Interacting Dark Matter and Radiation in Cosmology

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Dark Matter Evidence

- Rotation Curves of Galaxies
- Gravitational Lensing
- Large Scale Structure
- CMB anisotropies, …

All confirmed evidence comes from gravitational interaction, consistent with DM as particle

CDM: negligible velocity, WIMP
WDM: keV sterile neutrino
HDM: active neutrino
Merger History of Dark Halo

• standard picture
• DM halo grow hierarchically
• first small scale structures form
• then merge into larger halo

The formation history of a dark matter halo can be described by a 'merger tree' that traces all its progenitors, as illustrated in Fig. 1.3. Such merger trees play an important role in modern galaxy formation theory. Note, however, that illustrations such as Fig. 1.3 can be misleading. In CDM models part of the growth of a massive halo is due to merging with a large number of much smaller halos, and to a good approximation, such mergers can be thought of as smooth accretion. When two similar mass dark matter halos merge, violent relaxation rapidly transforms the orbital energy of the progenitors into the internal binding energy of the quasi-equilibrium remnant. Any hot gas associated with the progenitors is shock-heated during the merger and settles back into hydrostatic equilibrium in the new halo. If the progenitor halos contained central galaxies, the galaxies also merge as part of the violent relaxation process, producing a new central galaxy in the final system. Such a merger may be accompanied by strong star formation or AGN activity if the merging galaxies contained significant amounts of cold gas. If two merging halos have very different mass, the dynamical processes are less violent. The smaller system orbits within the main halo for an extended period of time during which two processes compete to determine its eventual fate. Dynamical friction transfers energy from its orbit to the main halo, causing it to spiral inwards, while tidal effects remove mass from its outer regions and may eventually dissolve it completely (see Chapter 12). Dynamical friction is more effective for more massive satellites, but if the mass ratio of the initial halos is large enough, the smaller object (and any galaxy associated with it) can maintain its identity for a long time. This is the process for the build-up of clusters of galaxies: a cluster may be considered as a massive dark matter halo hosting a relatively massive galaxy near its center and many satellites that have not yet dissolved or merged with the central galaxy.
Weakly Interacting Massive Particle (WIMP)

- Mass around $\sim 100\text{GeV}$
- Coupling $\sim 0.5$
- Correct relic abundance $\Omega \sim 0.3$
- Thermal History
  - Equilibrium XX$\leftrightarrow$ff
  - Equilibrium XX $\Rightarrow$ff
  - Freeze-out
- Cold Dark Matter (CDM)
$\Lambda$CDM: successful on large scales

Hlozek et al. 2012
(Self-)**Interacting dark matter**
Why?

• Theoretically interesting
  • Atomic DM, Mirror DM, Composite DM
• Eventually, all DM is *interacting* in some way, the question is how strongly?
  • Self-Interacting DM \( \frac{\sigma}{M_X} \sim \text{cm}^2/\text{g} \sim \text{barn}/\text{GeV} \)

• Possible new testable signatures
  • LSS, CMB, BBN,
  • other astrophysical effects,…

• Solution of CDM controversies
CDM Controversies on small scales?

- Cusp-vs-Core problem
- Missing satellites problem
- To-big-to-fail problem

tensions between *simulations* and *observations*

Be cautious!

*No consensus*, simulations are very complicated when including baryon effects.
Cusp vs. Core

DM density profiles

Angle from the GC [degrees]

10'' 30'' 1' 5' 10' 30' 1° 2° 5° 10° 20° 45°

$\rho_{DM}$ [GeV/cm$^3$]

$\rho_{\odot}$

$10^{-3}$ $10^{-2}$ $10^{-1}$ 1 10 100

$r_{\odot}$

$r$ [kpc]

galaxy F568-3

Cusp profiles, such as NFW, are predicted by N-body simulation of CDM

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“missing satellites” problem

- Projected dark matter distribution of a simulated CDM halo.
- The numerous small subhalos far exceed the number of known Milky Way satellites.
- Circles mark the nine most massive subhalos.
“too-big-to-fail” problem

- Right Panel: Observed circular velocity of the nine bright dSphs, along with rotation curves corresponding to NFW subhalo. The central densities of the sub halos are too high to host the dwarf satellites, predicting stellar velocity dispersions higher than observed.
Possible solutions

• Baryonic physics:
  gas cooling, star formation, supernova feedback,…

• Dark Matter:
  warm dark matter
  Decaying DM
  Self-Interacting DM

What is SIDM?

• **Strongly-Interacting Dark Matter?** or
• **Self-Interacting Dark Matter?**

More concretely, it refers the scenarios that

• DM-DM scattering cross section is around
  \[
  \frac{\sigma}{M_X} \sim \text{cm}^2/\text{g} \sim \text{barn}/\text{GeV}
  \]

• It can still be simple \(\varphi^3, \varphi^4\), even \(\varphi^5\) with \(M\sim O(100\text{MeV})\)

• composite DM, atomic DM…
WIMP as SIDM?

- DM-DM scattering cross section is around
  \[ \frac{\sigma}{M_X} \sim \text{cm}^2/\text{g} \sim \text{barn/GeV} \]
- It can still be the usual WIMP

\[
\begin{align*}
\sigma_{\text{SI}} & \sim \frac{\alpha^2}{m^2_\phi} \\
\sigma_{\text{ann}} & \sim \frac{\alpha^2}{M^2_X}
\end{align*}
\]
**Effects**

Spergel, Steinhardt (2000)

- In-falling dark matter is scattered before reaching the center of the galaxy. These collisions increase the entropy of the dark matter phase space distribution and lead to a dark matter halo profile with a shallower density profile.

- It can flatten the halo centre, solving the *cusp-vs-core* and *too-big-to-fail* problems. **But not “Missing Satellites” problem!**

- MeV mediator can provide the right elastic scattering cross section for TeV dark matter

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**Diagram:**

- In-falling dark matter is scattered before reaching the center of the galaxy.
- These collisions increase the entropy of the dark matter phase space distribution and lead to a dark matter halo profile with a shallower density profile.

**Figure 4,** based on Rocha et al. (2013), compares the structure and substructure are similar, but the SIDM halo is...
Radiation

- ultra relativistic particle $E \gg m$
- photon (CMB)
- neutrino when $T \gg m$
- light sterile neutrino
- ....

Extra radiation, $N_{\text{eff}}$, $N_{\text{eff}} = 3.046$ for neutrinos in standard cosmology
Cosmological Bounds

- Extra radiation contributes as hot dark matter, constrained by BBN, CMB, LSS

Joint CMB+BBN, 95% CL preferred ranges

$$N_{\text{eff}} = \begin{cases} 
  3.11^{+0.59}_{-0.57} & \text{He+Planck TT+lowP,} \\
  3.14^{+0.44}_{-0.43} & \text{He+Planck TT+lowP+BAO,} \\
  2.99^{+0.39}_{-0.39} & \text{He+Planck TT,TE,EE+lowP,} 
\end{cases}$$

Constraints on sterile neutrino mass

$$N_{\text{eff}} < 3.7$$

$$m_{\nu, \text{sterile}}^{\text{eff}} < 0.52 \text{ eV}$$

95%, Planck TT+lowP+lensing+BAO.
Cosmological Evolution

- all components are connected by Einstein’s equation
  \[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

- first-order perturbation of Boltzmann equation
  - anisotropy in CMB
  - power spectrum for LSS
Cosmological Evolution

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• first-order perturbation of Boltzmann equation
  • anisotropy in CMB
  • power spectrum for LSS

• (Self-)Interaction sometimes also matters
Late Kinetic Decoupling

Interaction with relativistic particles can induce a cut-off in the matter power spectrum by collisional damping, solving the “missing satellites” problem.

Y.Tang, arXiv.1603.00165

Matter Power Spectrum

\[
\delta_X = -\theta_X + 3\dot{\Phi},
\]

\[
\dot{\theta}_X = k^2\dot{\Psi} - H\theta_X + R^{-1}\Gamma_X (\theta_X - \theta_X),
\]

\[
\dot{\theta}_X = k^2\dot{\Psi} + k^2 (\delta_X/4 - \sigma_X) - \Gamma_X (\theta_X - \theta_X)
\]
Simulation

- DM-γ/v interaction $\sim 2 \times 10^{-9} \sigma_{Th} (m_{DM}/GeV)$

Boehm, Schewtschenko, Wilkinson, Baugh and Pascoli, 1404.7012
Interacting Radiation

- free-streaming

\[ \delta_v = -\frac{4}{3} \theta_v + 4\phi , \]
\[ \dot{\theta}_v = k^2 \left( \frac{1}{4} \delta_v - \sigma_v \right) + k^2 \psi , \]
\[ \dot{F}_{vl} = \frac{k}{2l+1} [lF_{v(l-1)} - (l + 1)F_{v(l+1)}] , \]

- perfect fluid \( \Gamma \gg \mathcal{H} \)

\[ \delta_v = -\frac{4}{3} \theta_v + 4\phi , \]
\[ \dot{\theta}_v = k^2 \left( \frac{1}{4} \delta_v - \sigma_v \right) + k^2 \psi , \quad \sigma_v = 0 \]
Dark U(1)

P.Ko, YT, 1404.0236(PLB)

We introduce two right-handed gauge singlets, a dark sector with an extra U(1)x gauge symmetry

\[
\mathcal{L} = \mathcal{L}_{SM} + \bar{N}_i i \phi N_i - \left( \frac{1}{2} m_{ij}^{R} \bar{N}_i N_j + y_{\alpha i} \bar{L}_\alpha H N_i + h.c \right) - \frac{1}{4} \hat{X}_{\mu \nu} \hat{X}^{\mu \nu} - \frac{1}{2} \sin \epsilon \hat{X}_{\mu \nu} \hat{B}^{\mu \nu} \\
+ \bar{\chi} (i \not{D} - m_\chi) \chi + \bar{\psi} (i \not{D} - m_\psi) \psi + D^\dagger_\mu \phi X D^\mu \phi X - \left( f_i \phi X \bar{N}_i \psi + g_i \phi X \bar{N}_i \psi \right) + h.c \\
- \lambda_\phi \left[ \left( \phi X \phi X - \frac{v_\phi^2}{2} \right) \right]^2 - \lambda_{\phi H} \left[ \left( \phi X \phi X - \frac{v_\phi^2}{2} \right) \right] \left[ H^\dagger H - \frac{v_h^2}{2} \right],
\]

\( v_\phi \sim \mathcal{O} \ (\text{MeV}) \)
A Toy Model


- fermionic DM $\psi$ and scalar radiation $\phi$

$$\delta L = \bar{\psi}(i\gamma^\mu - m_\psi)\psi - \bar{\psi}(g_i^s + ig_i^p\gamma_5)\psi\phi_i + \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \mathcal{V},$$

$$\mathcal{V} \supset \frac{1}{2}m_i^2\phi_i^2 + \frac{\mu_{ijk}}{3!}\phi_i\phi_j\phi_k + \frac{\lambda_{ijkl}}{4!}\phi_i\phi_j\phi_k\phi_l,$$

- No UV origin is assigned for the scalars, there could be some theoretical issues for a very light scalar, naturalness
A Toy Model


• fermionic DM $\psi$ and scalar radiation $\phi$

$$\delta L = \bar{\psi}(i\not{\partial} - m_\psi)\psi - \bar{\psi}(g_i^s + ig_i^p\gamma_5)\psi\phi_i + \frac{1}{2}\partial_\mu \phi_i \partial^\mu \phi_i - \mathcal{V},$$

$$\mathcal{V} \supset \frac{1}{2}m_i^2 \phi_i^2 + \frac{\mu_{ijk}}{3!}\phi_i\phi_j\phi_k + \frac{\lambda_{ijkl}}{4!}\phi_i\phi_j\phi_k\phi_l,$$

• If DM is a scalar field $X$,

$$X^\dagger X (\mu_i \phi_i + g_{ij} \phi_i \phi_j)$$

• connection with standard model

$$\lambda \phi^2 H^\dagger H, \quad \frac{1}{\Lambda} \bar{\psi}\psi H^\dagger H$$
Cosmological observables

- Scalar radiation contributes to $N_{\text{eff}}$

$$\delta N^\phi_{\text{eff}} \equiv \frac{\rho_1}{\rho_\nu} = \frac{4}{7} \frac{T^4_{\phi_1}}{T^4_\nu} = \frac{4}{7} \left[ \frac{g^s_\ast (T_\nu)}{g^s_\ast (T_{\phi_1})} \times \frac{g^\phi (T_{\phi_1}) T^3_{\phi_1}}{g^s_\ast (T_\nu) T^3_\nu} \right]^\frac{4}{3}$$

$$= \frac{4}{7} \left[ \frac{g^s_\ast (T_\nu)}{g^\phi (T_{\phi_1})} \frac{g^\phi (T_{\text{dec}}) (T_{\text{dec}}^3)}{g^s_\ast (T_{\text{dec}}) (T_{\text{dec}}^3)} \right]^\frac{4}{3} = \frac{4}{7} \left[ \frac{g^s_\ast (T_\nu)}{g^\phi (T_{\phi_1})} \frac{g^\phi (T_{\text{dec}}) (T_{\text{dec}}^3)}{g^s_\ast (T_{\text{dec}}) (T_{\text{dec}}^3)} \right]^\frac{4}{3},$$

$g^s_\ast$: effective dof in SM, or particles in KE with neutrinos
$g^\phi_\ast$: effective dof that are in KE with $\phi_1$
$T_{\text{dec}}$: kinetic decoupling temperature

typical value for $\delta N_{\text{eff}}$ would be around $\mathcal{O}(0.1)$.

if $T_{\text{dec}} \sim 1\text{GeV}$, we have $\delta N_{\text{eff}} \sim 0.045$
Interacting scalar radiation

- Interacting rate is given by

\[ \Gamma_{\phi_1} = n_{\phi_1} \times \langle \sigma v \rangle \sim T_{\phi_1}^3 \times \left[ \frac{3\mu_1^4}{T_{\phi_1}^6} + \frac{\lambda_1^2}{T_{\phi_1}^2} \right] = \frac{3\mu_1^4}{T_{\phi_1}^3} + \lambda_1^2 T_{\phi_1}, \]

- compare with Hubble parameter

\[ \mathcal{H}^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \sum_i \rho_i \Rightarrow \mathcal{H} = \sqrt{\frac{8\pi G}{3} \left[ \rho_{r0} \left( \frac{T_\gamma}{T_{\gamma_0}} \right)^4 + \rho_{m0} \left( \frac{T_\gamma}{T_{\gamma_0}} \right)^3 + \rho_{de} \right]^{1/2}}, \]
Self-Interacting Rate

1. $\mu_1 \neq 0$: There must be a time at which $\Gamma_{\phi_1} \gtrsim \mathcal{H}$.

2. $\mu_1 = 0$ but $\lambda_1 \neq 0$: $\Gamma_{\phi_1} \gtrsim \mathcal{H}$ happens at RD or MD.

3. $\mu_1 = 0$ and $\lambda_1 = 0$: free-streaming after KD, like neutrinos.
Interacting Radiation

- free-streaming

\[ \delta_v = -\frac{4}{3} \theta_v + 4\dot{\phi} , \]

\[ \dot{\theta}_v = k^2 \left( \frac{1}{4} \delta_v - \sigma_v \right) + k^2 \psi , \]

\[ \hat{F}_{vl} = \frac{k}{2l + 1} \left[ lF_{v(l-1)} - (l + 1)F_{v(l+1)} \right] , \]

- perfect fluid

\[ \delta_v = -\frac{4}{3} \theta_v + 4\dot{\phi} , \]

\[ \dot{\theta}_v = k^2 \left( \frac{1}{4} \delta_v - \sigma_v \right) + k^2 \psi , \quad \sigma_v=0 \]
DM-DR scattering rate

\[
\begin{align*}
\Gamma^{a+b}_{\psi \phi_1} &= n_{\phi_1} \langle \sigma v \rangle_{a+b} \sim T_{\phi_1}^3 \times \left[ \frac{(g_1^s)^4}{m_\psi^2} + \frac{(g_1^p)^4}{m_\psi^4} T_{\phi_1}^2 \right], \\
\Gamma^c_{\psi \phi_1} &= n_{\phi_1} \langle \sigma v \rangle_c \sim T_{\phi_1}^3 \times \left[ \frac{(g_1^s)^2 \mu_1^2}{T_{\phi_1}^4} + \frac{(g_1^p)^2 \mu_1^2}{m_\psi^2} \frac{1}{T_{\phi_1}^2} \right],
\end{align*}
\]

- $\Gamma > \mathcal{H}$ can happen at later times, unlike the baryon-photon case (BAO).
DM-DR scattering rate

\[ \Gamma^{a+b}_{\psi \phi_1} = n_{\phi_1} \langle \sigma v \rangle_{a+b} \sim T_{\phi_1}^3 \times \left[ \frac{(g^s_1)^4}{m_{\psi}^2} + \frac{(g^p_1)^4}{m_{\psi}^4} T_{\phi_1}^2 \right], \]

\[ \Gamma^c_{\psi \phi_1} = n_{\phi_1} \langle \sigma v \rangle_c \sim T_{\phi_1}^3 \times \left[ \frac{(g^s_1)^2 \mu_1^2}{T_{\phi_1}^4} + \frac{(g^p_1)^2 \mu_1^2}{m_{\psi}^2} \frac{1}{T_{\phi_1}^2} \right], \]

- \( \Gamma > \mathcal{H} \) can happen at later time, unlike the baryon-photon case (BAO).
Effects on LSS

\[ u_0 = \left[ \frac{\sigma_{\psi_1}}{\sigma_{\text{Th}}} \right] \left[ \frac{100 \text{GeV}}{m_{\psi}} \right], \quad u_\beta(T) = u_0 \left( \frac{T}{T_0} \right)^\beta, \]

- Dark acoustic oscillation arise
- Patterns depend on the interacting type, or underlying particle model
- Both at small and large scale
- Constraint, \( T \sim \text{keV} \) decoupling for \( \beta > 0 \)
Summary

• Interacting DM is an interesting possibility.
• Controversies in CDM paradigm, cusp-vs-core, too-big-to-fail, and missing satellites problems.
• Interaction with radiation could have observable effects. Effects also depend on the nature of DR.
• We also show with $U_x(1)$ with sterile neutrino, and a toy model about DM-DR system where scalar DR can have quite different late time behavior on LSS.
Thanks for your attention.