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WIMP Dark Matter in the Early Matter Dominated Universe

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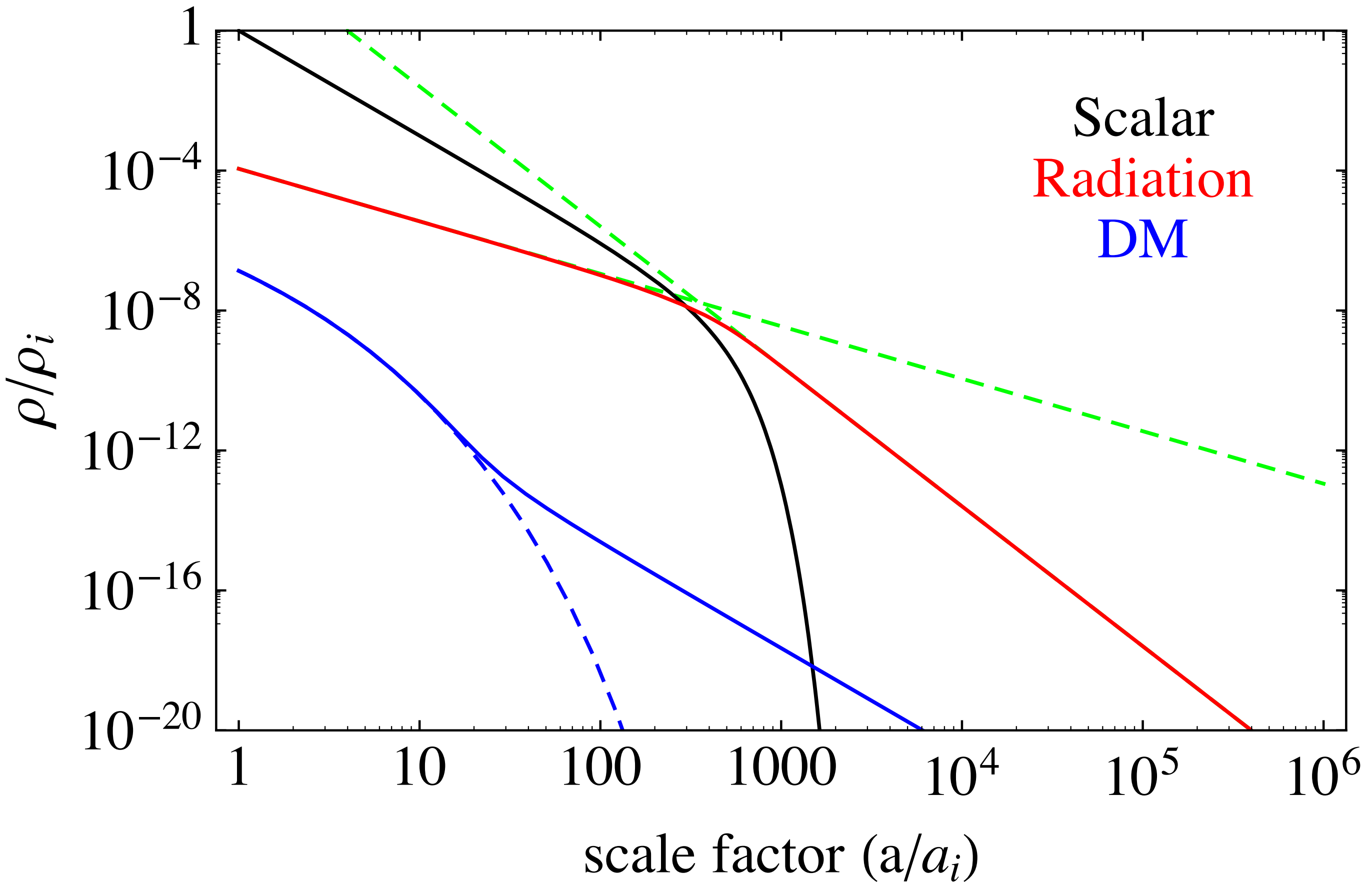
Contents

Early Matter Domination (eMD) and Low Reheating Temperature

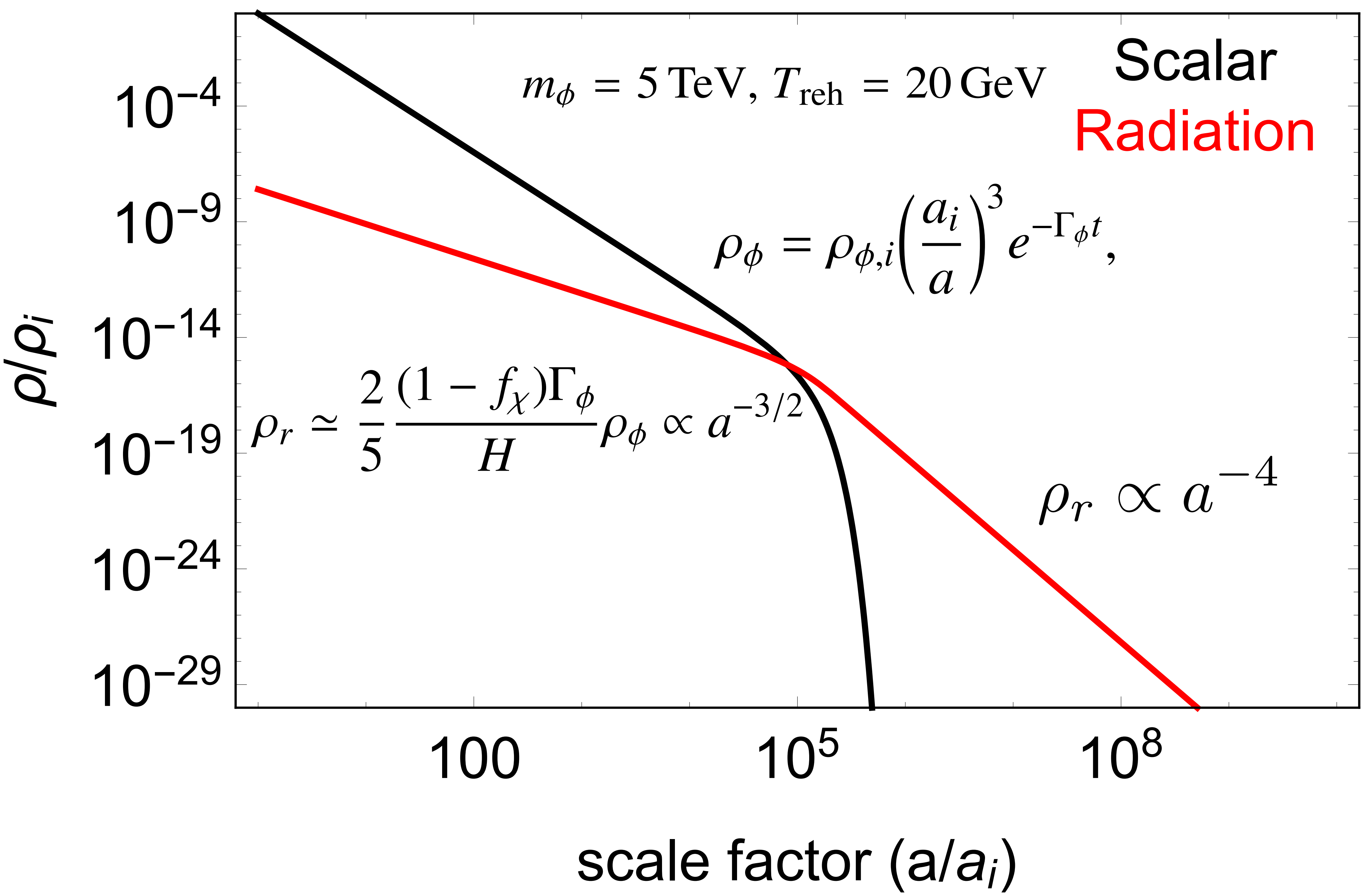
The Universe is dominated by heavy particles (early matter domination) and reheated (radiation domination) by the decay of them. It happens for:

- Inflaton oscillation
- Thermal inflation
- Curvaton domination
- Heavy axino and saxion
- Moduli
- .....

$$T_{\rm reh} \simeq \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{\Gamma M_P}$$



Background Energy Density



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1. The smallest scale of the objects in the Universe

Kinetic decoupling scale of WIMP $\stackrel{?}{=}$ the smallest scale of the structure formation?

Creation of Isocurvature Perturbation

After chemical decoupling and before reheating during scalar-domination:

Dark matter and radiation are still kinetically coupled: $\theta_m \approx \theta_r$.

$$\dot{\delta}_m \approx -\frac{\theta_r}{a},$$

$$\dot{\delta}_r \approx -\frac{4}{3}\frac{\theta_r}{a} + \frac{\Gamma_\phi \rho_\phi}{\rho_r}(\delta_\phi - \delta_r),$$

Radiation is still produced from decay of the dominating scalar, however dark matter is not produced any more.

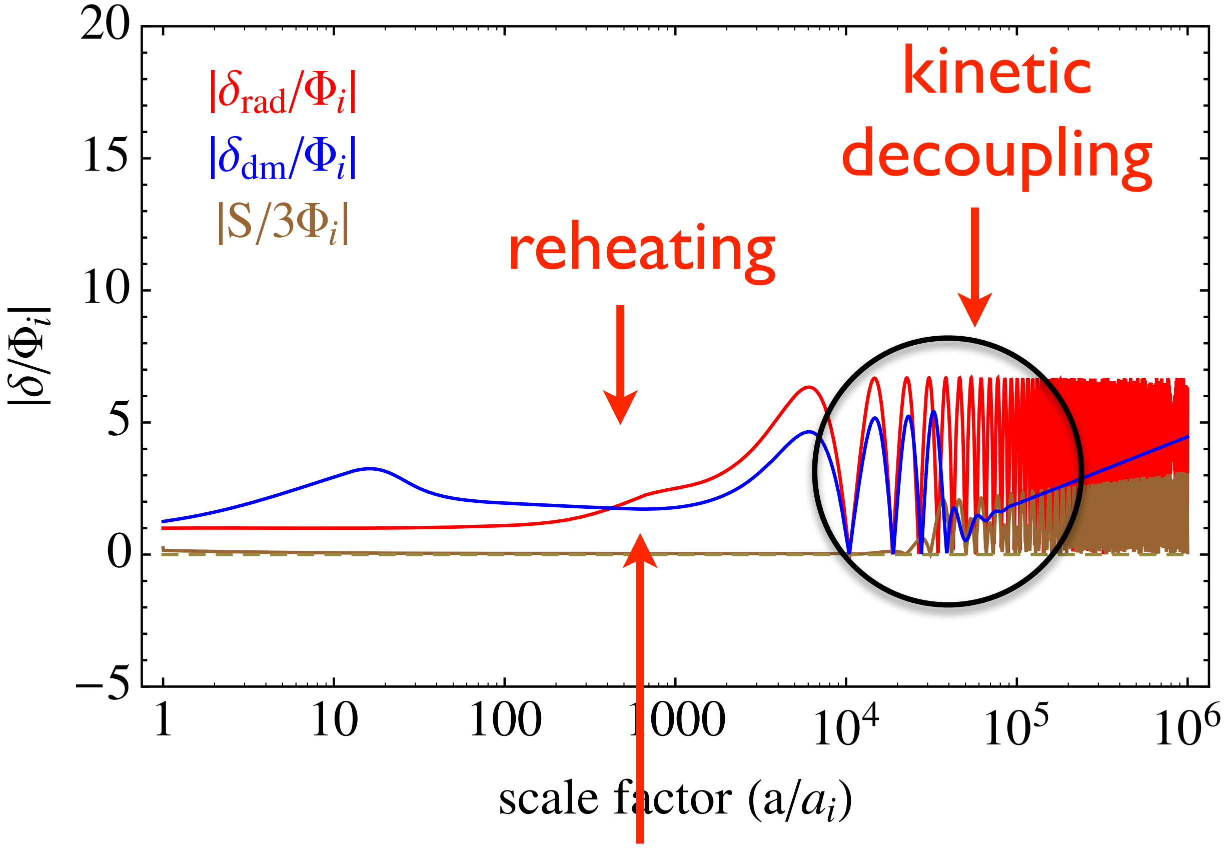
The difference in the number density creates the isocurvature perturbation between dark matter and radiation.

[KYChoi, Gong, Shin 2015]

$$S(t_{\rm reh}) \approx -\frac{3}{4}\int_{t_i}^{t_{\rm reh}} dt\, \frac{\Gamma_\phi \rho_\phi \delta_\phi}{\rho_r} \approx \frac{5}{4}\Phi_i \left(\frac{k}{k_{\rm reh}}\right)^2.$$

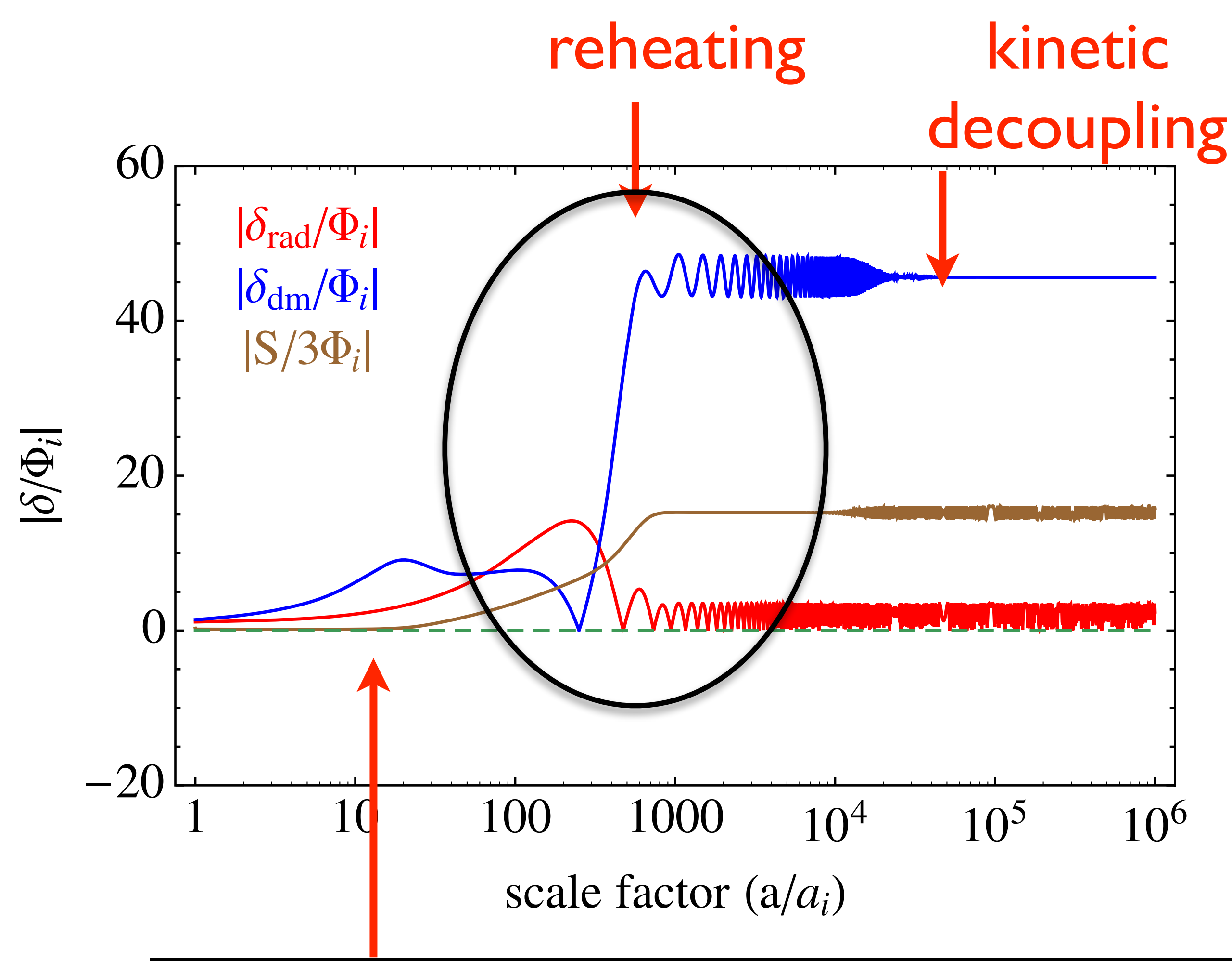
Creation of Isocurvature Perturbation

[KYChoi, Gong, Shin 2015]



Horizon entry after reheating

Damping erases the perturbations.

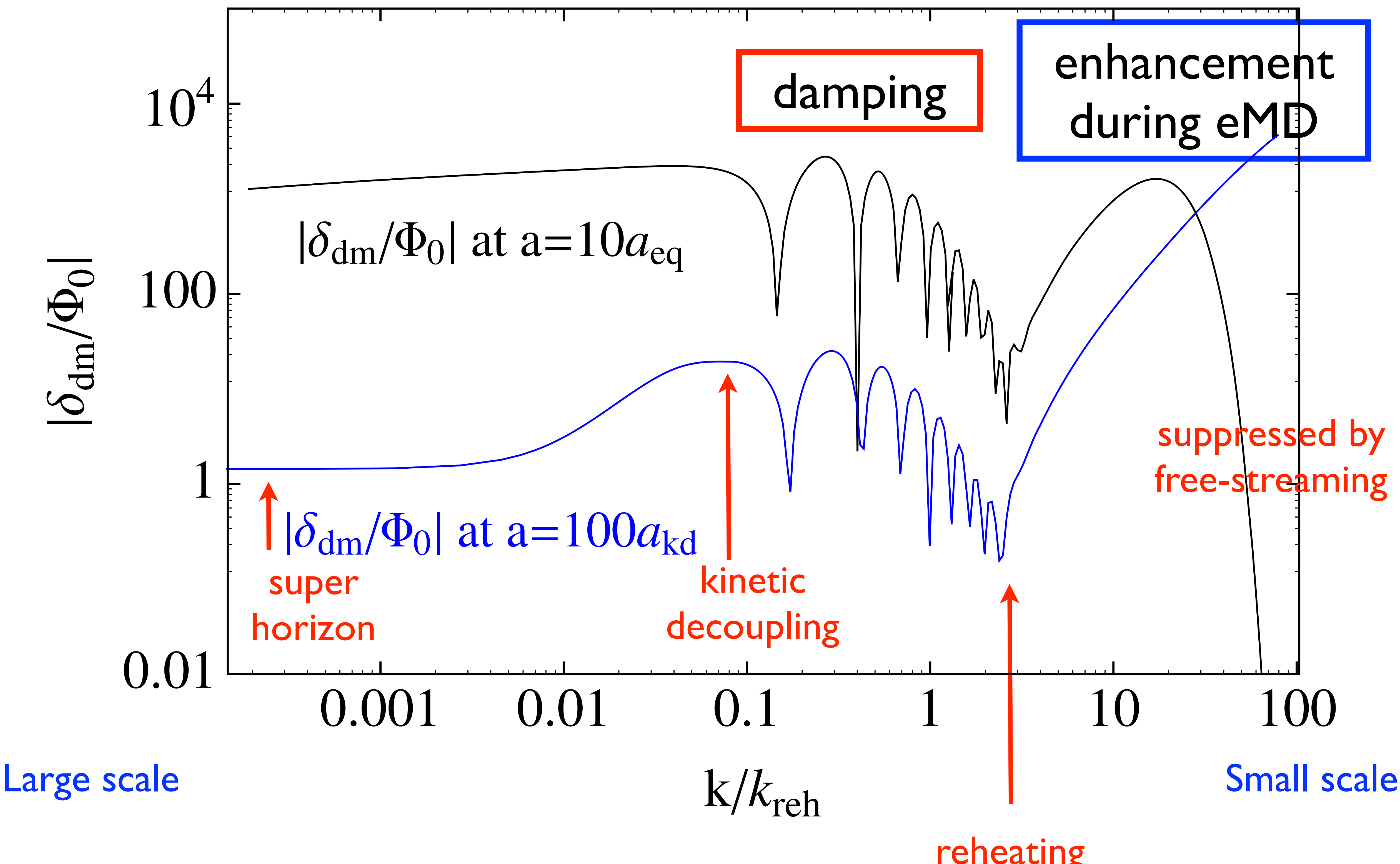


Horizon entry during early MD before reheating

Enhancement and No damping.

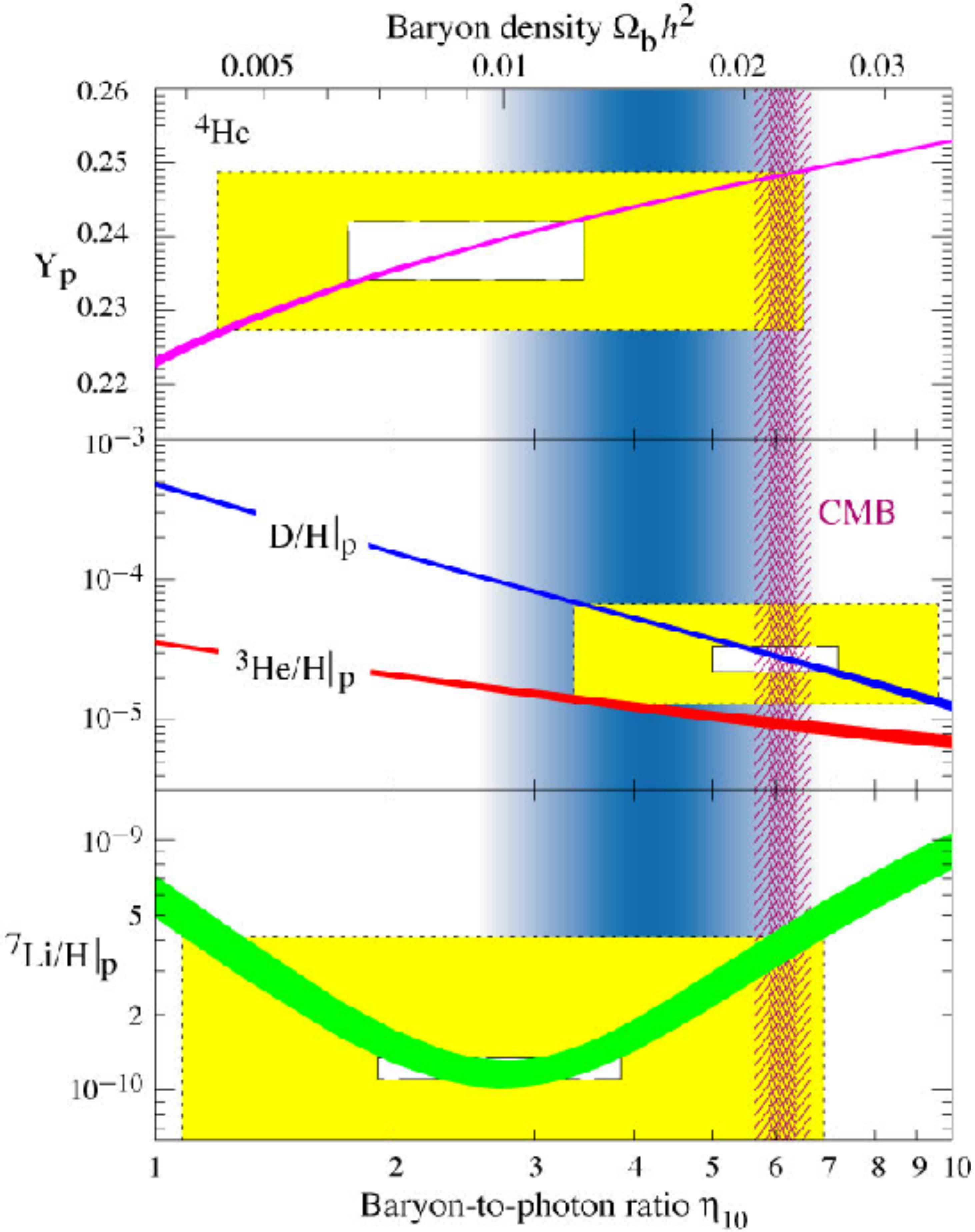
Damping and Enhancement of Density Perturbation

[KYChoi, Gong, Shin 2015]



The scale which enters during eMD, is not suppressed during the kinetic decoupling, and thus there exists smaller scale objects than the scale of kinetic decoupling.

2. Low-bound on reheating temperature with dark matter



BBN and CMB for baryon density

The comparison between the observed light element abundances and the theoretical calculation shows that the baryon-to-photon ratio is

$$\eta_{10} = \frac{n_b}{n_\gamma} \times 10^{10} \sim 6$$

or

$$Y_B \equiv \frac{n_B}{s} \simeq 0.86 \times 10^{-10}$$

Baryon energy density in the Universe

$$\rho_b = 4 \times 10^{-31}\, g/cm^3$$

corresponds to the baryon density

$$\Omega_b\, h^2 \simeq 0.02$$

Low bound on Reheating Temperature

1. Big Bang Nucleosynthesis
: at low-reheating temperature, neutrinos are not fully thermalised and the light element abundances are changed,

$$T_{\rm reh} \gtrsim 0.5 - 0.7\,{\rm MeV}$$

$$T_{\rm reh} \gtrsim 2.5\,{\rm MeV} - 4\,{\rm MeV}$$ for hadronic decays

[Kwasaki, Kohri, Sugiyama, 1999, 2000]

2. BBN+CMB
: precise calculation of the cosmic neutrino background and CMB

$$T_{\rm reh} \gtrsim 4.7\,{\rm MeV}$$

[Salas, Lattanzi, Mangano, Miele, Pastor, Pisanti, 2015]

New bound on low-reheating temperature

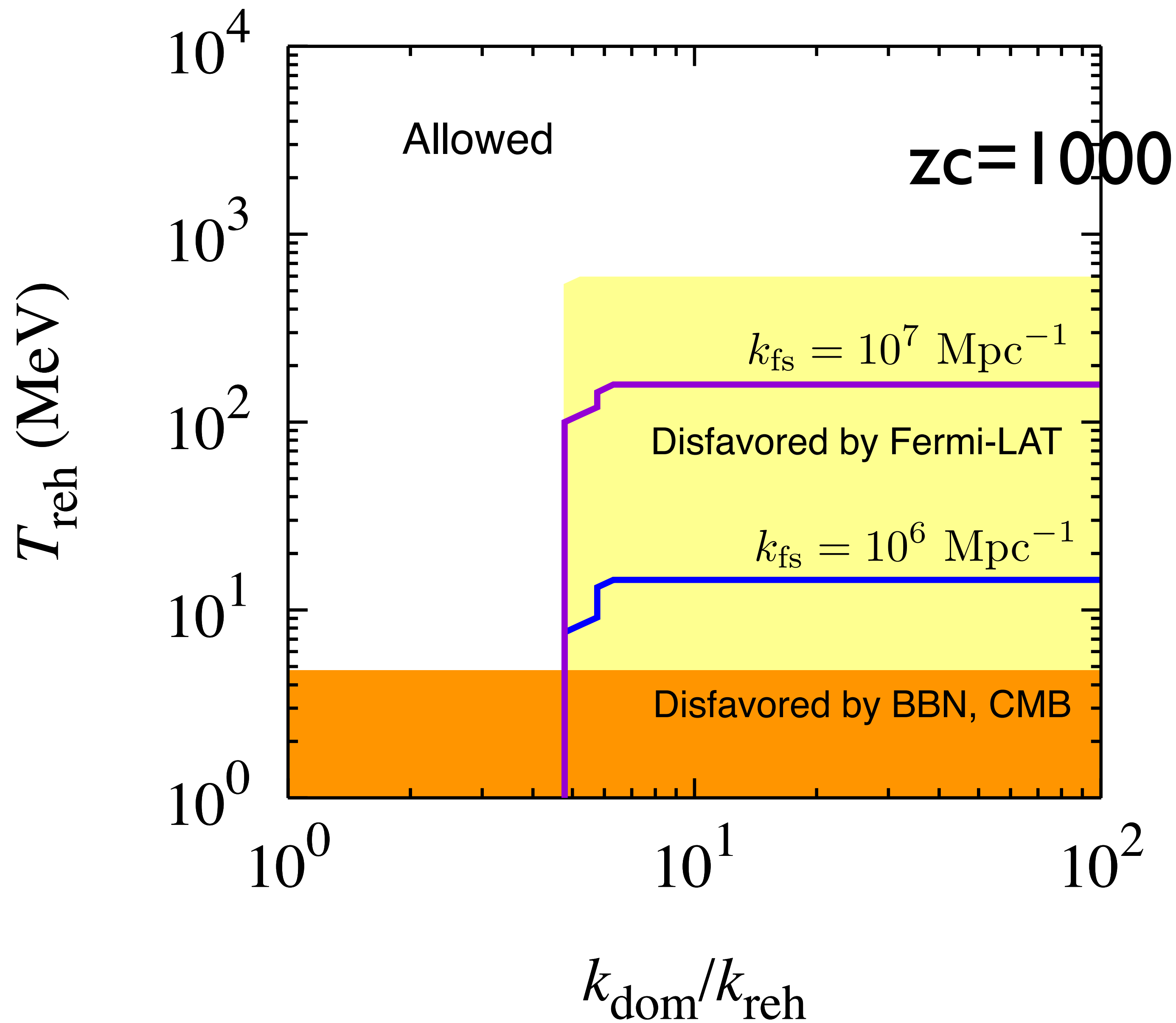
3. Dark matter halos
: density perturbation during early matter-domination and no observation of small scale DM halos.

$$T_{\rm reh} \gtrsim 10\,{\rm MeV} - 100\,{\rm MeV}$$

[KYChoi, Tomo Takahashi, PRD 2017]

Low bound on Treh with WIMP DM of UCMHs

UCMH production from the large perturbation



[Smoot's talk]

UCMH constraint by Fermi-LAT from annihilation of WIMP DM.

$$T_R \gtrsim 10 - 100\,{\rm MeV}$$

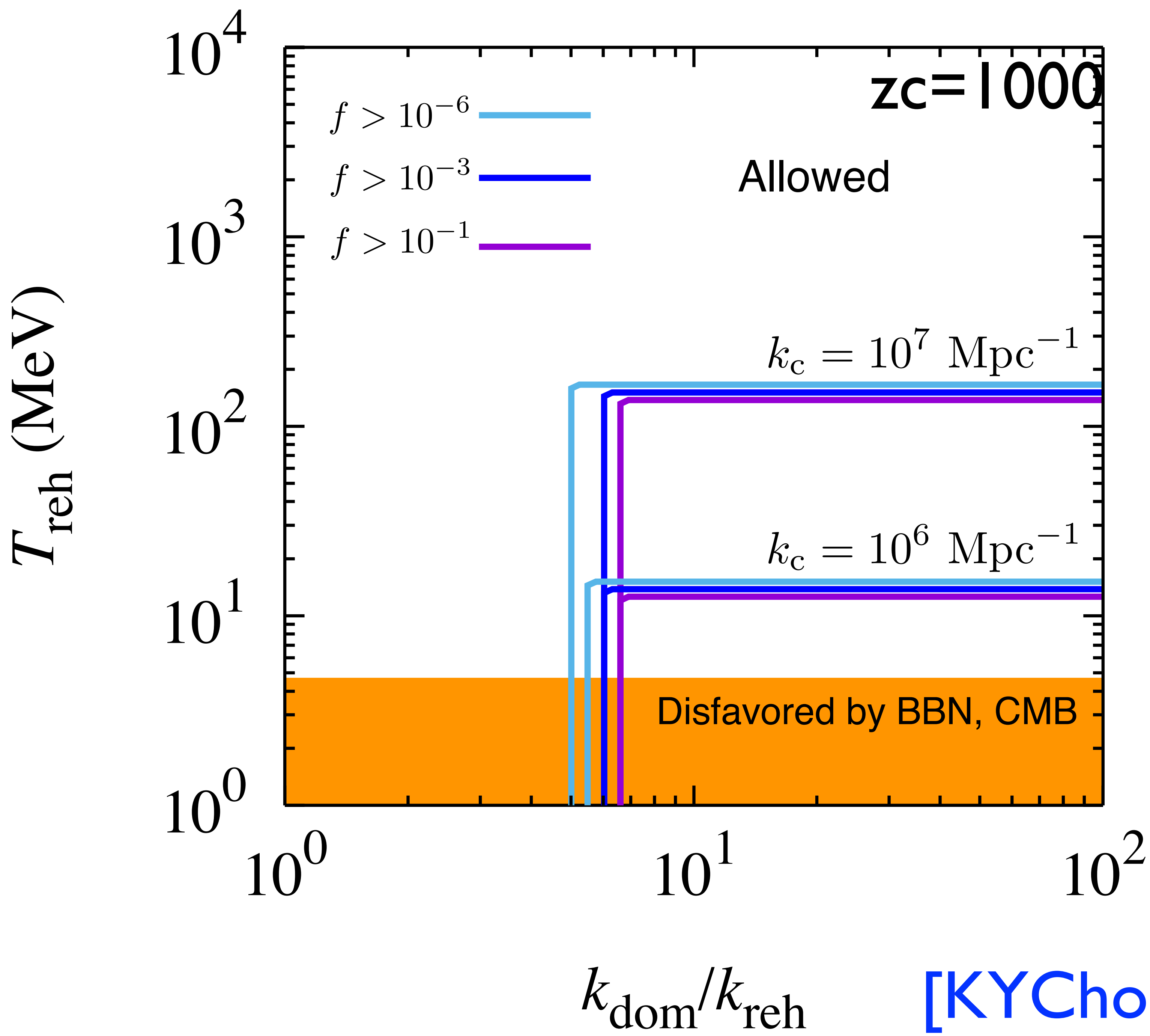
[KYChoi, Tomo Takahashi, 2017]

cf) $T_{\rm reh} \gtrsim 4.7\,{\rm MeV}$ BBN+CMB

[Kwasaki, Kohri, Sugiyama, 1999, 2000]
[Salas et al 2015]

$k_{1{\rm MeV}} = 10^4\,{\rm Mpc}^{-1}$

Future Low bound on Treh with non-WIMP DM



Future gravitational observations: lensing, pulsar timing

at the scale of

$$k_c$$

$$T_R \gtrsim 10 - 100\,\mathrm{MeV}$$

[KYChoi, Tomo Takahashi, 2017]

3. Baryogenesis with low-reheating temperature

[KYC, Jongkjuk Kim, Sinkyu Kang, PLB 2018]

[Jongkuk's talk today afternoon]

Matter >> anti-matter

We see only matters on Earth, and in the Universe.
Anti-matters are rare. They exist only in the laboratories or in the cosmic rays with small amount

Baryogenesis

Why there are more matters than anti-matter?
The amount of matter compared to the entropy (or photon):

$$Y_B \equiv \frac{n_B}{s} \simeq 0.86 \times 10^{-10}$$

$$s \simeq 7.04 n_\gamma$$

*Y is conserved quantity when s and n decreases as 1/a^3.

Non-thermal WIMP Baryogenesis

[KYC, Jongkjuk Kim, Sinkyu Kang, PLB 2018]

[Jongkuk's talk today afternoon]

Heavy particle

↓ decay

radiation + **WIMP dark matter**

: thermalized

$T < T_{\rm fr}$

: already decoupled

out-of-equilibrium

↓ annihilation $n_\chi \langle \sigma_{\rm A} v \rangle > H,$

with P, CP, B violation

Asymmetry of Baryon (Lepton)

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Non-thermal WIMP Baryogenesis

Baryogenesis model which is working for low-reheating temperature.

Summary

- Early Matter Domination (eMD) occurs often.

  :They decay and produced light particles for the later radiation domination

- The smallest scale of objects

  :The smallest scale may be smaller than the kinetic decoupling scale.

- Low-bound on the reheating temperature

  : a few MeV - 100 MeV

- Non-thermal WIMP Baryogenesis

  : Baryogenesis model from WIMP dark matter at low-reheating temperaure

Thank You!