The Sun as a Laboratory for Electromagnetic Dipole Dark Matter

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Outline

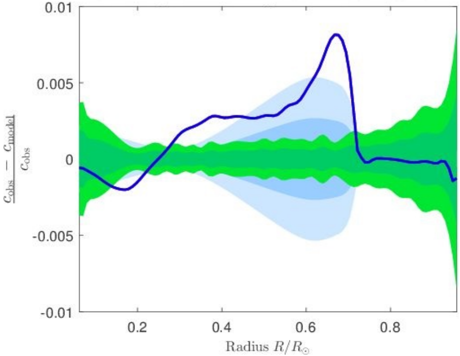
Introduction

- Dark Matter (DM) is well documented on galactic and cosmological scales
- Direct Detection of particle DM remains elusive and/or controversial
- Where else can we look?
- **Our understanding of the Sun has discrepancies where DM may be a solution**

Sound Speed Profile

Best measurements of the solar interior are from helioseismology, the study of pressure wave propagation in the Sun

- Can measure speed of sound as rate of pressure wave propagation, depends on temperature and elemental abundances
- Models and experiment disagree by up to 5σ
- Core is "too hot", Radiation zone is "too cold"
- Need additional energy transport mechanism?



$$\frac{\delta c_s}{c_s} \simeq \frac{1}{2}\frac{\delta T}{T} - \frac{1}{2}\frac{\delta\overline{\mu}}{\overline{\mu}}$$

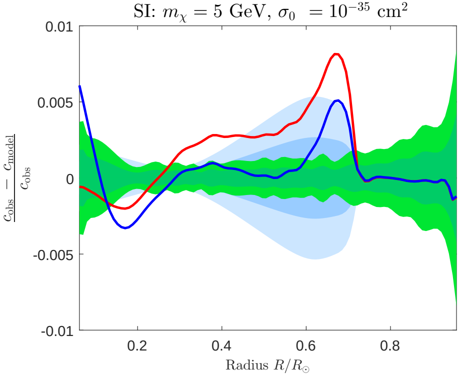
Vanilla Dark Matter

Dark matter is a candidate solution

- Particles get trapped in a 'halo' around the sun
- Collisions with nuclei can transfer energy efficiently

However

- Early attempts considered vanilla constant-cross section DM
- Tendency to over-correct in the core, ruining neutrino flux
- Poor resolution of parameter space implemented



Momentum and Velocity dependence

- Vincent, Serenelli & Scott (2015) investigated q and v dependent cross sections

$$\sigma \propto q^{-2}, q^2 \text{ or } q^4 \qquad (1)$$

$$\sigma \propto v^{-2}, v^2 \text{ or } v^4 \qquad (2)$$

- Discrepancies reduced to 2σ or less
- See arXiv:1311.2074, arXiv:1411.6626, arXiv:1504.04378 and arXiv:1605.06502 for details

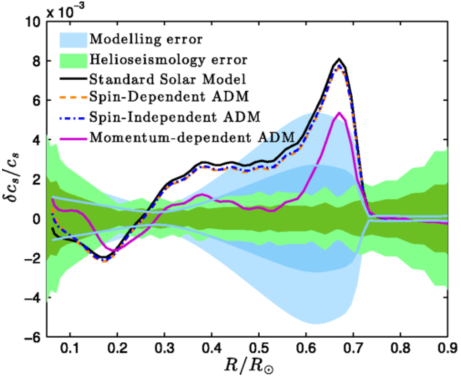
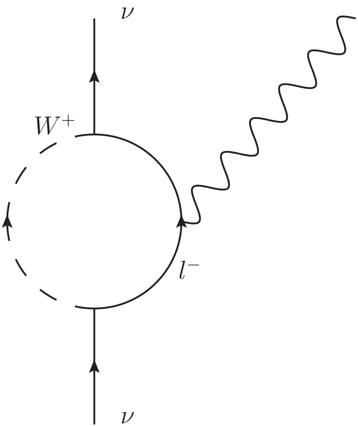


Image reproduced from arXiv:1411.6626

Motivation for dipolar dark matter

Electromagnetic dipole dark matter has momentum and velocity dependent cross sections

- Standard Model analogies:
    - Protons, neutrons & electrons have magnetic dipole moments
    - Neutrons are neutral charge, but are composite particles
    - Electrons are point particles with dipole moments
    - Even neutrinos are predicted to have magnetic dipoles due to loop corrections



Types of dipoles

We consider 3 types of dipoles:

- Electric dipole

$$H = -\mathcal{D}\vec{E} \cdot \vec{\sigma} \tag{3}$$

- Magnetic dipole

$$H = -\mu_\chi \vec{B} \cdot \vec{\sigma} \tag{4}$$

- Anapole

$$H = -\frac{g}{\Lambda^2} \vec{J} \cdot \vec{\sigma} \tag{5}$$

Anapoles

- Anapoles are an independent term in a multipole expansion
- A direct consequence of parity violation of the weak force
- Coupling of spin to solenoidal current
- Also called a toroidal moment
- Measured in cesium atoms in 1997

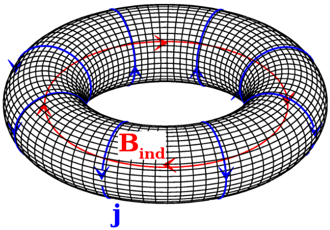


Image courtesy of Wikimedia commons

Dipole moment cross sections

Electric Dipole Moment

$$\frac{d\sigma}{dq^2} = \frac{Z^2 e^2 \mathcal{D}^2}{4\pi q^2 v^2} |F_E(q^2)|^2 \tag{6}$$

Magnetic Dipole Moment

$$\frac{d\sigma}{dq^2} = \frac{e^2 \mu_\chi^2 m_N}{2\pi v^2} \left[Z^2 \left(\frac{2 m_N v^2}{q^2} - \frac{1}{2m_N} - \frac{1}{m_\chi} \right) |F_E(q^2)|^2 + \frac{I_N + 1}{3 I_N} \frac{\lambda_N^2}{\lambda_n^2} \frac{m_N}{m_p^2} |F_M(q^2)|^2 \right] \tag{7}$$

Anapole Moment

$$\frac{d\sigma}{dq^2} = \frac{e^2 m_N^2 g^2}{\pi v^2 \Lambda^4} \left[Z^2 \left(v^2 - \frac{q^2}{4\mu_\chi^2} \right) |F_E(q^2)|^2 + \frac{I_N + 1}{3 I_N} \frac{\lambda_N^2}{\lambda_p^2} \frac{q^2}{2 m_p^2} |F_M(q^2)|^2 \right] \tag{8}$$

Framing Questions

- How much DM is in the Sun?
  - Solve differential equation

$$\frac{dN}{dt} = C(t) - 2A(t) - E(t) \tag{9}$$

- How does it modify the structure of the Sun?
  - Construct formalism for energy transport

Capture

- Dark Matter in galactic halo may collide with solar nuclei
- If DM velocity $w(r)$ is less than escape velocity $v_{\mathrm{esc}}(r,t)$, particle becomes gravitationally bound
- Calculating capture rate reduced to kinematics

$$C = 4\pi \int_0^{R_\odot} \int du \frac{f(u)}{u} w(r)\Omega(w) \tag{10}$$

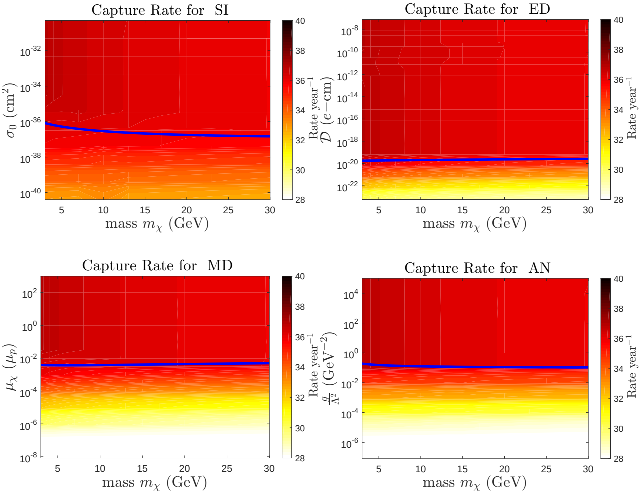
for

$$\Omega(w) = w(r) \sum_i n_i(r,t) \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \frac{d\sigma_i}{dE_R} dE_R \tag{11}$$

- There exists a maximum capture rate, independent of σ

$$C_{\mathrm{max}} = C_{\mathrm{max}}(f(u), R_\odot, M_\odot) \tag{12}$$

Capture



Capture Rate for SI
σ_0 (cm^2)
mass m_χ (GeV)
Rate year^{-1}
Capture Rate for ED
$\mathcal{D}$ ($e-$cm)
mass m_χ (GeV)
Rate year^{-1}
Capture Rate for MD
μ_χ (μ_p)
mass m_χ (GeV)
Rate year^{-1}
Capture Rate for AN
$\frac{g}{\Lambda^2}$ (GeV^{-2})
mass m_χ (GeV)
Rate year^{-1}

Annihilation

- DM population decreases via $\chi + \bar{\chi} \to \gamma + \gamma$ or similar
- Looking to maximize DM population
- **Naïve assumption:** $A(t) \simeq 0$
  - asymmetric Dark Matter
  - no self-conjugate Dark Matter

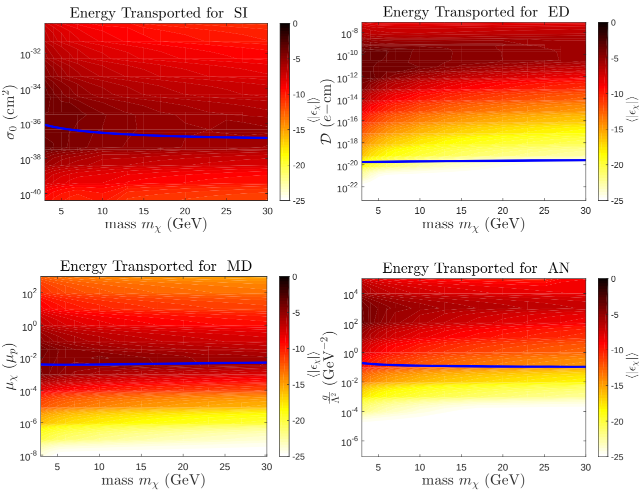
Evaporation

- If DM velocity $w(t) > v_{\rm esc}(r,t)$, particle may longer be gravitationally bound
- Non-trivial calculation
- Effect most significant if $m_\chi \simeq m_N$
- **Naïve assumption:** $E(t) \simeq 0$
- Further analysis necessary to confirm or reject assumption, but treat all low mass results with caution

Energy Transport

- Two mechanisms for heat transport, regime depends on mean free path l_χ and some scale height r_χ:
  - $l_\chi \ll r_\chi$: Local Thermal Equilibrium - increasing σ decreases energy transport
  - $l_\chi \gg r_\chi$: Knusden Transport (long range) - increasing σ increases energy tranport
- Possible to calculate energy transport for a given model, but depends on functional form of $\frac{d\sigma}{dq^2}$
- Separate calculation for each dipole moment model

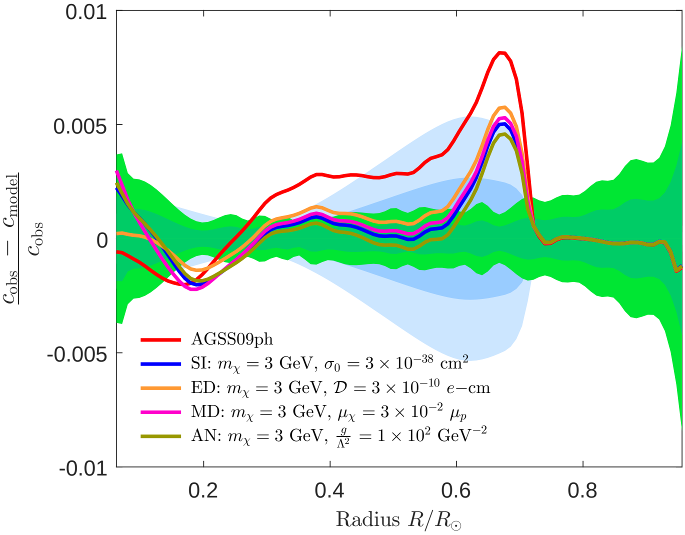
Energy Transport



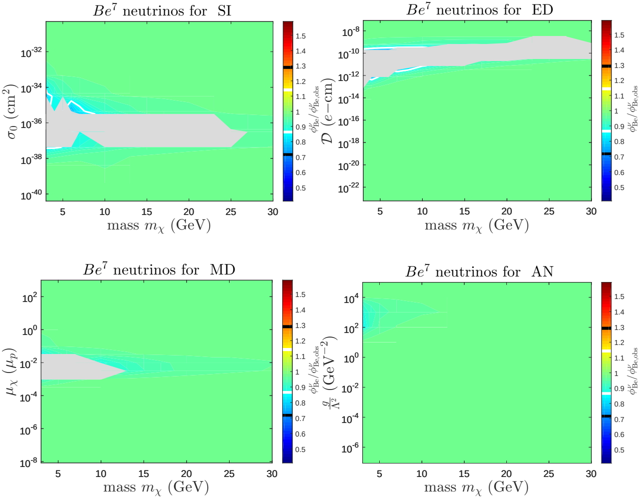
Simulations

- Perform simulations across a window in mass/dipole moment parameter space
- Numerically evolve a protostar to the Solar Age $\tau_\odot = 4.57\ \mathrm{Gyr}$ using `DarkStec` code
- Adjust input parameters to fit to present-day solar observables $L_\odot$, $R_\odot$ and $(Z/X)_\odot$
- Compare against simulations without DM and vanilla DM (spin independent)
- Some simulations do not converge to a solution

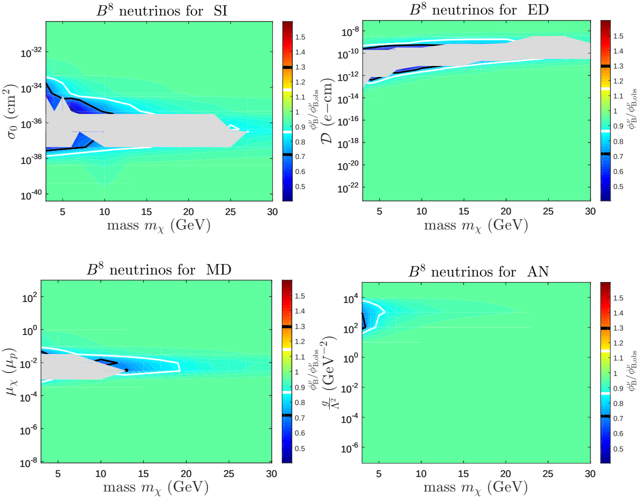
Sound Speed Profile



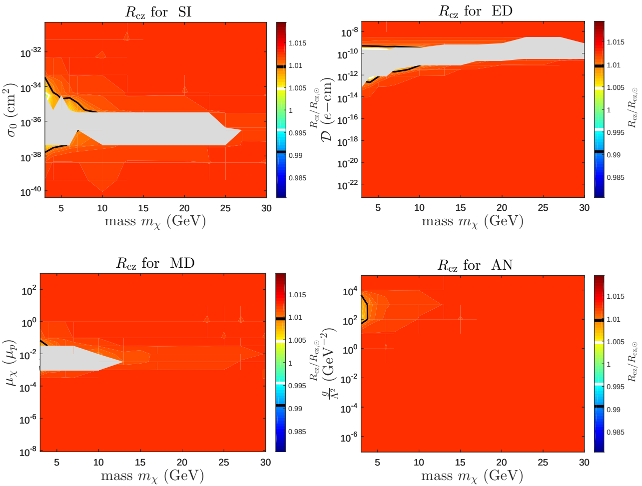
Neutrino Fluxes: Be^7



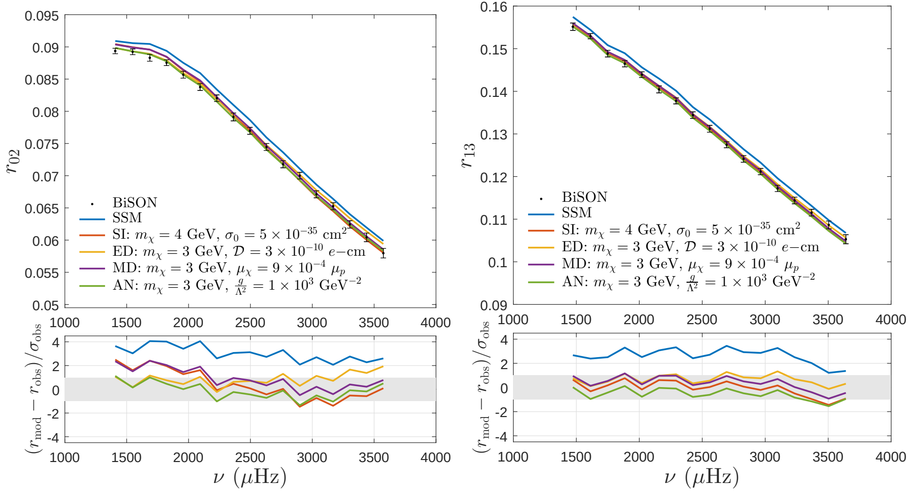
Neutrino Fluxes: B^8



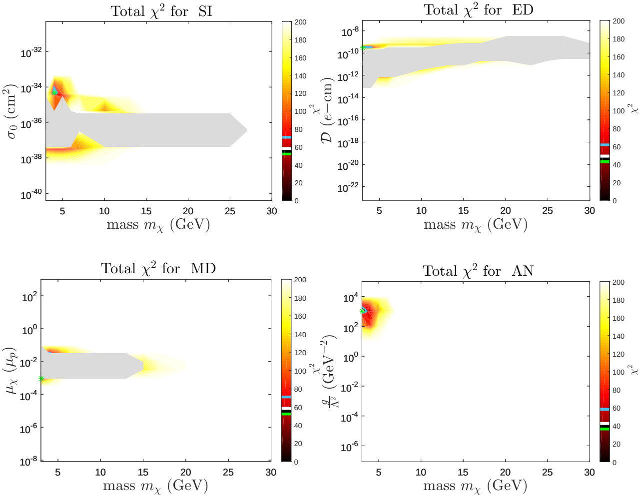
Convective Zone Radius



Small Frequency Separations



Total χ^2 fit



Total p-values

Model	m_χ	Coupling	p_{total}
no DM	-	-	$< 10^{-10}$
SI (σ_0)	4	$5 \times 10^{-35}\ \mathrm{cm}^2$	0.04
ED ($\mathcal{D}$)	3	$3 \times 10^{-10}\ e{-}\mathrm{cm}$	0.21
MD (μ_χ)	3	$9 \times 10^{-4}\ \mu_p$	0.05
AN ($\frac{g}{\Lambda^2}$)	3	$1 \times 10^{3}\ \mathrm{GeV}^{-2}$	0.45

Direct Detection Bounds

- *In isolation* the results appear promising
- However, limits from direct detection *rule out* the required values by **several orders of magnitude**
- For example, for the anapole model

$$\frac{\text{solution for the Sun}}{\text{direct detection bound}} \sim \mathcal{O}(10^7) \tag{13}$$

- The combined picture **does not stack up**

Conclusions

- It appears unlikely that electromagnetic dipole moments alone provide a unique solution to the Solar Abundance and Dark Matter Problems
- Lower mass DM may work, but requires implementation of evaporation calculation
- The Sun is an interesting tool to verify DM models, but not exclude them

Further Reading

- This work: Geytenbeek et. al. (2016) *Effect of electromagnetic dipole dark matter on energy transport in the solar interior* **arXiv:1610.06737**
- Momentum dependent dark matter in the Sun: Vincent et. al. (2016) *Updated constraints on velocity and momentum-dependent asymmetric dark matter* JCAP11(2016)007 **arXiv:1605.06502**
- Electric and Magnetic Dipole Moments: Massó et. al. (2009) *Dipolar Dark Matter* Phys. Rev. D 80:036009 **arXiv:0906.1979**
- Magnetic Dipole and Anapole Moments: Del Nobile et. al. (2014) *Direct detection of light anapole and magnetic dipole DM* JCAP06(2014)002 **arXiv:1401.4508**

Surface Helium Abundance