Probing the nature of dark matter
with the
cosmic microwave background

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CERN TH colloquium

Introduction

- We still don’t know what the dark matter is [please let me know if you do]
- It could even be made of several vastly different things
- Let’s keep an open mind

Plan

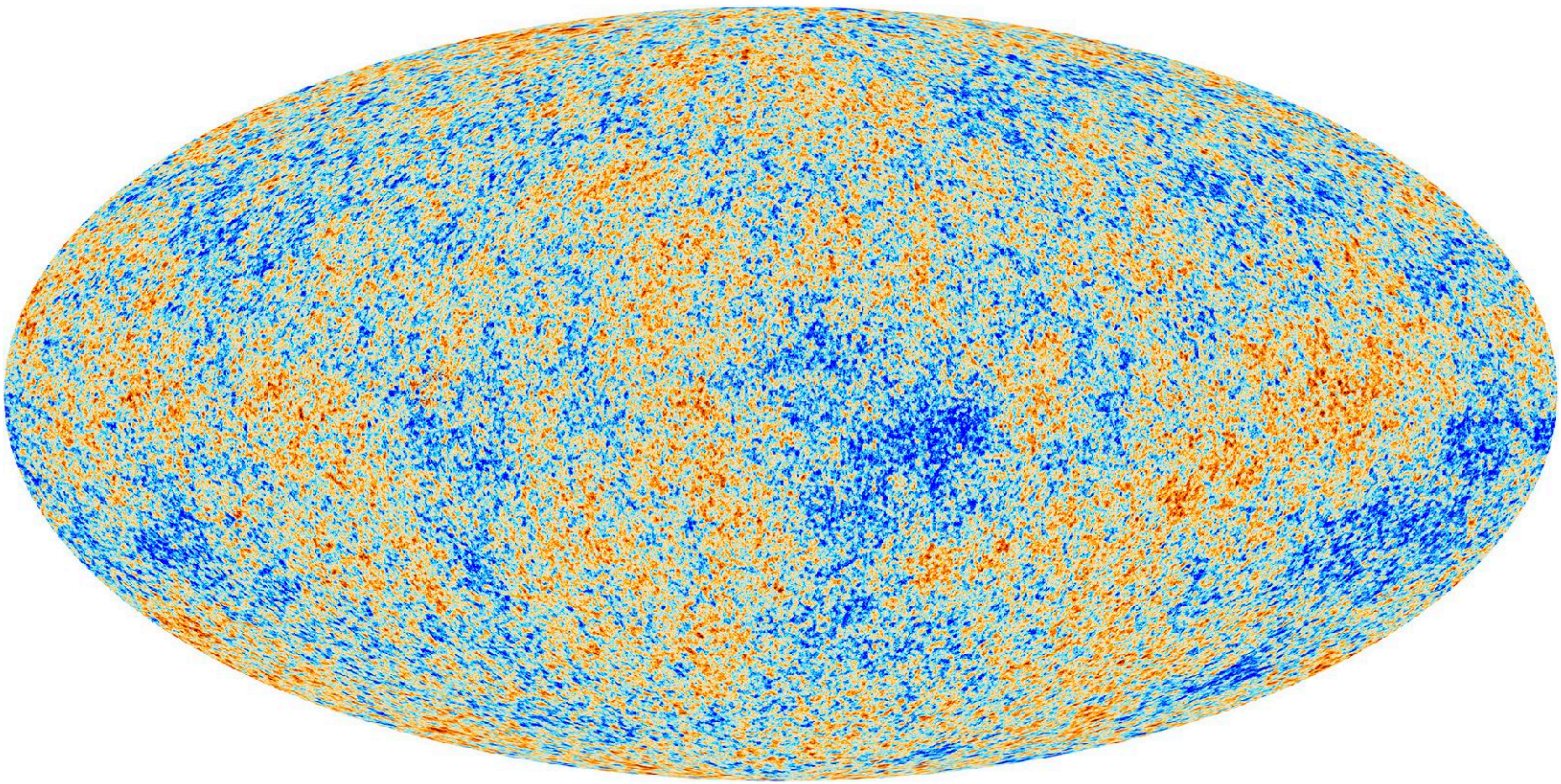
0. Brief overview of CMB physics

1. Annihilating dark matter

2. Scattering dark matter

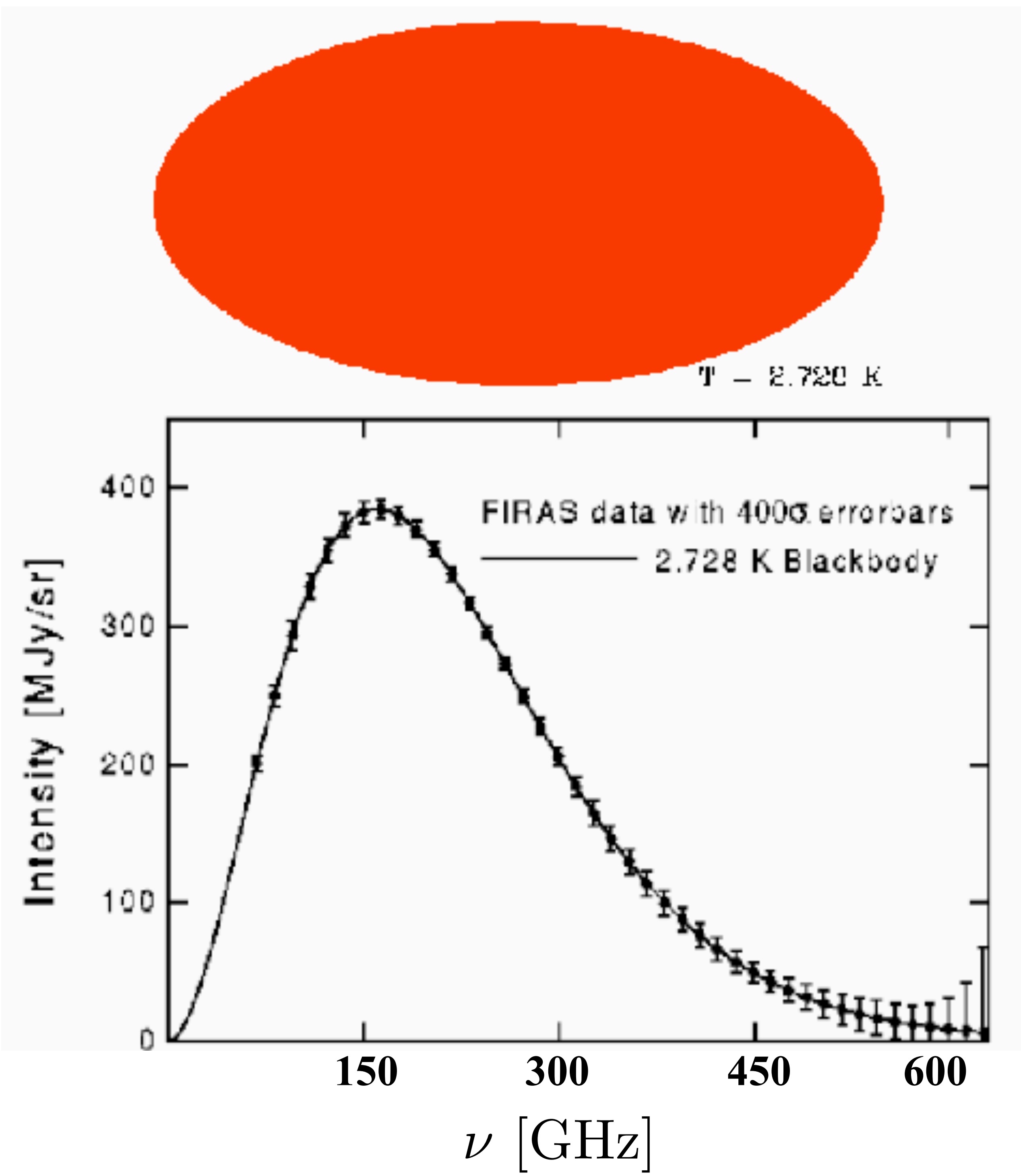
3. Primordial black holes

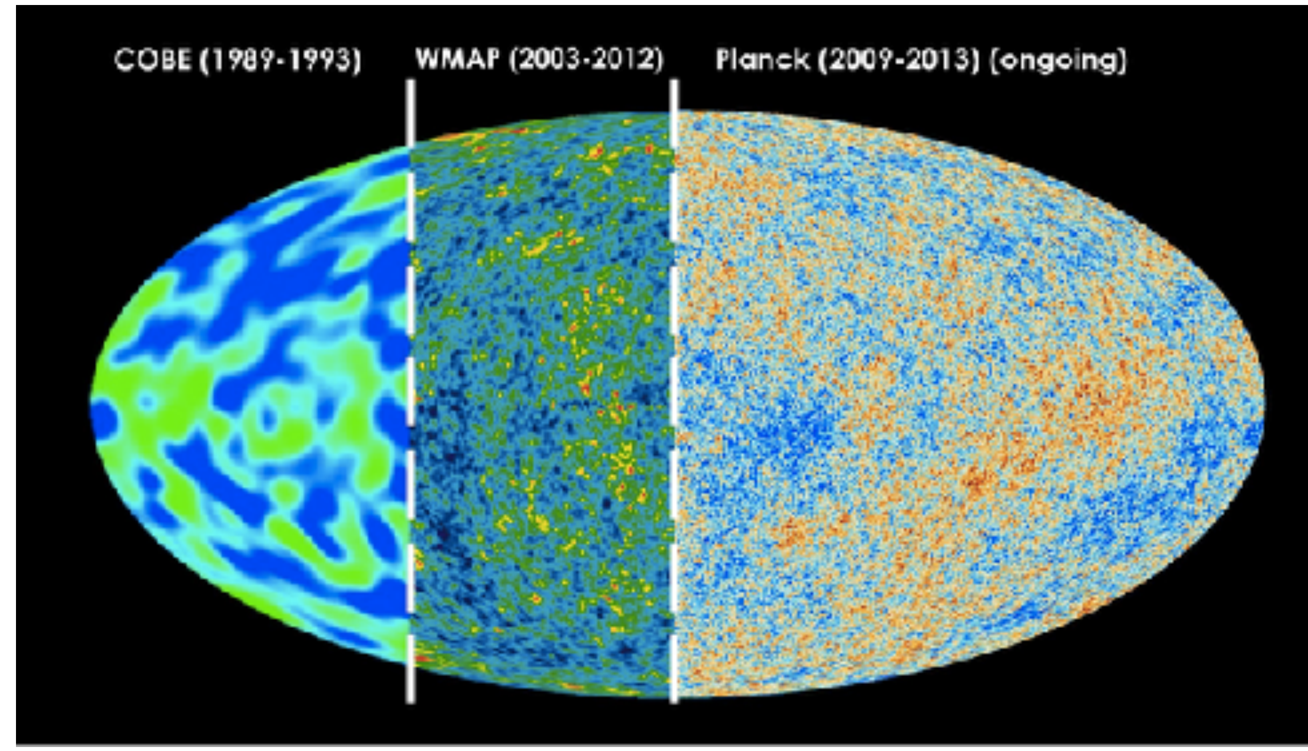
0. Brief overview of CMB physics

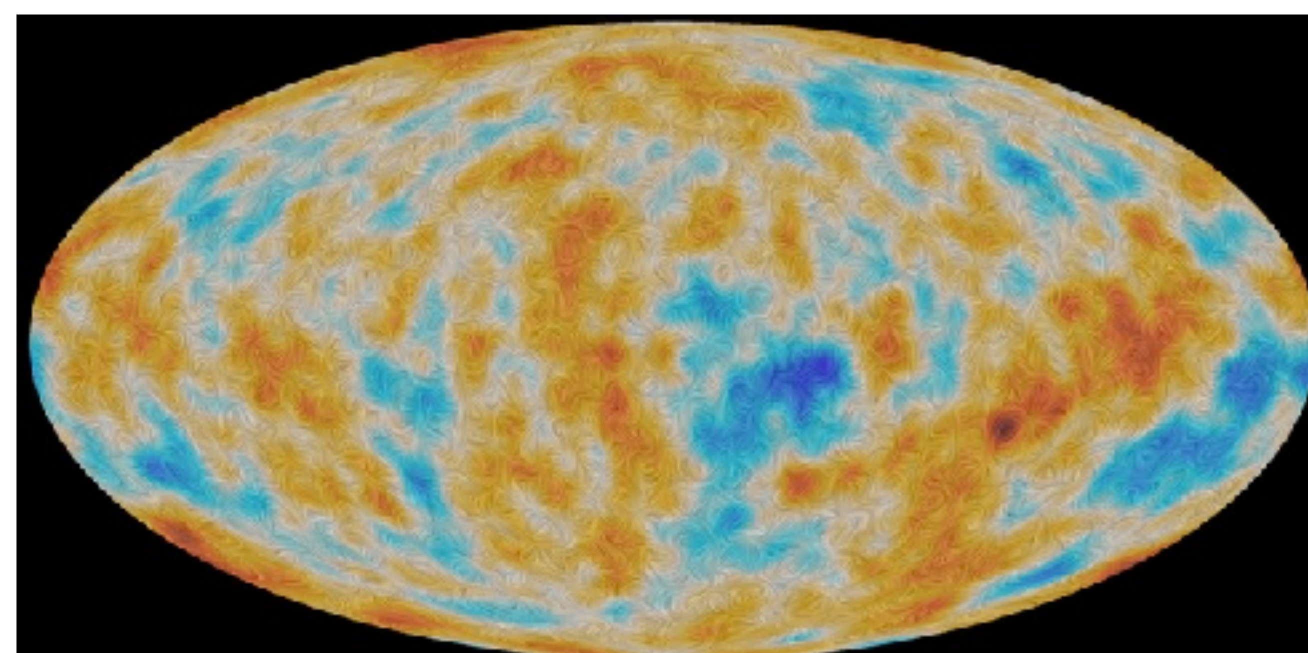


The CMB brightness is 2-dimensional function: frequency and direction

$$T(\nu,\hat{n}) = T_0 \ + \Delta T_{\rm spec}(\nu) + \Delta T_{\rm anis}(\hat{n}) + \delta T(\nu,\hat{n})$$





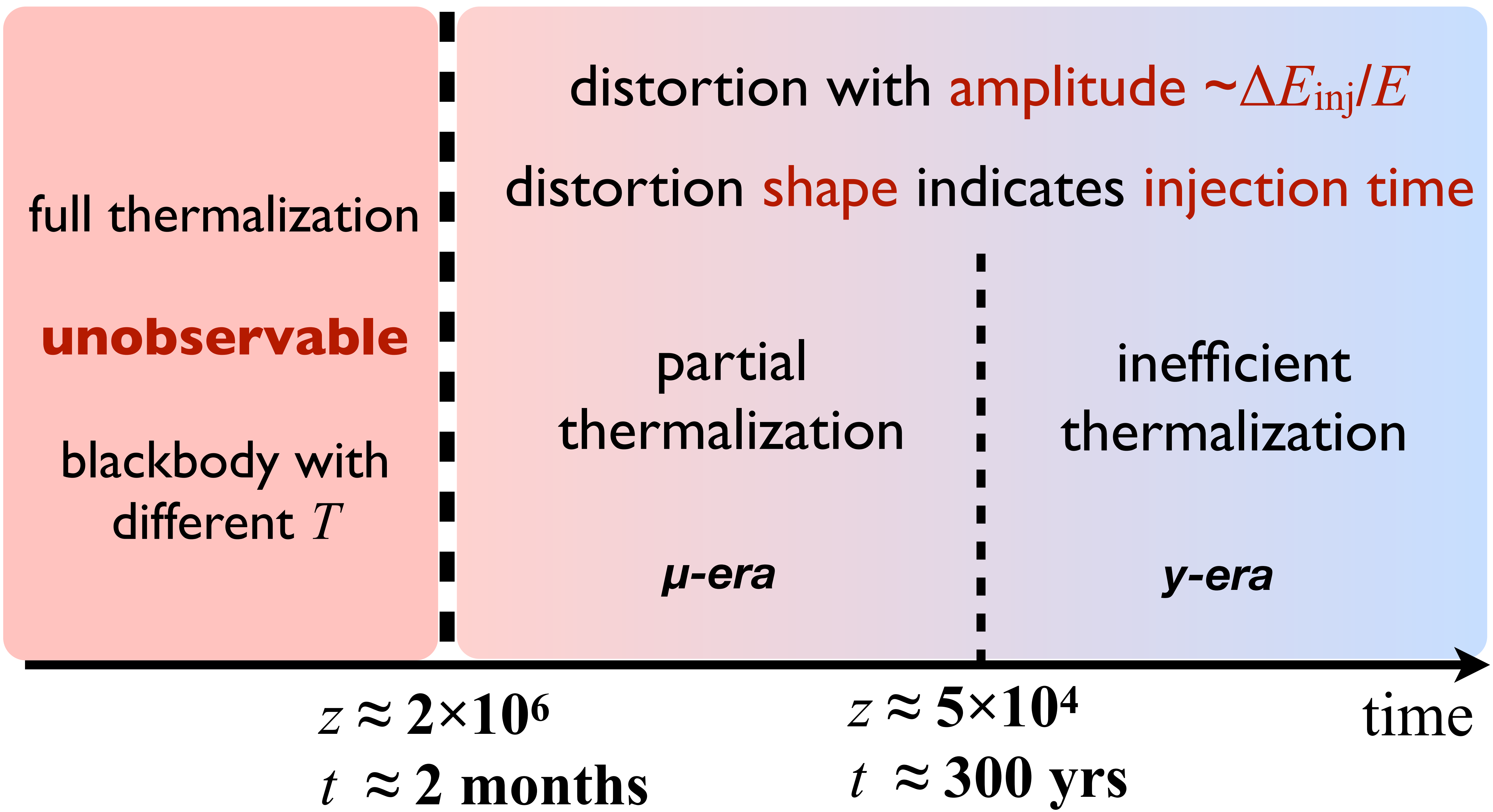


Planck polarization

Distortions tell us about thermal history

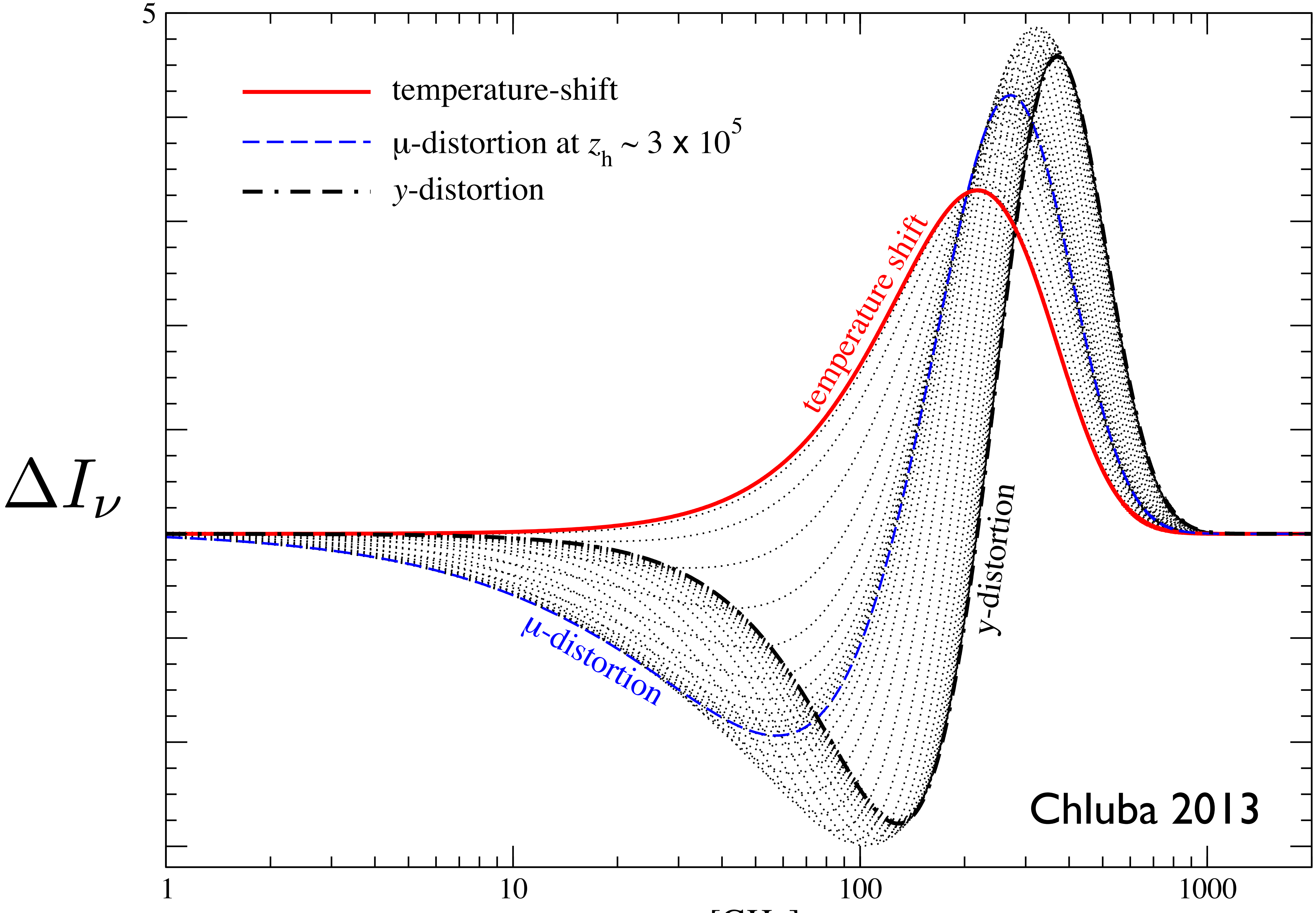
See e.g. Hu & Silk 1993, Chluba & Sunyaev 2012

Effect of heat injection as a function of time:



Shape informs us about the injection epoch

Amplitude of distortion ~ injected energy $\Delta U/U$.



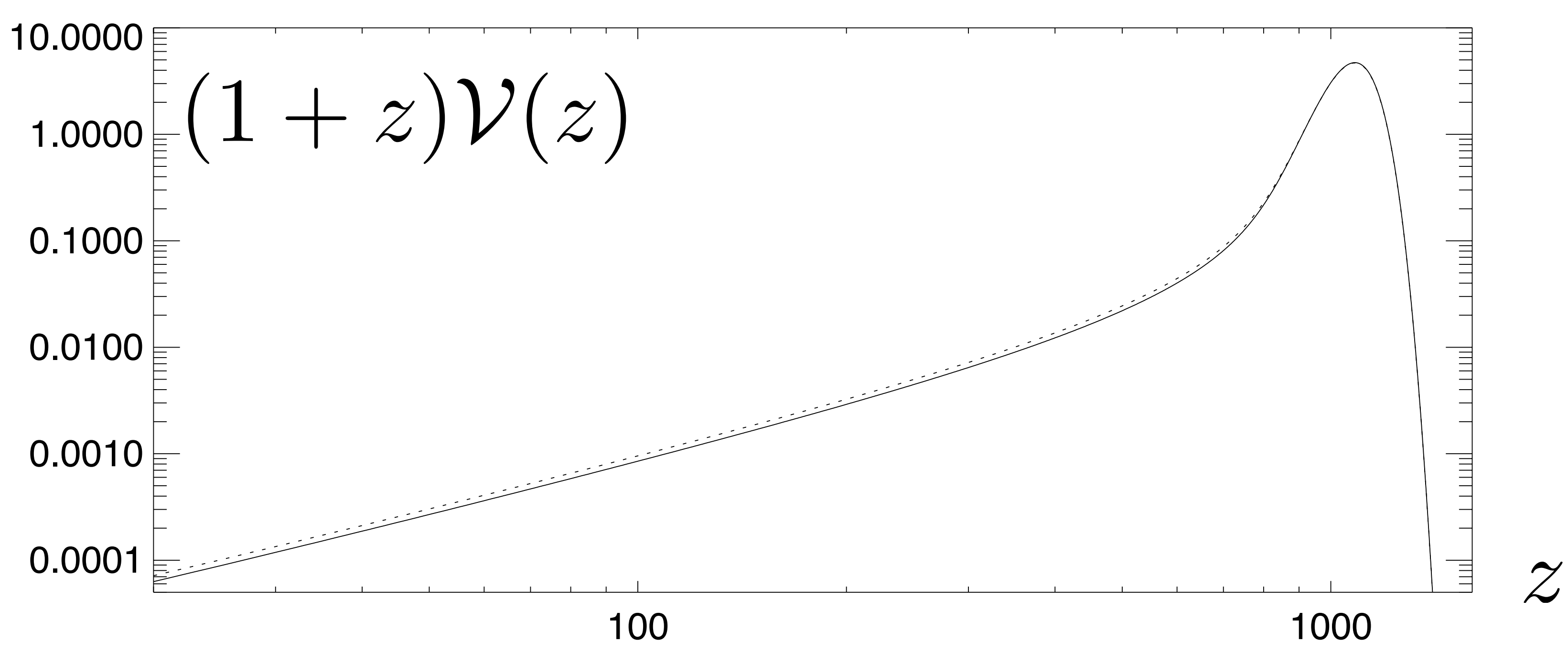
Anisotropies tell us about initial conditions, dynamics of perturbations and ionization history

$$\frac{\Delta T}{T}(z=0,\hat{n}) = \int dz\, \mathcal{V}(z)\, \mathcal{T}(z, r(z)\hat{n})\, \zeta_{\rm init} \quad [\ + \ \text{(I)SW}]$$

Transfer function (mostly photon monopole + dipole for temperature, quadrupole for polarization): result of linear evolution of photon + neutrino + baryon + DM.

Visibility function: probability of last Thomson scattering between z and z + dz.

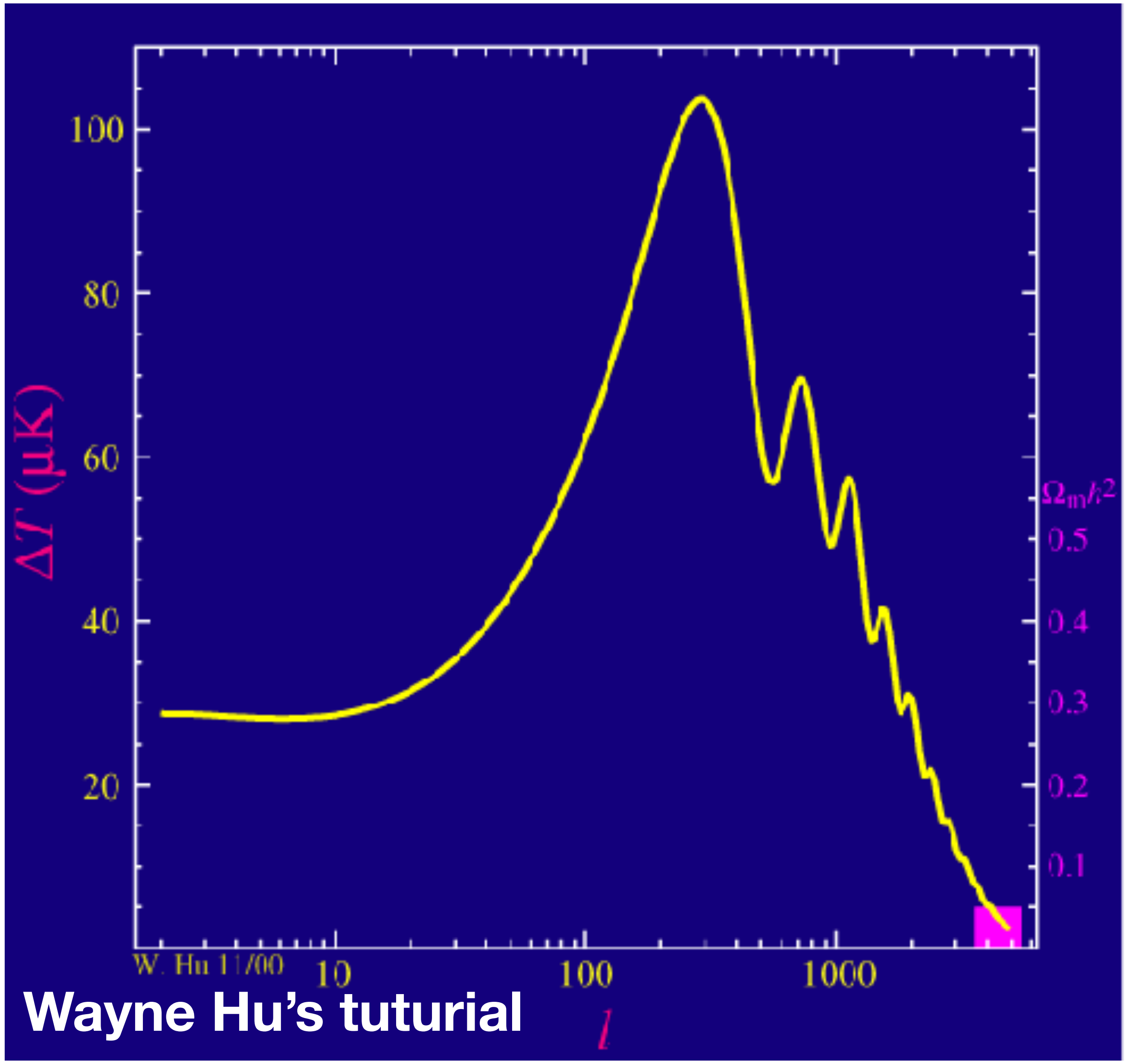
$$\mathcal{V}(z) = n_{\rm H} x_e \sigma_{\rm T} \frac{dt}{dz} \times \exp\left[-\int_0^z dz' \left(n_{\rm H} x_e \sigma_{\rm T} \frac{dt}{dz}\right)_{z'}\right]$$



0-th order measurement: total abundance of cold, collisionless dark matter

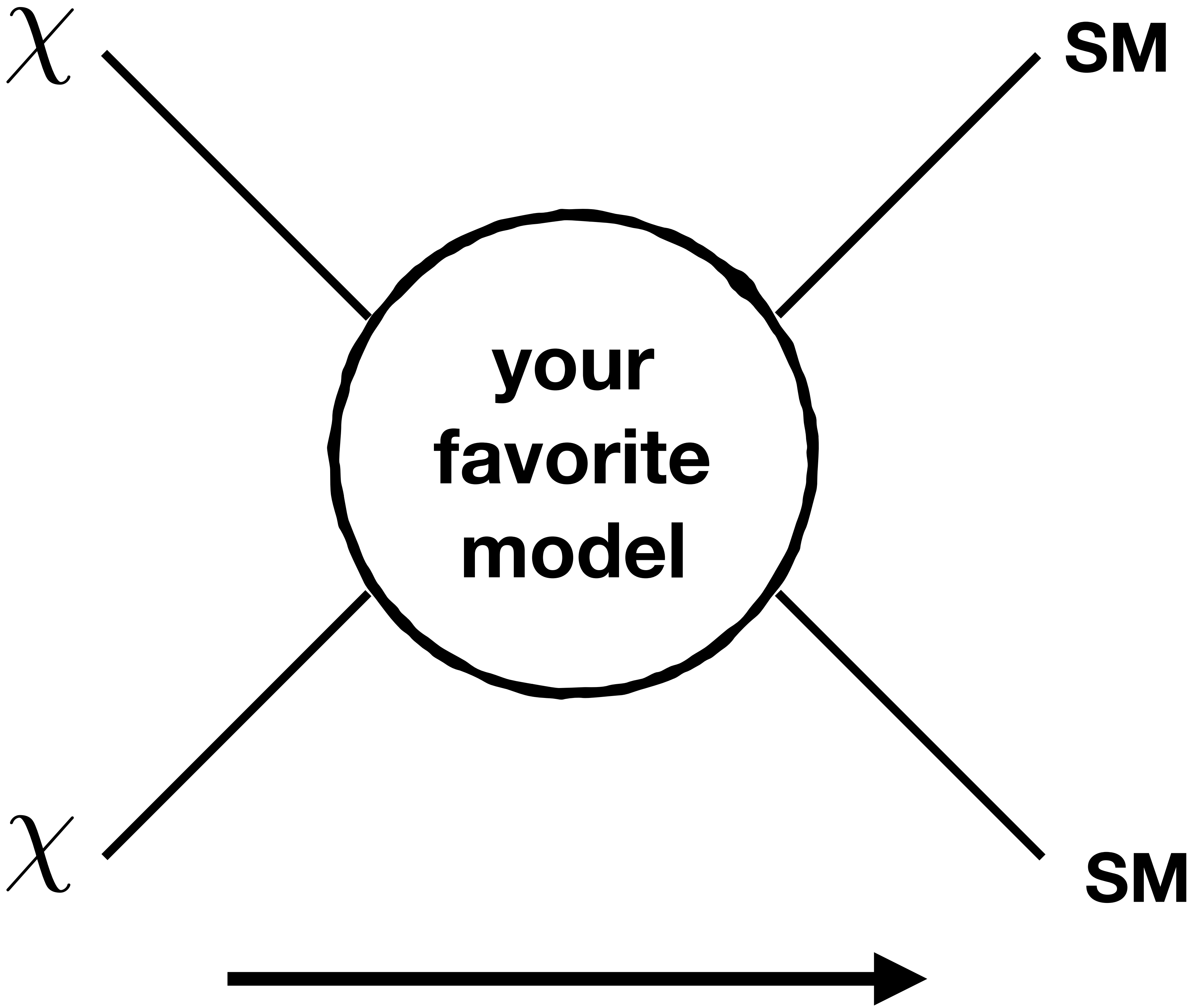
$$\Omega_c h^2 = 0.1199 \pm 0.0022$$

[Planck collaboration 2015]



What can the CMB tell us about the nature of DM?

1. Annihilating dark matter



Testing the vanilla WIMP with the CMB

``WIMP miracle”: DM abundance results from annihilation cross section

$$\langle \sigma v \rangle_{\rm relic} \sim 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Step 0: DM annihilations inject energy with volumetric rate

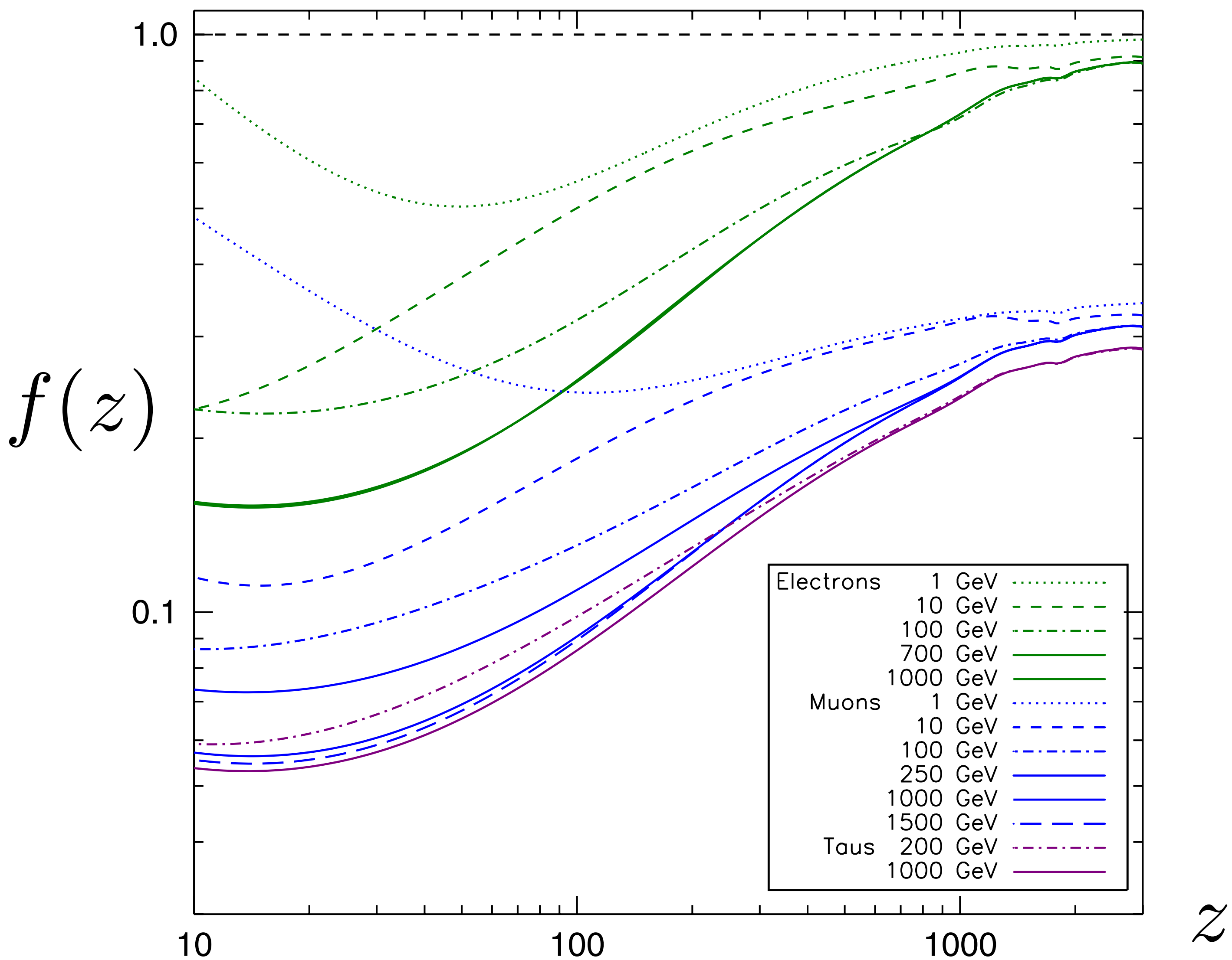
$$\dot{\rho}_{\rm inj} = \frac{1}{2} \left(\frac{\rho_c}{m_\chi} \right)^2 \langle \sigma v \rangle m_\chi = \frac{1}{2} \frac{\langle \sigma v \rangle}{m_\chi} \rho_c^2$$

=> CMB is mostly sensitive to $p_{\rm ann} = \frac{\langle \sigma v \rangle}{m_\chi}$

Step 1: compute energy deposited into the plasma

$$\dot{\rho}_{\rm dep}(z) = f(z)\ \dot{\rho}_{\rm inj}$$

Depends on the nature and spectrum of particles produced in annihilation, e.g. if the DM annihilates entirely to neutrinos, $f = 0$



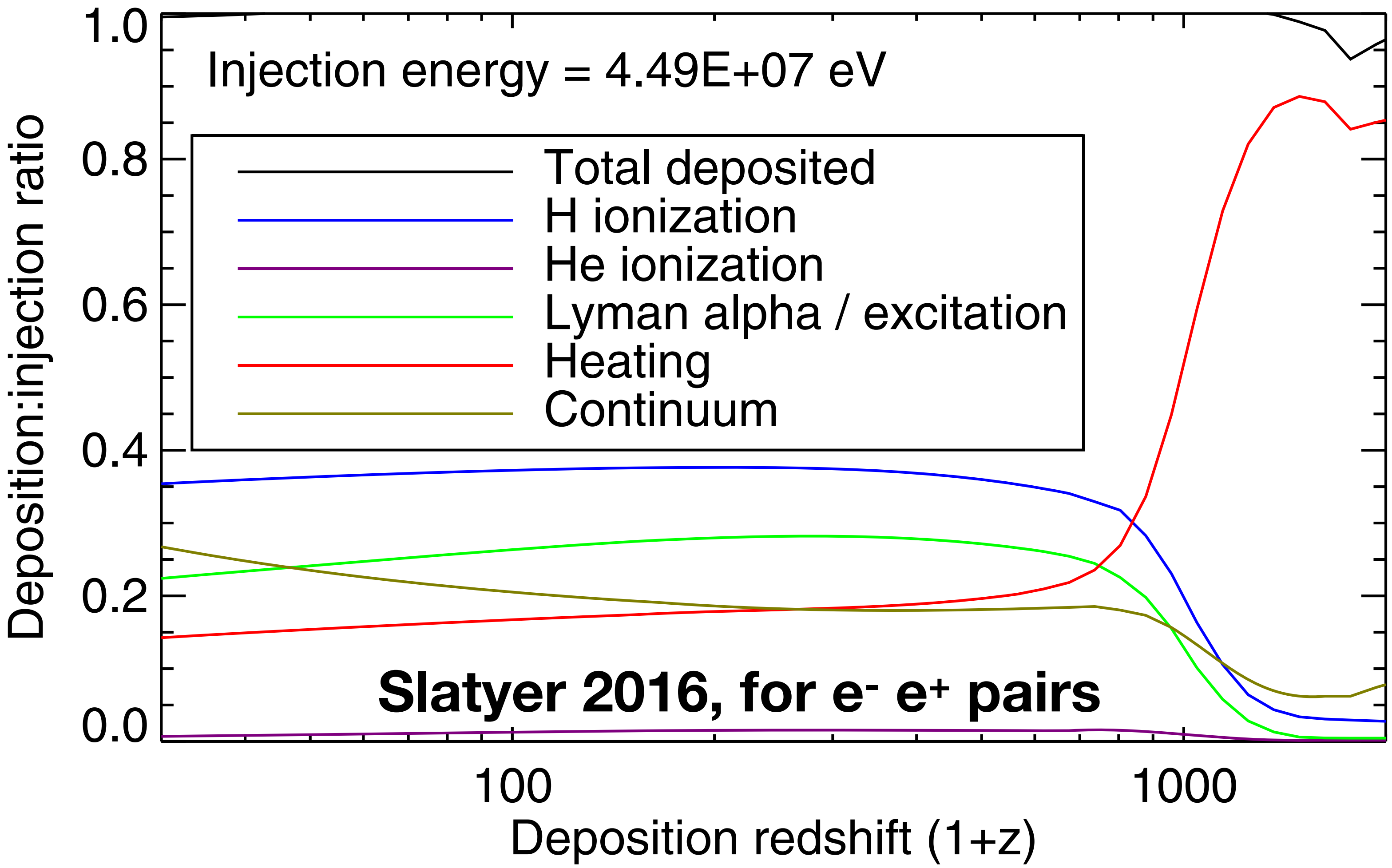
Slatyer, Padmanabhan & Finkbeiner 2009

Step 2: channel of energy deposition: heat / ionizations / excitations

Simple estimate of Chen & Kamionkowski 04 (based on numerical studies of Shull & Van Steenberg 85):

fraction in heat, ionization, excitation ~ $\left[\frac{1+2x_e}{3}, \frac{1-x_e}{3}, \frac{1-x_e}{3}\right]$

(in practice, depends on injected spectrum, e.g. Slatyer 2016)



Step 3: effect on CMB observables

- spectral distortions: $$\frac{\Delta I_\nu}{I_\nu^{\rm BB}} \sim \int dt\ f_{\rm heat} \frac{\dot\rho_{\rm dep}}{\rho_\gamma}$$

typically much less sensitive to DM annihilation than anisotropies

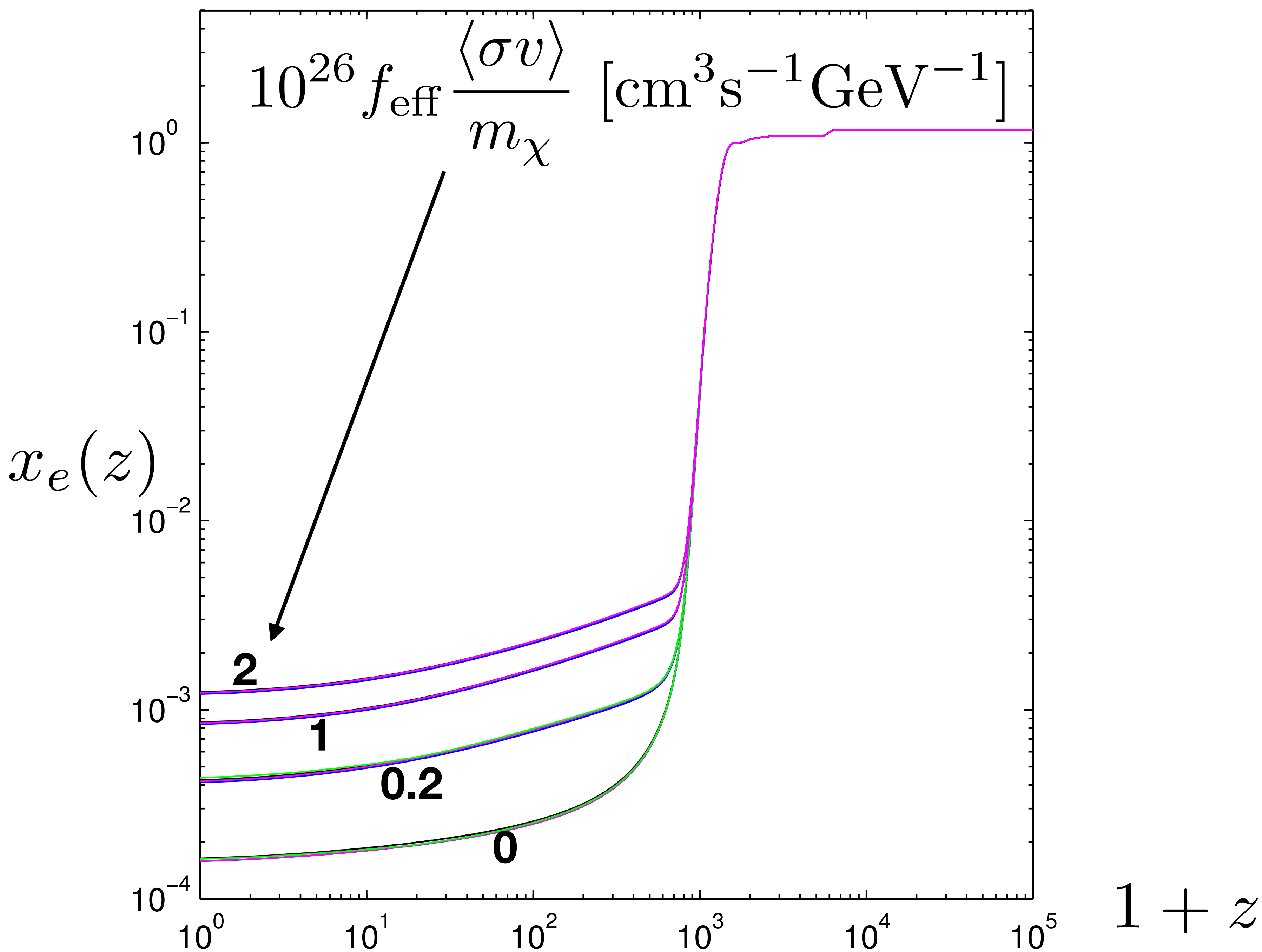
- recombination history: $$\dot x_e^{\rm direct} = \dot x_e^{\rm std} + f_{\rm ion} \frac{\dot\rho_{\rm dep}}{n_{\rm H} \times 13.6 \text{ eV}}$$

$$\dot x_2 = \dot x_2^{\rm std} + f_{\rm exc} \frac{\dot\rho_{\rm dep}}{n_{\rm H} \times 10.2 \text{ eV}}$$

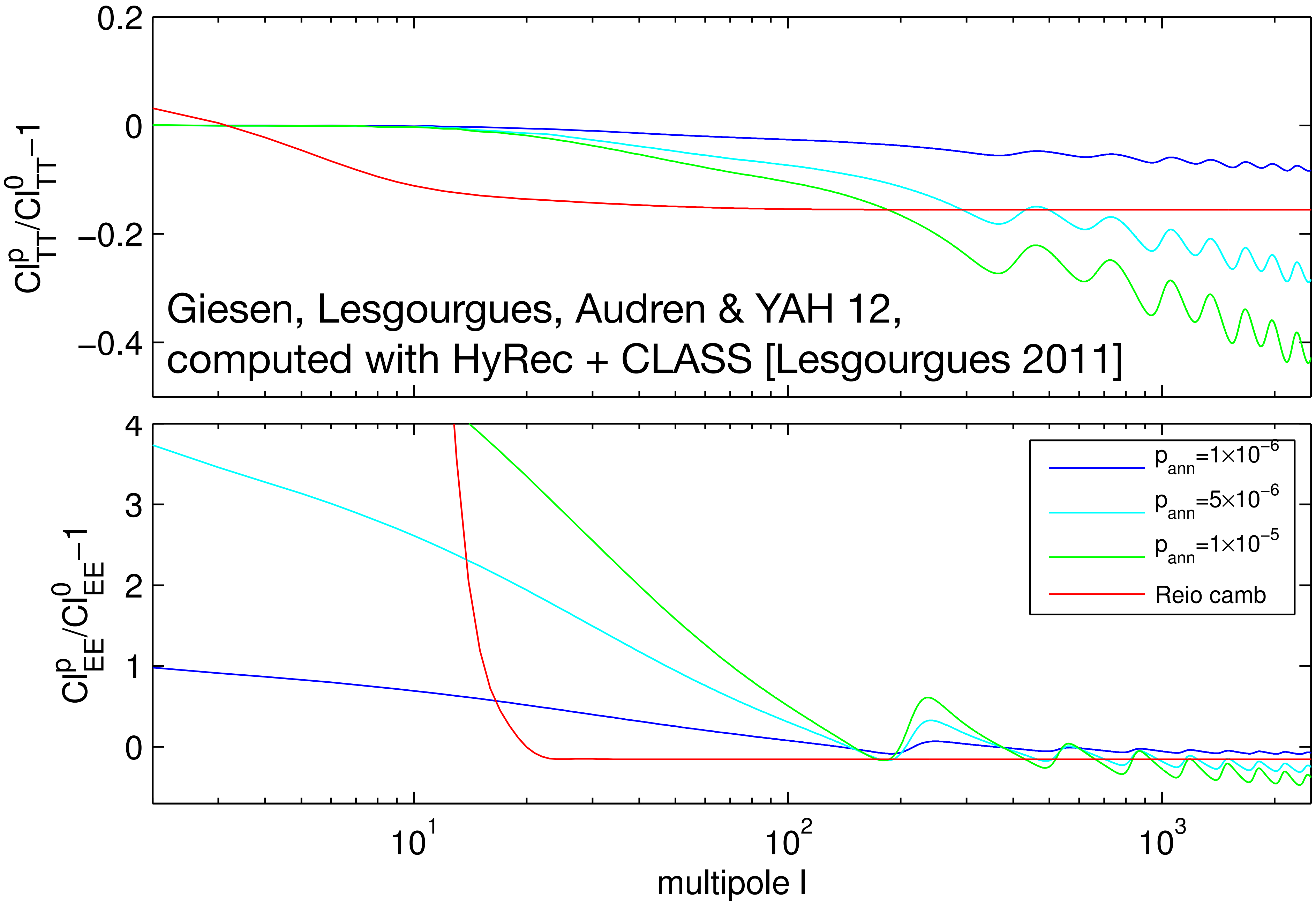
$$\dot T_{\rm gas} = \dot T_{\rm gas}^{\rm std} + \frac{2}{3 n_{\rm gas}} f_{\rm heat}\ \dot\rho_{\rm dep}$$

Requires highly accurate standard recombination theory
[YAH & Hirata 10, 11, Chluba ++ 11]

Implemented by several authors, e.g. Galli ++ 09, Slatyer ++09, Finkbeiner ++12, Green, Meerburg & Meyers 18

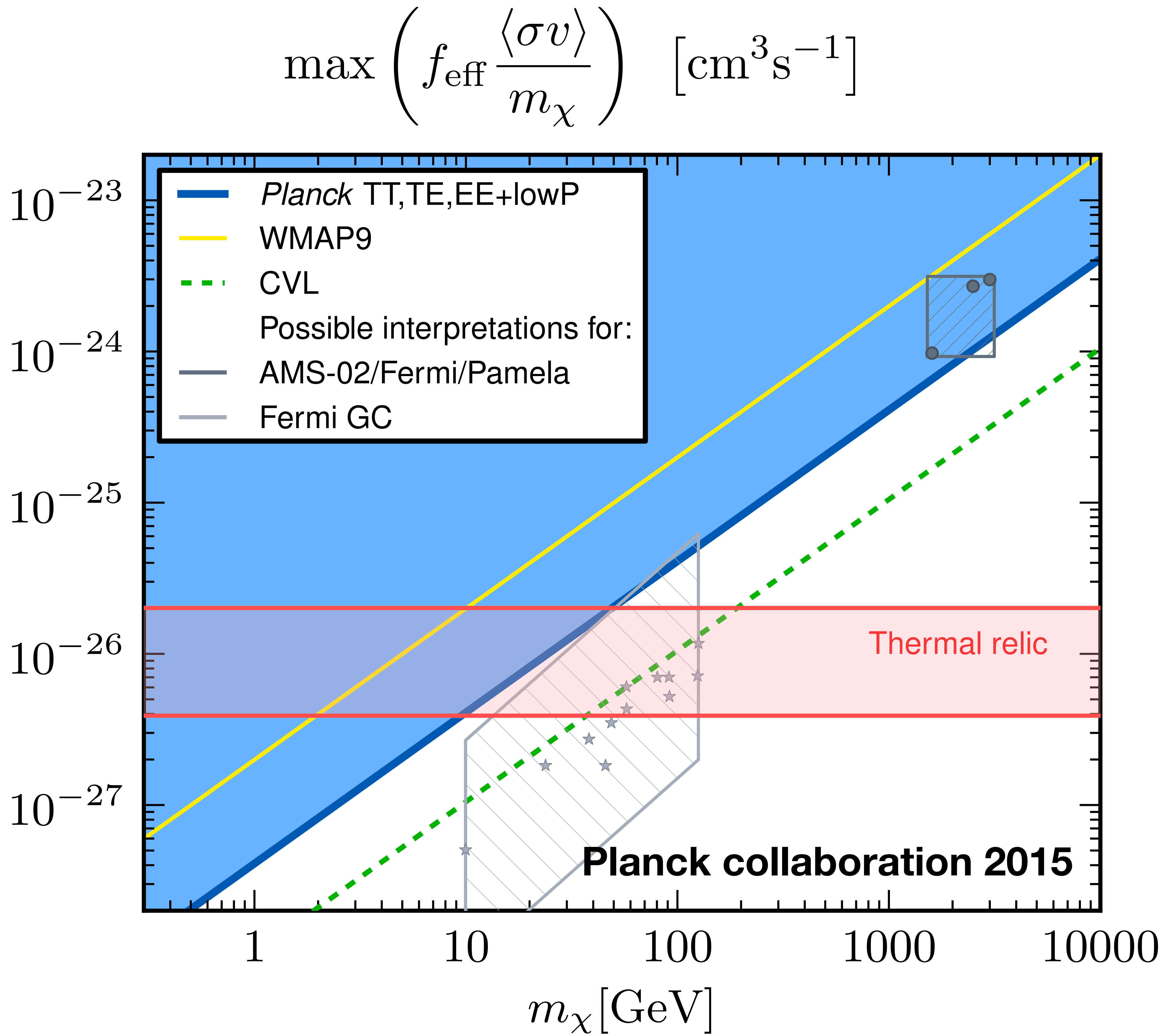


Giesen, Lesgourgues, Audren & YAH 12, computed with HyRec [YAH & Hirata, 2010, 2011]



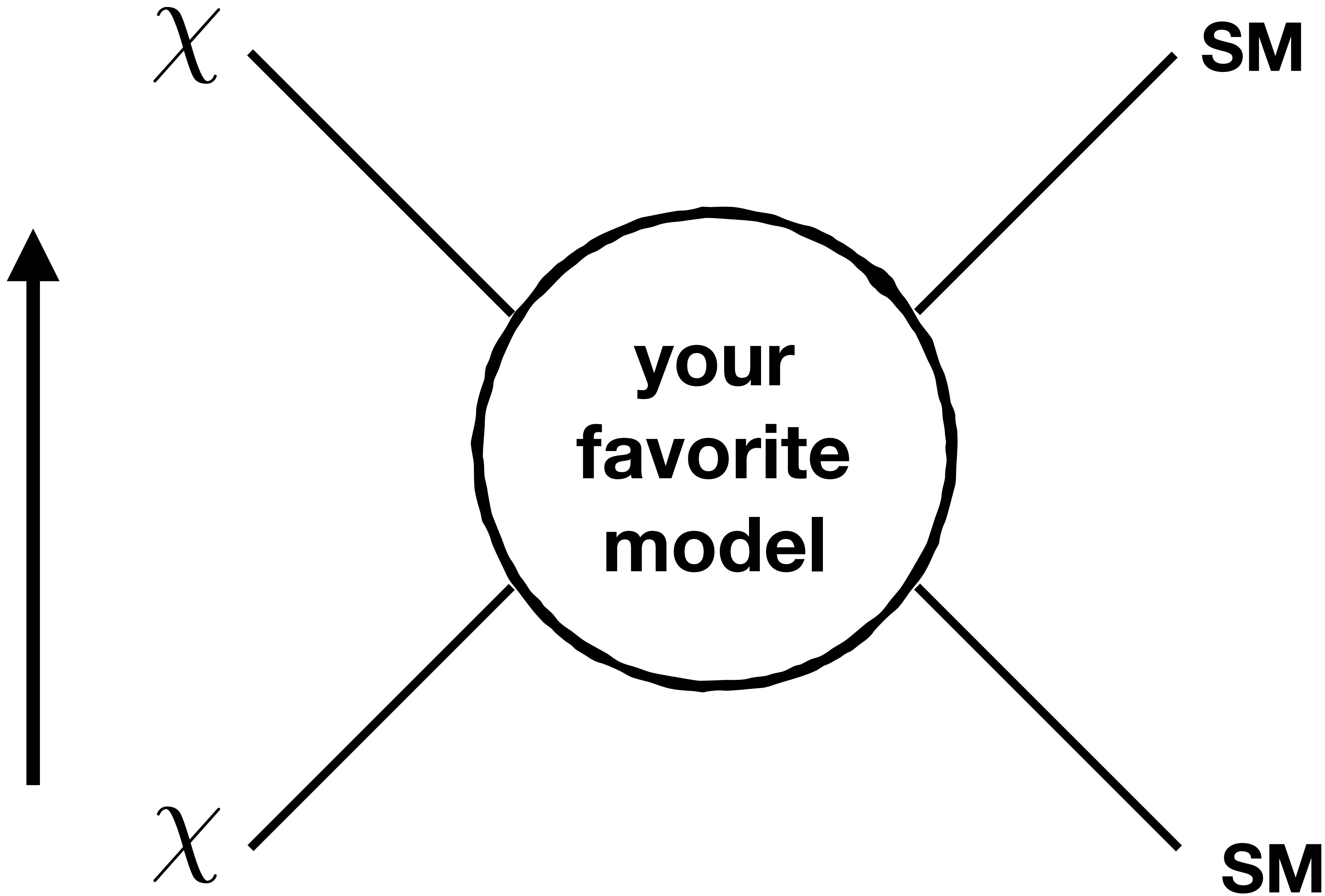
Same general picture holds to test any DM model injecting energy into the photon-baryon plasma (e.g. decaying DM):

energy injection → energy deposition → heat + ionizations



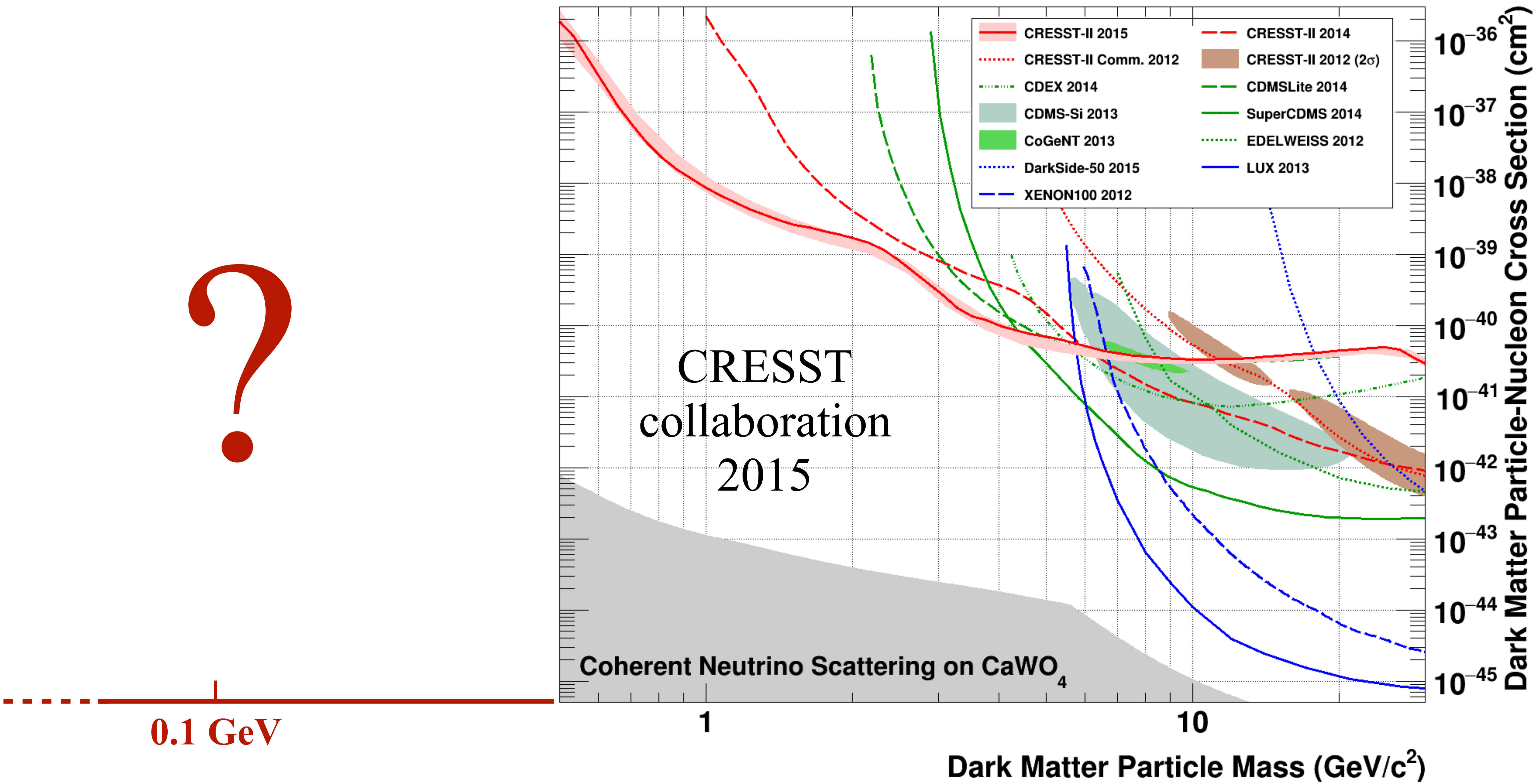
$\max\left(f_{\rm eff}\frac{\langle\sigma v\rangle}{m_\chi}\right)\quad[\mathrm{cm^3s^{-1}}]$
Planck TT,TE,EE+lowP
WMAP9
CVL
Possible interpretations for:
AMS-02/Fermi/Pamela
Fermi GC
Thermal relic
Planck collaboration 2015
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
1
10
100
1000
10000
$m_\chi[\mathrm{GeV}]$

2. Scattering dark matter



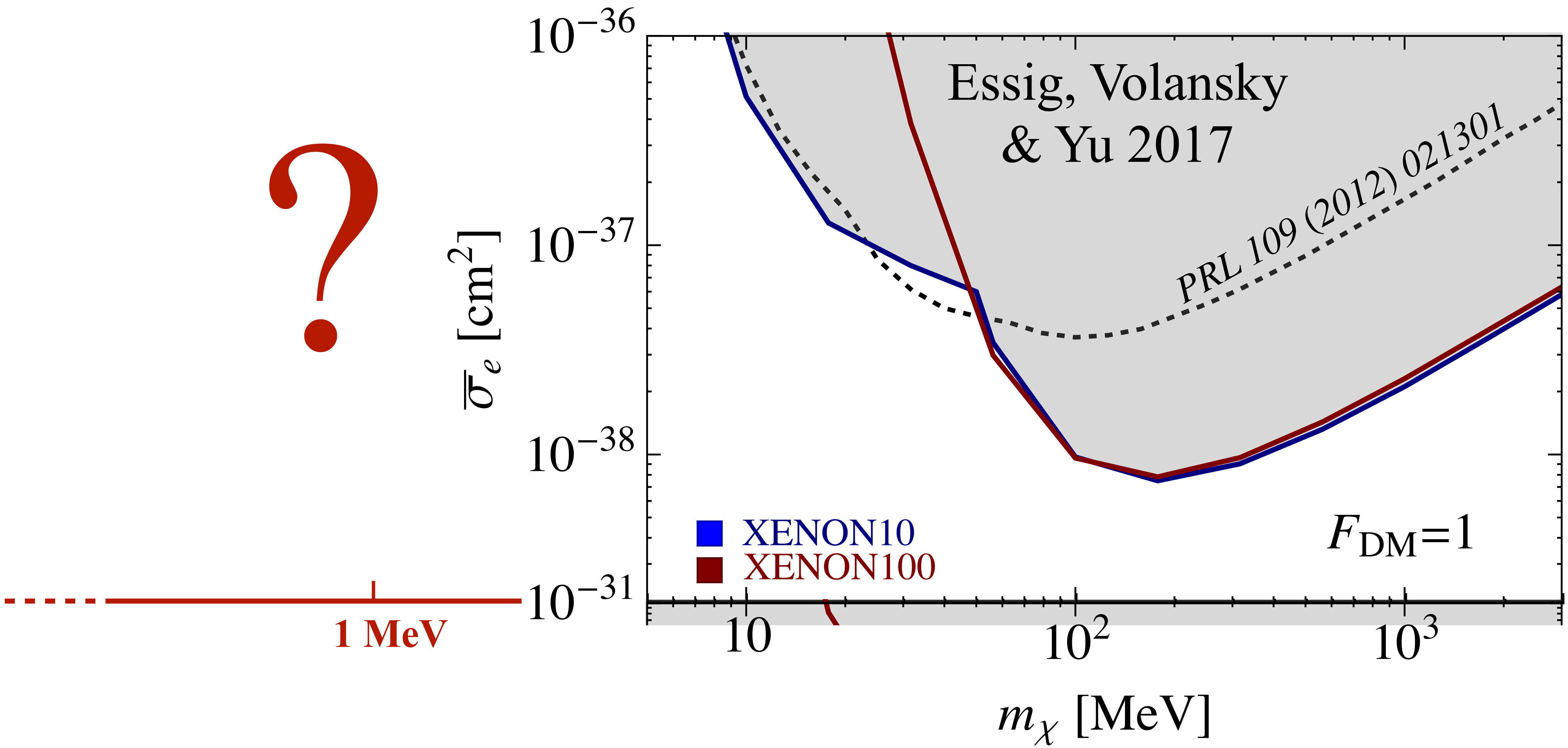
Direct detection constraints on DM-nucleon interactions

- Currently mostly sensitive to masses ≳ GeV
- Sensitive to assumptions about the local DM density and velocity distribution



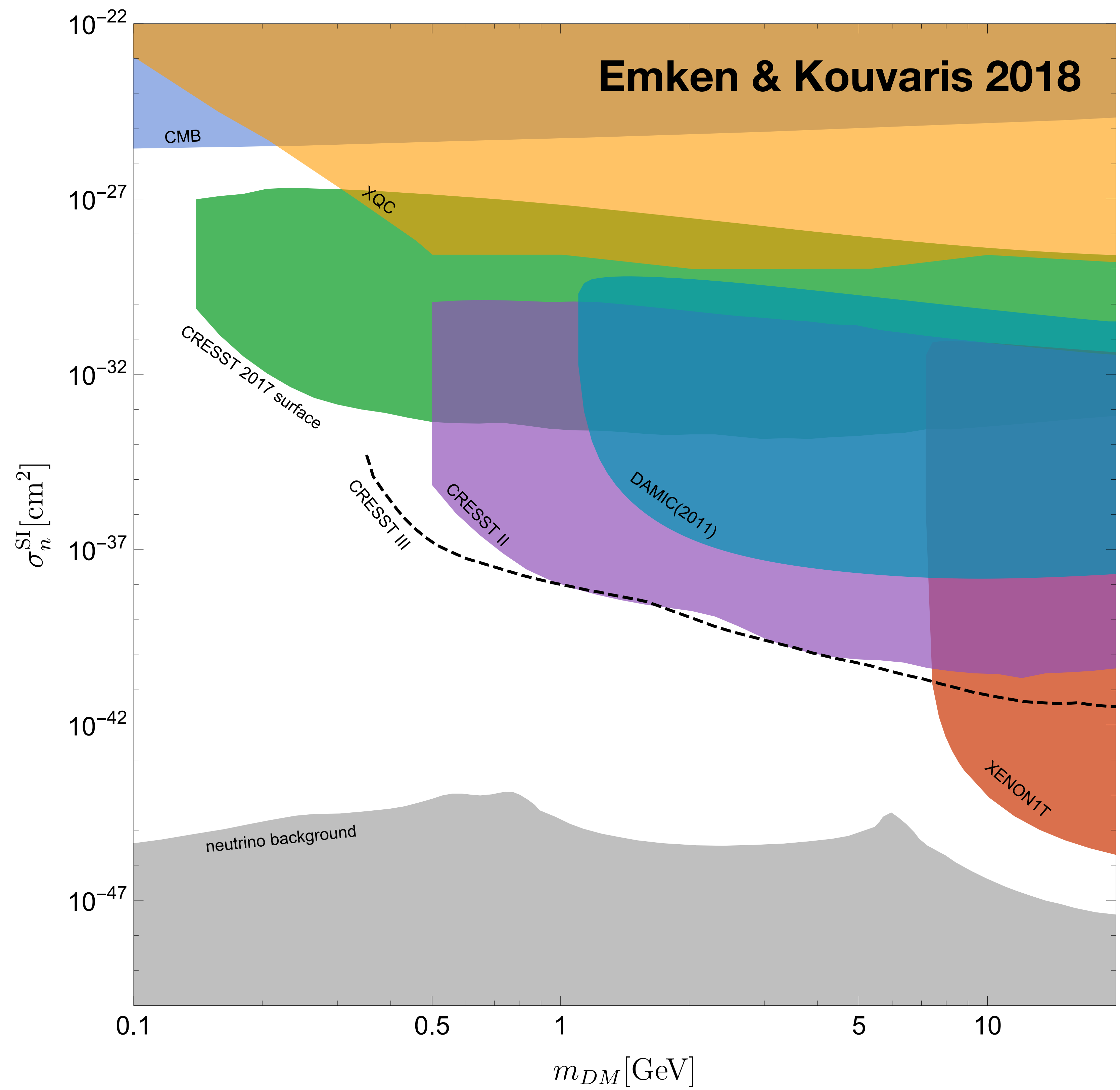
Direct detection constraints on DM-electron interactions

- Currently mostly sensitive to masses ≳ 10 MeV
- Sensitive to assumptions about the local DM density and velocity distribution



Cross-section ceiling due to shielding

[e.g. Zaharijas & Farrar 2005, Erickcek et al. 2005, Kouvaris & Shoemaker 2014]



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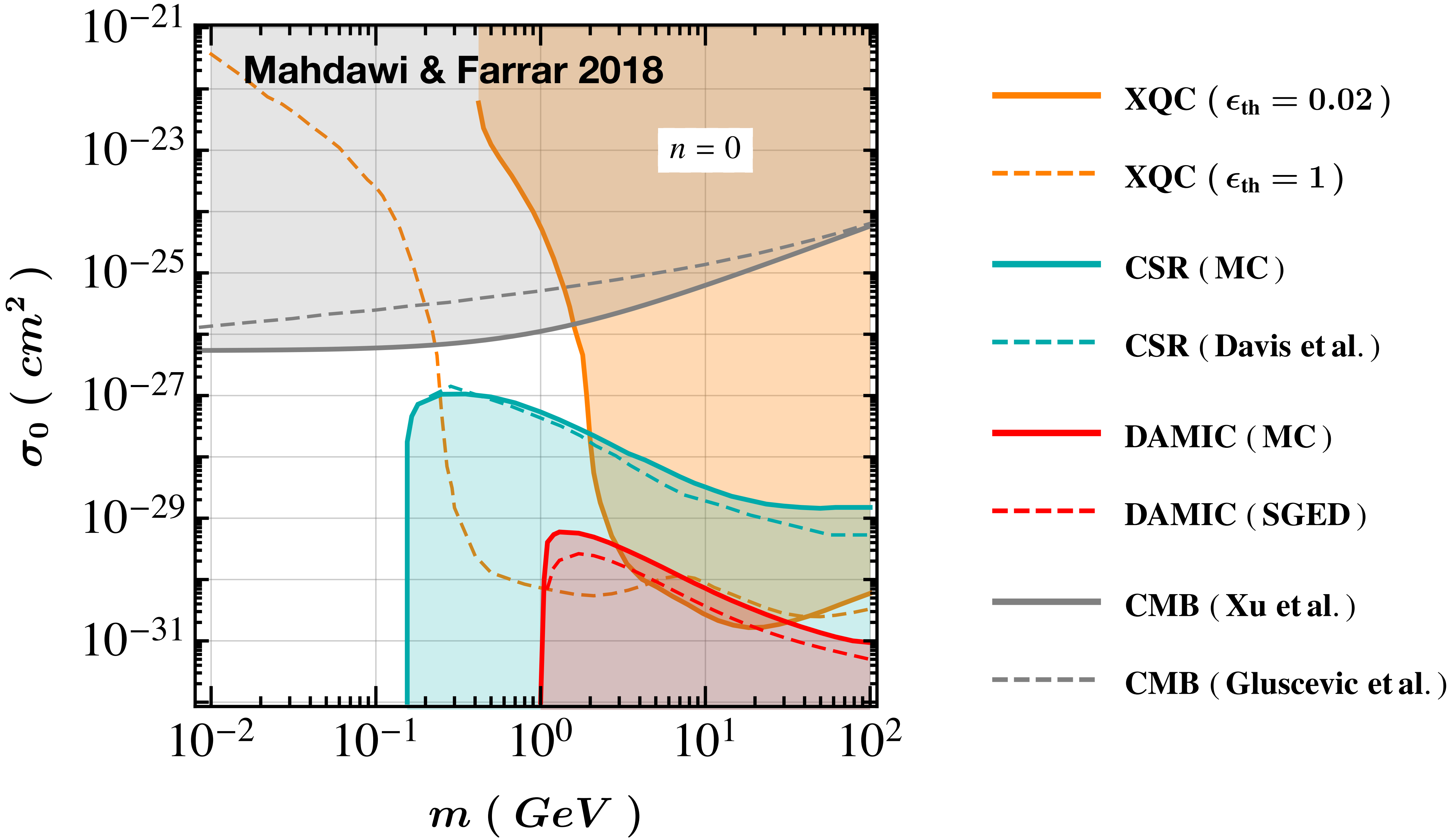


CMB anisotropies as a direct detection experiment

Basic effect: momentum exchange with the photon-baryon plasma

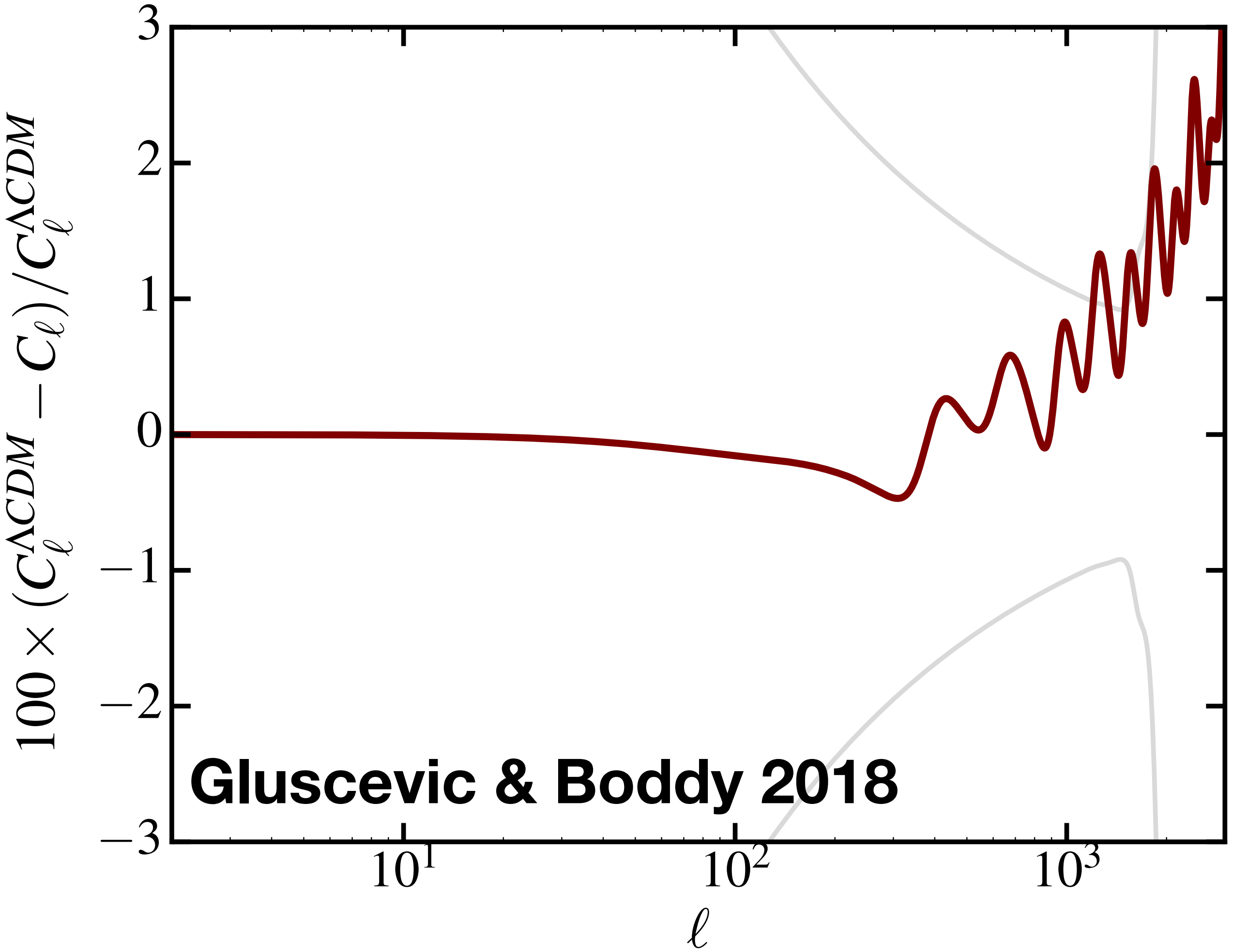
=> affects the linear evolution of perturbations
[Chen ++ 02, Sigurdson ++ 04, Dvorkin ++ 14, Boddy & Gluscevic 18]

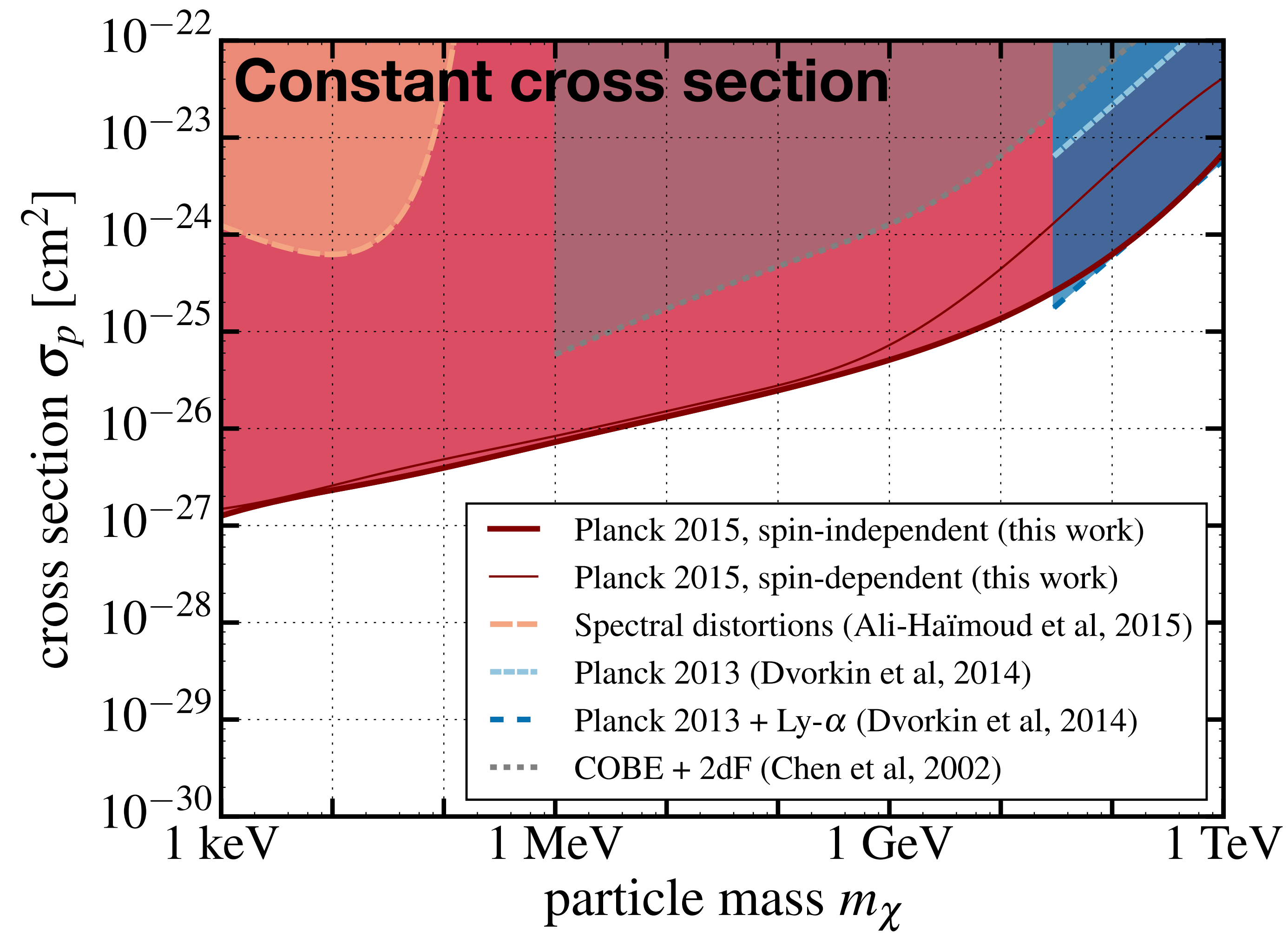
$$a^{-1}\frac{d}{dt}(a\vec{v}_b) = -\vec{\nabla}\phi + \Gamma_{\rm Compt}(\vec{v}_\gamma - \vec{v}_b) + \Gamma_{\chi b}(\vec{v}_\chi - \vec{v}_b)$$

$$a^{-1}\frac{d}{dt}(a\vec{v}_\chi) = -\vec{\nabla}\phi + \frac{\rho_b}{\rho_\chi}\Gamma_{\chi b}(\vec{v}_b - \vec{v}_\chi)$$

$$\Gamma_{\chi b} \sim \frac{\rho_\chi}{m_b + m_\chi}\langle \sigma v_{\rm rel}\rangle$$

CMB anisotropies as a direct detection experiment





See also Boddy & Gluscevic 2018, Xu, Dvorkin & Chael 2018 for constraints to general operators.

CMB spectrum as a direct detection experiment

YAH, Chluba & Kamionkowski 2015

Adiabatic cooling of CMB photons: $T_{\rm cmb}\big|_{\rm adiabatic} \propto (1+z)$

Adiabatic cooling of non-relativistic DM ($m_\chi >$ keV):

$$T_{\rm dm}\big|_{\rm adiabatic} \propto (1+z)^2$$

If DM + $\gamma \leftrightarrow$ DM + γ $\Rightarrow$ heat flows from photons to DM

$\Rightarrow$ CMB cools slightly faster than adiabatically

Maximum effect (if DM thermalizes with CMB):

$$T_{\rm cmb} \propto (1+z)^{1+\epsilon} \qquad \epsilon \sim \frac{n_{\rm dm}}{n_\gamma}$$

- What if DM scatters with electrons?
- Same story: indirect thermal coupling to photons through Compton scattering:

$$\mathrm{DM} + e \leftrightarrow \mathrm{DM} + e$$
$$e + \gamma \leftrightarrow e + \gamma$$

- What if DM scatters with nuclei?
- Same story: indirect thermal coupling to photons through Coulomb and Compton scattering:

$$\mathrm{DM} + p \leftrightarrow \mathrm{DM} + p$$
$$p + e \leftrightarrow p + e$$
$$e + \gamma \leftrightarrow e + \gamma$$

Fractional energy extracted from photons

$z_{\max} = 2e6$

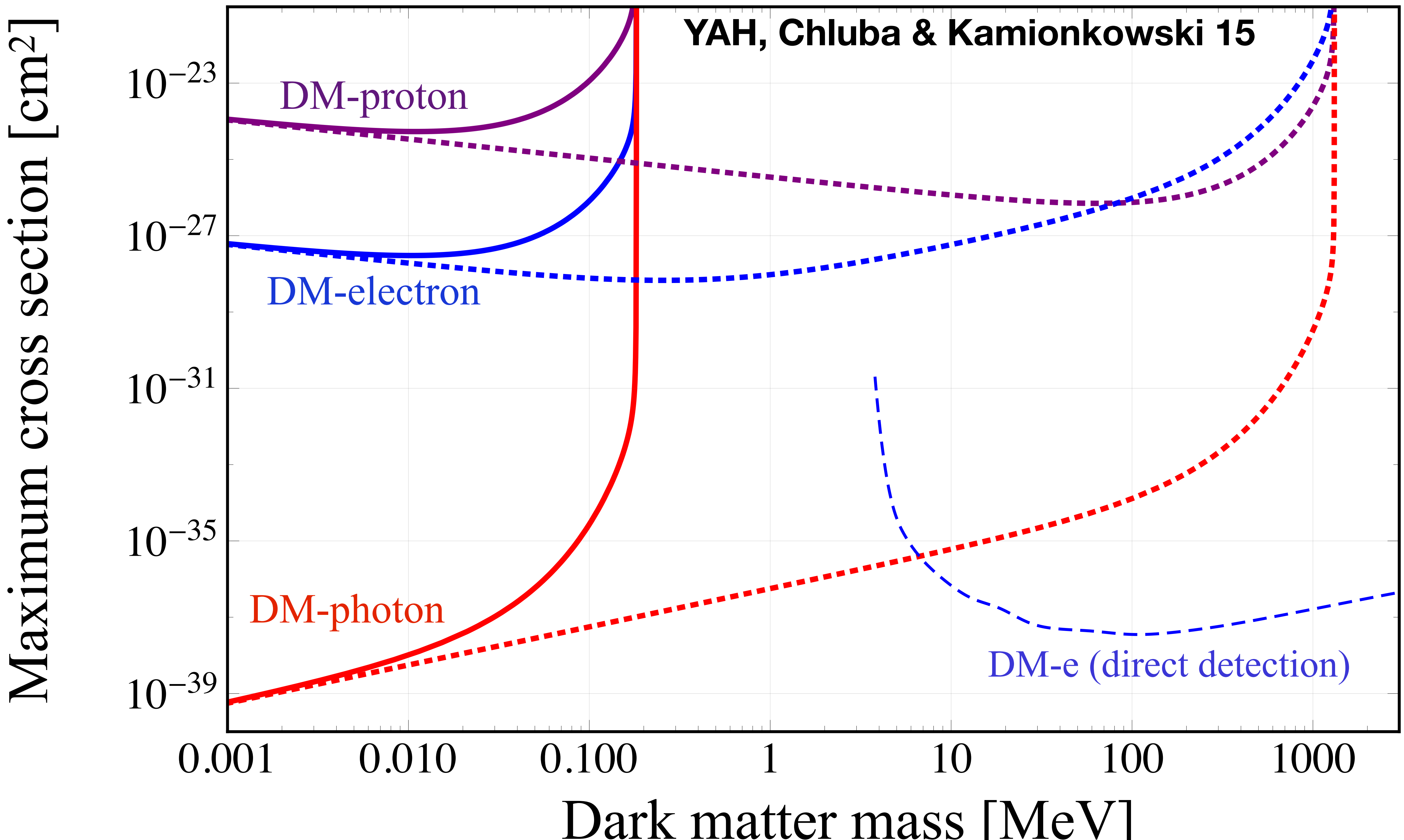
otherwise no distortion

$$\frac{\Delta\rho}{\rho_{\rm cmb}} \approx -\frac{n_{\rm dm}}{n_\gamma}\log\left(\frac{1+z_{\max}}{1+z_{\rm dec}}\right)$$

$$\sim 10^{-6}\frac{1\ {\rm MeV}}{m_{\rm dm}}$$

redshift at which DM and photons thermally decouple **depends on σ and m_{DM}**

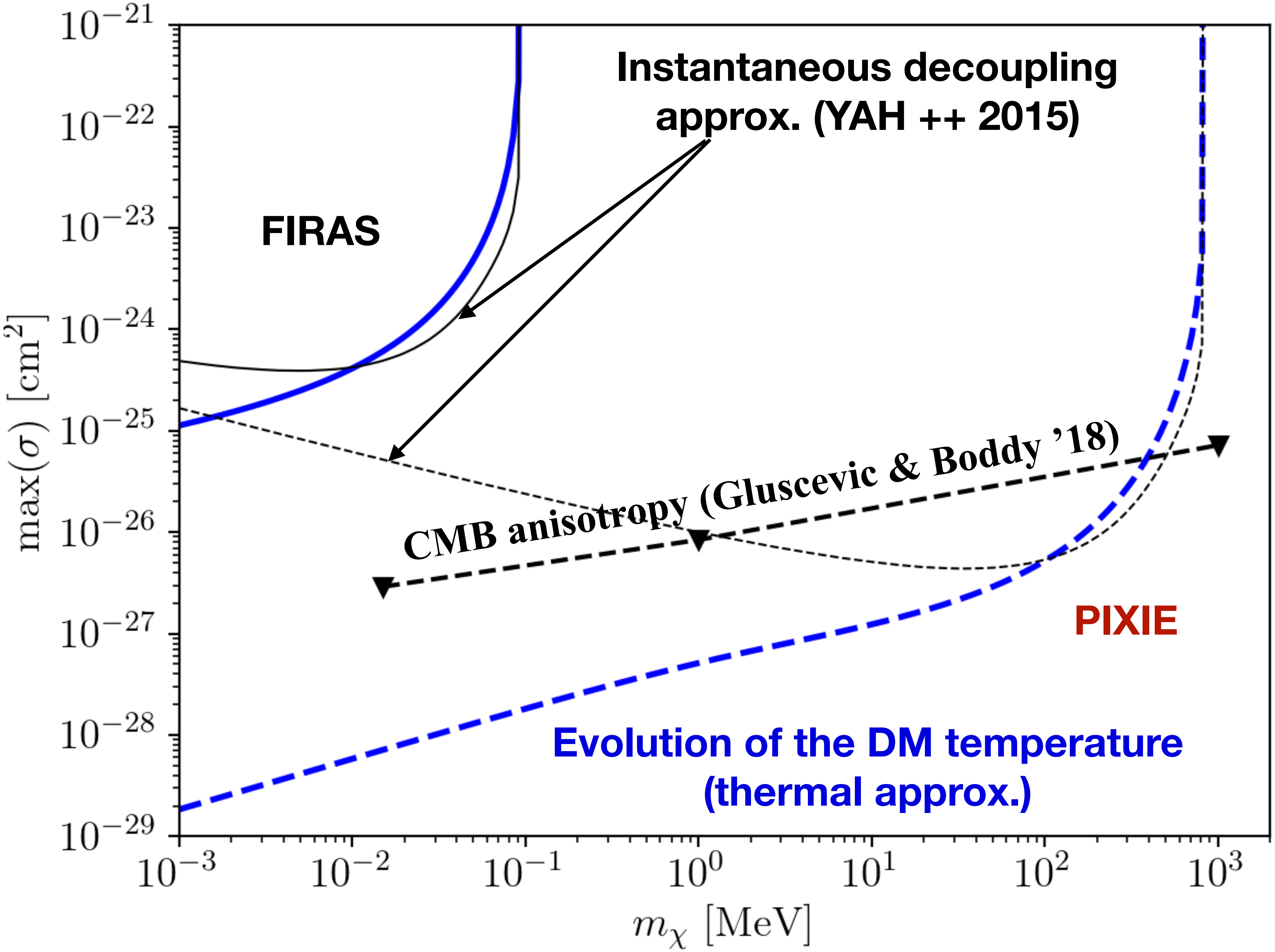
Constraints from spectral distortions



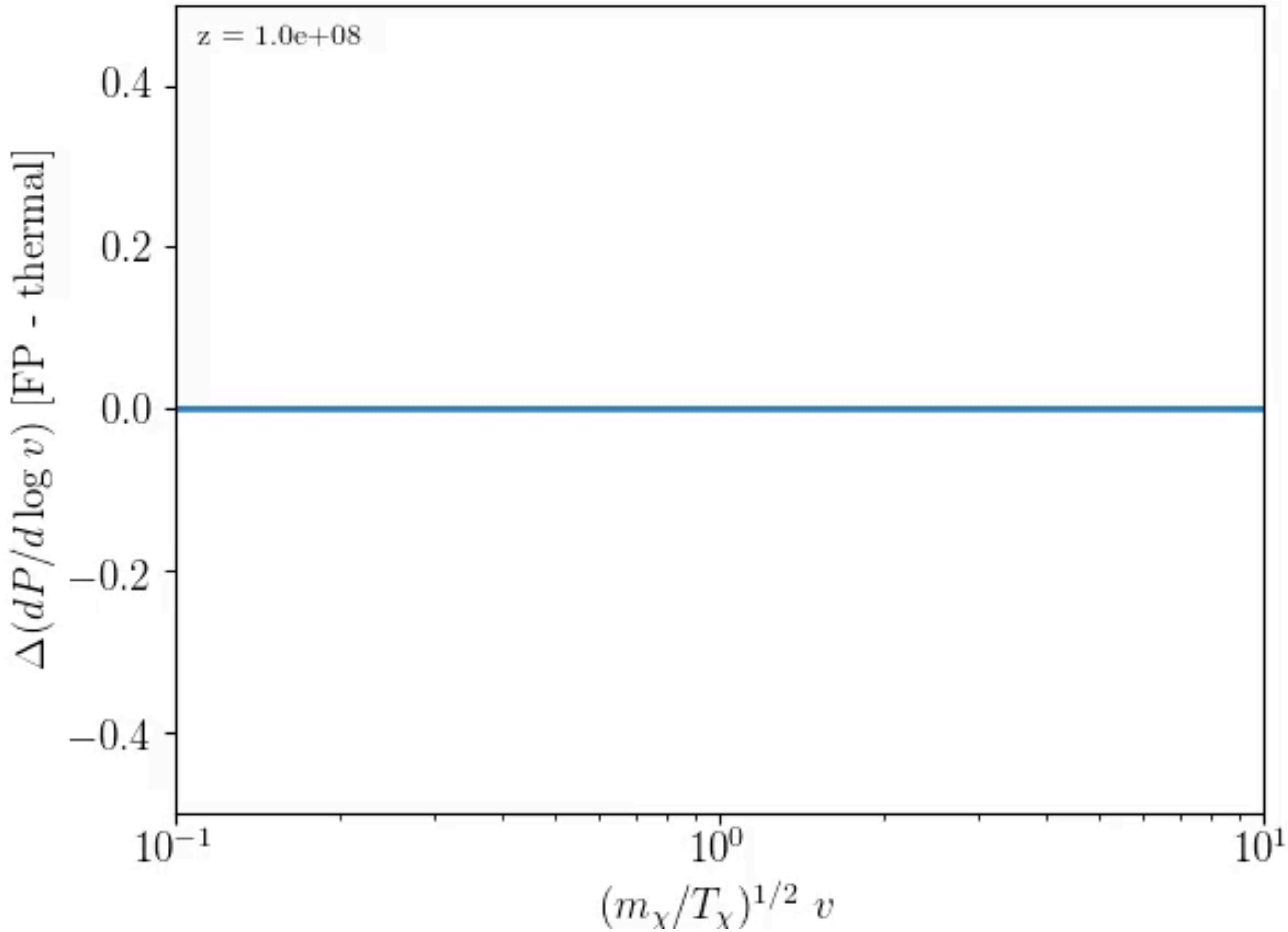
Also derived bounds for velocity- and energy-dependent cross sections

In progress: detailed study of thermal decoupling of DM

Updated limits for DM-proton scattering, assuming thermal distribution



In progress: non-thermal evolution of the DM velocity distribution



3. 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.

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.

PBH formation from large perturbations

- If $\delta > \delta_c$, a radiation perturbation collapses to form a BH (e.g. Niemeyer and Jedamzik 99, Shibata and Sasaki 99, Musco in prep.)

$M_{\rm pbh} \sim M_{\rm horizon} \, (\delta - \delta_c)^{\gamma}$

$$M_{\rm horizon} \sim M_{\odot} \left(\frac{10^6 \ {\rm Mpc}^{-1}}{k} \right)^2 \sim M_{\odot} \left(\frac{10^2 \ {\rm MeV}}{T} \right)^2$$

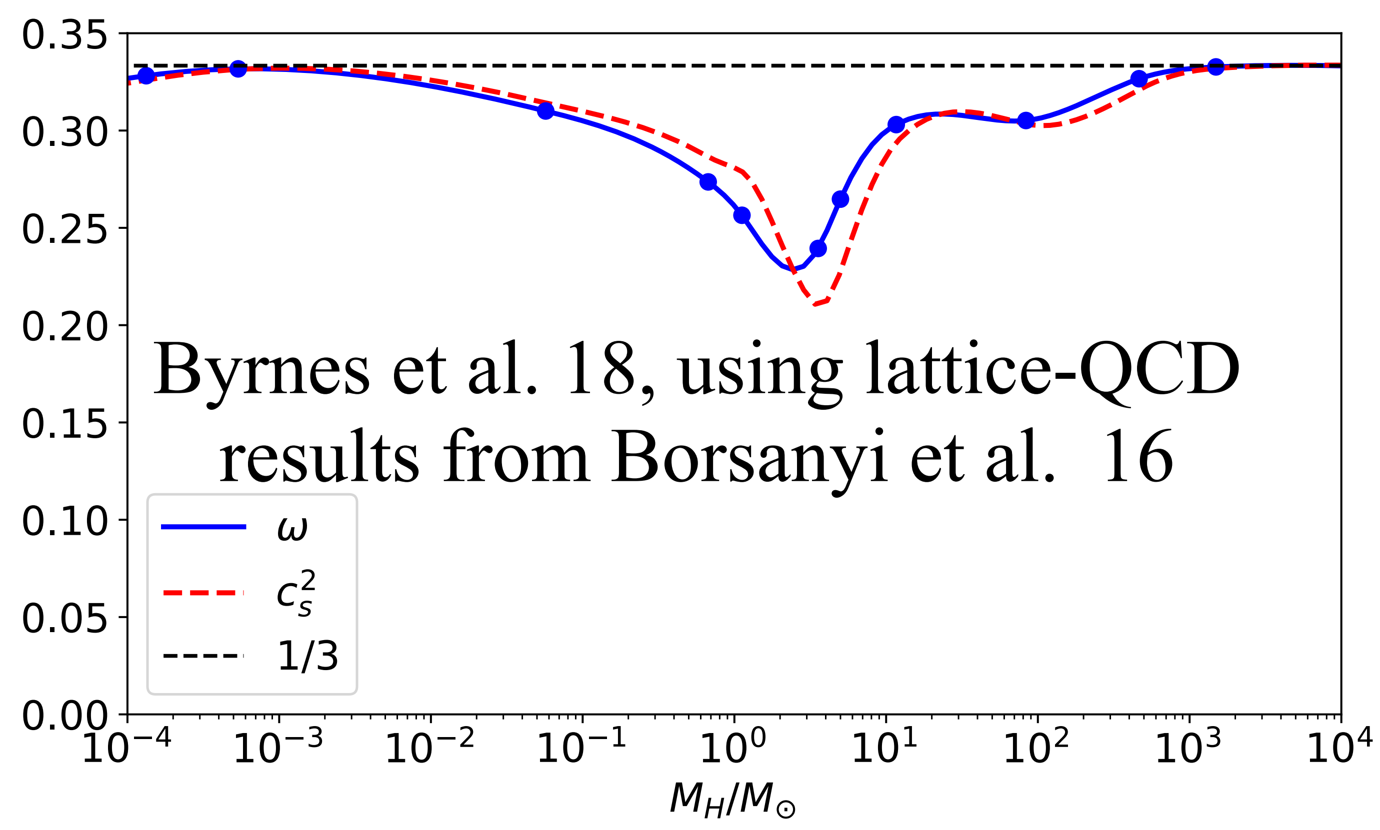
- Given large enough density perturbations a (tiny) fraction of the radiation collapses to BHs.

e.g. for Gaussian perturbations $\beta \approx {\rm erfc} \left(\frac{\delta_c}{\sqrt{2}\sigma} \right)$

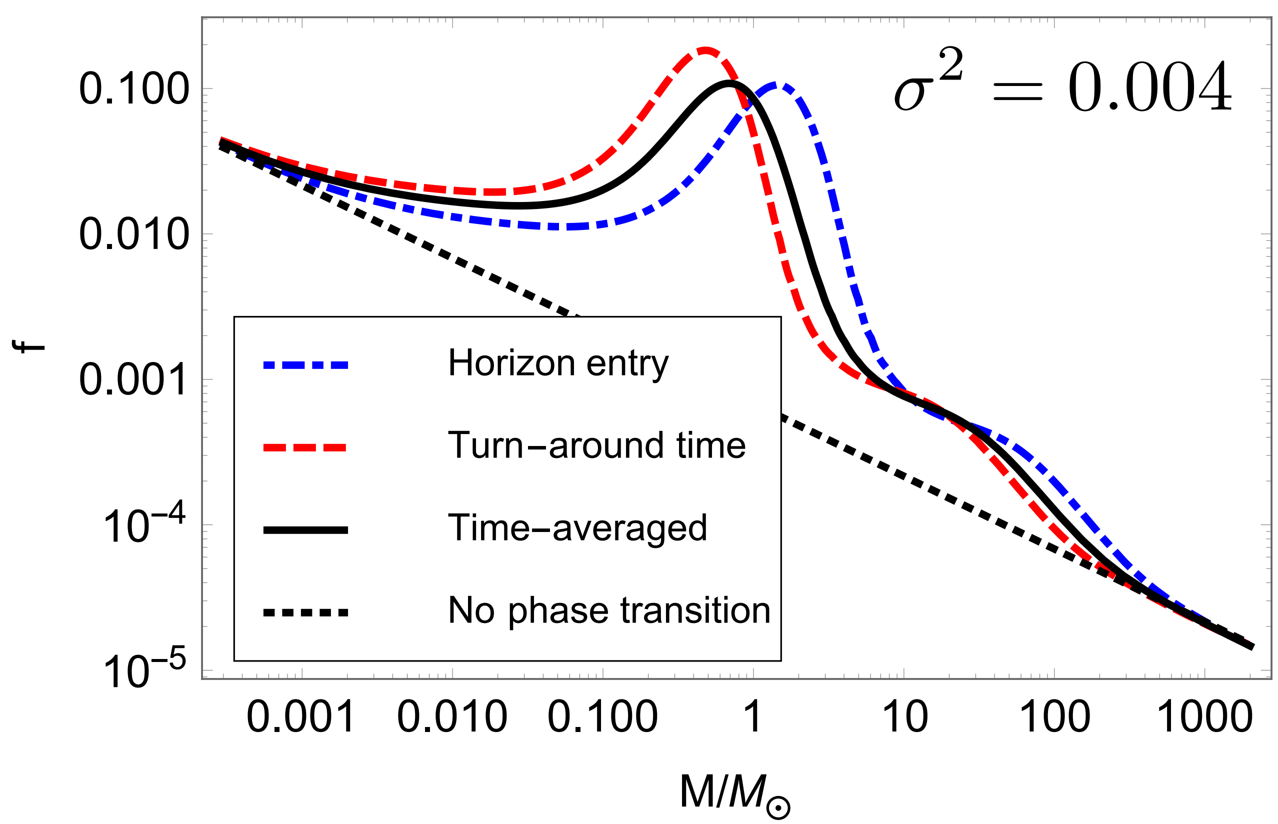
(non-Gaussianity changes the picture, e.g. Young++ 15, Nakama ++16)

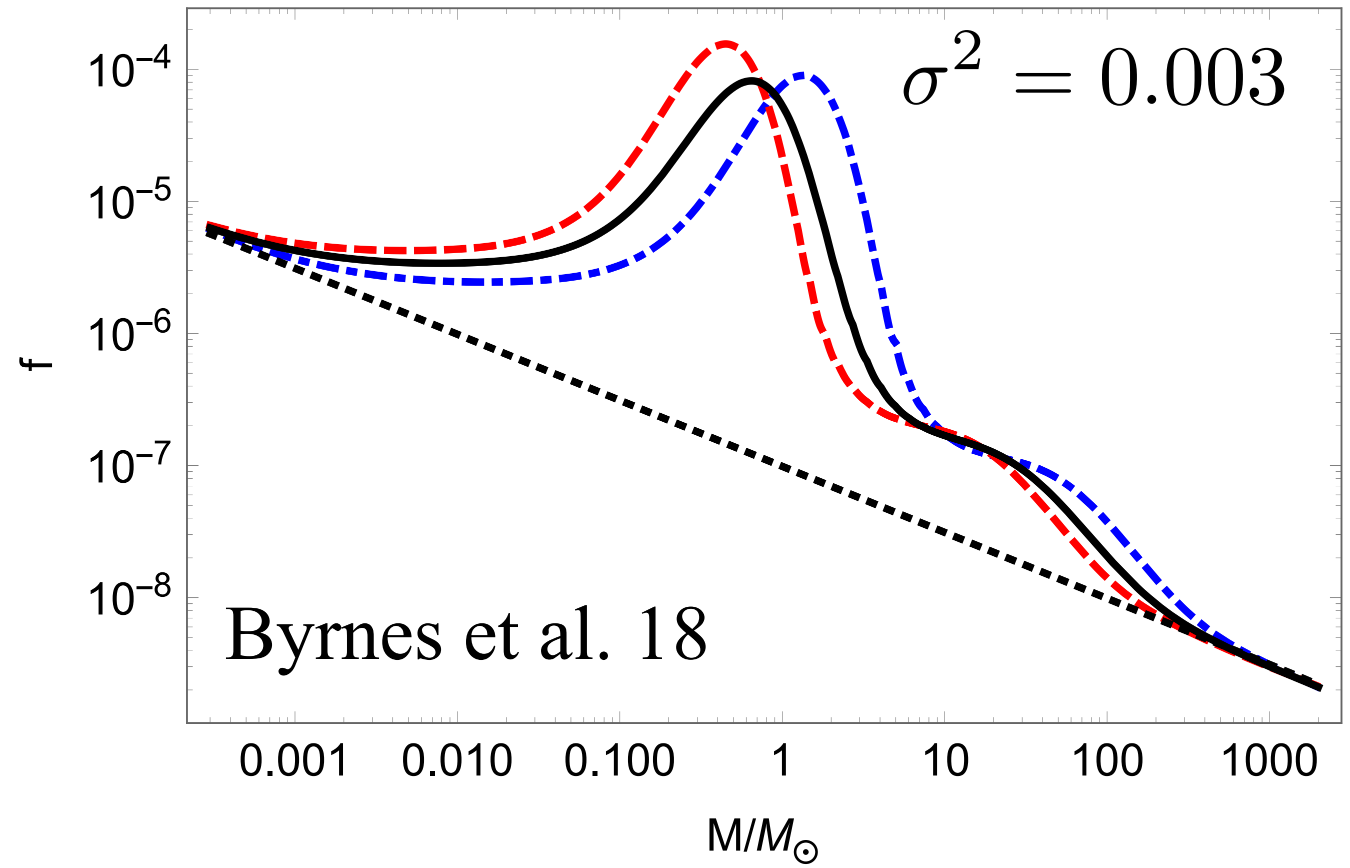
PBH formation from large perturbations

Collapse threshold lowered if
w = P/ρ < 1/3
e.g. during phase transitions.

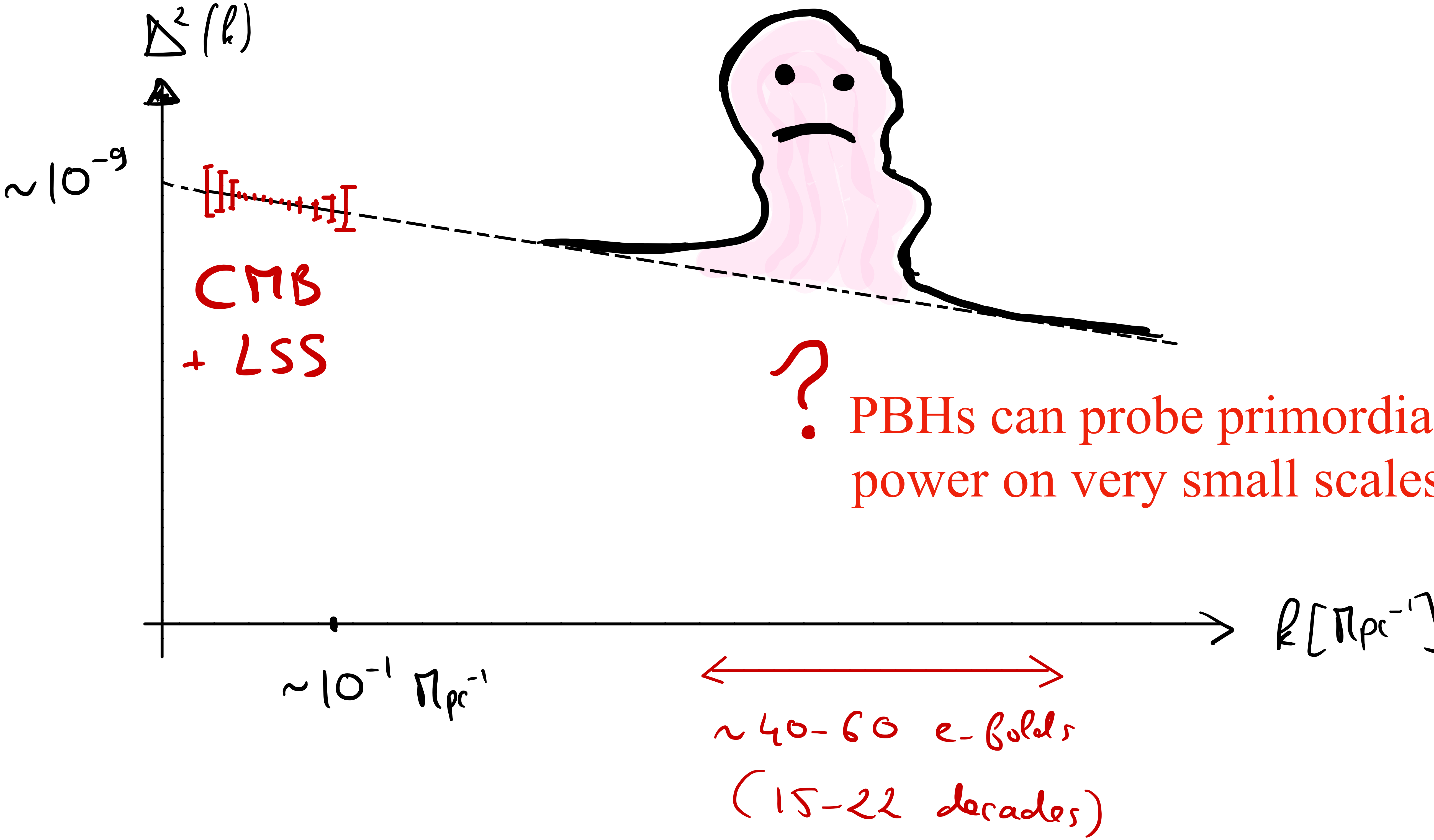


$$f = \frac{1}{\Omega_c} \frac{d\Omega_{\rm pbh}}{d\log(M)}$$



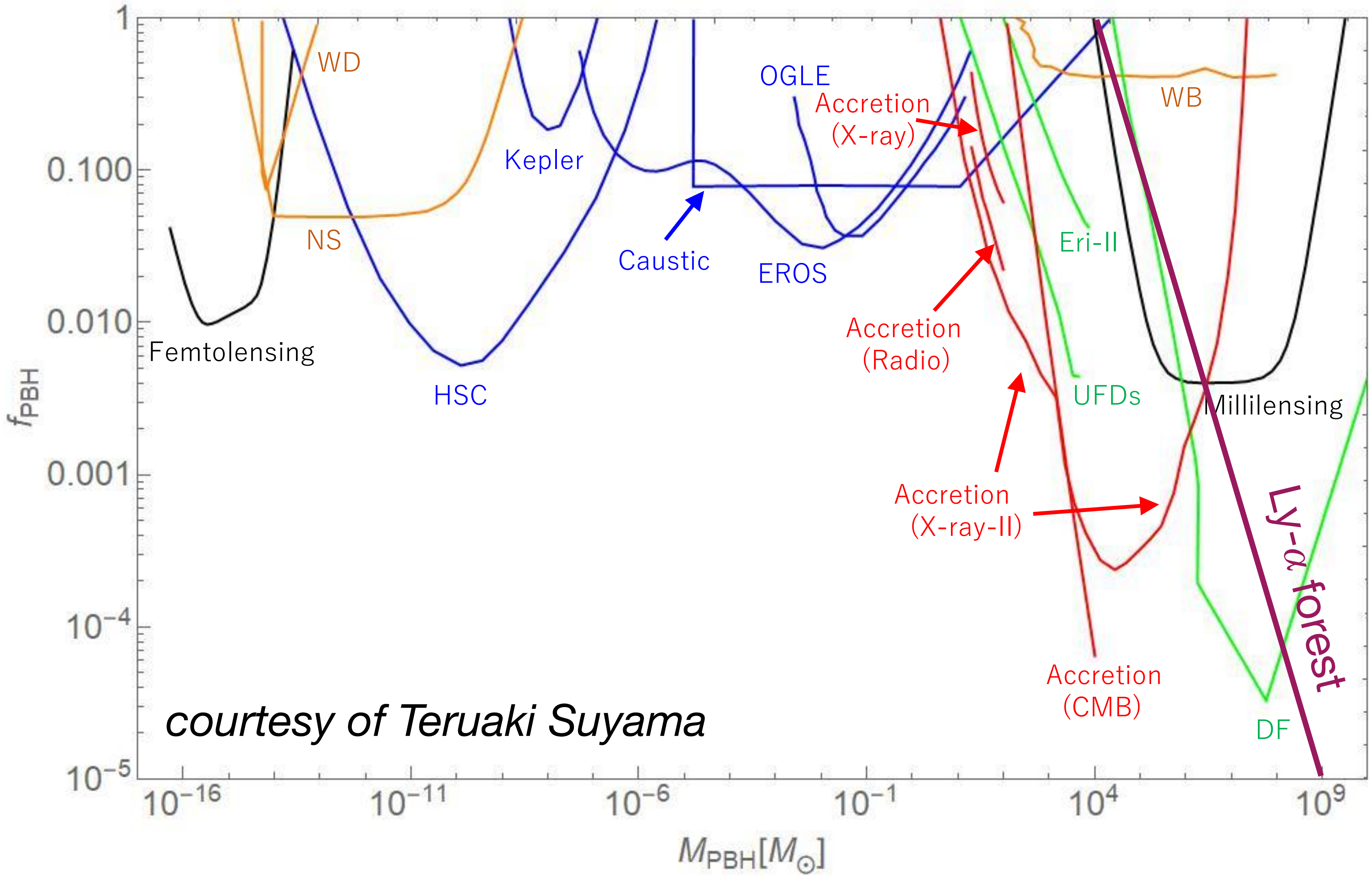


We have only measured the primordial curvature perturbation on 2-3 decades



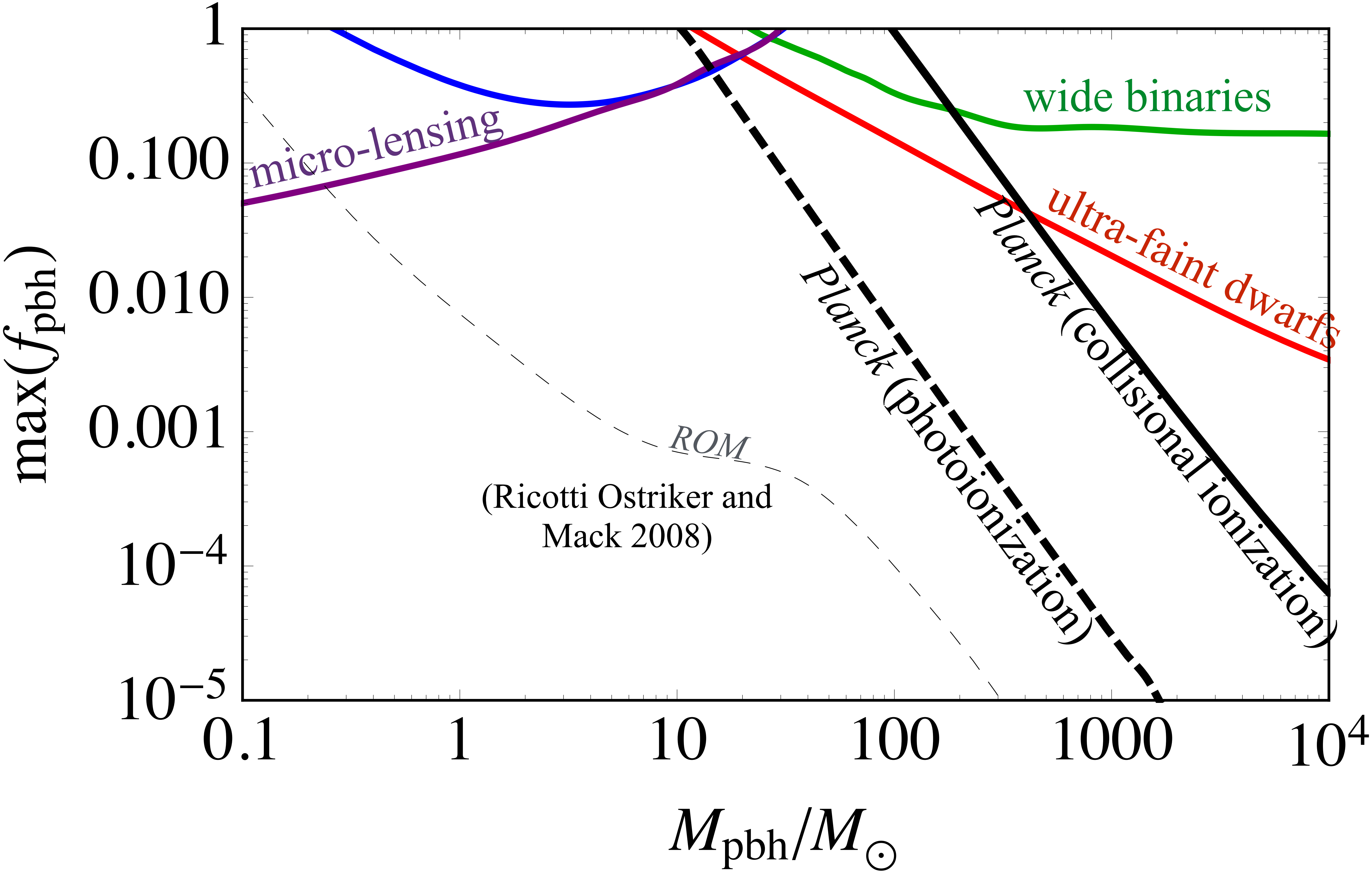
PBHs can probe primordial power on very small scales

Upper limits to fraction of dark matter in PBHs



CMB limits to accreting PBHs

YAH & Kamionkowski, 1612.05644



Underlying physics

Carr 1981, Ricotti, Ostriker & Mack 08, 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

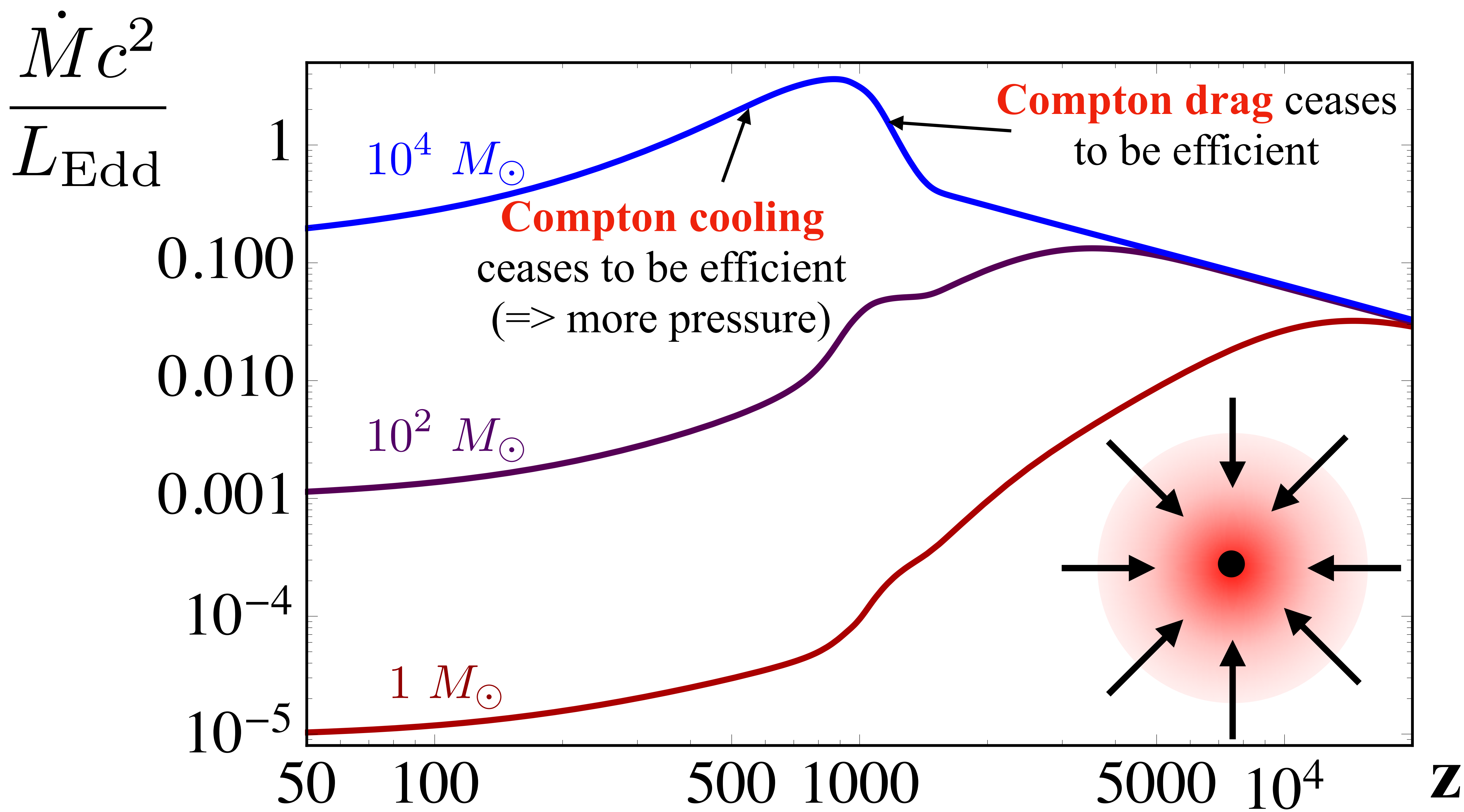
4. some is deposited as heat => CMB spectral distortions

5. some leads to extra ionizations
   => change the recombination history and visibility function
   => affects CMB temperature and polarization anisotropies

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

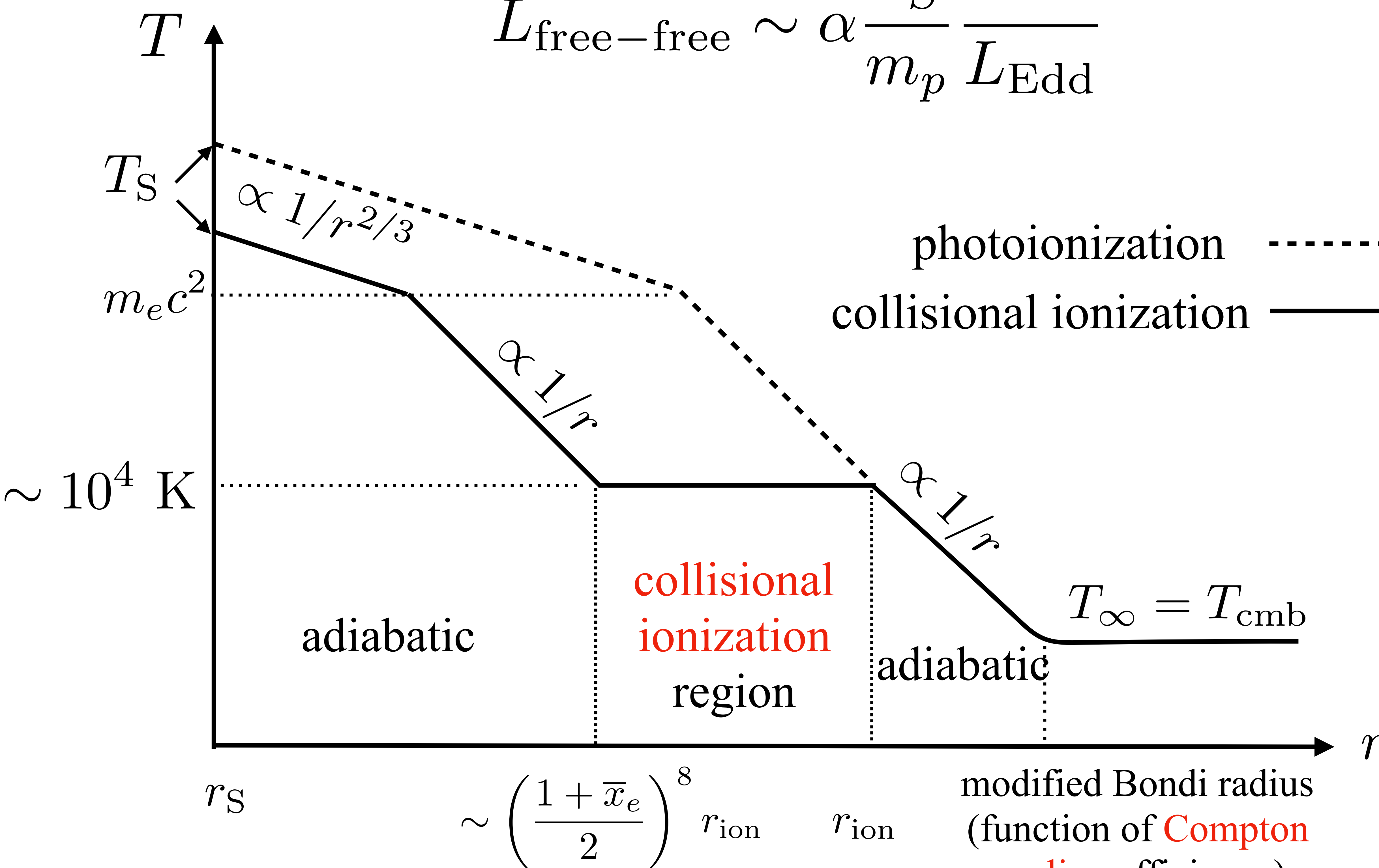
1. Accretion rate: Bondi-Hoyle-Lyttleton ++

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

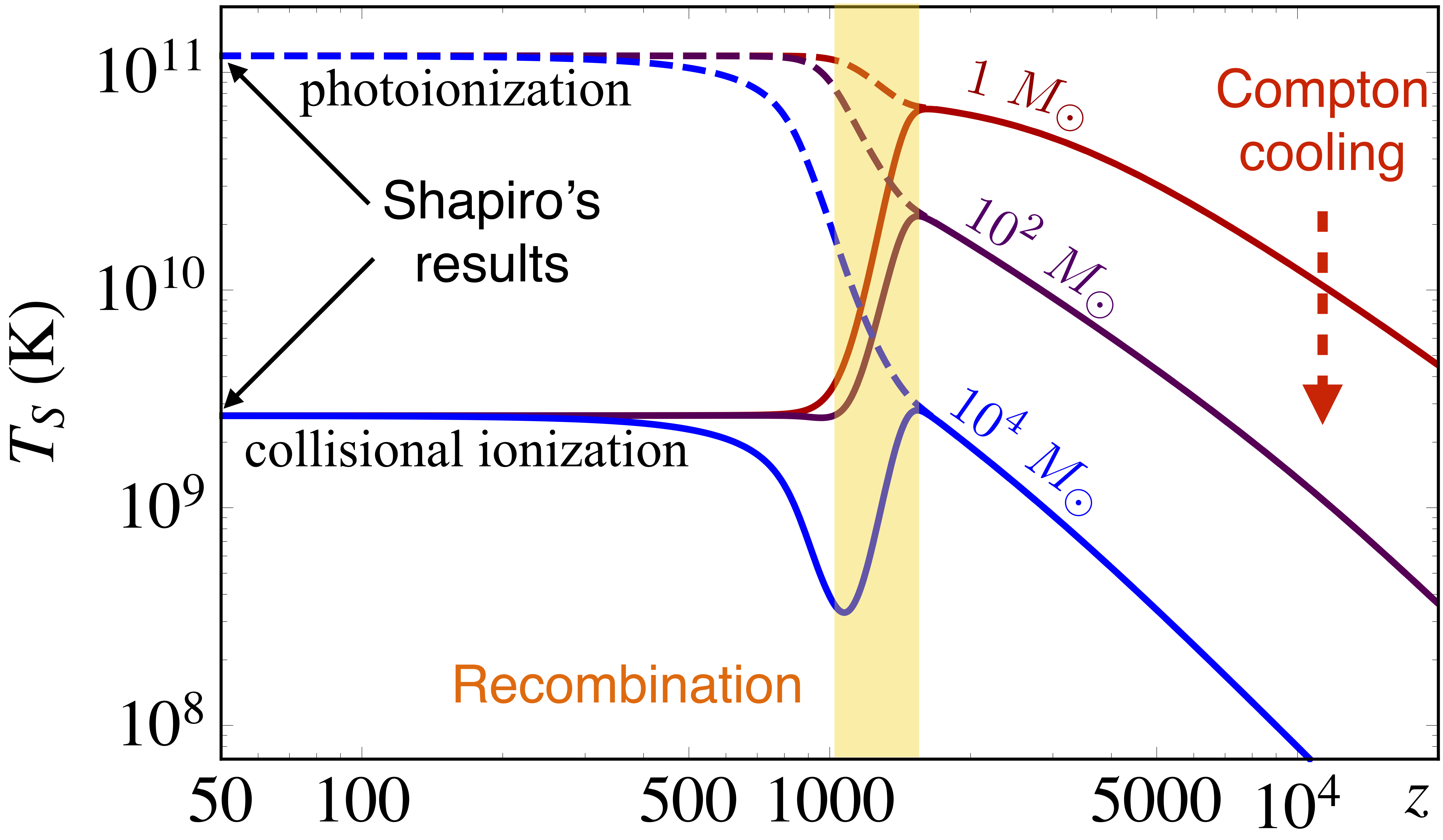


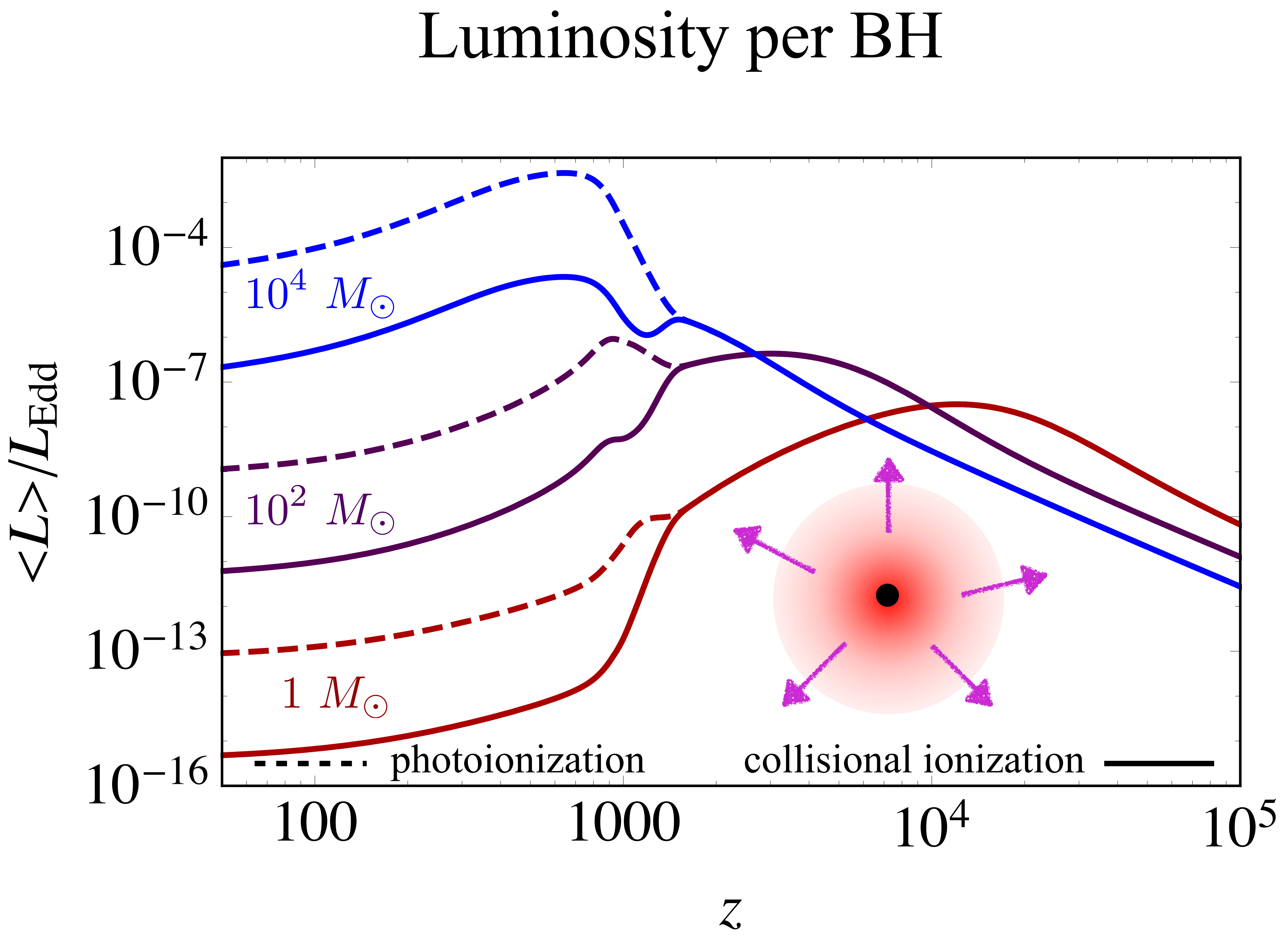
2. Radiative efficiency: Shapiro (1973) ++

$$L_{\mathrm{free-free}} \sim \alpha \frac{T_S}{m_p} \frac{\dot{M}^2}{L_{\mathrm{Edd}}}$$



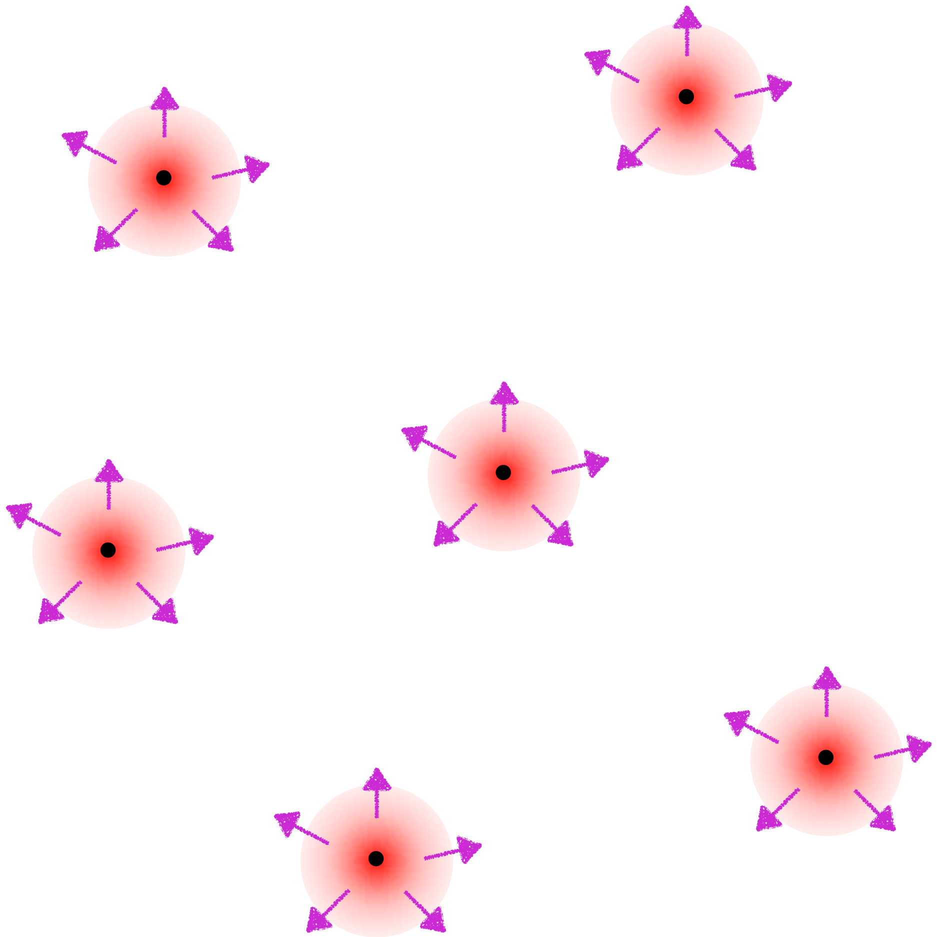
Temperature near the horizon



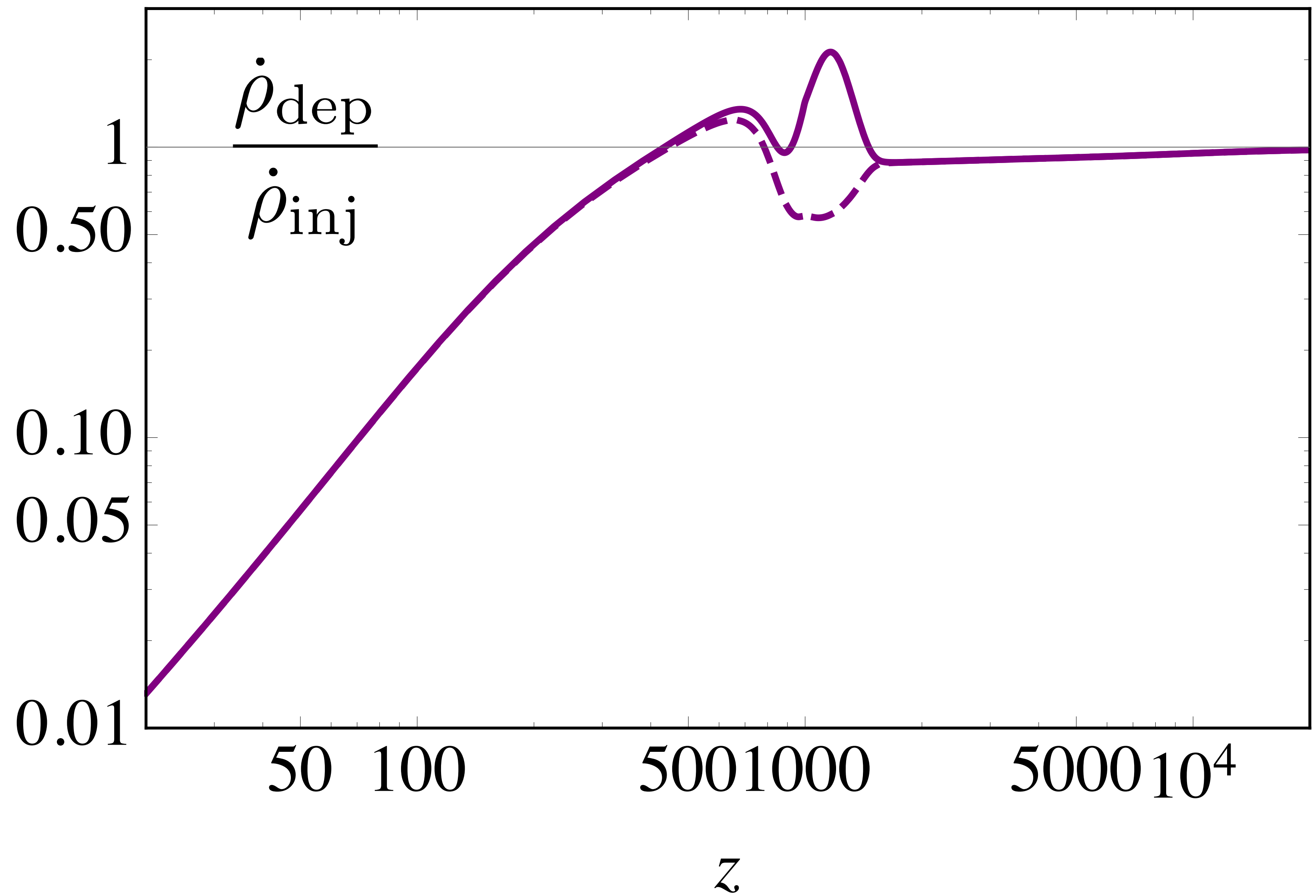


Luminosity per BH
$\langle L \rangle / L_{\rm Edd}$
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
$10^4\ M_\odot$
$10^2\ M_\odot$
$1\ M_\odot$
photoionization
collisional ionization
100
1000
10^4
10^5
z

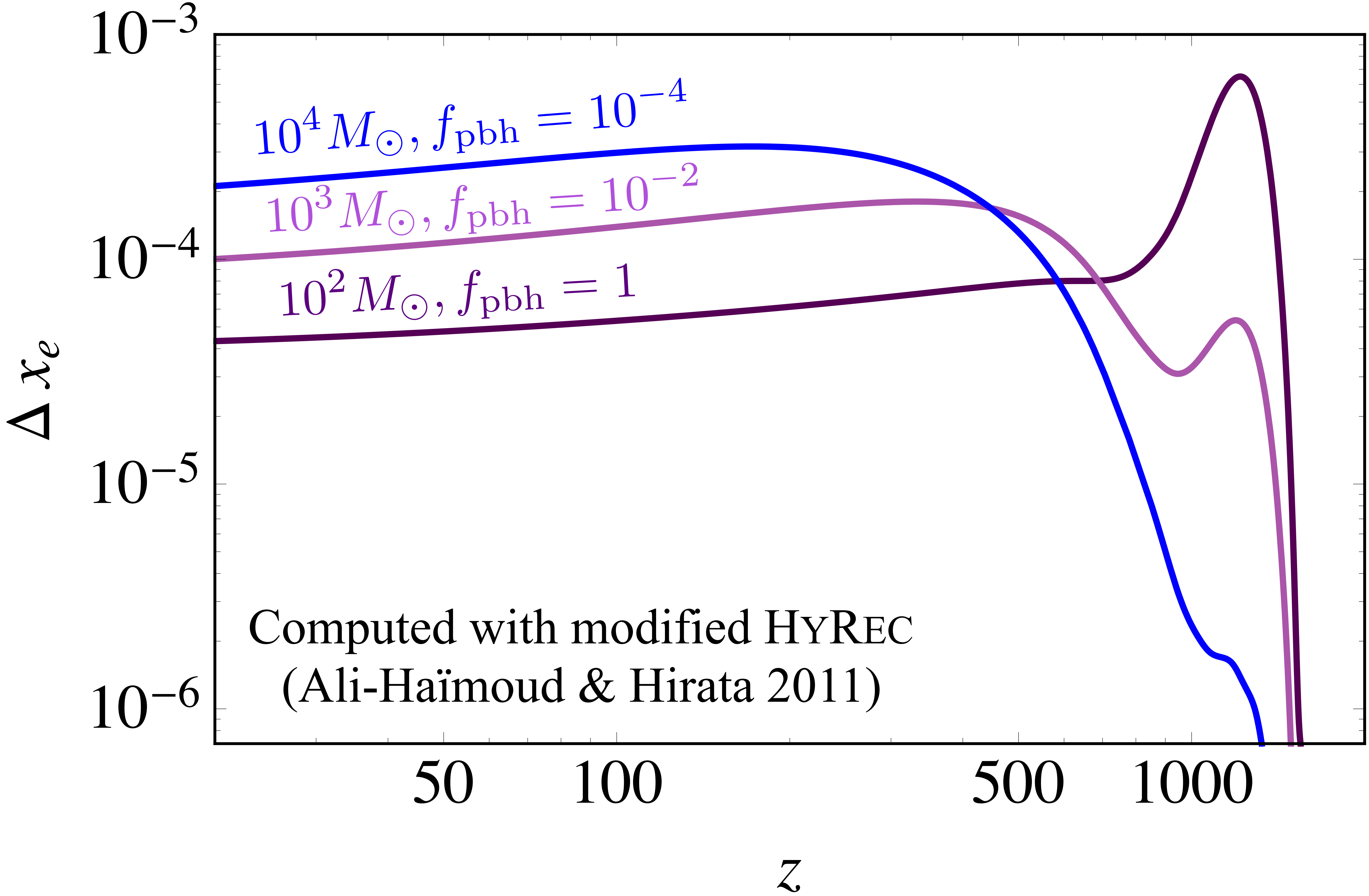
3. Energy deposition into the plasma



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



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

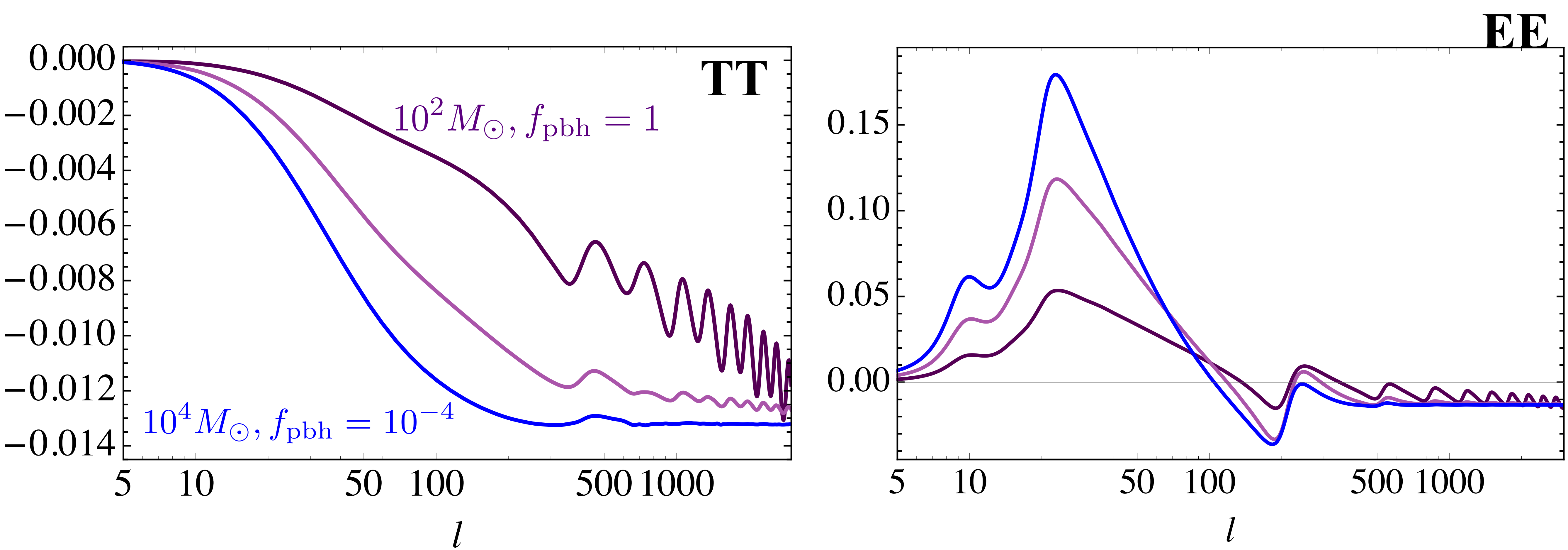


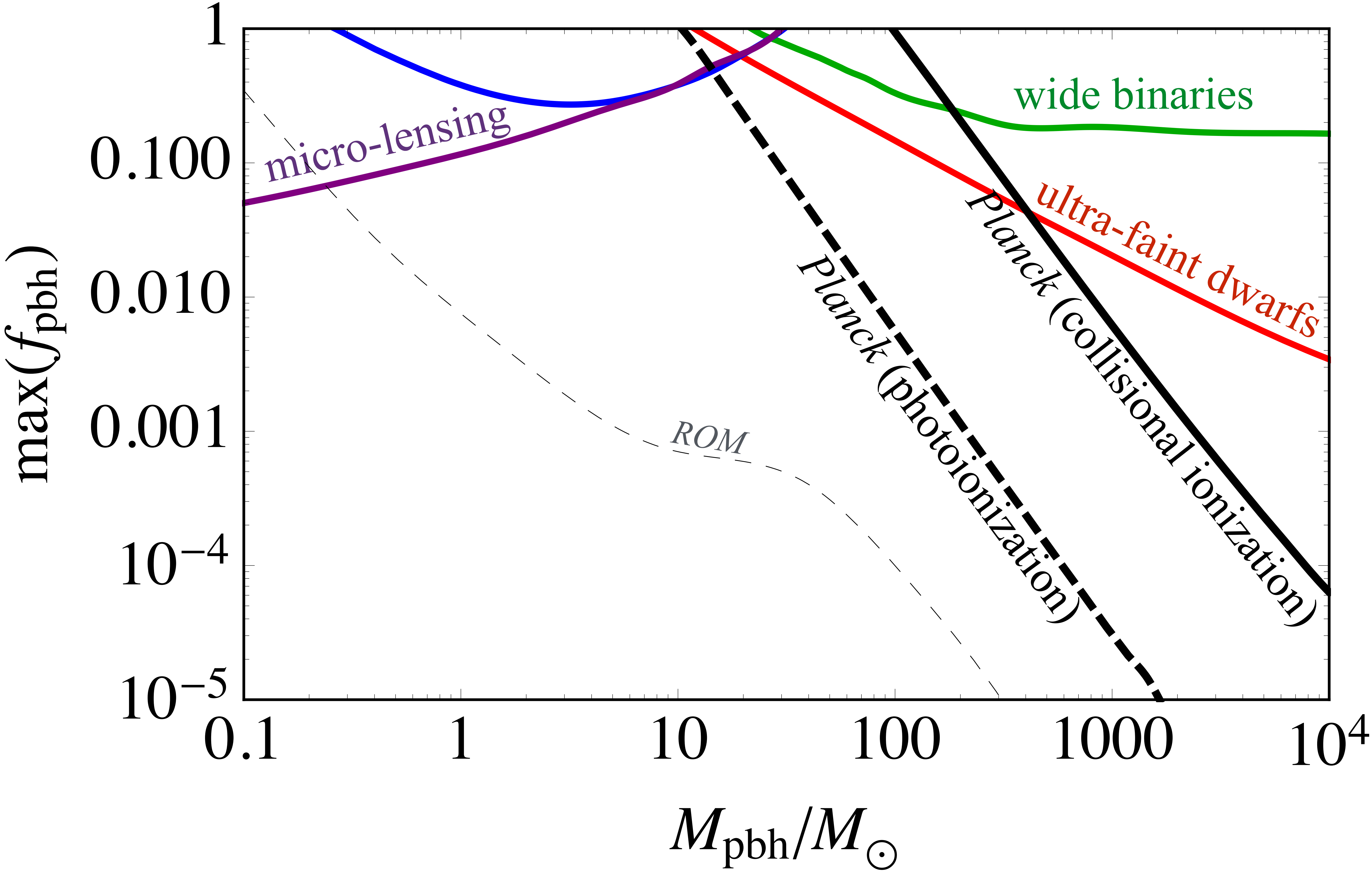
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Δx_e
$10^4 M_\odot, f_{\rm pbh} = 10^{-4}$
$10^3 M_\odot, f_{\rm pbh} = 10^{-2}$
$10^2 M_\odot, f_{\rm pbh} = 1$
Computed with modified HyRec
(Ali-Haïmoud & Hirata 2011)
50
100
500
1000
z

Effect on CMB anisotropies [effect on spectral distortions is negligible given anisotropy bounds]

$$\Delta C_\ell / C_\ell$$

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

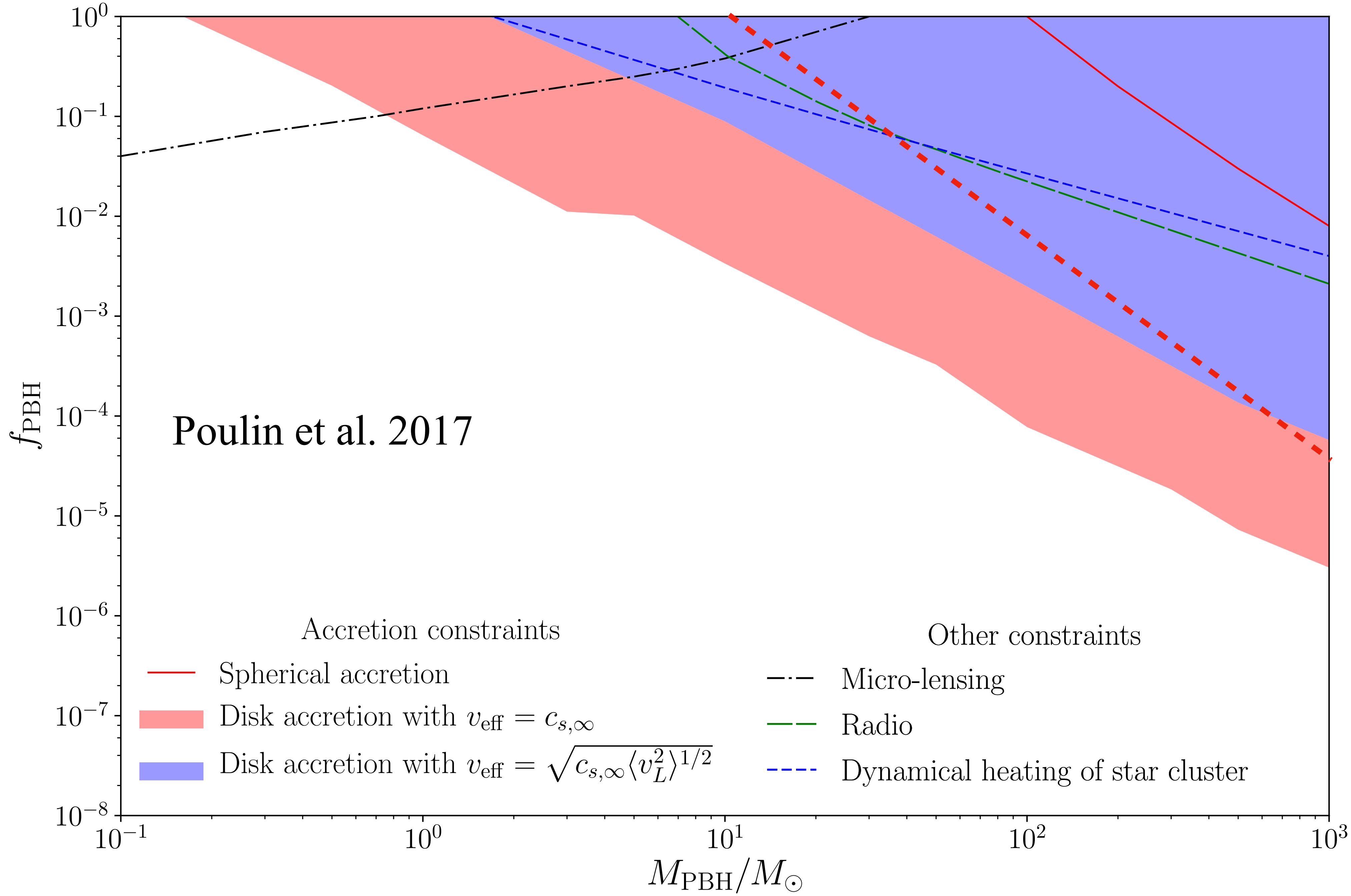




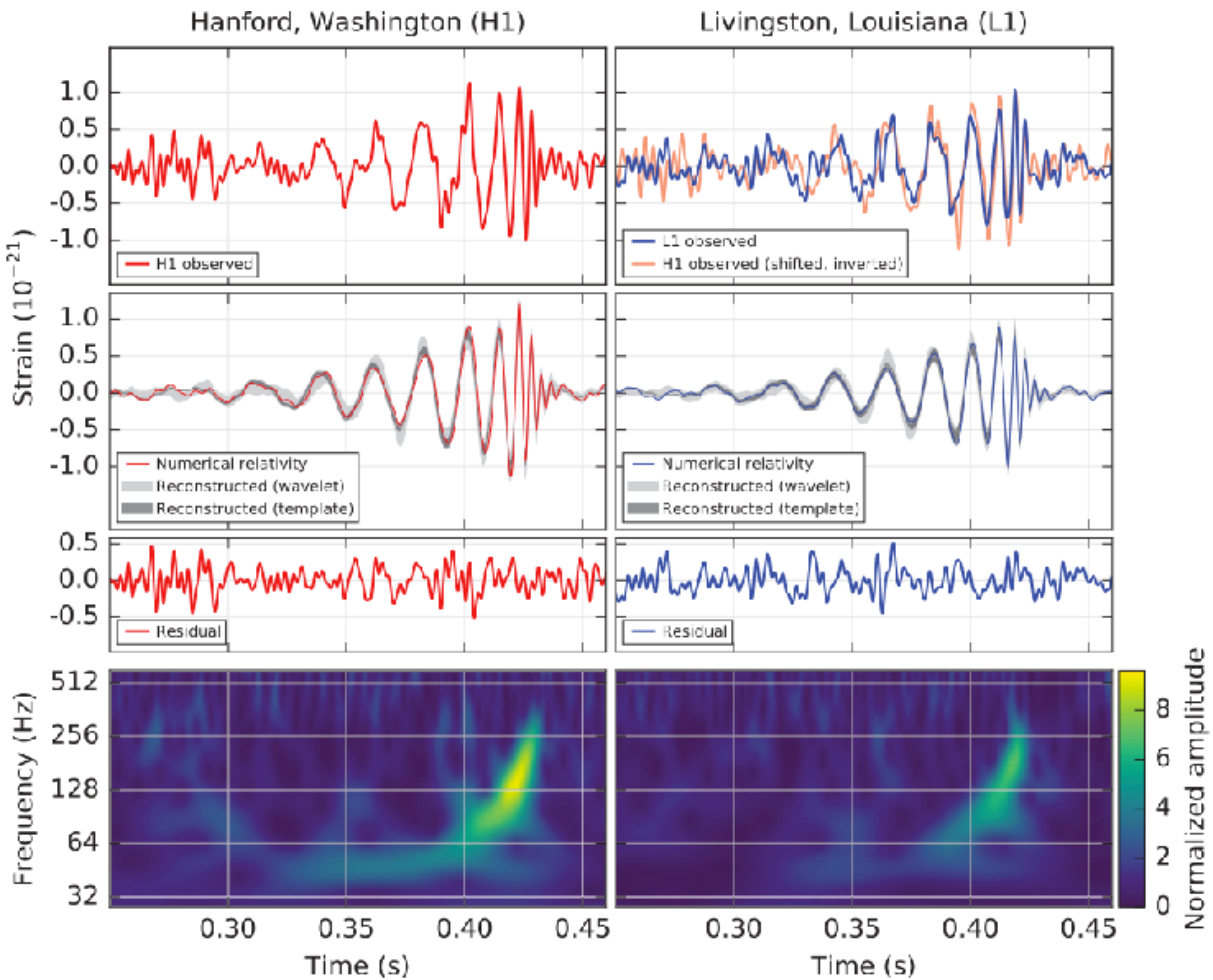
1
0.100
0.010
0.001
10^{-4}
10^{-5}
0.1
1
10
100
1000
10^4
$\max(f_{\rm pbh})$
$M_{\rm pbh}/M_\odot$
micro-lensing
wide binaries
ultra-faint dwarfs
Planck (photoionization)
Planck (collisional ionization)
ROM

Bounds rely on very simplified modeling of complex physics => to be taken at the order-of-magnitude level only.

Ought to be conservative. e.g., disk accretion would imply higher luminosity hence stronger possible bounds.



PBHs in the gravitational-wave era



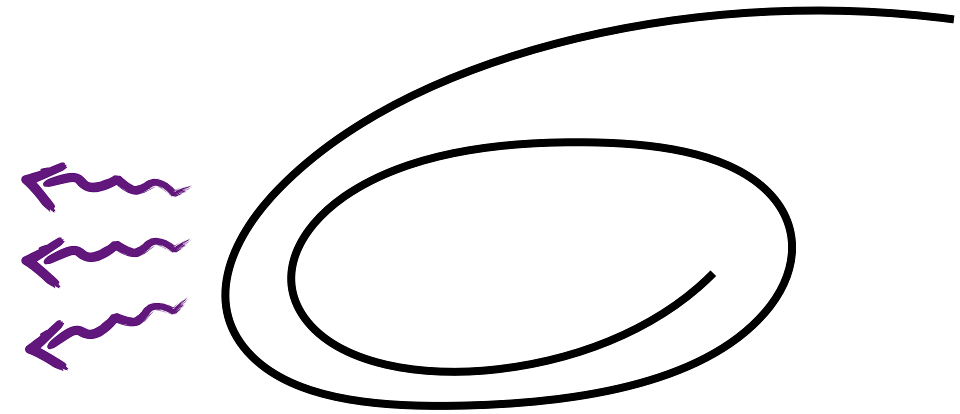
LIGO collaboration 2016

$(M_1, M_2) \approx (29, 36)\ M_\odot$

Did LIGO detect dark matter?

Bird, Cholis, Muñoz, YAH, Kamionkowski,
Kovetz, Raccanelli and Riess, 2016

- If 2 PBHs pass sufficiently close to one another, can lose enough energy through GW emission to become bound.



$$\sigma \sim \left(\frac{GM_\bullet}{c^2}\right)^2 (v/c)^{-18/7}$$

(Quinlan & Shapiro 1989)

see homework 8 of NYU GR class

Assuming standard halo properties and mass function, estimated merger rate ~ 1/Gpc^3/yr, r*oughly* consistent with LIGO inferred rate.

Order-of-magnitude estimate

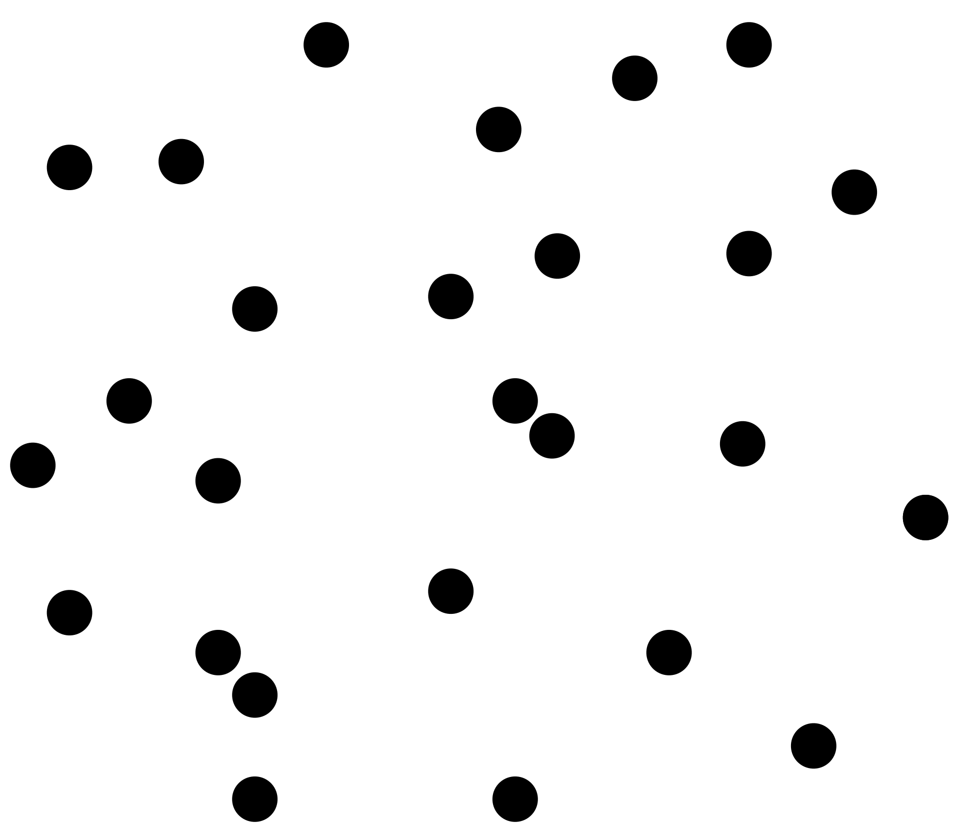
but interesting rate coincidence!

Does LIGO rule out PBH-dark matter?

YAH, Kovetz & Kamionkowski [1709.06576]

Basic idea: Nakamura, Sasaki, Tanaka & Thorne 1997

See also Sasaki et al. 2016



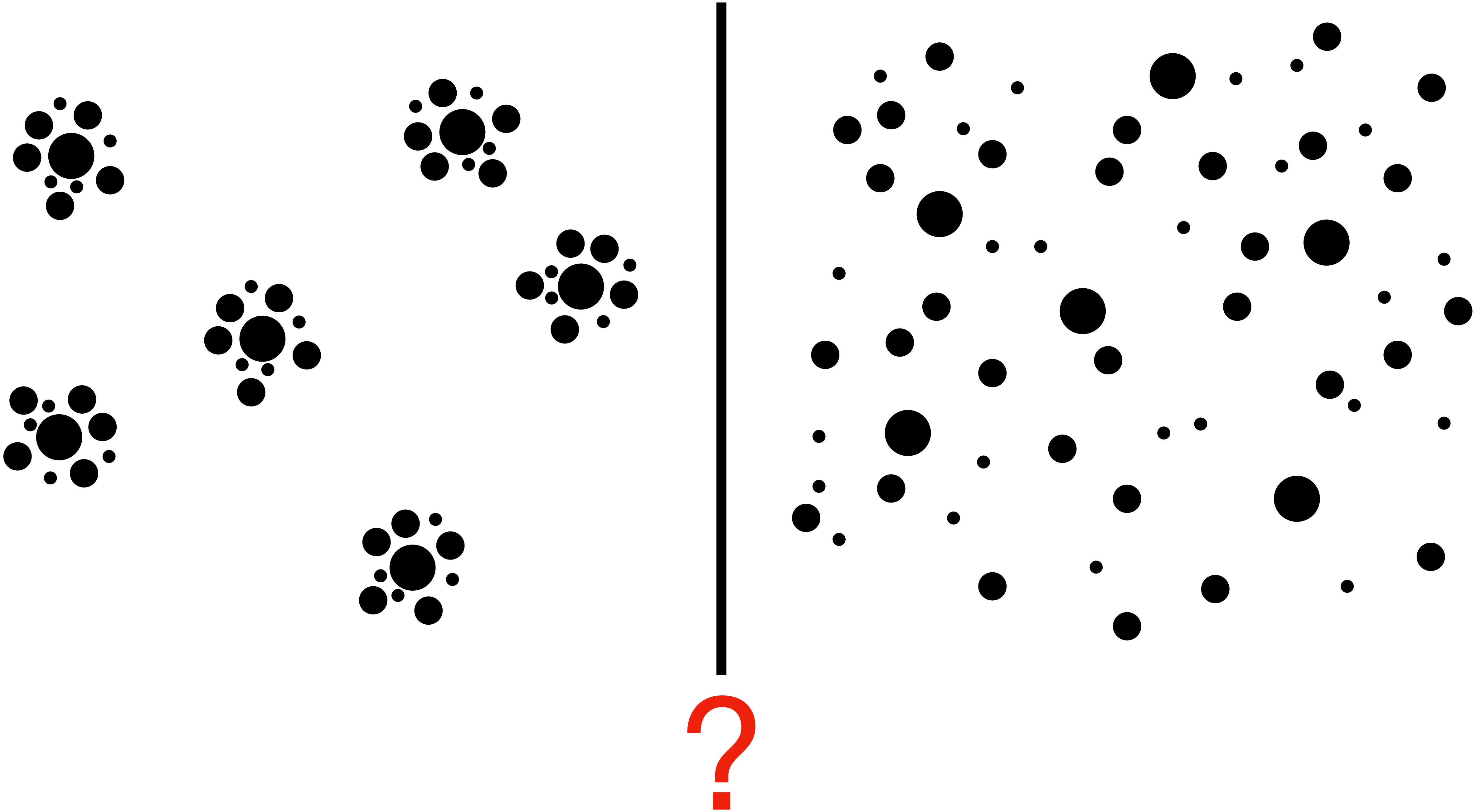
On small enough scales, PBHs are randomly distributed [YAH, arXiv:1805.05912]

Intermission on the initial clustering of PBHs [arXiv:1805.05912]

- What was known long before and is unquestioned:
  - PBHs cluster like dark matter on large scales (like any viable DM candidate consistent with CMB/LSS)
  - Due to graininess of PBHs, on small enough scales, they are Poisson-distributed (Meszaros 75, Carr 75)
  - These Poisson fluctuations grow through gravitational instability (like any perturbations). Carr & Silk 83
  - This effect was used to set upper limit to PBH mass (Afshordi, McDonald & Spergel 03)

Intermission on the initial clustering of PBHs [arXiv:1805.05912]

What was unclear:
initial clustering on ultra-small scales



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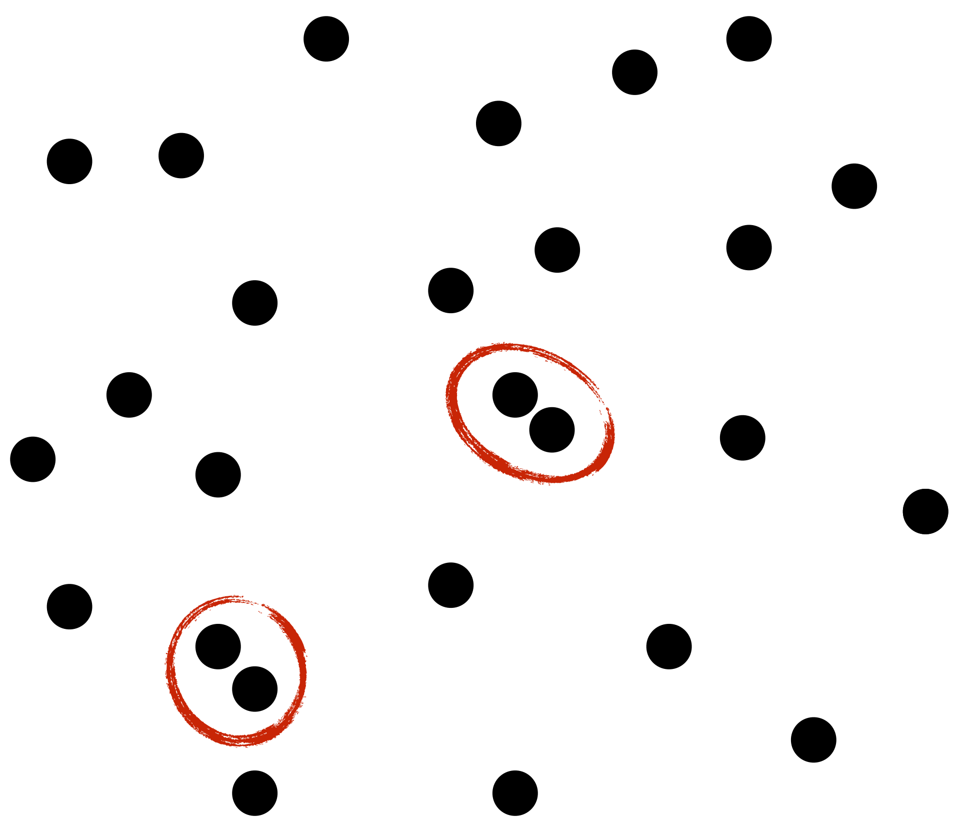


On small enough scales, PBHs are randomly distributed [YAH, arXiv:1805.05912]

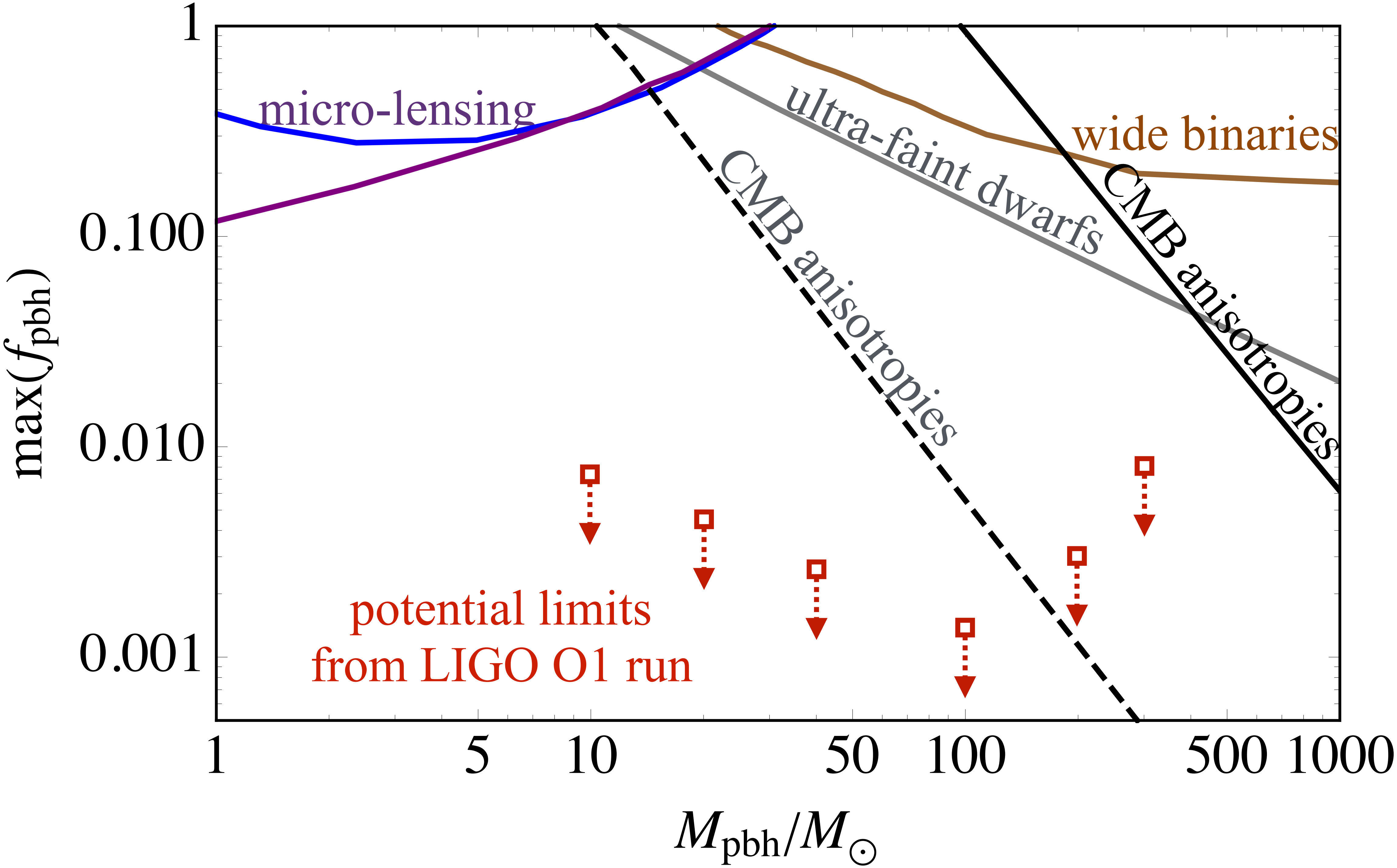
Some PBH pairs happen to be close enough that they decouple from the Hubble flow deep in the radiation era.

As they fall towards one another, torqued by other PBHs result in a non-zero angular momentum => eccentric orbit.

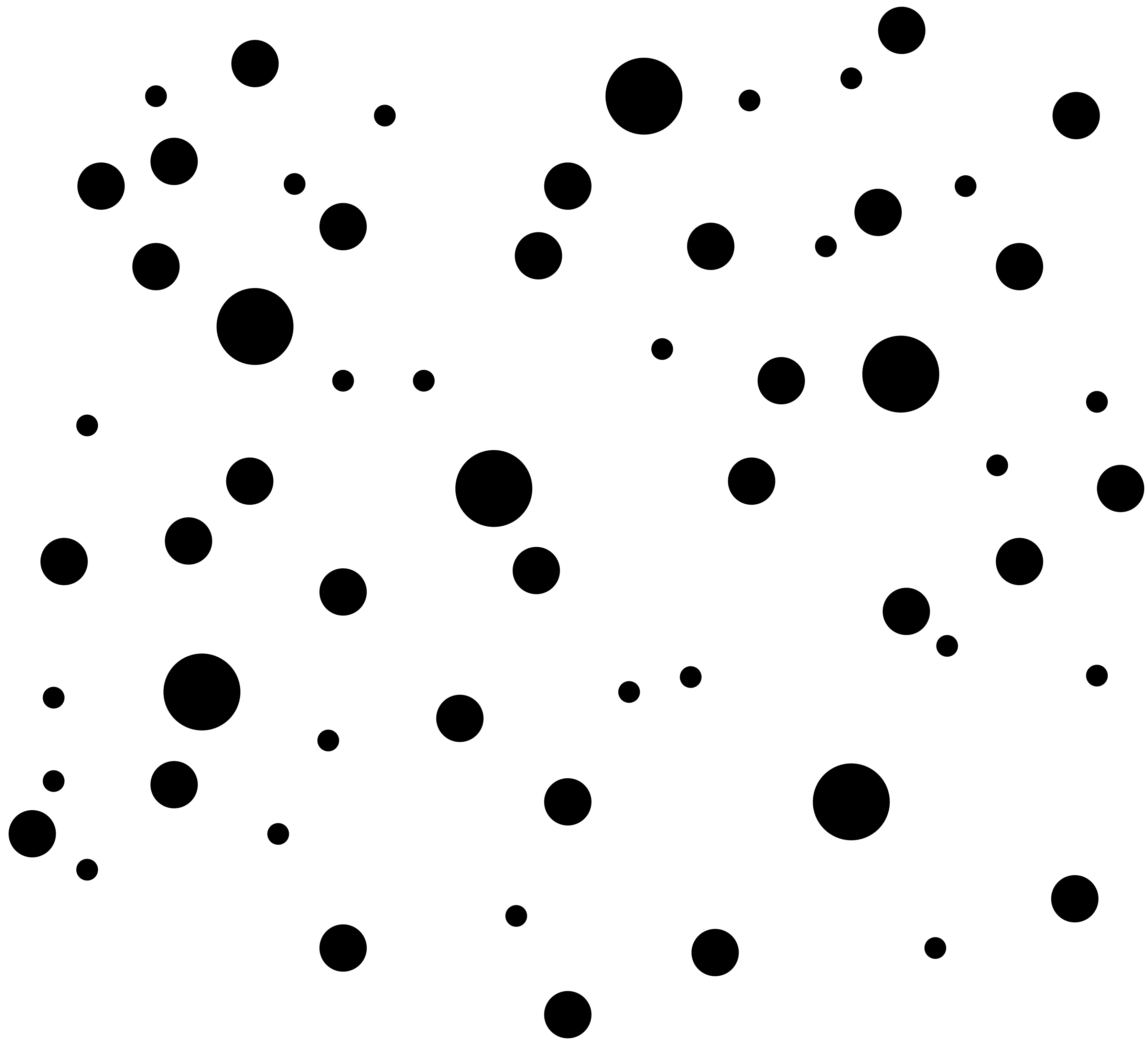
Inspiral through GW radiation, some merge at the present time.

Does LIGO rule out PBH-dark matter?

YAH, Kovetz & Kamionkowski [1709.06576]



Many simplifying assumptions to relax, e.g. mass distribution



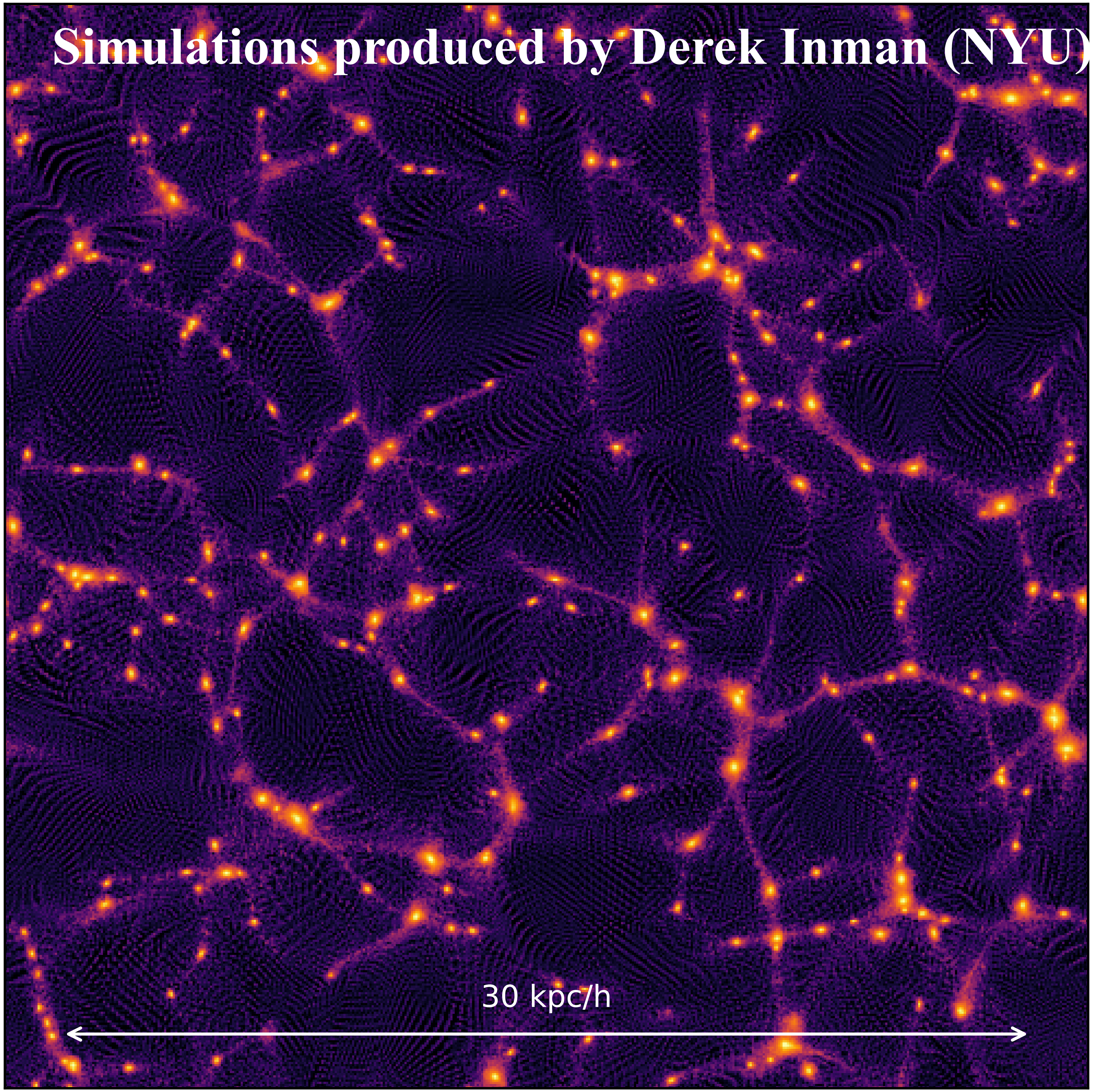
Outlook

- CMB temperature anisotropies almost fully harvested by Planck; lots of information still to be gained from polarization

- The frequency spectrum of the CMB is a sensitive calorimeter, and can work as a direct-detection experiment.

- Primordial black holes are an interesting DM candidate AND provide a window into initial conditions on ultra small scales.

- Mixed DM models to be explored.



$M_{\rm pbh} = 30 M_\odot$ $\quad$ $f_{\rm pbh} = 0.1$ $\quad$ $z = 100$