Probing the Neutrino Sector with Dark Matter Indirect Detection Searches

Rouzbeh Allahverdi

THE UNIVERSITY of NEW MEXICO

Arnowitt Symposium
and
Mitchell Workshop on Collider and Dark Matter Physics

MIFPA, Texas A&M University

May 18-22, 2015

Outline:

- Introduction
- Dark matter-neutrino connection and its footprints
- Flavored neutrino final states as a novel probe
- Some results
- Summary and outlook

Based on work with: B. Knockel (UNM),
S. Campbell (UC Irvine), B. Dutta (TAMU), A. Friedland (LANL), Y. Gao (TAMU),
D. Ghosh (IACS), I. Saha (IACS)

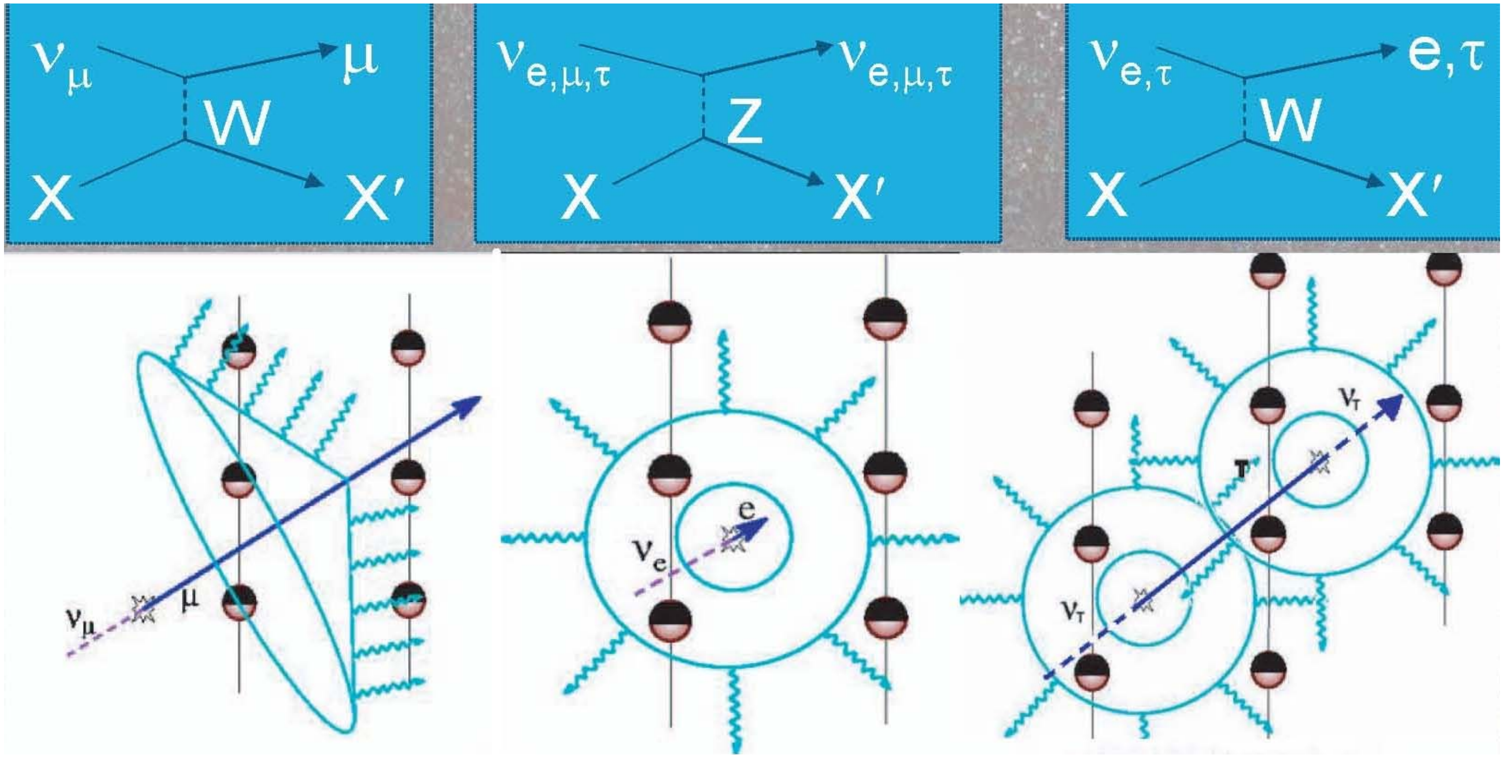
Introduction:

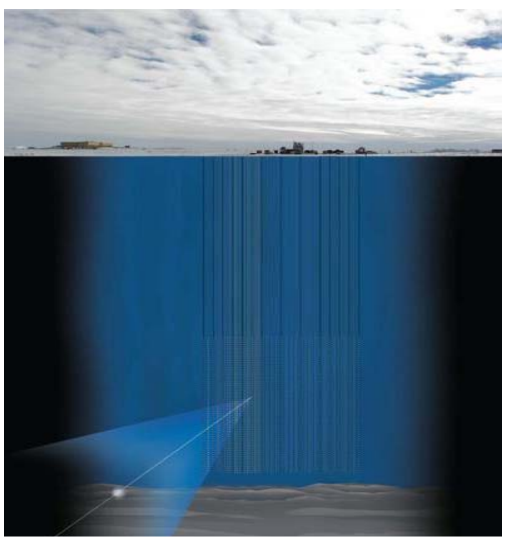
Indirect detection searches look for signals from annihilation of DM into SM particles:
Photons, **Neutrinos**, Antiparticles

Neutrinos provide a suitable probe since they are affected least from production point to detection point.

Neutrino telescopes (IceCube, ANTARES, …) look for neutrino signal from places with large DM density:
Milky Way, dwarf spheroidals, galaxy clusters,
nearby astrophysical bodies (**Sun**)

Neutrino interactions inside the detector:





Track length a proxy of muon energy:

$\approx 5m$ per GeV

DM-Neutrino Connection and its Footprints:

In most models DM is not connected to the neutrino sector.

For example, consider MSSM:

DM is the lightest neutralino → **Majorana fermion**

Neutrinos produced via gauge interactions → **flavor blind**

$$\begin{array}{cccc} & DM & & \\ \nu \leftarrow & + & \rightarrow \bar{\nu} \\ \Rightarrow & DM & \Rightarrow \end{array}$$

$$<\sigma_{ann} v> = a + bv^2 + \ldots$$

$$a \propto \left(\frac{m_\nu}{m_{DM}} \right)^2 , \quad v \sim 10^{-3}$$

(1) DM direct annihilation to neutrinos suppressed.

(2) Flavor of neutrinos decoupled from neutrino properties.

However, the situation completely changes in an interesting class of models where DM is tied to the neutrino sector.

In these models:

(1) DM is not necessarily a Majorana fermion

(2) DM can have leptonic flavor

(3) DM coupling to neutrinos not necessarily democratic

M. Lindenr, A. Merle, V. Niro PRD 82, 123529 (2010)
C. Boehm et al PRD 77, 043516 (2008)
Y. Farzan, S. Pascoli, M. Schmidt JHEP 1010, 111 (2010)
Y. Farzan PRD 80, 073009 (2009) & JHEP 1202, 091 (2012)
…

As an example, consider a minimal and well-motivated extension of SM that includes a gauged $U(1)_{B-L}$ symmetry.
R. Marshak, R. Mohapatra PRL 44, 1316 (1980)

Its SUSY version contains 3 RH neutrinos/sneutrinos $N / \tilde{N}$, one gauge boson Z' , and its gaugino partner $\tilde{Z}'$.

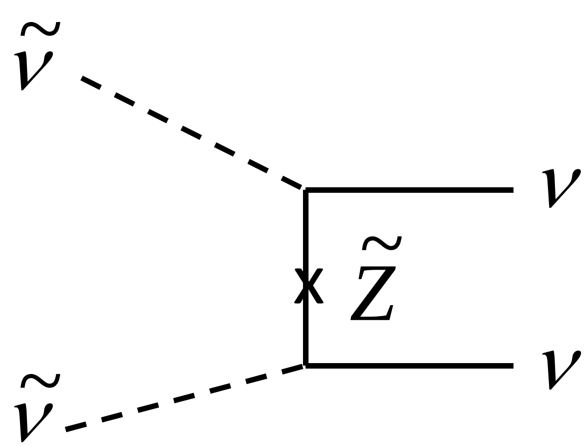
$$W = W_{MSSM} + hNH_1L + W_{B-L}$$

$$W_{B-L} = fH_2'NN + \mu' H_1' H_2'$$

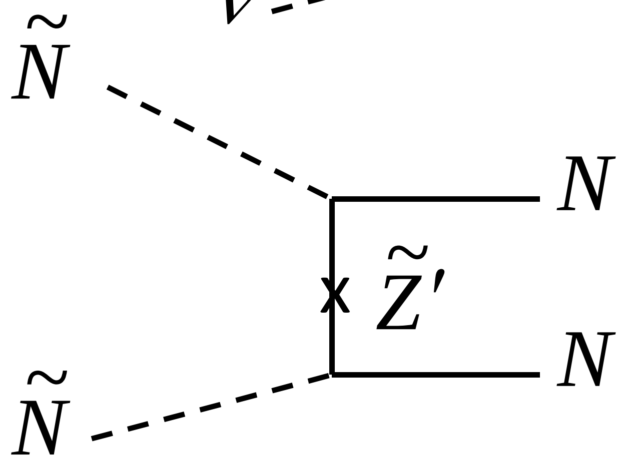
The lightest sneutrino is a DM candidate in this model.

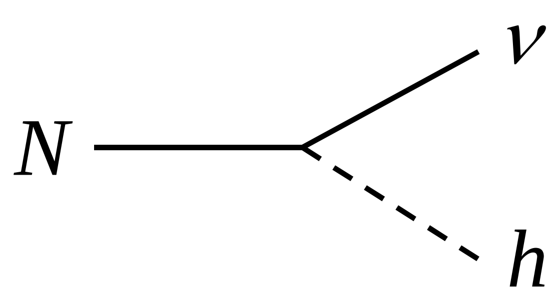
R. A., B. Dutta, K. Richardson, Y. Santoso PLB 677, 172 (2009)

LH sneutrino $\tilde{\nu}$:



RH sneutrino $\tilde{N}$:





DM dominantly annihilates into neutrino final states. The resulting neutrino signal has distinguishable signatures from that in MSSM.

R. A., S. Bornhauser, B. Dutta, K. Richardson PRD 80, 055026 (2009)
R.A., S. Campbell, B. Dutta PRD 85, 035004 (2012)
R.A., S. Campbell, B. Dutta, Y. Gao PRD 90, 073002 (2014)

Distinct possibilities in models that link DM to neutrinos:

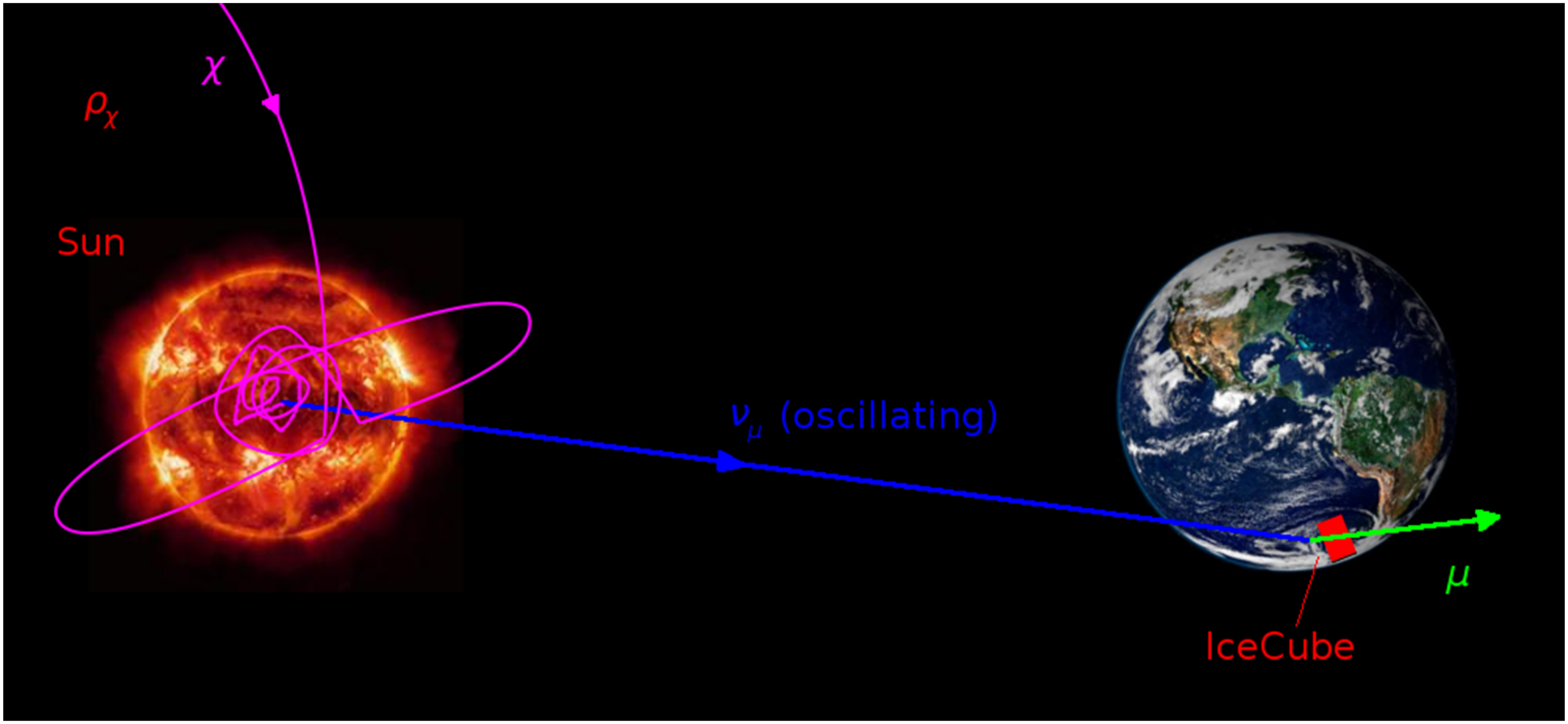
(1) DM direct annihilation to neutrino final states
(2) DM preferential annihilation to neutrinos/antineutrinos
(3) DM annihilation to flavored final states

Important questions:

(1) Consequences for indirect detection experiments?
(2) Indirect searches as a probe of neutrino properties?

Flavored Neutrino Final States as a Novel Probe:

DM-neutrino interplay best evident in the signal from Sun.



absorption
energy loss
matter effects

vacuum oscillations

conversion

$$\frac{dN(t)}{dt} = C - AN(t)^2 \quad \Rightarrow N(t) = \sqrt{\frac{C}{A}} \tanh(\sqrt{CA}t)$$

C : Capture rate, depends on σ_{SD}, σ_{SI}

A : Annihilation rate, depends on $< \sigma_{ann} v >_0$

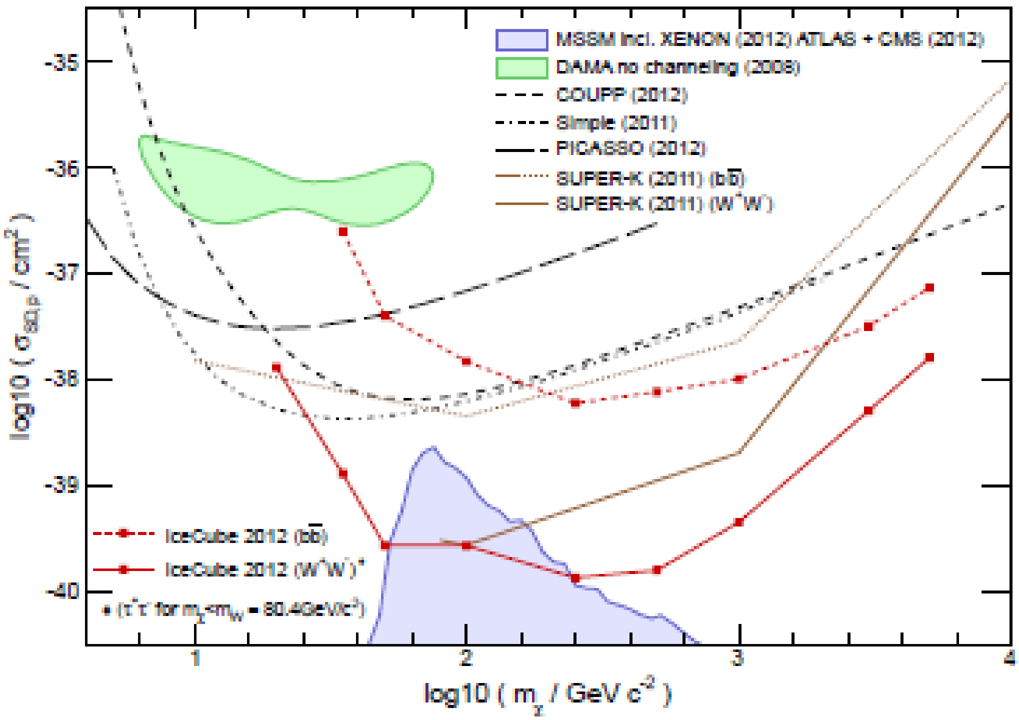
G. Jungman, M. Kamionkowski, K. Griest PR 267 (1996) 195

H. Baer, A. Belyaev, T. Krupovnickas, J. O'Farrill JCAP 0408, 005 (2004)

$$\Gamma_A = \frac{A}{2} \tanh^2(\sqrt{CA}t) \approx \frac{C}{2} \qquad t > \tau_{eq} \equiv (\sqrt{CA})^{-1}$$

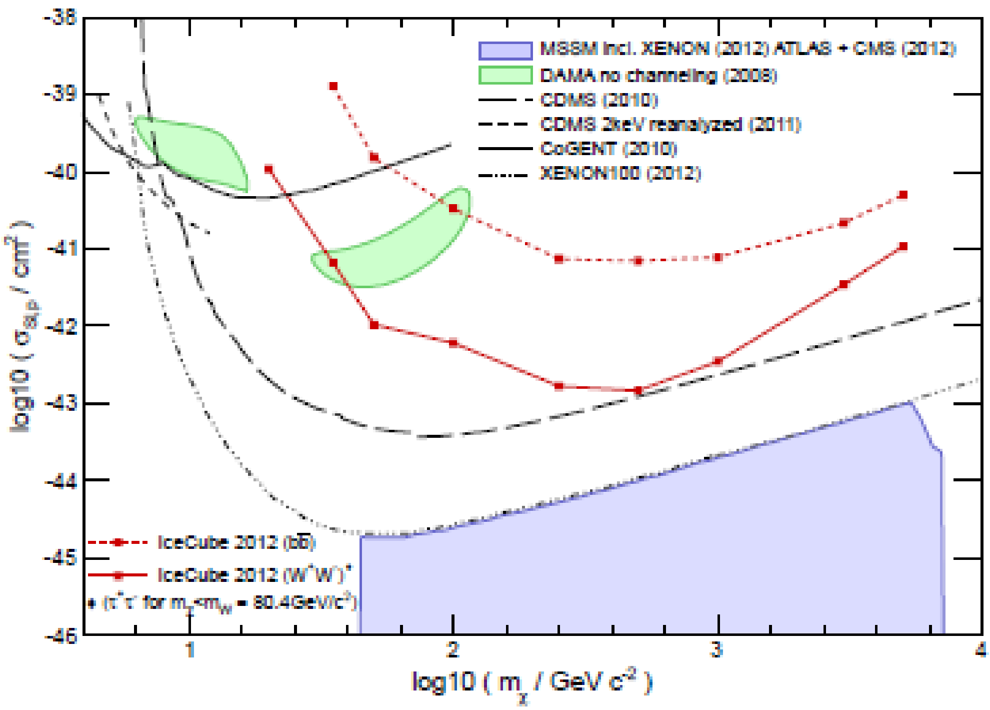
Equilibrium achieved for $< \sigma_{ann} v >_0 = 3 \times 10^{-26} \; cm^3 s^{-1}$, if:

$$\sigma_{SD} \geq 10^{-7} \; pb \qquad \sigma_{SI} \geq 10^{-10} \; pb$$



σ_{SD} limits much better than direct detection

IceCube Collaboration
PRL 110, 131302 (2013)



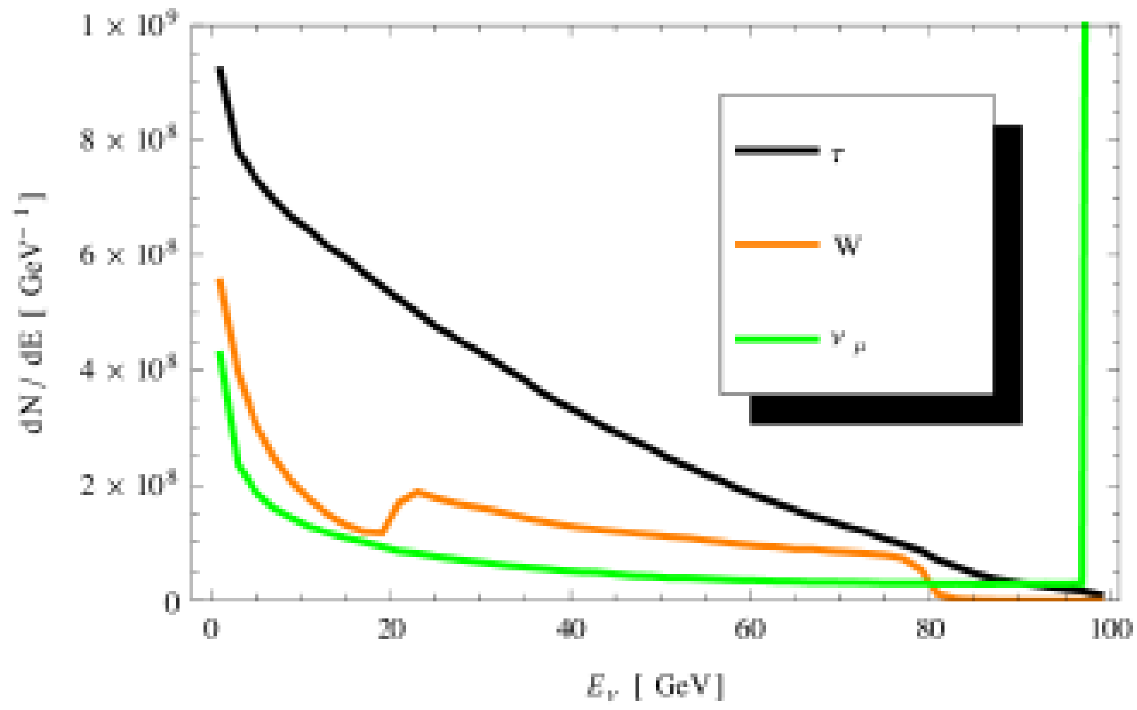
σ_{SI} limits not competitive with direct detection

Flavored neutrino final states bring in new prospects.

Flavor-dependent effects:
(1) Absorption and regeneration inside the Sun.
(2) Vacuum oscillations between the Sun and Earth.

To demonstrate these effects, consider monochromatic neutrinos from direct DM annihilation:

$$m_{DM} = 100 \ GeV$$



Absorption and regeneration inside the Sun:

Neutrino absorption occurs via CC interactions.

$$L_{abs} \propto E_\nu^{-1} \qquad E_\nu > 300\ GeV \Rightarrow L_{abs} \leq R_c$$

ν_e absorbed, peak of the spectrum is suppressed.

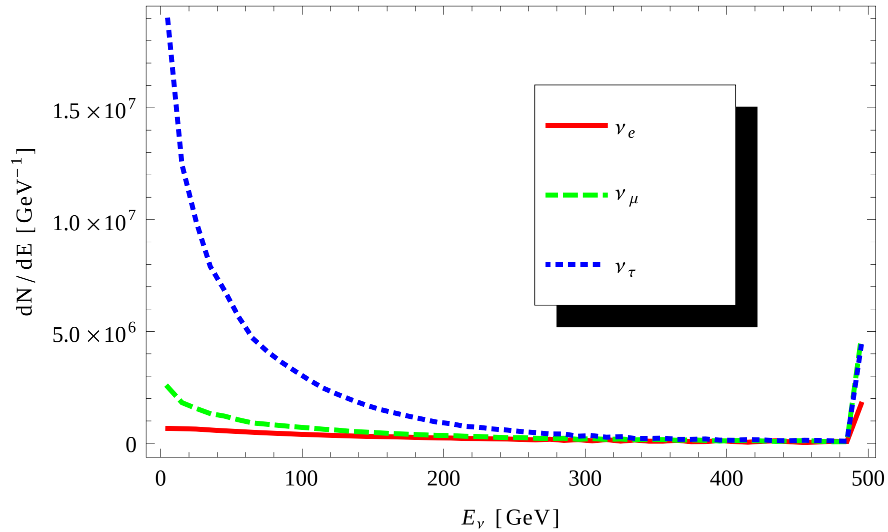
ν_τ absorbed, but reproduced at lower energies.

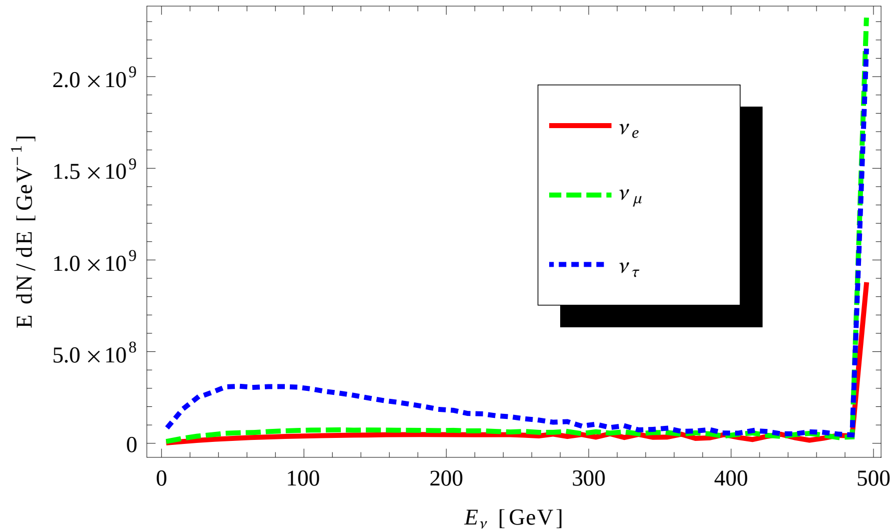
ν_μ mix with ν_τ via oscillations governed by Δm_{23} .

$$L_{osc} \propto E_\nu \qquad E_\nu > 500\ GeV \Rightarrow L_{osc} > 4L_{abs}$$

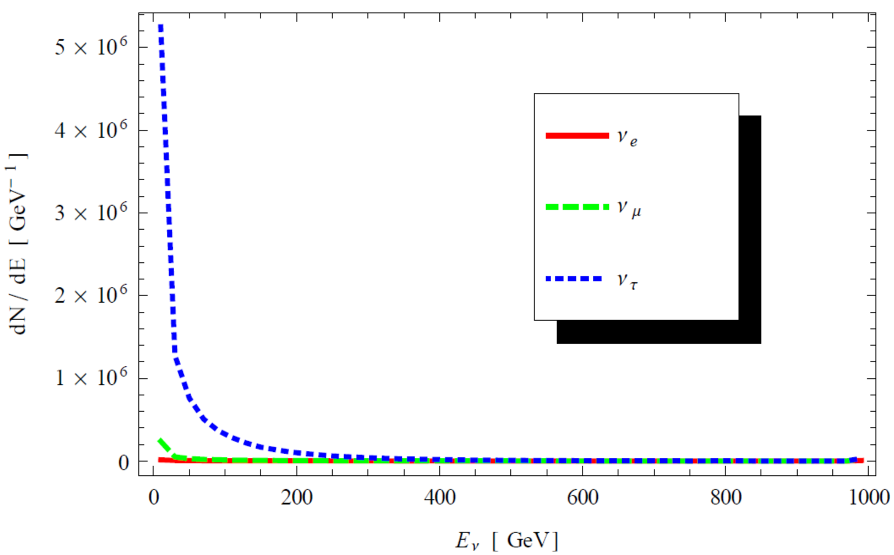
Neutrino spectra at the detector:

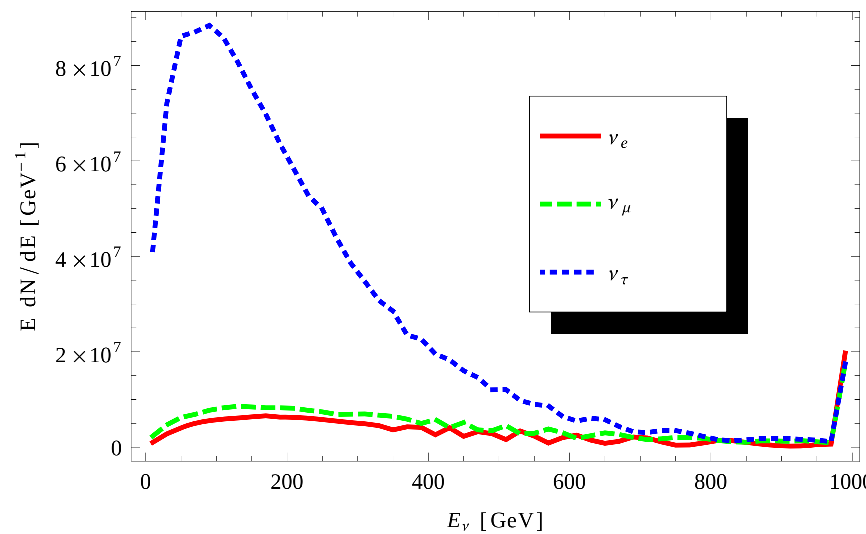
$m_{DM} = 500\ GeV$





$m_{DM} = 1000\ GeV$





Vacuum oscillations between the Sun and Earth:

Oscillations driven by Δm_{23} and Δm_{12} .

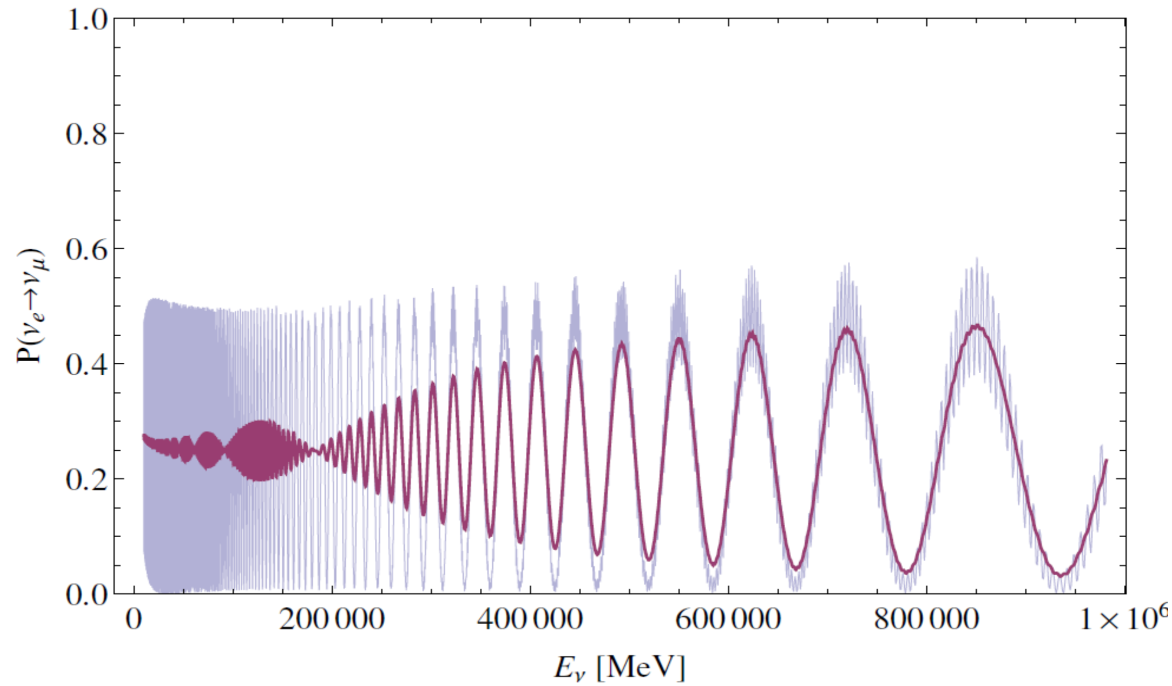
$$L_{sol} = \Delta m_{12}^2 / 2E_\nu \; , \; L_{atm} = \Delta m_{23}^2 / 2E_\nu$$

PDG Collaboration CPC 38, 090001 (2014)

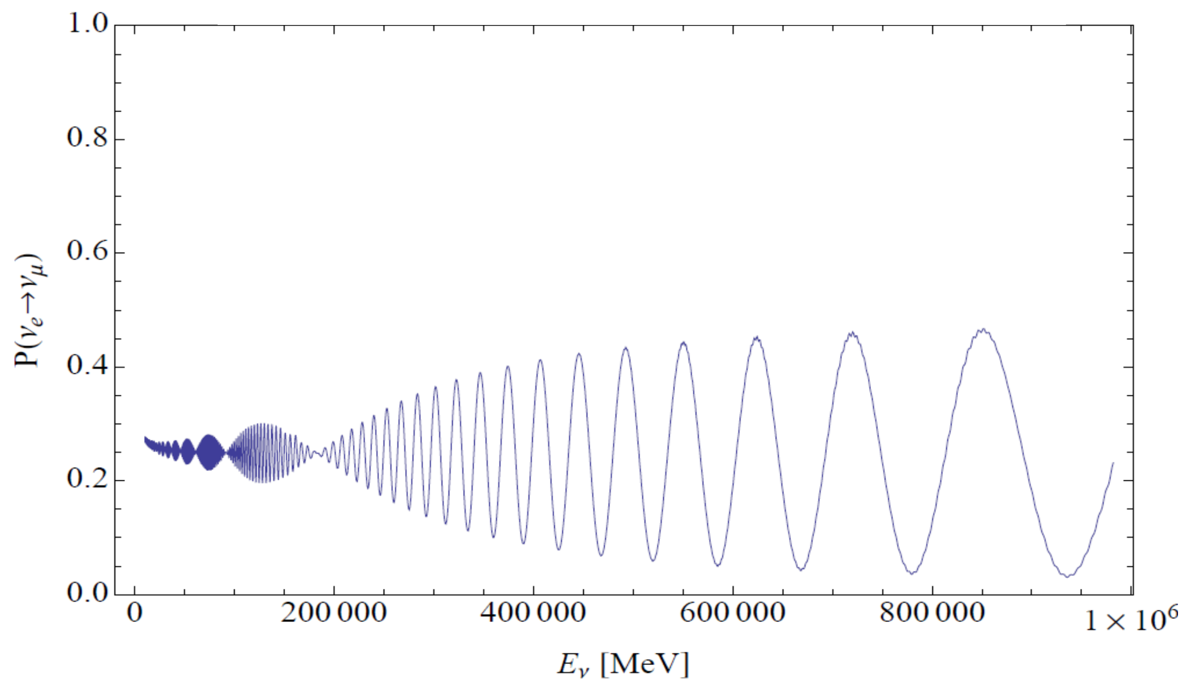
Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ ($2.19 - 2.56$)
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ ($1.31^{+0.29}_{-0.33}$)	$(0.00 - 0.16) \oplus (0.86 - 2.00)$ $((0.00 - 0.02) \oplus (0.70 - 2.00))$

$$E_\nu > 200 \;\; GeV \Rightarrow L_{sol} > 3{,}000{,}000 \;\; km$$

Transition probability as a function of energy:



Transition probability after being averaged over eccentricity:

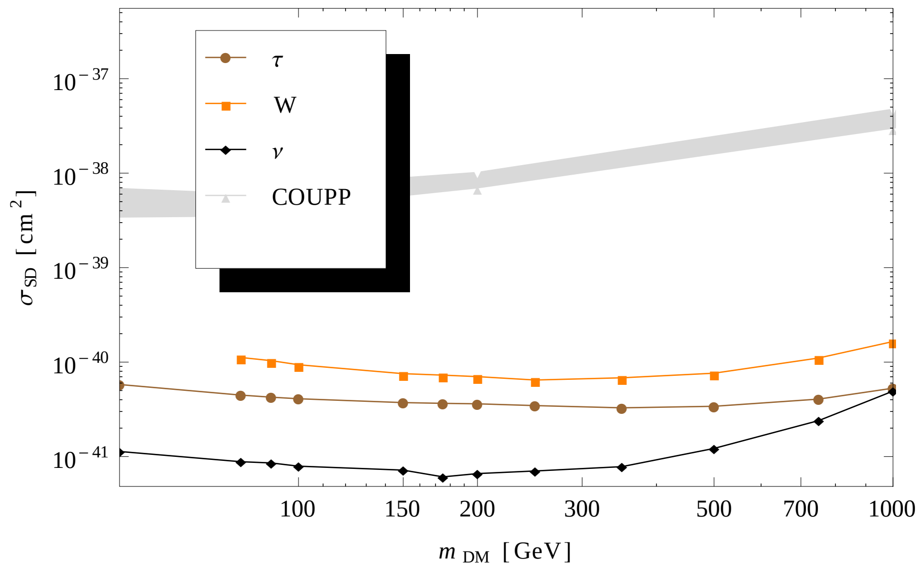


Some Results: R.A., B. Knockel, A. Friedland (in preparation)

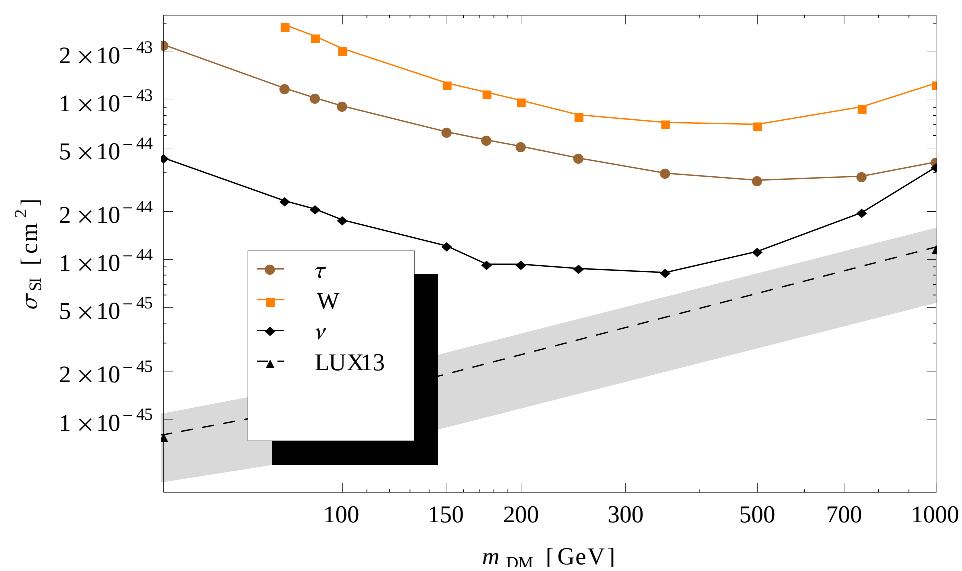
Sensitivity limits for democratic prompt neutrinos:

Spin-dependent:
Beats direct detection,
Competitive with LHC bounds

A. Rajaraman, W. Shepherd, T. Tait, A. Wijangco
PRD 84, 095013 (2011)
P. Fox, R. Harnik, R. Primulando, C-T Yu
PRD 86, 015010 (2012)

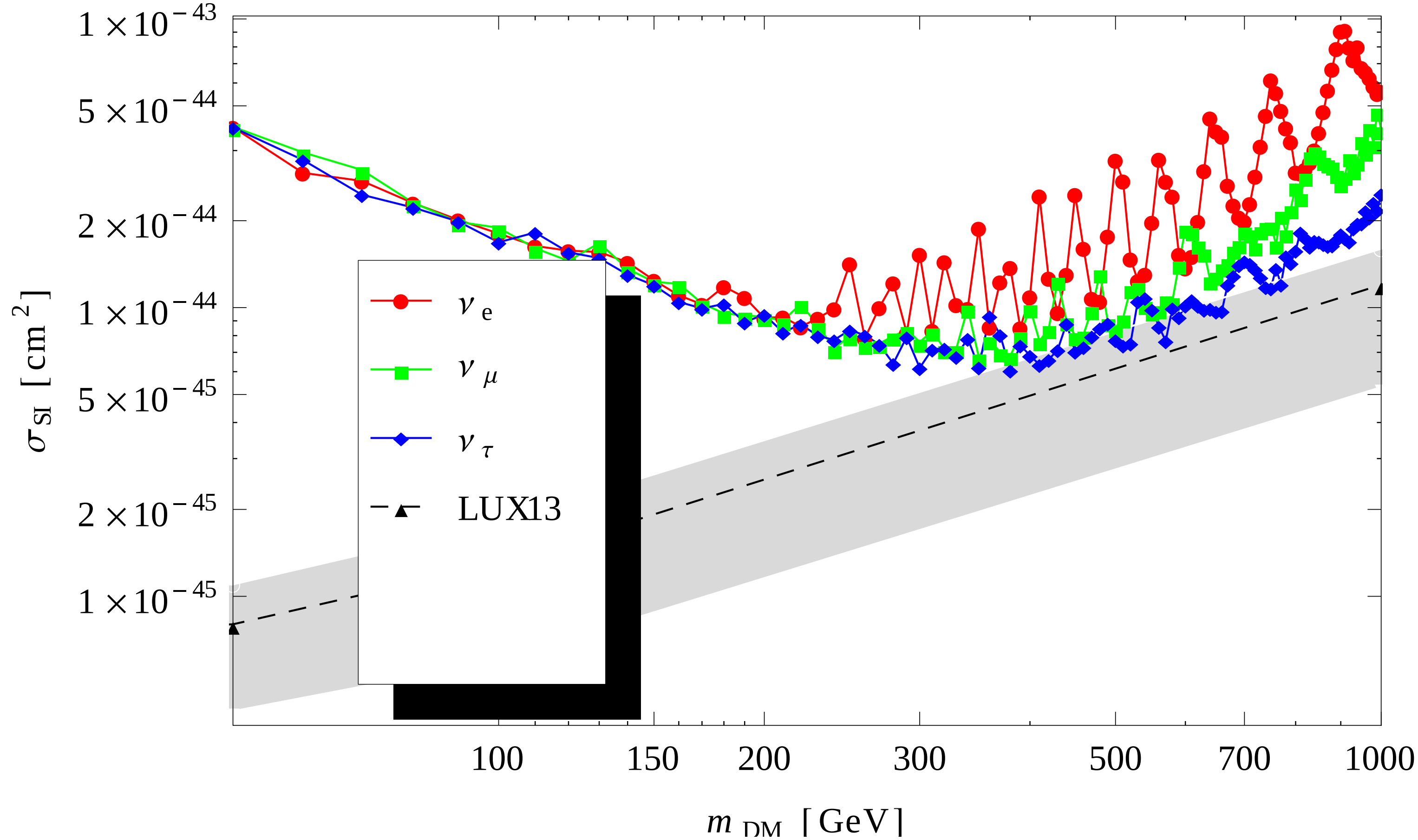


Spin-independent:
Weaker than direct detection



Sensitivity limits for flavored prompt neutrinos:

$\nu\bar{\nu}$ final state:



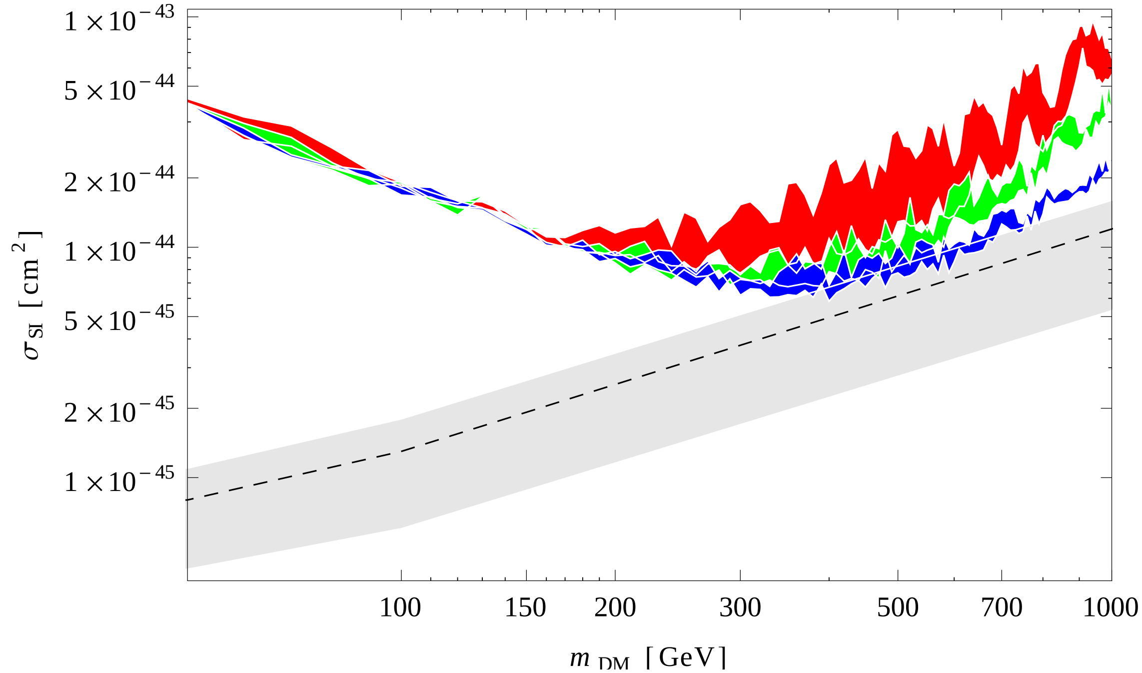
Scratching the LUX band with 1 year of data from IceCube!

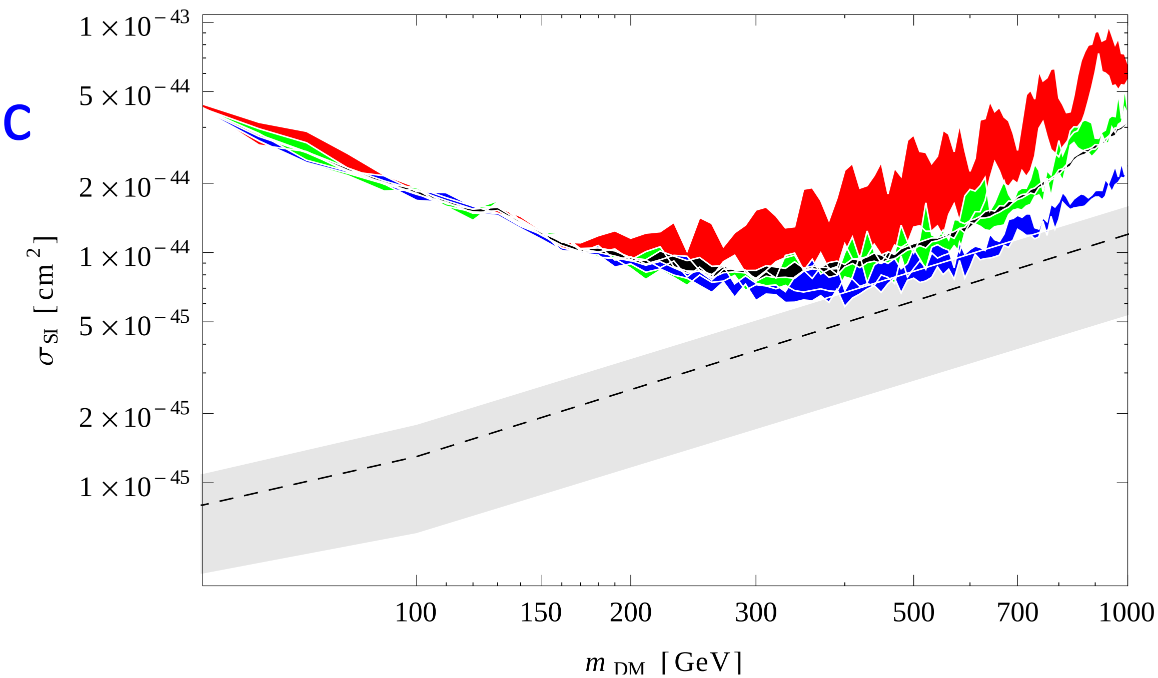
Rapid oscillations imply sensitivity to Δm_{12}.

Uncertainty in neutrino parameters affects DM detection!

Negligible for democratic final states.

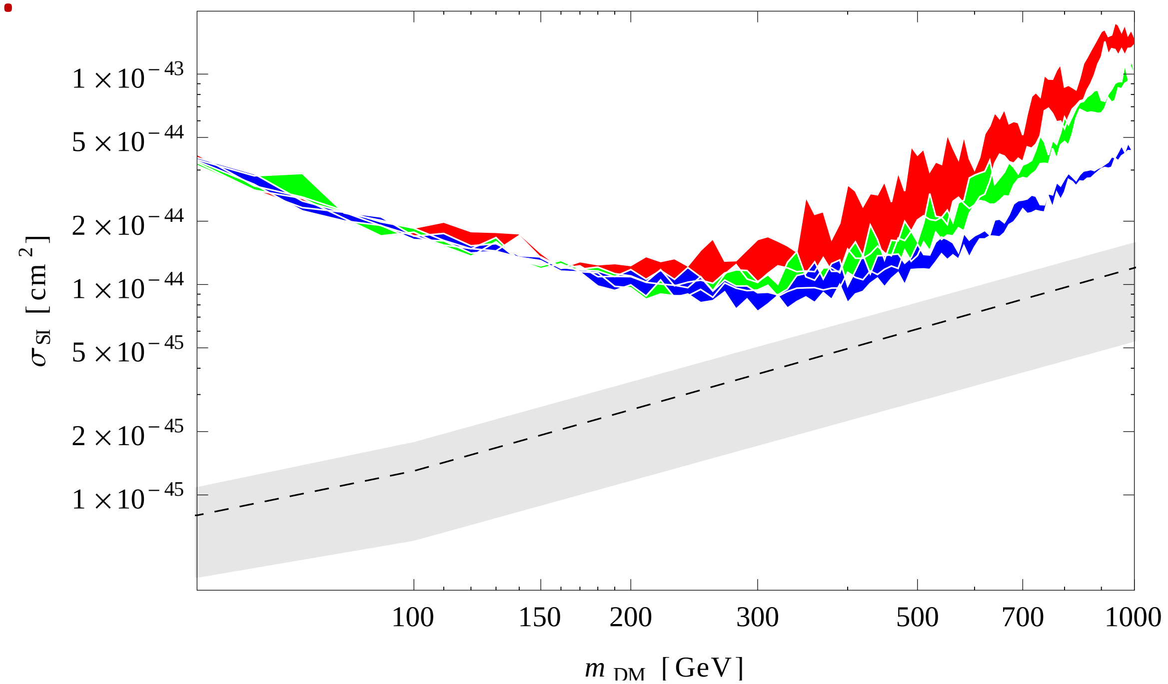
Not an issue for galactic DM annihilation.



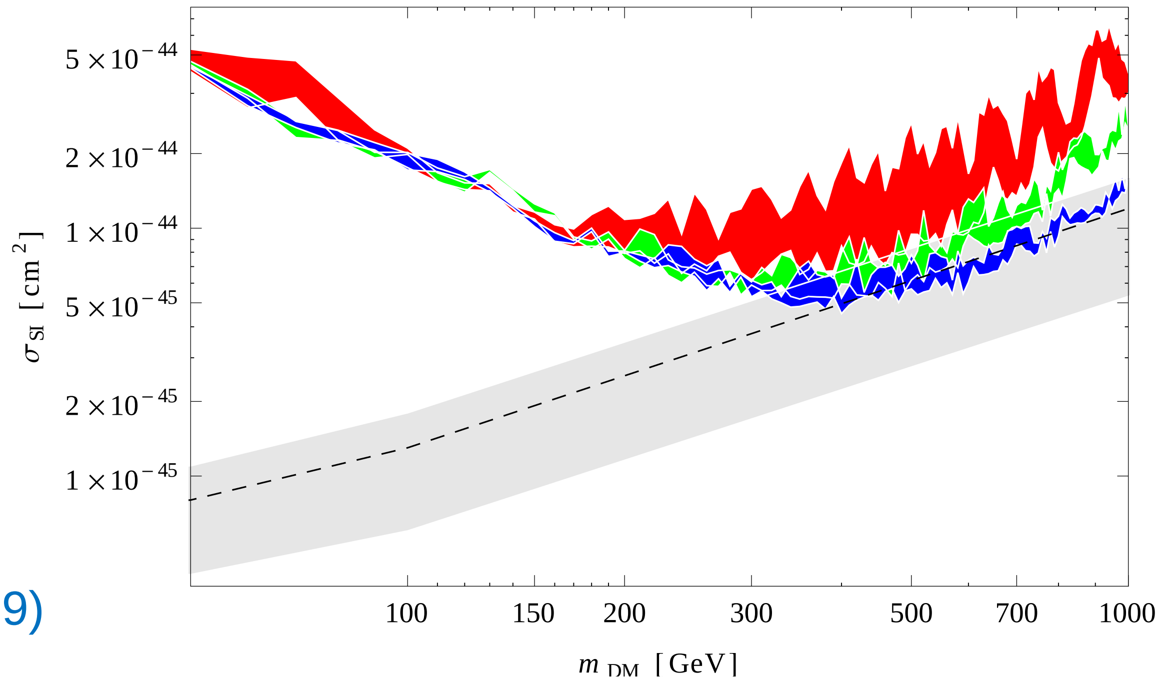


Case of asymmetric DM:

$\nu\nu$ final state:



$\bar{\nu}\bar{\nu}$ final state:



Inside the LUX band!

Even better with
DM self-interactions!

A. Zentner PRD 80, 063501 (2009)

In realistic models, DM annihilation produces all neutrino flavors instead of 100% of one flavor.

Flavor composition of the final state typically depends on the underlying neutrino mass model.

Neutrino signal from DM annihilation can be used to probe neutrino properties.

Examples:

Determining the nature of neutrinos (Majorana vs Dirac) in the $U(1)_{B-L}$ extension of MSSM.

R.A., S. Campbell, B. Dutta, Y. Gao PRD 90, 073002 (2014)

Determining the neutrino mass hierarchy (normal vs inverted) in the type-II see-saw.

R.A., B. Dutta, D. Ghosh, B. Knockel, I. Saha (in preparation)

Summary and Outlook:

- Models that connect DM with neutrinos have distinct indirect detection signals.

- They naturally give rise to prompt and/or flavored neutrino final states, providing a novel probe of DM and neutrinos.

- Limits from solar DM annihilation are competitive with the tightest collider (SD) and direct detection (SI) bounds.

- Uncertainties in the neutrino parameters significantly affect sensitivity limits for DM detection.

- The neutrino signal may also be used as a probe of neutrino nature and mass hierarchy.