Dark matter and the formation of small scale structure

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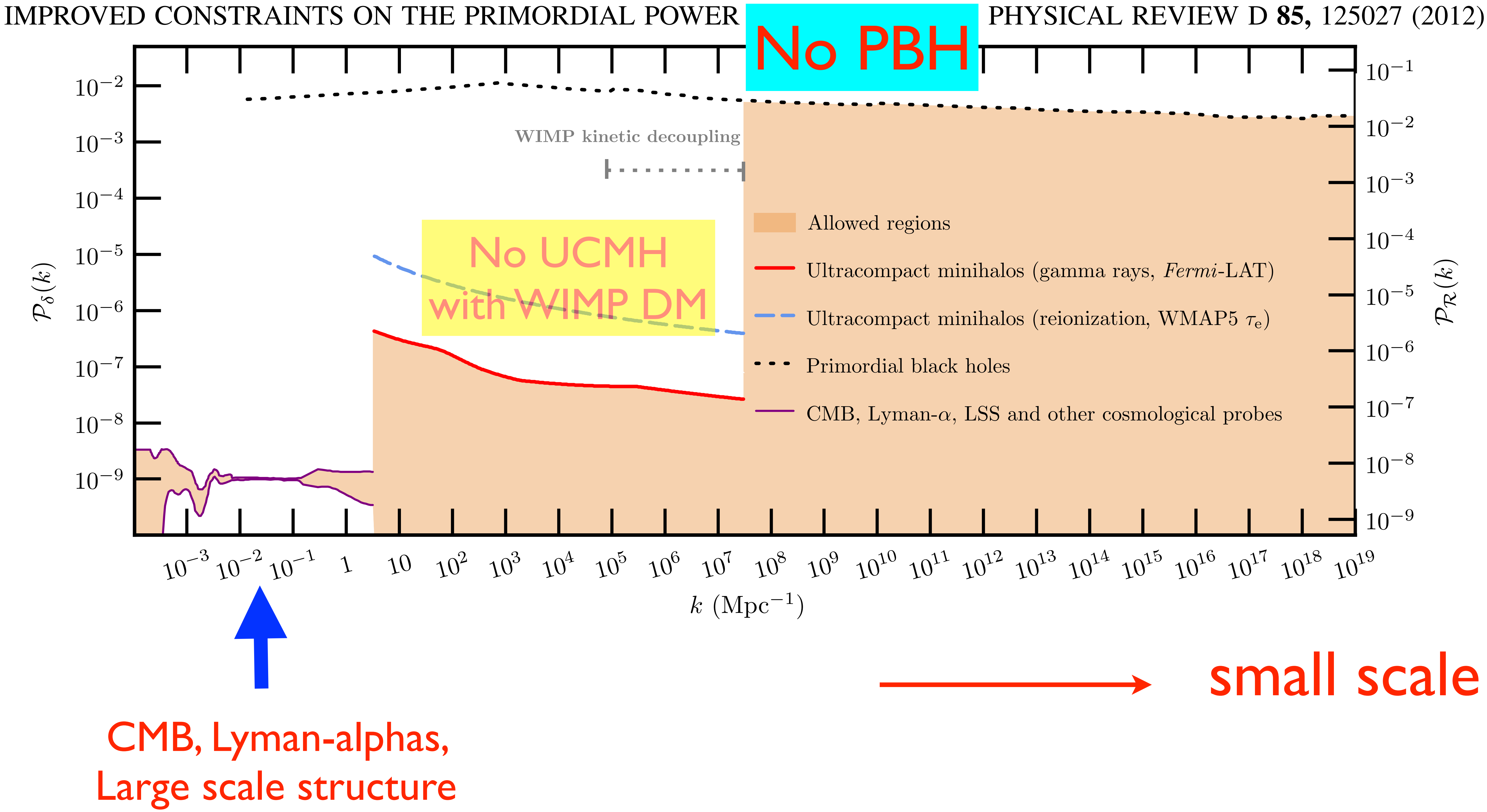
Constraints on the primordial power spectrum

[Bringmann, Scott, Akrami, 2012]



Constraints from UCMH on the power spectrum on small scales

-- assuming WIMP DM for UCMH at small scales.

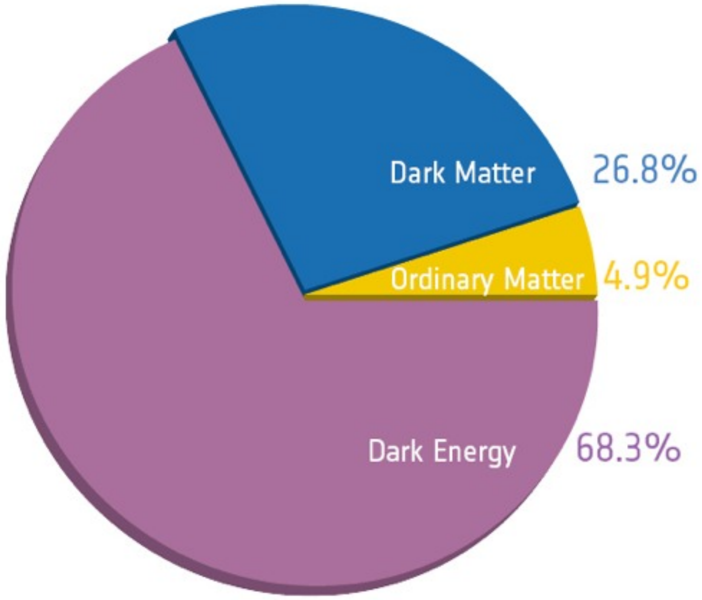
-- The constraint changes in a different scenario of cosmology and DM candidates.

-- DM can be weakly interacting but also superweakly interacting like gravitino or axino, or multiple DM with WIMP+super-WIMP.

-- We apply to the scalar-dominated epoch in the early Universe, such as oscillating inflaton, curvaton or moduli etc.

-- For a given power spectrum from inflation, those give constraints on the non-thermal Universe and the properties of DM.

Dark Matter



Dark Matter as a particle must (be)

1. have existed from early Universe up to now and located around galaxies, clusters

→ stable or lifetime longer than the age of universe

2. neutral : NO electromagnetic interaction

→ Only upper bounds on the self interaction

$\sigma/m \lesssim 10^{-24}\ \mathrm{cm}^2/\,\mathrm{GeV}$ from bullet cluster

No lower bound down to gravity!

In fact all the evidences are gravitational.

3. 25% of the present energy density of the universe

4. cold (or warm) : non-relativistic to seed the structure formation

- Candidates of dark matter

  : Motivated from beyond Standard Model

Strong CP problem : axion

Neutrino sector : sterile neutrino, RH neutrino, Majoron

Technicolor : Techni-baryon, Techni-dilaton

Supersymmetry : neutralino, gravitino, axino, scalar neurino

Extra dimension : Kaluza-Klein particle

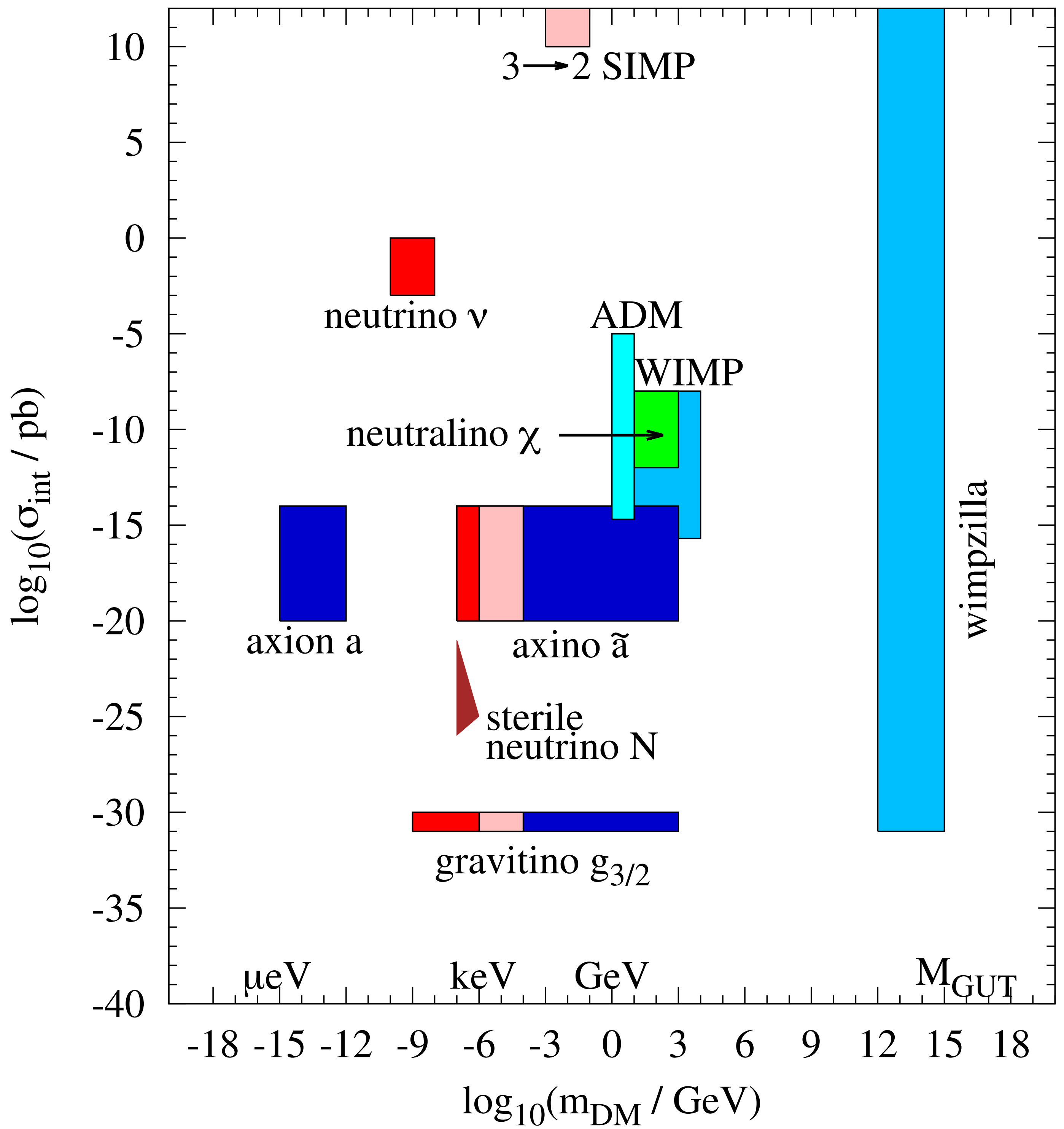
and WIMPzillas, Balck-Holes, light volume moduli, dilaton

and more ....

- Candidates of dark matter beyond Standard Model

Interaction

10^{40}



Mass 10^{40}

- How the DM are generated? : Production mechanism

In the early Universe,

in the thermal equilibrium, and freeze-out from the equilibrium

: WIMP, Asymmetric DM

already decoupled, however produced from thermal particles

: E-WIMP (Super WIMP), FIMP

➡ Thermal production

Non-thermal production : produced non-thermal way

: Oscillating DM or produced by decays of unstable objects

- Expanding Universe and decoupling

In the non-Expanding Universe and thermal equilibrium

After enough long time much larger than the interaction time, the system leads to the thermal equilibrium (chemical and kinetic).

$$t \gtrsim t_{\rm int} \simeq (nv\sigma)^{-1}$$

In the expanding Universe and decoupling

The expansion is faster than the interaction, the particles cannot maintain the equilibrium and decoupled from the thermal plasma.

equilibrium $\quad nv\sigma > H$

decoupling $\quad nv\sigma < H$

- The scattering cross section

Inelastic scatterings : Number changing interactions

→ Chemical equilibrium → Relic density

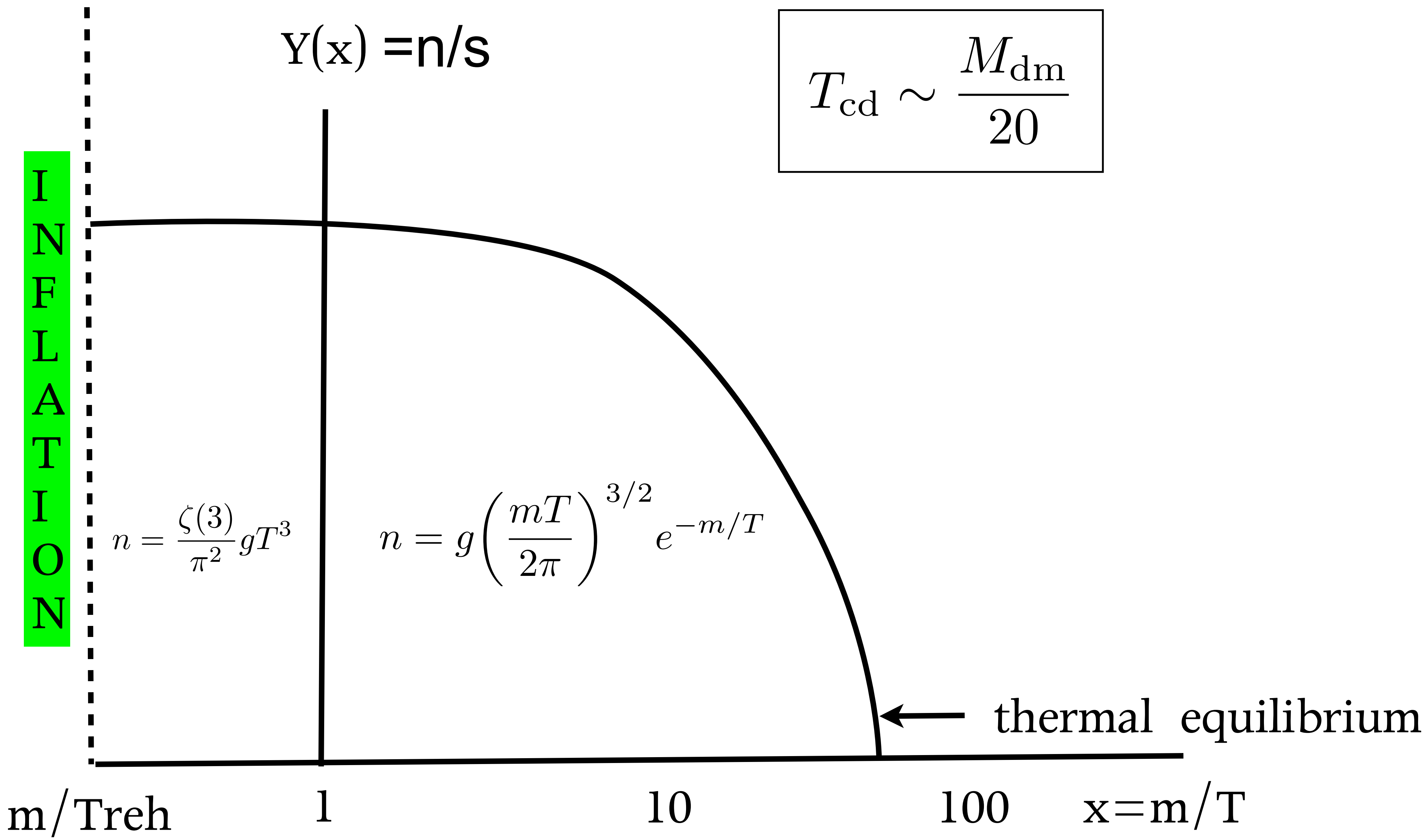
Elastic scatterings : Number changing interactions

→ 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.

WIMP : Weakly Interacting Massive Particle

Initially the particles are in the thermal equilibrium and decoupled when it is non-relativistic in the expanding Universe.



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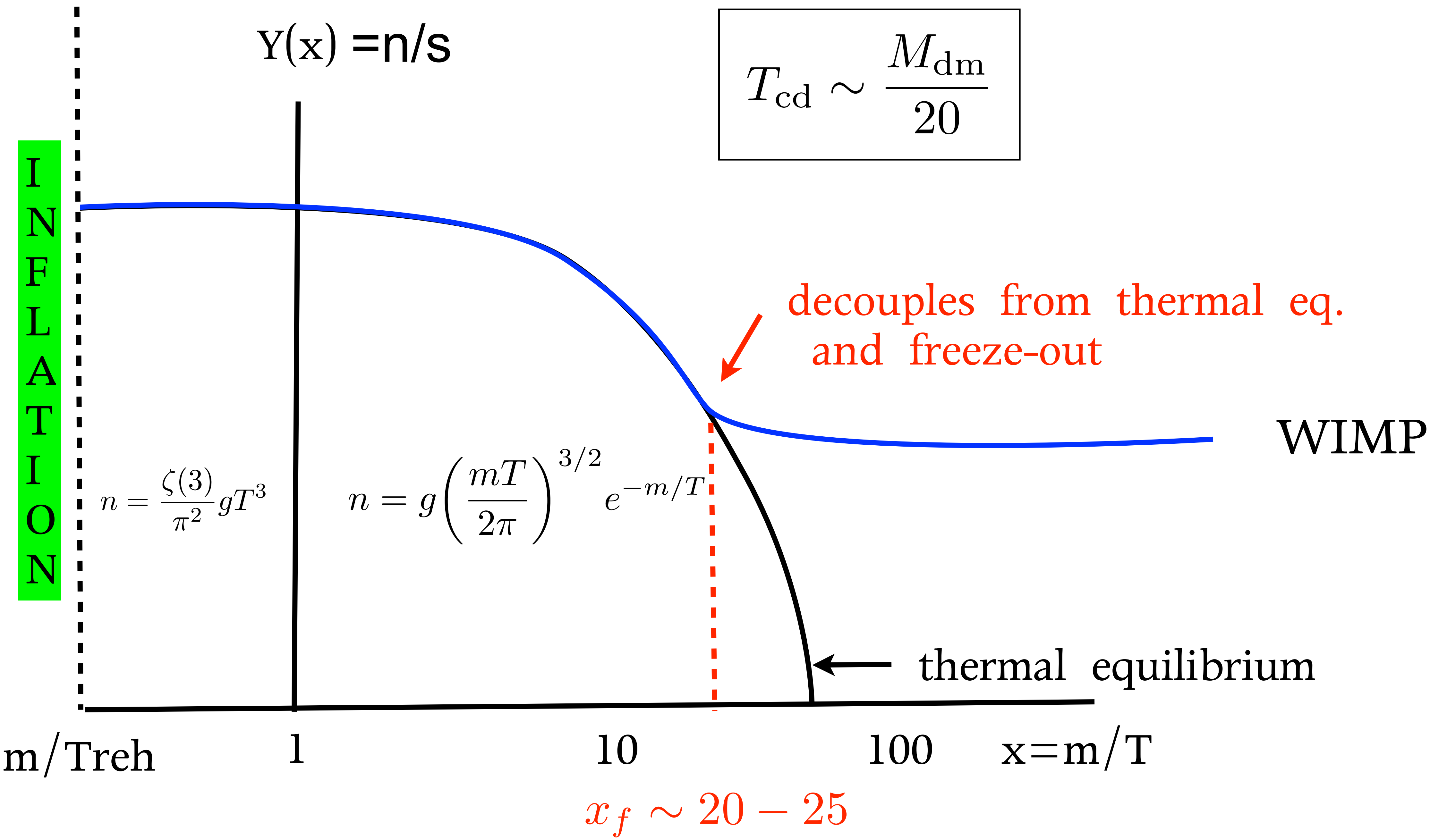
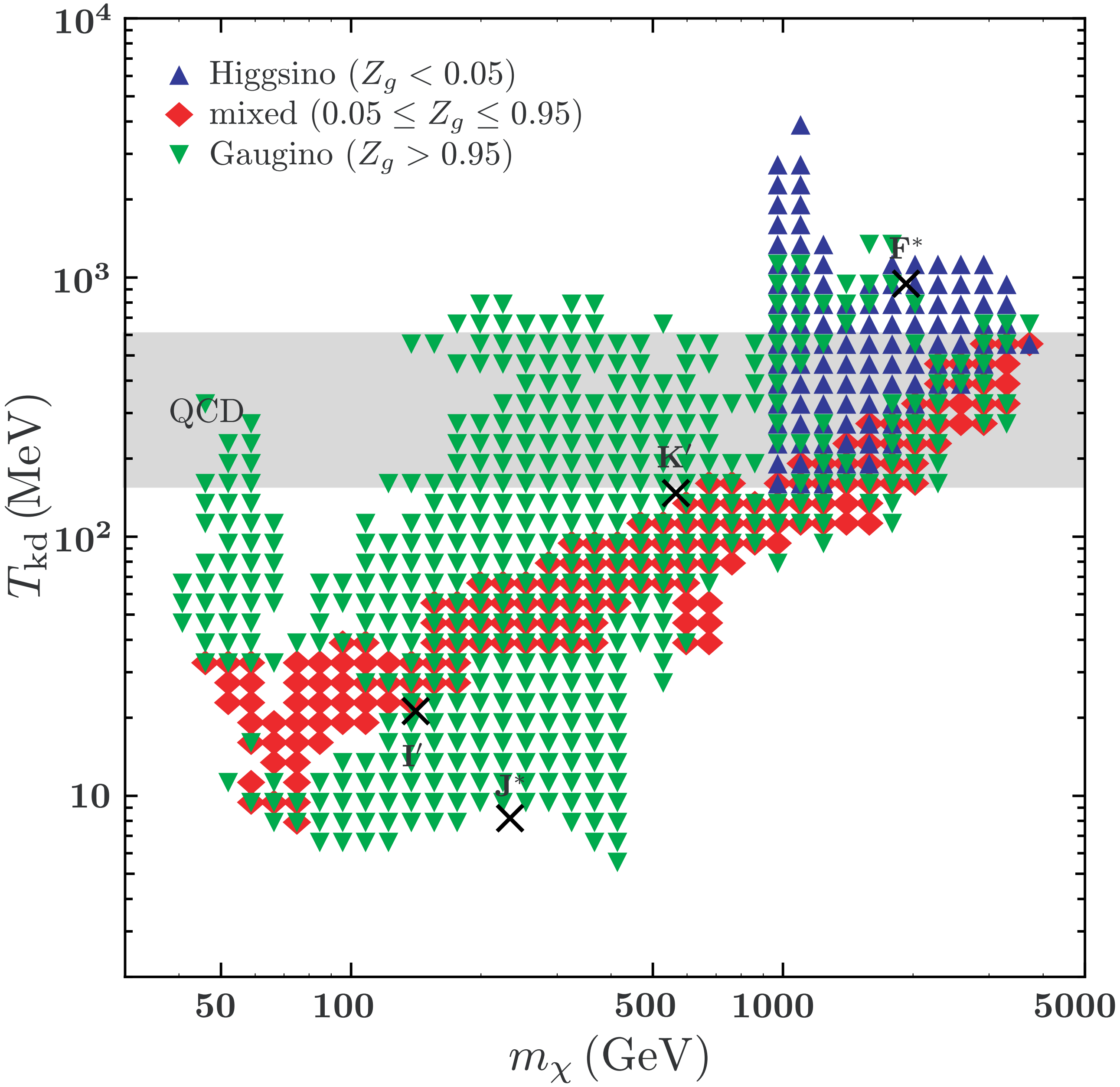
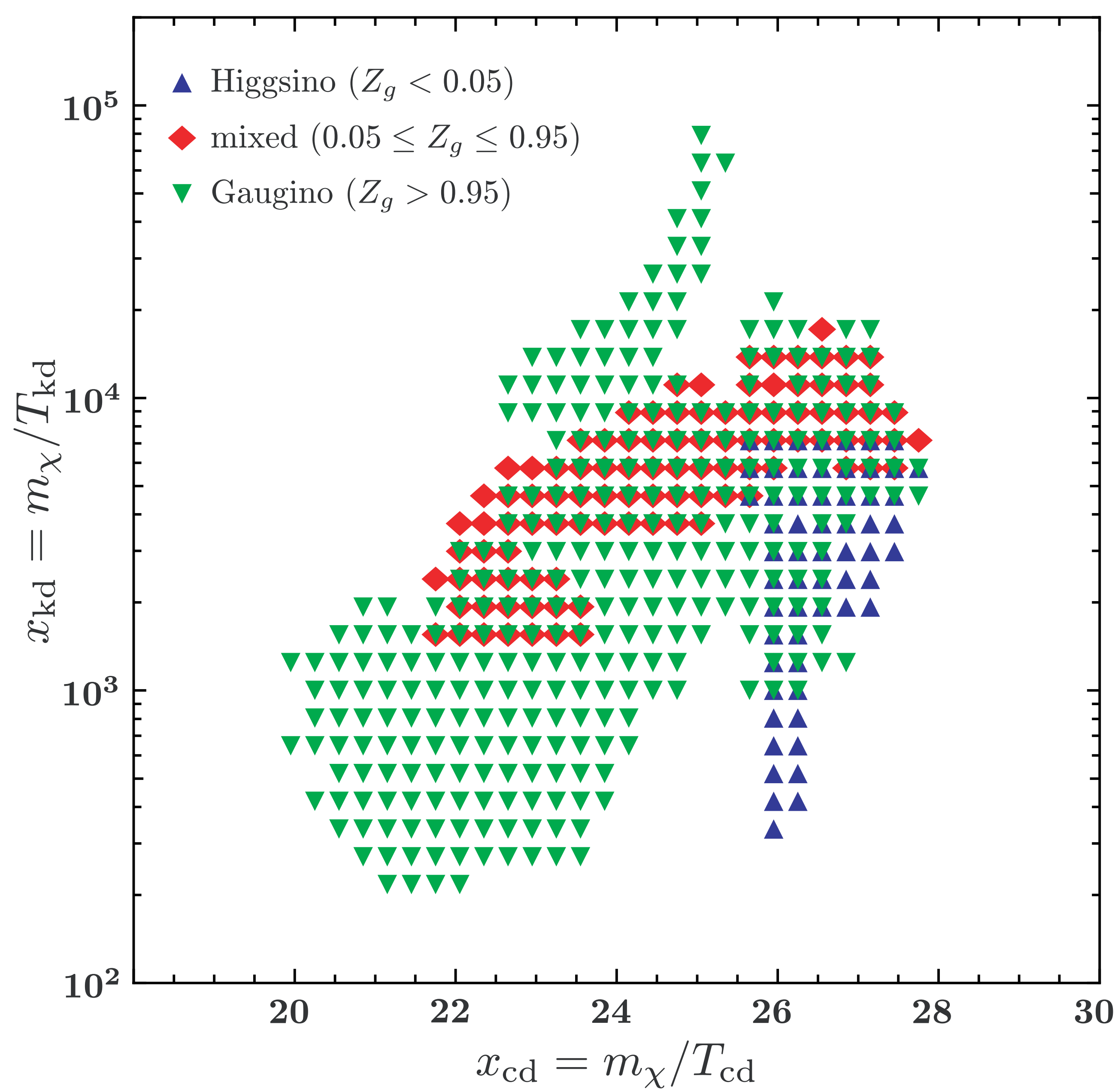


Kinetic decoupling temperature of neutralinos

[Bringmann, 2009]

Z_g : gaugino fraction

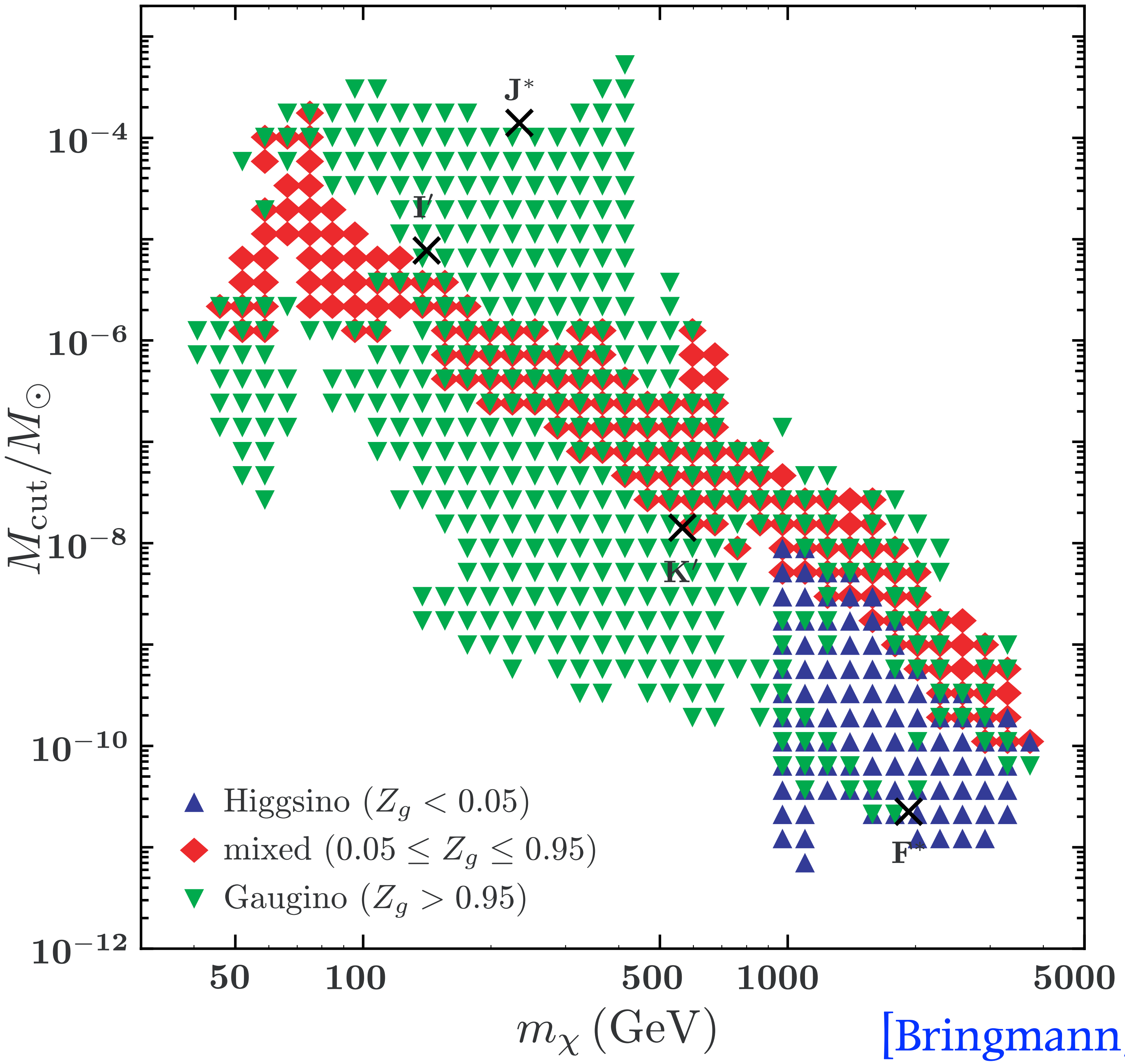




Kinetic decoupling takes place much later than chemical decoupling by a factor of 10 - 1000.

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

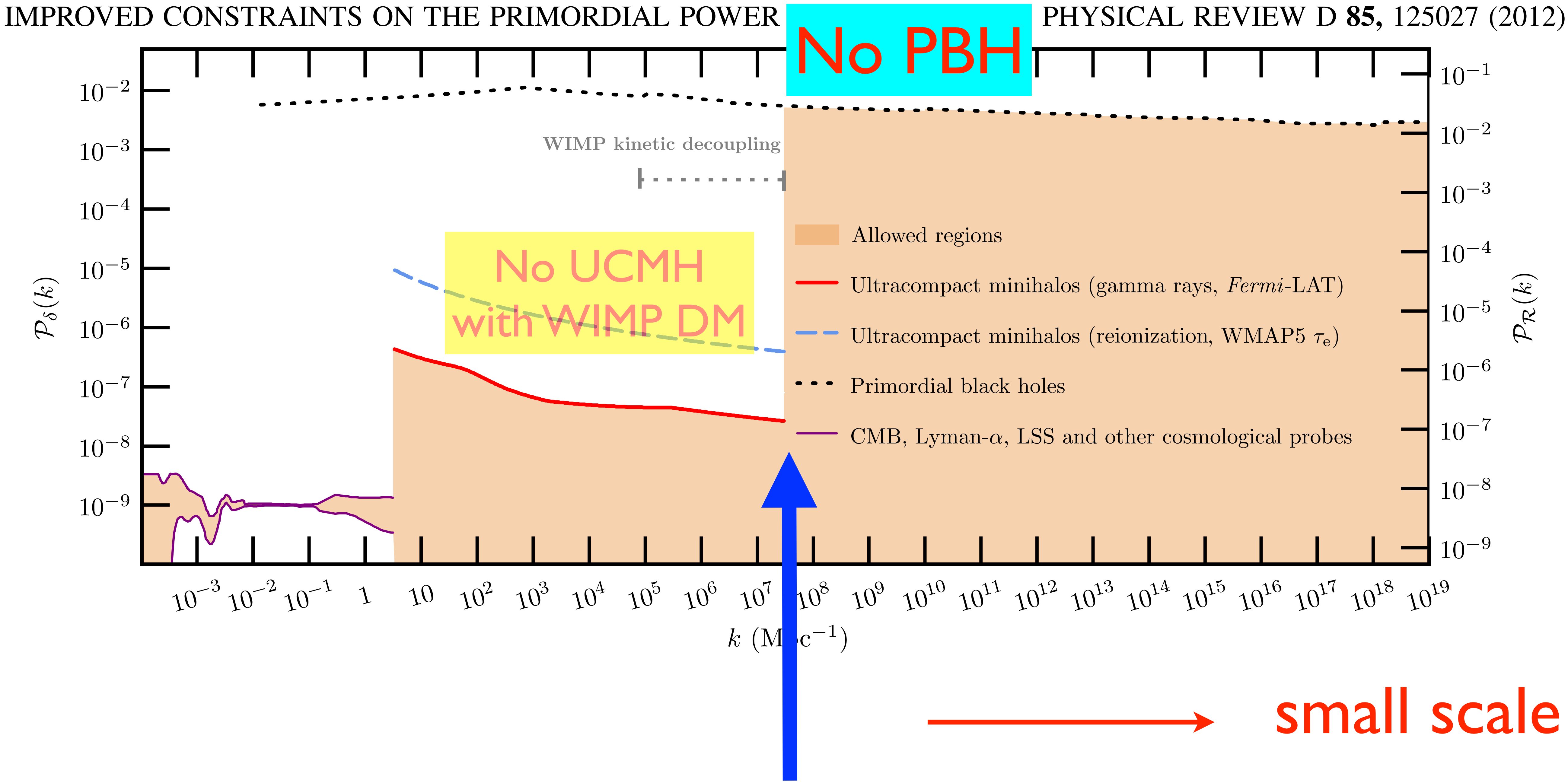
Earth mass ~



[Bringmann, 2009]

Constraints on the primordial power spectrum

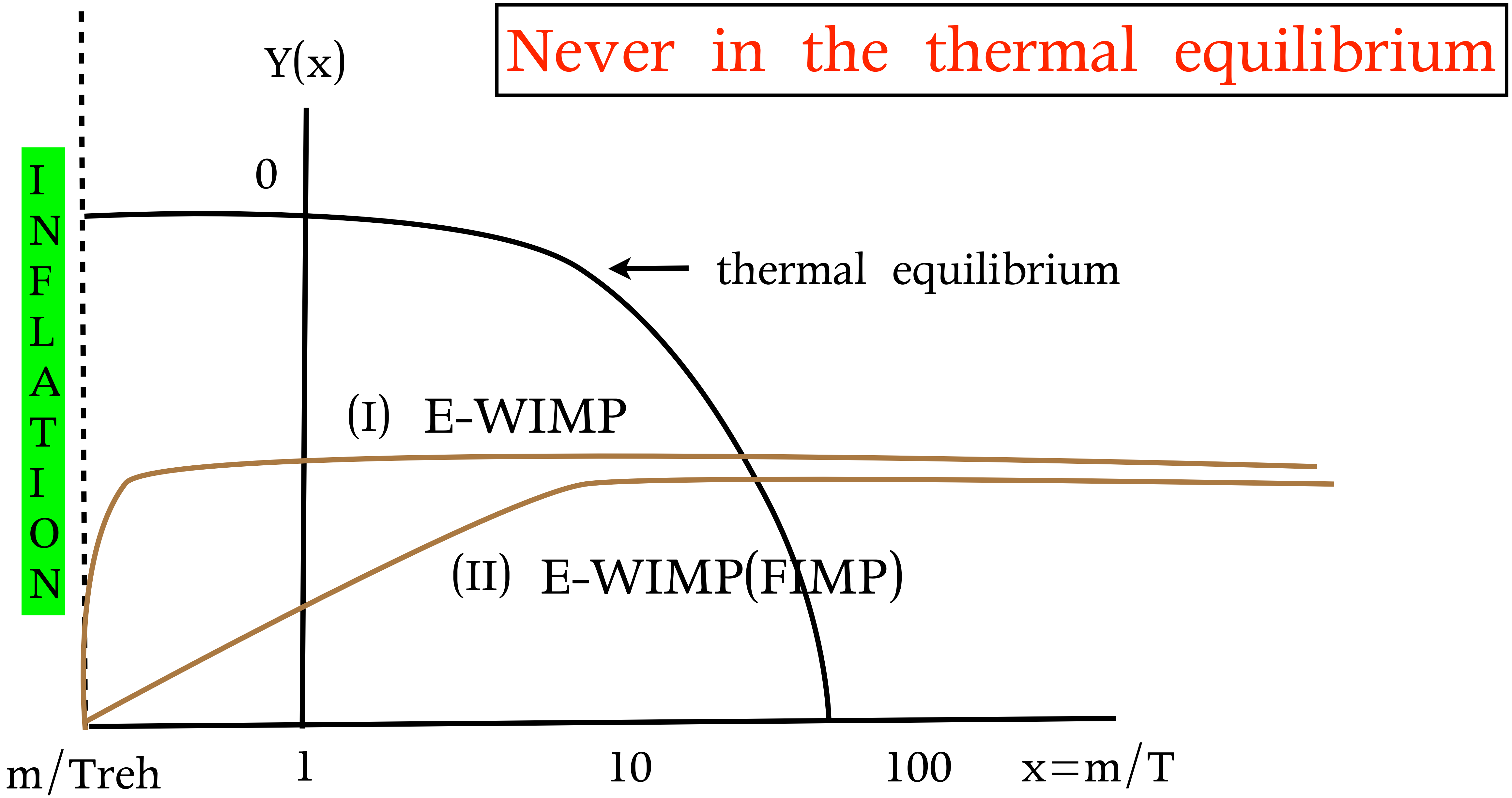
[Bringmann, Scott, Akrami, 2012]



small scale

cut-off at Kinetic decoupling

Extremely (Super-) weakly interacting massive particles



- No limit on the size of the smallest proto-halos
- No constraints from UCMH, since there is no signal

Small scale structures

- Linear growth of the perturbation

The growth of the primordial density perturbation in the expanding universe depends on the scale, type of matter and background matter.

Outside horizon : density perturbation $\frac{\delta\rho}{\rho}$ is constant with adiabatic condition $p = p(\rho)$

Inside horizon : density perturbation grows for larger than Jeans scale and oscillate for smaller scales.

$\frac{\delta\rho}{\rho} \propto$	Radiation dom.	Matter dom.
Non-Rel. matter	$\log a \propto \log t$	$a \propto t^{2/3}$
Rel. matter	oscillating	oscillating

UCMH (Ultra Compact Mini Halo)

- When the amplitude of the density perturbation is large UCMH can be created. It requires $\delta \gtrsim 10^{-3}$ at horizon entry, compared to the inflationary perturbations $\delta \sim 10^{-5}$.

- It is much more easier to make UCMH than PBH ($\delta \gtrsim 0.3$)

- It is seeded well before the matter-radiation equality and evolve finally to collapse after matter domination $z_c \gtrsim \mathcal{O}(100)$

- The mass is proportional to the horizon mass at the time such a density perturbation enters the horizon.

: the mass of UCMH is connected to the specific cosmological scale

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]

Formation of UCMH

The UCMH can be formed for [Ricotti, Gould, 2009]

$$10^{-3} \sim \delta_\chi^{\min} \lesssim \delta_\chi \lesssim \delta_\chi^{\max} \sim 0.3$$

model-dependent

1. Mass of radius R: seed of UCMH

$$M_{\rm i} \simeq \left[\frac{4\pi}{3}\rho_\chi {\rm H}^{-3}\right]_{a{\rm H}=1/R} = \frac{H_0^2}{2G}\Omega_\chi R^3$$

$$= 1.30 \times 10^{11}\left(\frac{\Omega_\chi h^2}{0.112}\right)\left(\frac{R}{\rm Mpc}\right)^3 M_\odot,$$

2. Around matter-radiation equality, the seed begins to grow by infall of both DM and baryonic matter after decoupling.

$$M_{\rm UCMH}(z) = \frac{z_{\rm eq}+1}{z+1} M_{\rm i}.$$

3. At around $z \sim 10$, the further accretion stops due to the dynamical friction between DM halos and hierarchical structure formation,

$$M^0_{\rm UCMH} \equiv M_{\rm UCMH}(z \lesssim 10) \approx 4 \times 10^{13} \left(\frac{R}{\rm Mpc}\right)^3 M_\odot.$$

UCMH population today

[Bringmann, Scott, Akrami, 2012]

The present density of UCMH with mass or greater than $M^0_{\rm UCMH}$

$$\Omega_{\rm UCMH}(M^0_{\rm UCMH}) = \Omega_\chi \frac{M^0_{\rm UCMH}}{M_{\rm i}} \beta(R),$$

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

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

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

Gamma ray emission and constraints [Bringmann, Scott, Akrami, 2013]

Non-observation of UCMHs from Fermi-LAT gives a upper limit on UCMH mass fraction in the Milky Way

$$f_{\rm max} \simeq -\left[\frac{\mathcal{F}_{\rm min}}{\mathcal{F}(d)}\right]^{3/2} \frac{3 f_\chi M^0_{\rm UCMH}}{4\pi\rho_\chi d^3} \ln\left(1-\frac{y}{x}\right),$$

$$f \equiv \Omega_{\rm UCMH}/\Omega_m \qquad \mathcal{F}_{\rm min} \equiv \mathcal{F}(d_{\rm obs})$$

using the observed gamma-ray flux from DM annihilations integrated above the threshold energy at distance d:

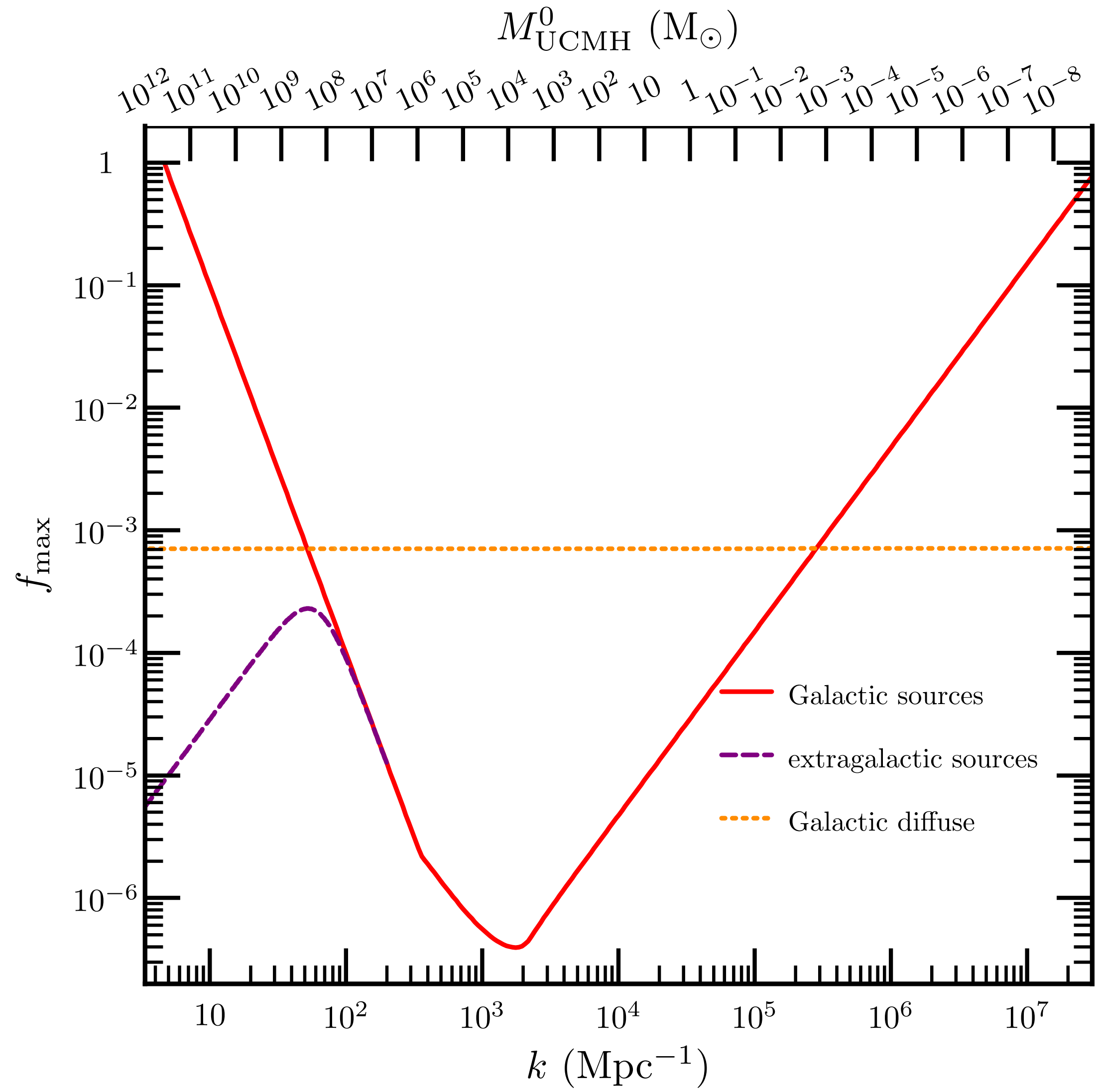
$$\mathcal{F}(d) = \sum_k \int_{E_{\rm th}}^{m_\chi} \frac{dN_k}{dE} dE \frac{\langle\sigma_k v\rangle}{2d^2 m_\chi^2} \int_0^{R^0_{\rm UCMH}} r^2\rho^2(r)dr.$$

The limit depends on the properties of DM.

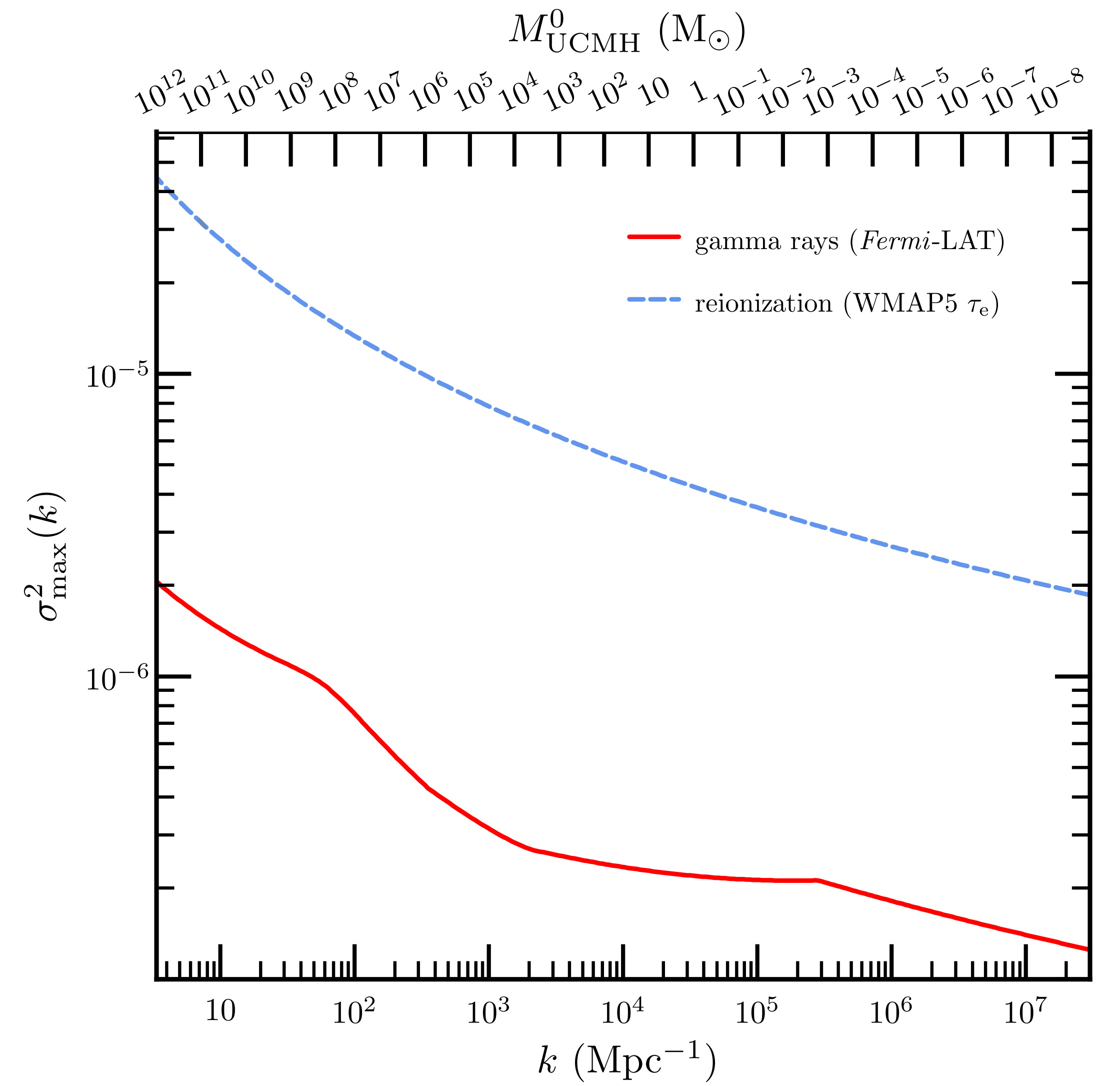
DM annihilation cross section: $\langle\sigma_k v\rangle$
DM mass, the ratio of WIMP , ...

In standard cosmology with WIMP DM [Bringmann, Scott, Akrami, 2012]

Fraction of DM in UCMH



Mass variance



$$\Omega_{\rm UCMH}(M^0_{\rm UCMH}) = \Omega_\chi \frac{M^0_{\rm UCMH}}{M_{\rm i}} \beta(R),$$

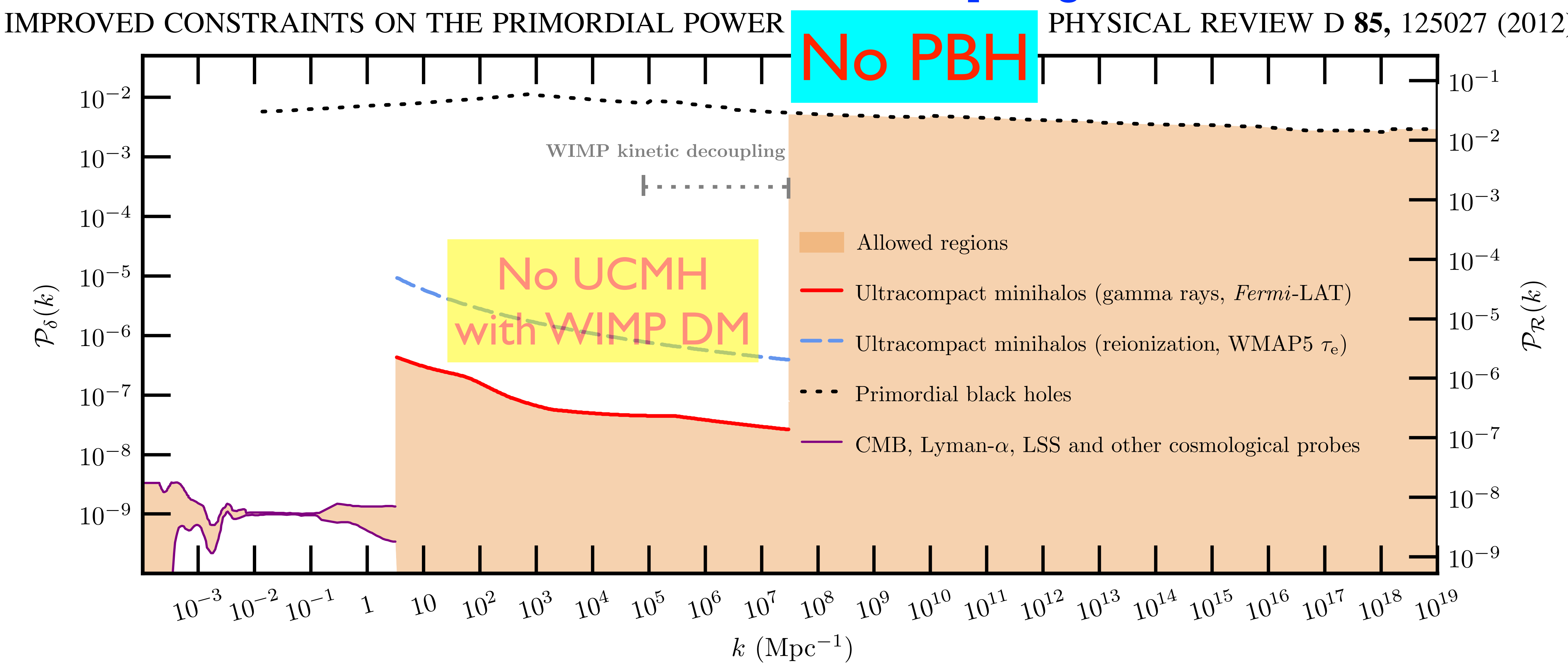
$$f \equiv \Omega_{\rm UCMH}/\Omega_m$$

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

for given $\delta_\chi^{\rm min}$

Constraints on the primordial power spectrum

[Bringmann, Scott, Akrami, 2012]



Then we find the upper limit on the primordial density perturbation from

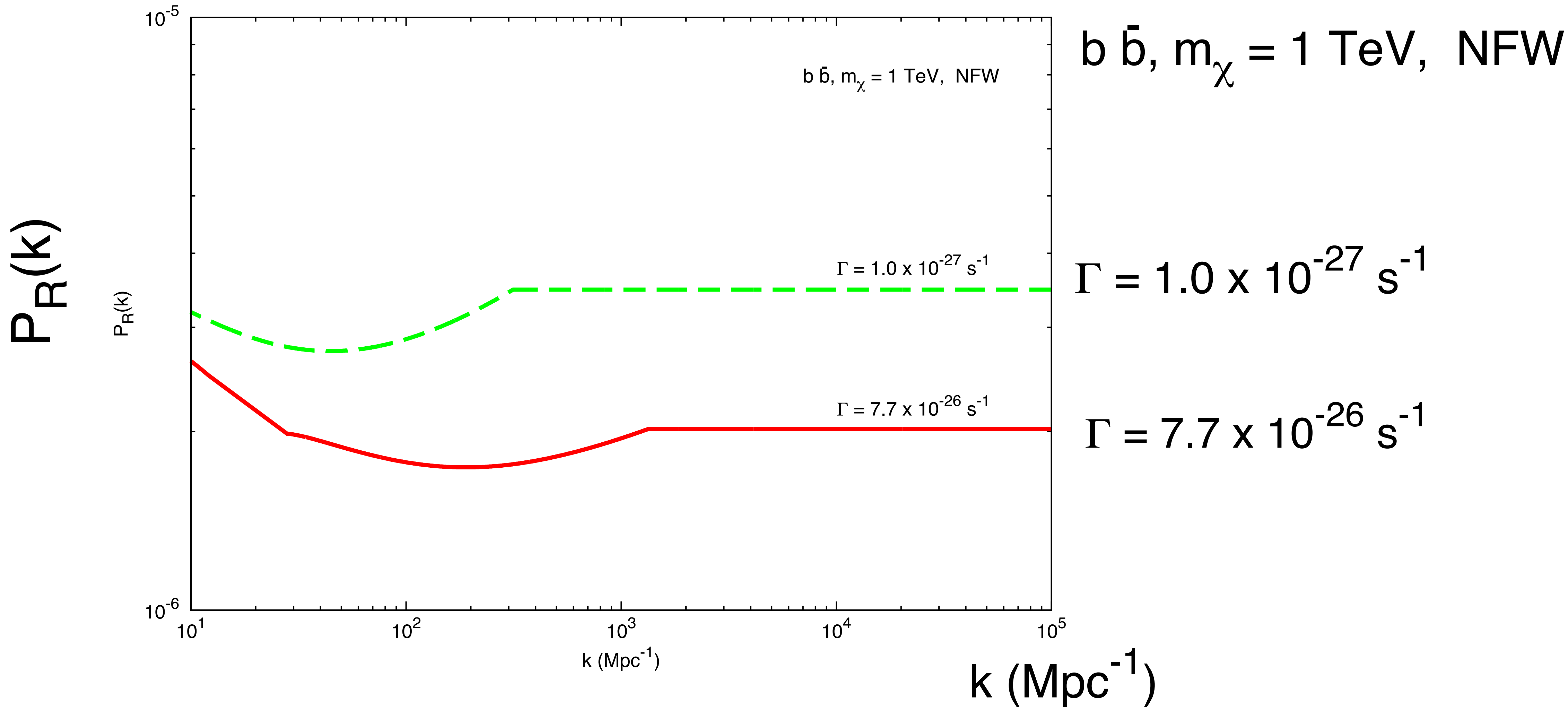
$$\sigma^2(R) = \int_0^\infty W_{\rm TH}^2(kR)\mathcal{P}_\delta(k)\frac{dk}{k}$$

Decaying DM into gamma-rays in UCMH [Yang, Yang, Zong, 2012]

The decay of DM in UCMH into gamma rays

$$\Phi = \frac{1}{4\pi d^2}\frac{\Gamma}{m_\chi}\sum^{i}\int_{E_{th}}^{m_\chi} B_{f_i}\frac{dN_i}{dE}dE\int \rho(r)d^3r$$

are constrained by Fermi-LAT.



Non-thermal Universe with non-WIMP DM

1. $\delta_\chi^{\min}$ changes
2. Constraints from gamma-ray changes

Non-thermal Universe : $\delta_\chi^{\rm min}$ changes

Prior to the radiation-dominated epoch, there could be a period when the Universe is dominated by a non-relativistic matter.

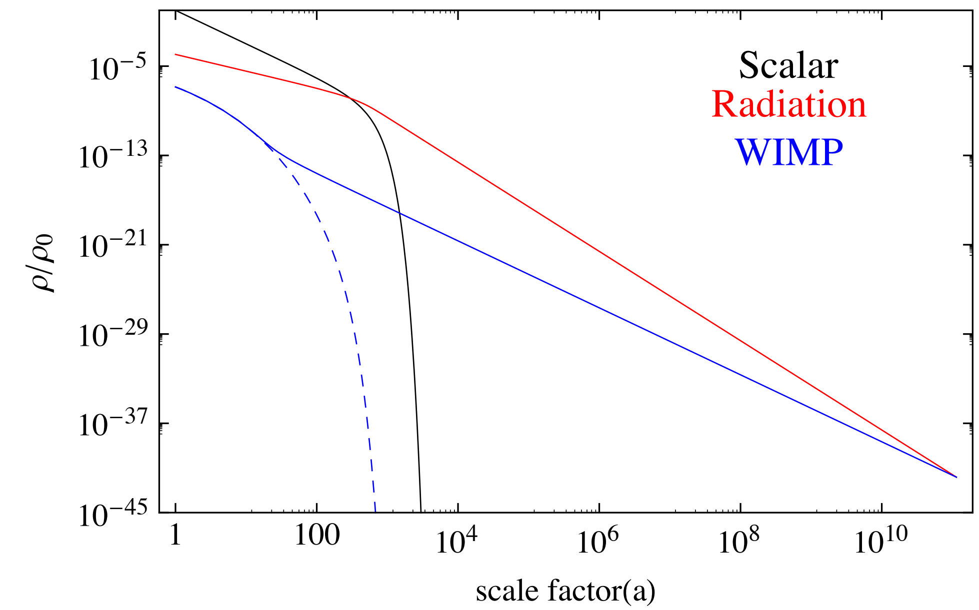
- phase transition, late-time dynamics of string moduli, inflaton, curvaton etc

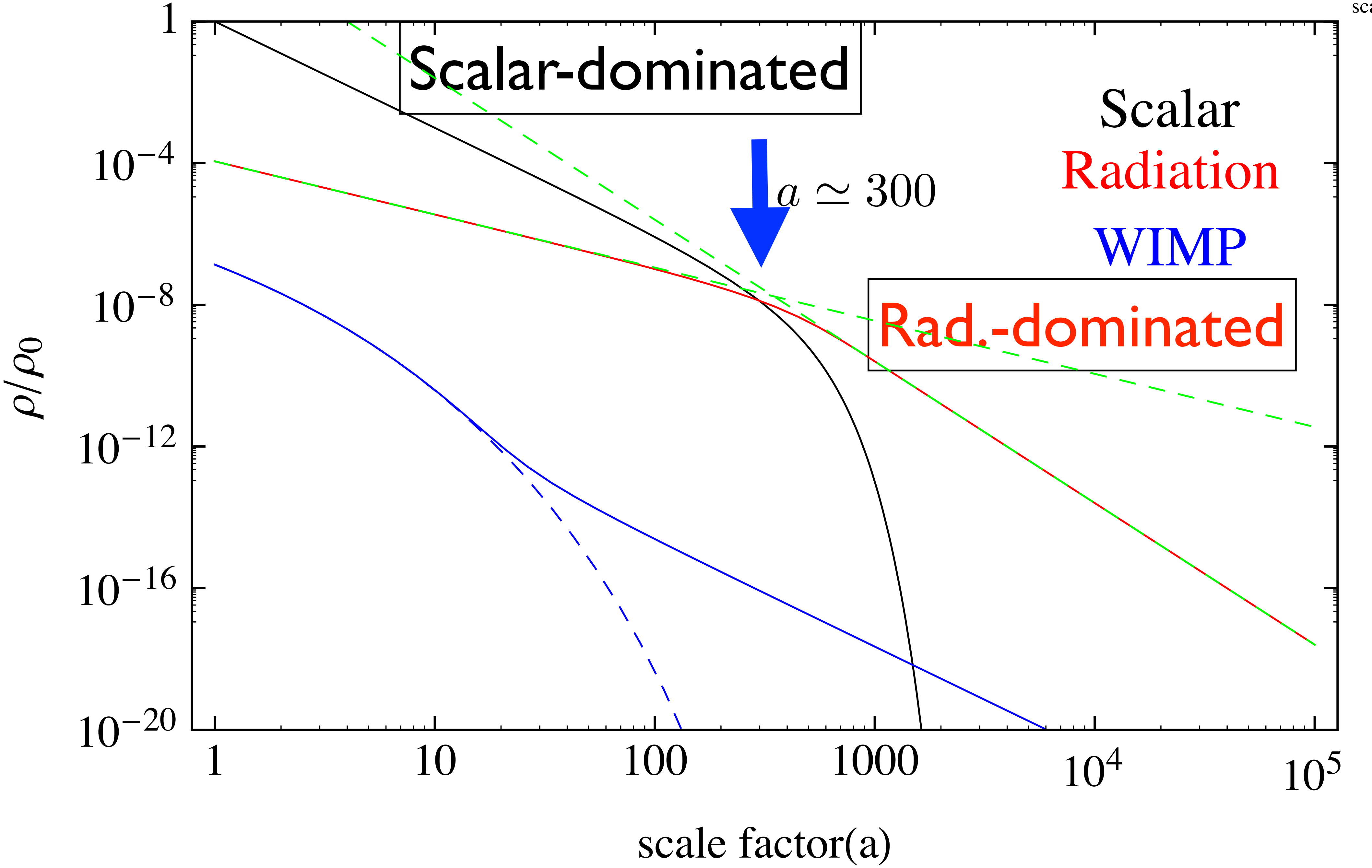
During that period, the density perturbation could grow and the power spectrum of dark matter can be enhanced.

However, the detailed growth depends also on the specific properties of the dark matters in the Universe.

- chemical equilibrium
- kinetic equilibrium

Non-thermal Universe dominated by a non-relativistic field

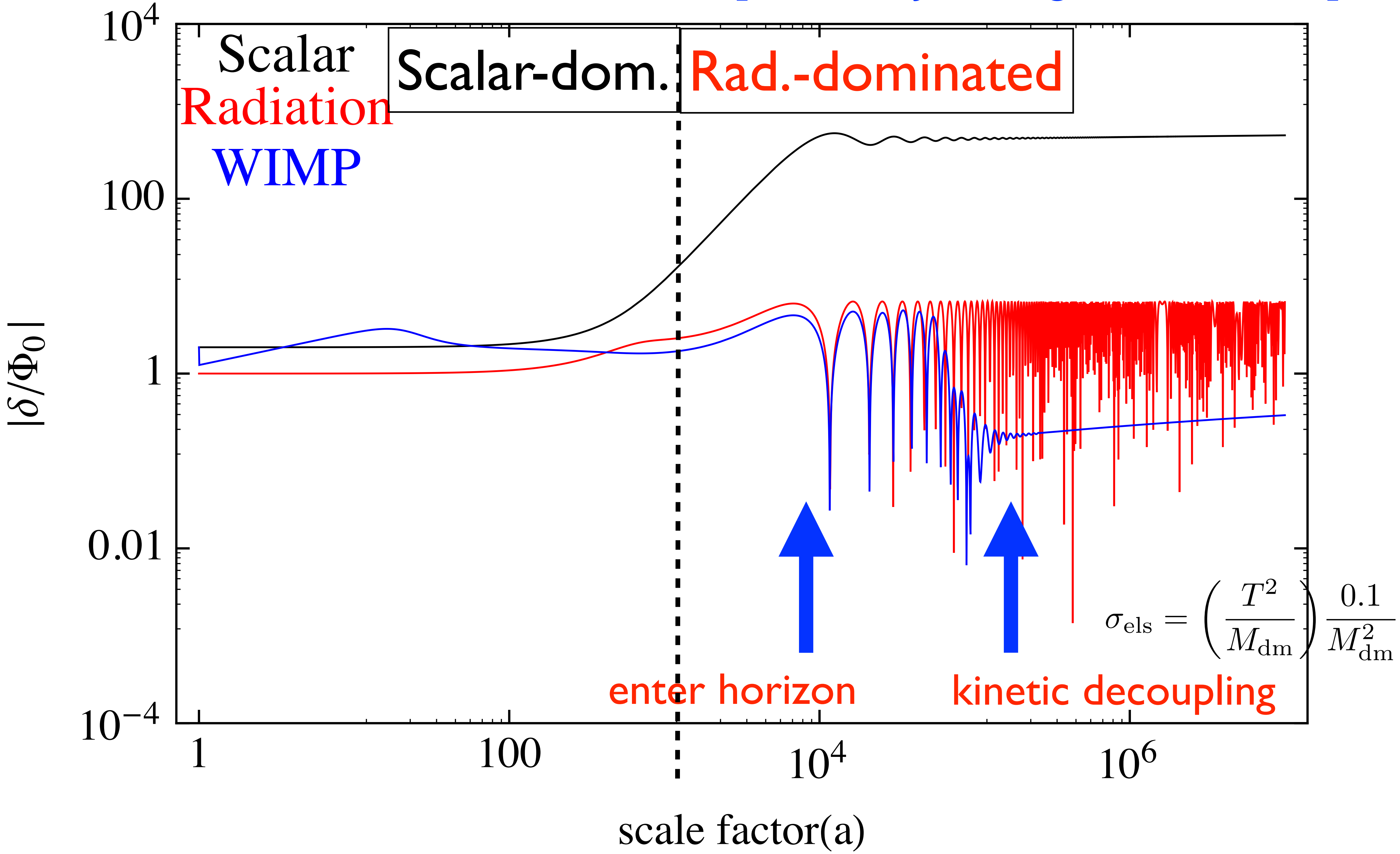




$k = 10^{-2} H_1$: the scale enters horizon during rad. dominated.

suppression of the perturbation of WIMP

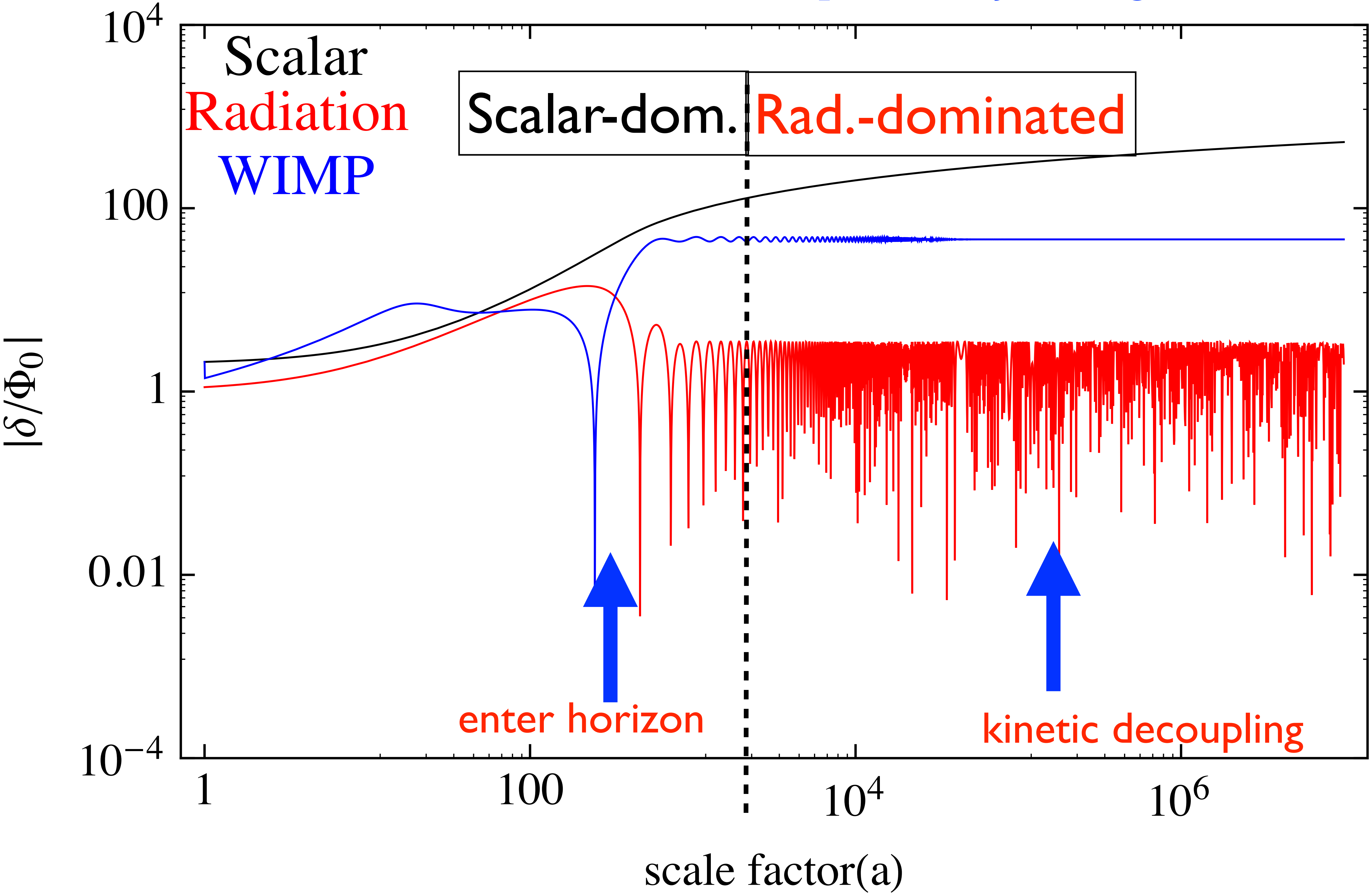
[KYChoi, JOGong, CSShin, 2014]



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

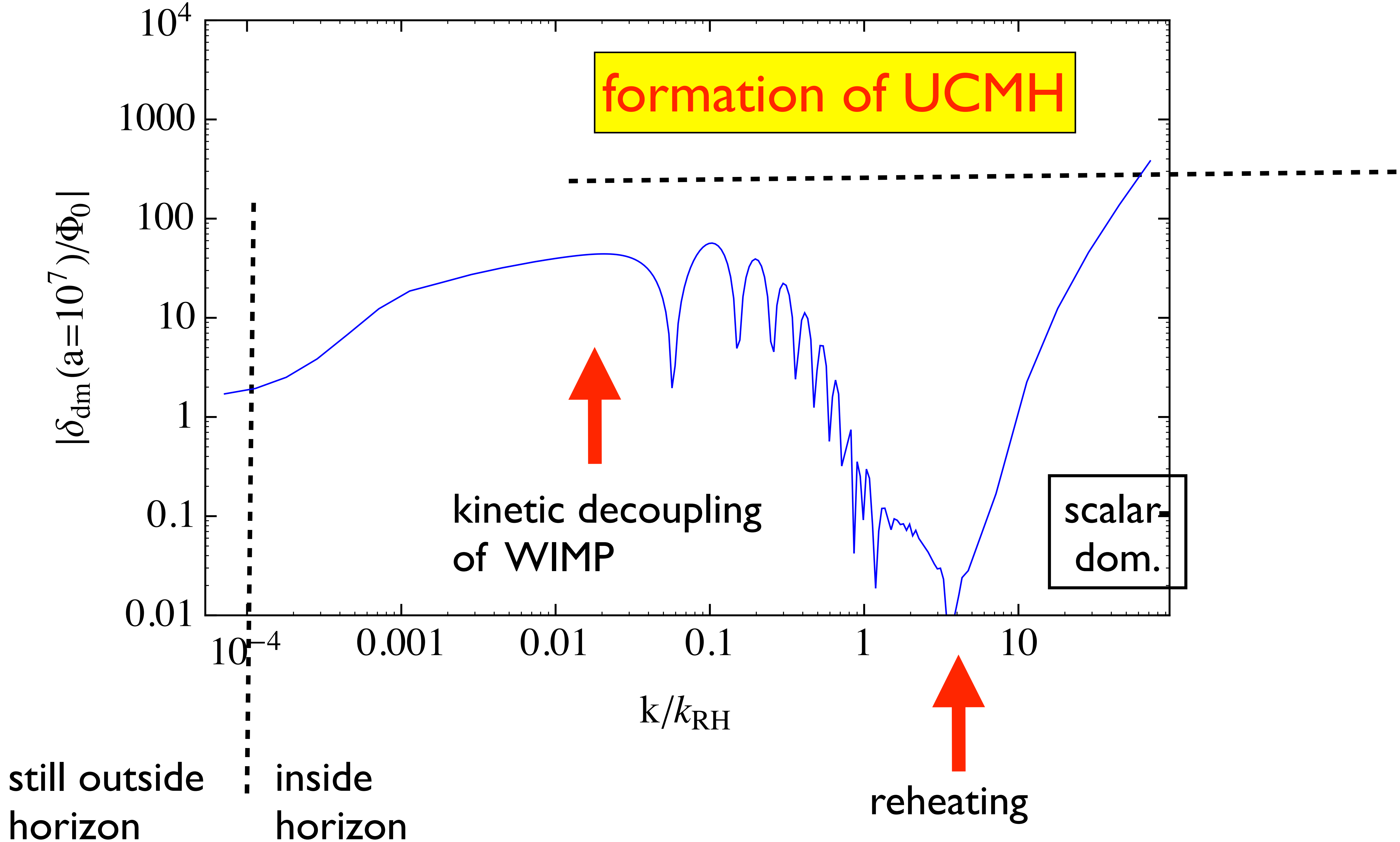
enhancement of the perturbation of WIMP

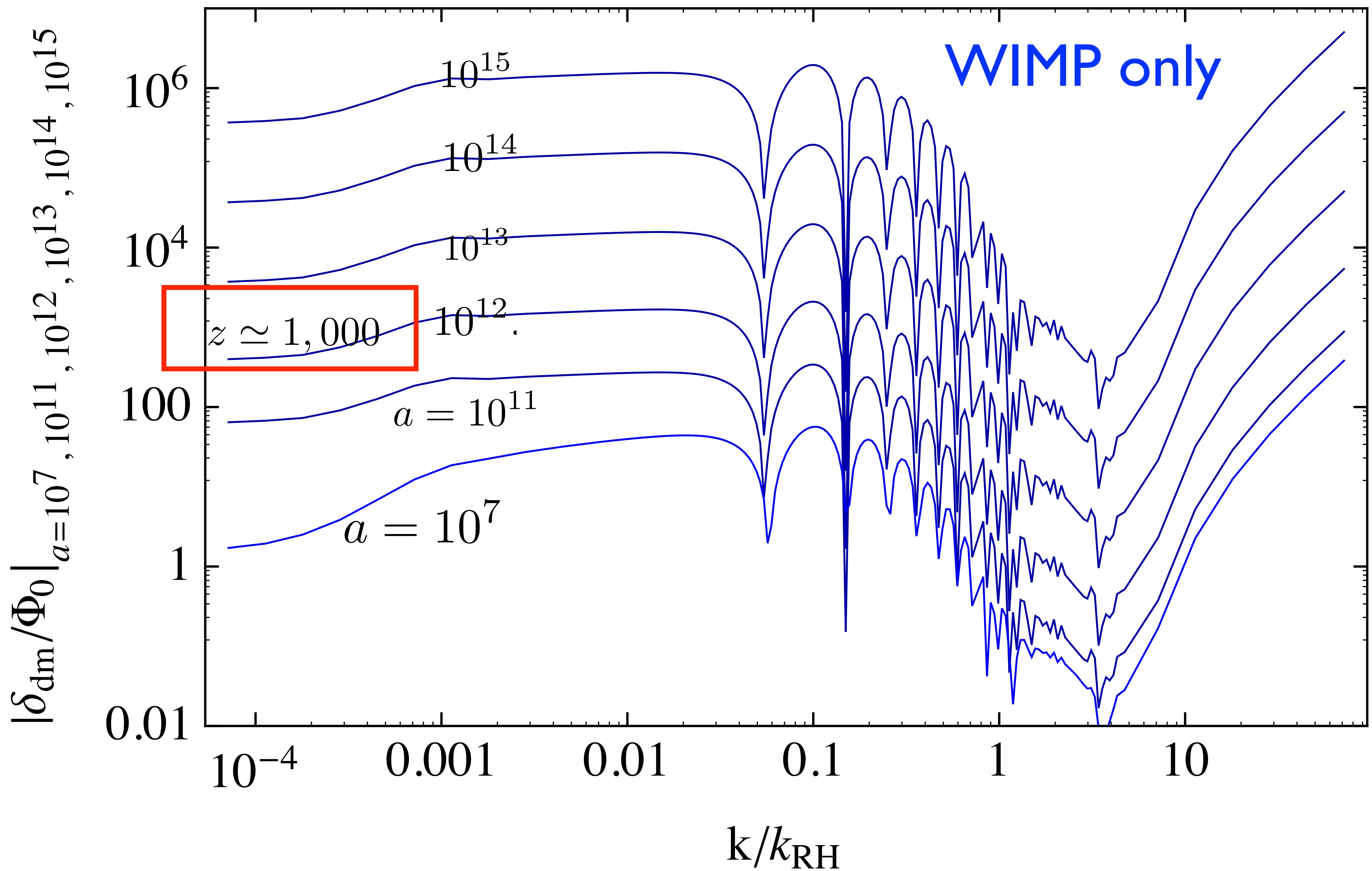
[KYChoi, JOGong, CSShin, 2014]



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

[KYChoi, JOGong, CSShin, 2014]




WIMP only
10^{15}
10^{14}
10^{13}
10^{12}.
$z \simeq 1,000$
$a = 10^{11}$
$a = 10^7$
$|\delta_{\rm dm}/\Phi_0|_{a=10^7,10^{11},10^{12},10^{13},10^{14},10^{15}}$
10^6
10^4
100
1
0.01
10^{-4}
0.001
0.01
0.1
1
10
$k/k_{\rm RH}$

Upper limit on $\delta_\chi^{\min}$ in the non-standard cosmology

We take $z_c = 1000$ as canonical value.

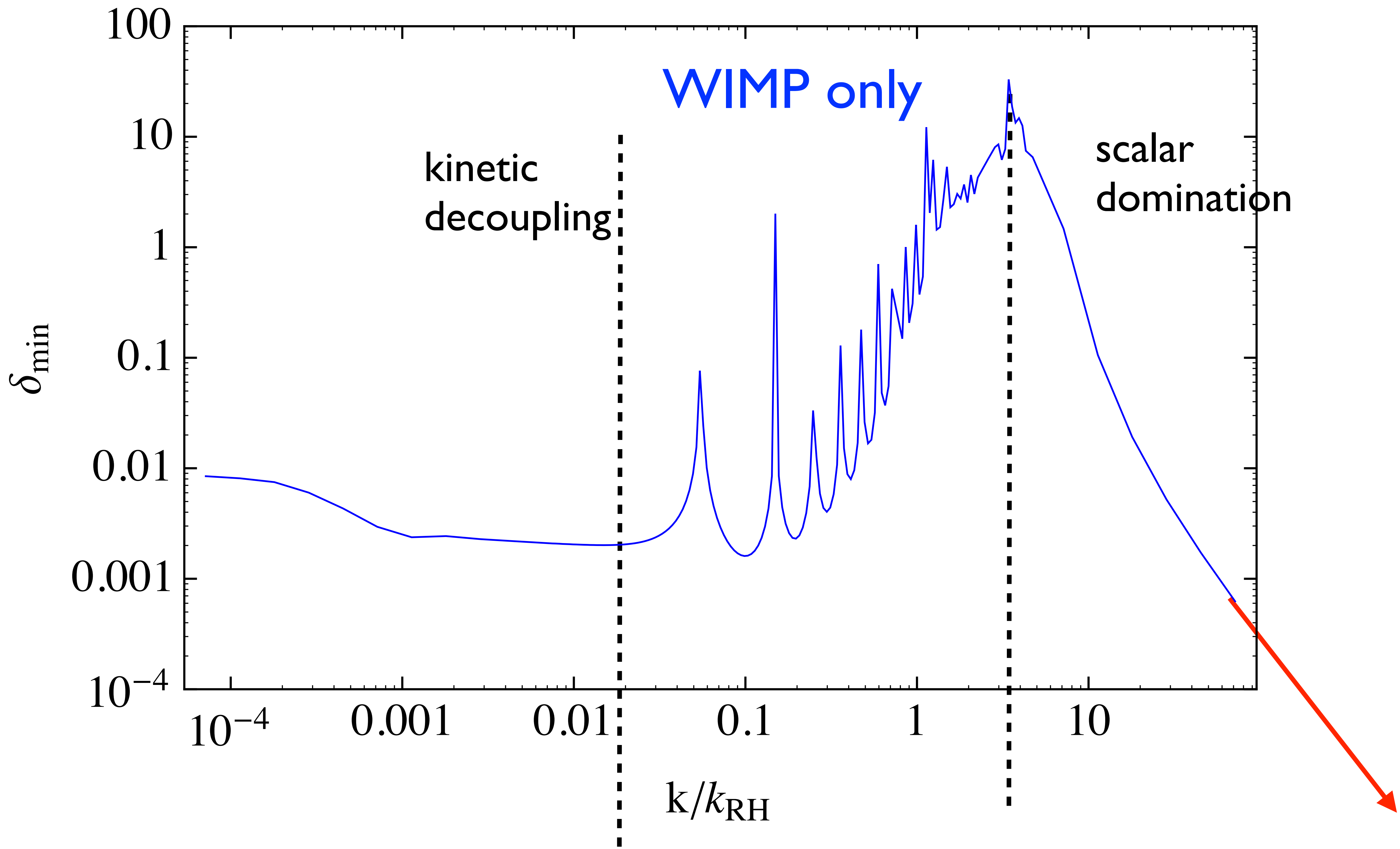
UCMH can collapse at this epoch if

$$\delta_{\rm dm} > \delta_c \qquad \delta_c = 1.686$$

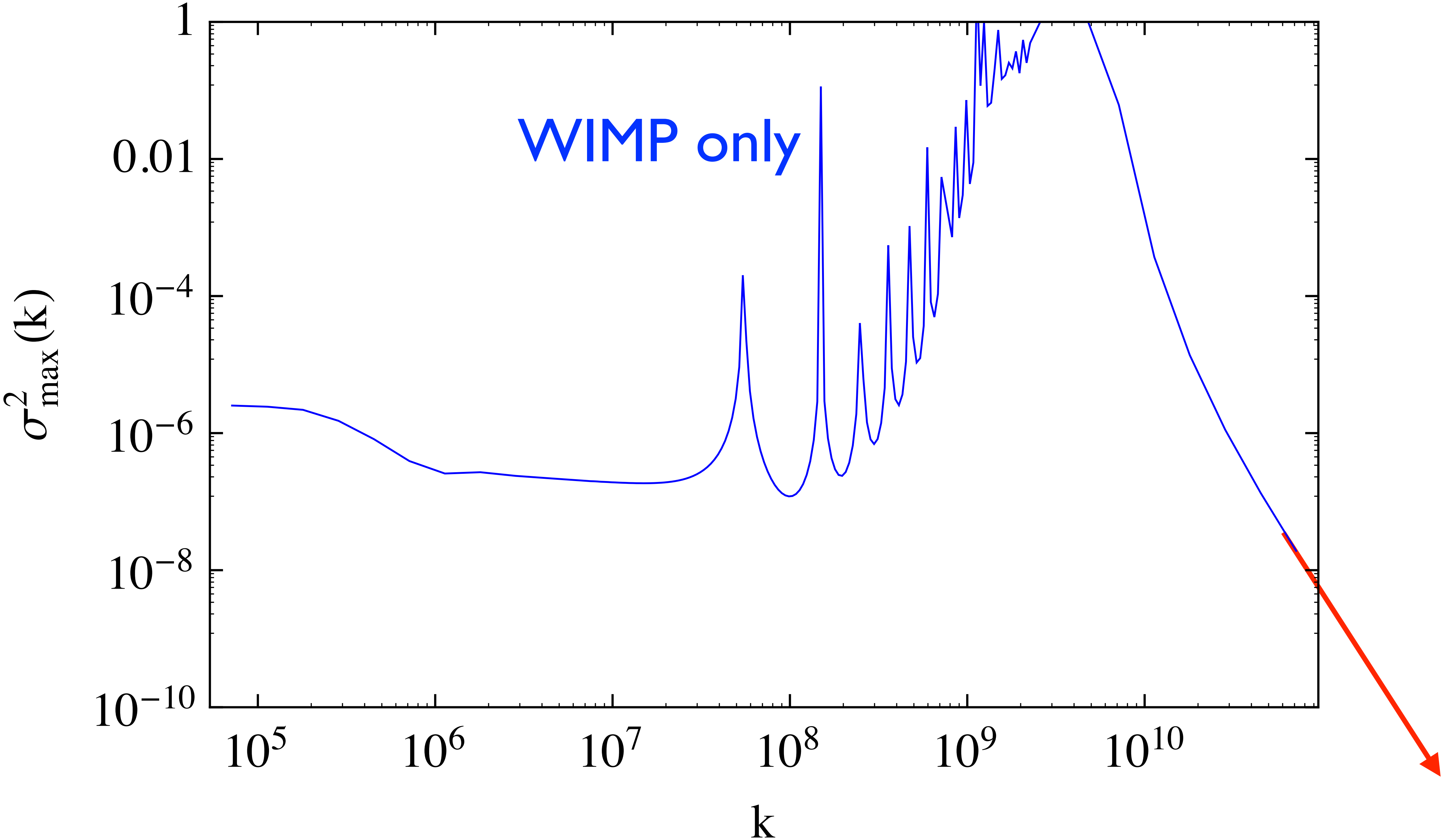
$\boxed{\delta_\chi^{\min}}$

: the value of δ_χ at horizon entry, which gives $\delta_{\rm dm} = \delta_c$ at z_c

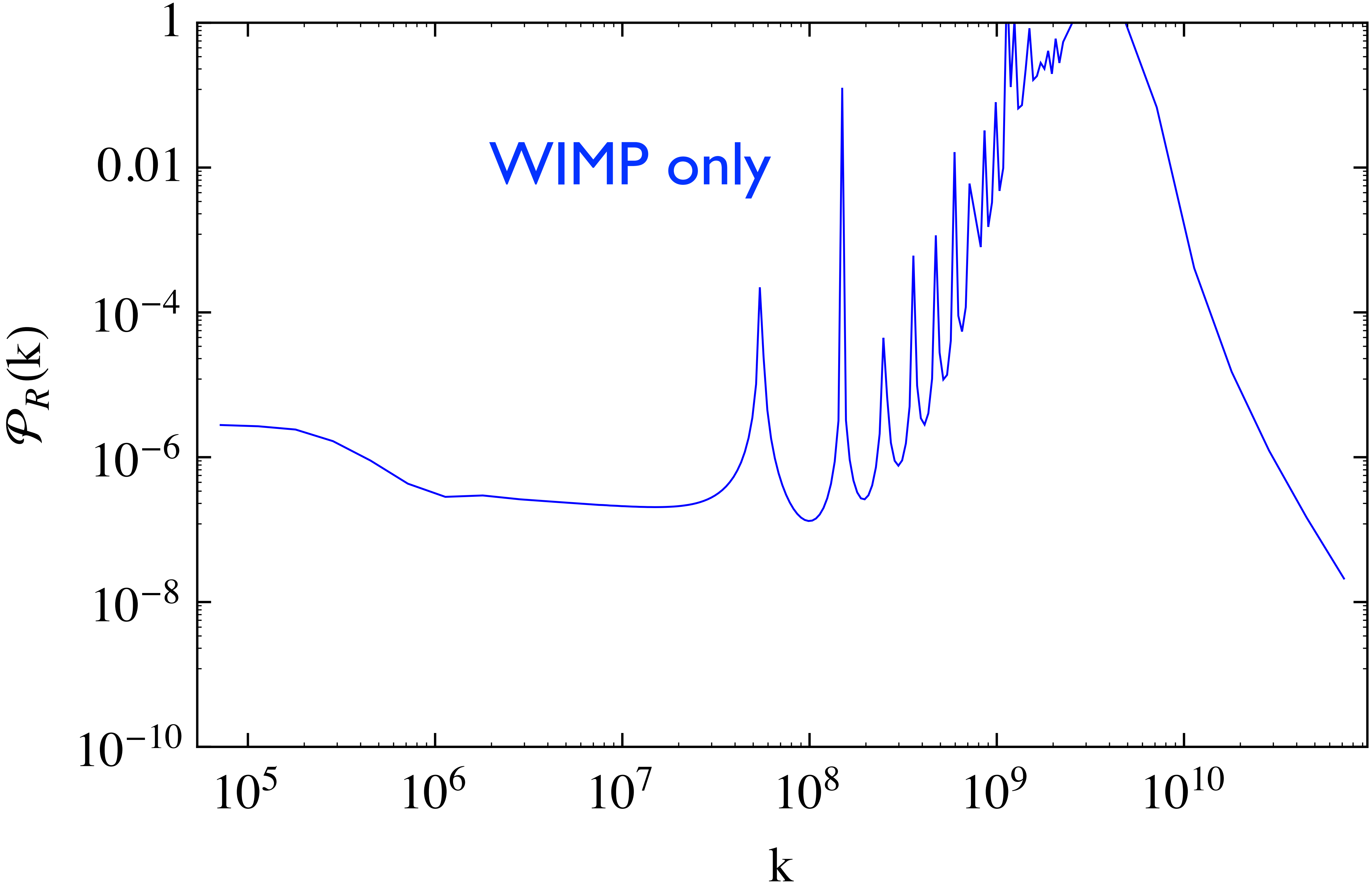
Upper limit on $\delta_\chi^{\min}$ with WIMP DM in the scalar-dom. phase.



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

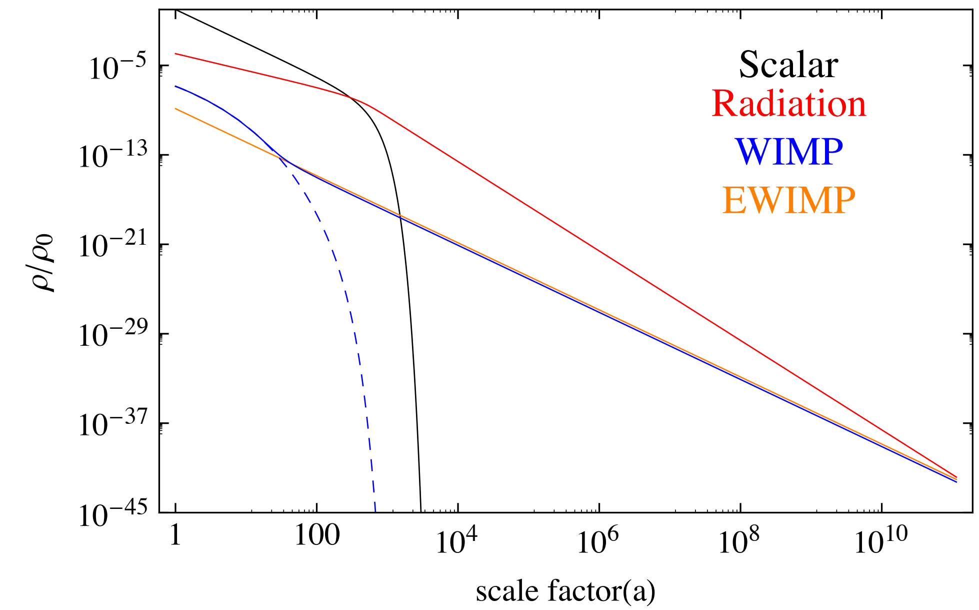


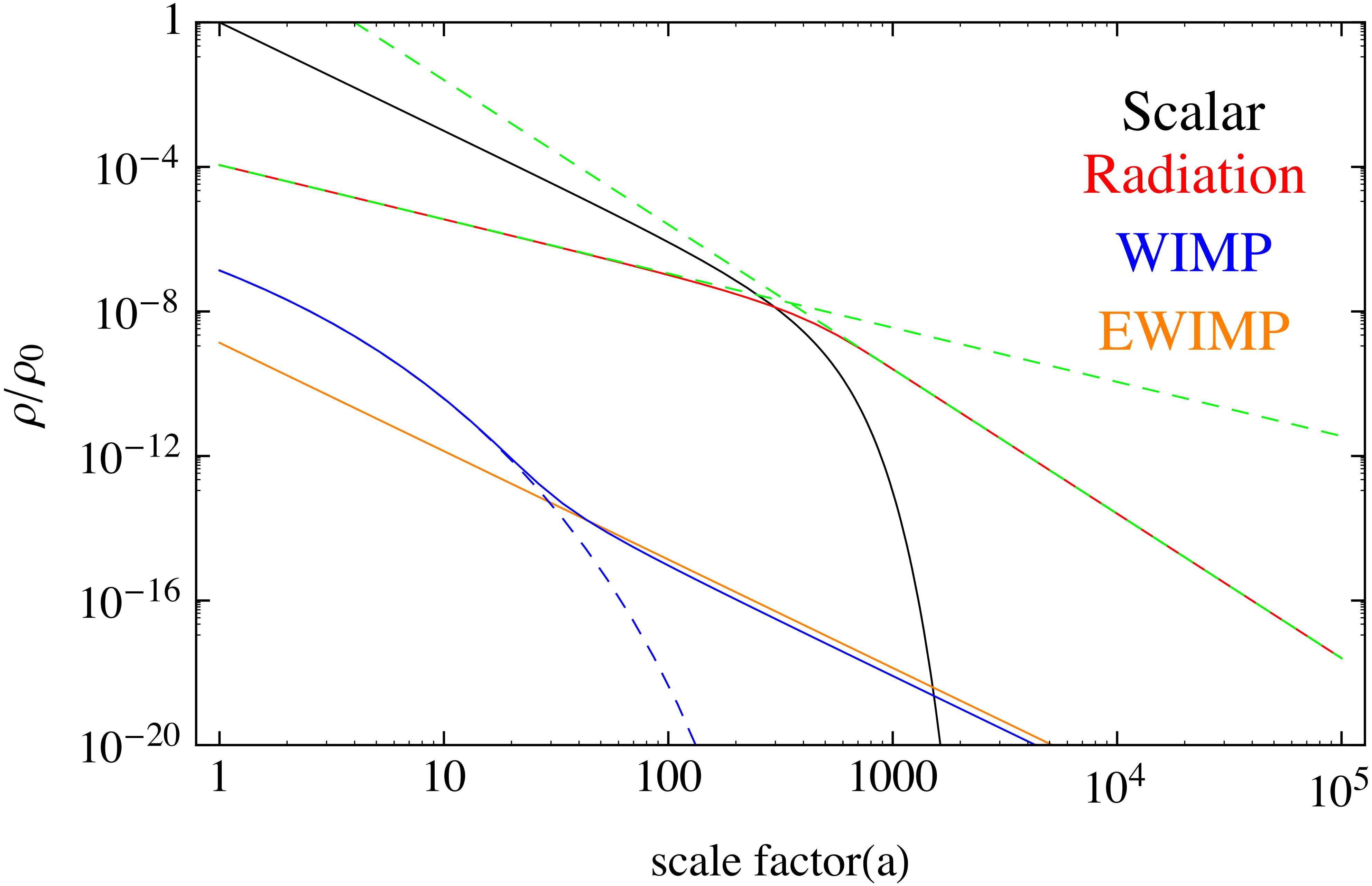
Upper limit on $\mathcal{P}_\delta(k)$ in the non-standard cosmology



Multi Dark Matter

WIMP DM + E-WIMP DM





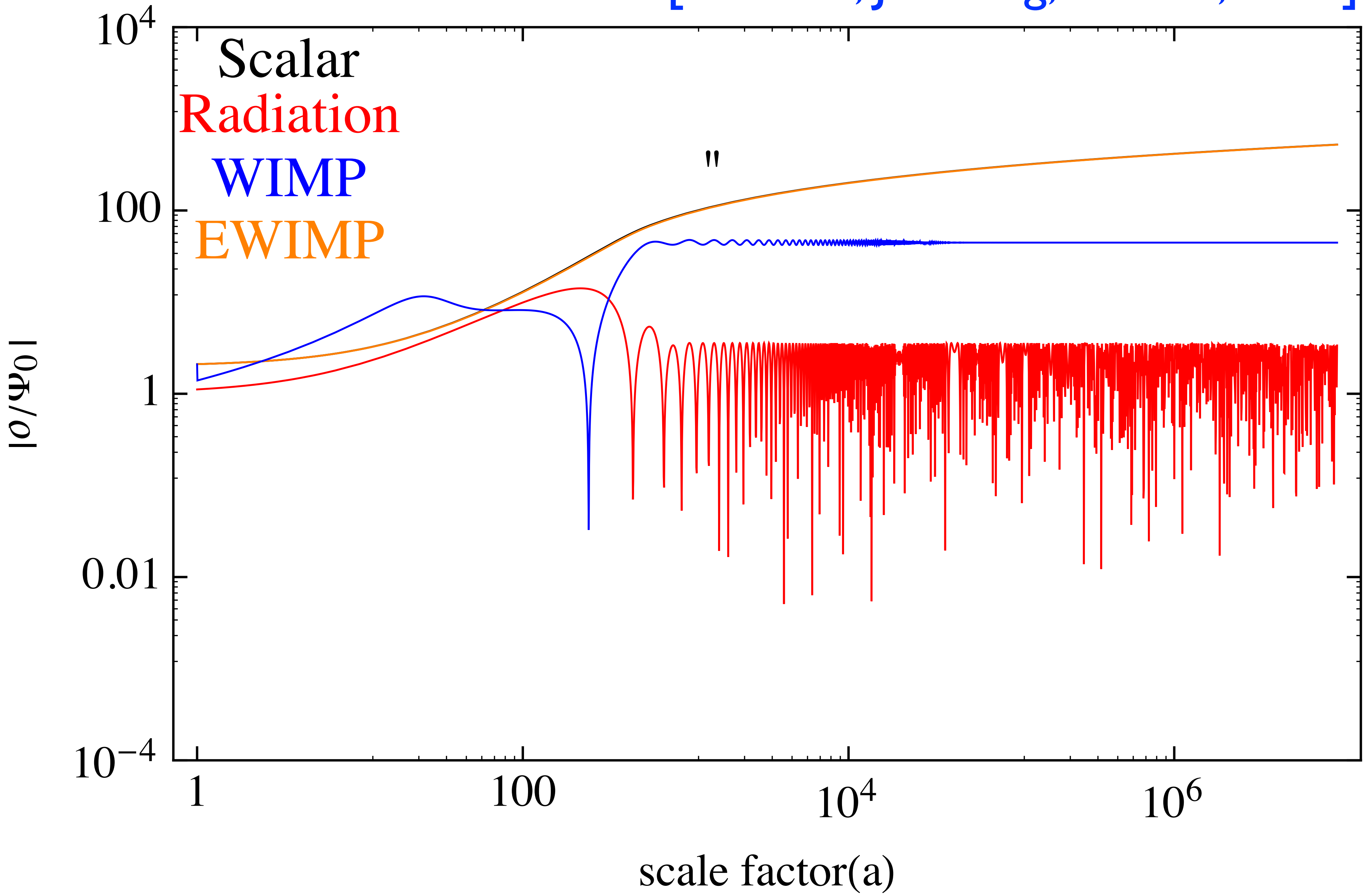
$$\frac{\Omega_{\rm WIMP}}{\Omega_{\rm EWIMP}} = \frac{1}{2}$$

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

WIMP perturbation is enhanced

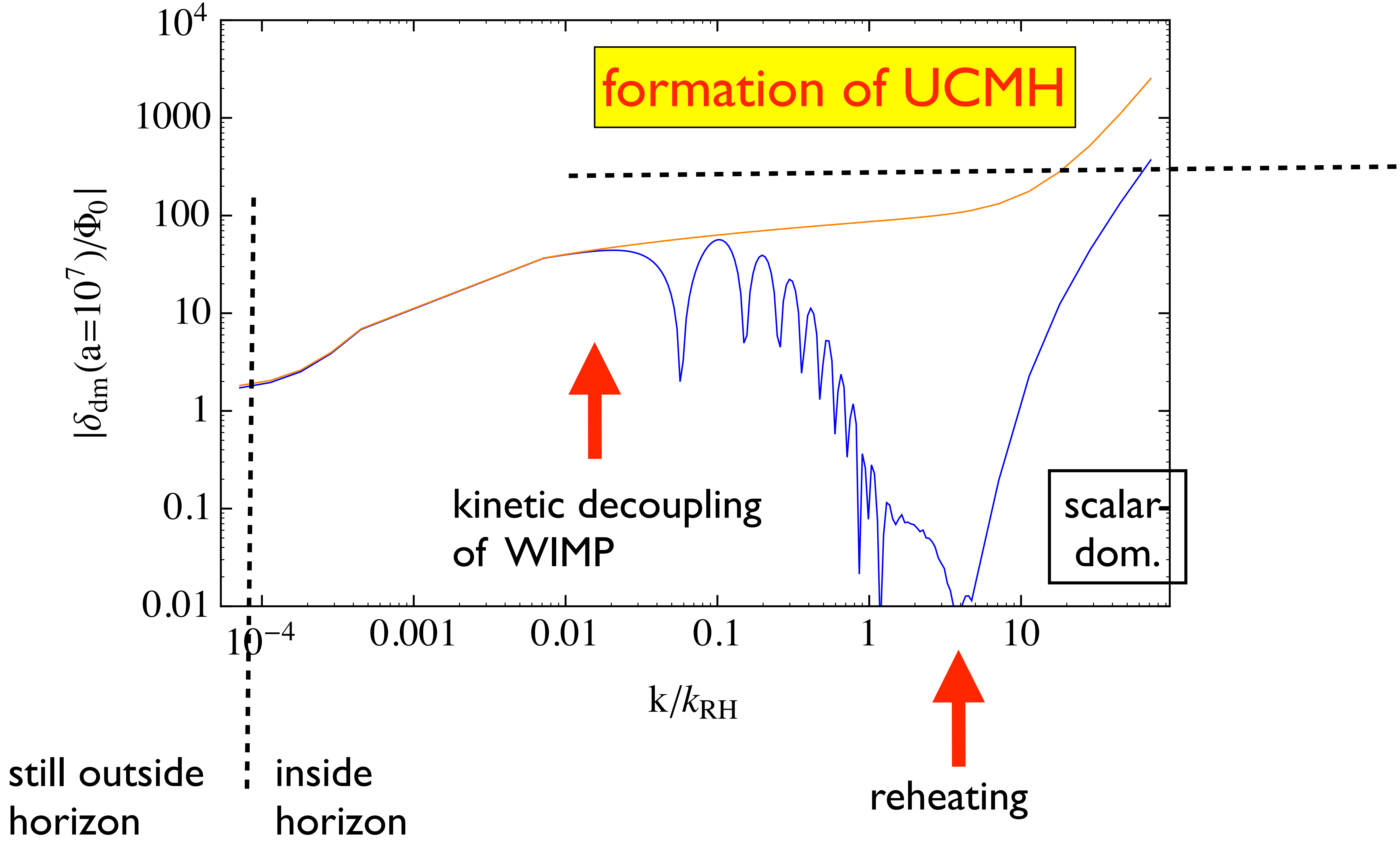
E-WIMP perturbation follows scalar

[KYChoi, JOGong, CSShin, 2014]



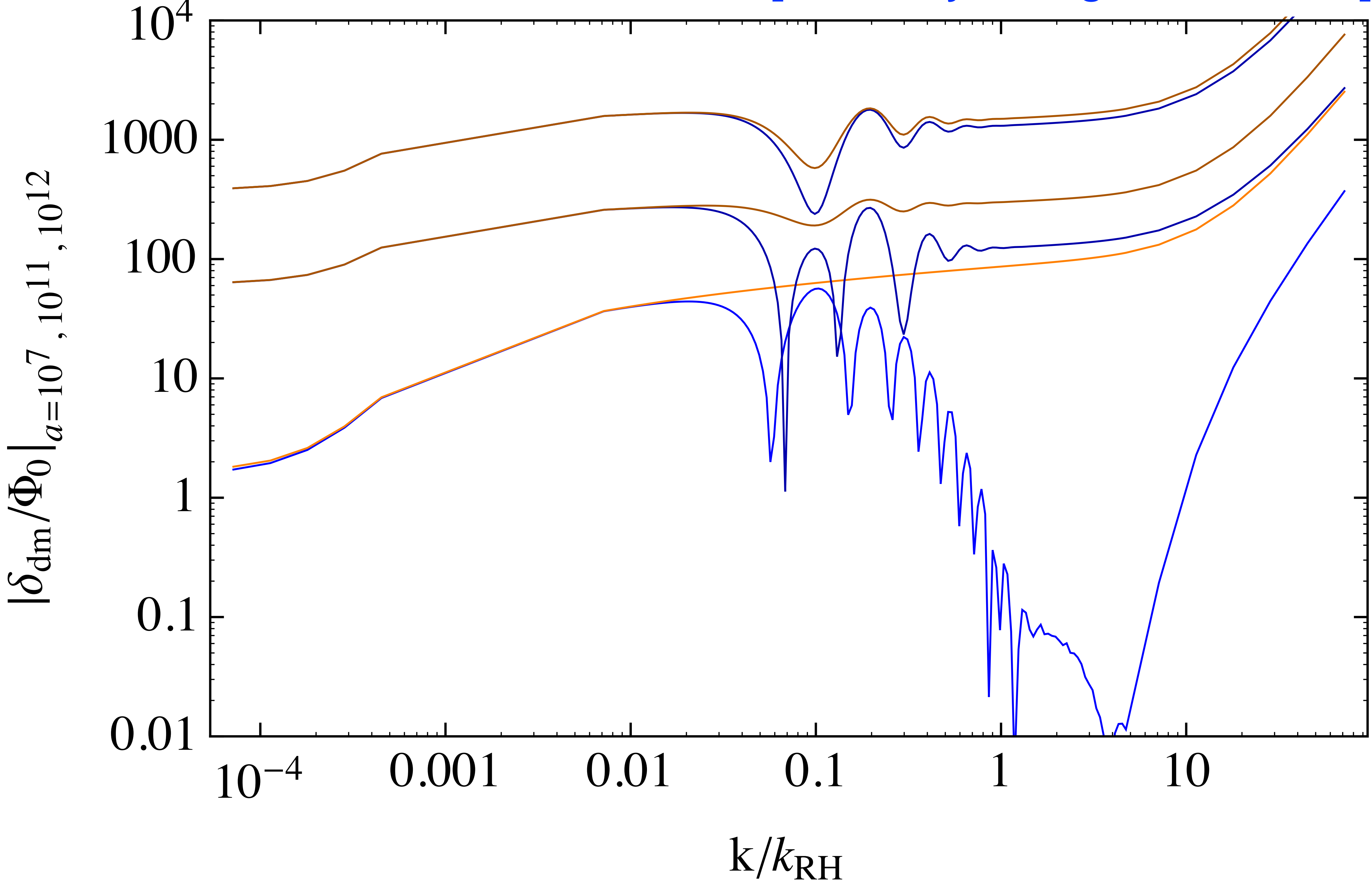
$$\delta_{\rm dm}(a = 10^7)$$

[KYChoi, JOGong, CSShin, 2014]



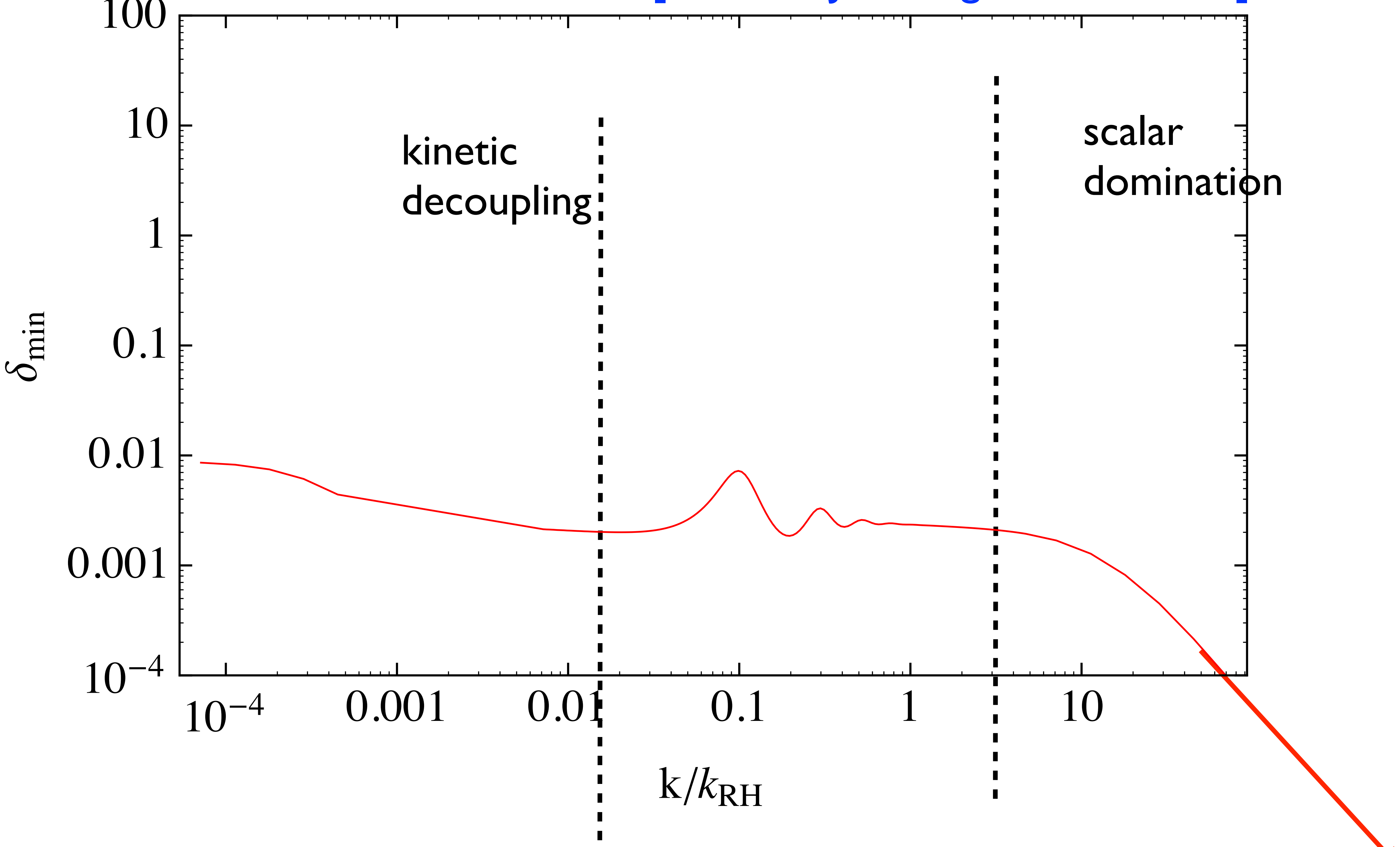
Evolution of the perturbations

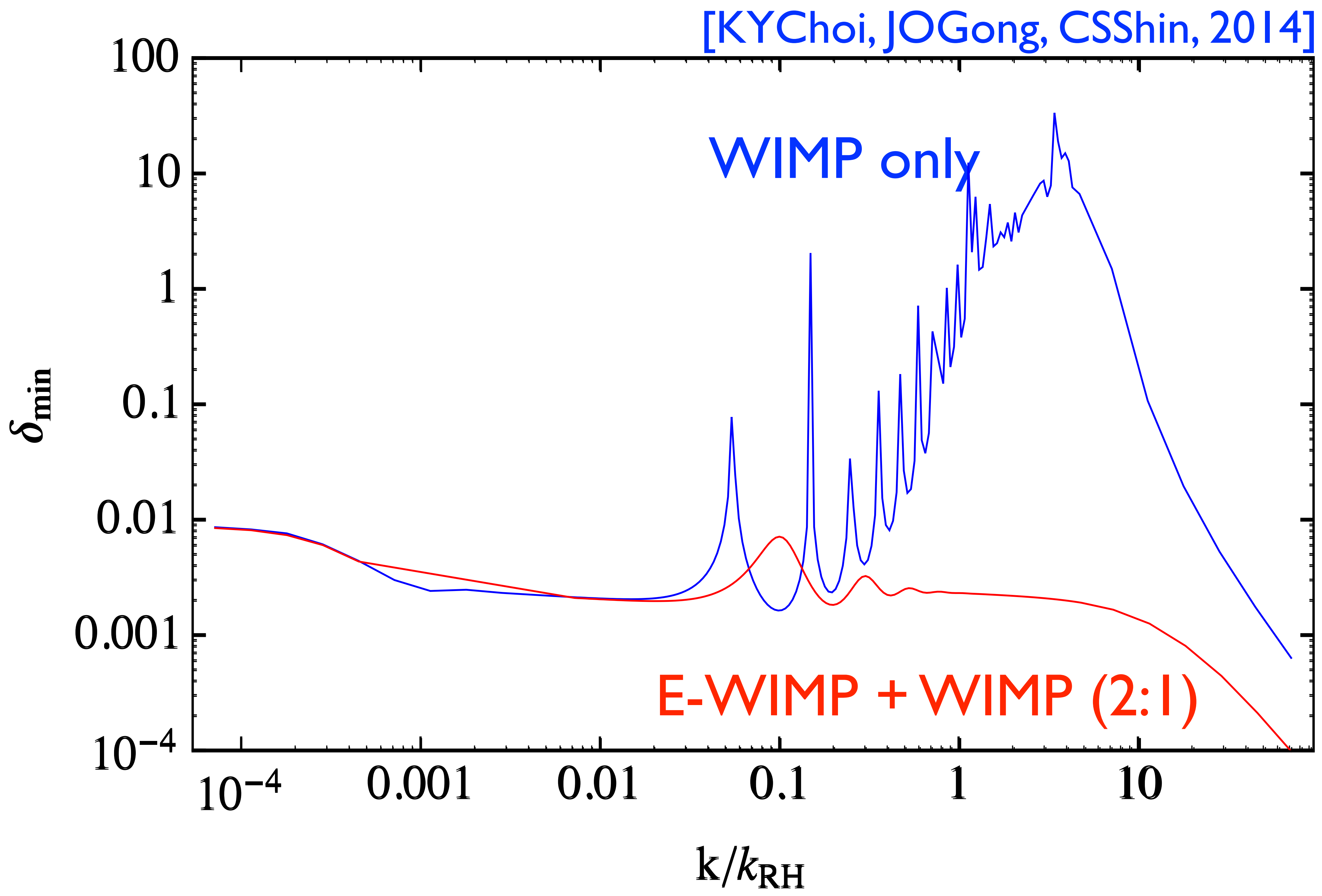
[KYChoi, JOGong, CSShin, 2014]



Upper limit on δ_χ^{min} with WIMP DM + EWIMP DM in the scalar-dom. phase.

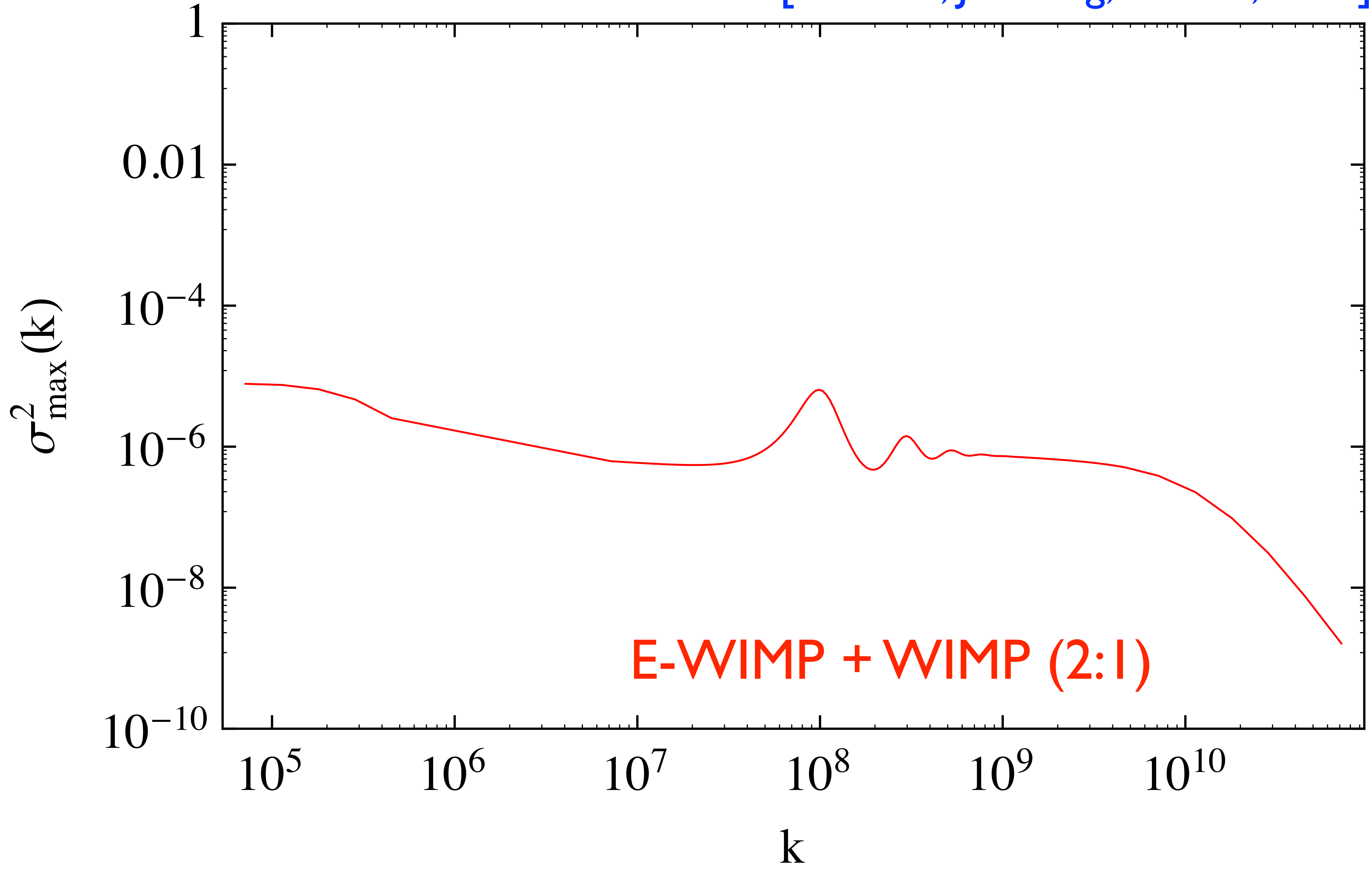
[KYChoi, JOGong, CSShin, 2014]




[KYChoi, JOGong, CSShin, 2014]
100
10
1
0.1
0.01
0.001
10^{-4}
δ_{min}
WIMP only
E-WIMP + WIMP (2:1)
10^{-4}
0.001
0.01
0.1
1
10
k/k_{RH}

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

[KYChoi, JOGong, CSShin, 2014]



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

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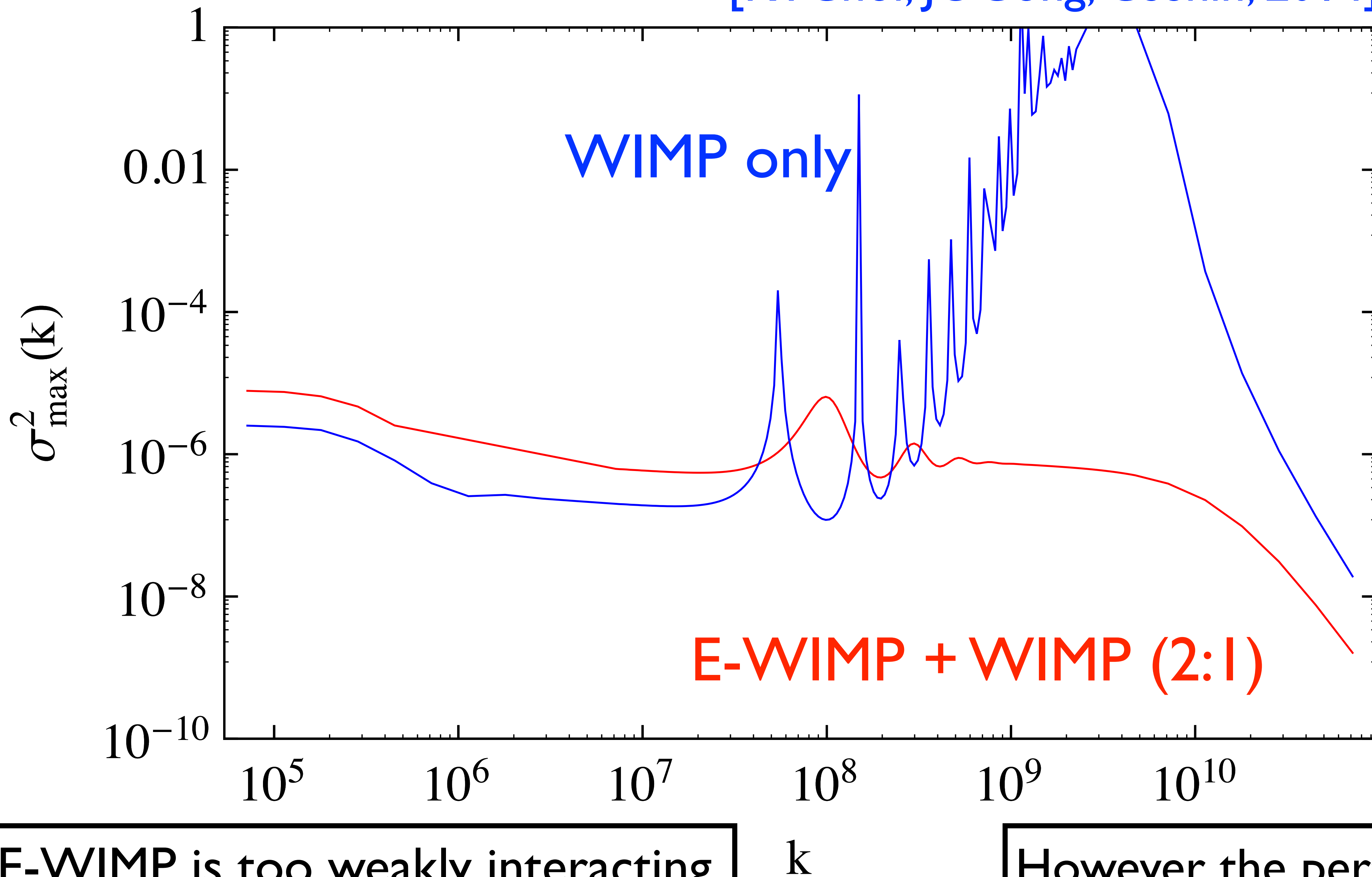
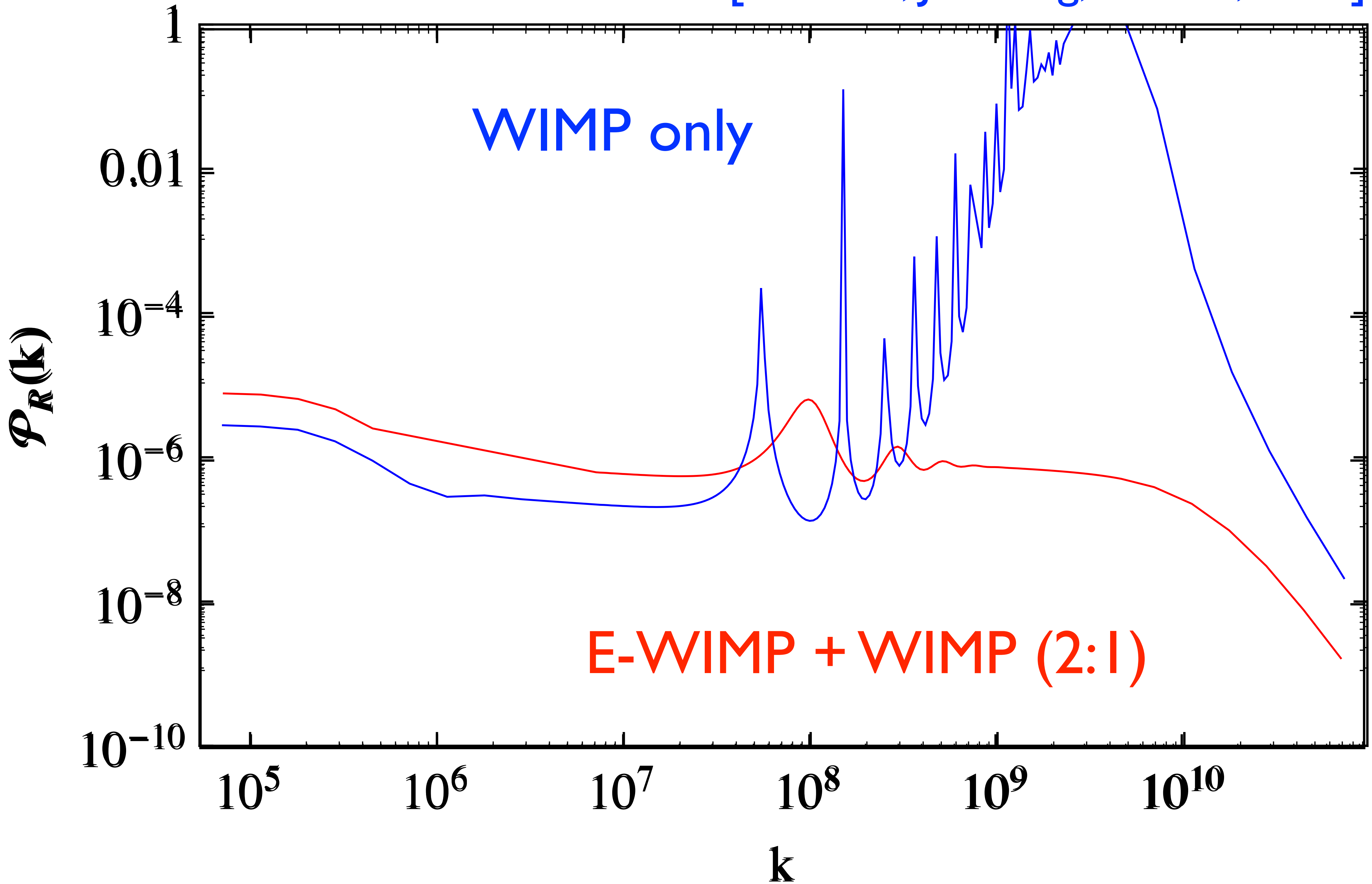


E-WIMP is too weakly interacting and does not emit gamma-ray.

However the perturbation is more enhanced.

Constraints on the primordial power spectrum

[KYChoi, JOGong, CSShin, 2014]



Discussion

1. The non-thermal Universe can enhance the density perturbation of dark matter at small scales.

2. Non-observation UCMH constrains the primordial density perturbation.

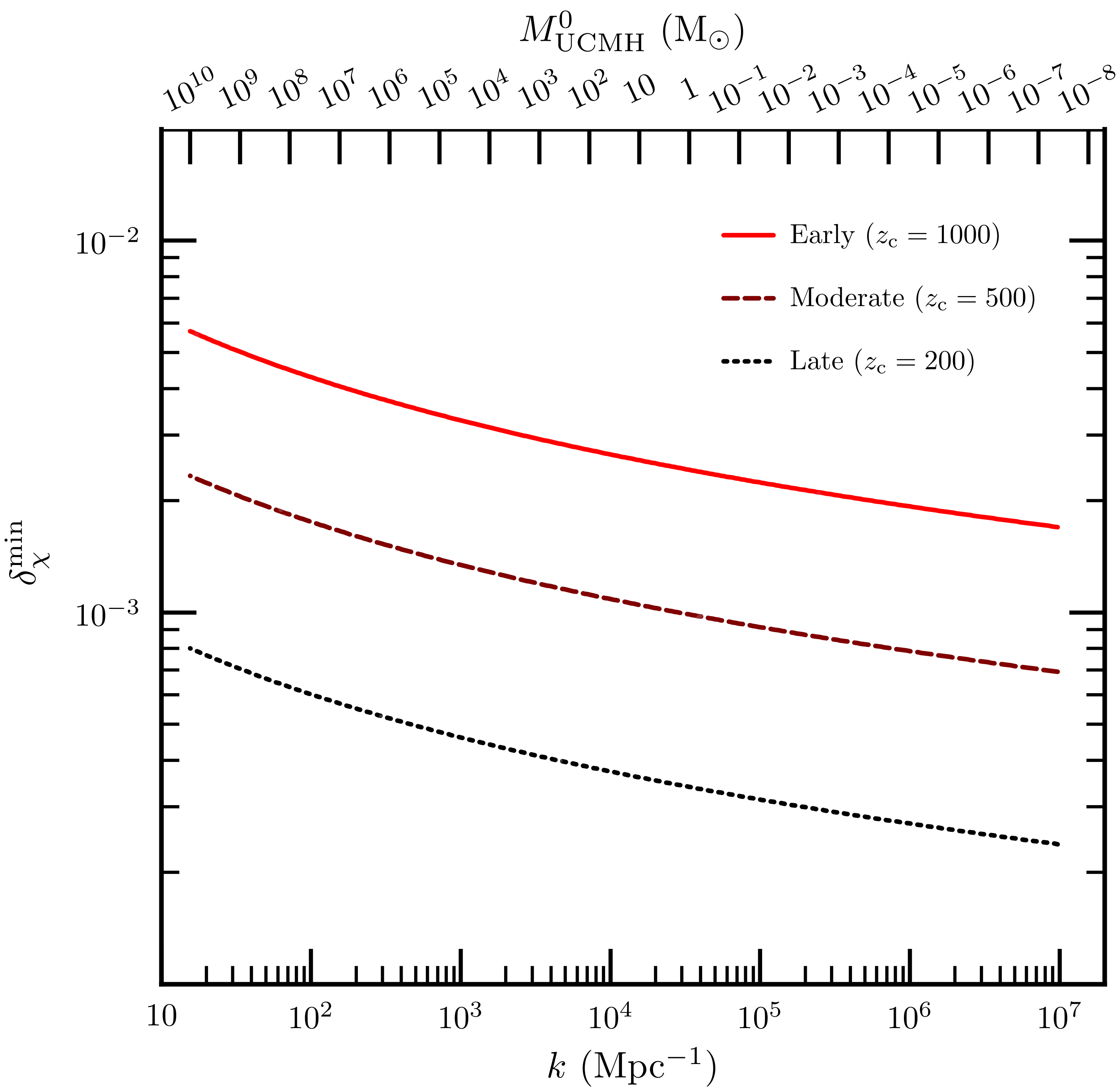
3. The small scale structure formation can be used to constrain the non-thermal evolution in the early Universe and the properties of dark matter.

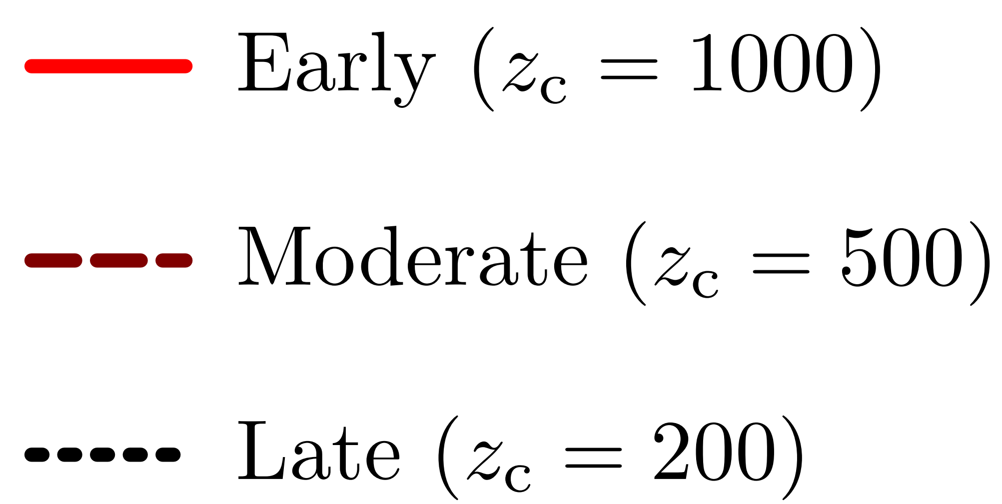
Lowe limit on $\delta_\chi^{\min}$ to have UCMH collapse before redshift Zc

It depends on the evolution of the Universe.

$$\delta_\chi(z_c) \gtrsim \mathcal{O}(1)$$

In standard cosmology,





[Bringmann, Scott, Akrami, 2012]