Deep Scintillation Detectors for Solar Neutrinos

"Here be Dragons"

Gabriel D. Orebi Gann

JinPing Town Meeting
8th Sept 2013

U. C. Berkeley
& LBNL

Solar Neutrinos in 2 Parts

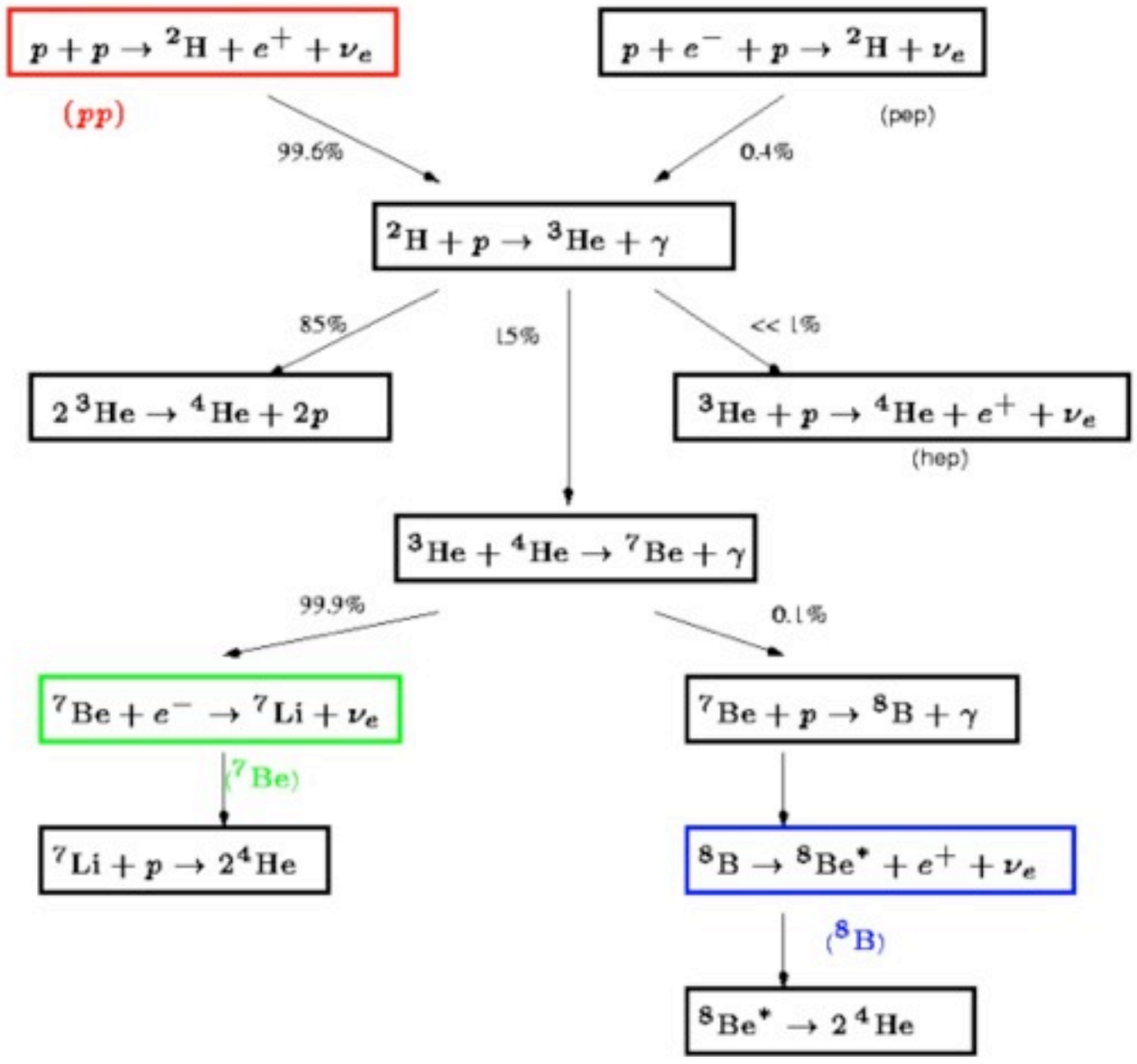
1. **The Solar Neutrino Problem (SNP)**
   - Developing the SSM
   - The search for solar νs
   - The SNO experiment
   - Resolution of the SNP

2. The road forward

- Open questions
- Current experiments
- The next generation

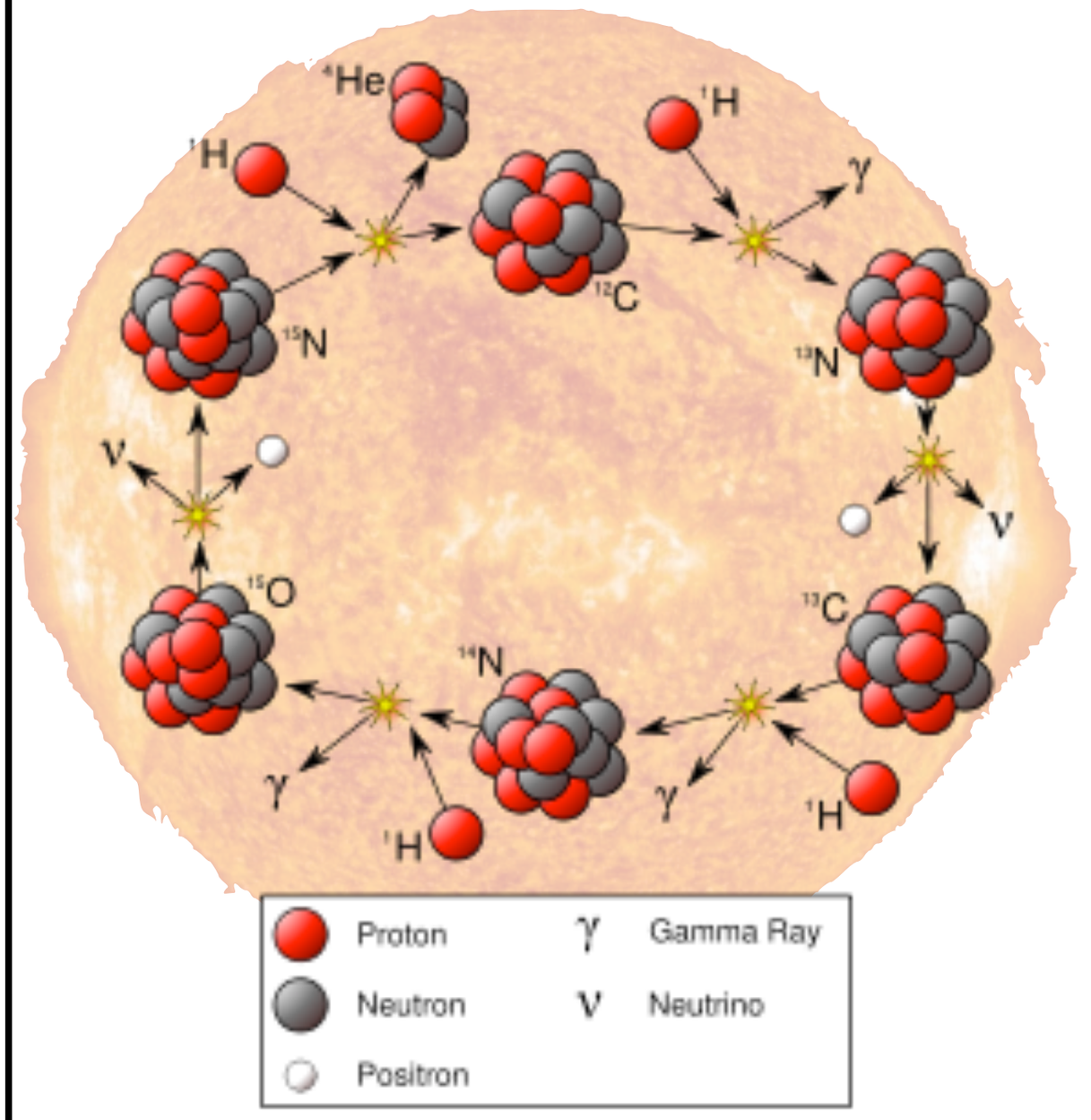
Modern Understanding

pp Chain



CNO Cycle

(contributes ~1% of solar energy)



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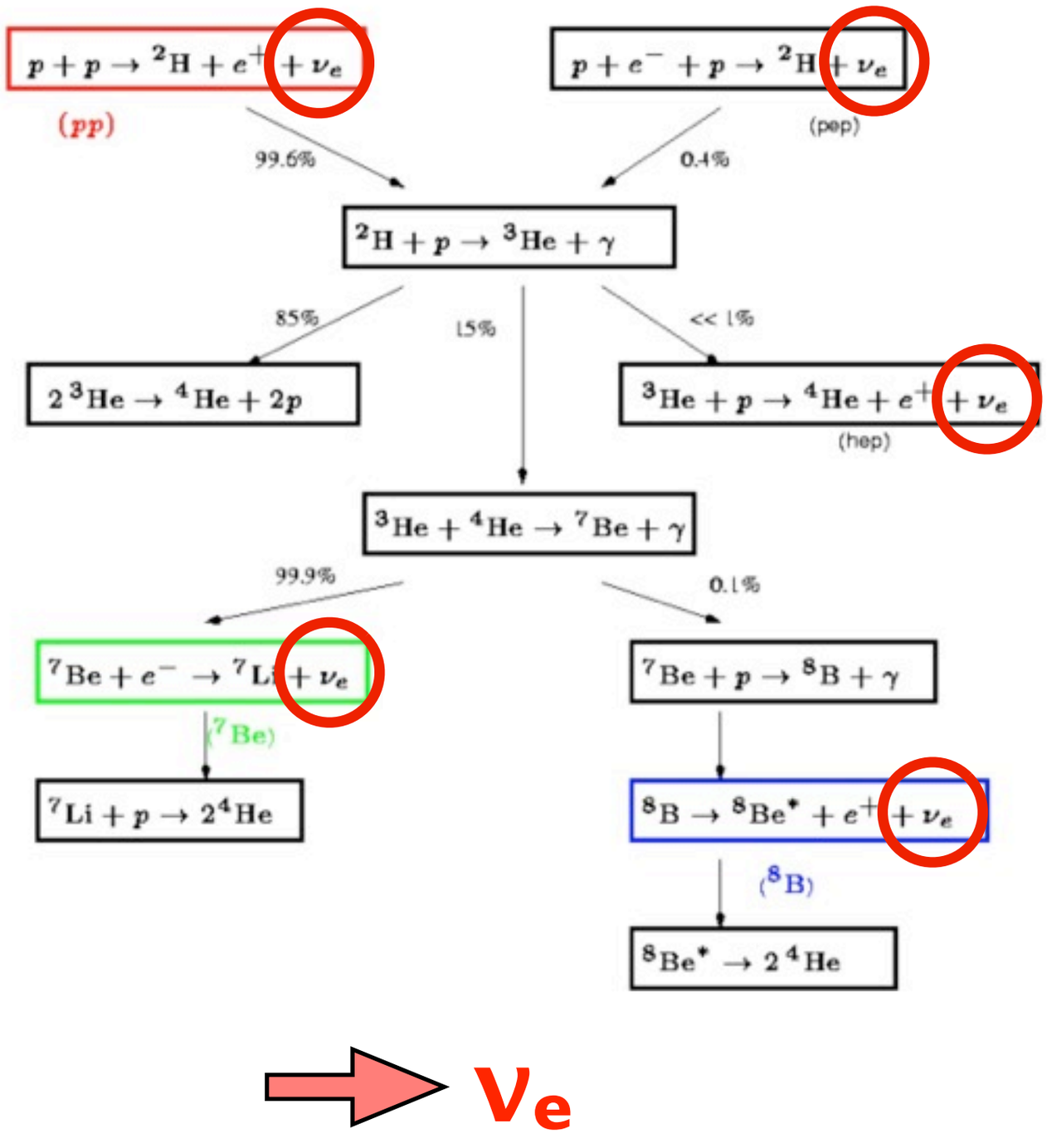

ν_e

CNO Cycle

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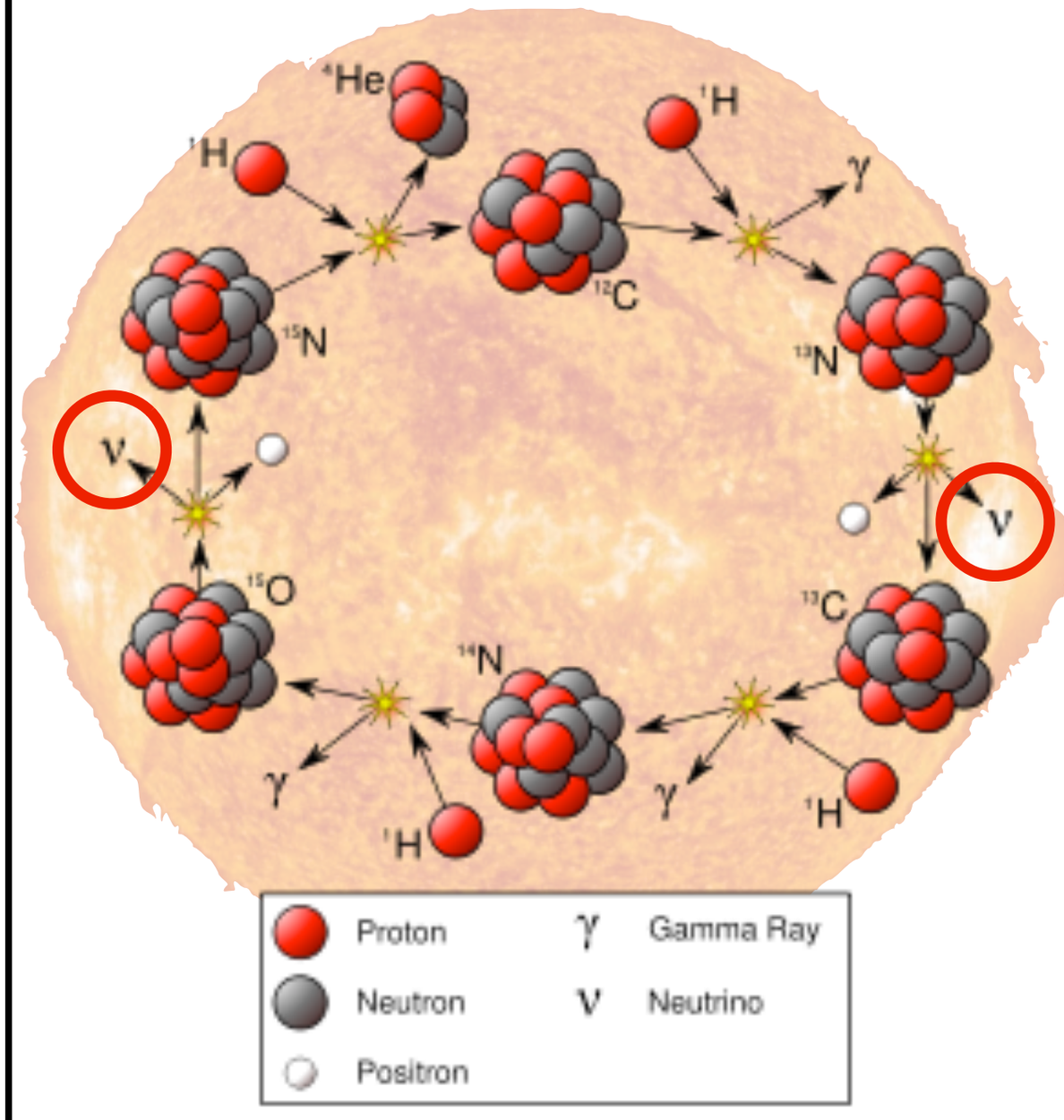
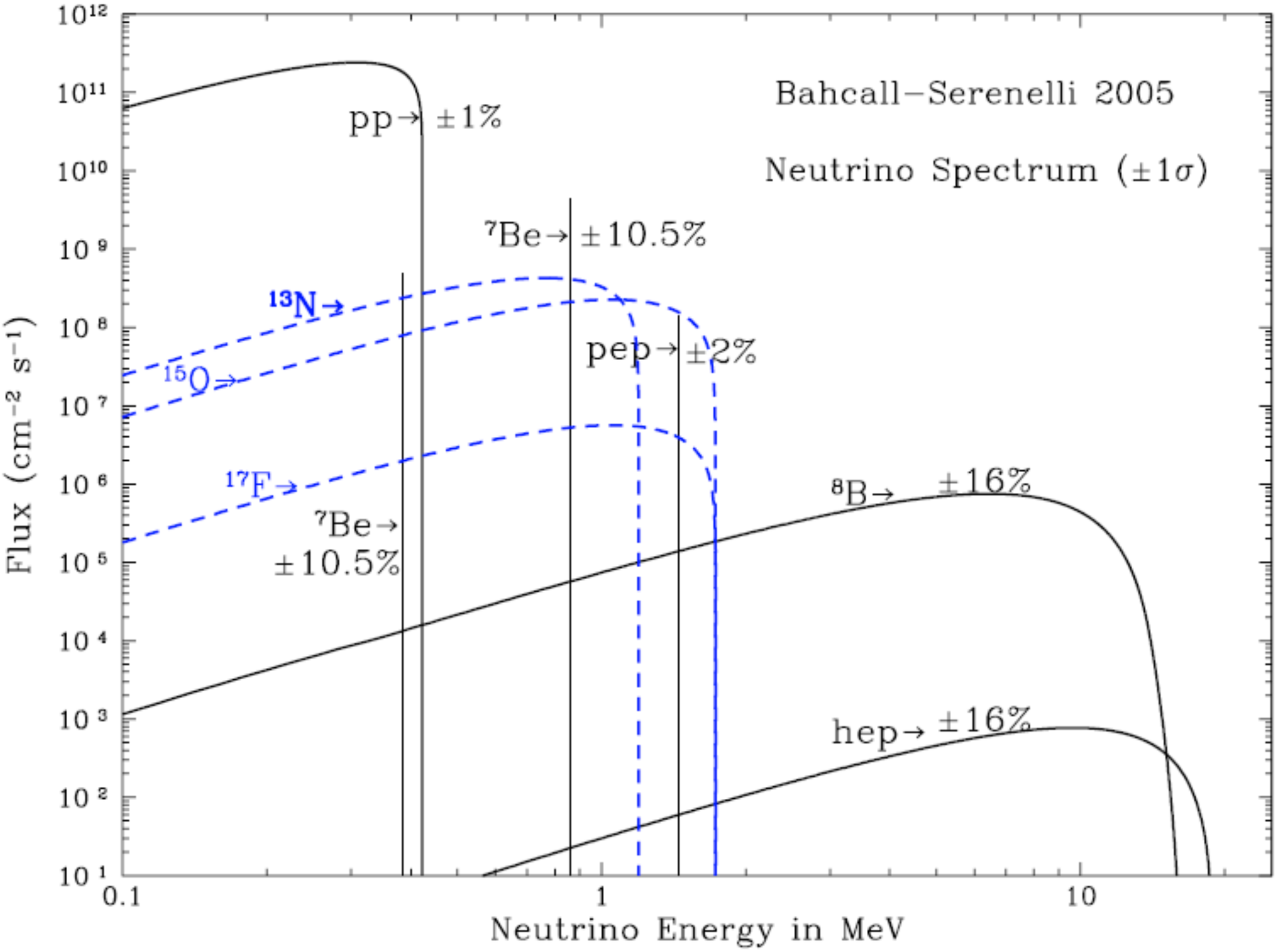


Solar υ Energy Spectra



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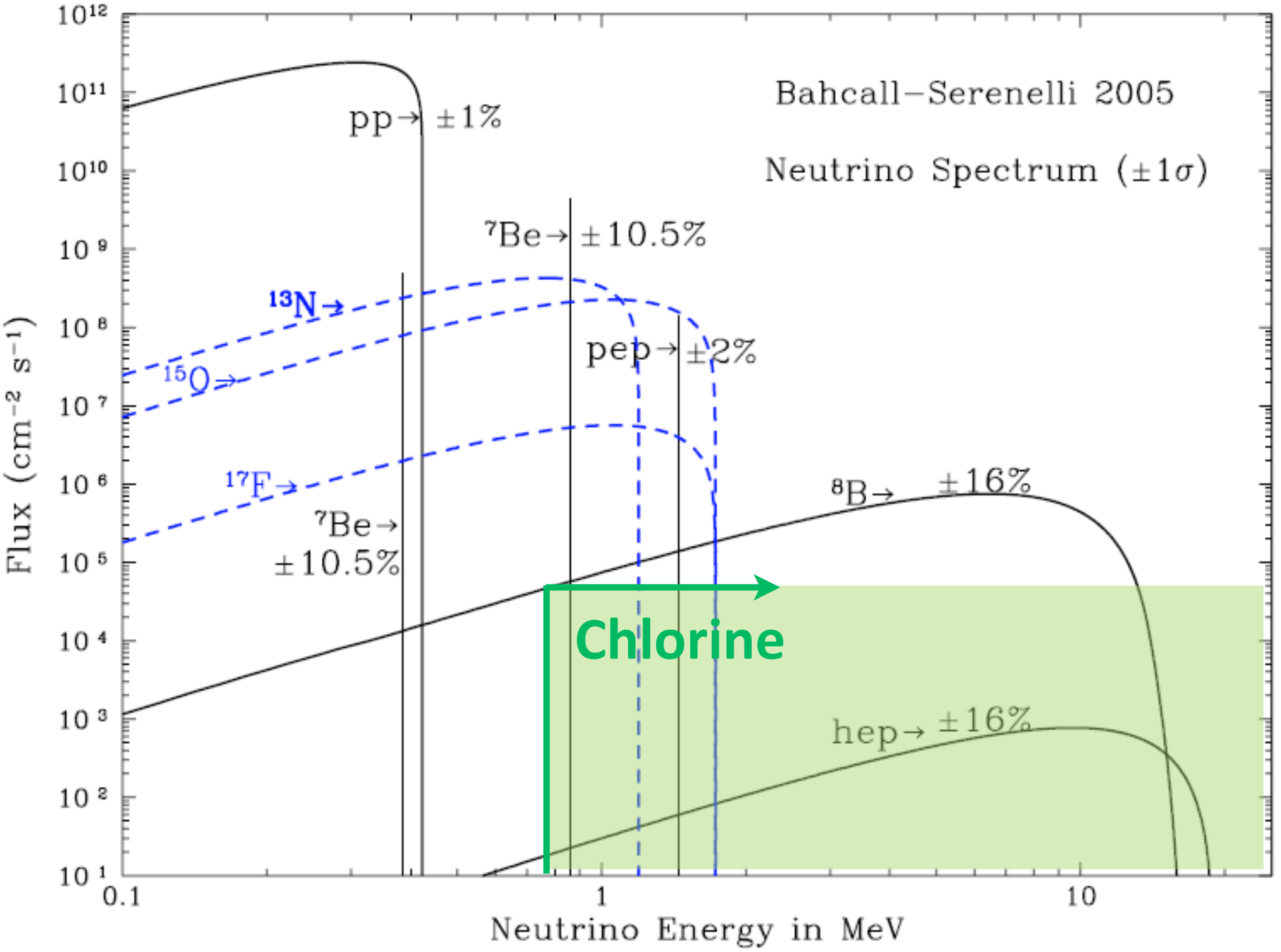

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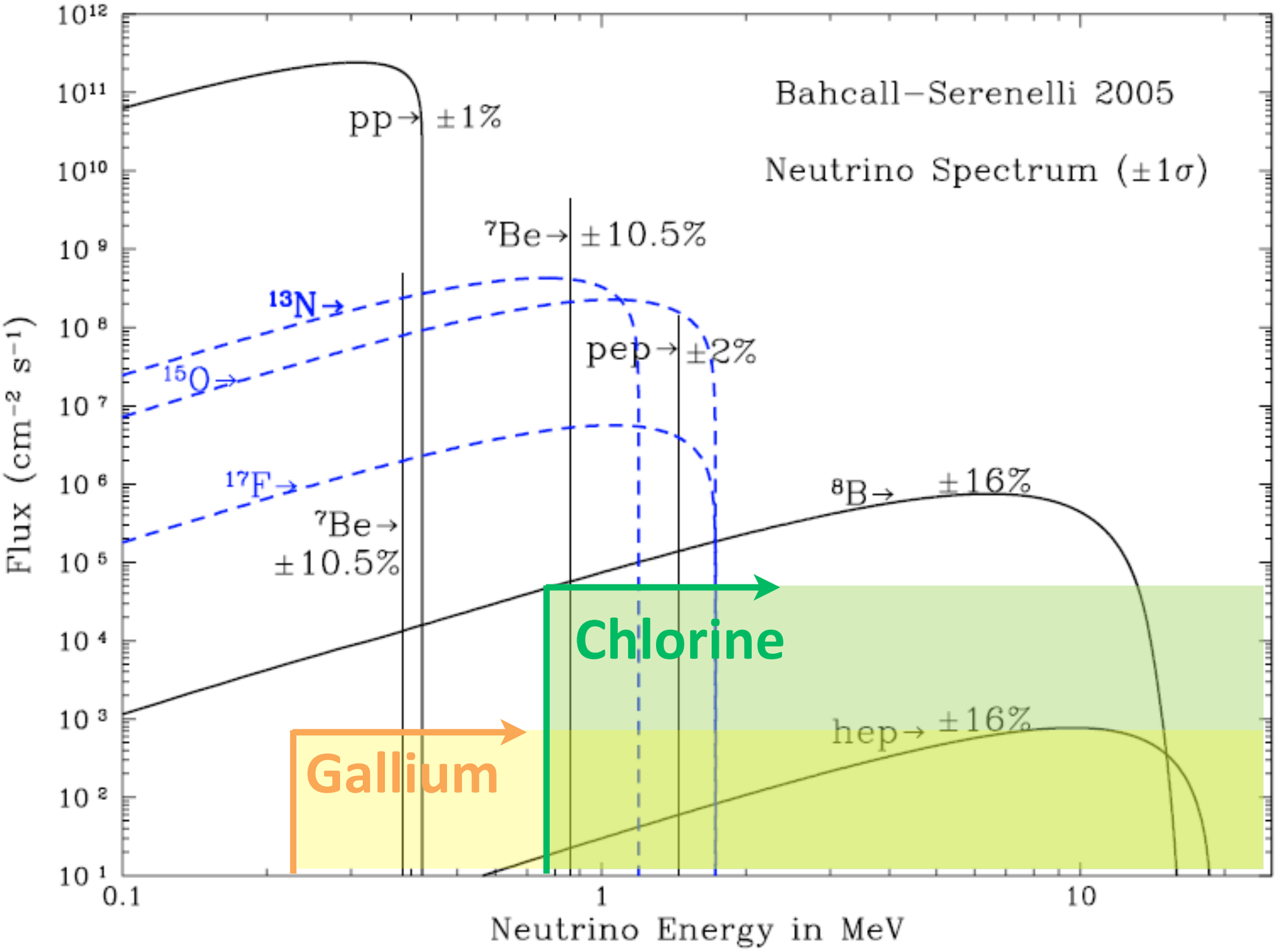

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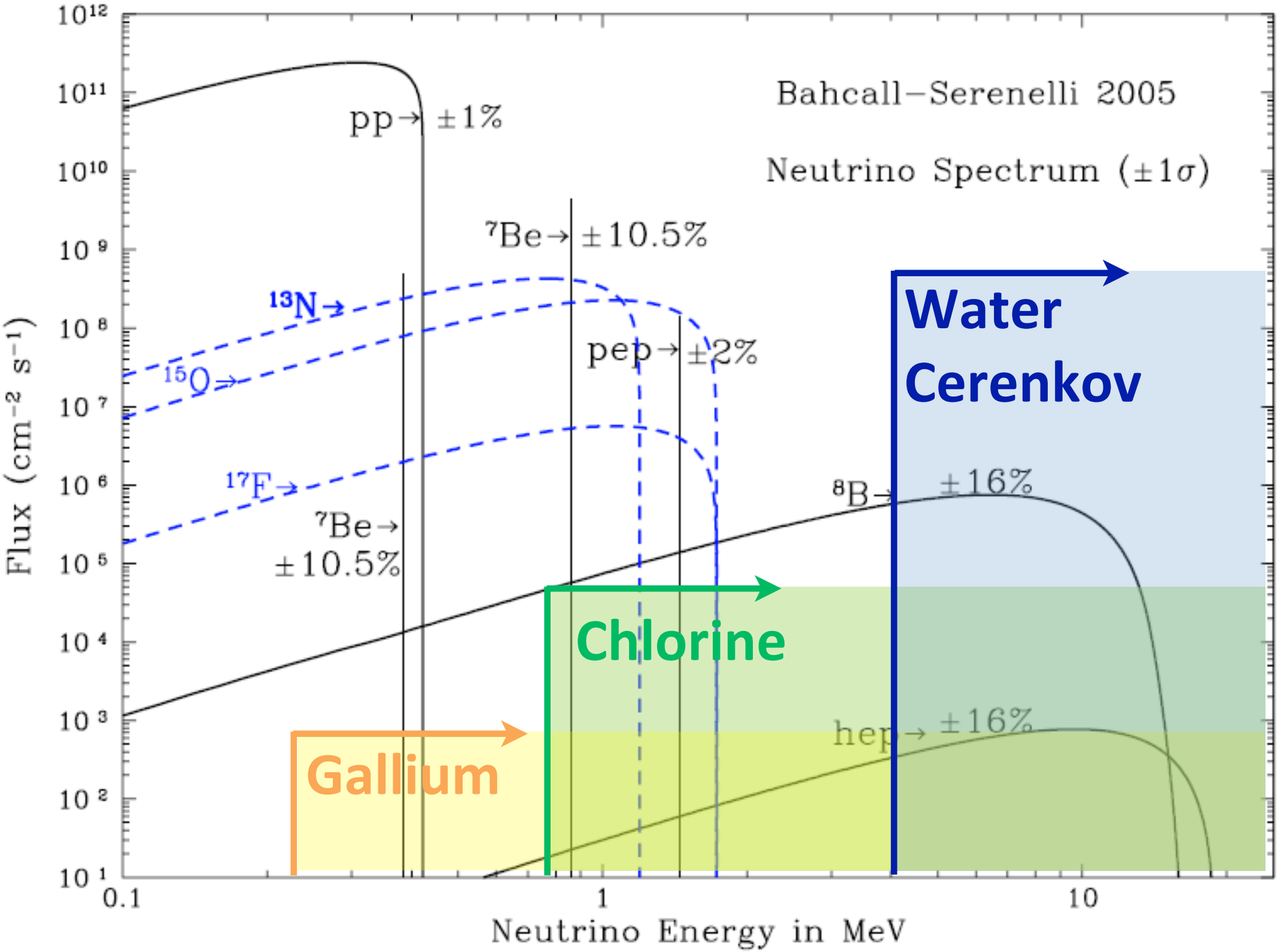

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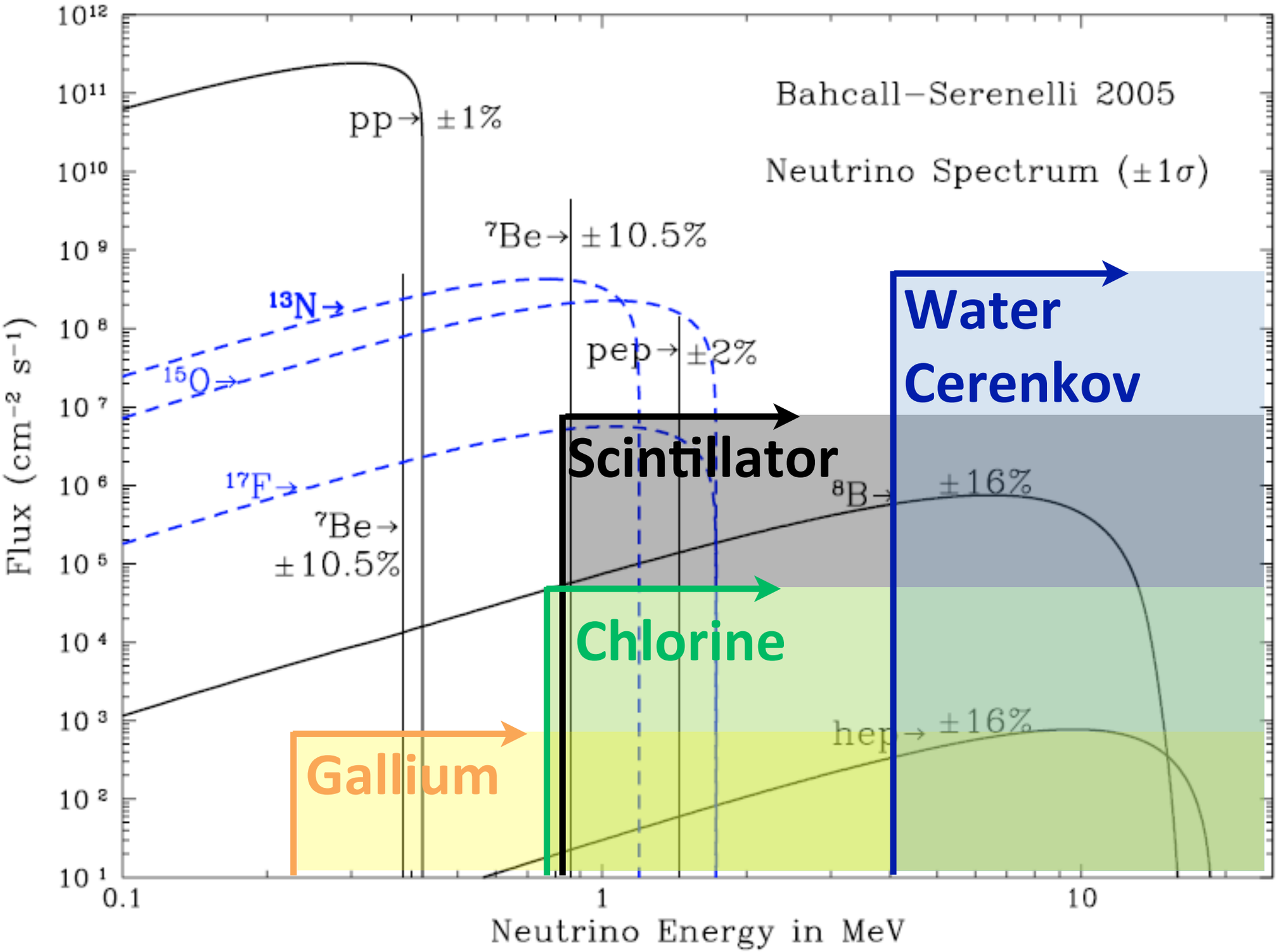

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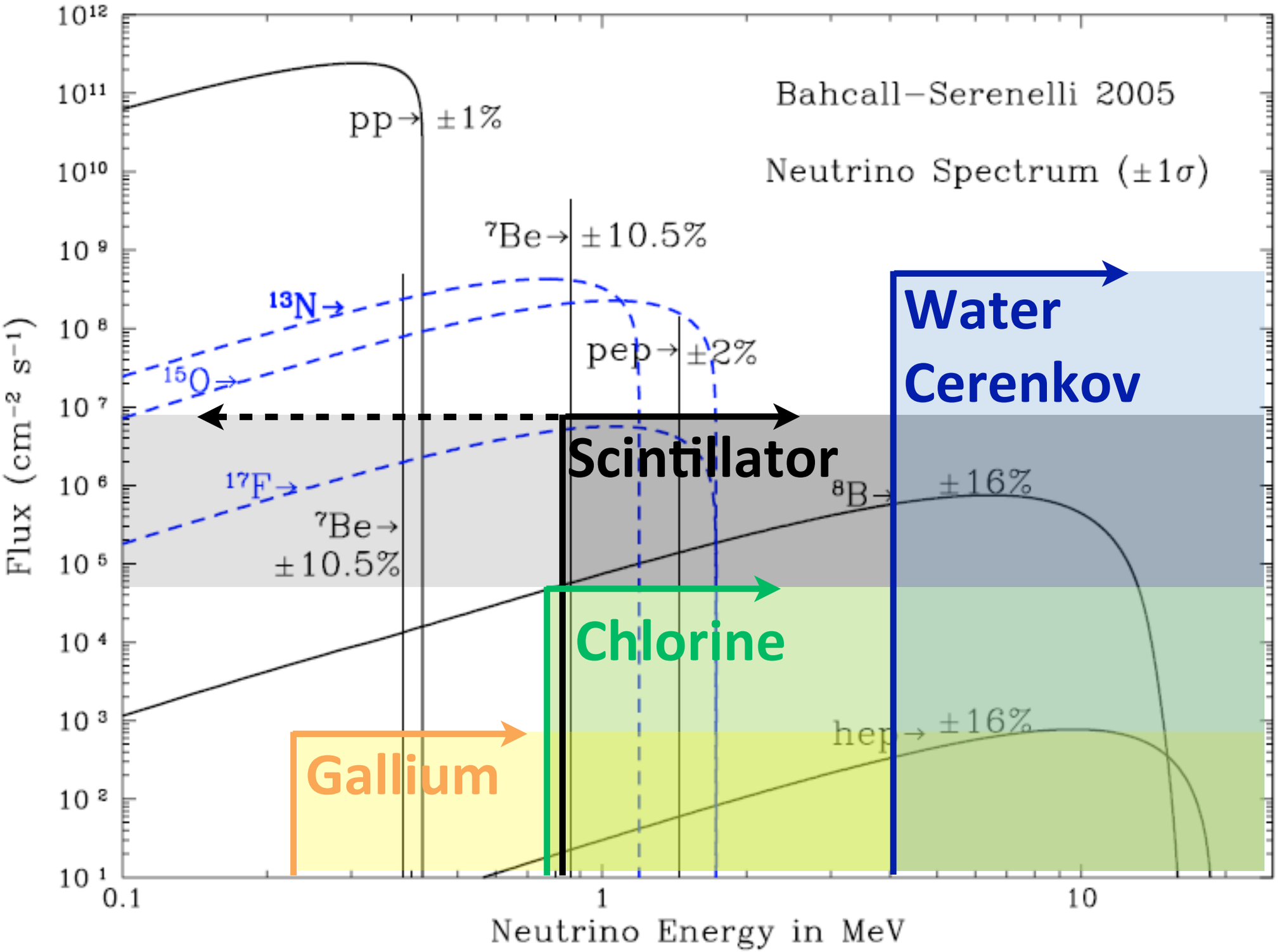
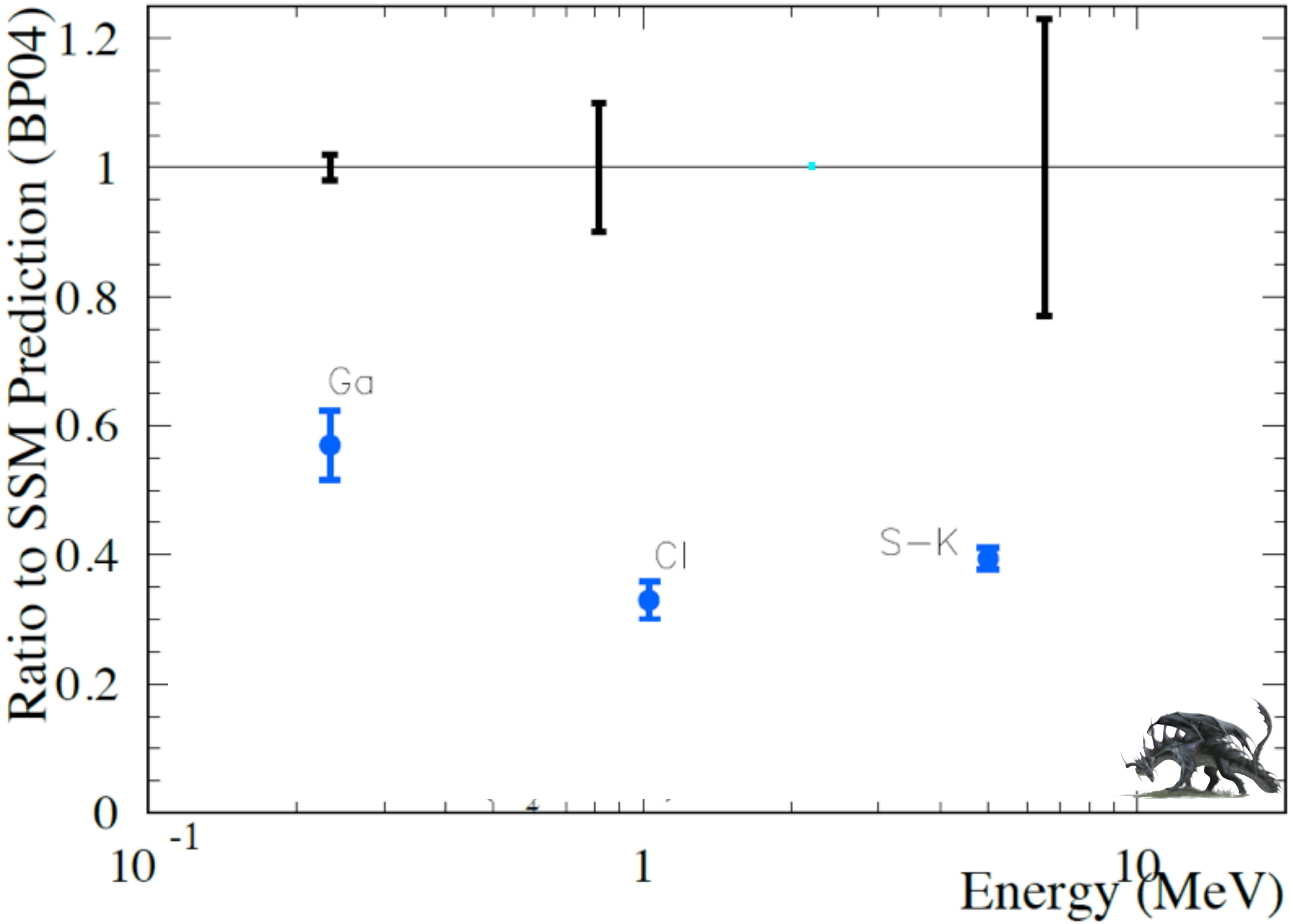


Solar Neutrino Problem



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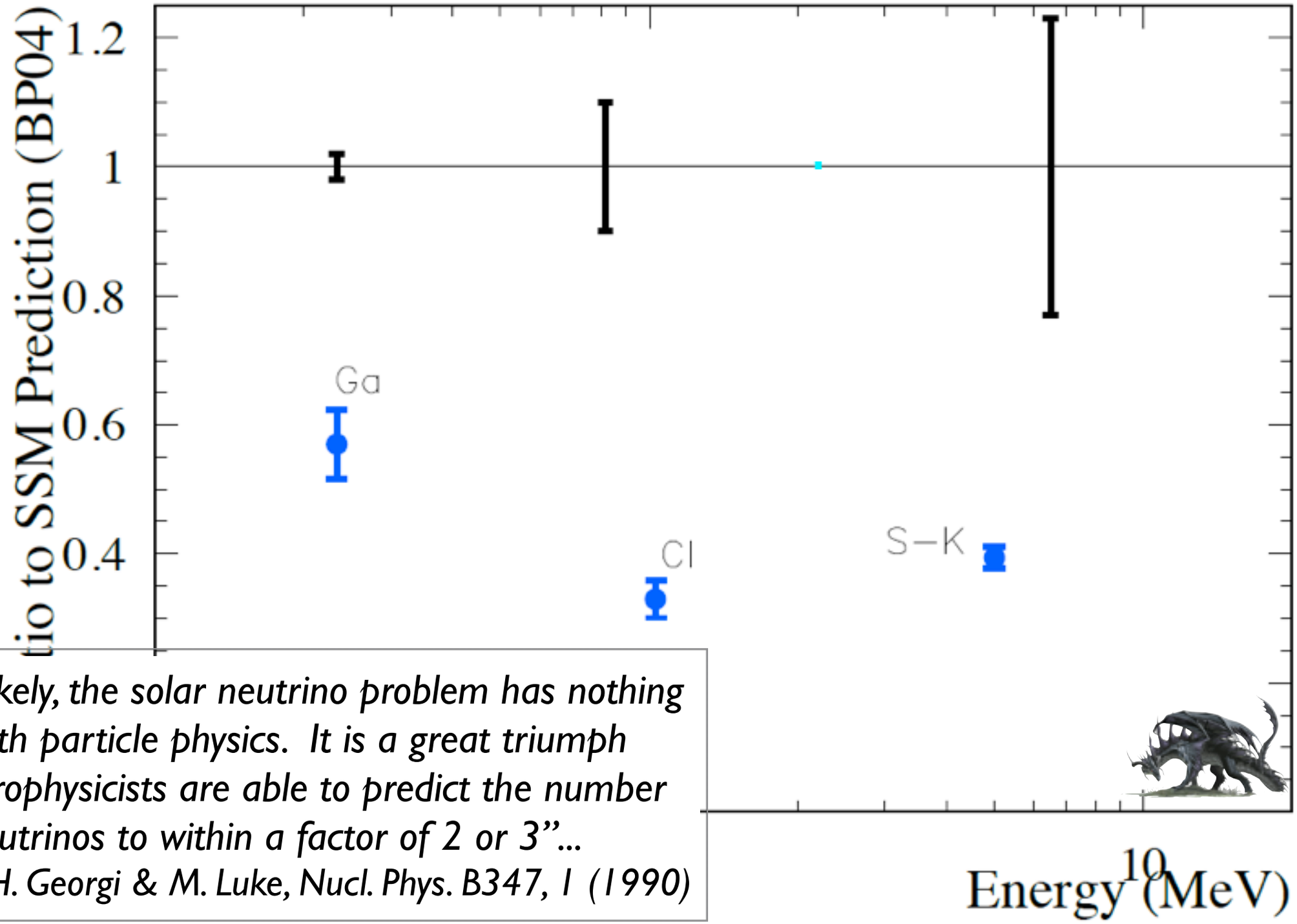
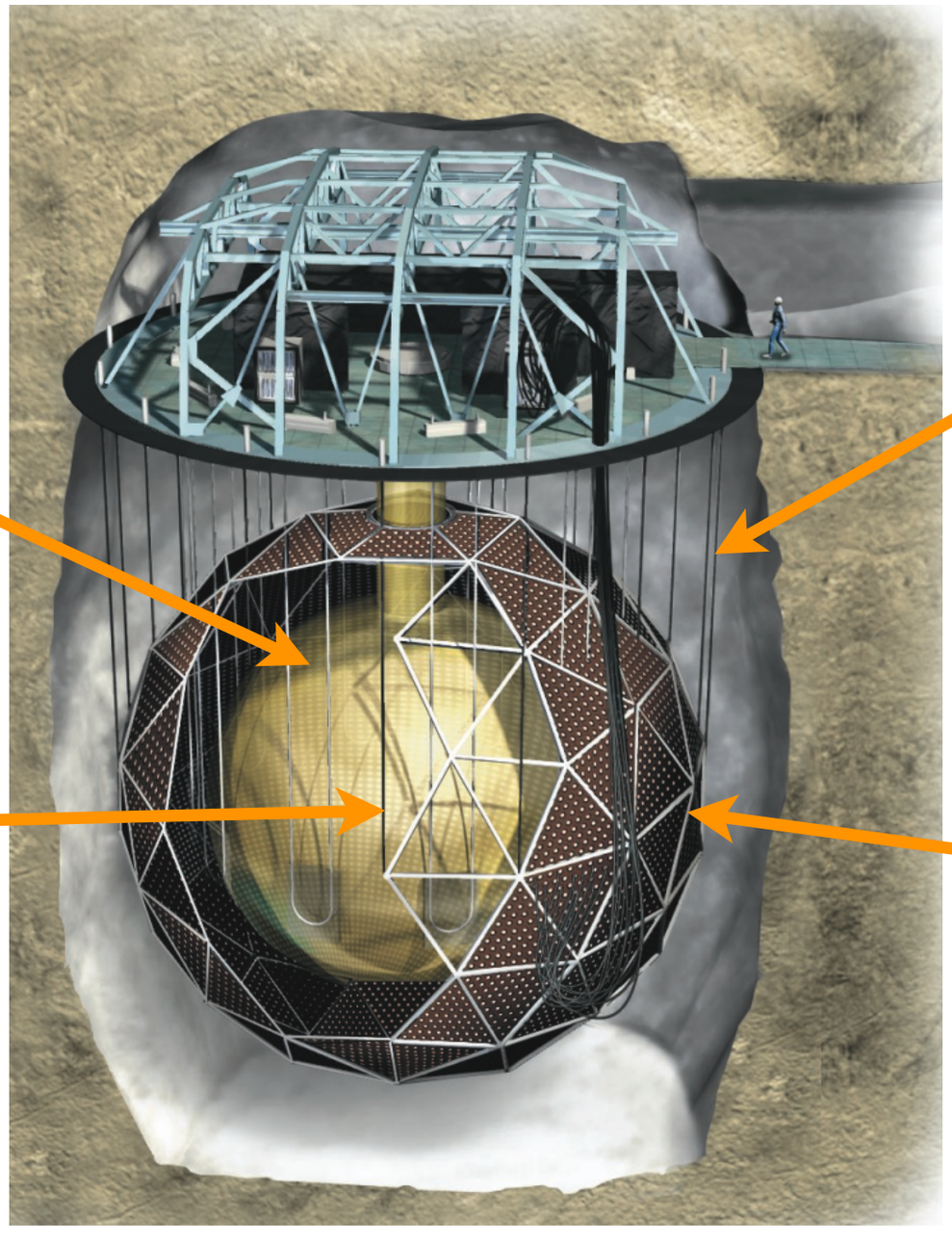


"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3"...

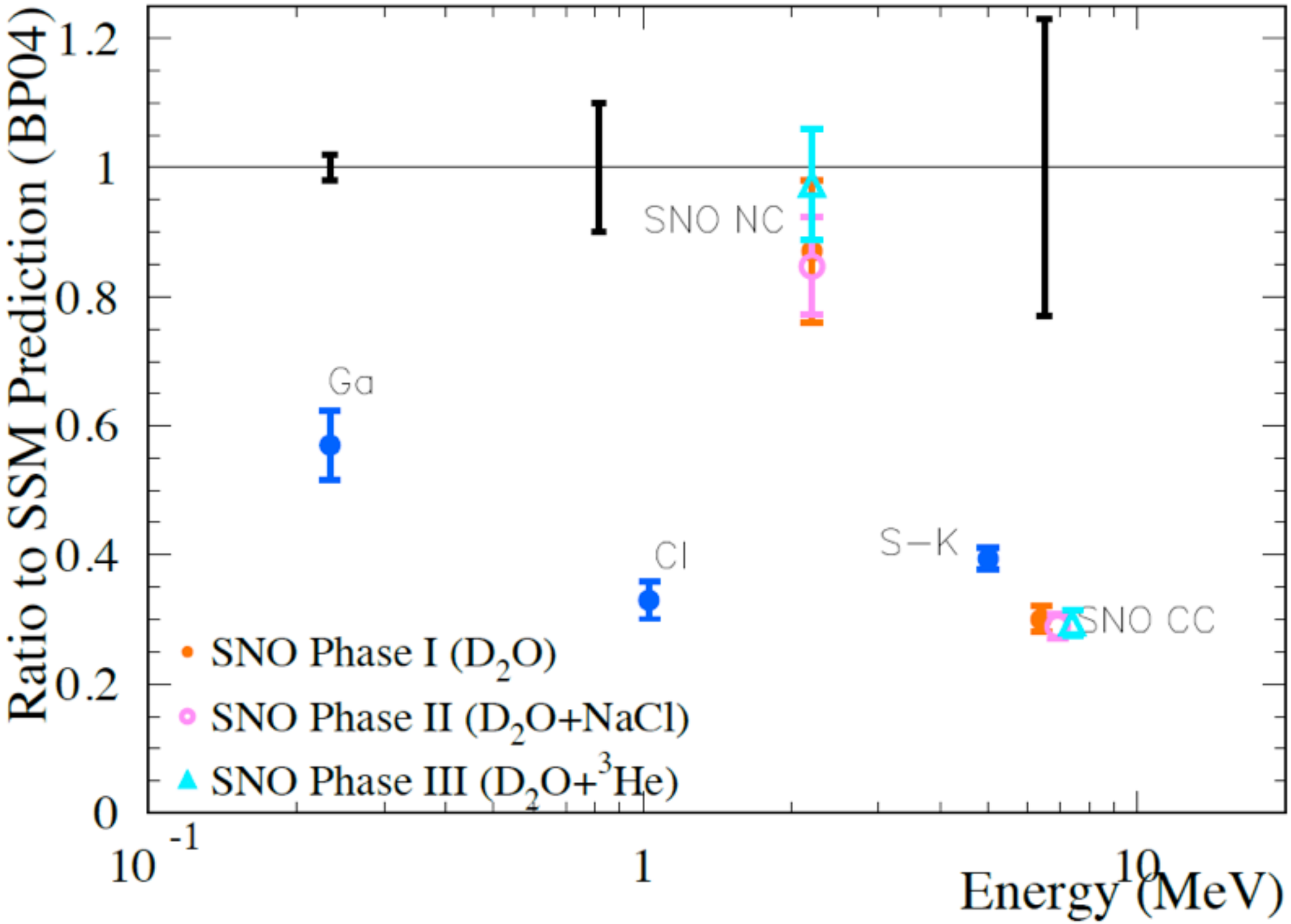
--H. Georgi & M. Luke, Nucl. Phys. B347, 1 (1990)

Sudbury Neutrino Observatory (SNO)



- 12m acrylic vessel
- 1kT D_2O
- 6800ft level
- 5890 m.w.e.
- 1.7kT + 5.3kT H_2O buffer
- 9500 PMTs, 60% coverage

Solar Neutrino Problem: Resolved



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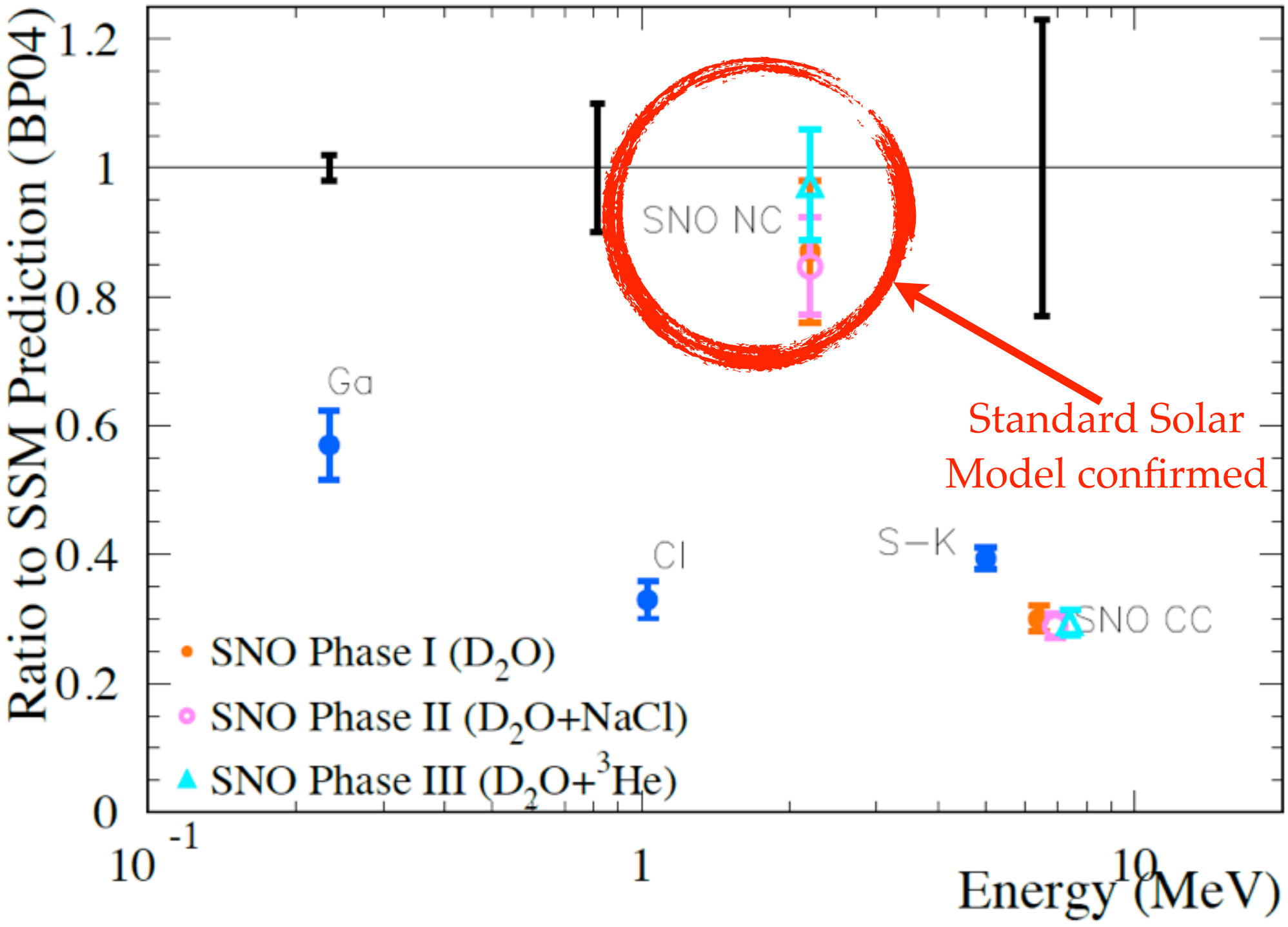


Solar Neutrinos

“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

Questions Beyond the SNP

(A) What is the true shape of the ν_e survival probability?

(B) Can we observe the Day / Night effect? (If not, why not??)

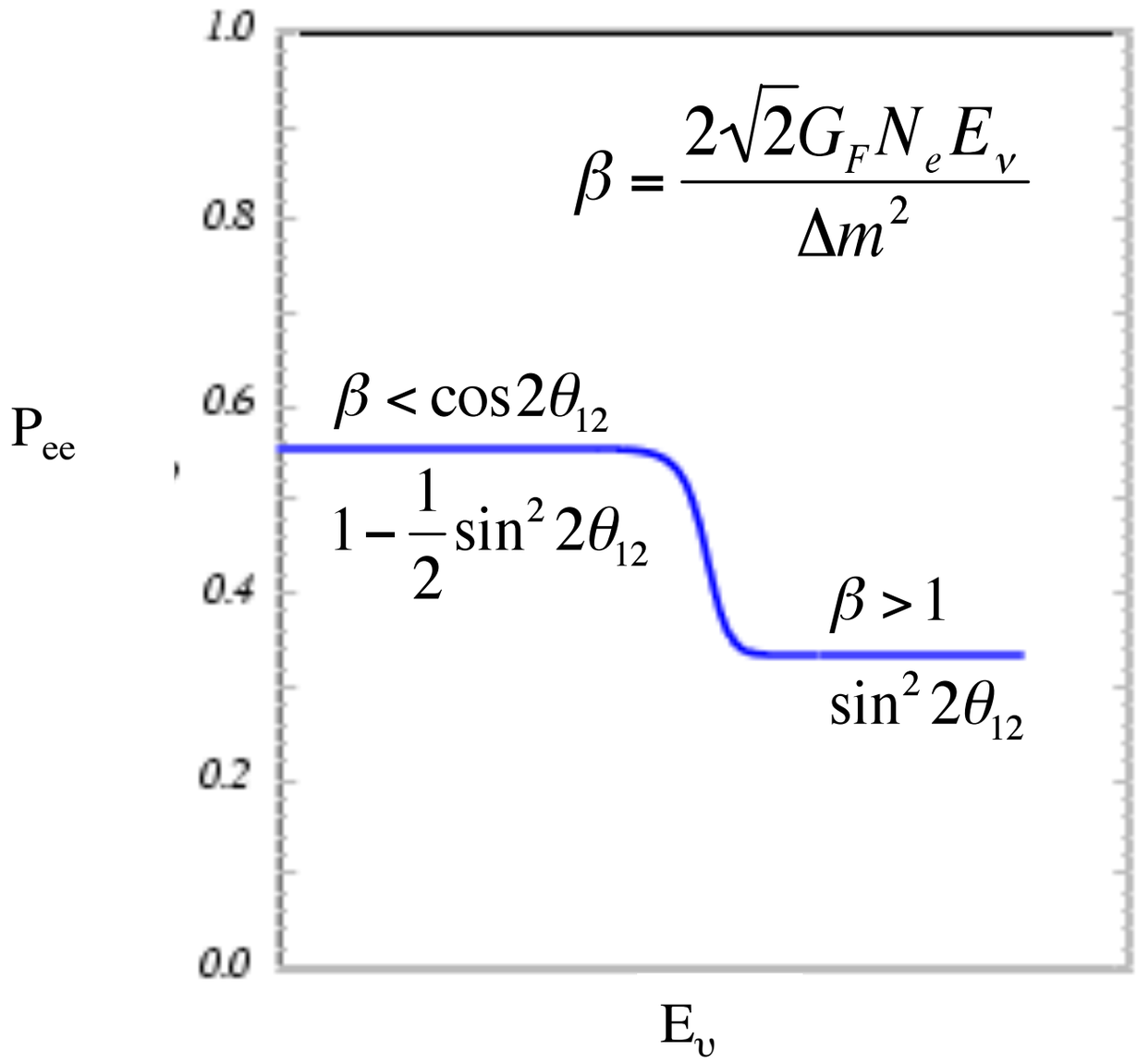
(C) What is the metallicity of the Sun's core?

(D) Can we measure the neutrino luminosity ($\mathcal{L}_\nu$)?

(E) (Are there periodicities / time-dependence to $\mathcal{L}_\nu$?)

(F) (Precision measurements of fluxes & oscillation parameters)

(A) Vacuum-Matter Transition



hep-ph/0305159

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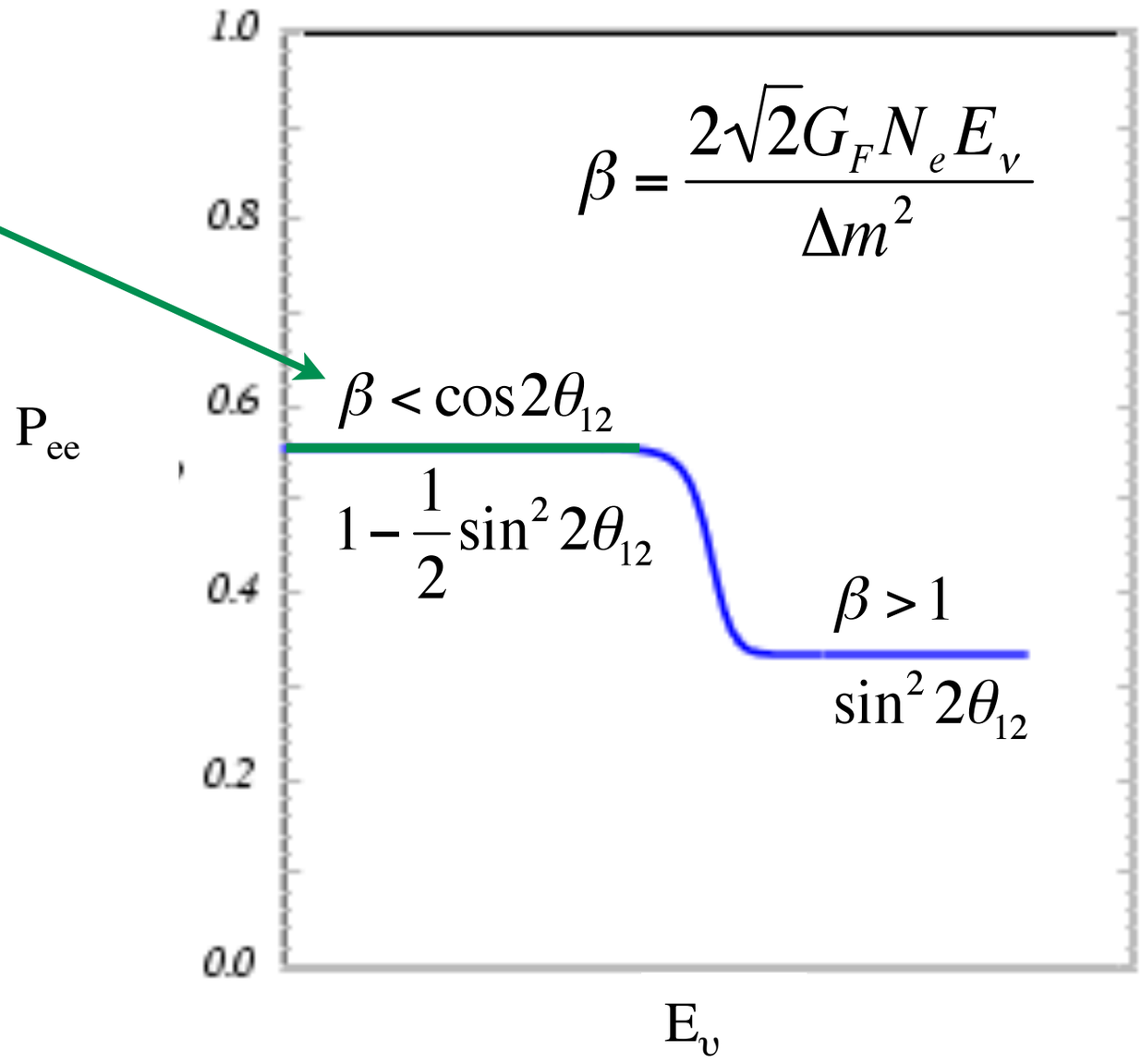
Low energy:
Phase-averaged
vacuum oscillations



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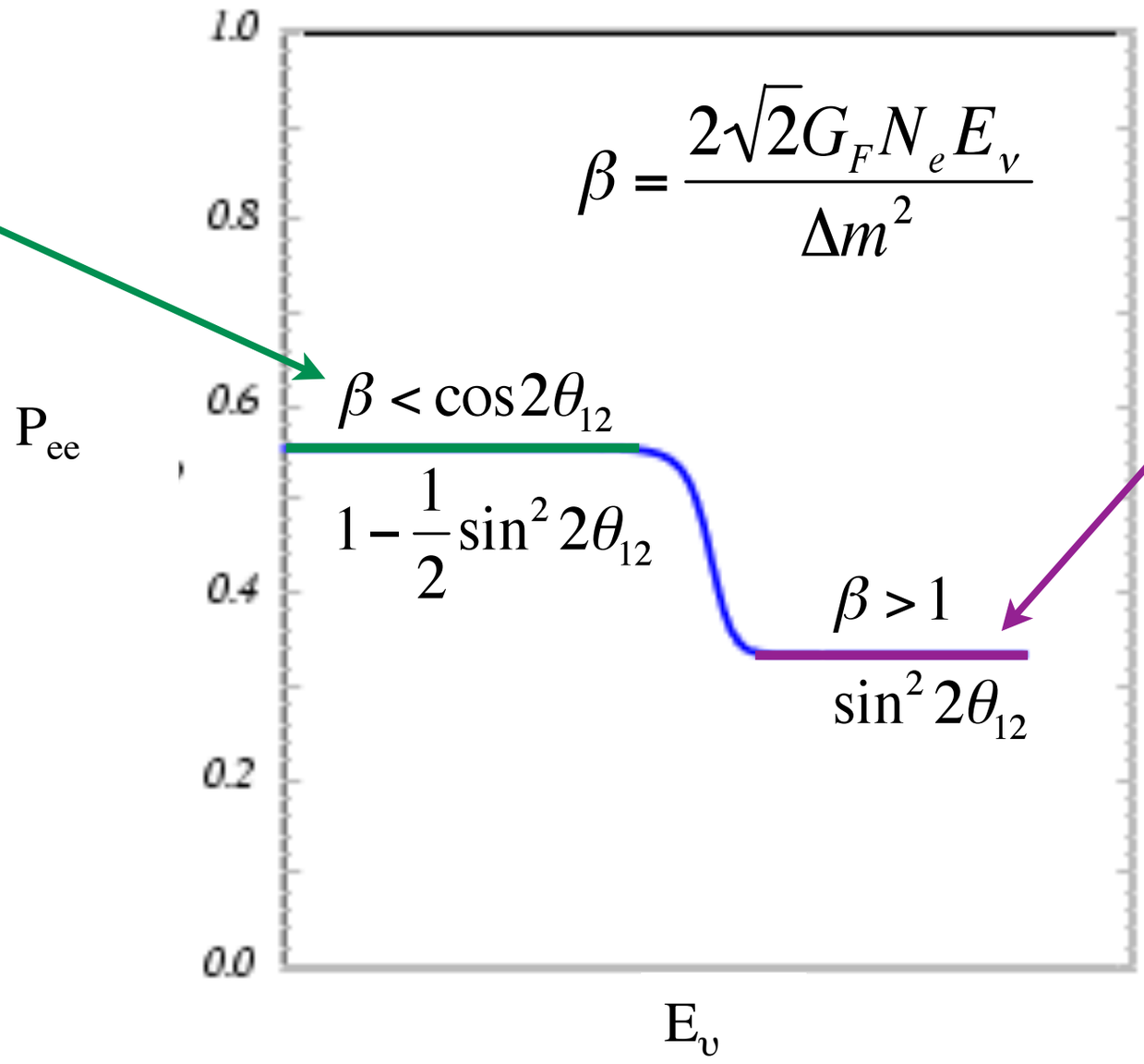

'High' energy:
Matter-dominated
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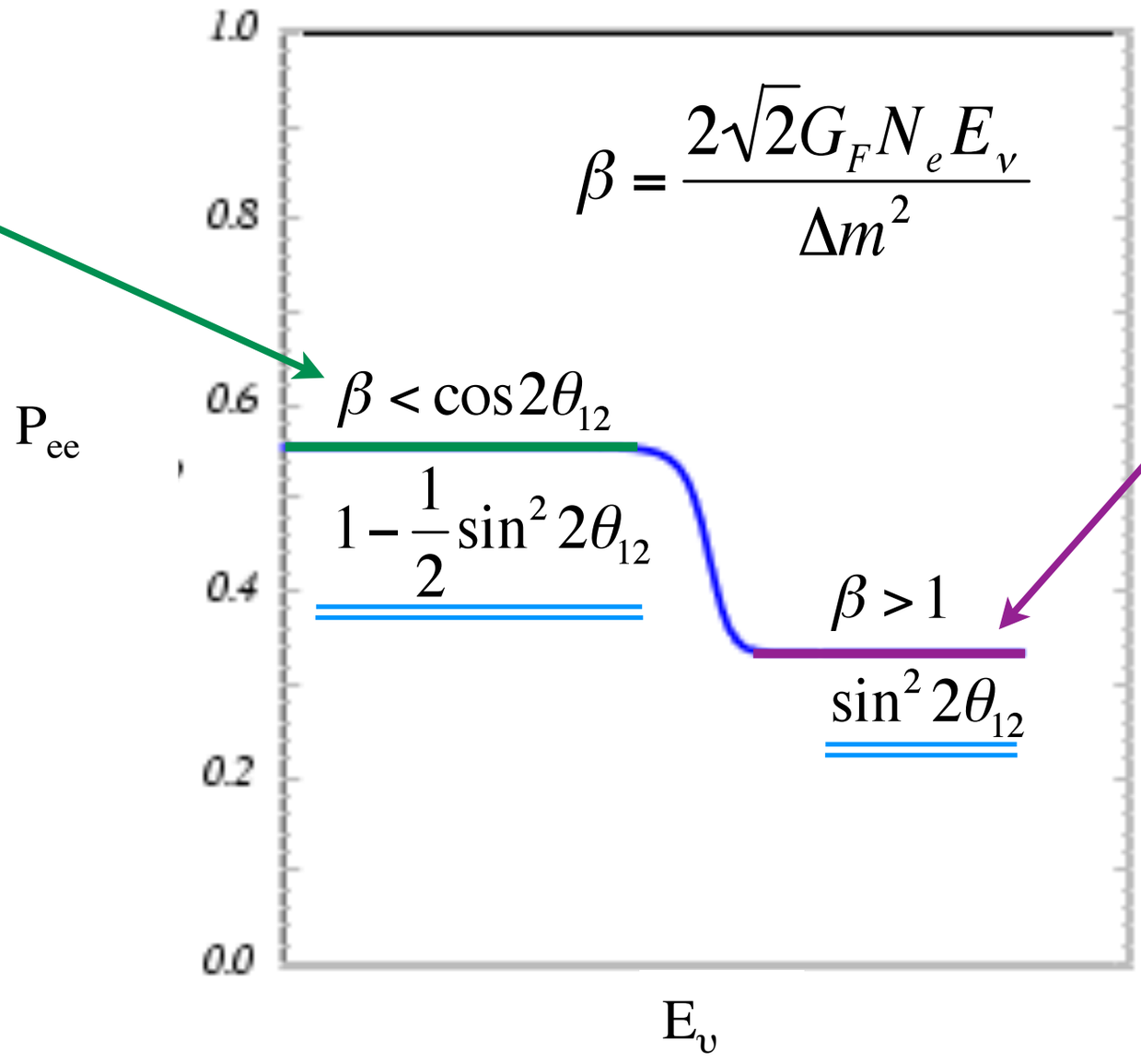

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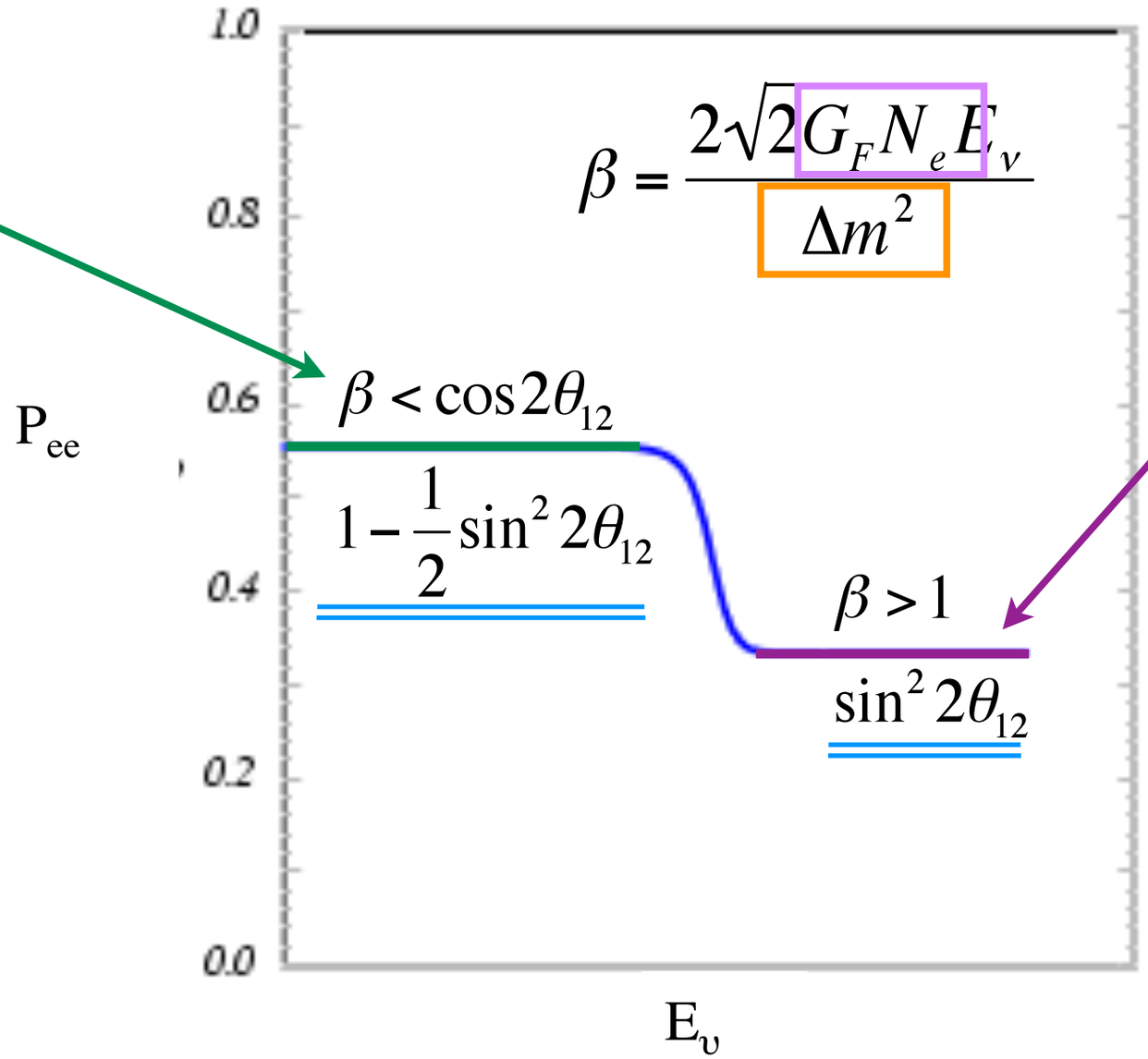

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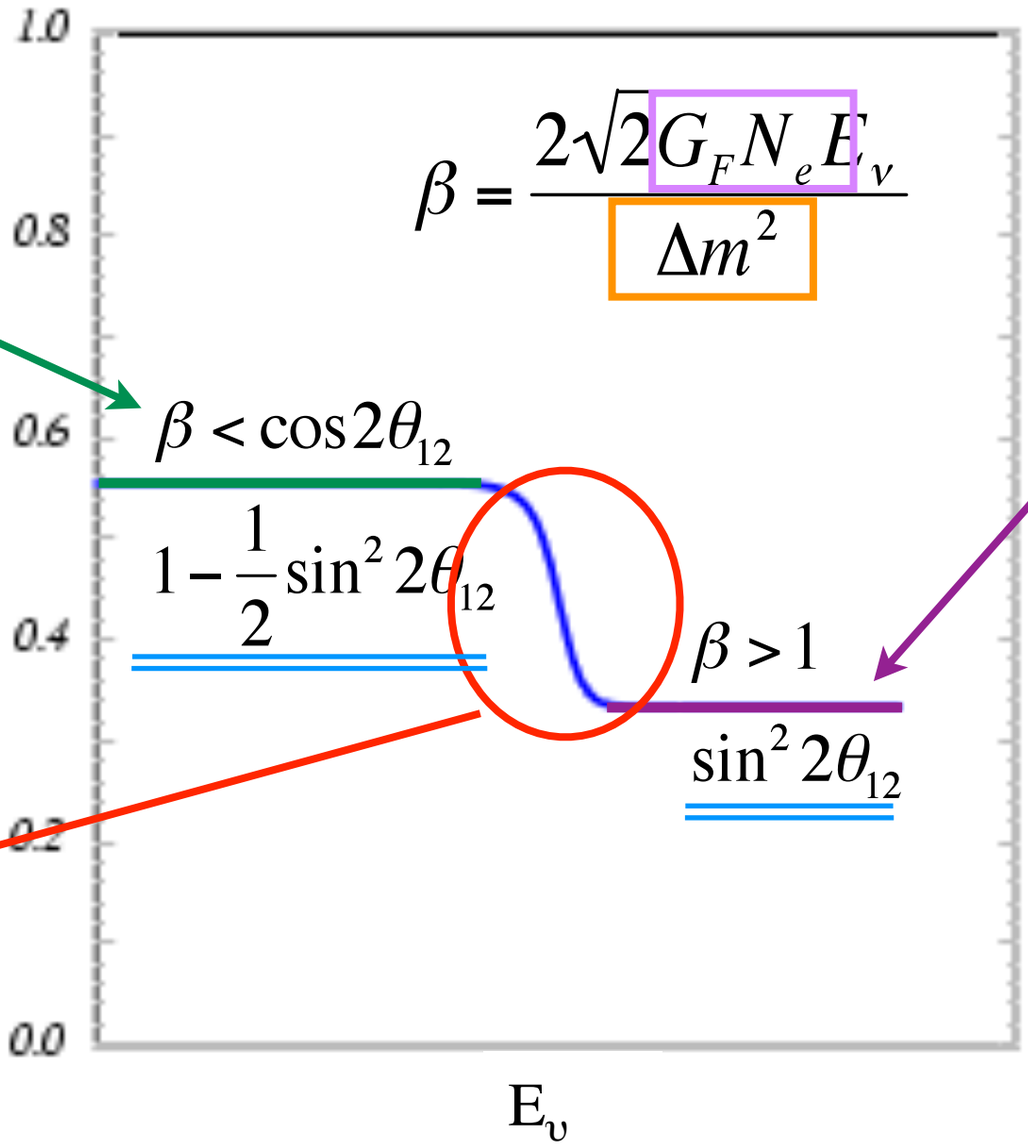

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Probe transition
region to
confirm MSW

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Probing the Unknown

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

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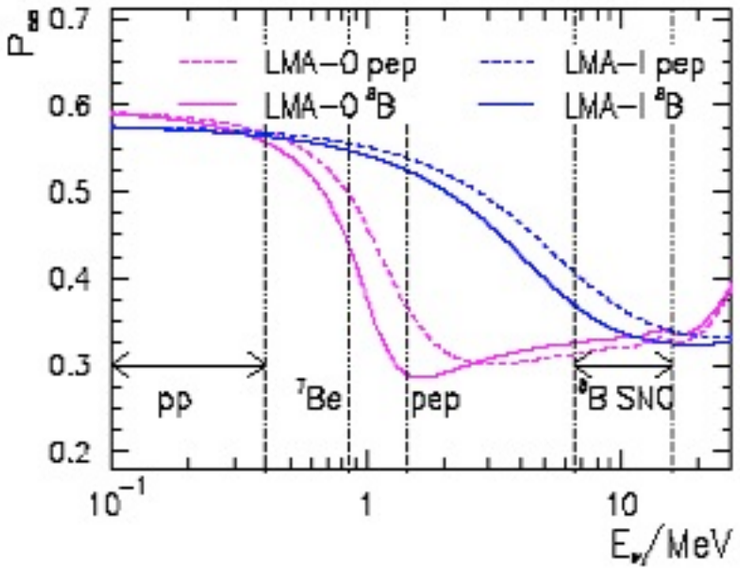
(flavour changing NC)



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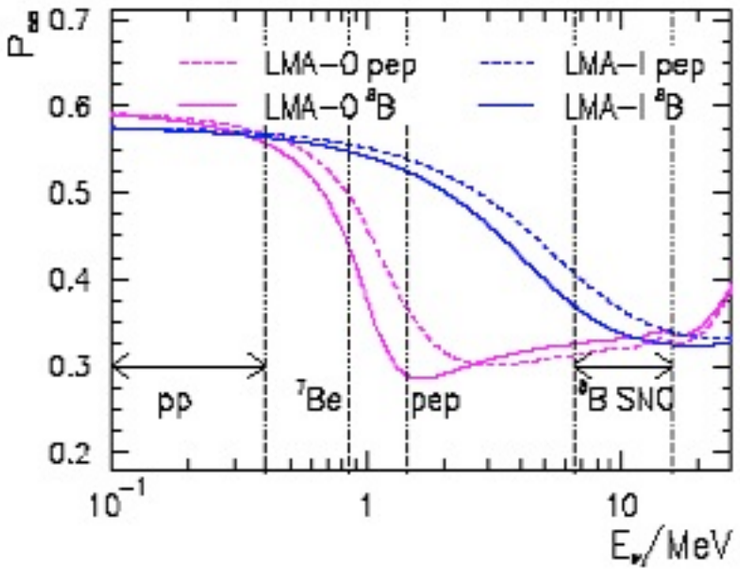

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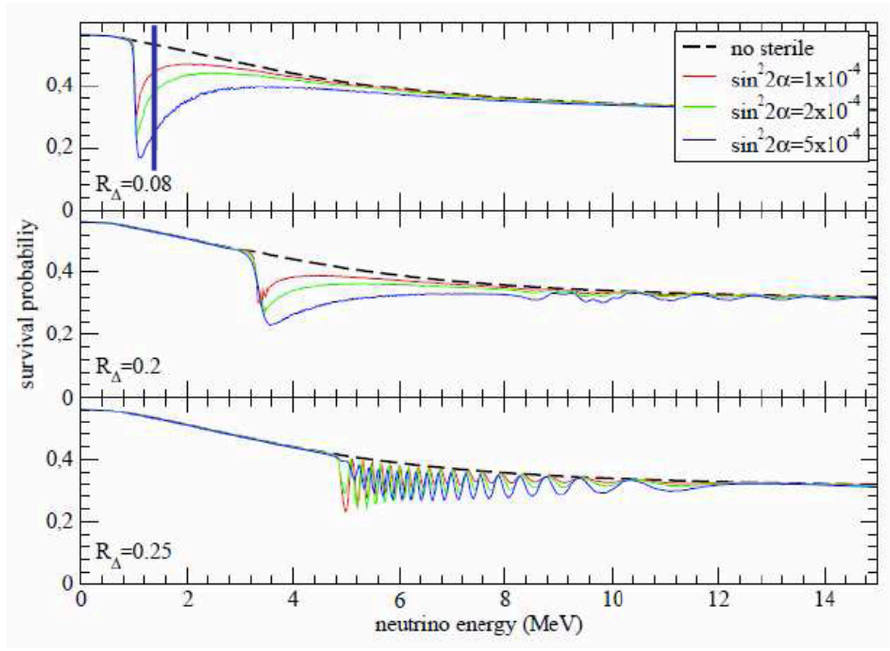
Sterile Neutrinos



Holanda & Smirnov arXiv:1012:5627 (2010)

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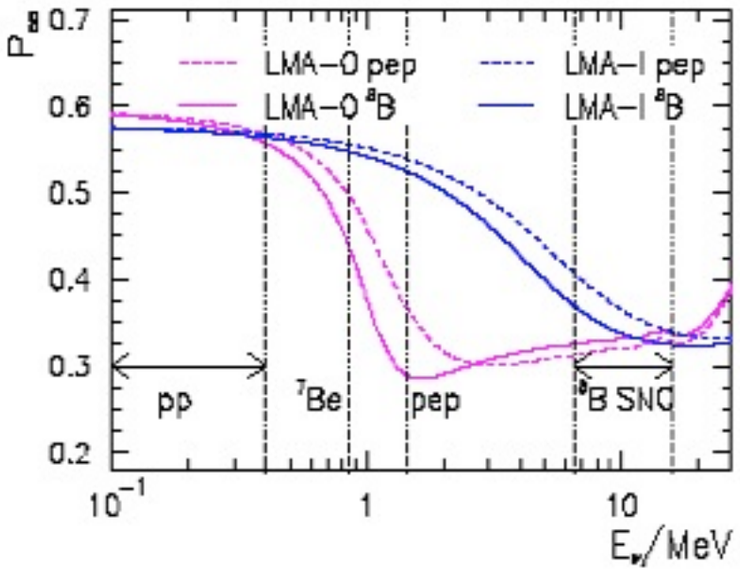

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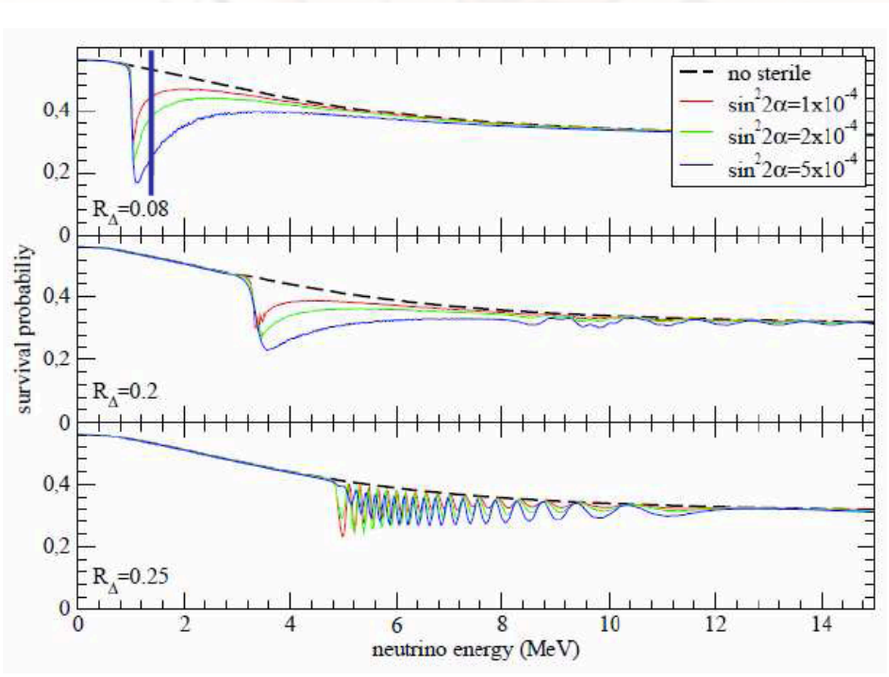

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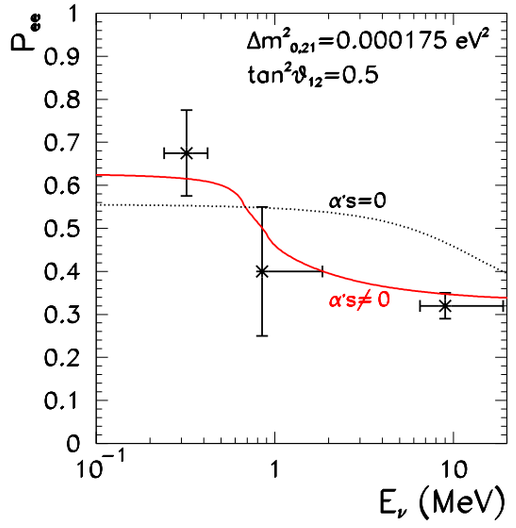
Mass varying neutrinos (MaVaNs)



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

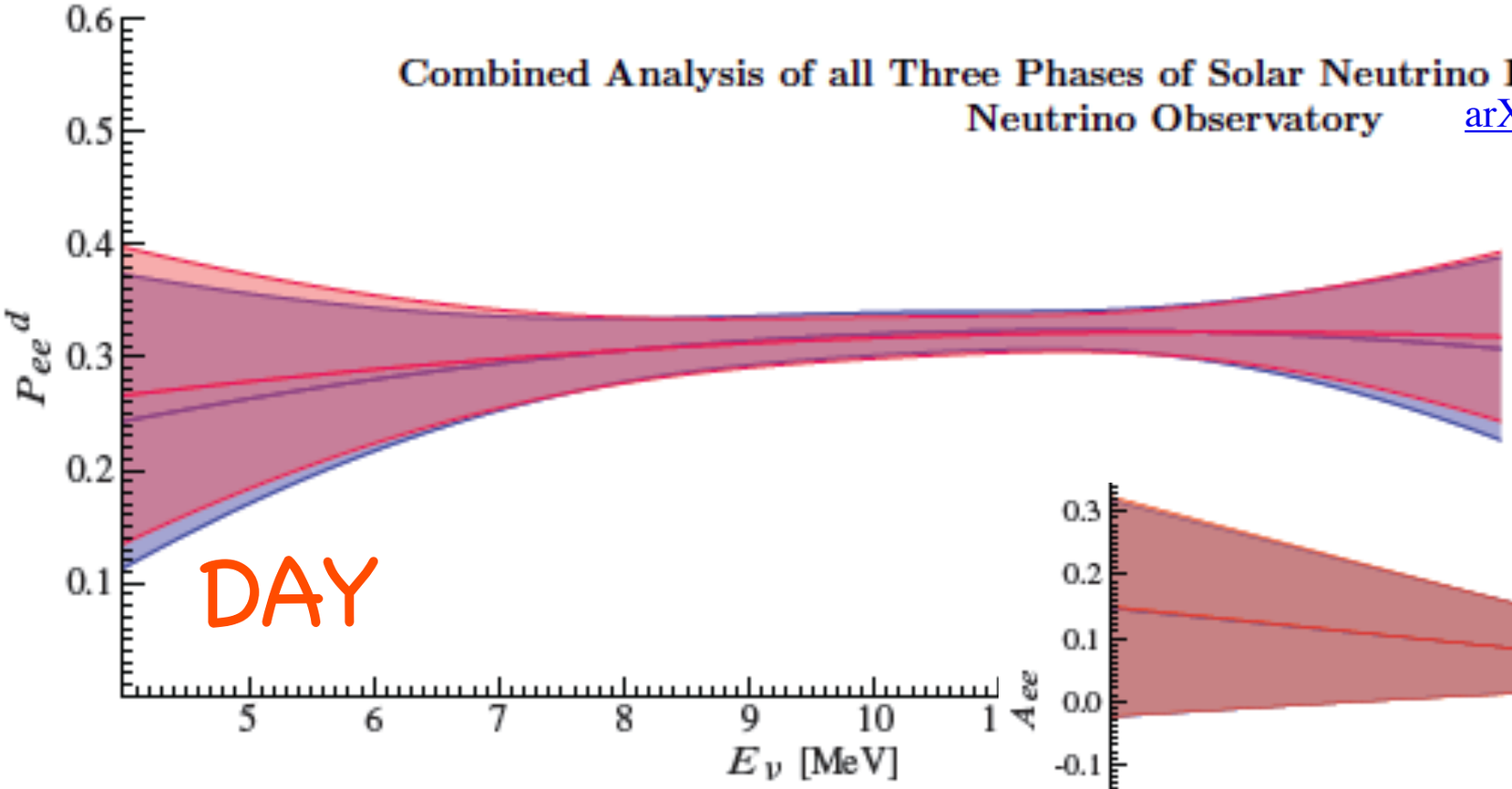
SNO: Precision Era

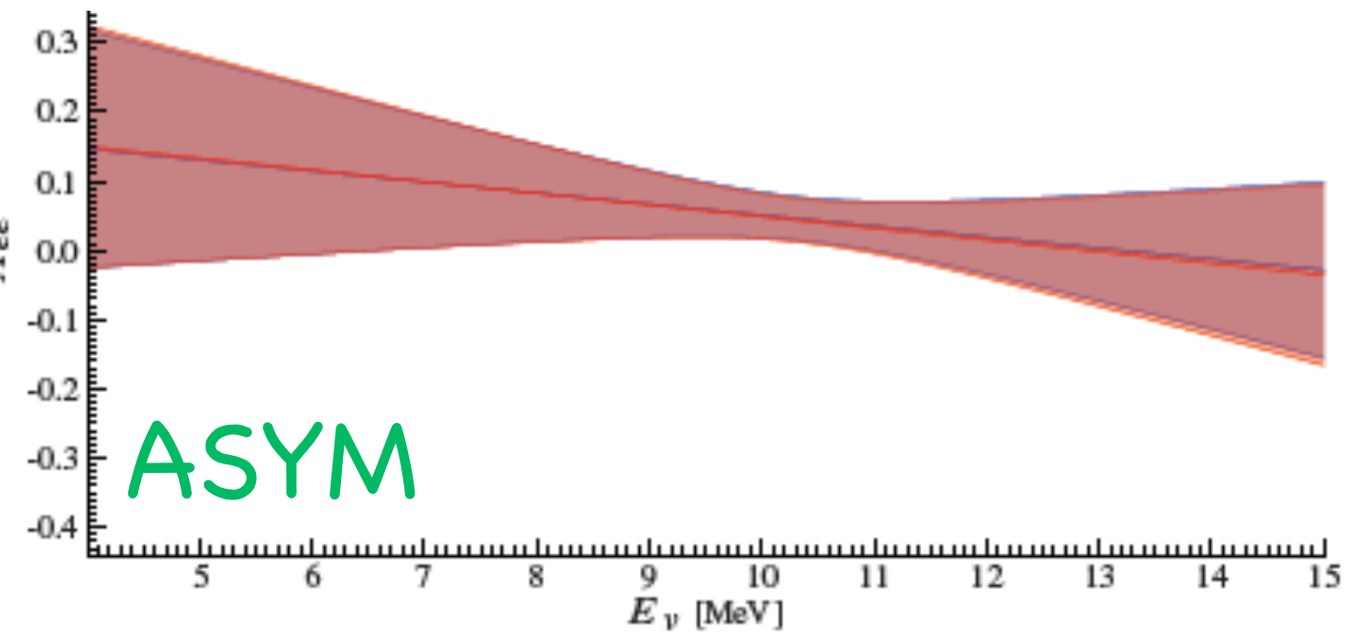
Low Energy Threshold Analysis

Recoil-electron energy threshold: 5.5 MeV ⇨ 3.5 MeV

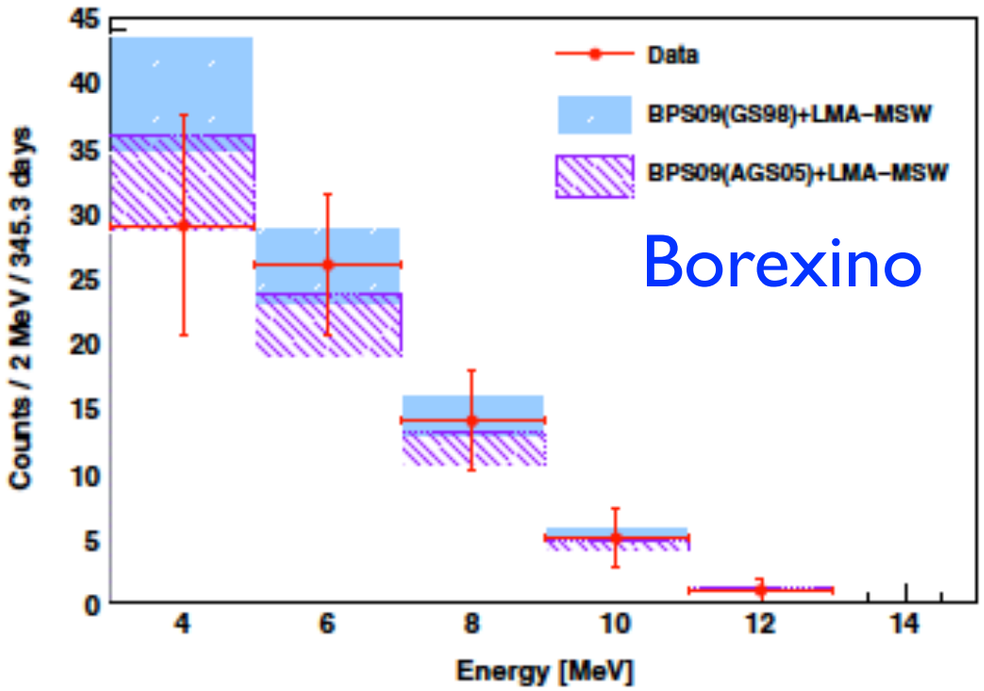
Direct Fit for Energy-Dependent Survival Probability

Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory arXiv:1109.0763v1 [nucl-ex]





Recoil-Electron Spectra



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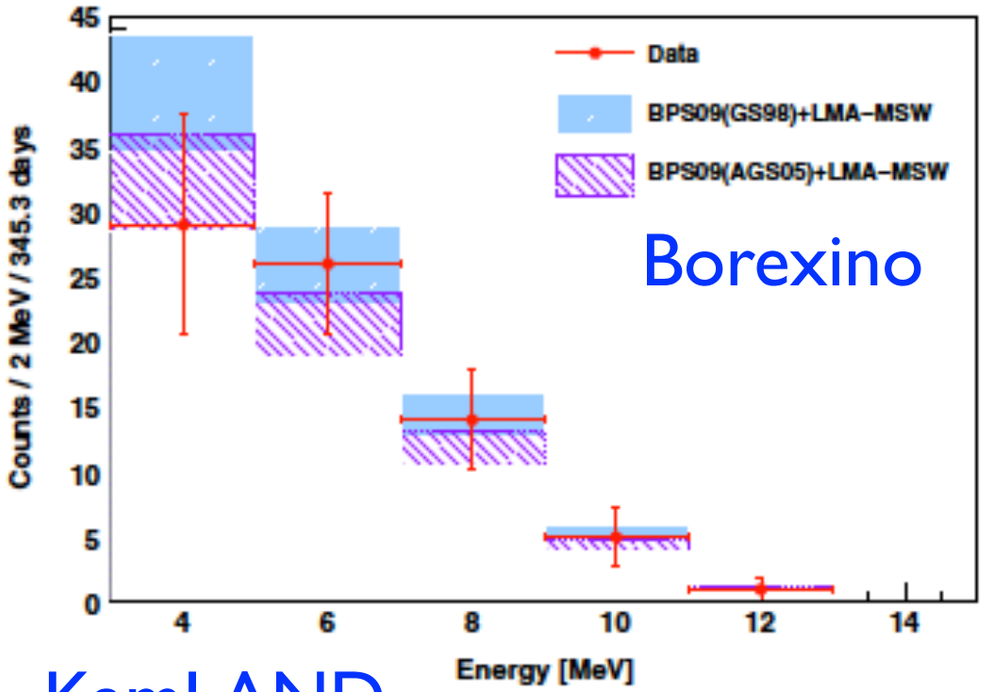
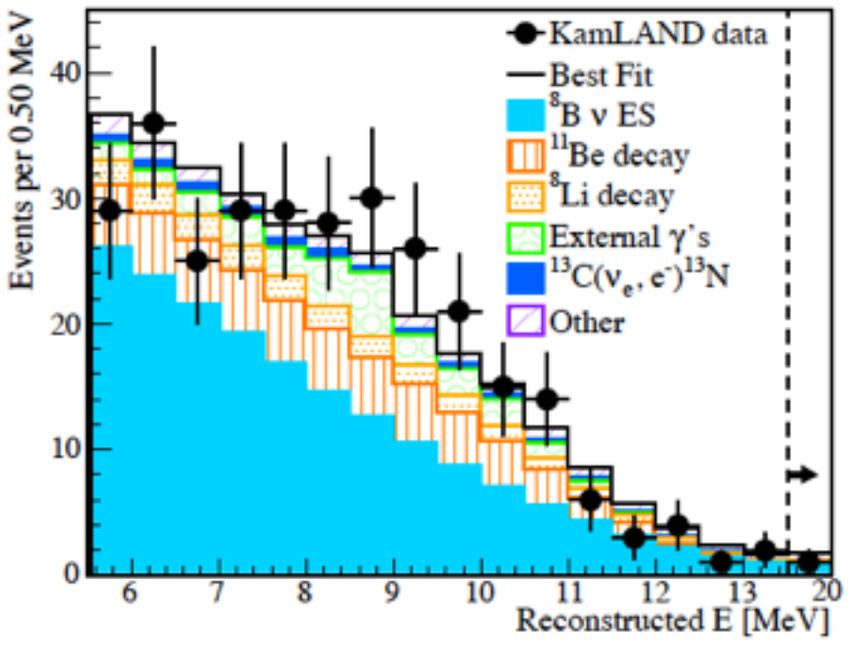


Borexino

KamLAND



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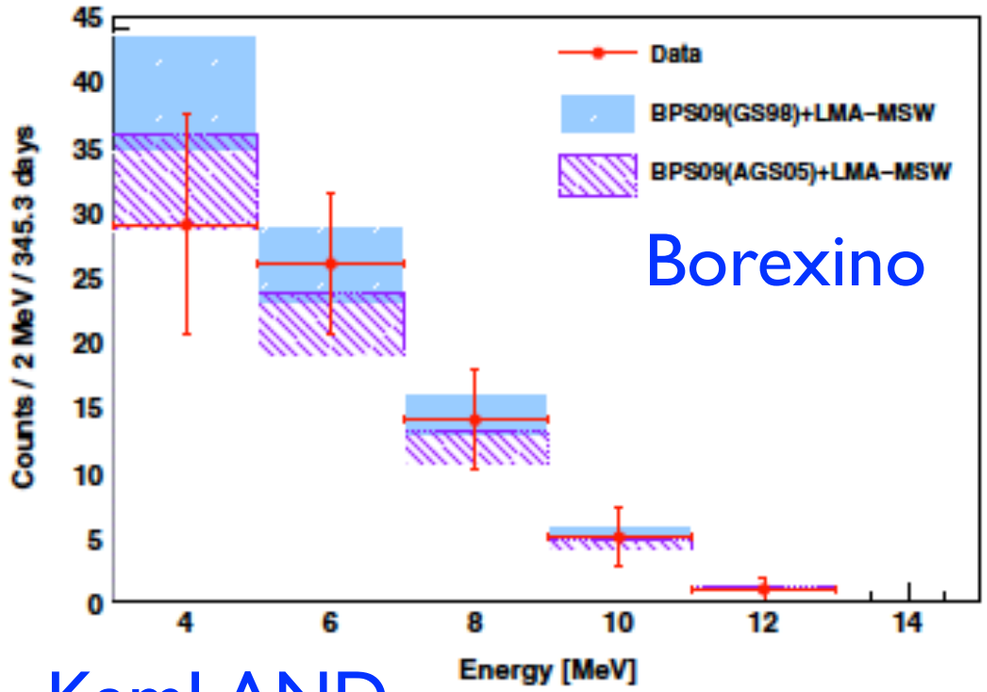

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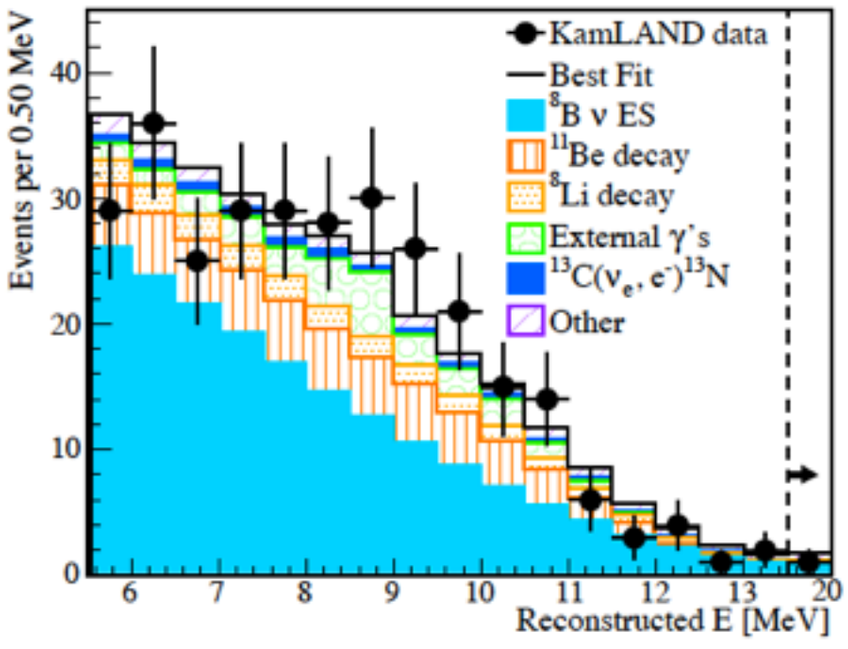
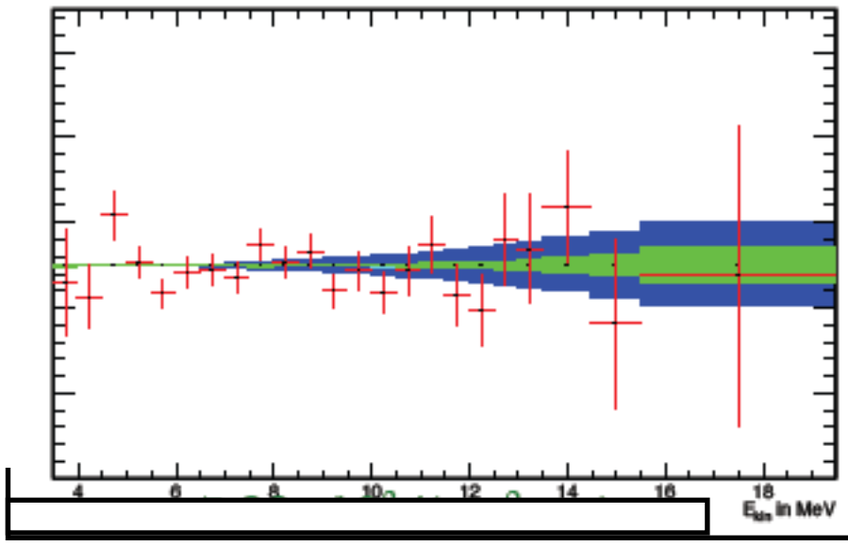


M. Smy Nu' 2012

SK-IV Spectrum



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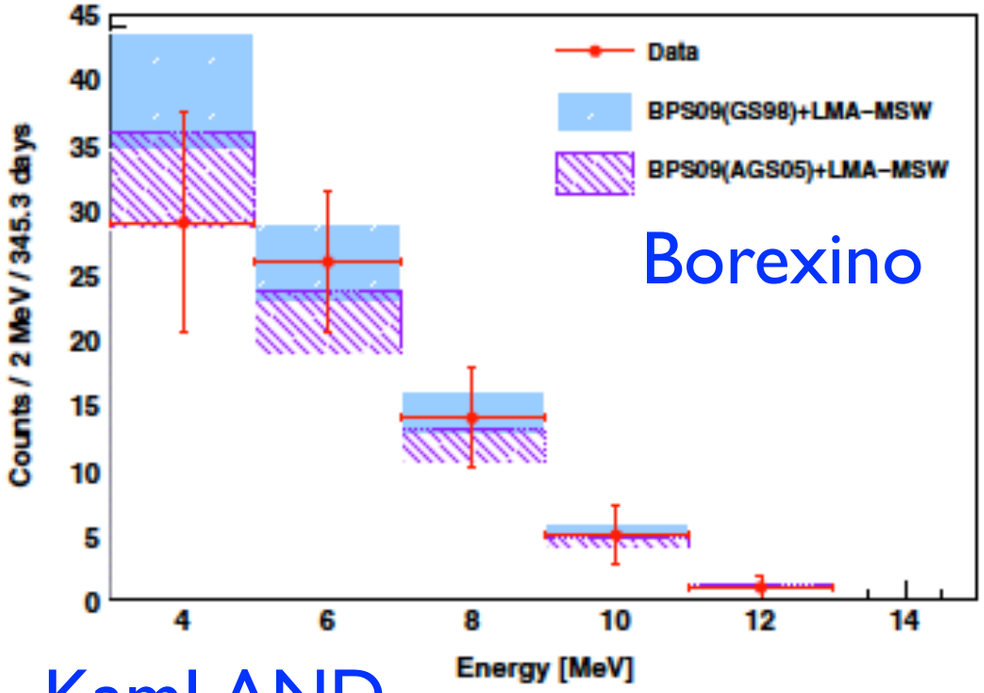

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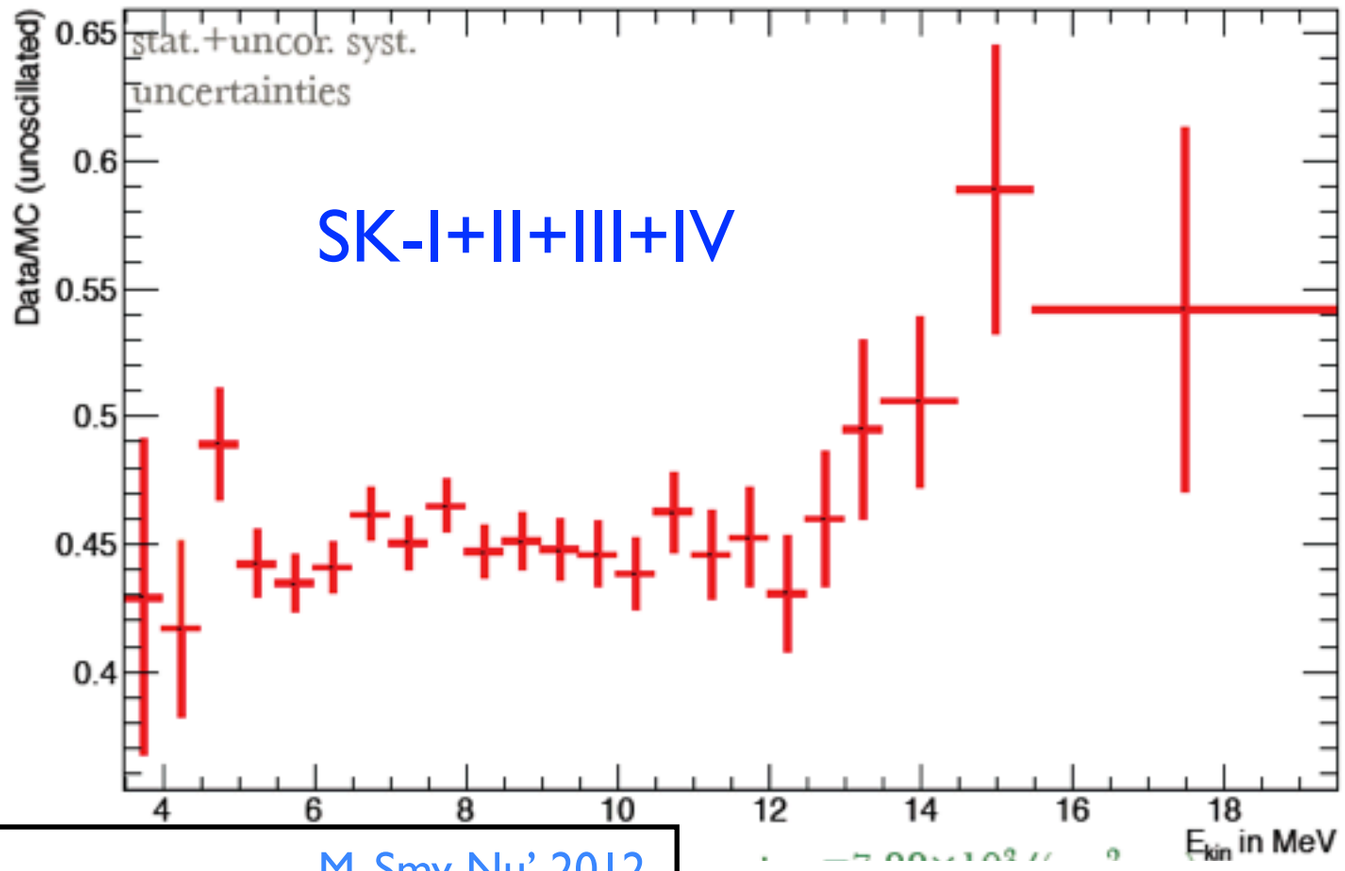

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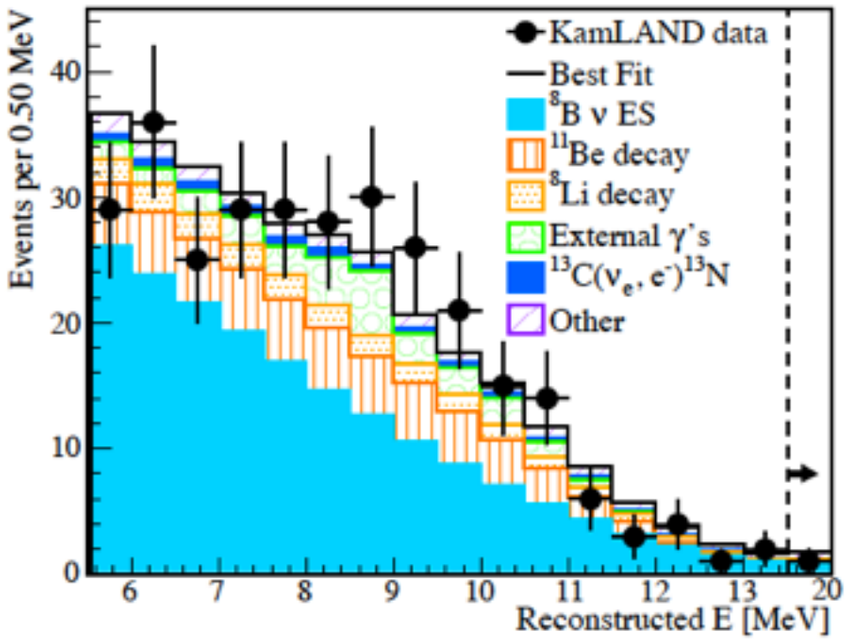

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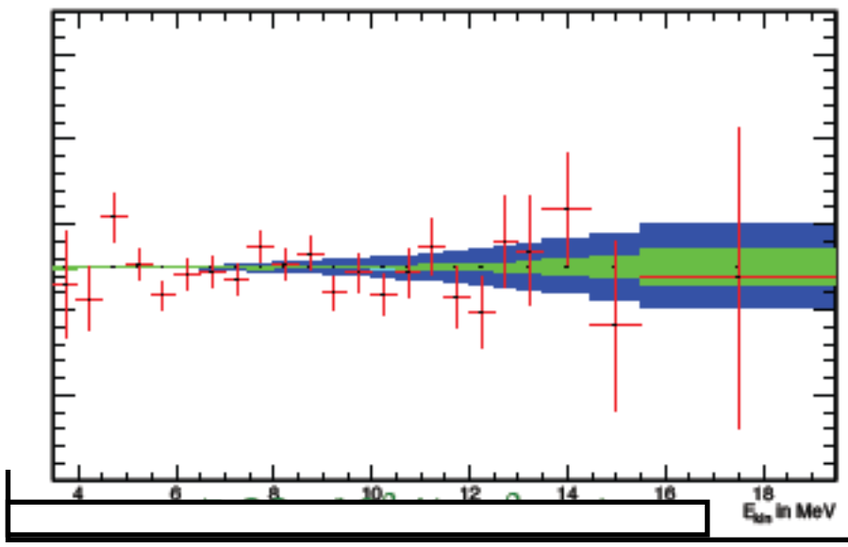

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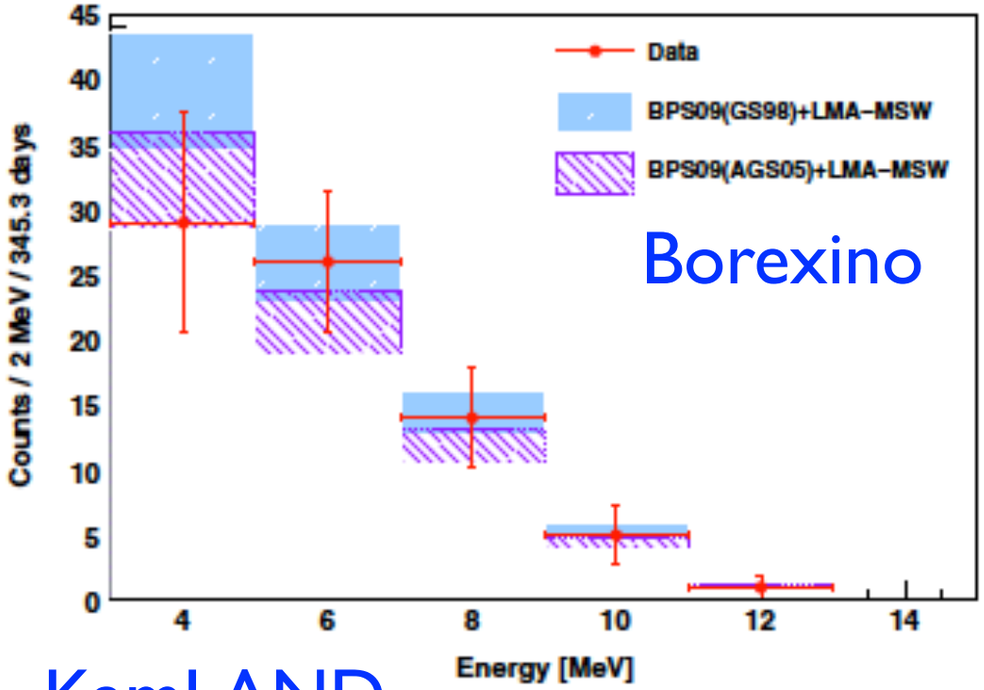

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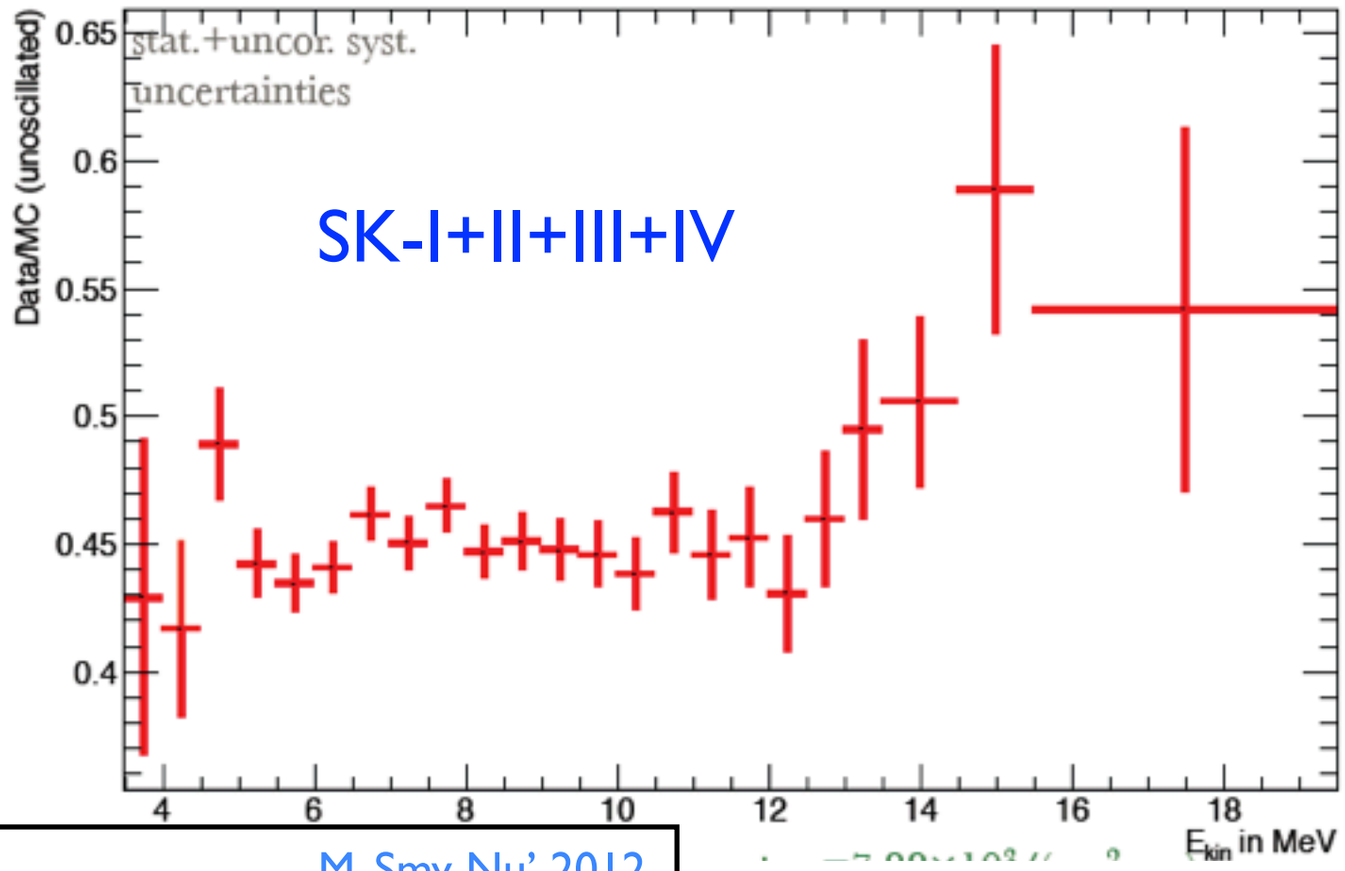

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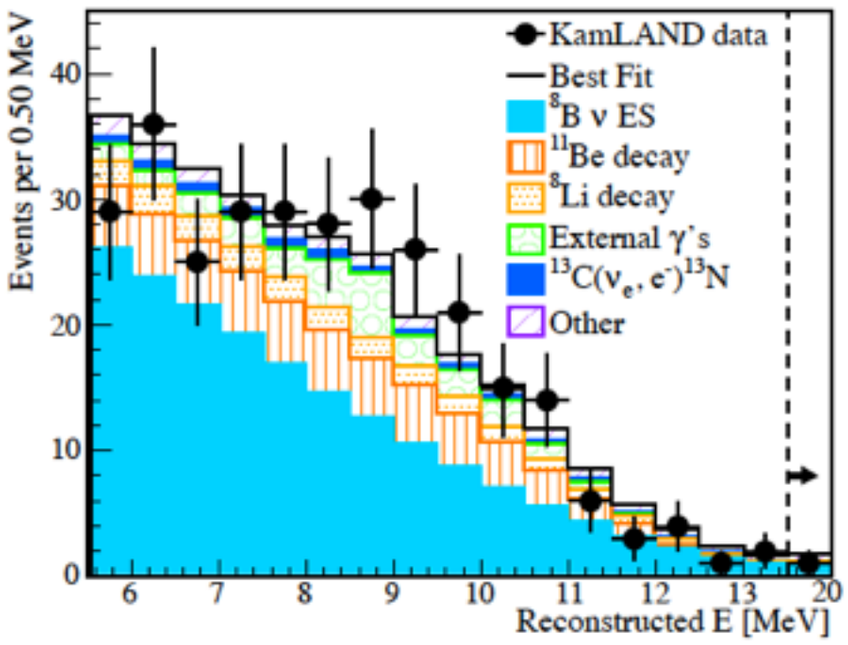

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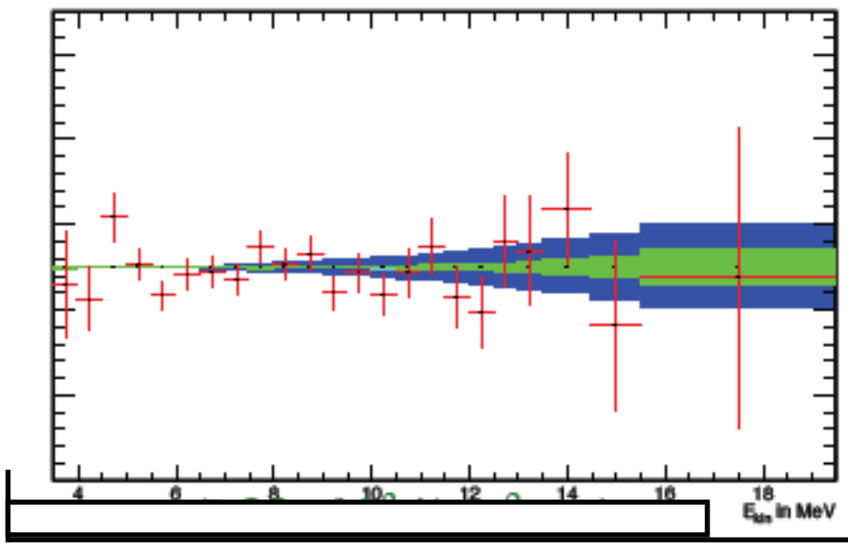
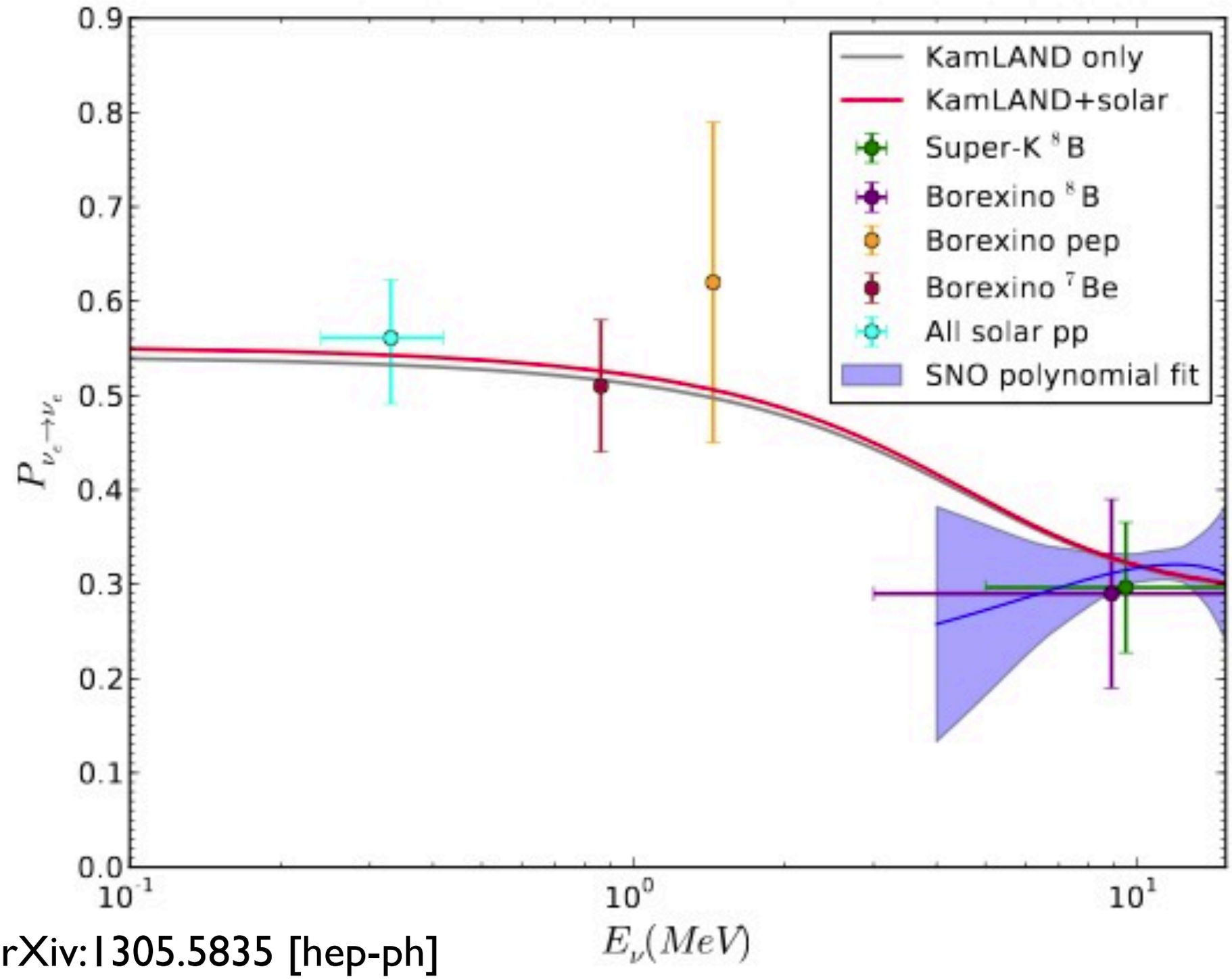


Very
Very
Flat

Survival Probability



arXiv:1305.5835 [hep-ph]

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} — arXiv:1305.5835 [hep-ph]

Considers:

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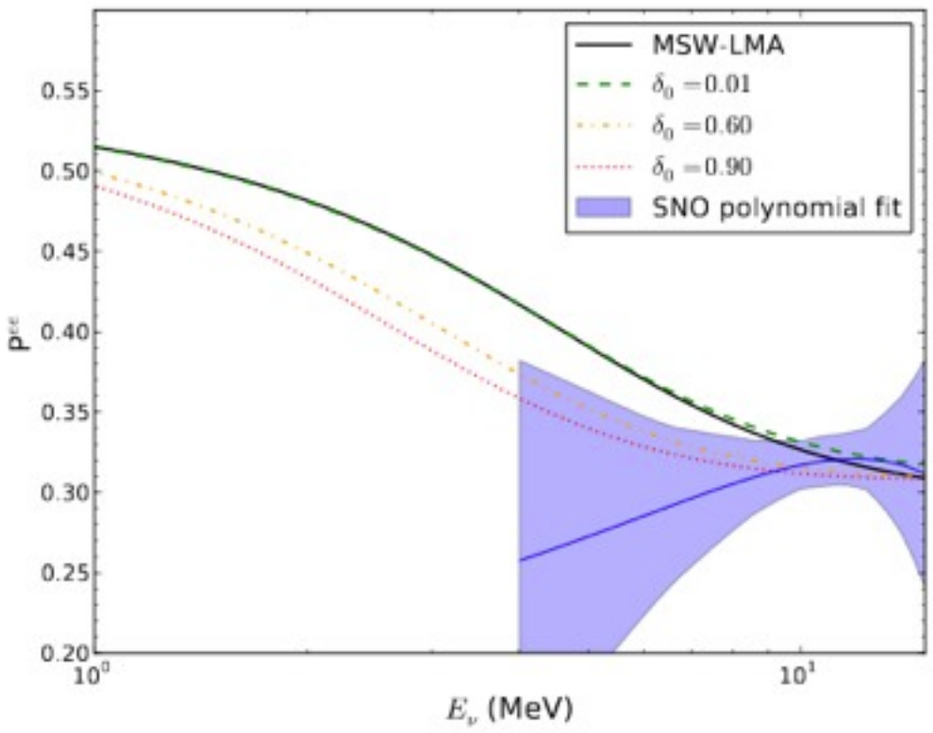

Need 90% change in core density to improve fit

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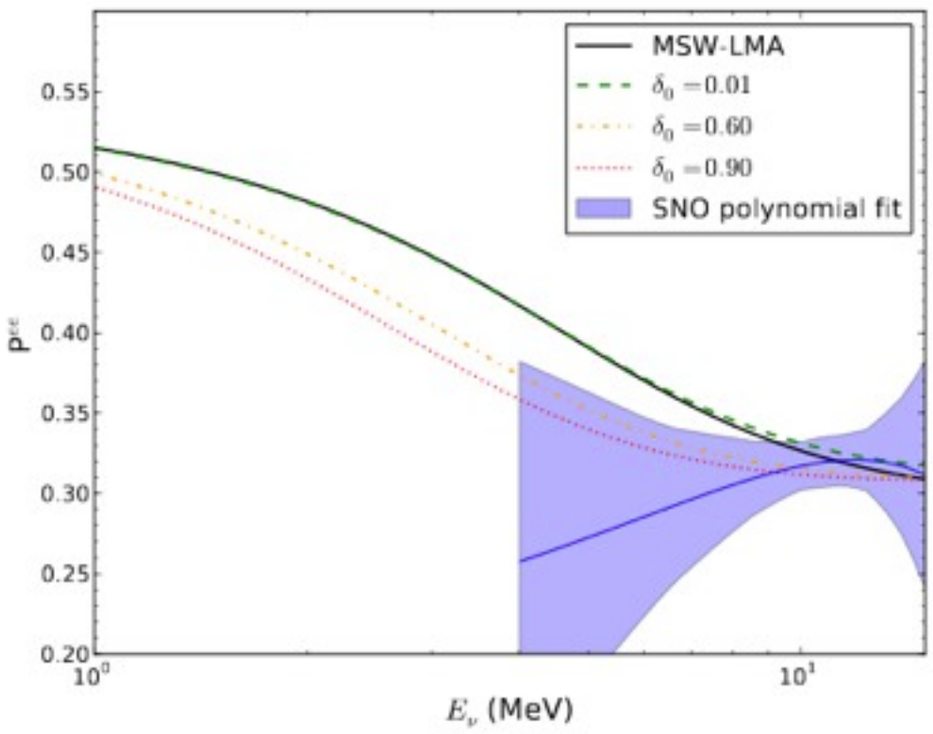

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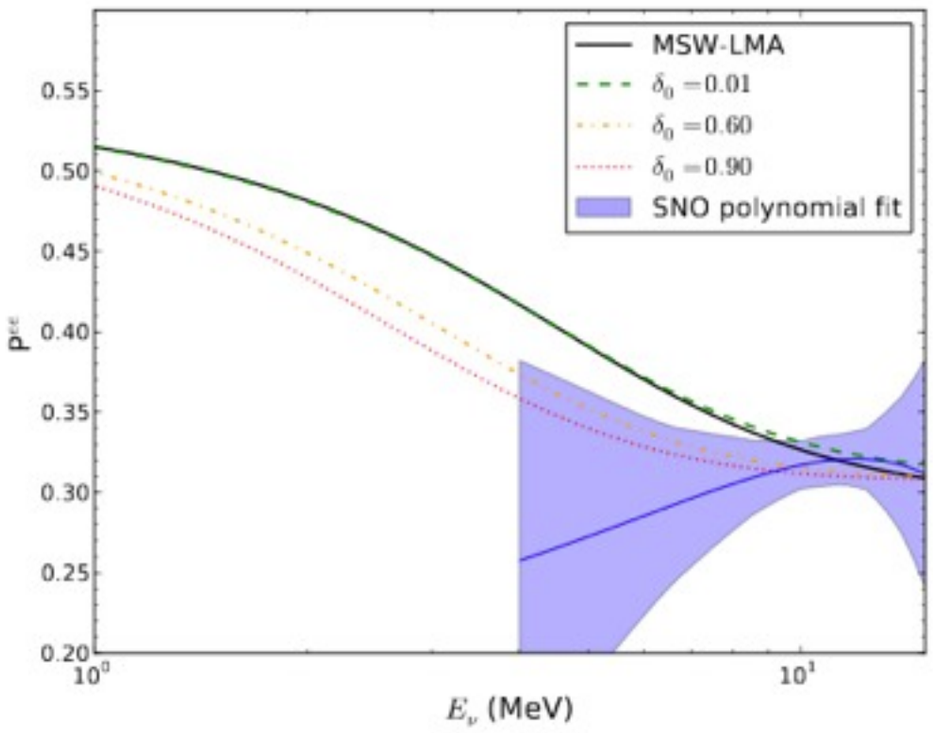

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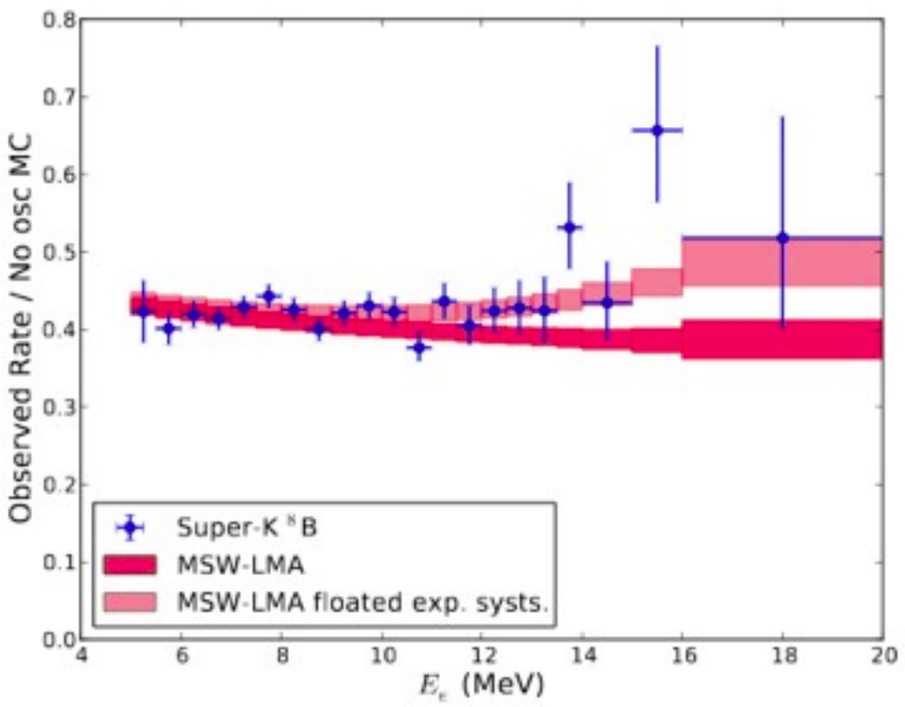
Results limited by experimental precision



(B) Day / Night Asymmetry

SuperK: -0.021 ± 0.020 (stat) ± 0.013 (syst)
SNO: 0.037 ± 0.040 (stat ⊕ syst)
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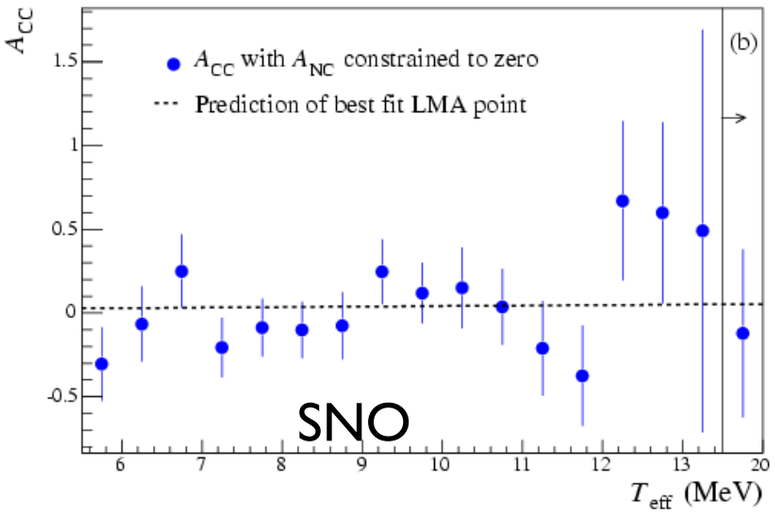

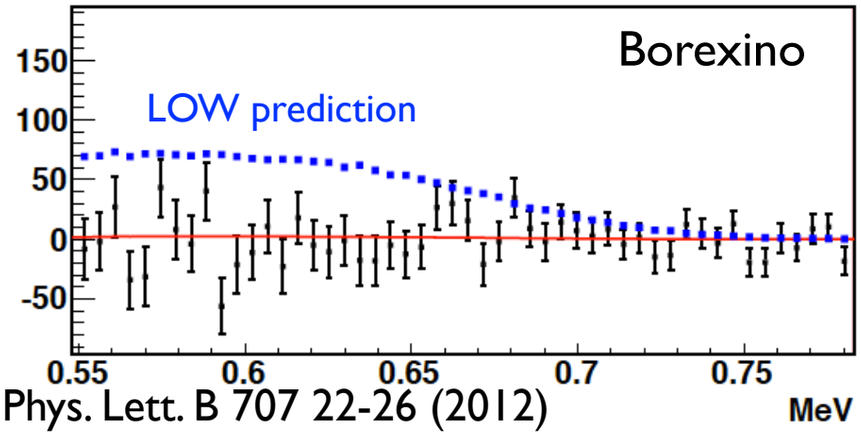

Phys. Lett. B 707 22-26 (2012)

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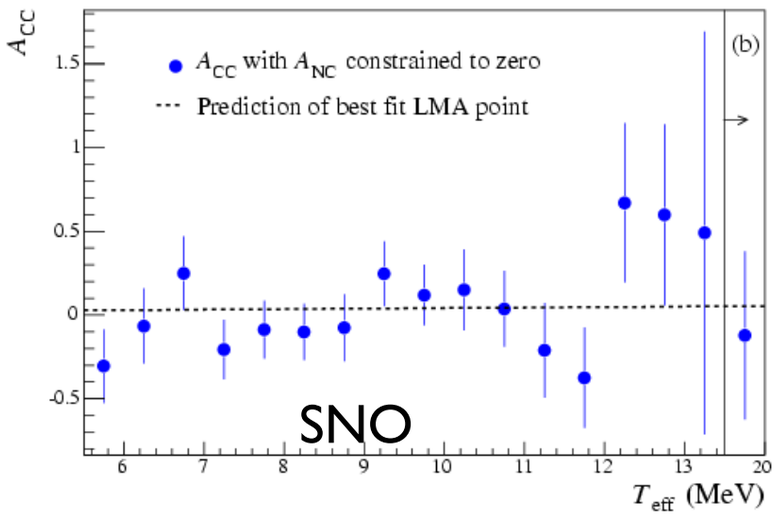

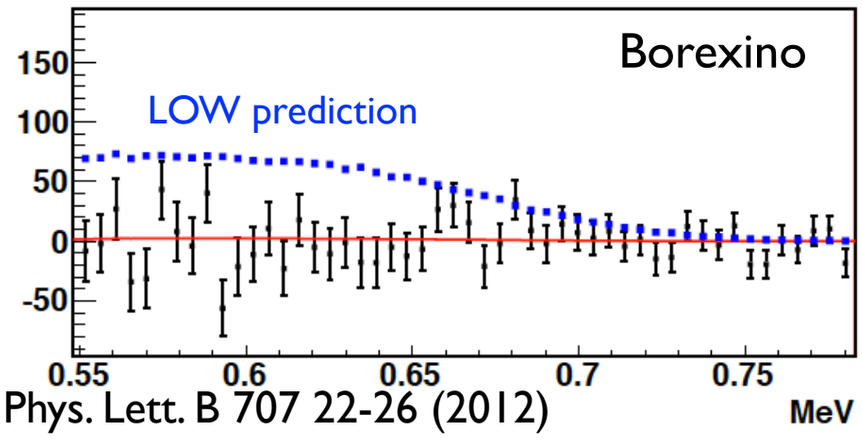

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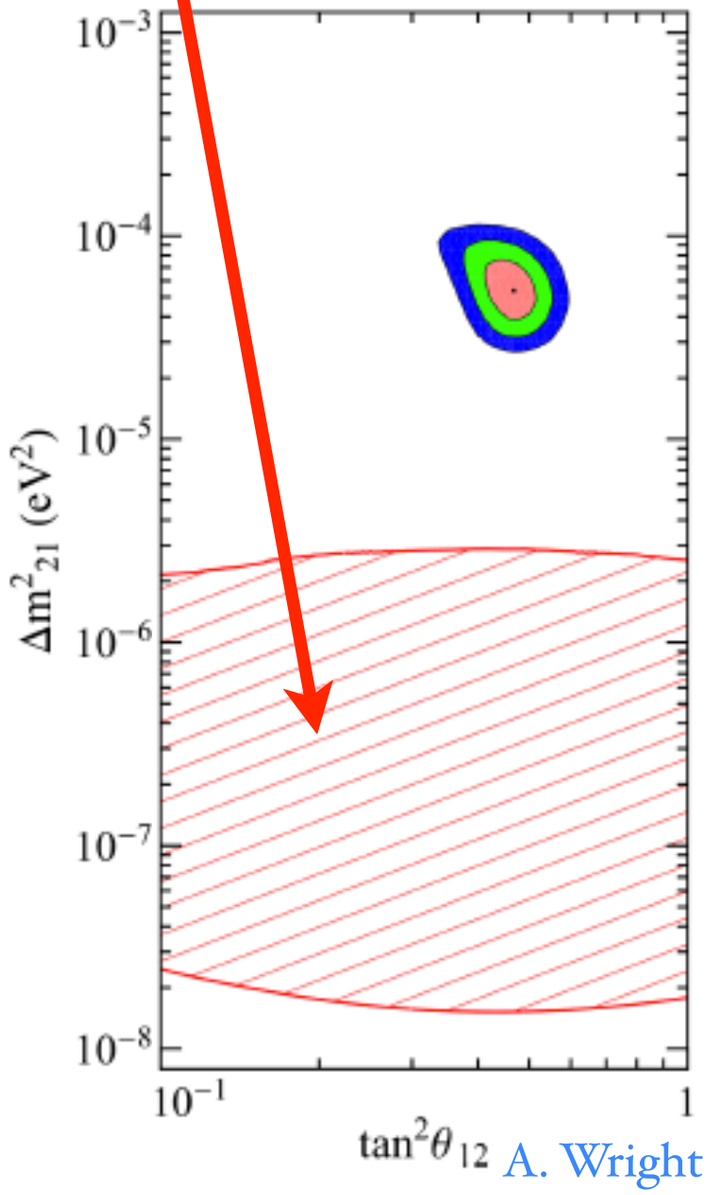
LOW region ruled out at > 3σ



A. Wright

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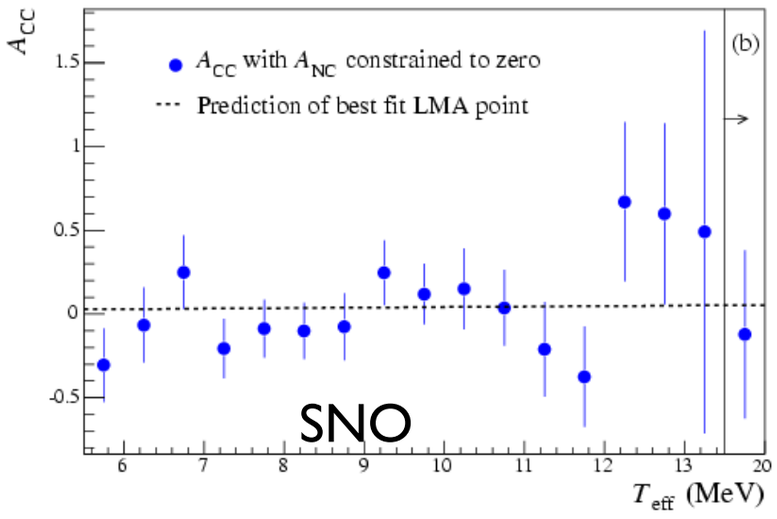
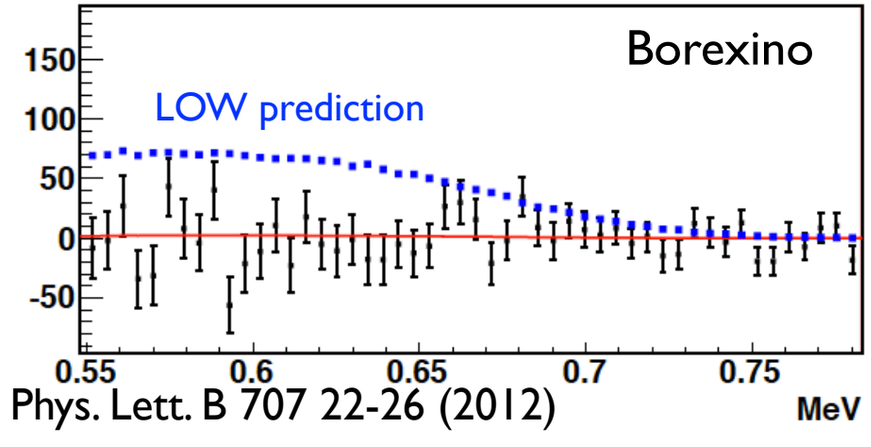
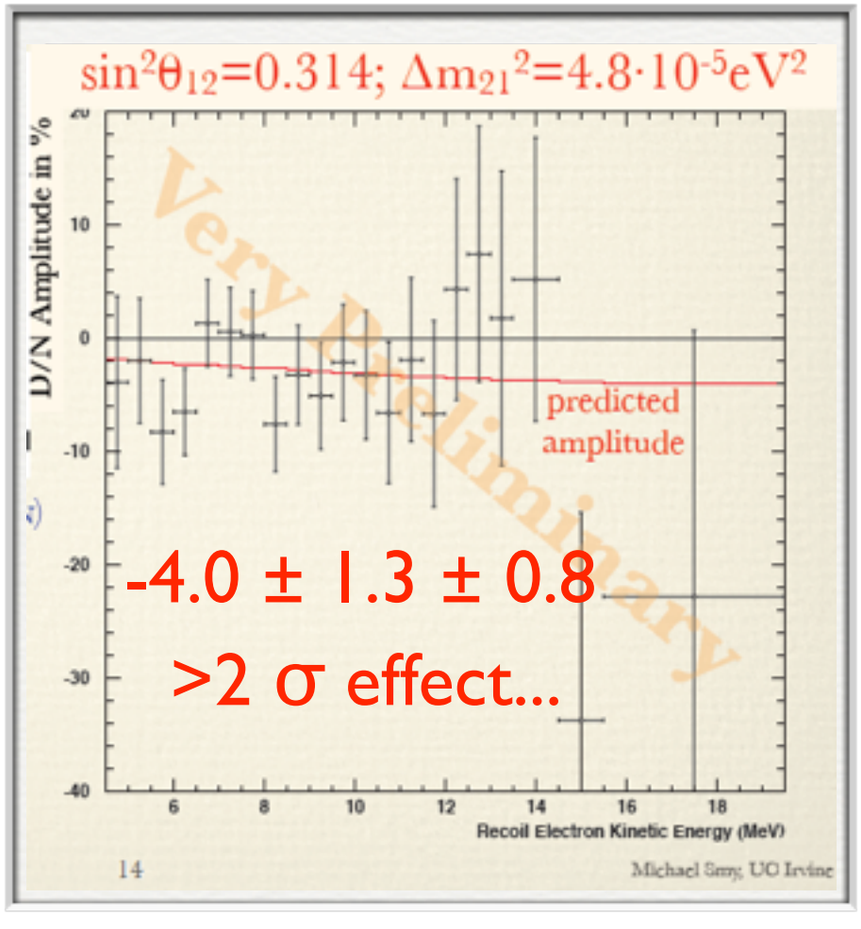




Phys. Lett. B 707 22-26 (2012)

Recent result



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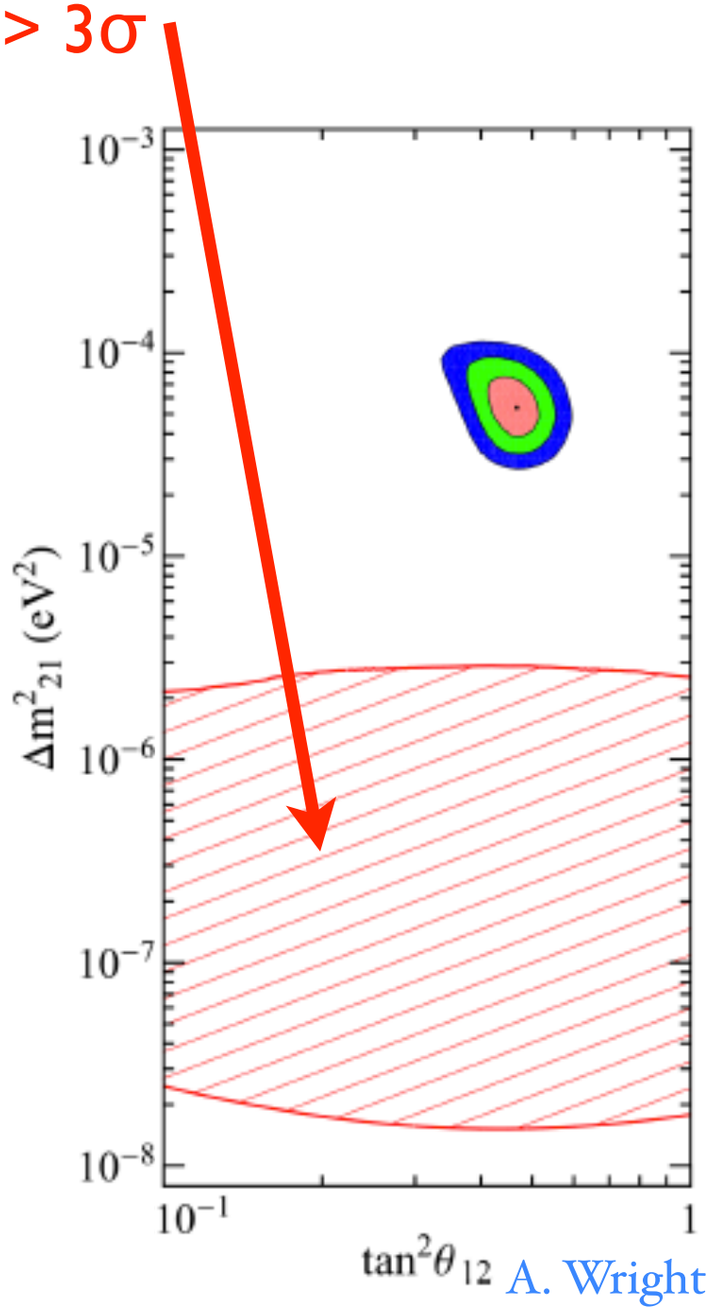

A. Wright

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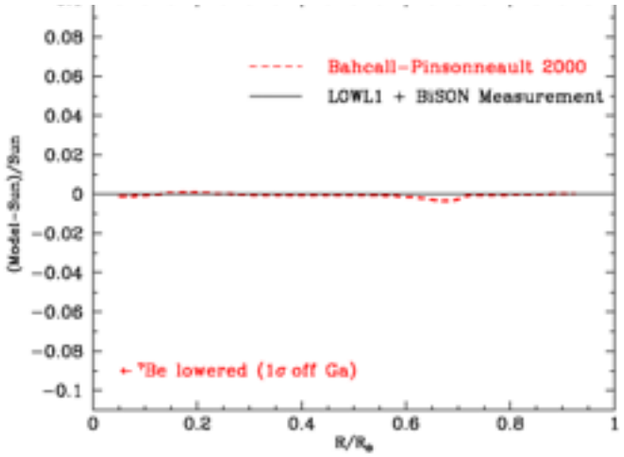

SSM predicts speed of sound through radial profile of the Sun

Beautiful agreement between SSM and helioseismology

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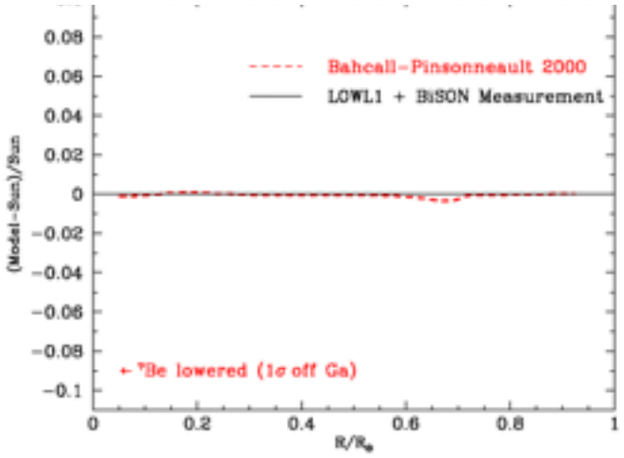

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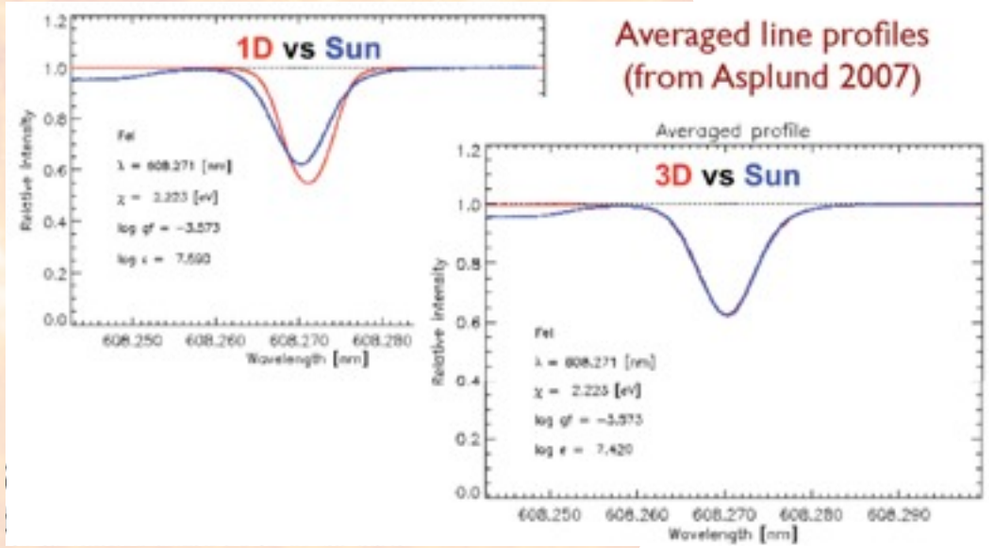

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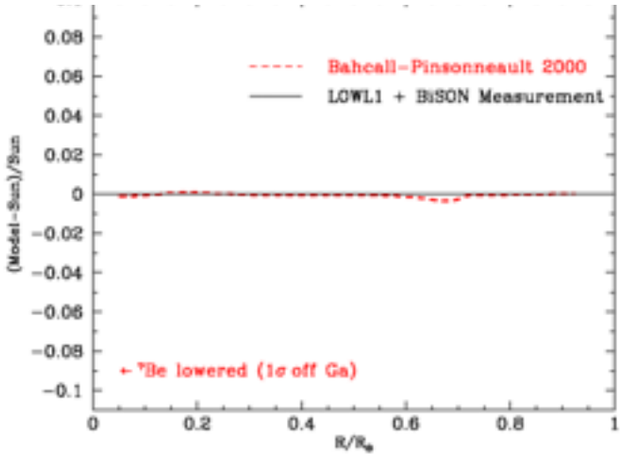

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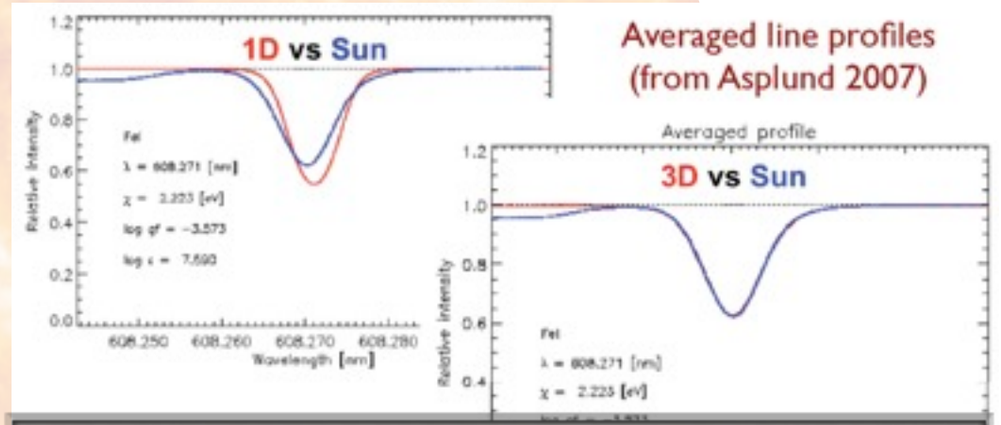

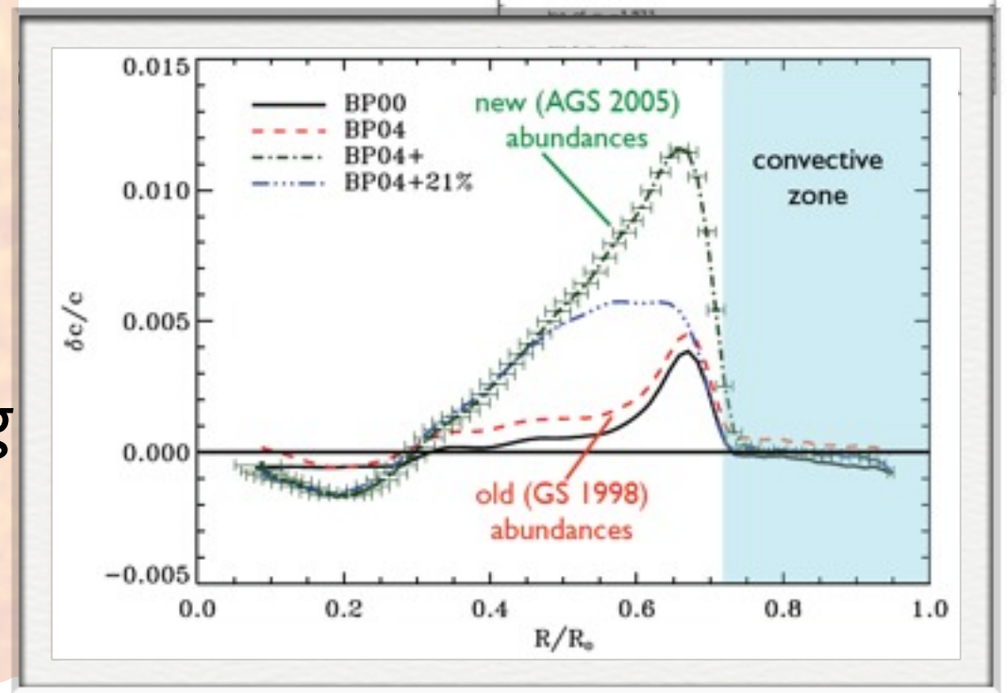

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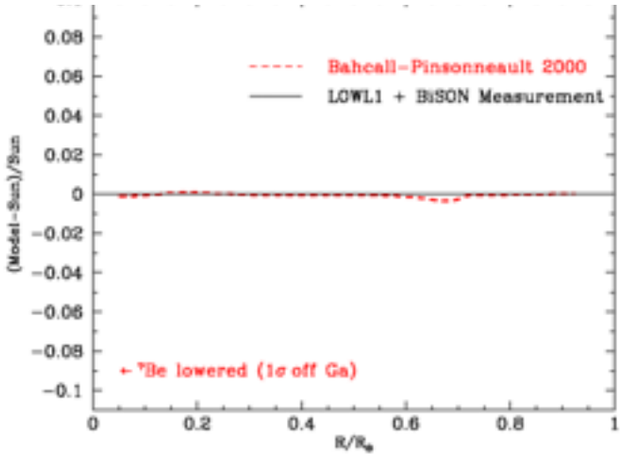

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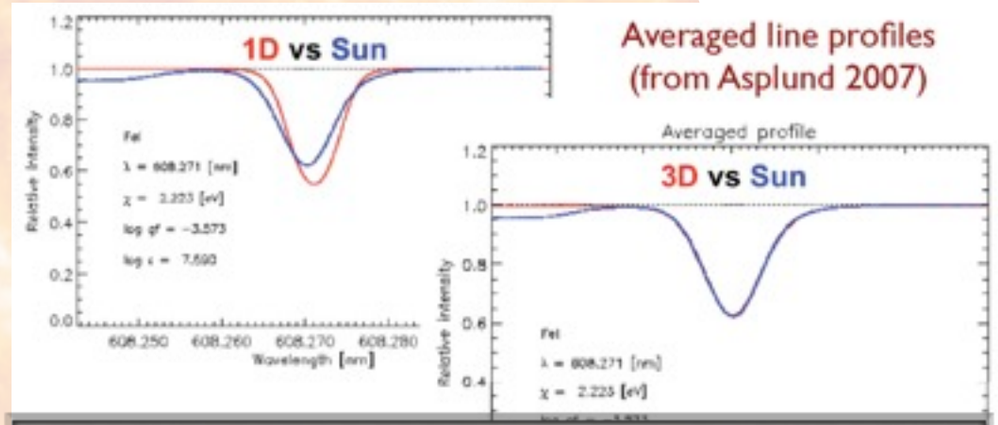
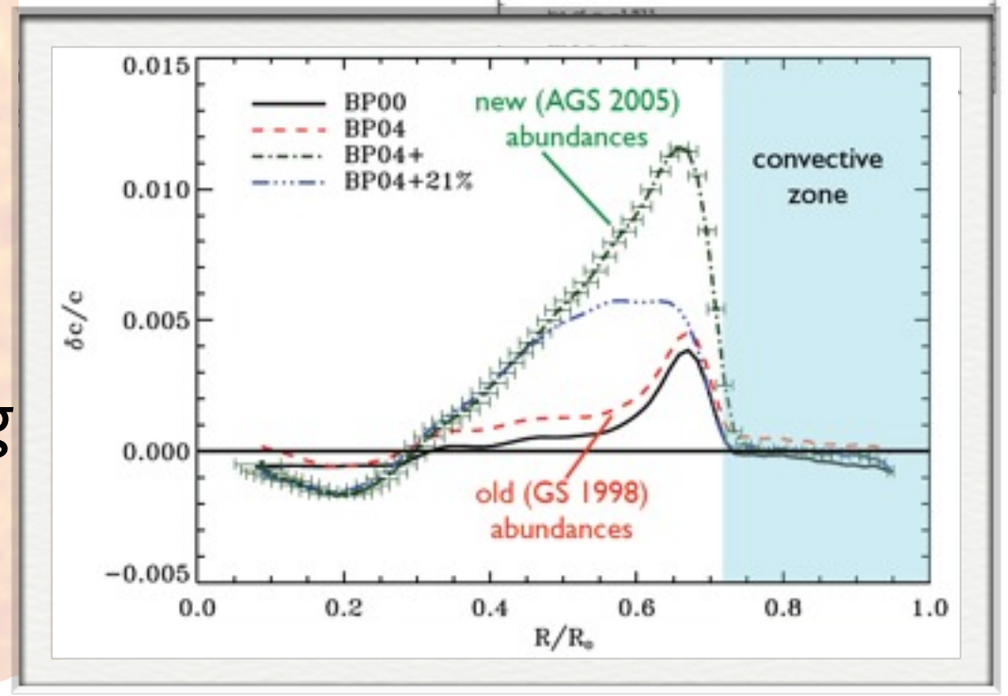


Averaged line profiles (from Asplund 2007)



(C) Metallicity Status

Largest effect on pp-chain flux:
~17% reduction of ^{8}B (± 14% theory)

- *Hard to distinguish*
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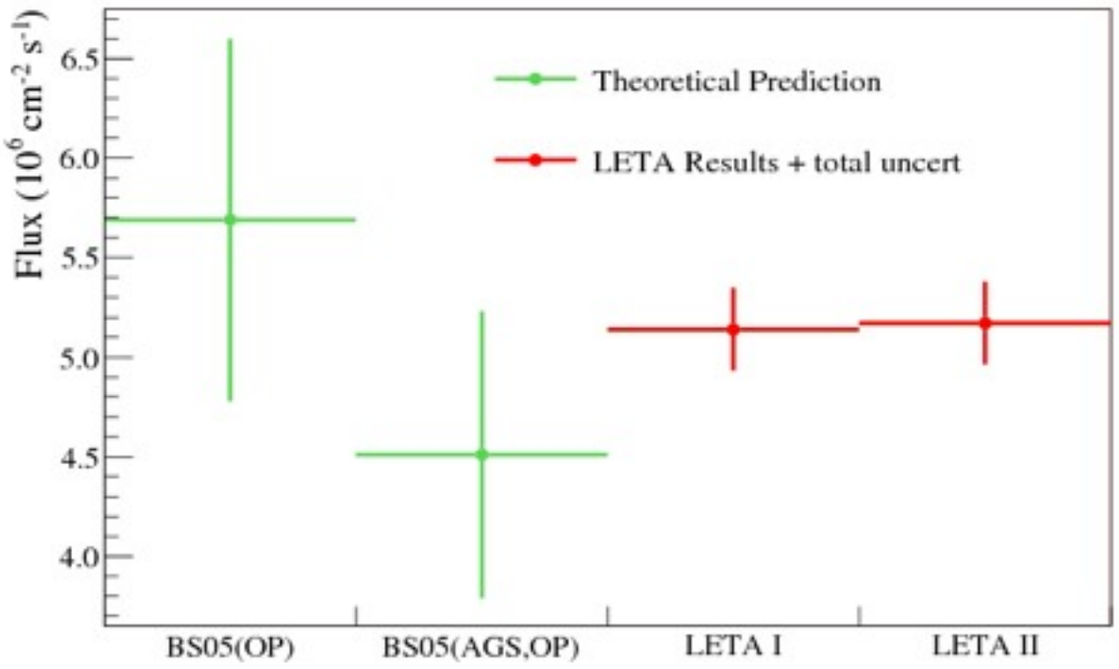

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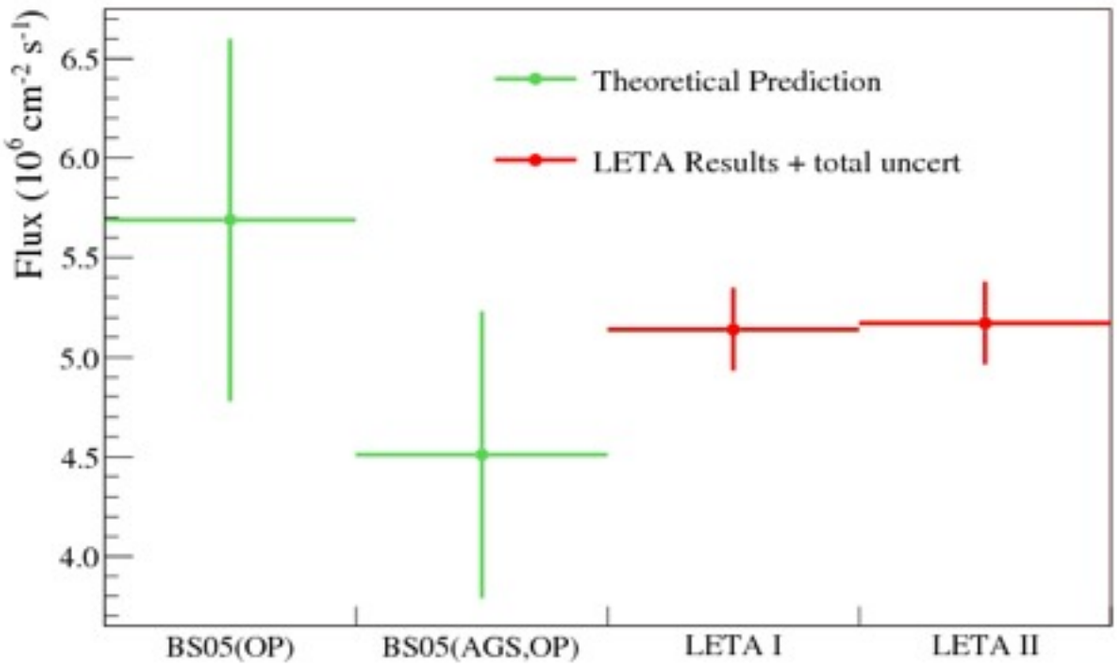

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CNO flux depends linearly on core metallicity

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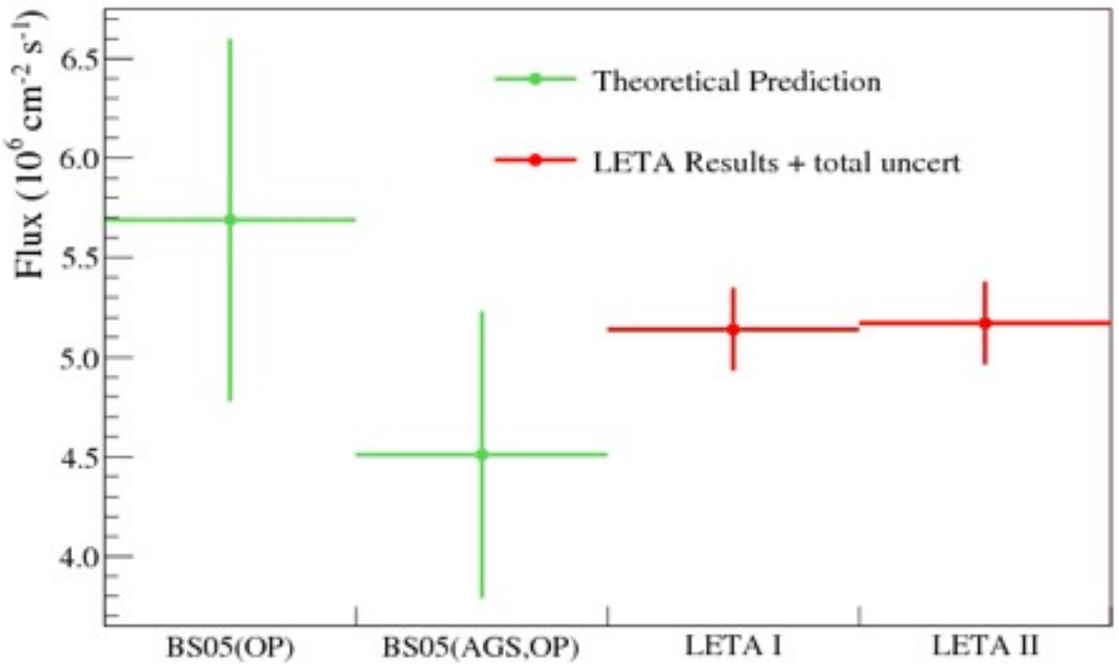

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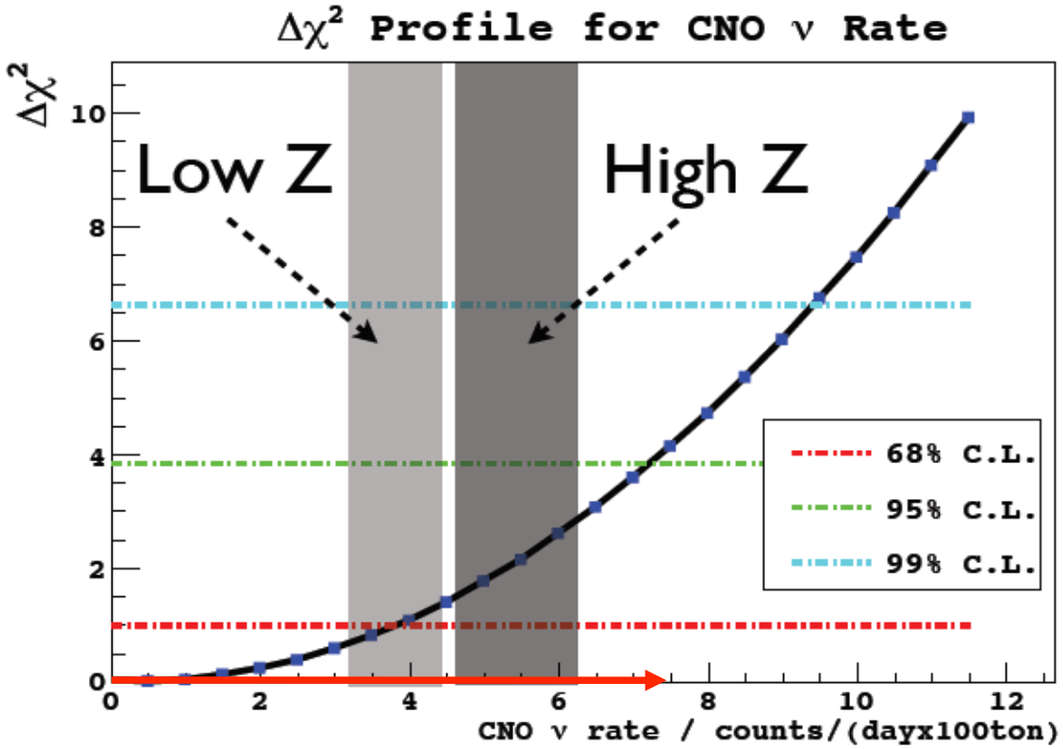
Borexino have the only direct limit:

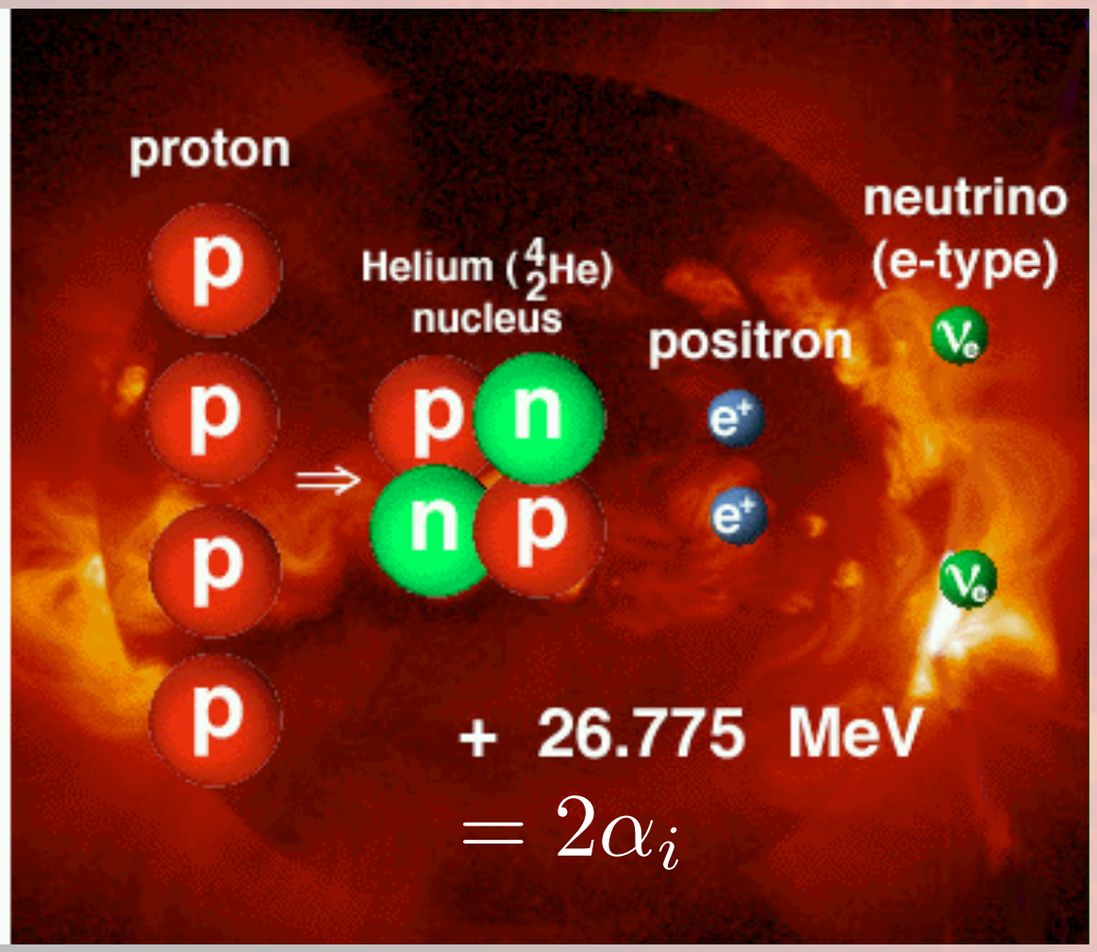
2-3 * SSM prediction

PRL 108, 051302 (2012)



(D) Solar Luminosity

Assume γs & νs produced only in fusion reactions:
⇛ relate γ luminosity to ν luminosity



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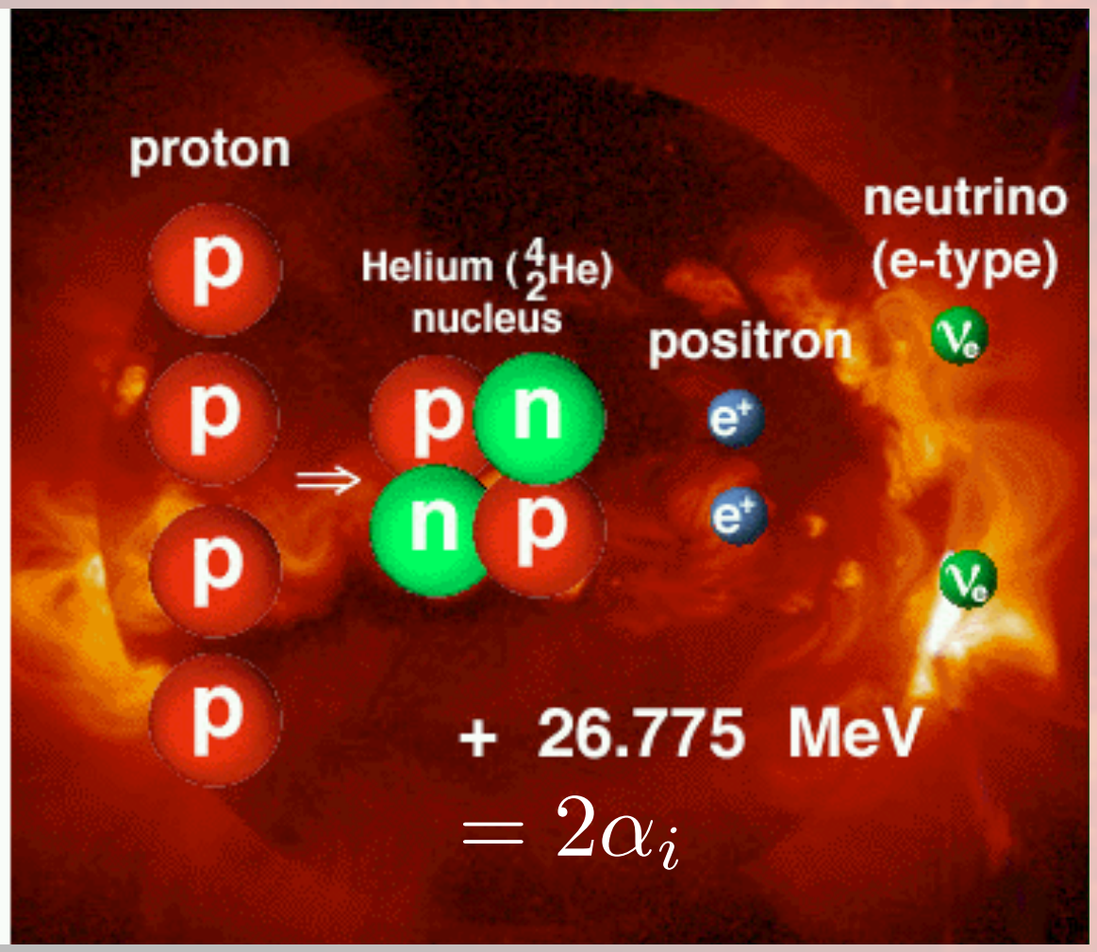

$$\frac{\mathcal{L}_\odot}{4\pi\left(A.U\right)^2} = \sum_i \alpha_i \Phi_i$$

The "Luminosity Constraint"

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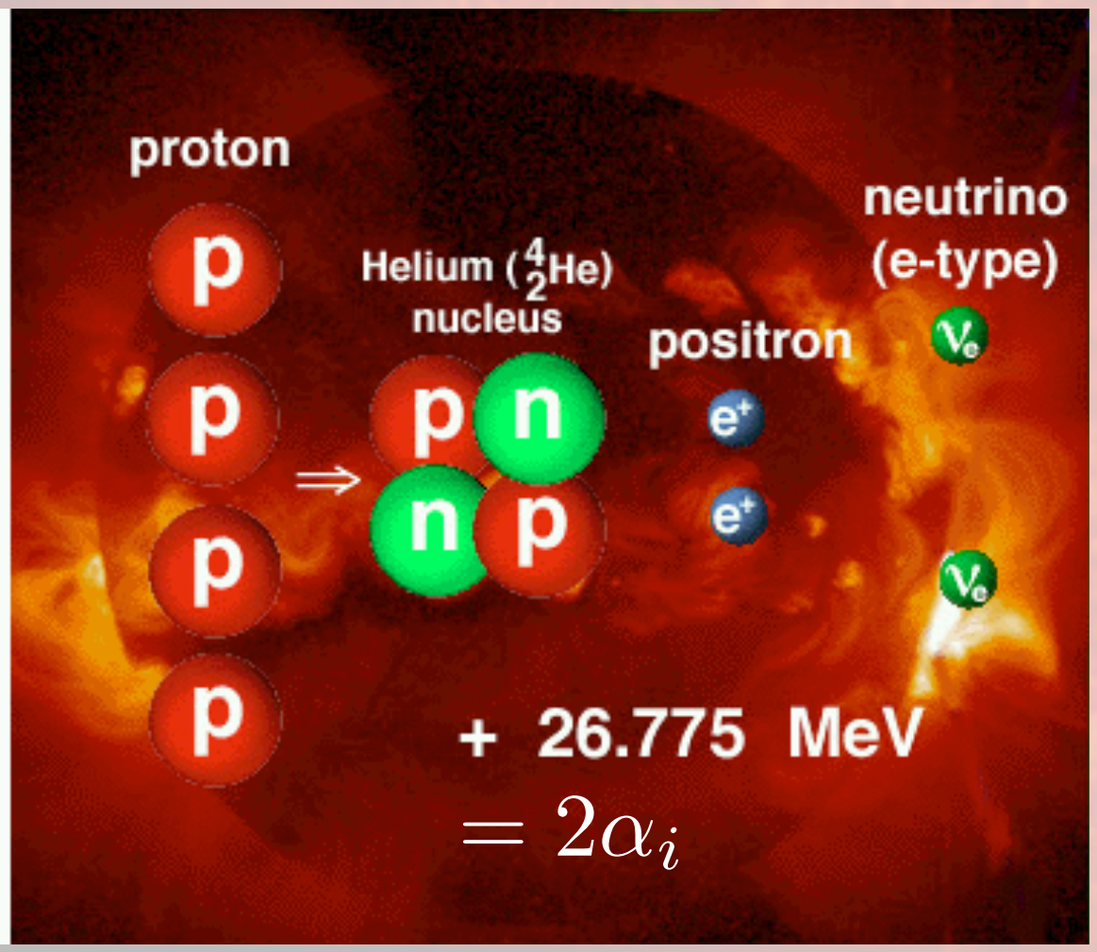

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The "Luminosity Constraint"

Test for:

ν appearance/disappearance

E loss/generation mechanisms

The Road Forward

- What neutrinos can tell us about the Sun

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"Gold ring of solar neutrino physics & astronomy"

--- John Bahcall

Continuous Source Experiments

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Inherent Challenges:

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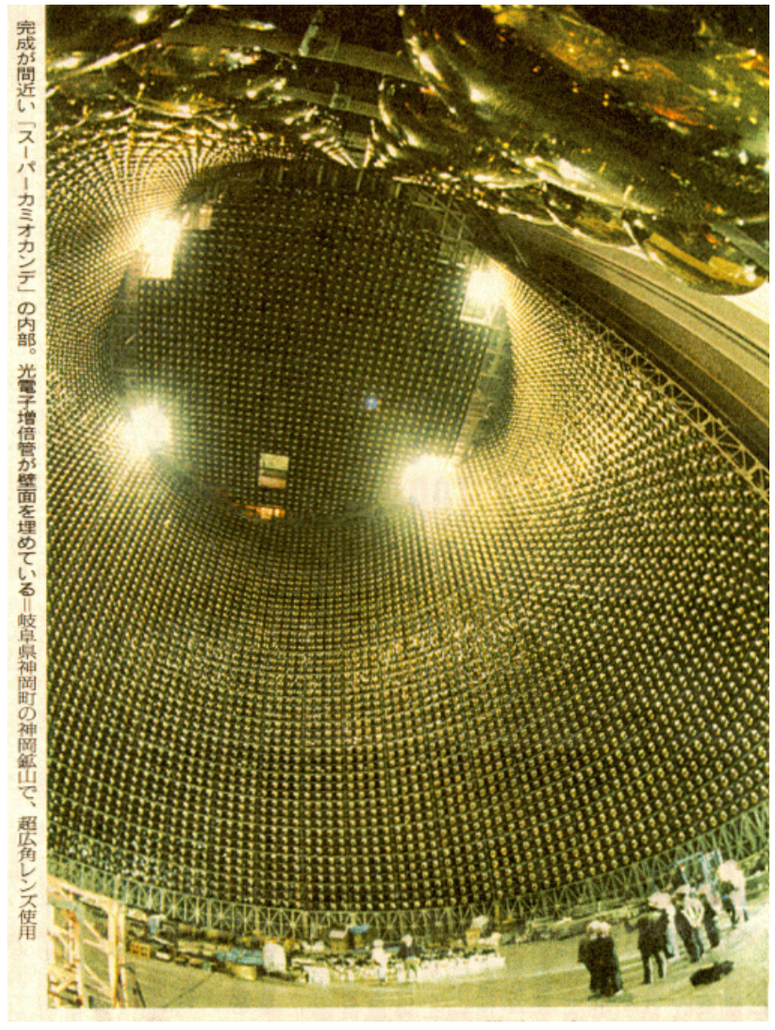
- *Need large, well-understood detectors*



Size is the only handle on low statistics
Is %-level understanding possible at this scale?

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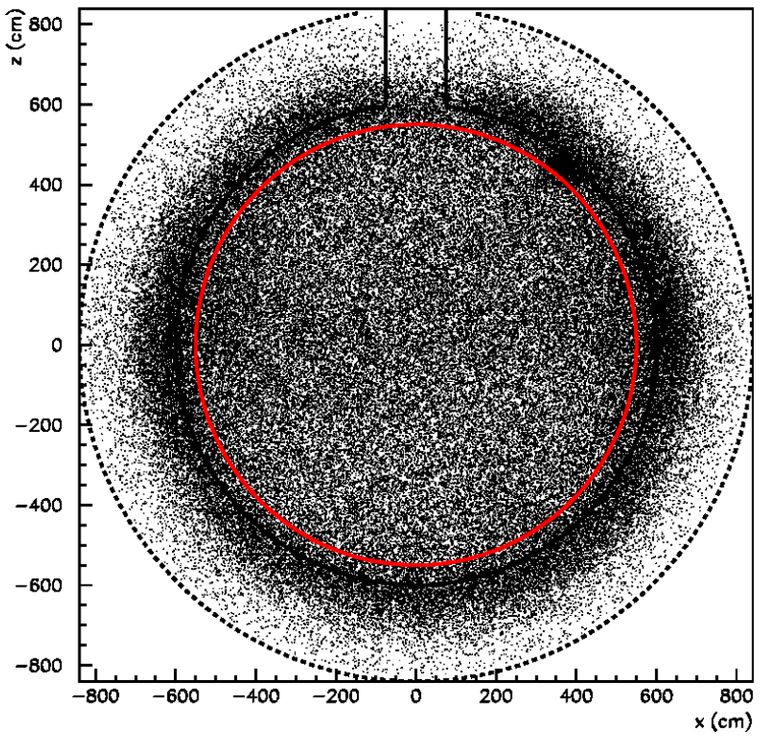
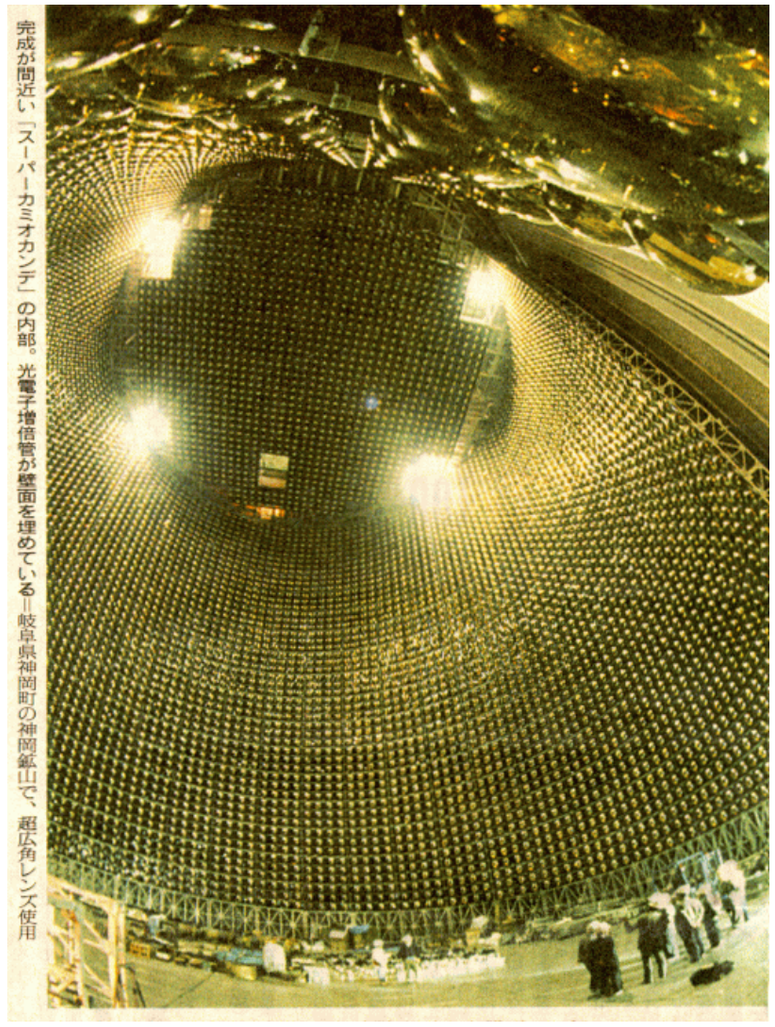


Can't turn 'beam' *or* backgrounds off
Find the 2000 ν events in SNO....



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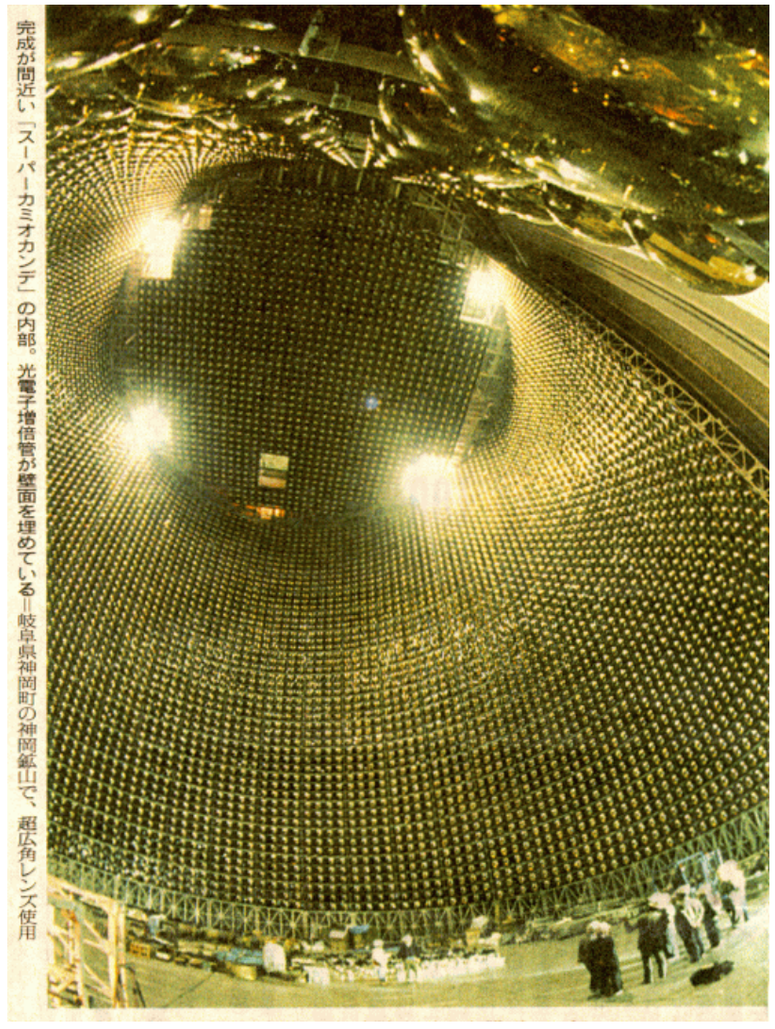
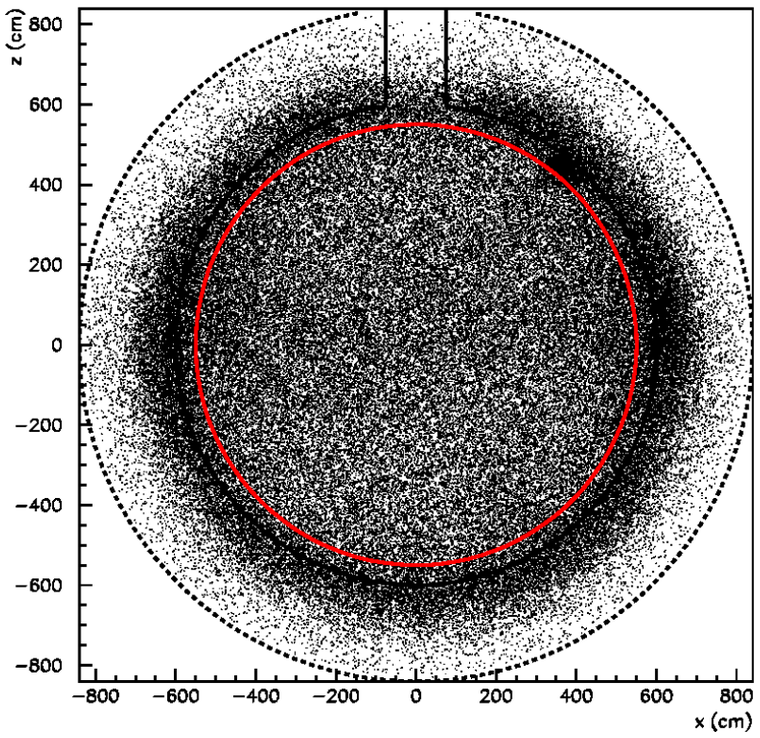


Solar flux uncertainty ~1-20%



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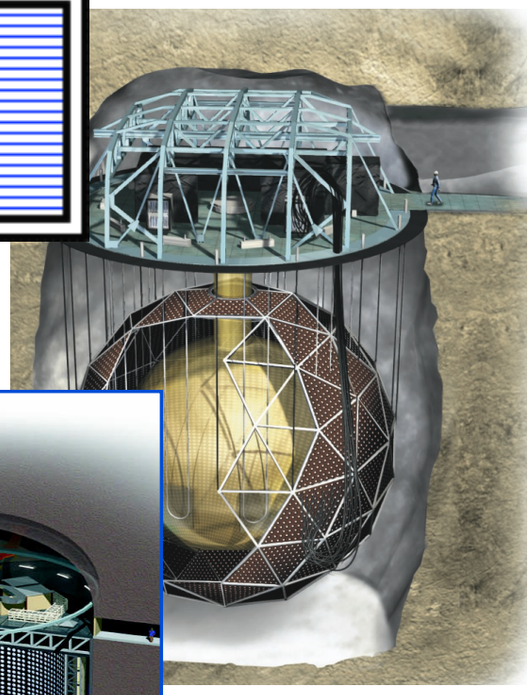
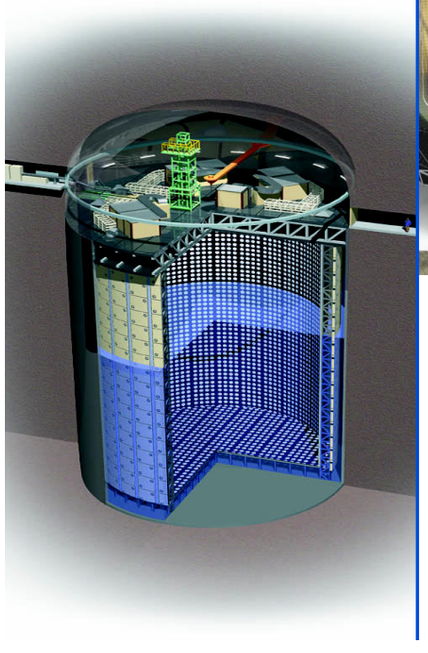
Experiments

Experiments

Water Cerenkov





SNO

SuperK

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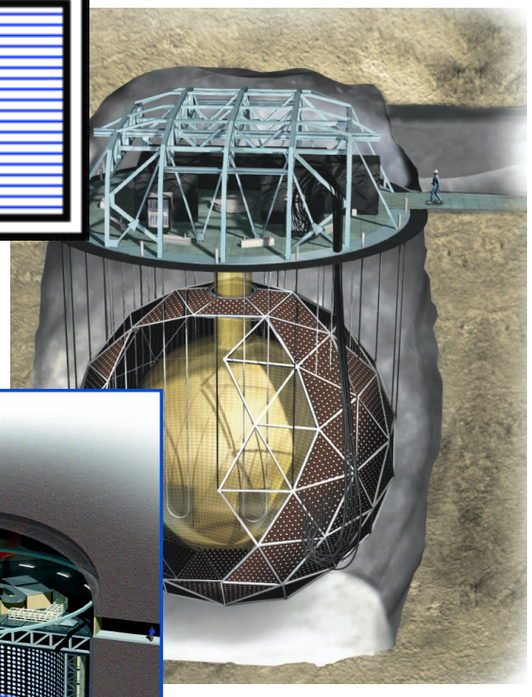
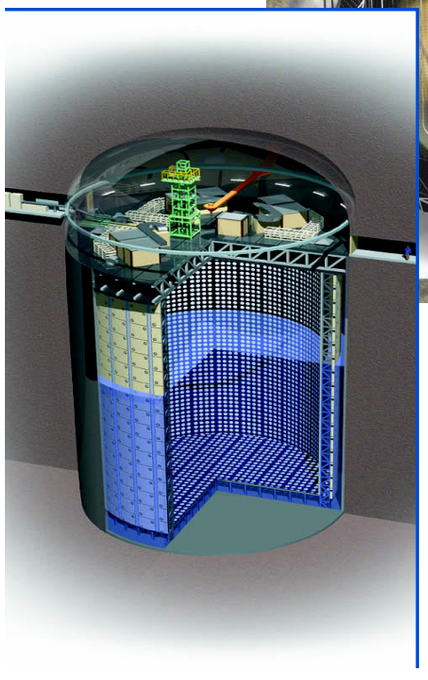
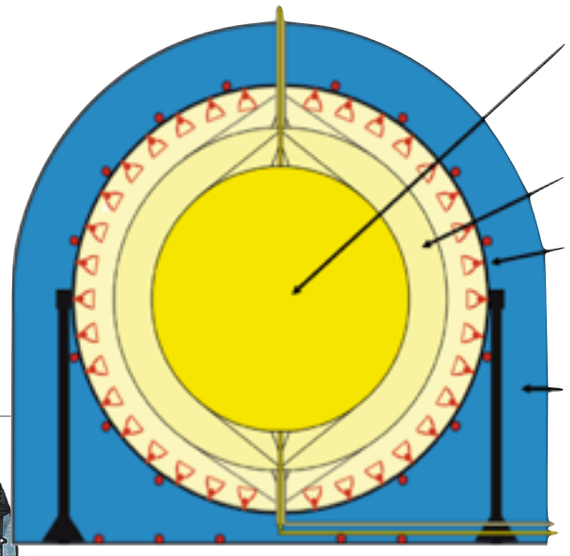


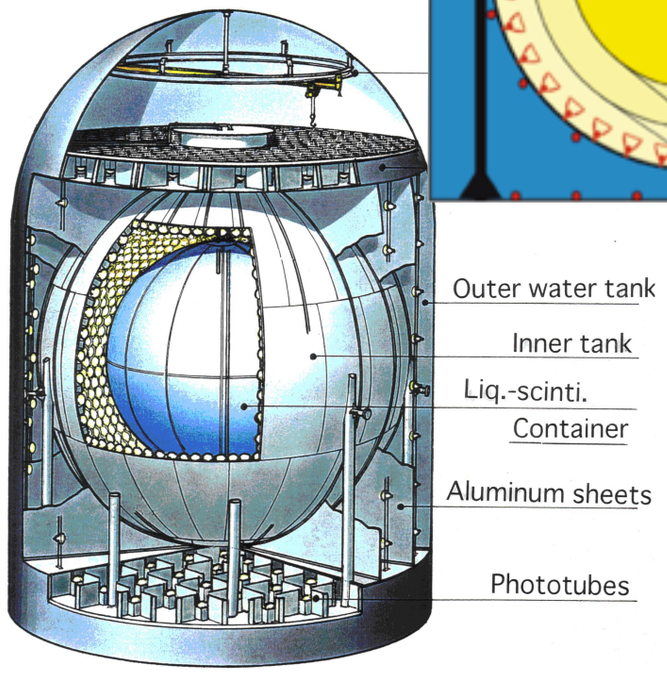


SNO
SuperK

Liquid Scintillator

Borexino
KamLAND





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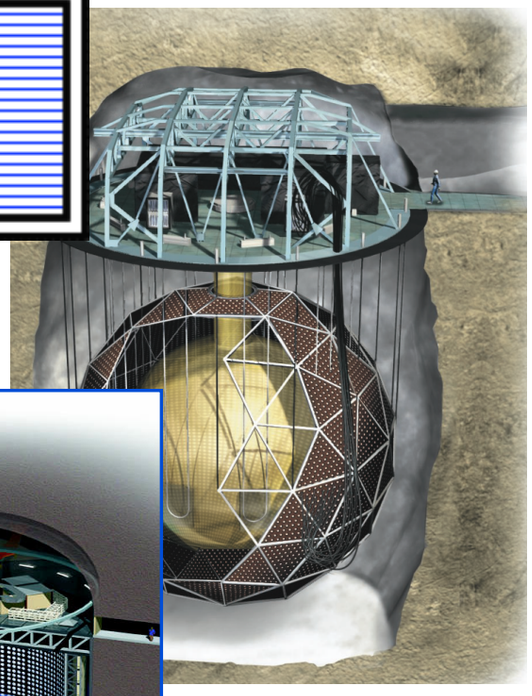

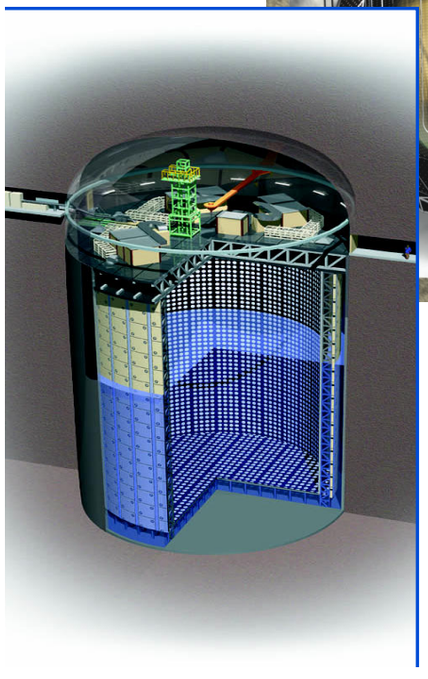

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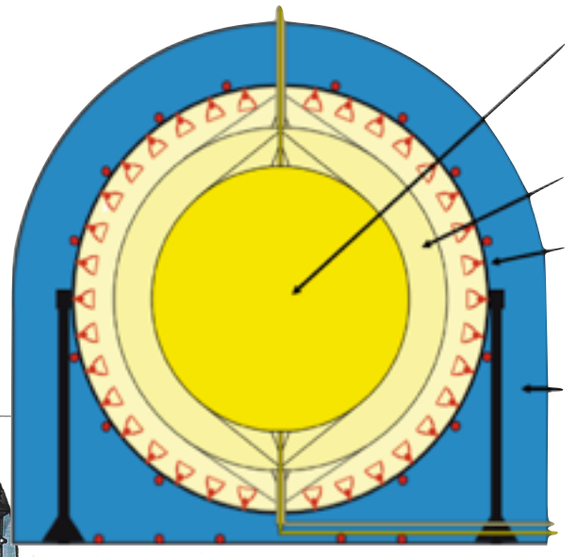
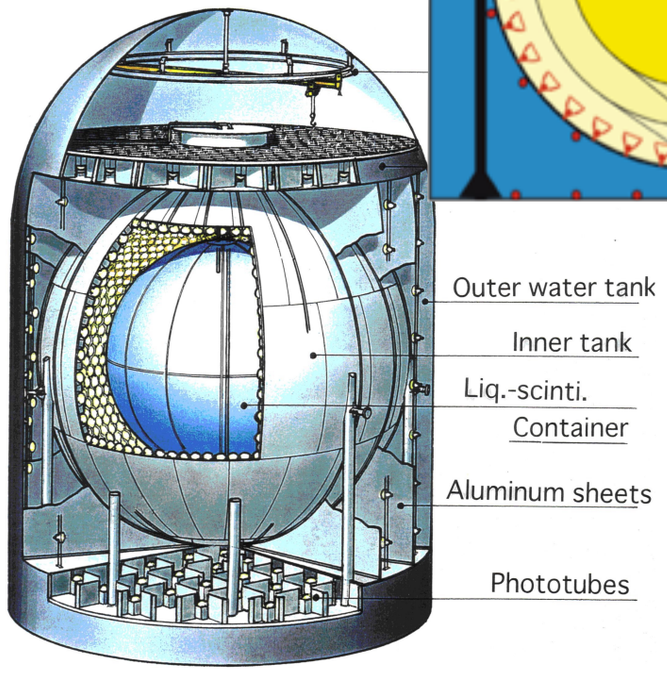




Radiochemical

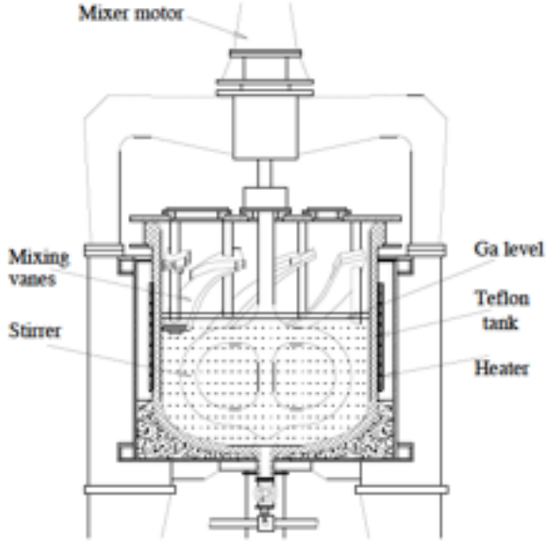


FIG. 1. Chemical reactor for extraction of Ge from Ga.

Phys.Rev.C60:055801,1999

SAGE

SNO+

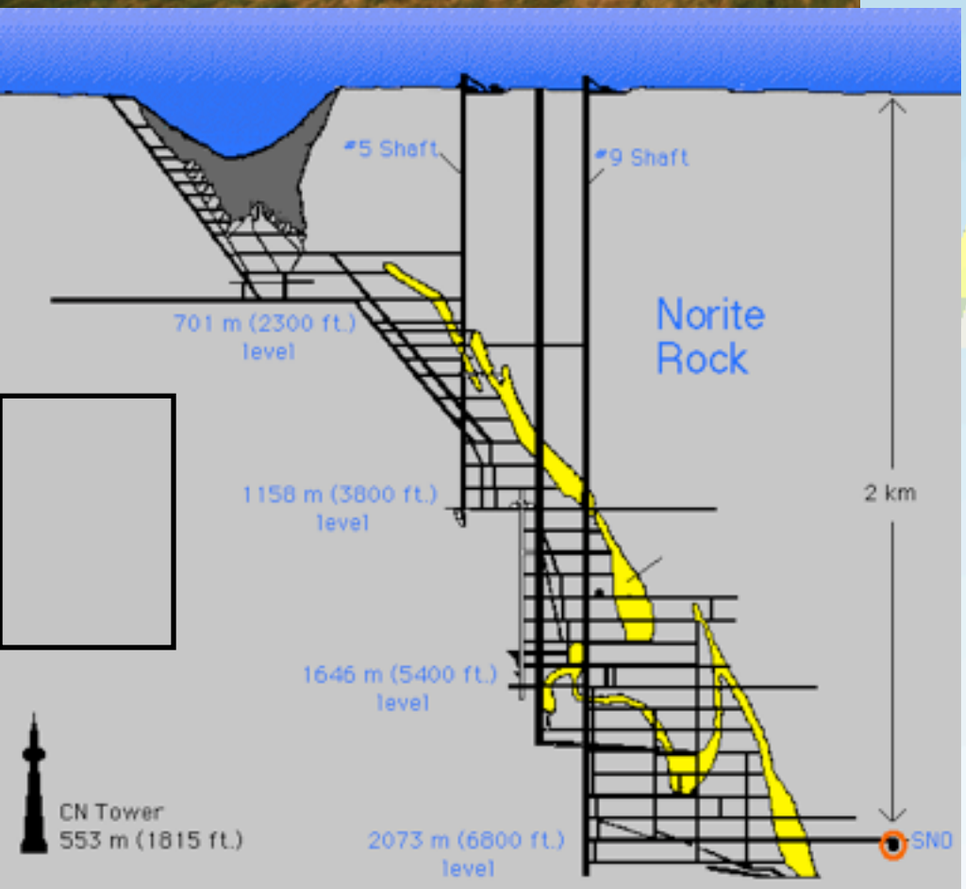
The only fully-funded new solar experiment

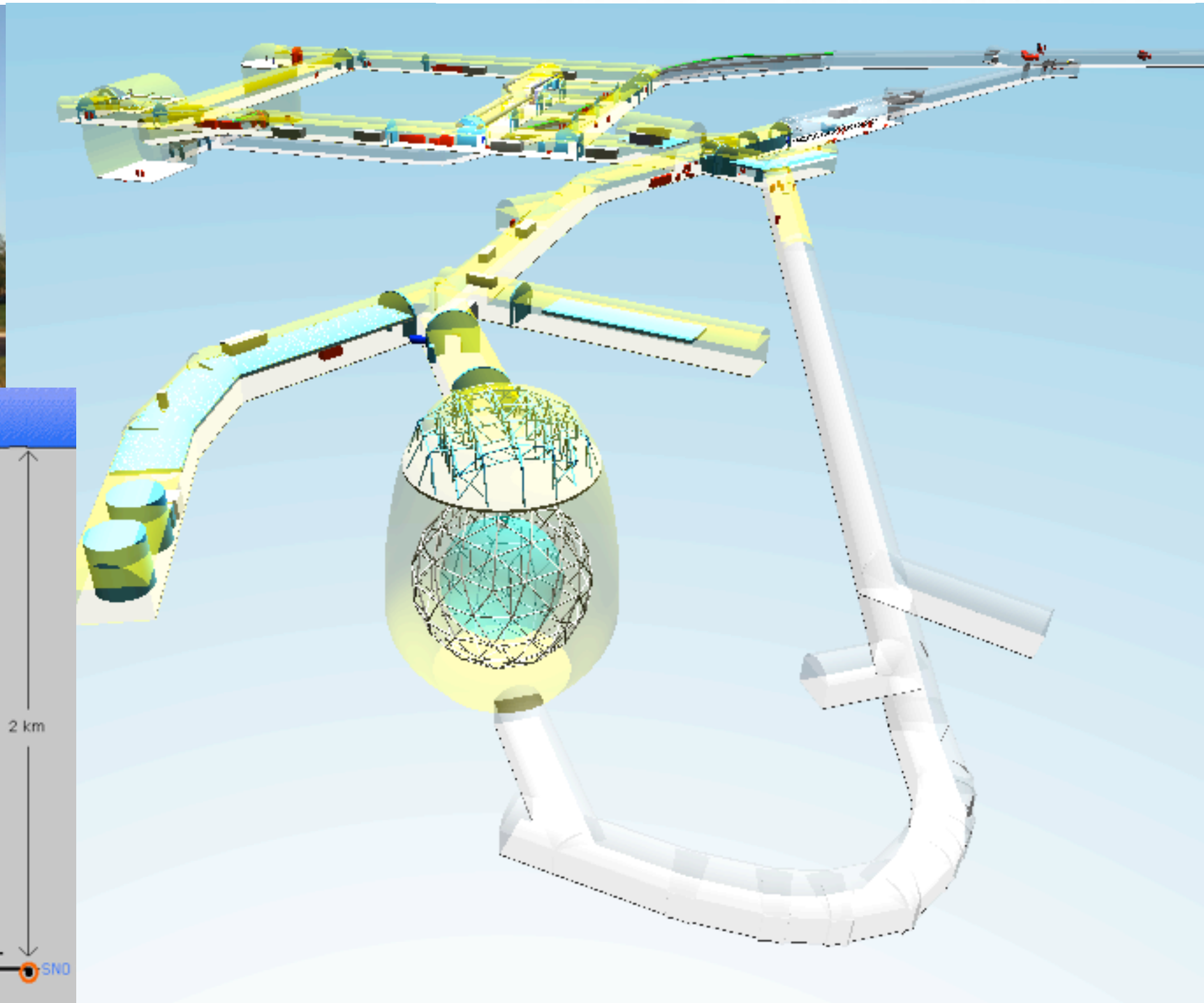
SNO+

SNOLAB

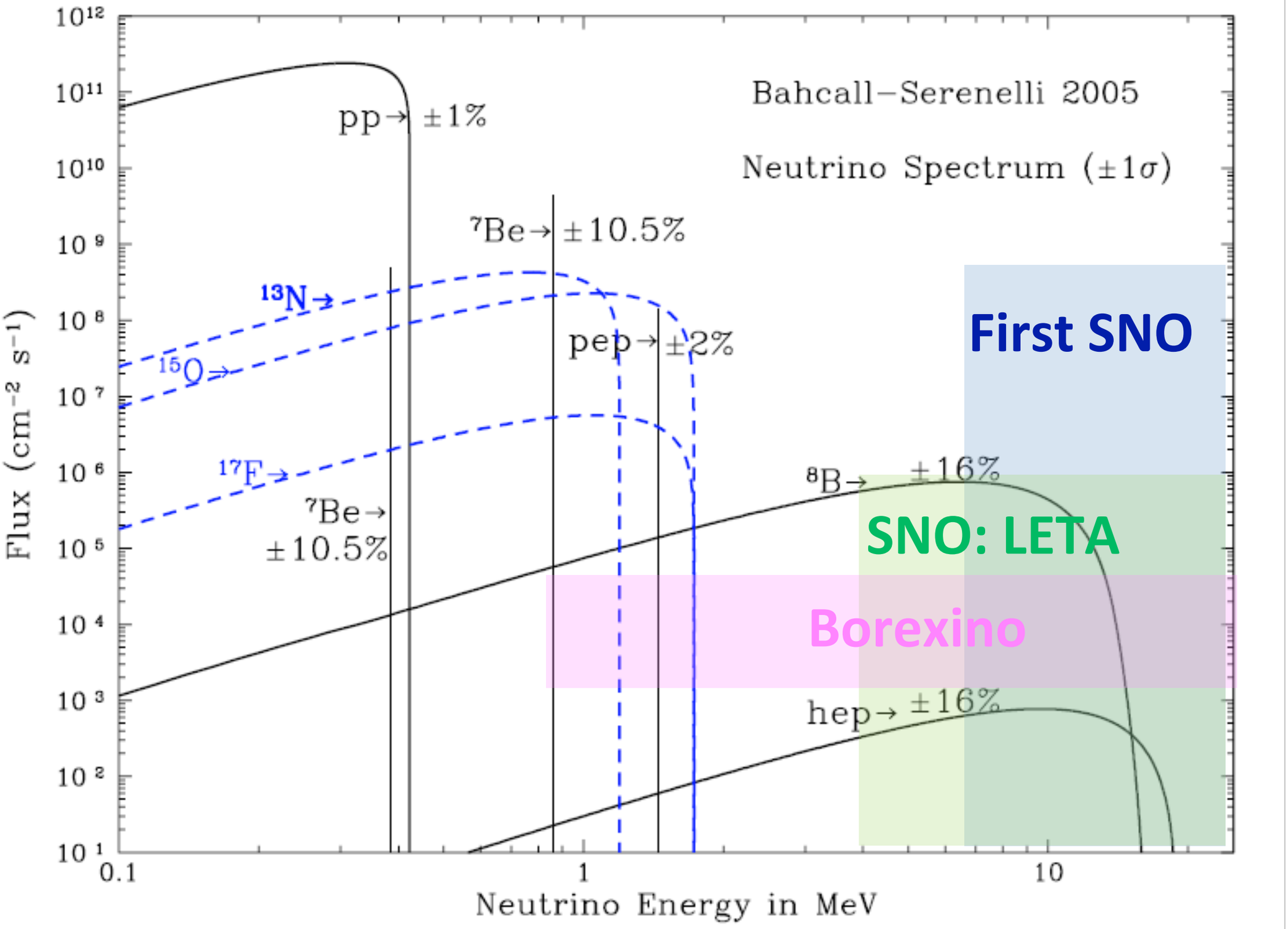
MINING FOR KNOWLEDGE

CREUSER POUR TROUVER... L'EXCELLENCE

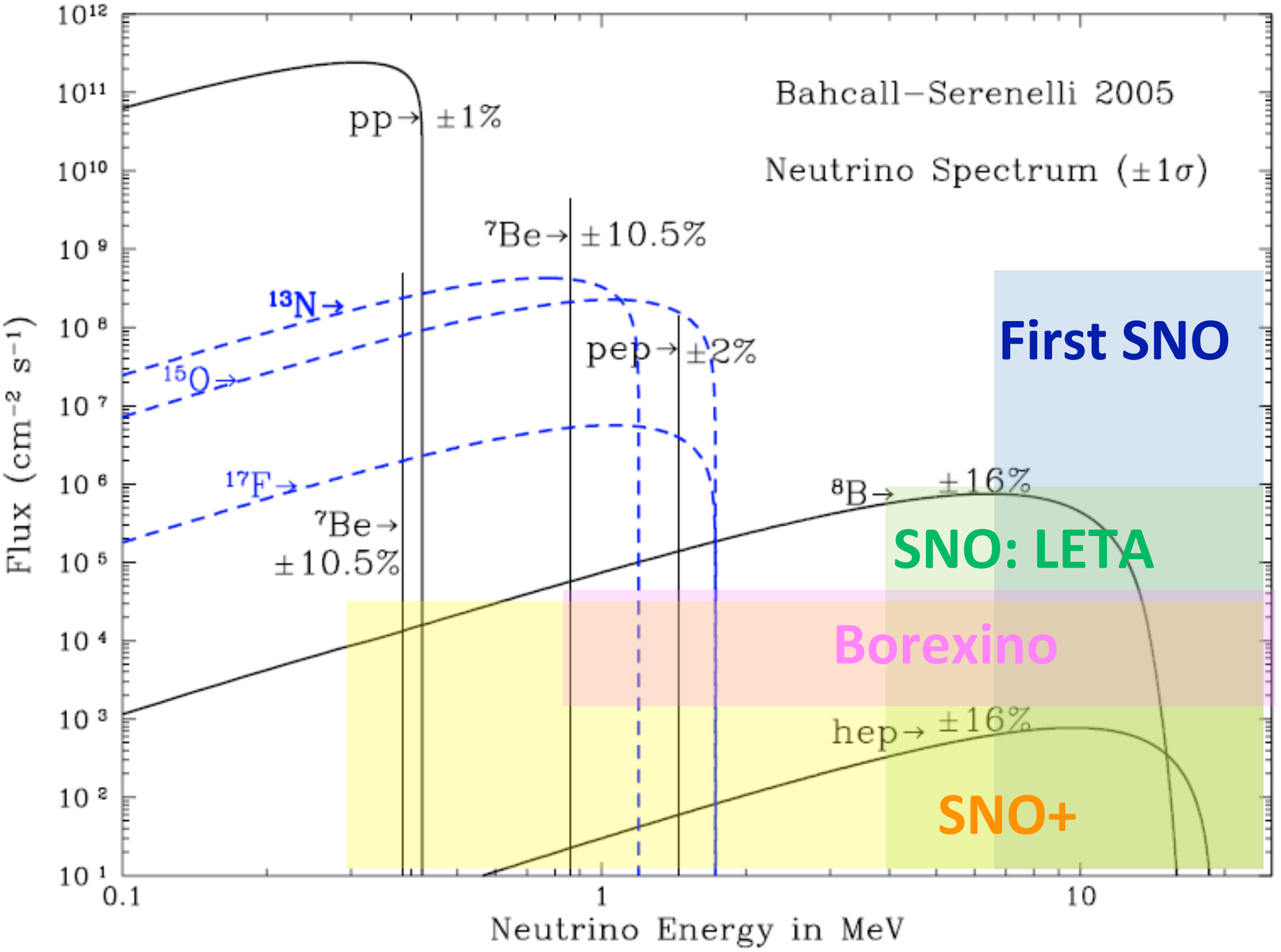




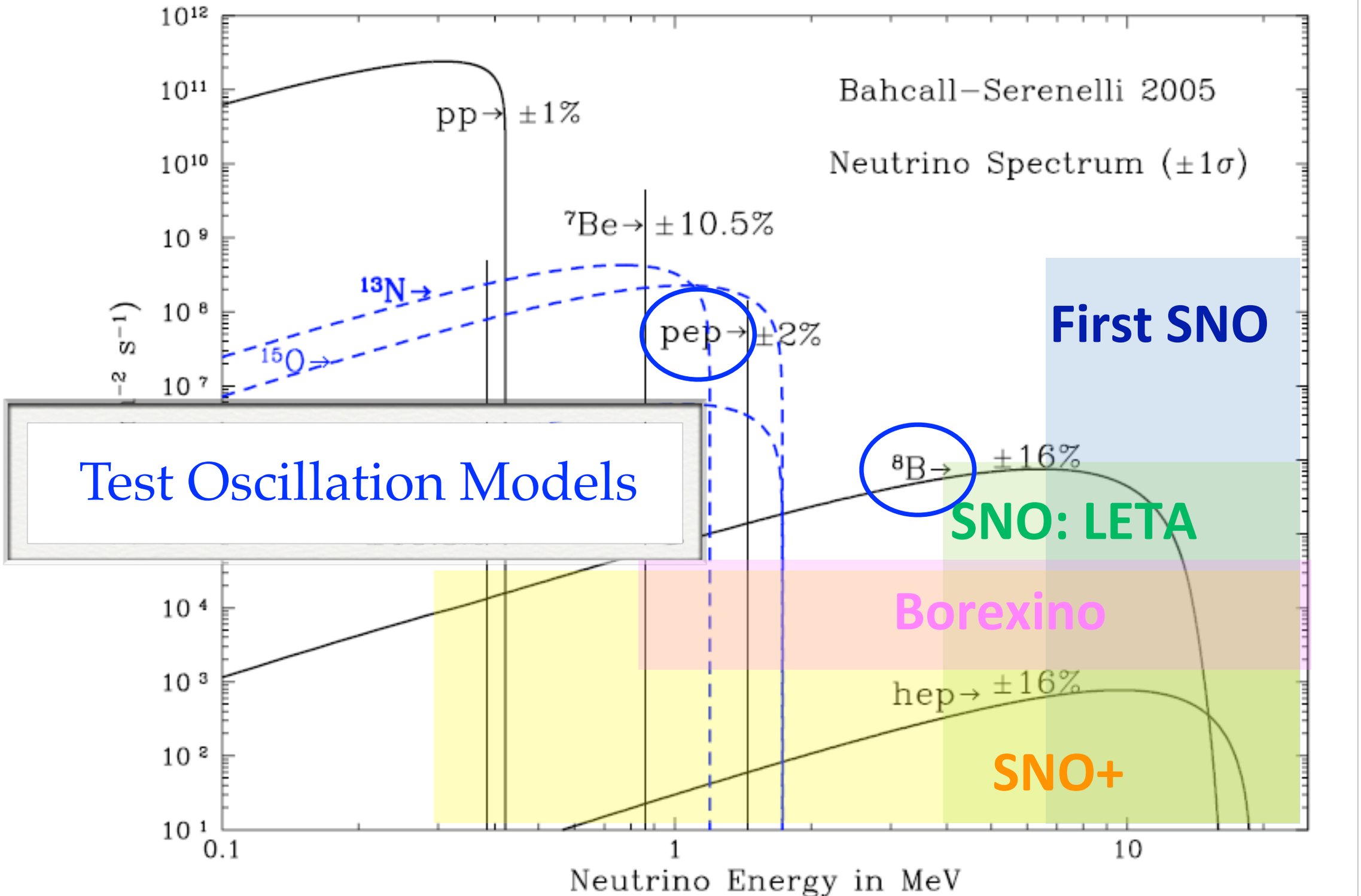
Solar ν Status



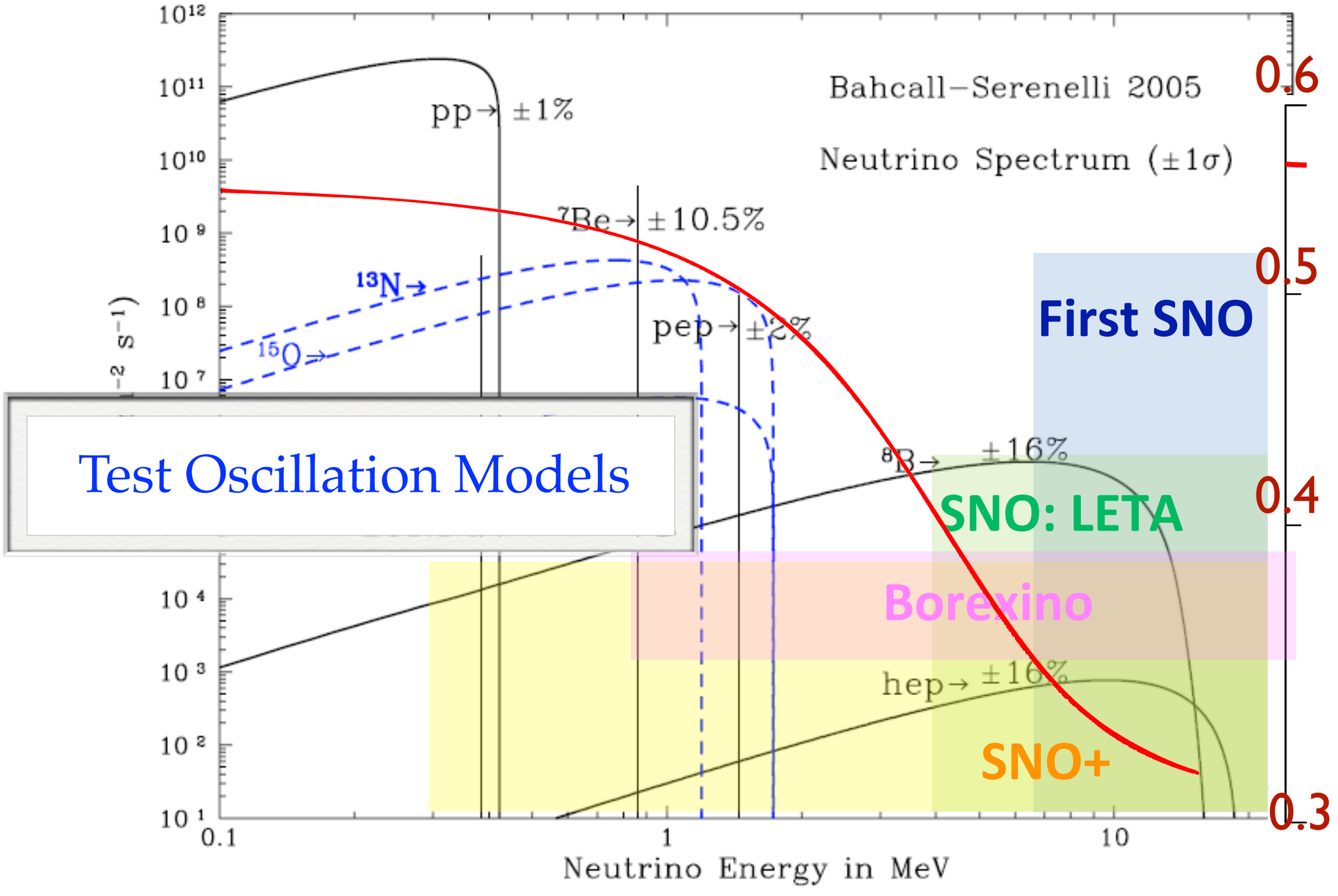
SNO+ Solar ν Prospects



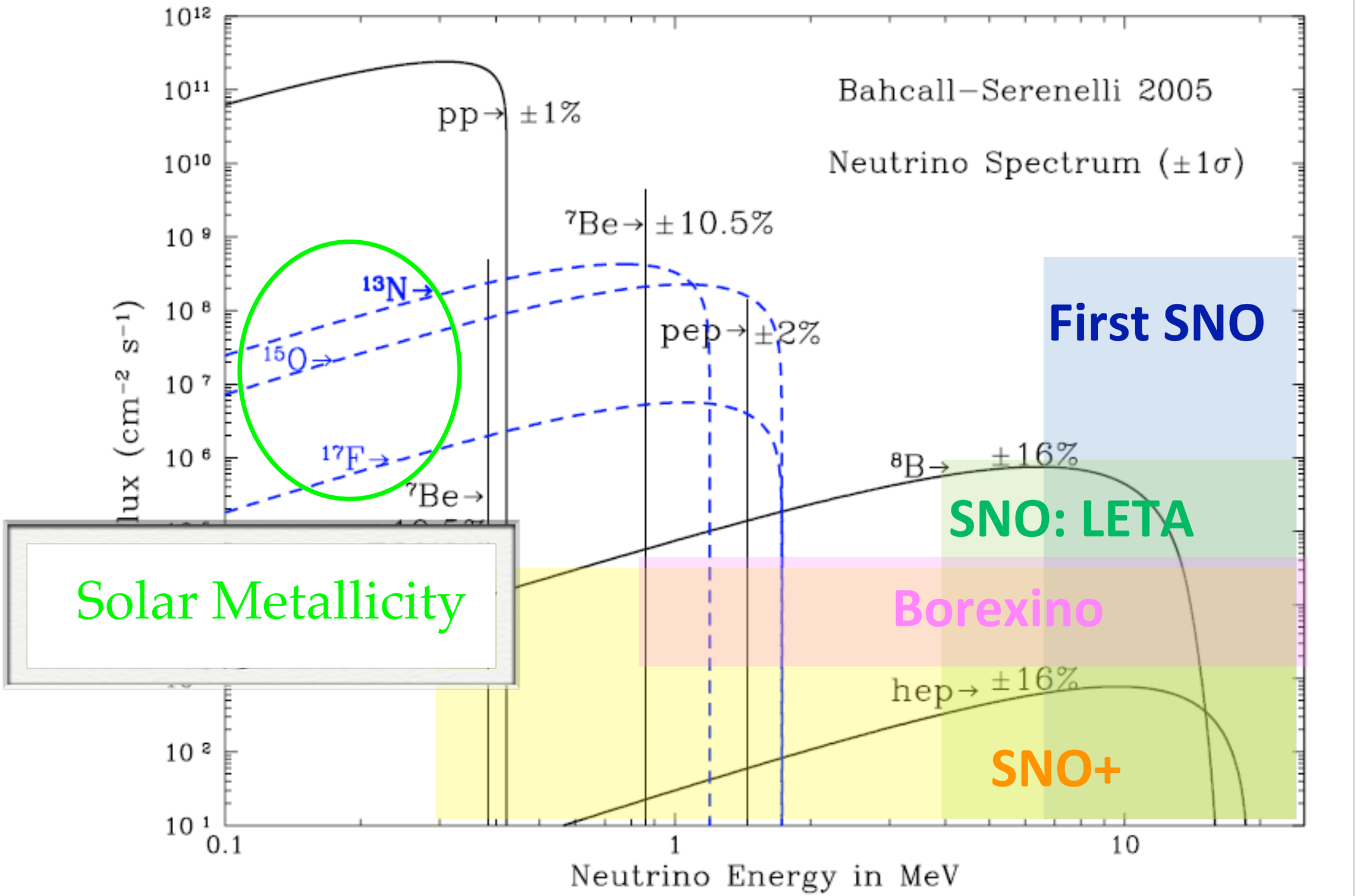
SNO+ Solar ν Prospects



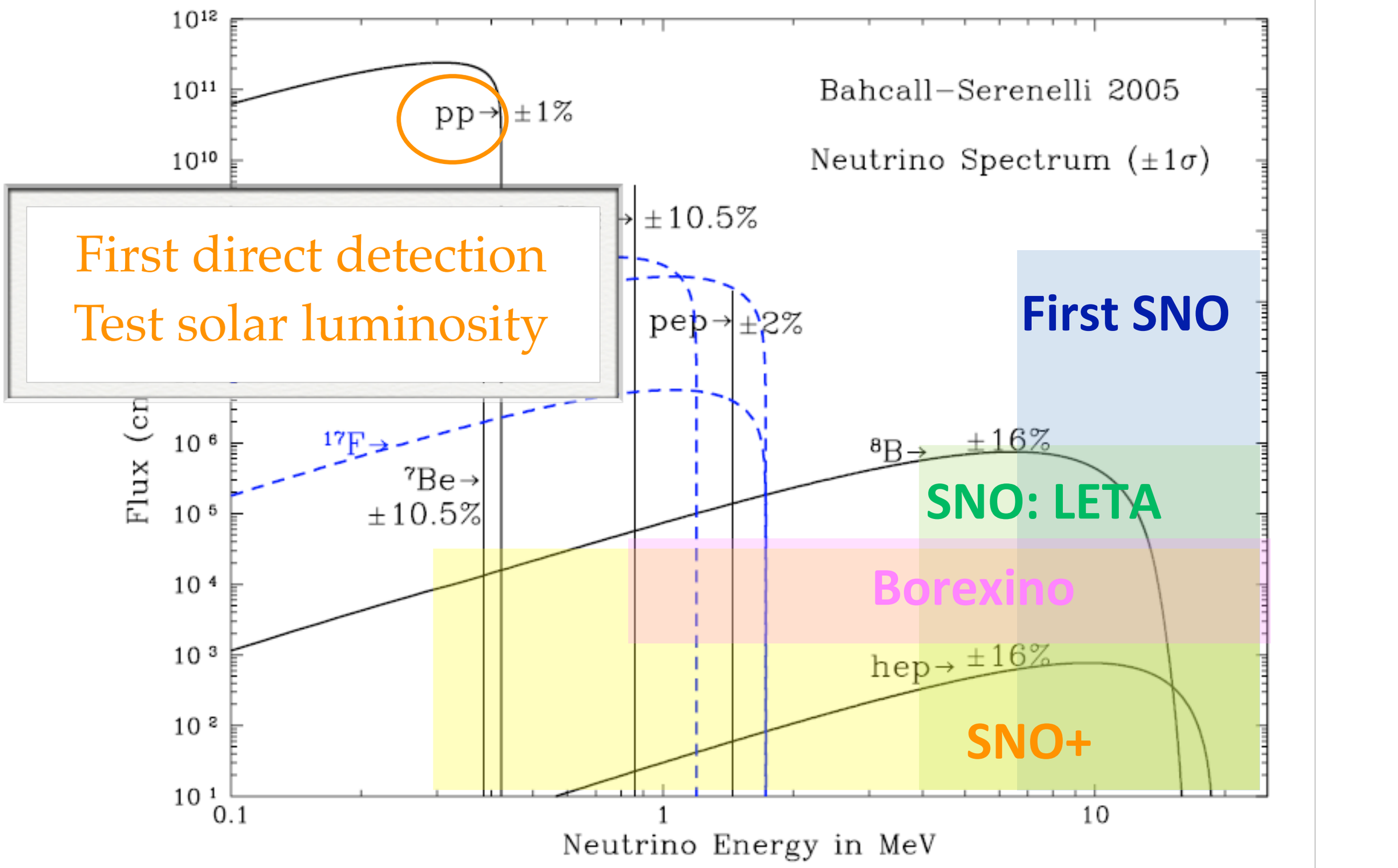
SNO+ Solar ν Prospects



SNO+ Solar ν Prospects



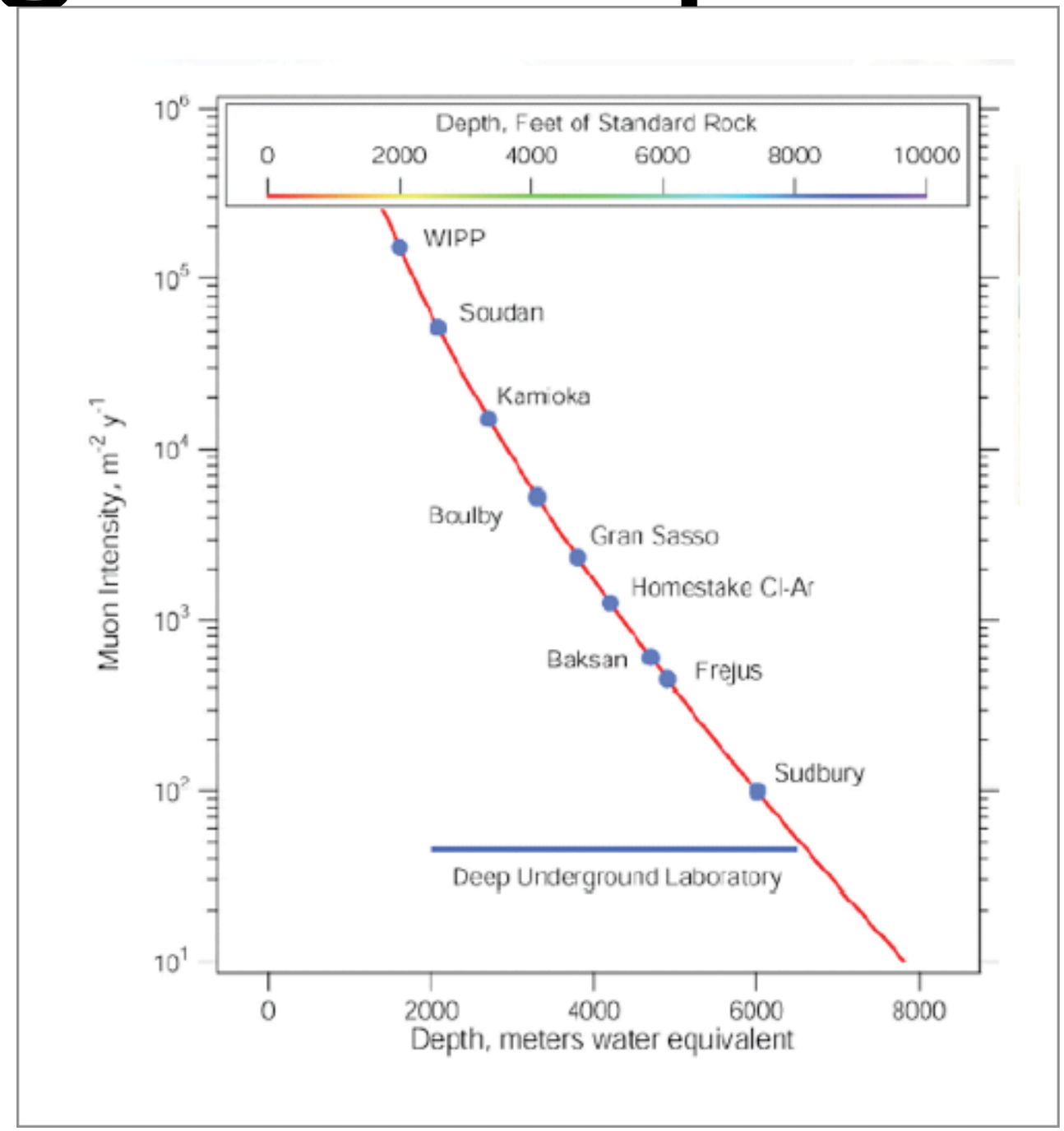
SNO+ Solar ν Prospects



The Advantages of Depth

^{11}C produced by cosmic μ hitting organic molecules

KamLAND: 2700 mwe
Borexino: 3500 mwe
SNO+: 6080 mwe

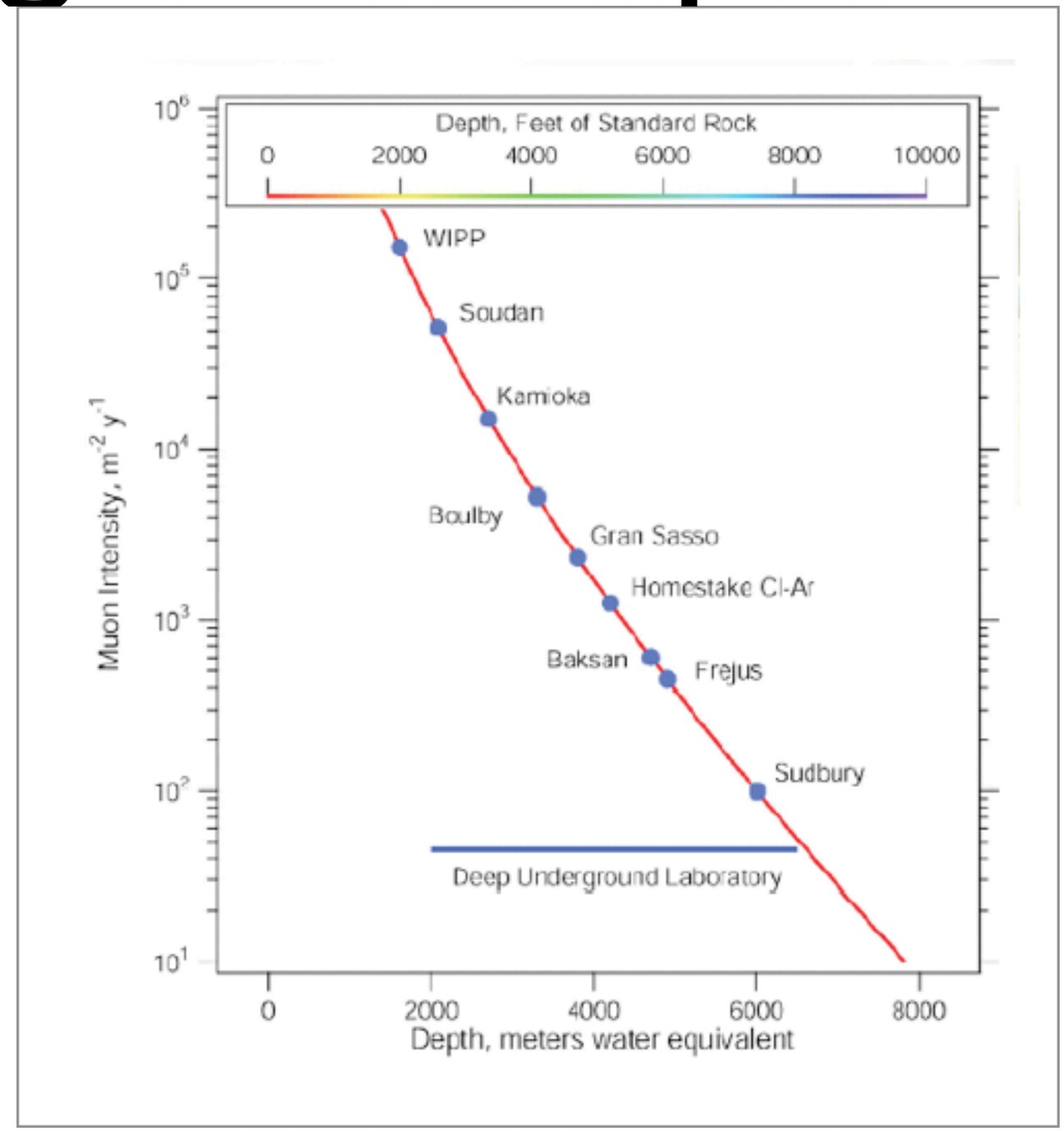


The Advantages of Depth

^{11}C produced by cosmic μ hitting organic molecules

KamLAND: 2700 mwe
Borexino: 3500 mwe
SNO+: 6080 mwe

>/100



The Advantages of Depth

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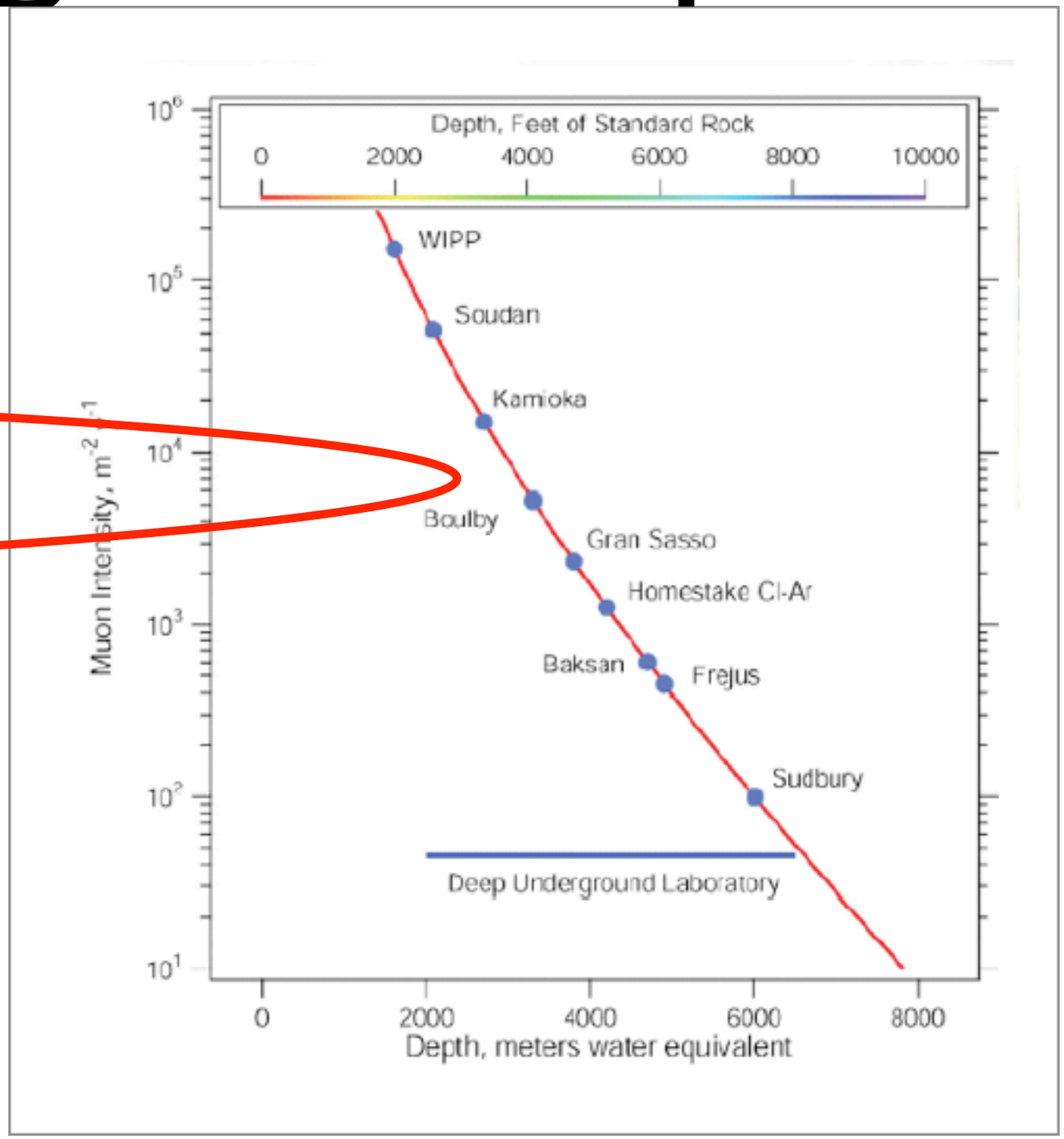
KamLAND: 2700 mwe
Borexino: 3500 mwe
SNO+: 6080 mwe

/100

/600



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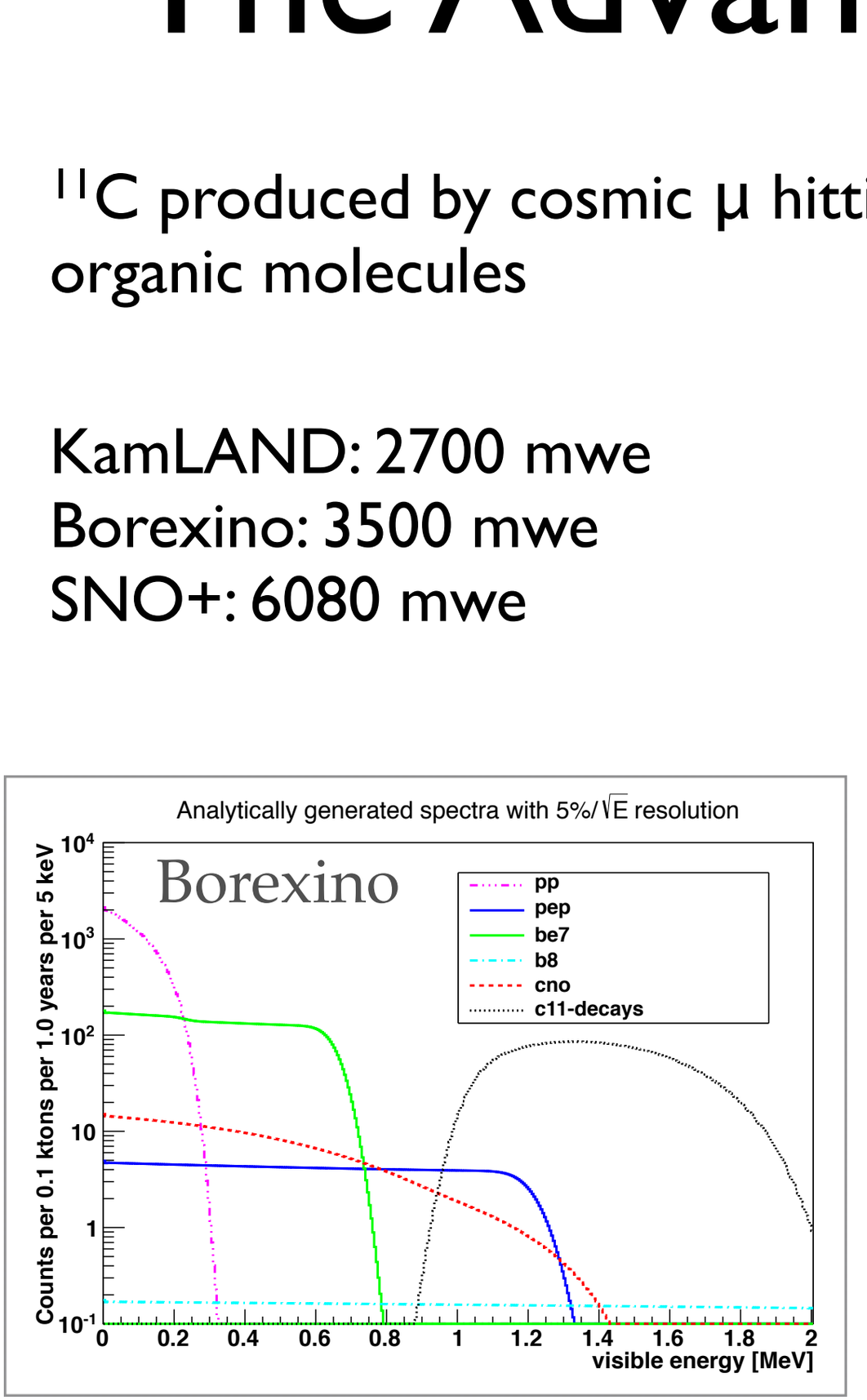
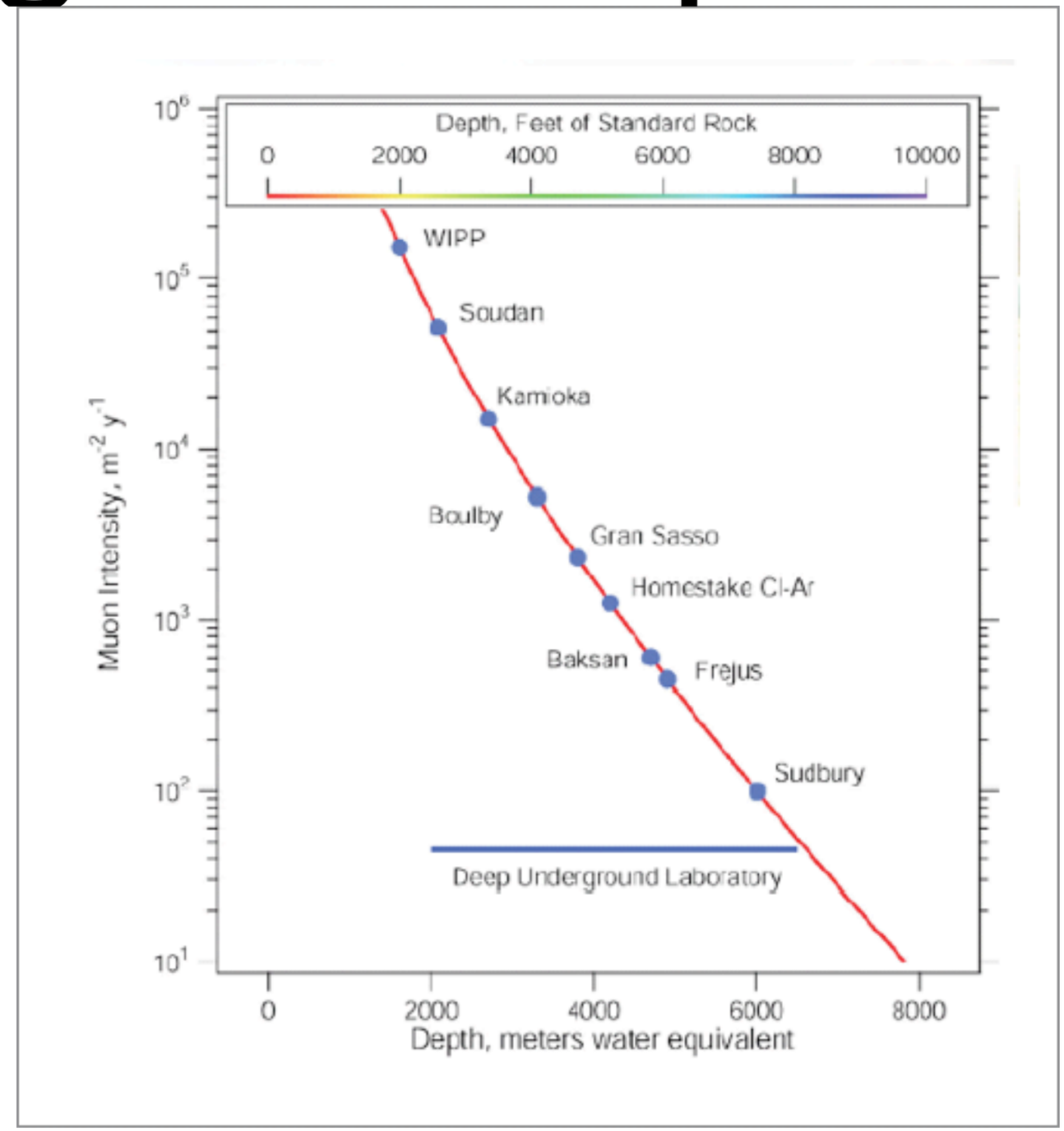


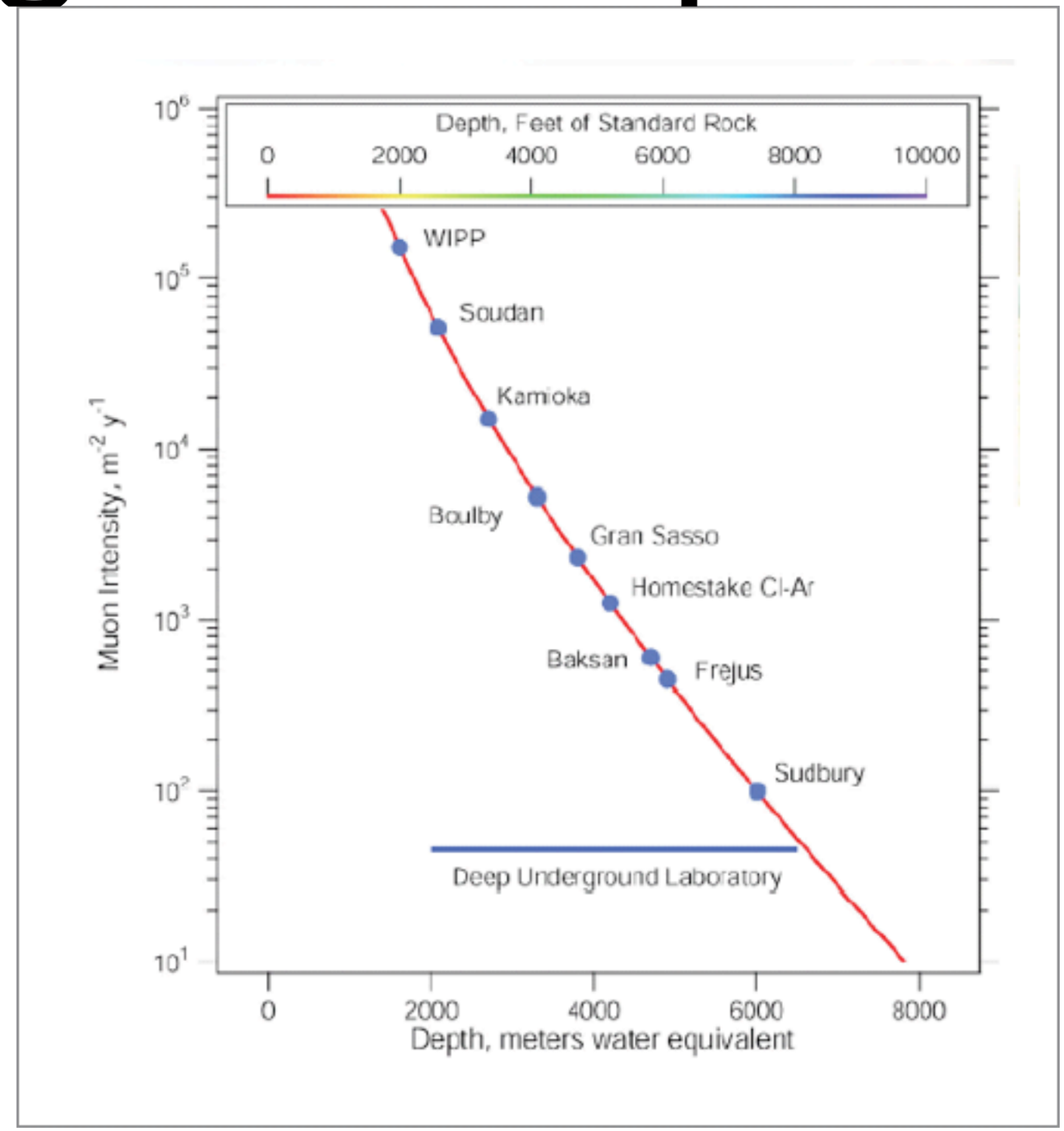


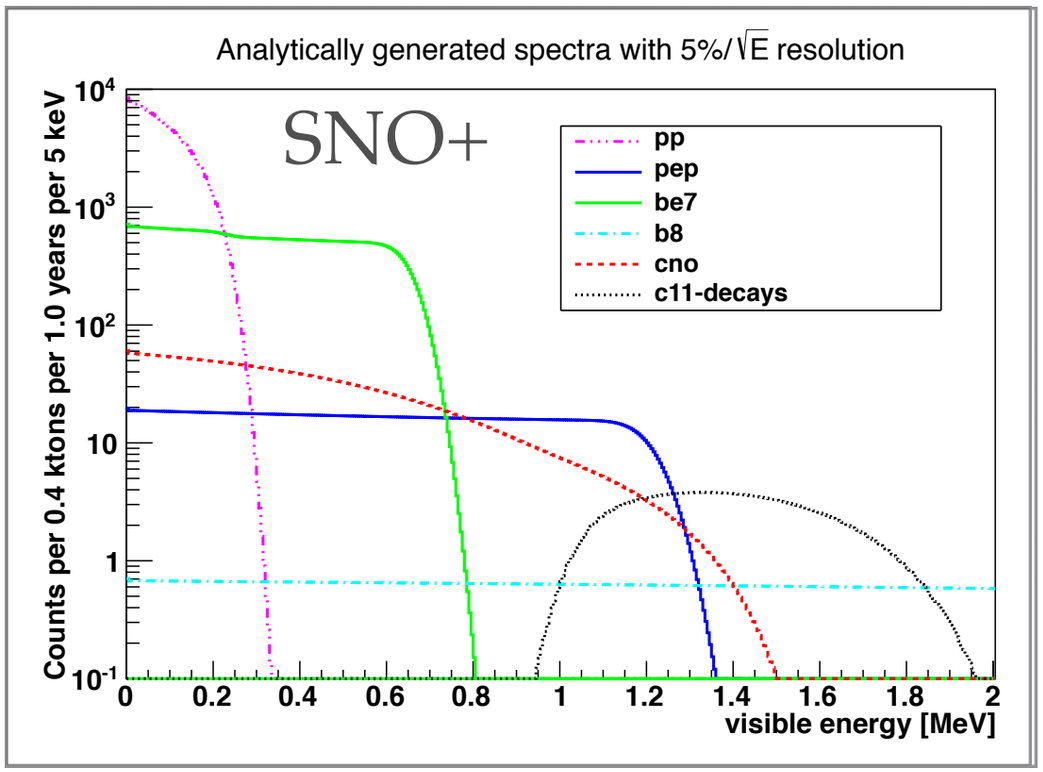
3-fold coincidence cut for 11C rejection
91% rejection, 52% signal loss

The Advantages of Depth

^{11}C produced by cosmic μ hitting organic molecules

KamLAND: 2700 mwe
Borexino: 3500 mwe
SNO+: 6080 mwe



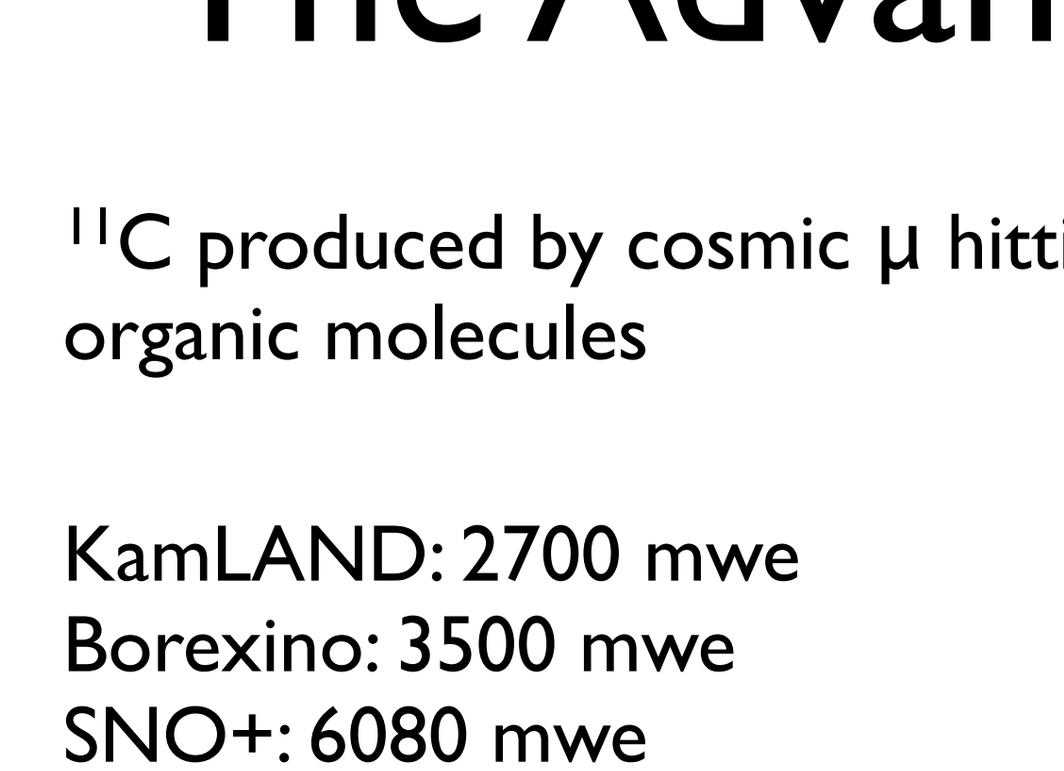


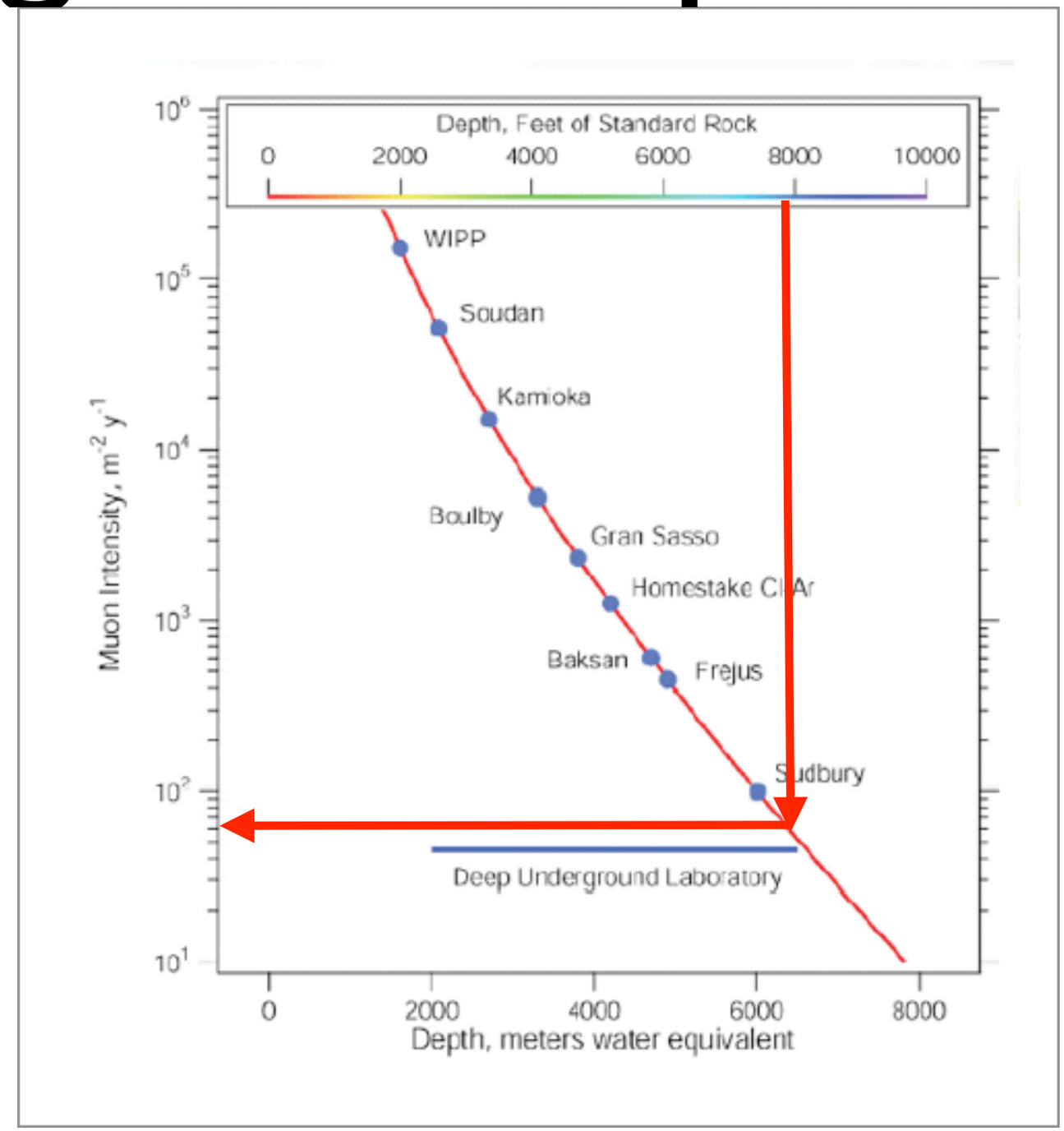
The Advantages of Depth

^{11}C produced by cosmic μ hitting organic molecules

KamLAND: 2700 mwe
Borexino: 3500 mwe
SNO+: 6080 mwe

JinPing: 7500 mwe





Ultra low cosmogenic backgrounds!

The Road Ahead

J.R. Klein

The Road Ahead

J.R. Klein

Needs going forwards:

Super-sized detector (stats)

Ultra low bkg

CC detection (spectrum)

On The Horizon

CC detection: LENS

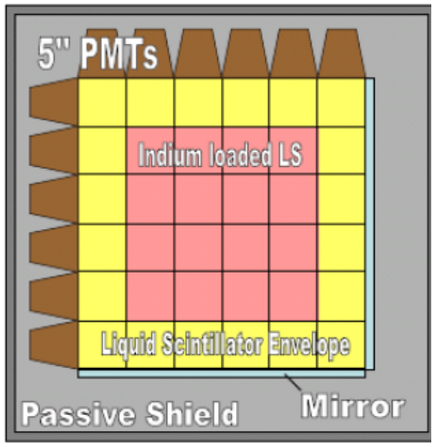
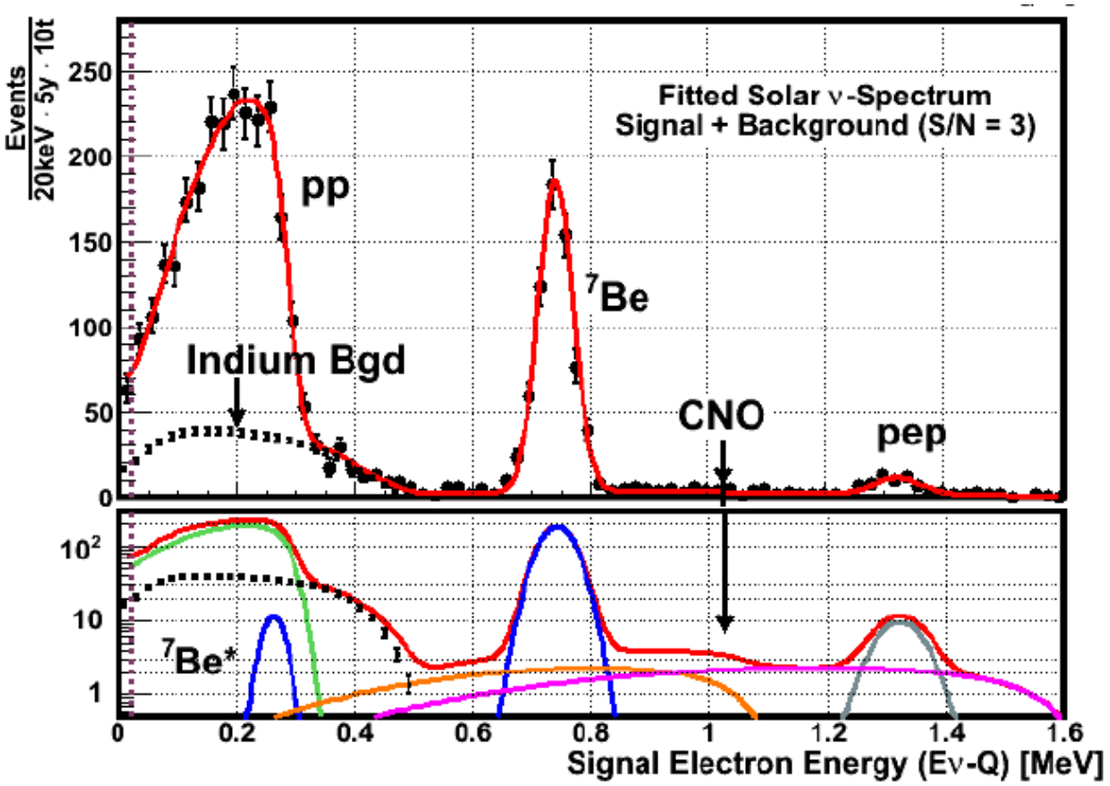


Fig. 12 Schematic design of MINILENS

$$\nu_e + {}^{115}In \rightarrow e^- + (\tau = 4.76\mu s)2\gamma + {}^{115}Sn$$



On The Horizon

CC detection: LENS

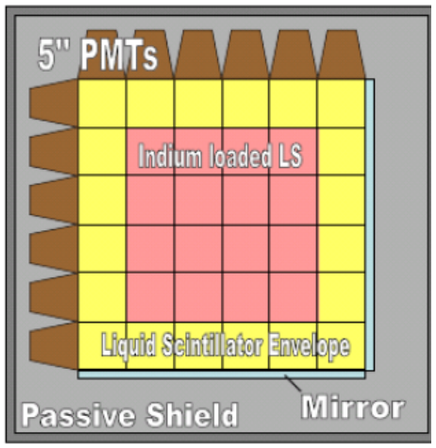


Fig. 12 Schematic design of MINILENS

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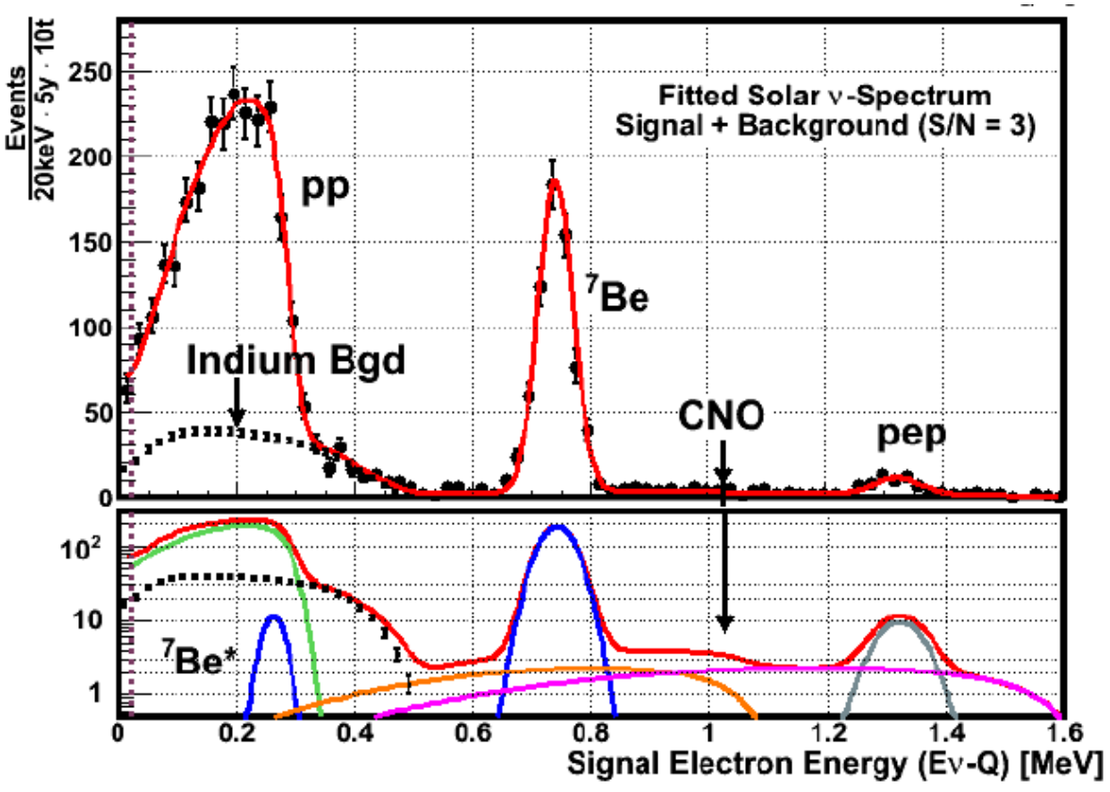
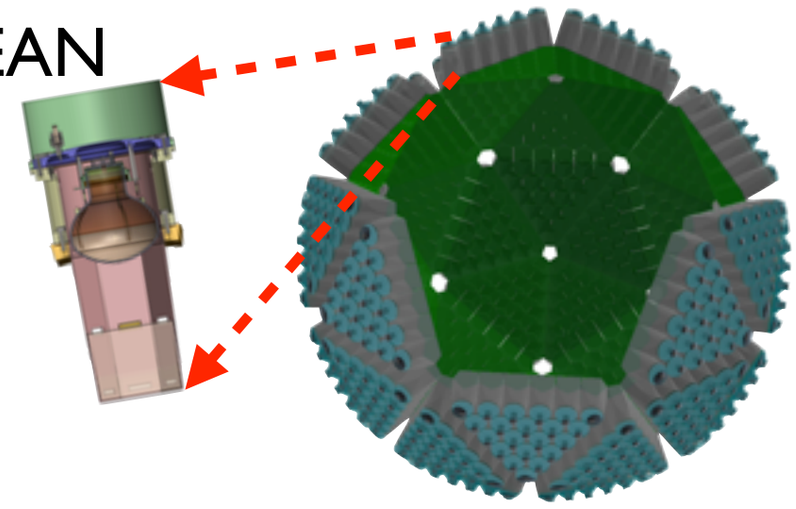
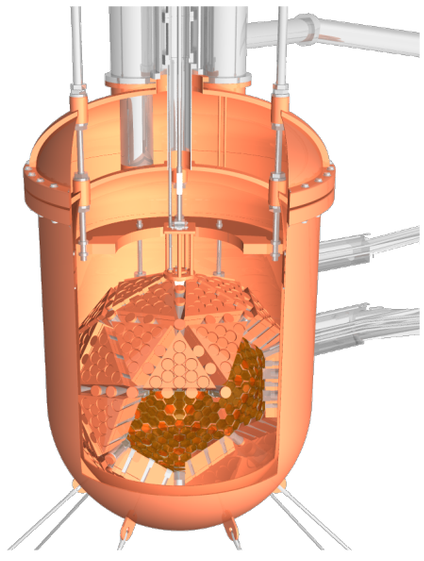


Noble Liquid DM

CLEAN



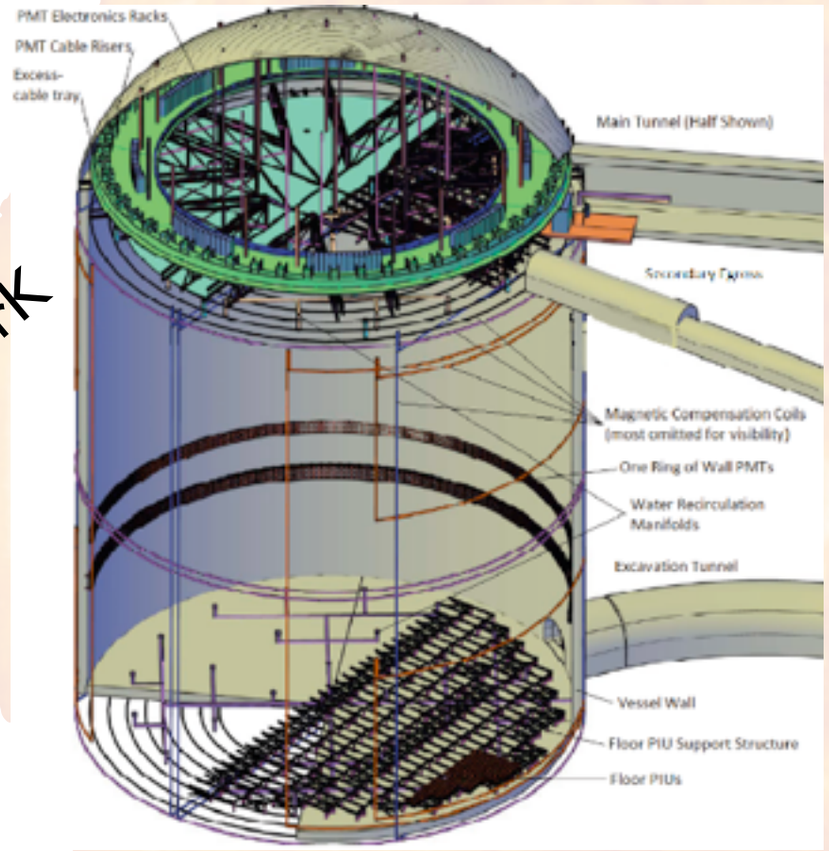
XMASS



Large-scale LXe, Ne, Ar
Low bkg
Elastic Scattering
Xe requires depletion of ^{136}Xe ($2\nu\beta\beta$) ~ 100*
Potential for %-level *pp*

Mega-Ton Scale

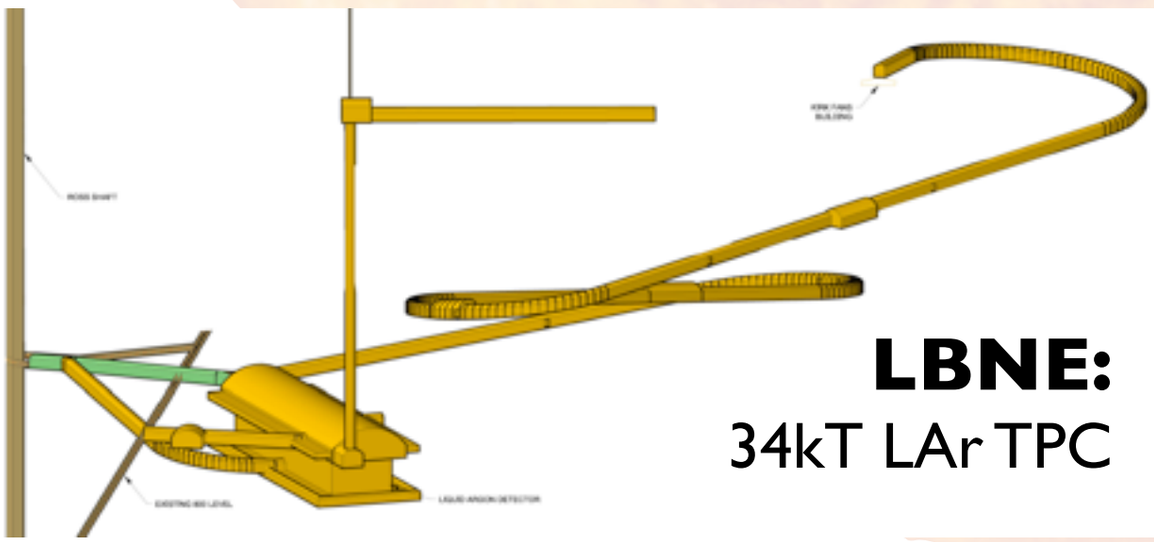
Hyper-Kamiokande



0.99e6 T
20* SuperK

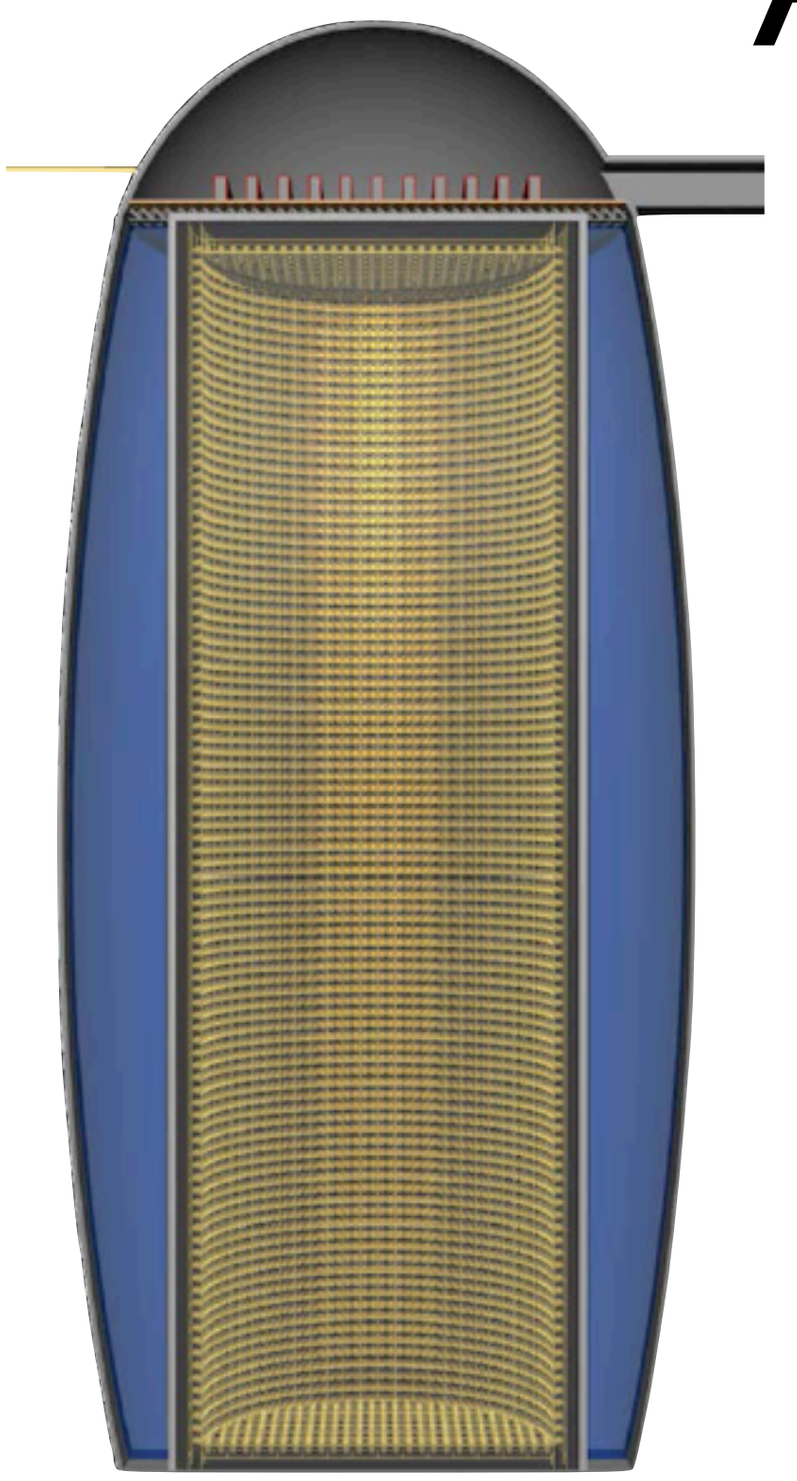
Laguna

LENA: ~50kT liquid scintillator
GLACIER: up to 100kt LAr TPC
MEMPHYS: >400kT Water Cerenkov



LBNE:
34kT LAr TPC

Low Energy Neutrino Astronomy



- 50kT (30kT FV solar), 30% coverage
- Unprecedented statistics
- 3σ discovery potential for 0.5%-amplitude temporal fluctuations in ^{7}Be

Detection Channel	Neutrino Source	BPS08(GS) (cpd) total	BPS08(GS) (cpd) >250 keV	BPS08(AGS) (cpd) total	BPS08(AGS) (cpd) >250 keV
$\nu e \rightarrow e\nu$	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
$^{13}C(\nu_e, e)^{13}N$	^{8}B	2.9±0.3		2.6±0.2	

- CC on ^{13}C

J. Winter et al, TAUP 2011 Proc.

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

Experimental Techniques

or "How to Scale Up?"

- Increase photocathode coverage
  - HQE PMTs + light concentrators
  - LAPPD (Large Area PS Photo Detector)
- Increase light yield
  - Reduce attenuation
  - Additive e.g. quantum dots (*)
- Increase information
  - Directionality from Cherenkov component

(*) "Next Generation Liquid Scintillator Based Detectors: Quantums Dots and Picosecond Timing" L. Windlow

Water-Based LS Target

Dissolution of LS into ultra-pure water

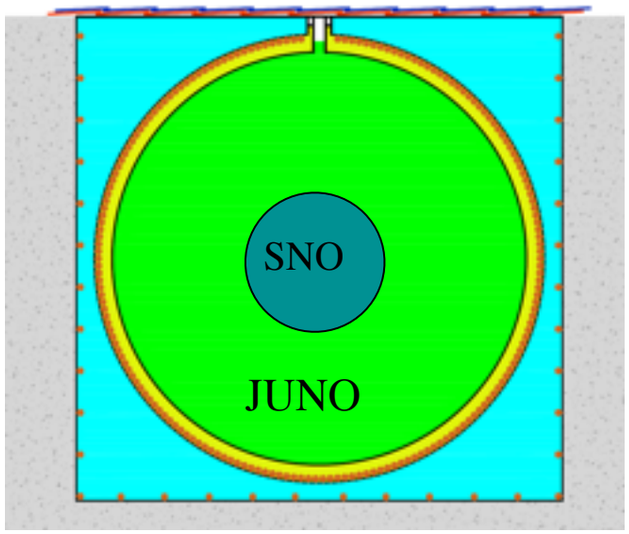
- ✳ High light yield of LS
  - ➡ Low energy threshold
  - ➡ Good energy resolution
- ✳ Directional info from Cherenkov in H_2O
- ✳ Long attenuation of water
- ✳ Increased metal loading (hydrophilic ions)

M. Yeh et al., BNL (arXiv 1308.0493)

Dream Detector

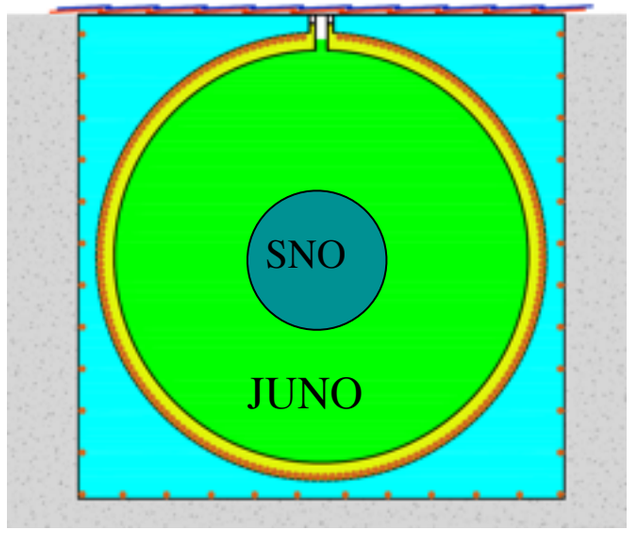
Dream Detector

- Large scale (50kT - MT)
- Simple design: minimise systematics
- Liquid scintillator: ⇒ t/h, resolution

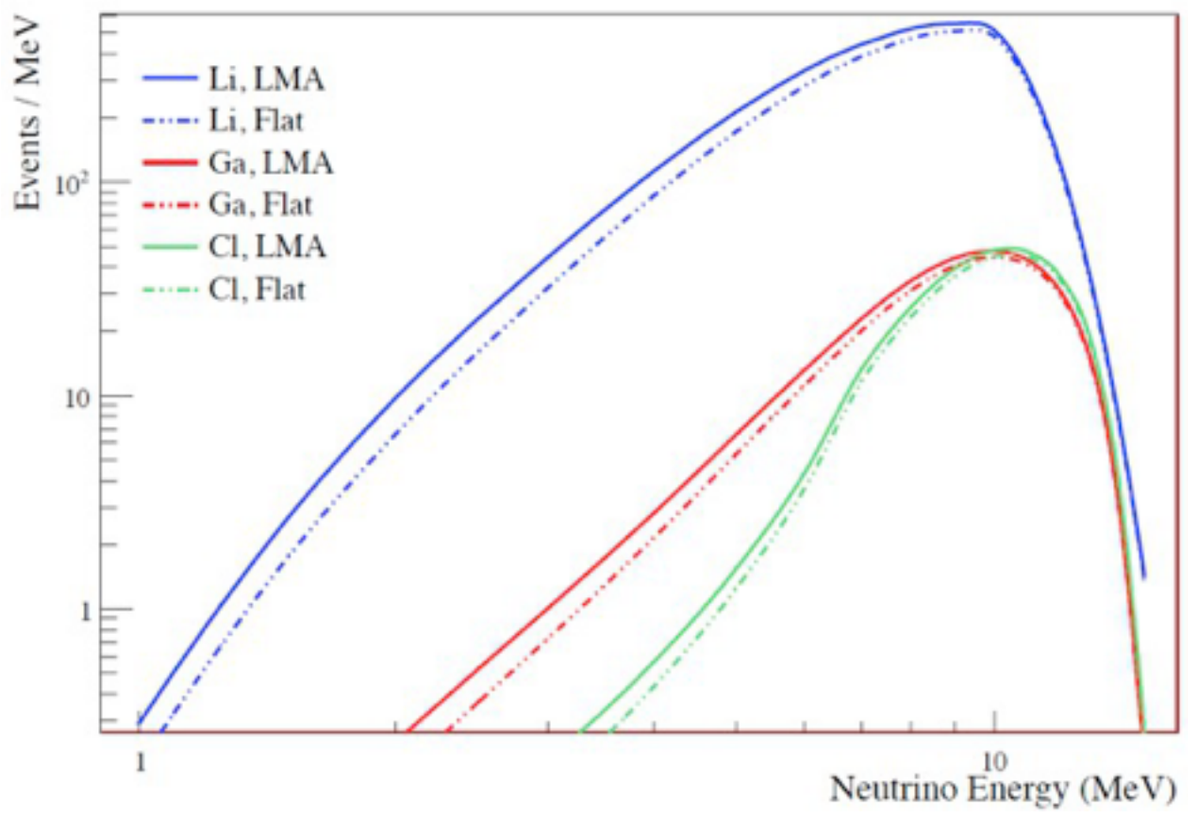


Dream Detector

- Large scale (50kT - MT)
- Simple design: minimise systematics
- Liquid scintillator: ⇒ t/h, resolution
- Load with isotope: CC detection

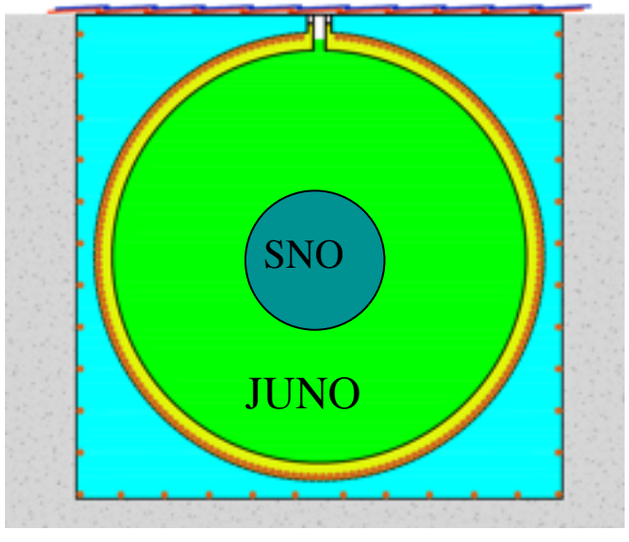


➡ ^{7}Li, ^{37}Cl, H-WbLS?

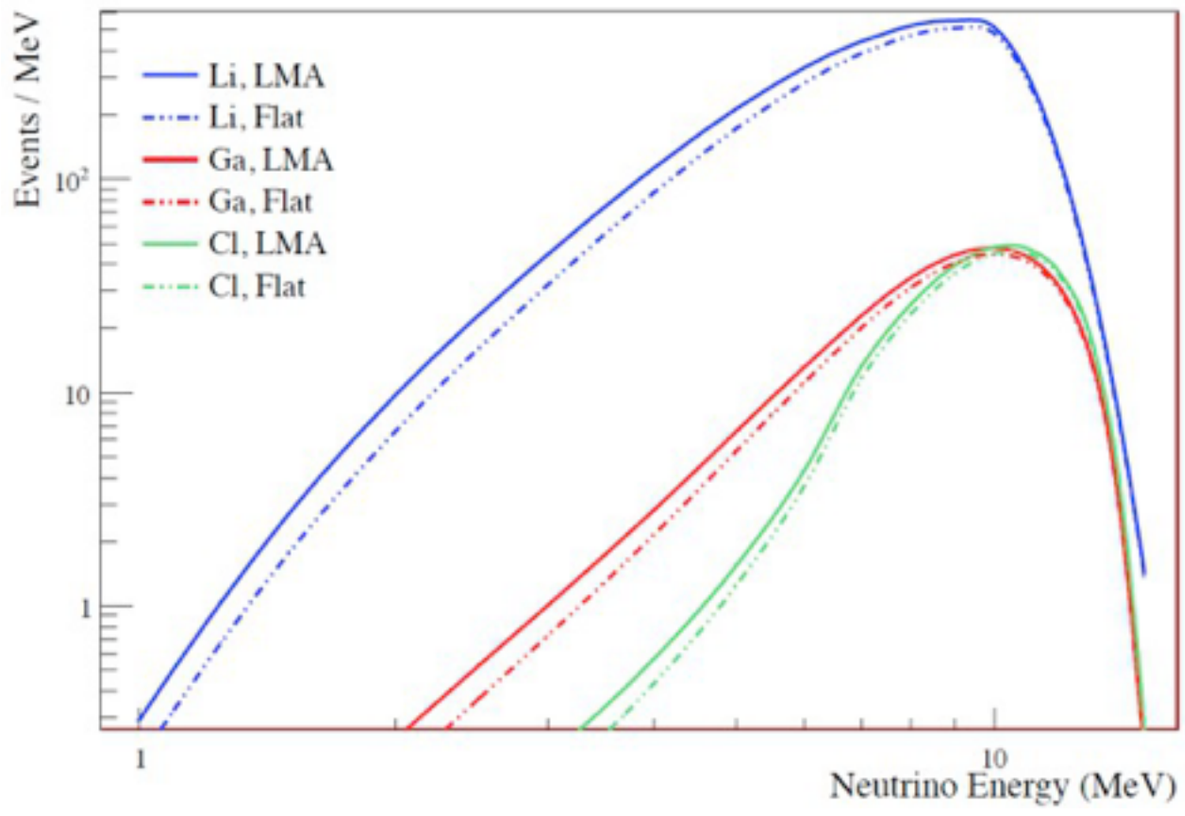


Dream Detector

- Large scale (50kT - MT)
- Simple design: minimise systematics
- Liquid scintillator: ⇒ t/h, resolution
- Load with isotope: CC detection
  - ➡ ^{7}Li, ^{37}Cl, H-WbLS?

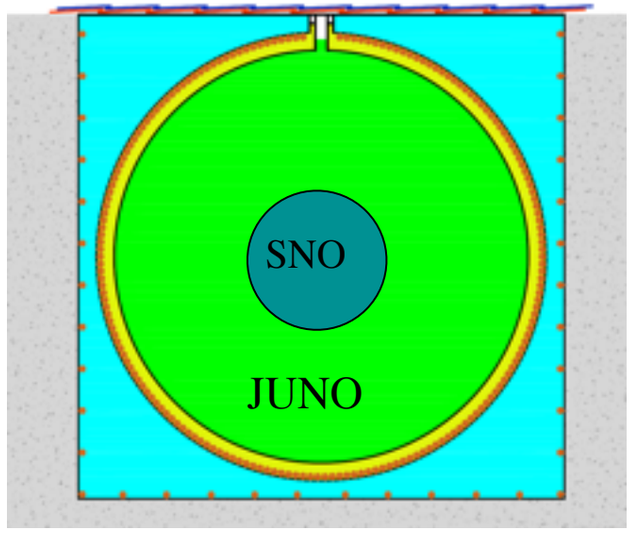


- *Comparable event rates for*
  - *a) 30kT $^{13}C_{nat}$*
  - *b) 5% ^{7}Li in 780T*



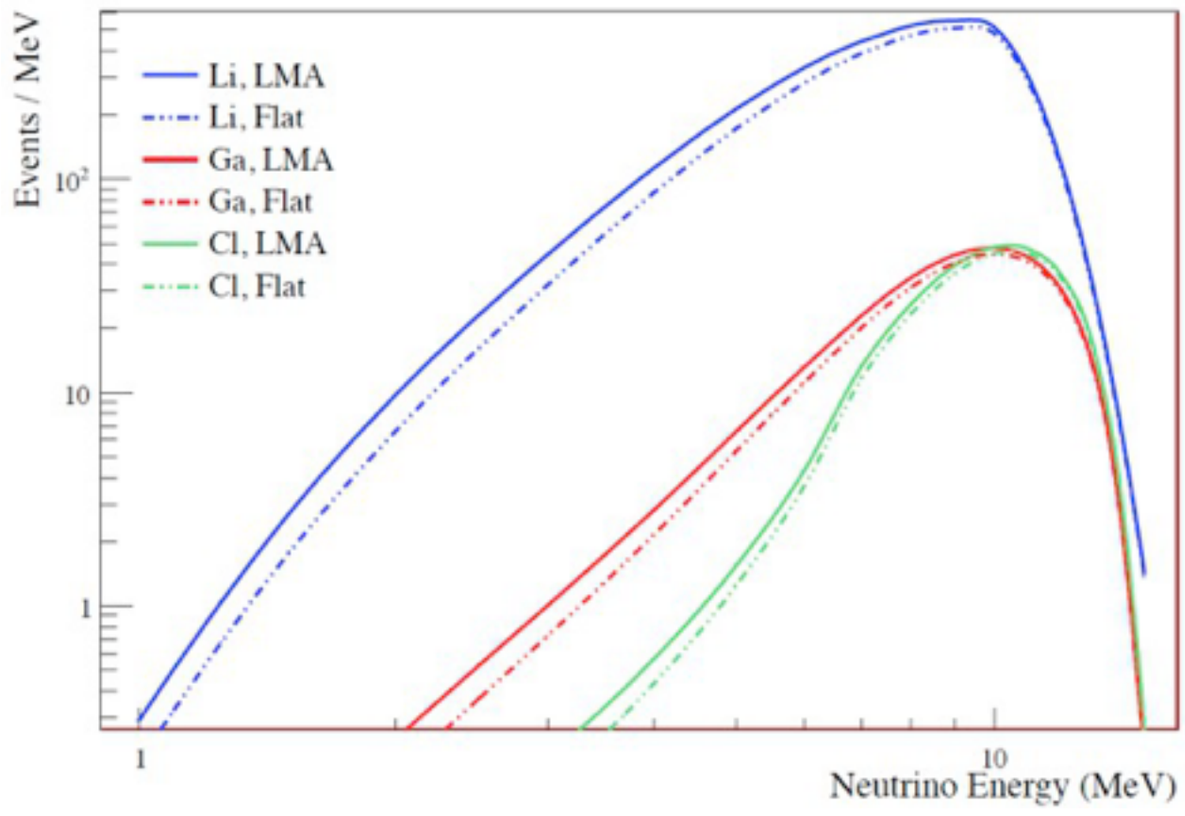
Dream Detector

- Large scale (50kT - MT)
- Simple design: minimise systematics
- Liquid scintillator: ⇒ t/h, resolution
- Load with isotope: CC detection

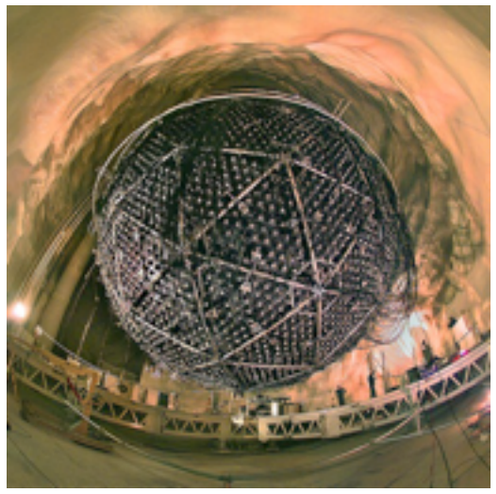


➡ ^{7}Li, ^{37}Cl, H-WbLS?

- *Comparable event rates for*
  - *a) 30kT $^{13}C_{nat}$*
  - *b) 5% ^{7}Li in 780T*
  - *6σ in 5 yrs (LMA vs flat)*

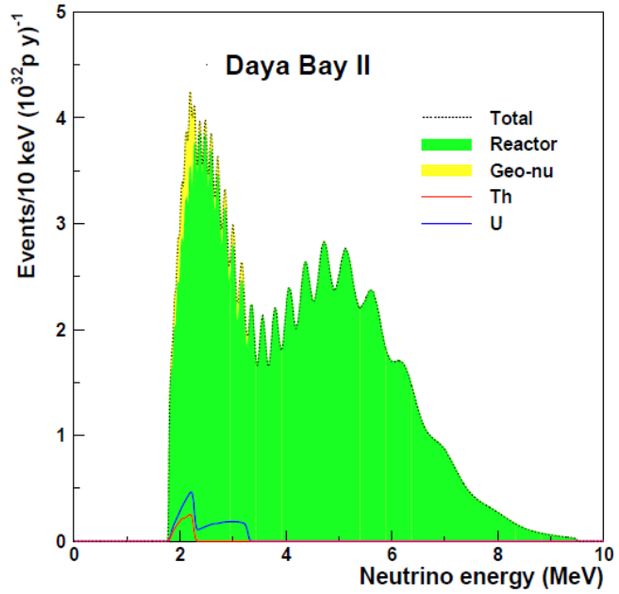


Other Physics (!)

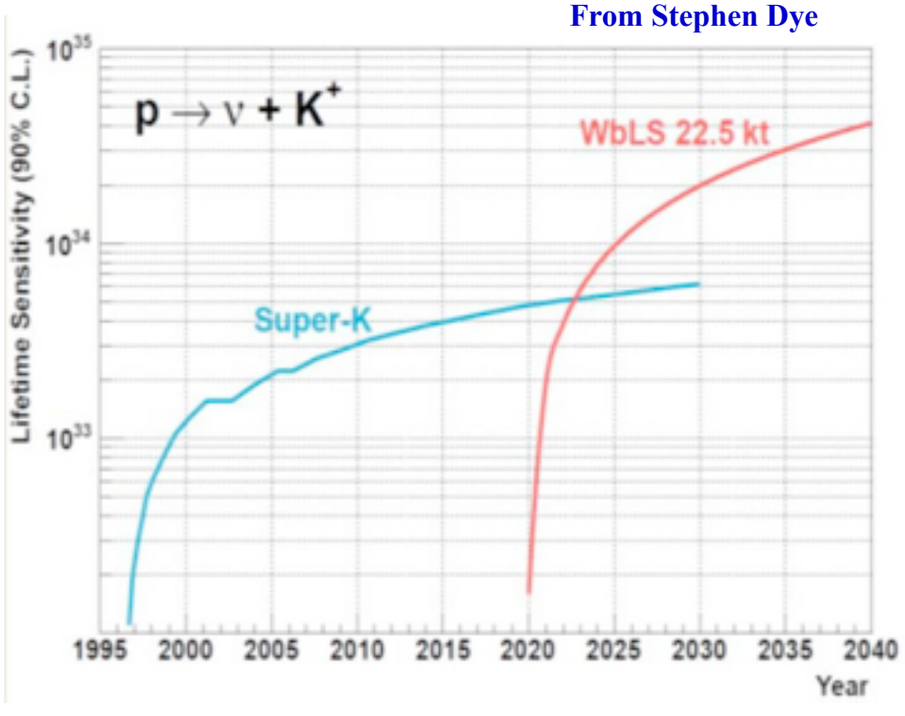


- Neutrinoless DBD
- Neutrino mass hierarchy

- Geoneutrinos
- Supernova neutrinos
- Proton decay

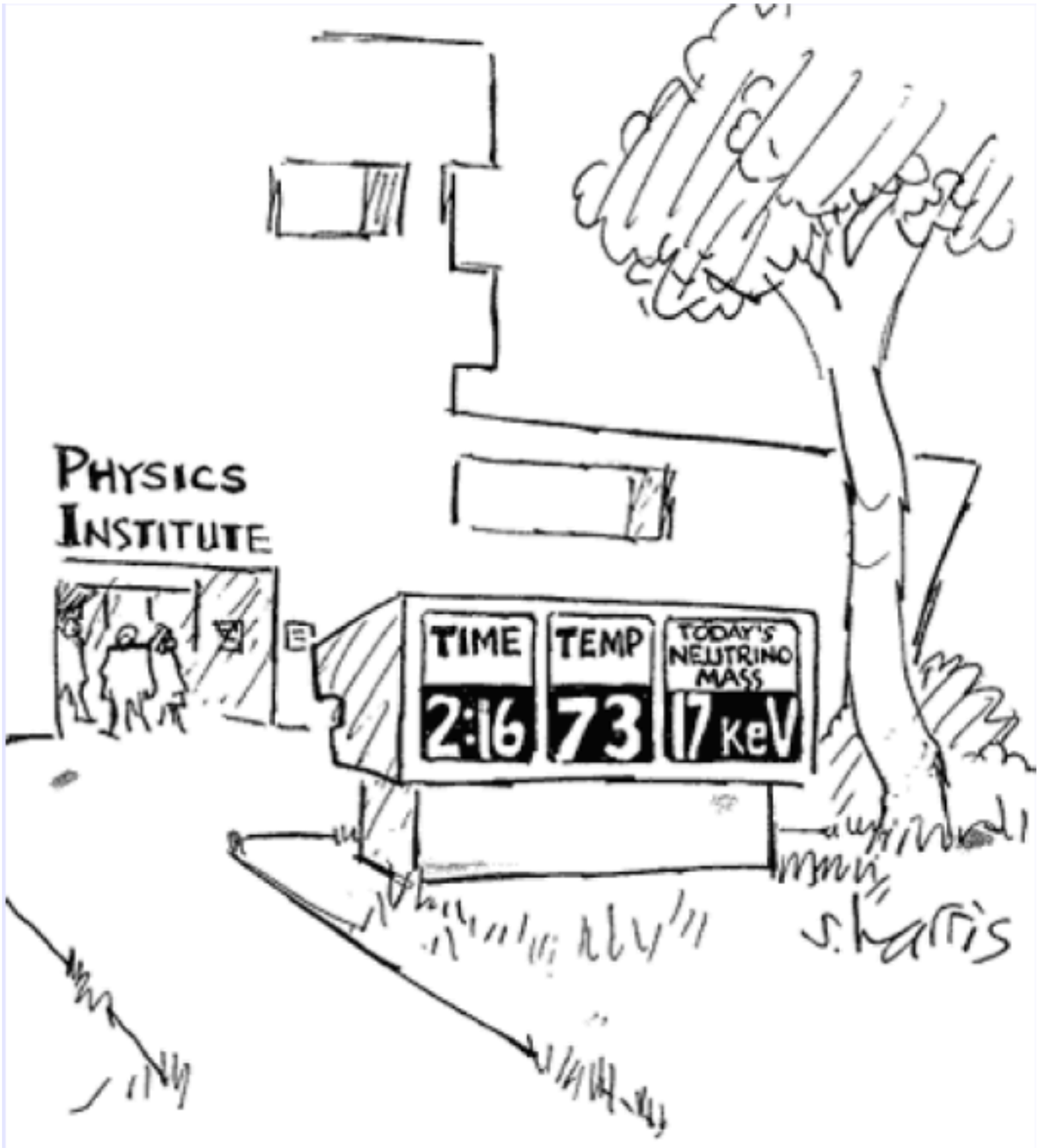


From Stephen Dye



Summary

- Major accomplishments in recent decades
- Many open questions remain
    - *Confirm MSW*
    - *Resolve metalicity*
    - *Determine L constraint*
- Unique opportunity to probe behaviour of neutrinos *and* solar structure
- Need a new, large-scale, high precision experiment!



Thank you for your attention