Small scale isocurvature perturbation of WIMP

Ki Young Choi

KASI 한국천문연구원
Korea Astronomy & Space Science Institute

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Dark Matter

No motivation or need in particle physics

It is necessary to explain the inconsistencies between visible matter and gravitational matter

Astrophysics and Cosmology

→ Existence of some EM/color neutral matters

Evidences for dark matter

In 1933, F. Zwicky first discovered Dark Matter in the velocity dispersion of galaxies in the COMA cluster.

Now there are many evidences for the existence of dark matter

- Galactic scales : rotation curves of galaxies

- Galaxy cluster scales : distribution of velocities, weak gravitational lensing, profile of X-ray emission

- Cosmological scales : acoustic peaks of CMB, large scale structure formation

Only Gravitational!

Single component of dark matter can explain all of them!

Dark Matter as a particle must (be)

1. exist in the early Universe and also now around galaxies, clusters

➡ stable or lifetime longer than the age of universe

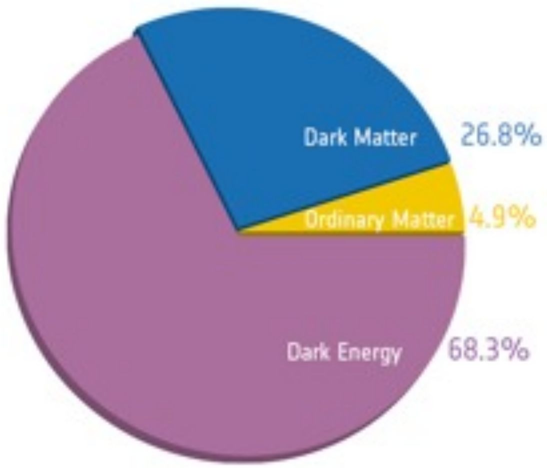
2. neutral : NO electromagnetic interaction

➡ 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 of DM are gravitational.



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

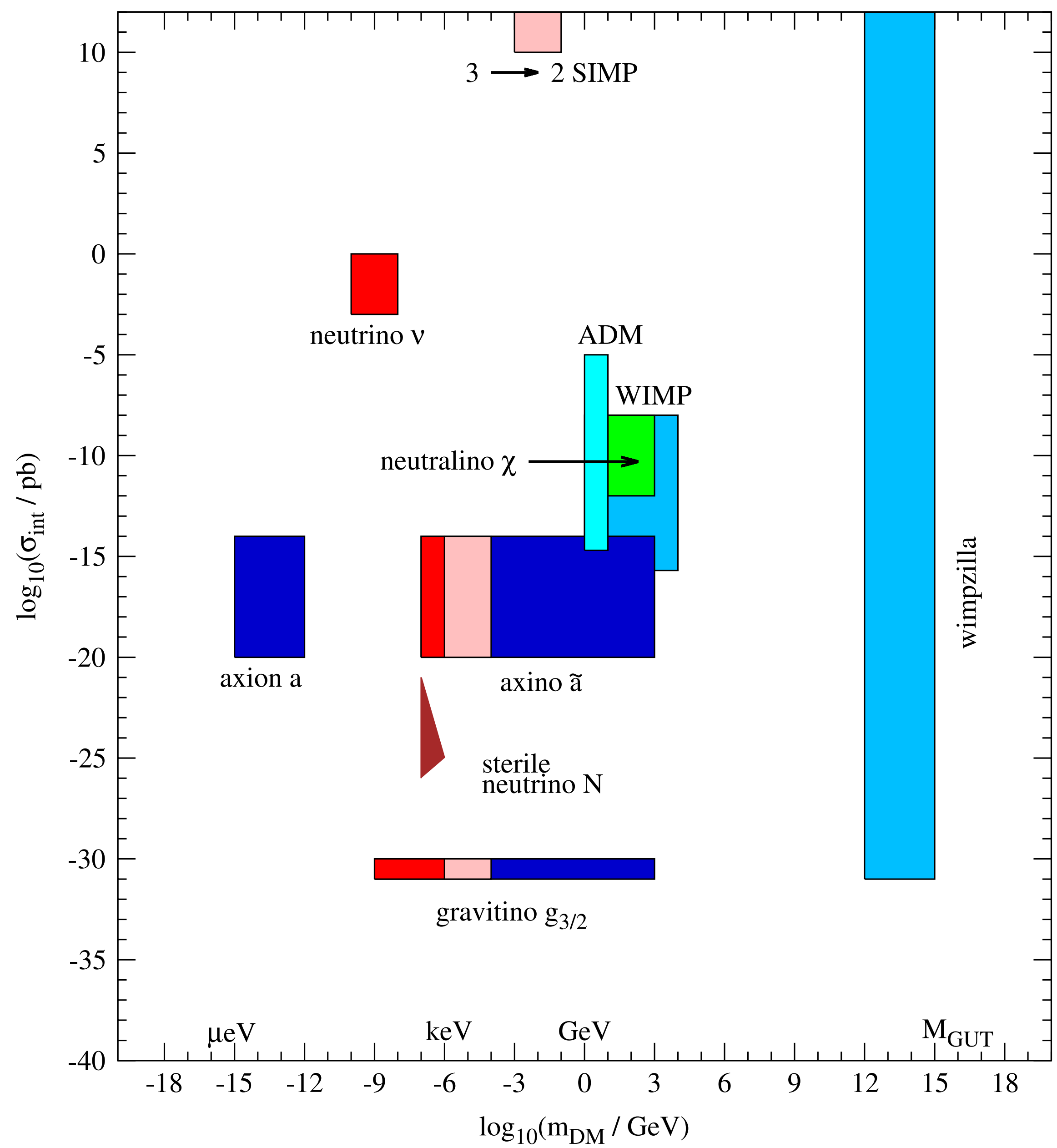
4. cold (or warm) : non-relativistic to seed the structure formation

DM candidates

H. Baer et al. / Physics Reports 555 (2015) 1–60

Interaction

10^{40}



Mass 10^{30}

WIMP Dark Matter

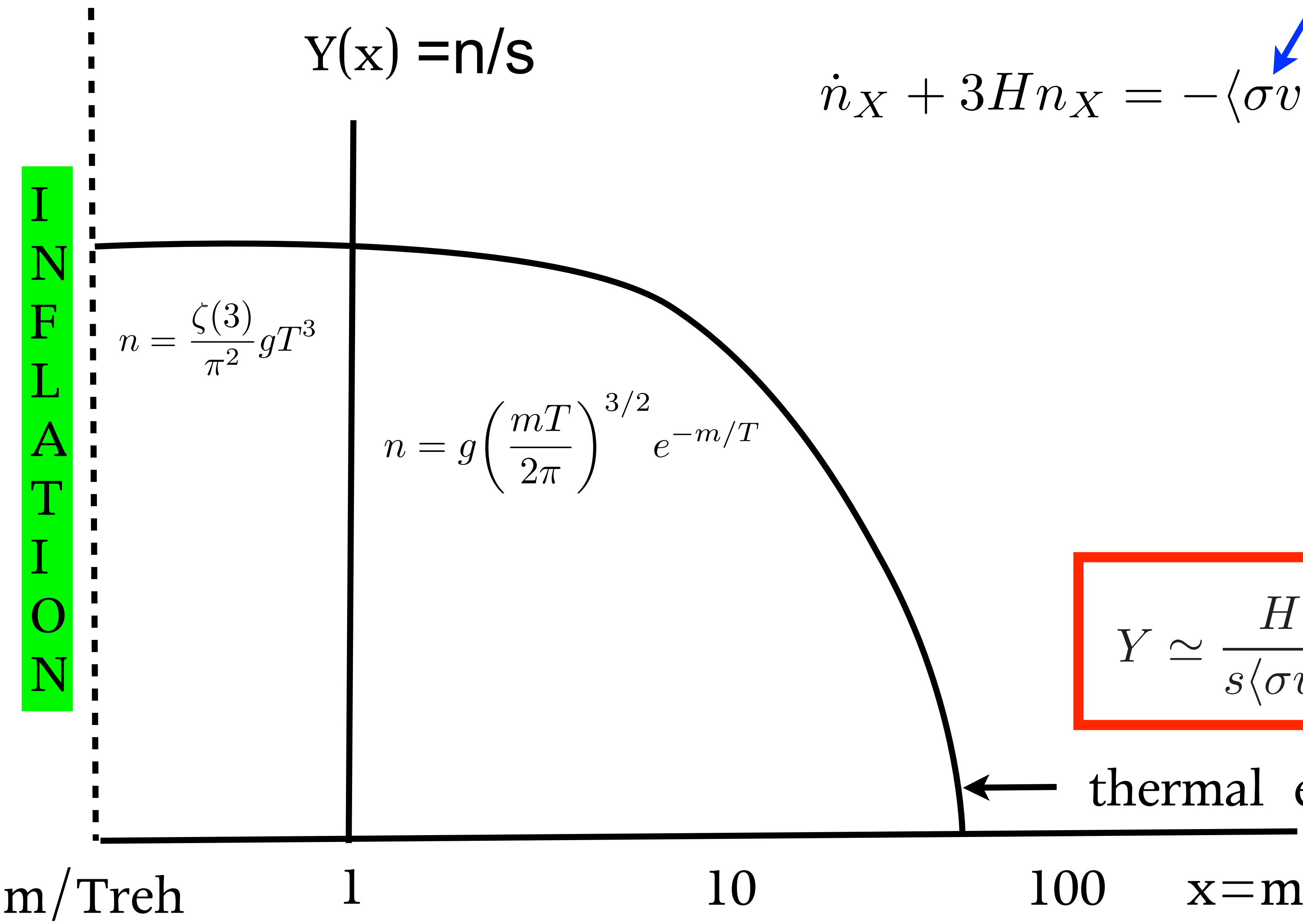
WIMP : Weakly Interacting Massive Particle

[B. W. Lee and S. Weinberg, PRL 1977]

Freeze-out temperature < Mass

annihilation cross section

$$\dot{n}_X + 3Hn_X = -\langle\sigma v\rangle(n_X^2 - (n_X^{eq})^2)$$



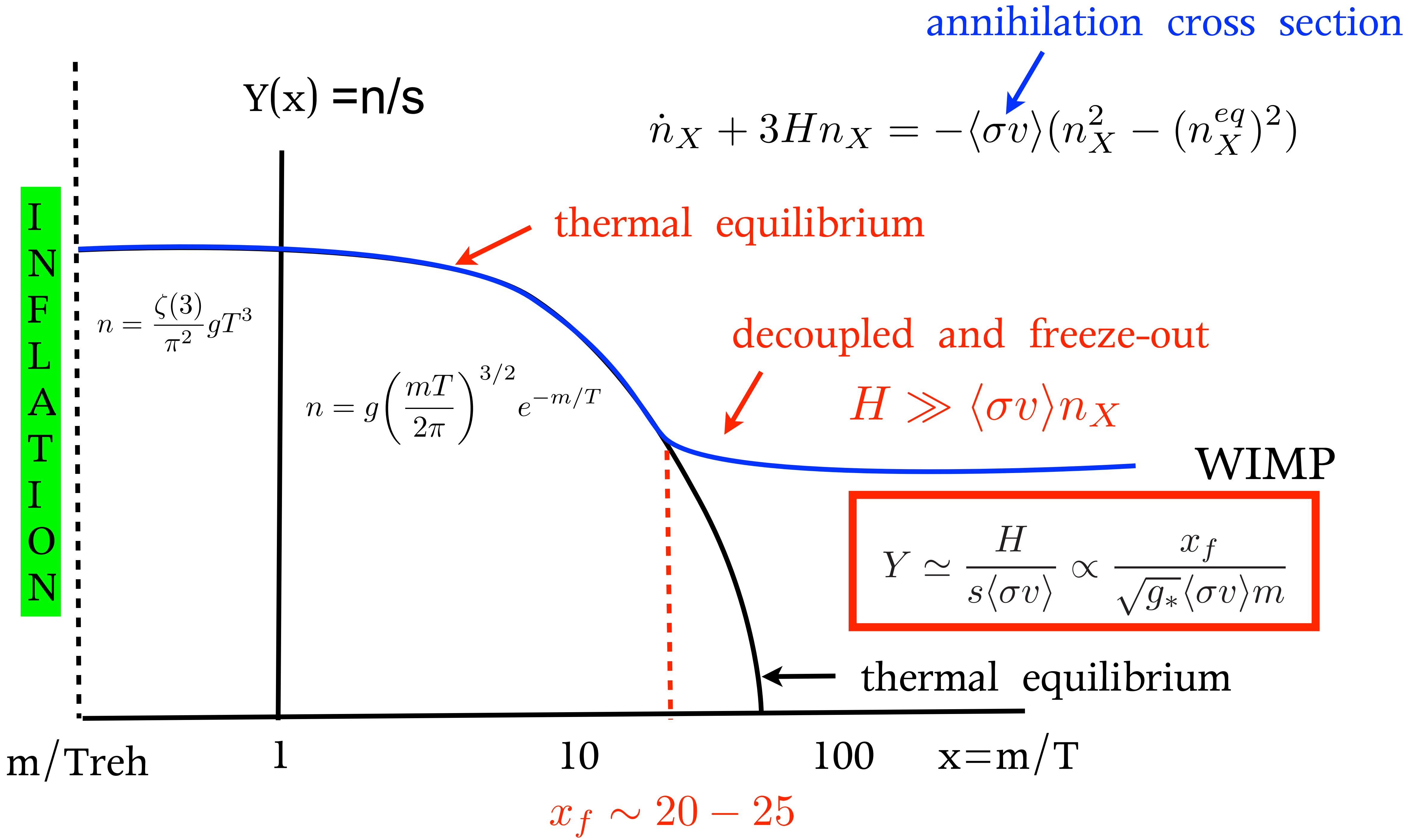
$$\boxed{Y \simeq \frac{H}{s\langle\sigma v\rangle} \propto \frac{x_f}{\sqrt{g_*}\langle\sigma v\rangle m}}$$

thermal equilibrium

WIMP : Weakly Interacting Massive Particle

[B. W. Lee and S. Weinberg, PRL 1977]

Freeze-out temperature < Mass



Weakly Interacting Massive Particles

$$\Omega h^2 \simeq \frac{2.5 \times 10^{-10}\,\mathrm{GeV}}{\langle \sigma_{\rm ann} v \rangle} \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{sec}^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$

New physics at weak scale!

Massive LH neutrino : ruled-out by Direct Detection.

RH sneutrino, many WIMP models in SUSY

Kaluza-Klein DM, minimal DM

Neutralino : Lightest SUSY Particle in the extension of SM.

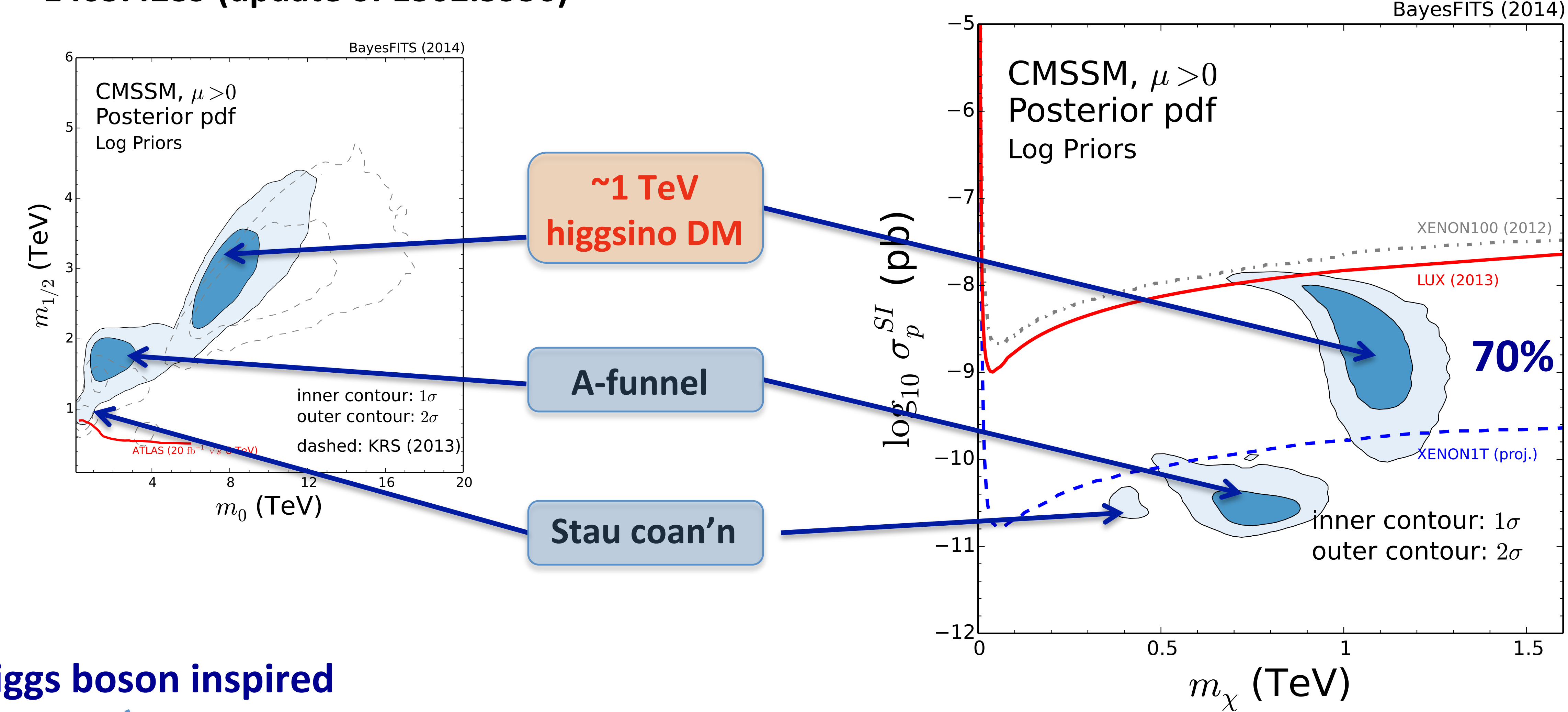
....

CMSSM and direct DM searches

After LHC

$\mu > 0$

1405.4289 (update of 1302.5956)



Higgs boson inspired

~1TeV higgsino DM: exciting prospects for LUX, X100 & 1t detectors

Focus point region ruled out by LUX (already tension with X100)

- The scattering cross section and chemical/kinetic decoupling

Inelastic scatterings : Number changing interactions $T_{\rm fr} \simeq \dfrac{m}{20}$

$\Rightarrow$ $\boxed{\text{Chemical equilibrium}}$ $\Rightarrow$ $\boxed{\text{Relic density}}$

Elastic scatterings : change momentum (number conserved)

$\Rightarrow$ $\boxed{\text{Kinetic equilibrium}}$ $\Rightarrow$ $\boxed{\text{Structure formation}}$

- The density perturbation can grow after kinetic decoupling

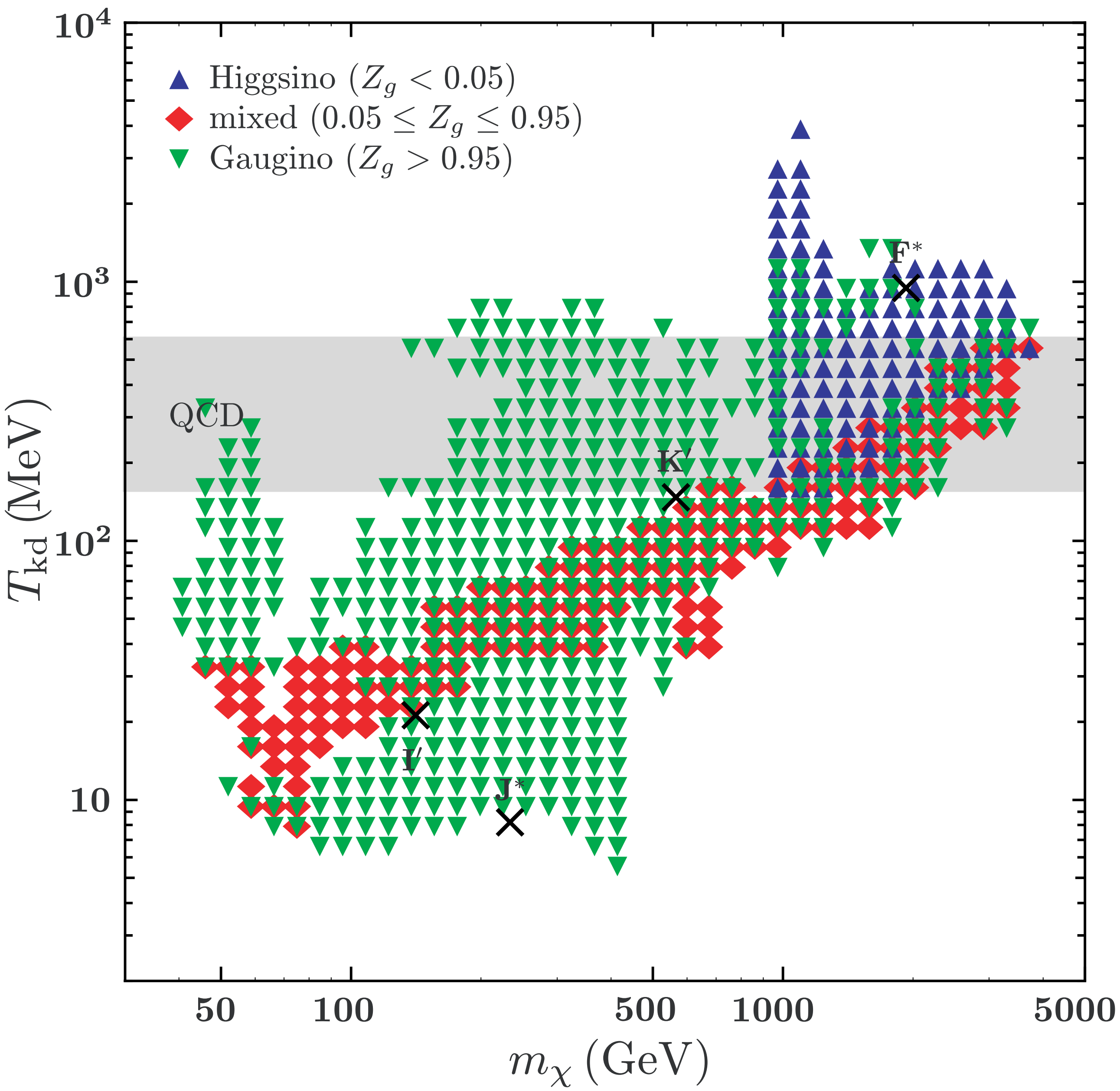
- This or free-streaming scale determines the minimum scale for the structure formation

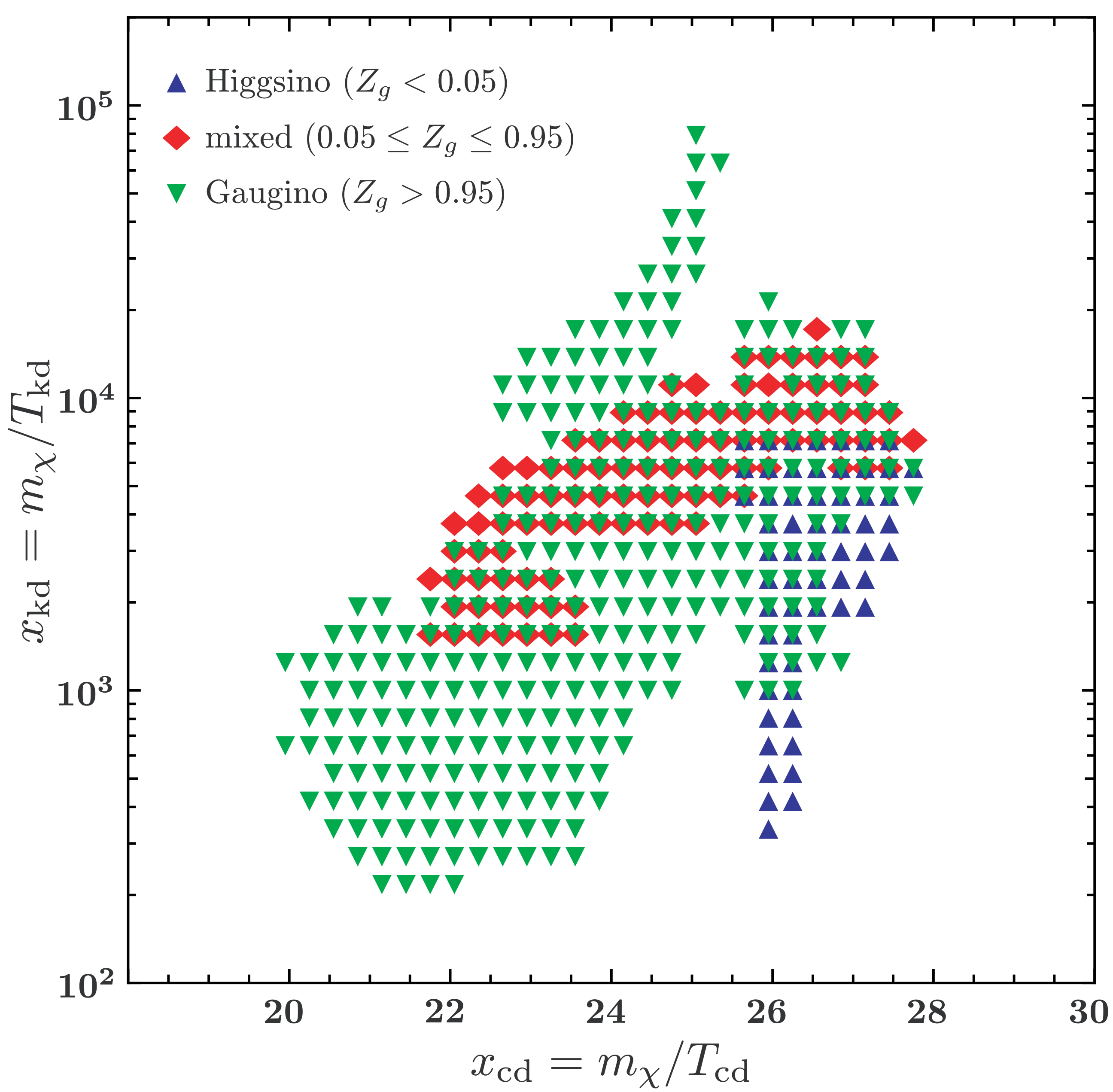
- Smaller scales are damped during kinetic decoupling

Kinetic decoupling temperature of neutralinos

[Bringmann, 2009]

Z_g : gaugino fraction

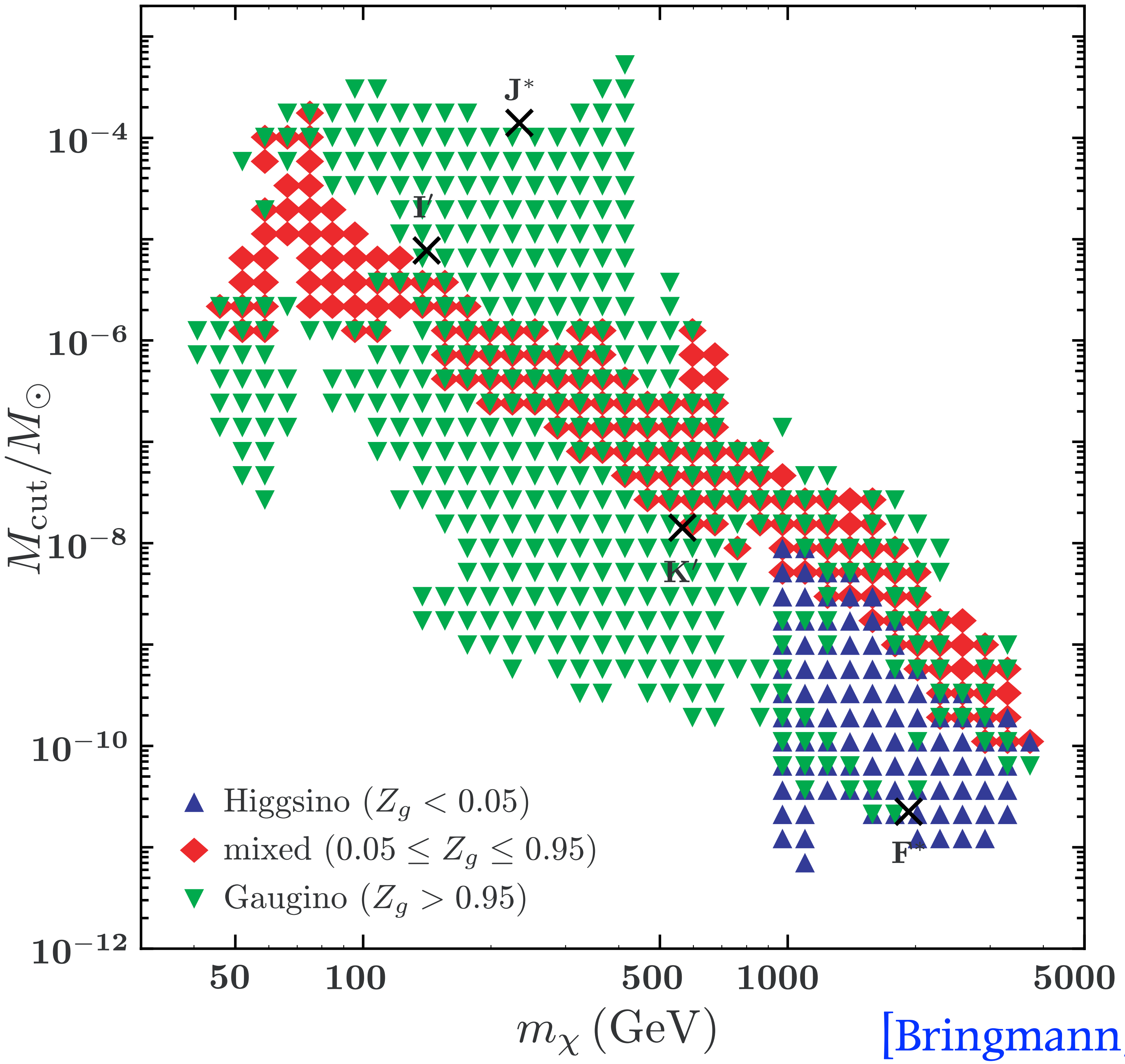




Kinetic decoupling takes place much later than chemical decoupling by a factor of 10 - 1000.

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

Earth mass ~



[Bringmann, 2009]

Isocurvature perturbation

$$S_i \equiv \frac{\delta\rho_i}{\rho_i} - \frac{3\delta\rho_\gamma}{4\rho_\gamma}.$$

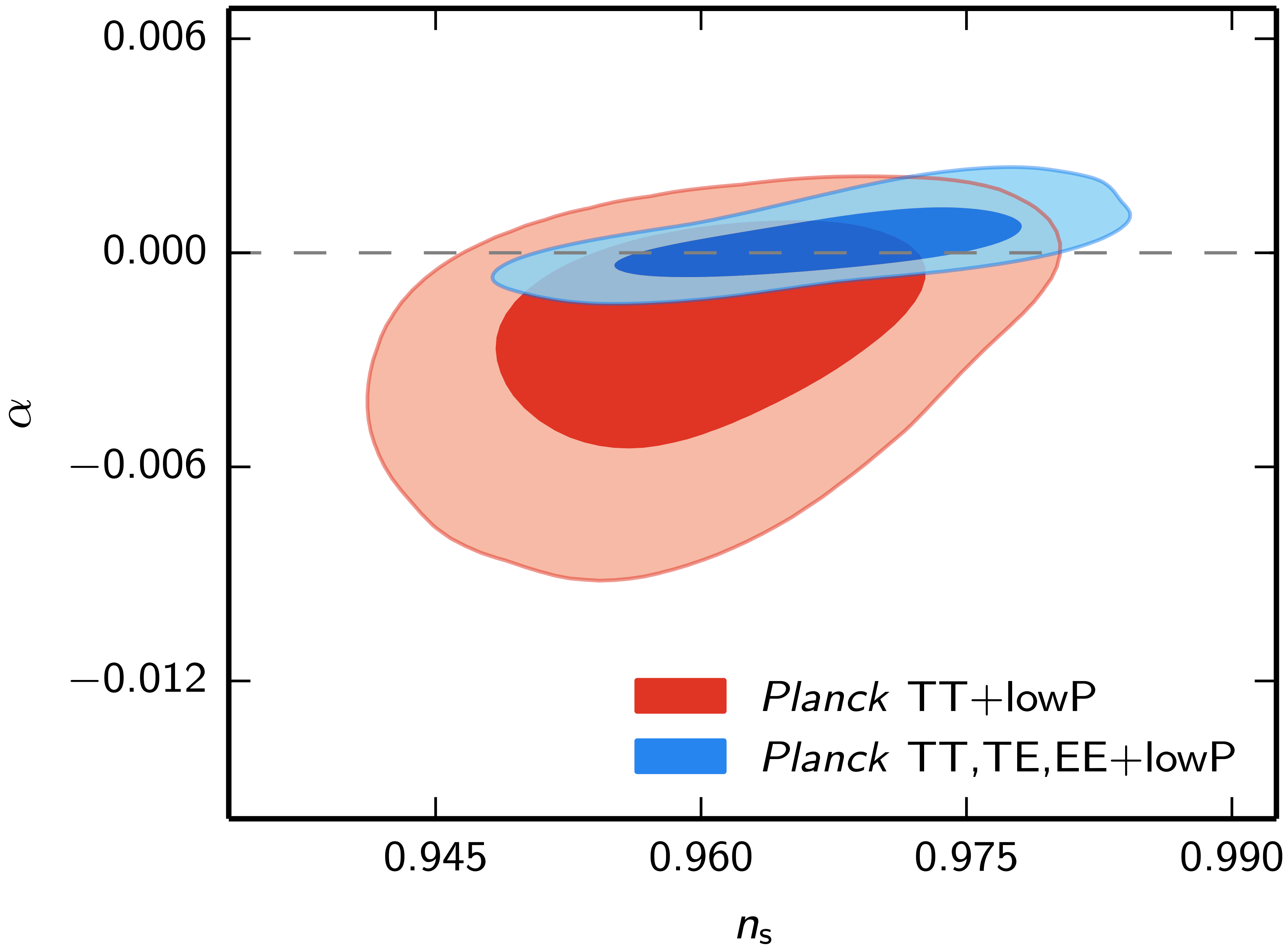
After BBN, there are 4 different species :

photon, neutrino (w/ velocity), dark matter, baryon

Isocurvature perturbations between these components.
We are focused on the DM isocurvature perturbation
and consider the neutrinos and baryons are produced from the photons in the standard scenario in radiation dominated era.

$$S \equiv 3H\left(\frac{\delta\rho_m}{\dot{\rho}_m} - \frac{\delta\rho_r}{\dot{\rho}_r}\right) = \delta_m - \frac{3}{4}\delta_r\,,$$

Constraint on the DM isocurvature perturbation



$$S_{\mathrm{m}} = \mathrm{sgn}(\alpha)\sqrt{\frac{|\alpha|}{1-|\alpha|}}\zeta, \qquad \alpha = -0.0025^{+0.0035}_{-0.0047} \quad (95\%, \textit{Planck}\ \mathrm{TT{+}lowP}),$$

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

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + (1/2)(dn_s/d\ln k)\ln(k/k_0)},$$

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

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

- 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 smaller scales.

Isocurvature perturbation of WIMP

WIMP dark matter is adiabatic on both large and small scales

- since it is produced from the relativistic thermal plasma when it was in the thermal equilibrium in standard Universe.
- It is consistent with observation, adiabatic power spectrum

Adiabatic perturbation is damped during the kinetic decoupling, for the smaller scales than the kinetic decoupling. [Peebles 1987]

However the isocurvature perturbation is not damped.

$$\dot{S} = \theta_r - \theta_m,$$

divergence of velocity

- Is it possible to have a large isocurvature perturbation at small scales with adiabatic at large scales?
- No in the standard WIMP.
- However there is a one case, where the generation is possible.

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COSMIC BACKGROUND TEMPERATURE ANISOTROPY IN A MINIMAL ISOCURVATURE MODEL FOR GALAXY FORMATION

P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University
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ABSTRACT

If the dominant components of the universe were radiation and baryons, and the primeval baryon distribution had a roughly flat spectrum normalized to galaxy clustering on scales ~ 20 Mpc, and young stars were able to keep the bulk of the matter ionized at redshifts $z \gtrsim 20$, then several encouraging results would follow. The first generation that starts to form when Compton drag becomes unimportant would have masses and radii comparable to galaxies. Mass fluctuations on scales ~ 200 Mpc could be relatively large and so perhaps favorable for development of large-scale structure. And the residual fluctuations in the background temperature would have coherence length ~ to 3°–5° and standard deviation $\delta T/T \approx 10^{-5}$, close to but below the observational bounds.

WIMP isocurvature perturbation and small scale structure

Ki-Young Choi,[1,*] Jinn-Ouk Gong,[2,3,†] and Chang Sub Shin[4,‡]

[1] *Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea*
[2] *Asia Pacific Center for Theoretical Physics, Pohang, 790-784, Korea*
[3] *Department of Physics, Postech, Pohang 790-784, Korea*
[4] *Department of Physics and Astronomy, Rutgers University, Piscataway NJ 08854, USA*

The adiabatic perturbation of dark matter is damped during the kinetic decoupling due to the collision with relativistic component on sub-horizon scales. However the isocurvature part is free from damping and could be large enough to make a substantial contribution to the formation of small scale structure. We explicitly study the weakly interacting massive particles as dark matter with an early matter dominated period before radiation domination and show that the isocurvature perturbation is generated during the phase transition and leaves imprint in the observable signatures for small scale structure.

[1507.03871]

The generation of the isocurvature perturbation in the subhorizon scales can happen when [KYChoi, Gong, Shin, 1507.03871]

1. During the matter domination, WIMP is chemically decoupled but still kinetically coupled to radiation,

2. After chemical decoupling, the phase transition happens from the matter-dom. to the radiation-dom.

Early matter dominated epoch with low-reheating temperature

Non-standard cosmology with early matter-dominated era and all radiation and DM are generated from the scalar again:

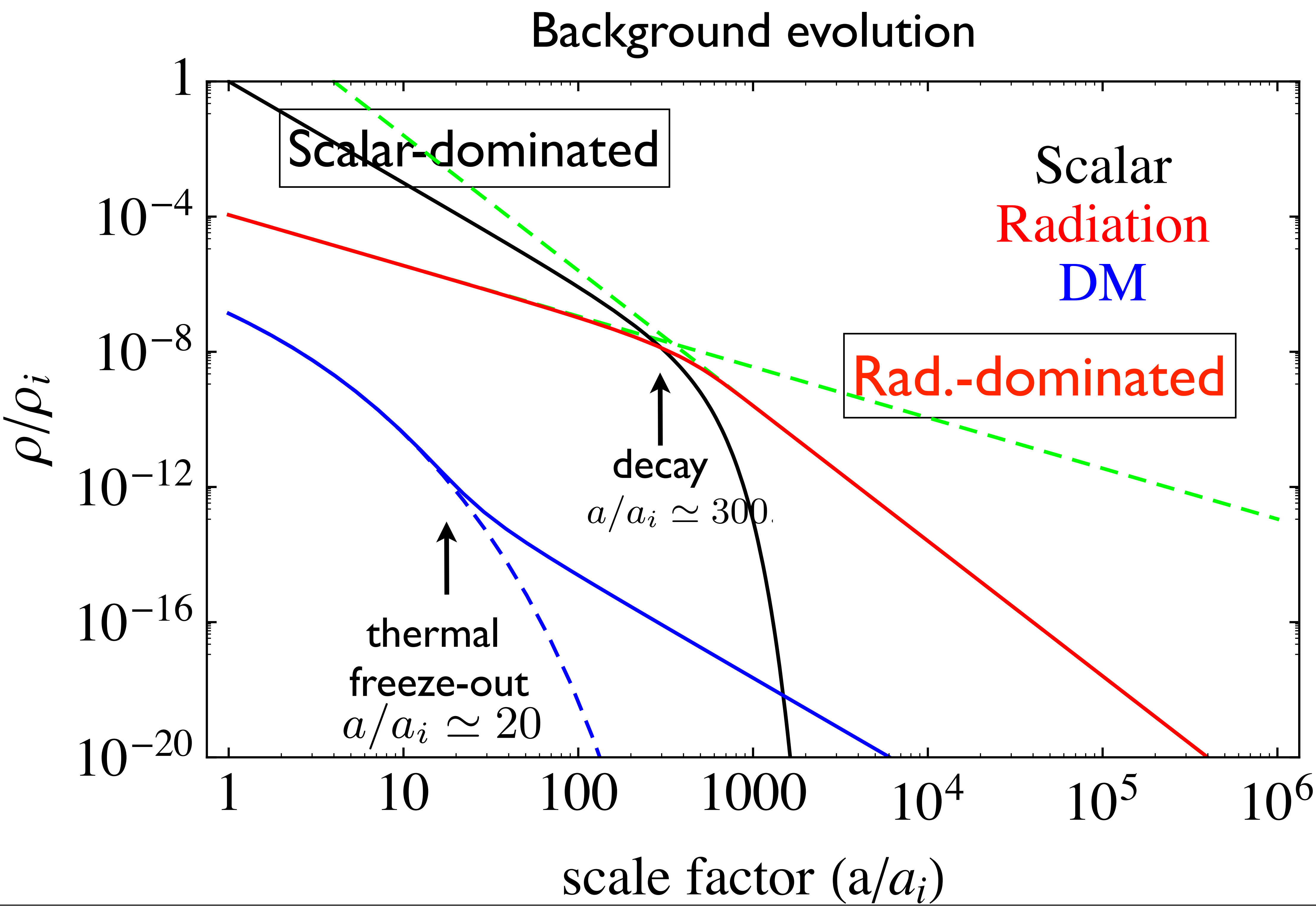
- Inflaton oscillation
- Thermal inflation
- Curvaton domination

- 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

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



Background evolution

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

$$\dot{\rho}_r + 4H\rho_r = (1 - f_m)\Gamma_\phi \rho_\phi + \frac{\langle \sigma_a v \rangle}{M} \left[\rho_m^2 - (\rho_m^{\rm eq})^2\right]$$

$$\dot{\rho}_m + 3H\rho_m = f_m \Gamma_\phi \rho_\phi - \frac{\langle \sigma_a v \rangle}{M} \left[\rho_m^2 - (\rho_m^{\rm eq})^2\right] \,,$$

We consider that the radiation is generated by the decay of the scalar and quickly thermalized. The DMs are produced from the annihilation of radiations like WIMP.

$$f_m = 0$$

$\langle \sigma_a v \rangle$ Thermal averaged annihilation cross section of DM

Perturbation equations

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

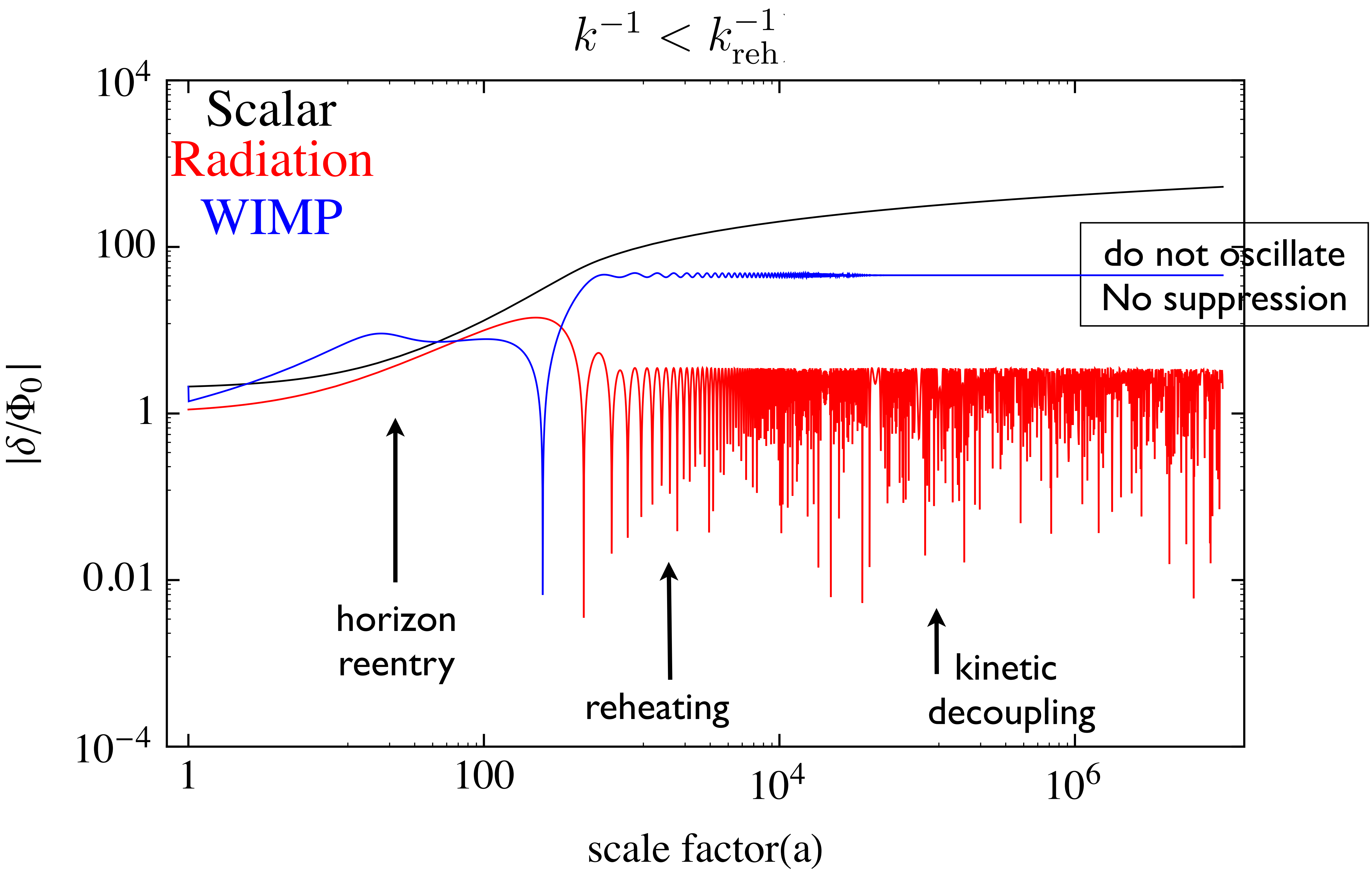
$$\dot{\delta}_\alpha + (1+w_\alpha)\frac{\theta_\alpha}{a} - 3(1+w_\alpha)\dot{\Psi} = \frac{1}{\rho_\alpha}\left(\delta Q_\alpha - Q_\alpha\delta_\alpha + Q_\alpha\Phi\right) \,,$$

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

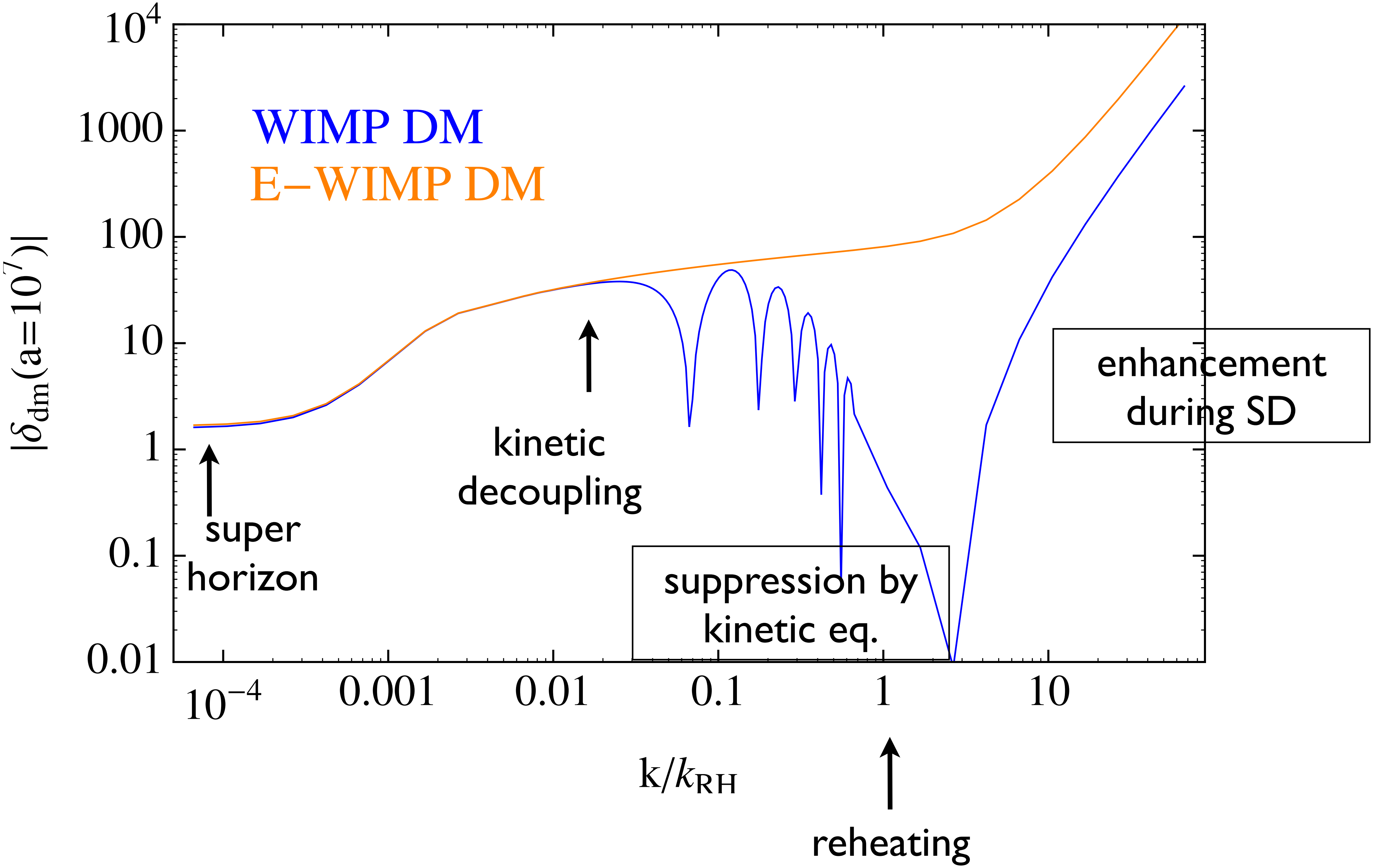
with

$$\begin{aligned}
Q_\phi &= -\Gamma_\phi\rho_\phi \,, \\
Q_r &= \Gamma_\phi\rho_\phi + \frac{\langle\sigma v\rangle}{M}\left[\rho_m^2 - (\rho_m^{\rm eq})^2\right] \,, \\
Q_m &= -\frac{\langle\sigma v\rangle}{M}\left[\rho_m^2 - (\rho_m^{\rm eq})^2\right] \,, \\
\delta Q_\phi &= -\Gamma_\phi\rho_\phi\delta_\phi, \\
\delta Q_r &= \Gamma_\phi\rho_\phi\delta_\phi + \frac{2\langle\sigma v\rangle}{M}\left[\rho_m^2\delta_m - (\rho_m^{\rm eq})^2\frac{M}{T}\frac{\delta_r}{4}\right] \,, \\
\delta Q_m &= -\frac{2\langle\sigma v\rangle}{M}\left[\rho_m^2\delta_m - (\rho_m^{\rm eq})^2\frac{M}{T}\frac{\delta_r}{4}\right] \,, \\
\partial_i Q^i_{(\phi)} &= -\Gamma_\phi\rho_\phi\theta_\phi \\
\partial_i Q^i_{(r)} &= \Gamma_\phi\rho_\phi\theta_\phi + \frac{\langle\sigma v\rangle}{M}\left[\rho_m^2\theta_m - (\rho_m^{\rm eq})^2\left(\frac{M}{2\pi T}\right)^{1/2}\theta_r\right] - \frac{4}{3}\frac{\sigma_e}{M}\rho_m\rho_r\left(\theta_r - \theta_m\right) \,, \\
\partial_i Q^i_{(m)} &= -\frac{\langle\sigma v\rangle}{M}\left[\rho_m^2\theta_m - (\rho_m^{\rm eq})^2\left(\frac{M}{2\pi T}\right)^{1/2}\theta_r\right] + \frac{4}{3}\frac{\sigma_e}{M}\rho_m\rho_r\left(\theta_r - \theta_m\right) \,,
\end{aligned}$$

(IV) The modes that enter the horizon during SD



The growth and suppression of the density perturbation.



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.

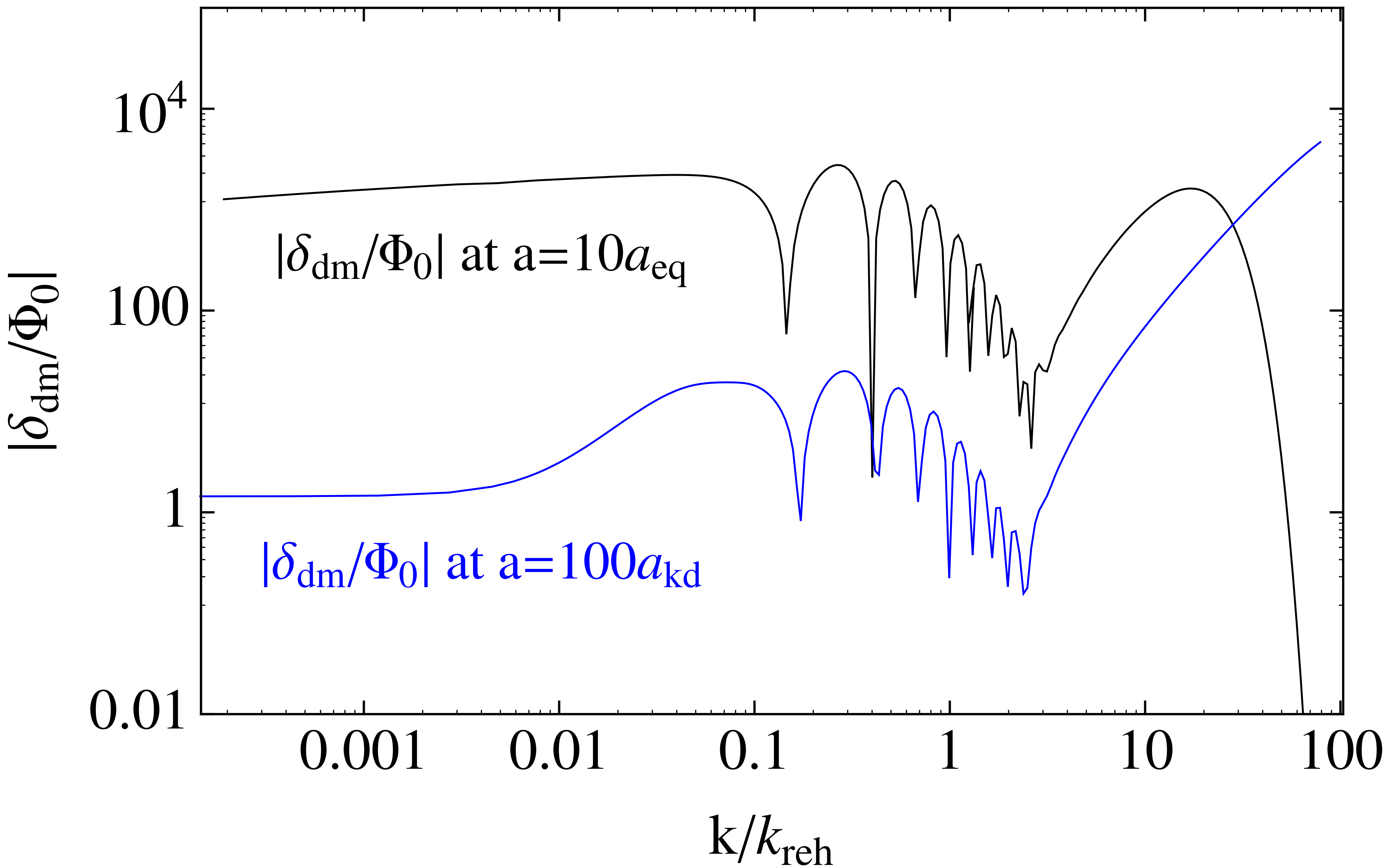
$$\lambda_f = \int_{t_i}^{t} \frac{v(t')}{R(t')} dt'.$$

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 $\quad c_s^2(T_{\rm kd}) \simeq \dfrac{T_{\rm kd}}{m}$

Density perturbation later times



Discussion

1. Isocurvature perturbation of DM is not suppressed. and can be probed in the small scale dark matter clumps.

2. The isocurvature perturbation of WIMP can be generated during the early matter domination.

3. The WIMP DM inside the small scale objects can be observed in the gamma-ray, cosmic rays or neutrinos and in the direct detection rate.

3. The power spectrum of WIMP shows non-trivial shape of structure formation at small scales. It implies one way to see the early Universe before BBN.