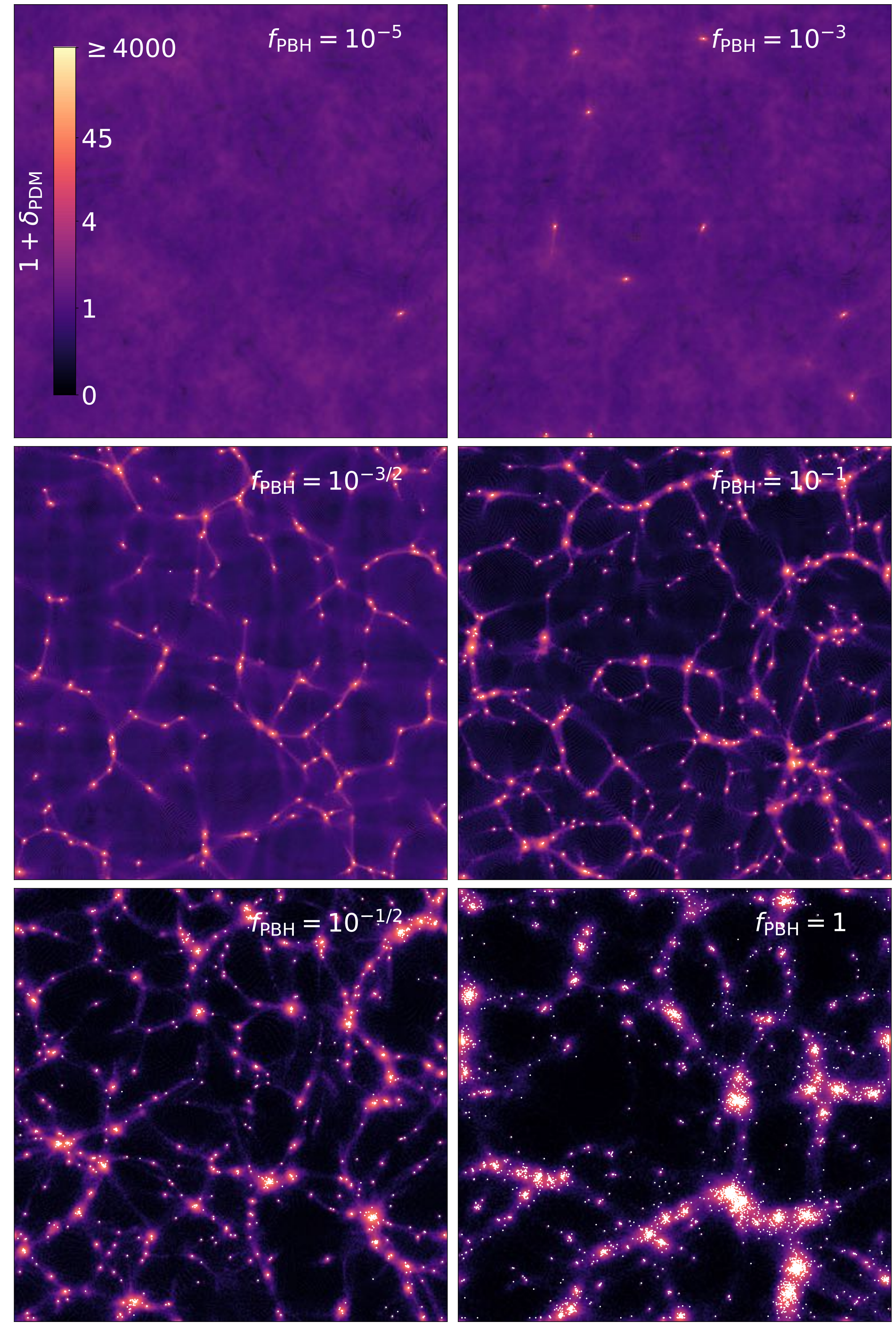
Primordial Black Hole Clustering and Gas Accretion

Derek Inman
Postdoc Colloquium
2021/10/01

KAVLI IPMU
INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE



Inman and Ali-Haïmoud (2019)
Serpico, Poulin, Inman and Kohri (2020)
Inman and Ali-Haïmoud (In progress)

Solar mass primordial black holes (PBHs)…

- …could be dark matter! Or some fraction of it:

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}}$$

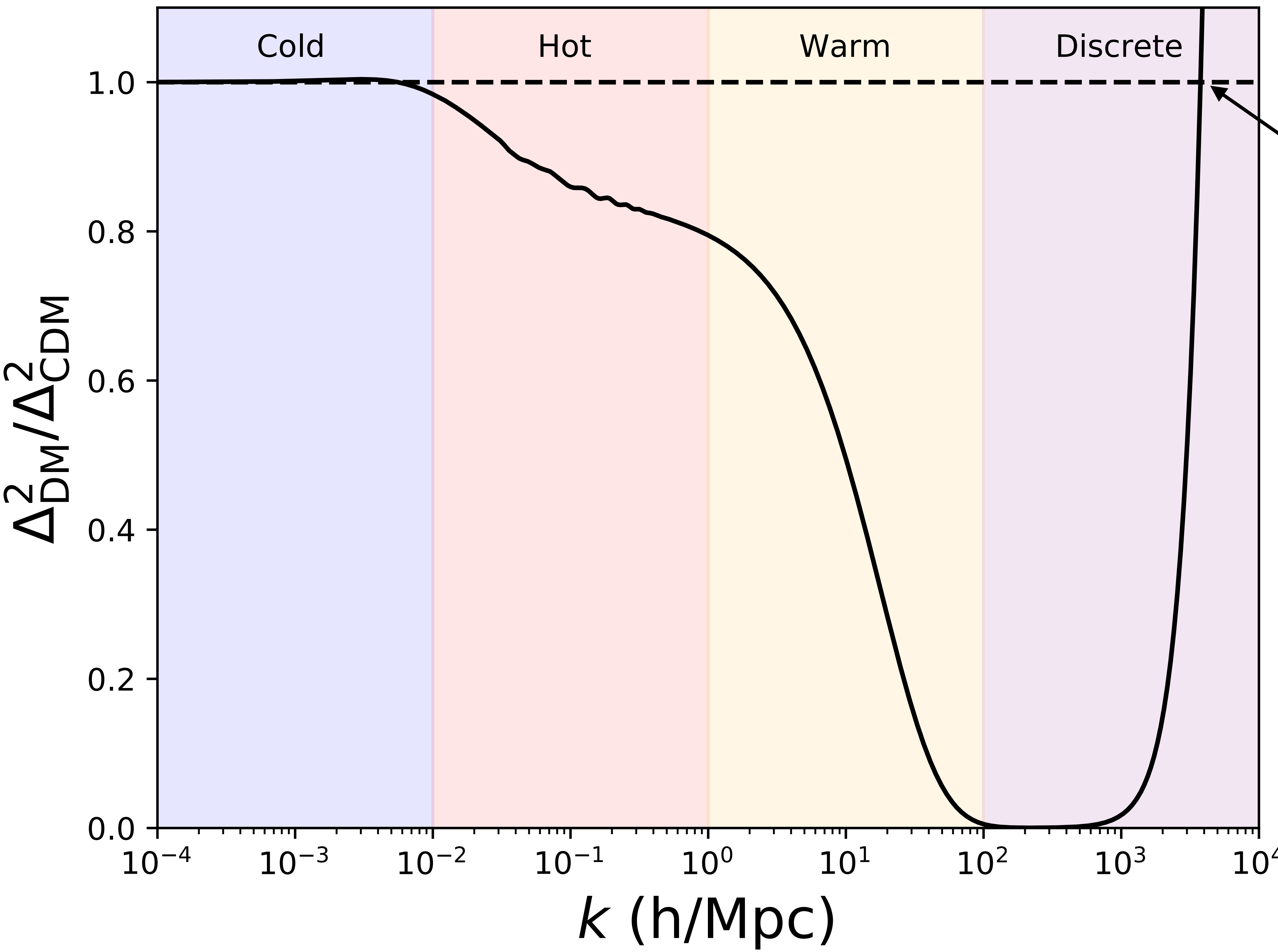
- …could be LIGO events!

Did LIGO Detect Dark Matter? Bird et al. (2016)
Also: Sasaki et al. 2016, Ali-Haïmoud et al. 2017

- …could be seeds for supermassive black holes!

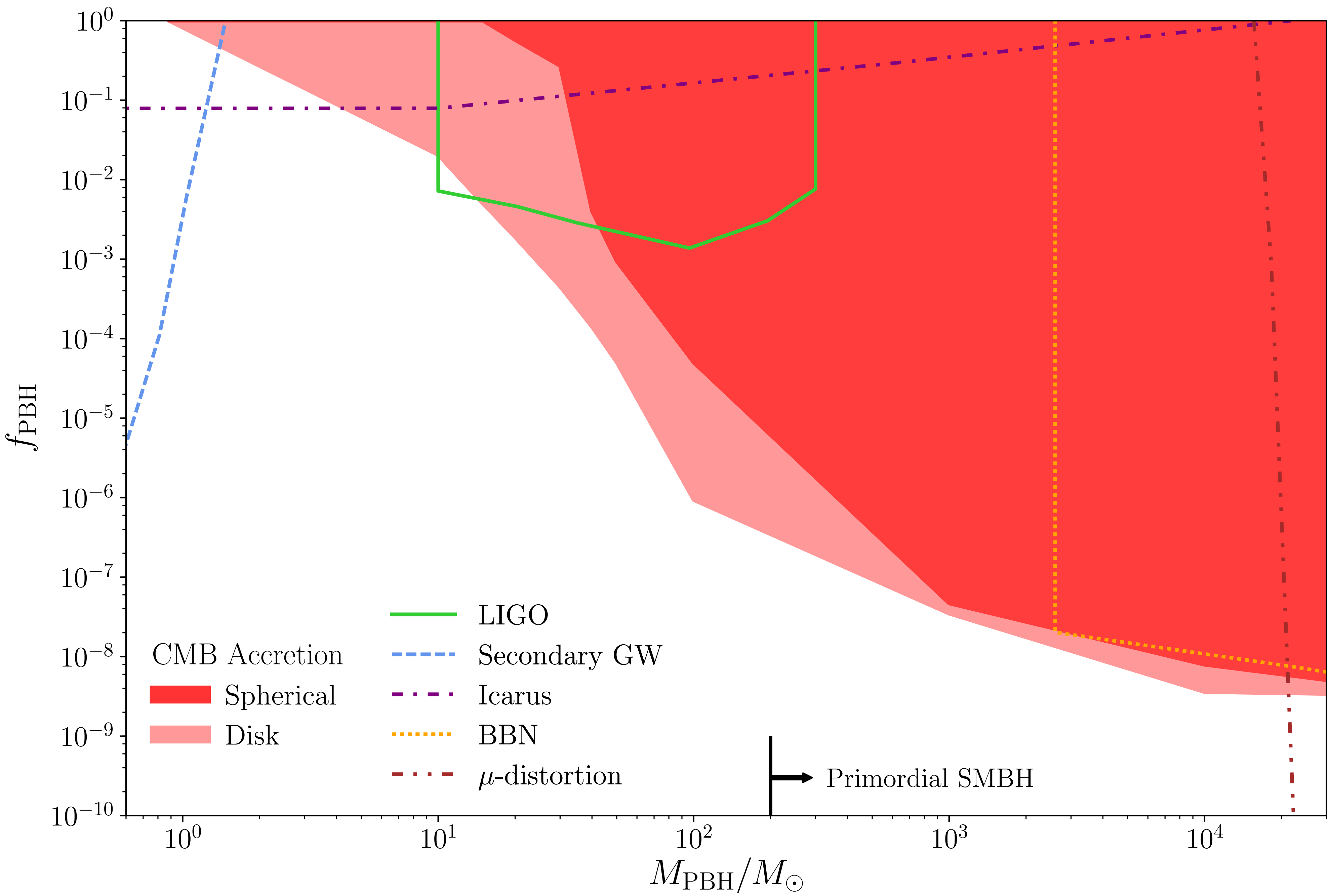
Serpico et al. (2020)

…could be dark matter…



$M_{\rm PBH} \lesssim 10^4 M_\odot$
Afshordi, McDonald and Spergel (2003)

…but there are constraints



Serpico et al. (2020)

Cosmic microwave background (CMB) constraints

- Where do they come from?
  - PBHs accrete gas after recombination
  - Gas heats up and radiation is emitted
  - Radiation changes thermal and ionization histories
  - More information: Ricotti, Ostriker and Mack (2008), Ali-Haïmoud and Kamionkowski (2017)
- Need to model gas accretion

Gas accretion

- Bondi-Hoyle-Littleton rate:

$$\dot{M} \propto \rho_\infty \frac{(GM)^2}{(V^2 + c_s^2)^{3/2}}$$

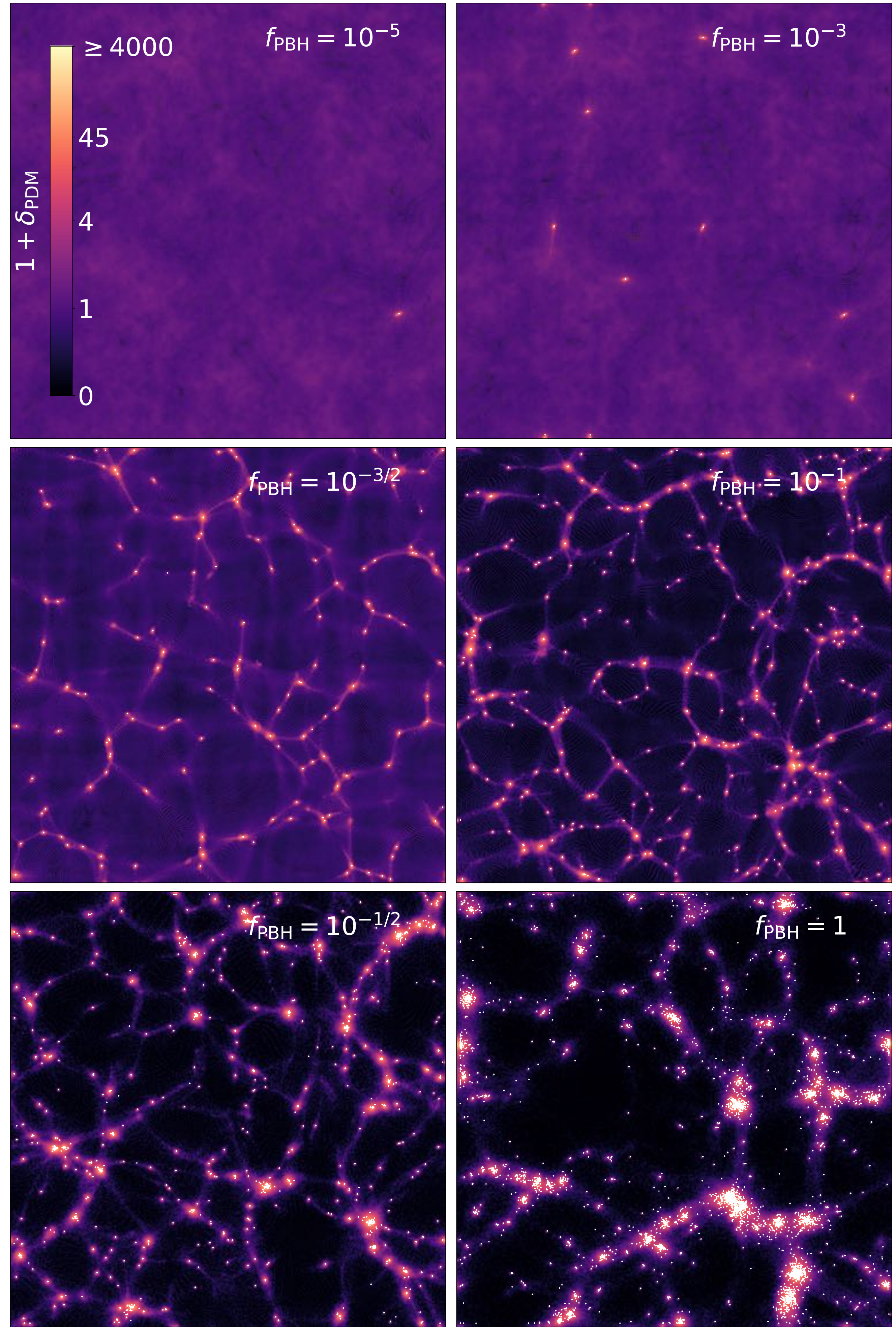
Bondi (1952)

- But what values to use?
    - $M = M_{\rm PBH}$
    - $V \propto \sigma_{\rm rel}$
    - $\rho_\infty = \bar{\rho}_b a^{-3}$
    - $c_s^2 \propto \bar{T}_b$

← Conservative choices, but are any of these values correct?

Simulations

- Redshift: $10^6 \geq z \geq 10^2$
- Volume: $(35\ \mathrm{kpc})^3$
- Cold dark matter
  - PBHs ($M_{\mathrm{PBH}} = 30\ M_\odot$)
    - Poisson distributed
  - Other DM if $f_{\mathrm{PBH}} < 1$
- Baryons?



Inman and Ali-Haïmoud (2019)

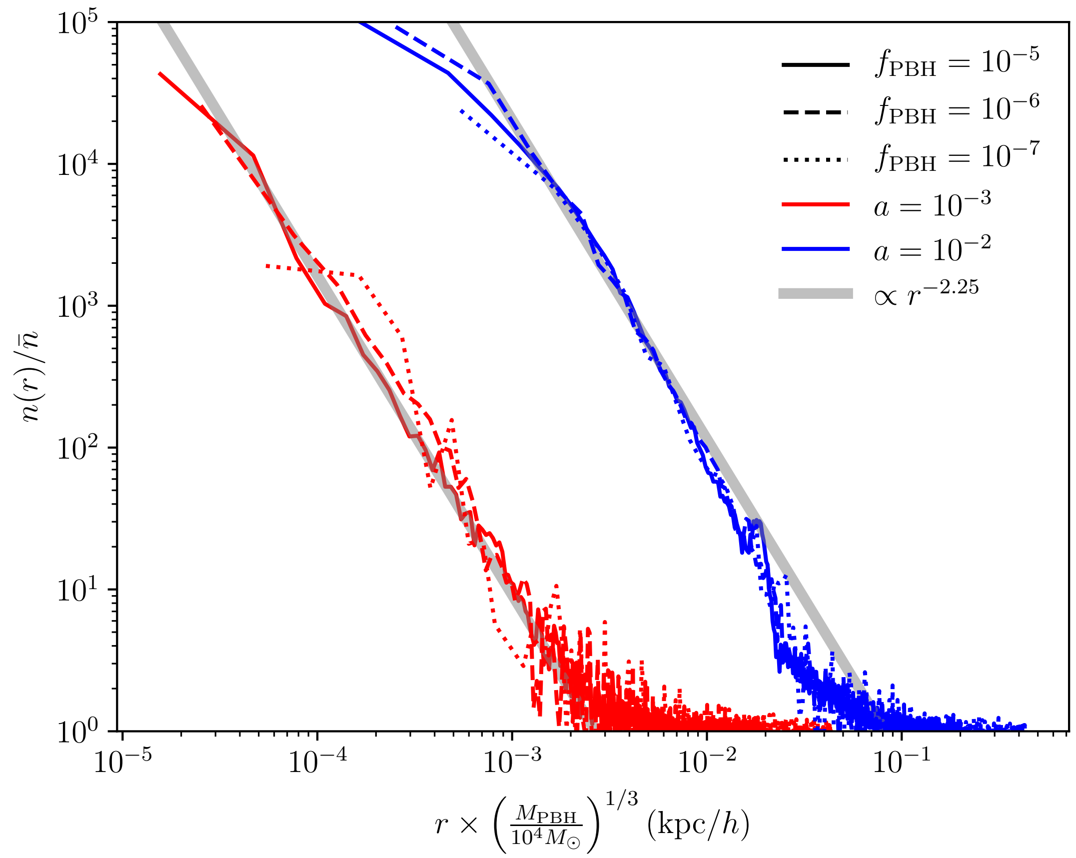
$$f_{\mathrm{PBH}} \ll 1$$

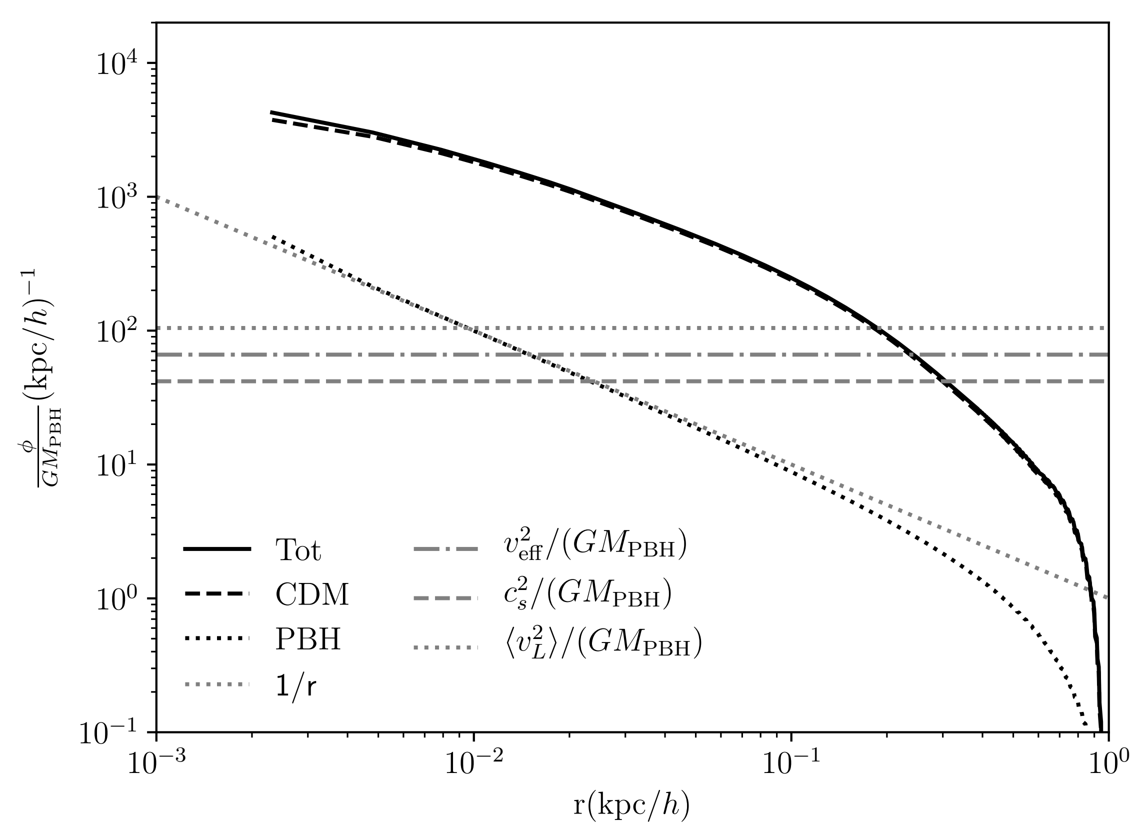
- PBHs are rare, and mostly isolated from one another
  - Can use background values for $\rho_\infty,\ c_s$

- Accretion will depend on what the rest of the dark matter is!
  - Other dark matter doesn't cluster
  - Other dark matter does cluster

$f_{\rm PBH} \ll 1$

- Other dark matter is cold, collisionless "particle dark matter," forms a halo around the PBH





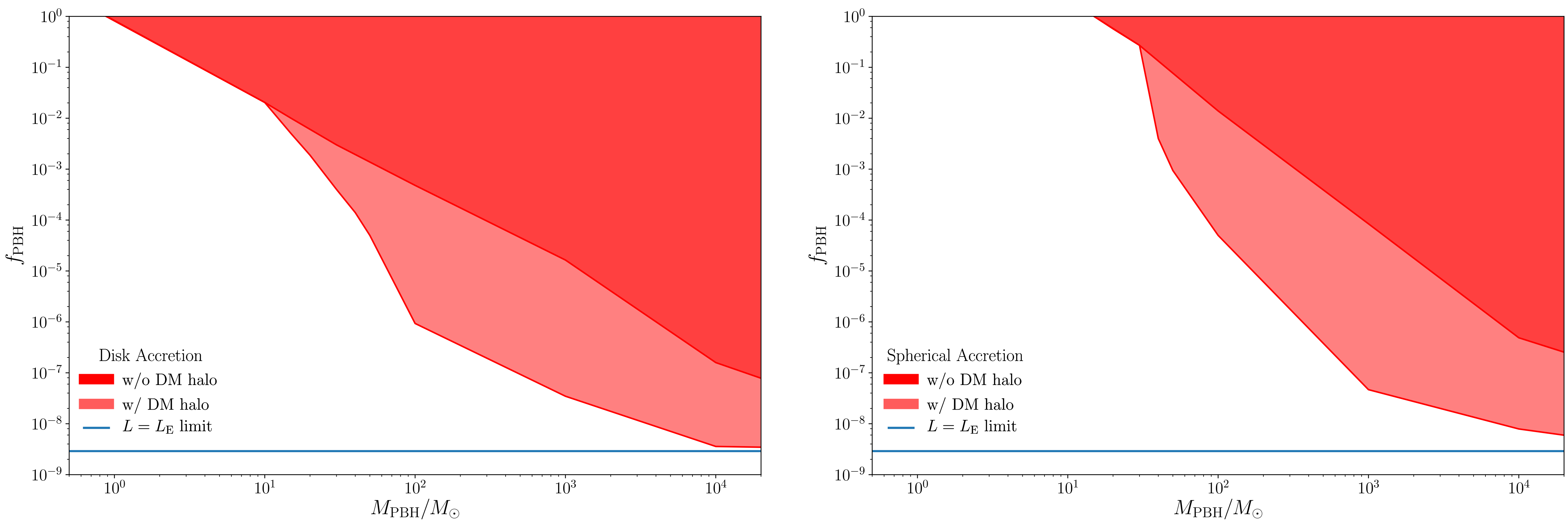
Serpico et al. (2020)

Self-similar Profile: $\rho \propto r^{-9/4}$
(Bertschinger 1985, see also Adamek et al. 2019)

$$\dot{M} \propto \rho_\infty \frac{(GM)^2}{(V^2 + c_s^2)^{3/2}} \rightarrow M \geq M_{\rm PBH}$$

$f_{\mathrm{PBH}} \ll 1$

- Constraints significantly improve…

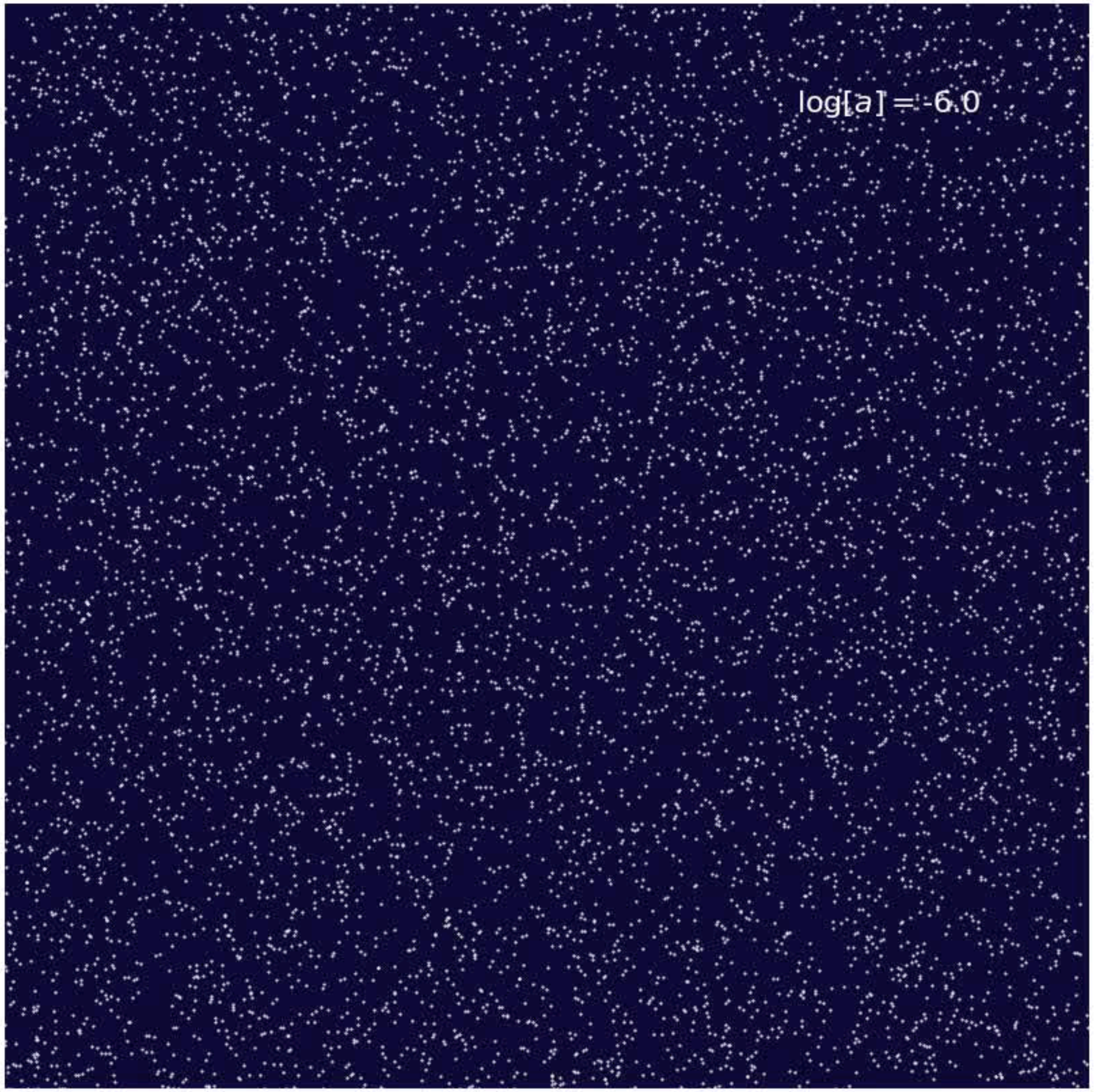


Serpico et al. (2020)

…but requires an additional assumption about dark matter

$f_{\rm PBH} \sim 1$

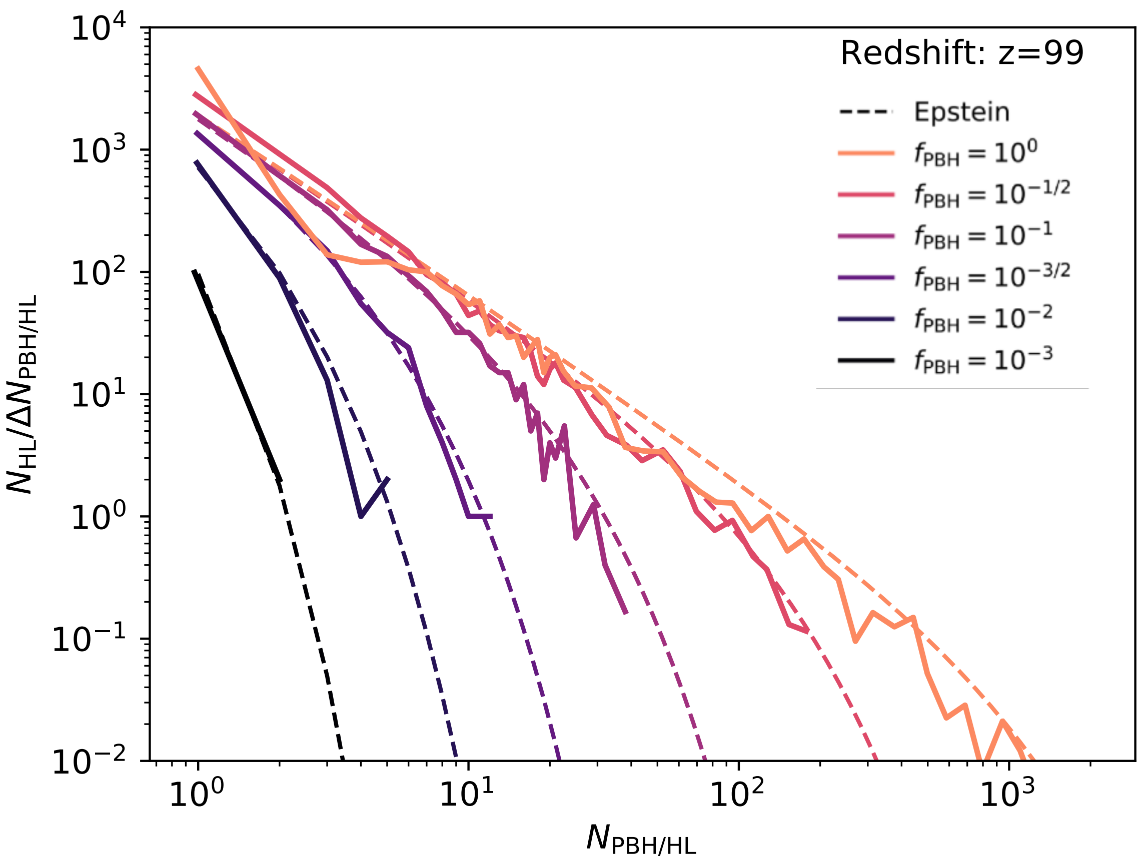
- PBHs are common, and interact with each other gravitationally

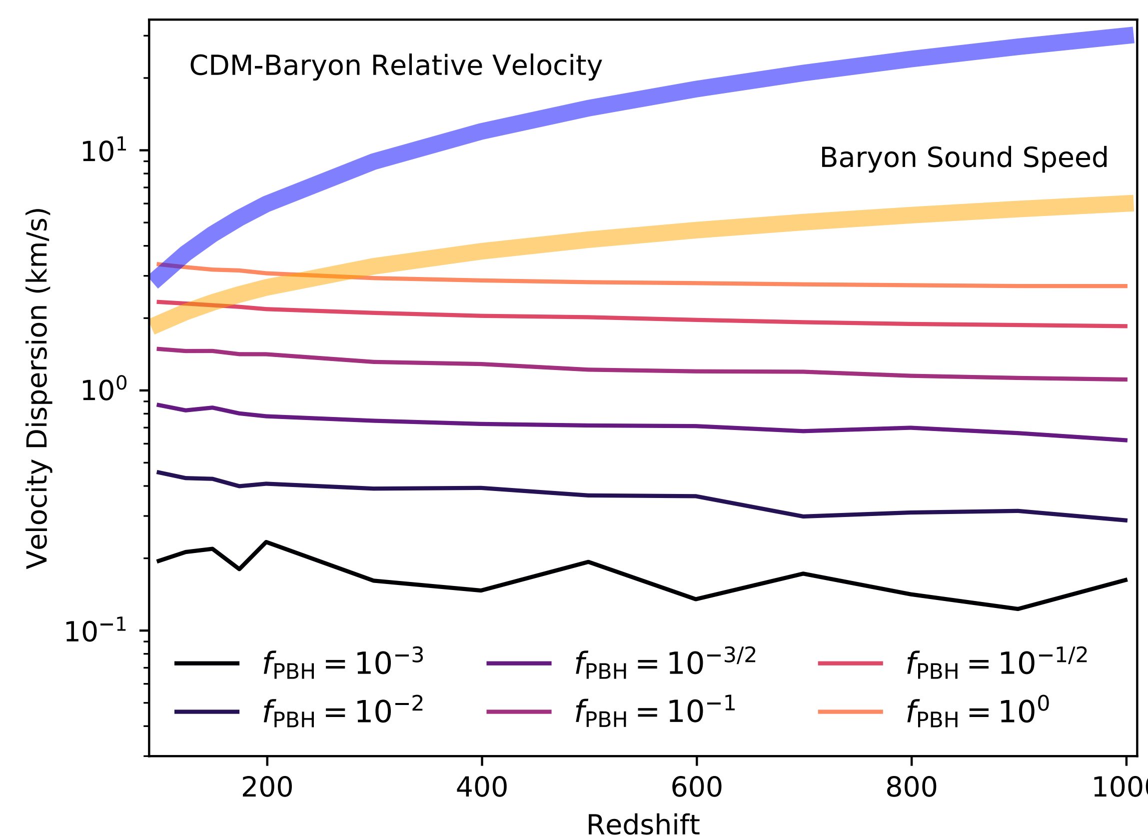


Inman and Ali-Haïmoud (2019)

$f_{\rm PBH} \sim 1$

- Halos composed of many PBHs form





Inman and Ali-Haïmoud (2019)

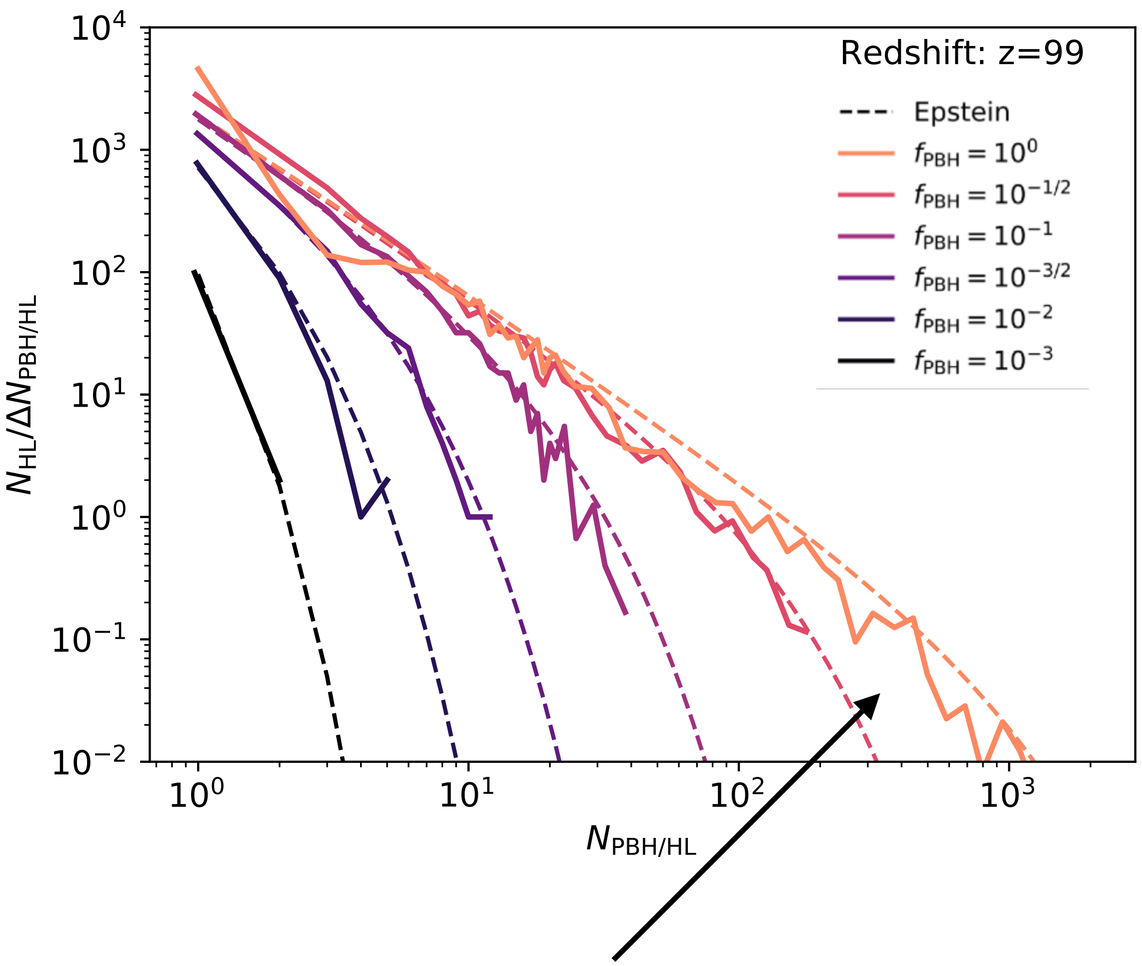
$$N_{\rm HL}(N) = \frac{N_{\rm PBH}}{N}\frac{\delta_*}{1+\delta_*}\left(\frac{N}{1+\delta_*}\right)^{N-1}\frac{\exp\left[-\frac{N}{1+\delta_*}\right]}{(N-1)!}$$

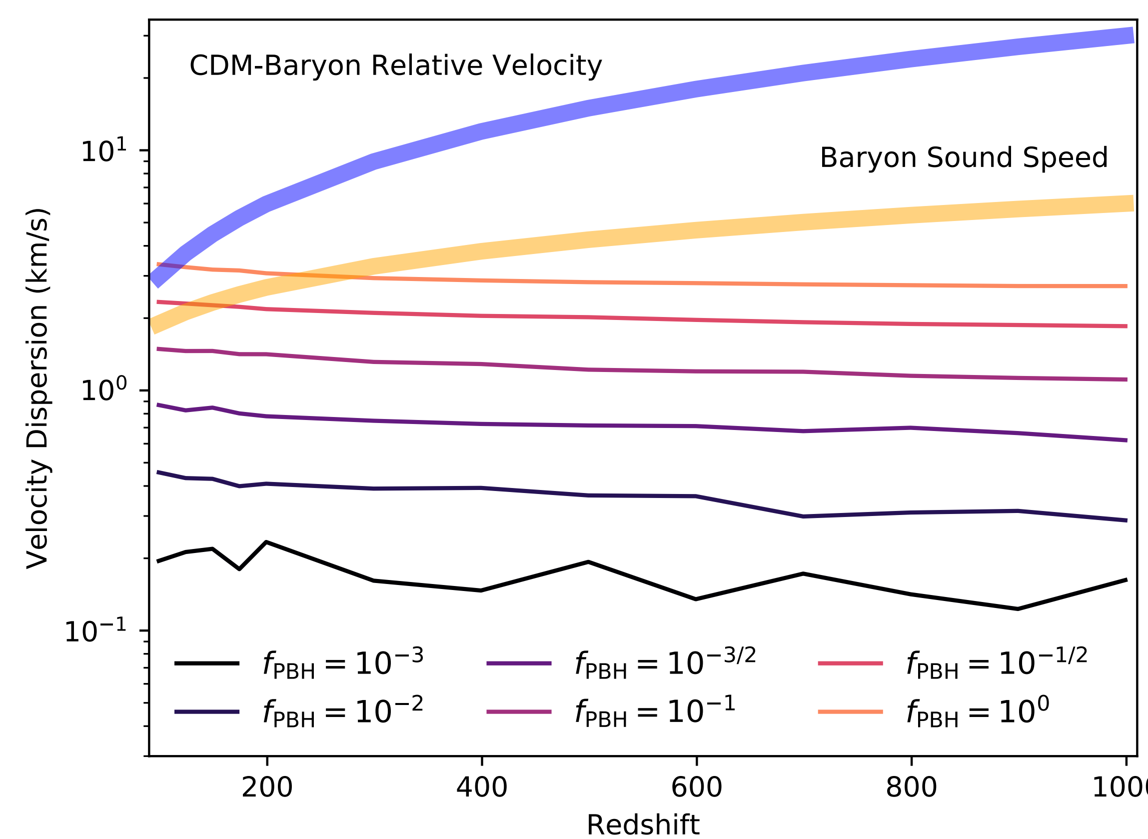
Epstein (1983), Sheth (1995)

$$\dot{M} \propto \rho_\infty \frac{(GM)^2}{(V^2+c_s^2)^{3/2}} \rightarrow V, c_s > V_{\rm Vir}$$

$f_{\mathrm{PBH}} \sim 1$

- Halos composed of many PBHs form





Inman and Ali-Haïmoud (2019)

Halos have $M \sim 1000\ M_{\mathrm{PBH}}$, so what about the baryons?

$$\dot{M} \propto \rho_\infty \frac{(GM)^2}{(V^2 + c_s^2)^{3/2}} \rightarrow \rho_\infty, c_s?$$

Gas dynamics - Preliminary

- Ideal gas coupled to CMB via Compton scattering

Ionization Fraction: currently use background value… but working on perturbed x_e

$$\frac{\partial \rho}{\partial t} + \nabla^k\left(\rho V^k\right) = 0$$

$$\frac{\partial \rho V^i}{\partial t} + \nabla^k\left(\rho V^i V^k + P\delta^{ik}\right) = \rho g^k + \rho \Gamma_V(a)\left(V^k_{\rm CMB} - V^k\right)$$

$$\frac{\partial E}{\partial t} + \nabla^k\left((E+P)V^k\right) = \rho V^k g^k + \rho V^k \Gamma_V(a)\left(V^k_{\rm CMB} - V^k\right) + \frac{P}{(\gamma-1)T}\Gamma_T(a)(T_{\rm CMB} - T)$$

$$\mu(a) = \frac{1+4f_{\rm He}}{1+x_e(a)+f_{\rm He}}$$

$$P = \rho k_B T/(\mu m_{\rm H})$$

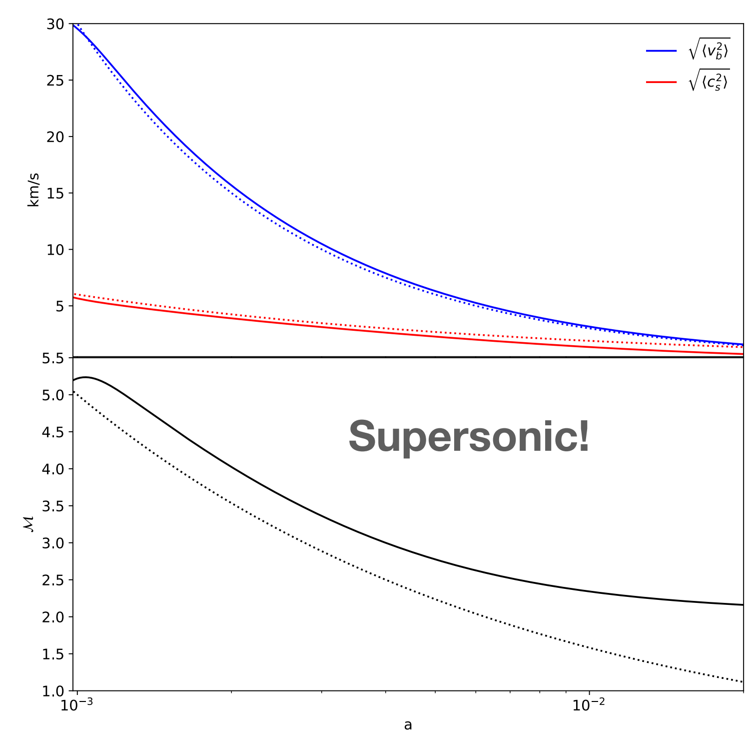
$$\Gamma = \frac{8\pi^2}{45}\frac{\sigma_T k_B T^4_{\rm CMB}}{m_e \hbar^3 c^4}$$

$$\Gamma_T(a) = \frac{x_e(a)}{1+x_e(a)+f_{\rm He}} a^{-2}\Gamma$$

$$\Gamma_V(a) = \frac{1}{2}\frac{m_{\rm e}}{\mu m_{\rm H}}\Gamma_T(a)$$

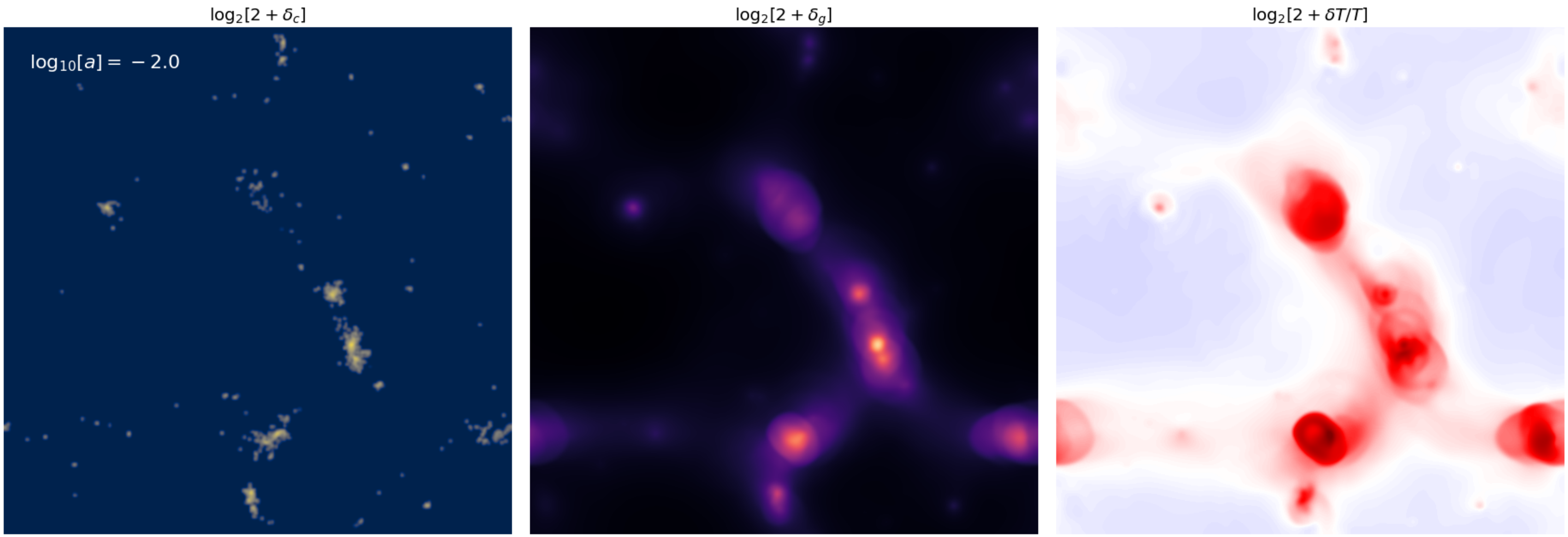
$$T_{\rm CMB} = 2.725(1+z)\ {\rm K}$$

Relative Velocity Effect: Gas moves w.r.t to CDM (Tseliakhovich and Hirata 2010)



Gas dynamics - Preliminary

- $f_{\rm PBH} \sim 1$



$$\dot{M} = 4\pi\lambda\rho_\infty \frac{(GM)^2}{(V^2 + c_s^2)^{3/2}} \rightarrow \rho_\infty, c_s?$$

Conclusions

- PBH dark matter significantly changes the structure formation history of the Universe
- CMB constraints can be substantially improved by taking halo formation into account
- Potential improvements by including baryons in the simulations
- Other consequences of early halos - star formation, magnetogenesis,…?

Thank you for your time!

References

- D. Inman and Y. Ali-Haïmoud, PRD 100, 083528 (2019), 1907.08129.
- P. D. Serpico, V. Poulin, D. Inman, and K. Kohri, PRR 2, 023204 (2020), 2002.10771.
- S. Bird, I. Cholis, J. B. Muñoz, Y. Ali-Haïmoud, M. Kamionkowski, E. D. Kovetz, A. Raccanelli, and A. G. Riess, PRL 116, 201301 (2016), 1603.00464.
- M. Sasaki, T. Suyama, T. Tanaka, and S. Yokoyama, PRL 117, 061101 (2016), 1603.08338.
- Y. Ali-Haïmoud, E. D. Kovetz, and M. Kamionkowski, PRD 96, 123523 (2017), 1709.06576.
- N. Afshordi, P. McDonald, and D. N. Spergel, ApJ 594, L71 (2003), astro-ph/0302035.
- M. Ricotti, J. P. Ostriker, and K. J. Mack, ApJ 680 (2008), 0709.0524.
- Y. Ali-Haïmoud and M. Kamionkowski, PRD 95, 043534 (2017), 1612.05644.
- H. Bondi, MNRAS 112, 195 (1952).
- E. Bertschinger, ApJS 58, 39 (1985).
- J. Adamek, C. T. Byrnes, M. Gosenca, and S. Hotchkiss, PRD 100, 023506 (2019), 1901.08528.
- R. I. Epstein, MNRAS 205, 207 (1983).
- R. Sheth, MNRAS 276, 796 (1995).
- D. Tseliakhovich and C. Hirata, PRD 82, 083520 (2010), 1005.2416.