Dark matter and Bounds on the low-reheating Temperature

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Based on the collaboration with Ki-Young Choi (Chonnam National University)

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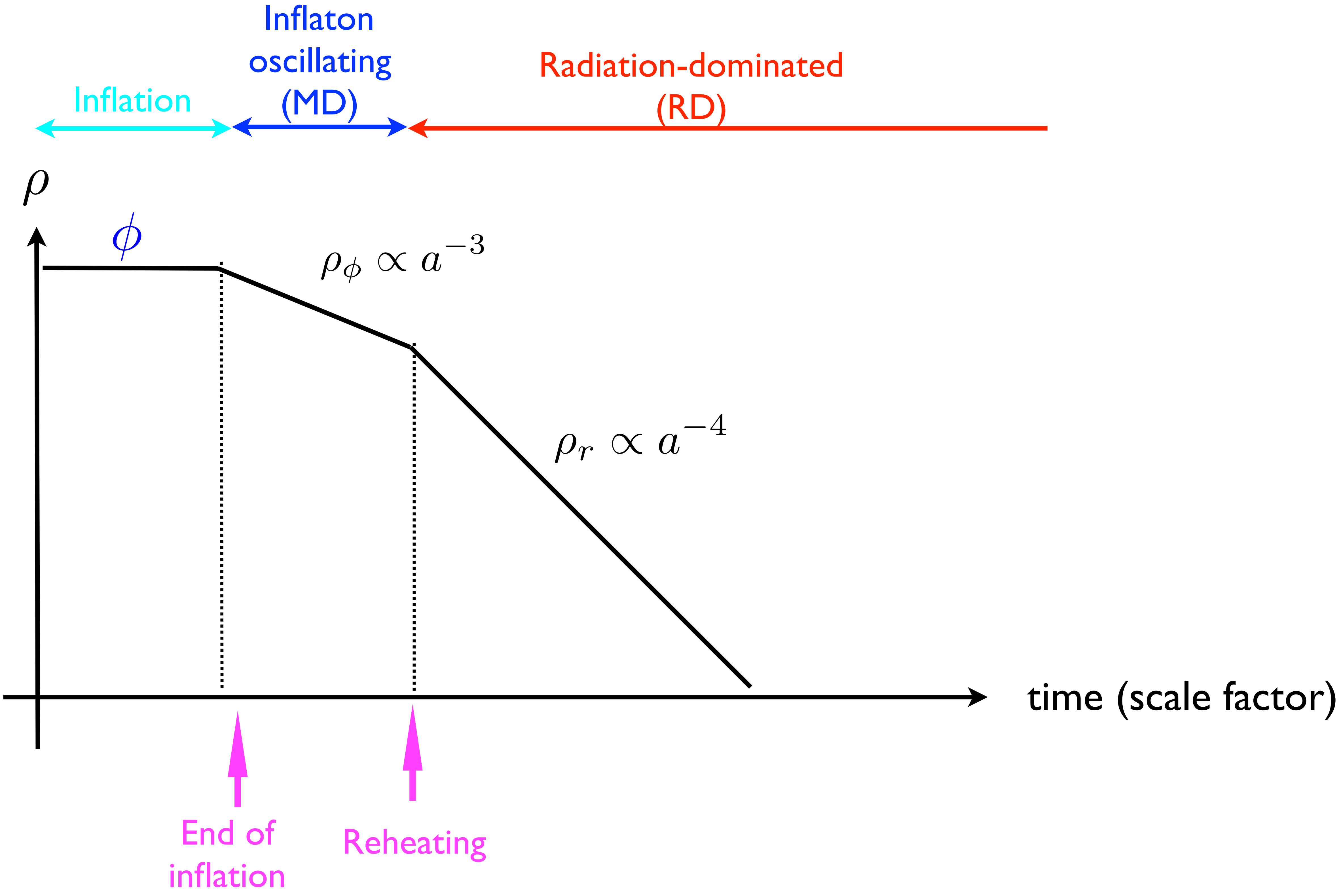
Thermal history of the Universe



Early matter-dominated period

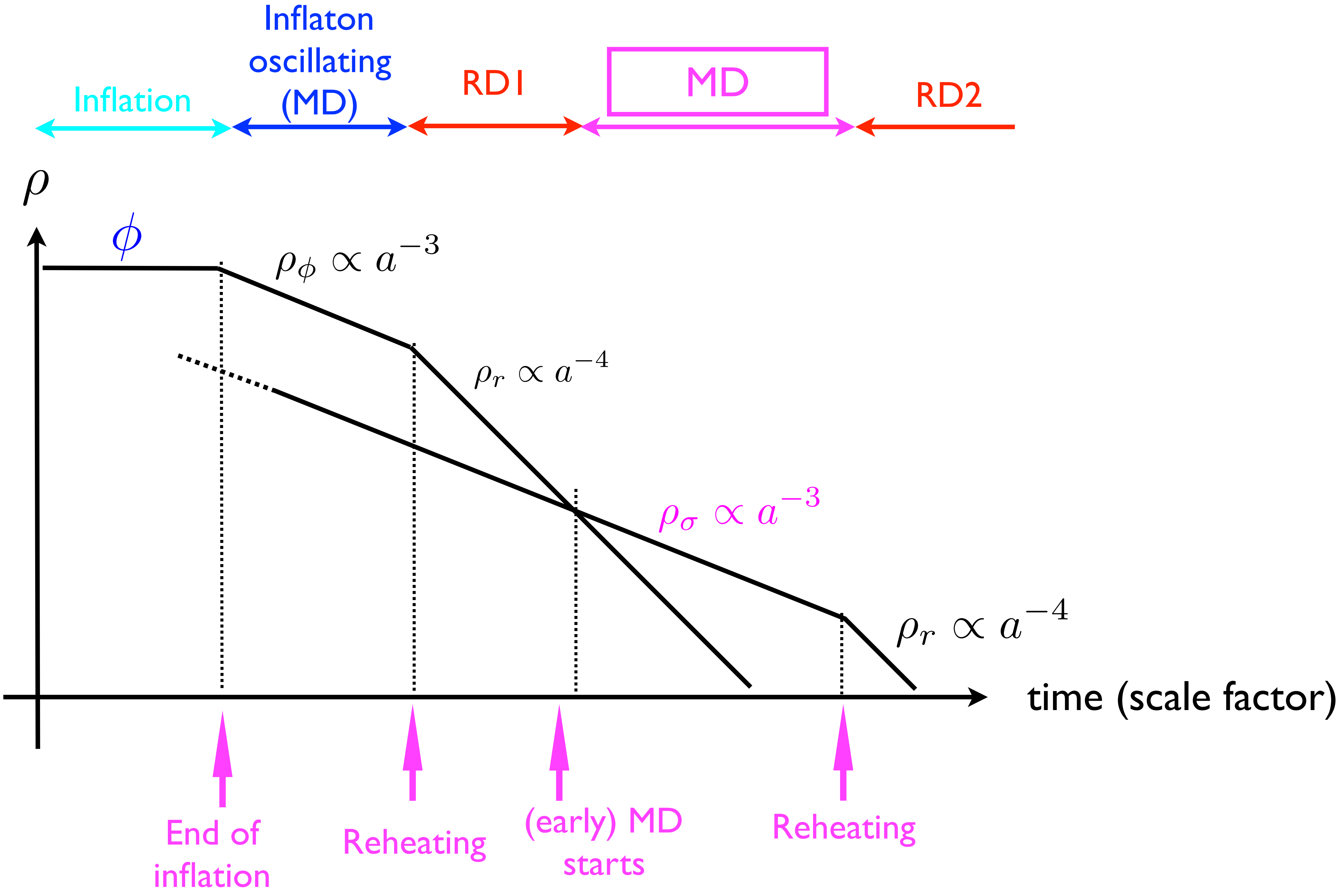
- In some models, non-relativistic particles (oscillating scalar fields, e.g., moduli) can dominate the Universe at some point after the inflaton reheating.

- There exists an early matter(like)-dominated era.

- After the early matter-dominated era, the Universe becomes radiation-dominated again.

- In this case, the reheating temperature could be low.

Thermal history of the Universe



Bounds on the low-reheating temperature

- Big bang nucleosynthesis (BBN)

[Kawasaki, Kohri, Sugiyama astro-ph/98111437; 0002127]

If large entropy production occurs at around BBN, a large fraction of neutrino cannot be thermalized (distribution function of neutrinos are affected.)

→ The freeze-out value of p/n ratio is changed.

→ The abundance of light element is affected.

$$T_{\rm reh} \gtrsim 0.7 \ {\rm MeV}$$

(95% C.L)

$$T_{\rm reh} \gtrsim 2.5 - 4.0 \ {\rm MeV}$$ [hadronic decay]

(for the hadronic branching ratio $B_h = 10^{-2} - 1$)

Bounds on the low-reheating temperature

- CMB (+BBN)

[de Salas et al., 1511.00672]

If large entropy production occurs at around BBN, a large fraction of neutrino cannot be thermalized (distribution function of neutrinos are affected.)

In the CMB analysis, we can also constrain the following quantities:

- The effective number of neutrino
- Helium abundance
- Baryon number

→ These are interconnected in BBN.

$$T_{\rm reh} \gtrsim 4.7 \ {\rm MeV}$$ [Planck2015 TT+ lowP] (95% C.L)

Bounds on the low-reheating temperature

- Bounds from ultracompact minihalos (UCMHs) (This talk)

[K.Y.Choi, TT in prep.]

Ultracompact mihihalos (UCMHs):

- DM halo undergoes collapse shortly after the recombination.
- denser than later forming minihalos.
- have a steep density profile $\rho \propto r^{-9/4}$

UCMHs may lead to some astrophysical signature.

Value of δ to form UCMHs

- Large dark matter perturbation δ leads to the formation of:

  - Primordial black holes (PBH)

    $$\delta \gtrsim 0.3 - 0.7$$

  - Ultra-compact minihalos (UCMHs)

    $$\delta \gtrsim 10^{-3}$$

    (Even if the DM perturbation is not so large enough to PBH, it will lead to a compact cloud of dark matter.)

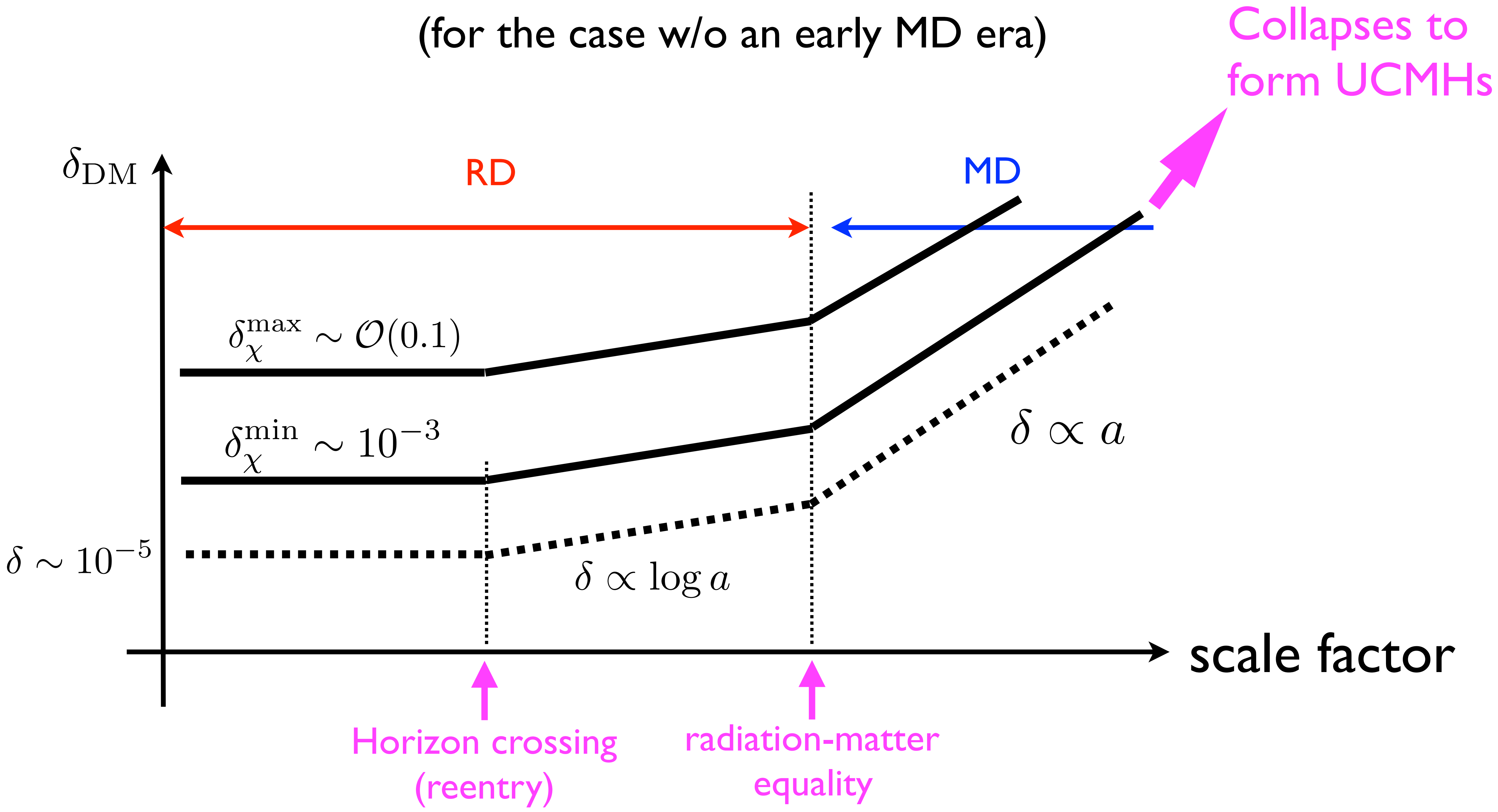
➜ UCMHs can be detected through:

- Gamma ray
- Pulsar timing
- Gravitational lensing

Minimum value of δ

- Minimum value of δ to form UCMHs $\delta_\chi^{\min}$

(for the case w/o an early MD era)



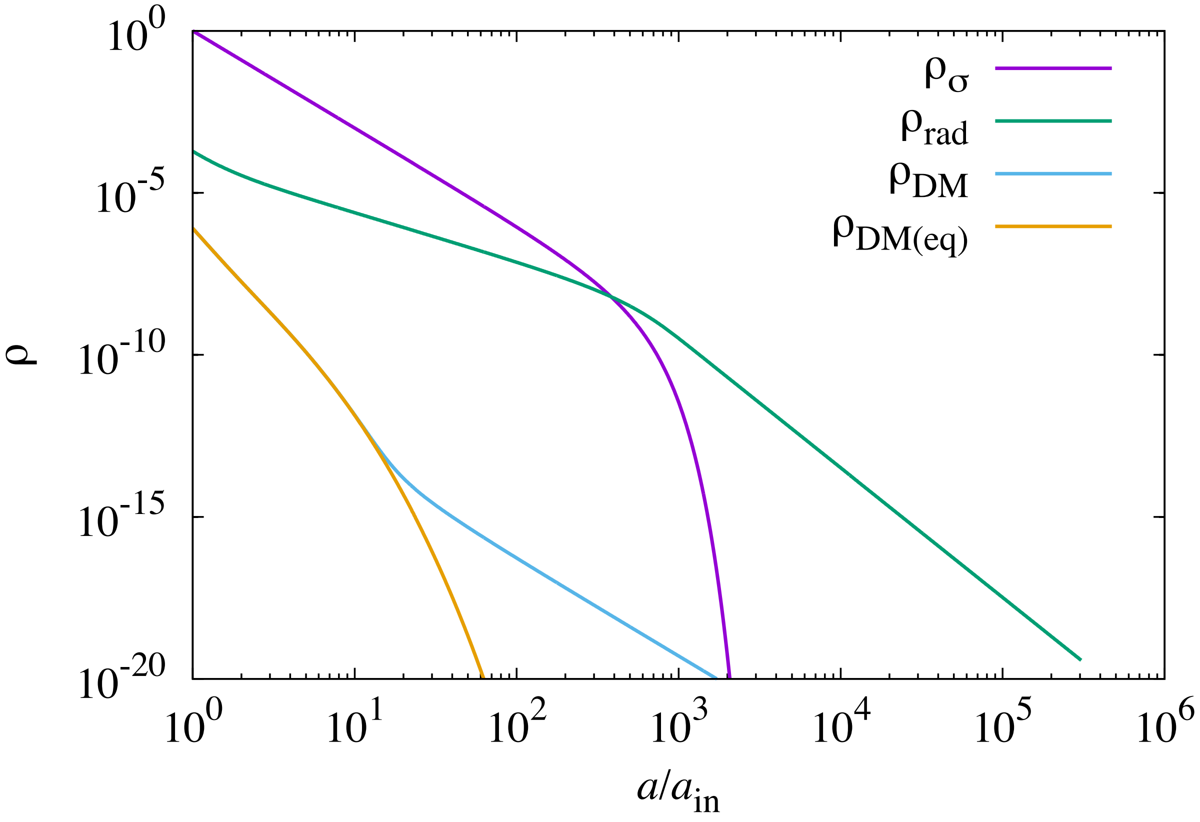
Evolutions of density perturbations

- Background evolution

$$\dot{\rho}_\sigma + 3H\rho_\sigma = -\Gamma_\sigma \rho_\sigma$$

$$\dot{\rho}_r + 3H\rho_r = \Gamma_\sigma \rho_\sigma + \frac{\langle \sigma_a v \rangle}{M_\chi} \left[\rho_\chi^2 - (\rho_\chi^{\rm eq})^2\right]$$

$$\dot{\rho}_\chi + 3H\rho_\chi = -\frac{\langle \sigma_a v \rangle}{M_\chi} \left[\rho_\chi^2 - (\rho_\chi^{\rm eq})^2\right]$$



Evolutions of density perturbations

- Perturbation equations (conformal Newtonian gauge)

[See e.g., Ma, Bertschinger 1995; Choi, Gong, Shin 1507.03871]

- Density perturbation $\delta_\alpha = \frac{\delta\rho_\alpha}{\rho_\alpha}$

$$\dot{\delta}_\alpha + (1+w_\alpha)\frac{\theta_\alpha}{a} - 3(1+w_\alpha)\dot{\Psi} = \frac{1}{\rho_\alpha}\left(\delta Q_\alpha - Q_\alpha\delta_\alpha + Q_\alpha\Phi\right)$$

- Velocity perturbation

$$\dot{\theta}_\alpha + (1-3w_\alpha)H\theta_\alpha + \frac{\Delta\Phi}{a} + \frac{w_\alpha}{1+w_\alpha}\frac{\Delta\delta_\alpha}{a} = \frac{1}{\rho_\alpha}\left[\frac{\partial_i Q^i_{(\alpha)}}{1+w_\alpha} - Q_\alpha\theta_\alpha\right]$$

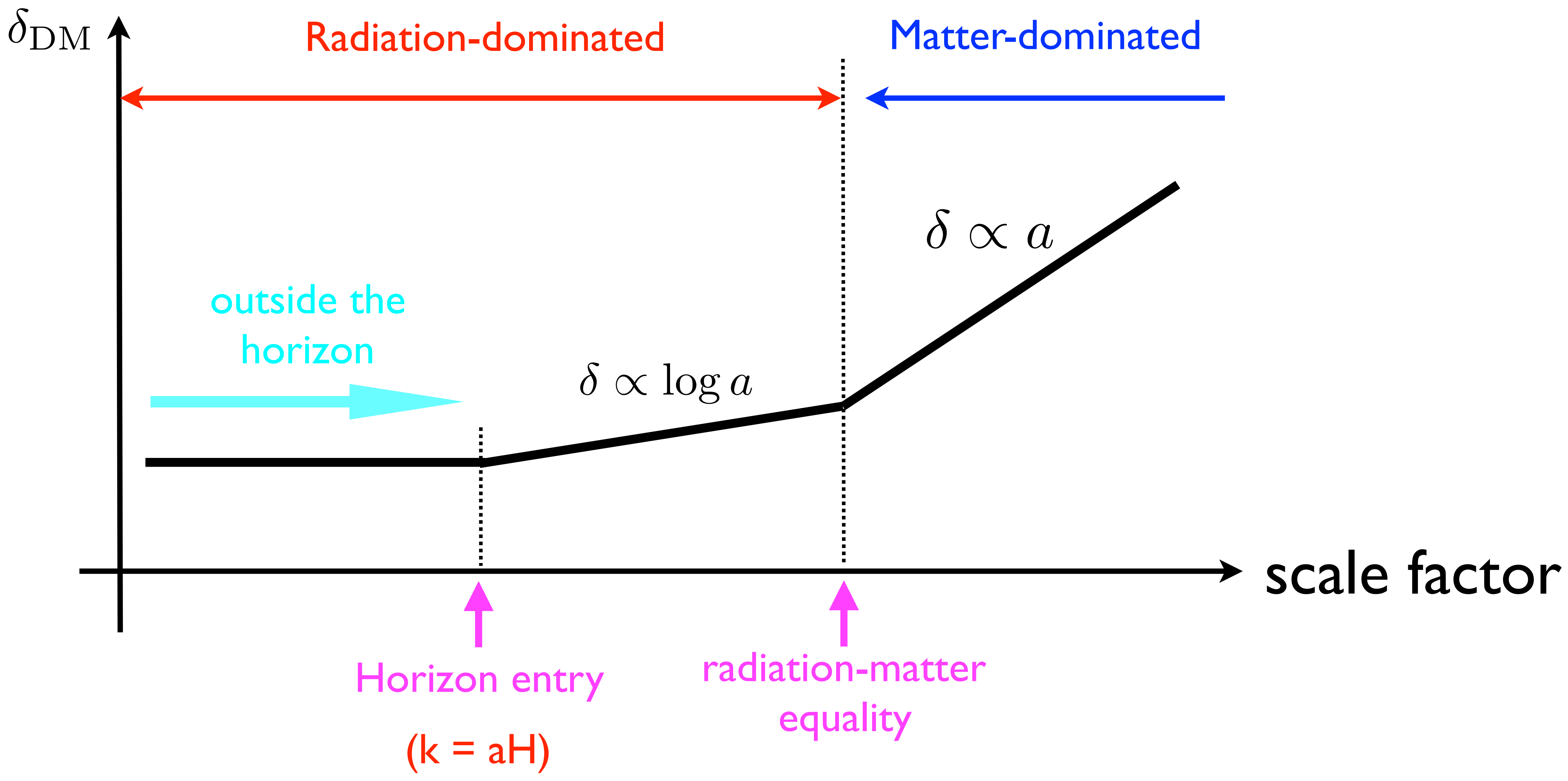
where

$$Q_\sigma = -\Gamma_\sigma\rho_\sigma \qquad Q_r = \Gamma_\sigma\rho_\sigma + \frac{\langle\sigma_a v\rangle}{M_\chi}\left[\rho_\chi^2 - (\rho_\chi^{\mathrm{eq}})^2\right] \qquad Q_\chi = -\frac{\langle\sigma_a v\rangle}{M_\chi}\left[\rho_\chi^2 - (\rho_\chi^{\mathrm{eq}})^2\right]$$

$$\delta Q_\sigma = -\Gamma_\sigma\rho_\sigma\delta_\sigma \qquad \delta Q_r = \Gamma_\sigma\rho_\sigma\delta_\sigma + \frac{2\langle\sigma_a v\rangle}{M_\chi}\left[\rho_\chi^2\delta_\chi - (\rho_\chi^{\mathrm{eq}})^2\frac{M_\chi}{T}\frac{\delta_r}{4}\right] \qquad \delta Q_\chi = -\frac{2\langle\sigma_a v\rangle}{M_\chi}\left[\rho_\chi^2\delta_\chi - (\rho_\chi^{\mathrm{eq}})^2\frac{M_\chi}{T}\frac{\delta_r}{4}\right]$$

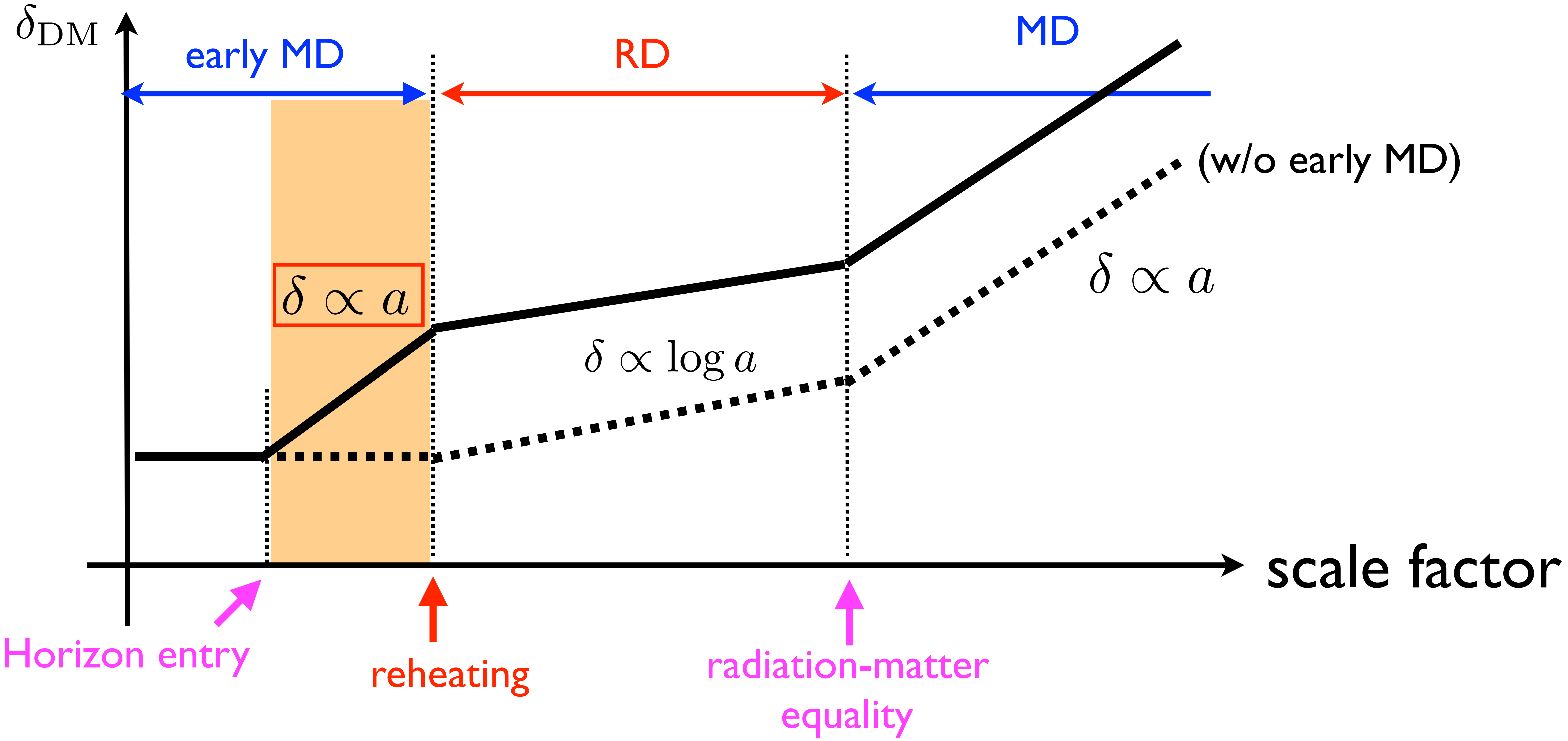
Evolution of DM density fluctuations $\delta_{\rm DM}$

- Standard case (no early MD era)



Evolution of DM density fluctuations δ_{DM}

- Case with an early MD era



The longer the early MD era is, δ is more enhanced.

Ultracompact minihalos: Gamma ray constraint

[Scott, Sivertsson 0908.4082; Josan Green 1006.4970; Bringmann, Scott, Akrami 1110.2484]

- Assume that DM is in the form of WIMP.
- Gamma rays from DM annihilation in UCMHs may be observable.
- Non-observations of such a signal gives a constraint on the abundance of UCMHs.
- The abundance depends on the size (growth) of DM perturbations.

→ The growth of DM perturbations depends on the reheating temperature (the duration of the early MD).

→ Constraints on the reheating temperature (and the duration of the early MD era.)

Abundance of UCMHs

- Abundance of UCMHs is characterized by the fraction of the local UCMH mass:

Present mass of UCMHs inside the comoving size R

$$f \equiv \frac{\Omega_{\mathrm{UCMH}}}{\Omega_m} = \beta(R) \frac{\Omega_\chi}{\Omega_m} \frac{M^0_{\mathrm{UCMH}}}{M_i}$$

Probability of forming UCMHs from the region with comoving size R

Mass inside the comoving size R

- Mass inside the comoving radius R: $M_i \simeq \left[\frac{4\pi}{3} \rho_\chi(a) R^3_{\mathrm{phys}} \right]_{R=1/(aH)}$

- Present mass of UCMHs: $M_{\mathrm{UCMH}}(z) = \frac{1+z_{\mathrm{eq}}}{1+z} M_i$

Abundance of UCMHs

$$\left(f \equiv \frac{\Omega_{\mathrm{UCMH}}}{\Omega_m} = \boxed{\beta(R)}\frac{\Omega_\chi}{\Omega_m}\frac{M^0_{\mathrm{UCMH}}}{M_i}\right)$$

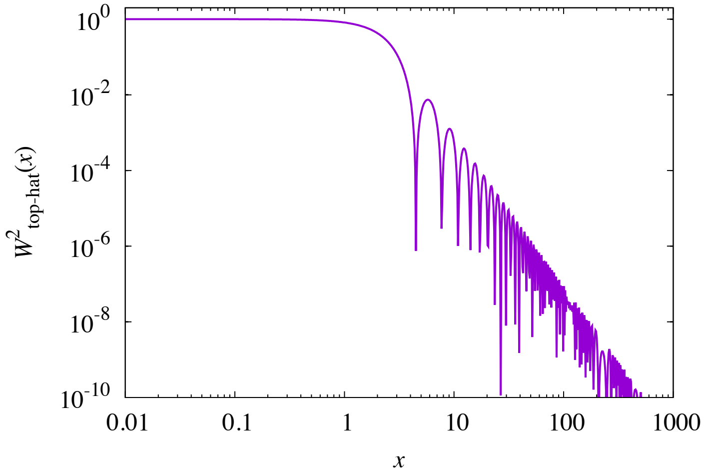
- **Probability** (assuming that δ obeys a Gaussian distribution)

$$\beta(R) = \frac{1}{\sqrt{2\pi\sigma_\chi^2(R)}}\int_{\delta_\chi^{\min}}^{\delta_\chi^{\max}} \exp\left(-\frac{\delta_\chi^2}{2\sigma_\chi(R)^2}\right) d\delta_\chi \simeq \frac{\sigma_\chi(R)}{\sqrt{2\pi}\delta_\chi^{\min}} \exp\left(-\frac{(\delta_\chi^{\min})^2}{2\sigma_\chi^2(R)}\right)$$

($\delta_\chi^{\max}, \delta_\chi^{\min}$ are the maximum and minimum value of δ to form UCMHs.)

\- Mass variance: $\sigma_\chi(R)^2 = \int_0^\infty W^2_{\mathrm{top-hat}}(kR)\mathcal{P}_\delta(k,t)\frac{dk}{k}$

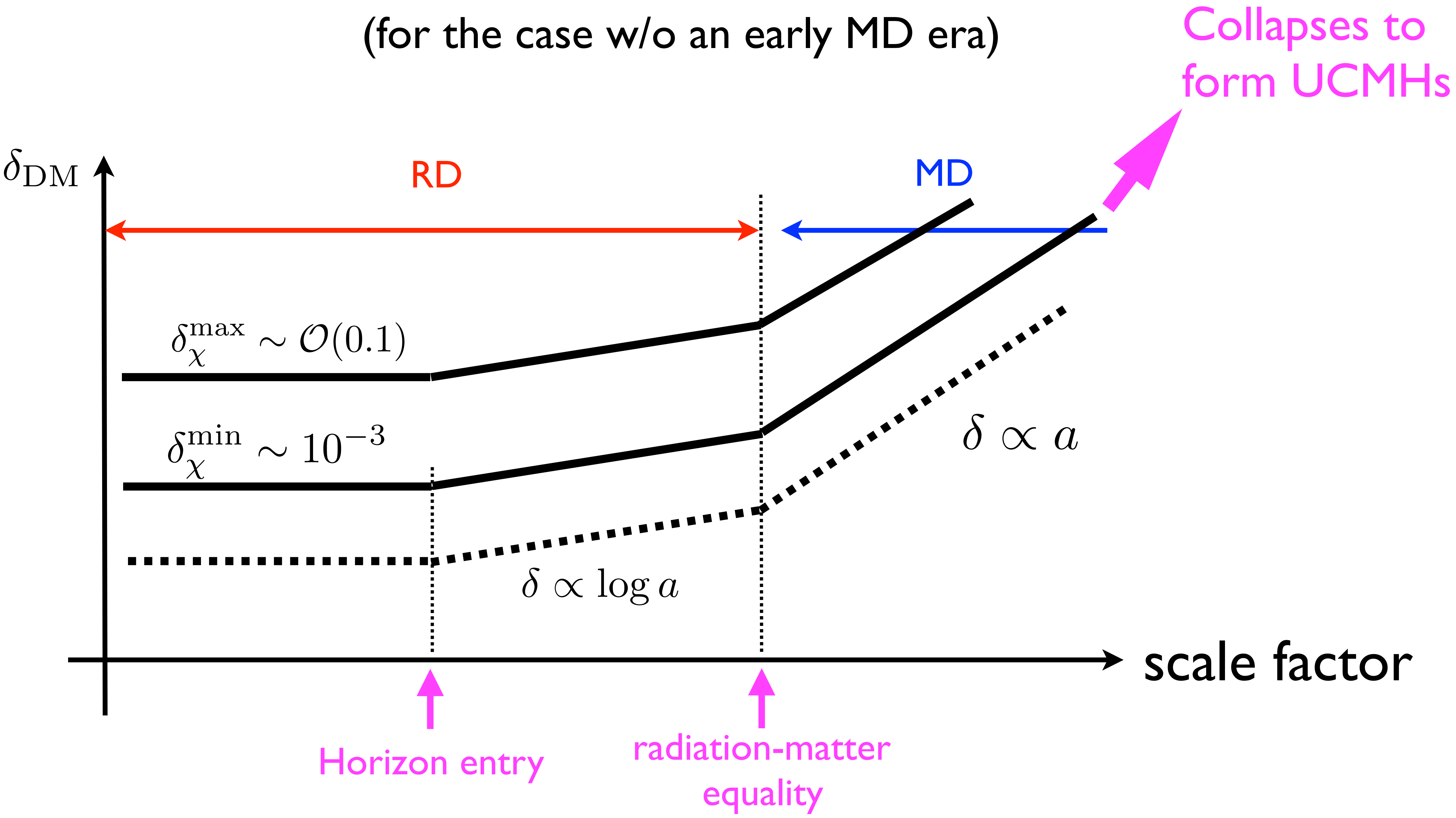
Top-hat window function



Minimum value of δ

- Minimum value of δ to form UCMHs $\delta_\chi^{\min}$

(for the case w/o an early MD era)

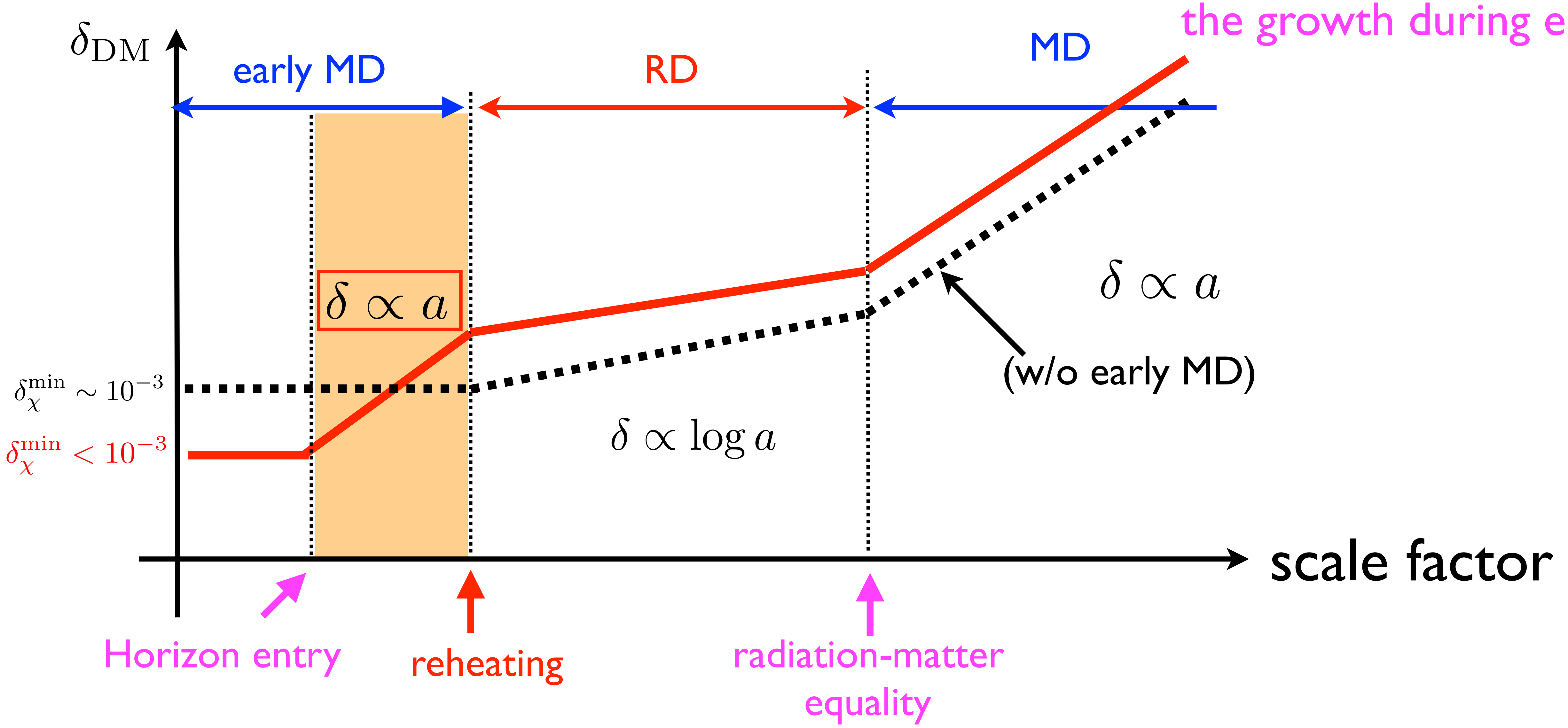


Minimum value of δ

- Minimum value of δ to form UCMHs $\delta_\chi^{\min}$

(for the case w/ an early MD era)

$\delta_\chi^{\min}$ can be smaller due to the growth during eMD.



Constraints on the low-reheating temperature

- When duration of the early MD era is longer, DM fluctuations experiences more growth (more enhancement).

The 2nd reheating occurred earlier, longer the duration

→ Constraints on the reheating temperature.

- The duration of the early MD era is also constrained.

→ Constraints on $H_{\rm dom}/H_{\rm reh} (= k_{\rm dom}/k_{\rm reh})$

$H_{\rm dom}$ ↗ Hubble parameter at the beginning of the early MD

$H_{\rm reh}$ ↖ Hubble parameter at the reheating

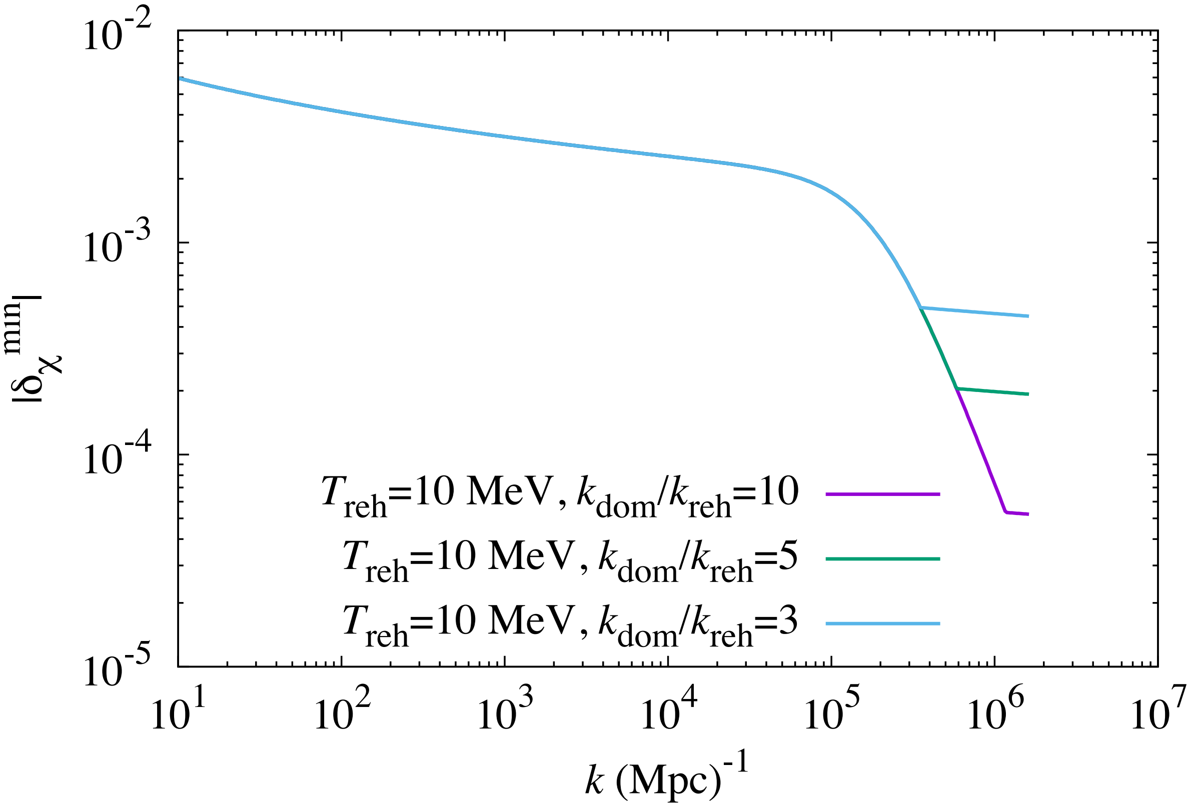
Constraint on the abundance from Gamma ray

- Minimum value of δ to form UCMHs $\delta_\chi^{\min}$

  - Standard case (w/o an early MD era): $\delta_\chi^{\min} \sim 10^{-3}$

  - Case with an early MD era:

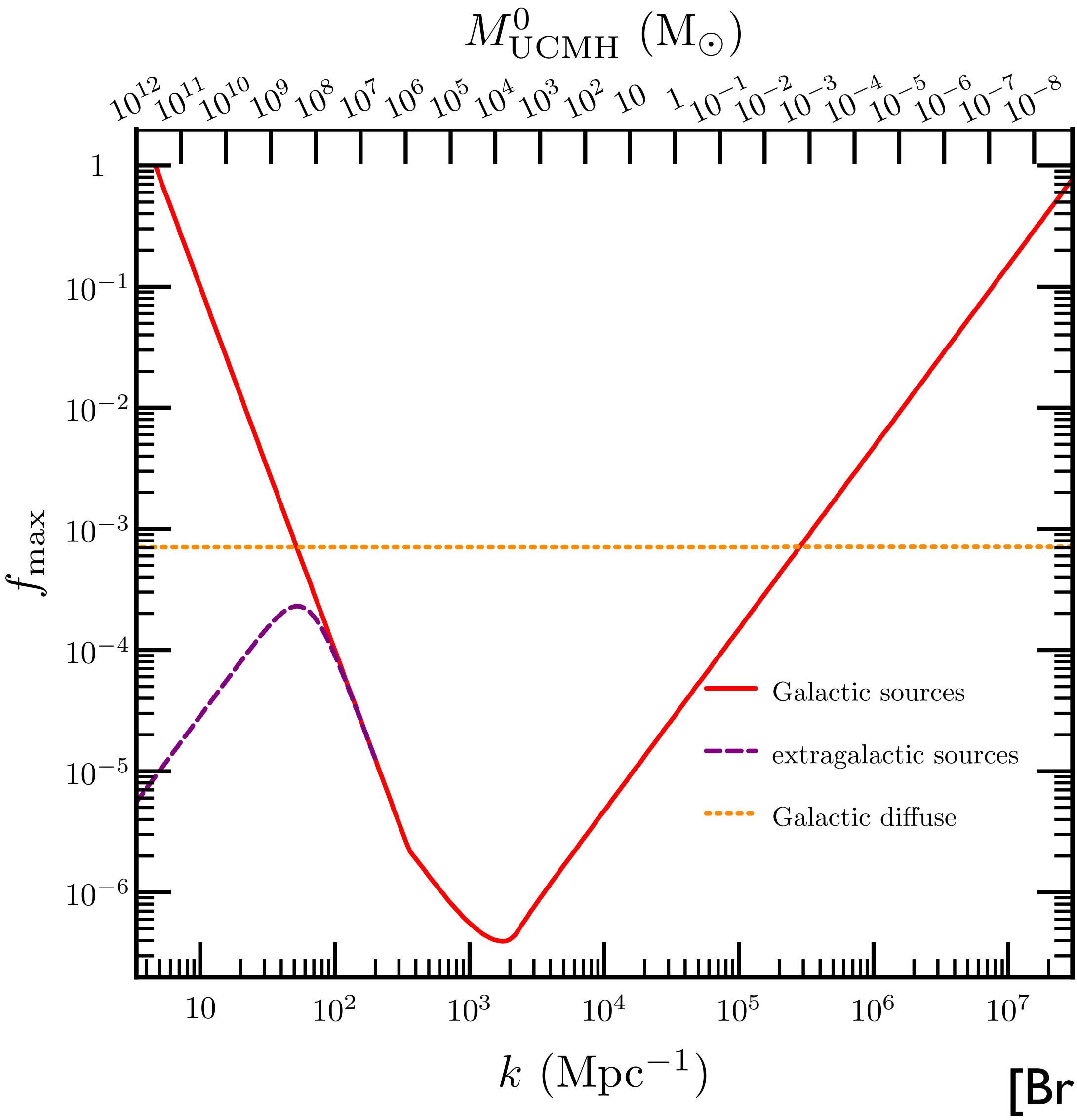
    Due to the growth after horizon entry, $\delta_\chi^{\min}$ can be smaller



→ More UCMHs can be formed.

Constraint on the abundance from Gamma ray

- Constraints on the UCMH mass fraction from Fermi-LAT



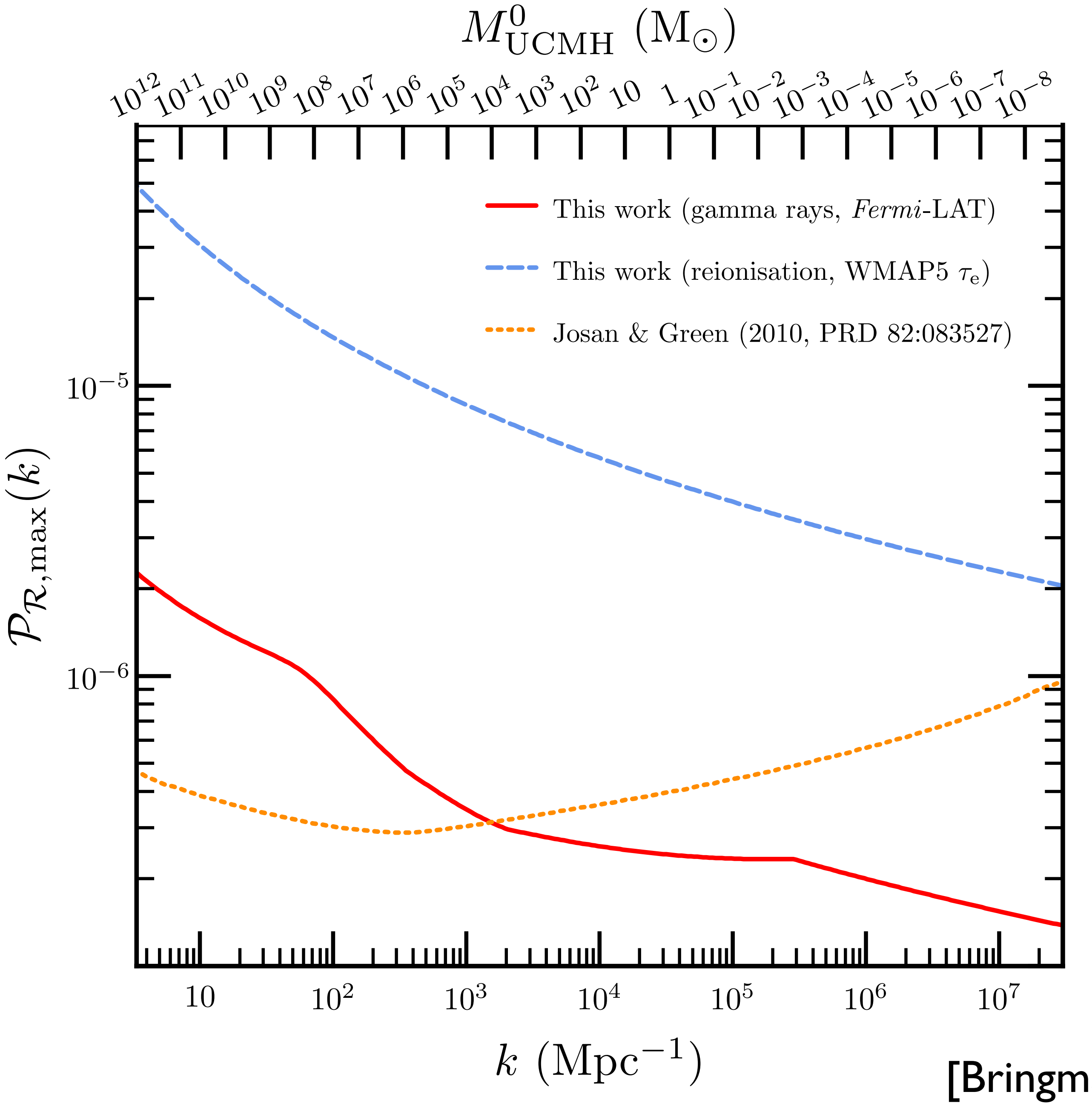
WIMP mass: $m_\chi = 1\ \rm TeV$

Annihilation cross section: $\langle \sigma v \rangle = 3 \times 10^{-26}\ \rm cm^3/s$

(100% annihilation is assumed to go to $b\bar{b}$ pairs.)

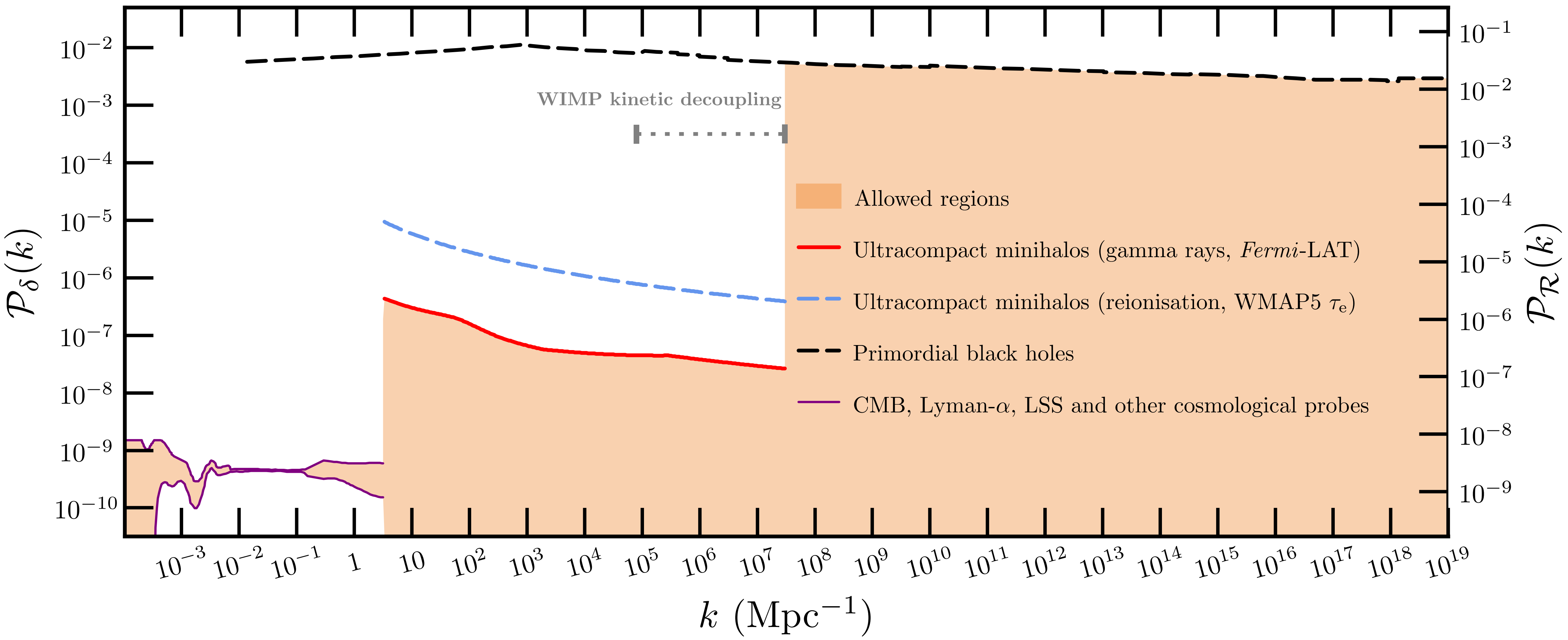
[Bringmann, Scott, Akrami 1110.2484]

Constraints on primordial power spectrum



[Bringmann, Scott, Akrami 1110.2484]

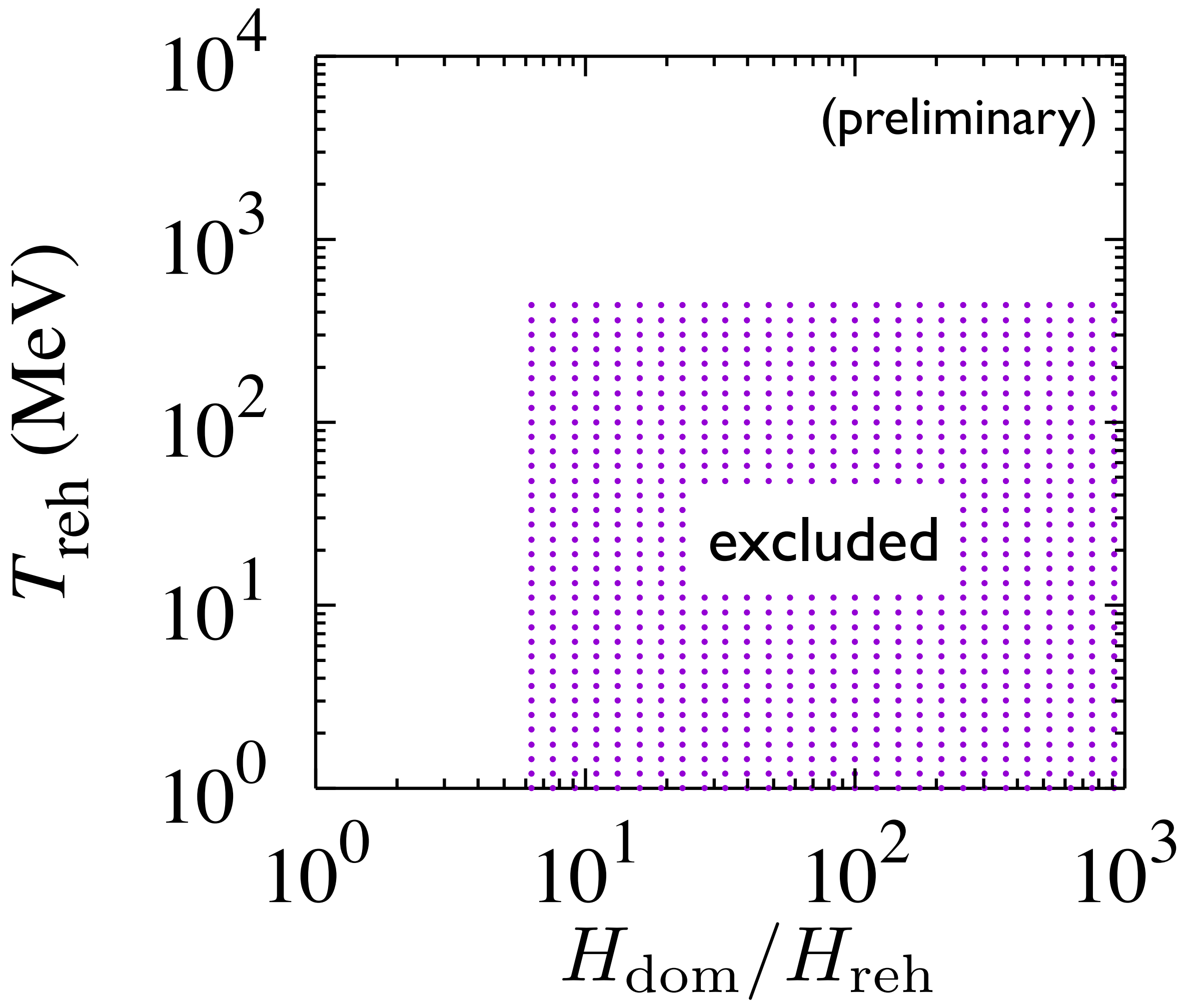
Constraints on primordial power spectrum



[Bringmann, Scott, Akrami 1110.2484]

Constraints on the low-reheating temperature

- Fermi constraint (WIMP case):



[Ki-Young Choi, TT in prep.]

(for WIMP case) $T_{\rm reh} \gtrsim 400\ {\rm MeV}$

Free-streaming

- Fluctuations are erased due to free-streaming effect on small scales:

$$\delta \propto \exp\left(-\frac{k^2}{2k_{\rm fs}^2}\right)$$

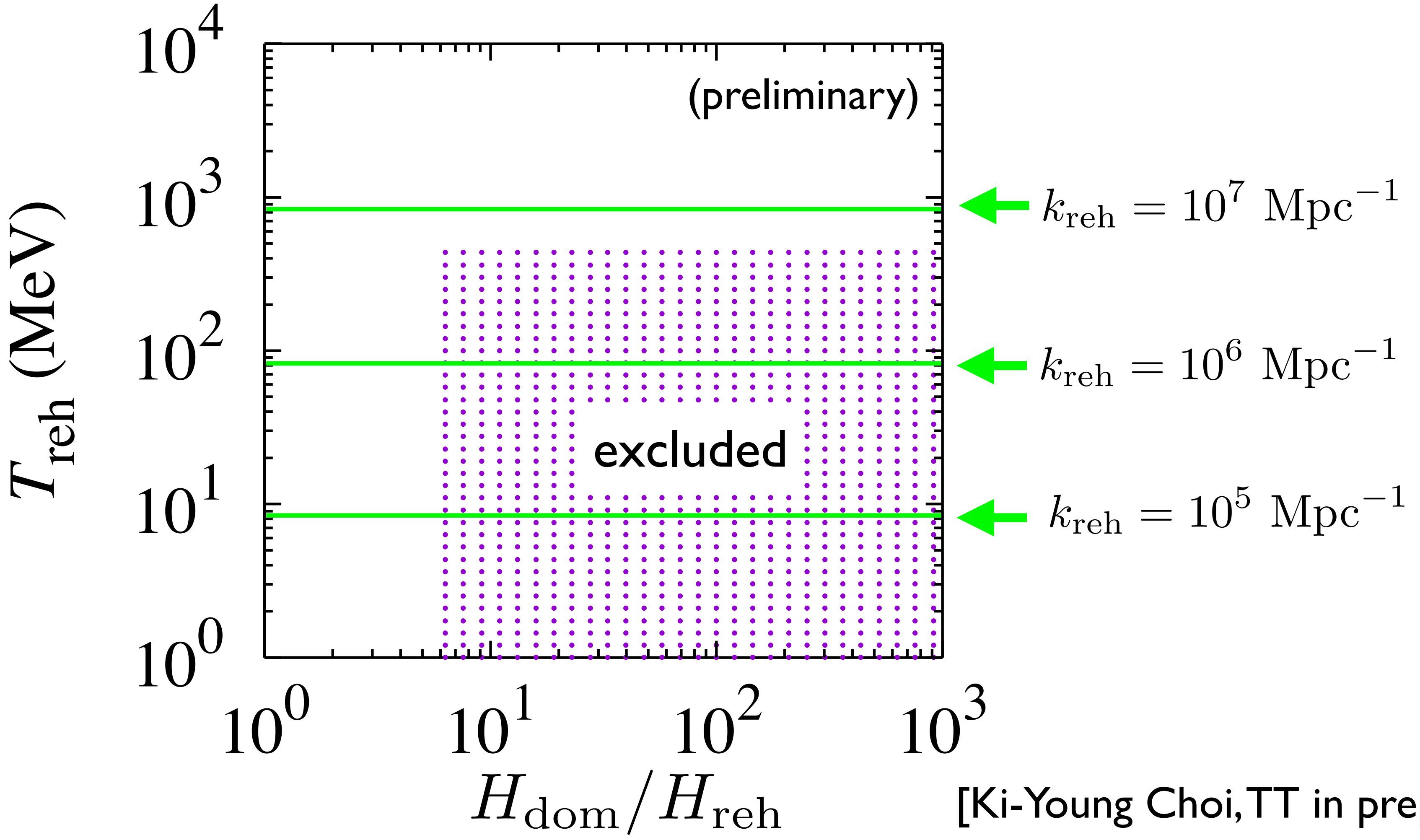
→ Even if fluctuations are enhanced, they are suppressed on scales $k > k_{\rm fs}$

(DM particles can free-stream after the kinetic decoupling.)

$$\lambda_{\rm fs} = \int_{t_{\rm kd}}^{t_0} \frac{v}{a} dt \simeq \sqrt{\frac{T_{\rm kd}}{m_\chi}} a(T_{\rm kd}) \int_{a(T_{\rm kd})}^{1} \frac{da}{a^3 H(a)}$$

Constraints on the low-reheating temperature

- Fermi constraint (WIMP case):



[Ki-Young Choi, TT in prep.]

Other probes of UCMHs

- UCMHs can be probed gravitationally from:

  - Astrometric microlensing $f \lesssim 0.1$

    [Li, Erickcek, Law 1202.1284]

  - Small-scale gravitational lensing $f \lesssim 0.01$

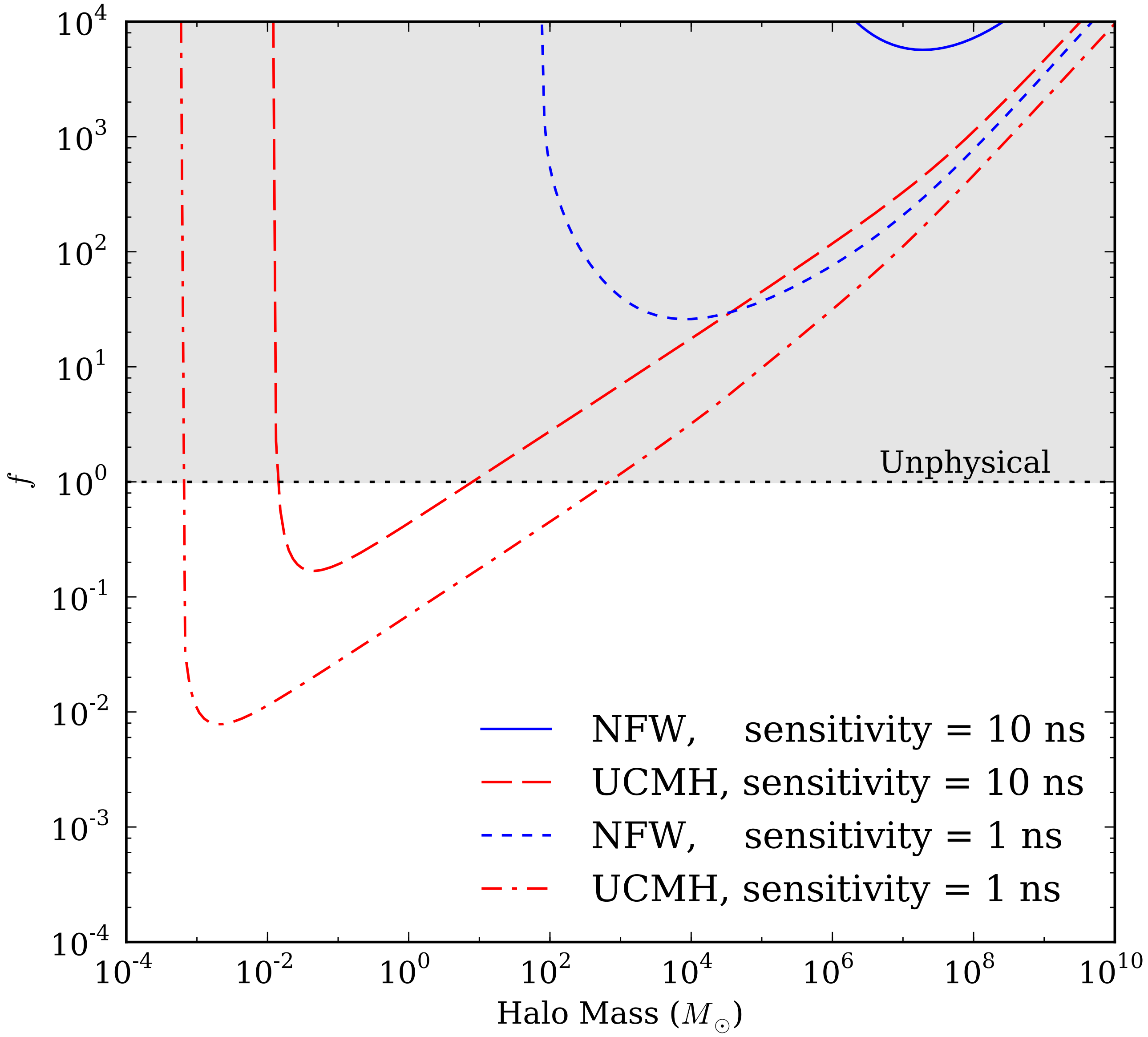
    [Zackrisson et al., 1208.5482]

  - Pulsar timing $f \lesssim 0.01$

    [Clark, Lewis, Scott 1509.02938]

These methods are model-independent.

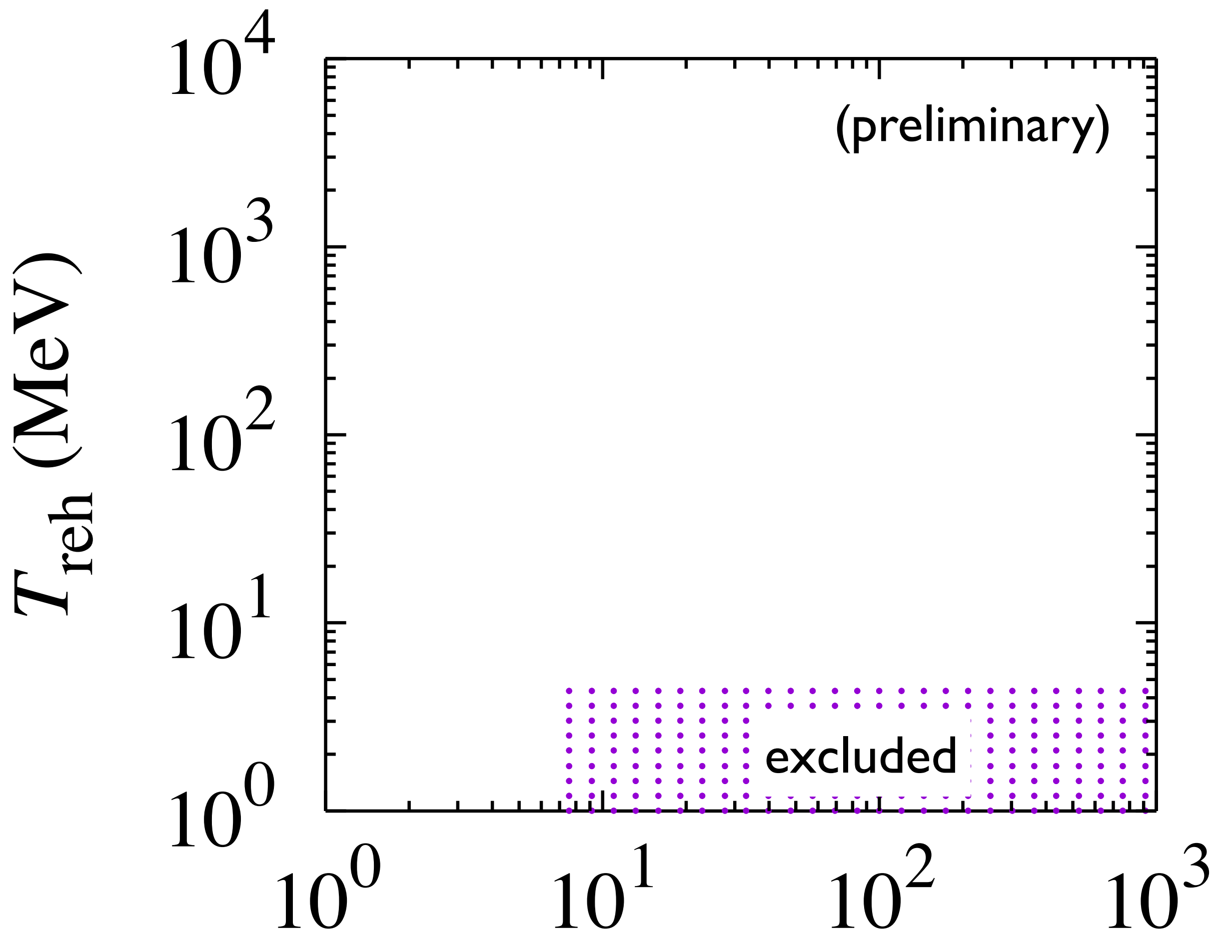
Pulsar timing constraint



[Clark, Lewis, Scott 1509.02938]

Constraints on the low-reheating temperature

- Pulsar constraint



[Ki-Young Choi, TT in prep.]

Summary

- The reheating temperature is an important quantity to understand the physics of the early Universe.

- Density fluctuations of dark matter grow with time during the early MD era.

- If small scale structure is enhanced, a lot of UCMHs can be formed, whose number is constrained by astrophysical observations.

- Low-reheating temperature can be constrained from the viewpoint of dark matter fluctuations, which can be severer (for some cases) than any other known constraints.