WIMP isocurvature perturbation and small scale structure

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Based on
1507.03871 (with Ki-Young Choi, Jinn-Ouk Gong)

Oct. 07th 2015 at Brookhaven Forum

Outline

Cosmic history for WIMP dark matters

- chemical decoupling
- kinetic decoupling

Evolution of density perturbations

- radiation (relativitic matter)
- matter (non-relativistic matter)

Adiabatic (curvature) v.s. Entropy (isocurvature) perturbation

- what is the effect of initial isocurvature perturbations for small scales

WIMP Isocurvature Perturbation

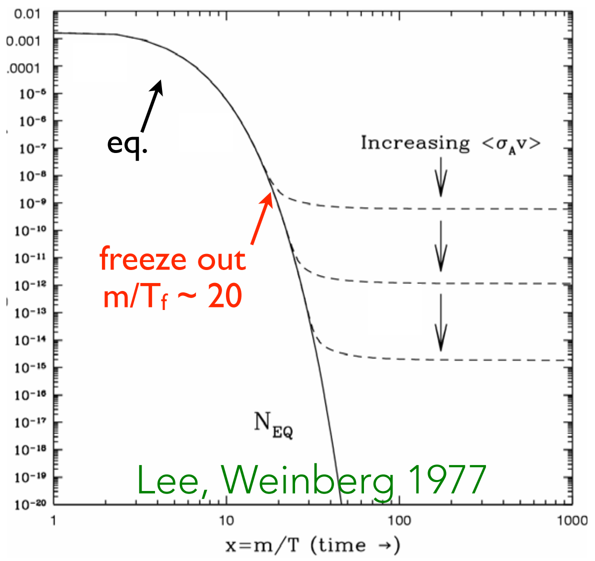
- how to generate WIMP isocurvature perturbations

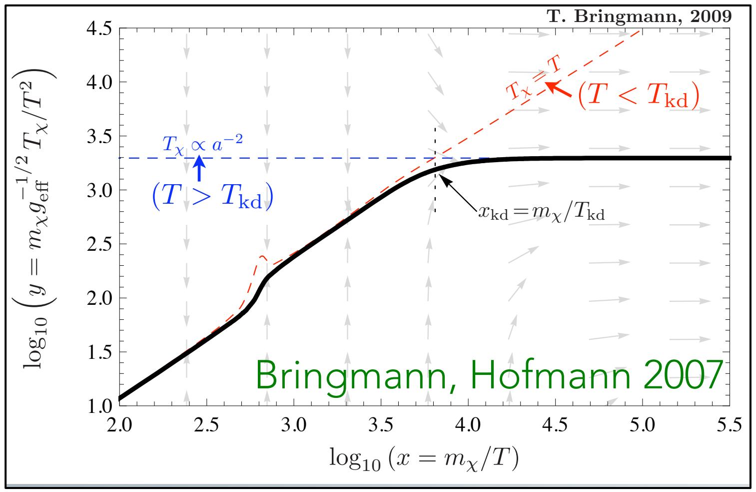
Small scale structure

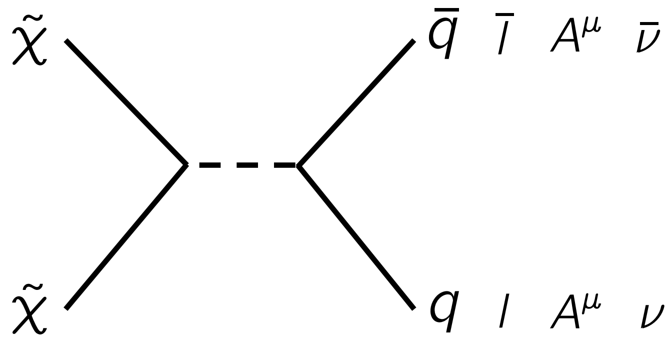
Conclusion

Weakly Interacting Massive Particle (WIMP)

One of promising candidates for dark matter







Weakly Interacting Massive Particle (WIMP)

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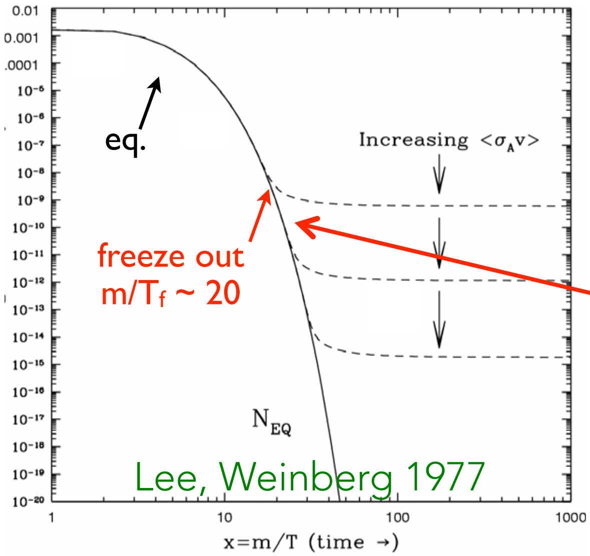
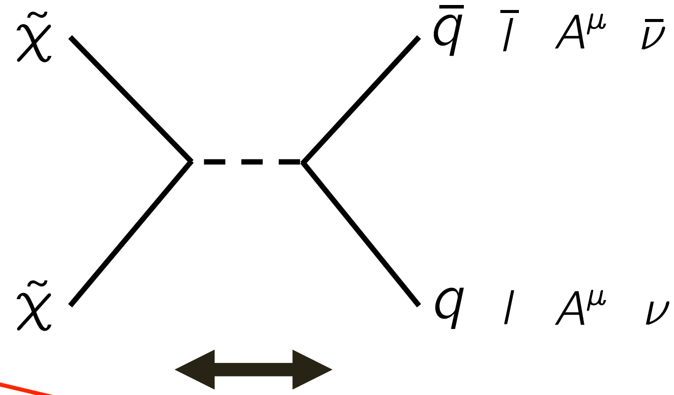
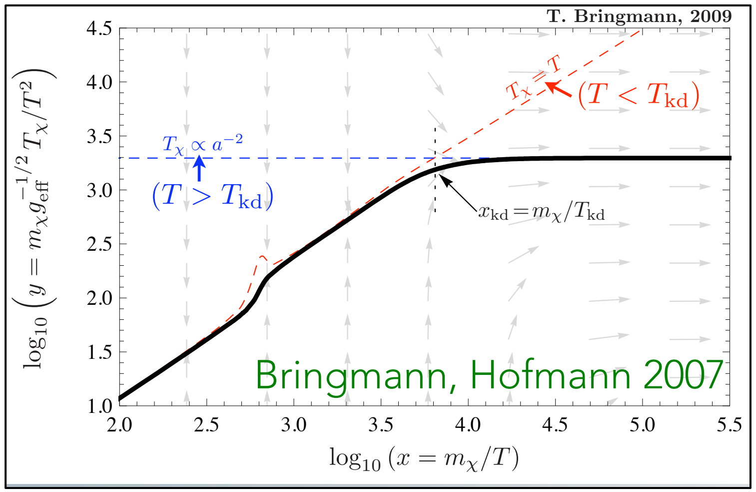




Chemical Decoupling

$$\langle \sigma_A v \rangle_{T_f} n_{\tilde{\chi}} = H(T_f)$$



Weakly Interacting Massive Particle (WIMP)

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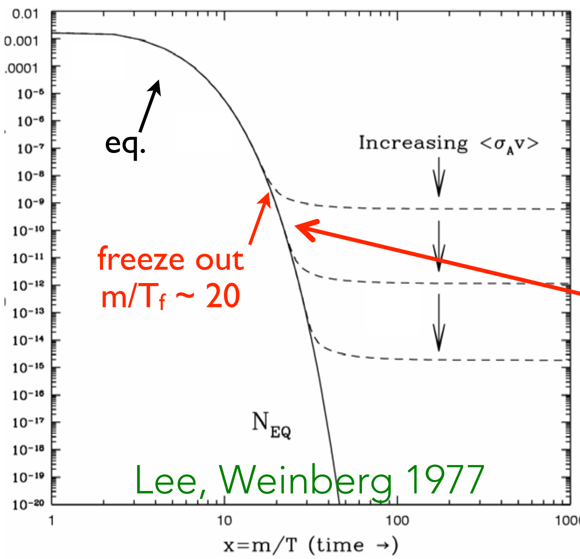
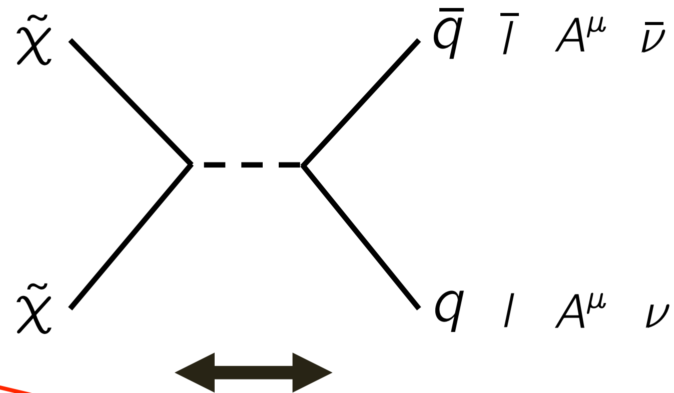


$$\langle \sigma_e v \rangle_{T_{\rm kd}} \frac{T_{\rm kd}}{m_{\tilde{\chi}}} n_{\rm rad} = H(T_{\rm kd})$$

Kinetic Decoupling



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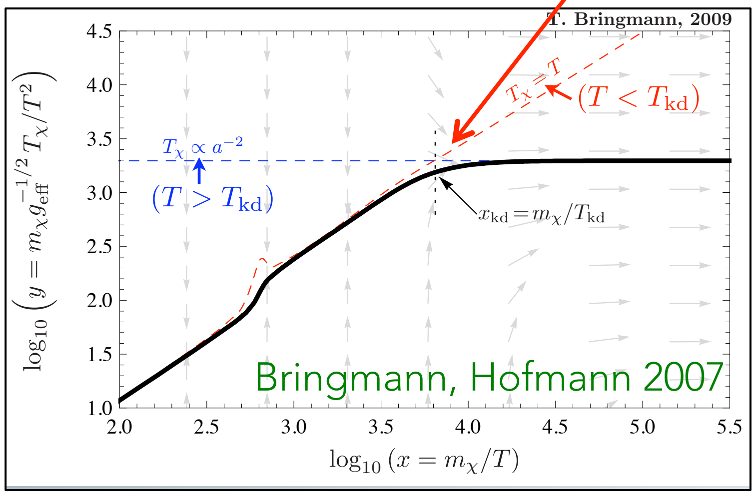

$$\langle \sigma_e v \rangle \sim \frac{1}{m_\phi^2}$$

$$\langle \sigma_a v \rangle \sim \frac{1}{m_{\tilde{\chi}}^2} \quad \text{for } m_\phi \ll m_{\tilde{\chi}}$$

$n_{\tilde{\chi}} \ll n_{\rm rad}$ for $T \ll m_{\tilde{\chi}}$

$$\boxed{T_{\rm kd} \ll T_{\rm fo}}$$

Weakly Interacting Massive Particle (WIMP)

What are the effects of late time kinetic decoupling ?

- Possibility of direct detection of DM (from large elastic scattering with baryons)

Many references

- Effects on CMB spectrum, 21cm power spectrum (from large scattering with radiations/baryons)

Tashiro, Kadota, Silk 2014
Ali-Haïmoud, Chluba, Kamionkowski, 2015, etc

- Suppression of small scales (from acoustic damping of DM density perturbation)

Green, Hofmann, Schwarz, 2004
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Evolution of density perturbation

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

Inside horizon : density perturbation grows

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

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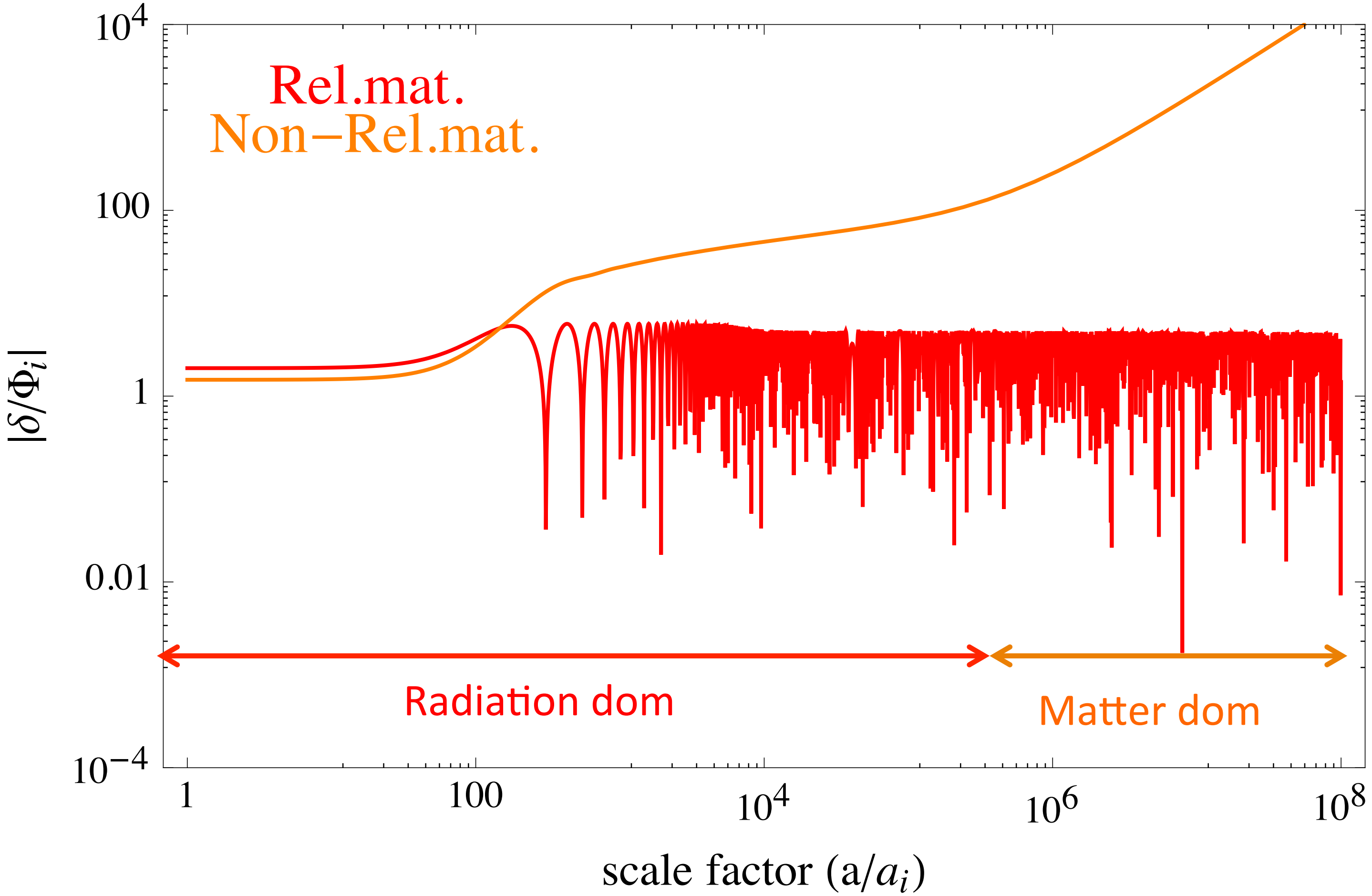

Evolution of density perturbation

Q. If there is strong elastic scattering between non-relativistic matter and relativistic matter, how do the perturbations change ?

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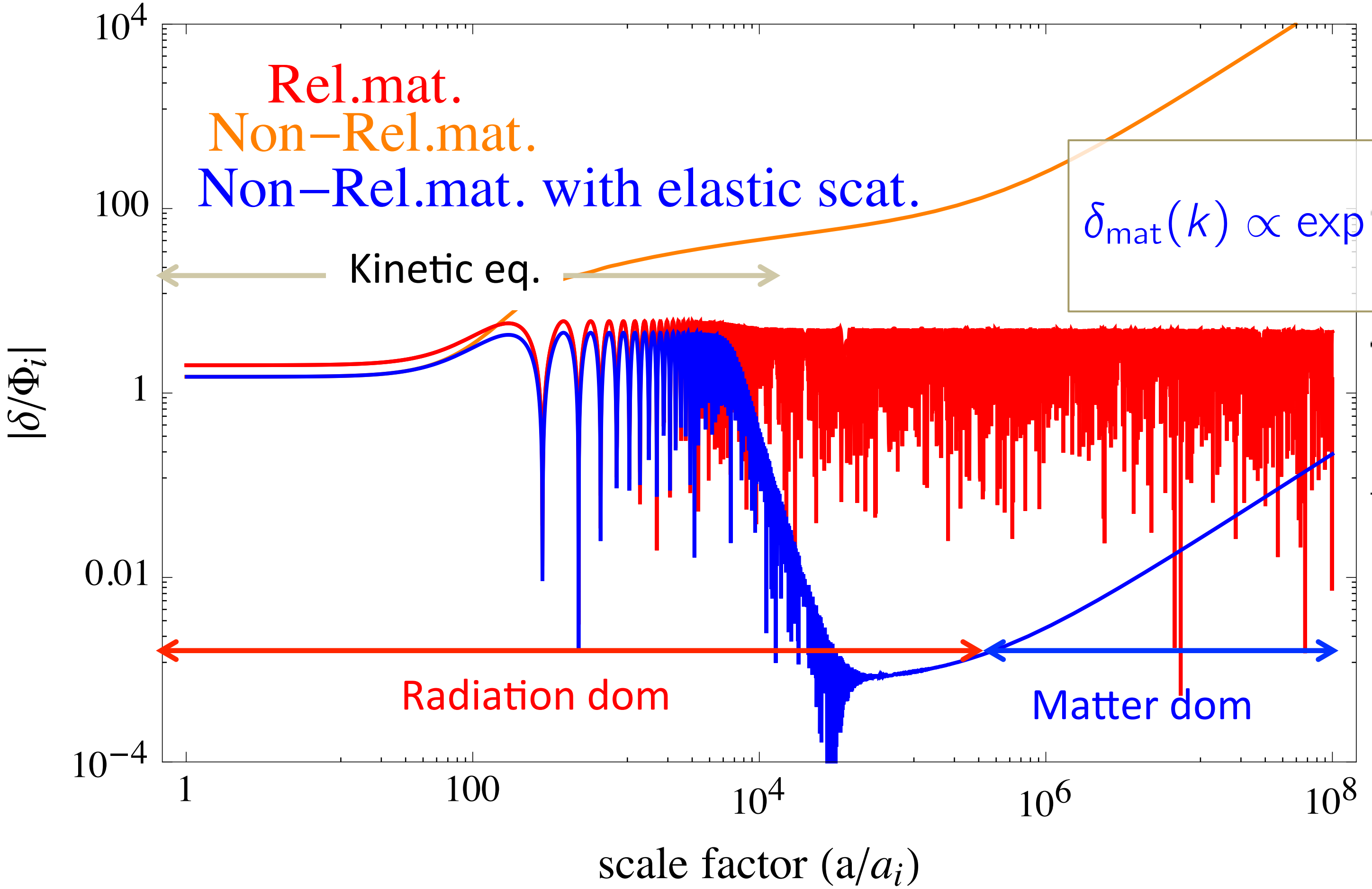
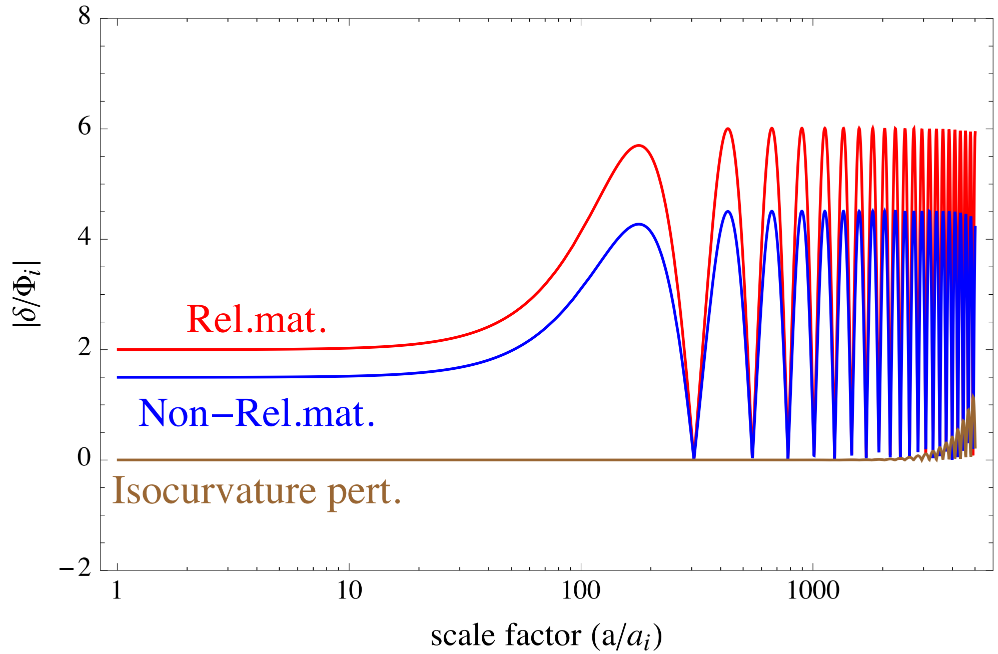


$$\delta_{\rm mat}(k) \propto \exp\left[-\left(\frac{k}{k_{\rm kd}}\right)^{4/5}\right]$$

Adiabatic (curvature) vs Entropy (isocurvature) perturbation

Perturbation during kinetic equilibrium : Adiabatic evolution

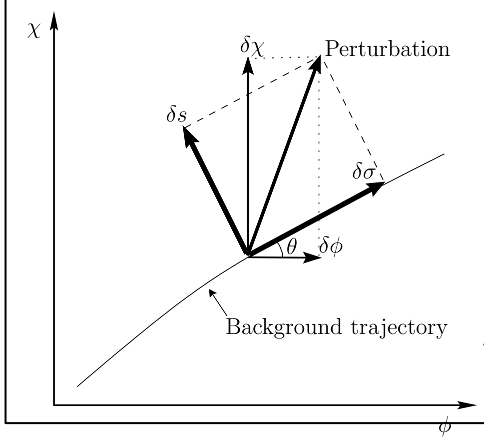


$$\dot{\delta}_{\rm mat} \approx -\frac{\theta_{\rm mat}}{a}$$

$$\dot{\delta}_{\rm rad} \approx -\frac{4}{3}\frac{\theta_{\rm rad}}{a}$$

during kinetic eq., $\theta_{\rm mat} = \theta_{\rm rad}$
(in tight coupling limit)

$$S = \delta_{\rm mat} - \frac{3}{4}\delta_{\rm rad}, \quad \dot{S} = 0$$



If $\rho_{\rm mat} = \rho^0_{\rm mat} a^{-3}, \ \rho_{\rm rad} = \rho^0_{\rm rad} a^{-4}$

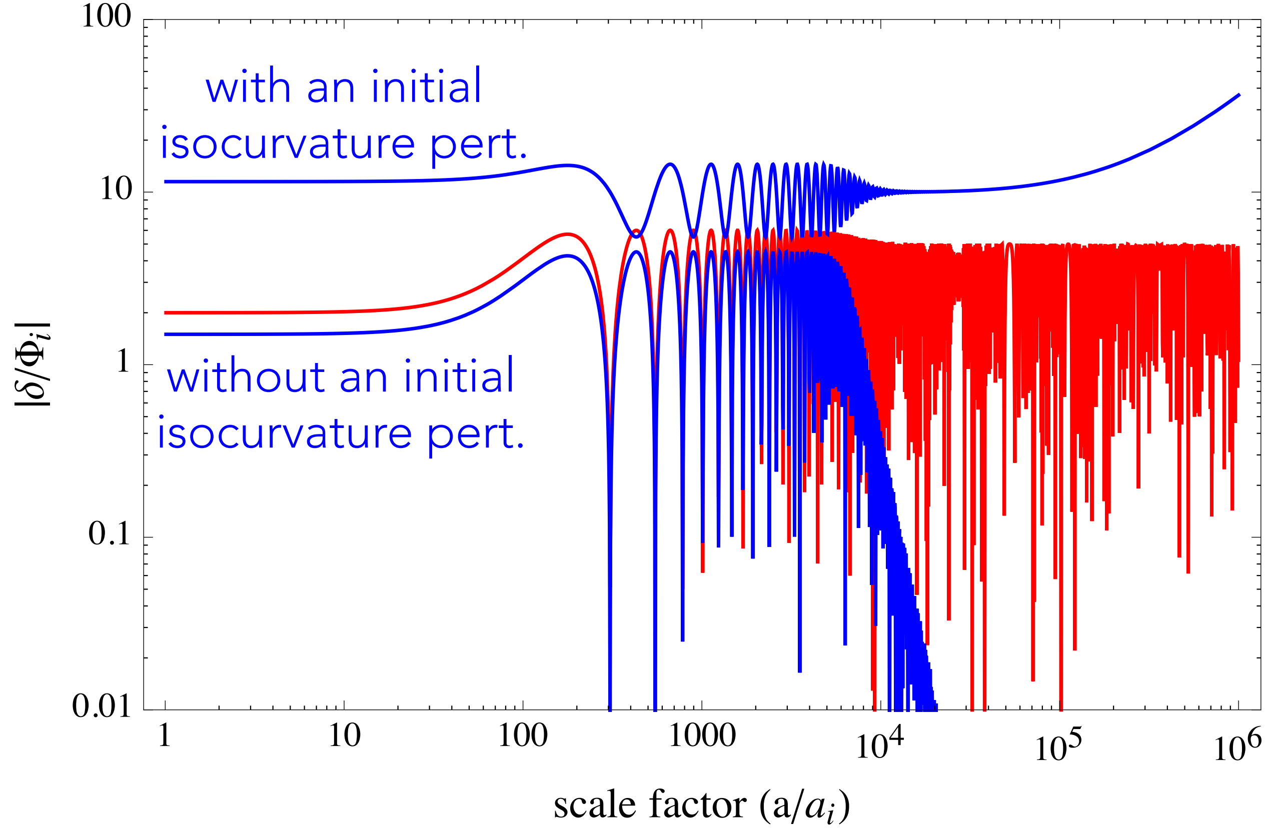
$$\Rightarrow \delta_{\rm mat} = \frac{3}{4}\delta_{\rm rad} = -3\frac{\delta a}{a} \Rightarrow S = 0$$

= isocurvature pert.

$$S = \frac{\delta n_{\rm mat}}{n_{\rm mat}} - \frac{\delta n_{\rm rad}}{n_{\rm rad}} = \frac{\delta(n_{\rm mat}/s)}{n_{\rm mat}/s}$$ = pert. of entropy per particle

Adiabatic (curvature) vs Entropy (isocurvature) perturbation

If there is an initial isocurvature perturbation for Non-Rel. matter ?



The isocur. component is not damped, and can grow to make substructures.

Peebles and his colleagues developed the baryon isocurvature perturbation model for structure formation Peebles 1987

Adiabatic (curvature) vs Entropy (isocurvature) perturbation

WIMPs are thermally produced, so that the initial isocurvature perturbation is absent. Consequently, the scales that enter the horizon before kinetic decoupling are all suppressed : smallest scale for gravitationally bound objects (R_{cut})

$$R_{\text{cut}} \text{ for WIMP} \sim 1/k_{\text{kd}}$$

Green, Hofmann, Schwarz, 2004
Loeb and M. Zaldarriaga 2005
Bertschinger 2006

Not always true. It depends on the history of the universe. There is a way to generate isocurvature perturbations for $1/k < 1/k_{kd}$ during kinetic equilibrium : ENTROPY INJECTION

Choi, Gong, Shin 2015

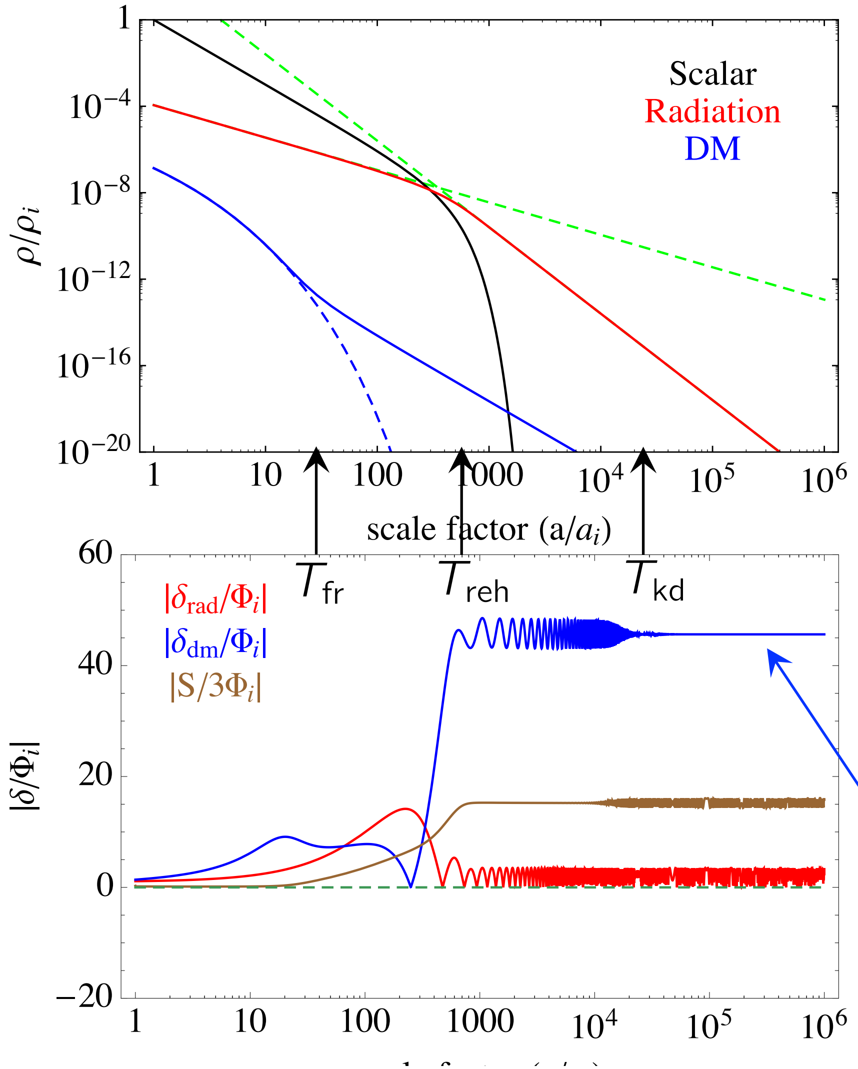
$$\begin{aligned} \dot{\delta}_{\text{mat}} &\approx -\frac{\theta_{\text{mat}}}{a} \\ \dot{\delta}_{\text{rad}} &\approx -\frac{4}{3}\frac{\theta_{\text{rad}}}{a} + J_{\text{source}} \end{aligned}$$

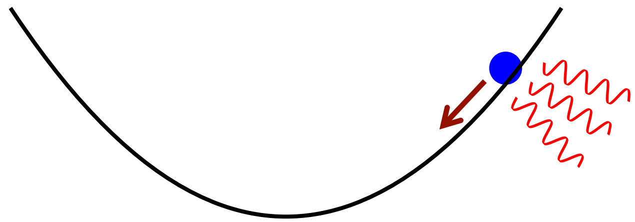
$$S = \frac{\delta(n_{\text{mat}}/(s+\Delta s))}{n_{\text{mat}}/(s+\Delta s)}$$

WIMP isocurvature perturbation

How to generate an additional entropy ? $dS_{\rm tot}/dt > 0$ Choi, Gong, Shin 2015

Out of equilibrium decay of heavy particles, e.g. low reheating temperature





$\rho_r \propto a^{-3/2}$ at early MD $\qquad S_{\rm tot} \propto a^{15/8}$

$\rho_r \propto a^{-4}$ at RD $\qquad S_{\rm tot} = {\rm const.}$

$$\dot{\delta}_{\rm mat} \approx -\frac{\theta_{\rm mat}}{a}$$

$$\dot{\delta}_{\rm rad} \approx -\frac{4}{3}\frac{\theta_{\rm rad}}{a} + \frac{\Gamma_\phi \rho_\phi}{\rho_{\rm rad}}(\delta_\phi - \delta_{\rm rad})$$

$$S = \frac{5}{4}\Phi_i\left(\frac{k}{k_{\rm reh}}\right)^2$$

WIMP isocurvature perturbation

Ex. The evolution of isocurvature perturbation for the scales that enter the horizon before freeze-out.

1) [early MD] Before chemical freeze-out ($T > T_{fr}$)

- DM are still produced from thermal bath – No isocur. pert. is generated

2) [early MD] Before radiation domination starts ($T_{fr} > T > T_{reh}$)

- DM number is fixed, entropy injection during early MD generates the isocur. pert.

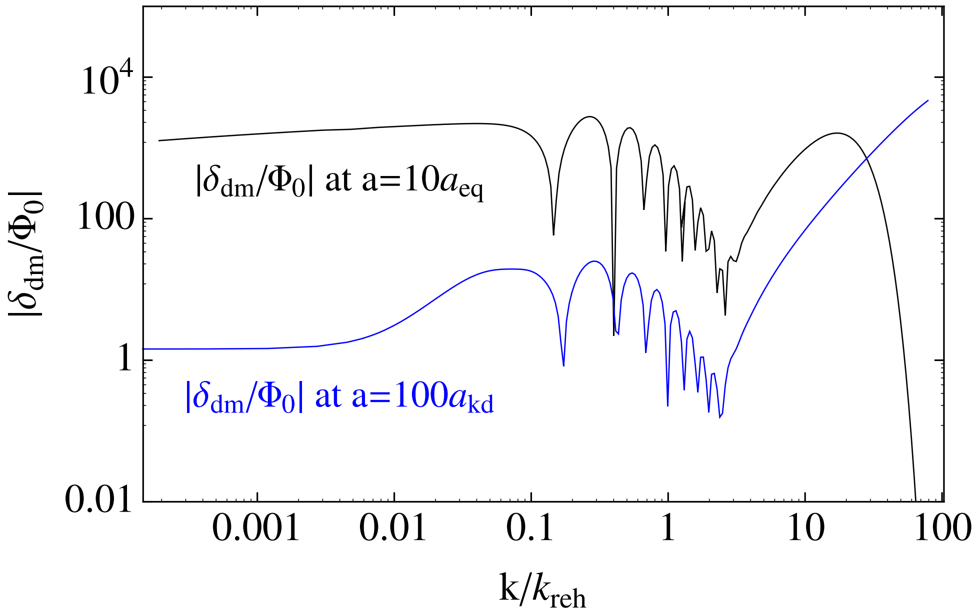
3) [RD] Before kinetic decoupling ($T_{reh} > T > T_{kd}$)

- the generated isocur. pert. becomes constant, and the adiabatic component oscillates and is damped through kinetic decoupling

4) [RD] After kinetic decoupling ($T_{kd} > T$)

- the isocur. pert. and the additional small logarithim contribution exists for DM

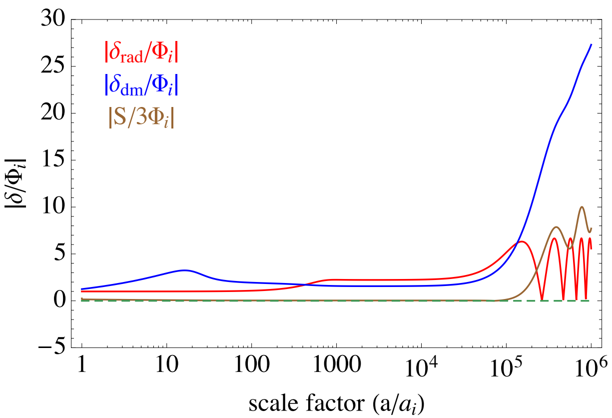
WIMP isocurvature perturbation



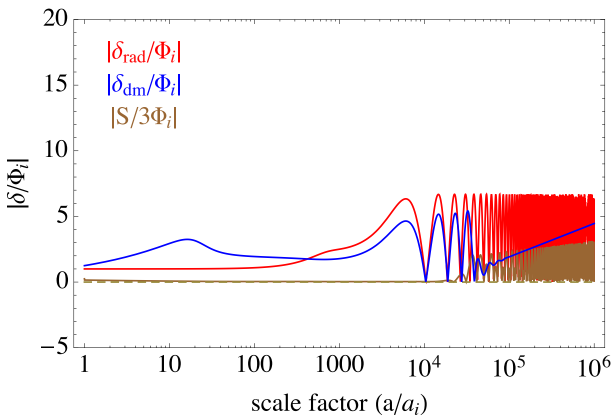
$$\delta_{mat} = \exp\left(-\frac{k^2}{2k_{fr}^2}\right)\frac{5}{4}\Phi_i\left(\frac{k}{k_{reh}}\right)^2$$

for $k < k_{reh}$

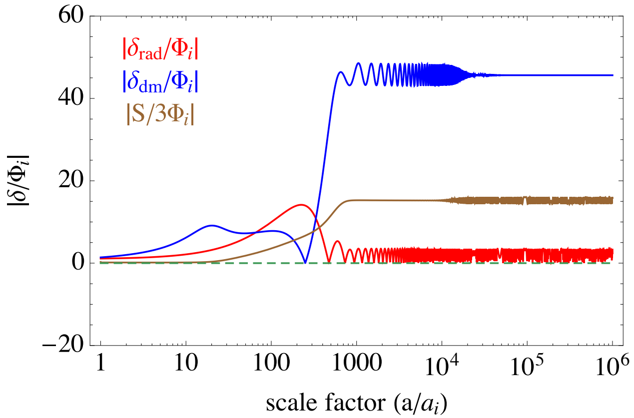
Density contrast of DM with $m_{dm} = 5\,\mathrm{TeV}$, $T_{reh} = 0.1\,\mathrm{GeV}$, $T_{kd} = 10\,\mathrm{MeV}$.



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

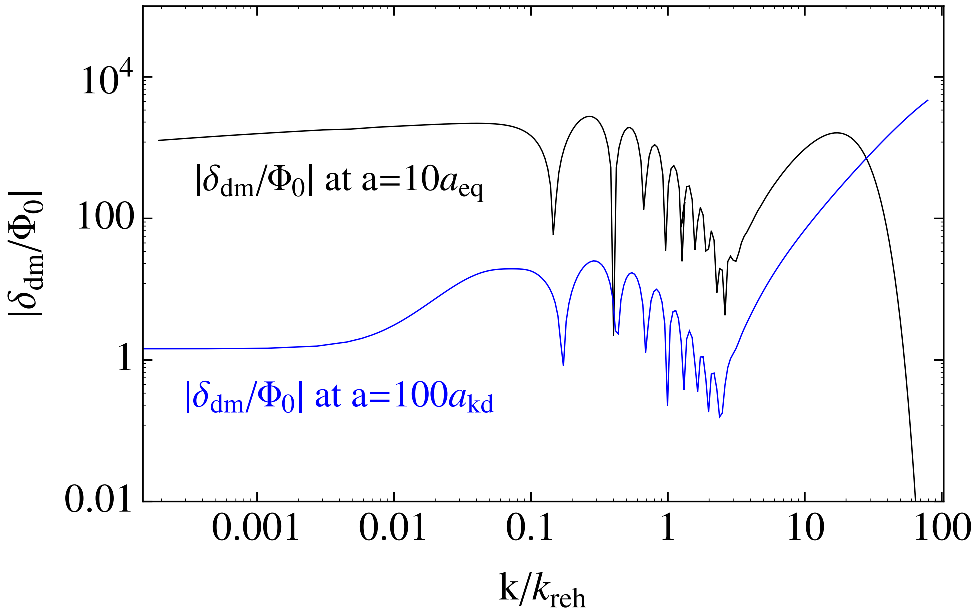


$k_{reh}^{-1} < k^{-1} < k_{kd}^{-1}$



$k_{fr}^{-1} < k^{-1} < k_{reh}^{-1}$

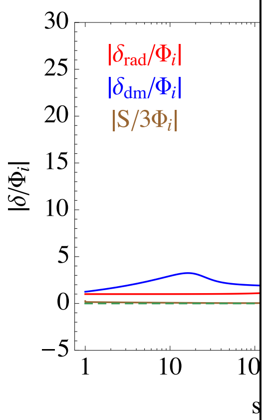
WIMP isocurvature perturbation



$$\delta_{\rm mat} = \exp\left(-\frac{k^2}{2k_{\rm fr}^2}\right)\frac{5}{4}\Phi_i\left(\frac{k}{k_{\rm reh}}\right)^2$$

for $k < k_{\rm reh}$

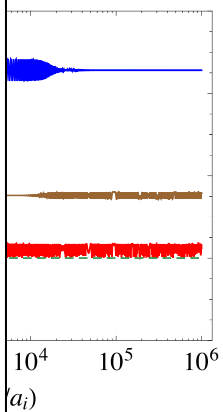
Density contras



$$k_{\rm kd}^{-1} = 0.86\,\frac{10\,{\rm MeV}}{T_{\rm kd}}\left(\frac{g_{*s}}{10.75}\right)^{1/3}\left(\frac{10.75}{g_*}\right)^{1/2}\ {\rm pc}\,,$$

$$k_{\rm reh}^{-1} = k_{\rm kd}^{-1}\frac{T_{\rm kd}}{T_{\rm reh}}\,,$$

$$k_{\rm fr}^{-1} = \int_{t_{\rm kd}}^{t_0}\frac{dt}{a}c_s \approx k_{\rm kd}^{-1}\sqrt{\frac{T_{\rm kd}}{M}}\log\left(\frac{T_{\rm kd}}{T_{\rm eq}}\right)\,,$$

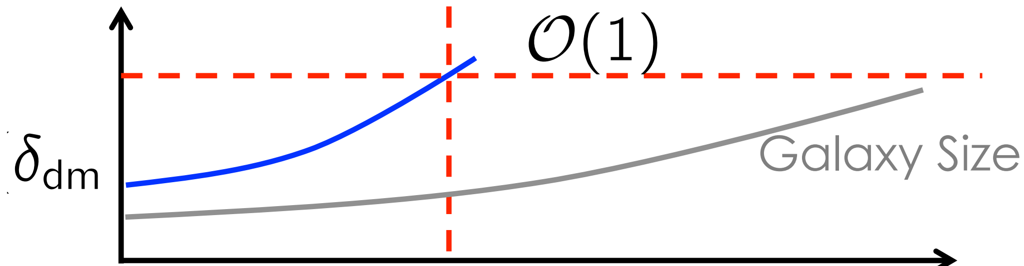


$k_{\rm kd}$ … $k_{\rm reh}$ … $k_{\rm kd}$ … $k_{\rm fr}$ … $< k_{\rm reh}^{-1}$

Small scale structure

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

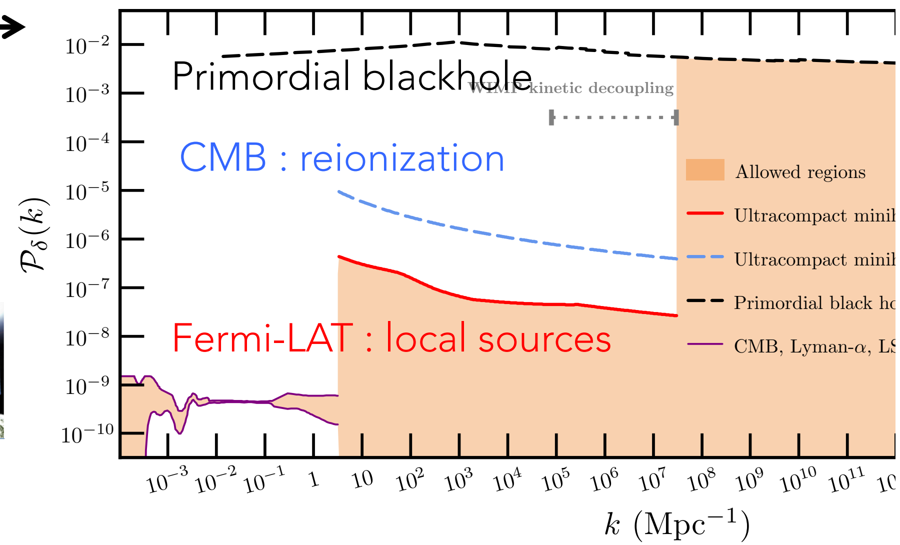
$$M^0_{\rm UCMH} \sim 4 \times 10^{-5} M_\odot \left(\frac{k^{-1}}{\rm pc}\right)^3$$



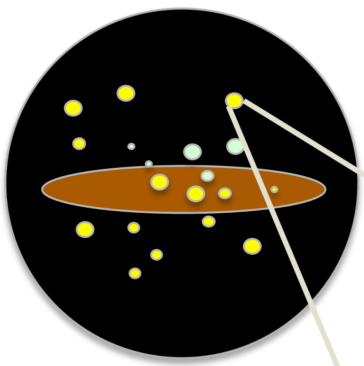
$z_c \sim 100 - 1000$

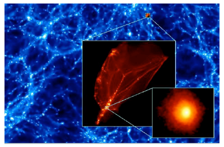
a small velocity dispersion at $z=z_c$

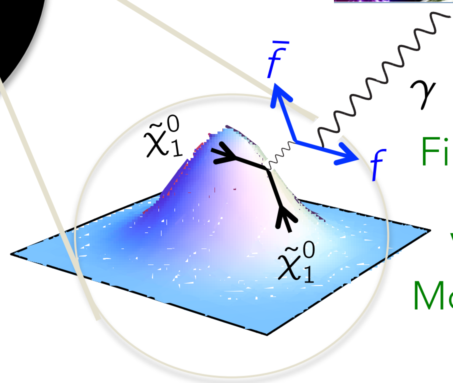
Ricotti, A. Gould 2009



Bringmann, Scott, Akram 2011







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

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

Conclusion

For small scale structures (sub pc) in WIMP dark matter scenario, the history of early universe and the detailed property of DM is important.

The WIMP isocurvature perturbations provide the source of small scale structure for the scales that enter the horizon before kinetic decoupling.

Low reheating temperature scenario can provide such (effective) initial isocurvature perturbations, so that the smaller scale objects, which are highly suppressed in standard cosmology, can be sizable : Proving early universe

In such a case, the UCMH, DM annihilation mediated by a light mediator, sizable elastic scattering to the nucleons can give the observable signature.