Bound on Reheating Temperature with Dark Matter

[Based on the work with Tomo Takahashi]

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Dark Matter from aeV to ZeV

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ibS 기초과학연구원 Institute for Basic Science

MultiDark Multimessenger Approach for Dark Matter Detection

IP3 University of Durham

Contents

Temperature of the Universe

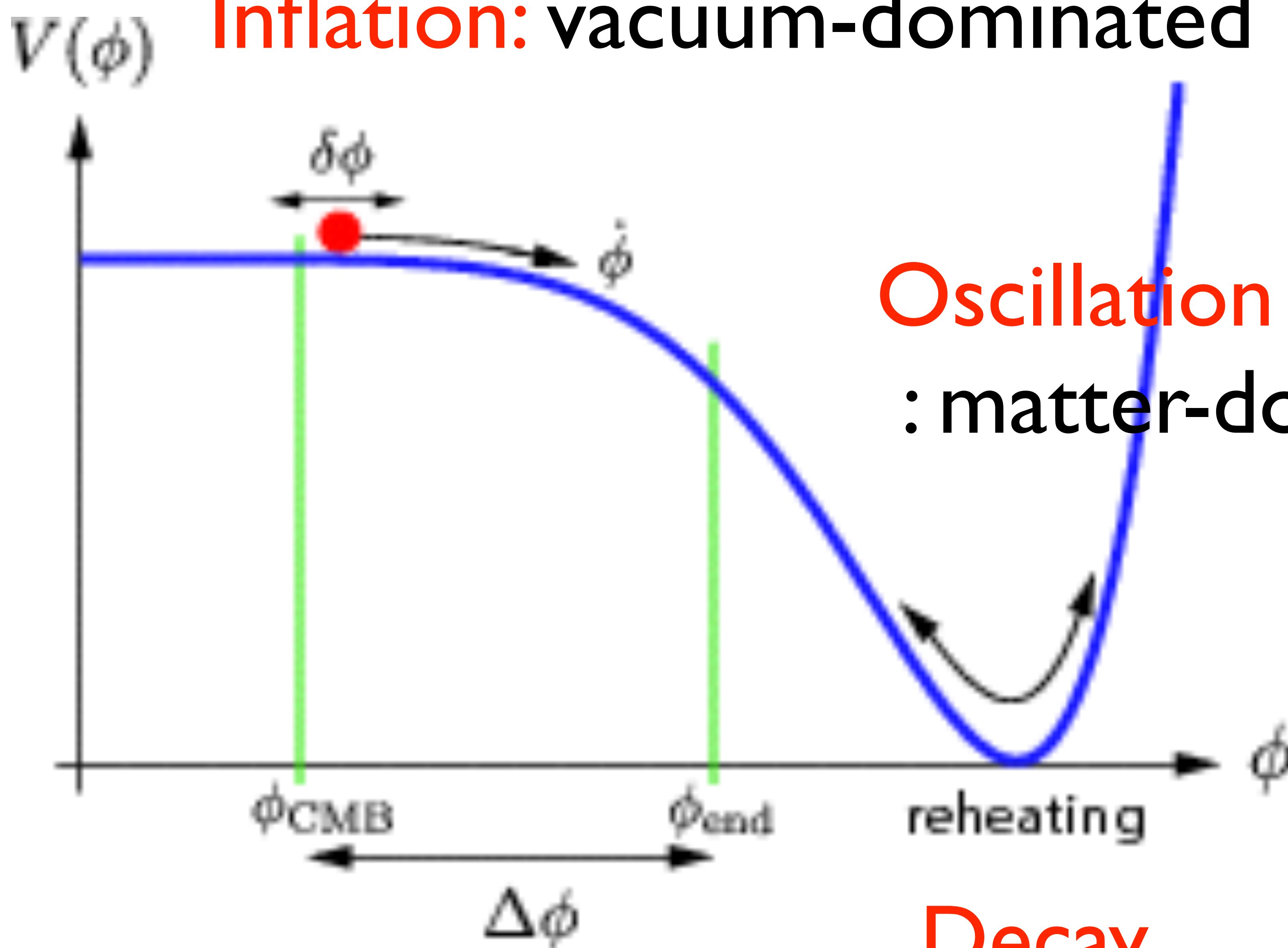
What is the available range of this initial high temperature?

What is the highest temperature?

What is the lowest temperature?

Inflation and Matter-Domination

Inflation: vacuum-dominated



Oscillation
: matter-dominated

Decay
: radiation-dominated

Reheating

During inflation, the Universe is cold.

After inflation, the energy of the inflation is converted to the production of the light particles. Usually the inflaton field oscillates around vacuum and decay to produce light particles.

The particles are thermalised and the Universe is heated to some temperature. We call the highest temperature when the radiation-domination starts, reheating temperature.

Early matter-domination (by inflaton) before reheating is inevitable.

$$H^2 \sim \rho \sim a^{-3}$$

Upper bound on Reheating Temperature

Energy scale of the inflation constrains the highest temperature of the reheating temperature.

$$\rho(T_{\rm reh}) < V$$ Energy during inflation

$$\rho(T) = \frac{\pi^2}{30} g_* T^4$$

$$V^{1/4} \sim \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\,\mathrm{GeV}$$

bound on tensor-to-scalar ratio

$$\boxed{T_{\rm reh} < 10^{16}\,\mathrm{GeV}}$$

Early Matter-Domination and Reheating

Reheating and early matter-domination also happen in the scenarios of Moduli, curvaton, thermal inflation, axino, gravitino, ...

$$\boxed{T_{\rm reh} \simeq \left(\frac{90}{\pi^2}\right)^{1/4} \sqrt{\Gamma M_{\rm P}}}$$

When decoupled heavy particles are very weakly interacting, they decay very late in the early Universe.

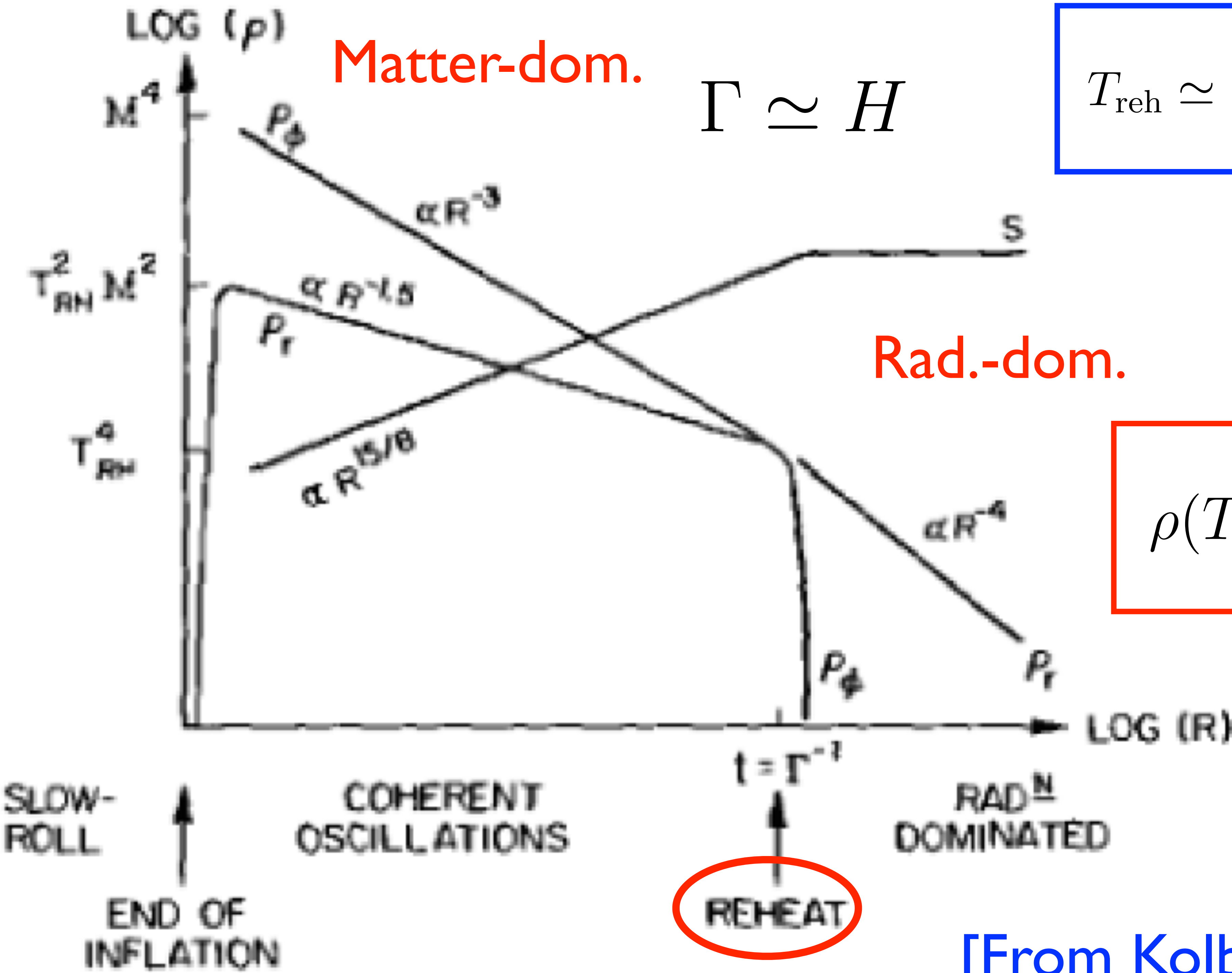
Temperature ~ MeV - GeV

Reheating Temperature

Matter-dom.

$$\Gamma \simeq H$$

$$\boxed{T_{\mathrm{reh}} \simeq \left(\frac{90}{\pi^2}\right)^{1/4} \sqrt{\Gamma M_{\mathrm{P}}}}$$



Rad.-dom.

$$\boxed{\rho(T) = \frac{\pi^2}{30} g_* T^4}$$

[From Kolb & Turner]

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+LSS

: precise calculation of the cosmic neutrino background and CMB

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

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

Big-Bang Nucleosynthesis

$T \gg 1$ MeV $(t \ll 1$ sec$)$

Local Thermal Equilibrium of protons and neutrons

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$T \sim 1$ MeV $(t \sim 1$ sec$)$

Weak freeze-out

$$\frac{n}{p} = e^{-(m_n - m_p)/T} \simeq \frac{1}{6}$$

Decay of free neutrons

$$\tau_n \simeq 880\,\mathrm{sec}$$

$$n + p \leftrightarrow D + \gamma$$

Deuterium bottleneck

$T \sim 0.07$ MeV $(t \sim 3\,\mathrm{min})$

$$n/p \simeq 1/7$$

most neutrons to He4
small D, He3 Li7

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T} \qquad m_n - m_p \simeq 1.29\ \mathrm{MeV}$$

New bound on low-reheating temperature

3. Dark matter halos

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

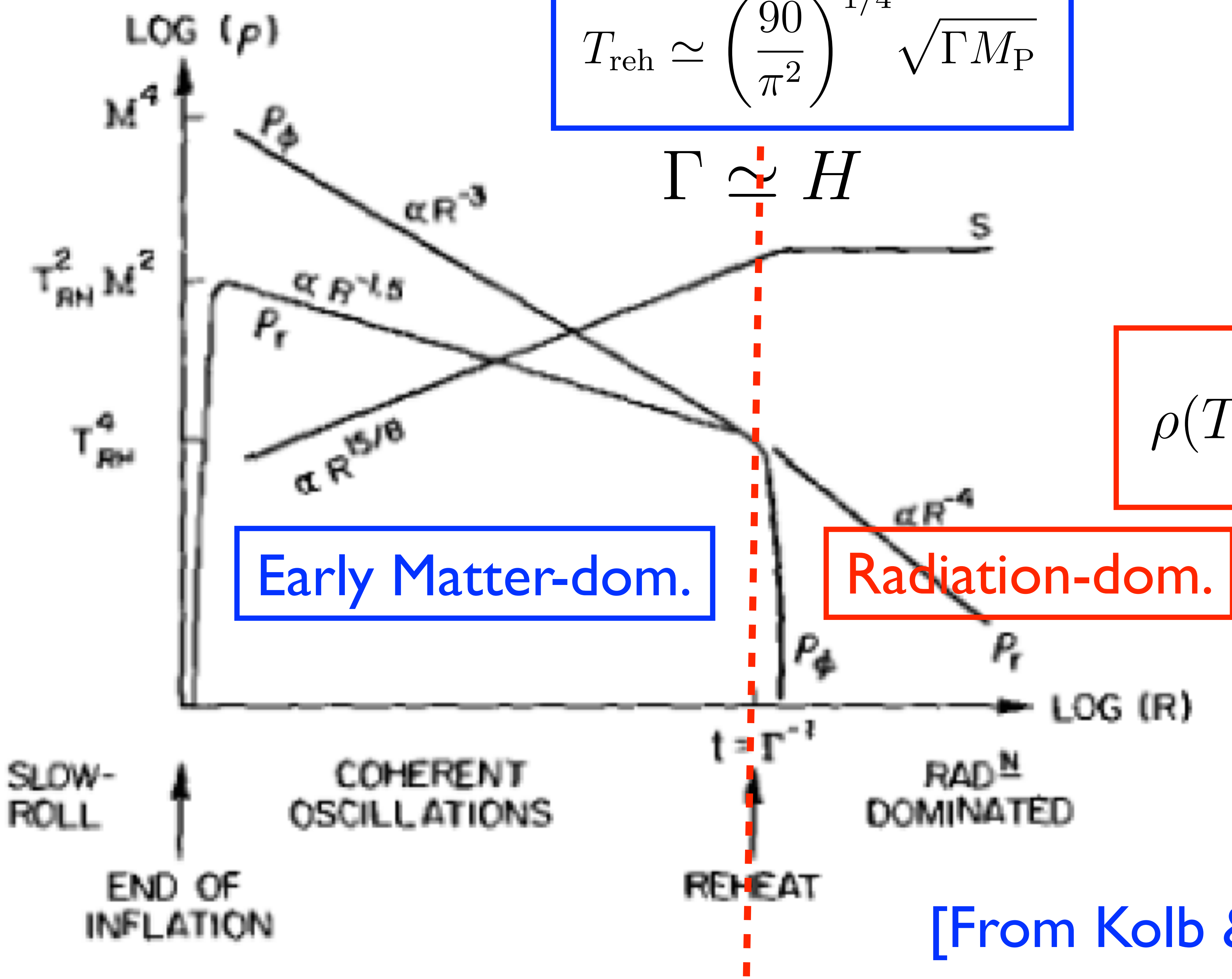
$$\boxed{T_{\mathrm{reh}} \gtrsim 30\,\mathrm{MeV}}$$

[KYChoi, Tomo Takahashi, in preparation]

Early Matter Domination and Reheating

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

$$\Gamma \simeq H$$



$$\rho(T) = \frac{\pi^2}{30} g_* T^4$$

[From Kolb & Turner]

Evolution of Density Perturbation

$$\delta \equiv \frac{\delta\rho}{\rho}$$

Inside horizon:

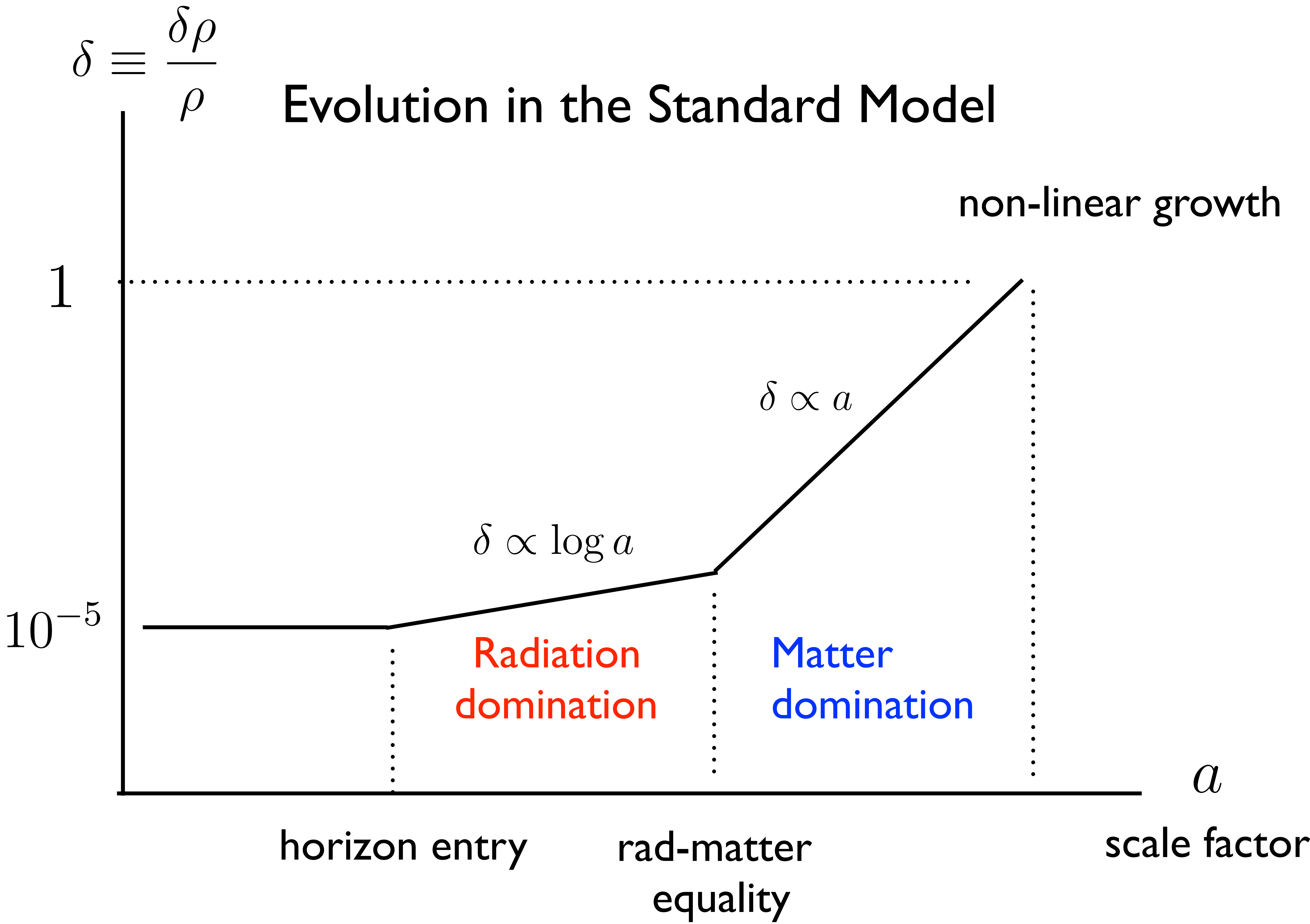
Radiation (rel. particles) : oscillates

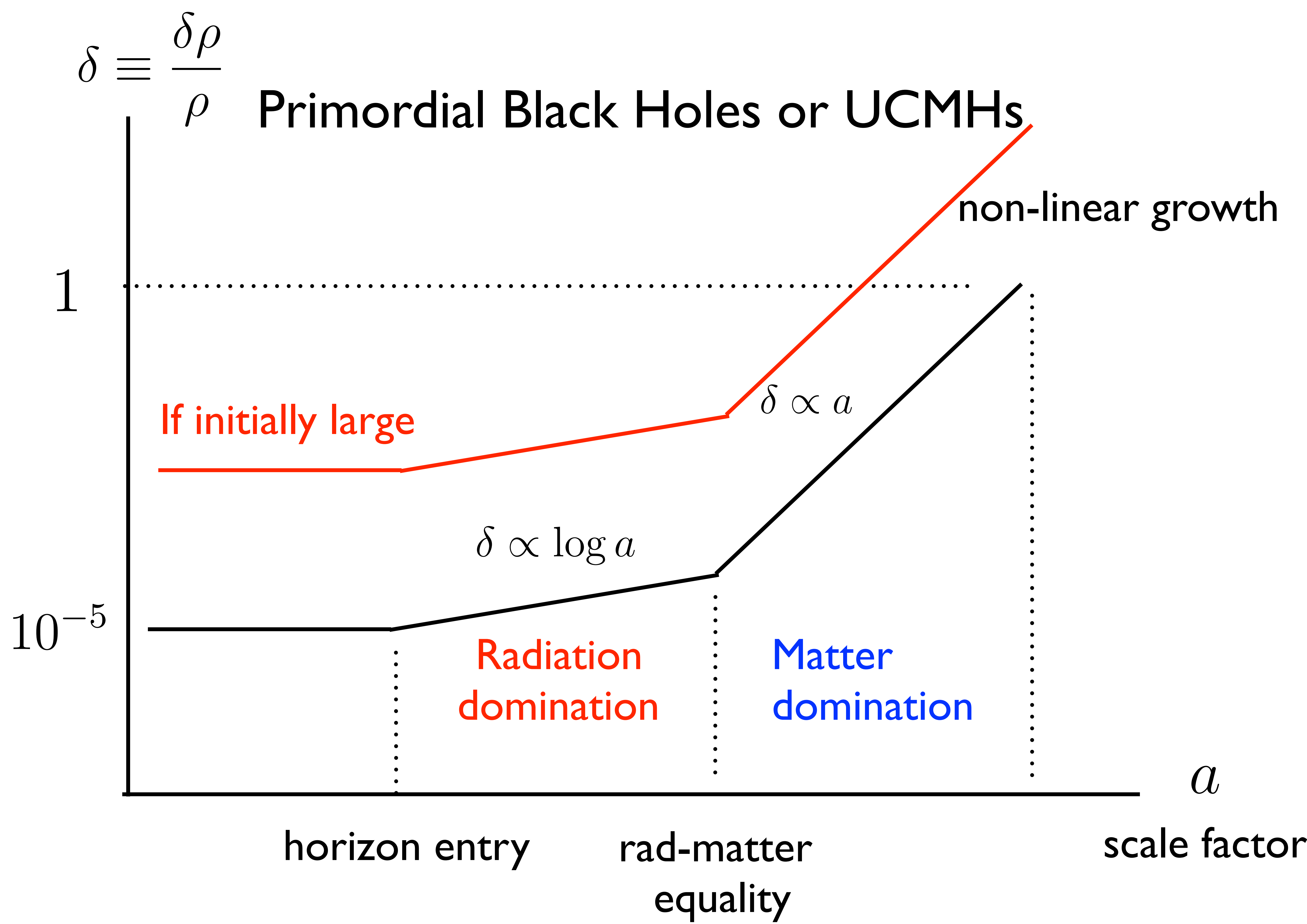
decoupled DM (non rel. particles with vanishing pressure) :

Rad-domination: logarithmically grows

Matter-domination: linearly grows

Evolution in the Standard Model





$\delta \equiv \frac{\delta\rho}{\rho}$
Primordial Black Holes or UCMHs
non-linear growth
1
If initially large
$\delta \propto a$
$\delta \propto \log a$
10^{-5}
Radiation domination
Matter domination
a
horizon entry
rad-matter equality
scale factor

Primordial Black Holes or UCMHs

If primordial density perturbation is large:

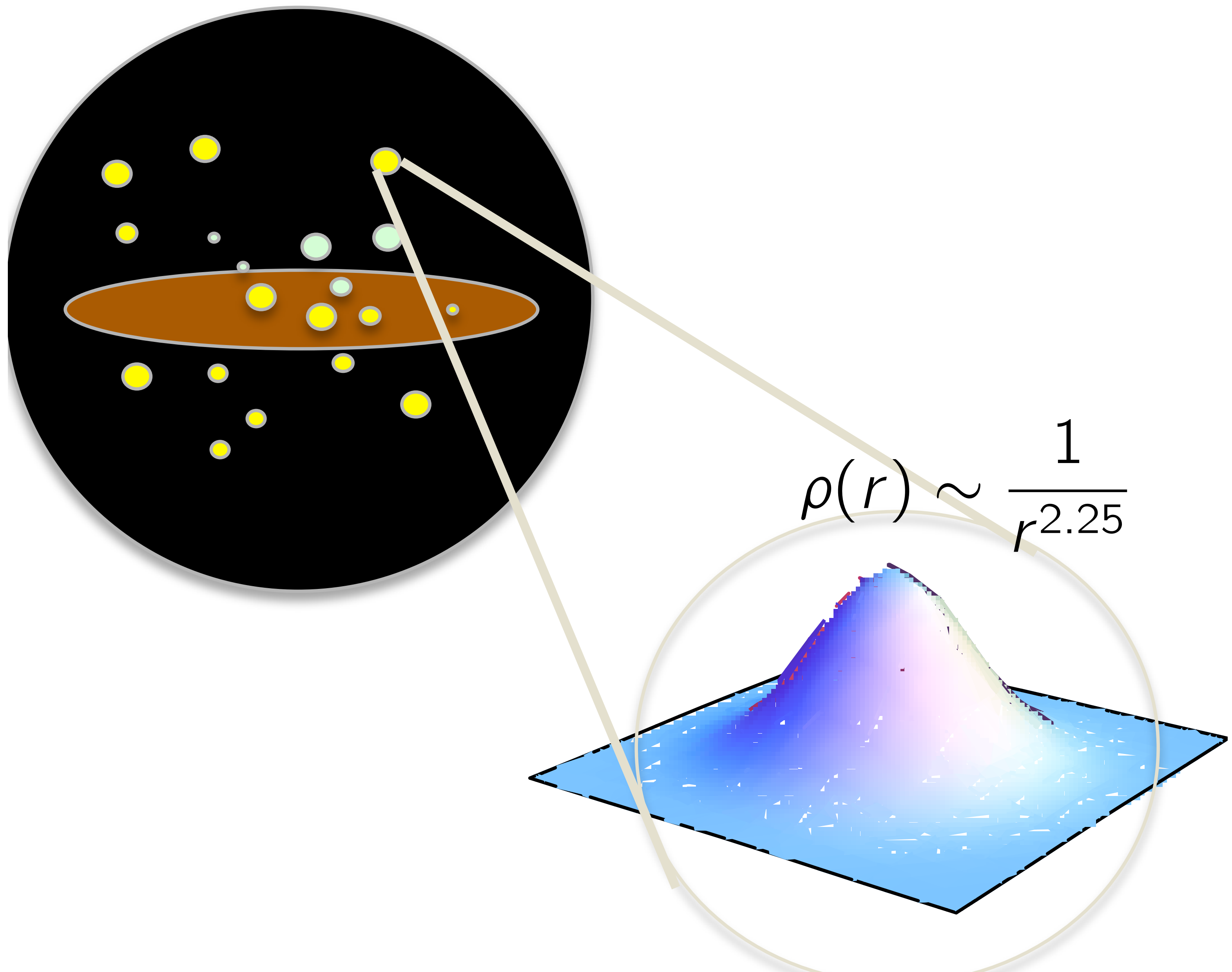
$\delta \gtrsim 0.1$ The matters and radiation collapse when they enters the horizon and make black holes (primordial black hole)

No observation of primordial black hole rule out this large density perturbation.

$\delta \gtrsim 10^{-3}$ It does not make black hole, but can make small scale dm dominated halos (ultra compact mini halo, UCMH)

No observation yet. The constraint depends on the properties of dark matter.

UCMHs in the Galaxy



$$\rho(r) \sim \frac{1}{r^{2.25}}$$

Observation of UCMHs with WIMP

WIMP dark matter

Annihilation or decay of WIMPs in the UCMHs
: gamma-ray, neutrino, cosmic rays.

Fermi-LAT constrains strongly

[Bringmann, Scott, Akrami, 2012]

UCMH Mass Fraction

UCMH mass fraction in the Milky Way

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

with DM fraction $f_\chi \equiv \Omega_\chi/\Omega_{\mathrm{m}}$ $\qquad M_i \simeq \left[\frac{4\pi}{3}\rho_\chi(a) R^3_{\mathrm{phys}}\right]_{R=1/(aH)}$

- increase of the mass by grav. infall during MD $\quad \dfrac{M^0_{\mathrm{UCMH}}}{M_i}$

- probability of comoving size R can collapse to form UCMH

$$\beta(R) = \frac{1}{\sqrt{2\pi}\sigma_{\chi,\mathrm{H}}(R)} \int_{\delta_\chi^{\mathrm{min}}}^{\delta_\chi^{\mathrm{max}}} \exp\left[-\frac{\delta_\chi^2}{2\sigma^2_{\chi,\mathrm{H}}(R)}\right] \mathrm{d}\delta_\chi$$

Probability to form UCMH

[Bringmann, Scott, Akrami, 2013]

- CDM mass variance at horizon entry from power spectrum

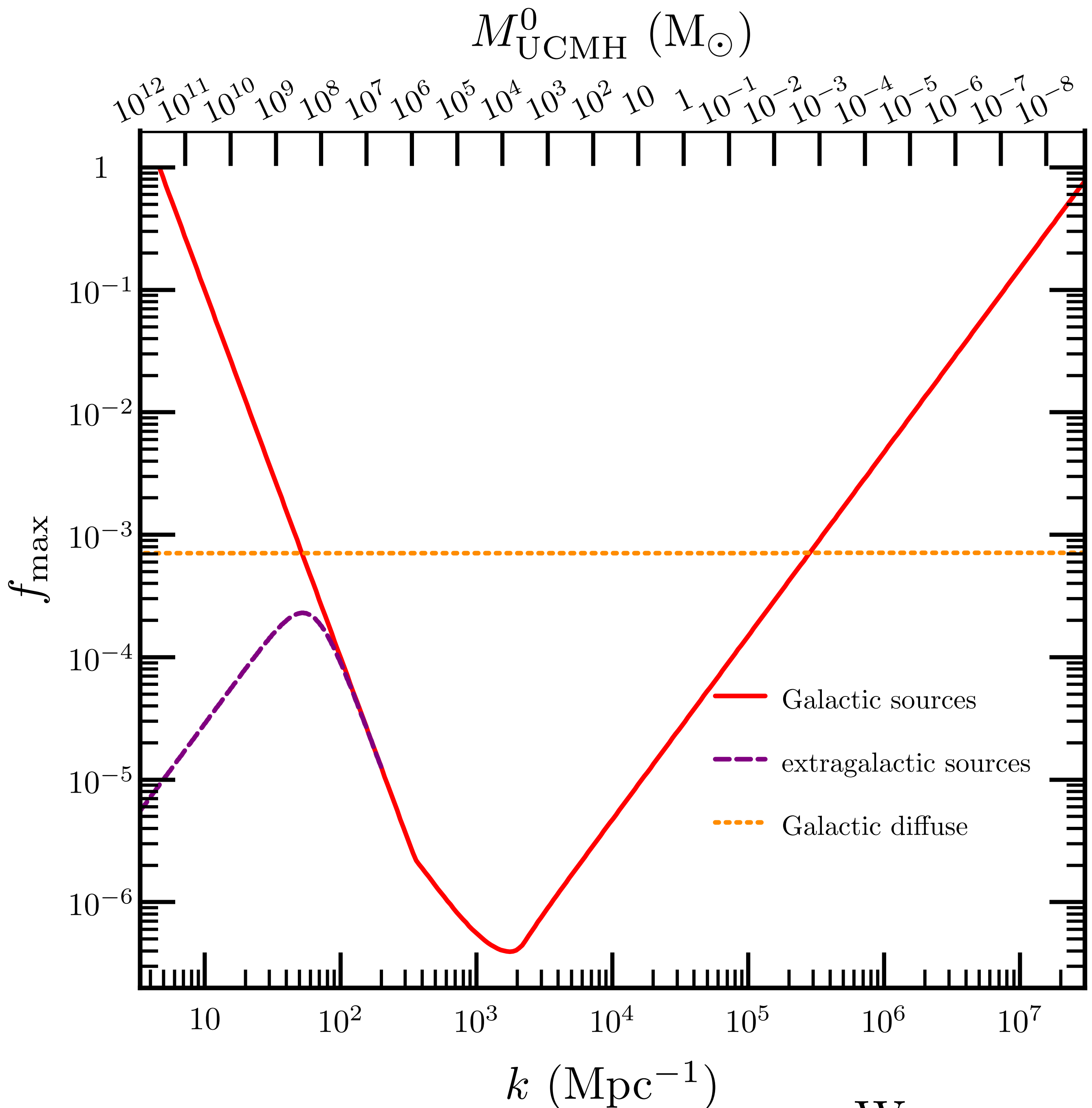
$$\sigma^2(R) = \int_0^\infty W_{\rm TH}^2(kR)\mathcal{P}_\delta(k)\frac{dk}{k}$$

: with minimum value of density contrast for UCMH at horizon entry

$$\delta_\chi^{\rm min}(k, t_k)$$

It is roughly 0.001 at horizon entry in the standard Rad.-dom. Universe.

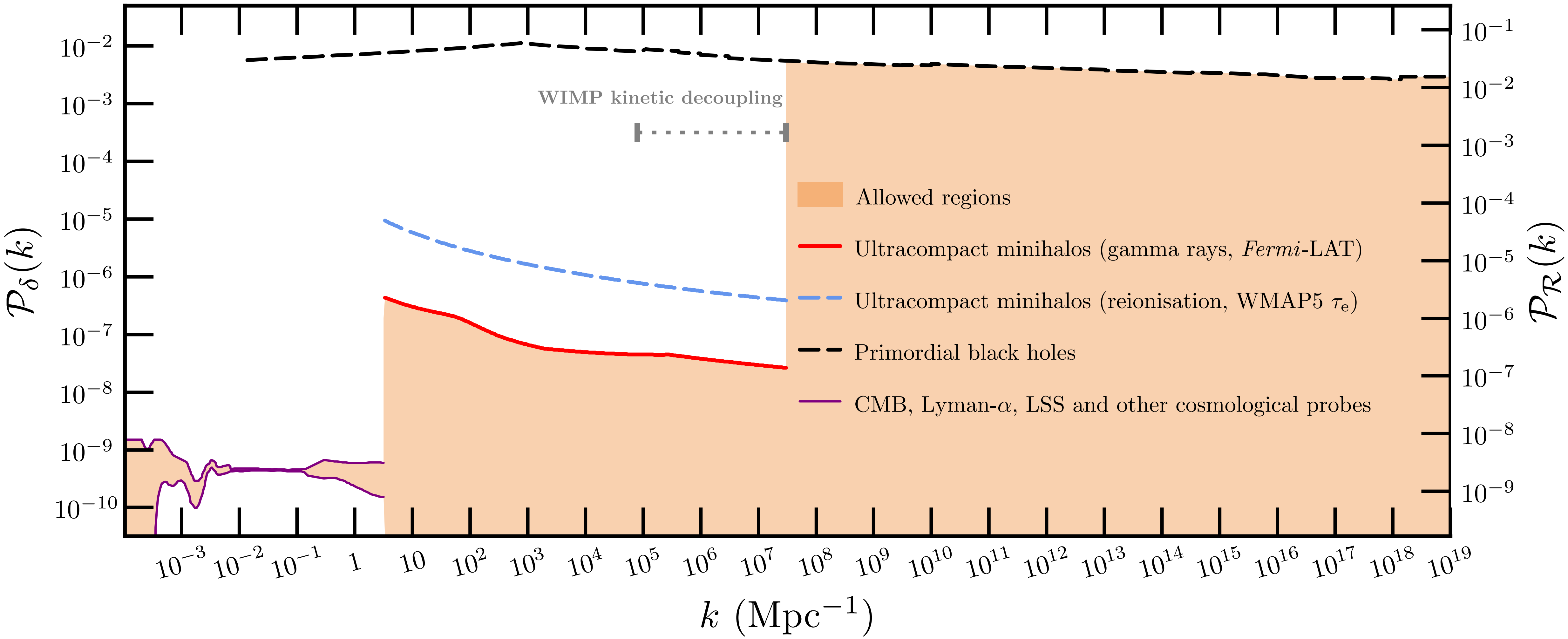
Constraints for UCMH with WIMP DM



[Bringmann, Scott, Akrami, 2013]

We assume 100% annihilation of WIMPs into $b\bar{b}$ pairs, a WIMP mass of $m_\chi = 1\,\mathrm{TeV}$ and an effective annihilation cross-section of $\langle\sigma v\rangle = 3\times10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$. These

Constraints on Primordial Power Spectrum



[Bringmann, Scott, Akrami, 2013]

Observation of UCMHs

UCMHs with non-WIMP dark matter $f \equiv \Omega_{\rm UCMH}/\Omega_{\rm m} = \beta(R) f_\chi \frac{M^0_{\rm UCMH}}{M_i}$

:To observe by Gravitational effects only

- distortion in the macrolensed quasars

$f \lesssim 0.1$ [Zackrisson 2013]

- astrometric microlensing

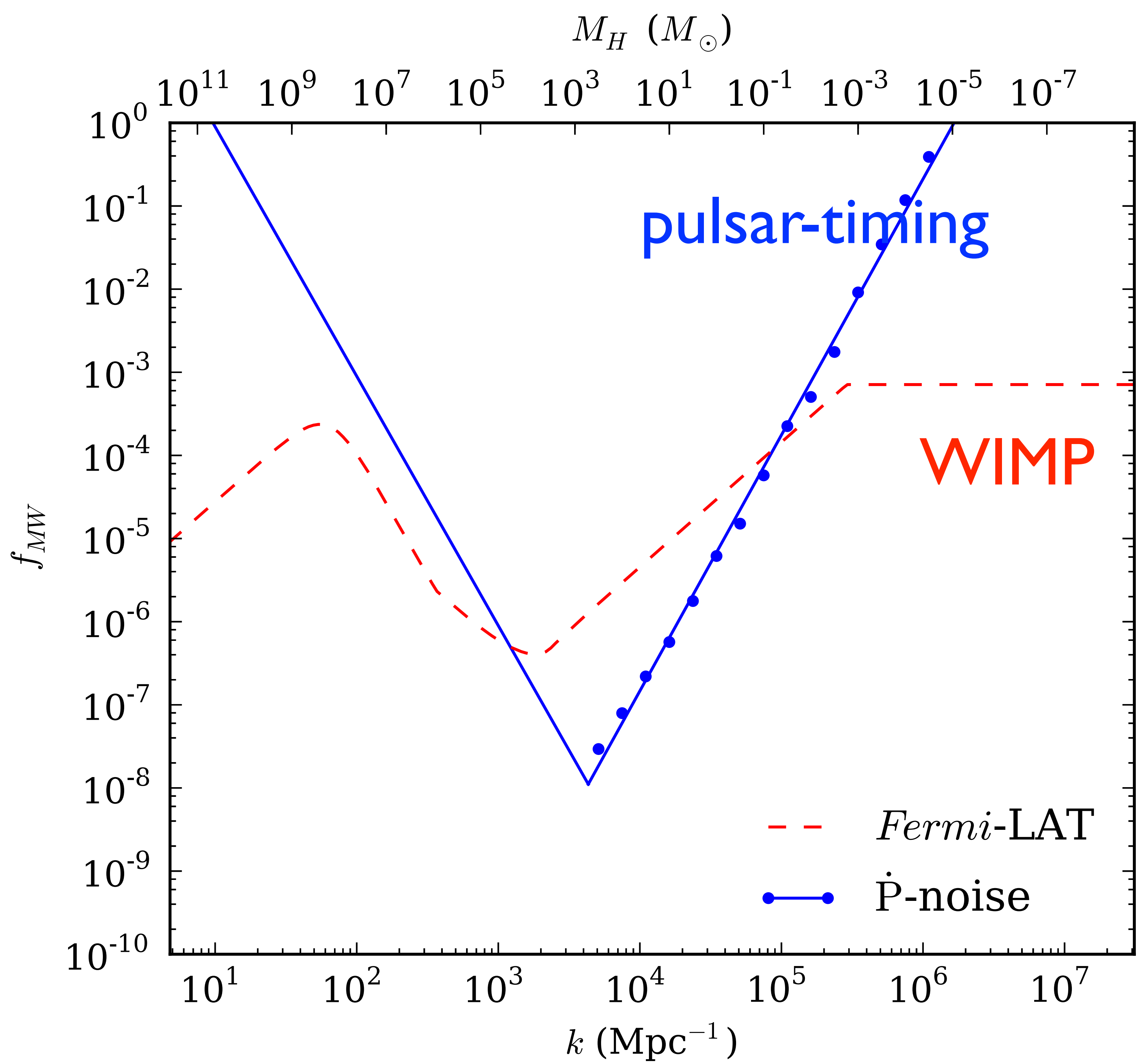
$f_{\rm eq} \lesssim 0.009$ [Li, Erickcek, Law, 2012]

- pulsar timing

$f \lesssim 10^{-6}$ [Clark, Lewis, Scott, 2015]

Constraints for UCMH by Pulsar Timing

[Clark, Lewis, Scott, 2015]



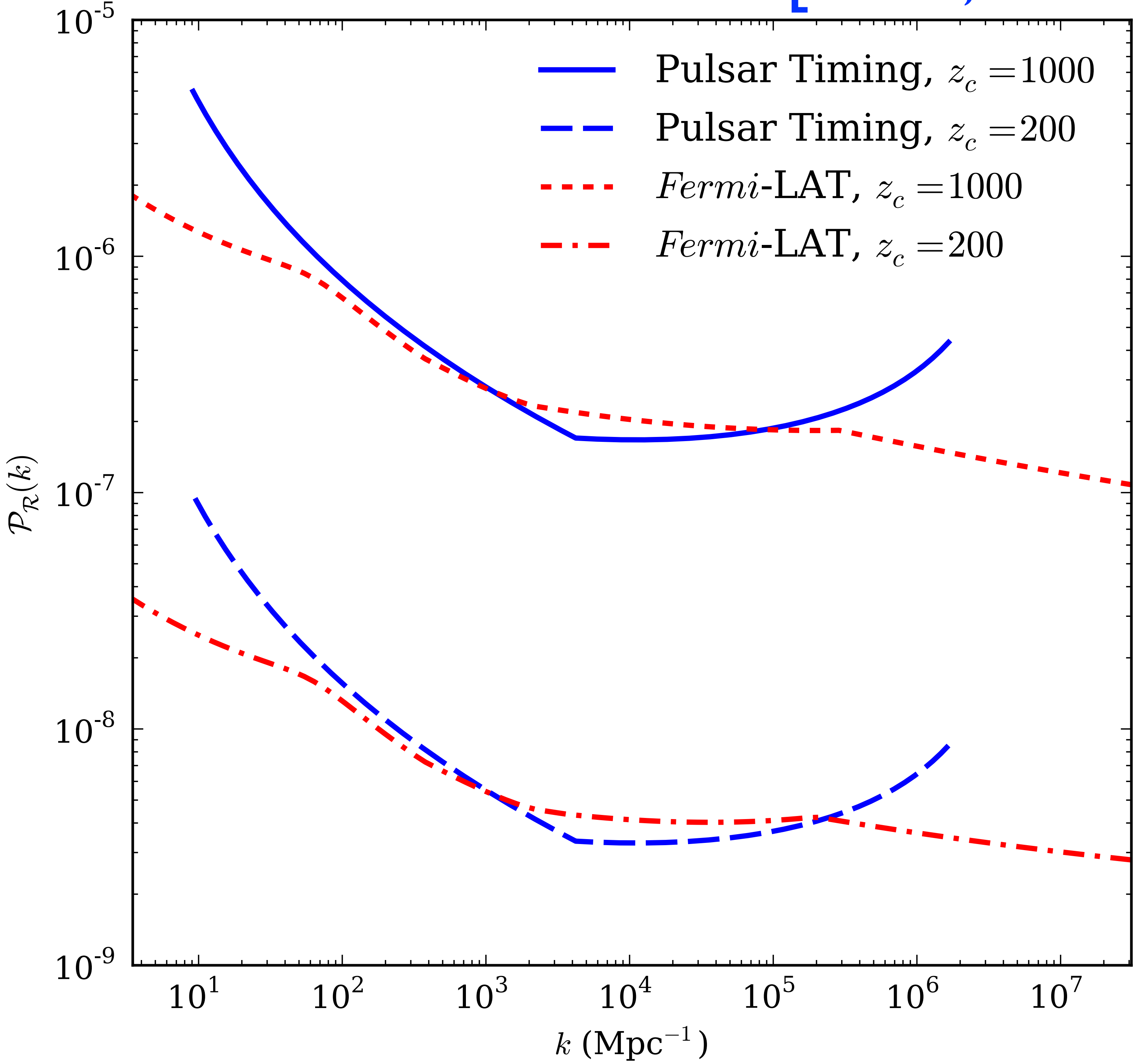
Pulsar time can change when the UCMHs are moving across the line of sight.

They obtain the bound on the fraction of UCMHs for different scales.

This is constraint is gravitational, so universal.

Constraints on Power Spectrum by Pulsar Timing

[Clark, Lewis, Scott, 2015]



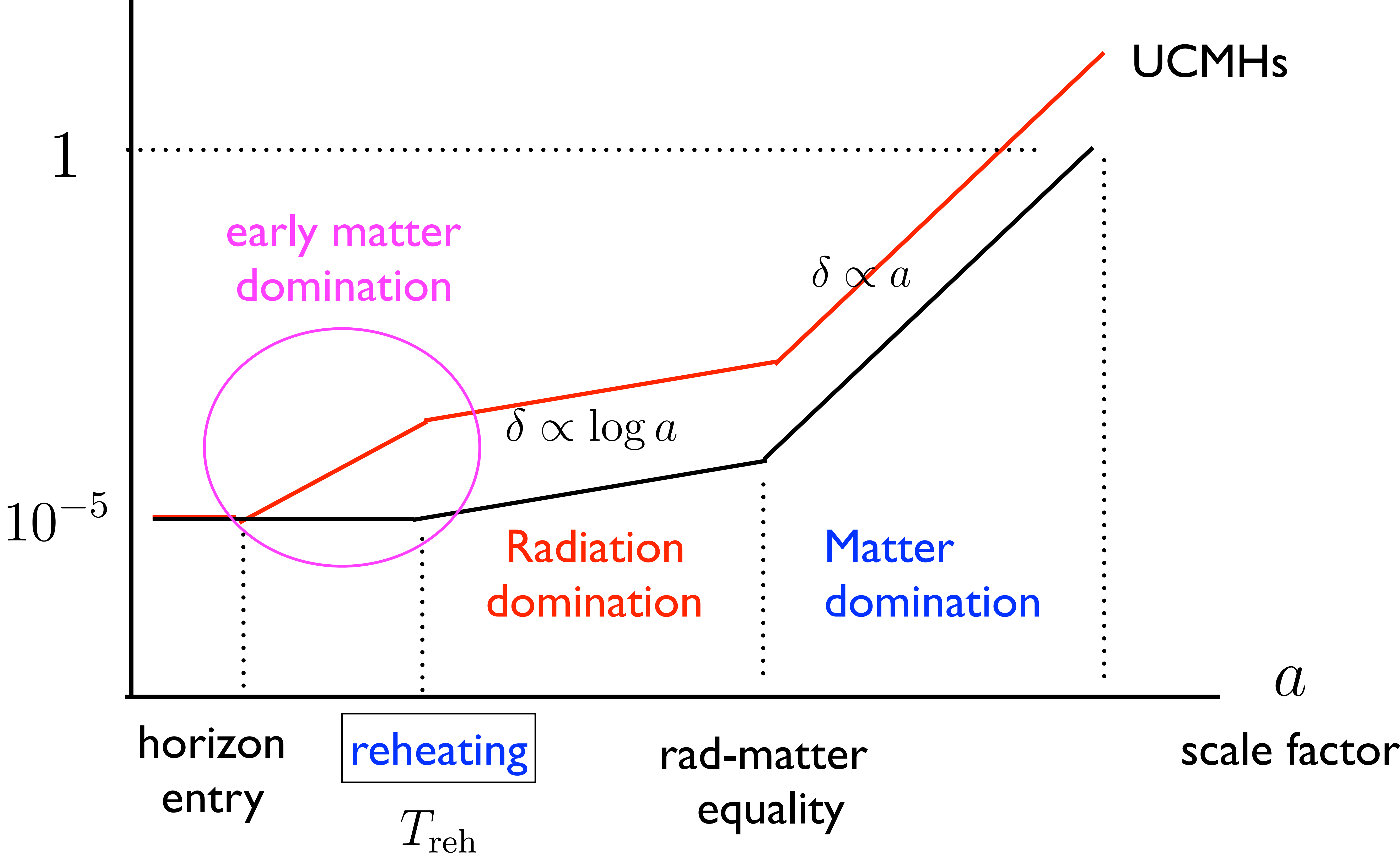
UCMHS with early MD

Before reheating, the epoch matter-domination exists (early matter-domination).

The perturbation which enters during early matter-domination can grow linearly and help to generate UCMHs.

Non-observation of UCMHs can constrain the primordial power spectrum and the stage of early matter-domination.

UCMHs and early Matter-Domination



To find $\delta_\chi^{\rm min}(k, t_k)$

It is roughly 0.001 at horizon entry in the standard Radiation -dominated Universe.

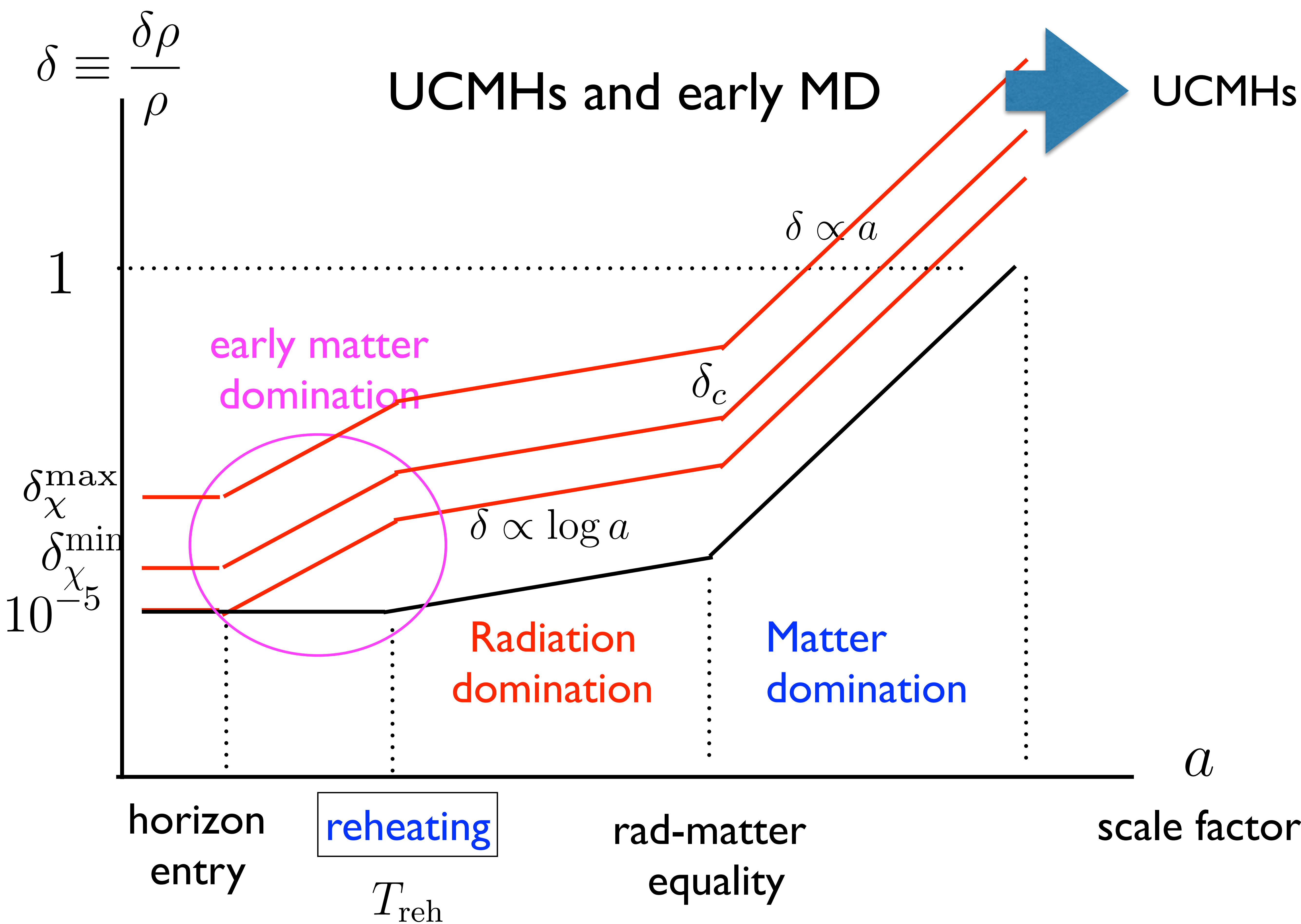
For early matter-domination, we need to make evolution from horizon entry to the deep inside until it forms the UCMHs.

linear evolution $\longrightarrow$ collapse

time of collapse using linear theory

$$\delta_c \equiv \frac{\delta\rho(t_c)_{\rm lin}}{\bar{\rho}(t_c)} = \frac{3}{5}\left(\frac{3\pi}{2}\right)^{2/3} \approx 1.686.$$

The collapse should happen before some epoch, here we choose z = 1000, conservatively.



UCMHs and early MD
$\delta \equiv \frac{\delta\rho}{\rho}$
UCMHs
$\delta \propto a$
1
early matter domination
δ_c
$\delta_\chi^{\mathrm{max}}$
$\delta_\chi^{\mathrm{min}}$
10^{-5}
$\delta \propto \log a$
Radiation domination
Matter domination
a
horizon entry
reheating
T_{reh}
rad-matter equality
scale factor

Growth of Density Perturbation

During matter-domination epoch,

Density perturbation contrast of the dominating heavy particles

$$\delta_\sigma = -2\Phi_0 - \frac{2}{3}\Phi_0 \left(\frac{k}{a_i H(a_i)} \right)^2 \frac{a}{a_i}$$

$$\delta_\sigma \equiv \delta\rho_\sigma / \rho_\sigma$$

Decoupled Dark Matter: super-WIMP

For decoupled dark matter, the evolution during early MD is same. Therefore at the time of reheating,

$$\delta_\chi \simeq -\frac{2}{3}\Phi_0\left(\frac{k}{k_{\rm reh}}\right)^2 \quad \text{for} \quad k < k_{\rm dom},$$

$$\delta_\chi \simeq -\frac{2}{3}\Phi_0\left(\frac{k_{\rm dom}}{k_{\rm reh}}\right)^2 \quad \text{for} \quad k > k_{\rm dom}$$

The scale of reheating is

$$k_{\rm reh} = 0.011967\,{\rm pc}^{-1}\left(\frac{T_{\rm reh}}{\rm MeV}\right)\left(\frac{10.75}{g_{*s}}\right)^{1/3}\left(\frac{g_*}{10.75}\right)^{1/2}$$

The scale of beginning early MD: $k_{\rm dom}$

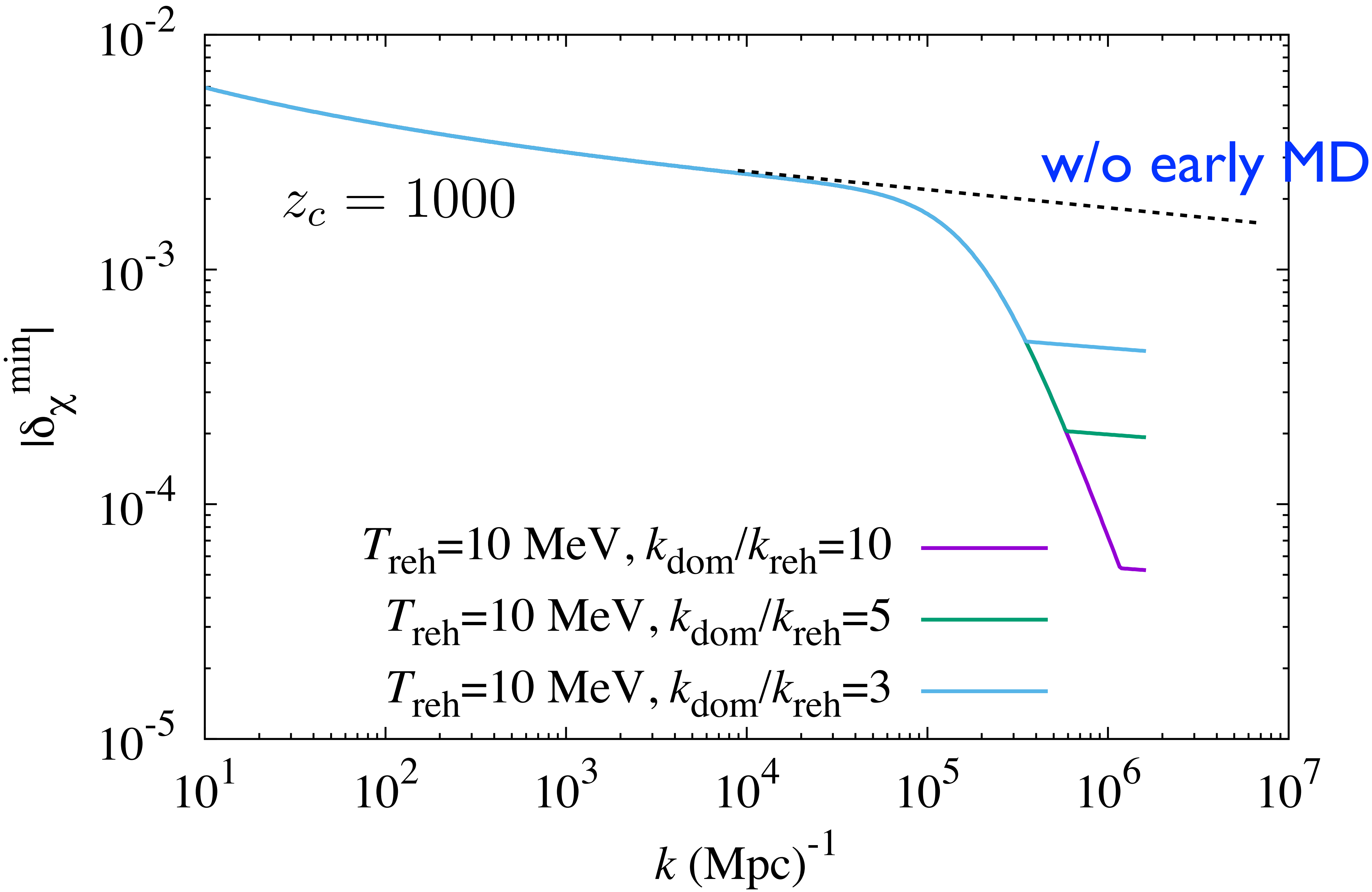
WIMP Dark Matter

For WIMP dark matter, it is still in the thermal equilibrium during early MD and freeze-out. After decoupling, the density of WIMP grows even in the kinetic equilibrium

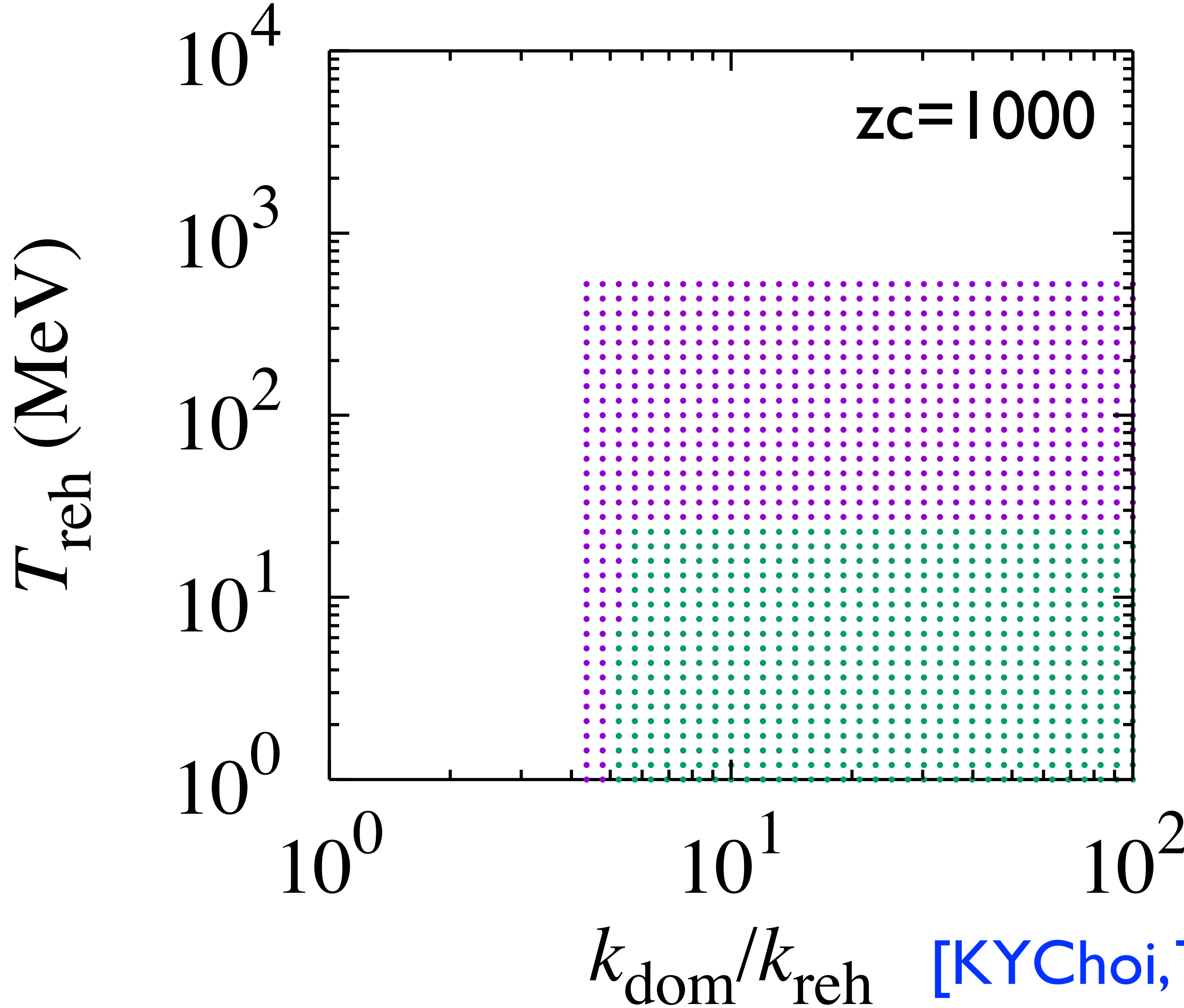
[KYChoi, Gong, Shin, 2015]

$$\delta_\chi \simeq \frac{5}{4}\Phi_0\left(\frac{k}{k_{\rm reh}}\right)^2, \qquad \text{at reheating epoch}$$

To form UCMSs with early MD



Bound on low-reheating Temperature



Fermi-LAT

$$T_{\rm reh} \gtrsim 500\,\mathrm{MeV}$$

pulsar timing

$$T_{\rm reh} \gtrsim 30\,\mathrm{MeV}$$

[KYChoi, Tomo Takahashi, in preparation]

Discussion

1. Reheating process follows the early matter-domination epoch.

2. Dark matter density perturbation growth during early matter-domination before reheating and can generate large number of UCMHs.

3. Non-observation of UCMHs can constrain the low-reheating temperature and gives new bound on the reheating temperature.