

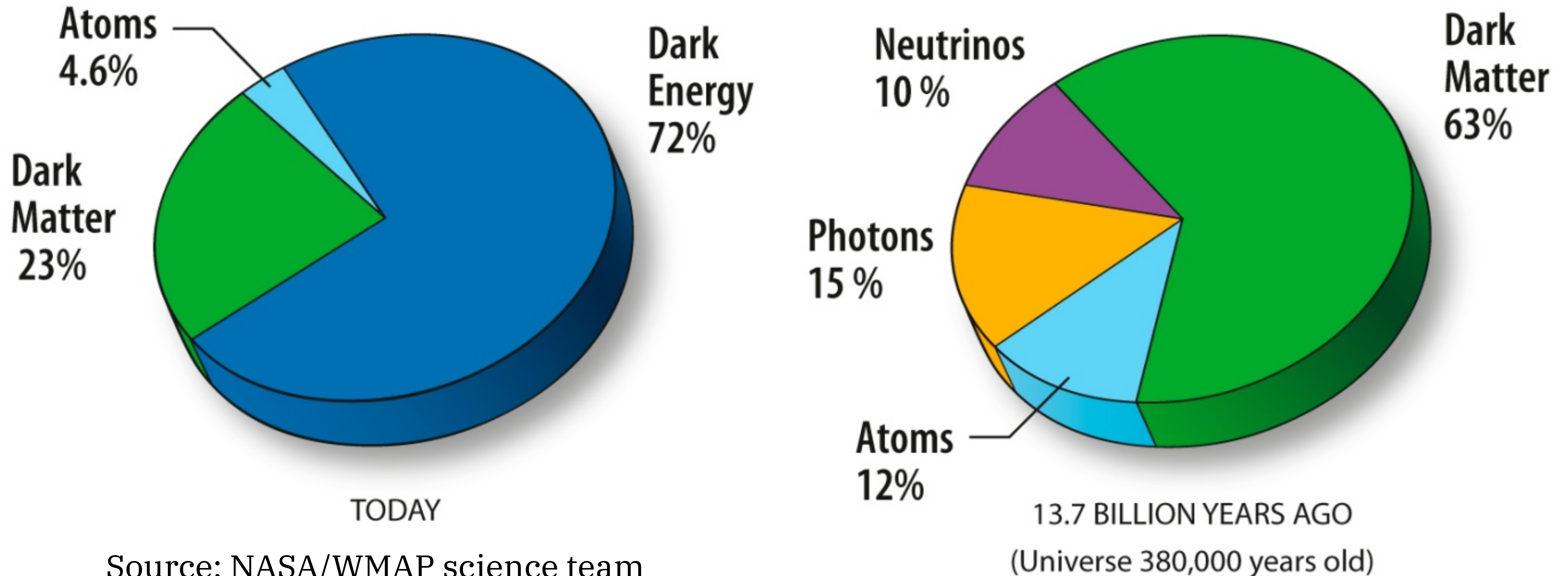
A road less traveled: The quest for small-scale power spectrum

Donghui Jeong
(Penn State)

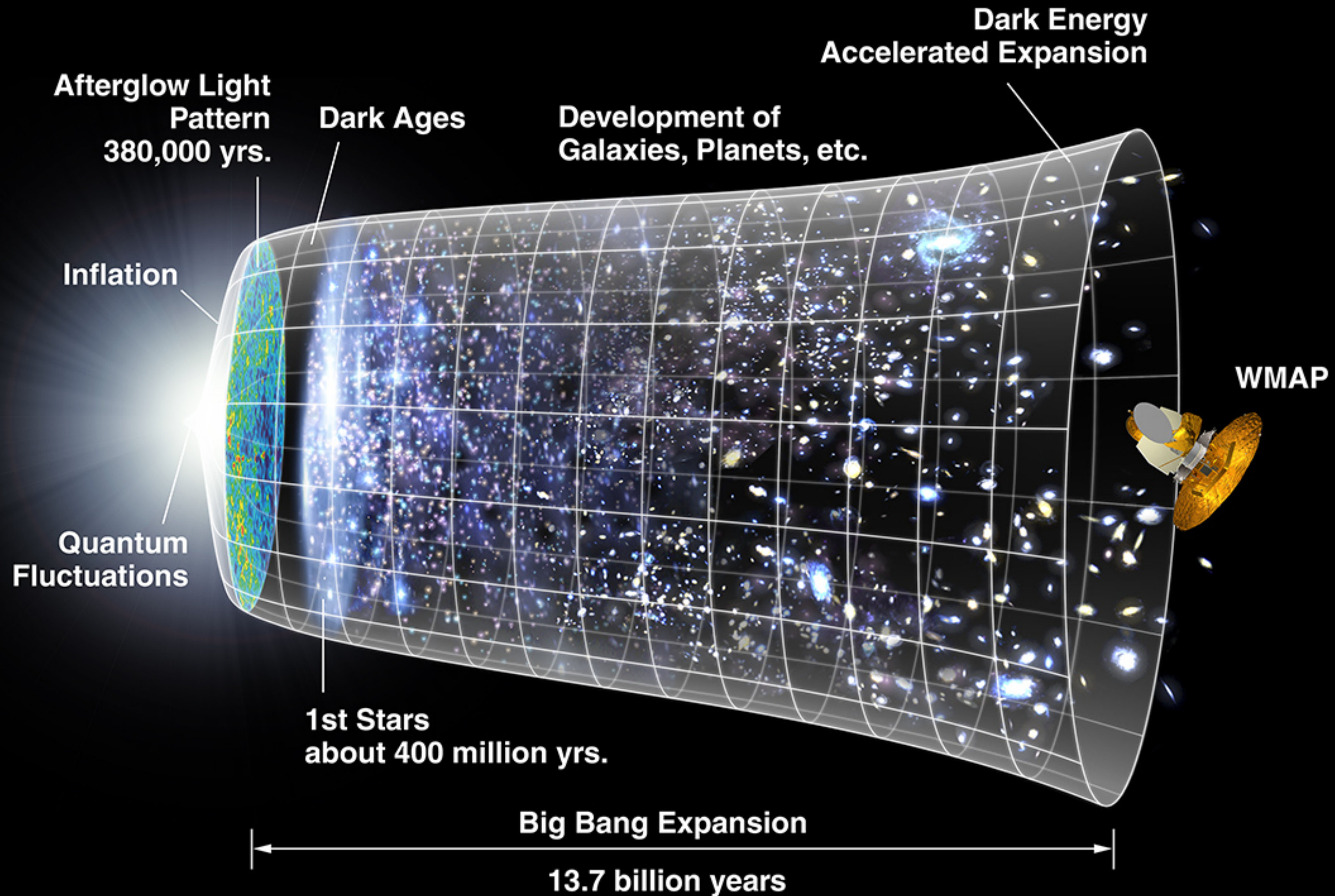
IBS workshop, 4 December 2018

Our Physical Cosmology

- The Universe is **spatially flat**, and **the expansion** is **accelerating**.



The concordance cosmology



Remaining big questions

- From ASTRO2010 decadal review: All related to the *nature of the building blocks* of the concordance model:
 - **Dark energy:** Why is the Universe accelerating now?
 - **Inflation:** How did the Universe begin?
 - **Dark matter:** What is dark matter?
 - **Neutrinos:** What are the properties of neutrinos?

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- From ASTRO2010 decadal review: All related to the *nature of the building blocks* of the concordance model:
 - **Dark energy:** Why is the Universe accelerating now?
 - **Inflation:** How did the Universe begin?
 - **Dark matter:** What is dark matter?
 - **Neutrinos:** What are the properties of neutrinos?
- Seize *every* opportunity to leave *no stone unturned!*

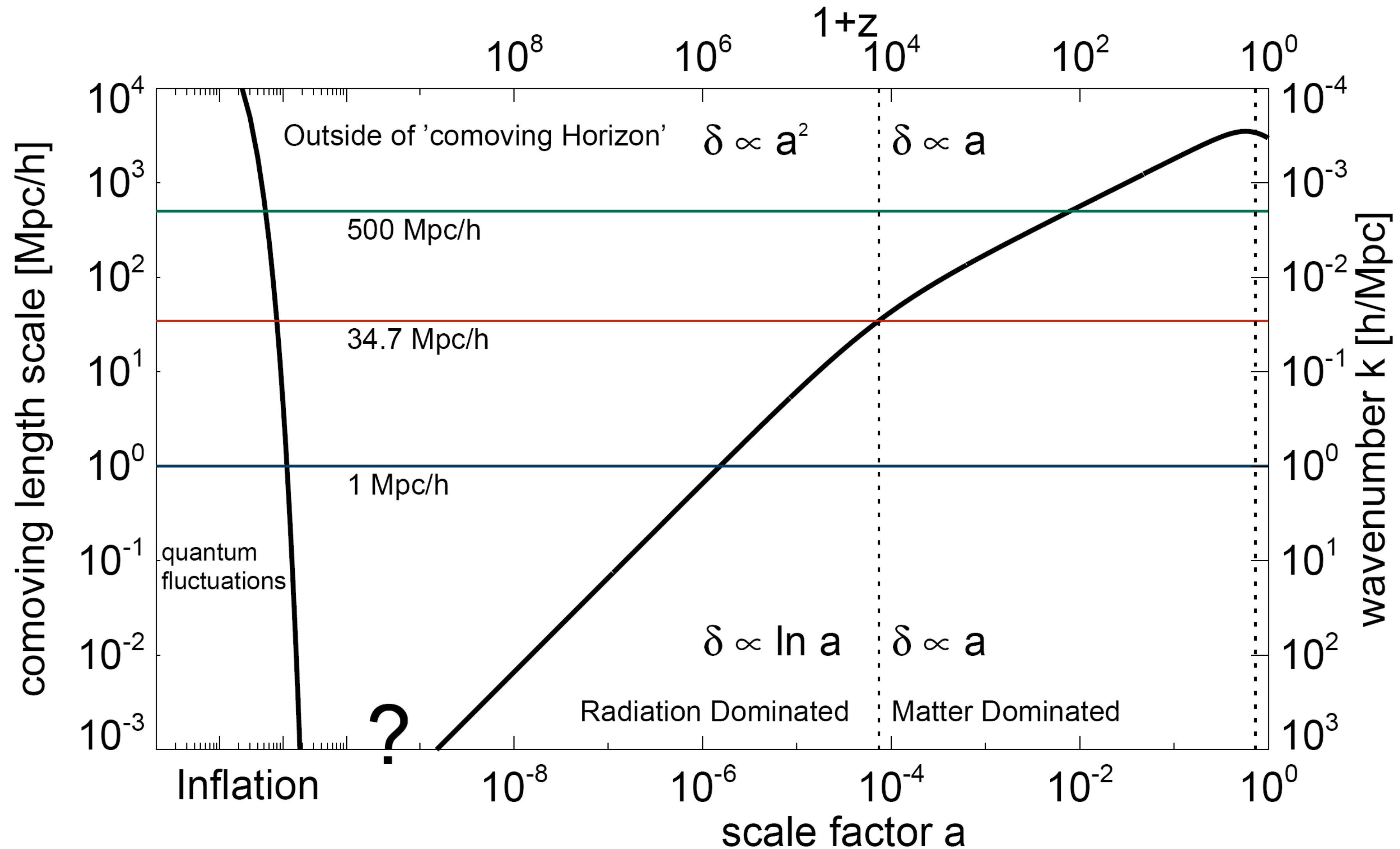
Inflation questions

- How did inflation begin?
- What accelerated the Universe?
- How did it end?
- How do we connect inflation to the beginning of the hot, dense initial state of the Big-bang cosmology?

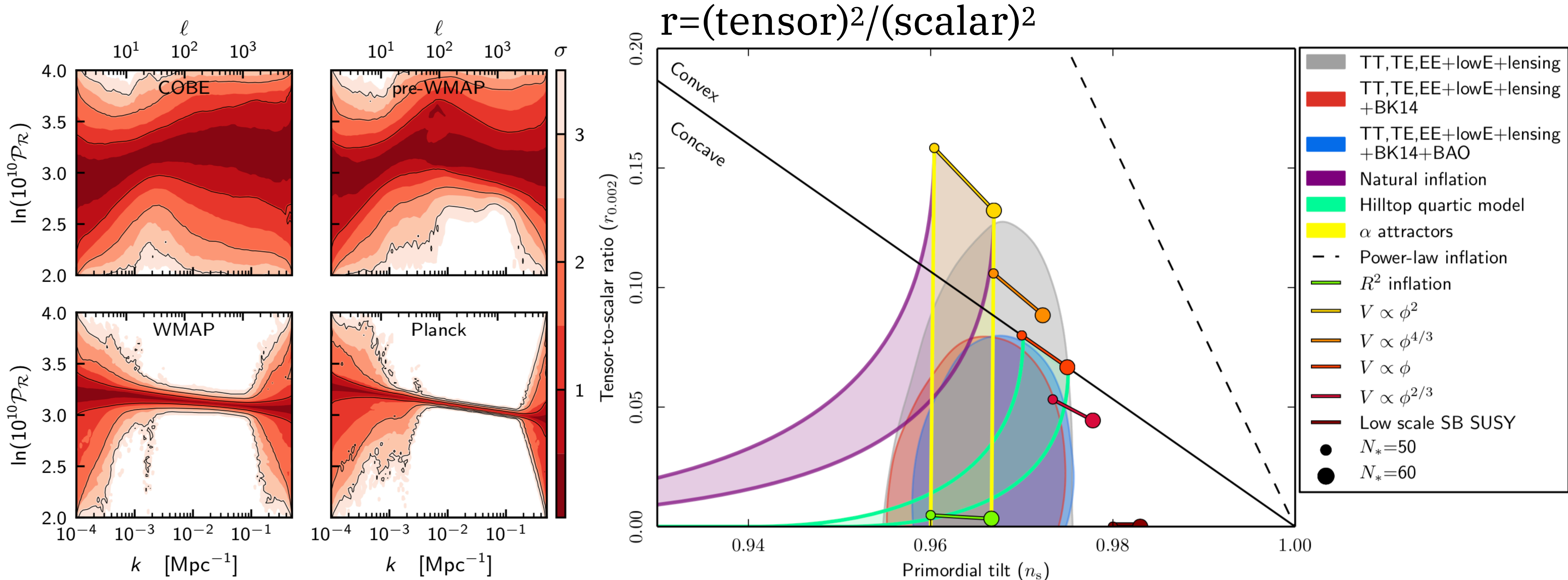
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A key to inflationary cosmology

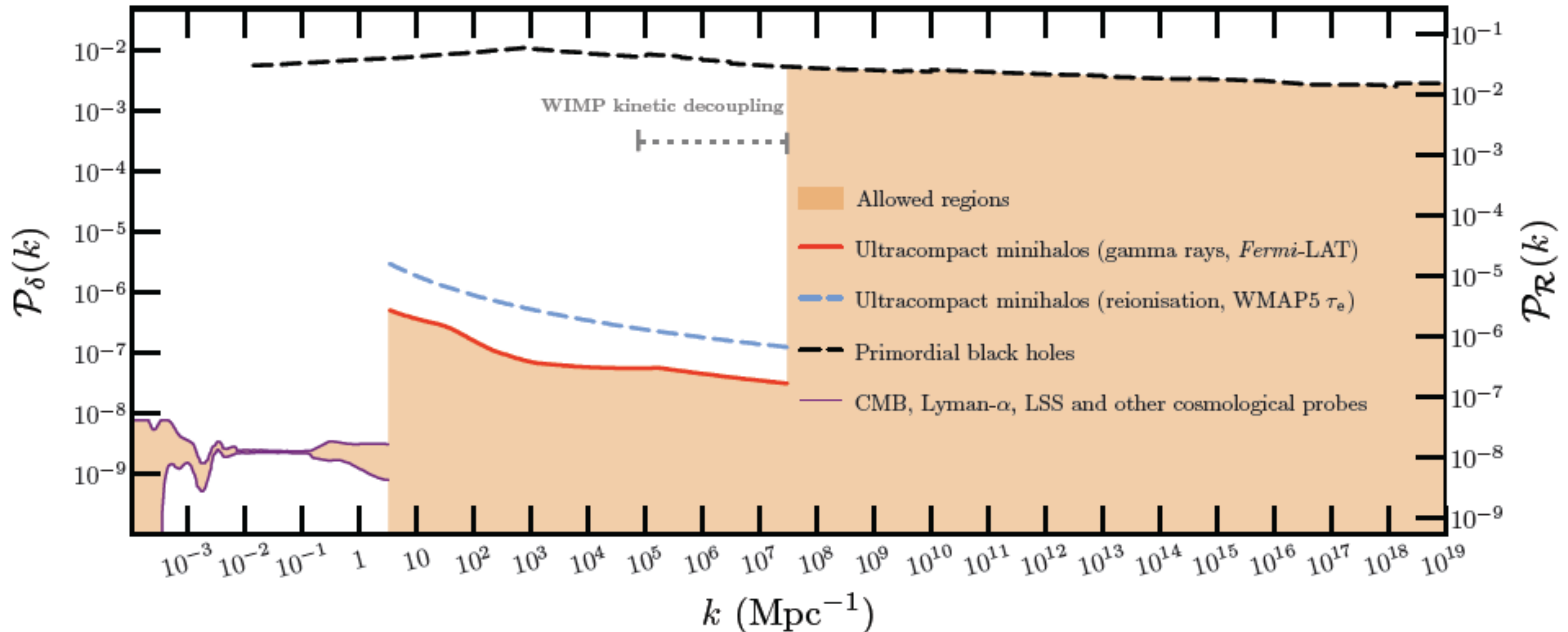


Constraining the *seed* fluctuations

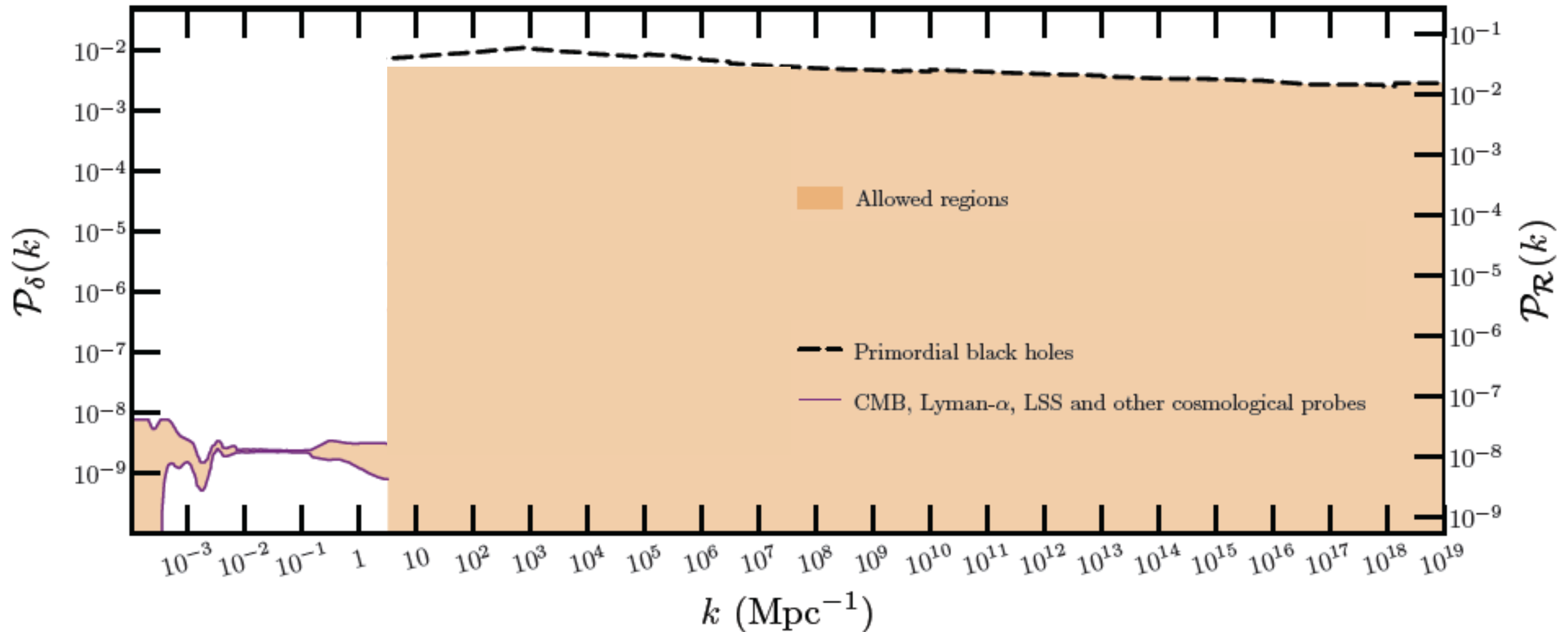


$$\mathcal{P}_{\mathcal{R}}(k) = A_s k^{n_s}$$

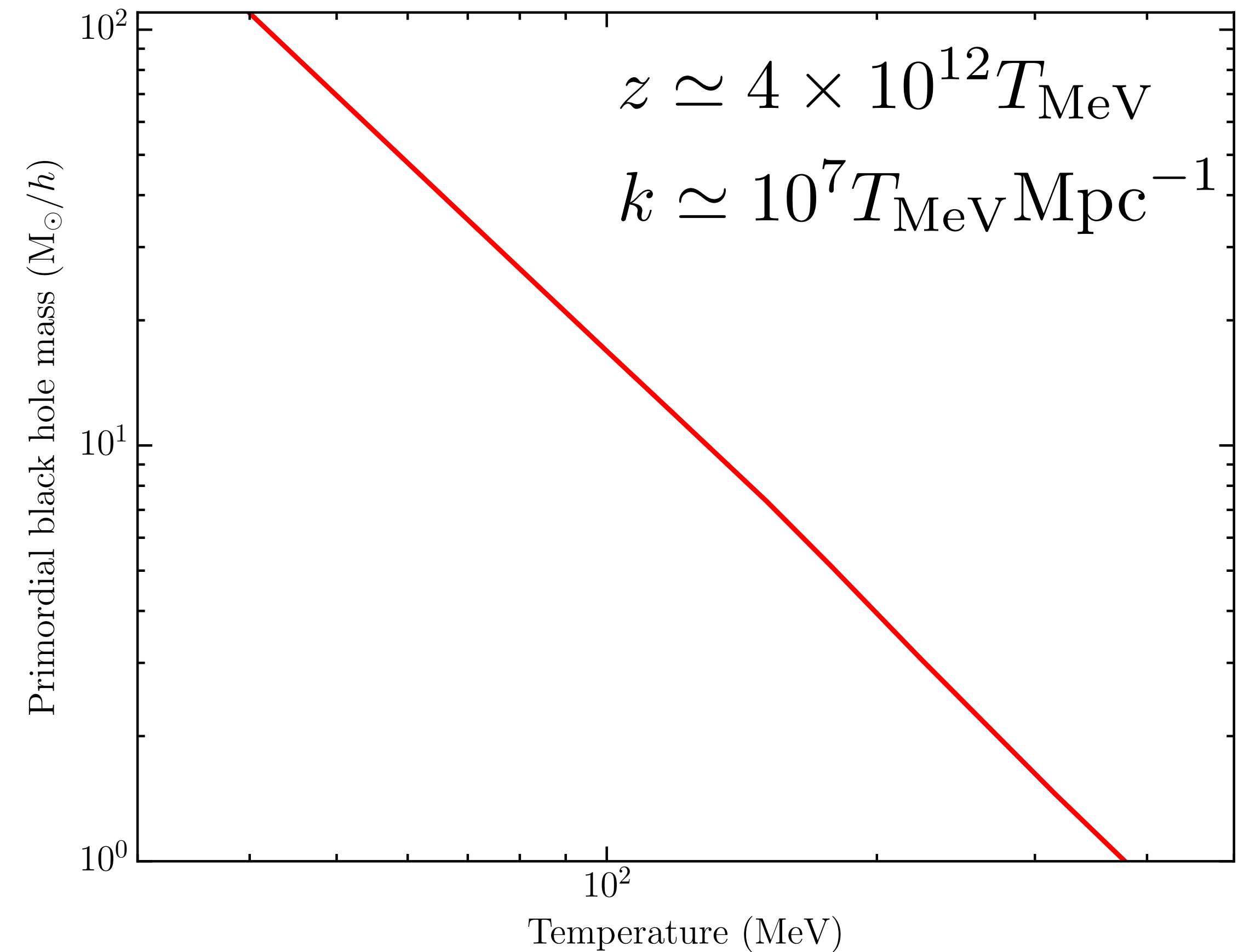
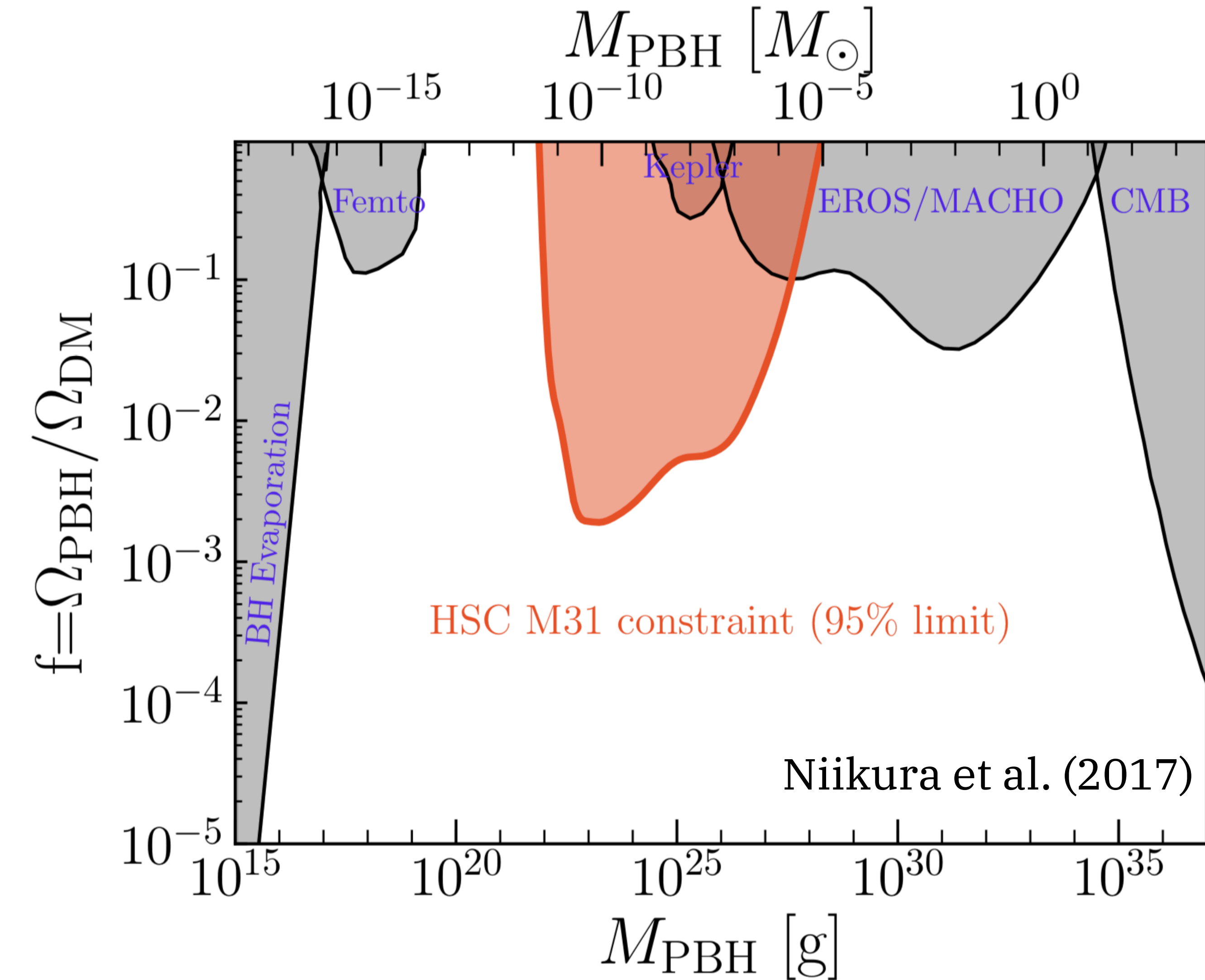
Constraint over the broader range



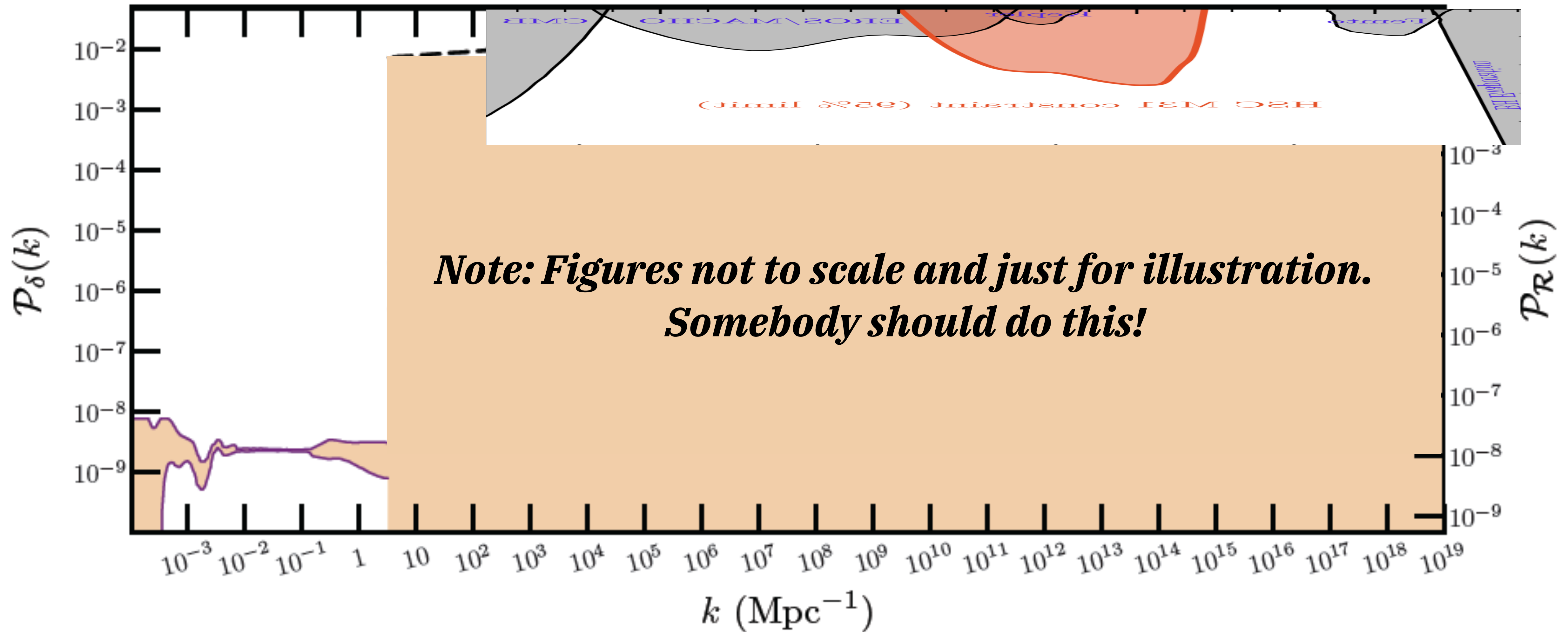
For secluded DM!



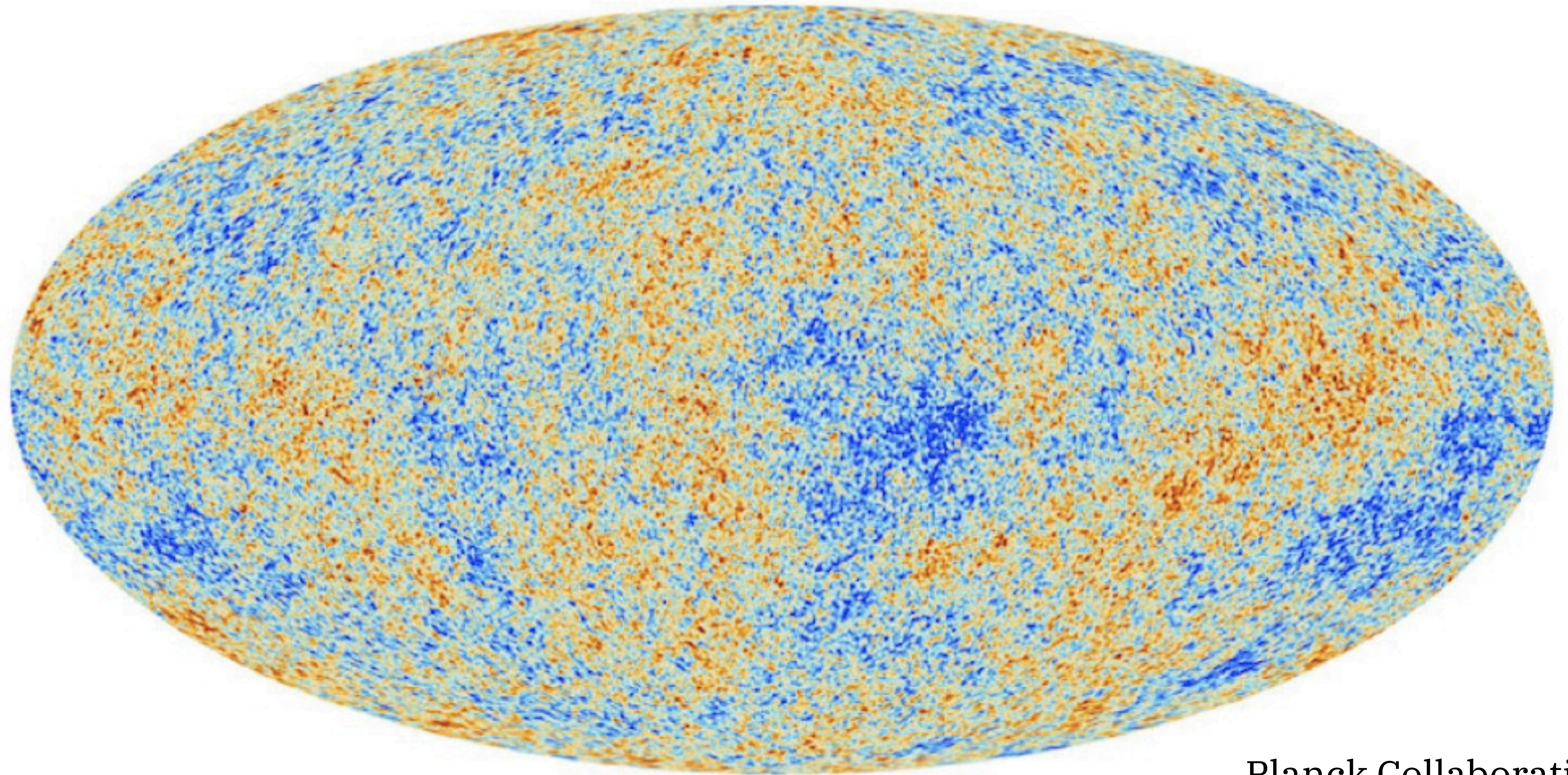
Constraint I. PBH abundance



For secluded DM + PBH

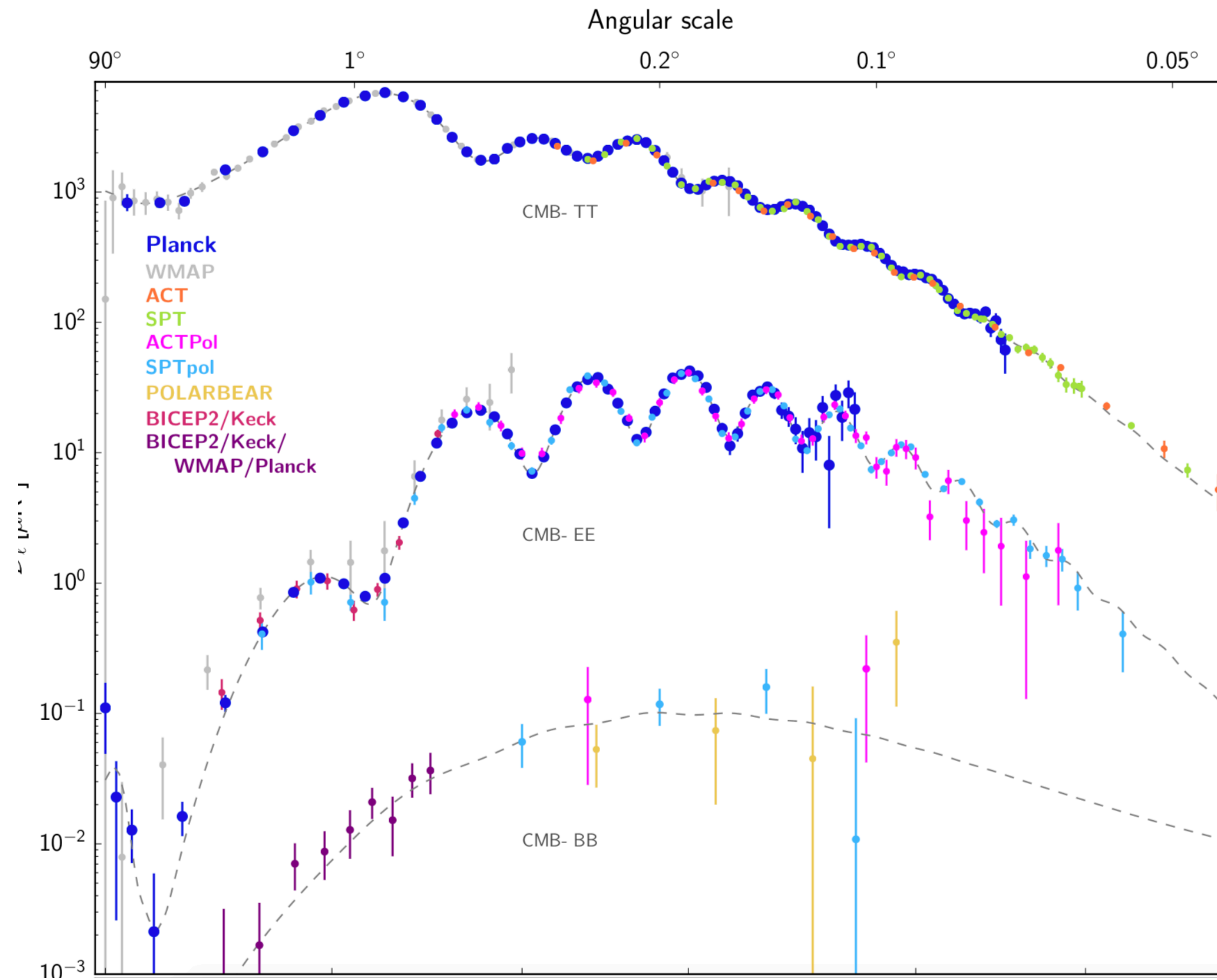


Constraint II. Thermal history



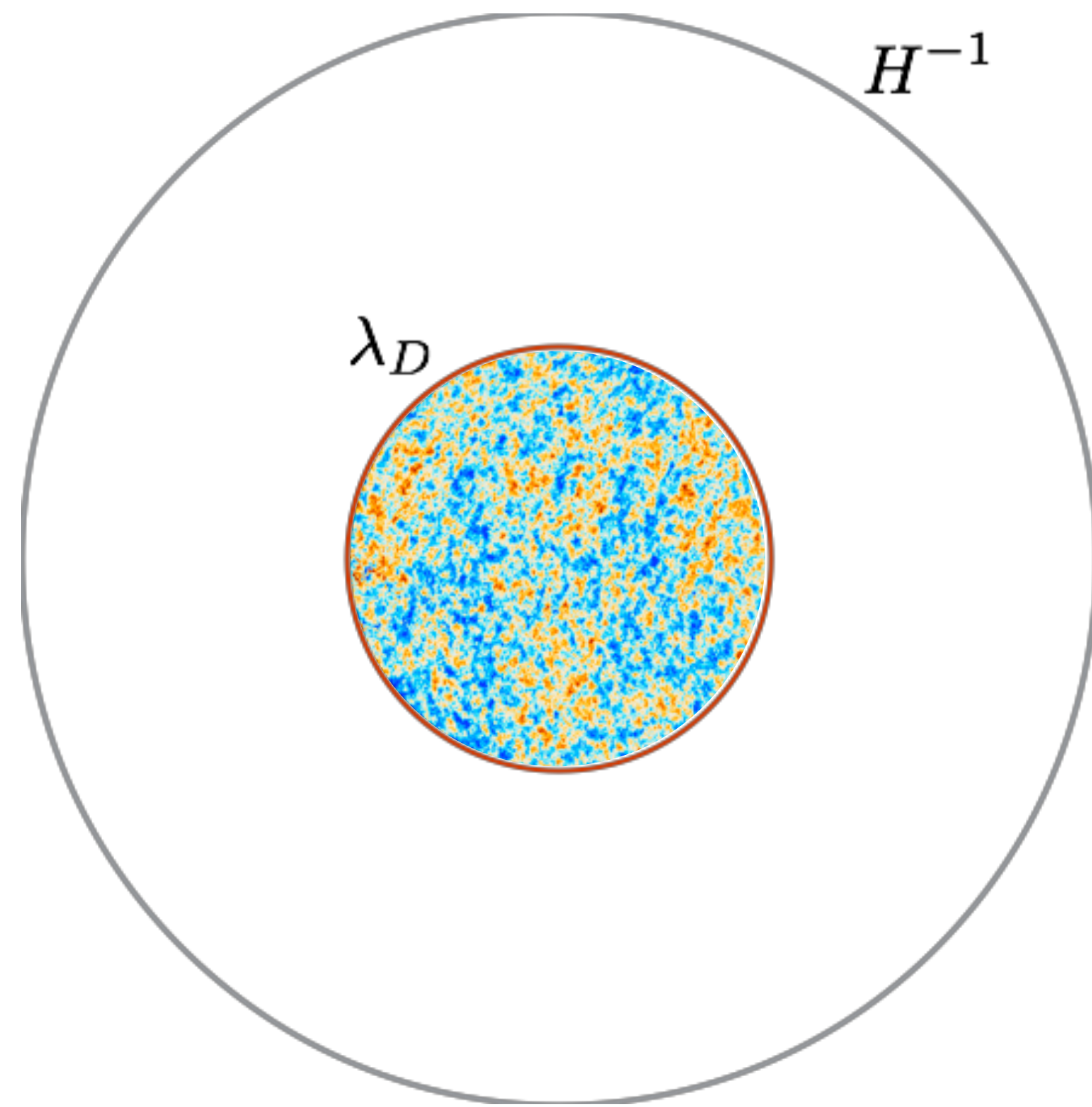
Planck Collaboration

Damping of CMB power spectrum



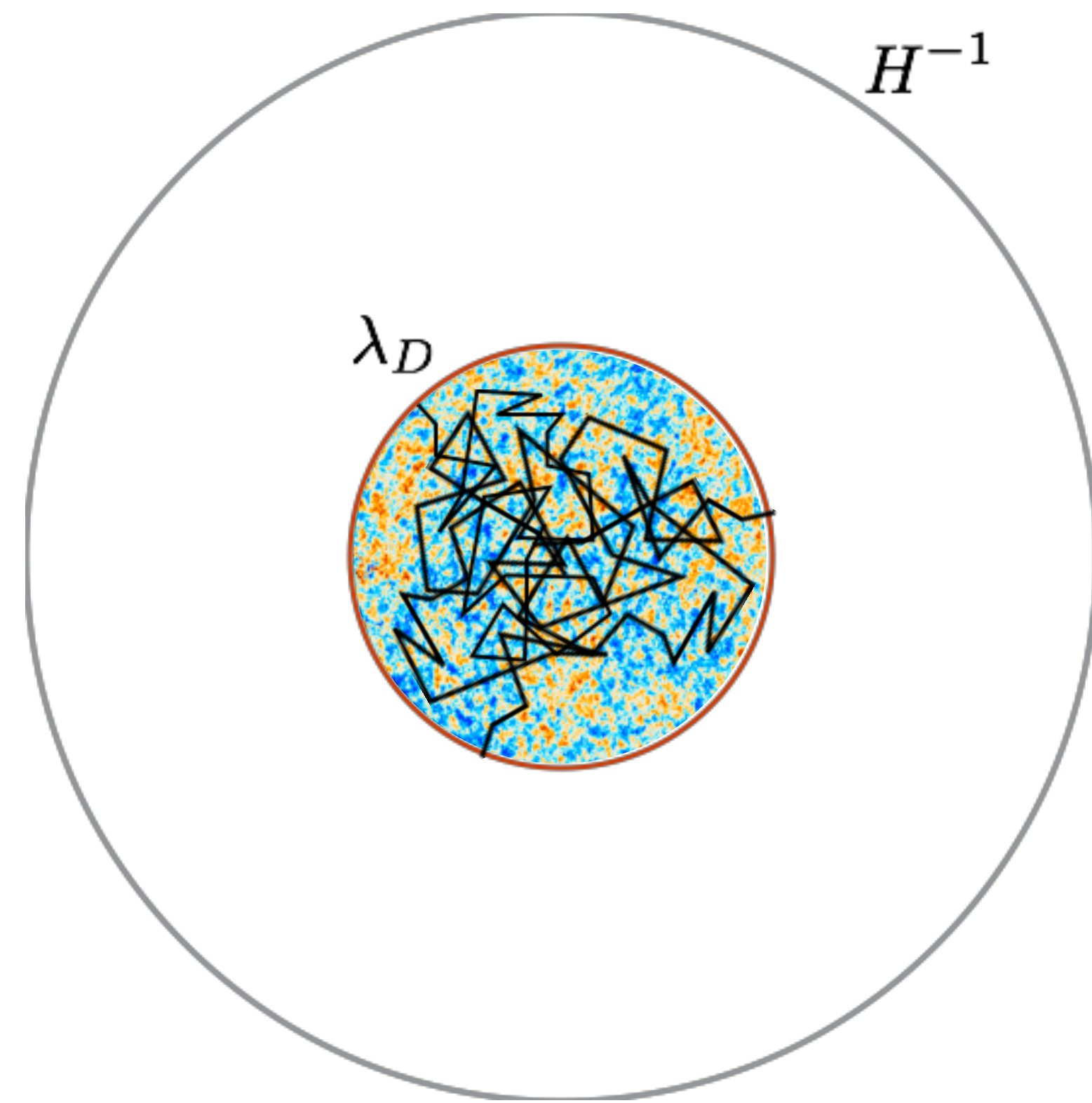
Planck Collaboration

Silk damping and Diffusion scale



temperature anisotropies
at $\sim 0.0001''$ scale

Silk damping and Diffusion scale



mean free path: $\lambda_{\text{mfp}} \simeq \frac{1}{\sigma_{e\gamma} n_e}$

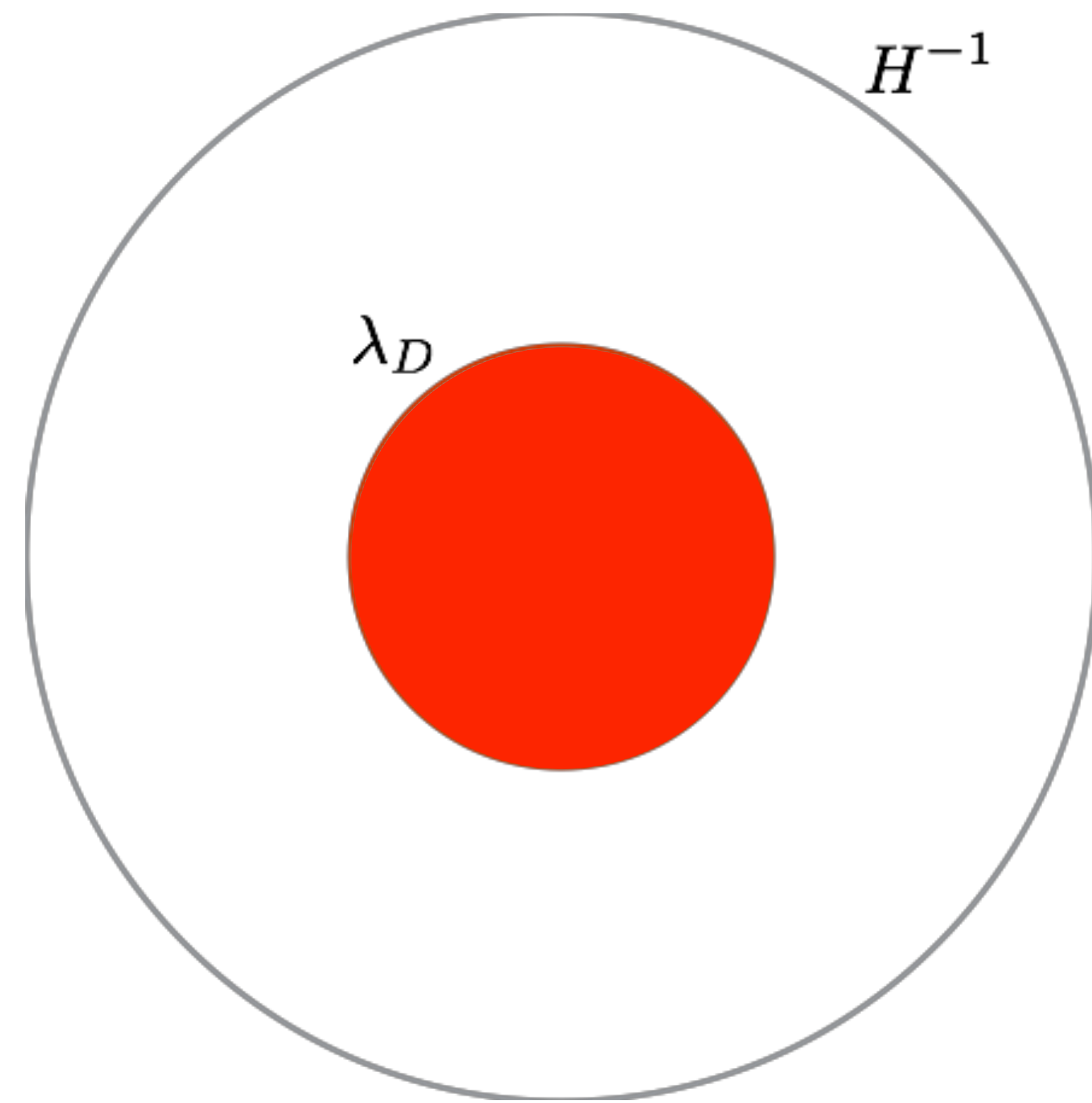
of scatters: $N \simeq \sigma_{e\gamma} n_e H^{-1}$

diffusion scale (r.m.s. of random walk):

$$\lambda_D \simeq \lambda_{\text{mfp}} \sqrt{N} \simeq \frac{1}{\sqrt{\sigma_{e\gamma} n_e H}}$$

temperature anisotropies
at $\sim 0.0001''$ scale

Silk damping and Diffusion scale



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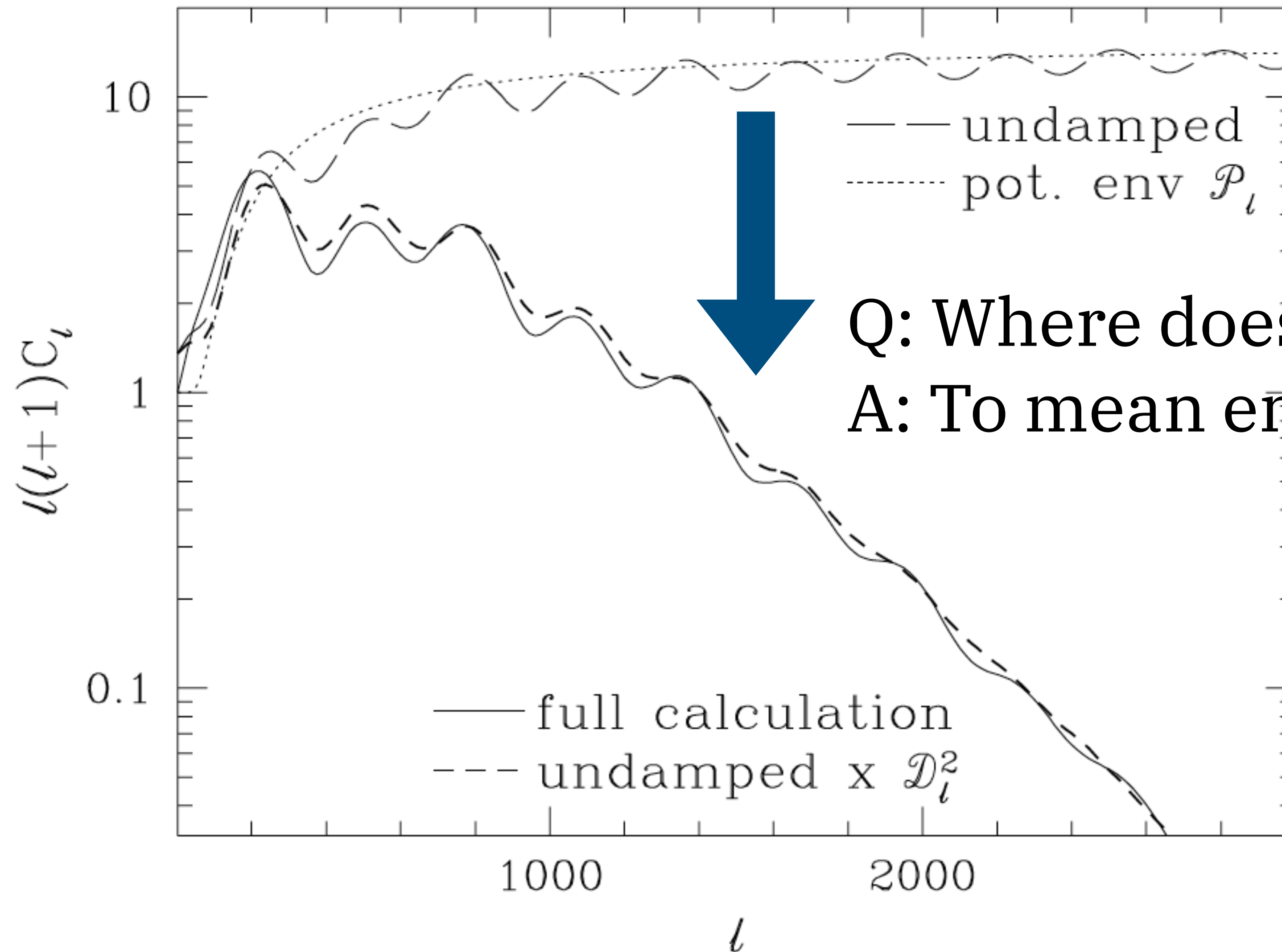
diffusion scale (r.m.s. of random walk):

$$\lambda_D \simeq \lambda_{\text{mfp}} \sqrt{N} \simeq \frac{1}{\sqrt{\sigma_{e\gamma} n_e H}}$$

Diffusion = temperature equalizer

Diffusion damps Acoustic Oscillation

Hu & White 1997



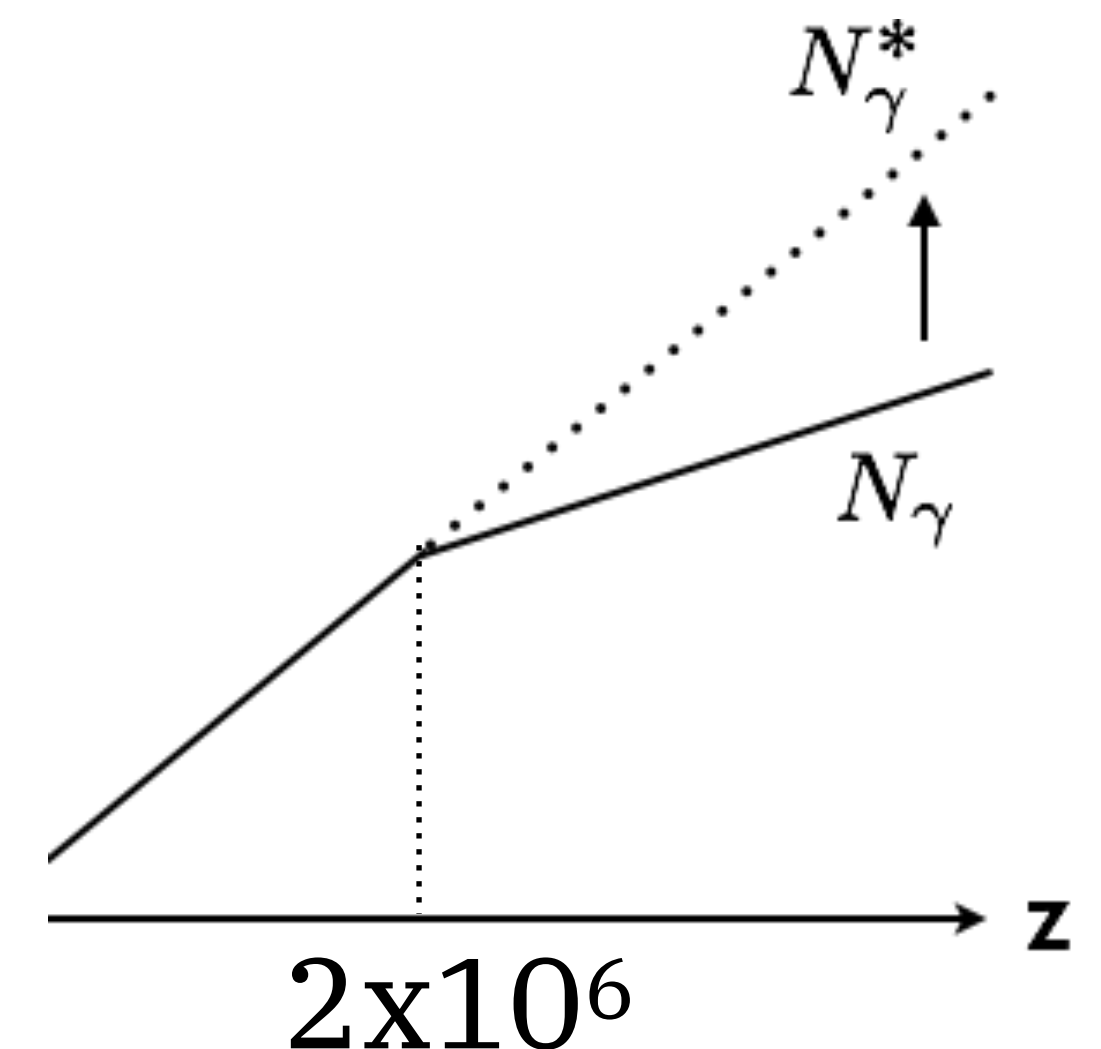
Q: Where does the acoustic energy go?
A: To mean energy spectrum

Thermal history @ $z > 2$ million

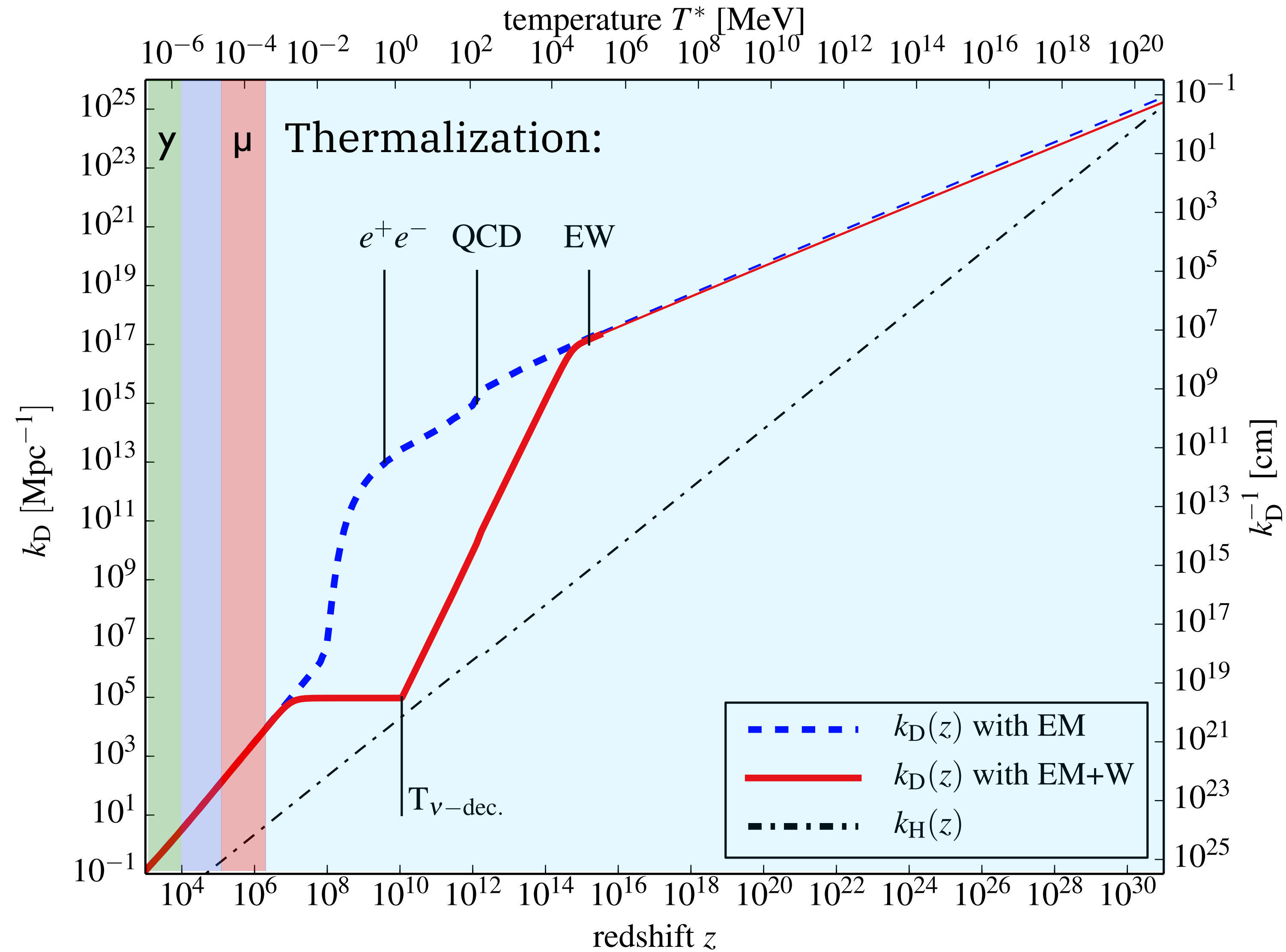
- Thermalization follows immediately after the diffusion b/c Double-Compton scattering and Bremsstrahlung very efficient
- The net entropy production is proportional to the small-scale scalar power spectrum:

$$N_\gamma(z) \simeq N_\gamma^*(z) \exp \left[-\frac{3}{2} C^2 \int_0^z \Delta_{\mathcal{R}}^2(k_D) \frac{d \ln k_D}{d \ln z} d \ln z \right]$$

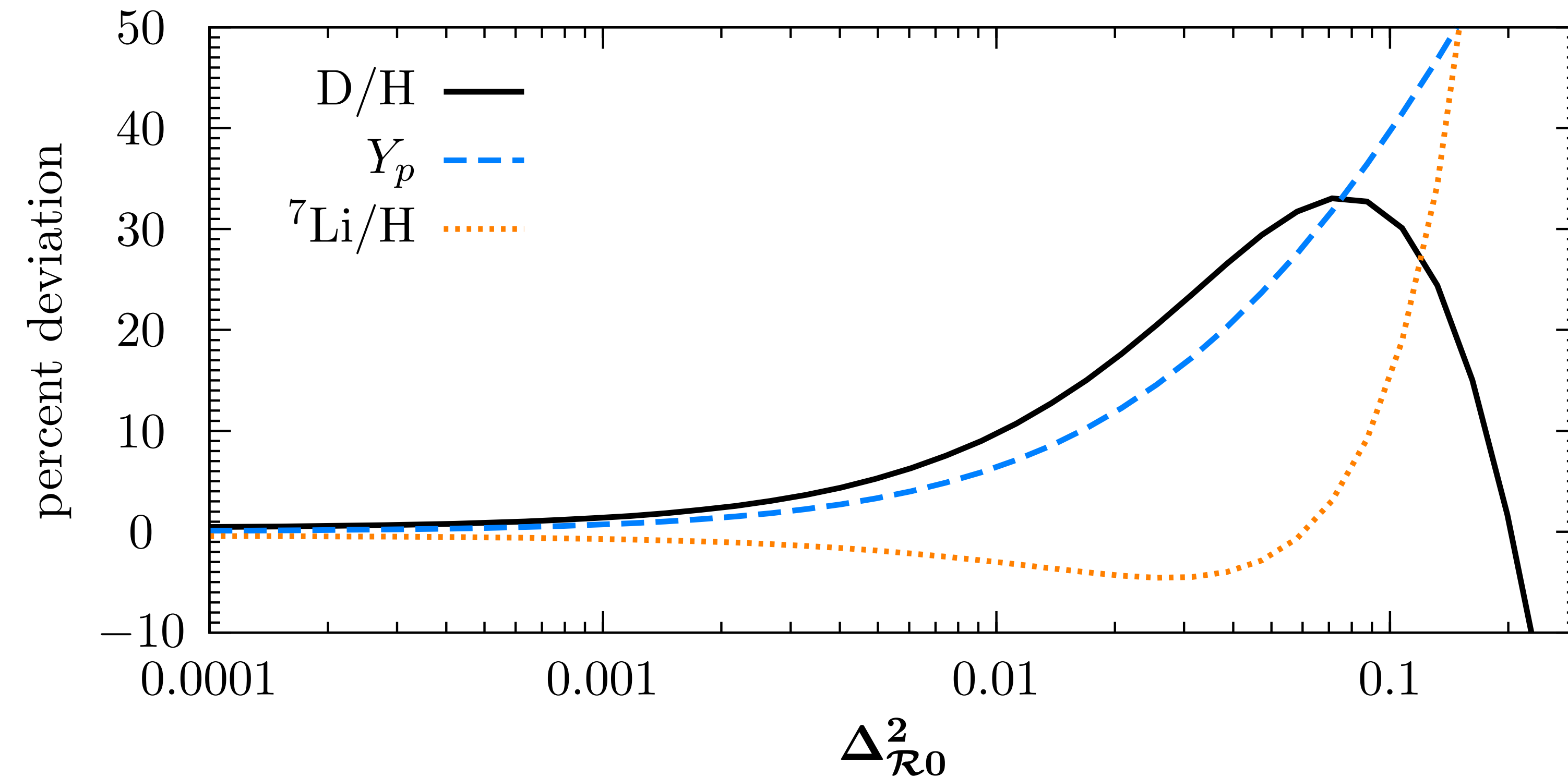
↑
number density extrapolated
from 411 cm^{-3} today



Silk damping scale (k_D)



Constraint from BBN



- BBN constraint comes from the modes dissipated *after* BBN:

$$Y_p : \Delta_{\mathcal{R}0}^2 < 0.007$$

$$(\text{D/H})_p : \Delta_{\mathcal{R}0}^2 < 0.2$$

$$10^4 \text{ Mpc}^{-1} \lesssim k \lesssim 10^5 \text{ Mpc}^{-1}$$

- No assumption beyond the standard model!

Other possibilities

- Increasing the required $\eta_B = N_B/N_\gamma$ at early times.
If quarks are thermalized, the principal bound: $\eta_B < 1$ gives

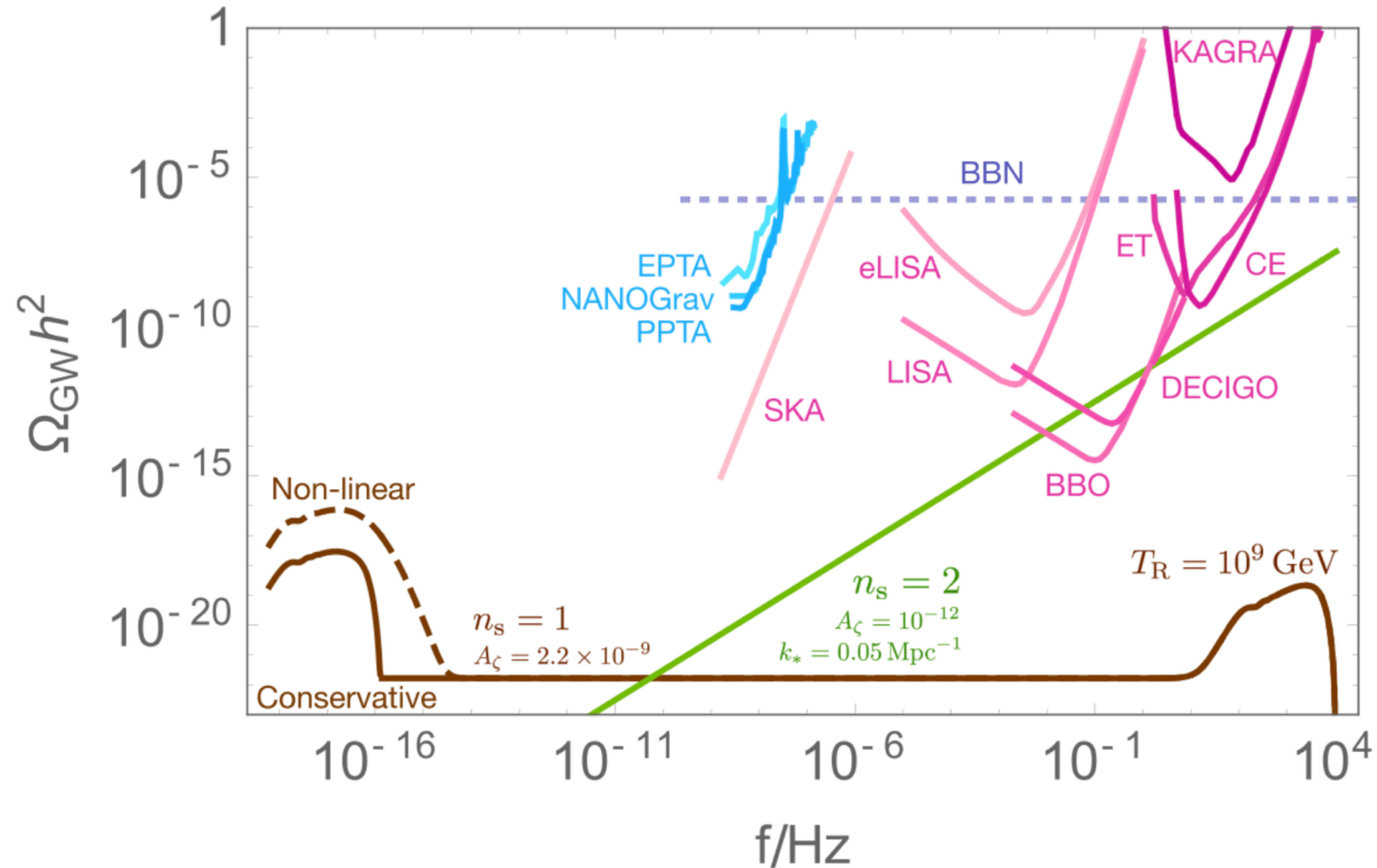
$$\Delta_R^2 < 0.3 \text{ at } k_D = 10^{20-25} \text{ Mpc}^{-1}!$$

- Change the temperature-redshift relation, to modify the WIMP constraints :
reduces required $\langle \sigma v \rangle$ to match the observed DM abundance

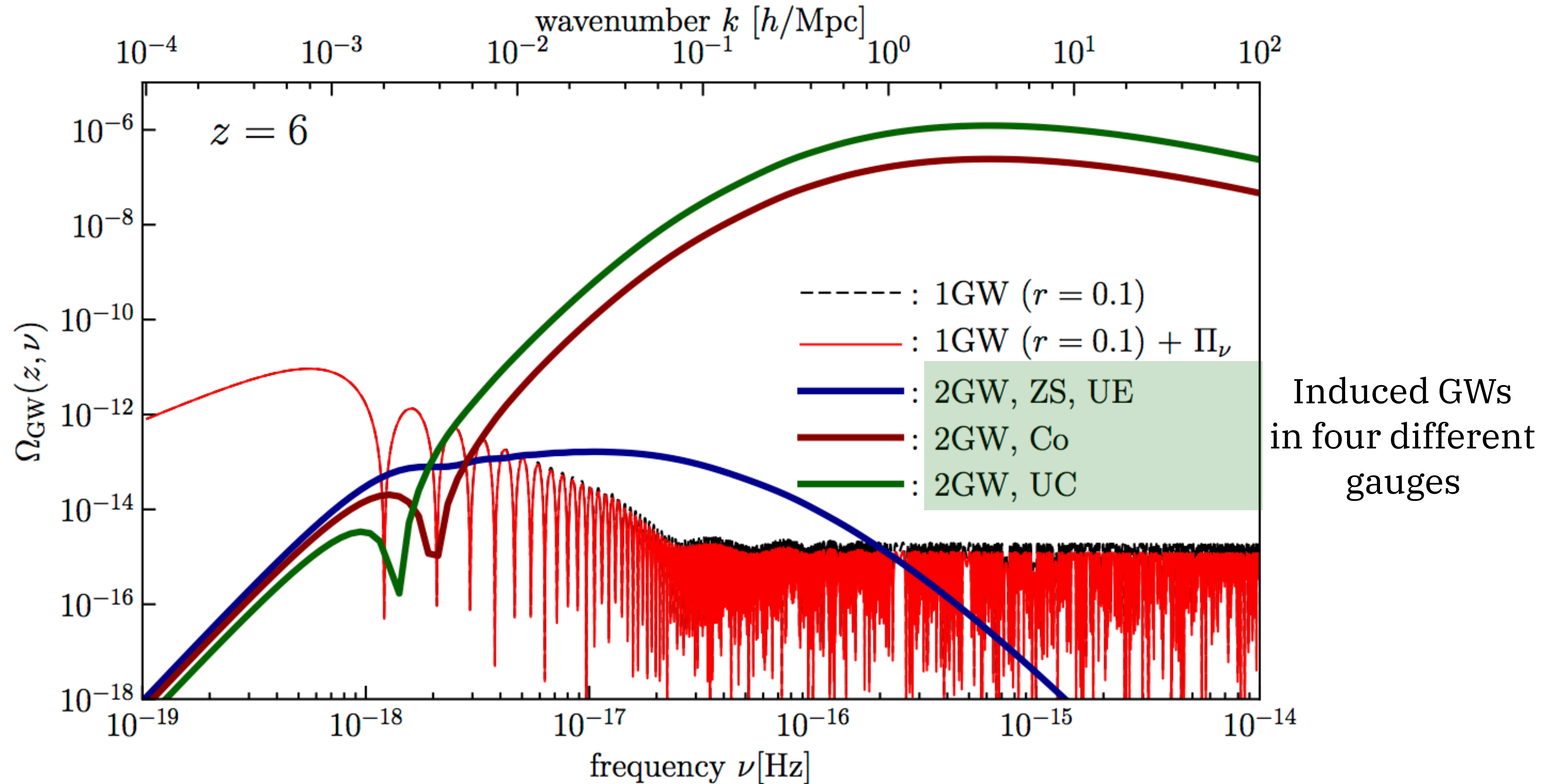
Constraint III. Stochastic GWs

- Evolution of Scalar-Vector-Tensor perturbations are decoupled *only* at linear order.
- At second order, scalar perturbations generate the anisotropic-stress in the energy-momentum tensor; hence, generating the induced gravitational waves.
- The induced-GWs are redshifted, falls into the observation frequency window of PTA/SKA, eLISA, and LIGO.

Induced GW as a stochastic source



Warning: gauge-dependence

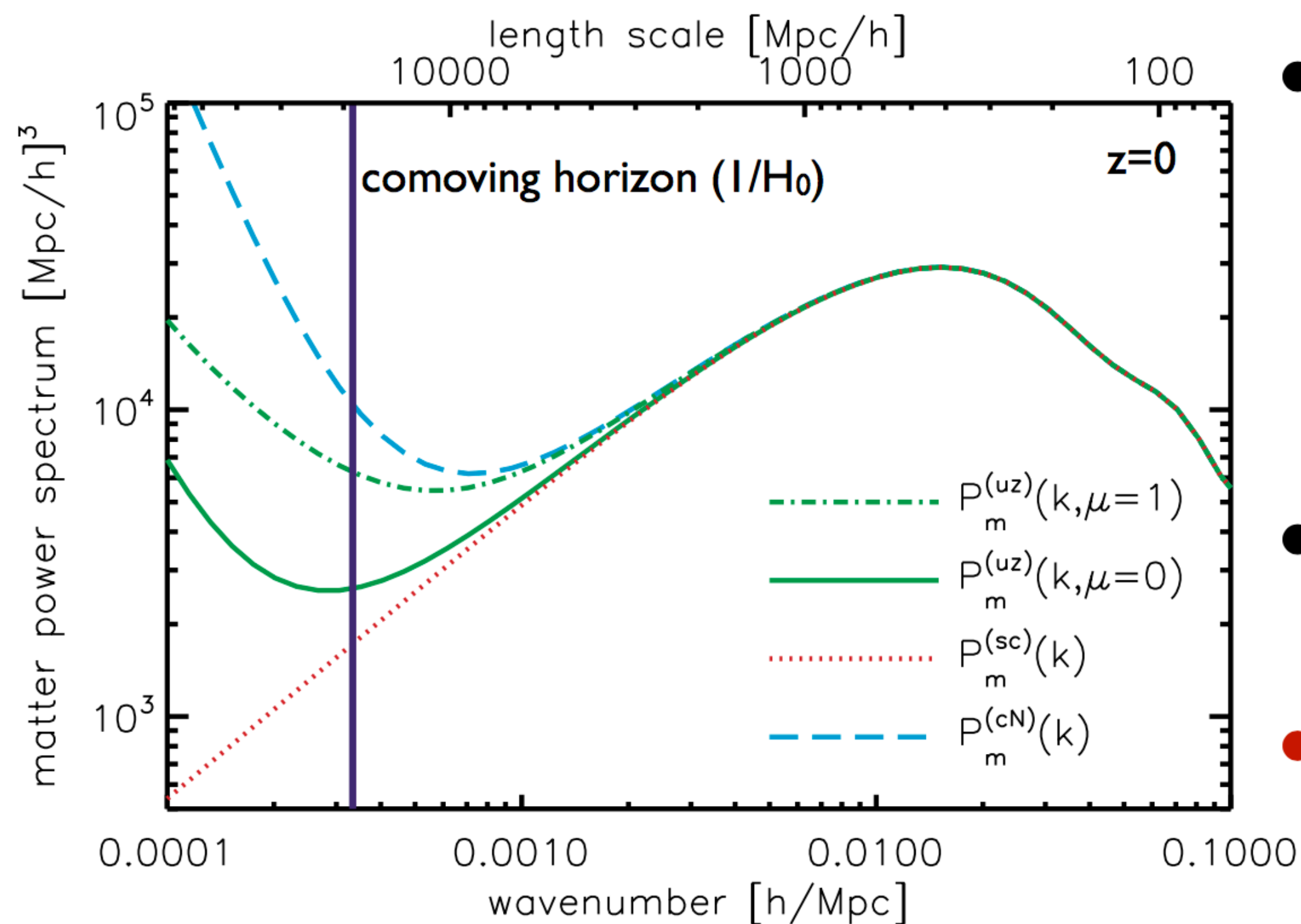


déjà vu!

Page 1 of my talk in 2011

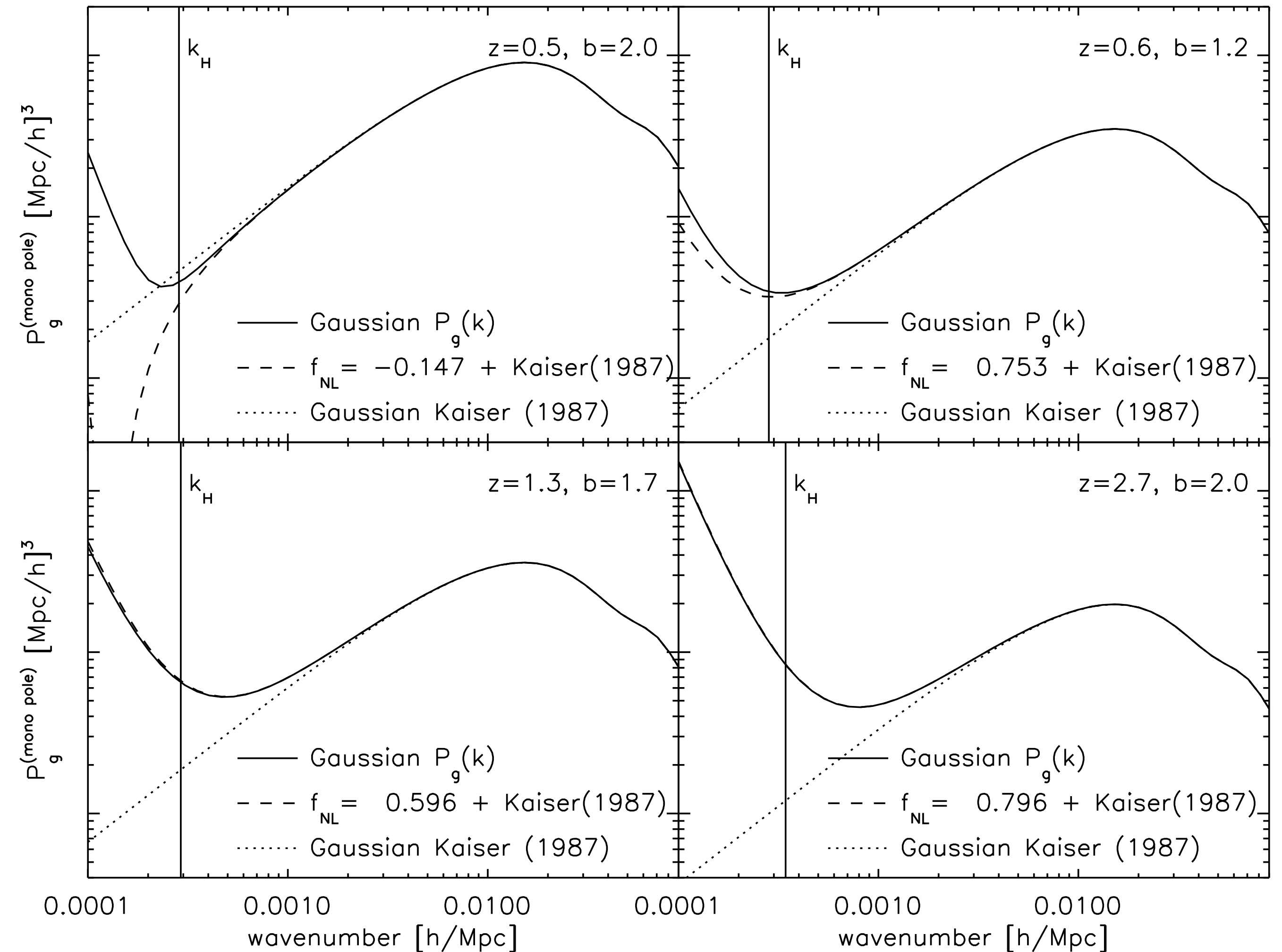
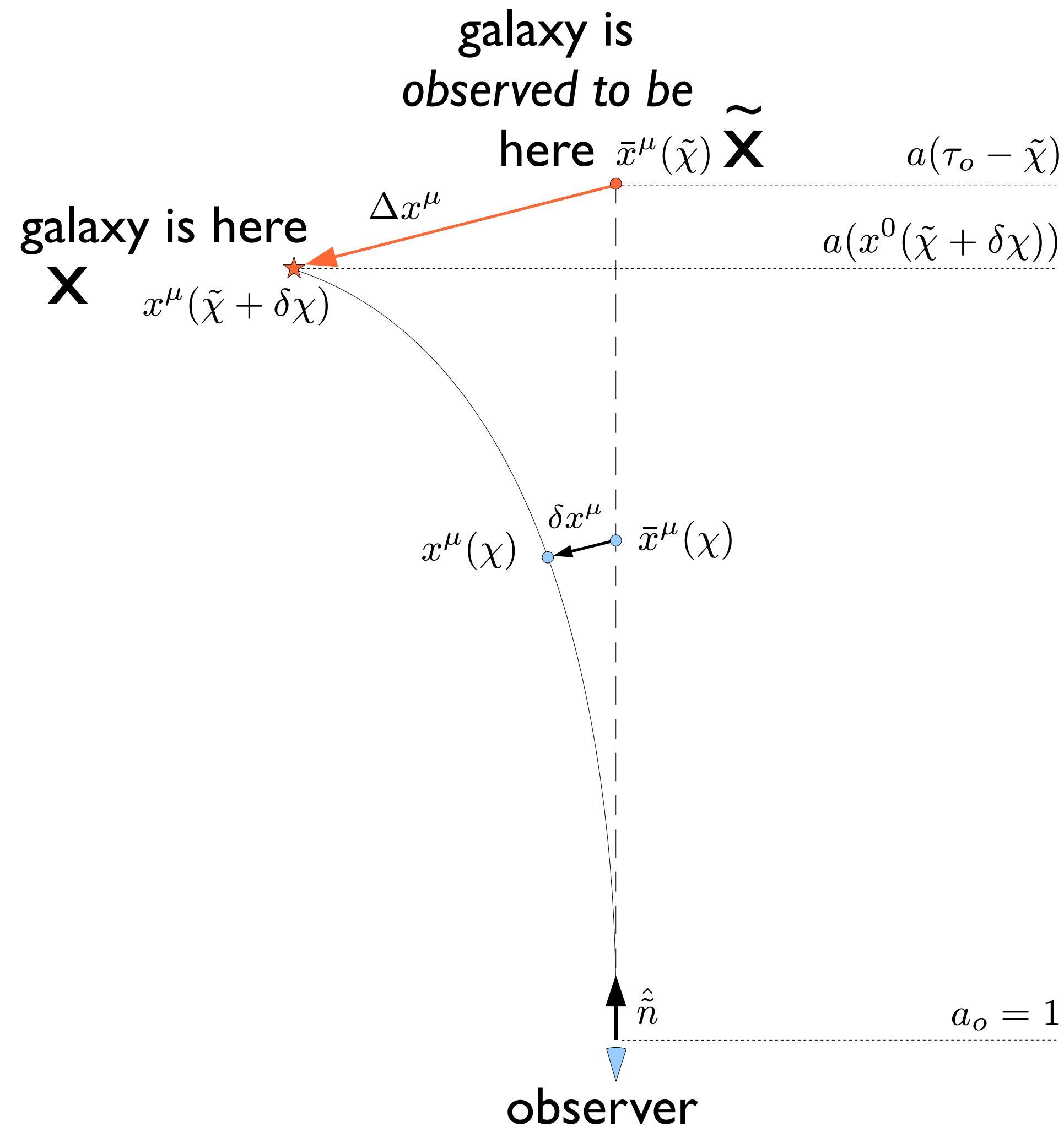
linear bias = linear in matter density

$P_g(k) = b^2 P_m(k)$. But, which $P_m(k)$?



- $P_m(k)$ from three gauges
 - conformal Newtonian (cN)
 - synchronous comoving (sc)
 - uniform redshift (uz)
- General covariance says all $P(k)$ s are equally good.
- **Q: what is $P_g(k)$ we will measure in the large scale galaxy surveys?**

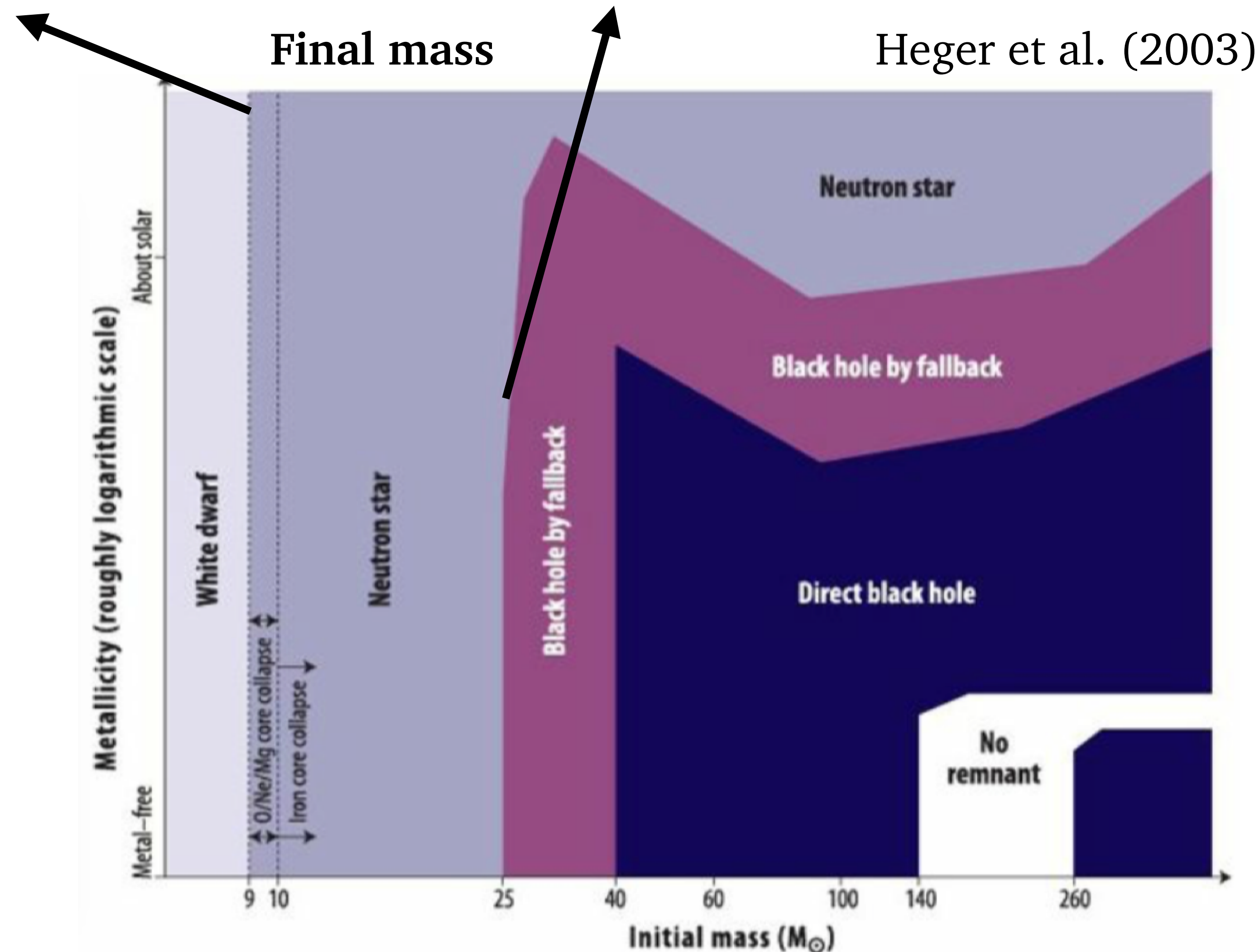
“Observable” must be gauge indep.



Usual Stars $\Rightarrow$ sub- $M_{\odot}$ Black Holes!

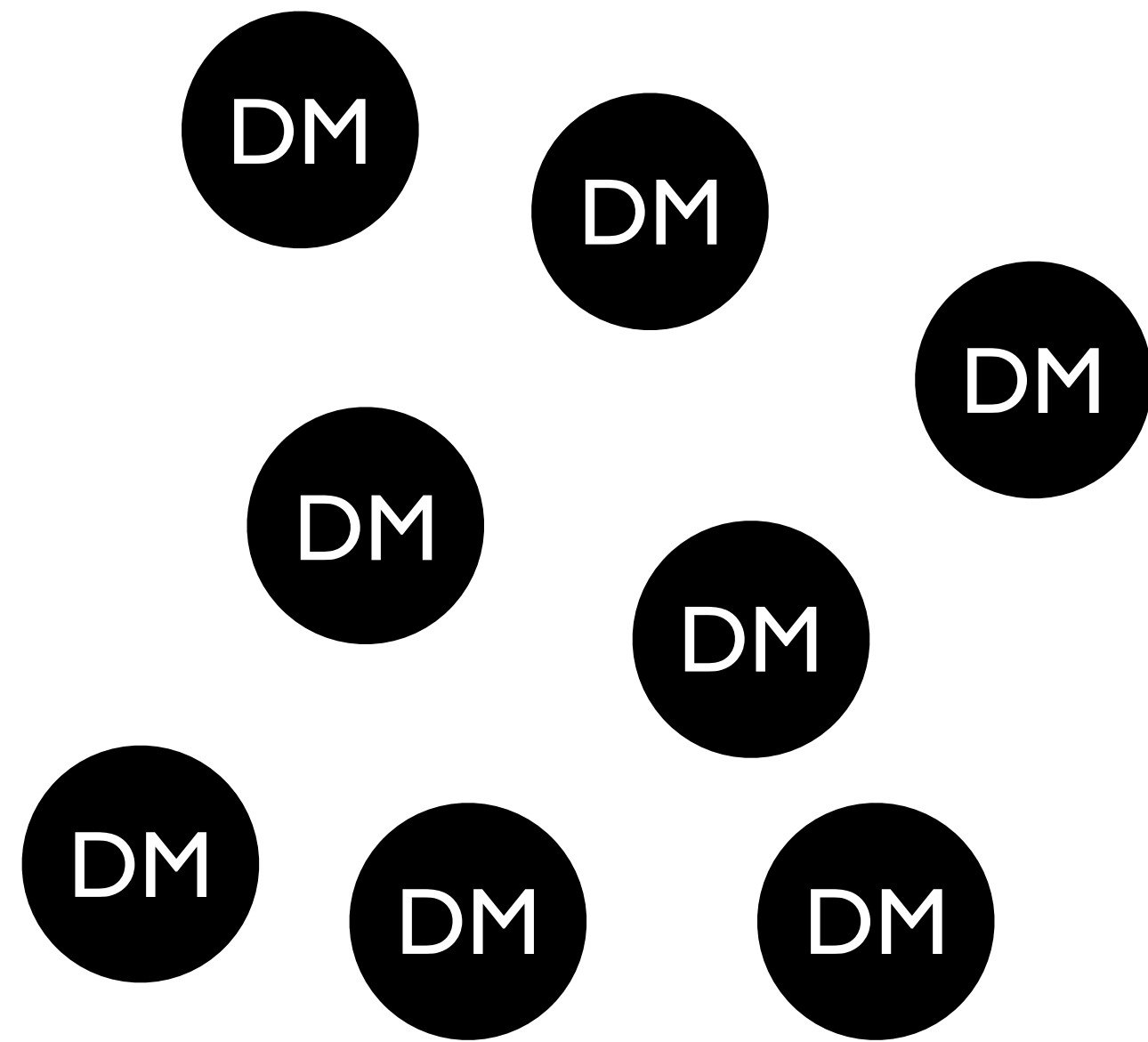
1.4 $M_{\odot}$ (Chandrasekhar mass)

2~3 $M_{\odot}$ (Maximum mass of the NSs)

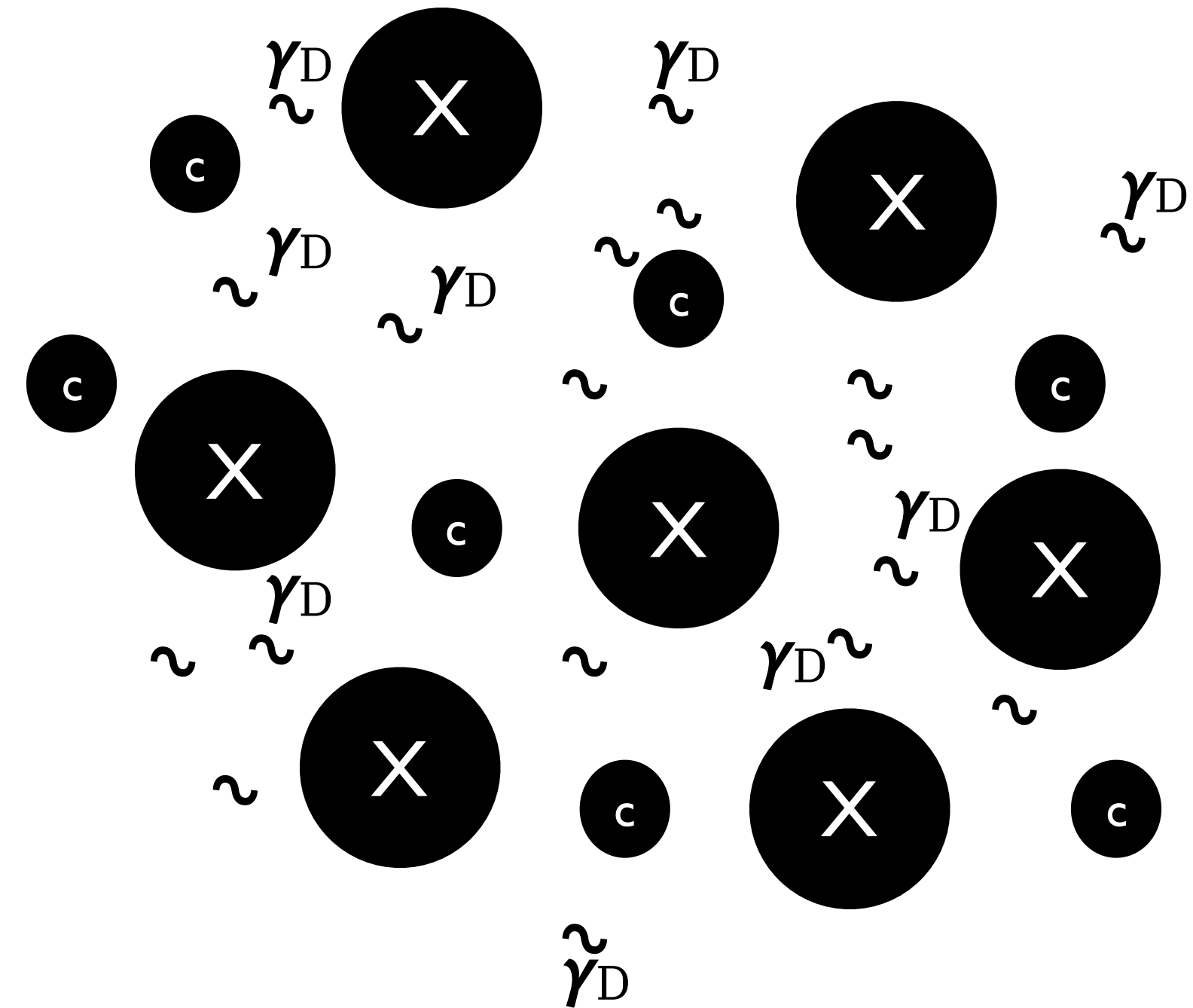
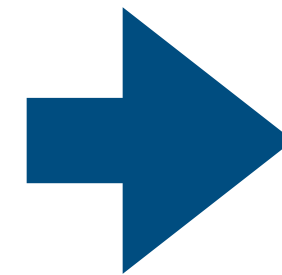


New possibility: Dark Black holes!

Set up: U(1)-interacting dark matter ($X, c = \text{Fermions}$, $\gamma_D = \text{Boson}$)



Boring single kind

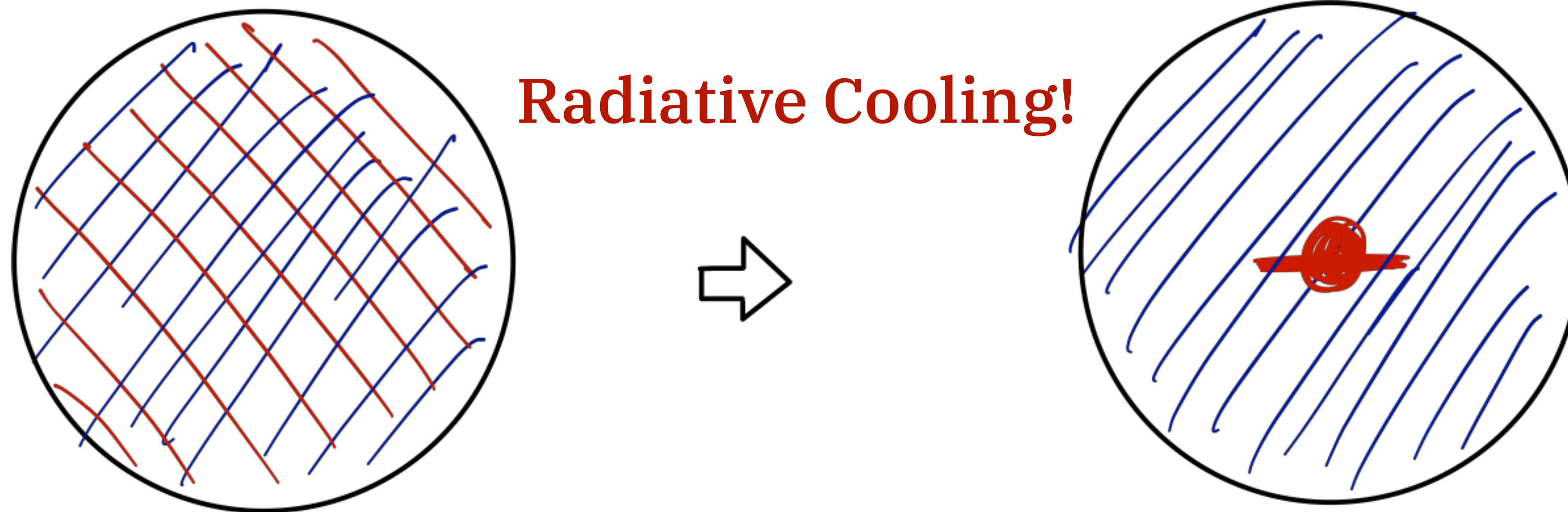


Three particle species

Particles in the dark sector

- In dark sector, we have
 - Dark **proton** (X)
 - Dark **electron** (c)
 - Dark **radiation** (γ_D)
- Free parameters in the theory: m_X , m_c , α_D ($\sim 1/137$), $\xi (=T_D/T_Y)$
- With dark radiation, we have a variety of dark structures by energy dissipation, including dark black holes.

Dissipation and cosmic structures



- **CDM**($\sim 5/6$): no interaction. responsible for growth of structure
- **Baryons**($\sim 1/6$): interaction with photon, can **radiate, cool down**
- With **Dark-atom**, DMs can also sink/form small structures.

Constraint on dark temperature

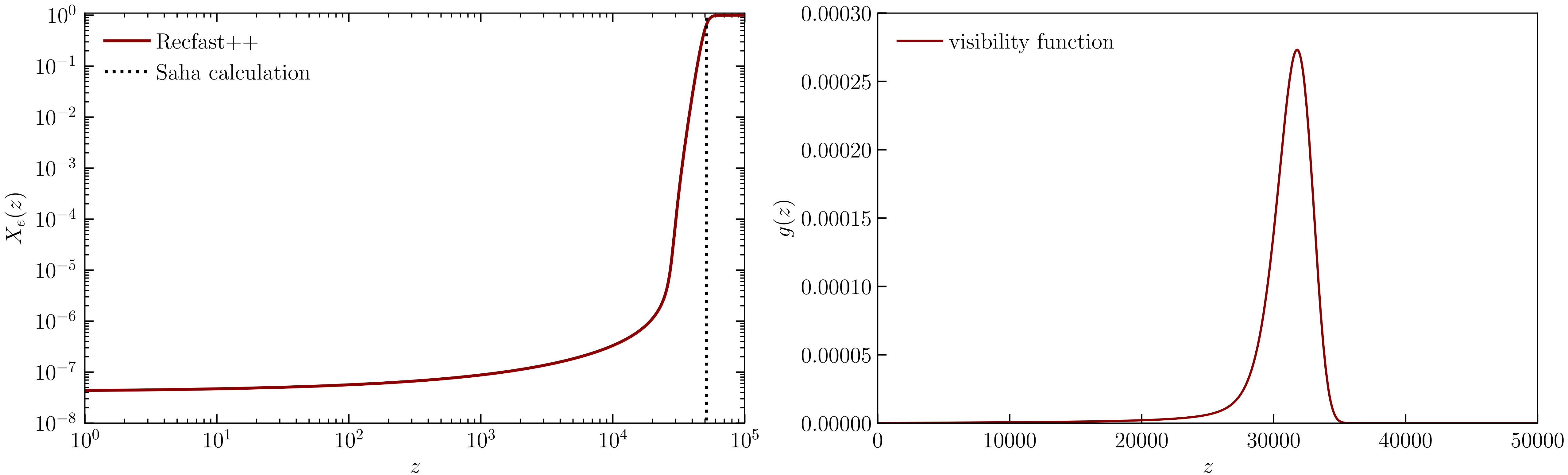
- The CMB anisotropies and BBN constrain the effective number of neutrino species N_{eff} with $\Delta N_{\text{eff}} \sim 0.2$ (Planck 2015),

$$N_{\text{eff}} = 3.046 + \frac{8}{7} \left(\frac{T_{\text{cmb}}}{T_\nu} \right)^4 \xi^4 \simeq 3.046 + 4.40 \xi^4$$

from which $\xi < 0.46$ (0.69) is allowed in $1\text{-}\sigma$ ($4\text{-}\sigma$) level.

- If thermally produced, we can lower ξ by decoupling dark sectors at high temperature where $g_{\star,s}$ is higher.
- But, for secluded dark sector, ξ can be anything below the limit.

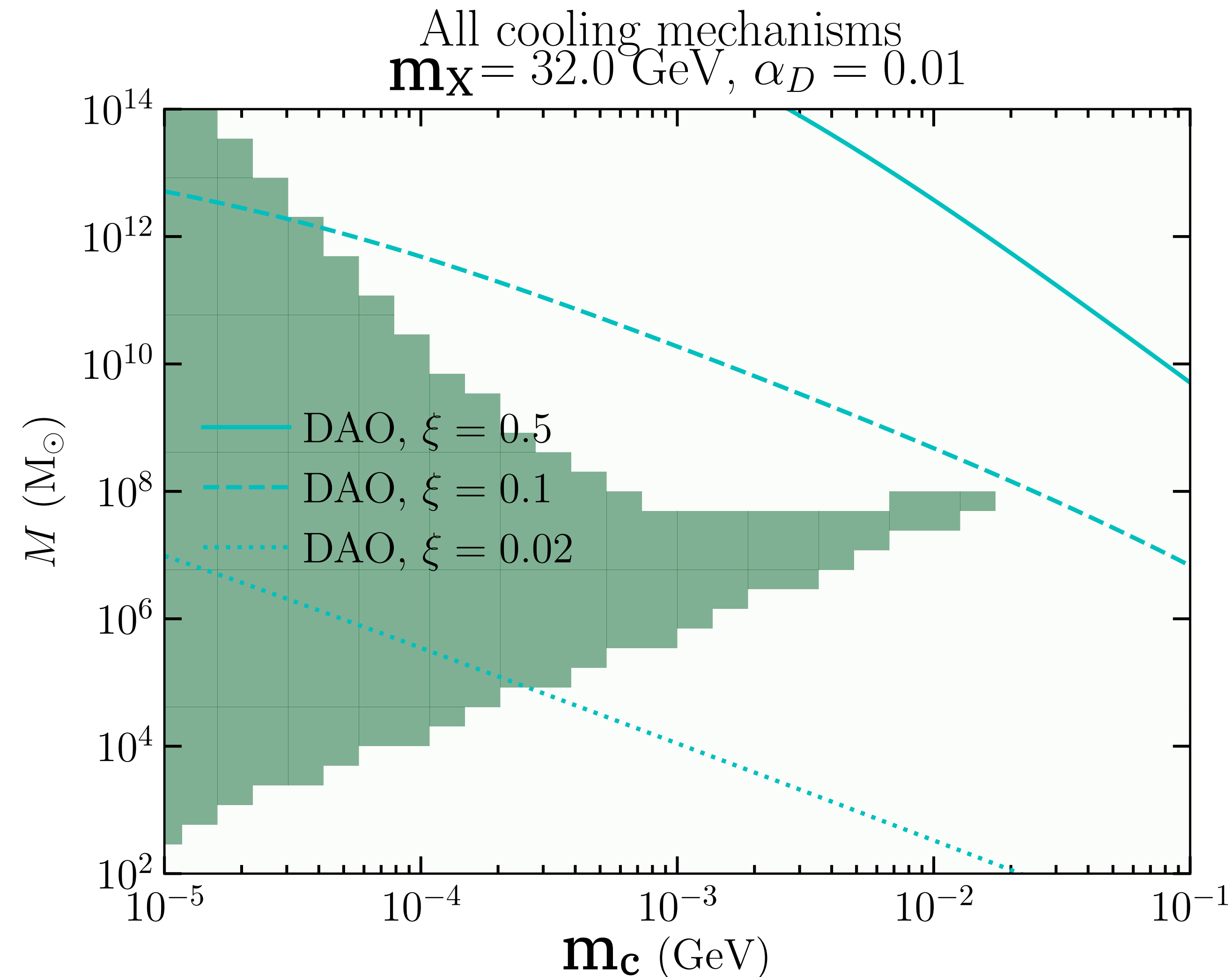
Dark recombination & decoupling



$m_X=16$ GeV, $m_c=140$ keV, $T_D=0.02 T_{\text{CMB}}$ case

$z_{\text{Recombination}} \sim 51000$, $z_{\text{decoupling}} \sim 32000$, $d_{\text{DAO}} \sim 0.02 \text{ Mpc}$, $1/k_D \sim 0.24 \text{ Mpc}$

DO NOT spoil large-scale structure



- With U(1)-DM, dark matters can cool by usual processes
- To explain observed large-scale structure, we invert the *Rees-Ostriker condition* to make cooling unimportant for $M > 10^{11} M_\odot$ halos,

$$t_{\text{cool}} > t_{\text{age}}$$

Dark star formation

- is parallel to the formation of first stars.
- Residual dark electrons from dark recombination catalyze the formation of dark Hydrogen molecule. These molecules can cool dark matters with energy level

$$\Delta E = \left(\frac{m_p}{m_X} \right) \left(\frac{m_c}{511 \text{ keV}} \right)^2 \left(\frac{\alpha_D}{0.0073} \right)^2 \times 512 \text{ K}.$$

- DS formation is similar to Pop-III except for the temperature.
- We, therefore, use the Pop-III binary literature extensively.

Two mass scales

- Chandrasekhar mass

$$M_{\text{Chand.}}^{\text{Dark}} = 1.457 M_{\odot} \left(\frac{m_p}{m_X} \right)^2$$

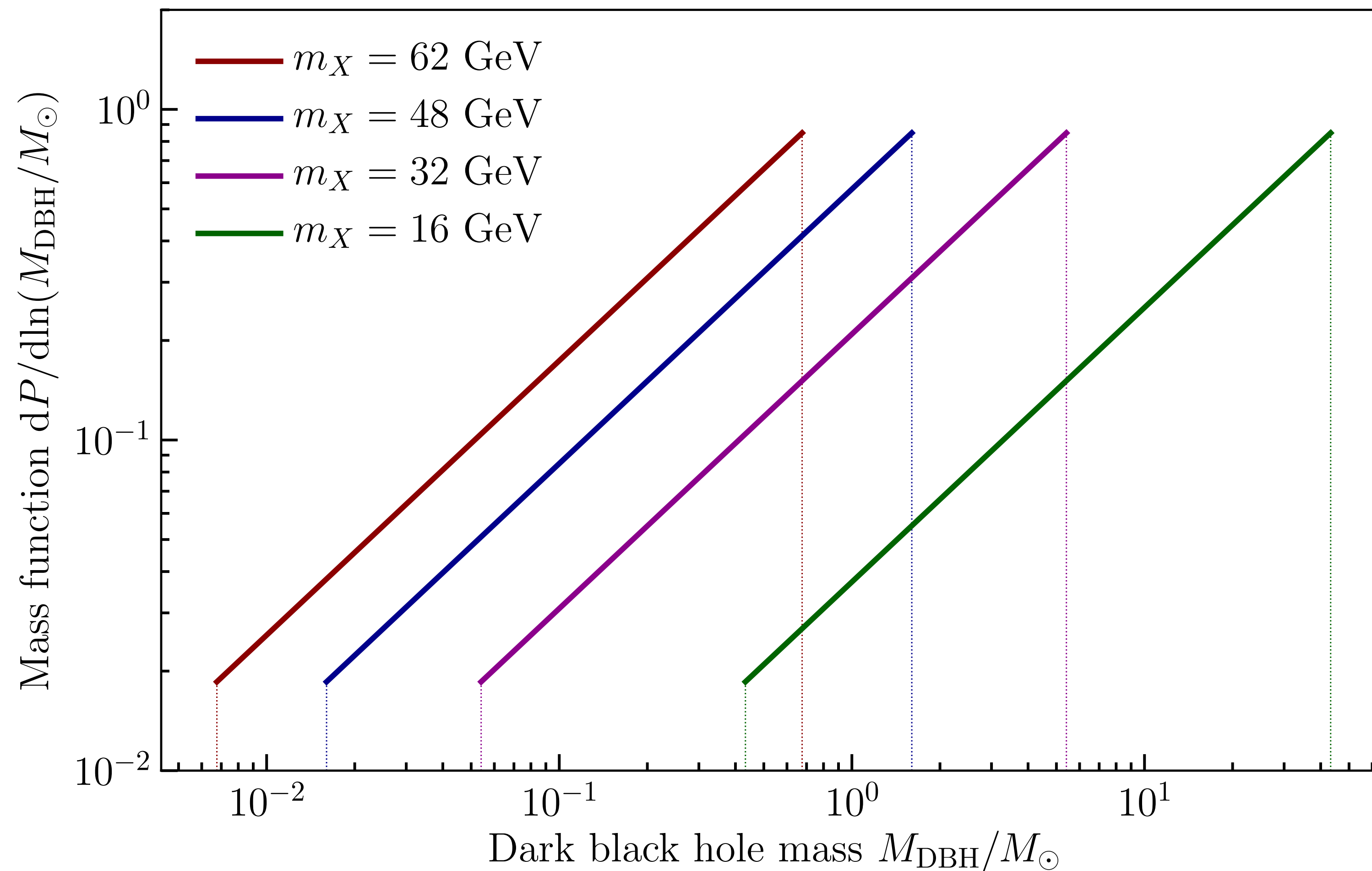
Chandrasekhar (1931)

- Opacity limit (minimum Jeans mass of fragmentation)

$$M_{\text{DBH,min}} \sim \left(\frac{m_p}{m_X} \right)^{9/4} \left(\frac{T}{10^3 K} \right)^{1/4} 10^3 M_{\odot}$$

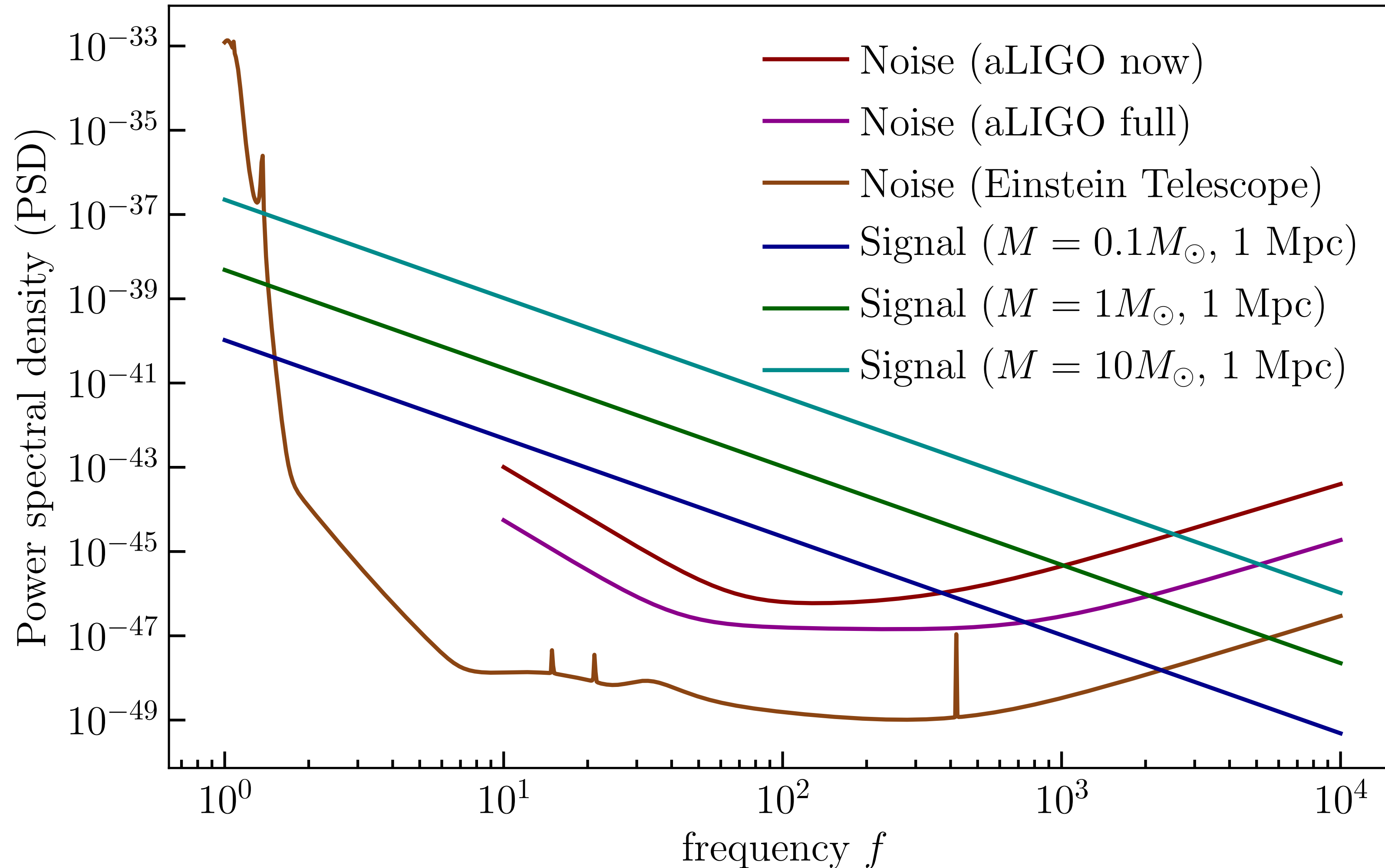
Rees (1976), Low & Lynden-Bell (1976)

Dark BH mass function



aLIGO is capable to *hear* sub- $M_{\odot}$ BHs!

During the in-spiral phase, Noise curve from B. S. Sathyaprakash

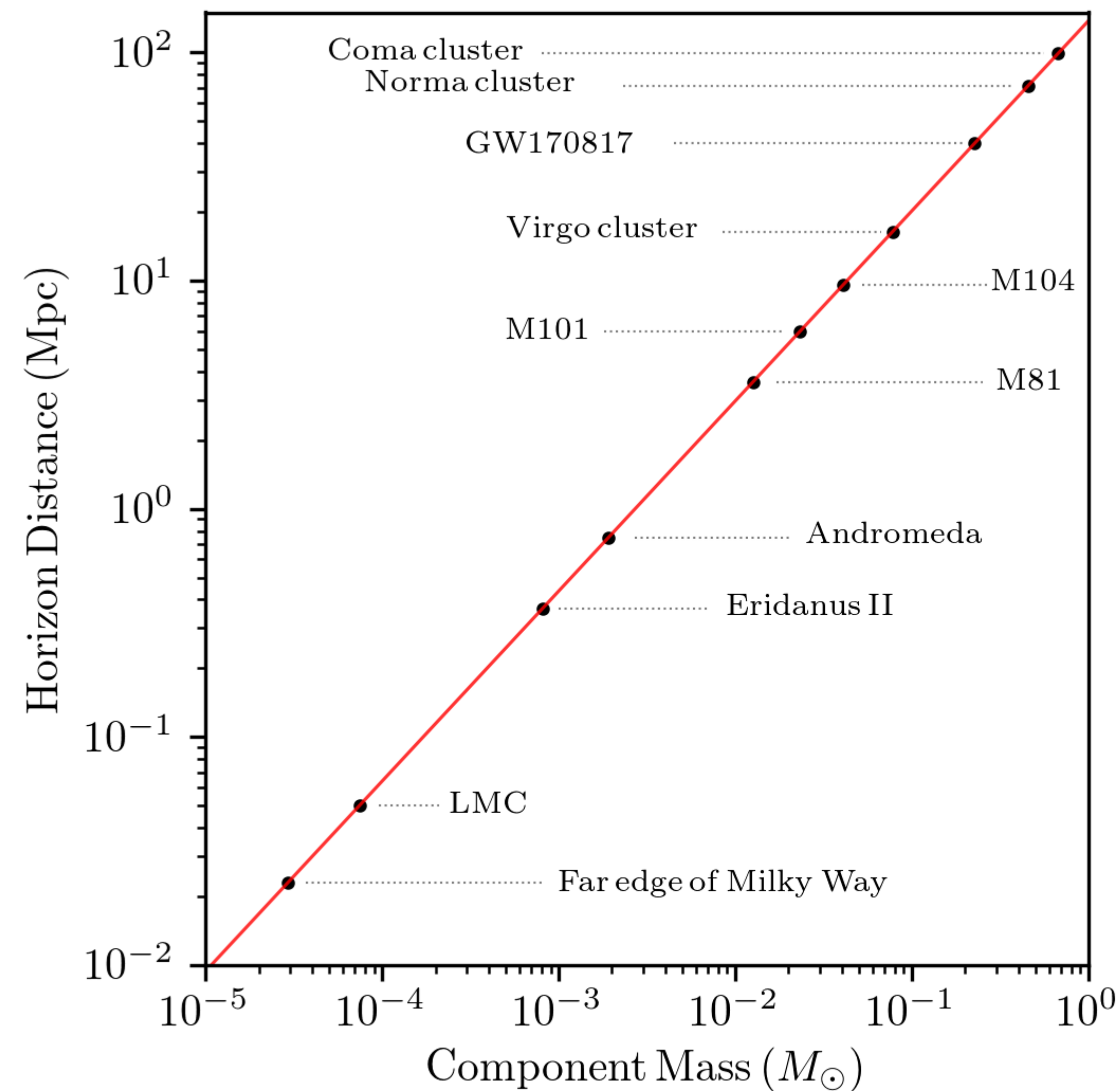
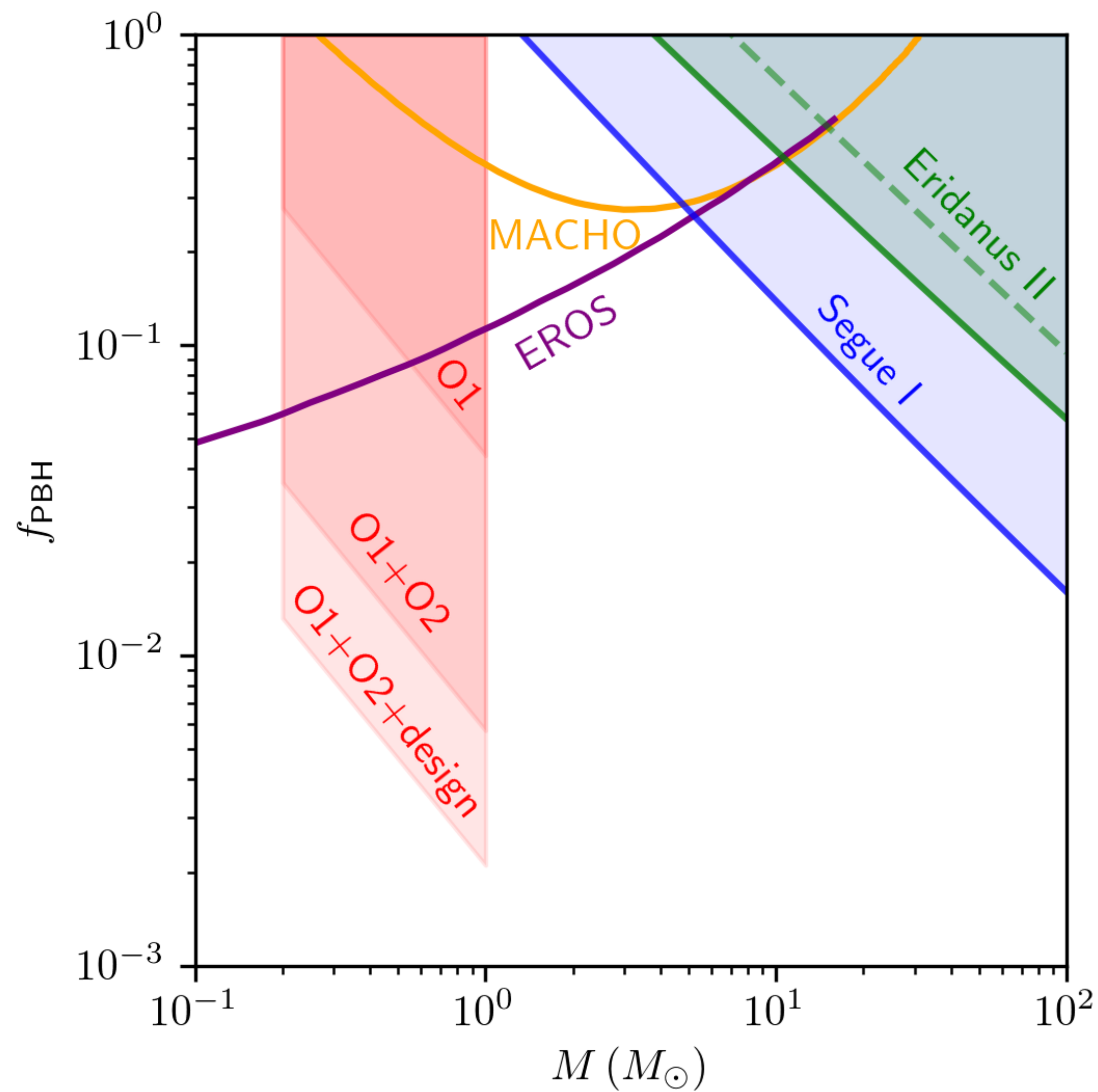


Yes, we can detect them!

m_X [GeV]	m_c [keV]	$M_{\text{Chand.}}^{\text{dark}}$ [$10^{-5} M_\odot$]	M_{DBH} [$M_\odot$]	Rates per year				$m_1 < 1.4$ [%]	$m_1, m_2 < 1.4$ [%]
				raw (MWE G^{-1})	aLIGO (current)	aLIGO (full)	Einstein T.		
62	30	33	0.0068 – 0.68	$2.0 \times 10^{-6} (10^{-4})$	0.0012 (0.12)	0.020 (2.0)	60 (6000)	100%	100%
48	47	56	0.016 – 1.6	$1.3 \times 10^{-6} (10^{-4})$	0.0065 (0.65)	0.11 (11)	330 (33k)	99%	79%
32	70	125	0.054 – 5.4	$6.6 \times 10^{-7} (10^{-5})$	0.068 (6.8)	1.1 (110)	3500 (350k)	53%	9.3%
16	144	500	0.43 – 43	$1.9 \times 10^{-7} (10^{-5})$	0.89 (89)	22 (2200)	92k (9200k)	9.8%	0.14%

TABLE I. Dark black hole masses and binary merger rates today, estimated using the procedure in the text, for several choices of dark proton mass m_X and dark electron mass m_c . All black hole masses are given in solar masses. In all cases we have set the dark fine structure constant to $\alpha_D = 0.01$ and the ratio of present day temperature of the dark sector to photon temperature to $\xi = 0.02$. The conservative (optimistic) rates use $f_{\text{cool}} \times f_{\text{form. eff.}} = 10^{-5} (10^{-3})$. Note that the optimistic rate for $m_X = 50$ GeV is high enough that it would be worth a more careful analysis to see if current aLIGO already constrains this parameter space. The last two columns show the percent of binaries where one or both black holes in the binary has a mass less than the standard Chandrasekhar mass ($1.4 M_\odot$).

Search result so far



Conclusion

- A complete model of inflation requires a solid understanding of the small-scale primordial power spectrum; yes, it is hard!
- Here, we discuss three possible constraints:
 - Abundance of primordial black hole
 - Alternative thermal history due to diffusion
 - Stochastic gravitational waves
- As usual, need to study the systematics and foreground.