Thermal decoupling in dark matter models with Sommerfeld-enhanced annihilation rates

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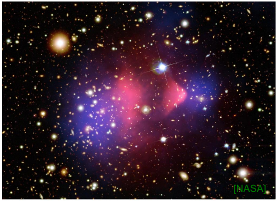
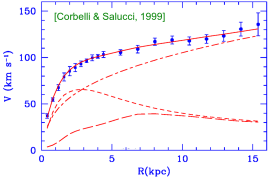
Outline

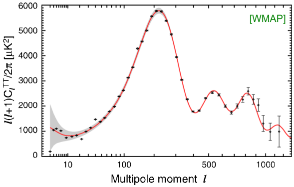
1. Thermal evolution of WIMPs
2. Leptophilic model
3. Evolution of DM after Kinetic Decoupling
4. Summary and outlook

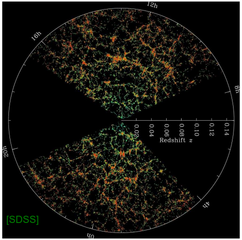
Dark matter and WIMPs

Evidence for Dark Matter is abundant









Properties

- non-baryonic
- collisionless
- electrically neutral
- cold
- $\Omega_{CDM} = 0.233 \pm 0.013$

Well motivated candidate:

Weakly
Interacting
Massive
Particle

The WIMP miracle and relic density

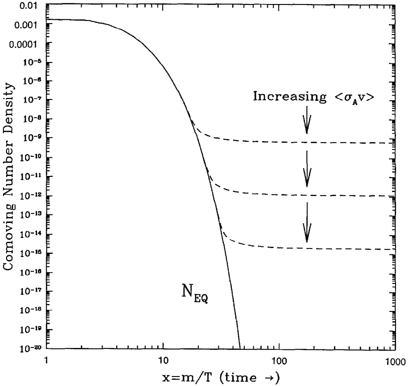
Evolution of WIMP number density

1st moment of Boltzmann equation:

$$\frac{dn_\chi}{dt}+3Hn_\chi = -\langle \sigma v_{\rm rel}\rangle \left(n_\chi^2 - n_{\chi,\rm eq}^2\right)$$

'Freeze out' or **Chemical decoupling**

when annihilation rate falls behind expansion rate.

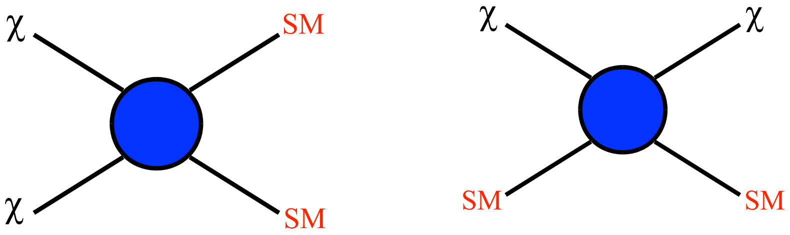


[Jungman, Kamionkowski, Griest, '96]

Relic density today

$$\Omega_\chi \sim \frac{3\times 10^{-26}\text{cm}^3/\text{s}}{\langle \sigma v_{\rm rel}\rangle} \sim \mathcal{O}(1) \text{ for WIMPs}$$

Chemical vs. Kinetic decoupling



Chemical decoupling

- annihilation
- decreases n_χ
- n_χ Boltzmann suppressed
- $x_{\mathrm{CD}} = \frac{m_\chi}{T_{\mathrm{CD}}} \sim 25$

Kinetic decoupling

- scattering
- keeps DM in thermal equilibrium with heat bath
- SM particles abundant
- $x_{\mathrm{KD}} > x_{\mathrm{CD}}$

Kinetic decoupling and WIMP temperature

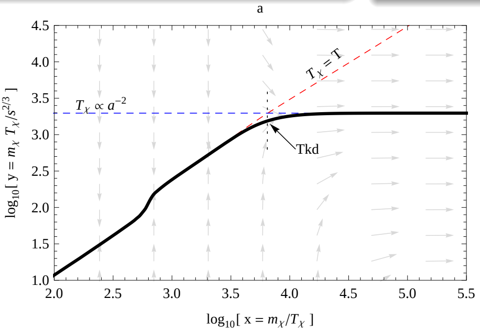
Define WIMP 'temperature'

$$T_\chi \equiv \frac{g_\chi}{3 m_\chi n_\chi} \int \frac{d^3 p}{(2\pi)^3} \vec{p}^2 f(\vec{p})$$

Evolution of $y \equiv m_\chi T_\chi s^{-2/3}$

2nd moment of Boltzmann equation:

$$\frac{y'}{y} = -\left(1 - \frac{x}{3}\frac{g'_{*S}}{g_{*S}}\right) \frac{2 m_\chi c(T)}{Hx} \left(1 - \frac{y_{eq}}{y}\right)$$



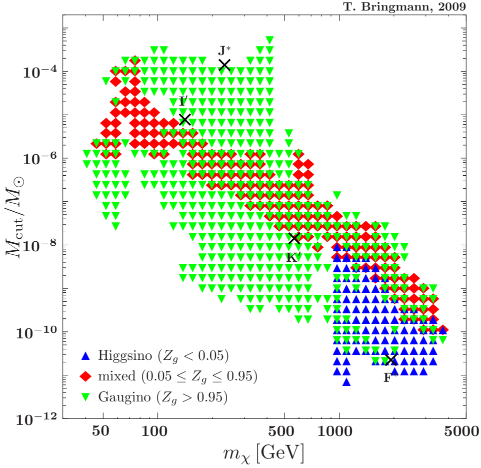
Decoupling almost instantaneous:

$$x_\chi \simeq \begin{cases} x & x < x_{KD} \\ x^2 / x_{KD} & x \geq x_{KD} \end{cases}$$

The smallest protohaloes

Free streaming of WIMPs after kinetic decoupling

- washes out density fluctuations on small scales (like baryonic oscillations)
- translates to mass-scale $M_{\rm cut}$ of smallest gravitationally bound objects
- depends strongly on particle physics $\Rightarrow$ not necessarily $M_{\rm cut} \sim 10^{-6} M_\odot$!



Leptophilic model

Motivation

Lepton excess in PAMELA (e^+)

Problems

- need σ larger than allowed by relic density today
- large annihilation into high energy leptons
- small annihilation into quarks (no excess antiprotons seen)

Concept [Arkani-Hamed et al., 2009]

- heavy DM particle χ ($m_\chi = 100$ GeV - 5 TeV)
- χ only couples to light boson ϕ ($m_\phi = 100$ MeV - 5 GeV), no direct coupling to SM
- small m_ϕ prohibits decay into (heavy) hadronic channels

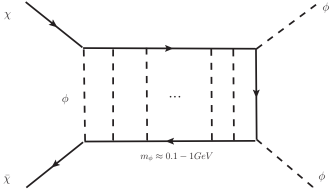
Sommerfeld enhancement

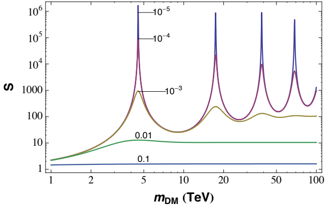
Generic mechanism in non-relativistic particle annihilation

- repeated exchange of virtual particles (ladder diagram)
- enlarges 'bare' cross section by enhancement factor S

$$\sigma = S\sigma_0$$

- Resonances expected near bound states
  - $S \propto 1/v$ off-resonance
  - $S \propto 1/v^2$ on-resonance

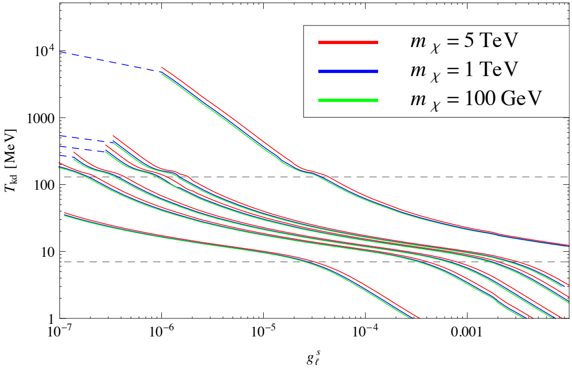




[Lattanzi & Silk, 2009]

Kinetic decoupling for a leptophilic model

PRELIMINARY!



top to bottom:

$$m_\phi(\text{MeV}) = \begin{cases} 5000 \\ 1000 \\ 800 \\ 500 \\ 360 \\ 100 \end{cases}$$

- $M_{\text{cut}}/M_\odot \approx 10^{-12}$ to 1
- See also [Pinzke, Pfrommer, Bergstrom, 2011]

Reentering an era of annihilation I

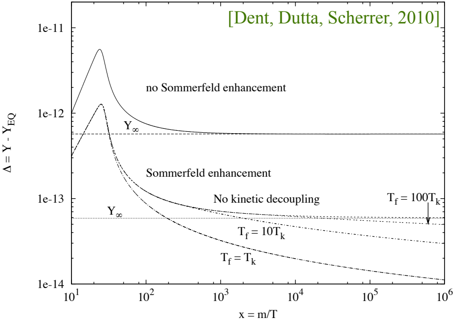
Evolution of relic density $Y = \frac{n_\chi}{s}$

$$\frac{dY}{dx} = -\lambda x^{-2}\left(Y^2 - Y_{\rm eq}^2\right)$$

where $\langle \sigma v_{\rm rel}\rangle = \sigma_0$ for s-waves, and $\lambda \propto \sigma_0$

Include Sommerfeld factor

- $S \sim 1/v \sim x_\chi^{1/2}$
- After kinetic decoupling: $x_\chi \simeq x^2/x_{\rm KD}$
- $\Rightarrow S \sim x$



Reentering an era of annihilation II

More general approach

For a full understanding of evolution of T_χ and n_χ in this regime, solve system of coupled differential equations:

$$
\begin{aligned}
\frac{Y'}{Y} &= -\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{Hx}\frac{2}{g_\chi} sY \left.\langle \sigma v_{\mathrm{rel}}\rangle\right|_{x=m_\chi^2/(s^{2/3}y)} \\
\frac{y'}{y} &= -\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{Hx}\left[2m_\chi c(T)\left(1-\frac{y_{\mathrm{eq}}}{y}\right)\right. \\
&\qquad \left. -\frac{2}{g_\chi} Ys\Big(\langle \sigma v_{\mathrm{rel}}\rangle - \langle \sigma v_{\mathrm{rel}}\rangle_2\Big)_{x=m_\chi^2/(s^{2/3}y)}\right]
\end{aligned}
$$

Conclusions

Summary

- Chemical decoupling $\neq$ kinetic decoupling
- Kinetic decoupling temperature T_{KD} translates to a small-scale cutoff M_{cut} for the protohalo mass, which is model dependent.
- DM annihilations can continue after kinetic decoupling when the cross section is Sommerfeld enhanced.

Outlook

- Paper coming soon...

Thank you for your attention!