Primordial black holes in the era of precision cosmology

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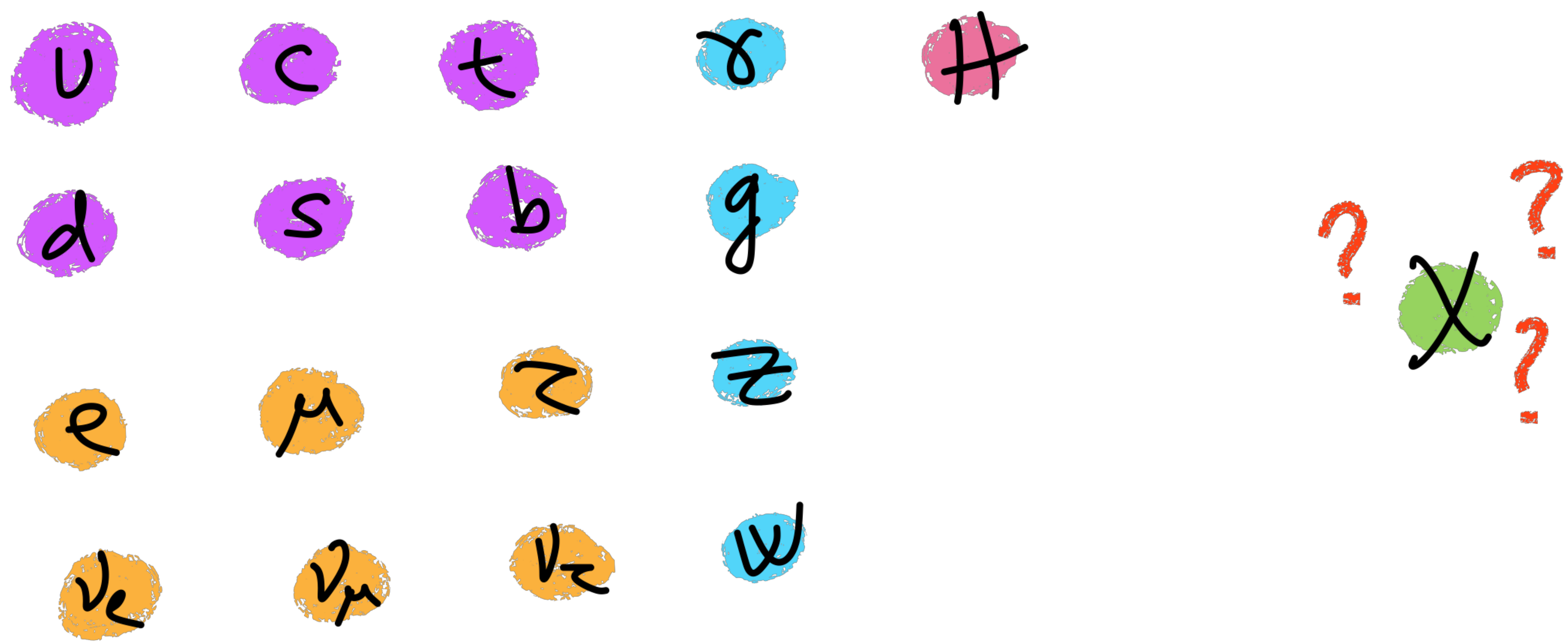
Solvay workshop, April 4th 2019

Why PBHs are interesting

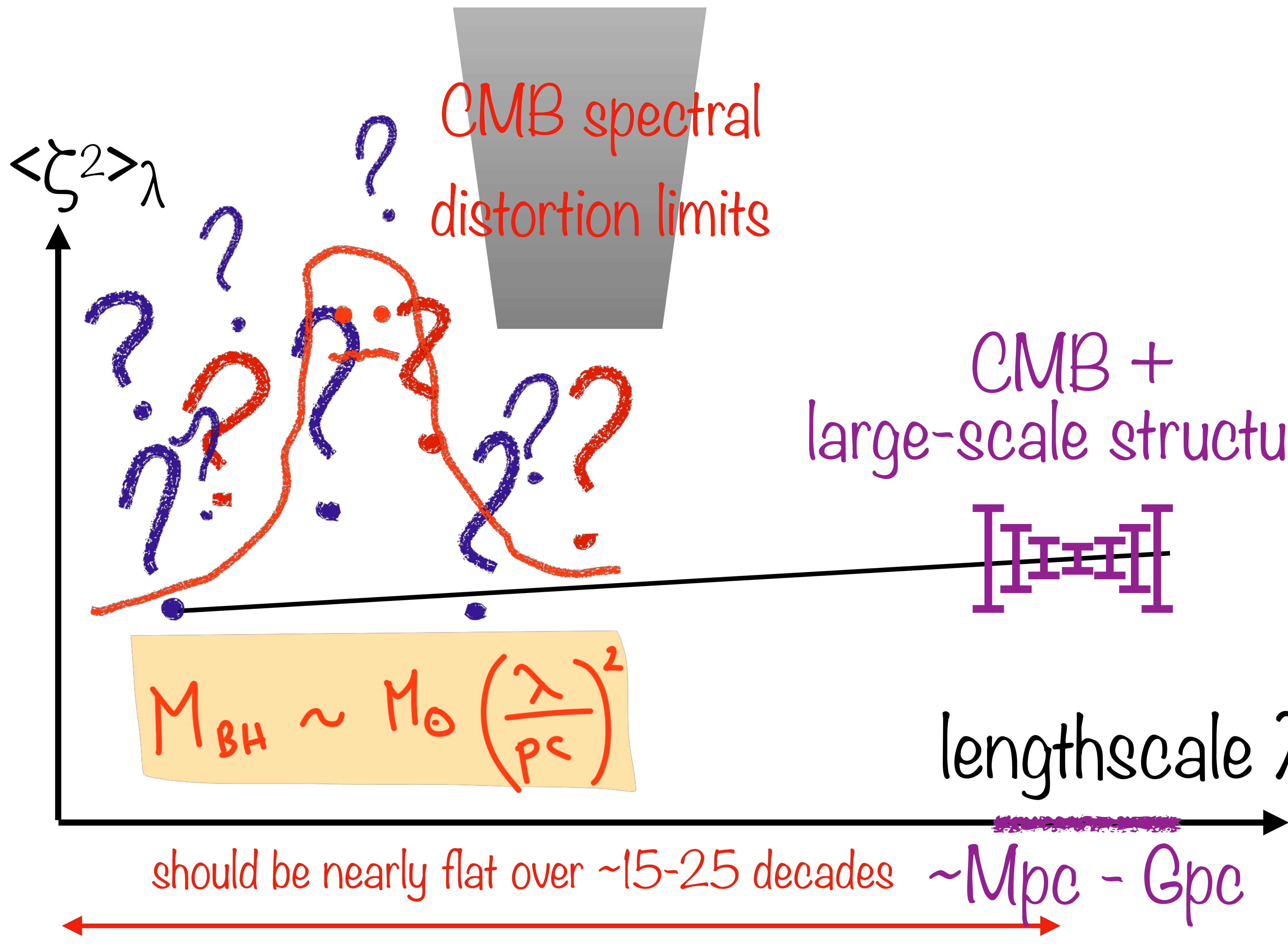
-if they are O(1) of the dark matter

- No need for a new fundamental particle?



- Dark matter is made of... (collapsed) radiation!
- Maybe a mixture of both?

-if they are a fraction f<< 1 of dark matter




PBHs
YOU'LL EITHER LOVE THEM
OR YOU'LL HATE THEM
MARMITE
CHEDDAR
BITES


MARMITE
CHEDDAR
BITES
OR YOU'LL HATE THEM
YOU'LL EITHER LOVE THEM
PBHs

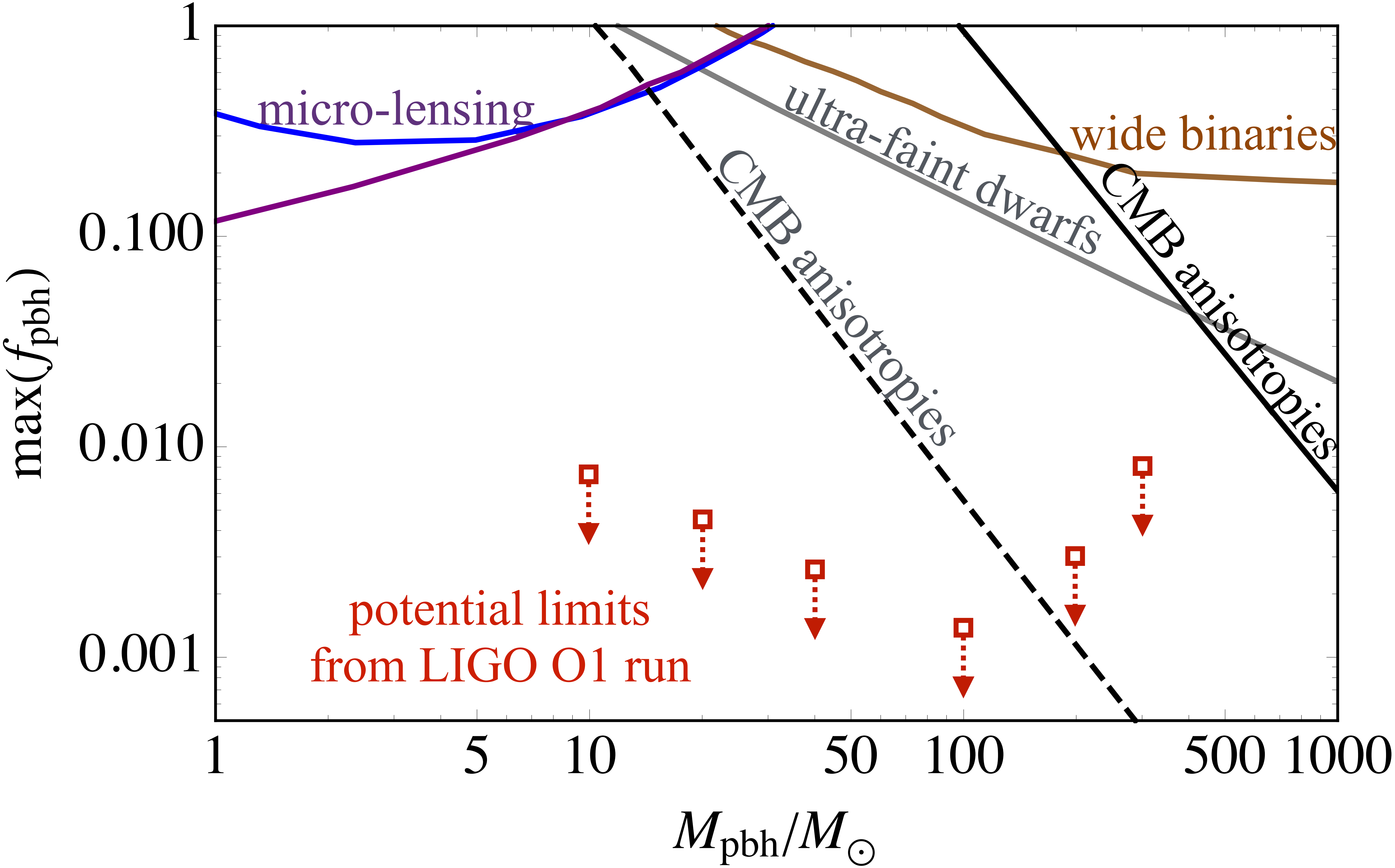
A plea regarding constraints to PBHs

- 95%-confidence exclusion requires confidence beyond reasonable doubt

➡ Constraints should qualify the level of confidence in the constraint plot

- Recent revival implies more scrutiny, hence large changes to old constraints.

- However, let's not dismiss constraints without spending at least as much effort as the authors…



CMB: Ali-Haïmoud & Kamionkowski 2017

LIGO: Ali-Haïmoud, Kovetz & Kamionkowski 2017

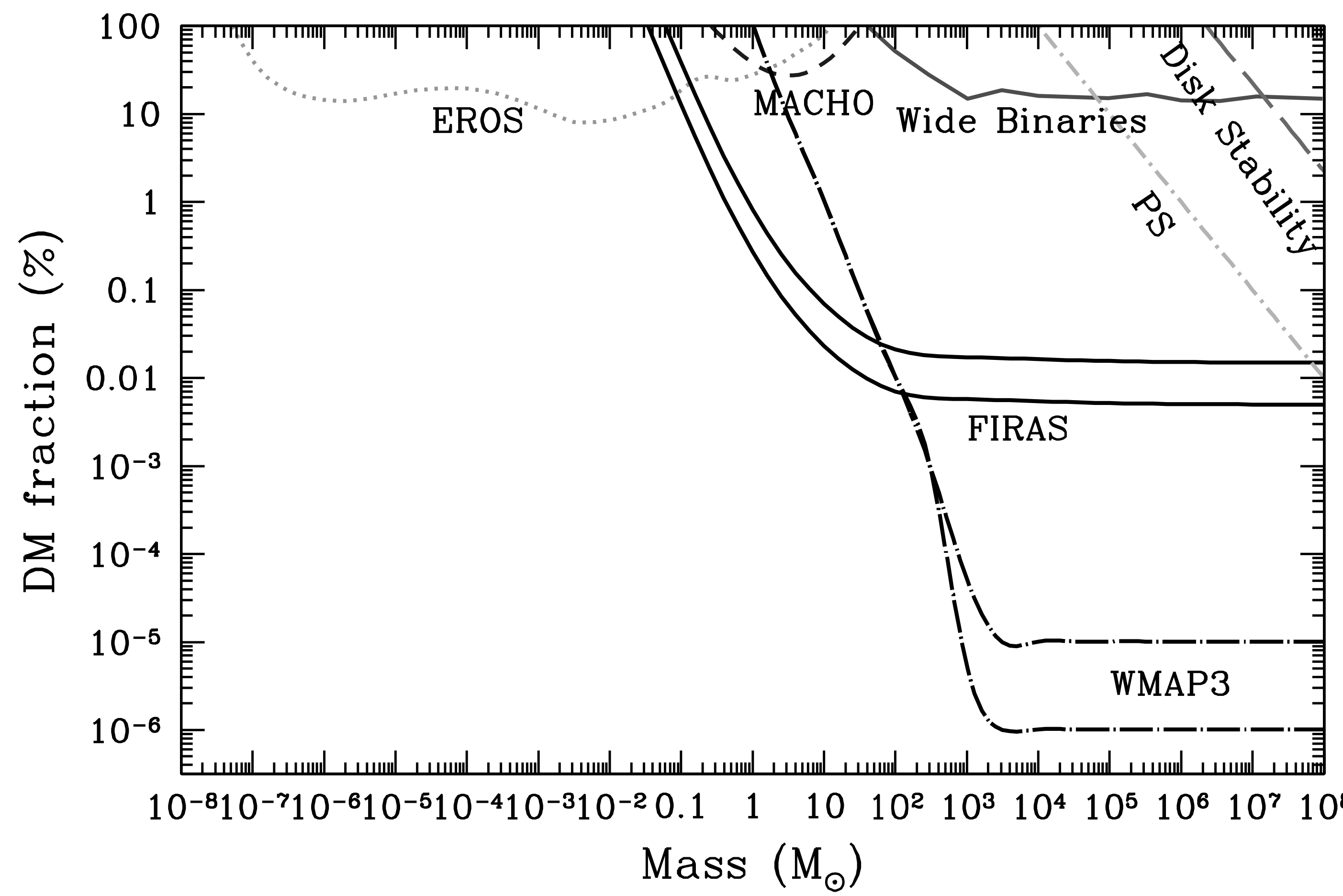
CMB limits to accreting PBHs

Pregalactic black hole accretion and the thermal history of the Universe *Mon. Not. R. astr. Soc.* (1981) 194, 639–668

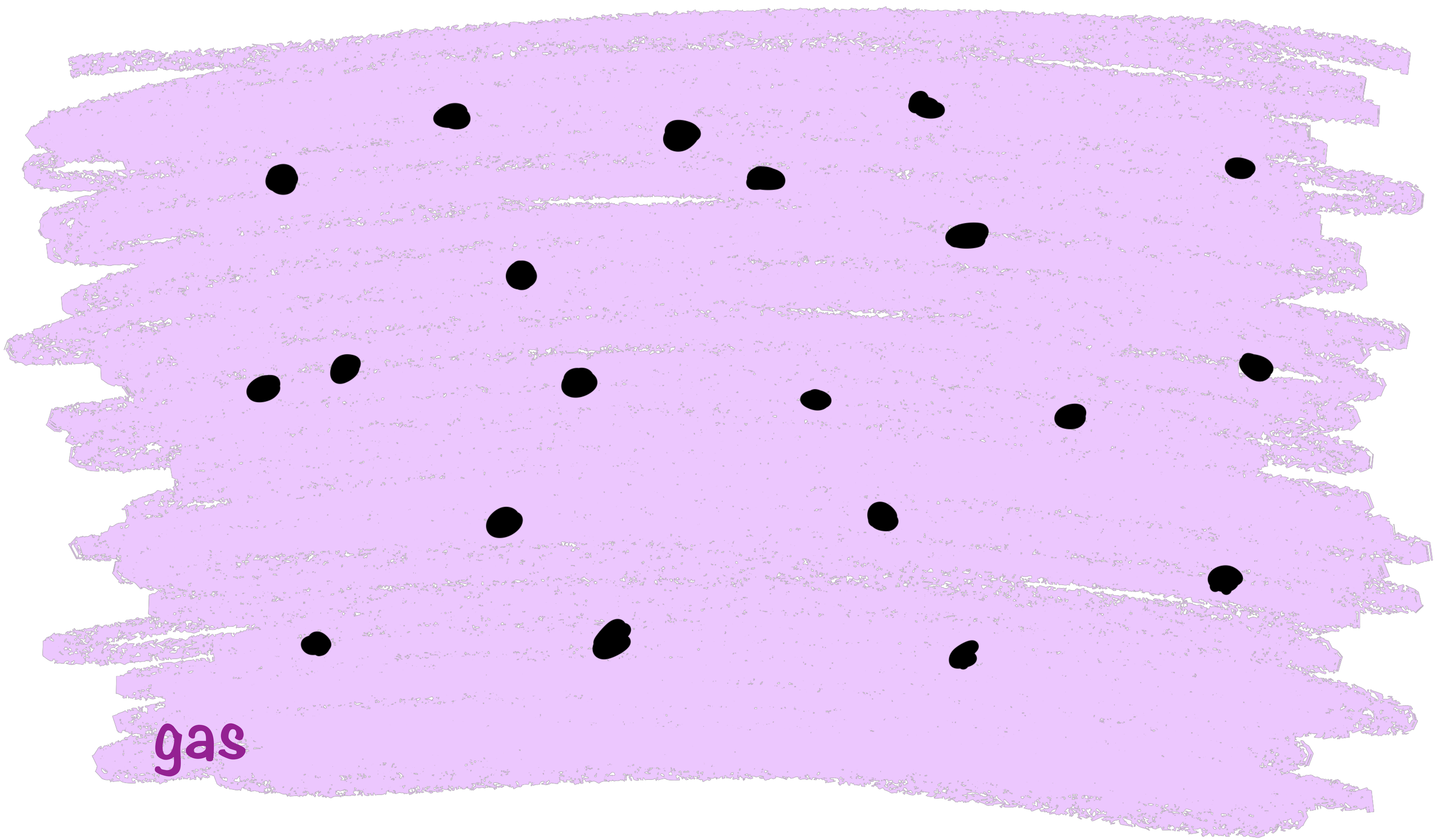
B. J. Carr *Astronomy Department, University of California, Berkeley,*

for a wide range of values for the mass and density of the holes, the matter would be completely re-ionized. In some circumstances, the Universe would never pass through a neutral phase at

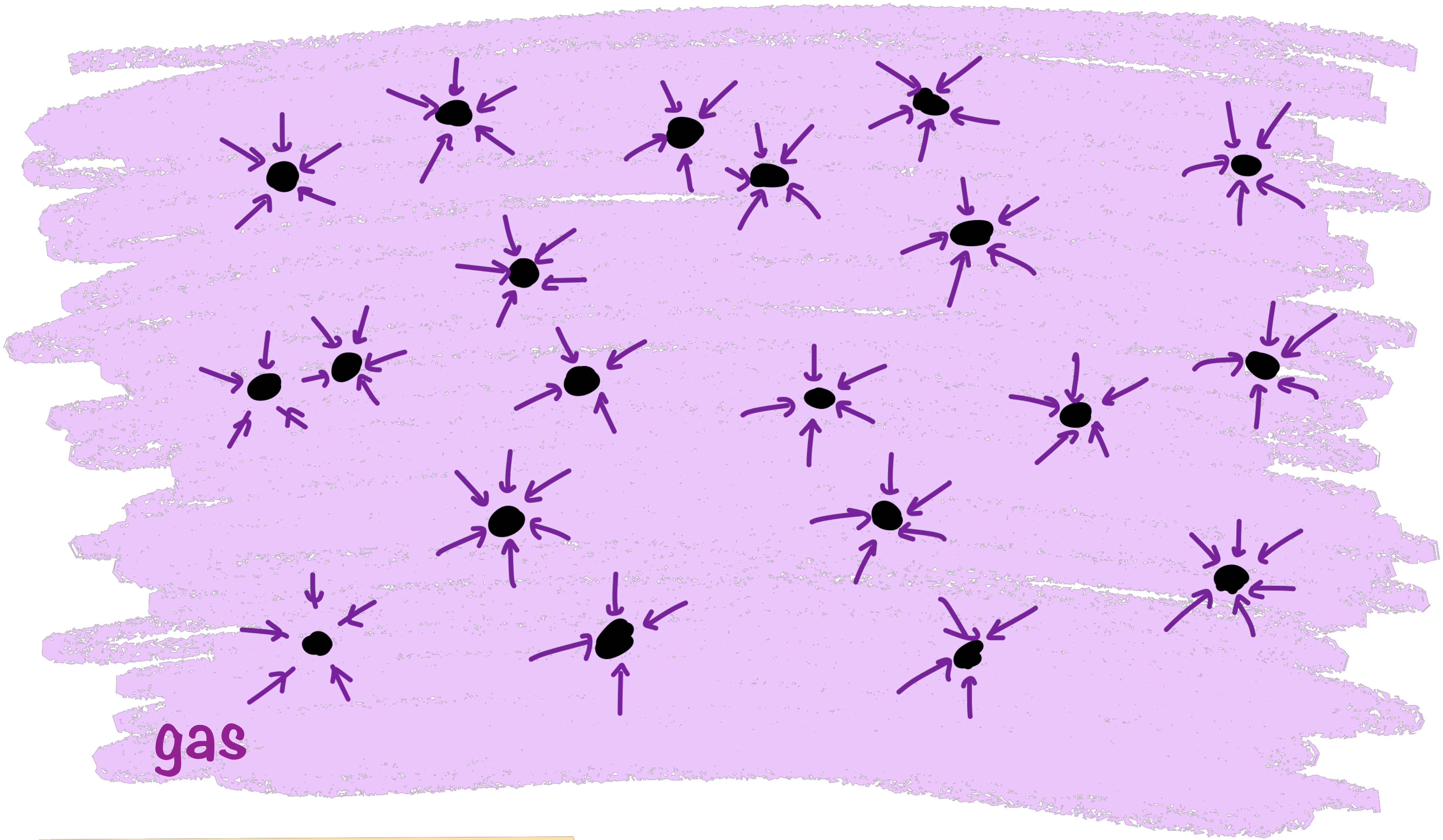
Ricotti, Ostriker & Mack 2008: first modern and detailed analysis of effect on CMB



Basic setup



1- Accretion rate



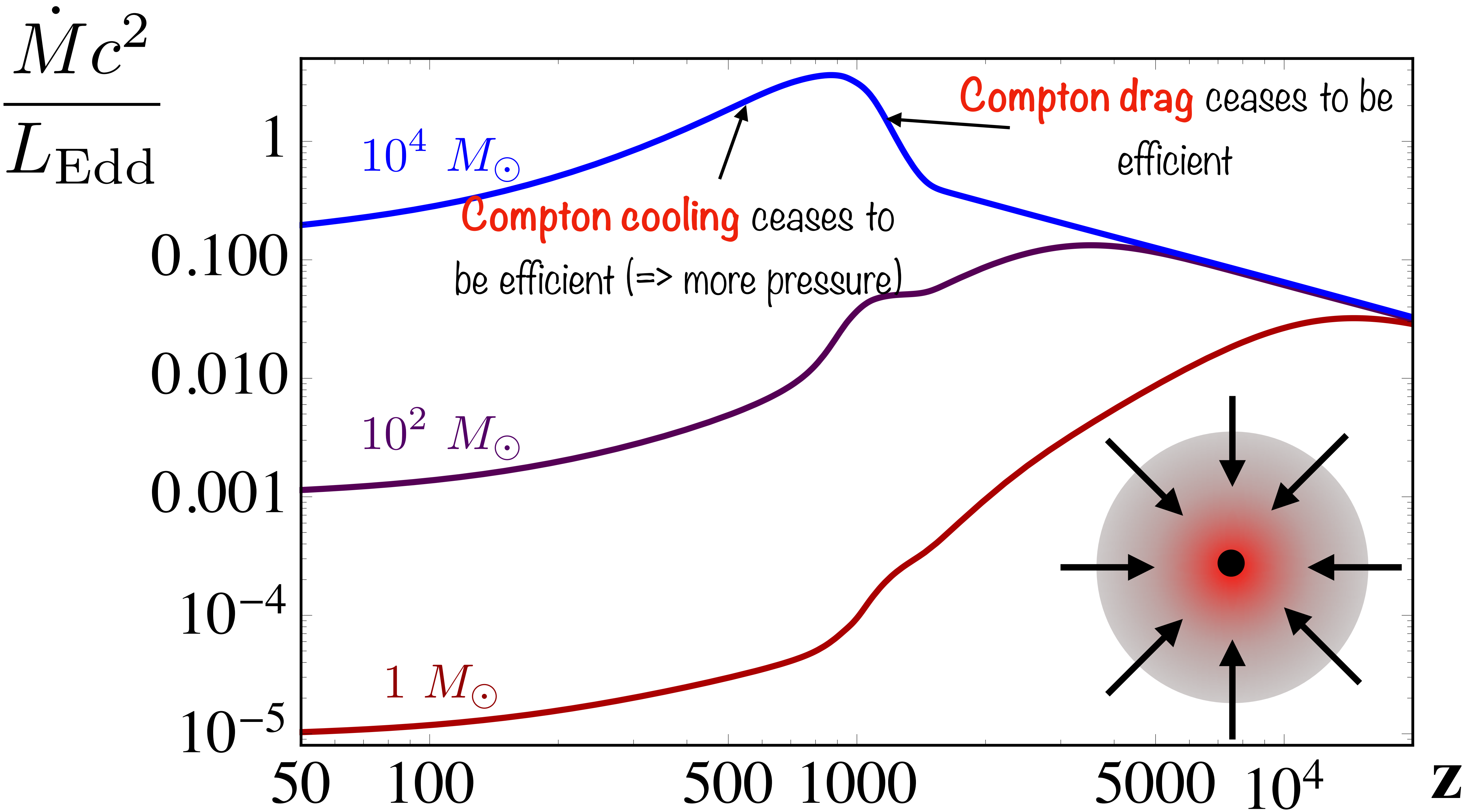
Accretion rate $\dot{M}$

I- Accretion rate

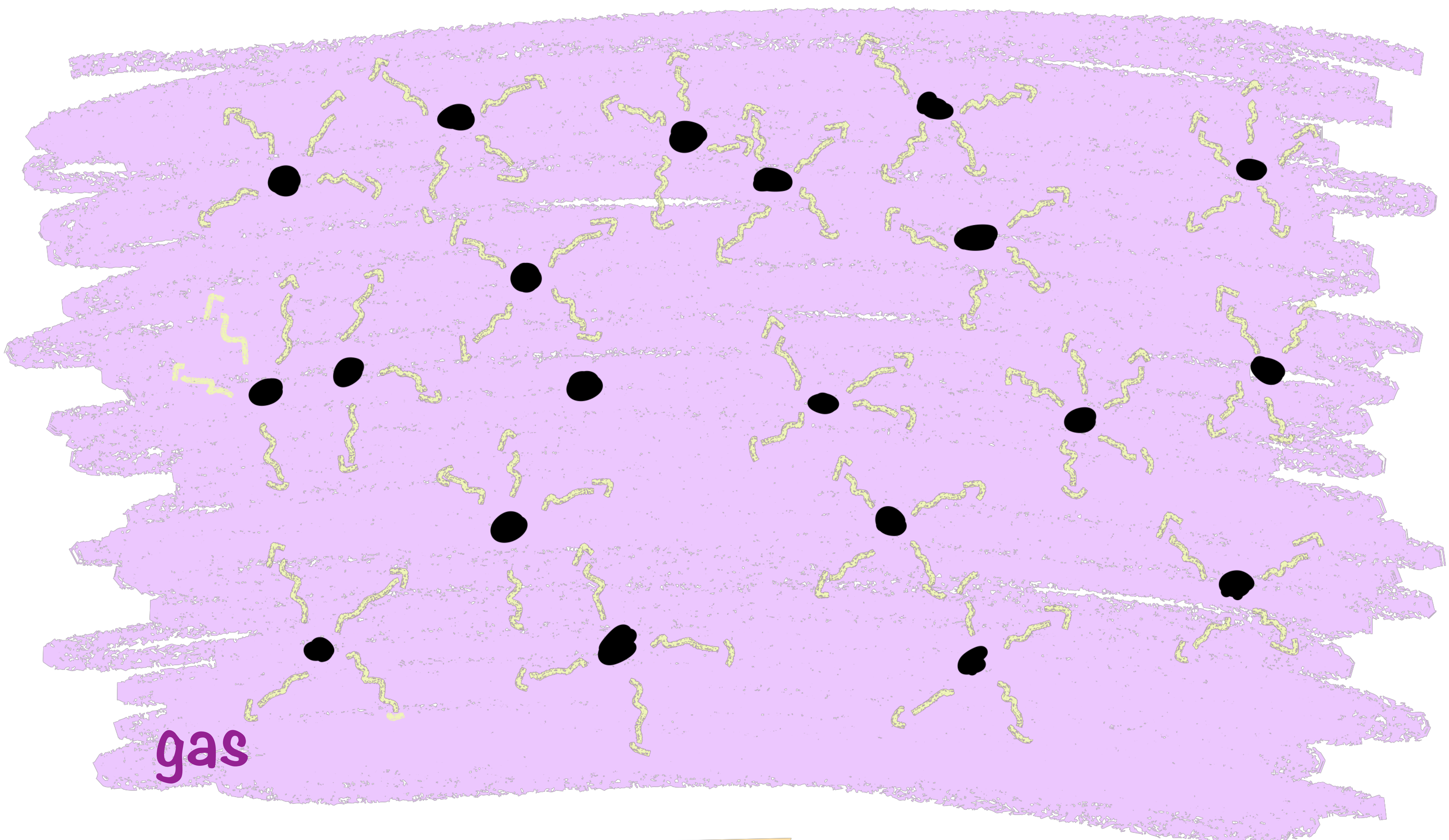
- Assume spherical accretion. Disk accretion typically more luminous => conservative hypothesis (confirmed by Poulin et al. 2017)
- Assume steady-state accretion (modified Bondi-Hoyle). **Self-consistent for $M \lesssim 3 \times 10^4 M_{sun}$.**
- Account for Compton drag and **(finite) Compton cooling** by CMB photons
- Account for relative velocity v_{rel} of PBHs wrt baryons: Gaussian random field with **supersonic rms ~30km/s at recombination** (Tseliakhovich & Hirata 2010)

I- Accretion rate

$$\dot{M}_{\rm Bondi} \sim \rho_b M^2 / c_s^3$$



2- Radiative efficiency



Luminosity per BH $L = \epsilon \dot{M} c^2$

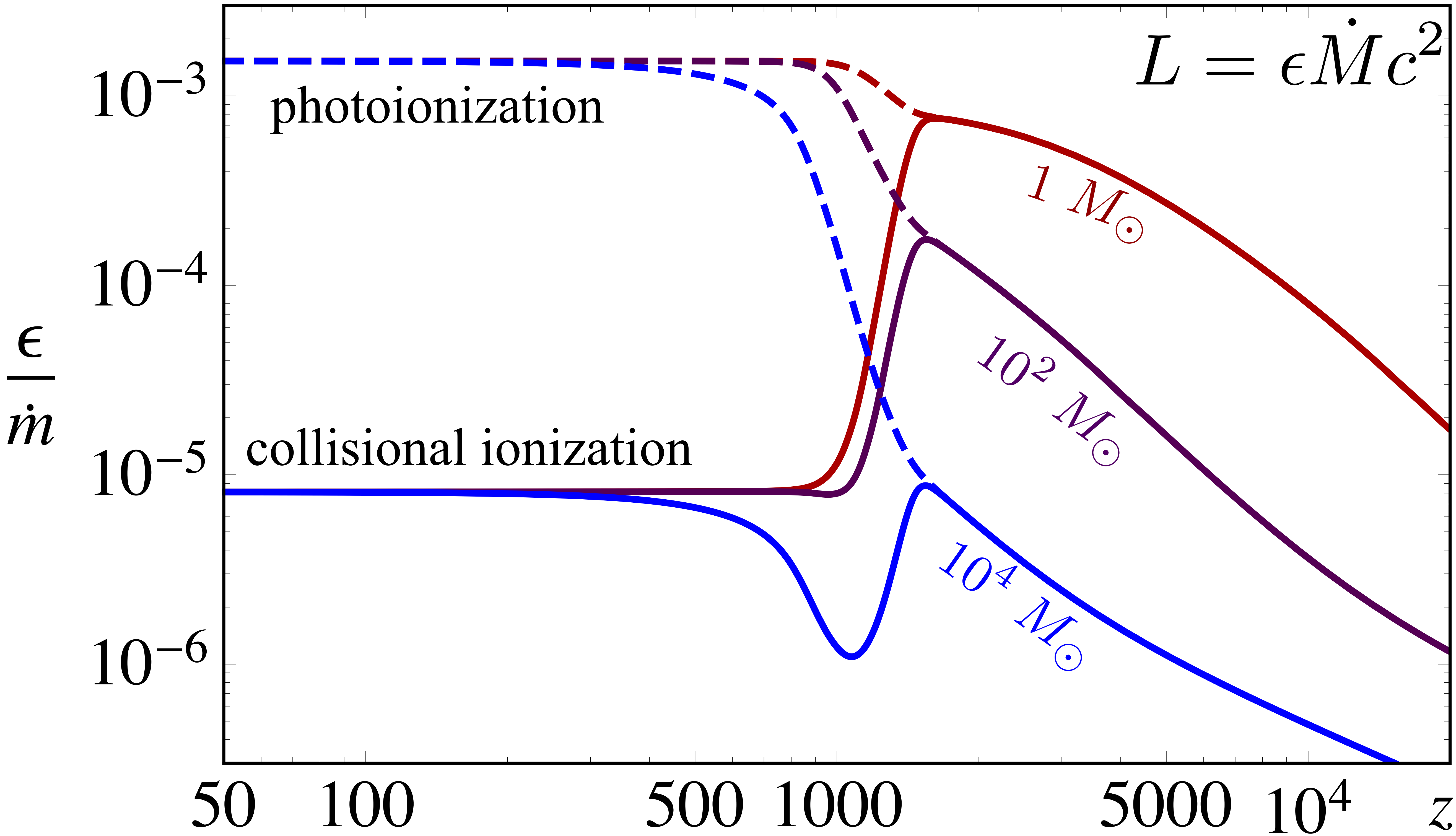
2- Radiative efficiency

- At minimum, ionized gas near the horizon emits free-free radiation

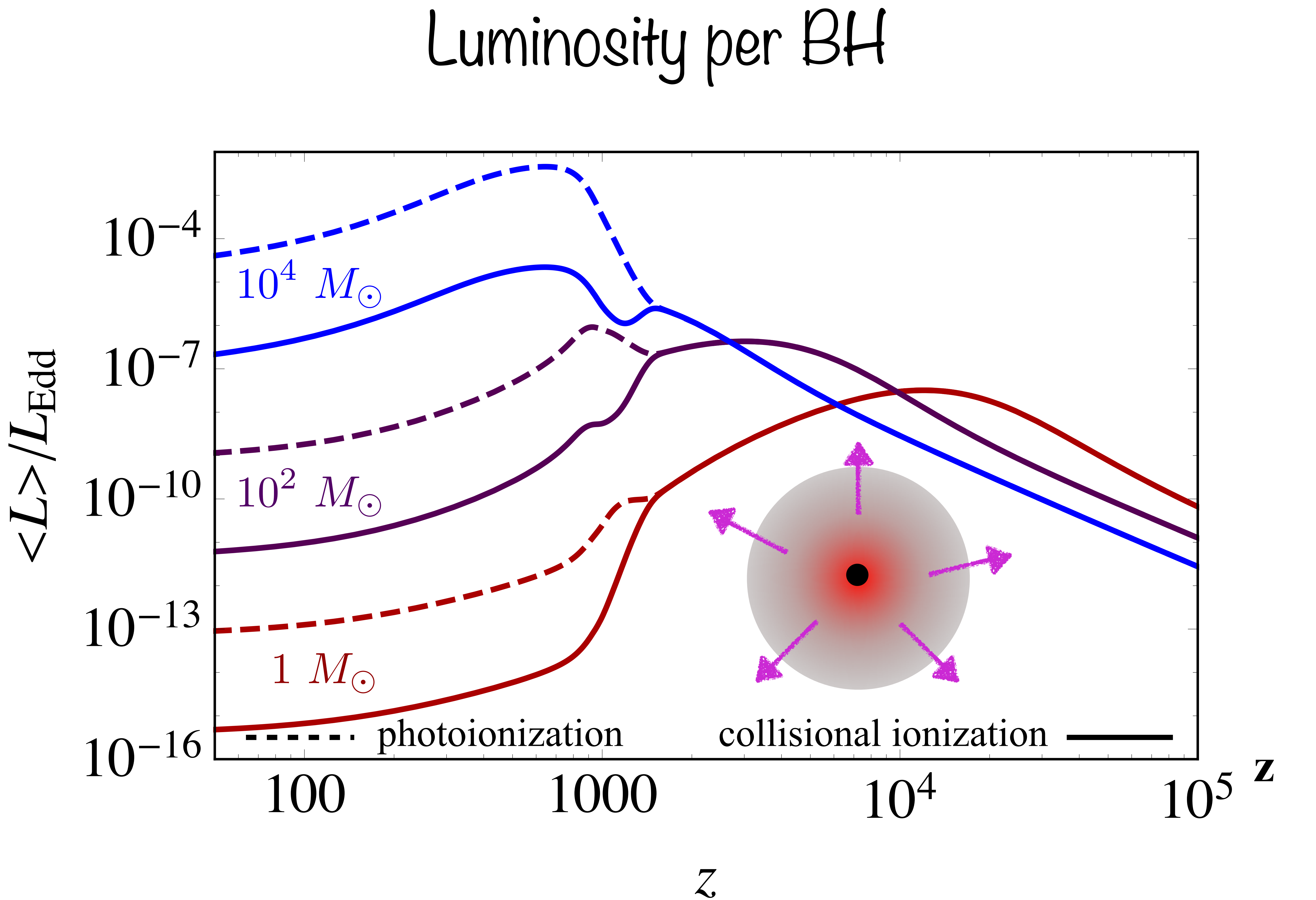
- Estimate the density and temperature profile around accreting BH using modified Shapiro (1973) model

- Consider two limiting cases: collisional ionization and (local) photoionization by BH radiation (neither is self-consistent)

2- Radiative efficiency

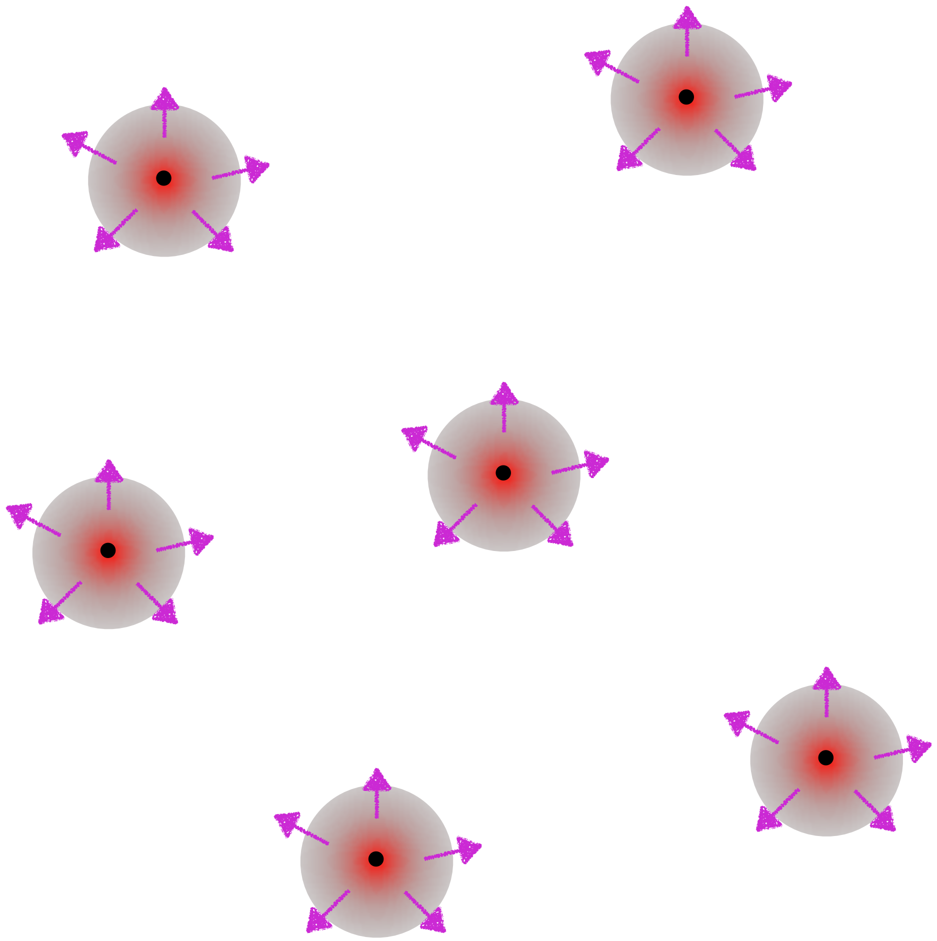


ROM assume $\epsilon/\dot{m} = 0.011$

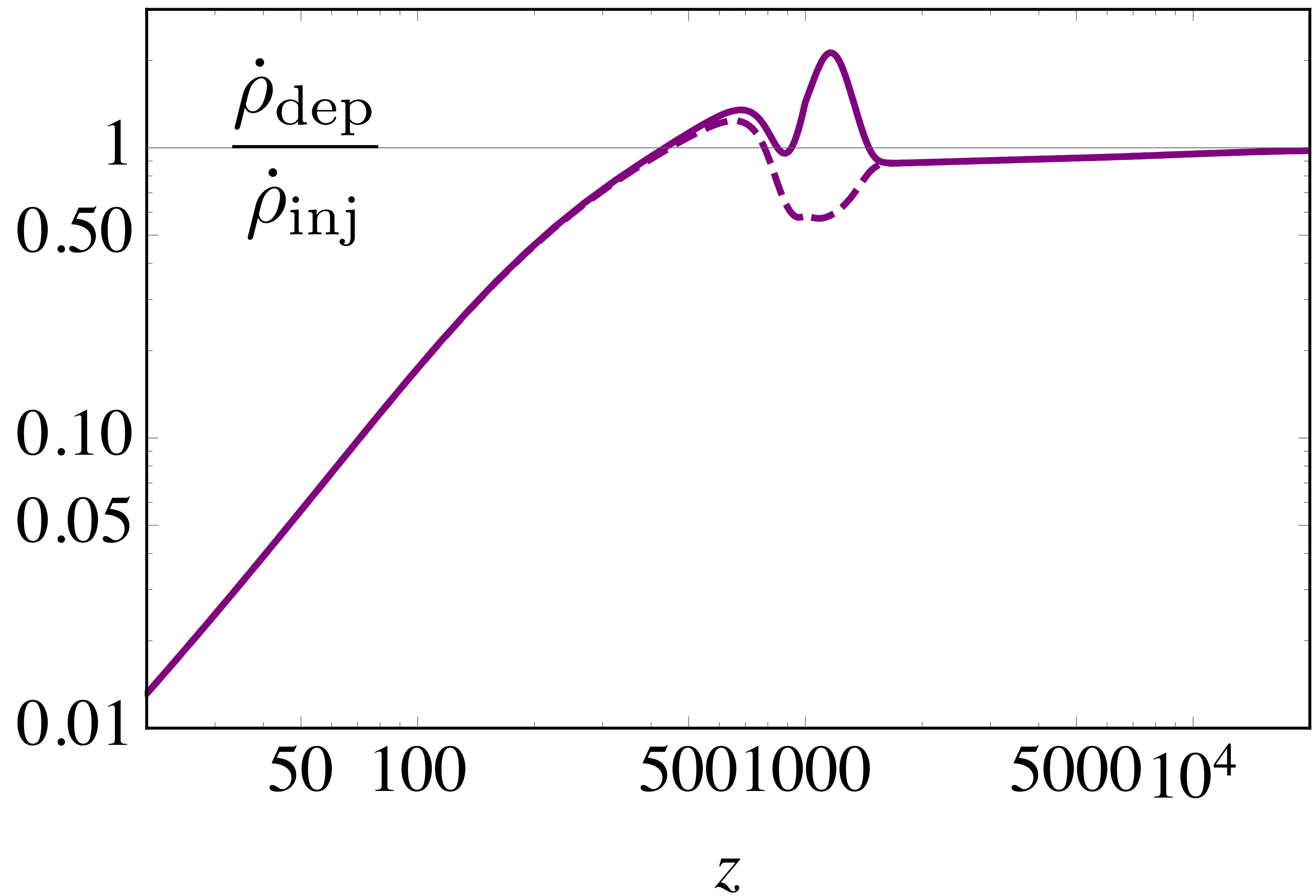


Luminosity per BH
$\langle L \rangle / L_{\rm Edd}$
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
$10^4\ M_\odot$
$10^2\ M_\odot$
$1\ M_\odot$
photoionization
collisional ionization
100
1000
10^4
10^5
z
z

3. Energy deposition efficiency

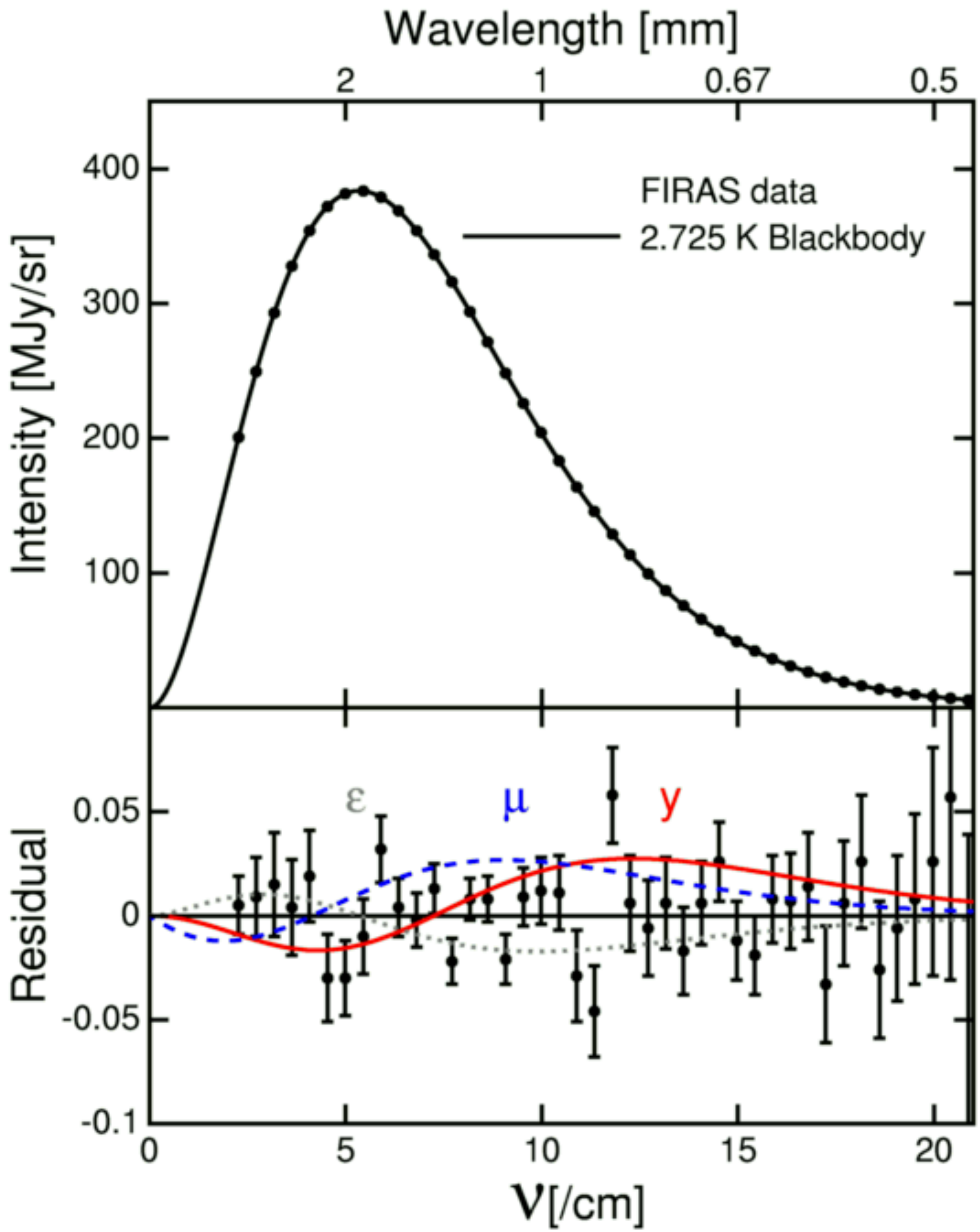


$$\dot{\rho}_{\rm inj} = n_{\rm pbh} L$$



Solve an approximate Boltzmann equation, assuming energy mostly deposited through Compton scattering of ~0.1-10 MeV photons

4. CMB spectral distortions?



$$\frac{I_\nu - B_\nu}{B_\nu} \sim \int_{t \geq 2\ \text{months}} dt\, \frac{\frac{dE}{dt\,dV}}{\rho_\gamma}$$

Planck function

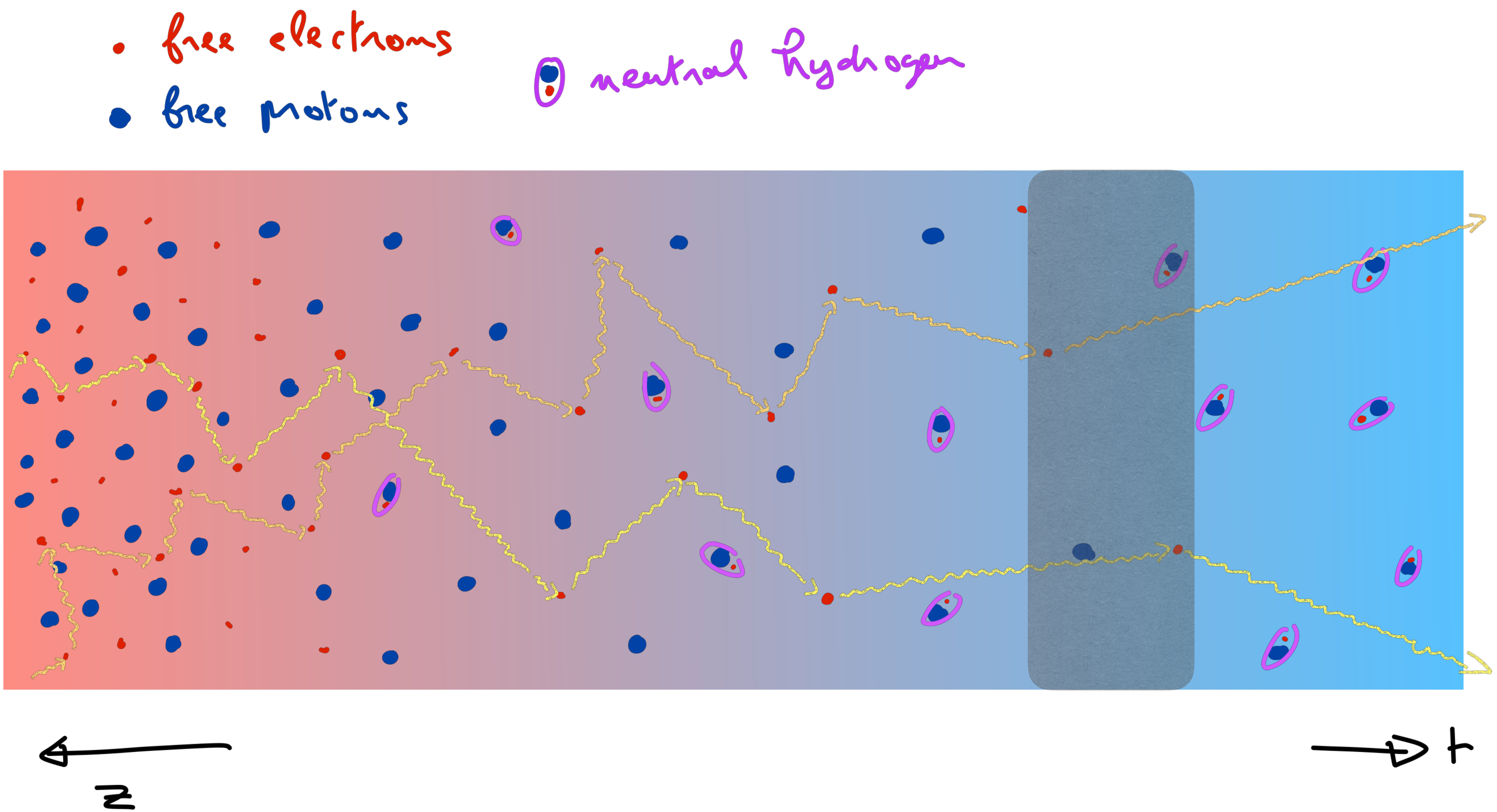
$$\mu \leq 6 \times 10^{-8} f_{\rm pbh} \max_{z \geq 5\times 10^4} \left(\frac{\langle L \rangle}{L_{\rm Edd}} \right).$$

$$y \approx 0.02\ f_{\rm pbh} \frac{\langle L \rangle}{L_{\rm Edd}} \Big|_{z\approx 200}$$

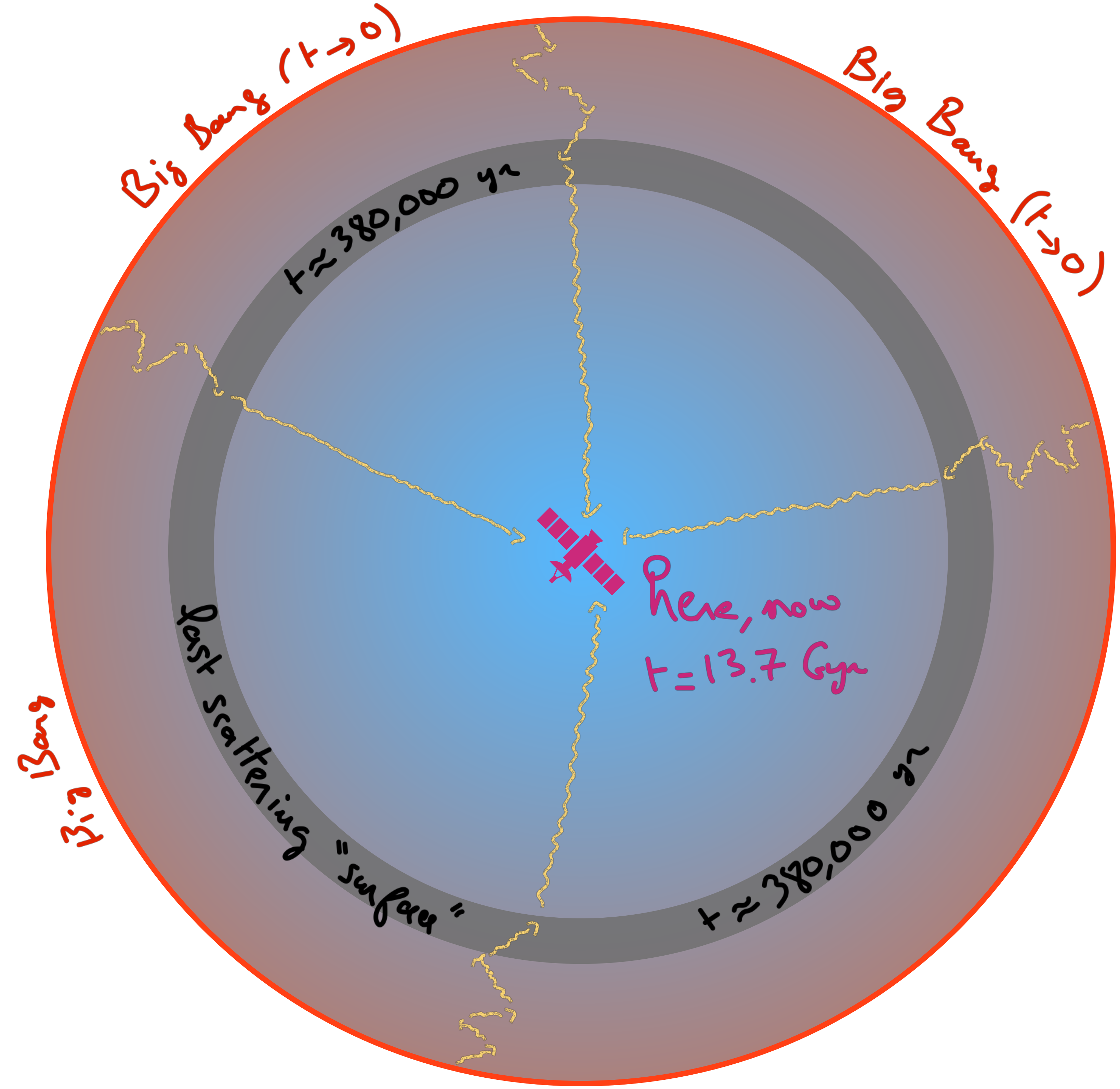
Undetectable by FIRAS (μ, $y \sim 10^{-5}$),

or even by PIXIE (μ, $y \sim 10^{-8}$)

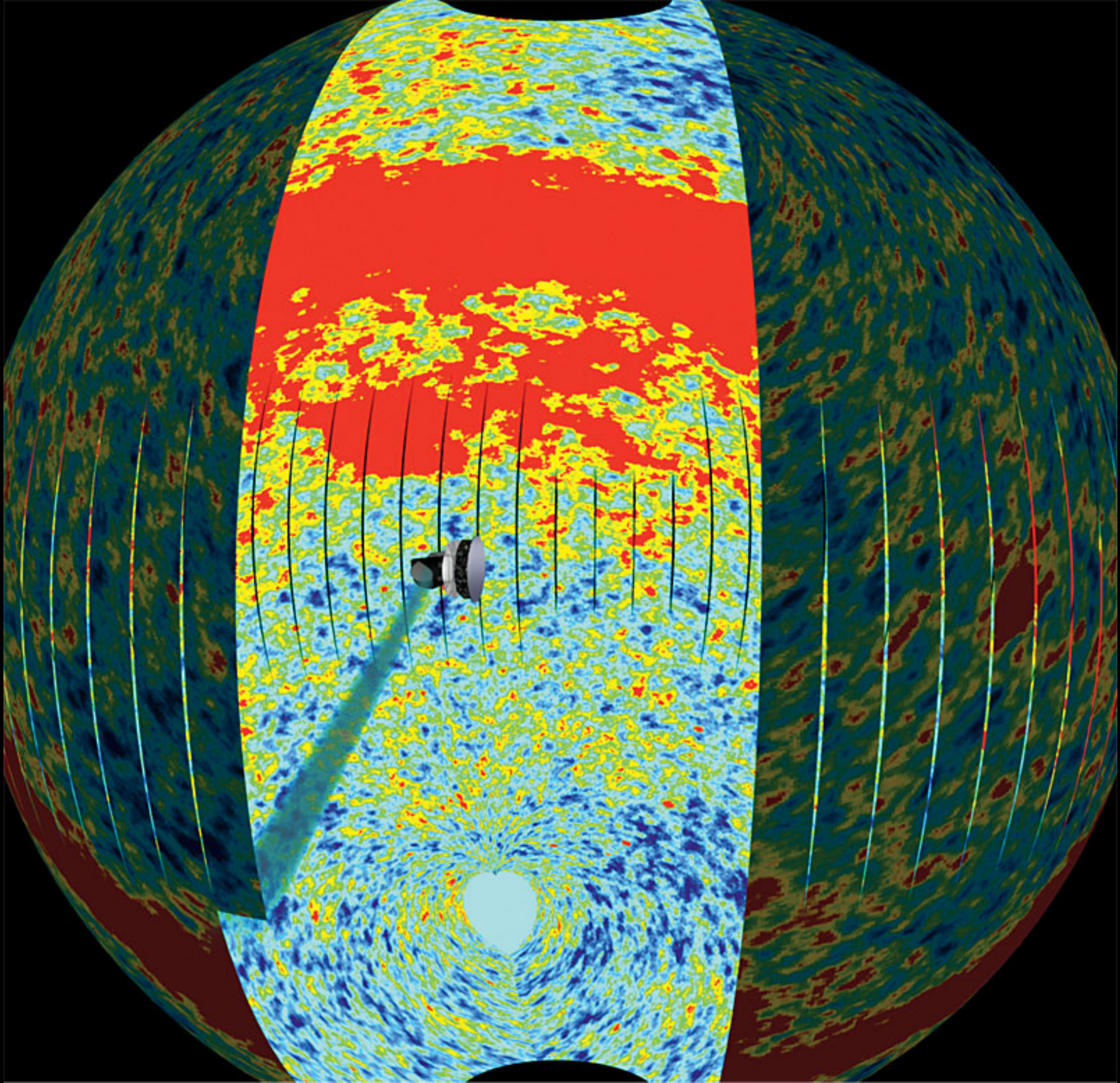
5-CMB anisotropies



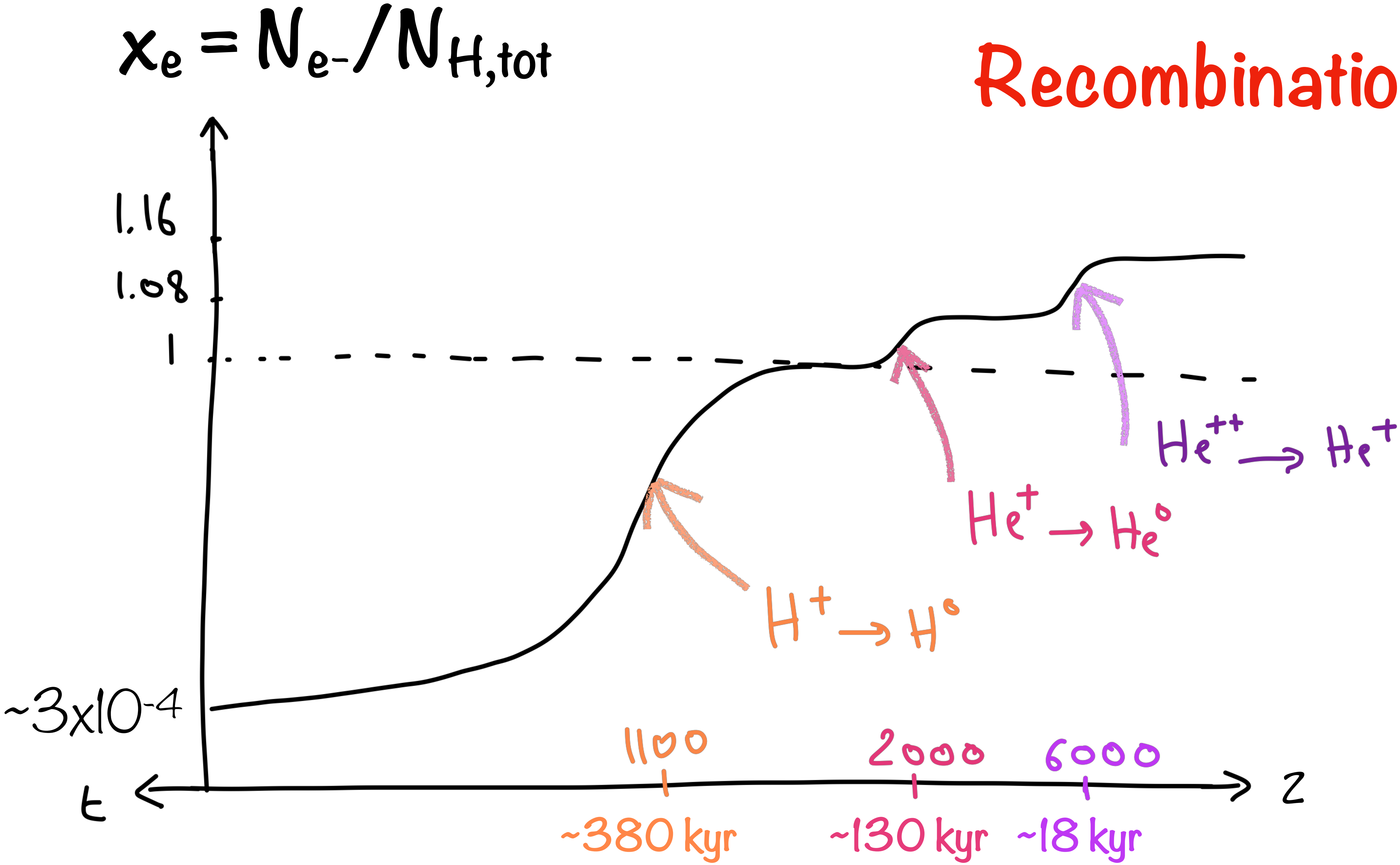
Last-scattering "surface": where **most** photons scatter for the last time



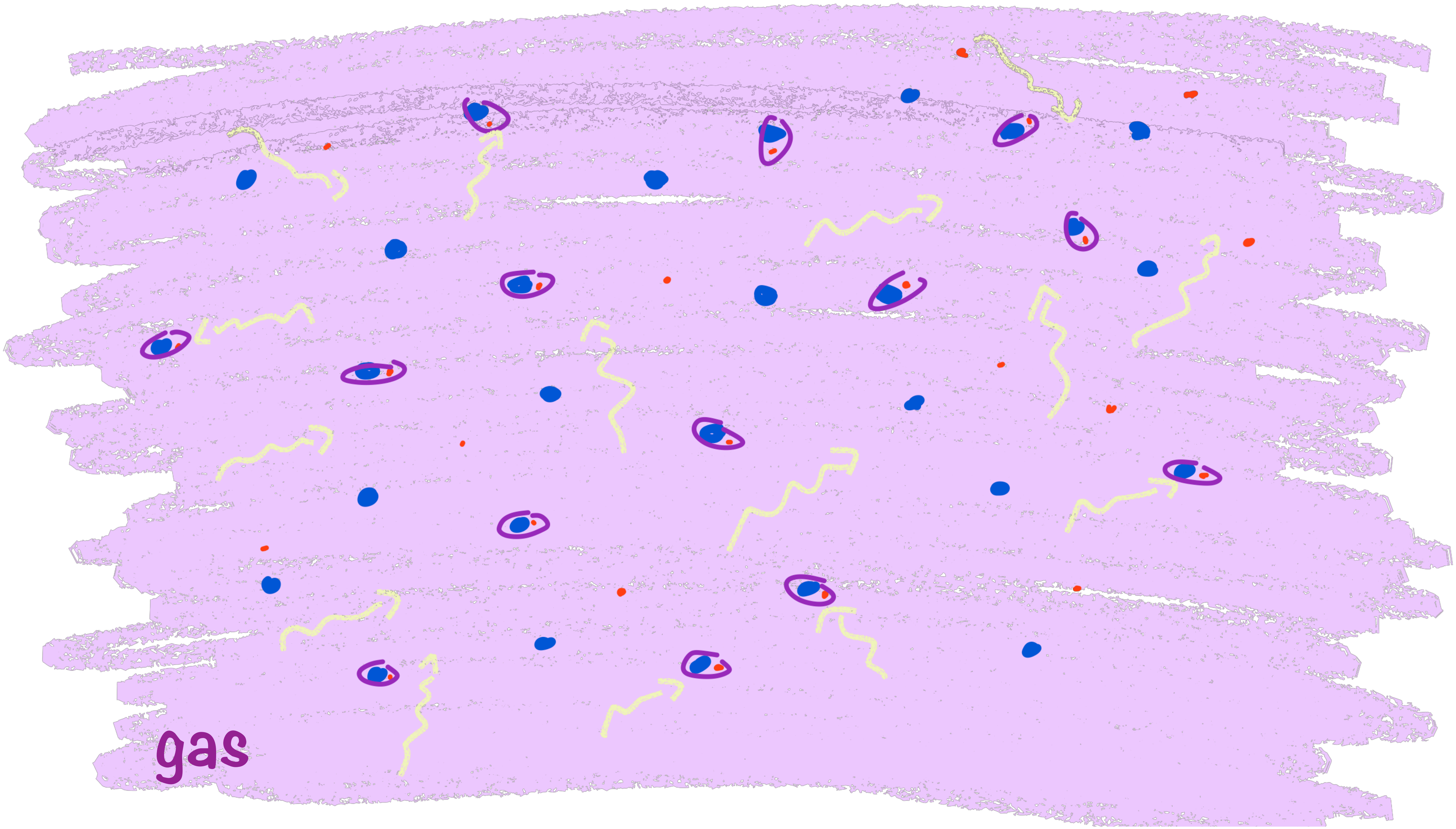
$$\frac{\Delta T}{T}(\vec{k}) \sim \int dz \frac{dP_{\rm last-scat}}{dz} \mathcal{S}(\vec{k}, z)$$



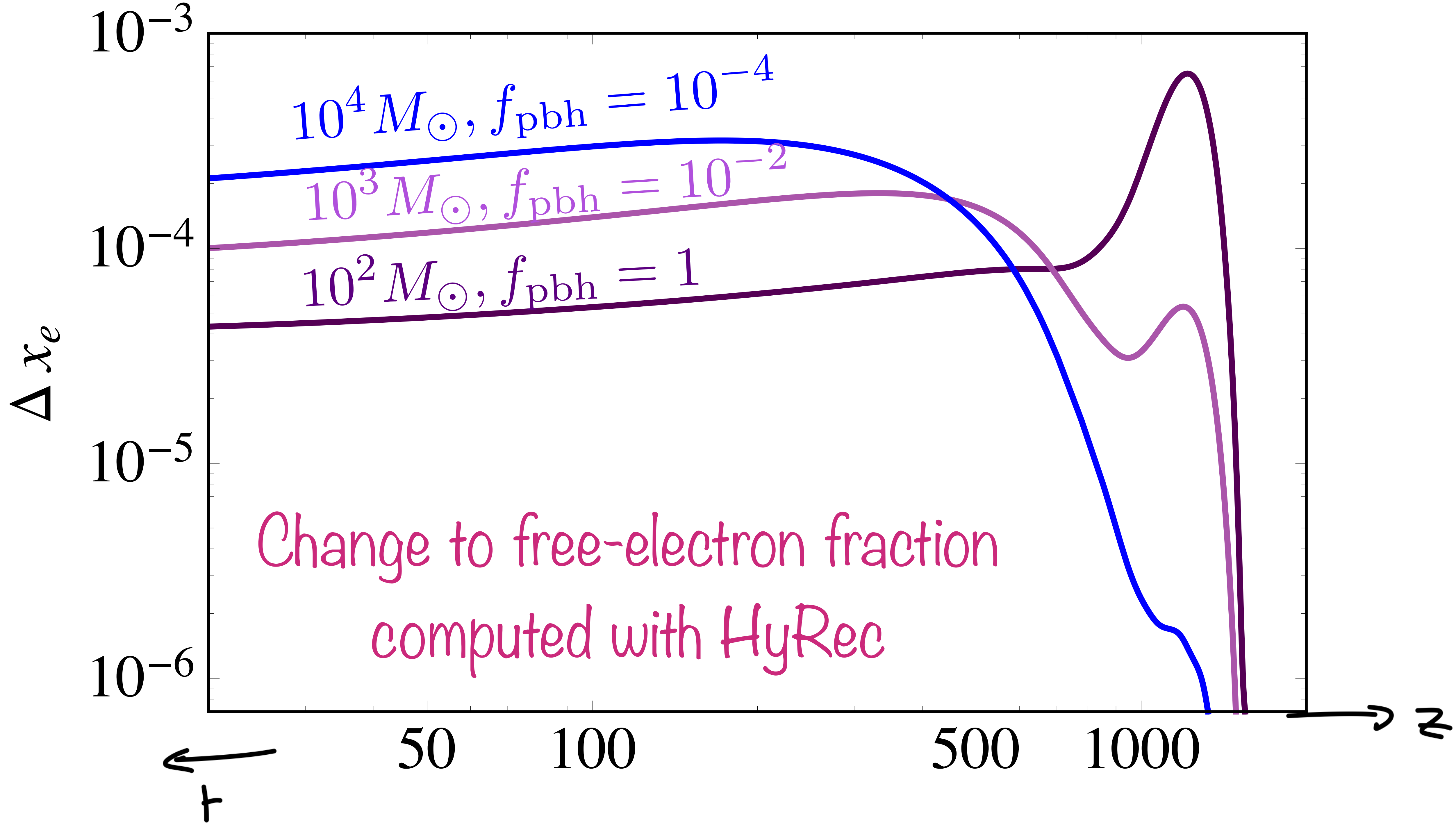
Recombination



Planck sensitive to ~ 0.1 % changes to this function



$$\dot{x}_e = \dot{x}_e^{\mathrm{std}} + \frac{1}{3}\frac{(1 - x_e)\dot{\rho}_{\mathrm{dep}}}{13.6\ \mathrm{eV}\ n_{\mathrm{H}}}$$

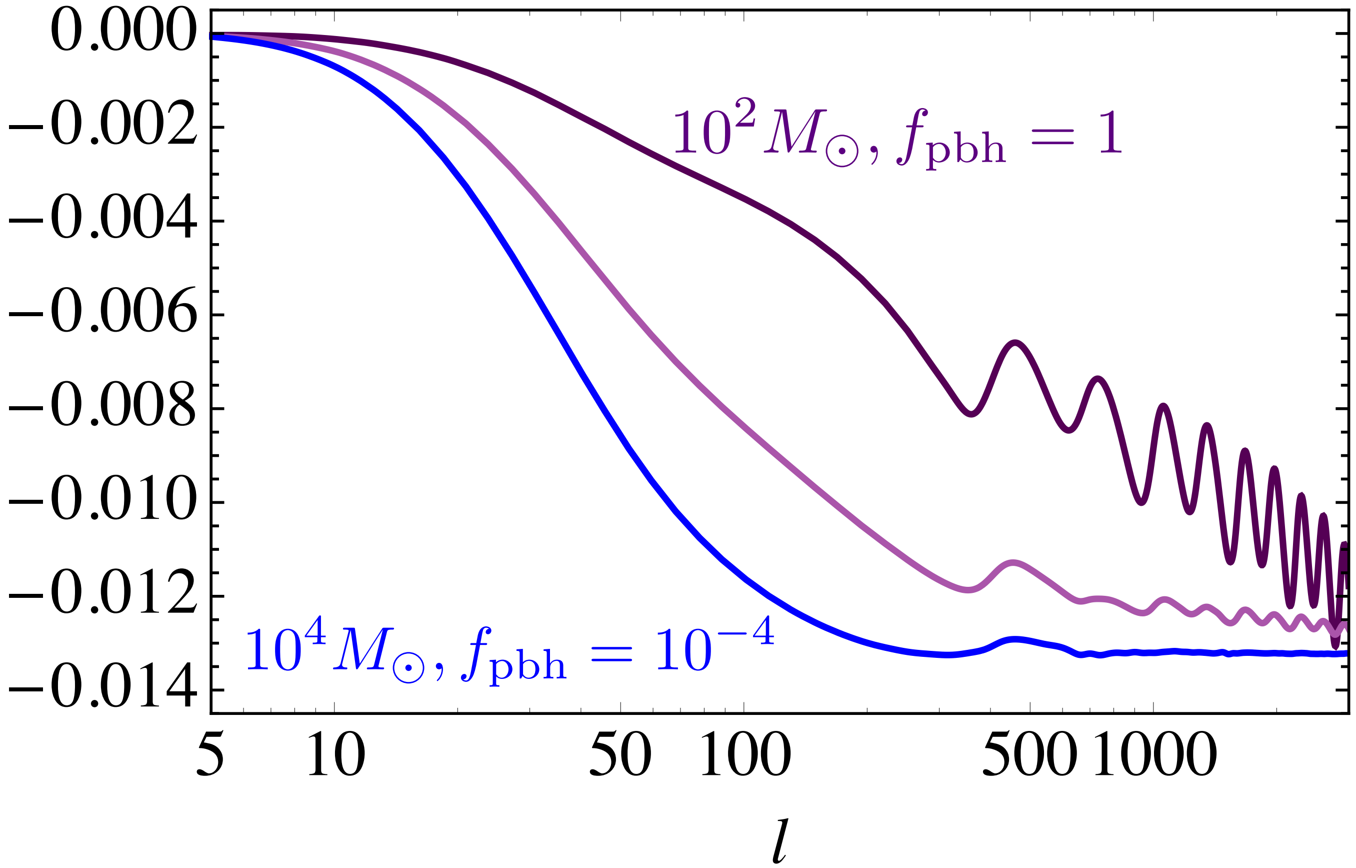


$10^{4}\,M_\odot,\, f_{\rm pbh} = 10^{-4}$
$10^{3}\,M_\odot,\, f_{\rm pbh} = 10^{-2}$
$10^{2}\,M_\odot,\, f_{\rm pbh} = 1$
$\Delta\, x_e$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
50
100
500
1000
z
t
Change to free-electron fraction
computed with HyRec

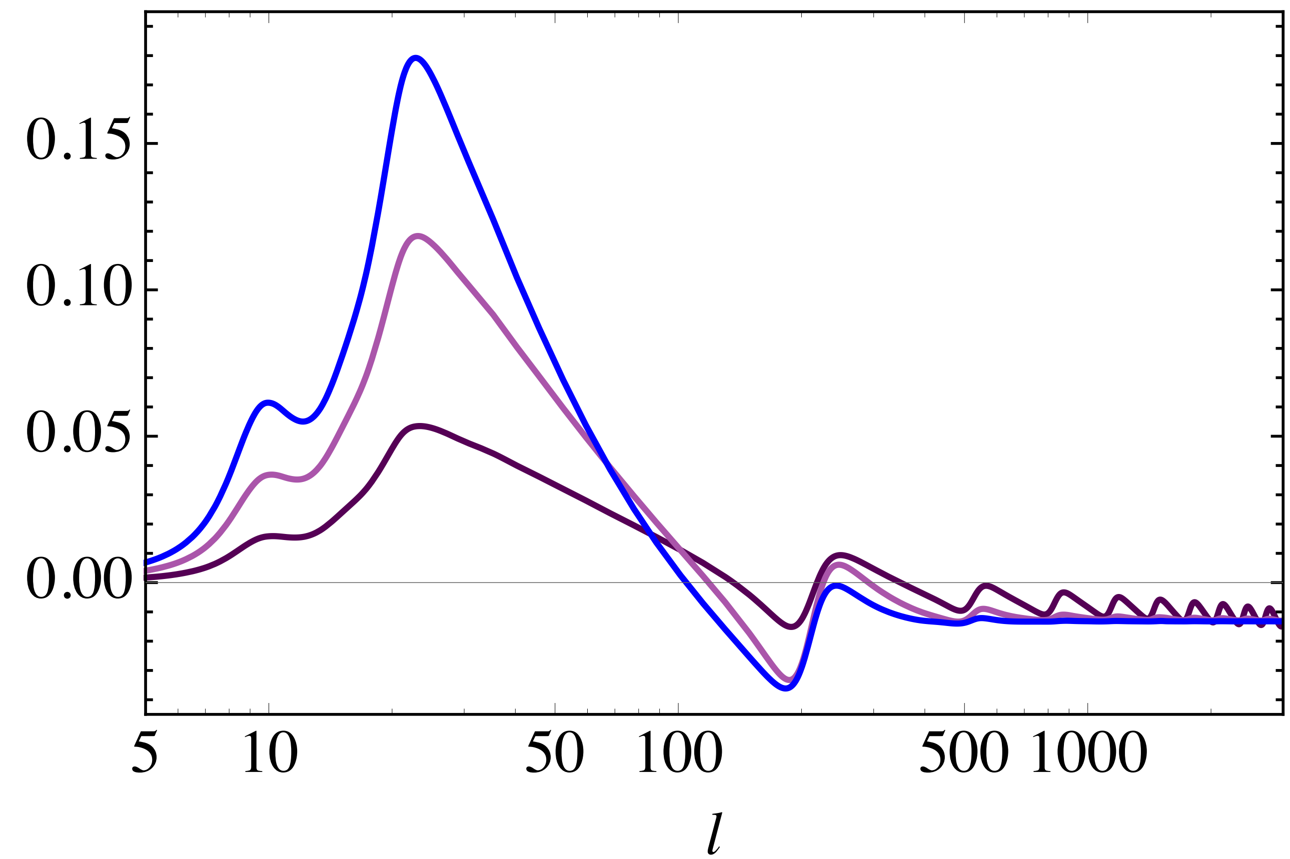
Effect on CMB anisotropies

with modified CLASS (Blas, Lesgourgues & Tram 2011)

Temperature $\Delta C_l/C_l$



Polarization $\Delta C_l/C_l$

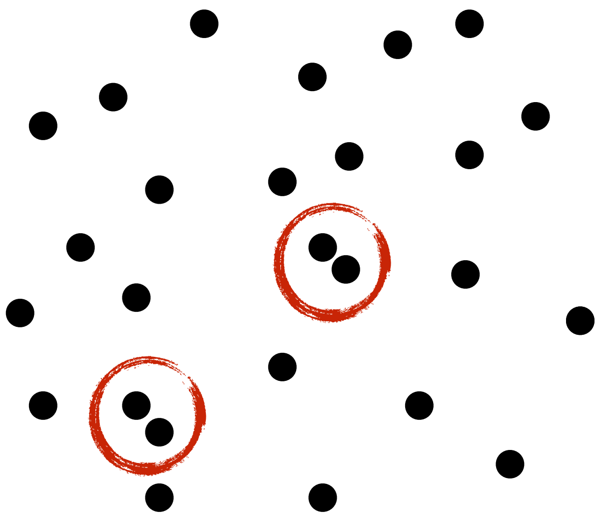


Qualitatively similar to increased reionization optical depth

- Very simplified treatment but bounds ought to be conservative
- Concrete suggestions on what might loosen the bounds are welcome. e.g. ideal fluid assumption may not hold (A Gruzinov)
- Most likely, can be made tighter:
  - accretion geometry and efficiency: disk vs spherical? e.g. Poulin et al. 2017
  - if $f < 1$, other-dark matter halo may enhance accretion rate (Ricotti, Ostriker & Mack 2008)
  - non-gaussianity from inhomogeneous recombination (in prep, with PhD student Trey Jensen)

Did LIGO detect dark matter?

Does LIGO rule out PBH dark matter?

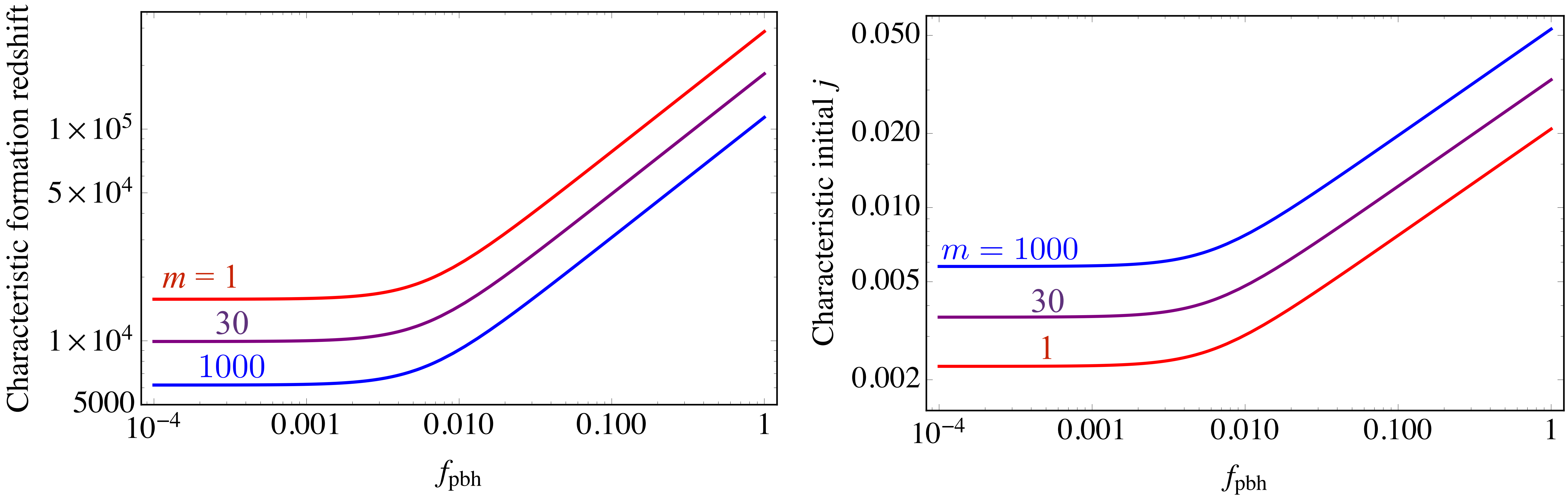


Basic idea: Nakamura et al. 1997, Sasaki et al. 2016
(cf Teruaki Suyama's talk)

Additions in paper with Kovetz & Kamionkowski:

- more accurate description of probability distribution of a, e at binary formation (cf. Raidal et al. 2018 for even more accurate description)
- analytically checked whether PBH binaries get significantly torqued by first non-linear structures (cf Kavanagh et al. 2019 for numerical check of effect of particle-dark matter halo).

Characteristic initial properties for binaries merging today:



Do binaries that form at $z \sim 10^4 - 10^5$ evolve

only through GW radiation until the present time?

Characteristic properties of early haloes

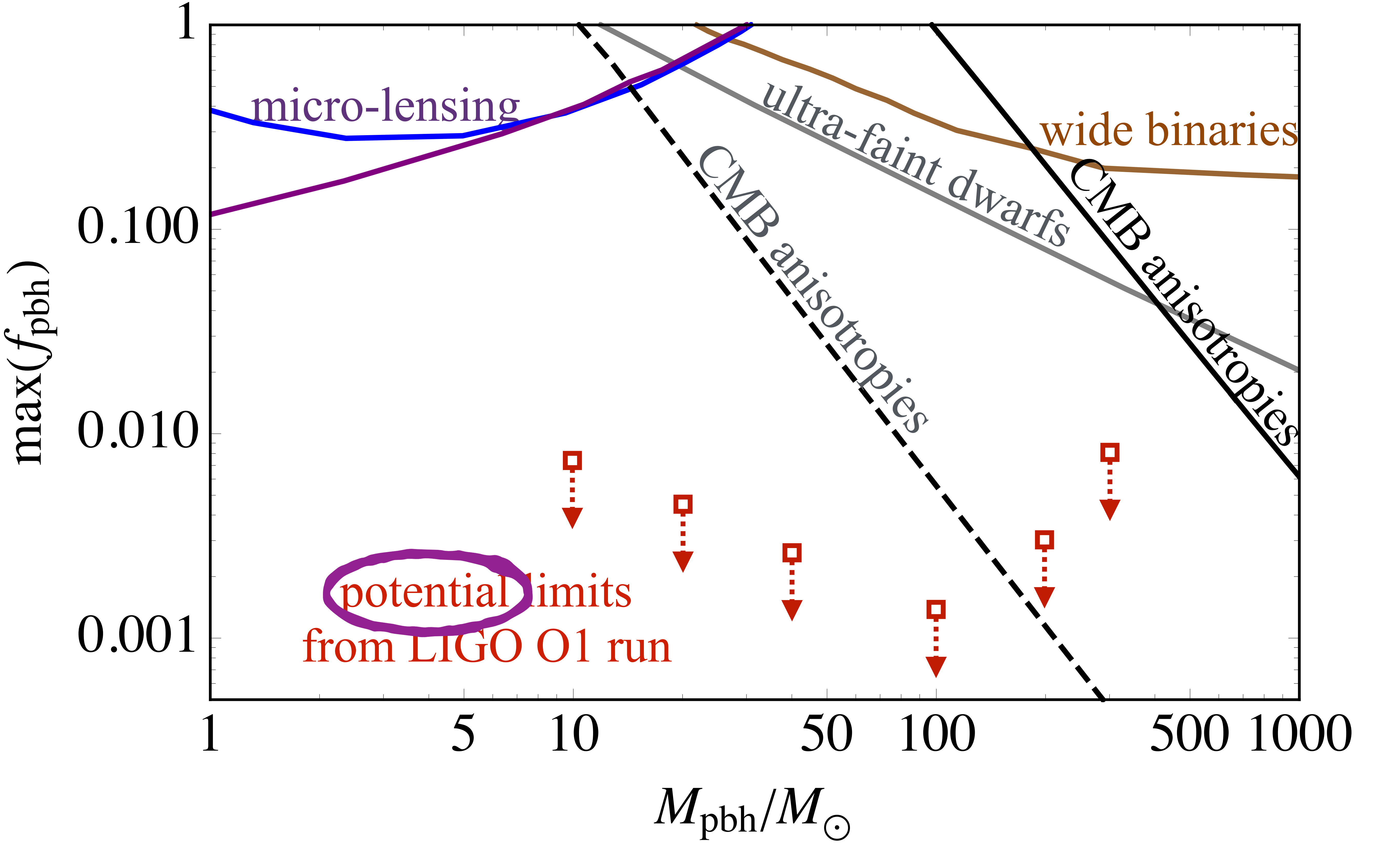
variance of perturbations on scale M_h	$\sigma^2(M_h;\mathrm{eq}) \approx \sigma^2_{\mathrm{eq}} + \frac{f^2}{\langle N \rangle} = \sigma^2_{\mathrm{eq}} + f\frac{M}{M_h}.$
characteristic collapse scale factor	$s_{\mathrm{coll}}(M_h) \approx \left(\sigma^2_{\mathrm{eq}} + fM/M_h\right)^{-1/2}$
characteristic density	$\rho_h \approx 200\ \overline{\rho}_m(s_{\mathrm{coll}})$
characteristic velocity dispersion	$v_h^2 \approx 2\left(\frac{4\pi\rho_h}{3}M_h^2\right)^{1/3}$
dynamical time	$t_h \approx \sqrt{\frac{3}{4\pi\rho_h}}.$

We assume that most of the mass lies in haloes currently collapsing.

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 $m \ll M$

Numerical checks needed



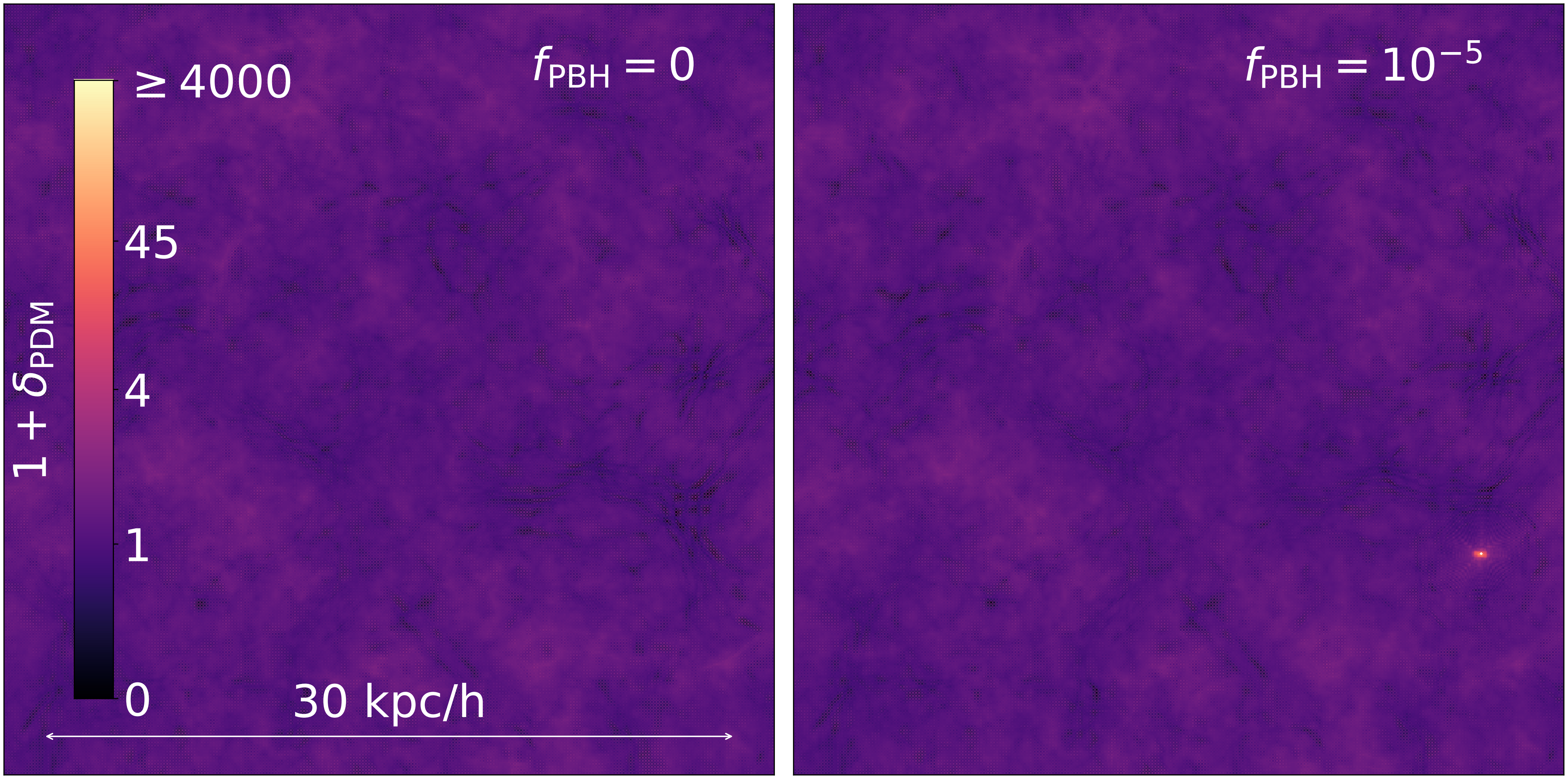
Structure formation in ΛPBH cosmology

with Derek Inman (in preparation)

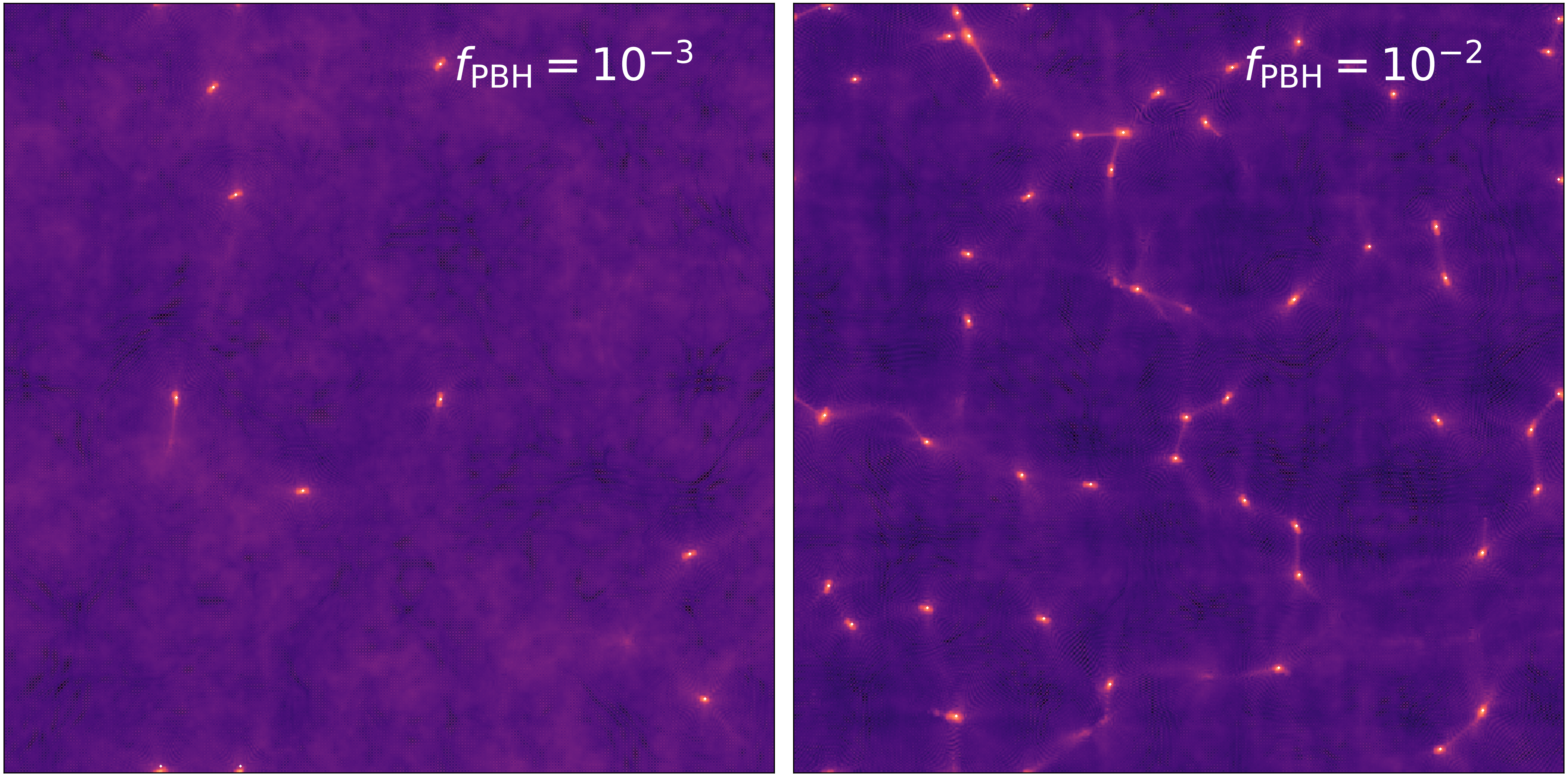
- Use N-body code CUBEP^{3}M (Merz et al. 2004, Harnois-Déraps et al. 2012, Emberson et al. 2016)
- fraction f_{pbh} in PBHs and $(1-f_{pbh})$ made of low-mass collisionless particles "PDM"
- PDM given adiabatic initial conditions consistent with (extrapolated) Planck
- PP force for $r < 3$ grid cells
- softening: 1/10 grid cell (unphysical for PBHs)

- **box size: $L = 45$ kpc**
- **PDM: 2×256^3 "particles", with mass $0.09\,(1-f_{pbh})\,M_{sun}$**
- **PBH mass: $30\,M_{sun}$. $N_{pbh} = 10^5\,f_{pbh}$**

snapshots at $z = 99$, slice width = 3 kpc



snapshots at $z = 99$, slice width = 3 kpc



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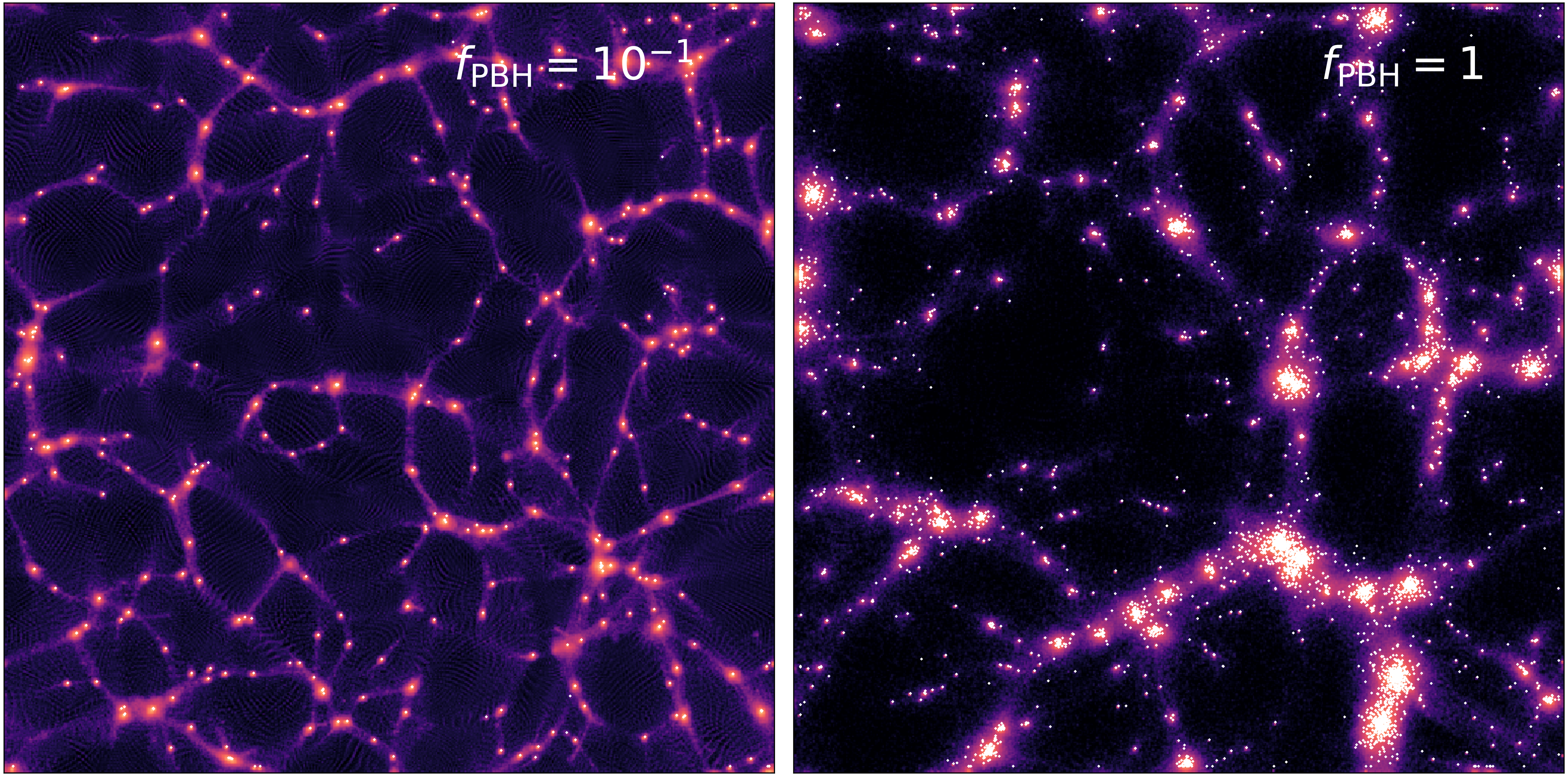
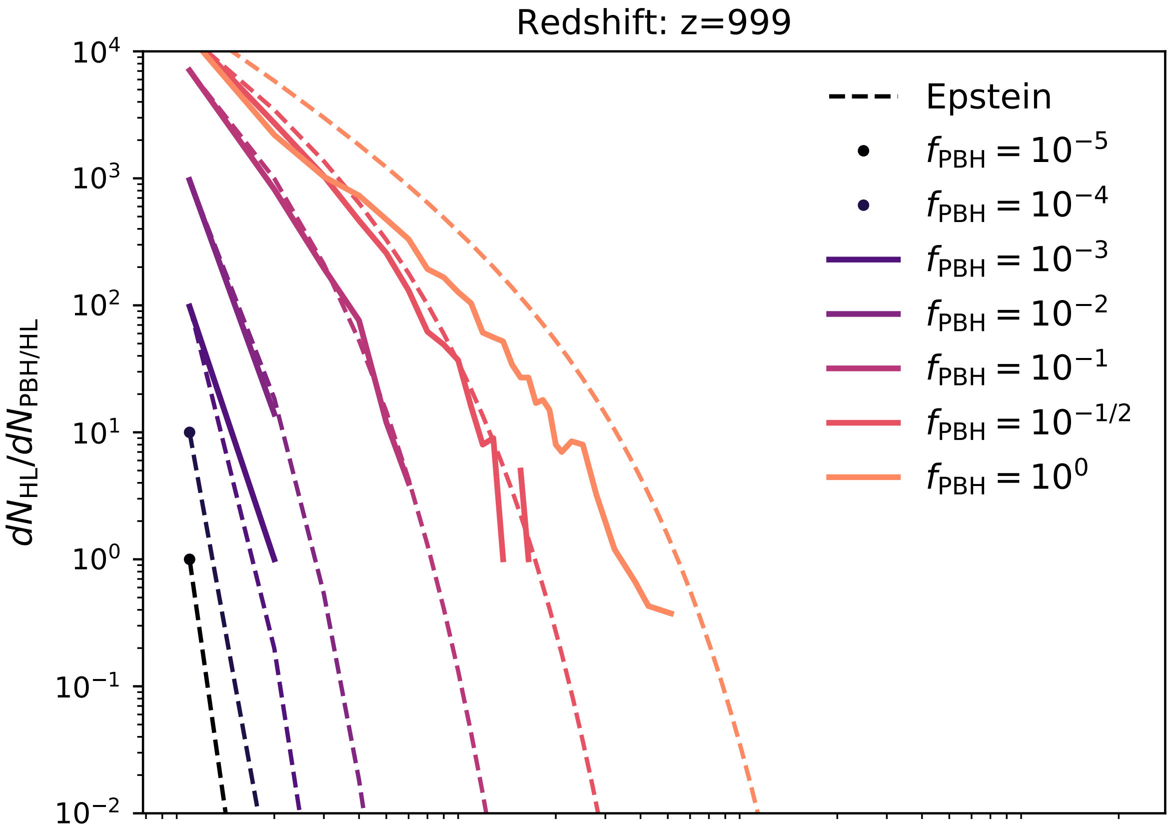
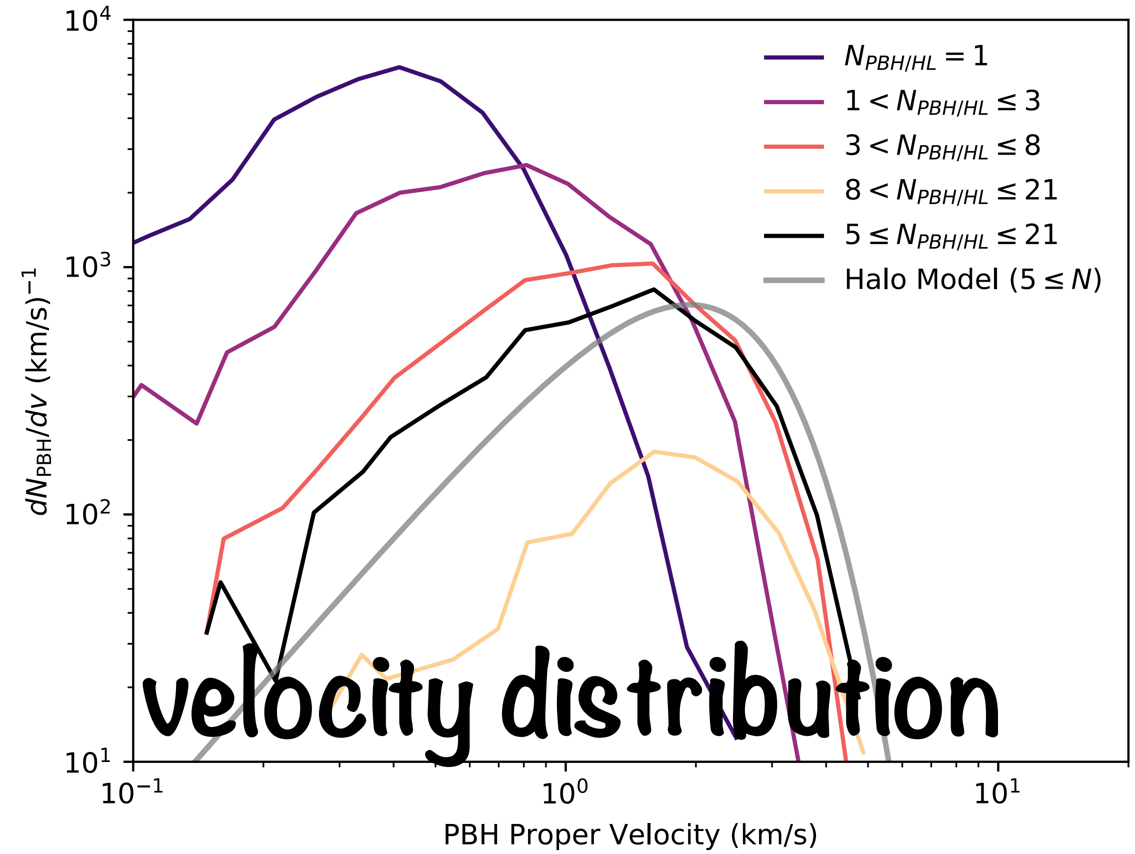
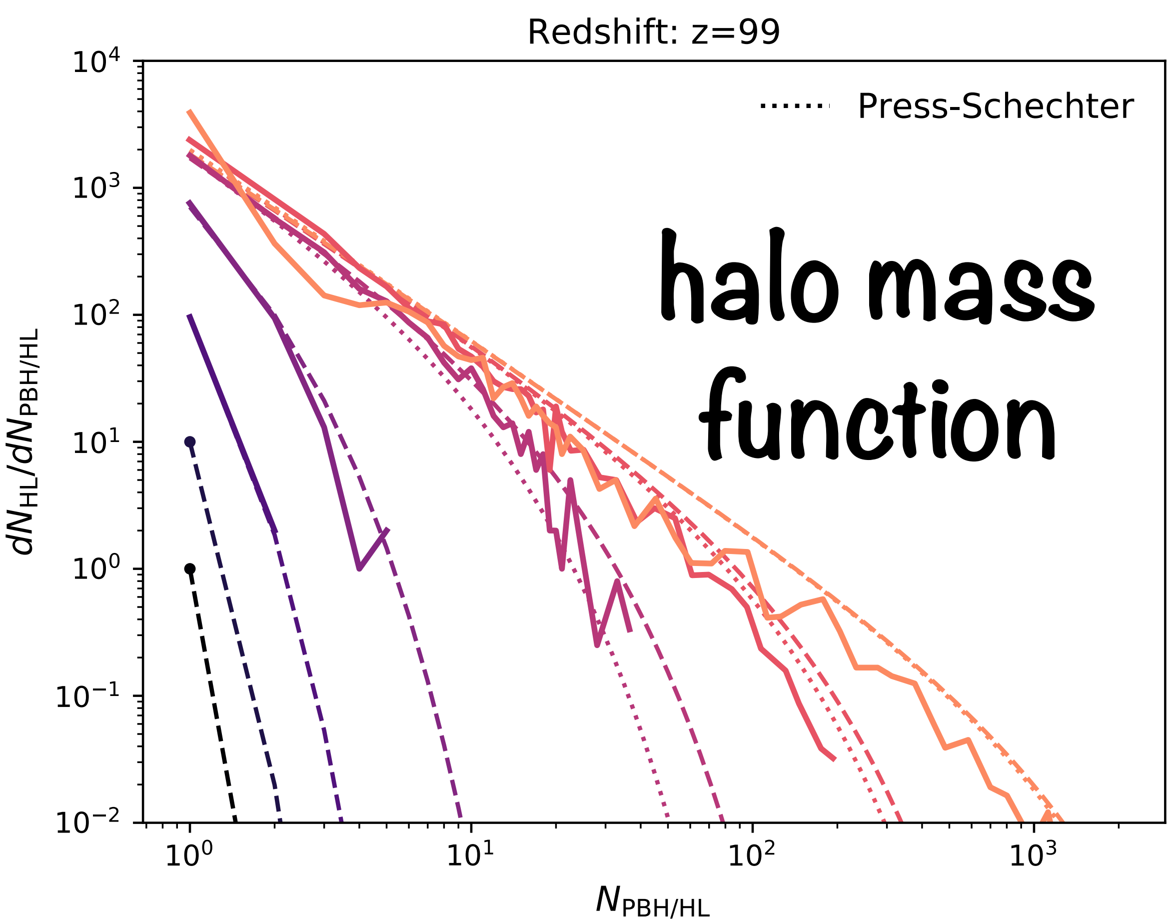
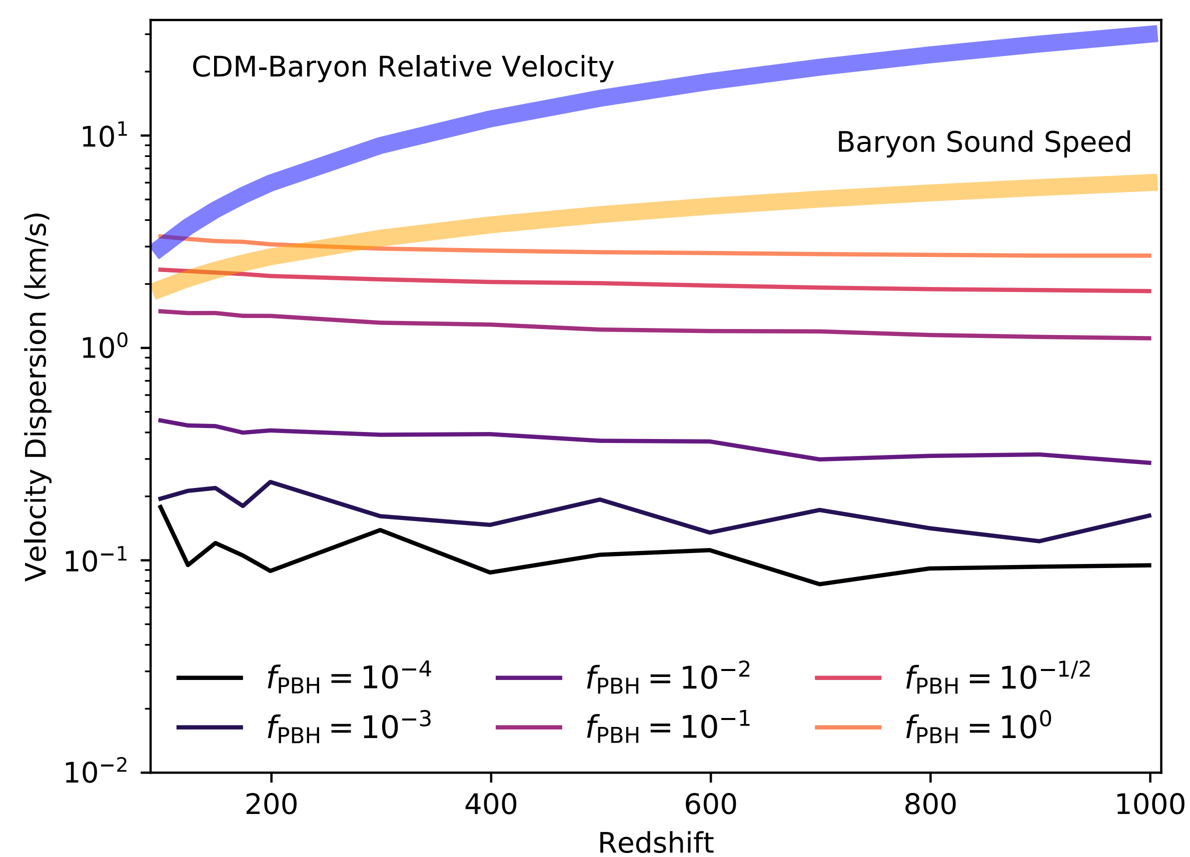


Sanity checks

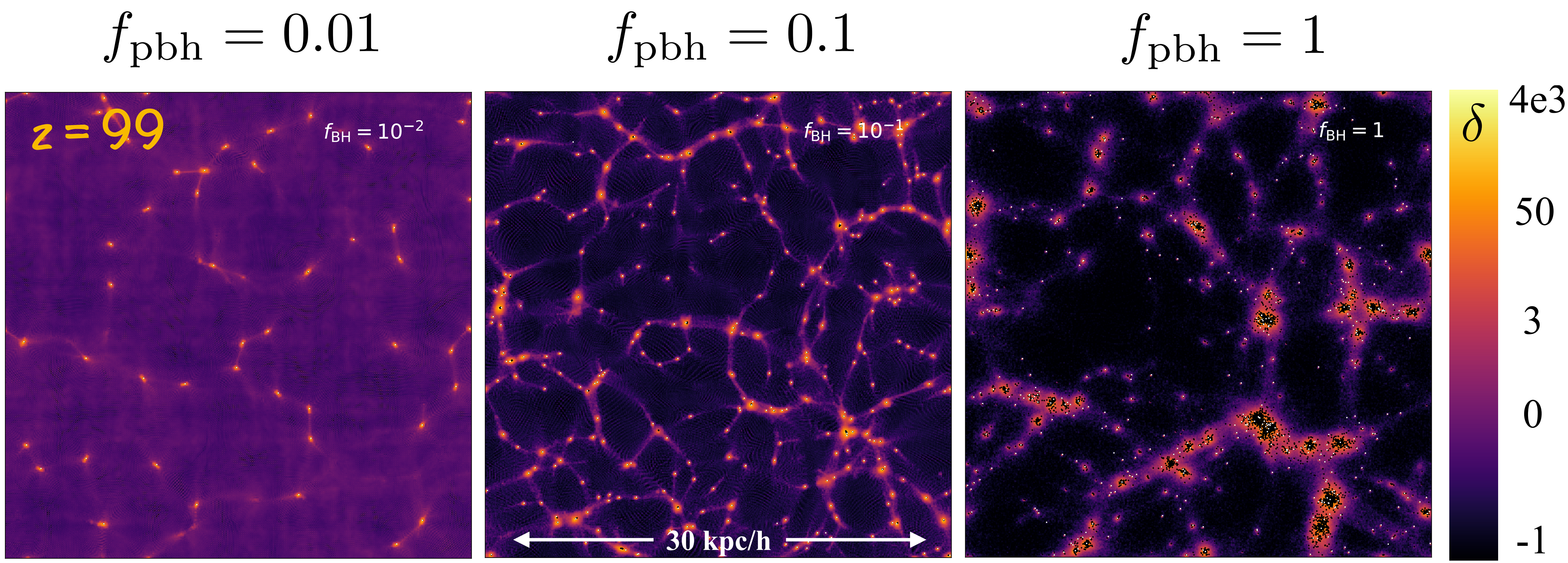








Program with N-body sims



Inman & Ali-Haïmoud, in prep.

- PBH binary survival
- More generally, impact on current bounds
- Formation of first stars (cf Kashlinsky)
- Impact on reionization, 21 cm?