Dynamics of dark matter bound to the solar system
(and why it matters for indirect detection)

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Detecting WIMPs

N.B. I will focus on standard WIMPs (e.g., supersymmetric neutralino, Kaluza-Klein photon)

- Direct detection $\chi \ N \rightarrow \chi \ N$ (CDMS, XENON, WARP, CRESST, EDELWEISS, DAMA/LIBRA, LUX, MIMAC, etc.)
- Indirect detection of annihilation products $\chi \chi \rightarrow e^+e^-, \chi \chi \rightarrow \gamma \gamma + \text{extra}, \chi \chi \rightarrow \nu's + \text{extra}$
  - Since the annihilation rate $\Gamma \propto \text{density}^2$, look for a signal in regions with high dark matter density:
    - Galactic center, substructure, smooth halo
    - In the solar system, the Sun and the Earth
Indirect Detection of Dark Matter in the Solar System

- $\nu$'s in the Sun
- $\nu$'s from the Earth
- $\gamma$'s outside the Sun (if time)

I will try to convince you that all of these probes depend on what happens to the dark matter after it becomes bound to the solar system!
ν’s in the Sun

• Standard Thermalization Model (Griest and Seckel, Gould):
  – WIMPs that scatter onto bound orbits are almost instantaneously thermalized.
  – Once thermalized to this dense core, they annihilate. Typically, \( \Gamma = \frac{C}{2} \) (unless the elastic scattering cross section is quite small), where C is the capture rate of WIMPs in the Sun.
  – We can see the neutrinos from these annihilations in terrestrial neutrino telescopes (Super-K, AMANDA, IceCube, Antares).
  – Currently the most sensitive probe of \( \sigma_p^{SD} \) (Desai et al. 2004).

• CHANGES:
  – Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as \( t \sim \frac{P_\chi}{\tau} \).
  – Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the solar system.
  – Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.
Simulations $\rightarrow$ Lifetime Distributions
(AHGP, arXiv:0902.1344, 0902.1347)

• 1.5 million orbits
• Integration is terminated if:
  – The particle rescatters onto an ```uninteresting````` orbit.
  – The particle is ejected.
  – $t > t_\odot$
• Realistic solar model: BS(OP), and Monte Carlo treatment of scattering in the Sun.
• Simplified solar system consisting of Jupiter and the Sun only to more easily understand the results (I will come back to the question of the other planets in the conclusions).
• See papers for details on integration method.
Lifetimes

• Three types of behaviors:
  – $a < 1.5$ AU: the typical time between scatters goes as $t \sim P_\chi / \tau$
  – $1.5 \text{ AU} < a < 2.6$ AU (half Jupiter’s semi-major axis): the time between scatters goes as $t \sim 300 P_\chi / \tau$ (due to interactions between the Kozai and mean-motion resonances)
  – $a > 2.6$ AU (Jupiter-crossing): ejected on timescales of $\sim$ Myr unless the timescale for rescattering in the Sun is shorter than the angular momentum diffusion timescale.

• The distribution of initial $a$ is skewed higher for higher WIMP masses.

• It takes more scatters to thermalize a heavier WIMP.
Suppression of the Annihilation Rate
(Standard Halo Model)
Suppression of the Annihilation Rate
(Standard Halo Model)

If $m_\chi > 1$ TeV and $\sigma_p^{SD} \lesssim 10^{-38}$ cm$^2$, $\Gamma$ will be heavily suppressed.

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$\nu$’s from the Earth

- Proposed by Freese in the mid-1980’s.
- Since the Earth has a shallow potential well ($v_{\text{esc}} \approx 15 \text{ km s}^{-1}$ at the center), only slow WIMPs can be captured in the Earth unless on a kinematic resonance (Gould 1988).
- WIMPs in the relevant geocentric speed range for capture in the Earth may be bound or unbound to the solar system (and ONLY bound if $m_{\chi} \gtrsim 400$ GeV).
  - > the $\nu$ event rate is EXTREMELY sensitive to the solar-bound WIMP population!
\( \nu \)'s from Solar-Bound WIMPs

- Previous work:
  - Gould 1991 and Damour & Krauss 1999 suggested that this population could be large (gravitational and solar capture, respectively) based on semi-analytic arguments.
  - Lundberg & Edsjö 2004 suggested the gravitational capture population might be smaller.

- My simulations (arXiv:0902.1344, 0902.1348) for the toy solar system suggests that it is smaller still. (based on \( 1.5 \times 10^6 \) solar captured orbits, \( \sim 10^{10} \) orbits in the gravitational capture simulation)
Estimate of $\nu$’s from Earth
(arXiv:0902.1348)

Using the seven-parameter phenomenological MSSM model in DarkSUSY (Gondolo et al. 2004).

Optimistic IceCube projection
Summary So Far
(using the Standard Halo Model)

• $\nu$’s from the Sun:
  – This should be looked at.
  – Predictions unchanged for $m_\chi \lesssim 1$ TeV, may be (strongly) suppressed for larger WIMP masses.

• $\nu$’s from the Earth:
  – Unlikely.

• However, there reason for optimism…
One Huge Astrophysical Systematic: The Dark Disk

- Standard Halo Model (approximate multivariate Gaussian, $\sigma \approx \sqrt{v/2^{1/2}}$) based on N-body simulations of dark matter-only galaxies.
- Simulations that include baryons show that the stellar disk drags satellites into the disk plane, where they dissolve.
- This yields a DARK DISK with properties similar to the stellar disk generated by these satellites.
- The dark disk properties are extremely sensitive to the merger history of the Galaxy.
- Typically, speeds wrt to the solar system are MUCH smaller--much easier to capture.

(Read et al. 2008, 2009)
The Dark Disk & $\nu$’s in the Sun
(Bruch, AHGP et al., arXiv:0902.4001)

“Median” dark disk

CMSSM

Rencontres de Moriond, March 2009
The Dark Disk & $\nu$’s in the Earth

(Bruch, AHGP et al., arXiv:0902.4001)
The Dark Disk

- **Upside:** much more of CMSSM parameter space can be probed!
- **Downside:** we don’t know the merger history of the Milky Way, so the dark disk becomes a huge systematic when trying to derive particle physics constraints from the data. *WIMP annihilation in the Sun and Earth* is the only observable that depends so sensitively on the dark disk (although one can cross-check with direct detection, Bruch et al. 2008; and maybe with stellar kinematics/spectroscopy), so characterizing the dark disk will be hard.
γ’s from outside the Sun

• Proposed by Straus 1999--Milagro should see hundreds-thousands of events.
• Idea: Build up WIMP population near just outside the Sun.
  – Preferential initial scatter (dE ∝ da /a²)
  – Thermalization process pushes captured WIMPs onto tighter orbits.
  – The Sun does not produce many γ-rays.
• Milagro puts upper limits $\sim 10^{-10}$-$10^{-9}$ cm$^{-2}$ s$^{-1}$ for line emission.
\(\gamma\)'s from the Sun: More recent perspectives

- Calculations by Hooper 2001, Sivertsson & Edsjö 2009 (as well as back-of-the-envelope calculations using my simulations) show that the \(\gamma\)-ray flux should actually be unobservably small:

<table>
<thead>
<tr>
<th>(\sigma_{SD})</th>
<th>(\sigma_{SI})</th>
<th>(m_{WIMP} = 100) GeV</th>
<th>(m_{WIMP} = 1) TeV</th>
<th>(m_{WIMP} = 10) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-3}) pb,</td>
<td>(0)</td>
<td>(4.0 \cdot 10^{-19})</td>
<td>(3.7 \cdot 10^{-21})</td>
<td>(3.5 \cdot 10^{-23})</td>
</tr>
<tr>
<td>(0), (10^{-5}) pb</td>
<td></td>
<td>(8.4 \cdot 10^{-20})</td>
<td>(2.5 \cdot 10^{-21})</td>
<td>(2.9 \cdot 10^{-23})</td>
</tr>
</tbody>
</table>

\*Table 1: The total flux (photons per m\(^2\) per second) at Earth of gamma rays from the Sun's WIMP halo.

- It's not clear where the error in Strausz’ calculation is.
- For \(m_\chi \gtrsim 1\) TeV, the Sivertsson & Edsjö estimates are still too high--ejection before thermalization.
Conclusion

• Indirect detection of WIMPs in the solar system depends sensitively on the bound orbits.

• $\nu$'s from WIMPs in the Sun: suppression in the annihilation rate for $m_\chi > 1$ TeV (this is insensitive to the presence of extra planets). The event rate may be boosted by a factor of $\sim 10$ for the dark disk.

• $\nu$'s from the Earth: for the Standard Halo Model alone, no signal in IceCube. The dark disk boosts the signal by $\sim 1000x$ -- may be observable! Signal sensitive to inner planets.

• $\gamma$'s from outside the Sun: the signal is TINY. Will be even more suppressed for large WIMP masses due to gravitational perturbations. The dark disk may raise this signal by $\sim 100$, still not enough to matter.