Primordial black holes as EM and GW sources

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New York University

Merging Visions: Exploring Compact-Object Binaries with Gravity and Light

KITP, June 24 2019

Brief history of PBHs

Hawking 1971 “Gravitationally collapsed objects of very low mass”

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- **Formation mechanism:**

"there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe"

See also Niemeyer and Jedamzik 99, Shibata and Sasaki 99, Musco et al. 05, Musco 18.

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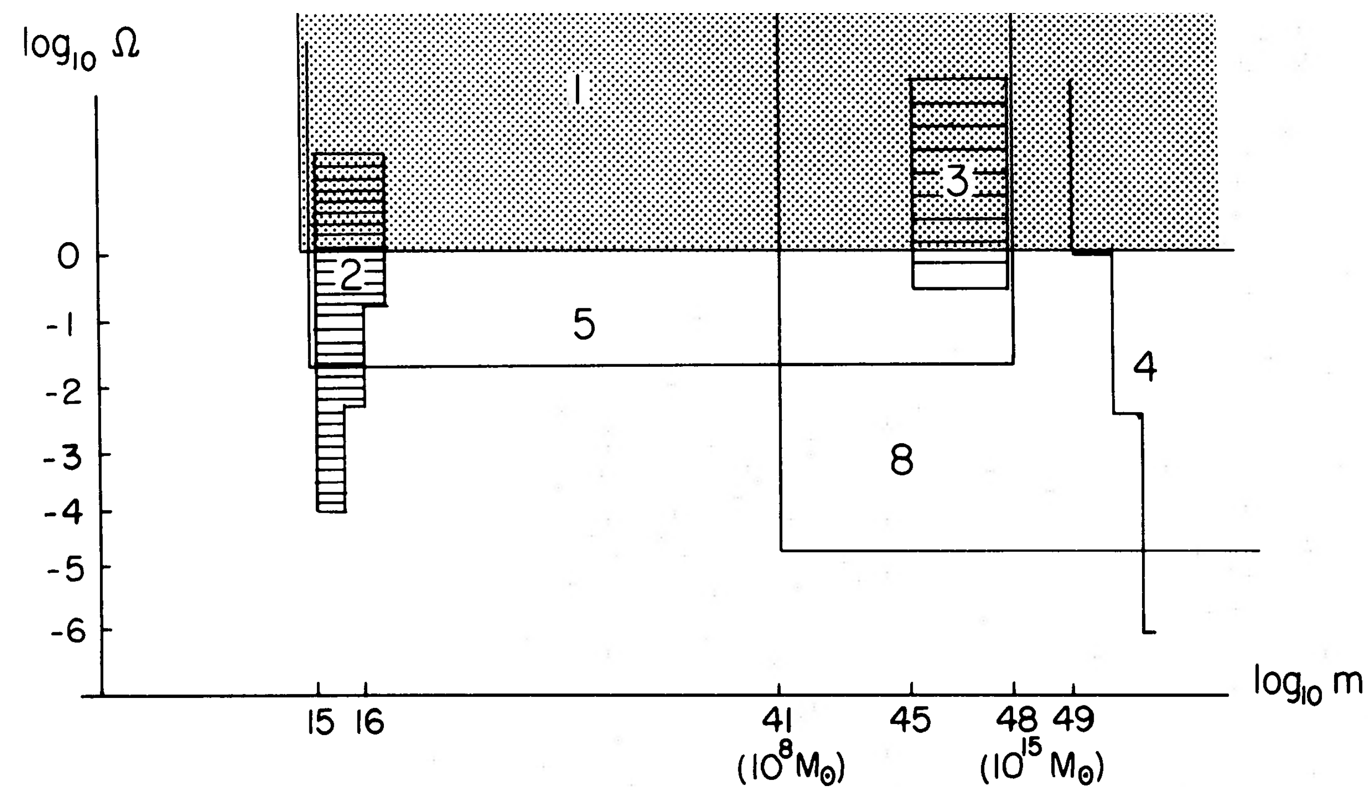
- **PBHs could be the dark matter:**

"This extra density [in collapsed objects] could stabilize clusters of galaxies which, otherwise, appear mostly not to be gravitationally bound"

Brief history of PBHs

Carr 1975 "The primordial black hole mass spectrum"

- First observational limits to PBH abundance



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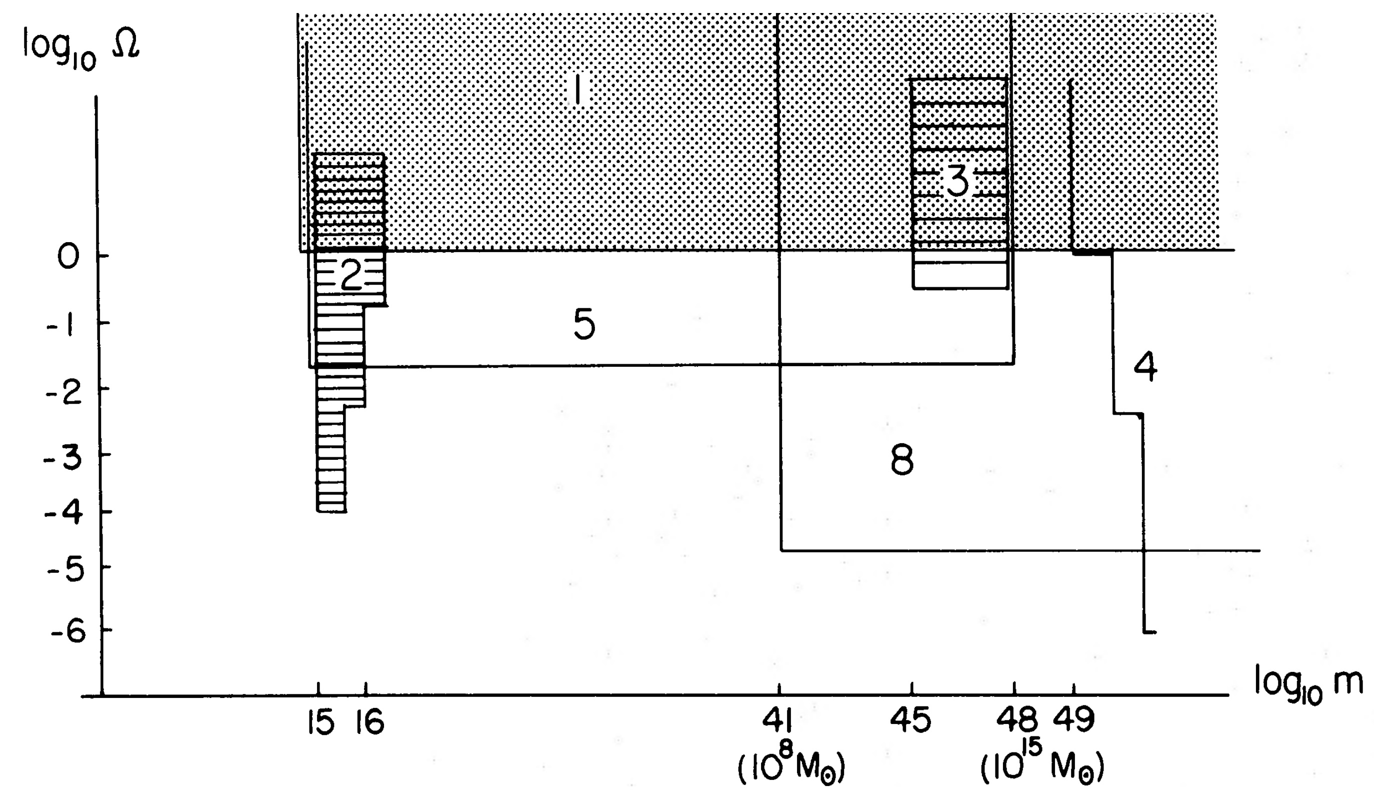
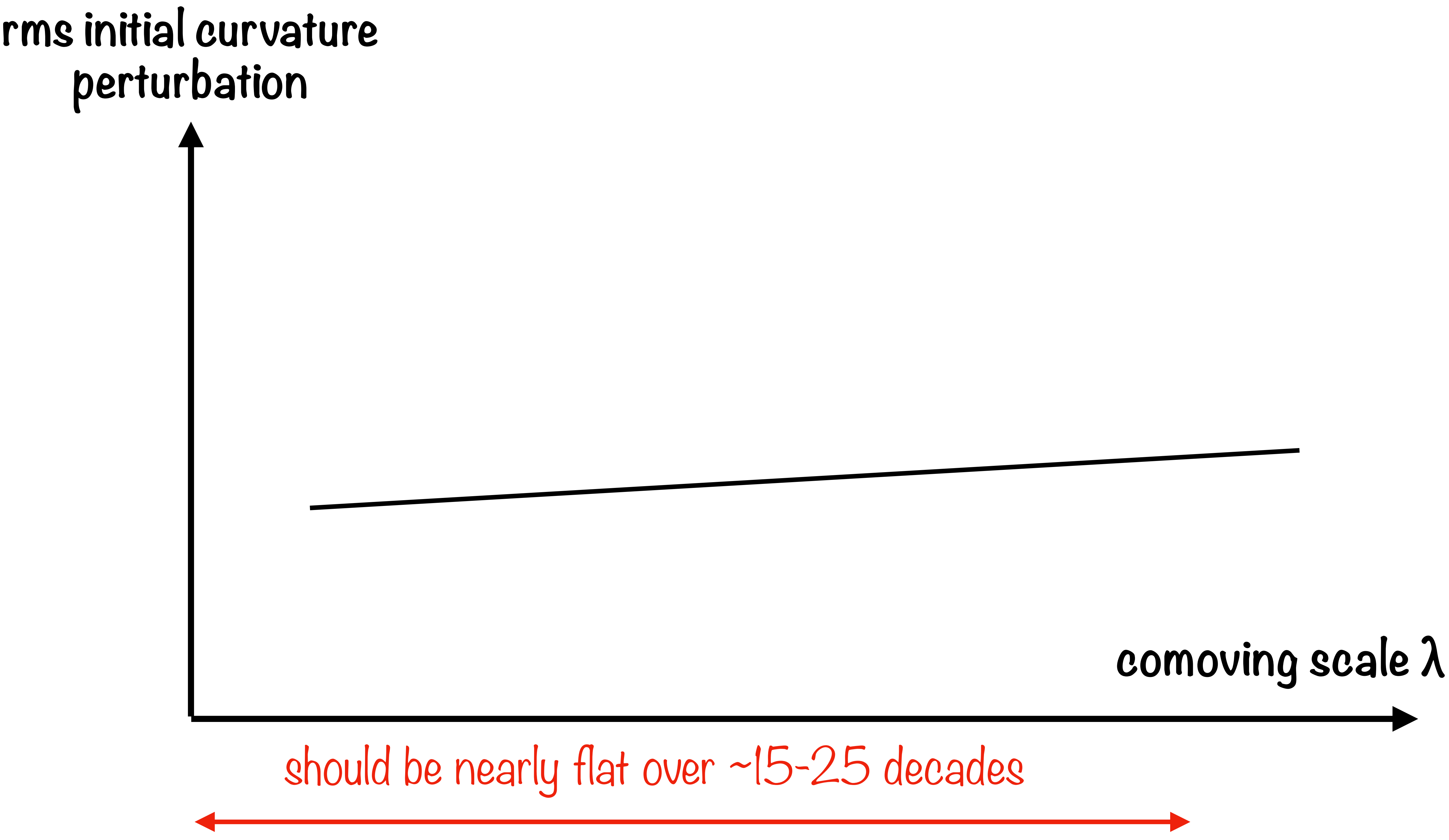


- PBHs inform about initial conditions (even if not all dark matter)

"Observational limits on the spectrum of primordial black holes place strong constraints on the magnitude of density fluctuations in the early universe"

Modern context



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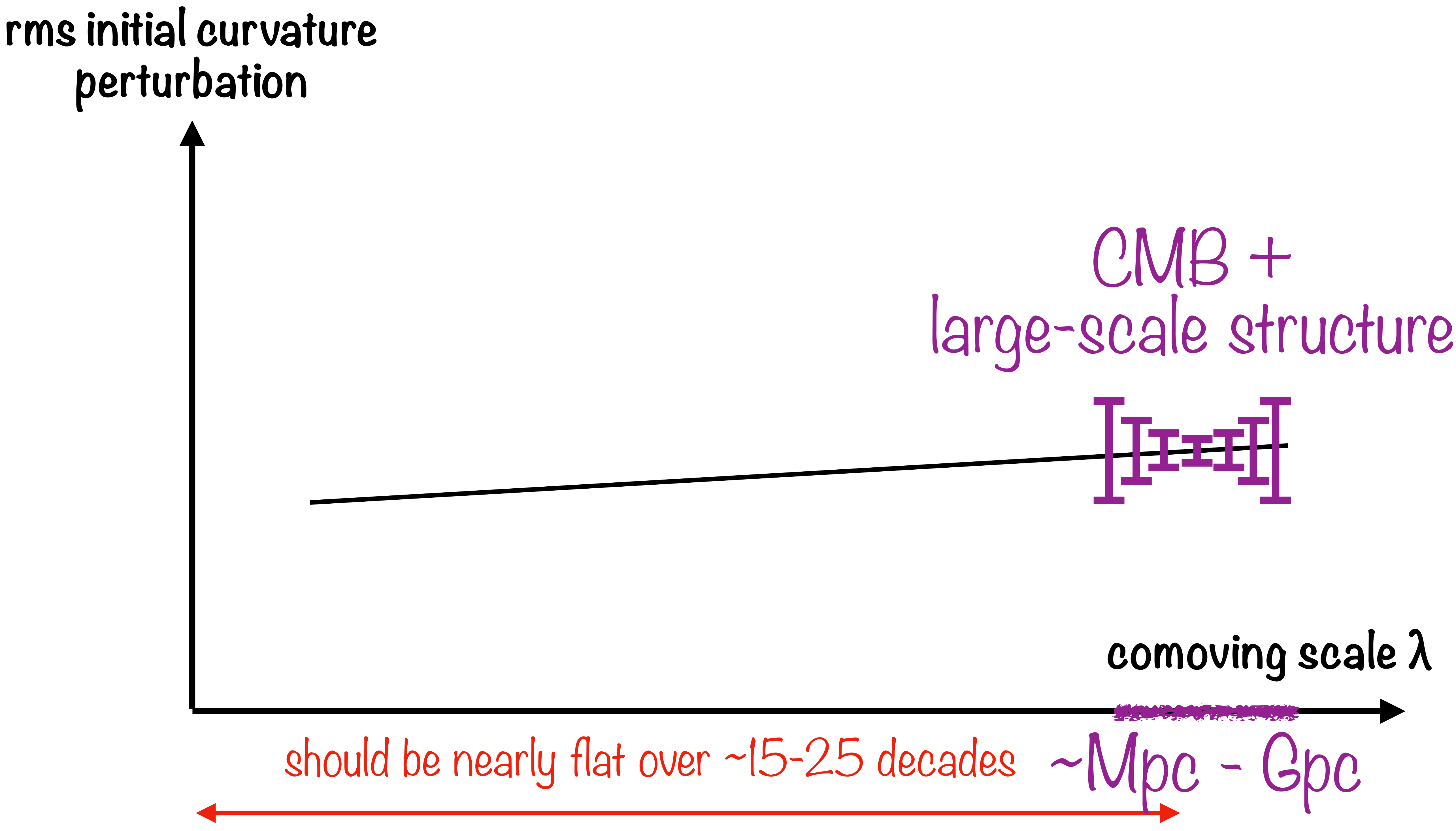

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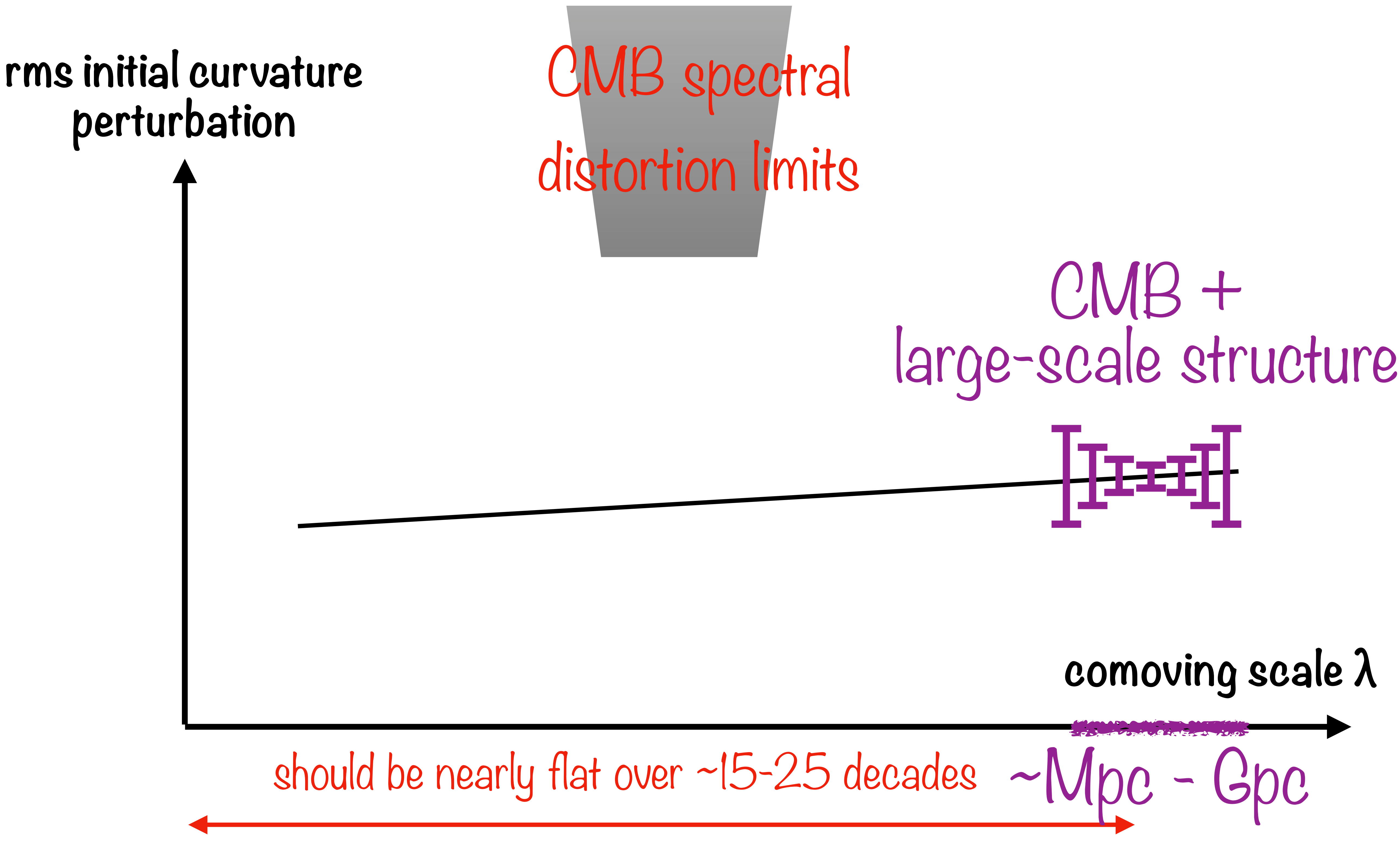

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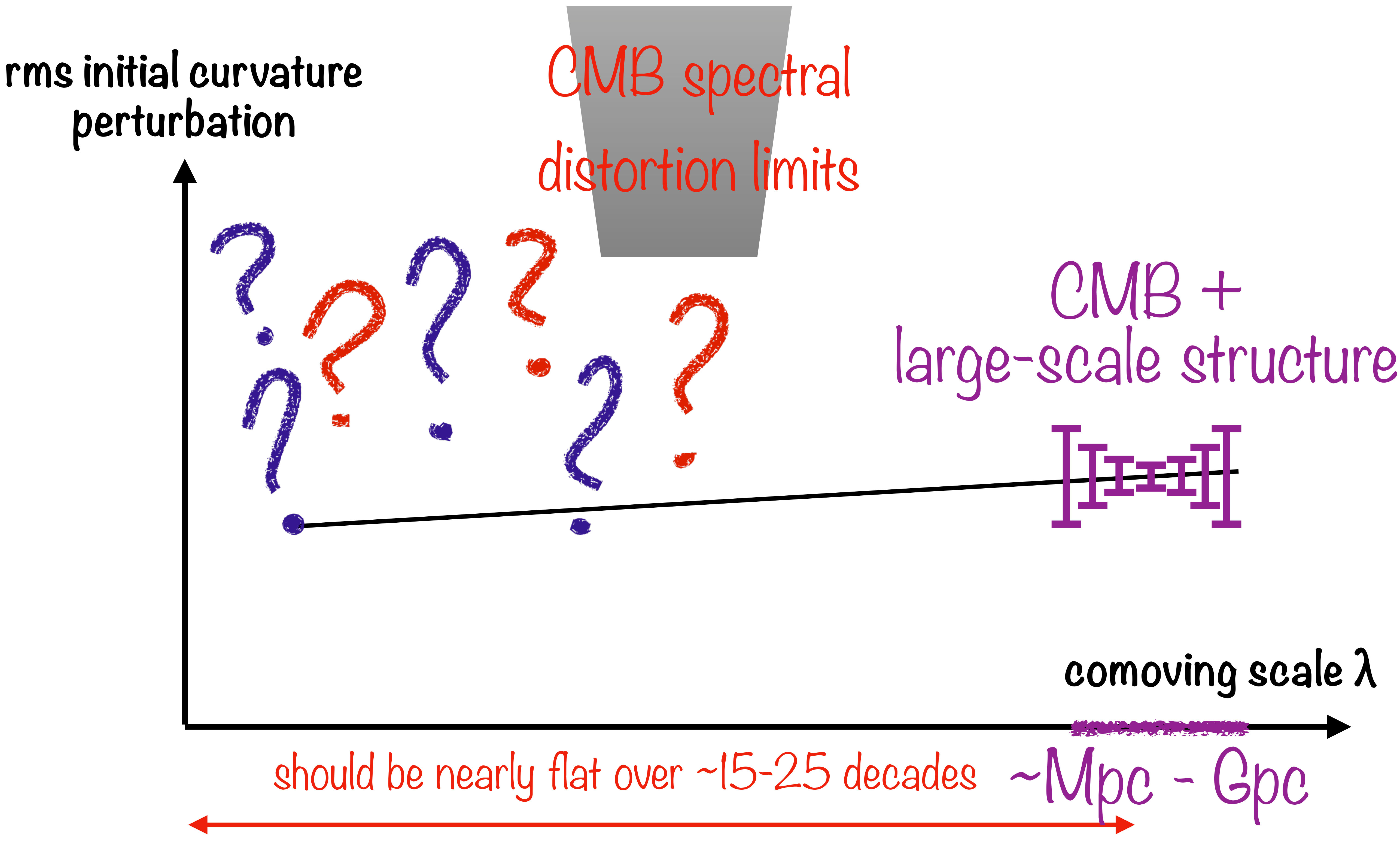

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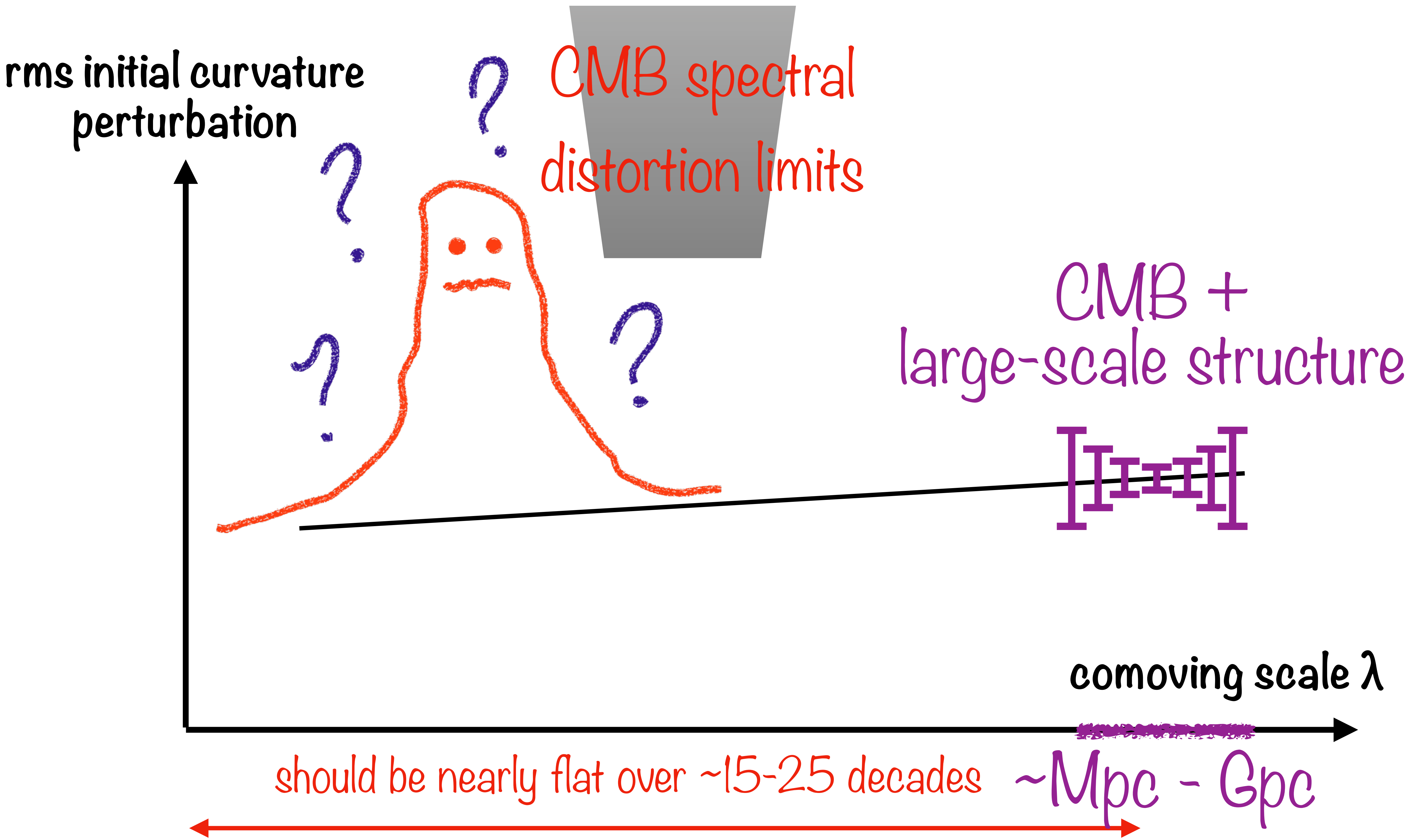

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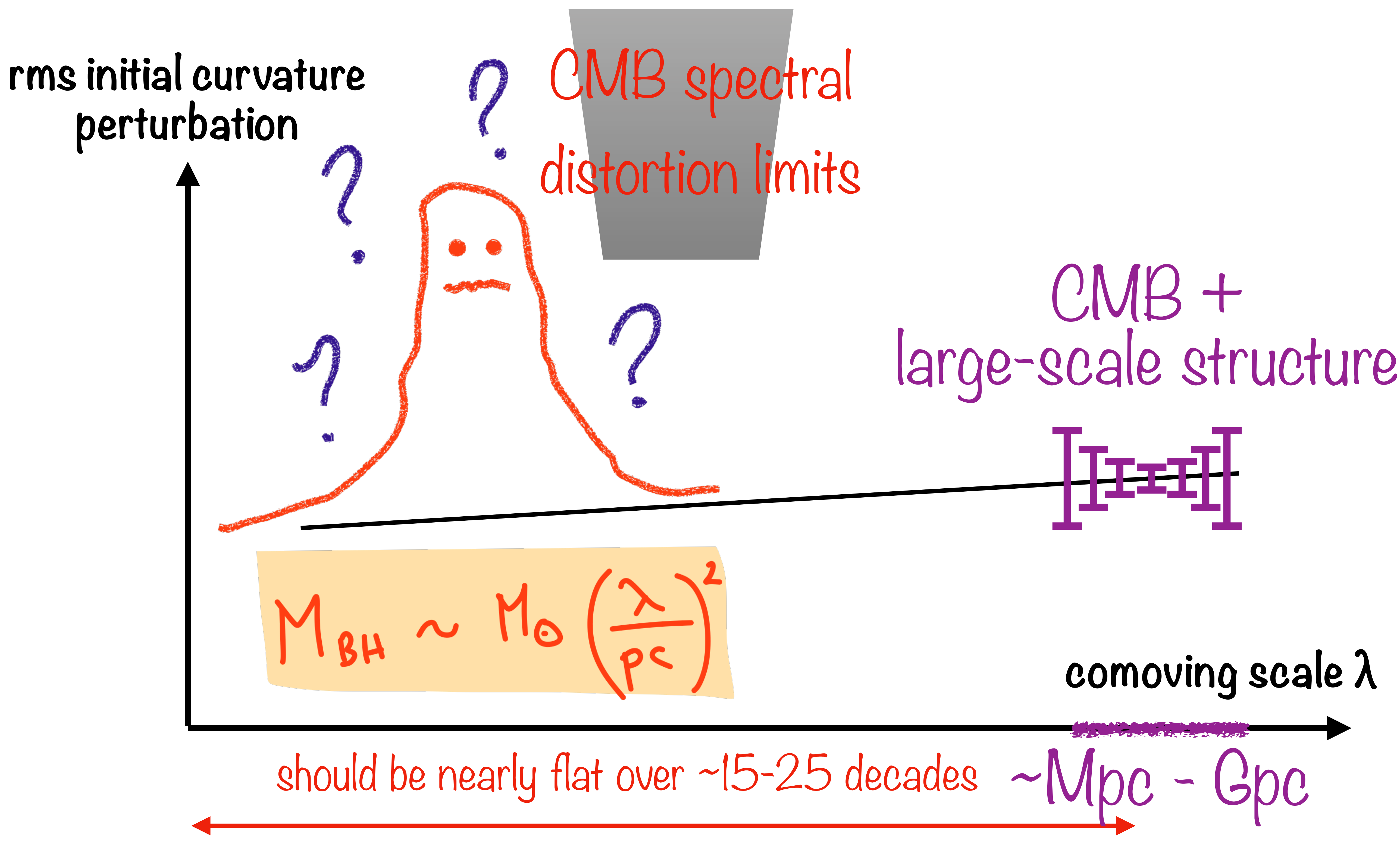

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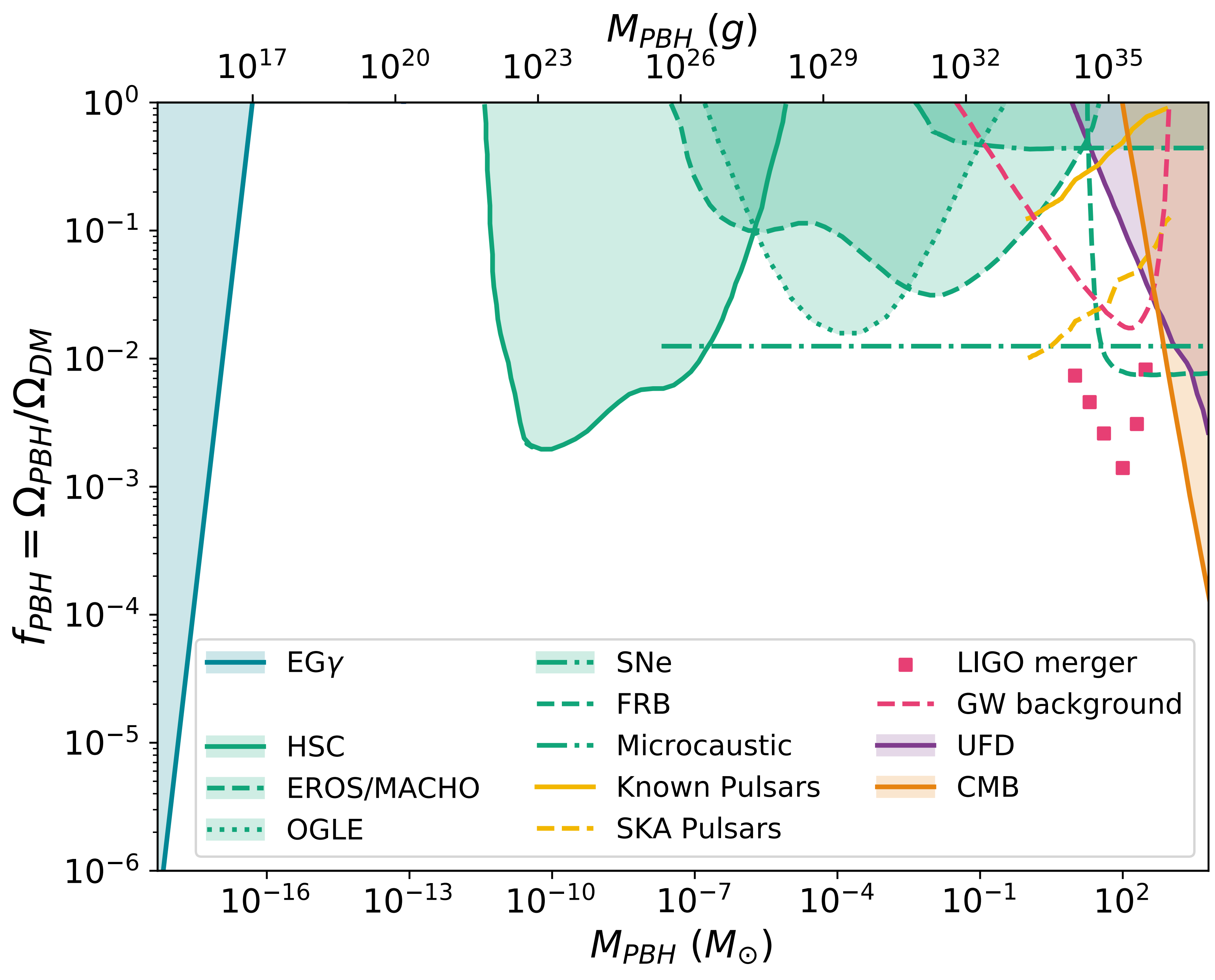

Figure from Sato-Polito, Kovetz & Kamionkowski 2019, adapted with results from Montero-Camacho et al. 2019

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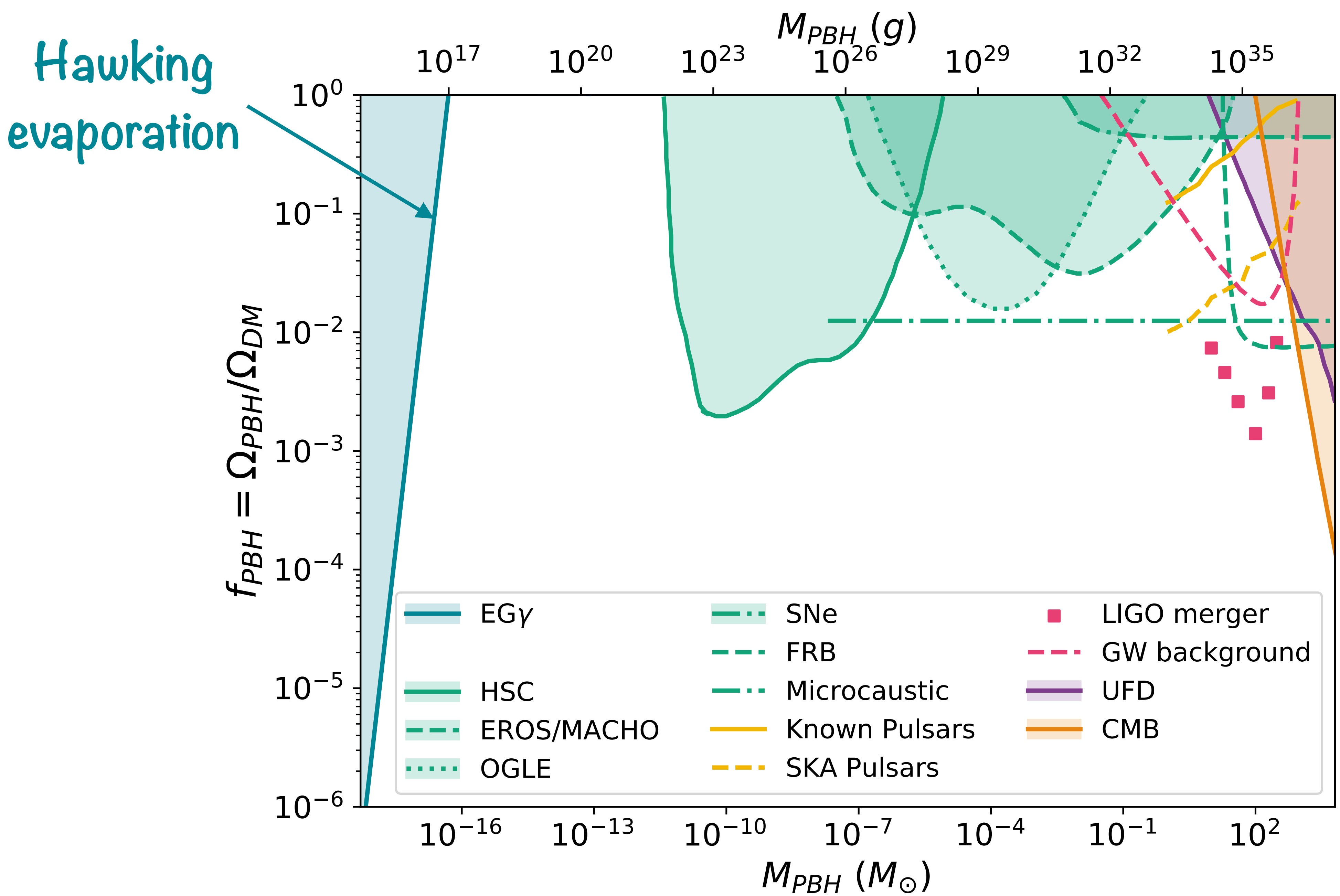

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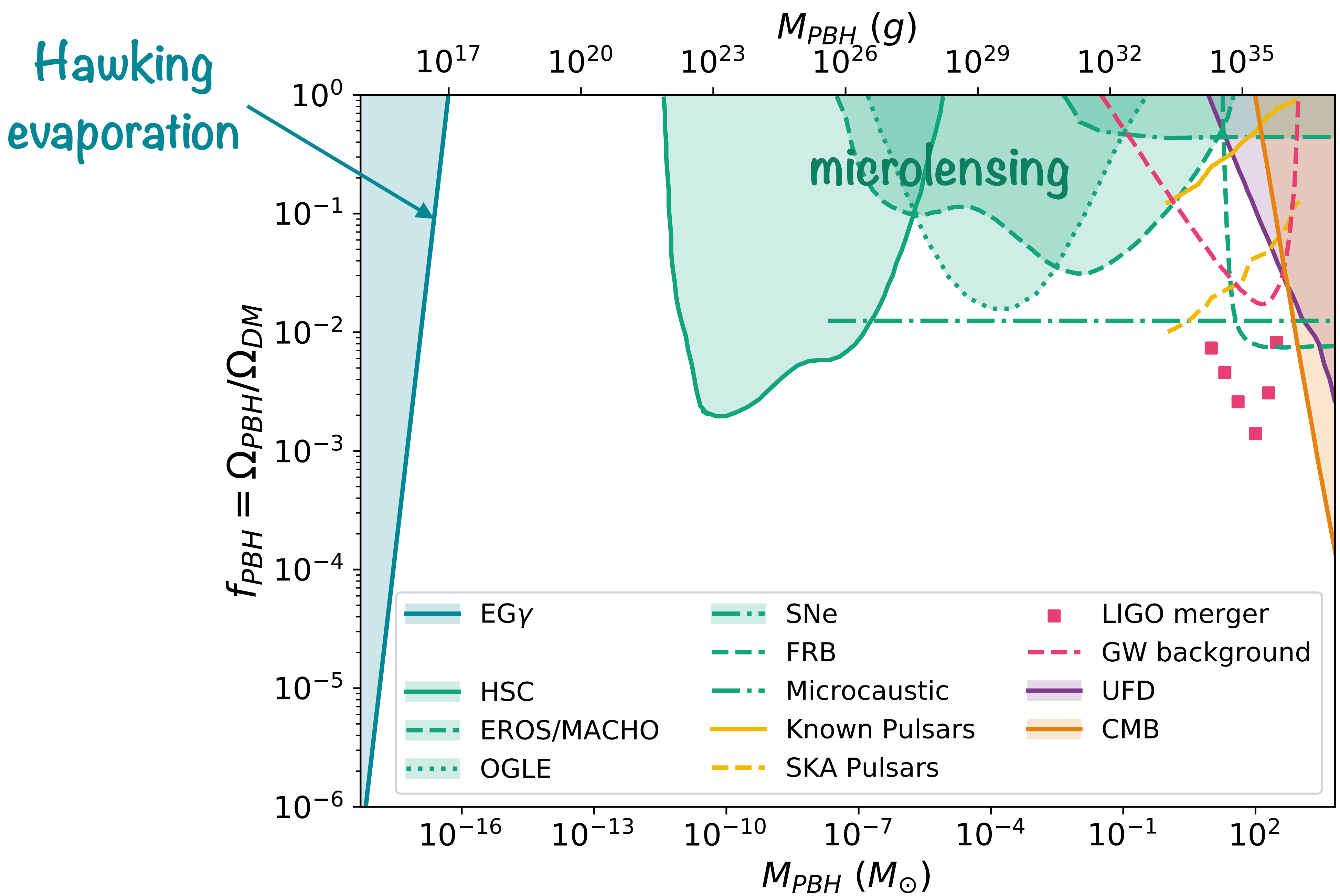

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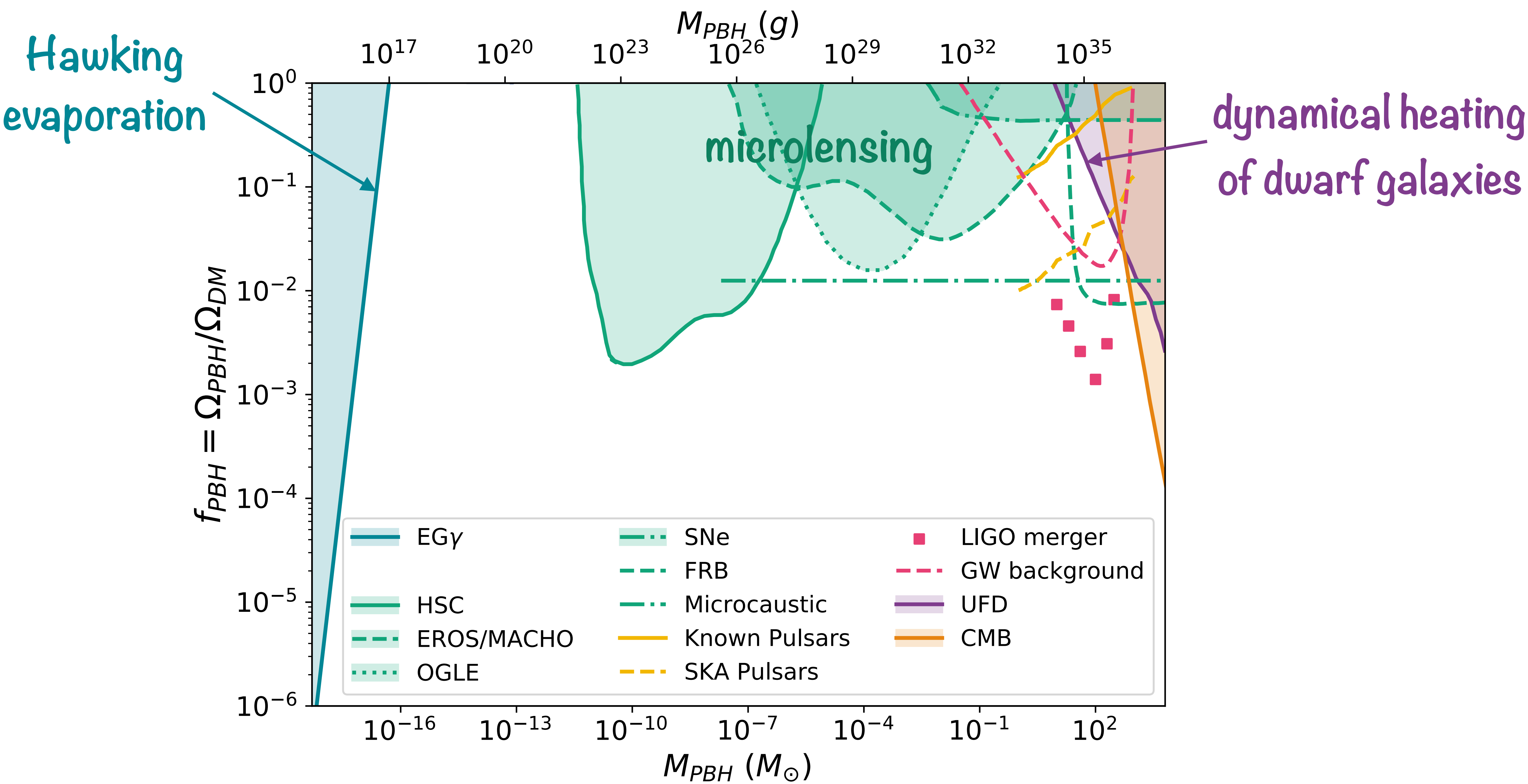

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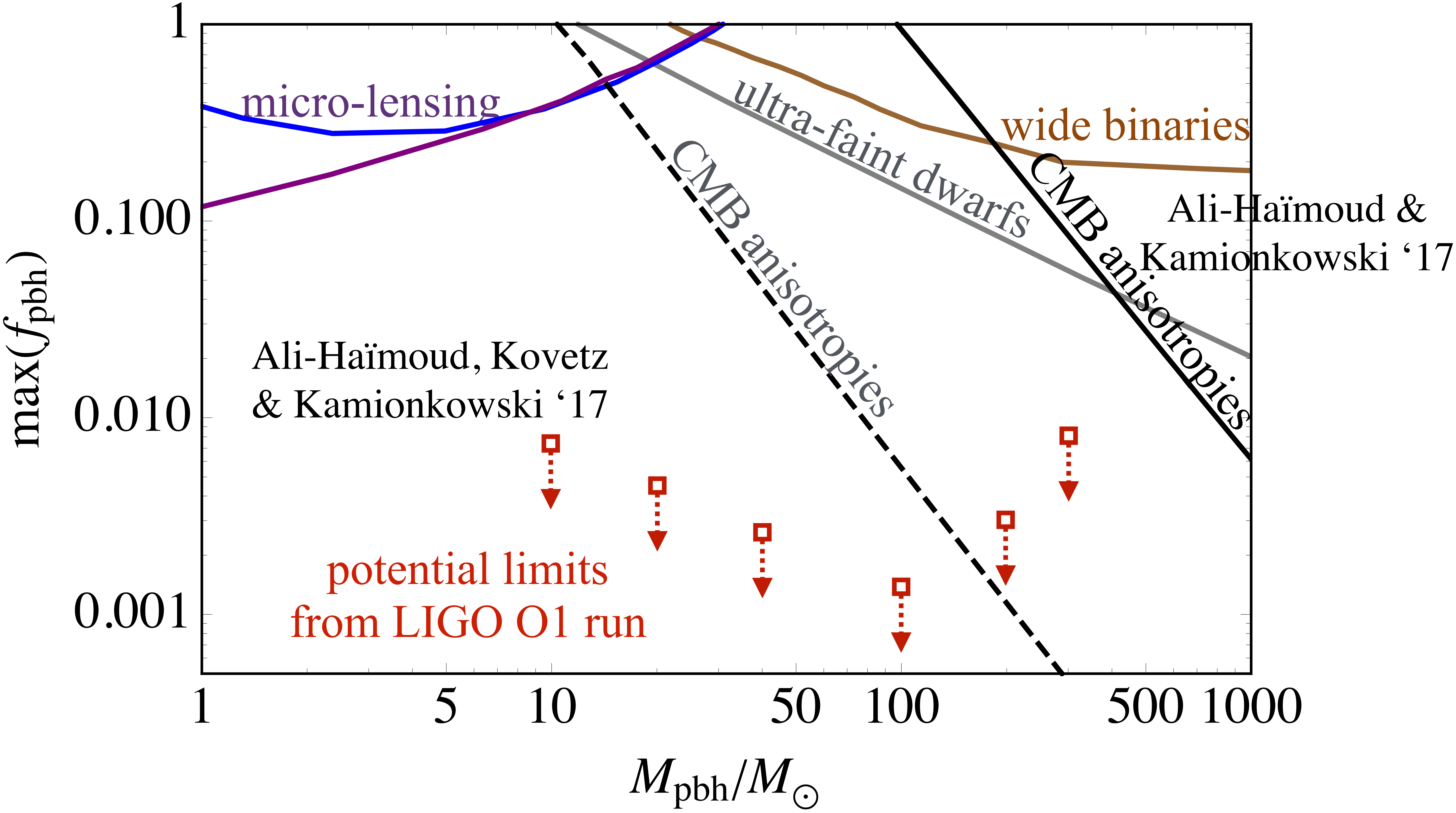
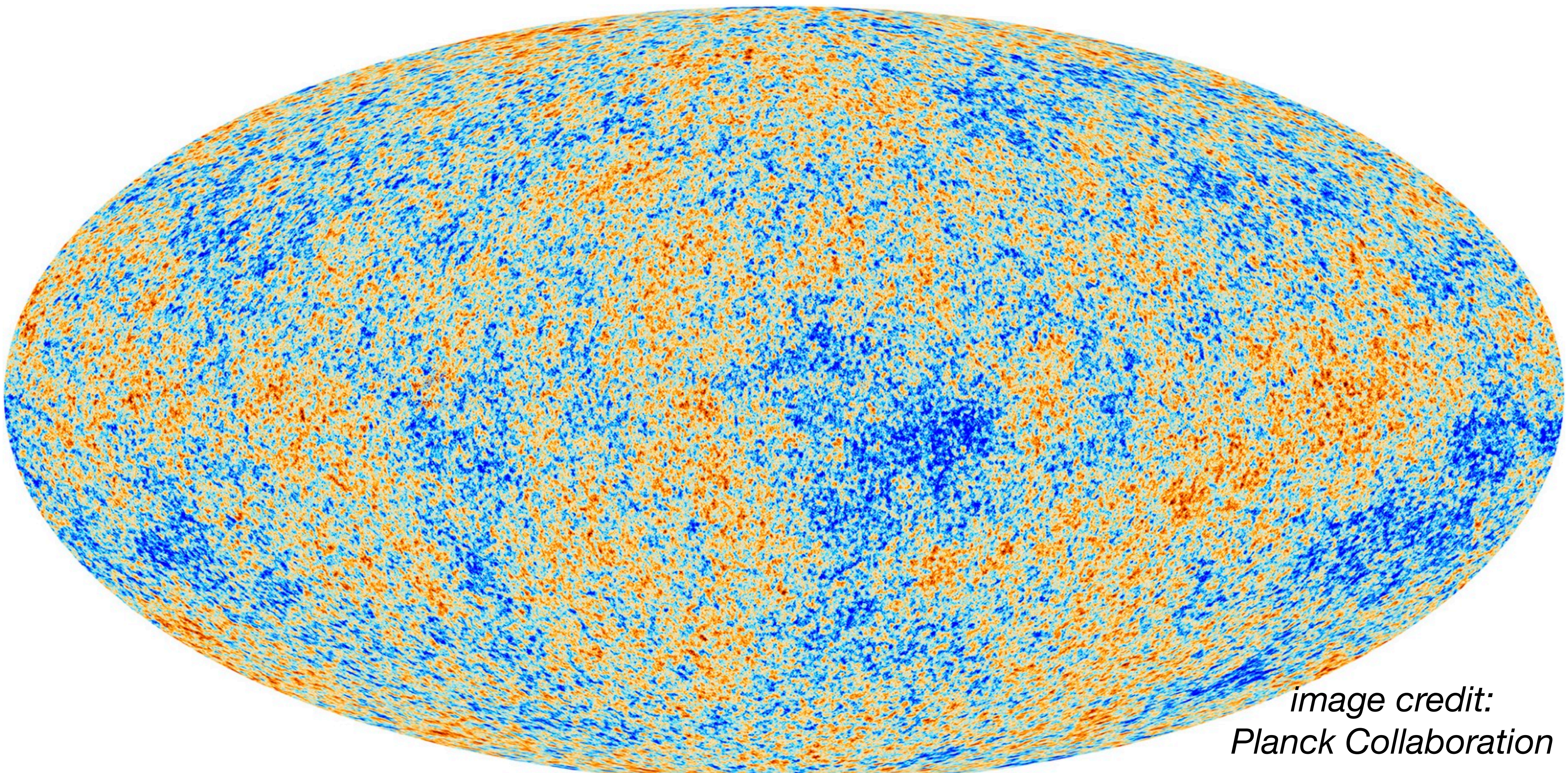
LIGO is likely the most sensitive probe of PBHs of ~1-500 M_{sun}



Primordial black holes as EM sources



Probing accreting PBHs with the CMB

Ali-Haïmoud & Kamionkowski 2017, Ricotti et al. 2008, Poulin et al. 2017

Suppose part of the dark matter is made of black holes

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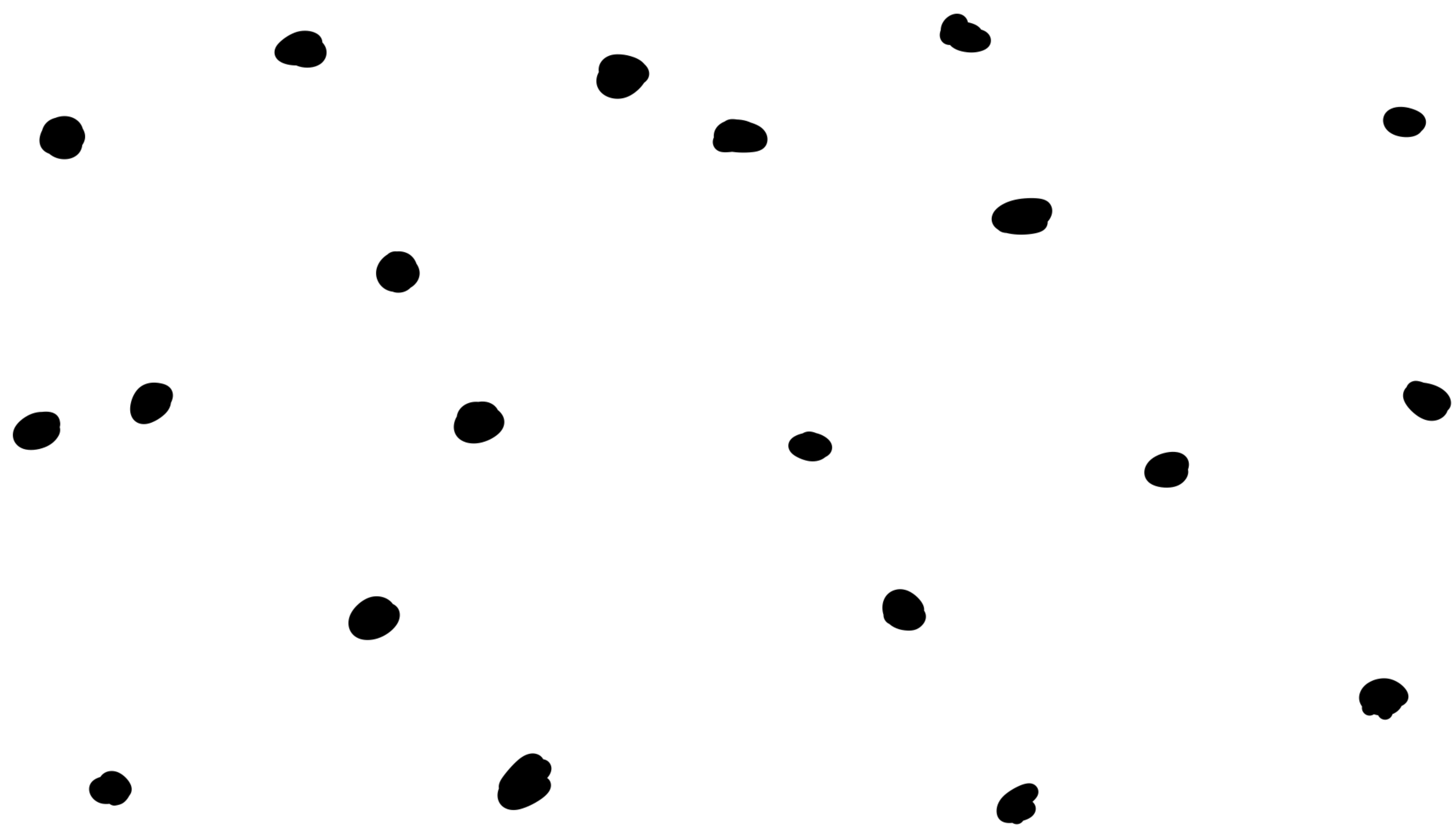

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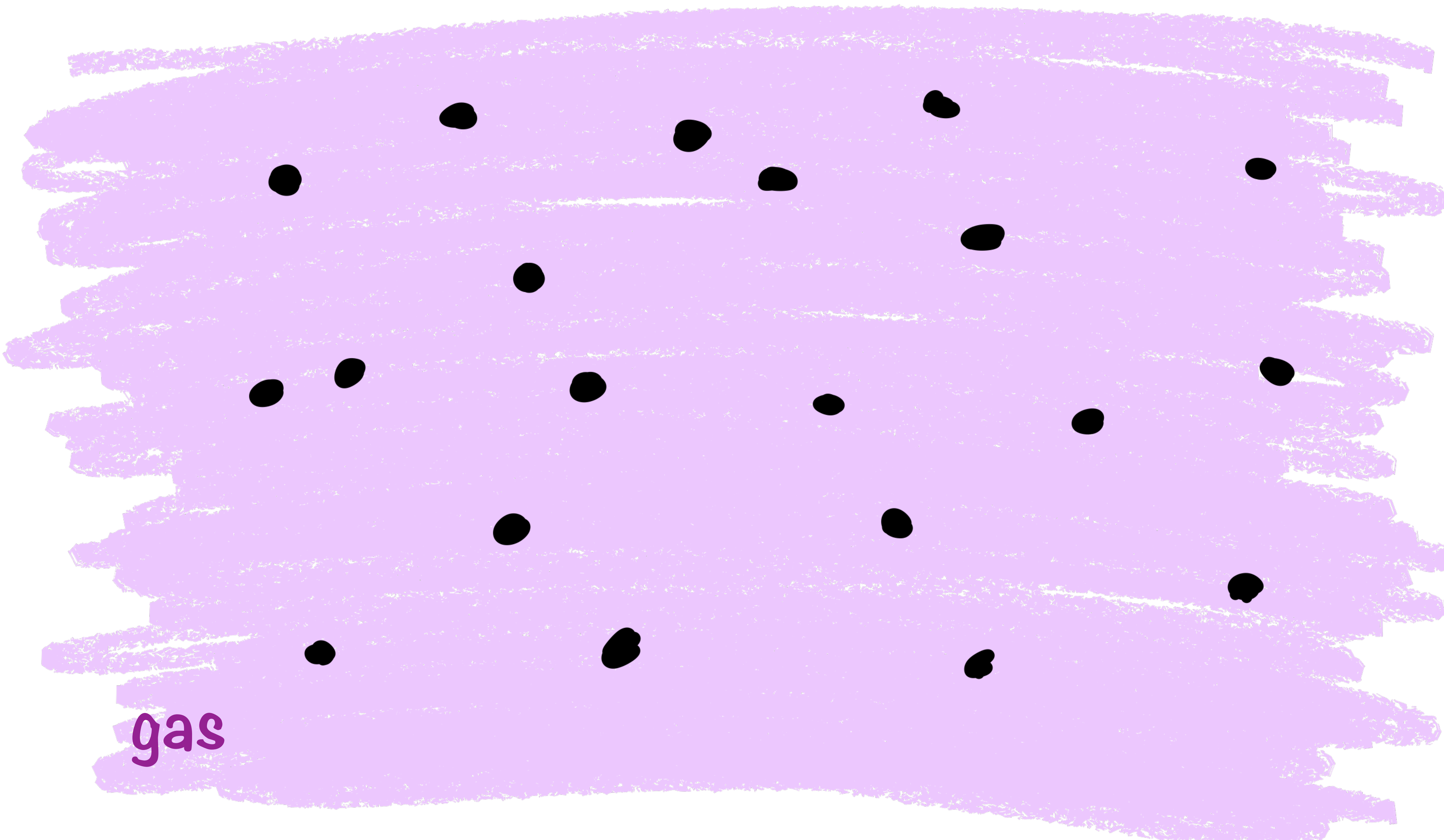

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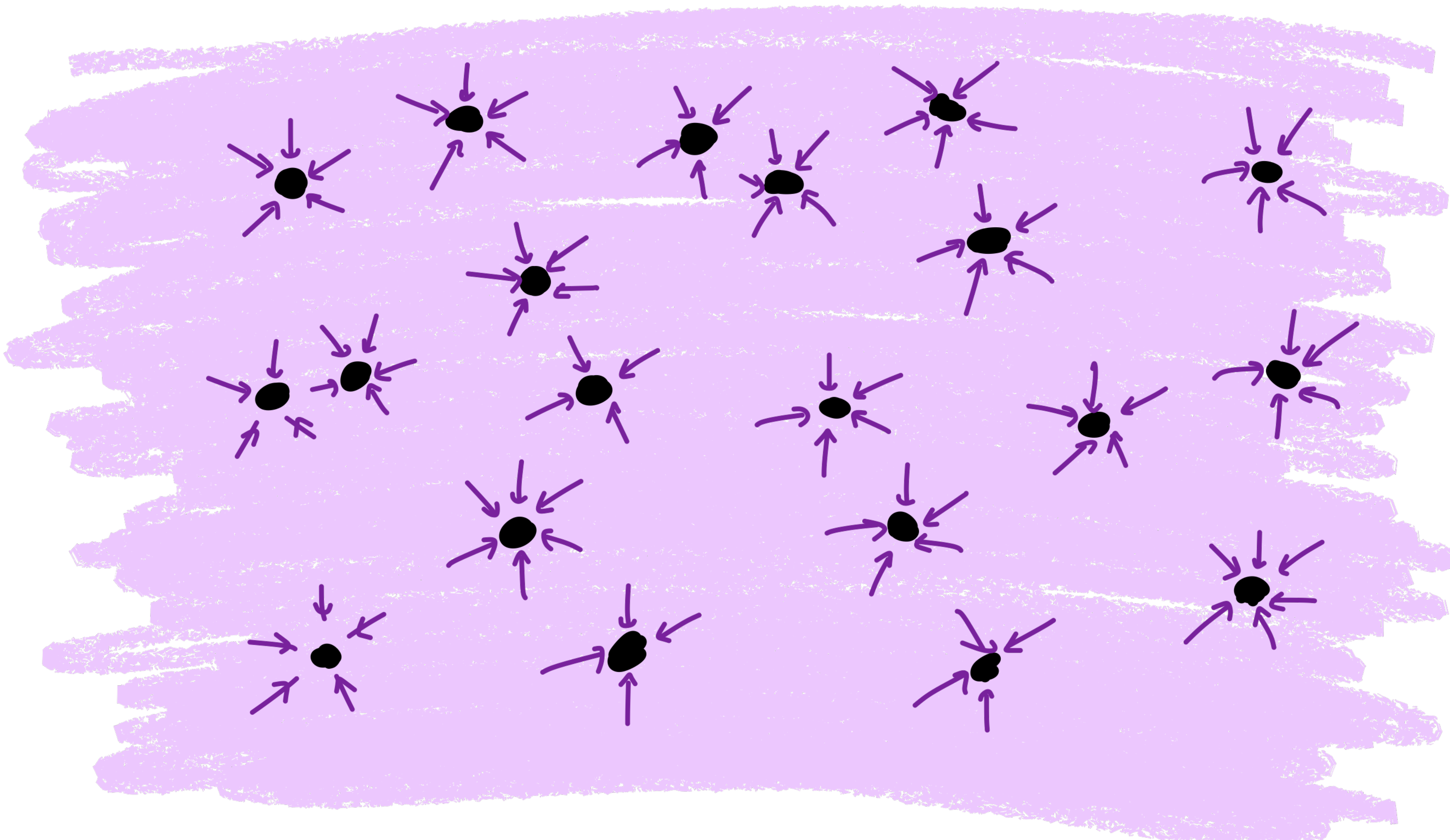

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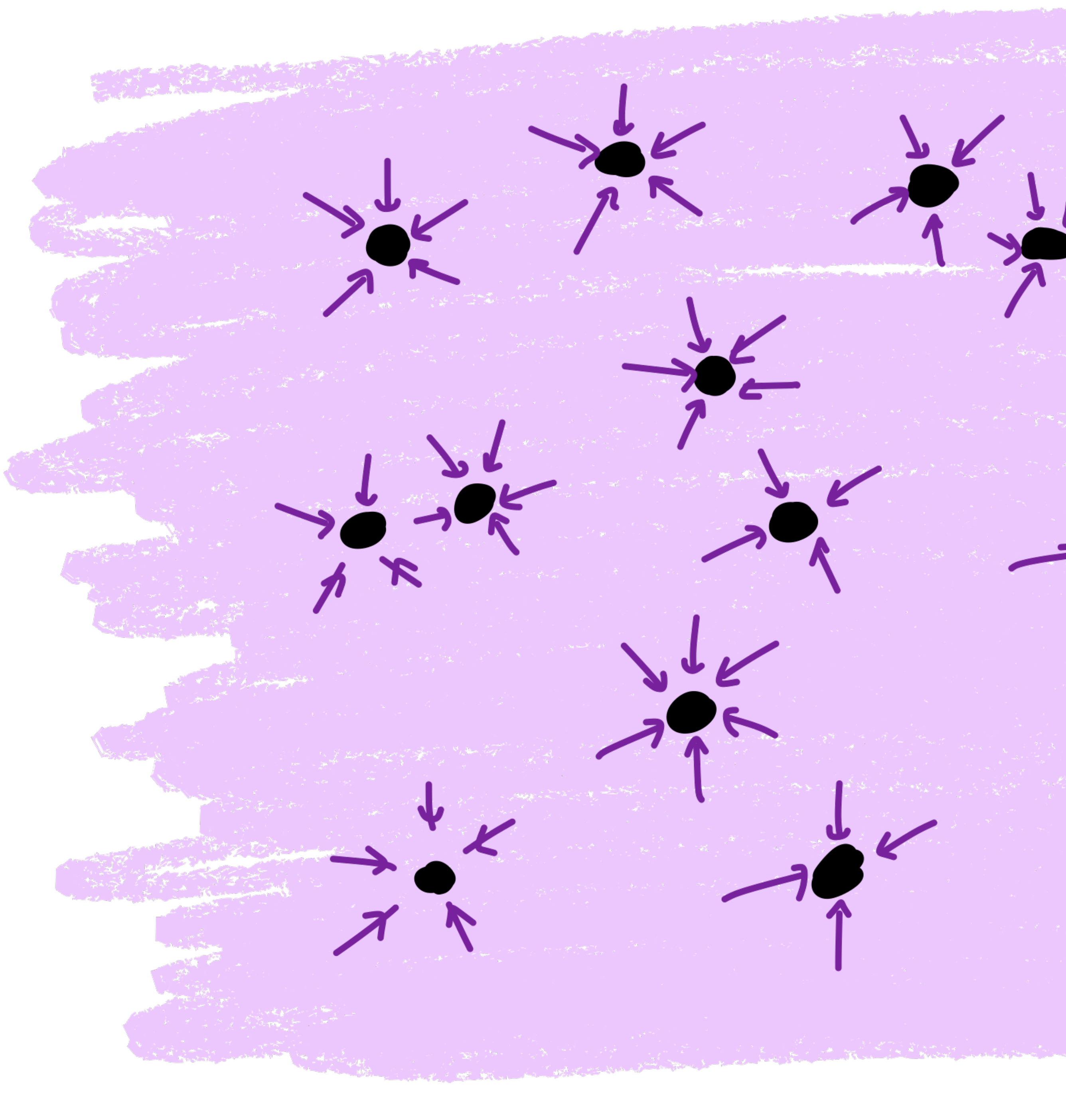
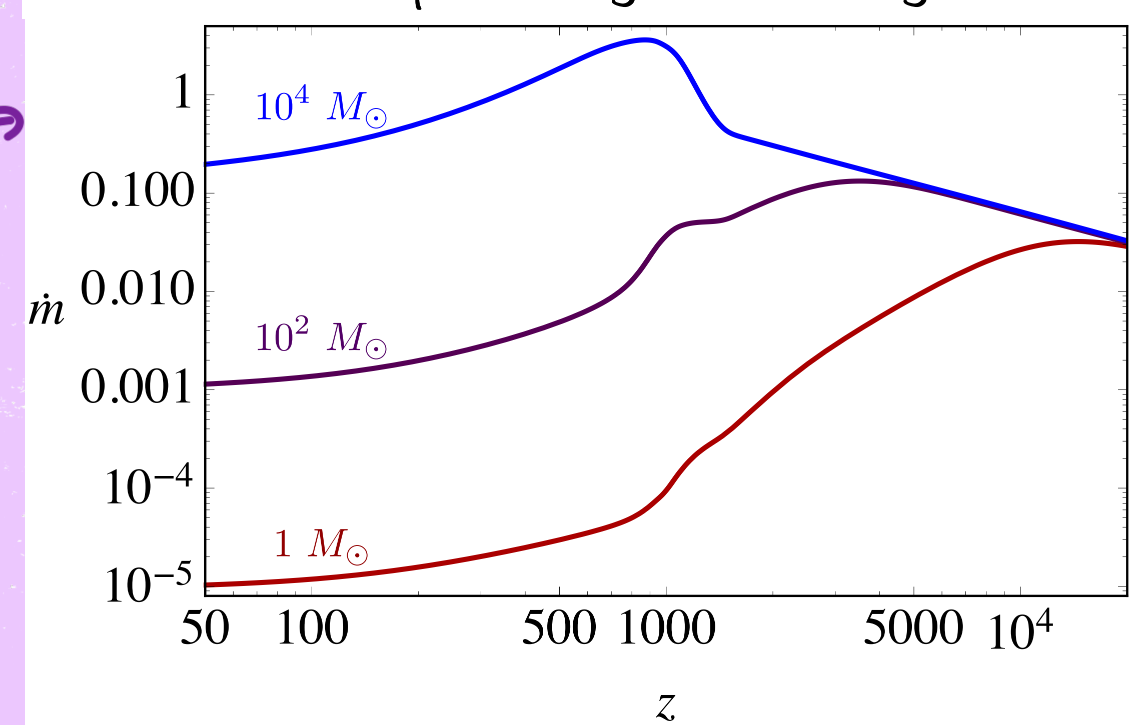


accretion model: Bondi-Hoyle-Lyttleton
+ Compton drag and cooling



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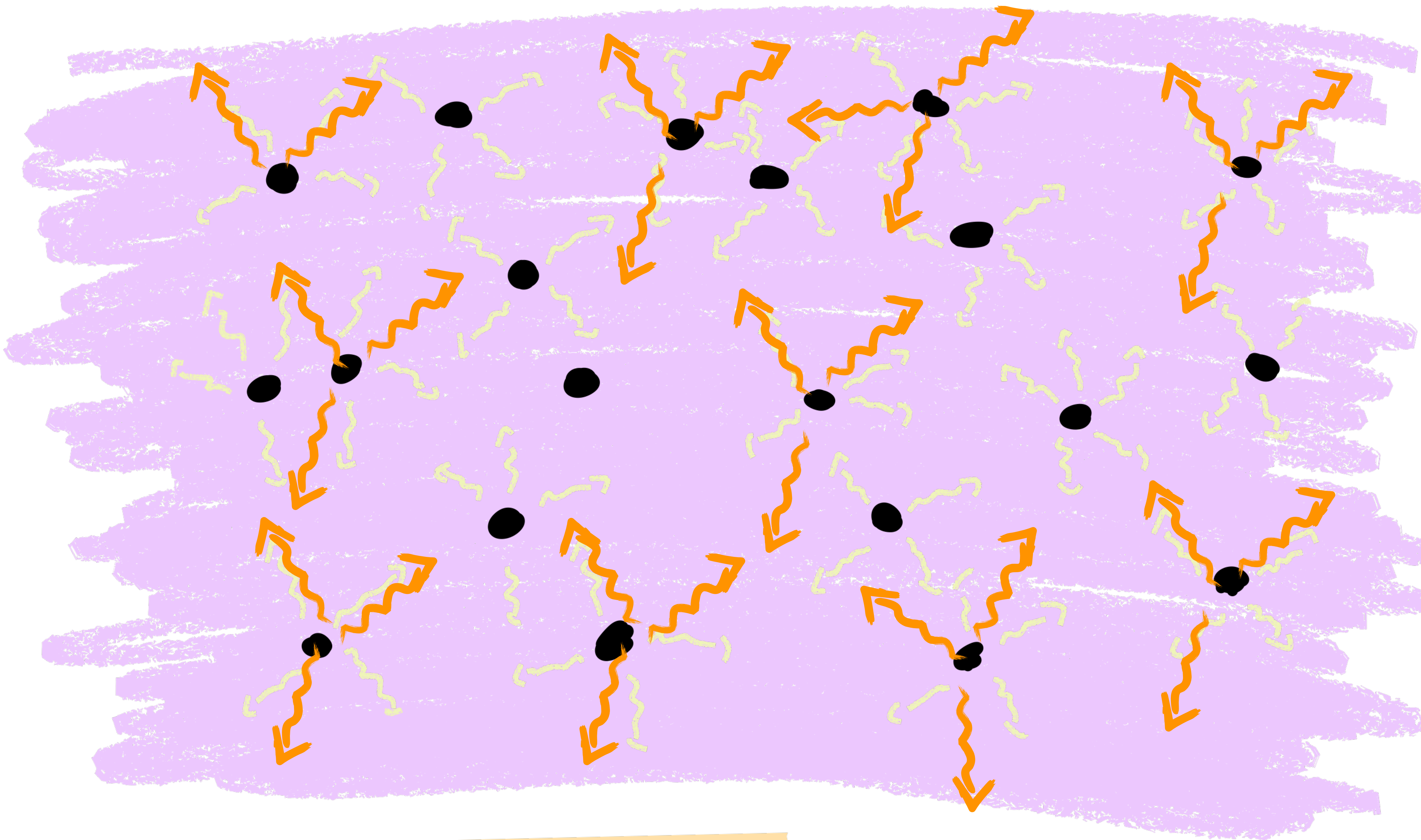

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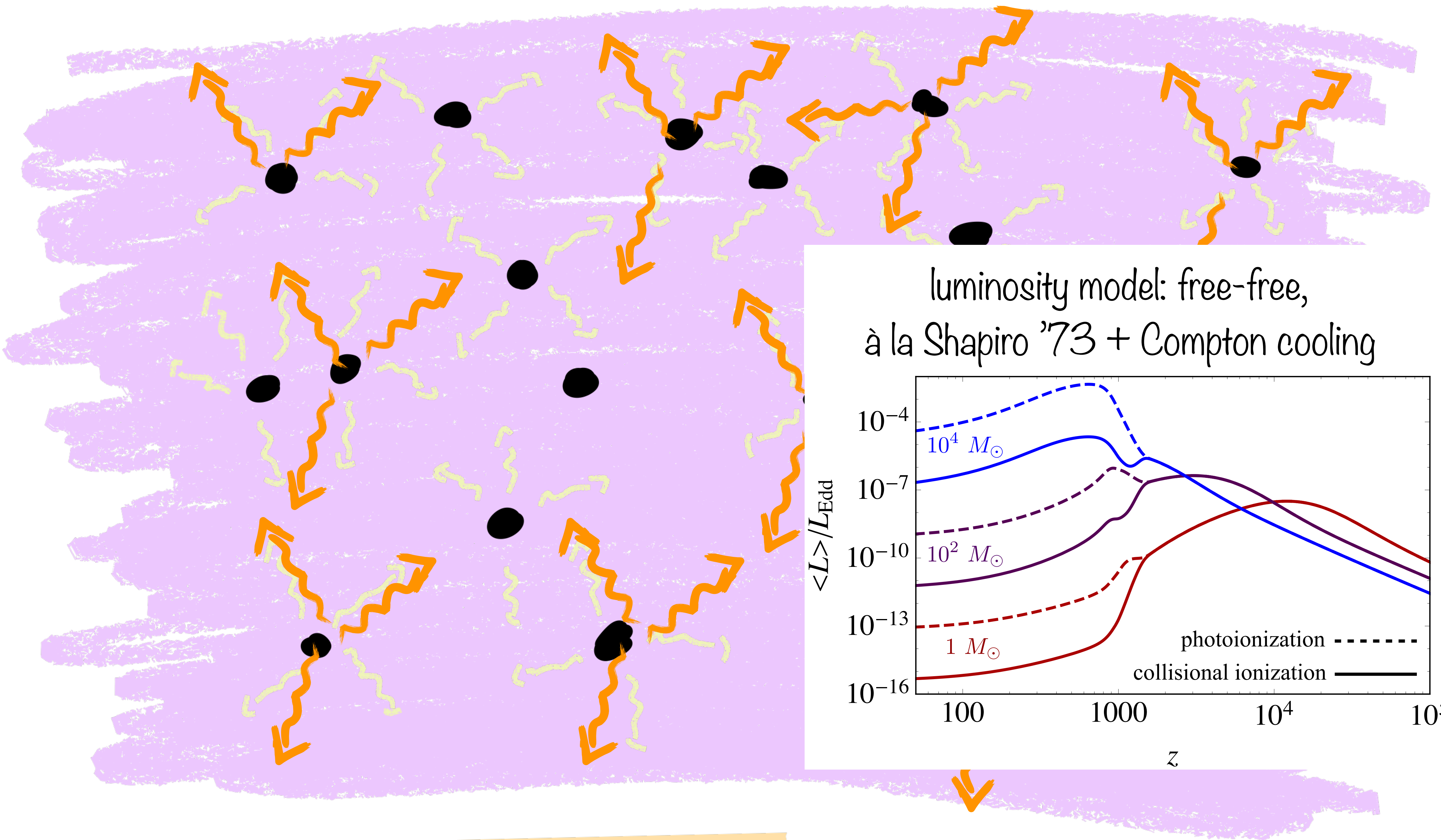

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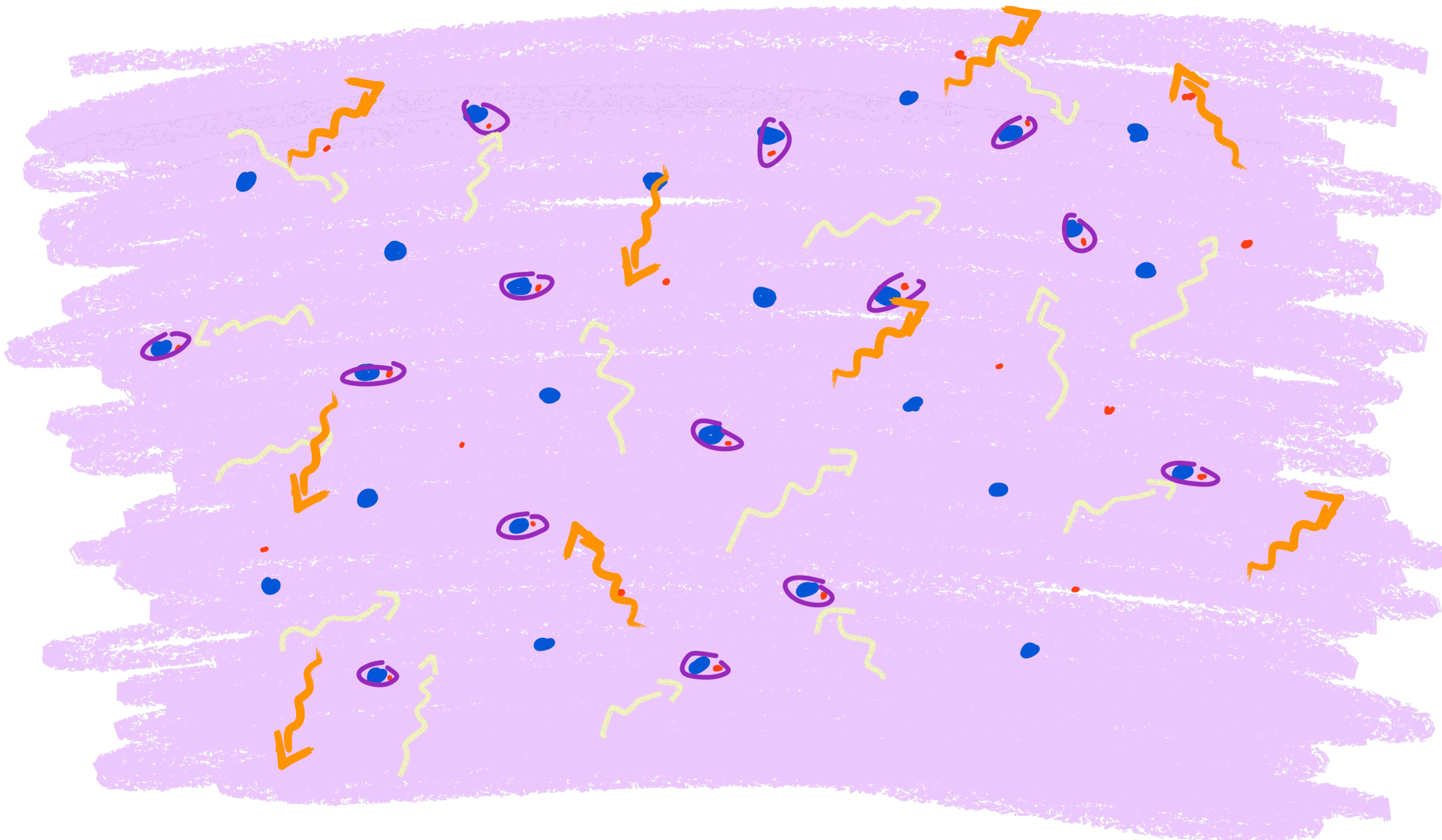

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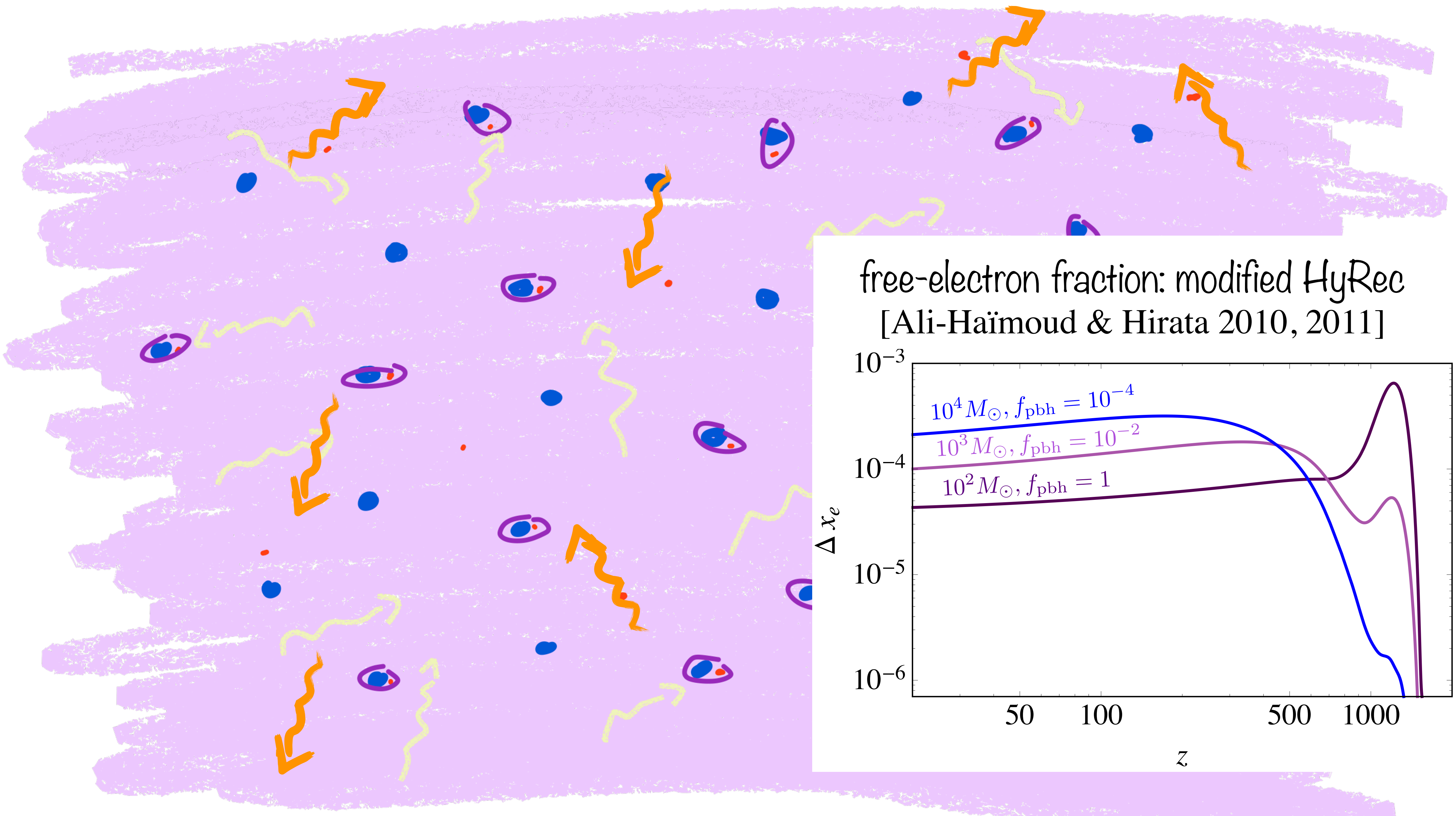
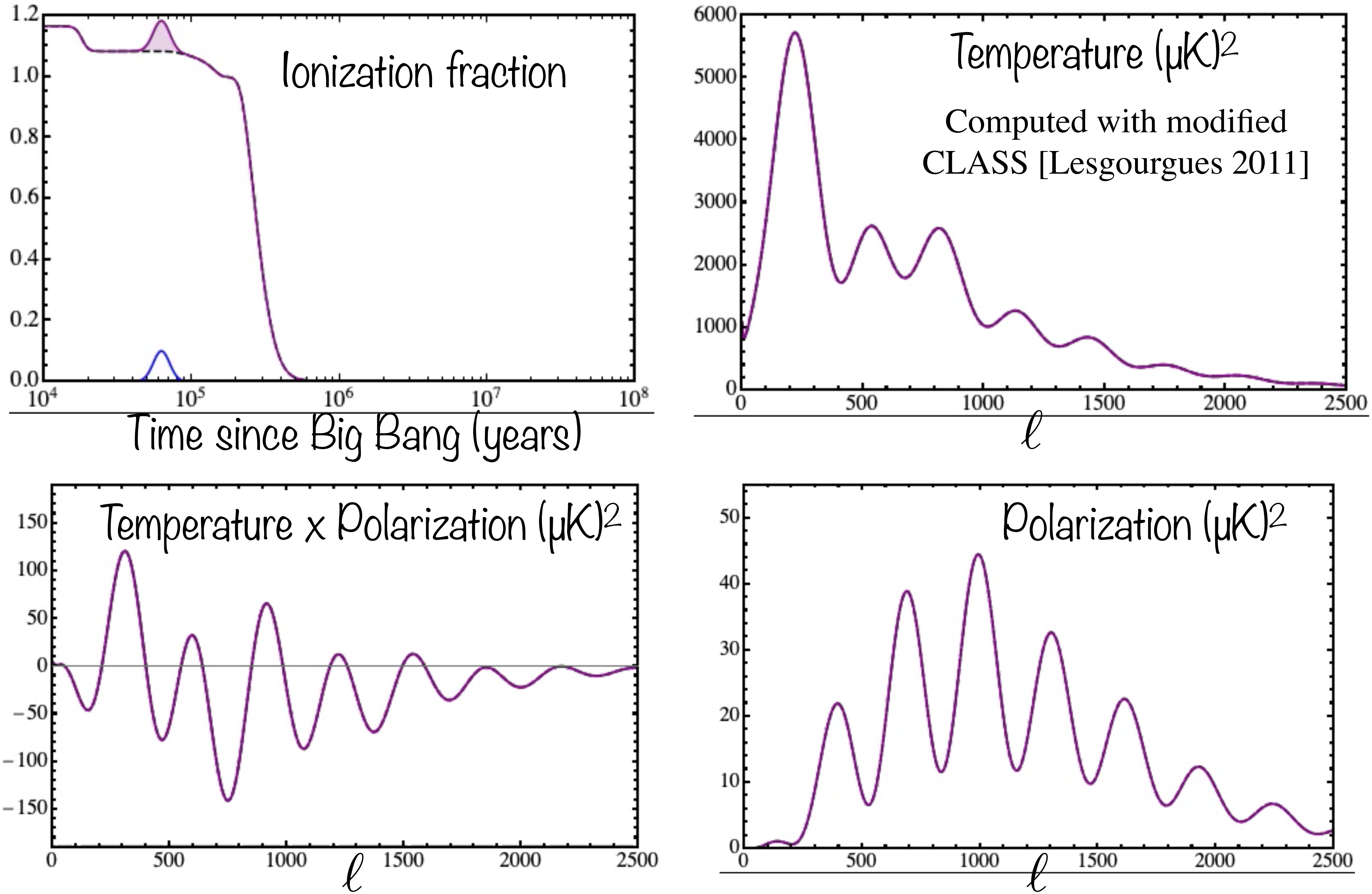


CMB anisotropies are **very sensitive** to the ionization history



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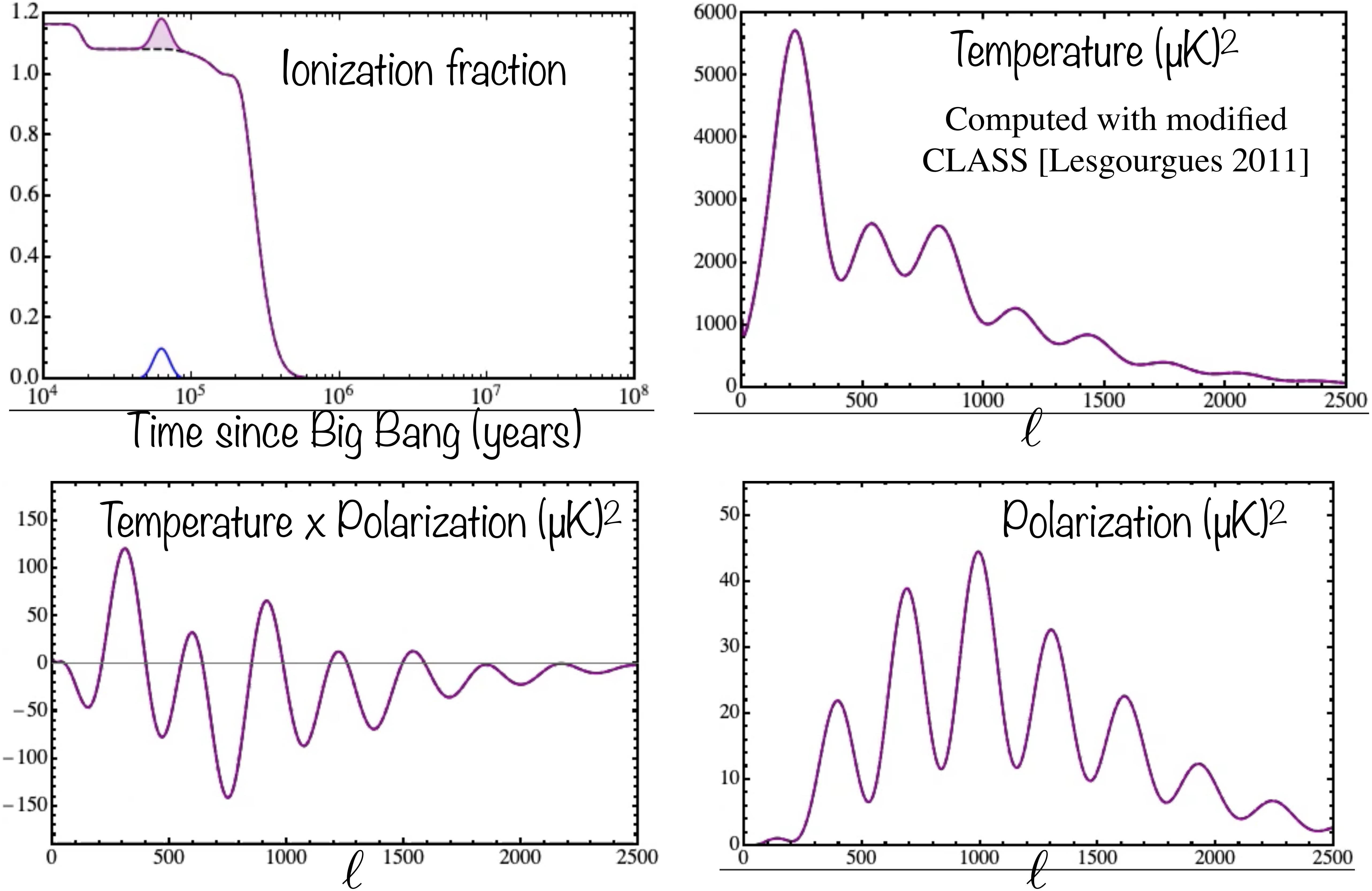
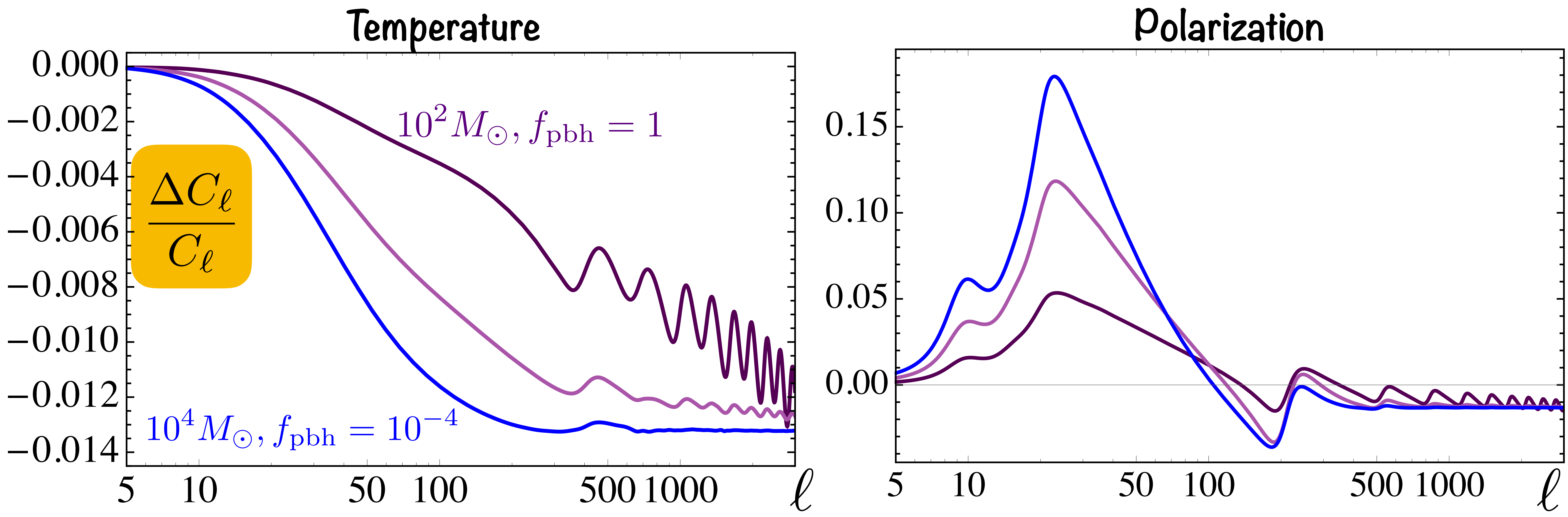


change to CMB power spectra due to accreting PBHs



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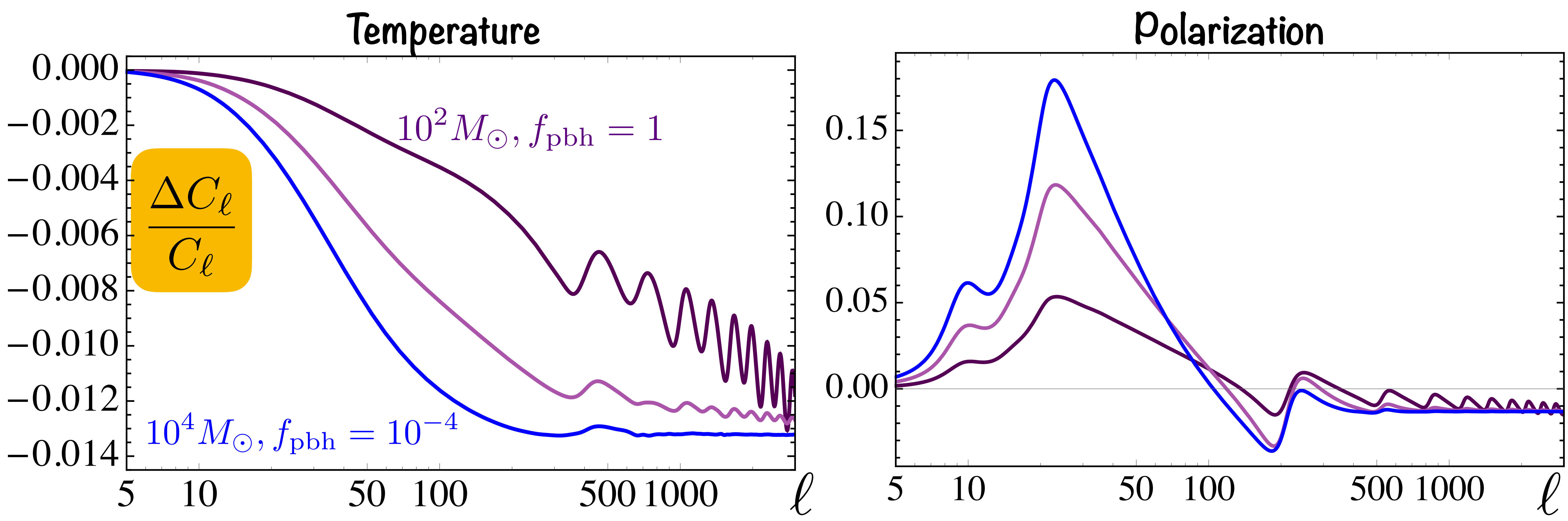

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CMB power spectra imply that primordial black holes

cannot be all the dark matter for black hole mass $\gtrsim$ 100 M_{sun}

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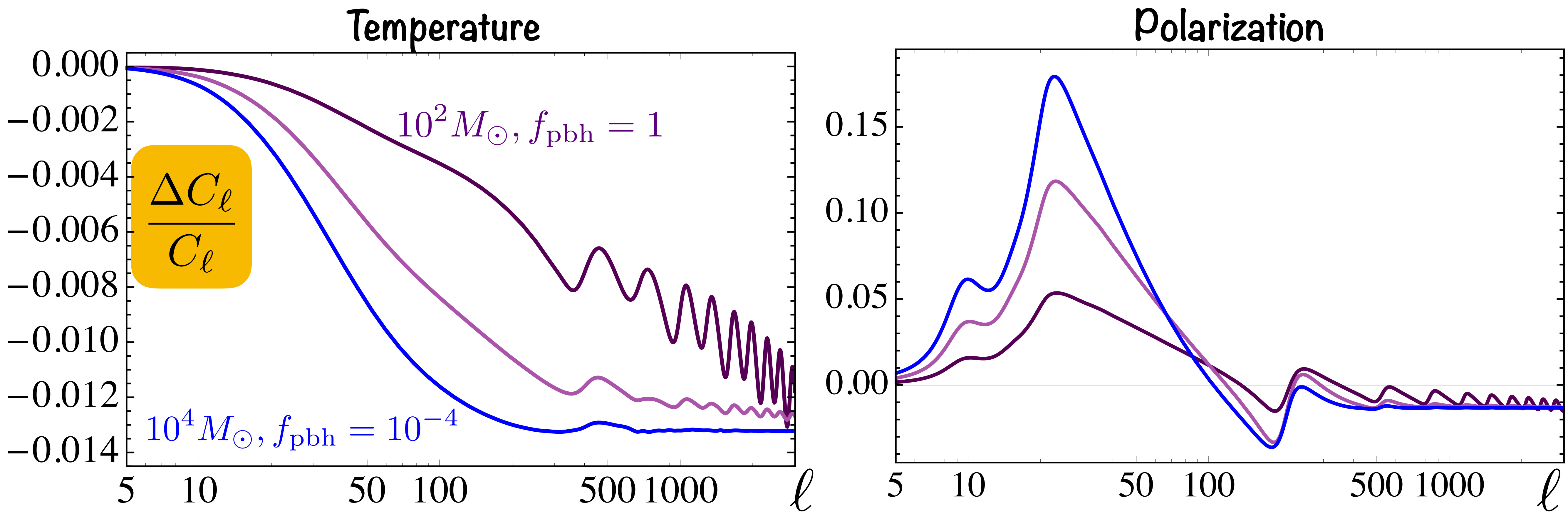

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but there may be more to say from higher-order statistics...

Primordial black holes as GW sources

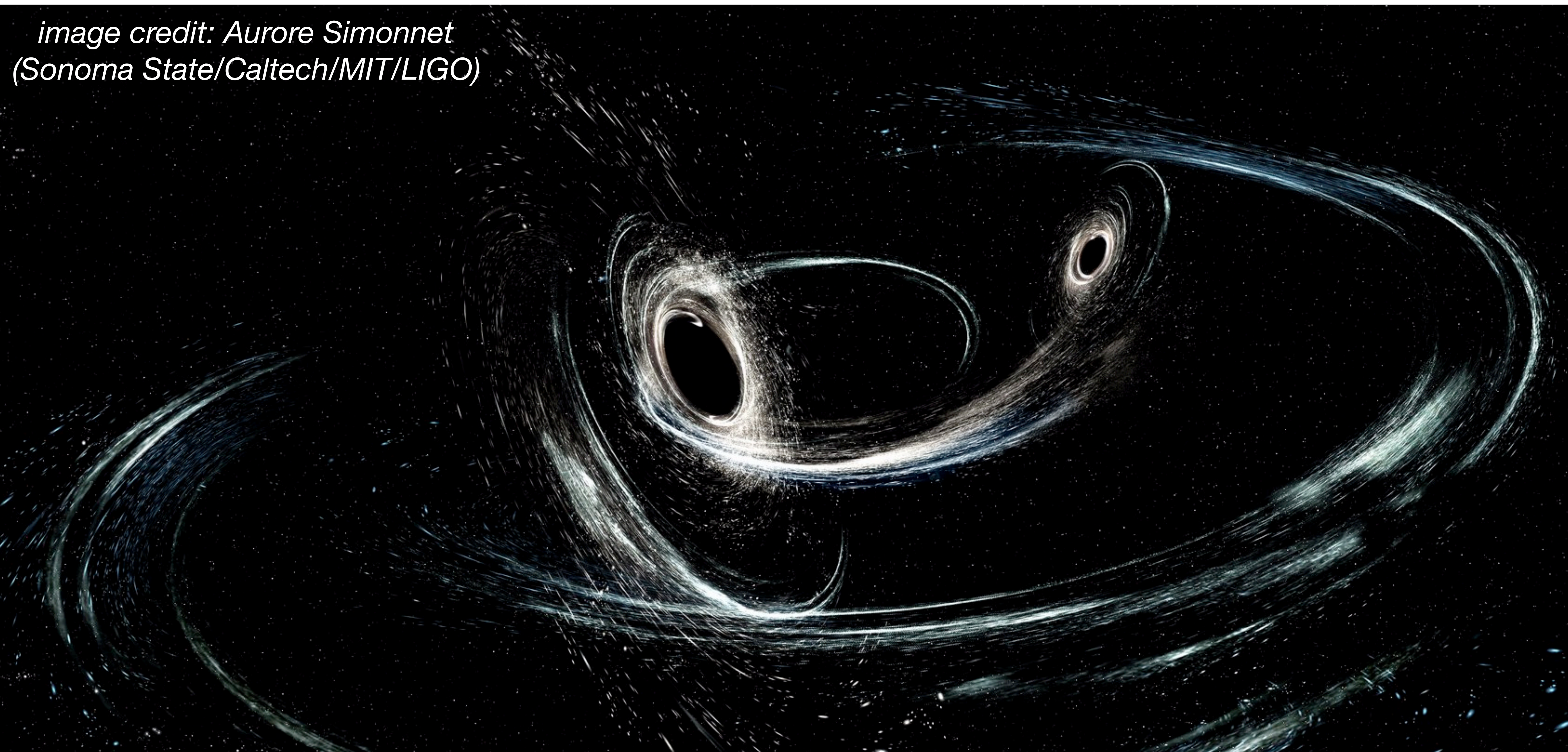


image credit: Aurore Simonnet (Sonoma State/Caltech/MIT/LIGO)

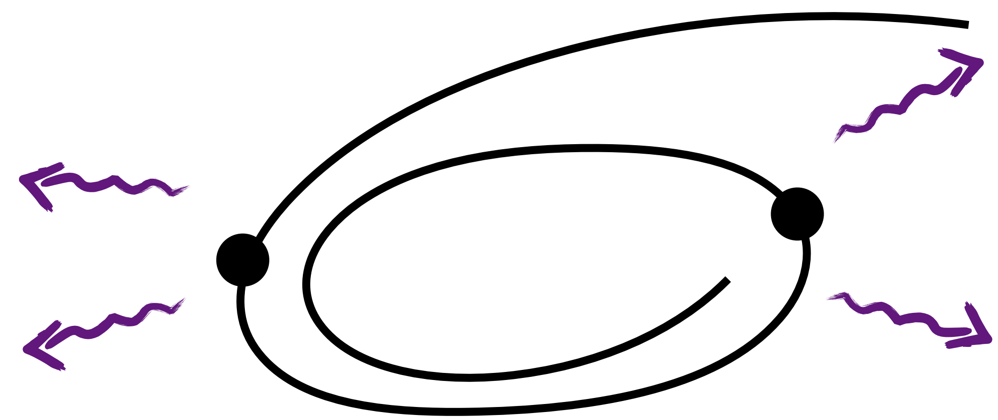
Formation of PBH binaries in the late Universe

Bird et al. 2016, Clesse & Garcia-Bellido 2017

GW-equivalent of radiative recombination

$$\sigma_{\text{capture}} \approx 45\ M^2\ v^{-18/7}$$

Quinlan & Shapiro 1989



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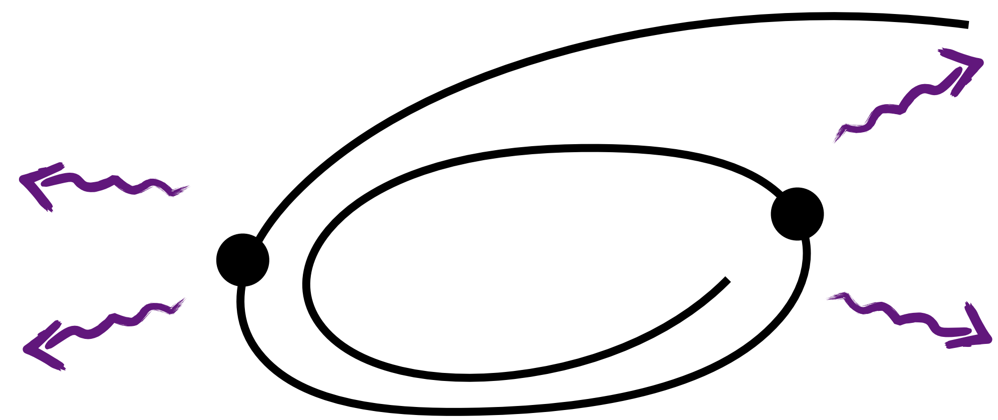

Merger rate per Gpc^3 = n <σ v>$|_{halo}$ x $N_{BH/halo}$ x dN_{halo}/dV

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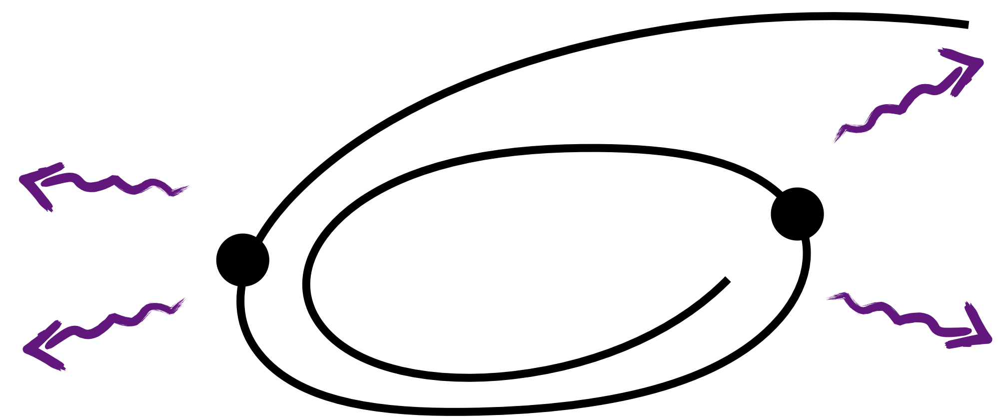

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Merger rate ~ **0.1 - 1 per Gpc^3 per year** if PBHs make all the DM

see also Ali-Haïmoud, Kovetz & Kamionkowski 2017

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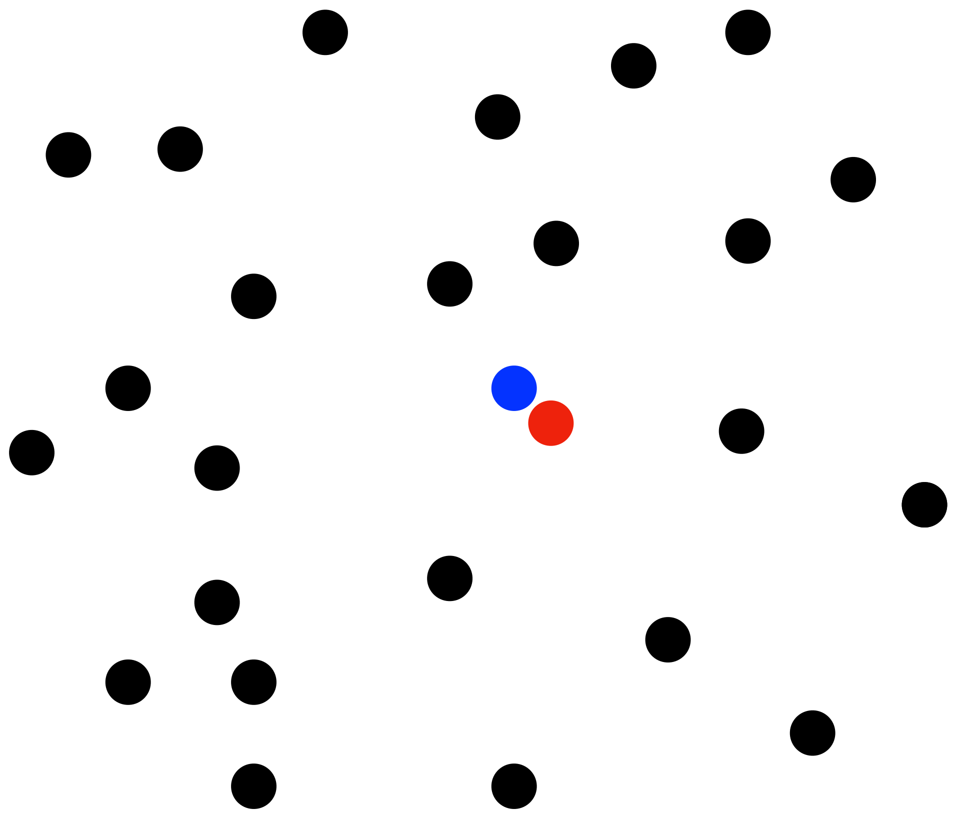

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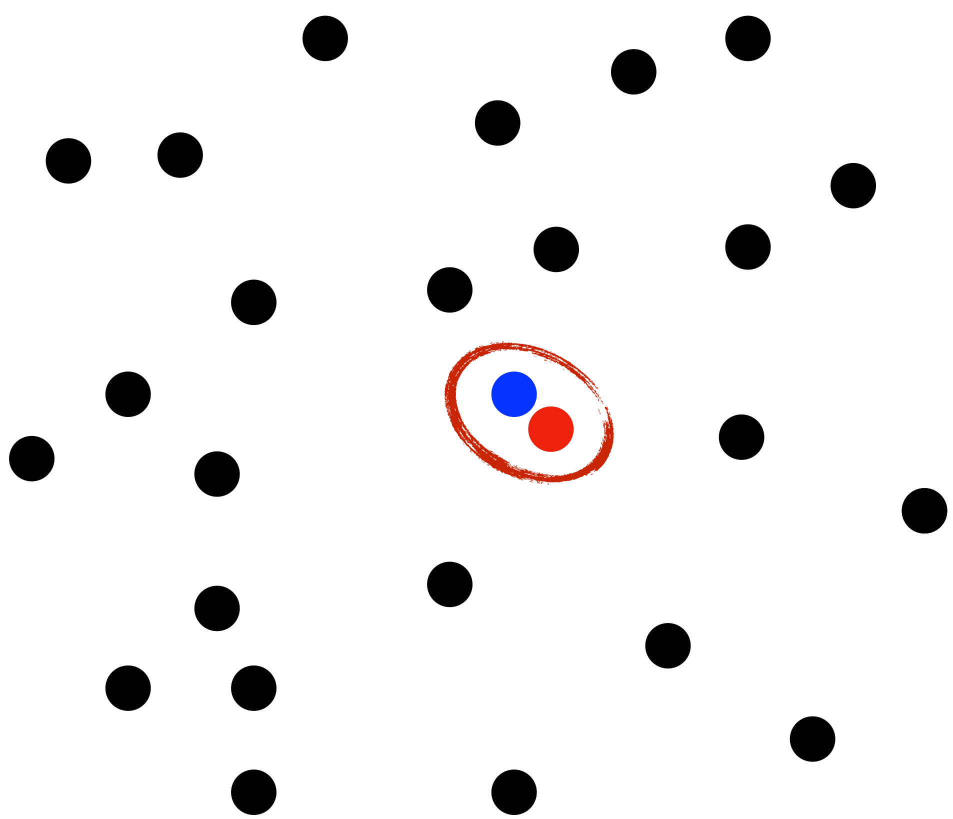

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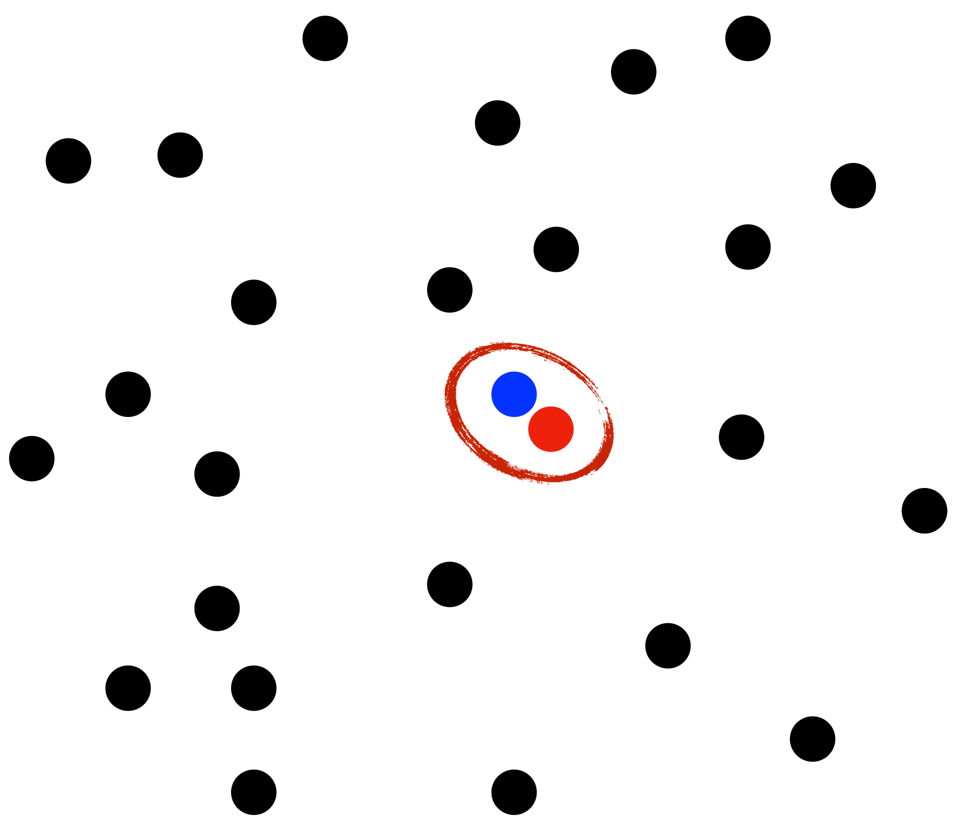

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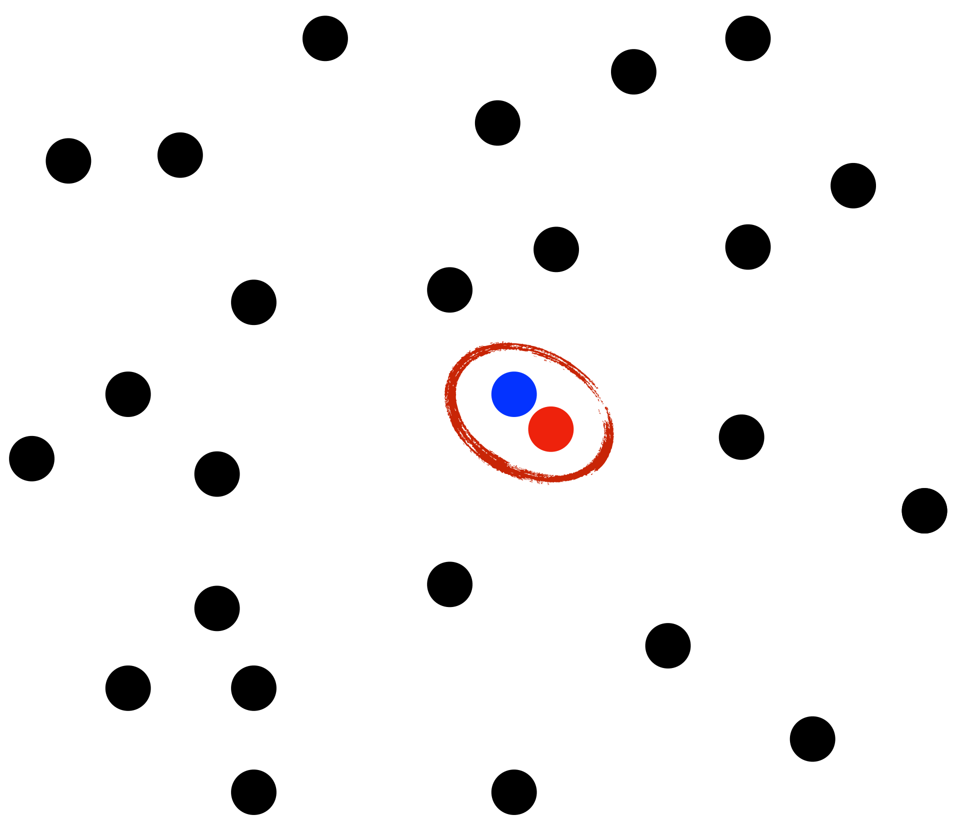

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Inspiral through GW radiation, merge throughout cosmic history, including today

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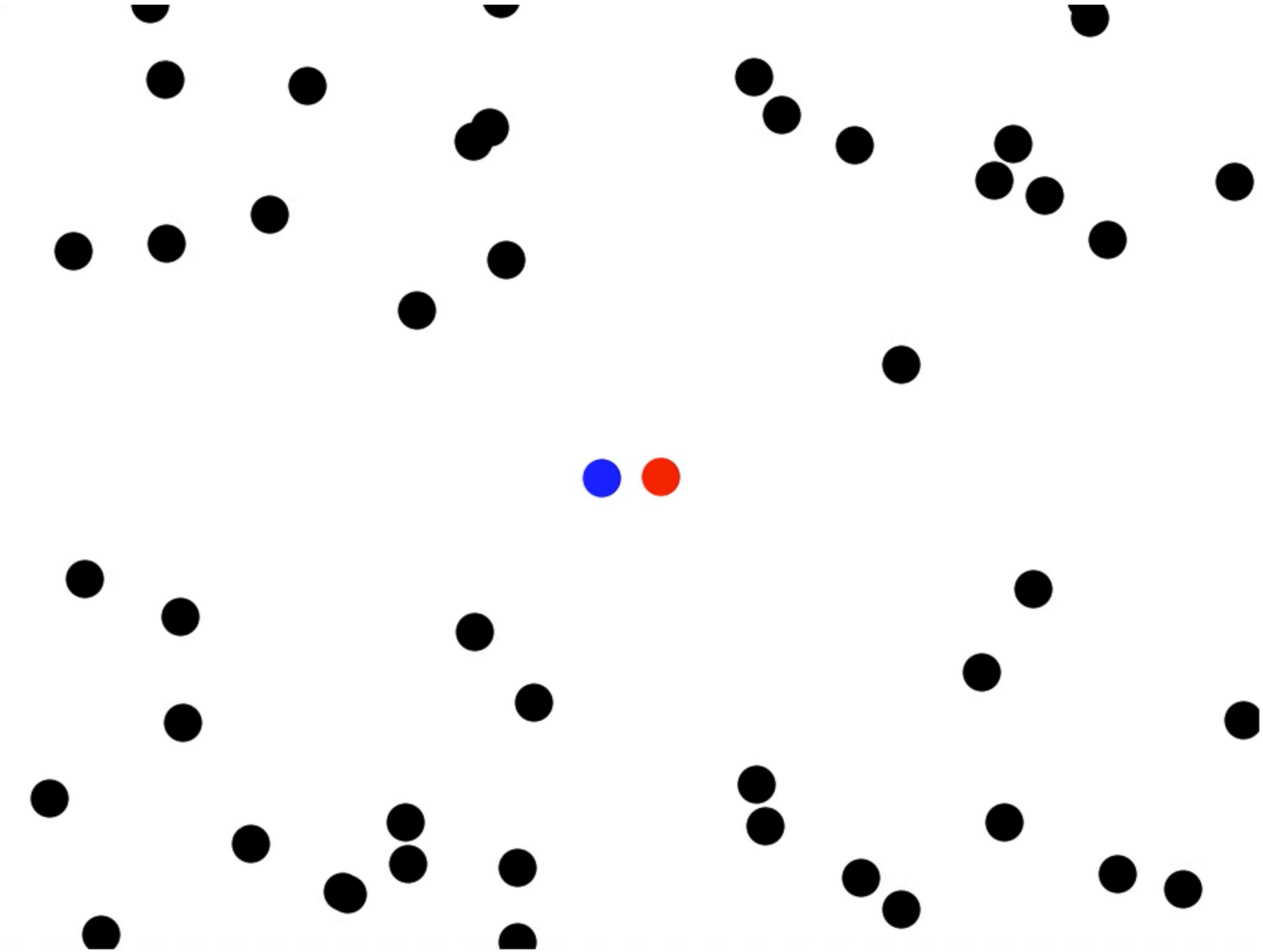

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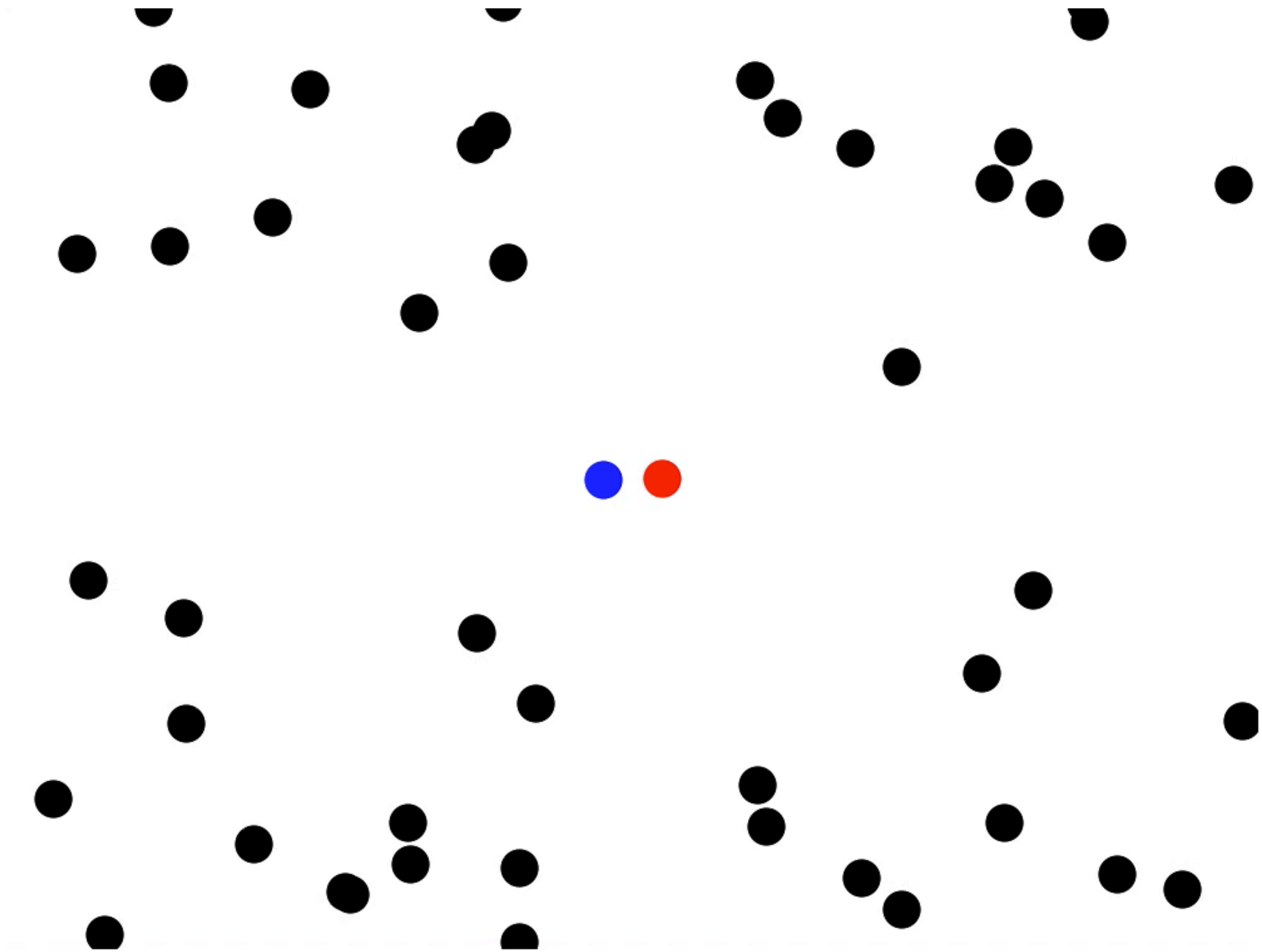

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- **Given initial spatial distribution of PBHs**

Effectively random (Poisson) on the scales of interest

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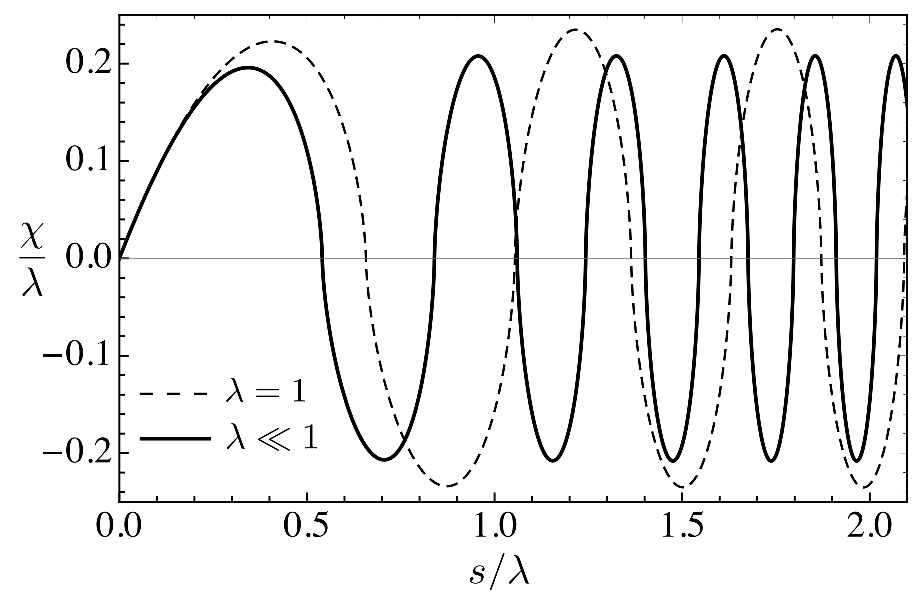

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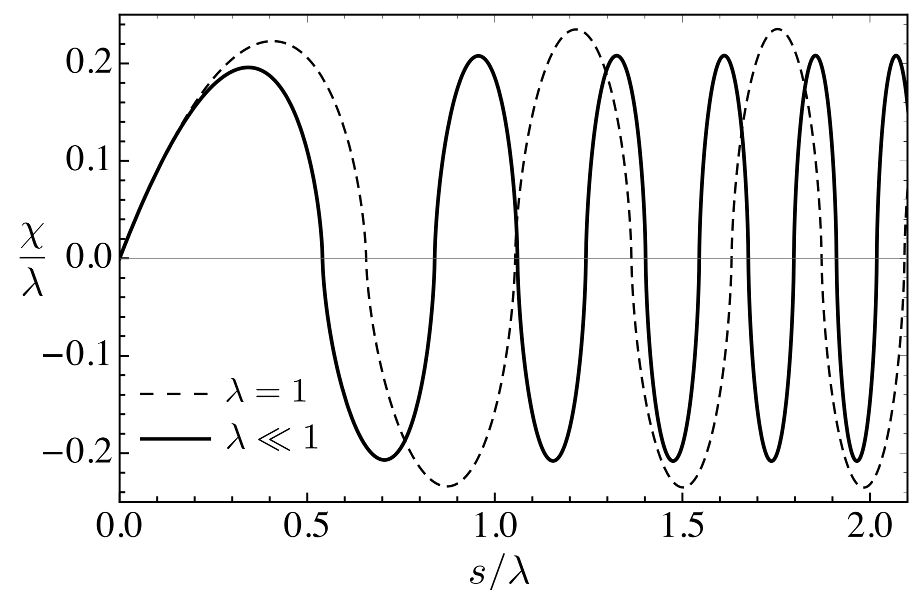

- **Get distribution of initial angular momentum / eccentricity**

  Compute torque by other PBHs (assumed fixed) + linear tidal field

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- from P(a, e), get distribution of merger time

$$t_{\rm merge} = \frac{3}{170}\frac{a^4}{M^3}(1-e^2)^{7/2}$$

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- Get merger rate at present time (more constraining)

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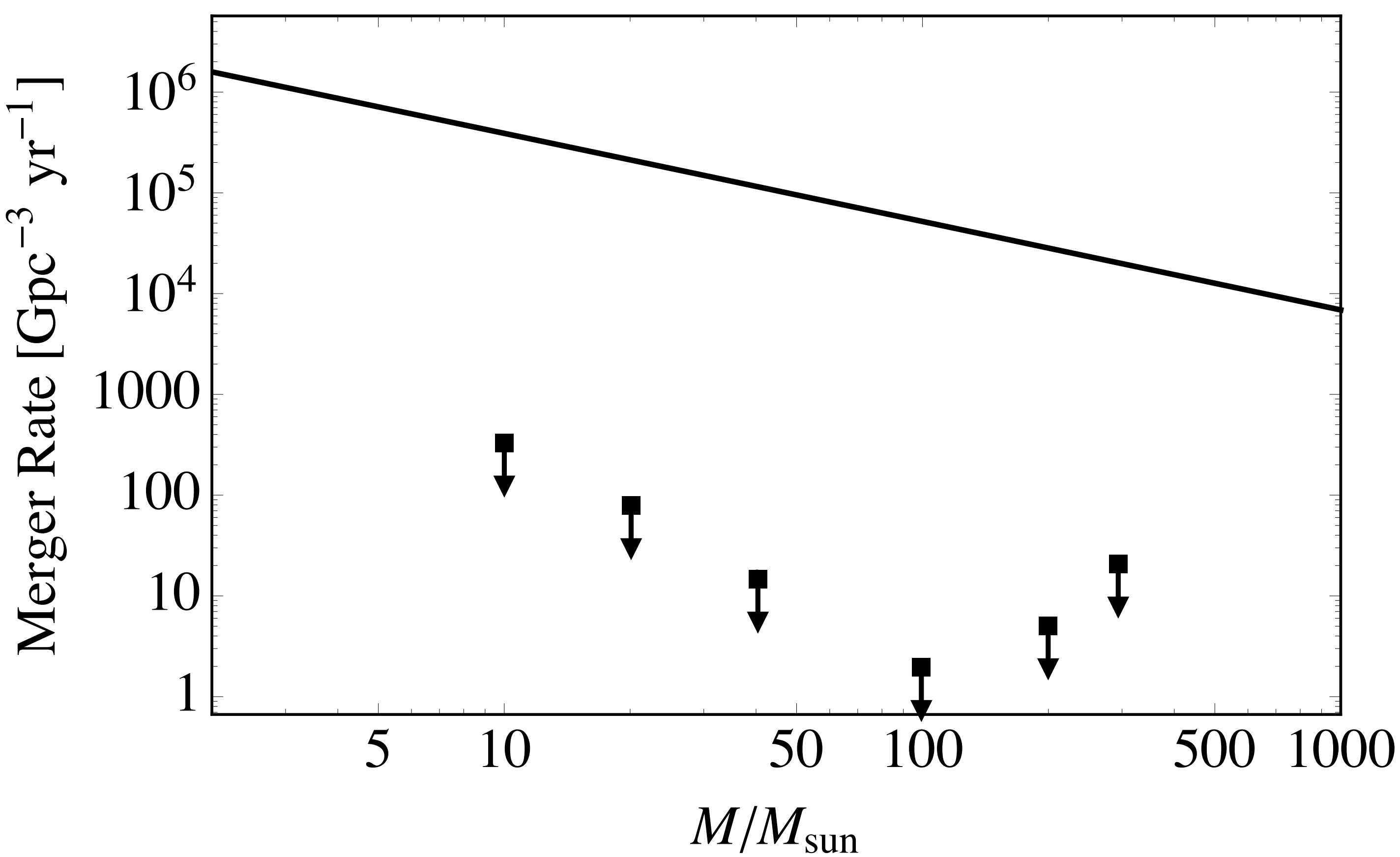
merger rate for 100% of DM in PBHs



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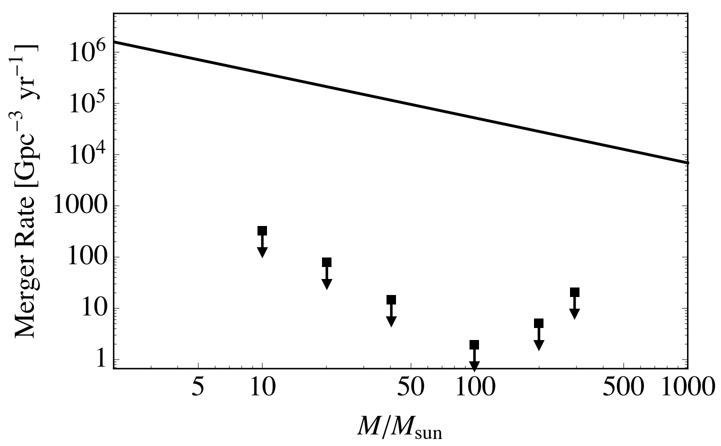
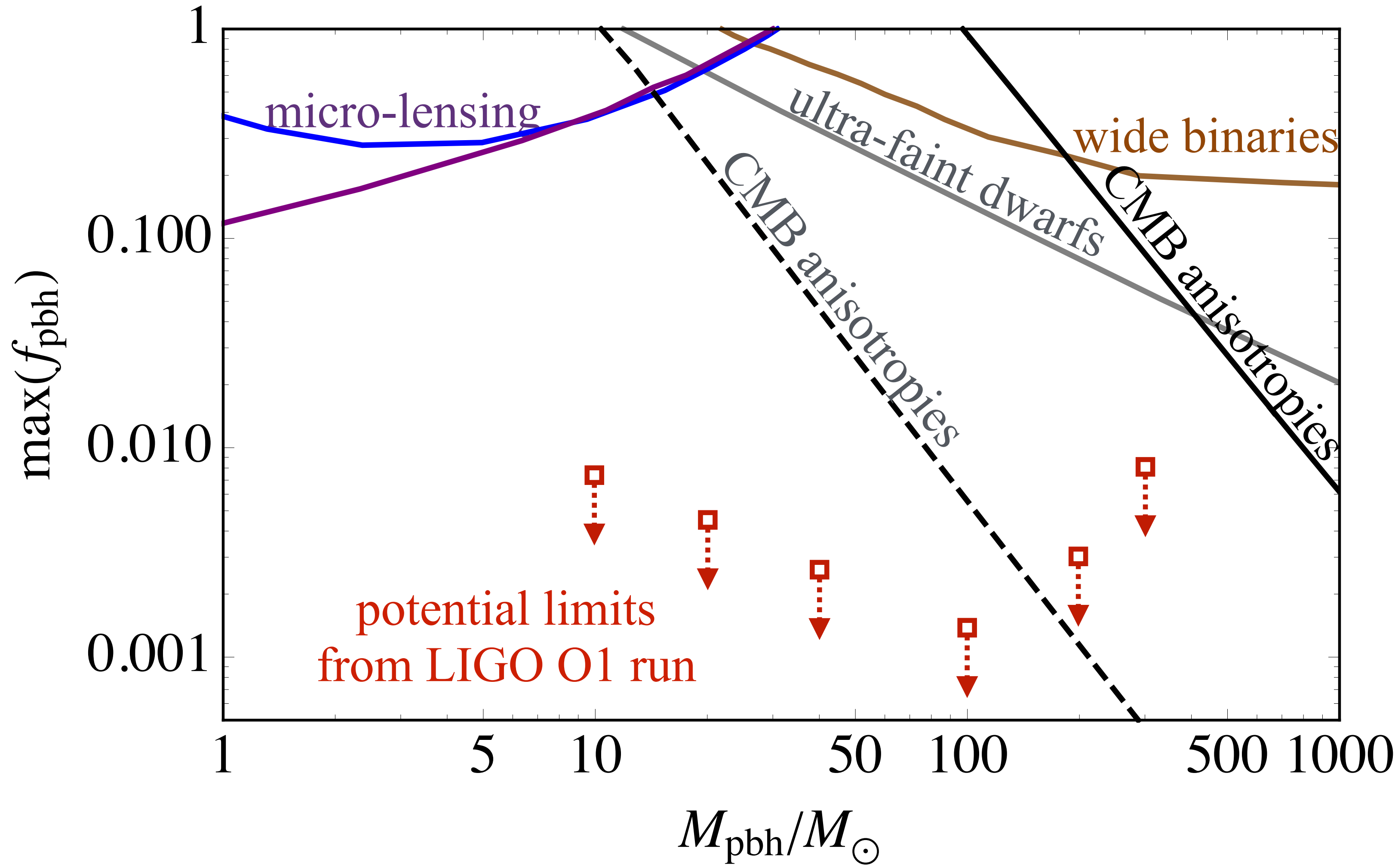


=> upper limits



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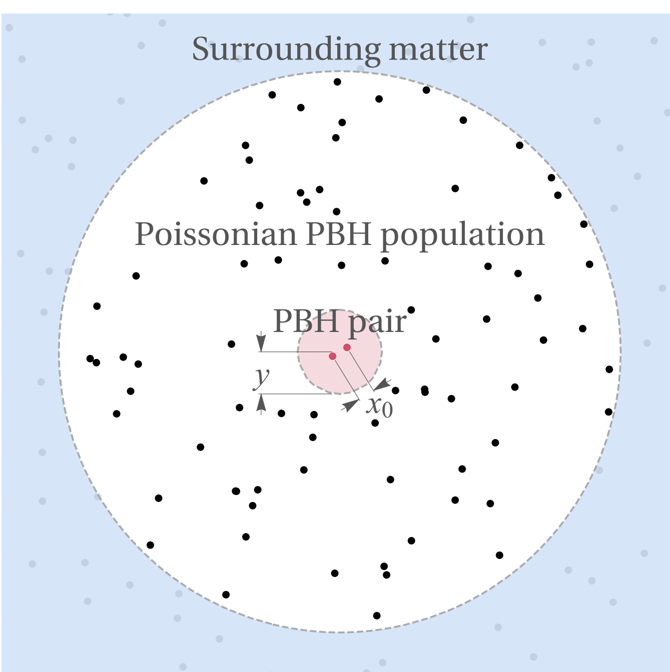

Raidal et al. 2019: 70-body simulations til $z = 1000$

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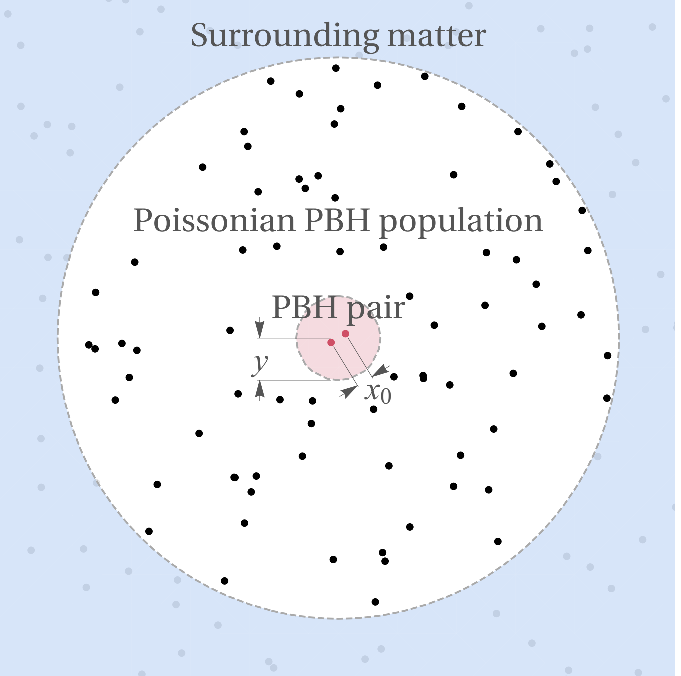

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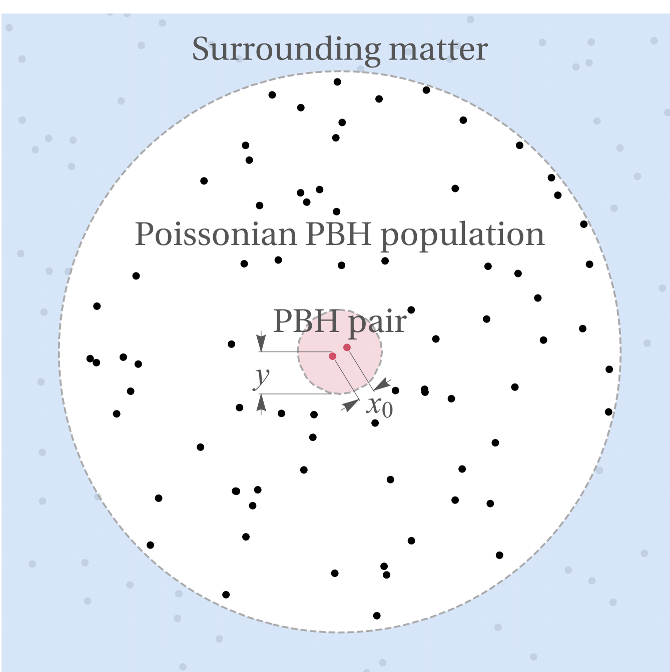

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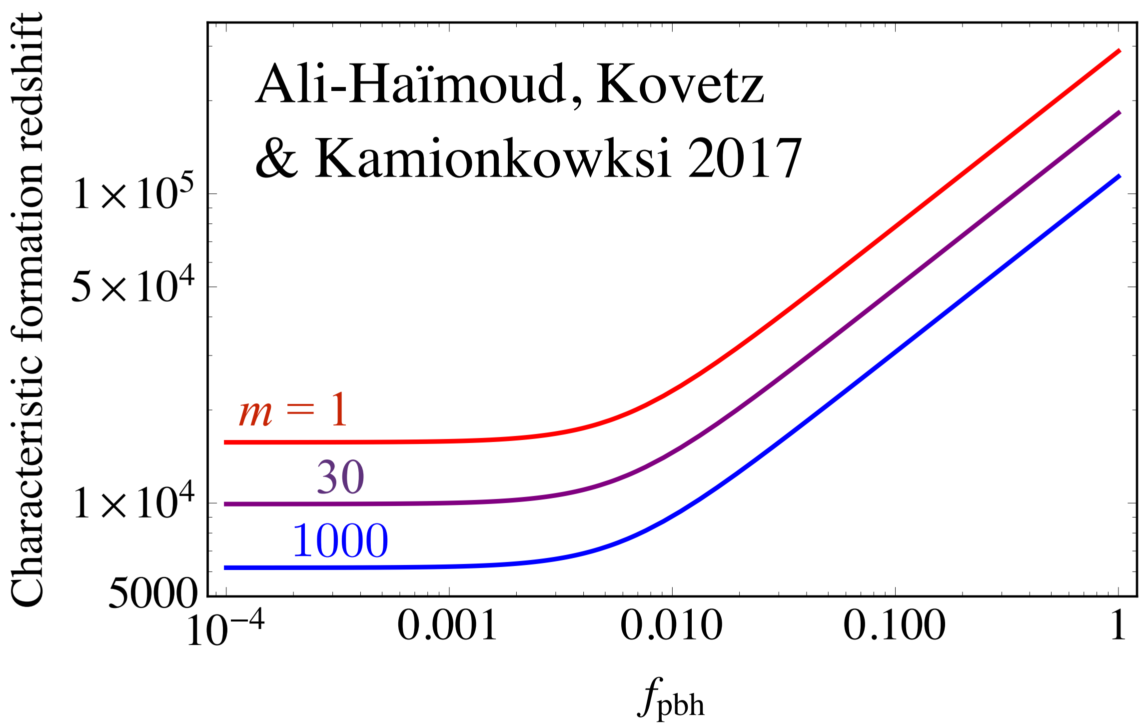
for $f_{pbh} \gtrsim 10\%$, typical initial separation of binaries merging today not very small relative to mean separation

- Are binaries significantly disturbed between formation and merger?



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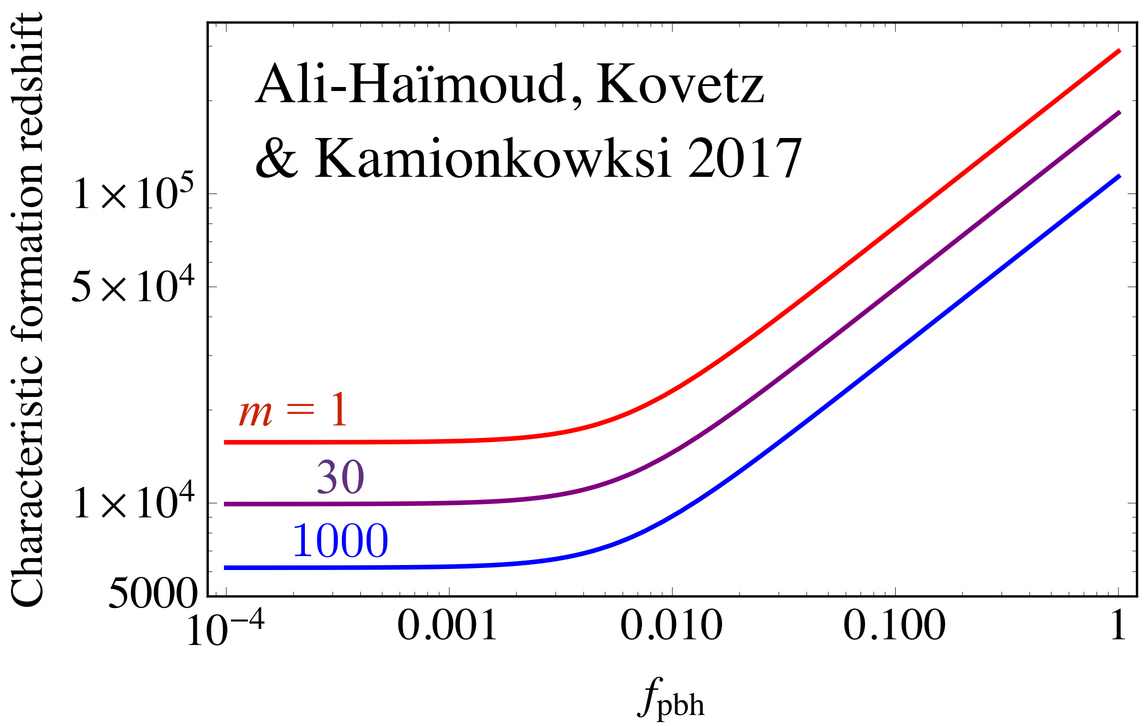
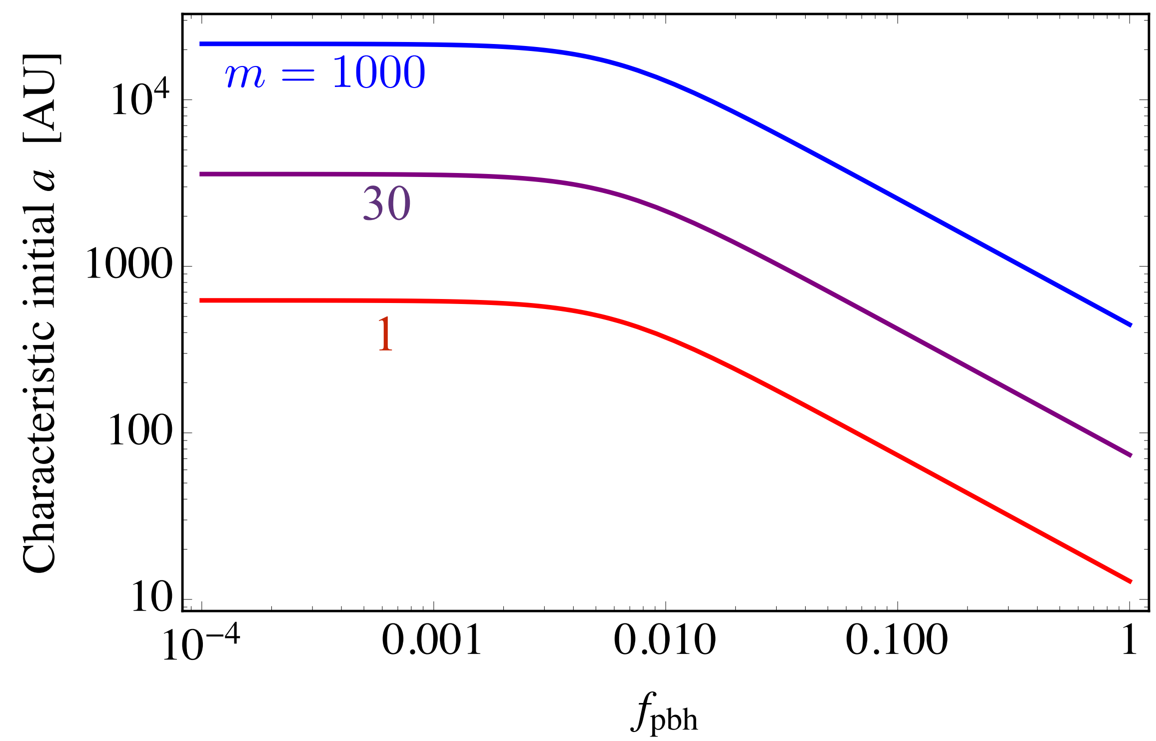
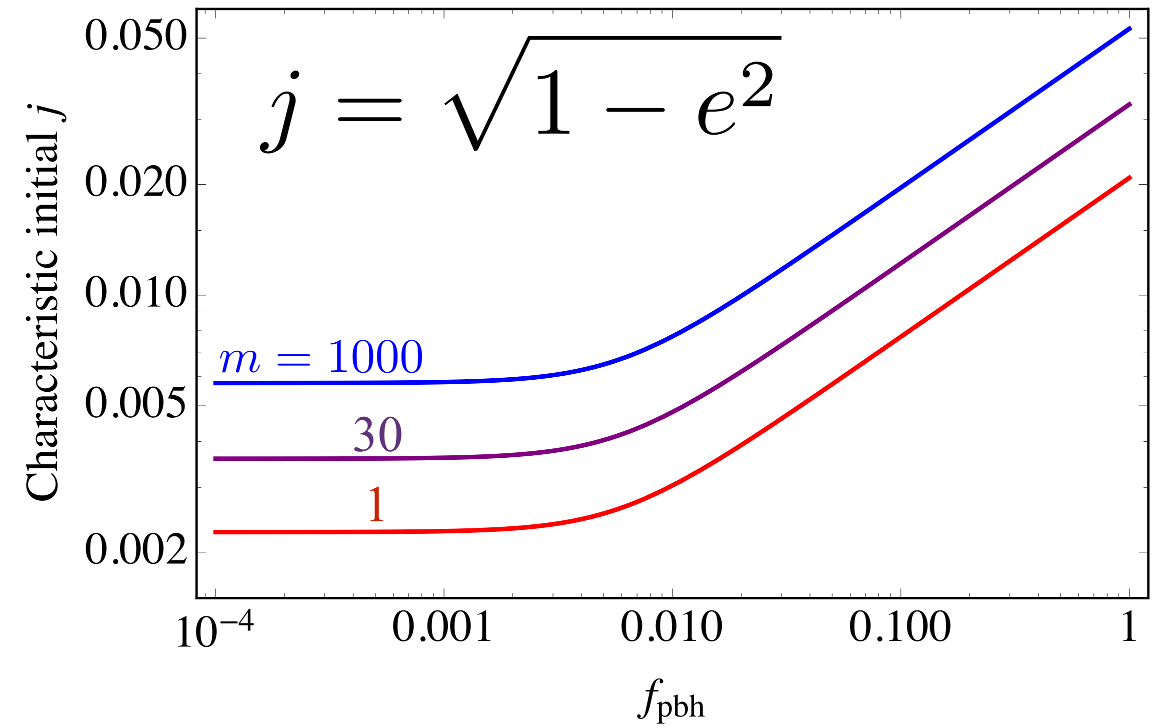
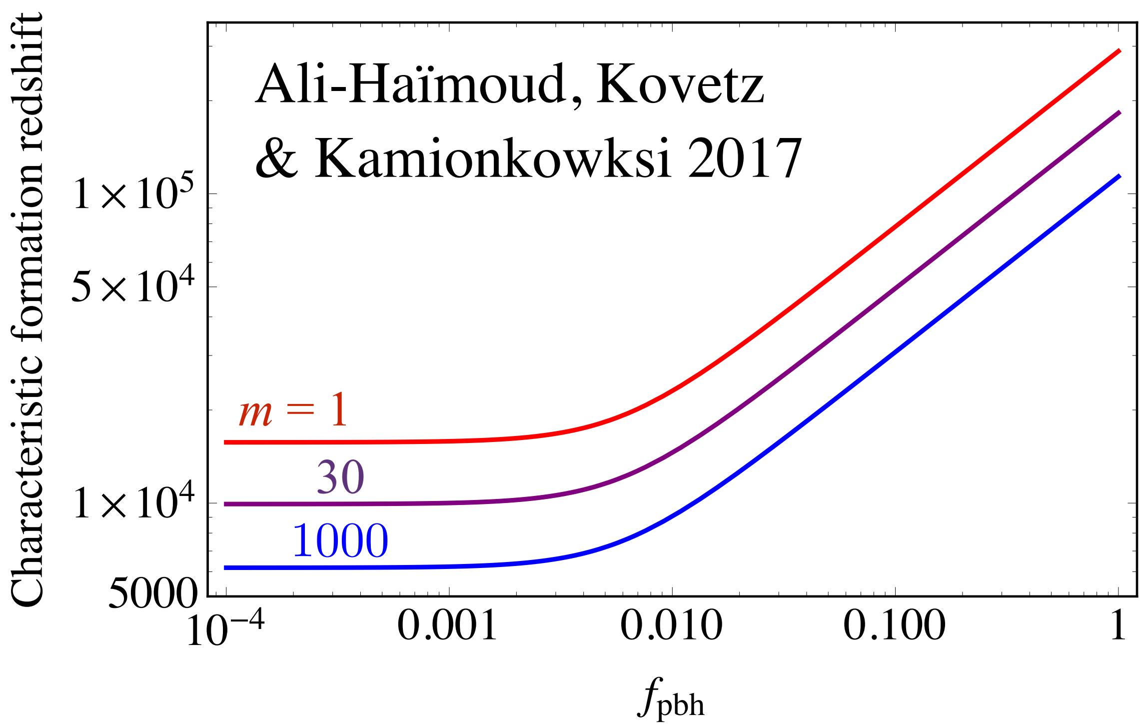
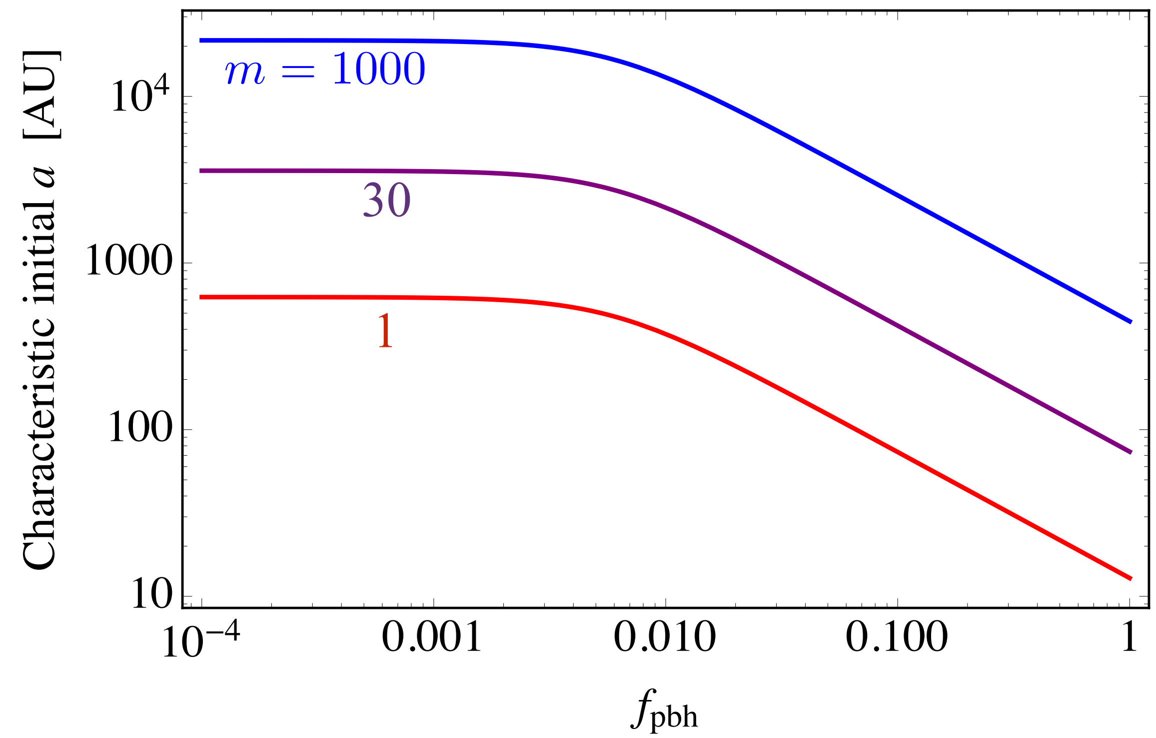


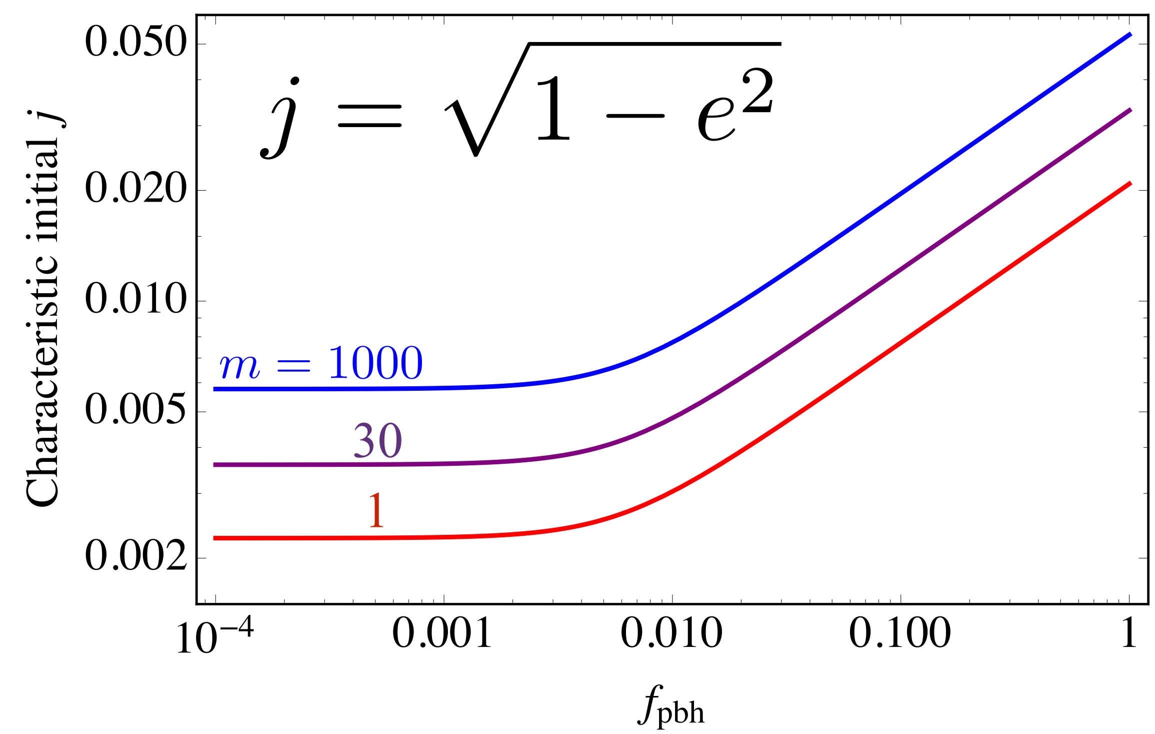




• Are binaries significantly disturbed between formation and merger?







Typical PBH binaries initially highly eccentric, easy to torque

➡ Can circumbinary accretion significantly torque PBH binaries?

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At some point Bondi radius > binary separation [Hayasaki et al. 2016]

We estimated $\frac{\dot{a}}{a} \sim \frac{dj}{dt} \sim -\frac{\dot{M}}{M}$ and $\int dt \frac{\dot{M}}{M} \sim 10^{-5} \frac{M}{M_\odot}$

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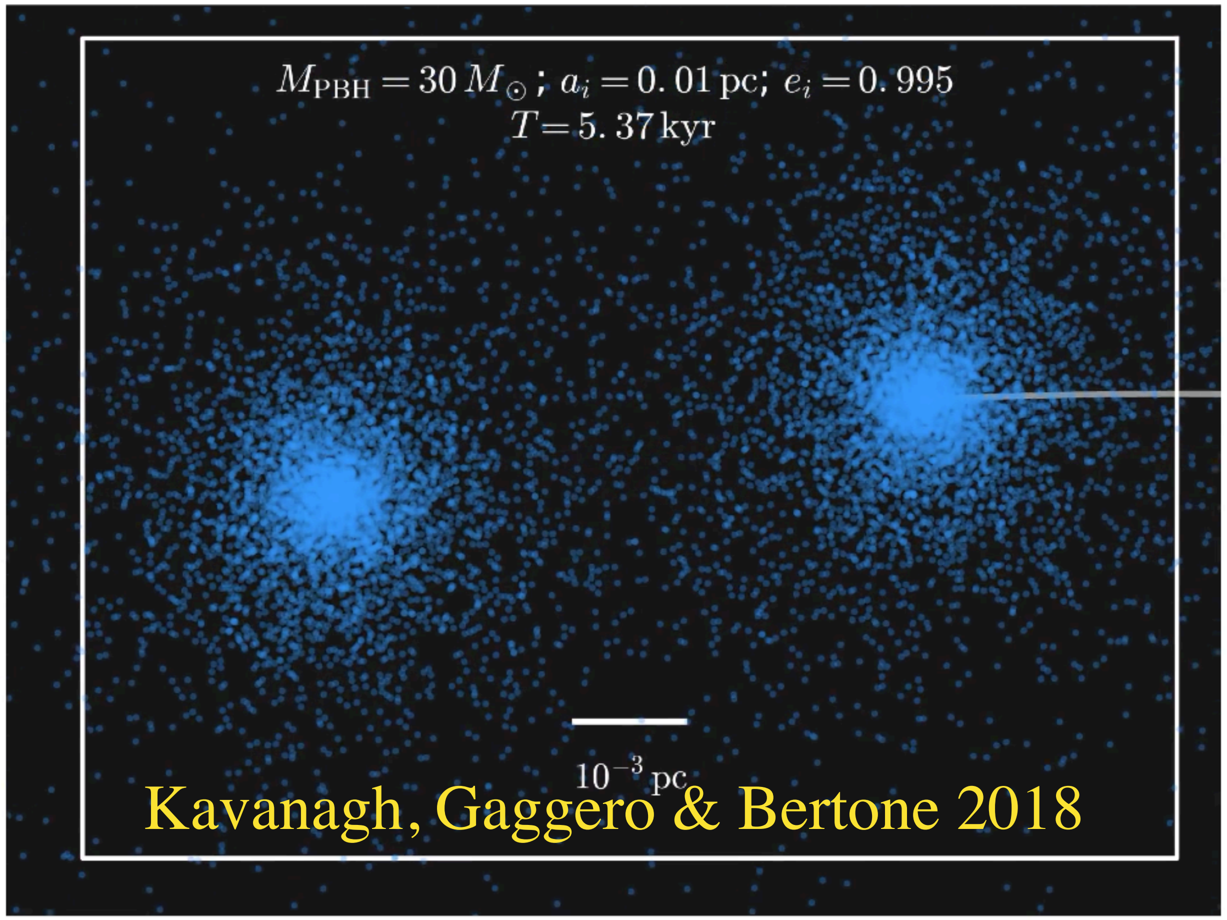
=> To be checked with numerical simulations. Any takers?

➡ If PBHs are not all the DM, can WIMP haloes affect PBH binaries?



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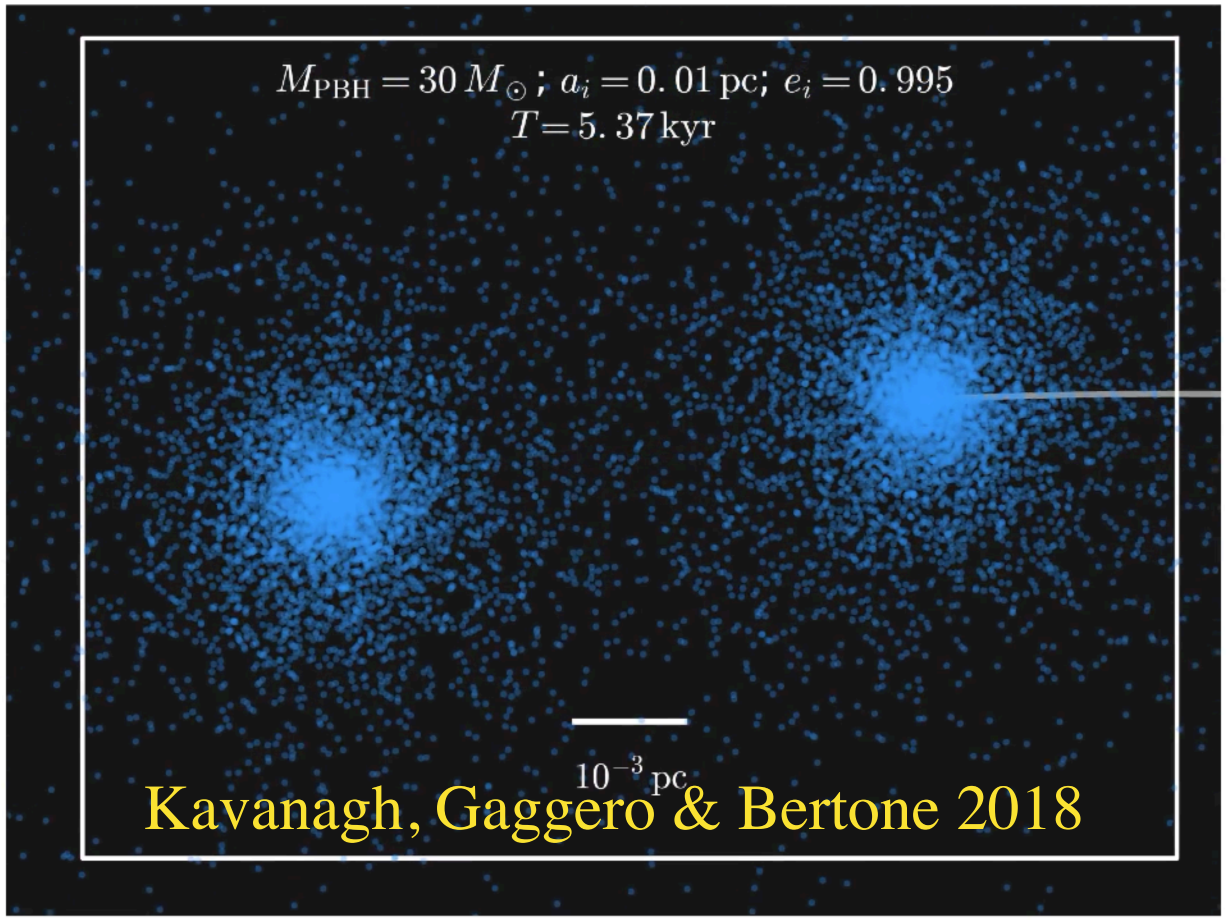

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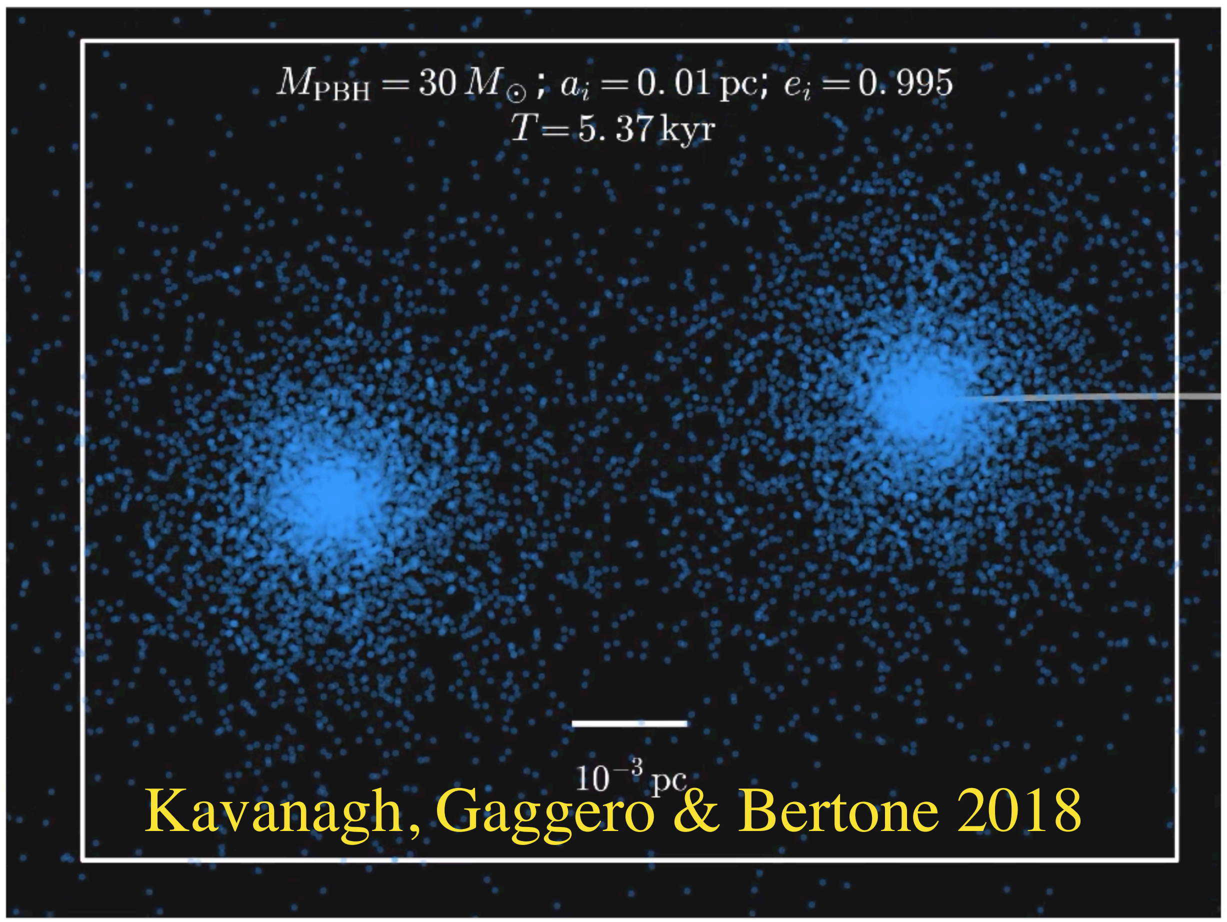
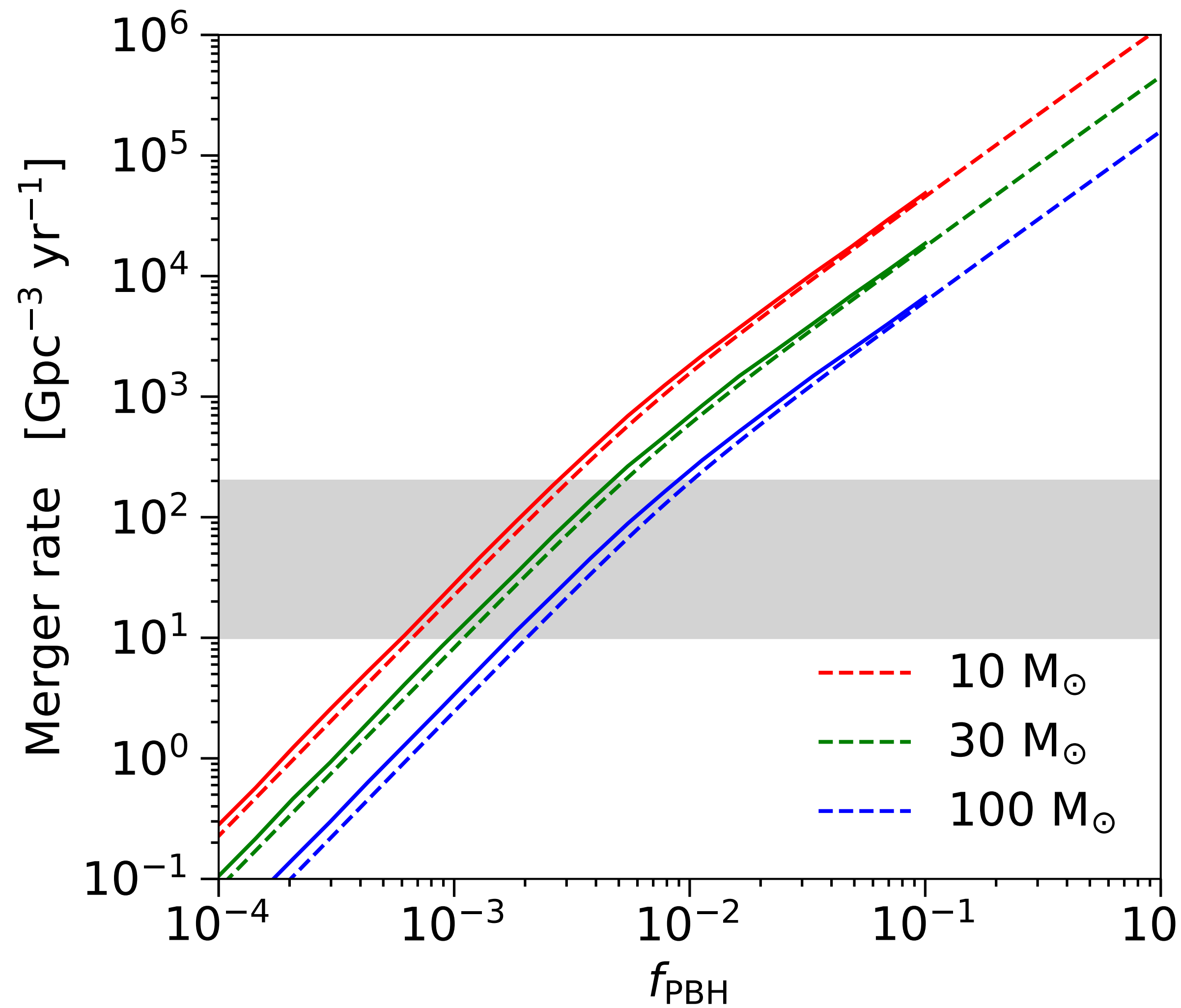




Shrinks the initial orbit and circularizes it, **merger time mostly unaffected.**

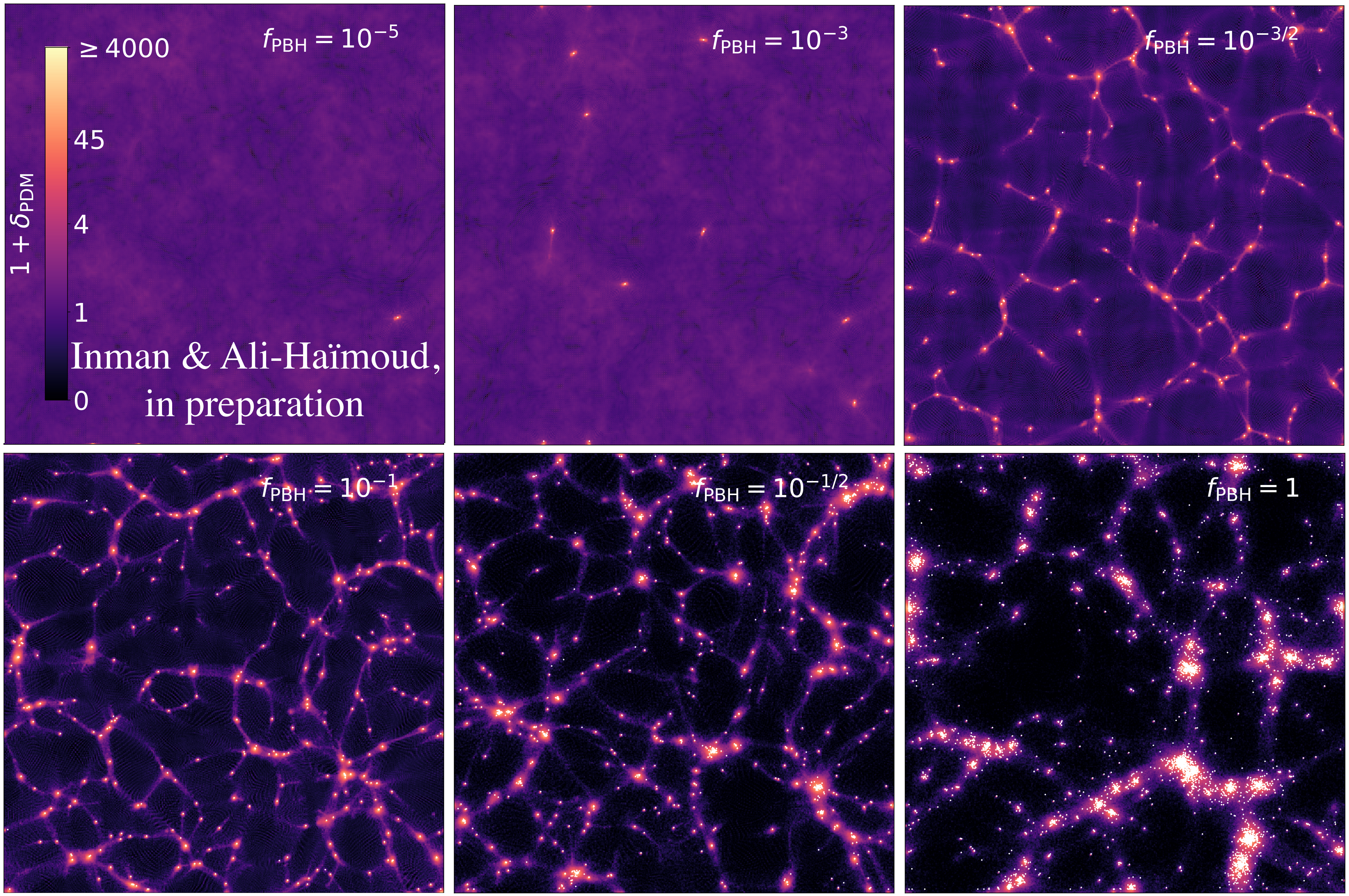
But: only consider isolated binaries, until they decouple from Hubble flow.

➡ What is the effect of the first non-linear structures?

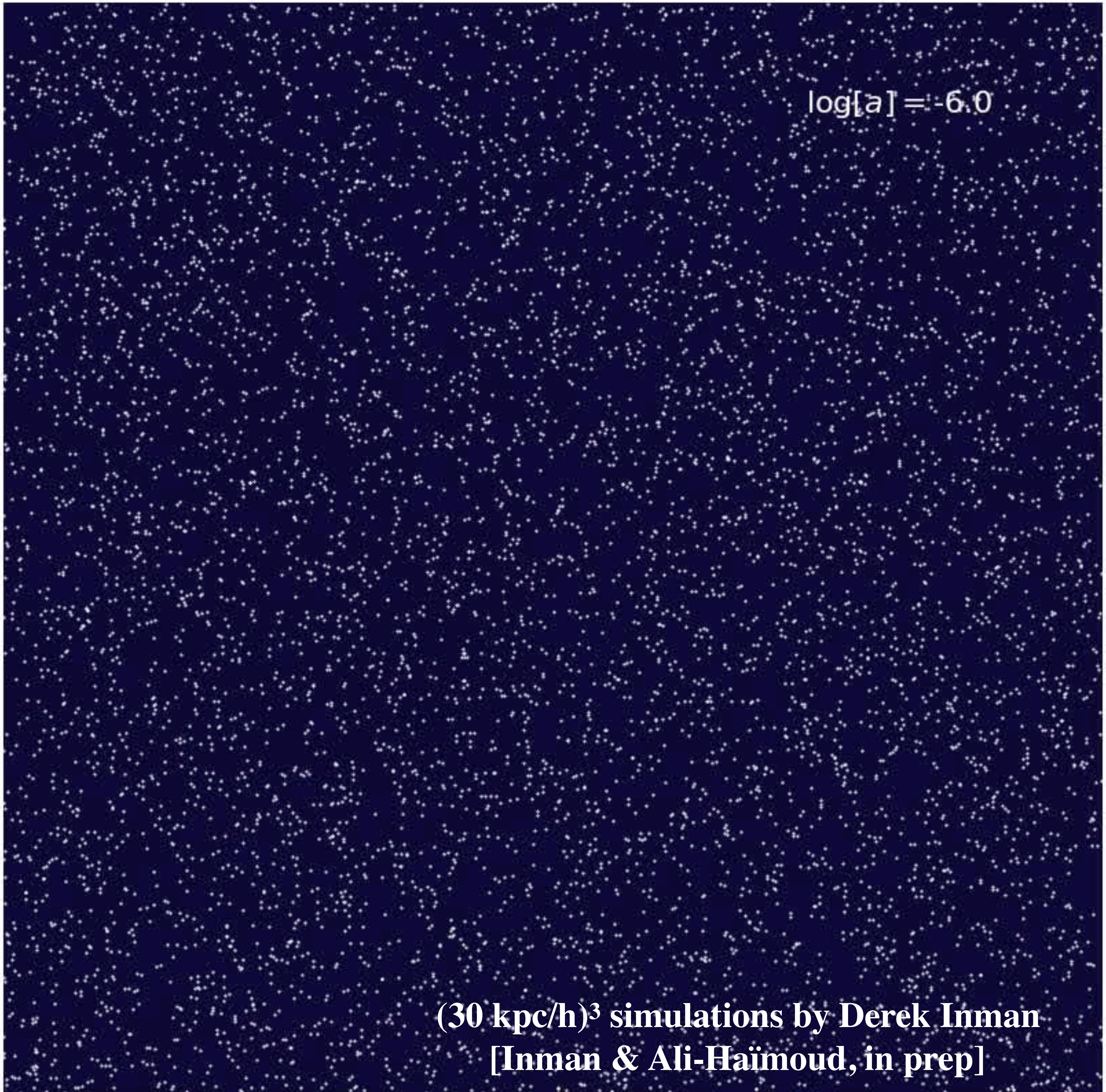
Estimated analytically and found to be negligible:

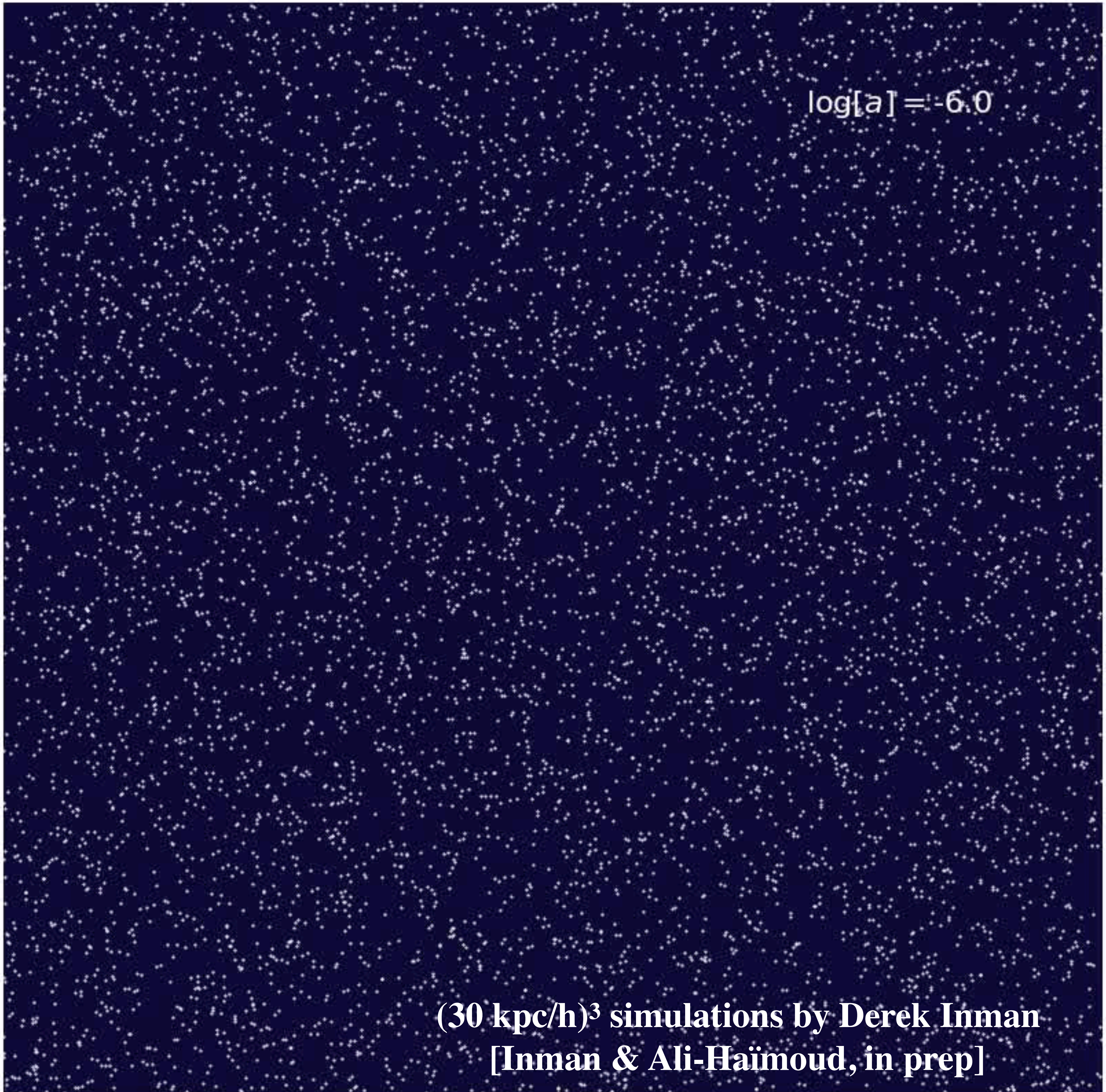
- Torques by the smooth halo tidal field
- Distant encounters with other PBHs
- Close encounters with other PBHs
- Dynamical friction by dark matter particles with $m \ll M$

➡ To be checked numerically



Snapshots of $(30\ {\rm kpc}/h)^3$ simulations, at $z = 100$, for different PBH fractions


log[a] = -6.0
(30 kpc/h)³ simulations by Derek Inman
[Inman & Ali-Haïmoud, in prep]



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Conclusions

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- **To test the PBH hypothesis with GWs:** mass function (Kovetz 17), correlation with LSS (Raccanelli++ 16), eccentricity (Cholis++ 16), spin (Mirbabayi et al 2019)

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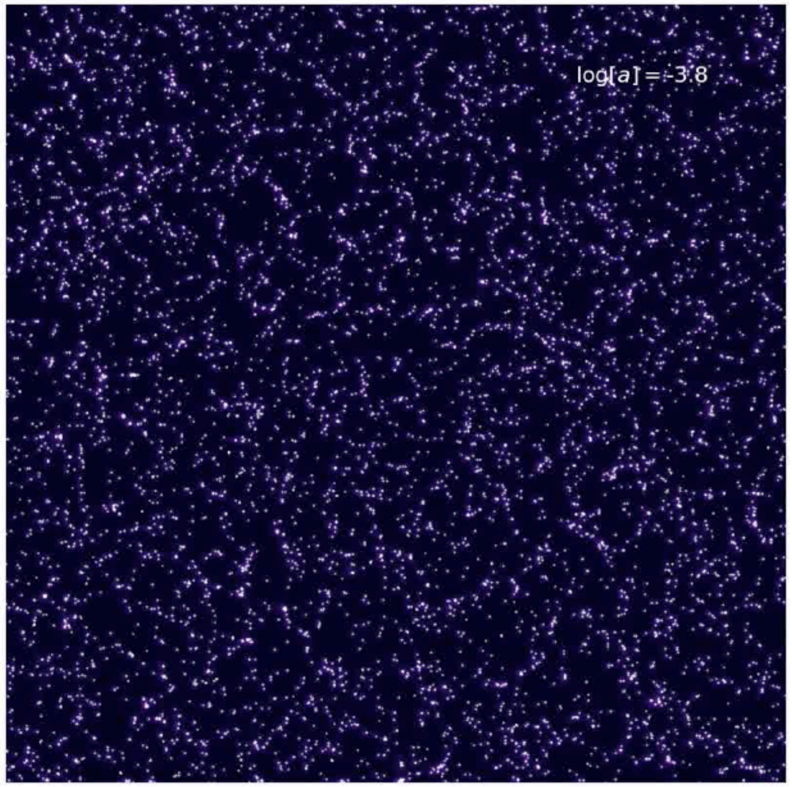

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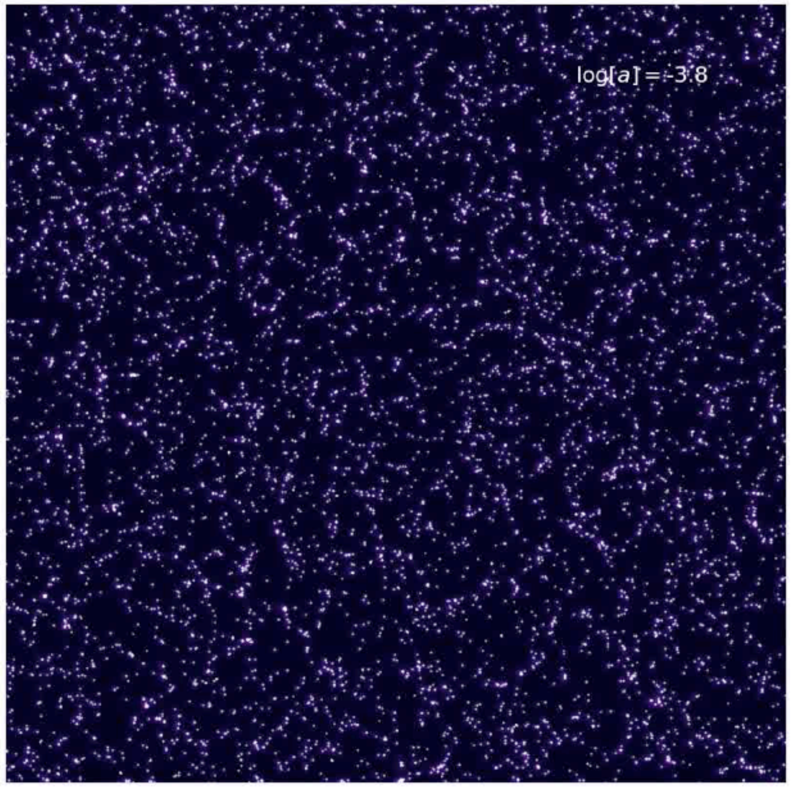

Circumbinary accretion

1- Assume quasi-spherical flow and Bondi-Hoyle-Lyttleton accretion onto each BH

$$M\dot{v} \sim -4\pi\rho_{\rm gas}^{(a)}\frac{M^2}{v^3}v \sim -4\pi\rho_{\rm gas}^{(a)}Ma \sim -\dot{M}\sqrt{M/a}.$$

=>

$$\dot{E} = -A\ \dot{M}\frac{M_{\rm bin}}{a},$$

$$\dot{L} = -B\ \dot{M}\sqrt{M_{\rm bin}a},$$

2- Assume a thin disk with surface density Σ, viscosity ν

$$\dot{L} \sim -3\pi\nu\Sigma\sqrt{M_{\rm bin}r_{\rm in}} \qquad \dot{M} \sim 3\pi\nu\Sigma \qquad \dot{E} \sim \Omega_b\dot{L}$$

=> get the same scalings for dE/dt, dL/dt