Small Scale Isocurvature Perturbation of WIMP Dark Matter

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Based on the work with Jinn-Ouk Gong and Chang sub Shin
PRL 115, 211301 (2015), arXiv:1507-03871

The 11th International Workshop

Dark Side of the Universe 2015

14th-18th December, Kyoto, Japan

1. If you are considering

WIMP dark matter

2. If you are considering low reheating temperature

$$\boxed{T_{\rm reh} < T_{\rm fr}}$$

3. You can see the signatures from

Isocurvature of WIMP

Weakly Interacting Massive Particles

1. WIMPs are weakly interacting.

In the early Universe, they were in the thermal equilibrium with background relativistic plasma, by changing energy, momentum and number.

2. WIMPs decouple

Due to the expansion of the Universe, the interaction rate becomes insufficient for the scatterings and finally the interaction freeze-out.

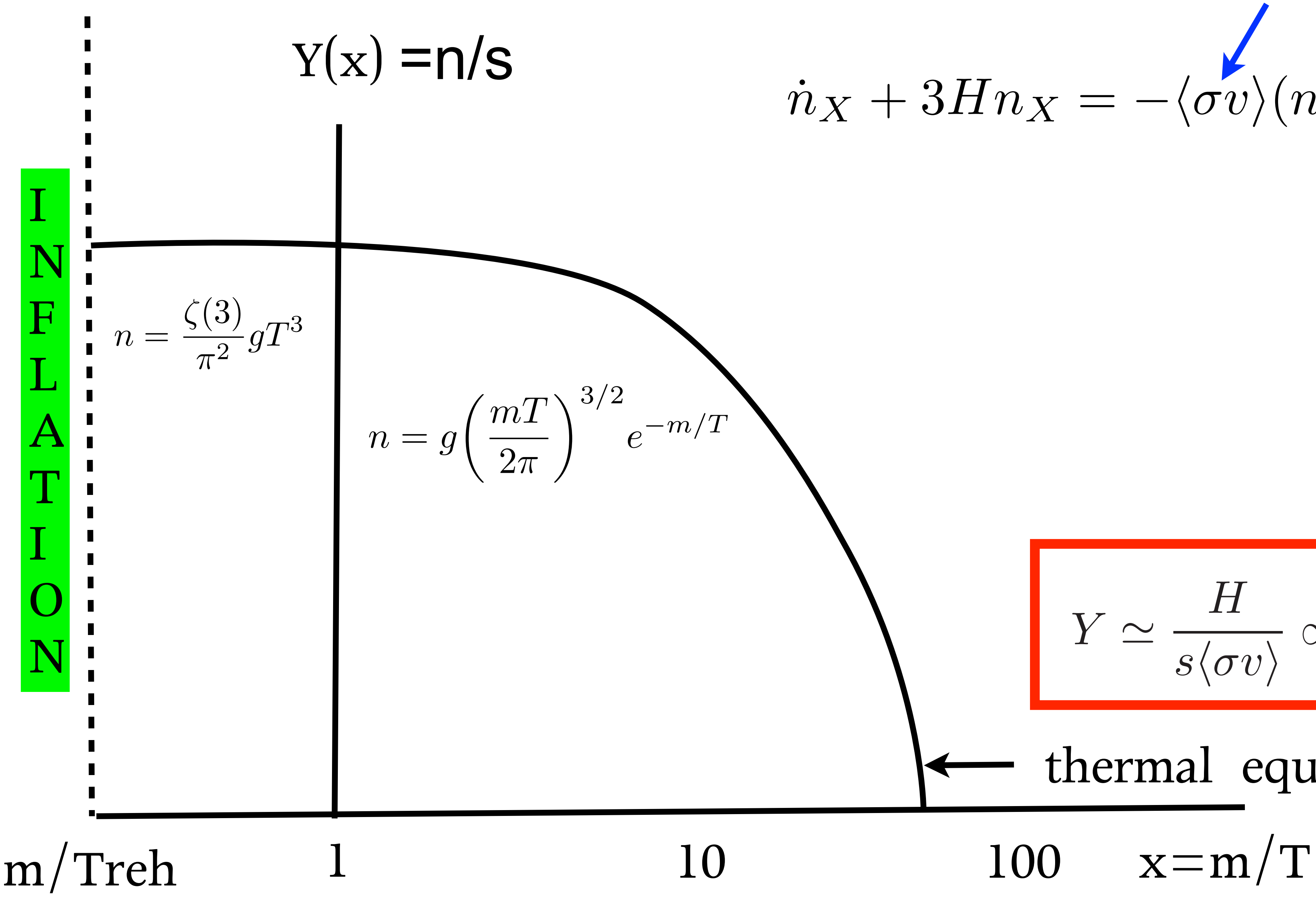
WIMP : Weakly Interacting Massive Particle

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

$$\boxed{\text{Freeze-out temperature < Mass}}$$

annihilation cross section

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



thermal equilibrium

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

WIMP : Weakly Interacting Massive Particle

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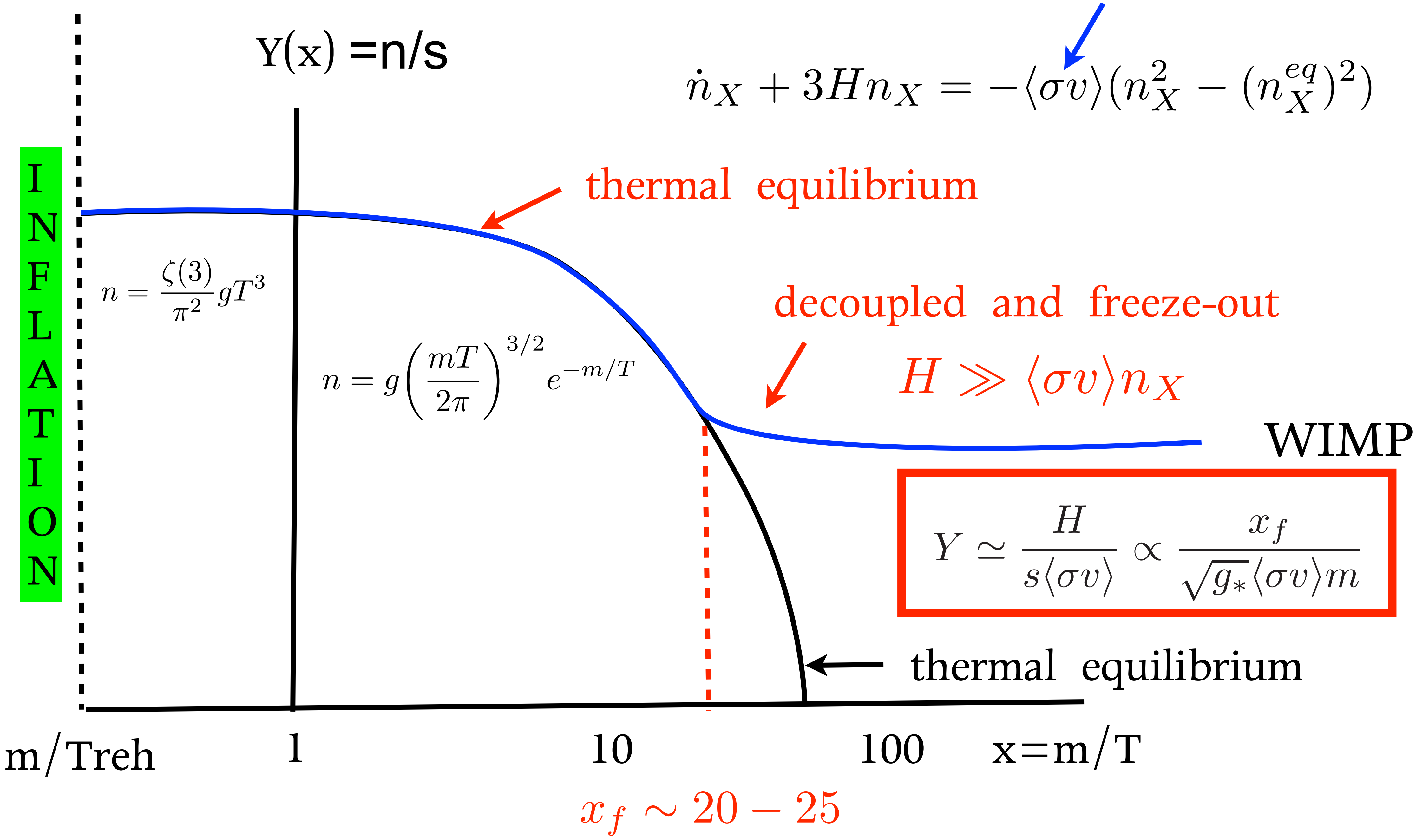
Freeze-out temperature < Mass



annihilation cross section

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

thermal equilibrium

decoupled and freeze-out

$$H \gg \langle\sigma v\rangle n_X$$

WIMP

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

thermal equilibrium

$$n = \frac{\zeta(3)}{\pi^2} g T^3$$

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$x_f \sim 20 - 25$

- The scattering cross section and chemical/kinetic decoupling

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

→ Chemical equilibrium → Relic density

Elastic scatterings : change momentum (number conserved)

→ Kinetic equilibrium → Structure formation

- The density perturbation can grow after kinetic decoupling

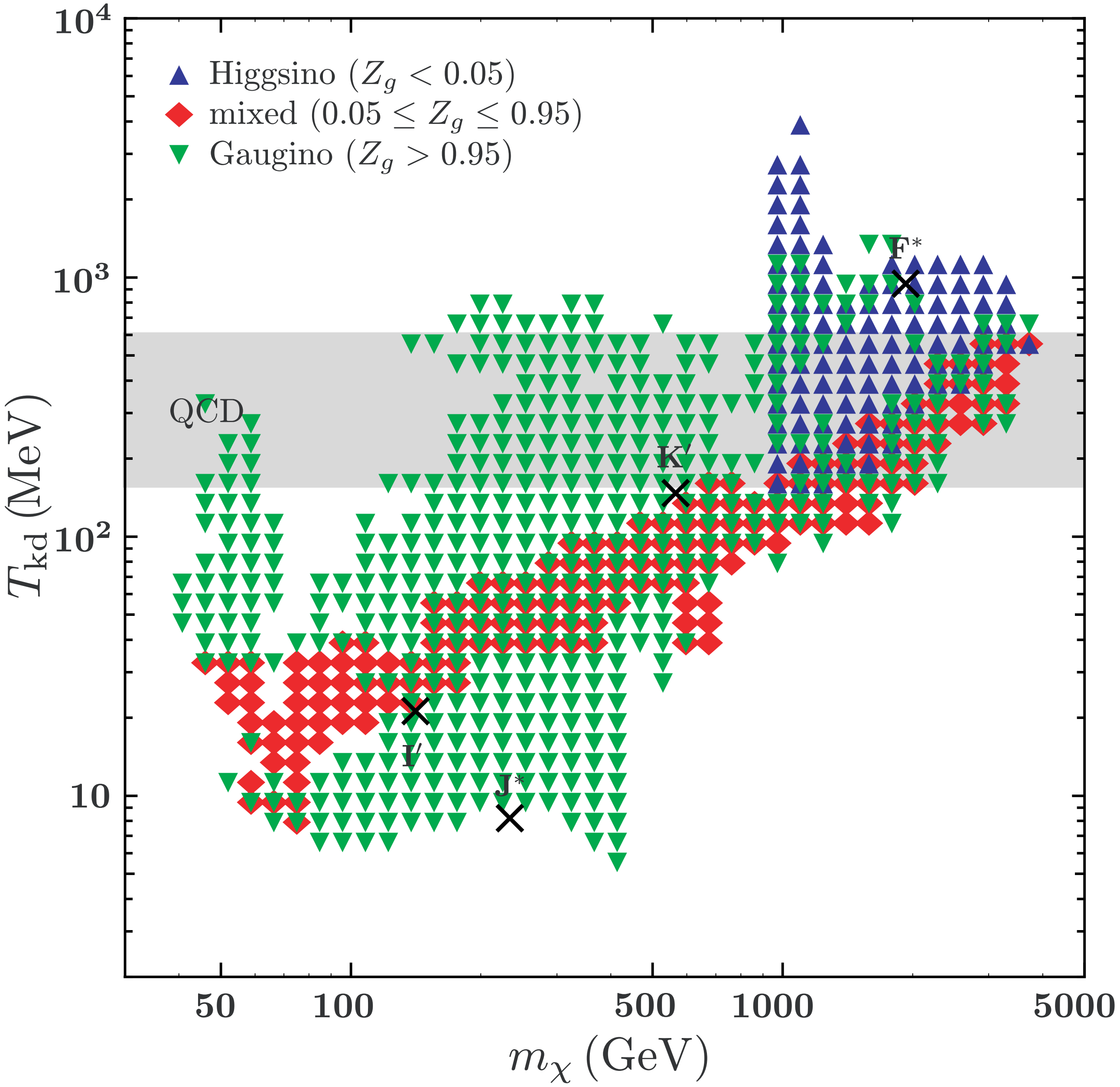
- Smaller scales are damped during kinetic decoupling

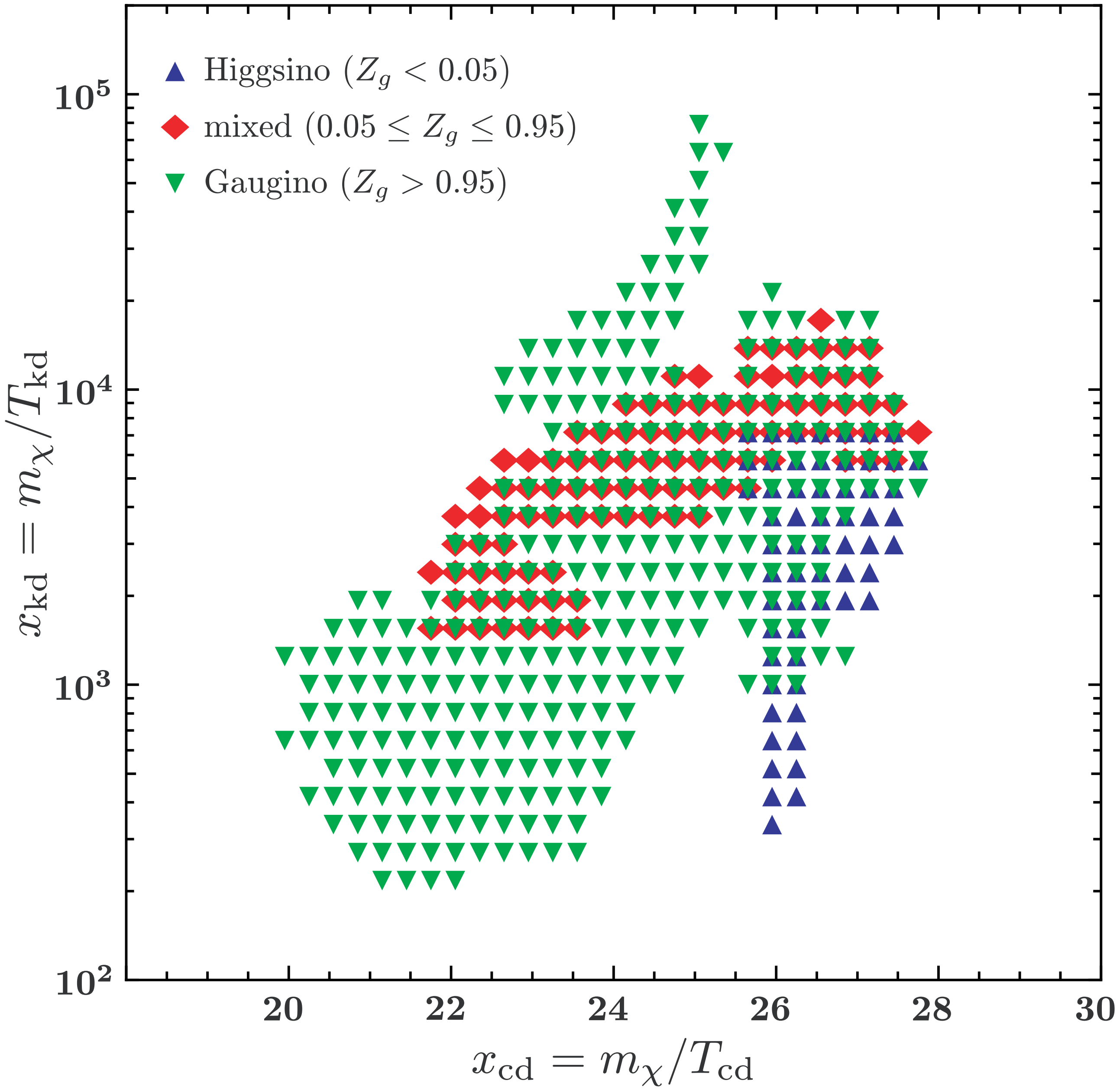
- Kinetic decoupling or free-streaming scale determines the minimum scale for the structure formation

Kinetic Decoupling Temperature of Neutralinos

[Bringmann, 2009]

Z_g : gaugino fraction





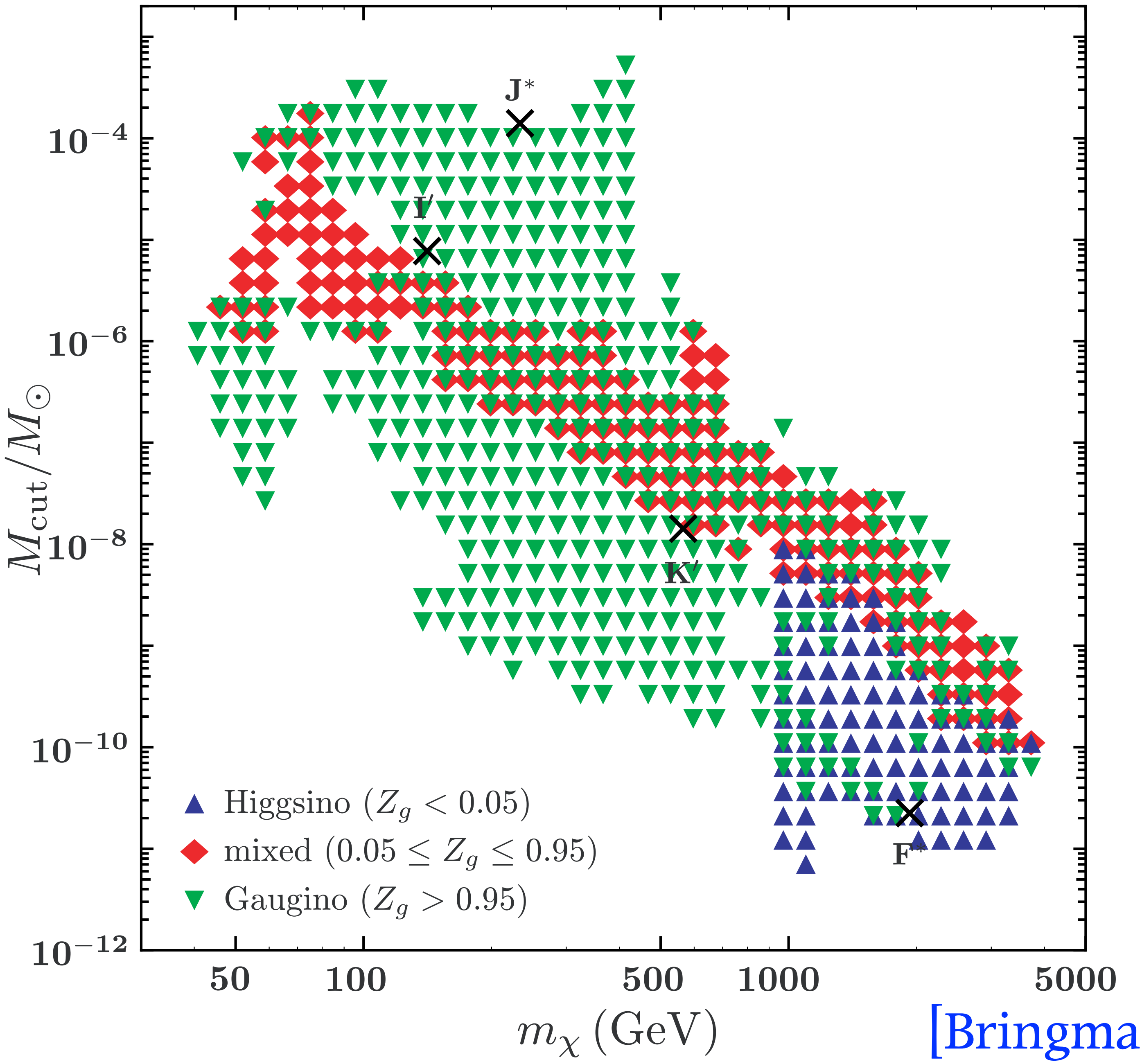
Kinetic decoupling takes place much later than chemical decoupling by a factor of 10 - 1000.

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

$T_{\rm kd} = 10\,\mathrm{MeV}$

Earth mass ~

$T_{\rm kd} = 1\,\mathrm{GeV}$



[Bringmann, 2009]

Primordial Perturbations

$$\delta(t,\mathbf{x}) \equiv \frac{\delta\rho}{\rho}(t,\mathbf{x}) \simeq \sum_k \delta_k(t)$$

For multiple fluids, for dark matter and radiation for example:

Adiabatic perturbation : contribute to the curvature perturbation

$$\zeta \equiv -H\frac{\delta\rho}{\dot\rho} = \frac{\delta\rho_m + \delta\rho}{3\rho_m + 4\rho_r} \qquad \text{(flat gauge)}$$

Isocurvature perturbation : does not contribute to the curvature perturbation but contribute to change it.

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

WIMP is Adiabatic

WIMPs are by definition adiabatic, since they are created from the background plasma (radiation) at all scales.

$$\delta_m = \frac{3}{4}\delta_r \quad \text{and so} \qquad S = 0$$

This is consistent with observation.

The constraints on the DM isocurvature modes from Planck (only for large scales).

$$\beta_{\rm iso} = \frac{P_S}{P_\zeta + P_S} \qquad\qquad \beta_{\rm iso} \lesssim 0.05$$

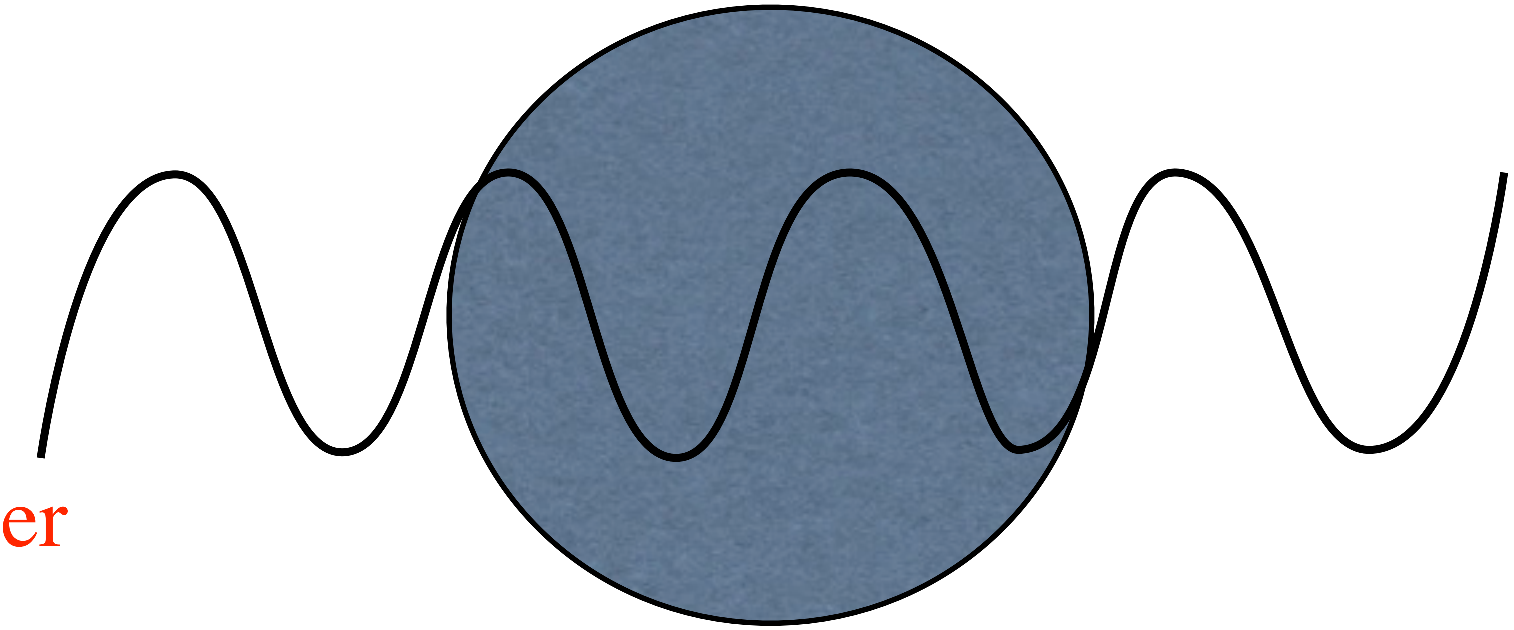
[Planck, 2015]

Perturbation of DM: Before Kinetic Decoupling

For sub-horizon mode, the perturbation of DM density δ_m :

Before kinetic decoupling: DMs are tightly coupled to the radiation.

Its perturbation oscillates in the same way as that of photons.

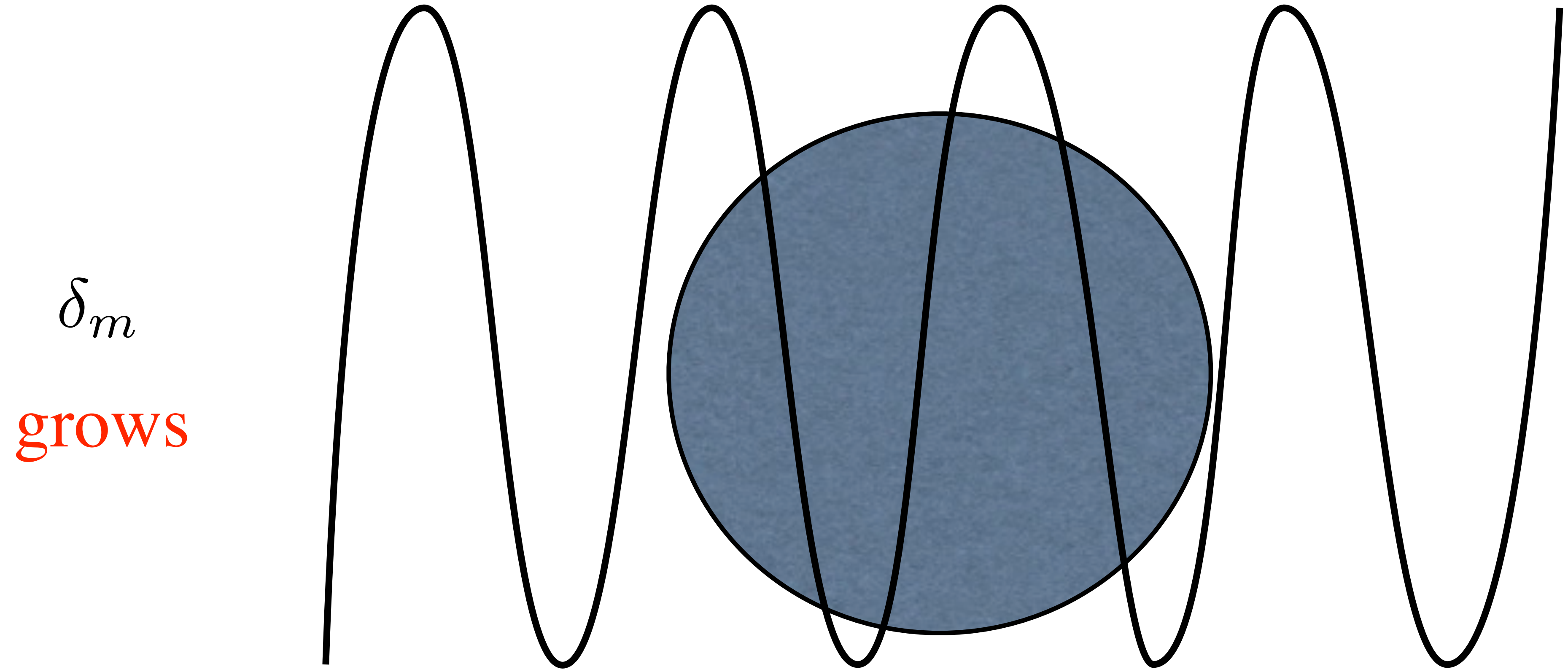


$\delta_r \quad \delta_m$

oscillates together

Perturbation of DM: After Kinetic Decoupling

After WIMP kinetic decoupling, the perturbation of WIMP can grow.



The DM density perturbation grows logarithmically during Radiation-Domination, and linearly to scale factor during Matter-Dominatoin.

Collisional Damping

However during kinetic decoupling, the density perturbation of WIMP is suppressed.

[Boehm, Fayet, Shaefer, 2000]
[Boehm, Riazuelo, Hansen, Schaefer, 2002]
[Boehm, Schaefer, 2004]

[Hofmann, Schwarz, Stoecker, 2001]
[Berezinsky, Dokuchaev, Eroshenko, 2003]
[Green, Hofmann, Schwarz, 2003, 2005]

When the radiation and DM are tightly coupled, they move together and behaves as a single fluid. $\theta_r = \theta_m$ $\theta \equiv \nabla \cdot \vec{v}$

When the coupling becomes less effective, then the difference of the velocities behaves as a friction, so that the density perturbation of DM becomes suppressed.

$$\dot{\delta}_m + \frac{\theta_m}{a} - 3\dot{\Phi} \approx 0\,,$$

$$\dot{\theta}_m + H\theta_m - \frac{k^2}{a}\Phi \approx c_e \frac{\langle \sigma_e v \rangle \rho_r}{M_{\rm DM}} (\theta_r - \theta_m)$$

Isocurvature perturbation

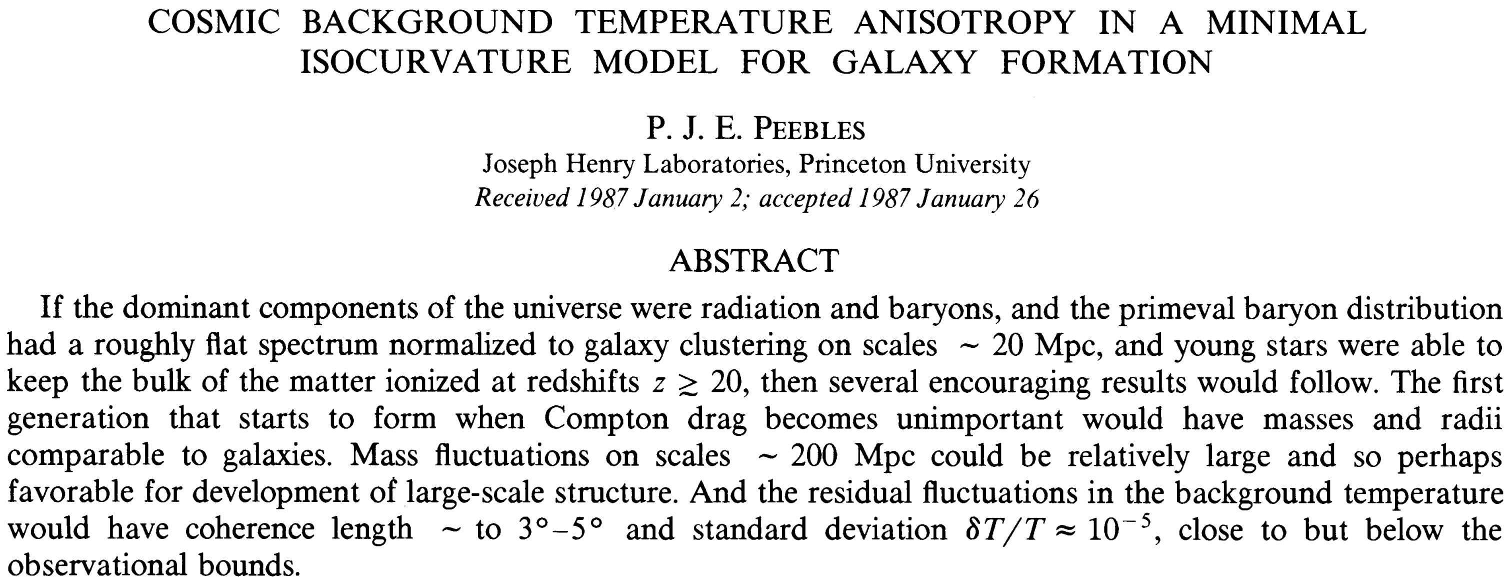
Isocurvature perturbations between DM and radiation

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

Isocurvature perturbation is not damped during kinetic decoupling.

Baryon isocurvature perturbation for structure formation.

[Peebles, ApJ 1987]



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

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Received 1987 January 2; accepted 1987 January 26

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

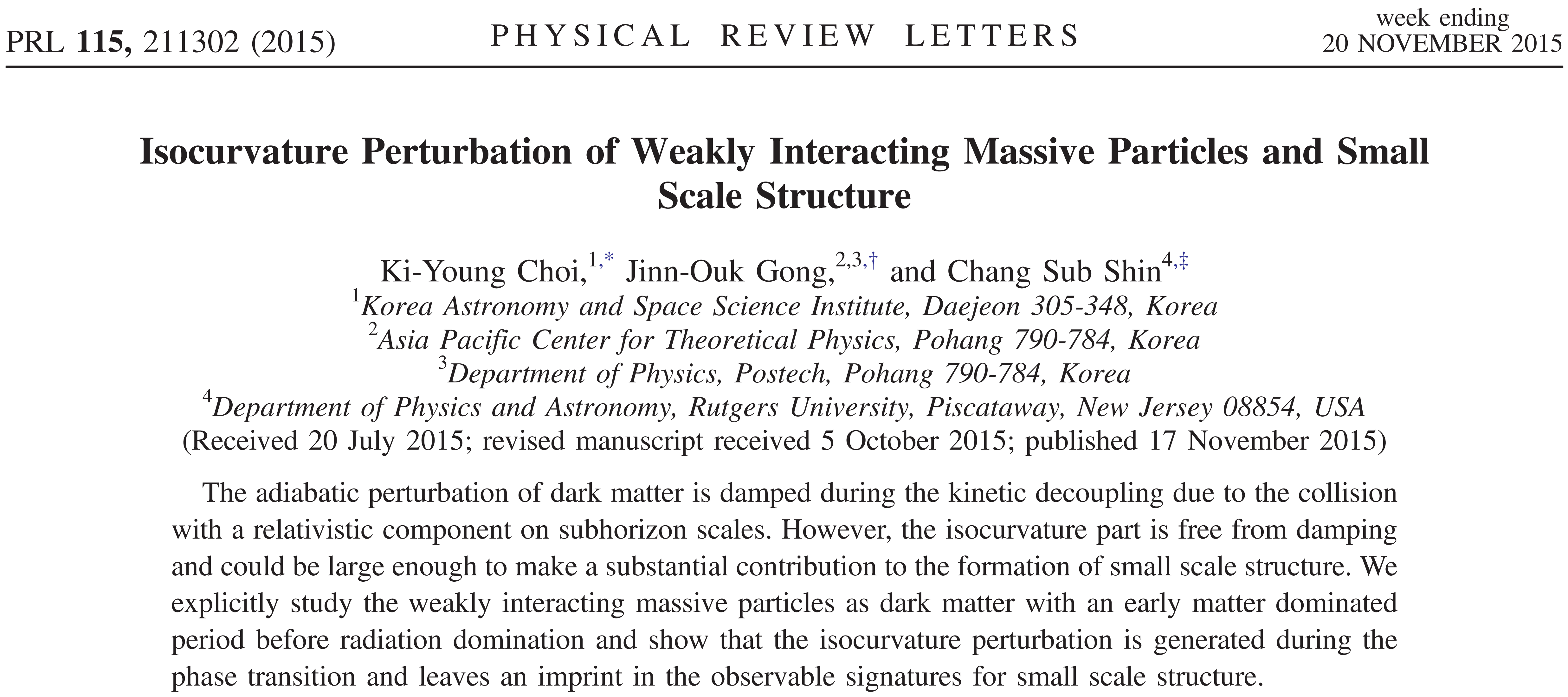
Is it possible to have a large isocurvature perturbation at small scales with adiabatic still at large scales?

- Not possible in the standard WIMP.

- However there is a one case, when

$$T_{\rm reh} < T_{\rm fr}$$

WIMP Isocurvature Perturbation



PRL **115,** 211302 (2015) PHYSICAL REVIEW LETTERS week ending 20 NOVEMBER 2015

Isocurvature Perturbation of Weakly Interacting Massive Particles and Small Scale Structure

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(Received 20 July 2015; revised manuscript received 5 October 2015; published 17 November 2015)

The adiabatic perturbation of dark matter is damped during the kinetic decoupling due to the collision with a relativistic component on subhorizon 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 an imprint in the observable signatures for small scale structure.

Published in Physical Review Letters (2015)

Low Reheating Temperature

The Universe is dominated by heavy particles (early matter domination) and reheated (radiation domination) by the decay of them. It happens for:

- Inflaton oscillation
- Thermal inflation
- Curvaton domination
- Heavy axino and saxion
- Moduli decay
- .....

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

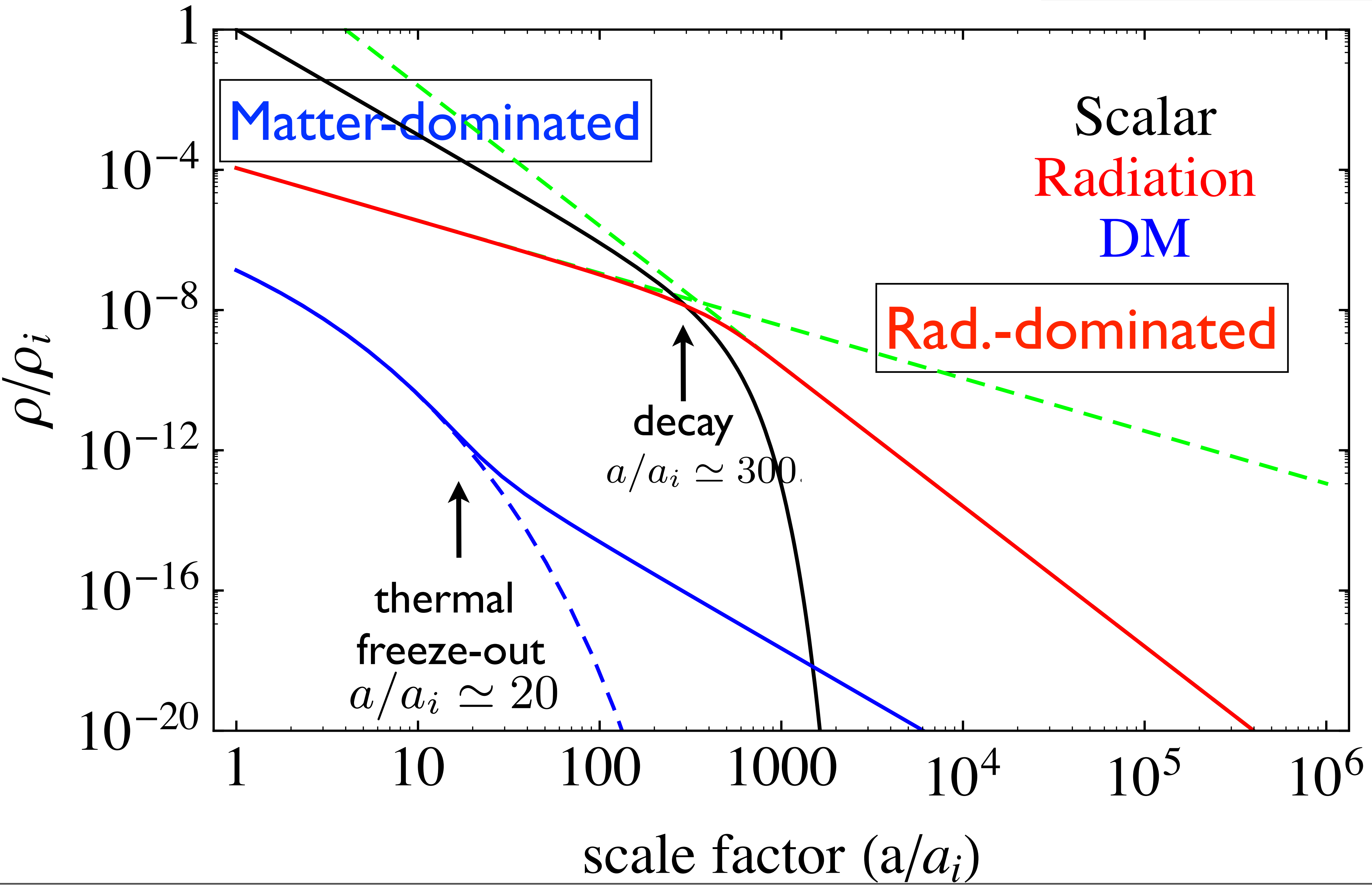
Early Matter Domination

: early matter domination by a scalar or fermion

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

10GeV 100 MeV 1 MeV

Background evolution



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

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

Creation of Isocurvature Perturbation

After chemical decoupling before reheating still scalar-dominated:

Dark matter and radiation are still kinetically coupled: $\theta_m \approx \theta_r.$

$$\dot{\delta}_m \approx -\frac{\theta_r}{a},$$

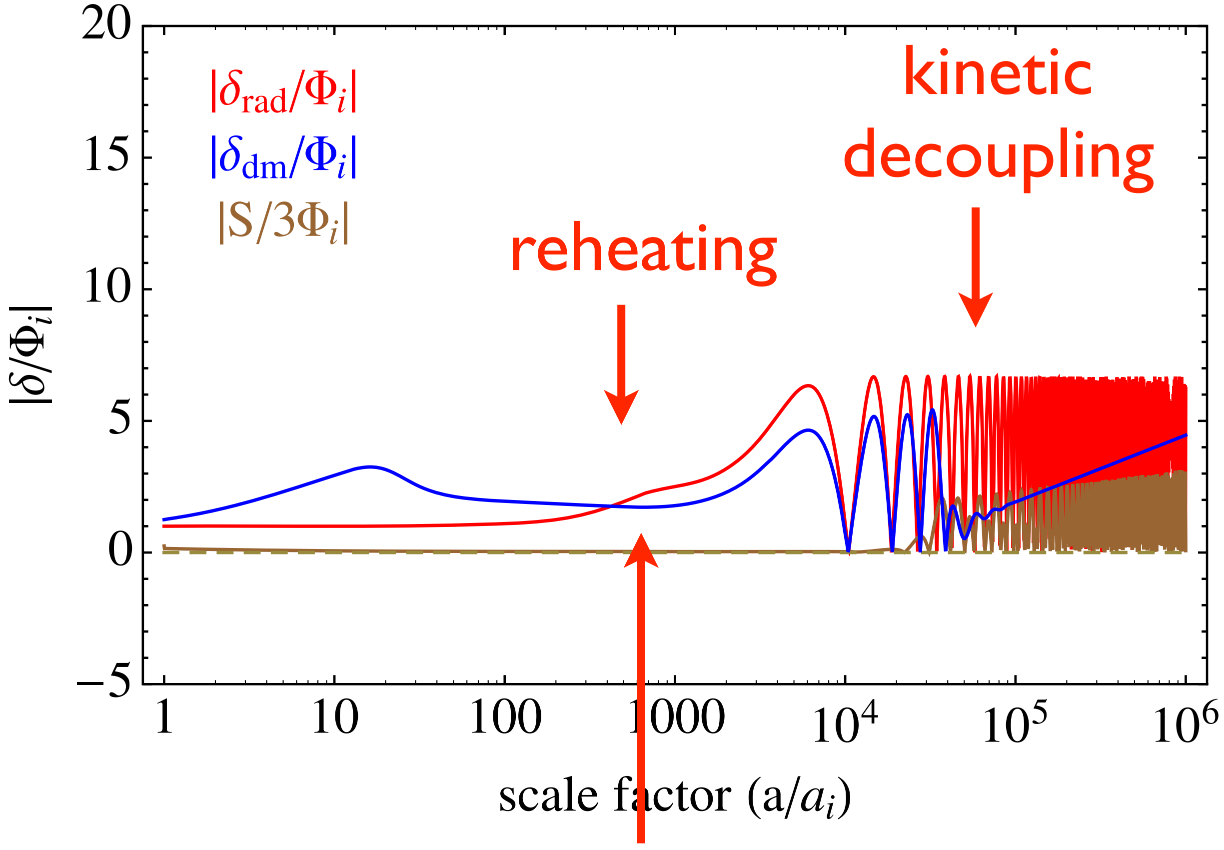
$$\dot{\delta}_r \approx -\frac{4}{3}\frac{\theta_r}{a} + \frac{\Gamma_\phi \rho_\phi}{\rho_r}(\delta_\phi - \delta_r),$$

Radiation is still produced from decay of the dominating scalar, however dark matter is not produced any more.

The difference in the number density creates the isocurvature perturbation between dark matter and radiation.

$$S(t_{\rm reh}) \approx -\frac{3}{4}\int_{t_i}^{t_{\rm reh}} dt \frac{\Gamma_\phi \rho_\phi \delta_\phi}{\rho_r} \approx \frac{5}{4}\Phi_i \left(\frac{k}{k_{\rm reh}}\right)^2.$$

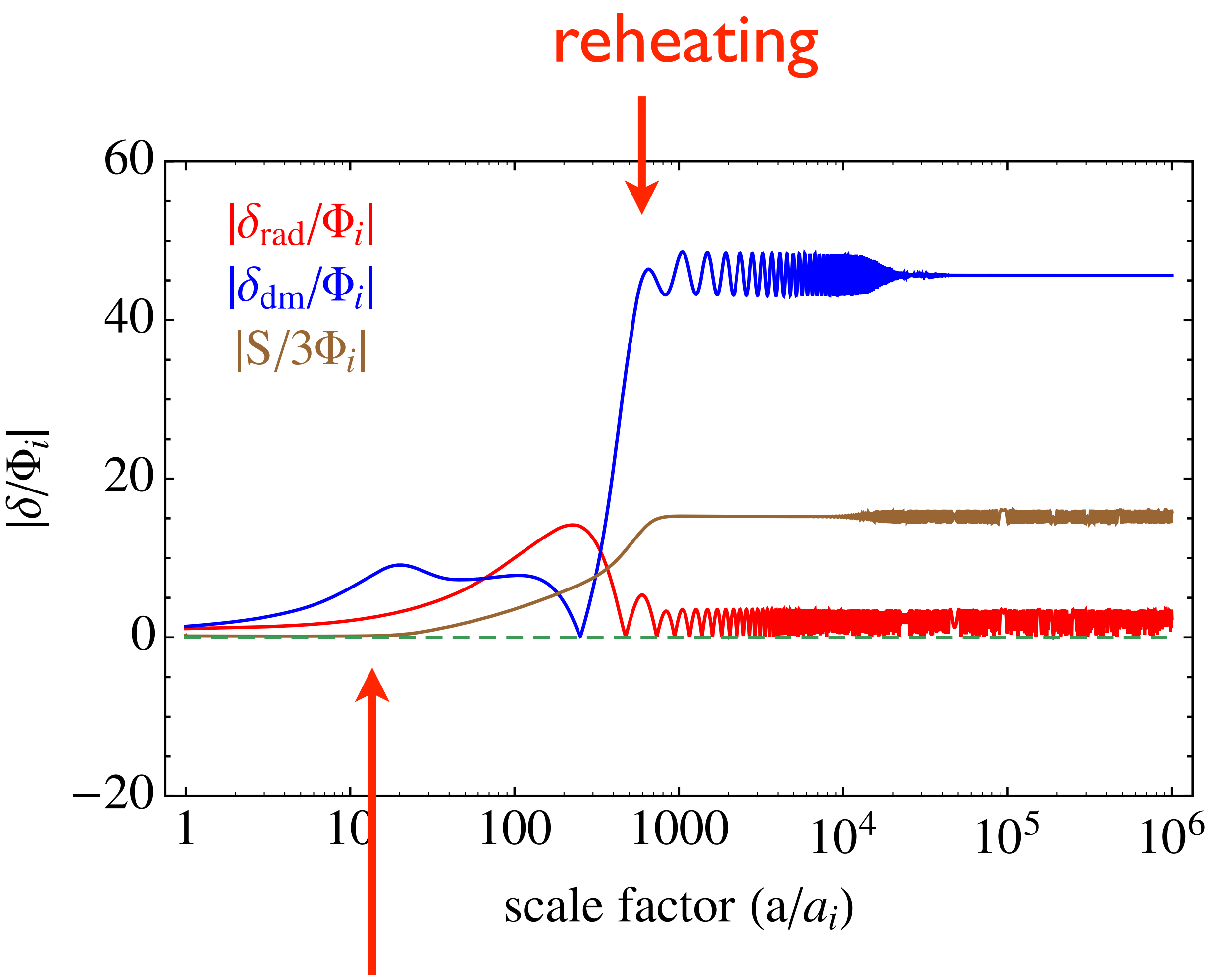
Evolution of Perturbation



kinetic decoupling

reheating

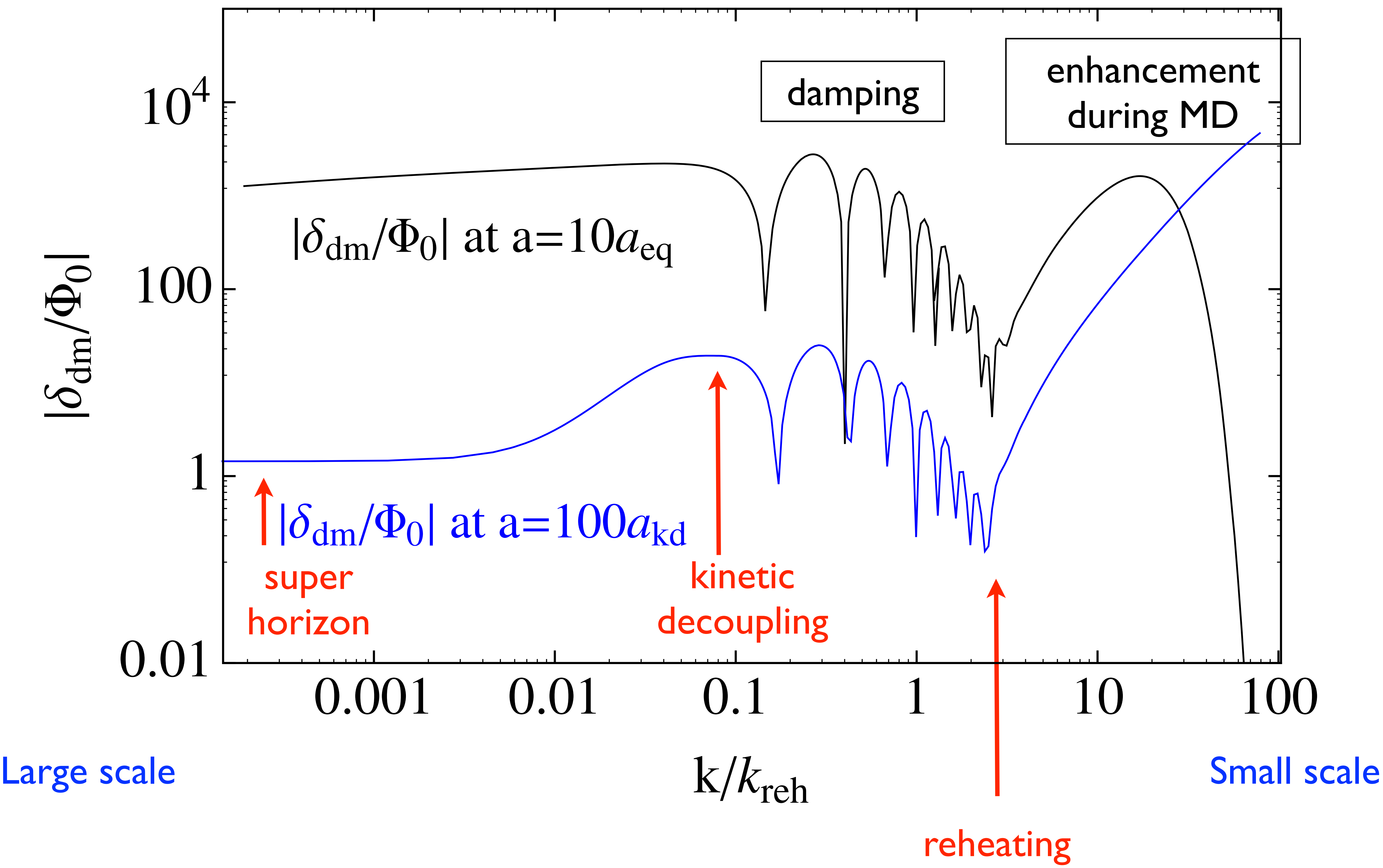
Horizon entry after reheating



reheating

Horizon entry during early MD before reheating

Scale Dependence of Density Perturbation



Discussion

1. Isocurvature perturbation of WIMP can be generated during the early matter domination and it is not damped during the kinetic decoupling.

2. The large isocurvature perturbation of WIMP at small scales form minihalos. The WIMP DM annihilation the minihalos can produce visible signals such as the gamma-ray, cosmic rays or neutrinos.

3. The non-trivial shape of the power spectrum of WIMP implies another way to see the early Universe before BBN.