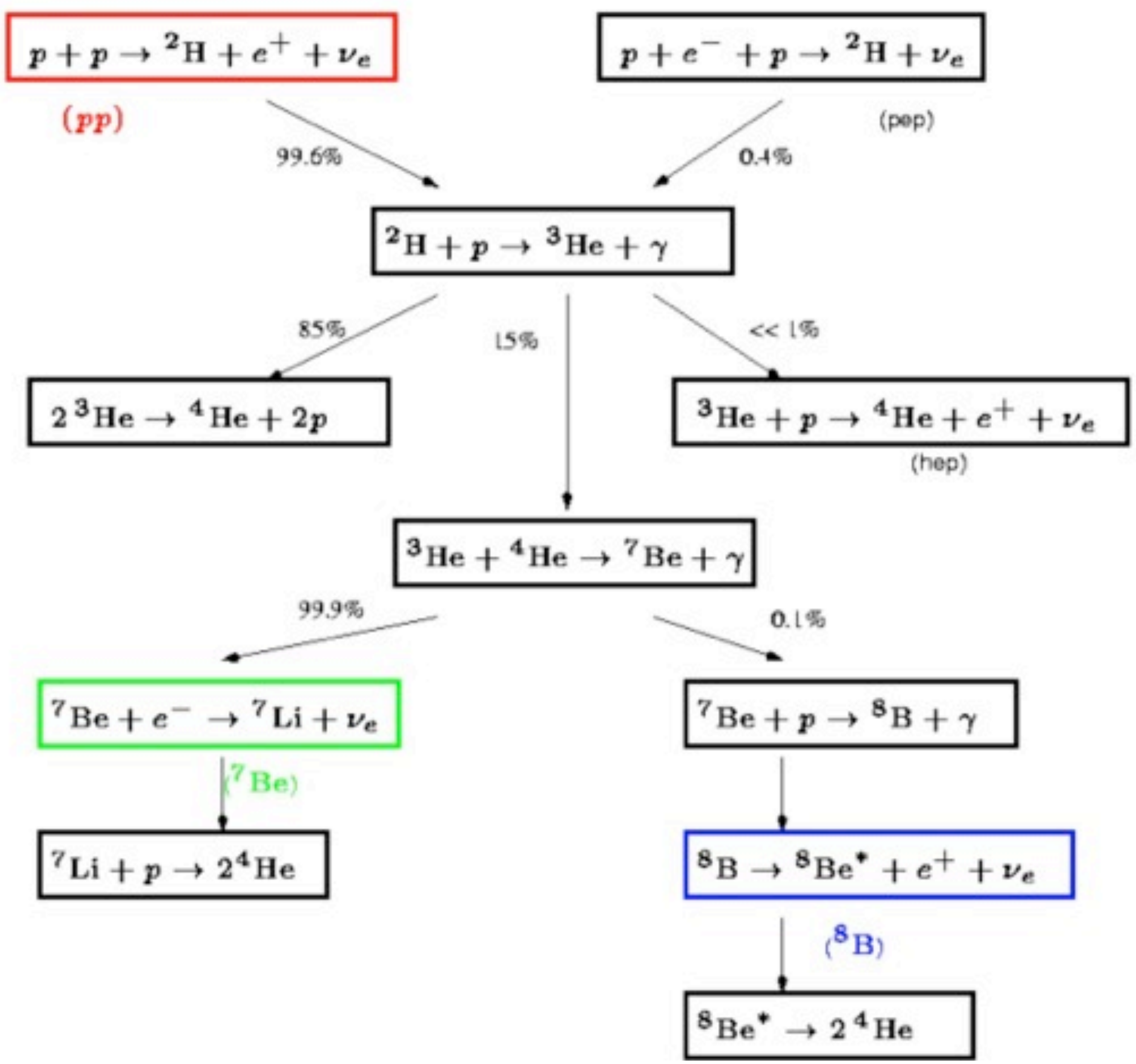
Everything Under the Sun

Gabriel D. Orebi Gann
Neutrino 2014, Boston
June 3rd, 2014

U. C. Berkeley
& LBNL

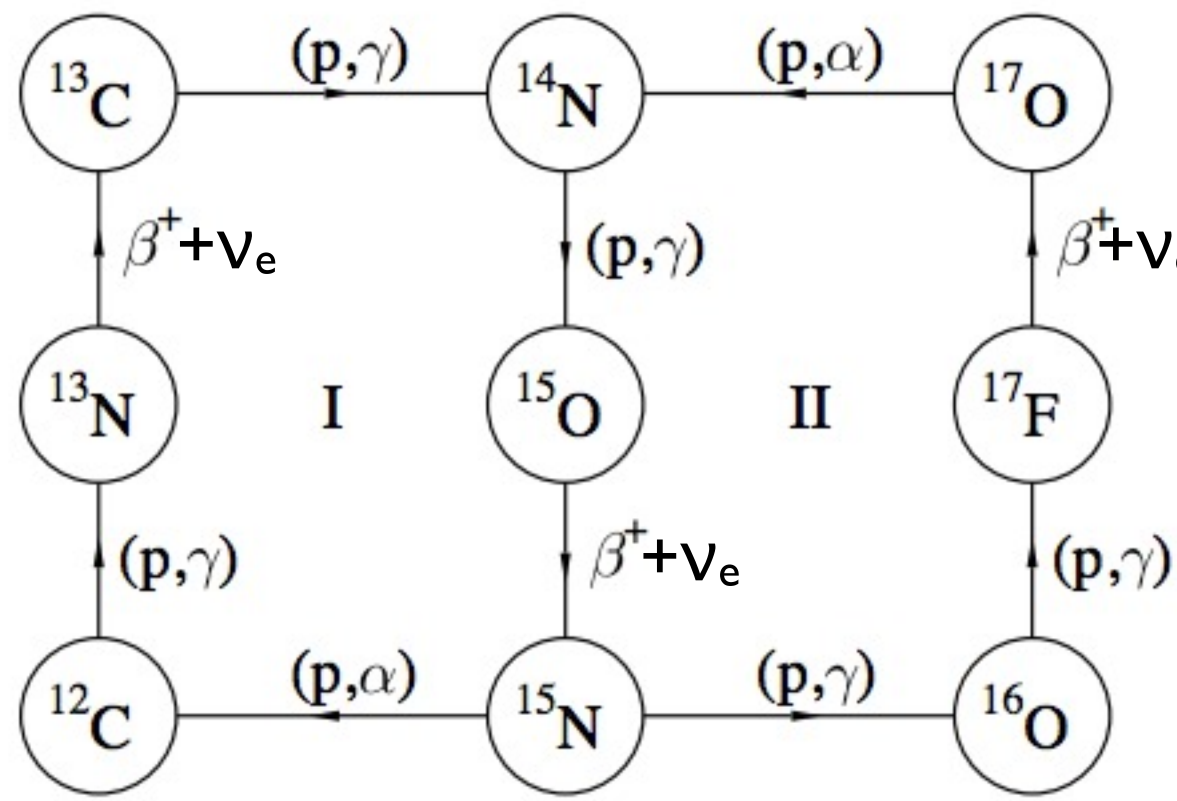
Modern Understanding

pp Chain



CNO Cycle

(contributes ~1% of solar energy)



The Astrophysical Journal **687** (2008) 678

Modern Understanding

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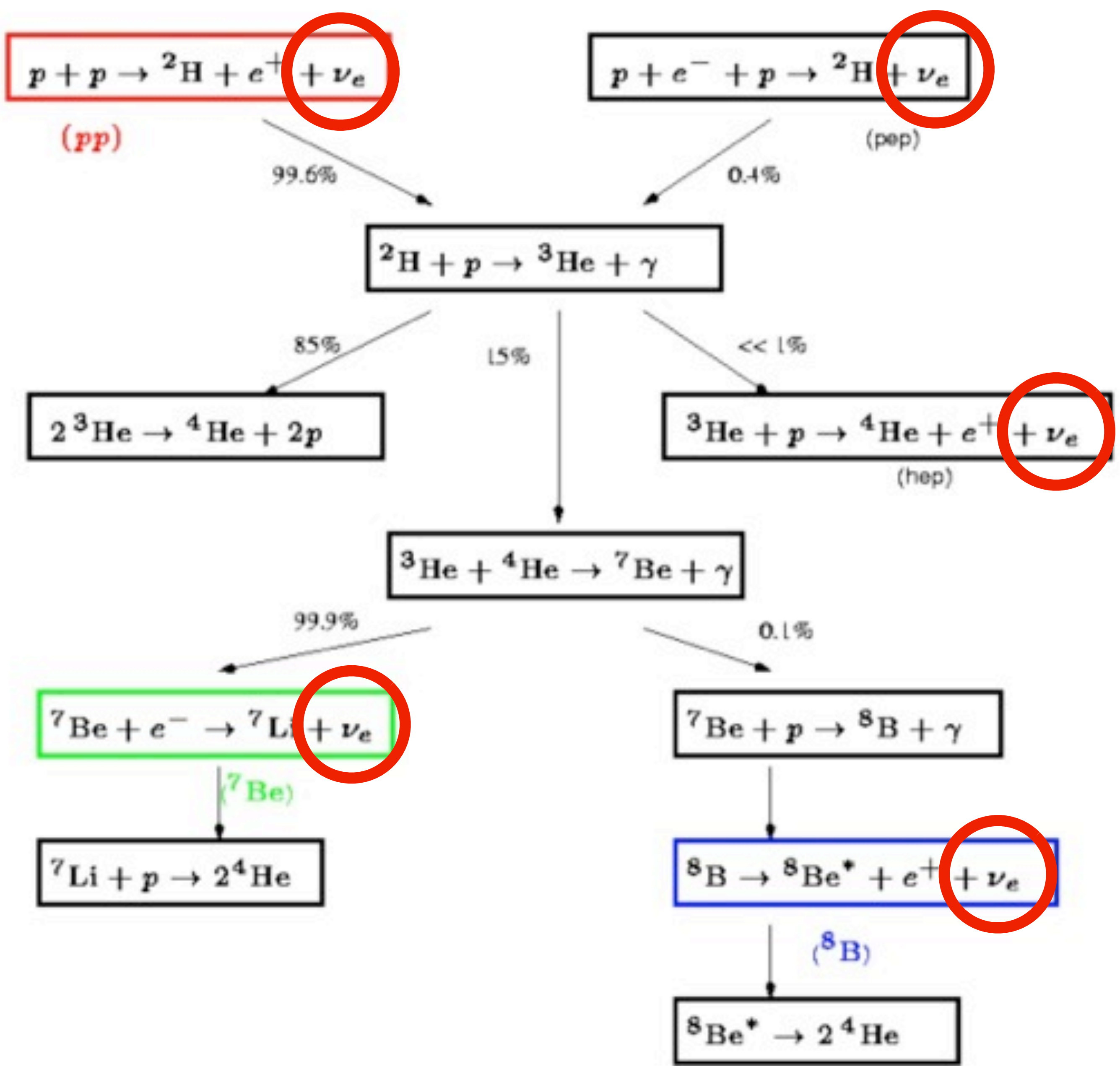

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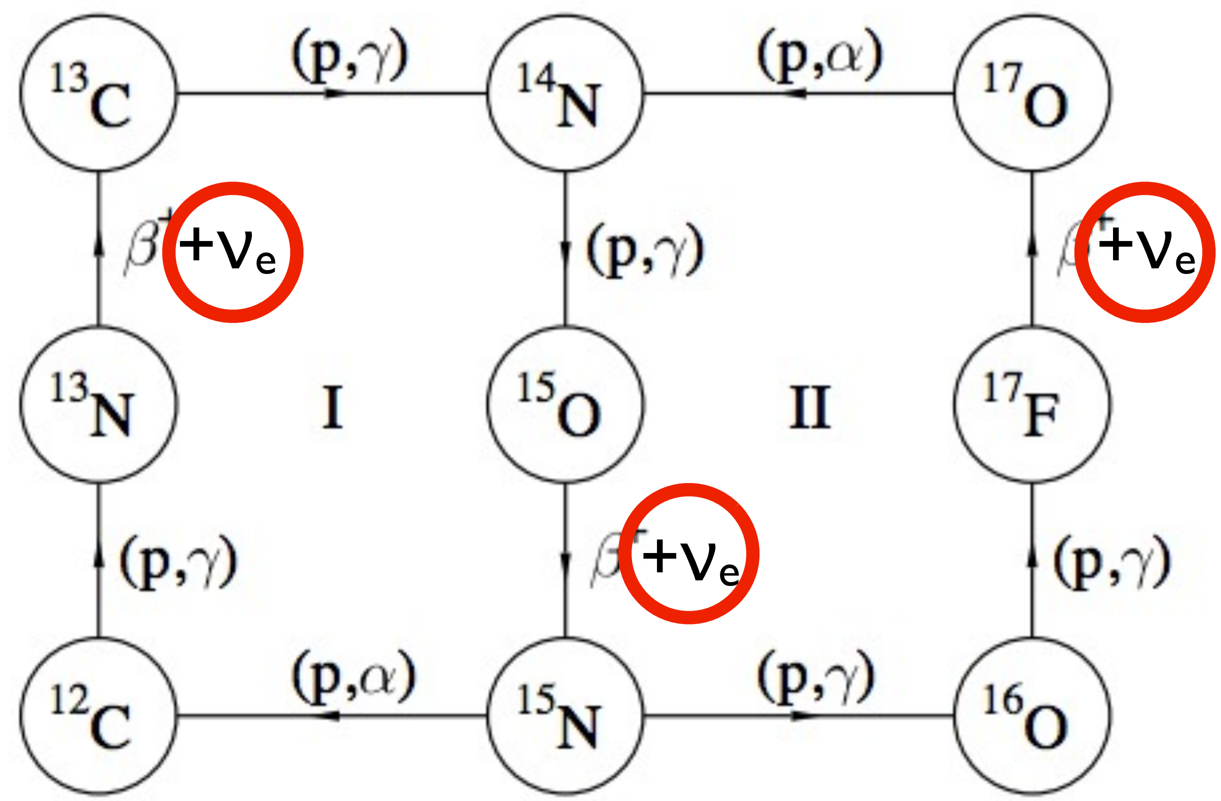
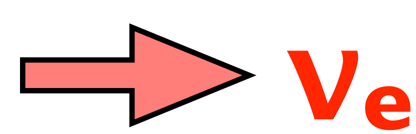
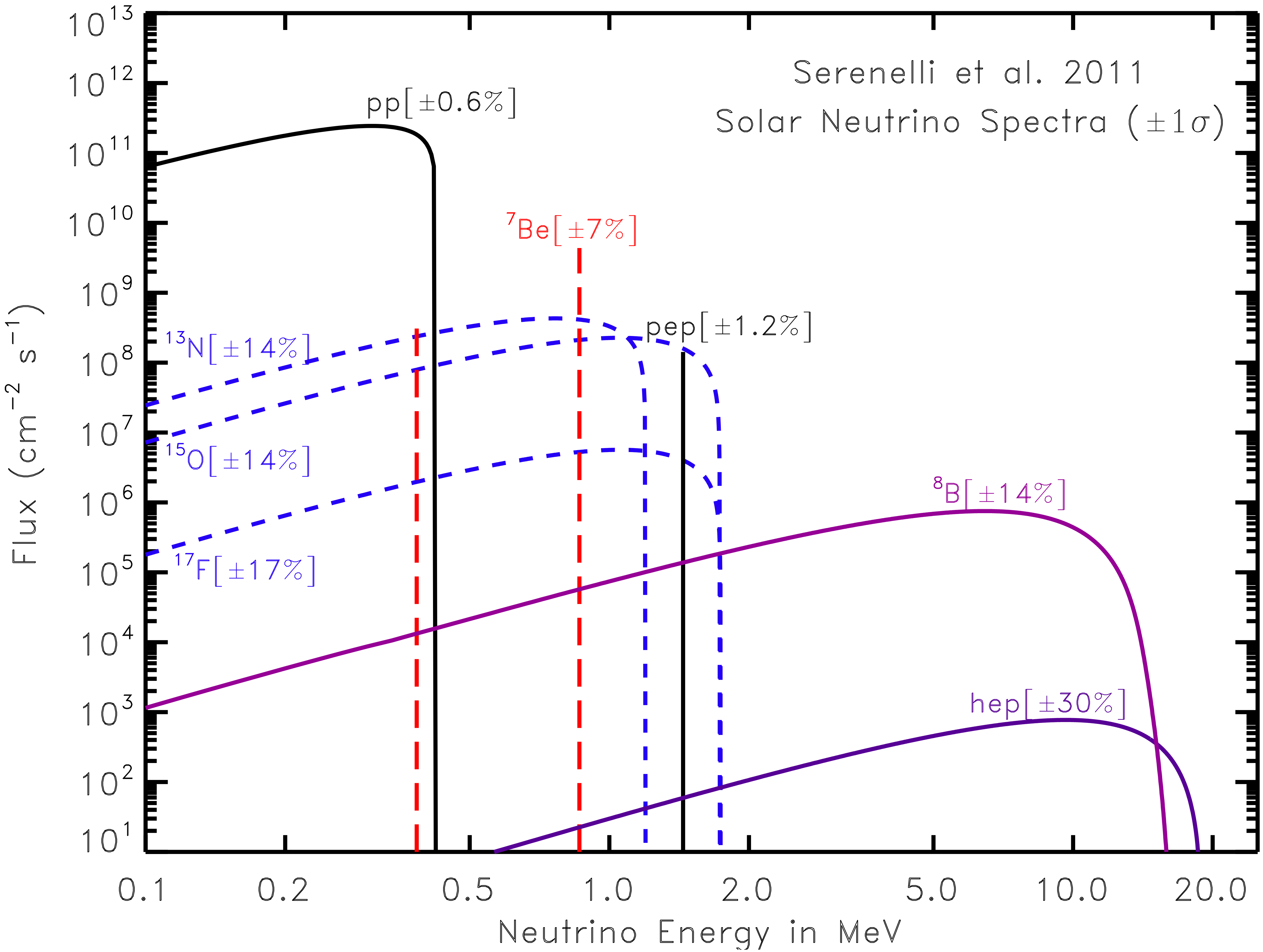




The Astrophysical Journal **687** (2008) 678

Solar Neutrino Energy Spectra



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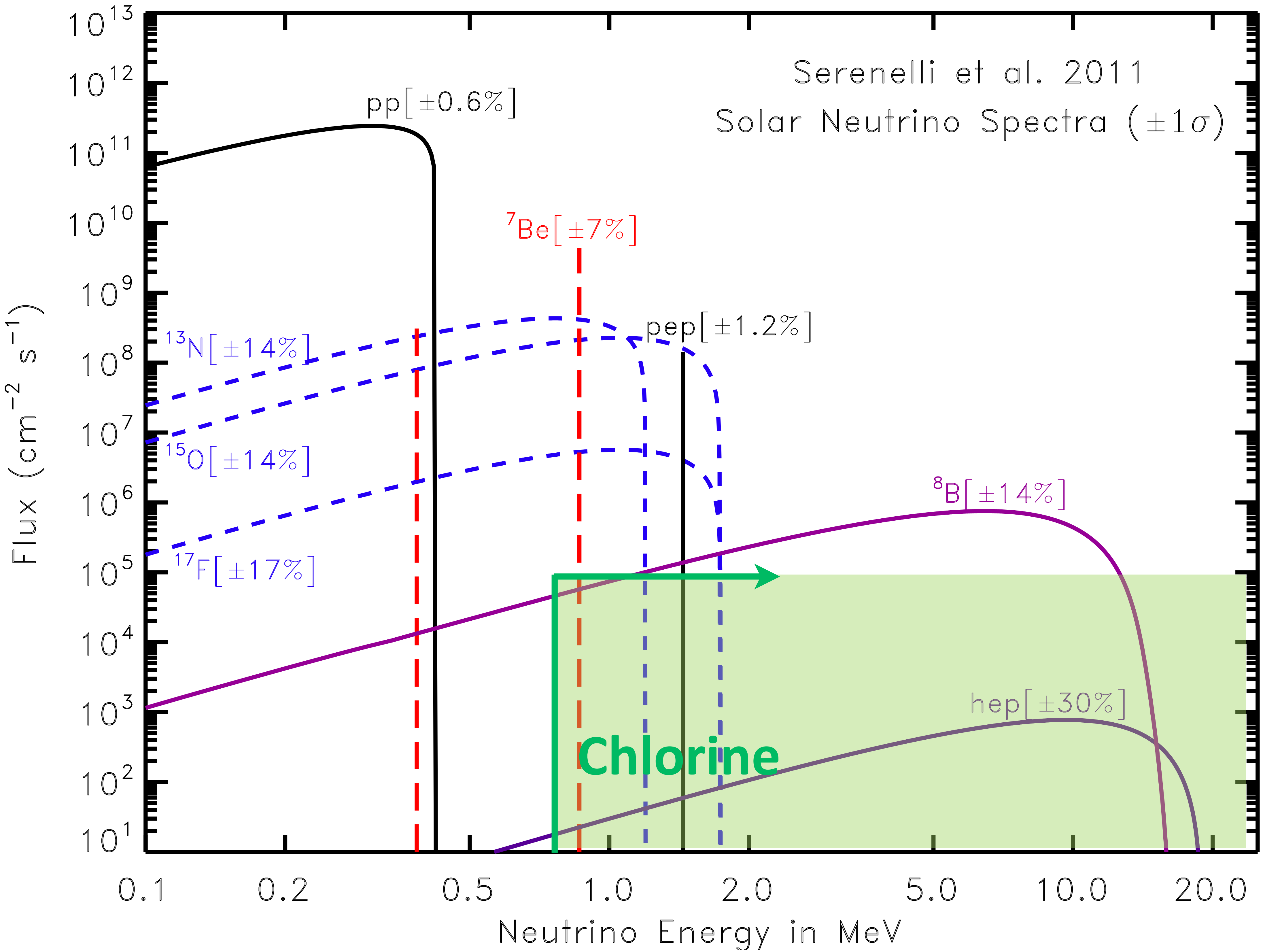

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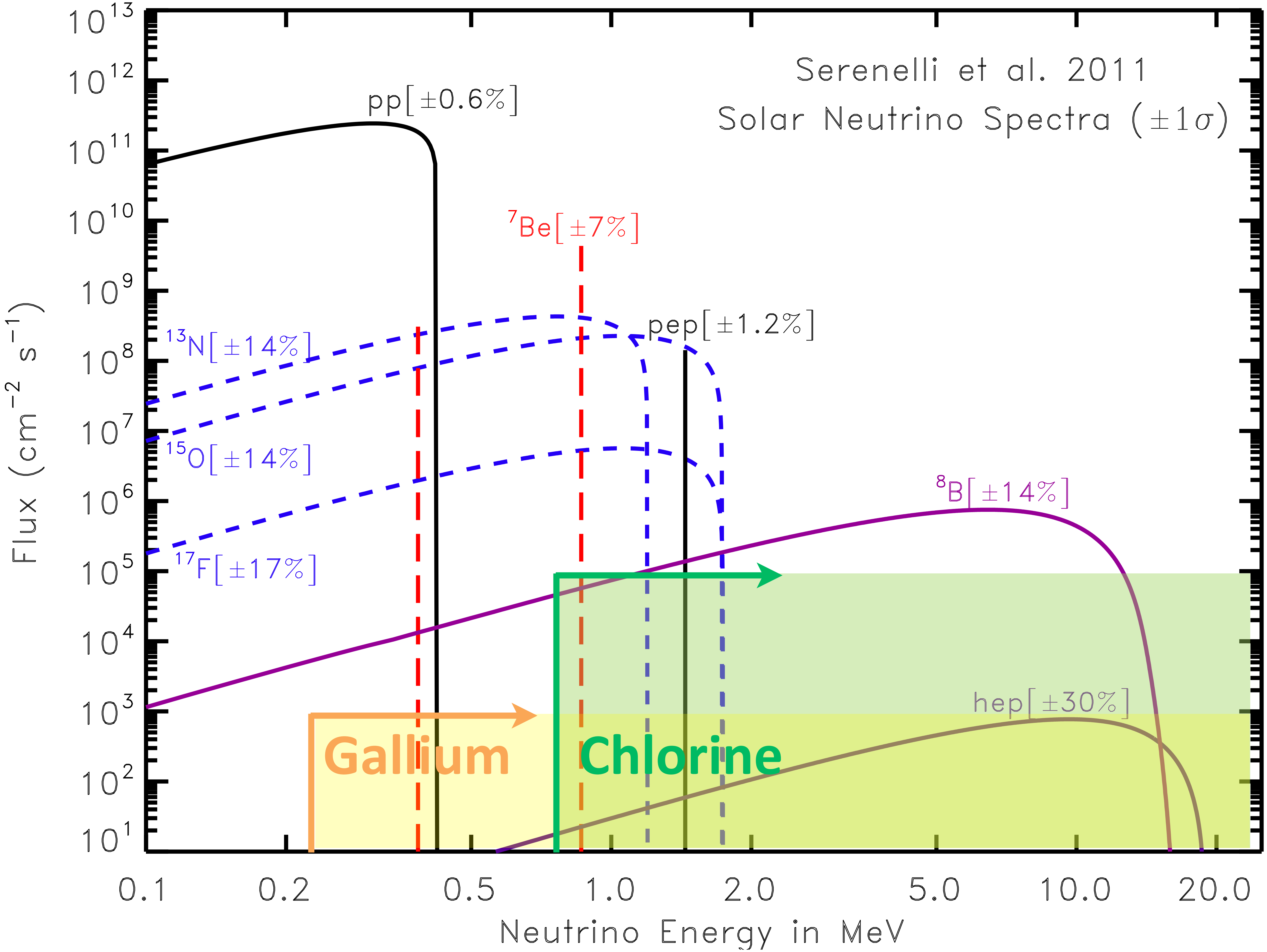

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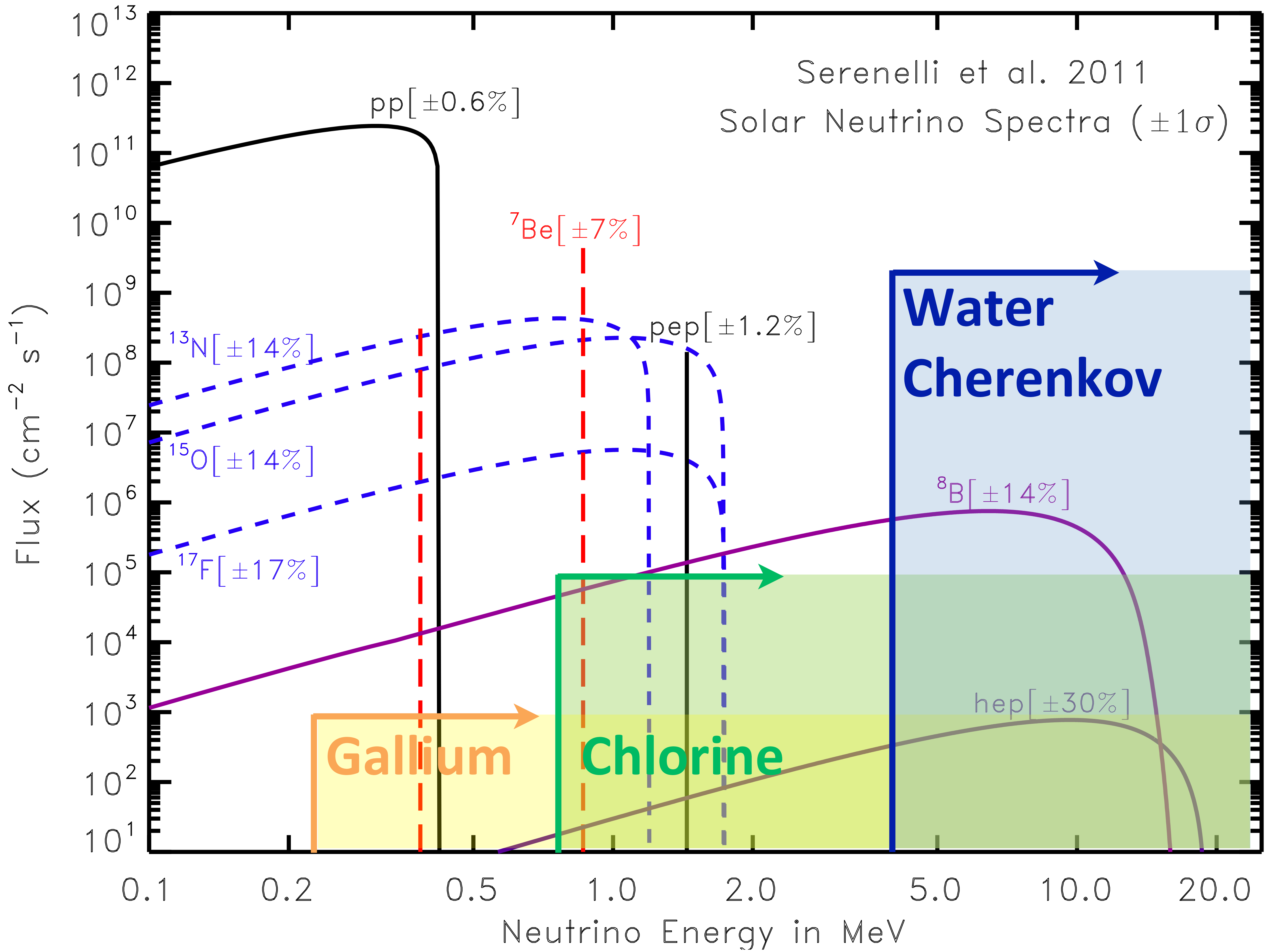

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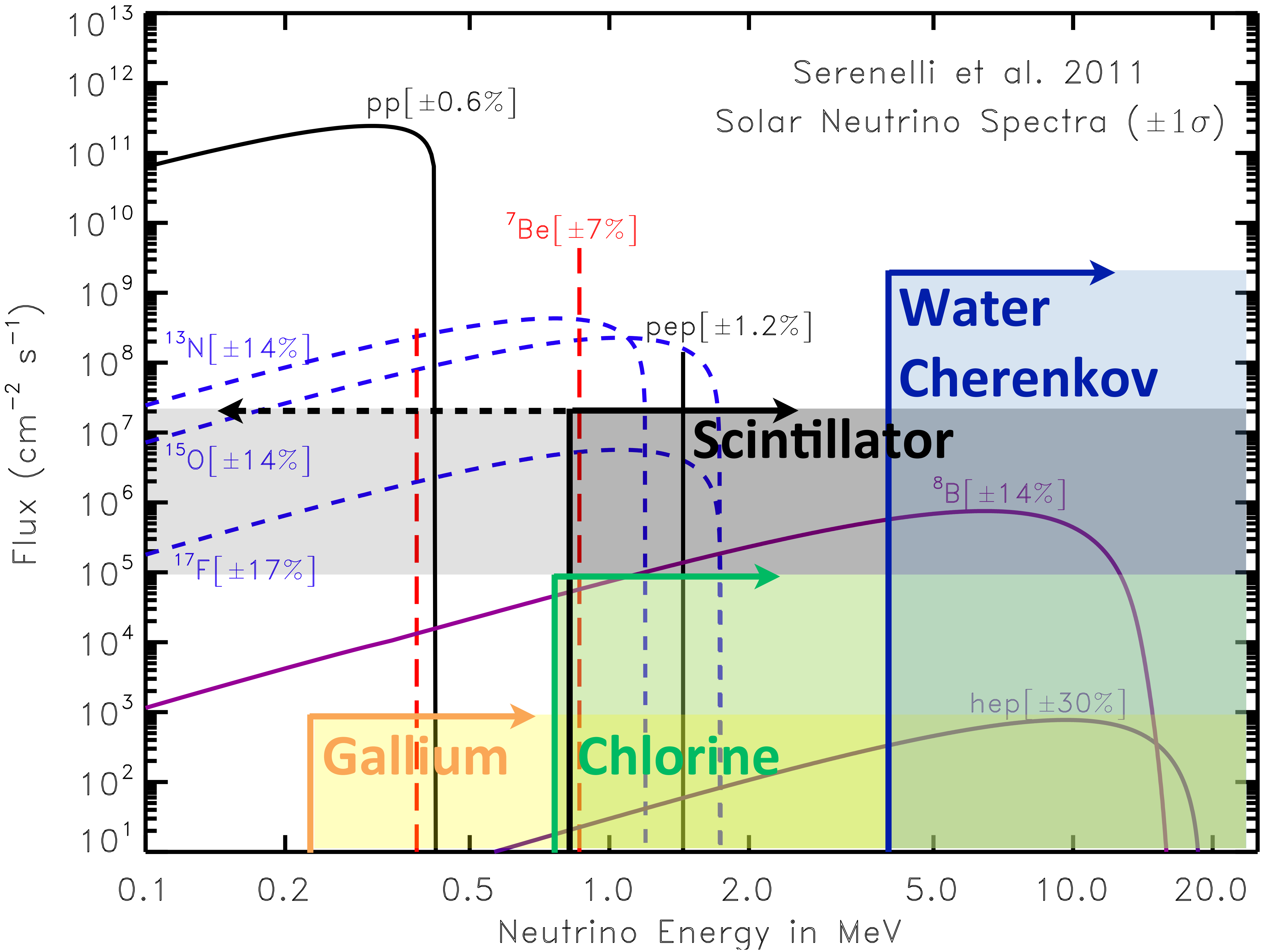


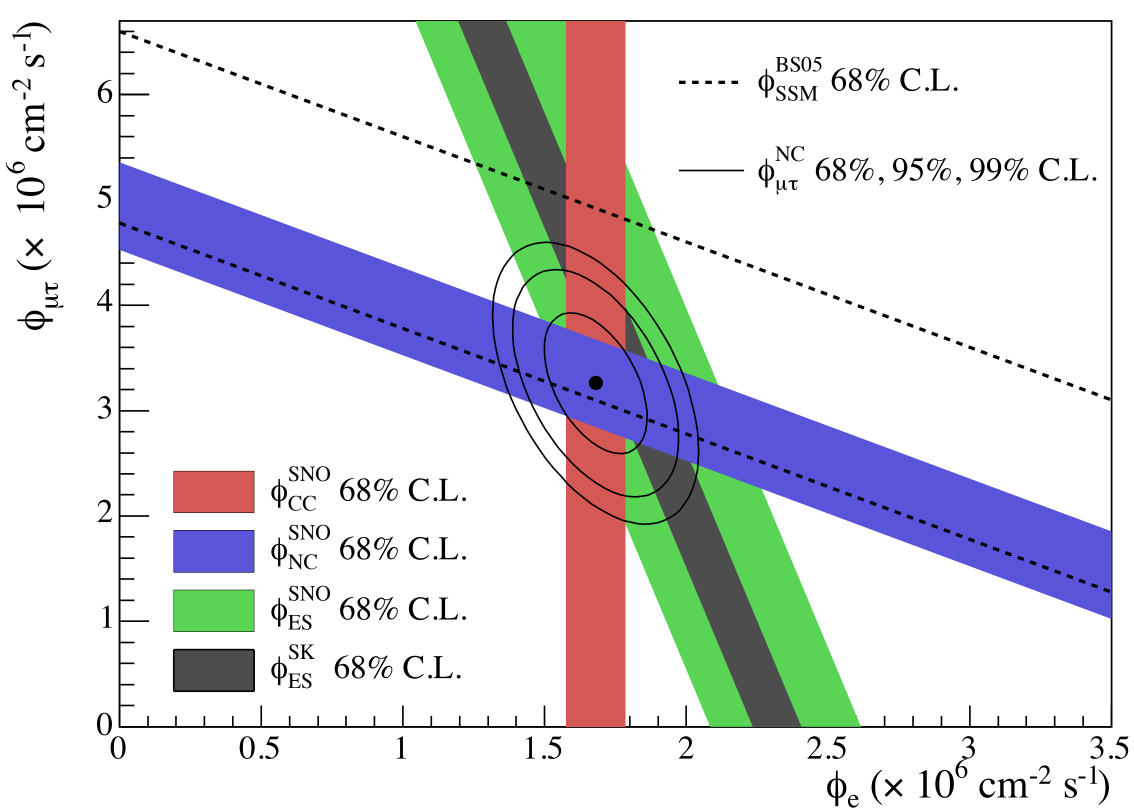
Solving the Solar Neutrino Problem

Inclusive appearance at the Sudbury Neutrino Observatory

ES: $\nu_x + e^- \rightarrow e^- + \nu_x$

CC: $\nu_e + {}^2H \rightarrow e^- + 2p$

NC: $\nu_x + {}^2H \rightarrow n + p + \nu_x$



PRL 87 (2001) 071301, PRL 89 (2002) 011301

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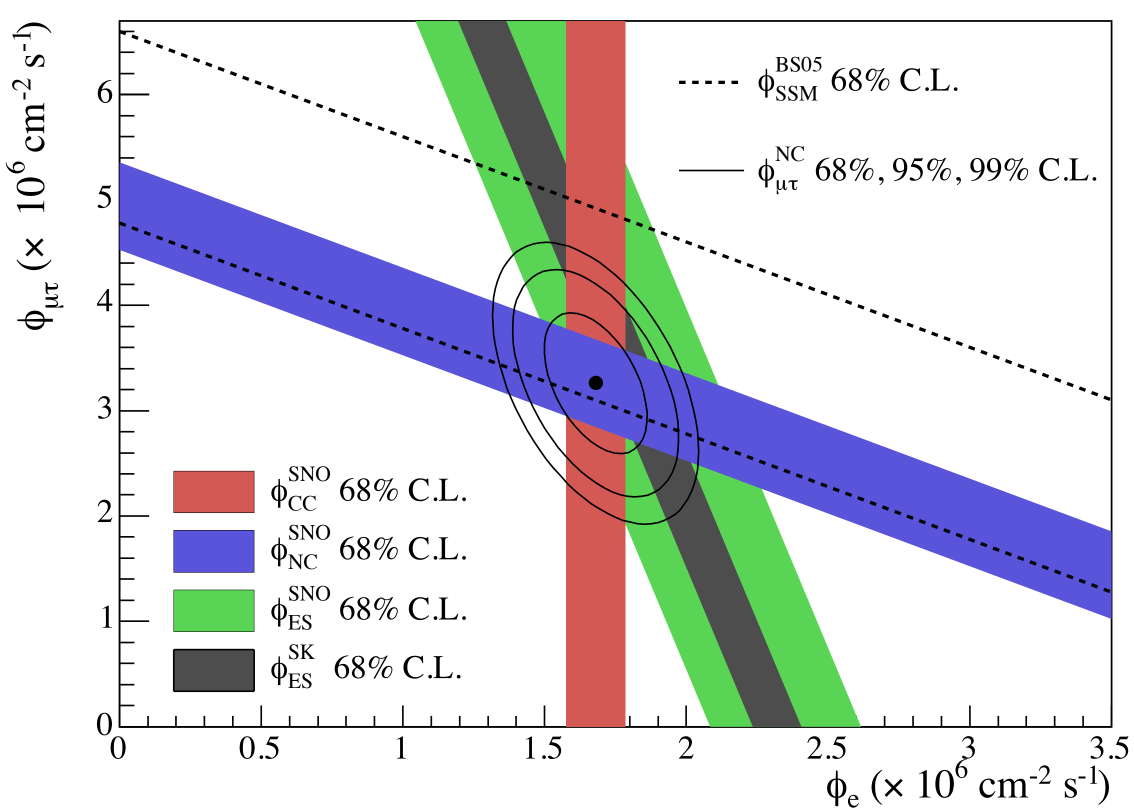
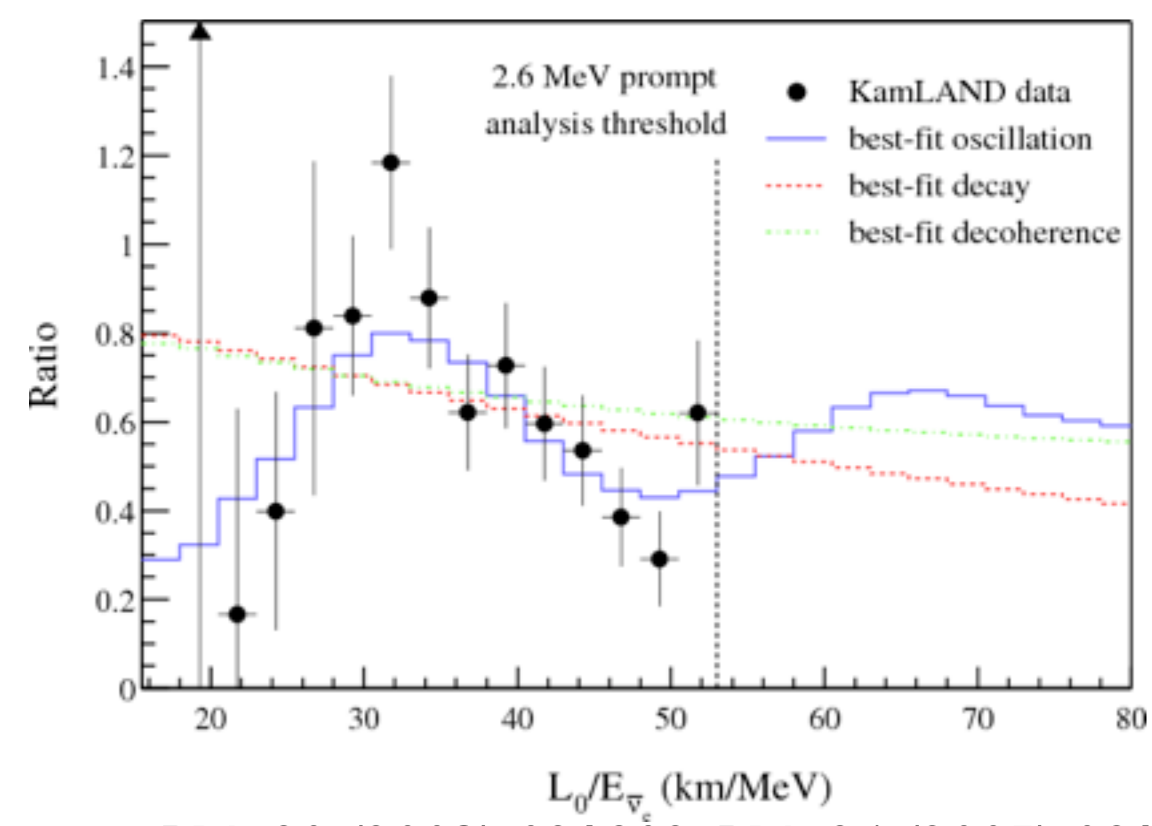


PRL 87 (2001) 071301, PRL 89 (2002) 011301

Oscillations at KamLAND

Disappearance at >99.99%

Clear oscillation pattern



PRL 90 (2003) 021802, PRL 94 (2005) 081801

Solar Neutrinos

"For 35 years people said to me: `John, we just don't understand the Sun well enough to be making claims about the fundamental nature of neutrinos, so we shouldn't waste time with all these solar neutrino experiments.'

Then the SNO results came out.

And the next day people said to me, `Well, John, we obviously understand the Sun perfectly well! No need for any more of these solar neutrino experiments.'"

--- John Bahcall, 2003

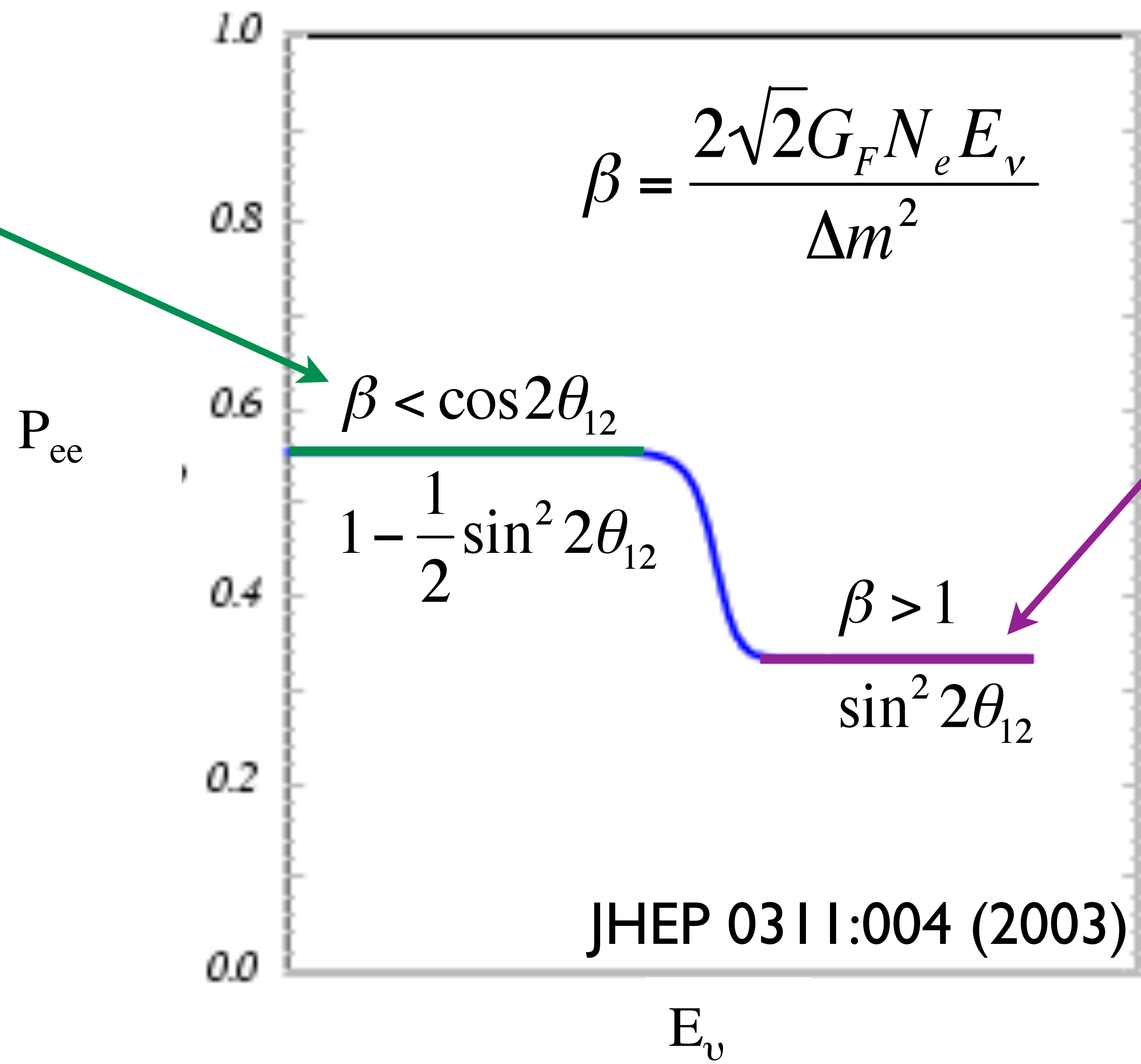
Physics Beyond the SNP

(1) Searching for new physics:

ν_e survival probability shape

(1) Vacuum-Matter Transition

Low energy (<1MeV):
Phase-averaged vacuum oscillations



'High' energy (>5MeV):
Matter-dominated resonant conversion

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In these regimes, P_{ee} depends only on θ_{12},
Not the mass splitting or neutrino-matter interaction

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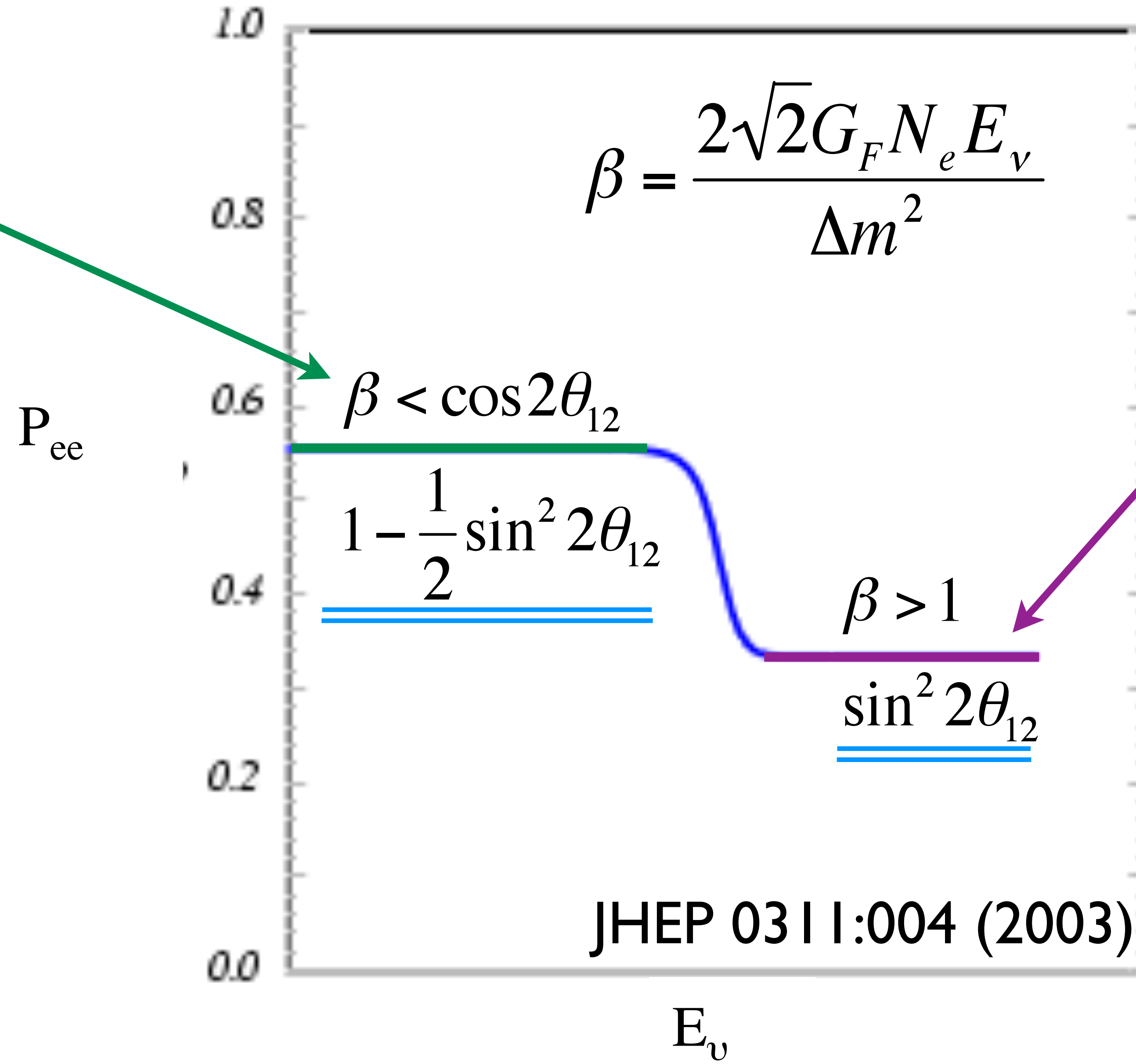

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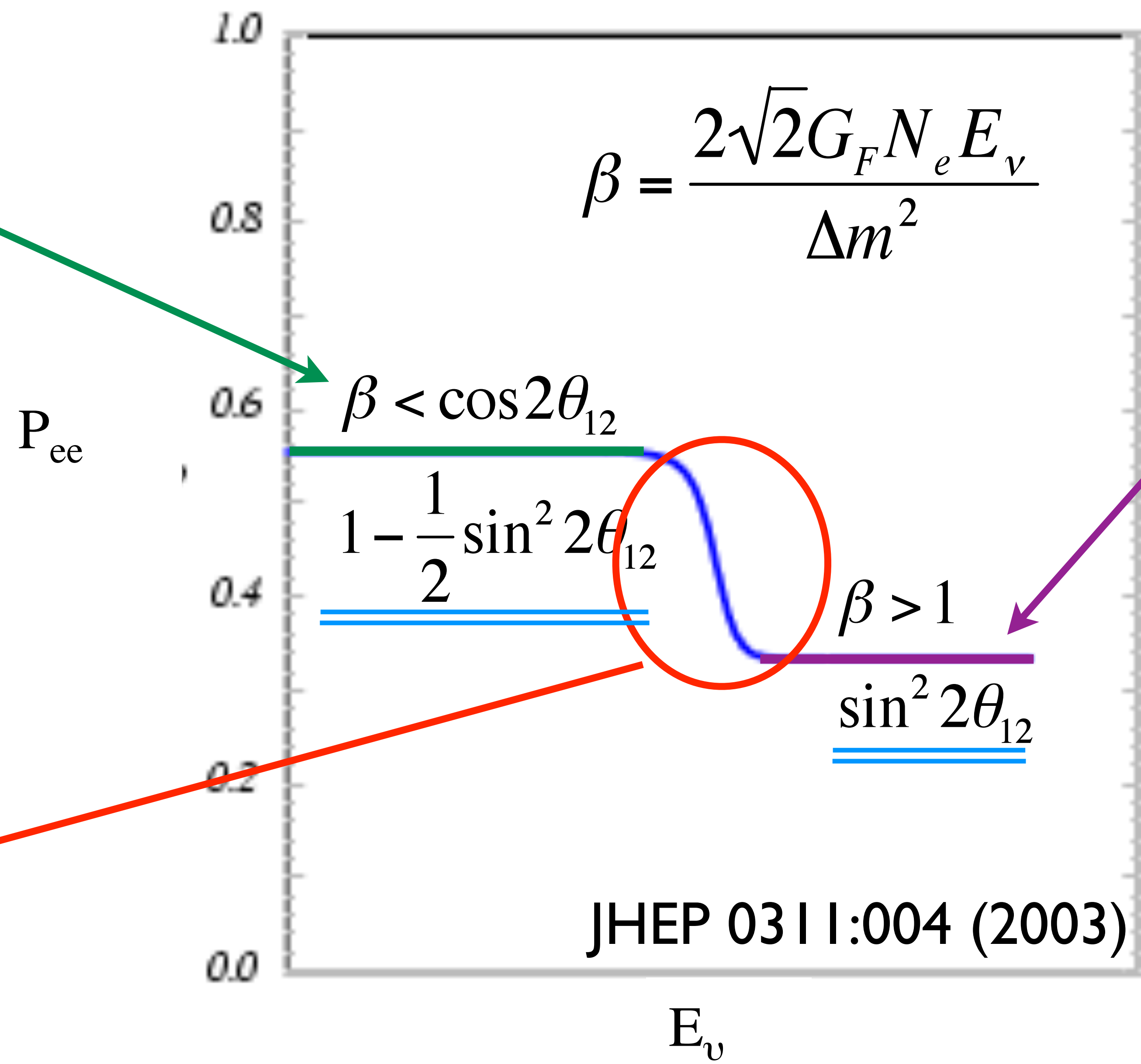


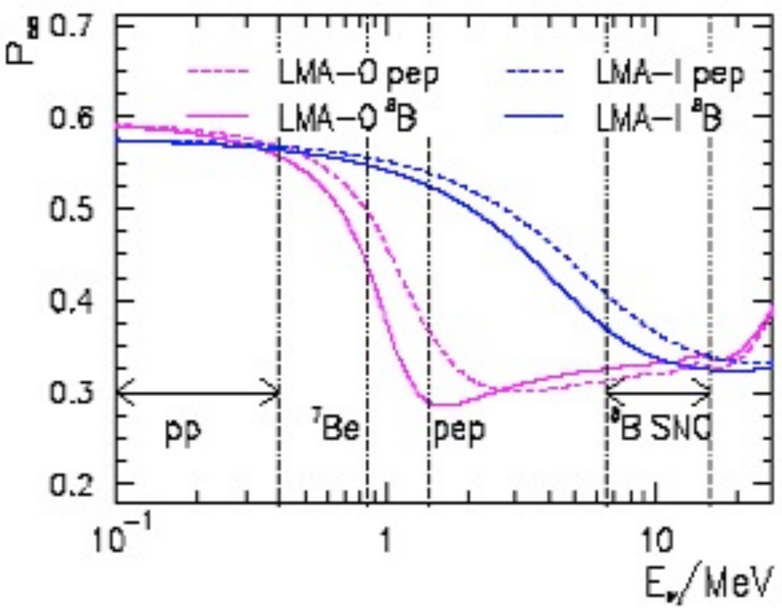
'High' energy (>5MeV):
Matter-dominated resonant conversion

Probe transition region to confirm MSW

Probing the Unknown

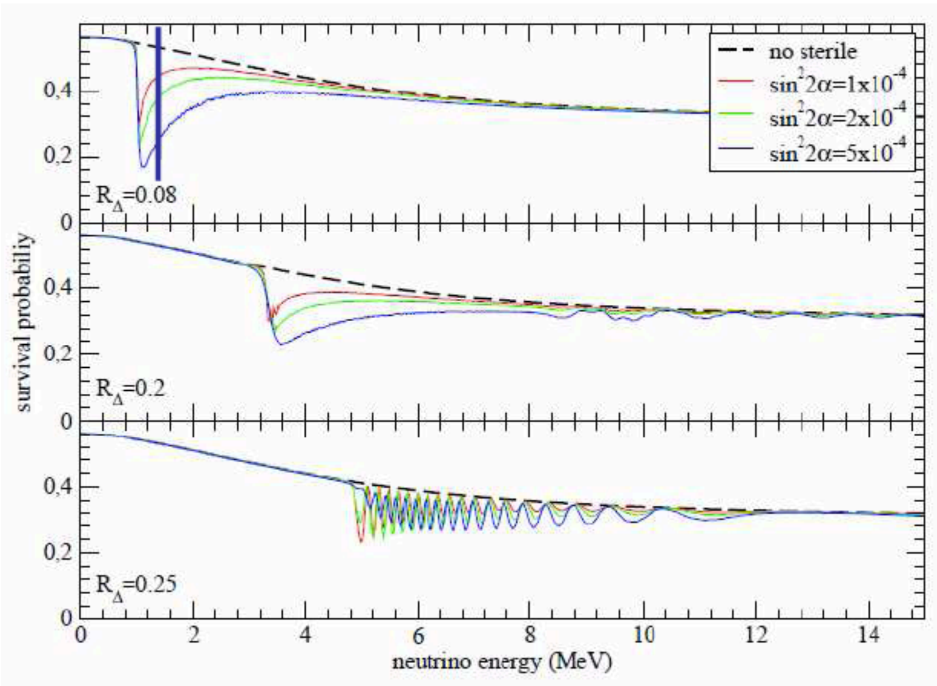
Non-standard physics effects can alter the shape / position of the "MSW rise"

Non-standard interactions (flavour changing NC)



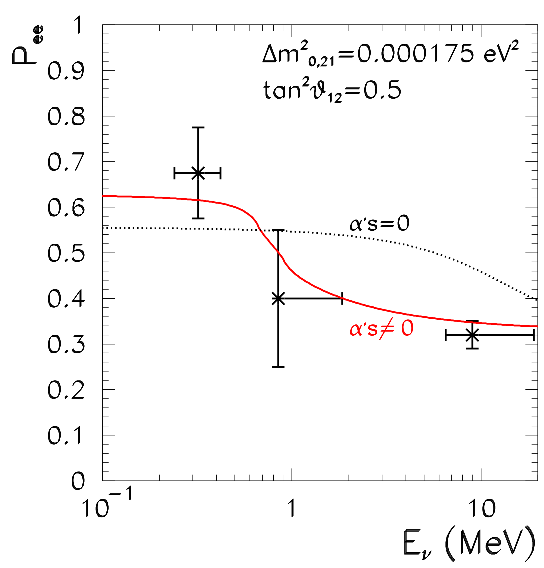
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov
PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)

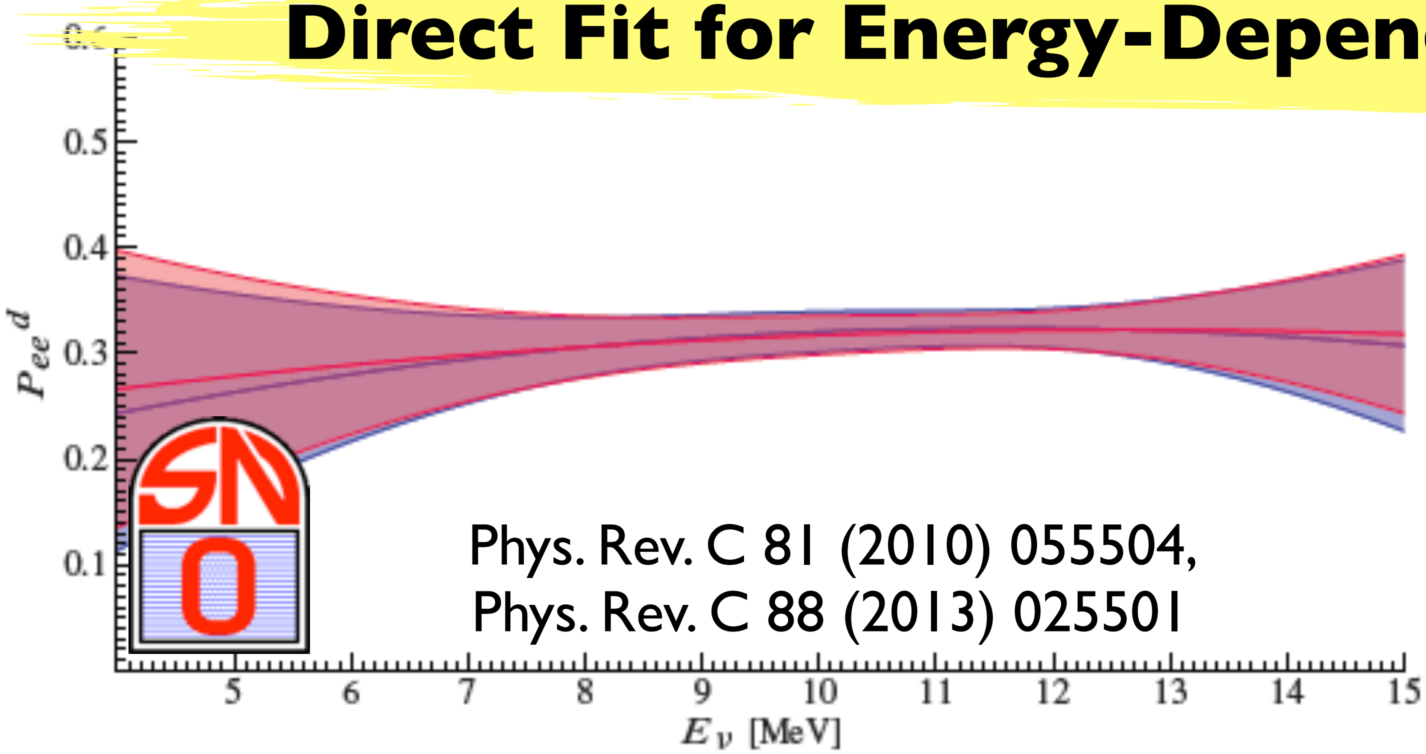


M.C. Gonzalez-Garcia, M. Maltoni
Phys Rept 460:1-129 (2008)

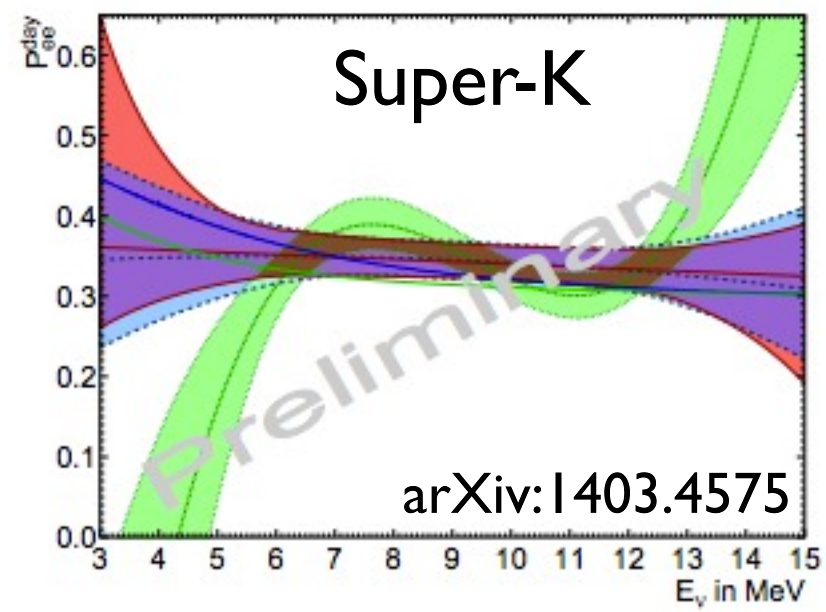
Precision Era

Low Energy Threshold Analysis

Direct Fit for Energy-Dependent Survival Probability



Phys. Rev. C 81 (2010) 055504,
Phys. Rev. C 88 (2013) 025501



arXiv:1403.4575

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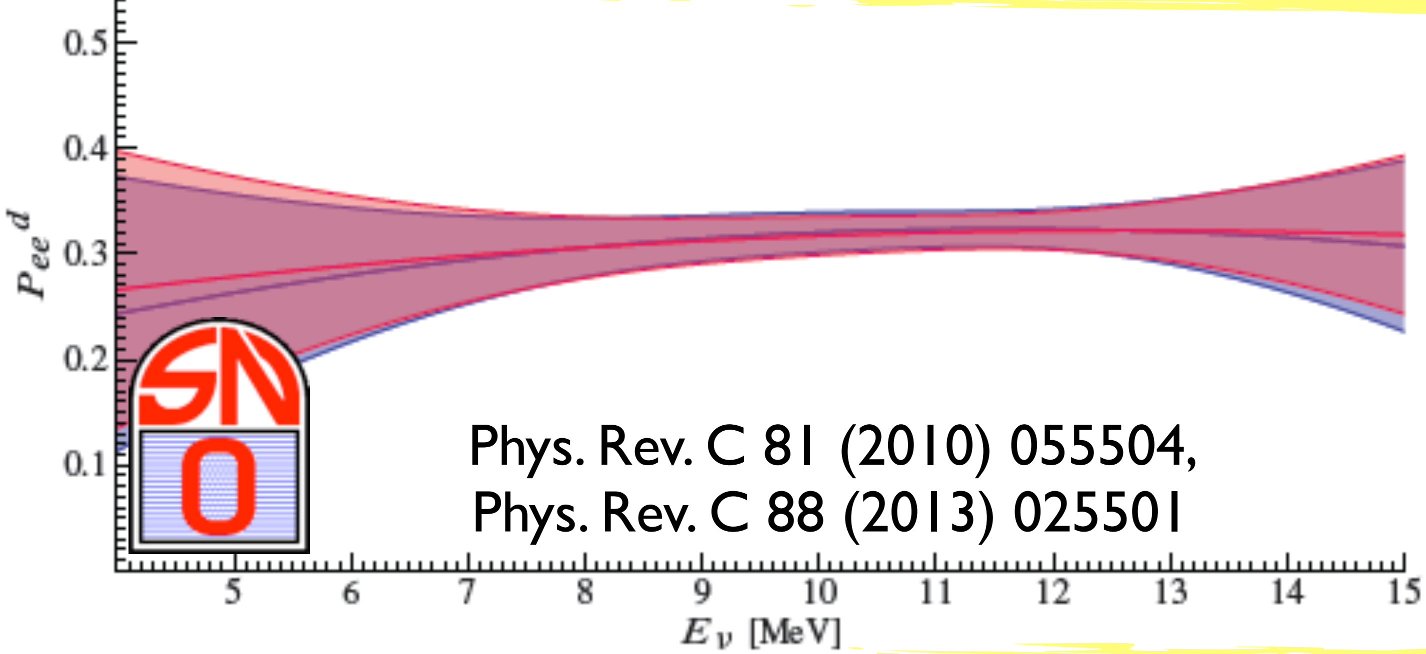

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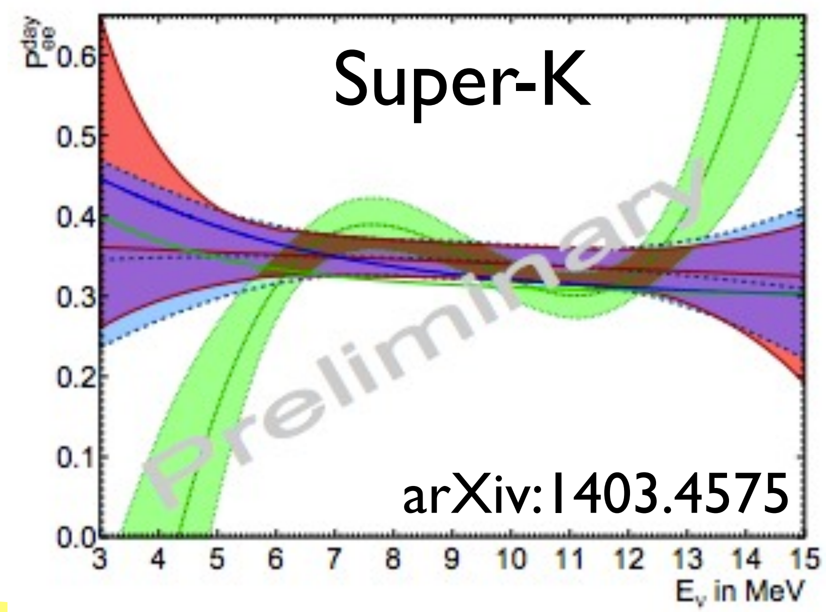
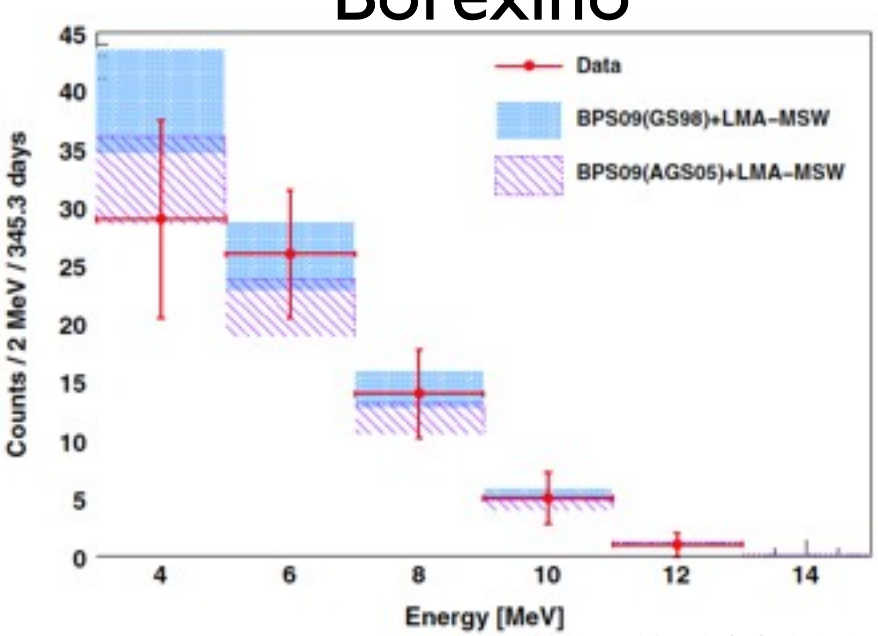


arXiv:1403.4575

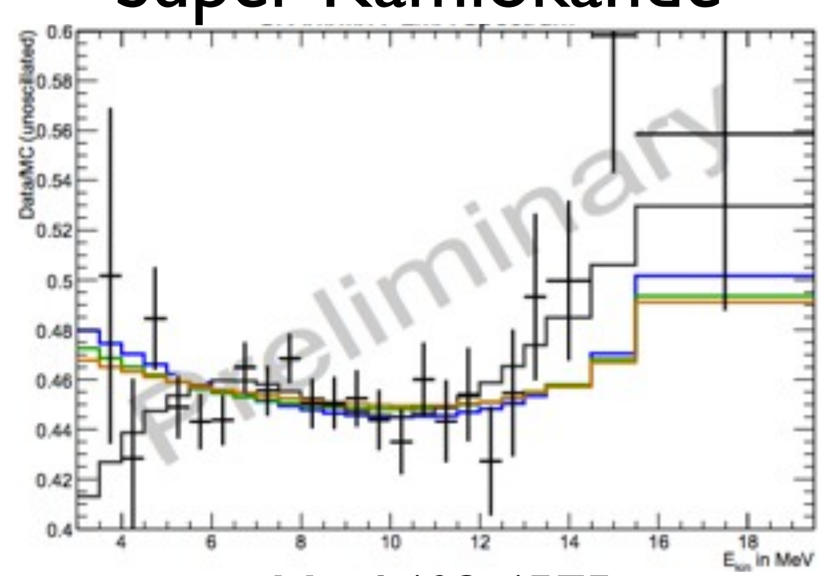
Electron recoil spectra

Borexino



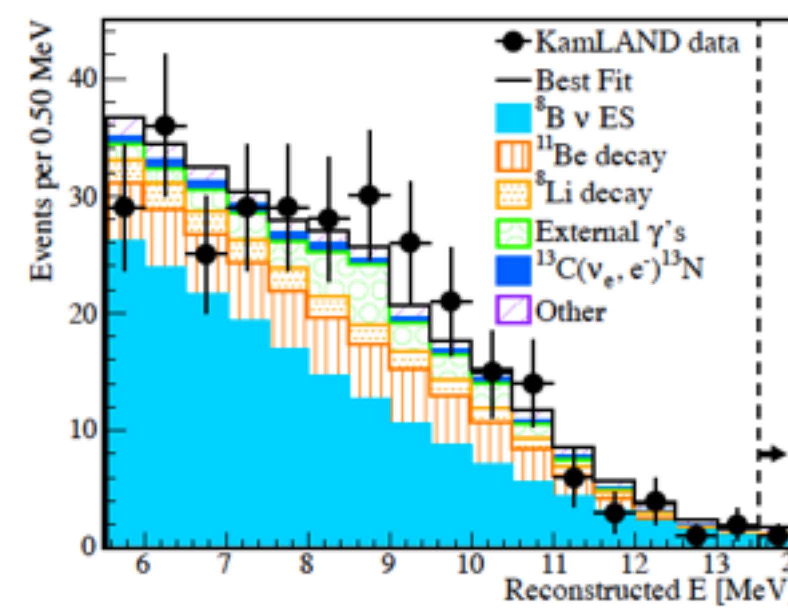
Phys. Rev. D 82 (2010) 033006

Super-Kamiokande



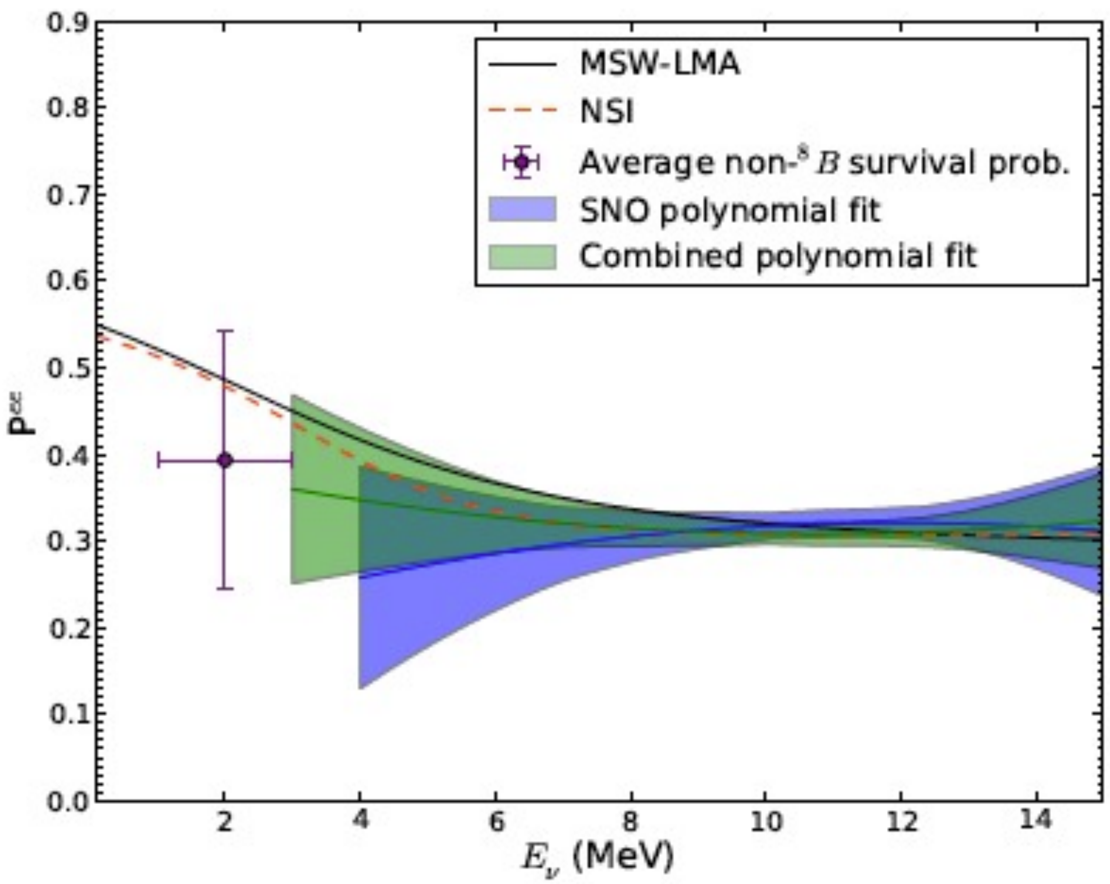
arXiv:1403.4575

KamLAND

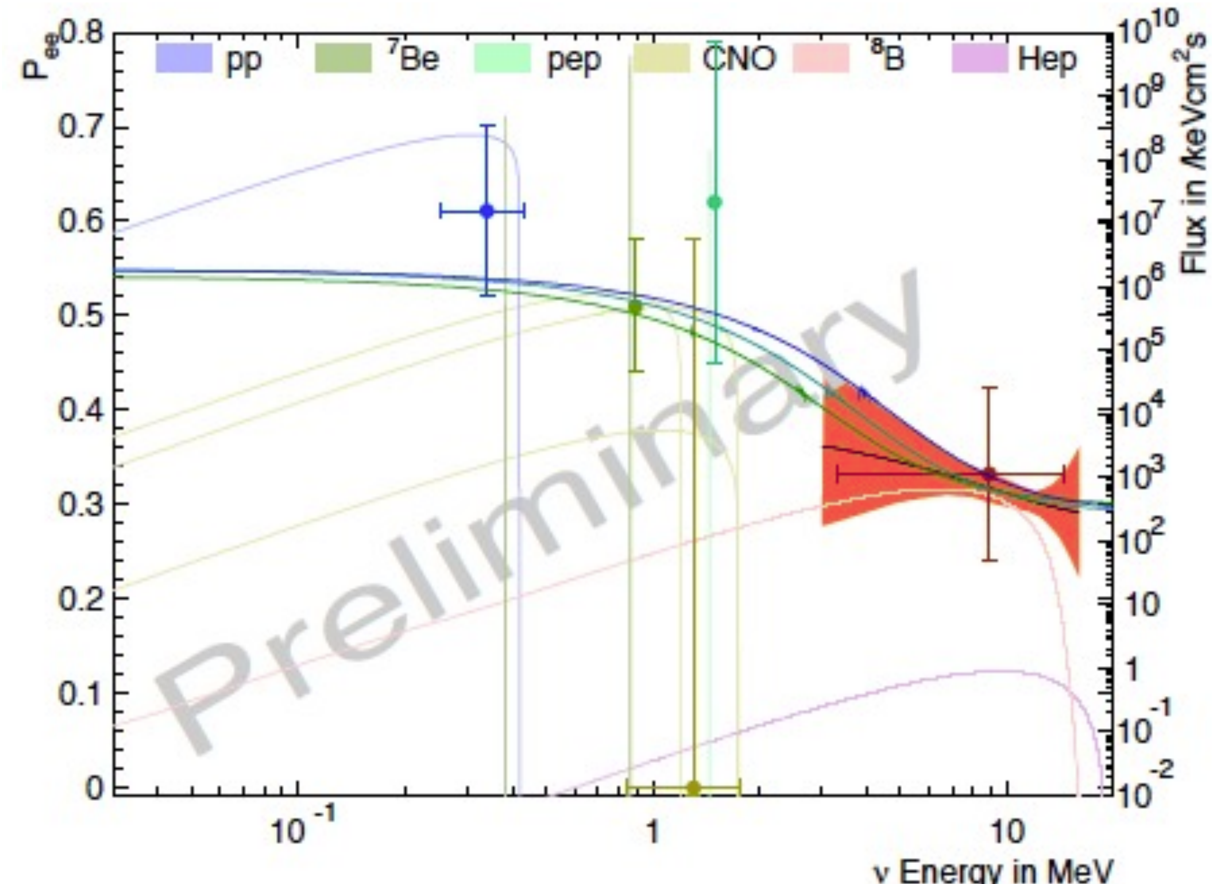


Phys. Rev. C 84 (2011) 035804

Survival Probability



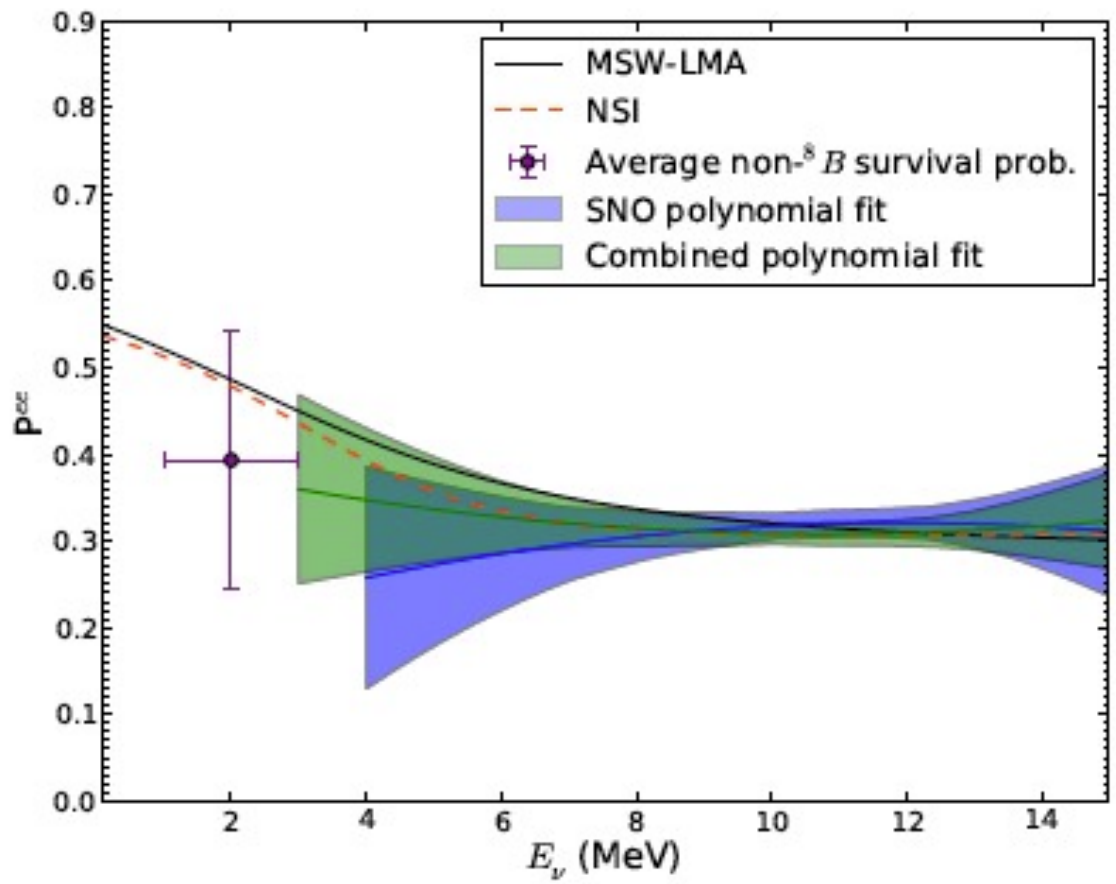
R. Bonventre et al.
arXiv 1305.5835 (May 2013)
Phys. Rev. D 88 (2013) 053010



Super-K collab
arXiv 1403.4575 (Mar 2014)

Posters:
Dr Nakano, #83

Survival Probability



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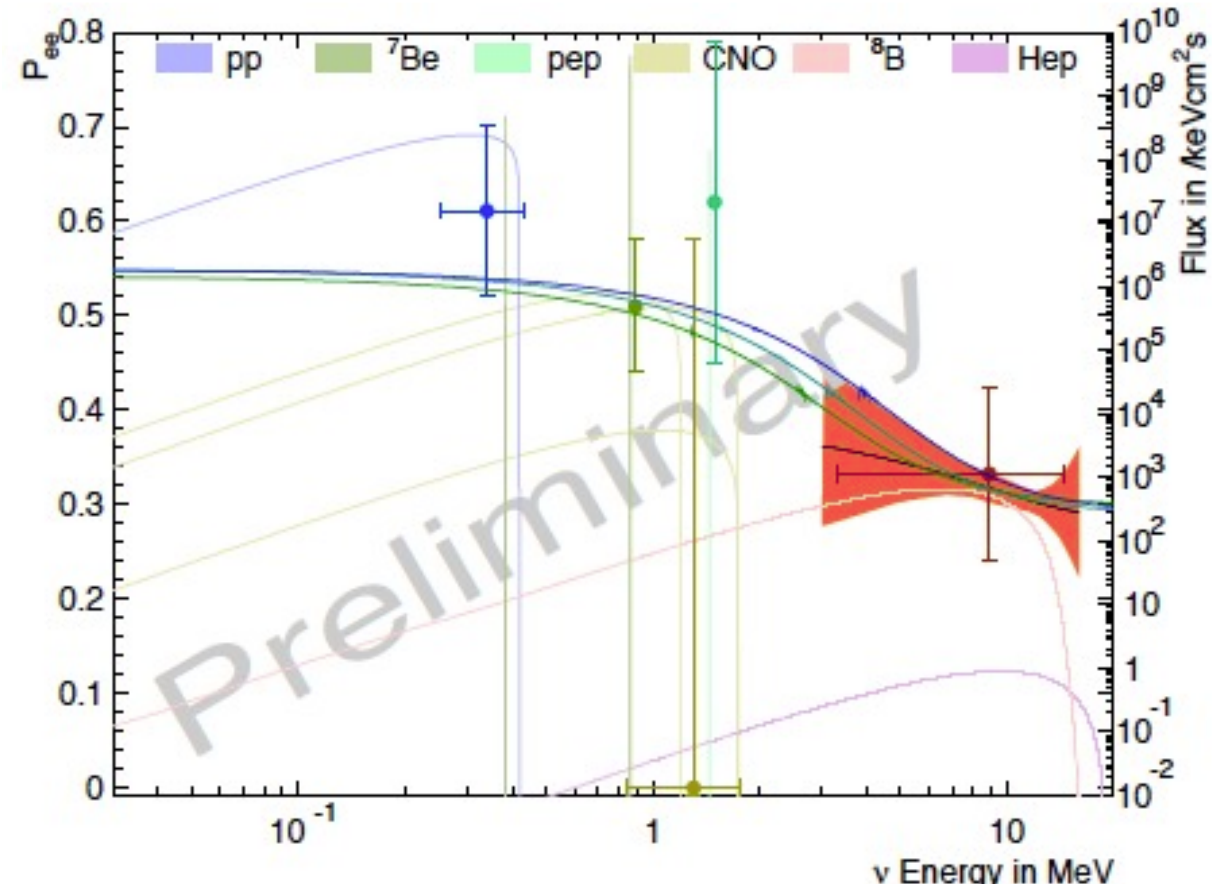

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Apparent turn-up is a feature of the quadratic parameterisation

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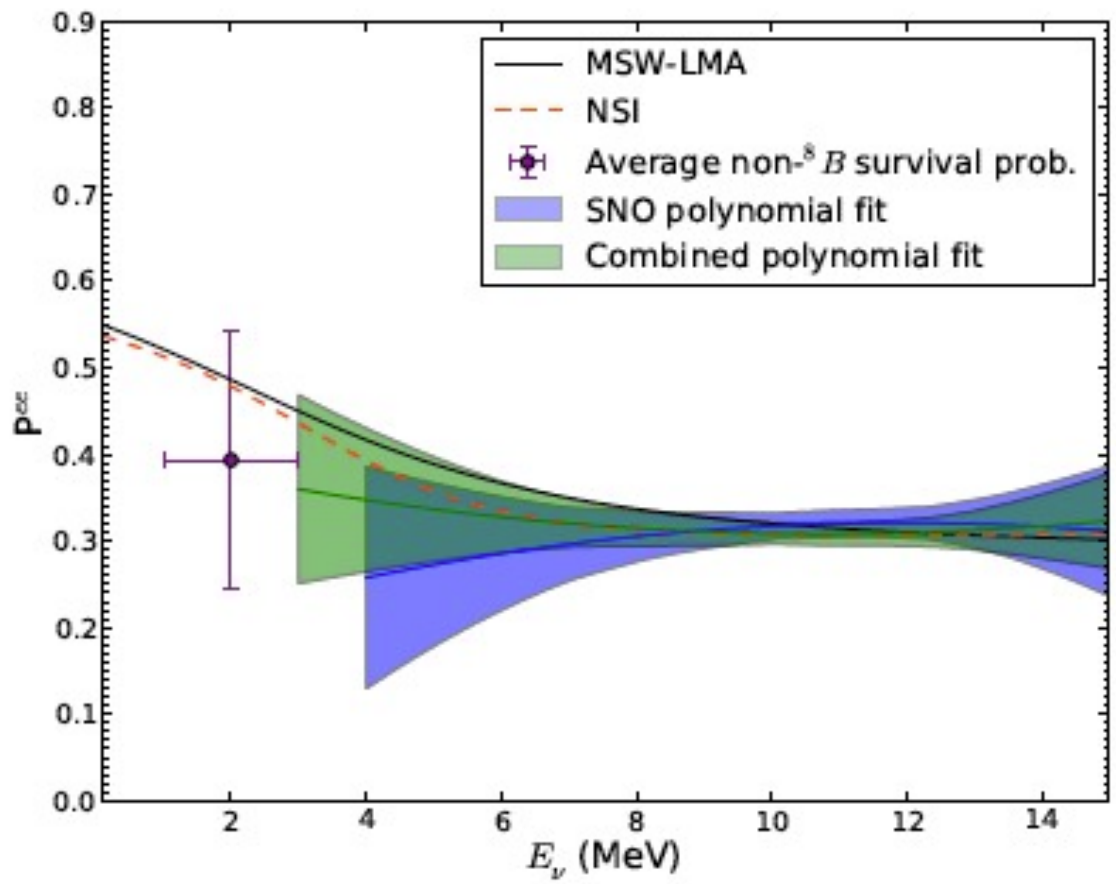

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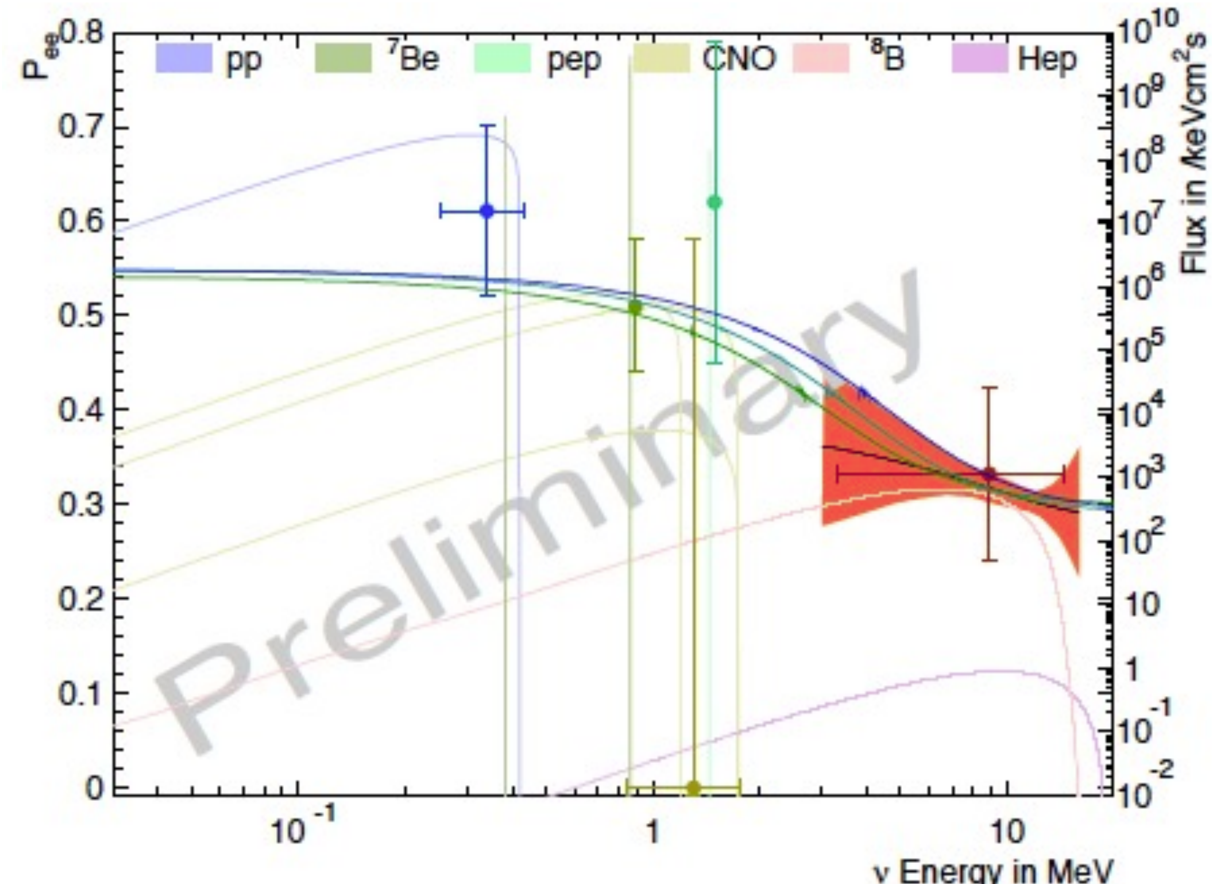

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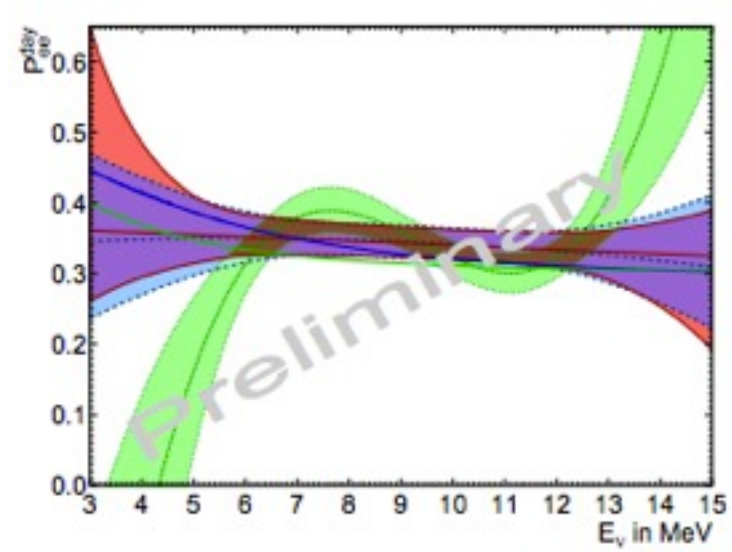

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Non-Standard Model Testing

Light sterile neutrino PRD 83:113011 (2011)

Non-standard MSW Dynamics PRD 83:101701 (2011)

Non-Standard Models, Solar Neutrinos and Large θ_{13} PRD 88: 053010 (2013)

- Non-standard forward scattering
- Mass-varying neutrinos
- Long-range leptonic forces
- Non-standard solar model

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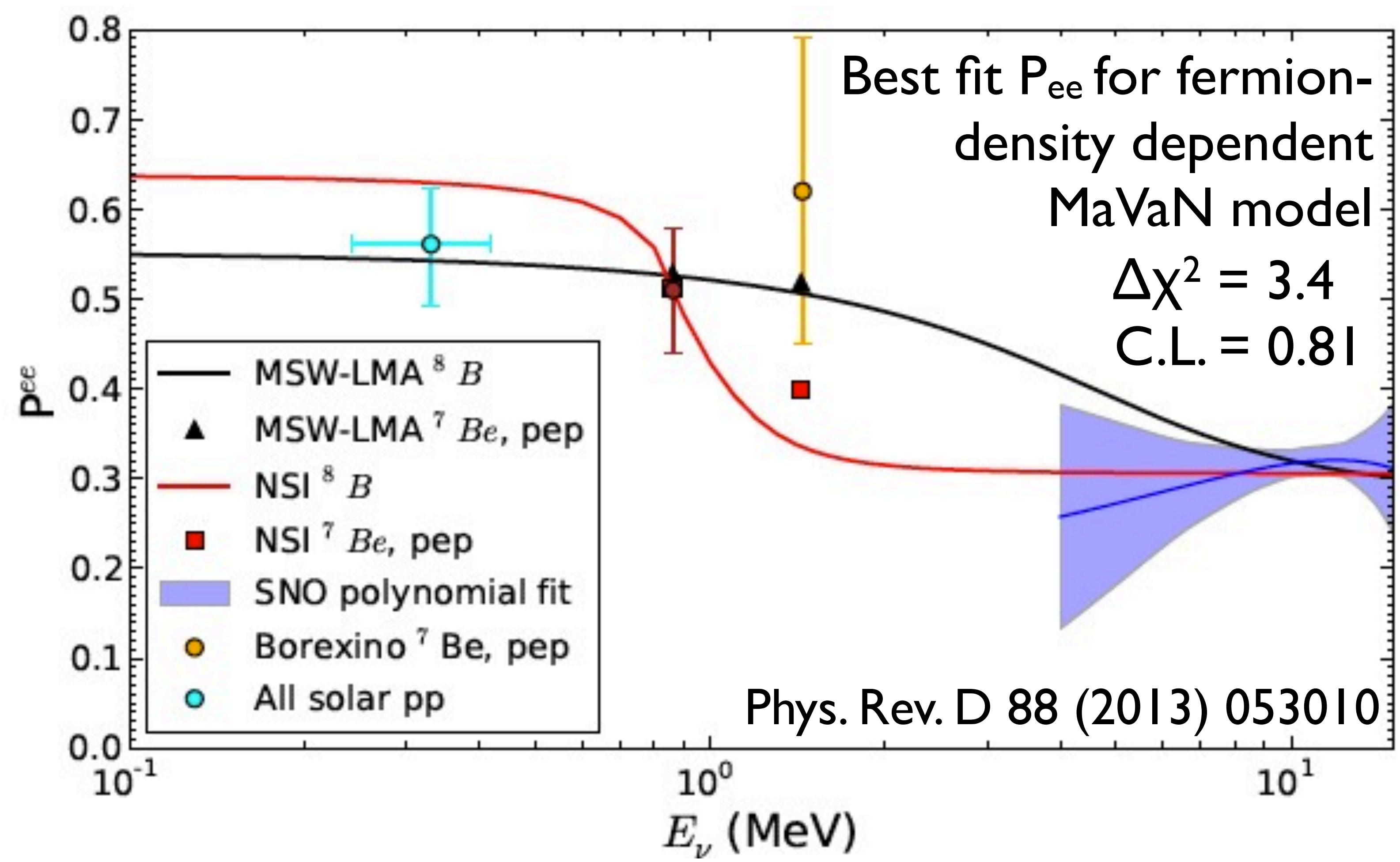

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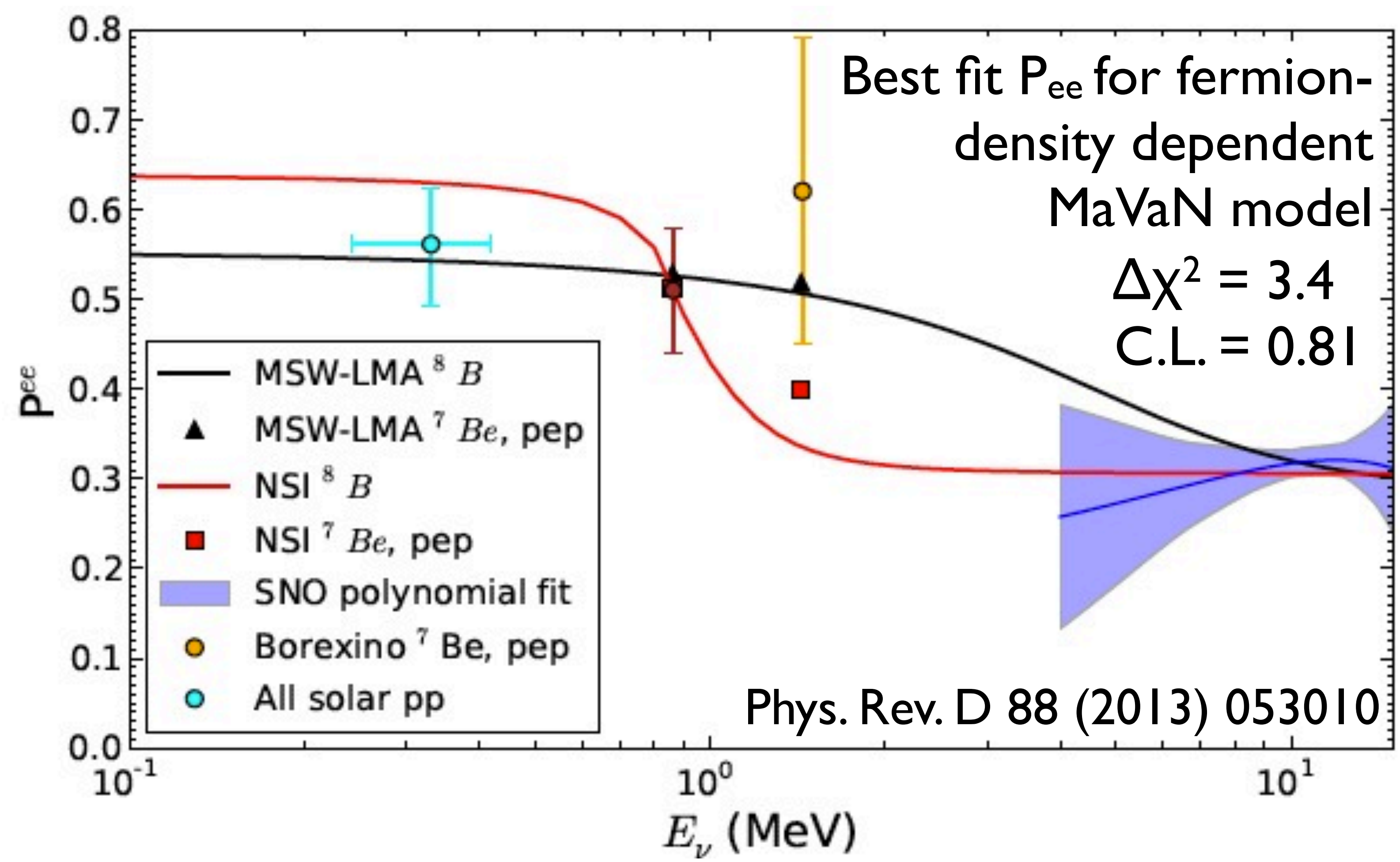
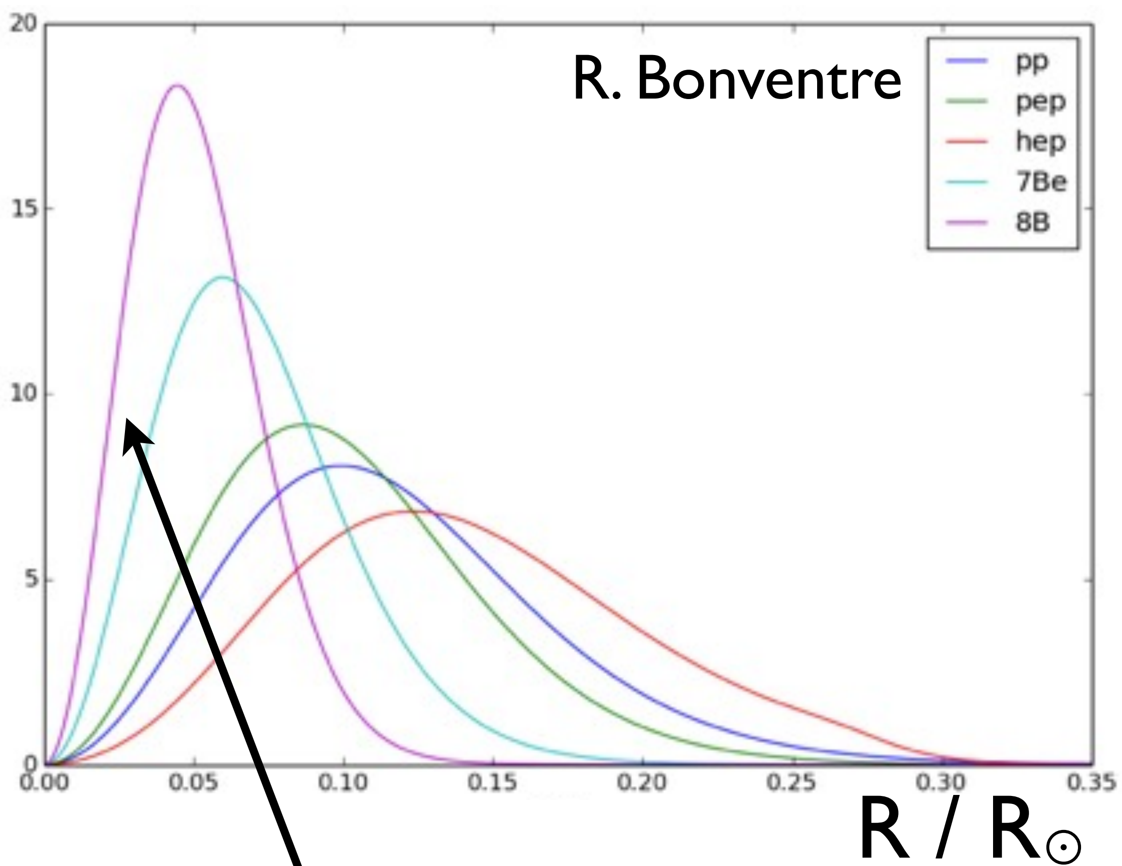
No significant effects (< 2σ)

Results limited by experimental precision



Probing the Transition Region: why we need ^8B



^8B produced closest into the core of the Sun

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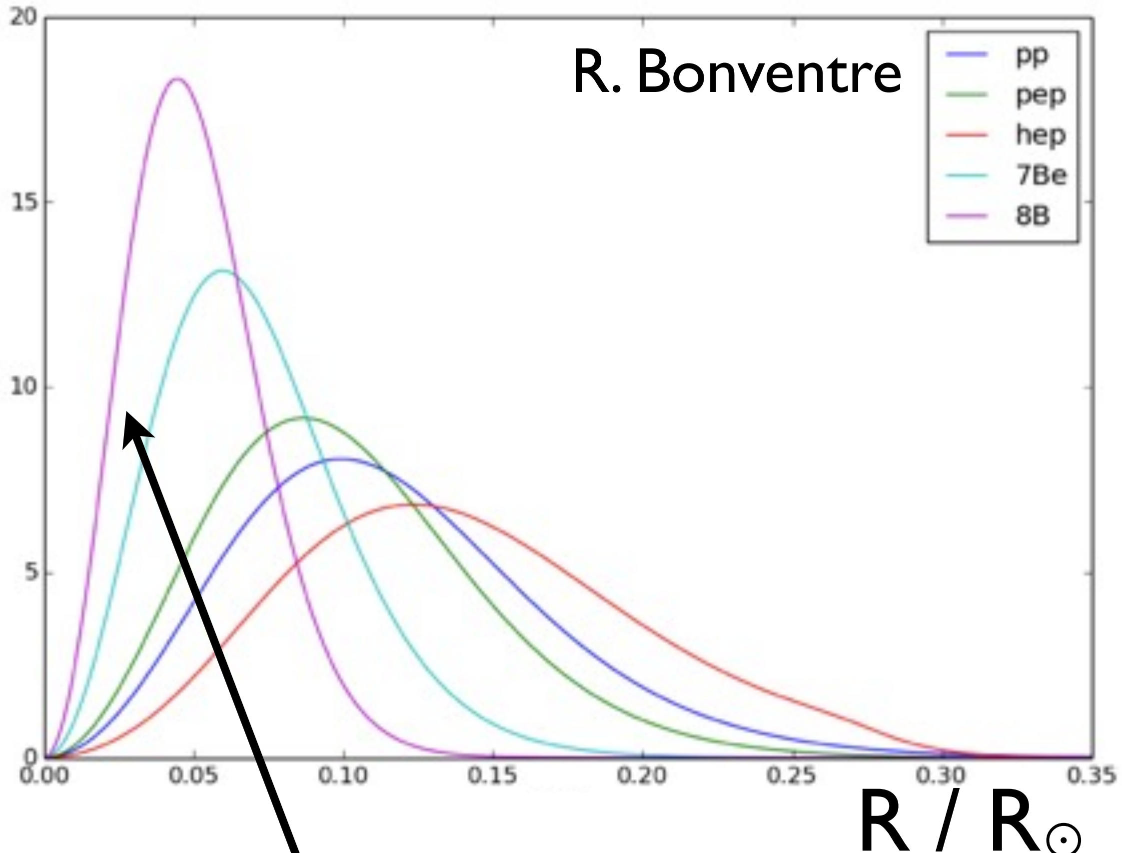
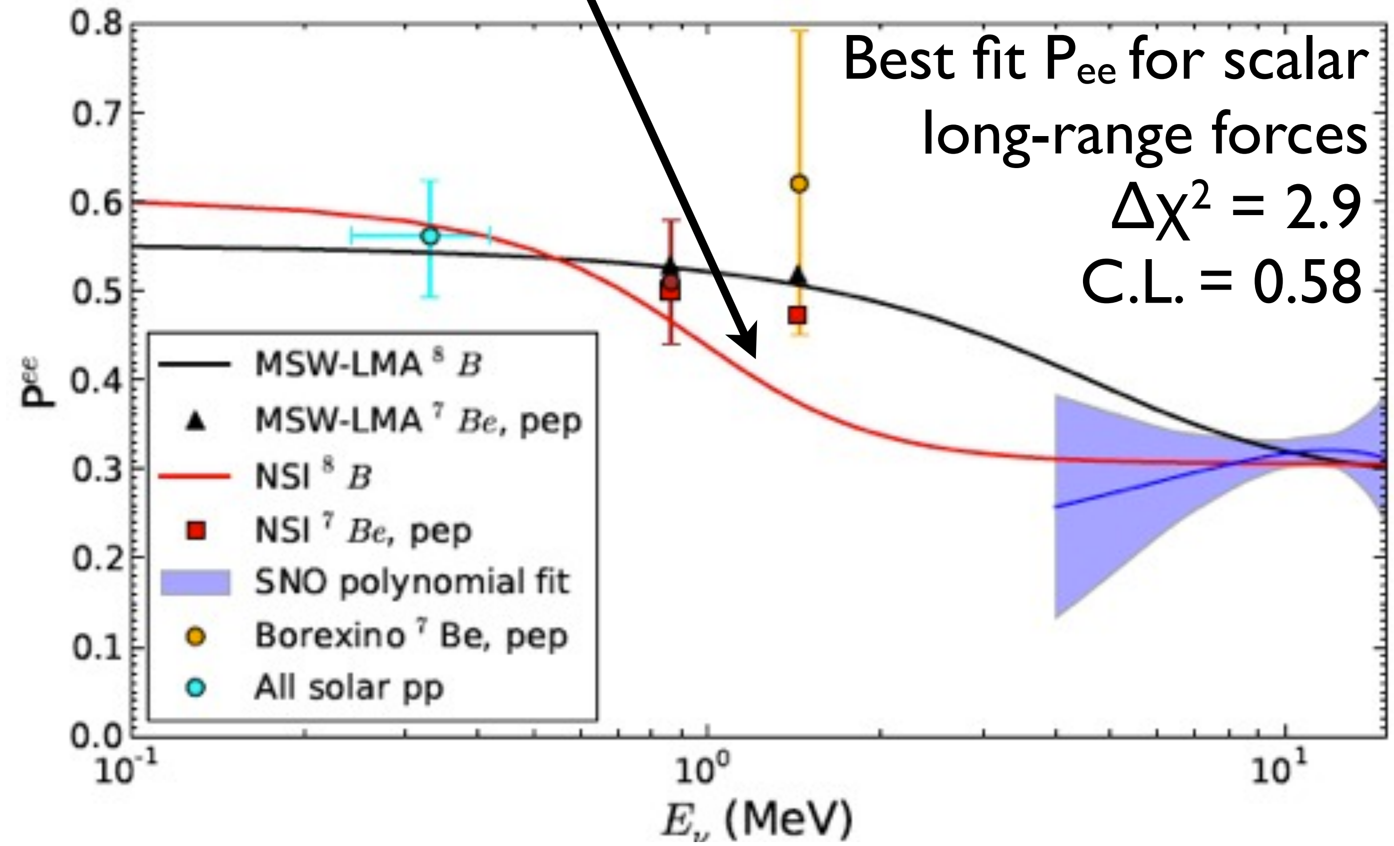


^{8}B produced closest into the core of the Sun

Largest affect on shape of survival probability



Phys. Rev. D 88 (2013) 053010

Physics Beyond the SNP

(1) Searching for new physics:

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(2) Understanding stellar formation:

The metallicity of the Sun's core

(2) Understanding the Sun

SSM takes initial metallicity as input

Predicts speed of sound through Sun's radial profile

Boundary conditions: today's mass, radius, luminosity

Beautiful agreement between SSM and helioseismology

Figures from Annual Reviews of Astronomy and Astrophysics, 2009, 47, 481

Posters:
Dr Villante, #81

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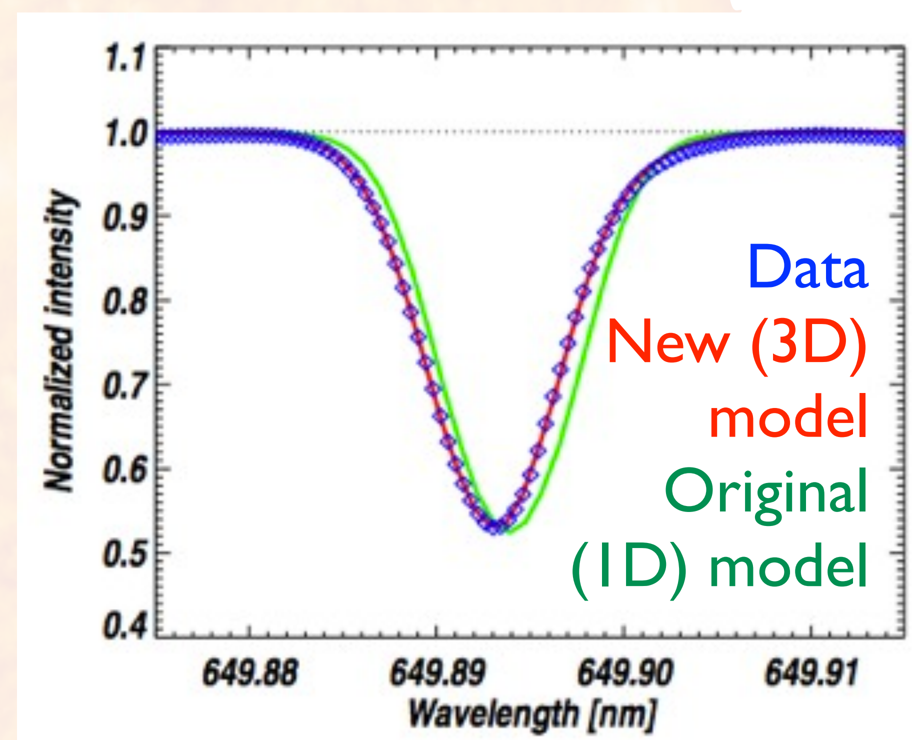
More sophisticated analyses of photospheric absorption lines

⇒ better agreement with data

⇒ lower abundance of metals (> H, He)



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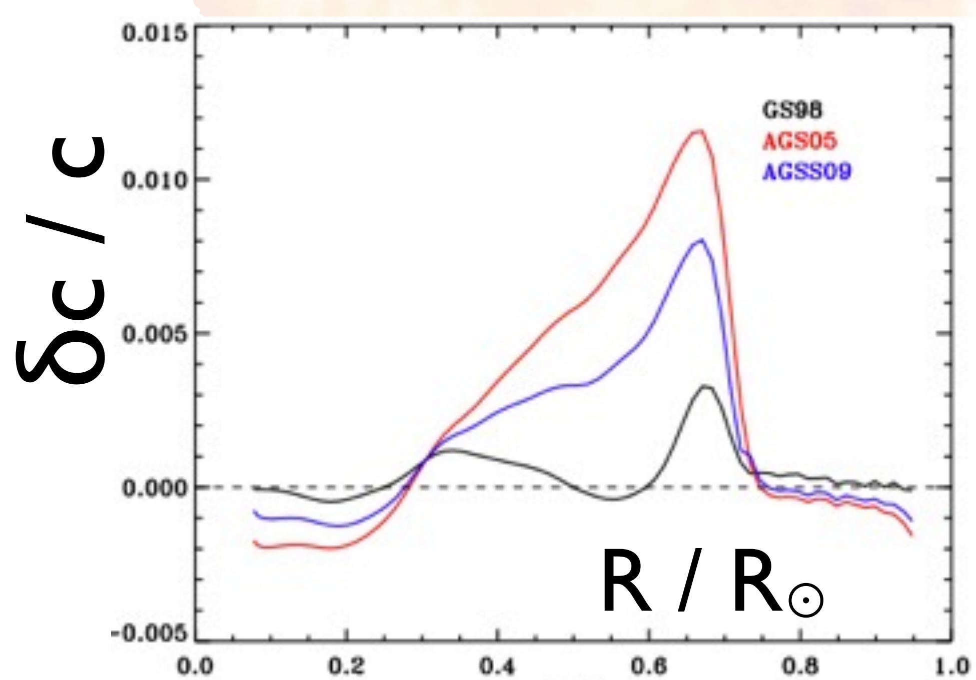

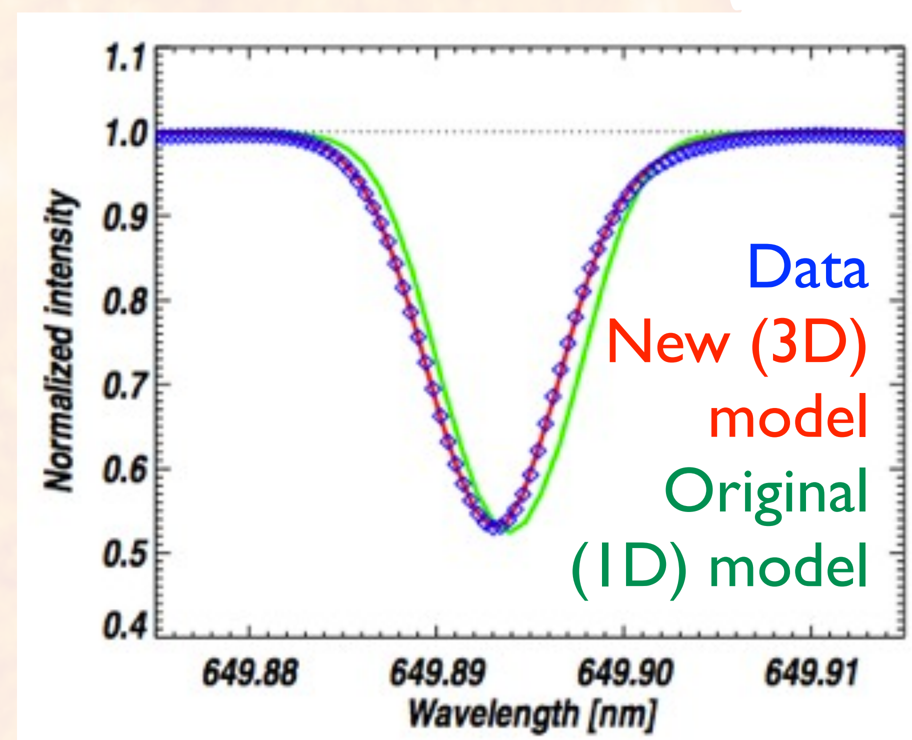

New discrepancy!

Figures from Annual Reviews of Astronomy and Astrophysics, 2009, 47, 481

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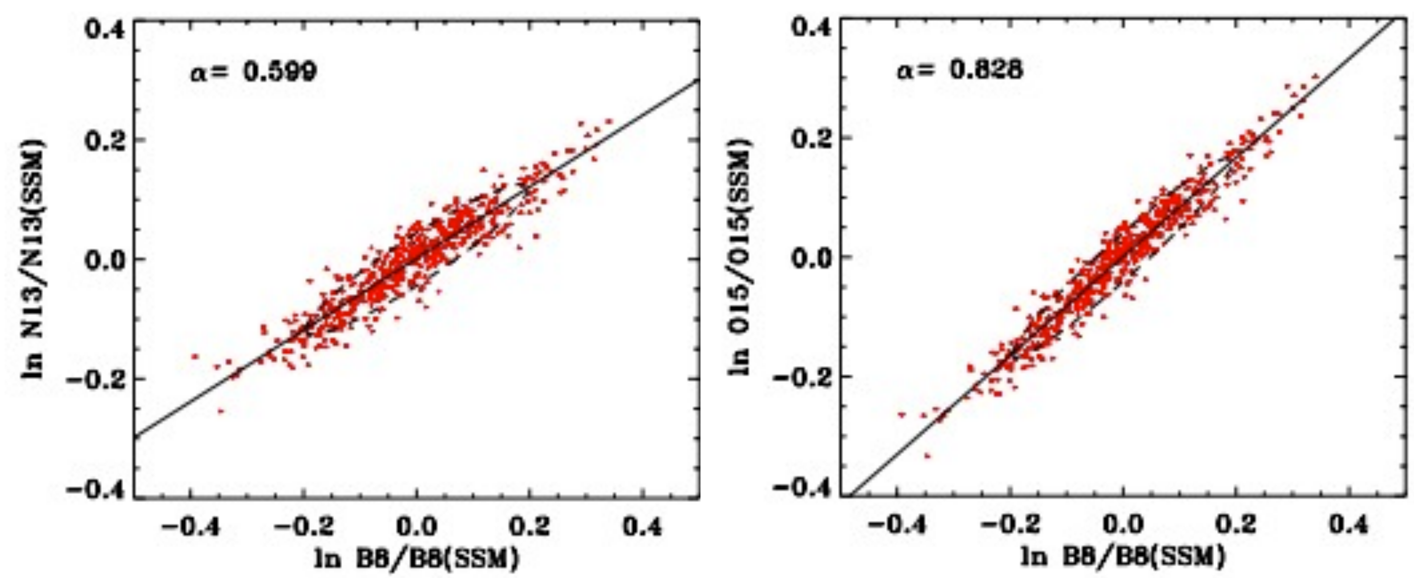
CN-Cycle Neutrinos

The Astrophysical Journal **687** (2008) 678

CN-Cycle Neutrinos

- Measure of solar metalicity
  Flux predictions differ by >30%
  Precision ^8B flux measurement constrains predictions



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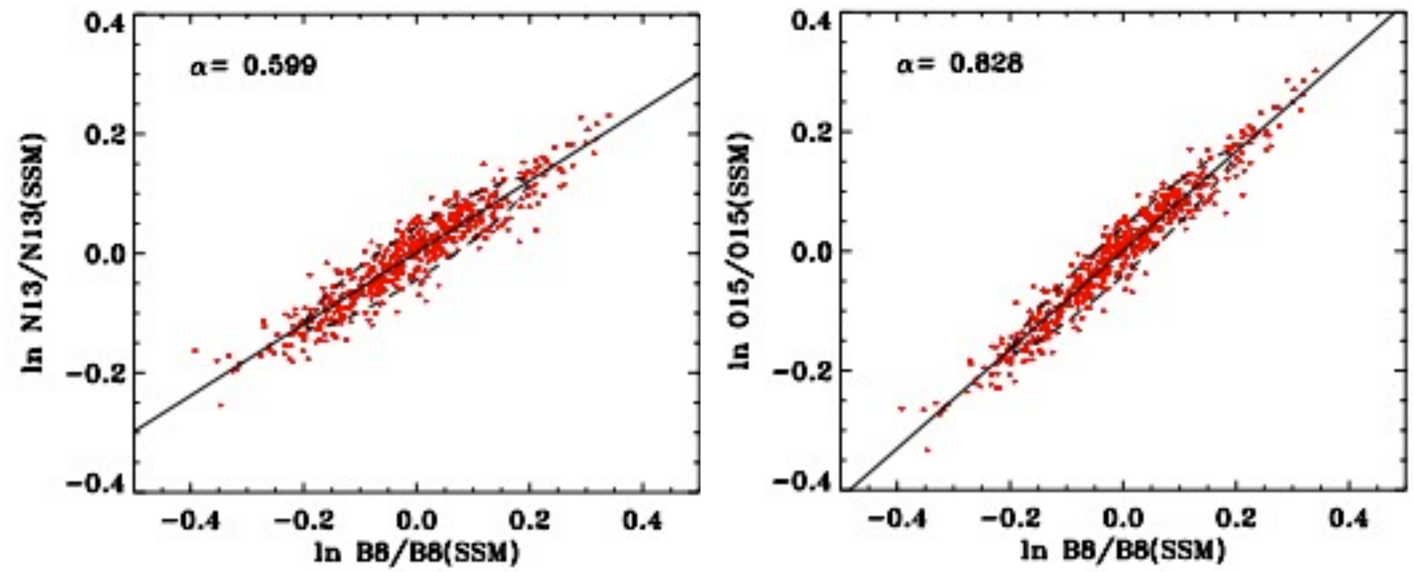
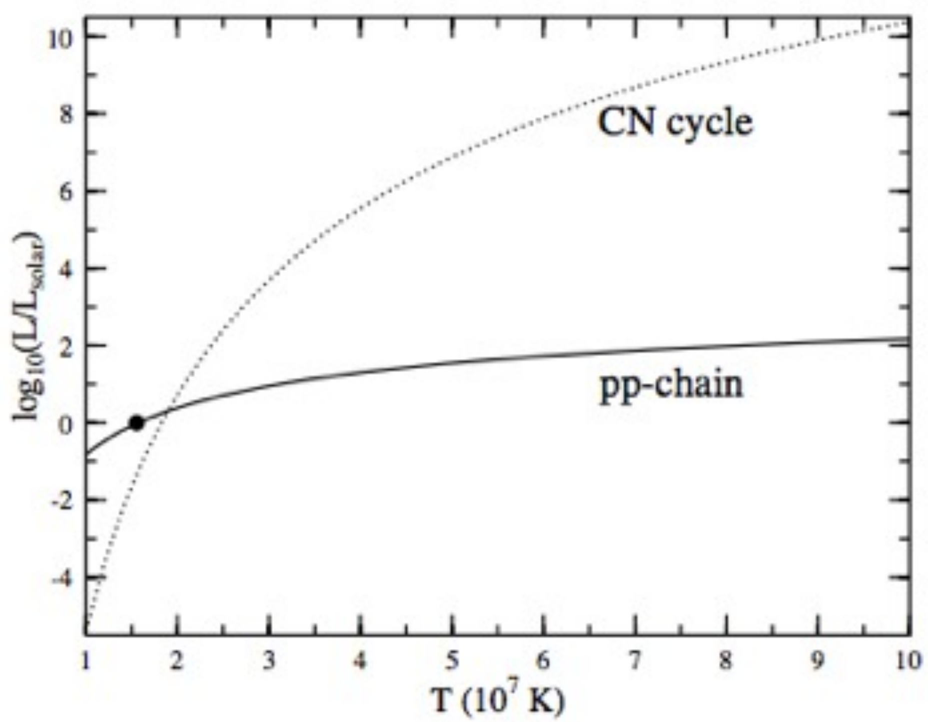


- Test understanding of heavier main-sequence stars



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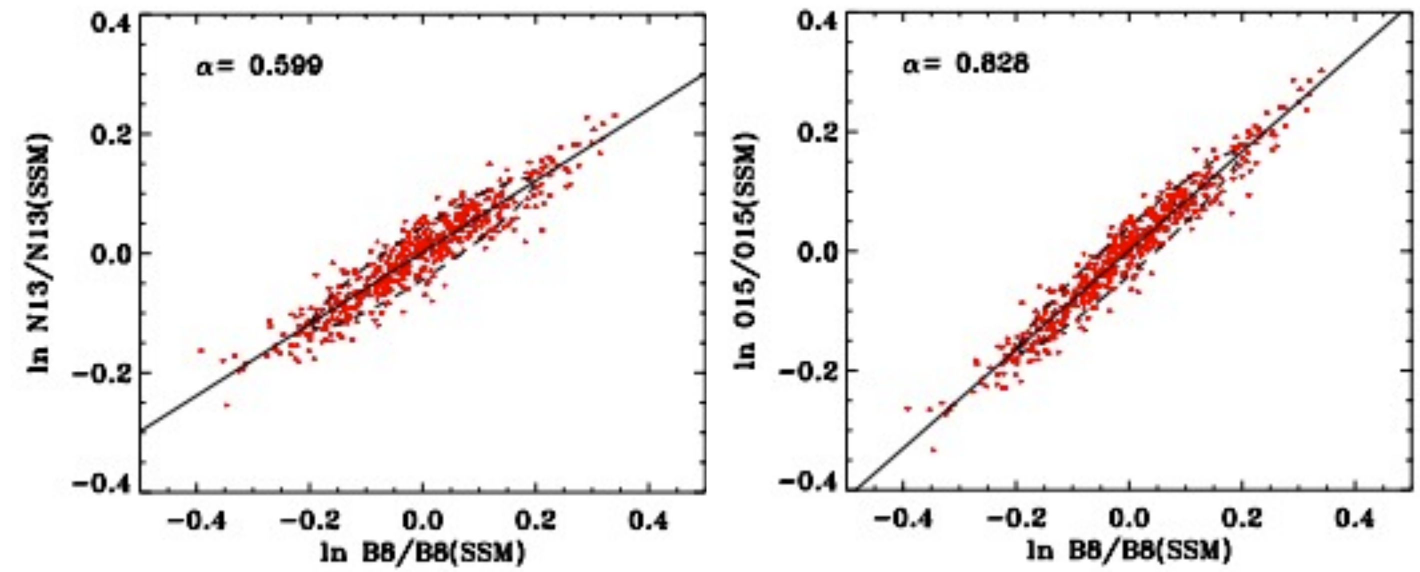

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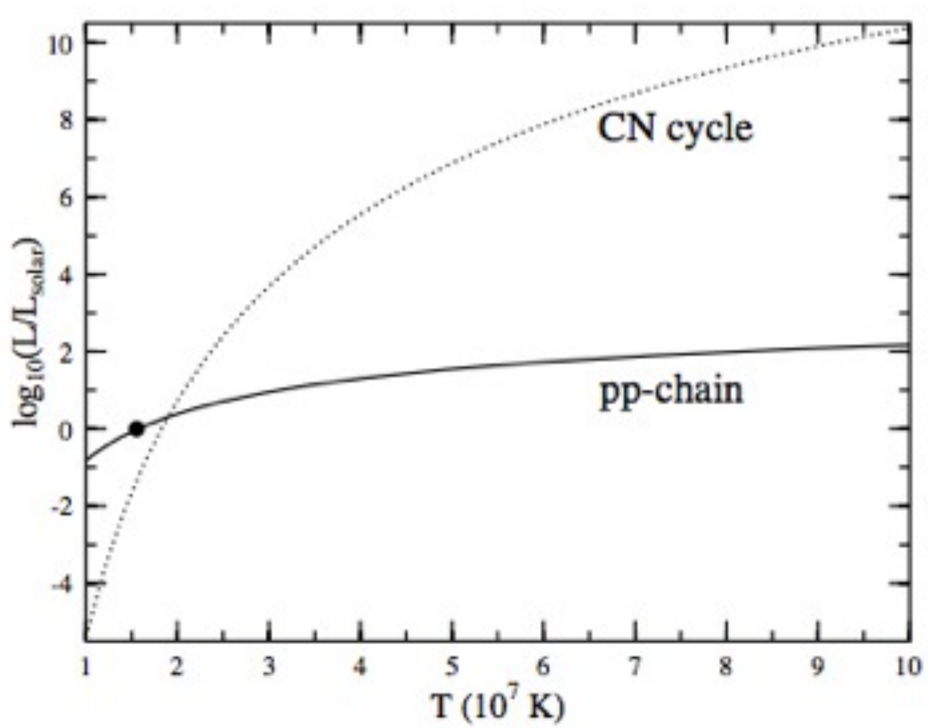

- Test postulate of homogeneous zero-age sun
- Constrain metal accretion during solar formation (did gas giants "sweep out" metals from convective zone?)
- Test extent of CN-cycle equilibrium

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(2) Understanding stellar formation:

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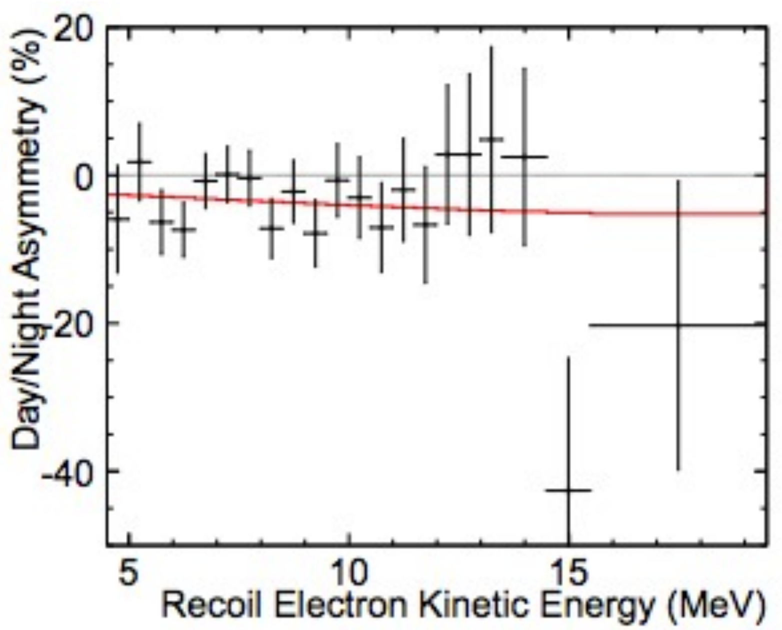
(3) Confirming MSW:

The Day / Night effect

Super-Kamiokande
Combined analysis of SK I-IV

PRL 112 (2014) 091805



$A_{DN} = -3.2\% \pm \mathit{1.1}$ *(stat)* $\pm\ \mathit{0.5}$ *(syst)* $= 2.7\sigma$

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(4) Probing energy loss/generation mechanisms:

Neutrino luminosity ($\mathcal{L}_\nu$)

Flux of νs

$$\frac{\mathcal{L}_\odot}{4\pi\,(A.U)^2} = \sum_i \alpha_i \Phi_i$$

Energy released per ν

Physics Beyond the SNP

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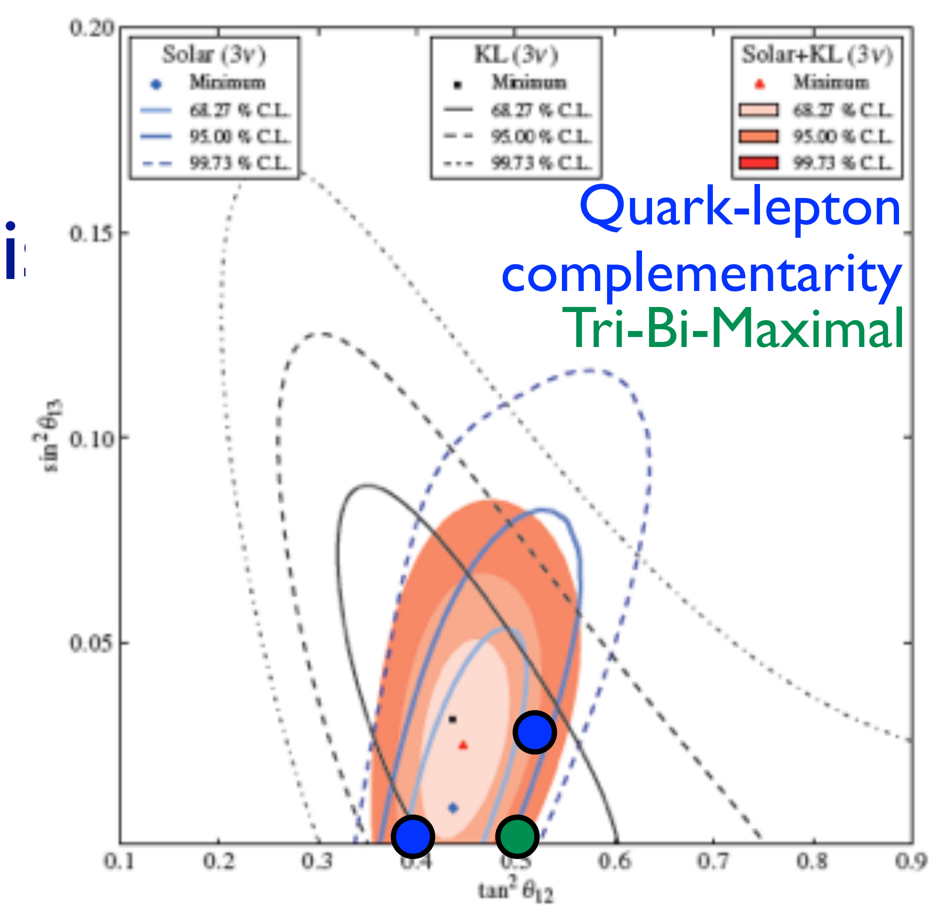
Neutrino luminosity ($\mathcal{L}_\nu$)

(5) Searching for symmetry:

Precision flux & oscillation parameter measurements



SNO+

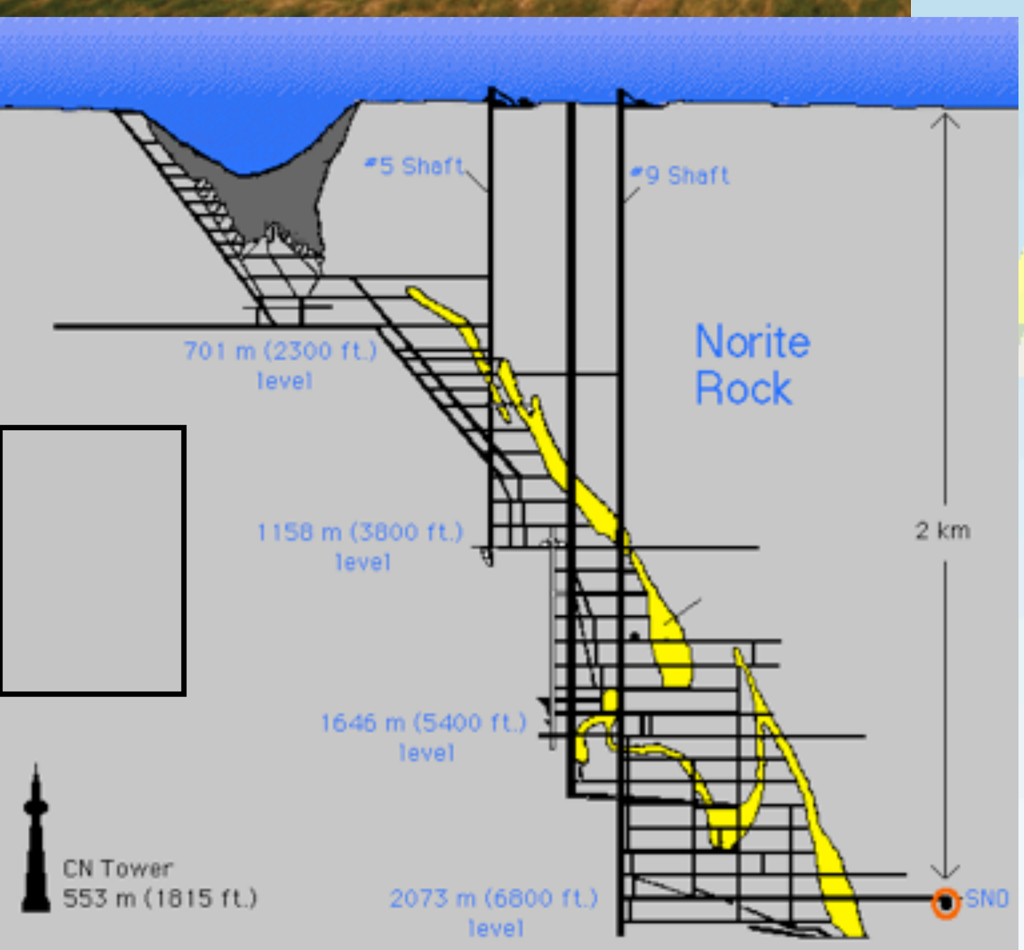
Posters:
Dr Caden,#76
Dr Hallman, #77
Dr Peeters, #134
(Dr Fatemighomi, #133)
(Dr Coulter, #135)
(Dr Grullon, #75)

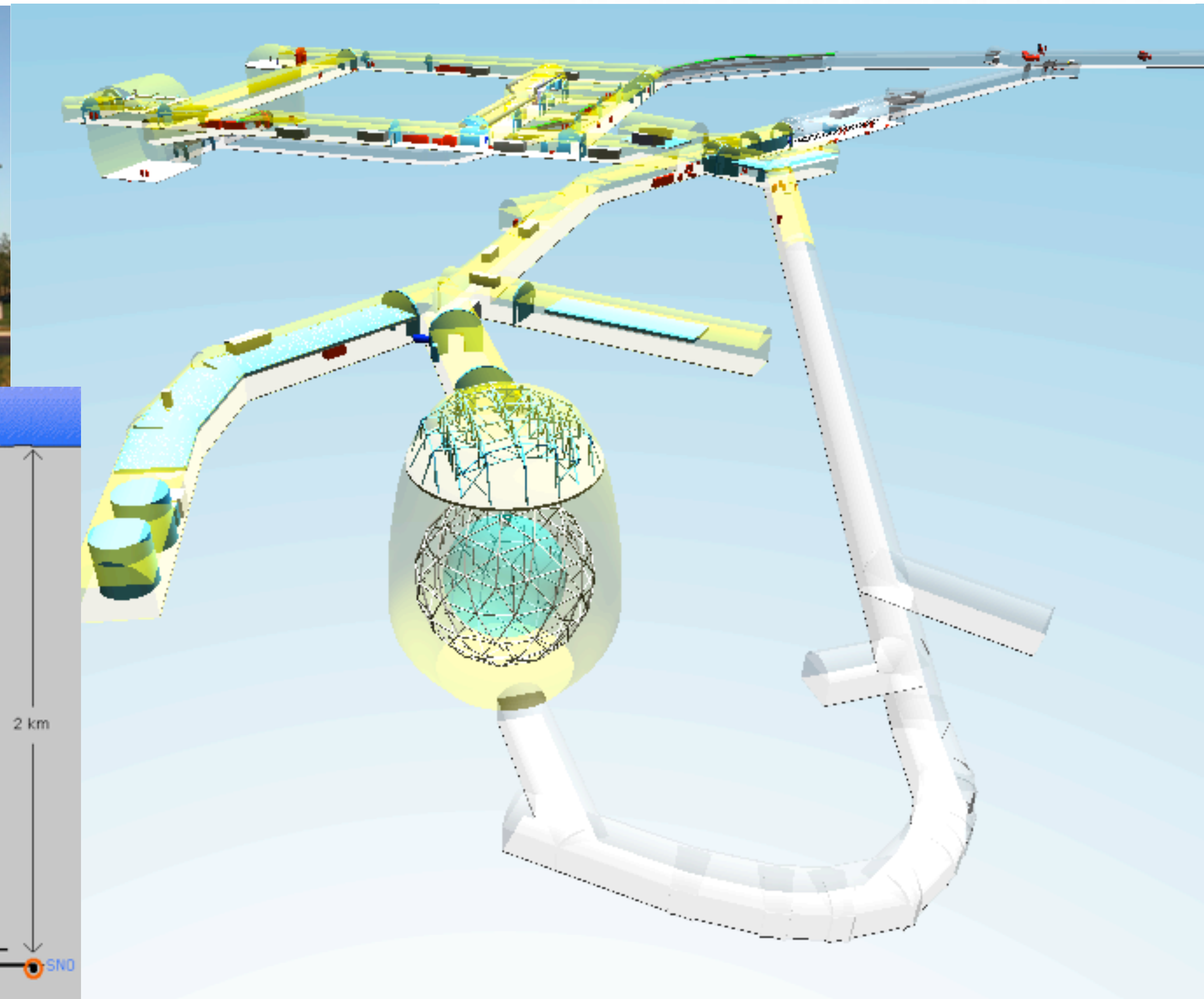
SNO+

SNOLAB

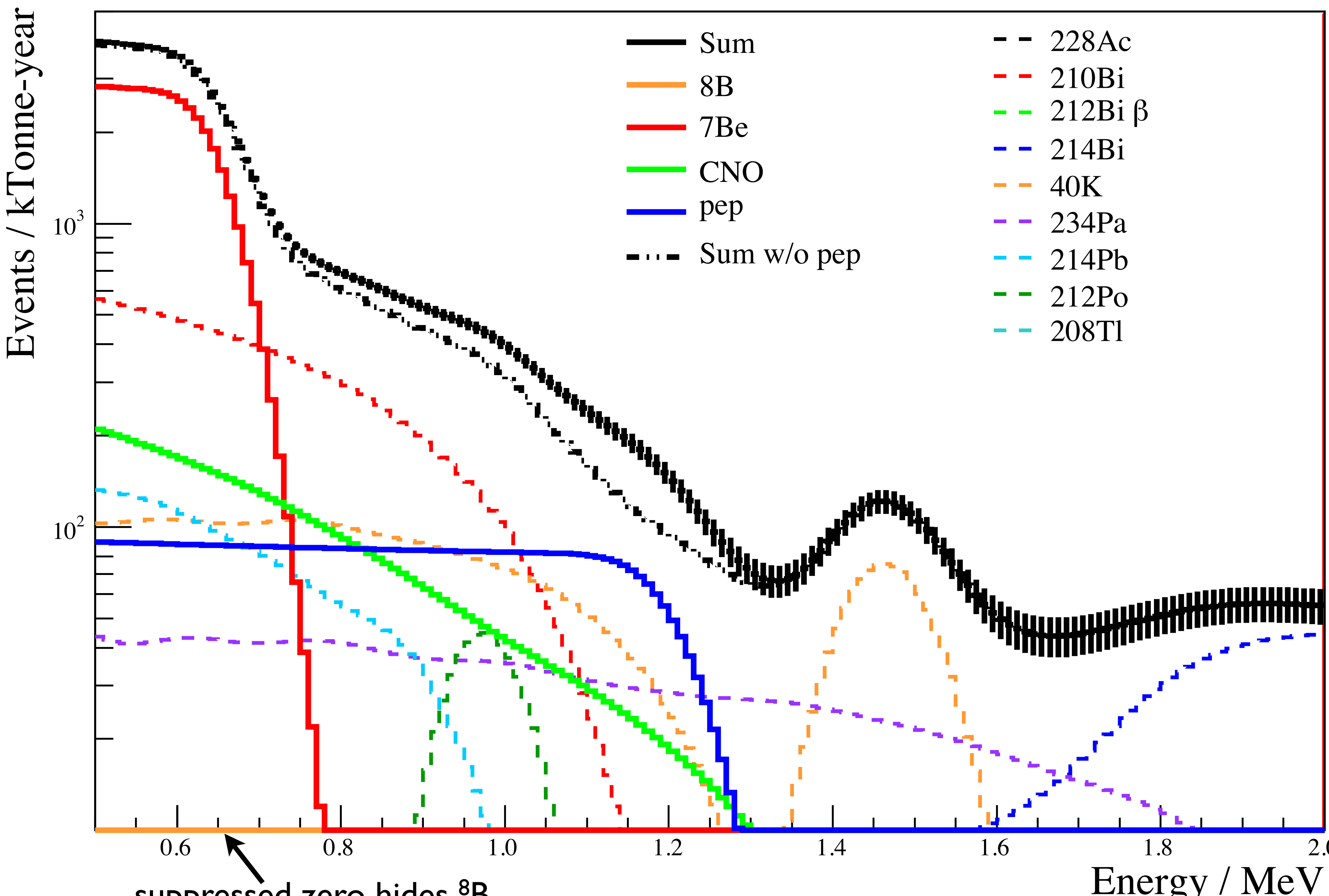
MINING FOR KNOWLEDGE

CREUSER POUR TROUVER... L'EXCELLENCE





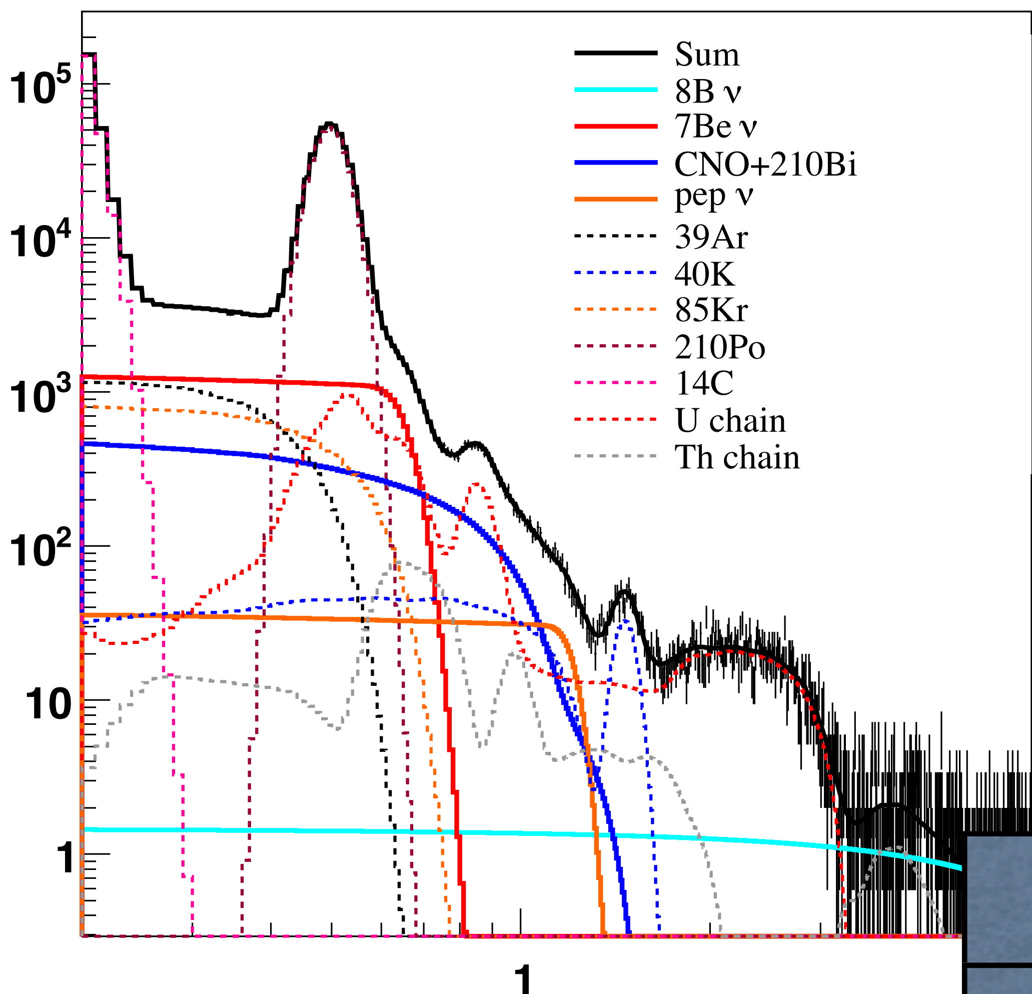
SNO+ Solar Neutrino Detection



suppressed zero hides ^{8}B

SNO+ Sensitivity

- 1 year livetime
- 50% fiducial volume (negligible external bkg)
- Assuming Borexino-level purification levels



(pp dependent on ^{14}C, ^{85}Kr)
(CNO dependent on ^{210}Bi)

	pep	^{8}B	^{7}Be	pp	CNO
1 yr	9%	7.5%	4%	~ a few %	~ 15 %
2 yr	6.5%	5.4%	2.8%		

SNO+ Sensitivity

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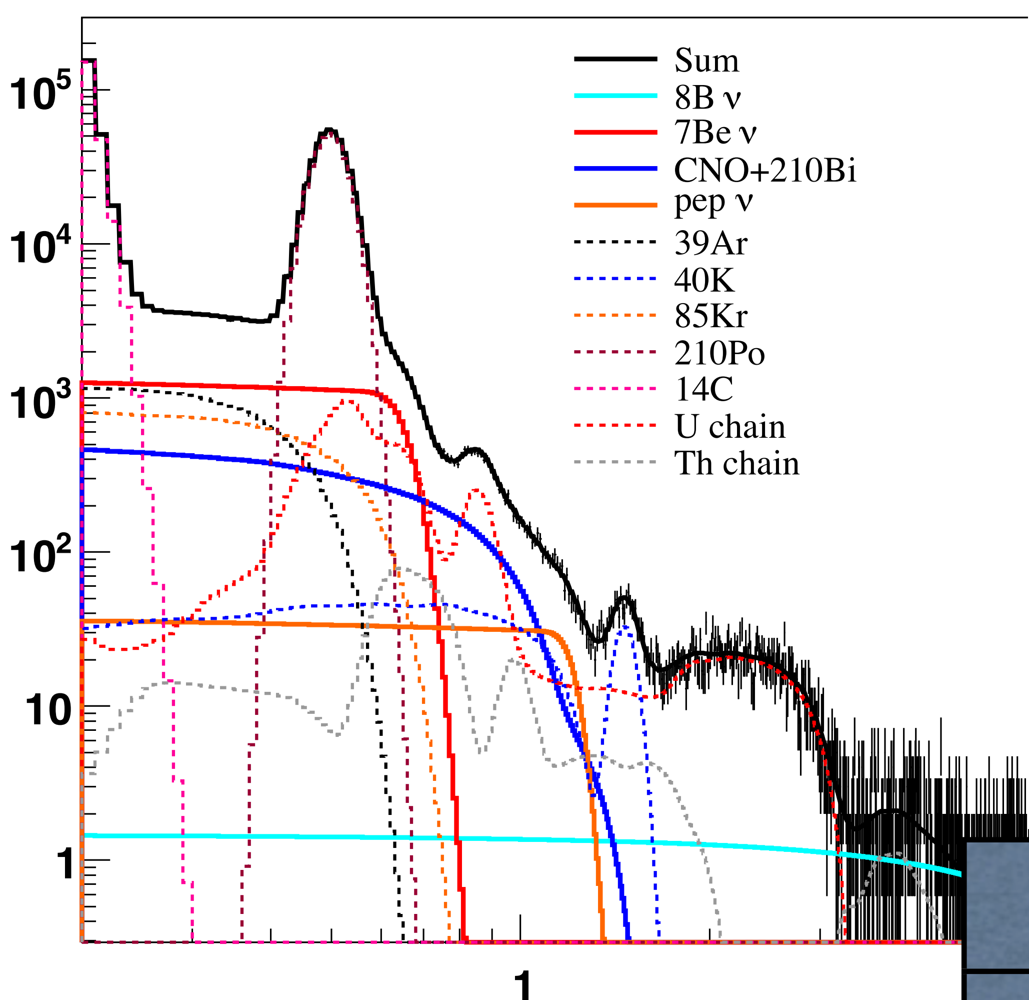

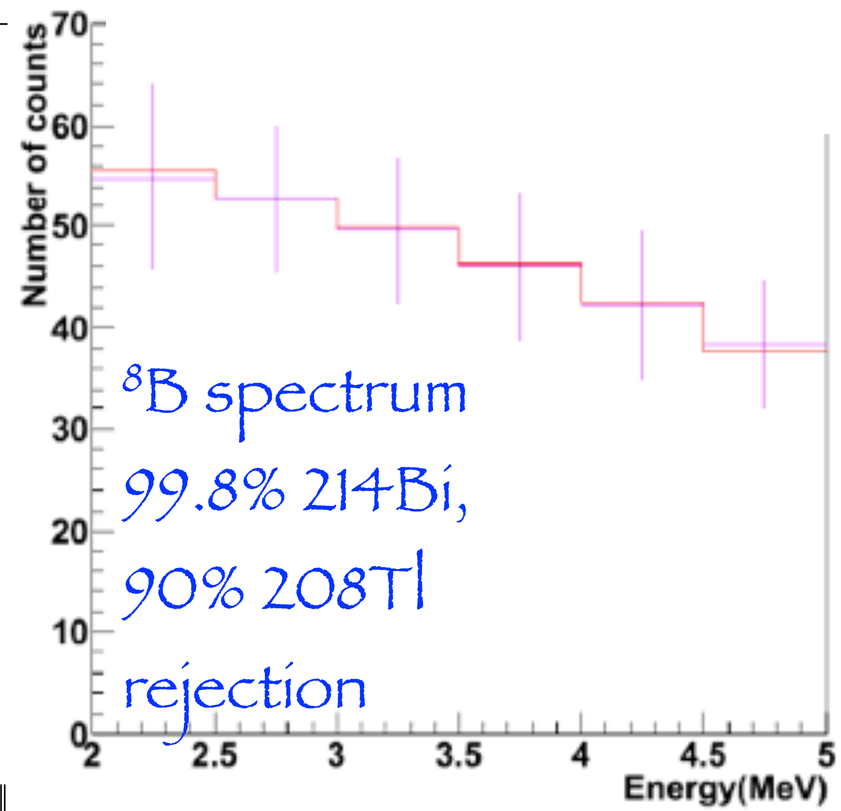

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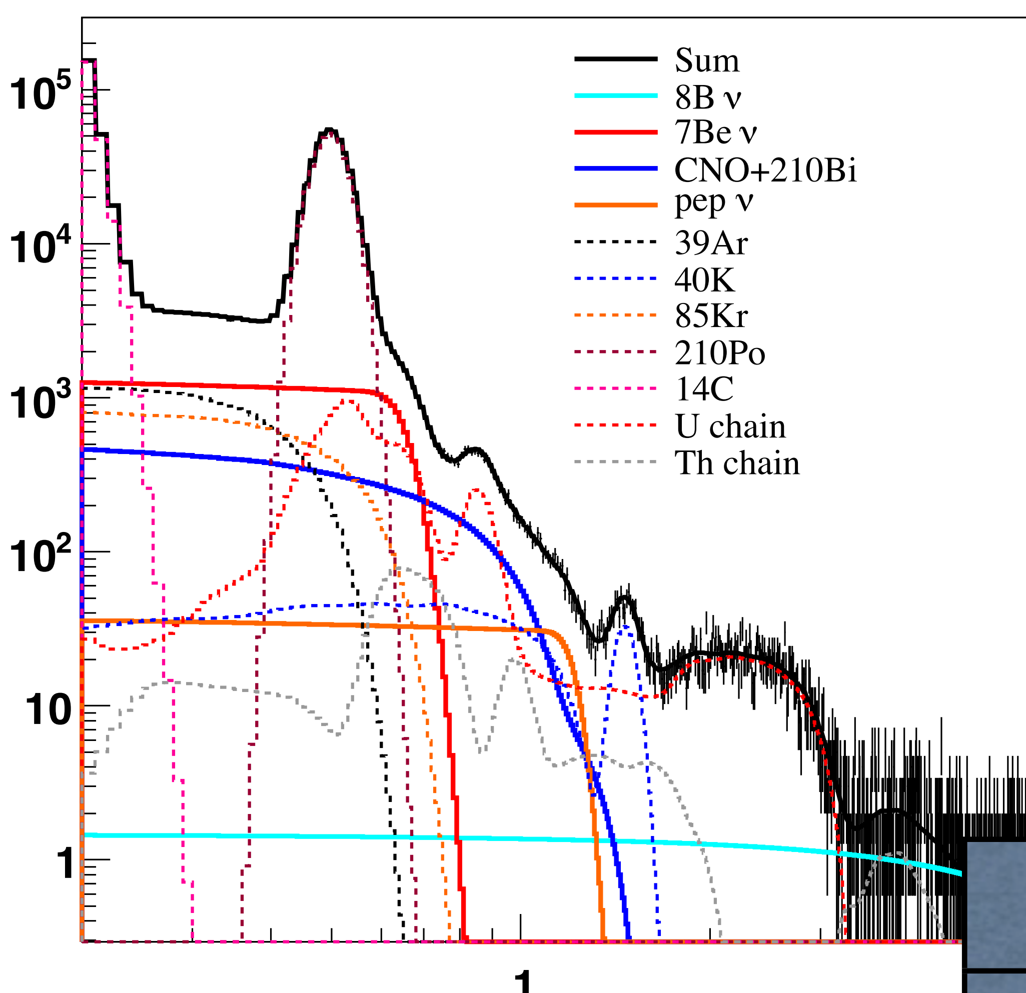

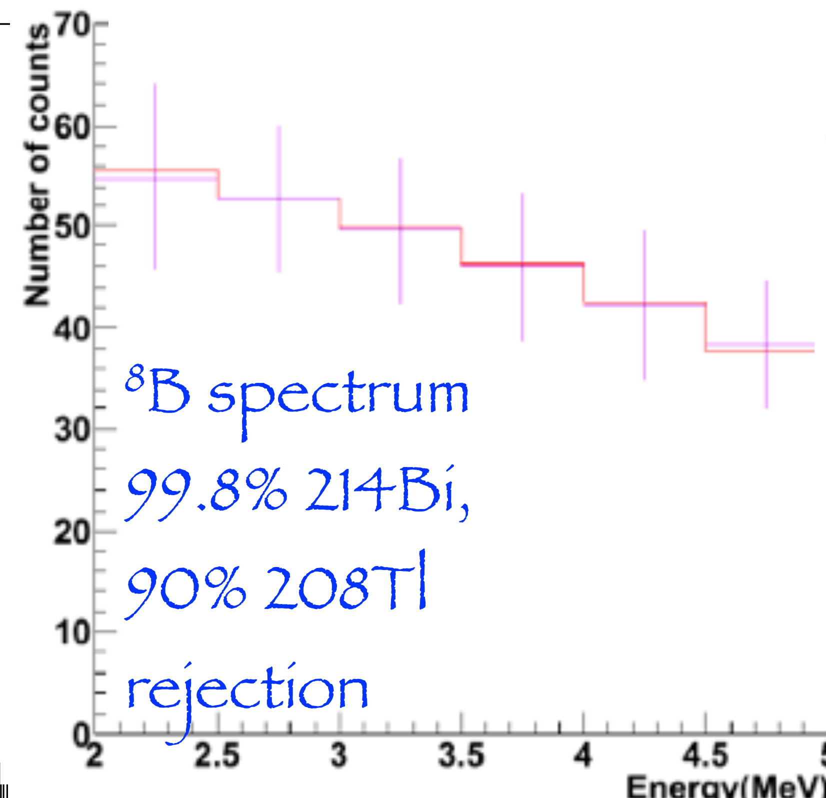

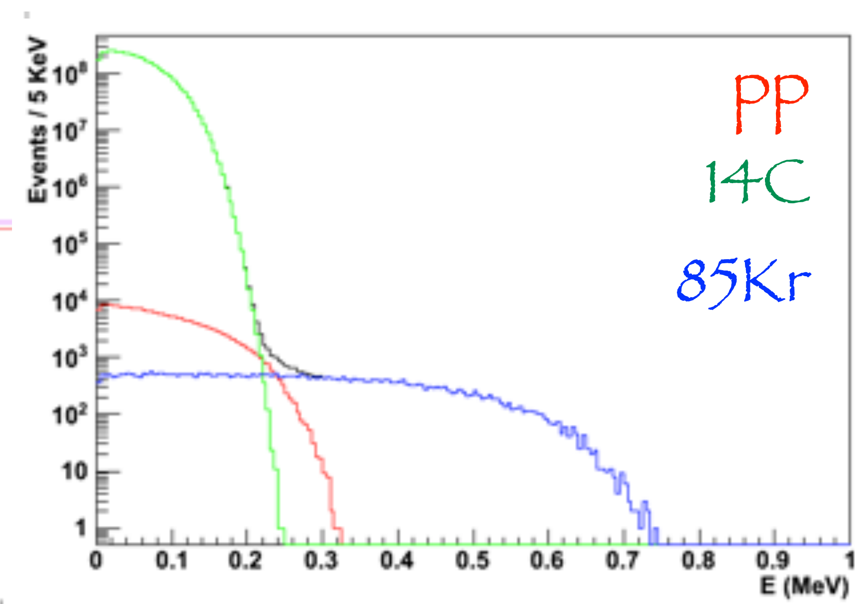

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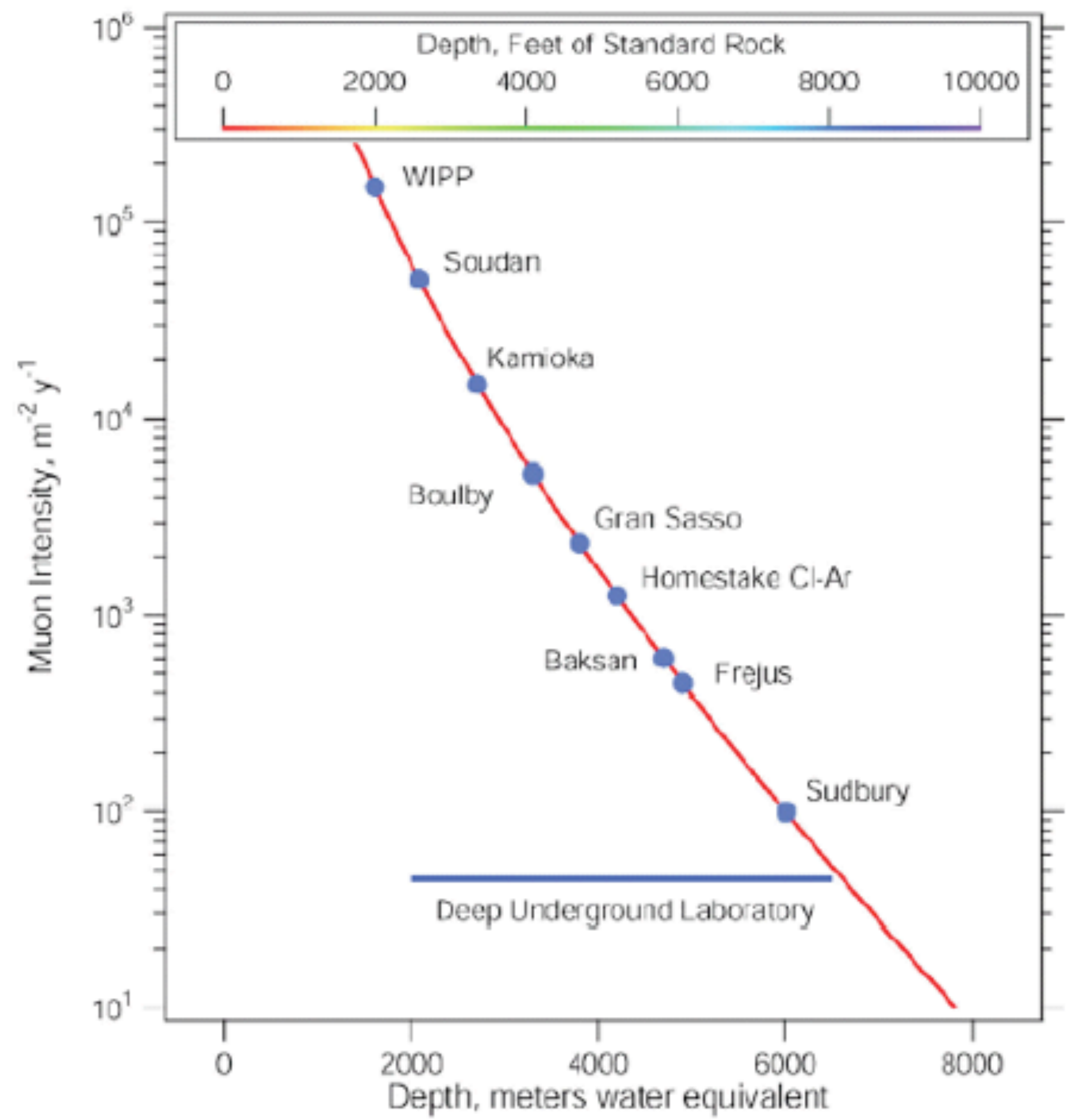
Gran Sasso: 3500 mwe
SNOLAB: 6080 mwe



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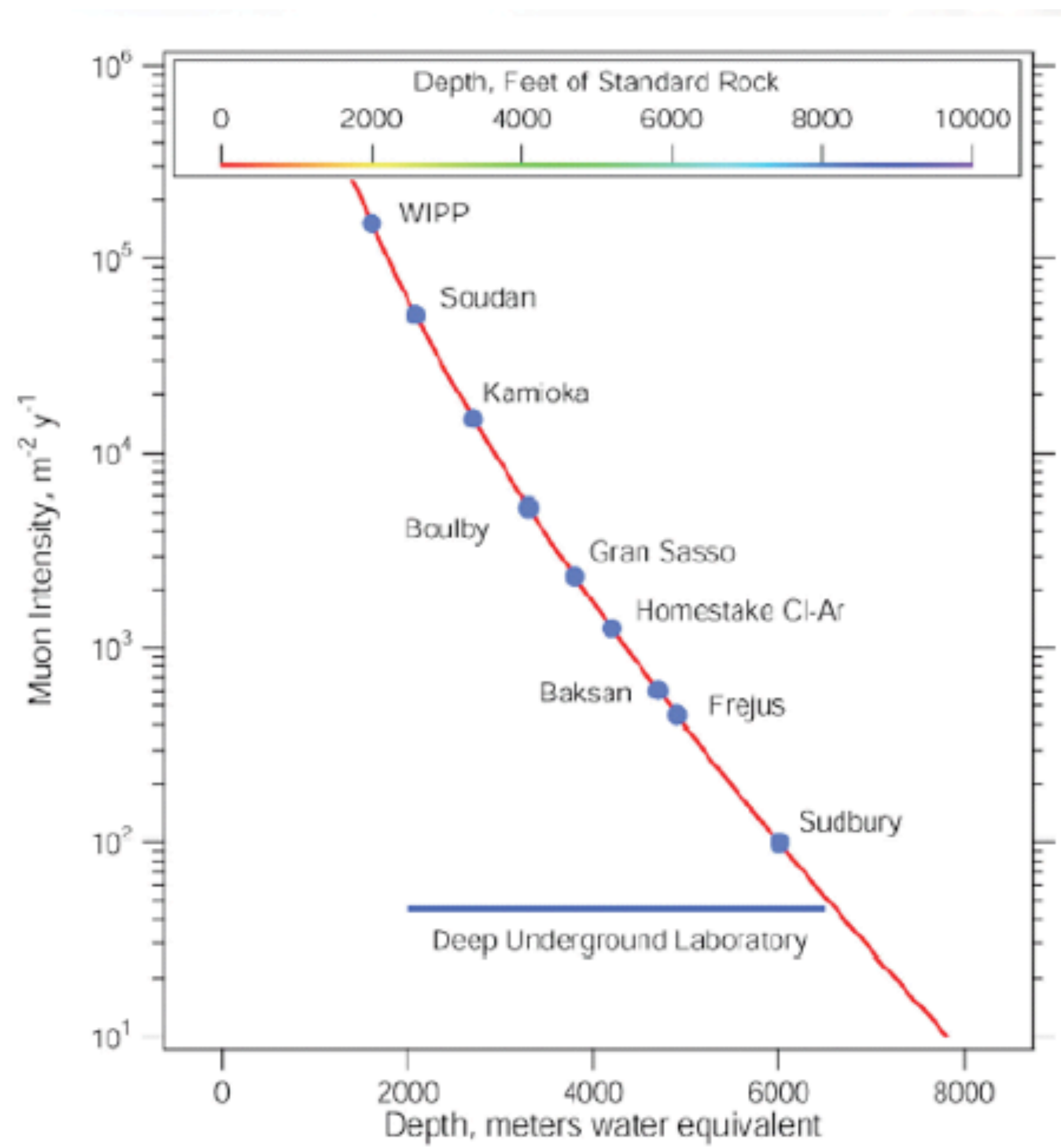

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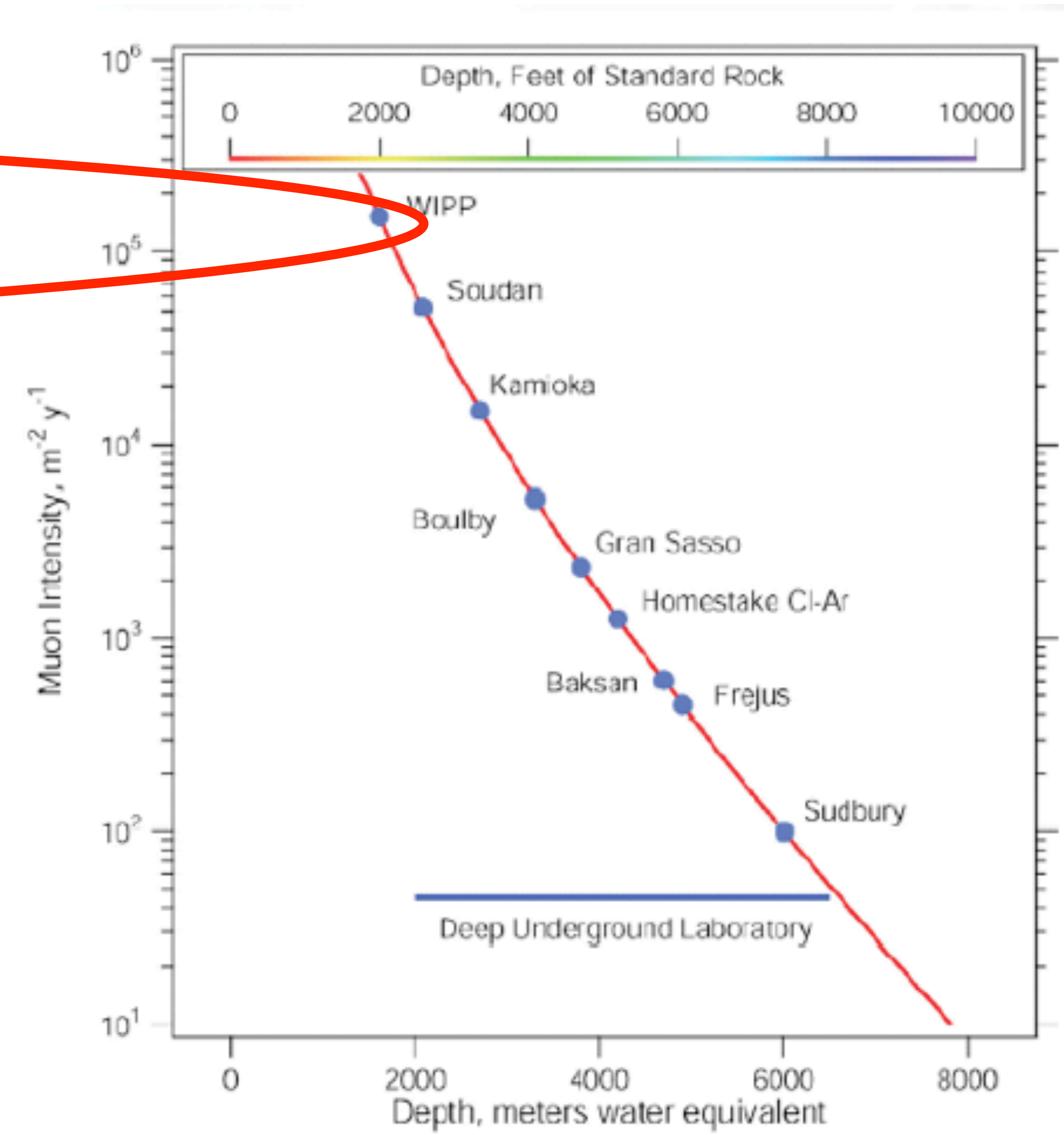

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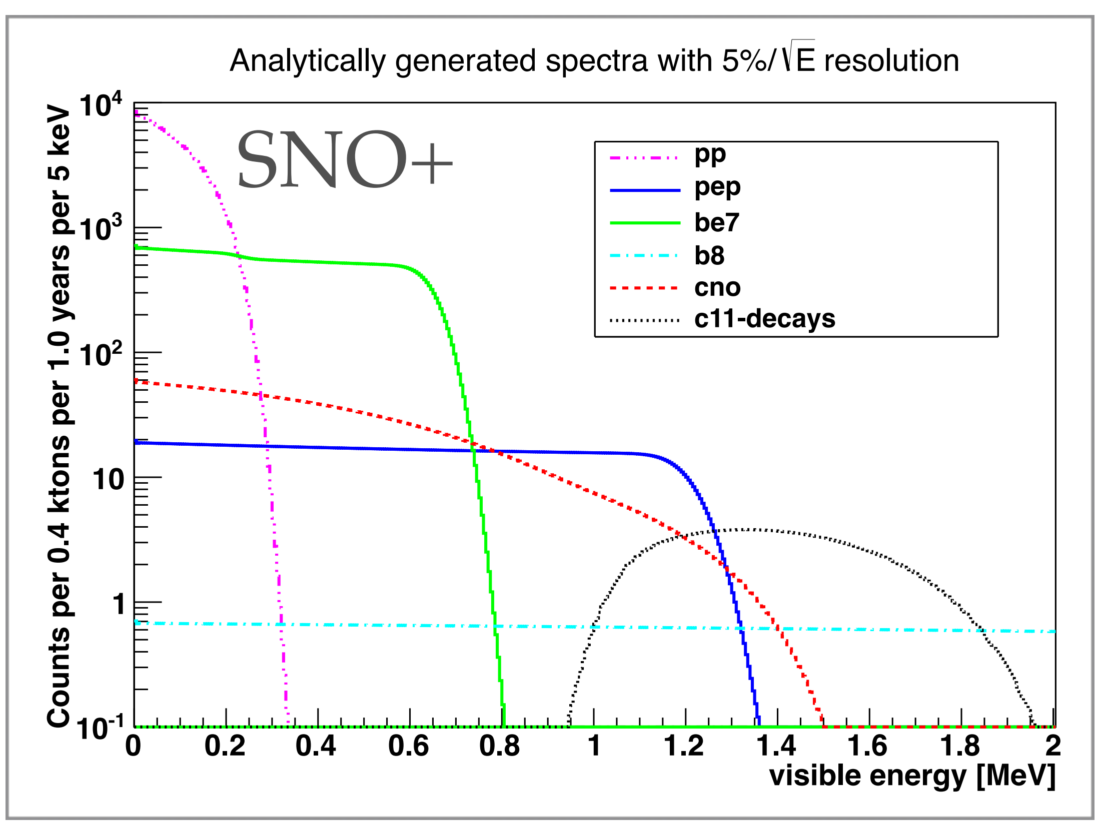

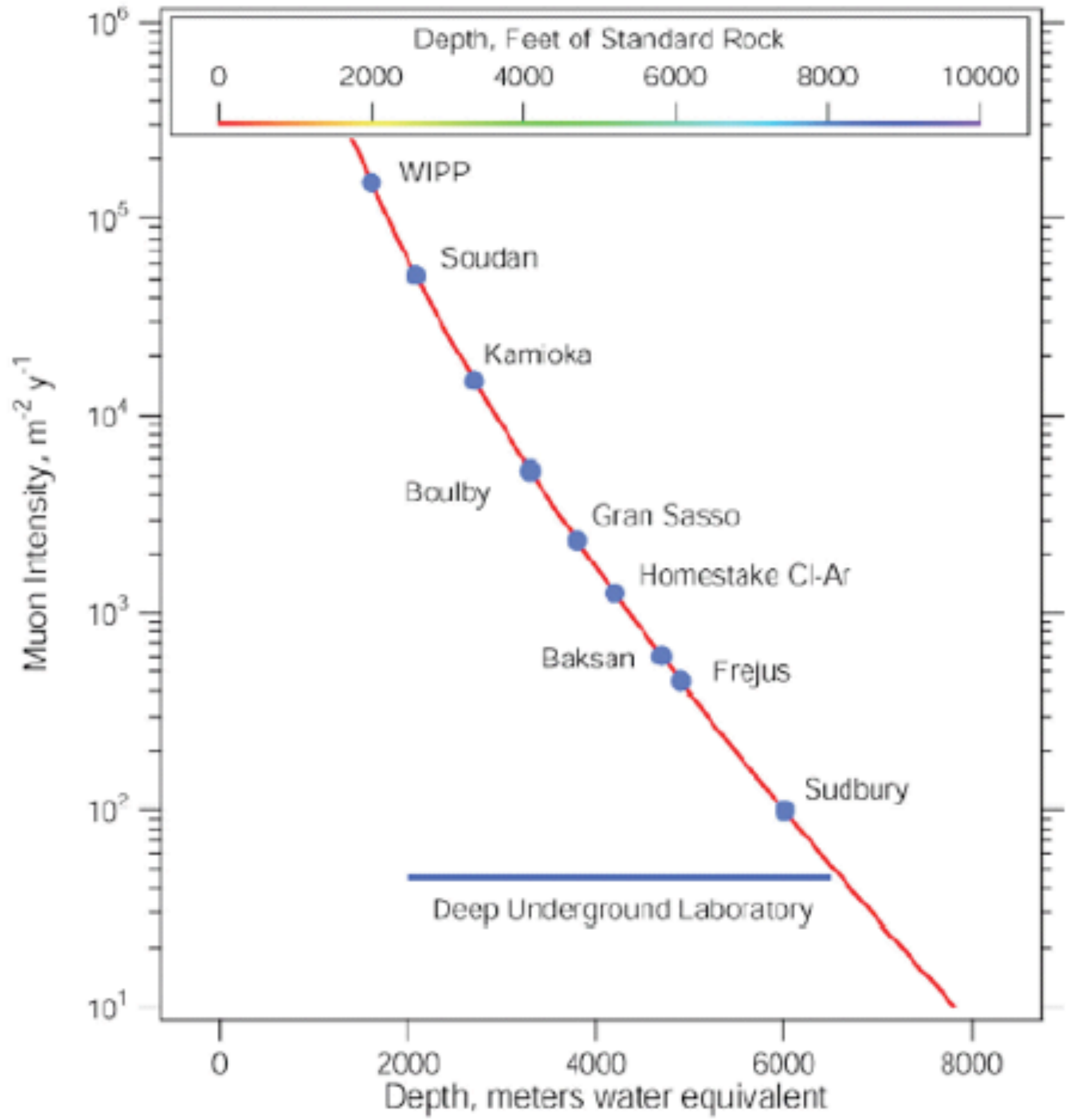

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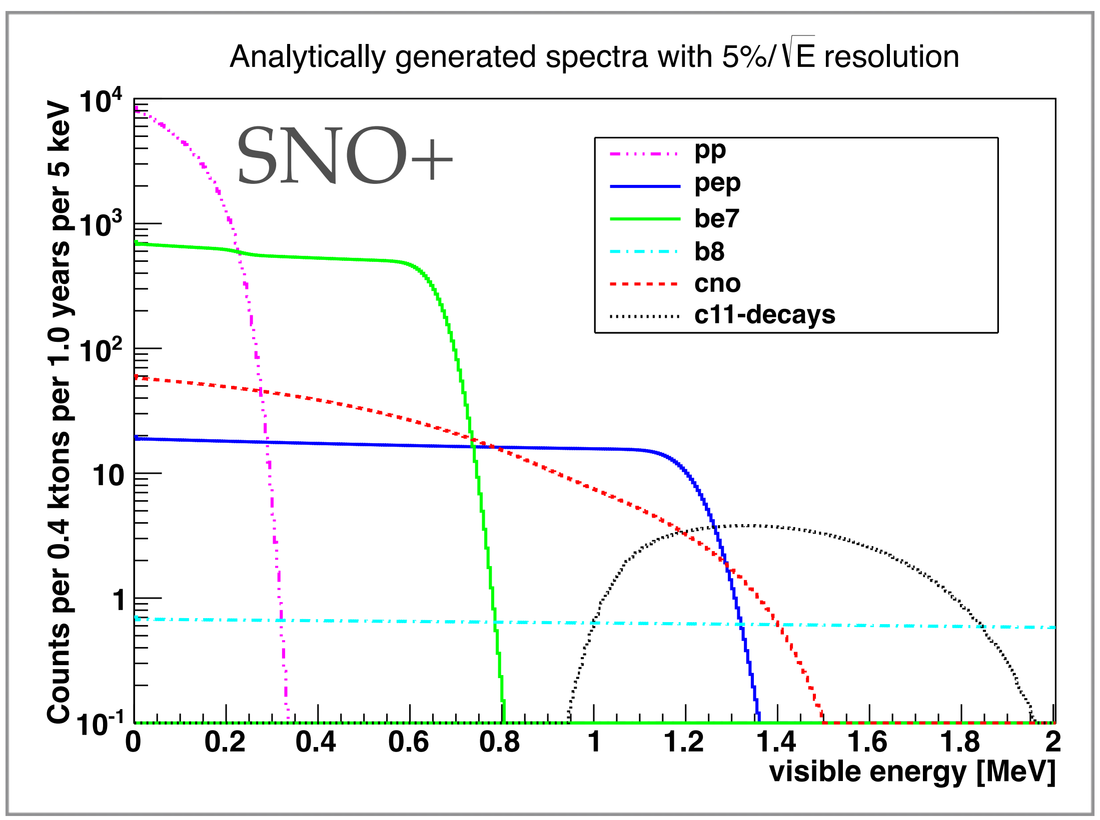

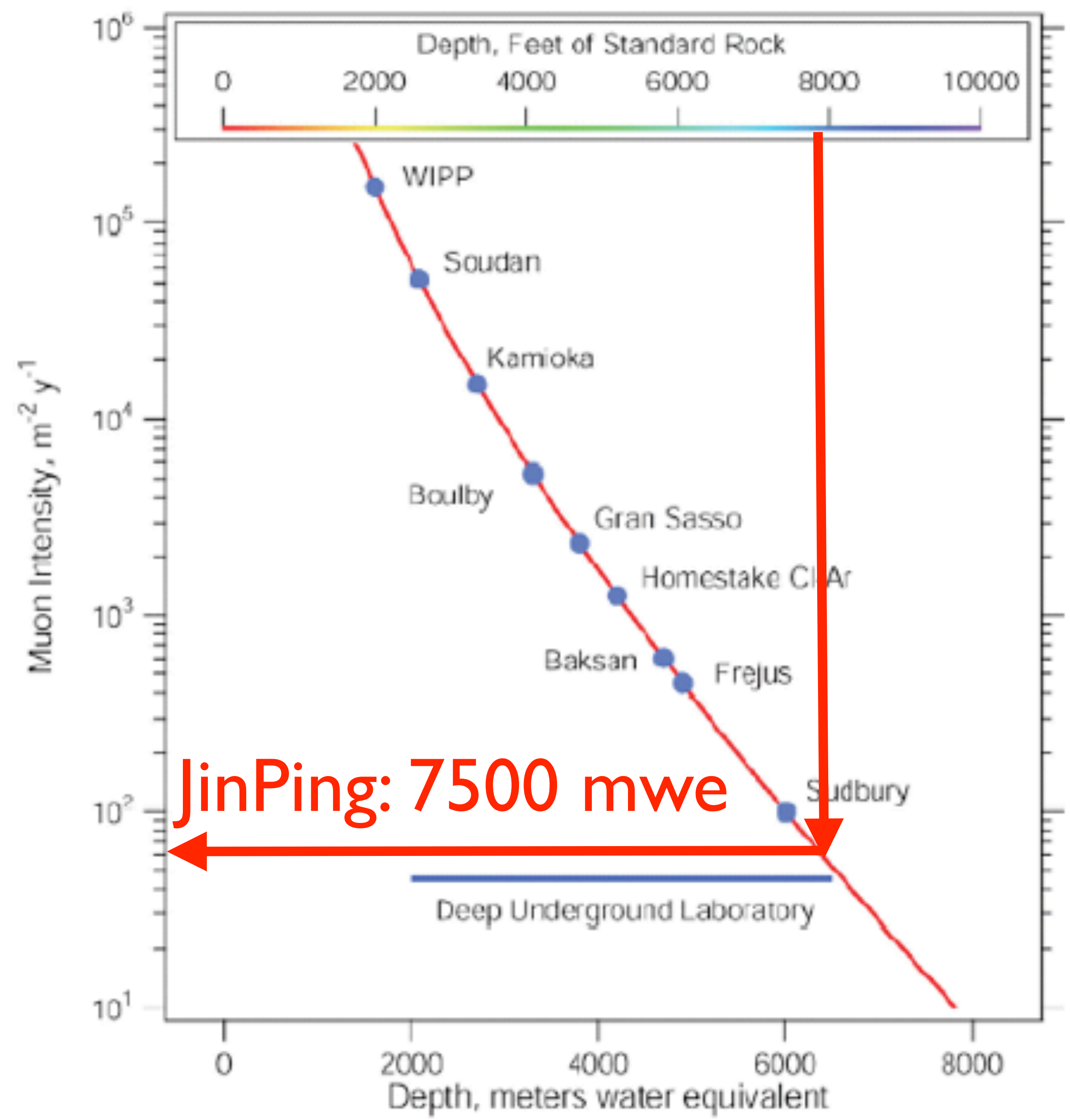

Ultra low cosmogenic backgrounds!

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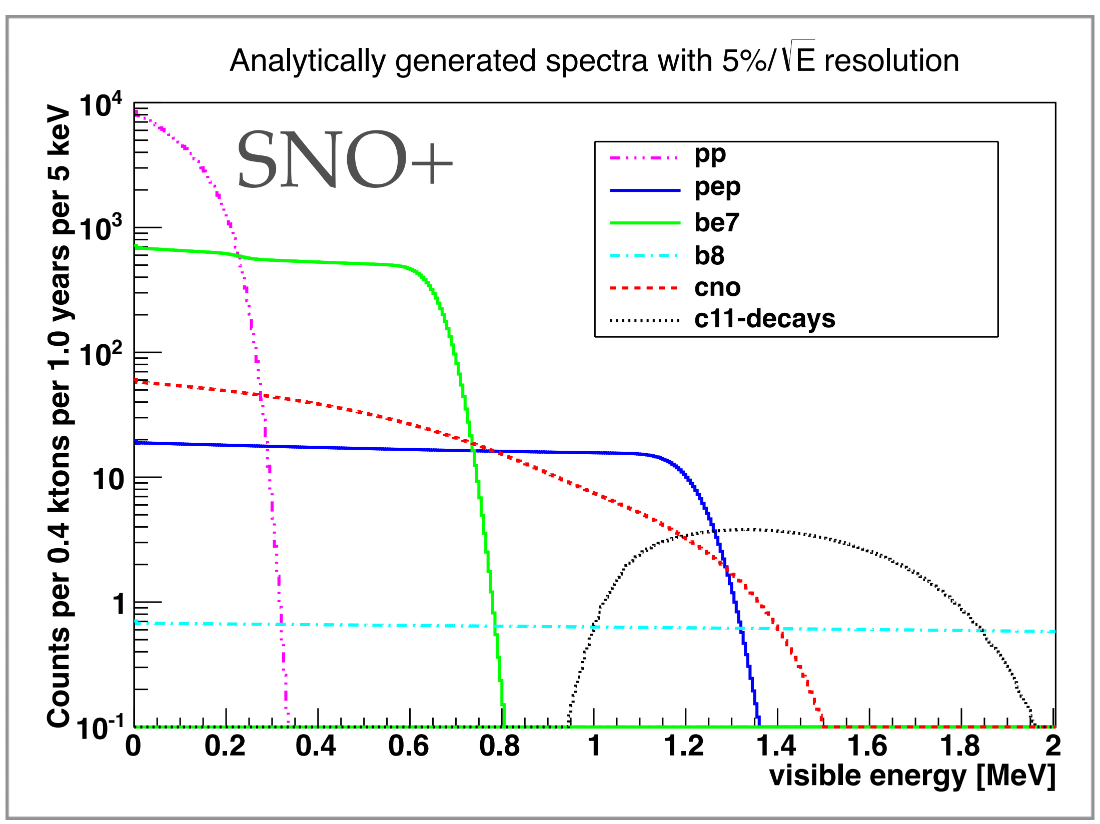

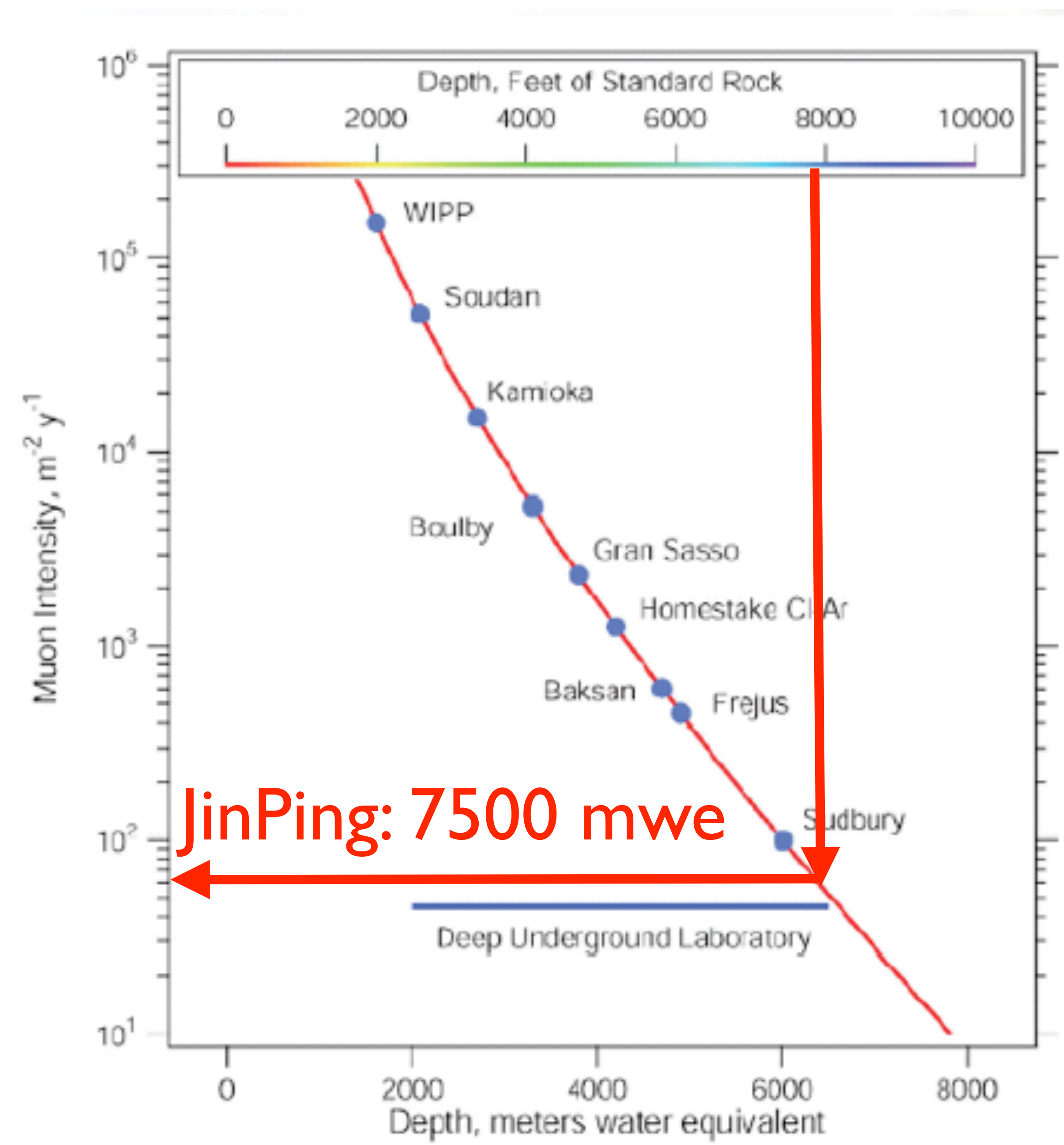

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Upcoming workshop:

http://underground.physics.berkeley.edu/SolarJinPing.html

Noble Liquid Dark Matter Searches

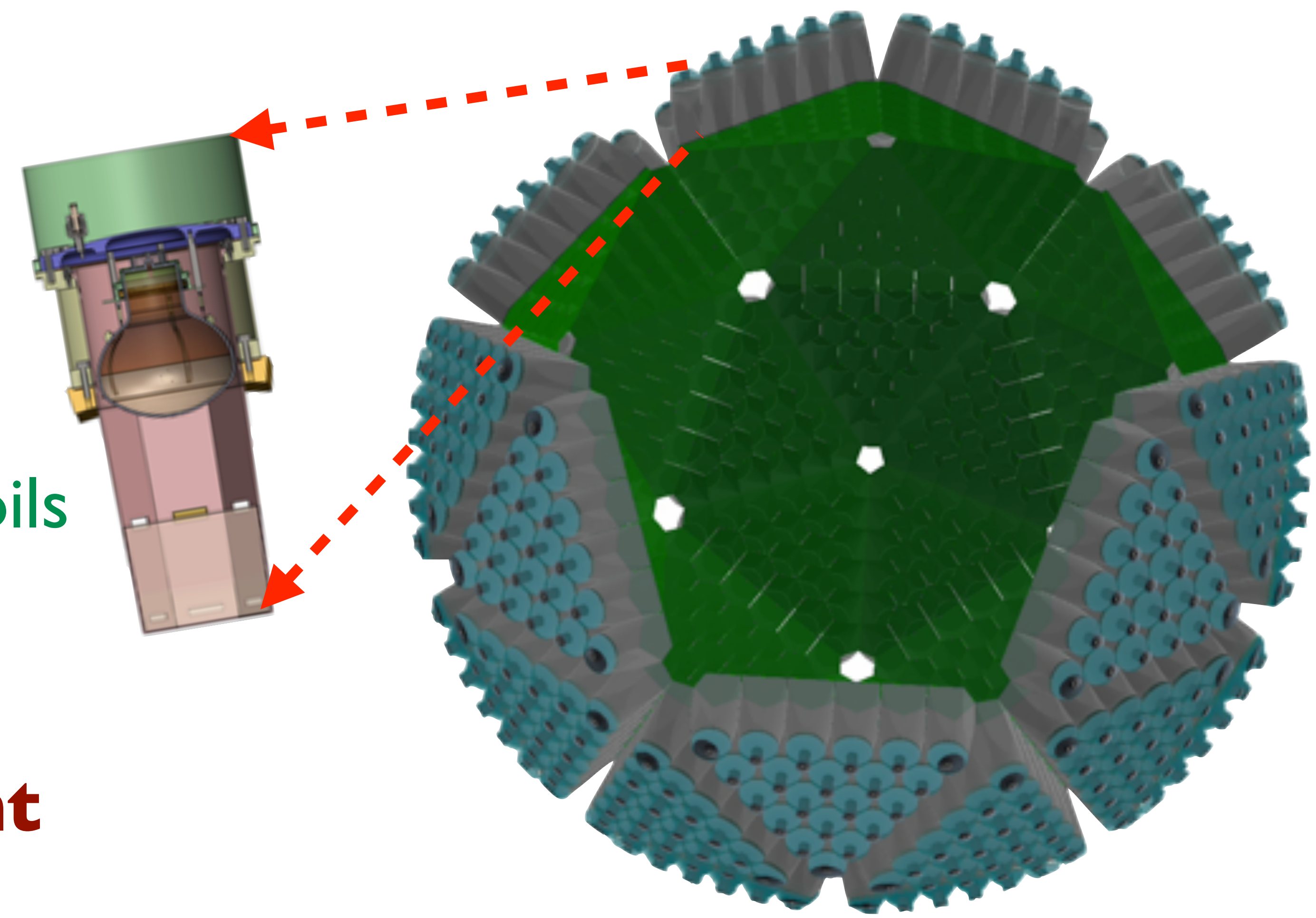
Liquid neon (CLEAN):

50-T scale dark matter expt
No intrinsic backgrounds
27K: most contaminants freeze out
PSD discriminates electron / nuclear recoils

⇛ reject neutrons

⇛ *Background free fiducial volume!*

⇛ **%-level (ES) pp measurement**



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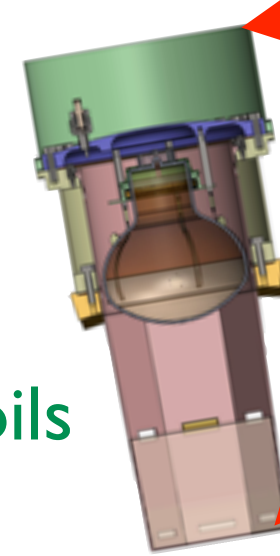
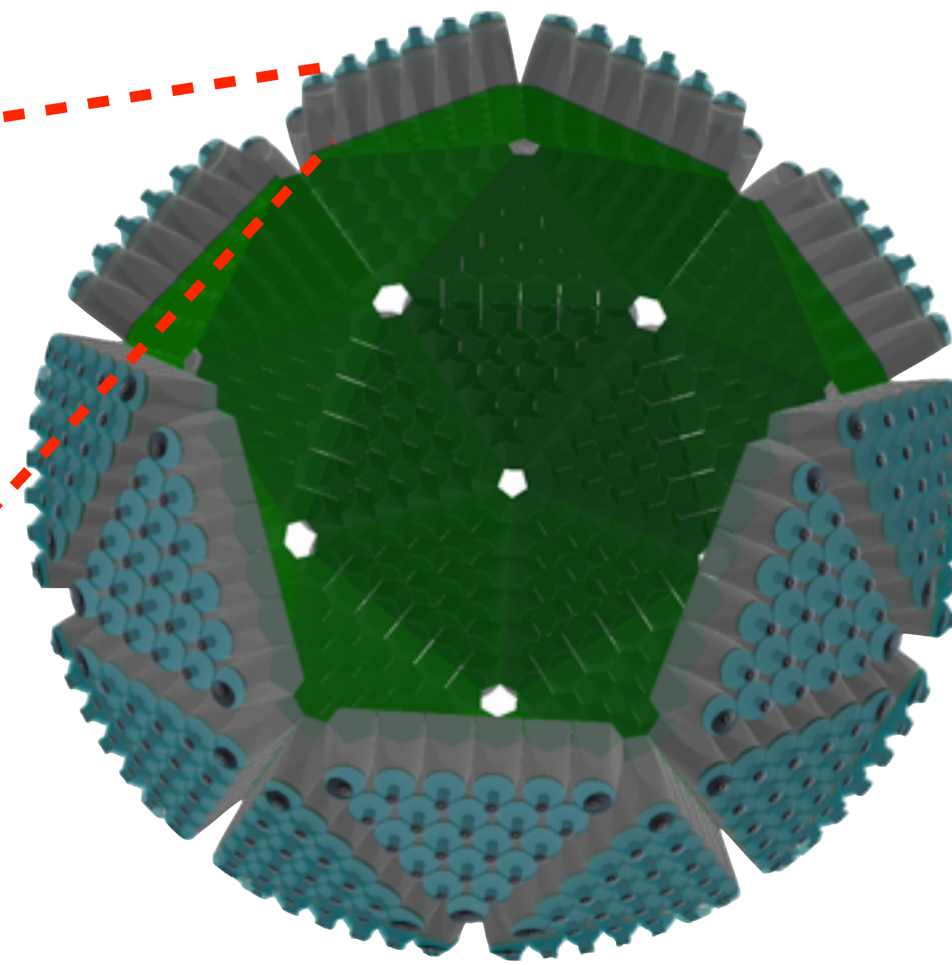
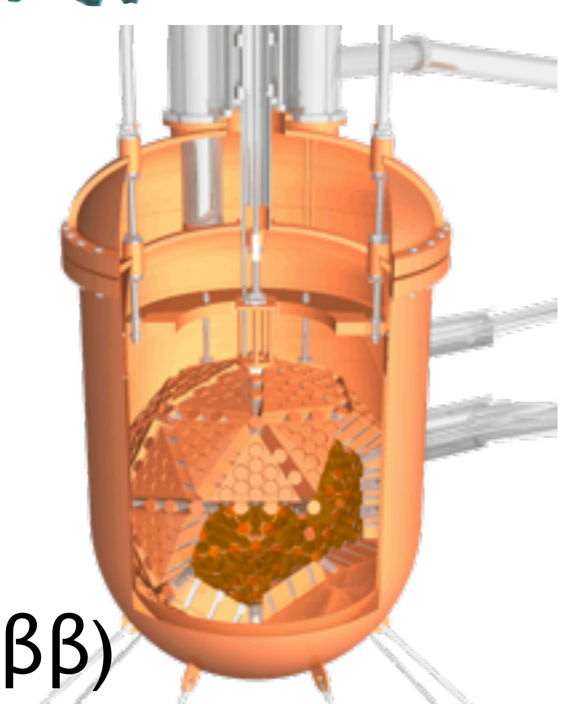




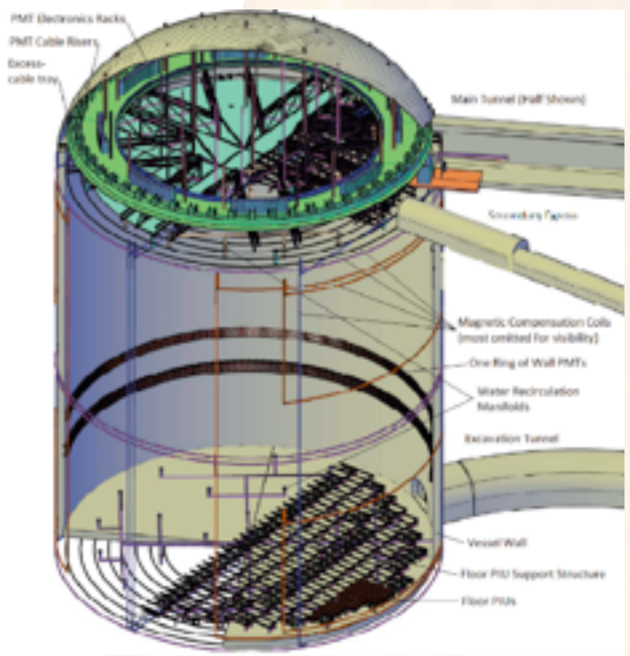
Liquid xenon (XMASS, LZ):

XMASS:
835kg prototype; 20 T goal
LUX (LZ):
0.37 under operation; 7.0 T goal
pp requires *100 depletion of ^{136}Xe ($2\nu\beta\beta$)



“Mega-Ton” Scale

Hyper-Kamiokande



- 0.99e6 T (20* Super-K)
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- 4σ confirmation of MSW

arXiv: 1309.0184

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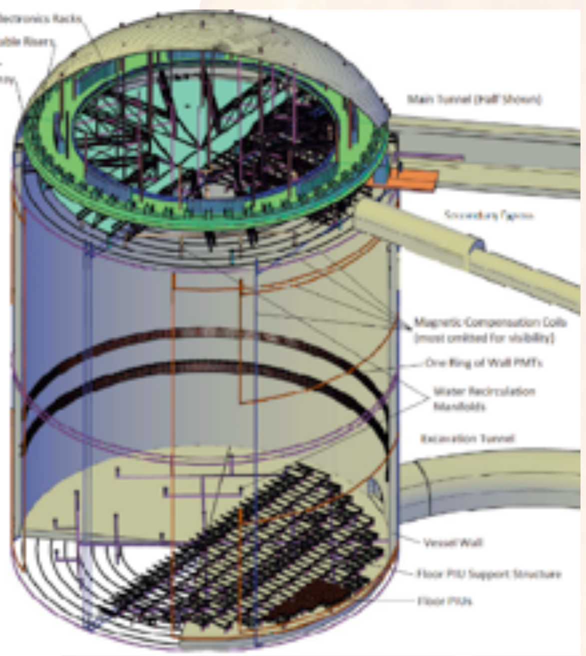

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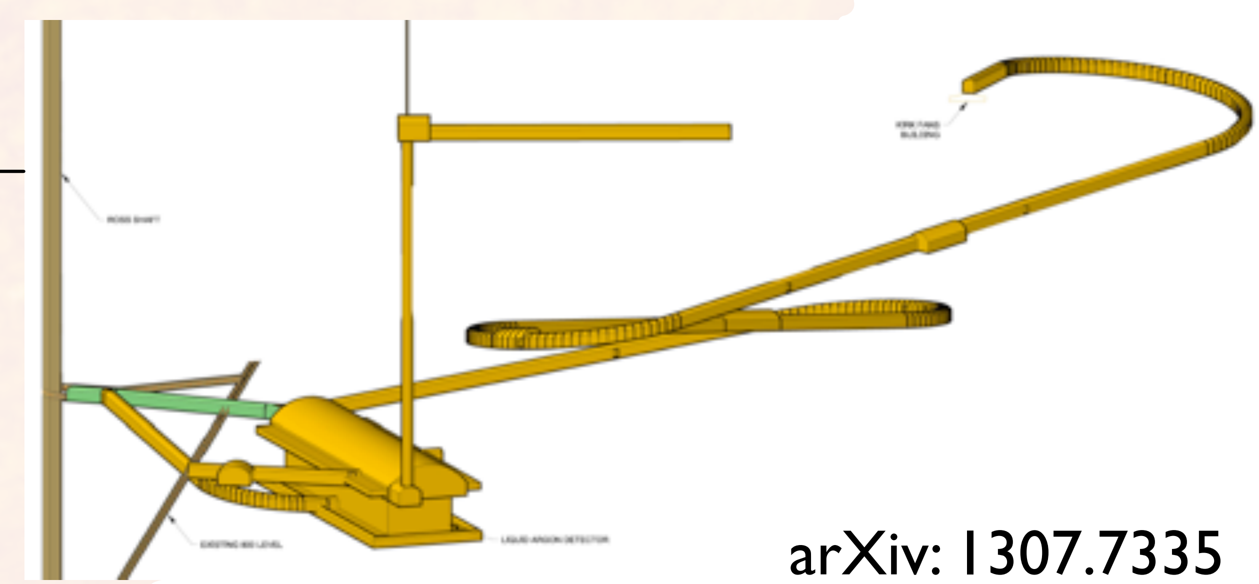
LBNF

- 40kT LAr (+ 50kT WCD?) - p5
  - CC on ^{40}Ar, E_{th} = 5MeV

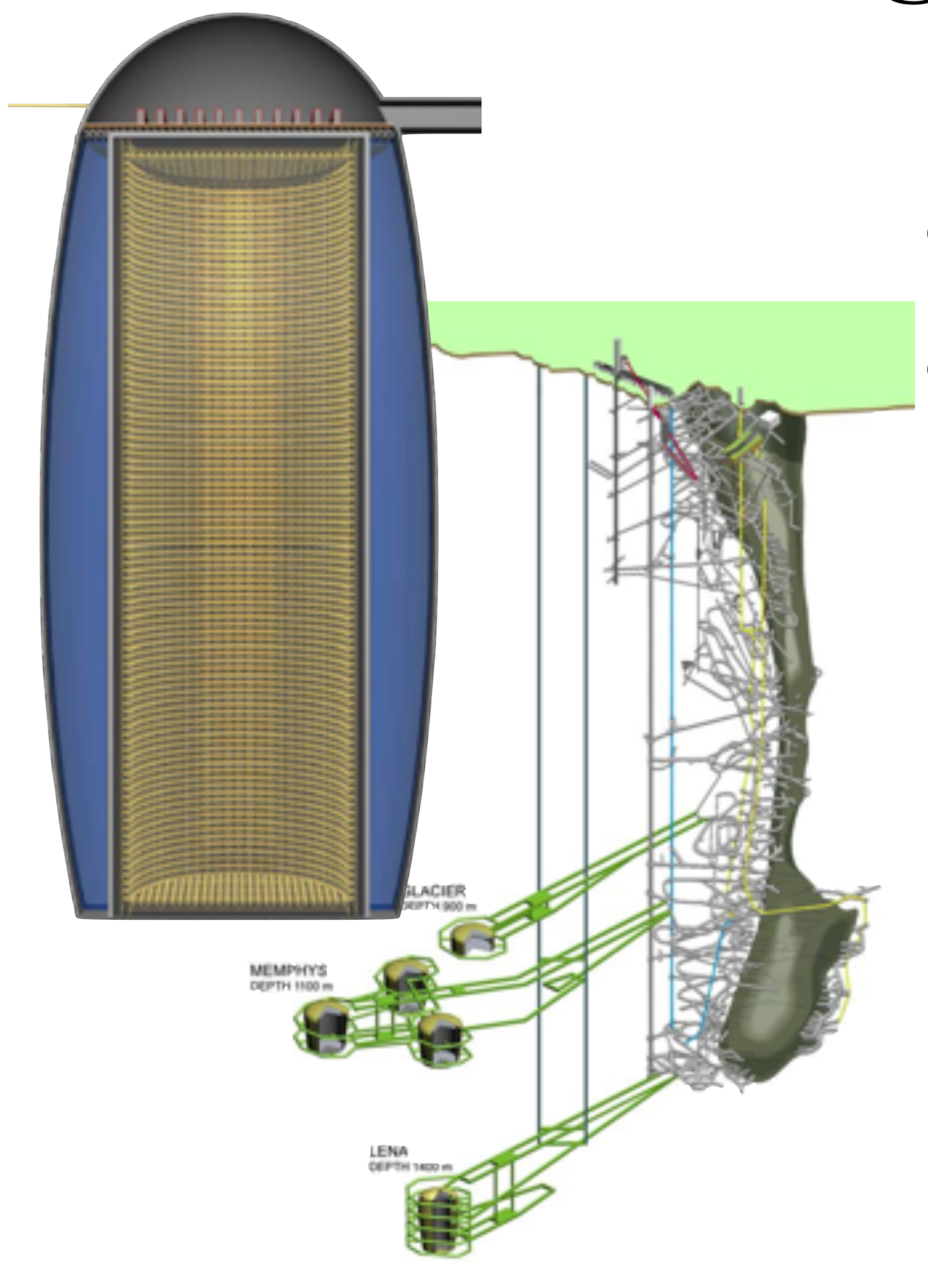
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

Transition	Rate (evts/day)
Fermi	31
Gamow-Teller	88



arXiv: 1307.7335

Low **E**nergy **N**eutrino **A**stronomy



Posters: Dr Bick, #84

- 50kT LS (30kT FV solar),   30% coverage
- Unprecedented statistics at low-energy
  - 3σ discovery potential for 0.1%-amplitude temporal modulations in ^{7}Be flux
  - CNO detection
  - Low-energy ^{8}B spectrum (+ CC on ^{13}C)

M. Wurm, TAUP 2013

http://www.e15.ph.tum.de/research_and_projects/lena/

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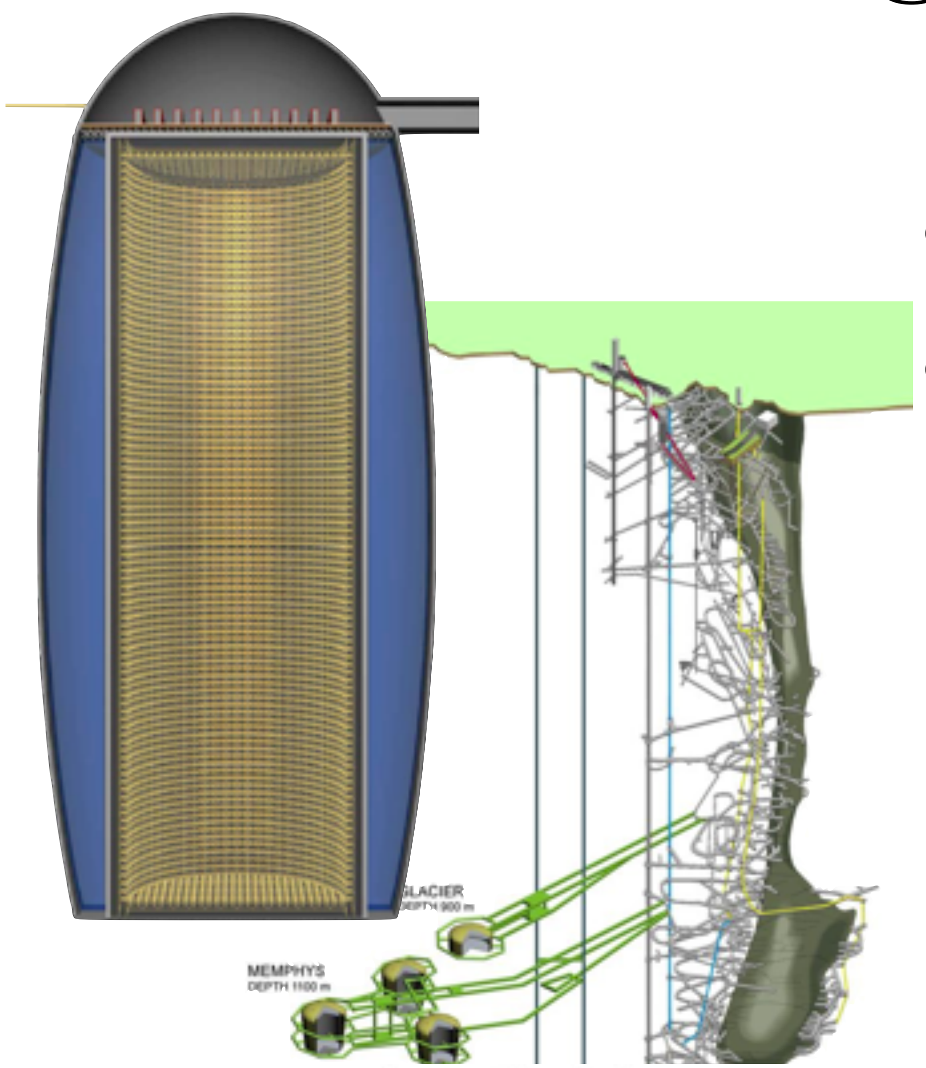

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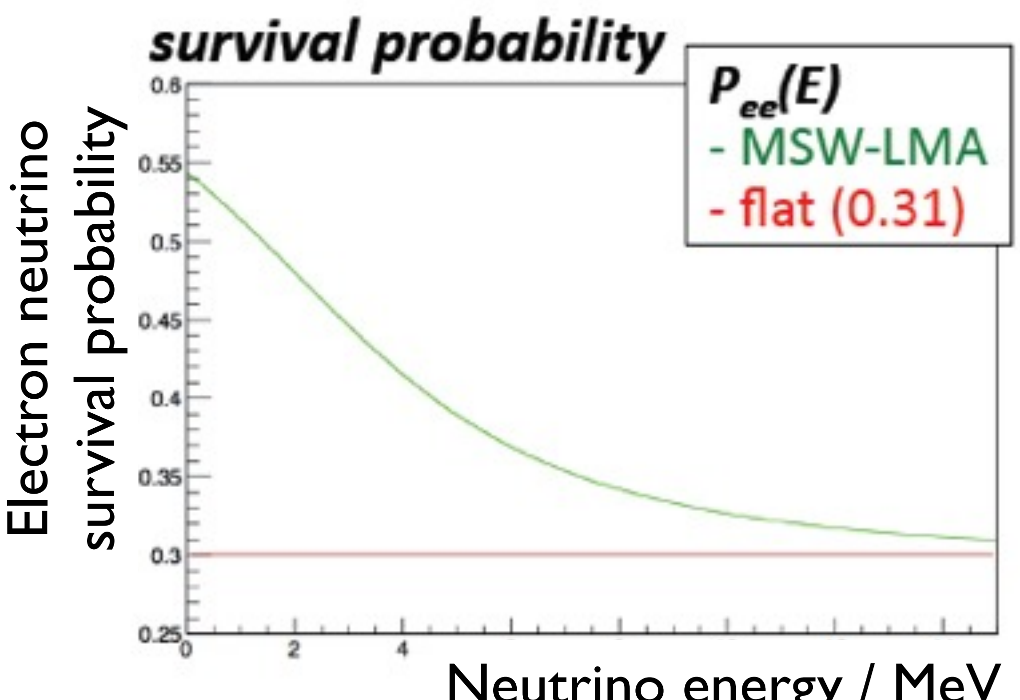

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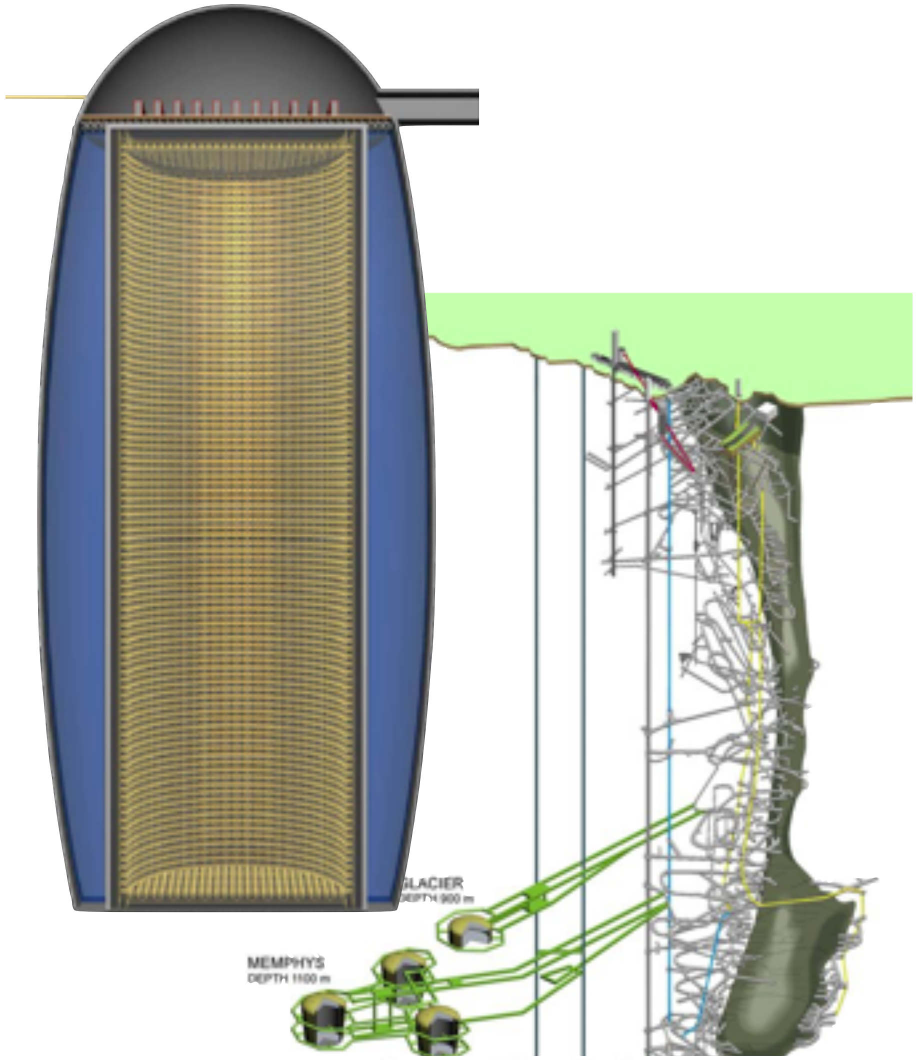

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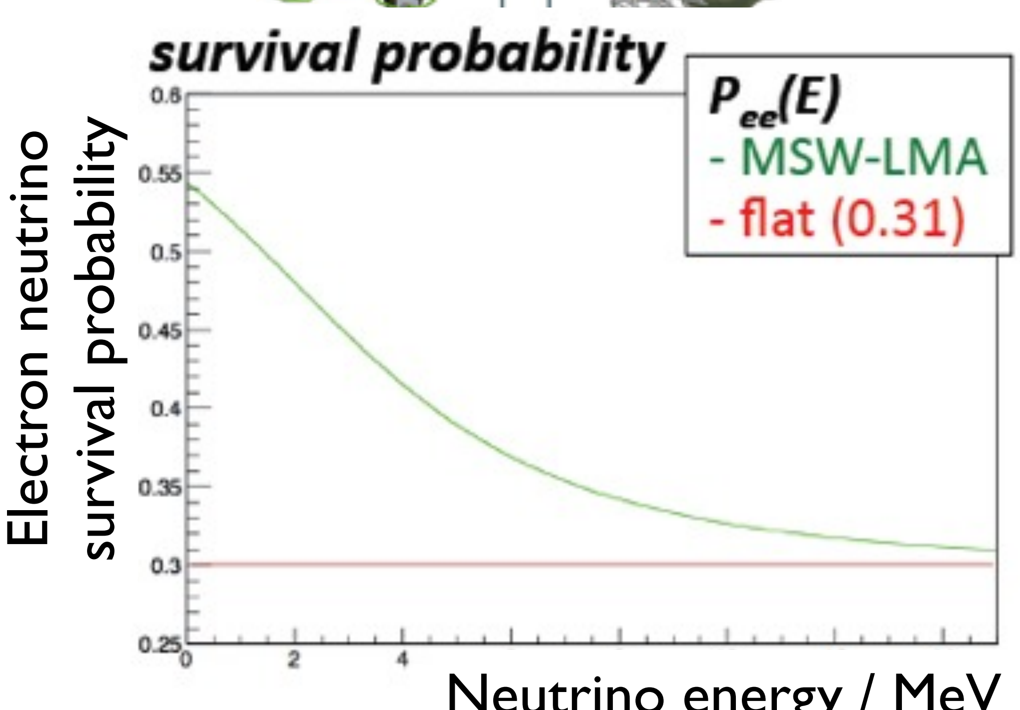

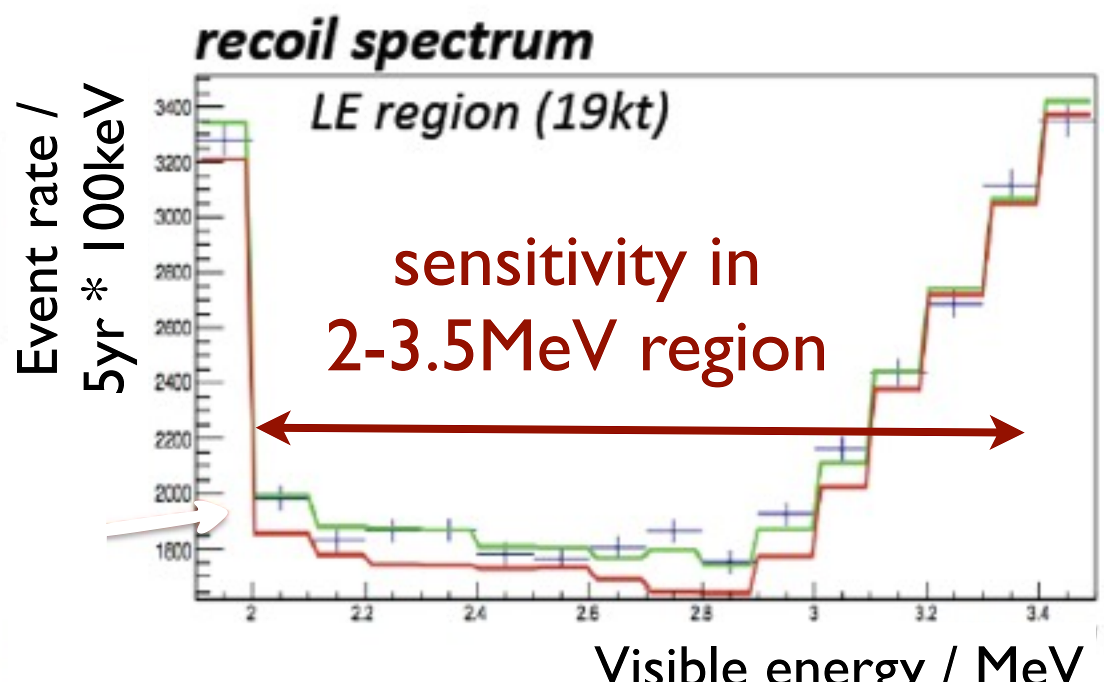

5σ after 3-5 years

M.Wurm, TAUP 2013

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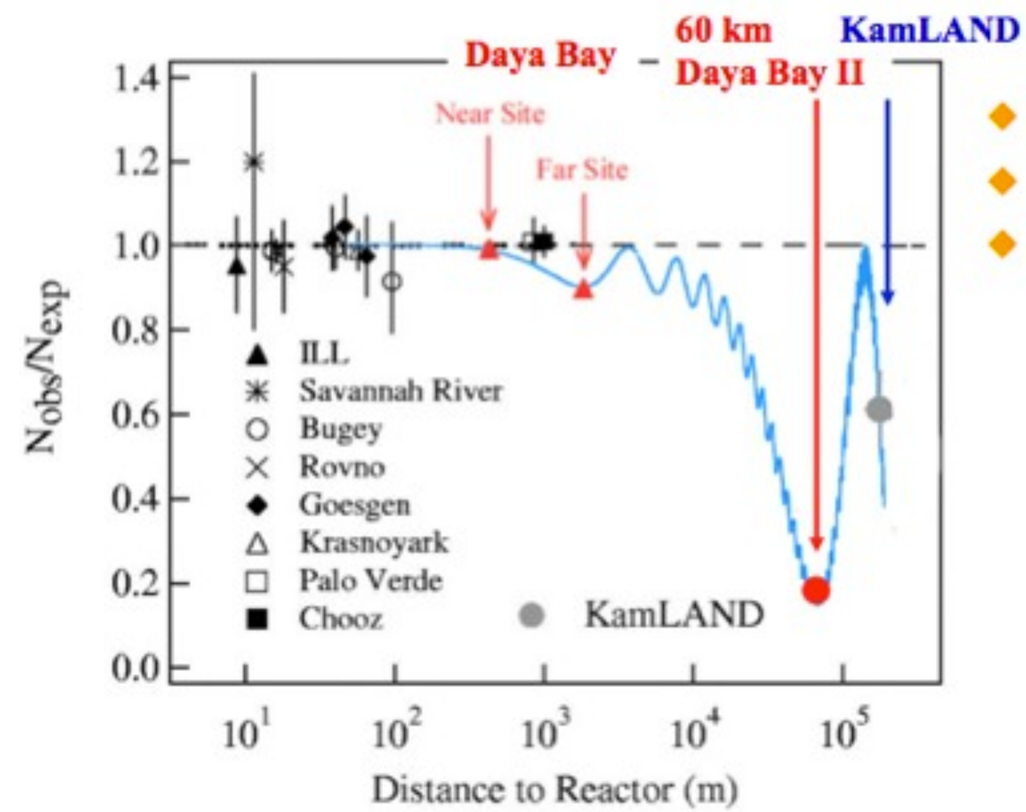
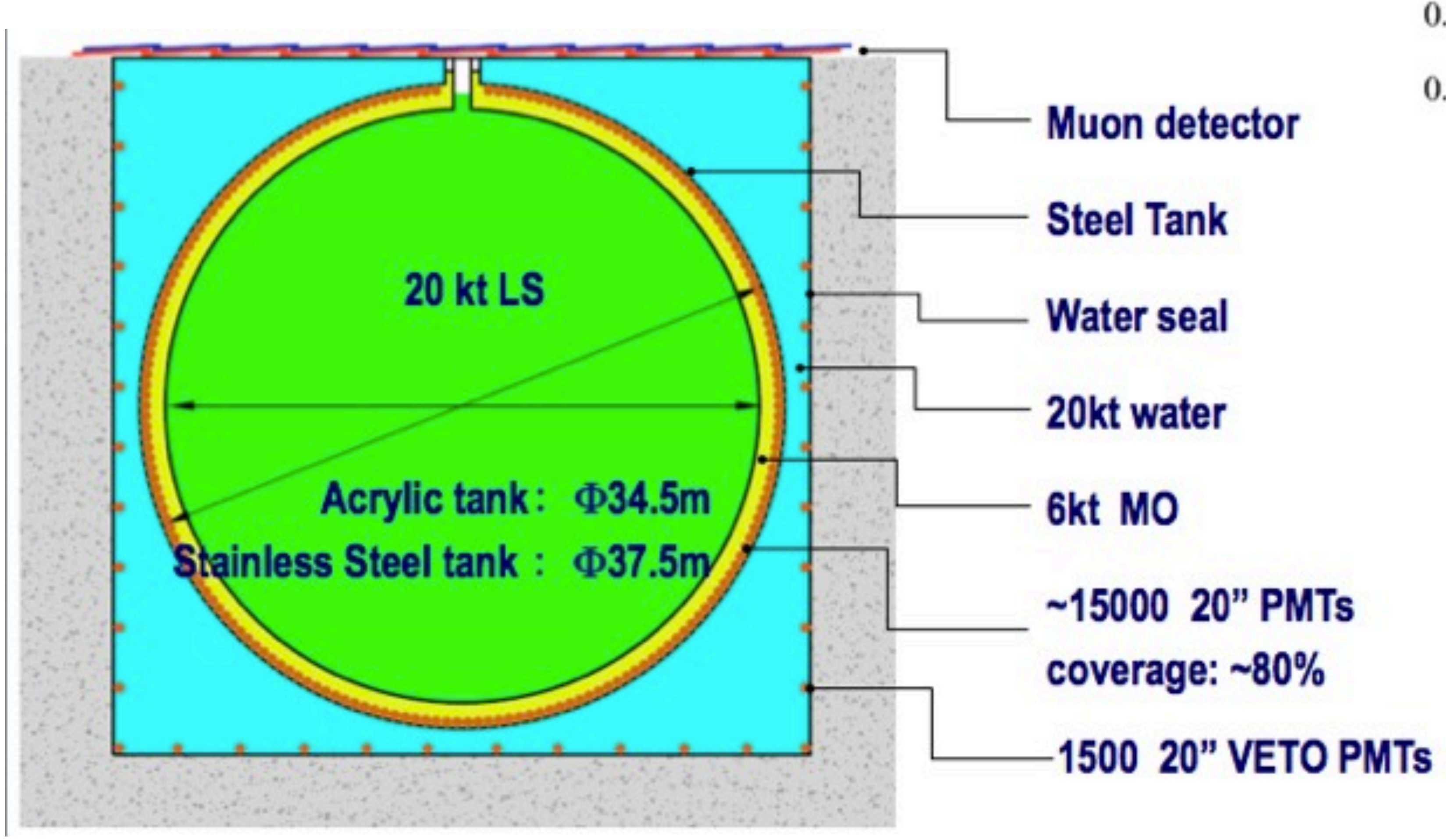
JUNO

- 20kT LS detector
- 700m rock overburden
- Goal of 3% /√E resolution



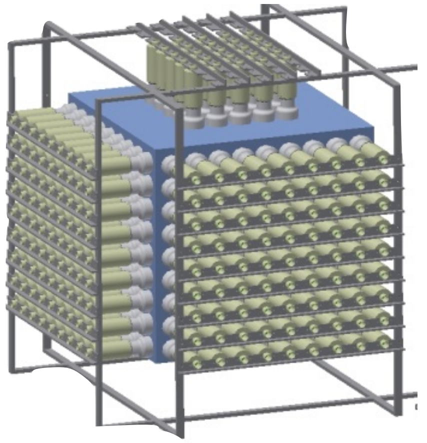


	Current	JUNO
Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

http://english.ihep.cas.cn/rs/fs/juno0815/

Posters:
Dr Li, #82

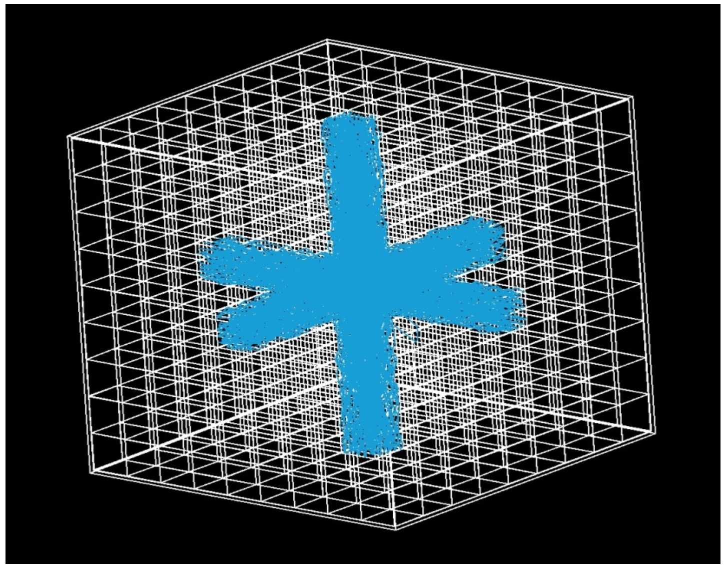
CC Detection: LENS

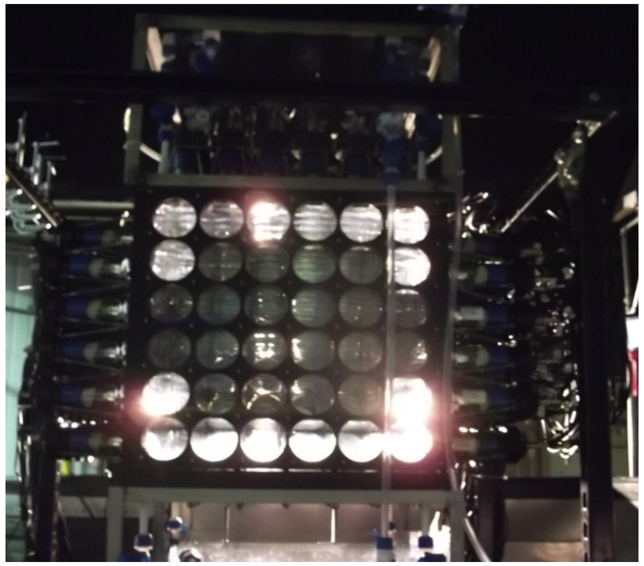


$$\nu_e + {}^{115}In \longrightarrow {}^{115}Sn^* + \beta^-$$

$$\tau = 4.76\mu s \hookrightarrow \gamma(115\mathrm{keV}) + \gamma(497\mathrm{keV}) + {}^{115}\mathrm{Sn}$$

- Delayed triple coincidence helps reject ^{115}In bkg (need 10^{11} rejection)
- Q = 115keV : 95% of pp spectrum
- Segmentation helps reject ext bkgs





Posters: Dr Yokley, #85

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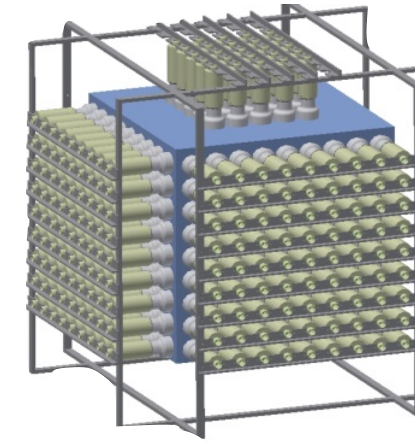

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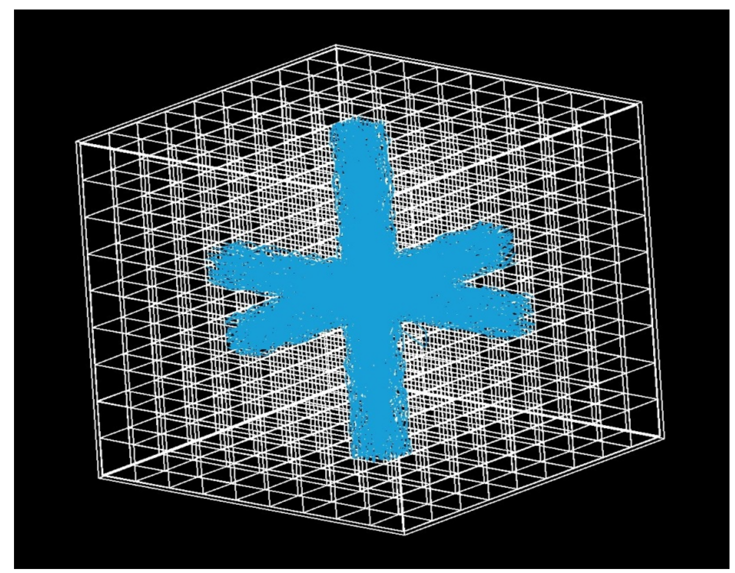

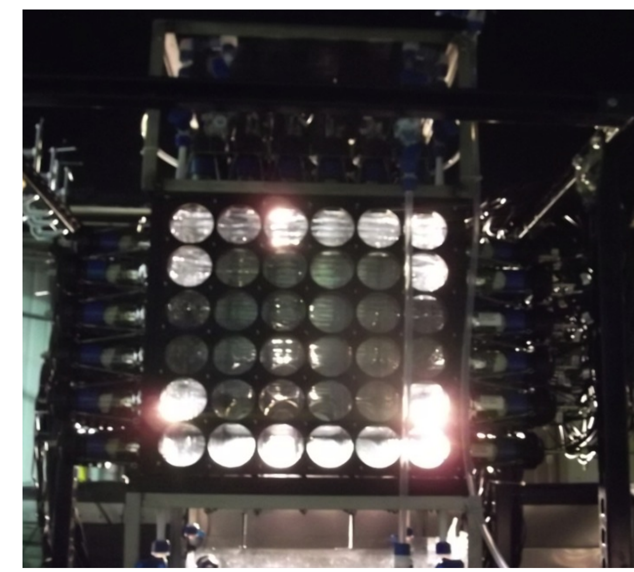

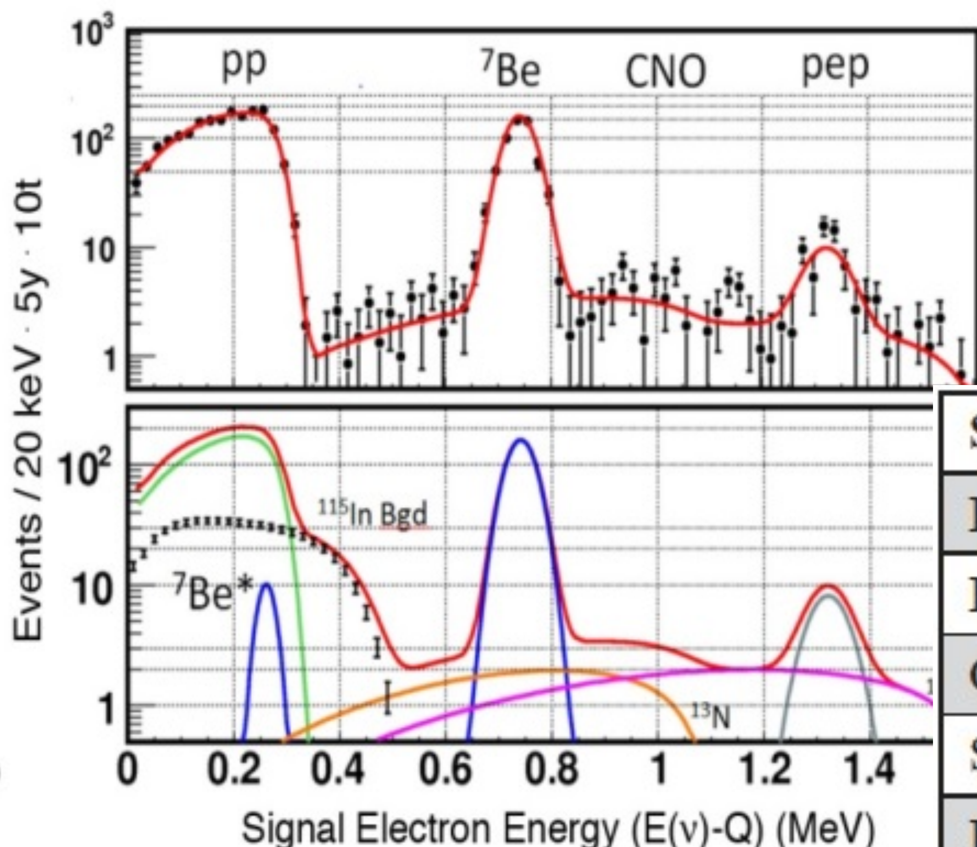

Source	pp	7Be	GS98 CNO*	AGSS09 CNO†
Flux (/cm2/s)	6.00E+10	4.70E+09	4.97E+08	3.74E+08
Flux (SNU) [Bah88]	468	116	15	11
Cross section[Rap85]	1.00E-44	2.50E-44	2.50E-44	2.50E-44
Survival probability	56	54	54	54
Rate (per ton year)	26	6.2	1.2	0.9
Rate (10 tons · 5 yr)	**1296**	**310**	**58**	**43**

Posters: Dr Yokley, #85

A “New” Idea for CC Detection

- Load large water Cherenkov detector with e.g. ^{7}Li for CC interaction

“Salty water Cherenkov detectors” W.C. Haxton PRL 76 (1996) 10

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Phys. Rev. C 88 (2013) 065502

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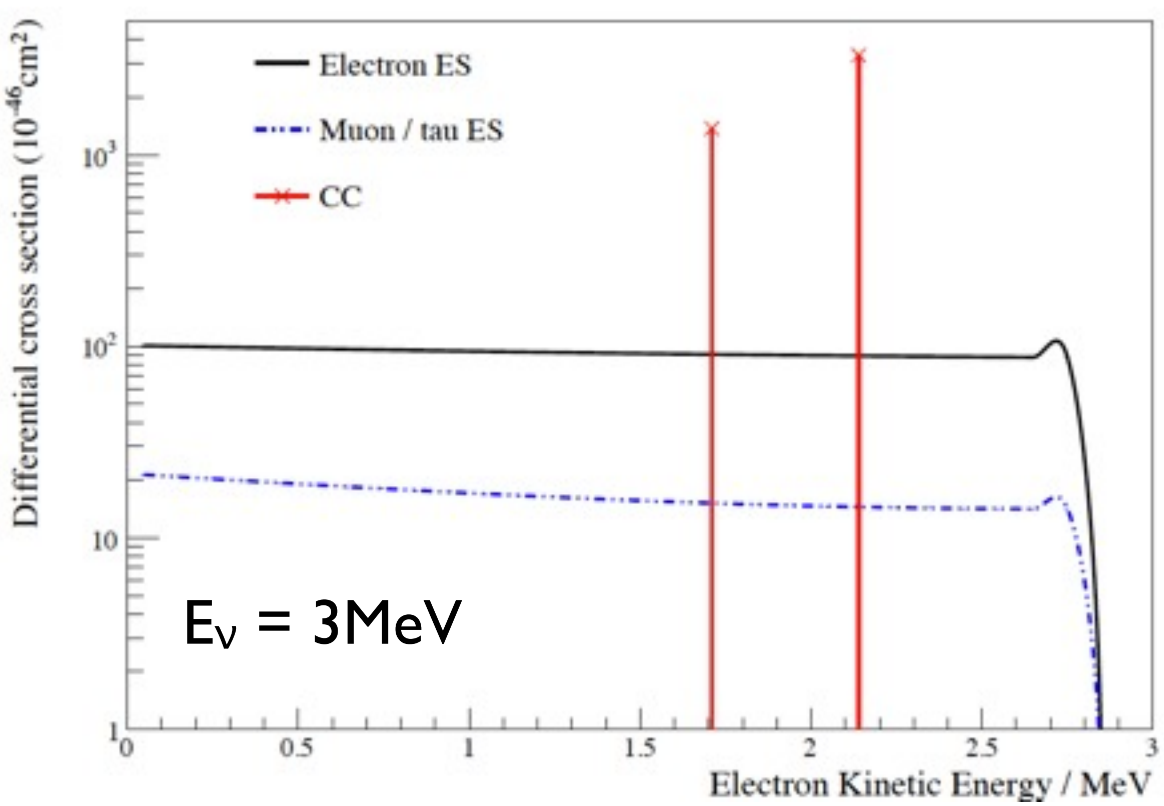

Cross section from W. C. Haxton

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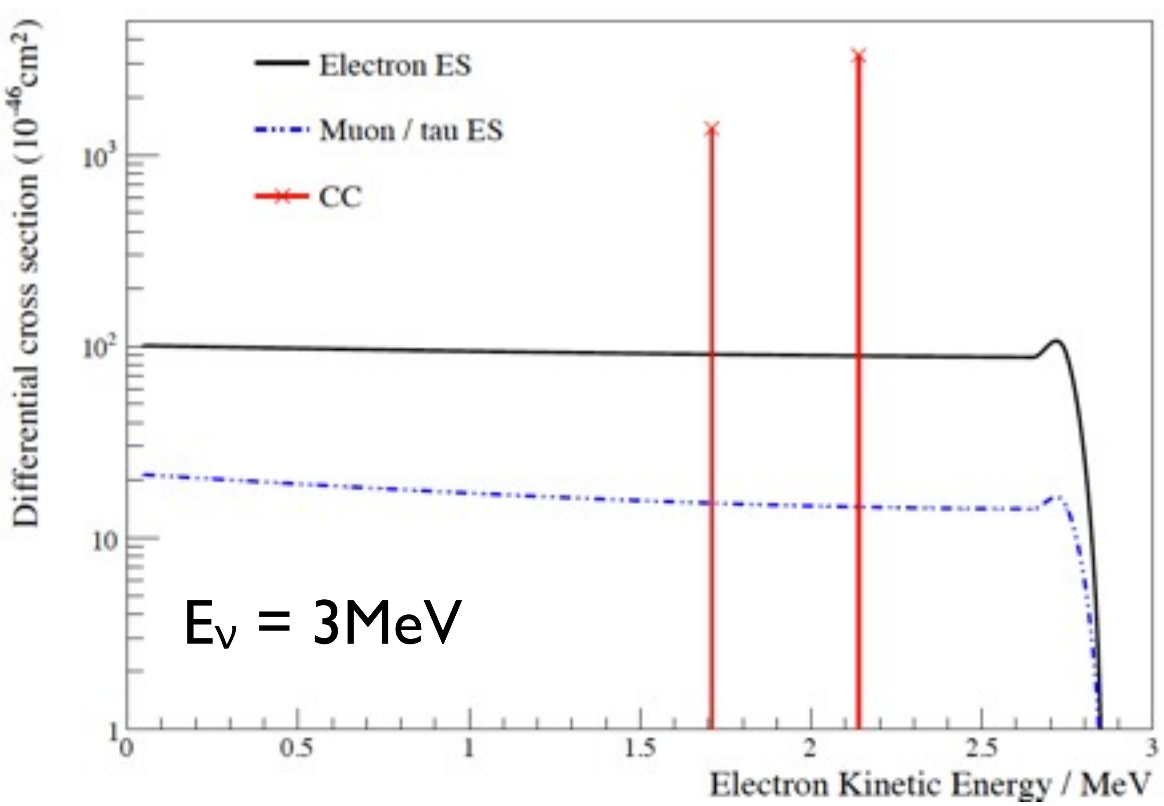

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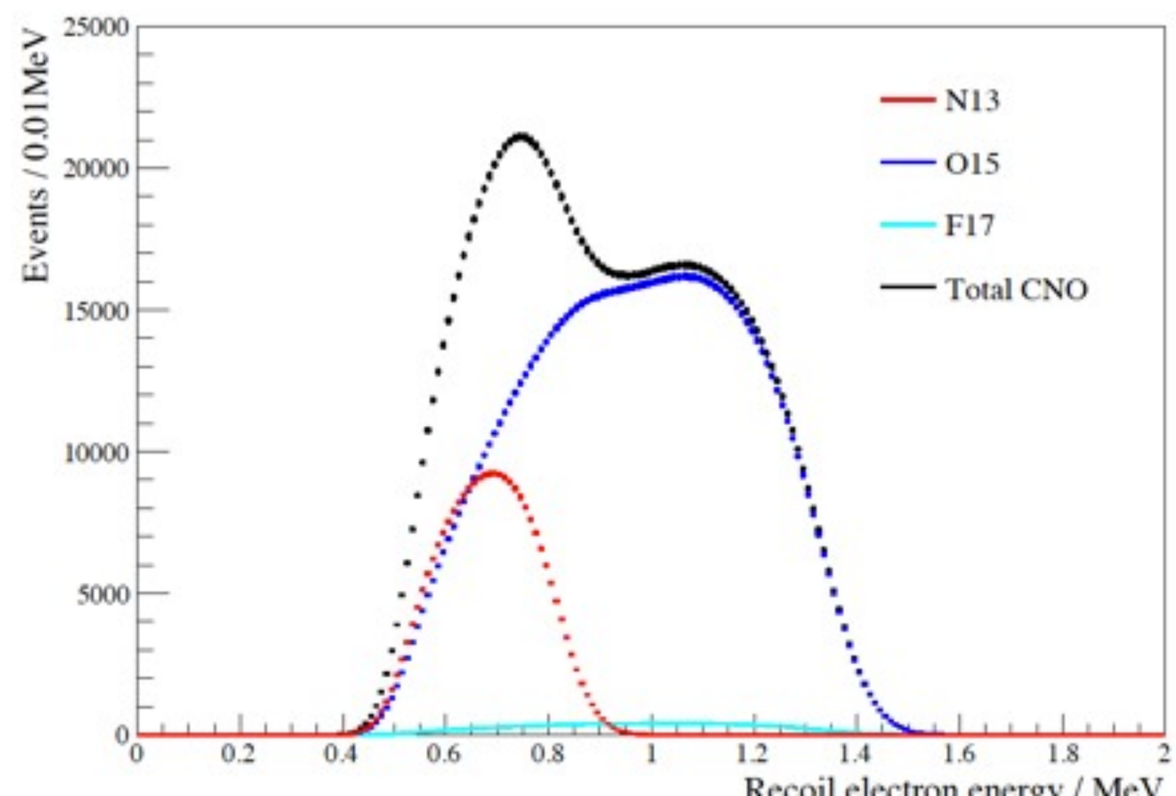

Critical Inputs to the Solar Program

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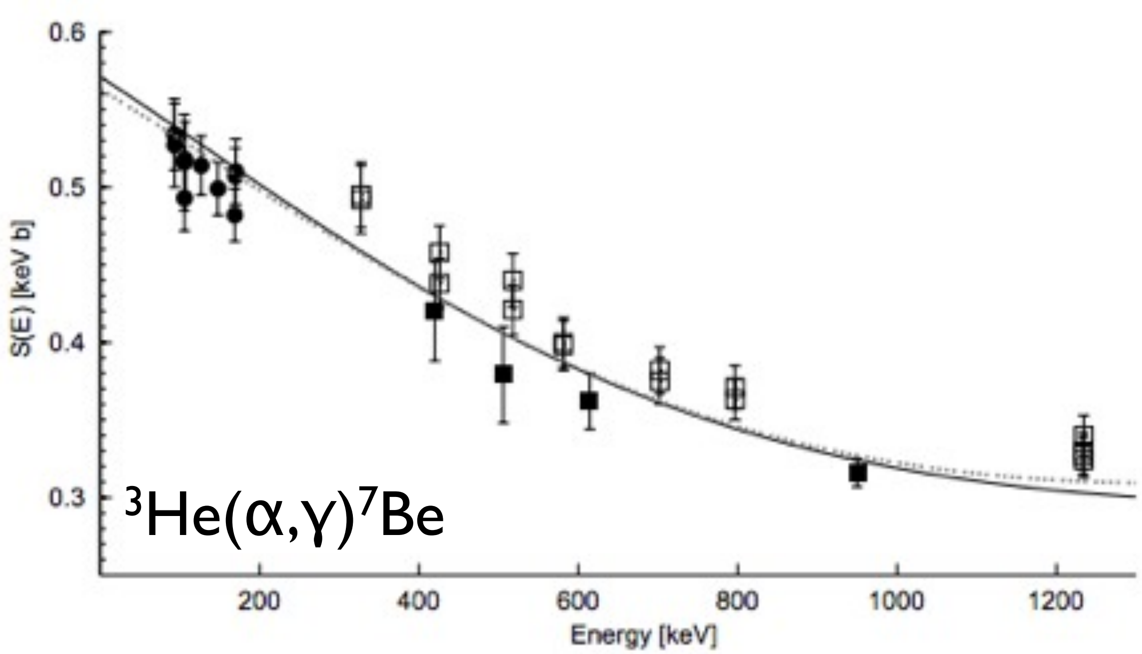

LUNA collaboration
Nuclear Physics, Section A 814 (2008), pp. 144-158

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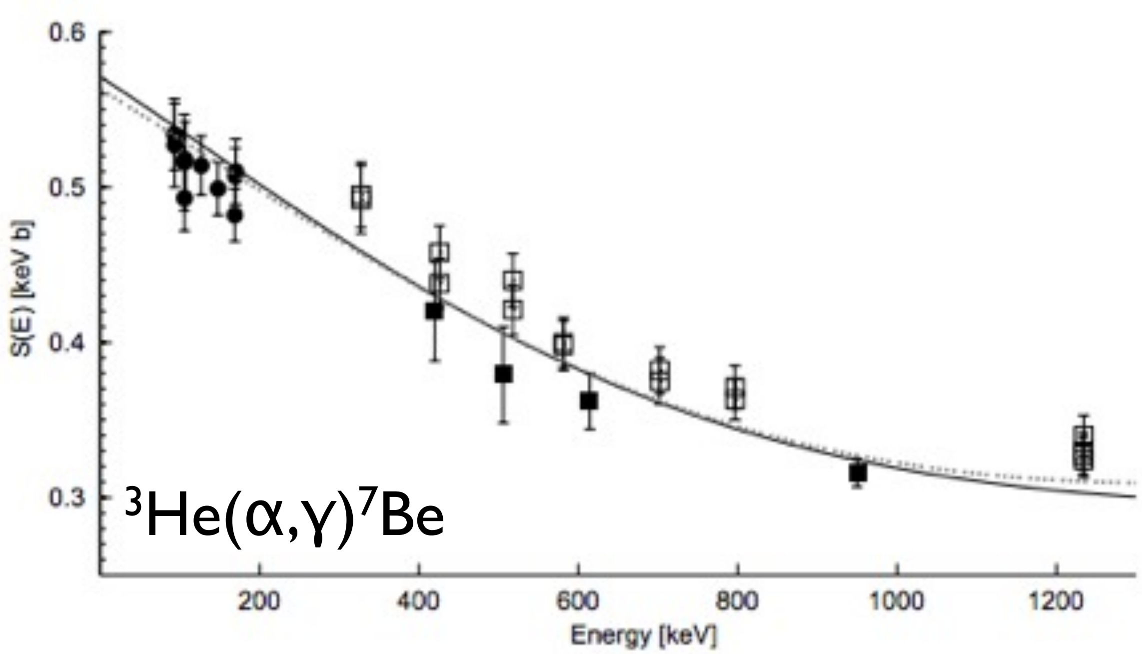

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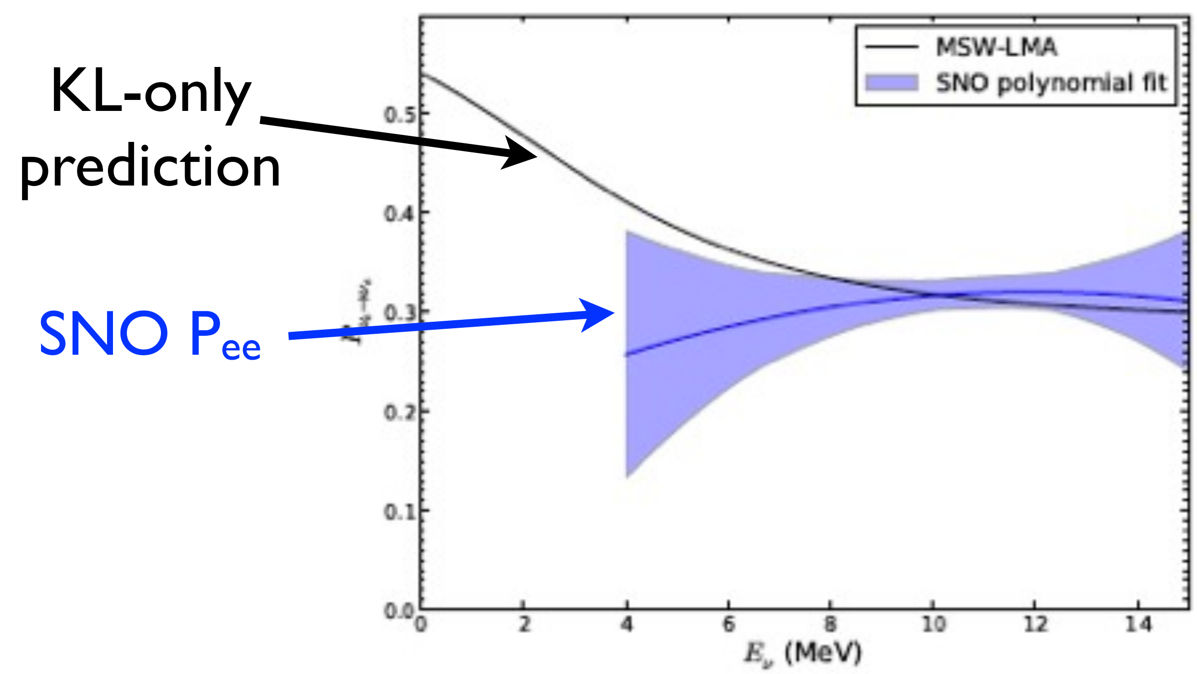
- Terrestrial oscillation parameter measurements



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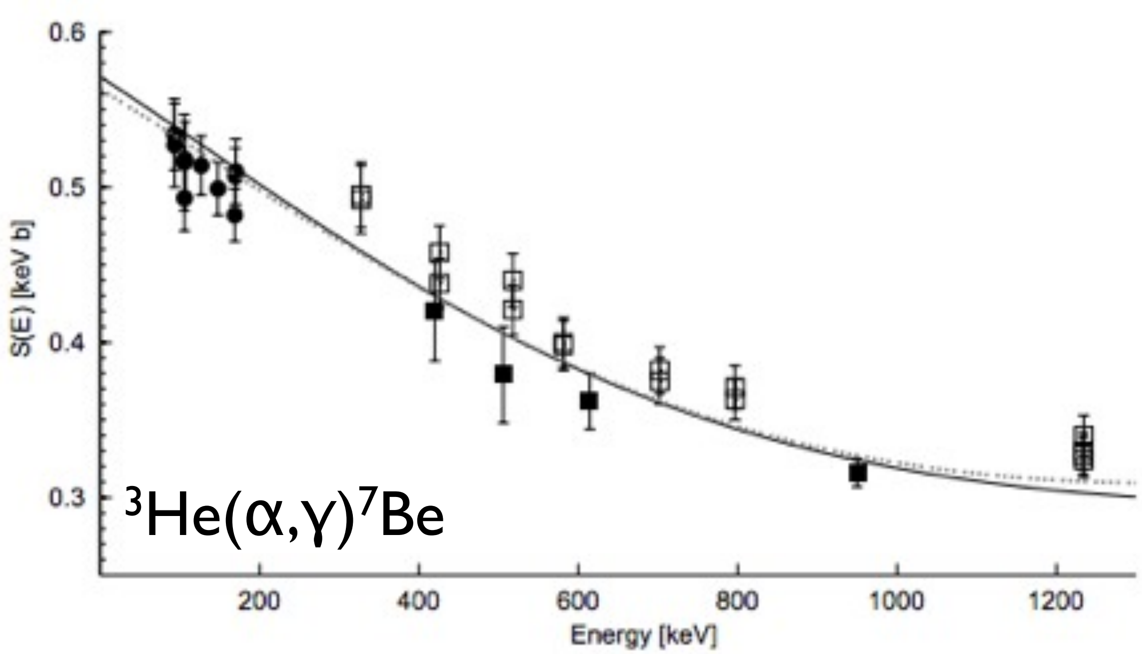

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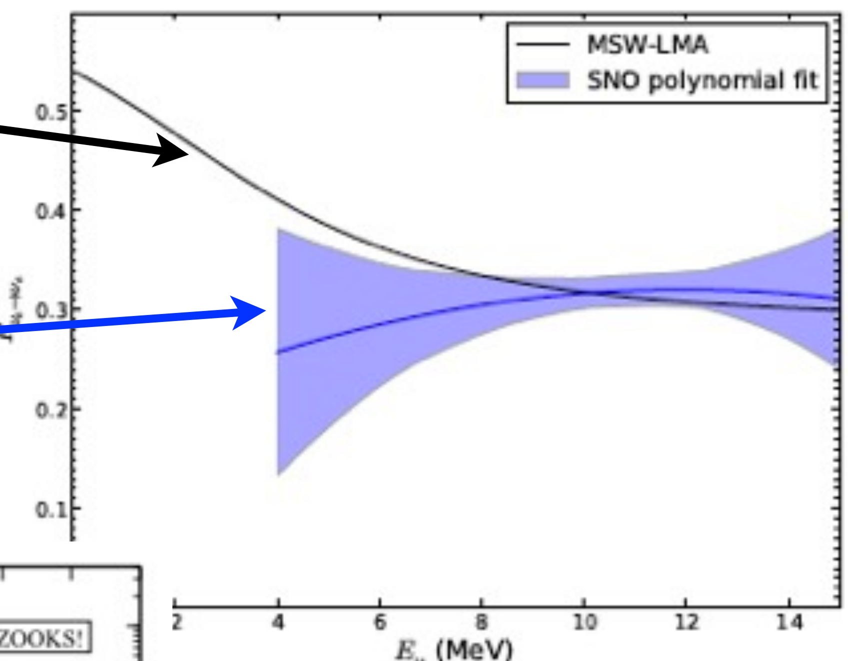
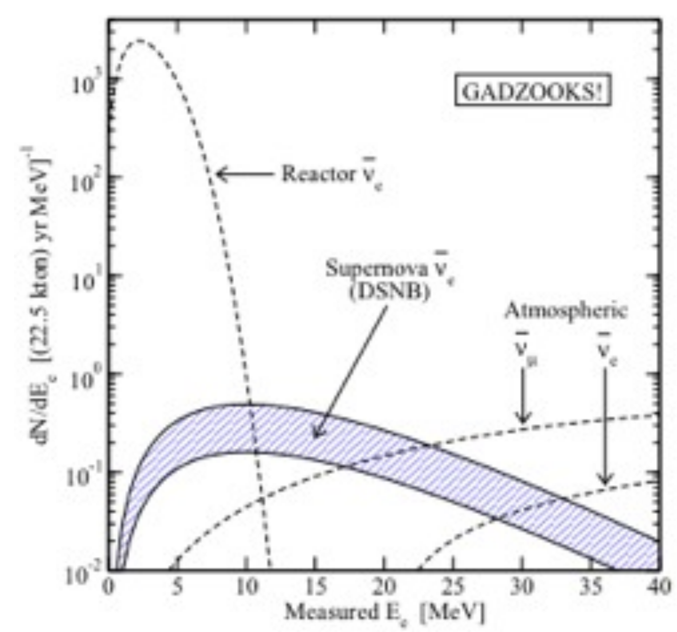
Nuclear Physics, Section A 814 (2008), pp. 144-158

- Terrestrial oscillation parameter measurements

KL-only prediction

SNO P_{ee}





PRL 93 (2004) 171101

e.g. Super-K + Gd (GADZOOKS!)
~50* KL fiducial mass

Summary

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- **Rich, diverse program of physics**
  - **Study neutrino properties**
  - **Sensitive search for new physics effects**
  - **Unique probe of solar structure & solar system formation**

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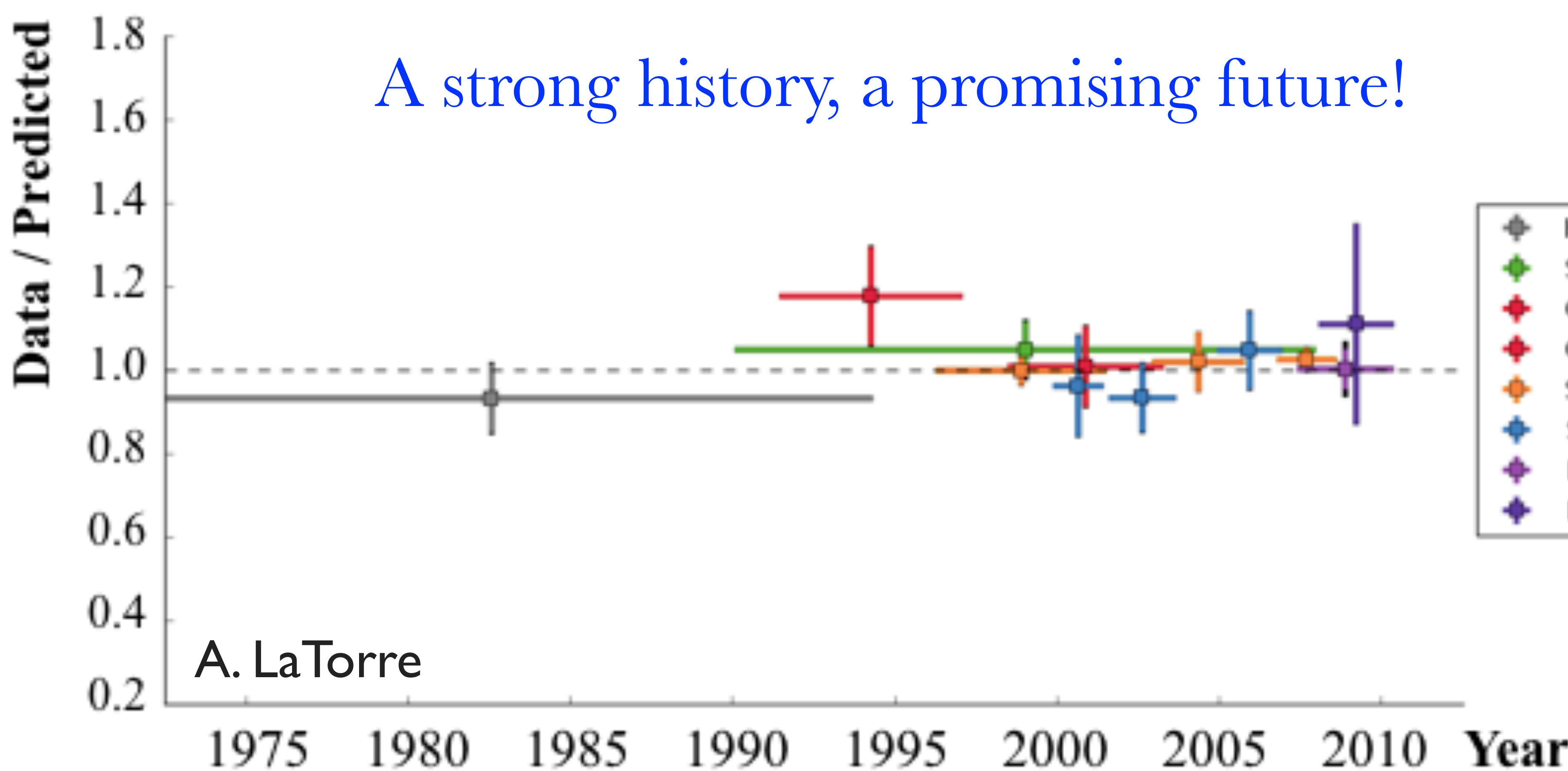
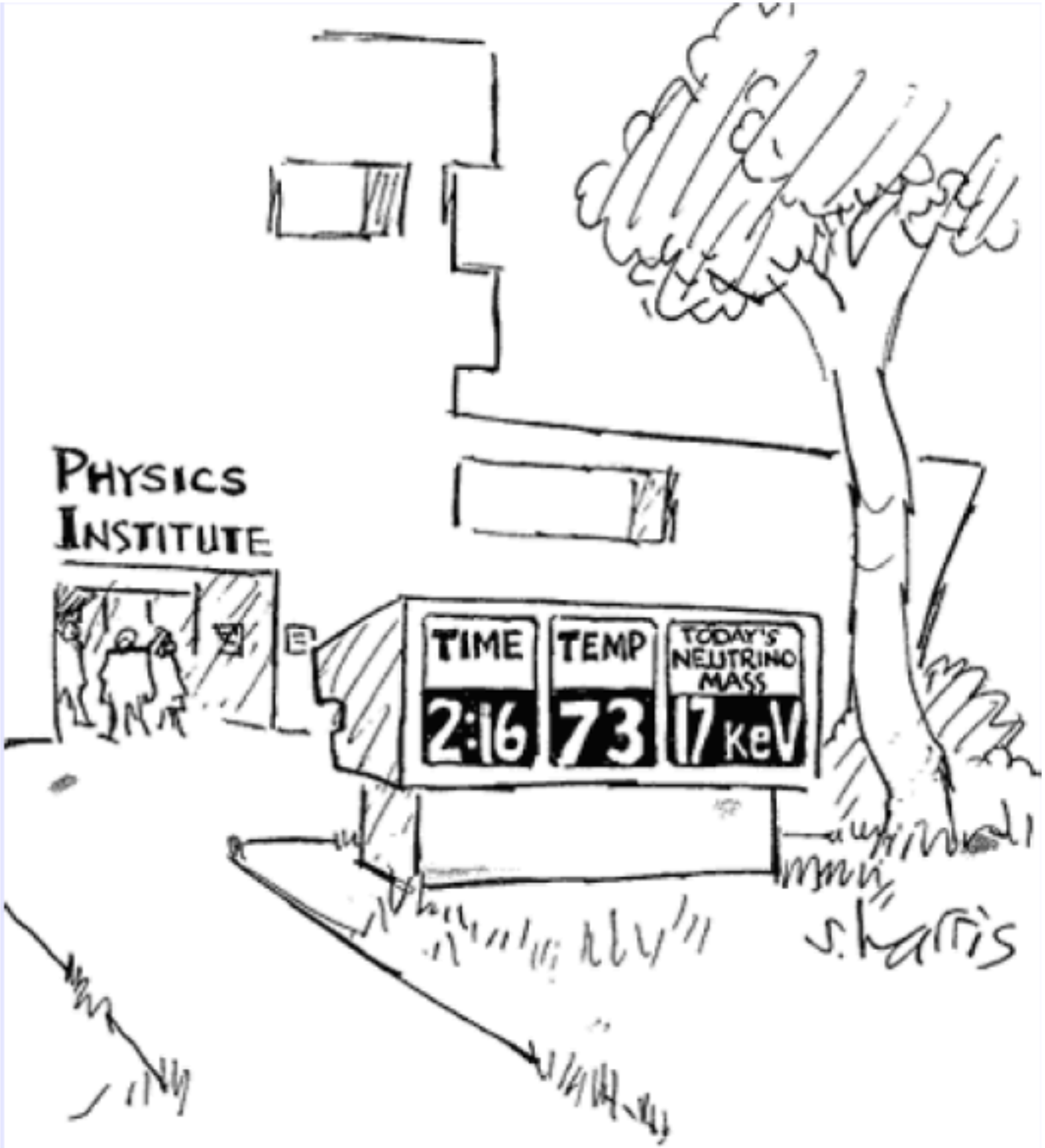




Thank you for your attention

Back-up slides

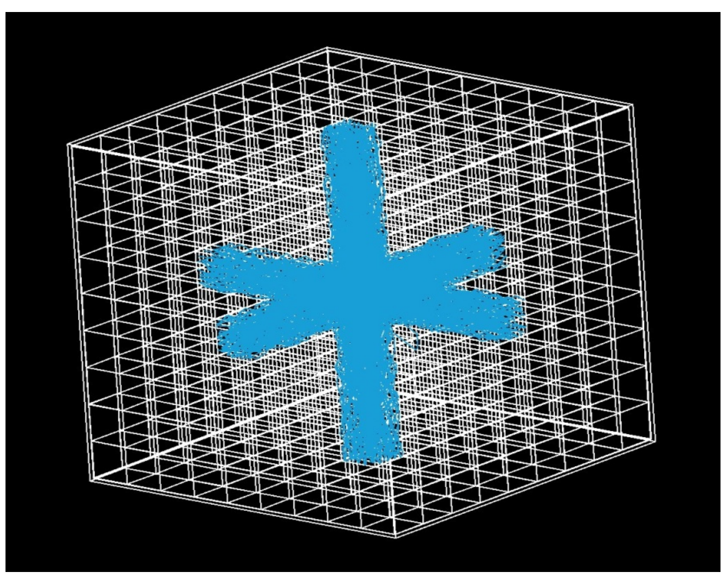
CC Detection: LENS

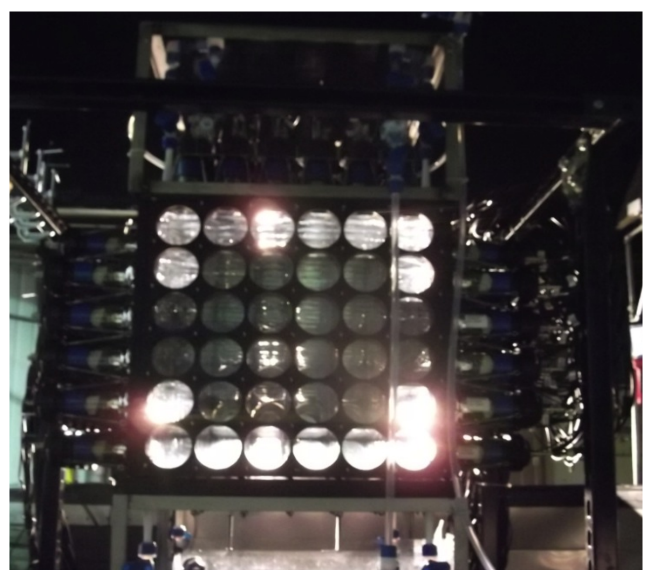
$$\nu_e + {}^{115}In \longrightarrow {}^{115}Sn^* + \beta^-$$
$$\tau = 4.76\mu s \hookrightarrow \gamma(115\mathrm{keV}) + \gamma(497\mathrm{keV}) + {}^{115}\mathrm{Sn}$$

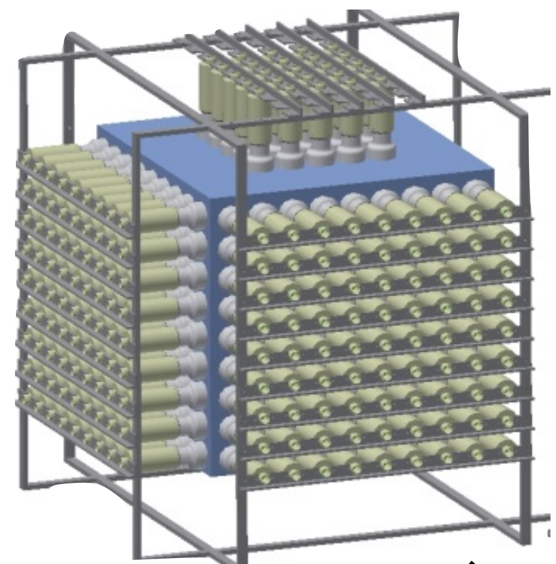
- Delayed triple coincidence helps reject ^{115}In bkg (need 10^{11} rejection)

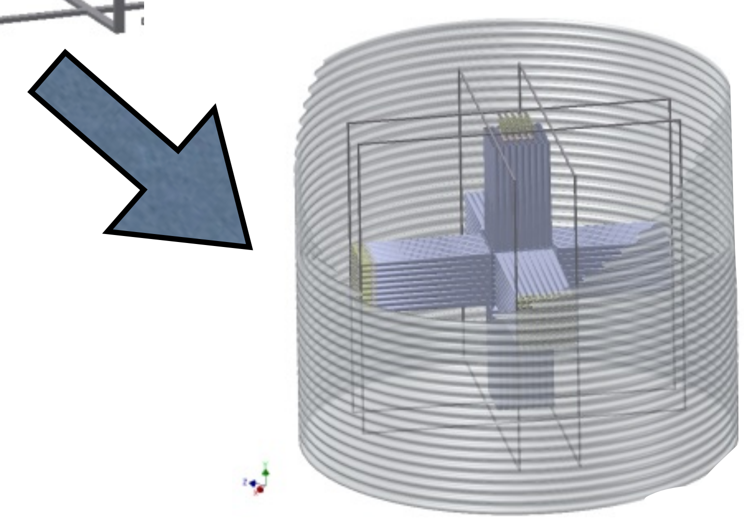
- Q = 115keV : 95% of pp spectrum

- Segmentation helps reject ext bkgs







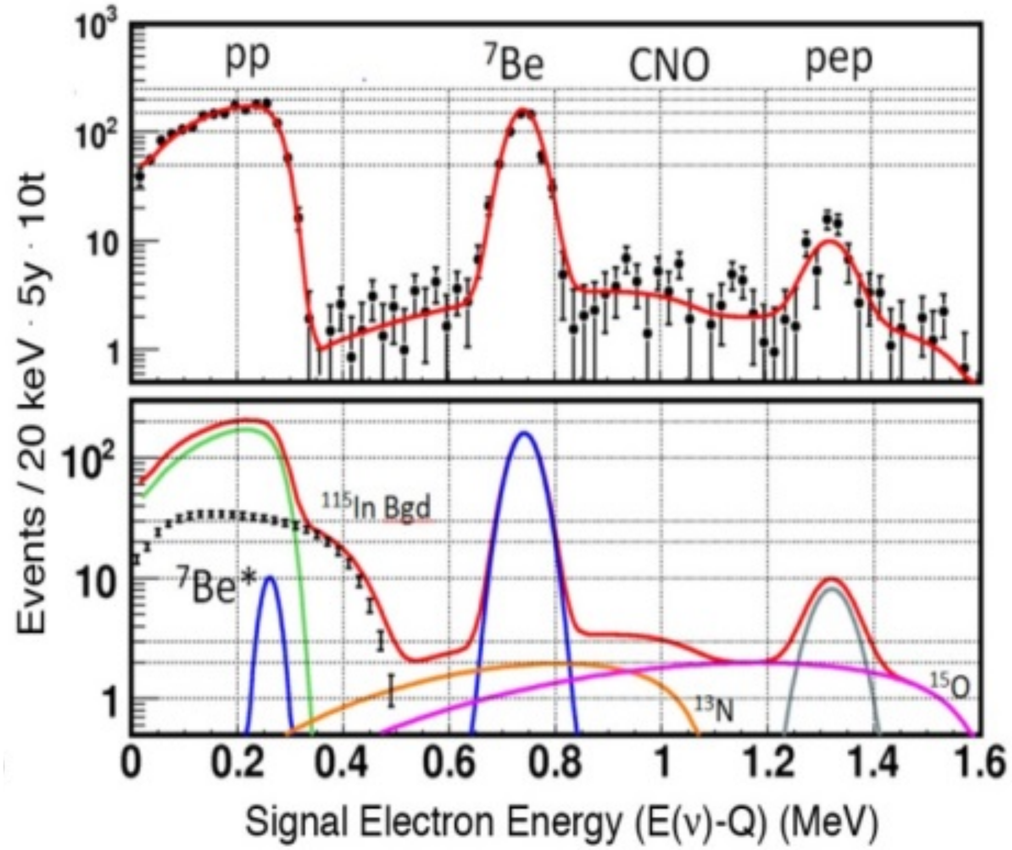


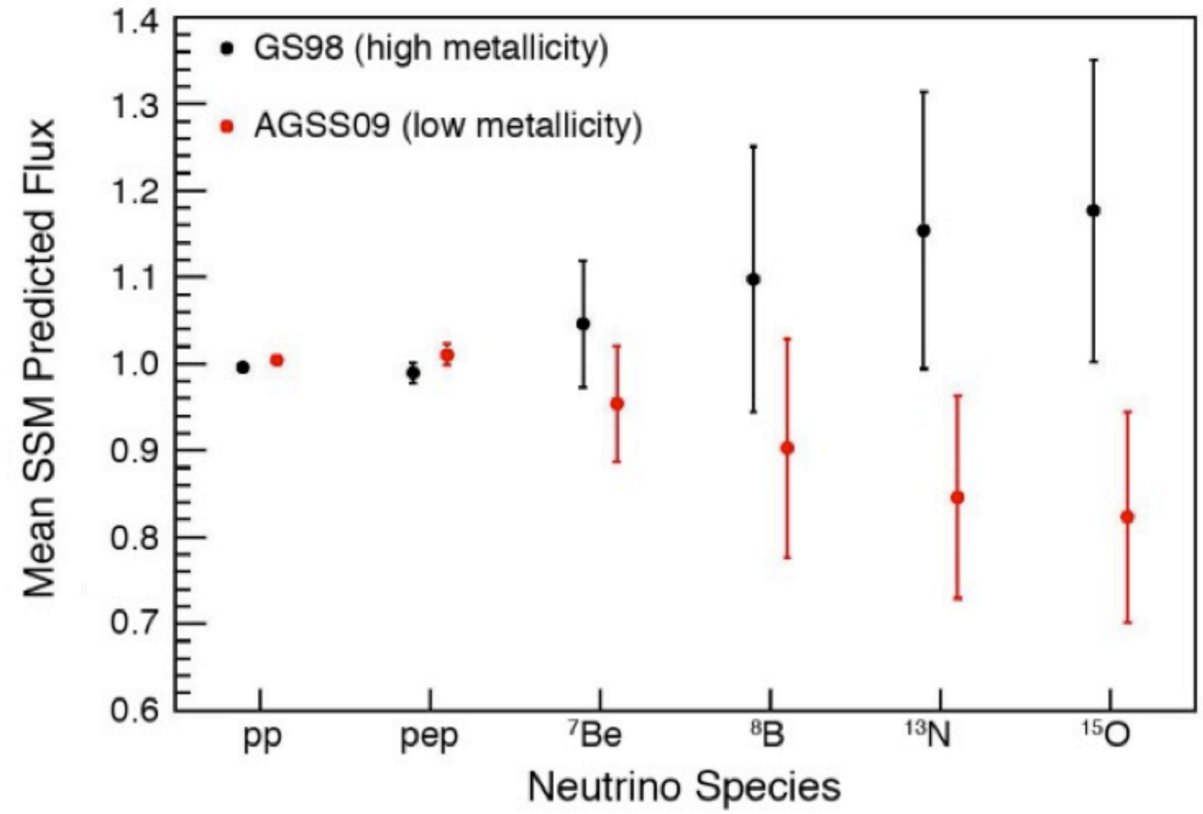
- Low index barriers provide light channeling

- μLENS completed: test detector optics

- mLENS under construction: air boundaries to study background rejection

LENS Sensitivity





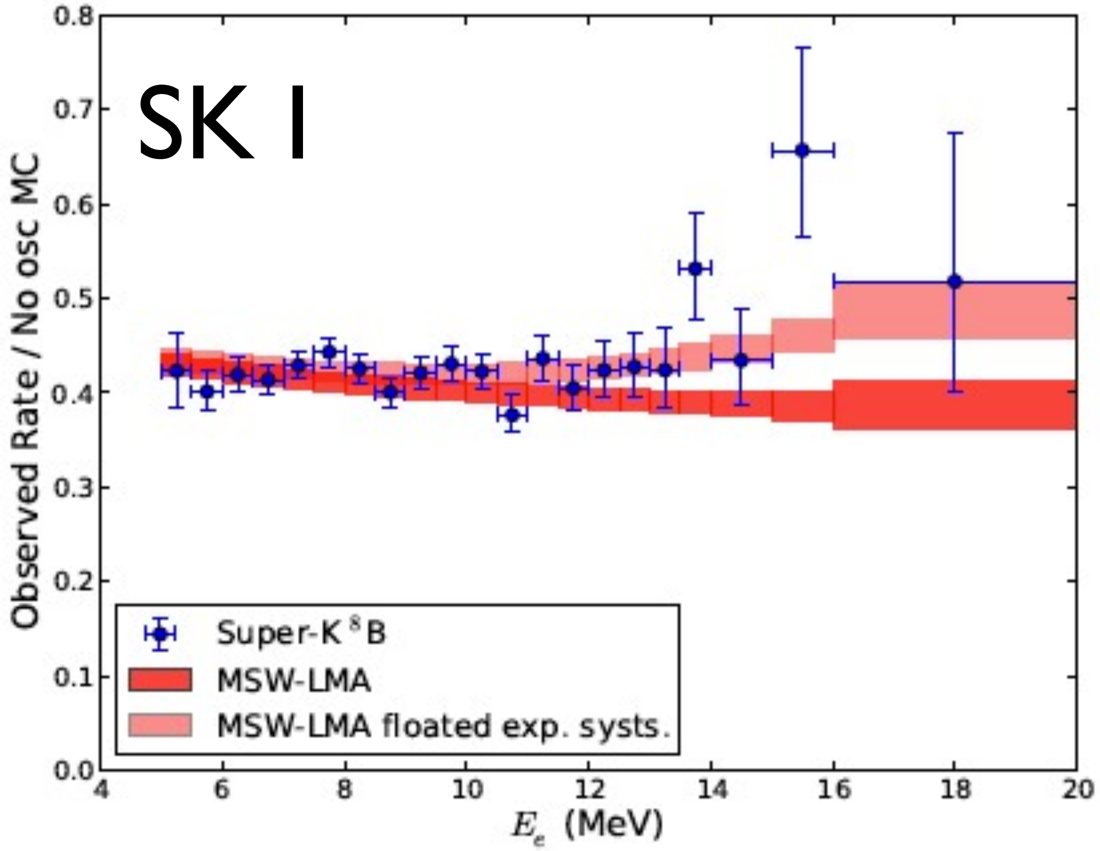
10T In, 5 years

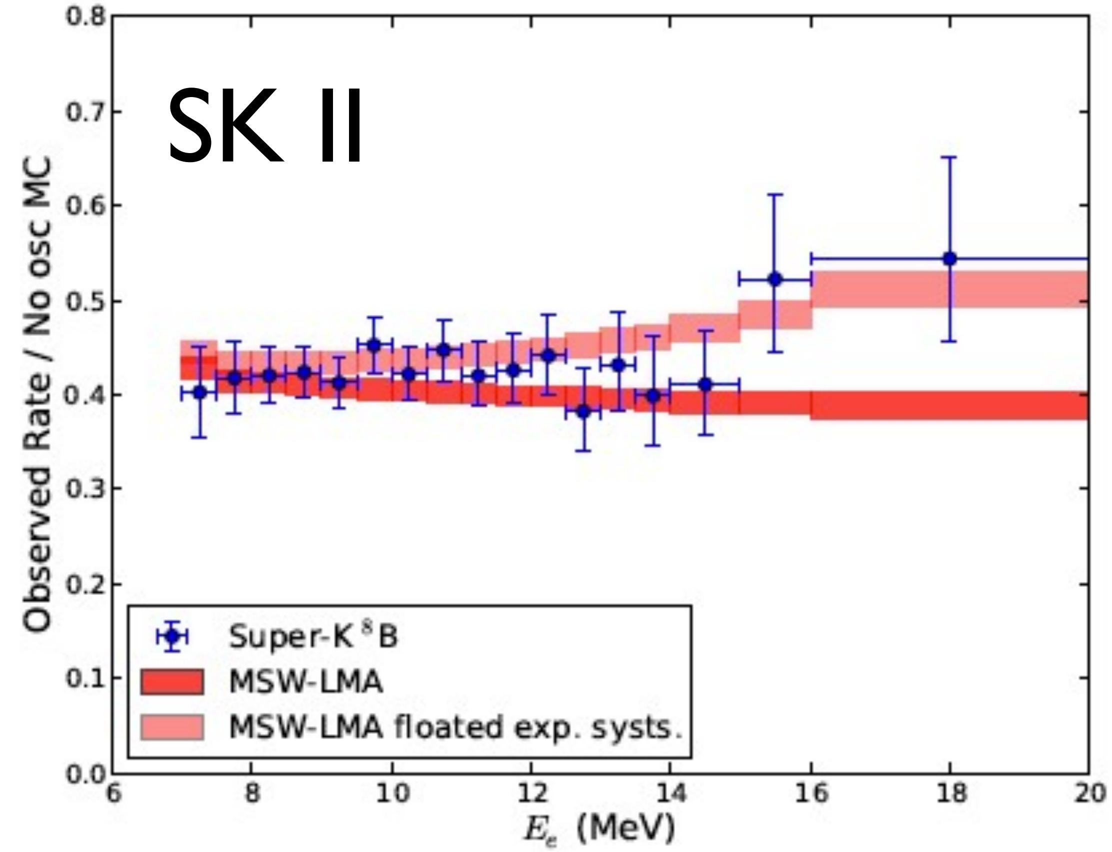
GS98 AGSS09

Source	pp	pep	7Be	CNO$^{\beta}$	CNO*	CNO†
Flux (/cm2/s)	6.00E+10	1.40E+08	4.70E+09	1.10E+09	4.97E+08	3.74E+08
Flux (SNU) [Bah88]	468	8	116	32	15	11
Cross section[Rap85]	1.00E-44	5.40E-44	2.50E-44	2.50E-44	2.50E-44	2.50E-44
Survival probability	56	52	54	54	54	54
Rate (per ton year)	26	0.4	6.2	2.5	1.2	0.9
Rate (10 tons · 5 yr)	**1296**	**21**	**310**	**127**	**58**	**43**

		high-Z SSM	low-Z SSM	luminosity constrained fit to data	
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	$5.58(1\pm0.14)$	$4.59(1\pm0.14)$	$5.00(1\pm0.03)$	$10^6/cm^2s$
${}^3He+p\to{}^4He+e^++\nu$	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%		

current issues focus on the two models above


SK I
Observed Rate / No osc MC
E_e (MeV)
Super-K ^{8}B
MSW-LMA
MSW-LMA floated exp. systs.


SK II
Observed Rate / No osc MC
E_e (MeV)
Super-K ^{8}B
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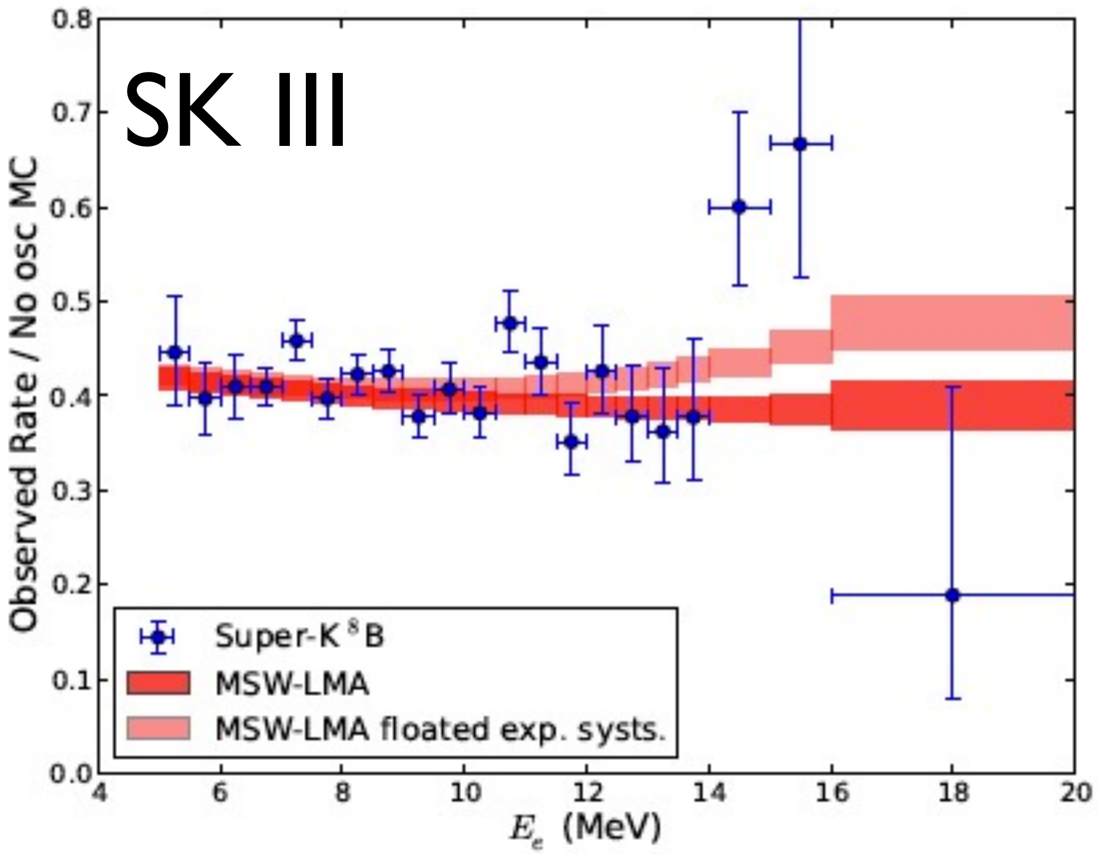
SK III
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E_e (MeV)
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MSW-LMA floated exp. systs.

A "New" Idea for CC Detection

- Load large water Cherenkov detector with e.g. ^{7}Li for CC interaction

"Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10

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- Water Cherenkov ⇒ water-based LS

Phys. Rev. C 88 (2013) 065502

http://underground.physics.berkeley.edu/WbLSWorkshop.html

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$$\sigma(E_\nu) = \frac{G_F^2 \cos^2\theta_c}{2\pi} k_e E_e \mathcal{F}(Z+1, E_e)\, d\cos\theta\, dE_e \Big[1.0(1+\cos\theta)\delta(E_\nu - 0.35 - E_e)$$
$$+ 1.7471(1 - \frac{1}{3}\cos\theta)\delta(E_\nu - 0.35 - E_e) + 1.6303(1 - \frac{1}{3}\cos\theta)\delta(E_\nu - 0.35 - 0.4291 - E_e)$$
$$+ 0.01135(1 - \frac{1}{3}\cos\theta)\delta(E_\nu - 0.35 - 6.73 - E_e) + 0.07317(1 - \frac{1}{3}\cos\theta)\delta(E_\nu - 0.35 - 7.21 - E_e)\Big]$$

Cross section from W. C. Haxton

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$$
\begin{aligned}
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\end{aligned}
$$

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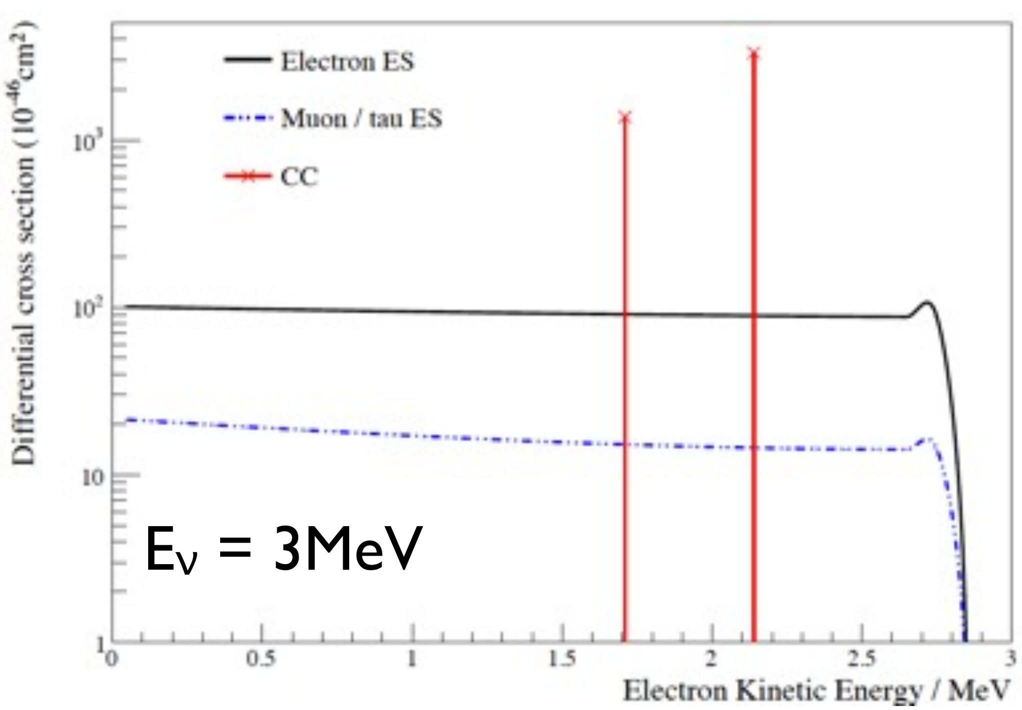

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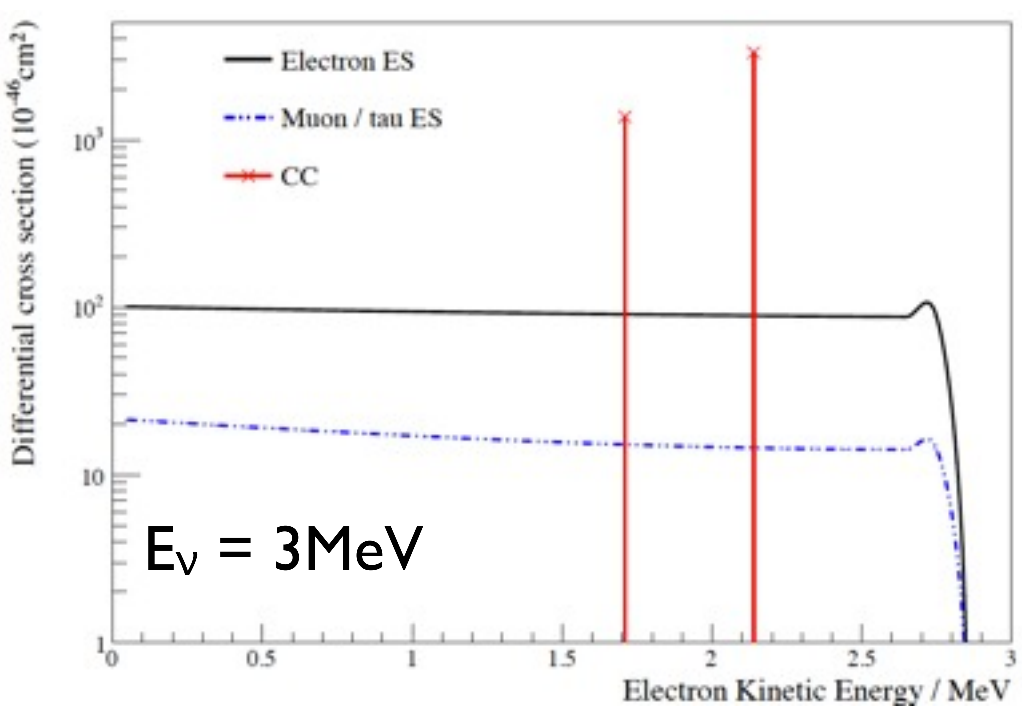

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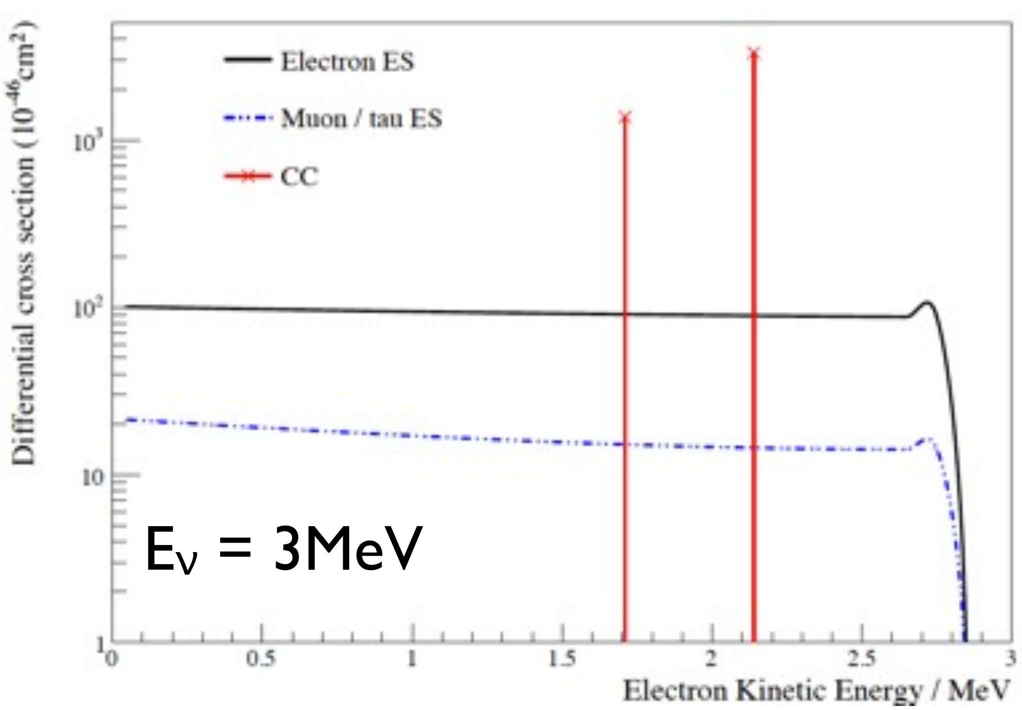
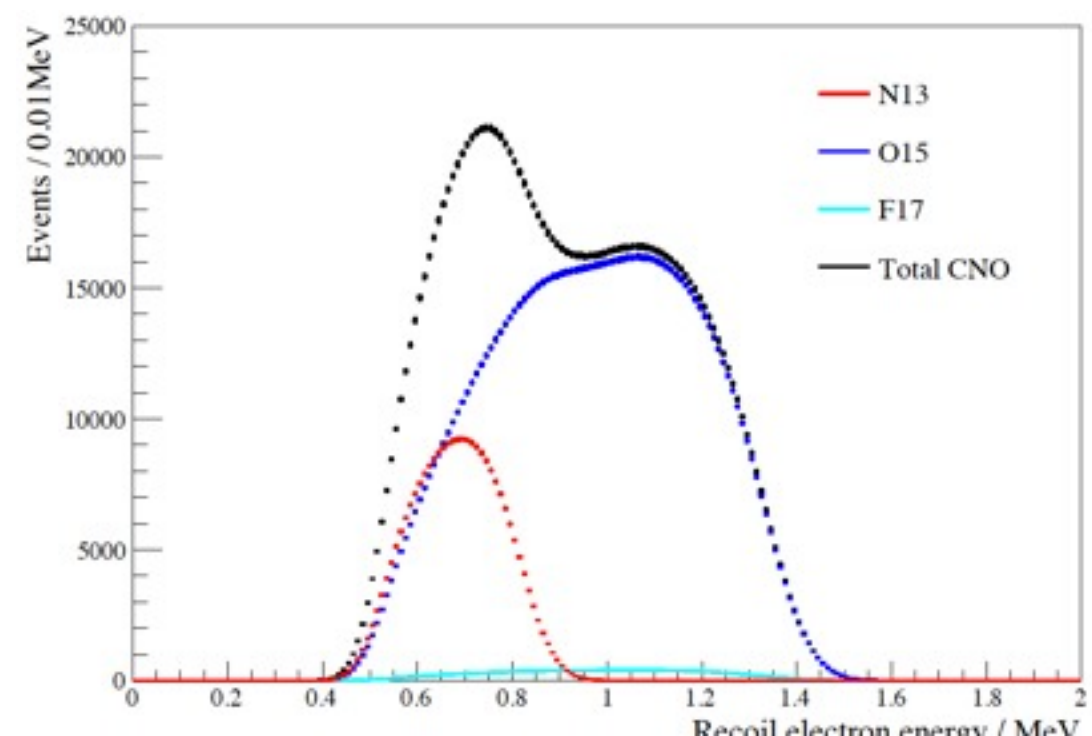
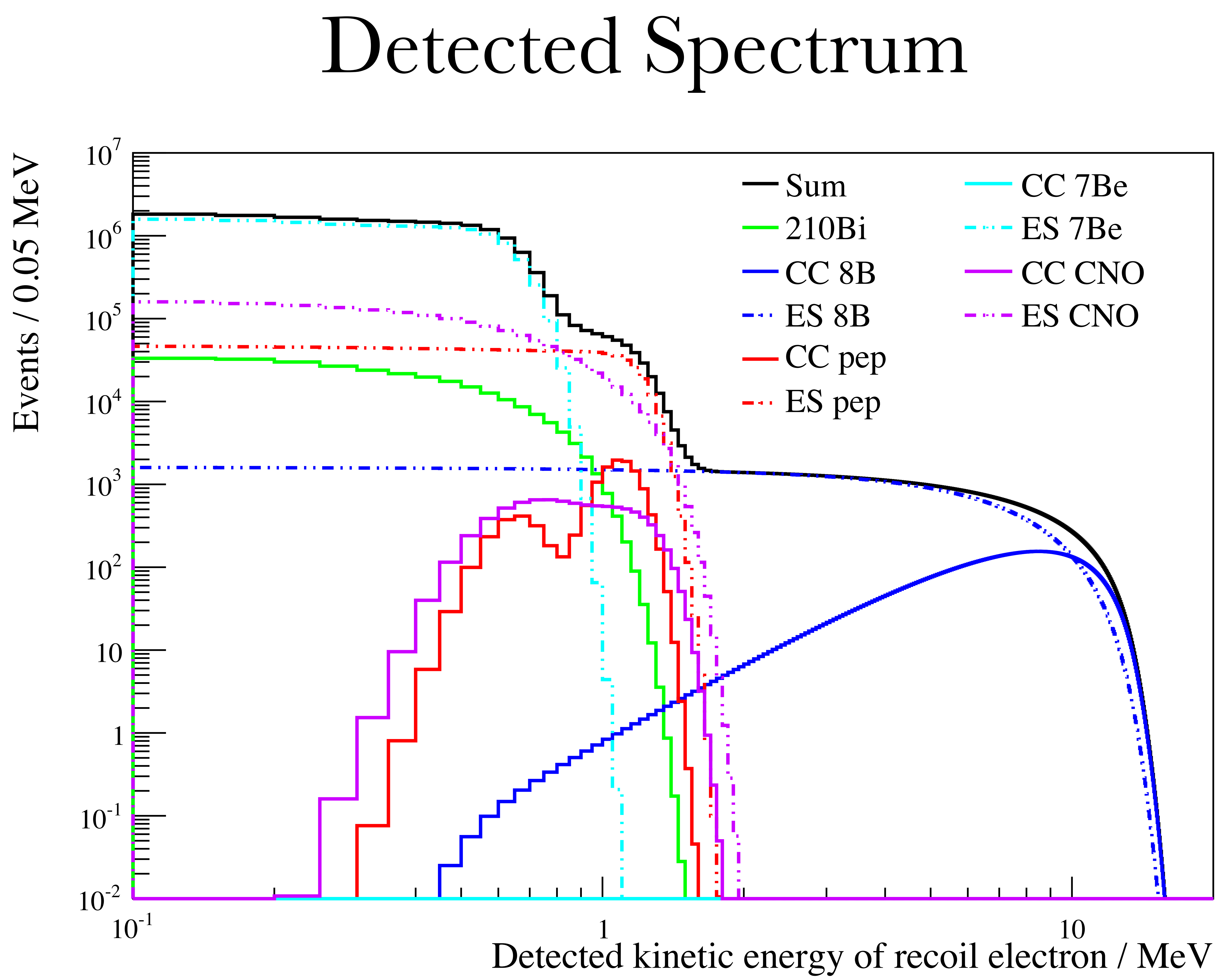
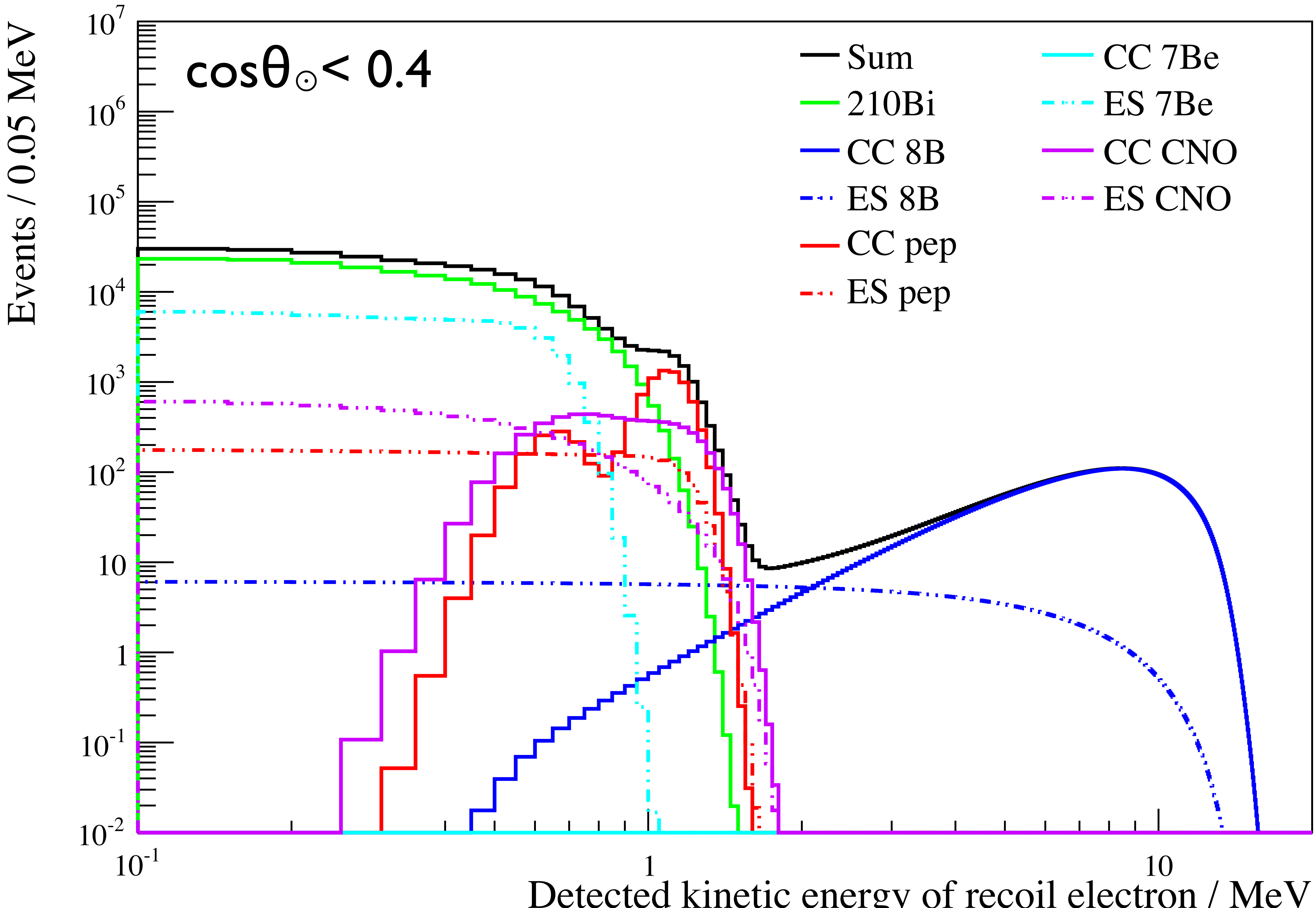


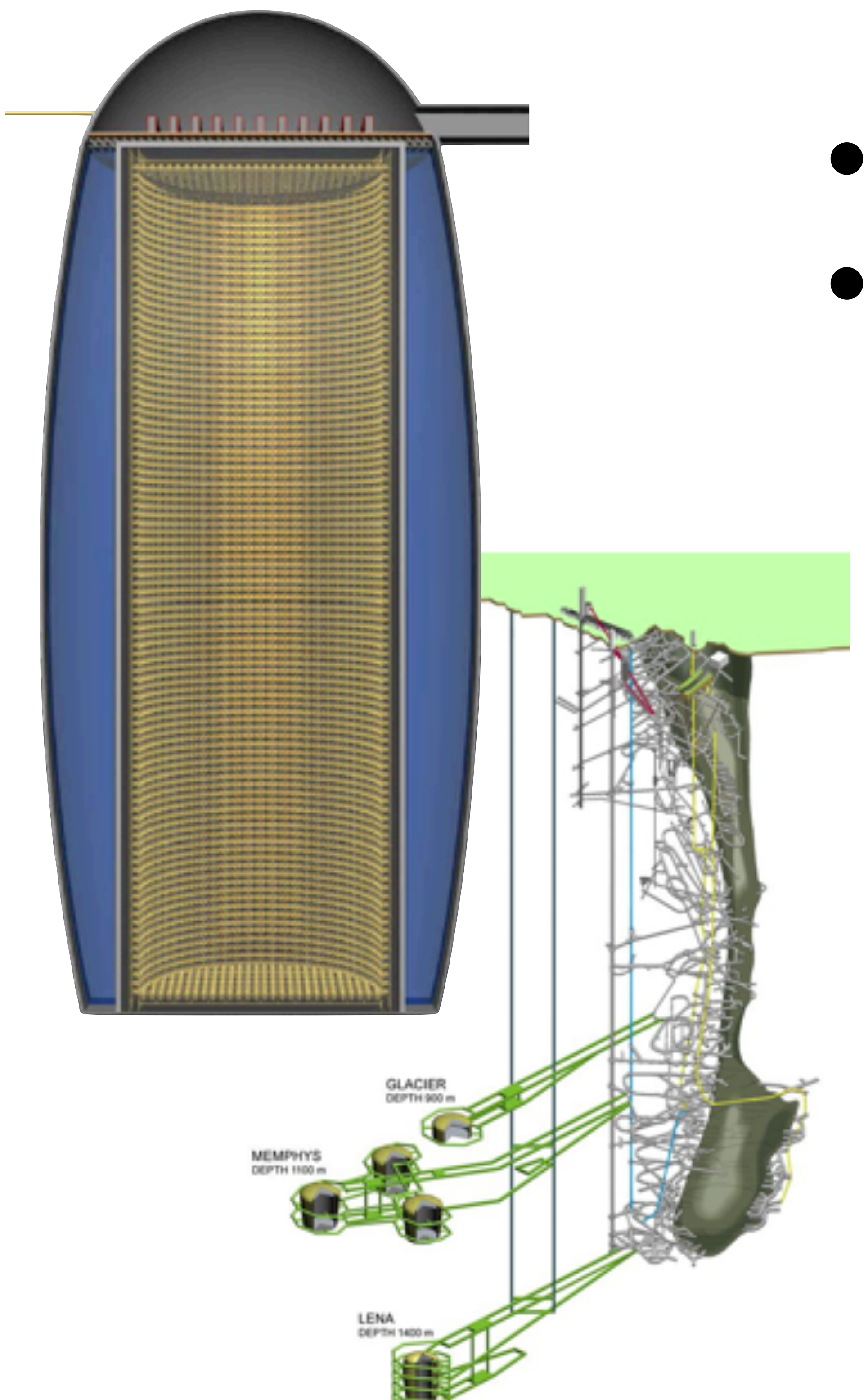



Detected Spectrum
Events / 0.05 MeV
Detected kinetic energy of recoil electron / MeV
Sum
210Bi
CC 8B
ES 8B
CC pep
ES pep
CC 7Be
ES 7Be
CC CNO
ES CNO
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-1}
1
10

Detected Spectrum



Low **E**nergy **N**eutrino **A**stronomy

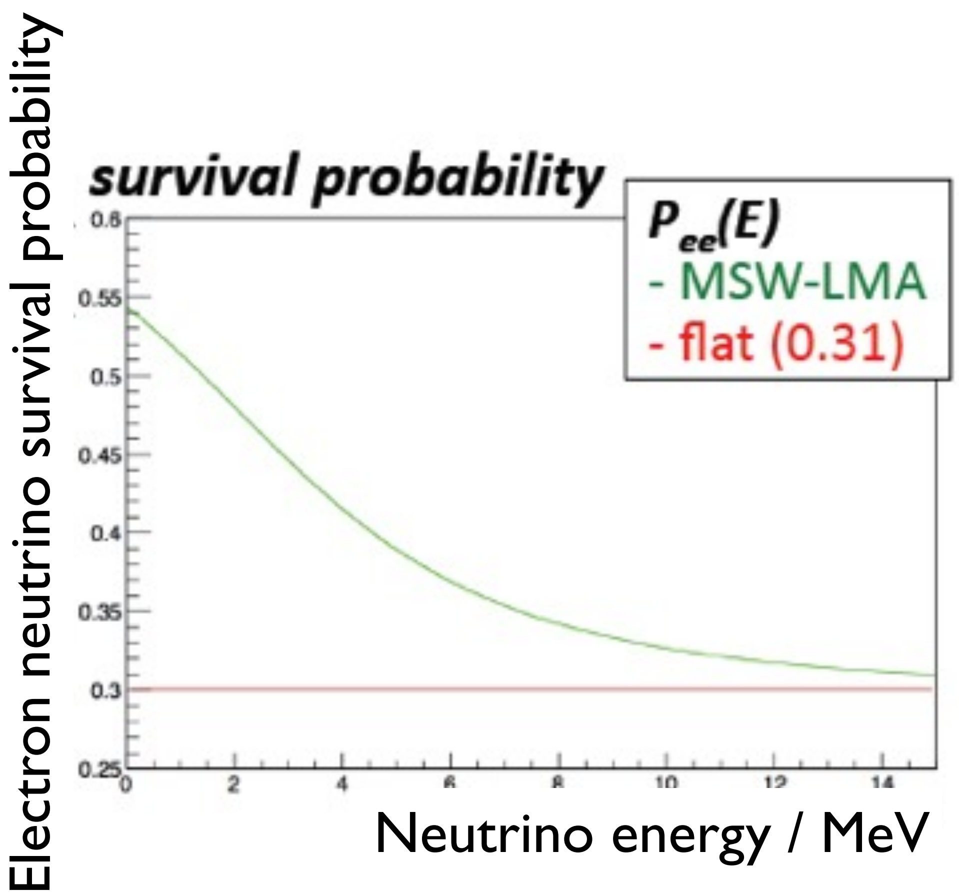


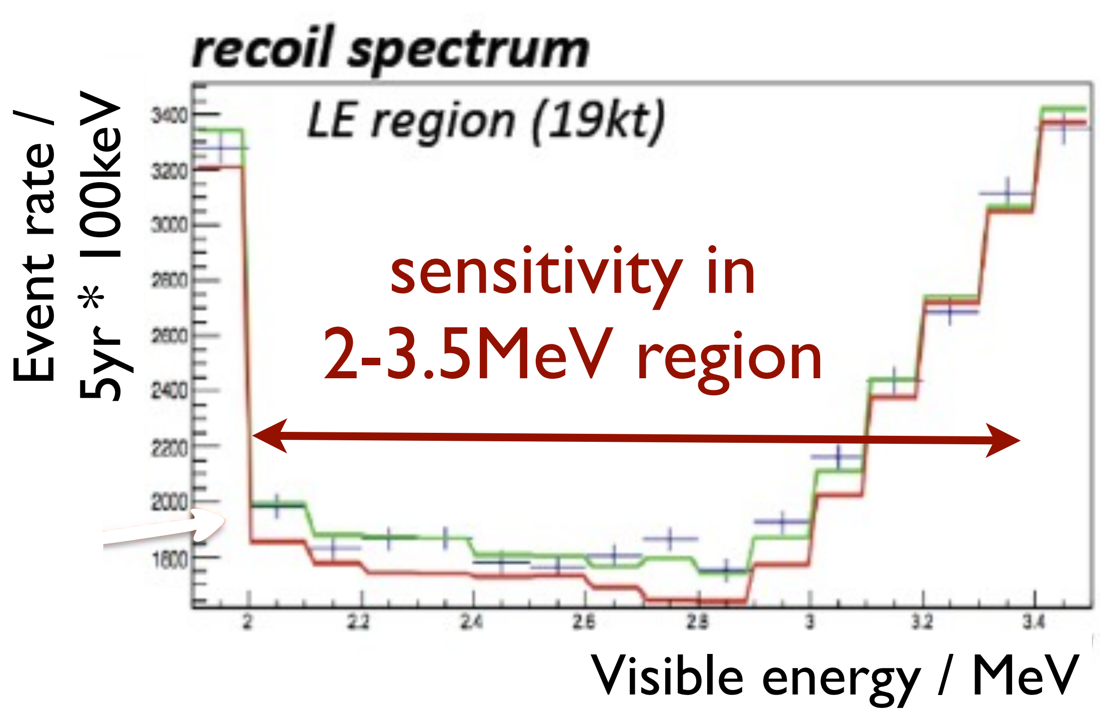
- 50kT LS (30kT FV solar), 30% coverage
- Unprecedented statistics at low-energy
  - Time modulations in ^{7}Be flux
  - Low-energy ^{8}B in transition region (+ CC on ^{13}C)
  - CNO detection

Detection Channel	Neutrino Source	BPS08(GS) (cpd) total	BPS08(GS) (cpd) >250 keV	BPS08(AGS) (cpd) total	BPS08(AGS) (cpd) >250 keV
$\nu e \to e\nu$	pp	626±3	41.5±0.3	632±3	42.0±0.2
	pep	785±8	609±6	806±8	626±6
	hep	0.29±0.03	0.27±0.03	0.30±0.05	0.29±0.05
	^{7}Be	14490±864	8307±495	12968±779	7434±447
	^{8}B	141±15	137±15	113±12	108±12
	CNO	2919±468	909±146	1874±279	584±87
$^{13}\mathrm{C}(\nu_e, e)^{13}\mathrm{N}$	^{8}B	2.9±0.3		2.6±0.2	

http://www.e15.ph.tum.de/research_and_projects/lena/

LENA Sensitivity

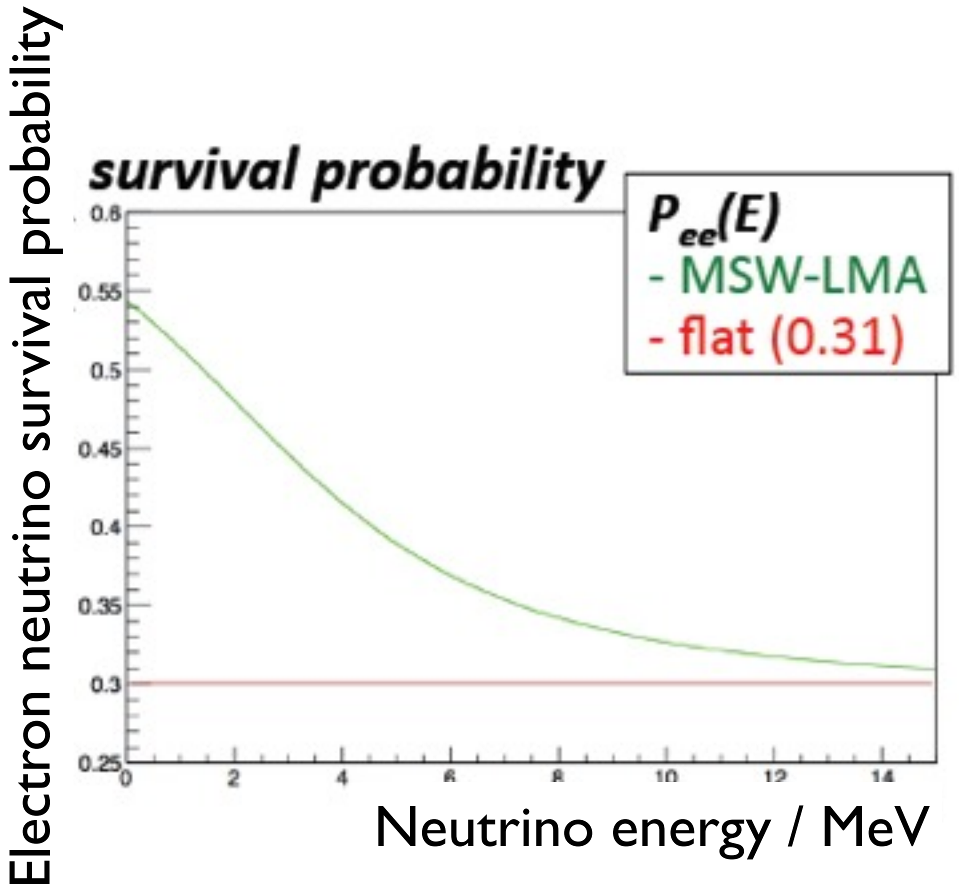




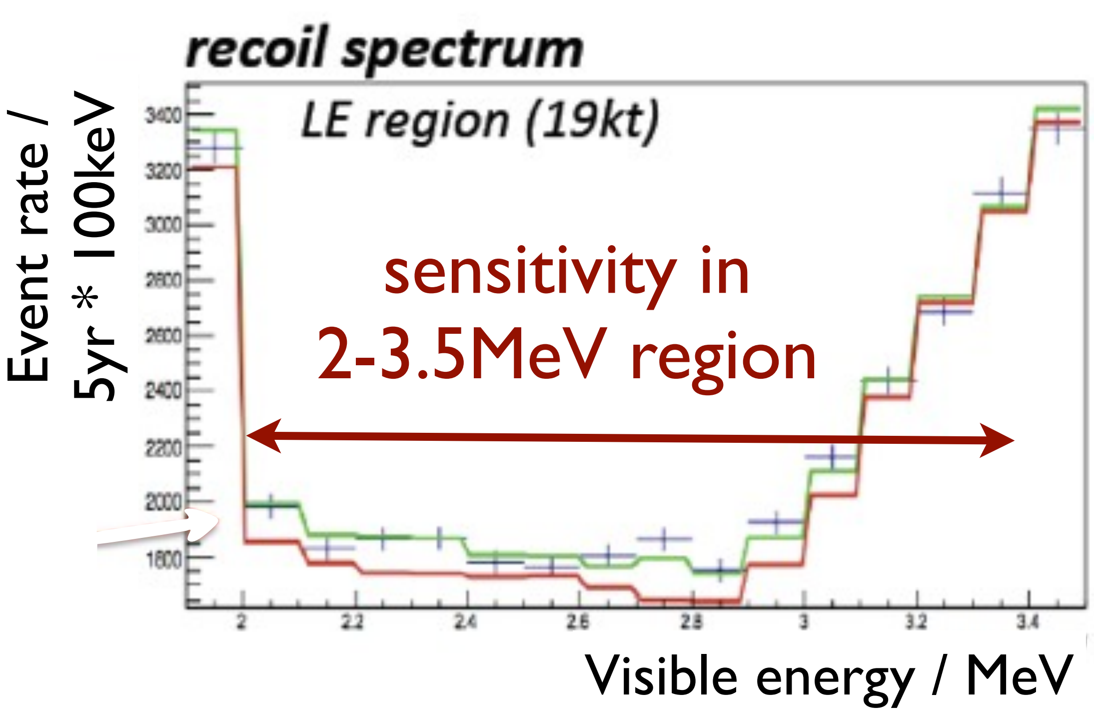
5σ discrimination after 3-5 years

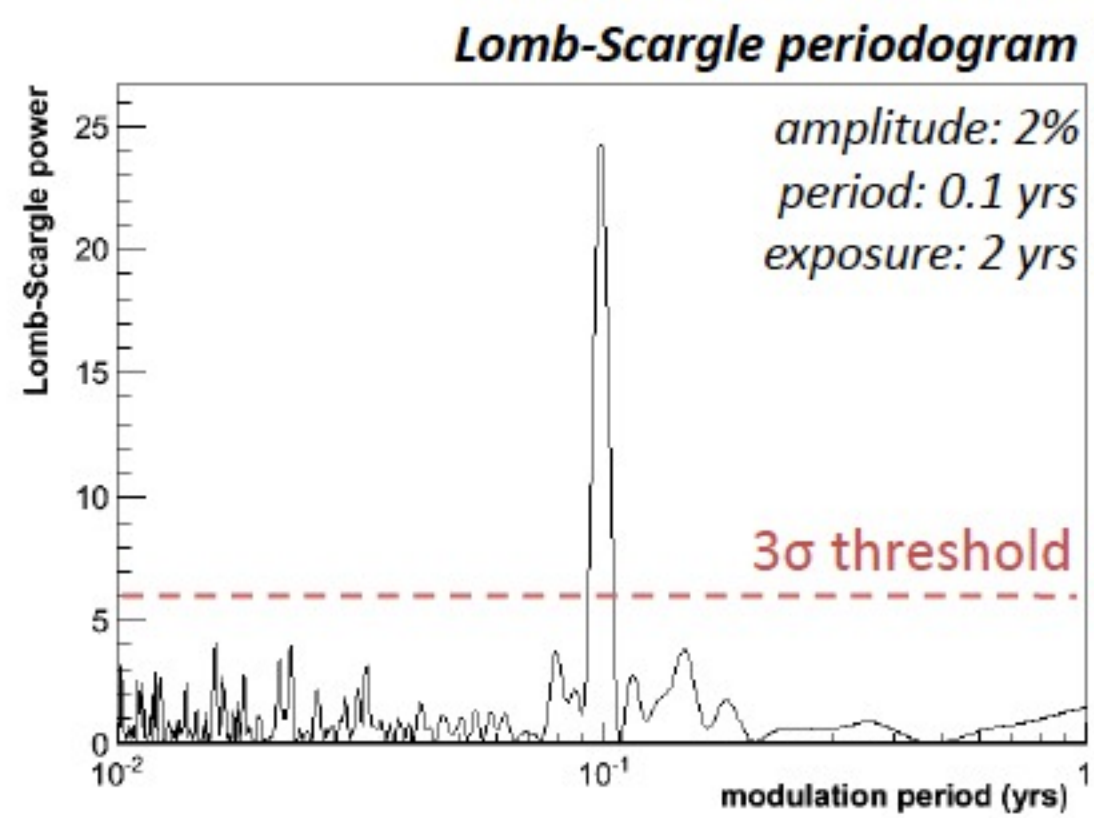
M. Wurm, TAUP 2013

LENA Sensitivity



- 3σ discovery potential for 0.1%-amplitude temporal fluctuations in ^{7}Be
  - Day-night effect (predicts A=0.1%)
  - Correlations to T=11 yr solar cycle
  - Helioseismic g-modes





5σ discrimination after 3-5 years

M. Wurm, TAUP 2013

(E) Time Dependence

SAGE

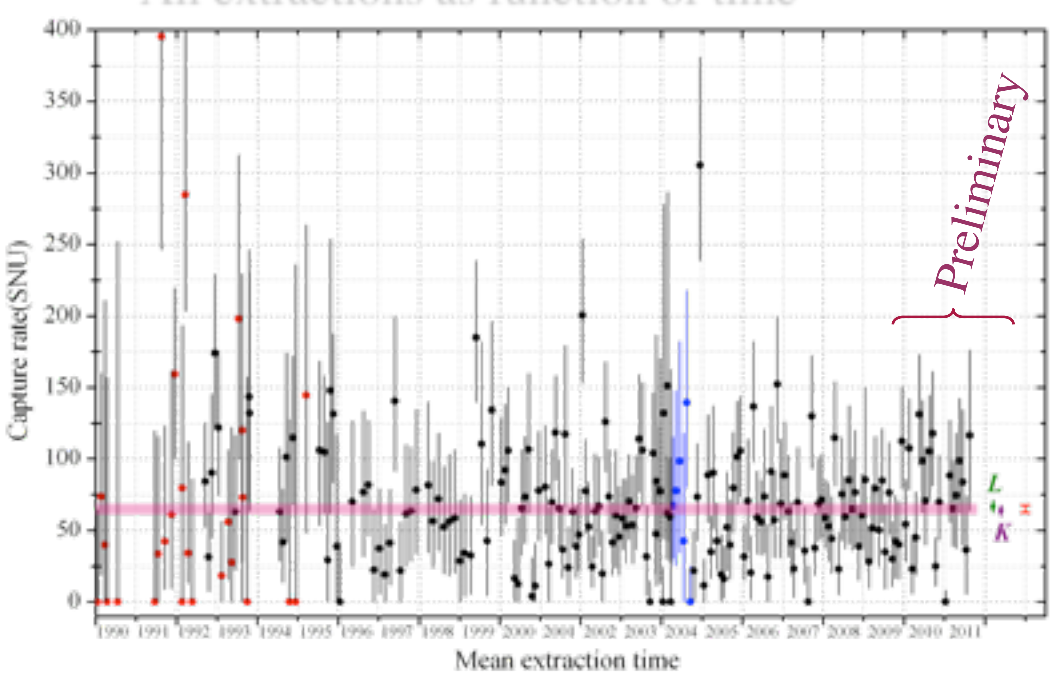
The longest (almost uninterrupted) running-time of any operating solar neutrino experiment

1 SNU = 1 interaction/s in target with 10^36 atoms of ν absorbing isotope

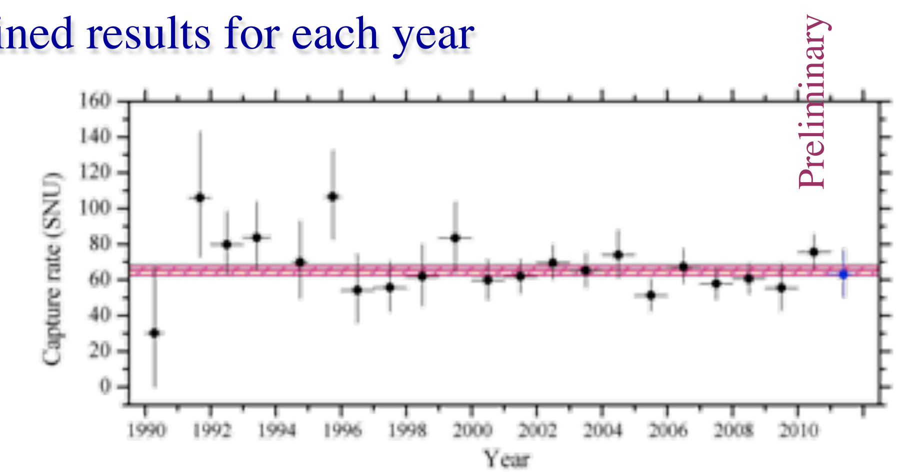
1990 - 11/2011: 214 runs, 396 data sets

Result : : $64.5\,^{+2.7}_{-2.7}(\mathrm{stat})\ ^{+2.6}_{-2.8}(\mathrm{syst})$ SNU or $64.5\,^{+3.7}_{-3.9}$ SNU

All extractions as function of time



Combined results for each year

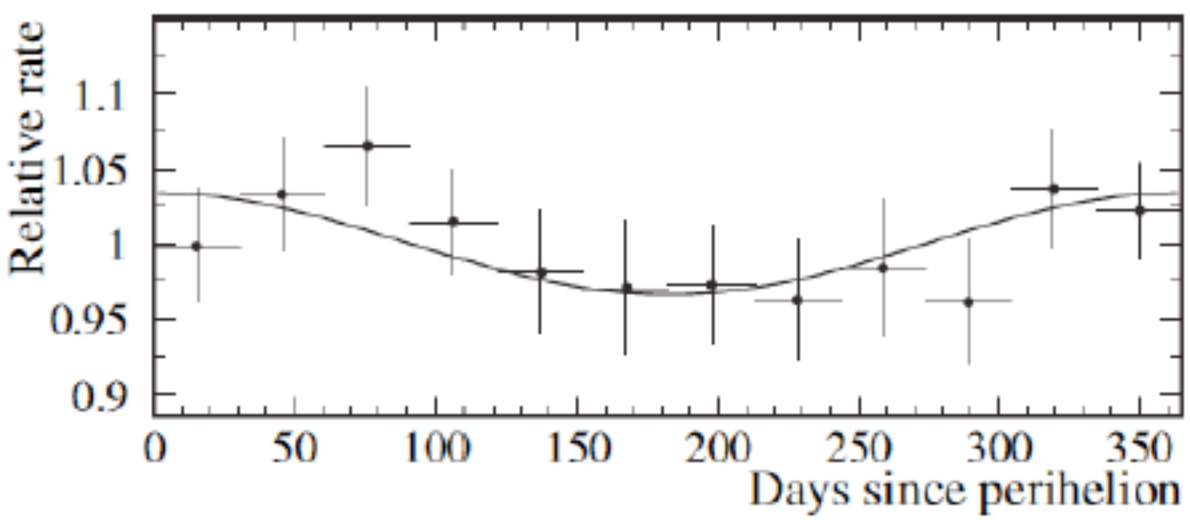


SAGE continues to perform regular extractions every 4 weeks

(E) Periodicity Searches

*Phys. Rev. D **72**, 052010 (2005)*

Variation due to eccentricity of Earth's orbit



No additional periodicity observed
T = [1 d , 10 yrs]

Inconsistent with Sturrock et al. claim of 7% modulation of ^{8}B neutrino flux in SK data

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Phys. Rev. D ***72****, 052010 (2005)*

Astro. Phys. J 710:540-548 (2010)

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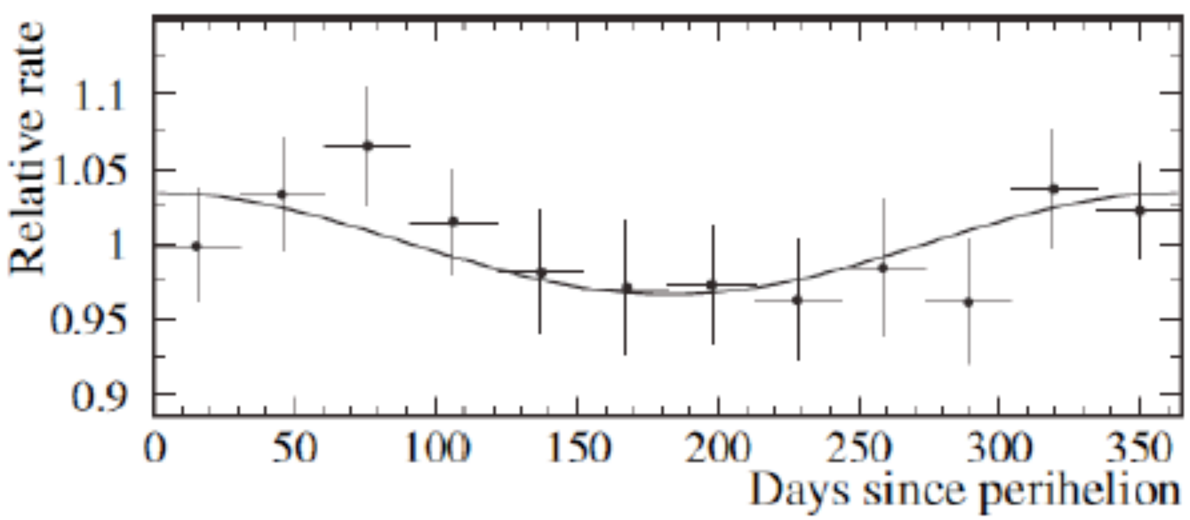

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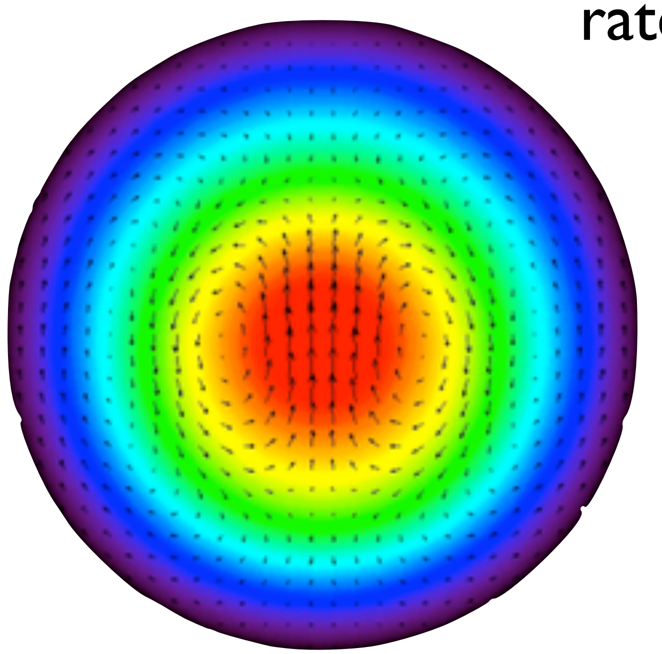
g-mode solar core oscillations can affect production rate / survival probability



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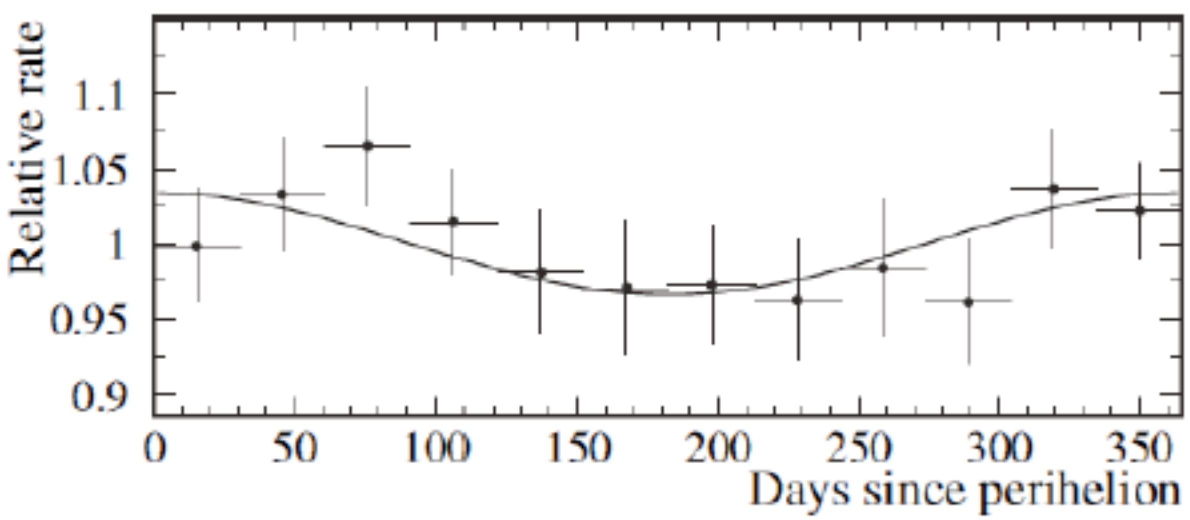

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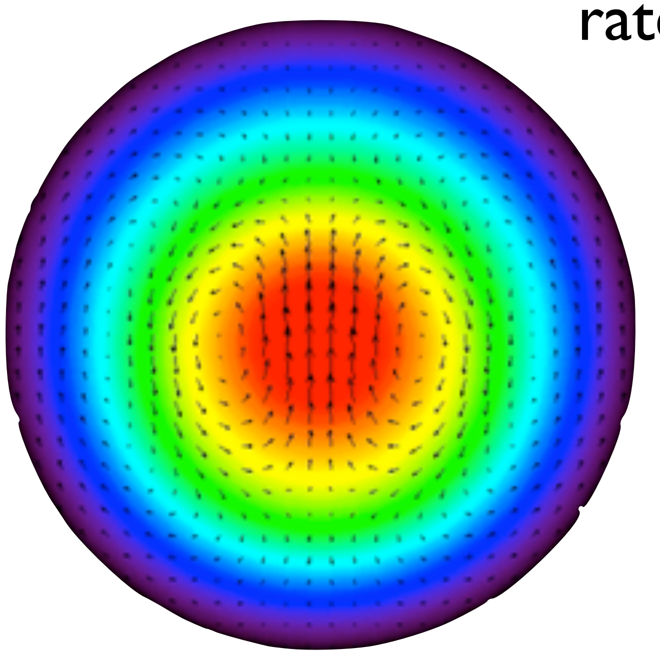

1. T ε [1, 144] /day
Sensitive to amplitude ≥ 12%

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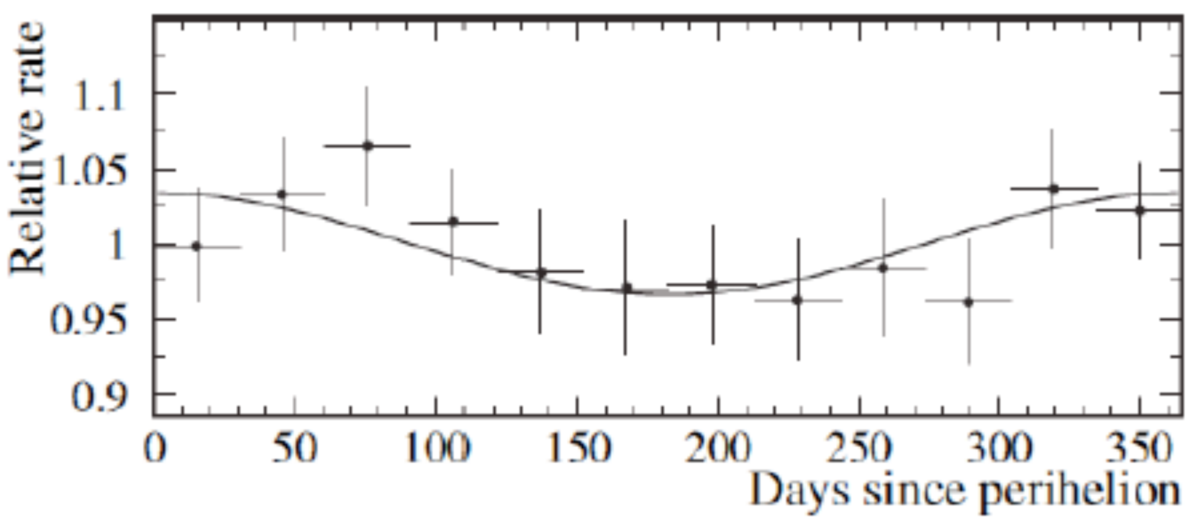

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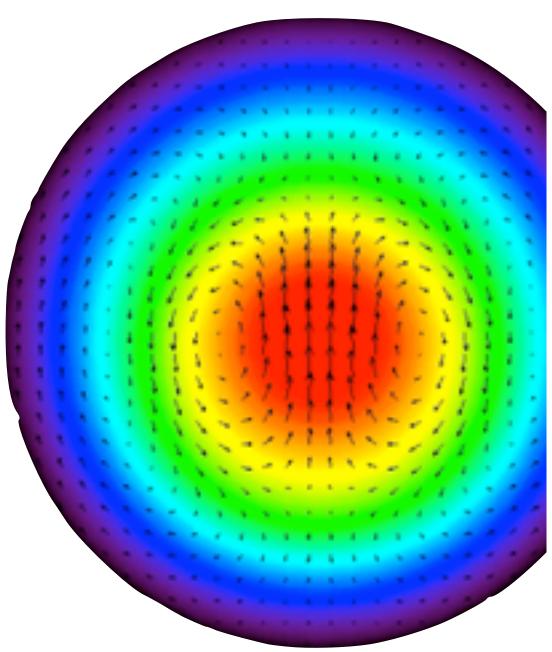

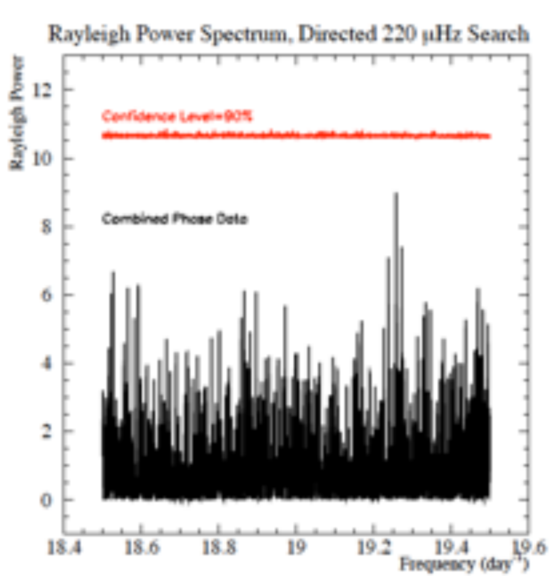

1. T ε [1, 144] /day
Sensitive to amplitude ≥ 12%

2. Directed search in region of claimed observations
Sensitive to amplitude ≥ 10%

(E) Periodicity Searches

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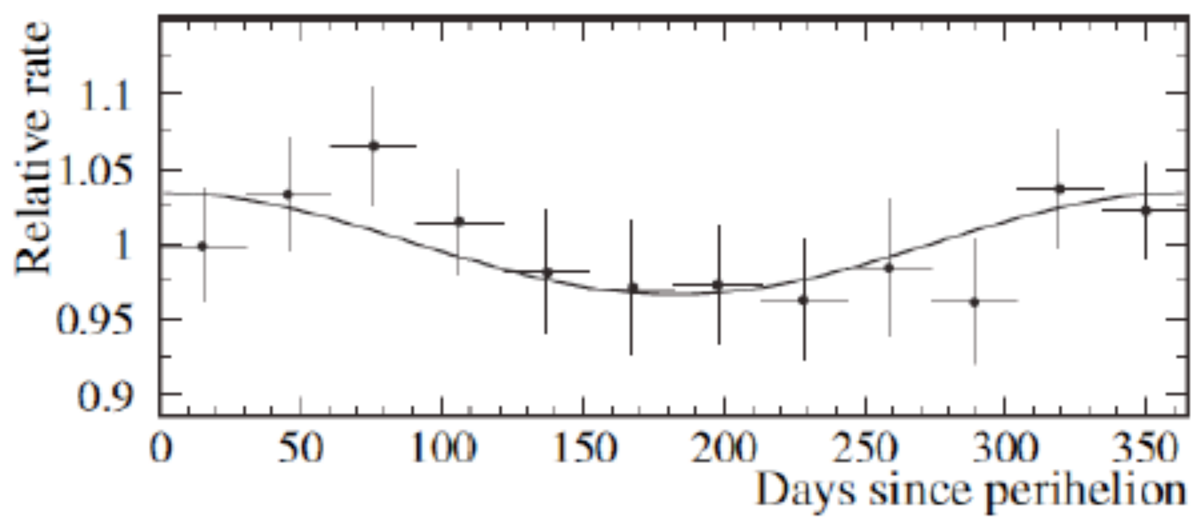

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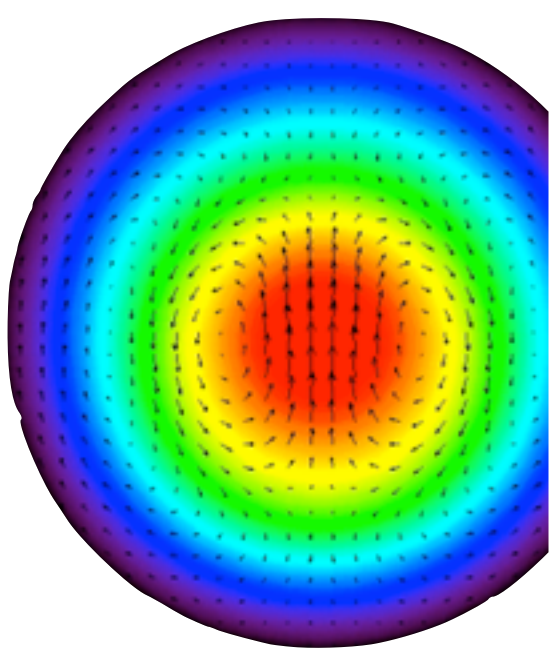
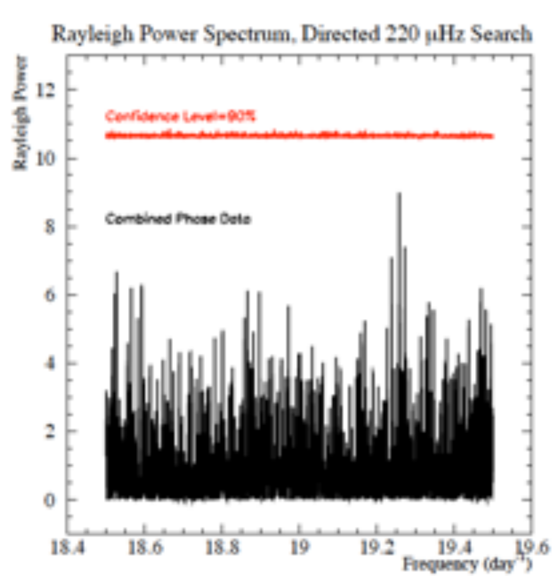
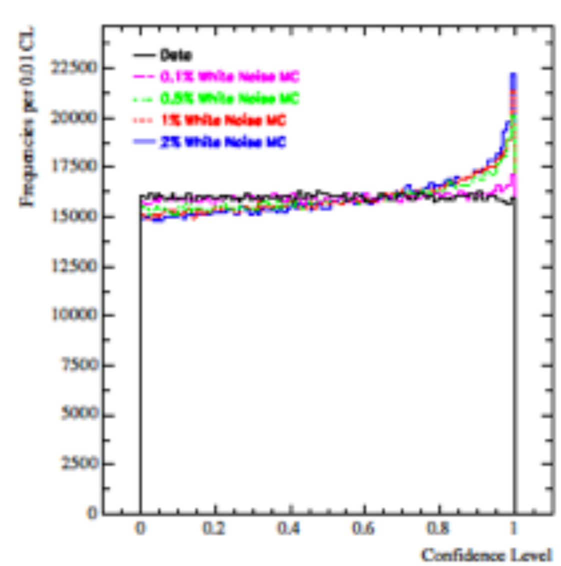






1. T ε [1, 144] /day
Sensitive to amplitude ≥ 12%

2. Directed search in region of claimed observations
Sensitive to amplitude ≥ 10%

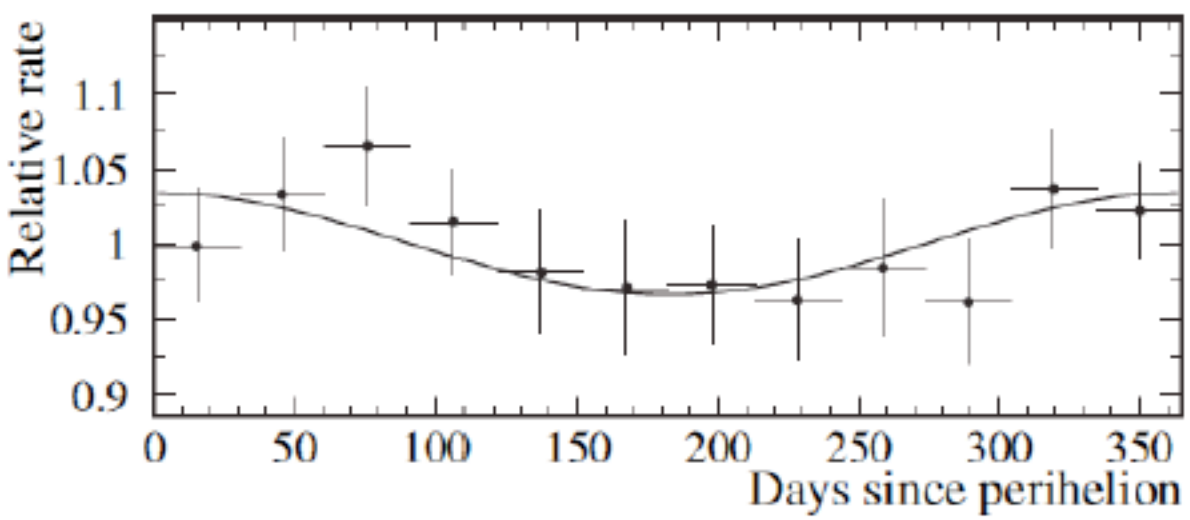
3. Broadband search (noise)

(E) Periodicity Searches

Phys. Rev. D **72**, *052010 (2005)*

Astro. Phys. J 710:540-548 (2010)

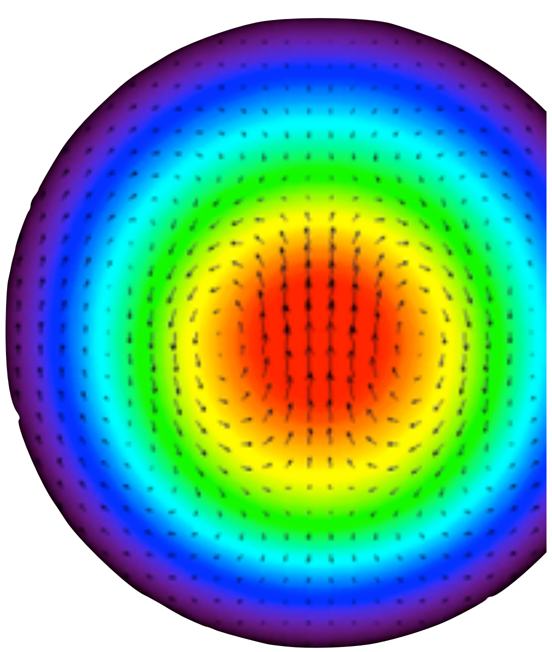
Variation due to eccentricity of Earth's orbit

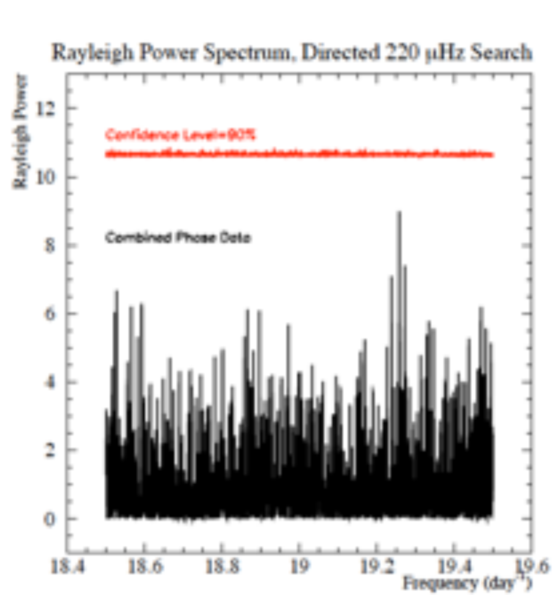


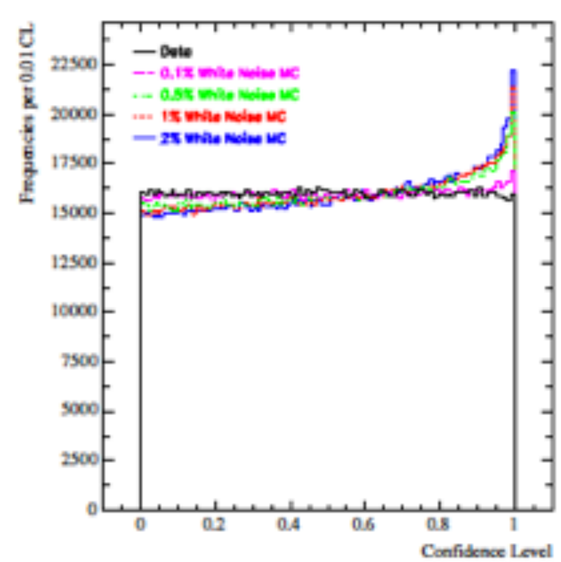
No additional periodicity observed
T = [1 d , 10 yrs]

Inconsistent with Sturrock et al. claim of 7% modulation of ^{8}B neutrino flux in SK data

g-mode solar core oscillations can affect production rate / survival probability







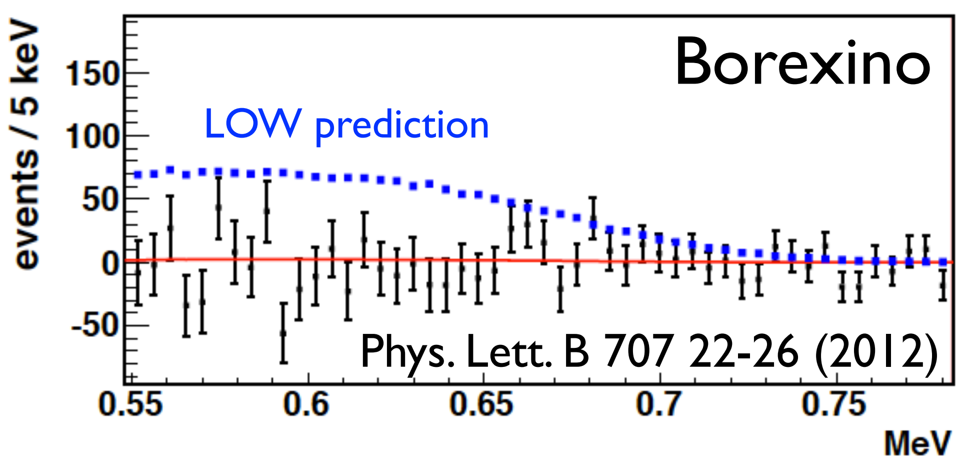
1. T ε [1, 144] /day
Sensitive to amplitude ≥ 12%

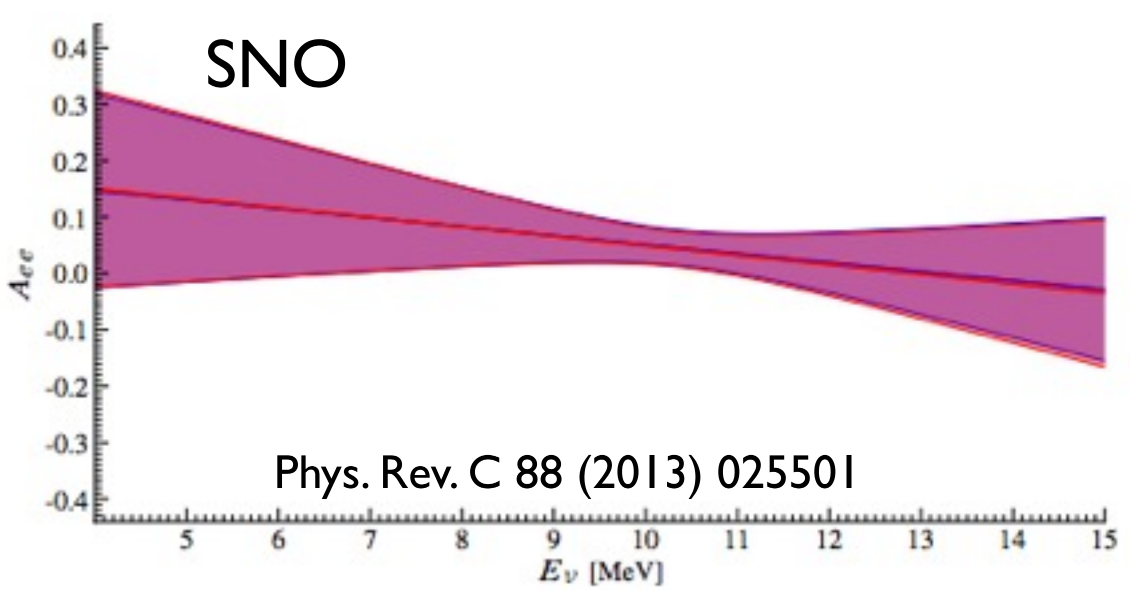
2. Directed search in region of claimed observations
Sensitive to amplitude ≥ 10%

3. Broadband search (noise)

No significant signal observed

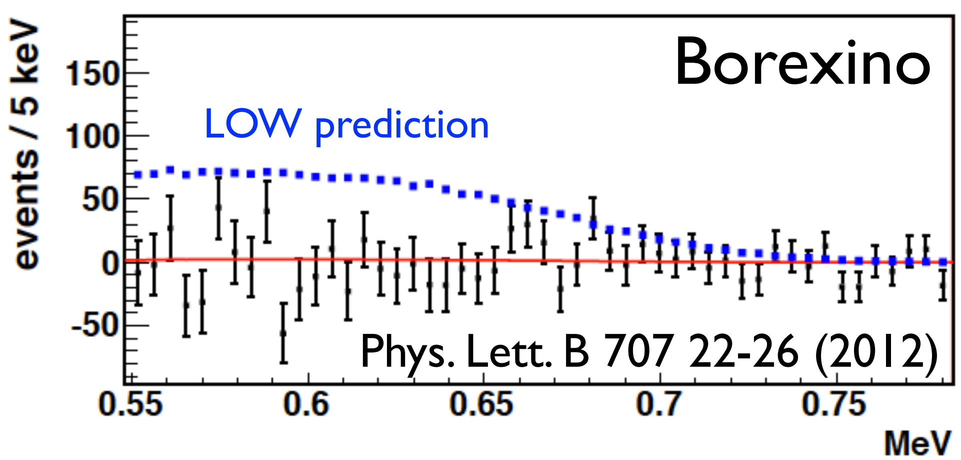
(2) Day / Night Asymmetry

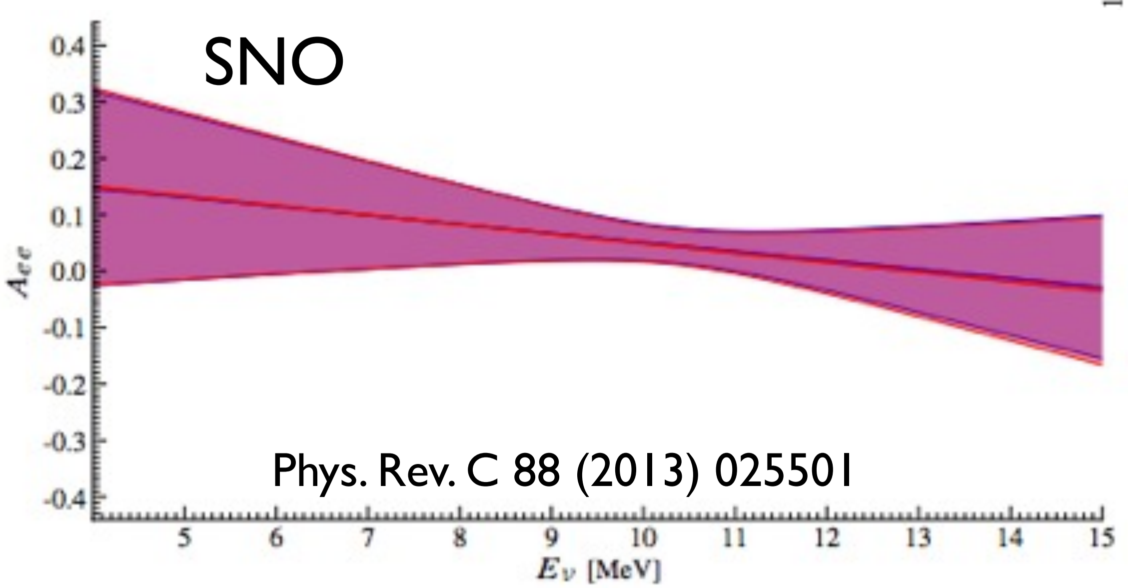


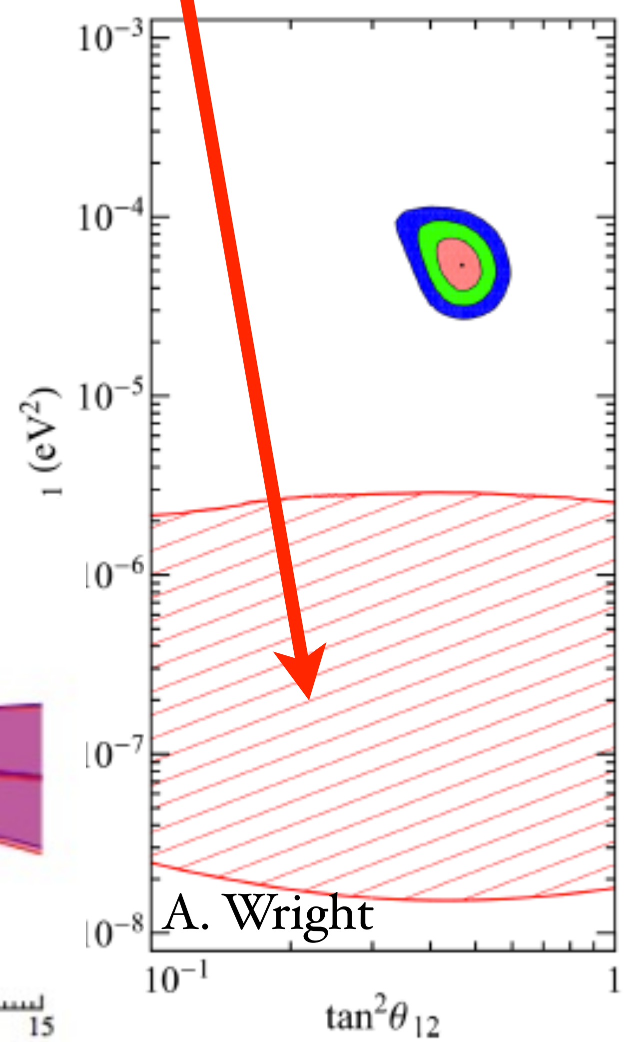


(2) Day / Night Asymmetry

Lack of D/N rules out LOW region at > 3σ







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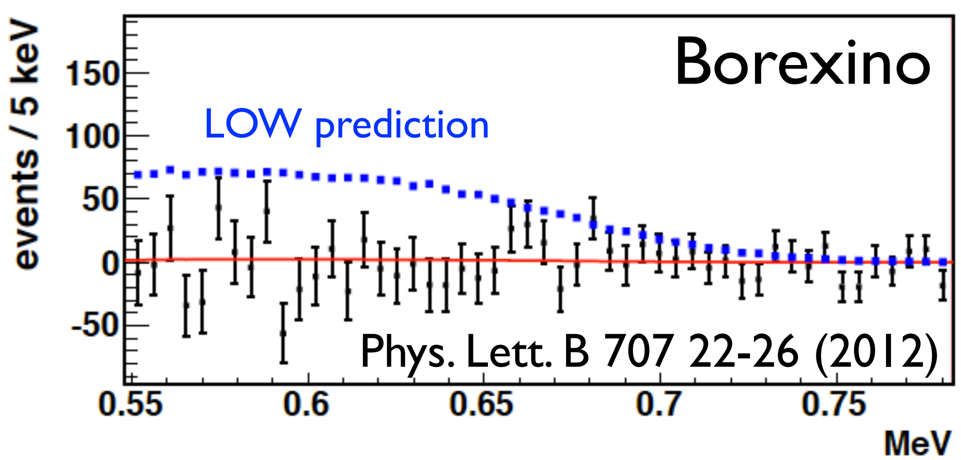
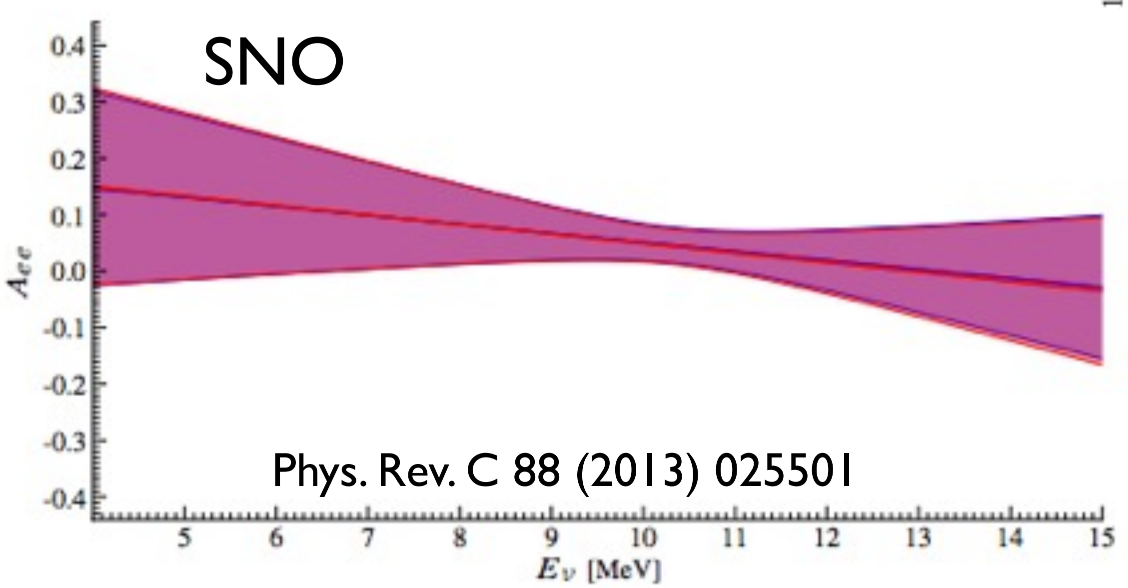
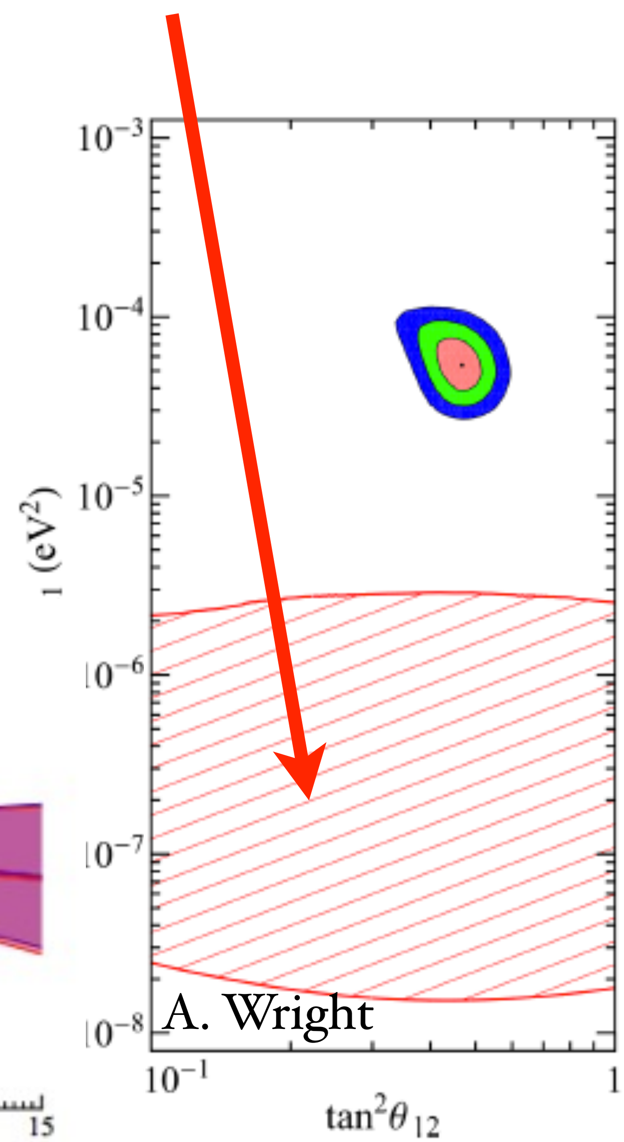
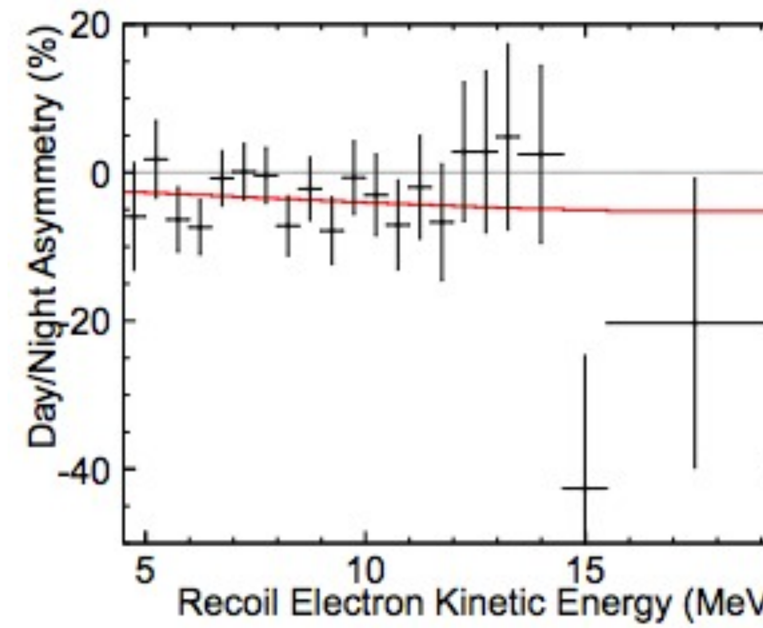






Super-Kamiokande
Combined analysis of SK I-IV

PRL 112 (2014) 091805



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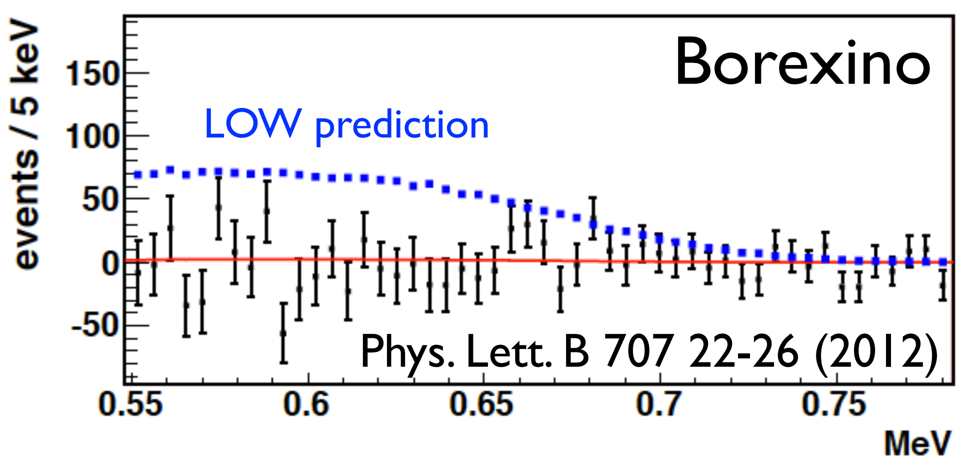
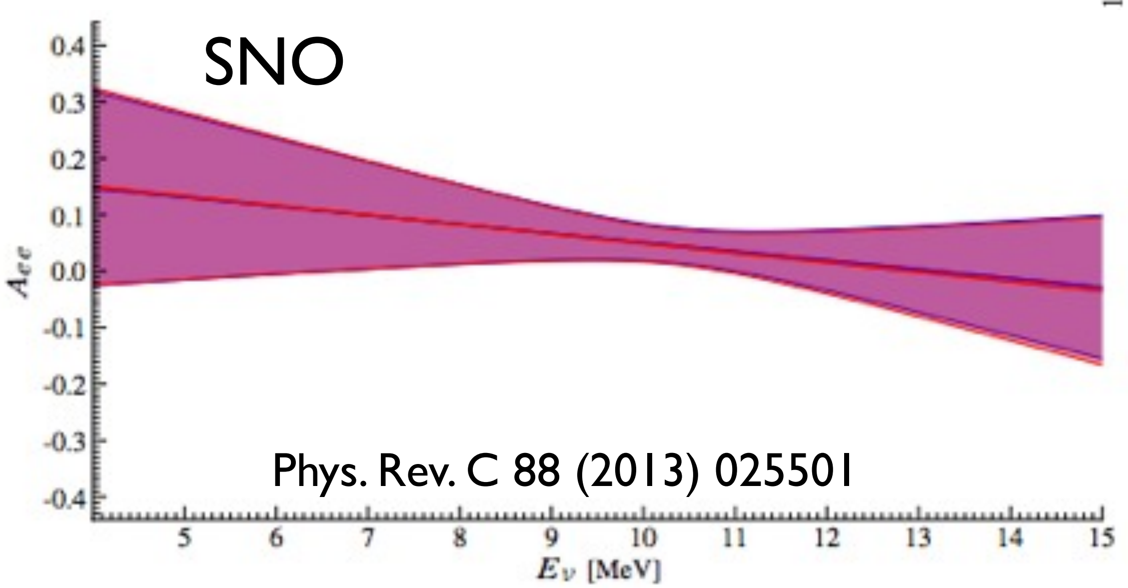
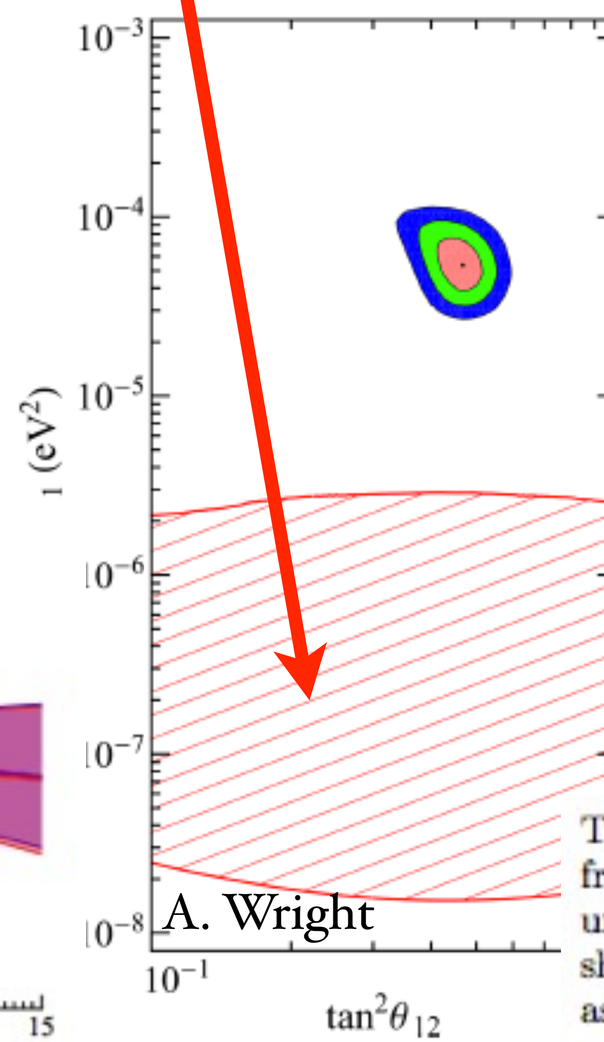
Lack of D/N rules out LOW region at > 3σ







Super-Kamiokande
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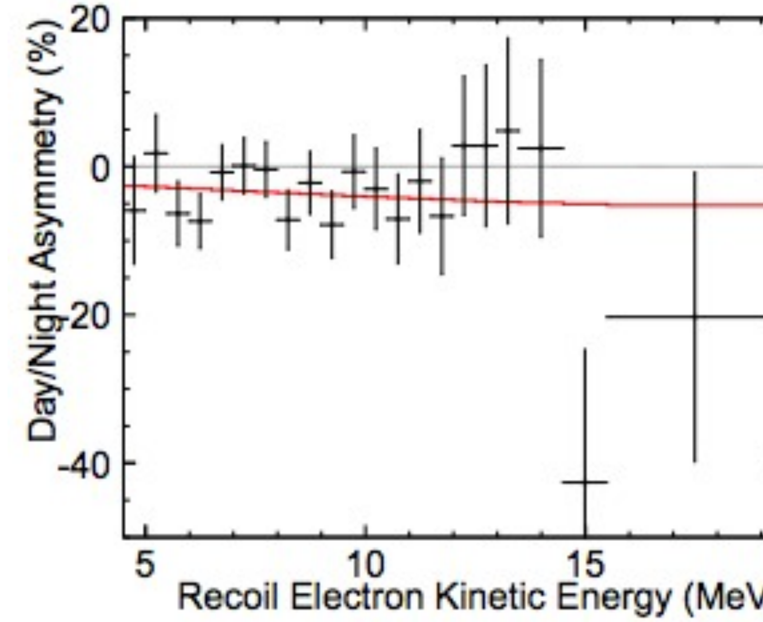


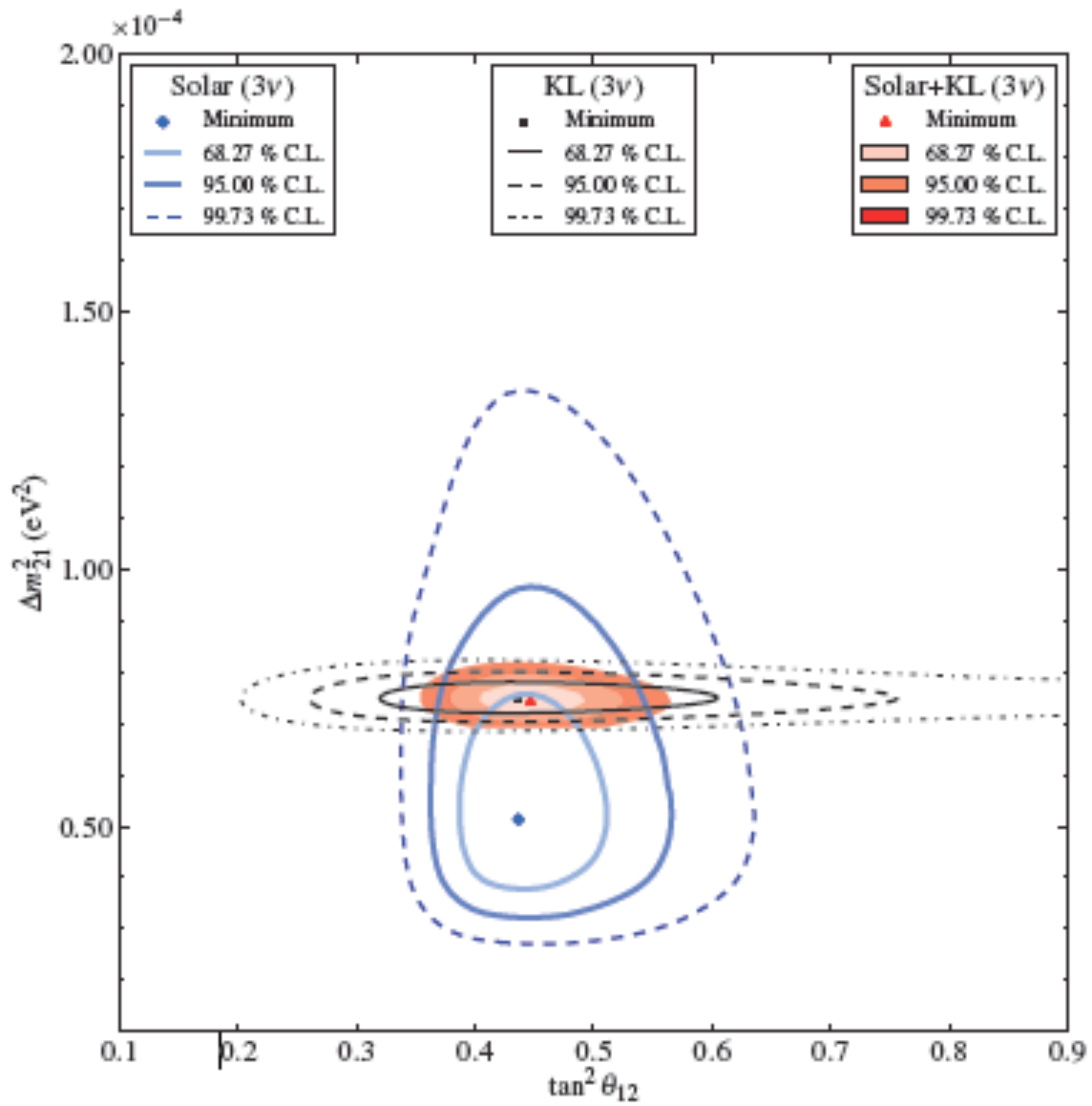
TABLE I. Day/night asymmetry for each SK phase, coming from separate day and night rate measurements (middle column) and the amplitude fit (right column). The uncertainties shown are statistical and systematic. The entire right column assumes the SK best-fit point of oscillation parameters.

	$A_{DN} \pm$ (stat) $\pm$ (syst)	$A_{DN}^{fit} \pm$ (stat) $\pm$ (syst)
SK-I	$(-2.1 \pm 2.0 \pm 1.3)\%$	$(-2.0 \pm 1.7 \pm 1.0)\%$
SK-II	$(-5.5 \pm 4.2 \pm 3.7)\%$	$(-4.3 \pm 3.8 \pm 1.0)\%$
SK-III	$(-5.9 \pm 3.2 \pm 1.3)\%$	$(-4.3 \pm 2.7 \pm 0.7)\%$
SK-IV	$(-5.3 \pm 2.0 \pm 1.4)\%$	$(-3.4 \pm 1.8 \pm 0.6)\%$
Combined	$(-4.2 \pm 1.2 \pm 0.8)\%$	$(-3.2 \pm 1.1 \pm 0.5)\%$

A_{DN} = -3.2% ± *1.1 (stat)* ± *0.5 (syst)* = 2.7σ

(F) Precision Measurements
Oscillation Parameters

Large Mixing Angle (LMA) solution clearly preferred



$$tan^2\theta_{12} = 0.446^{+0.030}_{-0.029}$$

$$\Delta m^2_{21} = 7.41^{+0.21}_{-0.19} \times 10^{-5}\mathrm{eV}^2$$

$$sin^2\theta_{13} = 2.5^{+1.8}_{-1.5} \times 10^{-2}$$

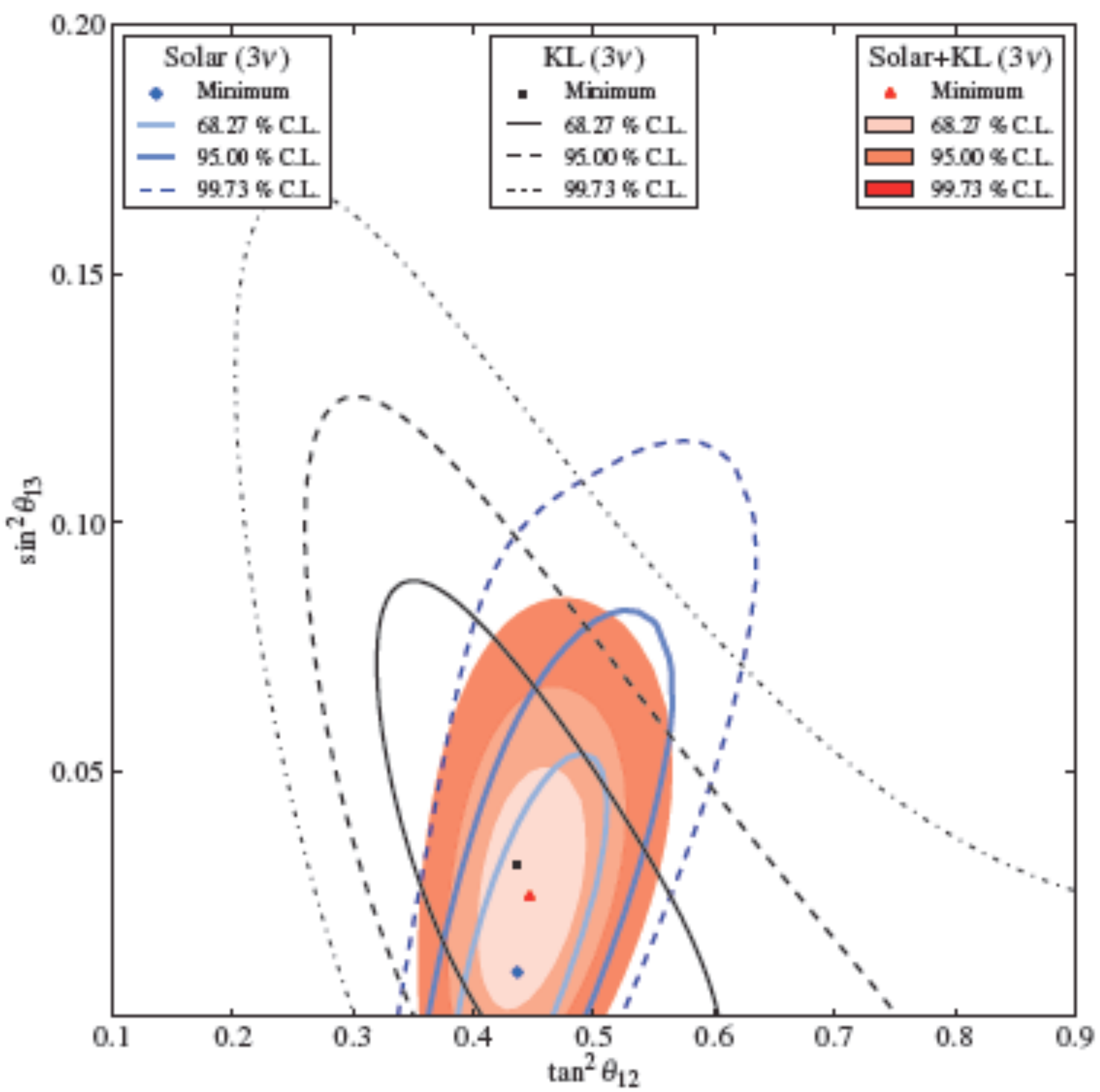
arXiv:1109.0763v1 [nucl-ex]

3-flavour fit

(F) Precision Measurements

Oscillation Parameters

Large Mixing Angle (LMA) solution clearly preferred



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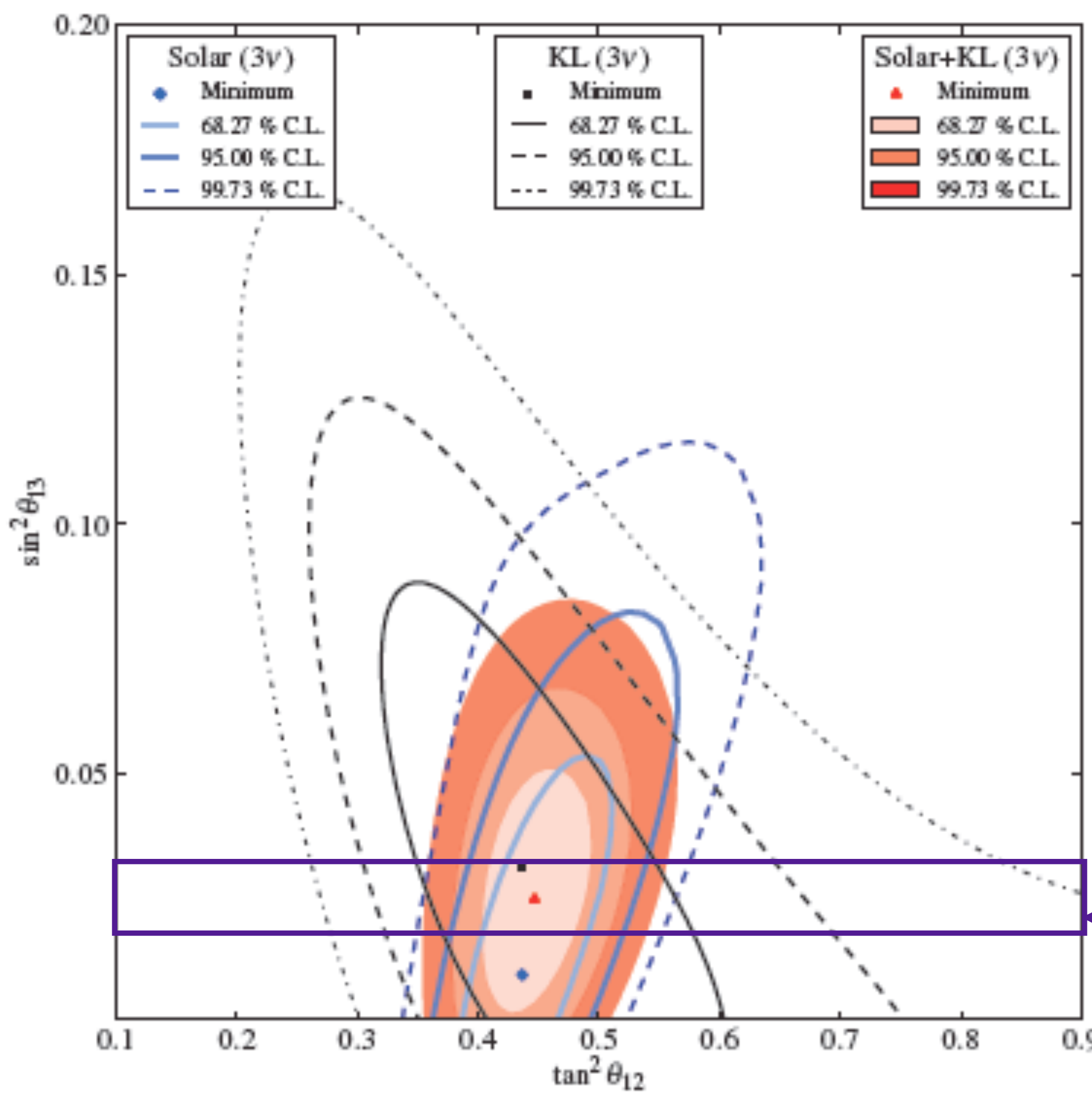

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$$\Delta m^2_{21} = 7.41^{+0.21}_{-0.19} \times 10^{-5}\mathrm{eV}^2$$

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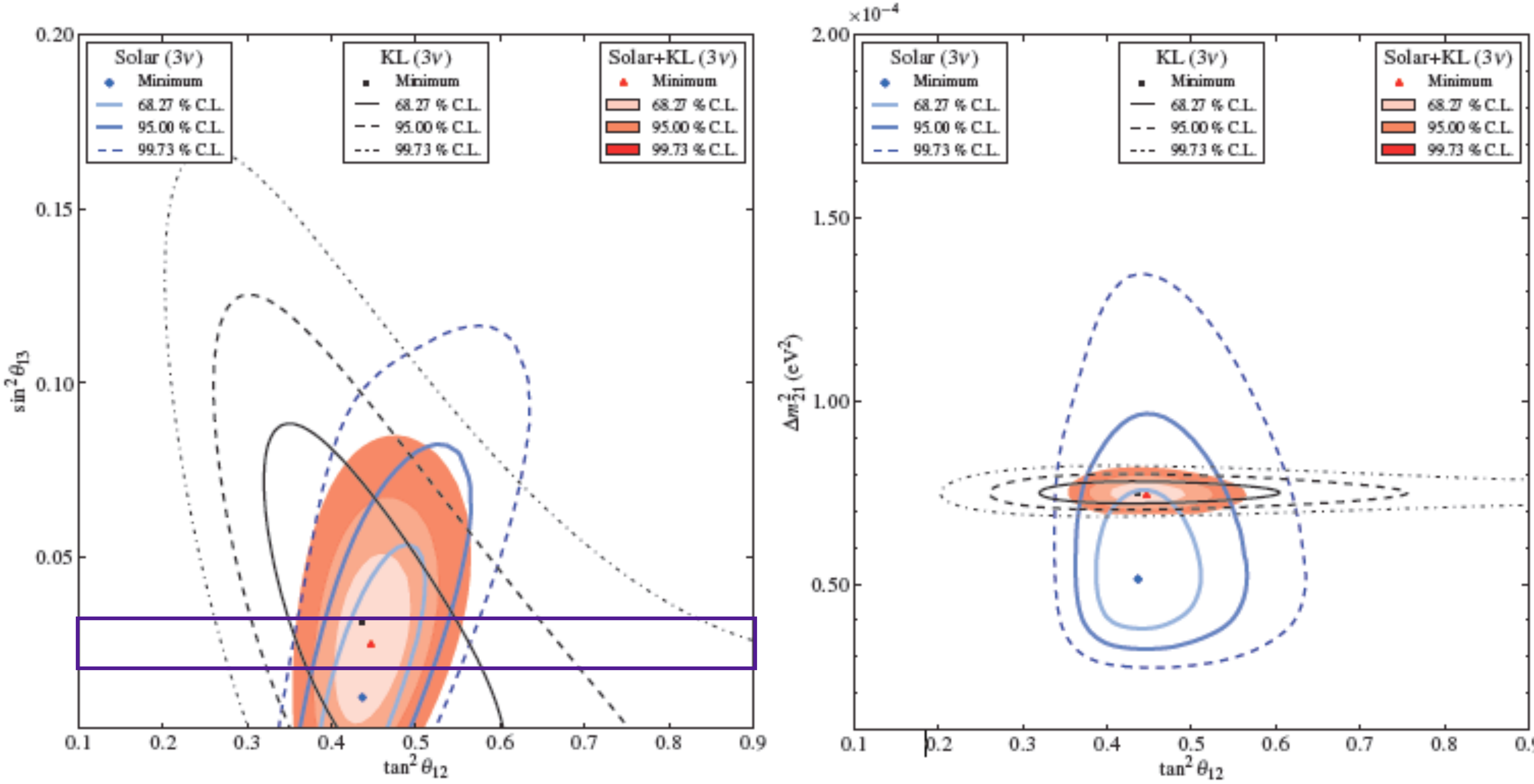
Hint of non-zero ϑ_{13} nicely confirmed by (5σ!) Daya Bay, Reno results

arXiv:1109.0763v1 [nucl-ex]

3-flavour fit

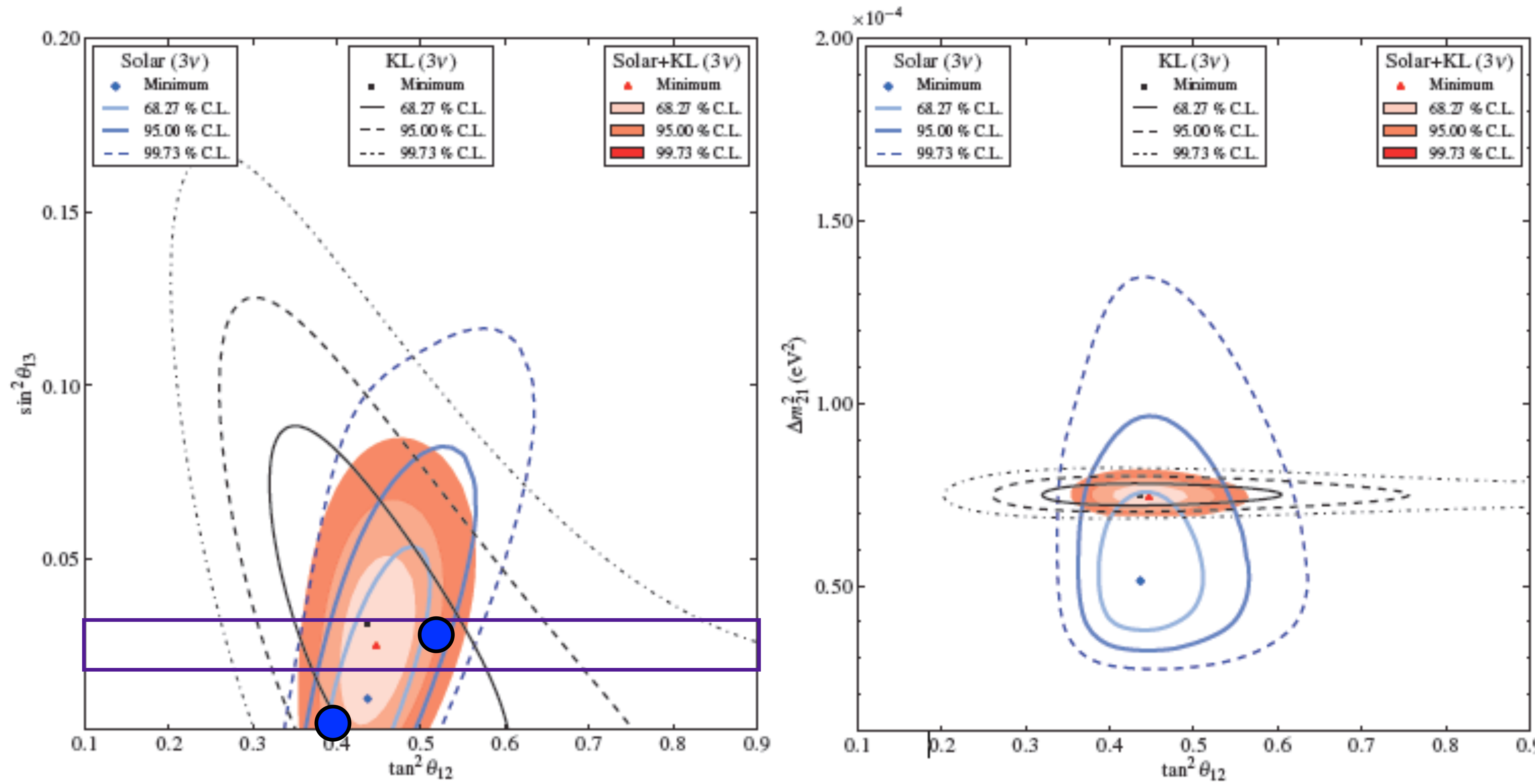
(F) Precision Measurements

Oscillation Parameters



(F) Precision Measurements

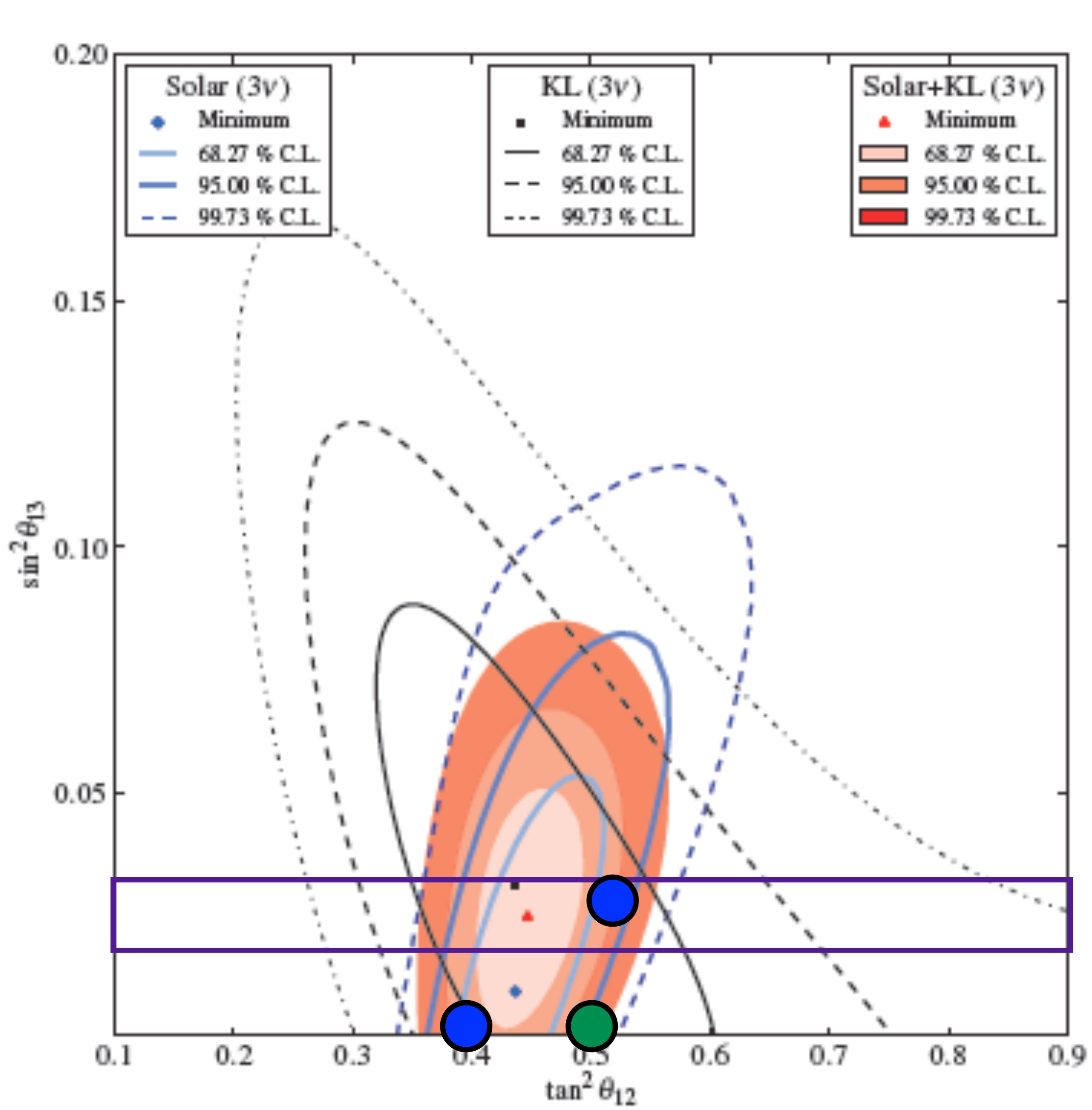
Oscillation Parameters

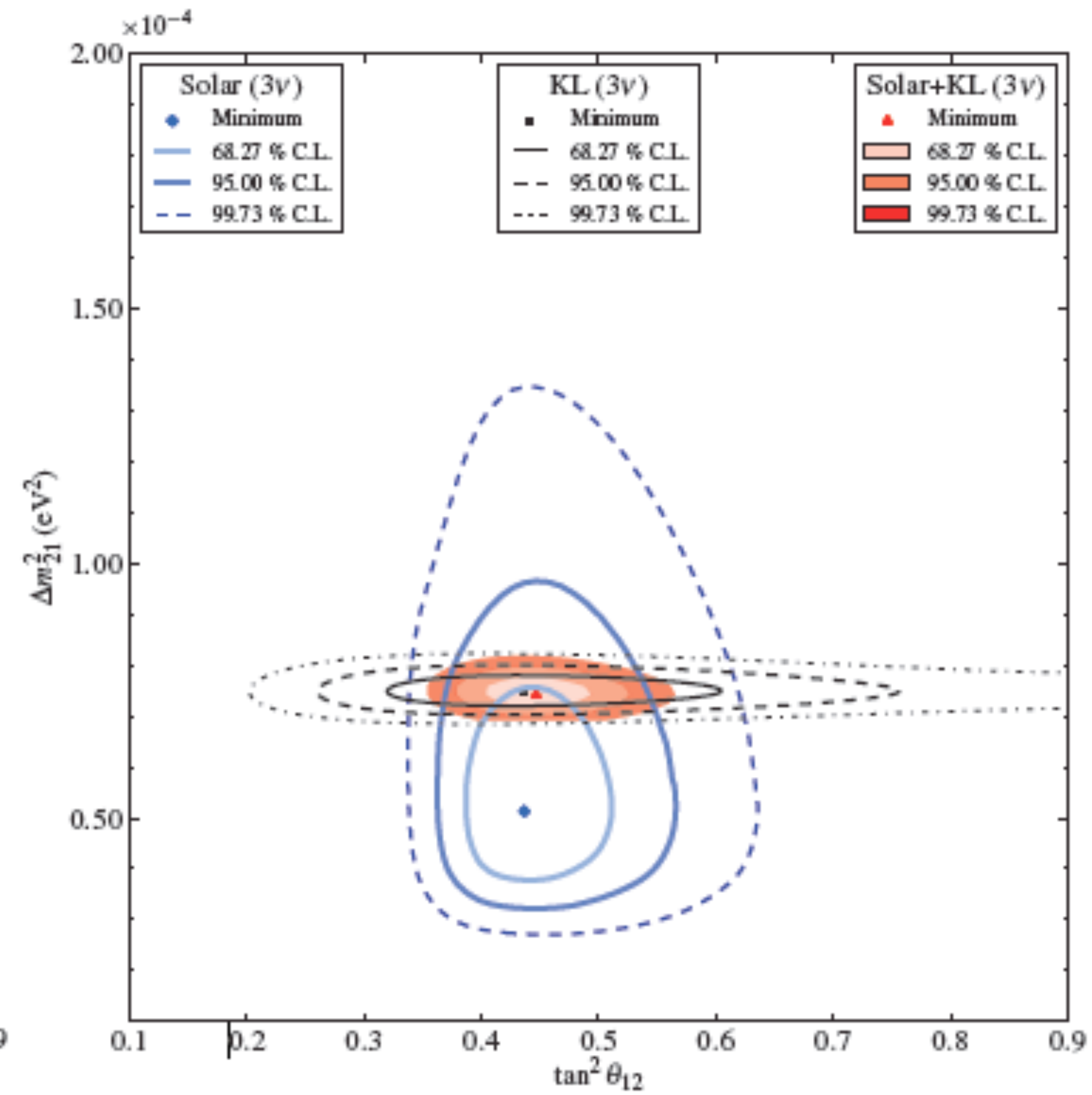


Quark-lepton complementarity

(F) Precision Measurements

Oscillation Parameters



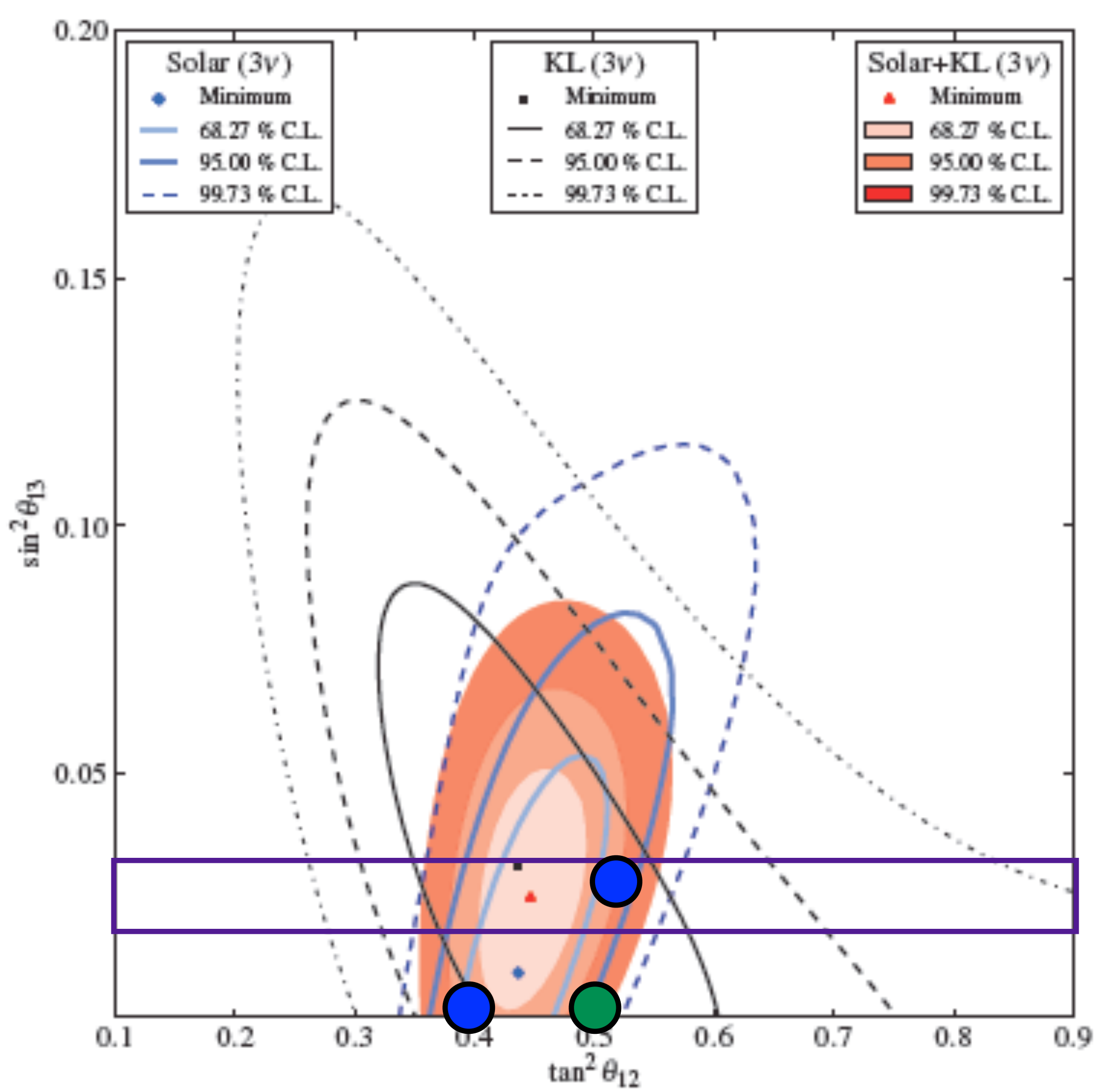


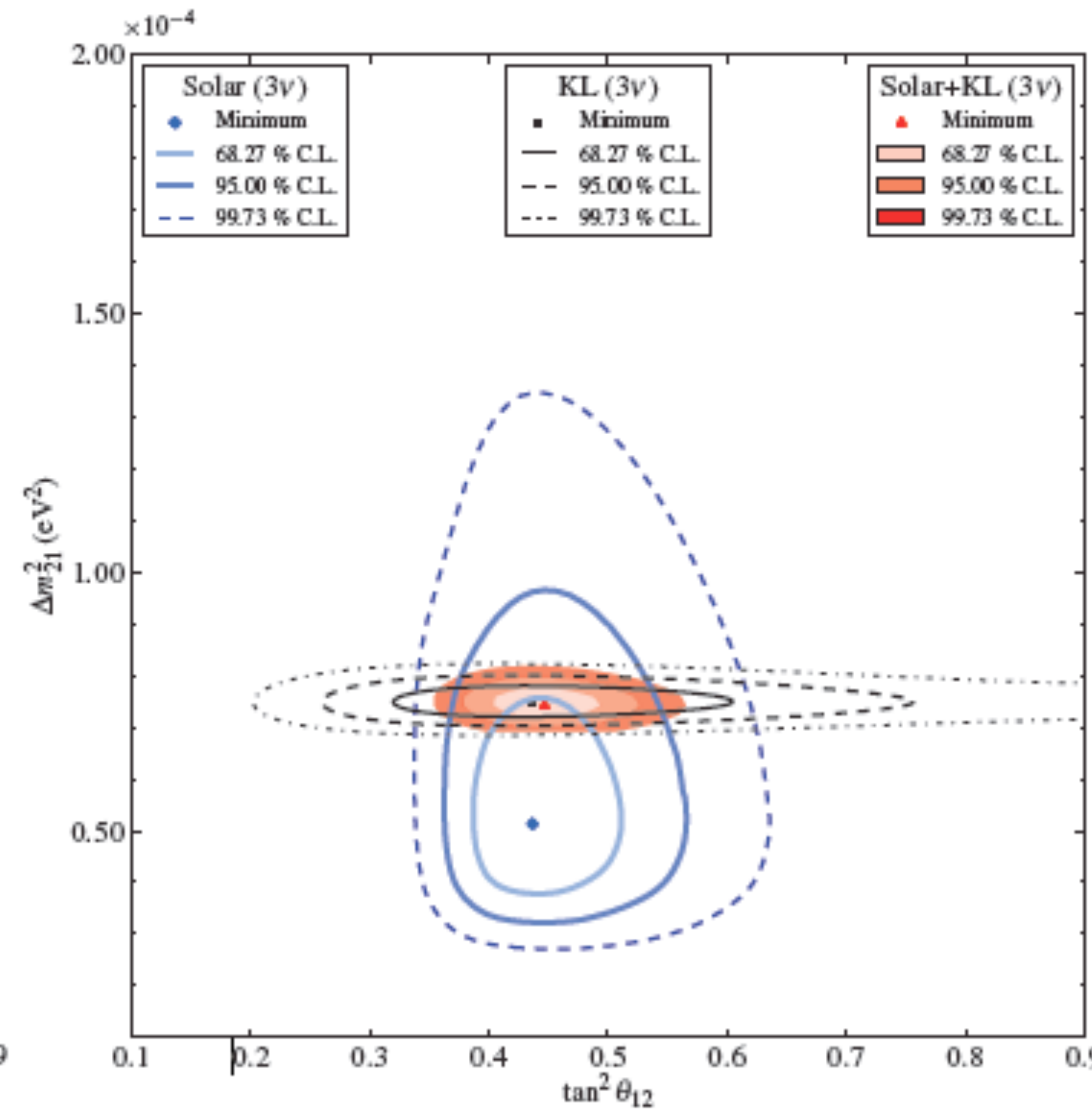
Quark-lepton complementarity

Tri-Bi-Maximal

(F) Precision Measurements

Oscillation Parameters





Quark-lepton complementarity

Tri-Bi-Maximal

θ_{12} non-maximal by > 5 σ