Late Kinetic Decoupling from Dark Matter - Dark Radiation Scattering

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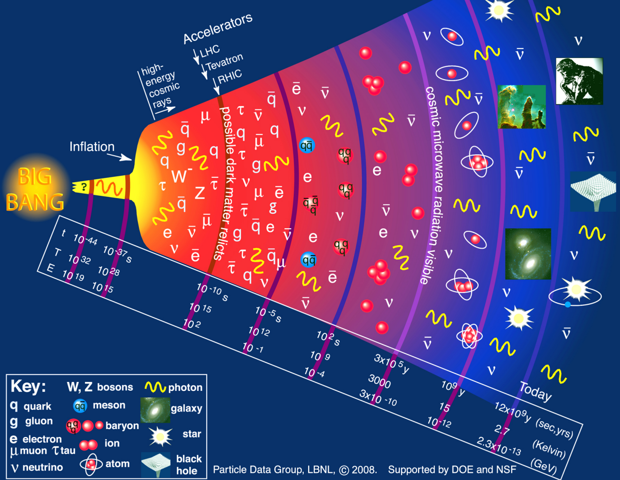
Overview

Motivation

- Particle dark matter (DM) is a first step beyond the standard models of both particle physics and cosmology
- 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

History of the Universe



Equlibrium Thermodynamics

- Universe expands and cools, $T \sim 1/a$
- $T \equiv T_\gamma$
- At high temperatures (possibly) all particles in thermal equilibrium
- Equilibrium as long as:

Interaction Rate		Expansion Rate
Γ	$\gg$	H

Back of the Envelope Estimates

$$(\hbar = c = k_B = 1)$$

$$f_i^{\text{eq}}(p, T) = \frac{1}{e^{\frac{E_i(p)}{T}} \pm 1} \quad (\mu_i \approx 0)$$

$$n_i^{\text{eq}}(T) \sim T^3 \quad \text{(Relativistic)}$$

$$\rho_i^{\text{eq}}(T) \sim T^4 \quad \text{(Relativistic)}$$

$$n_i^{\text{eq}}(T) \sim e^{-m_i/T} \quad \text{(Non-Relativistic)}$$

$$H \sim T^2/M_{Pl} \quad \text{(Radiation Dominated)}$$

Chemical and Kinetic equilibrium

- Useful to decompose thermodynamic equilibrium into two parts, *chemical equilibrium* and *kinetic equilibrium*
- Chemical eq:

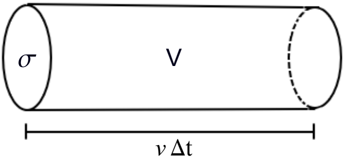
$$n_i = n_i^{\text{eq}}$$

- Kinetic eq:

$$f_i = \kappa f_i^{\text{eq}}, \ \ (T_i = T^{\text{eq}})$$

$$(\kappa = n_i / n_i^{\text{eq}})$$

Interaction Rate



- $V = \sigma v \Delta t$

$$\Gamma = \frac{\text{number of scatterings}}{\Delta t} = \frac{Vn}{\Delta t} = \sigma v n$$

Chemical Decoupling

Chemical Decoupling of Dark Matter

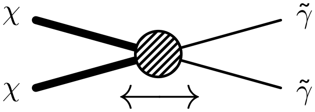
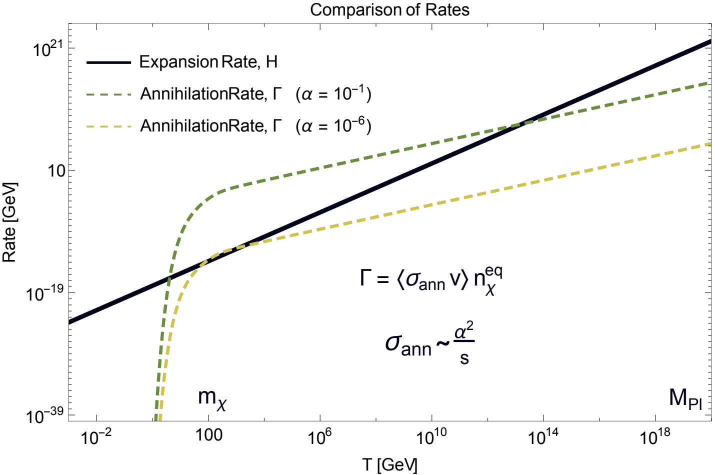
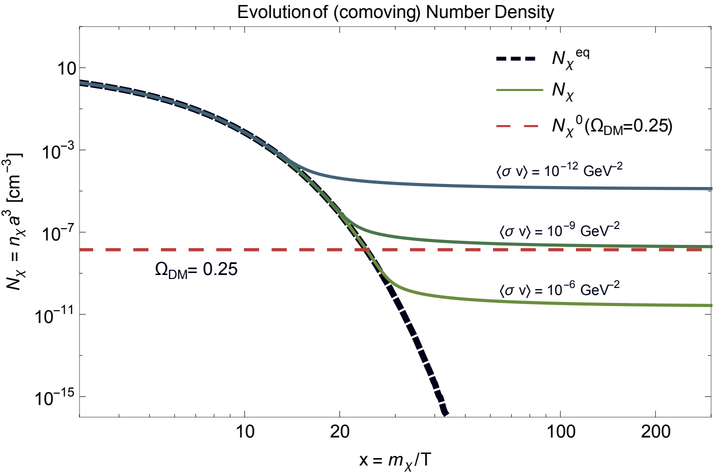


Figure 1: Processes that maintain chemical equilibrium

- $\tilde{\gamma}$ = Heat bath particle (SM or DR)
- Decoupling at $\Gamma_{\text{ann}} \sim H$



Comparison of Rates
Expansion Rate, H
AnnihilationRate, Γ (α = 10^−1)
AnnihilationRate, Γ (α = 10^−6)
Γ = ⟨σ_ann v⟩ n_χ^eq
σ_ann ~ α²/s
m_χ
M_Pl
Rate [GeV]
T [GeV]
10^21
10
10^−19
10^−39
10^−2
100
10^6
10^10
10^14
10^18



Evolution of (comoving) Number Density
N_χ^{eq}
N_χ
$N_\chi^{0}(\Omega_{DM}=0.25)$
$\langle\sigma v\rangle = 10^{-12}$ GeV^{-2}
$\langle\sigma v\rangle = 10^{-9}$ GeV^{-2}
$\langle\sigma v\rangle = 10^{-6}$ GeV^{-2}
Ω_{DM}= 0.25
$N_\chi = n_\chi a^3$ [cm^{-3}]
10
10^{-3}
10^{-7}
10^{-11}
10^{-15}
10
20
100
200
$x = m_\chi/T$

Kinetic Decoupling

Kinetic decoupling of DM

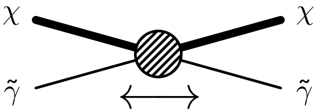


Figure 2: Processes that maintain kinetic equilibrium

- $\Gamma \approx v\sigma n_{\tilde{\gamma}}$
- Still relevant since $n_{\tilde{\gamma}} \gg n_{\chi}$
- Kinetic decoupling at $\Gamma \sim N_{coll} H$
- $N_{coll} \approx m_{\chi}/T$
- Typical WIMP candidates: $T_{\rm kd} \sim$ MeV

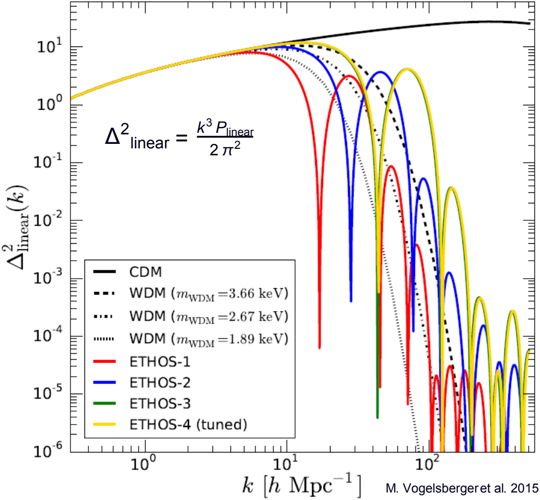
Structure formation in one slide

- Small initial overdensities of matter tend to grow
- Pressure counteracts this effect and tries to wash out overdensities
- Only overdensities on scales smaller than the horizon, $l_h \sim 1/H$ can grow
- CDM $\rightarrow$ no pressure $\rightarrow$ maximal growth of overdensities

Kinetic decoupling of DM

- $T_\chi \equiv \frac{2}{3}\langle p_\chi^2/2m_\chi\rangle$
- Kinetic equilibrium $\rightarrow T_\chi = T$
- DM still interacts with $\tilde{\gamma}$. The resulting pressure washes out DM overdensities
- Decides the size of the smallest DM structures today
- $M_{\text{cut}} \approx \frac{4\pi}{3}\frac{\rho_\chi(T_{\text{kd}})}{H(T_{\text{kd}})^3} \approx 7 \cdot 10^{10} M_\odot \left(\frac{T_{\text{kd}}}{100eV}\right)^{-3}$

Linear Matter Power Spectrum



M. Vogelsberger et al. 2015

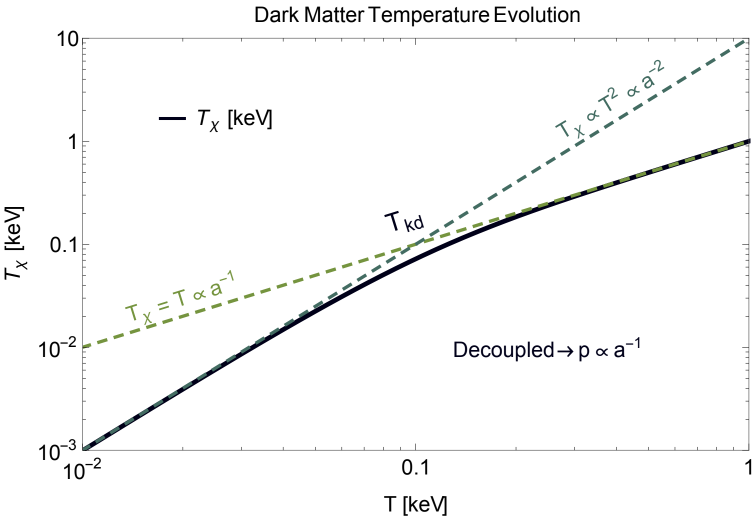
Boltzmann Equation for Kinetic Decoupling

- Multiply full BE with $p^2/2m_\chi$ and integrate over p to get BE for temperature:

$$\frac{dT_\chi}{dT} - 2\frac{T_\chi}{T} = \frac{\gamma(T)}{H(T)}(T_\chi - T)$$

- Momentum transfer rate:

$$\gamma(T) = \frac{1}{48\pi^3 g_\chi m_\chi^3} \int d\omega f_{\tilde{\gamma}}(\omega, T) \partial_\omega (k^4 \left\langle |\mathcal{M}|^2 \right\rangle_t)$$



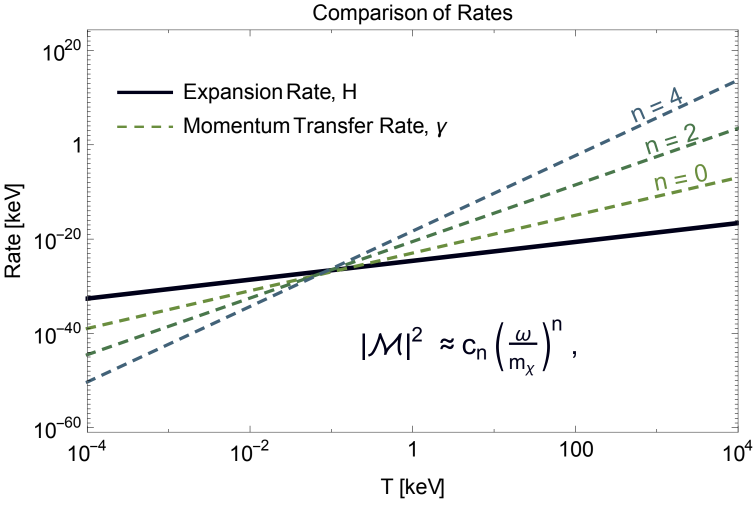
Dark Matter Temperature Evolution
T_χ [keV]
$T_\chi \propto T^2 \propto a^{-2}$
T_{kd}
$T_\chi = T \propto a^{-1}$
Decoupled → $p \propto a^{-1}$
T_χ [keV]
T [keV]
10
1
0.1
10^{-2}
10^{-3}
10^{-2}
0.1
1

Scattering Amplitude Squared

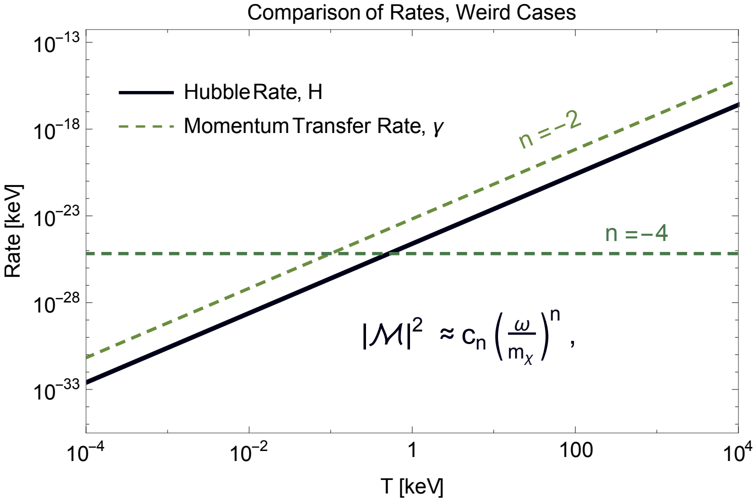
- In the limit where $m_\chi \gg \omega \gg m_{\tilde{\gamma}}$ we can often approximate the amplitude

$$|\mathcal{M}|^2 \approx c_n \left(\frac{\omega}{m_\chi}\right)^n$$

- For $n > -1$ we can then solve the BE analytically for T_{kd}



Comparison of Rates
Expansion Rate, H
Momentum Transfer Rate, γ
n = 4
n = 2
n = 0
$|\mathcal{M}|^2 \approx c_n \left(\frac{\omega}{m_\chi}\right)^n$,
Rate [keV]
T [keV]
10^{20}
1
10^{-20}
10^{-40}
10^{-60}
10^{-4}
10^{-2}
100
10^{4}



Comparison of Rates, Weird Cases
Hubble Rate, H
Momentum Transfer Rate, γ
n = −2
n = −4
$|\mathcal{M}|^2 \approx c_n \left(\frac{\omega}{m_\chi}\right)^n$,
Rate [keV]
T [keV]
10^{-13}
10^{-18}
10^{-23}
10^{-28}
10^{-33}
10^{-4}
10^{-2}
1
100
10^{4}

Important Caveat

- $T \not\propto 1/a$
- Photon bath heated by annihilating particles, as particles become non-relativistic
- If $\tilde{\gamma}$ is also decoupled (dark radiation), we generally expect $T_{\tilde{\gamma}} \neq T$.
- We take this into account by introducing

$$T_{\tilde{\gamma}} = \xi T$$

Important Caveat

- Entropy conservation:
  $\frac{d}{dt}(s\,a^3) = 0 \to T \propto g_*^{-1/3}(T)/a$
- $g_* = N_{\text{Bosons}}^{\text{rel.dof}} + 7/8 \times N_{\text{Fermions}}^{\text{rel.dof}}$
- $\xi \equiv \left(\frac{g_{*\text{dec}}^{\text{dark}} g_*^{\text{visible}}}{g_*^{\text{dark}} g_{*\text{dec}}^{\text{visible}}}\right)^{1/3}$
- Example $T_\nu = \left(\frac{2}{2+4\times 7/8}\right)^{1/3} T$

Late Kinetic Decoupling of Dark Matter

Suppressing structure formation at dwarf galaxy scales and below: late kinetic decoupling as a compelling alternative to warm dark matter

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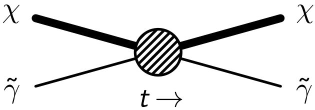
arXiv:1603.04884

Goals for Model Building

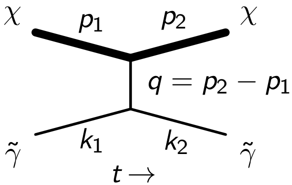
- Classify "all" models that result in late kinetic decoupling ($T_{\mathrm{kd}} \sim$ keV)
- Include constraints on model properties:
  - Get correct relic density (at least not deplete the relic density) $\rightarrow \alpha/m_\chi \lesssim 10^{-5}\mathrm{GeV}^{-1}$
  - $\tilde{\gamma} =$ Extra radiation $\rightarrow \Delta N_{\mathrm{eff}} \rightarrow$ constraint on ξ
  - 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 we want to enhance the scattering amplitude
- One way to do this, is to put a virtual particle almost "on-shell"
- We do this in the t-channel or the s/u-channels

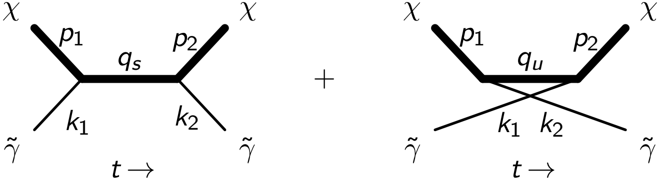
t-channel Enhancement



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

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

s/u-channel Enhancement

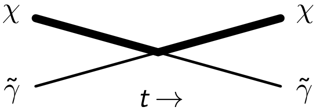


$$\mathcal{M} \propto \frac{1}{s - m_{\text{med}}^2} + \frac{1}{u - m_{\text{med}}^2}$$

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

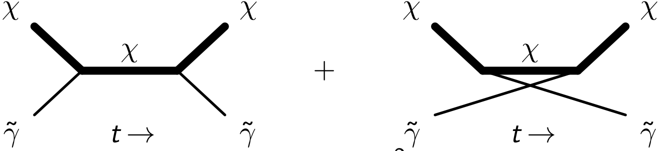
2-Particle models

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 $\xi = T_{\tilde{\gamma}}/T$

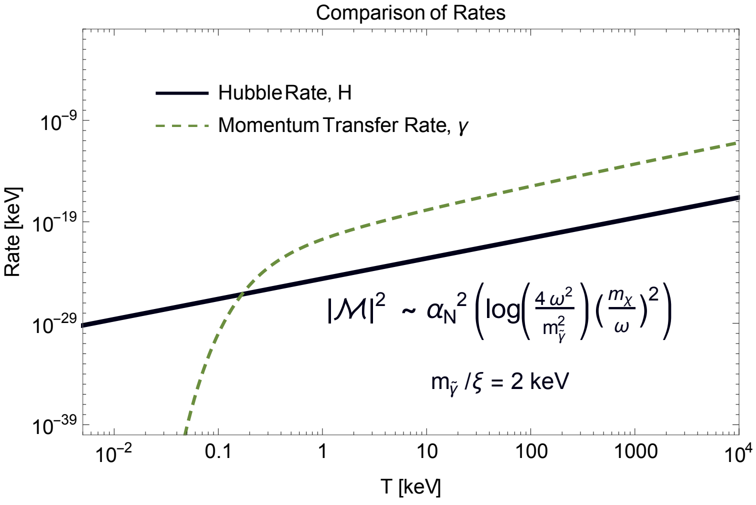
2-Particle Models in the s/u-channels



- $|\mathcal{M}_s|^2 \sim |\mathcal{M}_u|^2 \propto (m_\chi/\omega)^2$
- 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 $\rightarrow T_{\text{kd}} \gg$ keV

Dark Gluons

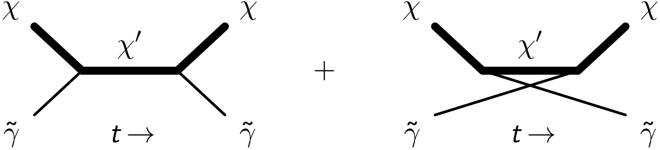
- Fermion or scalar χ charged under $SU(N)$ gauge symmetry
- $\tilde{\gamma}$ = dark gluons
- Interesting model with $|\mathcal{M}|^2 \propto (m_\chi/\omega)^2$ (almost)
- Need small coupling α_N to avoid confinement etc.



Comparison of Rates
Hubble Rate, H
Momentum Transfer Rate, γ
$|\mathcal{M}|^2 \sim \alpha_N^2 \left(\log\left(\frac{4\omega^2}{m_{\tilde{\gamma}}^2}\right)\left(\frac{m_\chi}{\omega}\right)^2\right)$
$m_{\tilde{\gamma}}/\xi$ = 2 keV
Rate [keV]
T [keV]
10^{-9}
10^{-19}
10^{-29}
10^{-39}
10^{-2}
0.1
1
10
100
1000
10^4

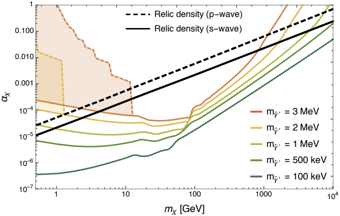
3-Particle models

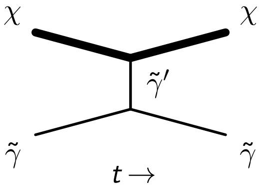
3-Particle Models in the s/u-channels



- $|\mathcal{M}|^2 \sim m_\chi^2/\Delta m^2$ 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
- Some interesting 2-particle models, and a large class of working 3-particle models
- More detailed study still needed

Thank you !