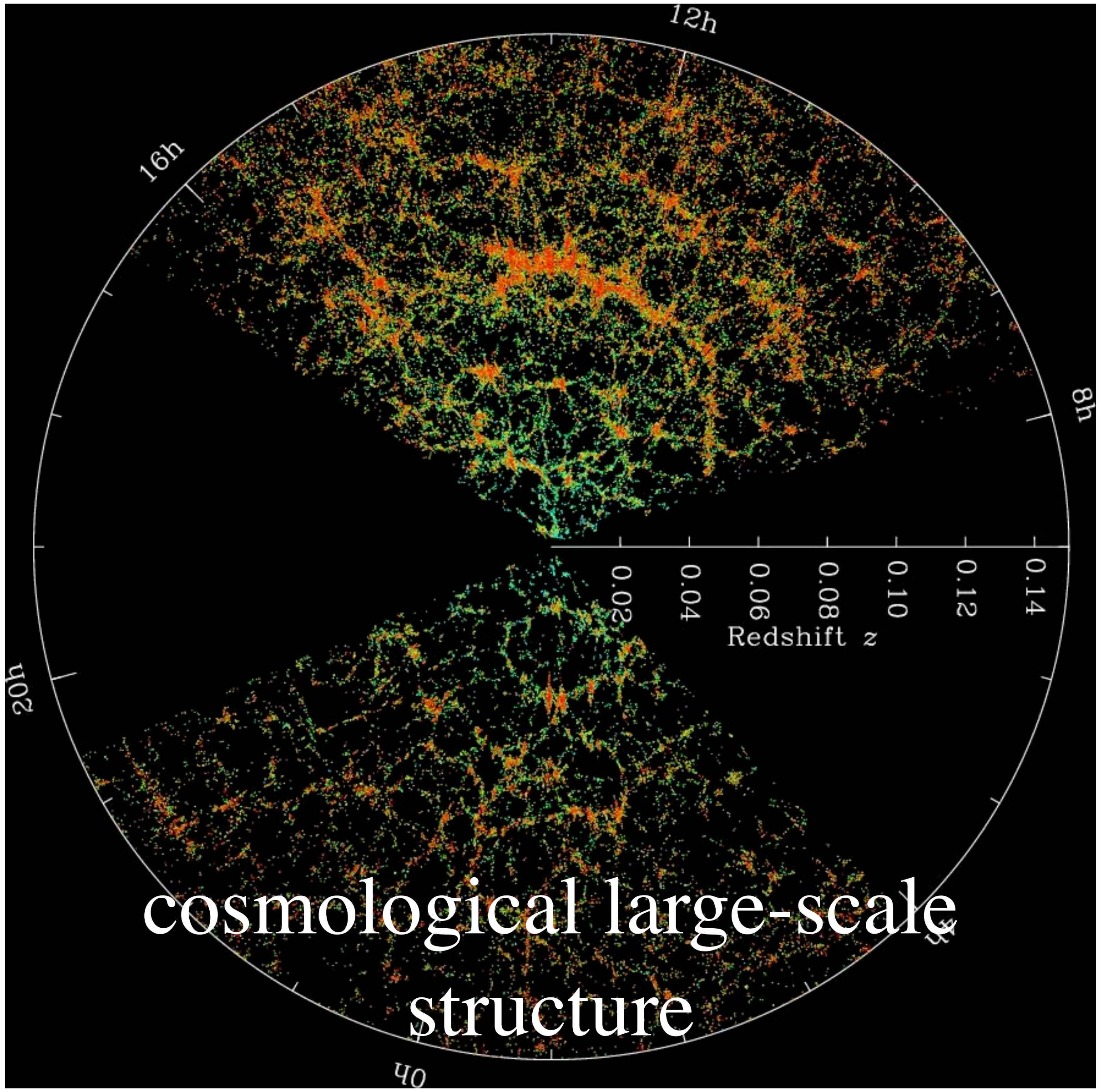
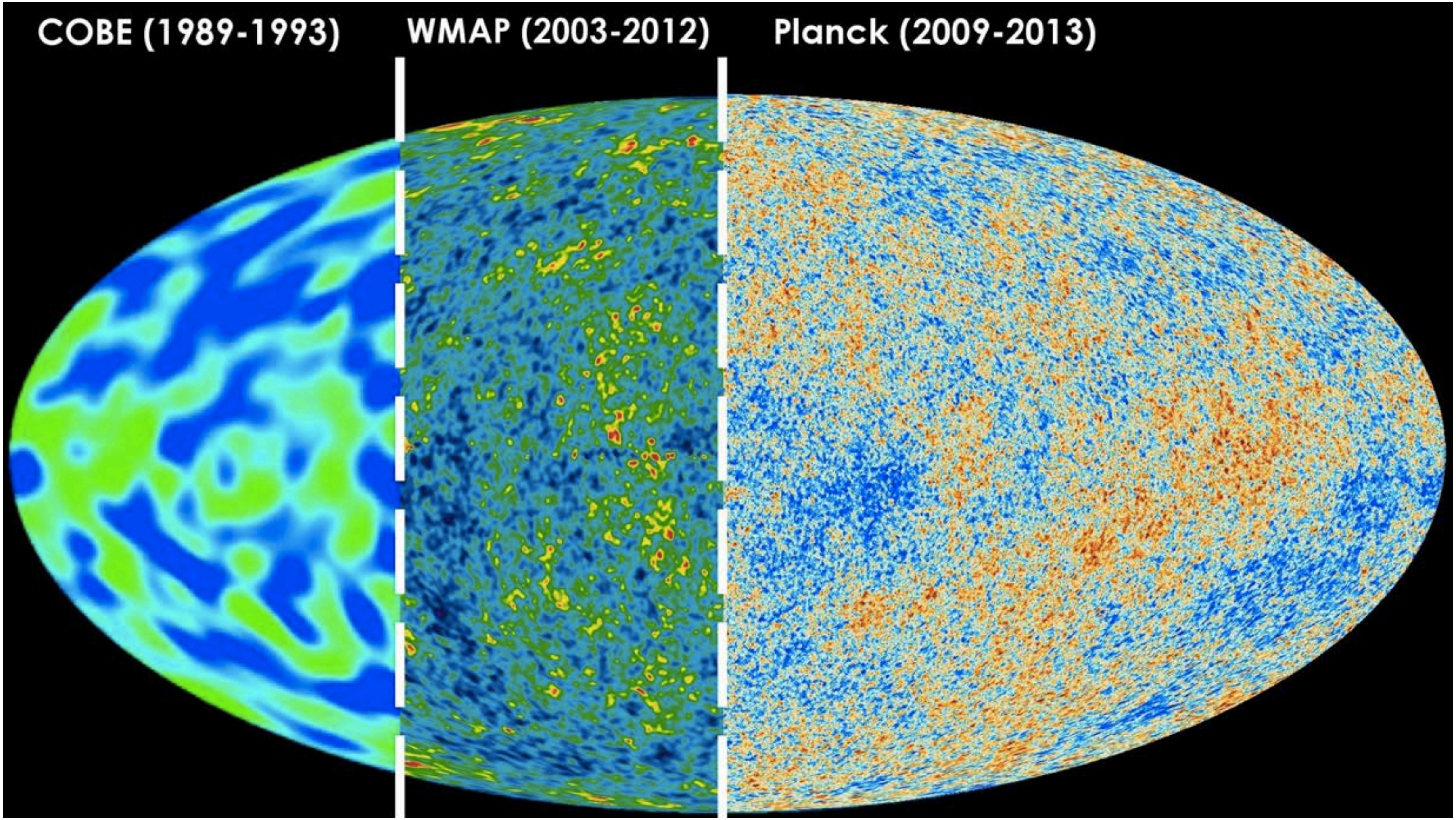
Hunting for dark matter in the early Universe

Yacine Ali-Haïmoud (NYU)

INAF-OAS joint Astrophysics colloquium **April 14, 2022**

Dark matter: executive introduction



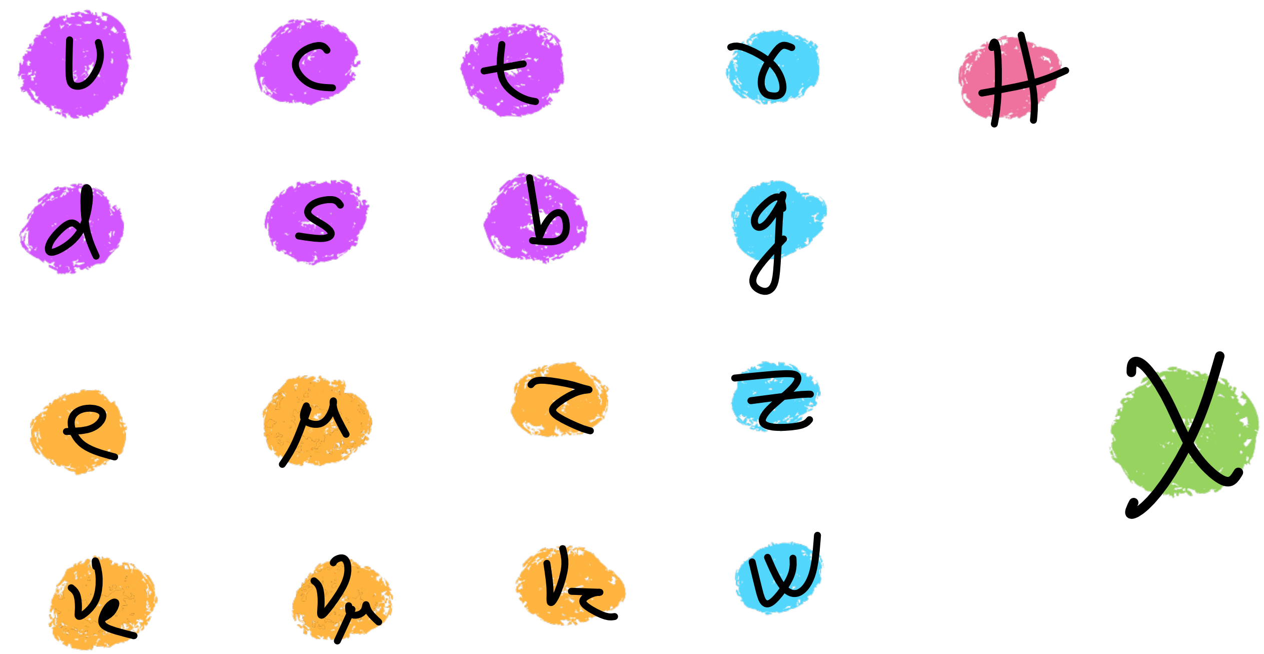


$$\frac{\text{density[dark matter]}}{\text{density [standard matter]}} \approx 5.36 \pm 0.05$$

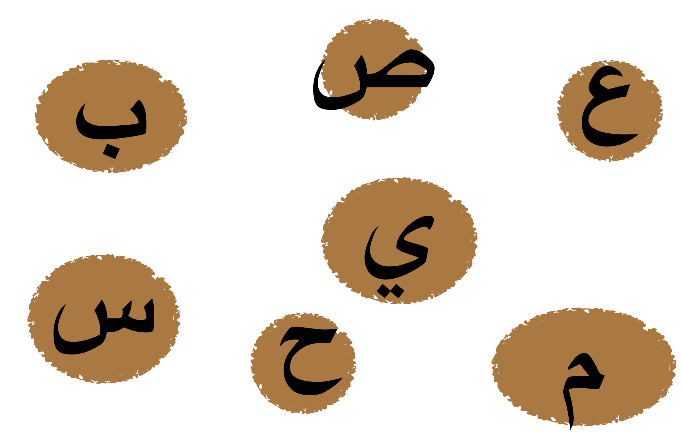
(Planck 2018)

Dark matter (DM) candidates

- A **new particle**?



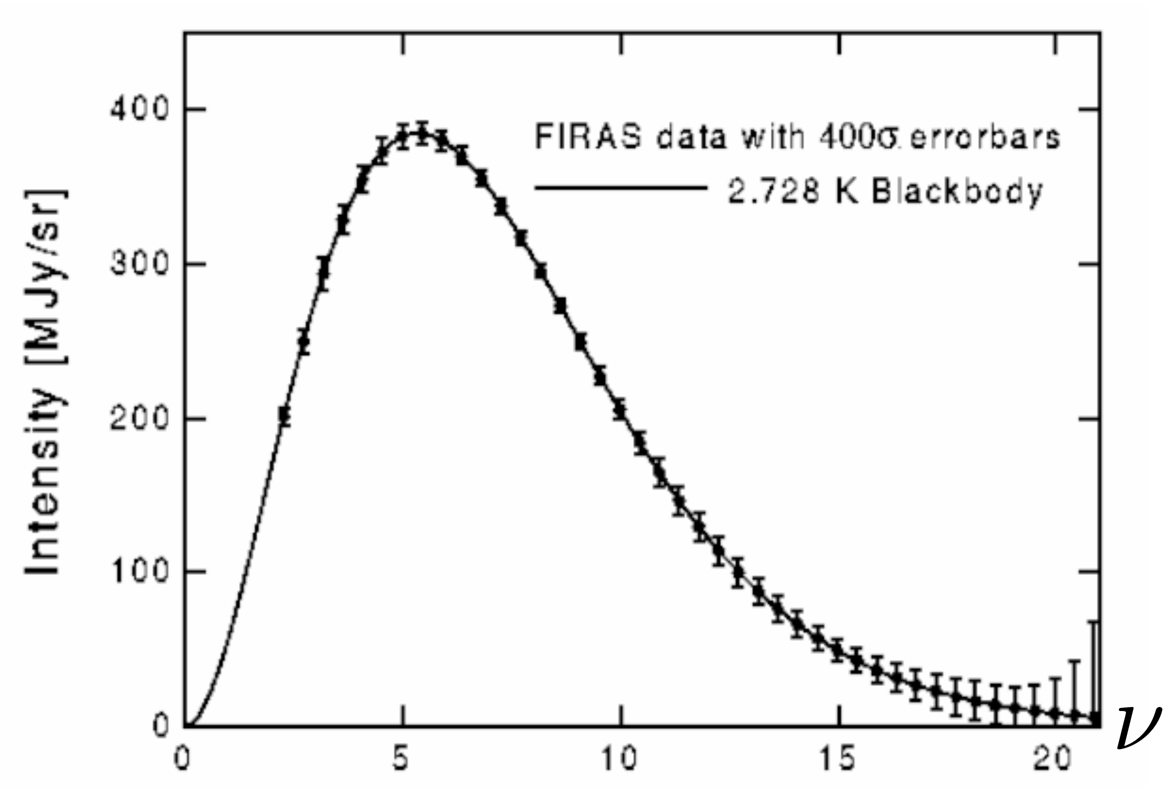
- A whole family of them?

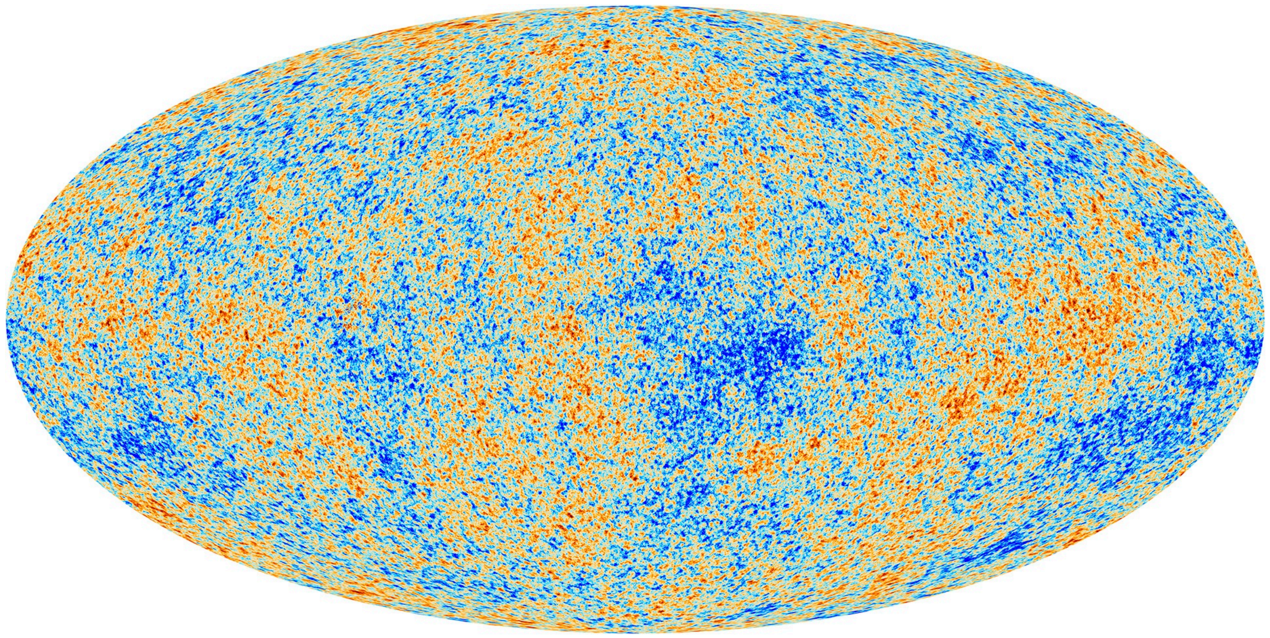


- **Primordial black holes (PBHs)?**

- **All of the above? None of the above?**

CMB observables





$$I(\nu, n) \equiv \frac{2h\nu^3}{\exp(h\nu/T) - 1}$$

ν: frequency

n: direction in the sky

$$T(\nu, n) = T_0 \quad +\Delta T(\nu) \quad +\Delta T(n) \quad +\delta T(\nu, n)$$

spectral distortions

anisotropies

spectral-spatial distortions (e.g. SZ)

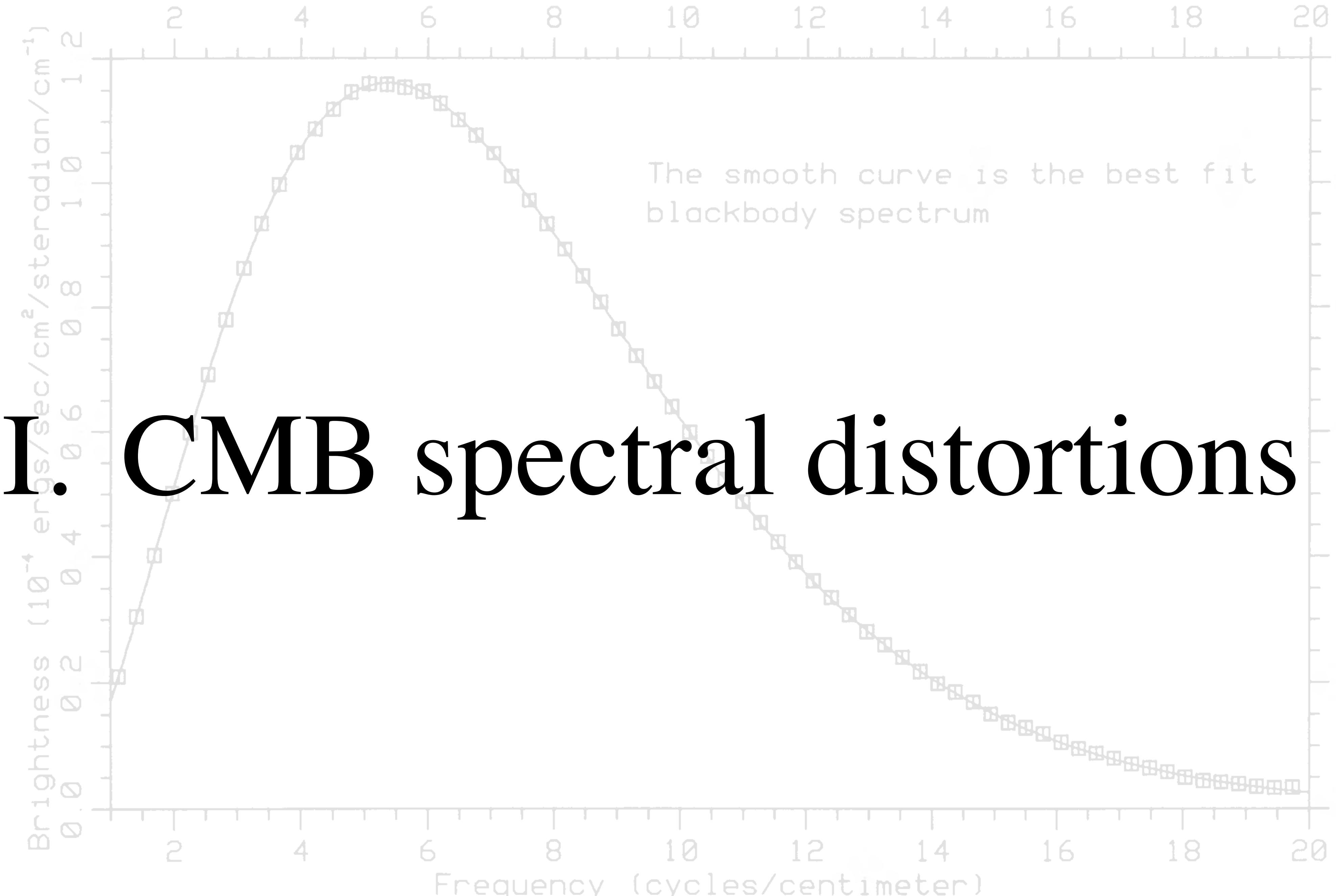
Outline

I. Brief review of CMB spectral distortion physics

II. Testing particle-DM scattering with spectral distortions

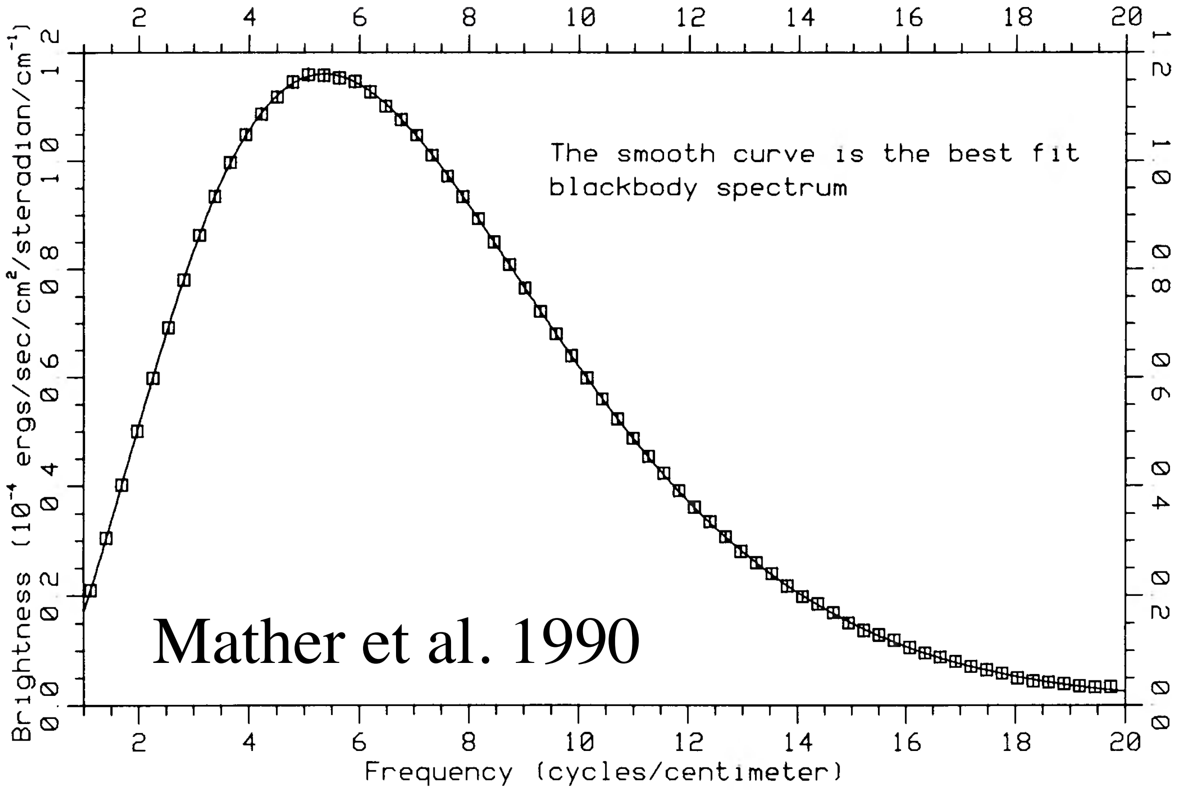
III. Brief review of CMB anisotropy physics

IV. Constraining accreting Primordial Black Holes with CMB anisotropies



I. CMB spectral distortions

Status of CMB frequency spectrum observations



COBE

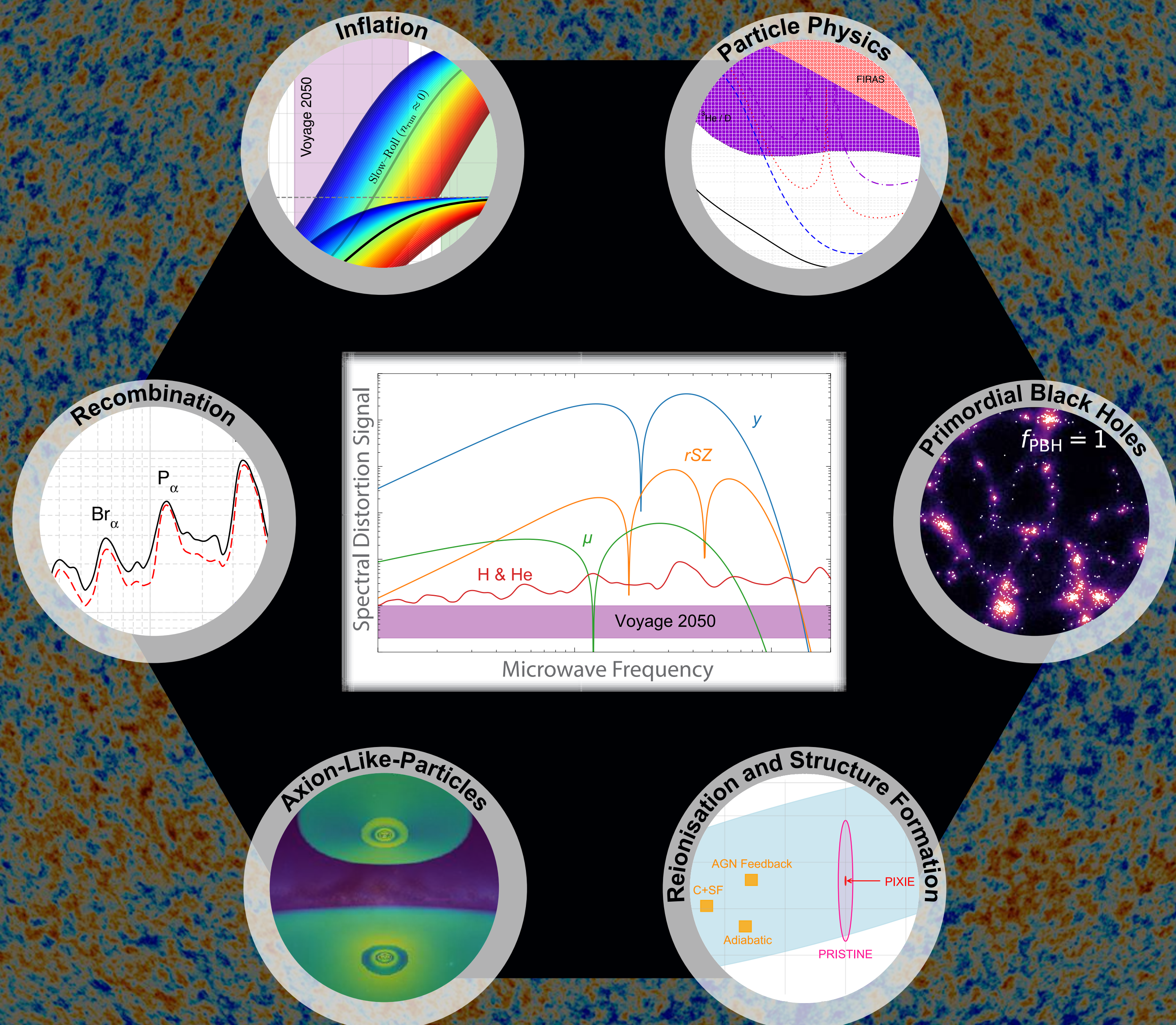
COBE-**FIRAS** limits on spectral distortions (Fixsen et al. 1996)

$$|\Delta I_\nu|/I_\nu \lesssim 10^{-4}$$

$$|y| \leq 1.5 \times 10^{-5}, \qquad |\mu| \leq 9 \times 10^{-5}$$

New Horizons in Cosmology with Spectral Distortions of the Cosmic Microwave Background

ESA Voyage 2050 Science White Paper



Contact:
Jens Chluba

Brief review of spectral distortion physics

Zeldovich & Sunyaev 1969, Hu & Silk 1993, Chluba & Sunyaev 2012

- At $z \gtrsim$ **2e6**: photons are easily created and destroyed, and thermalized

⇨ injection of energy into the photon-baryon plasma at $z \gtrsim$ 2e6 *does not distort* the CMB **blackbody spectrum** (it can only change its overall temperature)

$$I_\nu = \frac{2h\nu^3}{e^{h\nu/T} - 1}$$

Brief review of spectral distortion physics

Zeldovich & Sunyaev 1969, Hu & Silk 1993, Chluba & Sunyaev 2012

- At **6e4 ≲ *z* ≲ 2e6**: photons *no longer* easily created and destroyed, but their **energy is efficiently changed** by Thomson scattering with free electrons.

⇨ Photon spectrum reaches a Bose-Einstein distribution, regardless of the energy injection process.

$$I_\nu = \frac{2h\nu^3}{e^{h\nu/T+\mu} - 1}$$

$$\mu \approx 1.4 \int_{6e4 \leq z \leq 2e6} dt \, \frac{\dot{\rho}_{\rm inj}}{\rho_\gamma}$$

Brief review of spectral distortion physics

Zeldovich & Sunyaev 1969, Hu & Silk 1993, Chluba & Sunyaev 2012

- At $z \lesssim$ **6e4**: both photon number and energy no longer efficiently change.
- **If** energy is injected by heating baryons, and transferred to CMB by Thomson scattering, Compton-*y* (SZ) distortion

$$I_\nu = \frac{2h\nu^3}{e^{h\nu/T} - 1} + y\, Y_{\rm SZ}(h\nu/T) \qquad y \approx \frac{1}{4} \int_{z \leq 6e4} dt\, \frac{\dot{\rho}_{\rm inj}}{\rho_\gamma}$$

- In general, non-universal distortion shape, depending on energy injection channel(s) [e.g. direct injection of photons with narrow/broad spectrum, etc…]

Brief review of spectral distortion physics

Zeldovich & Sunyaev 1969, Hu & Silk 1993, Chluba & Sunyaev 2012

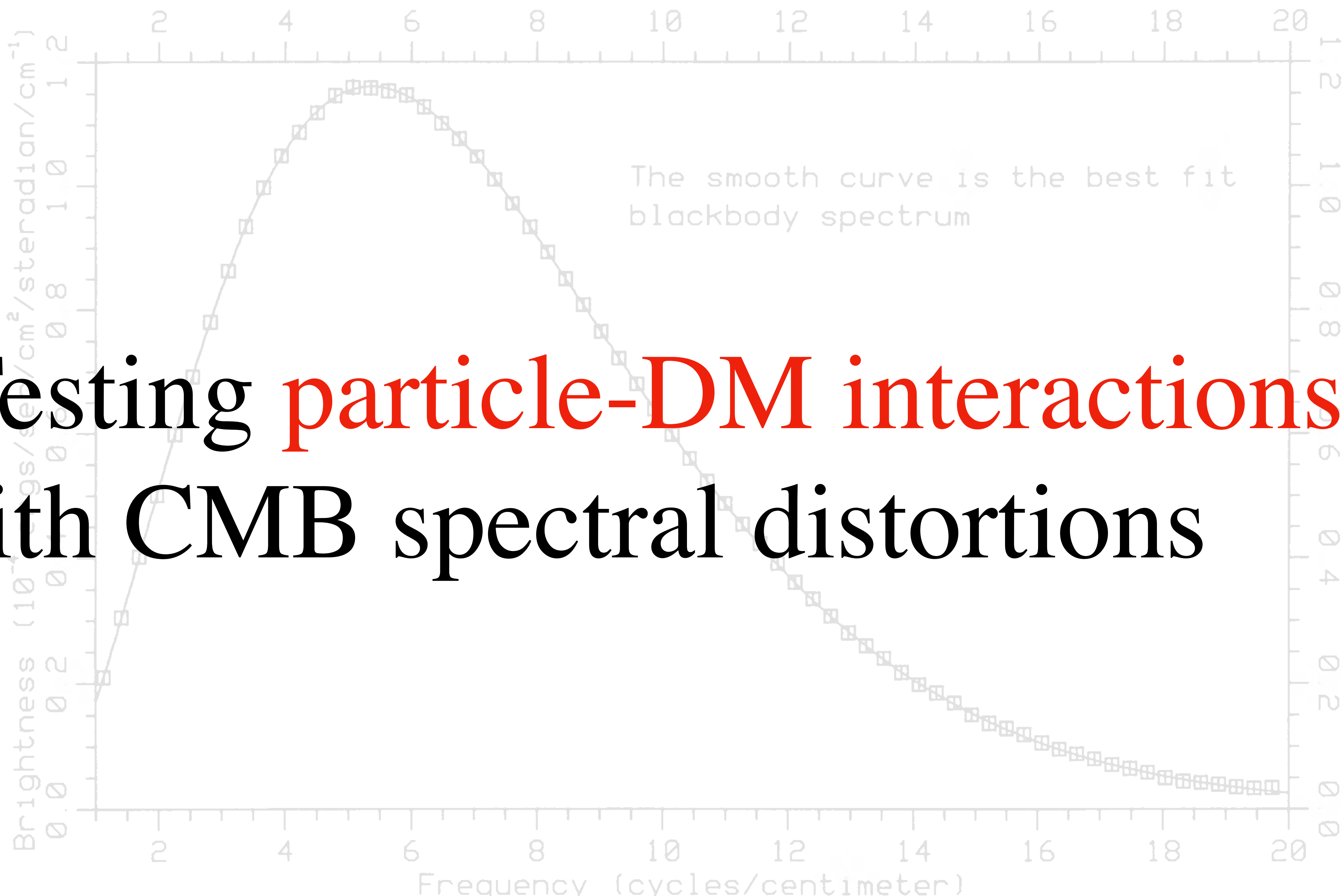
Bottom line:

$$\frac{\Delta I_\nu}{I_\nu} \sim \int_{z \lesssim 2e6} dt \, \frac{\dot{\rho}_{\rm inj}}{\rho_\gamma}$$

FIRAS limits:

$$|\Delta I_\nu|/I_\nu \lesssim 10^{-4}$$

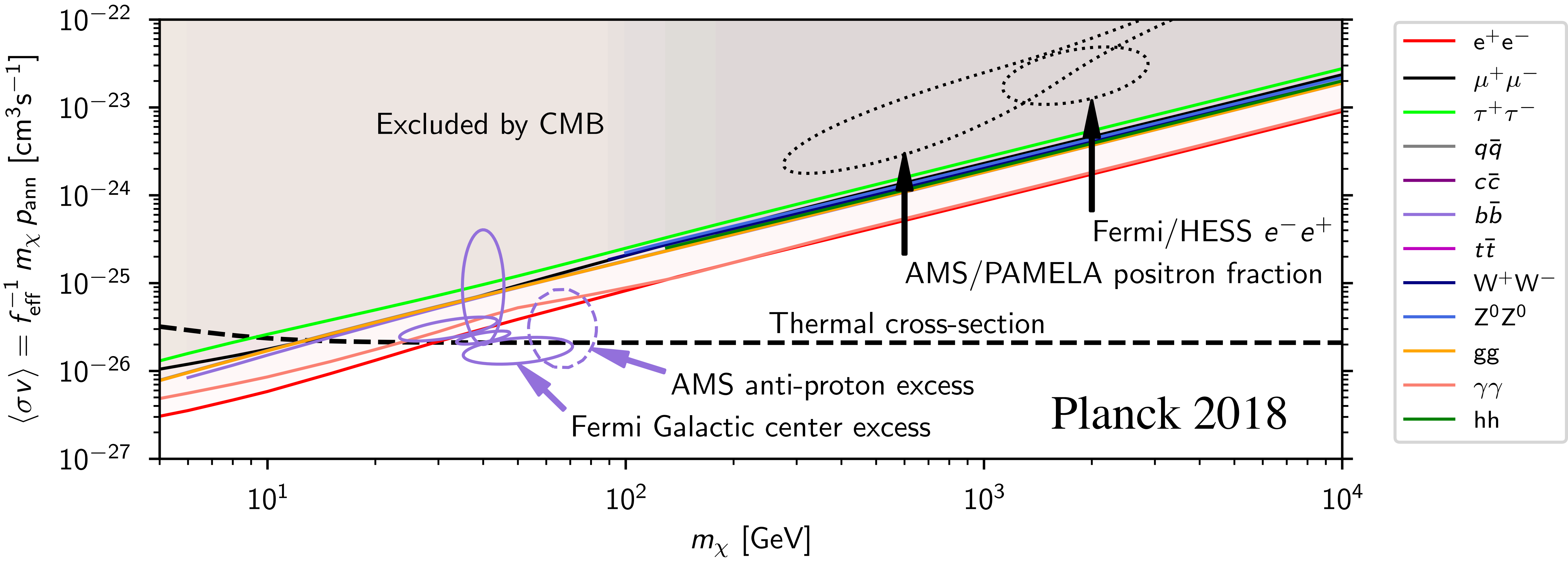
II. Testing particle-DM interactions with CMB spectral distortions



If DM is a **fundamental/composite particle χ**, could it **interact** feebly with "visible" matter?

$$\chi\bar{\chi} \to \gamma\gamma, e^+e^-, q\bar{q}, \ldots \qquad \text{annihilations}$$

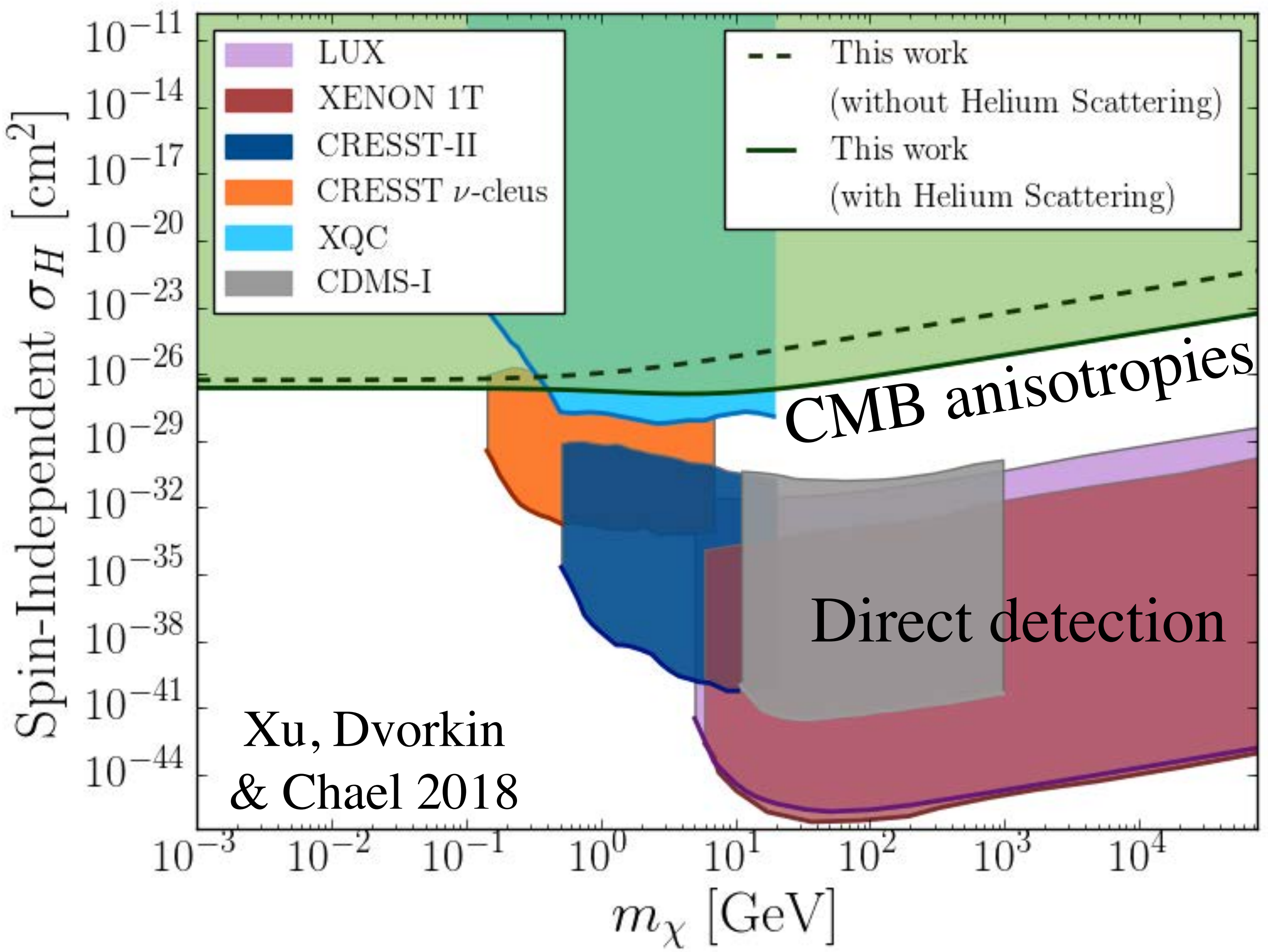
$$\chi \to \gamma\gamma, e^+e^-, q\bar{q}, \ldots \qquad \text{decays}$$



If DM is a **fundamental/composite particle χ**, could it **interact** feebly with "visible" matter?

$$\chi\gamma \leftrightarrow \chi\gamma$$
$$\chi e^- \leftrightarrow \chi e^-$$
$$\chi p \leftrightarrow \chi p$$

scattering



CMB spectral distortions from DM scattering

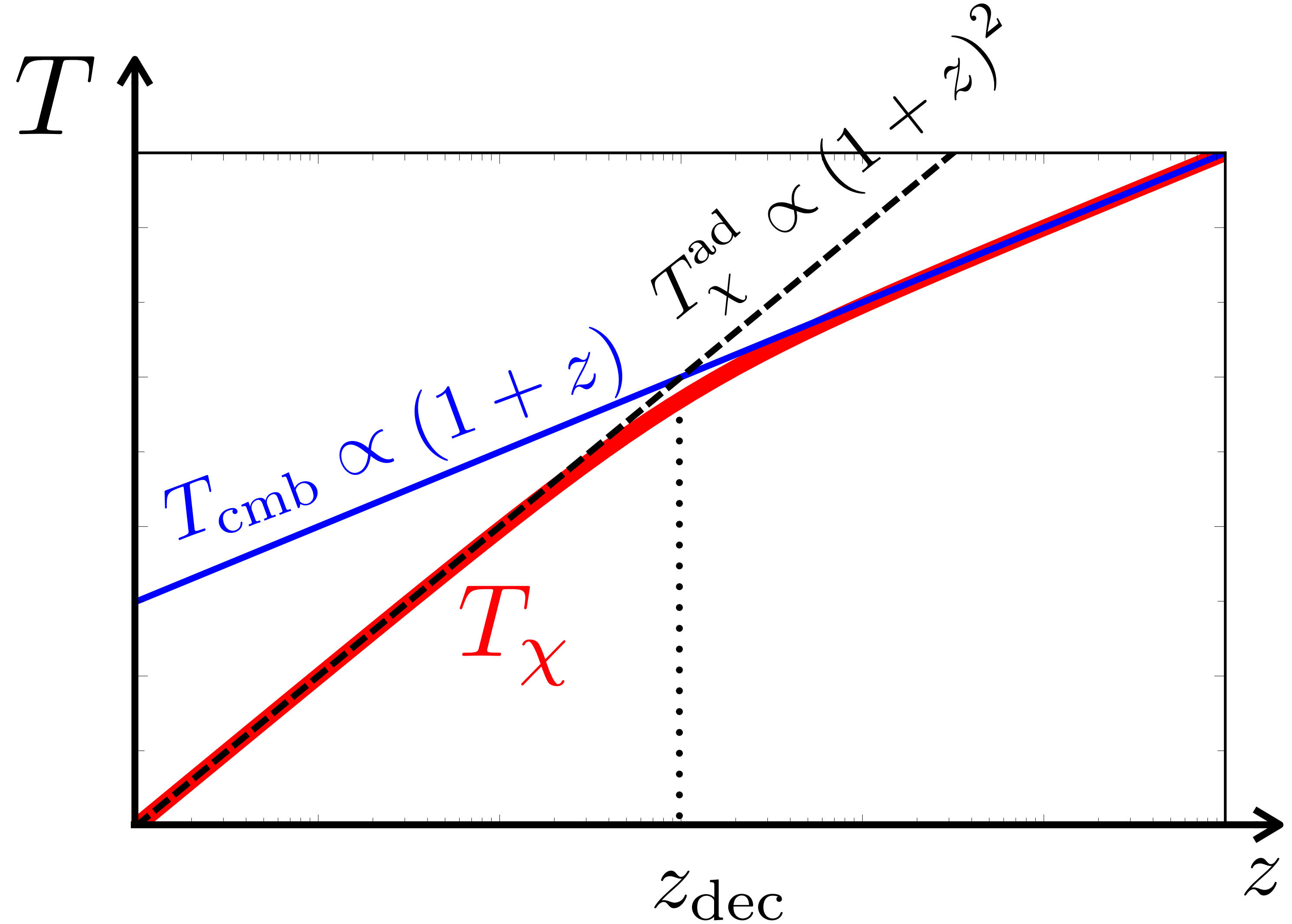
YAH, Chluba & Kamionkowski, PRL 2015

Suppose DM is non-relativistic, and scatters with $\gamma/e/p$

Scattering rate: $n_b\langle\sigma v\rangle \propto (1+z)^{3+1/2}$ (for constant σ)

Expansion rate: $H(z) \propto (1+z)^2$ (radiation domination)

$$\frac{n_b\langle\sigma v\rangle}{H} = \left(\frac{1+z}{1+z_{\rm dec}}\right)^{3/2}$$



While $z > z_{dec}$, the photon-baryon plasma constantly heats up DM to keep T_χ warmer than adiabatic evolution.

=> While $z > z_{dec}$, the DM constantly extracts heat from the photon-baryon plasma

$$\dot{\rho}_{\rm inj} = -\frac{3}{2} n_\chi \left(\dot{T}_\chi - \dot{T}_\chi \big|_{\rm ad} \right) \qquad \dot{T}_\chi \big|_{\rm ad} = -2HT_\chi$$

$$\dot{T}_\chi \approx \begin{cases} -HT_\chi, & z > z_{\rm dec} \\ \dot{T}_\chi \big|_{\rm ad}, & z < z_{\rm dec} \end{cases}$$

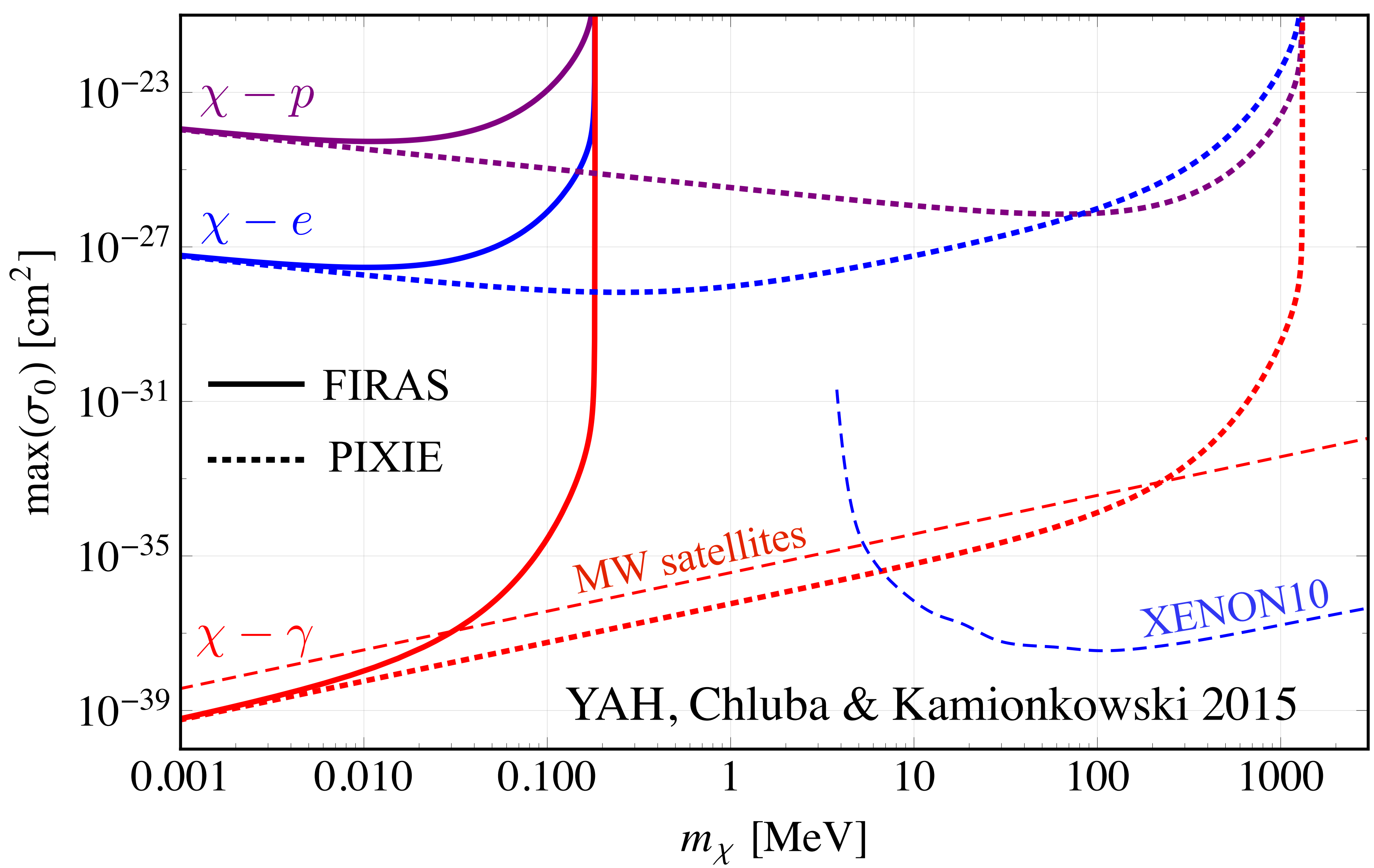
$$\Rightarrow \dot{\rho}_{\rm inj} \approx \begin{cases} -\frac{3}{2} n_\chi HT, & z > z_{\rm dec} \\ 0 & z < z_{\rm dec} \end{cases}$$

Instantaneous decoupling approximation

$$\frac{\Delta I_\nu}{I_\nu} \sim \int_{z \lesssim 2e6} dt \, \frac{\dot{\rho}_{\rm inj}}{\rho_\gamma} \sim \frac{n_\chi}{n_\gamma} \ln(2 \times 10^6 / z_{\rm dec})$$

$$\frac{\# n_b \langle \sigma_{\rm scat} v \rangle}{H}\bigg|_{\rm zdec} \sim 1$$

gives $z_{\rm dec}$ as a function of $\sigma_{\rm scat}$



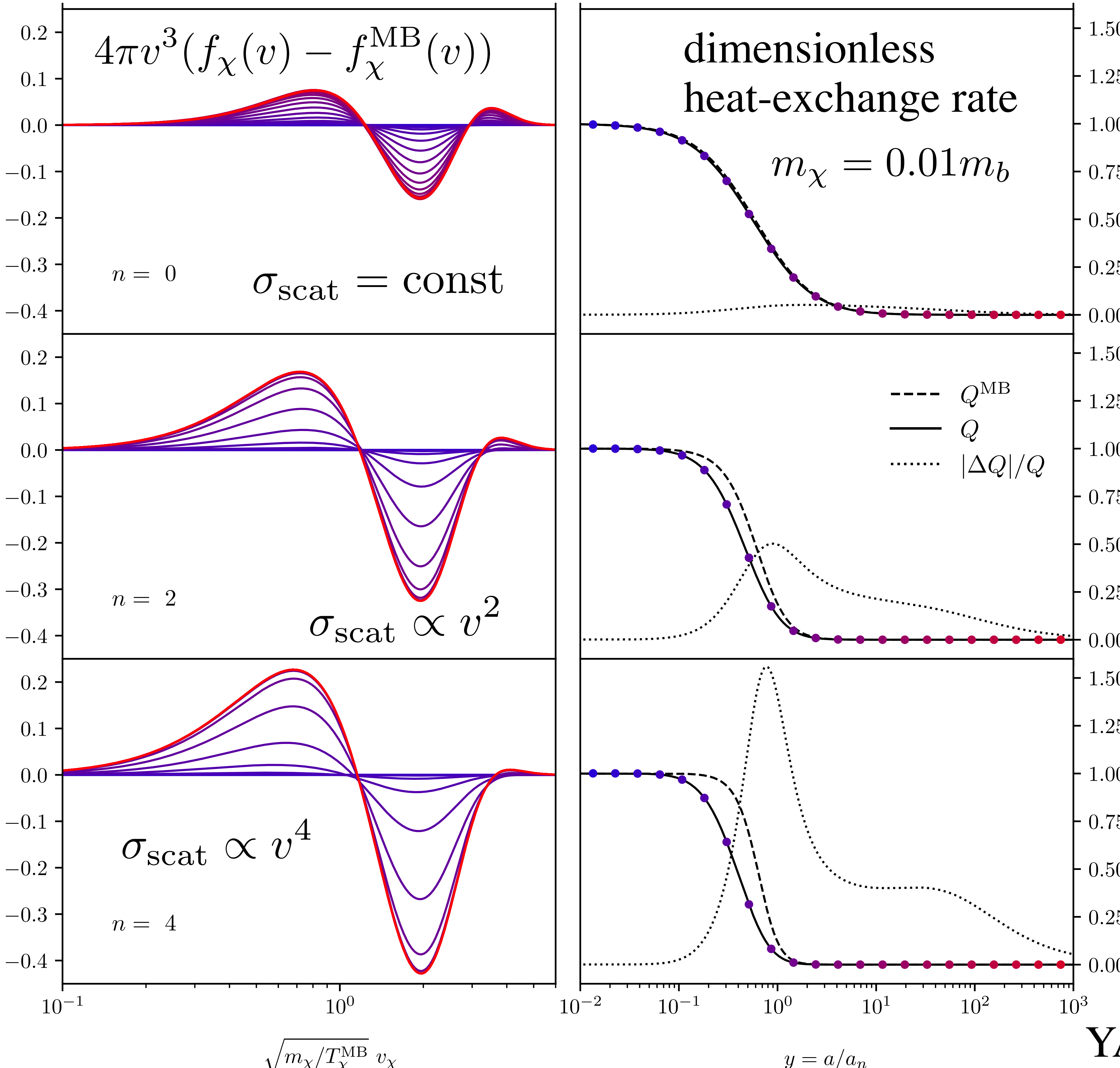
With instantaneous-decoupling approximation

Motivation for instantaneous-decoupling approximation:

- If χ-χ scattering rate >> H, DM has Maxwell-Boltzmann velocity distribution => only need to solve for T_χ

- But in general, one needs to follow the full DM velocity distribution $f_\chi(v)$.

=> lacking a full treatment at the time, made a simple approximation based on thermal decoupling redshift.



$4\pi v^3(f_\chi(v) - f_\chi^{\mathrm{MB}}(v))$
$n = 0$
$\sigma_{\mathrm{scat}} = \mathrm{const}$
$n = 2$
$\sigma_{\mathrm{scat}} \propto v^2$
$\sigma_{\mathrm{scat}} \propto v^4$
$n = 4$
$\sqrt{m_\chi/T_\chi^{\mathrm{MB}}}\, v_\chi$
dimensionless
heat-exchange rate
$m_\chi = 0.01 m_b$
Q^{MB}
Q
$|\Delta Q|/Q$
$y = a/a_n$

YAH 2019

=> Maxwell-Boltzmann approximation is accurate within $O(1)$ for the heat-exchange rate

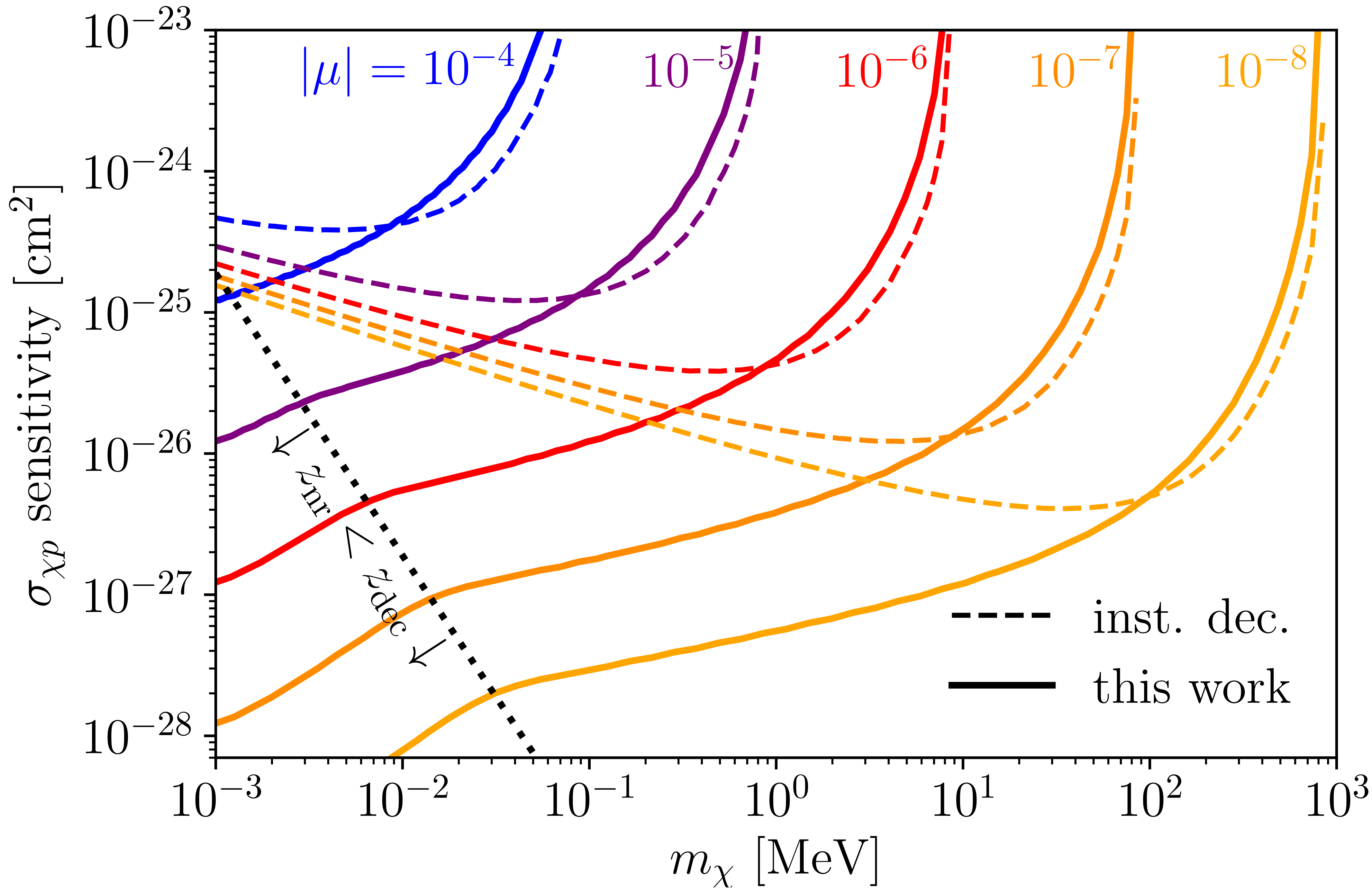
=> To estimate spectral distortion to O(unity) accuracy, solve for DM temperature evolution, then compute heat-exchange rate

$$a^{-2}\frac{d}{dt}(a^2T_\chi) = \Gamma_{\rm tot}(T_\gamma - T_\chi),$$

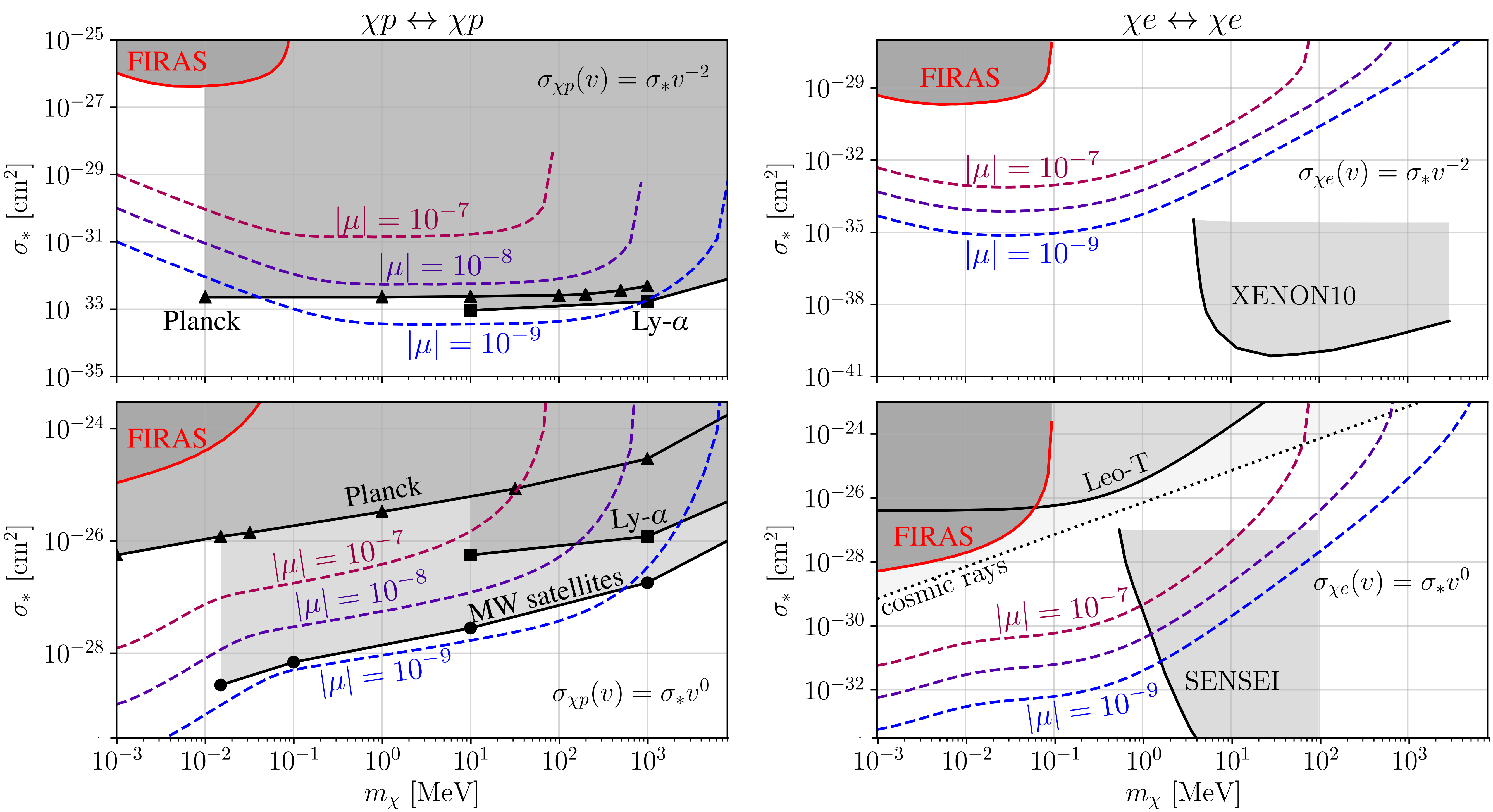
$$\Gamma_{\rm tot} \equiv \sum_{s=\gamma,e,p,{\rm He}} \Gamma_{\chi s}.$$

$$\dot{\rho}_{\rm inj} = -\frac{3}{2}n_\chi\ a^{-2}\frac{d}{dt}(a^2T_\chi)$$

Instantaneous-decoupling approximation can be **very inaccurate** due to **residual heat exchange after z_{dec}**



YAH, arXiv:2101.04070



YAH, arXiv:2101.04070

DM with an electric or magnetic dipole moment

$$\alpha_E \equiv \frac{\mathcal{D} m_\chi}{e}, \qquad \alpha_M \equiv \frac{\mathcal{M} m_\chi}{e}$$

annihilations into photons

$$\sigma_{\chi\chi\to\gamma\gamma}\, v = \frac{4\pi}{m_\chi^2}\alpha^2\alpha_\chi^4$$

annihilations into leptons-antileptons/ quarks-antiquarks

$$\sigma_{\chi\chi\to f\overline{f}}\, v \approx N_{c,f}\, \frac{\pi}{3m_\chi^2}\alpha^2\alpha_E^2\, v^2$$

$$\sigma_{\chi\chi\to f\overline{f}}\, v \approx N_{c,f}\frac{4\pi}{m_\chi^2}\alpha^2\alpha_M^2,$$

scattering with photons

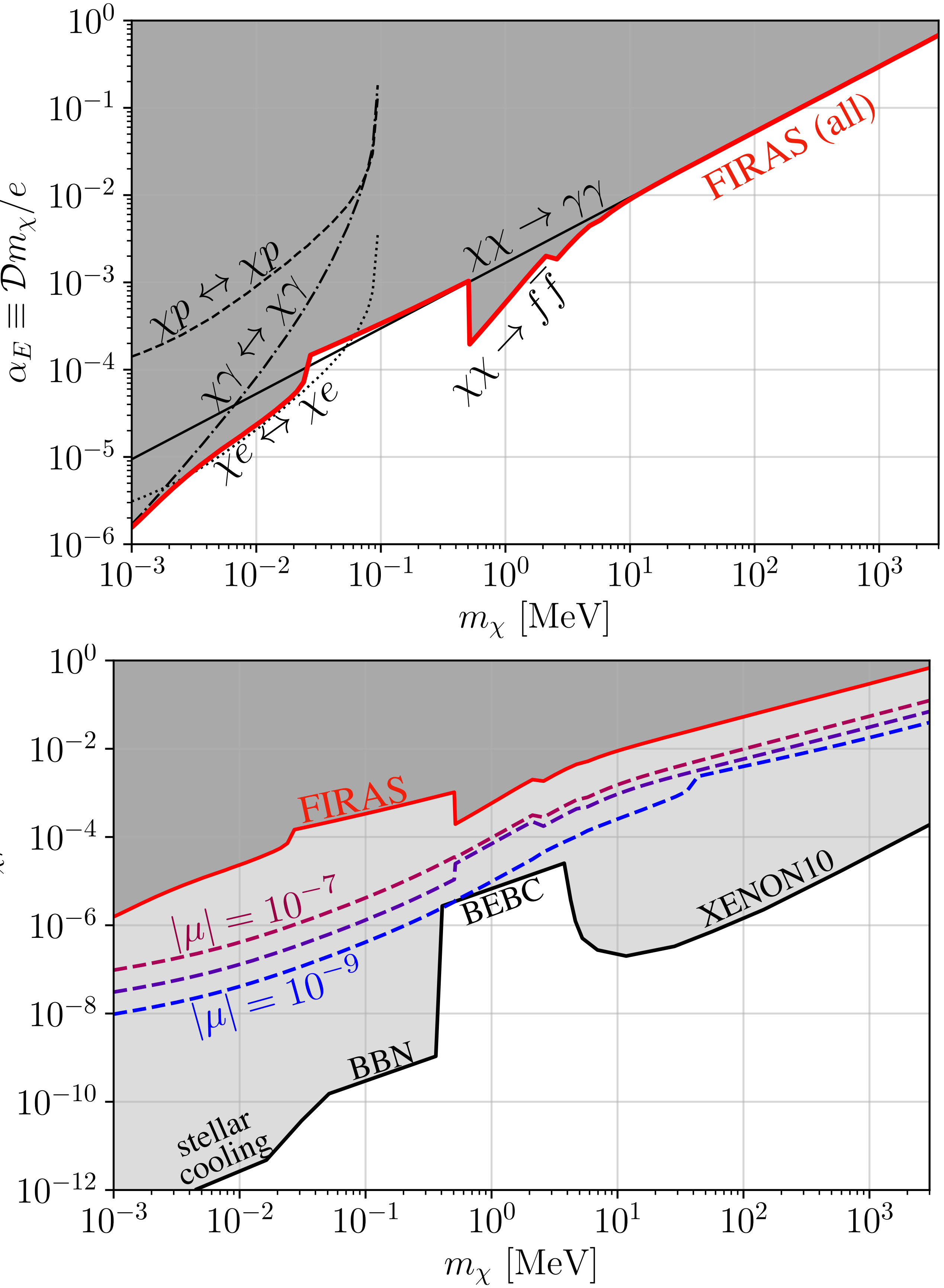
$$\sigma_{\chi\gamma}(E_\gamma) = \frac{64\pi}{3m_\chi^2}\alpha^2\alpha_\chi^4\left(\frac{E_\gamma}{m_\chi}\right)^2$$

scattering with electrons/nuclei

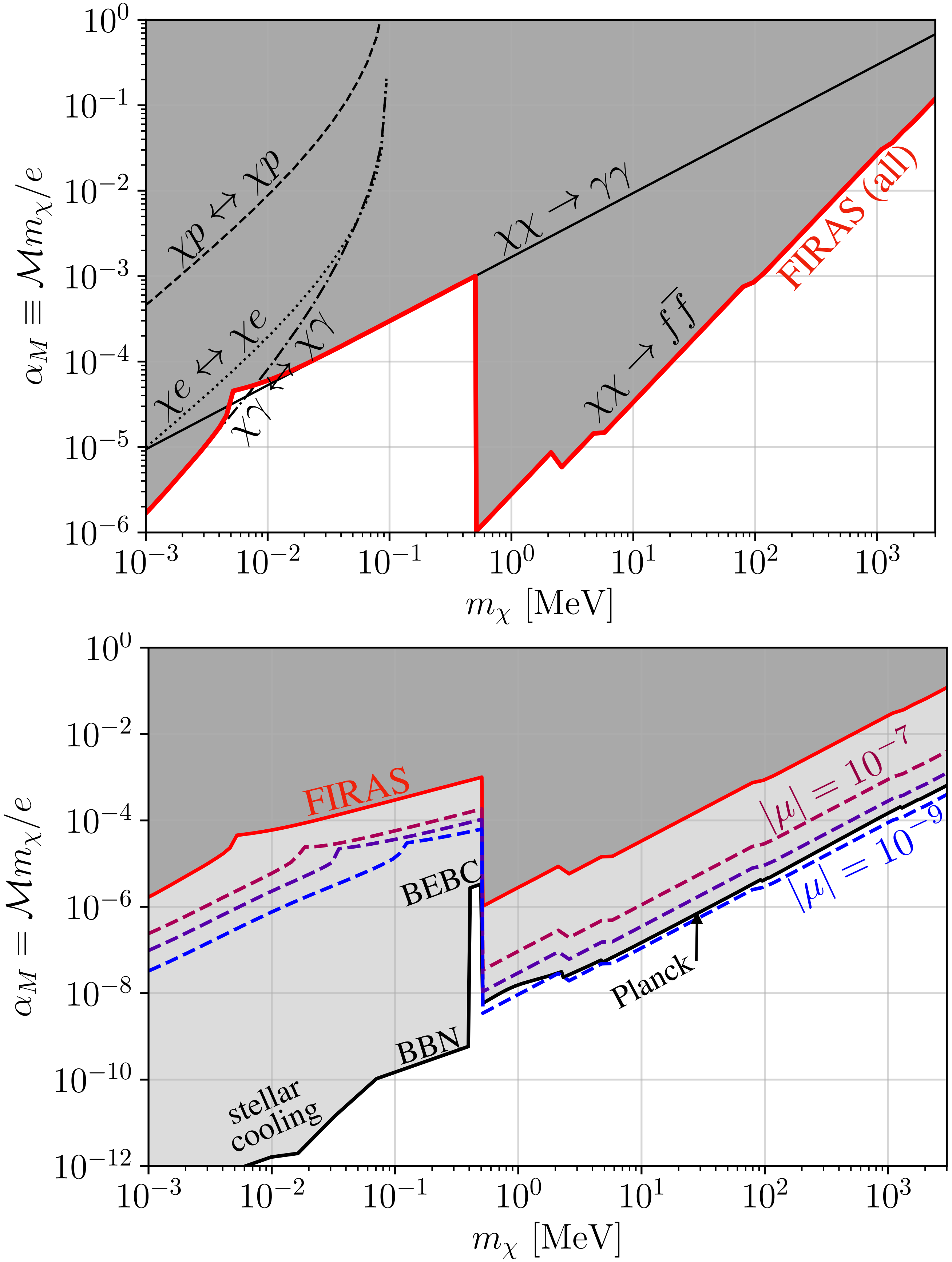
$$\sigma_{\chi s}(v) = \frac{8\pi Z_s^2}{m_\chi^2}\frac{\alpha^2\alpha_E^2}{v^2},$$

$$\sigma_{\chi s}(v) = \frac{8\pi Z_s^2}{m_\chi^2}R_{\chi s}\,\alpha^2\alpha_M^2$$

DM with an electric dipole moment



DM with a magnetic dipole moment



YAH, arXiv:2101.04070

https://cosmo.nyu.edu/yacine/dmdist/dmdist.html

DMDIST

A code to calculate CMB spectral distortions from dark matter interactions

DMDIST computes the CMB μ-distortion resulting from interactions of non-relativistic dark matter particles with Standard Model particles, including elastic scattering and annihilations.
Please cite the companion paper when using this code as part of any published work: Ali-Haïmoud, arXiv e-prints (January 2021)
Please consider also citing the following paper, presenting the original idea: Ali-Haïmoud, Chluba and Kaminkowski, PRL 115, 071304 (2015) (arXiv:1506.04745)
Note that this code is provided "as is" and no guarantees are given regarding its accuracy.

- **Python source code: DMDIST**
- Example use: iPython notebook (plus external data) used to make the figures in the companion paper, and the output files below.
- DMDIST output files for spectral-distortion upper limits and sensitivity forecasts for DM scattering with a single scatterer.

Columns are DM mass in MeV and "coupling" = σ_* in cm^2, for μ = 9e-5 (FIRAS limit), 1e-7, 1e-8, 1e-9 (see first 2 lines in file for description):

proton_minus2.txt: DM-proton scattering with cross section $\sigma_{\chi p}(v) = \sigma_* v^{-2}$

proton_0.txt: .... $\sigma_{\chi p}(v) = \sigma_* v^0$

proton_2.txt: .... $\sigma_{\chi p}(v) = \sigma_* v^2$

proton_4.txt: .... $\sigma_{\chi p}(v) = \sigma_* v^4$

proton_6.txt: .... $\sigma_{\chi p}(v) = \sigma_* v^6$

electron_minus2.txt: DM-electron scattering with cross section $\sigma_{\chi e}(v) = \sigma_* v^{-2}$

electron_0.txt: .... $\sigma_{\chi e}(v) = \sigma_* v^0$

electron_2.txt: .... $\sigma_{\chi e}(v) = \sigma_* v^2$

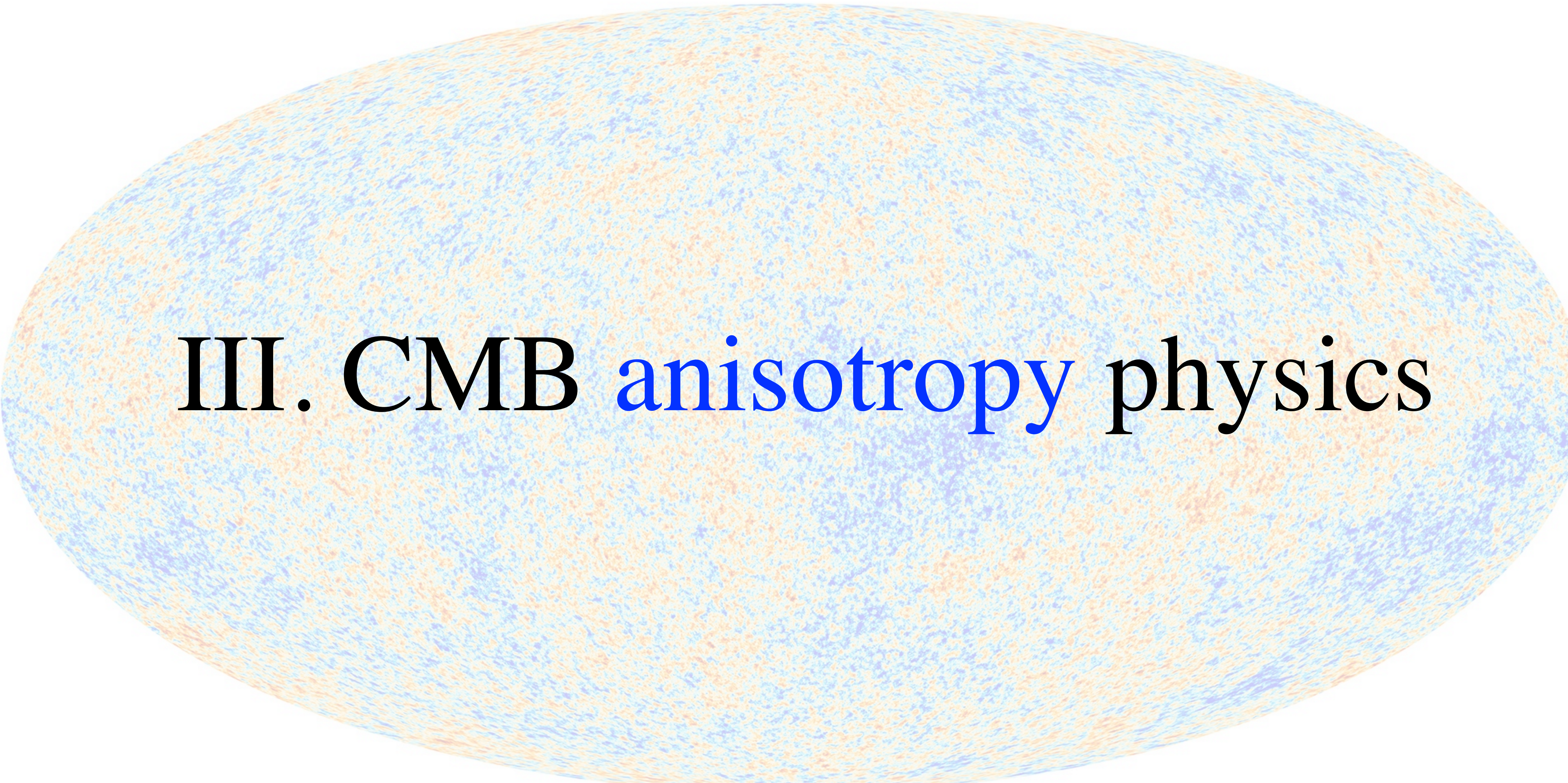
electron_4.txt: .... $\sigma_{\chi e}(v) = \sigma_* v^4$

electron_6.txt: .... $\sigma_{\chi e}(v) = \sigma_* v^6$

photon_0.txt: DM-photon scattering with cross section $\sigma_{\chi\gamma}(E_\gamma) = \sigma_*$

photon_2.txt: .... $\sigma_{\chi\gamma}(E_\gamma) = \sigma_*(E_\gamma/m_\chi)^2$

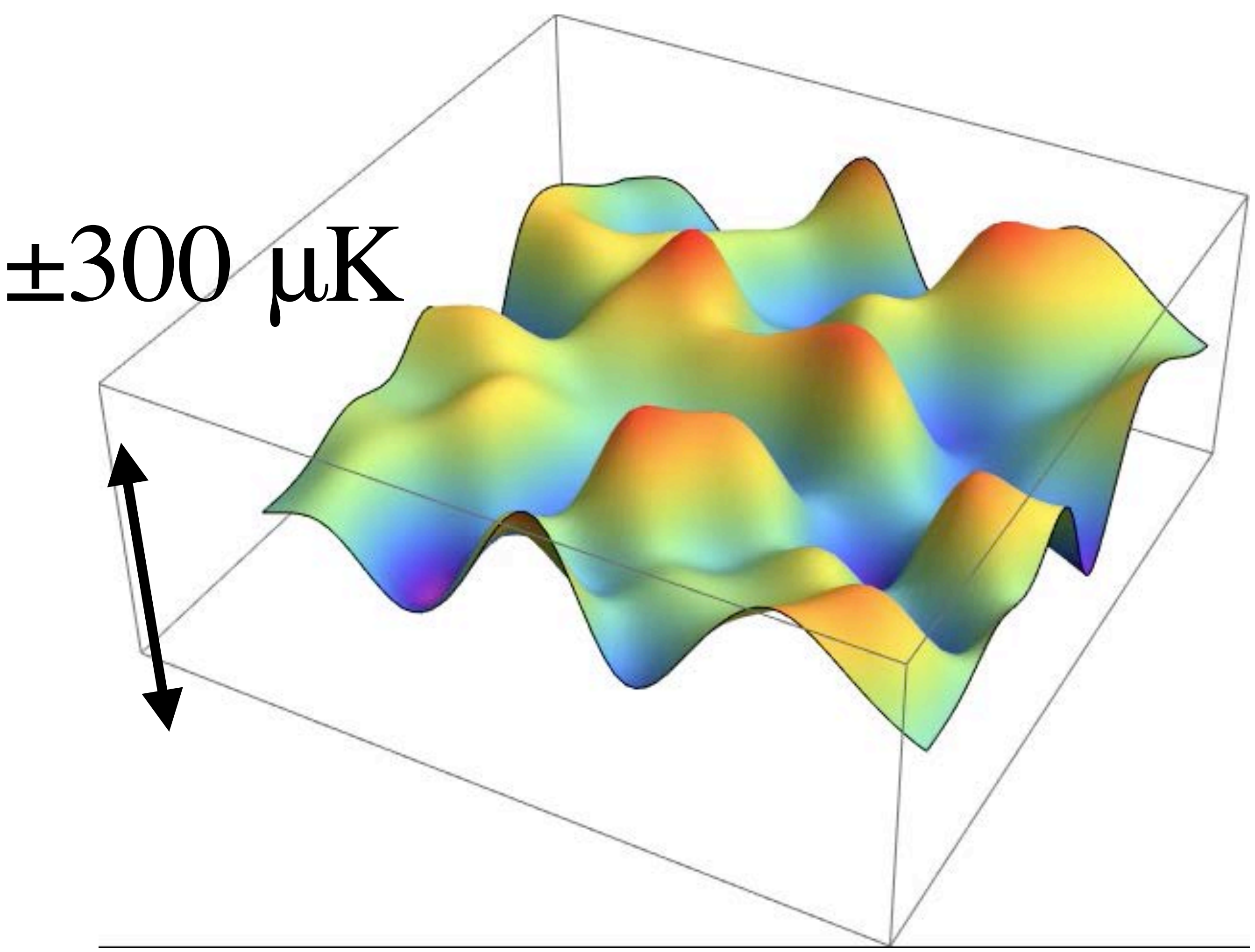
photon_4.txt: .... $\sigma_{\chi\gamma}(E_\gamma) = \sigma_*(E_\gamma/m_\chi)^4$

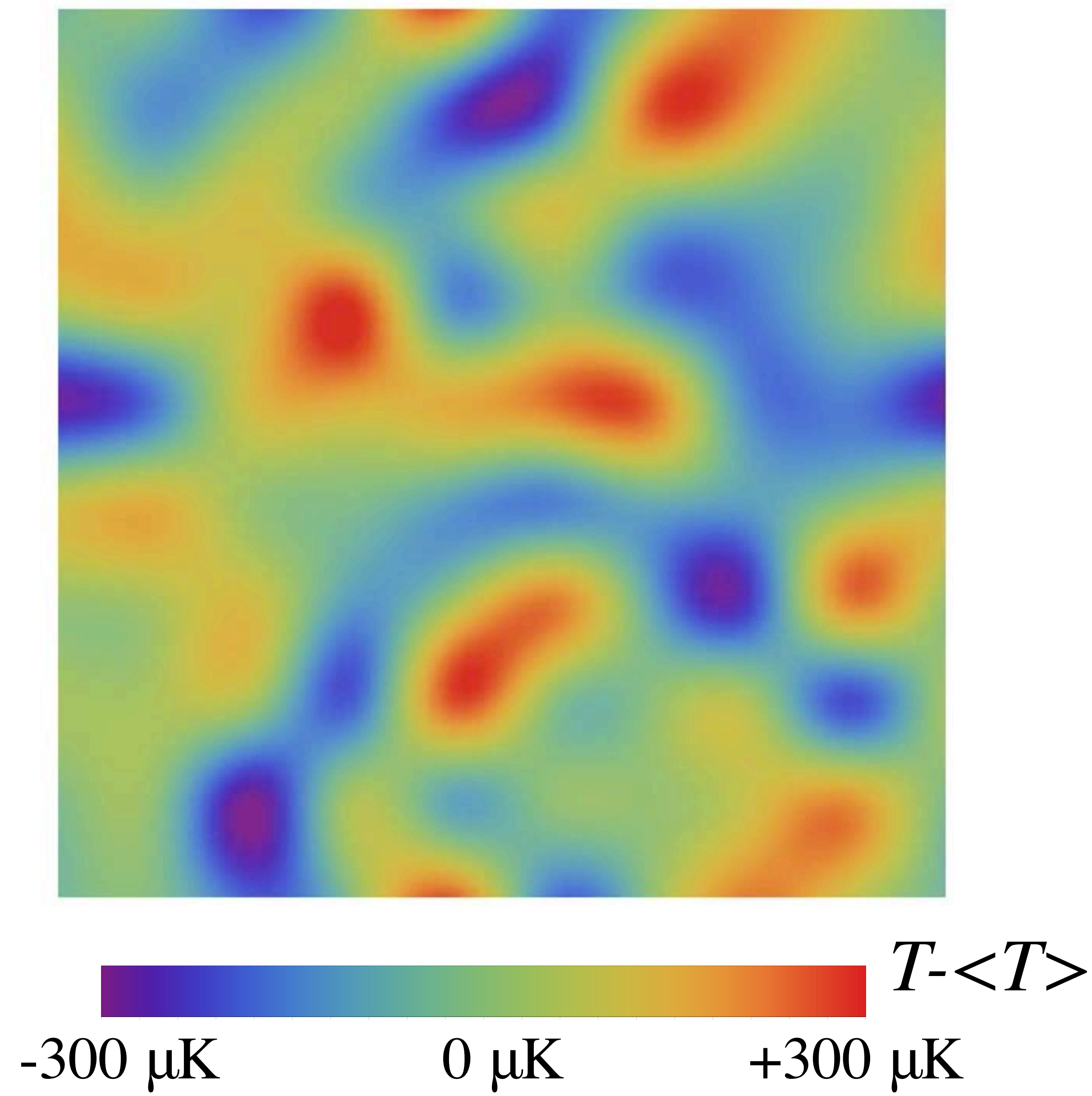


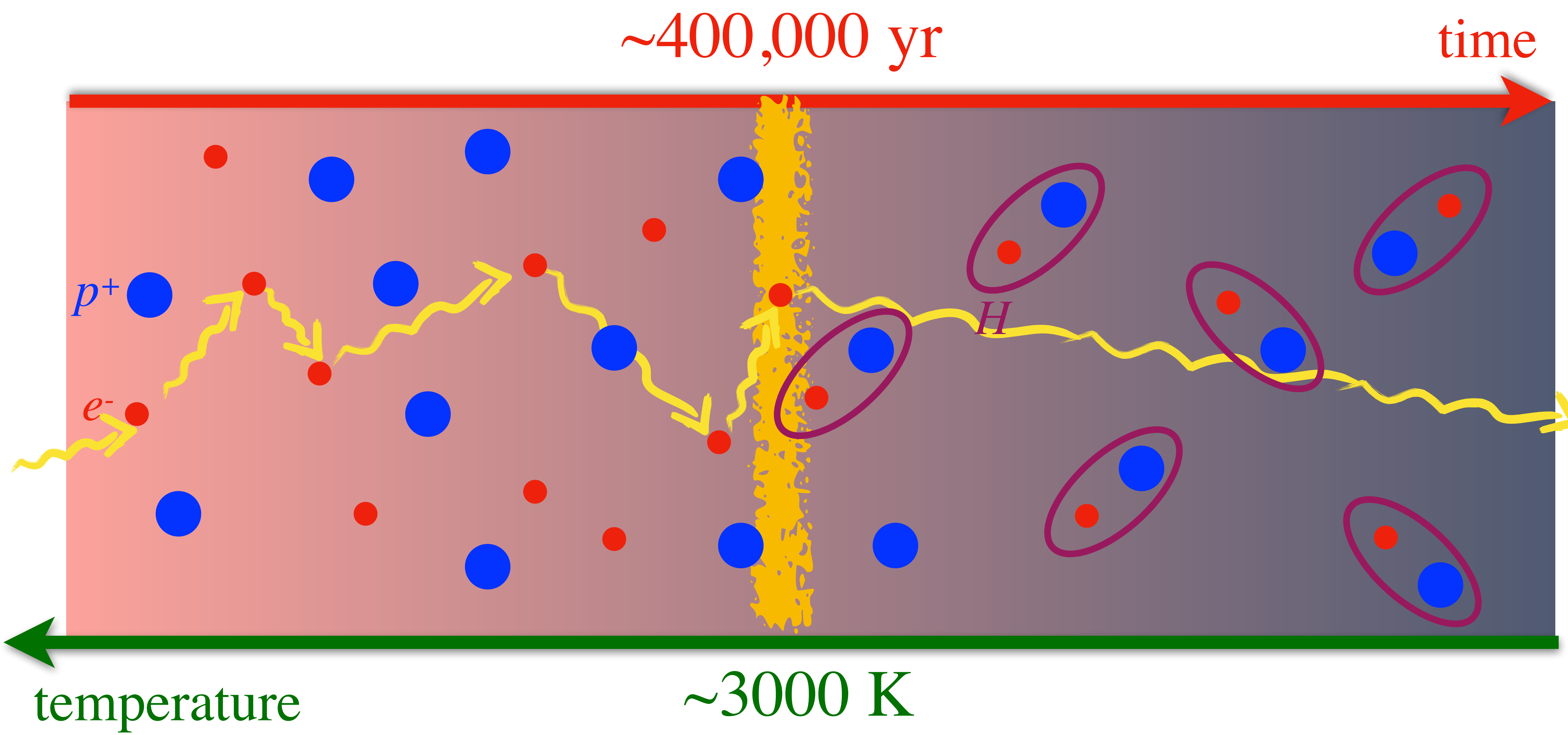
III. CMB anisotropy physics

In first ~400,000 yrs Thomson scattering rate >> Hubble rate.

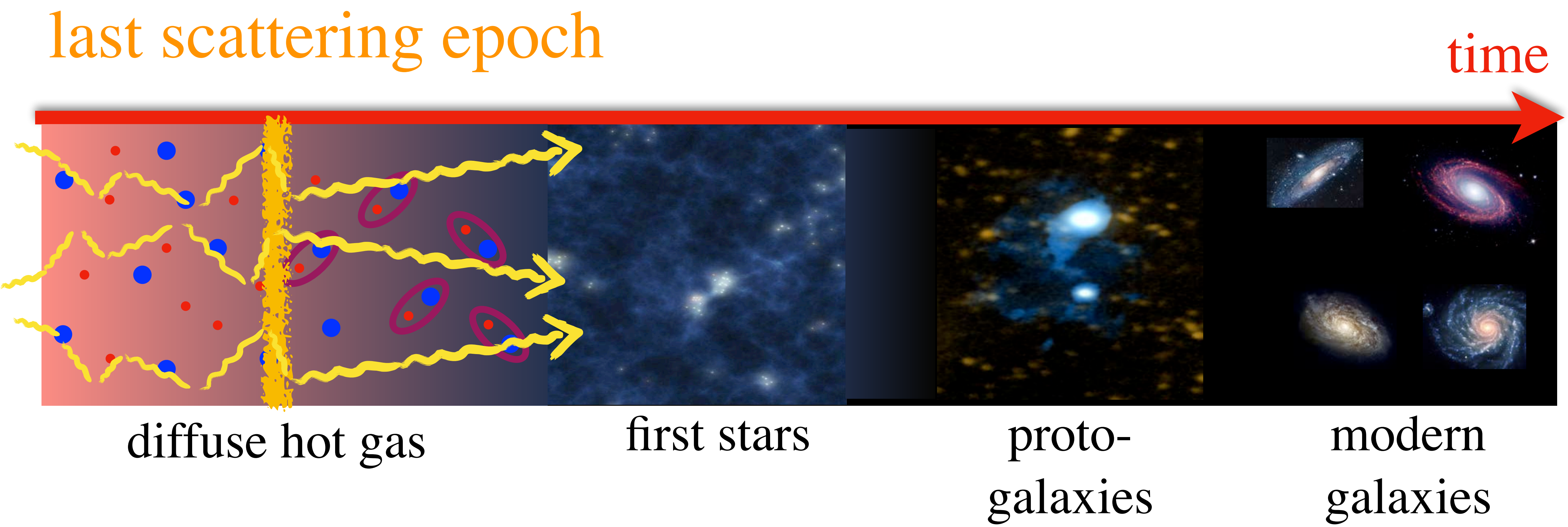
Photons and baryons are tightly coupled and undergo acoustic oscillations.

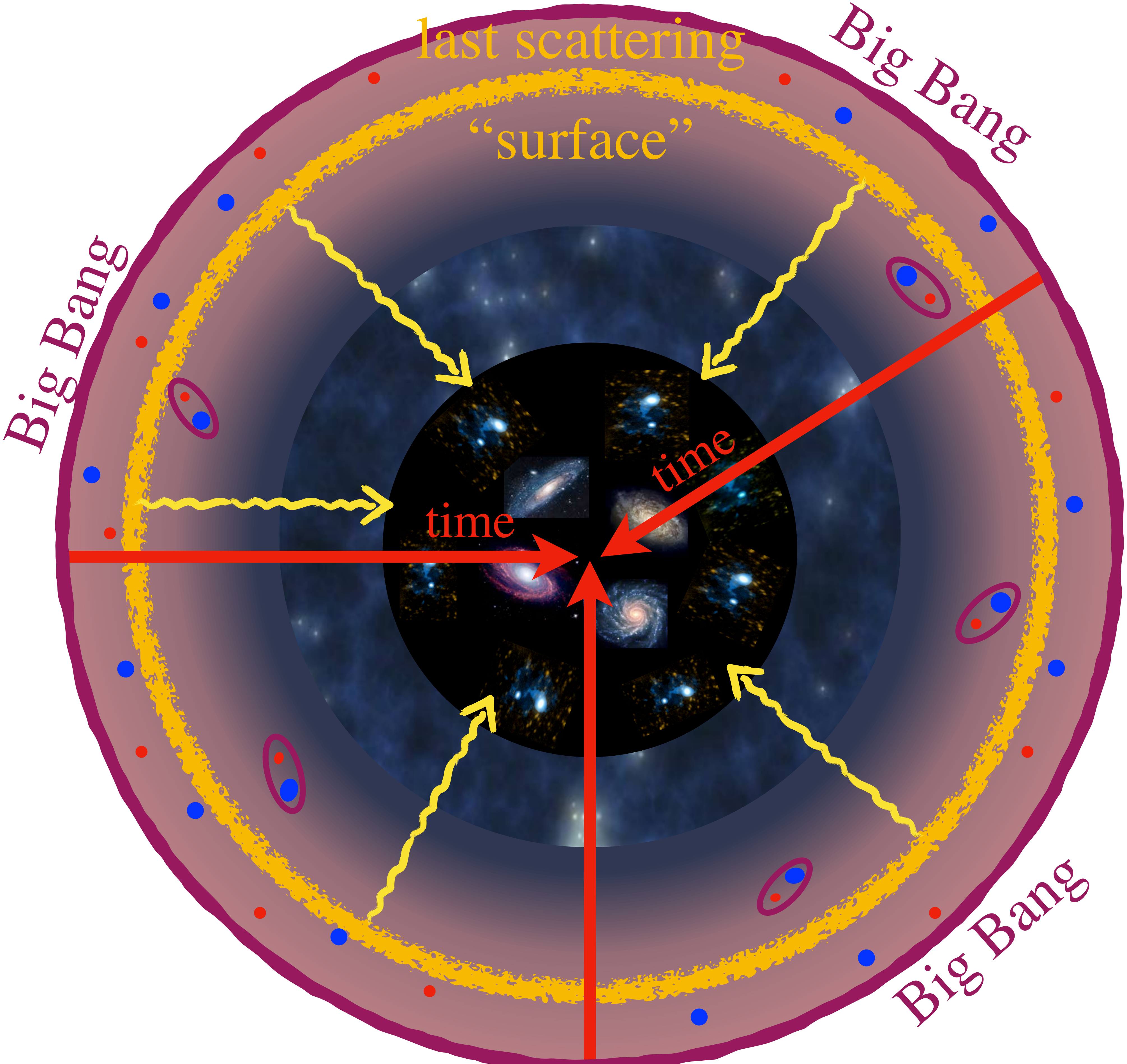


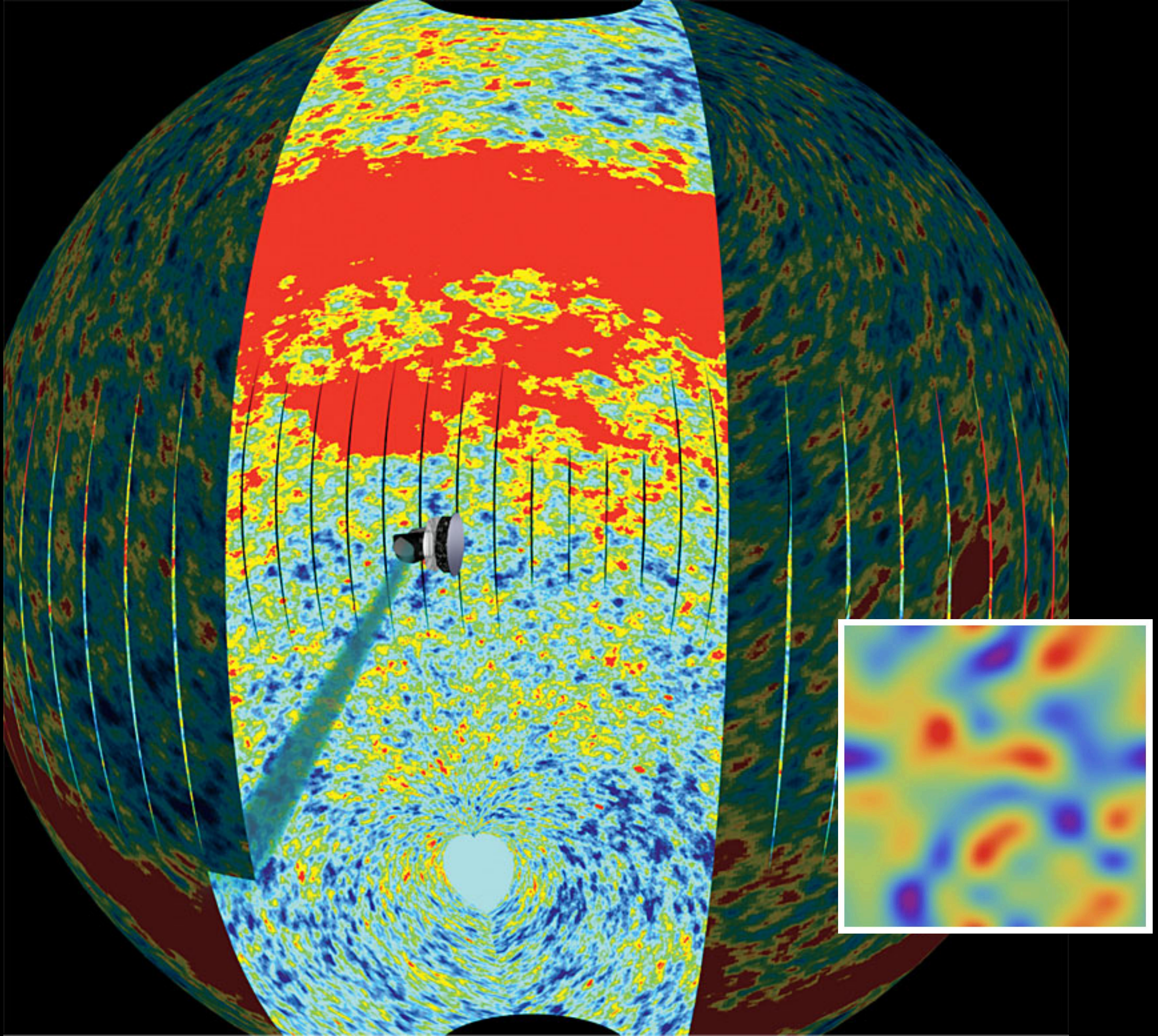


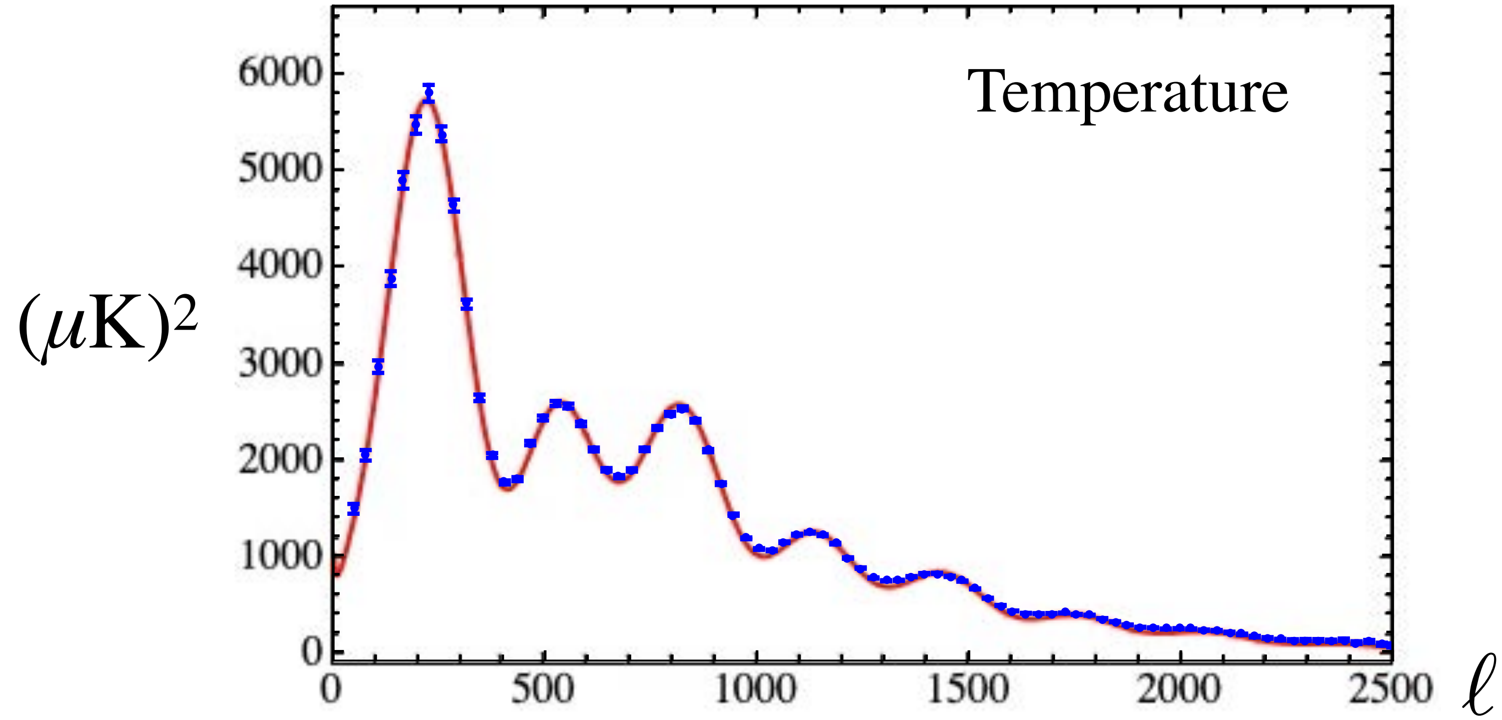


last scattering epoch

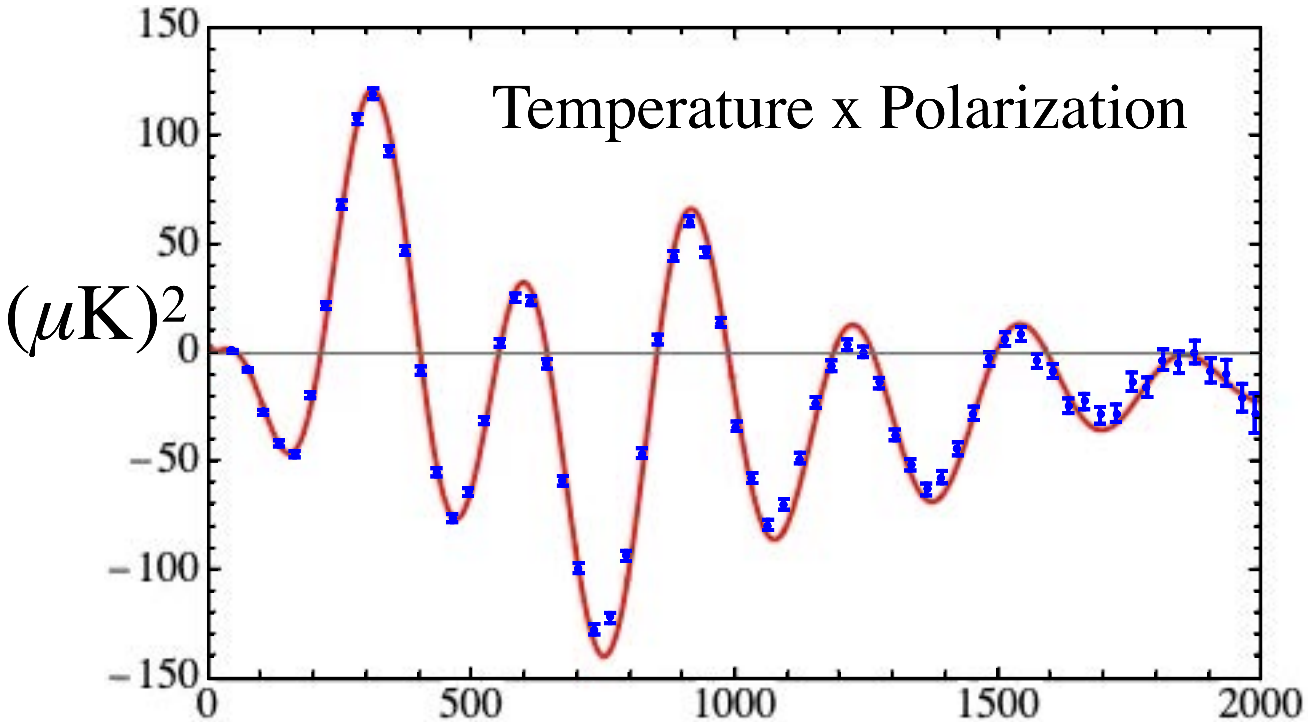

last scattering epoch
time
diffuse hot gas
first stars
proto-
galaxies
modern
galaxies

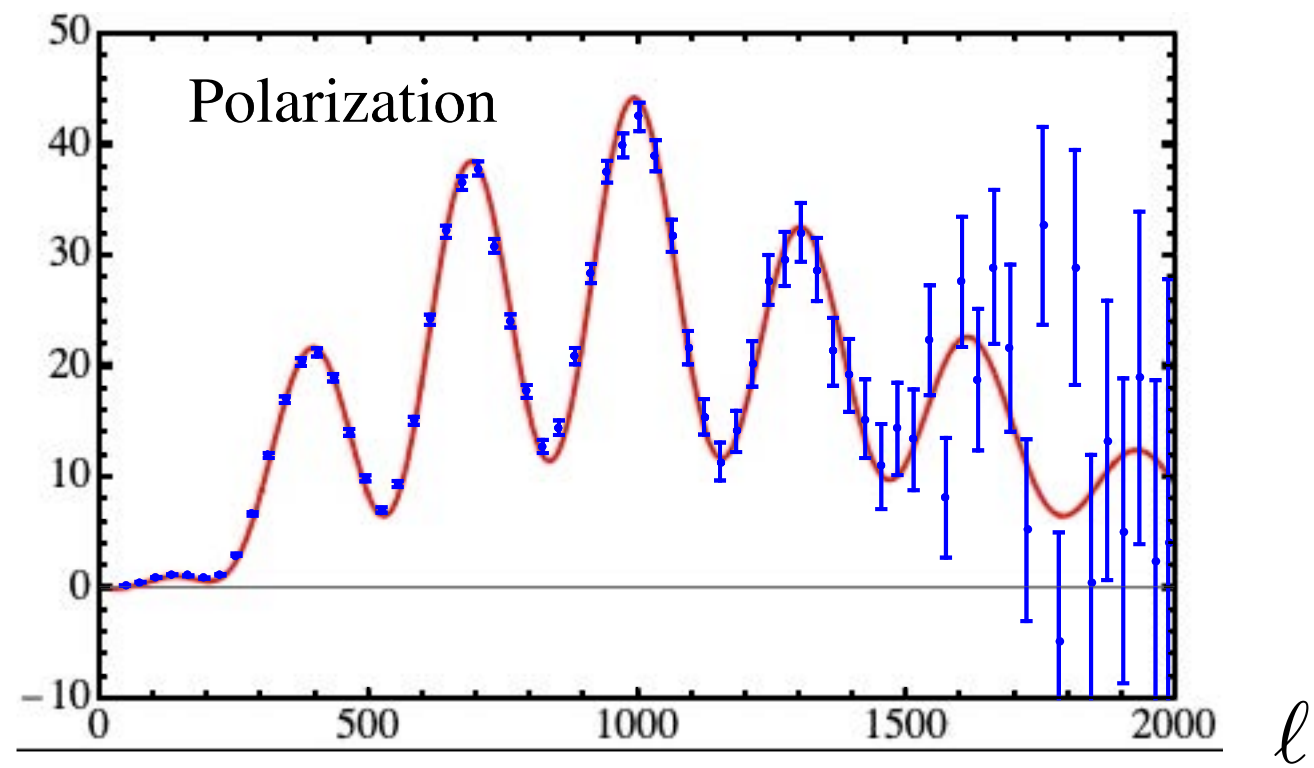

last scattering
"surface"
Big Bang
Big Bang
Big Bang
time
time



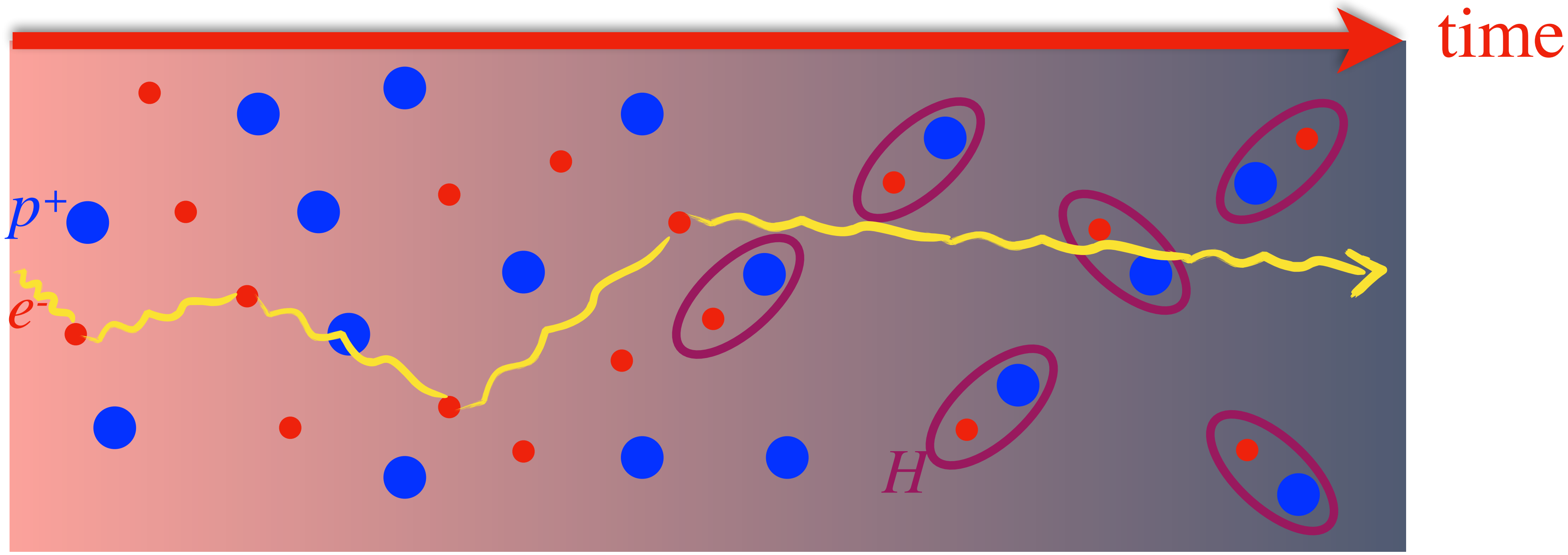


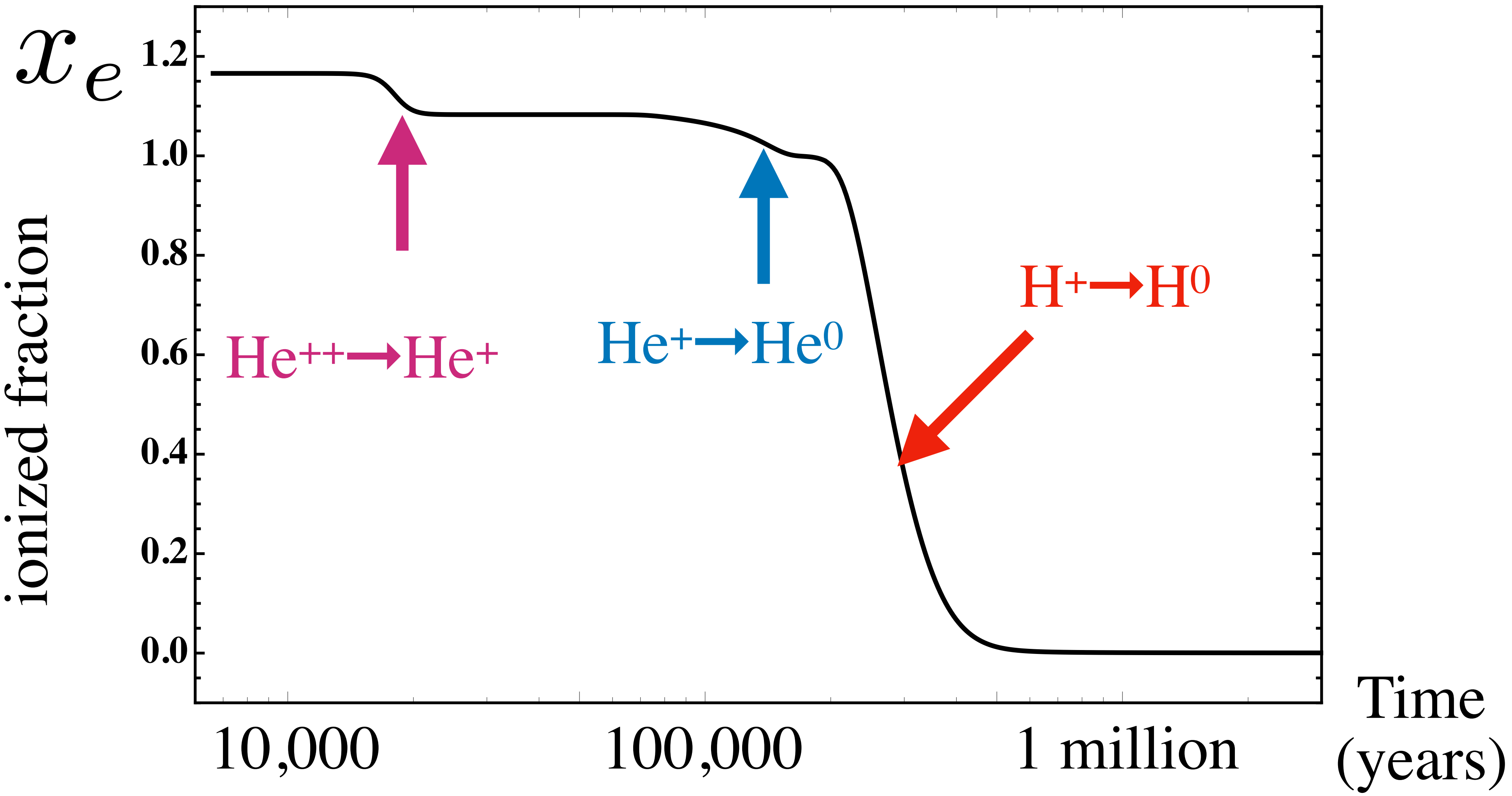
$$\frac{\text{dark matter}}{\text{baryons}} \approx 5.36 \pm 0.05 \text{ (Planck 2018)}$$



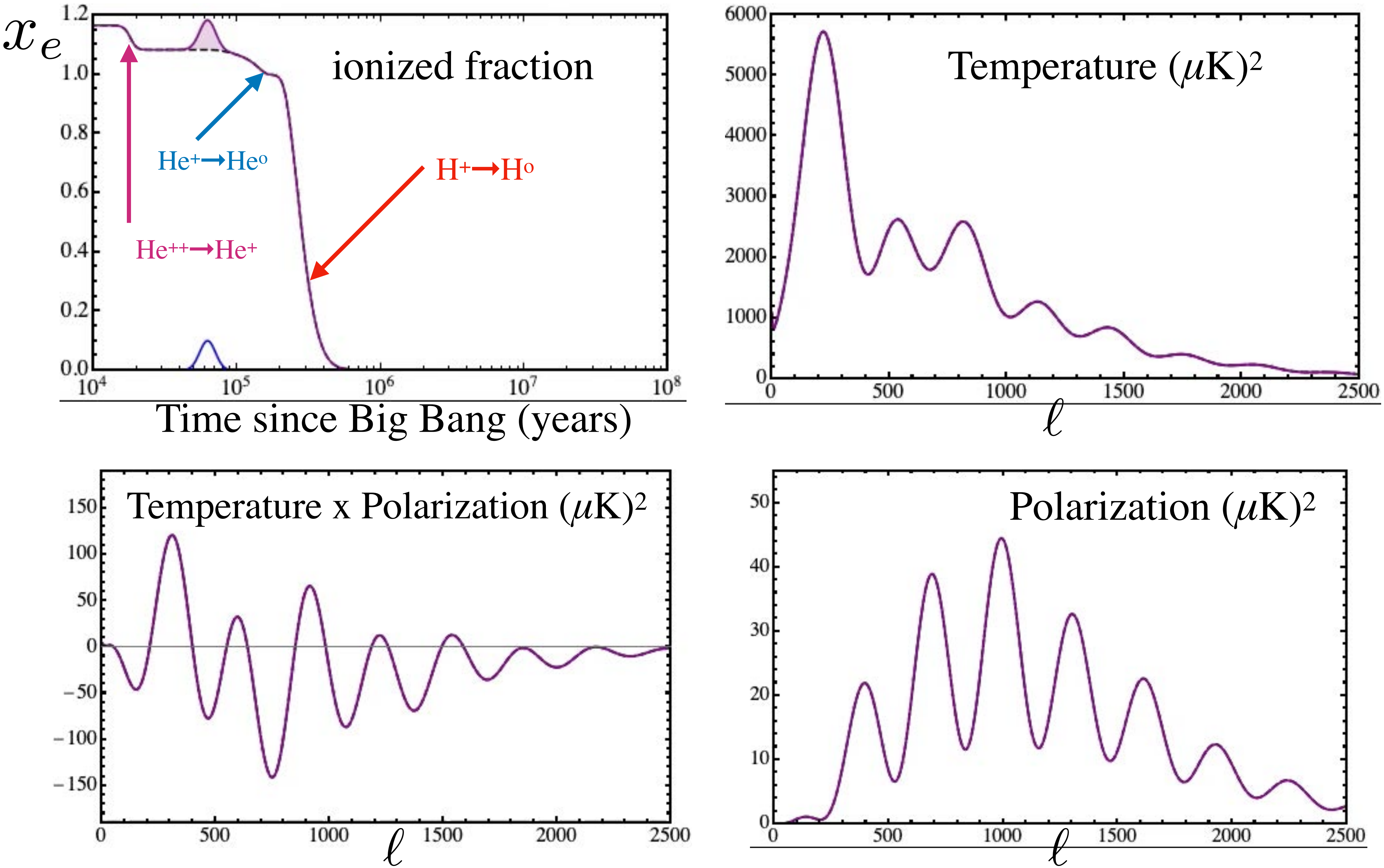


CMB anisotropies are ***very* sensitive** to the **ionization history**





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



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

State-of-the-art recombination codes:

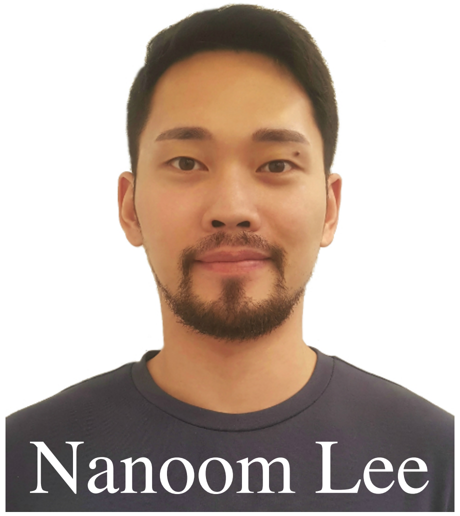
HYREC YAH & Hirata 2010, 2011

COSMOREC Chluba & Thomas 2011

compute x_e[standard] with accuracy ~few parts in 1e4, in ~1 second / cosmology

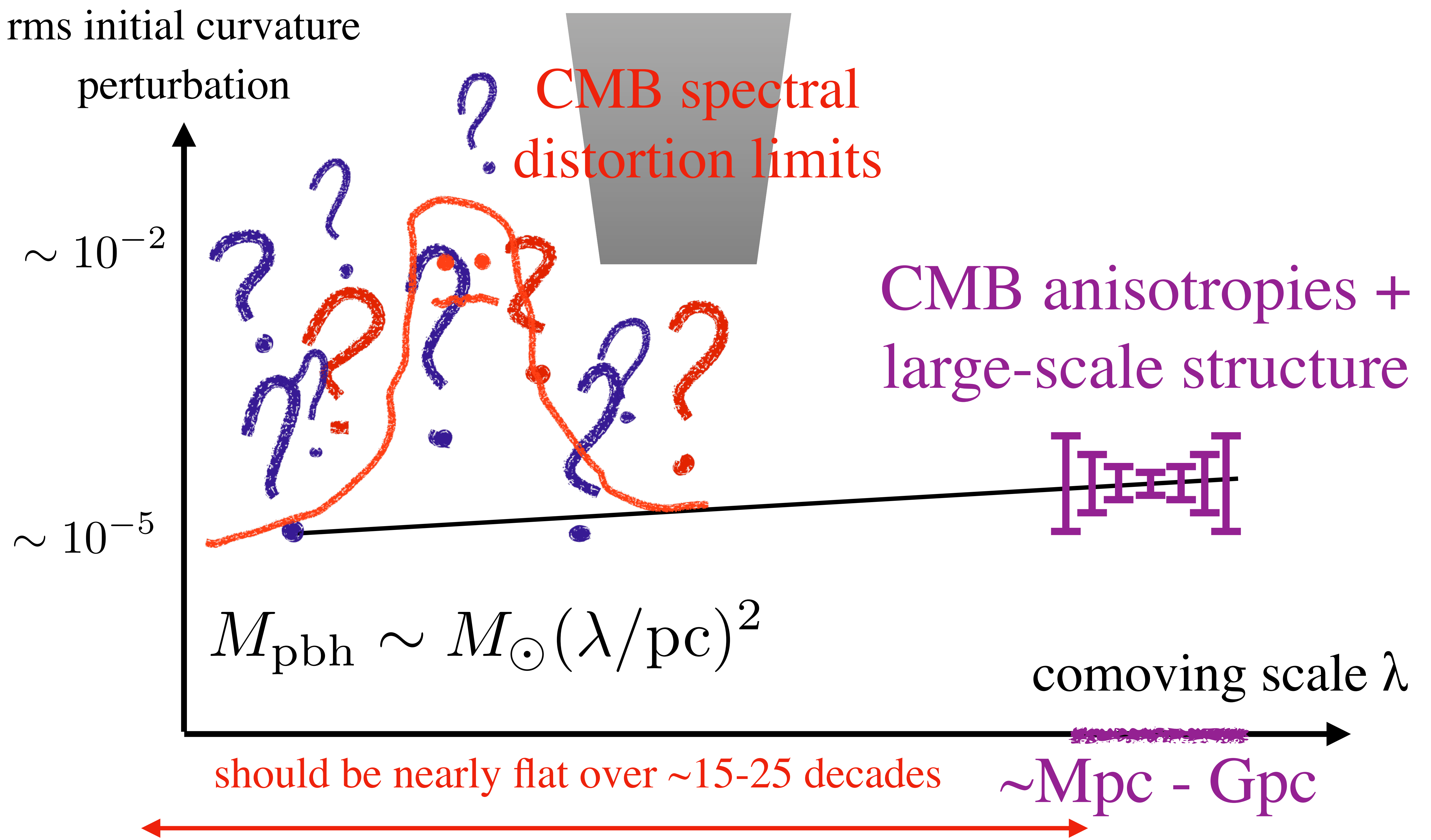
HYREC-2 Lee & YAH 2020

accuracy ~few parts in 1e4, in ~1 millisecond / cosmology

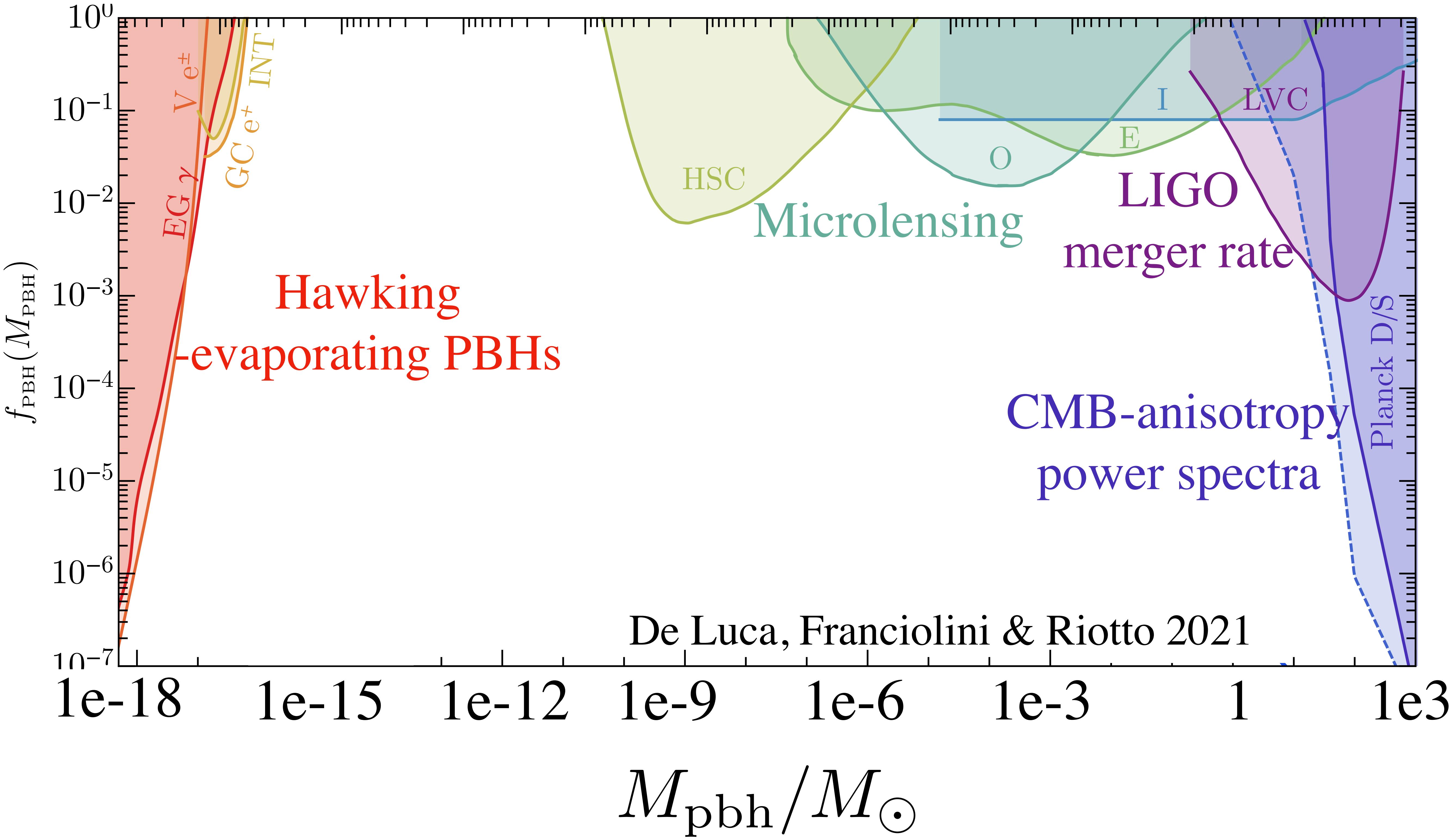


IV. Probing accreting PBHs with CMB anisotropies

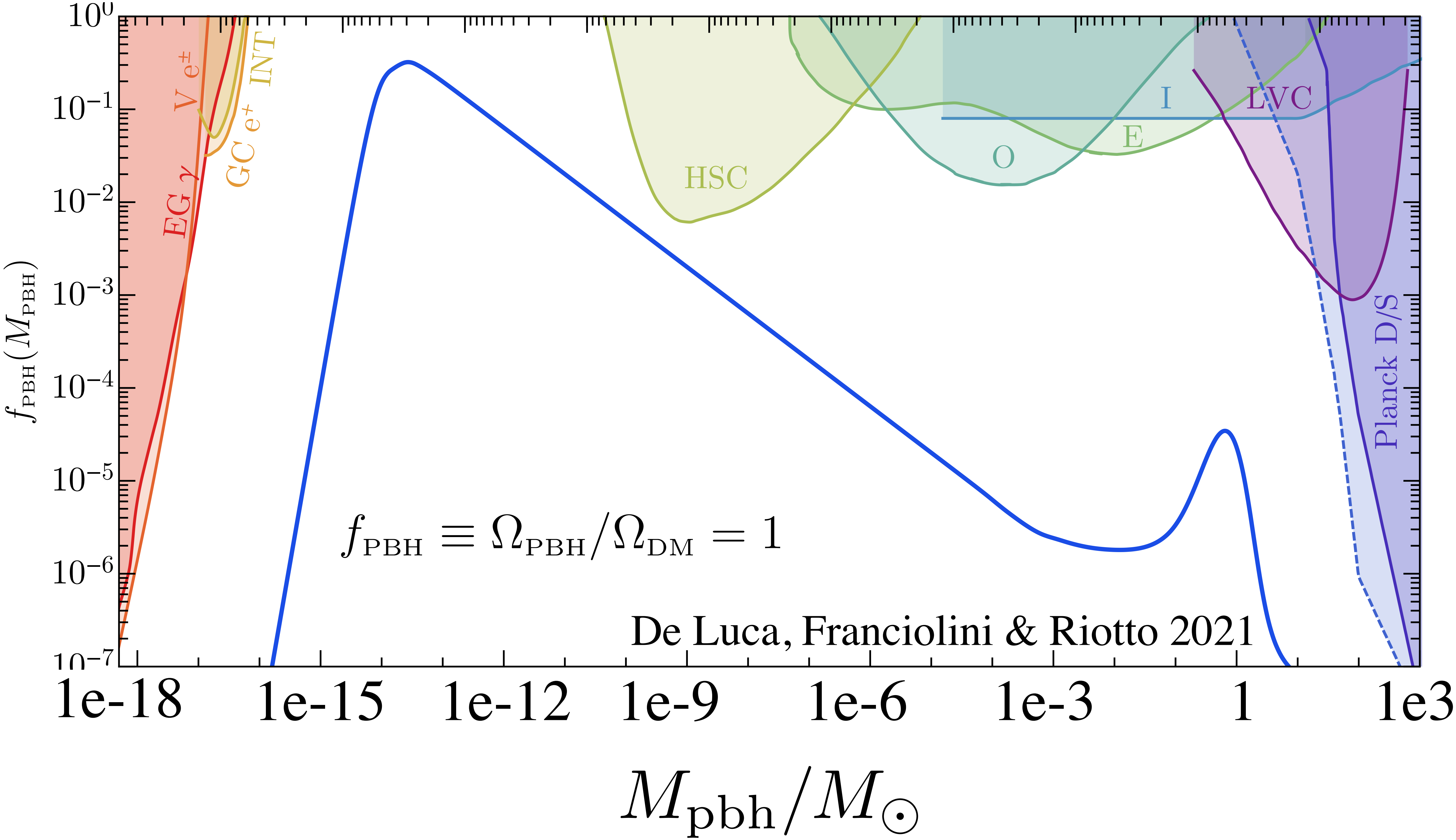
PBHs are not only a DM candidate, but also a window into small-scale initial conditions



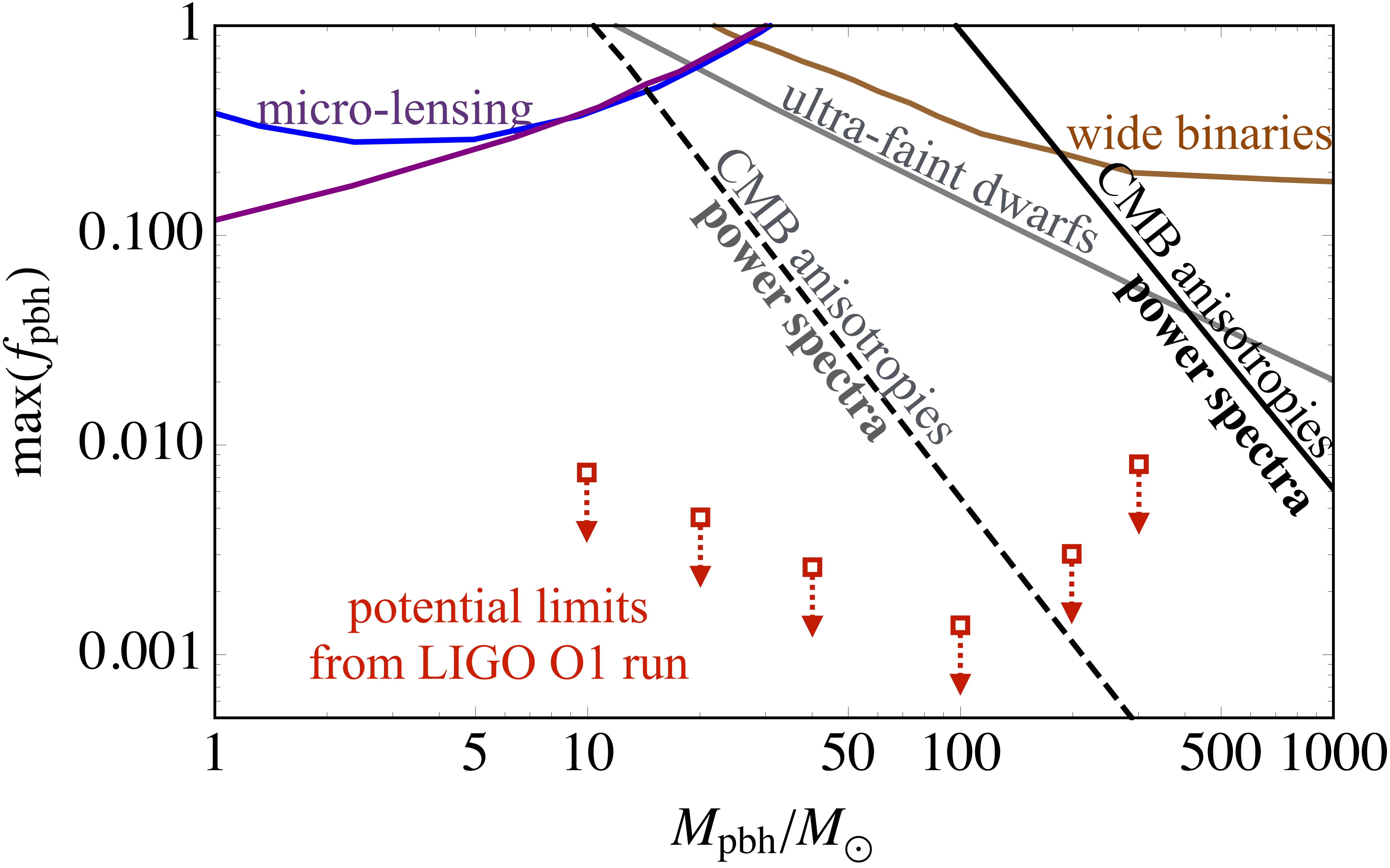
Status of limits on $f_{\rm PBH}$ (fraction of dark matter in PBHs) for Dirac-delta PBH mass function



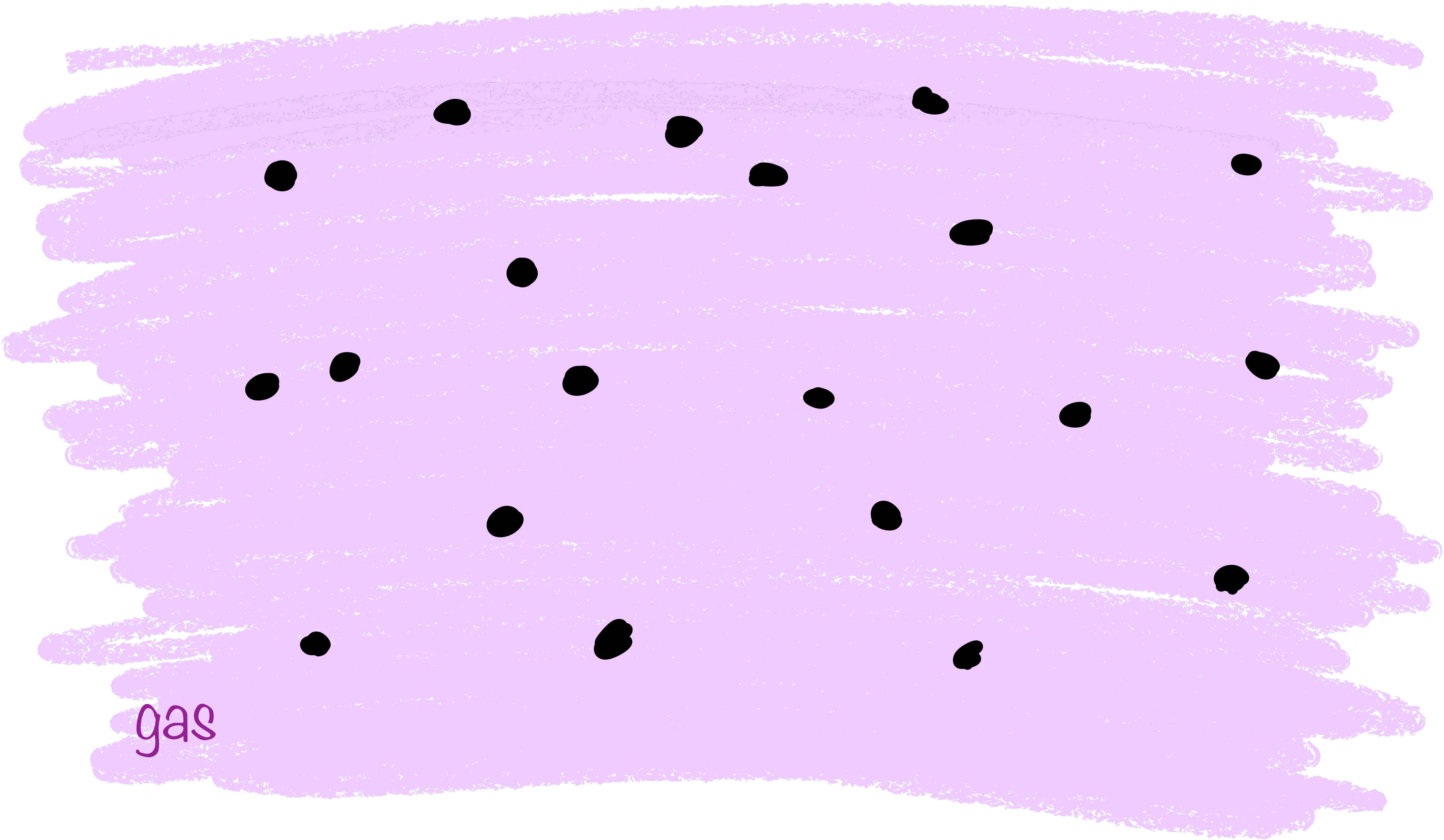
Limits to PBH abundance much below 100% of DM could constrain the tail of an extended mass function



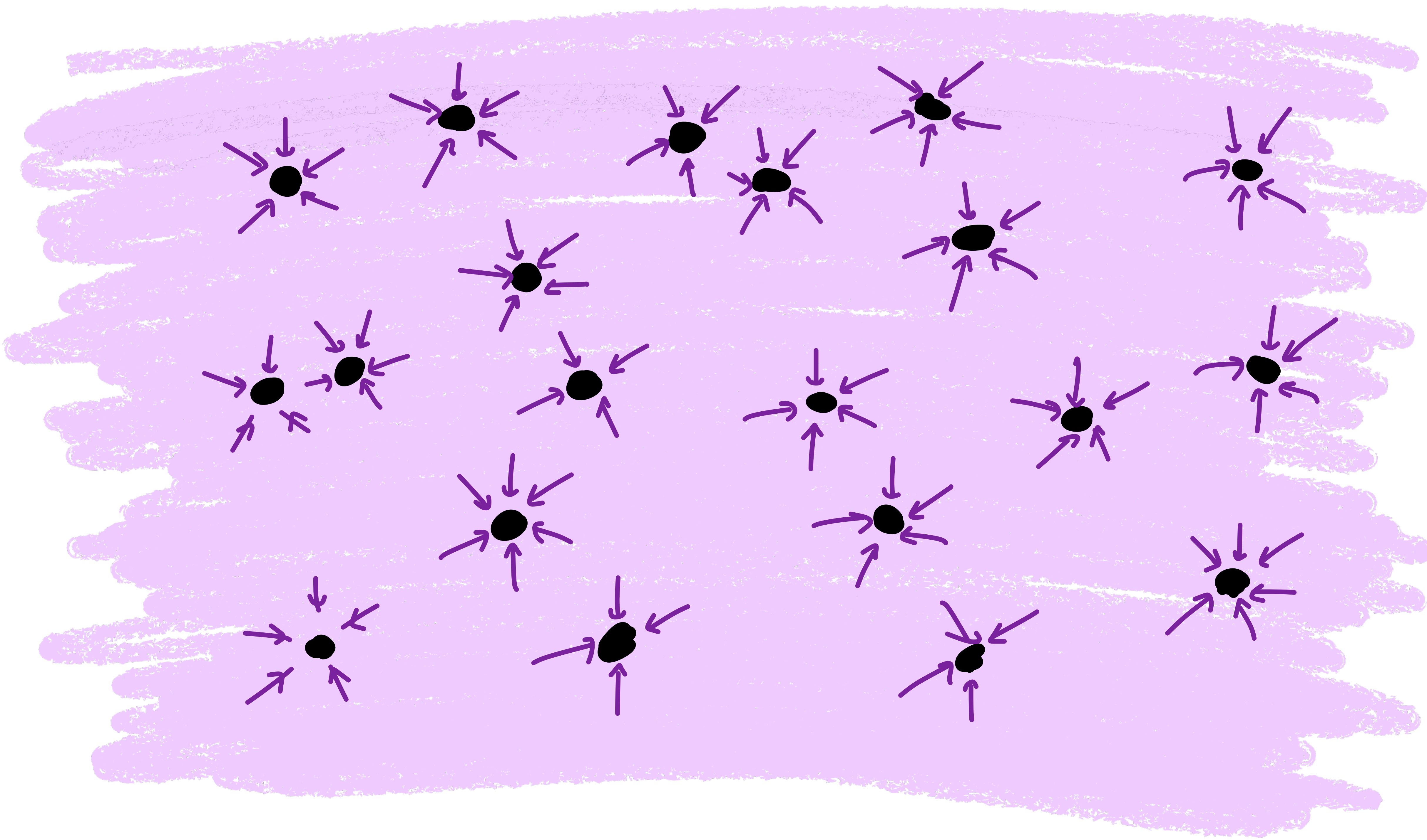
Zooming in on the 1-1000 solar-mass range



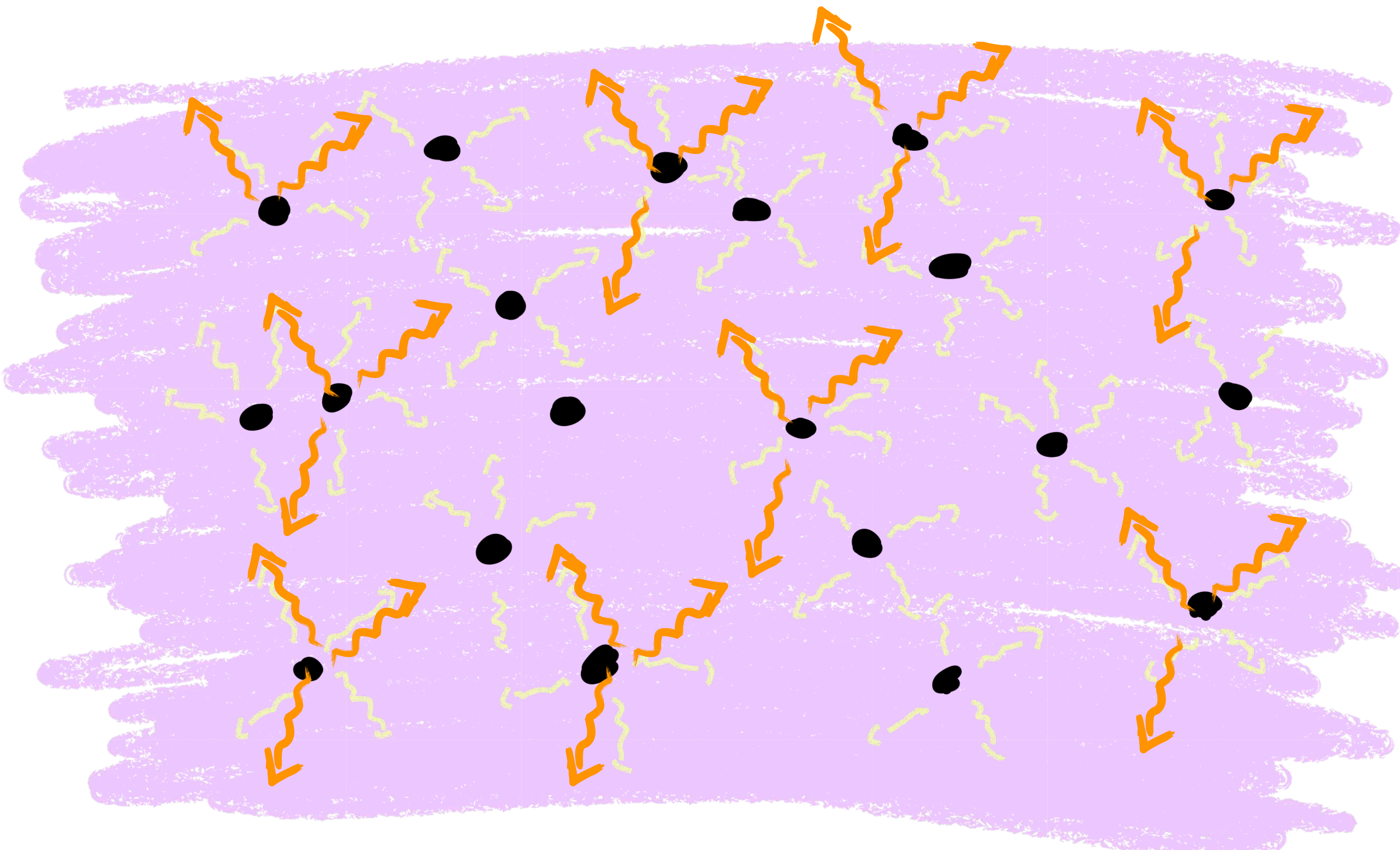
Suppose part of the dark matter is made of **black holes**



they **accrete gas** in the early Universe



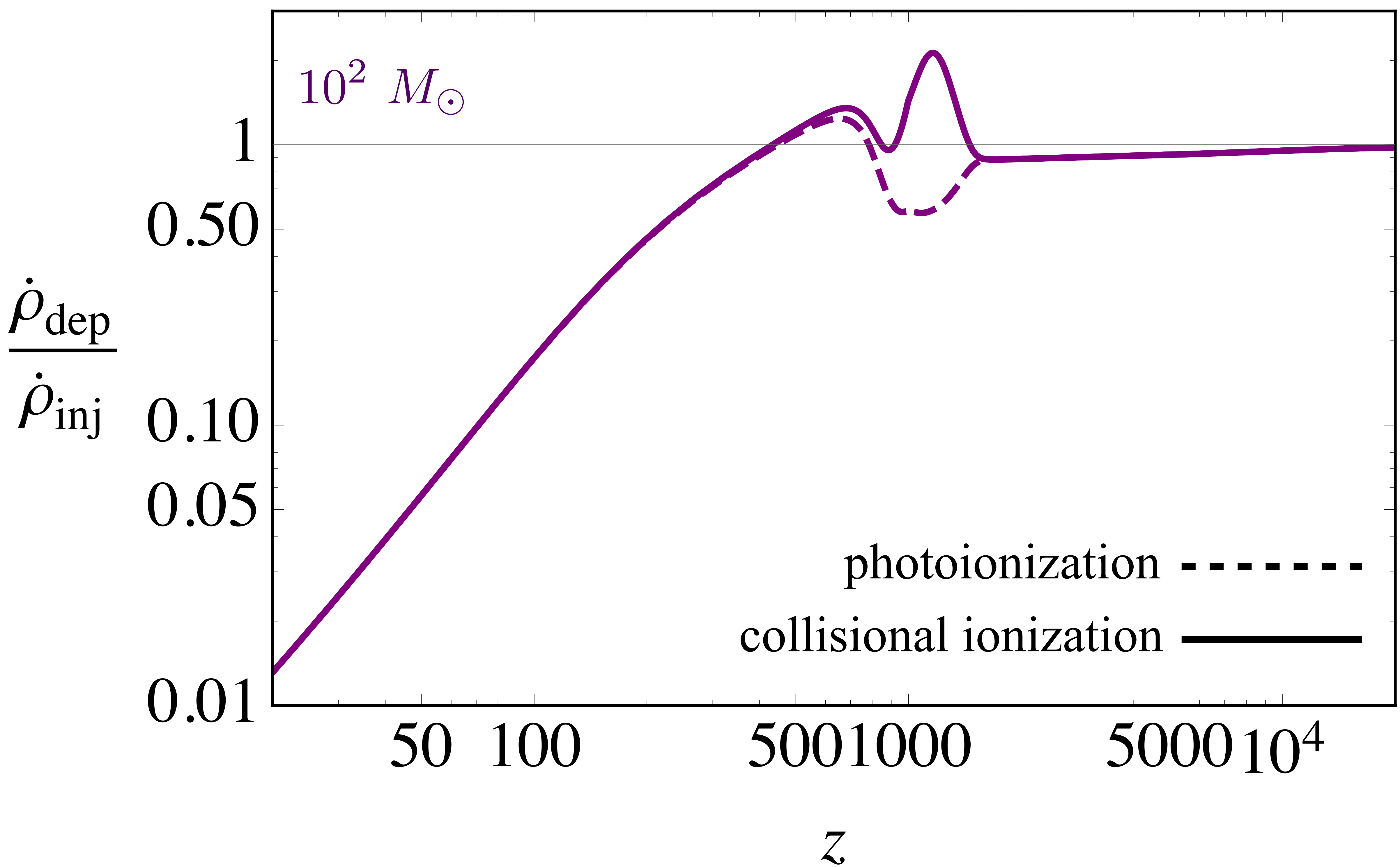
$\dot{M}$: Bondi-Hoyle-Lyttleton + Compton drag and cooling part of the accreted energy is **re-radiated**



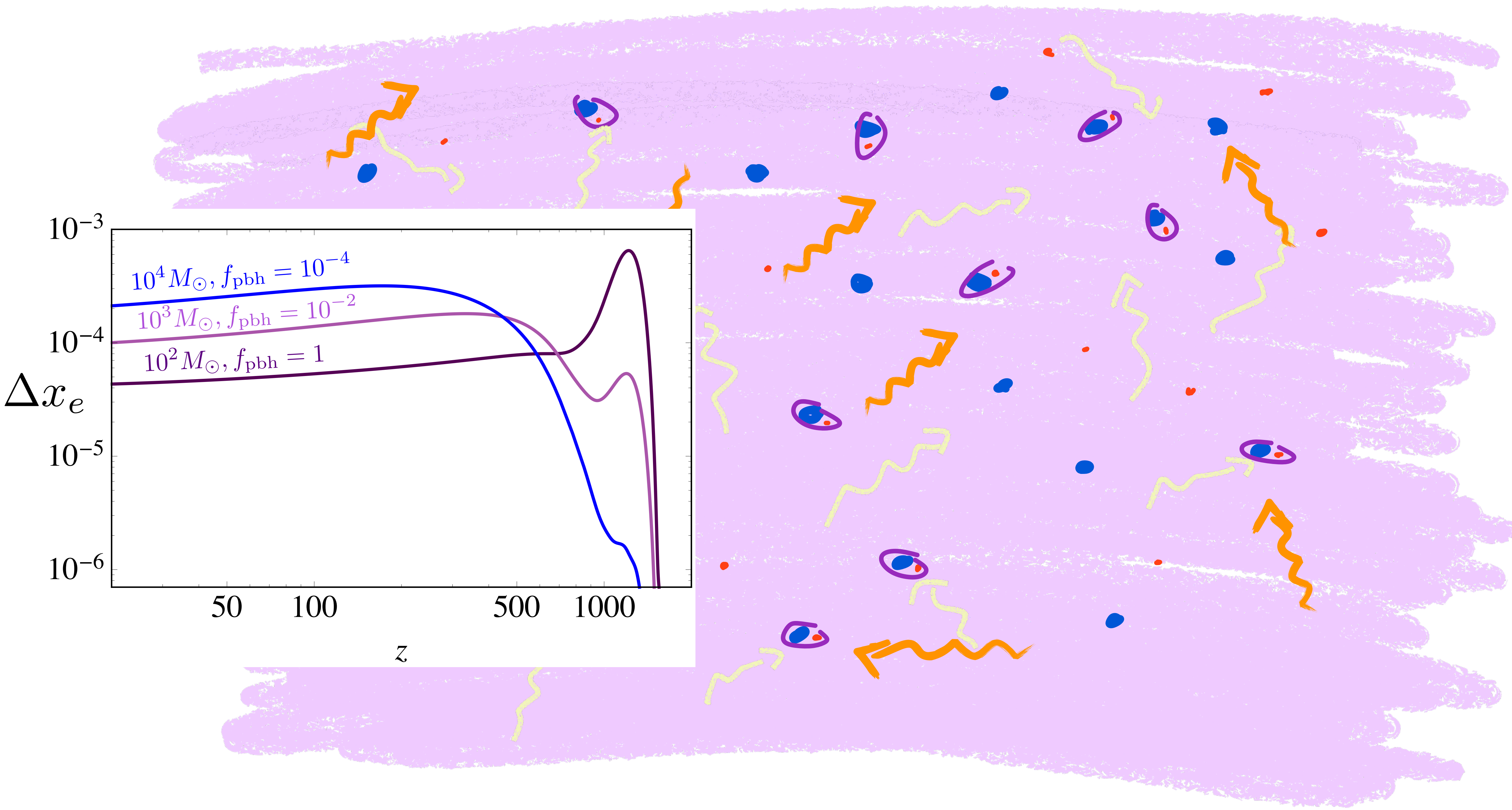
$$L = \epsilon \dot{M} c^2$$

Free-free emission
from ionized accreted gas

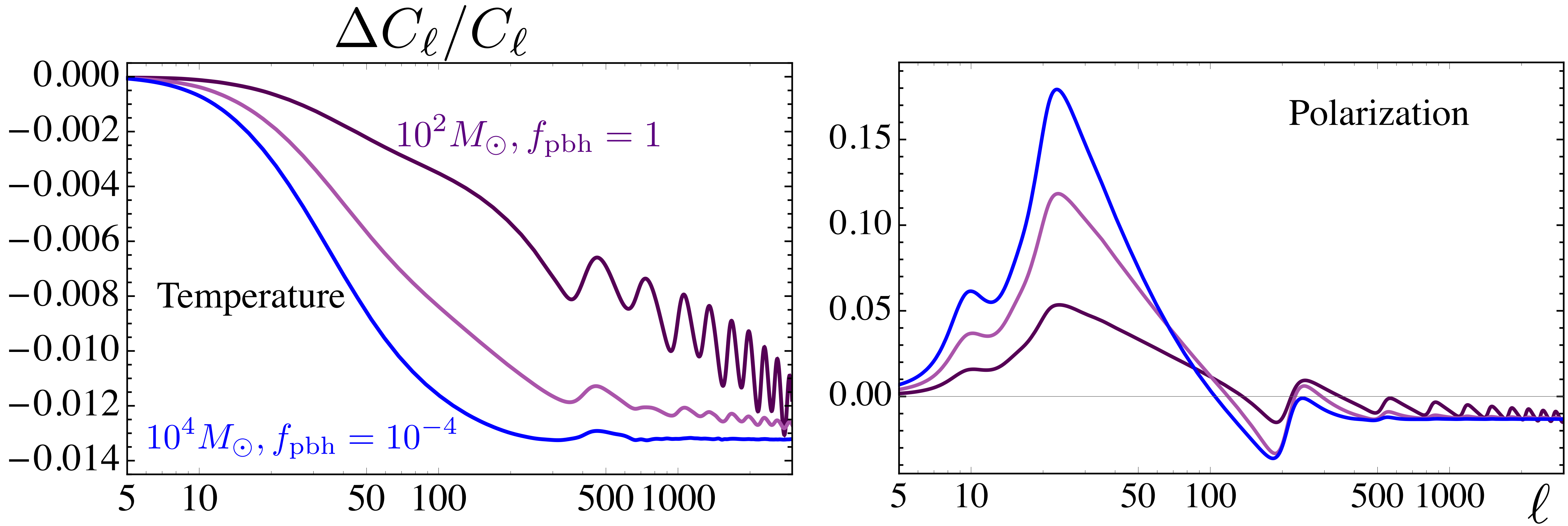
Part of the injected energy is deposited (with some delay) in the form of extra heating and ionizations

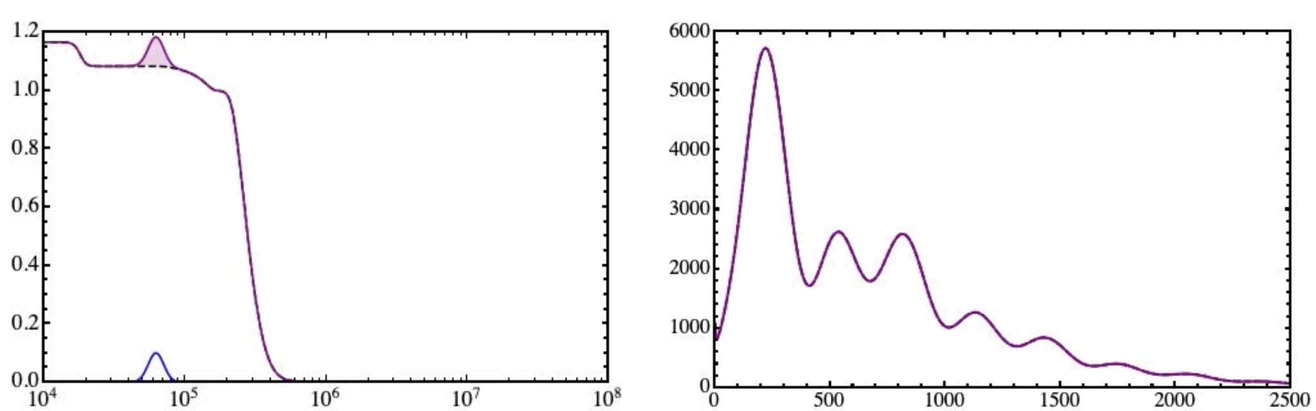


deposited energy ionizes hydrogen beyond normal

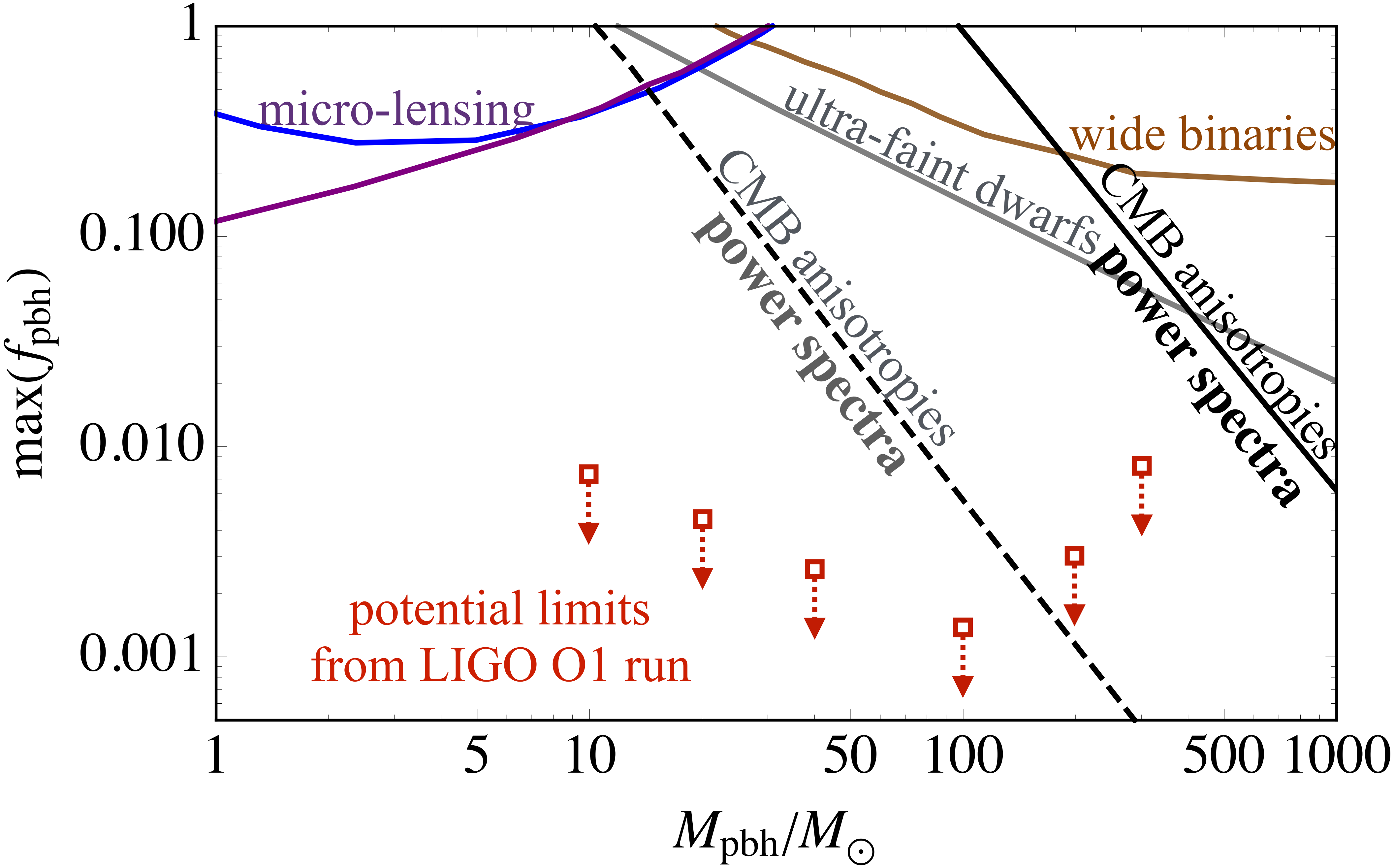


and impacts CMB temperature and polarization power spectra





Main result: CMB power spectra imply that PBHs cannot be all the dark matter for black hole mass $\gtrsim 100\ M_{sun}$



YAH & Kamionkowski 2017.

See also: Miller 2000, Ricotti et al. 2008, Poulin et al. 2017

Work in progress: non-Gaussian signatures of accreting PBHs

- PBH accretion rate and luminosity depends on the local gas (relative) velocity

$$\dot{M}_{\rm Bondi} \sim \rho_b \frac{(GM)^2}{(c_s^2 + v_{\rm rel}^2)^3} \qquad L_{\rm free-free} \propto \dot{M}^2$$

- Baryons and dark matter have supersonic relative velocities at z~1000, fluctuating on ~10^2 Mpc (Tseliakhovich & Hirata 2010)

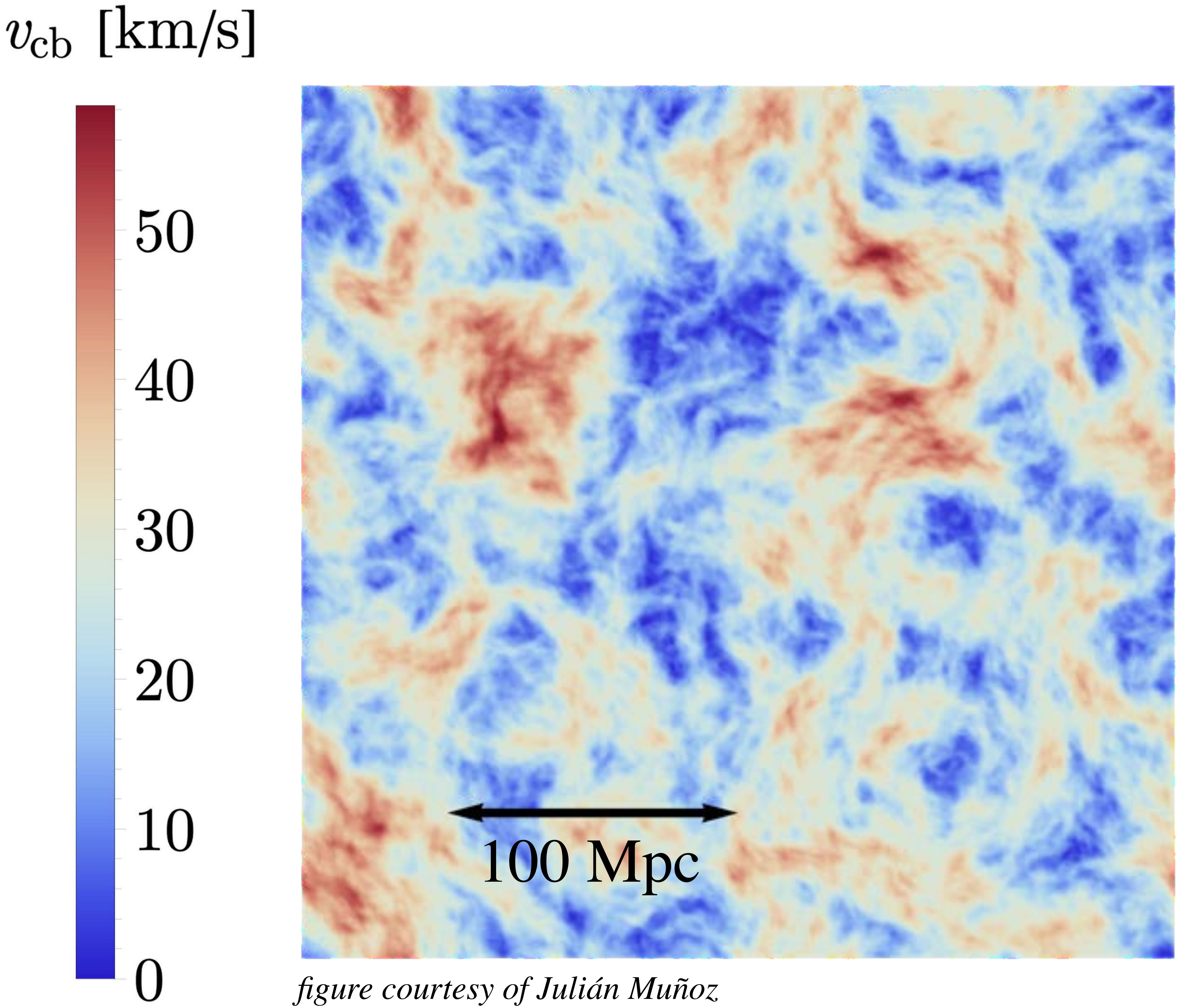


figure courtesy of Julián Muñoz

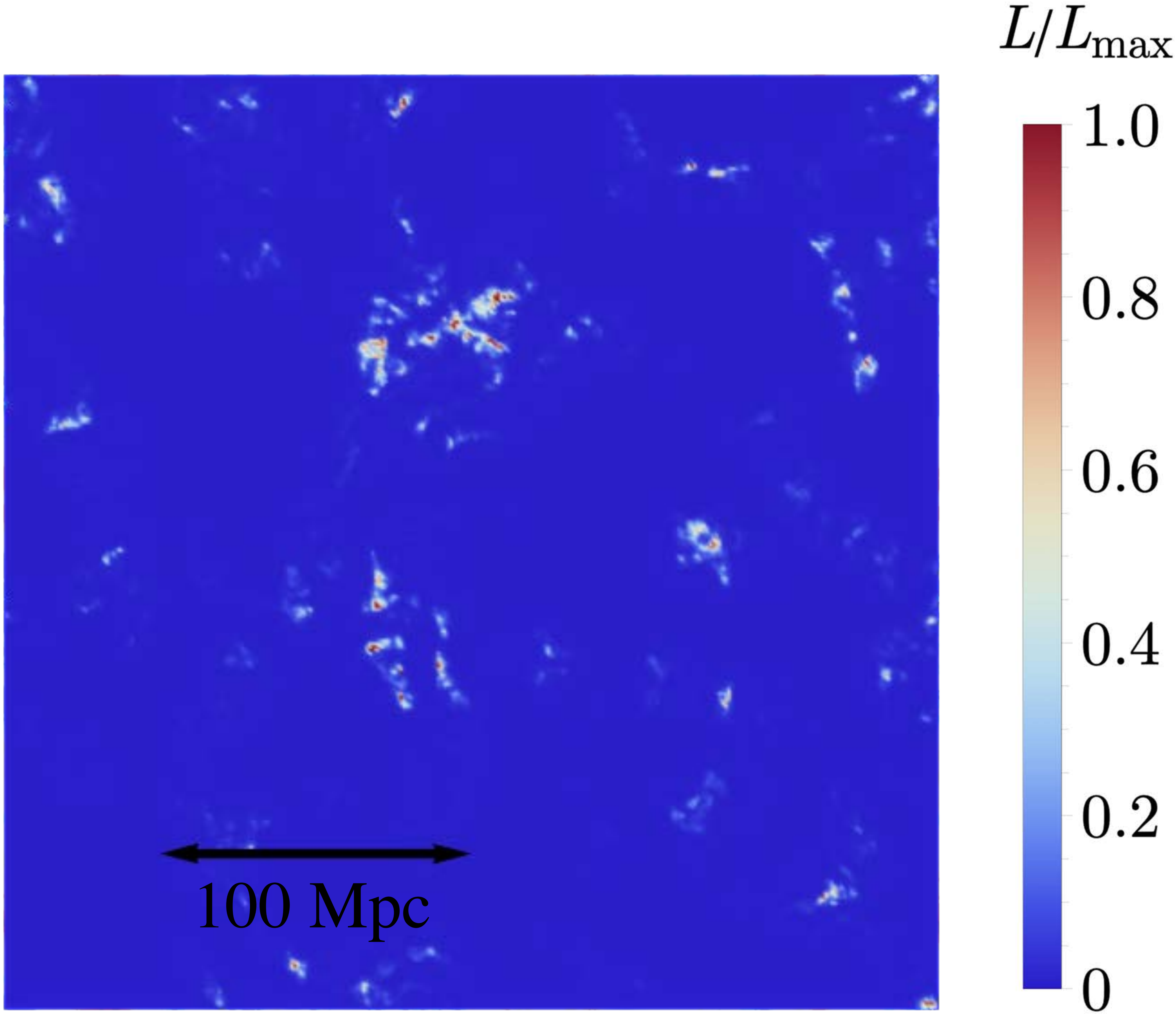


figure courtesy of Julián Muñoz

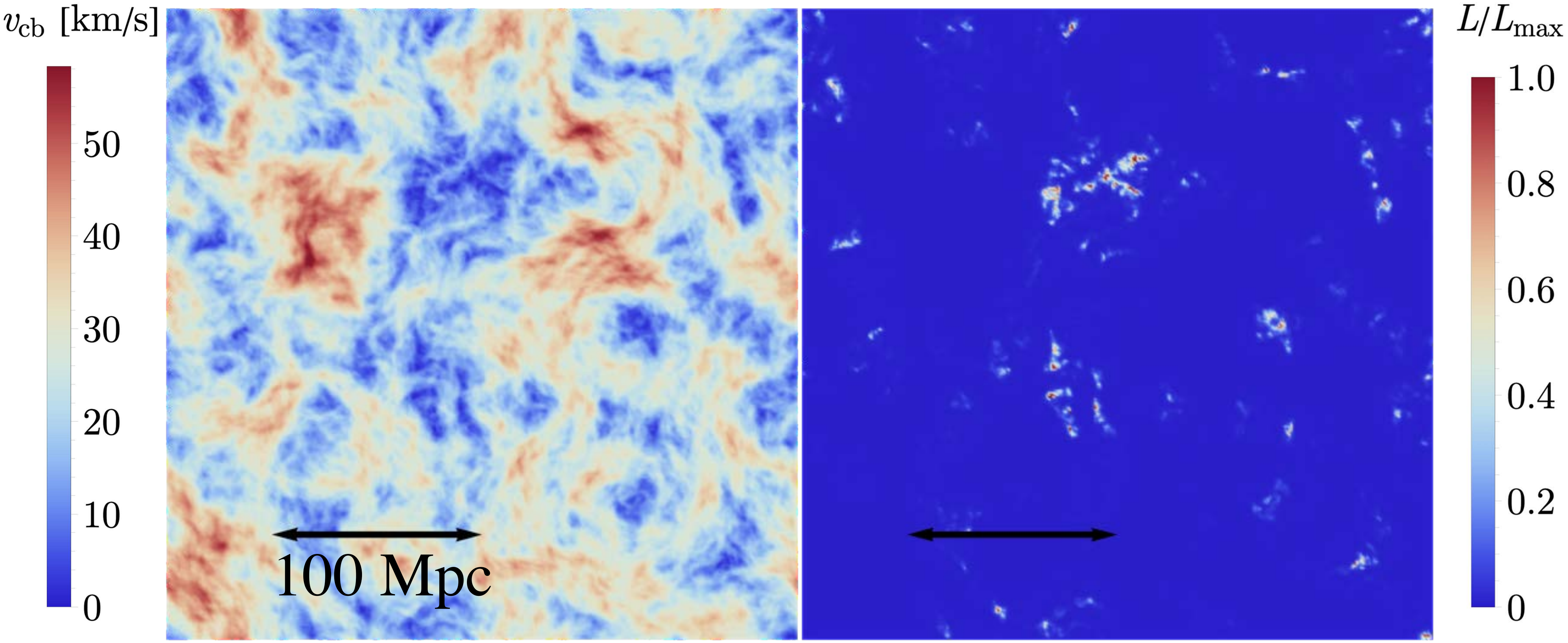


figure courtesy of Julián Muñoz

=> Energy injection from accreting PBHs is
$\mathcal{O}(1)$ inhomogeneous

=> Perturbations to standard recombination could be ***up to $\mathcal{O}(1)$*** inhomogeneous

$$x_e(t,\vec{x}) = x_e^{\rm std}(t) + \Delta x_e(t,\vec{x})$$

$$\Delta x_e(t,\vec{x}) = \langle \Delta x_e \rangle(t) + \delta x_e(t,\vec{x})$$

$$\delta x_e(t,\vec{x}) \lesssim \langle \Delta x_e \rangle(t)$$

For $f_{\rm PBH}$ saturating CMB power spectra limits:

$$\frac{\langle \Delta x_e \rangle(t)}{x_e^{\rm std}(t)} \sim 1\ \%$$

Corresponds to (up to) $\mathcal{O}(1\%)$ spatial fluctuations in the ionization fraction

Spatial fluctuations in the ionization fraction lead to CMB non-Gaussianities

Standard linear perturbation produces $\delta x_e / x_e \sim$ 1e-4

Generates a bispectrum with S/N ~ 0.5 for Planck

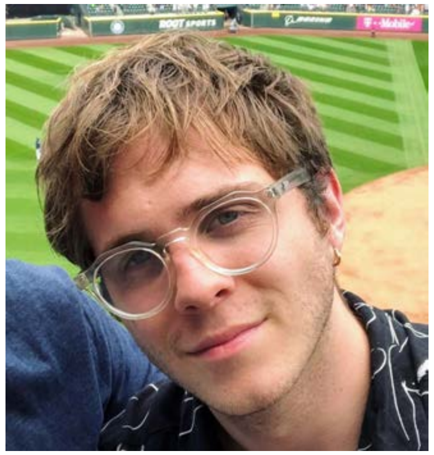
(Creminelli & Zaldarriaga 2004, Senatore et al. 2009, Pettinari et al. 2014)

For f_{PBH} saturating CMB power spectra limits

$\delta x_e / x_e \sim$ 1e-2

=> Planck should be sensitive to f_{PBH} ~ 1e2 times smaller than current CMB power spectra limits

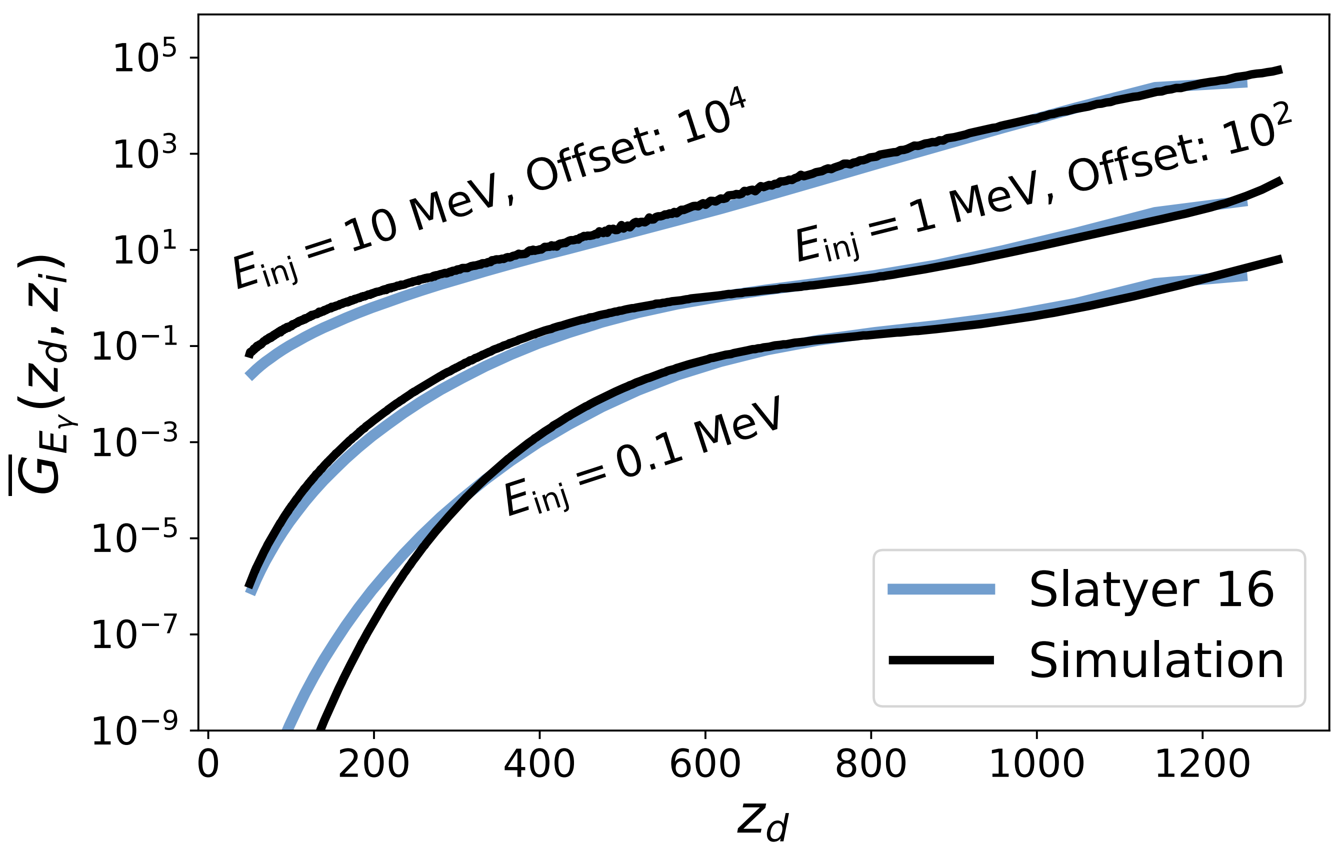
First question: do inhomogeneities in energy injection get washed out by finite propagation of injected photons?

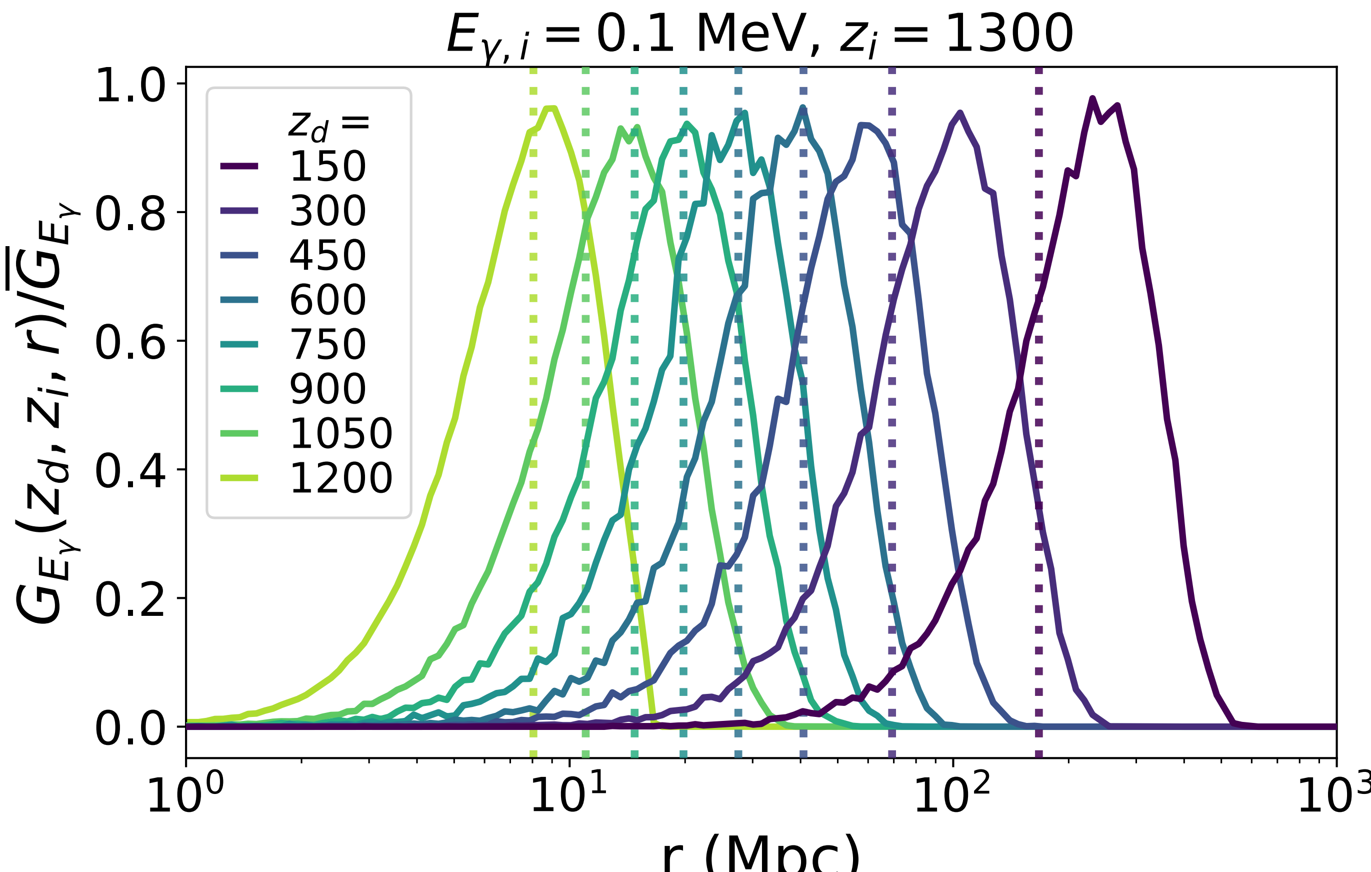


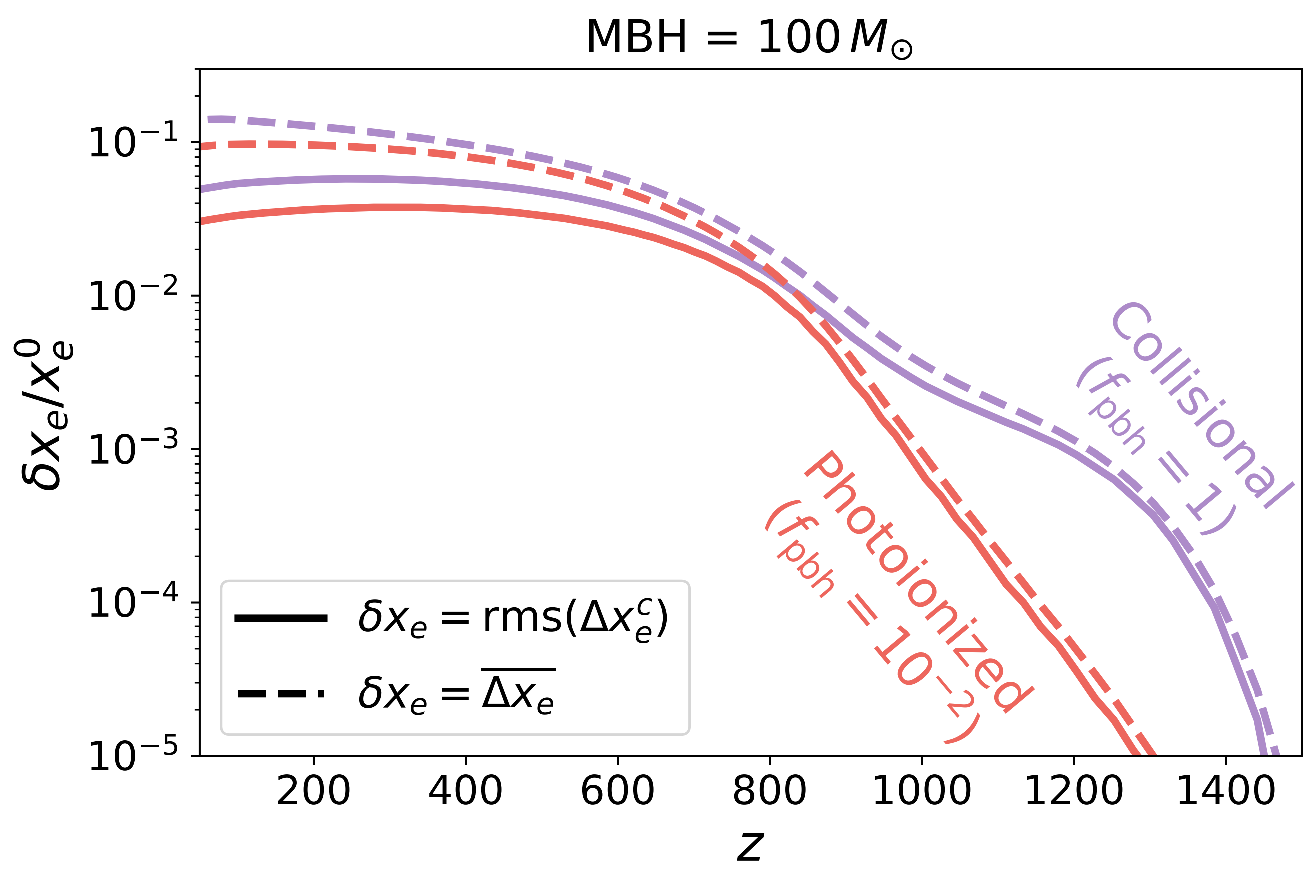
Jensen & YAH, arXiv:2106.10266

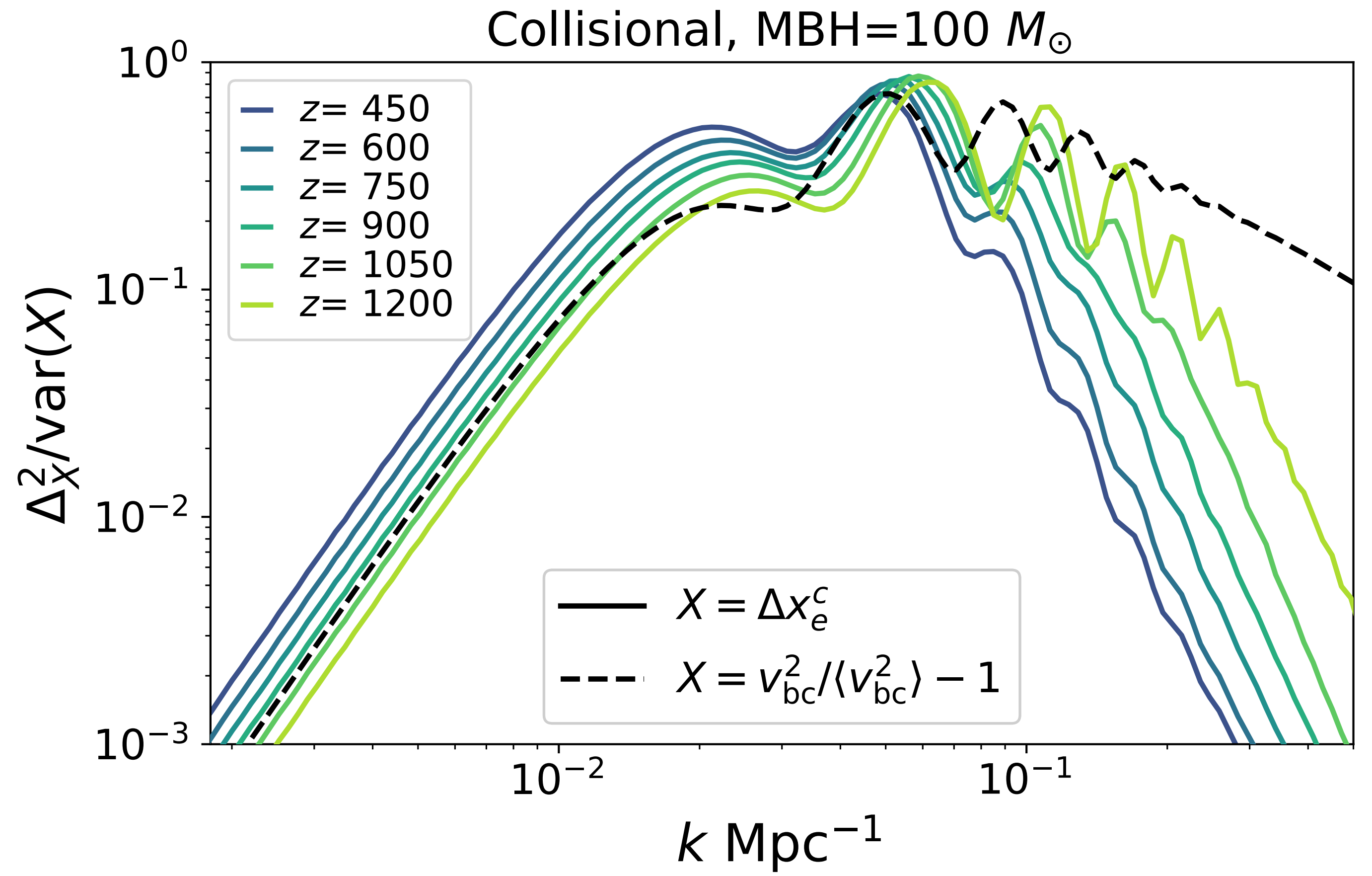
Trey Jensen

Time and scale-dependent Green's function for energy deposition, computed with radiation transport simulations + new analytic results







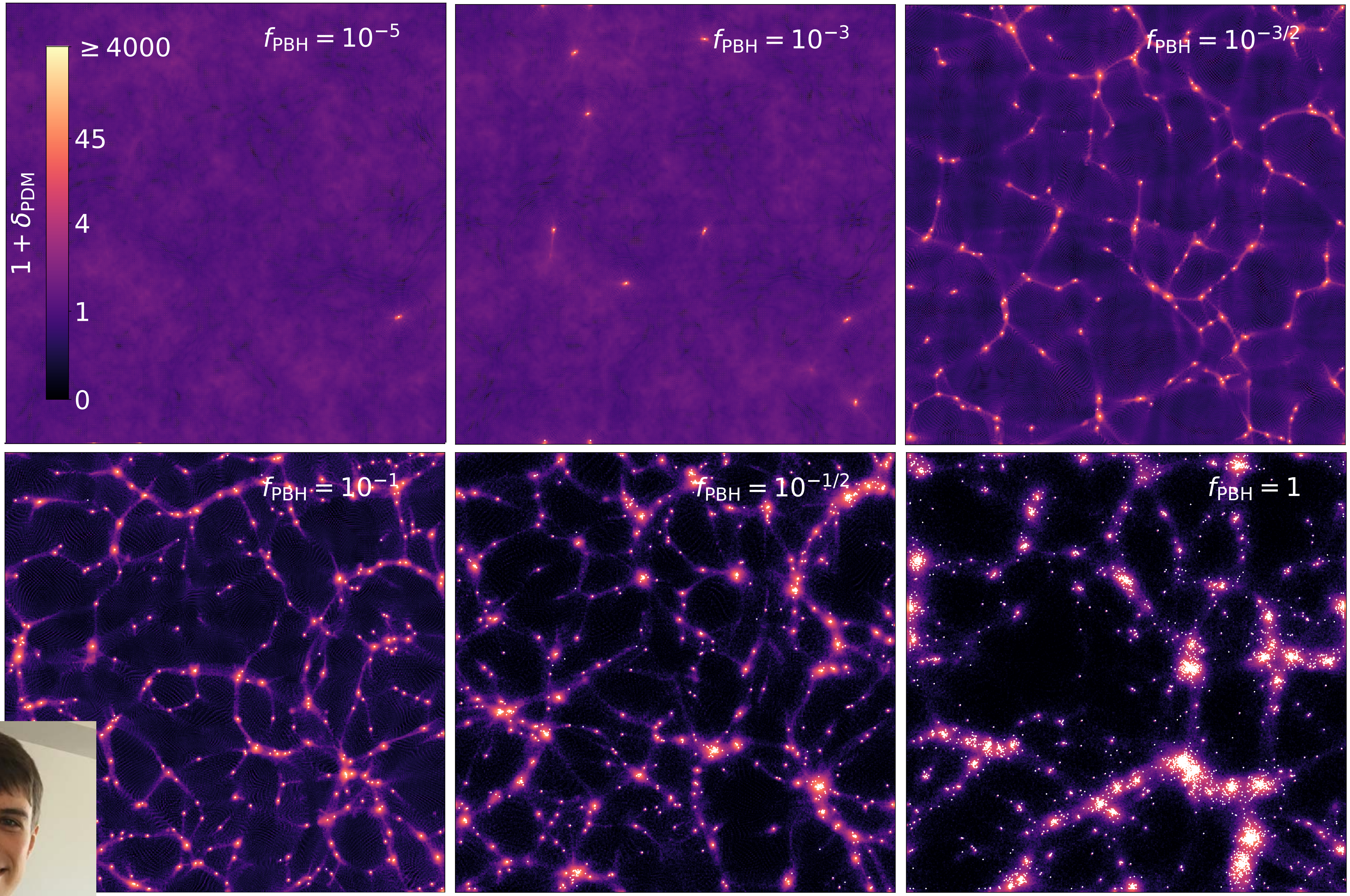


Spatial fluctuations in ionization fraction are comparable to mean effect

Ionization fluctuations peak at k ~0.01-0.1/Mpc, comparable to CMB anisotropy scales

Ongoing work: computation of the CMB trispectrum resulting from inhomogeneously-accreting PBHs.

Epilogue: PBH clustering



$z = 100$

Derek Inman

$(30\ \text{kpc/h})^3$ simulations of 30-M_{sun} PBHs + particle dark matter

Inman & YAH 2019


log[time (years)] = -0.1