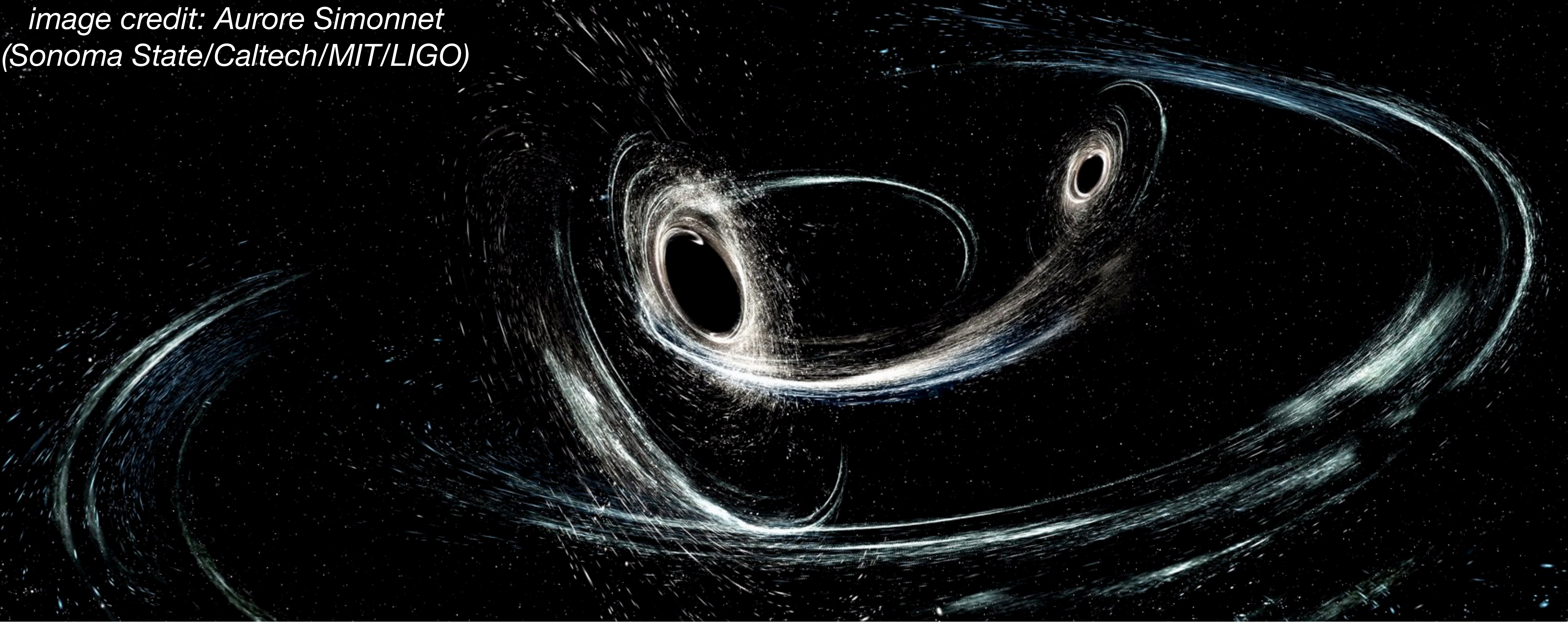
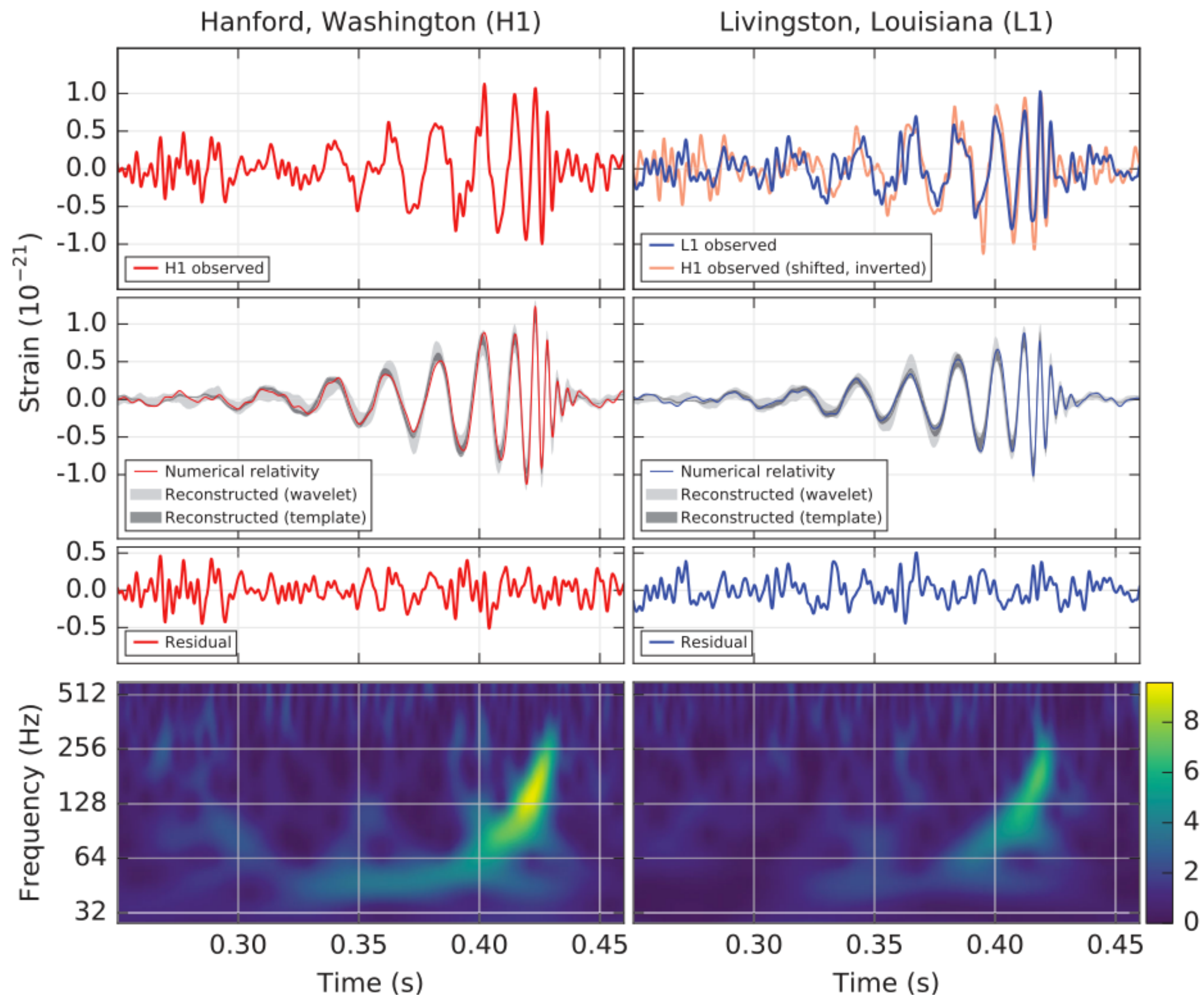


Yacine Ali-Haïmoud, NYU

Probing dark matter with spectral distortions (and other probes)

February 2016

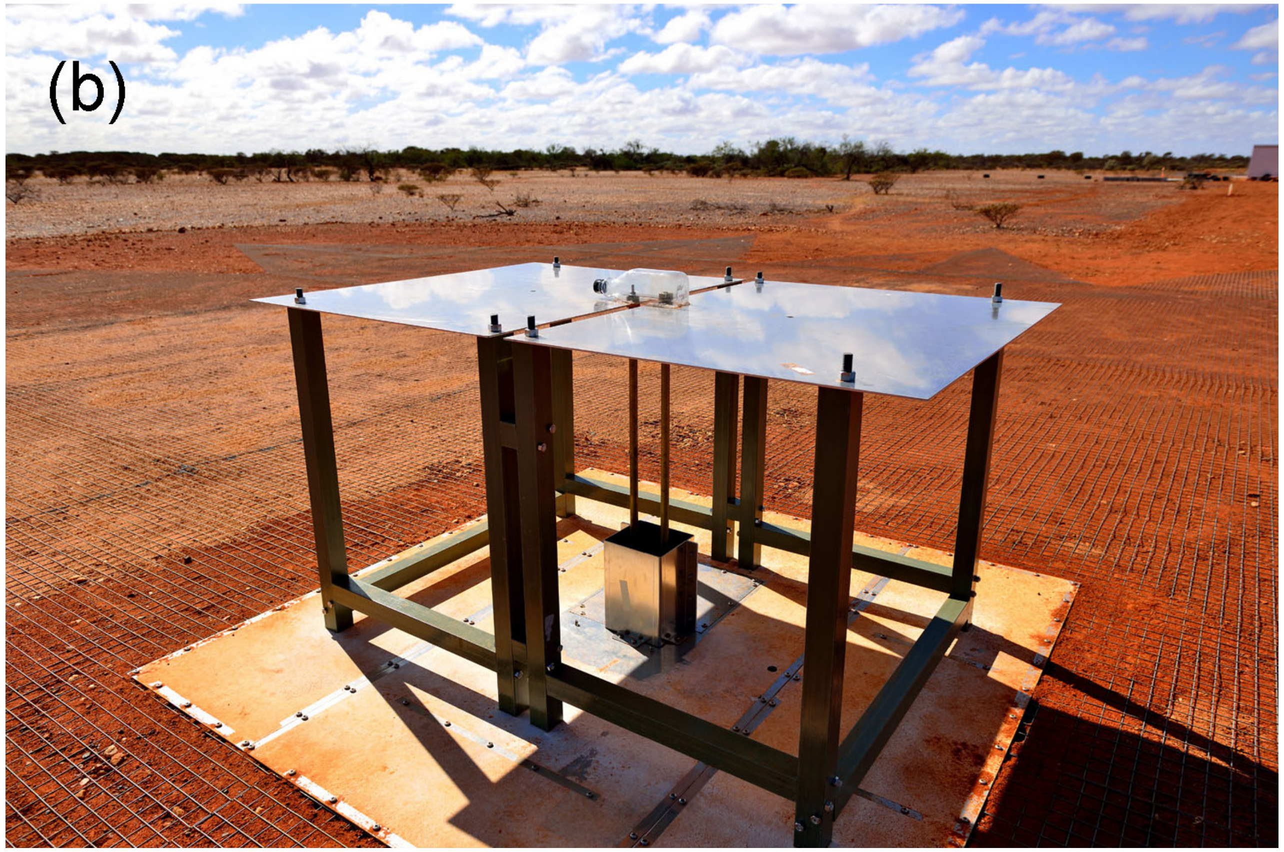


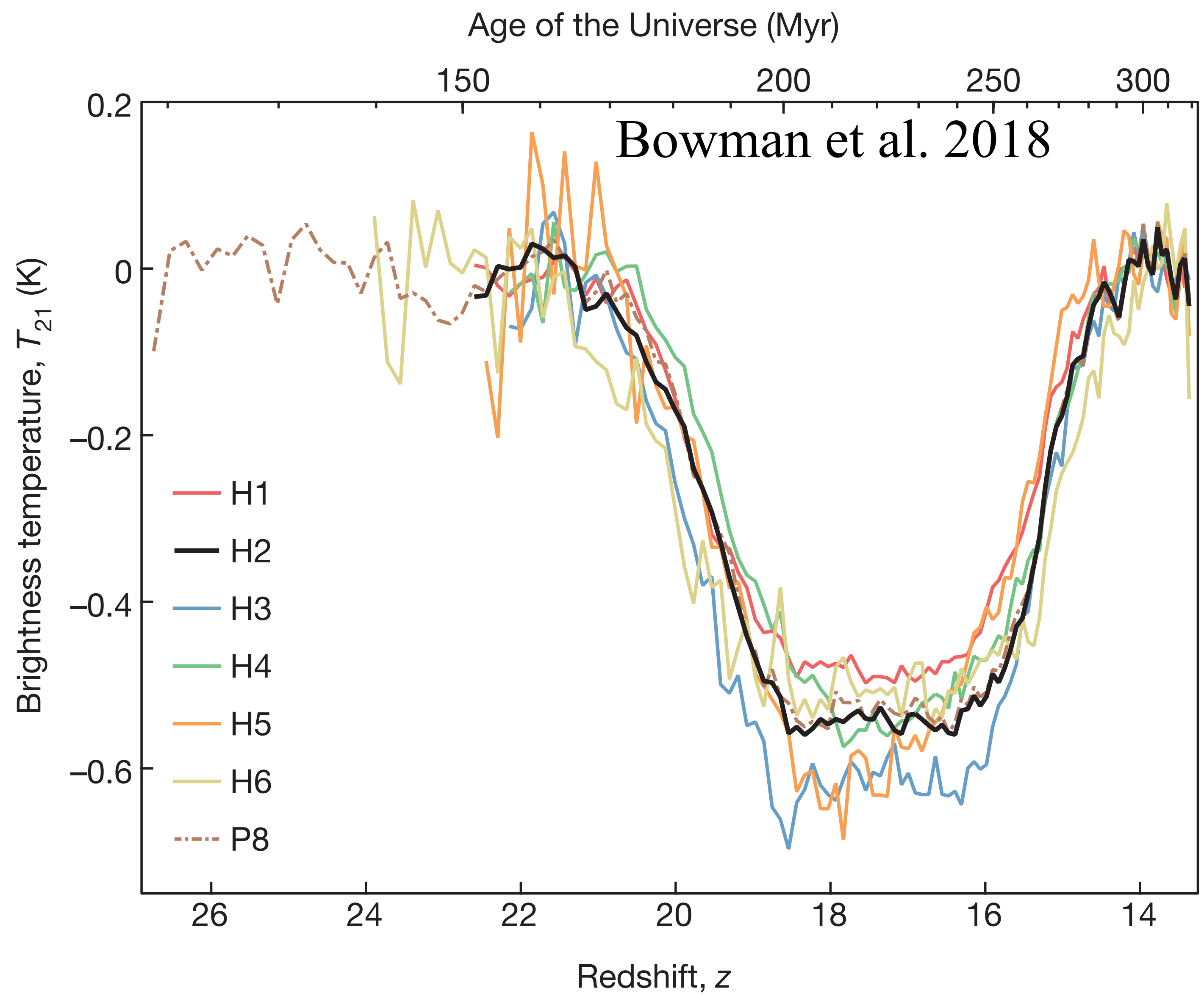
Did LIGO detect dark matter? Bird et al.

The clustering of massive PBHs as Dark Matter:Measuring their mass distribution with advanced LIGO. Clesse & Garcia-Bellido

PBH Scenario for the Gravitational-Wave Event GW150914. Sasaki et al.

February 2018





Possible interaction between baryons and DM particles revealed by the first stars
Barkana

Insights on Dark Matter from Hydrogen during Cosmic Dawn
Muñoz & Loeb

Signs of Dark Matter at 21-cm? Barkana et al.

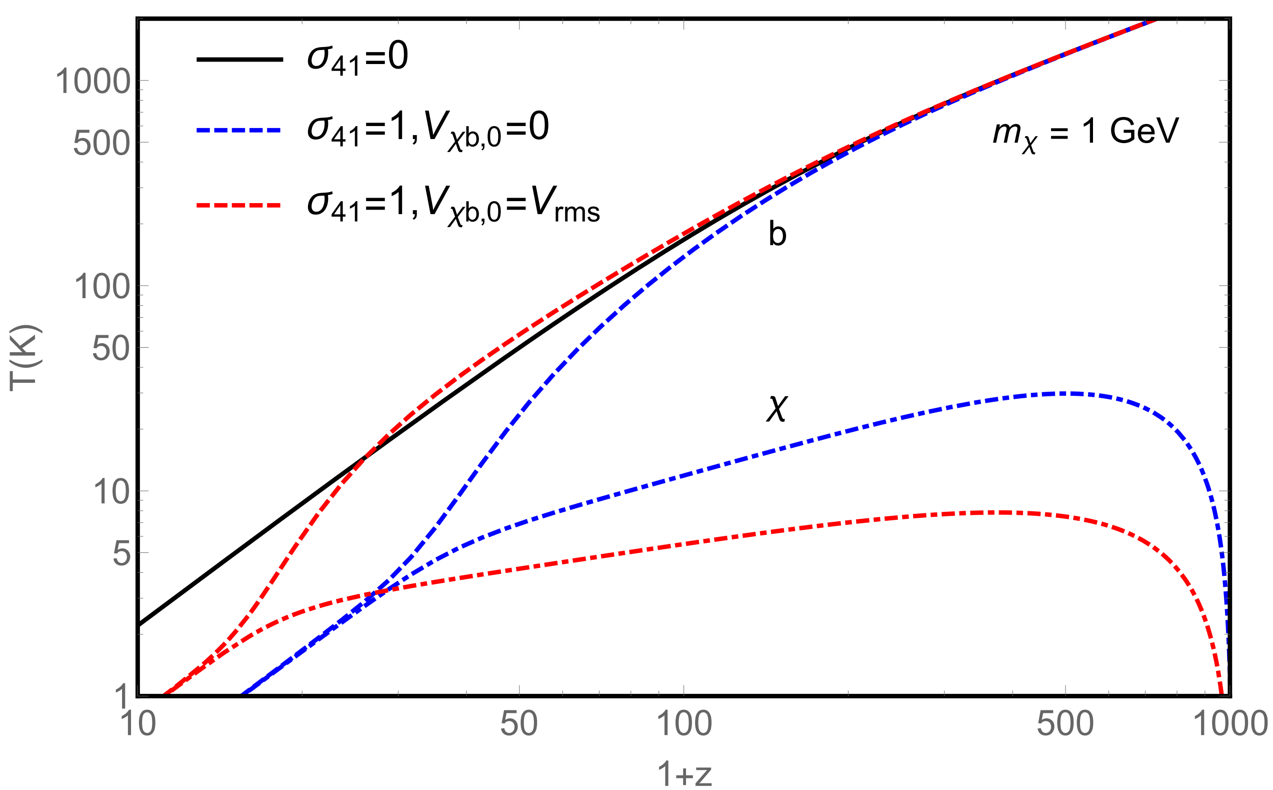
Interacting dark matter as a heat sink: 21-cm signal

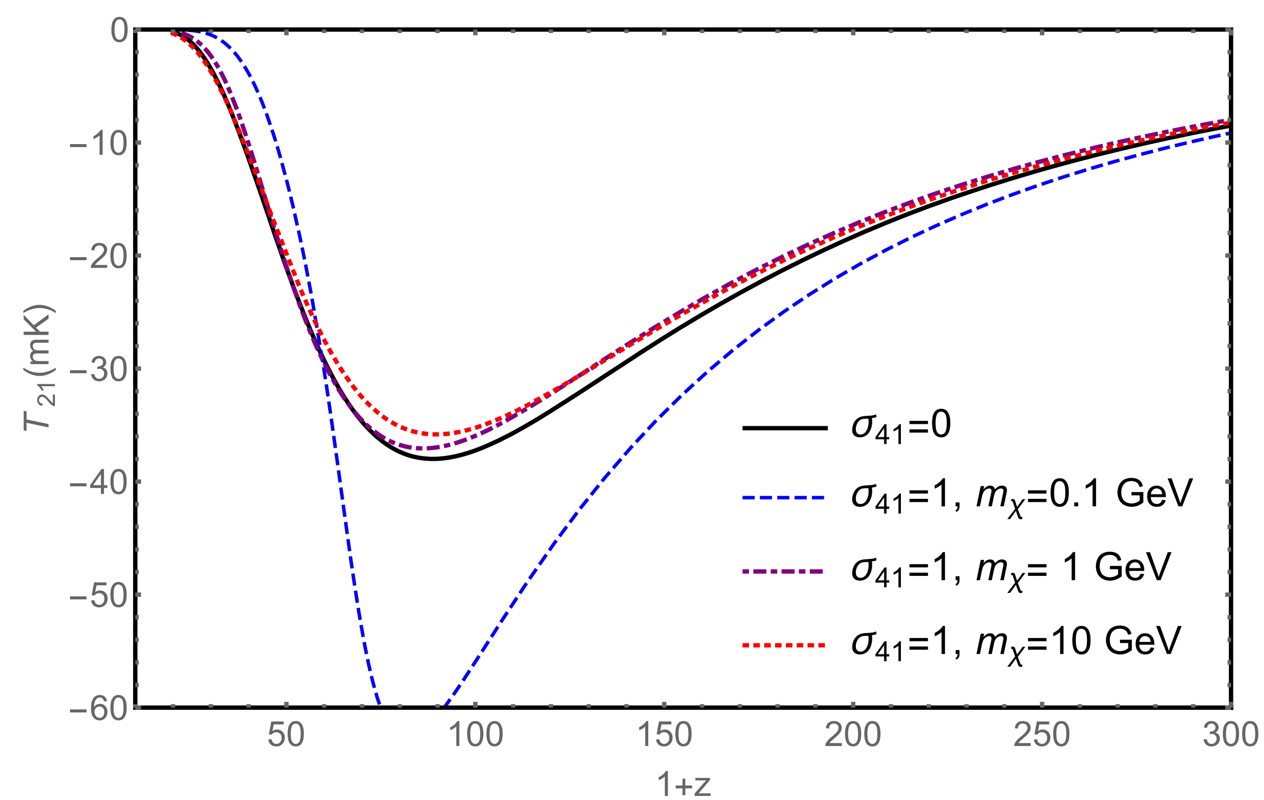
Tashiro, Kadota and Silk 2014

$$\frac{dT_\chi}{da} = -2\frac{T_\chi}{a} + \frac{2\dot{Q}_\chi}{3aH}, \qquad \frac{dT_b}{da} = -2\frac{T_b}{a} + \frac{\Gamma_C}{aH}(T_\gamma - T_b) + \frac{2\dot{Q}_b}{3aH},$$

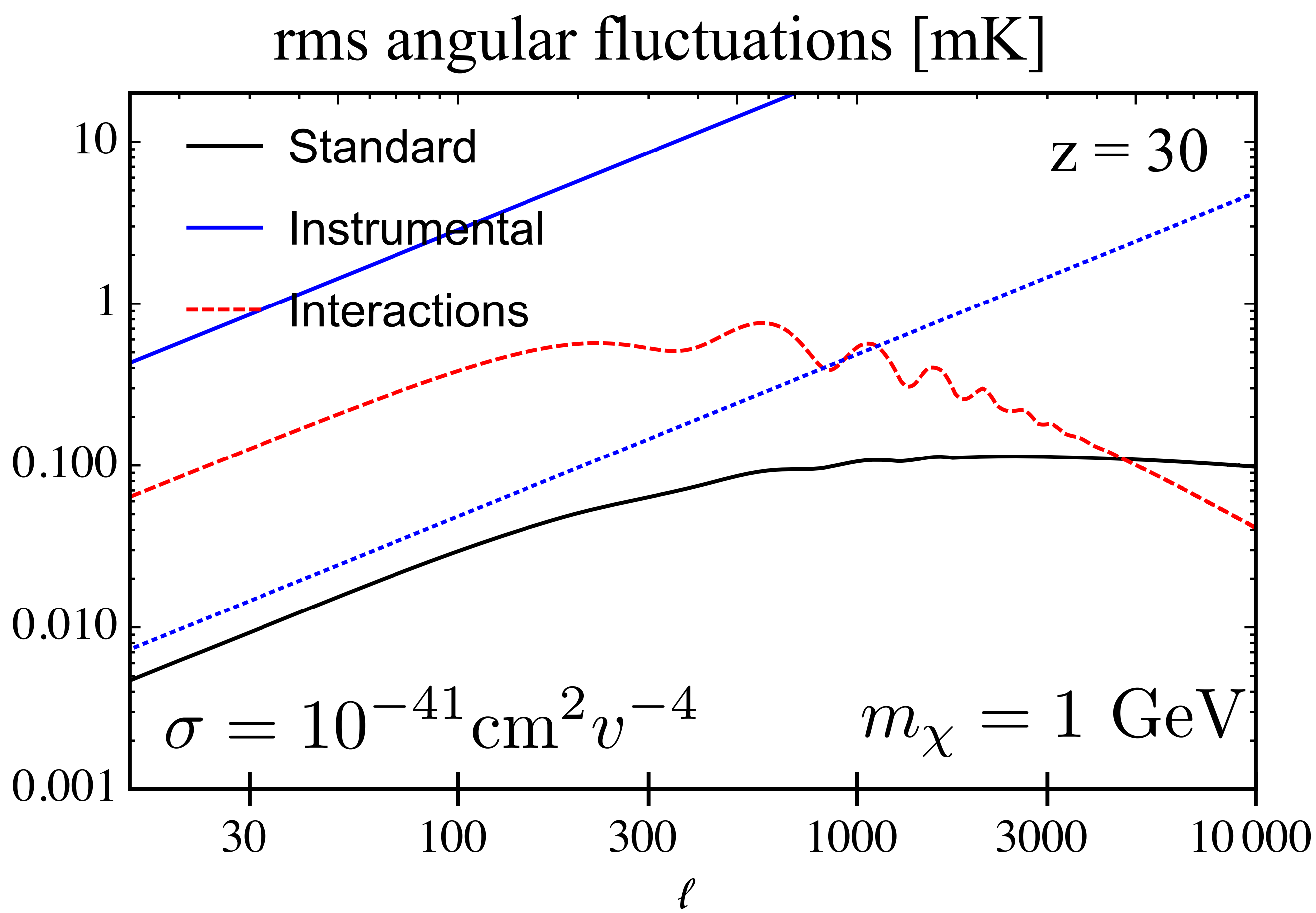
Muñoz, Kovetz & YAH 2015: accounted for heating through dissipation of relative motion

$$\dot{Q}_b = F(V_{\chi b})(T_\chi - T_b) - \frac{\rho_\chi}{\rho_m}\frac{m_\chi m_b}{m_\chi + m_b}\frac{d}{dt}\left(\frac{1}{2}V_{\chi b}^2\right)$$

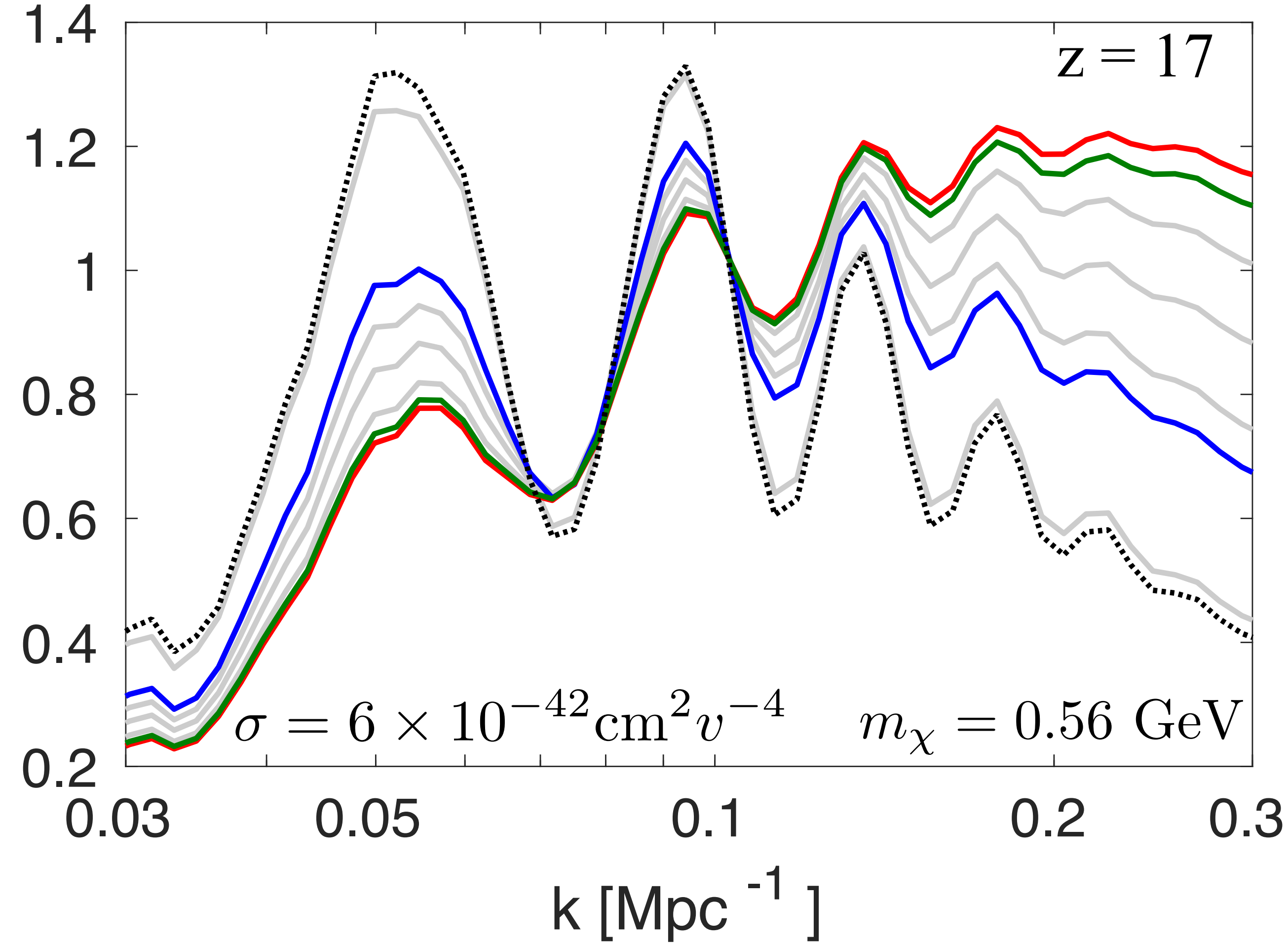




Strong dependence of interaction on relative motion implies large-scale fluctuations on ~BAO scales

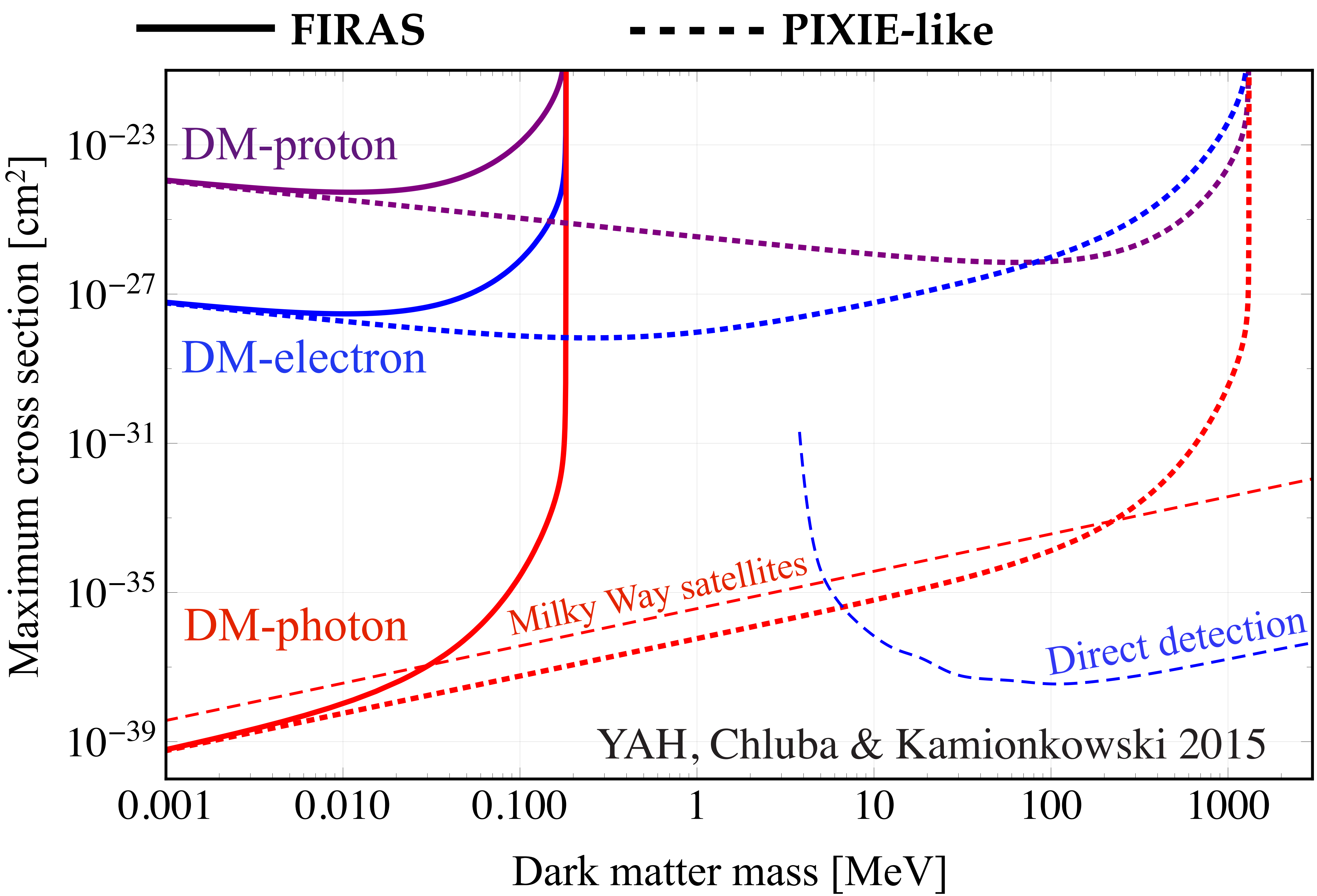


Muñoz, Kovetz & YAH 2015



Fialkov, Barkana & Cohen 2018

Interacting dark matter as a heat sink: spectral distortions



Can spectral distortions say anything about millicharge DM?

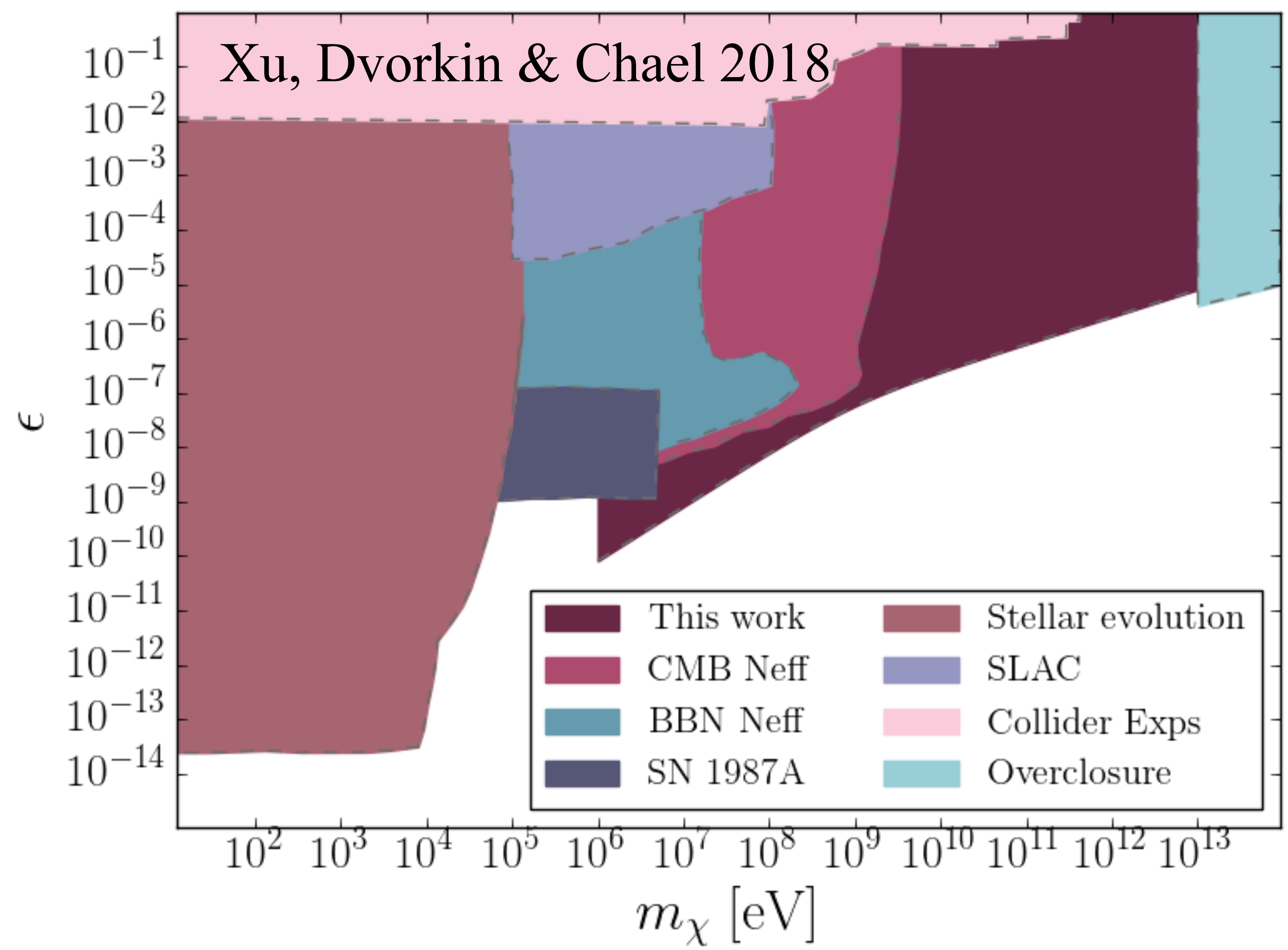
- scattering with baryons: $\sigma \sim 1/v^4$, heat and momentum exchange more important at low-z

- scattering with photons: $$\sigma_{\chi\gamma} = \epsilon^4 \left(\frac{m_e}{m_\chi}\right)^2 \sigma_{\rm T}$$

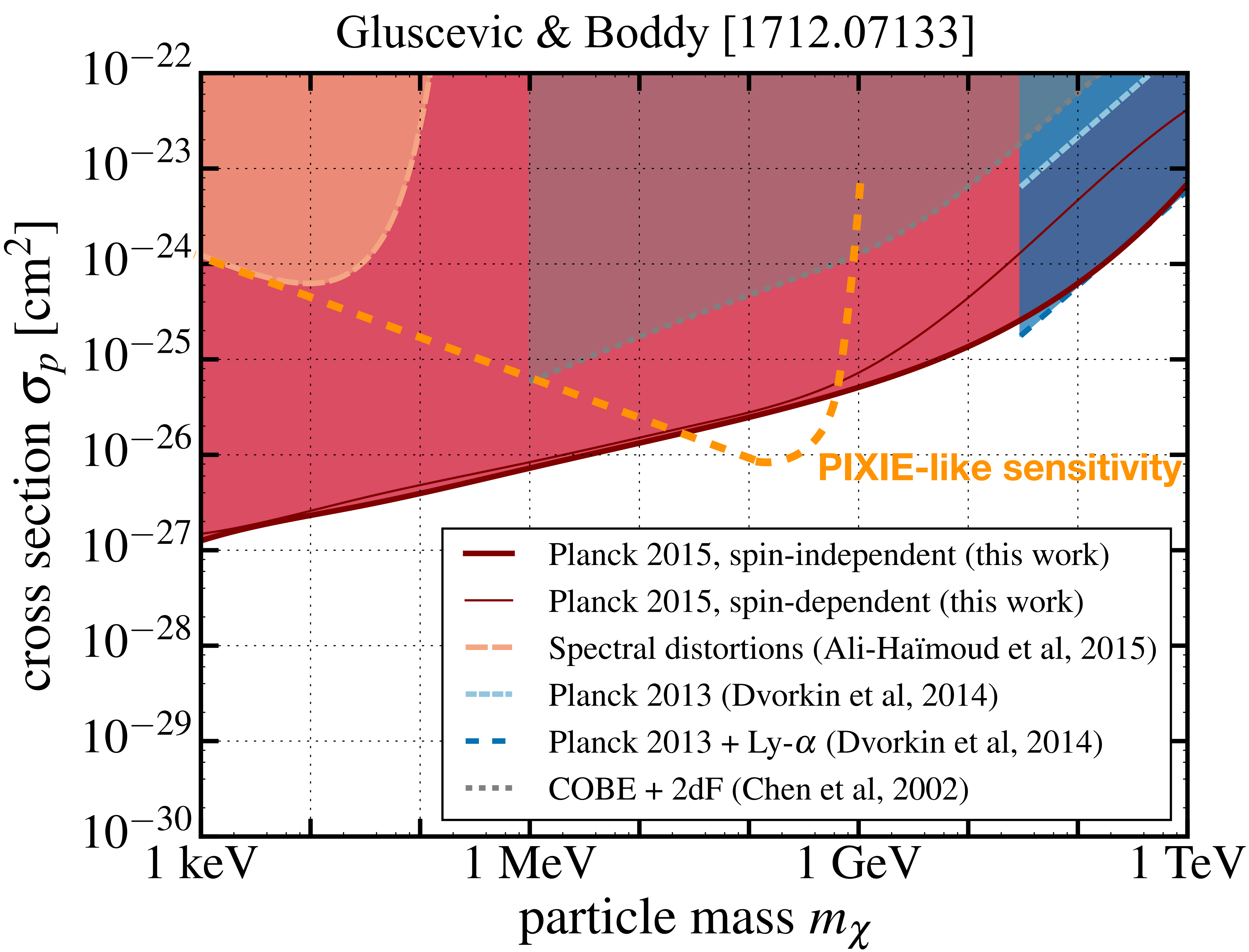
low-mass limit from SD: $$\frac{\sigma_{\chi\gamma}}{\sigma_{\rm T}} \lesssim 10^{-12} \frac{m_\chi}{m_e}$$

$$\Rightarrow \epsilon \lesssim 10^{-3} \left(\frac{m_\chi}{m_e}\right)^{3/4}$$

meh

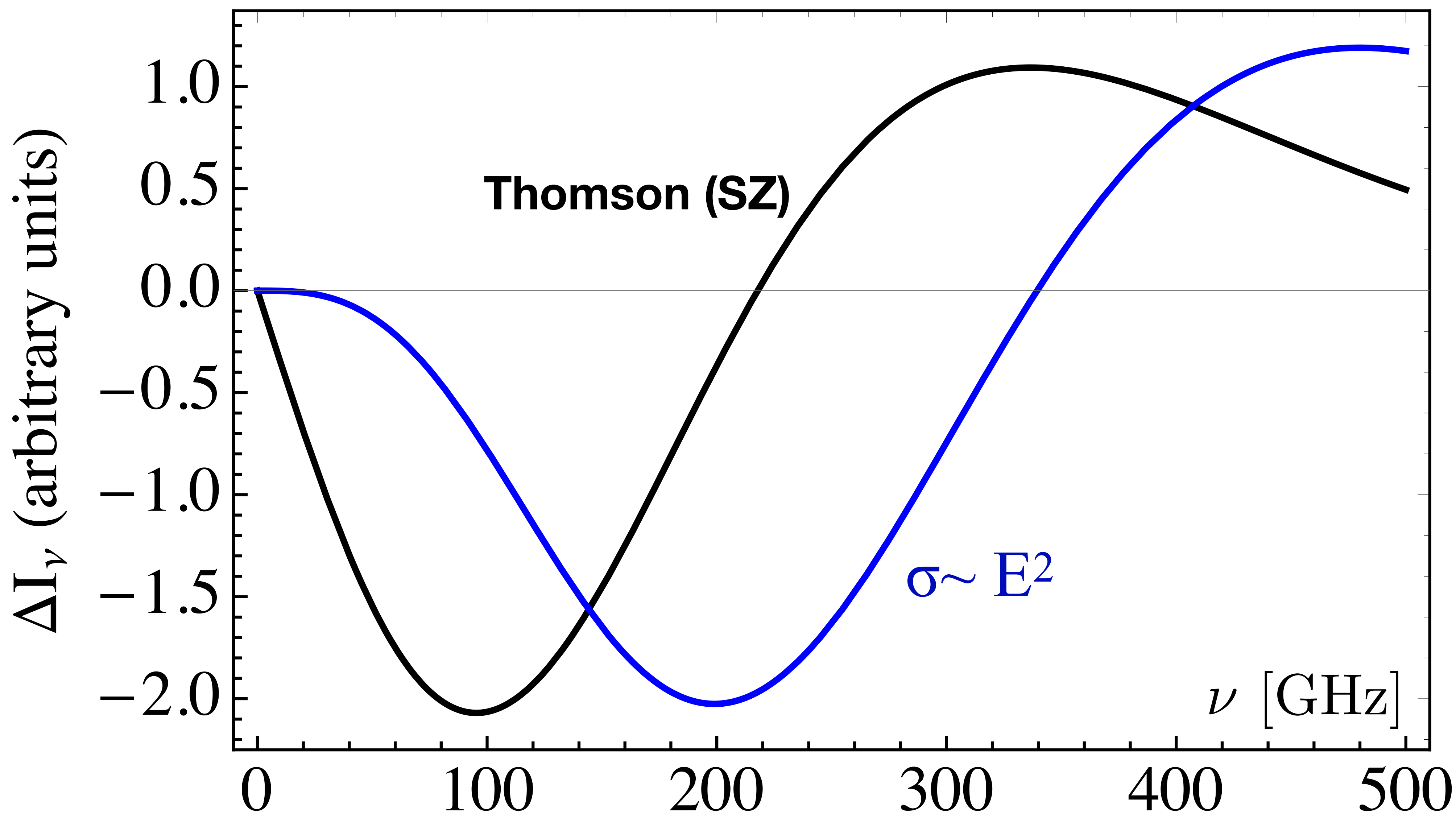


For constant cross section with protons, CMB anisotropy do better



Dark-y distortion for chromatic DM-photon scattering, e.g. dipolar dark matter $\sigma \sim E^2$

different from standard energy injection through heating of baryons



Primordial Black Holes

Mon. Not. R. astr. Soc. (1971) **152**, 75–78.

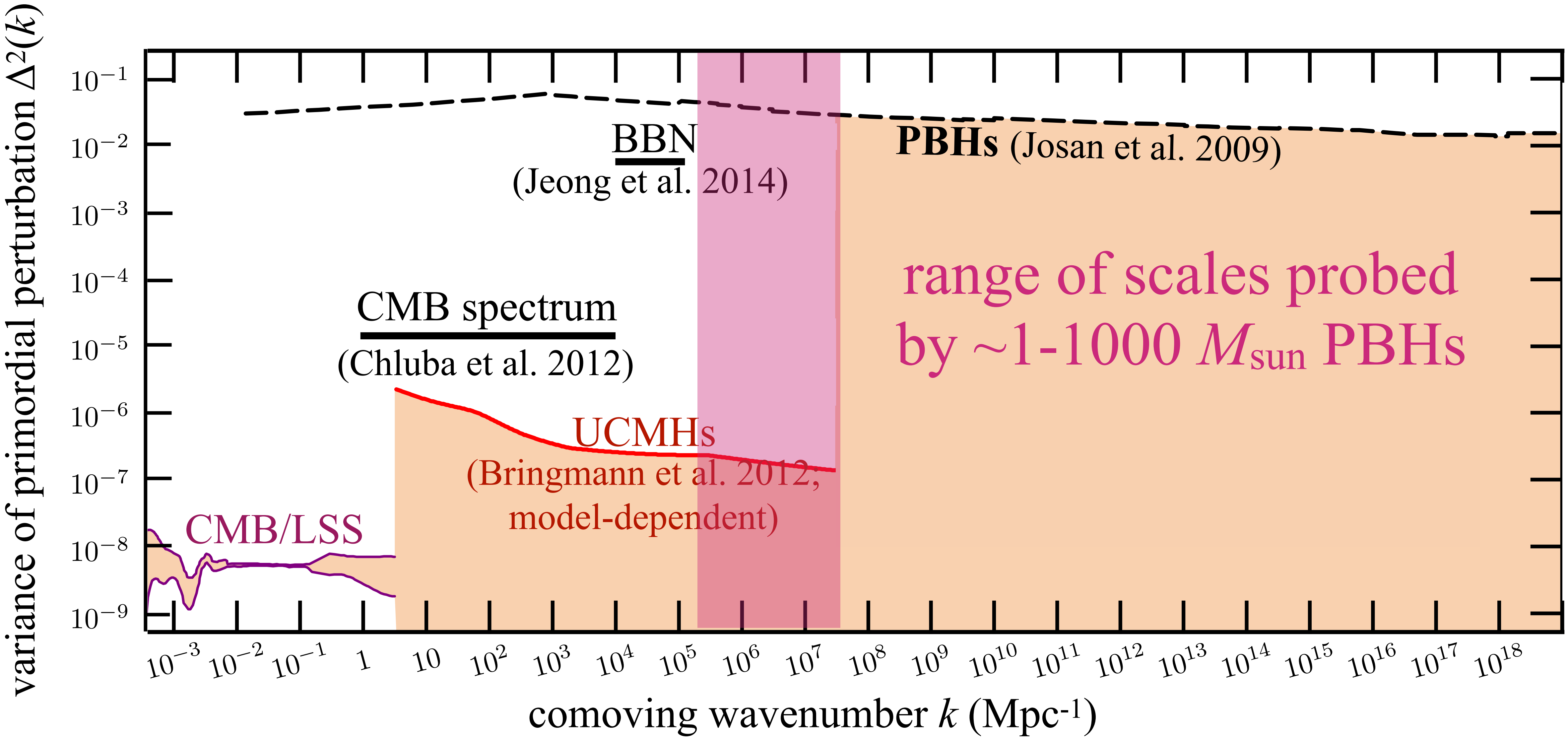
GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

It is suggested that 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.

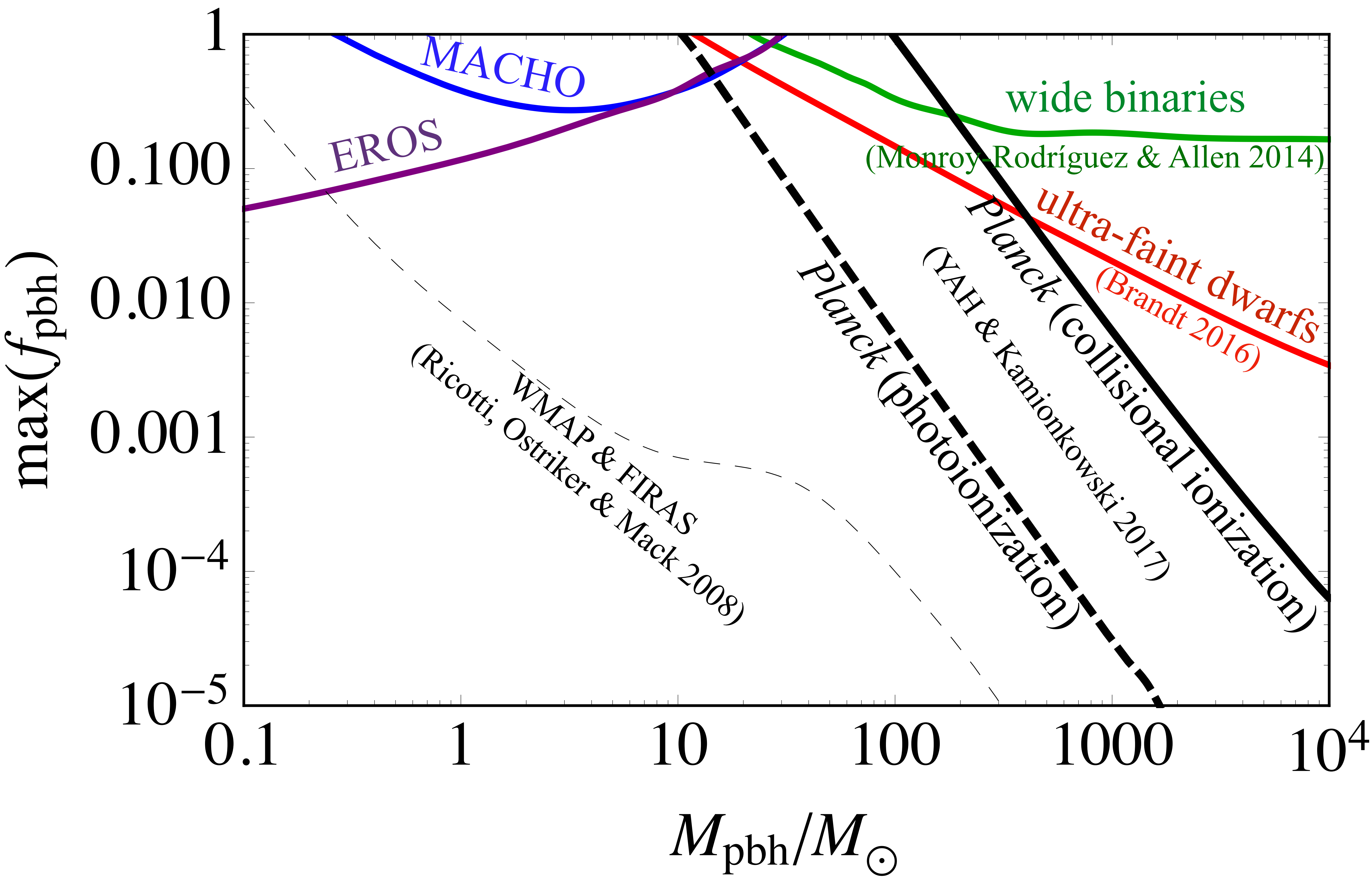
measurements indicate that the average density of the Universe cannot be greater than about 10^{-28} g cm^{-2}. Since the average density of visible matter is only about 10^{-31} g cm^{-2}, it is tempting to suppose that the major part of the mass of the Universe is in the form of collapsed objects. This extra density could stabilize clusters of galaxies which, otherwise, appear mostly not to be gravitationally bound.

PBHs are one of the very few (model-dependent) probes of the **ultra-small-scale primordial power spectrum.**



It's a nutty idea. But every idea of what dark matter might be is a nutty idea.

Marc Kamionkowski, Science Magazine 2/17



max($f_{\rm pbh}$)
1
0.100
0.010
0.001
10^{-4}
10^{-5}
0.1
1
10
100
1000
10^4
$M_{\rm pbh}/M_\odot$
MACHO
EROS
wide binaries
(Monroy-Rodríguez & Allen 2014)
ultra-faint dwarfs
(Brandt 2016)
Planck (collisional ionization)
(YAH & Kamionkowski 2017)
Planck (photoionization)
WMAP & FIRAS
(Ricotti, Ostriker & Mack 2008)

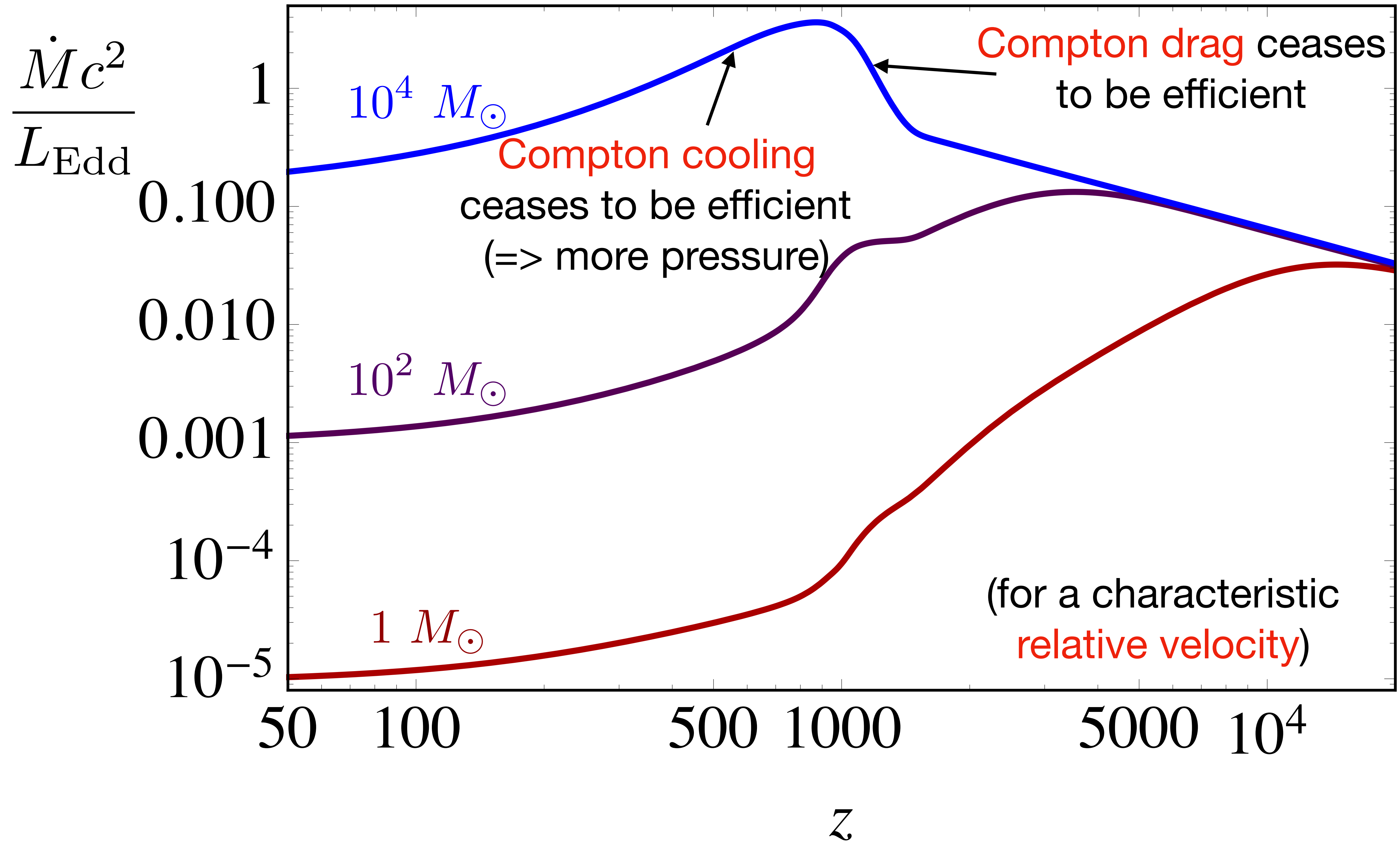
Underlying physics for CMB bounds

Carr 1981, Ricotti et al. 2008, YAH & Kamionkowski 2017

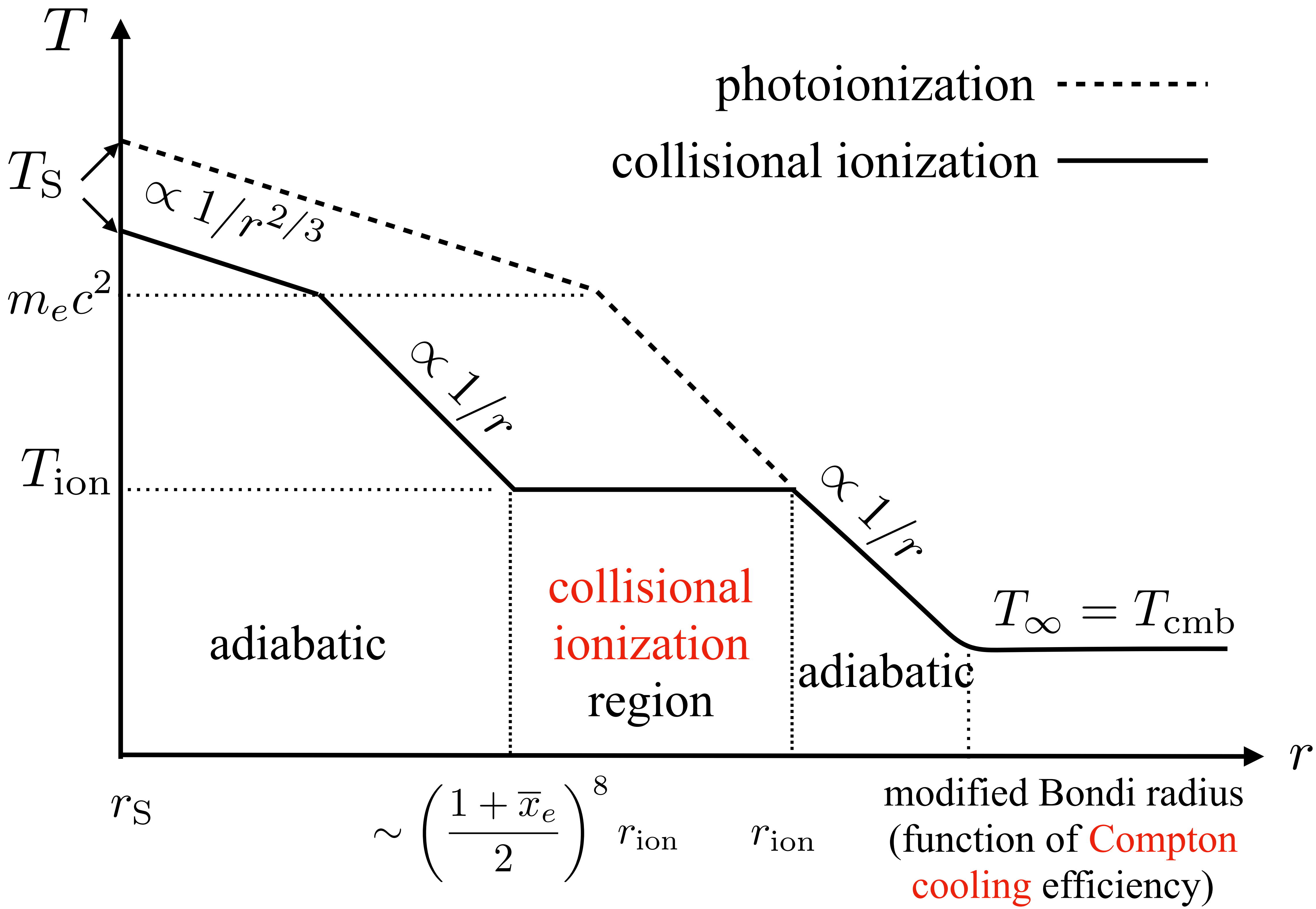
1. PBHs accrete baryons
2. a fraction of the accreted mass is re-radiated
3. a fraction of this luminosity is deposited into the plasma
4. some is deposited as heat => CMB spectral distortions
5. some leads to extra ionizations
   => change the recombination history and visibility function
   => affects CMB temperature and polarization anisotropies

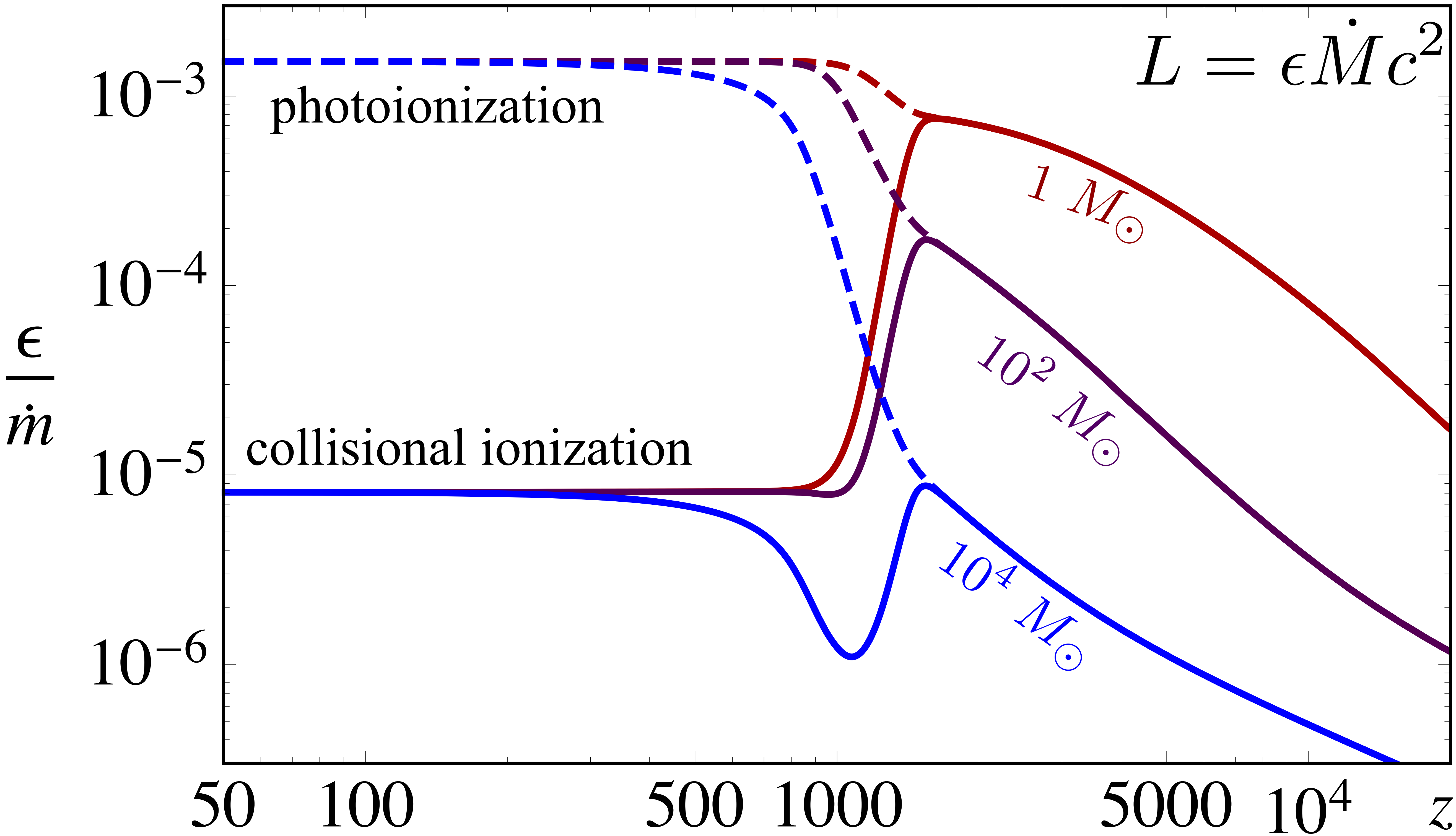
Our philosophy: (i) first-principles, low-fudge-number calculation (ii) estimate the minimal physically plausible effect in order to set conservative upper limits

1. Accretion rate: Bondi-Hoyle-Lyttleton with a few twists

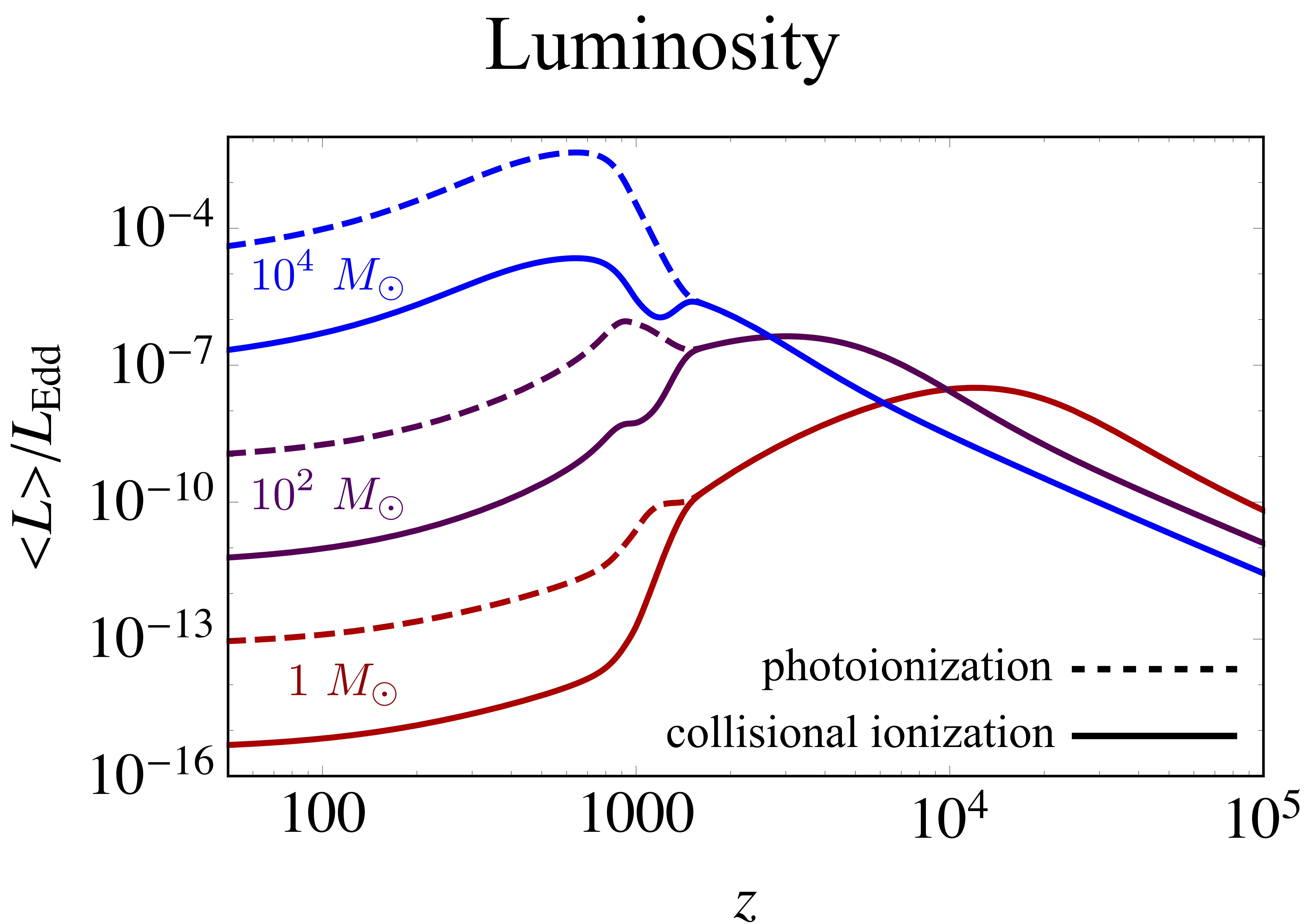


2. Radiative efficiency: Shapiro (1973) with a few twists





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



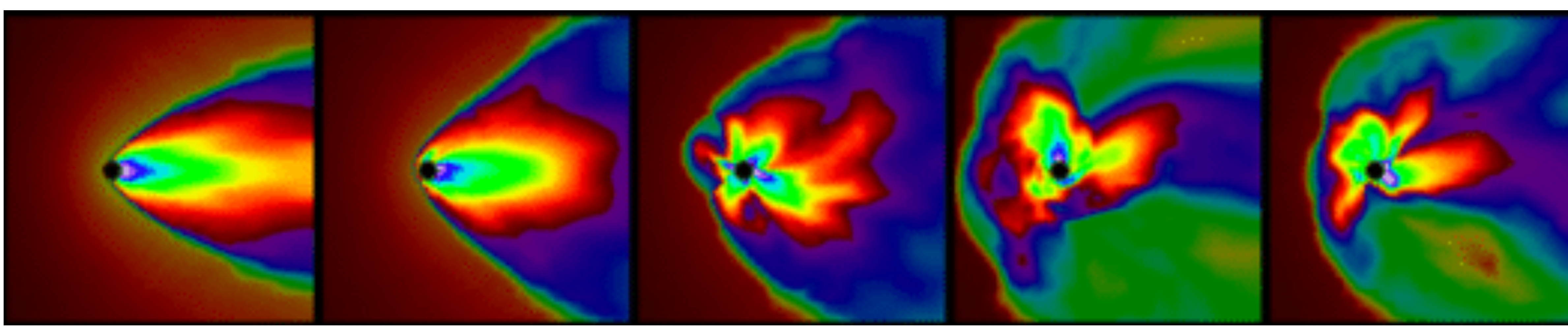
Luminosity
$\langle L \rangle / L_{\rm Edd}$
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
$10^4\ M_\odot$
$10^2\ M_\odot$
$1\ M_\odot$
photoionization
collisional ionization
100
1000
10^4
10^5
z

Baryon-dark matter relative velocity

Baryons and dark matter have large-scale relative motions
(see e.g. Tseliakhovich & Hirata 2010 for effect on small-scale structure)

- before recombination $v_{\rm rel} \approx 30\ \mathrm{km/s} \approx 5\ c_s$
- after recombination: baryons become cold like DM. $v_{\rm rel} \propto 1/a$

Ricotti et al. 2008 assumed $v_{\rm rel} \approx 4\ \mathrm{km/s} \lesssim c_s$



Ruffert's website

Baryon-dark matter relative velocity

Simple fudge (à la Bondi-Hoyle): $c_s \rightarrow (c_s^2 + \mathrm{v}_{\mathrm{rel}}^2)^{1/2}$

in the simple Bondi case: $$L \propto \dot{M}^2 \propto \frac{1}{(c_s^2 + v_{\mathrm{rel}}^2)^3}$$

$$\langle L \rangle \propto \left\langle \frac{1}{(c_s^2 + v_{\mathrm{rel}}^2)^3} \right\rangle \approx \frac{1}{c_s^3 \langle v_{\mathrm{rel}}^2 \rangle^{3/2}}, \quad \langle v_{\mathrm{rel}}^2 \rangle \gg c_s^2$$

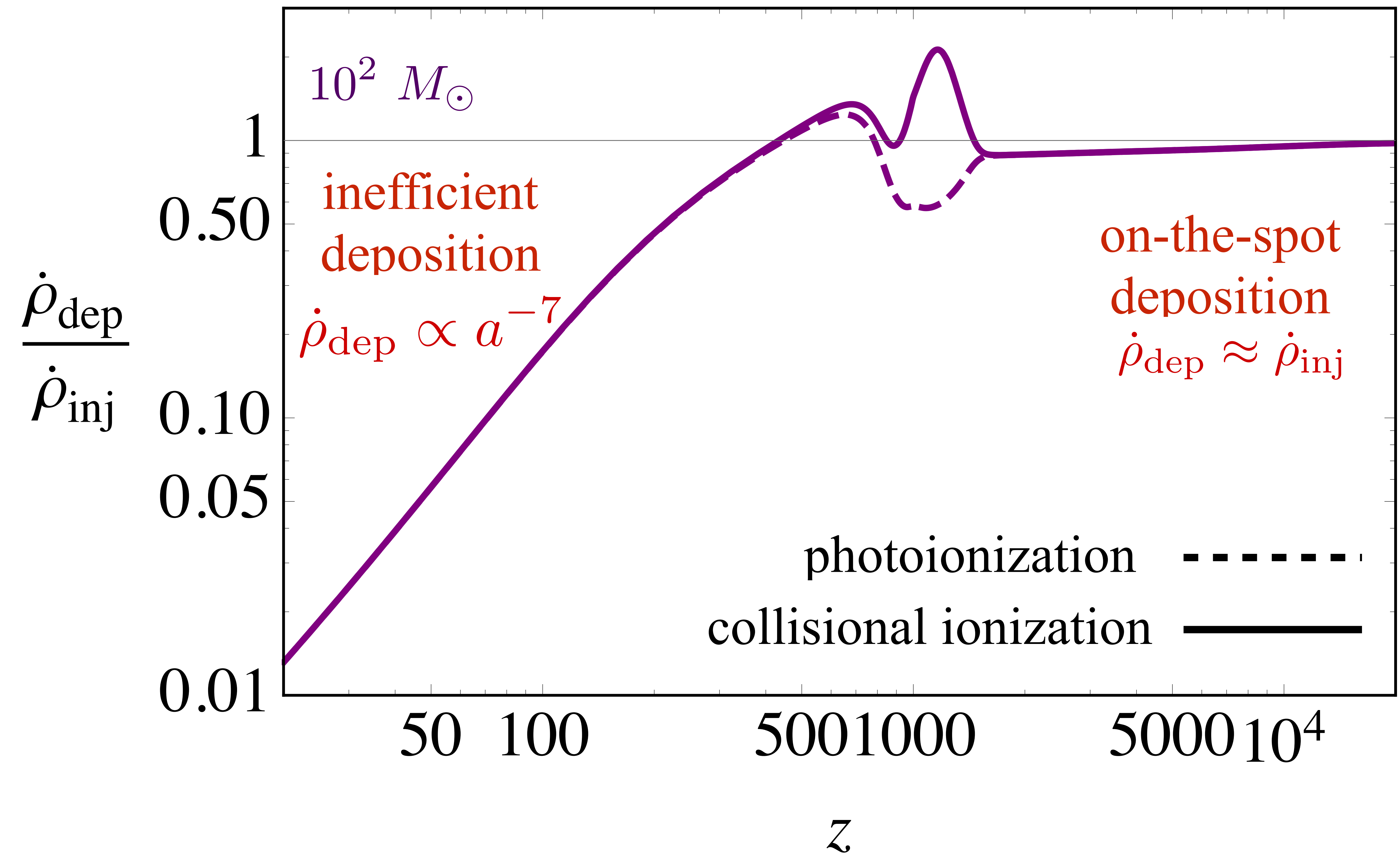
$$\frac{\langle L \rangle}{L(v_{\mathrm{rel}} = 0)} \sim 10^{-2}$$

See also Horowitz 2016, Aloni, Blum & Flauger 2017

Notes: (1) detailed suppression is not highly relevant: average luminosity is dominated by subsonically accreting BHs.
(2) there are small-scale motions due to non-linear clustering.
We do not account for those.

3. Energy deposition into the plasma

Mostly through Compton scattering of ~ 0.1-10 MeV photons



4-CMB spectral distortions

$$\mu \approx 1.4 \int_{5\times10^4}^{2\times10^6} d\ln(1+z)\,\frac{\dot{\rho}_{\rm dep}^{\rm heat}}{H\rho_{\rm cmb}},$$

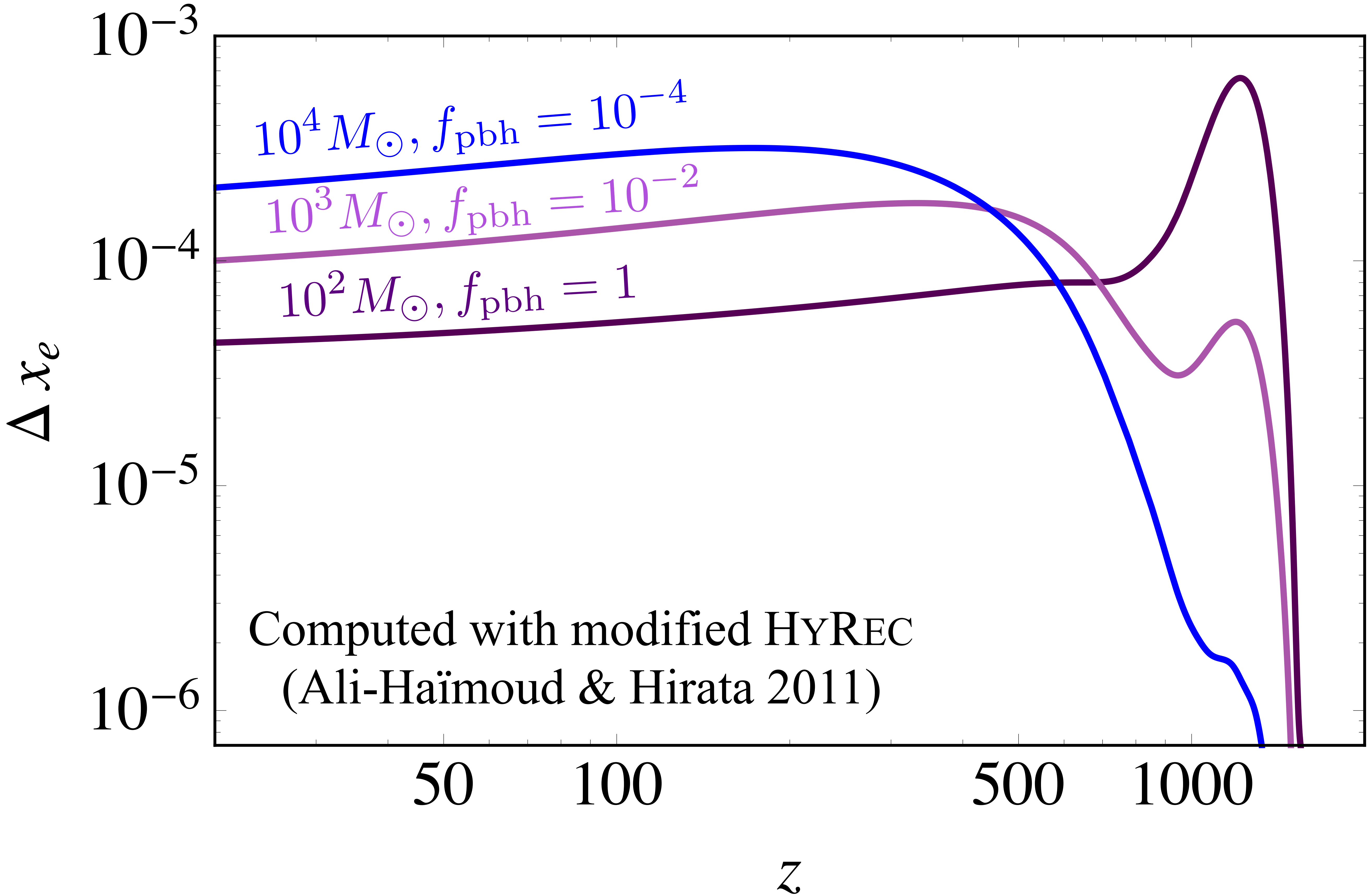
$$y \approx \frac{1}{4}\int_{200}^{5\times10^4} d\ln(1+z)\,\frac{\dot{\rho}_{\rm dep}^{\rm heat}}{H\rho_{\rm cmb}}$$

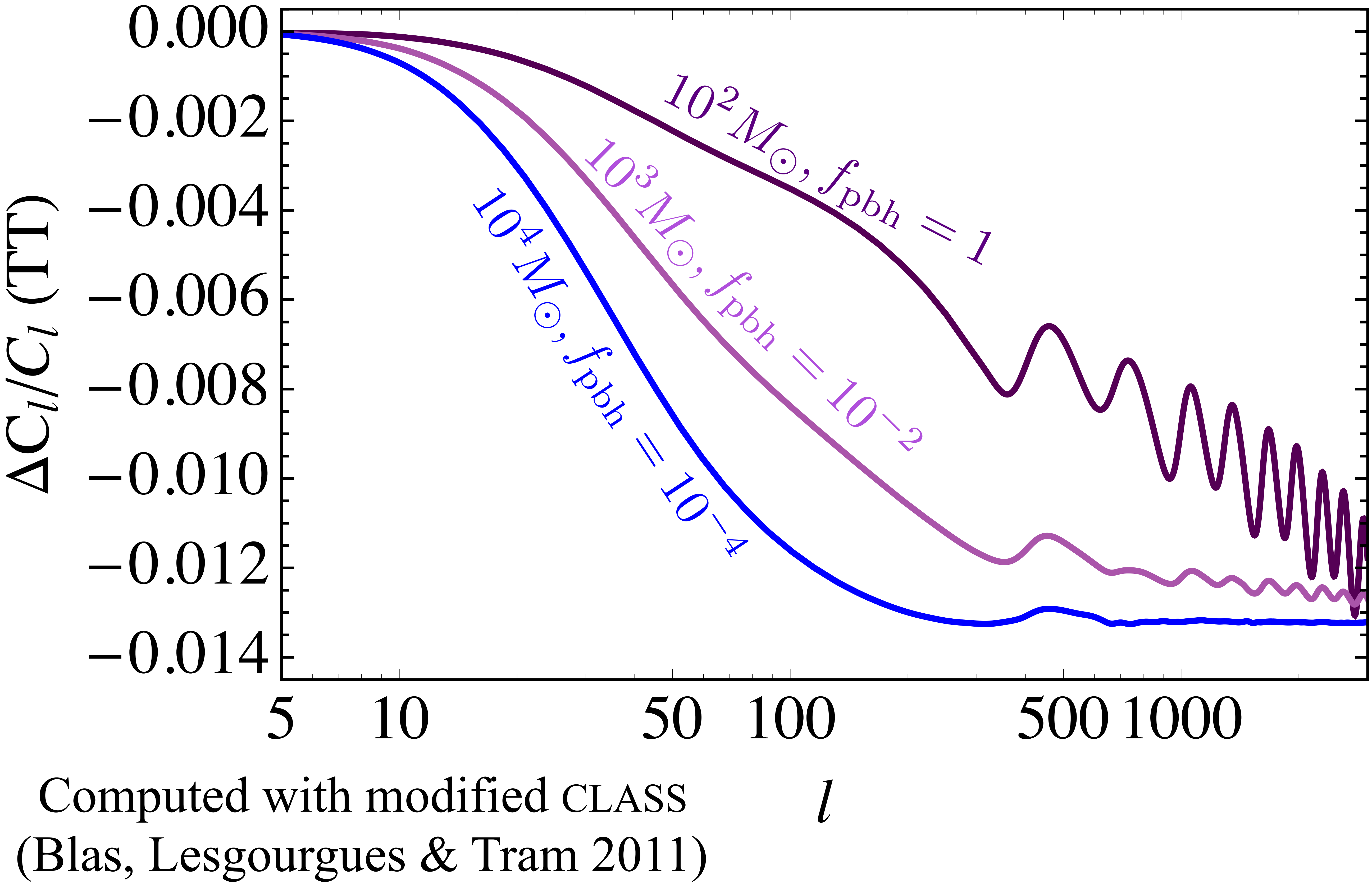
$$\mu \leq 6\times10^{-8} f_{\rm pbh} \max_{z\geq5\times10^4}\left(\frac{\langle L\rangle}{L_{\rm Edd}}\right).$$

$$y \approx 0.02\; f_{\rm pbh}\frac{\langle L\rangle}{L_{\rm Edd}}\bigg|_{z\approx200}$$

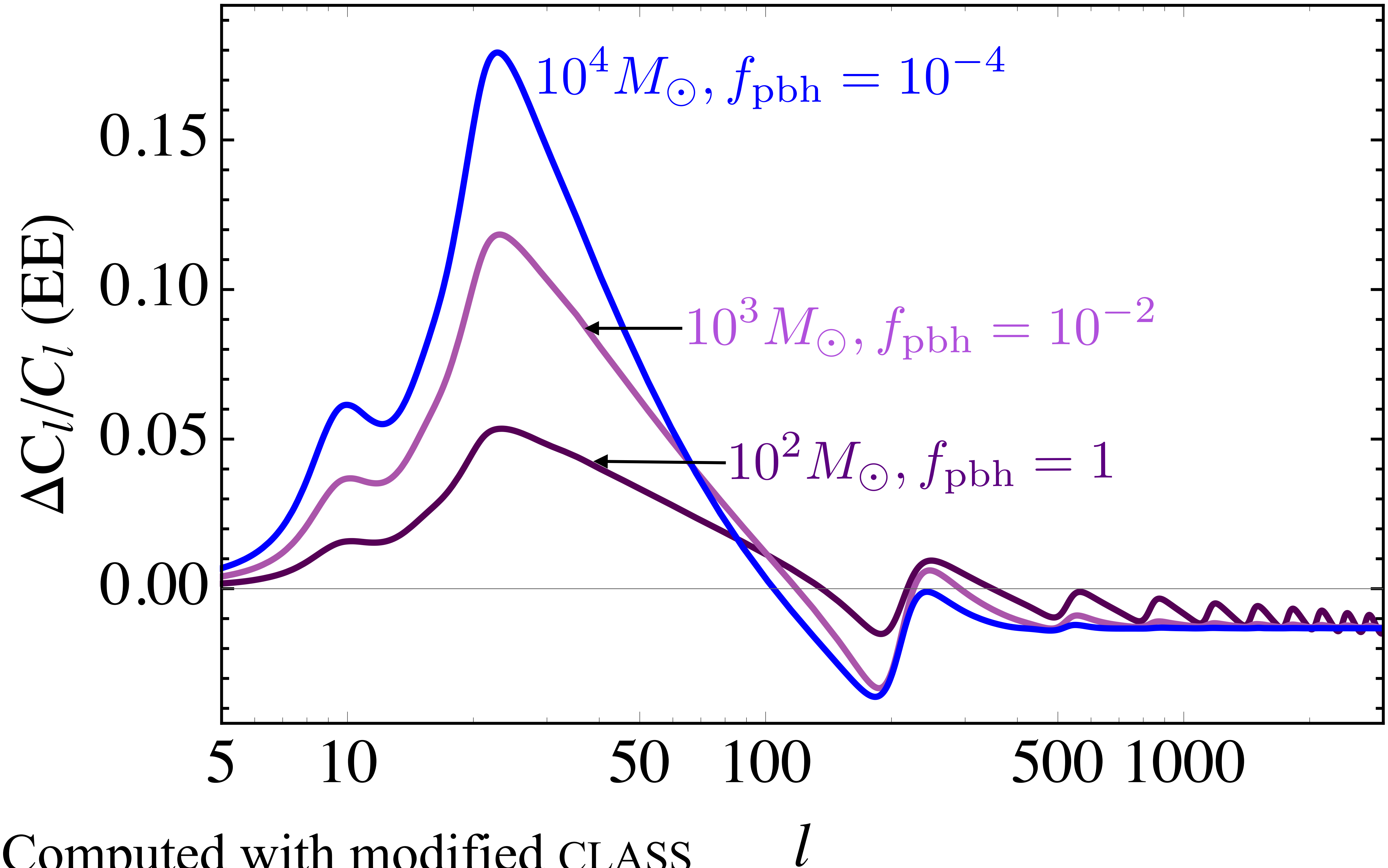
Undetectable by FIRAS (μ, y ~10^{-5}), or even by PIXIE (μ, y ~10^{-8})

5. Effect on recombination history and CMB anisotropies

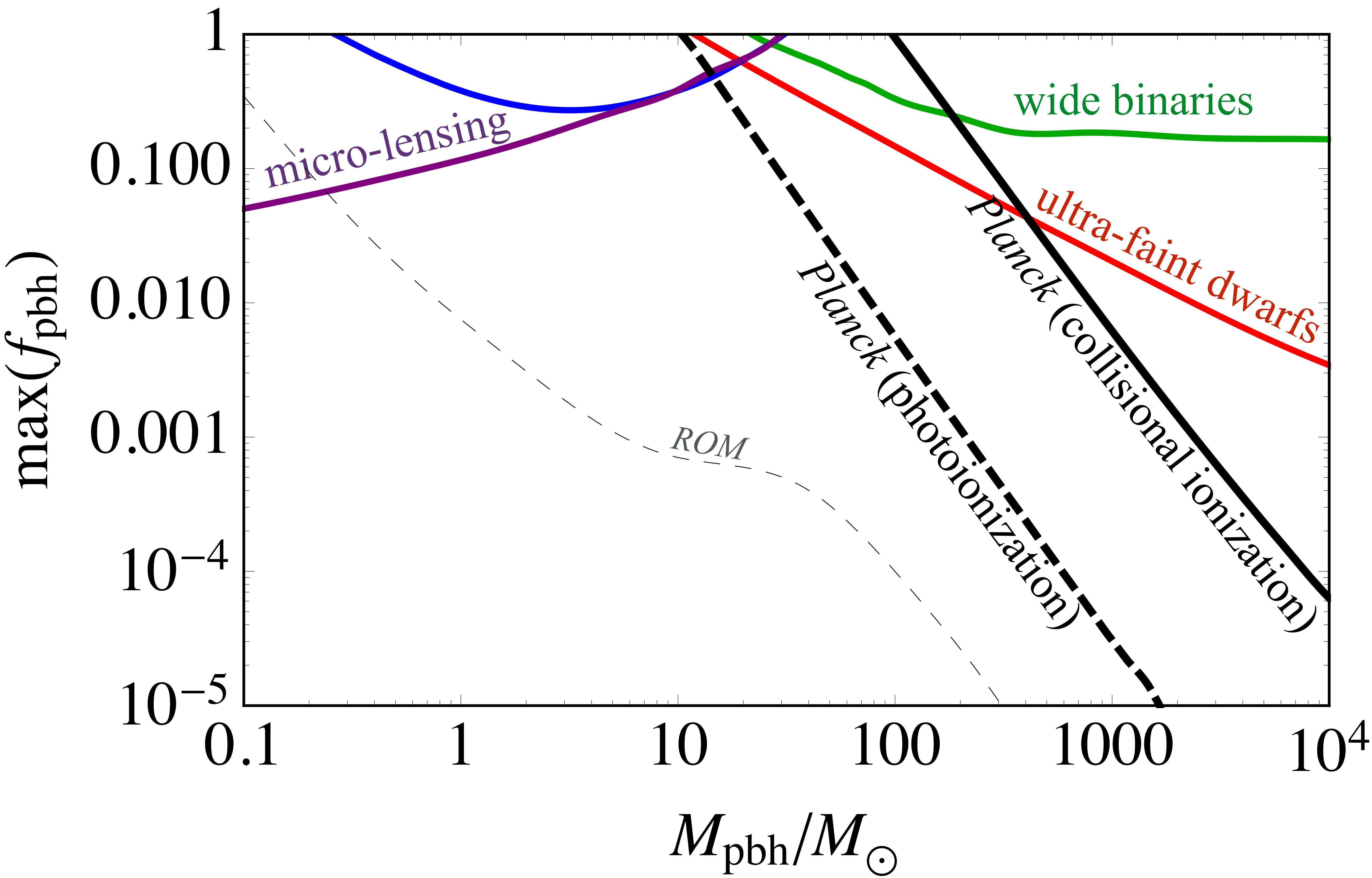




0.000
−0.002
−0.004
−0.006
−0.008
−0.010
−0.012
−0.014
$\Delta C_l/C_l$ (TT)
5
10
50
100
500
1000
l
$10^2 M_\odot, f_{pbh} = 1$
$10^3 M_\odot, f_{pbh} = 10^{-2}$
$10^4 M_\odot, f_{pbh} = 10^{-4}$
Computed with modified CLASS
(Blas, Lesgourgues & Tram 2011)



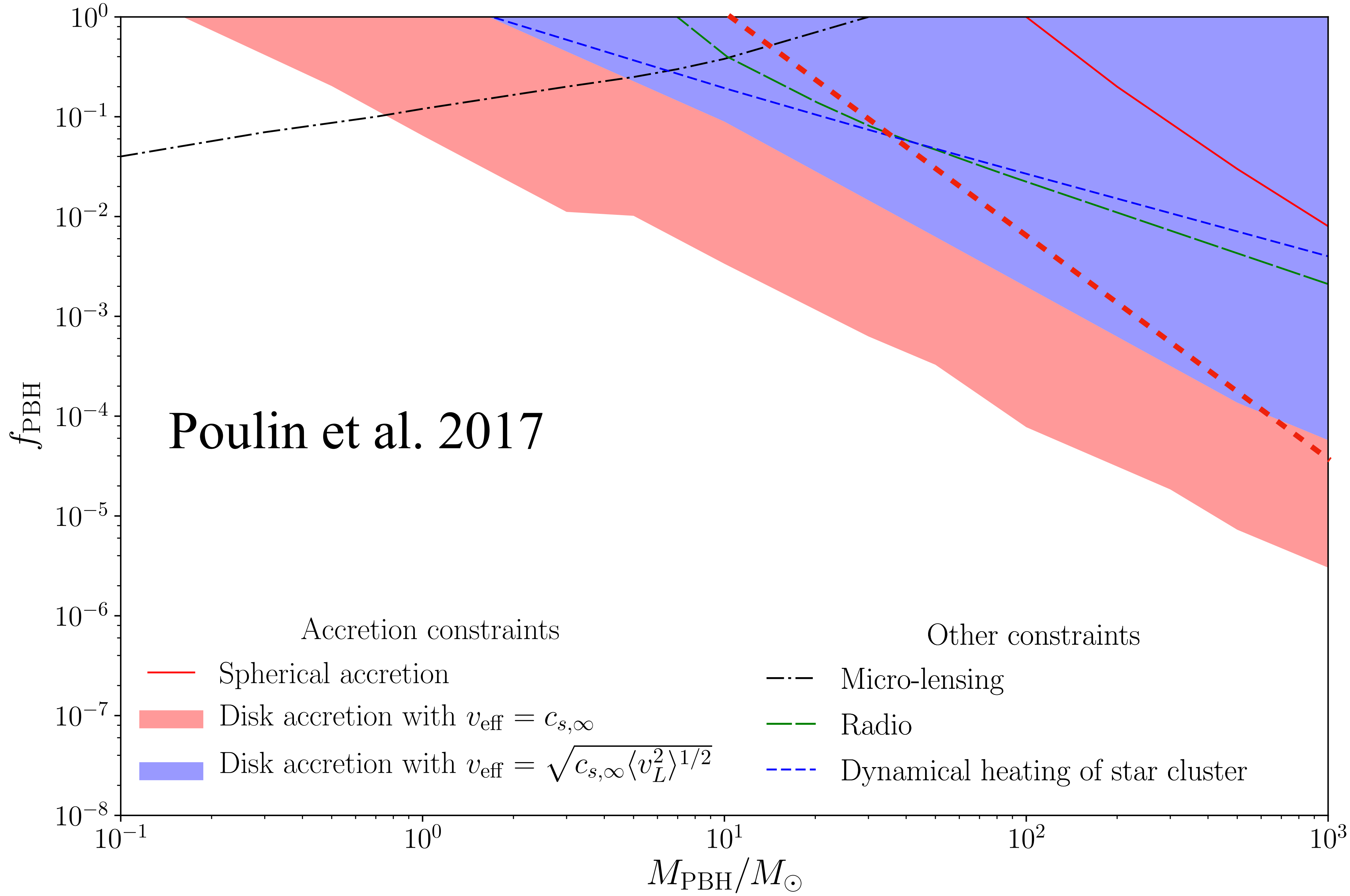
Computed with modified CLASS
(Blas, Lesgourgues & Tram 2011)



wide binaries
micro-lensing
ultra-faint dwarfs
Planck (collisional ionization)
Planck (photoionization)
ROM
max($f_{\rm pbh}$)
1
0.100
0.010
0.001
10^{-4}
10^{-5}
0.1
1
10
100
1000
10^4
$M_{\rm pbh}/M_\odot$

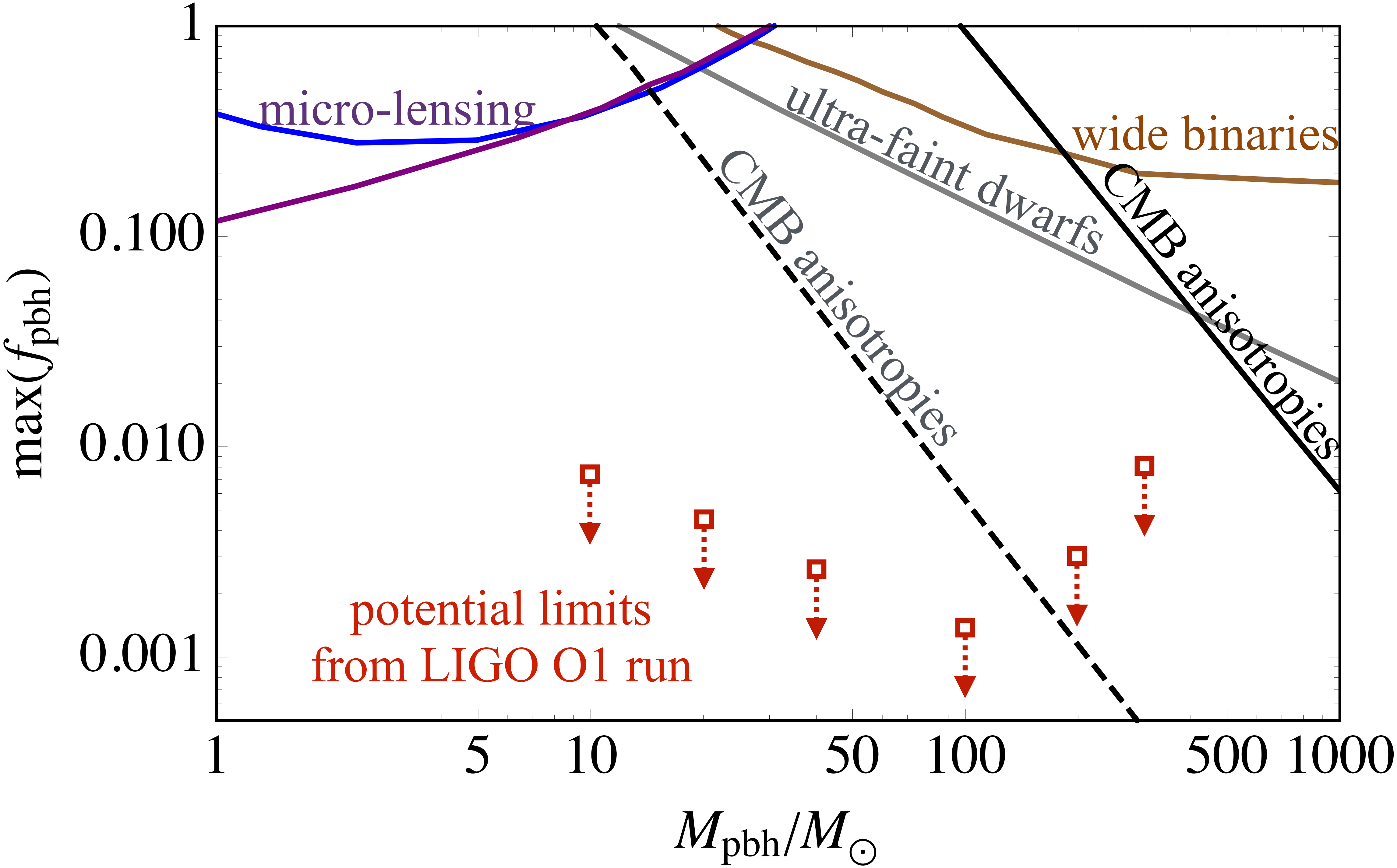
Bounds to be taken at the order-of-magnitude level only.

Rely on very simplified modeling of complex physics, but ought to be conservative.
e.g., disk accretion would imply higher luminosity hence stronger possible bounds.

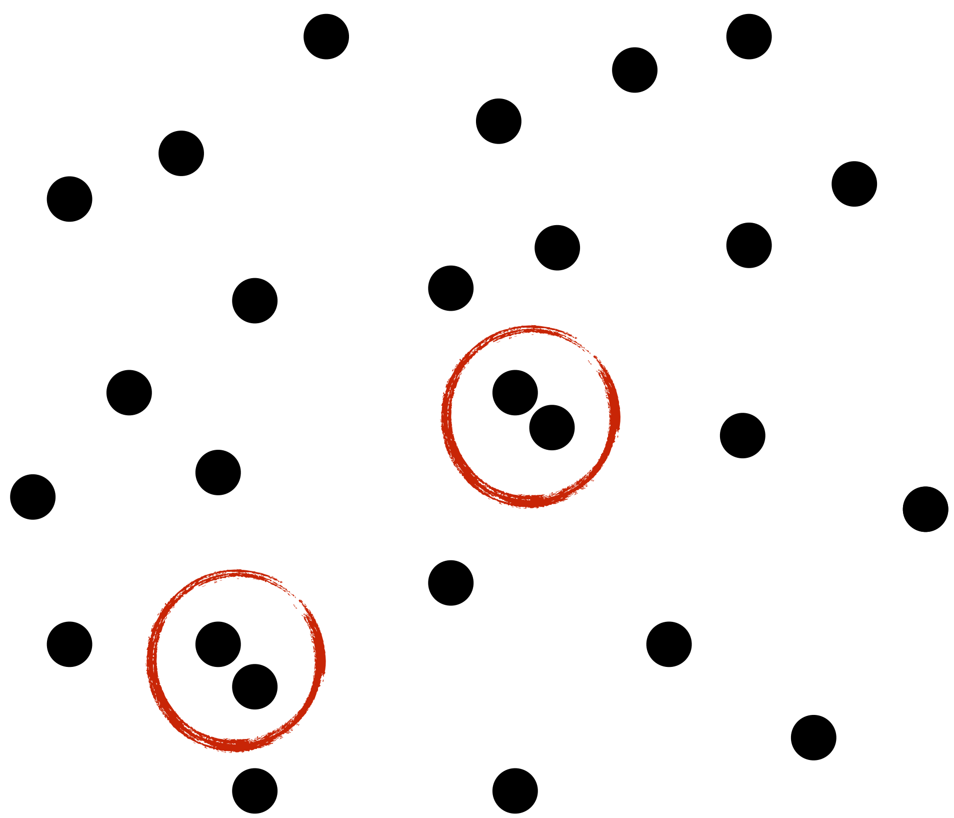


Does LIGO rule out PBH-dark matter?

Ali-Haïmoud, Kovetz & Kamionkowski [1709.06576]



Basic idea: Nakamura, Sasaki, Tanaka & Thorne 1997



On small enough scales, PBHs are randomly distributed (or maybe not quite!)

Some PBH pairs happen to be close enough that they decouple from the Hubble flow deep in the radiation era.

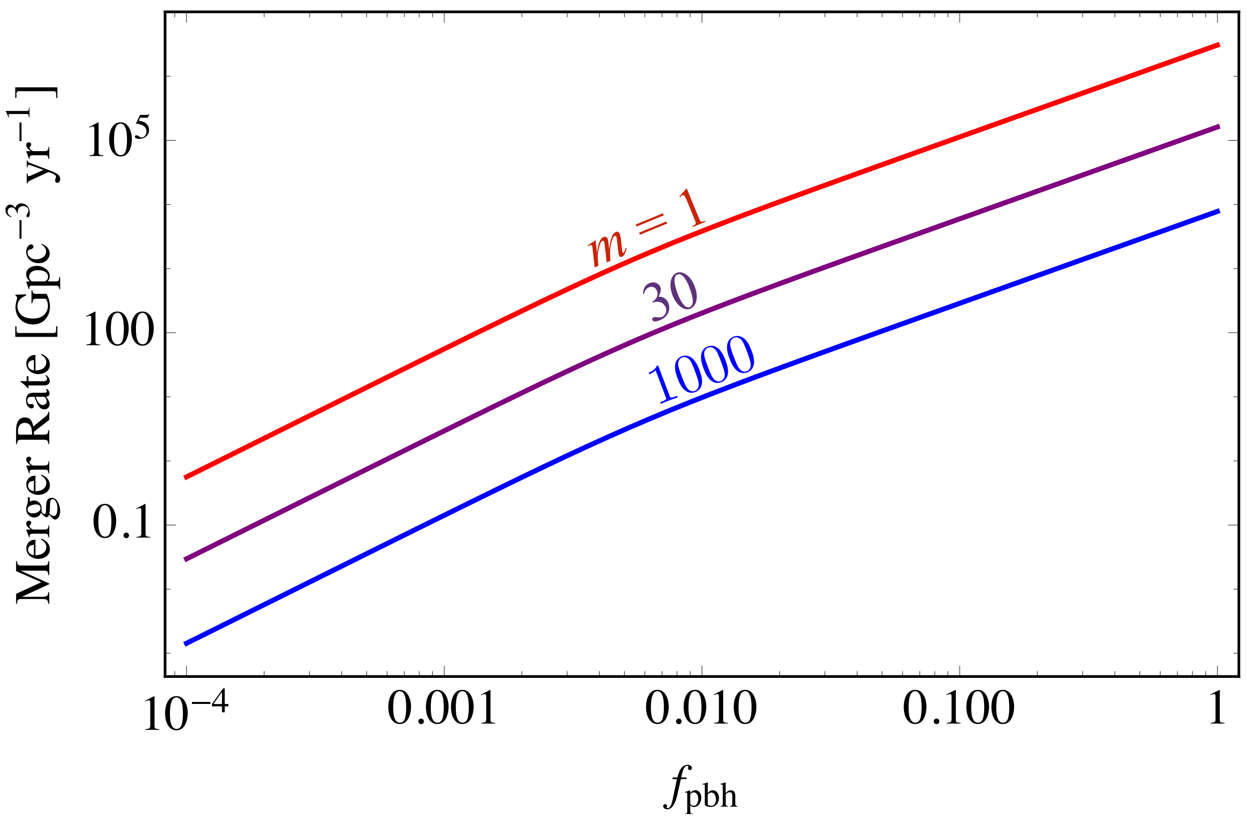
As they fall towards one another, torqued by other PBHs result in a non-zero (but small) angular momentum

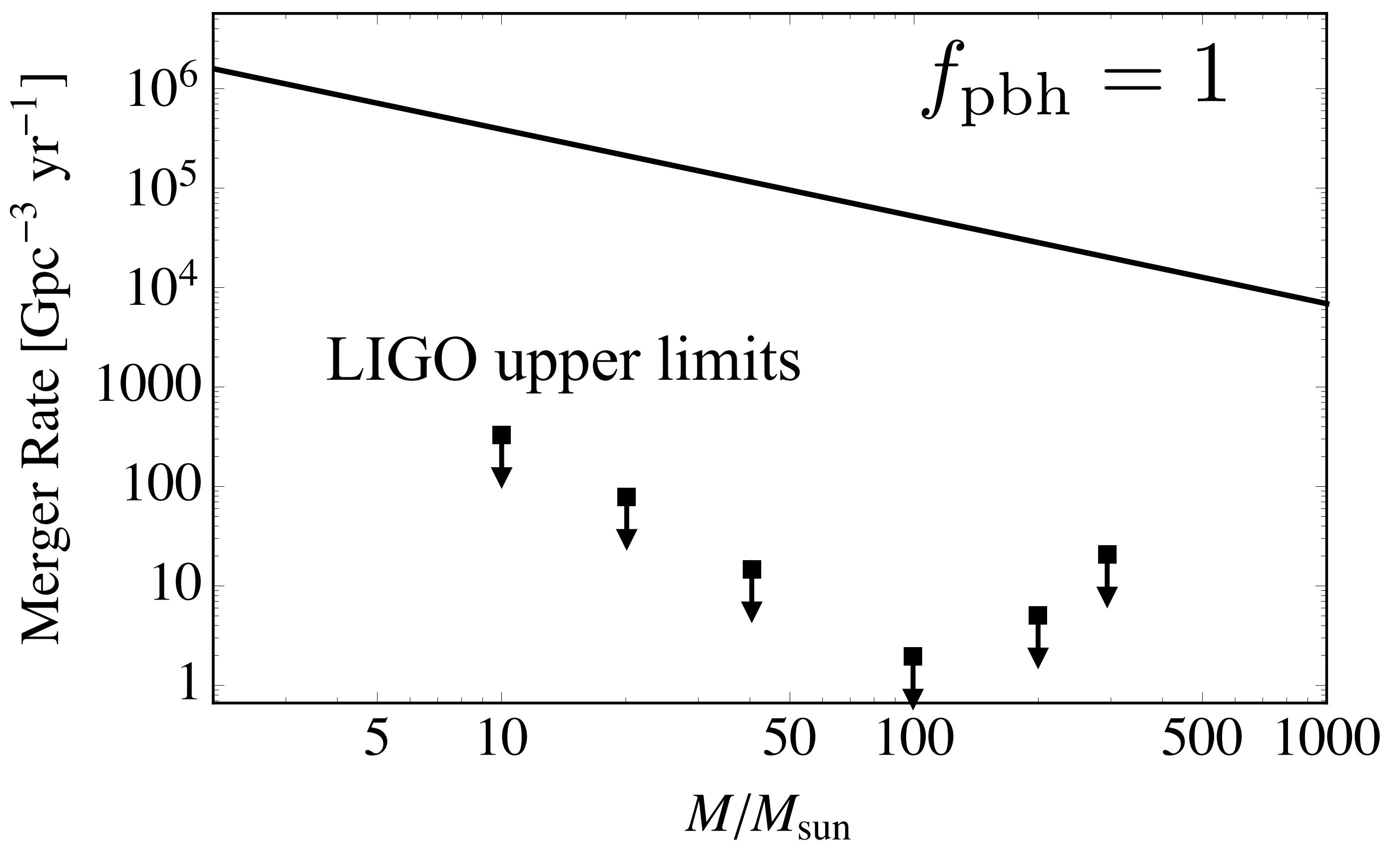
Inspiral through GW radiation, some merge at the present time.

Merger rate

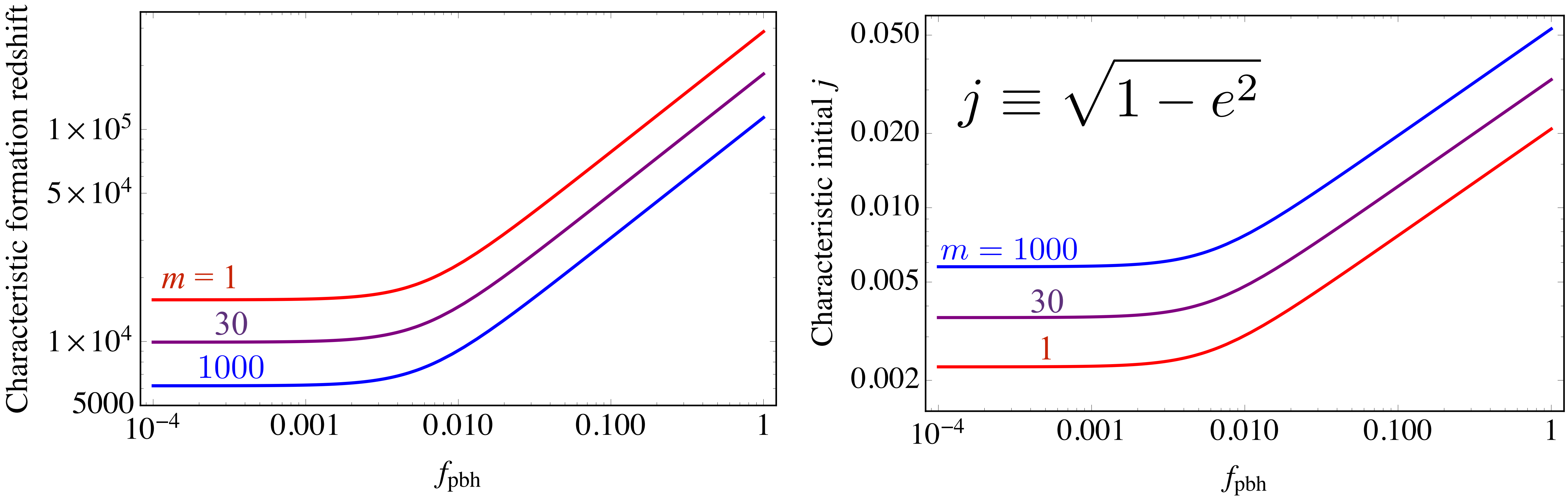
Time to merge for $j << 1$ (Peters 1964): $$t = \frac{3}{170}\frac{a^4}{M^3}j^7$$

Given the probability distributions for *a* and *j*, get probability distribution for *t*, hence merger rate





Characteristic initial properties for binaries merging today



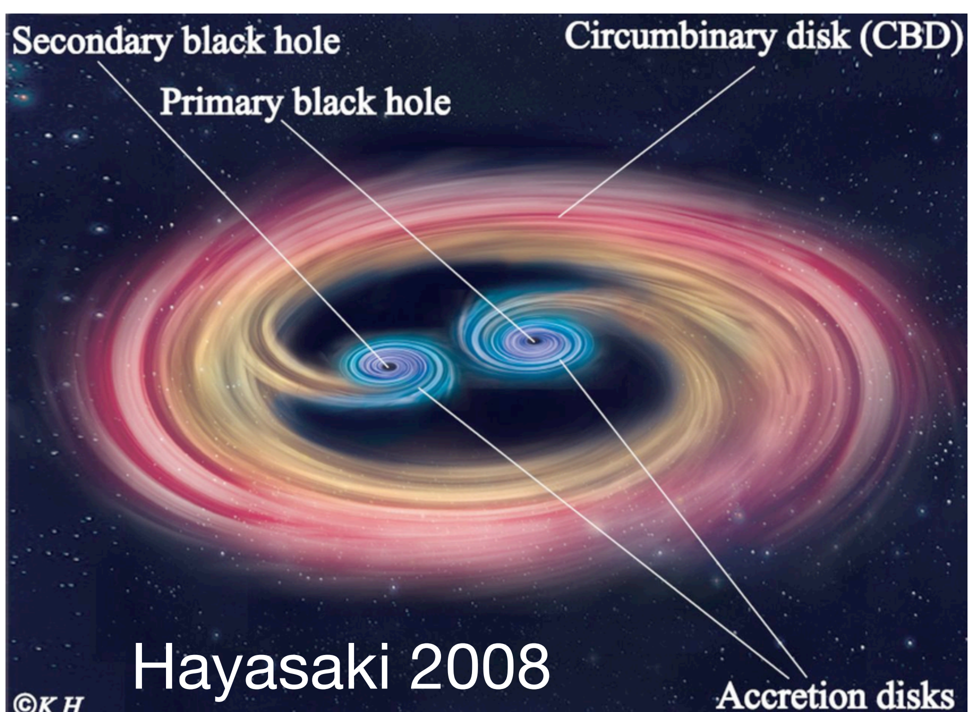
PBH binaries are typically highly eccentric.
Merger timescale strongly depends on eccentricity.

Do binaries that form at $z \sim 10^4$ - 10^5 evolve only through GW radiation until the present time?

- Gravitational interactions with other PBHs and rest of dark matter

Using simple analytic estimates of the properties of the first structures, we found that torques due dark matter (PBHs or WIMPs) do not significantly affect PBH binaries.

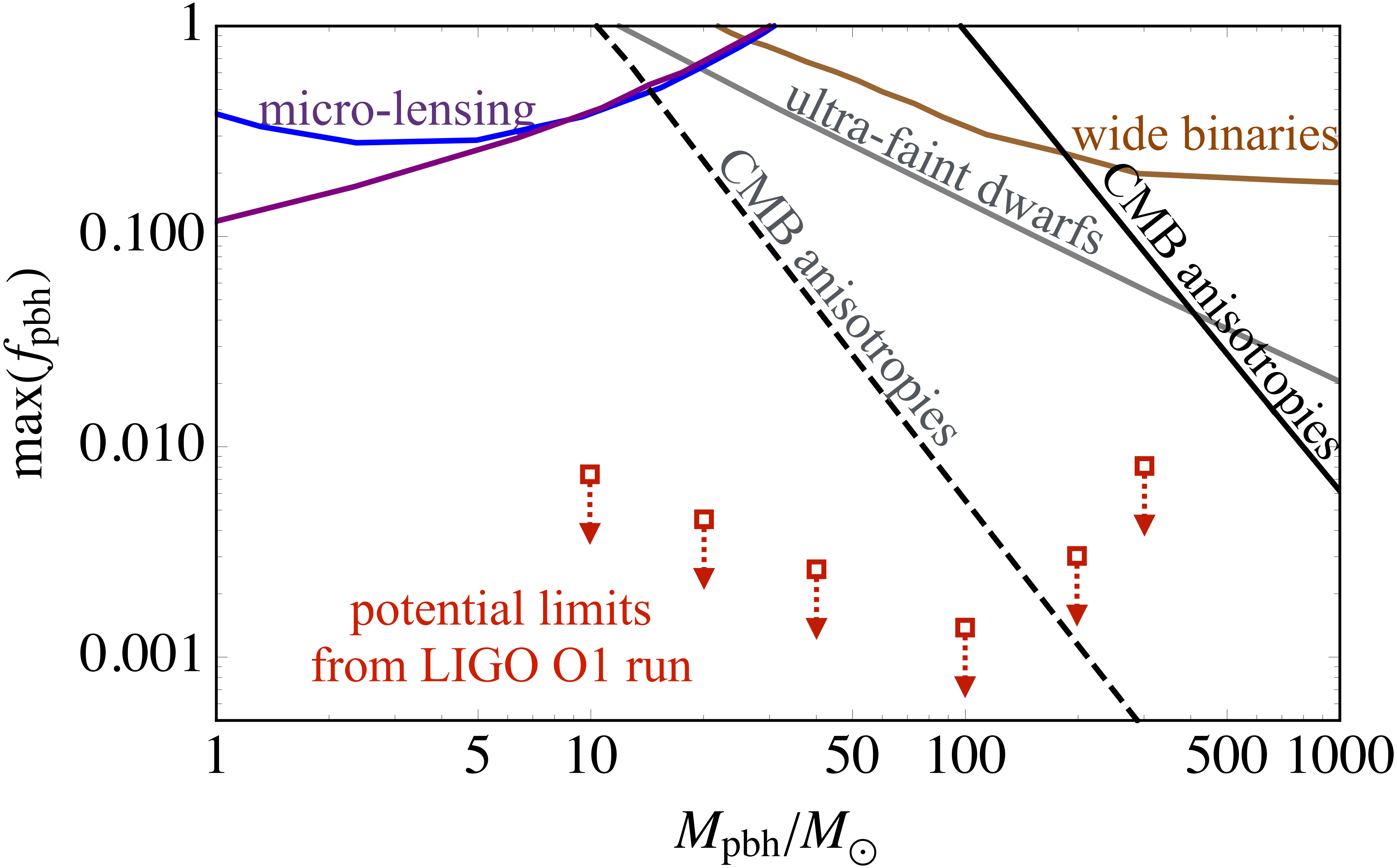
- Exchange of energy and angular momentum with accreting baryons



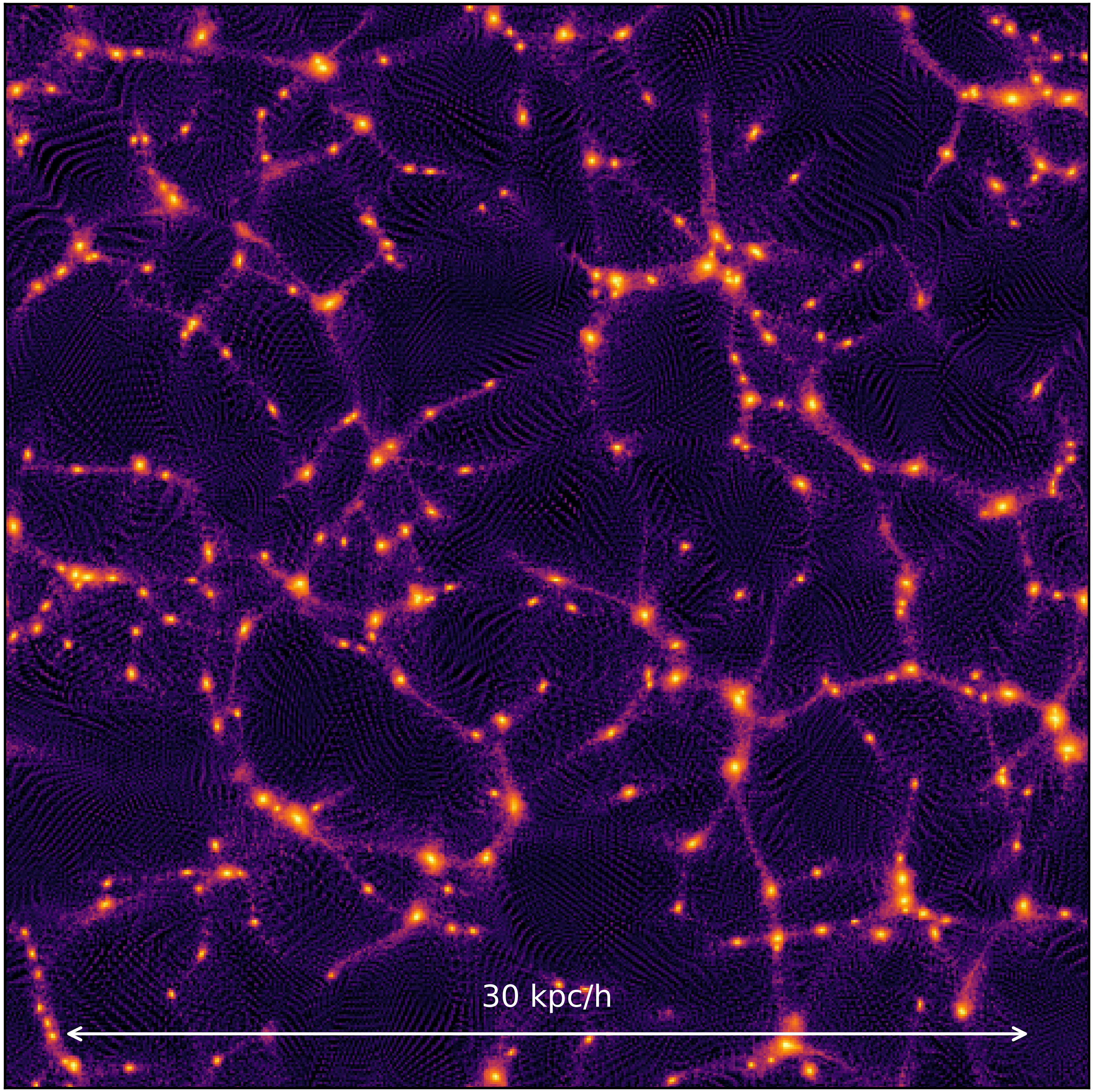
Most uncertain piece. Estimated that torques could be marginally relevant. Subject of active research (e.g. Tang, Haiman & MacFadyen 2018).

Does LIGO rule out PBH-dark matter?

It *might*, but more checks are needed



Simulations produced by Derek Inman (NYU)



$$M_{\rm pbh} = 30 M_\odot$$

$$f_{\rm pbh} = 0.1$$