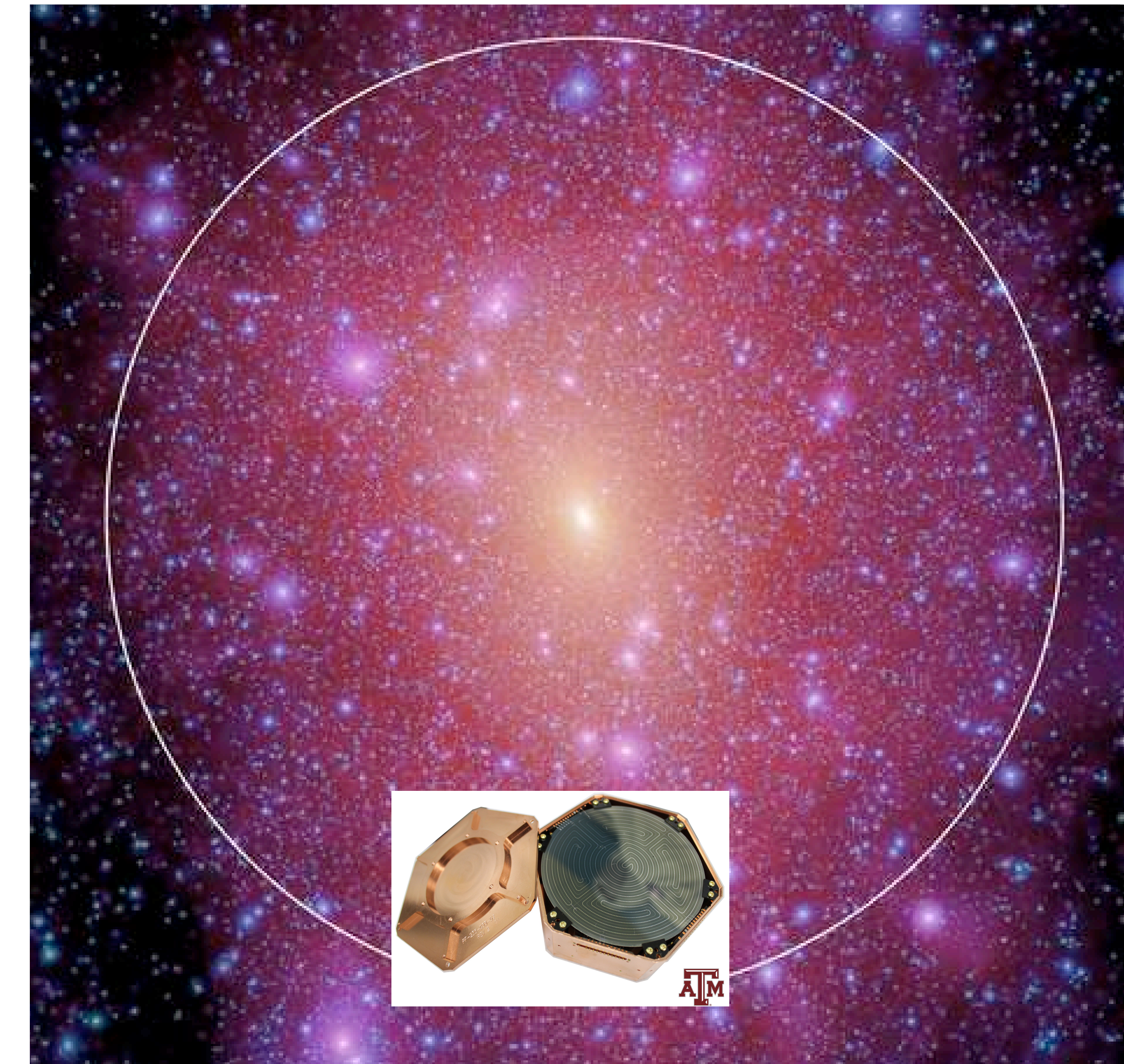


Neutrinos in dark matter detectors

Louis E. Strigari
Texas A&M University
Mitchell Institute for Fundamental Physics and Astronomy
CPAD workshop, UT Arlington
Oct 5, 2015

History: Neutrino-Nucleus Coherent Scattering

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

NEUTRINO OPACITIES AT HIGH TEMPERATURES AND DENSITIES

DAVID L. TUBBS AND DAVID N. SCHRAMM
University of Chicago, Enrico Fermi Institute
Received 1975 February 28; revised 1975 April 18

ABSTRACT

A detailed calculation is made of the major cross sections contributing to neutrino opacities at high temperatures and densities such as those encountered in gravitational collapse. These calculations include the effects of neutral currents, where applicable, and electron degeneracy. The processes considered are electron-neutrino scattering (including both electron and muon neutrinos and antineutrinos), neutrino-nucleon absorption and scattering, and coherent neutrino scattering. Results for these interactions are also given for the average energy transferred by the neutrino as well as the mean scattering angle (thus yielding momentum transfer).

History: Neutrino astronomy

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10–10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Bolometric Detection of Neutrinos

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)

Elastic neutrino scattering off electrons in crystalline silicon at 1–10 mK results in measurable temperature changes in macroscopic amounts of material, even for low-energy (< 0.41MeV) pp ν's from the sun. We propose new detectors for bolometric measurement of low-energy ν interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical (~ 100 kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum of pp, ^{7}Be, and ^{8}B solar ν's, and supernovae anywhere in our galaxy (~ 10 tons of Si).

History: Connection to WIMPs

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Experimental source	Event rate in $\mathrm{kg}^{-1}\,\mathrm{day}^{-1}$	Recoil energy range
Spallation source	10^2-10^3	10—100 keV
Reactor	10	50—500 eV
Solar neutrinos		
pp cycle	$10^{-3}-10^{-2}$	1—10 eV
^{7}Be	$10^{-2}-5\times10^{-2}$	5—50 eV
^{8}B	$10^{-3}-10^{-2}$	100 eV—3 keV
Galactic halo		
coherent $m \sim 2$ GeV	50—1000	10—100 eV
$m \gtrsim 100$ GeV	up to 10^4	10—100 keV
Spin dependent		
$m \sim 2$ GeV	0.1—1	10—100 eV
$m \gtrsim 100$ GeV	up to 1	10—100 keV

Direct dark matter searches: progress

Laboratory Limits on Galactic Cold Dark Matter

D. O. Caldwell, R. M. Eisberg, D. M. Grumm, and M. S. Witherell
Department of Physics, University of California, Santa Barbara, California 93106

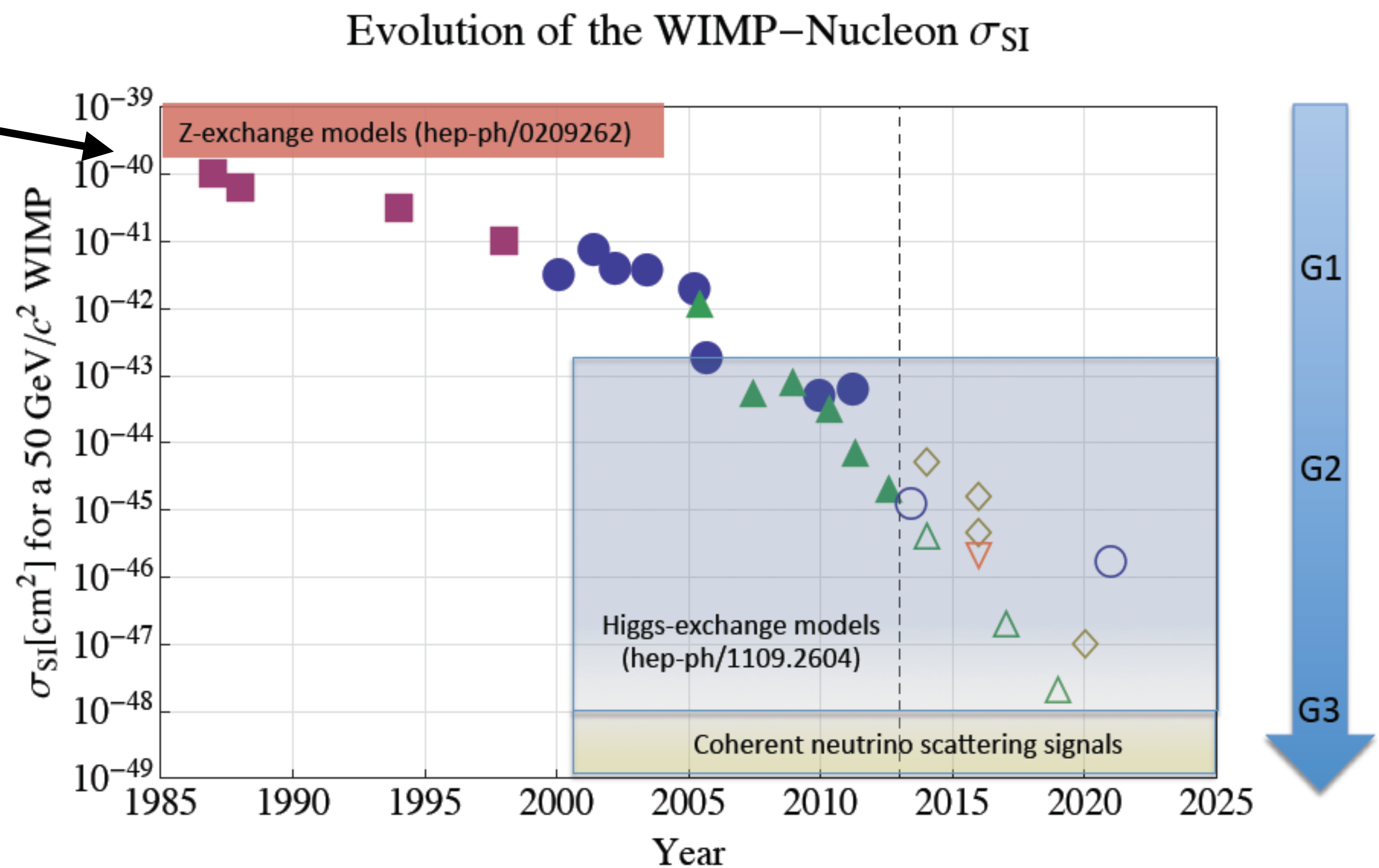
B. Sadoulet
Physics Department, University of California, Berkeley, California 94720

and

F. S. Goulding and A. R. Smith
Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 13 November 1987; revised manuscript received 16 May 1988)

Interesting limits are set on candidates for cold-dark-matter particles in the halo of our Galaxy from their interaction with a very-low-background Ge detector used to search for double-β decay. Dirac neutrinos constituting all of dark matter are excluded for masses between 12 GeV/c^2 and 1.4 TeV/c^2. There are slightly better limits on magninos and cosmions, proposed massive particles which also explain the solar-neutrino problem but which interact more strongly with Ge. In addition, millicharged shadow matter is ruled out as the main form of dark matter.

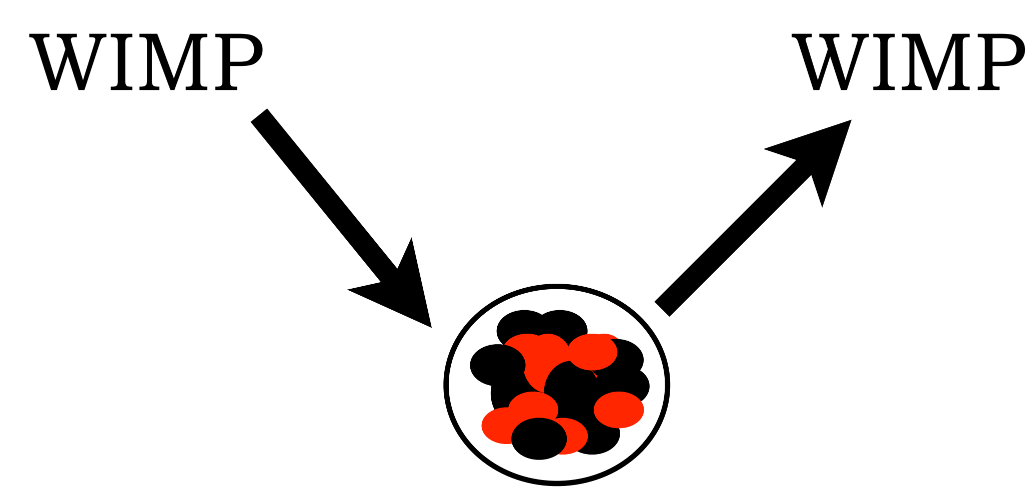
PACS numbers: 98.60.Ln, 14.60.Gh, 14.80.Pb, 96.60.Kx

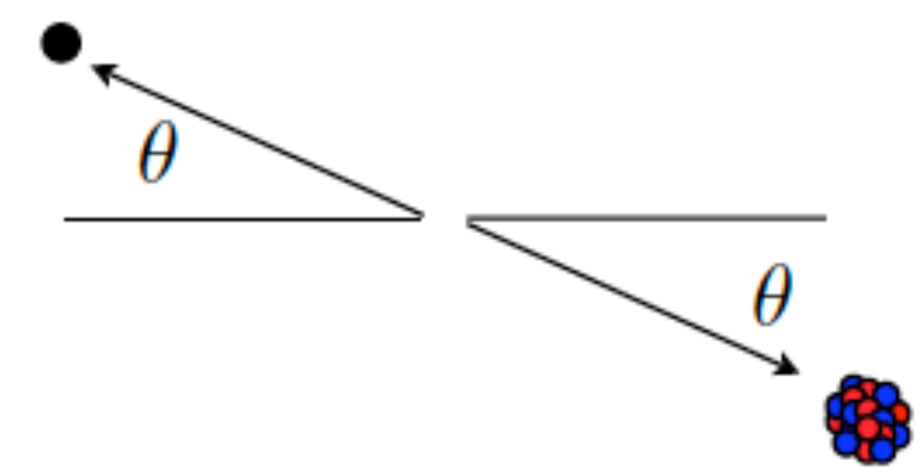


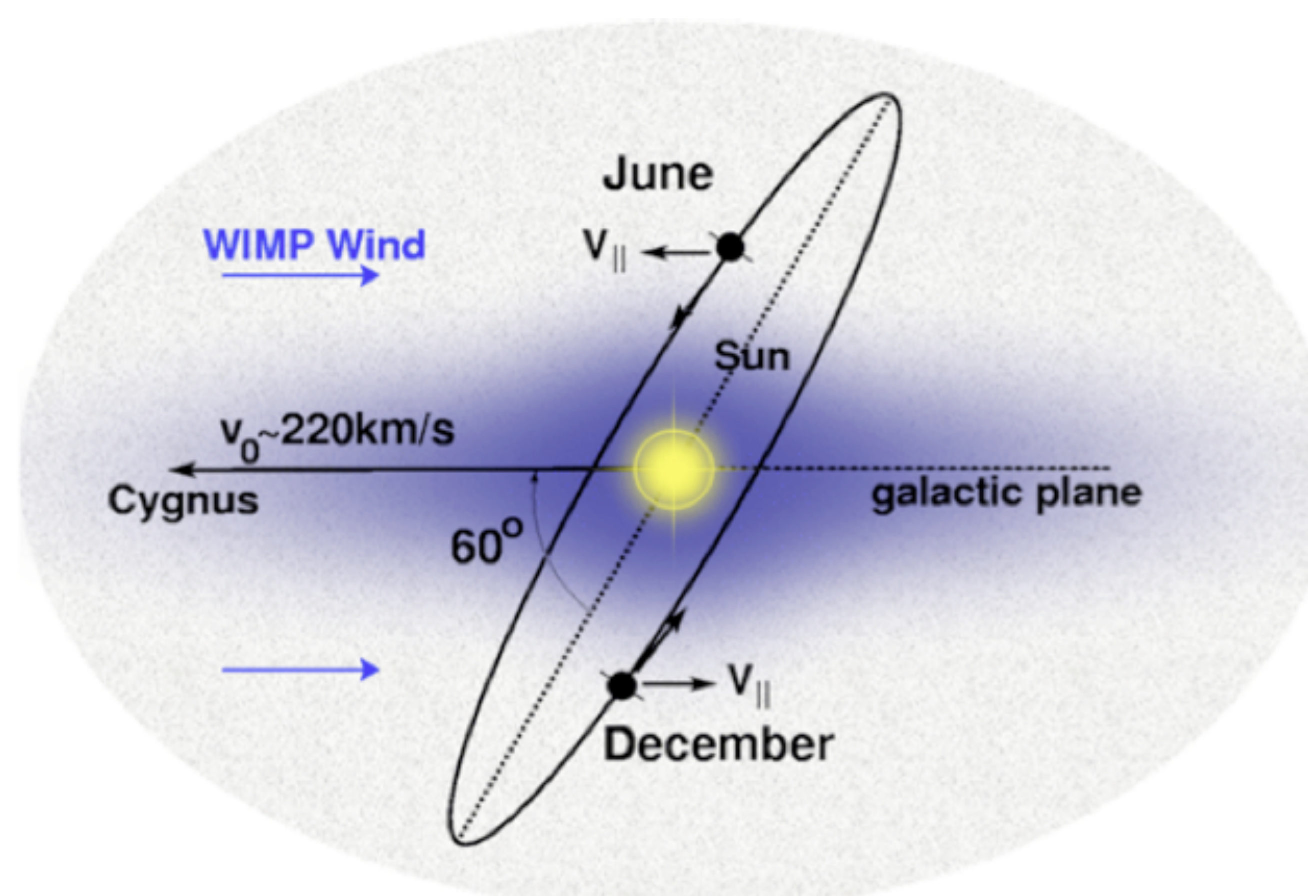
Adapted from SNOWMASS

Reminder: WIMP kinematics

- *Spin-Independent:* Cross section scales as the mass number of nucleus.
- *Spin-dependent:* Cross section depends on angular momentum
- WIMP-nucleus scattering assumed isotropic
- Laboratory velocity points towards Cygnus







Goodman & Witten 1984, Ellis & Flores 1988, Engel 1991

Coherent neutrino-nucleus scattering

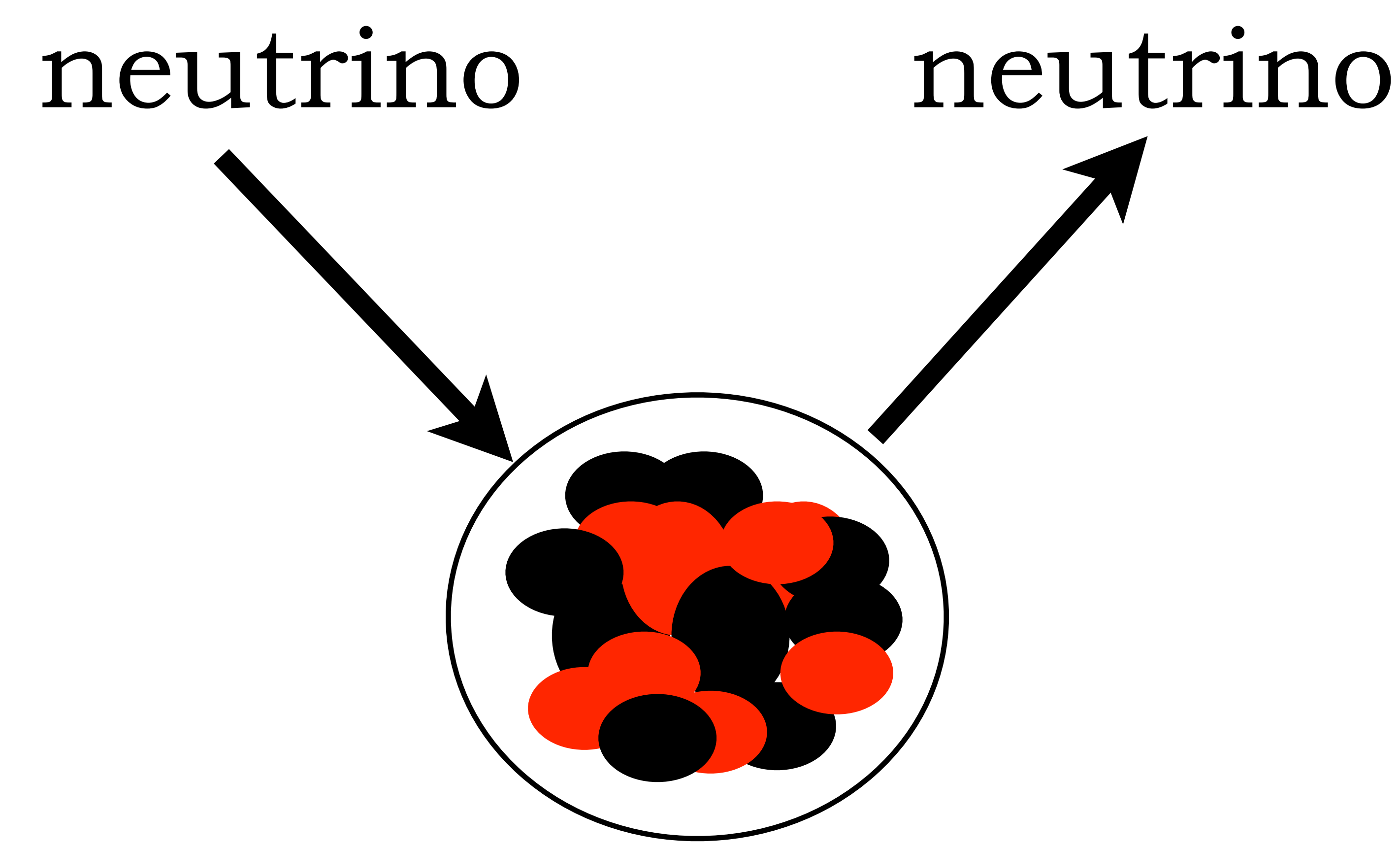
- Proportional to the number of neutrons^2 due to vector current coupling

$$\frac{d\sigma_{CNS}(E_\nu, T_R)}{dT_R} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N T_R}{2E_\nu^2}\right) F^2(T_R)$$

- Compare to spin-independent WIMP-nucleus cross section which is proportional to A^2

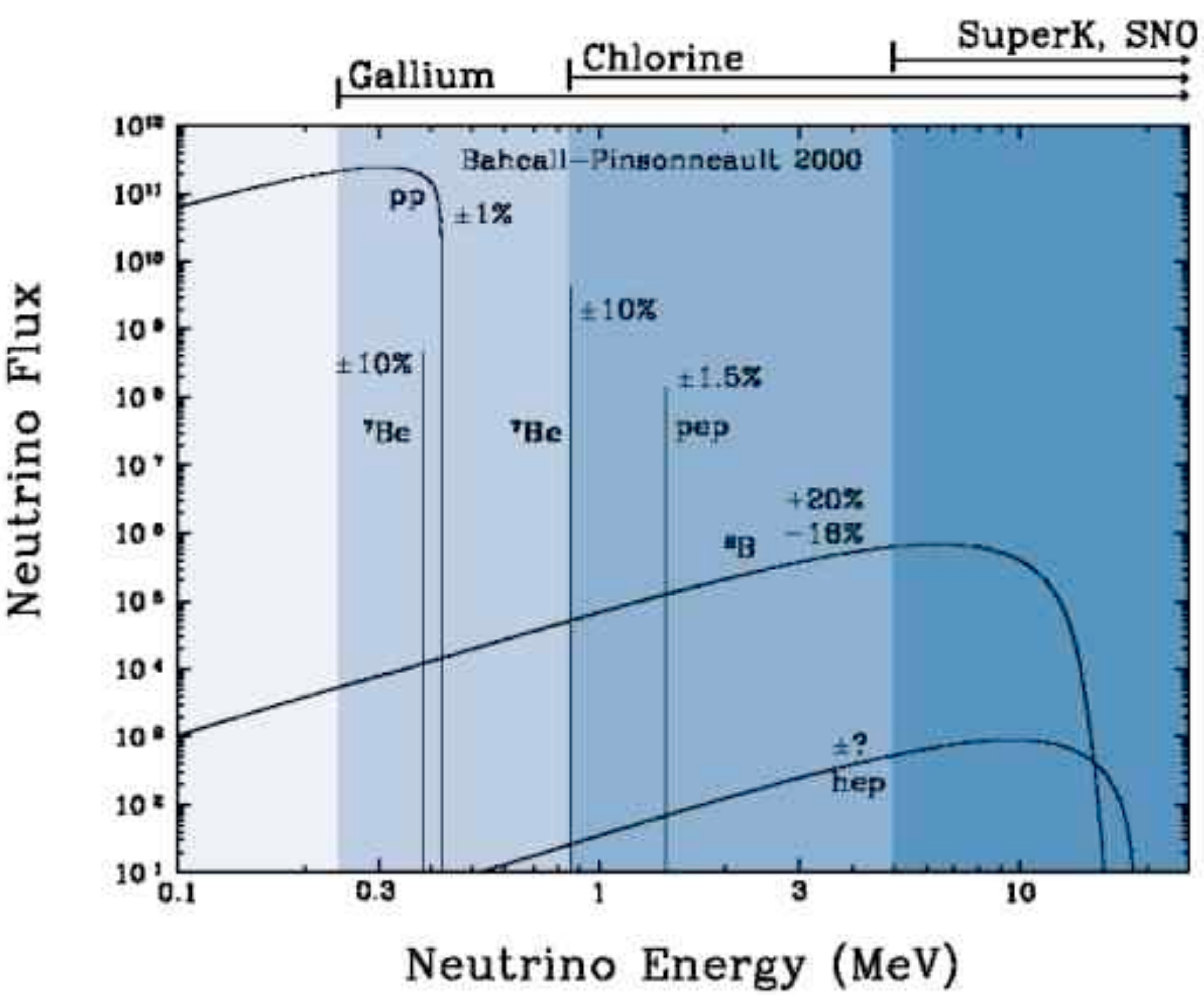
- Straightforward prediction of Standard Model. Though not yet detected.

- Also will consider neutrino-electron elastic scattering



✦ *Coherent neutrino scattering will produce a signal similar to a WIMP*

Solar neutrinos



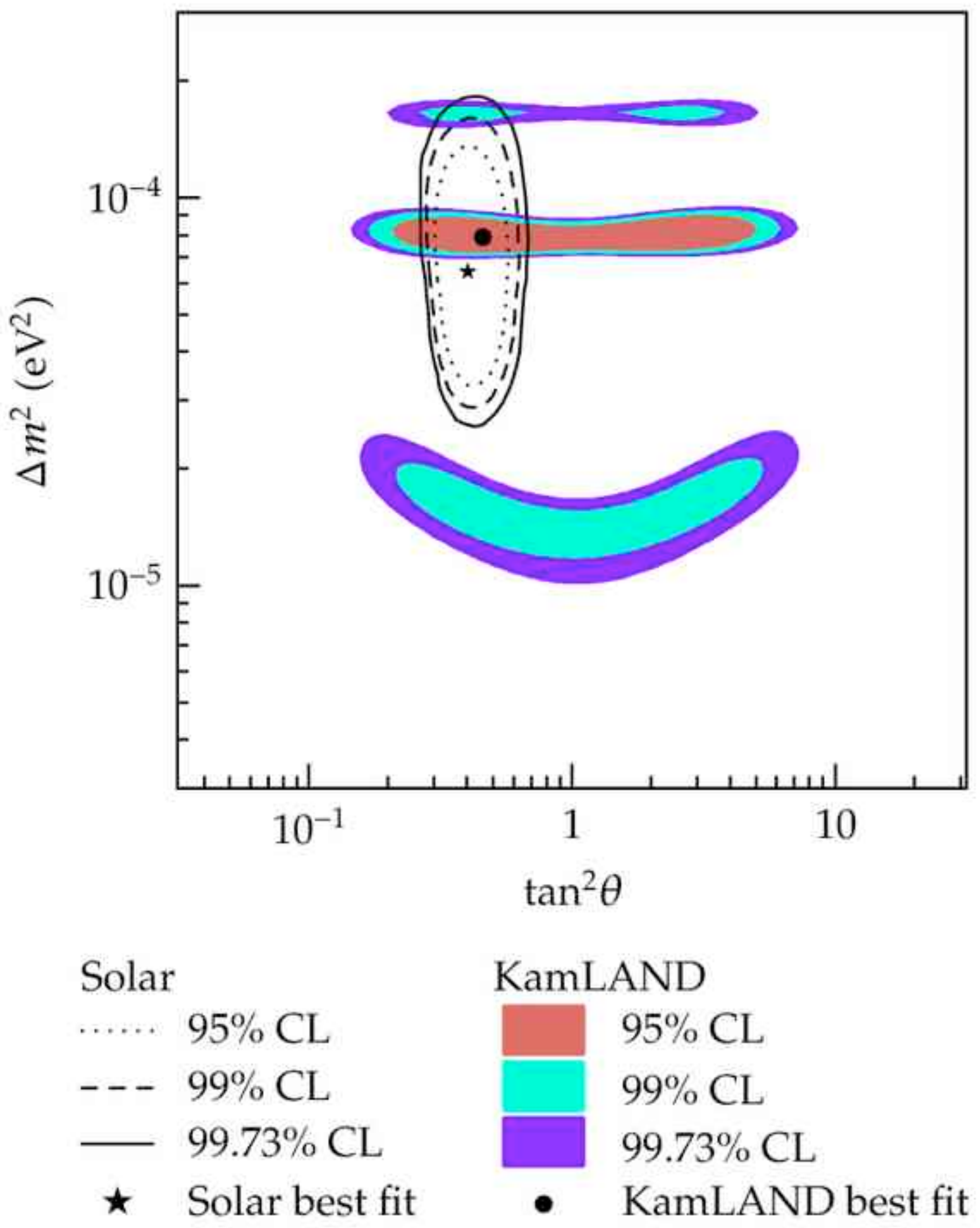
High metallicity | Low metallicity

ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p\to{}^2H+e^++\nu$	0.42	$5.98(1\pm0.006)$	$6.03(1\pm0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^-+p\to{}^2H+\nu$	1.44	$1.44(1\pm0.012)$	$1.47(1\pm0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^8/cm^2s$
${}^7Be+e^-\to{}^7Li+\nu$	0.86 (90%)	$5.00(1\pm0.07)$	$4.56(1\pm0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^9/cm^2s$
	0.38 (10%)				
${}^8B\to{}^8Be+e^++\nu$	$\sim$ 15	$5.58(1\pm0.14)$	$4.59(1\pm0.14)$	$5.00(1\pm0.03)$	$10^6/cm^2s$
${}^3He+p\to{}^4He+e^++\nu$	18.77	$8.04(1\pm0.30)$	$8.31(1\pm0.30)$	—	$10^3/cm^2s$
${}^{13}N\to{}^{13}C+e^++\nu$	1.20	$2.96(1\pm0.14)$	$2.17(1\pm0.14)$	≤ 6.7	$10^8/cm^2s$
${}^{15}O\to{}^{15}N+e^++\nu$	1.73	$2.23(1\pm0.15)$	$1.56(1\pm0.15)$	≤ 3.2	$10^8/cm^2s$
${}^{17}F\to{}^{17}0+e^++\nu$	1.74	$5.52(1\pm0.17)$	$3.40(1\pm0.16)$	$\leq 59.$	$10^6/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		

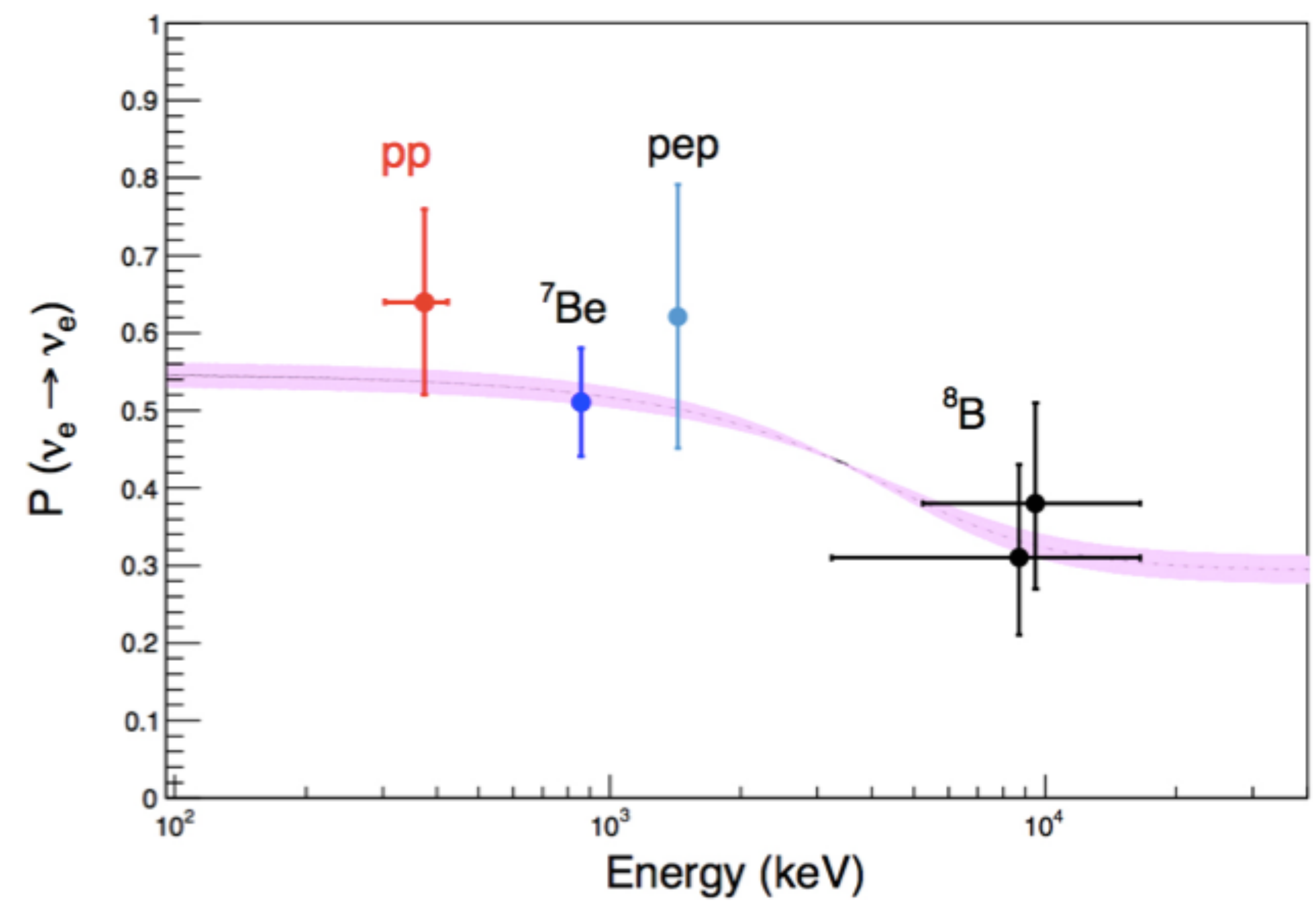
Haxton et al, 2013

SNO NC measurement (5.25 x 10^6) right in between predictions of low and high metallicity SSMs

Solar neutrinos



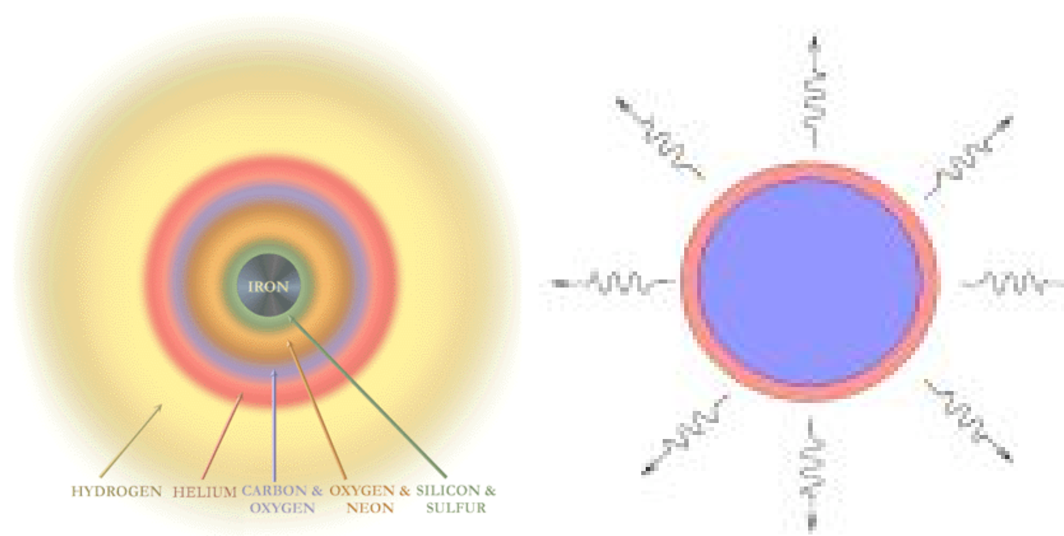
Electron neutrino survival probability



Borexino collaboration, Nature 2014

Atmospheric and supernova neutrinos

SN Neutrinos

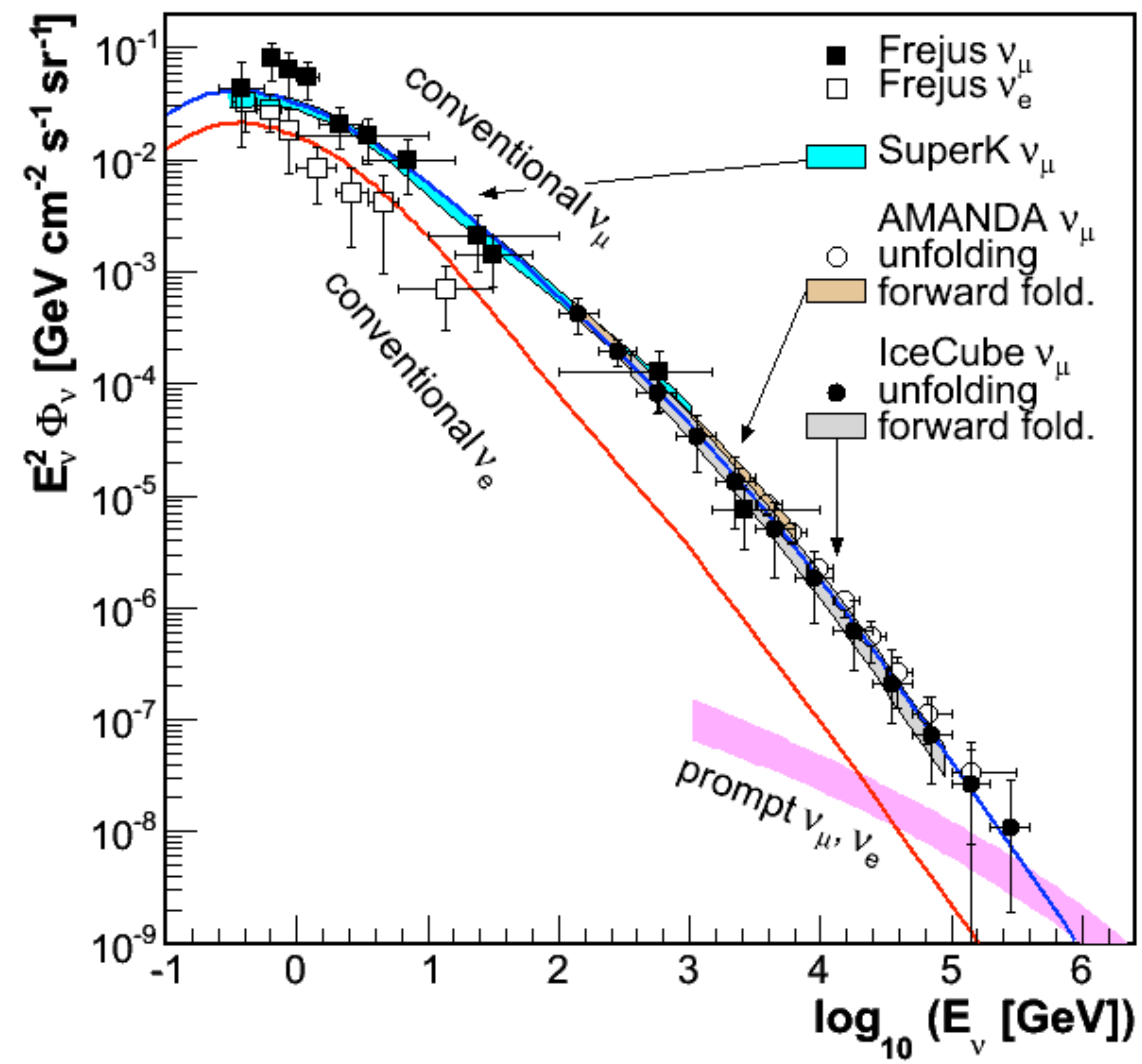


$$\pi^{\pm} \rightarrow \quad \mu^{\pm} \quad + \nu_\mu(\overline{\nu}_\mu)$$

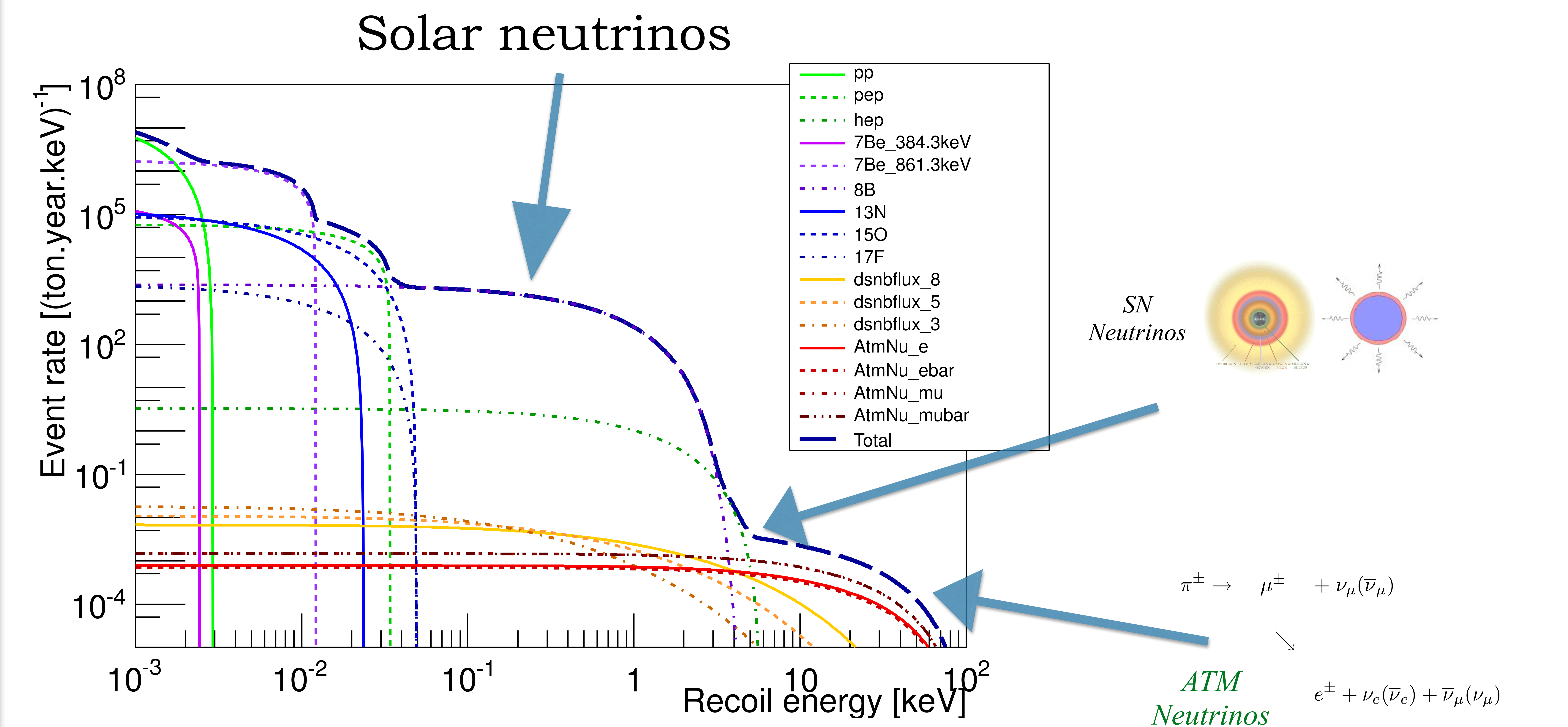
$$\searrow$$

ATM Neutrinos

$$e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$

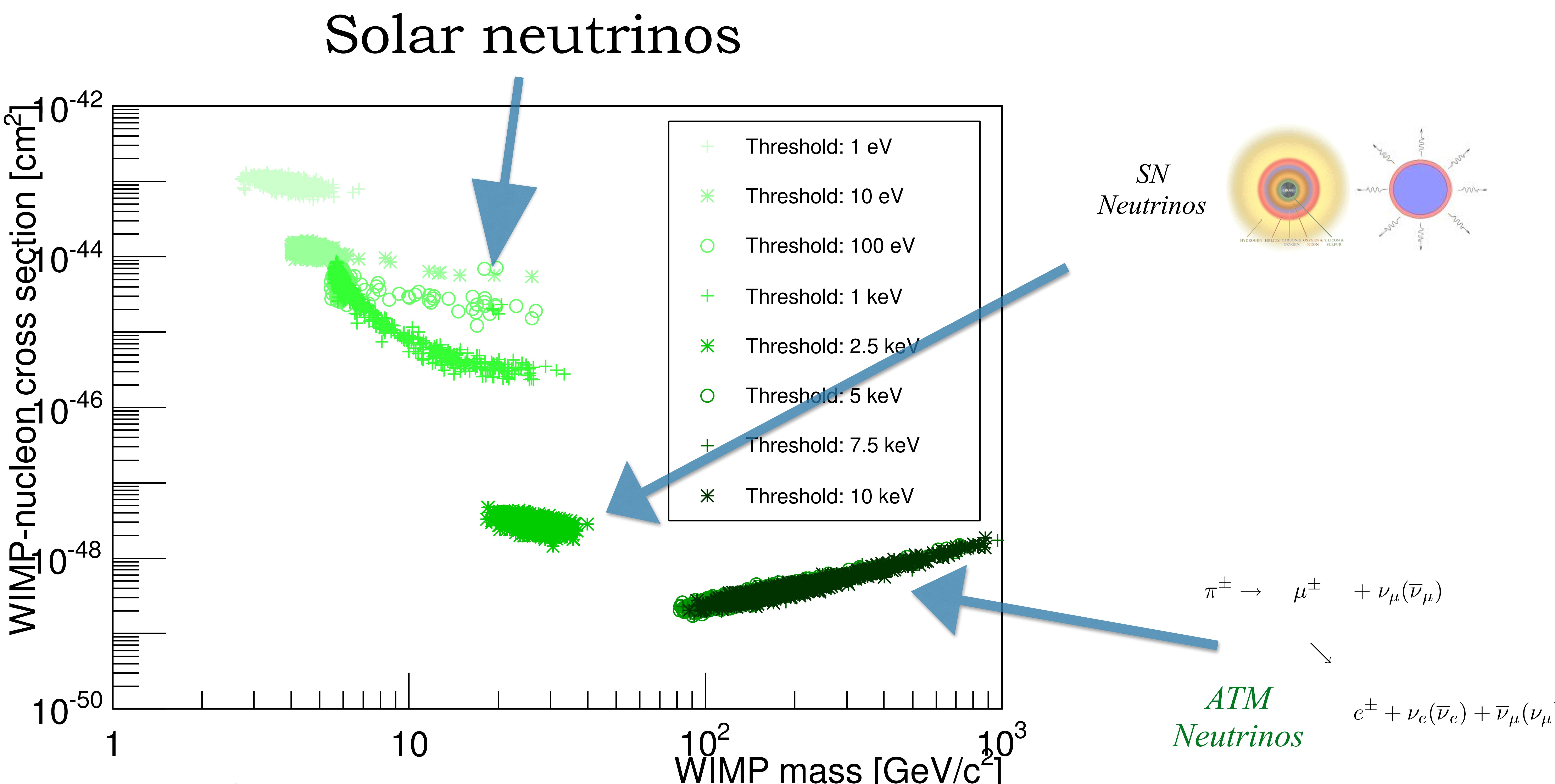


Event rate predictions



Billard, Strigari, Figueroa-Feliciano PRD 2014

Can neutrinos mimic the WIMP signal?



Billard, Strigari, Figueroa-Feliciano PRD 2014

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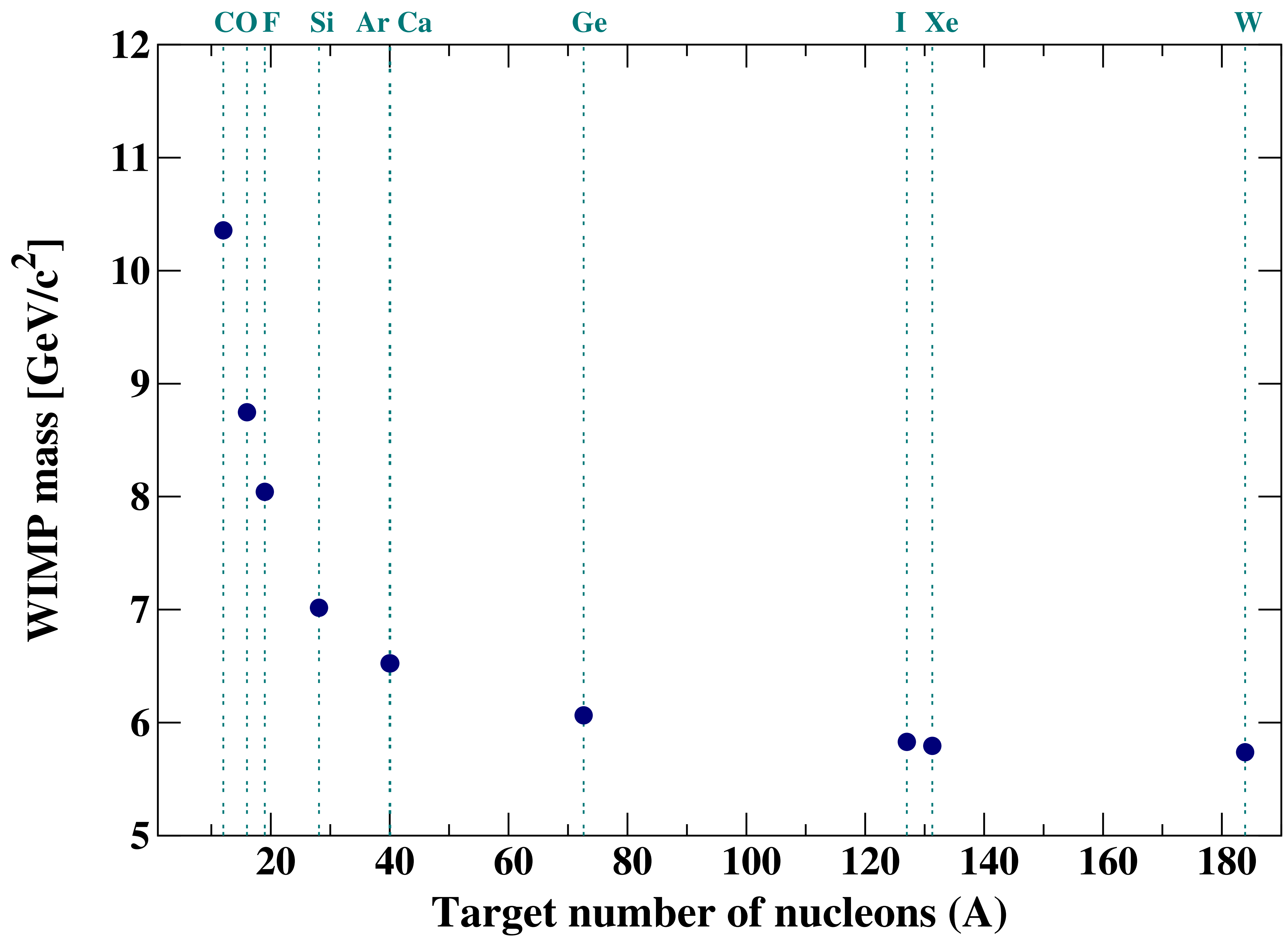
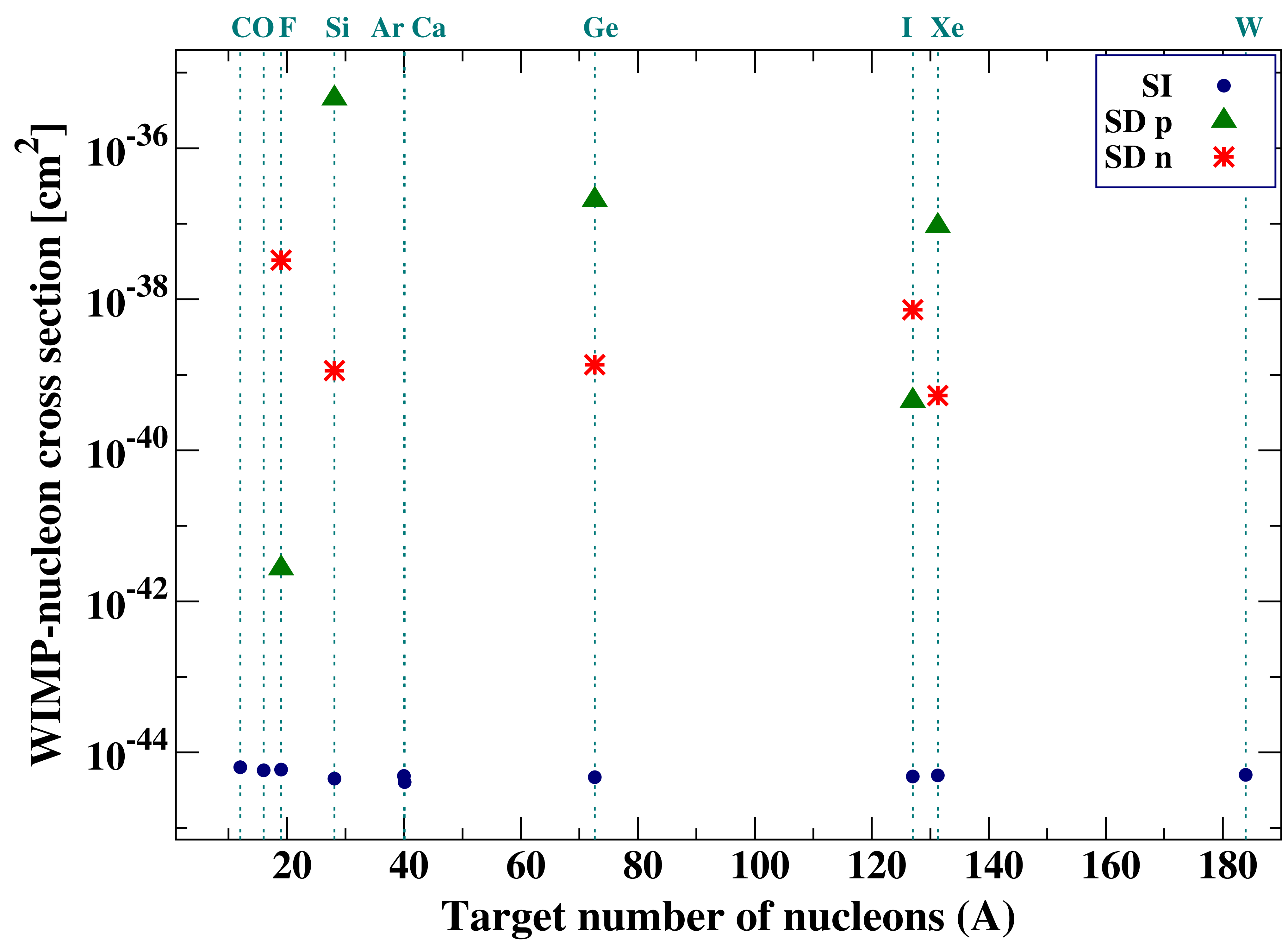
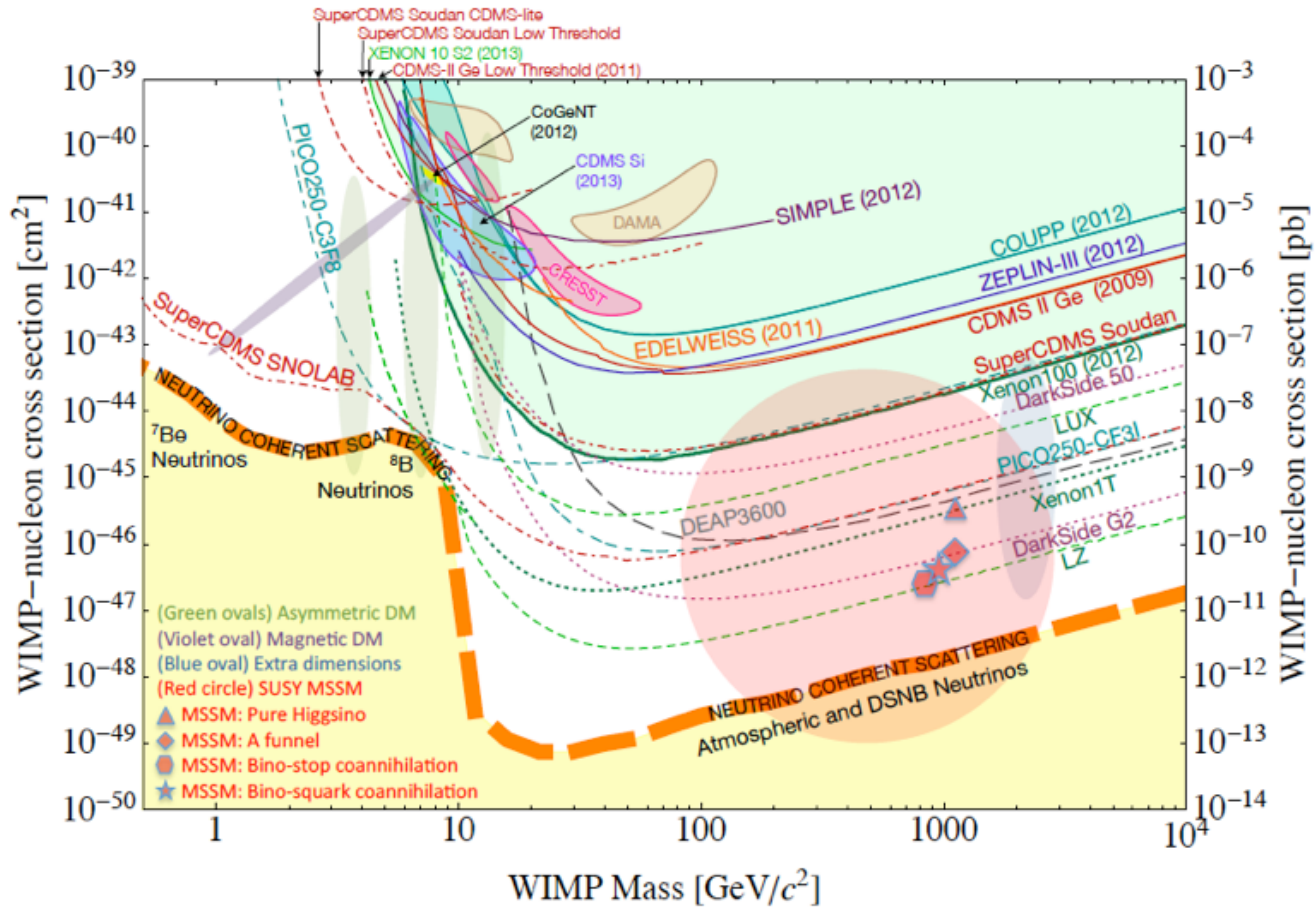




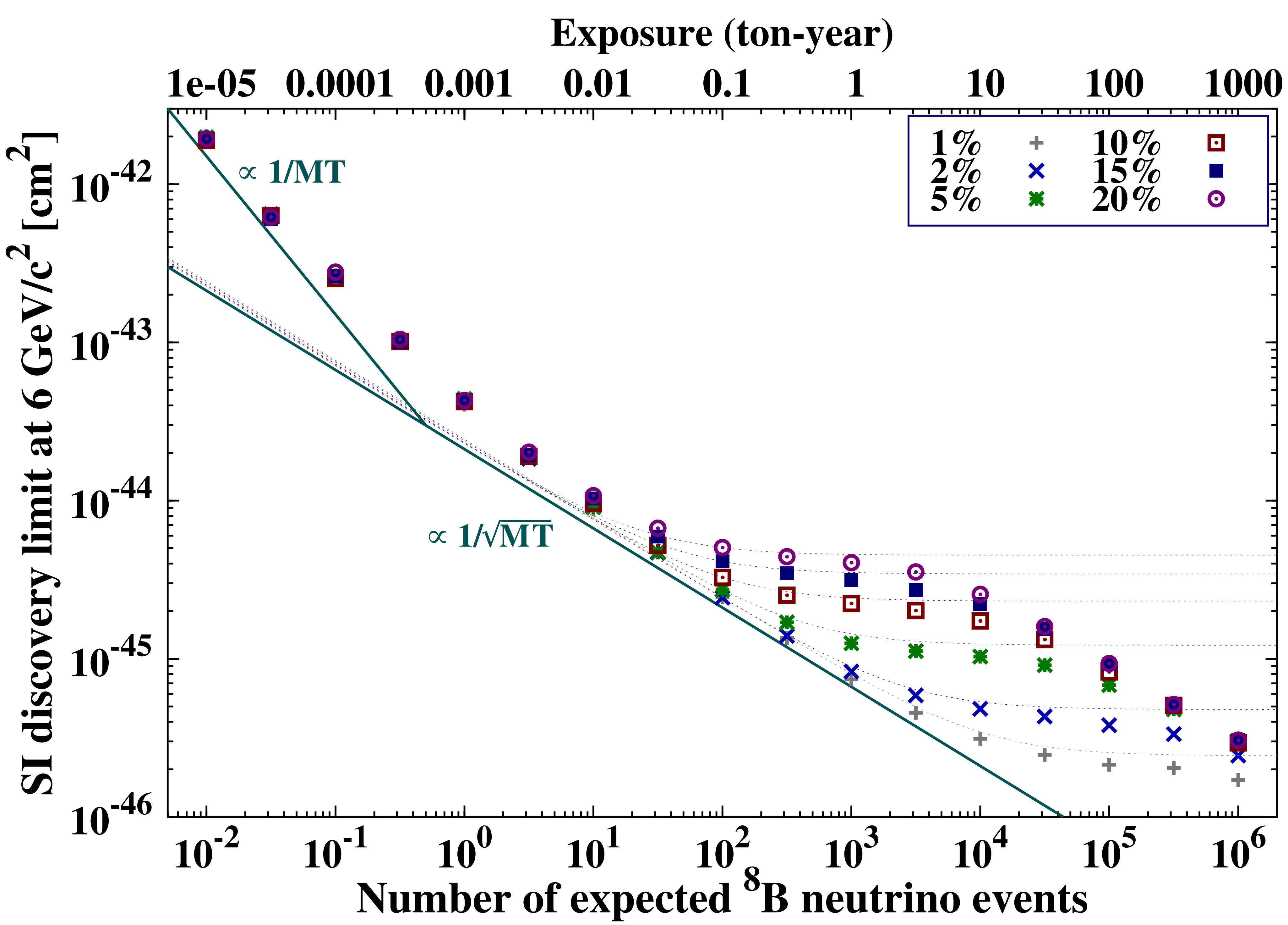
Using the standard SI/SD formalism (Lewin & Smith)

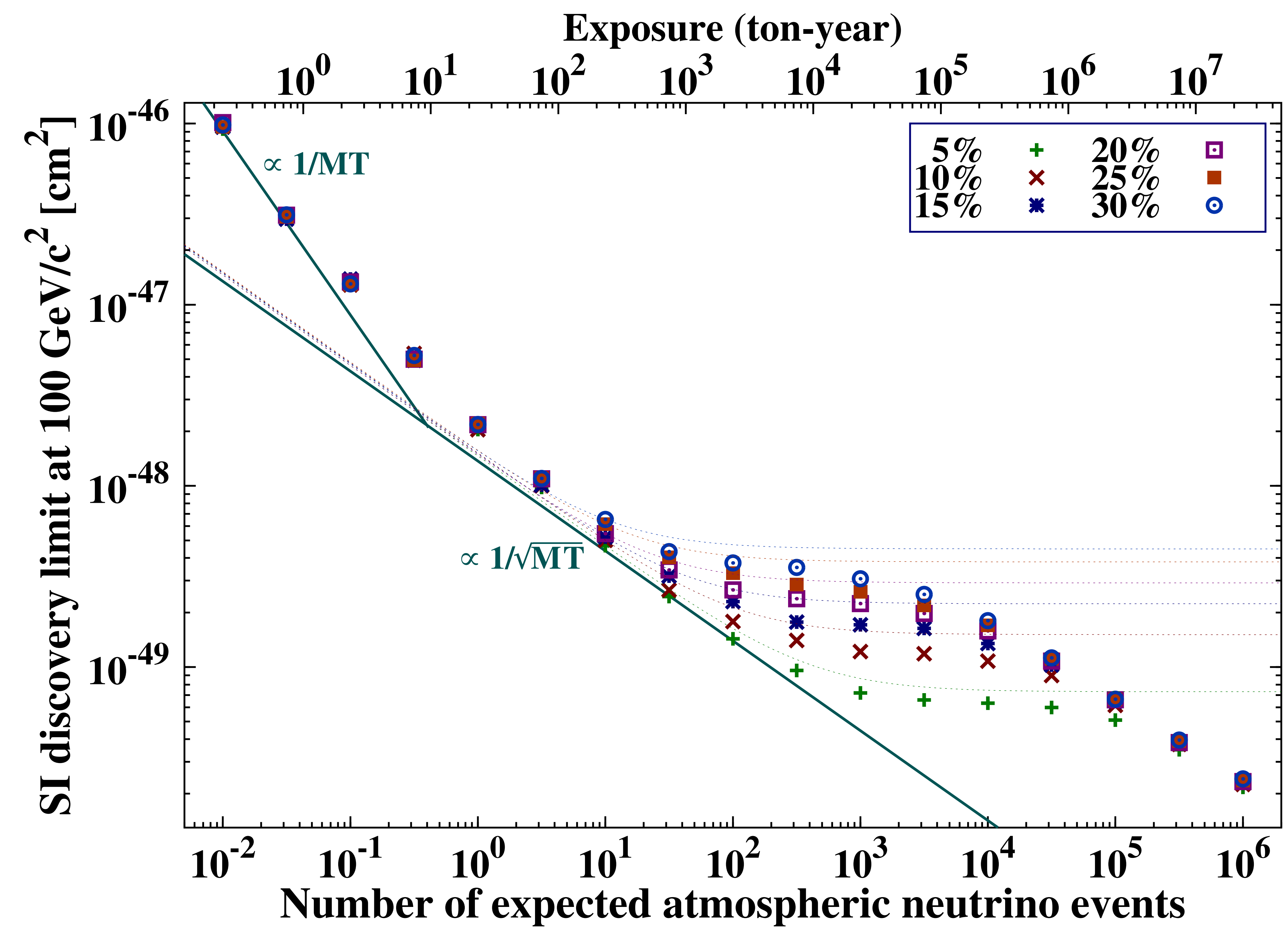
Ruppin, Billard, Figueroa-Feliciano, Strigari PRD 2014



Billard, Strigari, Figueroa-Feliciano PRD 2014

Going beyond the neutrino background: Bigger detectors

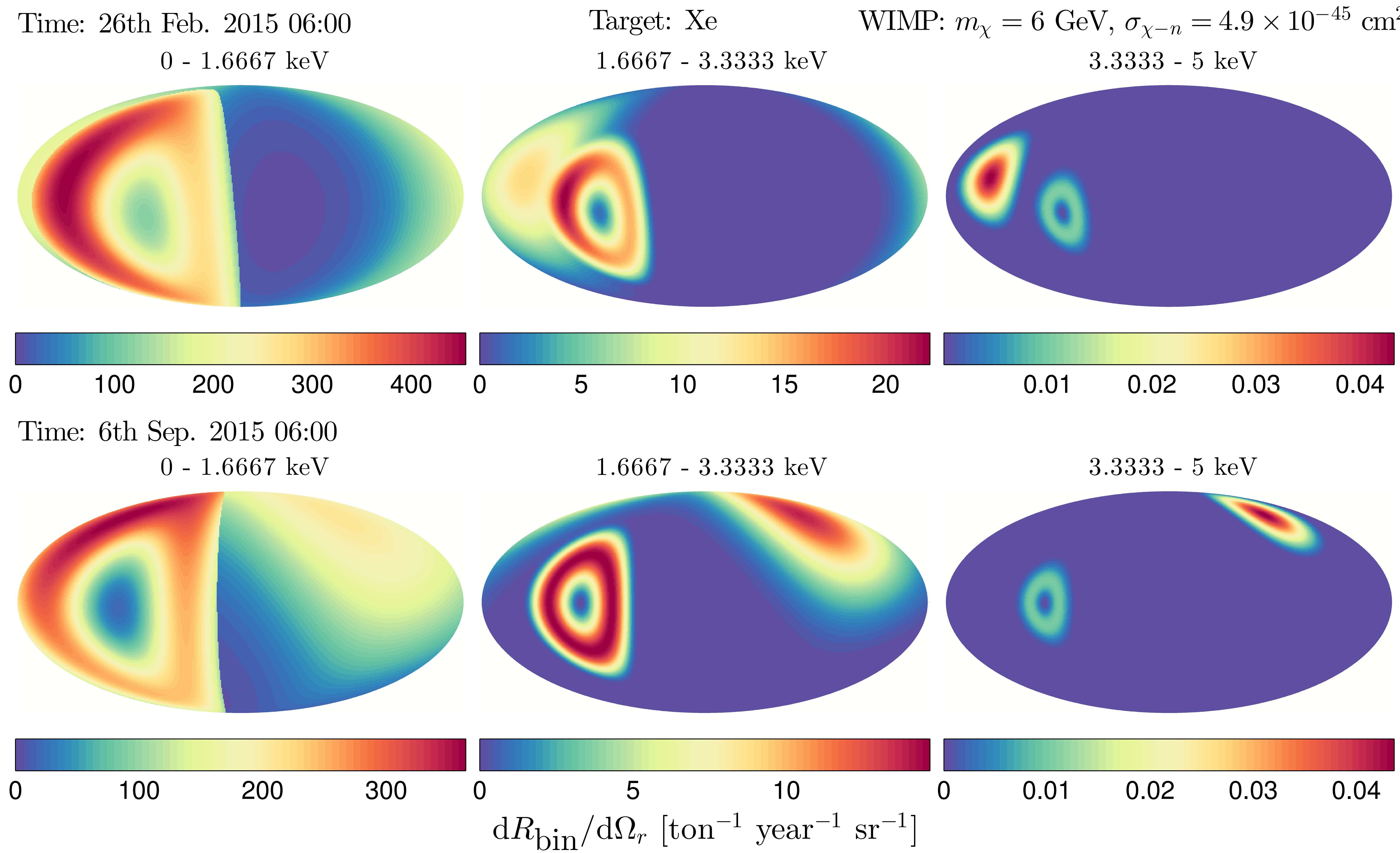




Ruppin, Billard, Figueroa-Feliciano, Strigari PRD 2014

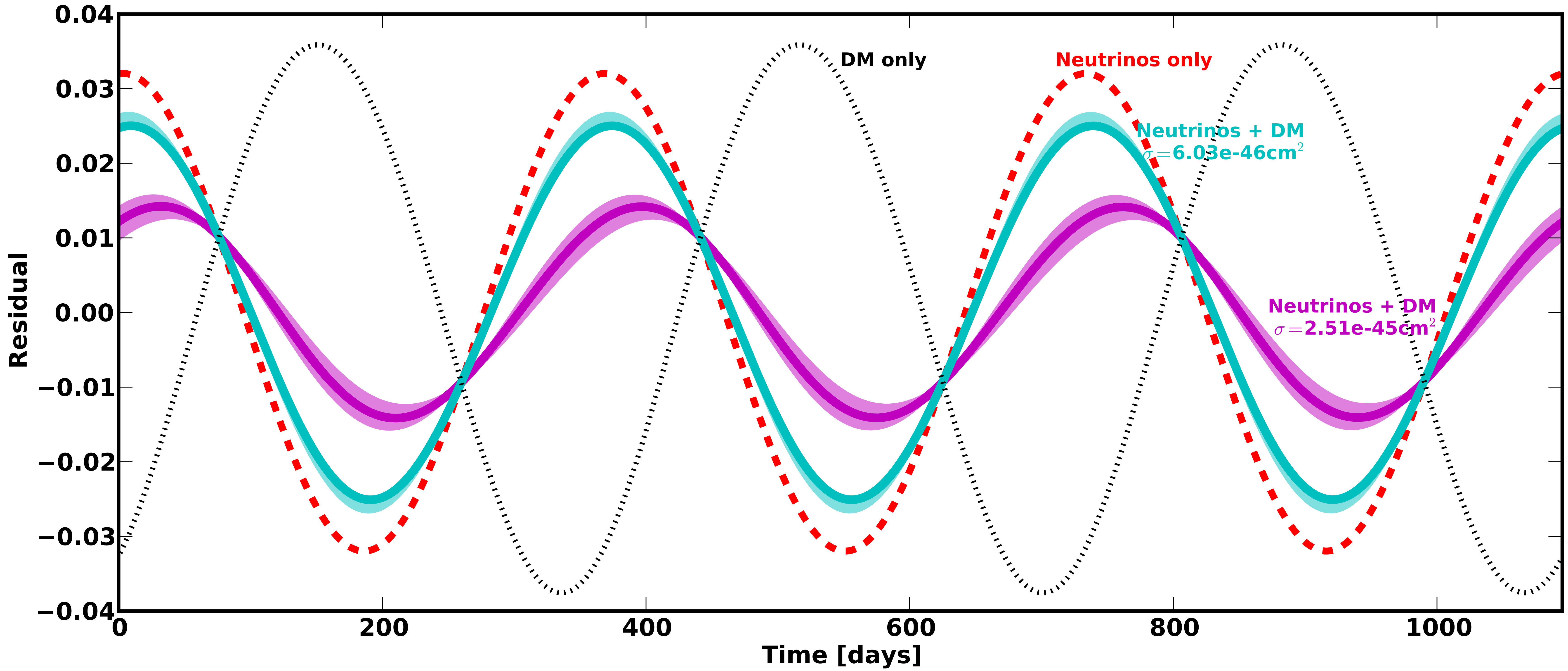
Going beyond the neutrino background: Directional detection

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi}\, Q_W^2\; E_\nu^2\; (1+\cos\theta)\; F(Q^2)^2$$



Grothaus et al. 2014; O'Hare, Billard, Green, Figueroa-Feliciano, Strigari PRD 2015

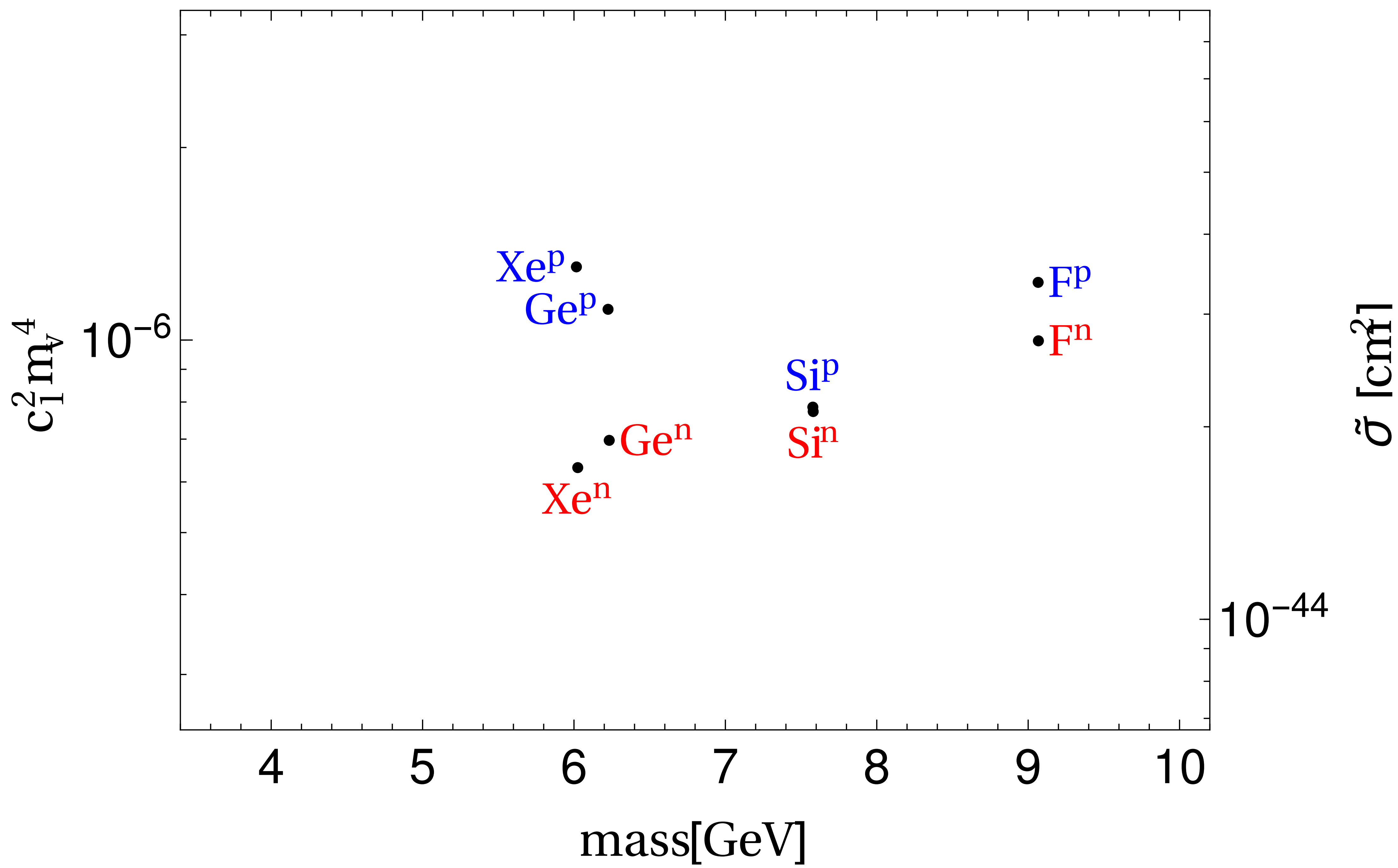
Going beyond the neutrino background: Annual modulation



J. Davis 2014; O'Hare, Billard, Green, Figueroa-Feliciano, Strigari PRD 2015

Going beyond the neutrino background: Non-relativistic Effective Field Theory

$\mathcal{O}_1$	$1_\chi 1_N$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$



Dent, Dutta, Newstead, Strigari, to appear

Going beyond the neutrino background: Non-relativistic Effective Field Theory

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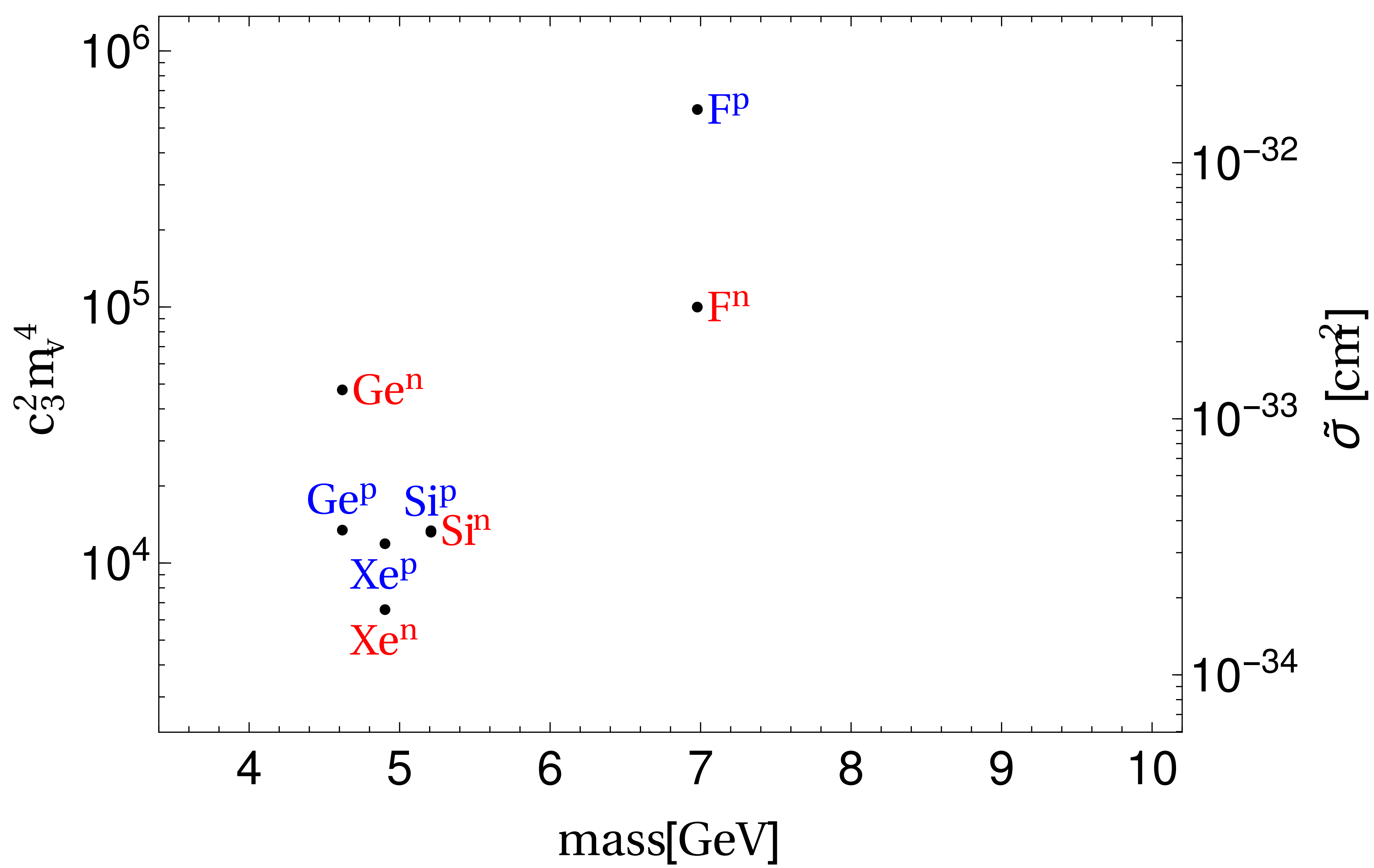
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$



Dent, Dutta, Newstead, Strigari, to appear

Extracting new physics from Solar neutrinos

Solar neutrinos: Outstanding issues

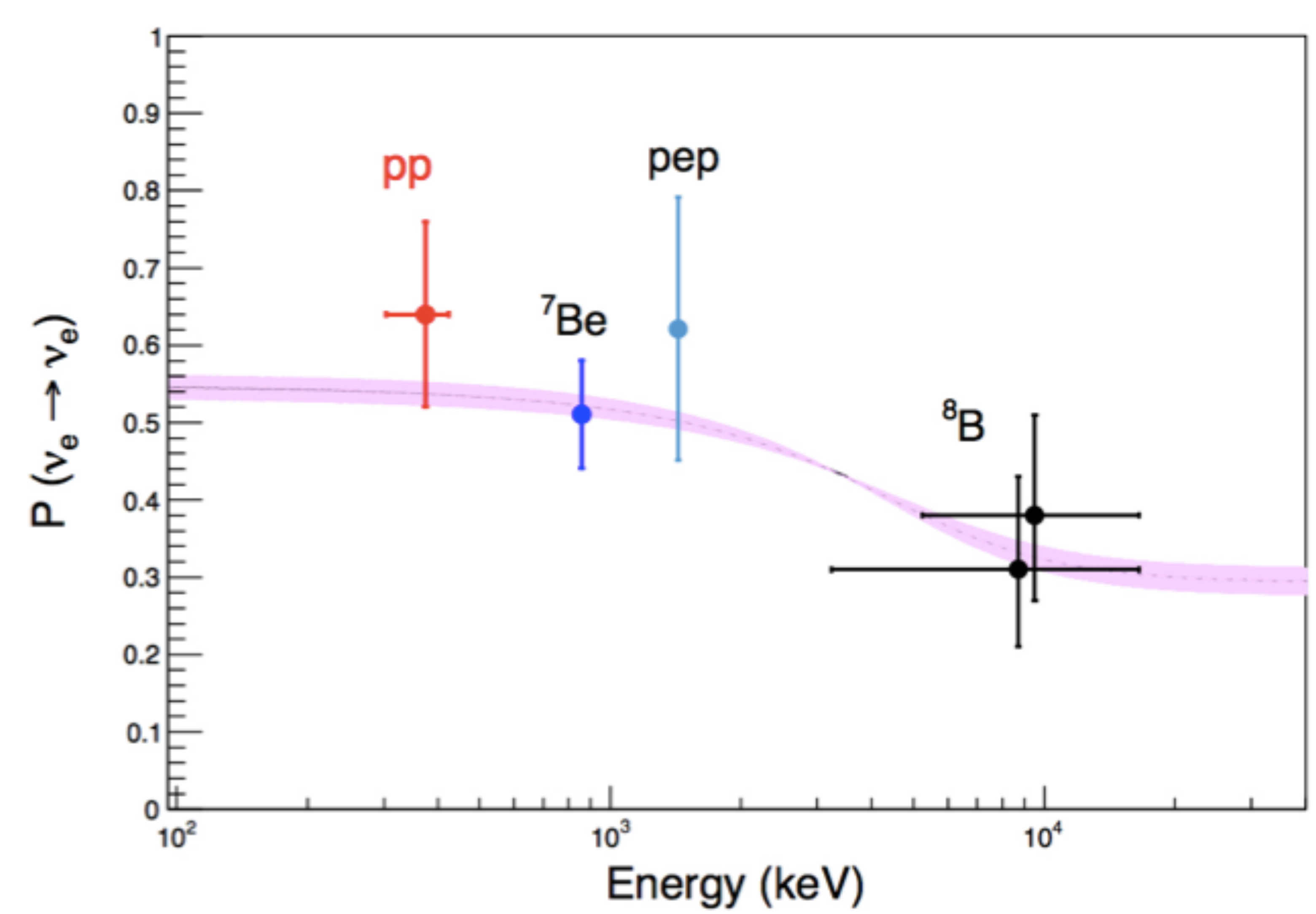
1. Solar Metallicity problem

New 3D rotational hydrodynamical simulations suggest lower metallicity in Solar core [Asplund et al. 2009]

However the low metallicity appears in conflict with helioseismology data

2. Intermediate energy survival probability

SK, Borexino, SNO CC data seem to not indicate an 'upturn' in the electron neutrino survival probability



Sterile neutrinos

If sterile neutrinos exist, how can one determine the total solar neutrino fluxes?

John N. Bahcall,[1,*] M. C. Gonzalez-Garcia,[2,3,4,†] and C. Peña-Garay[3,‡]
[1]*School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540*
[2] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland*
[3]*Instituto de Física Corpuscular, Universitat de València–CSIC, Edificio Institutos de Paterna, Apt 22085, 46071 València, Spain*
[4]*C. N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3840*
(Received 9 May 2002; published 19 September 2002)

- Main SNO CC and NC results do not account for sterile neutrinos

- To get constraints on sterile neutrinos from the Sun, combine with KamLAND data and assume LMA-MSW solution

Evidence for a ~ 1 eV sterile neutrino?

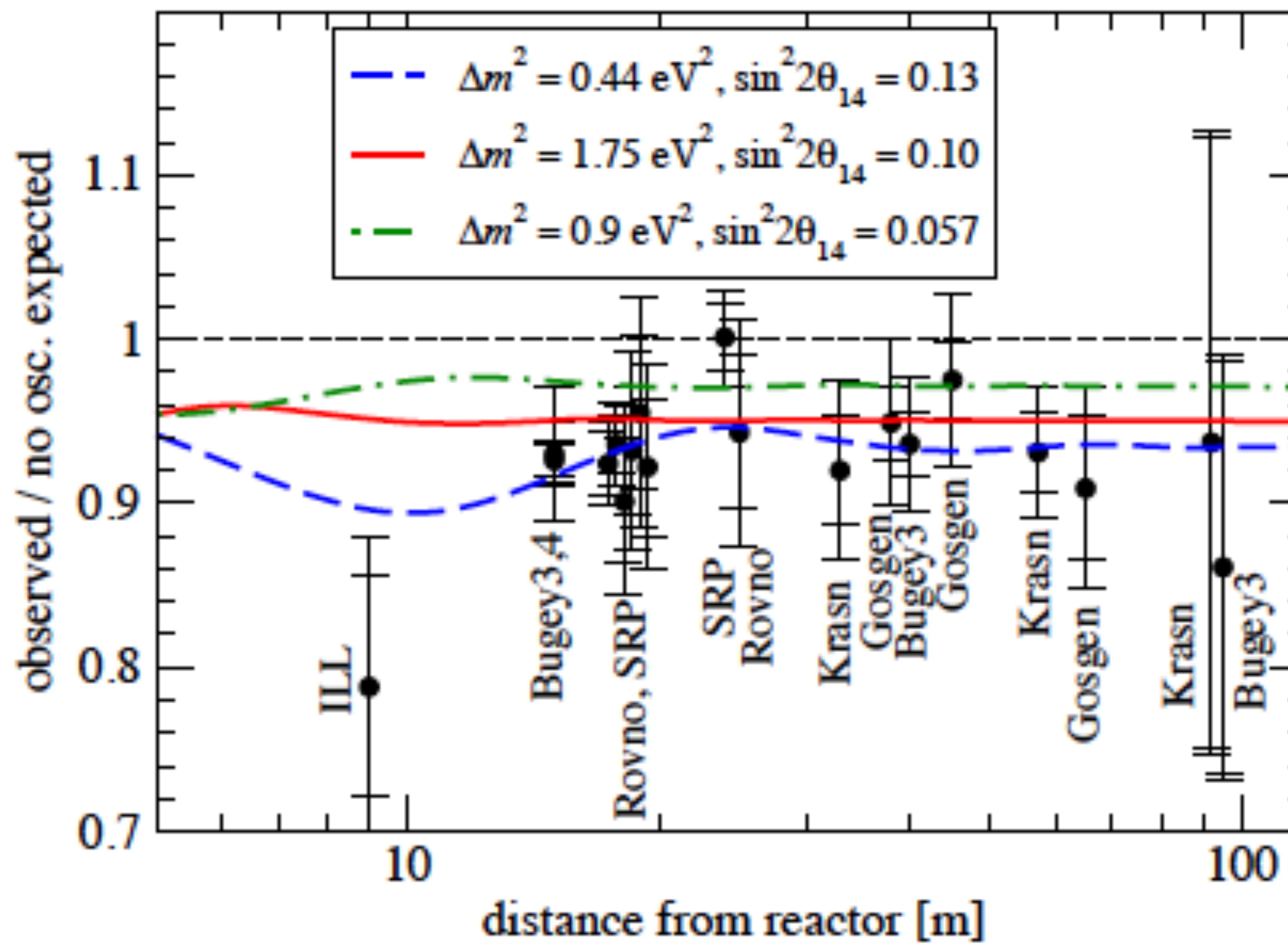
Hints for sterile neutrinos from:

- *electron neutrino disappearance* experiments: Gallium, reactor anomaly (Giunti & Lavedar 2006; Mention et al. 2011)

- *muon to electron neutrino appearance* experiments (LSND, MiniBooNE)

No hints for sterile neutrino from:

- *muon neutrino disappearance* experiments (Super-K, MiniBooNE, MINOS)



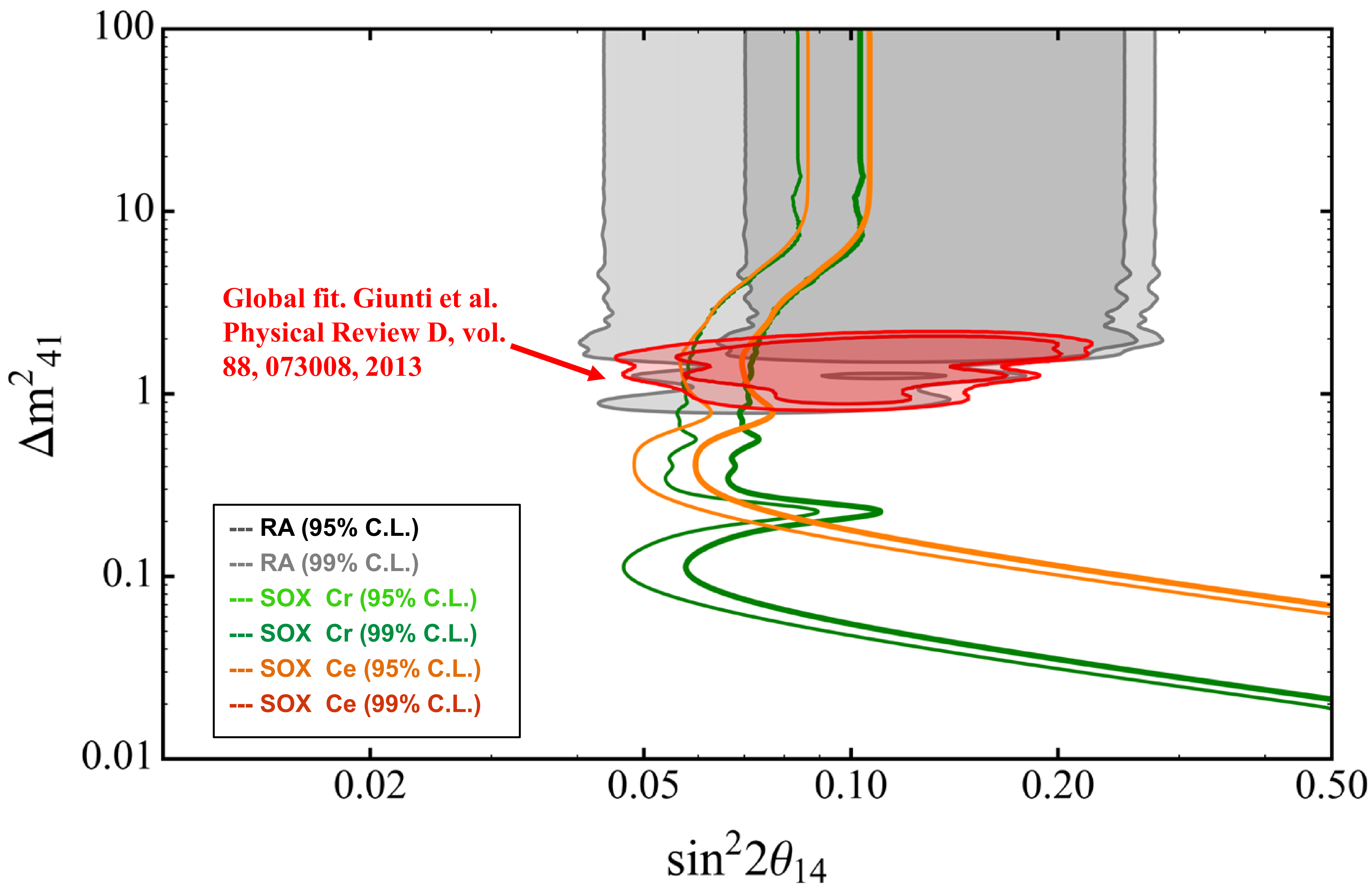
Kopp et al., sterile neutrino review 2013

Evidence for a ~ 1 eV sterile neutrino?

- Also, possible evidence from cosmology (Giusarma et al.; Dvorkin et al.; Zhang et al. 2014)

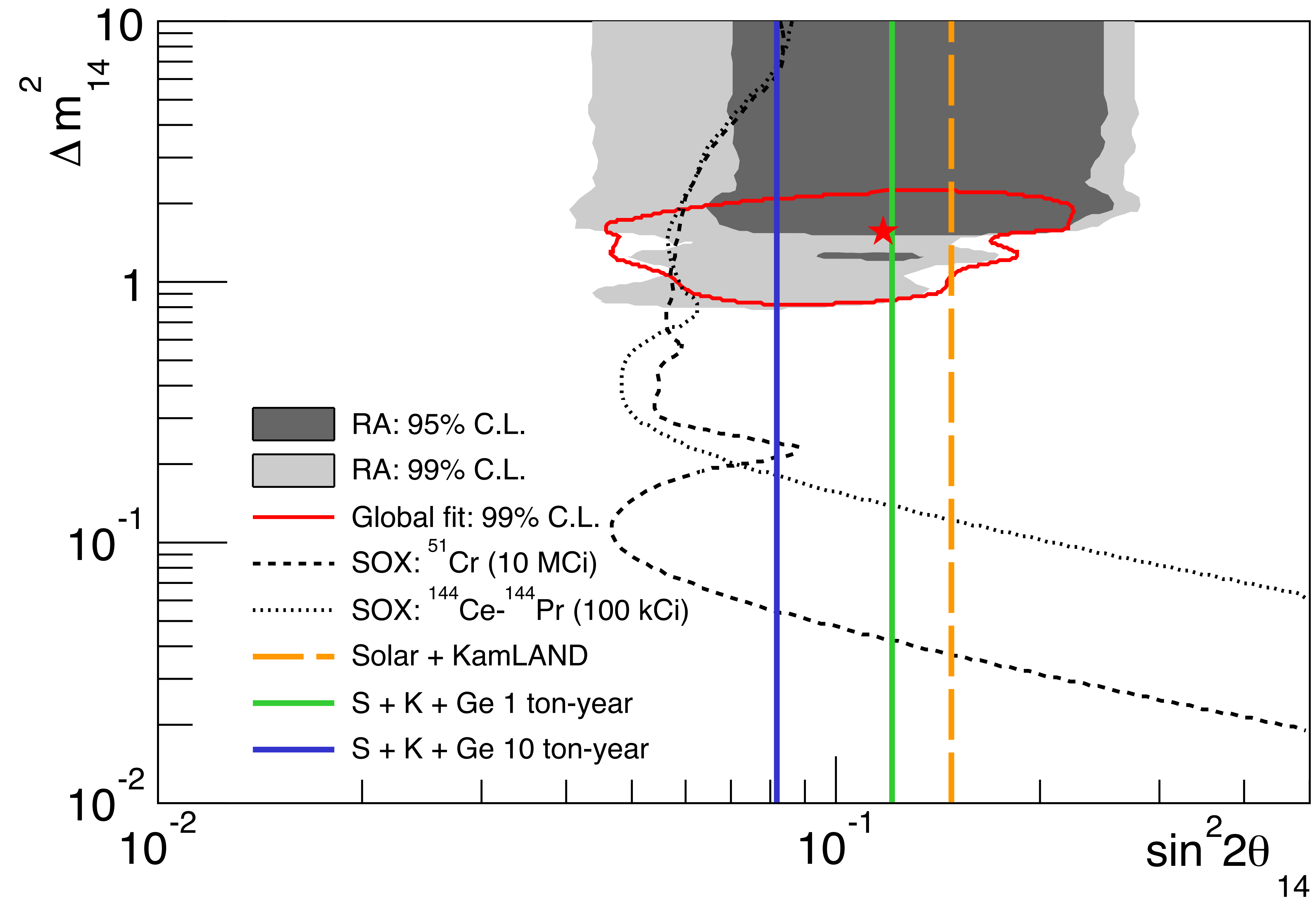
- Most generally constraints on sterile neutrinos are model-dependent (3+1,3+2, etc).

- We considered a 3+1 sterile neutrino model (Giunti & Li 2009; Palazzo 2011, Giunti et al. 2013). Electron neutrino mixes with 4th mass eigenstate



Sterile neutrinos with low threshold DM detectors

- Sterile neutrino sensitivity of DM detectors complementary to terrestrial searches for eV scale sterile neutrinos



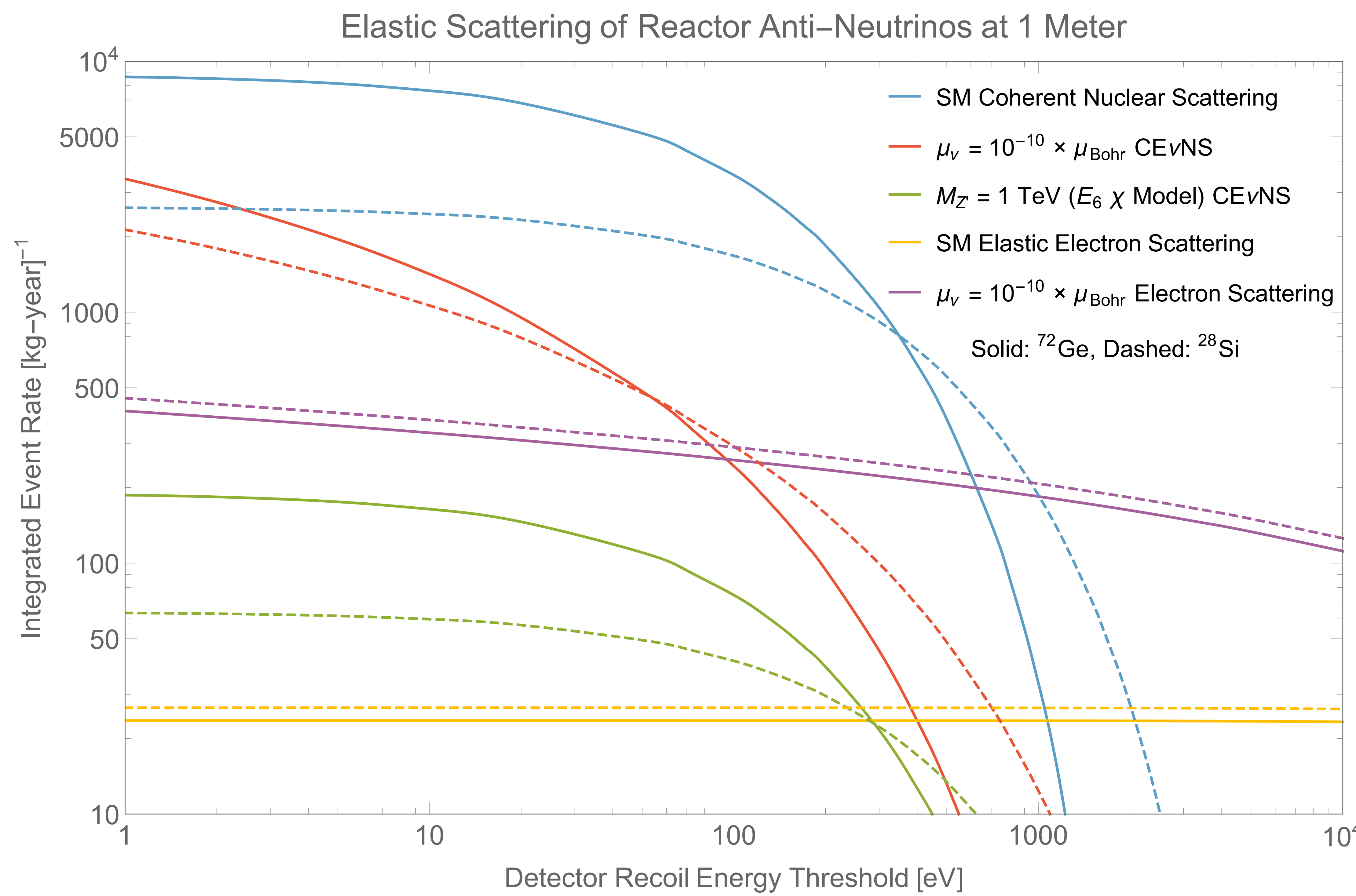
Billard, Strigari, Figueroa-Feliciano, arXiv:1409.0050

Extracting new physics from reactor neutrinos

Neutrino magnetic moment

$$\left.\frac{d\sigma}{dT_{\rm R}}\right|_{\mu_\nu} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1 - T_{\rm R}/E_\nu}{T_{\rm R}} + \frac{T_{\rm R}}{4E_\nu^2}\right]$$

- Magnetic moment interactions off of protons or electrons (Vogel & Engel 1989)
- Bounds from GEMMA collaboration give a limit of 3.2 x 10^{-11} Bohr magneton
- Astrophysical bounds from energy loss in stars of 3 x 10^{-12} Bohr magneton
- Some Majorana neutrino models predict magnetic moment ~10^{-14} Bohr magneton



See N. Mirabolfathi talk

Dutta, Mahapatra, Strigari, Walker, arXiv:1508.07981

Neutrino magnetic moment

$$\left.\frac{d\sigma}{dT_{\mathrm{R}}}\right|_{\mu_\nu} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1-T_{\mathrm{R}}/E_\nu}{T_{\mathrm{R}}} + \frac{T_{\mathrm{R}}}{4E_\nu^2}\right]$$

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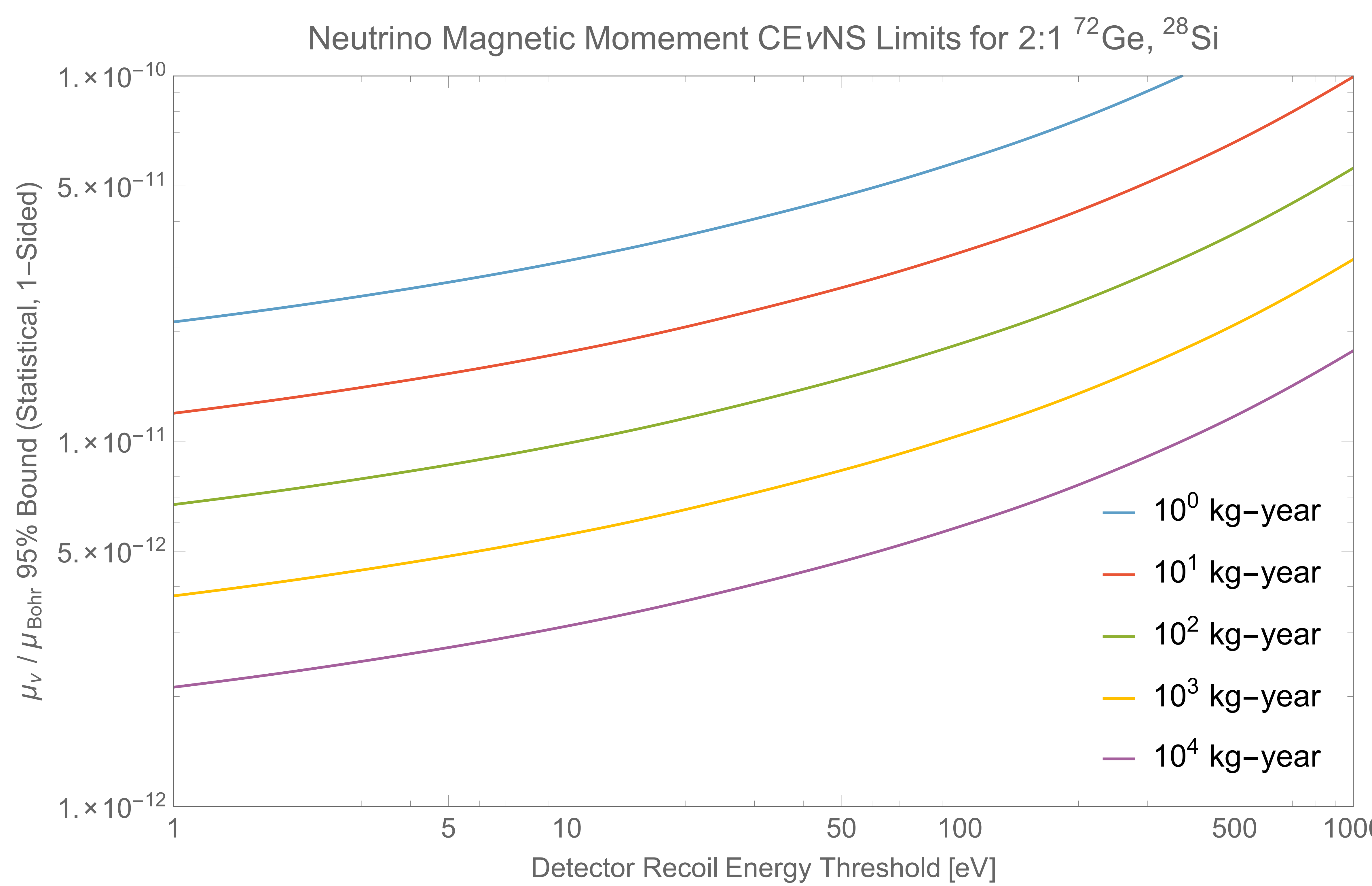
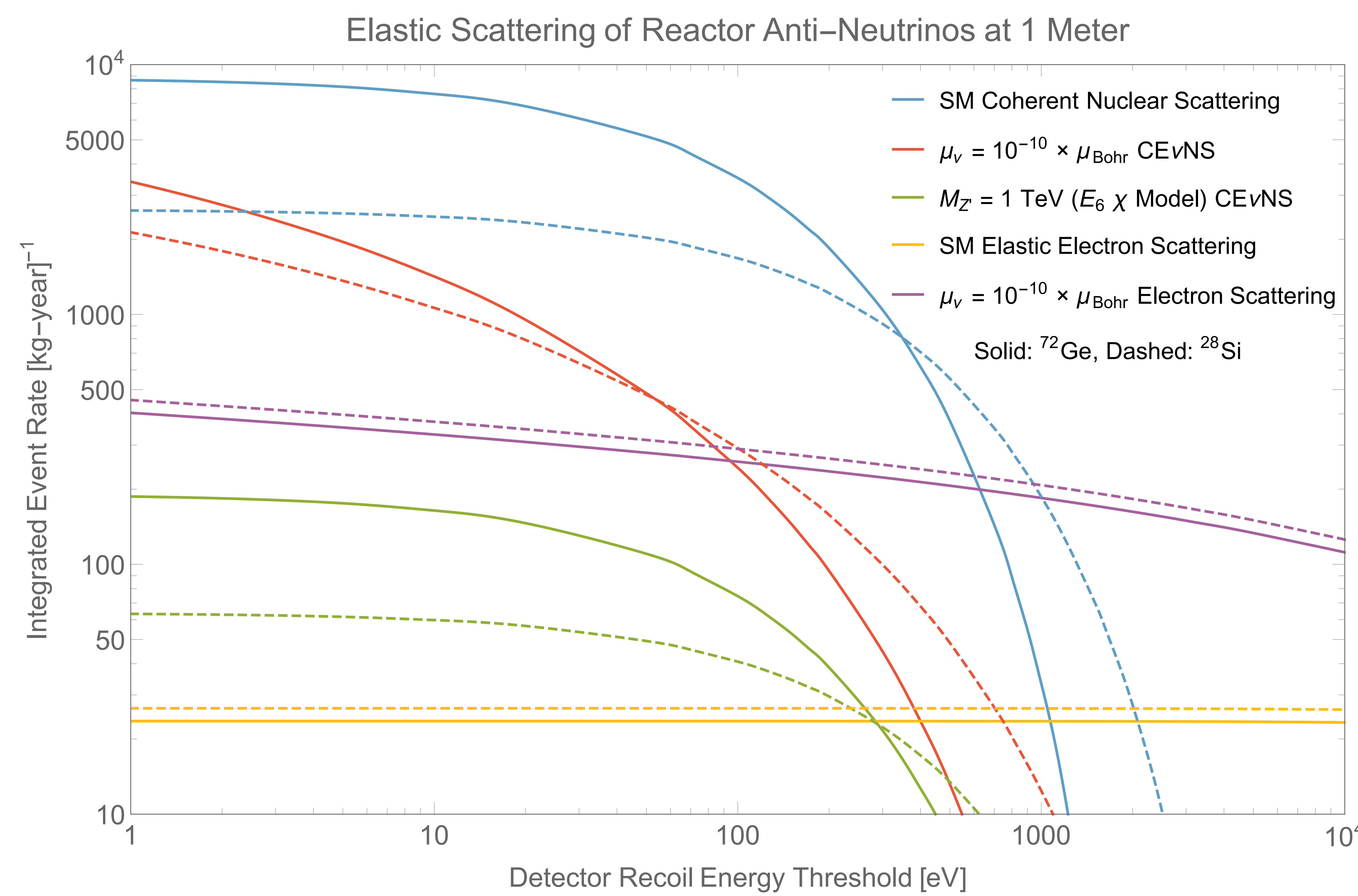


See N. Mirabolfathi talk

Dutta, Mahapatra, Strigari, Walker, arXiv:1508.07981

Z-prime and non-standard neutrino interactions

- Sensitivity to Z-prime of order a few TeV, complementary to LHC in the near term



See N. Mirabolfathi talk

Dutta, Mahapatra, Strigari, Walker, arXiv:1508.07981

Discussion

- Best approach between: Spectral, directional, timing information

- Which questions are most interesting: sterile neutrinos? non-standard neutrino interactions? neutrino astrophysics?

- Room for a joint neutrino + DM program?