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**

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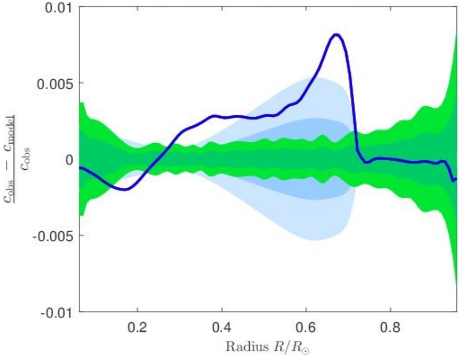
Sound Speed Profile

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?



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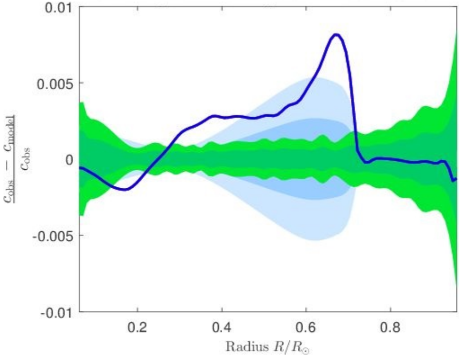

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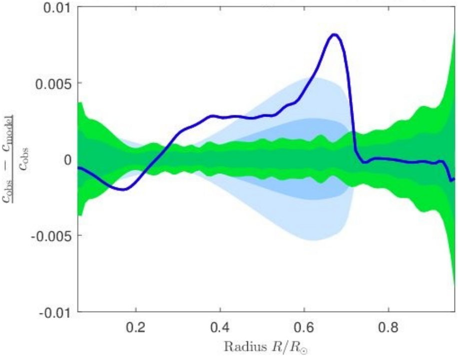

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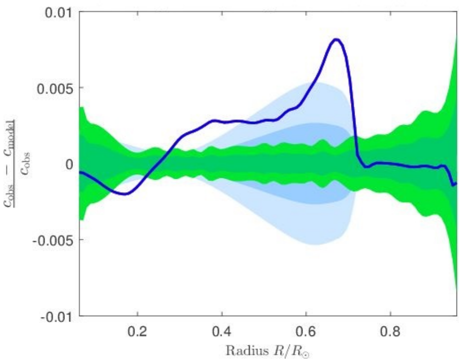

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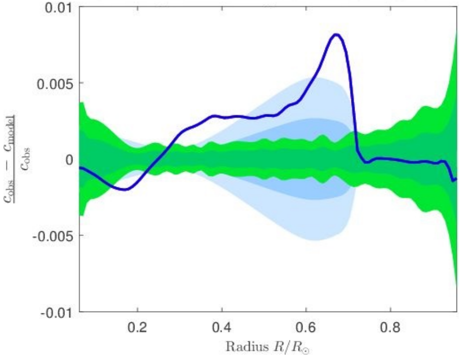

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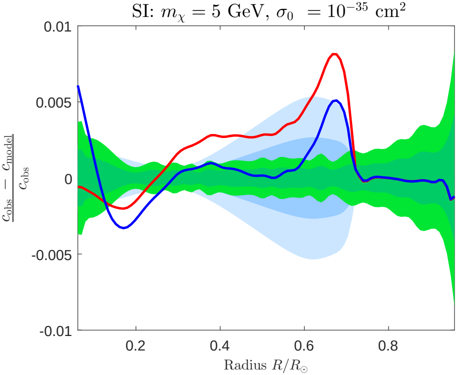
Vanilla Dark Matter

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



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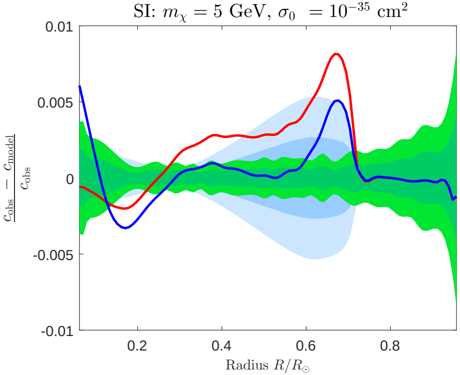

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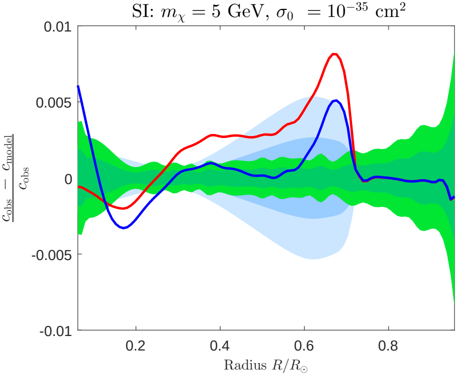

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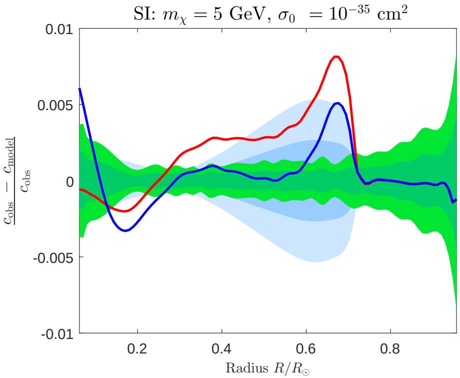

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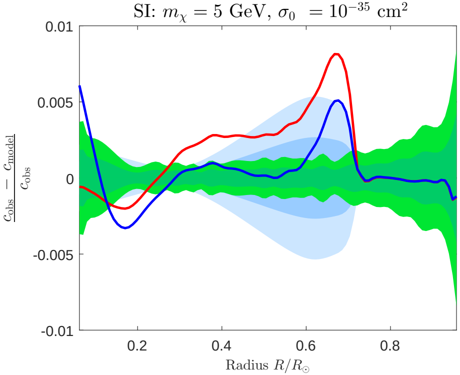

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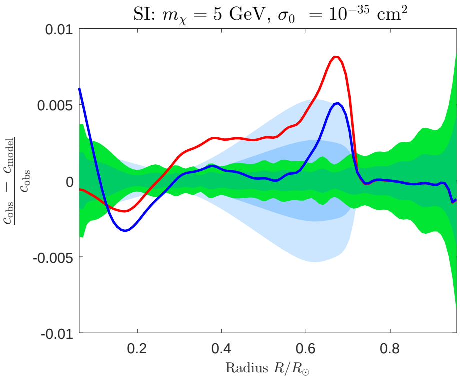


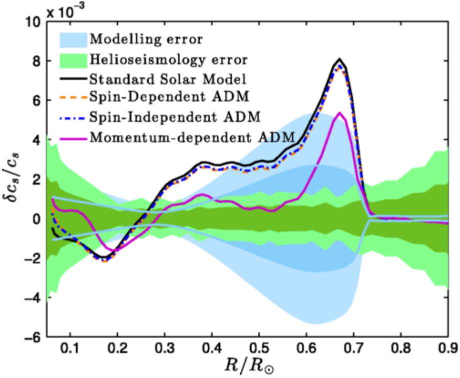
Momentum and Velocity dependence

- 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



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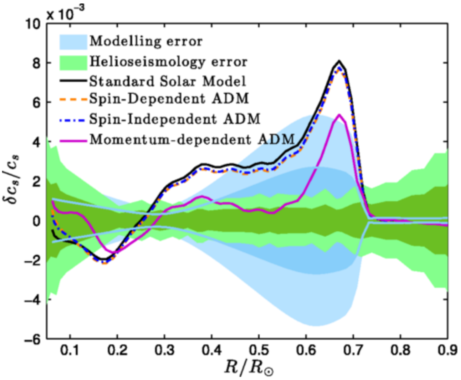

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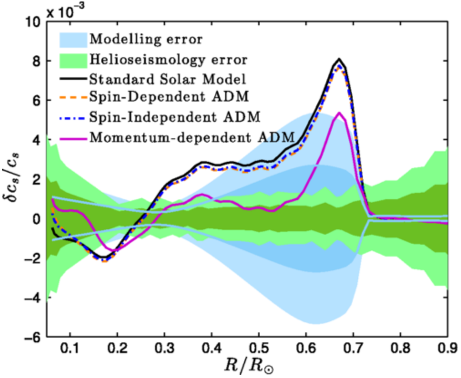

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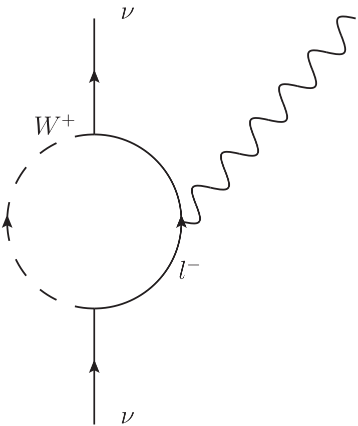
Motivation for dipolar dark matter

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



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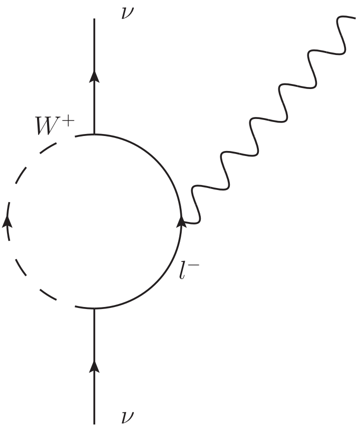

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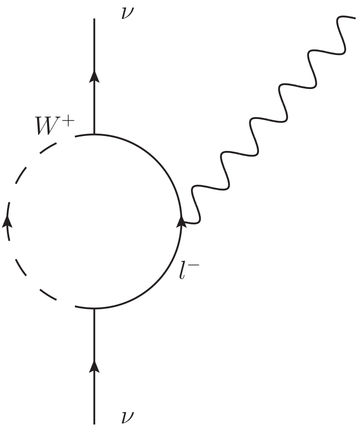

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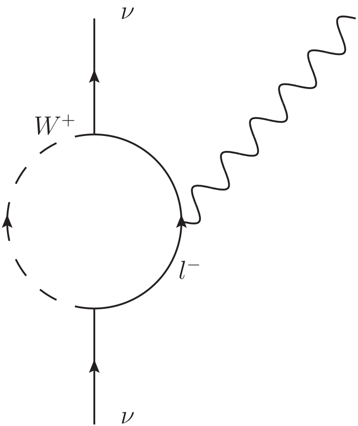

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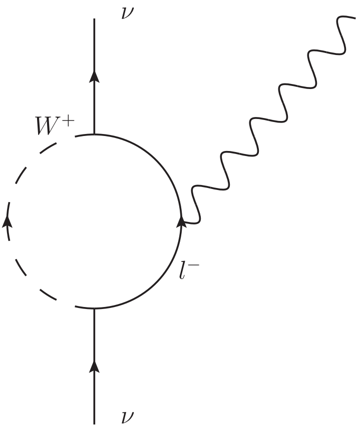

Types of dipoles

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

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

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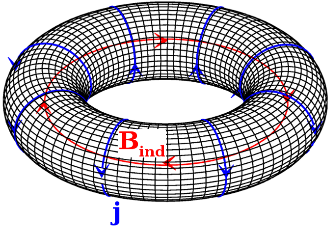
Anapoles

- 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



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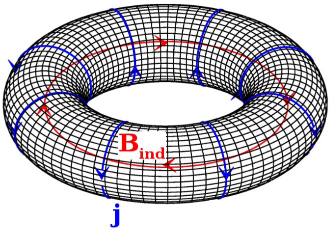

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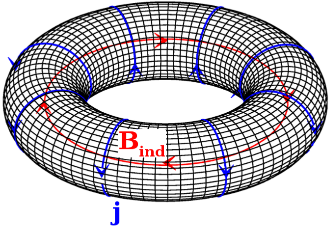

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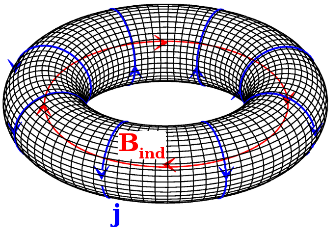

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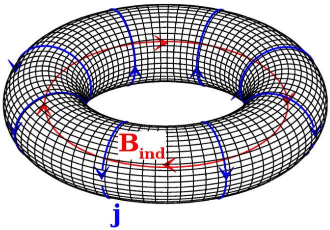

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Dipole moment cross sections

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

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

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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

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Capture

- Dark Matter in galactic halo may collide with solar nuclei
- If DM velocity $w(r)$ is less than escape velocity $v_{\rm esc}(r,t)$, 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

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

- There exists a maximum capture rate, independent of σ

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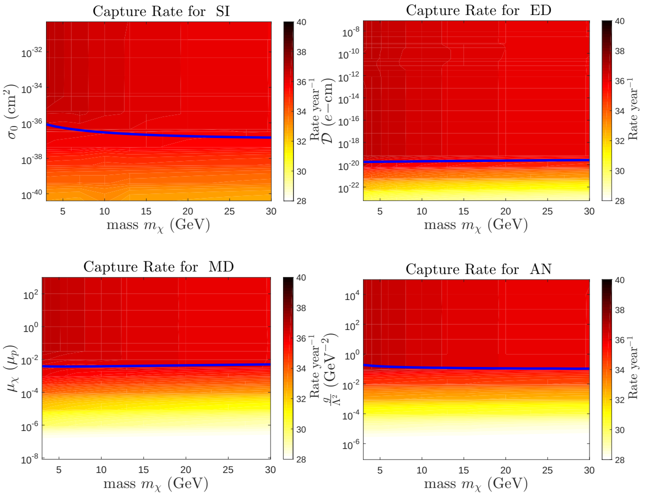
Capture Rate for SI
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mass m_χ (GeV)
Rate year^{-1}
Capture Rate for ED
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Capture Rate for AN
$\frac{g}{\Lambda^2}$ (GeV^{-2})
mass m_χ (GeV)
Rate year^{-1}

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
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- If DM velocity $w(t) > v_{\rm esc}(r, t)$, particle may longer be gravitationally bound
- Non-trivial calculation
- Effect most significant if $m_\chi \simeq m_N$
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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 $\frac{d\sigma}{dq^2}$
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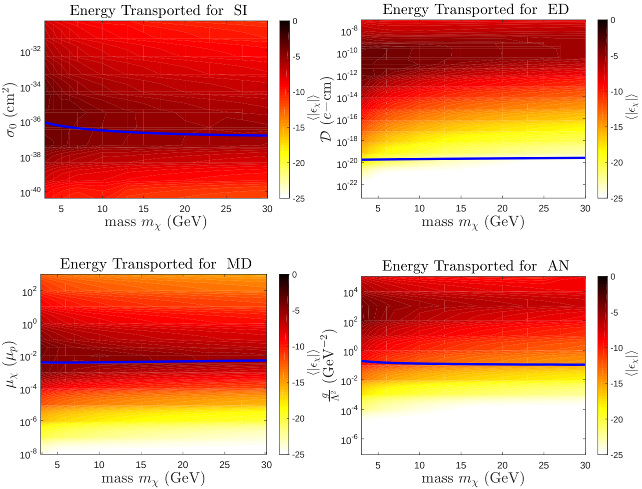

Simulations

- 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 $(Z/X)_\odot$
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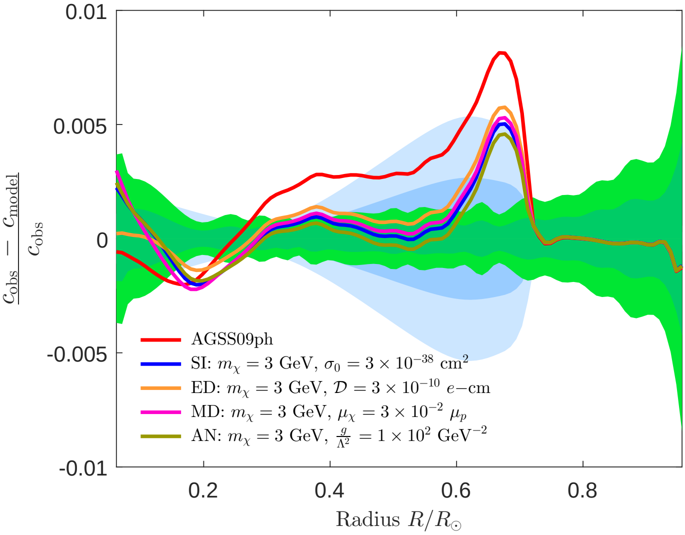
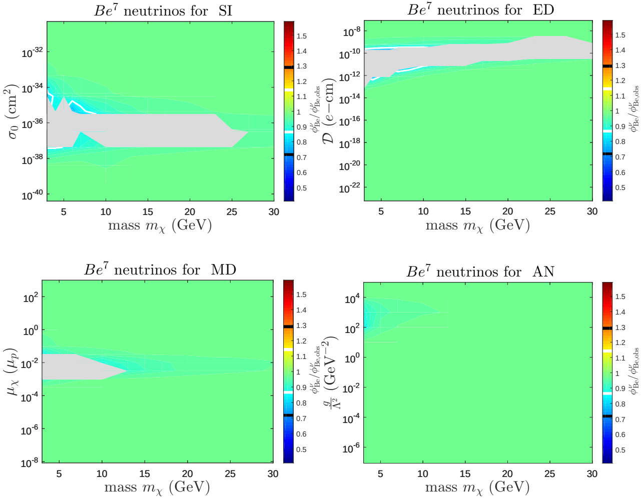
Sound Speed Profile



Neutrino Fluxes: Be^7



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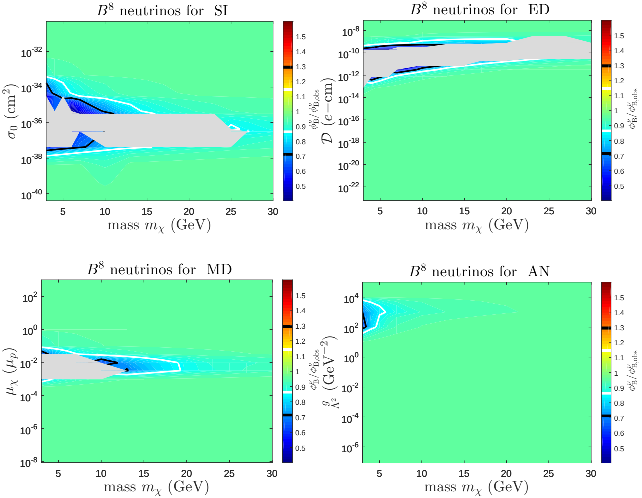
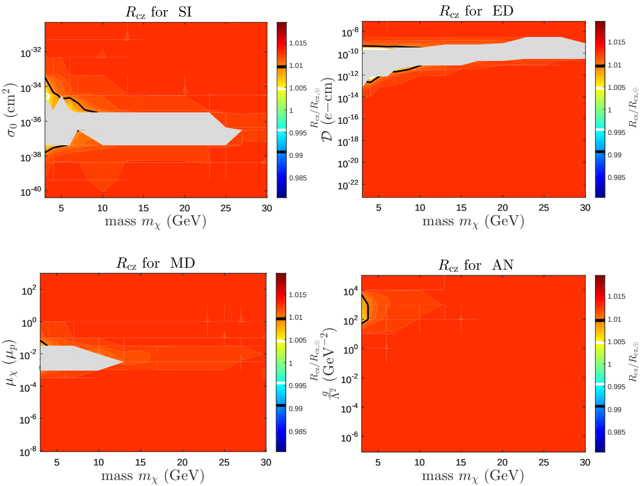
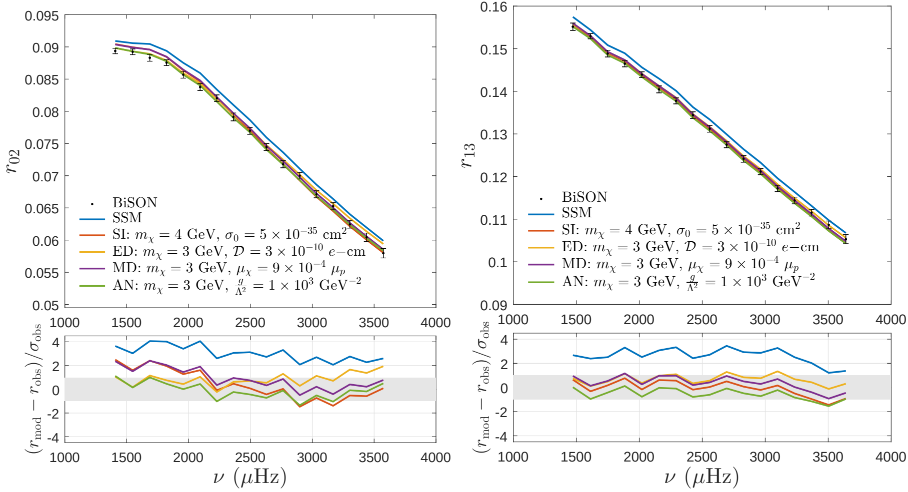


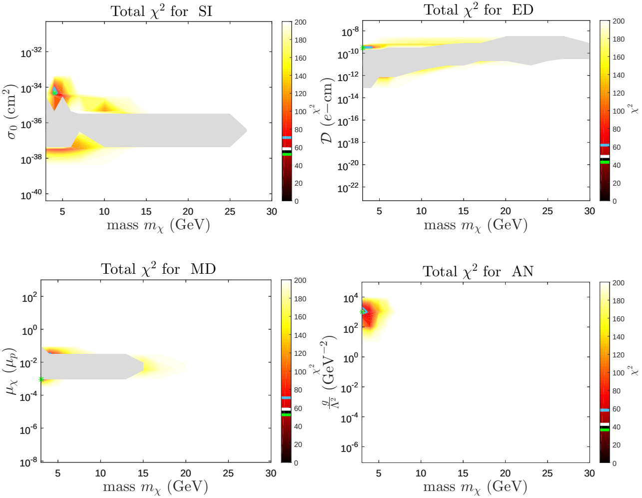
Convective Zone Radius



Small Frequency Separations



Total χ^2 fit



Total p-values

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

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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