Astrophysical applications of coherent neutrino-nucleus scattering

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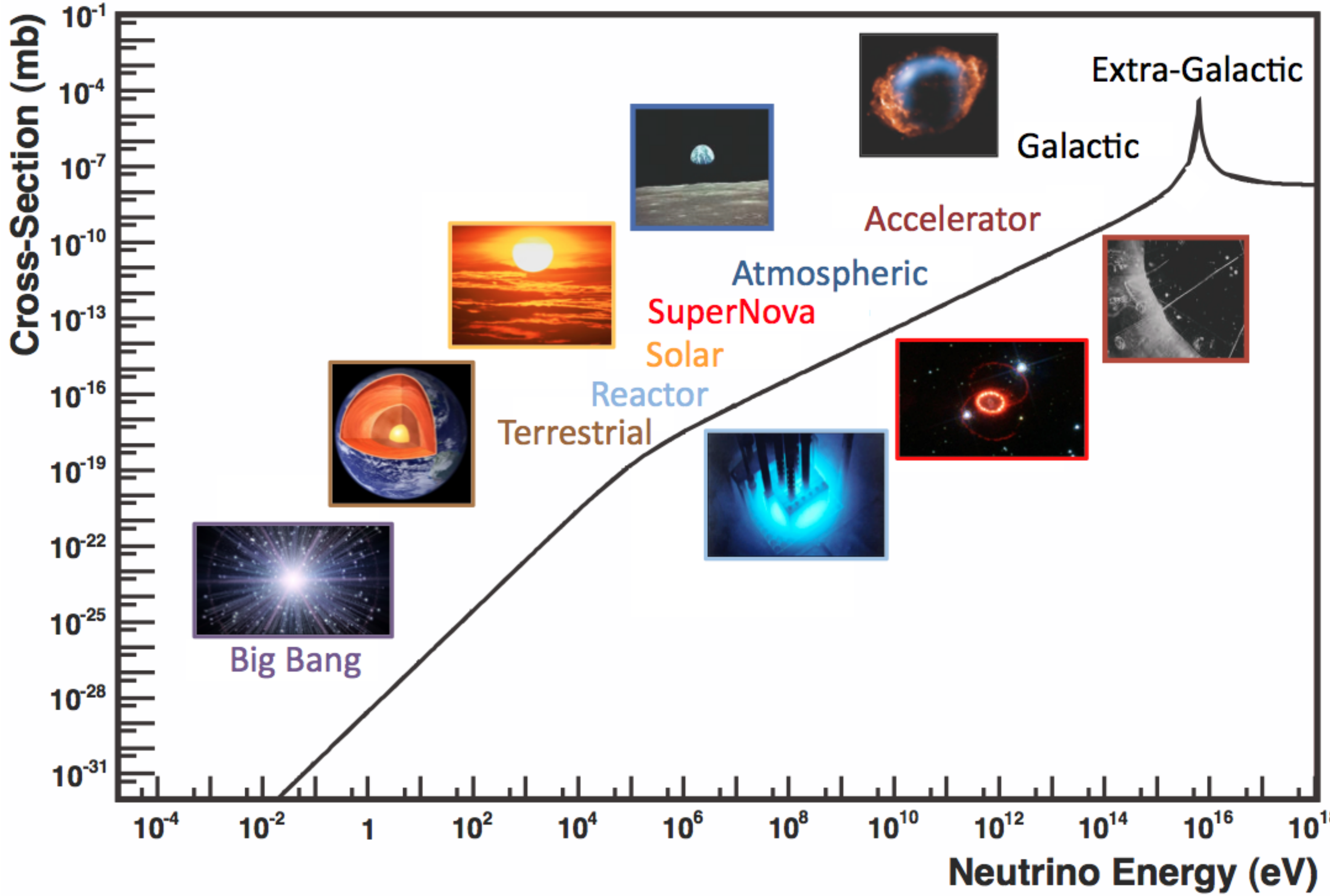
Chicago/EFI Magnificent CEvENS
Nov 2, 2018

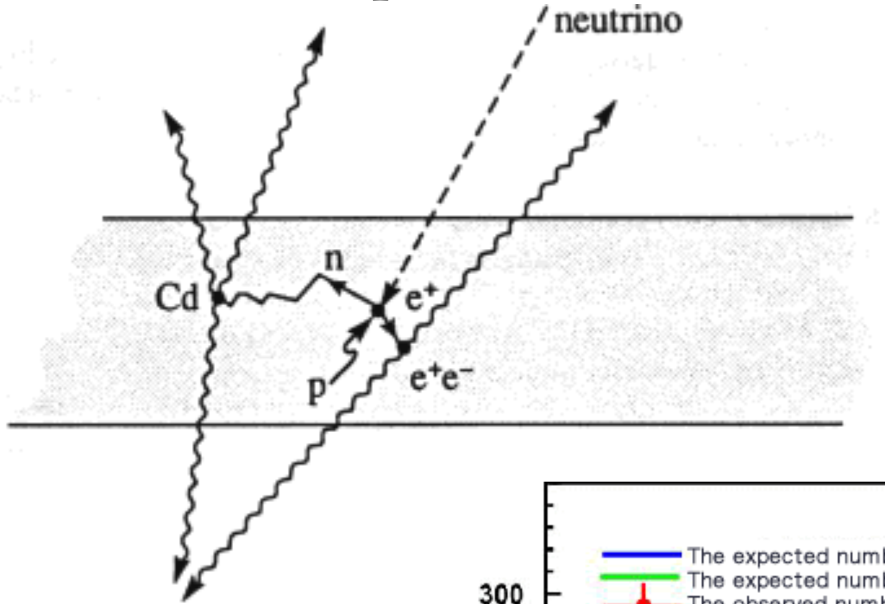
Artwork by Sandbox Studio, Chicago with Ana Kova



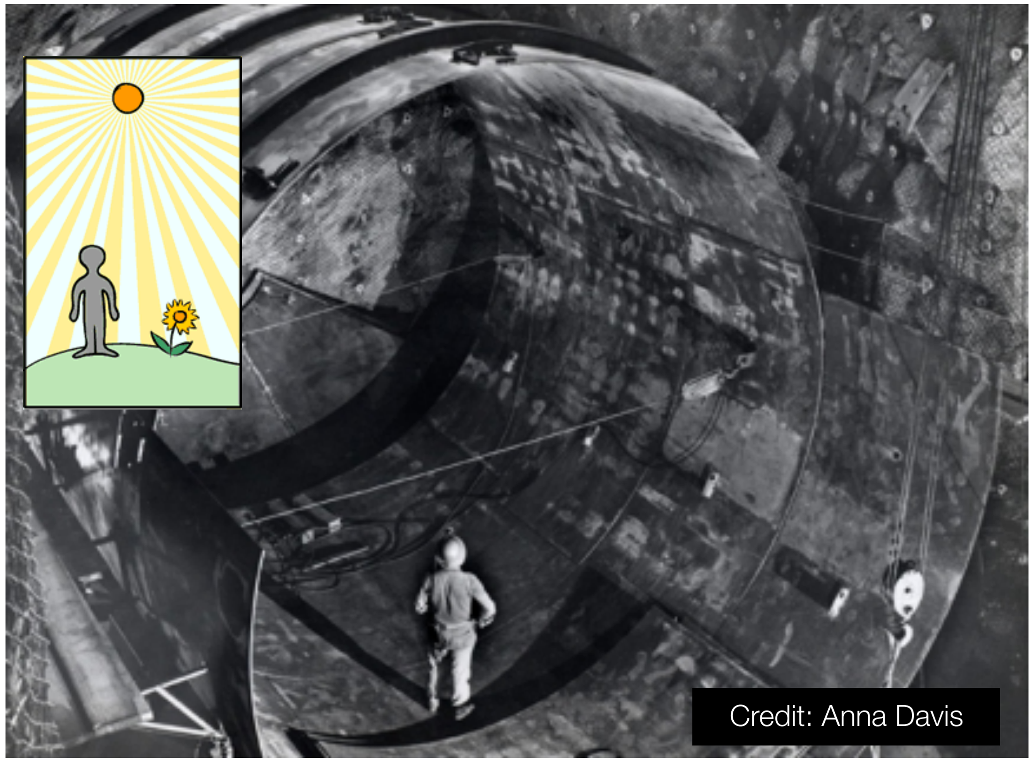
Formaggio & Zeller 2012

New (astro)-physics from neutrino detections

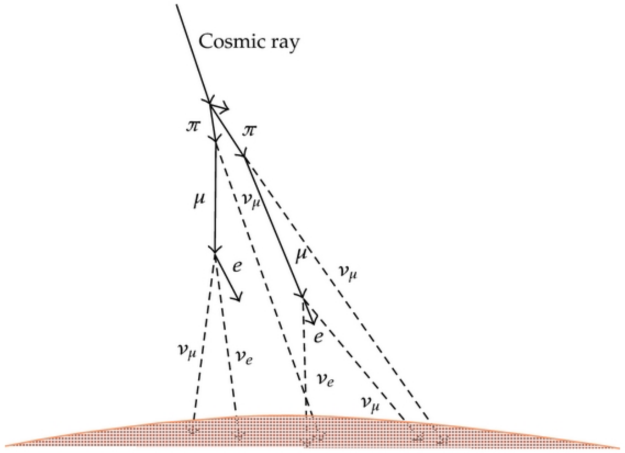
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

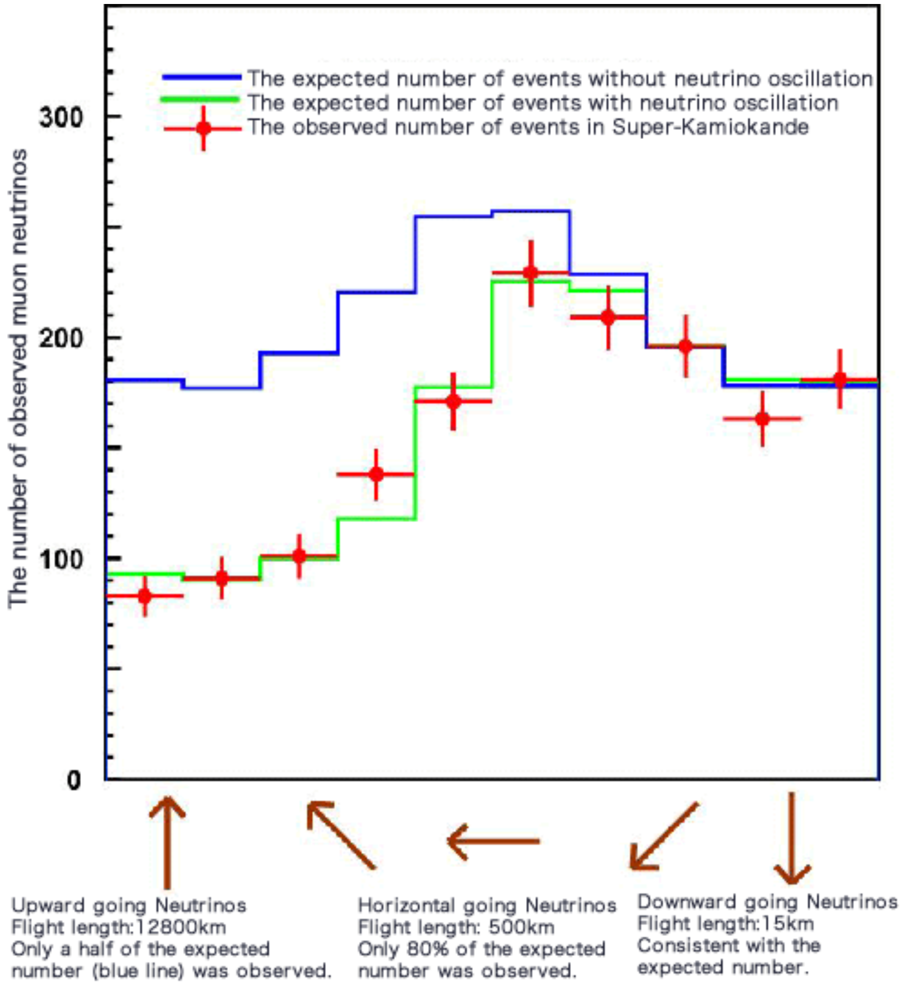


$$\nu_e + (A, Z) \rightarrow (A, Z+1) + e^-$$



$$\nu + e \rightarrow \nu + e$$





Coherent neutrino nucleus scattering: Predictions & Implications

Coherent effects of a weak neutral current

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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.

- Implications for neutrino transport in supernovae
- Large cross section important for understanding how neutrinos emerge from supernovae

THE WEAK NEUTRAL CURRENT AND ITS EFFECTS IN STELLAR COLLAPSE

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David N. Schramm[1] *and David L. Tubbs*[2]
Enrico Fermi Institute (LASR), University of Chicago, Chicago, Illinois 60637

Coherent neutrino nucleus scattering: Detection methods

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

Bolometric Detection of Neutrinos

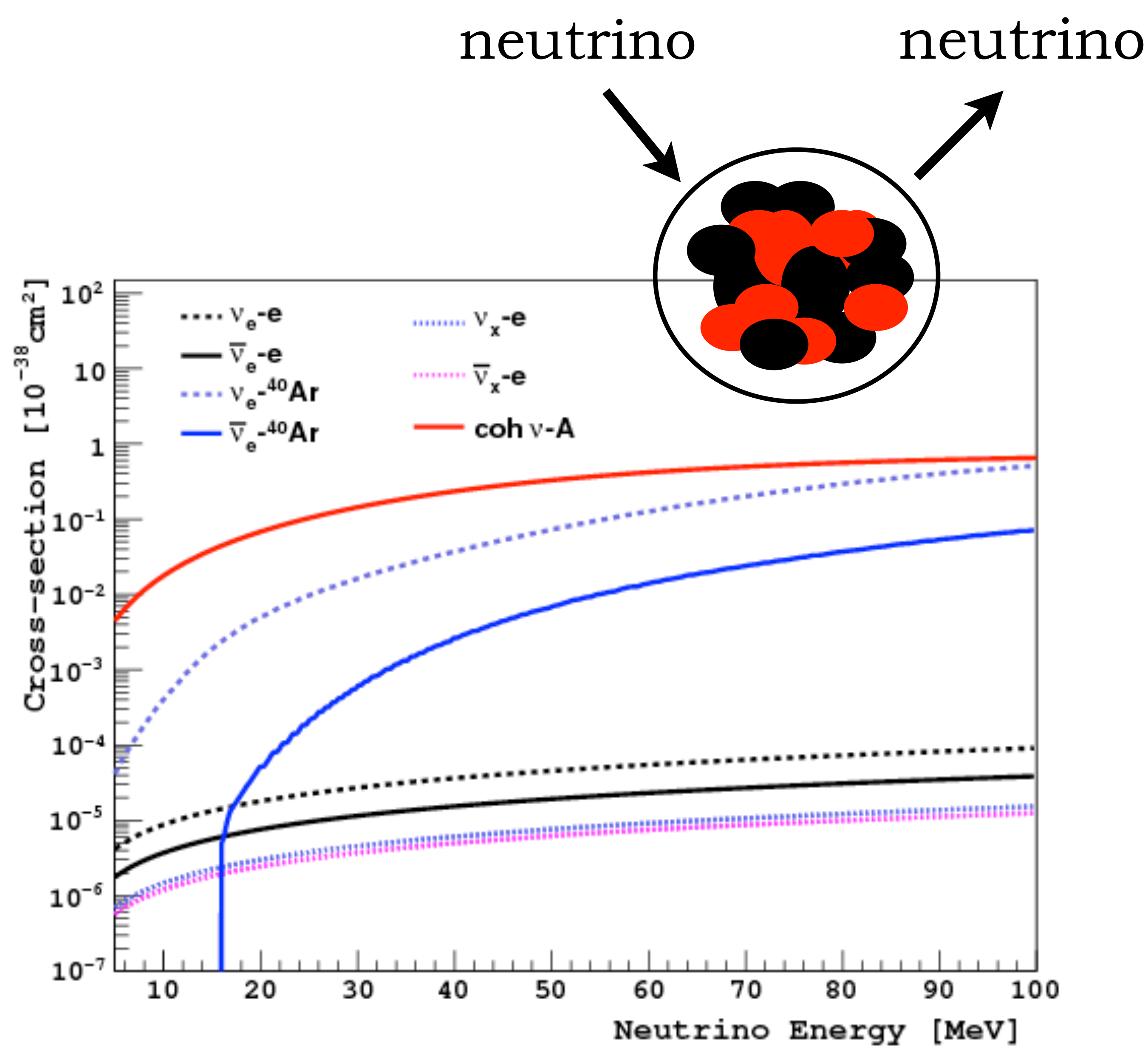
Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received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

Neutrino-nucleus coherent scattering

- Neutral current interaction; Total scattering amplitude sum of that on constituent nucleons
- Small momentum transfer wrt to the target size implies coherent enhancement
- Due to Standard Model couplings coherent enhancement due to neutrons
- Low energy recoil distribution implies difficult to detect

Before the end of this past summer, this was ``…a *well known prediction of the Standard Model, but is yet to be detected*….”



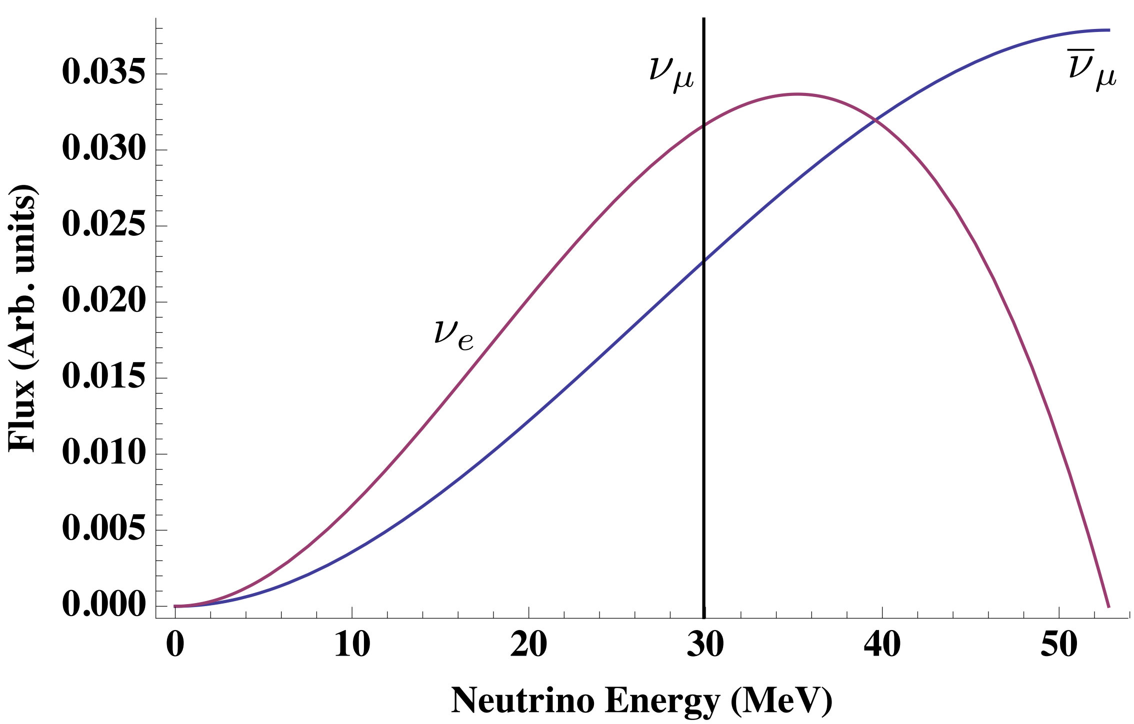
Brice et al, 1311.5958

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

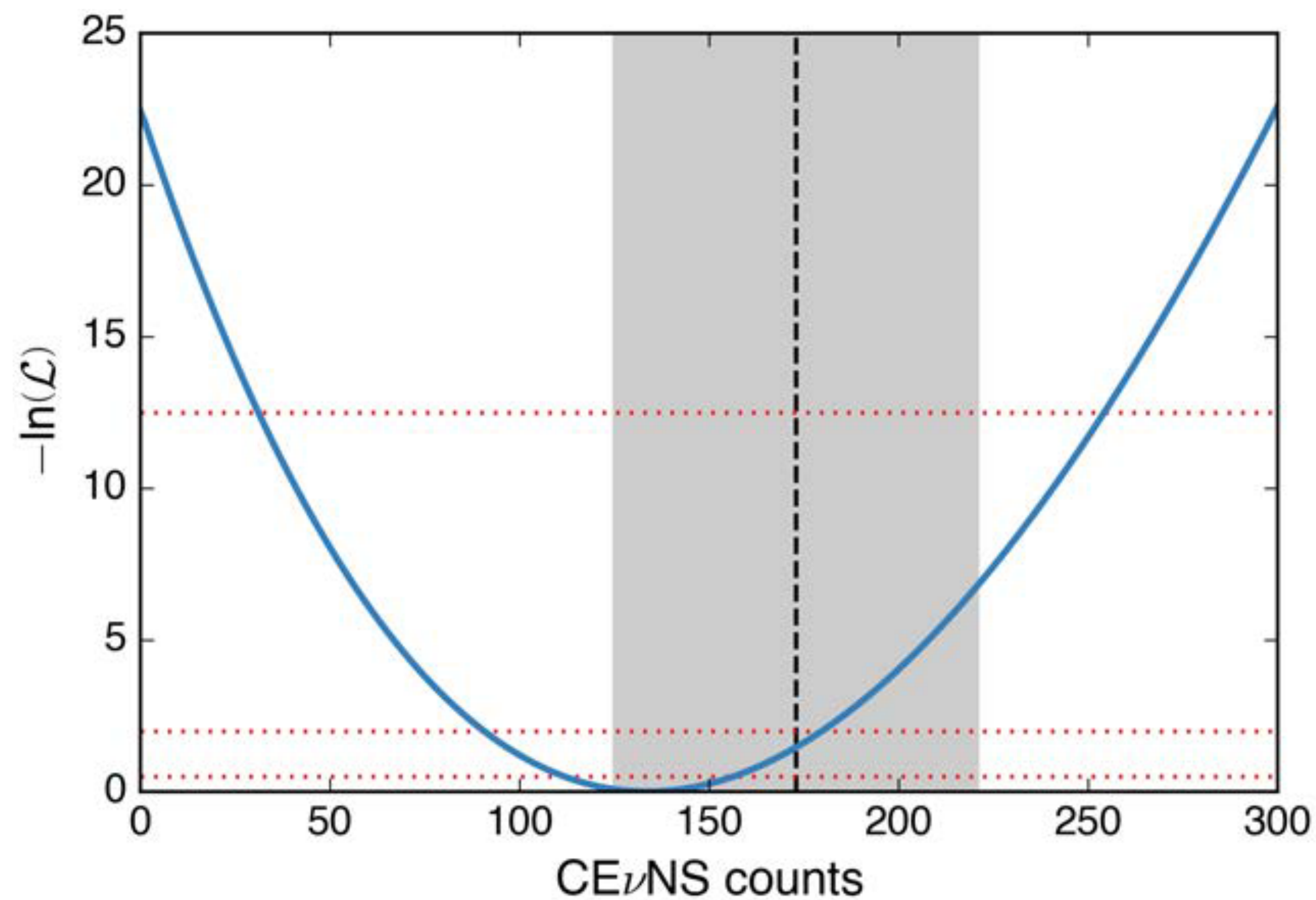
Detection 40+ years in making!

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov, J. B. Albert, P. An, C. Awe, P. S. Barbeau, B. Becker, V. Belov, A. Brown, A. Bolozdynya, B. Cabrera-Palmer, M. Cervantes, J. I. Collar,* R. J. Cooper, R. L. Cooper, C. Cuesta, D. J. Dean, J. A. Detwiler, A. Eberhardt, Y. Efremenko, S. R. Elliott, E. M. Erkela, L. Fabris, M. Febbraro, N. E. Fields, W. Fox, Z. Fu, A. Galindo-Uribarri, M. P. Green, M. Hai, M. R. Heath, S. Hedges, D. Hornback, T. W. Hossbach, E. B. Iverson, L. J. Kaufman, S. Ki, S. R. Klein, A. Khromov, A. Konovalov, M. Kremer, A. Kumpan, C. Leadbetter, L. Li, W. Lu, K. Mann, D. M. Markoff, K. Miller, H. Moreno, P. E. Mueller, J. Newby, J. L. Orrell, C. T. Overman, D. S. Parno, S. Penttila, G. Perumpilly, H. Ray, J. Raybern, D. Reyna, G. C. Rich, D. Rimal, D. Rudik, K. Scholberg, B. J. Scholz, G. Sinev, W. M. Snow, V. Sosnovtsev, A. Shakirov, S. Suchyta, B. Suh, R. Tayloe, R. T. Thornton, I. Tolstukhin, J. Vanderwerp, R. L. Varner, C. J. Virtue, Z. Wan, J. Yoo, C.-H. Yu, A. Zawada, J. Zettlemoyer, A. M. Zderic, COHERENT Collaboration



Anderson et al., 1201.3805



Coherent neutrino scattering at reactors

The CONNIE experiment

A. Aguilar-Arevalo[1], X. Bertou[2], C. Bonifazi[3], M. Butner[4], G. Cancelo[4], A. Castaneda Vazquez[1], B. Cervantes Vergara[1], C.R. Chavez[5], H. Da Motta[6], J.C. D'Olivo[1], J. Dos Anjos[6], J. Estrada[4], G. Fernandez Moroni[7,8], R. Ford[4], A. Foguel[3,6], K.P. Hernandez Torres[1], F. Izraelevitch[4], A. Kavner[9], B. Kilminster[10], K. Kuk[4], H.P. Lima Jr.[6], M. Makler[6], J. Molina[5], G. Moreno-Granados[1], J.M. Moro[11], E.E. Paolini[7,12], M. Sofo Haro[2], J. Tiffenberg[4], F. Trillaud[1], and S. Wagner[6,13]

Coherent Neutrino Scattering with Low Temperature Bolometers at Chooz Reactor Complex

J. Billard[1], R. Carr[2], J. Dawson[3], E. Figueroa-Feliciano[4], J. A. Formaggio[2], J. Gascon[1], M. De Jesus[1], J. Johnston[2], T. Lasserre[5,6], A. Leder[2], K. J. Palladino[7], S. H. Trowbridge[2], M. Vivier[5], and L. Winslow[2]

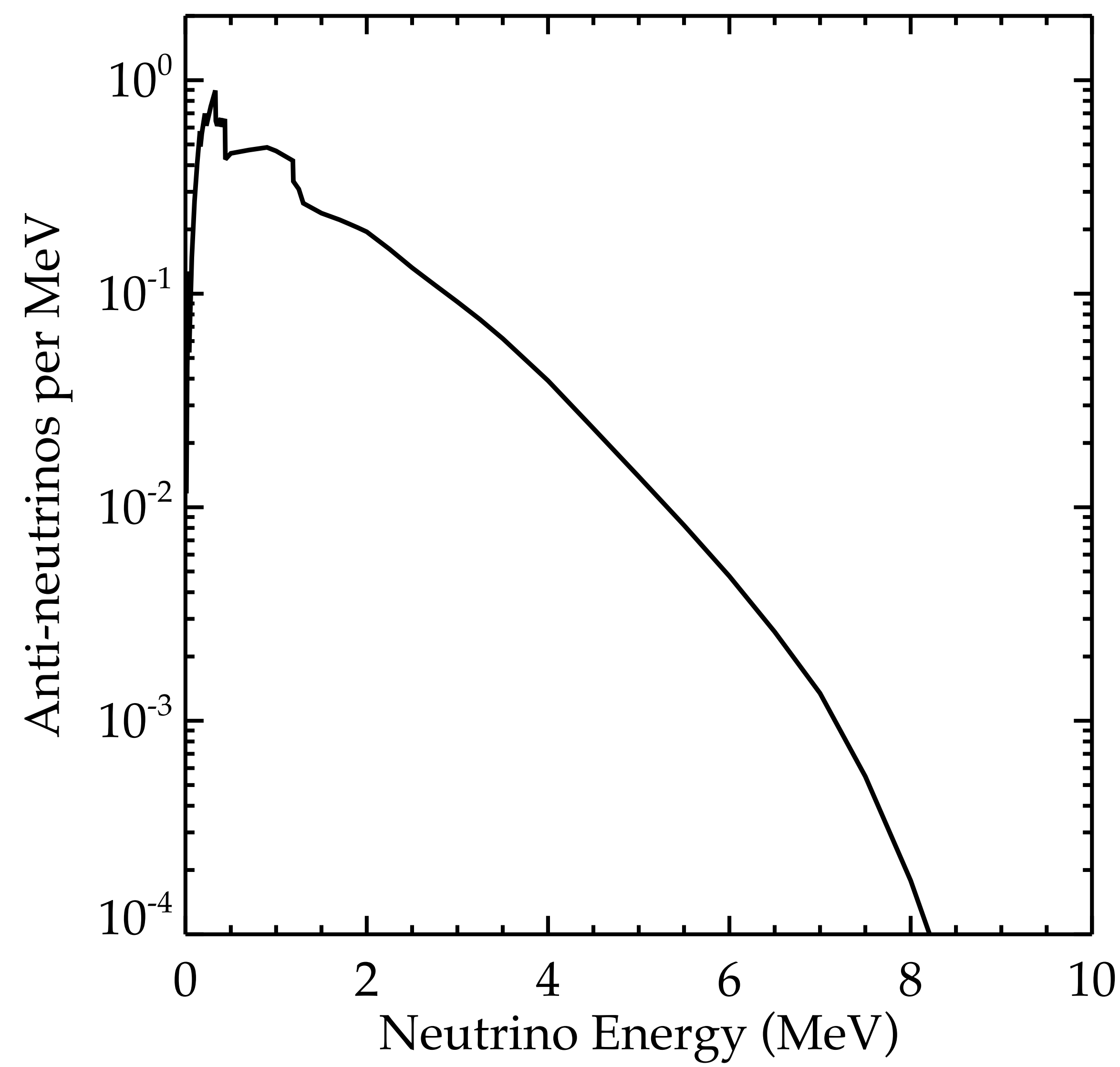
Research program towards observation of neutrino-nucleus coherent scattering

H T Wong[1,*], H B Li[1], S K Lin[1], S T Lin[1], D He[2], J Li[2], X Li[2], Q Yue[2], Z Y Zhou[3] and S K Kim[4]

[1] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan.
[2] Department of Engineering Physics, Tsing Hua University, Beijing 100084, China.
[3] Department of Nuclear Physics, Institute of Atomic Energy, Beijing 102413, China.
[4] Department of Physics, Seoul National University, Seoul 151-742, Korea.

Background Studies for the MINER Coherent Neutrino Scattering Reactor Experiment

G. Agnolet[a], W. Baker[a], D. Barker[b], R. Beck[a], T.J. Carroll[c], J. Cesar[c], P. Cushman[b], J.B. Dent[d], S. De Rijck[c], B. Dutta[a], W. Flanagan[c], M. Fritts[b], Y. Gao[a,e], H.R. Harris[a], C.C. Hays[a], V. Iyer[f], A. Jastram[a], F. Kadribasic[a], A. Kennedy[b], A. Kubik[a], I. Ogawa[g], K. Lang[c], R. Mahapatra[a], V. Mandic[b], R.D. Martin[h], N. Mast[b], S. McDeavitt[i], N. Mirabolfathi[a], B. Mohanty[f], K. Nakajima[g], J. Newhouse[i], J.L. Newstead[j], D. Phan[c], M. Proga[c], A. Roberts[k], G. Rogachev[l], R. Salazar[c], J. Sander[k], K. Senapati[f], M. Shimada[g], L. Strigari[a], Y. Tamagawa[g], W. Teizer[a], J.I.C. Vermaak[i], A.N. Villano[b], J. Walker[m], B. Webb[a], Z. Wetzel[a], S.A. Yadavalli[c]

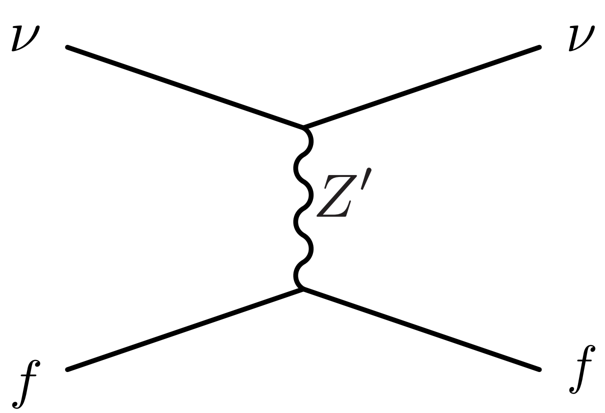


CONUS 2.4 sigma measurement— Neutrino 2018

Searches for new physics

Non-standard/generalized interactions

Scholberg 2005; Barranco 2005; Coloma et al. 2018;
Liao & Marfatia 2017; Aristizabal-Sierra et al. 2018

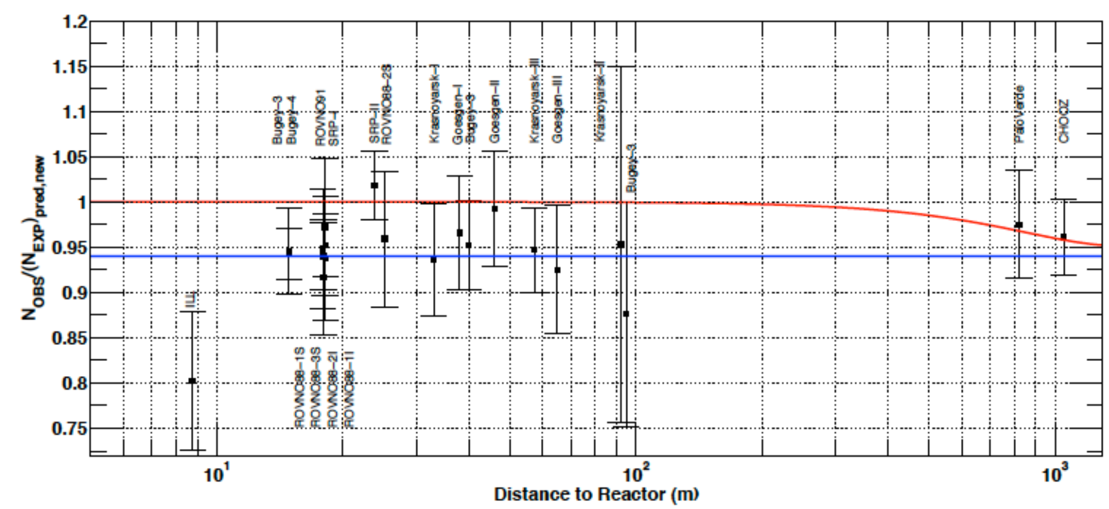


$$\mathcal{L}_{int} = 2\sqrt{2}G_F \bar{\nu}_{\alpha L}\gamma^{\mu}\nu_{\beta L}\left(\epsilon^{fL}_{\alpha\beta}\bar{f}_L\gamma_{\mu}f_L + \epsilon^{fR}_{\alpha\beta}\bar{f}_R\gamma_{\mu}f_R\right)$$

Sterile neutrinos

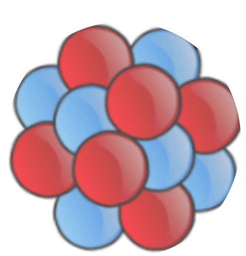
Anderson et al. 2010; Dutta et al. 2015; Kosmas et al. 2017

Reactor, Gallium anomalies



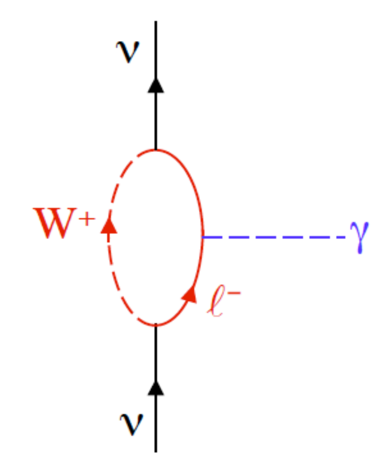
Nuclear form factors/charge radius

Patton et al. 2013; Cadeddu et al. 2018;
Ciuffoli et al. 2018



Magnetic moment

Vogel & Engel 1989

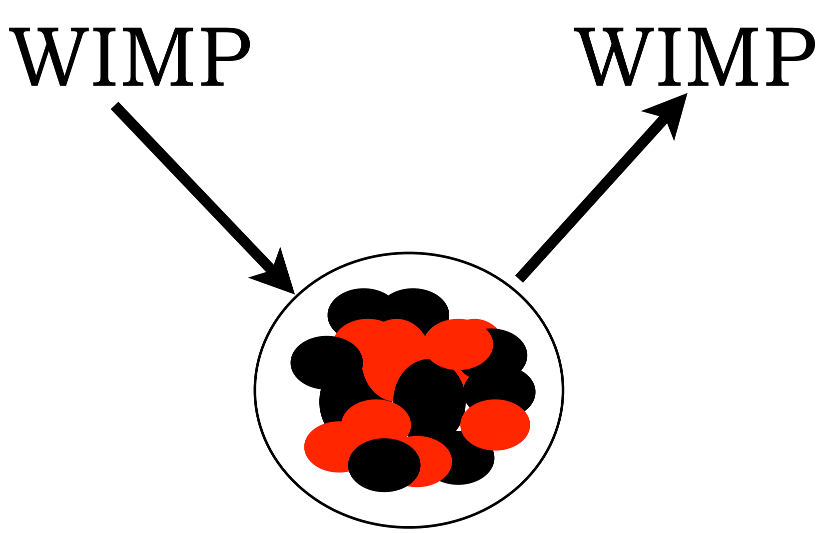


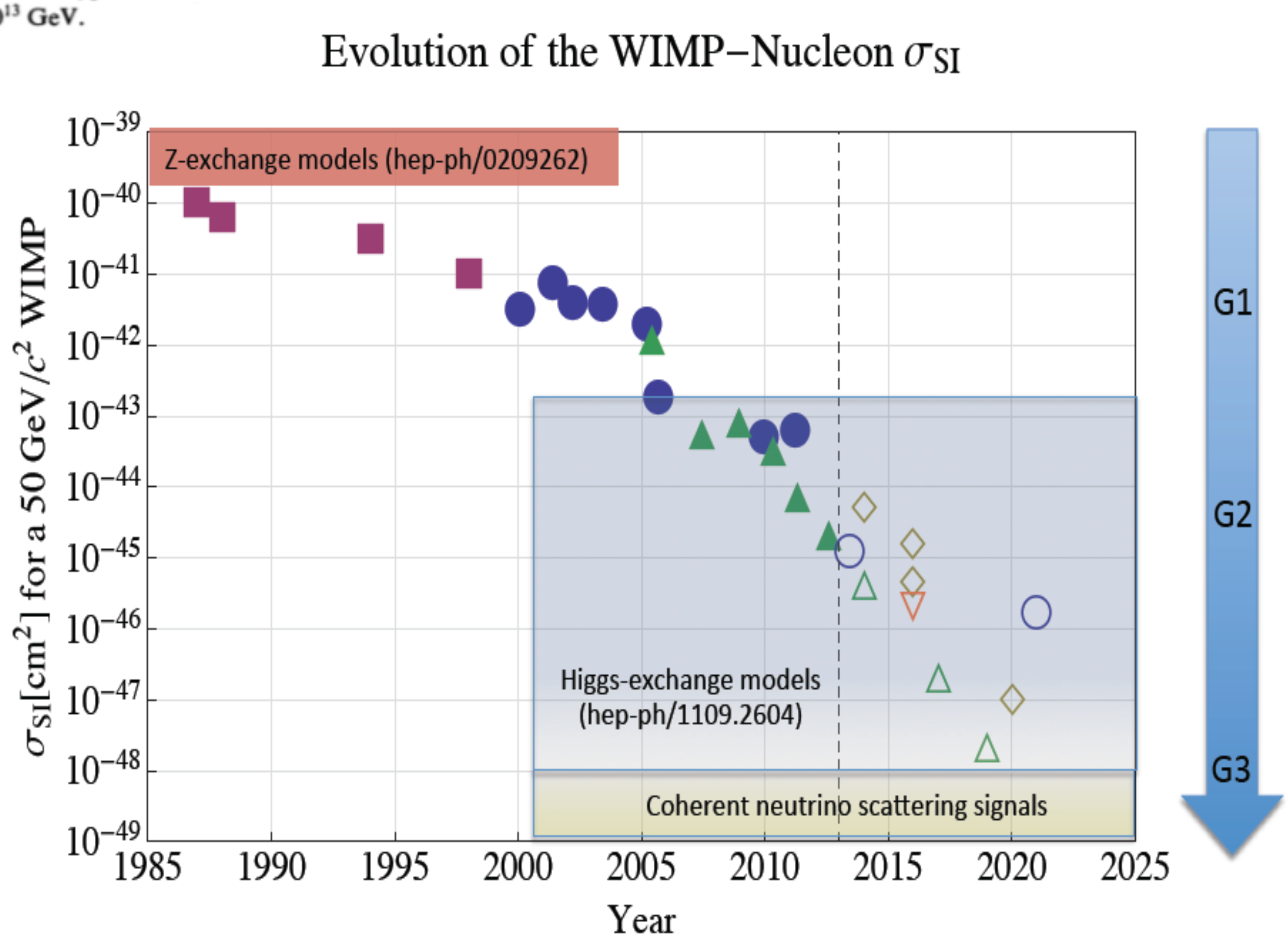
Direct dark matter detection

Detectability of certain dark-matter candidates

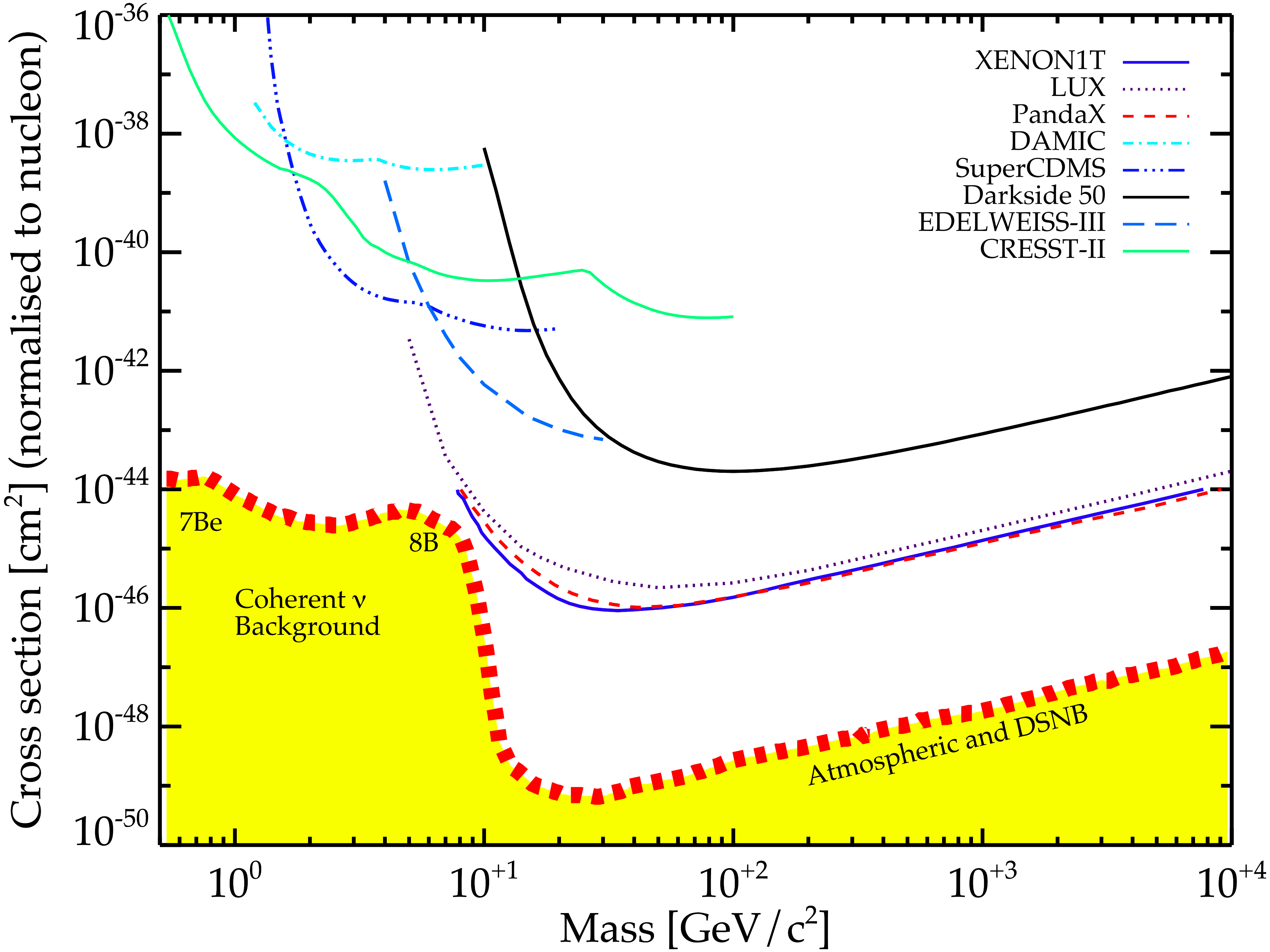
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

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.

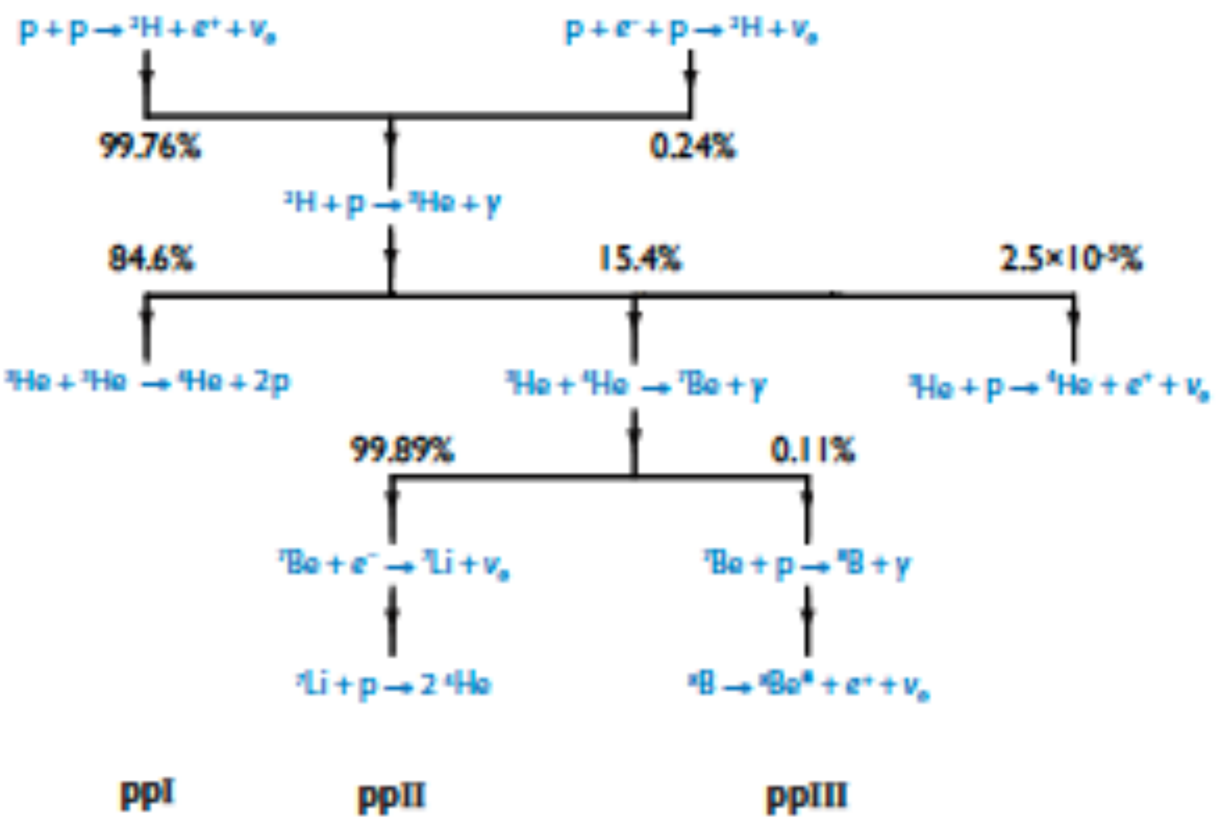


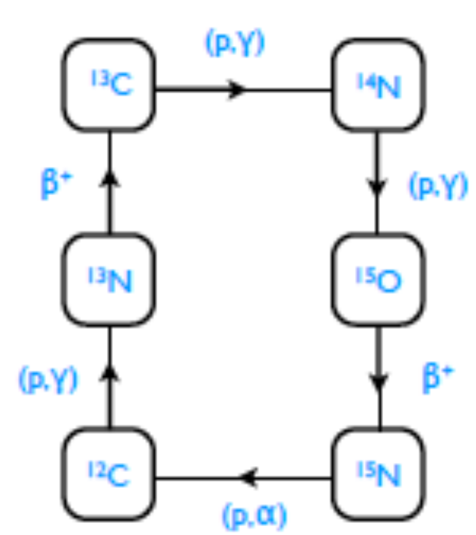


Direct dark matter detection

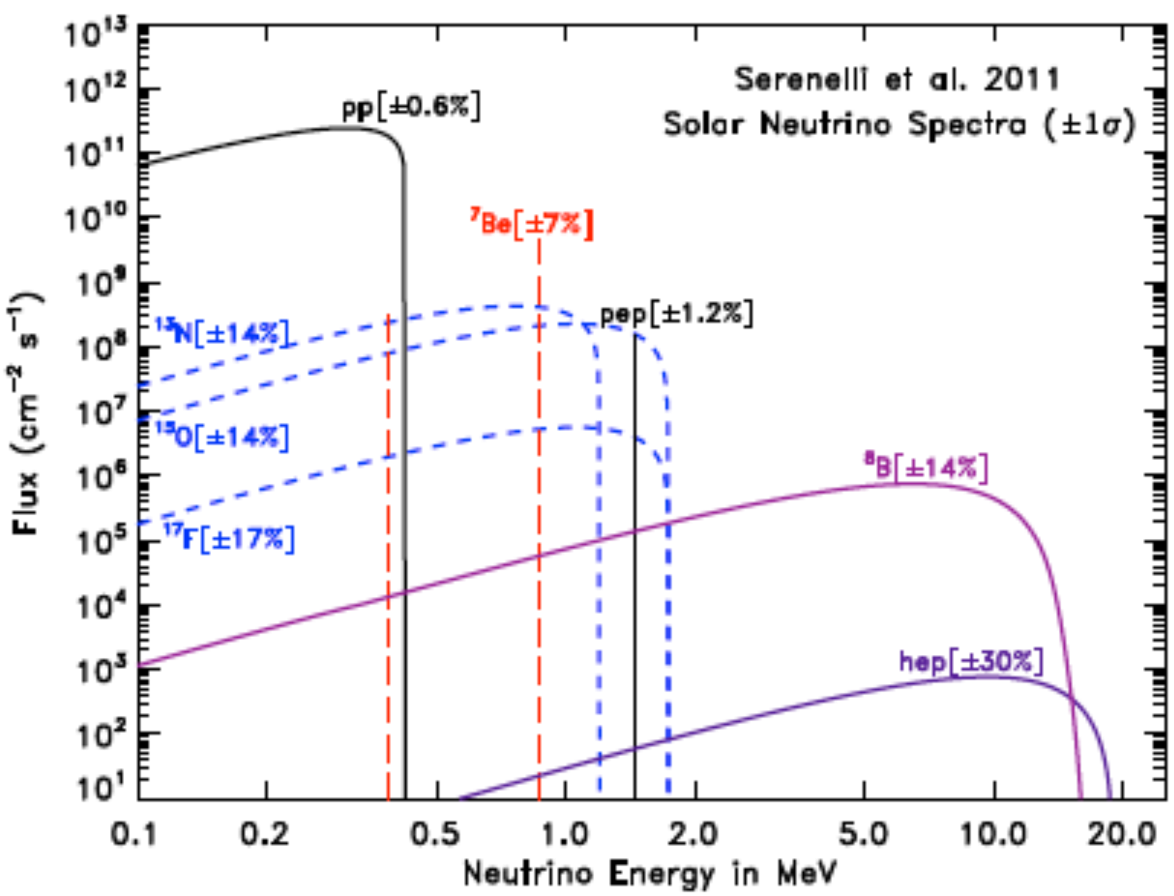


Solar neutrinos: Redux

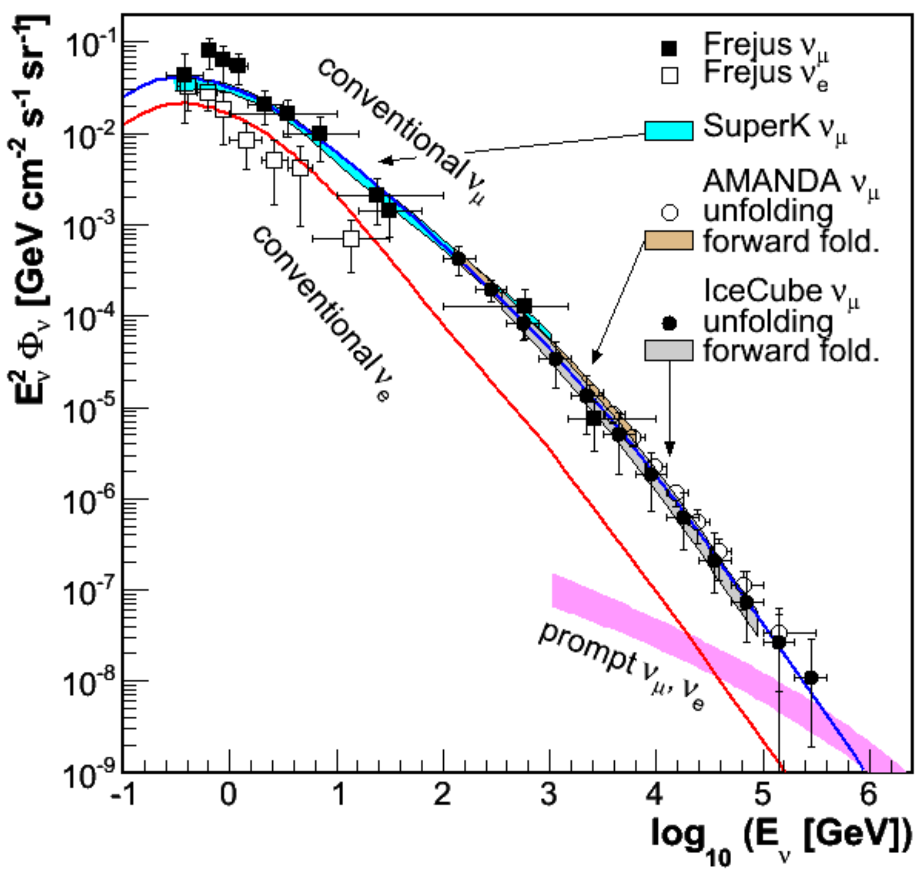


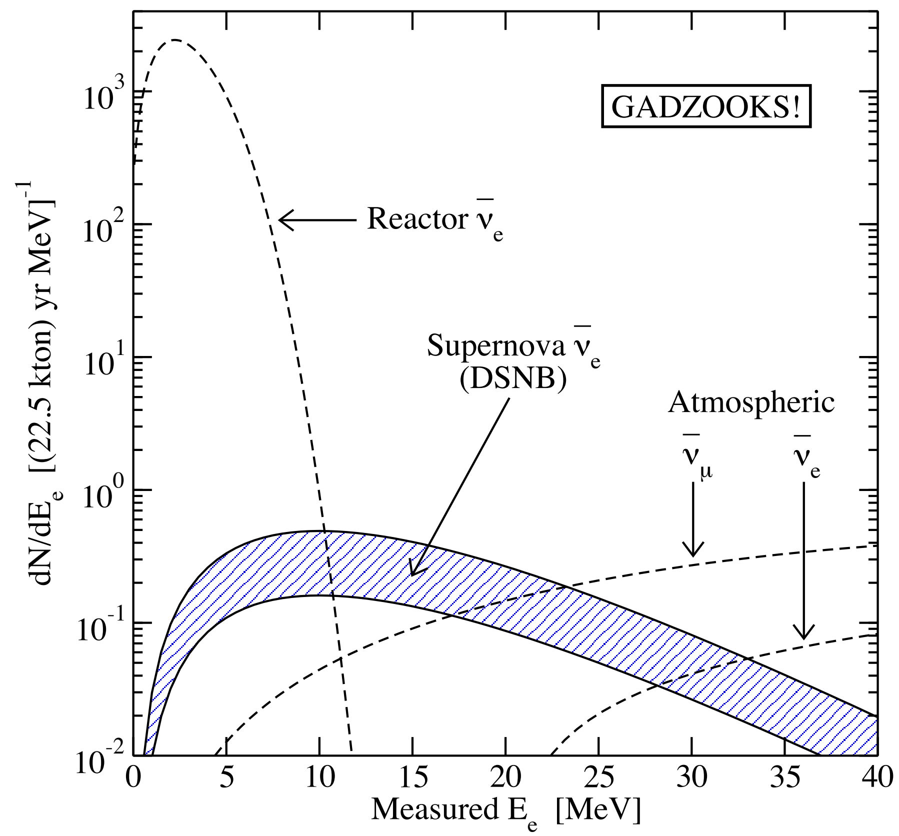


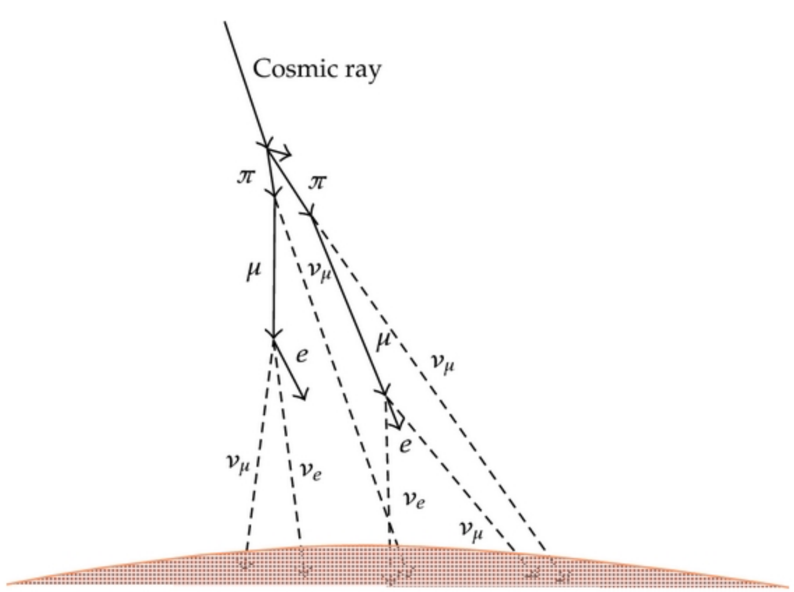
CN cycle

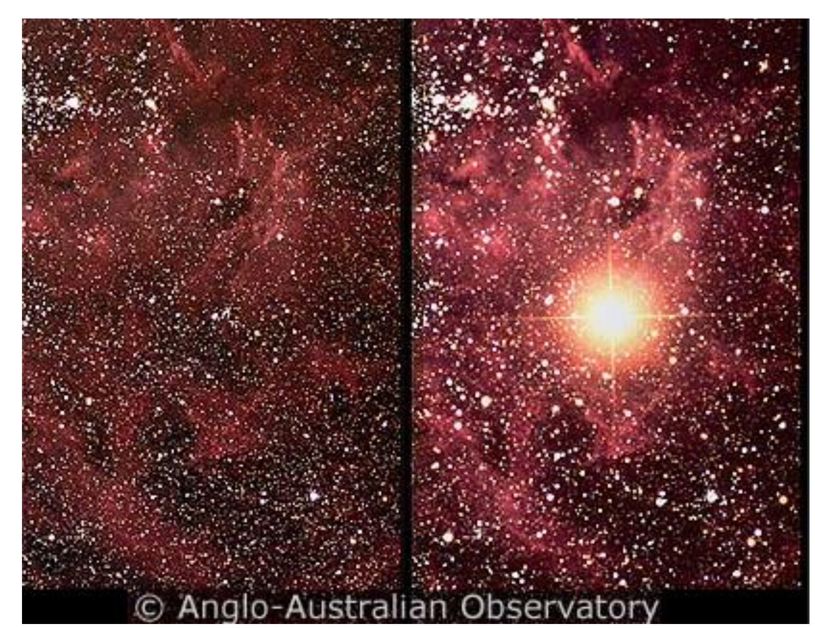


Atmospheric and SN neutrinos

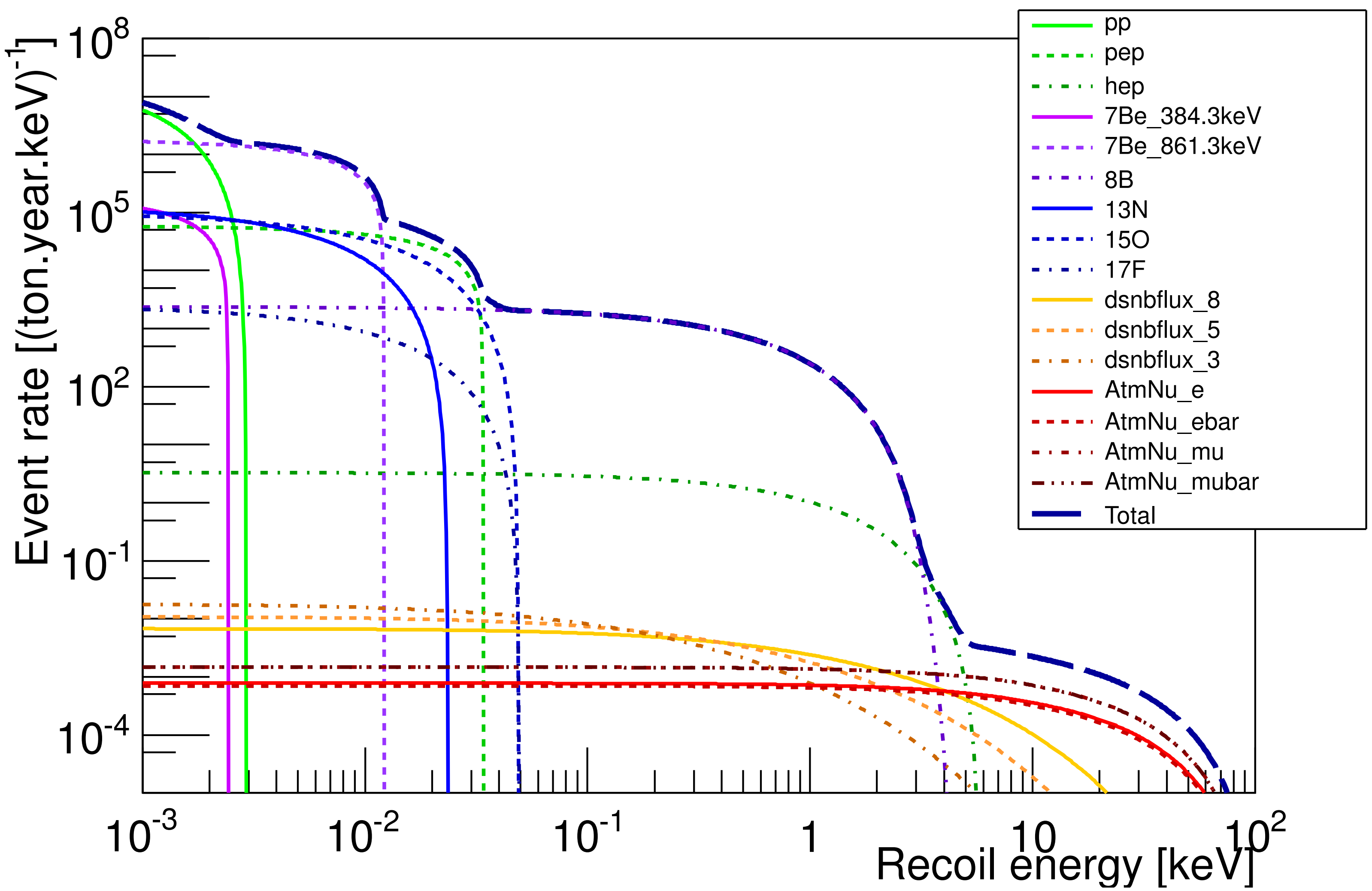






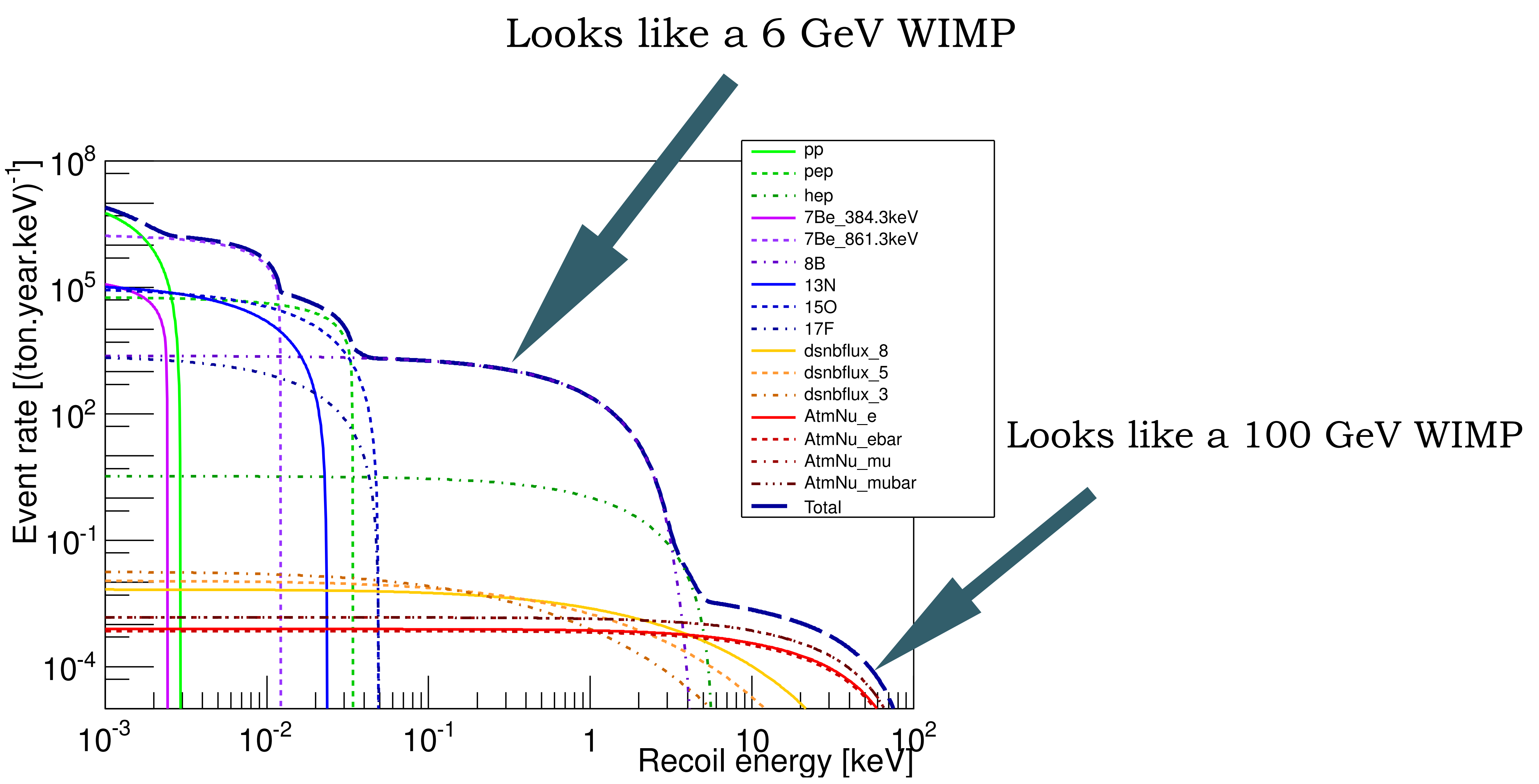


Astrophysical neutrinos

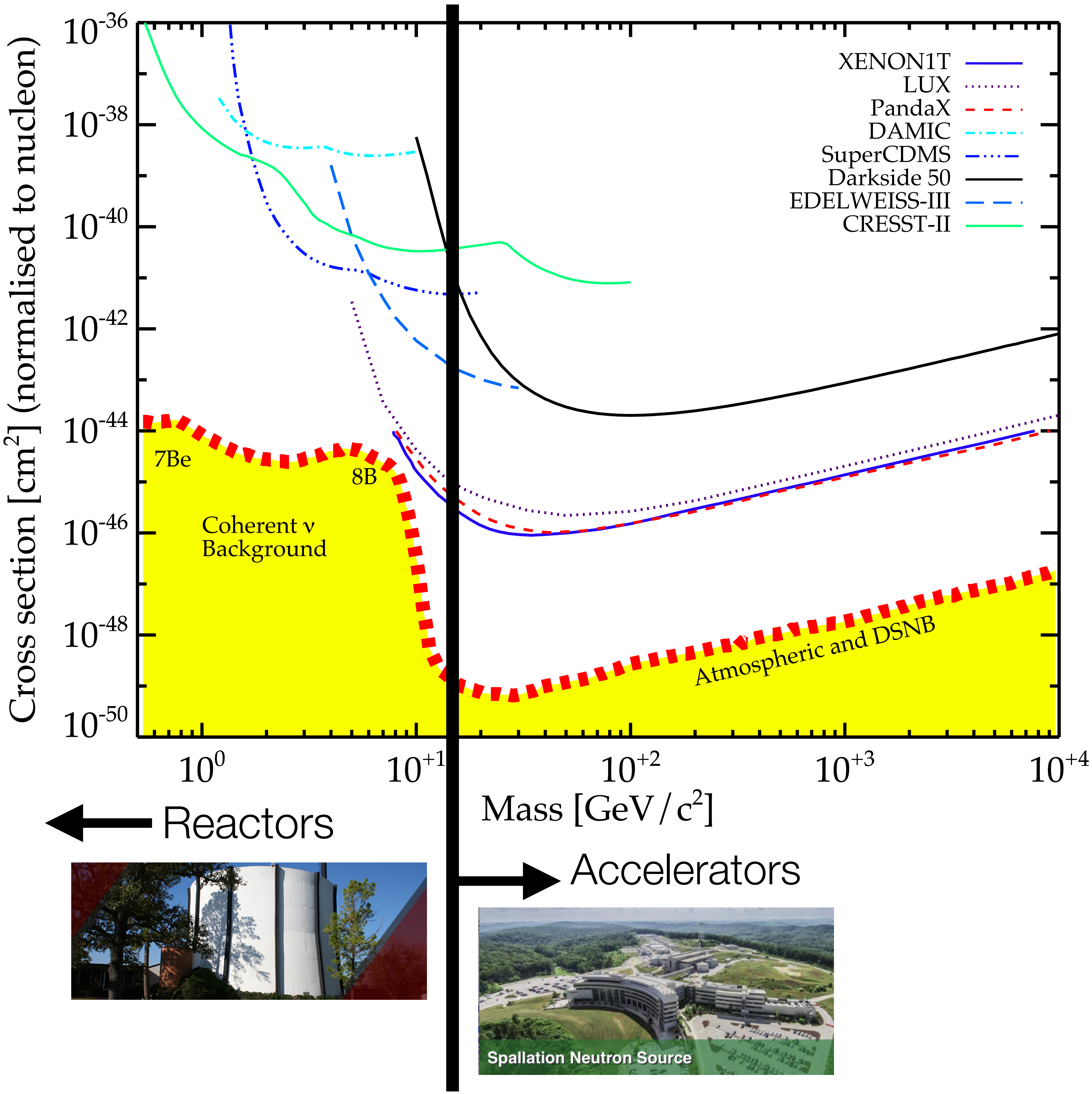


Billard, Figueroa-Feliciano, LS 2014

Astrophysical neutrinos

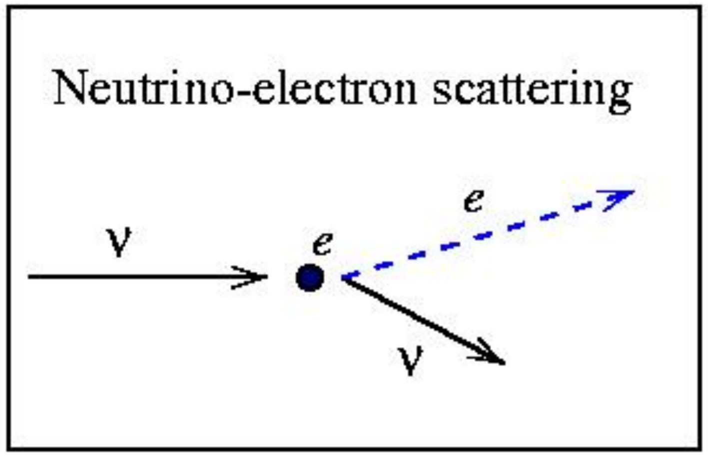


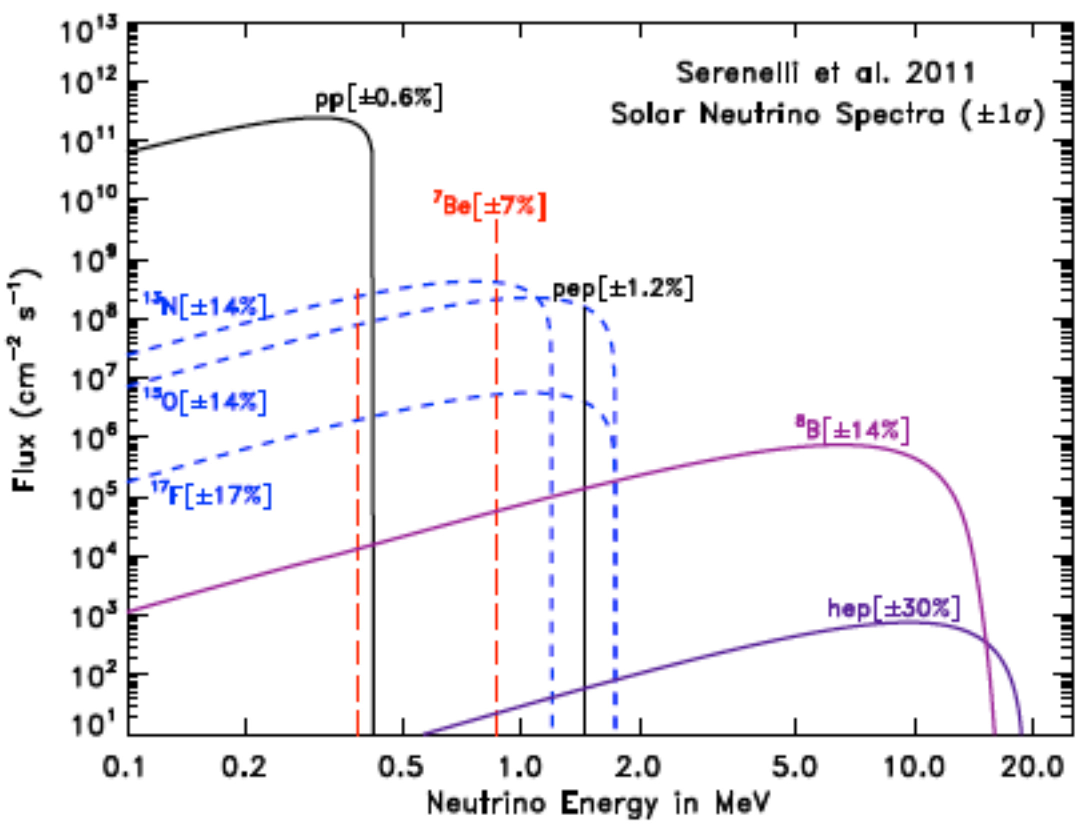
Billard, Figueroa-Feliciano, LS 2014

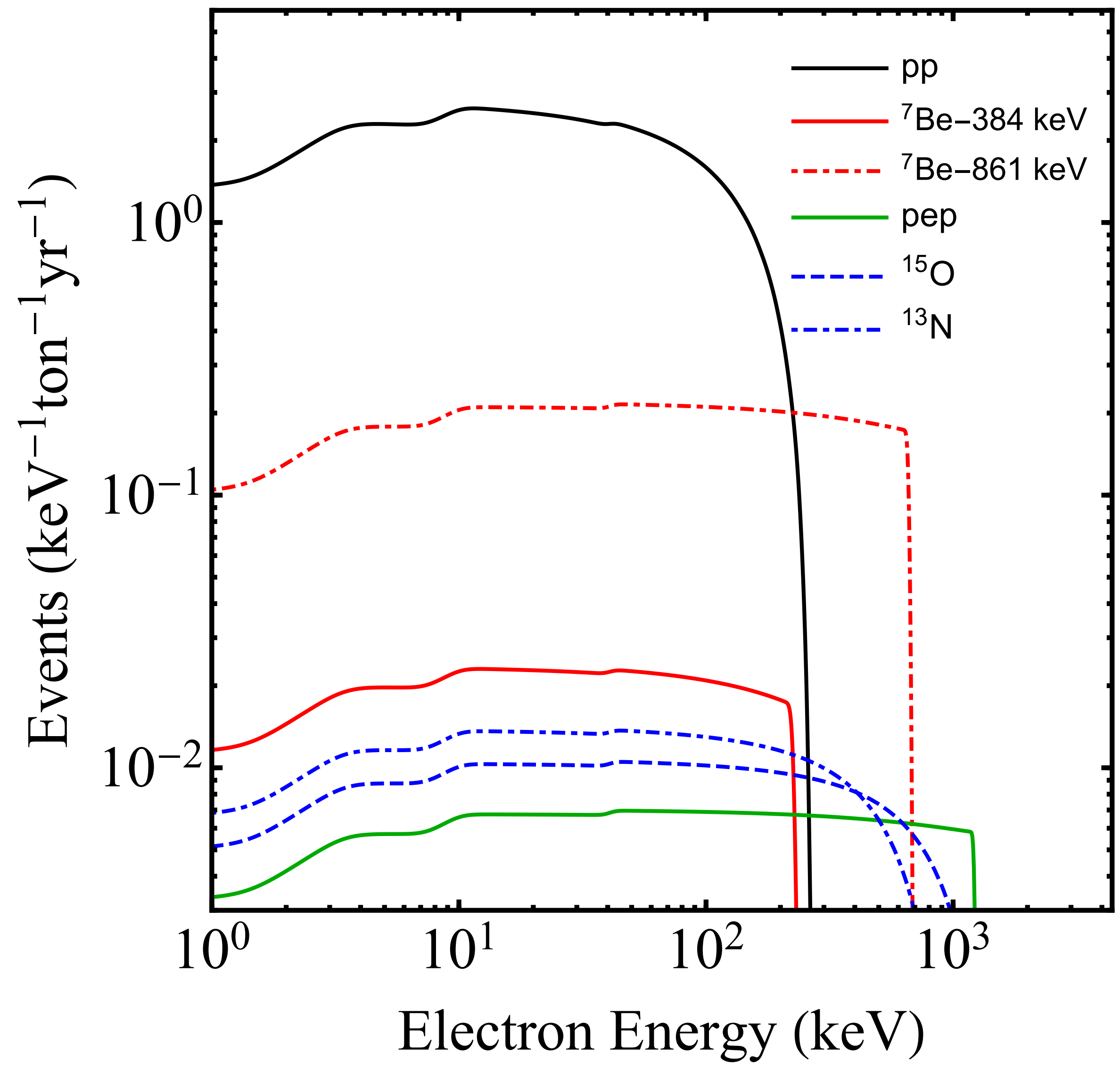


Cross section [cm^2] (normalised to nucleon)
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{0}
10^{+1}
10^{+2}
10^{+3}
10^{+4}
Mass [GeV/c^2]
XENON1T
LUX
PandaX
DAMIC
SuperCDMS
Darkside 50
EDELWEISS-III
CRESST-II
7Be
8B
Coherent ν
Background
Atmospheric and DSNB
Reactors
Accelerators
Spallation Neutron Source

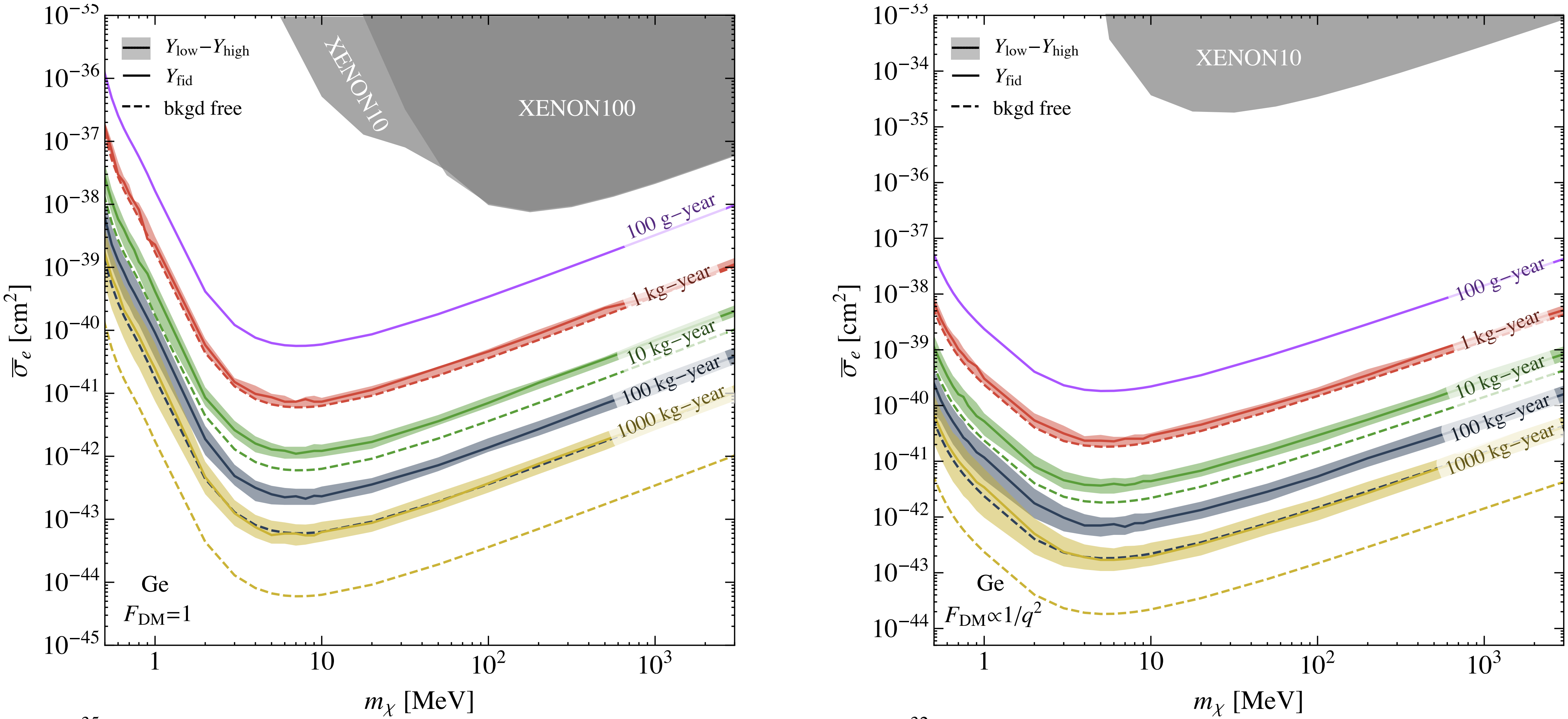
Elastic Solar neutrino-electron scattering







Neutrino floor for light DM



- At low mass, neutrino floor from solar neutrinos
- Particularly important for detectors that lack electron/nuclear discrimination

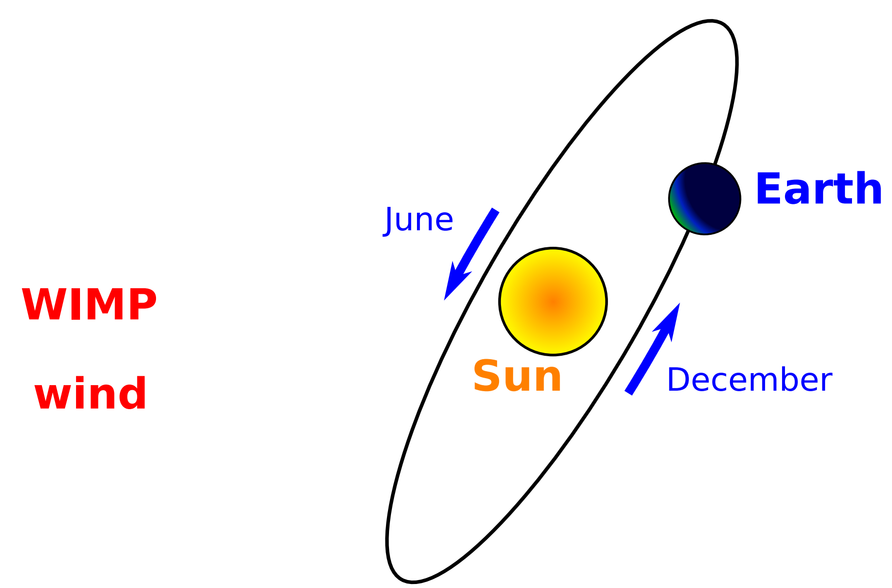
Essig et al. 2018; Wyenberg and Shoemaker 2018

Annual modulation and Directionality

- WIMP signal annually modulates due to motion through the 'WIMP wind'

- Solar neutrino signal annually modulations because of the small eccentricity of the Earth's orbit

- Both WIMP and Solar neutrino rate have ~few % annual variation, but peak at times separate by ~5 months

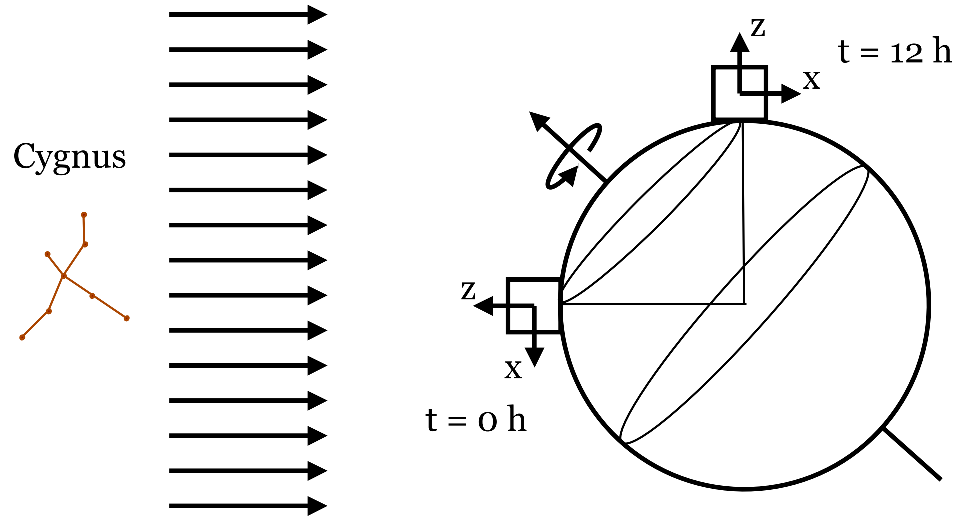


J. Davis 2014

Annual modulation and Directionality

- WIMP signal predicted to point towards the direction of Cygnus constellation
- Daily amplitude modulation depending on location of detector on Earth
- Solar neutrino signal points back to the Sun (ignore size of the Sun)

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



Grothaus Fairbairn, Monroe PRD 2014

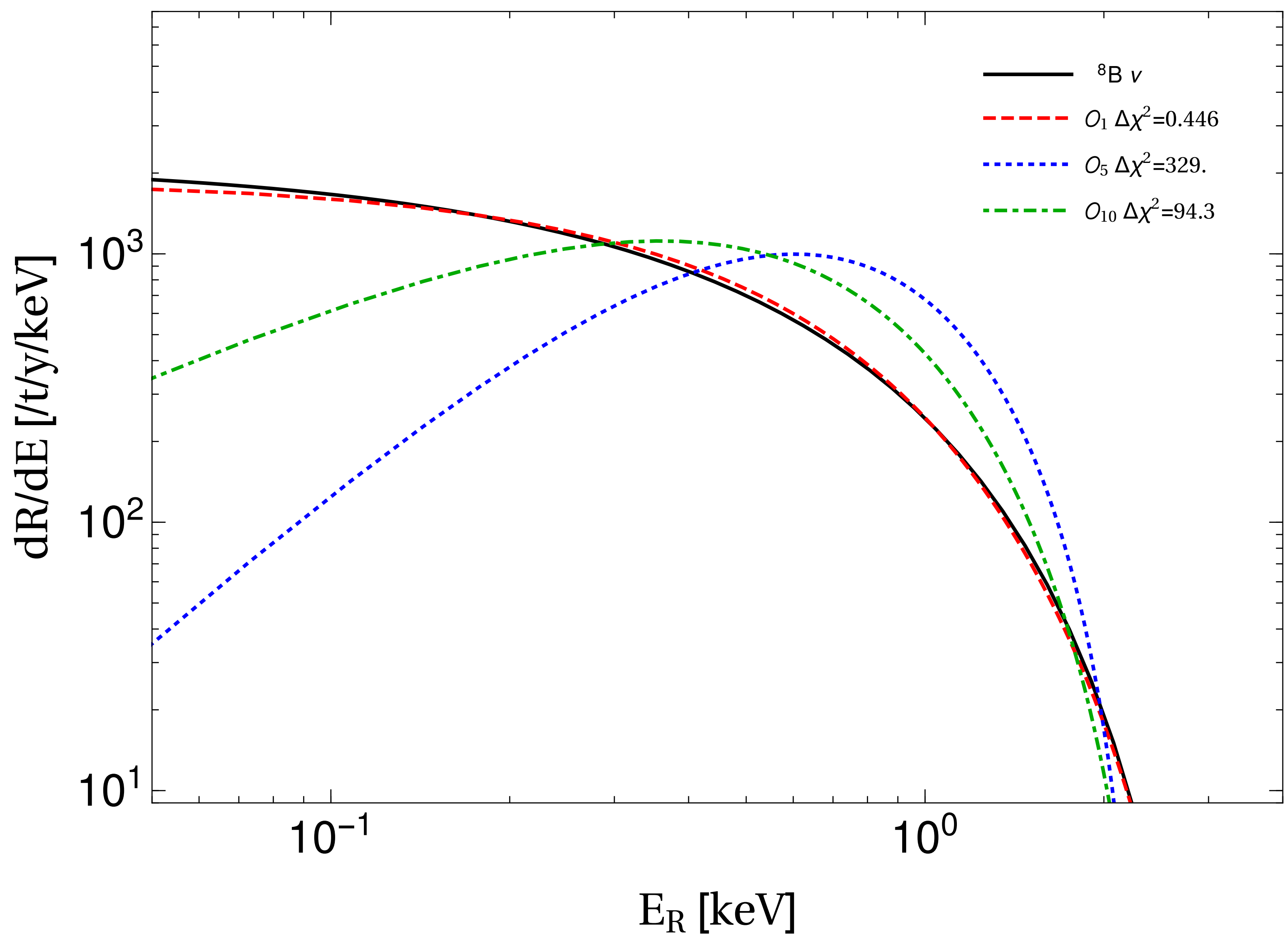
O'Hare, Billard, Green, Figueroa-Feliciano, Strigari PRD 2015

Beyond standard formalism: non-relativistic EFT

- Heavy mediators

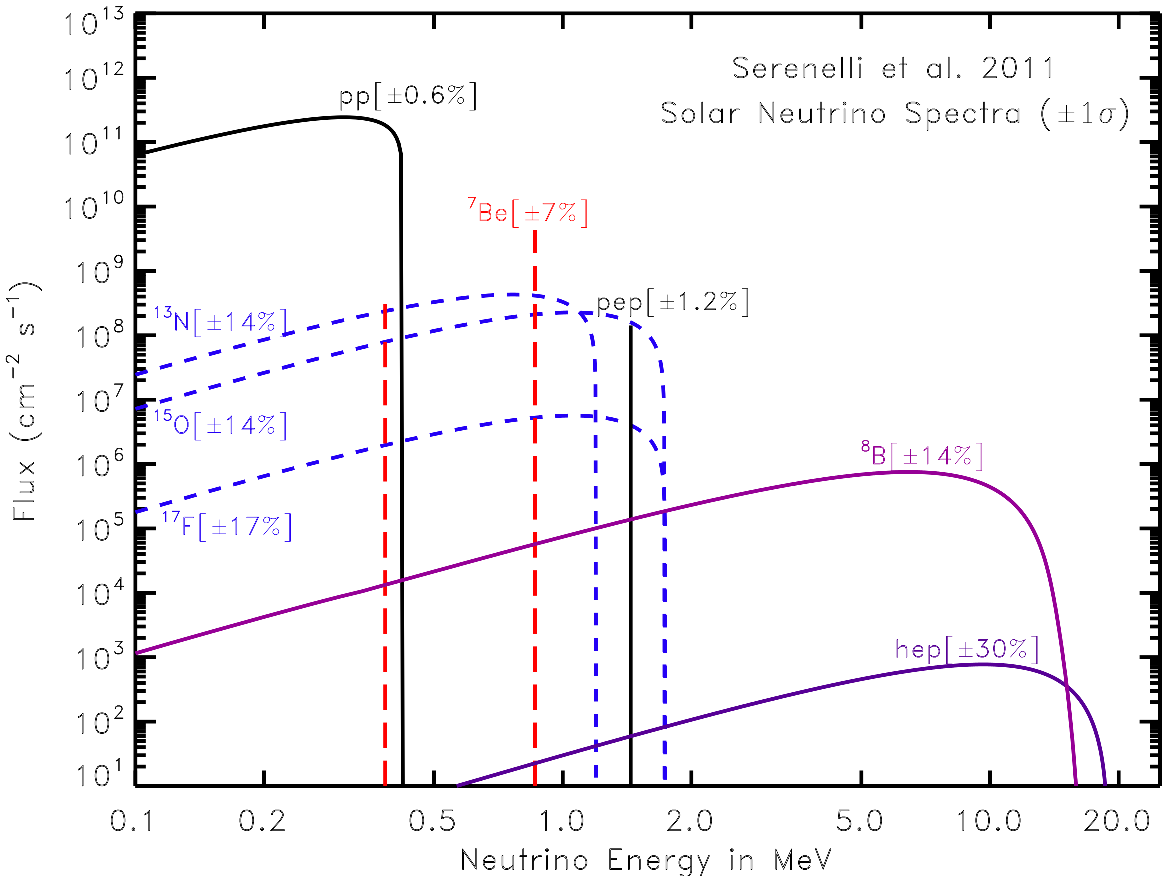
Fan, Reece, Wang, 2010; Fitzpatrick et al. 2012; Anand et al. 2014

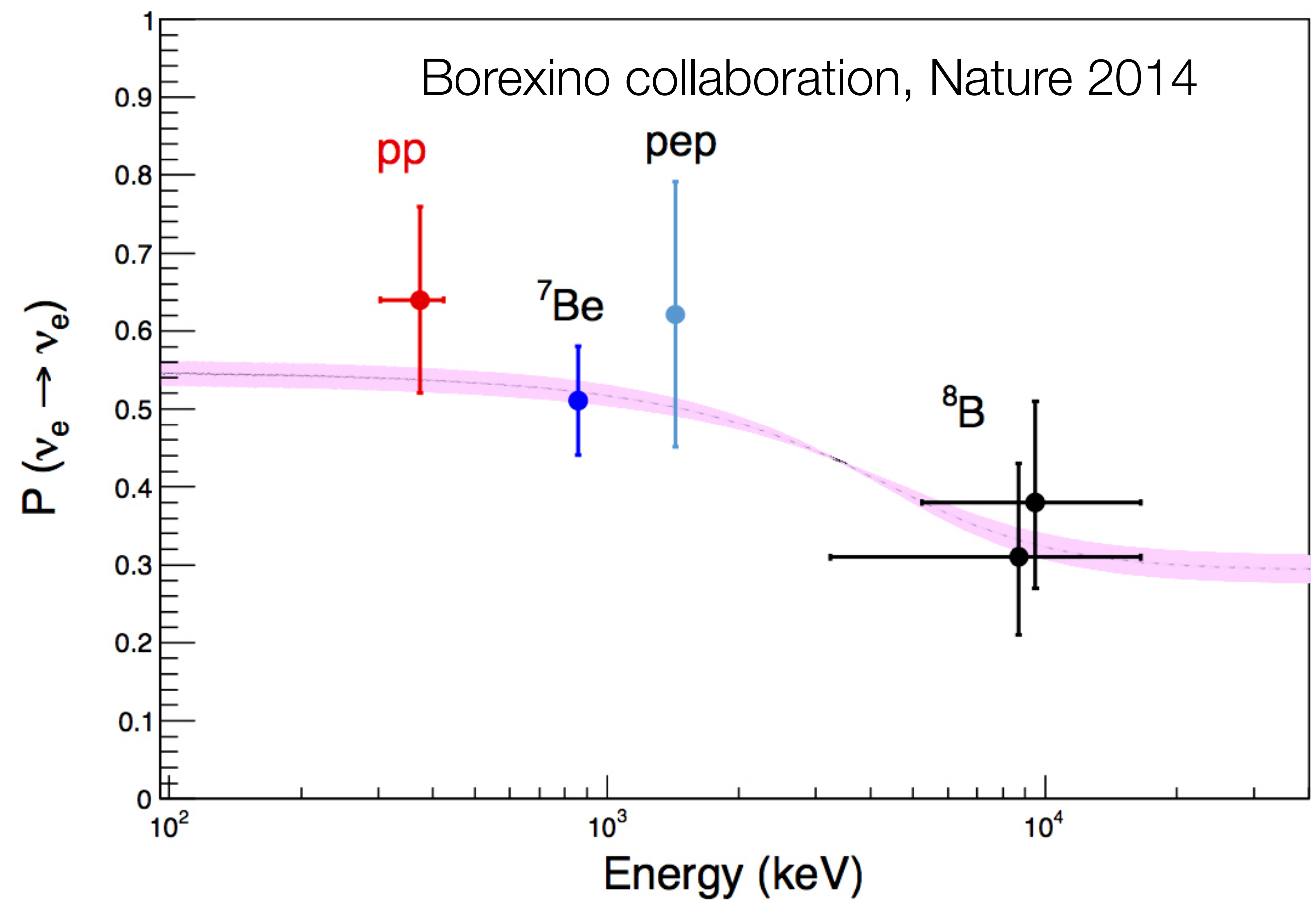
$\mathcal{O}_1$	$1_\chi 1_N$	SI
$\mathcal{O}_2$	$(v^\perp)^2$	
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$	SD
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N}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



Dent, Dutta, Newstead, Strigari, PRD 2016

Solar neutrinos: Status





Solar Neutrinos:
Status and Prospects

W.C. Haxton,[1] R.G. Hamish Robertson,[2] and Aldo M. Serenelli[3]

The program of solar neutrino studies envisioned by Davis and Bahcall has been only partially completed. Borexino has extended precision measurements to low-energy solar neutrinos, determining the flux of ^{7}Be neutrinos to 5%, and thereby confirming the expected increase in the ν_e survival probability for neutrino energies in the vacuum-dominated region. First results on the pep neutrino

High-Z Low-Z

ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p \to {}^2H+e^+ + \nu$	0.42	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^- + p \to {}^2H+\nu$	1.44	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^8/cm^2s$
${}^7Be+e^- \to {}^7Li+\nu$	0.86 (90%)	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^9/cm^2s$
	0.38 (10%)				
${}^8B \to {}^8Be+e^+ + \nu$	~ 15	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$	$10^6/cm^2s$
${}^3He+p \to {}^4He+e^+ + \nu$	18.77	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	—	$10^3/cm^2s$
${}^{13}N \to {}^{13}C+e^+ + \nu$	1.20	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7	$10^8/cm^2s$
${}^{15}O \to {}^{15}N+e^+ + \nu$	1.73	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2	$10^8/cm^2s$
${}^{17}F \to {}^{17}0+e^+ + \nu$	1.74	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	$\leq 59.$	$10^6/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		

Haxton et al. 2013

- 3D rotational hydrodynamical simulations suggest lower metallicity in Solar core (Asplund et al. 2009)
- Low metallicity in conflict with heliosiesmology data
- SNO Neutral Current measurement right in between predictions of low and high metallicity SSMs

High-Z   Low-Z

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%)				
${}^8B\to{}^8Be+e^++\nu$	~ 15	$5.58(1\pm0.14)$	$4.59(1\pm0.14)$	$5.00(1\pm0.03)$	$10^6/cm^2s$
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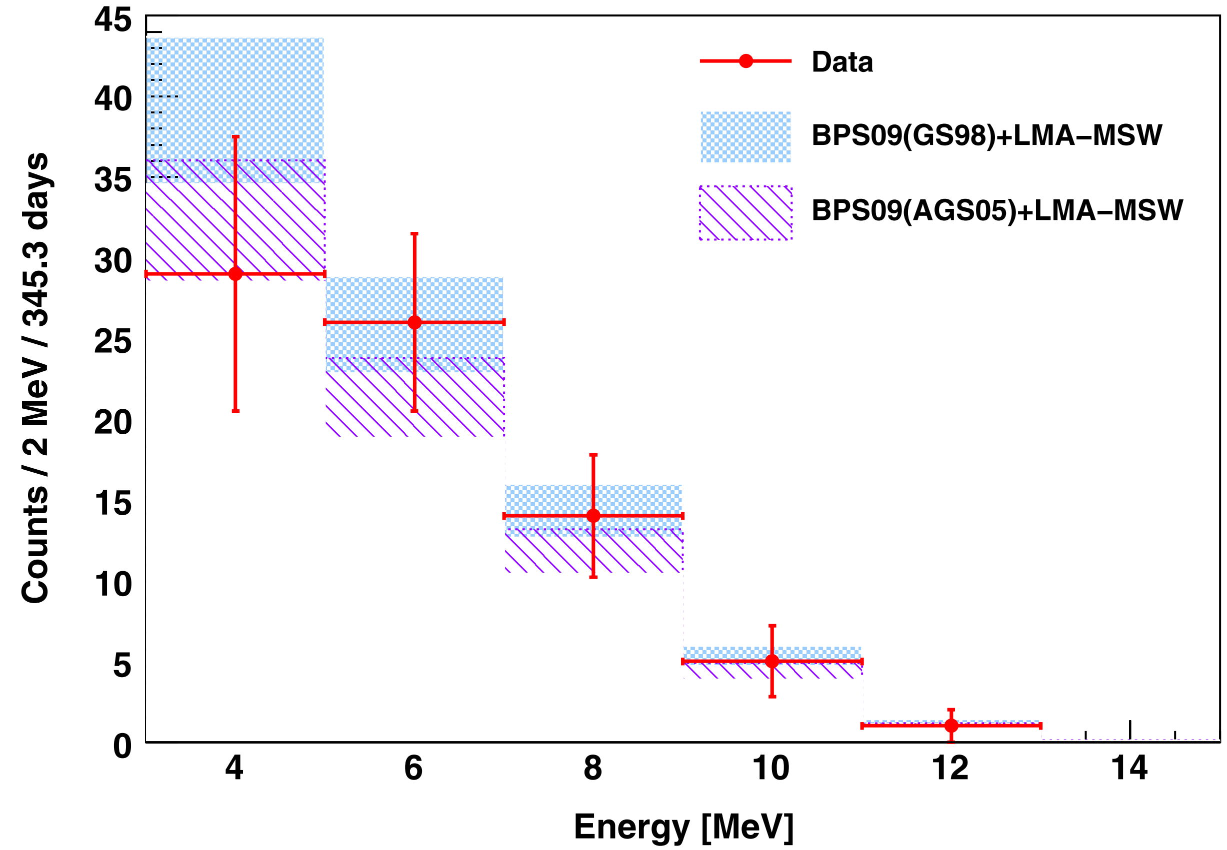
Haxton et al. 2013



Borexino collaboration

- 3D rotational hydrodynamical simulations suggest lower metallicity in Solar core (Asplund et al. 2009)
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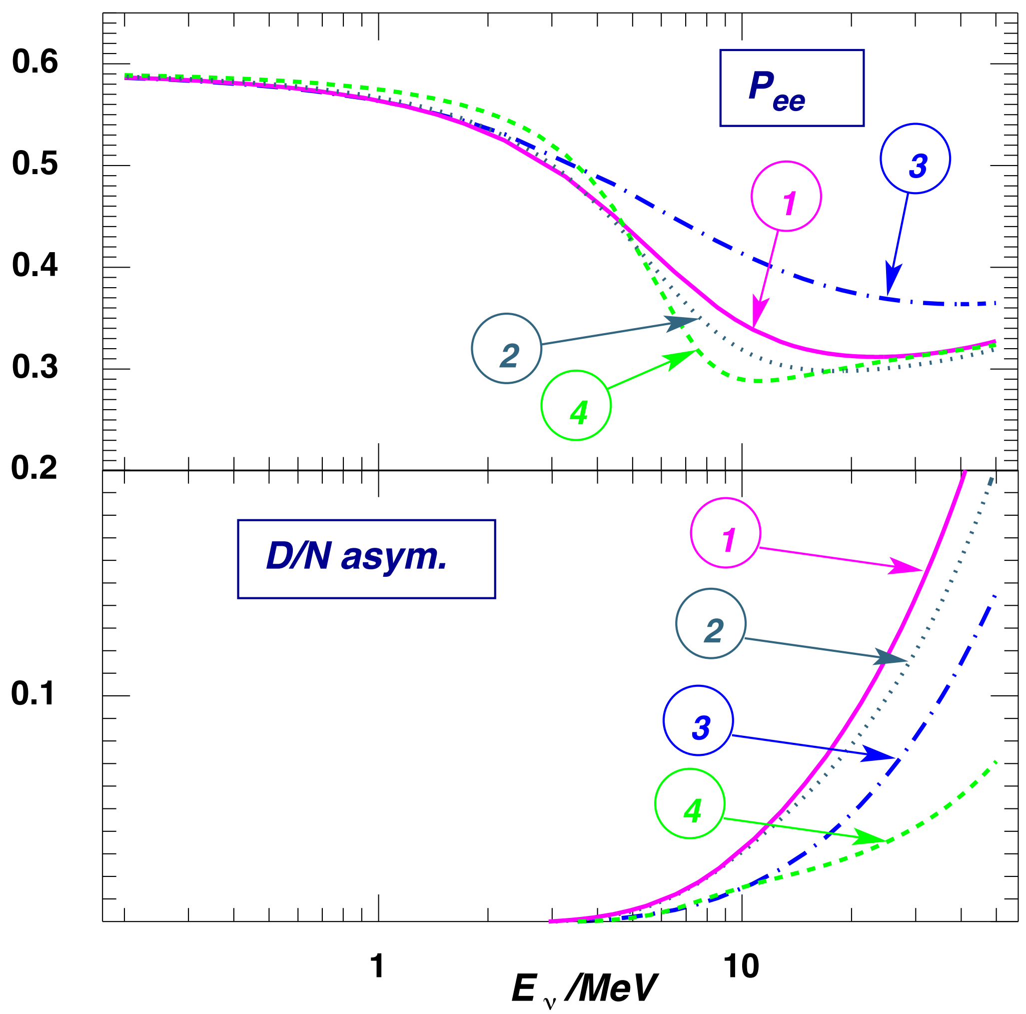
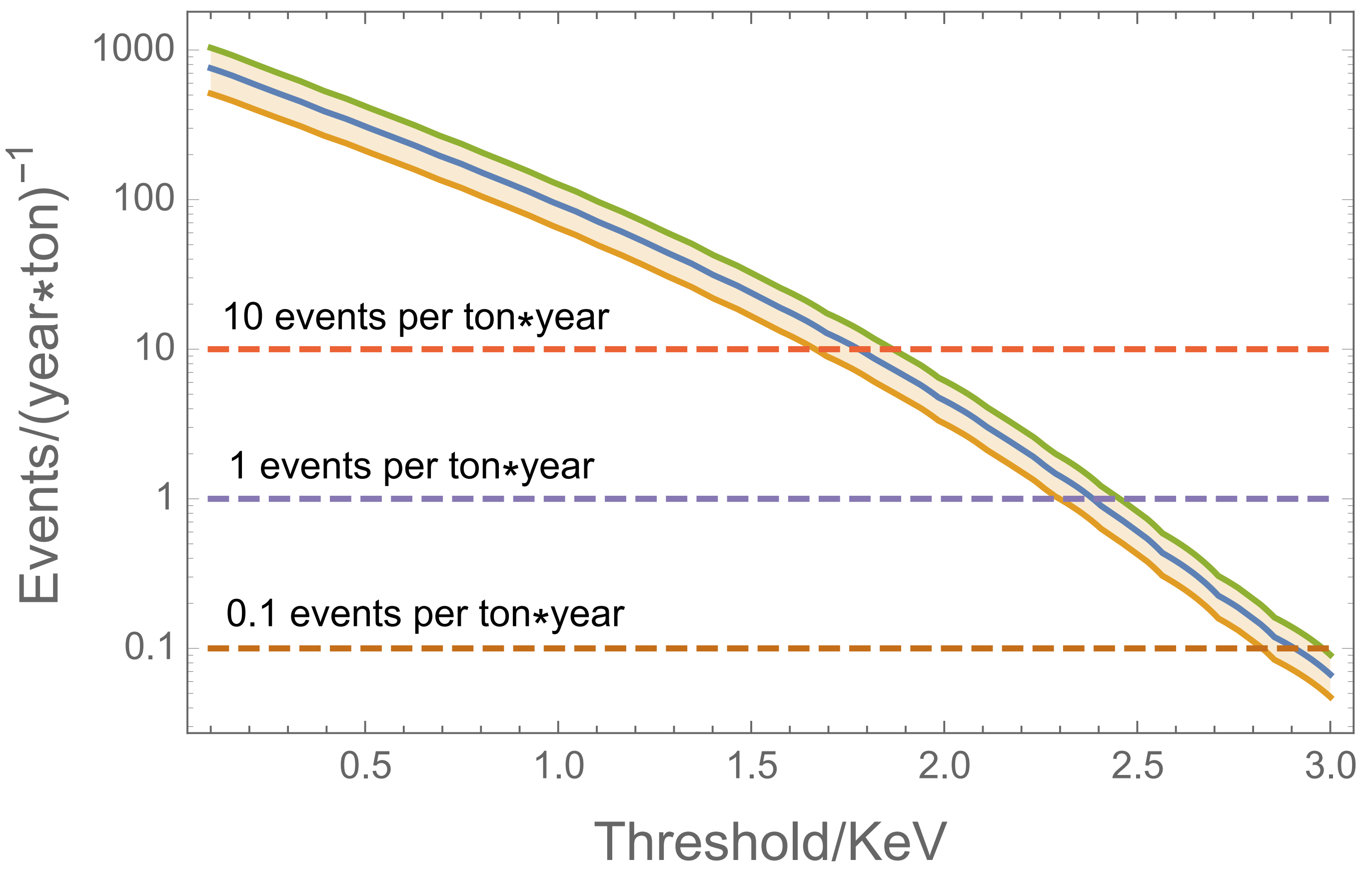
- SNO Neutral Current measurement right in between predictions of low and high metallicity SSMs

- Borexino, SNO, SK indicate the low energy ES data lower than MSW predicts
- Upturn in MSW survival probability not been measured
- May indicate new physics (e.g. Holanda & Smirnov 2011)

Non-standard interactions + MSW + DM detectors



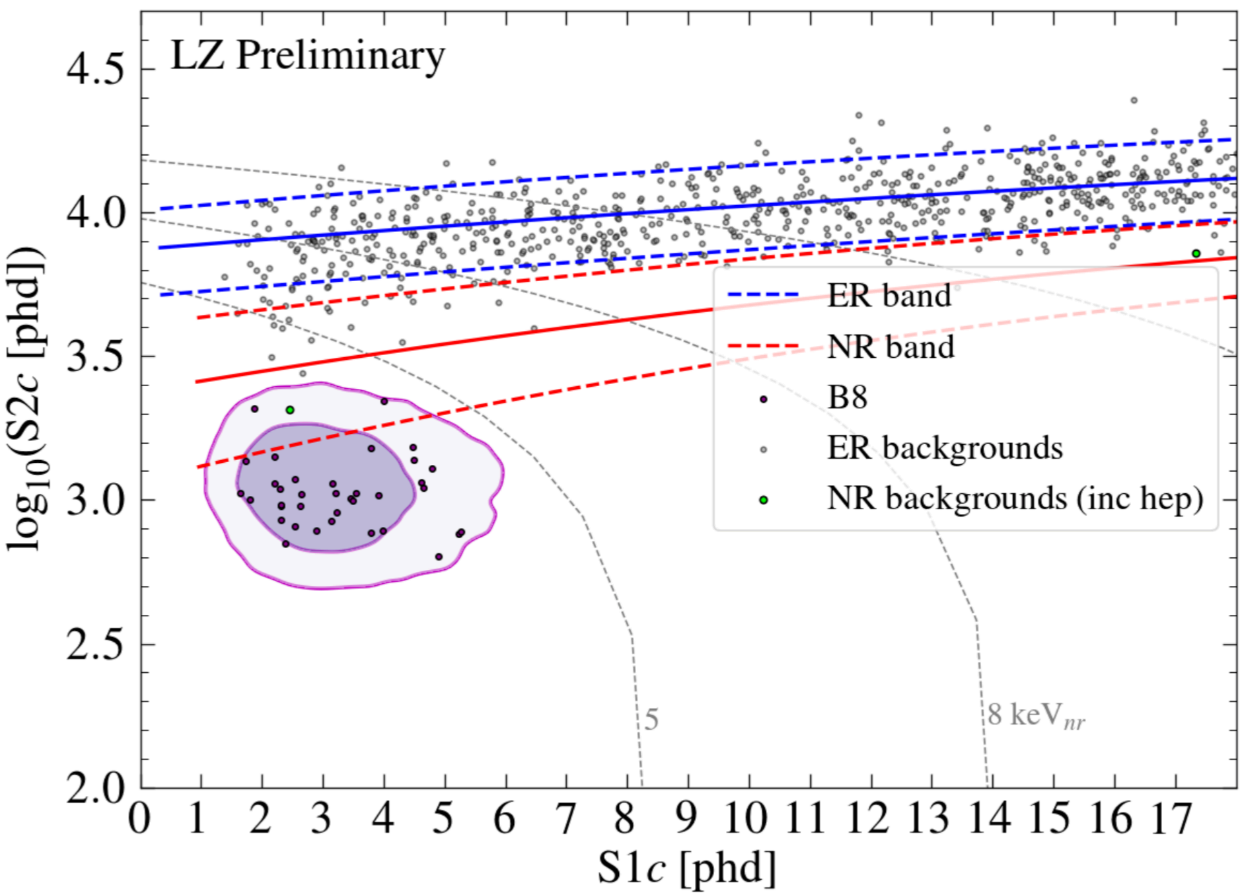
Friedland, Lunardini, Pena-Garay PLB 2004



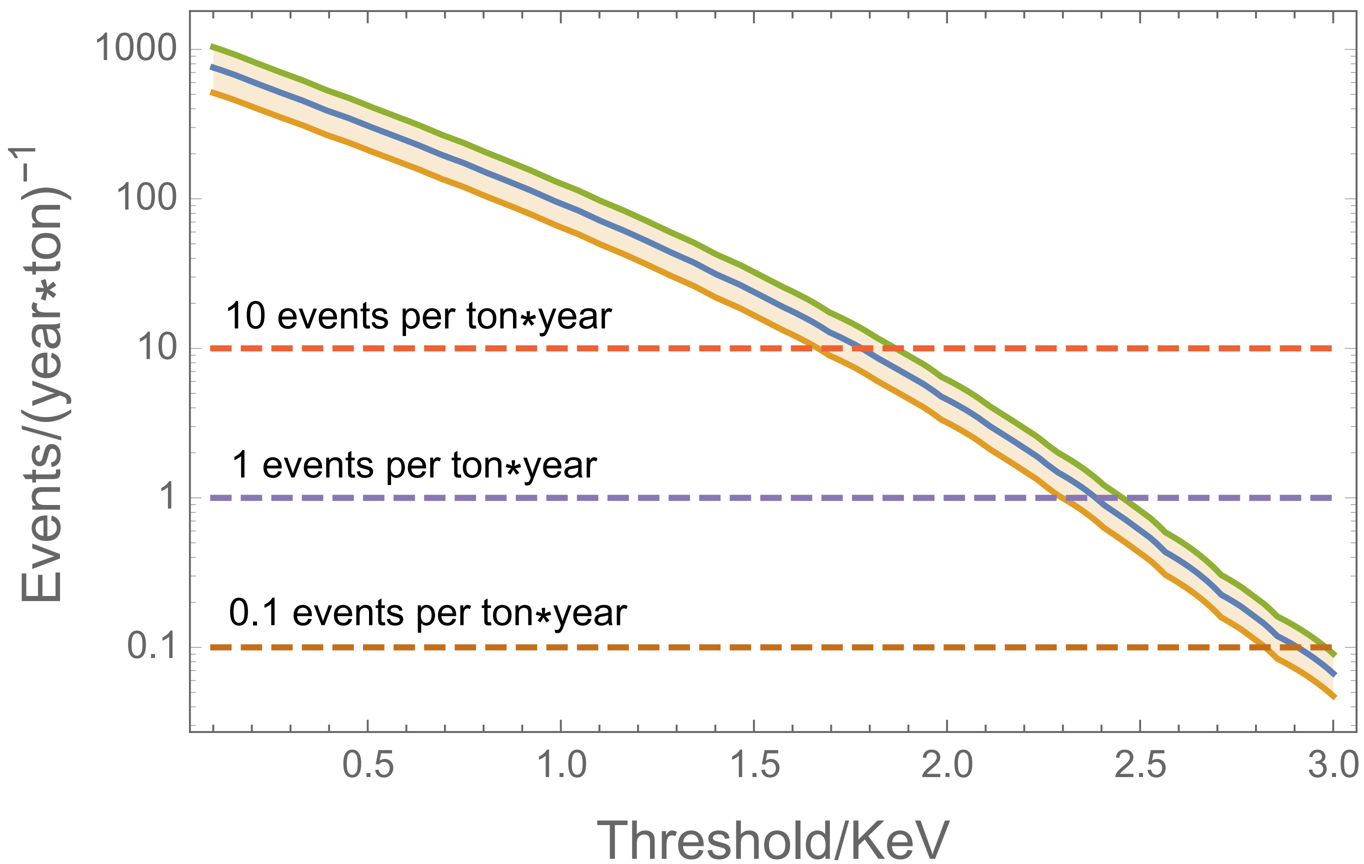
B. Dutta, ***Shu Liao***, L. Strigari, J. Walker, PLB 2017

- NSI may increase or decrease event rate in Xenon
- 1t sensitive to models still consistent with nu oscillations

Non-standard interactions + DM detectors



Carter Hall NDM 2018



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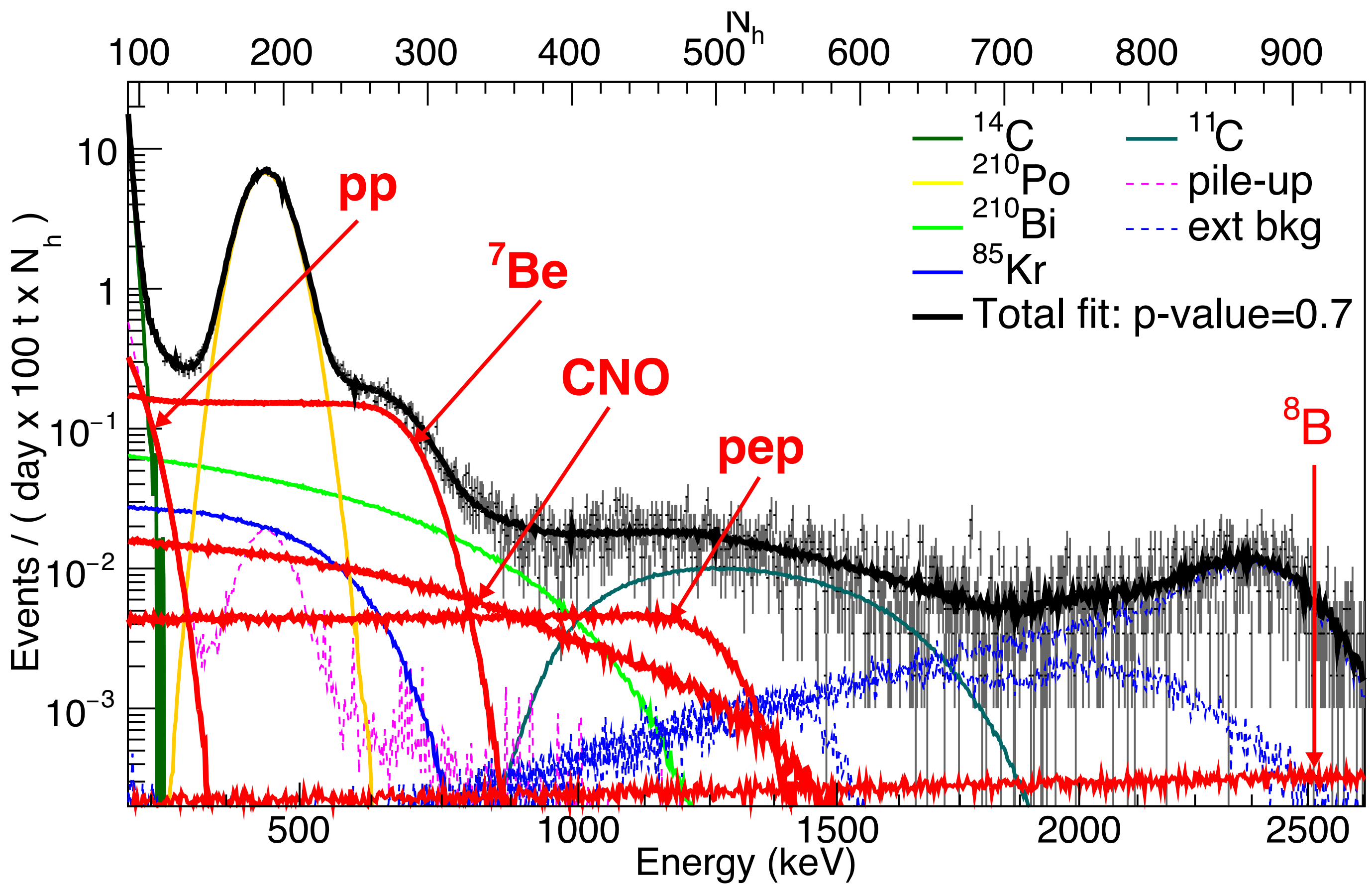
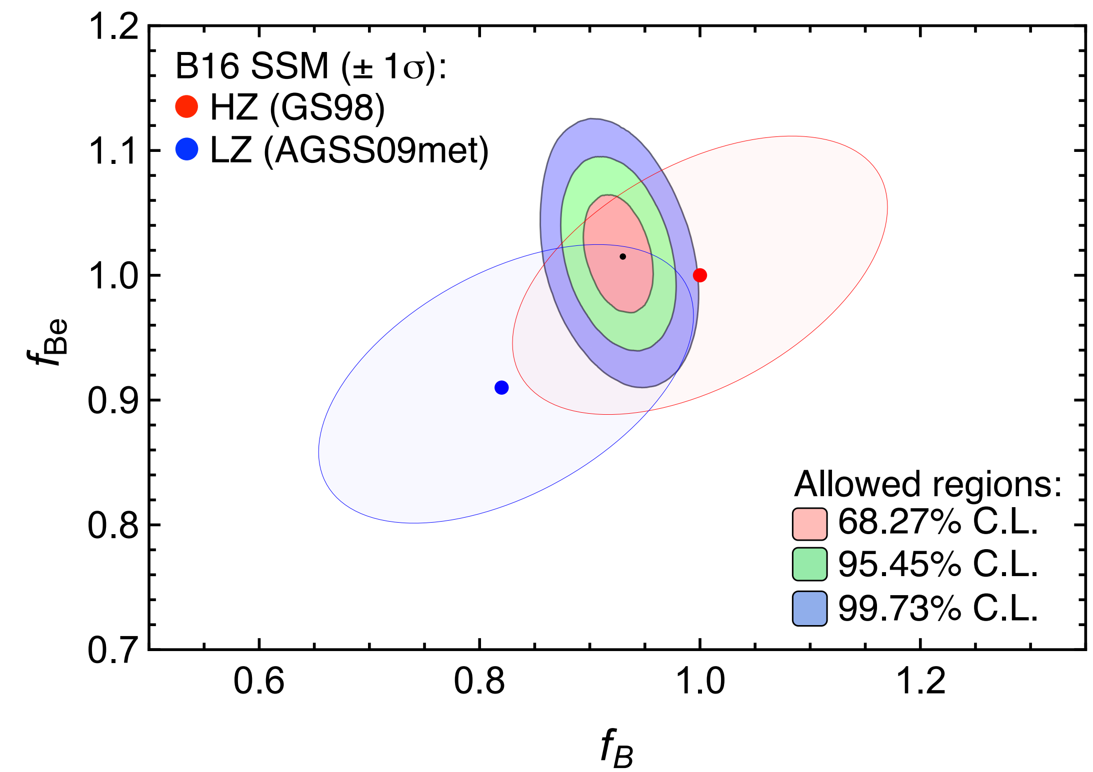
Low energy solar neutrino spectroscopy

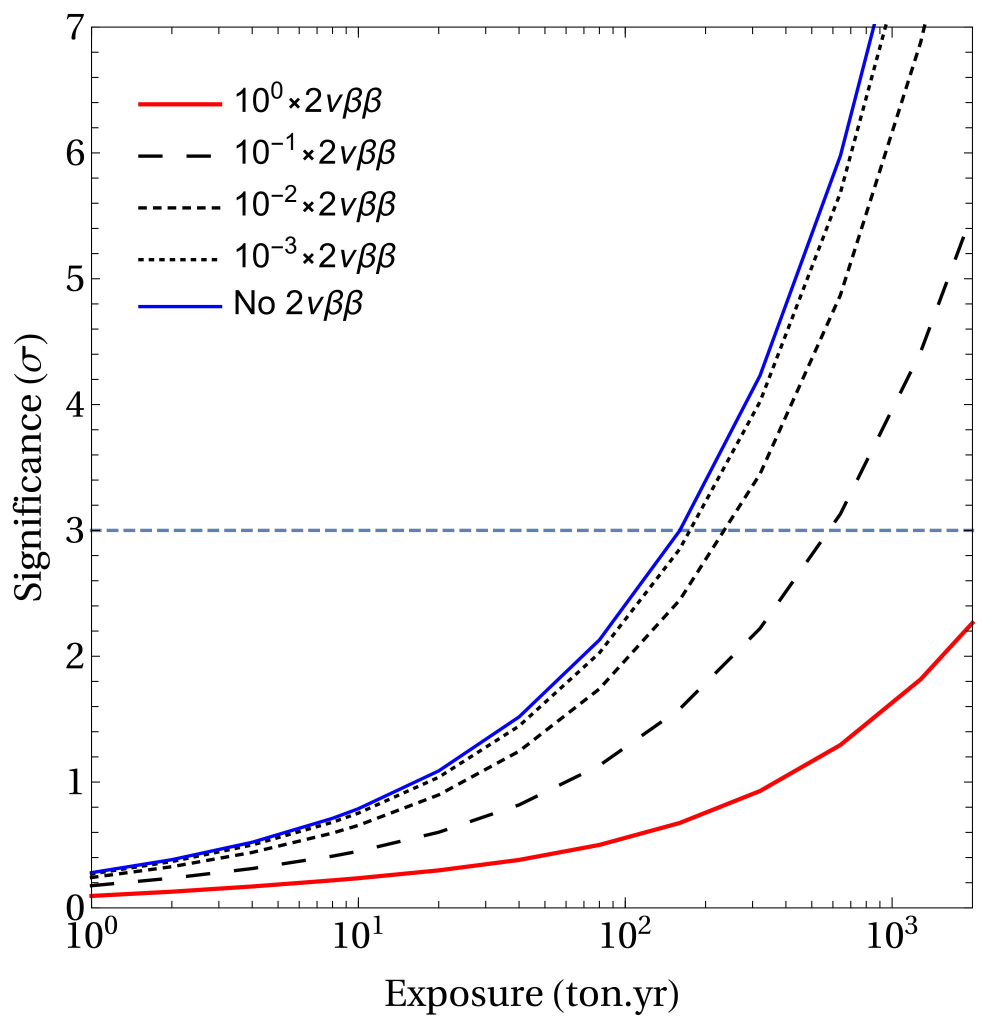


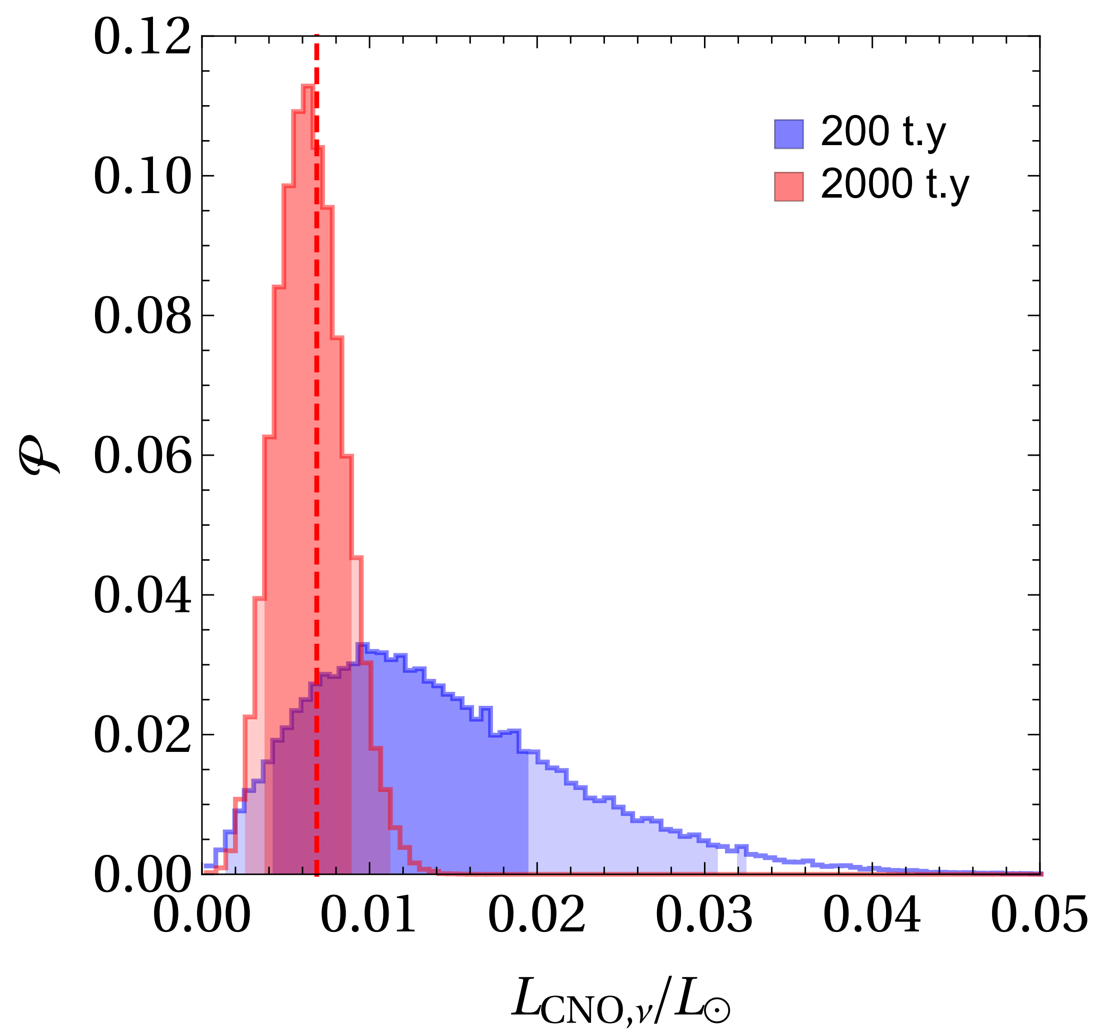


- Multicomponent spectral analysis of low energy solar neutrinos
- 2.7% precision on 7Be
- Strongest upper bound on CNO neutrinos

Borexino collaboration 2017

CNO Solar neutrinos and neutrino luminosity



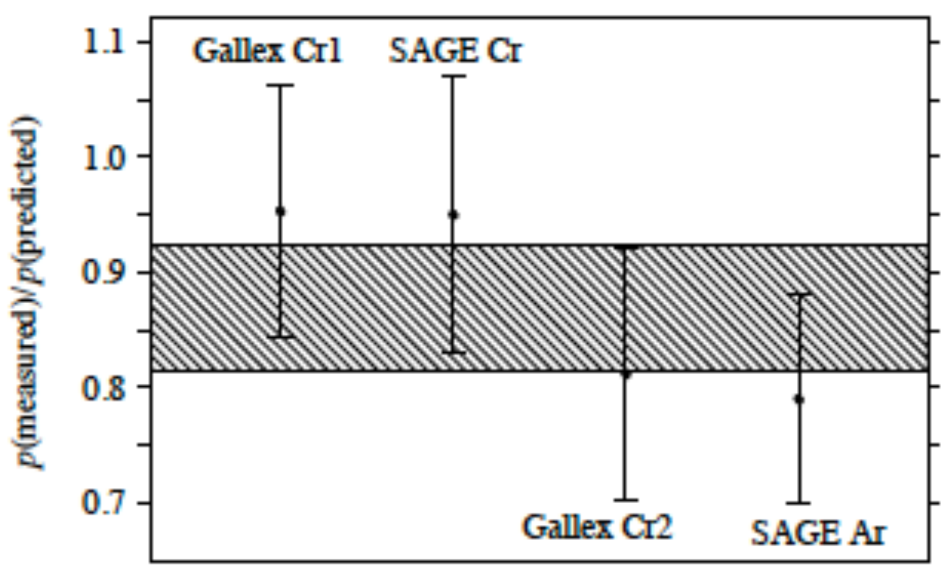


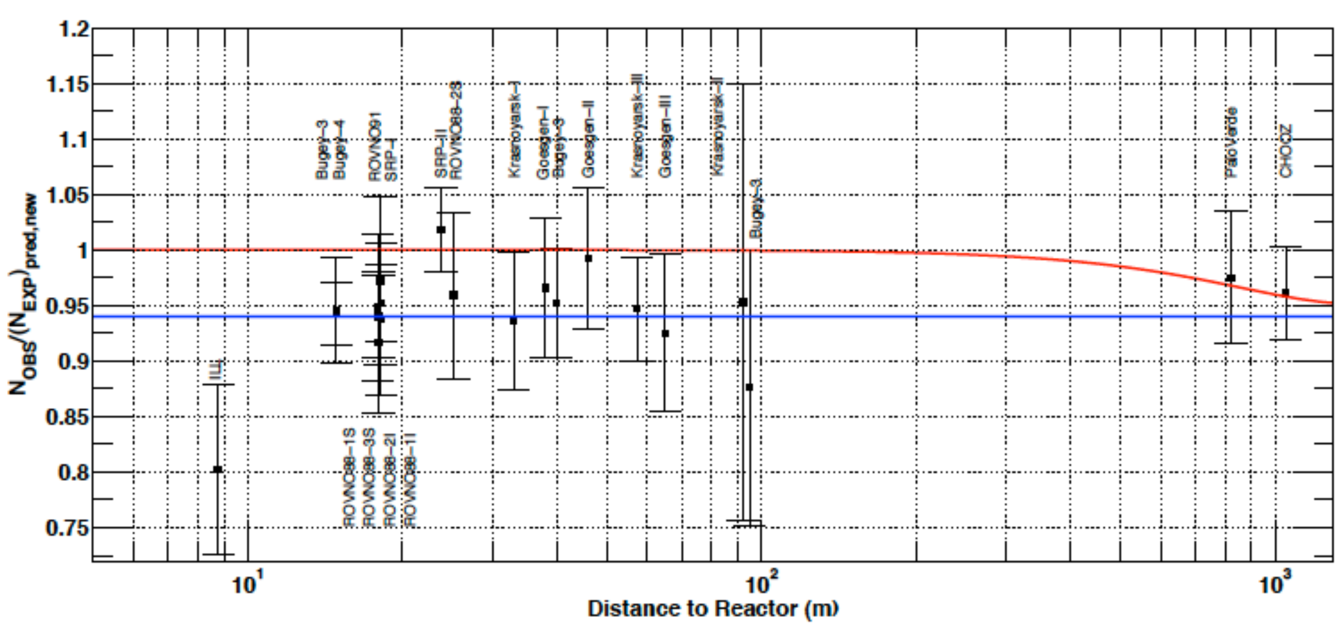
- Experimental efforts to measure CNO fluxes (Bonventre & Orebi Gann 2018; Cerdeno et al. 2018)
- CNO measurement via electron scattering in G3 Xe experiments depends on 136Xe depletion

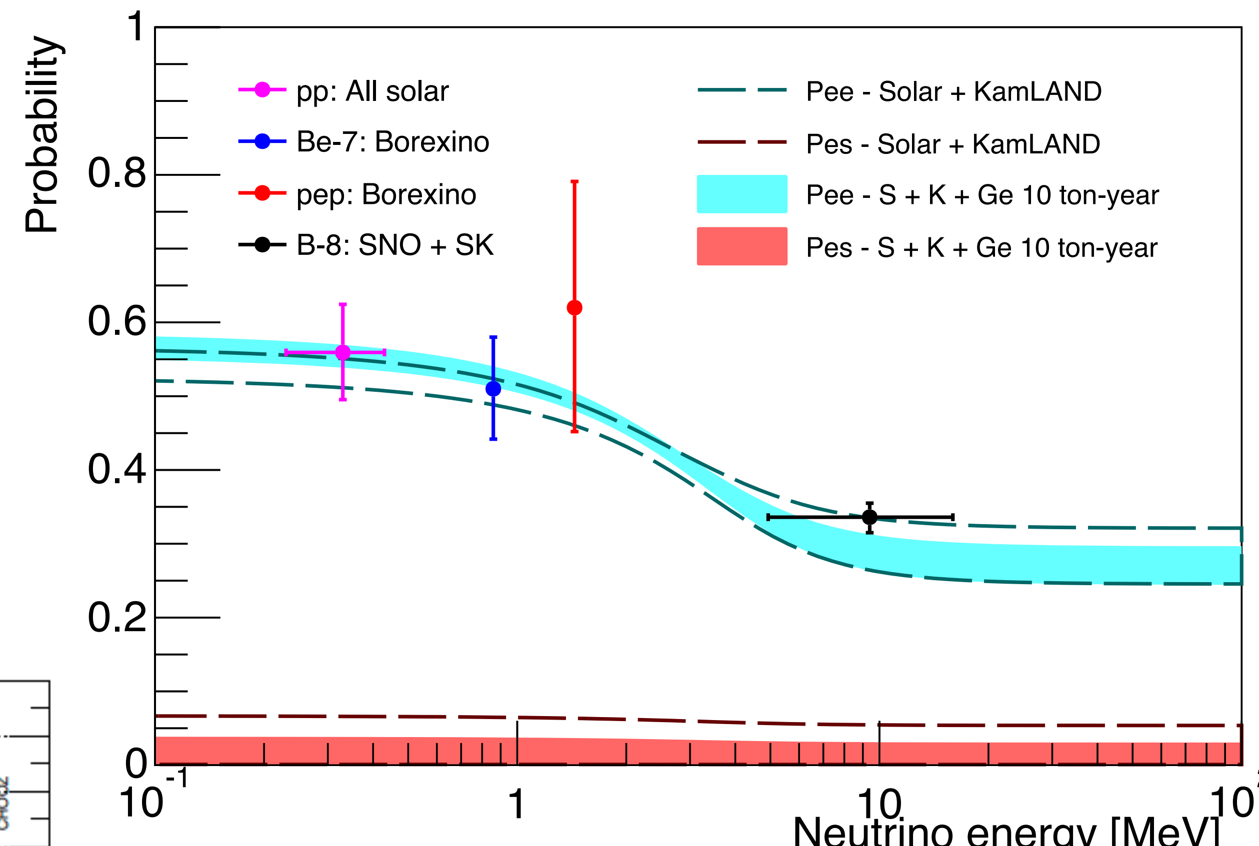
- Linear combination of neutrino fluxes equals the photon luminosity
- Deviation between *neutrino luminosity* and photon luminosity could hint at alternative sources of energy generation
- Neutrino luminosity constraints improved by a factor of seven compared to global analysis (Bergstrom et al. 2016; Newstead, LS, Lang, 2018)

eV-scale sterile neutrinos

- Combined with ‘reactor anomaly’, gallium results may hint at new physics, i.e. ~ eV sterile neutrino (Giunti & Laveder 2010; Mention 2011)

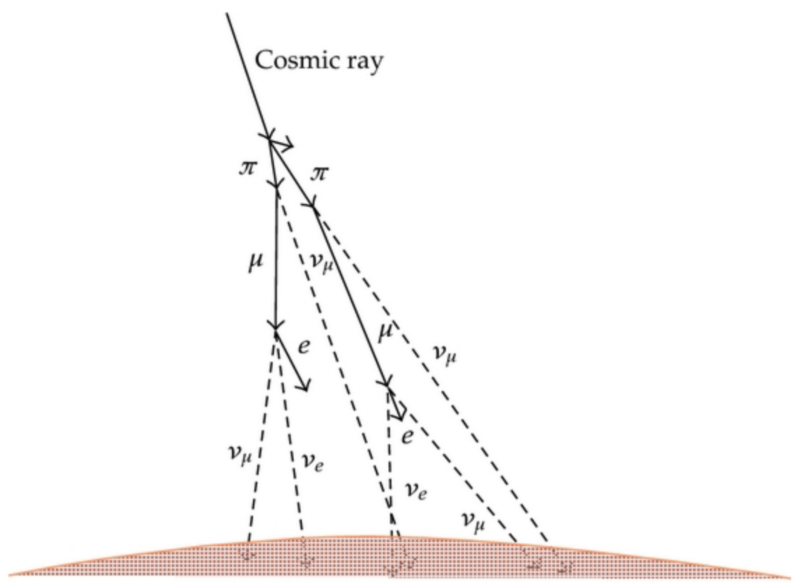


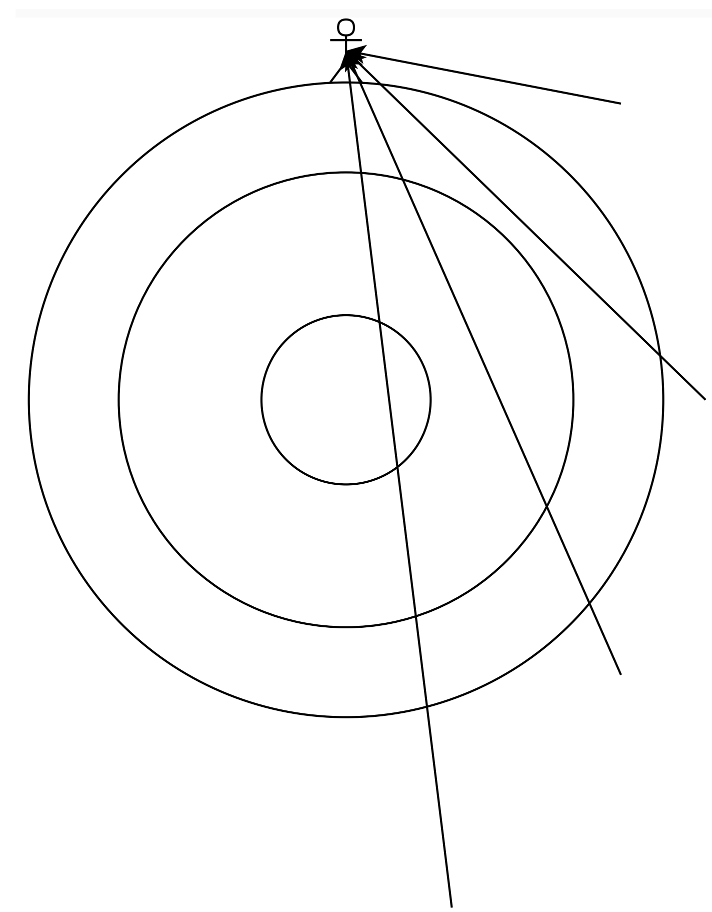




G3 detector can provide a test of the reactor/galium anomaly (Billard, LS, Figueroa-Feliciano, PRD 2014, 1409.0050)

New physics with atmospheric neutrinos





- G3 Xe detectors sensitive to NSI through atmospheric neutrinos
- Dependence on CP phases due to matter-induced oscillations

Talk by Shu Liao

Recap: Neutrinos in dark matter experiments

Astrophysics

- First measurement of the 8B neutral current energy spectrum
- First direct measurement of the survival probably for low energy solar neutrinos
- Direct measurement of the CNO flux
- PP flux measurement to ~ few percent will provide most stringent measurement of the ``neutrino luminosity” of the Sun

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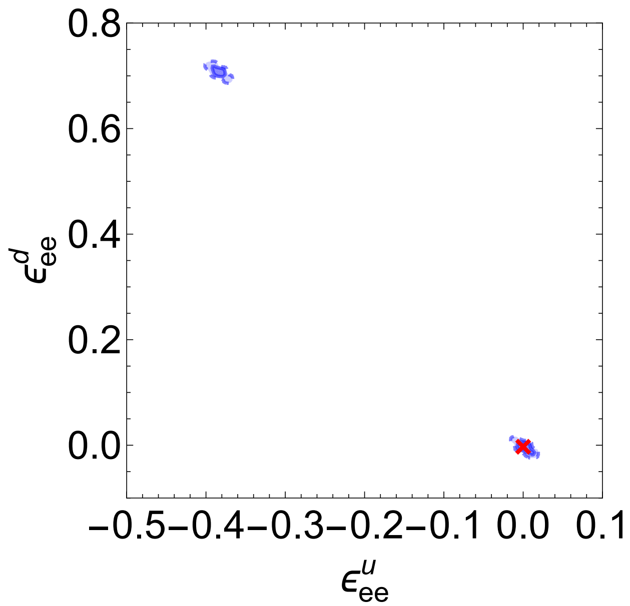
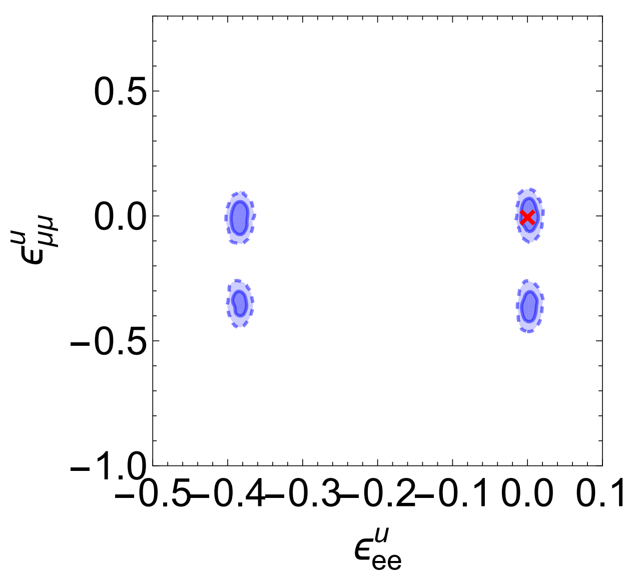
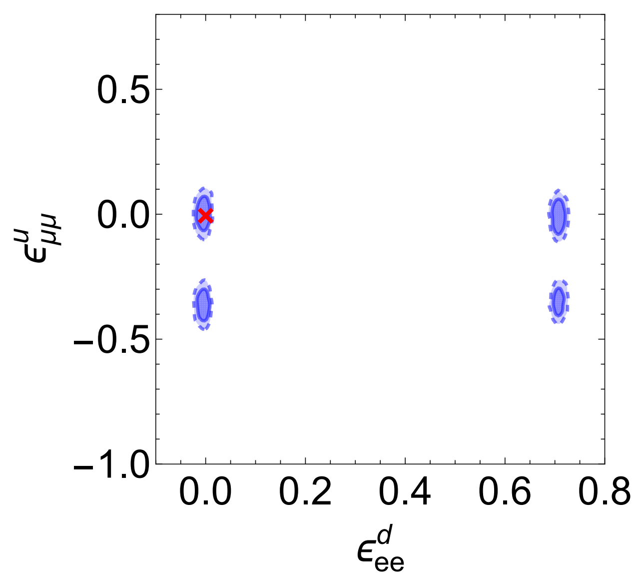
Particle physics

- NSI affects both neutrino-coherent scattering and neutrino-electron elastic scattering channels
- Independent probe of eV-scale sterile neutrinos

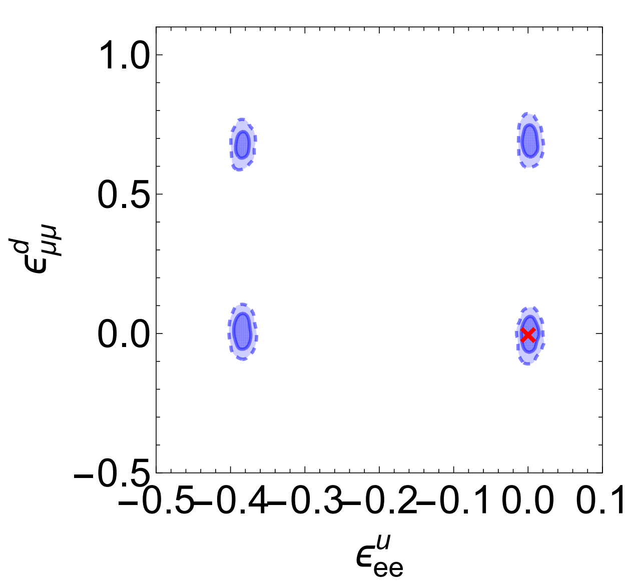


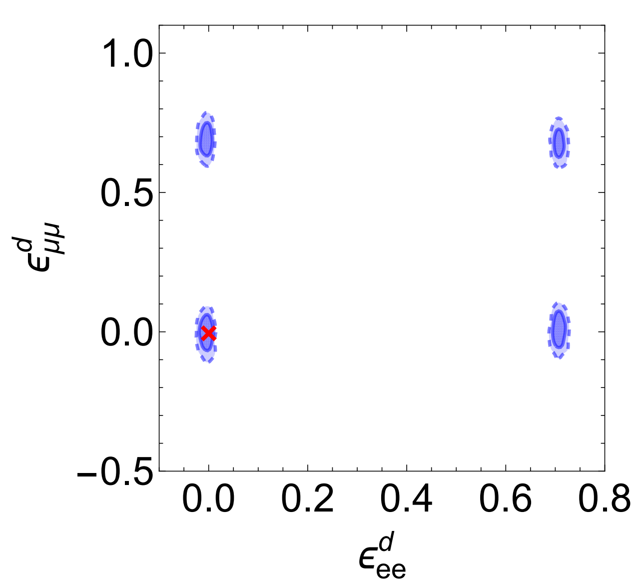
Reactor, accelerator, solar complementarity

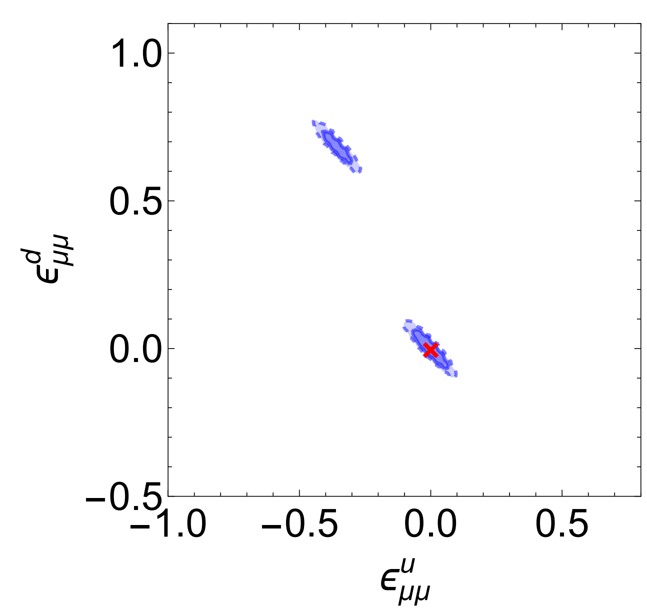




Solar neutrinos add sensitivity to NSI from neutrino propagation

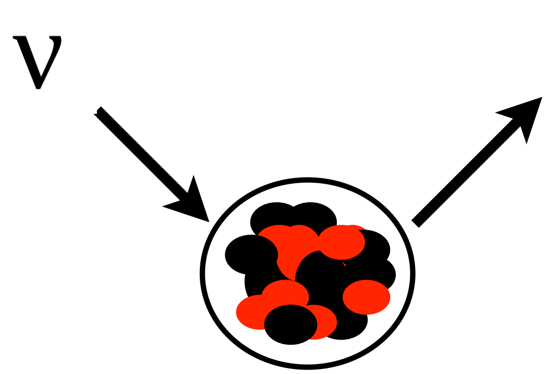


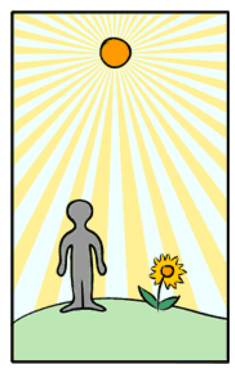




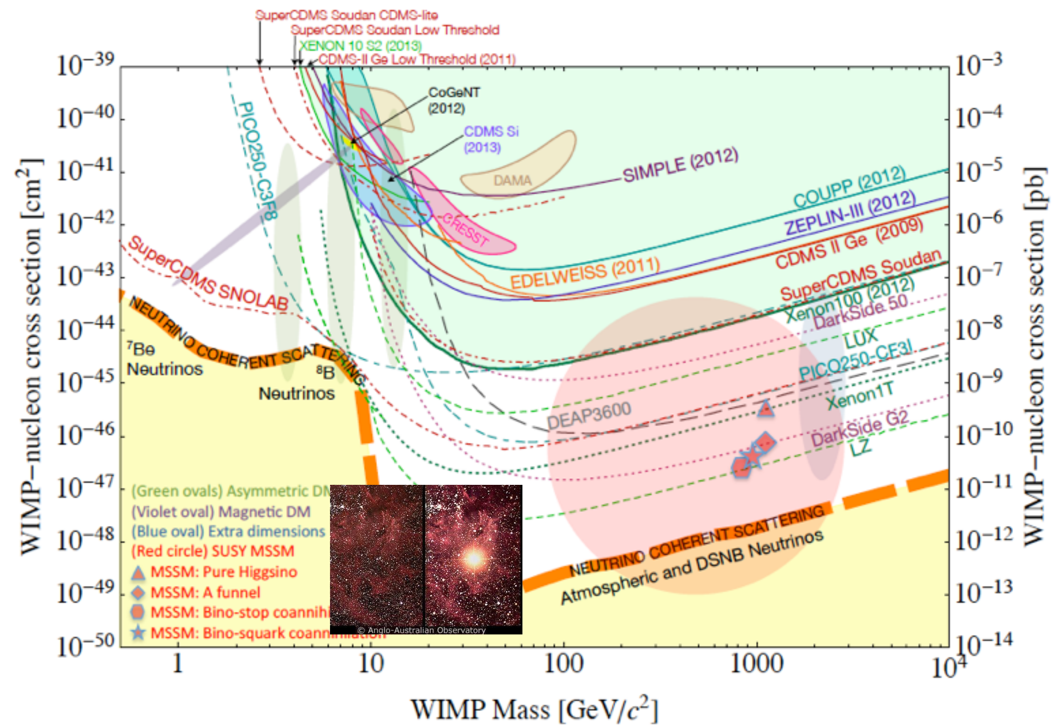
Dent, Dutta, Liao, Newstead, LS, Walker PRD 2018

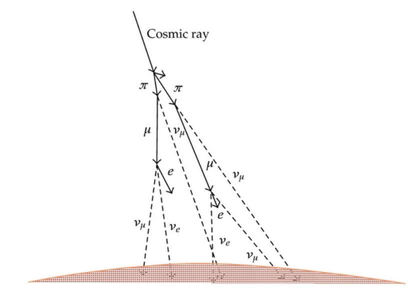
New directions in dark matter and neutrino physics





Astrophysical sources





Reactors

Accelerators