Can Primordial Black Hole Clusters Evade Microlensing Constraints?

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Based on:
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Primordial Black Holes (PBHs)

May form from collapse of overdense regions in the early Universe

Zel'dovich & Novikov (1967); Hawking (1971)

Cold dark matter candidate:

- Black holes evaporate: PBHs with $M_{\mathrm{PBH}} \gtrsim 10^{15}\ \mathrm{g}$ have a lifetime longer than age of Universe
- Form before nucleosynthesis
  => non-baryonic

Formation:

- Most commonly studied model: overdensities seeded by inflation

Microlensing

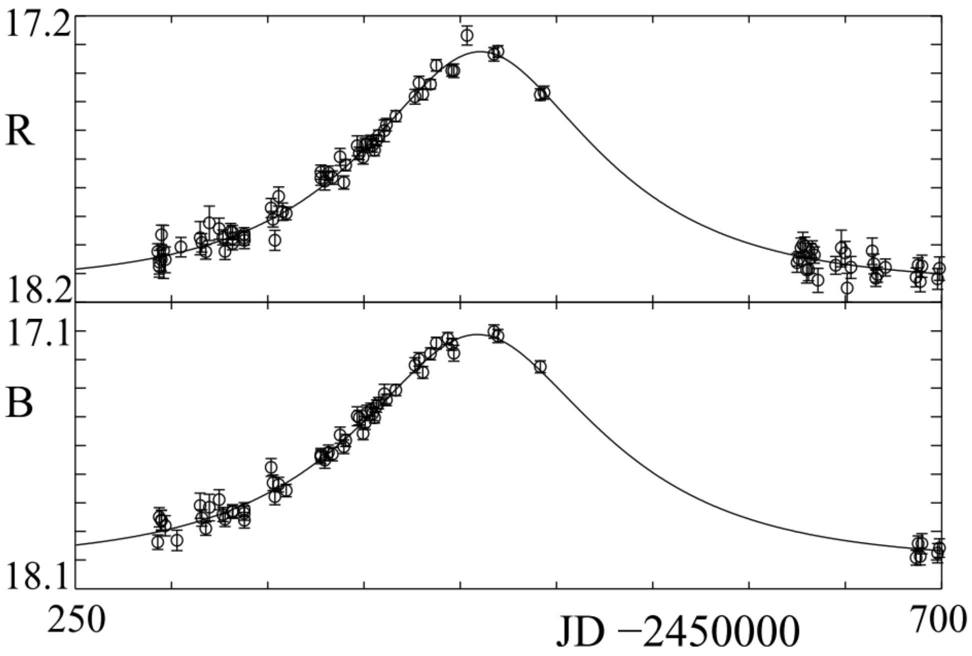
Temporary brightening of star when a compact object passes close to line of sight

Microlensing event duration $\propto M_{\mathrm{PBH}}^{1/2}$

$\Rightarrow$ Long-duration surveys probe larger PBH masses

Unclustered PBHs:

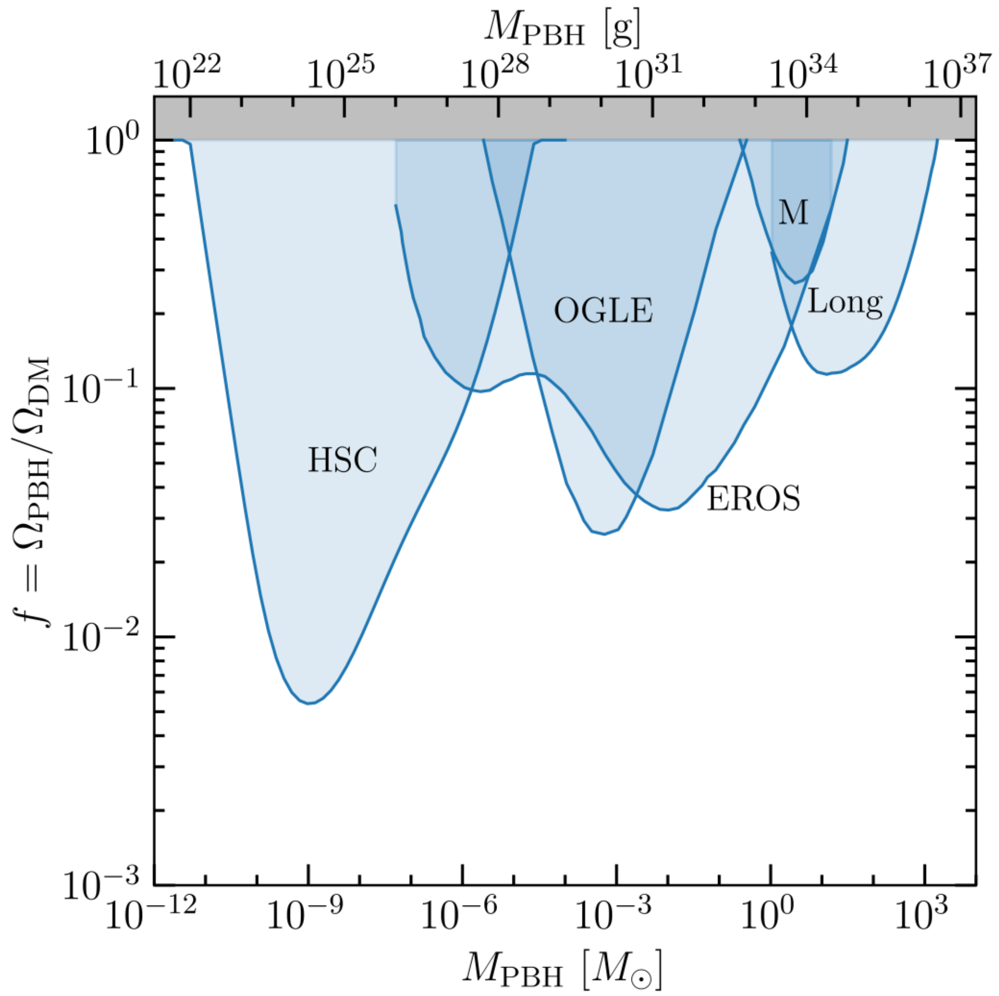
- Number of events Poisson-distributed with mean N_{ex}



Light curve from candidate microlensing event

Tisserand et al. (2007)

Microlensing constraints on PBHs



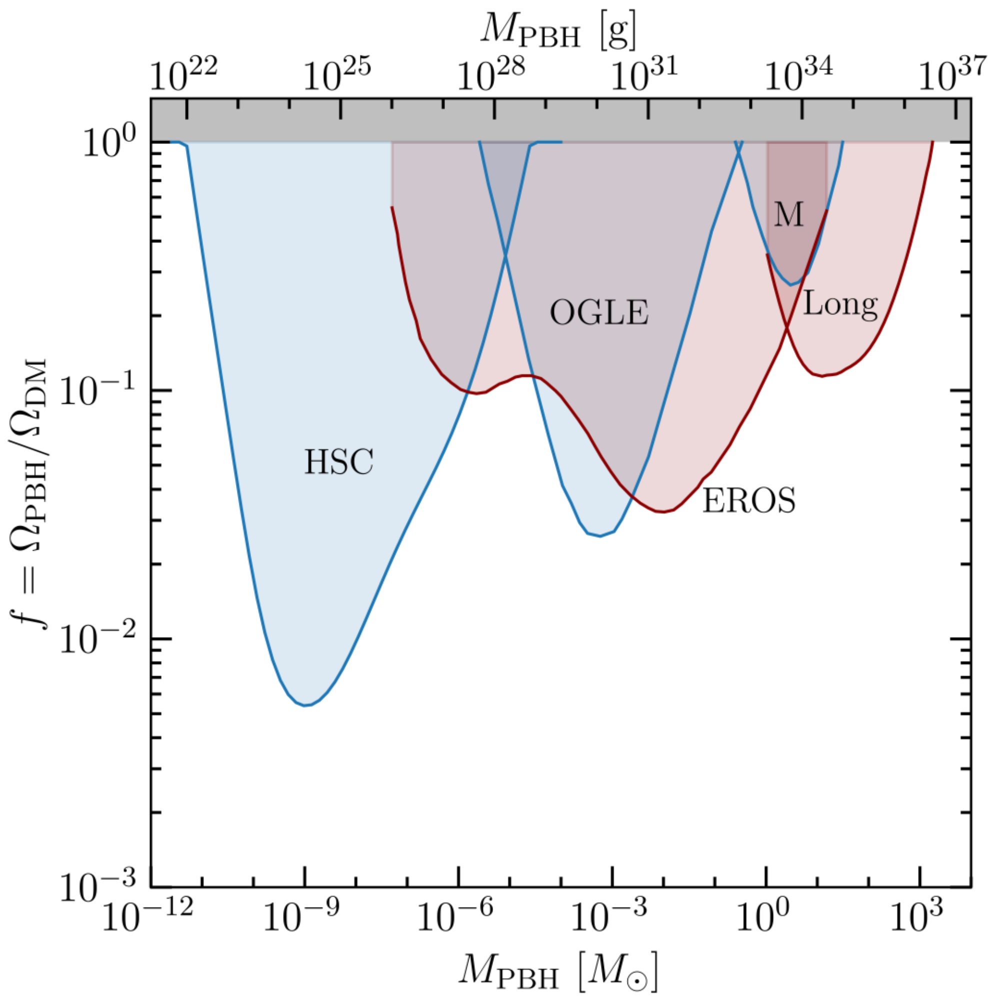
Constraints on fraction of dark matter in PBHs, f, produced using PBHbounds
https://github.com/bradkav/PBHbounds

Constraints shown assume PBHs are unclustered

Claims that PBH clustering removes microlensing constraints for $M_{\rm PBH} \sim 1 - 10\ M_\odot$

García-Bellido & Clesse (2018); Calcino et al. (2018)

Microlensing constraints on PBHs



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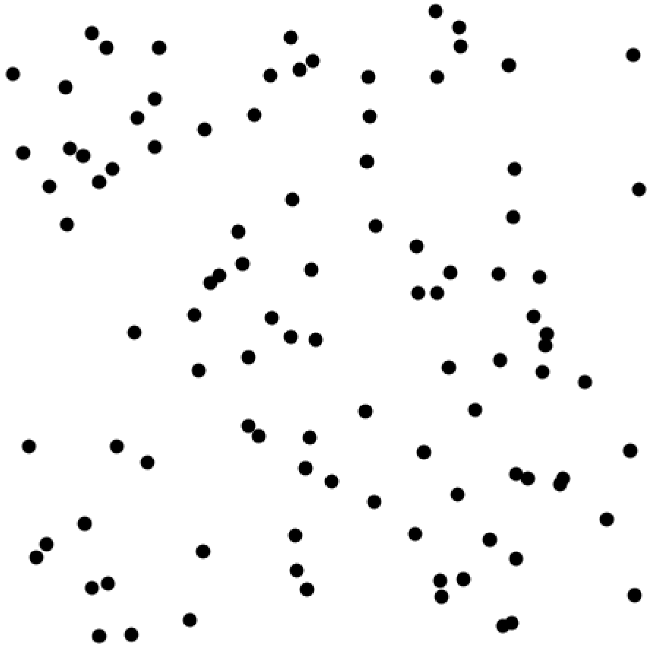
PBH clustering

Most commonly studied PBH formation model:

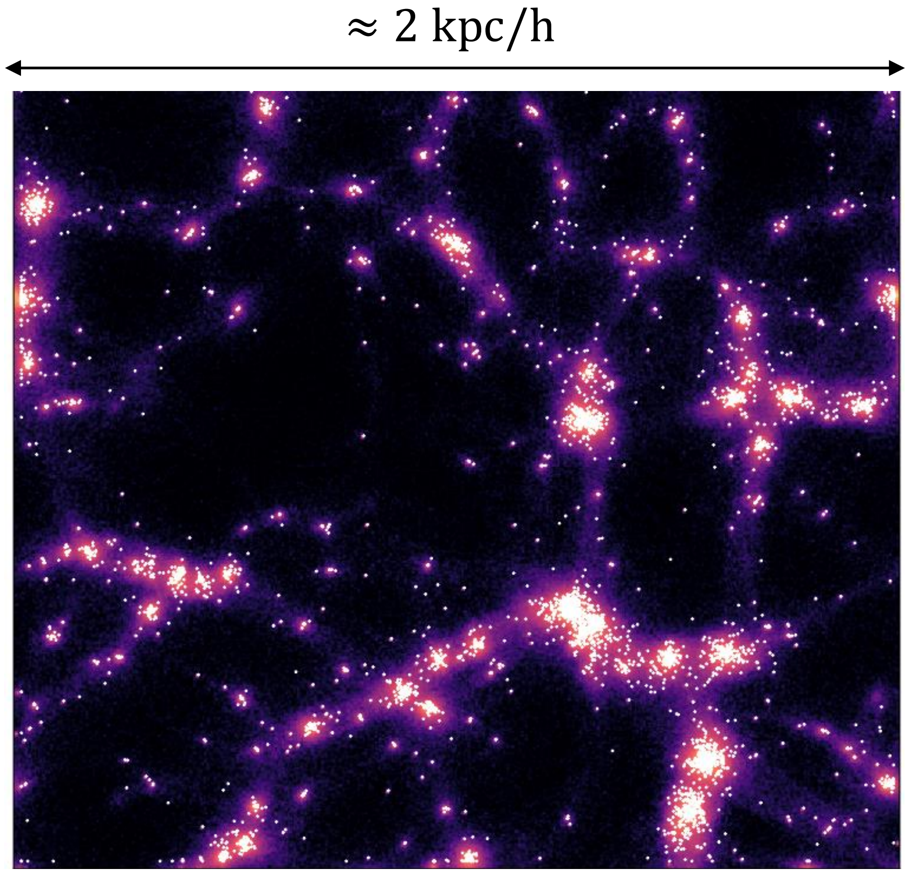
- PBHs not formed in clusters (Gaussian curvature perturbation)
- Poisson fluctuations
- If PBHs make up a significant fraction of DM, form clusters shortly after matter-radiation equality

Open problem:

- Modelling PBH cluster evolution to present



Initial PBH distribution



PBH distribution at z=99 (all DM in PBHs)
Inman & Ali-Haïmoud (2019)

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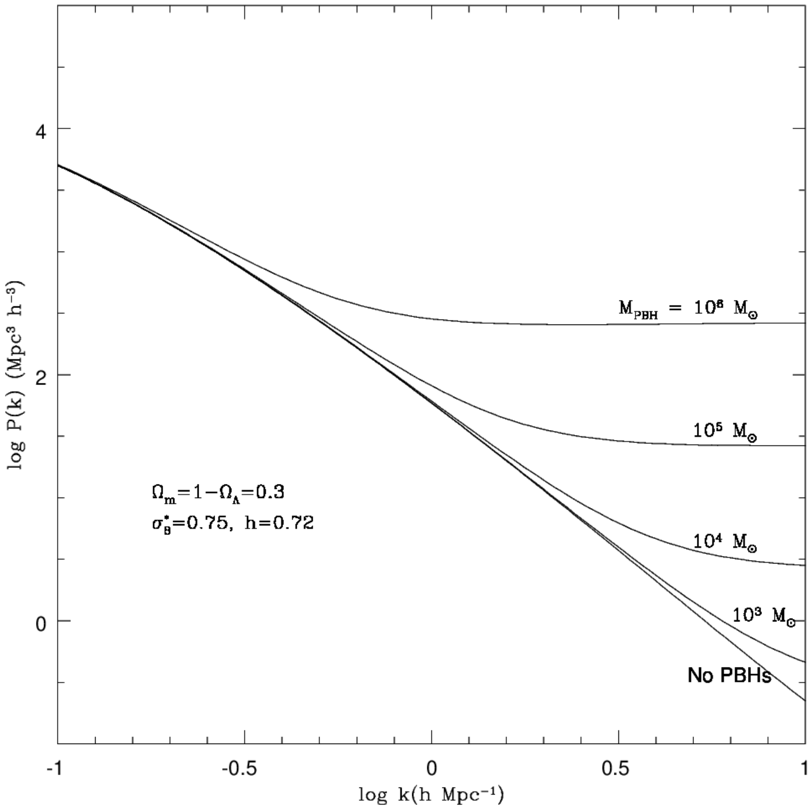
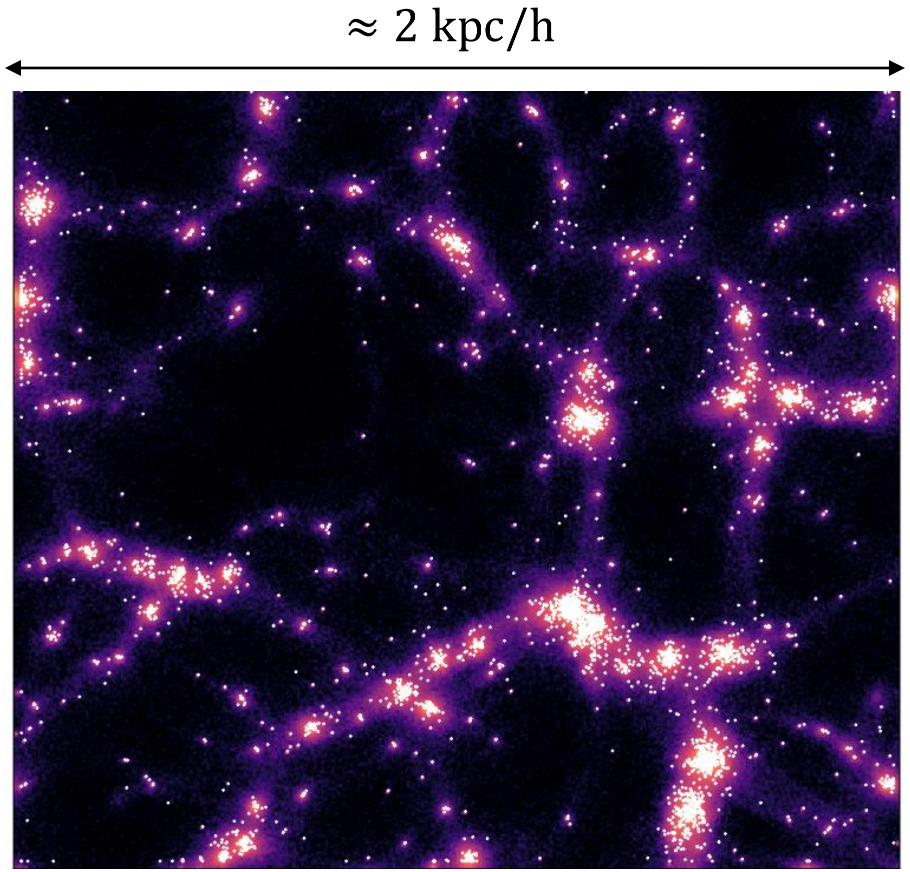


Primordial matter power spectrum
Afshordi, MacDonald & Spergel (2003)



PBH distribution at z=99 (all DM in PBHs)
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PBH clustering

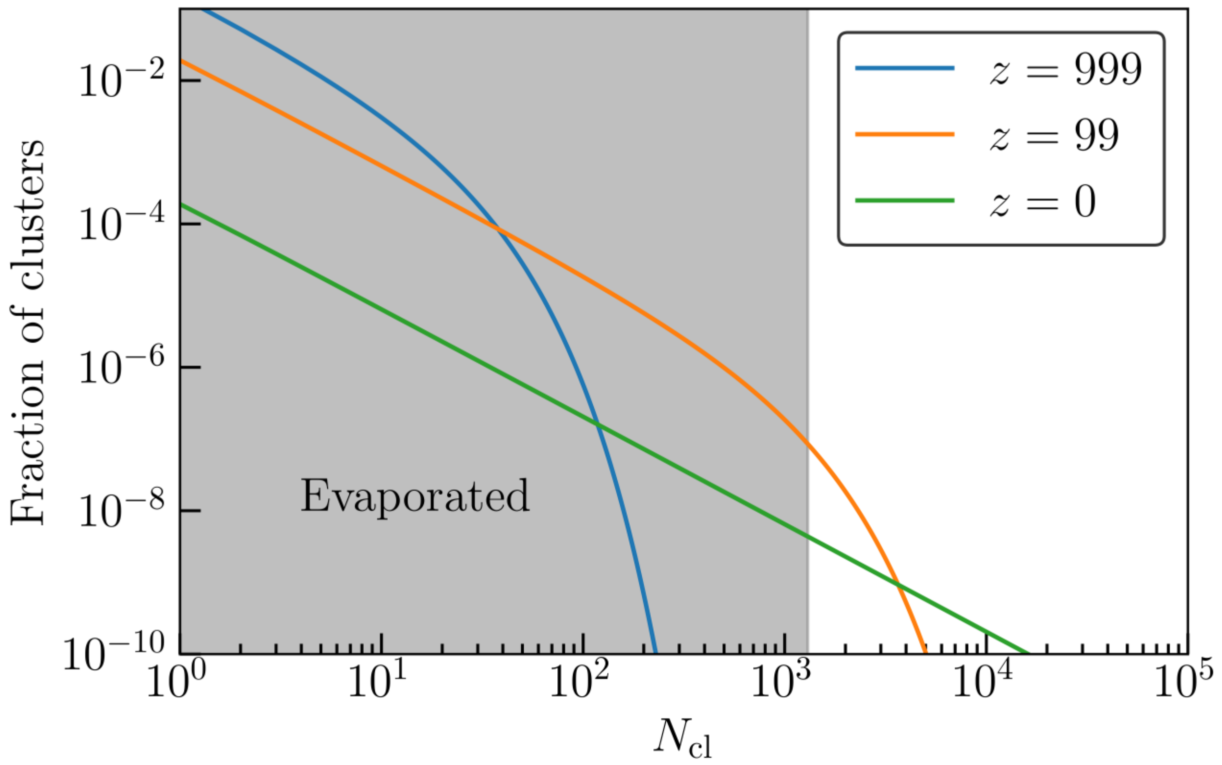
N_{cl} : Number of PBHs per cluster

- More massive PBH clusters are rarer
- Light clusters evaporate Jedamzik (2020)

$\Rightarrow N_{\mathrm{cl}} \sim 10^3$

Assume:

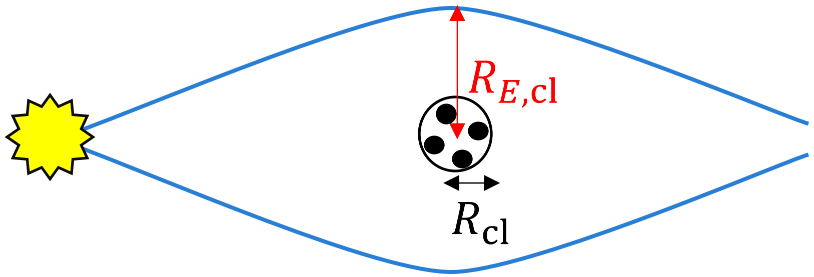
- All PBHs in PBH clusters
- All clusters contain N_{cl} PBHs



Fraction of PBH clusters containing N_{cl} PBHs

Compact and Diffuse clusters

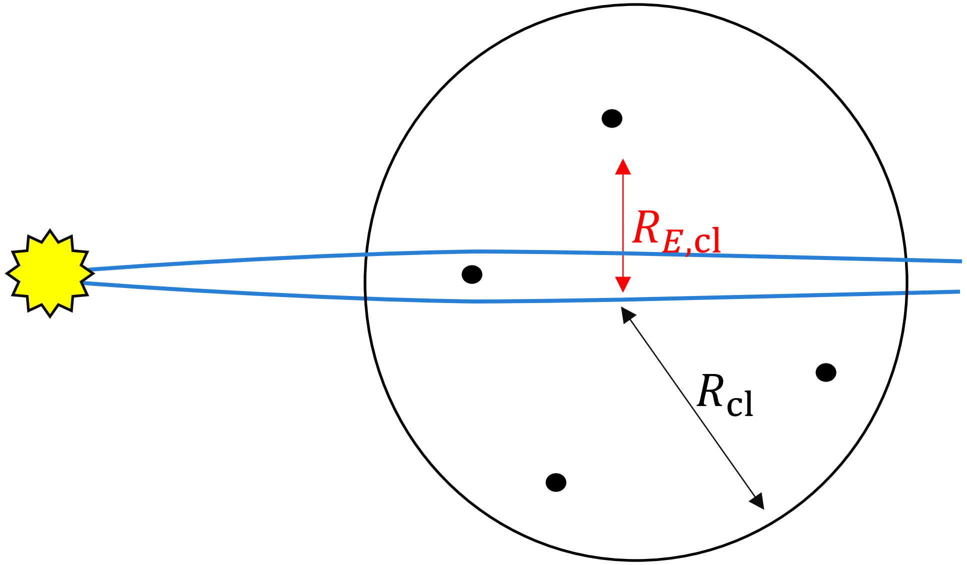
Compact



$$R_{E,\mathrm{cl}} \gg R_{\mathrm{cl}}$$

Entire PBH cluster acts as a single lens

Diffuse

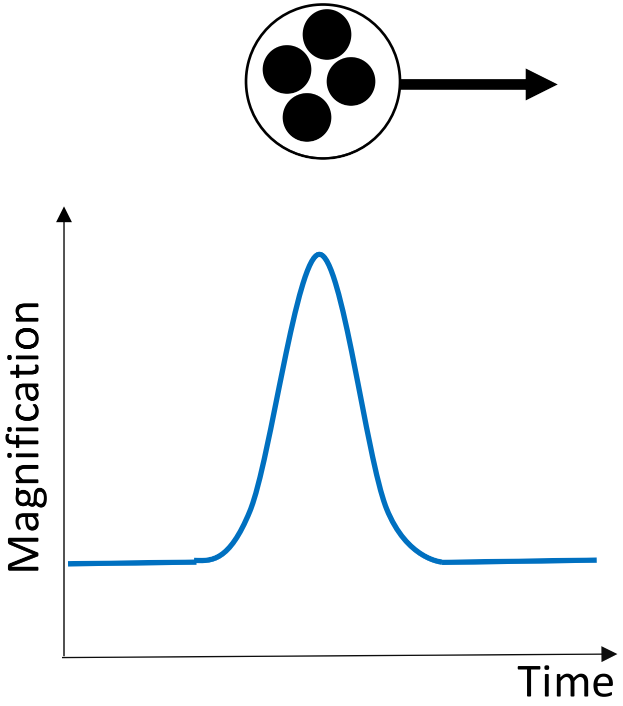


$$R_{E,\mathrm{cl}} \ll R_{\mathrm{cl}}$$

Individual PBHs act as separate lenses

Compact and Diffuse clusters

Compact



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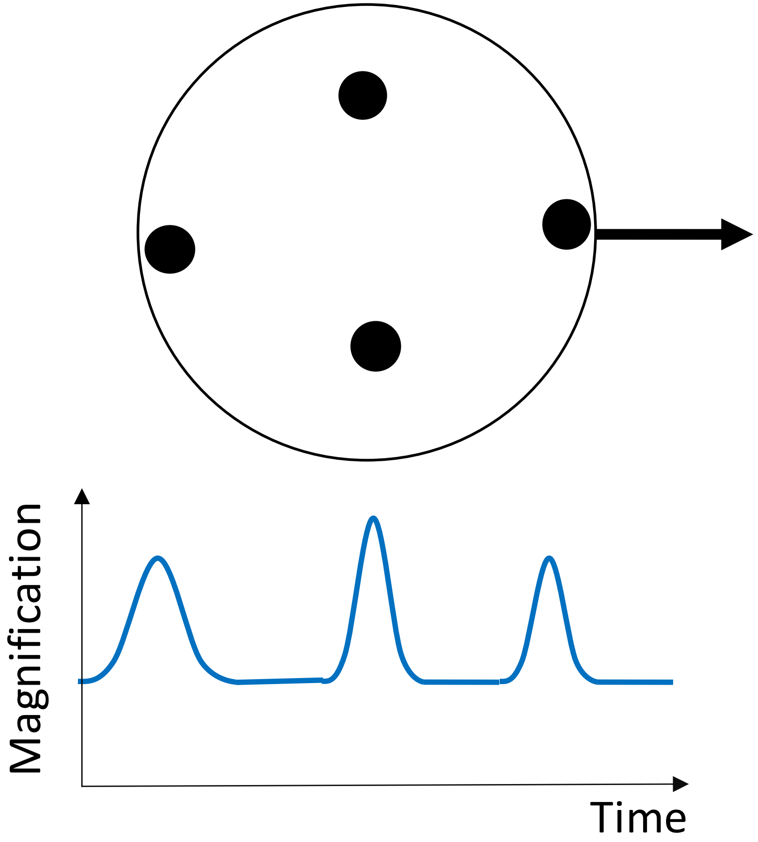
Diffuse



Individual PBHs act as separate lenses

PBH clustering: compact or diffuse?

Jedamzik (2020) derived cluster properties from the spherical top-hat collapse model:

Cluster radius:

$$R_{\mathrm{cl}} \approx 0.011\, N_{\mathrm{cl}}^{5/6} \left(\frac{M_{\mathrm{PBH}}}{M_\odot}\right)^{1/3} \mathrm{pc} \approx 3.5\ \mathrm{pc}$$

Blue:
$M_{\mathrm{PBH}} = M_\odot$
$N_{\mathrm{cl}} = 10^3$

Einstein radius of cluster:

$$R_{E,\mathrm{cl}} \approx 2 \times 10^{-5} \left(\frac{M_{\mathrm{PBH}}}{M_\odot}\right)^{1/2} N_{\mathrm{cl}}{}^{1/2}\ \mathrm{pc} \approx 6 \times 10^{-4}\ \mathrm{pc}$$

$R_{E,\mathrm{cl}} \ll R_{\mathrm{cl}}$

$\Rightarrow$ **PBH clusters are diffuse** (true for the other M_{PBH} and N_{cl} values considered)

Probability distribution of number of events ($M_{\rm PBH} = M_\odot$)

$N_{\rm cl} \lesssim 10^5$

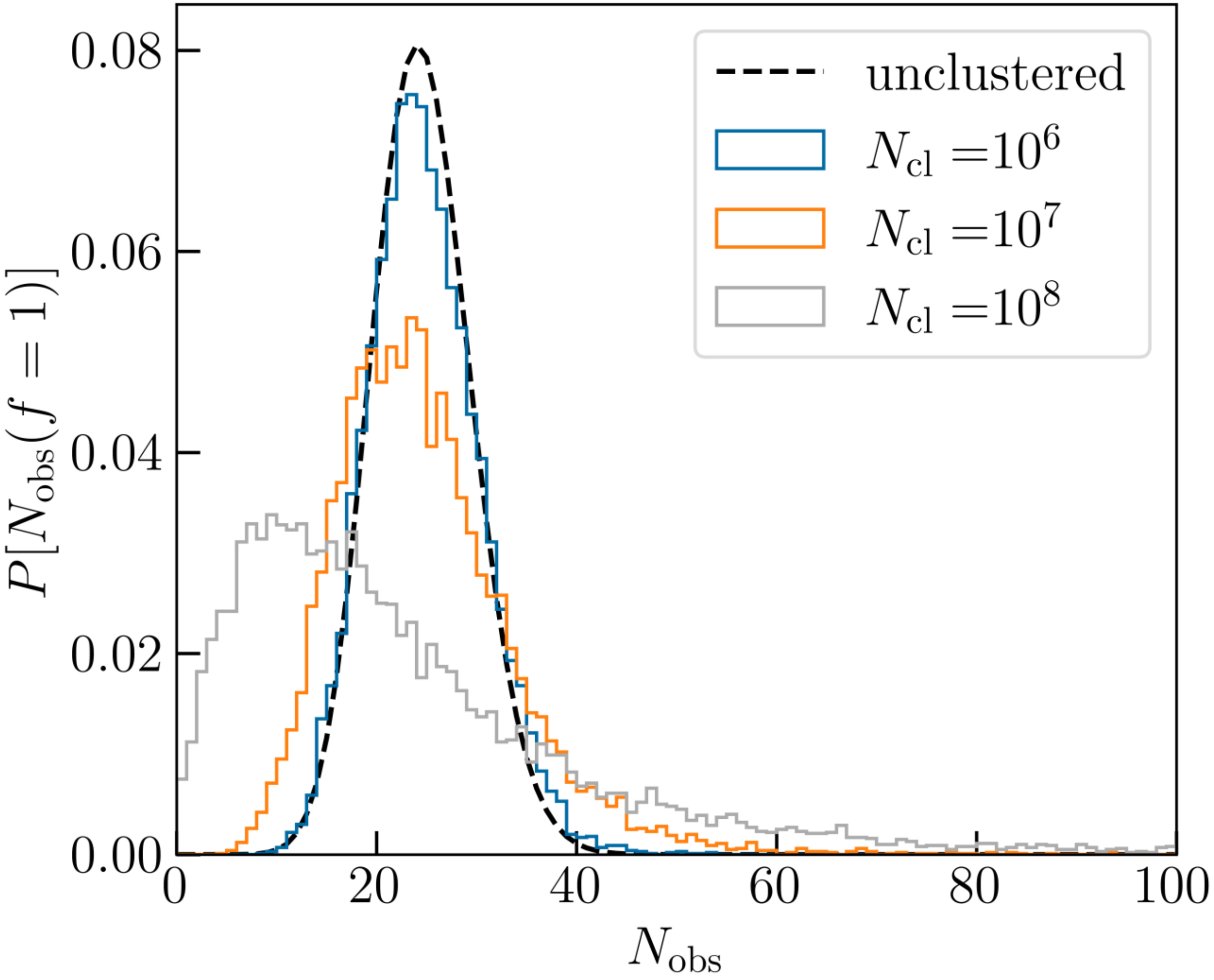
PBH clustering has a negligible effect

$N_{\rm cl} \gtrsim 10^6$

Significant difference from unclustered PBHs

Good agreement with Petač et al. (2022)

$\lesssim 10^3$ PBH clusters in observing region



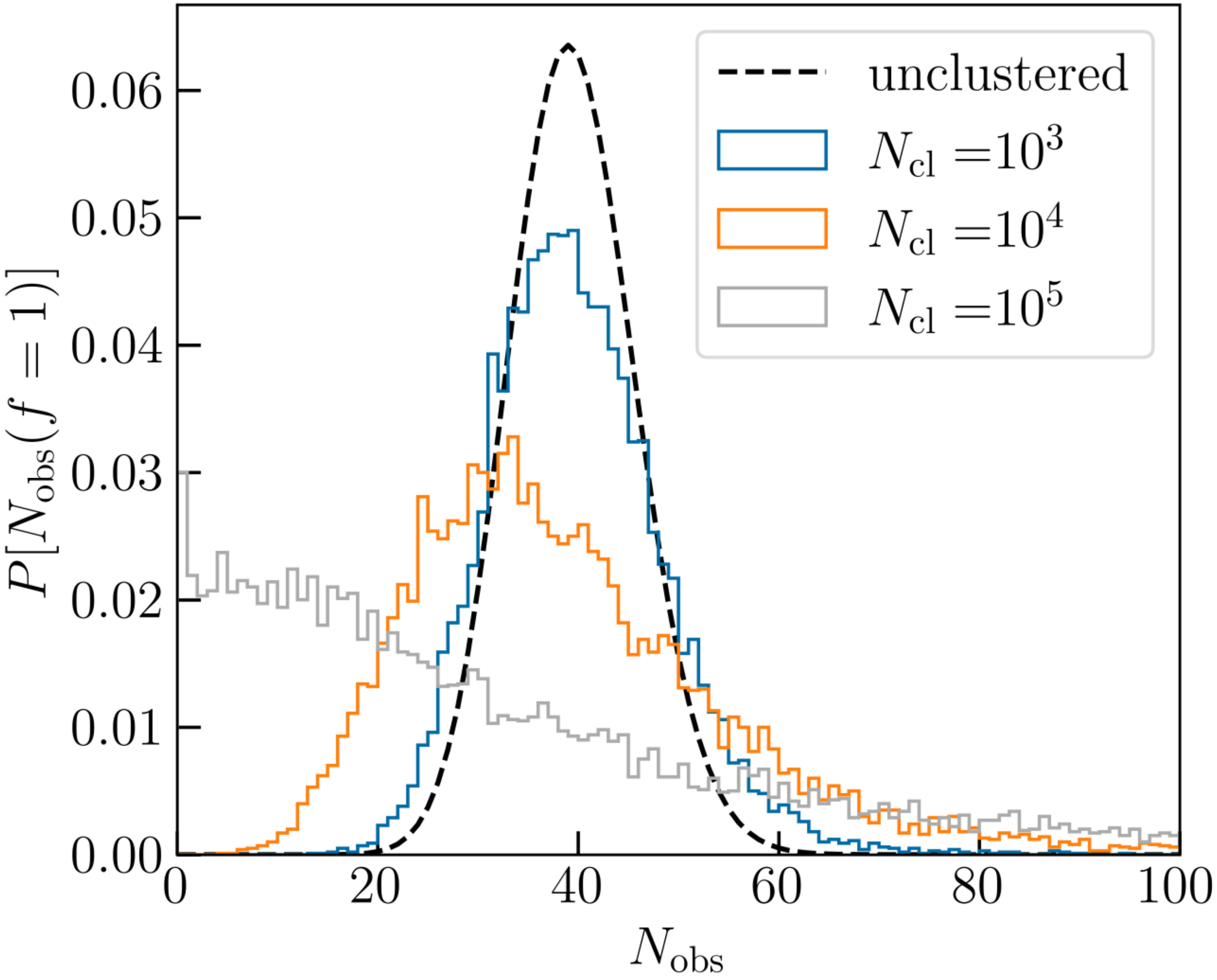
Probability distribution of number of events ($M_{\mathrm{PBH}} = 1000 M_\odot$)

$N_{\mathrm{cl}} = 10^3$

$\lesssim 10^3$ clusters in observing region

For zero microlensing events, 95% confidence interval:

- $f < 0.076$ (unclustered)
- $f < 0.096$ (clustered)



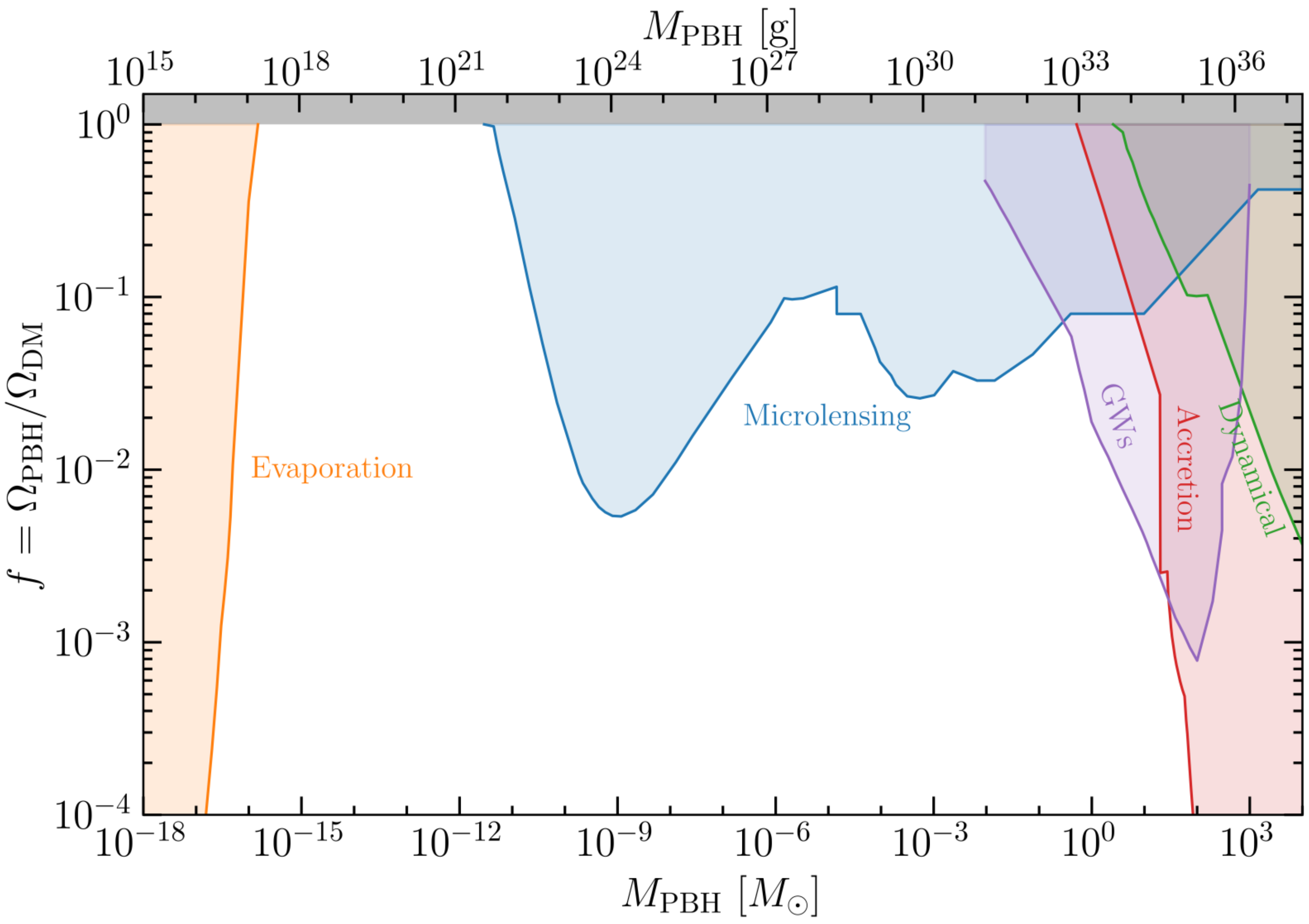
Conclusions

Most commonly-studied PBH formation mechanism

- Diffuse PBH clusters
- Clusters contain too few PBHs to significantly change microlensing constraints
- Caveat: assume Gaussian curvature perturbation

To change constraints more significantly requires very compact, or very massive, PBH clusters

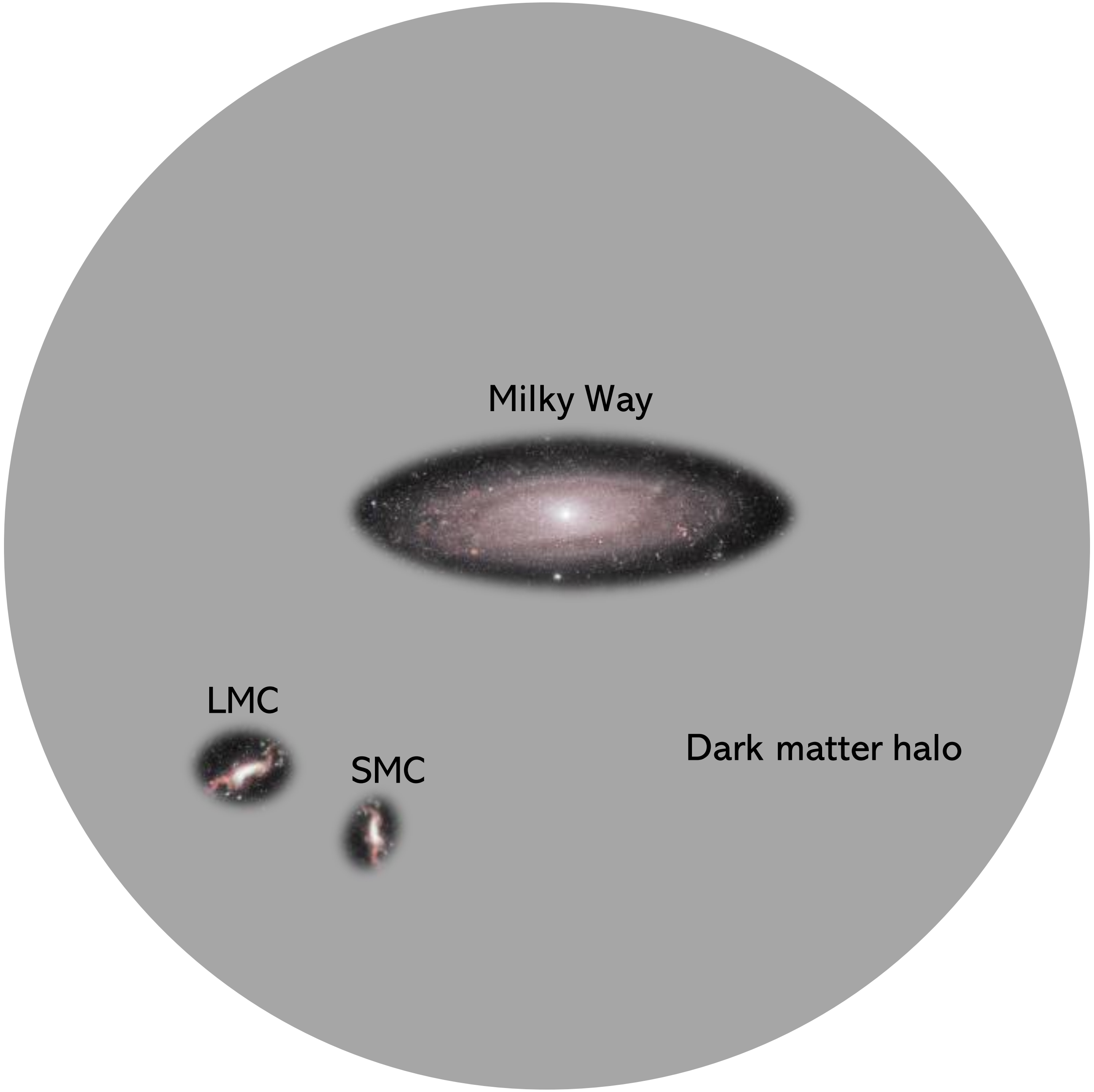
Constraints on PBHs



Constraints on fraction of dark matter in PBHs, f, produced using PBHbounds (https://github.com/bradkav/PBHbounds)

Assumes:

- All PBHs have equal mass
- Unclustered PBHs


Milky Way
LMC
SMC
Dark matter halo

Differential event rate

Rate of microlensing events of duration $\hat{t}$:

$\hat{t} \equiv 2\, R_{E,\mathrm{PBH}} / v_{\perp}$

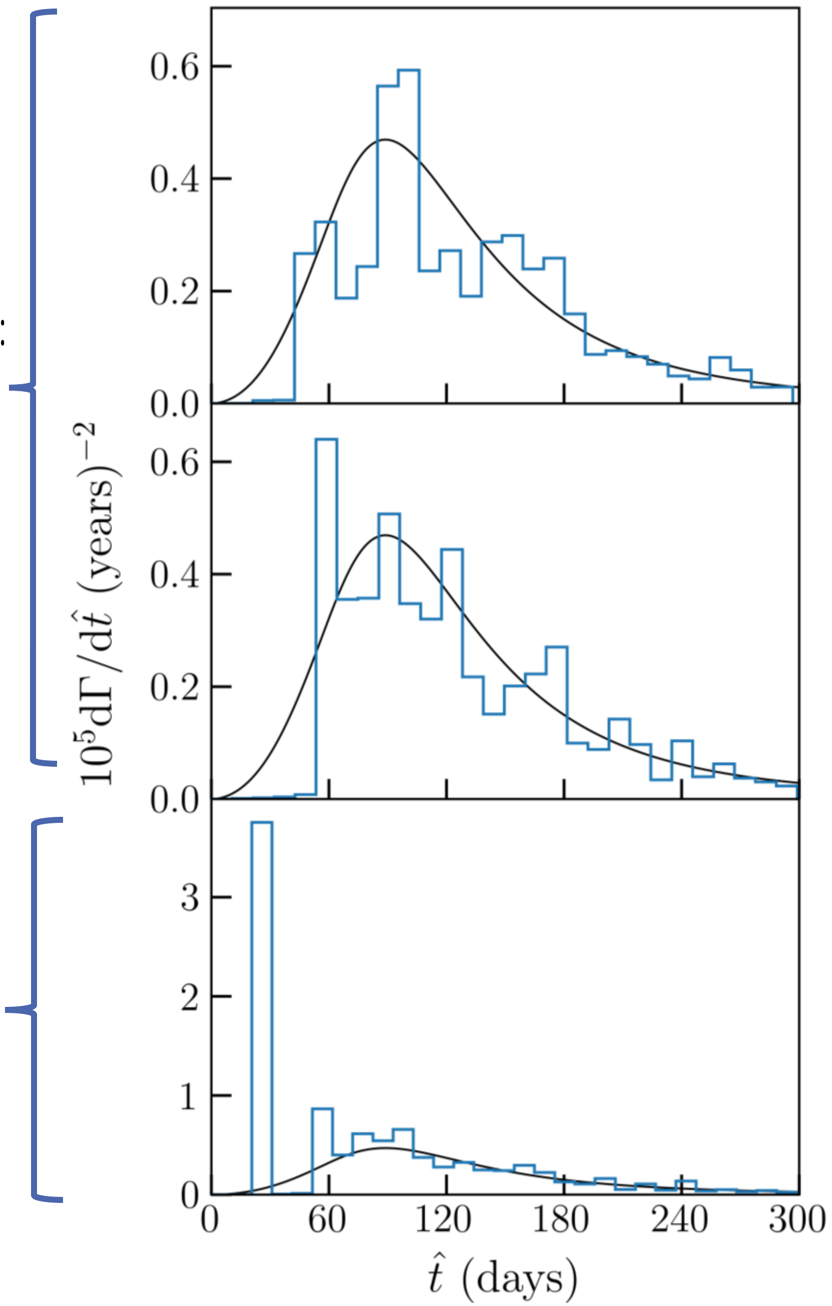
$R_{E,\mathrm{PBH}}$: Einstein radius of PBH

$v_{\perp}$: Transverse velocity of PBH

$R_{E,\mathrm{PBH}}$ is small at small line of sight distances, therefore $\hat{t}$ is typically small.

Black line: unclustered

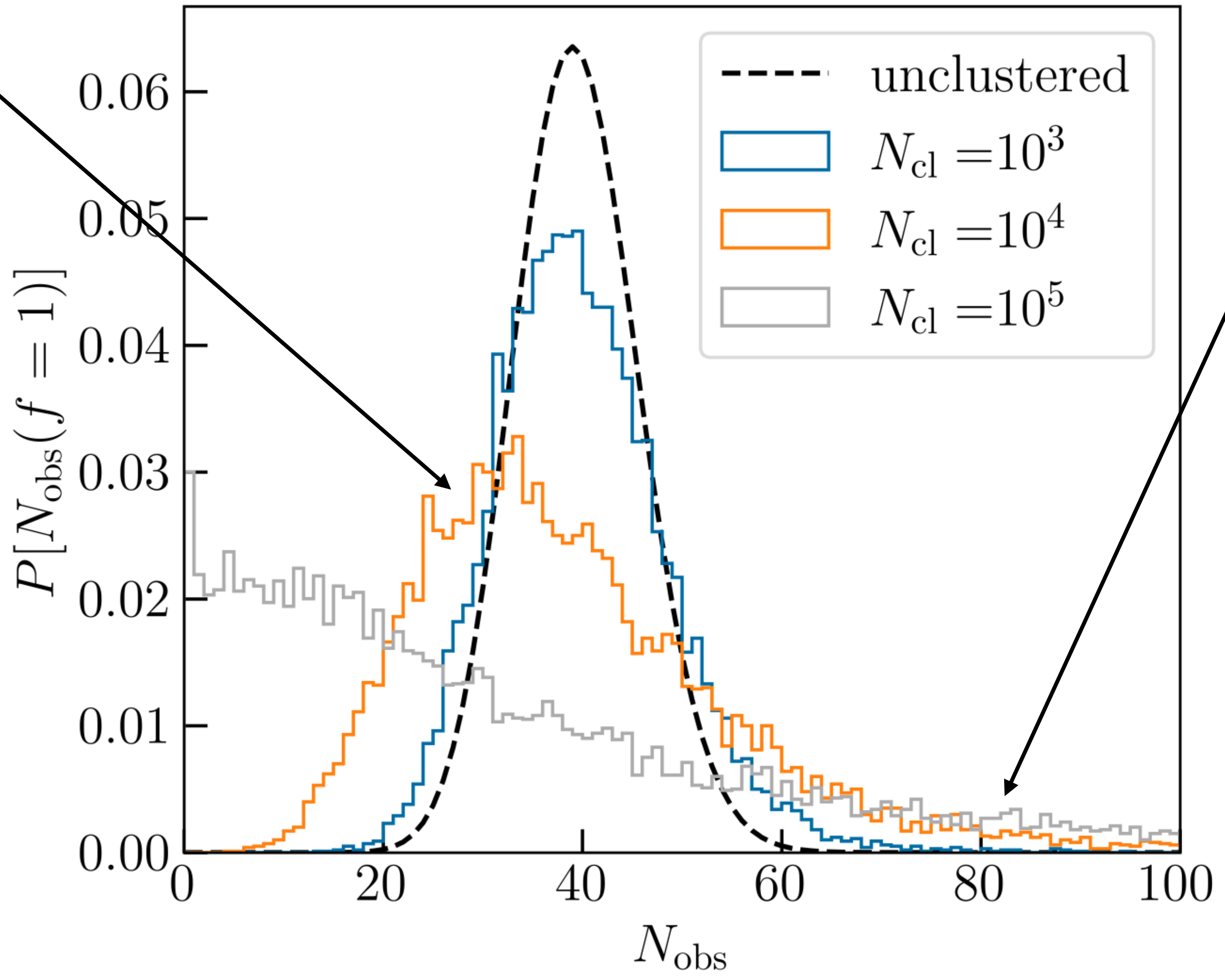
Blue: $N_{\mathrm{cl}} = 10^6$, $M_{\mathrm{PBH}} = M_{\odot}$



Typical realisations: deficit of short-duration events

Rare realisations: excess of short duration events

Explanation of shape of probability distribution



Peak at low numbers of events

From common realisations with deficit of short-duration events

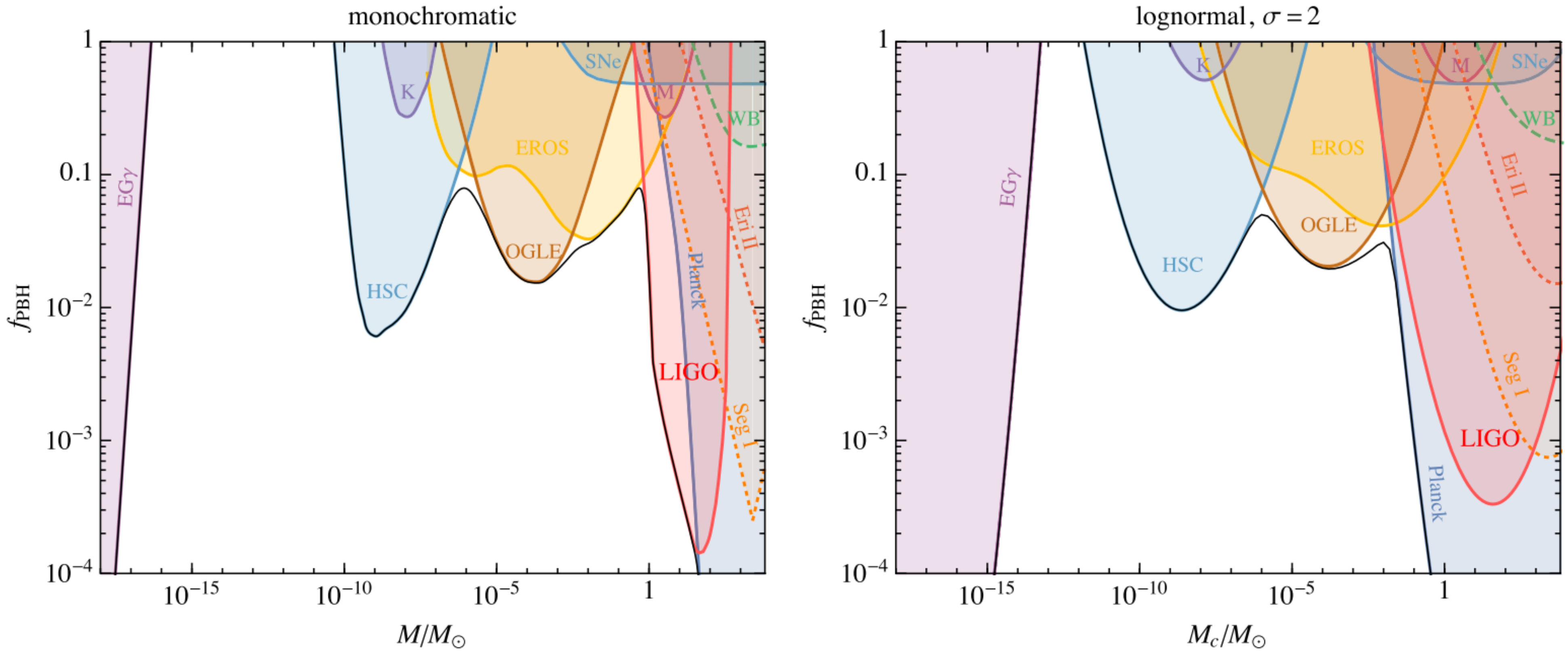
Tail of large numbers of events

From rare realisations with excess of short-duration events

Extended mass functions

E.g. log-normal mass function
Green (2016), Kannike et al. (2017)

$$\psi(M) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\sigma M}\exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$



Plots from Carr et al. (2021)