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 χ N $\rightarrow$ χ N (CDMS, XENON, WARP, CRESST, EDELWEISS, DAMA/LIBRA, LUX, MIMAC, etc.)
- Indirect detection of annihilation products $\chi\,\chi \rightarrow e^+e^-$, $\chi\,\chi \rightarrow \gamma\,\gamma$ + extra, $\chi\,\chi \rightarrow \nu$'s + extra
  - Since the annihilation rate $\Gamma \propto$ 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

- ν's in the Sun
- ν's from the Earth
- γ'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, Γ = 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 σ_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 $\sim$ P_χ/τ.
  - 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.

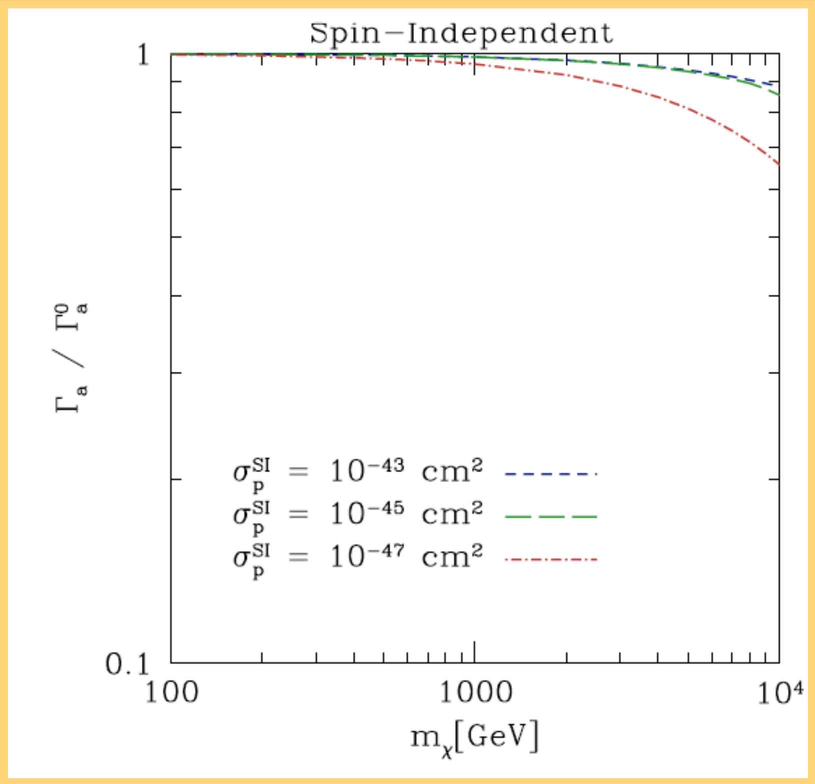
Simulations $\rightarrow$ Lifetime Distributions (AHGP, arXiv:0902.1344, 0902.1347)

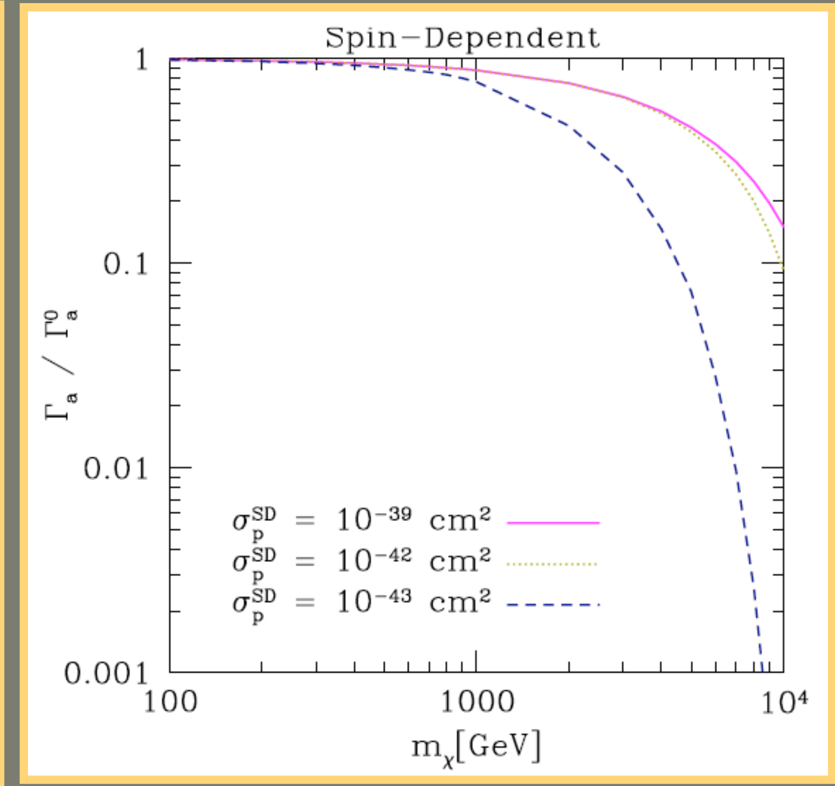
- 1.5 million orbits
- Integration is terminated if:
  - The particle rescatters onto an ``uninteresting'' orbit.
  - The particle is ejected.
  - $t > t_{\odot}$
- Realistic solar model: BS(OP), and Monte Carlo treatment of scattering in the Sun.
- Simplified solar system consisting of Jupiter and the 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 AU < a < 2.6 AU (half Jupiter's semi-major axis): the time between scatters goes as t $\sim$ 300 P_χ/τ (due to interactions between the Kozai and mean-motion resonances)
  - a > 2.6 AU (Jupiter-crossing): ejected on timescales of ~ 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)





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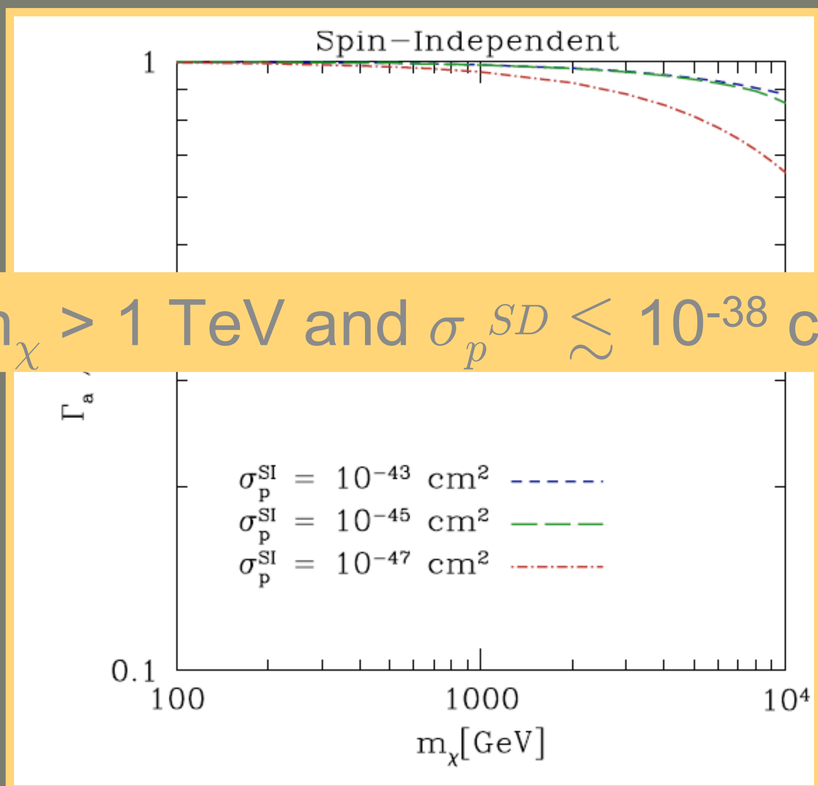
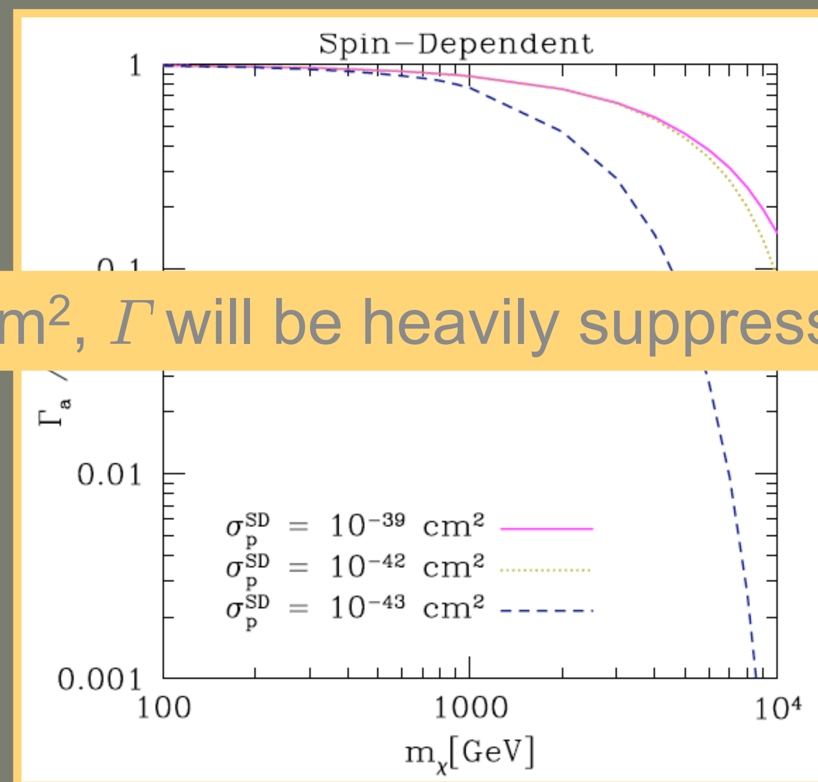




If m_χ > 1 TeV and $\sigma_p{}^{SD} \lesssim 10^{-38}$ cm^2, Γ will be heavily suppressed

ν's from the Earth

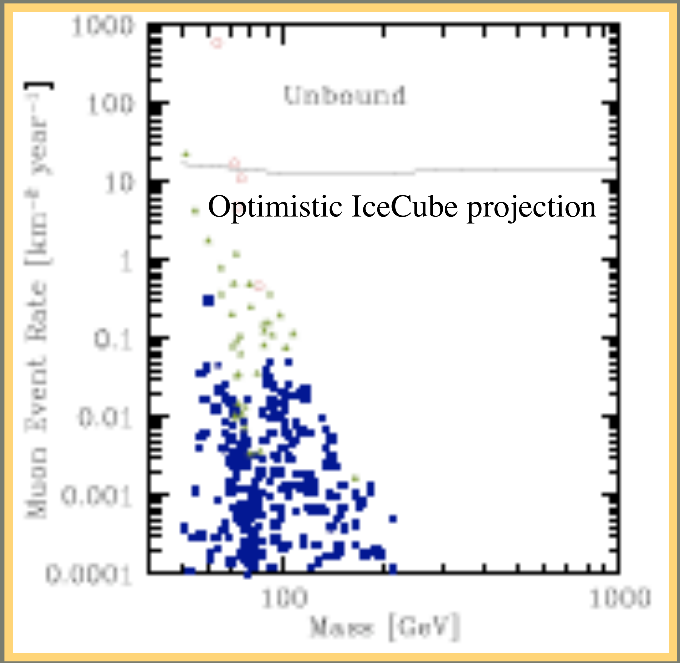
- Proposed by Freese in the mid-1980's.
- Since the Earth has a shallow potential well ($v_{esc} \approx$ 15 km s^{-1} at the center), only slow WIMPs can be captured in the Earth unless on a kinematic resonance (Gould 1988).
- WIMPs in the relevant geocentric speed range for capture in the Earth may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

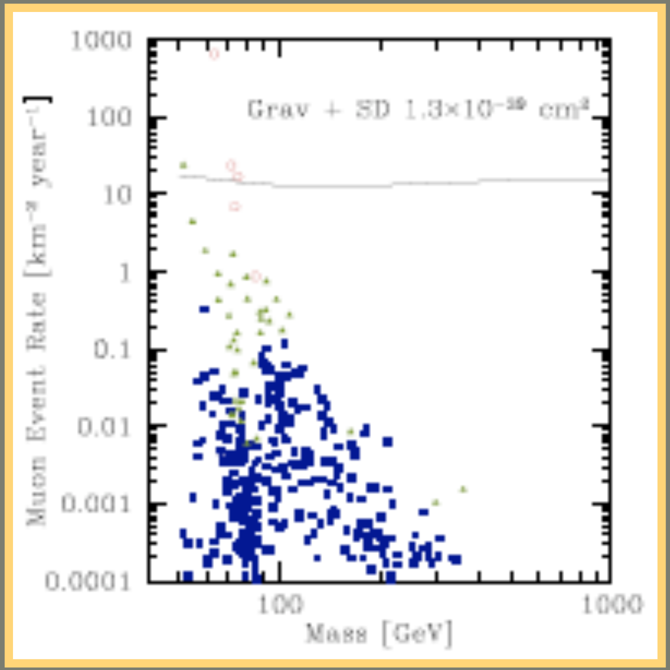
ν's from Solar-Bound WIMPs

- Previous work:
  - Gould 1991 and Damour & Krauss 1999 suggested that this population could be large (gravitational and solar capture, respectively) $\leftarrow$ 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 1.5×10^6 solar captured orbits, $\sim 10^{10}$ orbits in the gravitational capture simulation)

Estimate of ν's from Earth

(arXiv:0902.1348)





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

Summary So Far

(using the Standard Halo Model)

- ν'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.
- ν's from the Earth:
  - Unlikely.
- However, there reason for optimism…

One Huge Astrophysical Systematic: The Dark Disk

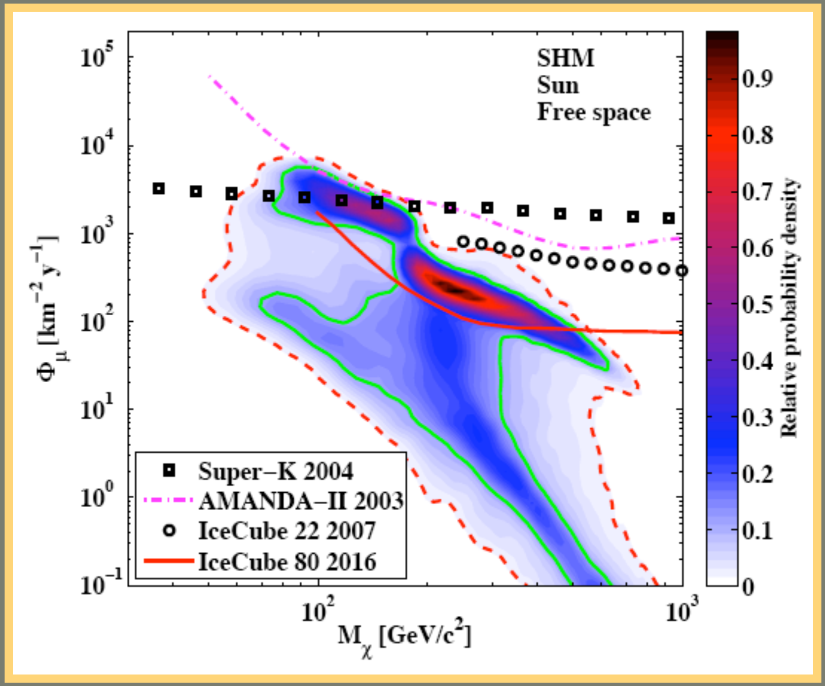
- Standard Halo Model (approximate multivariate Gaussian, $\sigma \approx v_{\odot}/2^{1/2}$) based on N-body simulations of dark matter-only galaxies.
- Simulations that include baryons show that the stellar disk drags satellites into the disk plane, where they dissolve.
- This yields a DARK DISK with 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.

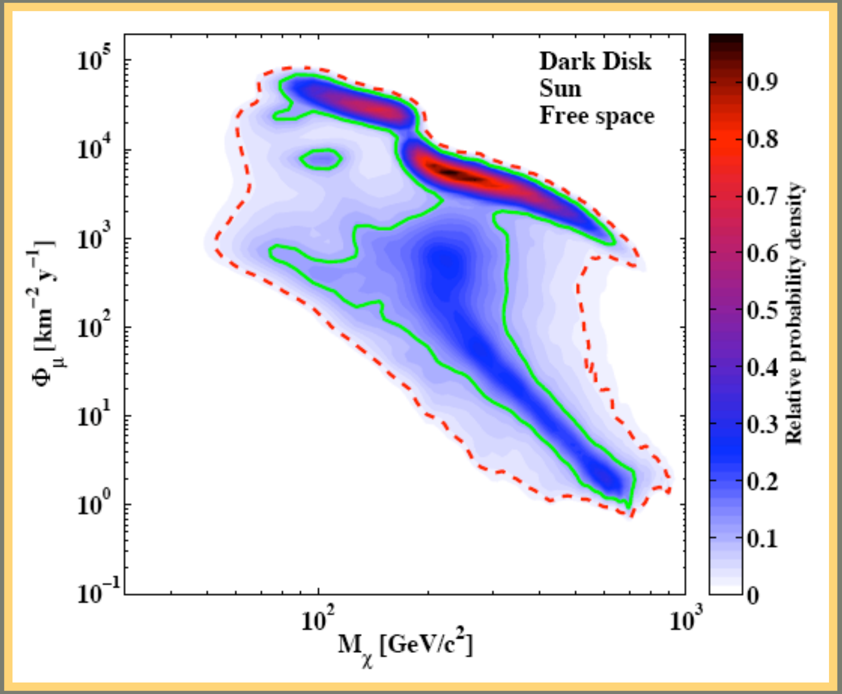
(Read et al. 2008, 2009)

The Dark Disk & ν's in the Sun

(Bruch, AHGP et al., arXiv:0902.4001)

"Median" dark disk

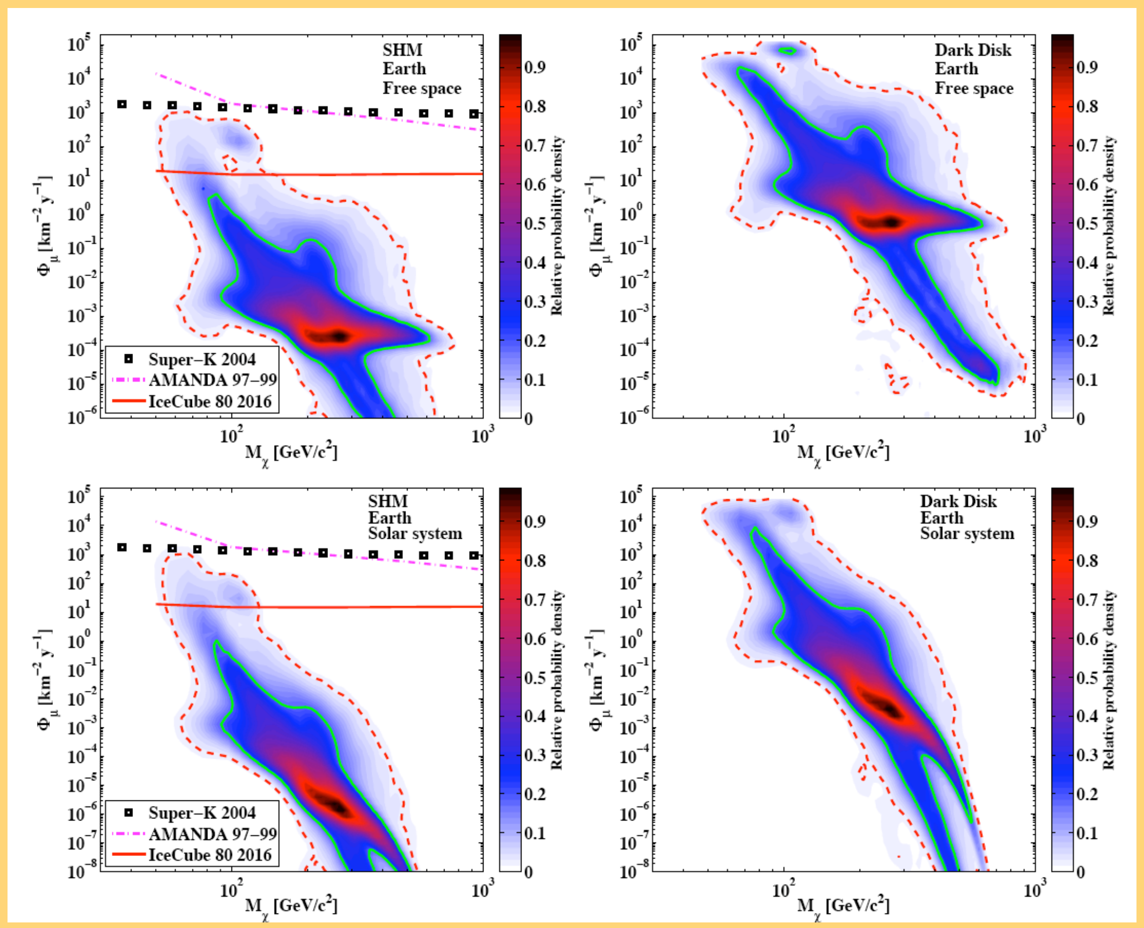




CMSSM

The Dark Disk & ν'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 Strausz 1999--Milagro should see hundreds-thousands of events.
- Idea: Build up WIMP population near just outside the Sun.
  - Preferential initial scatter ($dE \propto da/a^2$)
  - 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.

γ'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 γ-ray flux should actually be unobservably small:

	$m_{WIMP} = 100$ GeV	$m_{WIMP} = 1$ TeV	$m_{WIMP} = 10$ TeV
$\sigma_{SD} = 10^{-3}$ pb, $\sigma_{SI} = 0$	$4.0 \cdot 10^{-19}$	$3.7 \cdot 10^{-21}$	$3.5 \cdot 10^{-23}$
$\sigma_{SD} = 0$, $\sigma_{SI} = 10^{-5}$ pb	$8.4 \cdot 10^{-20}$	$2.5 \cdot 10^{-21}$	$2.9 \cdot 10^{-23}$

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

(from Sivertsson & Edsjö, arXiv:0903.0796)

- 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.
- ν's from WIMPs in the Sun: suppression in the annihilation rate for $m_\chi \gtrsim$ 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.
- ν'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.
- γ'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.