Low energy solar neutrinos

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Low energy neutrino electron scattering
U Mass, Amhearst
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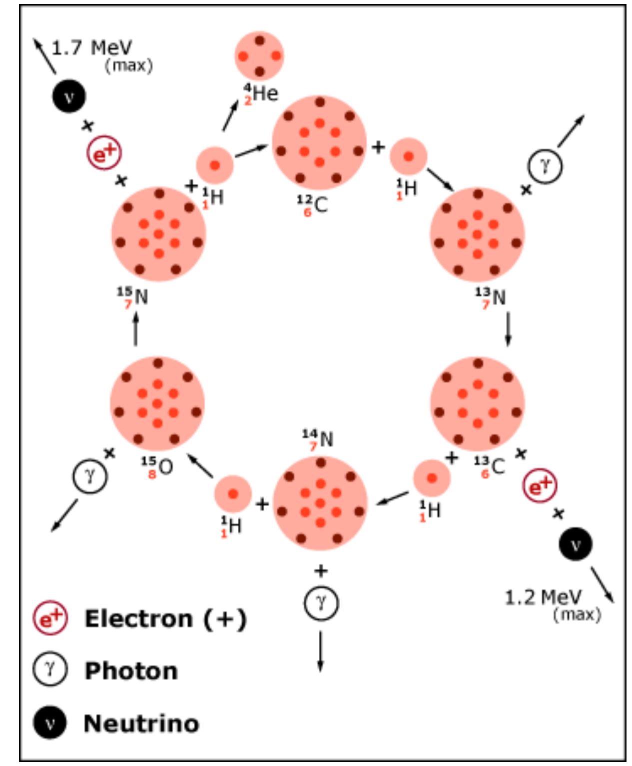
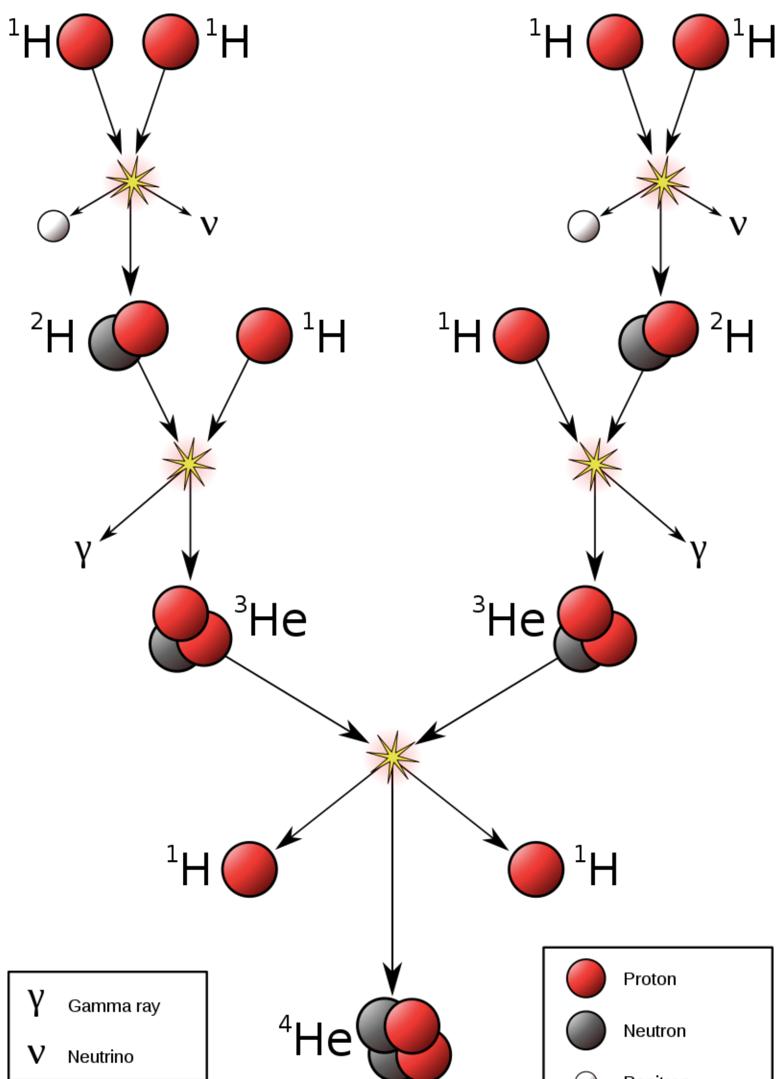
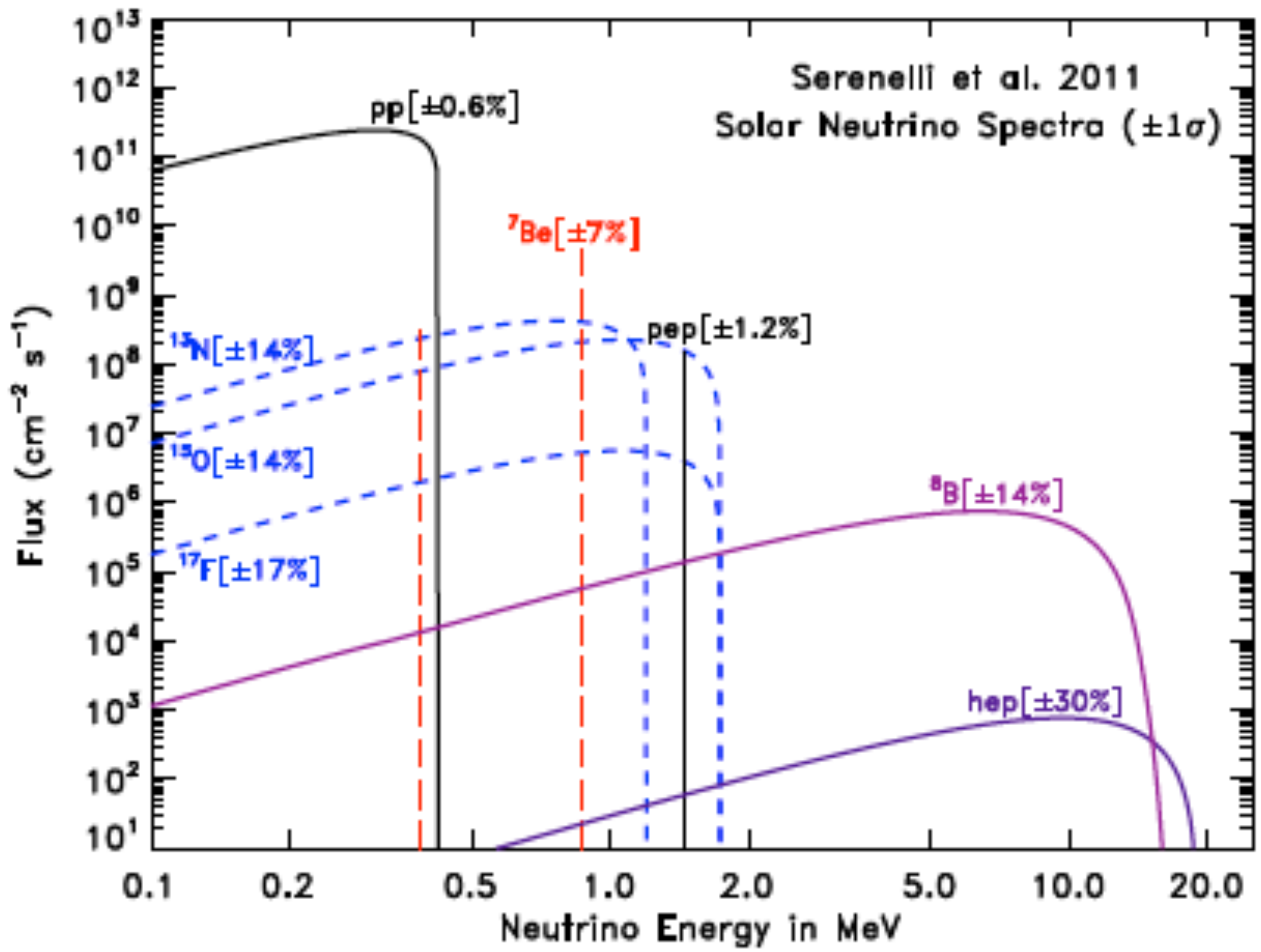
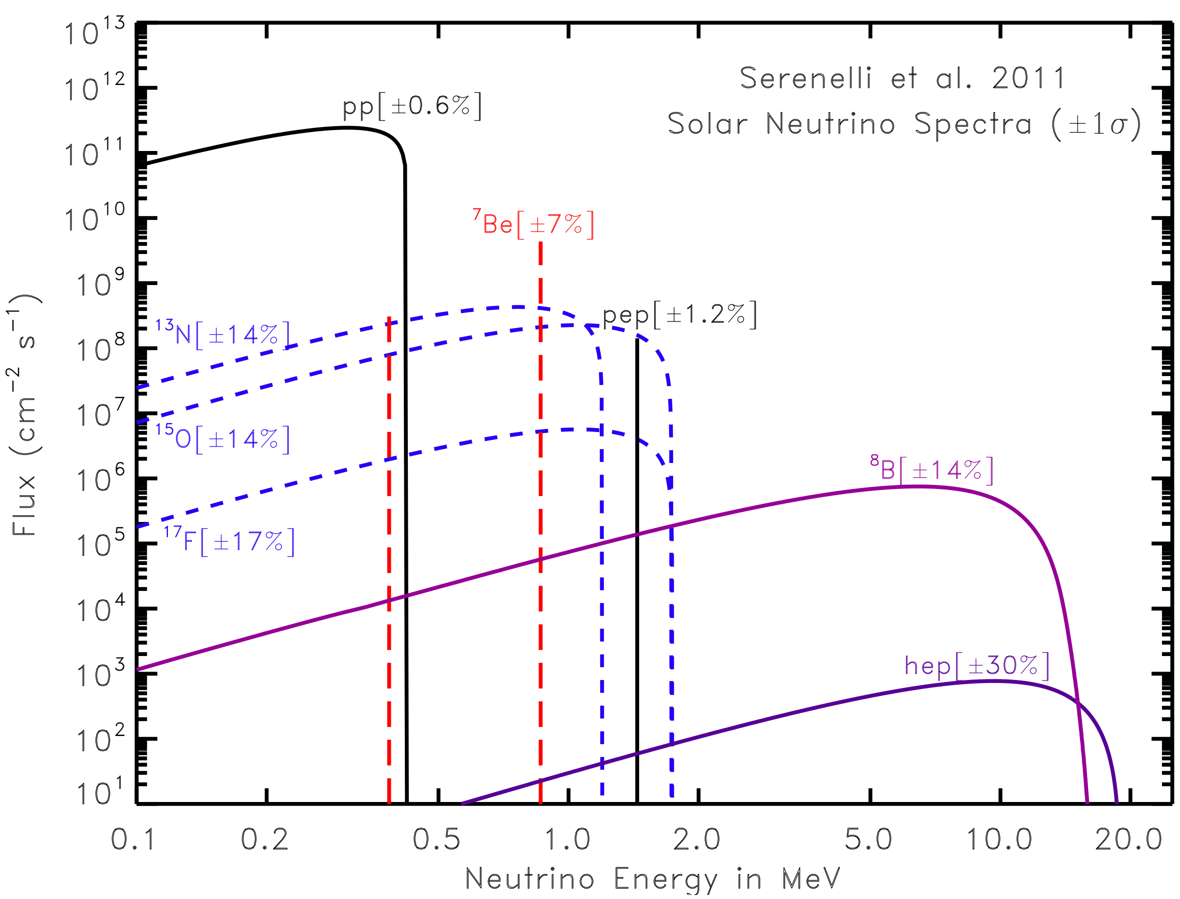
Solar neutrinos:
PP chain and CN cycle

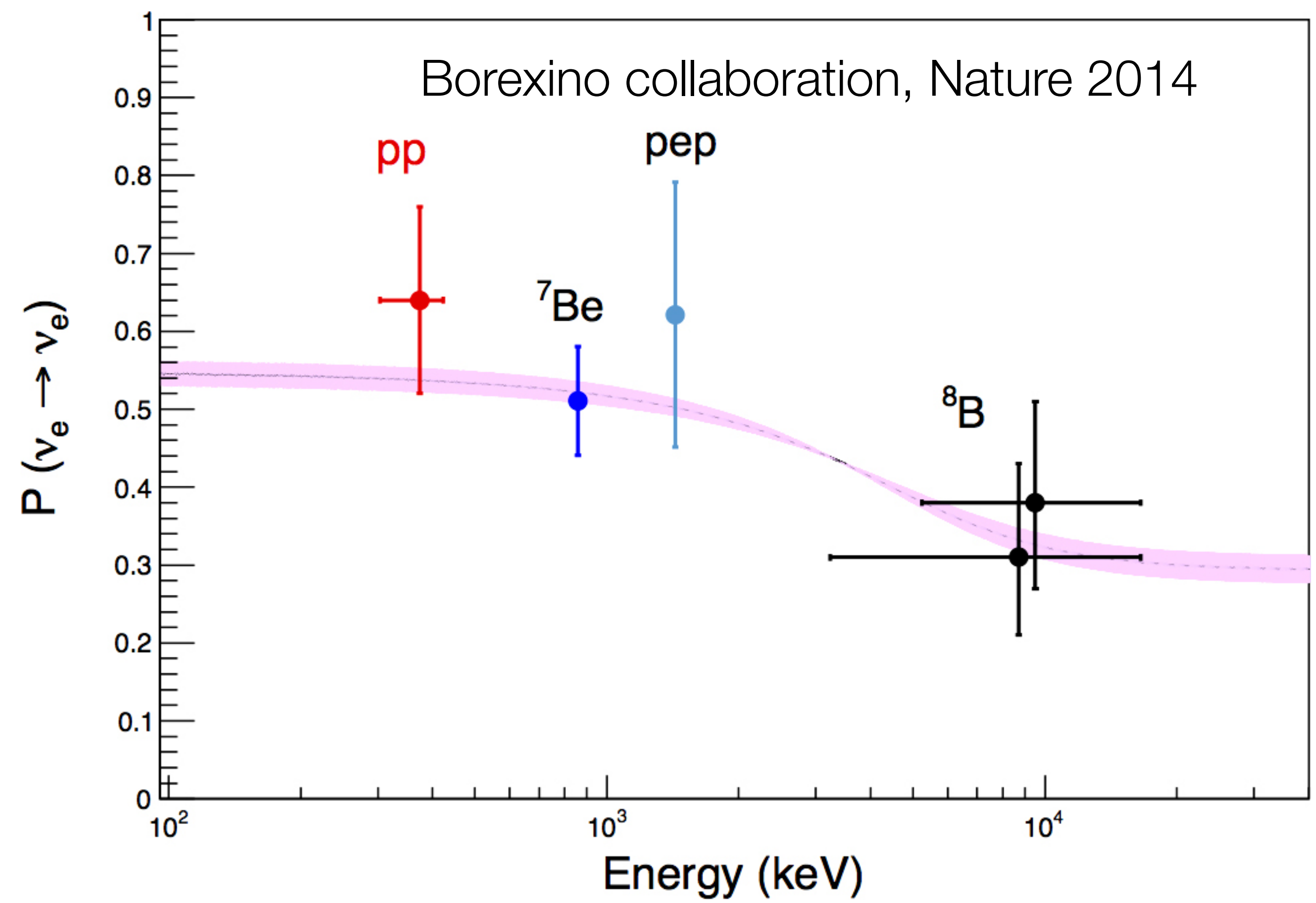






Solar neutrinos: Status





Experimental channels

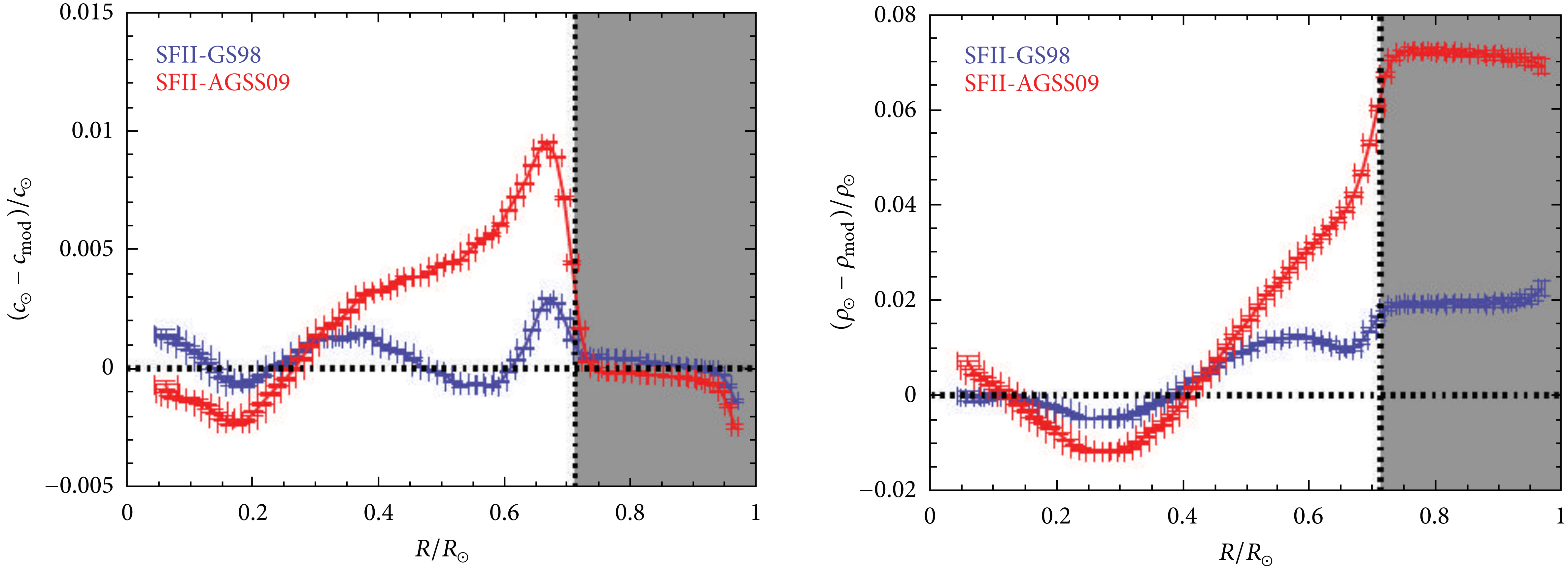
- **Radiochemical experiments:** $\nu_e + (A, Z) \rightarrow (A, Z+1) + e^-$
    - Neutrinos capture on nuclei to form radioisotopes; isotopes chemically separated for counting
    - Chlorine measured a survival probability ~ 1/3; Gallium measured a survival probability ~ 1/2
- **Kiloton scale experiments**:
    - Super-K, SNO, Borexino measured neutrino electron elastic scattering
    - Borexino first ‘low threshold’ experiment
    - SNO also measured the charged current reactions

$$\nu + e^- \rightarrow \nu + e^-$$

$$\nu_e + d \rightarrow e^- + p + p$$

$$\nu + d \rightarrow \nu + p + n$$

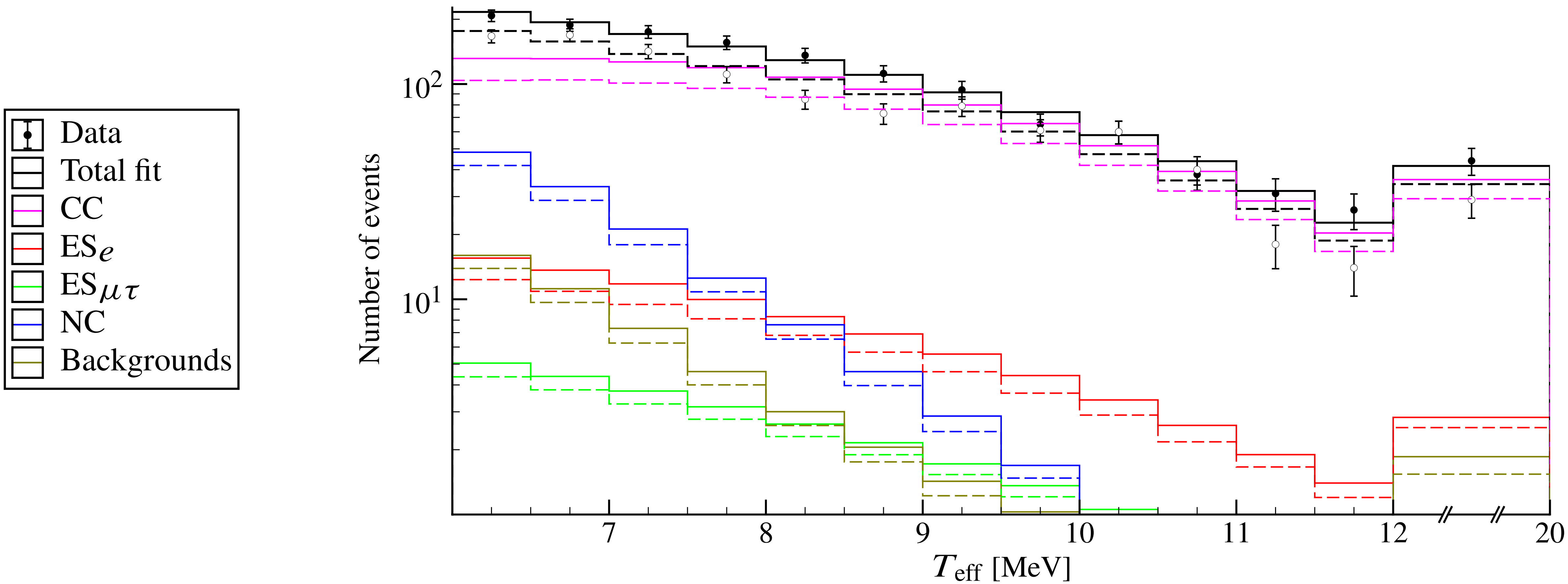
Standard Solar Model Status



Antonelli et al. 2013

- Initially chemically homogeneous
- Match the luminosity, radius, and surface metal abundance
- 3D rotational hydro simulations suggest lower metallicity in the Solar core (Asplund 2009)
- Low metallicity in conflict with heliosiesmology data

SNO combined analysis (Phases I-III)



SNO combined analysis (Phases I-III)

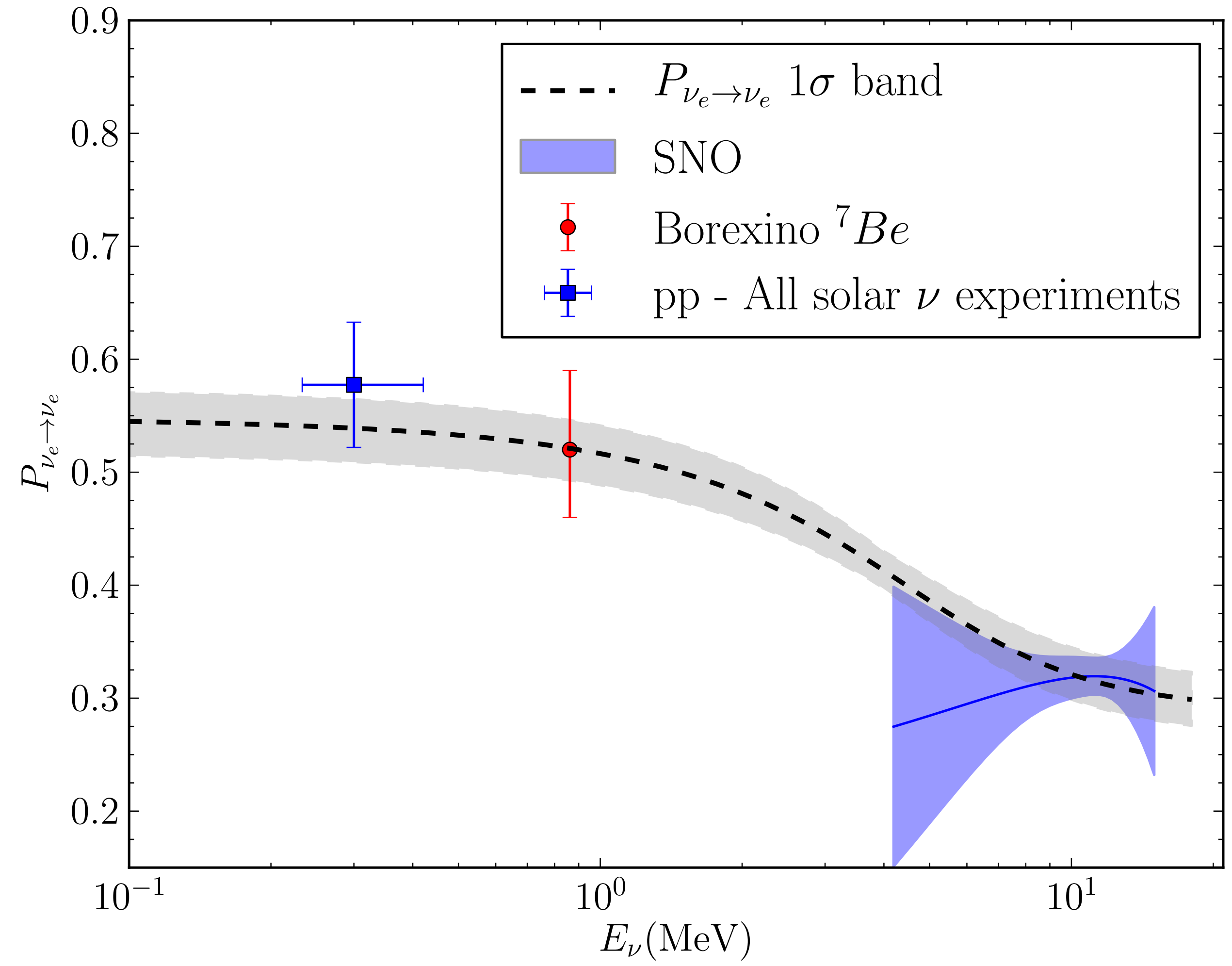
- Parametric fit to survival probability:

$$P_{ee}(E_\nu) = c_0 + c_1\left(\frac{E_\nu}{\text{MeV}} - 10\right) + c_2\left(\frac{E_\nu}{\text{MeV}} - 10\right)^2$$

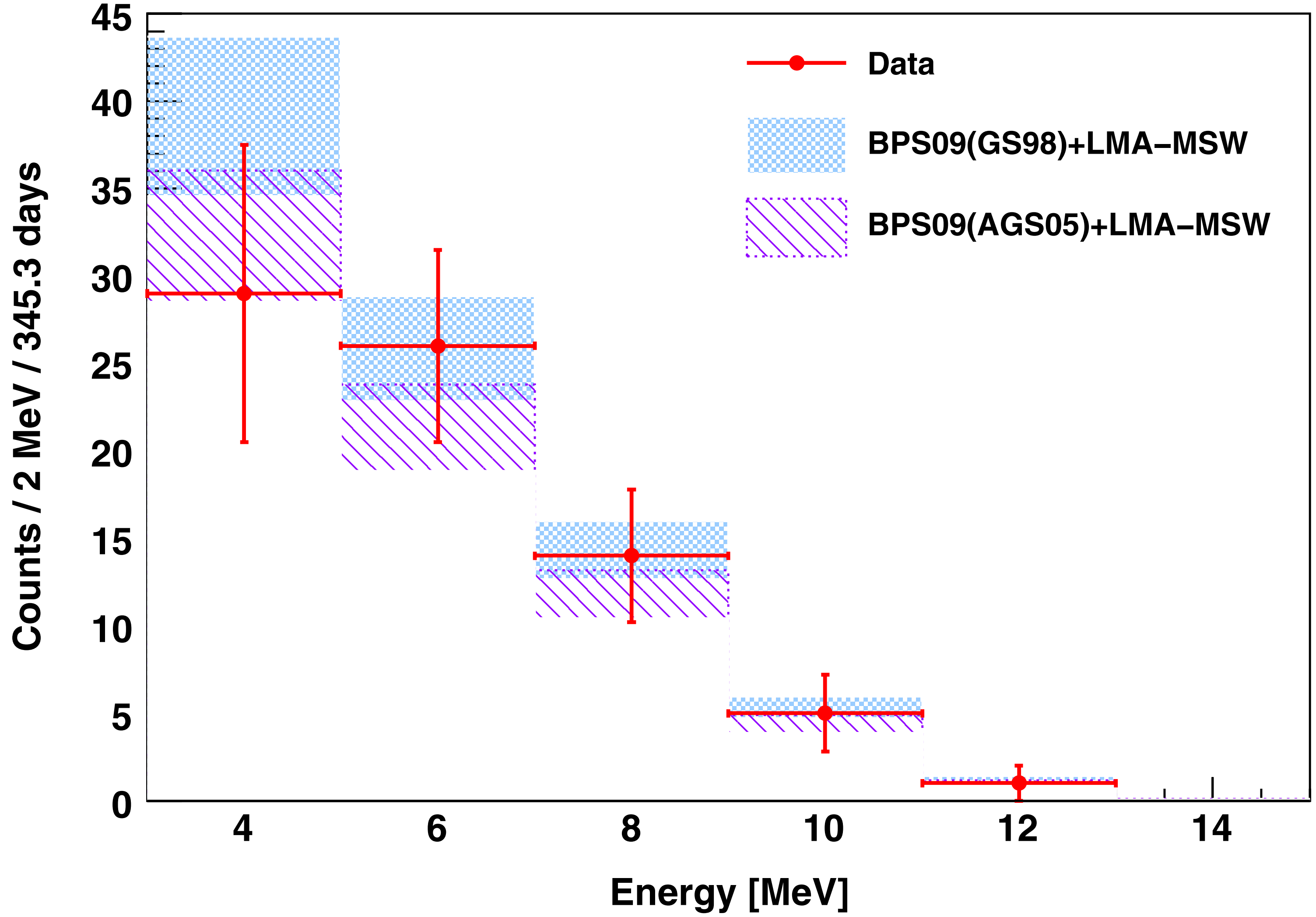
- Parametric fit to day/night asymmetry:

$$A_{ee}(E_\nu) = 2\frac{P^{\text{n}}_{ee}(E_\nu) - P^{\text{d}}_{ee}(E_\nu)}{P^{\text{n}}_{ee}(E_\nu) + P^{\text{d}}_{ee}(E_\nu)}$$

$$A_{ee}(E_\nu) = a_0 + a_1(E_\nu[\text{MeV}] - 10)$$



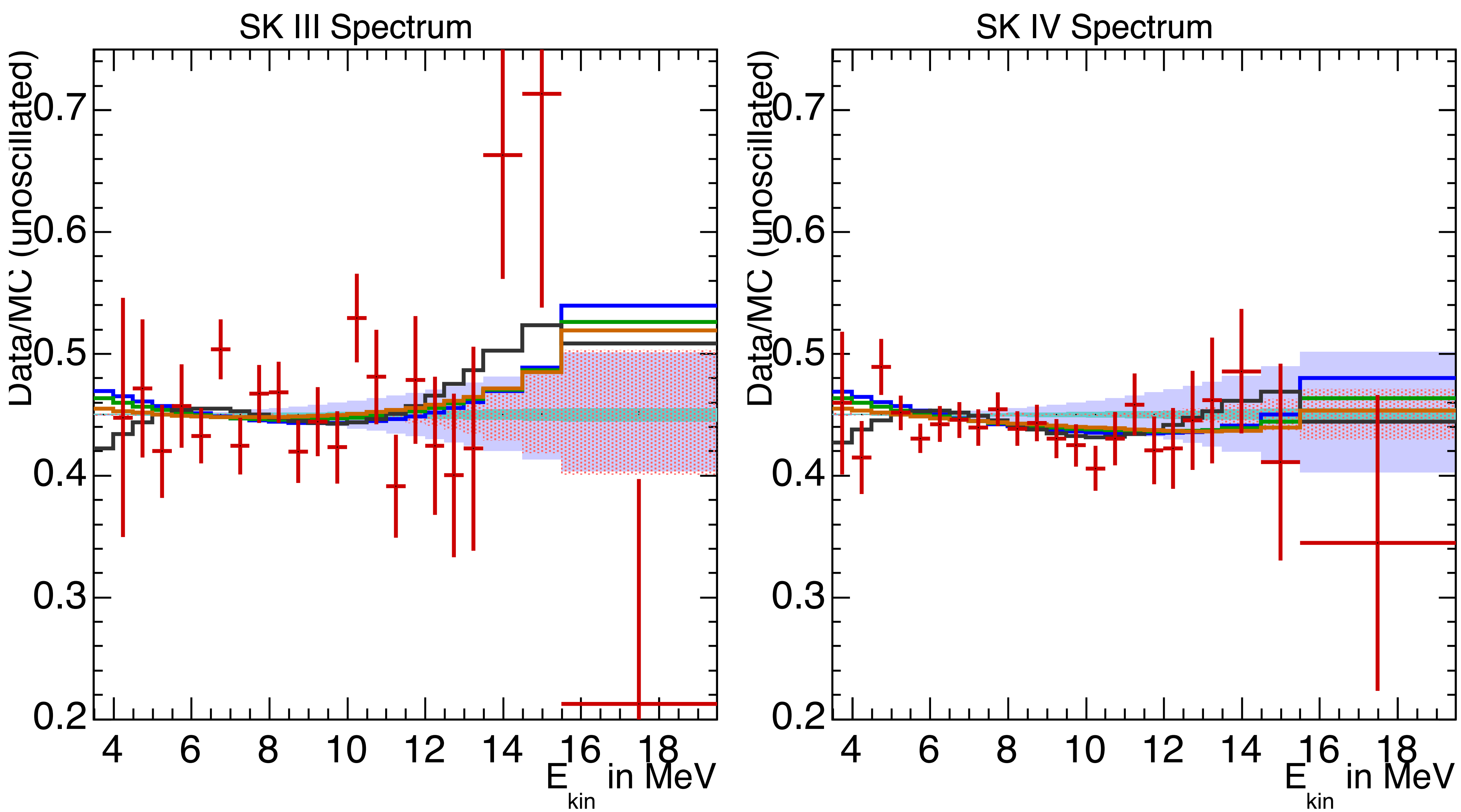
Neutrino-electron elastic scattering



Borexino collaboration

- Borexino, SNO, SK (I-III) indicate the low energy ES data lower than MSW predicts
- No clear upturn in MSW survival probability not been measured
- May indicate new physics (e.g. Holanda & Smirnov 2011)

Super-K IV electron recoil spectrum



- Possible indication of 'upturn' in SK IV spectrum at low energy, but not statistically significant

SNO+ 8B elastic scattering

- ES flux consistent with the SK measurement:

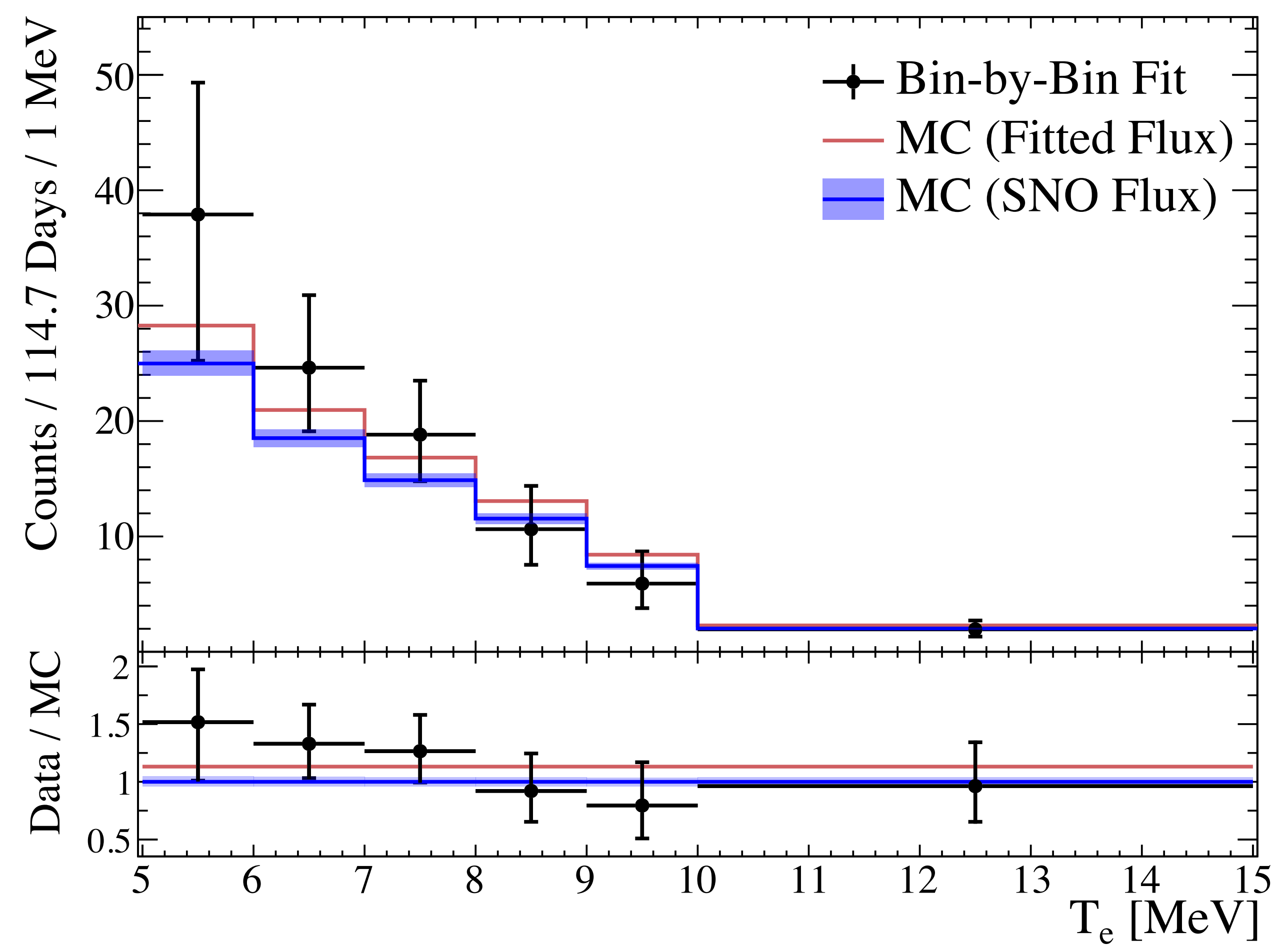
$$\Phi_{ES} = 2.53^{+0.31}_{-0.28}(\text{stat.})^{+0.13}_{-0.10}(\text{syst.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$ (SNO+)

$$\Phi_{ES}=(2.345 \pm 0.039)\times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$ (Super-K)

- Assuming mixing parameters implies total 8B flux consistent with SNO:

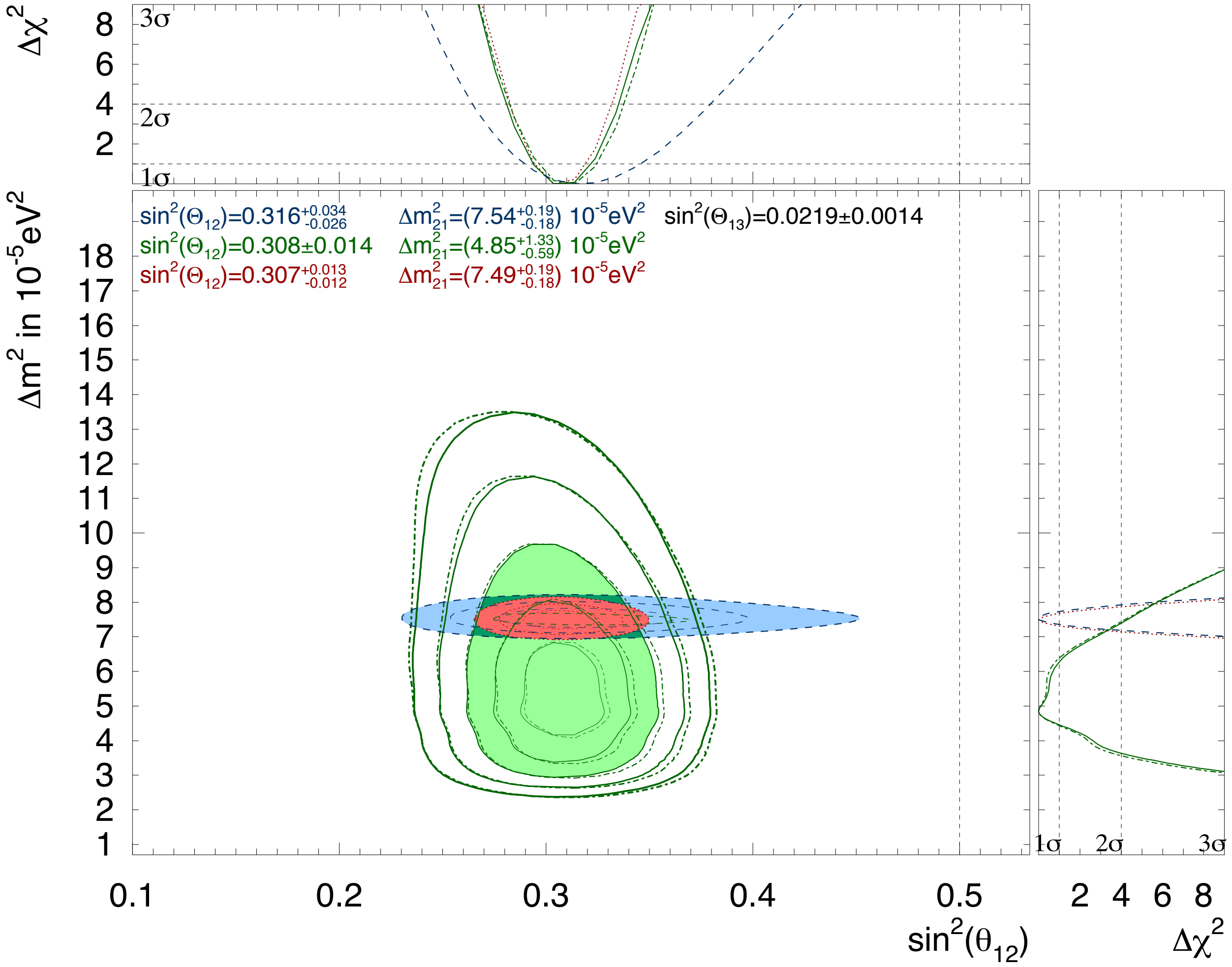
$$\Phi_{^8\text{B}} = 5.95^{+0.75}_{-0.71}(\text{stat.})^{+0.28}_{-0.30}(\text{syst.}) \times 10^6\text{cm}^{-2}\text{s}^{-1}$$ (SNO+)

$$\Phi_{^8\text{B}}=(5.25 \pm 0.20)\times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$ (SNO)

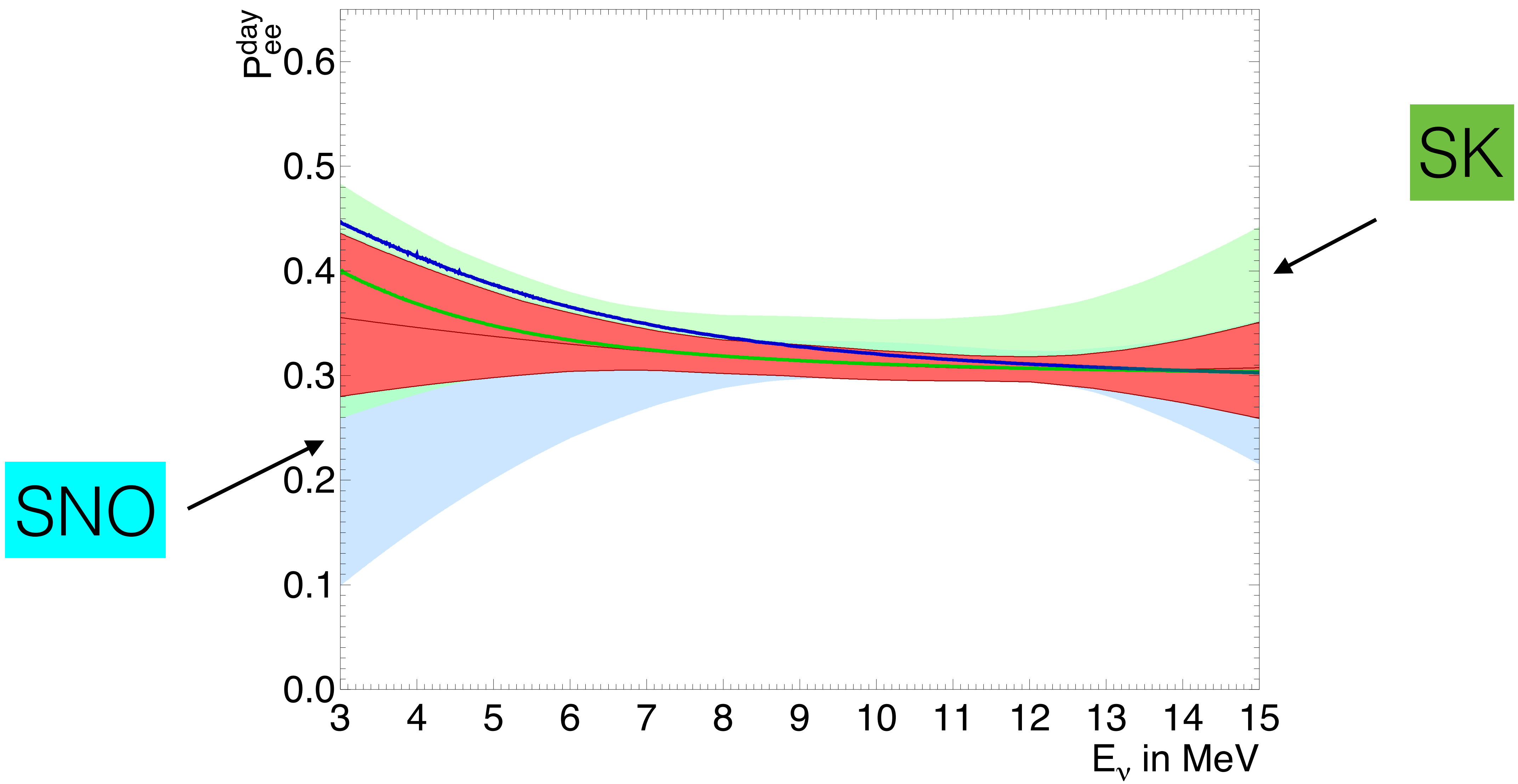


Super-K Solar mass splitting

- Approximately 2sigma difference between reactor and solar measurements of solar mass splitting (Maltoni and Smirnov 2015)
- Mostly from day-night asymmetry in Super-K data
- Solutions in the form of Non-Standard Interactions (NSI)



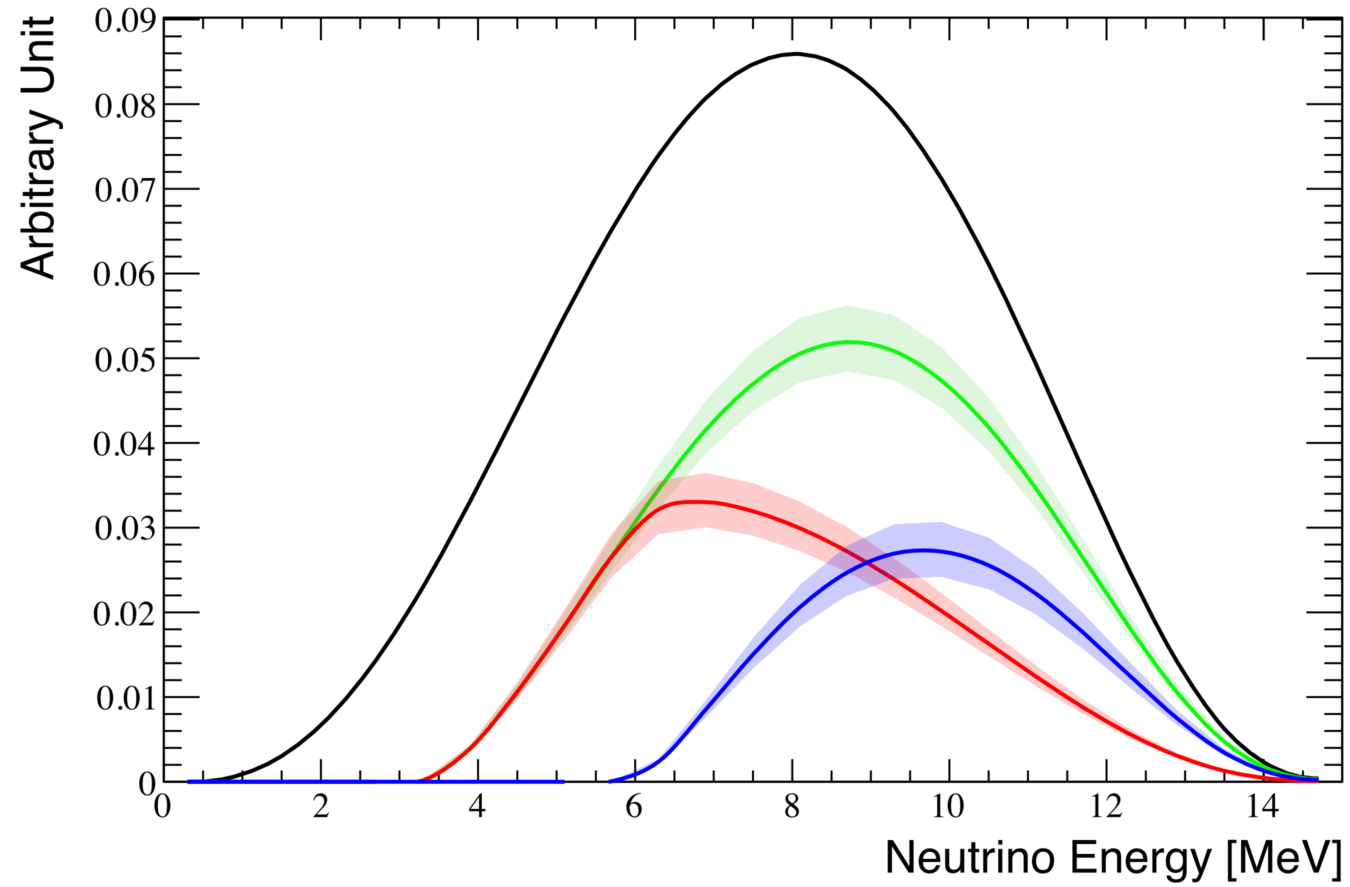
Super-K and SNO survival probability



Updated Borexino 8B results

- ES flux in agreement with SK, factor of 2 improvement over previous Borexino 8B results

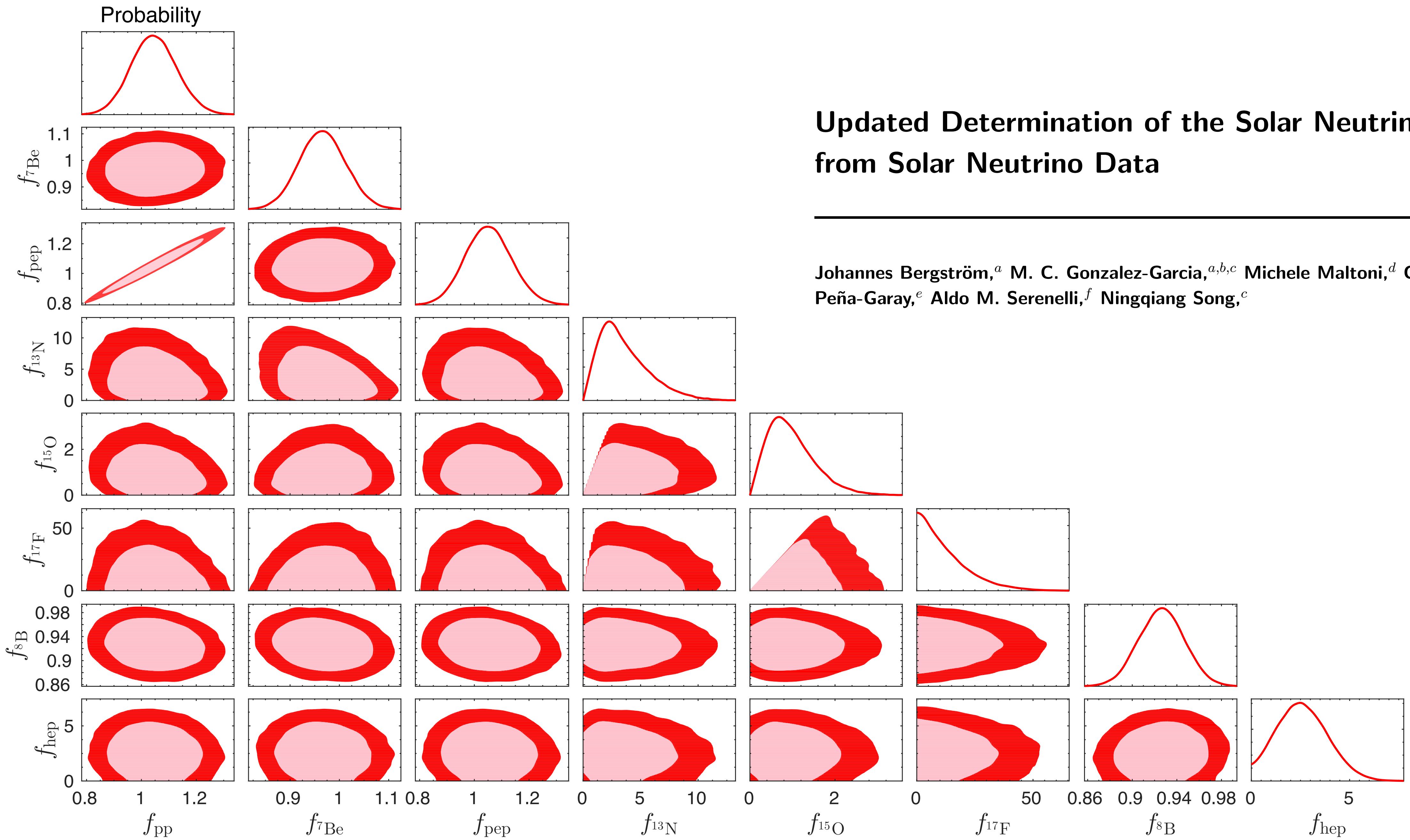
$$2.55^{+0.17}_{-0.19}(stat)^{+0.07}_{-0.07}(syst)\times 10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$



for the LE and HE ranges are fully compatible (albeit with weak discrimination power) with the presence of an "upturn" of $\bar{P}_{ee}$ in the transition region between matter and vacuum flavor conversion predicted by MSW-LMA.

Global analysis

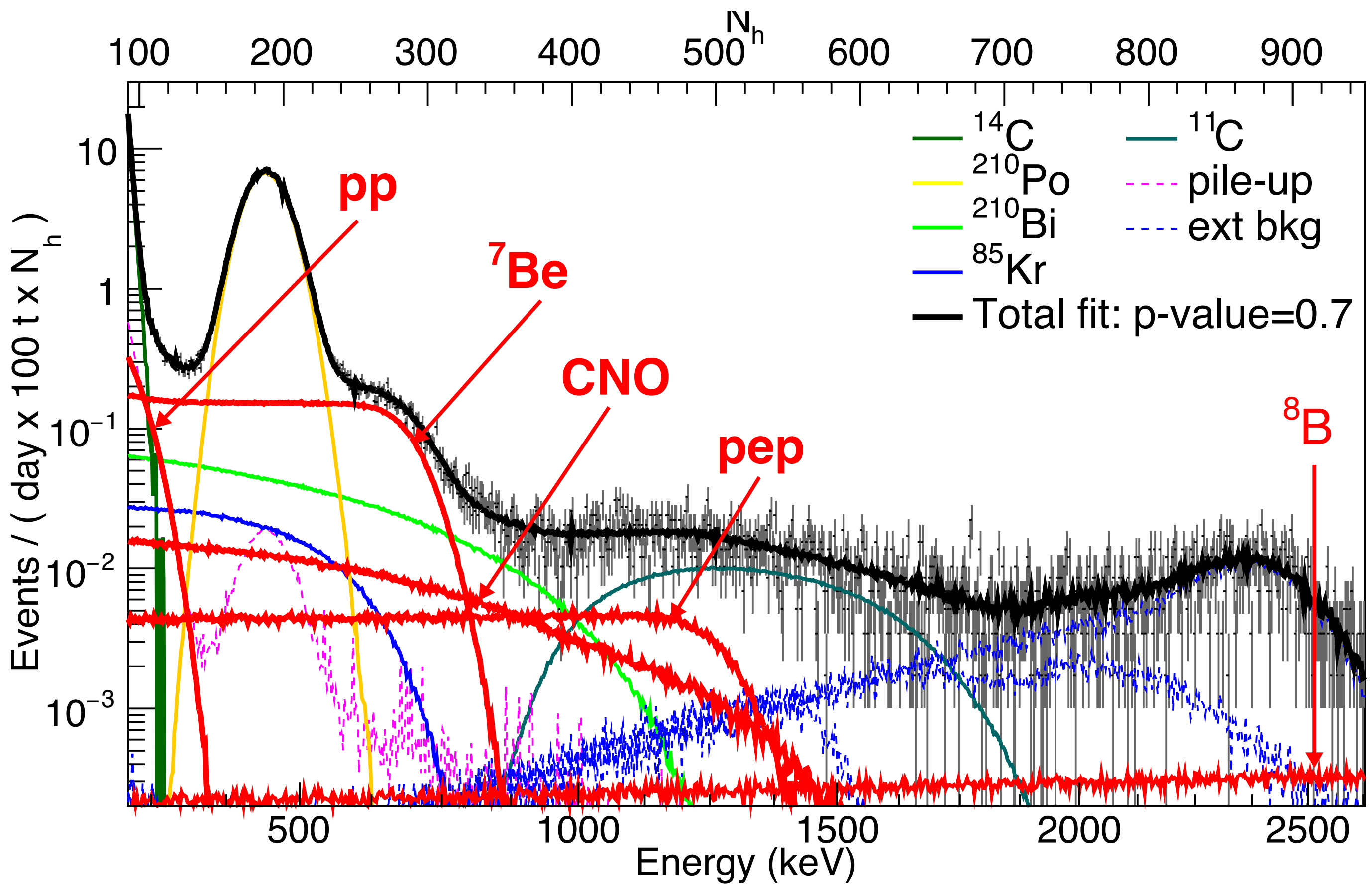
$$\frac{L_{\text{pp-chain}}}{L_\odot} = 1.03^{+0.08}_{-0.07}\,\left[^{+0.21}_{-0.18}\right] \qquad \text{and} \qquad \frac{L_{\text{CNO}}}{L_\odot} = 0.008^{+0.005}_{-0.004}\,\left[^{+0.014}_{-0.007}\right]$$

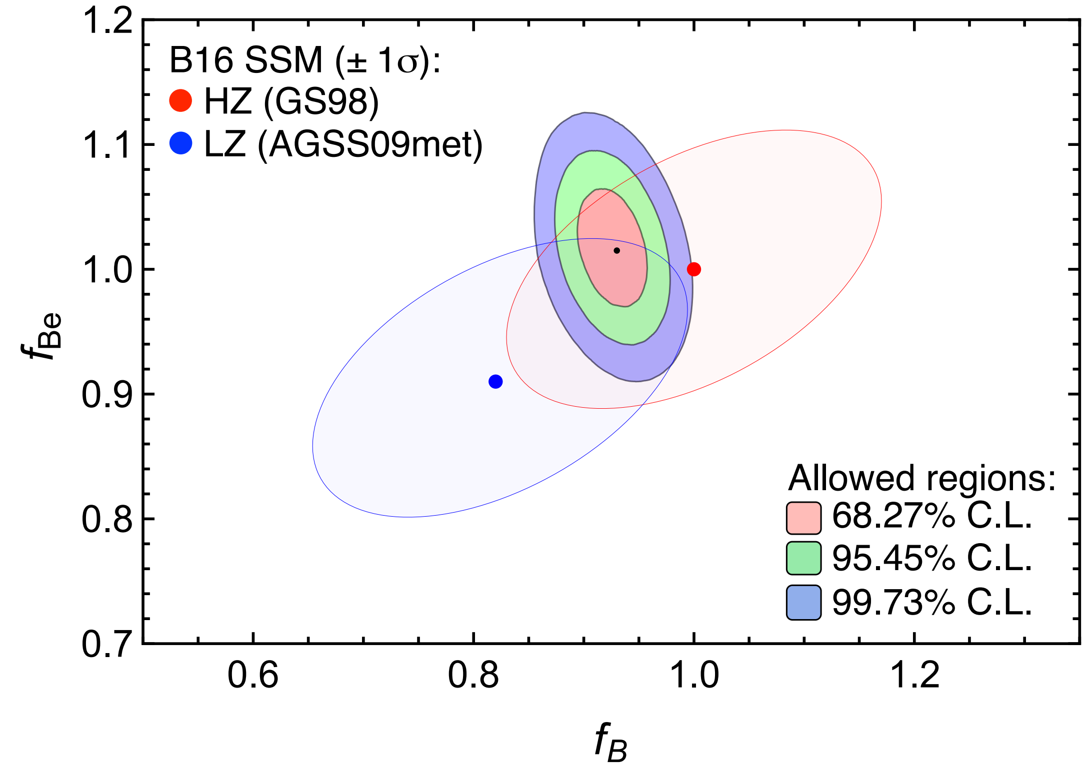


Updated Determination of the Solar Neutrino Fluxes from Solar Neutrino Data

Johannes Bergström,[a] M. C. Gonzalez-Garcia,[a,b,c] Michele Maltoni,[d] Carlos Peña-Garay,[e] Aldo M. Serenelli,[f] Ningqiang Song,[c]

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

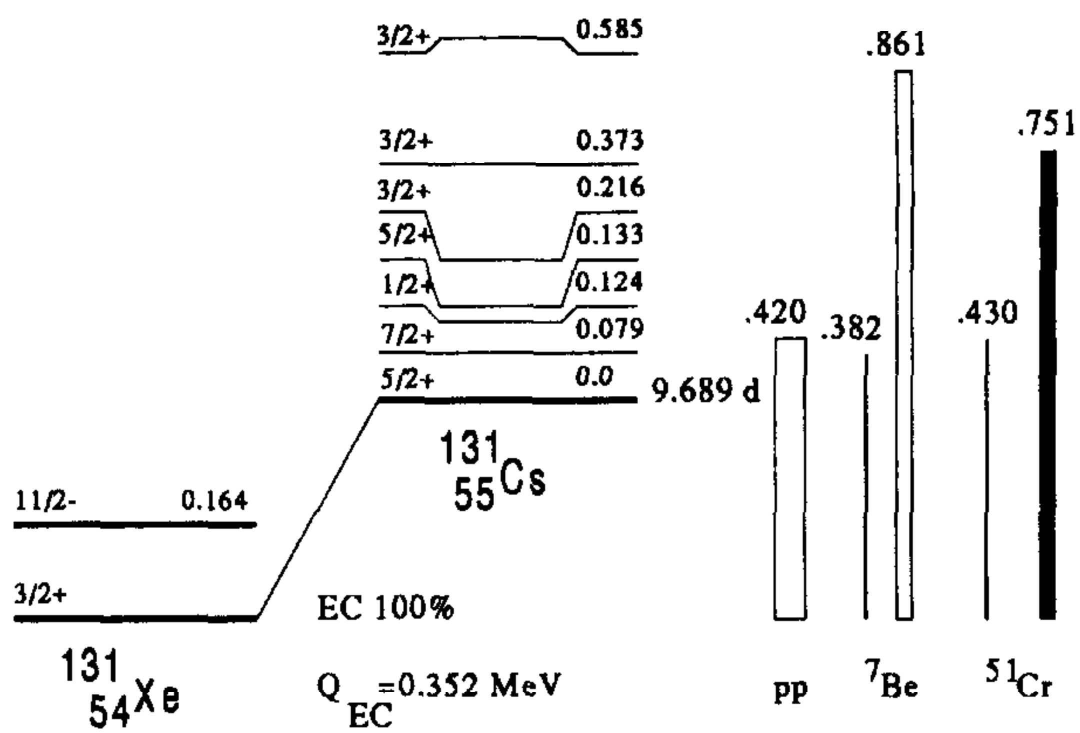
Xenon solar neutrino detector?

A Xenon Solar Neutrino Detector

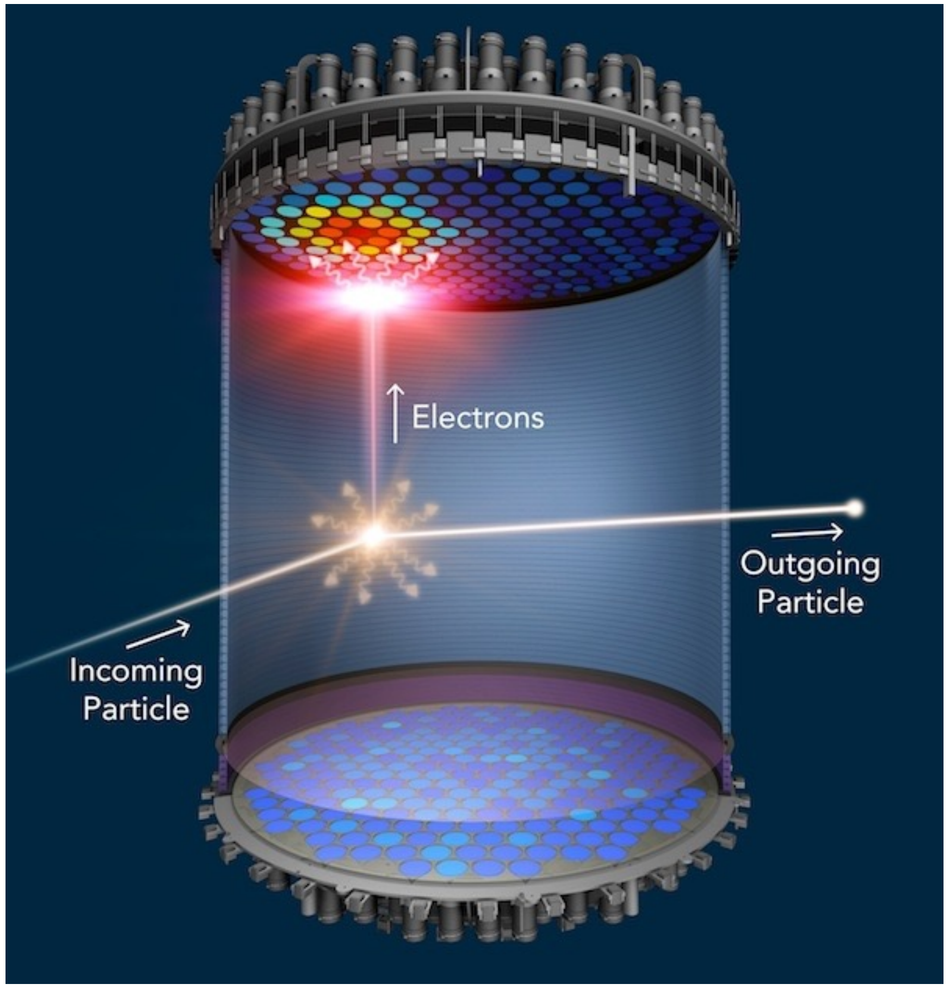
A.Sh. Georgadze [1], H.V. Klapdor-Kleingrothaus [2], H. Päs [2] and Yu.G. Zdesenko [1]

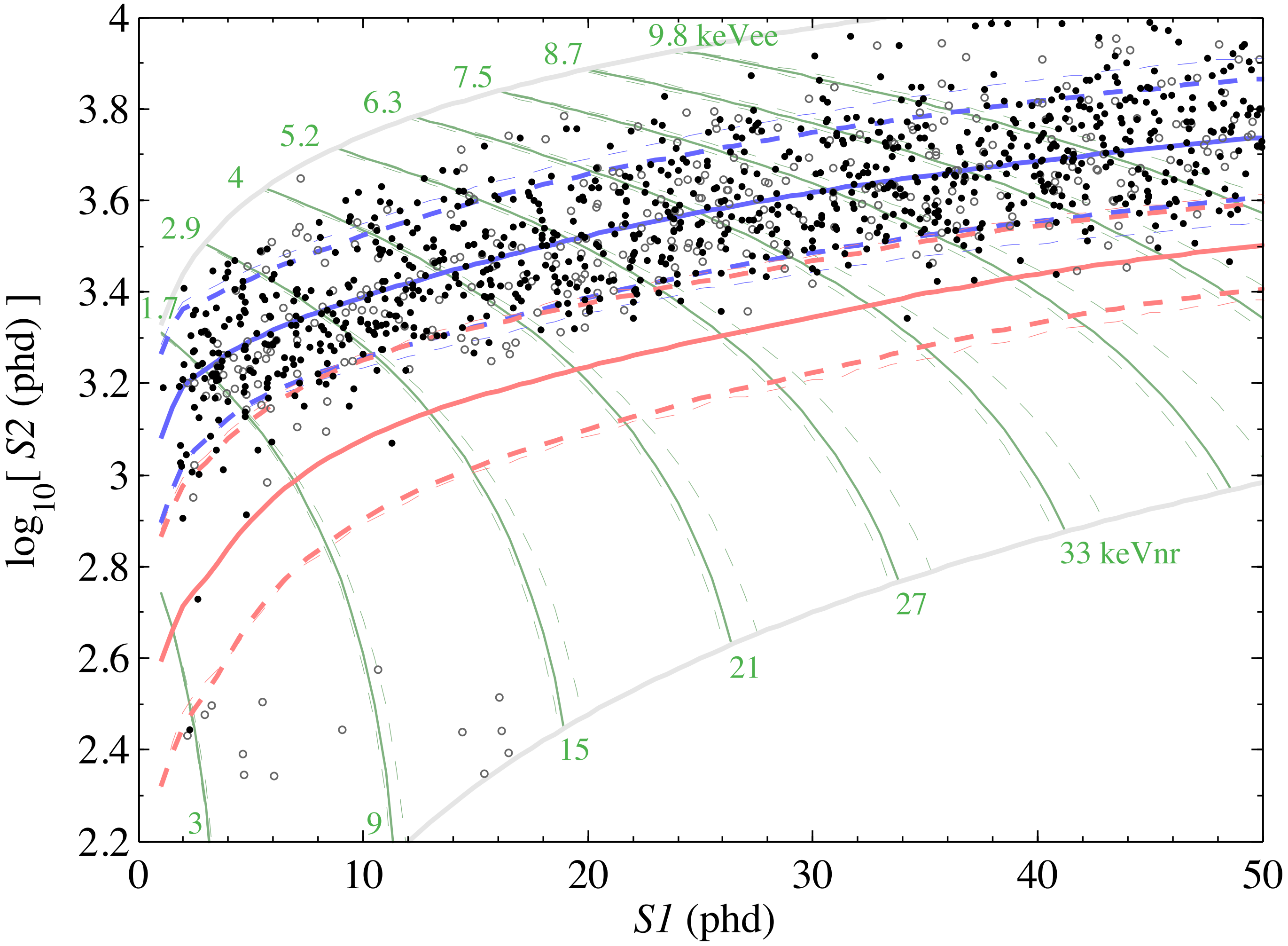
[1]Institute for Nuclear Research, 252650 Kiev, Ukraine
[2]Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany

The neutrino capture reaction by ^{131}Xe with the threshold of 352 keV is suggested for solar neutrinos detection. The most important feature of this process is its high sensitivity to beryllium neutrinos, that contribute approximately 40% to the total capture rate predicted in the Standard Solar Model (45 SNU). The expected counting rate of the xenon detector from the main solar neutrino sources predicted by the Standard Solar Model is ≈1500 events/yr.

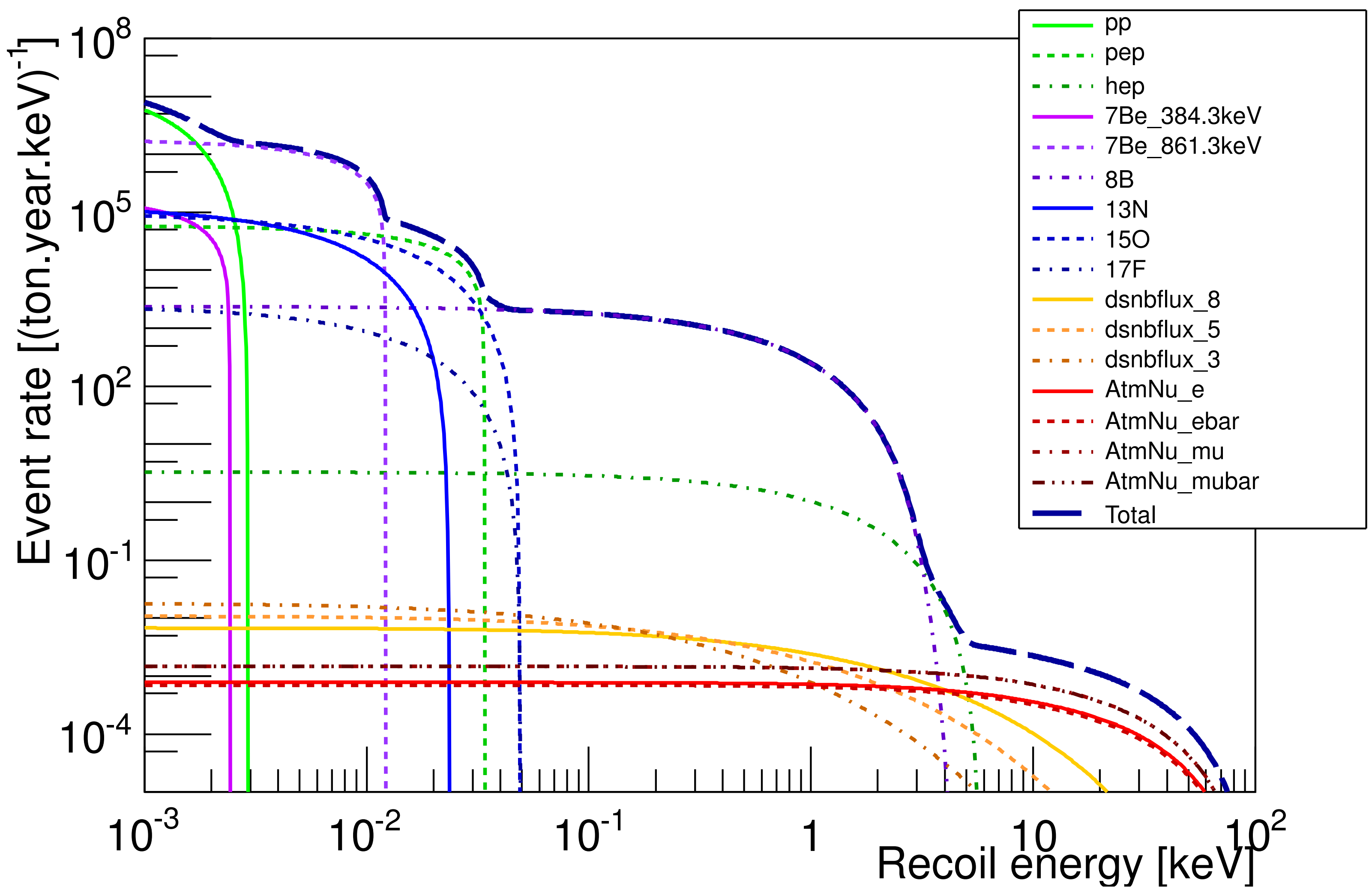


Direct dark matter detection



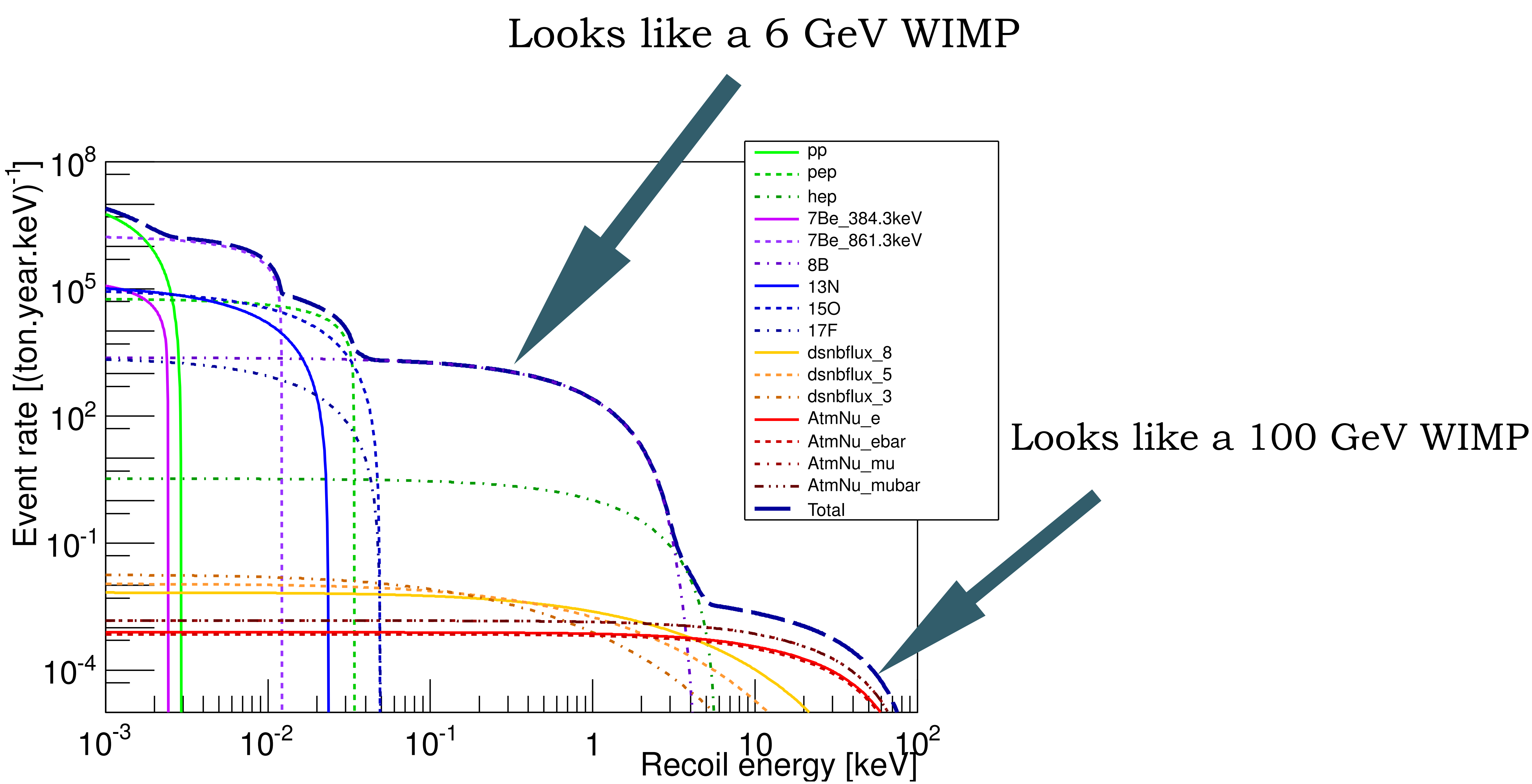


Astrophysical neutrino signals



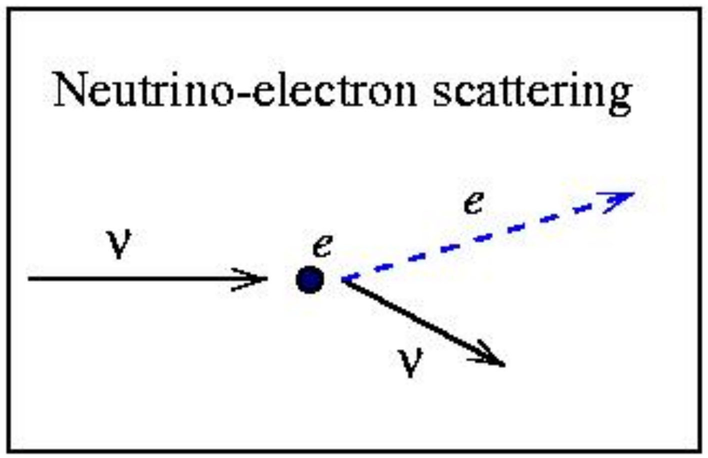
Billard, Figueroa-Feliciano, LS 2014

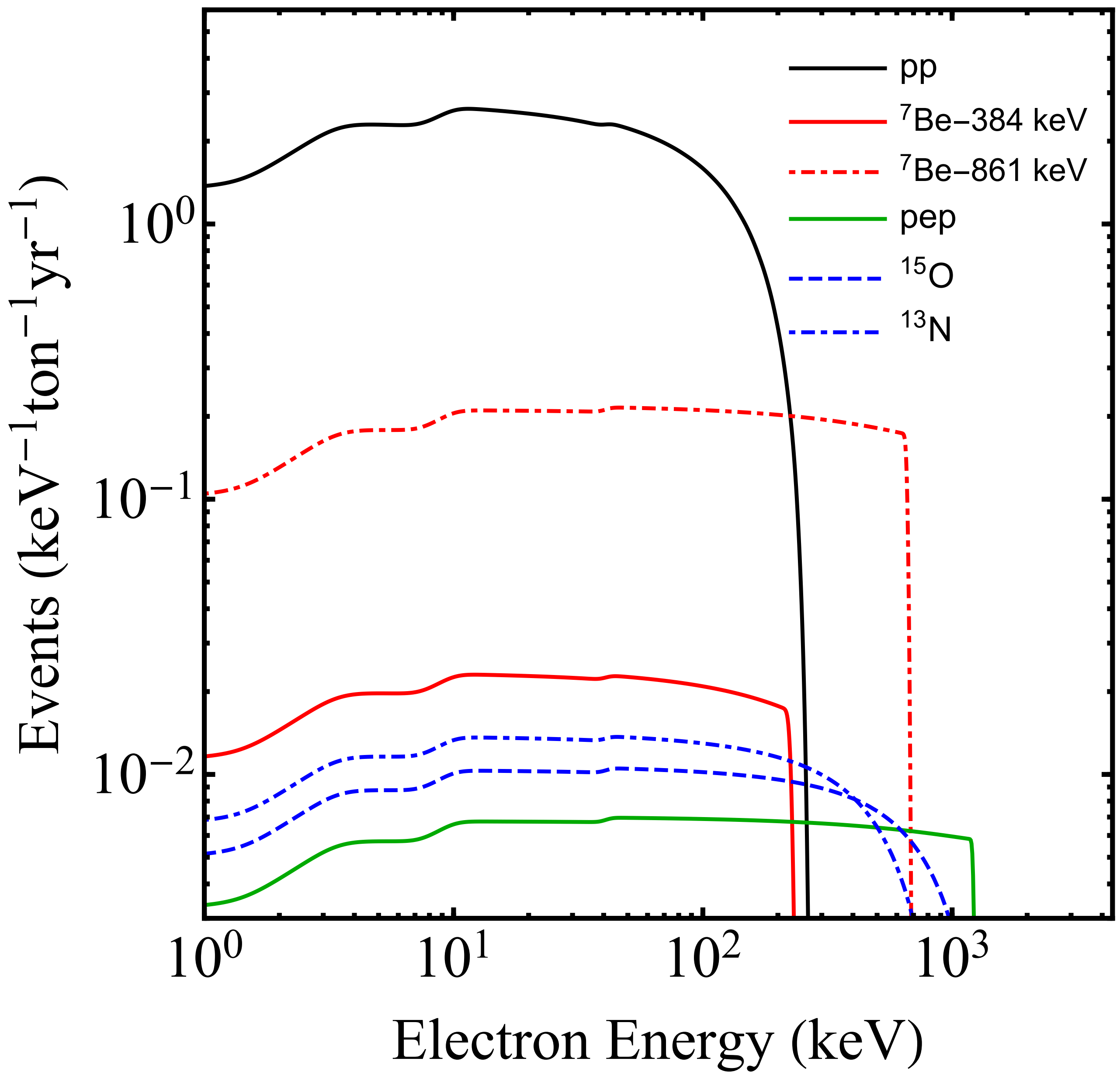
Astrophysical neutrino signals



Billard, Figueroa-Feliciano, LS 2014

Elastic Solar neutrino-electron scattering

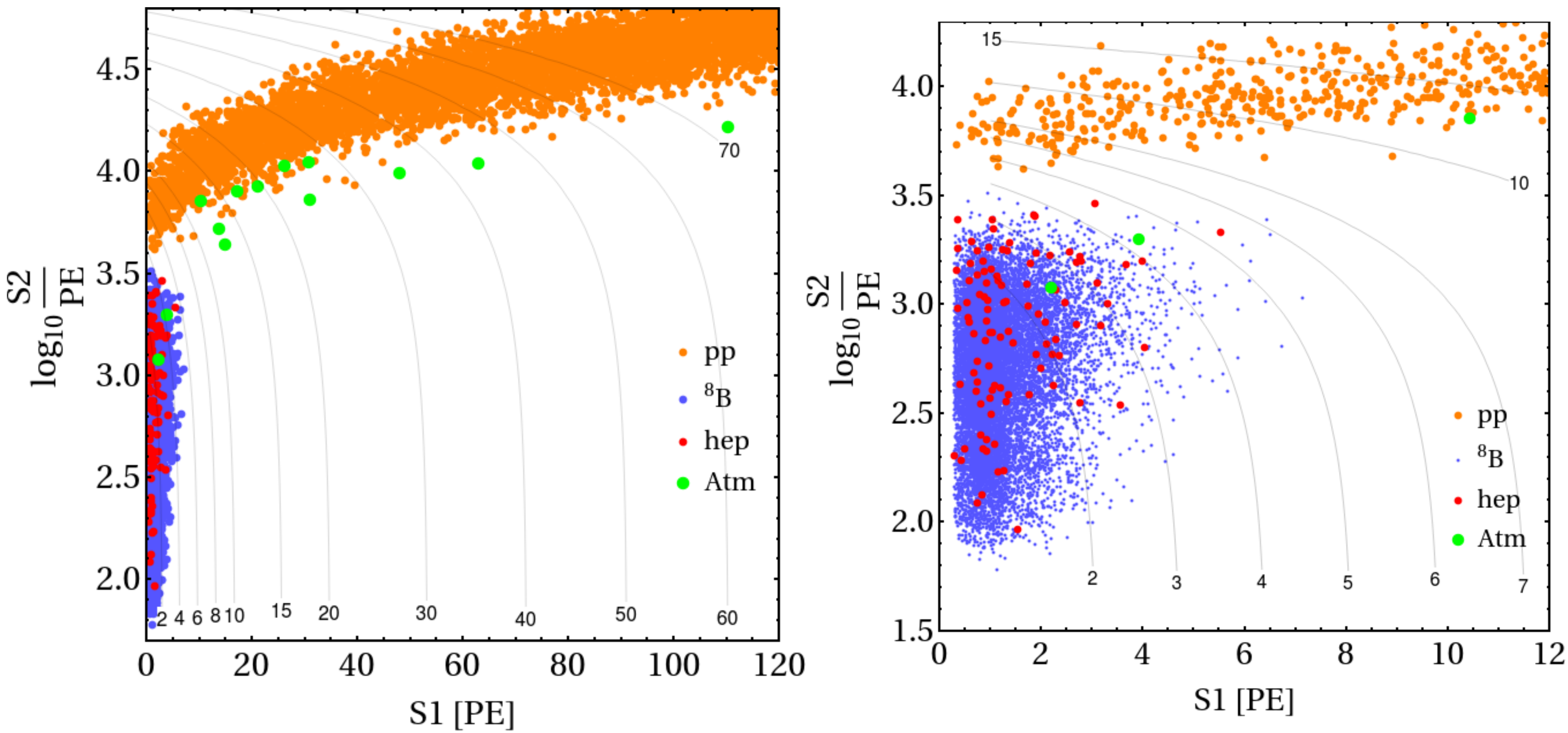




- Primary sensitivity to low energy solar neutrino components, pp, 7Be
- Sensitivity to lower energy electron recoils than any solar neutrino experiment
- Several events in Xenon 1T data, but buried under detector backgrounds

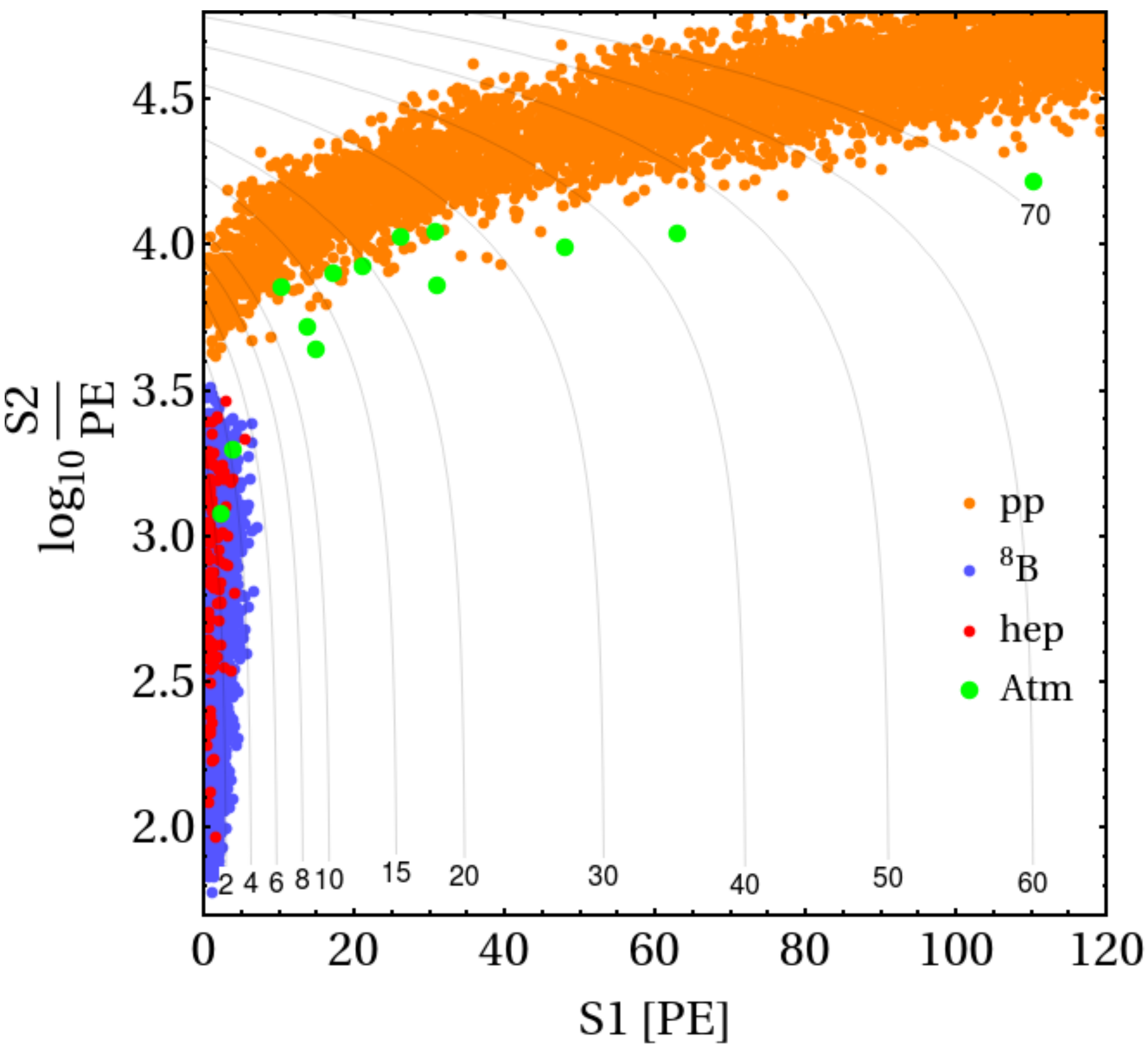
Newstead, Lang, LS 2018

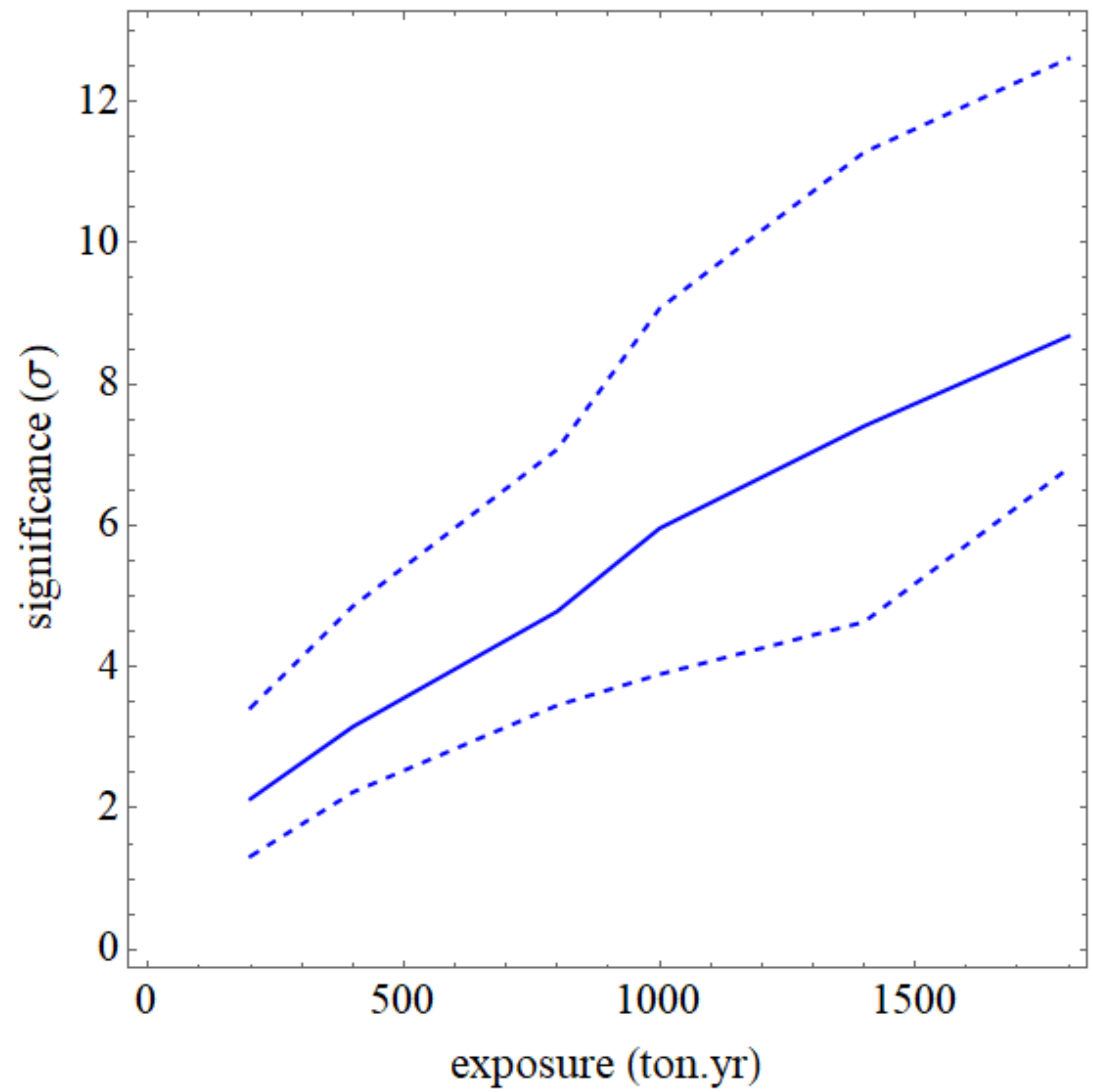
Nuclear/electron recoil discrimination



J. Newstead et al.

Nuclear/electron recoil discrimination





J. Newstead et al.

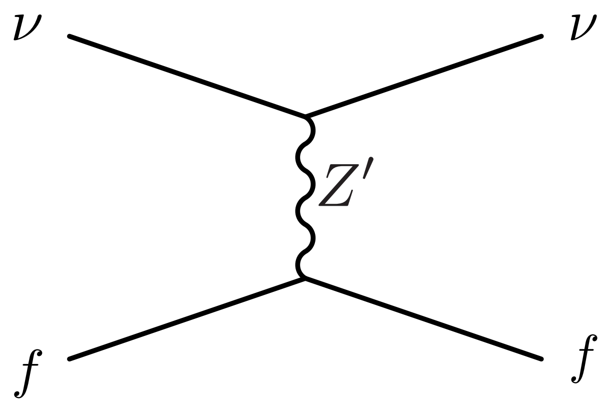
Solar metallicity

High-Z Low-Z

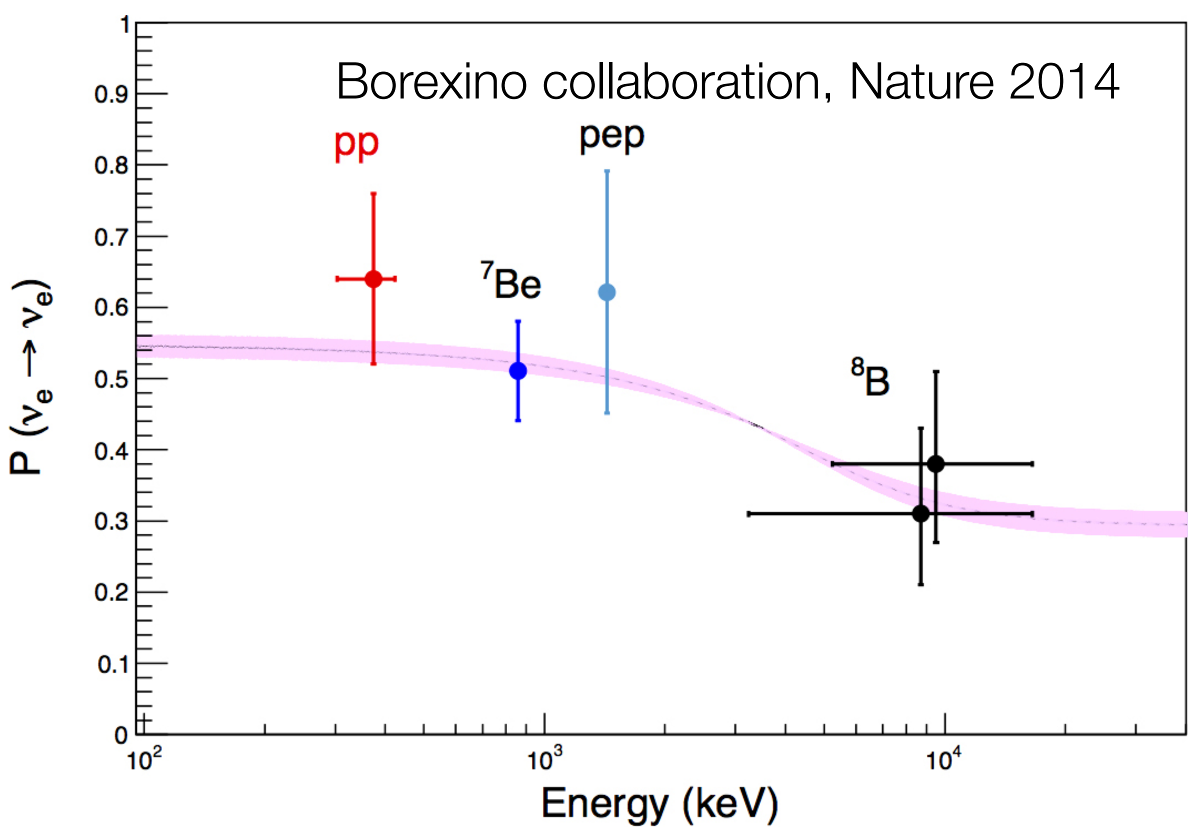
ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p \to {}^2H+e^++\nu$	0.42	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^-+p \to {}^2H+\nu$	1.44	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^{8}/cm^2s$
${}^7Be+e^- \to {}^7Li+\nu$	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

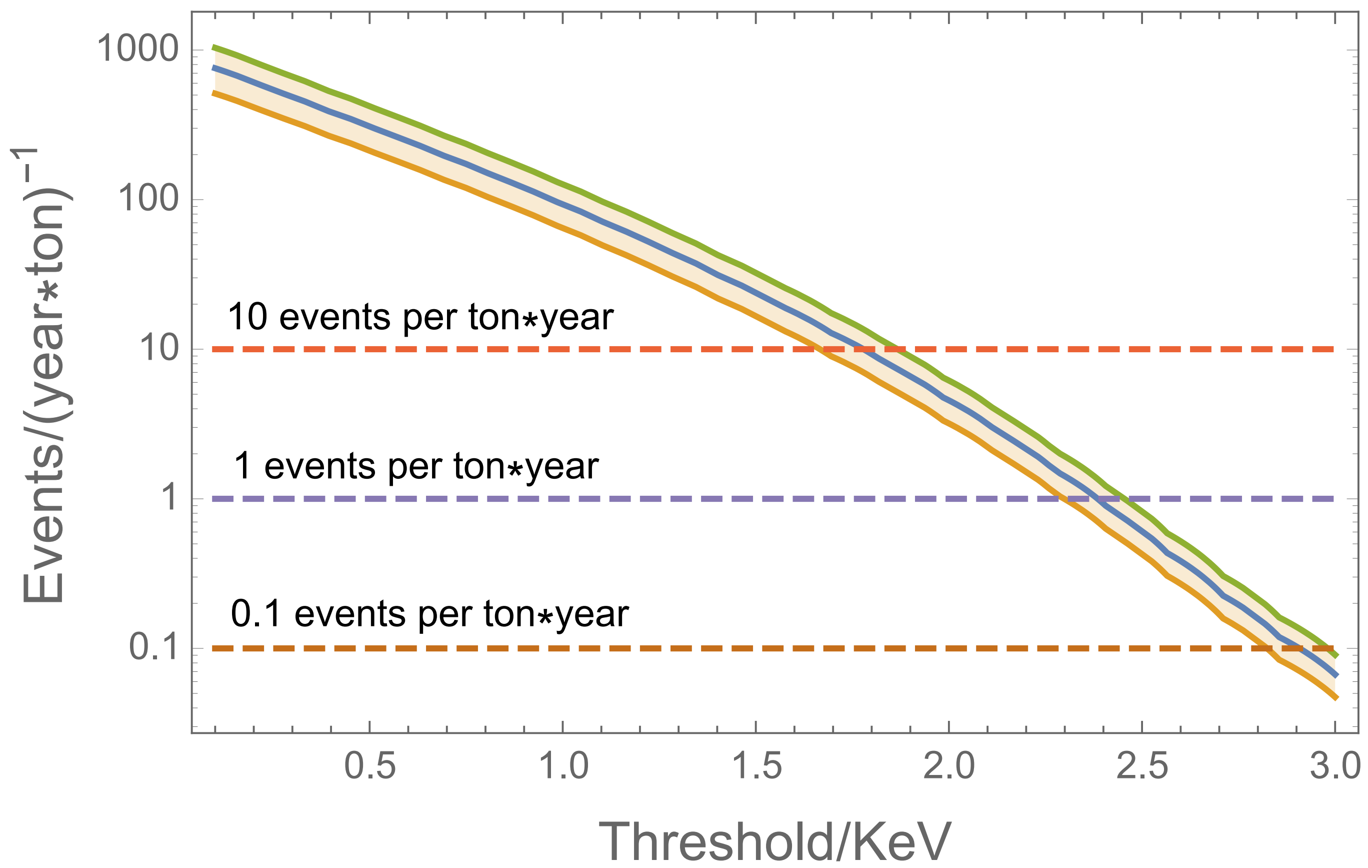
Non-Standard Neutrino Interactions



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



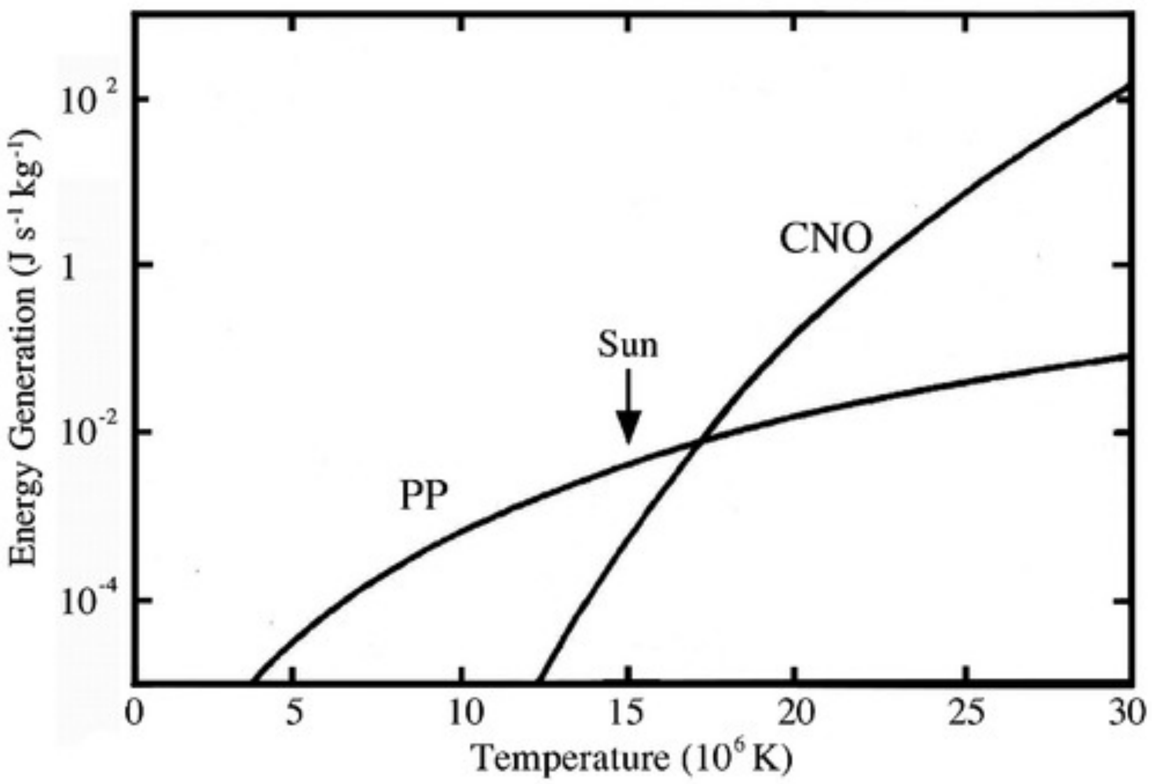
Friedland, Lunardini, Pena-Garay PLB 2004

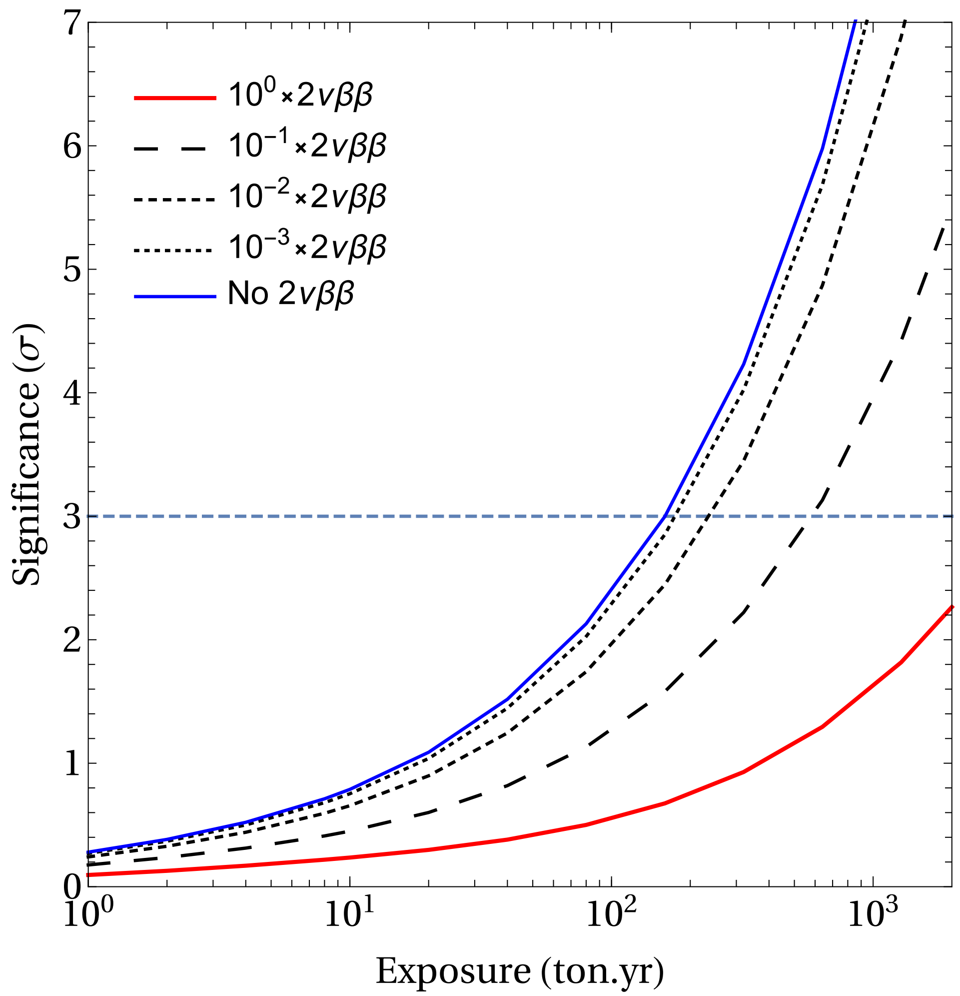


B. Dutta, S. Liao, L. Strigari, J. Walker, PLB 2017 (1705.00661)

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

CNO Solar neutrinos

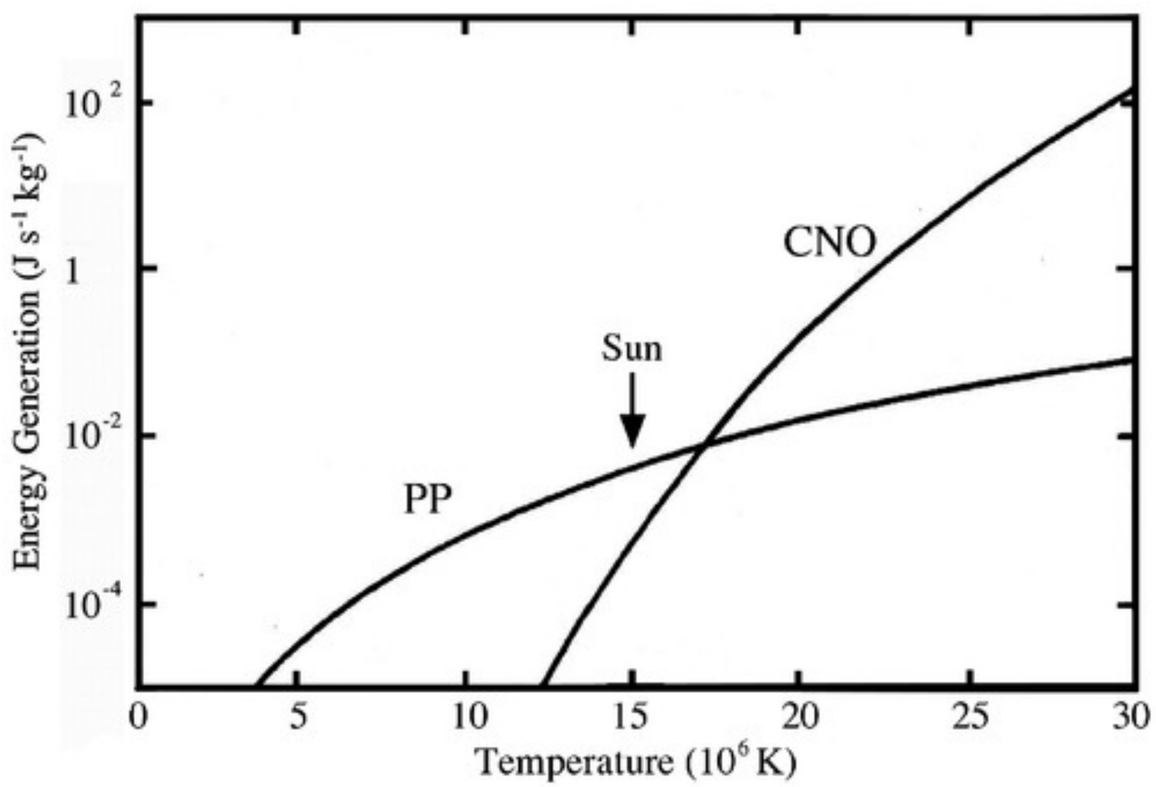


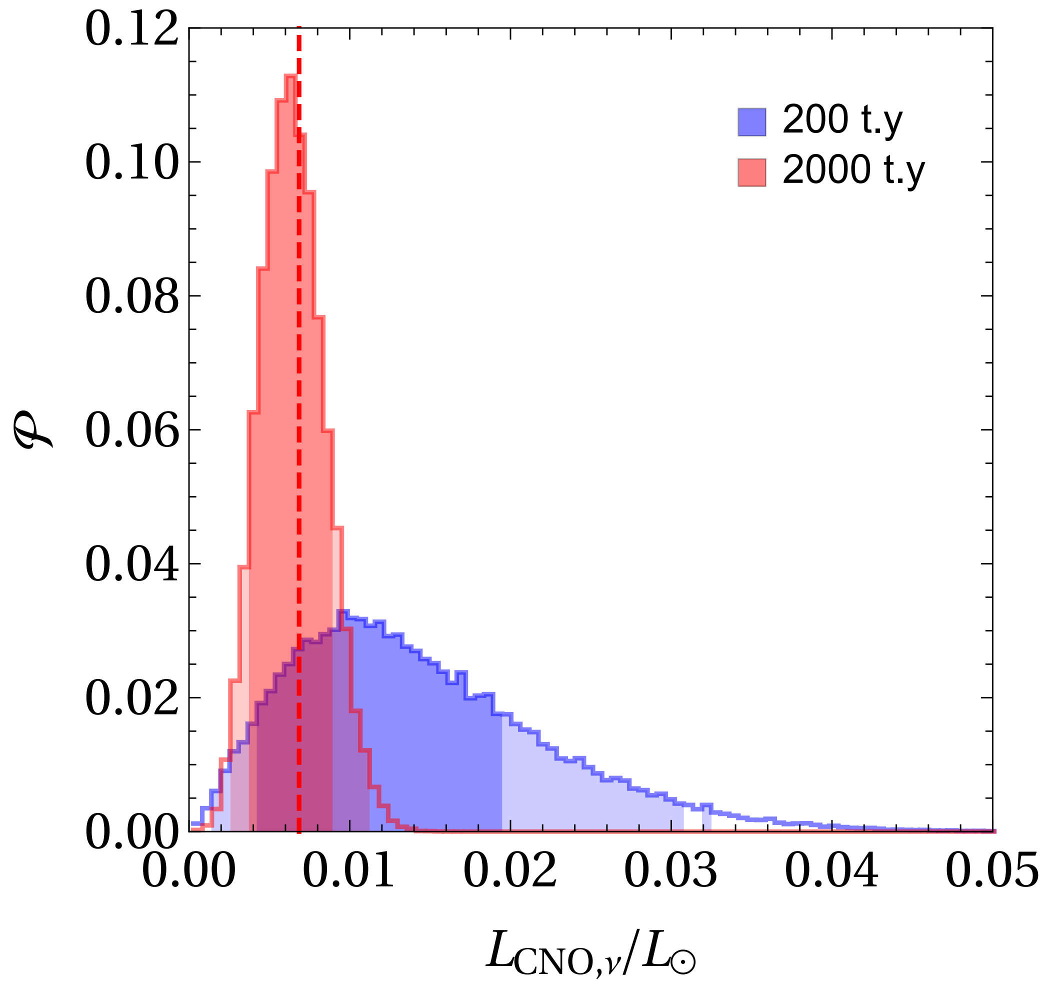


Newstead, LS, Lang, PRD 2018

- 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

Neutrino luminosity of the Sun





- 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)

Conclusions

- **8B solar neutrino flux**:
  - Measurement of the neutral current energy spectrum
  - Implications for solar metallicity
  - New means to study Non-Standard Neutrino Interactions and sterile neutrinos
- **pp solar neutrinos**
  - ~1-10 keV electron recoils; measures the ``neutrino luminosity" of the Sun
  - New physics from lowest-energy detected nuclear recoils?
- **CNO solar neutrino flux**
  - High energy (> 100 keV) electron recoils
- **Interplay with terrestrial searches for new physics**