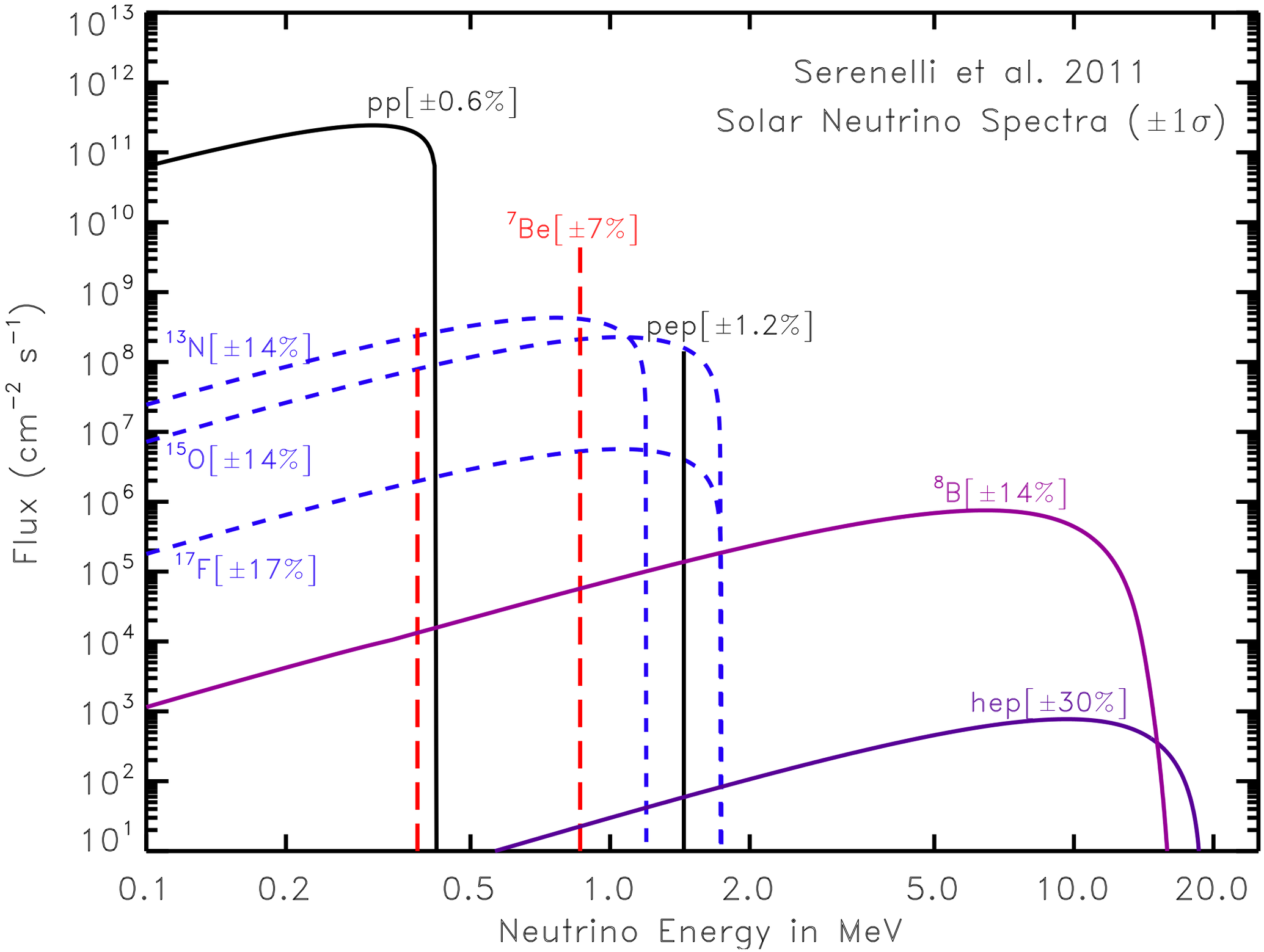
Solar Neutrinos: The Next Decade

Gabriel D. Orebi Gann
FSNu Town Hall, Chicago
Sept 28th 2014

U. C. Berkeley
& LBNL

Solar Neutrino Energy Spectra



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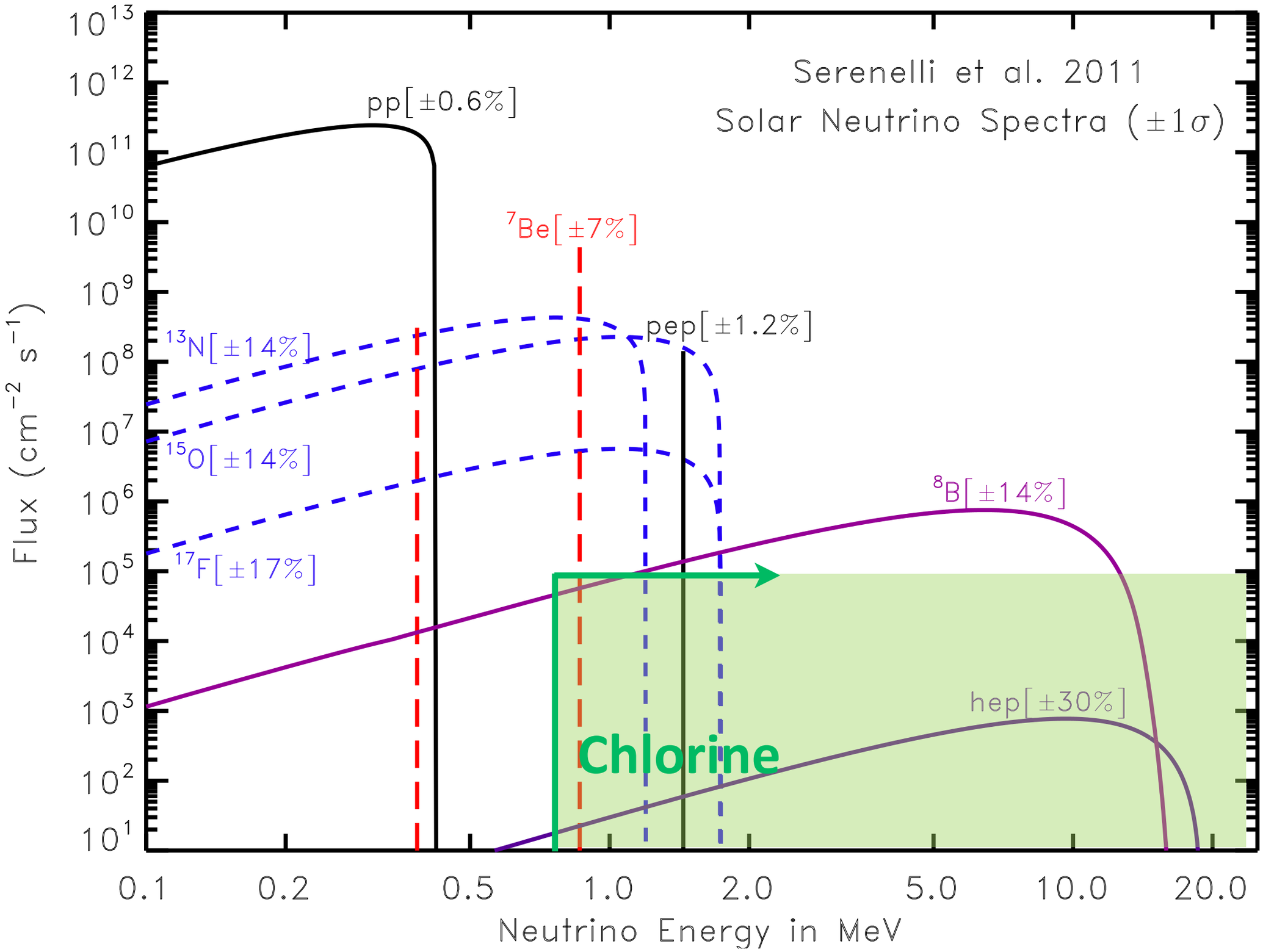

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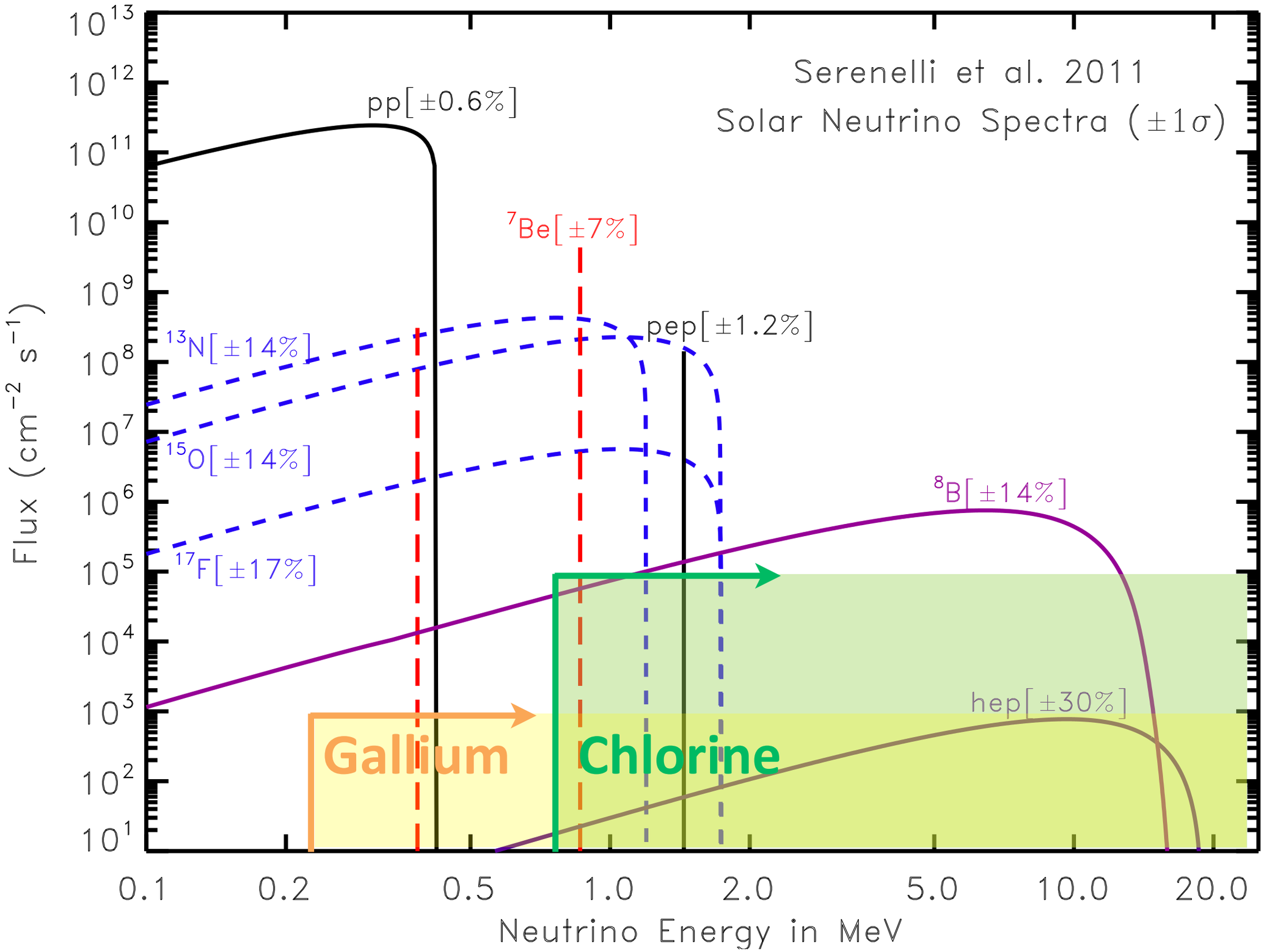

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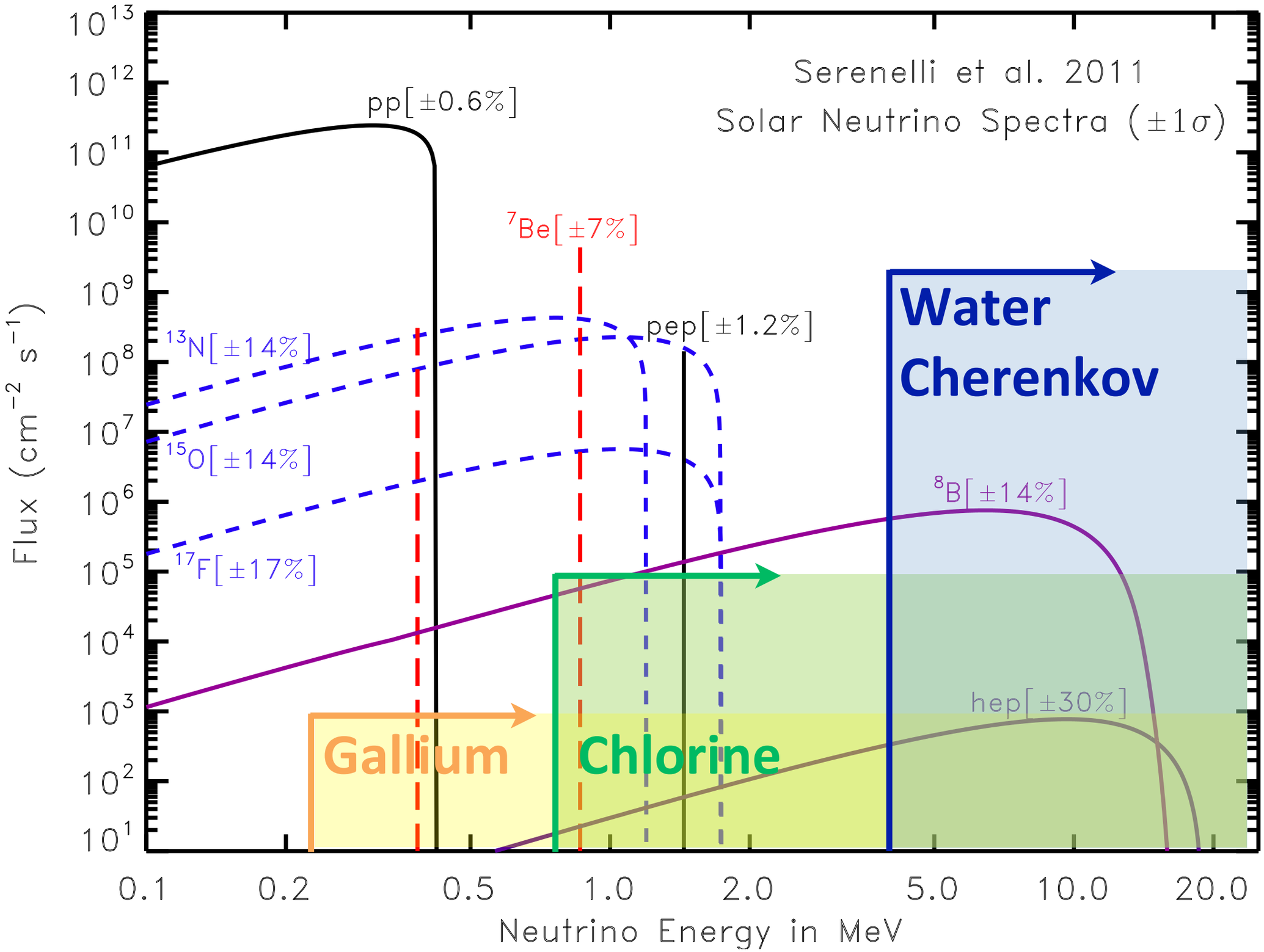

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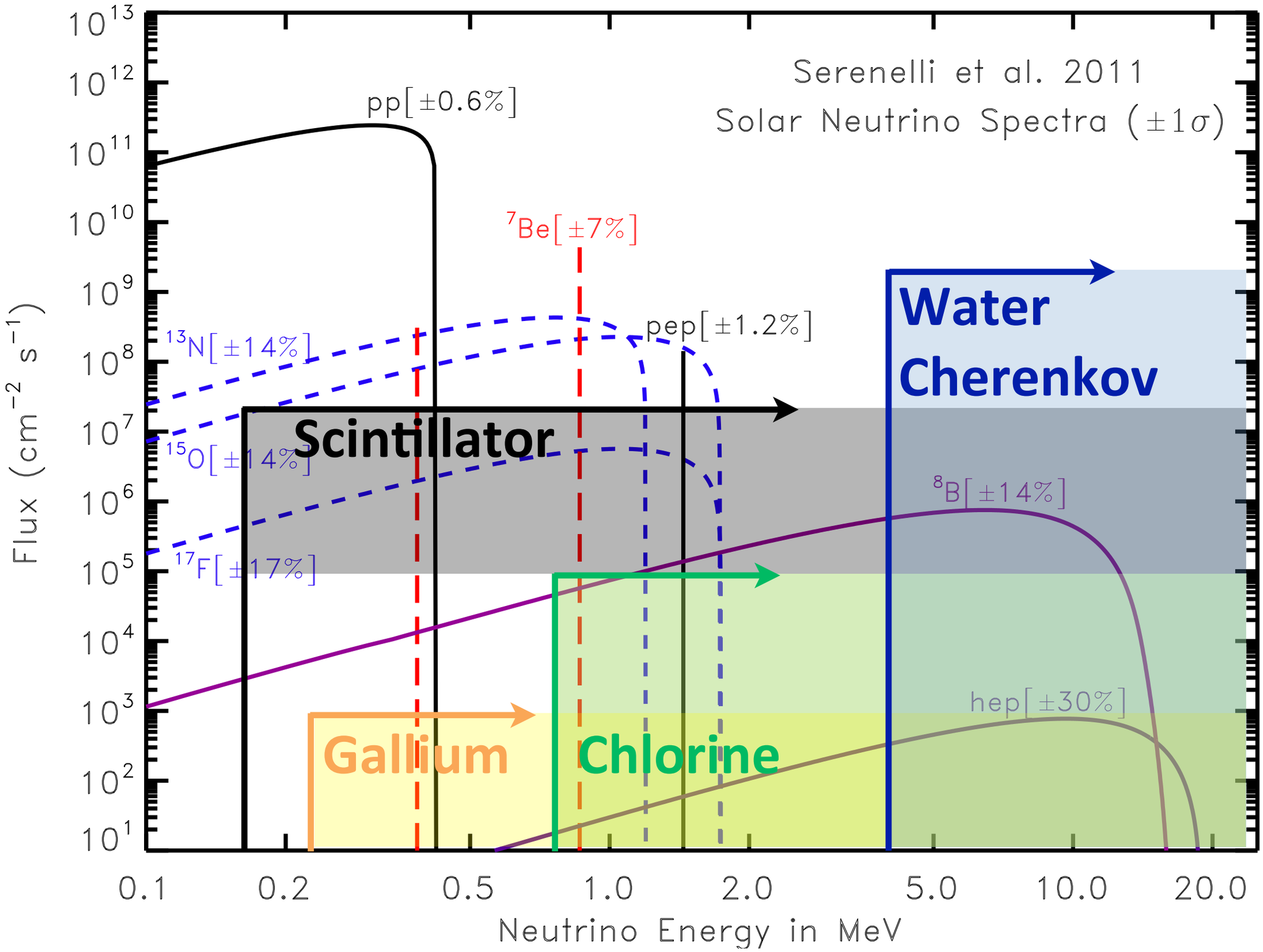


Solving the Solar Neutrino Problem

"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

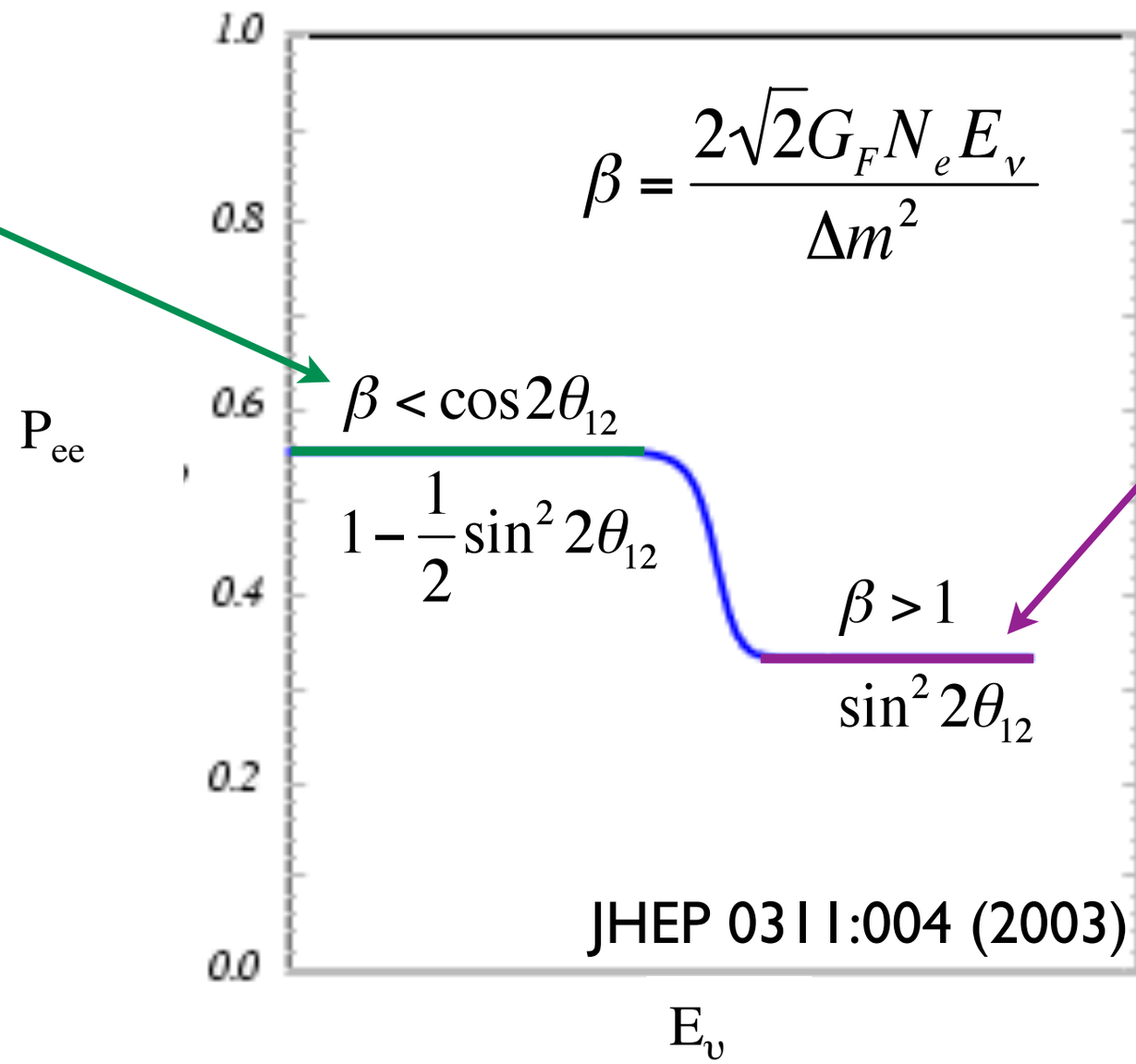
Physics Beyond the SNP

(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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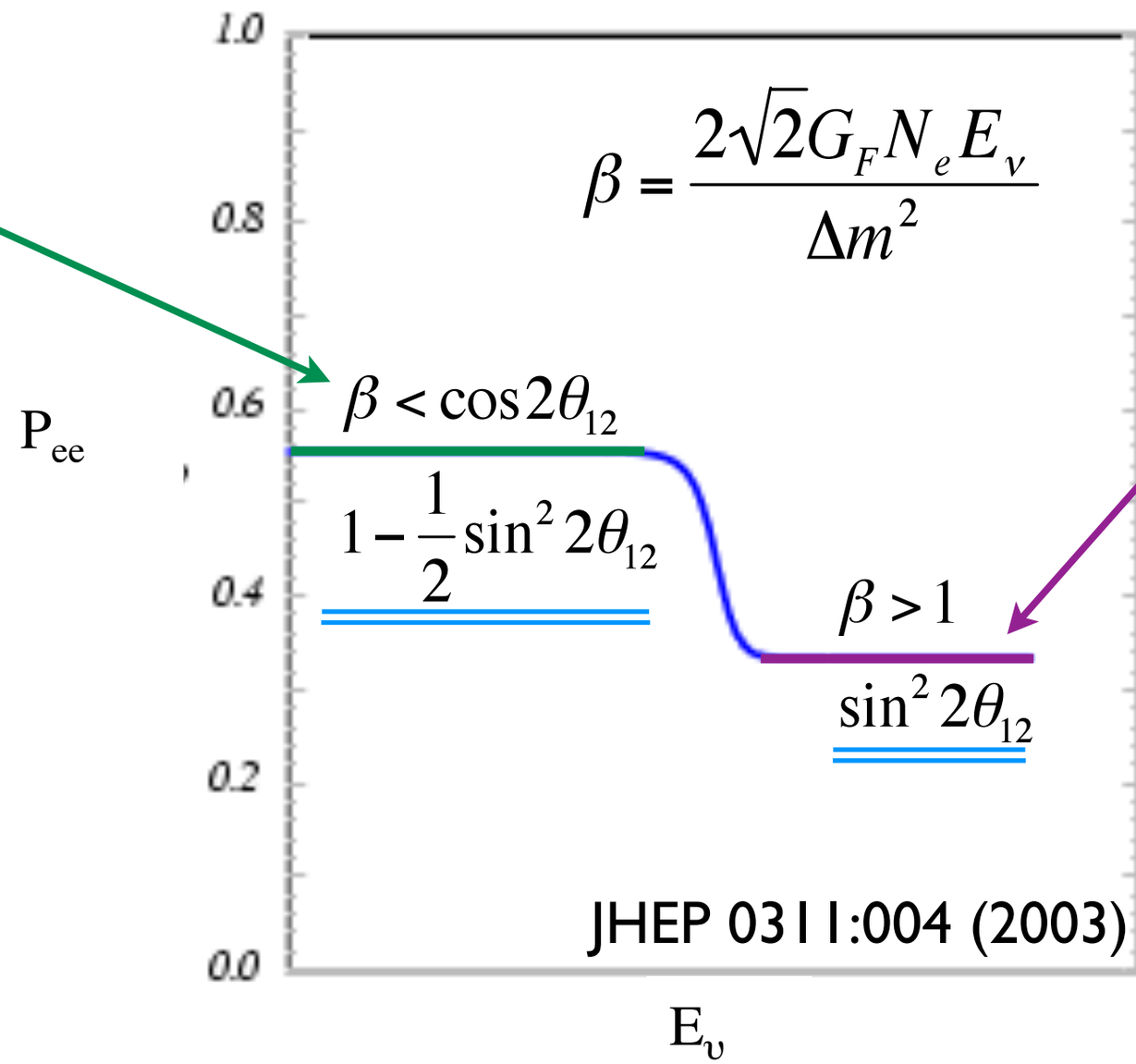

JHEP 0311:004 (2003)

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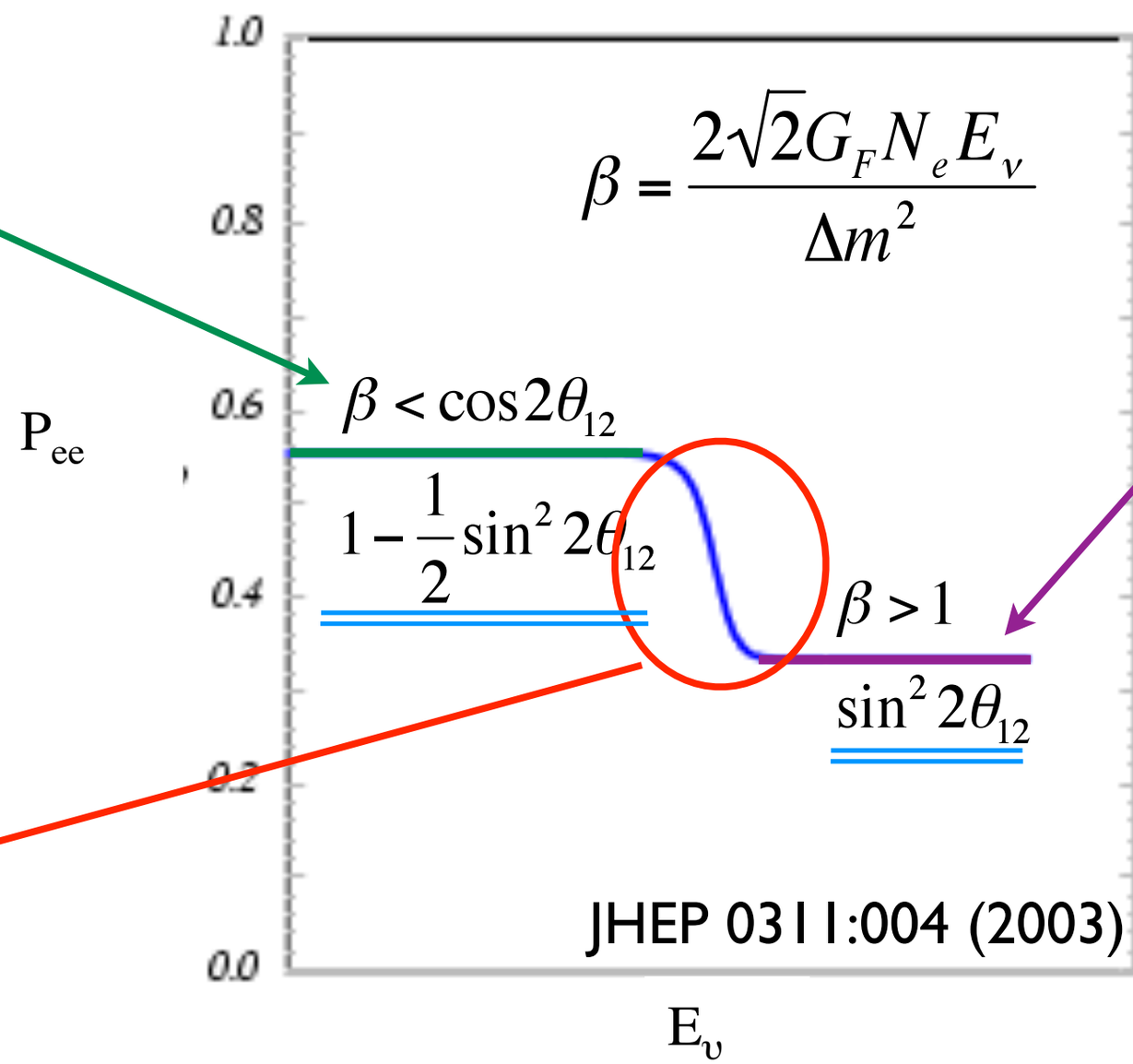


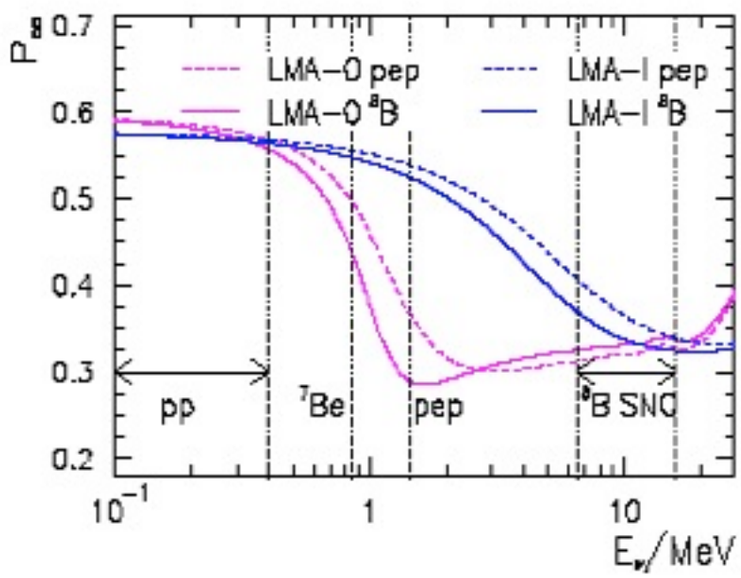
'High' energy (>5MeV):
Matter-dominated resonant conversion

Probe transition region to confirm MSW

Probing the Unknown

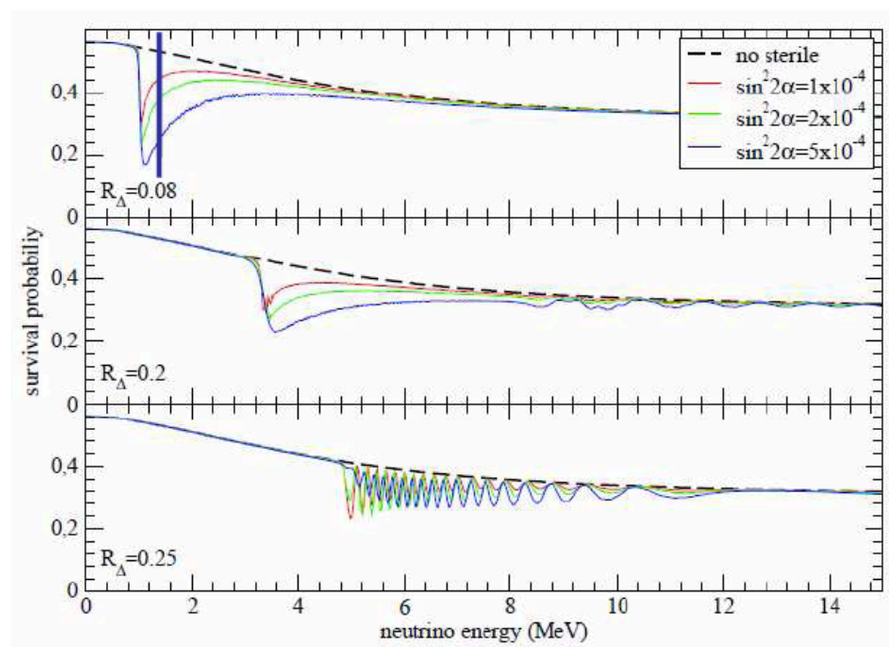
Non-standard physics effects can alter the shape / position of the "MSW rise"

Non-standard interactions (flavour changing NC)



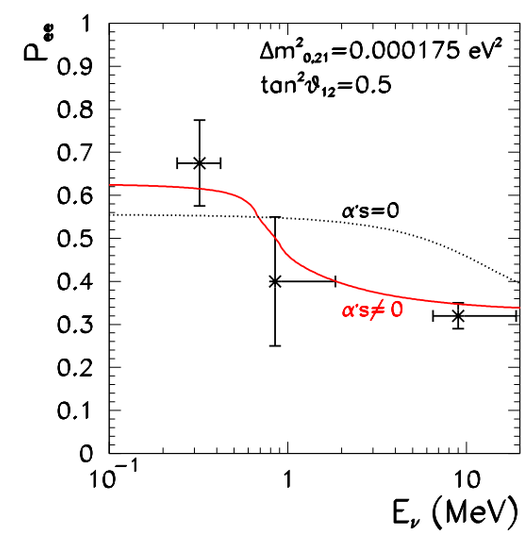
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov
PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)

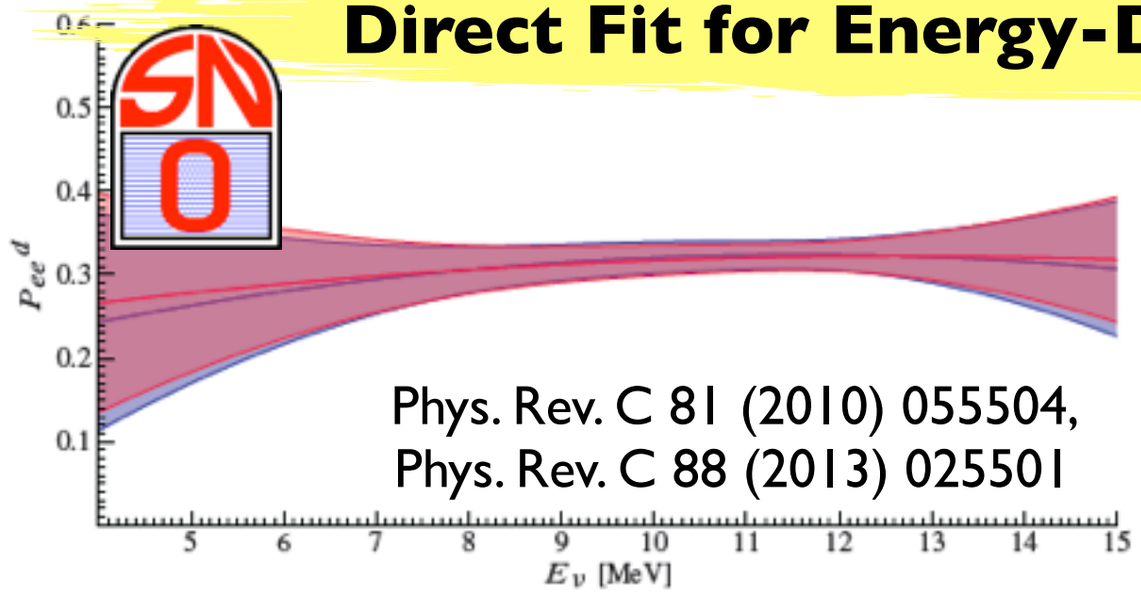


M.C. Gonzalez-Garcia, M. Maltoni
Phys Rept 460:1-129 (2008)

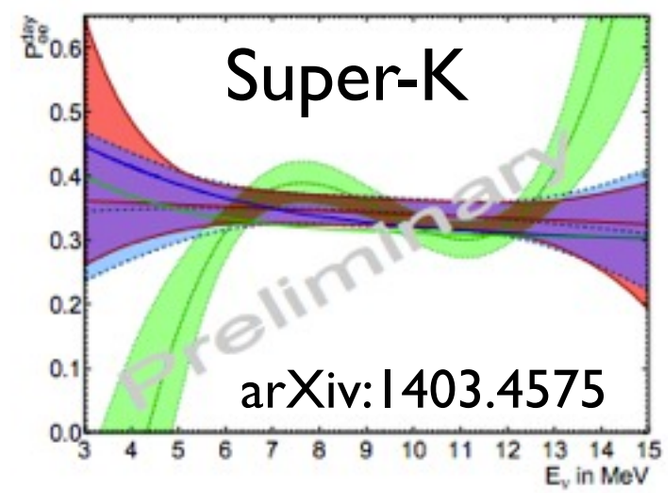
Precision Era

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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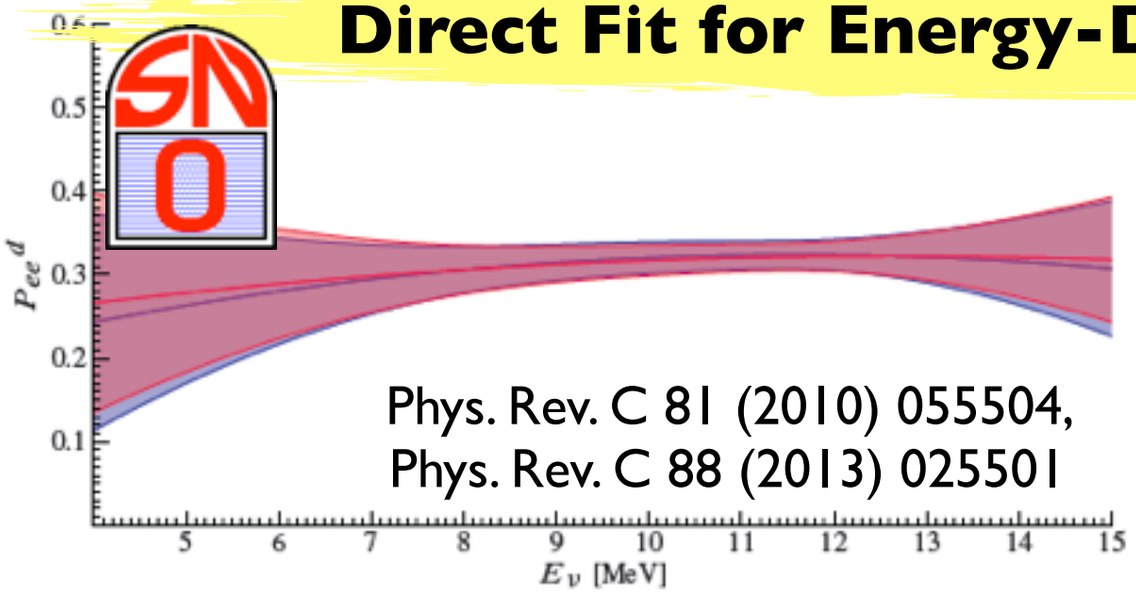

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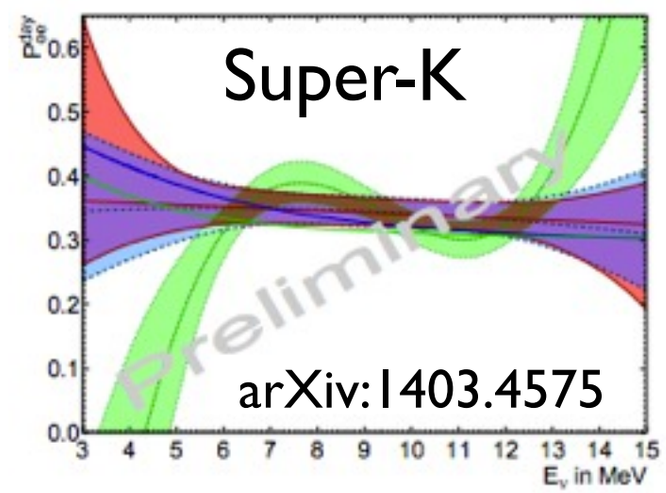

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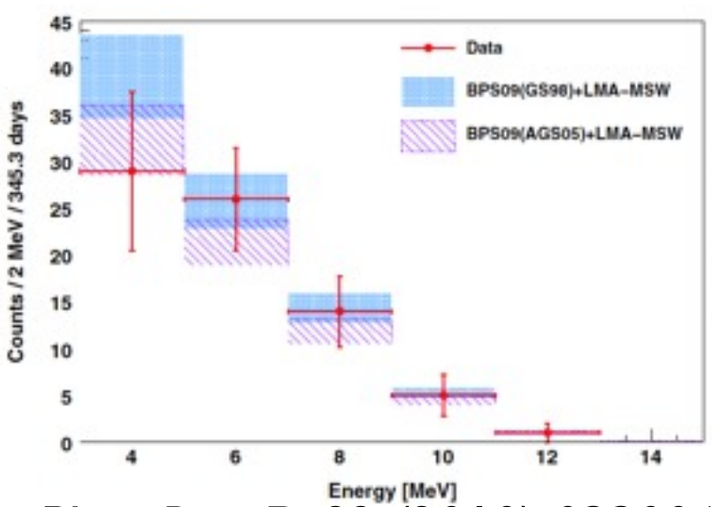
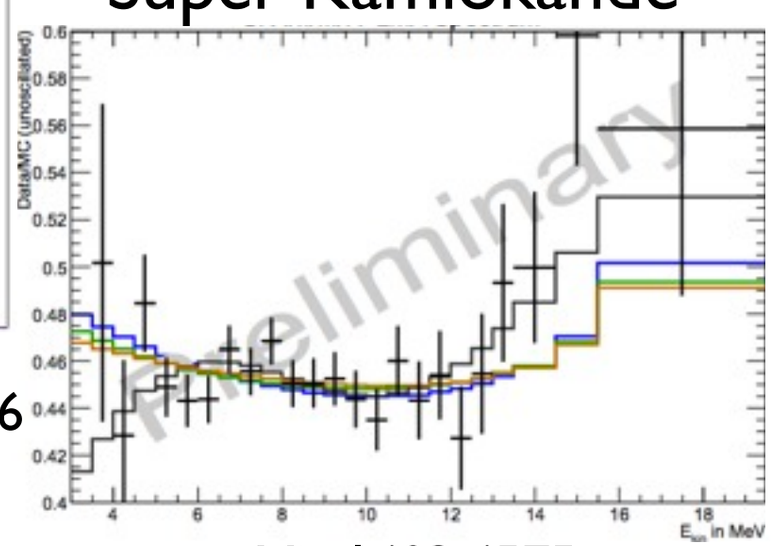
Electron recoil spectra

Borexino



Phys. Rev. D 82 (2010) 033006

Super-Kamiokande



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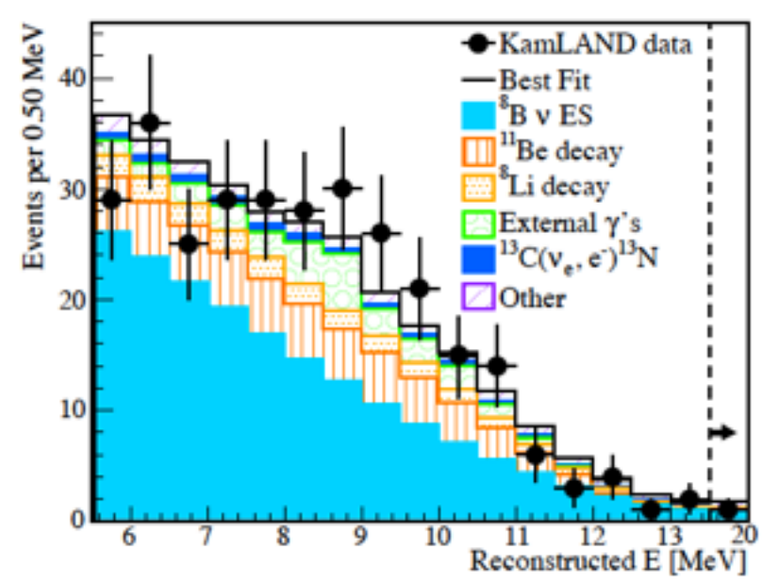
KamLAND



Phys. Rev. C 84 (2011) 035804

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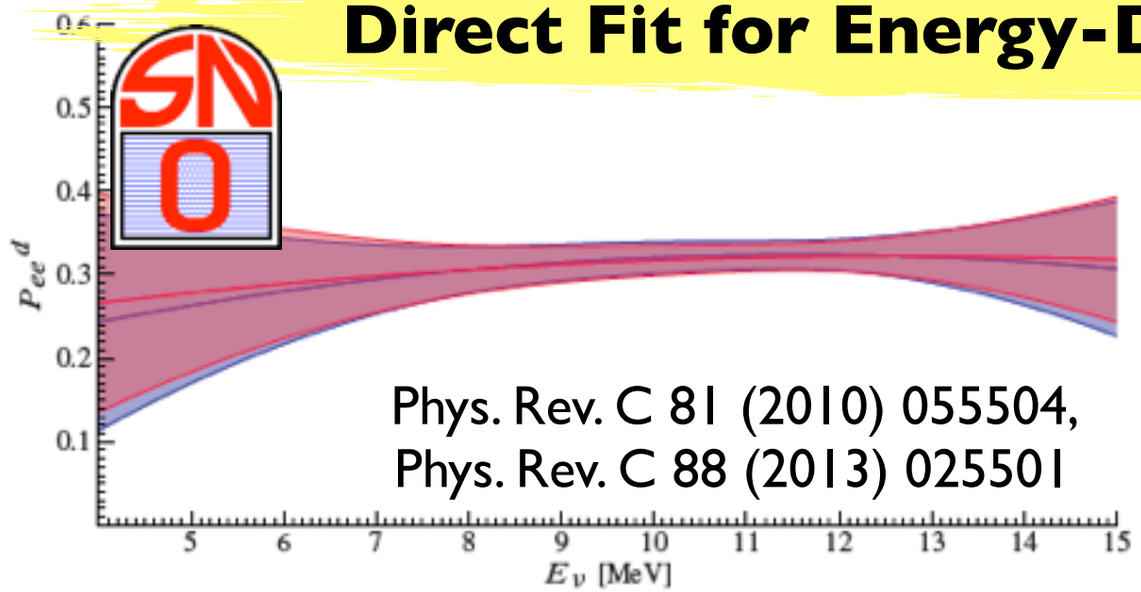
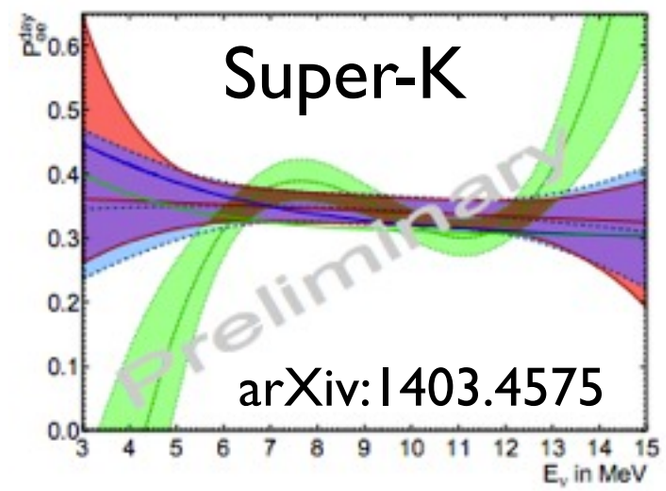


Phys. Rev. C 81 (2010) 055504,
Phys. Rev. C 88 (2013) 025501



arXiv:1403.4575

No significant effects (< 2σ)

Results limited by experimental precision

PRD 88: 053010 (2013)

Electron recoil spectra

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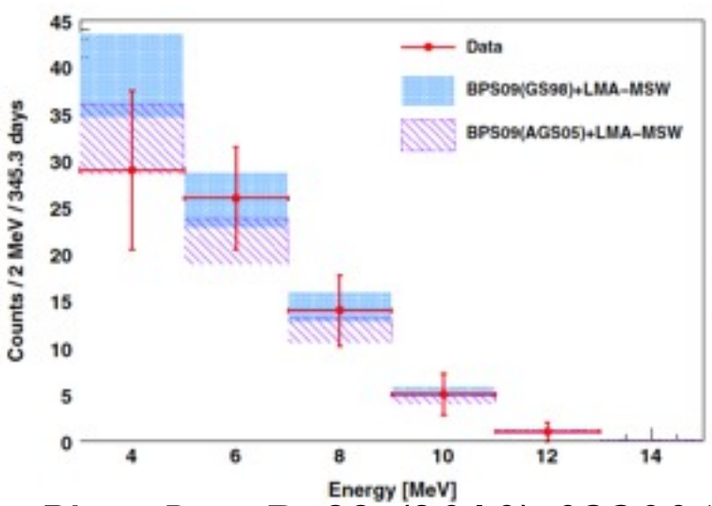

Phys. Rev. D 82 (2010) 033006

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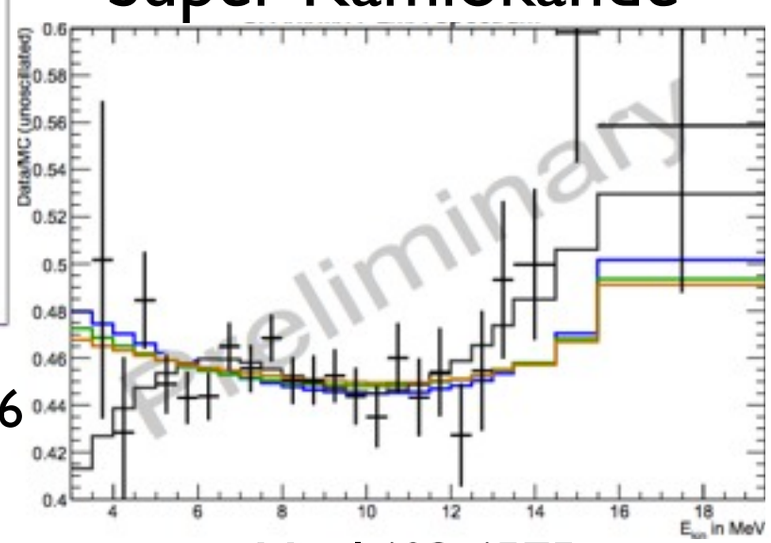

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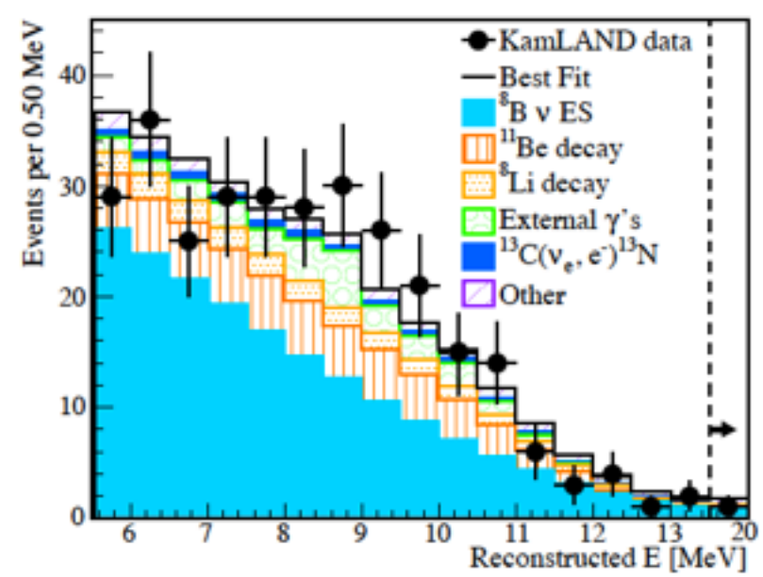
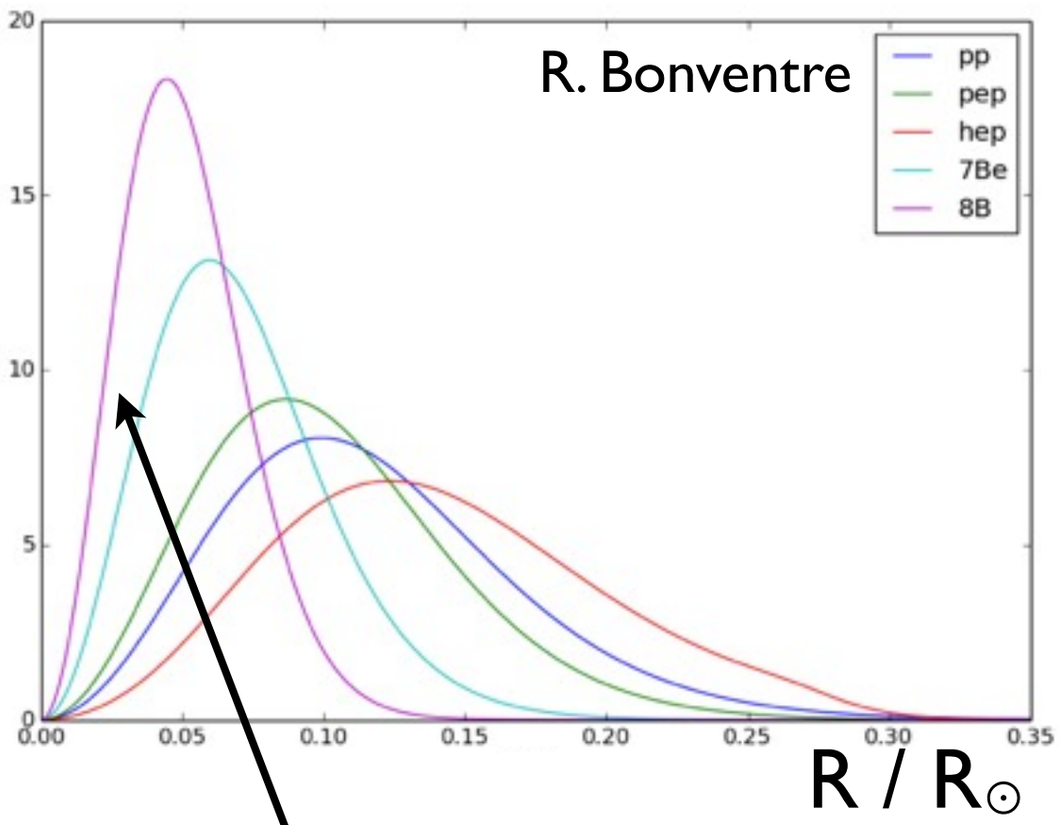


Phys. Rev. C 84 (2011) 035804

Probing the Transition Region: why we need ^{8}B



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

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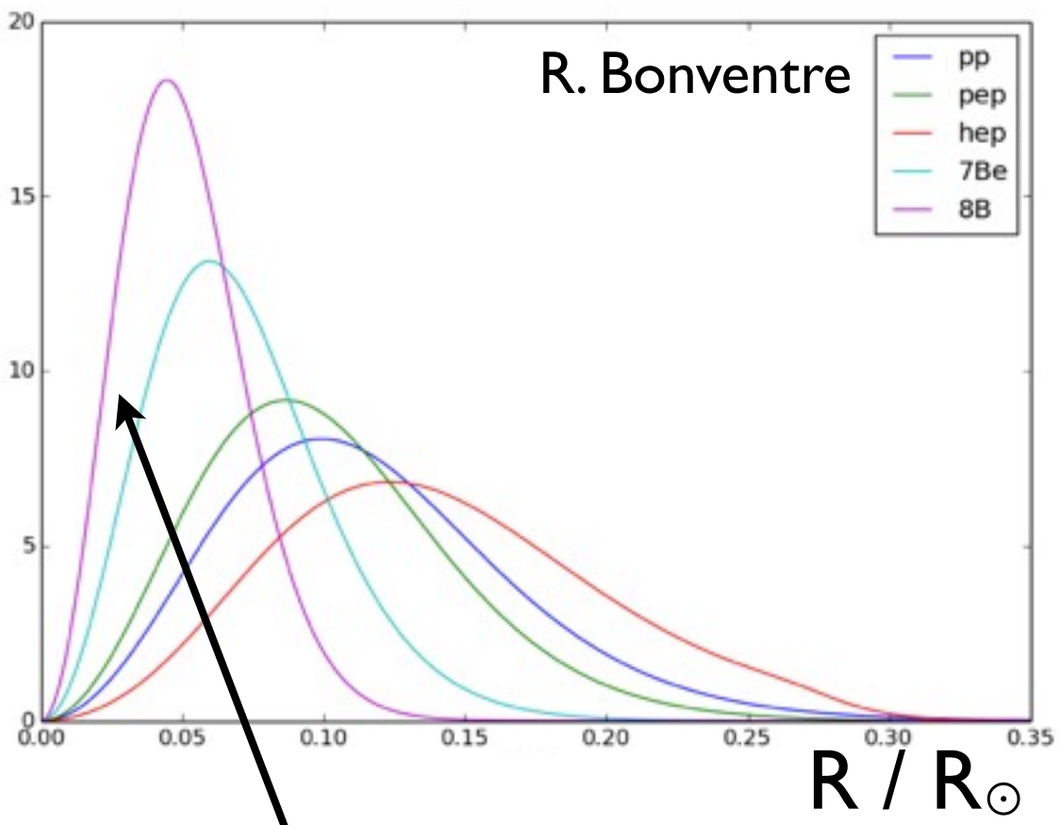

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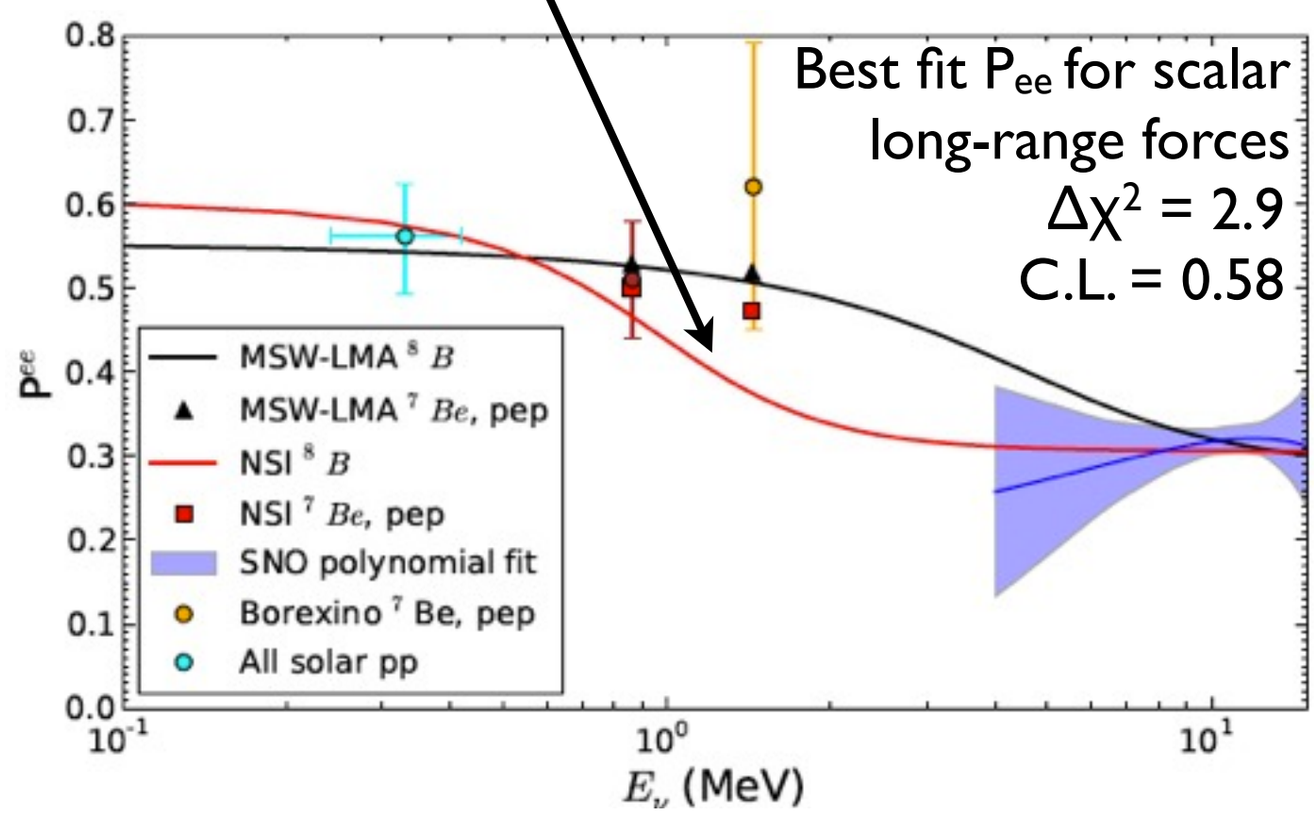
Largest affect on shape of survival probability



Phys. Rev. D 88 (2013) 053010

Physics Beyond the SNP

(1) Searching for new physics:

ν_e survival probability shape

(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

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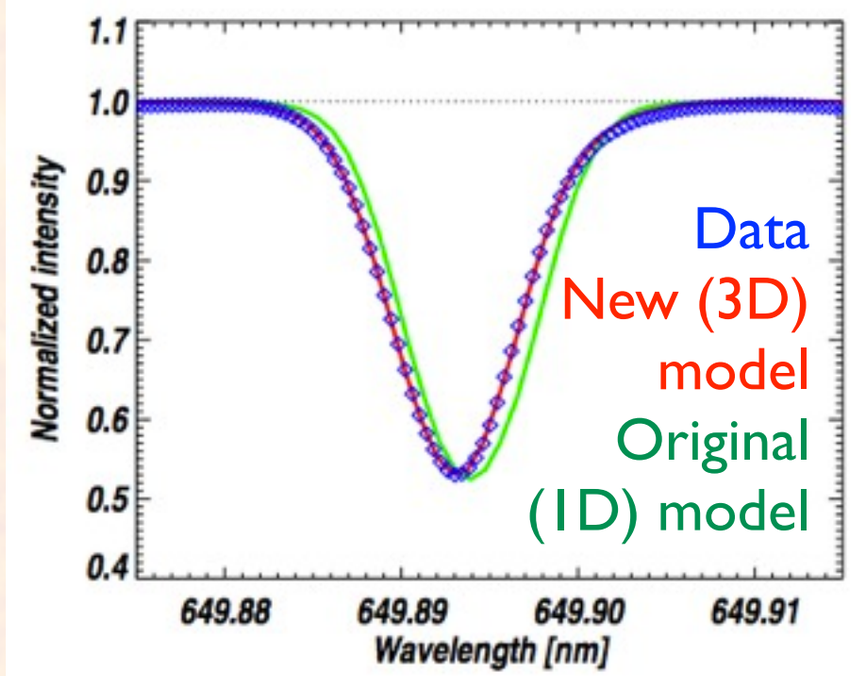
More sophisticated analyses of photospheric absorption lines

⇒ better agreement with data

⇒ lower abundance of metals (> H, He)



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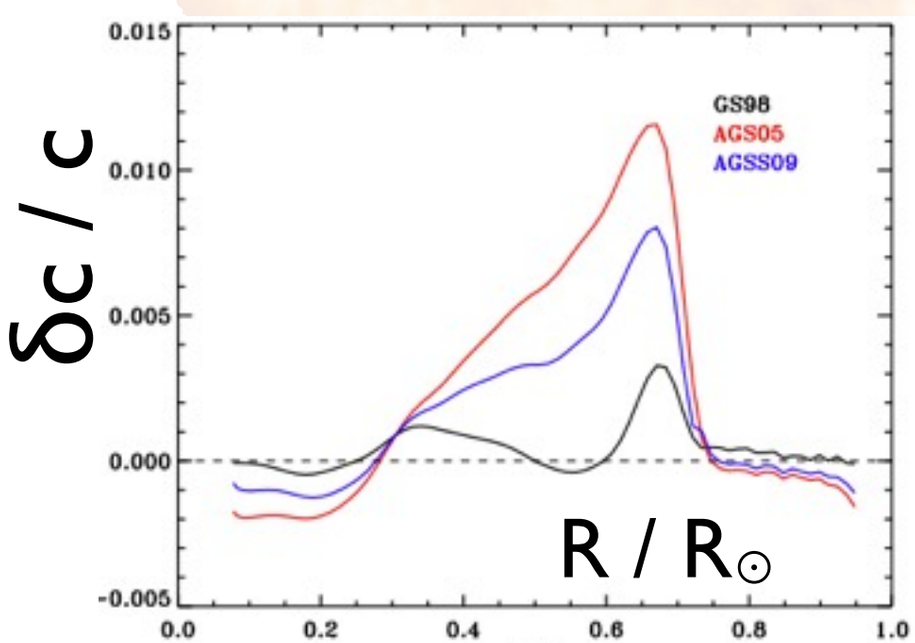
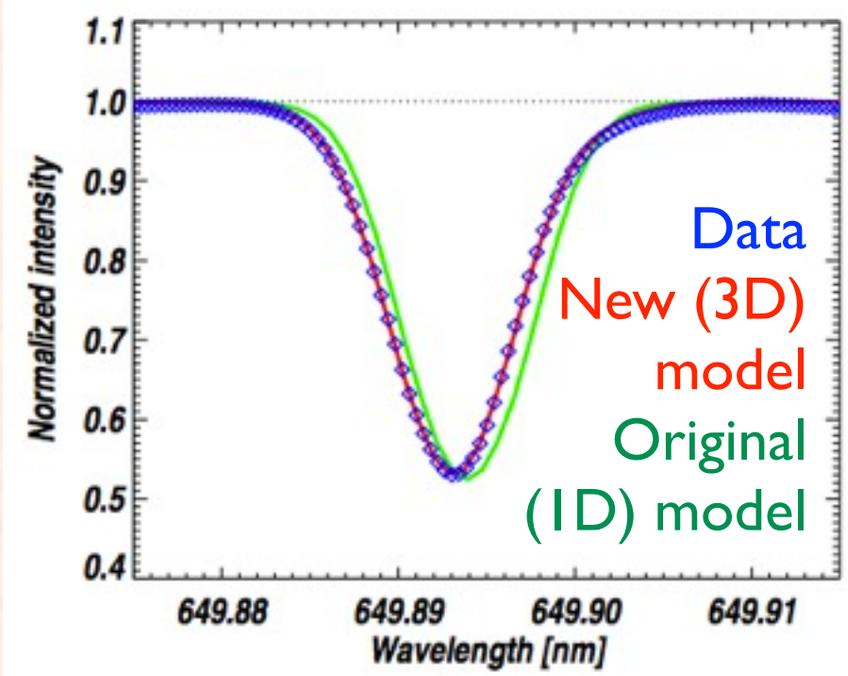


New discrepancy!



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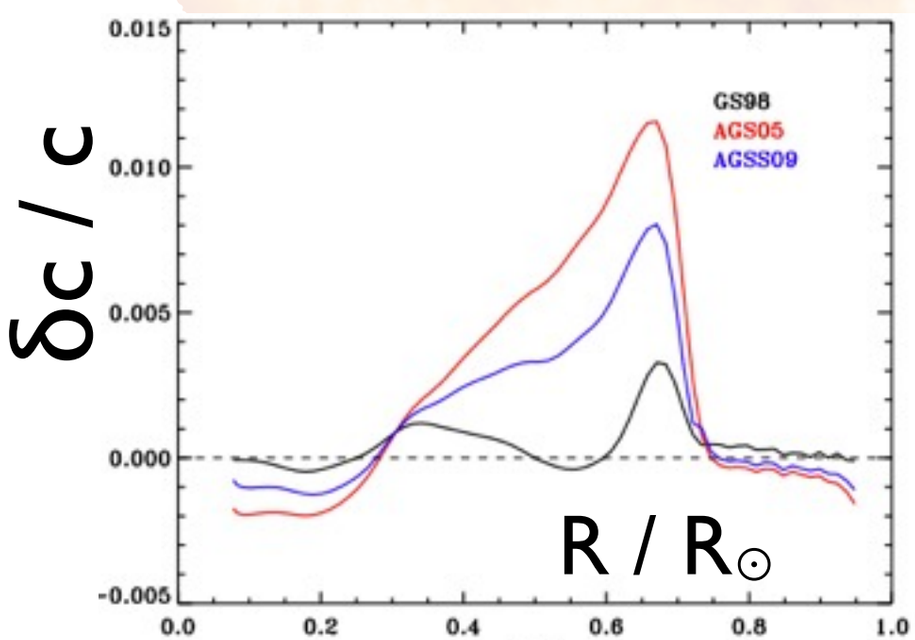

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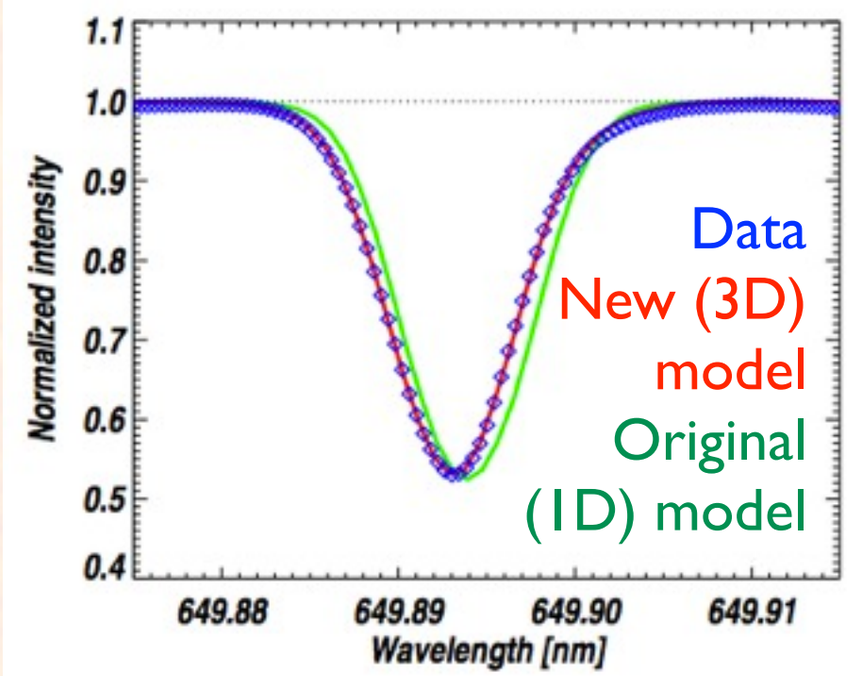

Requires measurement of CN neutrinos!

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

Physics Beyond the SNP

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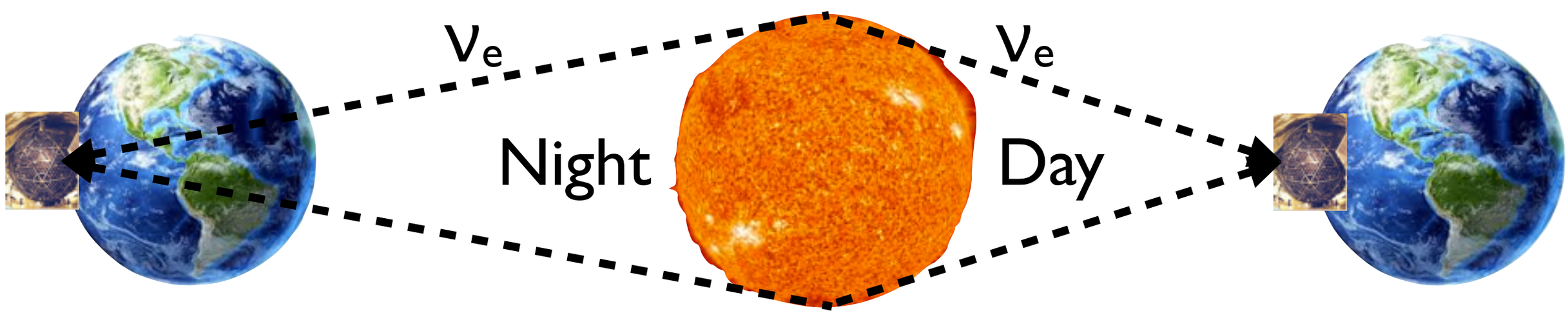
(2) Understanding stellar formation:

The metallicity of the Sun's core

(3) Confirming MSW:

The Day / Night effect



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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

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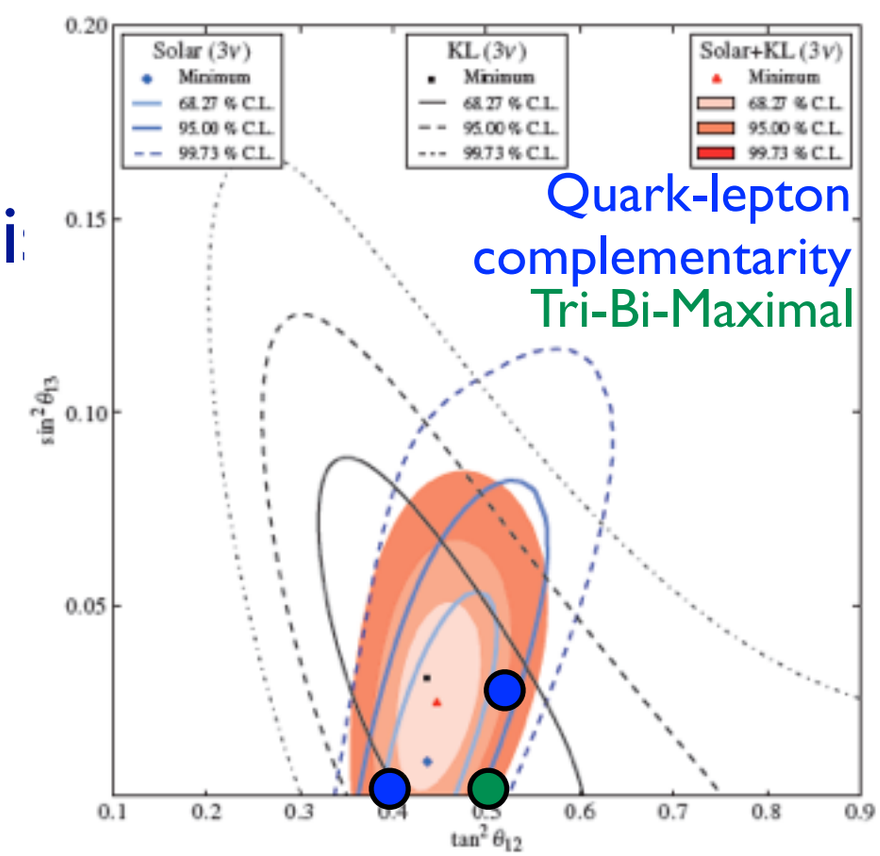
Neutrino luminosity ($\mathcal{L}_\nu$)

(5) Searching for symmetry:

Precision flux & oscillation parameter measurements

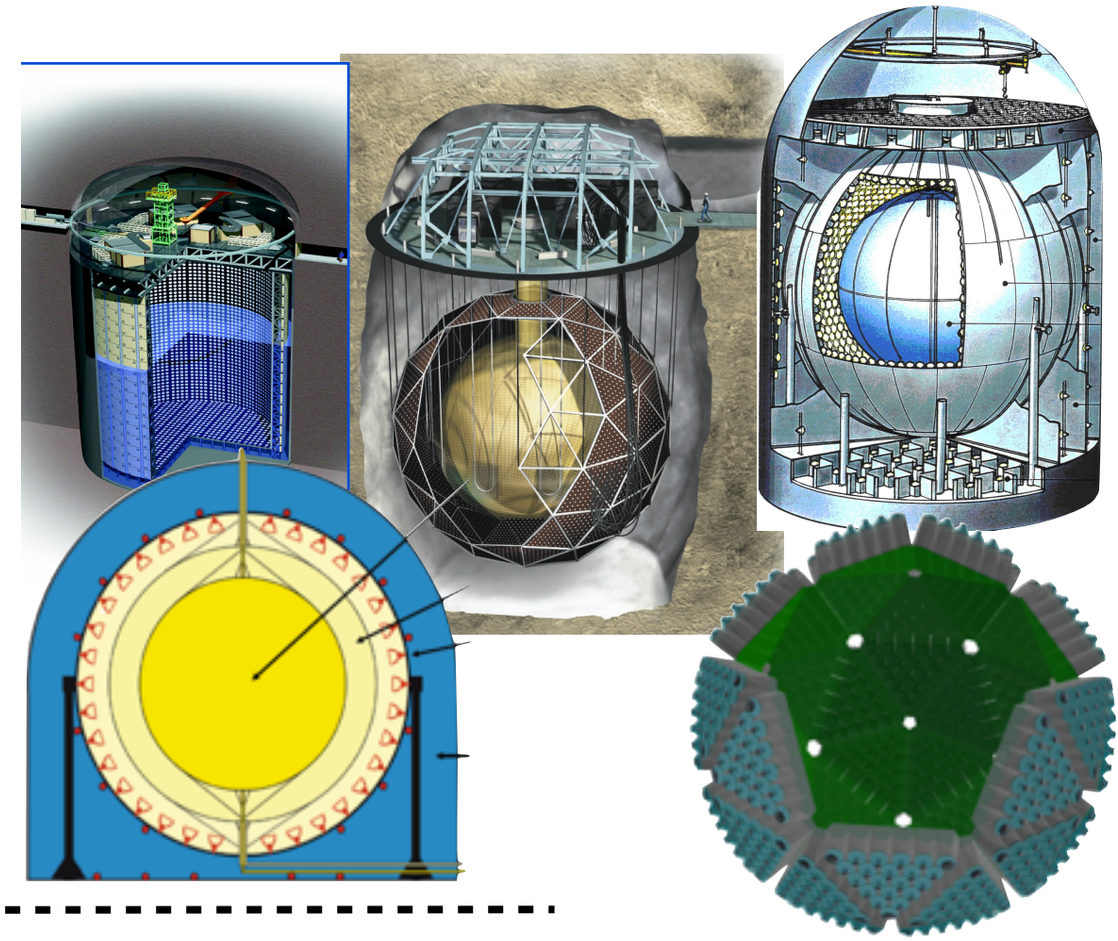


Experimental Requirements

	High statistics (big detector!)	Low threshold	Low backgrounds
ν_e P_{ee} shape	Critical	1 MeV	U, Th chains, cosmogenics
Solar metallicity	Important	0.5 MeV	cosmogenics, ^{210}Bi
Day / Night effect	Dominant	> 5MeV ok	~
Neutrino luminosity (pp)	~	0.2 MeV	^{14}C, ^{85}Kr
Flux & oscillation parameters	Important	<< 1 MeV	All

Experimental Program

- Elastic Scattering detection
  - Large-scale water Cherenkov
  - Large-scale liquid scintillator
  - Inorganic scintillator



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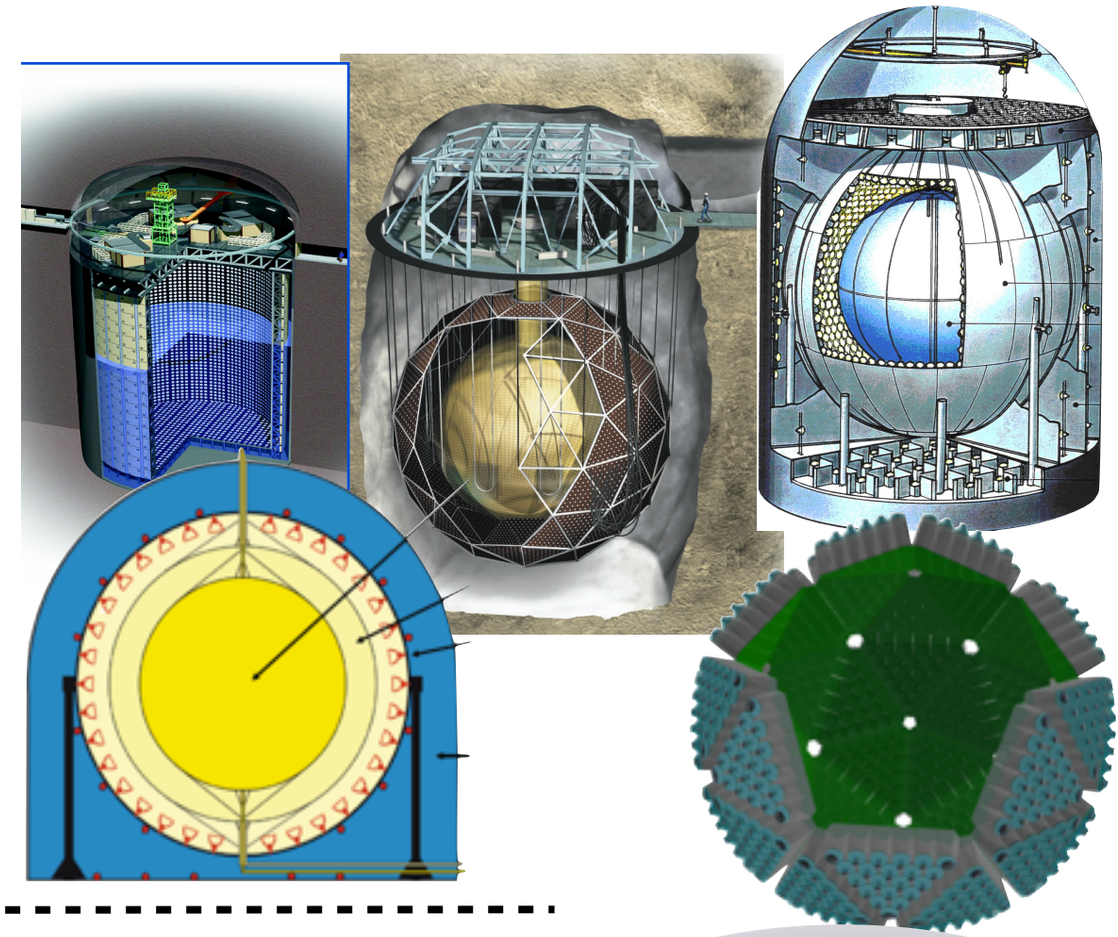
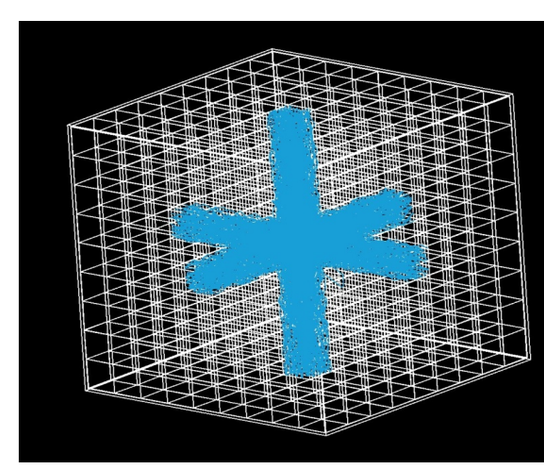
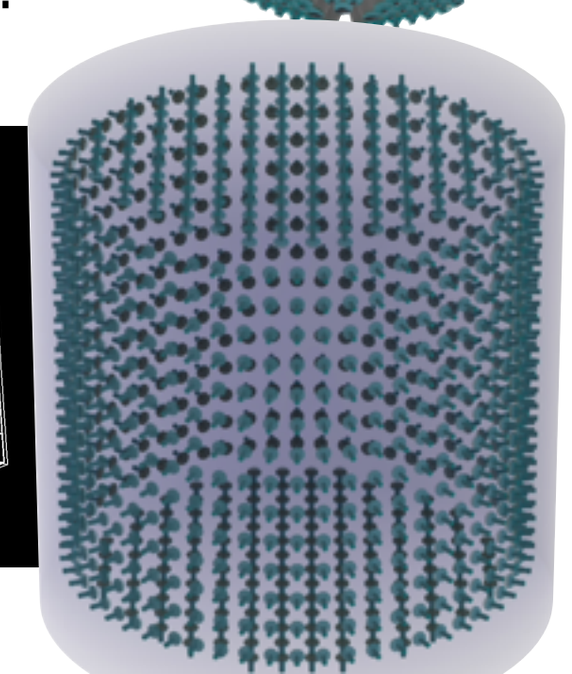


- Charged Current detection
  - Segmented detector
  - Large-scale water-based LS

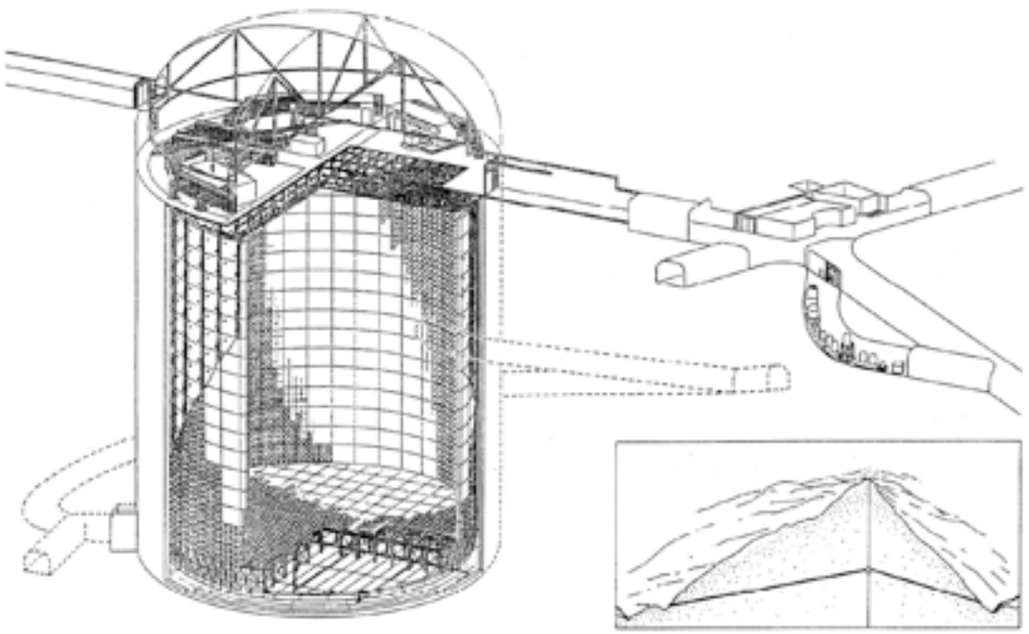




Large-Scale WCD

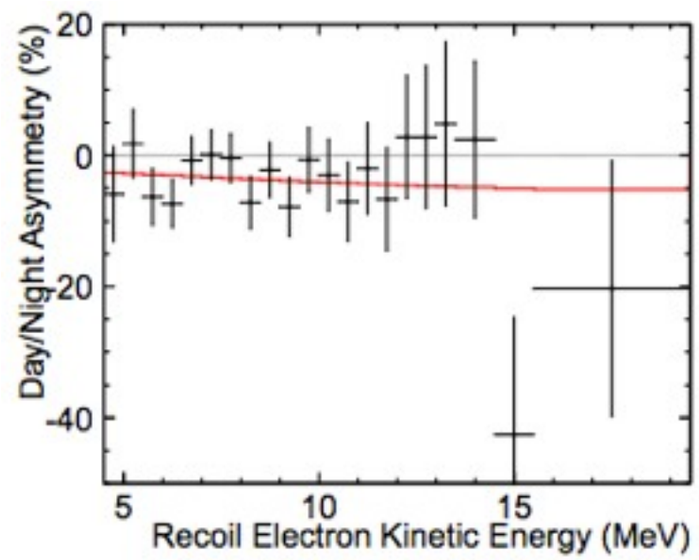
- ✔ High stats
- ☐ Low t/h
- ☐ Low bkg

Super-Kamiokande



Super-Kamiokande
Combined analysis of SK I-IV

PRL 112 (2014) 091805



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

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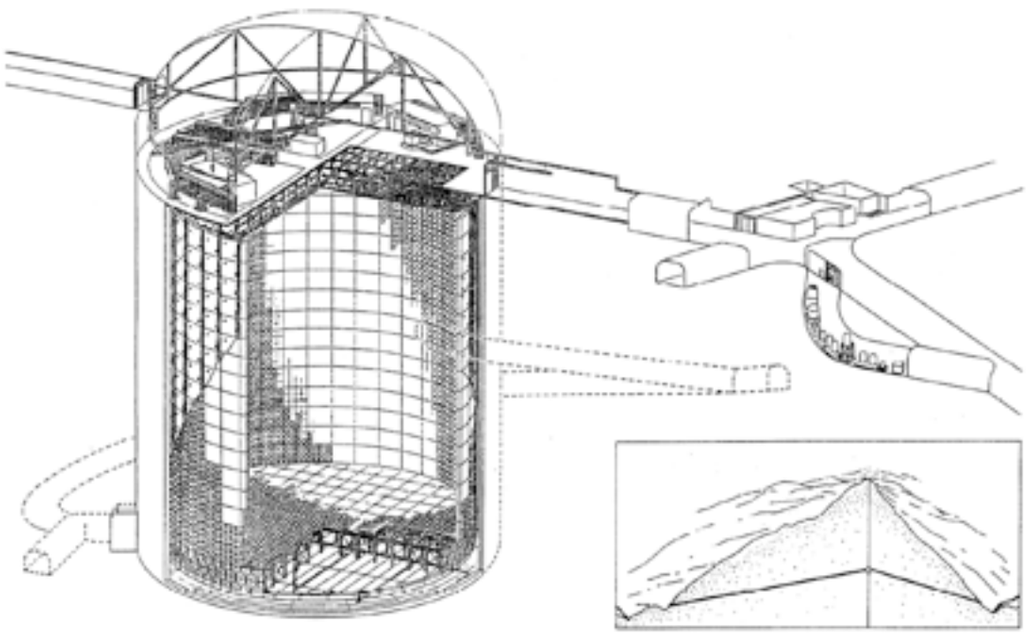

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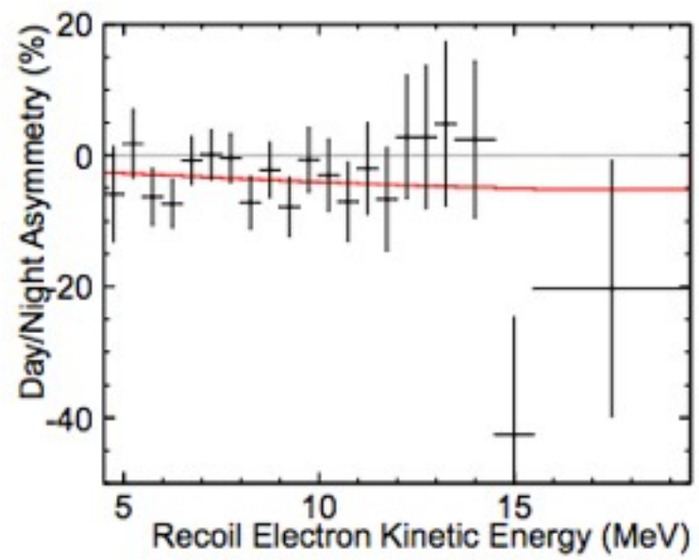

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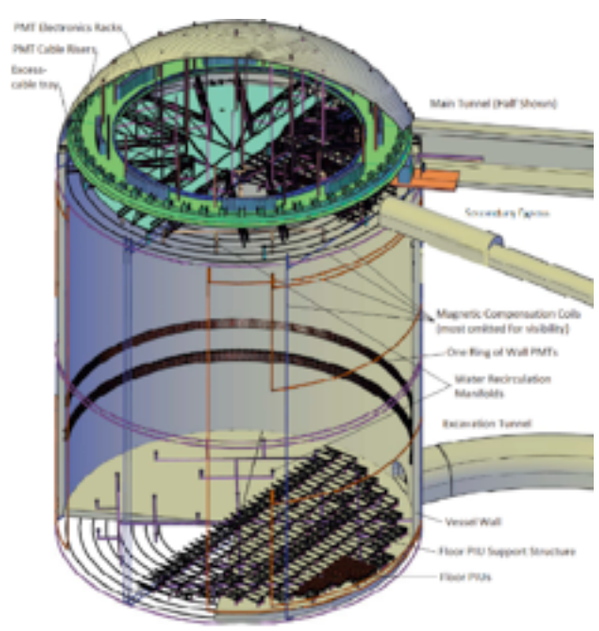
Hyper-Kamiokande



- 0.99e6 T (20* Super-K)
- 1750 mwe depth
- 115,000 8B ES / year
- 0.5% sensitivity to D-N amplitude variation
- 4σ confirmation of MSW

arXiv: 1309.0184

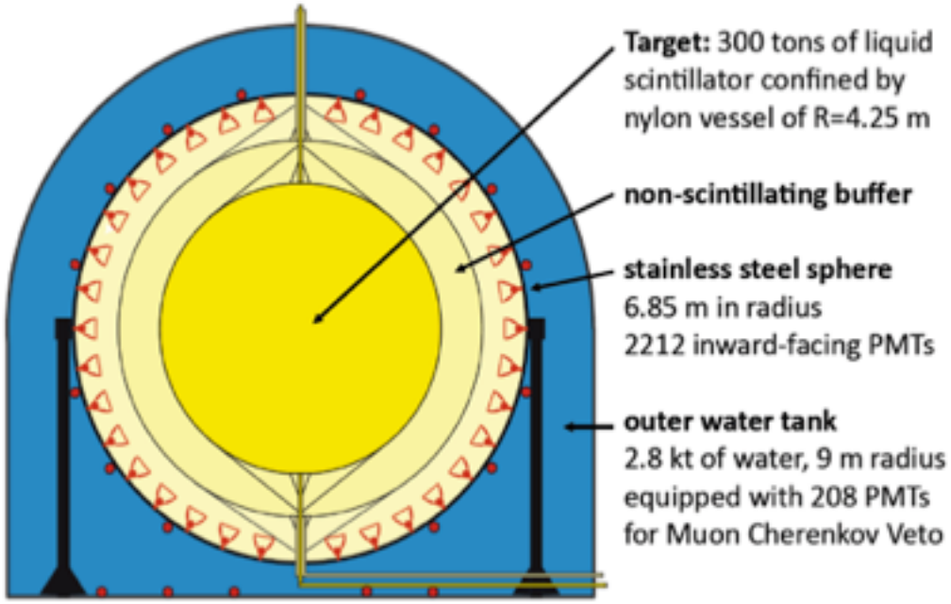
Large-Scale LS: Borexino

High stats
Low t/h
Low bkg

Unprecedented low LS background!

<0.8 counts per year /100t!

- ^{238}U < 8 x 10^{-20} g/g (^{214}Bi-^{214}Po)
- ^{232}Th <1 x 10^{-18} g/g (^{212}Bi-^{212}Po)
- ^{210}Bi = 20 ± 5 cpd/100t
- ^{85}Kr < 5 cpd/100t



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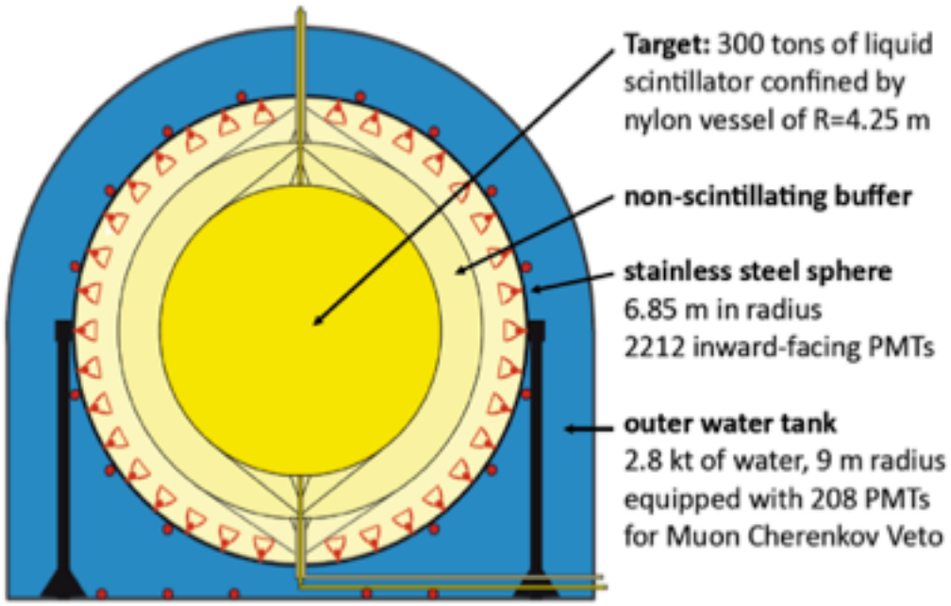

Large-Scale LS: Borexino

- ☐ High stats
- ☑ Low t/h
- ☑ Low bkg

Unprecedented low LS background!

<0.8 counts per year /100t!

- ^{238}U < 8 x 10^{-20} g/g (^{214}Bi-^{214}Po)
- ^{232}Th <1 x 10^{-18} g/g (^{212}Bi-^{212}Po)
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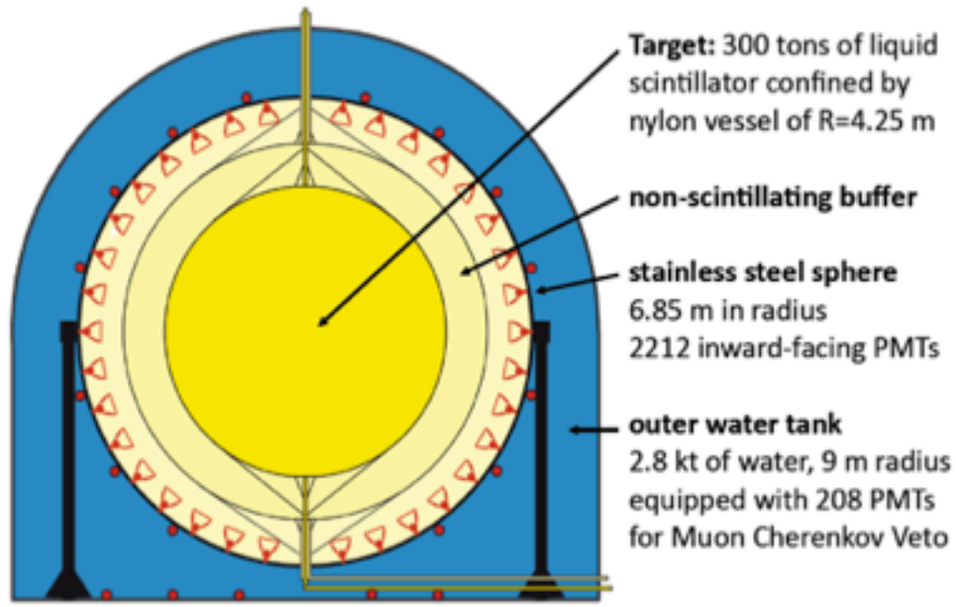

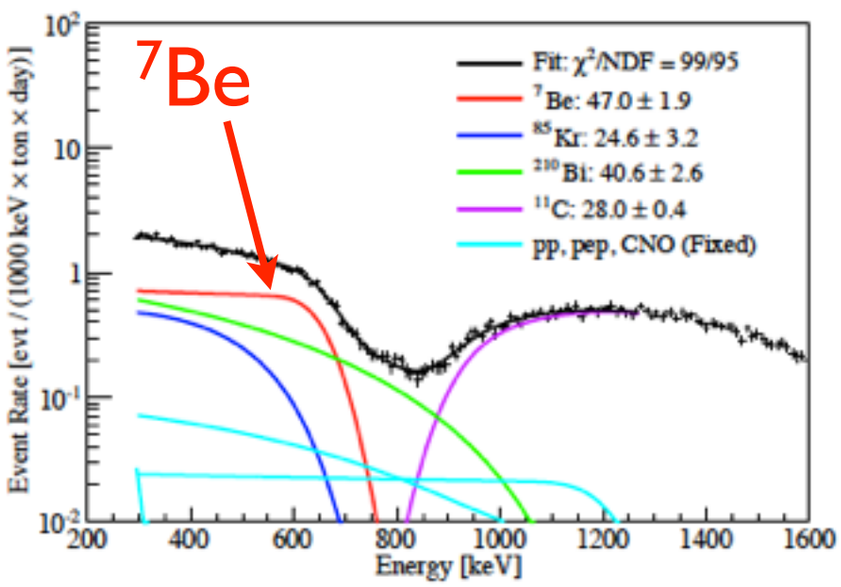

Phys. Rev. Lett. 107:141302 (2011)

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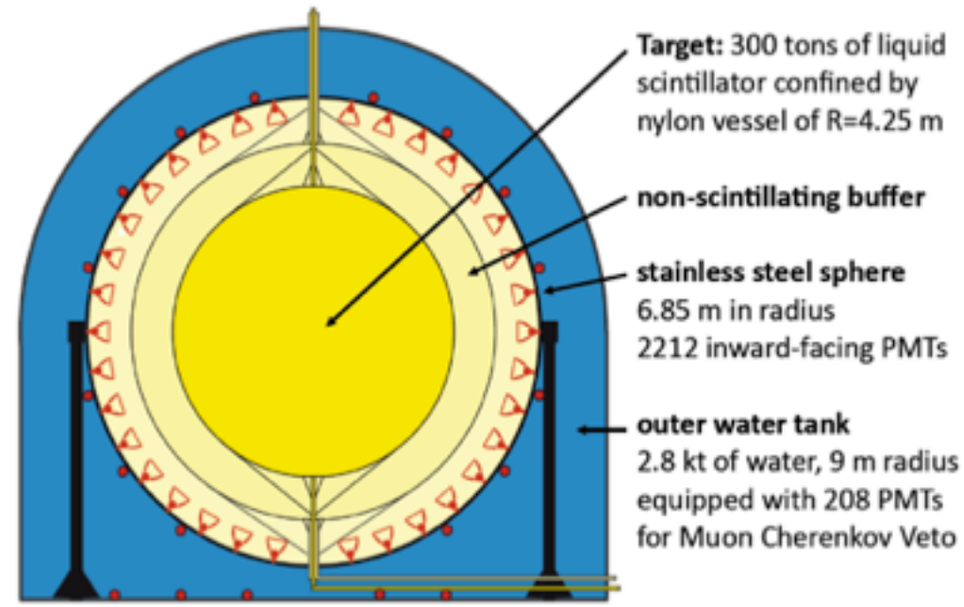

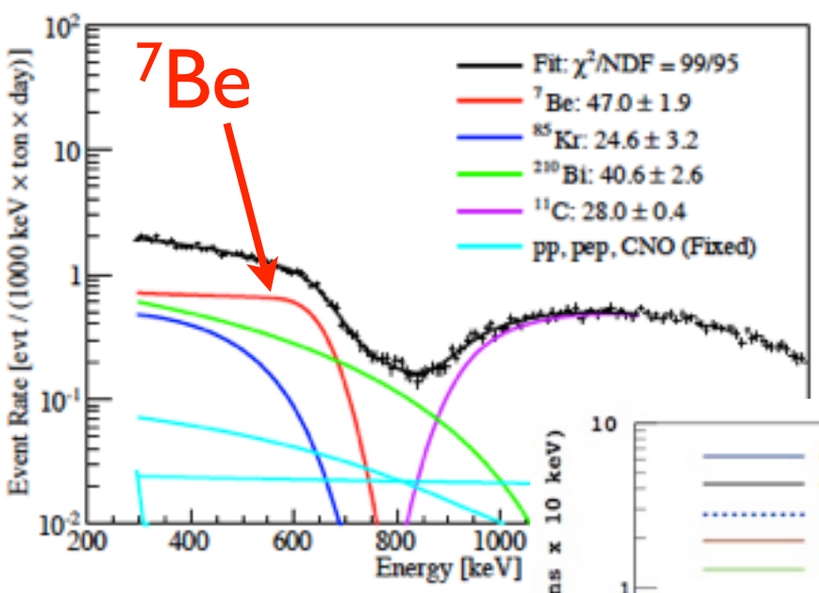

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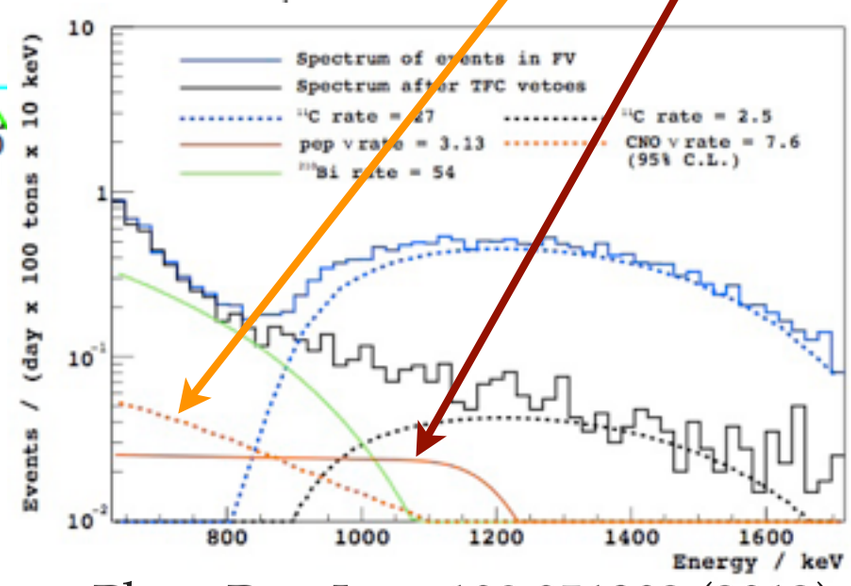

Phys. Rev. Lett. 108:051302 (2012)

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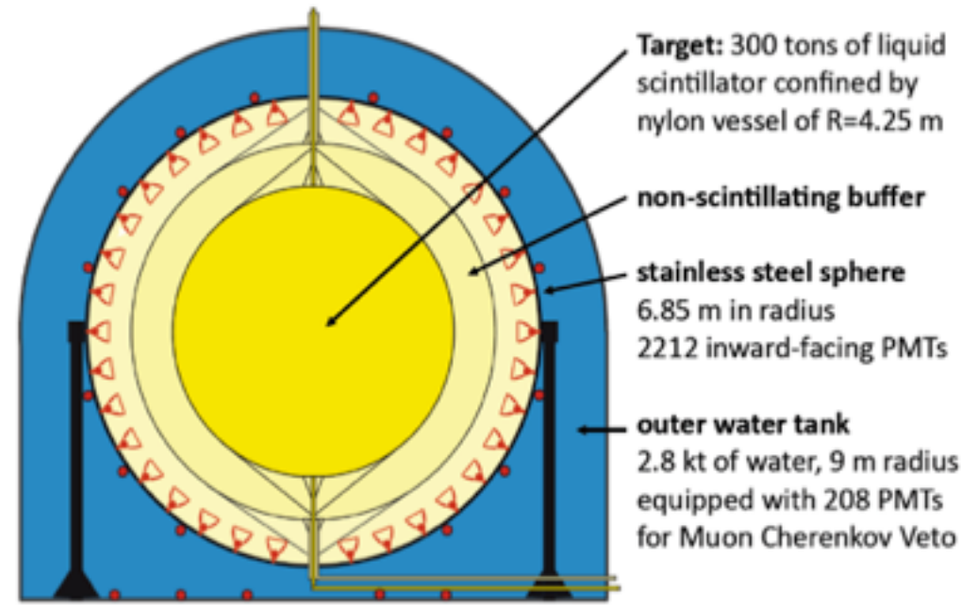
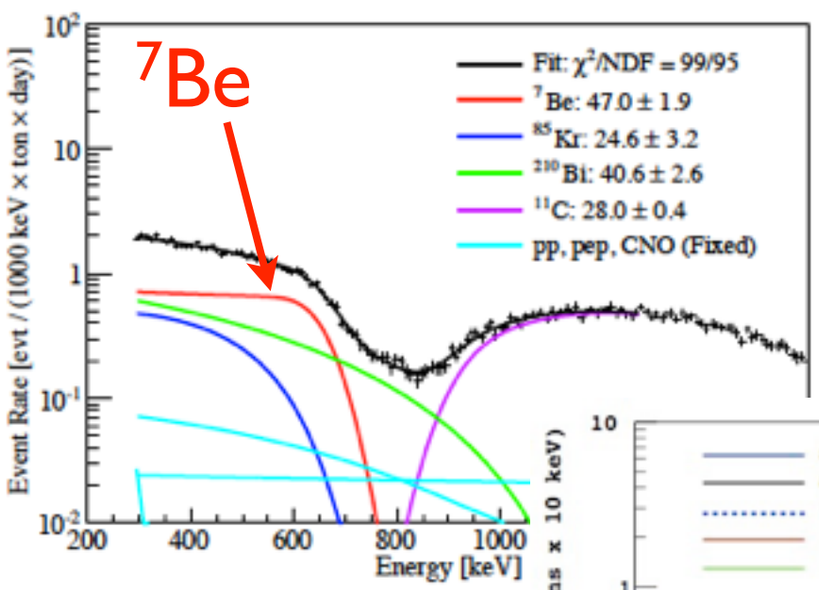
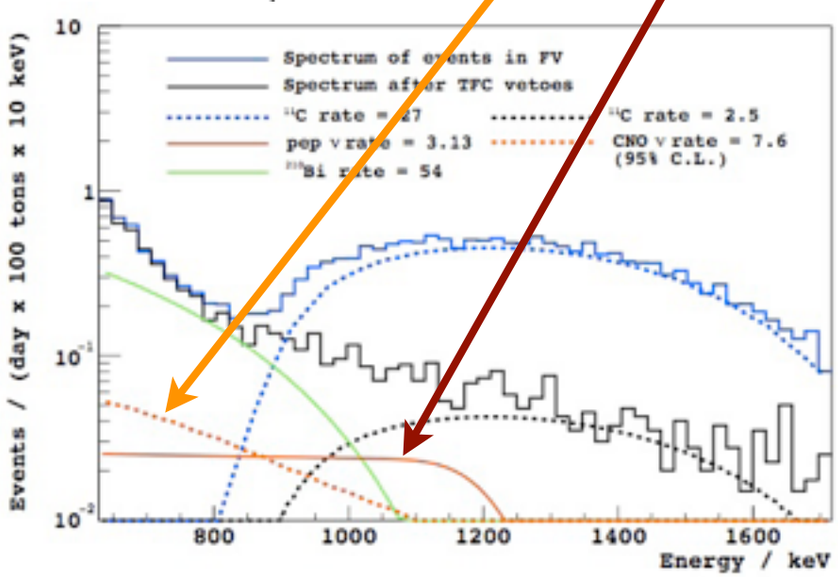




Phys. Rev. Lett. 107:141302 (2011)

CNO

pep



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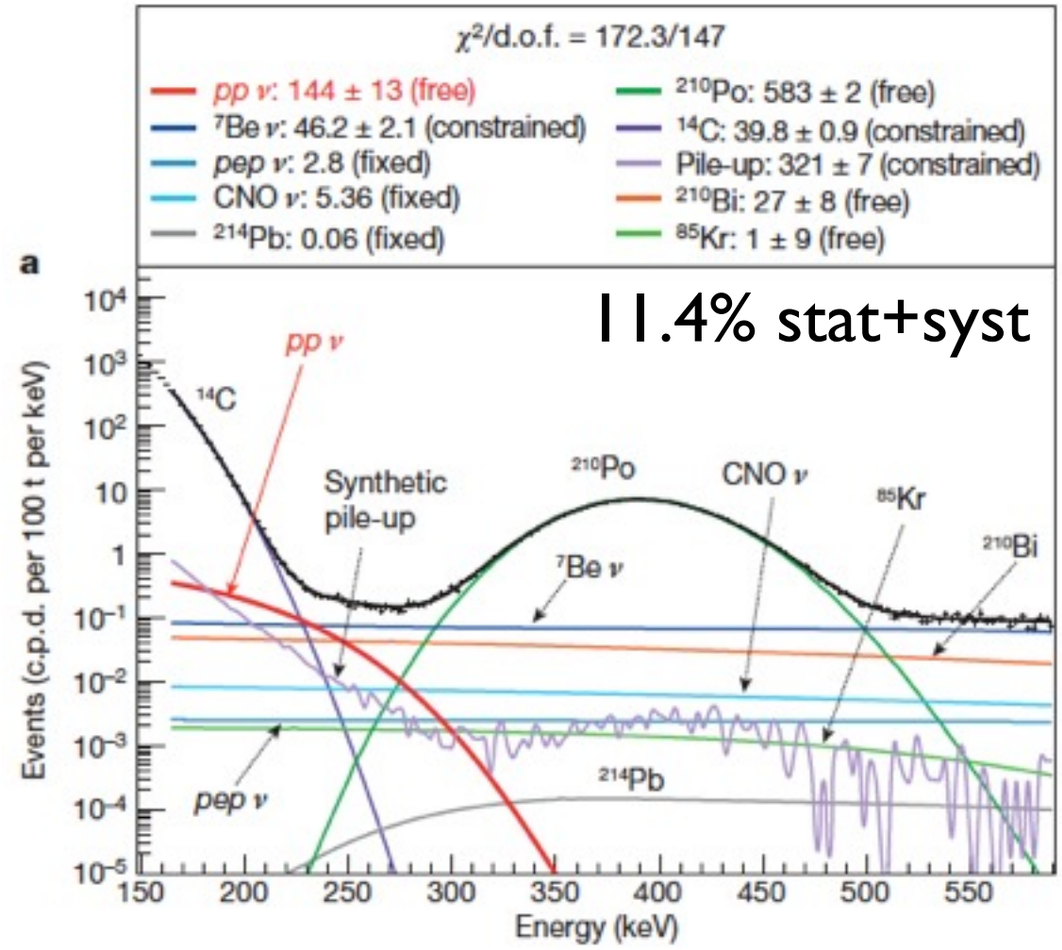

Large-Scale LS: SNO+

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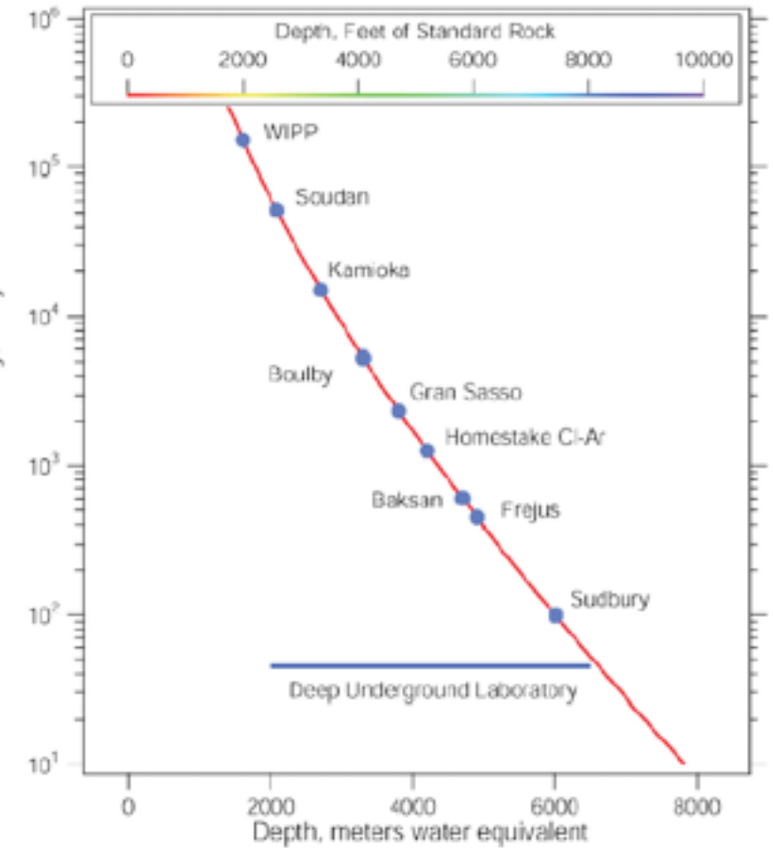

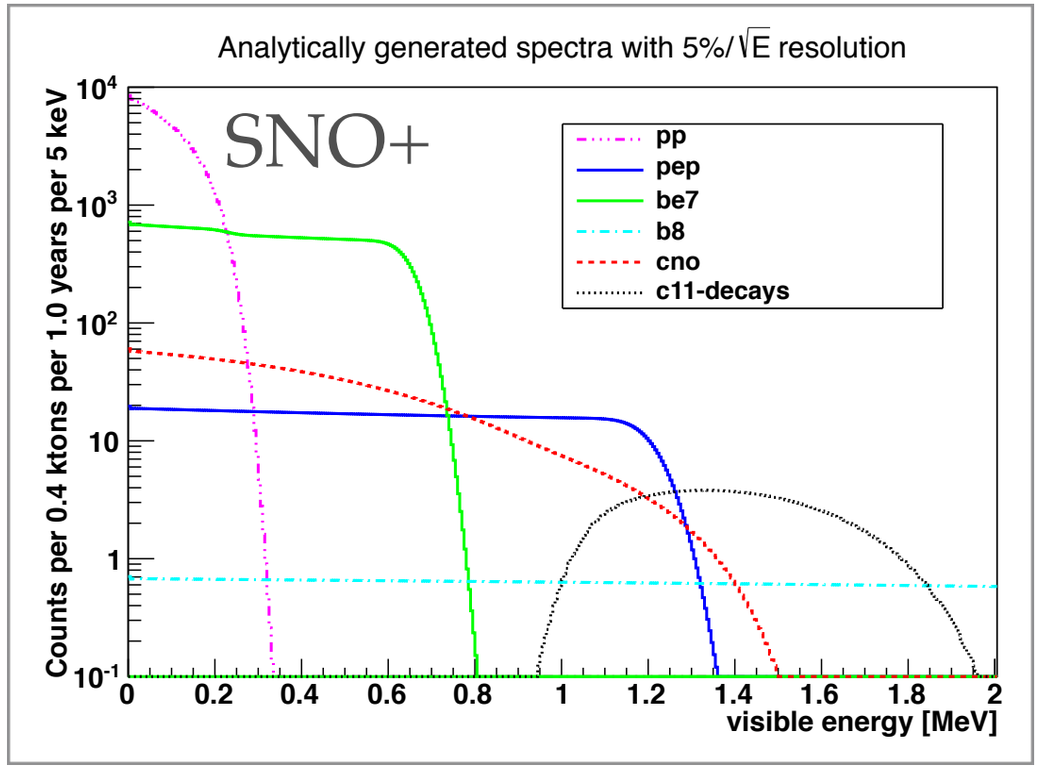

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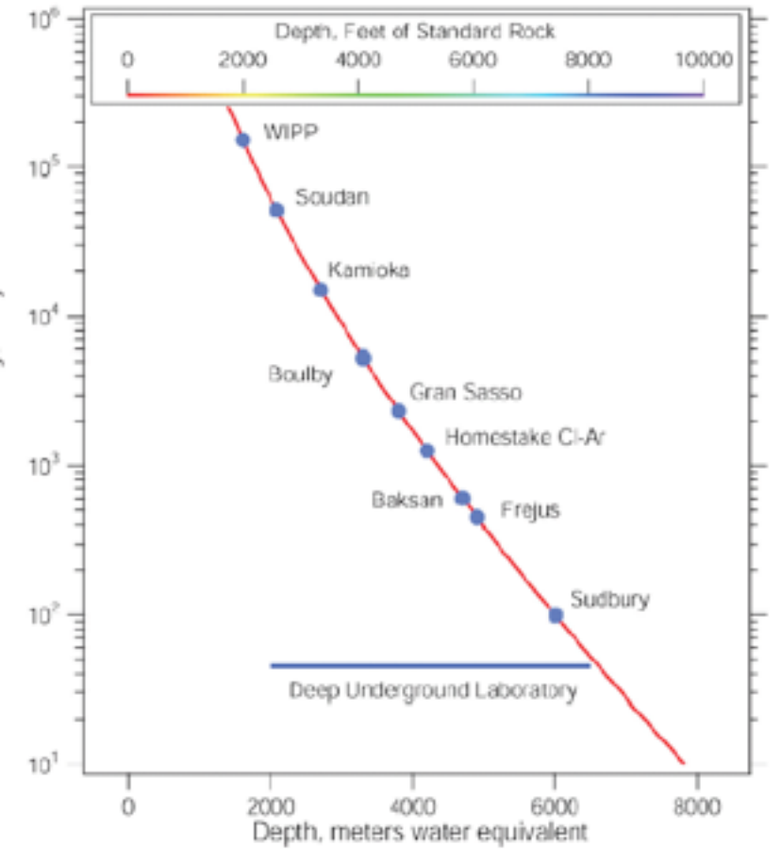

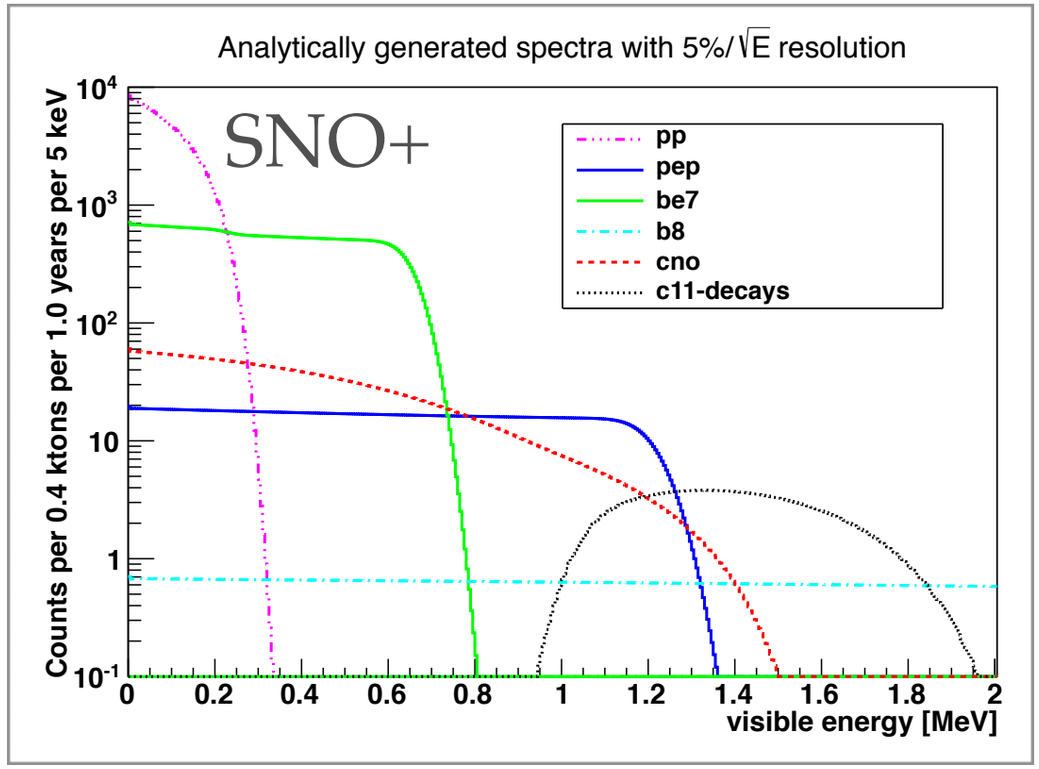

- 1 year livetime
- 50% fiducial volume (negligible external bkg)
- **Assuming Borexino-level purification levels**

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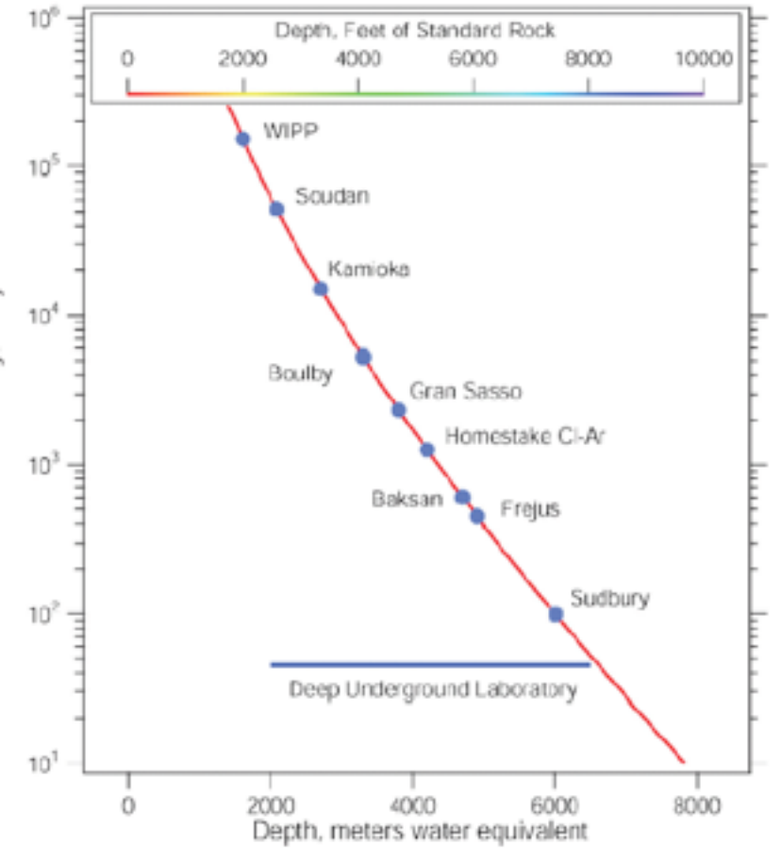

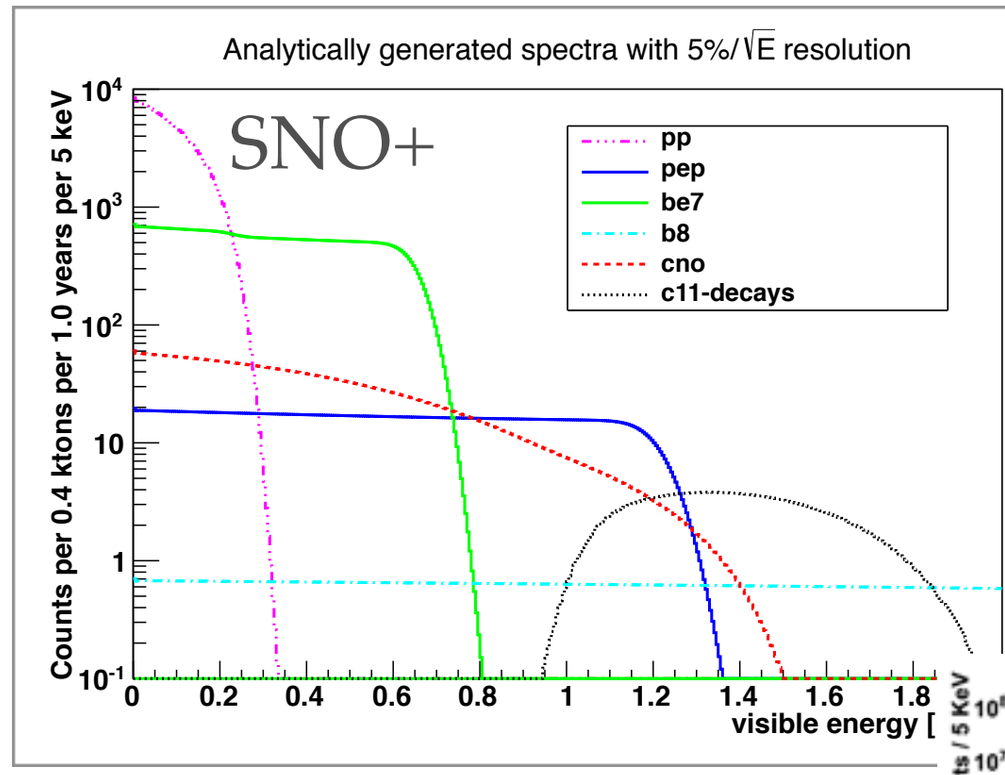

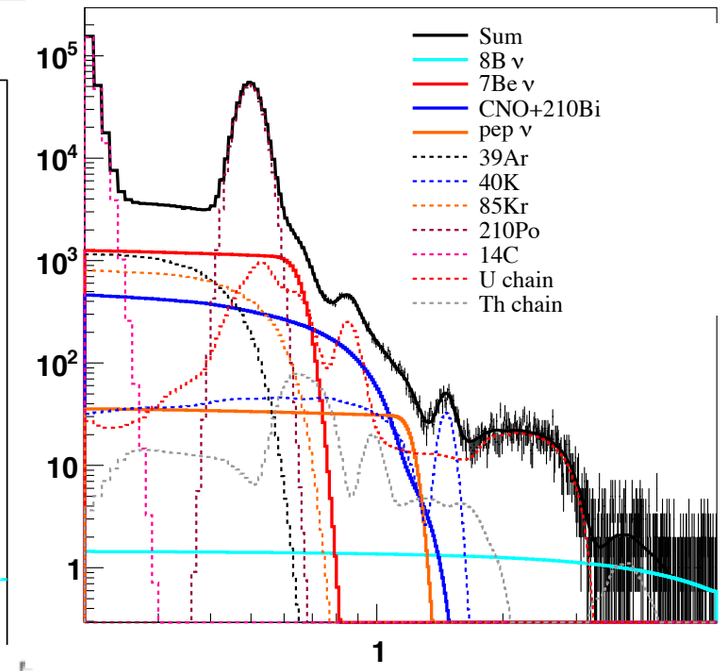

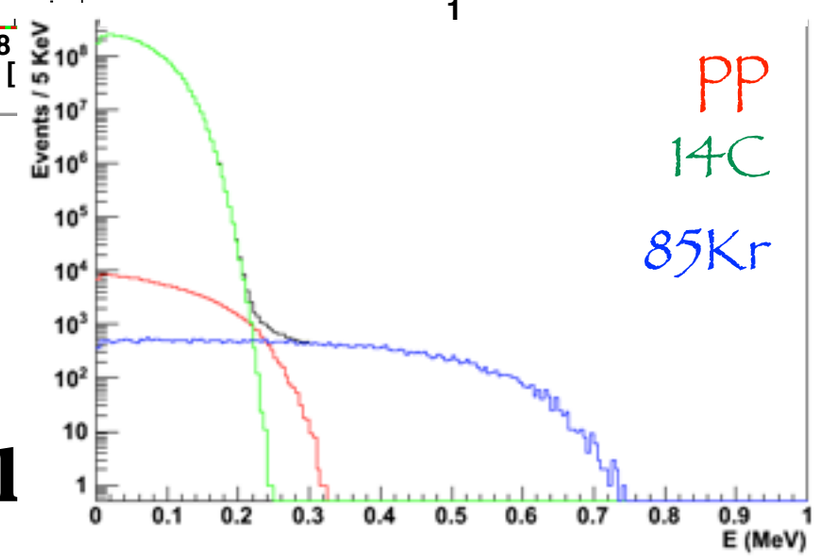

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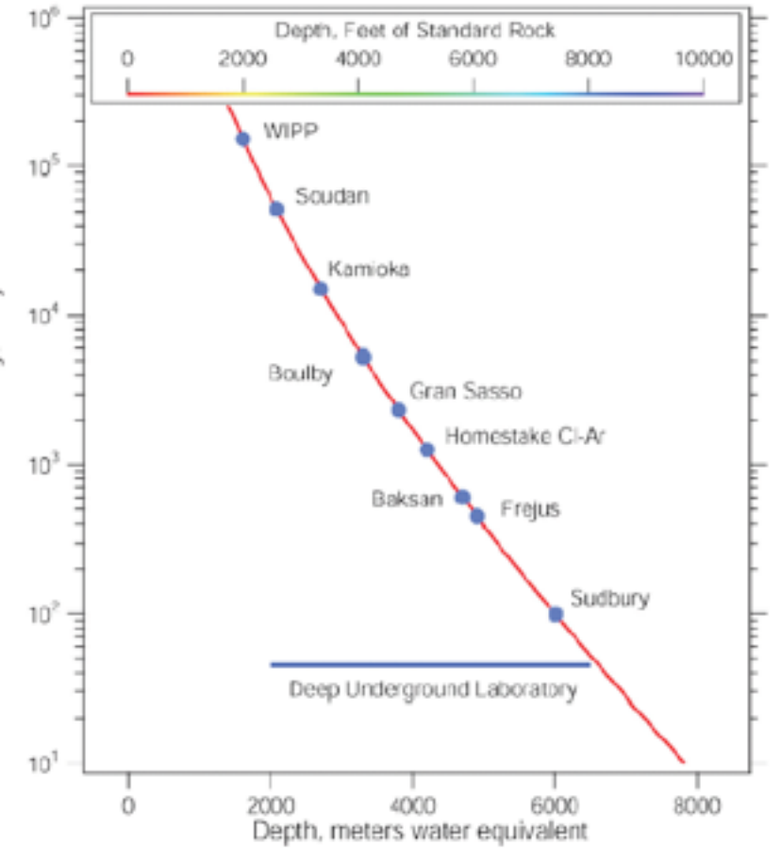

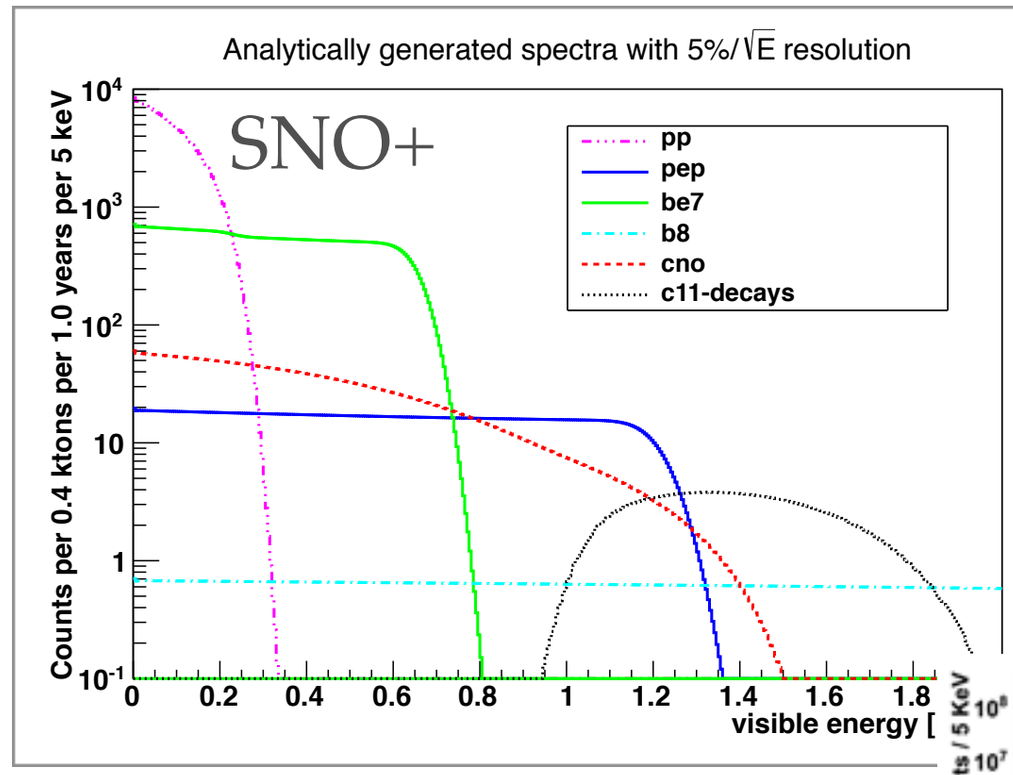

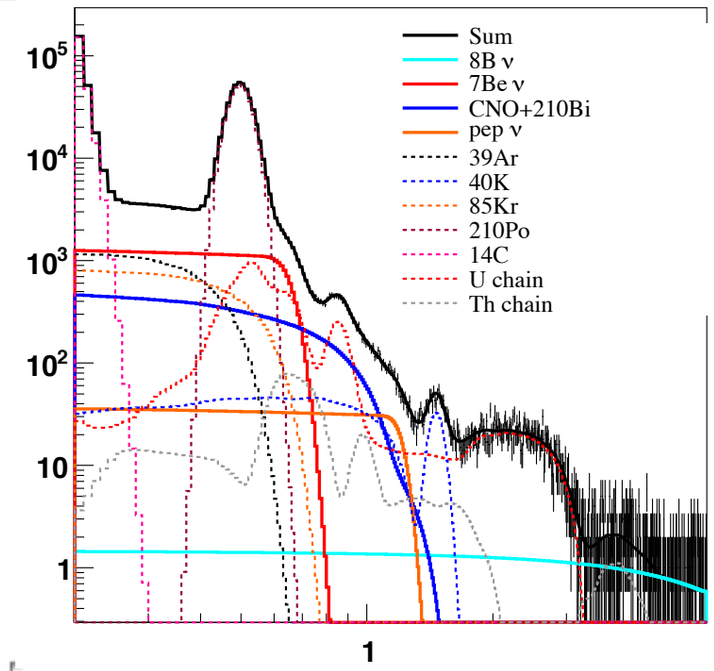

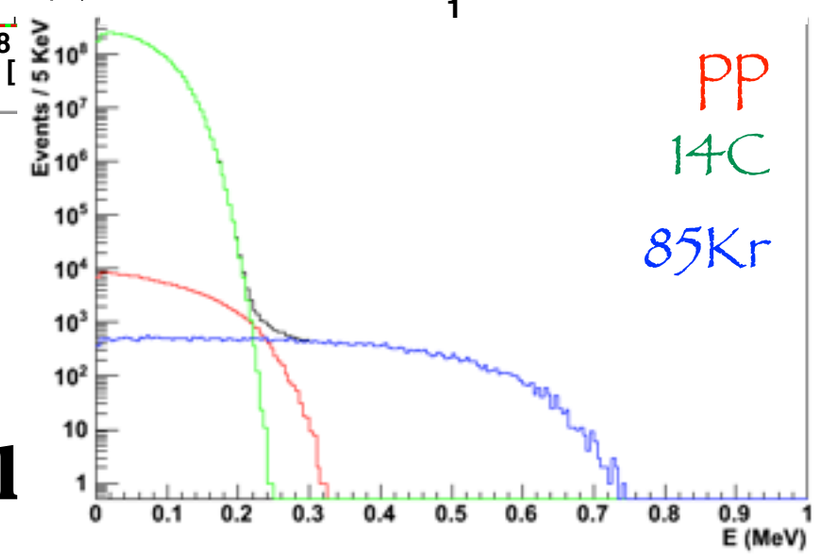

- 1 year livetime
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- **Assuming Borexino-level purification level**

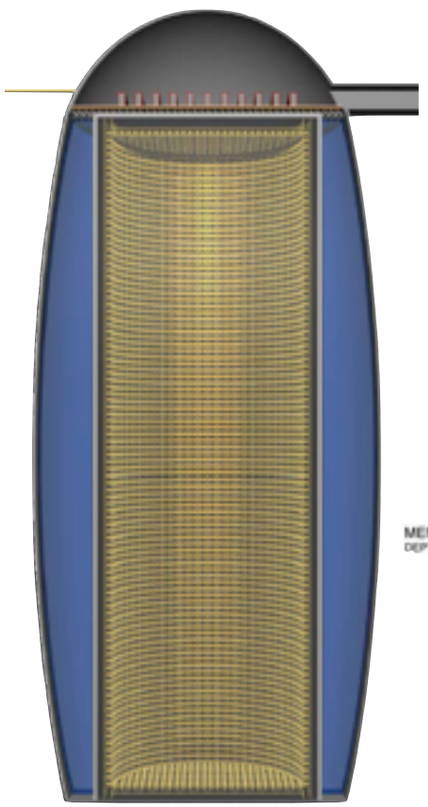
(pp dependent on ^{14}C, ^{85}Kr)
(CNO dependent on ^{210}Bi)

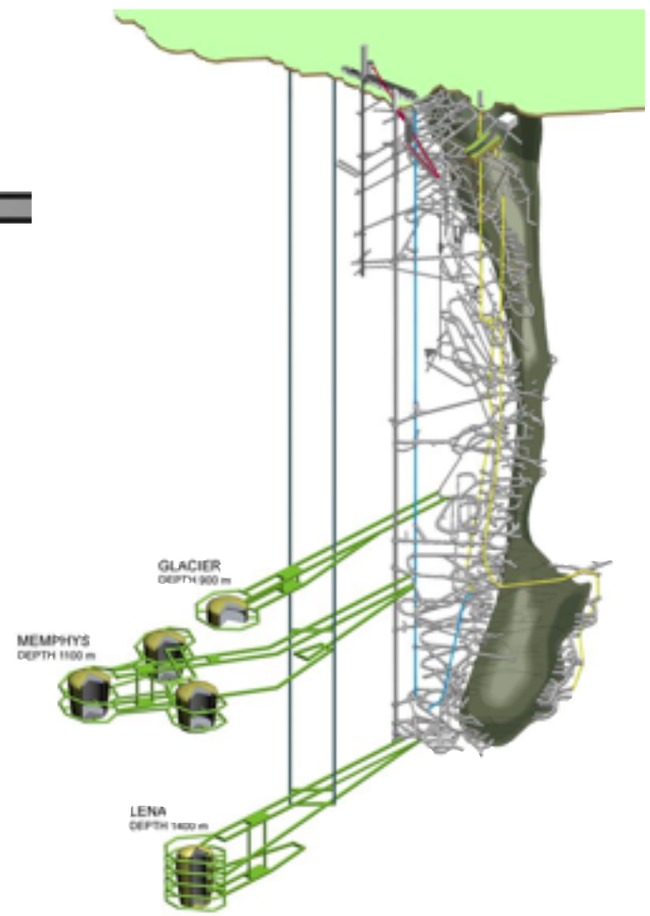
	pep	^{8}B	^{7}Be	pp	CNO
1 yr	9%	7.5%	4%	~ a few %	~ 15 %
2 yr	6.5%	5.4%	2.8%		

High stats
Low t/h
Low bkg

Large-Scale LS

LENA





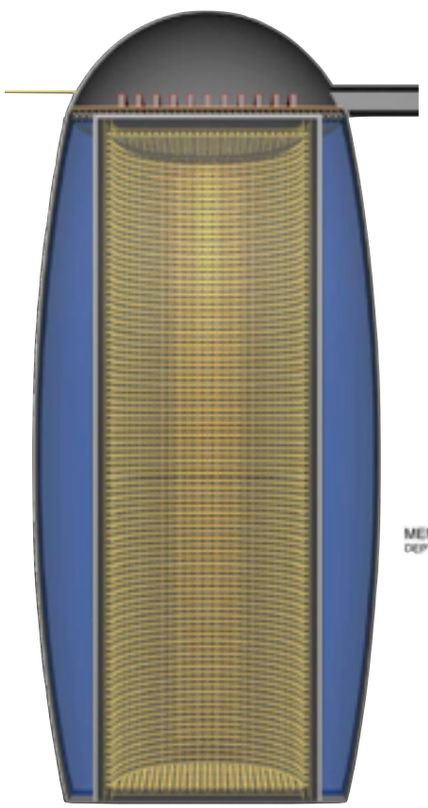
- 50kT LS (30kT FV solar), 30% coverage
- Unprecedented statistics at low energy
  - 3σ discovery potential for 0.1%-amplitude temporal modulations in ^{7}Be flux
  - CNO detection
  - Low-energy ^{8}B spectrum (+ CC on ^{13}C)

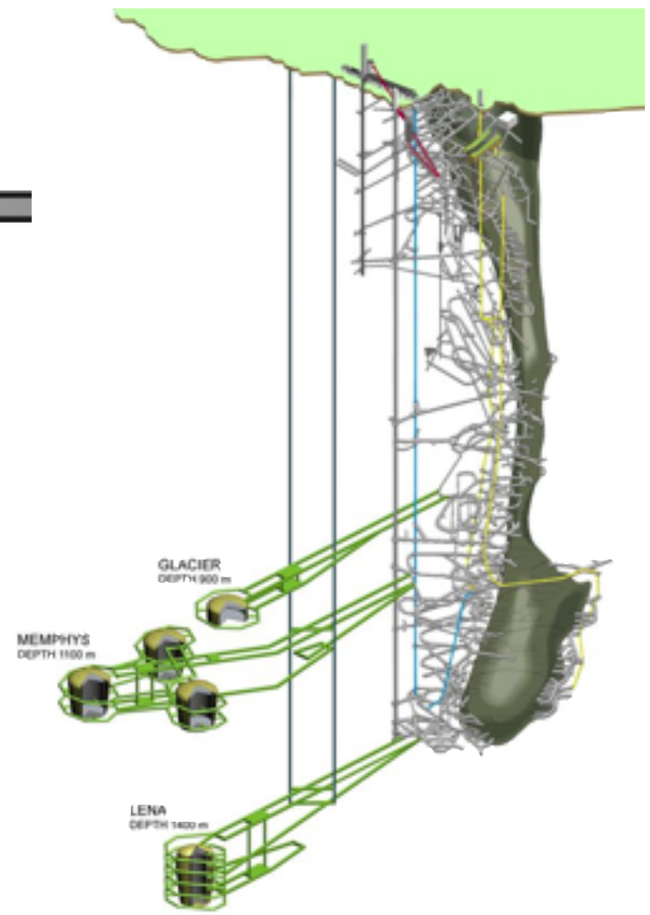
High stats
Low t/h
Low bkg

Large-Scale LS

High stats
Low t/h
Low bkg

LENA





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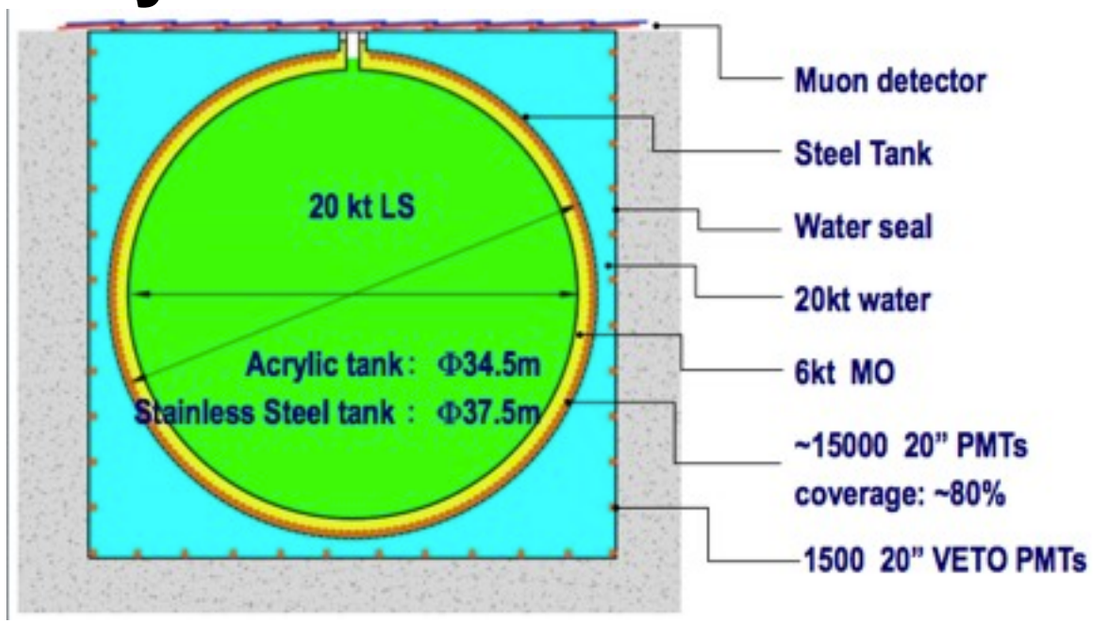
JUNO



- 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%

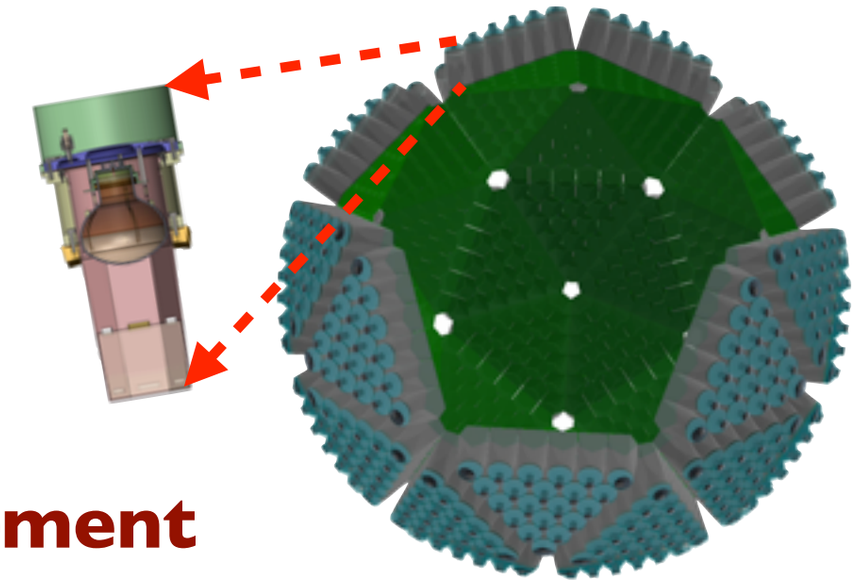
Inorganic LS

- ☐ High stats
- ☑ Low t/h
- ☑ Low bkg

LNe (CLEAN):

50-T scale

Background-free fiducial volume



⇛ **%-level (ES) pp measurement**

Inorganic LS

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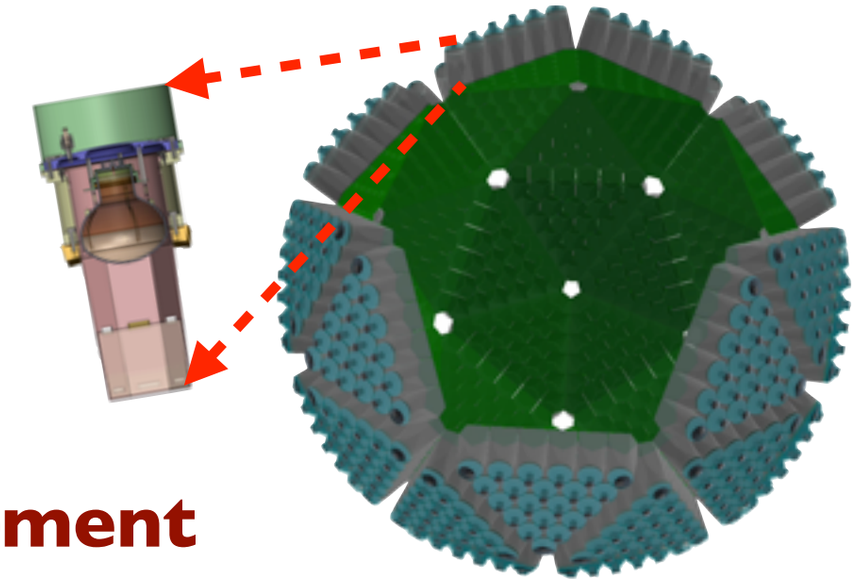
LNe (CLEAN):

50-T scale
Background-free
fiducial volume



⇛ **%-level (ES) pp measurement**

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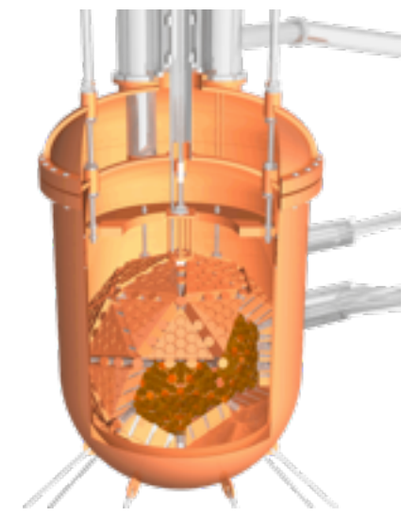
Liquid xenon (XMASS, LZ):

T-scale experiments
Requires *100
depletion of ^{136}Xe



Inorganic LS

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Low t/h
Low bkg

LNe (CLEAN):

50-T scale
Background-free
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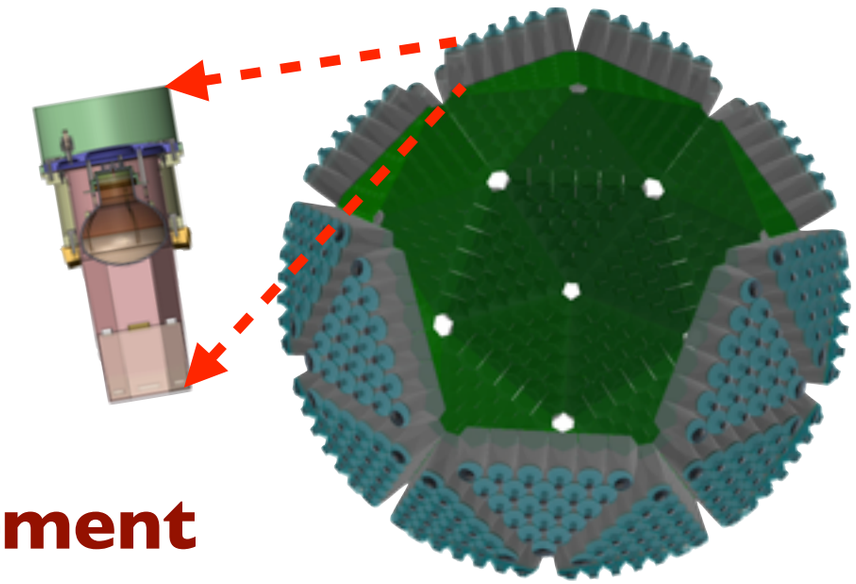


High stats
Low t/h
Low bkg

⇛ **%-level (ES) pp measurement**

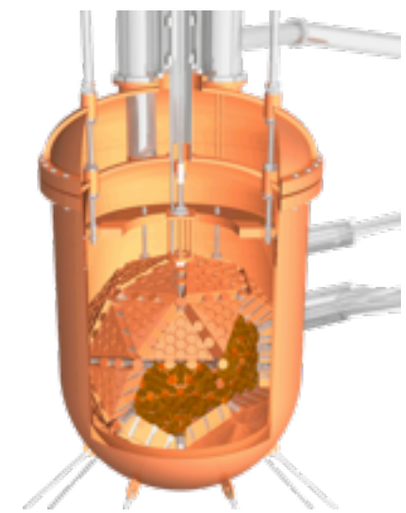
LBNF

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

High stats
Low t/h
Low bkg

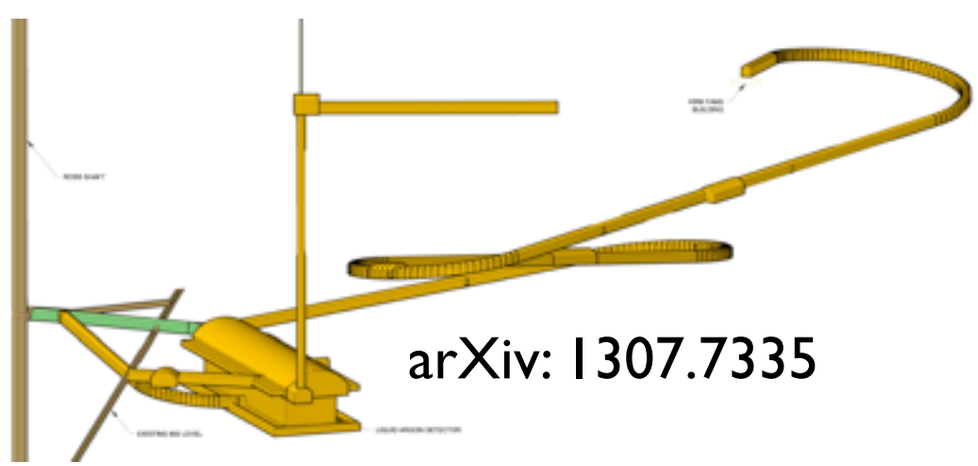
Liquid xenon (XMASS, LZ):

T-scale experiments
Requires *100
depletion of ^{136}Xe



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

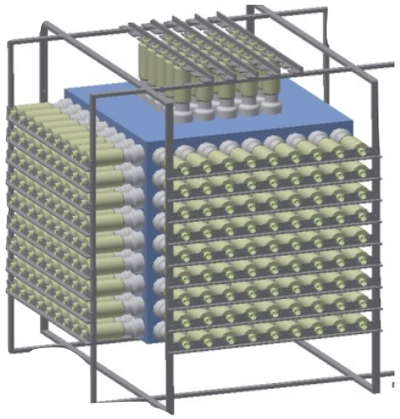
Transition	Rate (evts/day)
Fermi	31
Gamow-Teller	88



arXiv: 1307.7335

- [ ] High stats
- [x] Low t/h
- [x] Low bkg

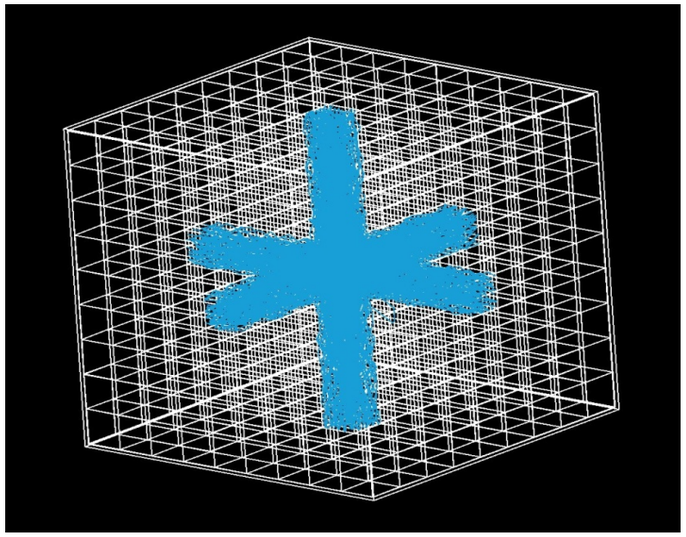
CC Detection: LENS

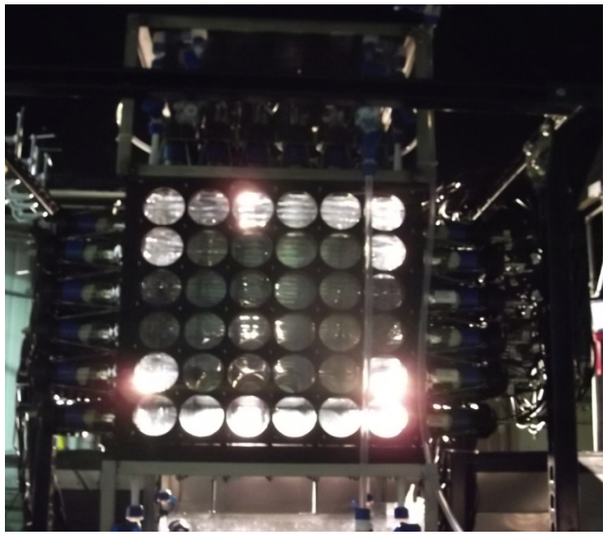


$$\nu_e + {}^{115}In \longrightarrow {}^{115}Sn^* + \beta^-$$

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

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





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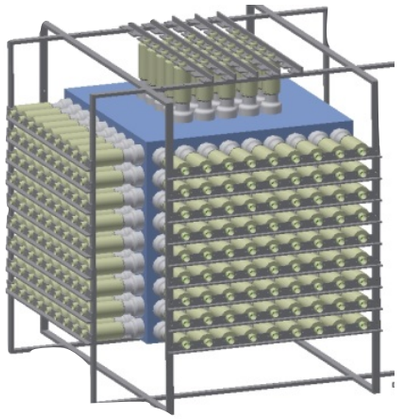
CC Detection: LENS



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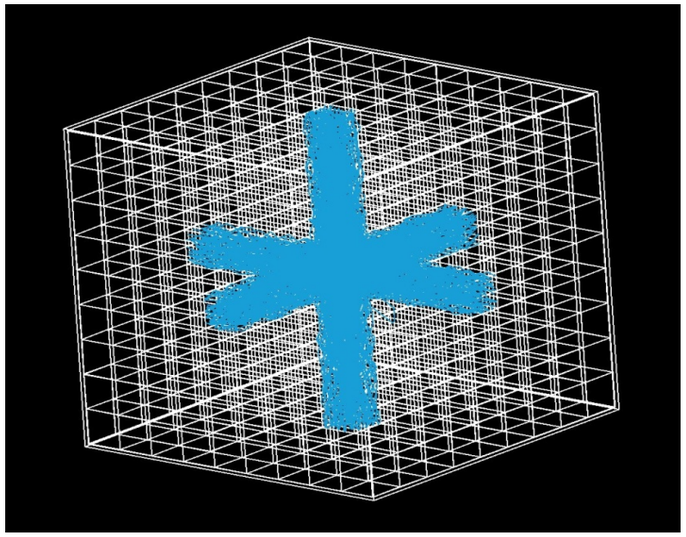

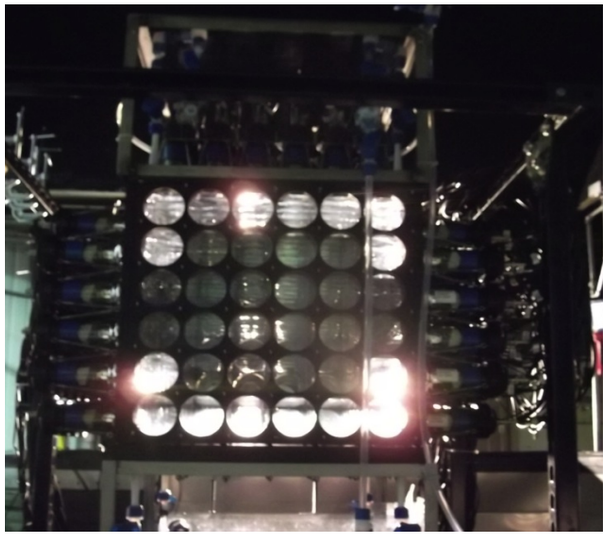

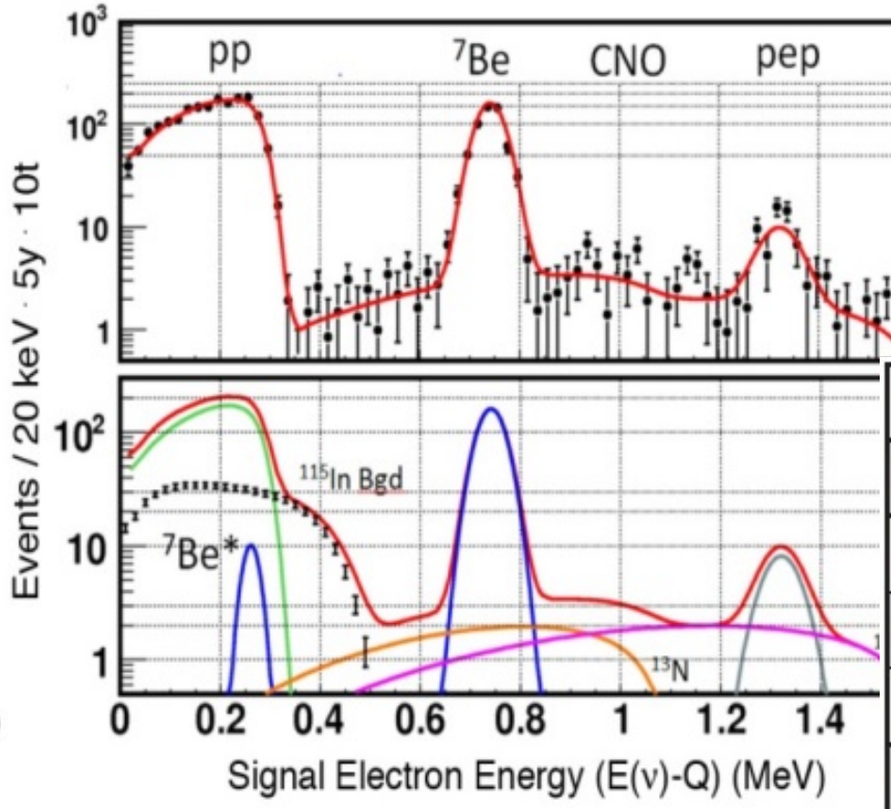

Source	pp	7Be	CNO* (GS98)	CNO† (AGSS09)
Flux (/cm2/s)	6.00E+10	4.70E+09	4.97E+08	3.74E+08
Flux (SNU) [Bah88]	468	116	15	11
Cross section[Rap85]	1.00E-44	2.50E-44	2.50E-44	2.50E-44
Survival probability	56	54	54	54
Rate (per ton year)	26	6.2	1.2	0.9
Rate (10 tons · 5 yr)	**1296**	**310**	**58**	**43**

High stats
Low t/h
Low bkg

The ASDC

- ASDC: Advanced Scintillation Detector Concept (see ASDC talk, Monday, J. R. Klein)
- Water Cherenkov ⇒ water-based LS

  Nucl. Inst. & Meth. A660 51 (2011)
  http://underground.physics.berkeley.edu/WbLSWorkshop.html
- 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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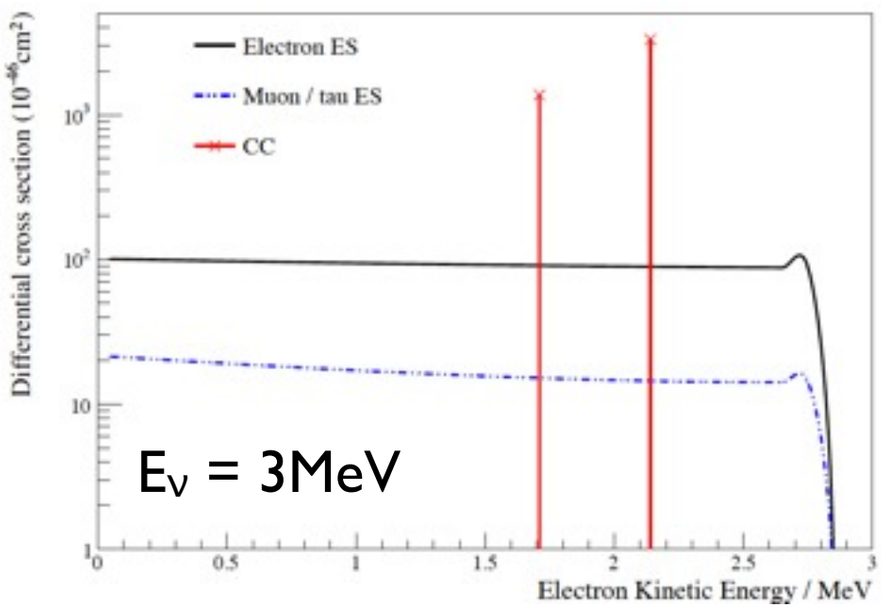

Cross section from W. C. Haxton

High stats
Low t/h
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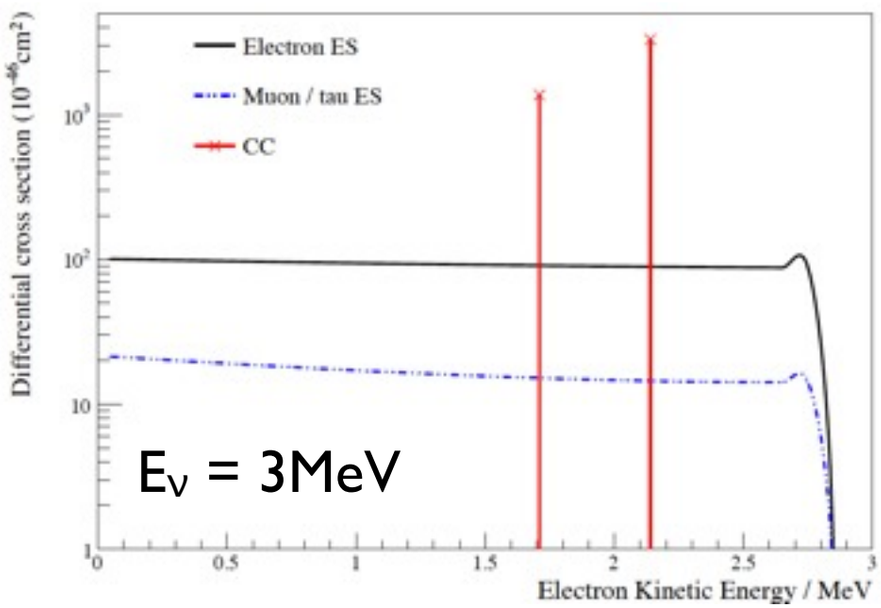

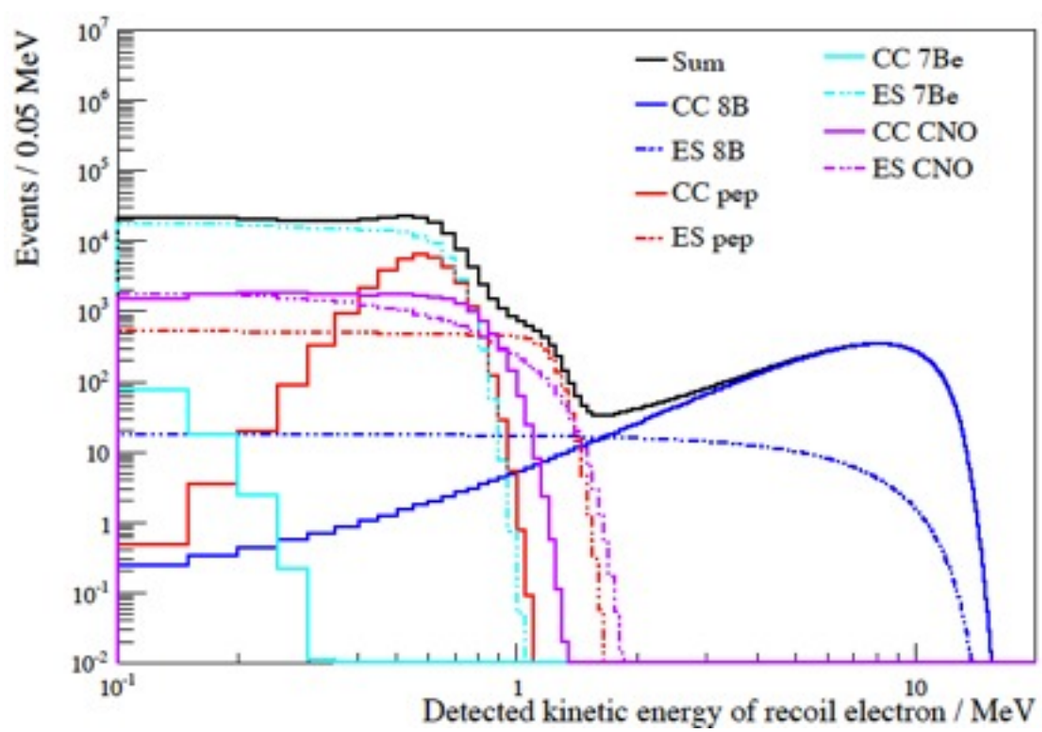

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High stats
Low t/h
Low bkg

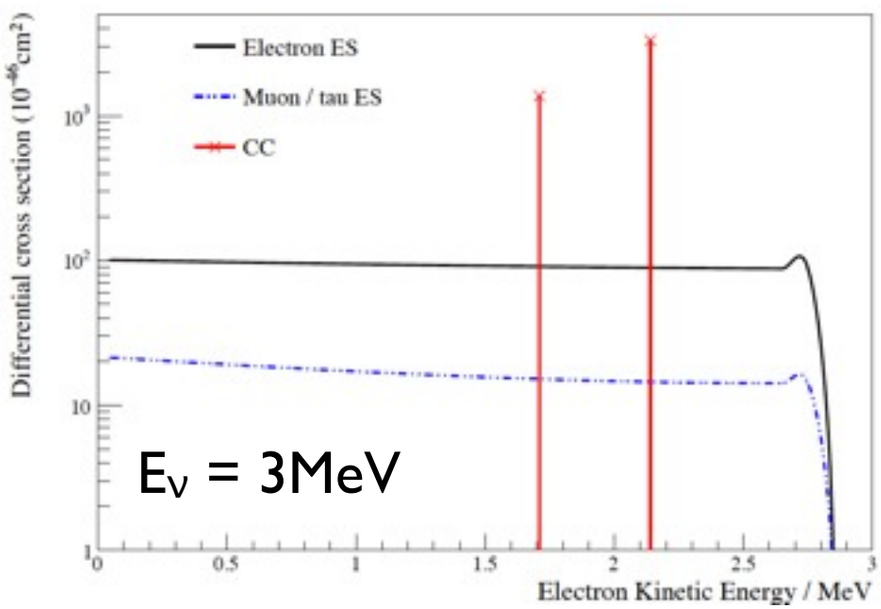
The ASDC

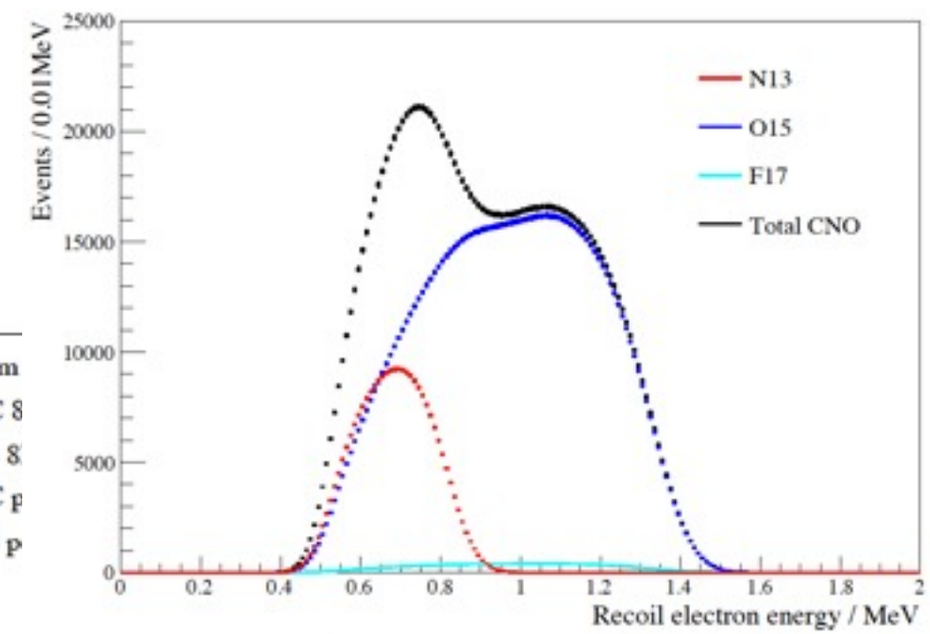
- ASDC: Advanced Scintillation Detector Concept (see ASDC talk, Monday, J. R. Klein)
- Water Cherenkov ⇒ water-based LS

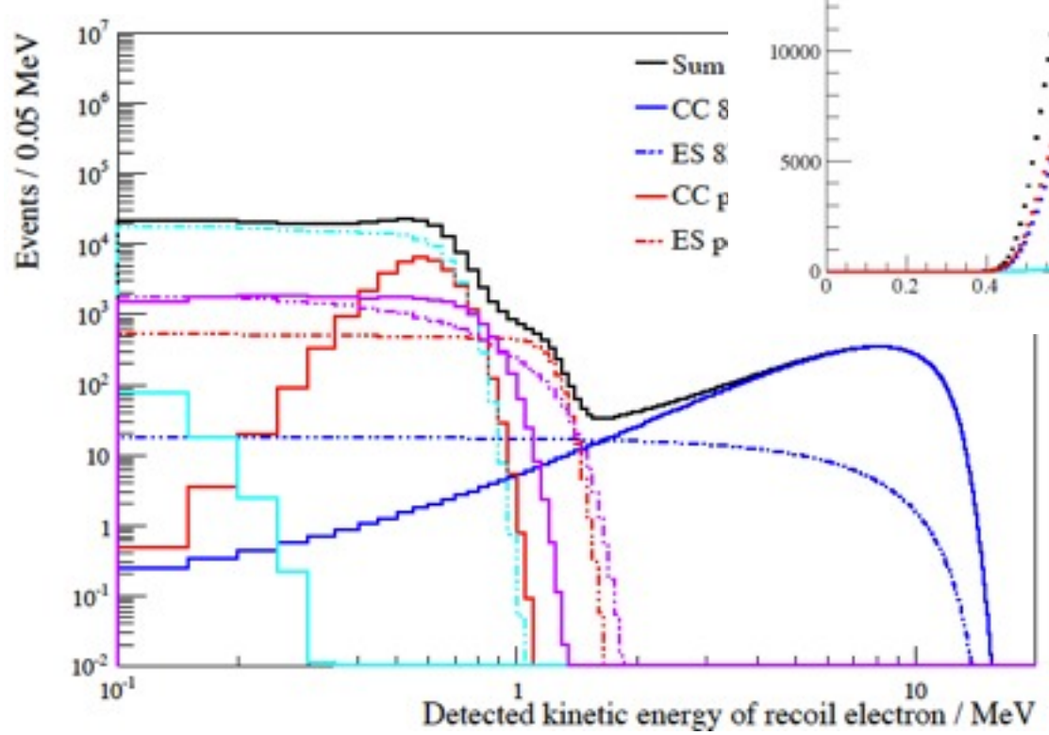
Nucl. Inst. & Meth. A660 51 (2011)
http://underground.physics.berkeley.edu/WbLSWorkshop.html

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

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







Cross section from W. C. Haxton

Critical Inputs to the Solar Program

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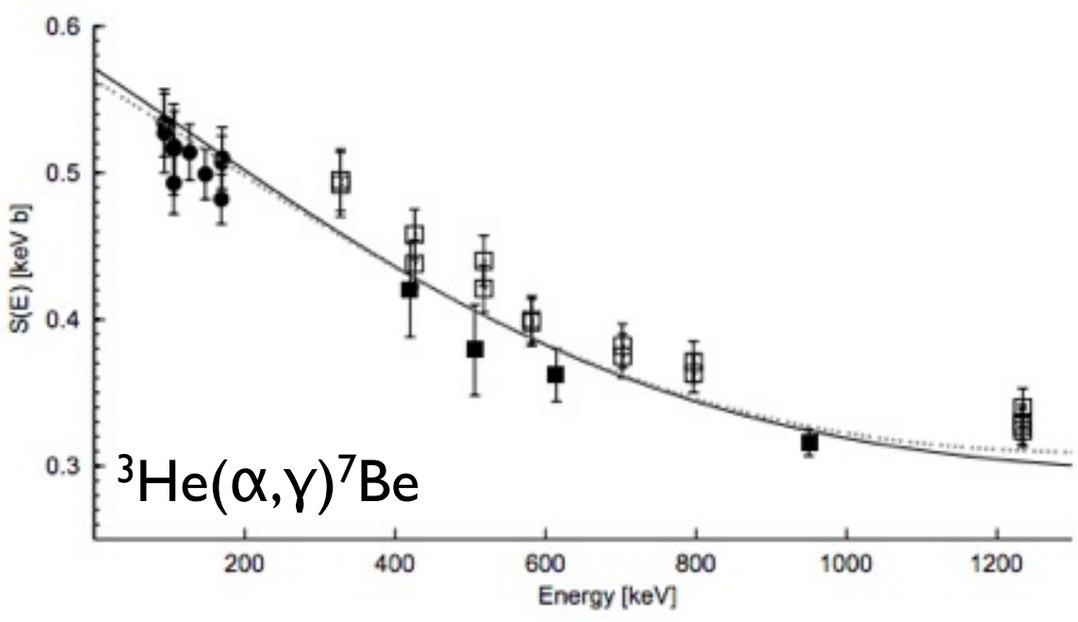
- Nuclear cross section measurements
  e.g. $^{3}He(\alpha,\gamma)^{7}Be$
  $^{7}Be(p,\gamma)^{8}B$
  $^{14}N(p,\gamma)^{15}O$



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

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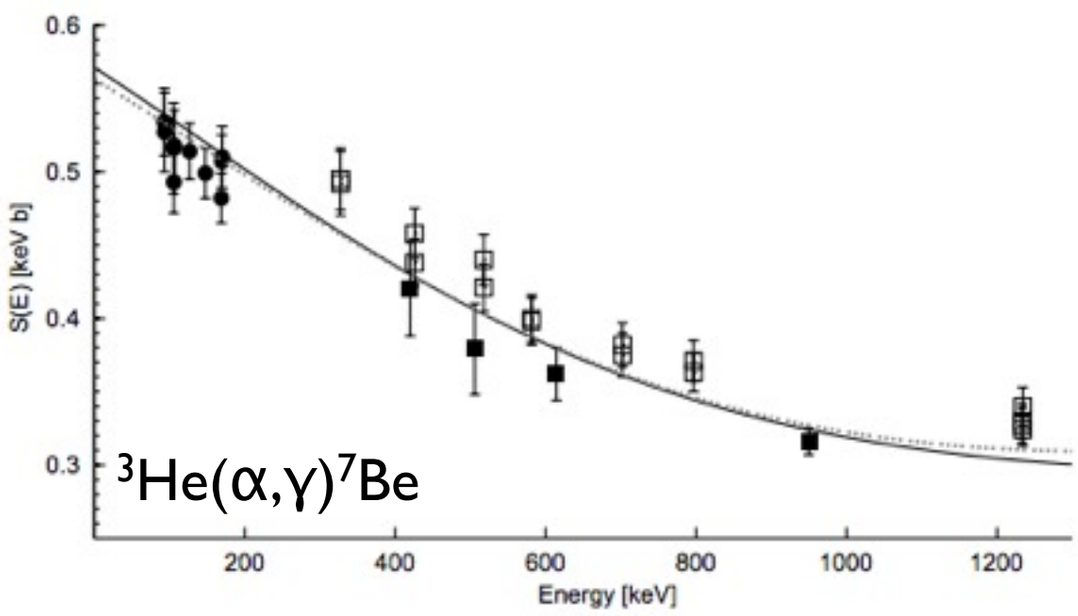
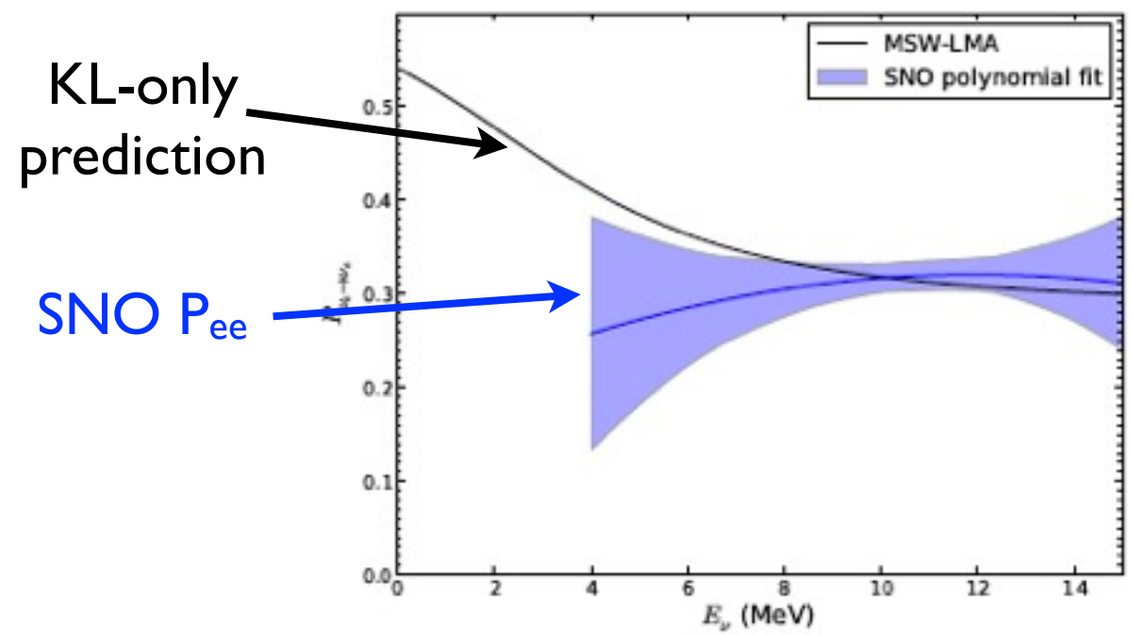


LUNA collaboration
Nuclear Physics, Section A 814 (2008), pp. 144-158

- Terrestrial oscillation parameter measurements



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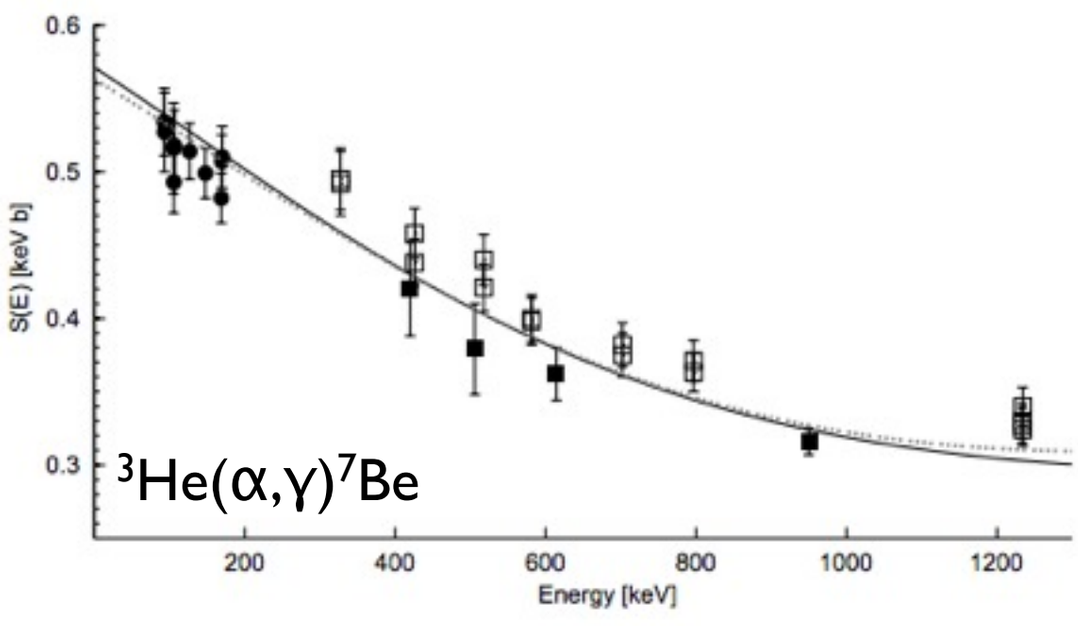

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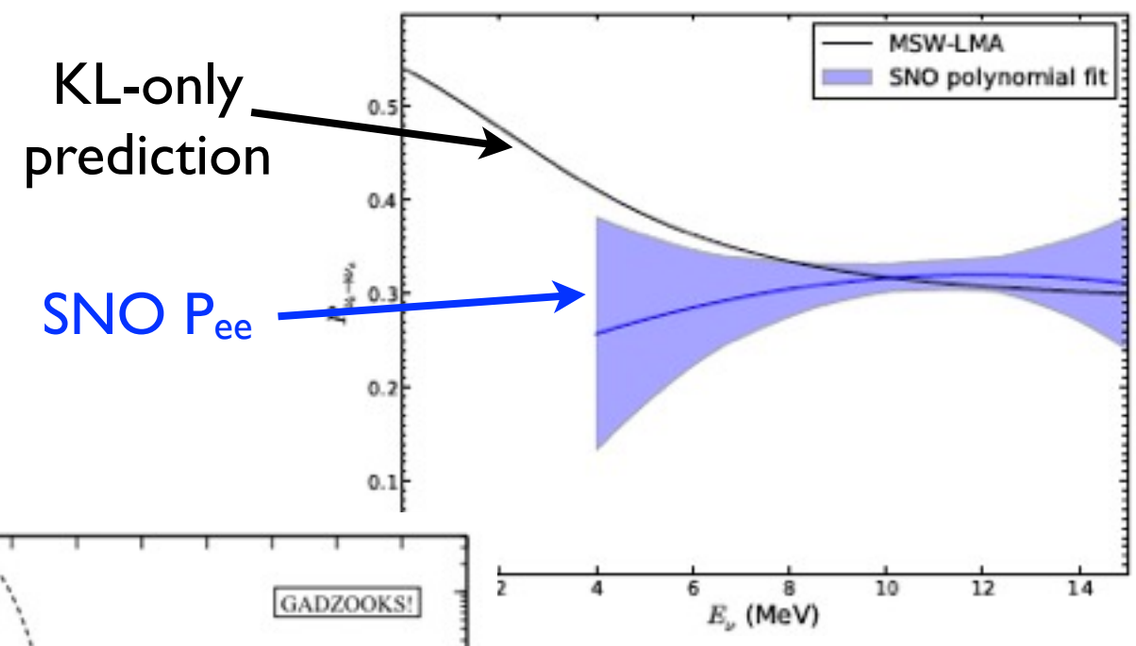

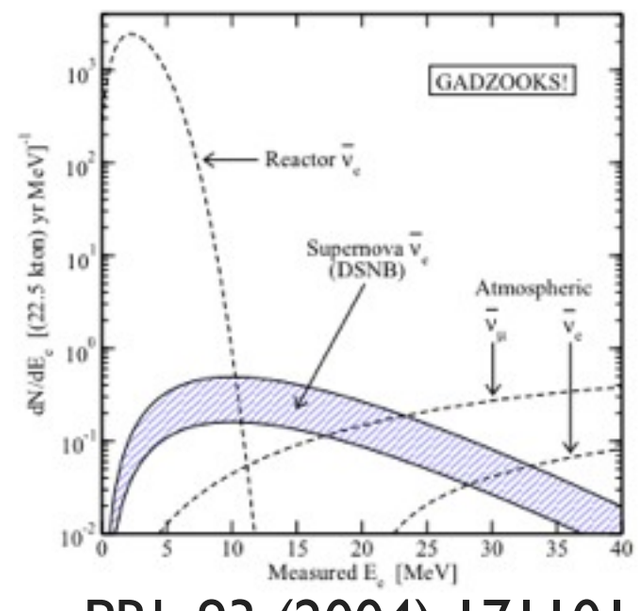

PRL 93 (2004) 171101

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

Summary

Summary

- **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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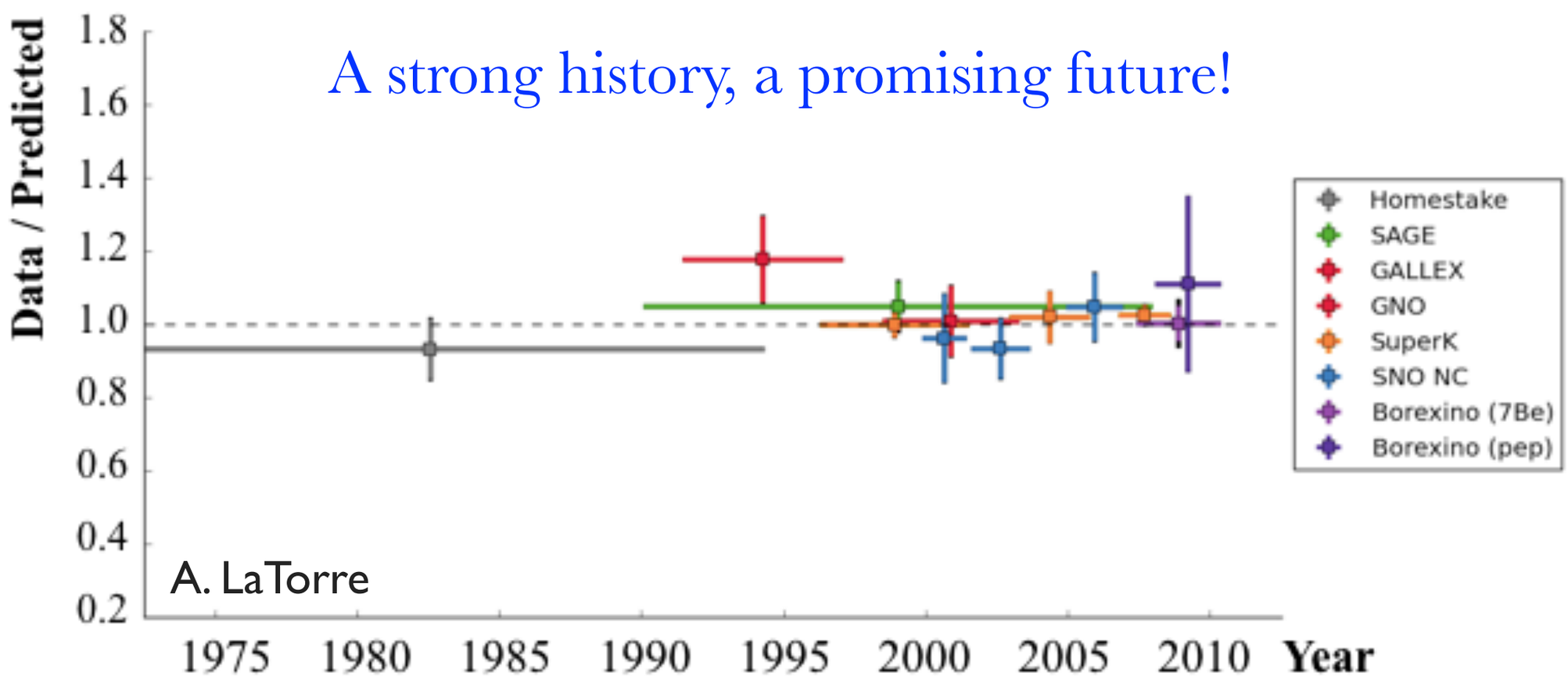
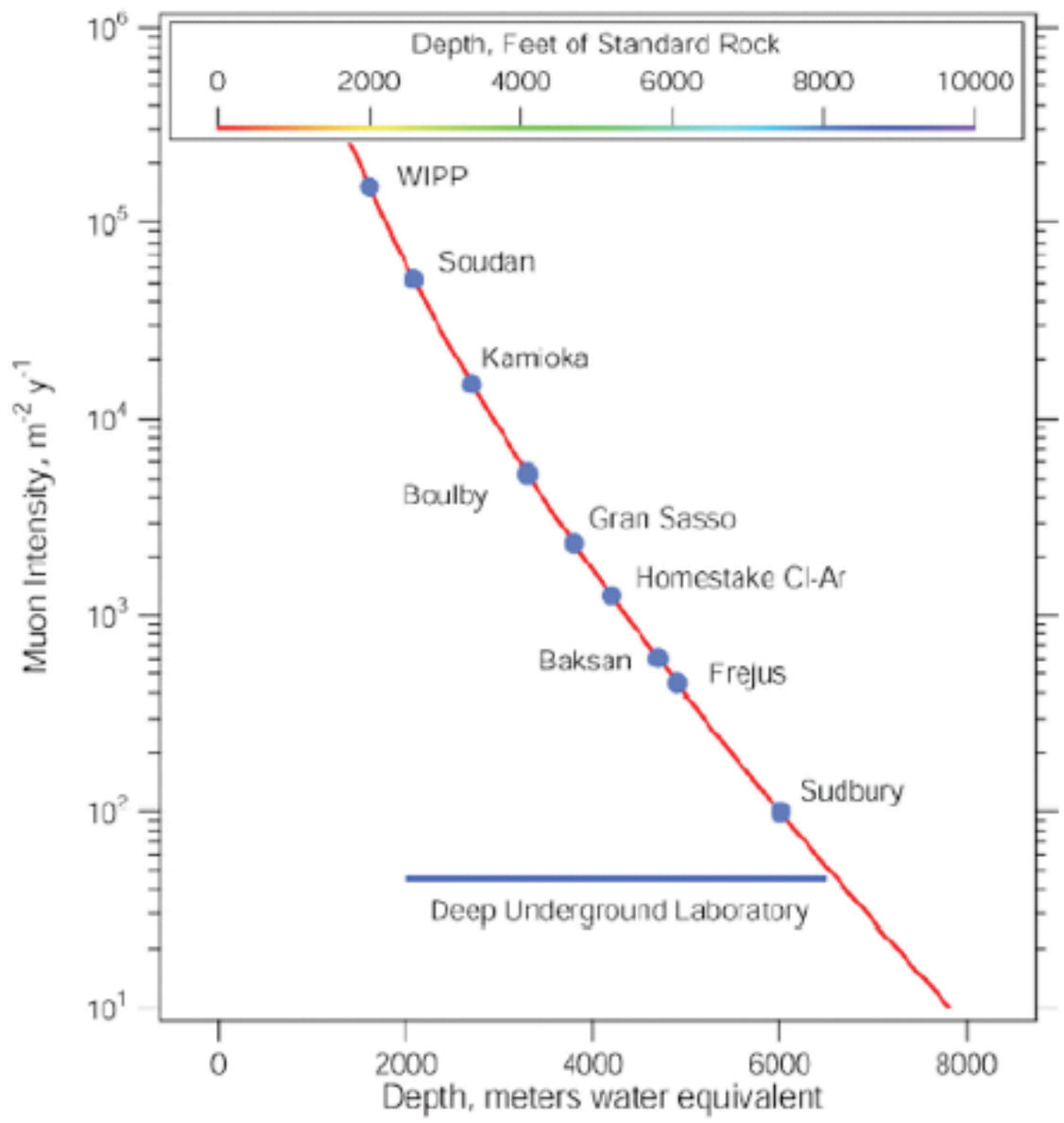


Thank you for your attention

Back-up slides

The Advantages of Depth

Kamioka: 2700 mwe
Gran Sasso: 3030 mwe
SNOLAB: 6080 mwe



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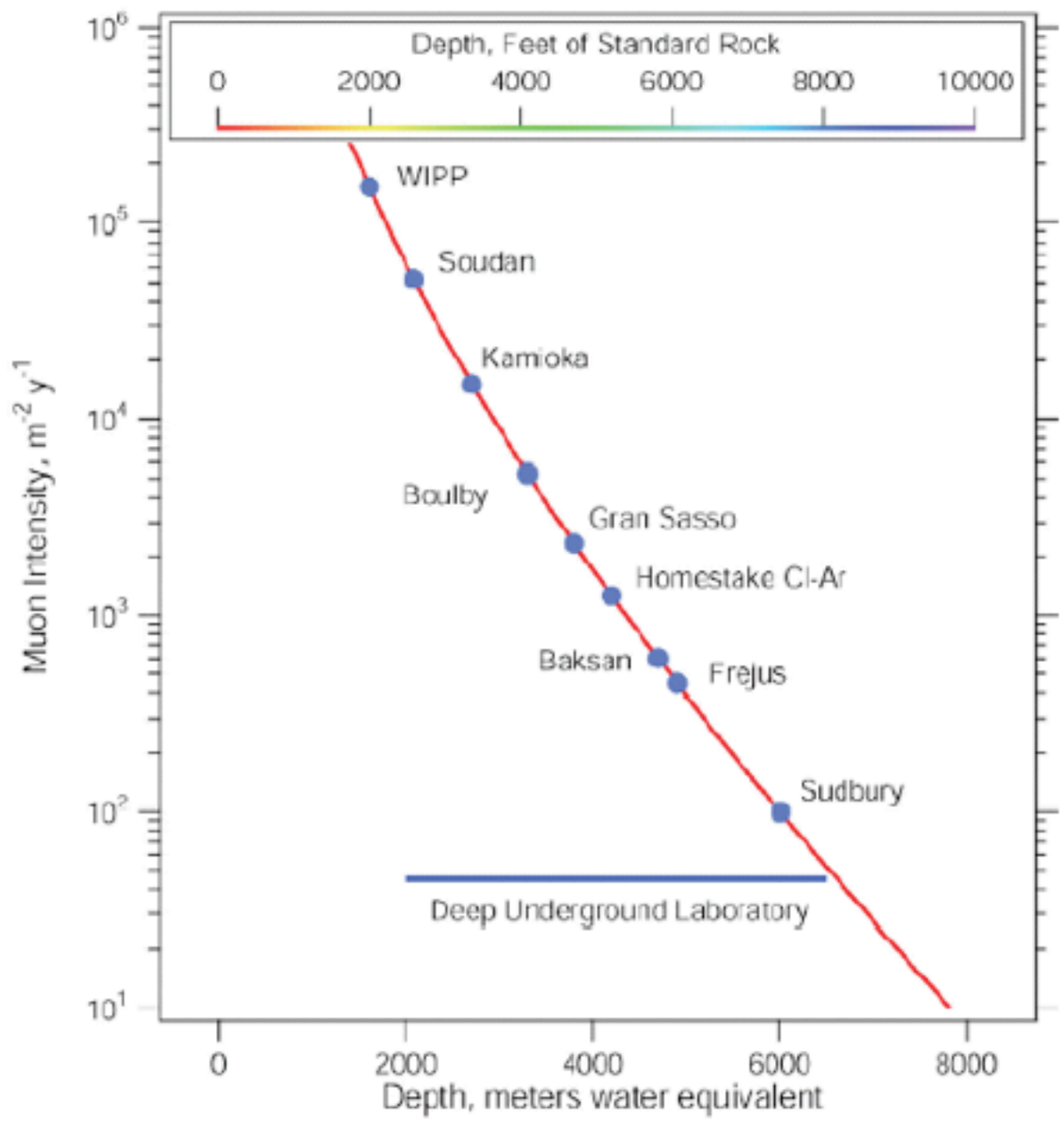

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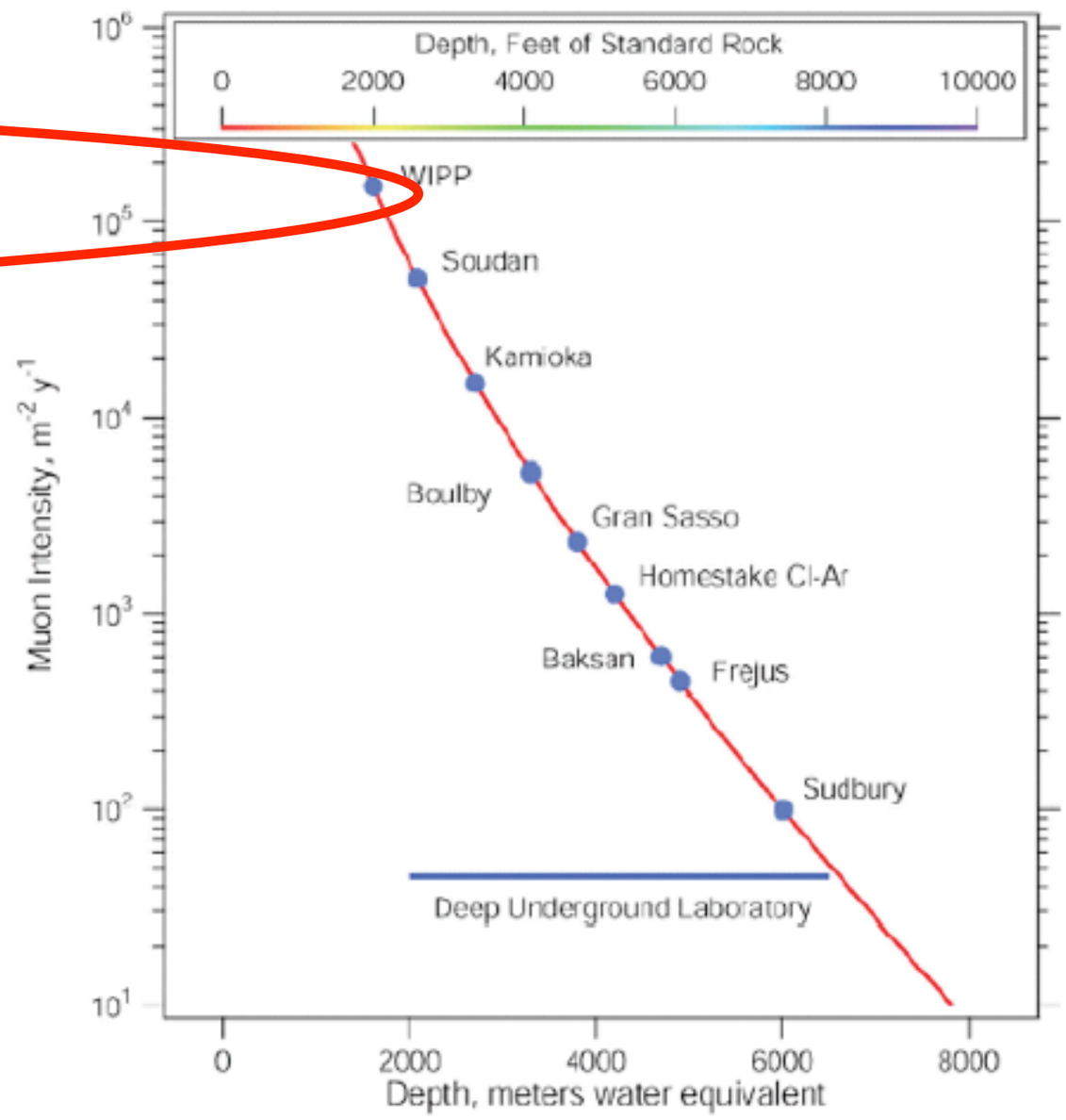

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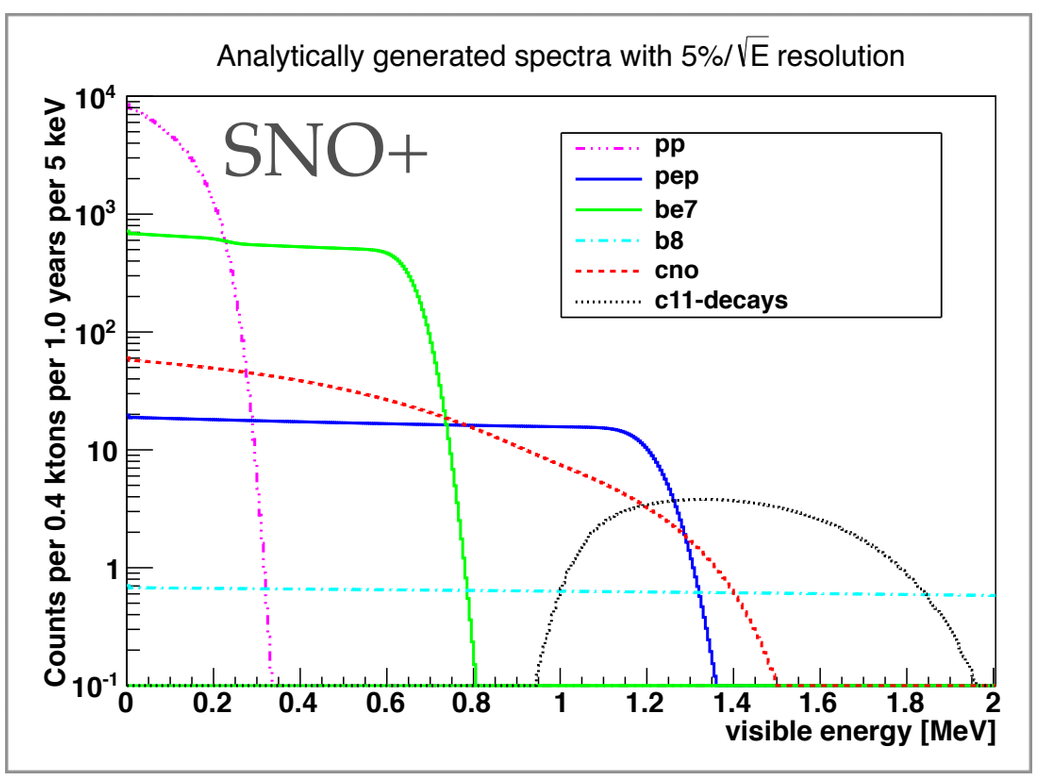

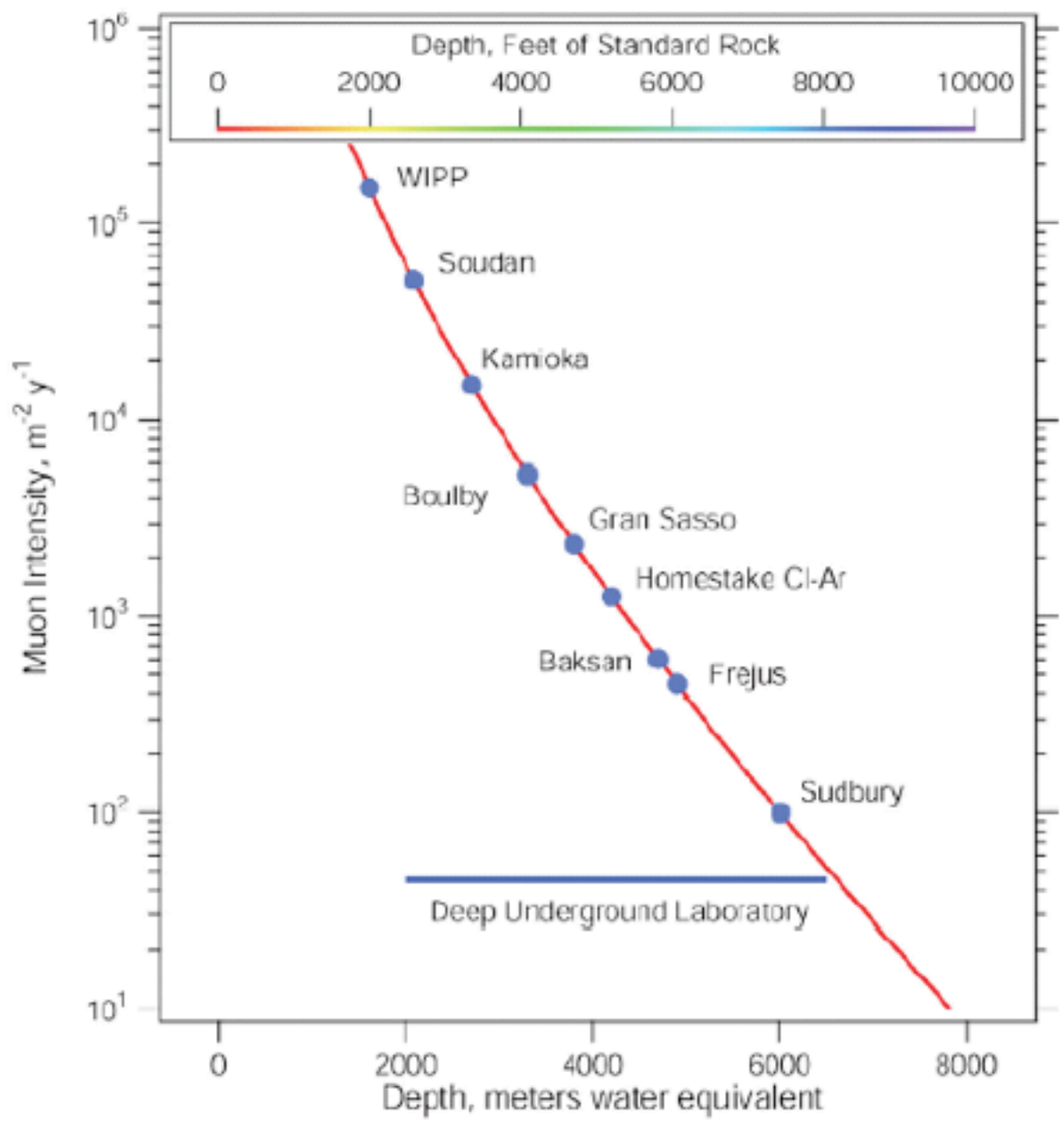

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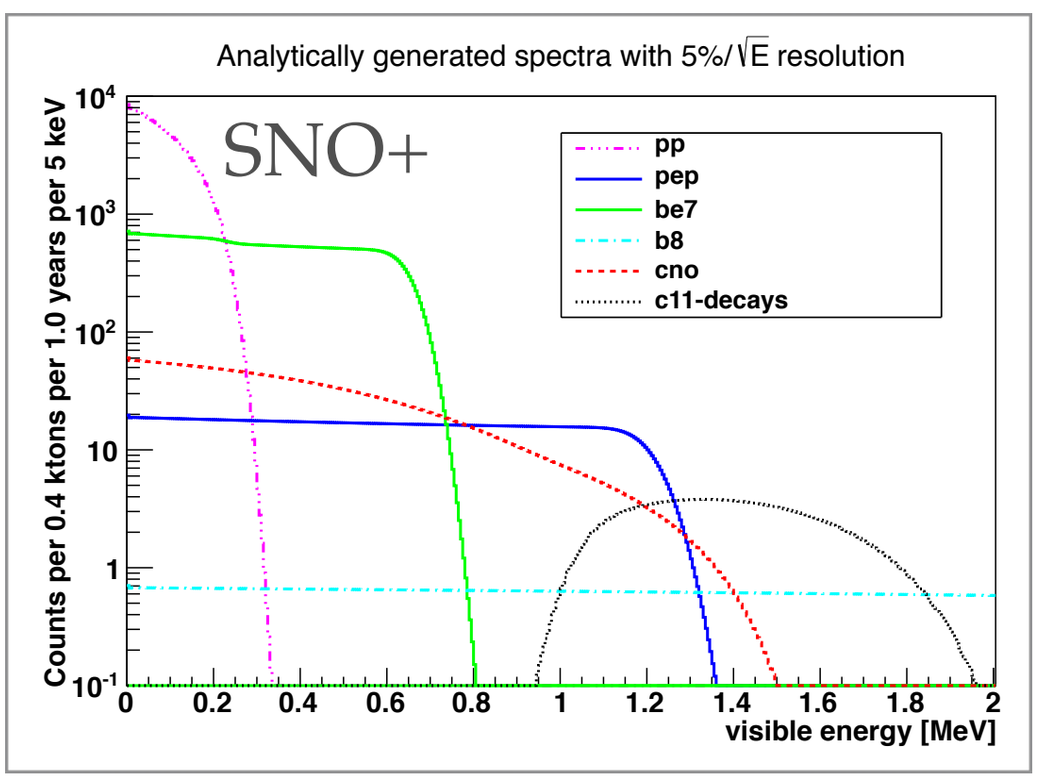

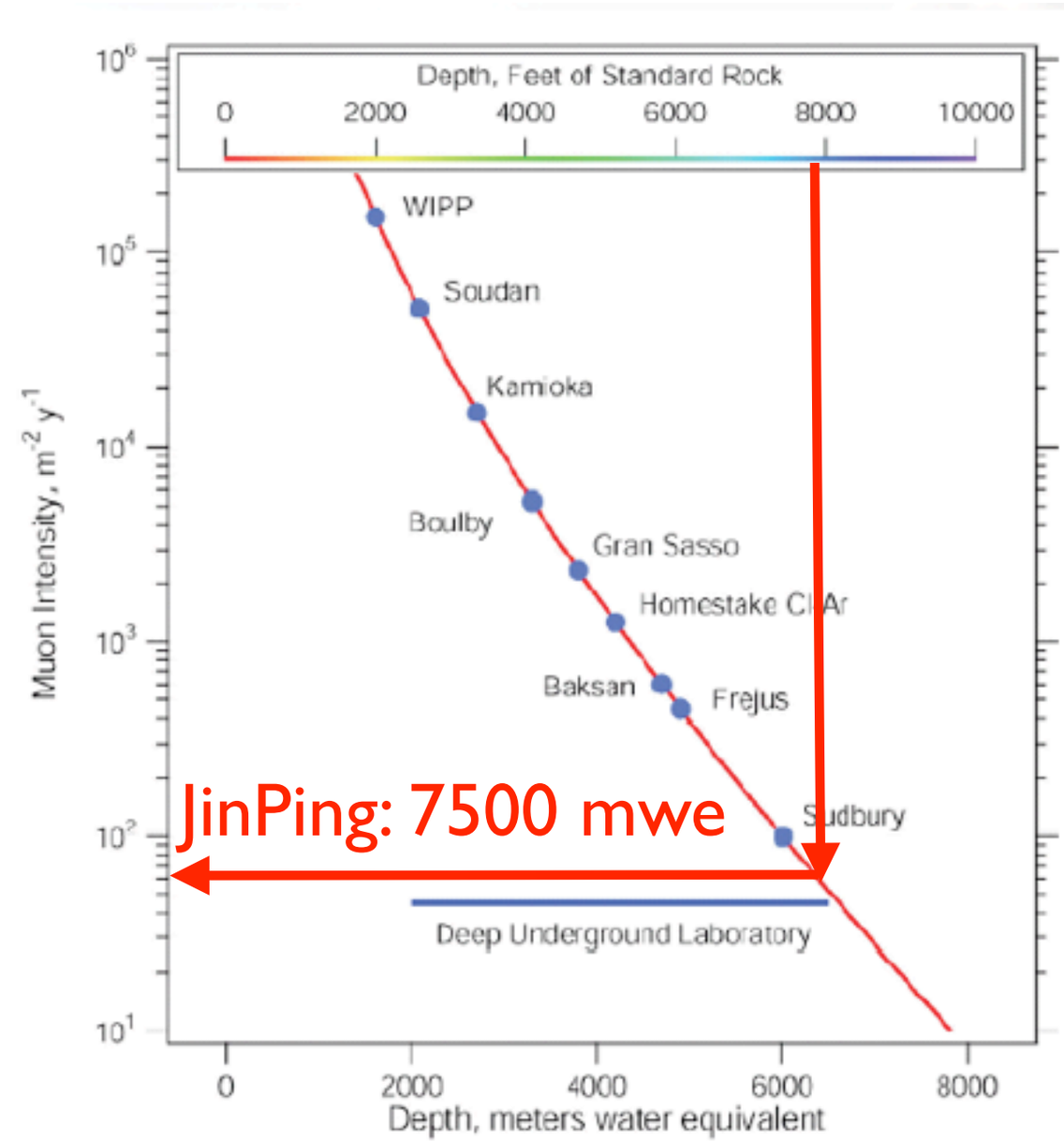

Ultra low cosmogenic backgrounds!

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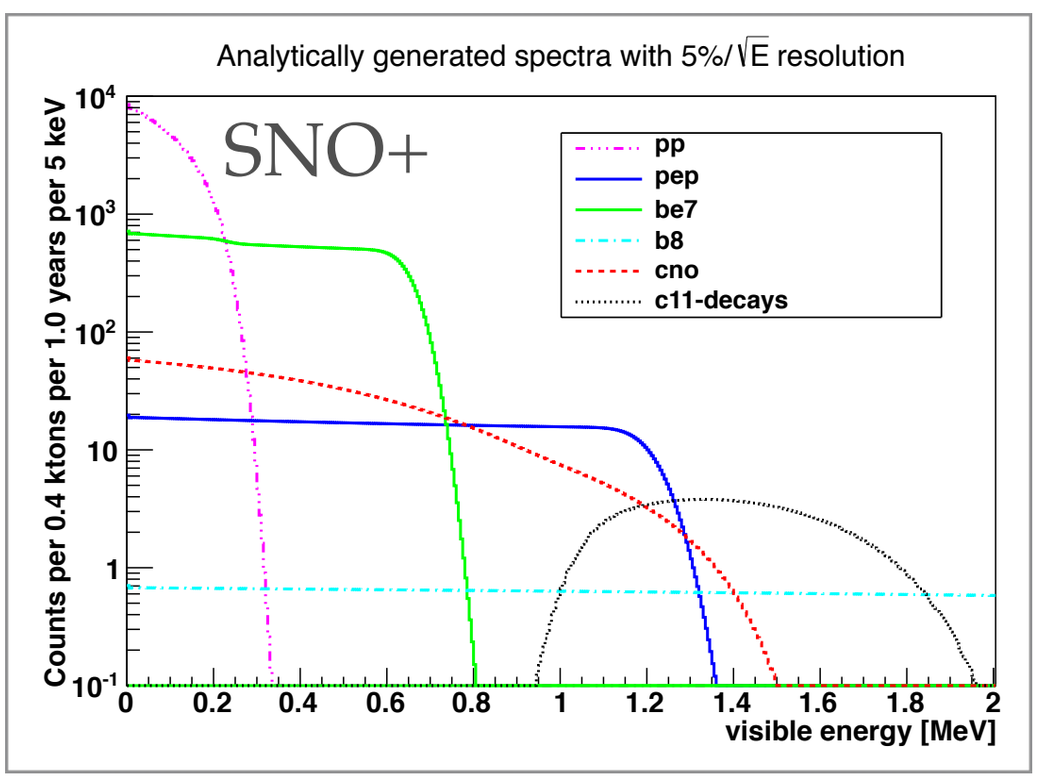
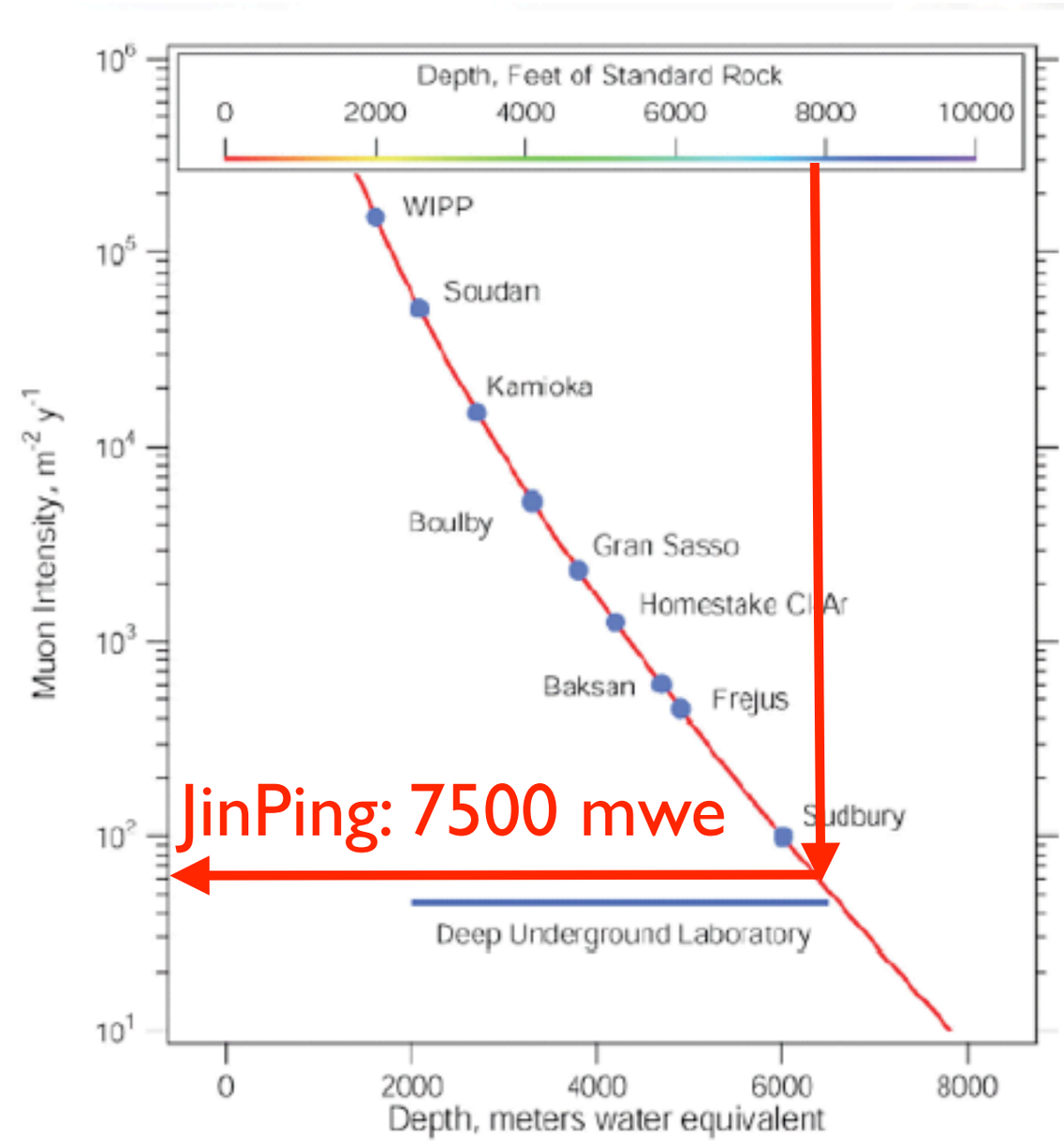


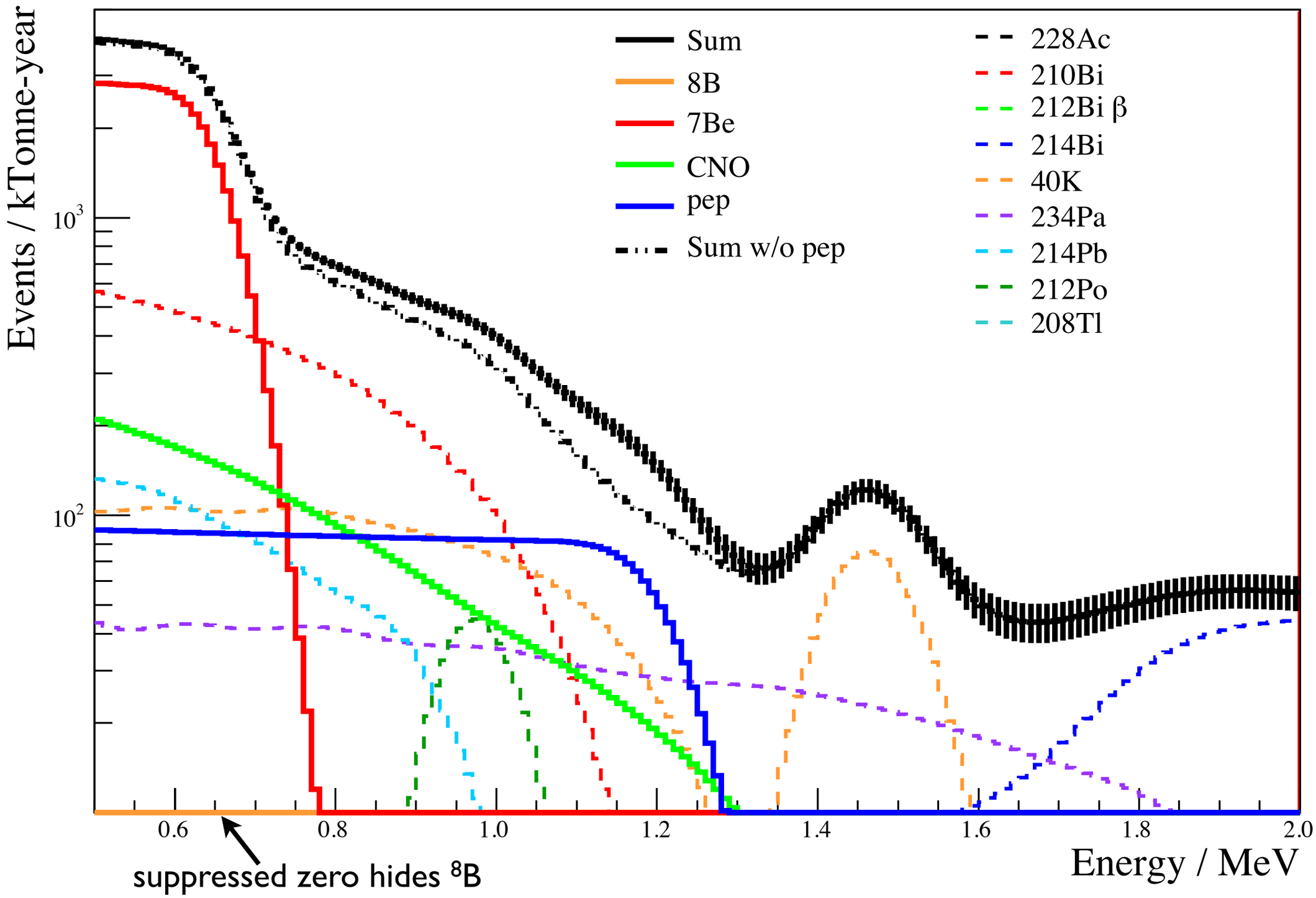


Ultra low cosmogenic backgrounds!

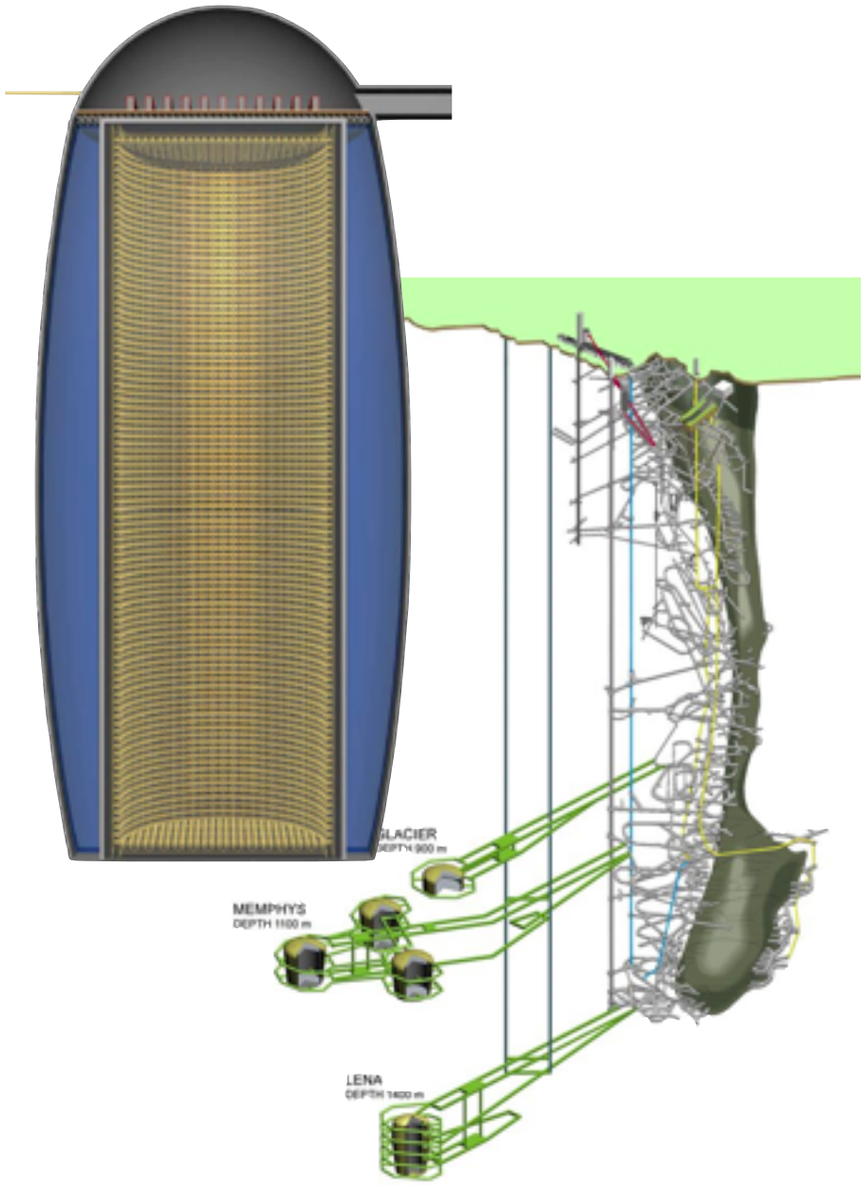
Recent workshop:

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

SNO+ Solar Neutrino Detection



Low Energy Neutrino Astronomy



- 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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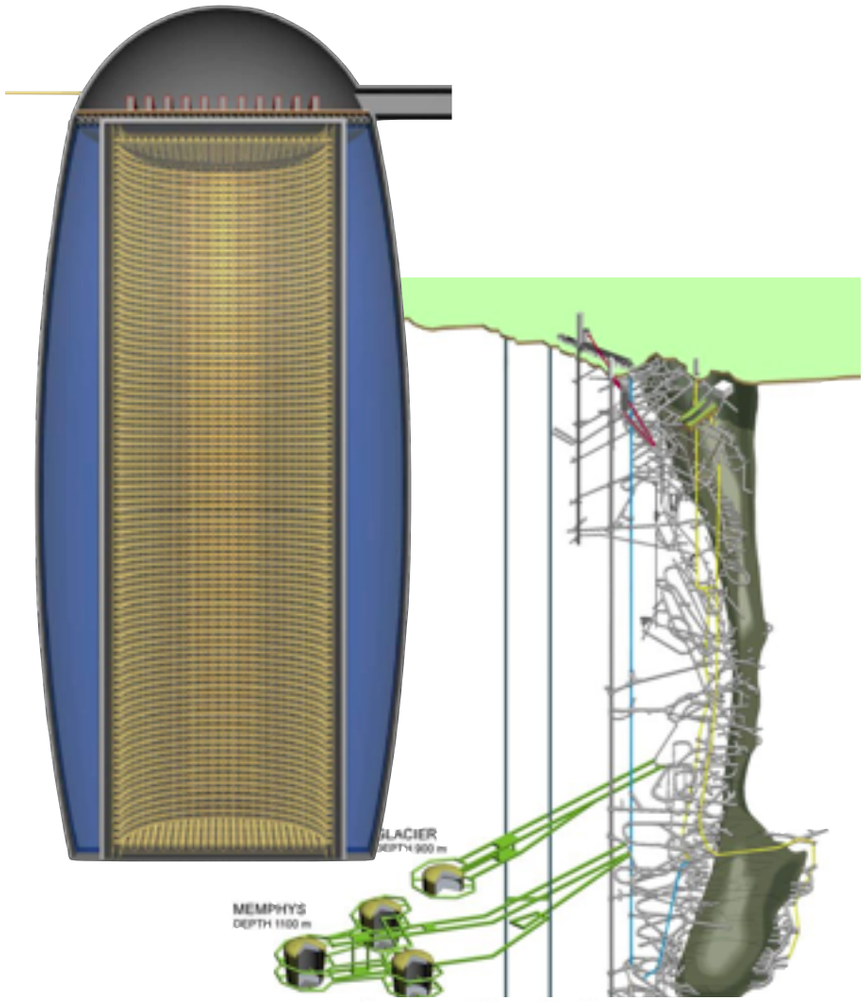

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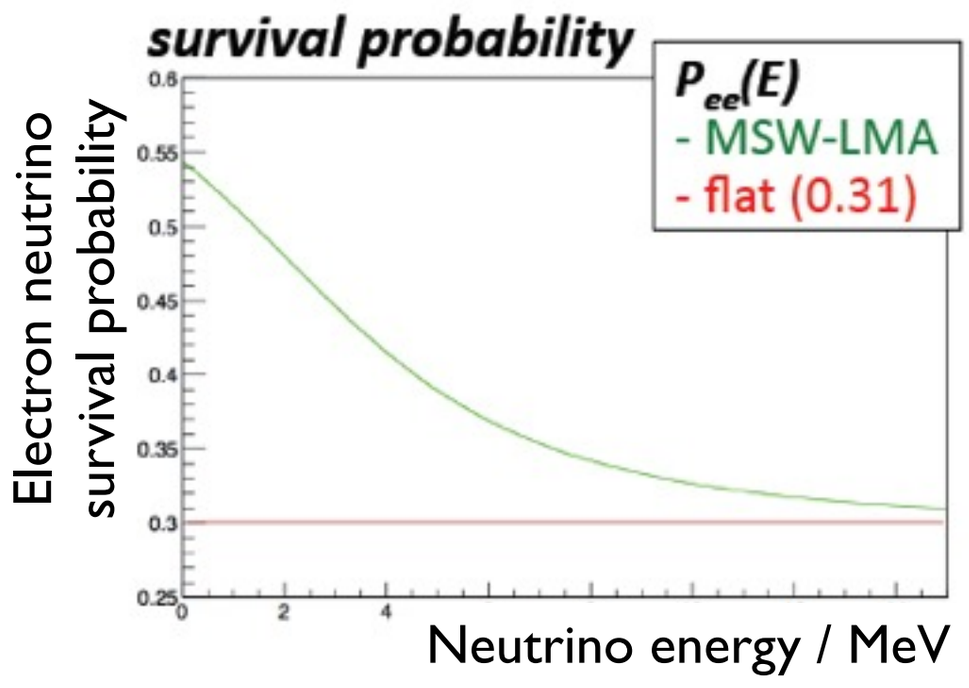

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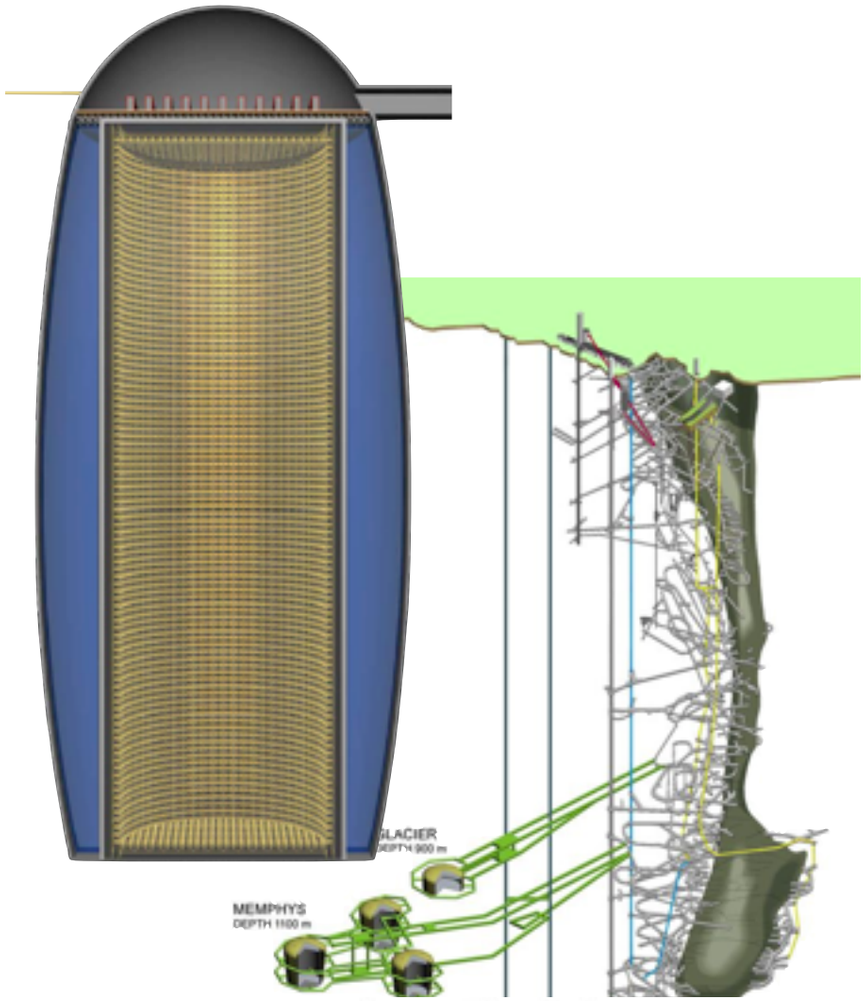

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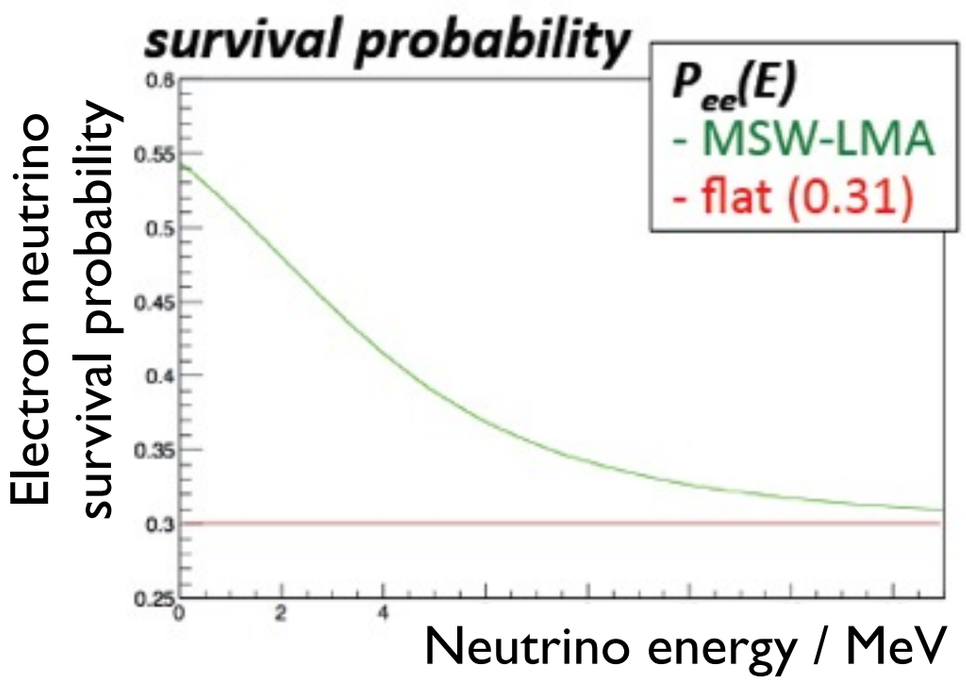
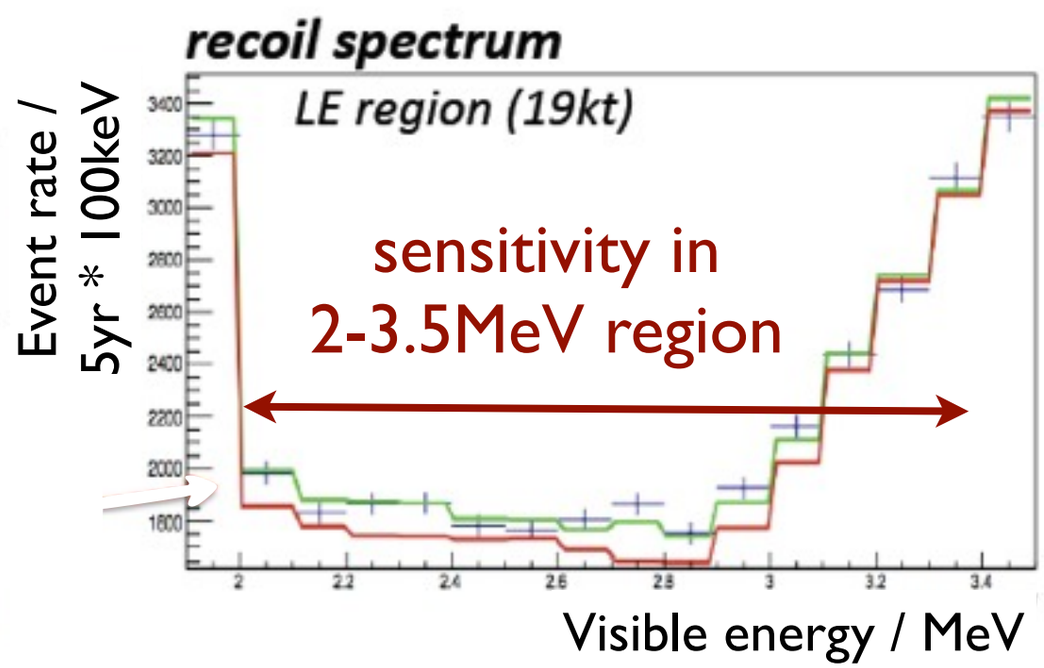




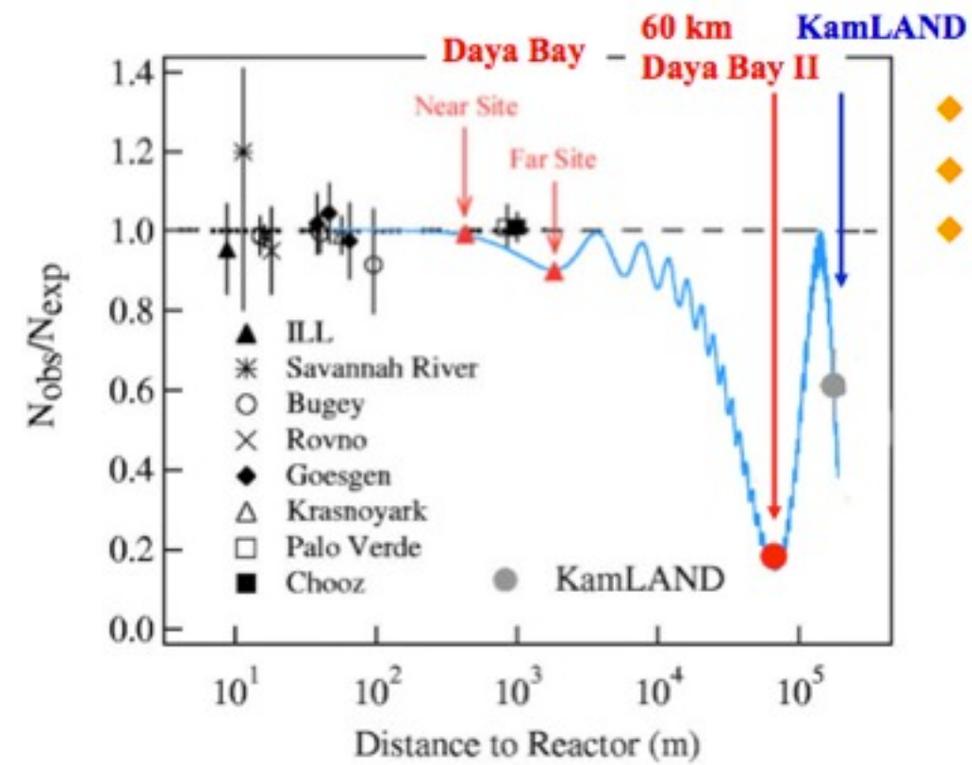
5σ after 3-5 years

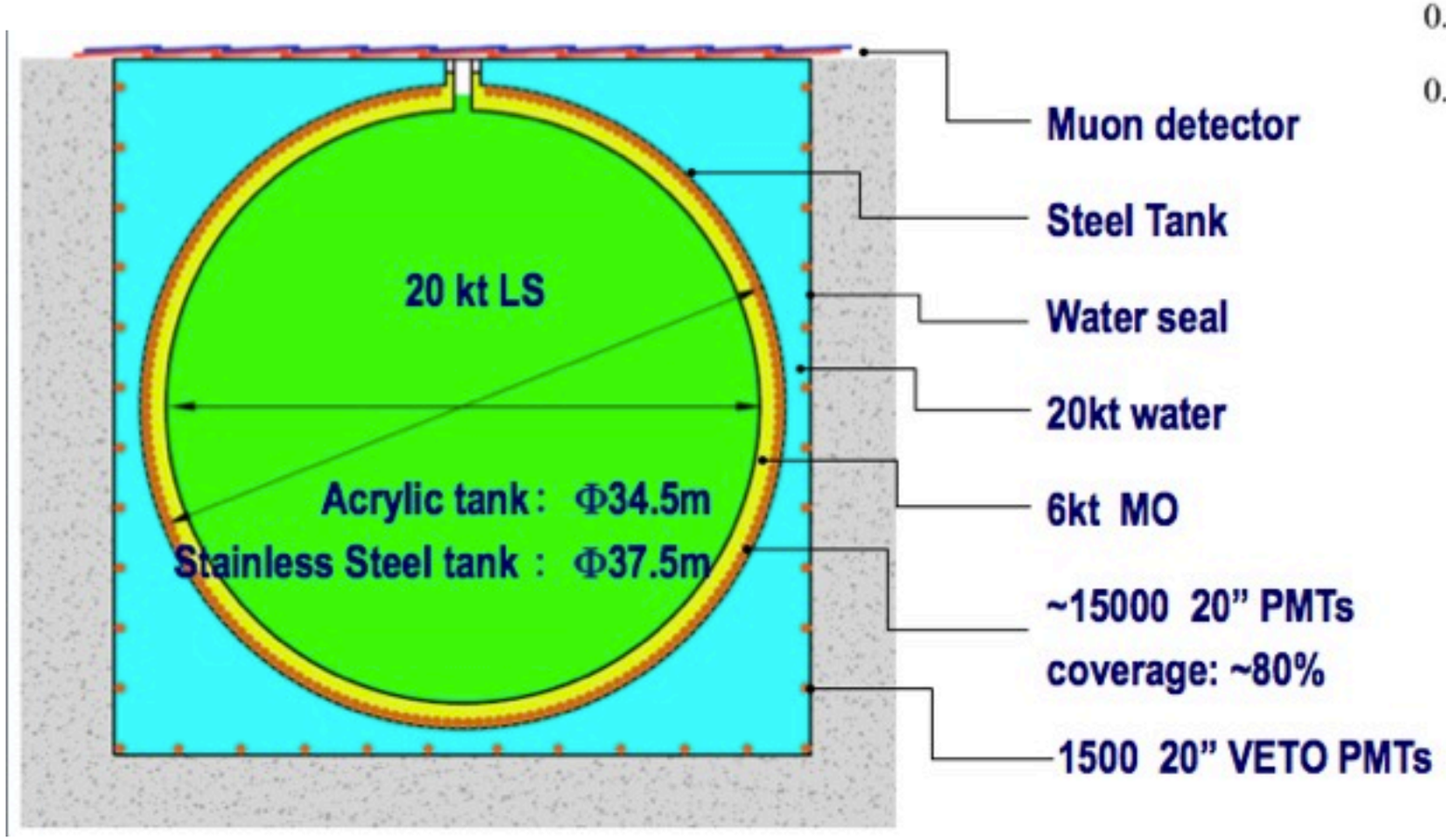
M. Wurm, TAUP 2013

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

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/

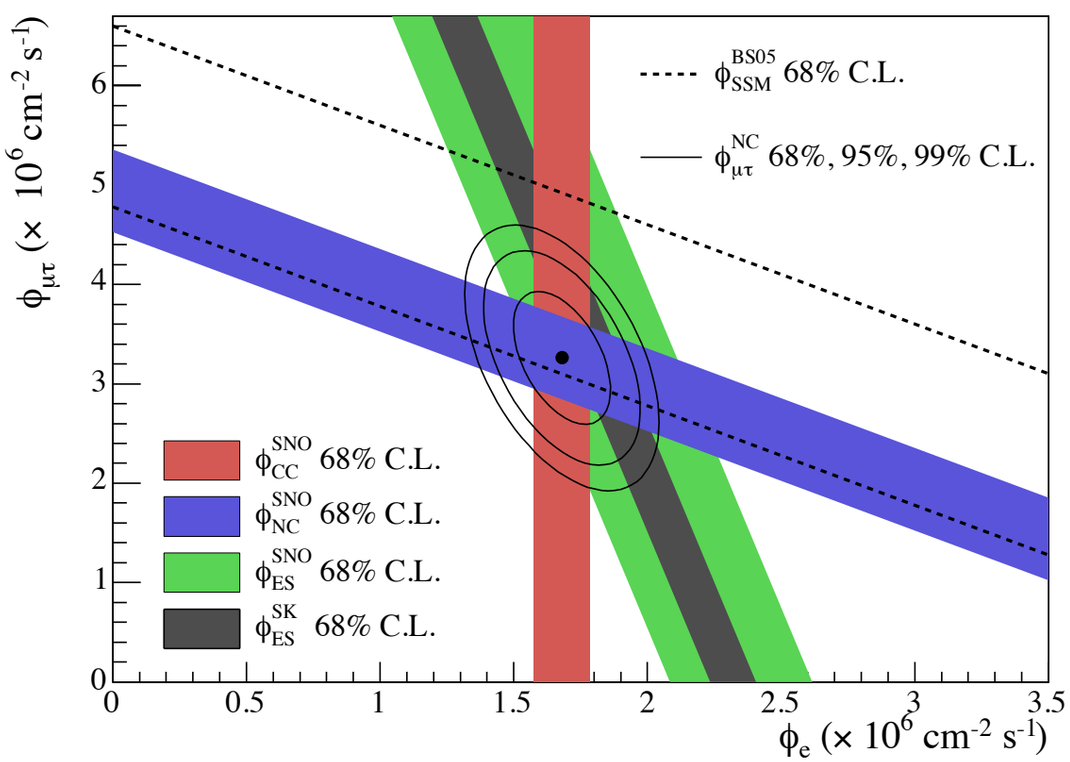
Solving the Solar Neutrino Problem

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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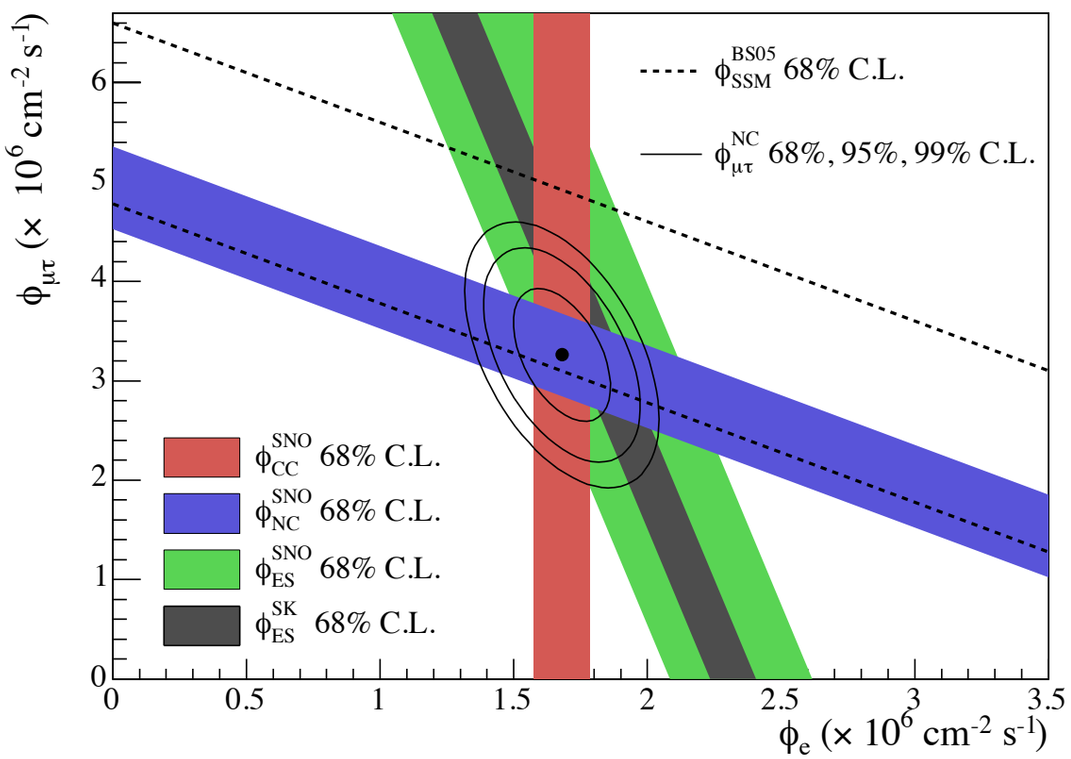
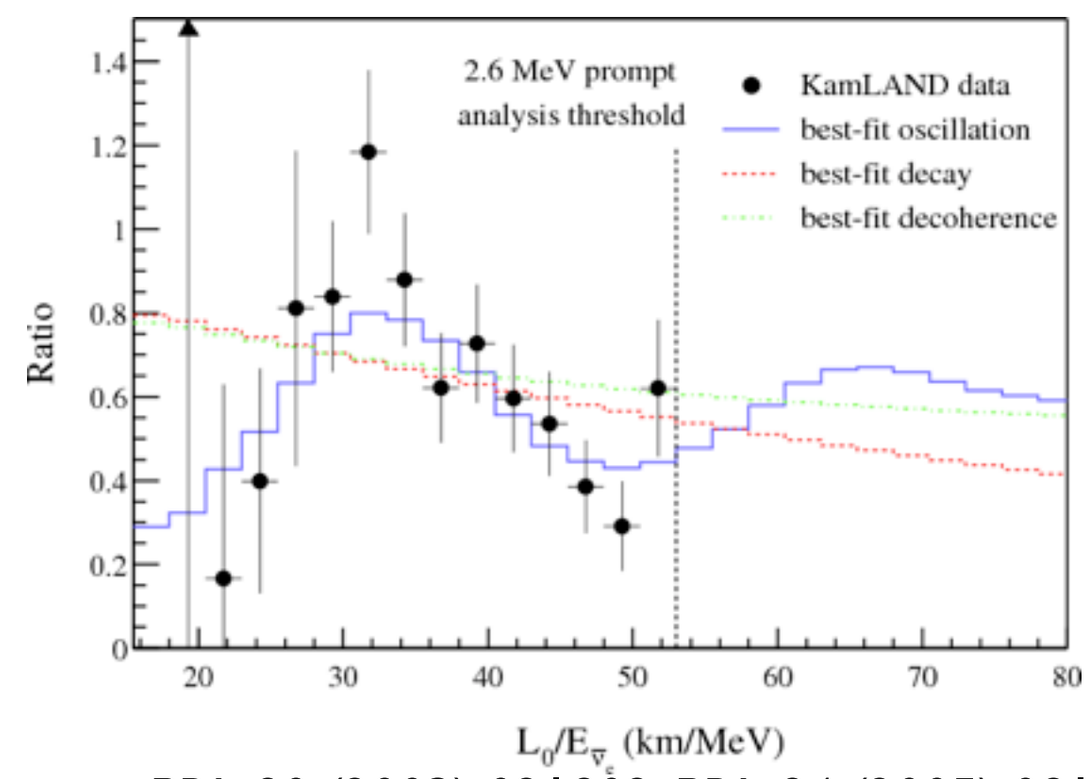


PRL 87 (2001) 071301, PRL 89 (2002) 011301

Oscillations at KamLAND

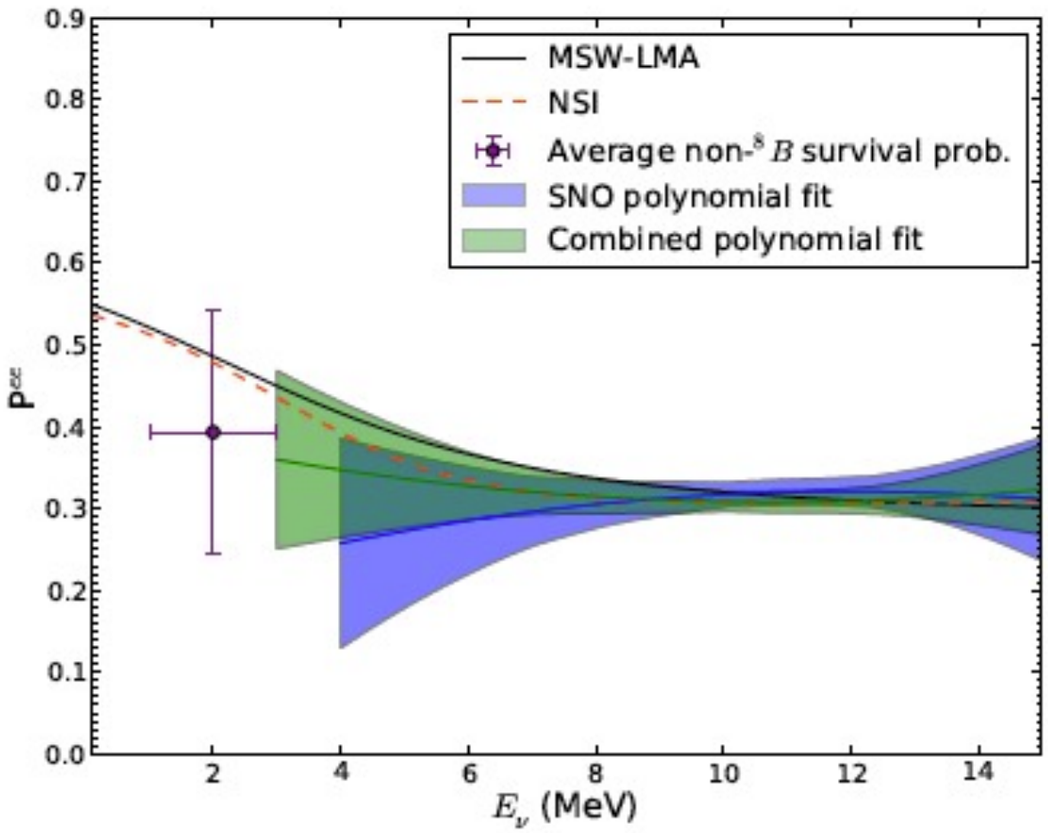
Disappearance at >99.99%

Clear oscillation pattern

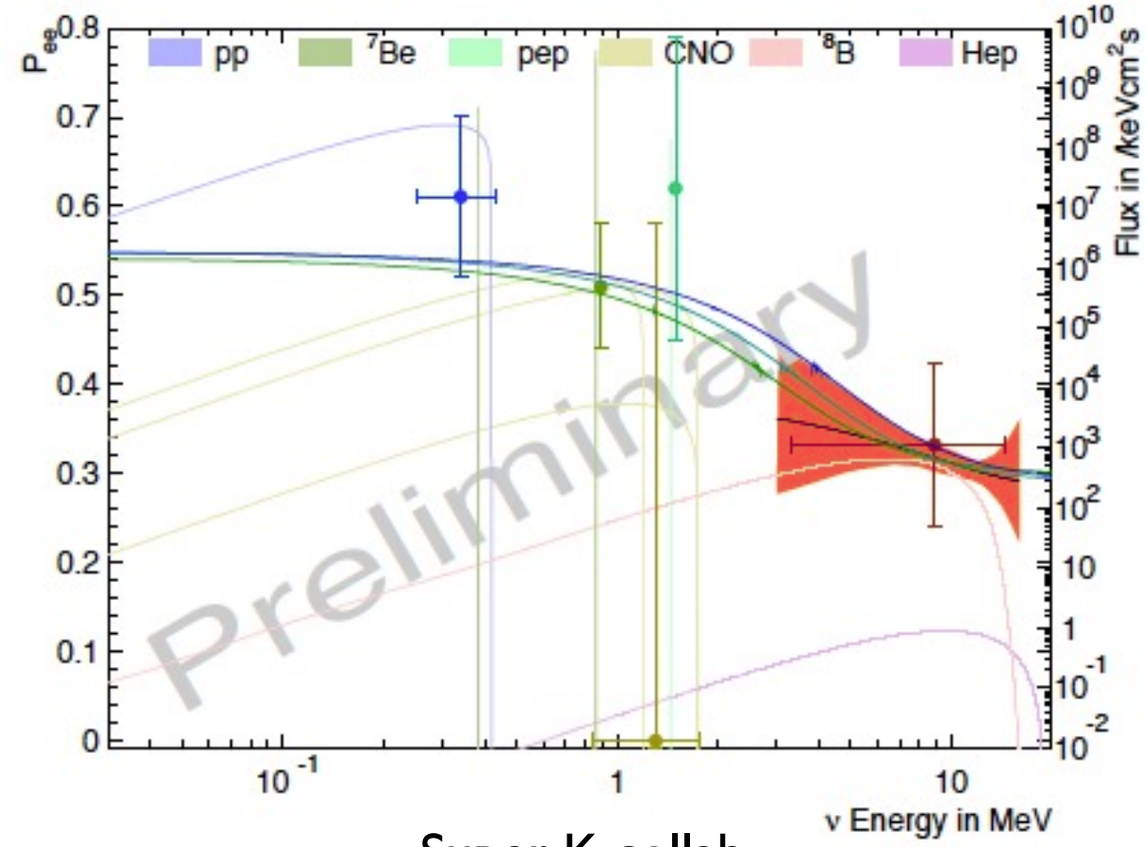


PRL 90 (2003) 021802, PRL 94 (2005) 081801

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)

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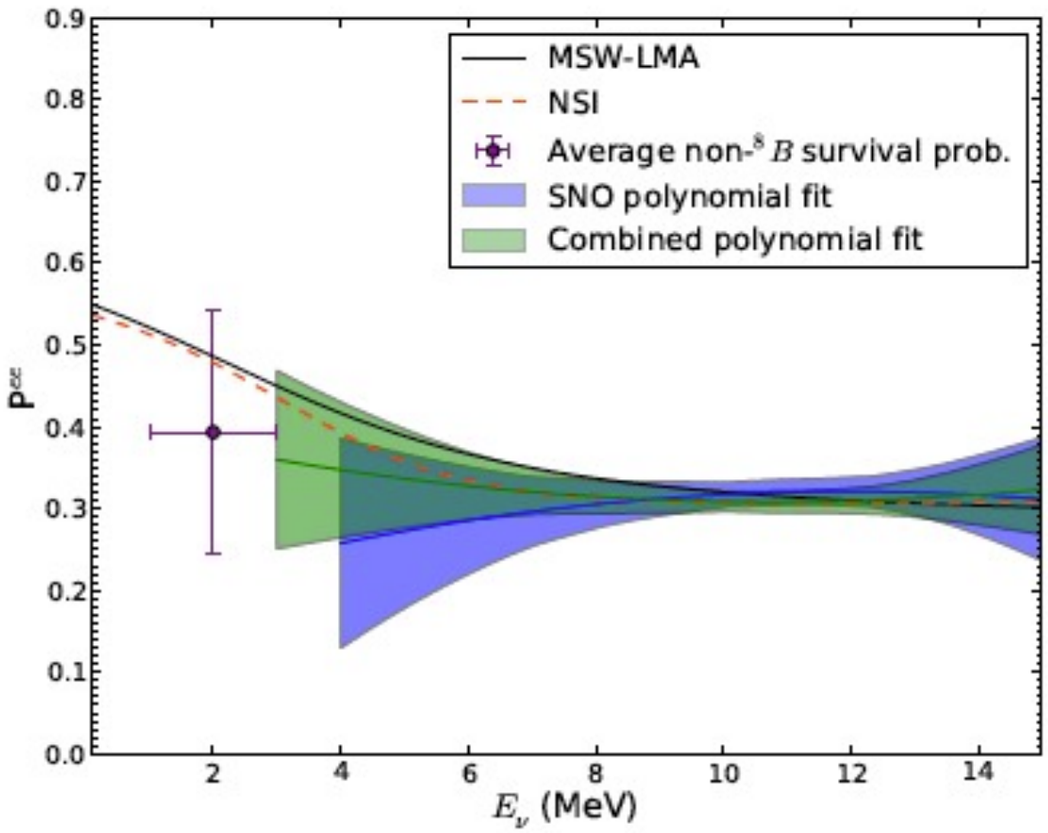

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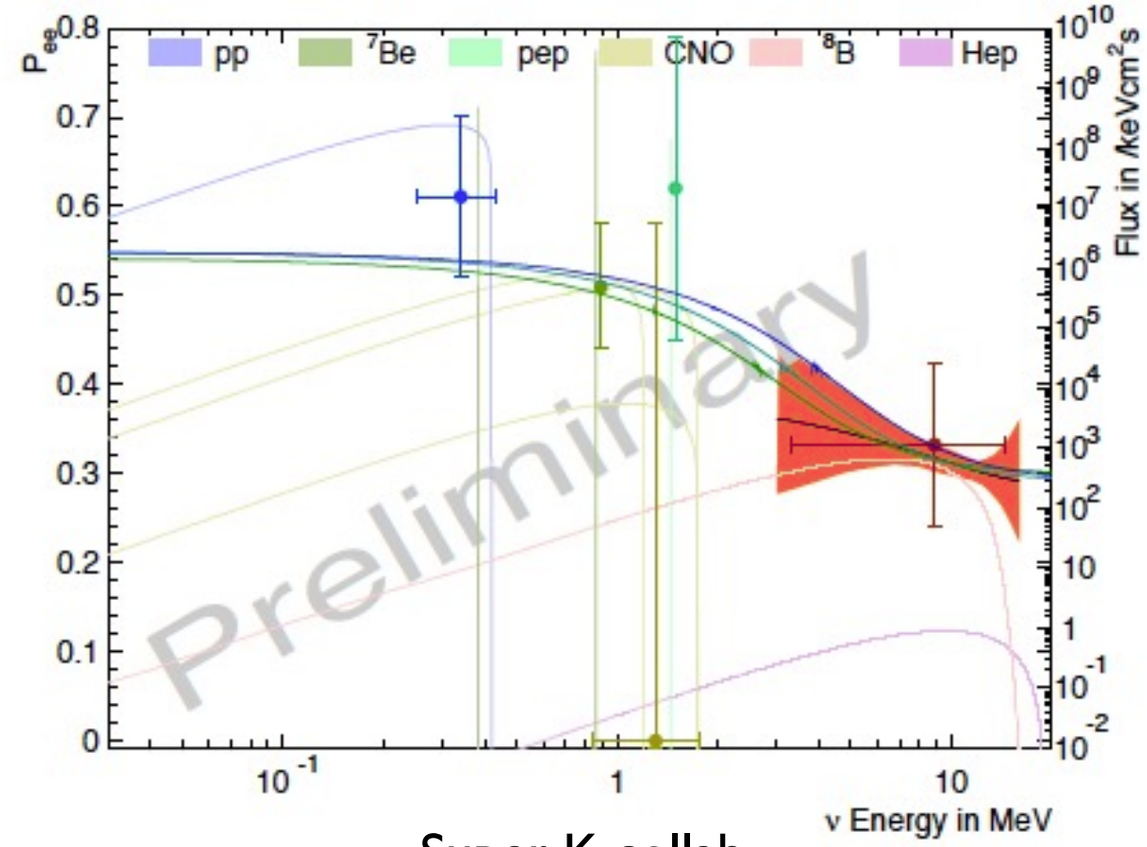

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Apparent turn-up is a feature of the quadratic parameterisation

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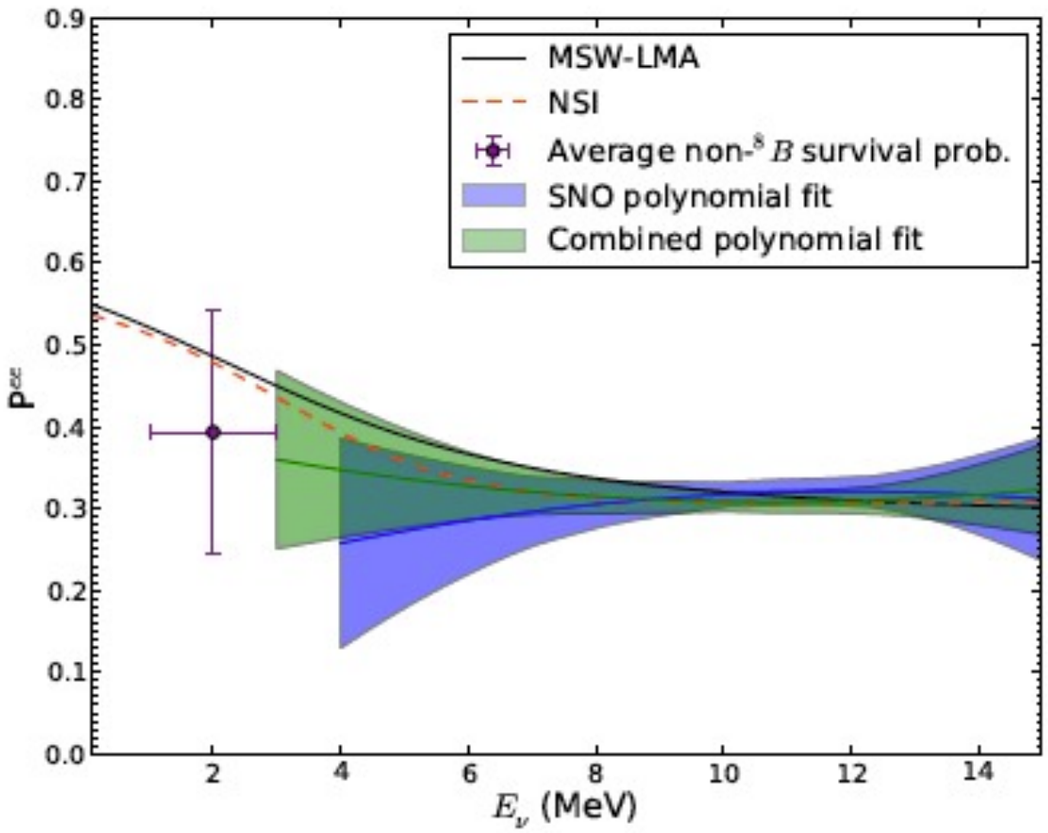

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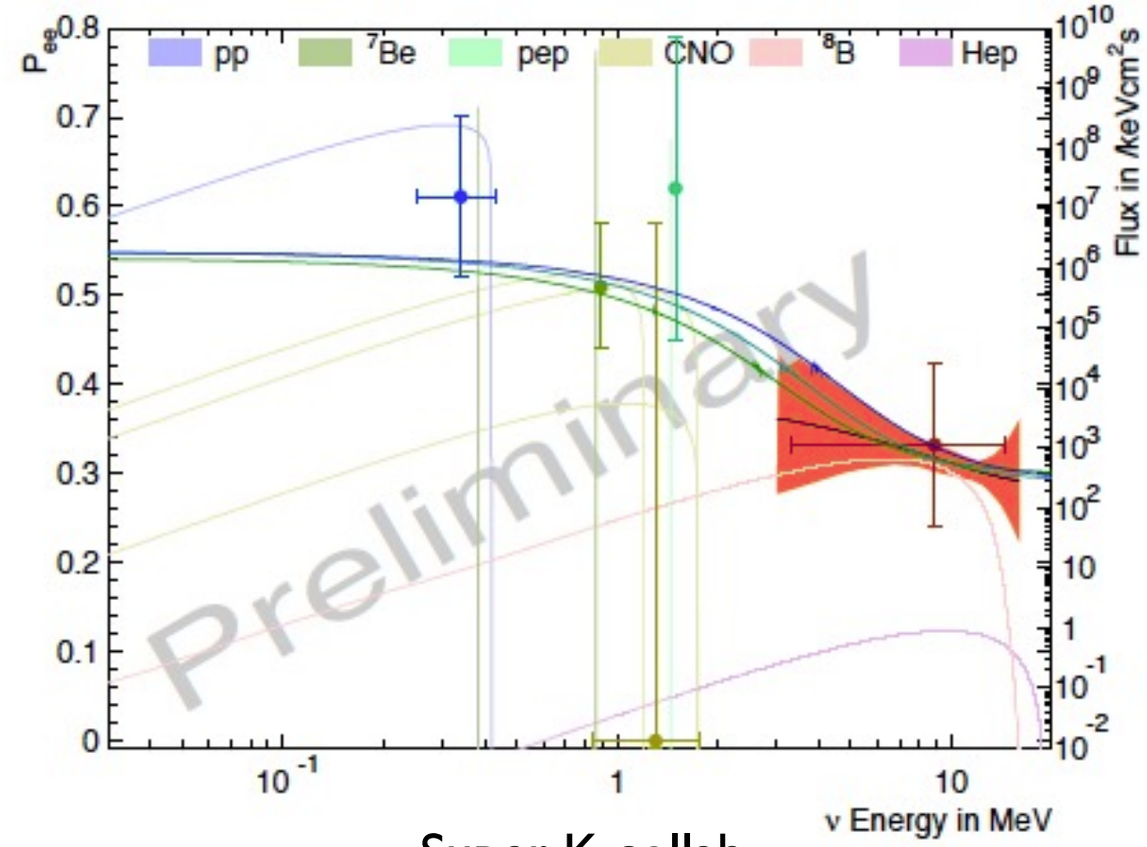

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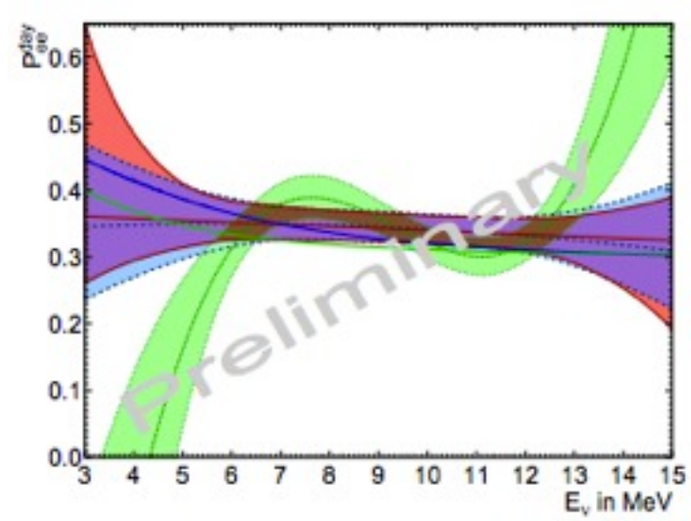
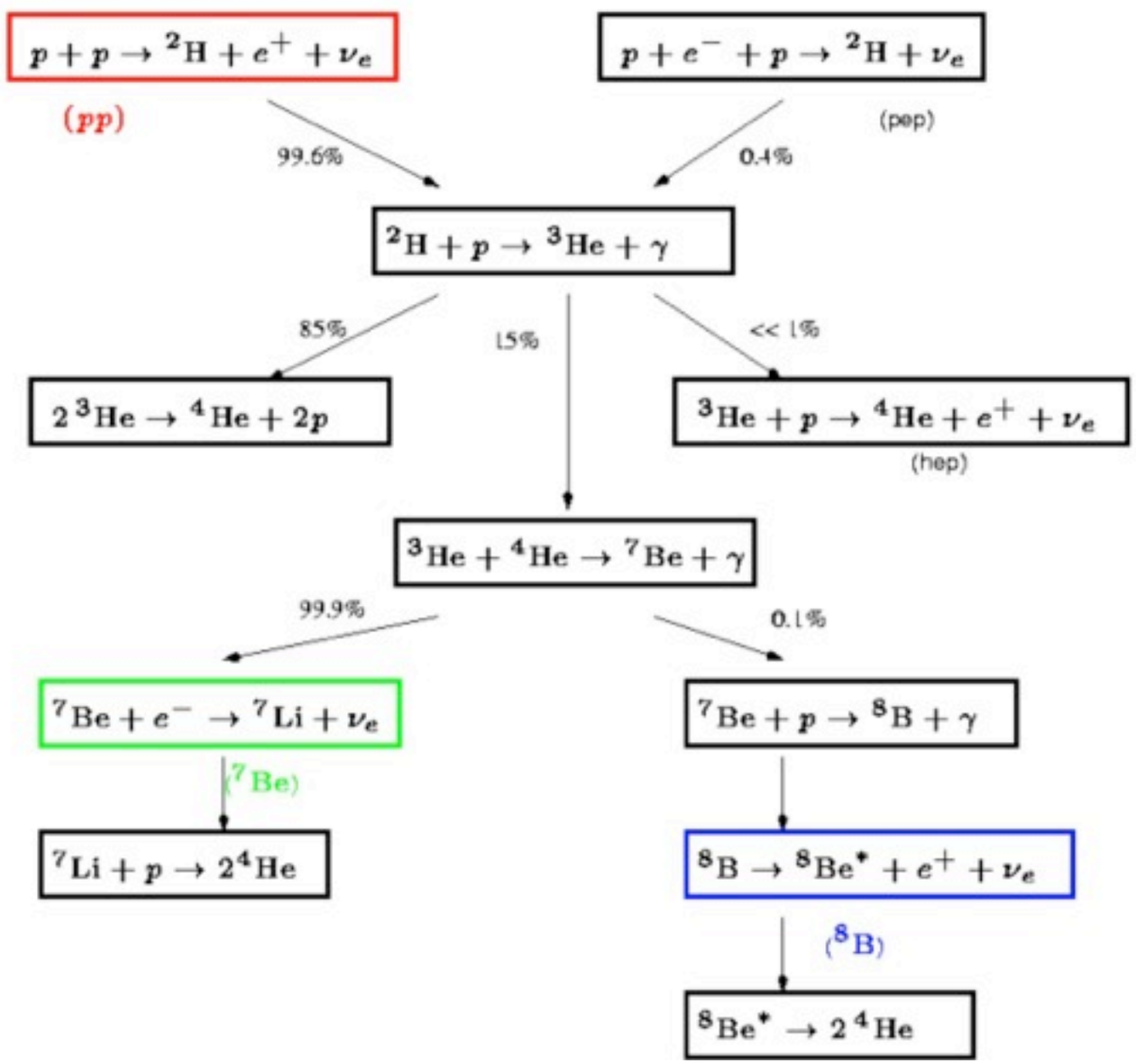


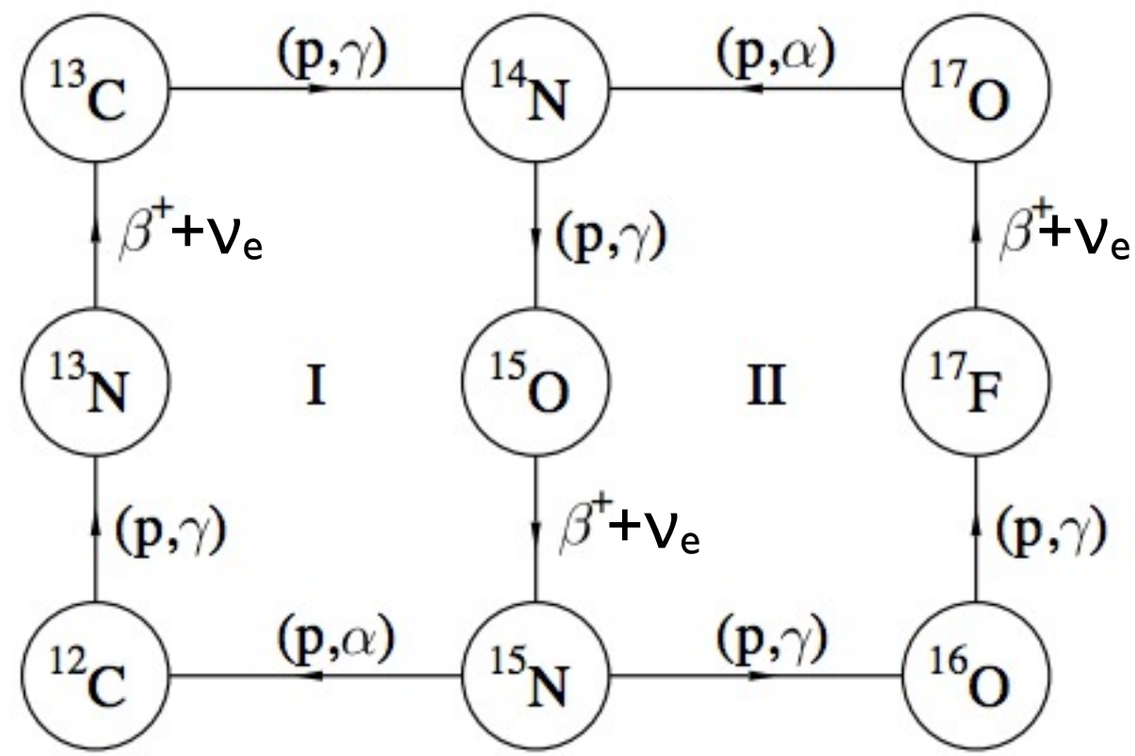
Modern Understanding

pp Chain



CNO Cycle

(contributes ~1% of solar energy)



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

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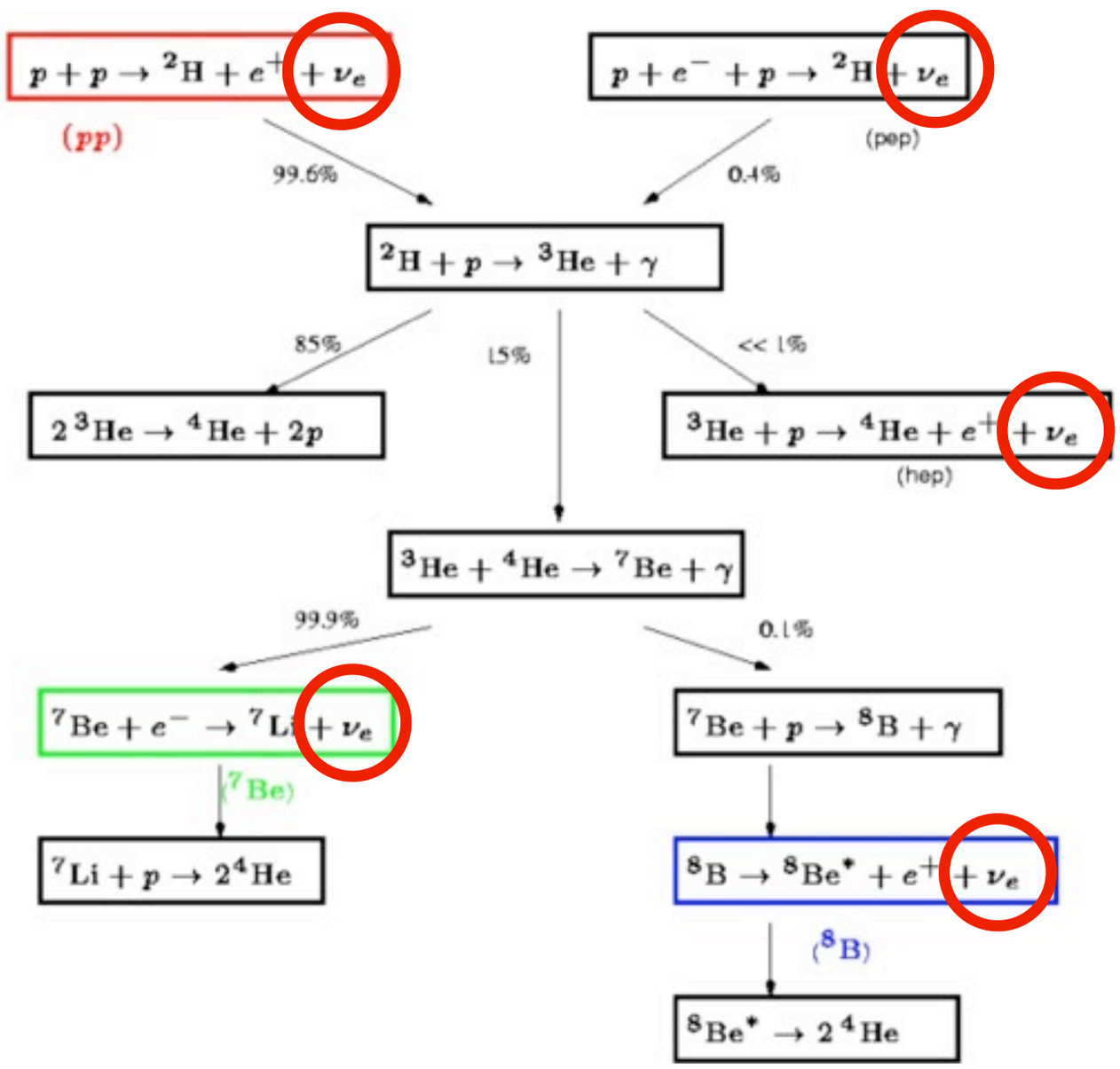

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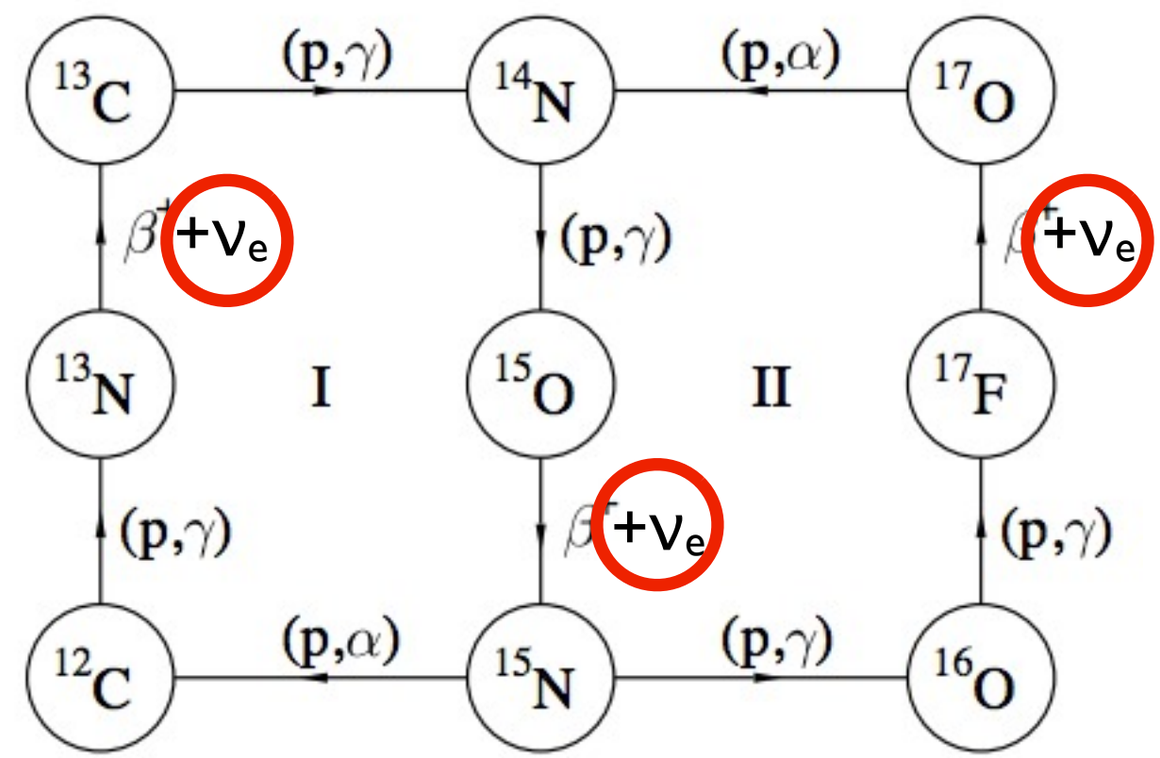

ν_e

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

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
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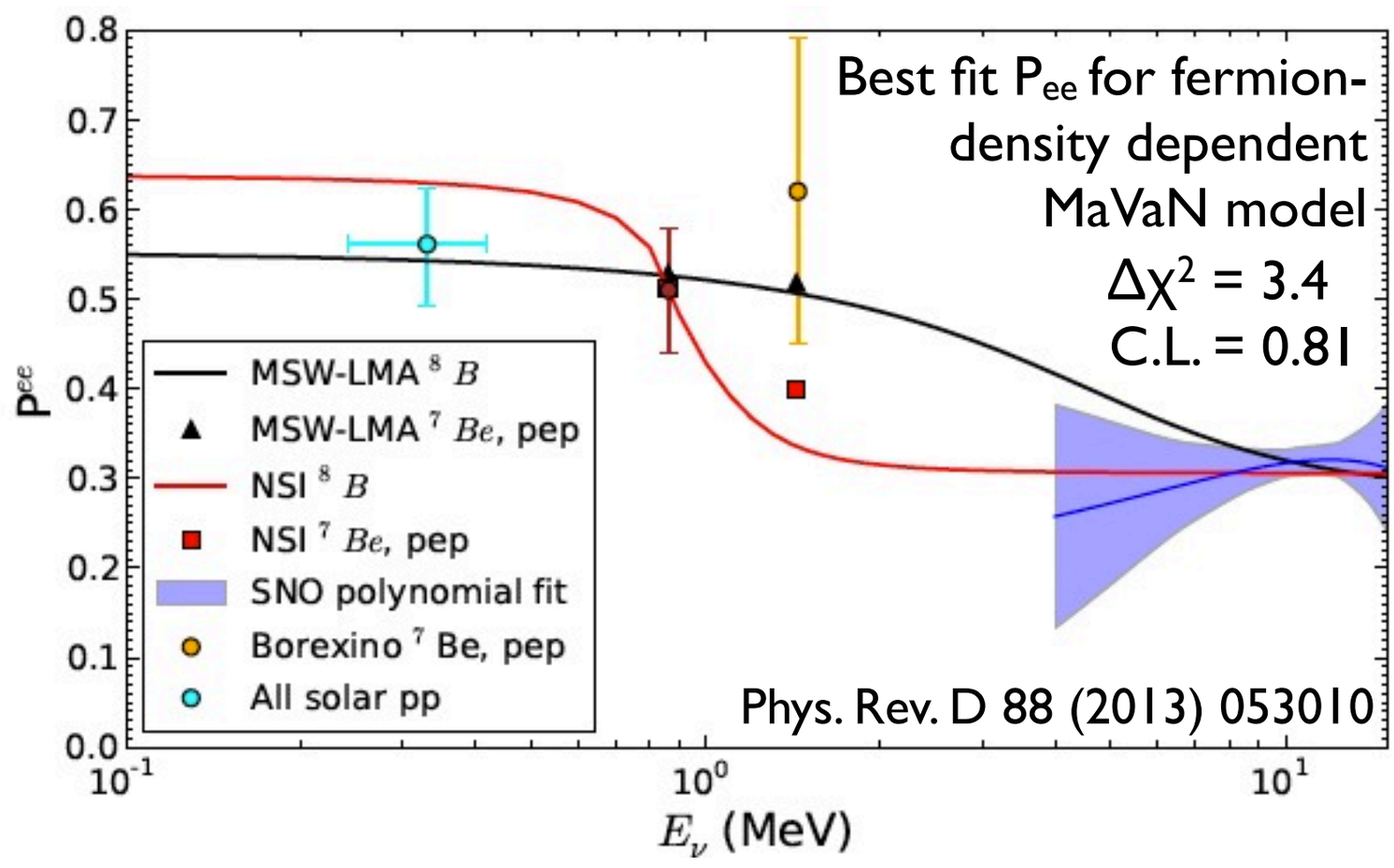

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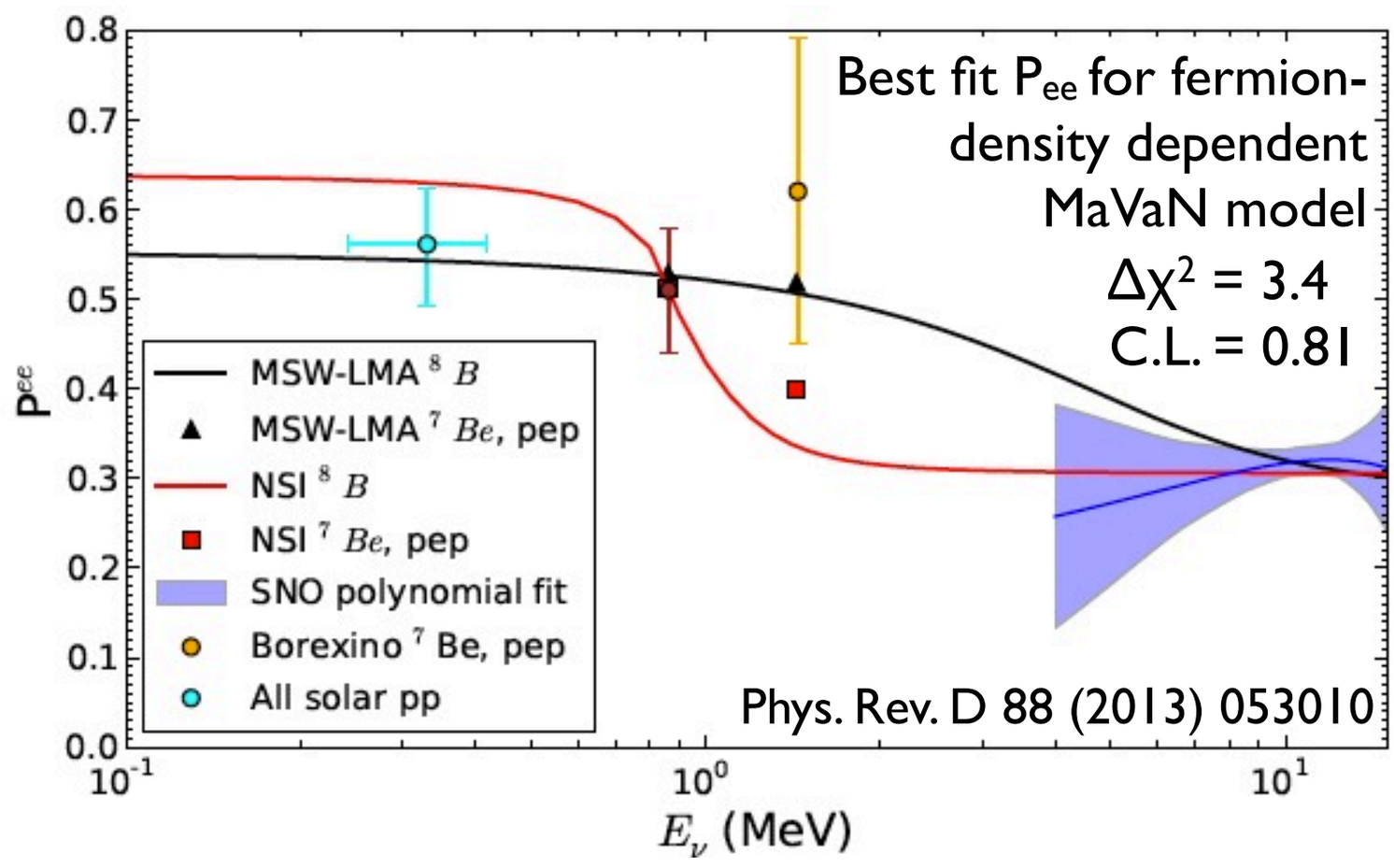
No significant effects (< 2σ)

Results limited by experimental precision

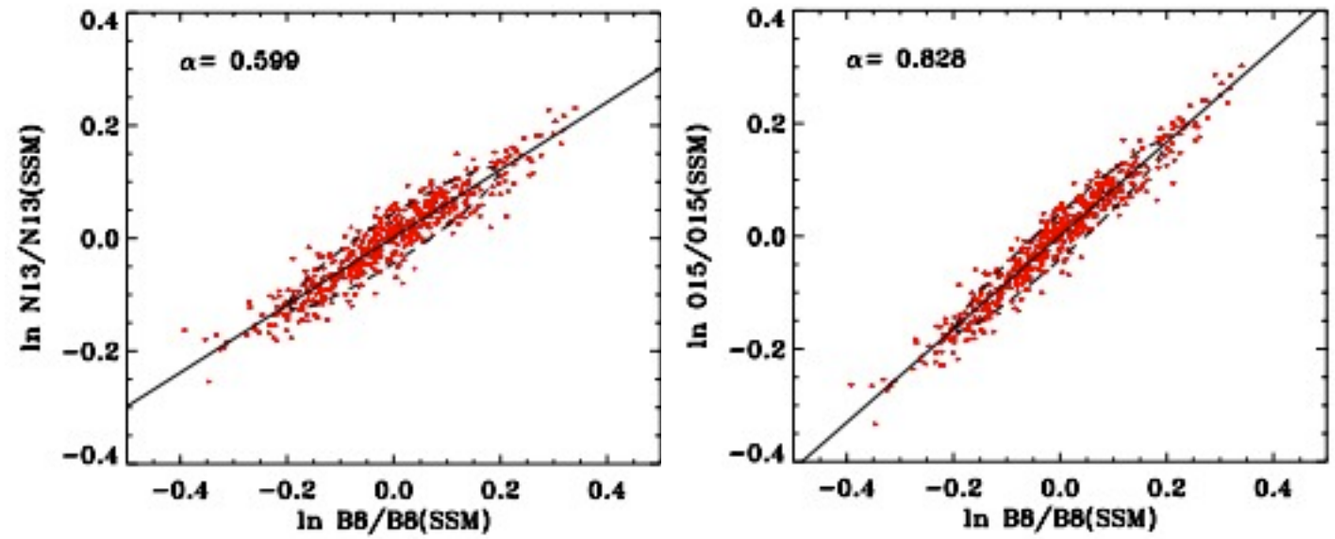


CN-Cycle Neutrinos

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

CN-Cycle Neutrinos

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



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CN-Cycle Neutrinos

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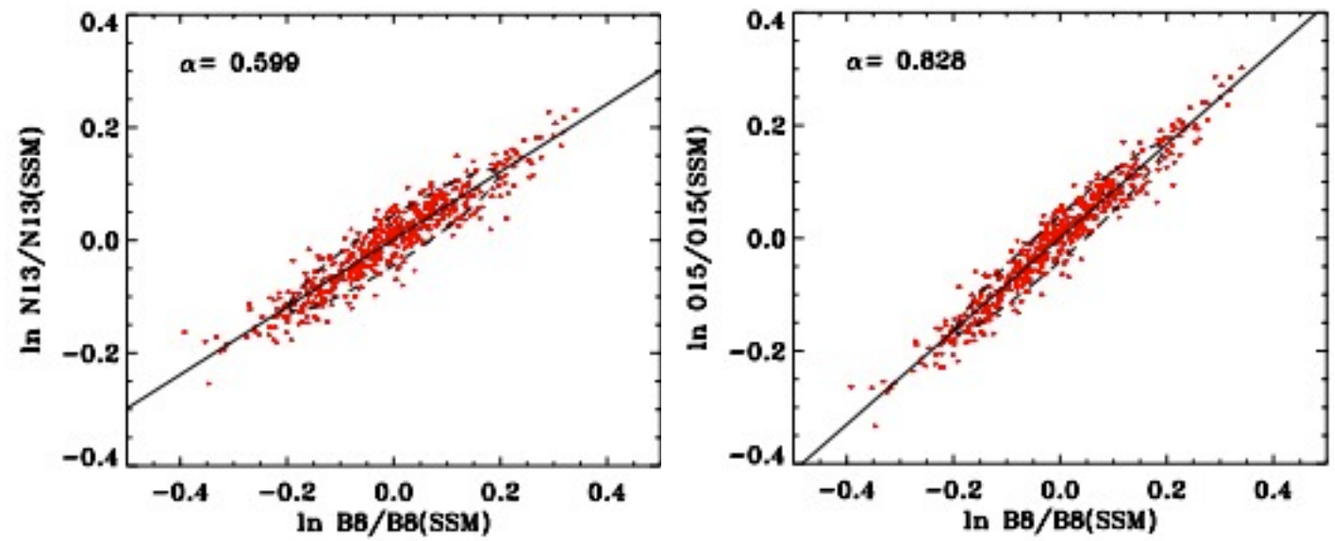
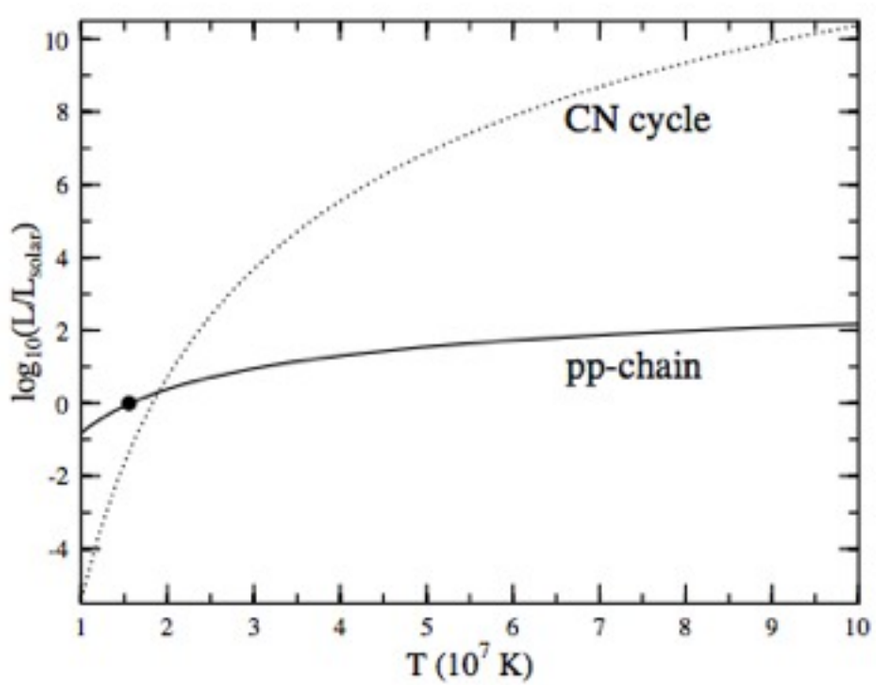


- Test understanding of heavier main-sequence stars



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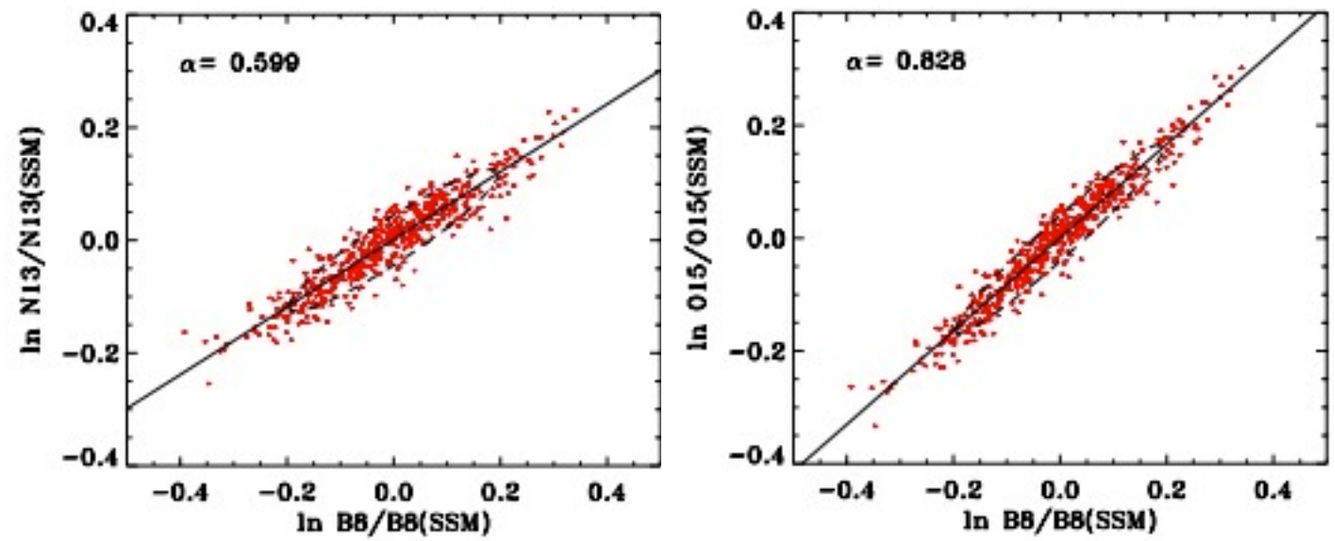

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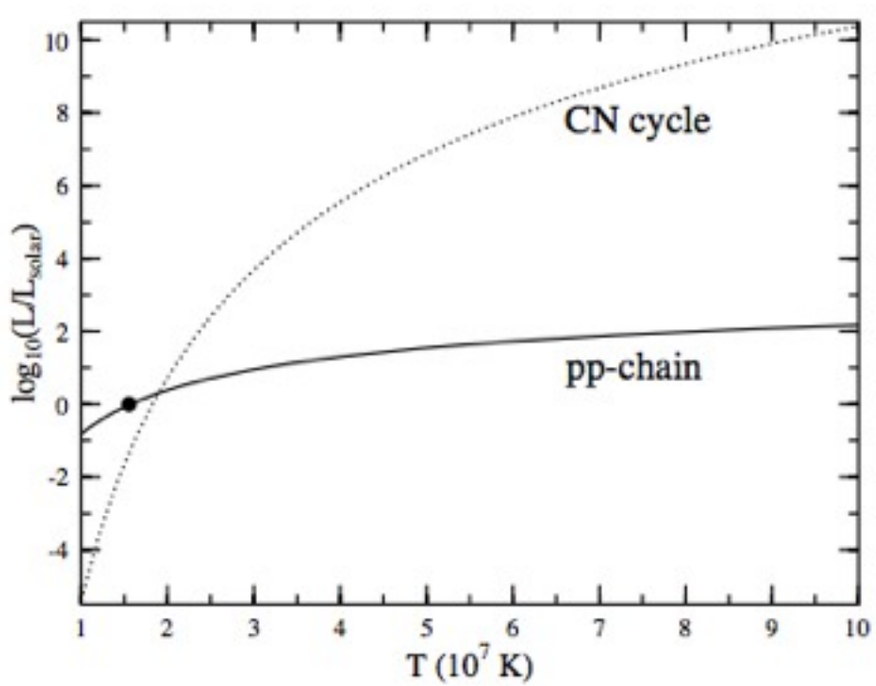

- Test postulate of homogeneous zero-age sun
- Constrain metal accretion during solar formation (did gas giants "sweep out" metals from convective zone?)
- Test extent of CN-cycle equilibrium

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