Dark Matter on the Smallest Scales

Annika Peter, 7/20/09

Things I would like to address:

- Using stars and planets to constrain dark matter models.
- What I think is the biggest uncertainty with these things (and with prospects for direct and indirect detection of dark matter in our Galaxy): WHERE IS IT? More specifically, what is f(x,v,t), and how well do we need to know this?

Stars and Planets as DM Constraints

- Evolution (look for changes in ν for stars or heat/luminosity output in stars or planets). Can deposit or remove mechanical energy (during the scattering/thermalization processes) or deposit energy via annihilation byproducts.
- Counting annihilation byproducts (mostly high energy ν's, although some have suggested high energy γ's! But those people are wrong.)

Origin/Status of DM Effects on Stellar Evolution

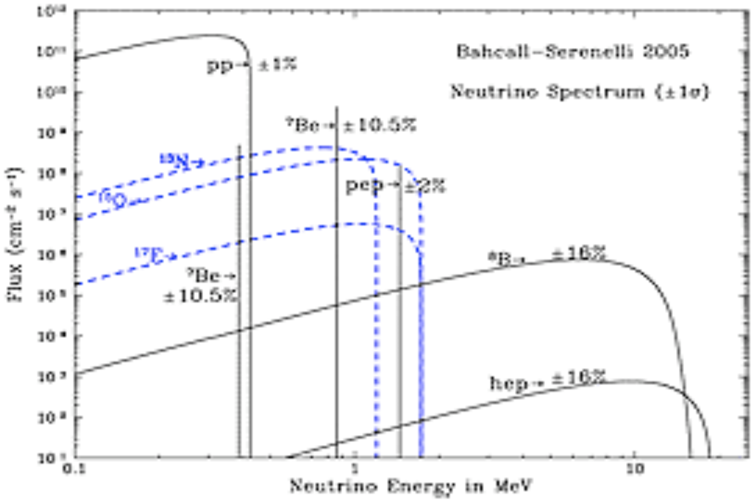
- Origin: Spergel & Press (mid-1980’s) to explain the solar neutrino problem (mechanical transport); Salati & Silk (1989) consider annihilation. Transport later more cleanly analyzed by Gould & Raffelt (1990), who showed the optimum WIMP-baryon cross section for transport ~ 10^{-35} cm^2
- That cross section is currently well above the limits for standard WIMPs in the mass range of interest.
- Also, there is no longer a solar neutrino problem.

Origin/Status of DM Effects on Stellar Evolution

- Now: Unless the local dark matter density is/has been high in the past, SOL for the Sun.
- However, there have been suggestions of two new places to look:
  - First stars (Spolyar, Freese, etc.)
  - Galactic Center (Scott, Fairbairn, Edsjö). Very interesting work, although nothing on neutrinos.
  - In both of these cases, the size of the effect depends sensitively on the density distribution at the very centers of halos, and for GC stars, the velocity distribution also REALLY matters.
- Caveat: These things have been worked out for generic WIMPs (ie, no self-interaction, inelasticity, etc).

Other ideas people have talked about here or other places

- Looking at solar neutrino constraints again--this time, focusing on neutrinos like ^{8}B, ^{7}Be from the very center of the Sun where annihilation energy is likely to be injected. (Conversations with Antonio Palazzo @ Moriond) Put in helioseismology constraints? (Kris)



From John Bahcall’s website

Other ideas people have talked about here or other places

- Constrain the local ρ(t) from stellar ev/annihilation ν's since unlike some other probes, these will have a "memory" of time-variation in ρ (Kris?).

Constraints from Planet Heat Output

- Mack et al. 2007: Limits on strongly interacting dark matter (*NOT* strongly self-interacting dark matter) from heat output of the Earth. Others (e.g., Mitra, Adler) have considered heat output from gas giants.

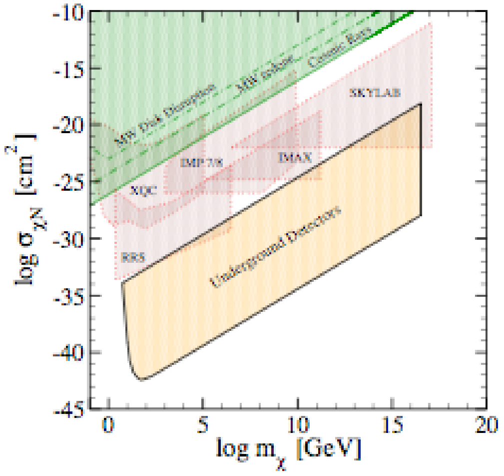


FIG. 1: Excluded regions in the $\sigma_{\chi N}$–m_χ plane, not yet including the results of this paper. From top to bottom, these come from astrophysical constraints (dark-shaded) [2, 3, 4, 5], re-analyses of high-altitude detectors (medium-shaded) [2, 10, 11, 12], and underground direct dark matter detectors (light-shaded) [6, 7, 8, 9]. The dark matter number density scales as $1/m_\chi$, and the scattering rates as $\sigma_{\chi N}/m_\chi$; for a fixed scattering rate, the required cross section then scales as m_χ. We will develop a constraint from Earth heating by dark matter annihilation to more definitively exclude the window between the astrophysical and underground constraints.

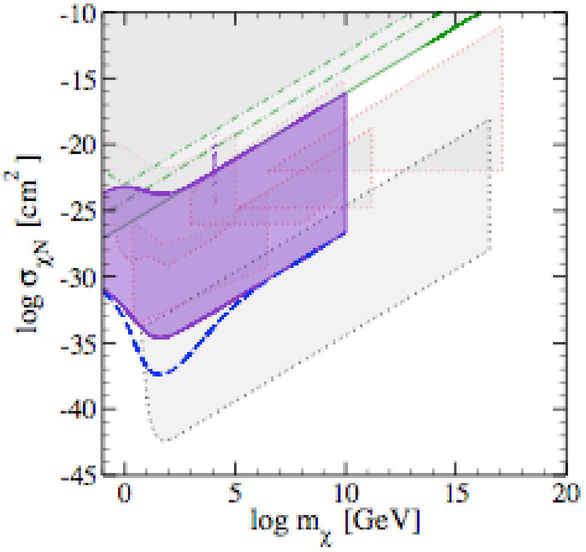


FIG. 2: Inside the heavily-shaded region, dark matter annihilations would overheat Earth. Below the top edge of this region, dark matter can drift to Earth's core in a satisfactory time. Above the bottom edge, the capture rate in Earth is nearly fully efficient, leading to a heating rate of 3260 TW (above the dashed line, capture is only efficient enough to lead to a heating rate of $\gtrsim 20$ TW). The mass ranges are described in the text, and the light-shaded regions are as in Fig. [1]

ν's from the Sun and Earth

- Work initially done in the 1980's and early 1990's by Freese, Spergel, Kamionkowski, Gould, Griest, Seckel, Frieman, Edsjö etc.
- Get high energy ν's (~GeV-TeV, as opposed to ~MeV from nuclear processes) which may be observable in ν telescopes.
- For conventional WIMPs, non-detection of high energy ν's from the Sun sets the current best bound on the elastic WIMP-proton spin-dependent cross section.
- Next-gen neutrino telescopes (ICECUBE, KM3NeT) will have 1-2 orders of magnitude better sensitivity than now…starting to get into interesting regions of parameter space.

Original Standard WIMP Picture

- Most things worked out for a SUSY neutralino WIMP (with respect to prospects for observation, relative solar/terrestrial \nu flux, etc.)
- Generally worked out with a standard halo model for f(x,v,t).
- Everything that gets captured stays captured.

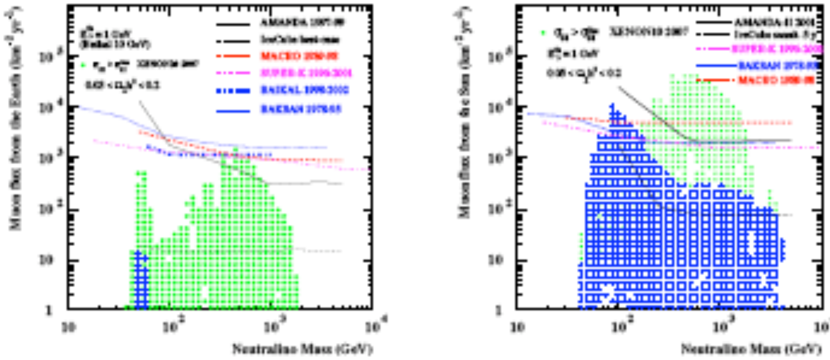


Figure 1.5. 90% CL upper limit on the muon flux from neutralino annihilations in the center of the Earth (left) and from the Sun (right). Markers show predictions for cosmologically relevant MSSM models, the dots representing models excluded by XENON10 [22].

From de los Heros et al. 2008

Modifications

- In the Sun: WIMPs may not thermalize if they are heavy! Gravitational perturbations from the planets can strip WIMPs from the system before they have a chance to settle down and annihilate. (Peter 2009)
- In the Earth: the annihilation rate is EXTREMELY sensitive to the low speed WIMP DF at the Earth. The low speed distribution function (DF) has yet to be definitively pinned down. The direction in general seems to be towards reduced signal. (Peter 2009) In general, the ever-better limits on ${\sigma_p}^{SI}$ make it unlikely that ν's will be seen unless vanilla assumptions about dark matter mass and phase density are violated.
- For both: Since the capture rate depends quite sensitively on the low speed WIMP DF, any significant deviation from the standard halo model can have huge effects on the signal. In particular, the existence of a co-rotating dark disk could dramatically boost the annihilation signal, even though it would likely be dynamically unimportant. (Read et al. 2009, Purcell et al. 2009, Bruch et al. 2009) This could make ν's from the Earth observable, although that depends greatly on what the low speed DF actually is.

Other WIMP Models: Kaluza-Klein photon

- Much of the analysis is identical to that of SUSY WIMPs--the main difference is in branching fractions (non-zero branching directly to neutrinos) and the fact that σ_p^{SD} >> σ_p^{SI}. Little flux from the Earth.

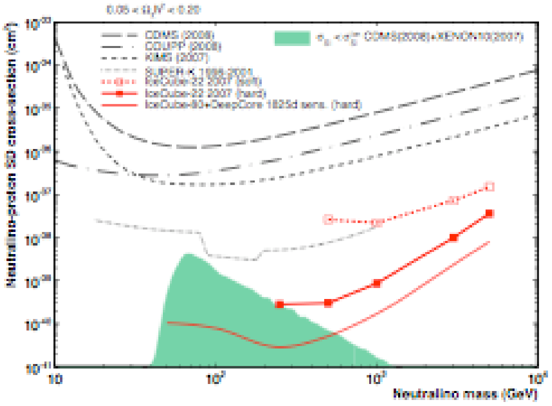


FIG. 4: Upper limits at 90% confidence level on the spin-dependent neutralino-proton cross-section σ^{SD} for soft ($b\bar{b}$) and hard (W^+W^-) annihilation channel, adjusted for systematic effects, as a function of neutralino mass. The shaded area represents MSSM models not disfavoured by direct searches [18, 19] based on σ^{SI}. The limits from CDMS [18], COUPP [22], KIMS [21] and Super-K [15], and the expected sensitivity of IceCube, are shown for comparison.

From IceCube collaboration publications

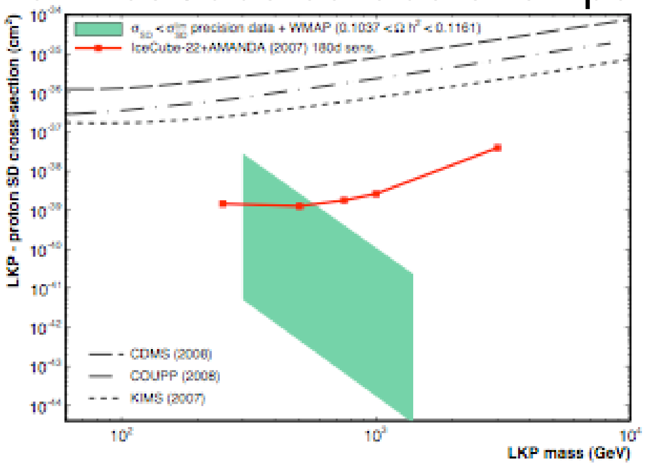


Fig. 3. Theoretically predicted spin-dependent $B^{(1)}$-on-proton elastic scattering cross sections are indicated by the shaded area [22]. The cross-section prediction vary with the assumed mass of the first KK excitation of the quark, constrained by $0.01 \leq r = (m_{q^{(1)}} - m_{B^{(1)}})/m_{B^{(1)}} \leq 0.5$. The current 'best' limits, set by direct search experiments are plotted together with the sensitivity of the combined detector IceCube-22+AMANDA. The region below $m_{B^{(1)}} = 300$ GeV is excluded by collider experiments [5], [6] and $m_{B^{(1)}} > 1500$ GeV is strongly disfavored by WMAP observations [23].

Other WIMP Models: Sommerfeld enhancement (enhancement to the annihilation cross section ~ 1/v)

- Delaunay et al. 2009: Boost to the annihilation rate of WIMPs in the Earth (due to a higher <σ v> velocity averaged cross section, since the typical speed of WIMPs captured in the Earth is quite small), although unless there is a significant branching ratio directly to neutrinos, it is still unlikely to show up in IceCube. No boost to the annihilation rate in the Sun because the typical captured WIMP speed is much higher than in the Earth.
- Observable: If you could actually measure the ν flux from the Earth, it would be relatively larger wrt the solar flux than for a SUSY or KK WIMP.

Other WIMP Models: Inelastic dark matter

χ + N $\rightarrow$ χ^{*}+ N

χ-χ^{*} mass splitting δ ~ 100 keV

- Limits on ν's from the Sun puts significant pressure on a model designed to harmonize the DAMA experiment with all others--in order to work, require “leptophilic” interactions or large branching fractions to light quarks (Nussinov et al. 2009, Menon et al. 2009)

Other WIMP Models: Strongly self-interacting dark matter

- Zentner 2009 (should appear on arXiv soon): Capture in the Sun both by baryonic interactions and dark matter self-interactions. Would boost flux ν flux from the Sun even more relative to that from the Earth (no boost, and maybe even loss, of signal from the Earth). For self-interaction cross sections still allowed, could potentially get boosts of ~10, but order-unity or less boosts more likely. May be less affected by gravitational stripping due to resonant capture. In any case, prospects for observation go up.

Questions:

- Are the 1980’s models for capture and stellar evolution good enough, or do these need fresh eyes (you can probably guess what my opinion is…)? Especially if we are entering interesting parameter space for a variety of WIMP models?
- Most things have only been worked out for a vanilla WIMP. How important is it to work things out for more exotic WIMPs?
- I think the biggest uncertainty, in terms predicting the magnitude of the effects of WIMPs on stars and planets, and in terms of distinguishing between models, and constraining model properties, is f(x,v,t), and how that might depend on the dark matter model.

F(x,v,t) of DM, ie where is it and how fast is it?

- There are both MACROscopic as well as MICROscopic issues.
- MACRO:
  - Is there a dark disk? If so, what are its properties? This will have strong implications for direct detection, too, but stronger for indirect detection.
  - DM at the Galactic Center?
  - Halo profile in the presence of a disk?
- MICRO:
  - Survival of dark matter clumps locally? Is this a scale-dependent statement? Which processes matter? Tidal shocks? Hierarchical structure formation? Interactions with baryons in the disk (molecular clouds, stars)?
  - Tidal streams: how long do they stay relatively coherent? Is the central limit theorem argument wrt the velocity distribution relevant for submilliparsec scales?
  - What scales in variation are relevant for indirect detection? Direct detection?
- PS, these issues are hugely important for direct detection and for indirect detection of our Galaxy.
- Can we extrapolate back any of these things from indirect observations (e.g., Siegal-Gaskins on C_l's of the fluctuations in the γ-ray background)?
  - Could such measurements help distinguish between models (WDM inclusive)?
- Could errors in our understanding of f(x,v,t) cause difficulty in distinguishing between models? E.g., SIDM degenerate with dn/drdm?