Dark Matter and Structure Formation

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Based on the work with Jinn-Ouk Gong and Chang sub Shin
PRL 115, 211301 (2015) [arXiv:1507.03871]
and extended work by Choi, Gong, Shin and Sohyun Park.

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Cold Dark Matter

1. Very non-relativistic

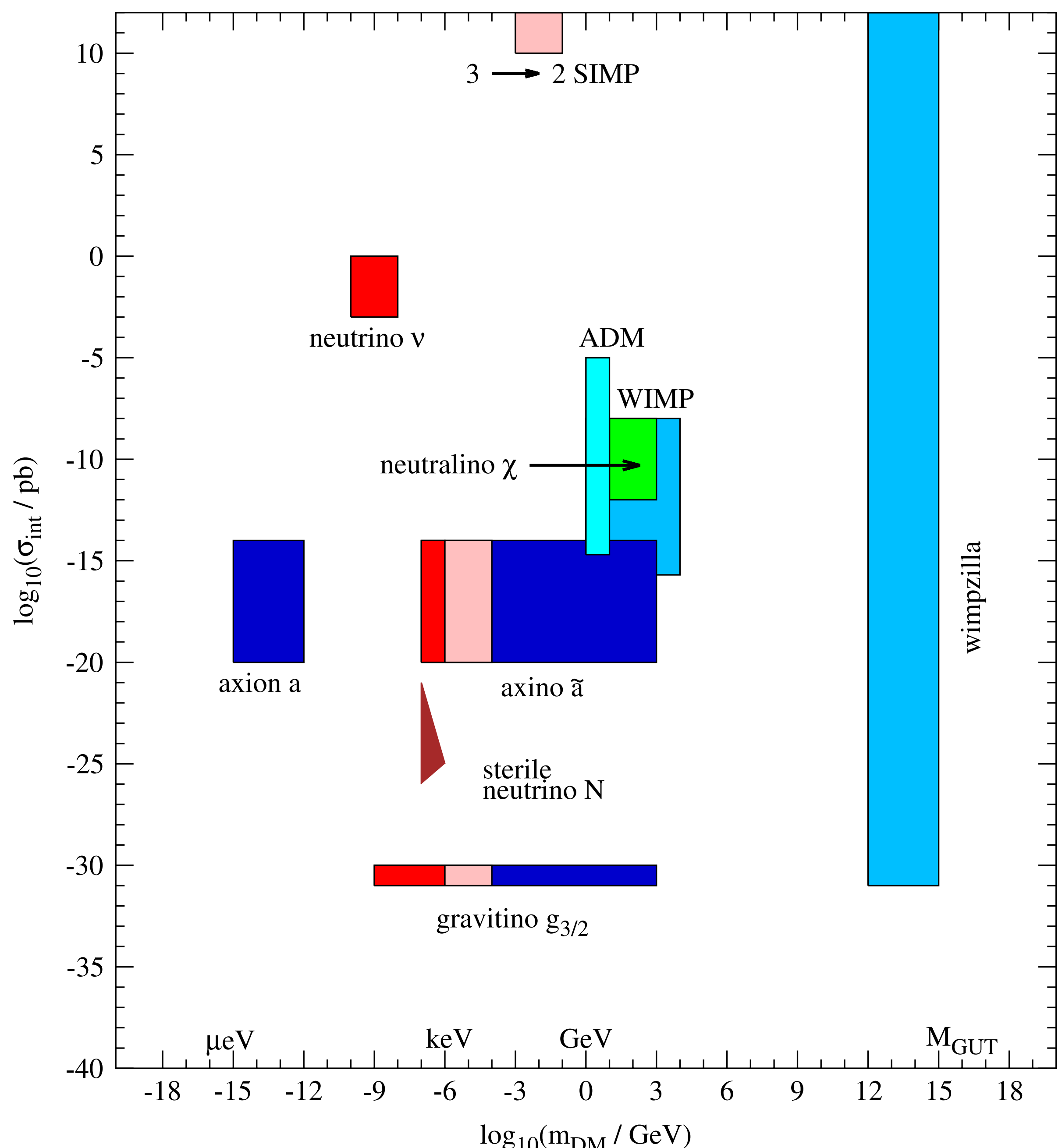
It must be cold to make proper formation of structures.
The warmness is constrained by the small scale structures such as Lyman alpha observation.
The hot matter like neutrinos cannot be the main DM.

2. Very weak interacting: gravitationally

All the observational evidences of DM are gravitational.
However the interactions of DM can be larger up to weak interaction.
The strength of interaction is constrained by the bullet cluster, direct dark matter detection, and particle colliders.

Candidates of Dark Matter

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



Interaction

10^{40}

Mass 10^{40}

Weakly Interacting Massive Particles

1. WIMPs are massive.

They are non-relativistic and cold.

2. WIMPs are weakly interacting.

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

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

- The scattering cross section and chemical/kinetic decoupling

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

→ Chemical equilibrium → Relic density

Elastic scatterings : change momentum (number conserved)

→ Kinetic equilibrium → Structure formation

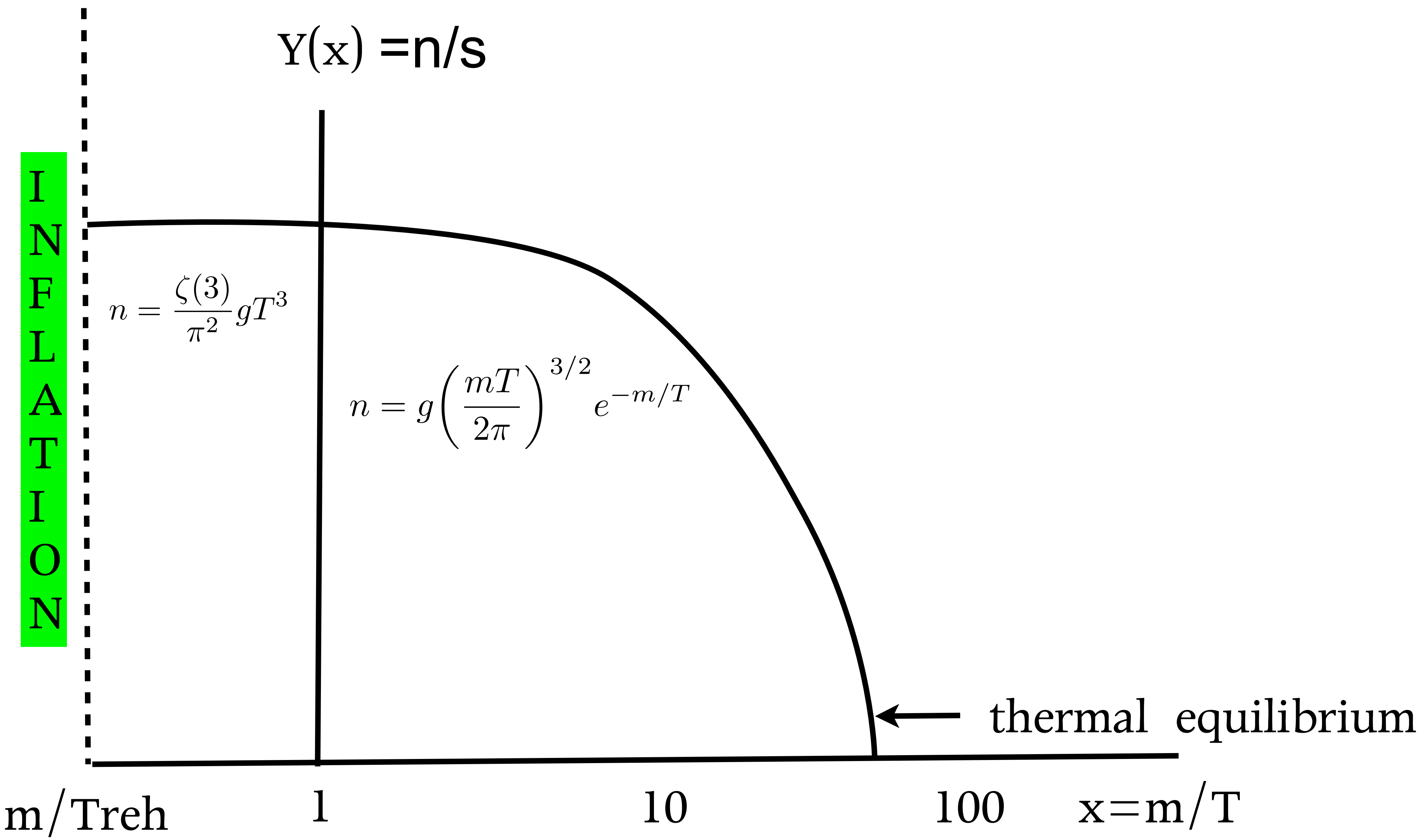
- The density perturbation can grow after kinetic decoupling

- Smaller scales are damped during kinetic decoupling

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

WIMP : Weakly Interacting Massive Particle

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



WIMP : Weakly Interacting Massive Particle

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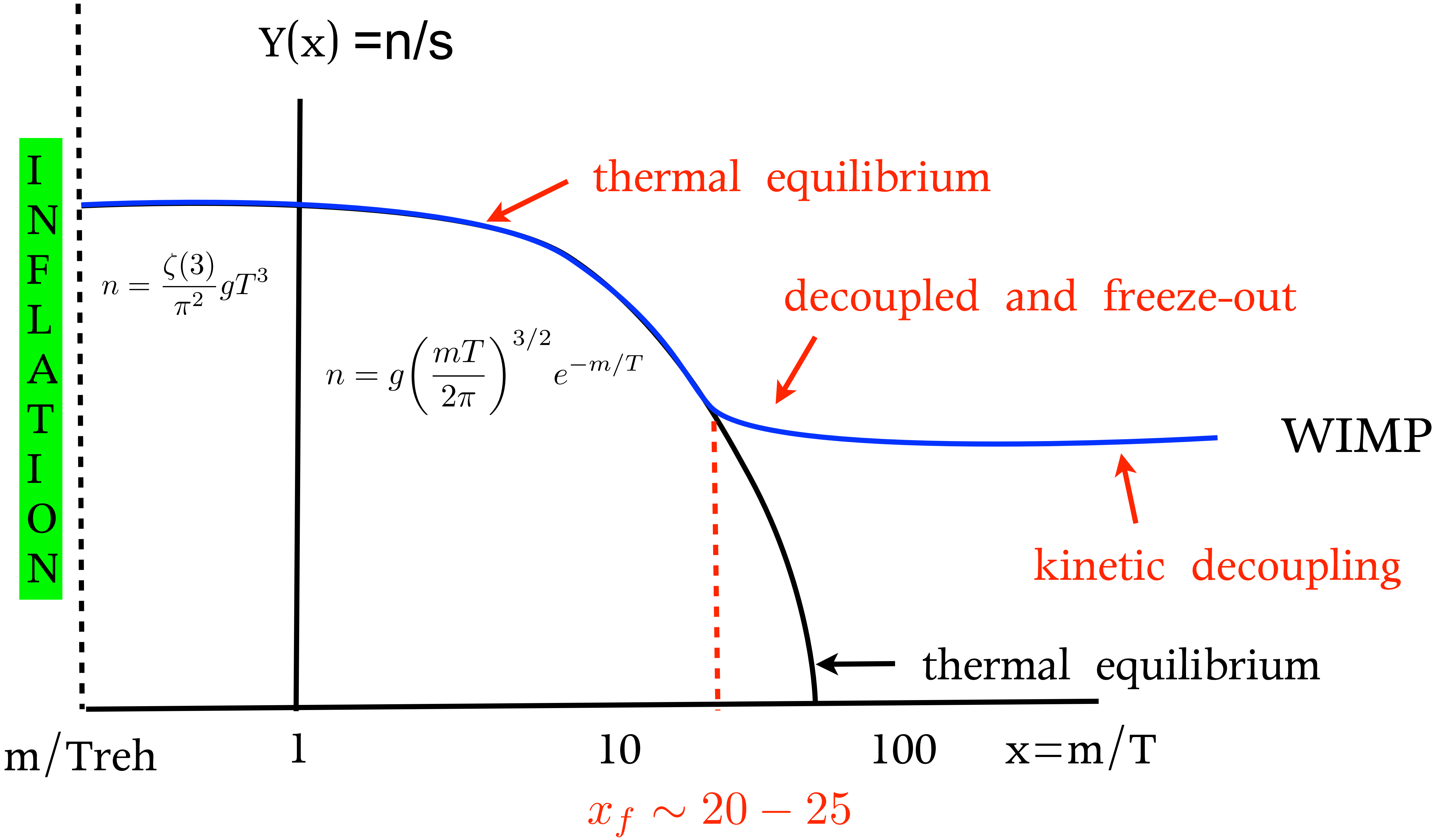
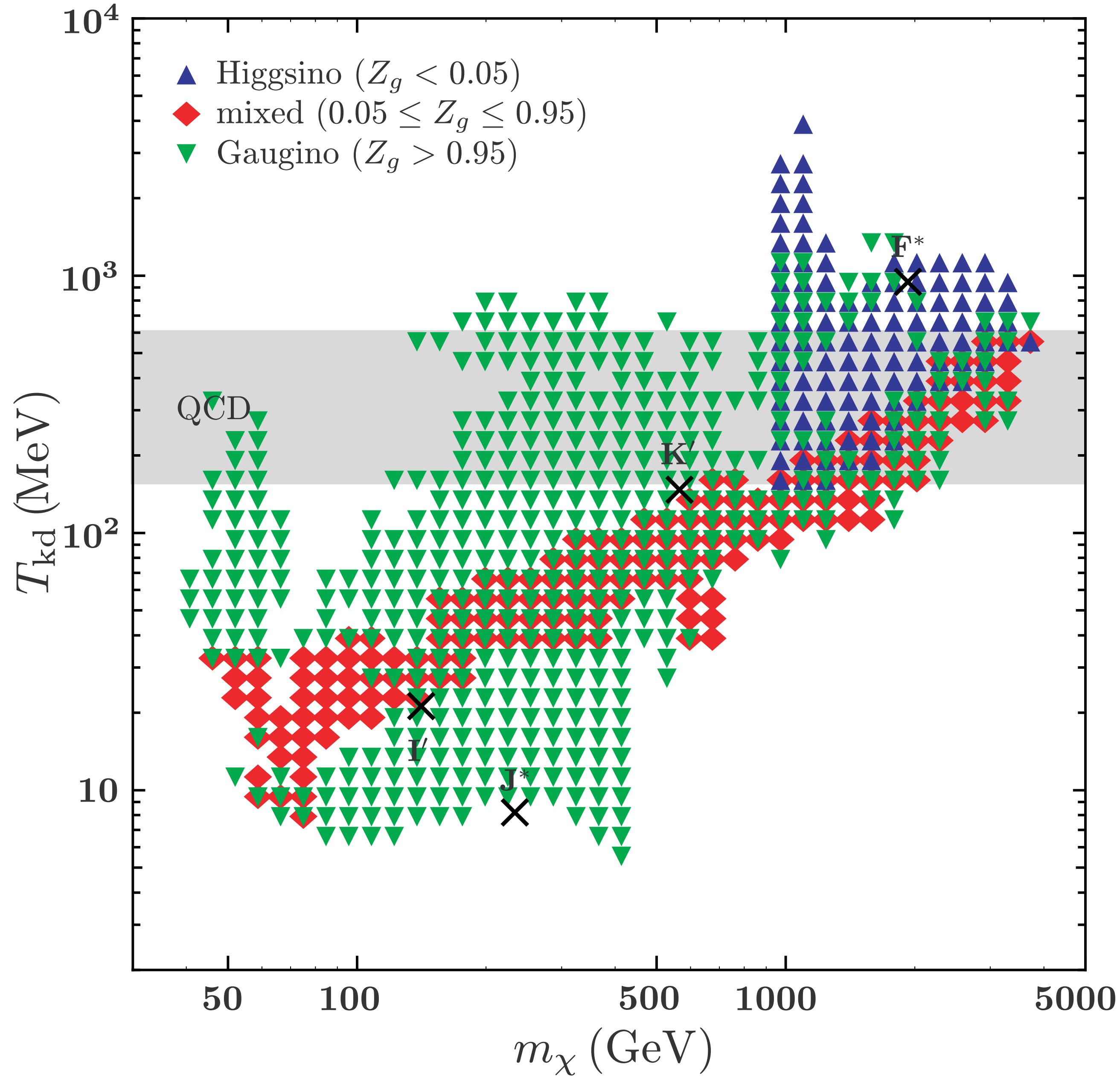


Kinetic Decoupling Temperature of Neutralinos

[Bringmann, 2009]

Z_g : gaugino fraction



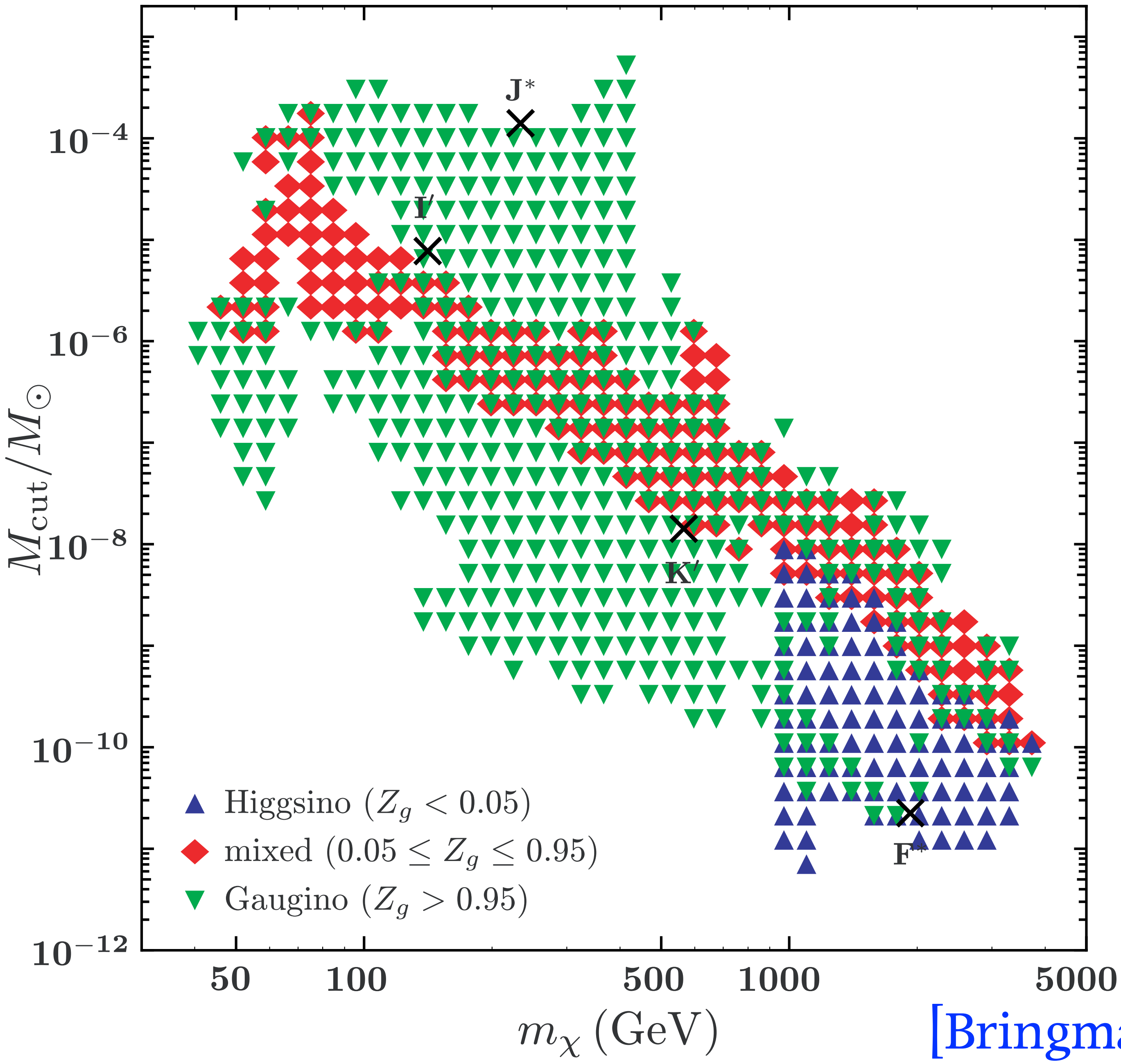
The chemical decoupling happens around m/20 = 1 - 100 GeV

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

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

Earth mass ~

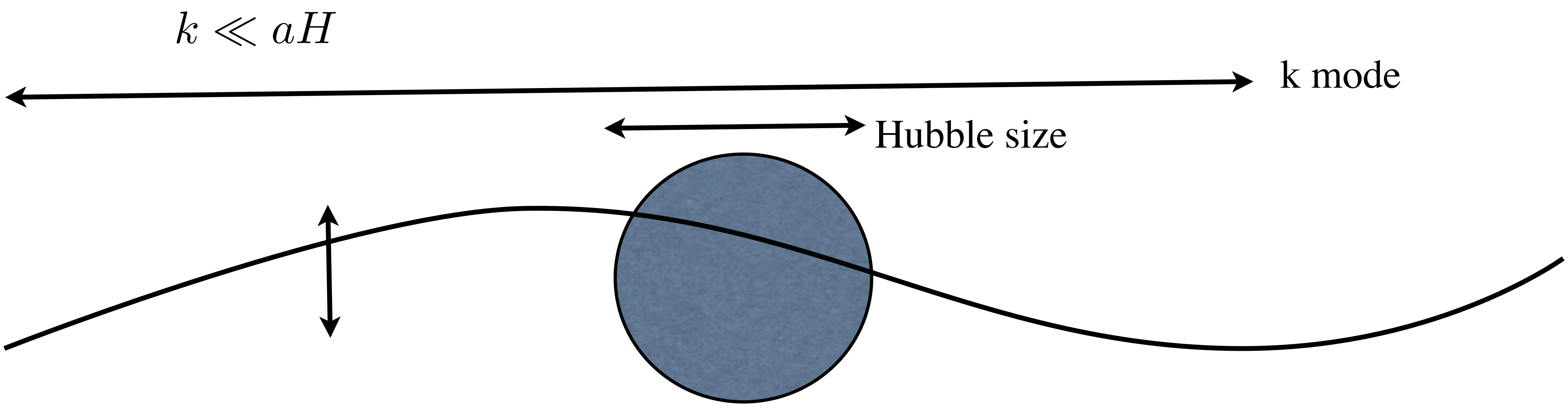
$T_{\rm kd} = 1\,{\rm GeV}$



[Bringmann, 2009]

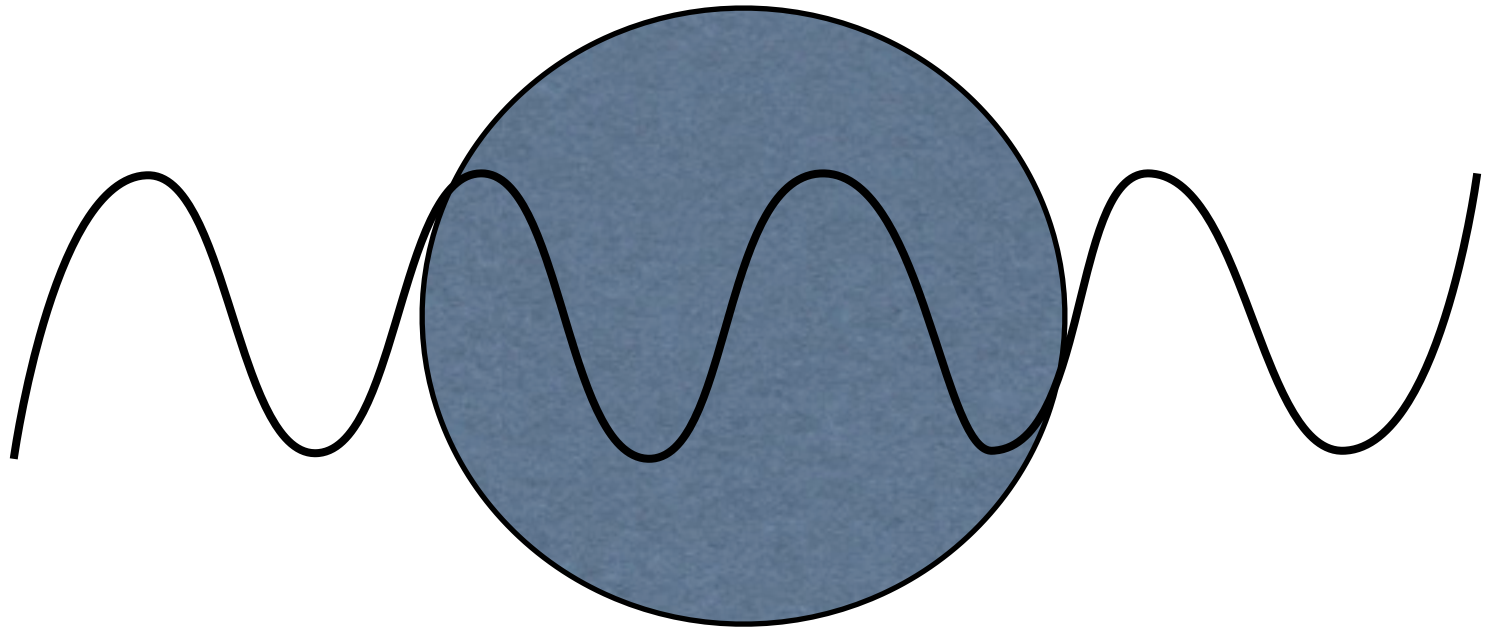
Evolution: Superhorizon Mode

For super-horizon mode, δ_m and δ_r constant.



Evolution: Subhorizon Mode of Radiation

For sub-horizon mode, δ_r oscillates between gravity and pressure, which is the origin of the CMB acoustic oscillation.



Perturbation of DM: Before Kinetic Decoupling

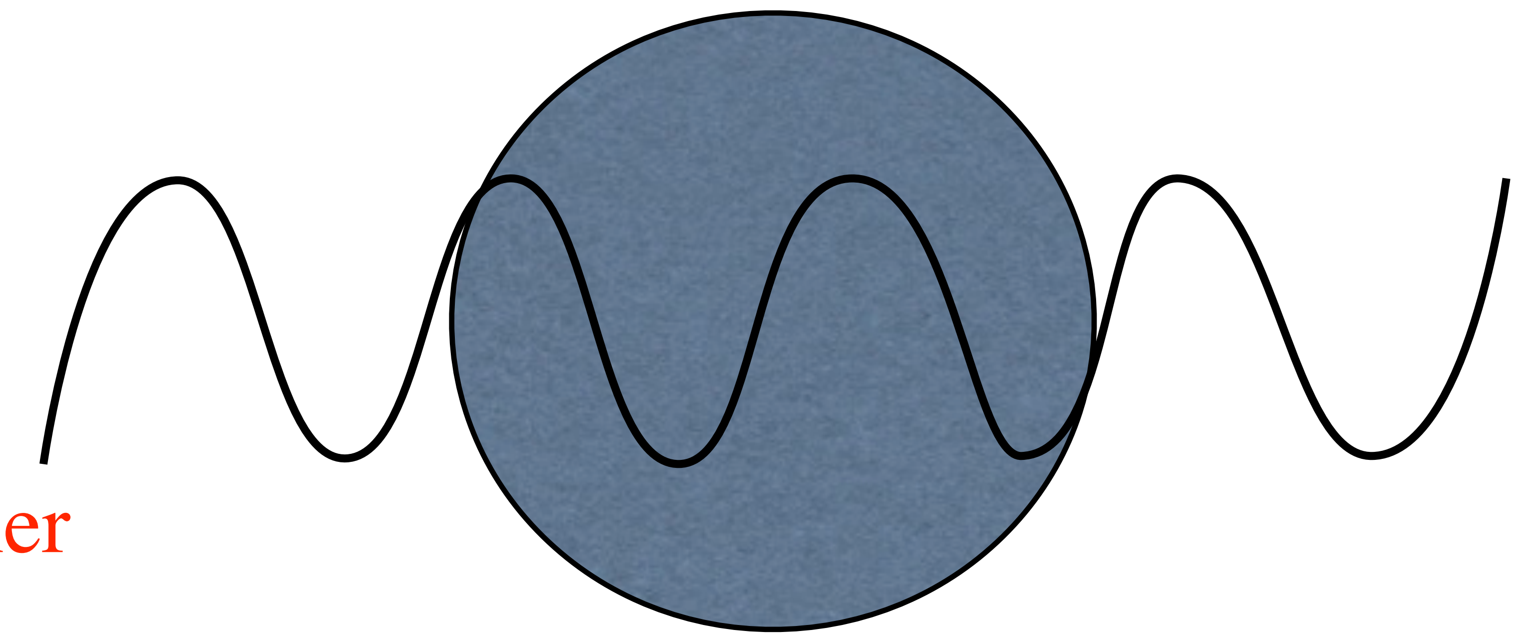
For sub-horizon mode, the perturbation of DM density δ_m :

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

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

δ_r δ_m

oscillates together

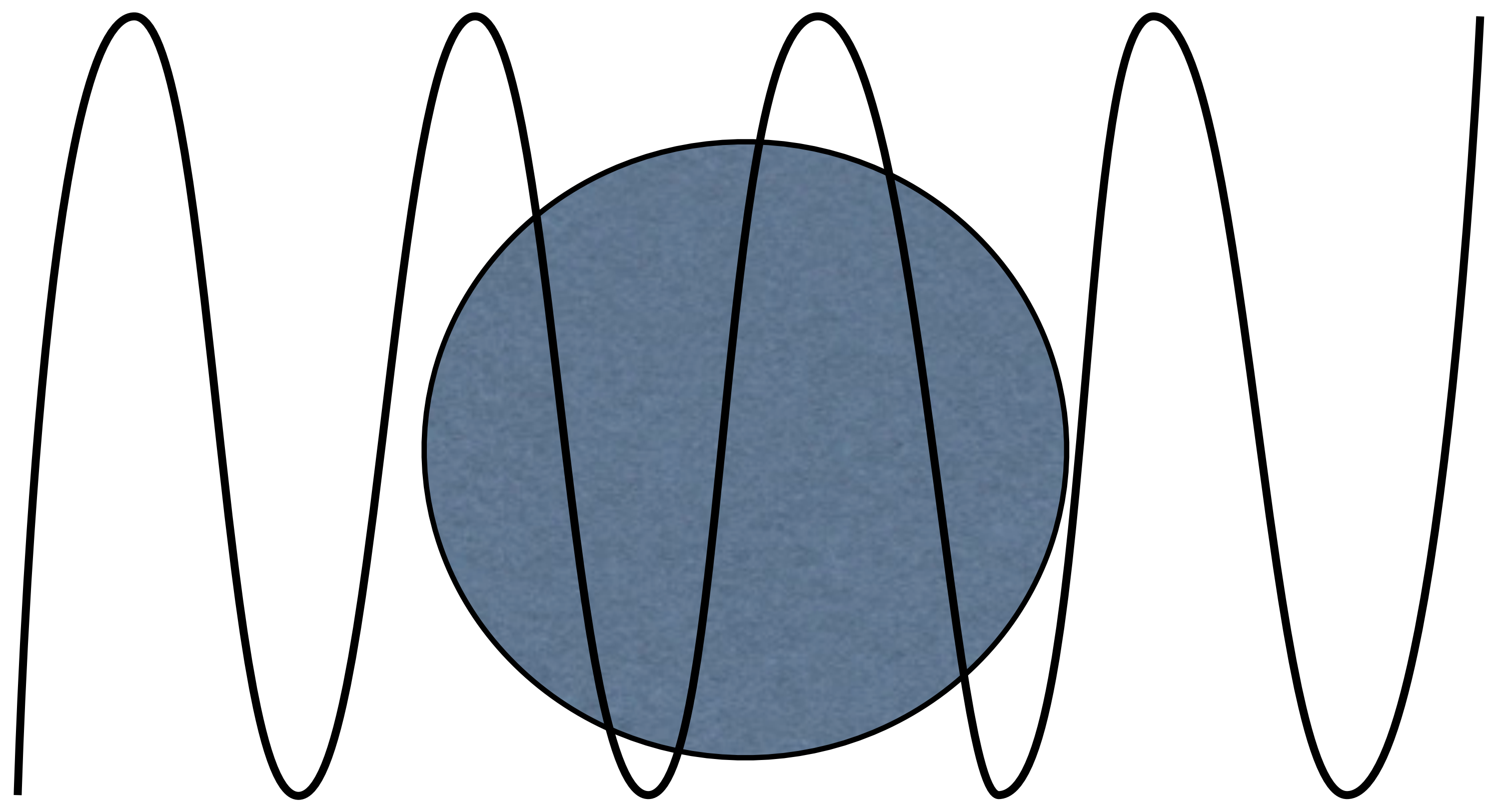


Perturbation of DM: After Kinetic Decoupling

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

δ_m

grows



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 exponentially 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. $\theta_r = \theta_m$ $\qquad \theta \equiv \nabla \cdot \vec{v}$

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.

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

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

Kinetic decoupling scale of WIMPs determines the minimum size in the structure formation

Isocurvature Perturbation

Different density perturbation between different fluids.

Adiabatic perturbation : contribute to the curvature perturbation

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

Isocurvature perturbation between DM and radiation

: contribute to the change of the curvature perturbation

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

Constraint on Isocurvature Perturbation

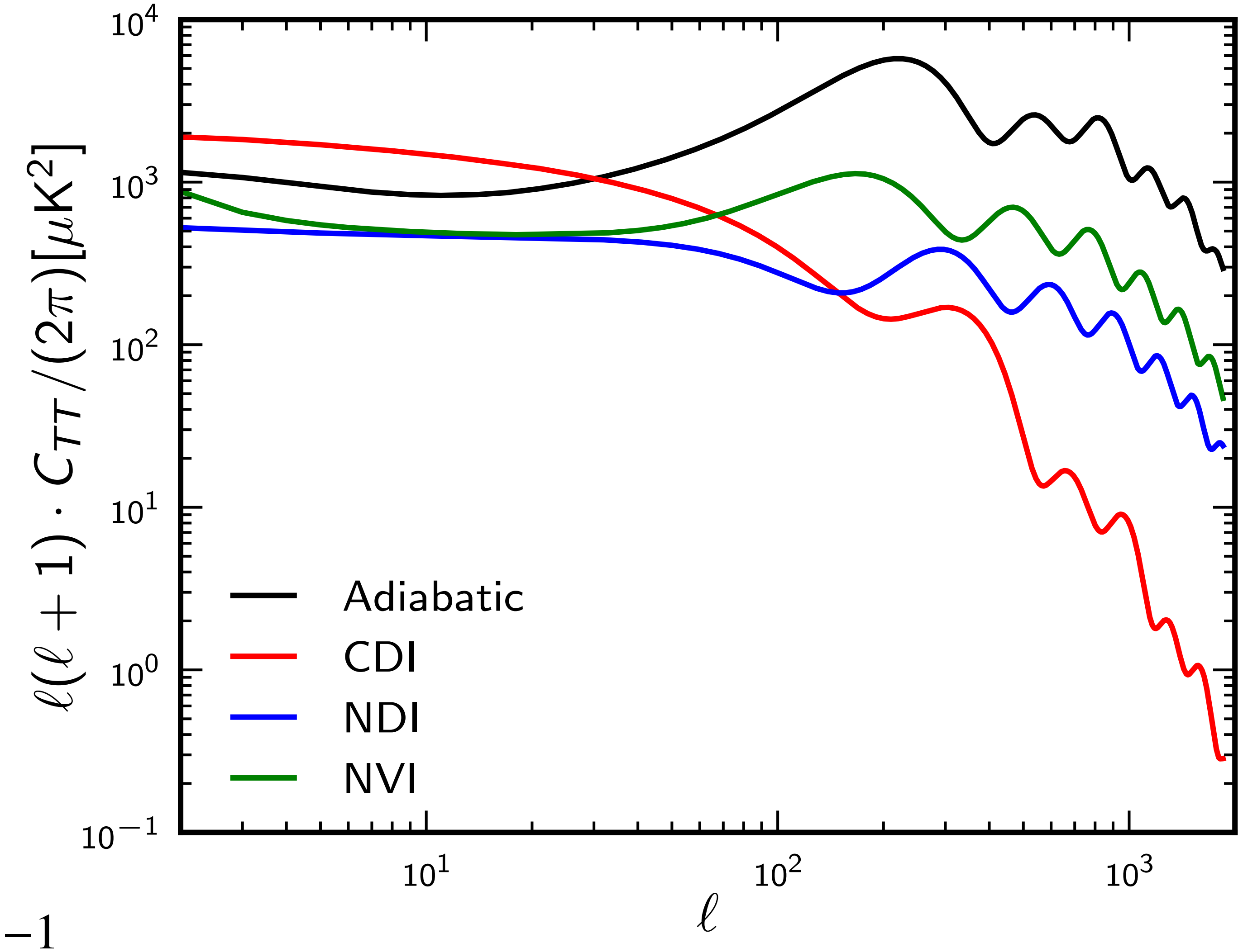
Fraction of isocurvature

$$\beta_{\rm iso}(k) = \frac{\mathcal{P}_{\mathcal{II}}(k)}{\mathcal{P}_{\mathcal{RR}}(k) + \mathcal{P}_{\mathcal{II}}(k)}$$

$$\beta_{\rm iso} < 0.039$$

(95% CL, *Planck*+WP),

at the scale $k_{\rm mid} = 0.05\,{\rm Mpc}^{-1}$,



The constraint from CMB is applied only to the large scale modes.

No constraint on smaller scales.

WIMP is Adiabatic

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

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

This is fully consistent with observation.

WIMP Isocurvature Perturbation?

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

- Not possible in the standard WIMP.

- However there is one case, when

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

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

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

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

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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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
- .....

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

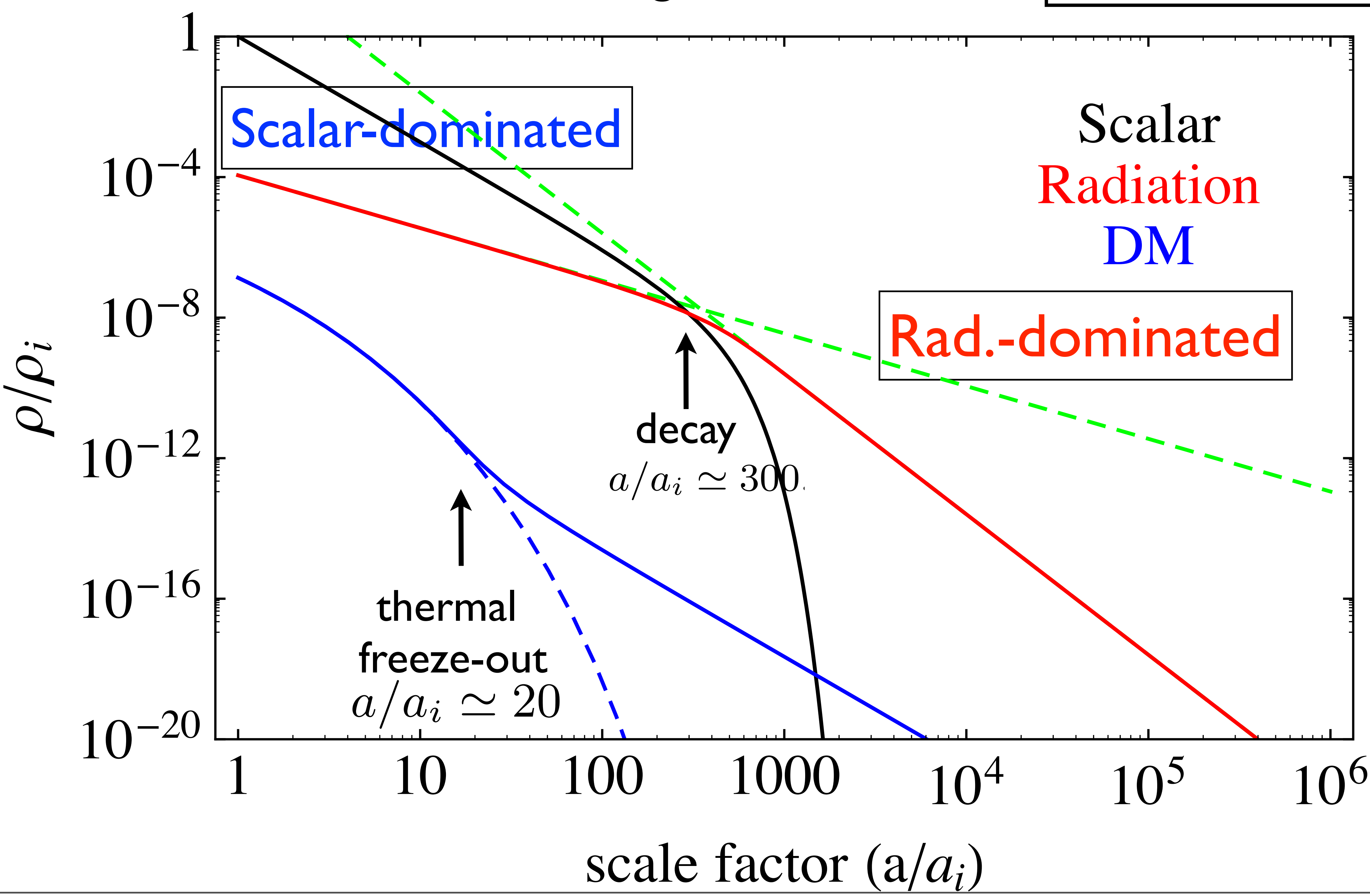
Early Matter Domination

: early matter domination by a scalar

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

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

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

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

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

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

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

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

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

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

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

Creation of Isocurvature Perturbation

After chemical decoupling and before reheating during scalar-domination:

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

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

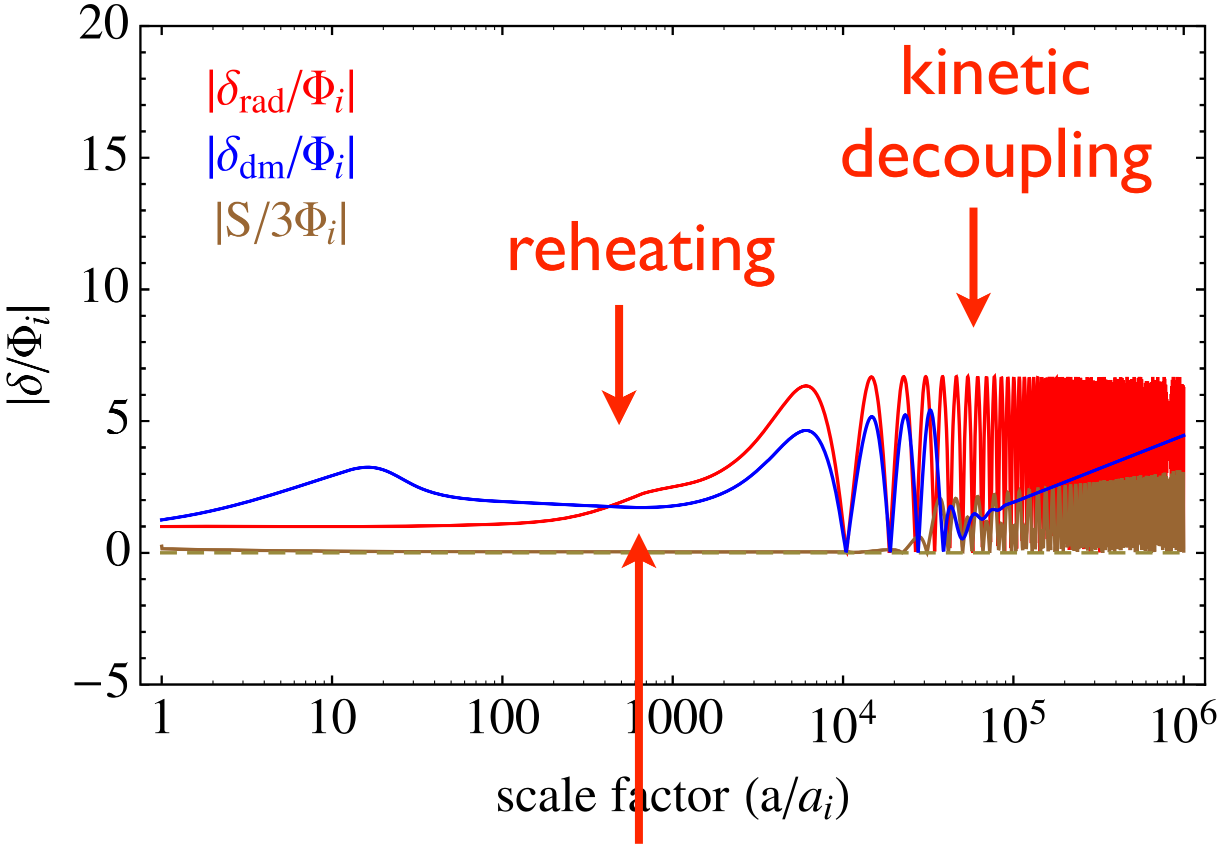
$$\dot{\delta}_r \approx -\frac{4}{3}\frac{\theta_r}{a} + \frac{\Gamma_\phi \rho_\phi}{\rho_r}(\delta_\phi - \delta_r),$$

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

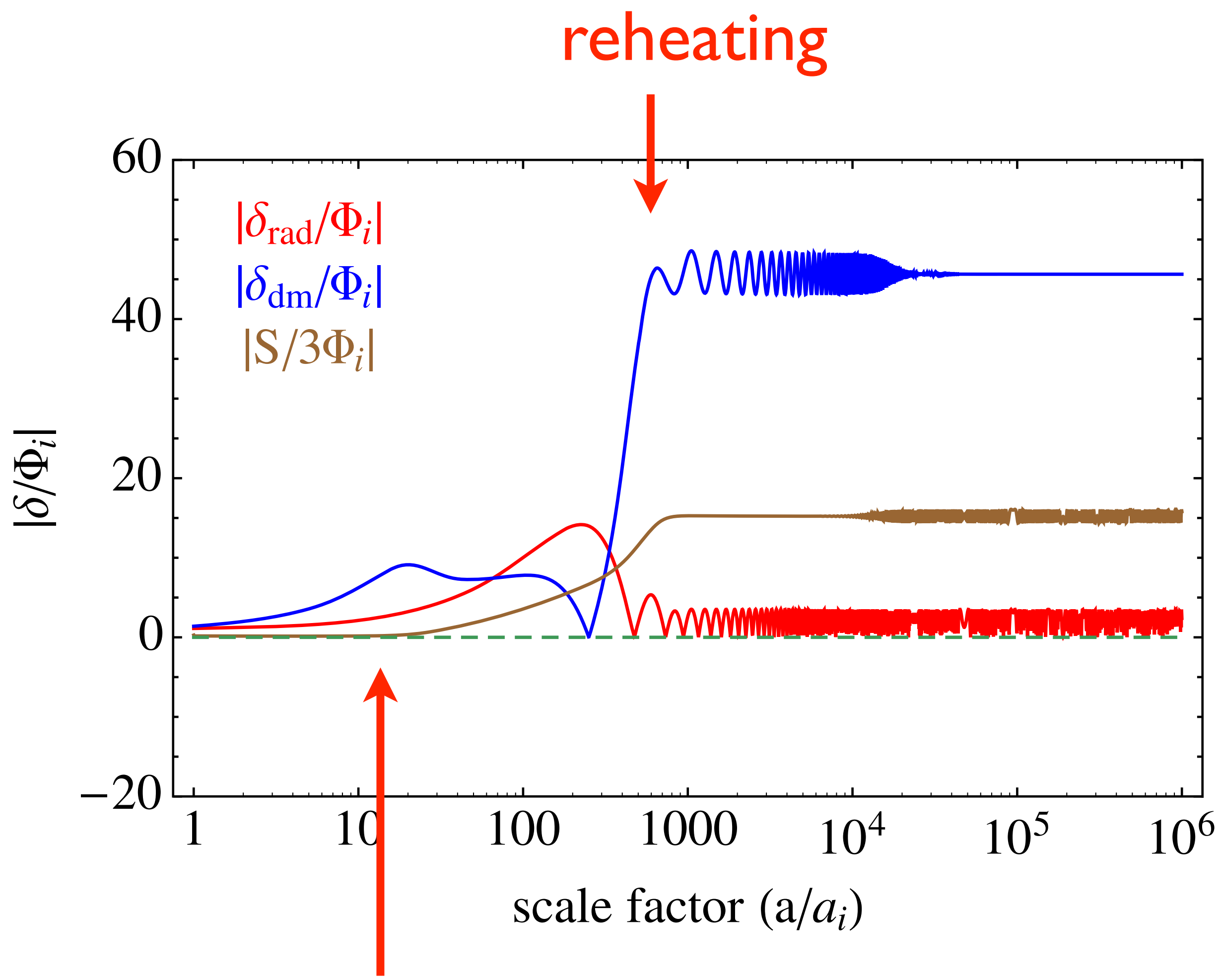
The difference in the number density creates the isocurvature perturbation between dark matter and radiation.

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

Evolution of Perturbation

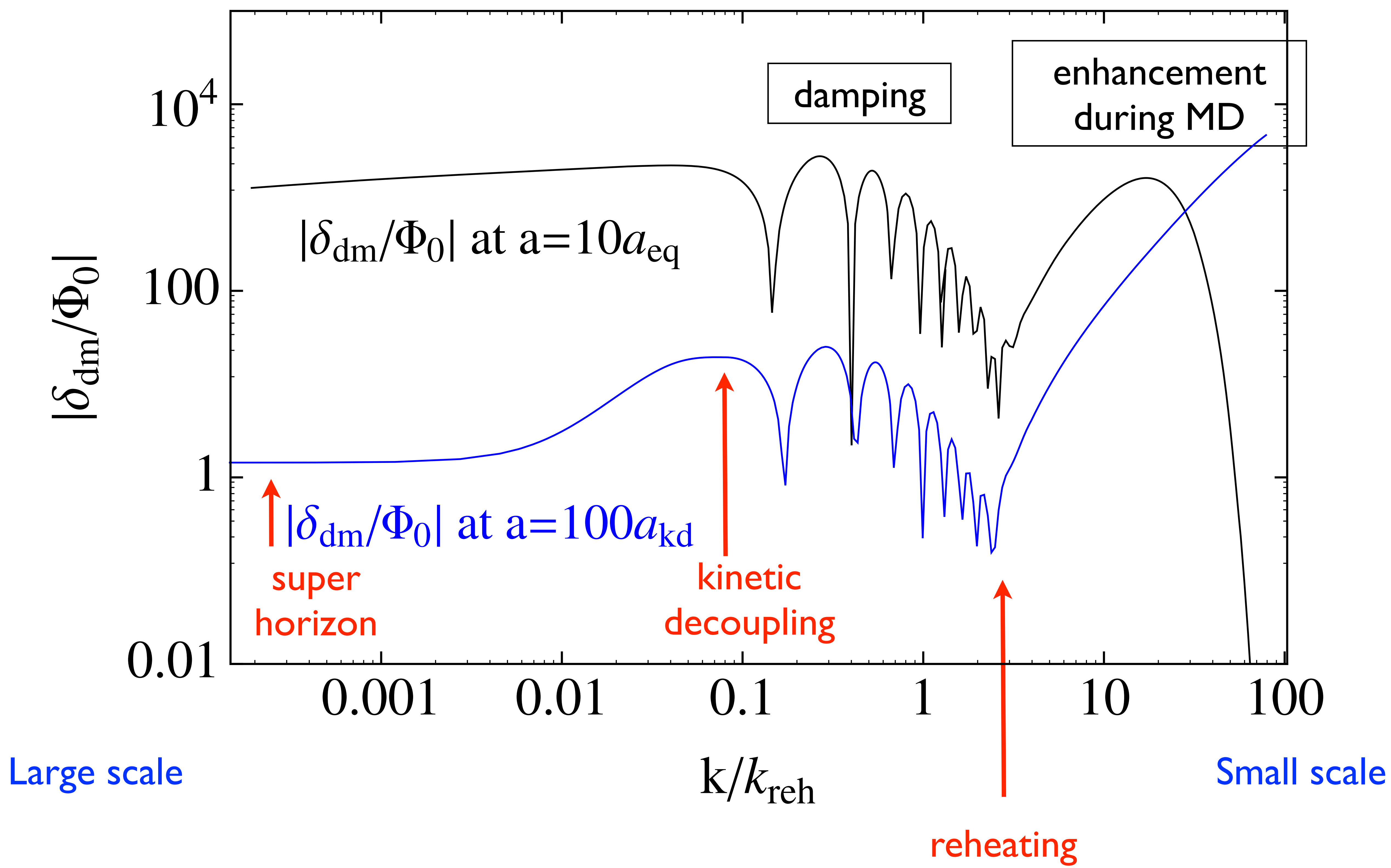


Horizon entry after reheating



Horizon entry during early MD before reheating

Scale Dependence of Density Perturbation

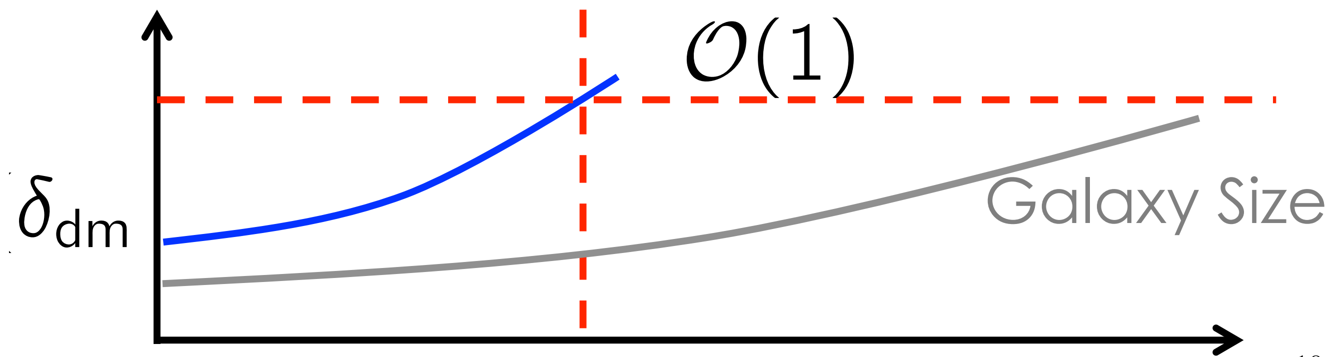


Implications

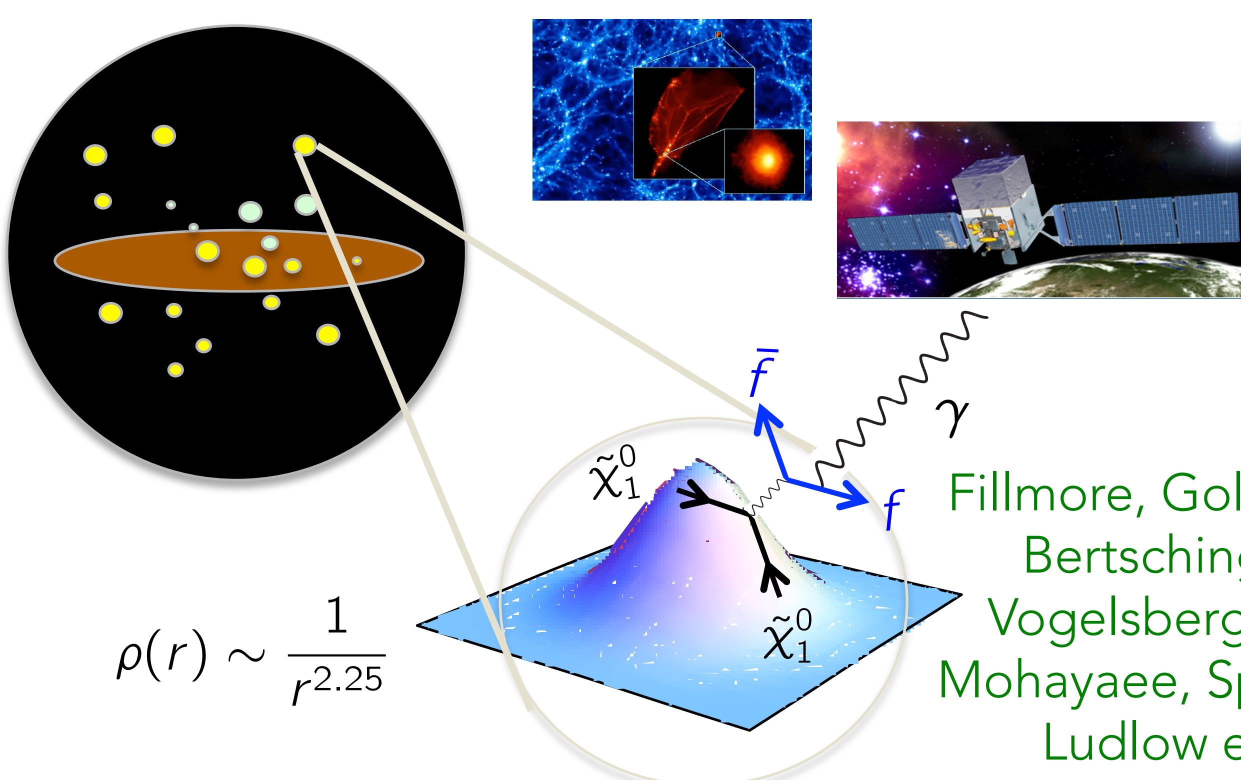
Formation of Minihalos

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

$$M^0_{\rm UCMH} \sim 4 \times 10^{-5} M_\odot \left(\frac{k^{-1}}{\rm pc}\right)^3$$

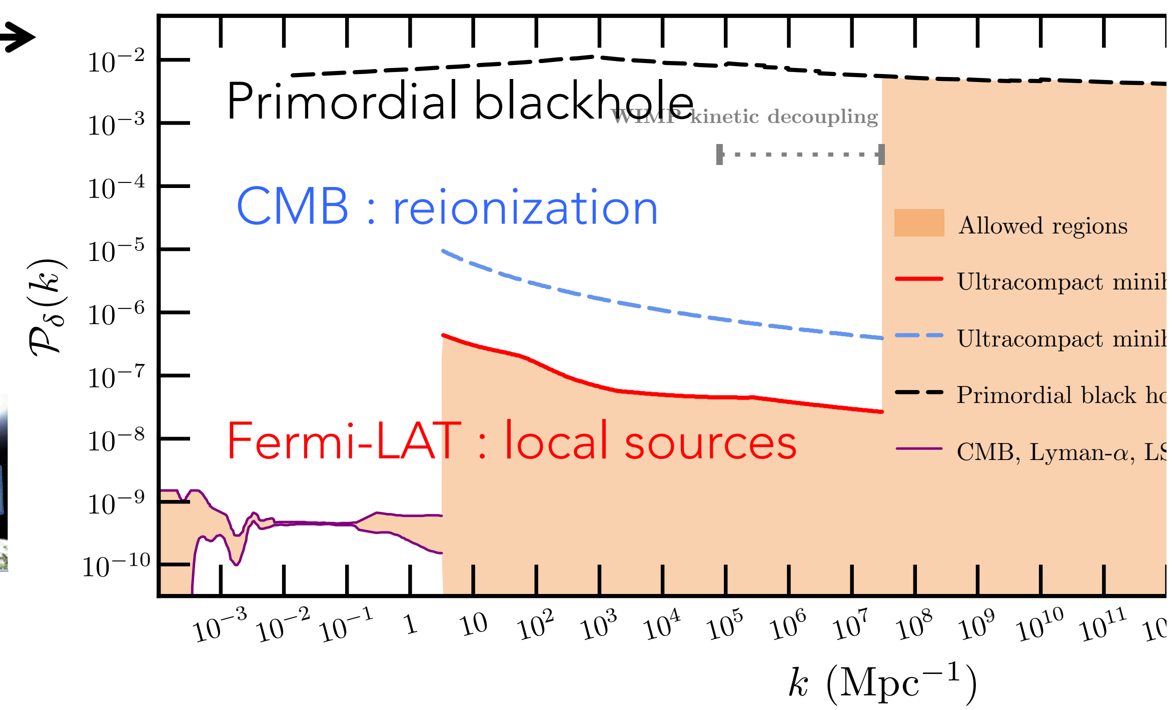


$z_c \sim 100 - 1000$
a small velocity dispersion at $z=z_c$
Ricotti, A. Gould 2009



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

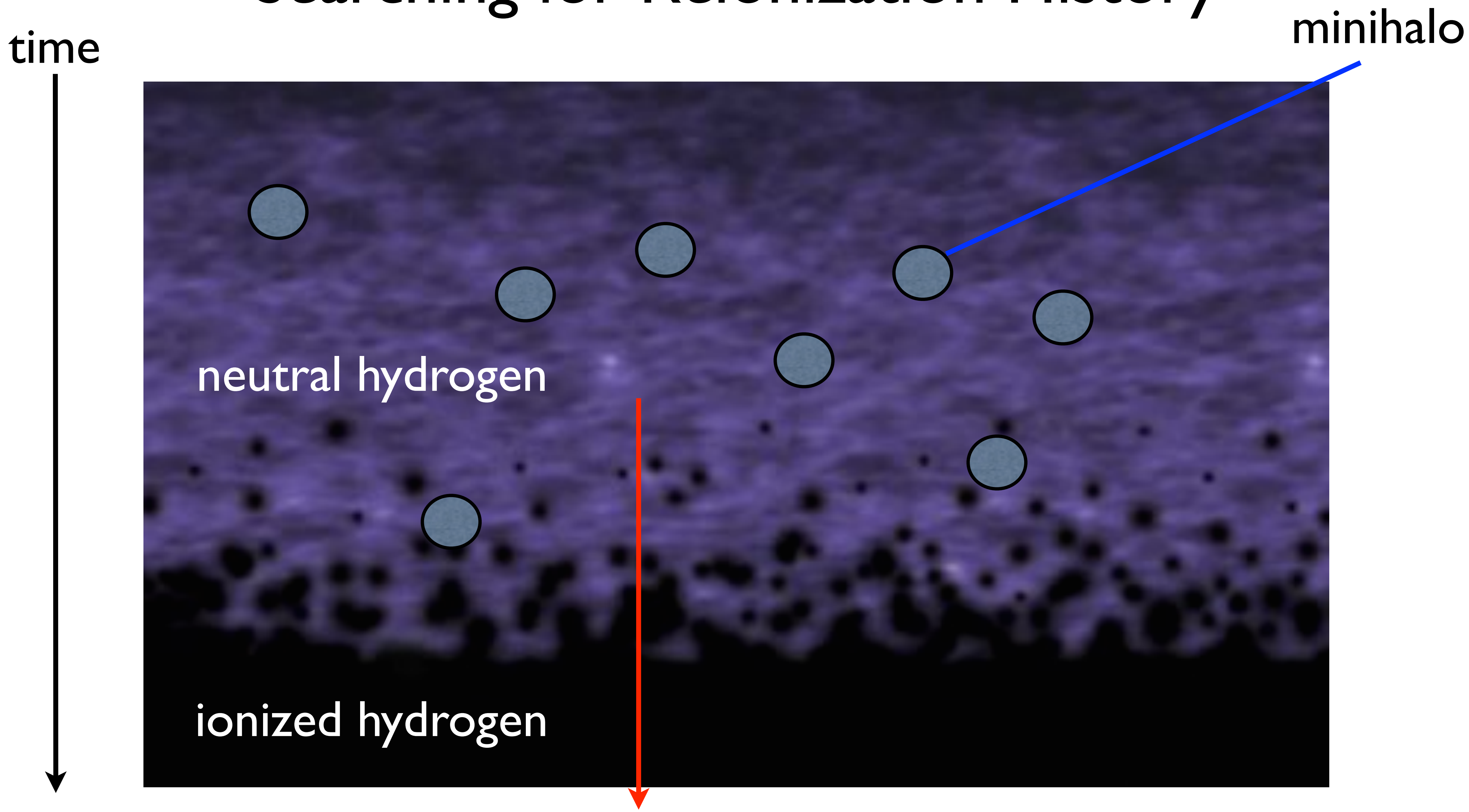
Fillmore, Goldreich 1984
Bertschinger 1985
Vogelsberger, White, Mohayaee, Springel 2009
Ludlow et al. 2010



Bringmann, Scott, Akram 2011

[Slide from Chang Sub Shin]

Searching for Reionization History



21 cm line from neutral hydrogen hyperfine structure

21 cm line from around minihalos can be observed by SKA etc.

1. When you are considering

WIMP dark matter

2. When the reheating temperature is low

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

3. You have to consider

Isocurvature perturvation of WIMP

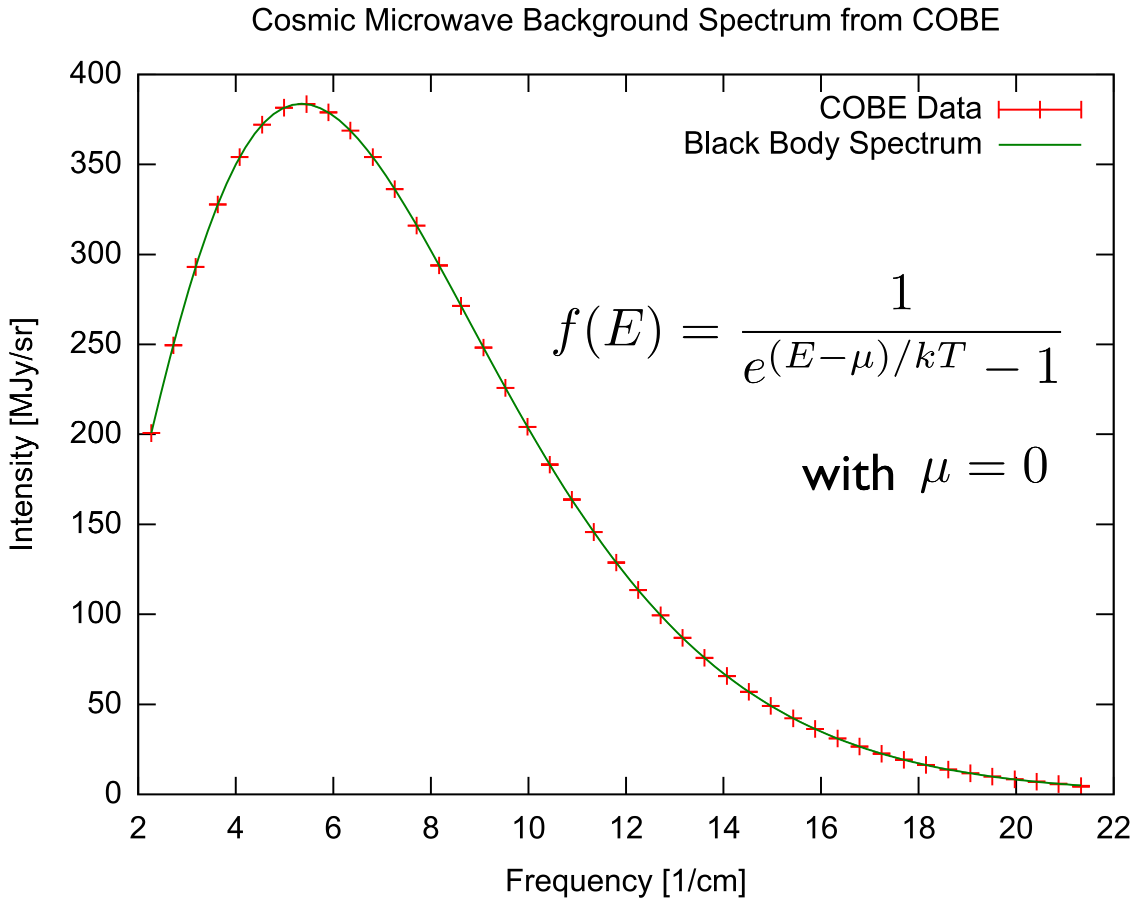
Discussion

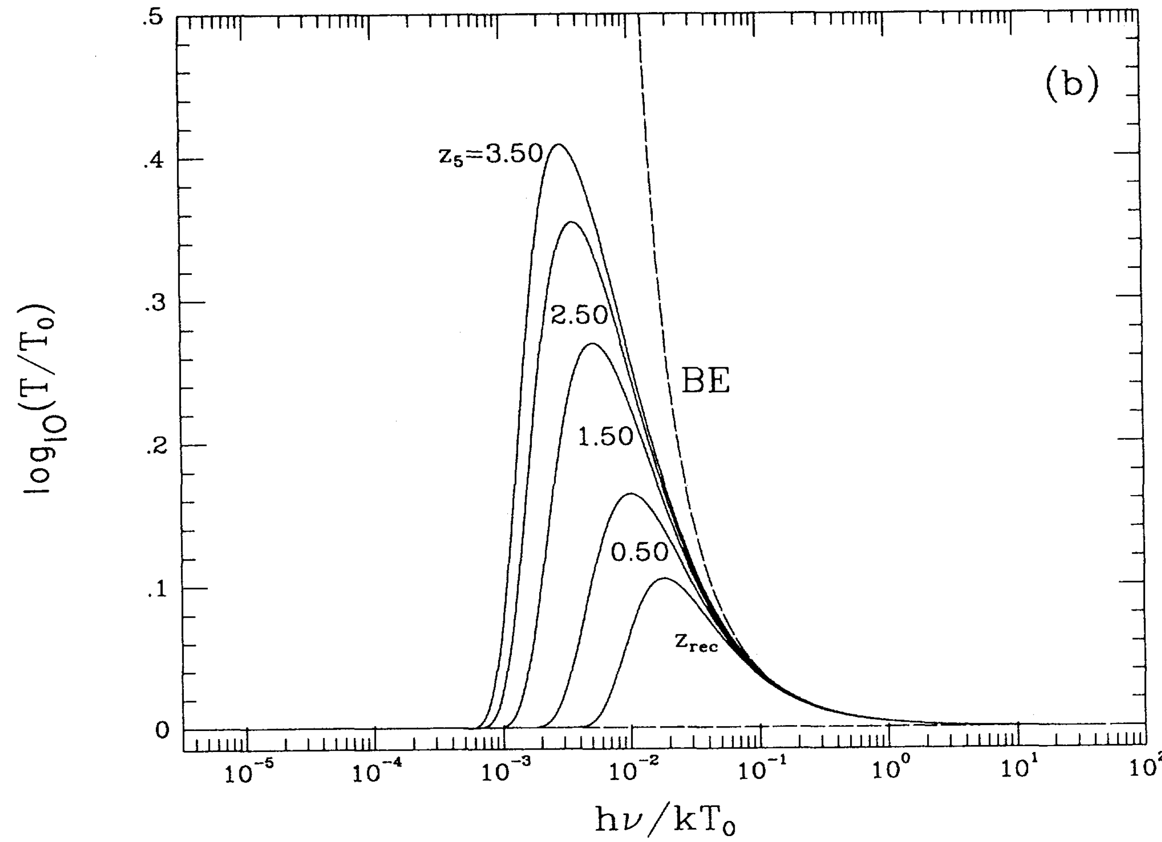
1. Isocurvature perturbation of DM is not suppressed during kinetic decoupling.

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

3. The large isocurvature perturbation of WIMP at small scales form minihalos. The WIMP DM inside the small scale objects can be observed in the gamma-ray, cosmic rays or neutrinos.

CMB Distortion from Planck shape





[COBE, FIRAS (1992)] $|\mu| < 9 \times 10^{-5}$ [Hu, Silk (1993)]

The acoustic waves dissipates its energy by Silk damping, which produces the distortion of CMB from Planck distribution.

Future satellite like PIXIE can measure up to $|\mu| < 10^{-8}$

Standard Power spectrum distorts the CMB with $|\mu| \sim 10^{-8}$