Late Kinetic Decoupling from Dark Matter - Dark Radiation Scattering

Håvard Tveit Ihle,
Institute of Theoratical Astrophysics,
University of Oslo

Based on 1603.04884,
with T.Bringmann, J. Kersten and P. Walia

DSU Bergen, July 27, 2016

Overview

Motivation

1. Kinetic Decoupling of Dark Matter
2. Late Kinetic Decoupling of Dark Matter
   - General Considerations
   - Examples of Models

Conclusion

Motivation

- Small-scale problems in ΛCDM
- Dark acoustic oscillations can wash out structure on small scales. May address *missing satellite problem*
- SIDM can be relevant for other small-scale problems

Kinetic Decoupling of Dark Matter

Kinetic equilibrium between DM and DR

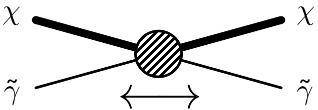
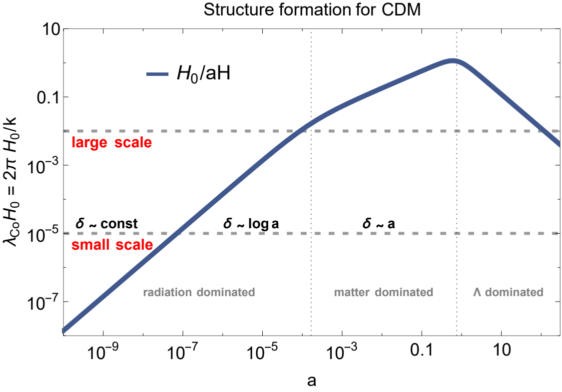


Figure 1: Processes that maintain kinetic equilibrium

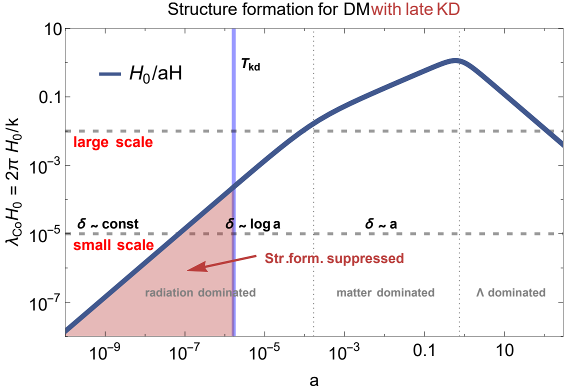
- χ = Dark Matter
- $\tilde{\gamma}$ = Rel. heat bath particle (SM or DR)
- Kinetic eq. $\rightarrow T_\chi = T_{\tilde{\gamma}}$, $(T_\chi \equiv \frac{2}{3}\langle p_\chi^2/2m_\chi\rangle)$
- As DM interacts with $\tilde{\gamma}$. The resulting pressure washes out DM overdensities

Kinetic decoupling of DM

- Scattering rate: $\Gamma \approx v\sigma n_{\tilde{\gamma}}$
- Kinetic decoupling at $\Gamma \sim N_{coll} H$
- $N_{coll} \approx m_\chi / T_{\text{kd}}$
- Typical WIMP candidates: $T_{\text{kd}} \gtrsim \text{MeV}$
- KD decides the size of the smallest DM structures today
- $M_{\text{cut}} \approx \frac{4\pi}{3} \frac{\rho_\chi(T_{\text{kd}})}{H(T_{\text{kd}})^3} \approx 7 \cdot 10^{10} M_\odot \left(\frac{T_{\text{kd}}}{100eV} \right)^{-3}$

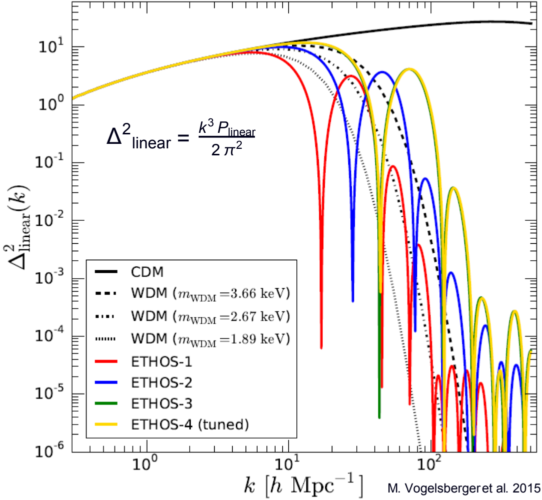


Structure formation for CDM
H_0/aH
large scale
small scale
δ ~ const
δ ~ log a
δ ~ a
radiation dominated
matter dominated
Λ dominated
$\lambda_{Co}H_0 = 2\pi\, H_0/k$
a
10
0.1
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
0.1
10



Structure formation for DM with late KD
H_0/aH
T_{kd}
large scale
small scale
$\delta \sim$ const
$\delta \sim \log a$
$\delta \sim a$
Str.form. suppressed
radiation dominated
matter dominated
Λ dominated
$\lambda_{Co} H_0 = 2\pi\, H_0/k$
10
0.1
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
0.1
10
a

Linear Matter Power Spectrum



M. Vogelsberger et al. 2015

Late Kinetic Decoupling of Dark Matter

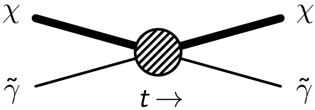
Previous work

- DM coupling to (sterile-) neutrinos:
  - Aarssen, Bringmann, and Pfrommer, 2012
  - Shoemaker, 2013
  - Bringmann, Hasenkamp, and Kersten, 2014
  - Dasgupta and Kopp, 2014
  - Ko and Tang, 2014
  - Cherry, Friedland and Shoemaker, 2014
  - Bertoni et al., 2014
  - Binder et al., 2016
- Other work on late KD:
  - Chu and Dasgupta, 2014
  - Vogelsberger et al., 2015 (ETHOS)
  - Cyr-Racine et al., 2015 (ETHOS)
  - Tang, 2016

Our goal

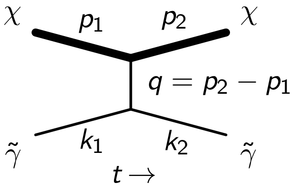
- Classify "all" models that result in late kinetic decoupling ($T_{\text{kd}} \sim$ keV)
- Include constraints on model properties:
  - Get correct relic density (at least not deplete the relic density) $\rightarrow \alpha/m_\chi \lesssim 10^{-5}\text{GeV}^{-1}$
  - If $\tilde{\gamma} =$ Extra radiation $\rightarrow \Delta N_{\text{eff}} \rightarrow$ constraint on $\xi = T_{\tilde{\gamma}}/T$
  - Not too much self interaction, $\chi\chi \rightarrow \chi\chi$ (a little bit is good though!)

Scattering



- In order to get a later kinetic decoupling (i.e. $T_{\text{kd}} \sim$ keV) we typically want to enhance the scattering amplitude
- One way to do this, is to put a virtual particle almost "on-shell"
- Can be done in the t- or the s/u-channels

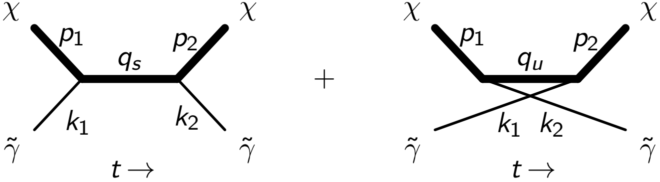
t-channel Enhancement



$$\mathcal{M} \propto \frac{1}{t - m_{\text{med}}^2}$$

- $p_2 - p_1$ is small, so if m_{med} is also small, this will give a large enhancement

s/u-channel Enhancement

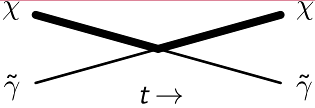


$$\mathcal{M} \propto \frac{1}{s - m_{\text{med}}^2} + \frac{1}{u - m_{\text{med}}^2}$$

- $s \approx u \approx m_\chi^2 \rightarrow$ enhanced if $m_{\text{med}} \sim m_\chi$

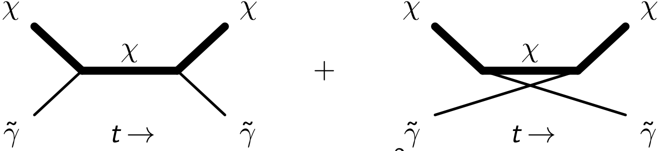
Examples of Models

Simplest Possible Model™



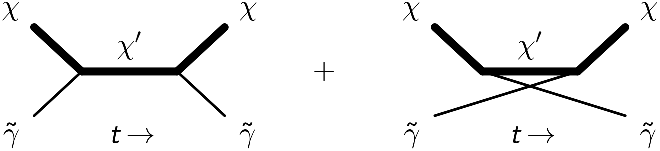
- Four point vertex with scalar χ and scalar $\tilde{\gamma}$
- *Can* result in late kinetic decoupling, but relic density depletion $\rightarrow m_\chi \lesssim 1$ MeV
- How small mass we need also depends strongly on $\xi = T_{\tilde{\gamma}}/T$
- Free-streaming important for $m_\chi \ll$ MeV

2-Particle Models in the s/u-channels



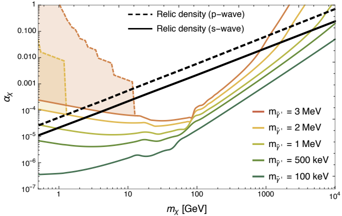
- $|\mathcal{M}_s|^2 \sim |\mathcal{M}_u|^2 \propto (m_\chi/\omega)^2$
- But! In QM, add *amplitudes*, *then* square
- $\mathcal{M}_s \approx -\mathcal{M}_u \rightarrow$ leading terms vainsh!
- $|\mathcal{M}|^2 \sim \alpha^2$ (boring)
- Strong SI constraints $\rightarrow T_{\rm kd} \gg$ keV

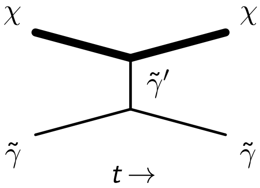
3-Particle Models in the s/u-channels



- $|\mathcal{M}|^2 \sim m_\chi^2/\Delta m^2$ or $\omega^2/\Delta m^2$.
- $\Delta m \equiv m_{\chi'} - m_\chi$
- $m_\chi \gg \Delta m \gg \omega \gg m_{\tilde{\gamma}}$
- Works for late kinetic decoupling and relic density, but usually negligible self-interaction

3-Particle Models in t-channel





- New light mediator particle $\tilde{\gamma}'$
- $m_\chi \gg m_{\tilde{\gamma}'} \gg \omega \gg m_{\tilde{\gamma}}$
- Late kinetic decoupling + SI + RD !

Conclusion

- Dark acoustic oscillations from LKD can possibly address *missing satellites problem*
- LKD can be achieved by putting a virtual particle "on-shell", or reducing m_χ
- Self-interaction constraints severely restrict $\chi - \chi - \tilde{\gamma}$ coupling
- LKD simplified model classification: Significantly extended the list of options discussed so far in the literature
- More detailed study still needed

Thank you !