Title: Capture of Inelastic Dark Matter in the Sun

Date: Jun 13, 2009 12:00 PM

URL: http://pirsa.org/09060054

Abstract: TBA

Capture of Inelastic Dark Matter in the Sun

Lian-Tao Wang
Princeton University

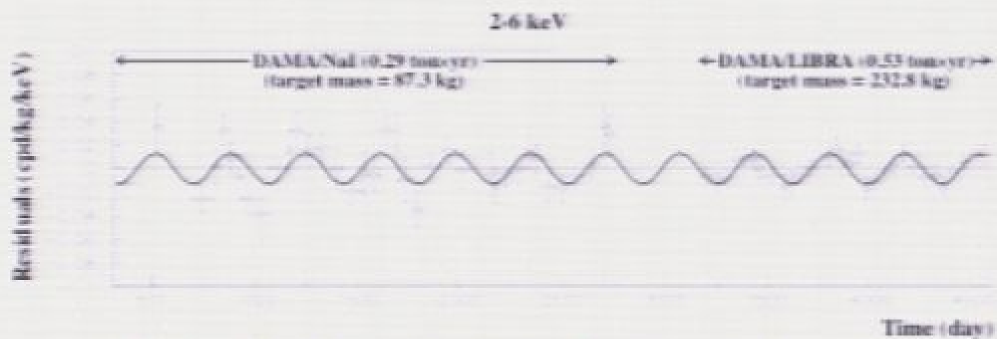
Based on:
S. Nussinov, LTW and I. Yavin, arXiv:0905.1333

Outline

- Inelastic dark matter (iDM).
- Neutrino signal from iDM annihilation.
  - Rough estimate.
  - Details of our calculation.
  - Results and implications.
- Conclusions.

DAMA/LIBRA

- Observation: annually modulated signal at 8-sigma. R. Bernabei et al. (DAMA) (2008), 0804.2741. Pierluigi Belli, talk earlier in this workshop.



- Typical WIMP (~100 GeV) elastic scattering

$$\sigma_{\mathrm{WIMP-nucleon}} \sim 10^{-40}\mathrm{cm}^2$$

  - Inconsistent with CDMS and XENON by several orders of magnitude.

Attempts at reconciliation.

- Very light DM, elastic scattering.

  G. Gelmini and P. Gondolo, hep-ph/0405278.
  F. Petriello and K. Zurek, arXiv:0806.3989.
  M. Fairbairn and T. Schwetz, arXiv:0808.0704
  S. Chang, A. Pierce, and N. Weiner, arXiv:0808.0196

- Scattering with electrons (?).

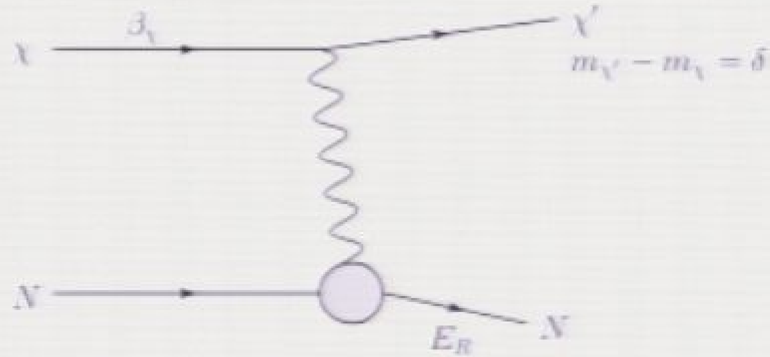
  R. Bernabei et. al., arXiv:0172.0562

- I will focus on inelastic Dark Matter.

  D. Tucker-Smith and N. Weiner, hep-ph/0101138.
  S. Chang, G. D. Kribs, D. Tucker-Smith, and N. Weiner, arXiv:0807.2250.

Inelastic Dark Matter.

- Scattering into excited states.



- The condition for scattering

$$\beta_{\min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$

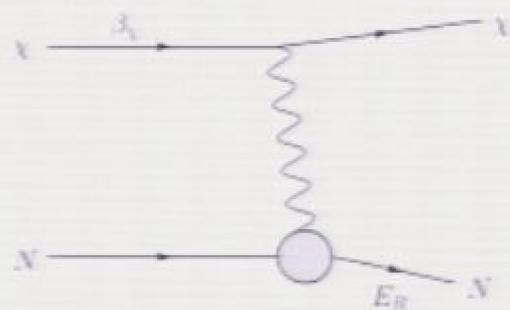
  - It is possible to scatter on heavier nucleus such as Iodine (A=127), but not on lighter nucleus such as Ge (A=73).

Typical model ingredients

- Multiple states, with mass splitting:

$$\delta \sim 100 - 150 \text{ keV}$$

- Force carrier with off-diagonal coupling.
- Elastic channel suppressed.
  - Not hard to achieve.

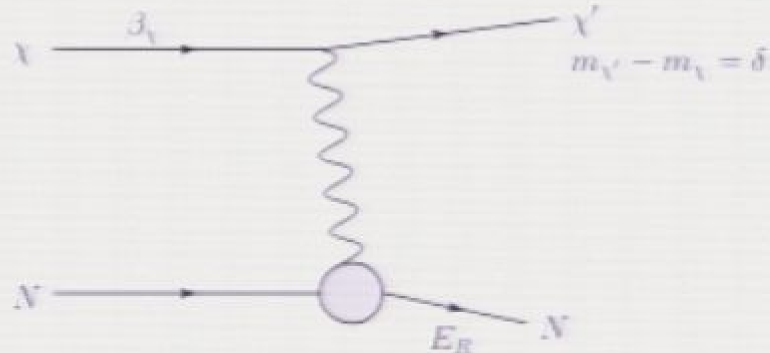


Some Models:

D. Tucker-Smith and N. Weiner, hep-ph/0101138.
N. Arkani-Hamed, D. Finkbeiner, T. Slatyer, N. Weiner, arXiv:0810.0713.
M. Baumgart, C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0901.0283.
Y. Cui, D. Morrissey, D. Poland, L. Randall, arXiv:0901.0557.

Inelastic Dark Matter.

- Scattering into excited states.



- The condition for scattering

$$\beta_{\min} = \sqrt{\frac{1}{2m_N E_R}}\left(\frac{m_N E_R}{\mu} + \delta\right)$$

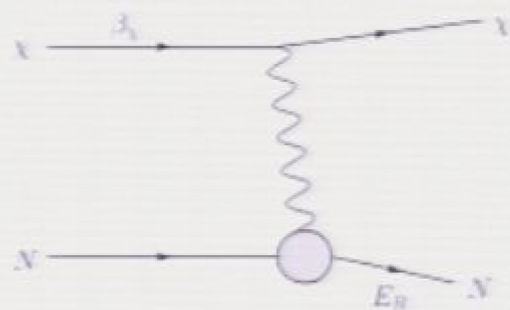
  - It is possible to scatter on heavier nucleus such as Iodine (A=127), but not on lighter nucleus such as Ge (A=73).

Typical model ingredients

- Multiple states, with mass splitting:

$$\delta \sim 100 - 150 \text{ keV}$$

- Force carrier with off-diagonal coupling.
- Elastic channel suppressed.
  - Not hard to achieve.



Some Models:

D. Tucker-Smith and N. Weiner, hep-ph/0101138.
N. Arkani-Hamed, D. Finkbeiner, T. Slatyer, N. Weiner, arXiv:0810.0713.
M. Baumgart, C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0901.0283.
Y. Cui, D. Morrissey, D. Poland, L. Randall, arXiv:0901.0557.

Experimental tests of iDM

- Direct detection experiment.
  - CRESST, LUX, ZEPLIN, KIMS...
  - De-excitation and more:

    D. P. Finkbeiner, T. Slatyer, N. Weiner and I. Yavin, arXiv0903.1037
    B. Batell, M. Pospelov, A. Ritz. arXiv:0903.3396

- Colliders: indirect tests of possible model ingredients of iDM model.
  - e.g.: GeV dark sector ↔ DM self-interaction.

Tevatron and LHC: lepton jets
N. Arkani-Hamed and N. Weiner, arXiv:0810.0714.
M. Baumgart, C. Cheung, J. Ruderman, LTW, I. Yavin, arXiv:0901.0283.

Low energy e+ e-:
B. Batell, M. Pospelov, and A. Ritz, arXiv:0903.0363.
R. Essig, P. Schuster, and N. Toro, arXiv:0903.3941.
M. Reece and LTW, arXiv:0904.1743. (also on fixed target)

Fixed target:
J. Bjorken, R. Essig, P. Schuster, and N. Toro, arXiv:0906.0580.
B. Batell, M. Pospelov, and A. Ritz, talk at this workshop.

I will focus on:

- Neutrino signal from the sun due to capture and annihilation of iDM.
- Strong constraints on the properties of the iDM couplings to the SM.

Neutrino signal of DM

- DM captured through scattering against nuclei in the sun.
- DM annihilation gives energetic neutrinos, several - hundreds GeV, which travel to the earth.
- Neutrinos scatter against the rock under the detector, and produce energetic upward going muons.

Neutrino signal of DM

- Muon yield in the detector:

$$\text{muon yield} \sim (10^{-19}\ \text{km}^{-2}\text{yr}^{-1})\left(\frac{C}{\text{s}^{-1}}\right)\left(\frac{m_\chi}{100\ \text{GeV}}\right)^2 ...$$

C : capture rate

- For WIMP elastic scattering with rate consistent with CDMS/XENON

$$C \sim 10^{21-22}\ \text{s}^{-1} \ \rightarrow\ \mu\ \text{Yield} \sim 10^{2-3}\ \text{km}^{-2}\ \text{yr}^{-1}$$

$$\text{Super-K bound: } \mu\ \text{Yield} < \text{ several} \times 10^3$$

- For iDM with DAMA rate.
  - About a factor of 1000 enhancement.

- Difference between elastic and inelastic scattering? The rest of this talk.

Capture rate calculation

- Velocity of in-falling WIMp

$$\omega(r)^2 = u^2 + v(r)^2$$

$u:$ WIMP velocity at $r = \infty$

$v(r):$ escape velocity at r

- Condition for capture: lose enough energy in scattering process so that the WIMP velocity is below escape velocity.
- Capture rate per unit shell

A. Gould, Astrophyiscal Jounrnal, 321:571-585, 1987

$$\frac{dC}{dV} = \int du \frac{f(u)}{u} \omega \Omega(\omega)$$

$\Omega(\omega):$ rate of WIMP scatter to $v_{\mathrm{WIMP}} < v$

Condition for inelastic scattering

- Condition for inelastic scattering:

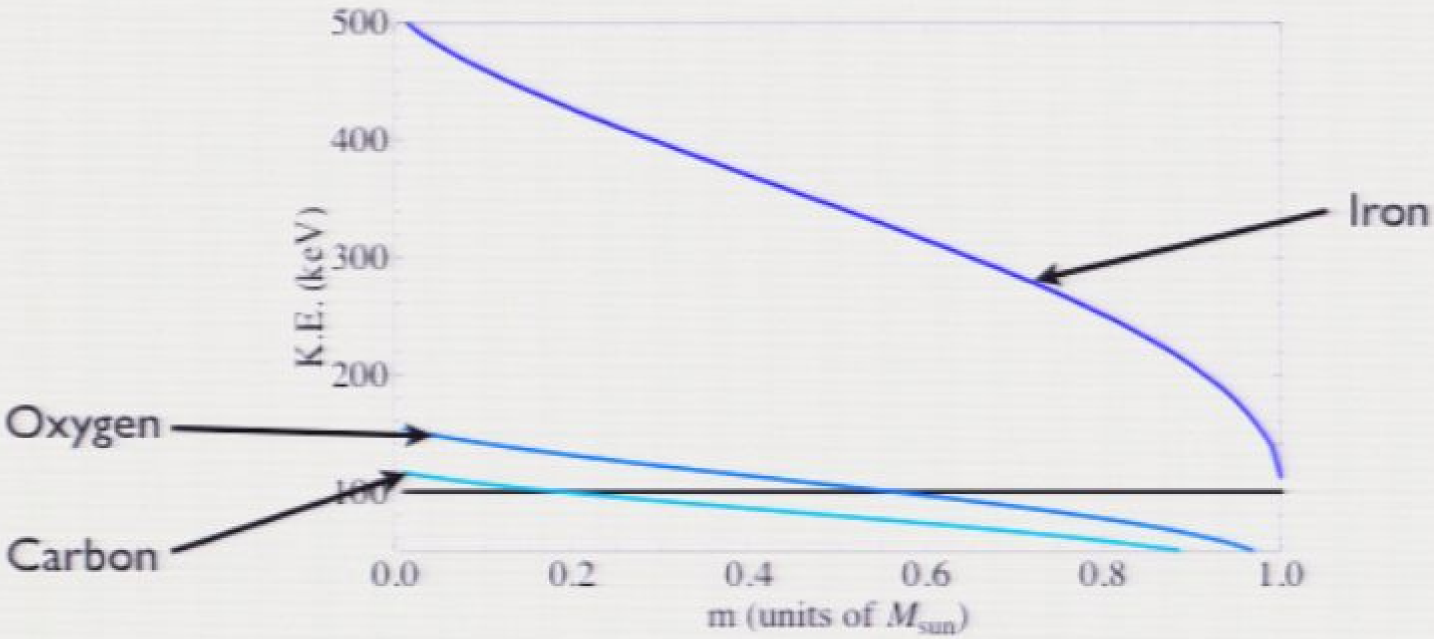
$$\frac{1}{2}\mu\omega^2 > \delta$$

- Condition for inelastic scattering can be easily satisfied in the sun since

$$v_{\rm esc} \simeq 600 - 1300 {\rm km/s}$$

Condition for iDM scattering

- Kinetic energy



- Iron is the most important scatter.

Capture rate calculation for iDM

- Scattering rate.

$$\sigma = \sqrt{1 - \frac{\delta}{\mu\omega^2/2}} \left(\frac{\mu^2}{\mu_{ne}^2}\right) \left(\frac{f_p^2 Z^2 + f_n(A-Z)^2}{f_p^2}\right) \sigma_n$$

μ_{ne} : WIMP-nuclean reduced mass

$\sigma_n = 10^{-40}\ \mathrm{cm}^2$

- Kinematical boundaries.

$$Q_{\max} = \frac{1}{2} m_\chi \omega^2 \left(1 - \frac{\mu^2}{m_\chi^2} \left(1 - \frac{m_N}{m_\chi} \sqrt{1 - \frac{\delta}{\mu\omega^2/2}}\right)^2\right) - \delta$$

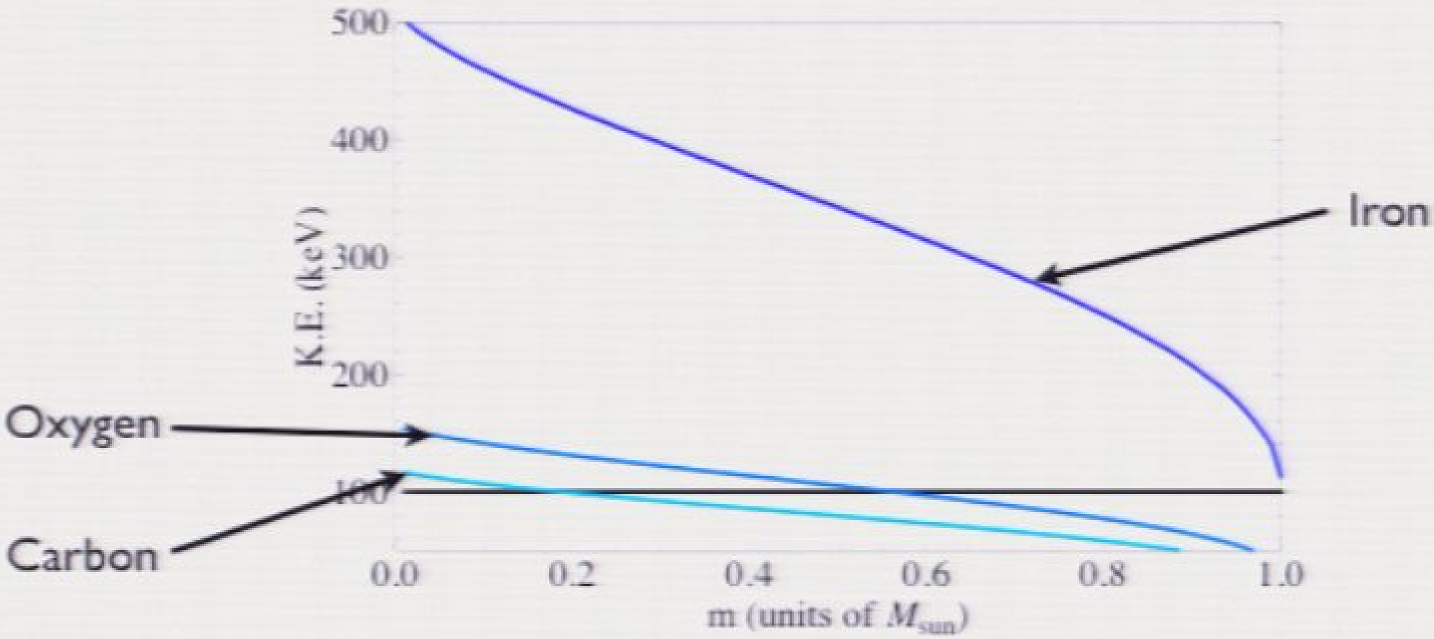
$$Q_{\min} = \frac{1}{2} m_\chi \omega^2 \left(1 - \frac{\mu^2}{m_\chi^2} \left(1 + \frac{m_N}{m_\chi} \sqrt{1 - \frac{\delta}{\mu\omega^2/2}}\right)^2\right) - \delta$$

$$Q_{\mathrm{cap}} = \frac{1}{2} m_\chi (\omega^2 - v^2) - \delta$$

lower $Q_{\max}$ $\rightarrow$ some suppression of cap. rate

Condition for iDM scattering

- Kinetic energy



- Iron is the most important scatter.

Capture rate calculation for iDM

- Scattering rate.

$$\sigma = \sqrt{1 - \frac{\delta}{\mu\omega^2/2}} \left(\frac{\mu^2}{\mu_{ne}^2}\right) \left(\frac{f_p^2 Z^2 + f_n (A-Z)^2}{f_p^2}\right) \sigma_n$$

μ_{ne} : WIMP-nuclean reduced mass

$\sigma_n = 10^{-40}\ \mathrm{cm}^2$

- Kinematical boundaries.

$$Q_{\max} = \frac{1}{2} m_\chi \omega^2 \left(1 - \frac{\mu^2}{m_\chi^2}\left(1 - \frac{m_N}{m_\chi}\sqrt{1 - \frac{\delta}{\mu\omega^2/2}}\right)^2\right) - \delta$$

$$Q_{\min} = \frac{1}{2} m_\chi \omega^2 \left(1 - \frac{\mu^2}{m_\chi^2}\left(1 + \frac{m_N}{m_\chi}\sqrt{1 - \frac{\delta}{\mu\omega^2/2}}\right)^2\right) - \delta$$

$$Q_{\mathrm{cap}} = \frac{1}{2} m_\chi (\omega^2 - v^2) - \delta$$

lower $Q_{\max}$ $\rightarrow$ some suppression of cap. rate

Taking into account form factor

$$\Omega(\omega) = \frac{n\sigma\omega}{Q_{\max} - Q_{\min}} \int_{Q_{\rm cap}}^{Q_{\max}} e^{-Q/Q_0} dQ$$

$$Q_0 = \frac{3}{2m_N R^2}, \quad R = 10^{-13}\left(0.91\left(\frac{m_N}{\rm GeV}\right) + 0.3\right) \text{ cm}$$

- Form factor suppression in elastic case:

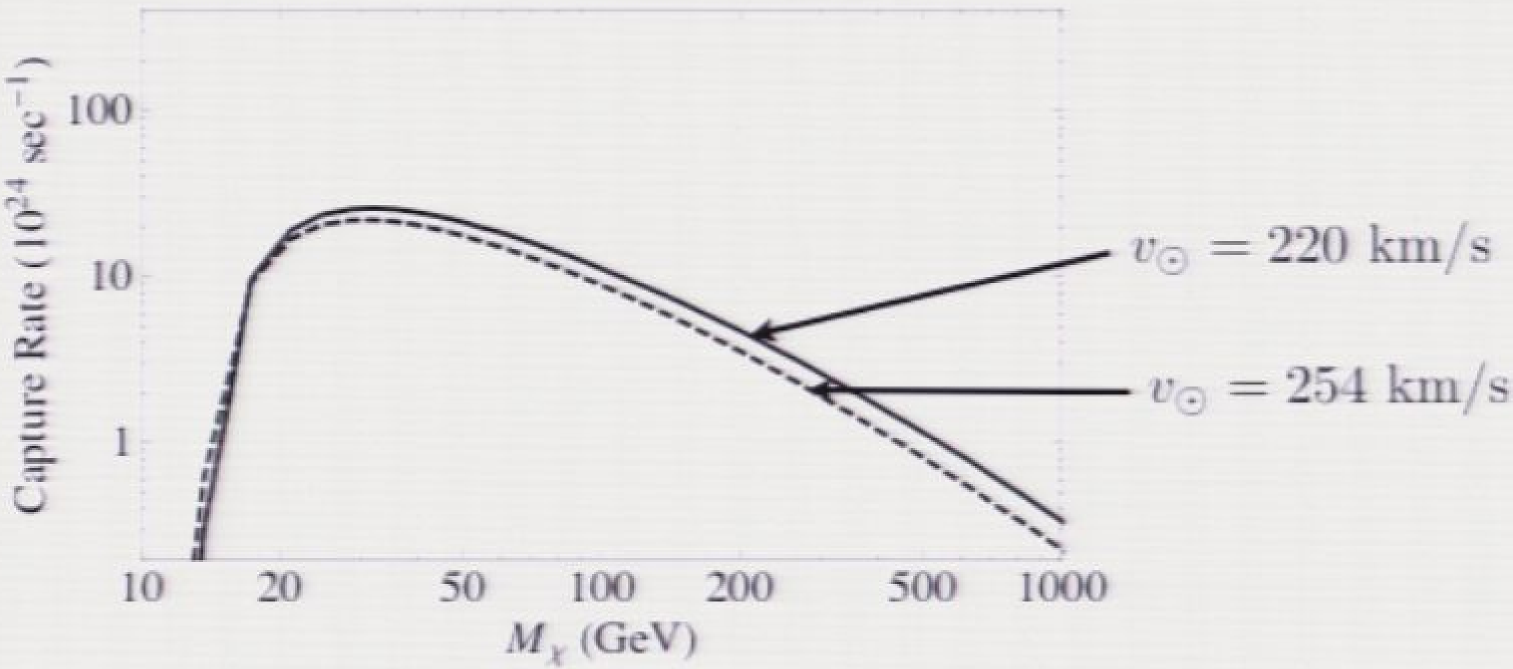
  Iron: $Q_0 = 82$ keV

  For $m_\chi \sim 100$ GeV: factor of 10 reduction

- Less suppression in the iDM case.
  - Some of the loss in energy have to go into excited state.

    Enhanced by $\exp(\delta/Q_0) \sim 3$

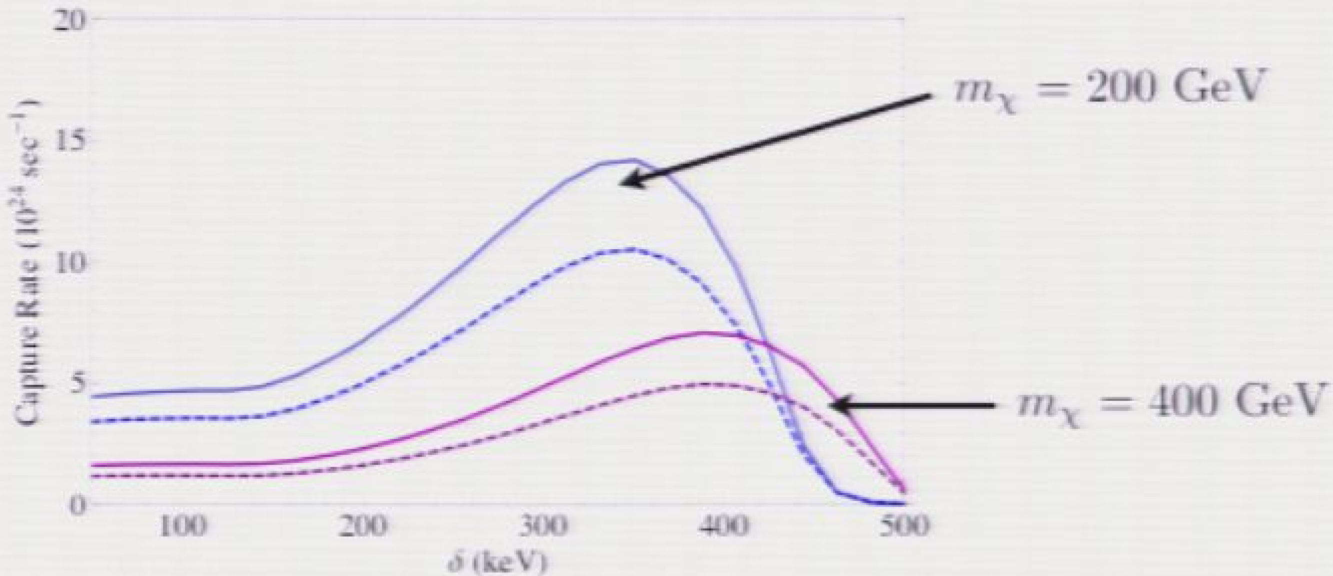
Capture rate: results



$\delta = 125$ keV

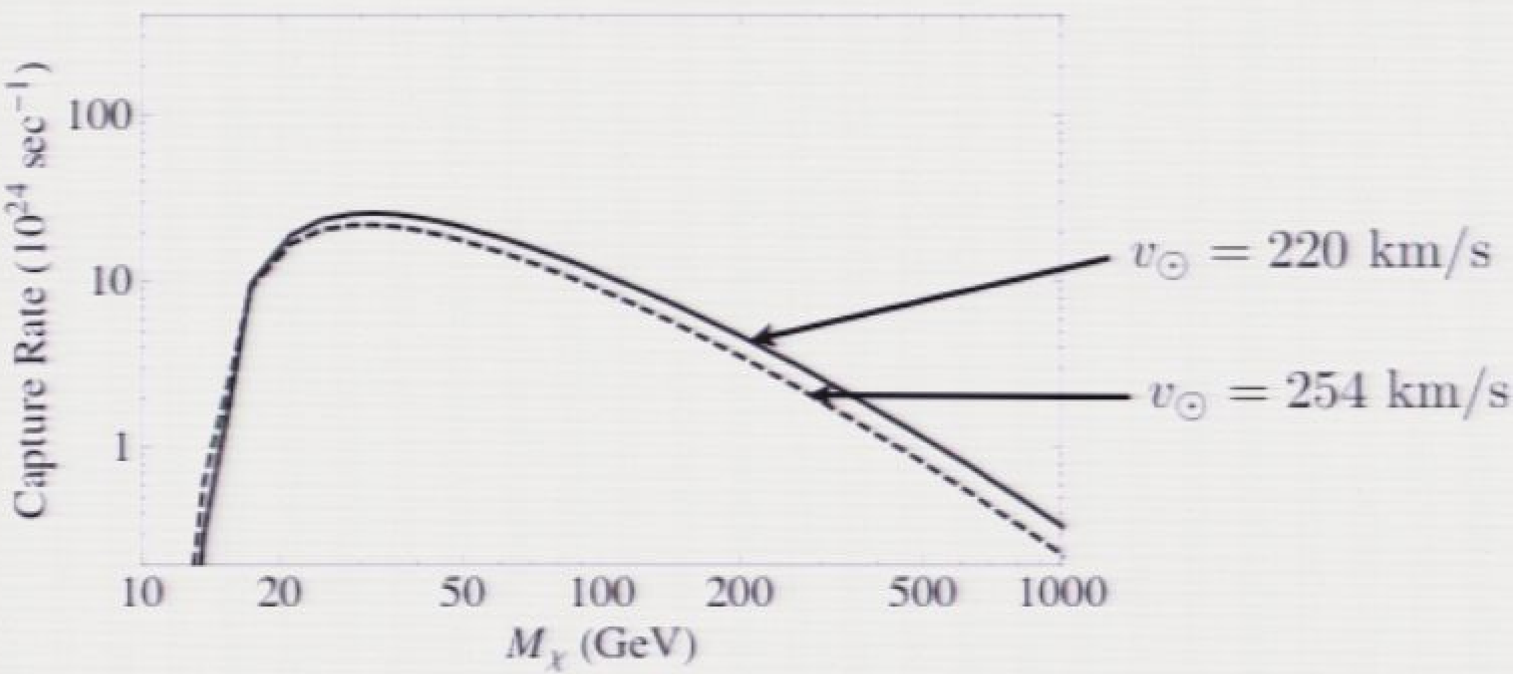
- Harder to capture for higher solar velocity.

Capture rate vs mass splitting:



- Form factor suppression curbed as mass splitting increases.

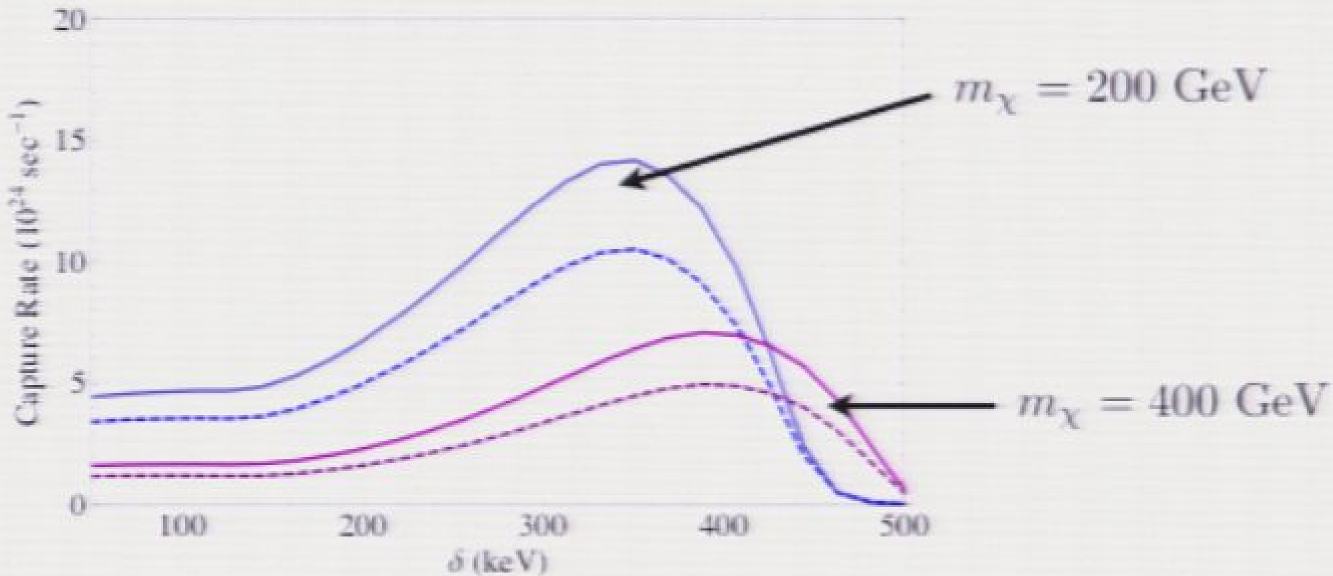
Capture rate: results



$\delta = 125$ keV

- Harder to capture for higher solar velocity.

Capture rate vs mass splitting:



- Form factor suppression curbed as mass splitting increases.

Capture and annihilation.

- Rate of WIMP annihilation in the sun:

$$\Gamma_A = \frac{C}{2}\tanh^2(t_\odot/\tau_{\rm eq}), \quad \tau_{\rm eq} = 1/\sqrt{CC_A}$$

$$C: \text{ cap. rate; } C_A = \frac{\int d^3r\, n(r)^2 \,\langle\sigma_A v\rangle}{\left(\int d^3r\, n(r)\right)^2}$$

- Elastic scattering

$$n_{\rm collision} = t_\odot \langle \sigma_n v\rangle n_\odot = 3\times 10^7 \left(\frac{\sigma_n}{10^{-43}\ {\rm cm}^2}\right) \ \rightarrow\ \text{thermalize}$$

$$n(r) = n_{\rm center} e^{-r^2/r_{\rm th}^2}, \text{ with } r_{\rm th} = 0.01 R_\odot$$

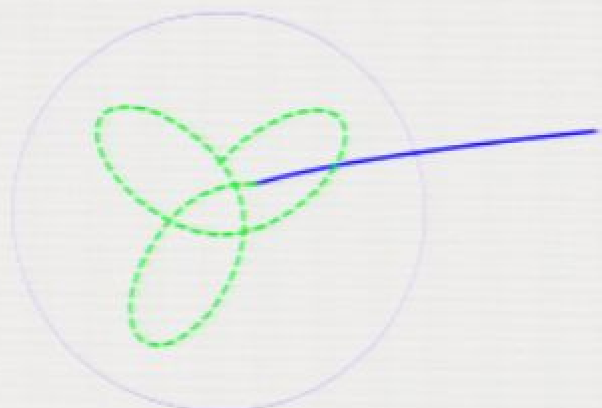
$$\frac{t_\odot}{\tau_{\rm eq}} = 10^3 \left(\frac{C}{10^{25}{\rm s}^{-1}}\right)^{1/2} \left(\frac{\langle\sigma_A v\rangle}{3\times 10^{-26}{\rm cm}^3{\rm s}^{-1}}\right)^{1/2} \left(\frac{0.01\times R_\odot}{r_{\rm th}}\right)^{3/2}$$

- Rate is controlled by capture rate (enhancement!).

$$\Gamma_A = \frac{C}{2}$$

Capture and annihilation of iDM.

- Typically not in thermal equilibrium.
  - Inelastic scattering cannot occur once the velocity is dropped below the inelastic threshold everywhere in the orbit, typically after a few scatterings.



  - Distribution of WIMP? Equilibrium?

An elastic component?

- Elastic scattering rate near CDMS/XENON bound is sufficient to thermalize.
- Can thermalize for $\sigma_n > 10^{-47}\ \mathrm{cm}^2$
- However, the sizes of elastic scattering in iDM models are model dependent.

Dirac fermion with m_χ and small Majorana mass m.

Mass splitting: $m_{\chi'} - m_\chi = \delta = m^2/m_\chi \simeq 100$ keV

Small diagonal coupling to a vector $\sim \delta/m_\chi \simeq 10^{-6}$

$\rightarrow$ Too small to thermalize

Estimation of iDM distribution:

- Difficult to lose angular momentum if they cannot scatter.
  - Density vanishes towards the center.
- However, most collision happen near the core (most solar mass) $< 0.2 R_\odot$.
  - Effective radius of WIMP should not be much bigger. If so,

$$\frac{t_\odot}{\tau_{\rm eq}} = 10^3 \left(\frac{C}{10^{25}{\rm s}^{-1}}\right)^{1/2} \left(\frac{\langle\sigma_A v\rangle}{3\times10^{-26}{\rm cm}^3{\rm s}^{-1}}\right)^{1/2} \left(\frac{0.01\times R_\odot}{r_{\rm eff}}\right)^{3/2} > 1$$

$$\rightarrow \tanh(t_\odot/\tau_{\rm eq}) = 1 \ \rightarrow \Gamma_A = \frac{C}{2}\tanh^2(t_\odot/\tau_{\rm eq}) = \frac{C}{2}$$

Same as thermal equilibrium

Numerical study of the density of iDM.

- We approximate the potential by

$$U(r) = \frac{GM_\odot m_\chi}{2bR_\odot}\left(1 - \frac{2b}{b + \sqrt{b^2 + r^2}}\right)$$

$b = 0.0884 R_\odot$ fitting to potential in

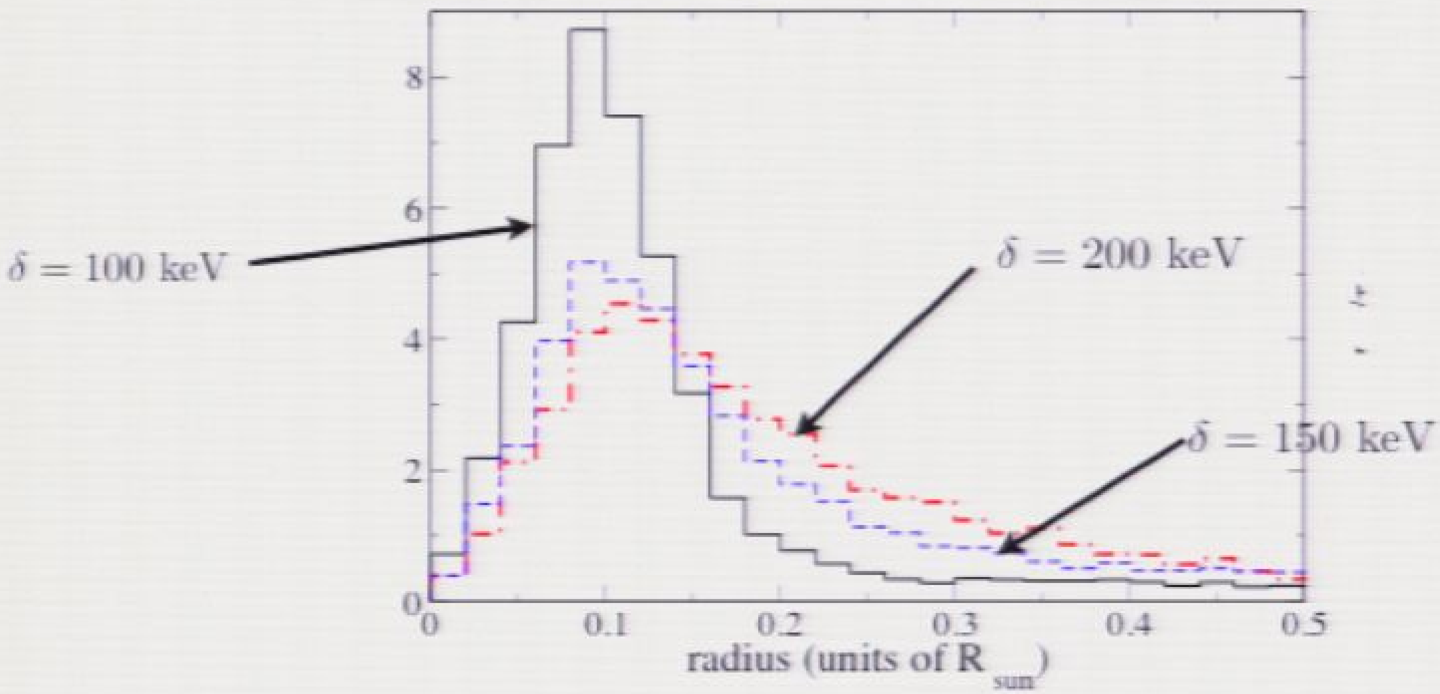
J. Bachall, M. Pinsonneault, and S. Basu, Astrophys. J. 555 (2001)

- M.C. simulation of WIMP scattering and motion using exact solutions of orbits.

M. Henon, *Annales d'Astrophysique* 22 (1959) 126.
M. Henon, *Annalesd'Astrophysique* 22 (1959) 491.

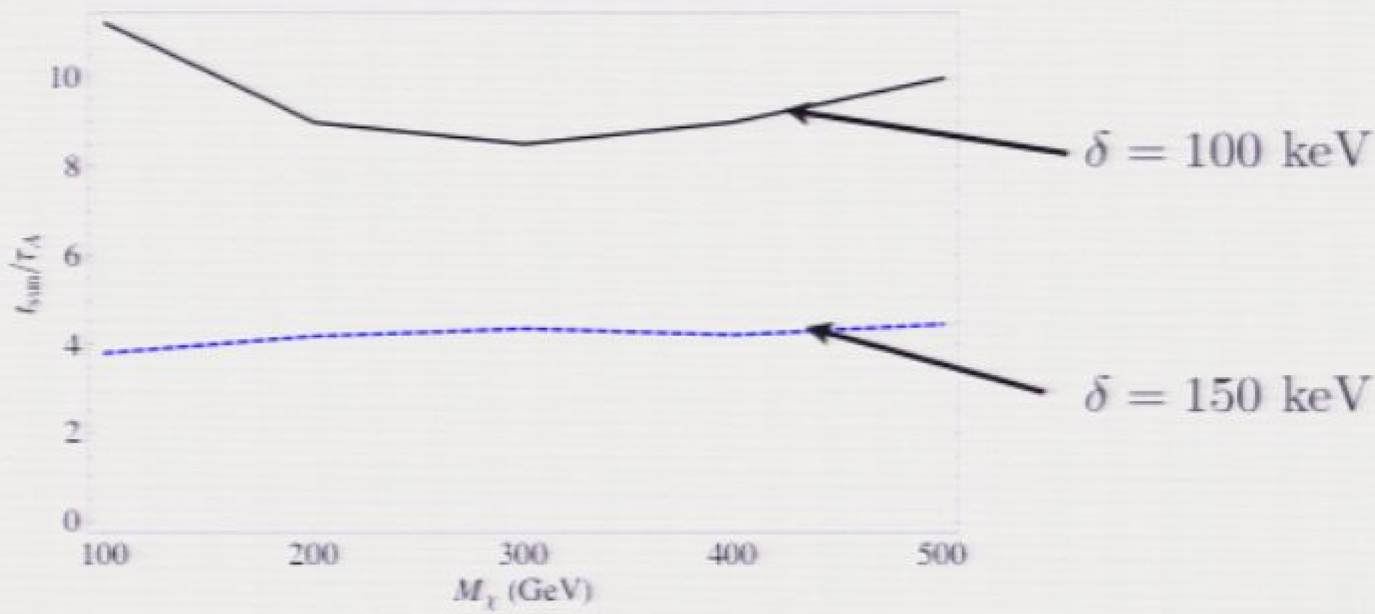
- Sampling in time along the orbits to find density distribution.

Numerical result of density



- Larger mass splitting, more energy in the orbit, more spread out.

Equilibrium condition vs WIMP mass



- Heavier WIMP, harder to lose angular momentum, but also scatters more.
- Always in equilibrium.

Putting everything together

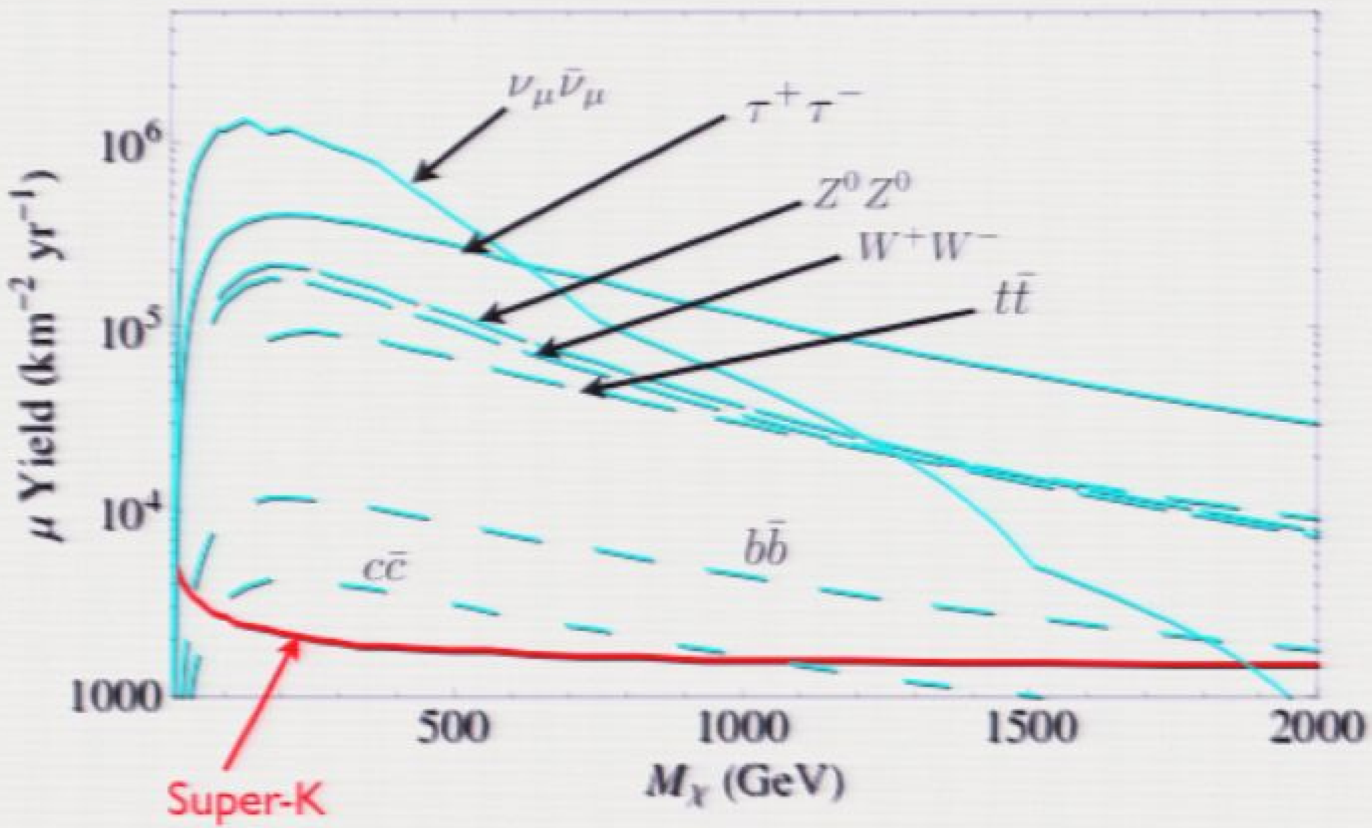
- We studied a collection of typical channels.

$$\chi\chi \rightarrow \nu_\mu \bar{\nu}_\mu,\ \tau^+\tau^-,\ Z^0 Z^0,\ W^+W^-,\ t\bar{t},\ b\bar{b},\ c\bar{c}, \ldots$$

- We modified DarkSUSY to calculate the capture rate of iDM.
- DarkSUSY is then used for calculating muon yields in various annihilation channels.

DarkSUSY: P. Gondolo *et. al.* JCAP 0407 (2004) 008.

Results of muon yield:

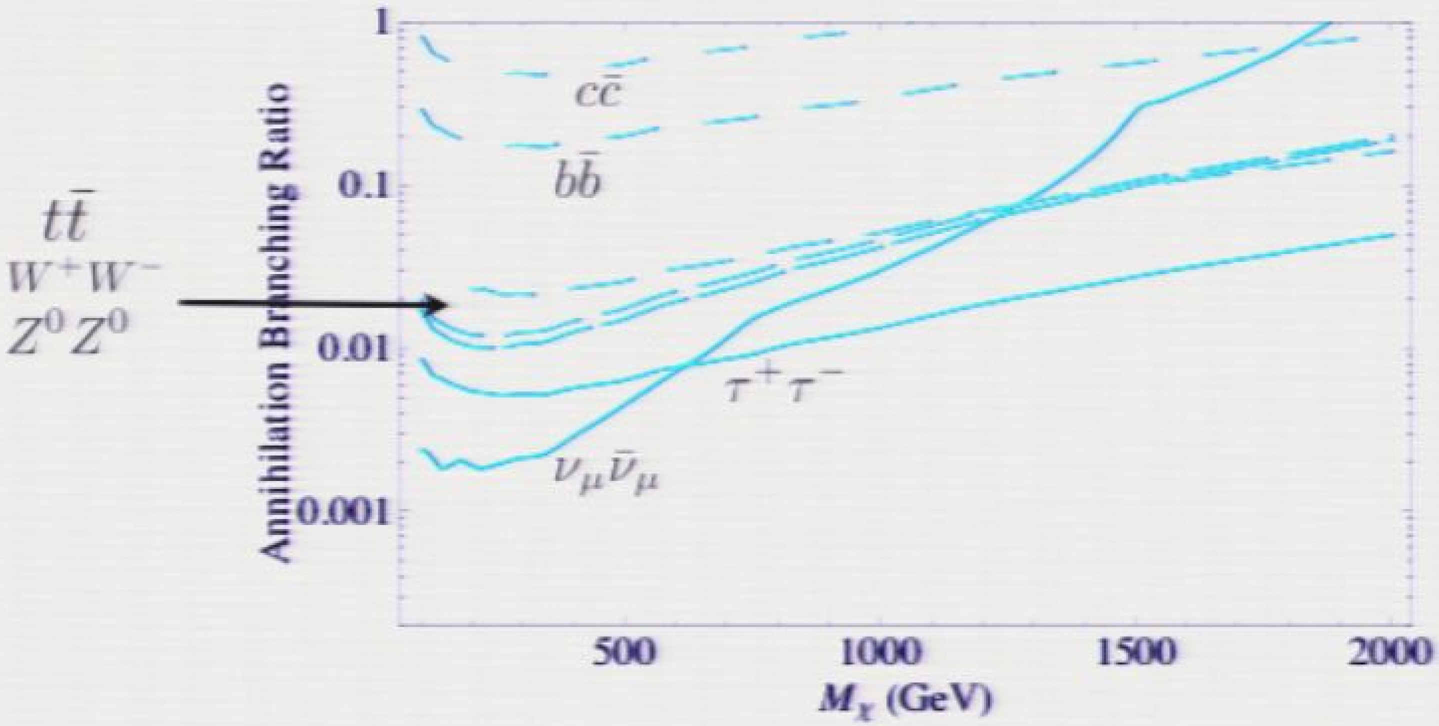


S. Desai et. al. hep-ex/0404025

See also a recent work with similar results:

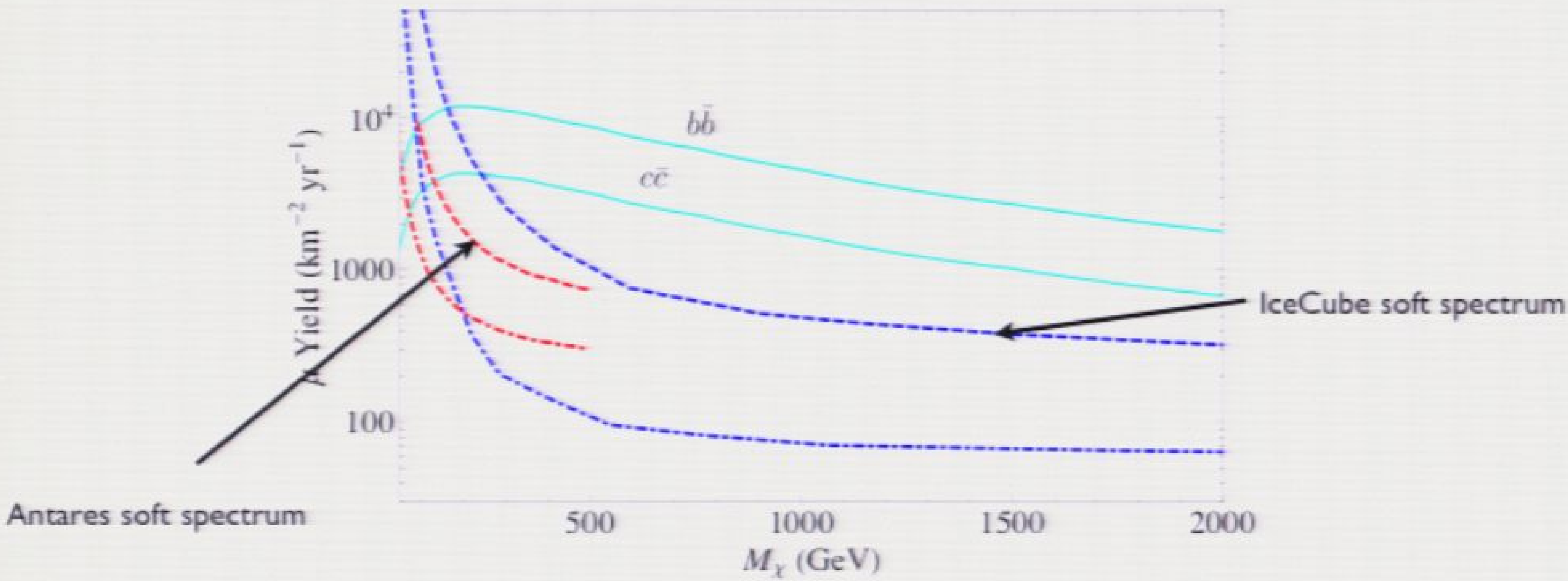
A. Menon, R. Morris, A. Pierce, and N. Weiner, arXiv:0905.1847

Bounds on ann. branching ratio.



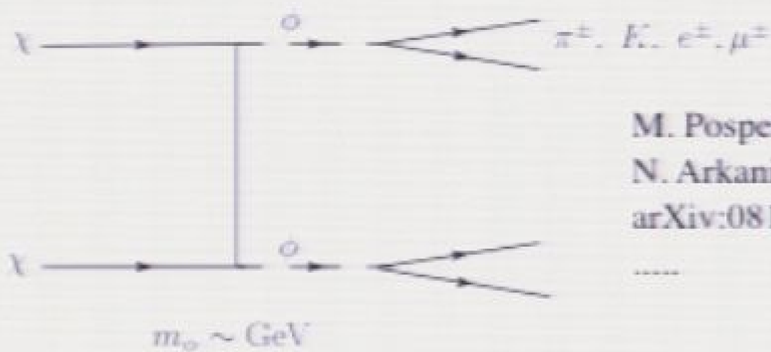
Strong constraints on $\chi\chi \to \nu_\mu\bar{\nu}_\mu,\ \tau^+\tau^-,\ Z^0Z^0,\ W^+W^-,\ t\bar{t}$;
Mild constraints on $\chi\chi \to b\bar{b},\ c\bar{c}$ for smaller m_χ.

Prospects at Antares and IceCube



An important case with no constraint.

- DM annihilating into GeV-ish light states.



M. Pospelov, A. Ritz, and M. B. Voloshin, arXiv:0711.4866
N. Arkani-Hamed, D. Finkbeiner, T. Slayter, and N. Weiner, arXiv:0810.0713.
......

$\pi^\pm,\ K,\ \mu^\pm,$ stopped in the sun before decaying

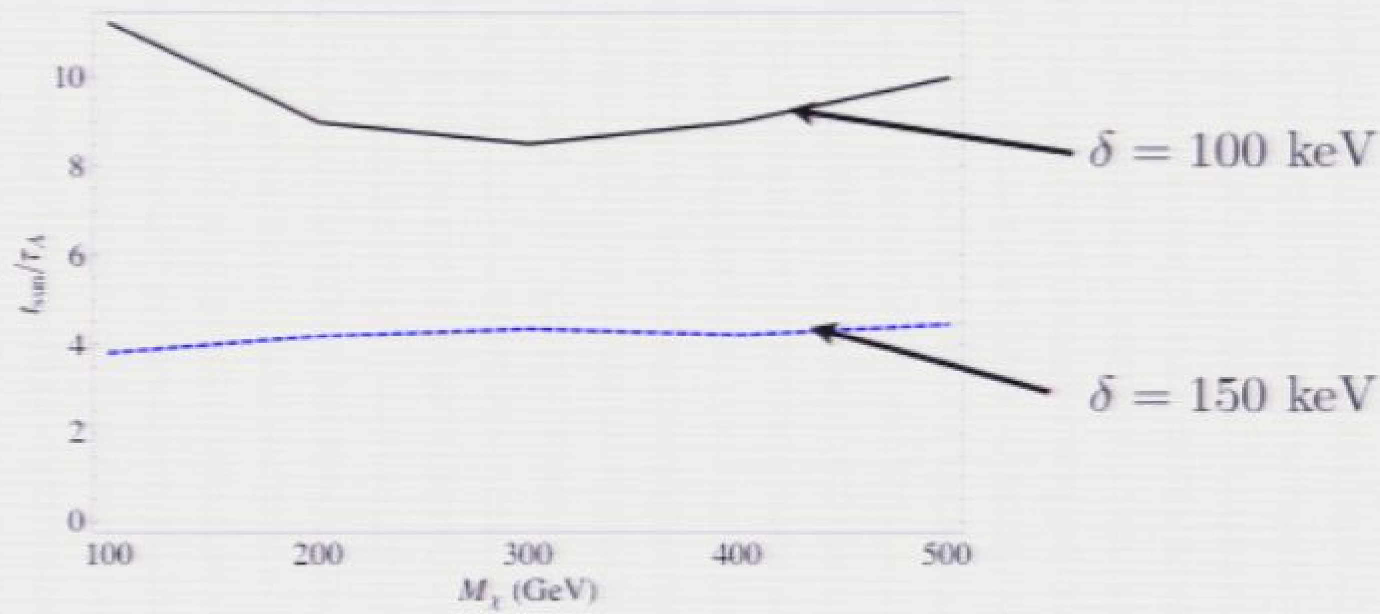
$\rightarrow$ very soft neutrinos

S. Ritz and D. Seckel, Nucl. Phys. B304 (1988)

Conclusions.

- Inelastic dark matter is an interesting possibility.
- With the rate measured by DAMA/LIBRA, iDM annihilation directly into SM neutrino, tau, Z/W, top are severely constrained by neutrino signal from iDM capture and annihilation in the sun.
- Future limits from Antares and IceCube will further constrain the channel into bottom and charm.
- Models with GeV dark sectors are not constrained.

Equilibrium condition vs WIMP mass



- Heavier WIMP, harder to lose angular momentum, but also scatters more.
- Always in equilibrium.

Capture and annihilation.

- Rate of WIMP annihilation in the sun:

$$\Gamma_A = \frac{C}{2} \tanh^2(t_\odot/\tau_{\rm eq}), \ \ \tau_{\rm eq} = 1/\sqrt{CC_A}$$

$$C: \ \text{cap. rate}; \ C_A = \frac{\int d^3r \ n(r)^2 \ \langle \sigma_A v \rangle}{\left(\int d^3r \ n(r)\right)^2}$$

- Elastic scattering

$$n_{\rm collision} = t_\odot \langle \sigma_n v \rangle n_\odot = 3 \times 10^7 \left(\frac{\sigma_n}{10^{-43} \ {\rm cm}^2} \right) \ \rightarrow \ \text{thermalize}$$

$$n(r) = n_{\rm center} e^{-r^2/r_{\rm th}^2}, \ \text{with} \ r_{\rm th} = 0.01 R_\odot$$

$$\frac{t_\odot}{\tau_{\rm eq}} = 10^3 \left(\frac{C}{10^{25} {\rm s}^{-1}} \right)^{1/2} \left(\frac{\langle \sigma_A v \rangle}{3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}} \right)^{1/2} \left(\frac{0.01 \times R_\odot}{r_{\rm th}} \right)^{3/2}$$

- Rate is controlled by capture rate (enhancement!).

$$\Gamma_A = \frac{C}{2}$$