Using Cosmological Data to study Dark Matter Interactions with Radiation

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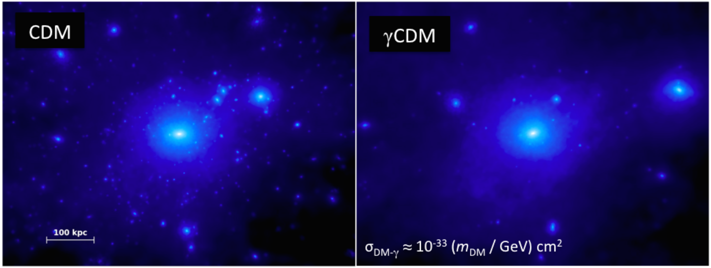
DMUK Meeting 2014

Outline

1. **Motivation**
2. **Implementation**
3. **Results**
   - Cosmic Microwave Background (CMB)
   - Large-Scale Structure
   - N-Body Simulations

Motivation

- DM interactions can have a large impact on structure formation:

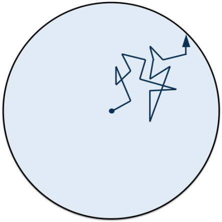


(C. Bœhm, J. Schewtschenko, RW, C. Baugh & S. Pascoli, 2014)

- They erase small-scale objects, in a similar way to Silk damping:

  (Silk, Nature 215 (1967) 1155-1156)

- How "weak" do these interactions need to be?



Implementation

- For e.g. DM–photon interactions:

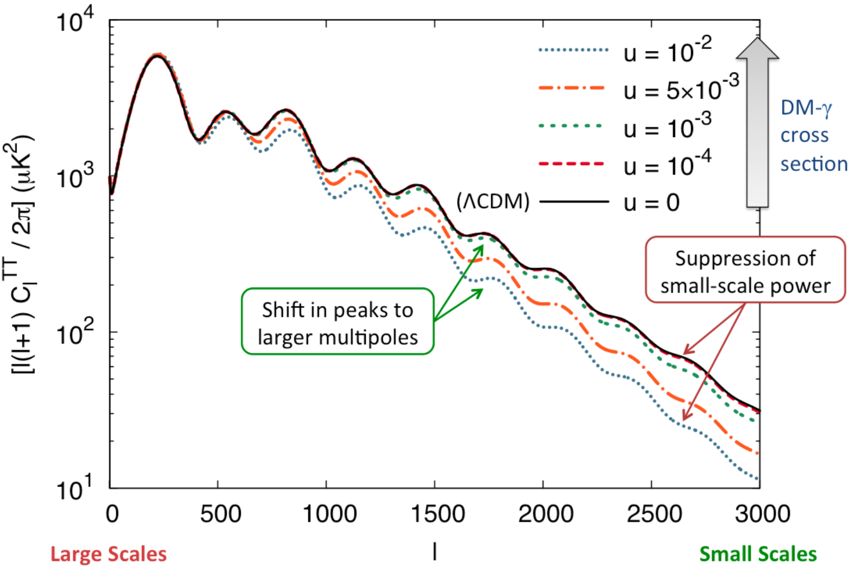
$$
\begin{aligned}
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_{\rm b}) - \boxed{\dot{\mu}(\theta_\gamma - \theta_{\rm DM})} \\
\dot{\theta}_{\rm DM} &= k^2\psi - \mathcal{H}\theta_{\rm DM} - \boxed{S^{-1}\dot{\mu}(\theta_{\rm DM} - \theta_\gamma)}
\end{aligned}
$$

  where $S \equiv (3/4)(\rho_{\rm DM}/\rho_\gamma)$ and $\dot{\mu} \equiv a\,\sigma_{{\rm DM}-\gamma}\,c\,n_{\rm DM}$.
- Modifications are made in CLASS. *(Lesgourgues, arXiv:1104.2932)*
- We can observe the effect in:
  - CMB spectra
  - Matter power spectrum and N-body simulations
- The magnitude of the damping will depend on:

$$
\boxed{u = \left[\frac{\sigma_{{\rm DM}-i}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\ {\rm GeV}}\right]^{-1}}
$$

(Bœhm et al., astro-ph/0012504, astro-ph/0410591)

CMB Temperature Spectrum



Constraints from *Planck*

- To fit our spectra to the data, we vary:

$\Omega_{\mathrm{b}} h^2$	$\Omega_{\mathrm{DM}} h^2$	n_s	A_s	H_0	z_{reio}	u

  plus N_{eff} in the case of DM-neutrino interactions.
- We use:
  - '*Planck*+WP' dataset *(Planck Collaboration, arXiv:1303.5076)*
  - The likelihood code, MONTE PYTHON *(Audren et al., arXiv:1210.7183)*
- For e.g. DM–photon interactions:

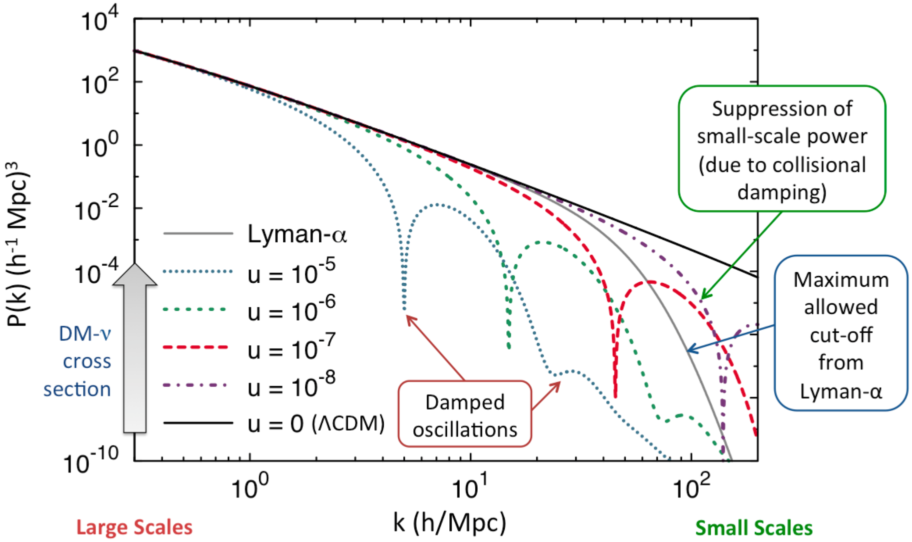
$$\sigma_{\mathrm{DM}-\gamma} = \text{constant} \quad : \quad \sigma_{\mathrm{DM}-\gamma} \lesssim 10^{-30} \, (m_{\mathrm{DM}}/\mathrm{GeV}) \, \mathrm{cm}^2$$

$$\sigma_{\mathrm{DM}-\gamma} \propto T^2 \quad : \quad \sigma_{\mathrm{DM}-\gamma,0} \lesssim 10^{-39} \, (m_{\mathrm{DM}}/\mathrm{GeV}) \, \mathrm{cm}^2$$

(RW, J. Lesgourgues & C. Bœhm, arXiv:1309.7588)

- Important as they probe the physics at $T \sim \mathrm{eV}$.

Matter Power Spectrum



Constraints from the Lyman-α Forest

- Limit on WDM mass from Lyman-α: $m_{\mathrm{WDM}} \gtrsim 3.3\,\mathrm{keV}$

(Viel et al., arXiv:1306.2314)

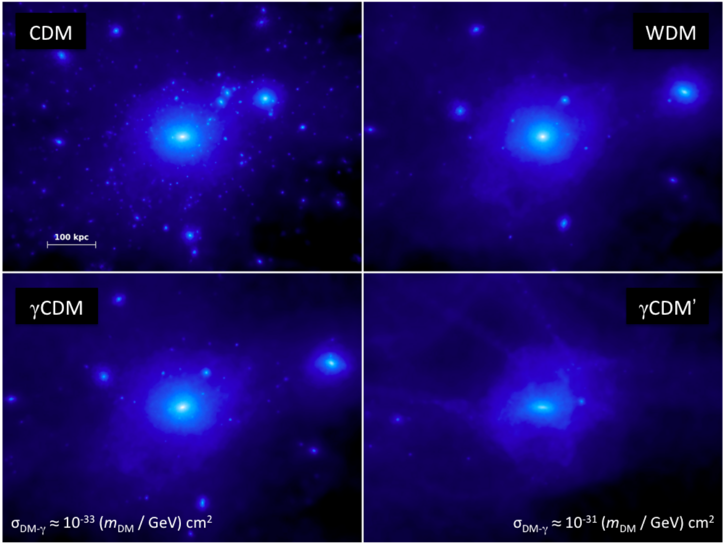
- We can compare the cut-off in the P(k) to our interacting models.
- For e.g. DM–neutrino interactions:

$$\begin{aligned} \sigma_{\mathrm{DM}-\nu} = \mathrm{constant} \quad &: \quad \sigma_{\mathrm{DM}-\nu} \lesssim 10^{-33}\,(m_{\mathrm{DM}}/\mathrm{GeV})\,\mathrm{cm}^2 \\ \sigma_{\mathrm{DM}-\nu} \propto T^2 \quad &: \quad \sigma_{\mathrm{DM}-\nu,0} \lesssim 10^{-45}\,(m_{\mathrm{DM}}/\mathrm{GeV})\,\mathrm{cm}^2 \end{aligned}$$

(RW, C. Bœhm, J. Lesgourgues, arXiv:1401.7597)

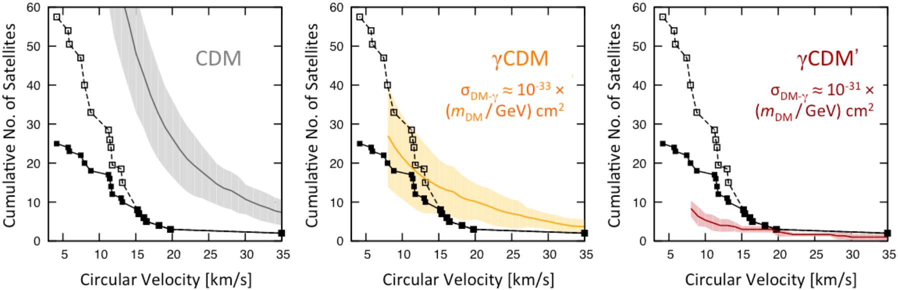
- If $m_{\mathrm{DM}} \lesssim \mathrm{MeV}$, LSS constraints $\implies$ weak interactions.
- Deviation from ΛCDM on very small scales so it is important to check with N-body simulations…

N-Body Simulations



(Simulation video at `youtu.be/YhJHN6z_0ek`*)*

N-Body Simulations



- DM interactions with radiation can solve the MW satellite problem with viable cross sections.
- Don't require the free-streaming of light particles i.e. WDM.
- We can set strong constraints (similar in magnitude to Lyman-α).

(C. Bœhm, J. Schewtschenko, RW, C. Baugh & S. Pascoli, arXiv:1404.7012)

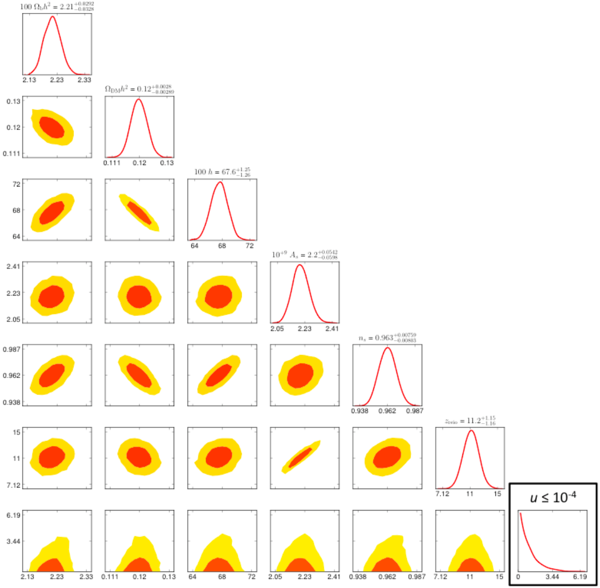
Summary

- We have used cosmological data to study the impact of DM interactions with radiation (photons and neutrinos).
- The strongest constraints come from structure formation and N-body simulations.
- Even small interactions can have an appreciable effect on our galactic environment.

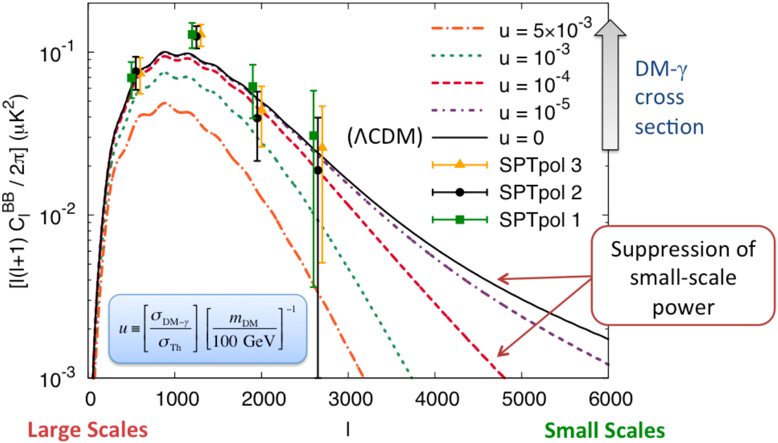
- Outlook:
  - Simulations of DM–neutrino interactions
  - Energy-dependent cross sections
  - An extensive analysis to consider the "too big too fail" and "cusp vs. core" problems

Thank you!

Constraints from *Planck*

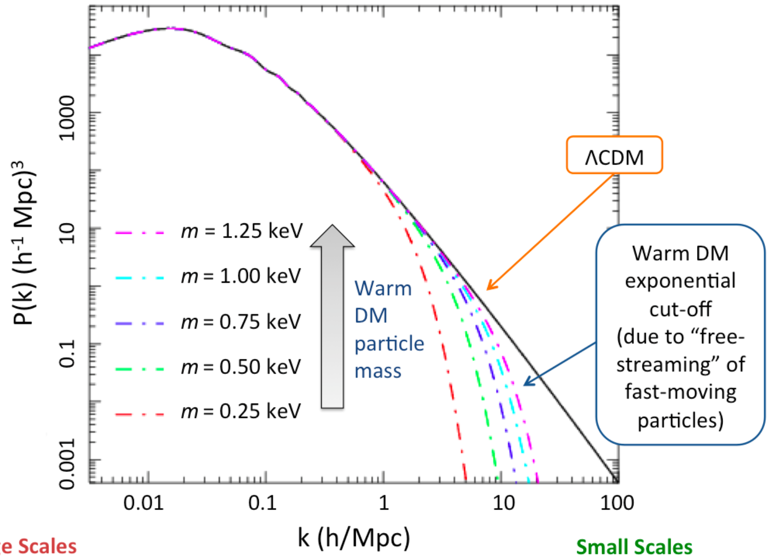


Effect on the Polarisation Spectrum



- First data from SPTpol $\Longrightarrow$ $\sigma_{\mathrm{DM}-\gamma} \lesssim 10^{-29}(m_{\mathrm{DM}}/\mathrm{GeV})\ \mathrm{cm}^2$
- Future polarisation constraints from e.g. *Planck*, *SPT* and *ACT*.

Matter Power Spectrum



Large Scales

Small Scales

Setup

- N-body simulations using GADGET-3. *(Springel, astro-ph/0505010)*
- Matter power spectra from CLASS. *(Lesgourgues, arXiv:1104.2932)*
- Simulation details:
  - Best-fit ΛCDM parameters from '*Planck*+WP'
  - Simulations begin at $z = 49$
  - Box sizes: $(30\ \mathrm{Mpc/h})^3$ and $(100\ \mathrm{Mpc/h})^3$
  - Resolution: $(512/1024\ \mathrm{particles})^3$
- Selection criteria for a Milky Way-like DM halo:
  - $0.8 \times 10^{12}\ M_\odot < M_{\mathrm{vir}} < 2.7 \times 10^{12}\ M_\odot$
  - Sufficiently isolated (no object of similar size within 2 Mpc)

(Piffl et al., arXiv:1309.4293; Boylan-Kolchin et al., arXiv:1210.6046)

Lyman-alpha Forest