Dark matter with ultra compact mini halos

(probing early matter-dominated epoch)

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Early matter dominated epoch

Non-standard cosmology with early matter-dominated era before radiation-dominated :

- Inflaton oscillation

- Thermal inflation

- Curvaton domination

- During this period, the perturbation grows linearly inside horizon.
- The signatures of the large density perturbation on small scales
- It is not suppressed by the kinetic equilibrium
- It can be erased by free streaming

- The suppression of the power spectrum of DM on small scales

  - Free streaming scale

  - kinetic decoupling scale

: Restrict the formation of the objects smaller than these scales

- It is not always true if the density perturbation of DM is already large at the beginning of the Radiation domination.

  - Free streaming scale suppression remains

  : No suppression by the kinetic equilibrium

- The early Universe was almost homogeneous and isotropic, and there was no stars, galaxies, cluster of galaxies.

- There exists small perturbations in the density, which grows inside the horizon and finally becomes the seed for the formation of the structures of the large scale such as the galaxy, clusters of galaxy.

- The photons has the same density perturbations which results in the temperature anisotropy in the cosmic microwave background radiation.

- The primordial power spectrum of the curvature perturbation is adiabatic, Gaussian, and almost scale invariant.
- In Fourier space, with power law spectrum,

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_0}\right)^{n_{\rm s}-1+(1/2)(dn_{\rm s}/d\ln k)\ln(k/k_0)},$$

$$\mathcal{P}_\zeta = (2.198 \pm 0.056) \times 10^{-9}$$

$$n_\zeta = 0.959 \pm 0.007$$

- The above measurement is only for the range of the scale of

$$10^{-3} \lesssim k/\mathrm{Mpc}^{-1} \lesssim 10^{-1}$$

- No measurement on the other range of the scales.

- The scattering cross section

Inelastic scatterings : Number changing interactions

→ Chemical equilibrium → Relic density

Elastic scatterings : Number changing interactions

→ Kinetic equilibrium → Structure formation

✳ After decoupling from chemical equilibrium, the co-moving number density is conserved. However the exchange of the energy and momentum is still active and they are in the kinetic equilibrium. Somewhat later they are decoupled from kinetic decoupling.

Small scale suppression of power spectrum

- Chemical decoupling

- DM can have interaction with radiation and decoupled.
- For WIMP, chemical decoupling happens around

$$T_{\rm fr} \simeq \frac{m}{20}$$

- The comoving number density is frozen.

- Kinetic decoupling

- However the kinetic equilibrium may continue to the lower temperature around 5 - 1000 MeV.

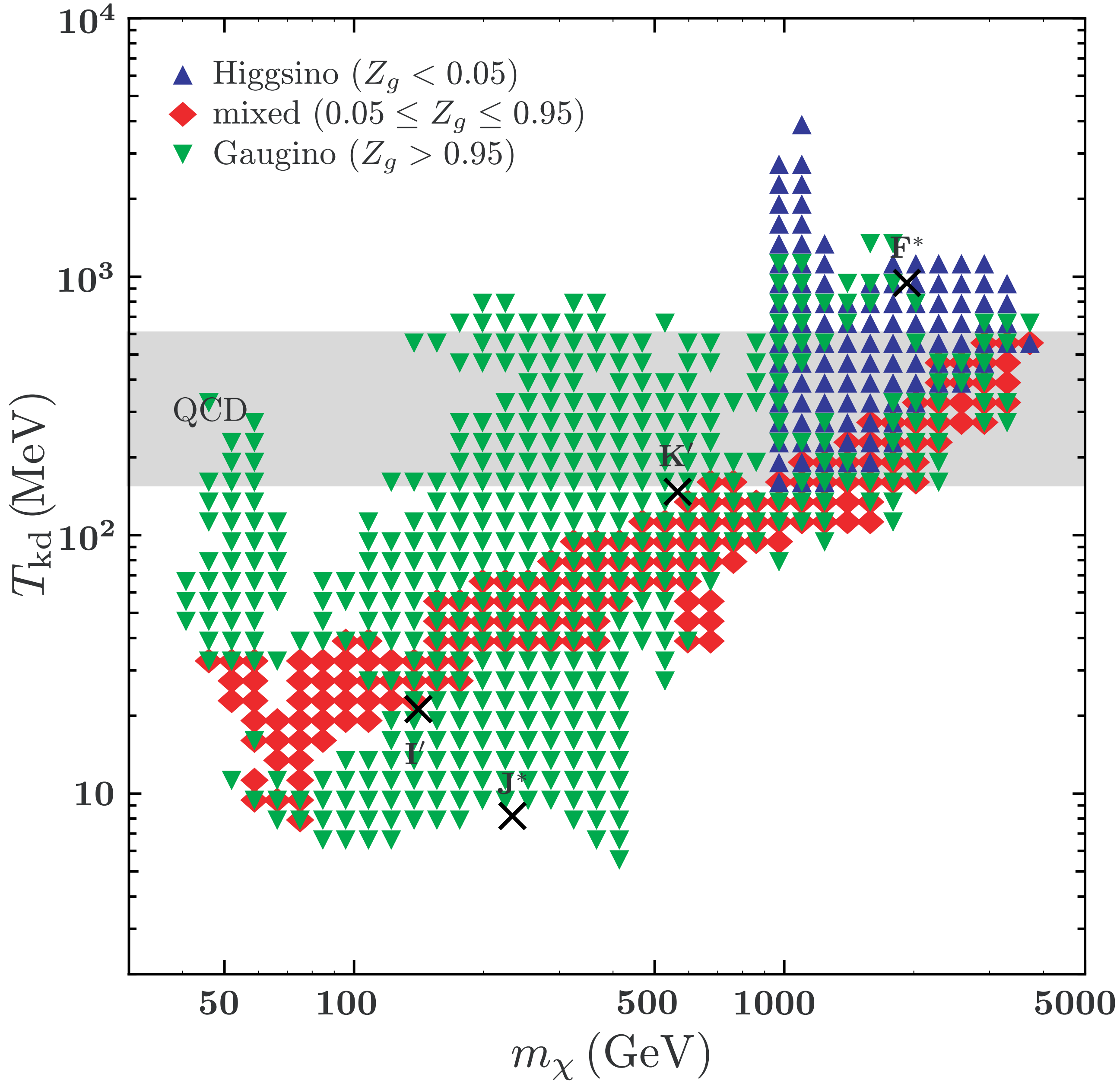
- The density perturbation can grow after kinetic decoupling
- This determines the minimum scale for the structure formation

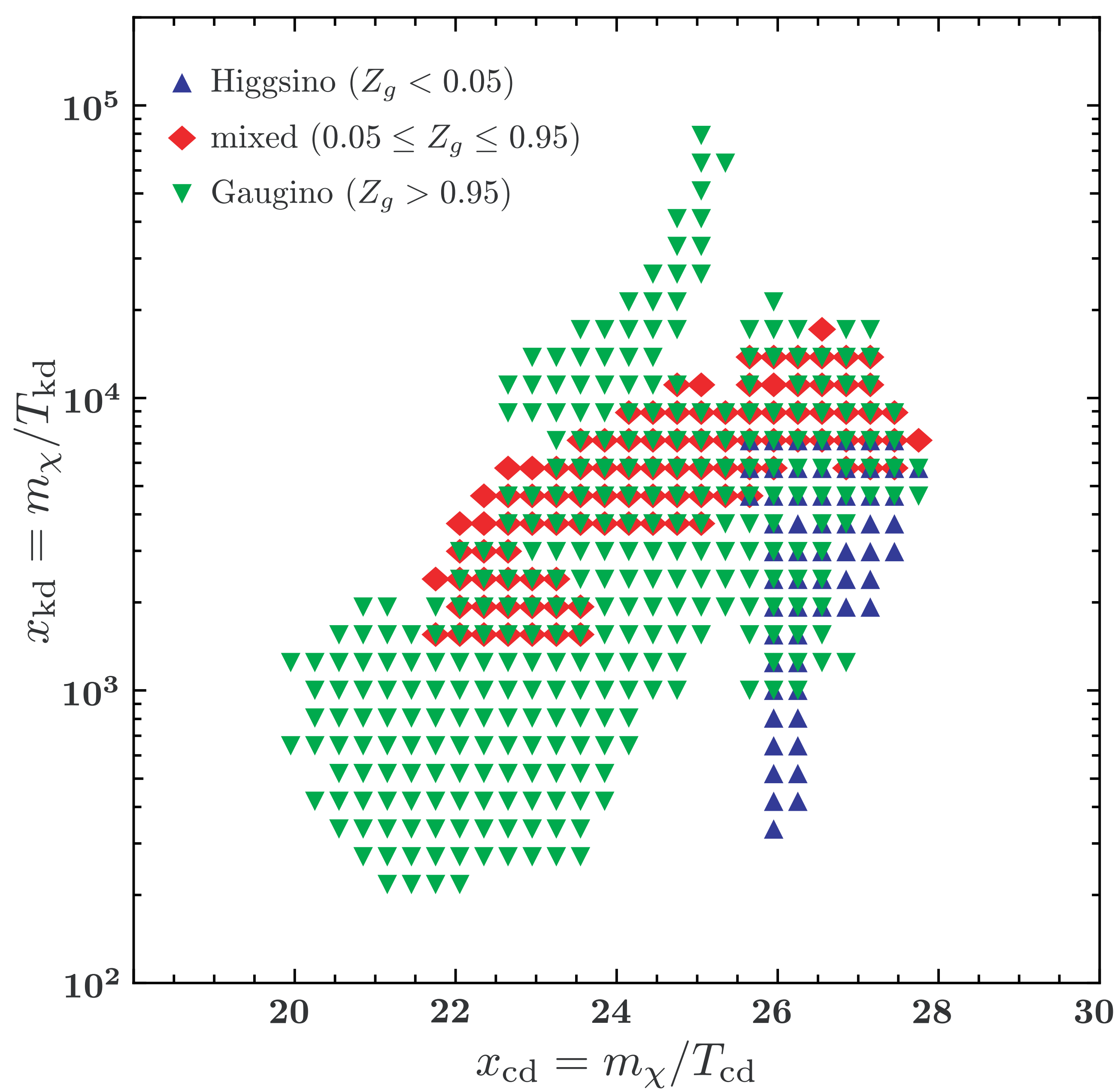
[Loeb, Zaldarriaga, 2005]

Kinetic decoupling temperature of neutralinos

[Bringmann, 2009]

$Z_{\rm g}$: gaugino fraction

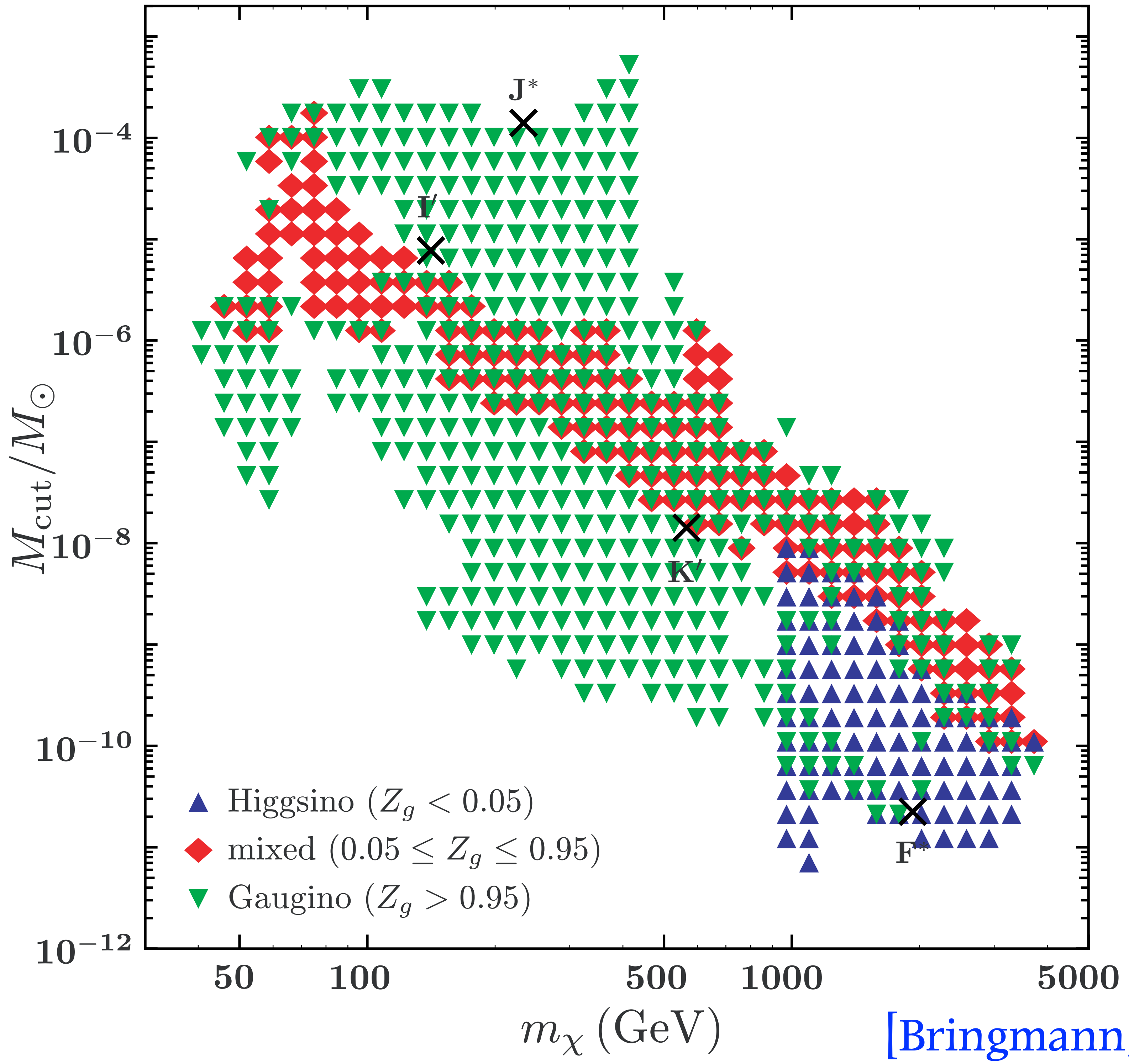




Kinetic decoupling takes place much later than chemical decoupling by a factor of 10 - 1000.

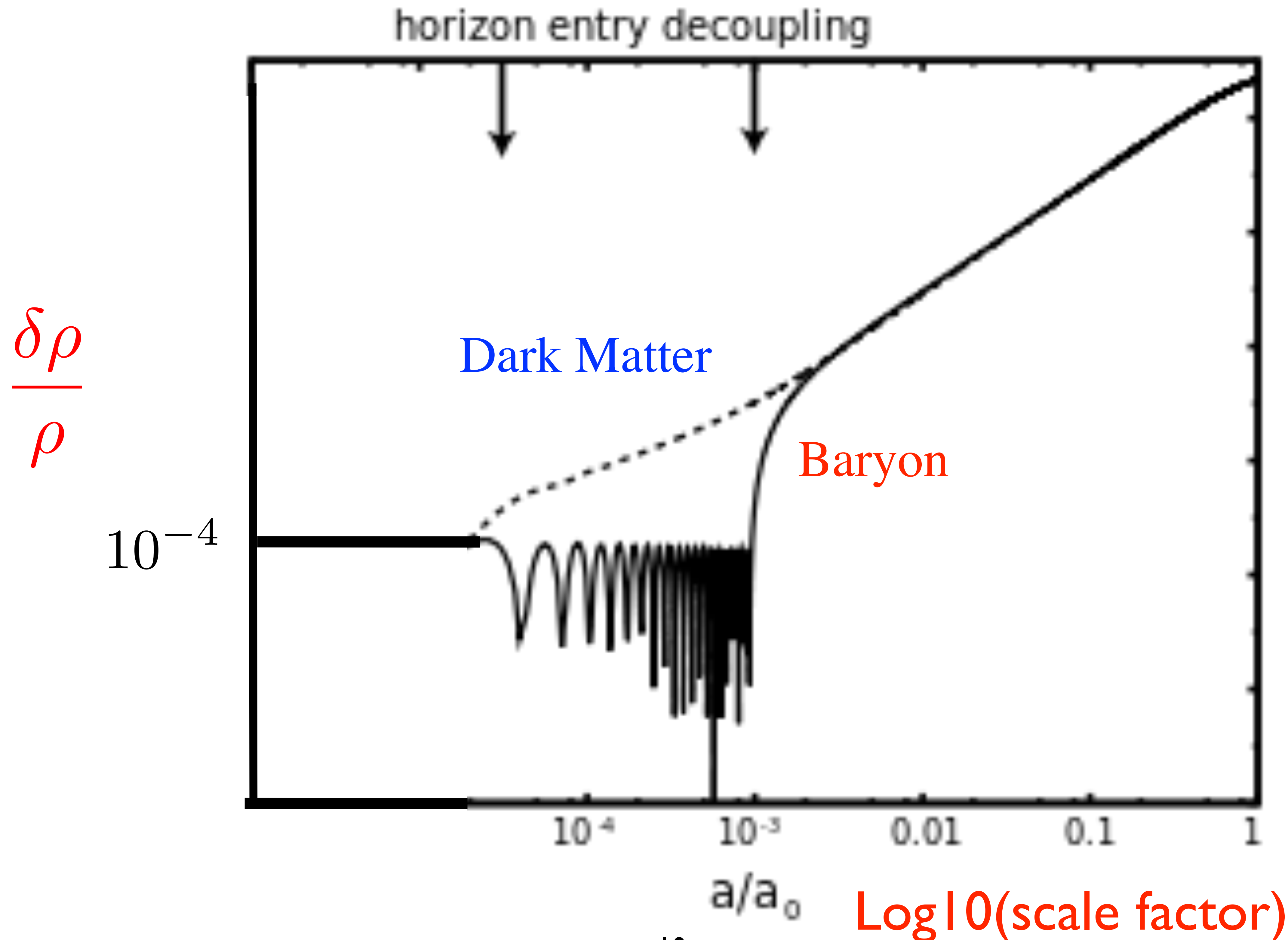
Typical size of the smallest proto-halos : $10^{-11} M_\odot$ to a few times $10^{-4} M_\odot$,

Earth mass ~



[Bringmann, 2009]

Standard cosmology: the cosmologically relevant scale enters horizon during RD and grows logarythmically, and mainly grows during matter-dominated.



Small scale suppression of power spectrum

- Free streaming

The free streaming (collision-less damping, Landau damping) of dark matter from dense regions to under-dense regions smoothes out inhomogeneities for the smaller than the free streaming length scale.

$$\lambda_f = \int_{t_i}^{t} \frac{v(t')}{R(t')} dt'.$$

For WIMPs,

$$k_{\rm fs} \simeq \left(\frac{0.01}{c_s(T_{\rm kd})}\right)\left(\frac{14}{1+0.07\ln(\frac{T_{\rm kd}}{\rm MeV})}\right)\left(\frac{T_{\rm kd}}{\rm MeV}\right)\left(\frac{1}{12\,{\rm pc}}\right)$$

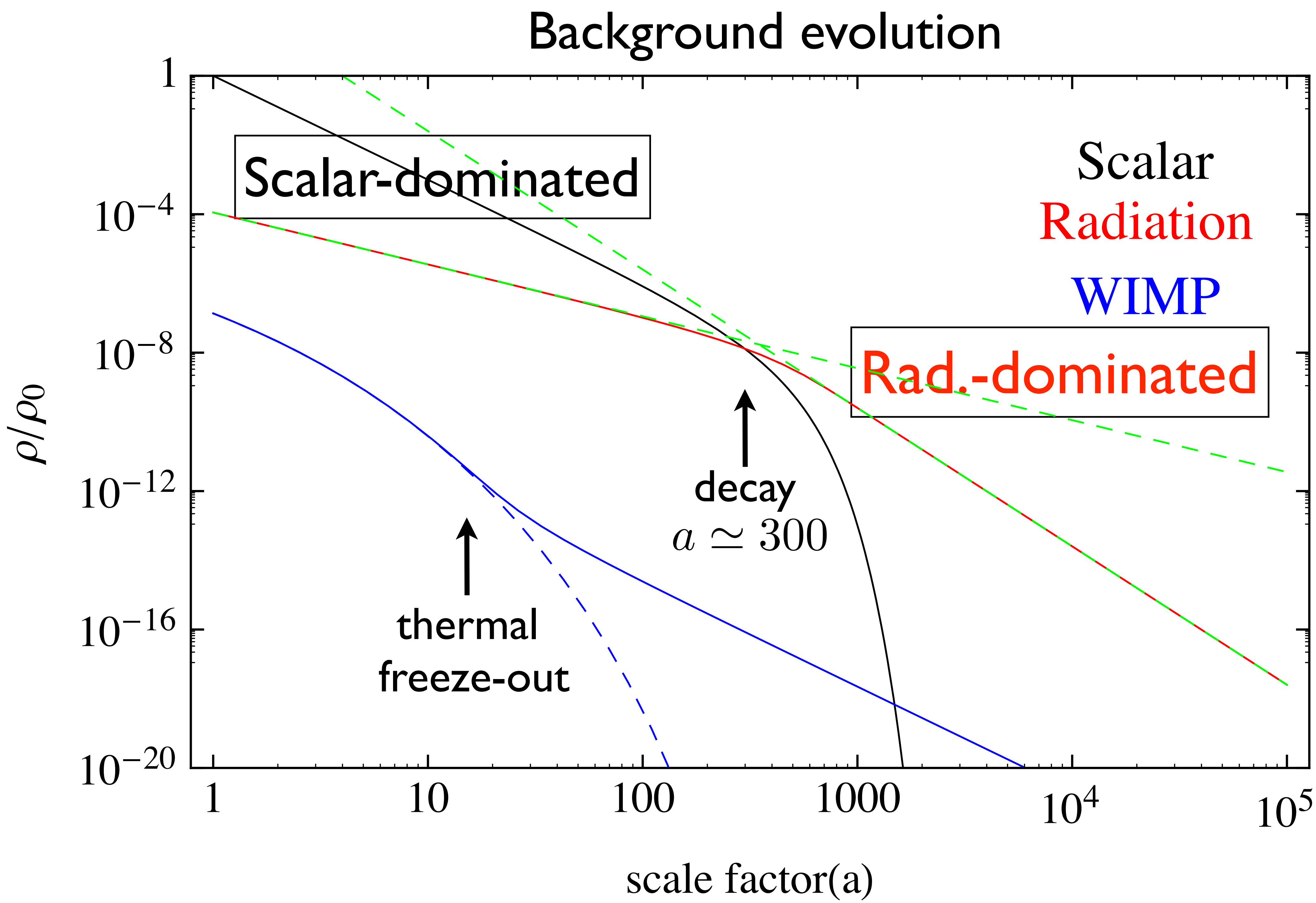
with effective sound speed squared of DM $\quad c_s^2(T_{\rm kd}) \simeq \dfrac{T_{\rm kd}}{m}$

Evolution

Non-thermal Universe dominated by a non-relativistic field (scalar domination)

$$T_{\rm fr} > T_{\rm reh} > T_{\rm kd}$$

10GeV 100 MeV 1 MeV



During scalar domination, the radiation is produced from the decay of the scalar and DM is produced from thermal plasma by scatterings.

The perturbations are adiabatic on superhorizon scales, since the radiation and DM are produced from the same source of dominating scalar.

On super-horizon scales, when DM is non-relativistic in the thermal equilibrium, the initial conditions are

$$\delta_\phi(a_i) = 2\Phi_0\,,$$
$$\delta_r(a_i) = \Phi_0\,,$$
$$\delta_m(a_i) \approx \frac{M}{4T_i}\delta_r(a_i) = \frac{M}{4T_i}\Phi_0 \qquad \text{(WIMP in thermal equilibrium)},$$

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

Newtonian gauge $ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)\delta_{ij}dx^i dx^j$

Perturbation equations

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

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

with

$$Q_\phi = -\Gamma_\phi\rho_\phi ,$$

$$Q_r = \Gamma_\phi\rho_\phi + \frac{\langle\sigma v\rangle}{M}\left[\rho_m^2 - (\rho_m^{\rm eq})^2\right] ,$$

$$Q_m = -\frac{\langle\sigma v\rangle}{M}\left[\rho_m^2 - (\rho_m^{\rm eq})^2\right] ,$$

$$\delta Q_\phi = -\Gamma_\phi\rho_\phi\delta_\phi,$$

$$\delta Q_r = \Gamma_\phi\rho_\phi\delta_\phi + \frac{2\langle\sigma v\rangle}{M}\left[\rho_m^2\delta_m - (\rho_m^{\rm eq})^2\frac{M}{T}\frac{\delta_r}{4}\right] ,$$

$$\delta Q_m = -\frac{2\langle\sigma v\rangle}{M}\left[\rho_m^2\delta_m - (\rho_m^{\rm eq})^2\frac{M}{T}\frac{\delta_r}{4}\right] ,$$

$$\partial_i Q^i_{(\phi)} = -\Gamma_\phi\rho_\phi\theta_\phi$$

$$\partial_i Q^i_{(r)} = \Gamma_\phi\rho_\phi\theta_\phi + \frac{\langle\sigma v\rangle}{M}\left[\rho_m^2\theta_m - (\rho_m^{\rm eq})^2\left(\frac{M}{2\pi T}\right)^{1/2}\theta_r\right] - \frac{4}{3}\frac{\sigma_e}{M}\rho_m\rho_r\left(\theta_r - \theta_m\right) ,$$

$$\partial_i Q^i_{(m)} = -\frac{\langle\sigma v\rangle}{M}\left[\rho_m^2\theta_m - (\rho_m^{\rm eq})^2\left(\frac{M}{2\pi T}\right)^{1/2}\theta_r\right] + \frac{4}{3}\frac{\sigma_e}{M}\rho_m\rho_r\left(\theta_r - \theta_m\right) ,$$

Horizon reentry depending on the scale

(I) The modes that remain outside even after reheating and kinetic decoupling

$$k^{-1} > k_{\rm kd}^{-1}$$

(II) The modes that enter the horizon during RD after kinetic decoupling

$$k_{\rm kd}^{-1} < k^{-1}$$

(III) The modes that enter the horizon during RD before kinetic decoupling

$$k_{\rm reh}^{-1} < k^{-1} < k_{\rm kd}^{-1}$$

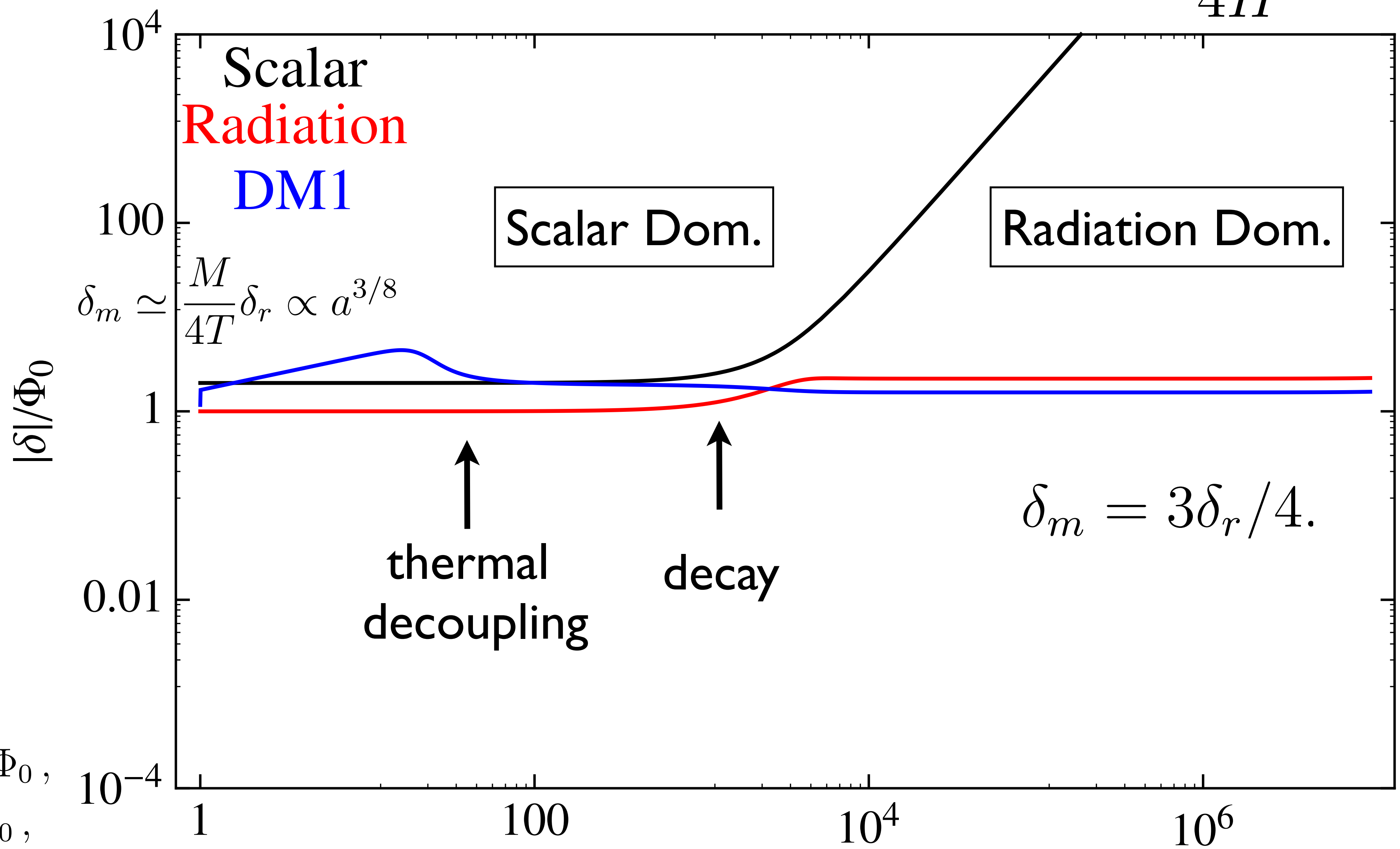
(IV) The modes that enter the horizon during SD

$$k^{-1} < k_{\rm reh}^{-1}$$

(I) The modes that remain outside even after reheating and kinetic decoupling

$$k^{-1} > k_{\rm kd}^{-1}$$

$$\delta_\phi \simeq \frac{\Gamma_\phi}{4H}\delta_r \propto a^2$$ during decay



$$\delta_\phi(a_i) = 2\Phi_0\,,$$

$$\delta_r(a_i) = \Phi_0\,,$$

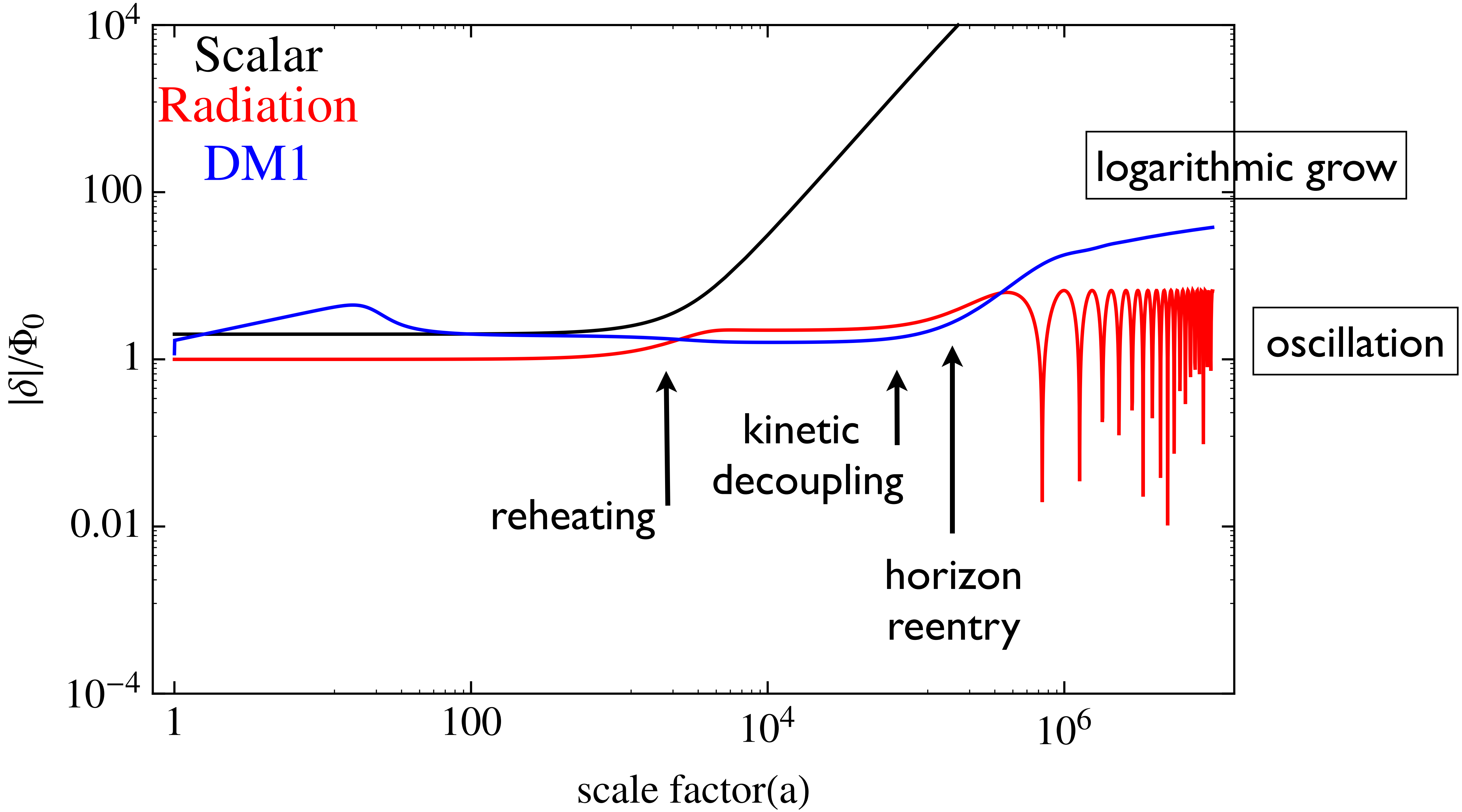
$$\delta_m(a_i) \approx \frac{M}{4T_i}\delta_r(a_i) = \frac{M}{4T_i}\Phi_0$$

RD, $\theta \equiv k\tau/\sqrt{3},$

$$\Phi = \Psi \;=\; -\frac{3}{\theta^3}(\sin\theta - \theta\cos\theta)$$

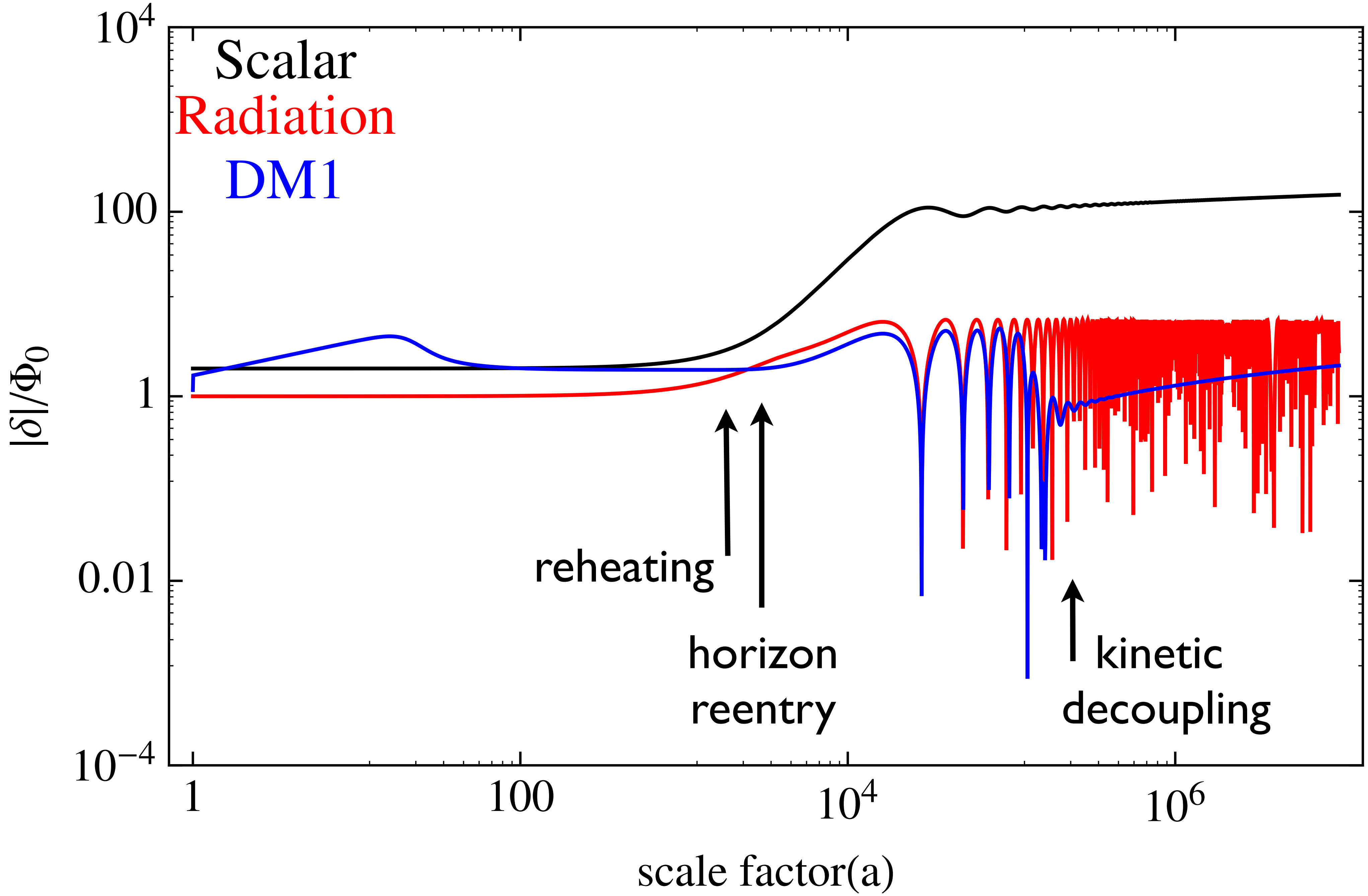
(II) The modes that enter the horizon during RD after kinetic decoupling

$$k_{\rm kd}^{-1} < k^{-1}$$



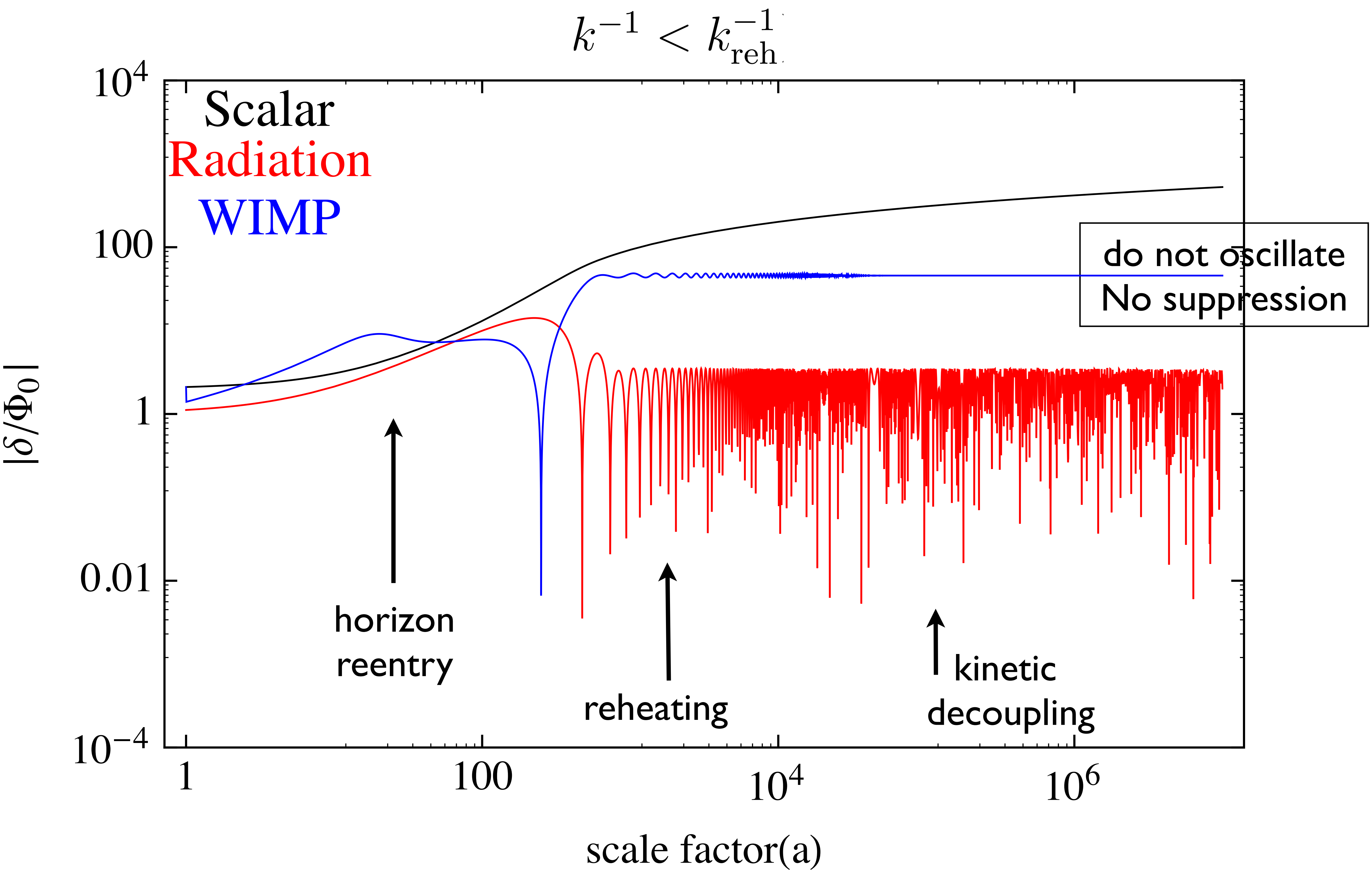
(III) The modes that enter the horizon during RD before kinetic decoupling

$$k_{\rm reh}^{-1} < k^{-1} < k_{\rm kd}^{-1}$$

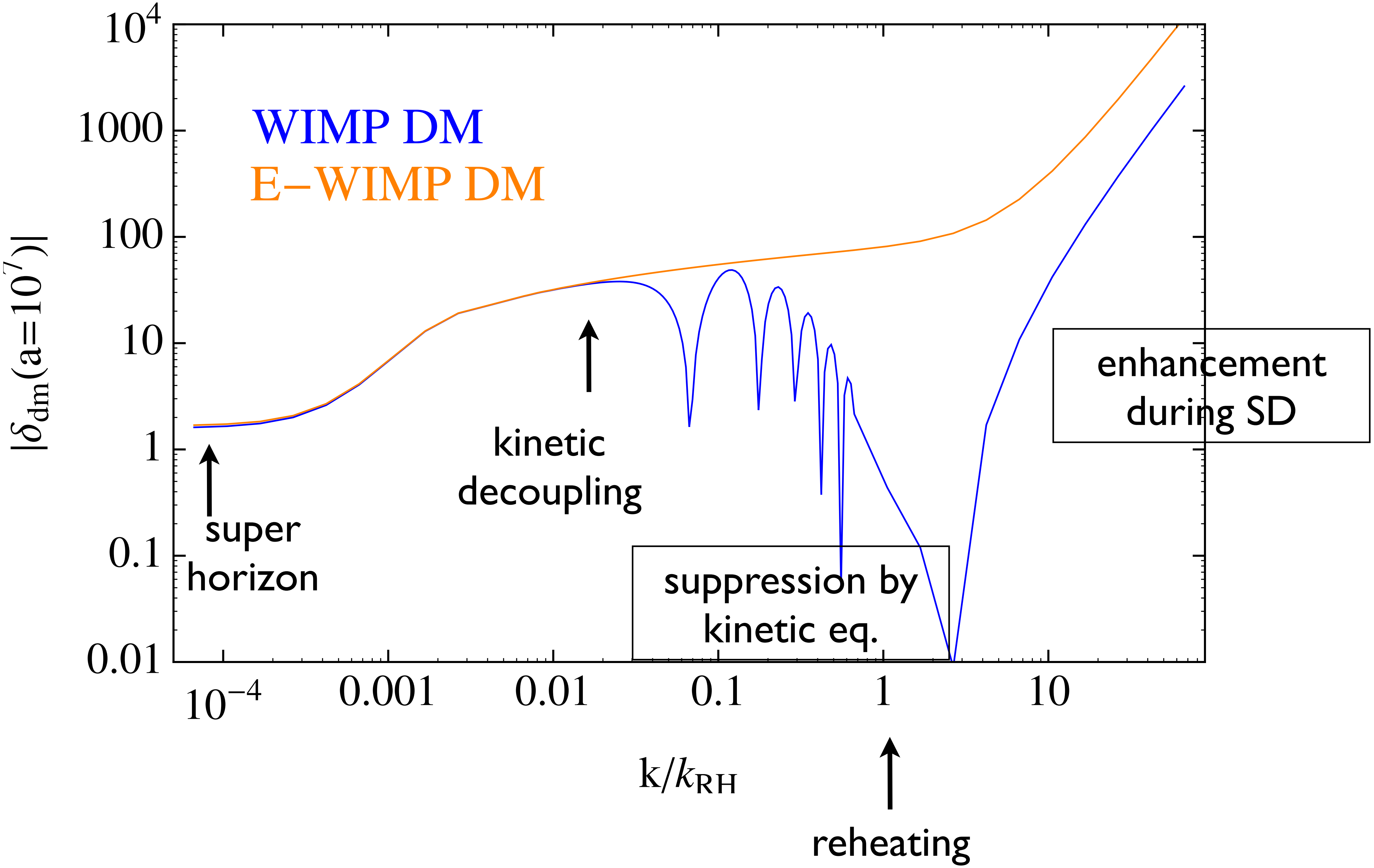


oscillation and log. growth

(IV) The modes that enter the horizon during SD



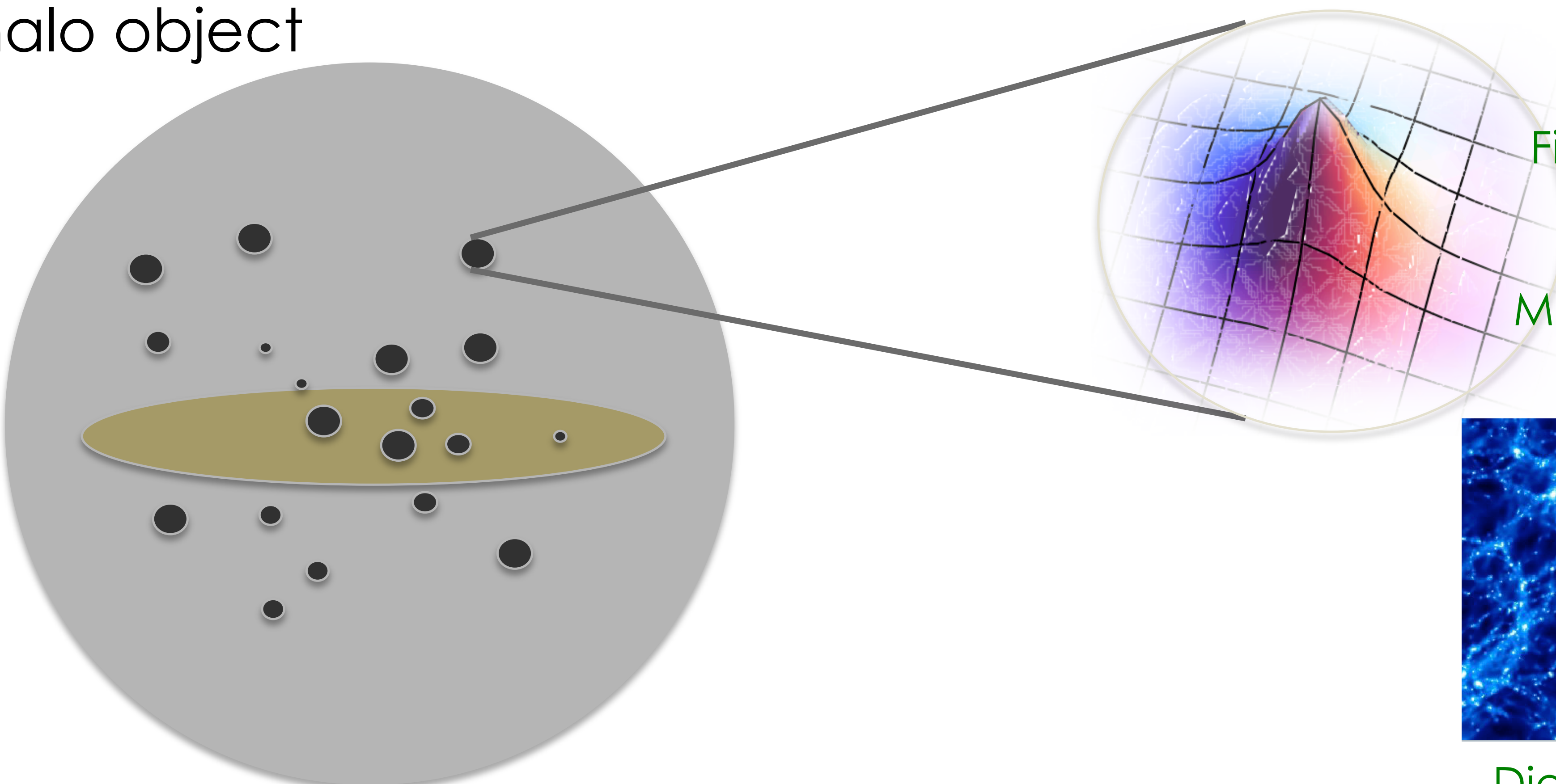
The growth and suppression of the density perturbation.



Probing the DM halo

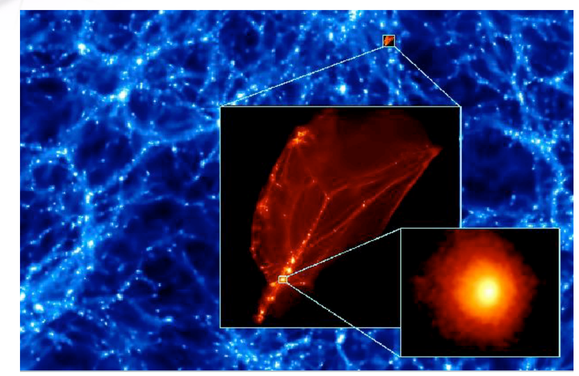
Primordial perturbation

Ultra Compact Mini Halo (UCMH) : Non-baryonic Massive compact halo object

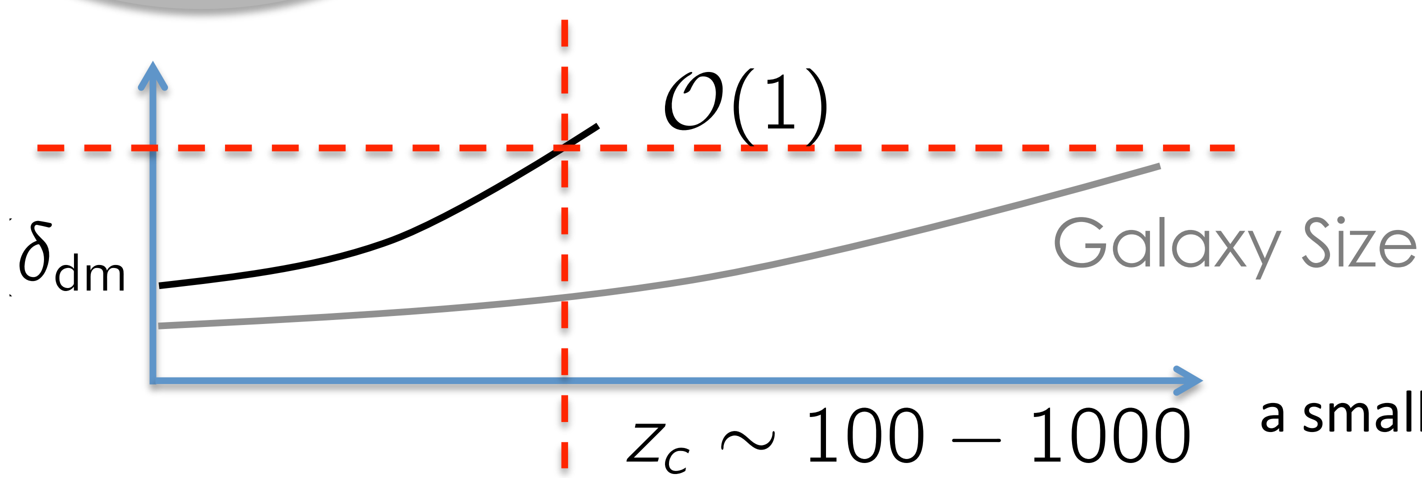


$$\rho(r) \sim \frac{1}{r^{2.25}}$$

Fillmore, Goldreich 1984
Bertschinger 1985
Vogelsberger, White, Mohayaee, Springel 2009
Ludlow et al. 2010



Diemand et al, Nature 05 at z=26



a small velocity dispersion at z=zc

Ricotti, A. Gould 2009

How is the large perturbation generated?

- Features in the inflationary potential : large perturbation at small scales

- Matter-dominated epoch before radiation domination
  : oscillating inflation, curvaton, moduli, thermal inflation etc

Observing UCMH?

- UCMH is an DM dominated isolated objects
- Very steep density profile $\rho \propto r^{-9/4}$
- Lensing targets [Ricotti, Gould, 2009] [Li et al, 2012]
- Indirect detection [Scott, Siverstsson, 2009] [Lacki, Beacom, 2012]

Probing UCMH with WIMP dark matter

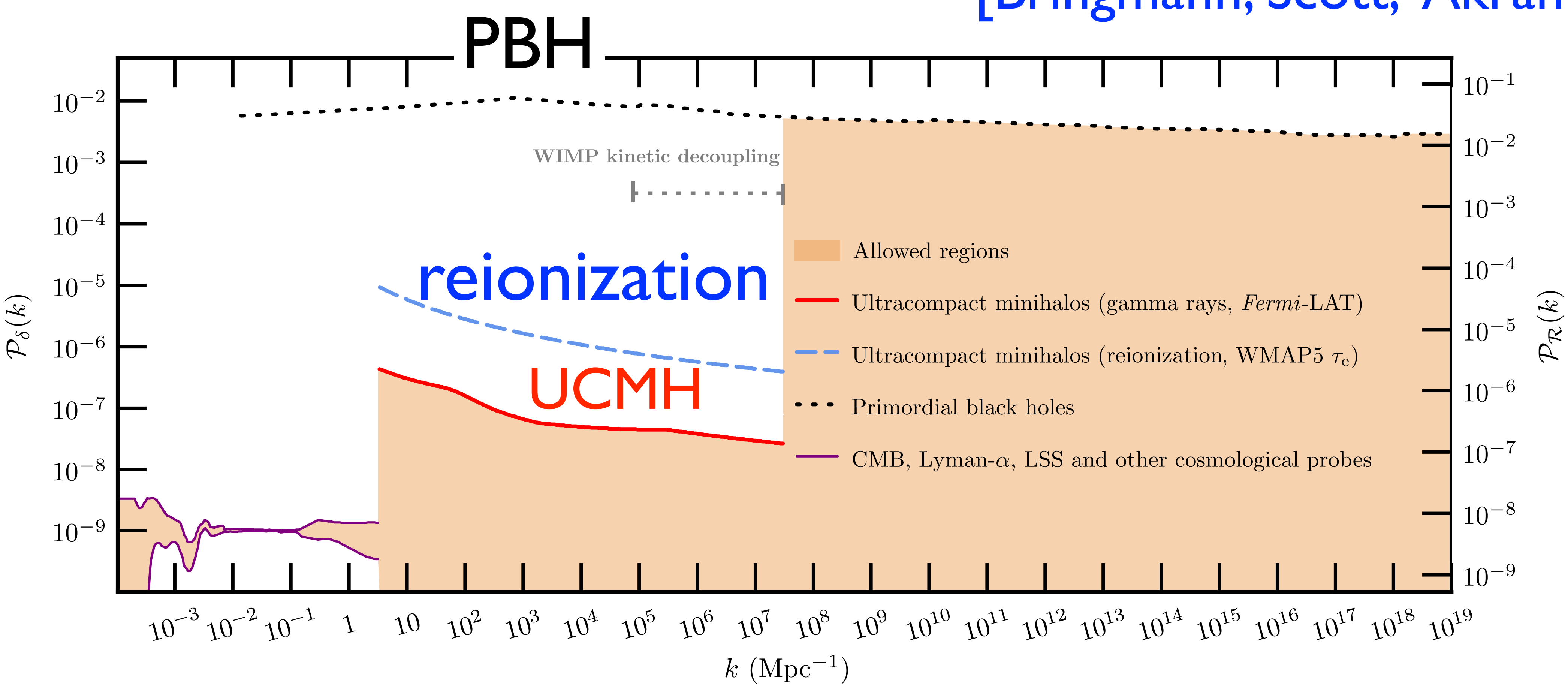
[Diemand, Moore, Stadel, 2005]

- WIMPs in the Earth-mass clumps annihilate and produce gamma-rays that can be probed by gamma-ray telescopes.

- The annihilation of DM can affect the reionization process.

- Up to now, Non-observation of UCMH put strong constraints on the primordial spectrum at small scales.

[Bringmann, Scott, Akrami, 2012]



Probability to create UCMH

- the probability that a region of comoving size R, at the time of 1/R=aH, will collapse later into UCMH for Gaussian perturbation,

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

- mass variance with top-hat window function

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

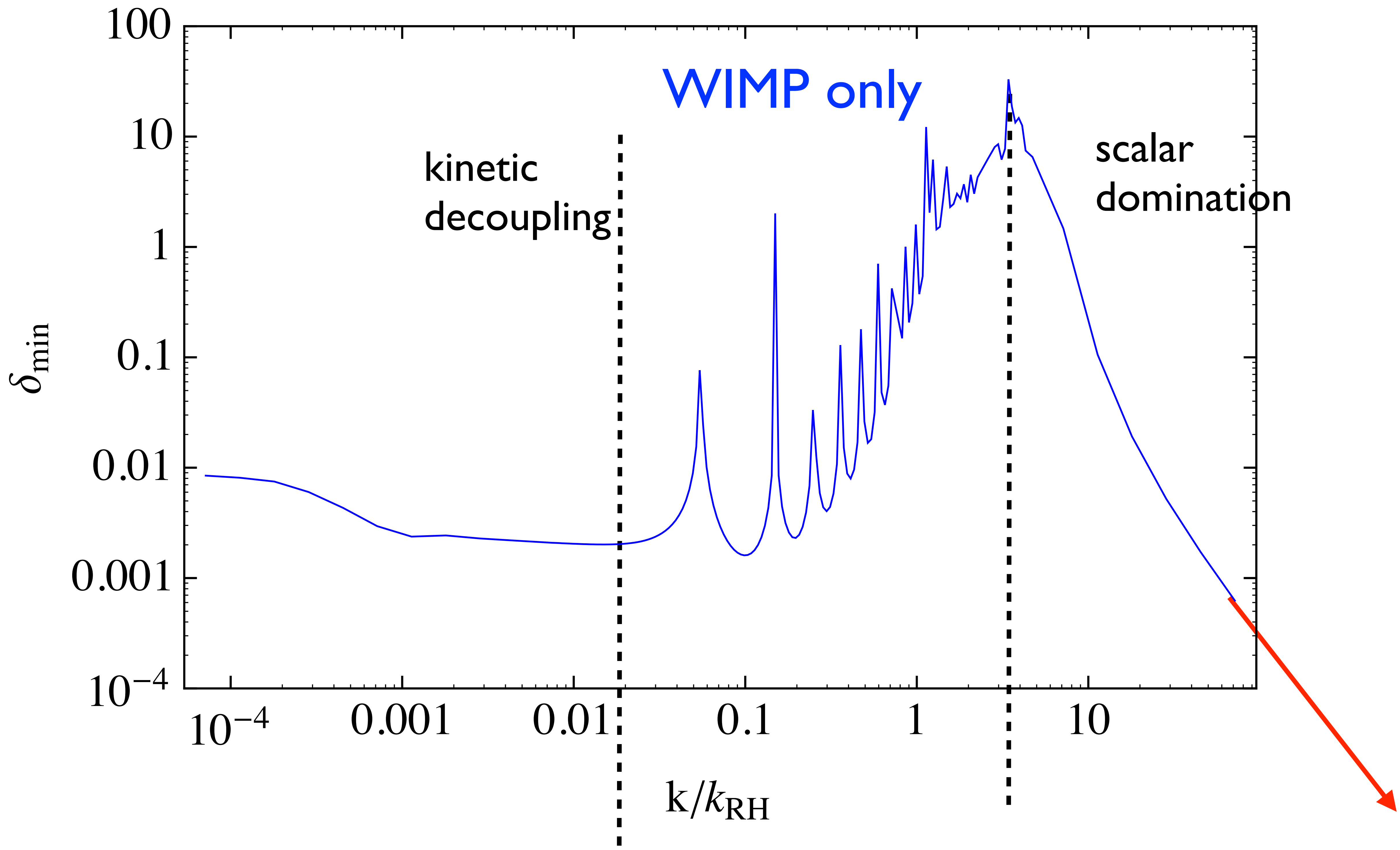
- the determination of $\delta_\chi^{\min}$ depends on the specific model of early Universe

- $\sigma^2(R)$ depends on the primordial power spectrum

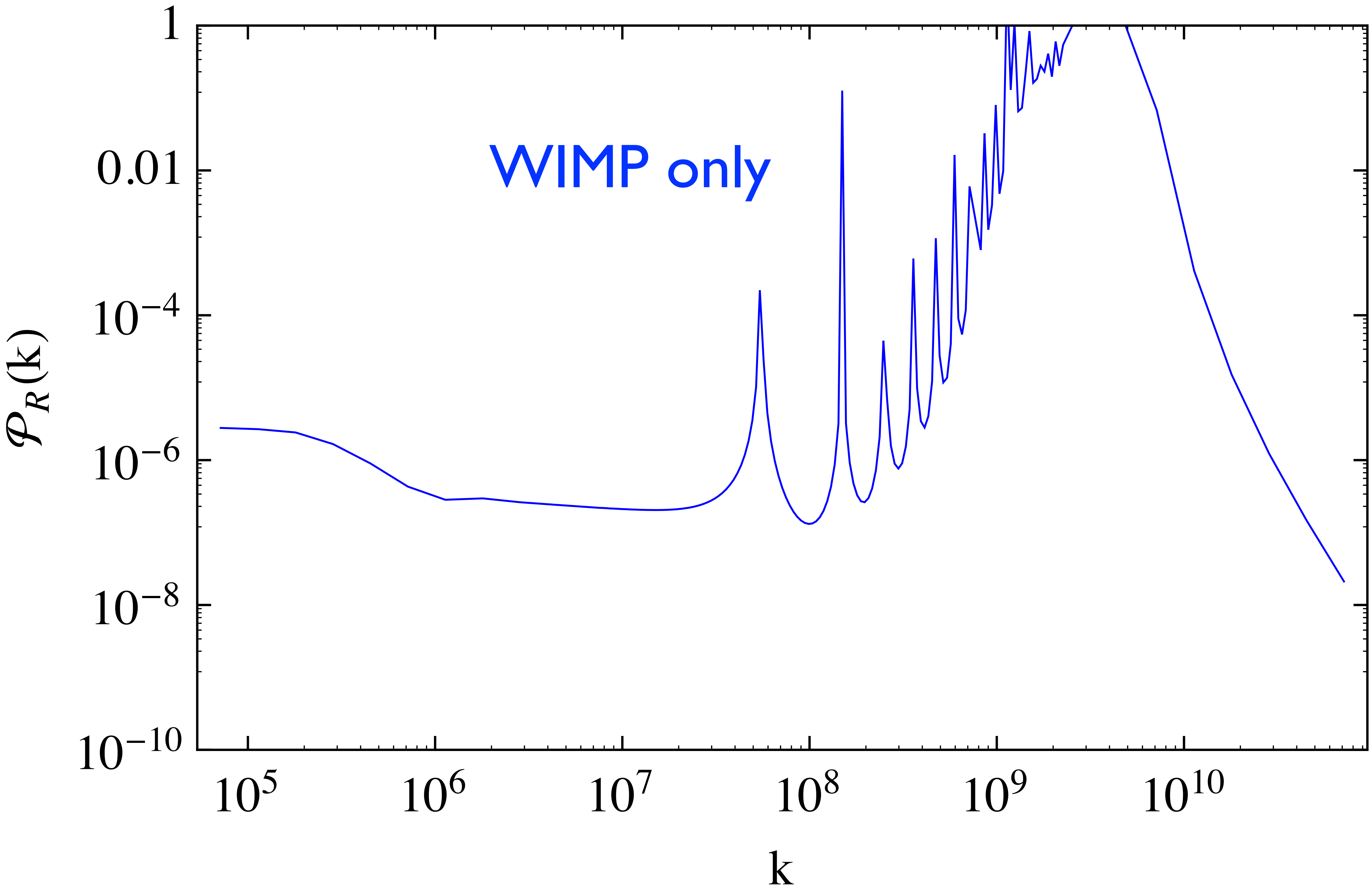
However the constraint changes depending on the dark matter properties or the model of early Universe.

- If DM is not WIMP, there is no signal from the UCMH and no constraints.
- The growth and evolution of DM perturbation also changes depending on the DM properties: kinetic decoupling etc.
- If there was a non-standard Universe before the radiation-dominated era, the constraint also changes.
- Matter-dominated era before RD makes the constraints stronger.

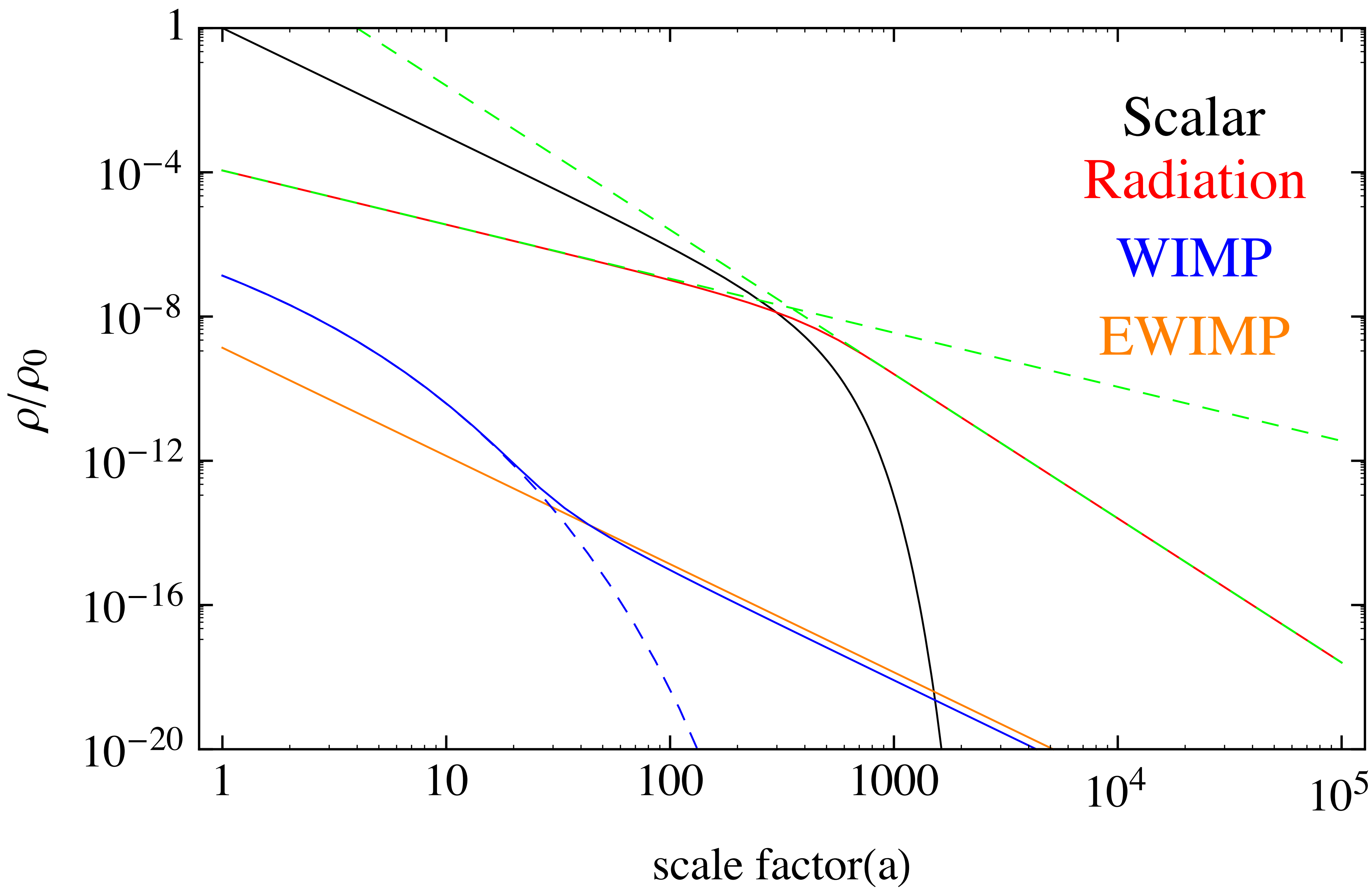
Upper limit on $\delta_\chi^{\min}$ with WIMP DM in the scalar-dom. phase.



Upper limit on $\mathcal{P}_\delta(k)$ in the non-standard cosmology



WIMP DM + E-WIMP DM



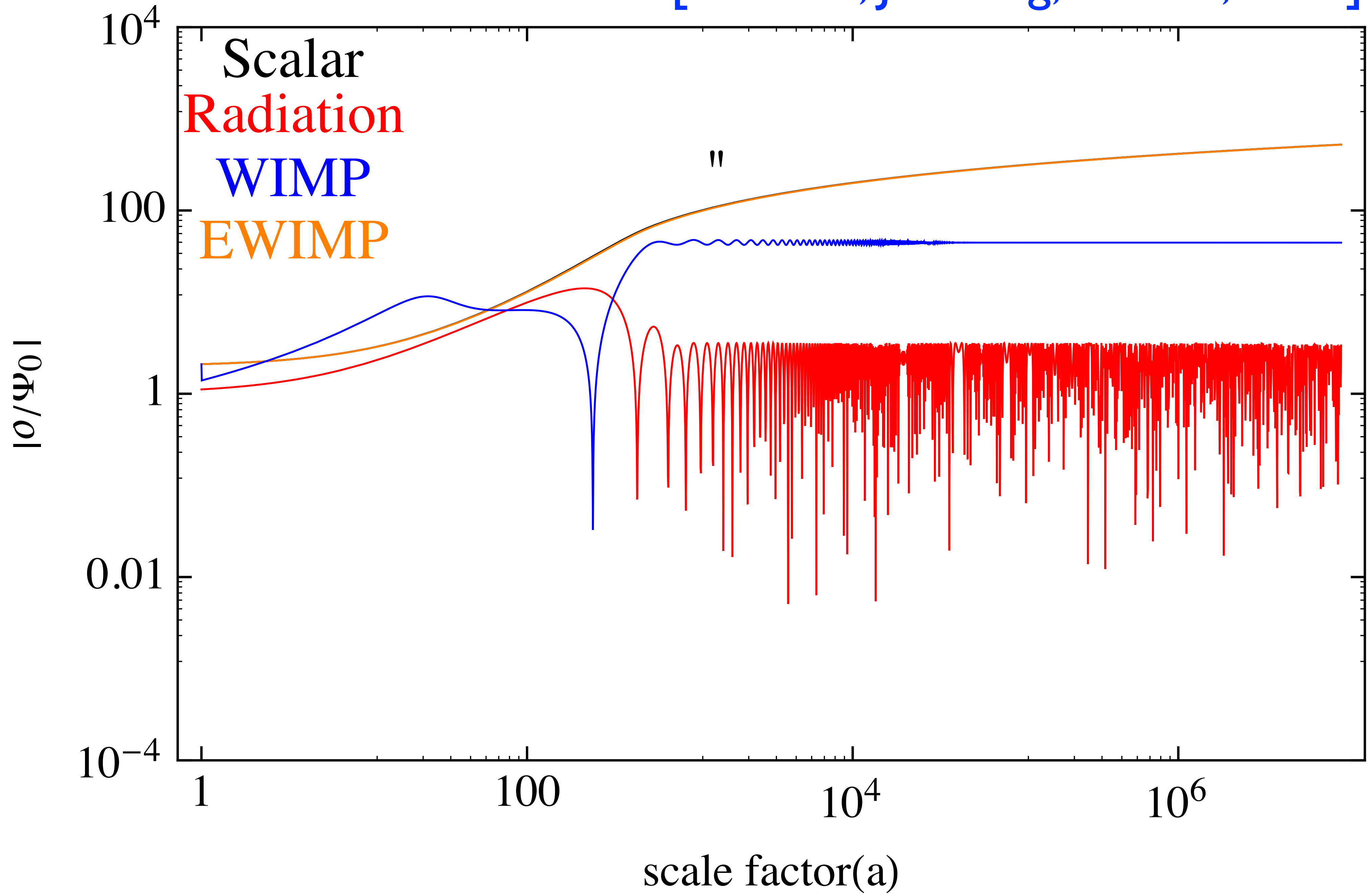
$$\frac{\Omega_{\rm WIMP}}{\Omega_{\rm EWIMP}} = \frac{1}{2}$$

$k = 10^{-0.4} H_1$: the scale enters horizon during scalar dominated.

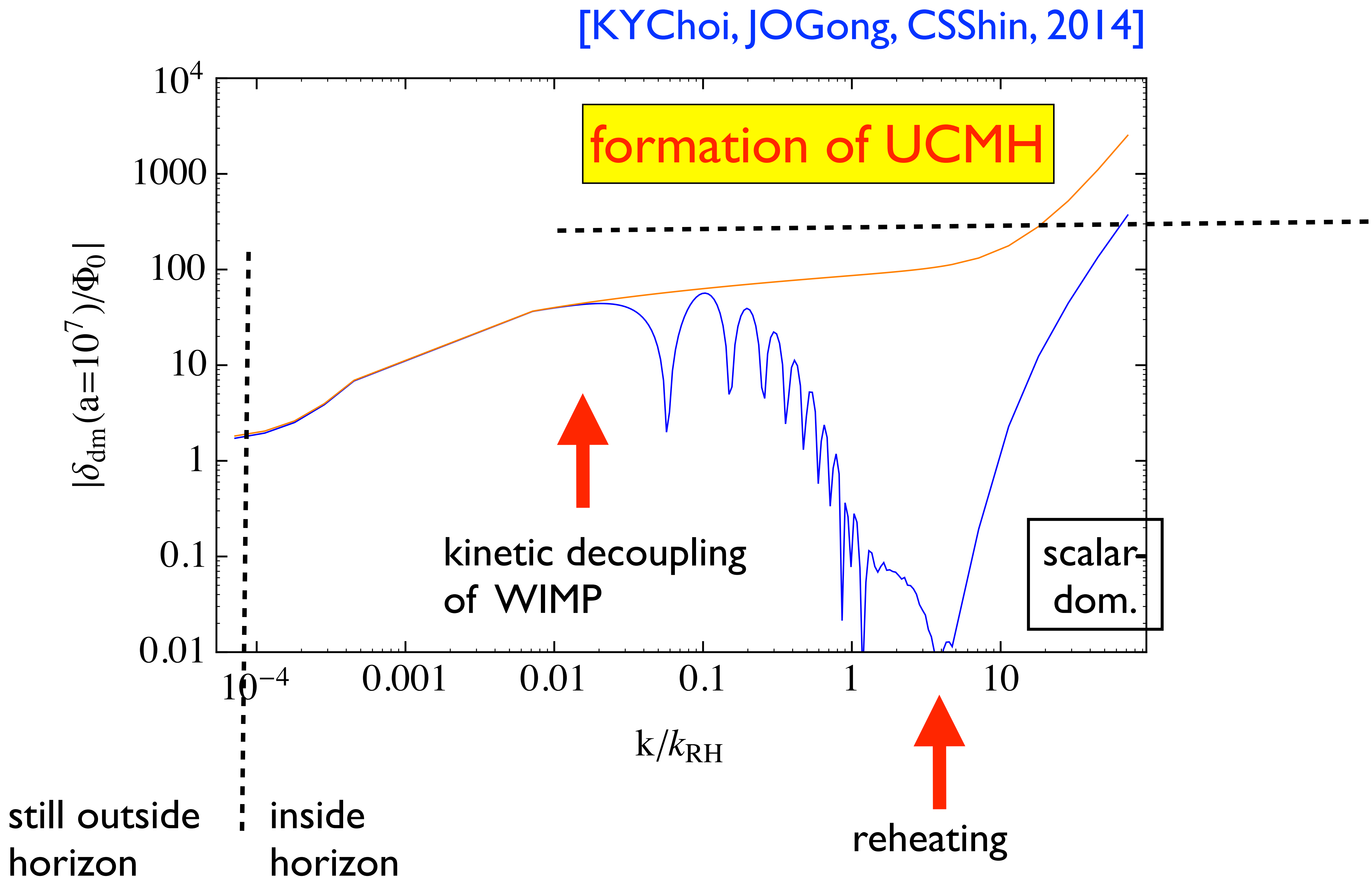
WIMP perturbation is enhanced

E-WIMP perturbation follows scalar

[KYChoi, JOGong, CSShin, 2014]

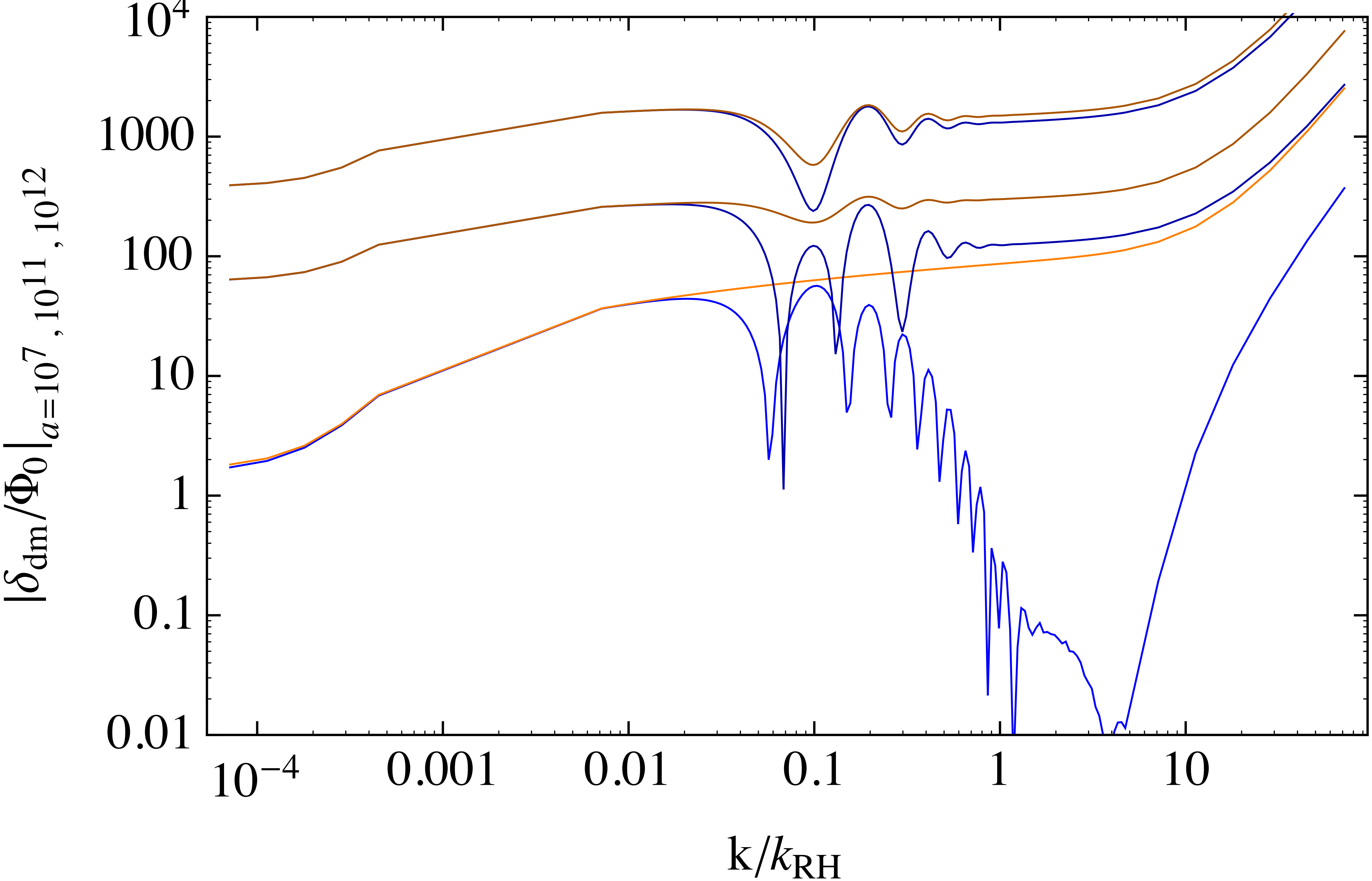


$$\delta_{\rm dm}(a = 10^7)$$



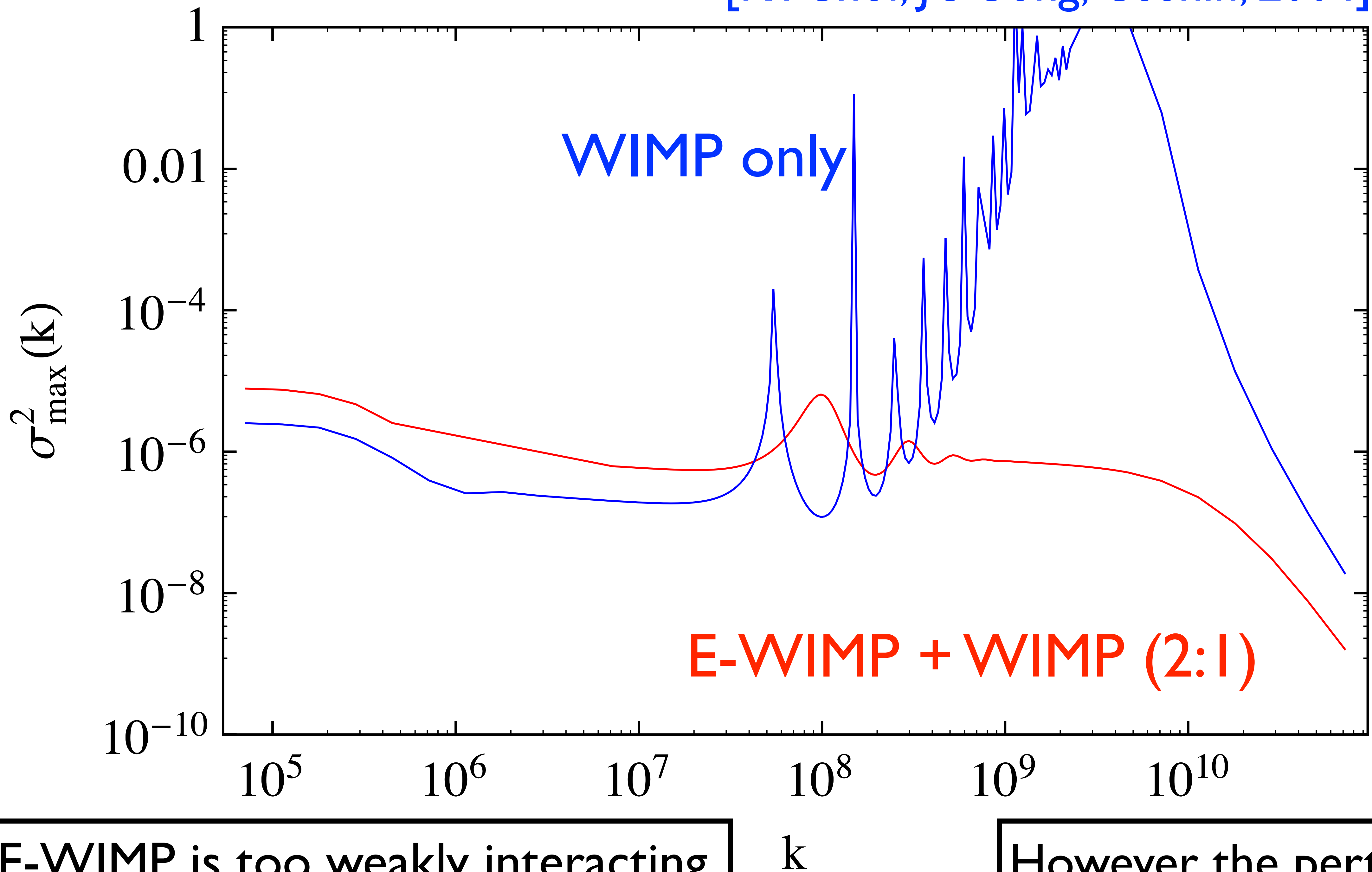
Evolution of the perturbations after matter domination

[KYChoi, JOGong, CSShin, 2014]



Upper limit on $\sigma^2_{\max}(k)$ in the non-standard cosmology

[KYChoi, JOGong, CSShin, 2014]



E-WIMP is too weakly interacting and does not emit gamma-ray.

However the perturbation is more enhanced.

Discussion

1. There might be a matter dominated era before radiation domination in the big bang Universe.

2. The growth during this epoch gives a way to probe the existence of the matter dominated epoch.

3. From the non-observation of UCMH, the models of scalar domination and the DM are constrained.

Thank You!

Smallest scale cut-off

1. WIMP DM

$$k_{\rm cutoff} = \min(k_{\rm ao},\ k_{\rm fs})$$: from kinetic decoupling or free streaming

$$= \min\left[\left(\frac{T_{\rm kd}}{\rm MeV}\right)\frac{1}{90{\rm pc}},\ \left(\frac{0.01}{c_s(T_{\rm kd})}\right)\left(\frac{14}{1+0.07\ln\frac{T_{\rm kd}}{\rm MeV}}\right)\left(\frac{T_{\rm kd}}{\rm MeV}\right)\frac{1}{12{\rm pc}}\right]$$

2. e-WIMP DM (gravitino, axino)

$$k_{\rm cutoff} = k_{\rm fs} \simeq \frac{k_{\rm fs}^{\rm WIMP}}{c_s(T_{\rm kd}^{\rm WIMP})}$$: free streaming after it is produced

$$= \left(\frac{m_{\rm DM}}{100\ {\rm GeV}}\right)\left(\frac{7}{1+0.03\ln\frac{m_{\rm DM}}{100\ {\rm GeV}}}\right)\frac{1}{0.012{\rm pc}}$$

3. axion-like particle DM

[Hu, Barkana, Gruzinov, 2000, Hwang 2009]

$$k_{\rm cutoff} = k_J(a_c) \simeq (6a_c\Omega_m)^{1/4}\sqrt{H_0 m_a}$$: Jeans scale / de Broglie scale

$$= \left(\frac{a_c}{1000}\right)^{1/4}\left(\frac{m_a}{10^{-5}{\rm eV}}\right)^{1/2}\frac{1}{0.9\times10^{-5}\ {\rm pc}}$$