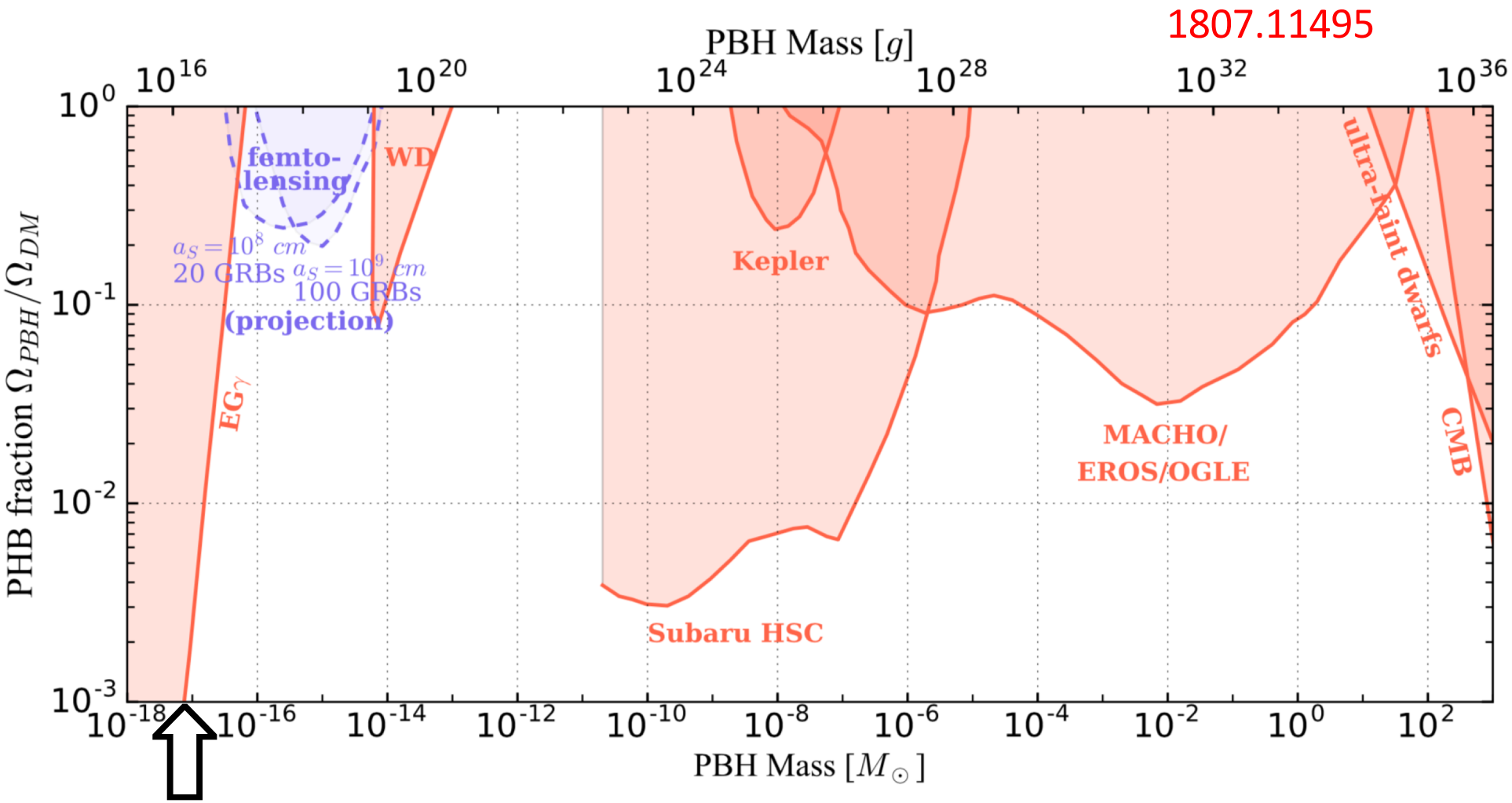
- At large scale PBHs are an ideal collisionless DM candidate, all the success of ΛCDM persists
- Predicts deviations from WIMPs at small scales
  - Small scale structure formation problems solved (core vs. cusp)
  - Seeds for galaxies and SMBHs even if f<<1
  - PBHs are the DM we want
- Provides new astrophysical probes of the DM
  - Stochastic GWs, reionisation and CMB, lensing, anomalous stars in Gaia, mass and spin of BHs, CR anomalies by accretion, predictions for inflation, 21 cm anomaly etc

LIGO discovery of GW changed physics: multi-messenger astronomy, tests of gravity with GW, tests of BH properties

Constraints from Carr et al., arXiv:1705.05567



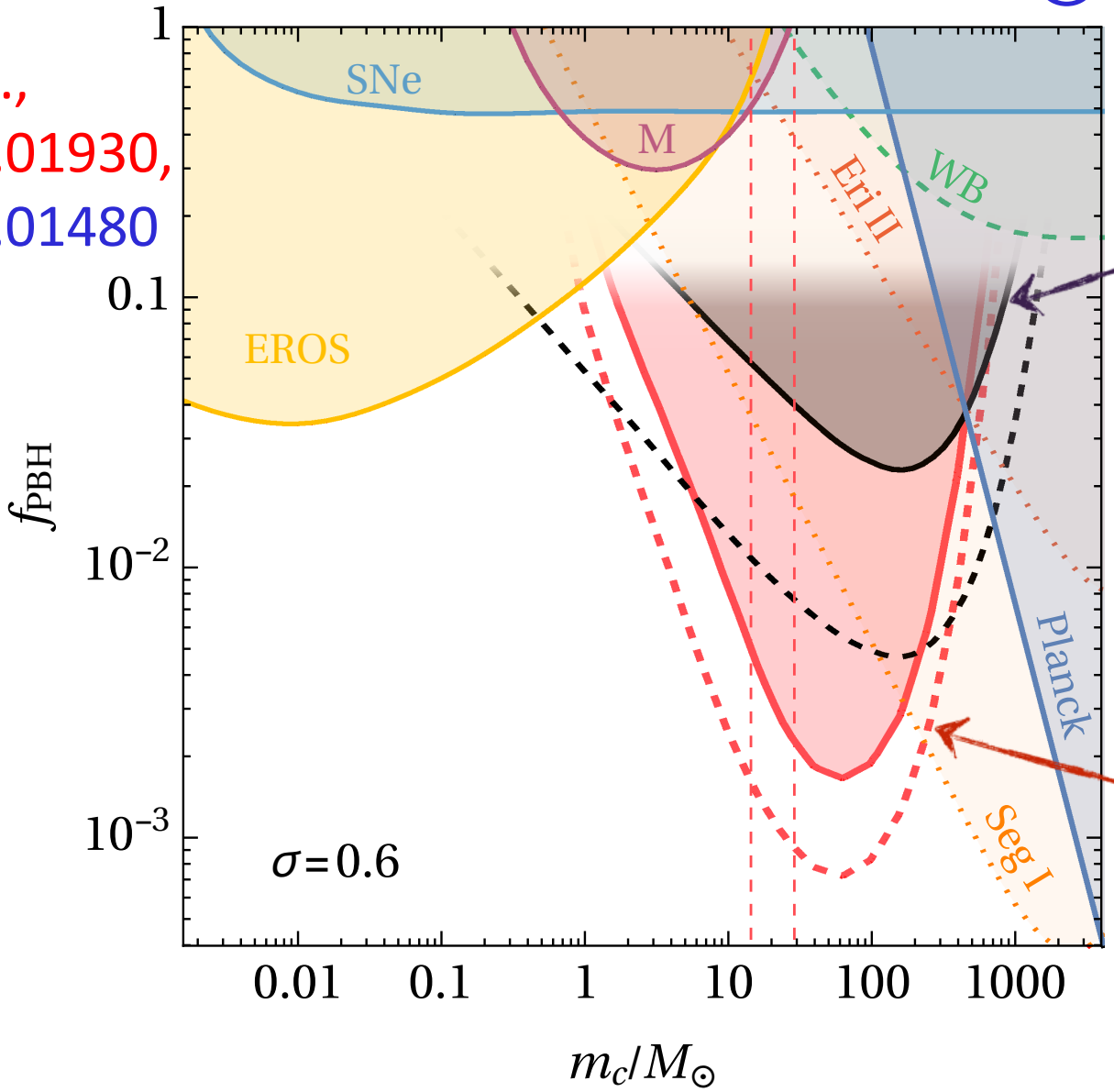
Wave optics and GRB finite size effects



Raidal et al., arXiv:1802.07728 (bound from Hawking radiation can be removed)

The LIGO region of 20 $M_\odot$ PBHs

Raidal et al., arXiv:1812.01930, arXiv:1707.01480



GW background from PBH binaries

The strongest bounds in this region come from the LIGO GW measurements

PBH binary mergers

The merger rate of PBH binaries

Merger rate of PBH binaries at t

=

Density of initial conditions (pairs)

×

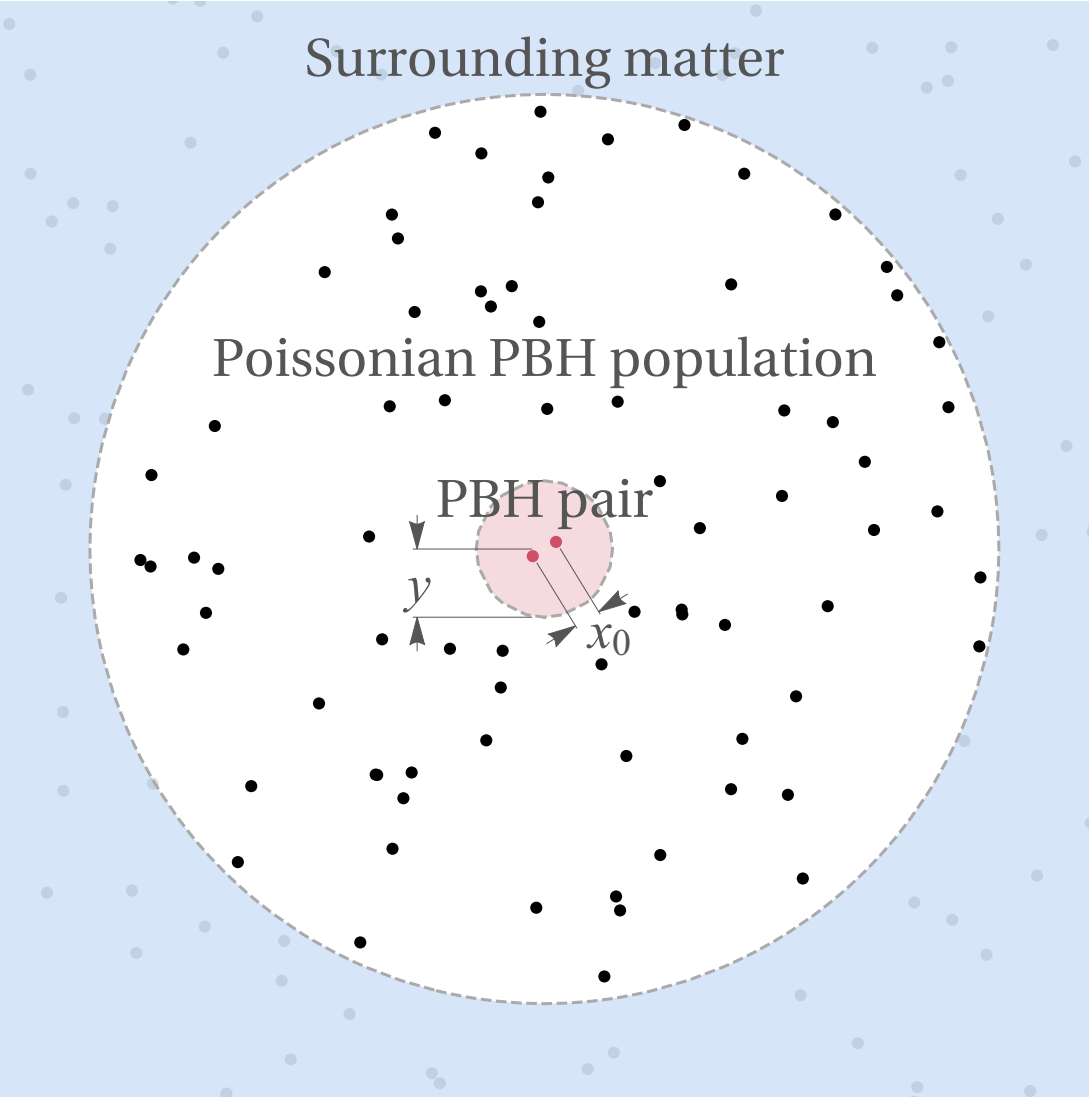
P(PBH binary with coalescence time t | initial conditions)

astro-ph/9708060
astro-ph/9807018
arXiv:1707.01480
arXiv:1709.06576

$$\mathrm{d}R = \int \mathrm{d}n_{\mathrm{b}} \mathrm{d}j \frac{\mathrm{d}P}{\mathrm{d}j} \delta\left(\tau - \frac{3}{85} \frac{r_a^4}{\eta M^3} j^7\right)$$

$$= \frac{1}{14\tau} \mathrm{d}n(m_1) \mathrm{d}n(m_2) \int \mathrm{d}V(x_0) e^{-\bar{N}(y)} j \frac{\mathrm{d}P(j|x_0, y)}{\mathrm{d}j}\bigg|_{j=j(\tau)}$$

Formation of PBH binaries in early Universe



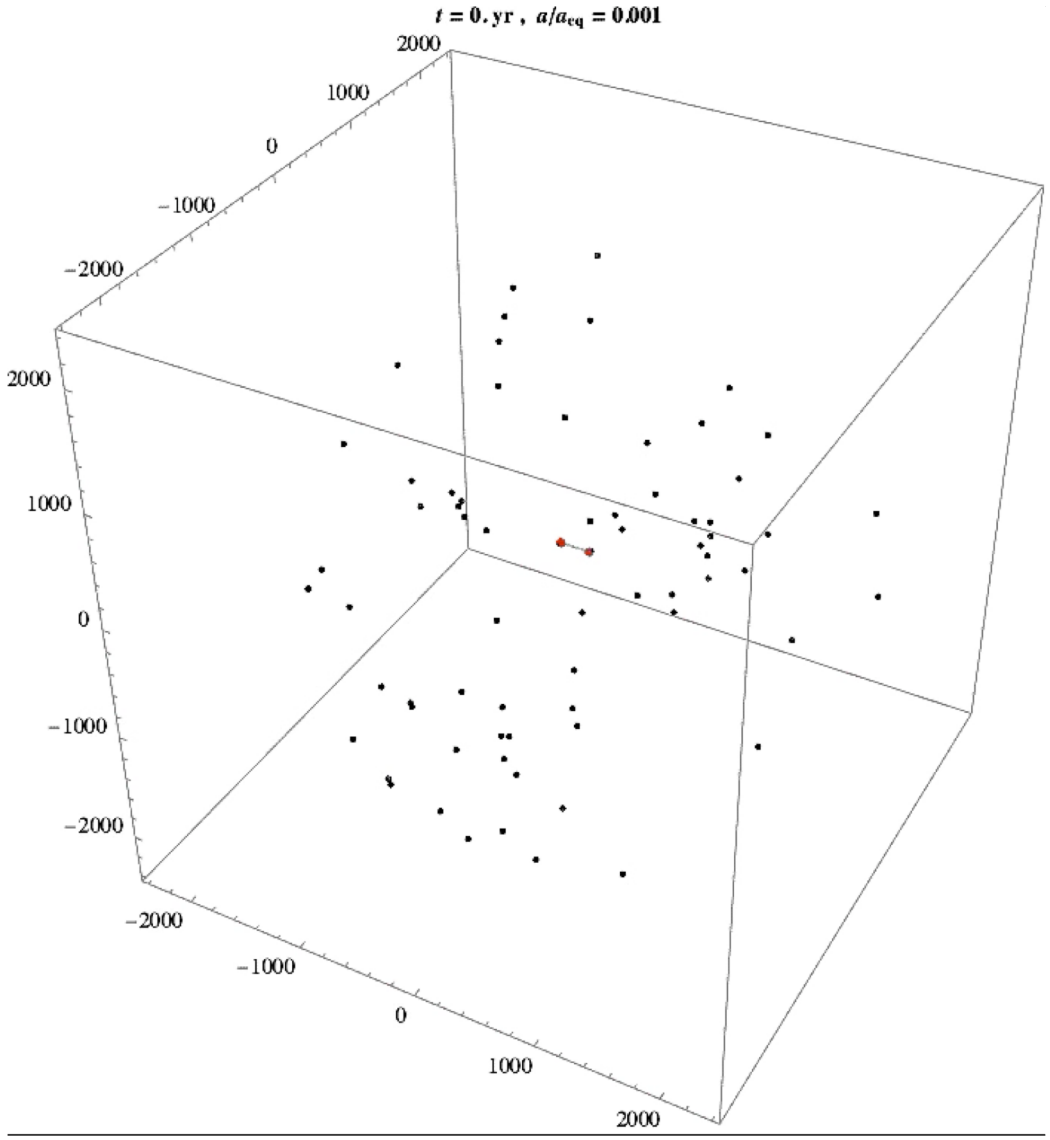
- Initially close pairs form binaries
- Tidal forces fix the eccentricity
- Coalescence time

$$\tau = \frac{3}{85}\frac{r_a^4}{\eta M^3} j^7$$

- Approximation: the binary evolution depends on x, y:

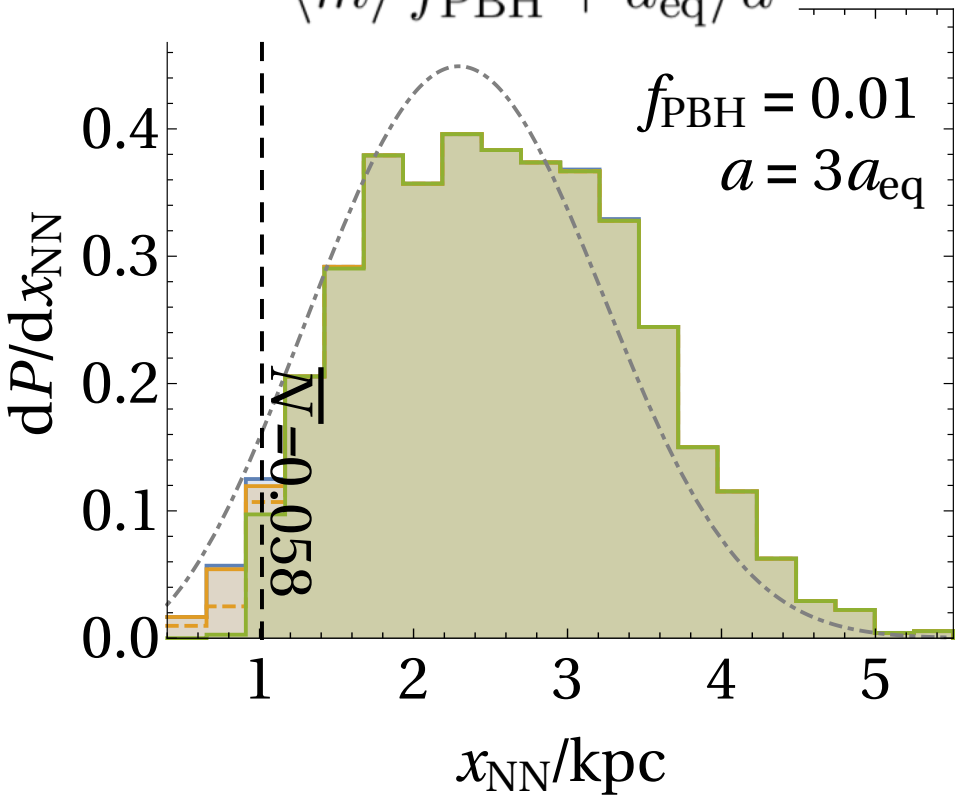
$$\bar{N}(y) \equiv nV(y)$$

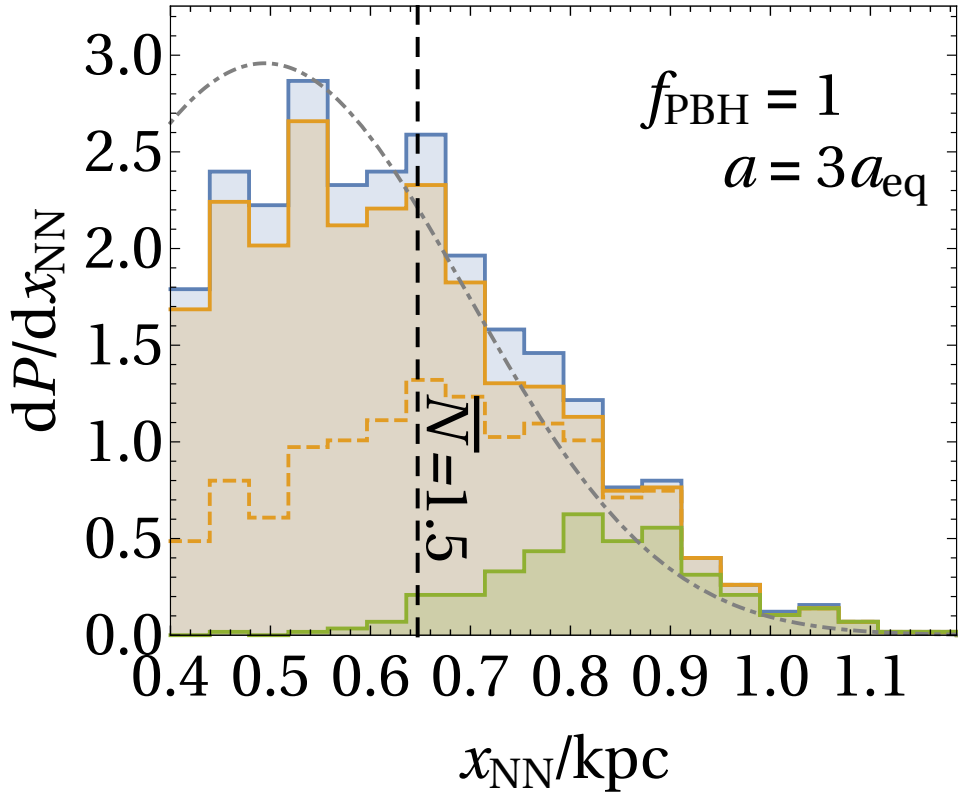
Binary destroyed by a mini-cluster



The fate of initial binaries

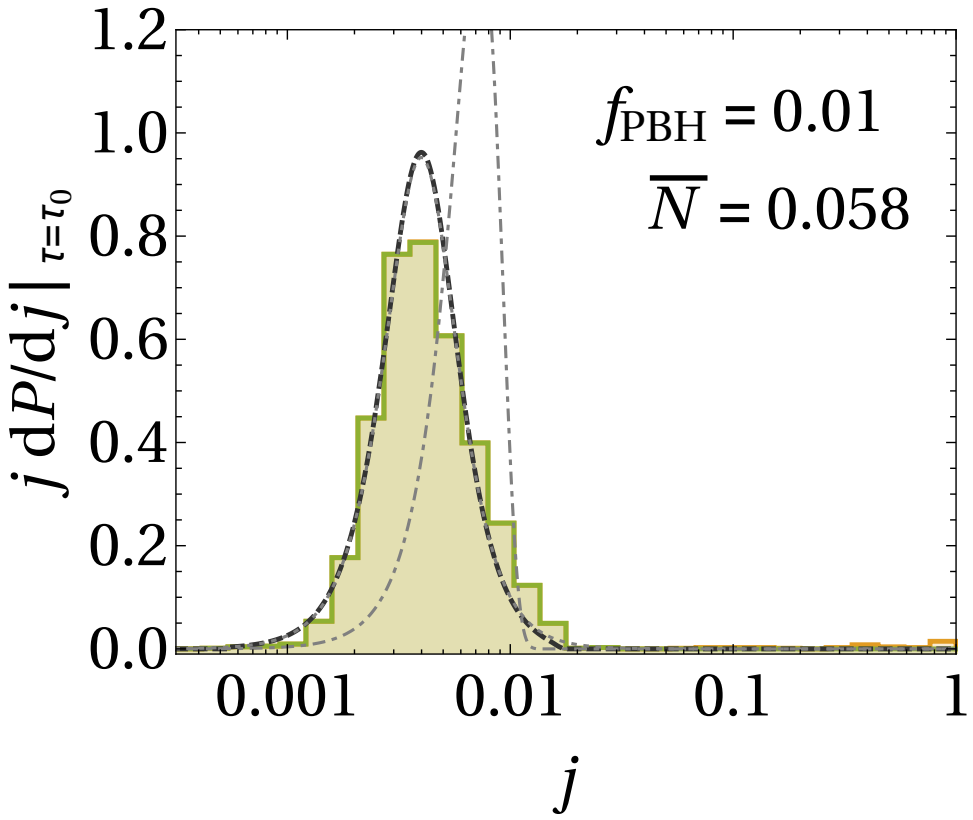
$$\bar{N}(y) \approx \frac{M}{\langle m \rangle} \frac{f_{\rm PBH}}{f_{\rm PBH} + a_{\rm eq}/a}$$

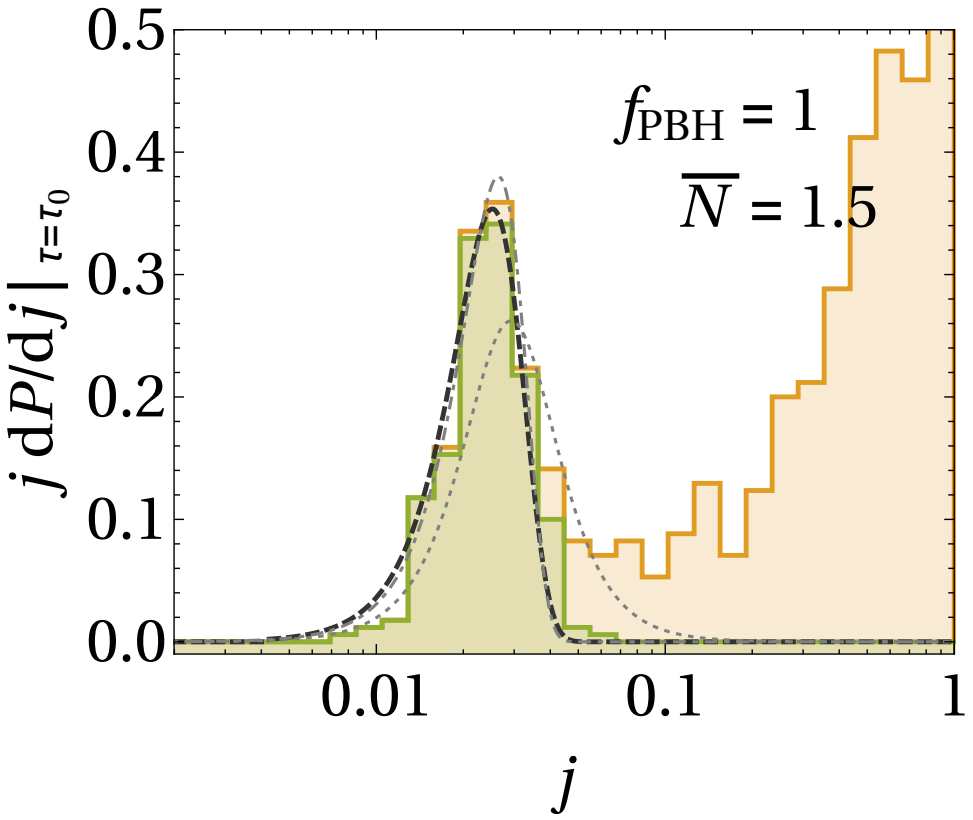




- For small f_{PBH}: most of the initial binaries remains un-disturbed
- For f_{PBH}=1: most of the initial binaries are destroyed

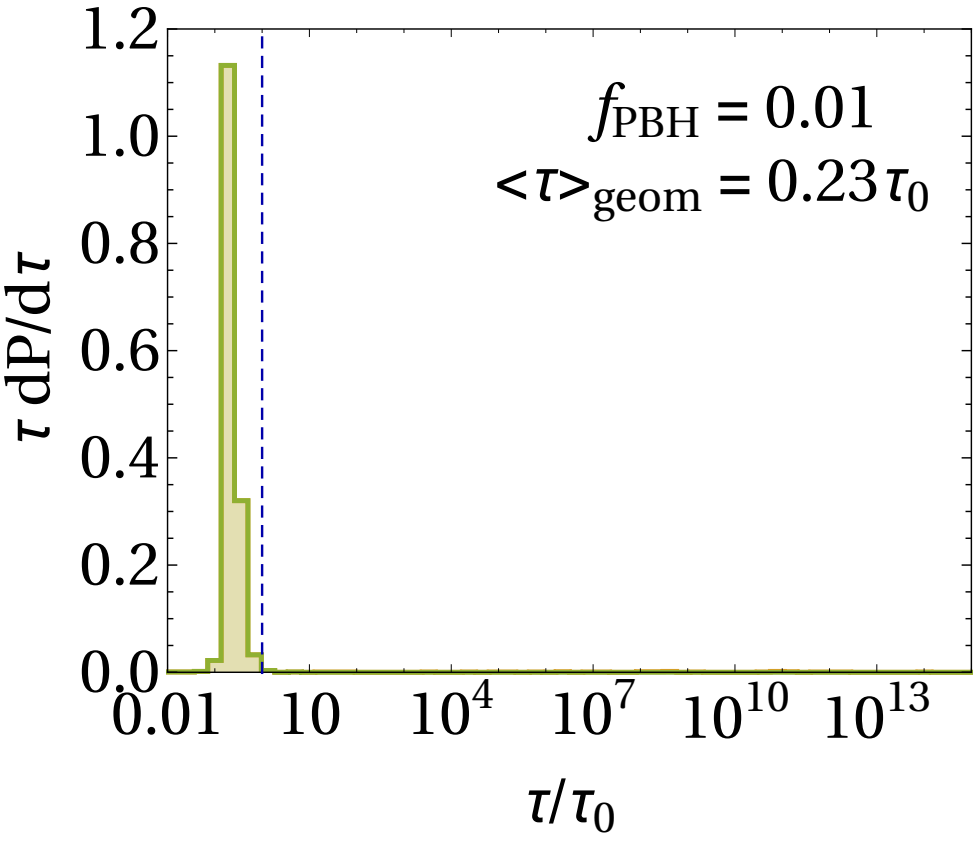
Initial binaries are highly eccentric

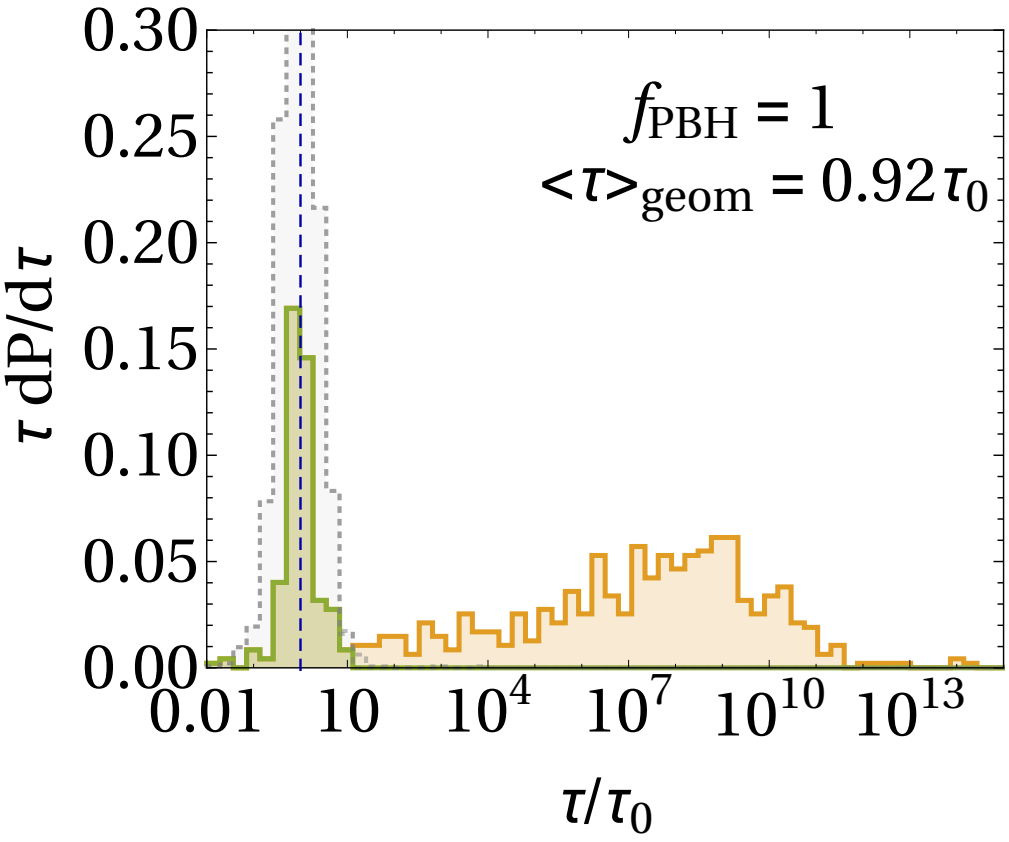




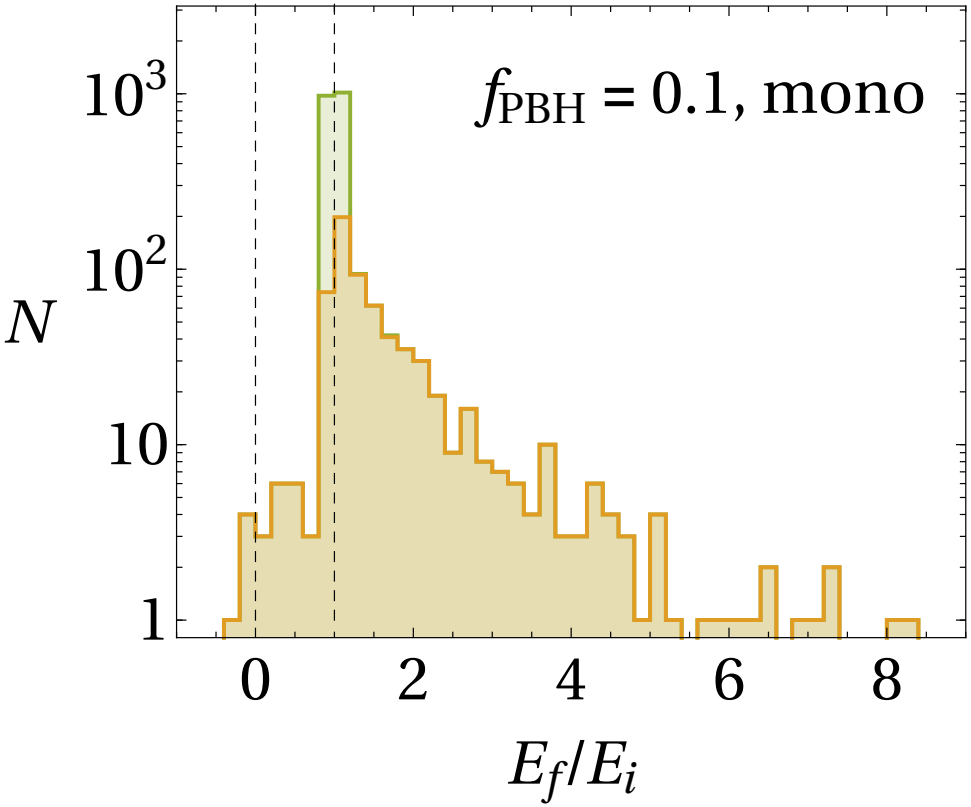
The perturbed binaries tend to have more circular orbits

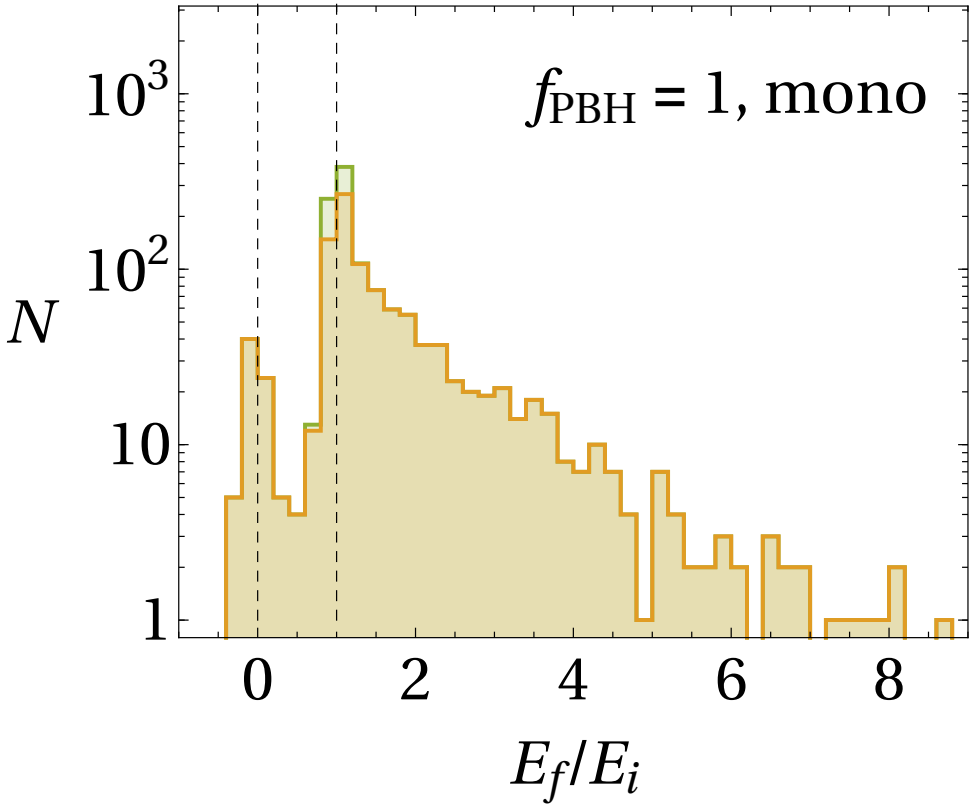
Coalescence time increased by many orders of magnitude





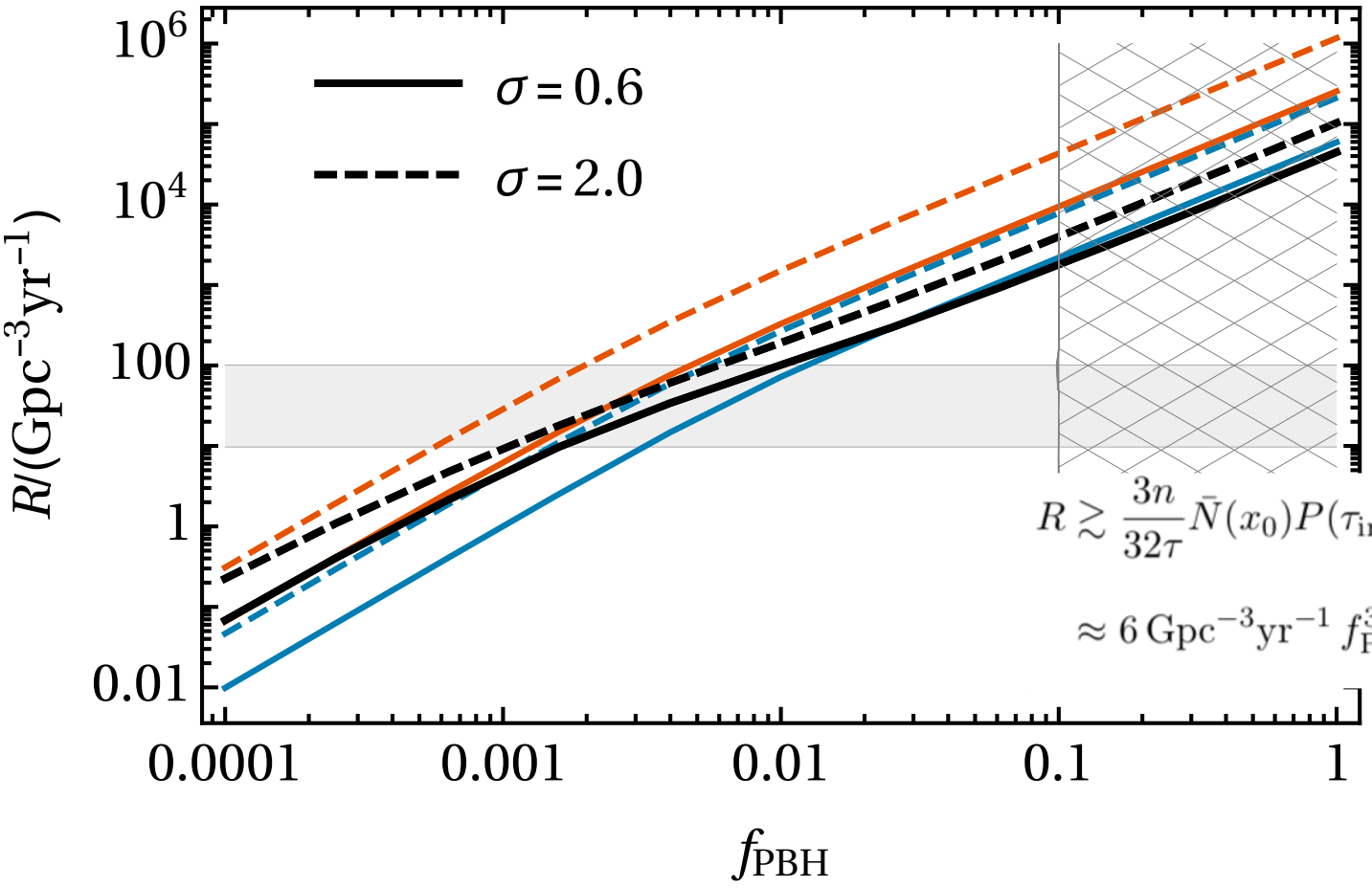
Binding energy is increased





The disturbed binaries become hard

The LIGO/VIRGO rate



Lower bound on the rate

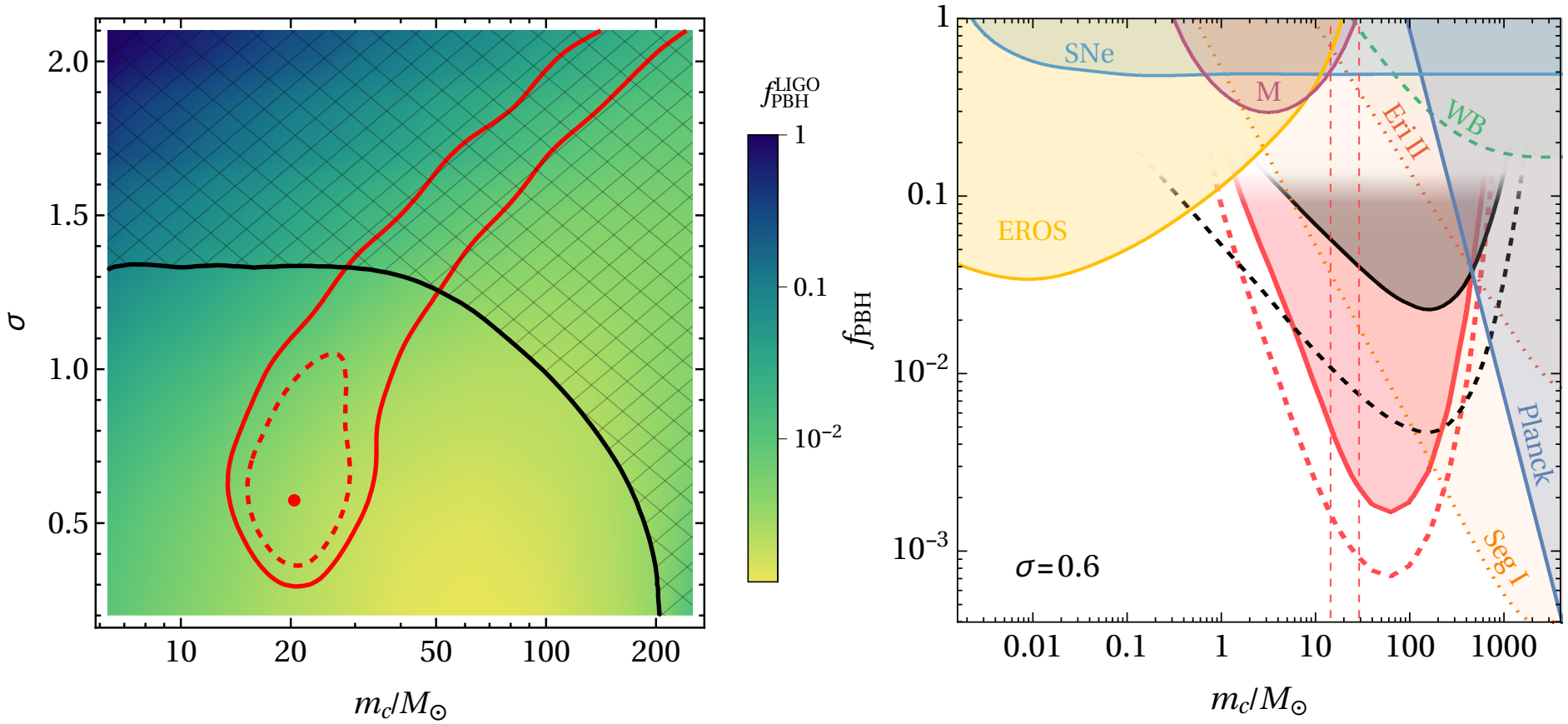
$$R \gtrsim \frac{3n}{32\tau}\bar{N}(x_0)P(\tau_{\mathrm{init}} > \tau_c|x_0)$$

$$\approx 6\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}\, f_{\mathrm{PBH}}^3 \left(\frac{m_c}{10M_\odot}\right)^{-\frac{3}{8}} \left(\frac{\tau}{t_0}\right)^{-\frac{27}{56}},$$

We do not know what happens for $f_{PBH}>0.1$

Confirmed by Yacine Ali-Haimoud in 1907.08129

A fit to LIGO/Virgo data



Do the bounds apply for the f_{PBH}=1 case too?

OR

Are all binaries destroyed by clustering for f_{PBH}=1 and no bounds apply?

Implications for the CMB

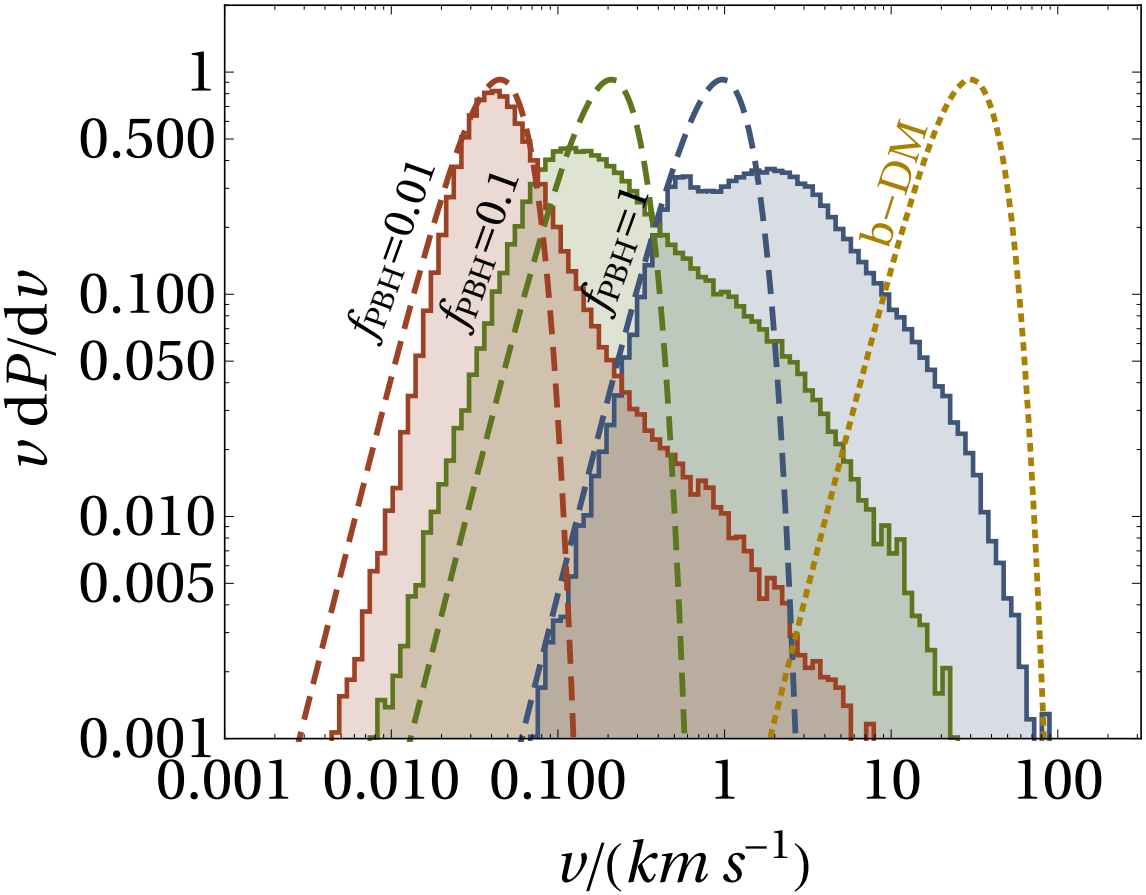
- Photons radiated by accretion of gas by PBHs results in the bound on the PBH abundance Yacine Ali-Haimoud

- Two competing effects due to clustering:
  - **$1/v^6$ reduction** of accretion due to the extra velocity of PBHs inside the early clusters (ADAF accretion model):

$$L \simeq 4\times10^{29}\,\frac{\mathrm{erg}}{\mathrm{s}}\,f\lambda^2\left(\frac{M_{\rm BH}}{10\,M_\odot}\right)^3\left(\frac{n_{\rm H}}{1\,\mathrm{cm}^{-3}}\right)^2\left(\frac{v_{\rm eff}}{10\,\mathrm{km\,s}^{-1}}\right)^{-6},$$

  - Possible **N^2 coherent accretion enhancement** if the accretion radius=the distance between PBHs

The velocity floor and clustering



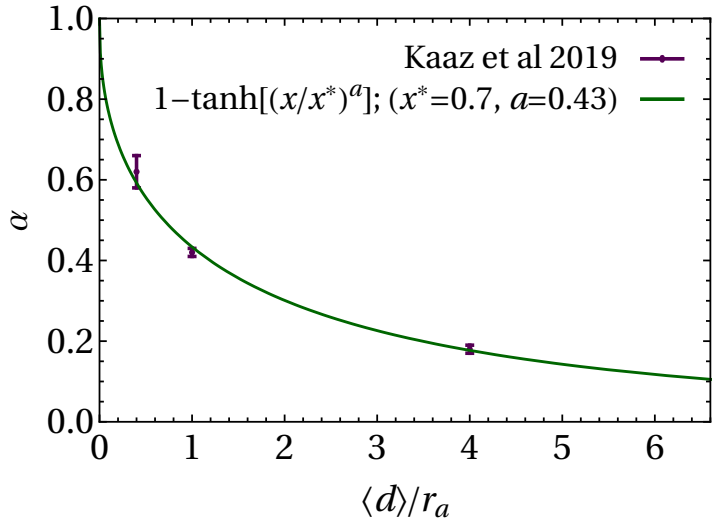
However, DM–baryon streaming velocity at recombination is 30km/s

Just a few % effect for the CMB bound

but the effect might be large later - revise PBH bounds from radio astronomy

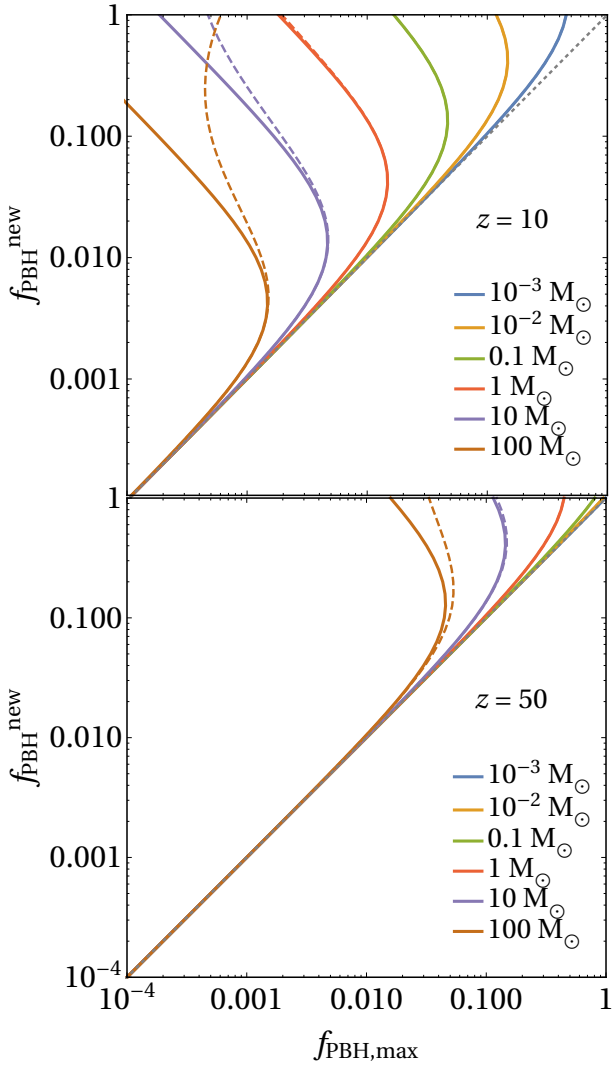
Coherent accretion due to clustering

- arXiv:1901.03649 argued that if the accretion radius exceeds the distance between PBHs, the accretion is coherent and enhanced by N^2



- The CMB bounds on PBH abundance could be approximately N times more stringent

The effects are negligible for CMB but important for z<20

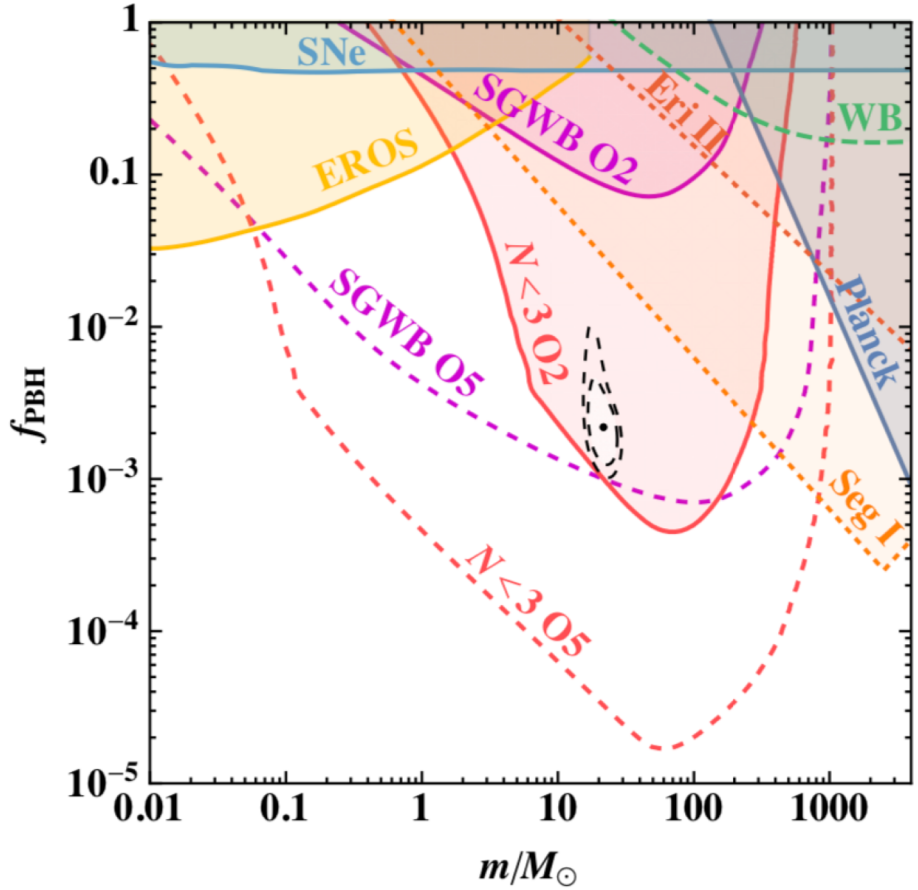


Constraints do disappear for z<20,

The clustering effects MUST be taken into account when calculating cosmological constraints from 21 cm until today

A lower bound on the PBH merger rate

- Hardi Veermäe and Ville Vaskonen, **arXiv:1908.09752 [astro-ph.CO]**



Conclusions

- **For f_{PBH}<<1** most initial binaries are unperturbed
  - Results in literature are qualitatively valid
  - The strongest bound for 10 $M_\odot$ PBHs is given by LIGO
- **For f_{PBH}=1** most binaries are disrupted
  - Late evolution of binaries needed for sure results
  - Lower bound on the LIGO rate from 3-body systems
- **Enhanced small scale structures** already at recomb.
- **The velocity floor and clustering effects:**
  - Are not important for CMB
  - Are very important for z<20