Neutrinos at SNO+:

Precision Measurements and Paths to New Physics

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University of Pennsylvania
UC Berkeley: 22nd Mar 2011

Outline

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- Introduction: Neutrinos & SNO

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- ✳ The SNO+ Experiment

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  - ✦ Neutrinoless double beta decay
  - ✦ Reactor antineutrinos

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  - ✦ Physics motivation
  - ✦ Status & latest results (SNO)
  - ✦ SNO+ potential

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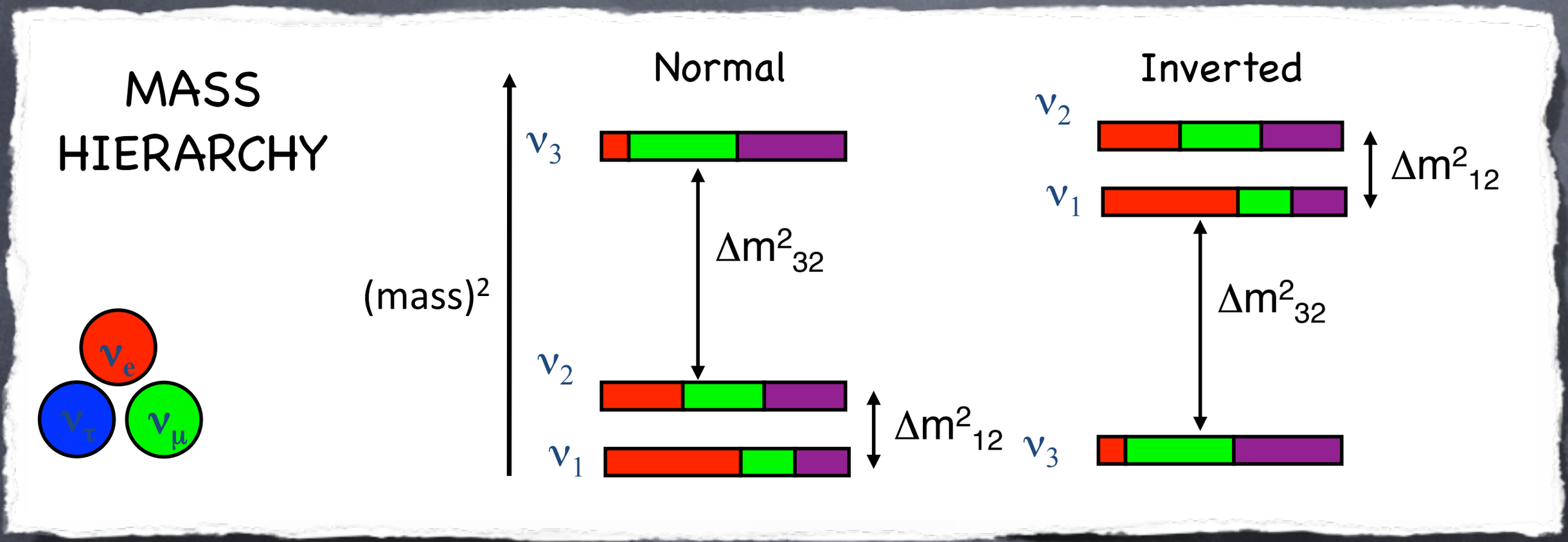
  - ✦ SNO+ potential
- ✳ SNO+ Status
- ✳ Summary

Neutrinos



MIXING

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

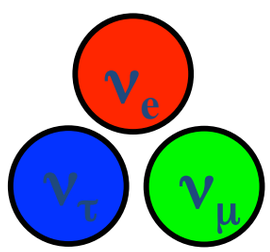
$$\theta_{12} = 34.5 \pm 1.4$$
$$\theta_{23} = 42.3^{+5.1}_{-3.3}$$
$$\theta_{13} = 0.0^{+7.9}_{-0.0}$$

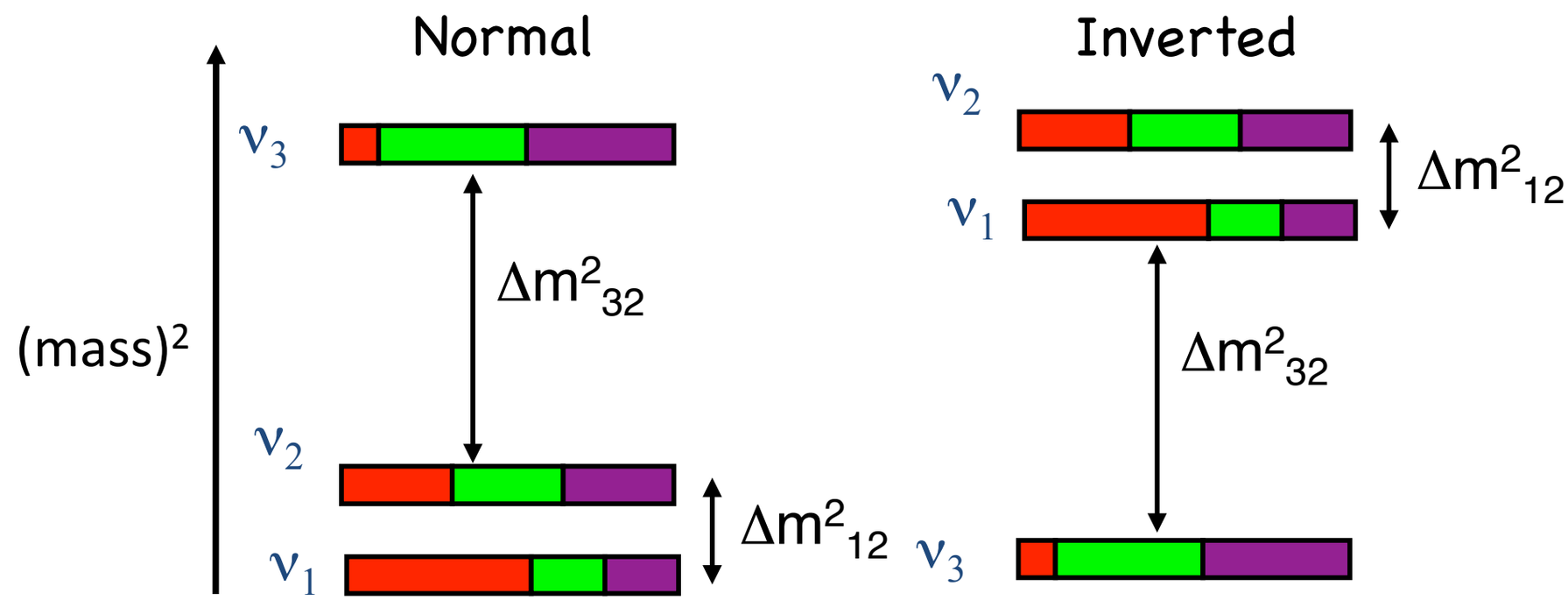
$$(|U_{l\nu}|^2) \approx \begin{array}{c} e \\ \mu \\ \tau \end{array} \begin{pmatrix} 2/3 & 1/3 & 0 \\ 1/6 & 1/3 & 1/2 \\ 1/6 & 1/3 & 1/2 \end{pmatrix}$$

Global Analysis
Phys.Rept.460:1-129,2008

Neutrinos

MASS HIERARCHY





MIXING

Atmospheric well measured

T.B.C.

Solar well measured

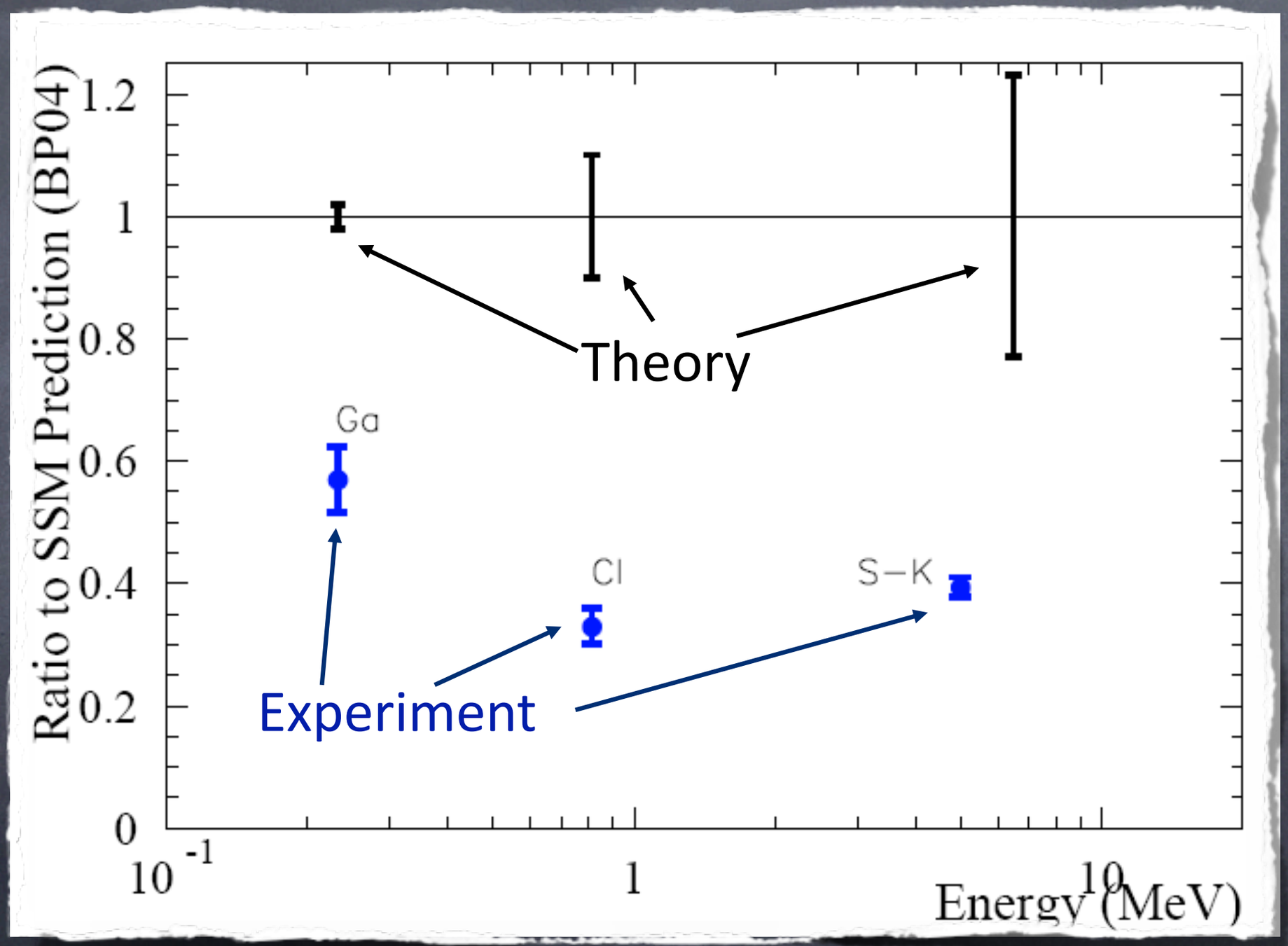
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{\mathrm{CP}}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{\mathrm{CP}}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U^{\mathrm{diag}}_{\mathrm{Maj}}$$

MINOS, SuperK

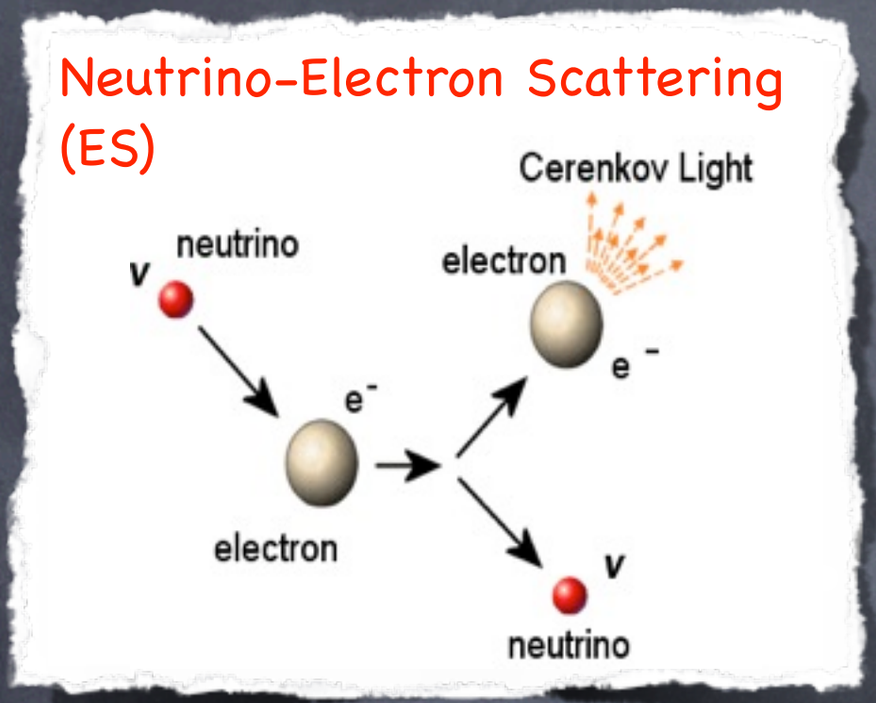
Short-baseline reactor, long-baseline accelerator

SNO, KamLAND

Solar Neutrino Problem



Neutrino Detection

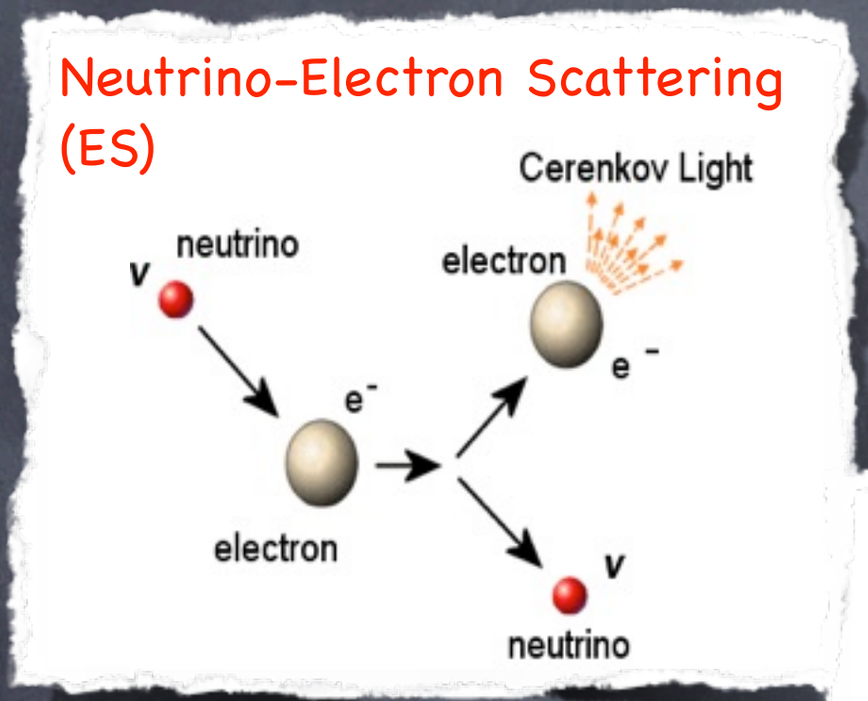


1. Elastic Scattering

Primarily sensitive to ν_e

Measures ν direction

The Answer: Heavy Water



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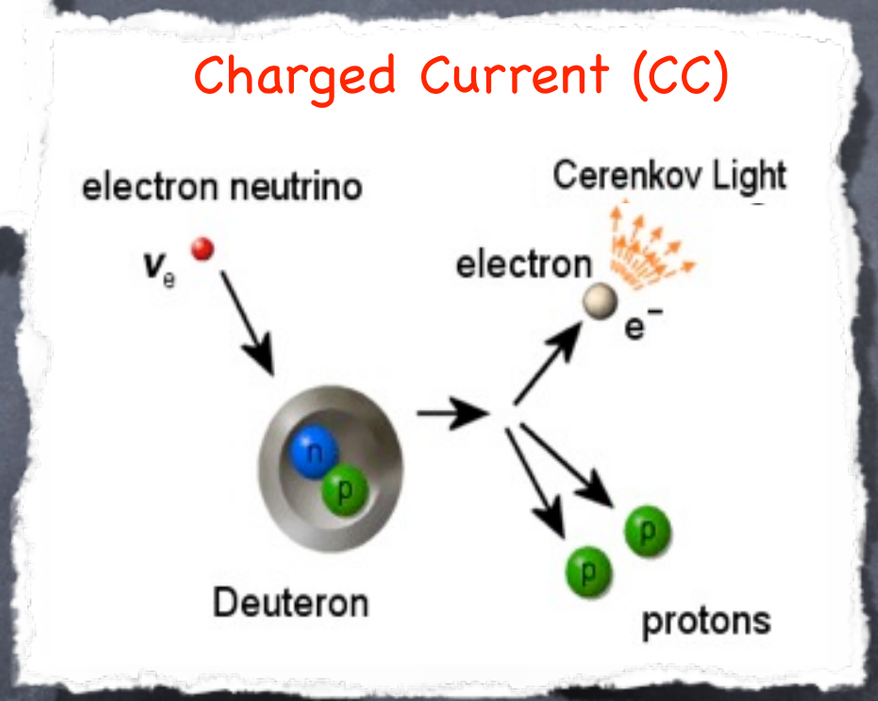
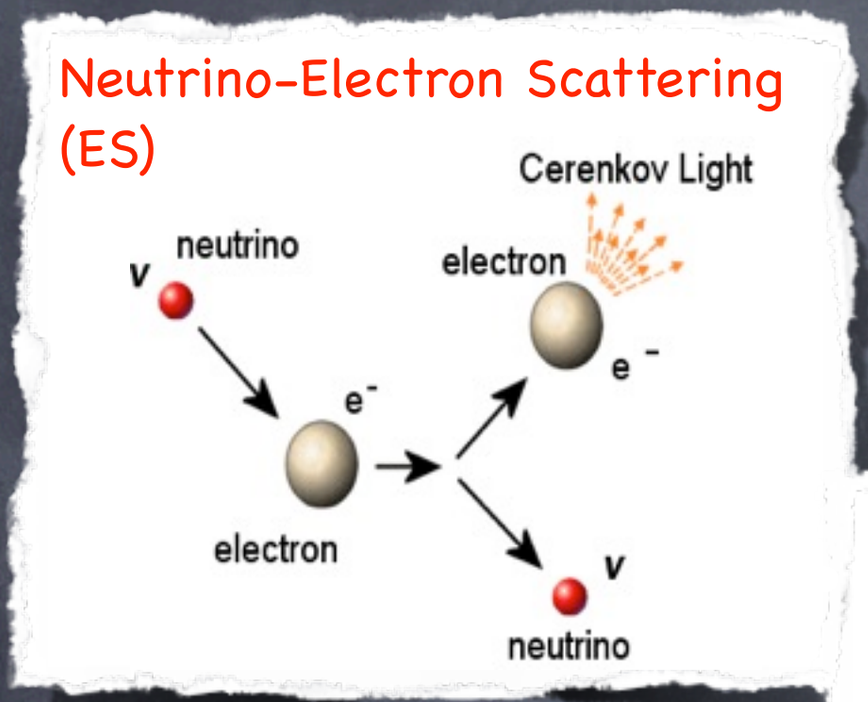


2. Charged Current
Sensitive only to ν_e
Measures ν energy

The Answer: Heavy Water



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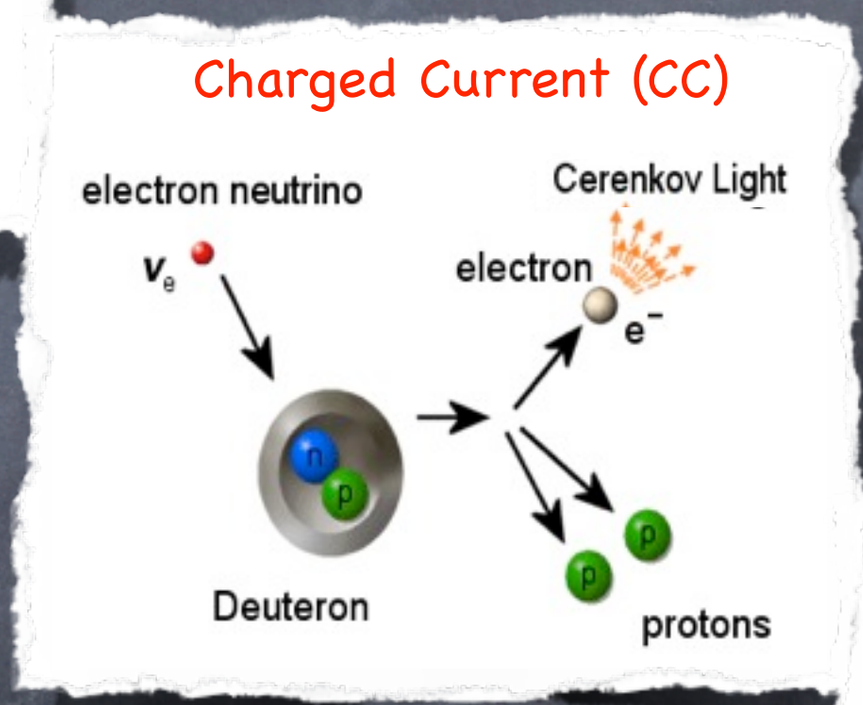

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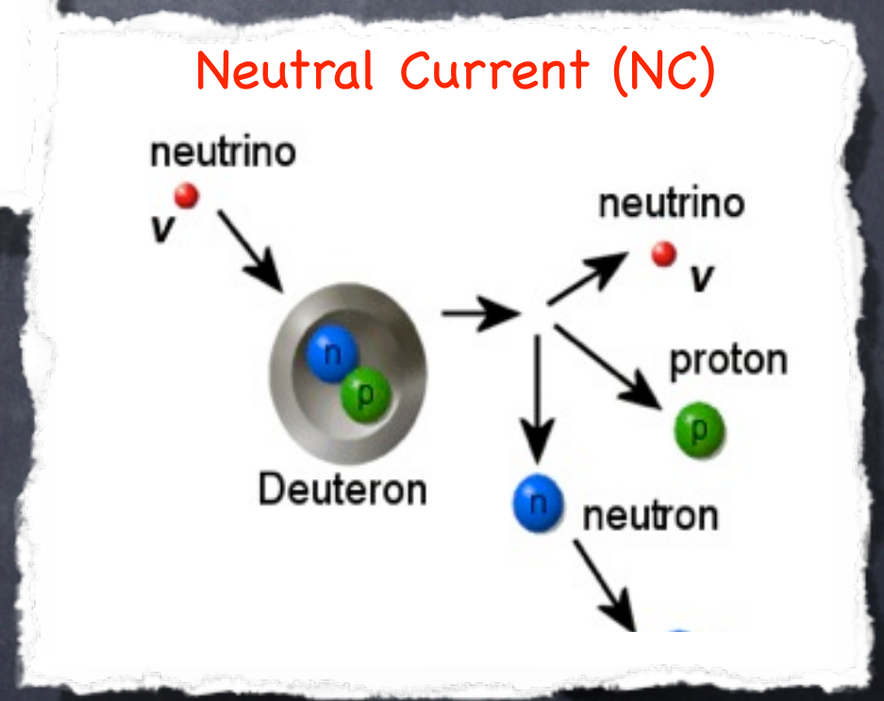
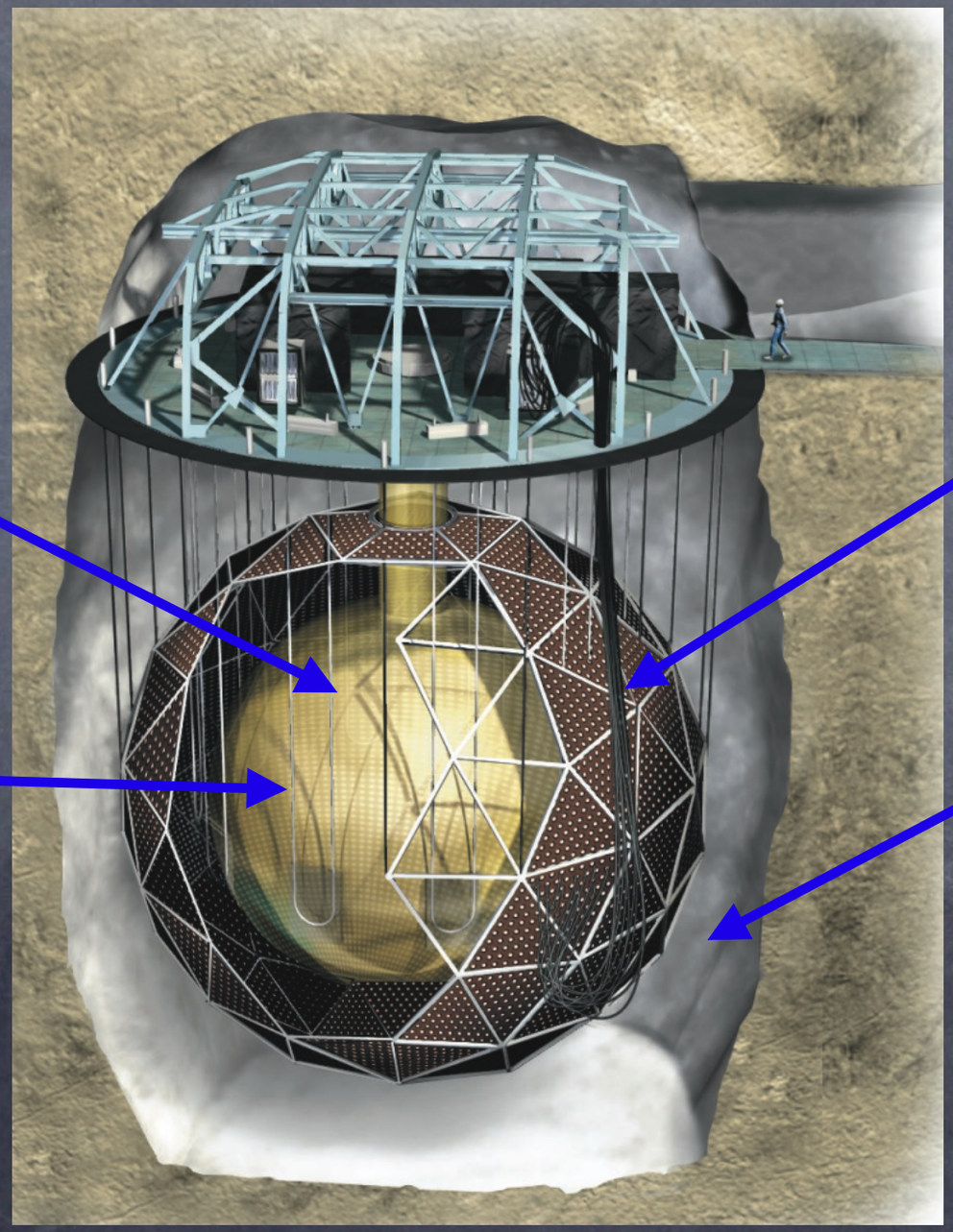


3. Neutral Current
Sensitive to all flavours
Measures total ^8B ν flux

The Sudbury Neutrino Observatory



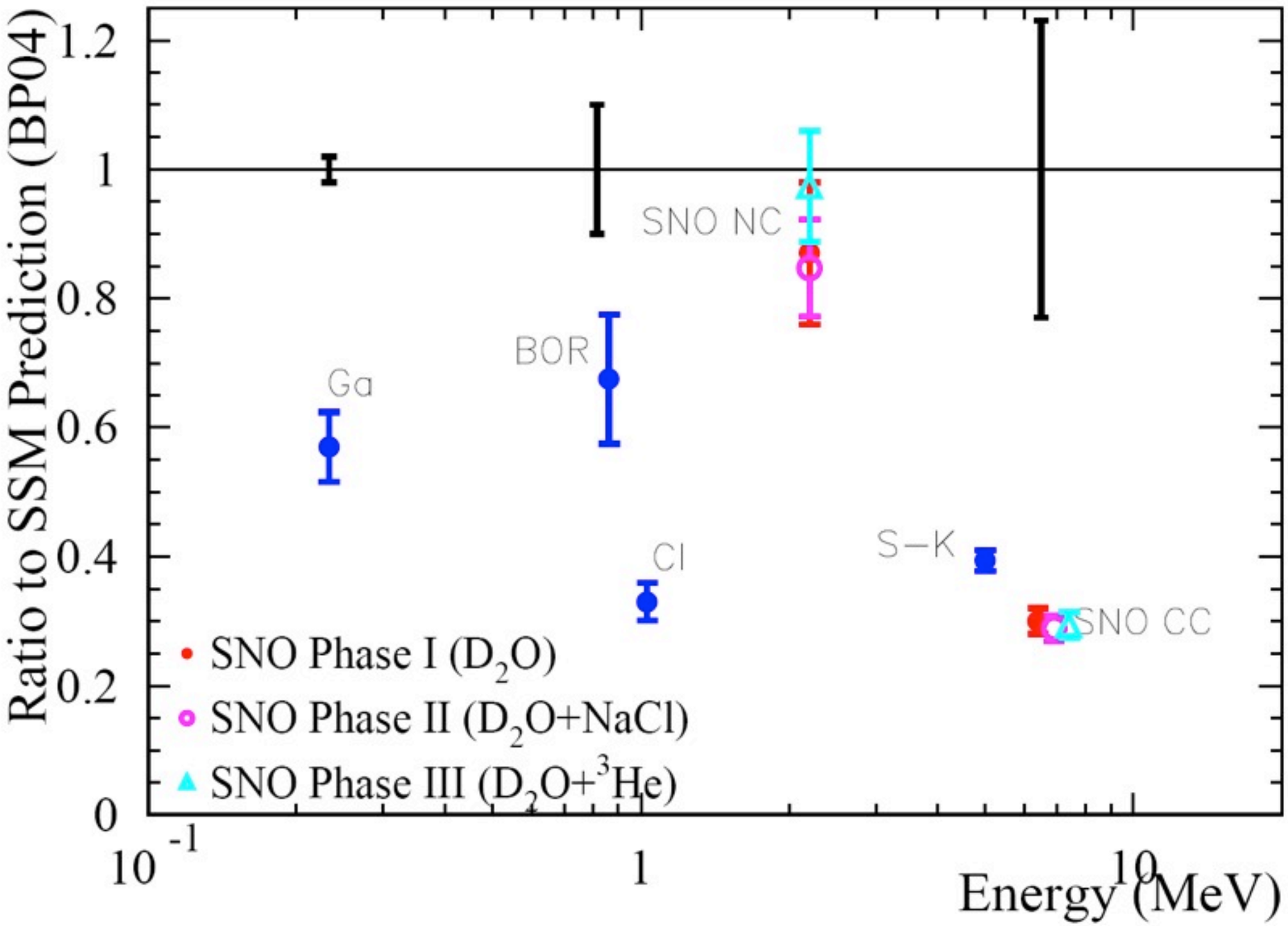
1000 tonnes D_2O

12 m diameter acrylic vessel

Support structure for 9500 PMTS 54% coverage

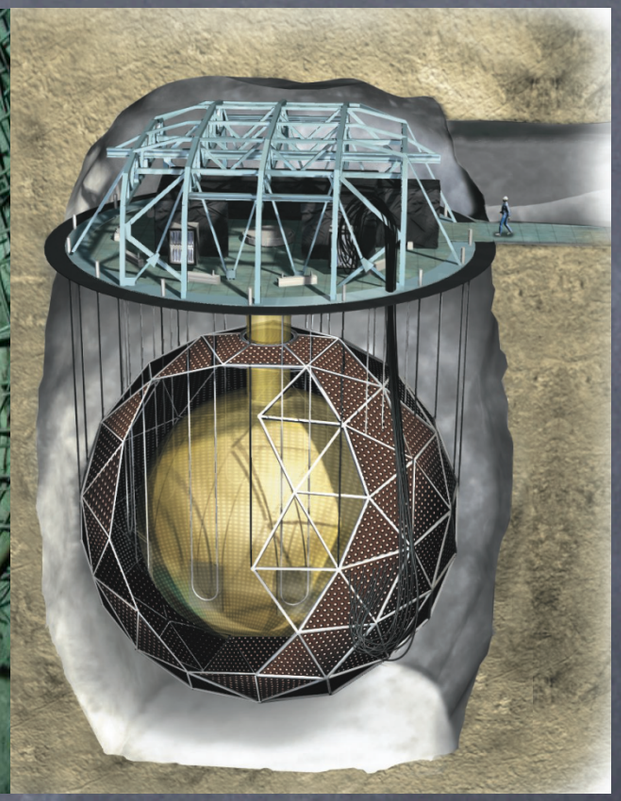
7000 tonnes H_2O shielding

What SNO told us



SNO ⇨ SNO+

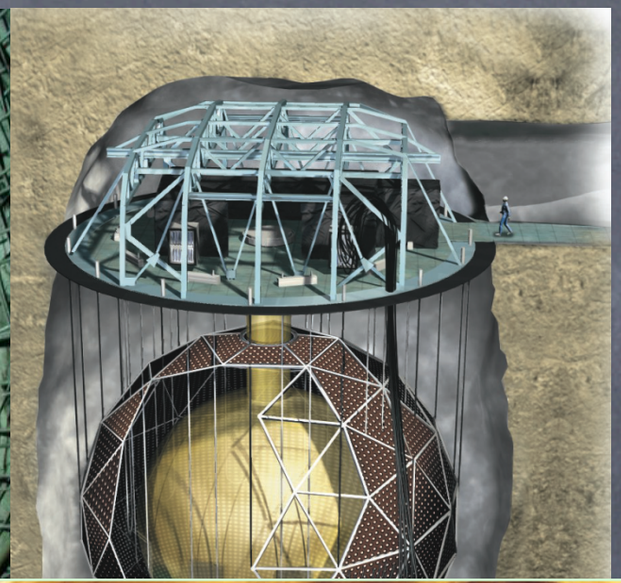
Re-use SNO detector

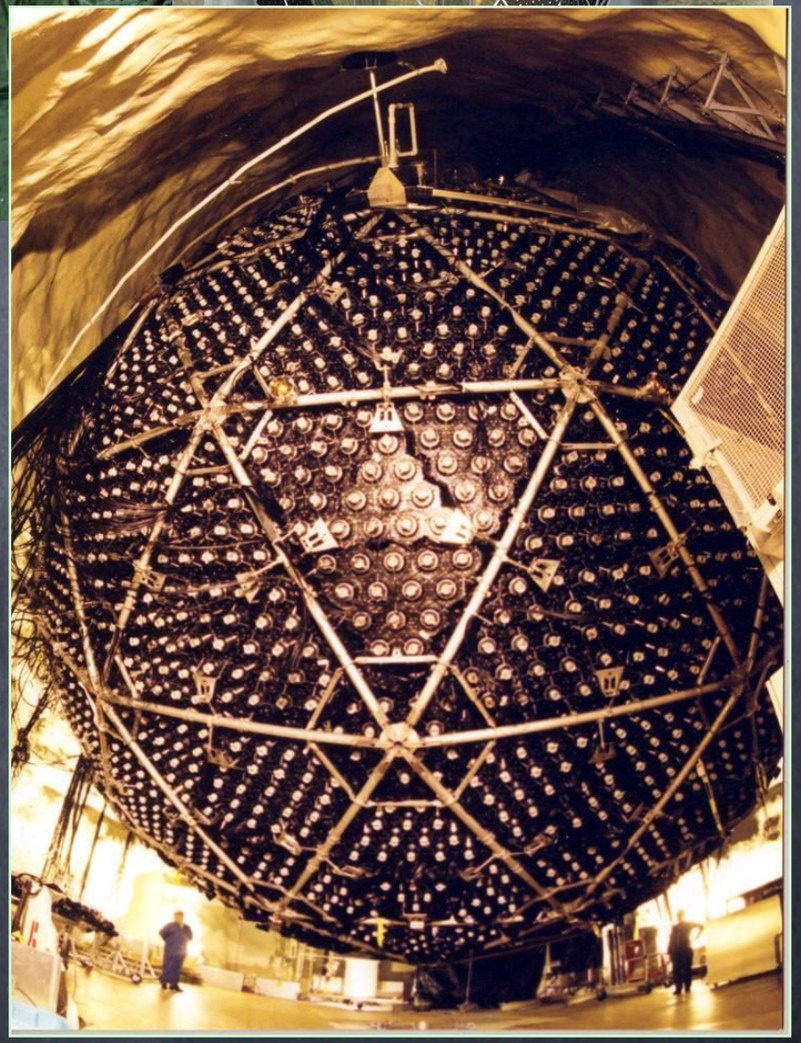


SNO ⇨ SNO+

Re-use SNO detector

Upgrade electronics



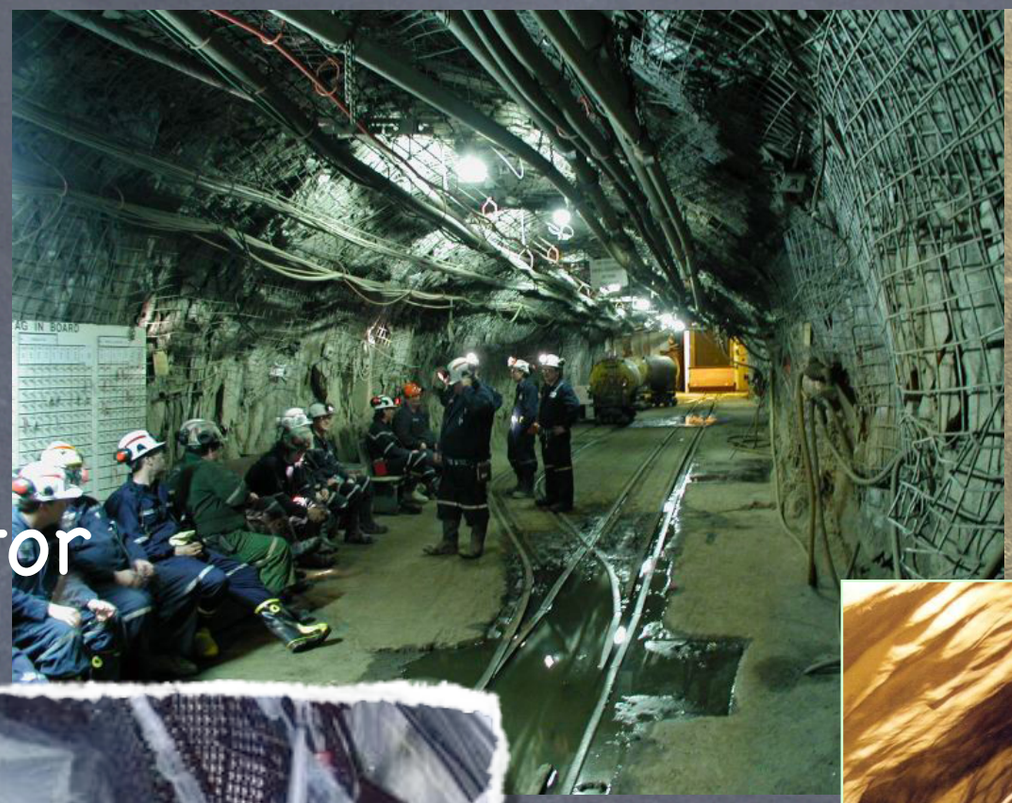


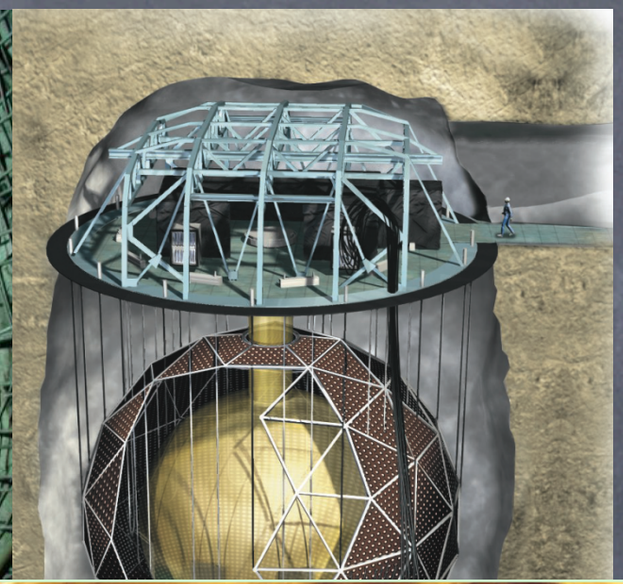
SNO ⇨ SNO+

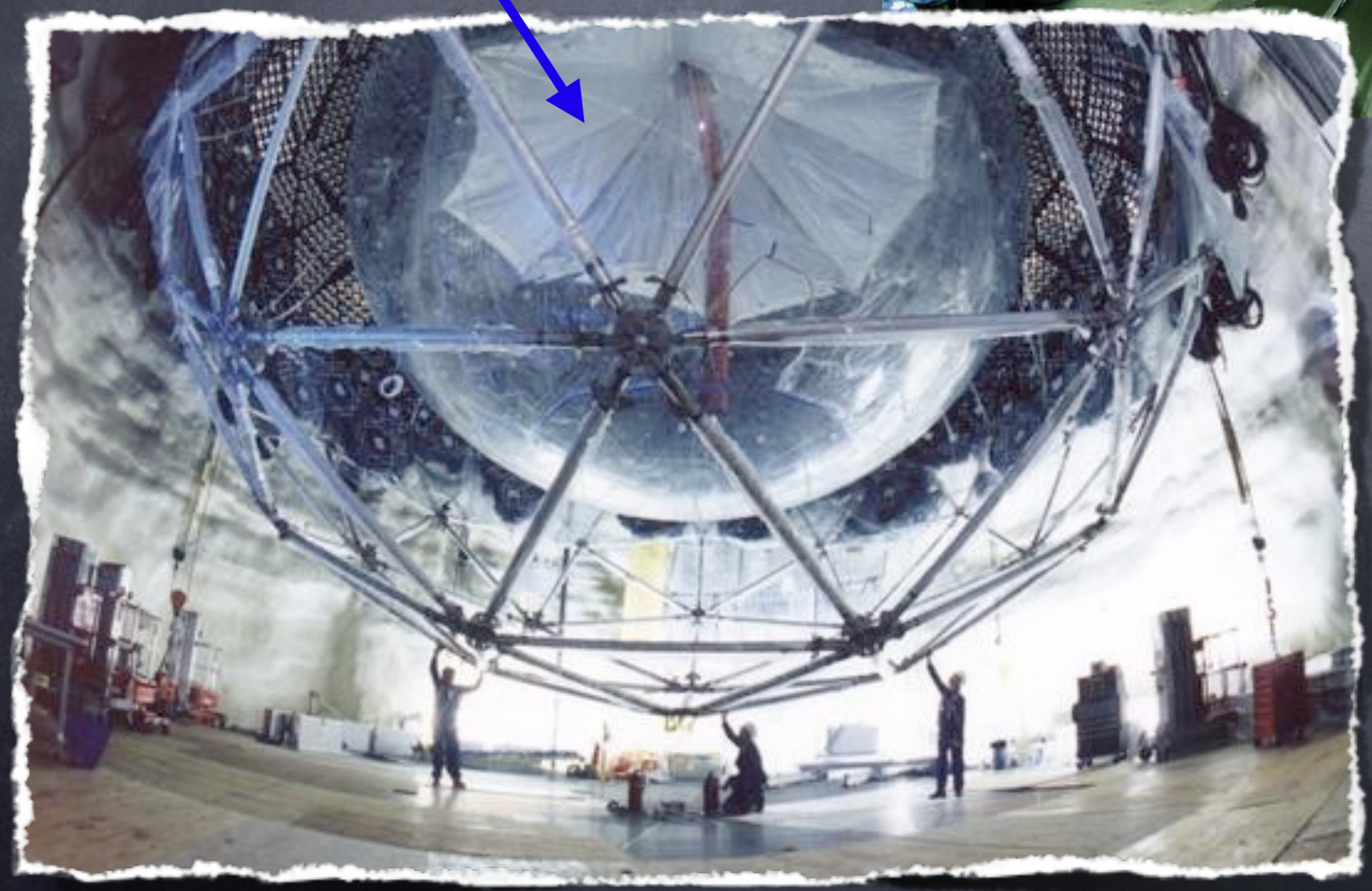
Re-use SNO detector

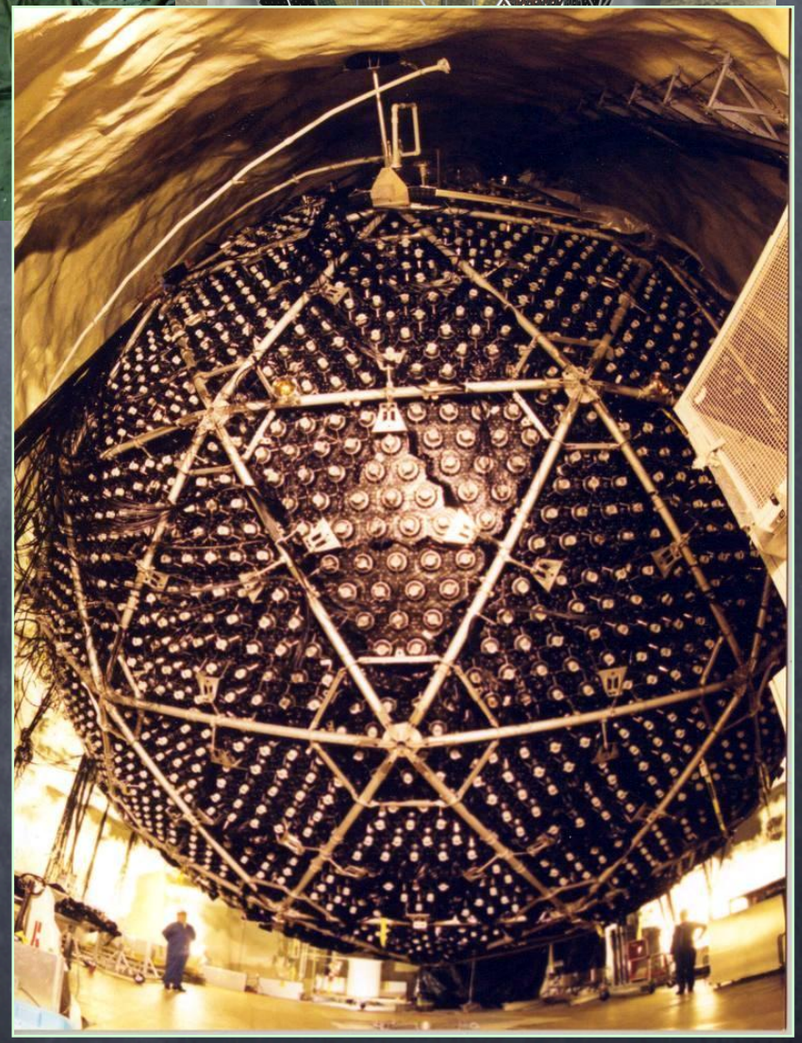
Upgrade electronics

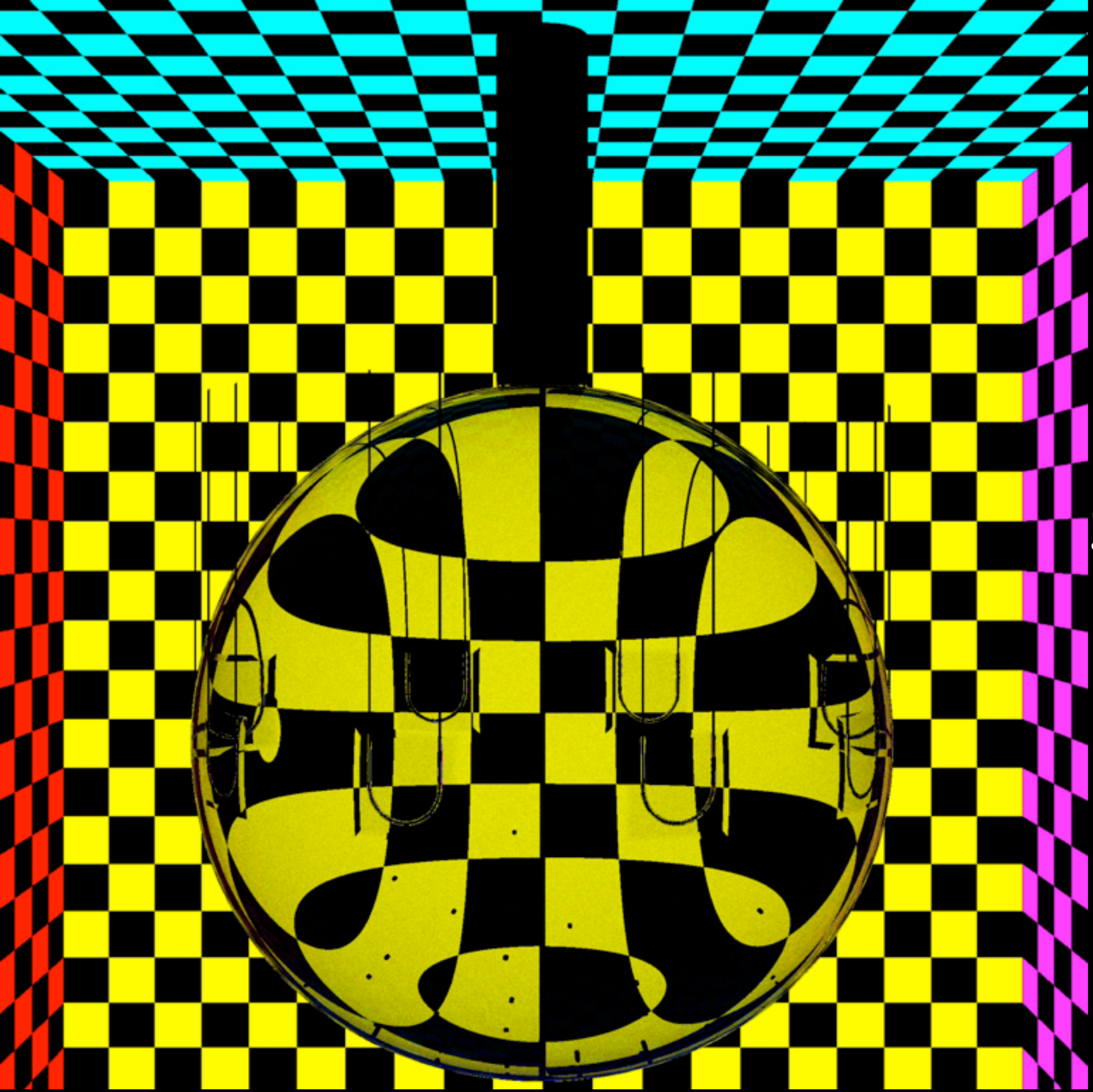
D_2O ⇒ liquid scintillator







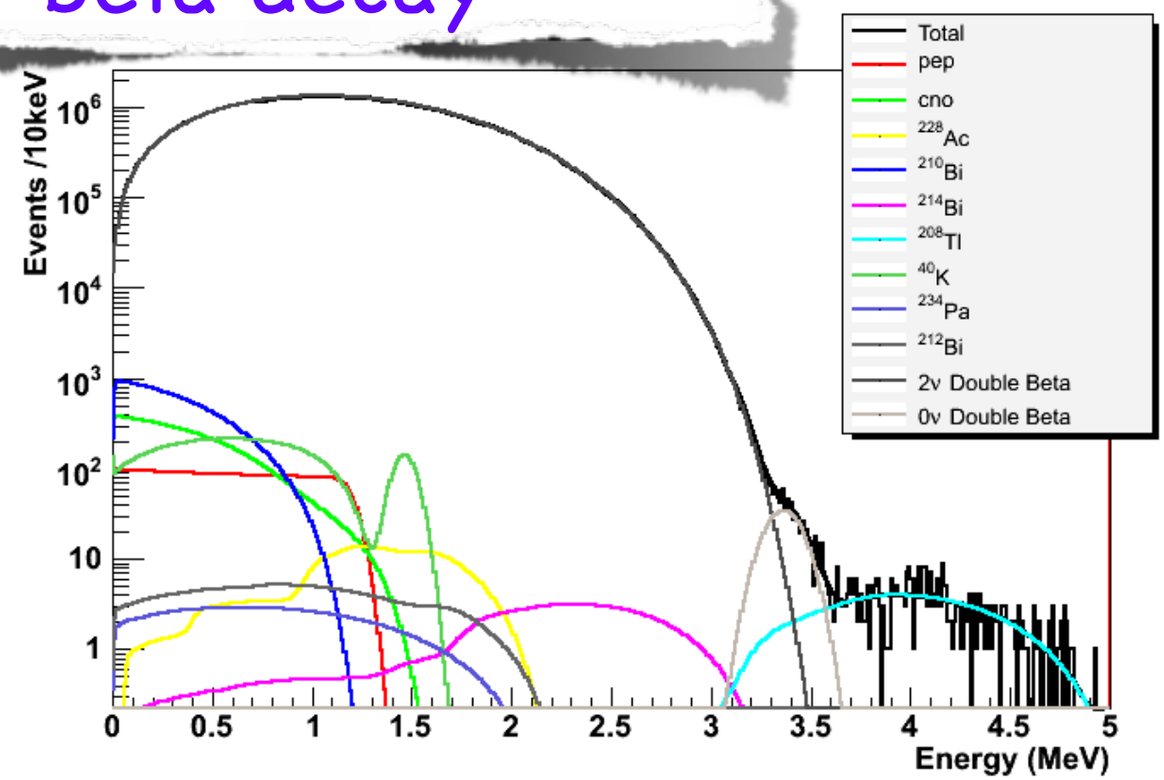




World's Largest Spherical Lens?

SNO+ Physics Programme

Neutrinoless double beta decay



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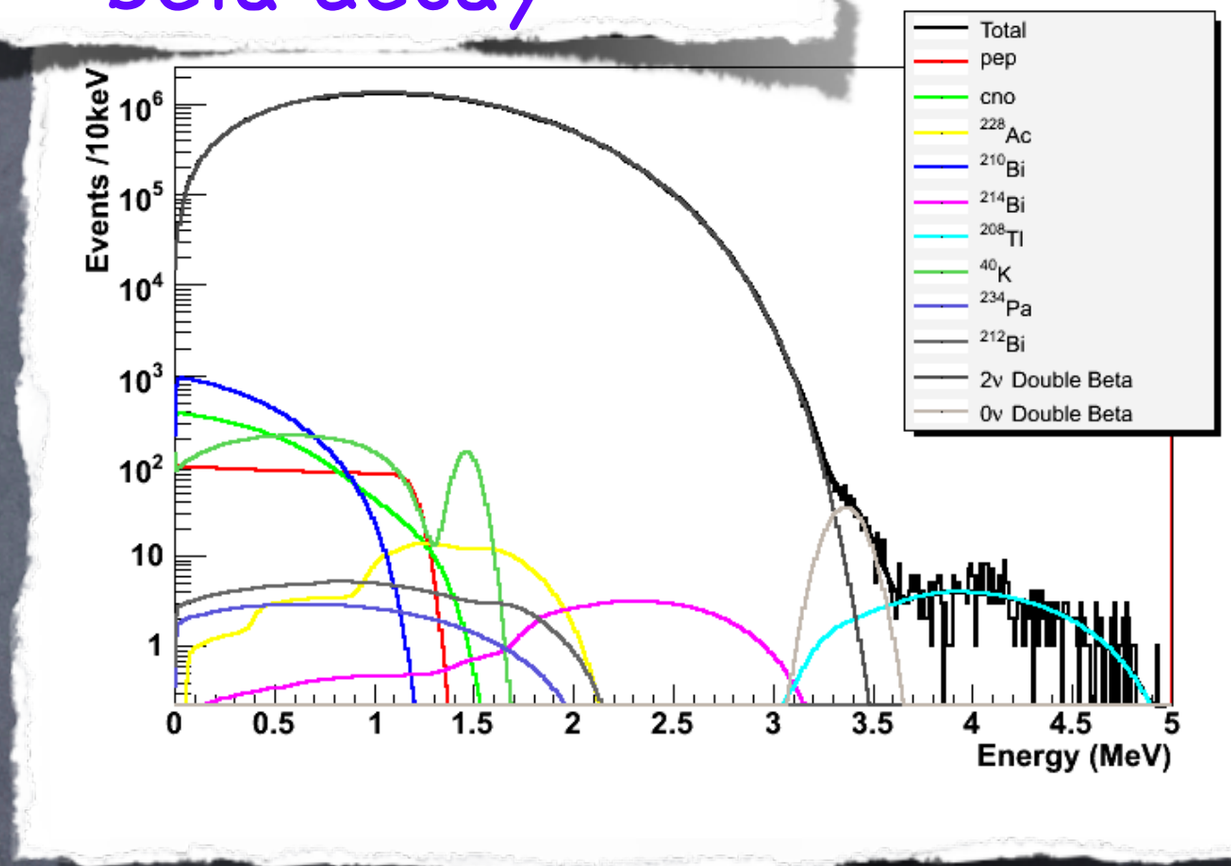
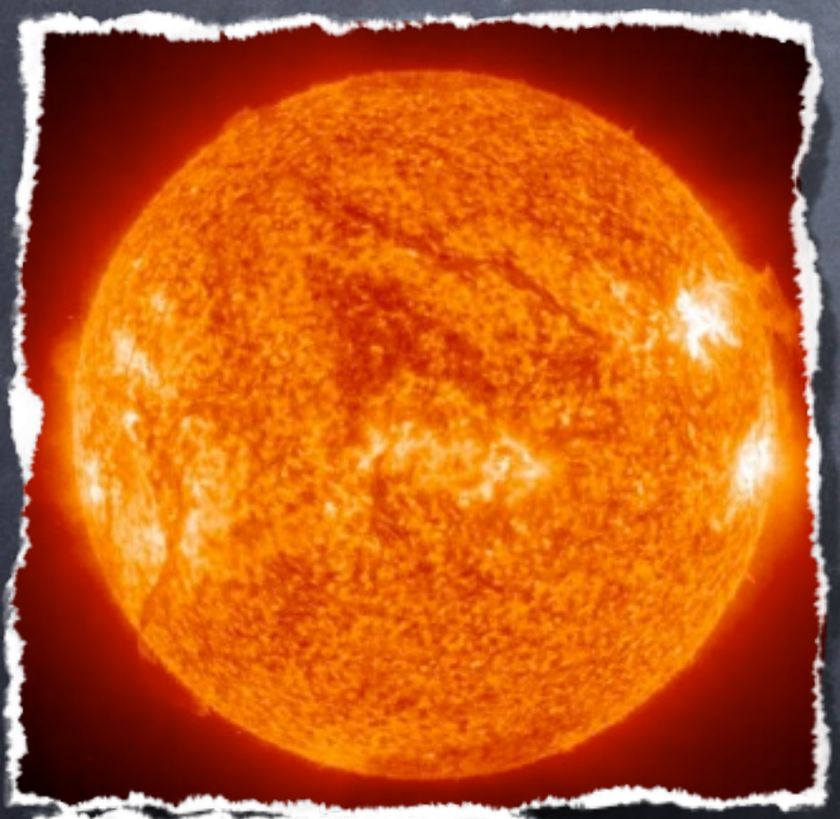
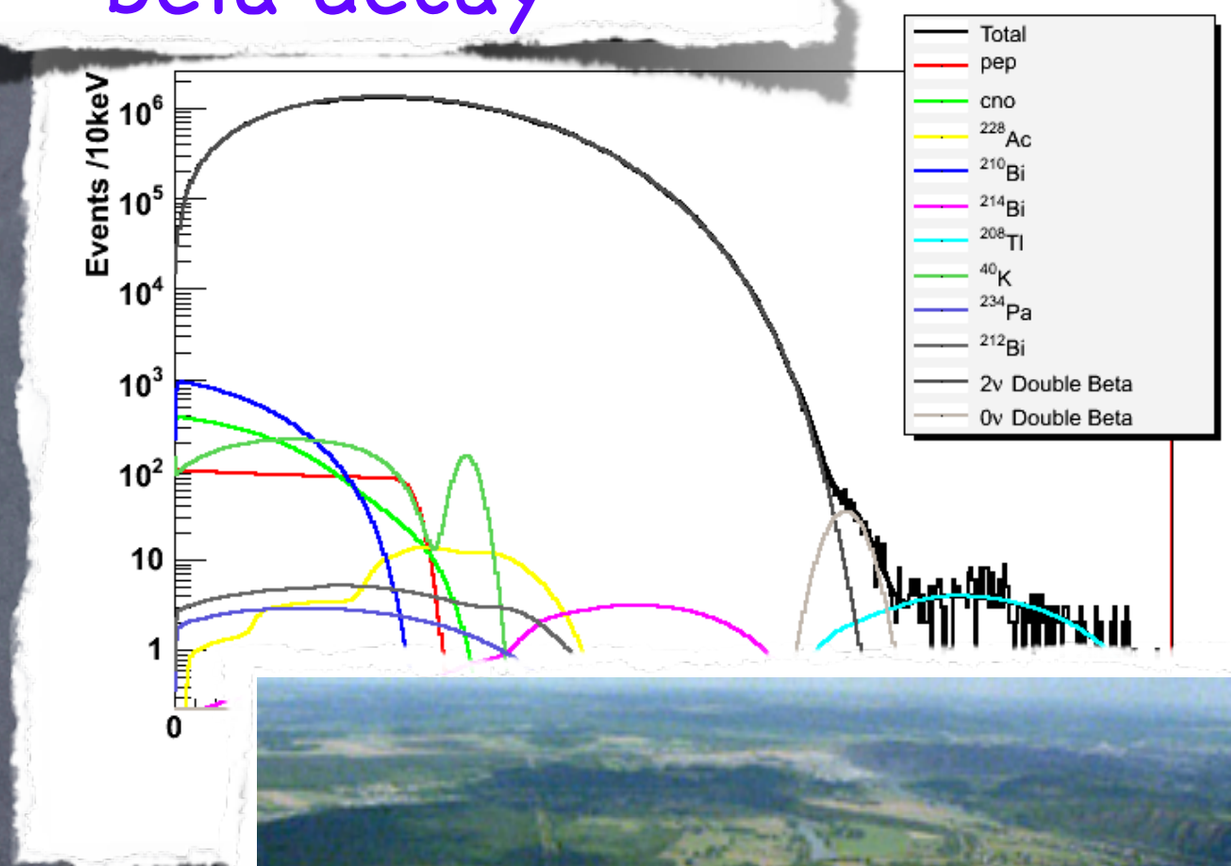


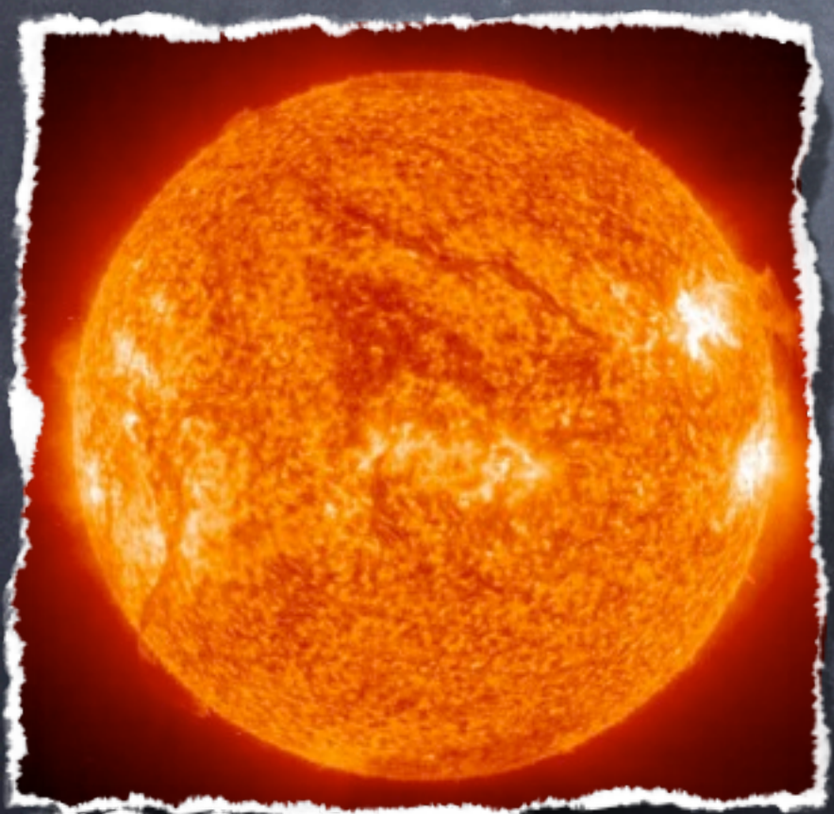


Solar neutrinos

SNO+ Physics Programme

Neutrinoless double beta decay



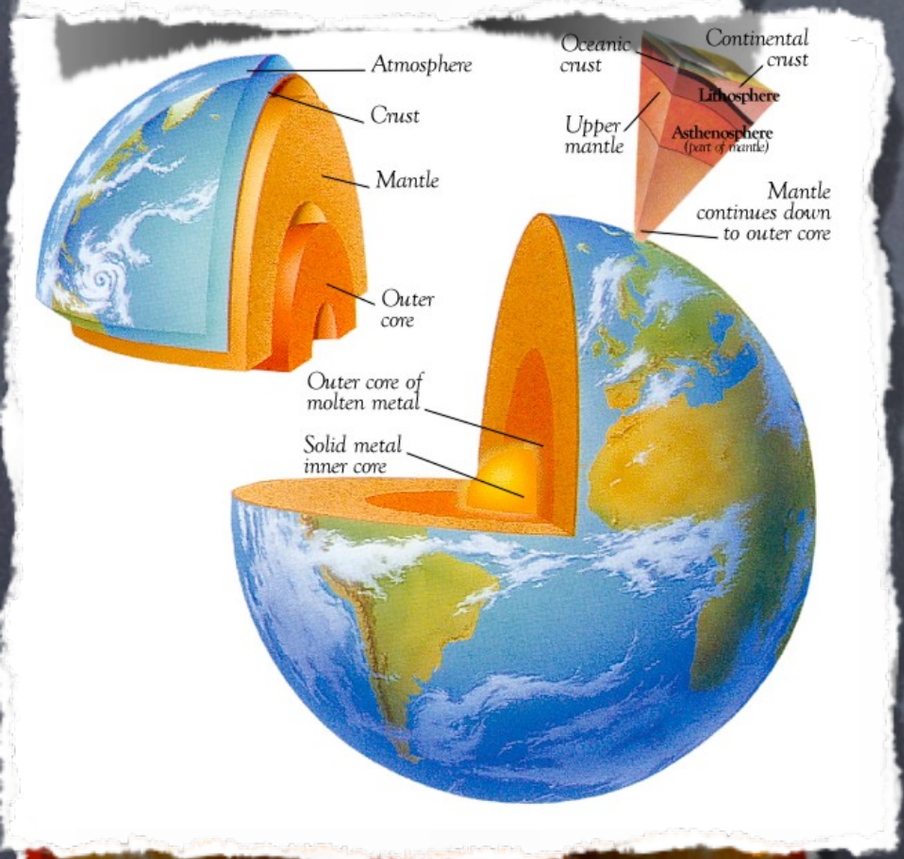


Solar neutrinos

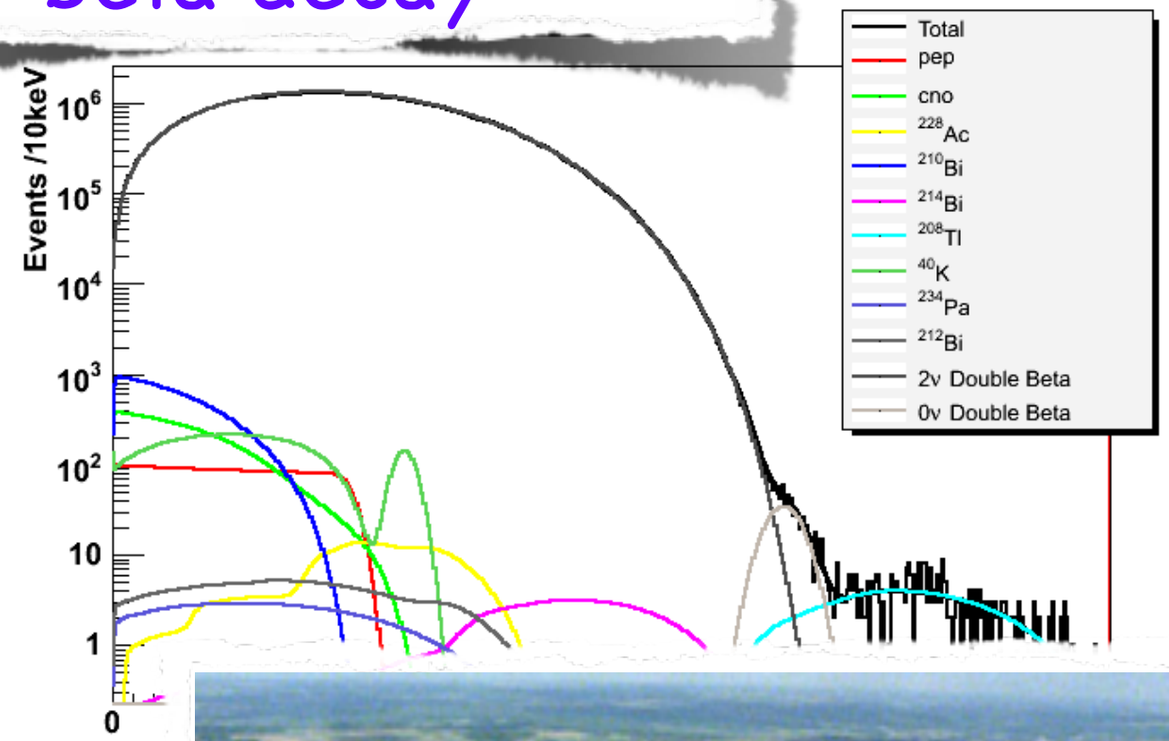
Reactor neutrinos

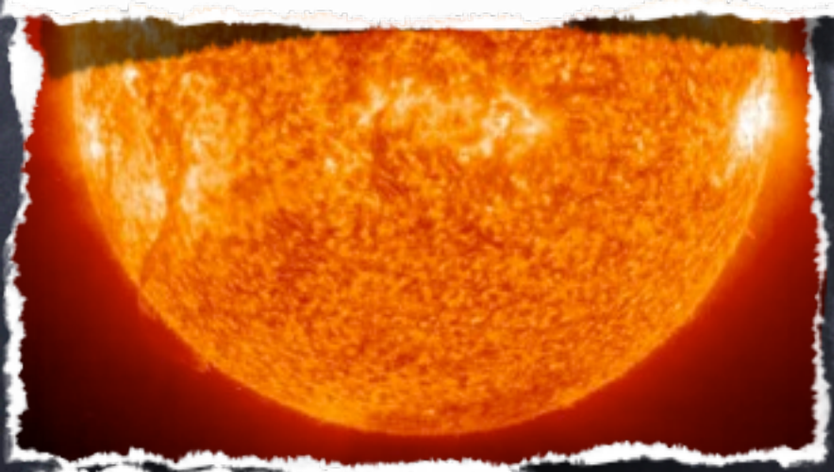
SNO+ Physics Programme

Geo neutrinos



Neutrinoless double beta decay





Solar neutrinos

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SNO+ Physics Programme

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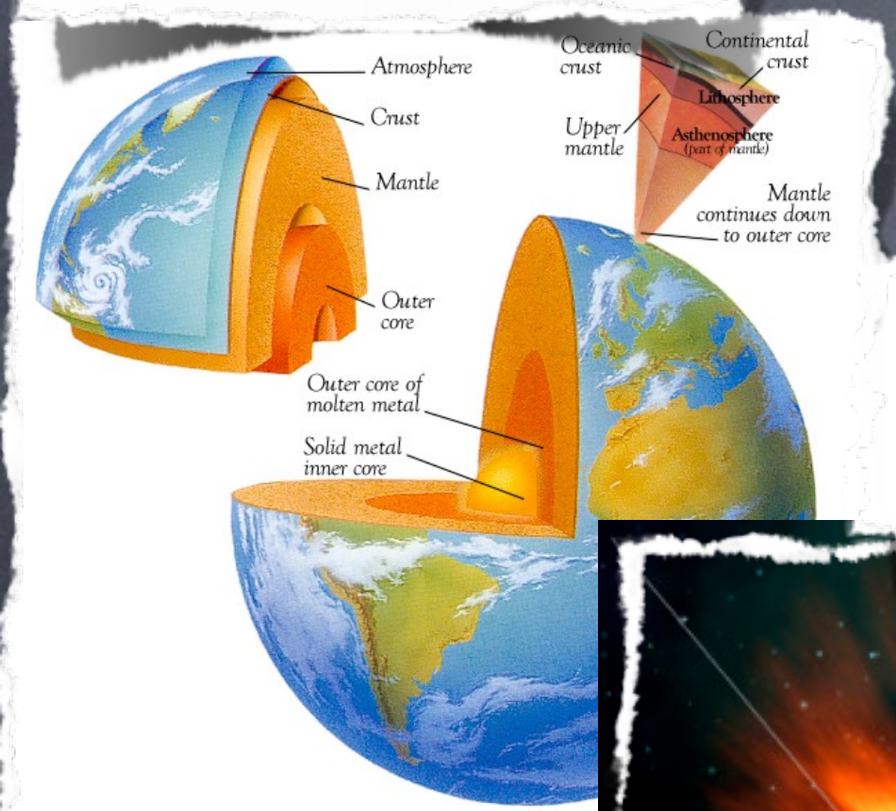
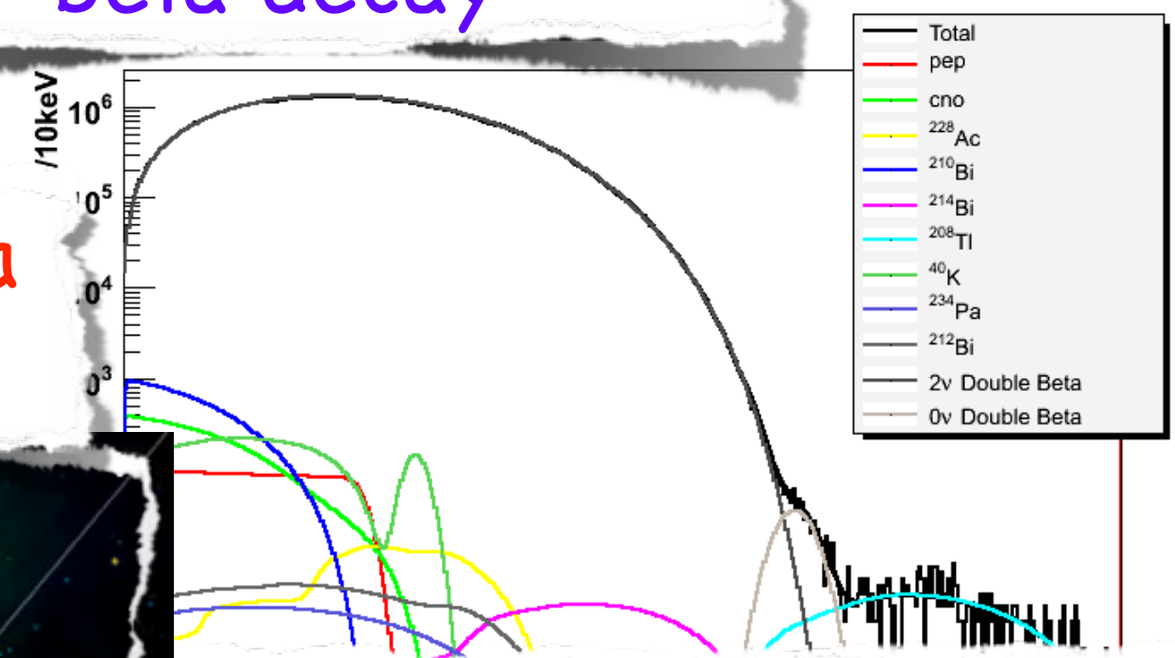
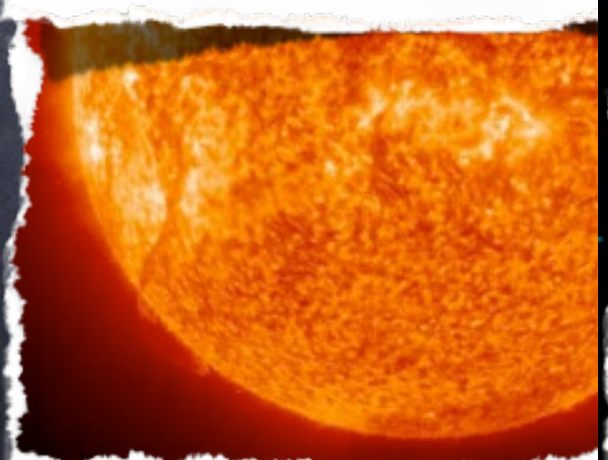


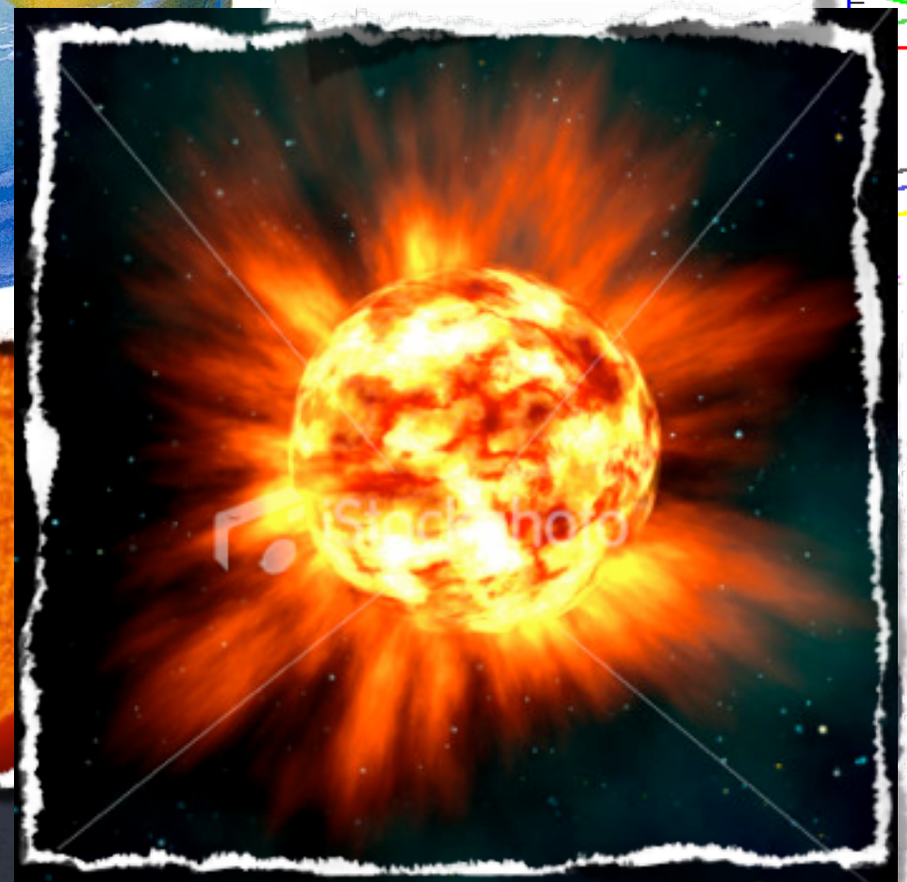
Neutrinoless double beta decay



Supernova neutrinos



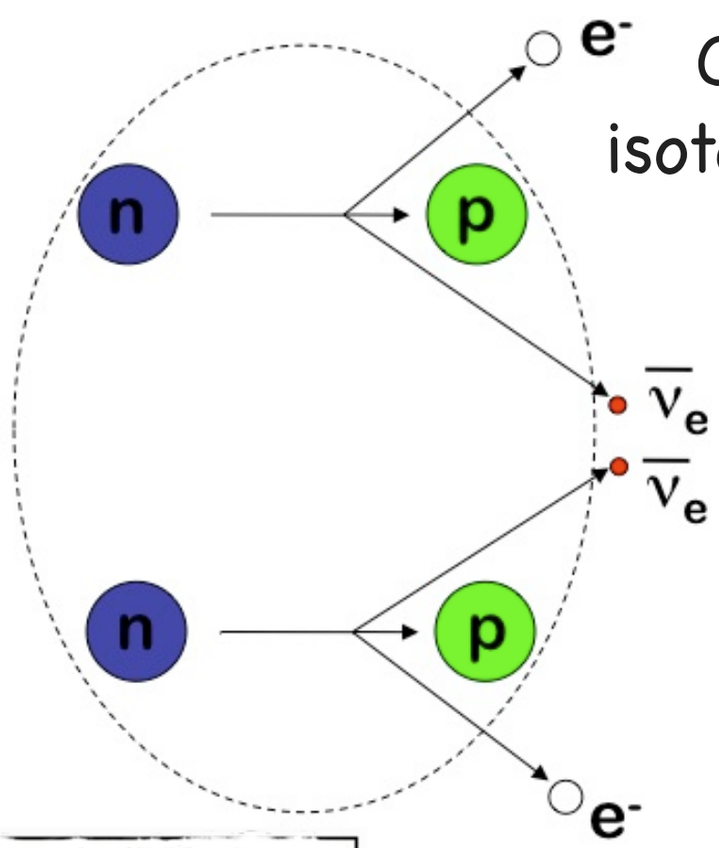
Solar neutrinos



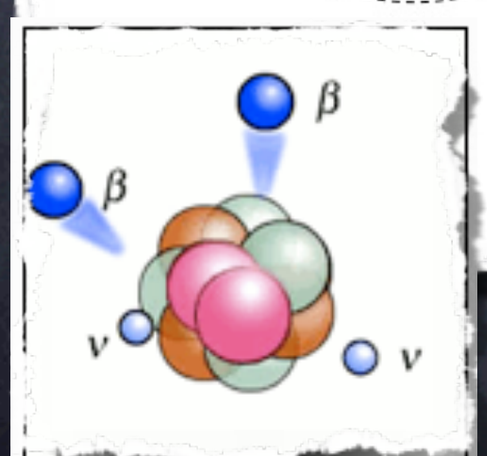
Reactor neutrinos

Double Beta 2νββ Decay

Double Beta Decay



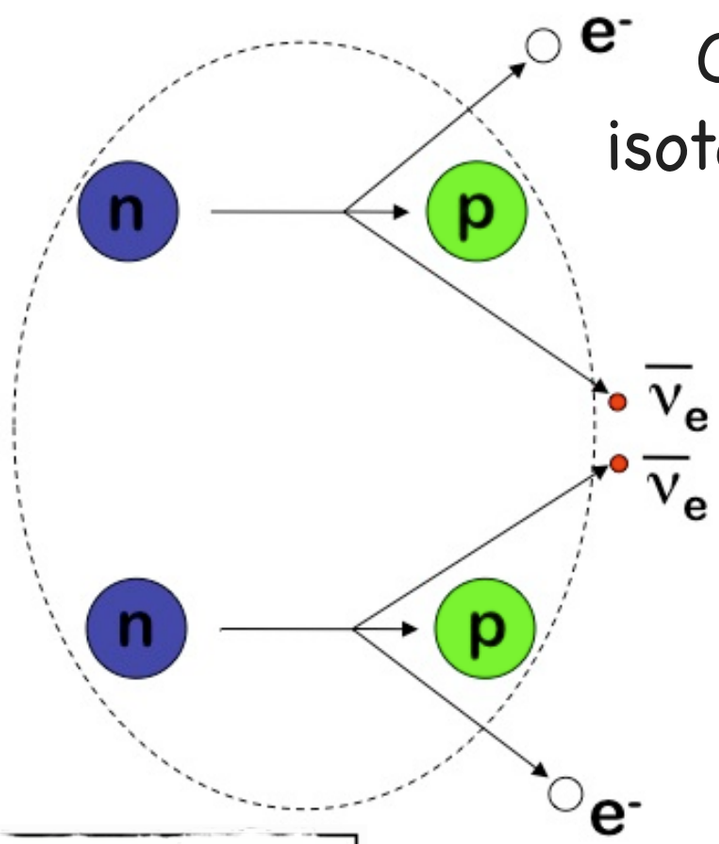
Only 35 known isotopes in nature



$(A,Z) \rightarrow$
$(A,Z+2) + 2e^- + 2\overline{\nu}_e$

0νββ Decay

Double Beta Decay



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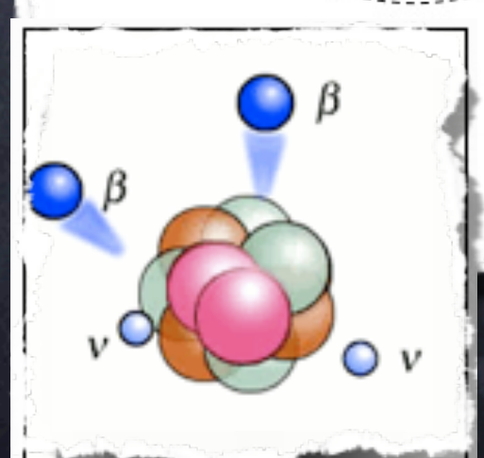
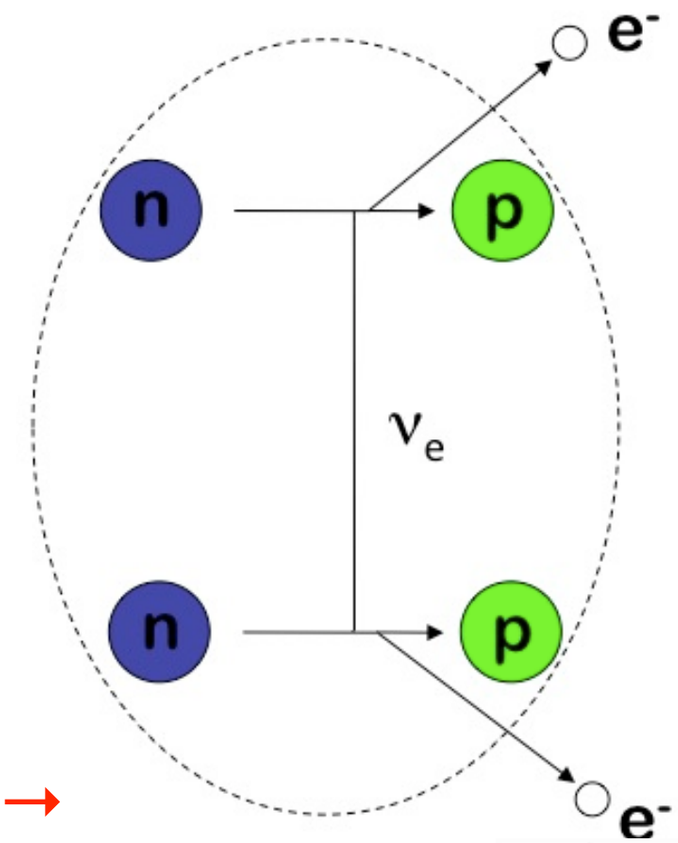


$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

Neutrinoless Double Beta Decay



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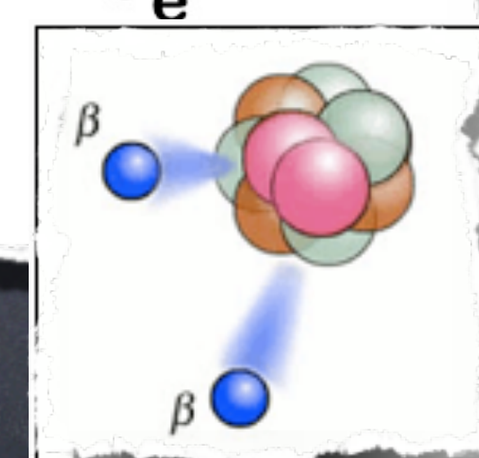
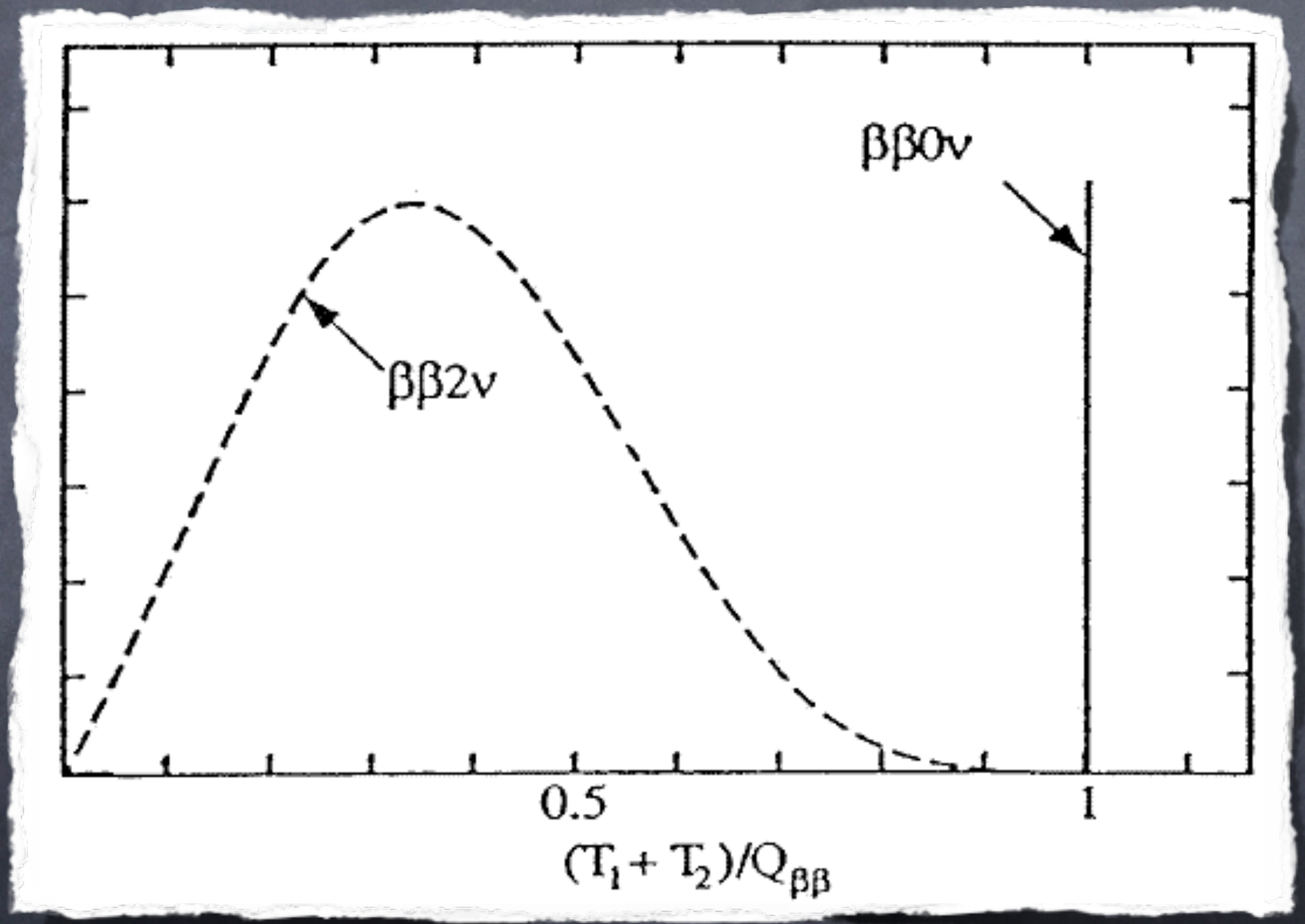


0νββ Signature

Energy Spectrum



0νββ Decay Rate

Decay Rate

$$\Gamma = (T_{\frac{1}{2}})^{-1} = G_{0\nu}|M_{0\nu}|^2\langle m_\nu\rangle^2$$

Phase space factor
Calculable

Nuclear Matrix Element
Not so calculable

Effective
Neutrino Mass

0νββ Decay Rate

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Effective
Neutrino Mass

Probes absolute neutrino mass scale
Also sensitive to mass hierarchy

$$\langle m_\nu\rangle = \sum_i m_i U_{ei}^2$$

$$= \cos^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_1$$

$$+ \sin^2\theta_{12}\cos^2\theta_{13}e^{i\beta}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3$$

0νββ Decay Rate

Decay Rate

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Majorana Phases

Isotope Choice

Isotope	$Q_{\beta\beta}$	Natural abundance	$\lvert M_{0\nu}\rvert$	$\lvert G_{0\nu}\rvert^{-1}$ (10^{25} y eV^2)	$T^{0\nu}_{1/2}$ (10^{27} y)	$N_{0\nu}$ / $N_{0\nu}$(Ge)
^{76}Ge	2.04 MeV	7.8%	4.15 ± 0.65	4.09	0.95	1.0
^{82}Se	3.00 MeV	9.2%	3.75 ± 0.45	0.93	0.26	3.3
^{130}Te	2.53 MeV	34.5%	3.65 ± 0.15	0.59	0.18	3.1
^{136}Xe	2.46 MeV	8.9%	2.95 ± 0.25	0.55	0.25	2.1
^{150}Nd	**3.37 MeV**	**5.6%**	**1.85 ± 0.55**	**0.13**	**0.15**	**3.3**

Sense and Sensitivity of ββ expts: arxiv/1010.5112

Isotope Choice

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^{150}Nd	3.37 MeV	5.6%	1.85 ± 0.55	0.13	0.15	3.3

Sense and Sensitivity of ββ expts: arxiv/1010.5112

Backgrounds in SNO+

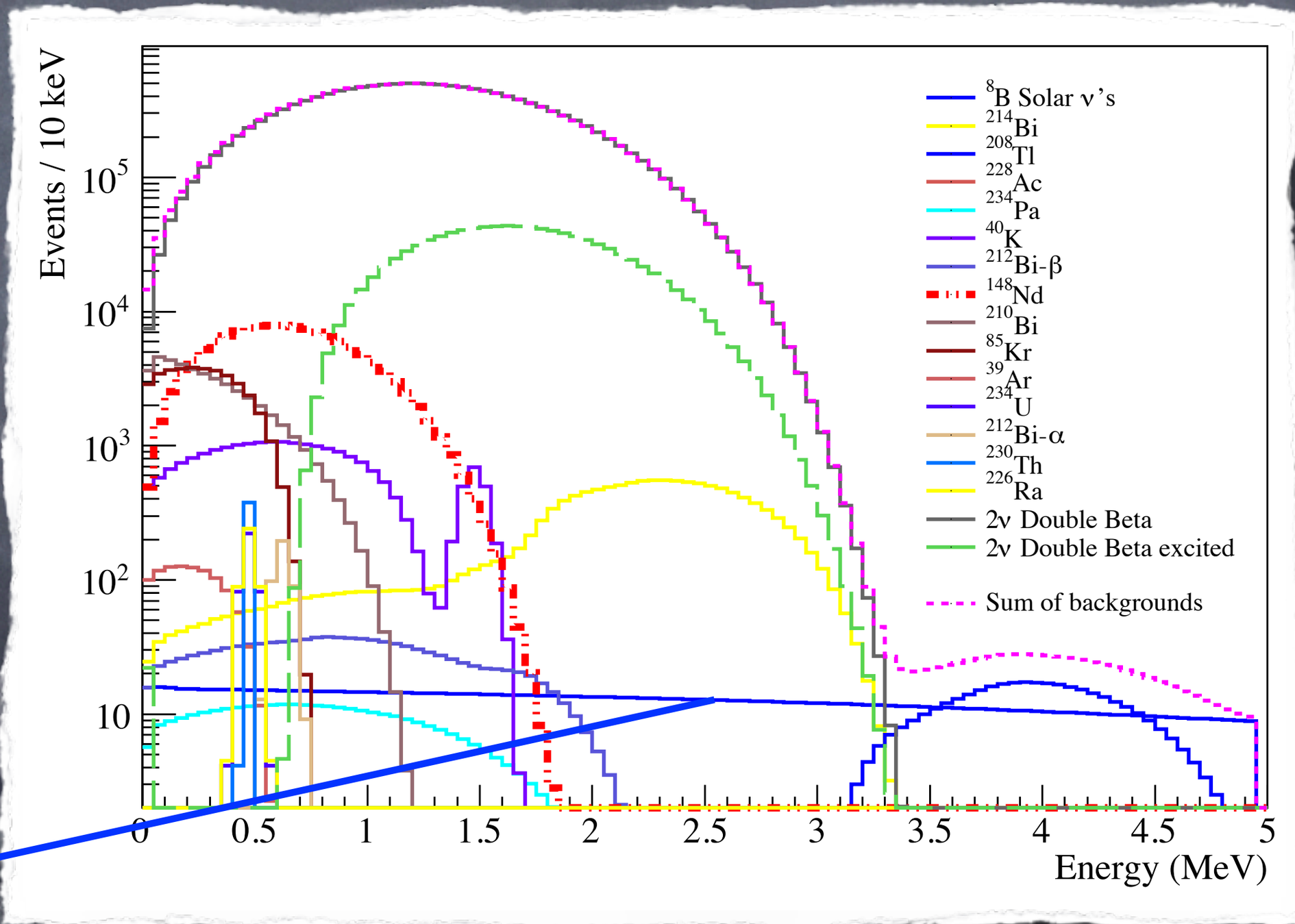
Load scintillator with ^{150}Nd

i) Large, homogeneous detector

ii) Source in / source out capability

iii) Well defined background model

Borexino bkg levels



Well-known "background" from solar neutrinos

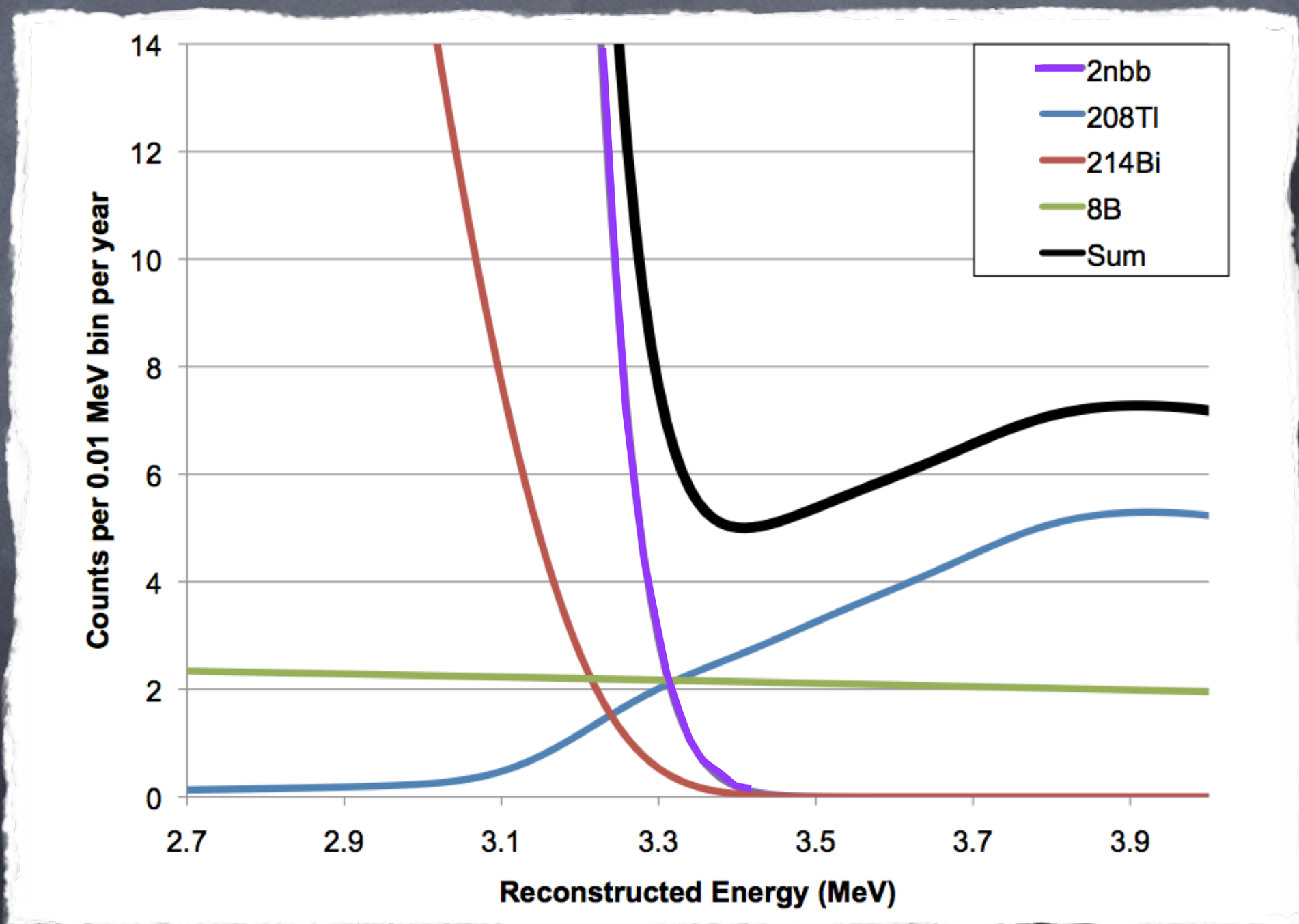
0νββ Decay in SNO+

i) Large, homogeneous detector

ii) Source in / source out capability

iii) Well defined background model

iv) High statistics



0νββ Decay in SNO+

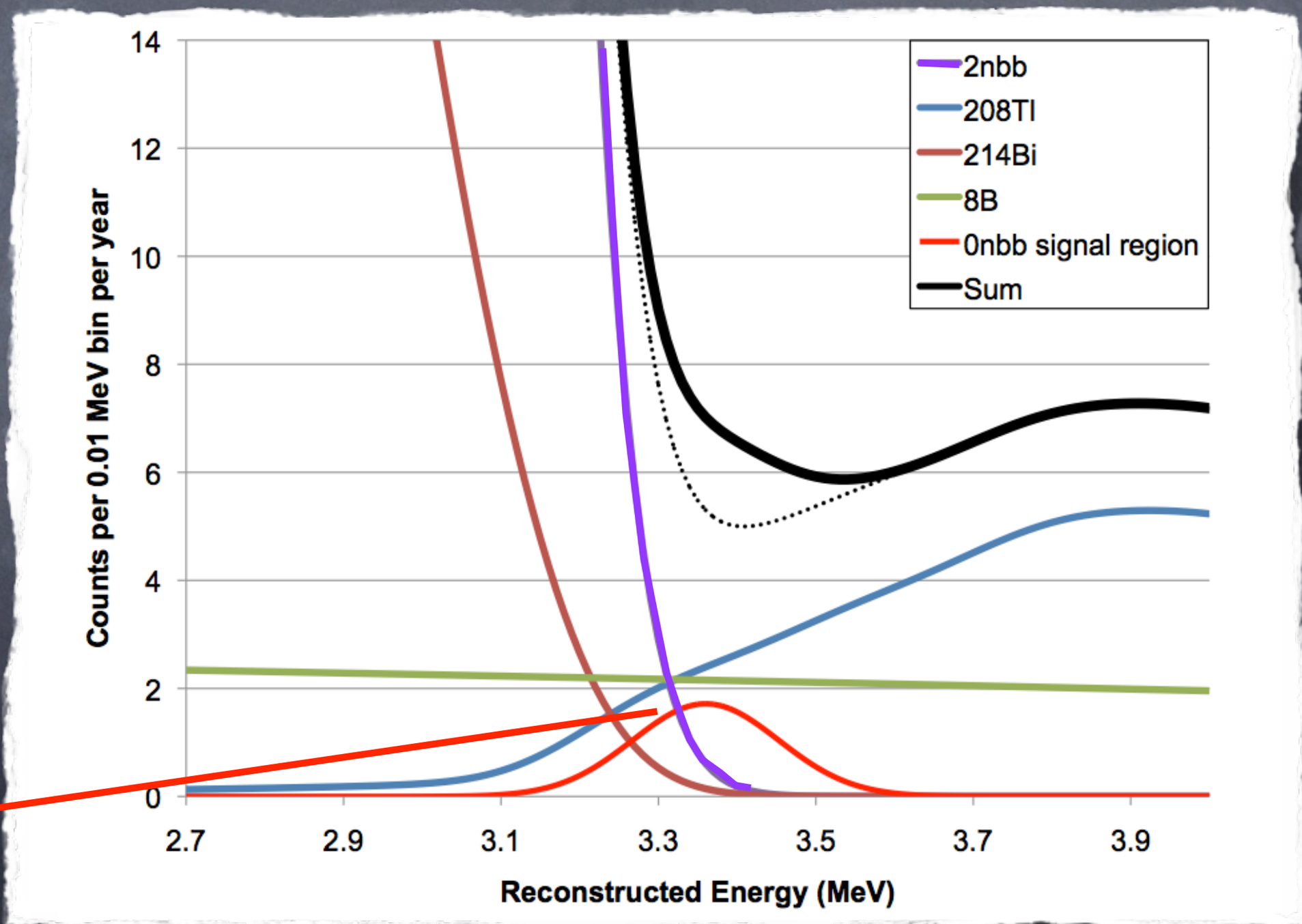
i) Large, homogeneous detector

ii) Source in / source out capability

iii) Well defined background model

iv) High statistics

Expected signal:
$\langle m_\nu \rangle$=270meV

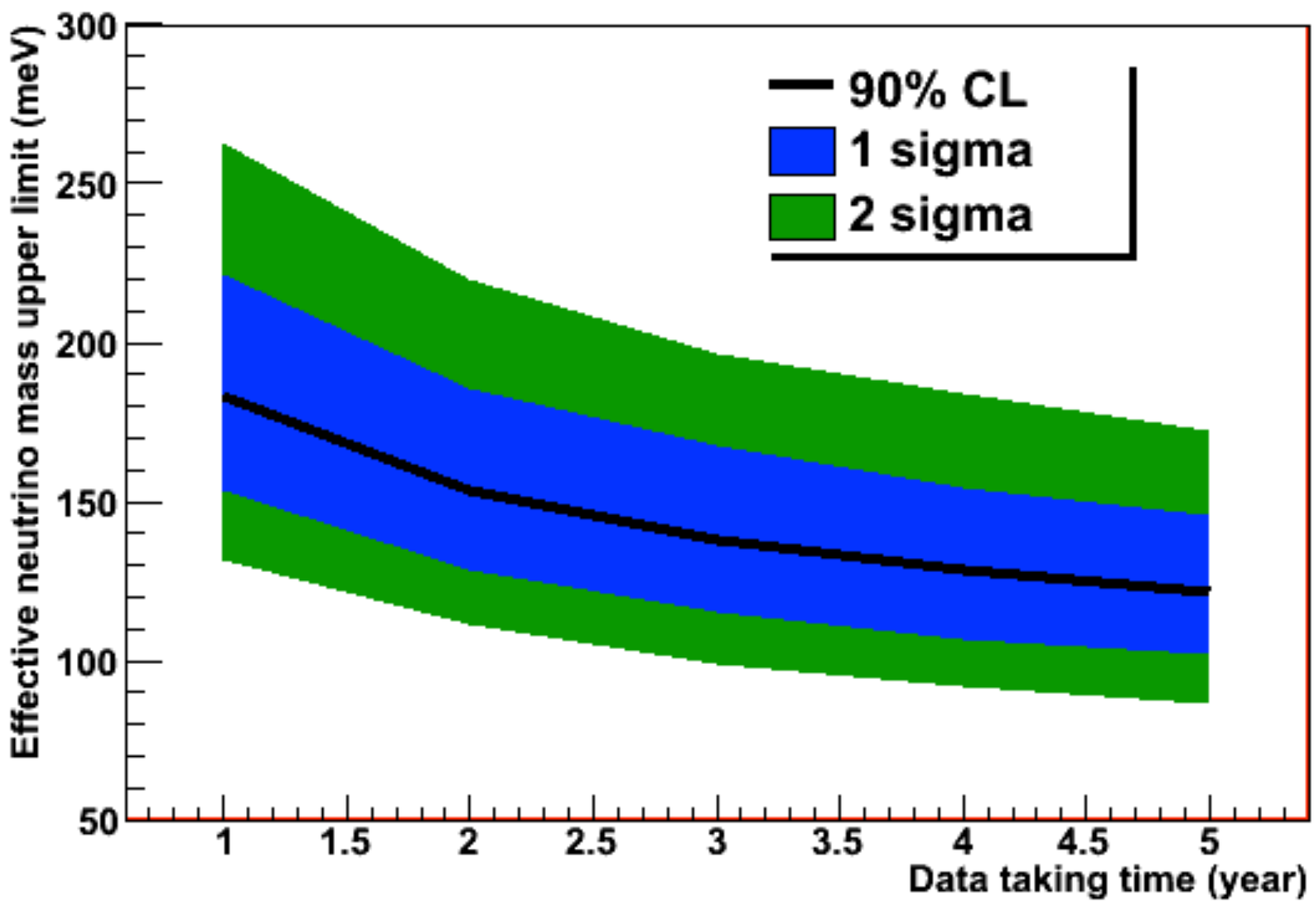


0νββ signal

SNO+ Sensitivity

0.1% loading natural Nd ⇒ 44kg ^{150}Nd

light yield ~400p.e. /MeV



Uses IBM-2 NME (Most conservative NME calc for ^{150}Nd)

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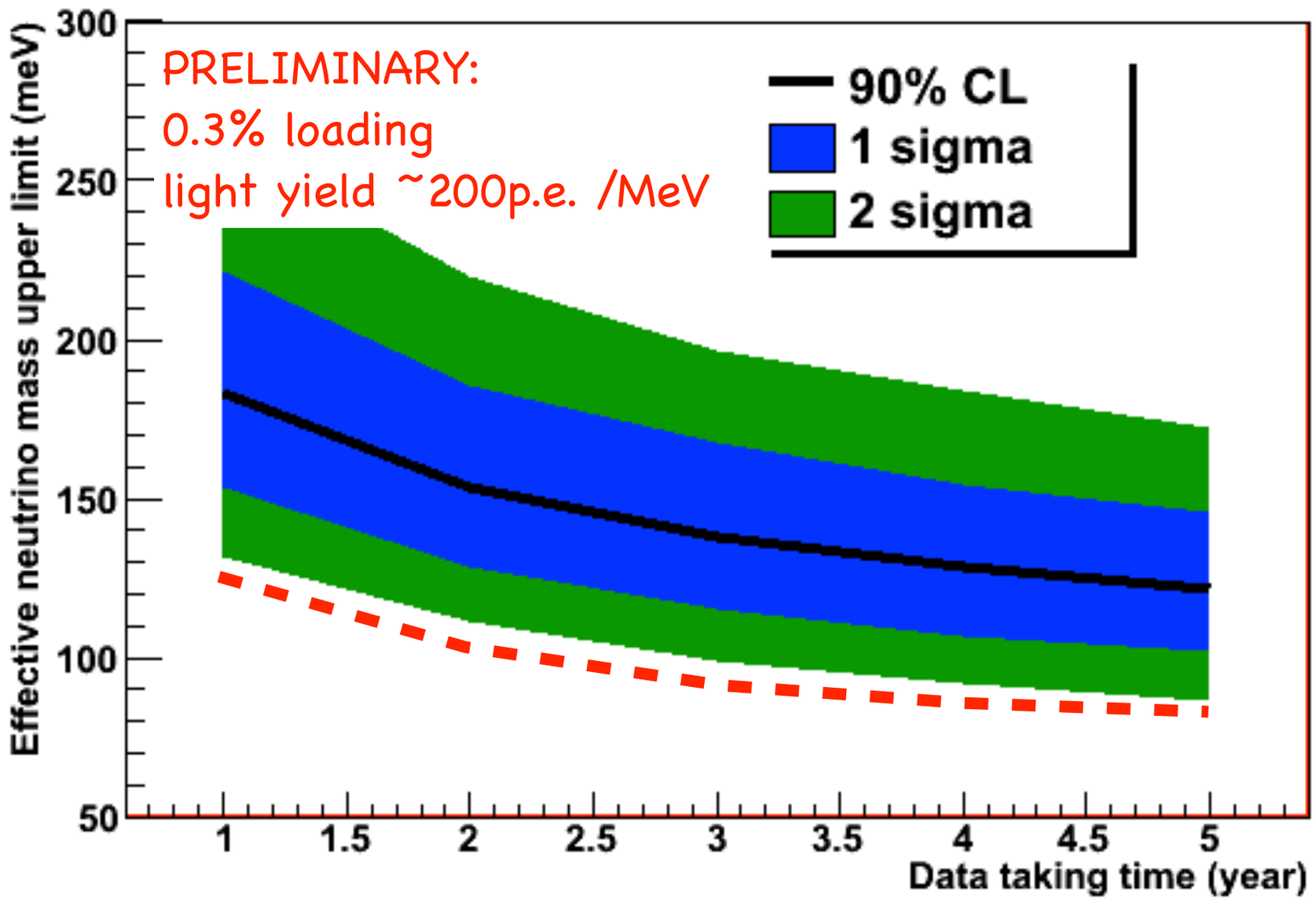


Uses IBM-2 NME (Most conservative NME calc for ^{150}Nd)

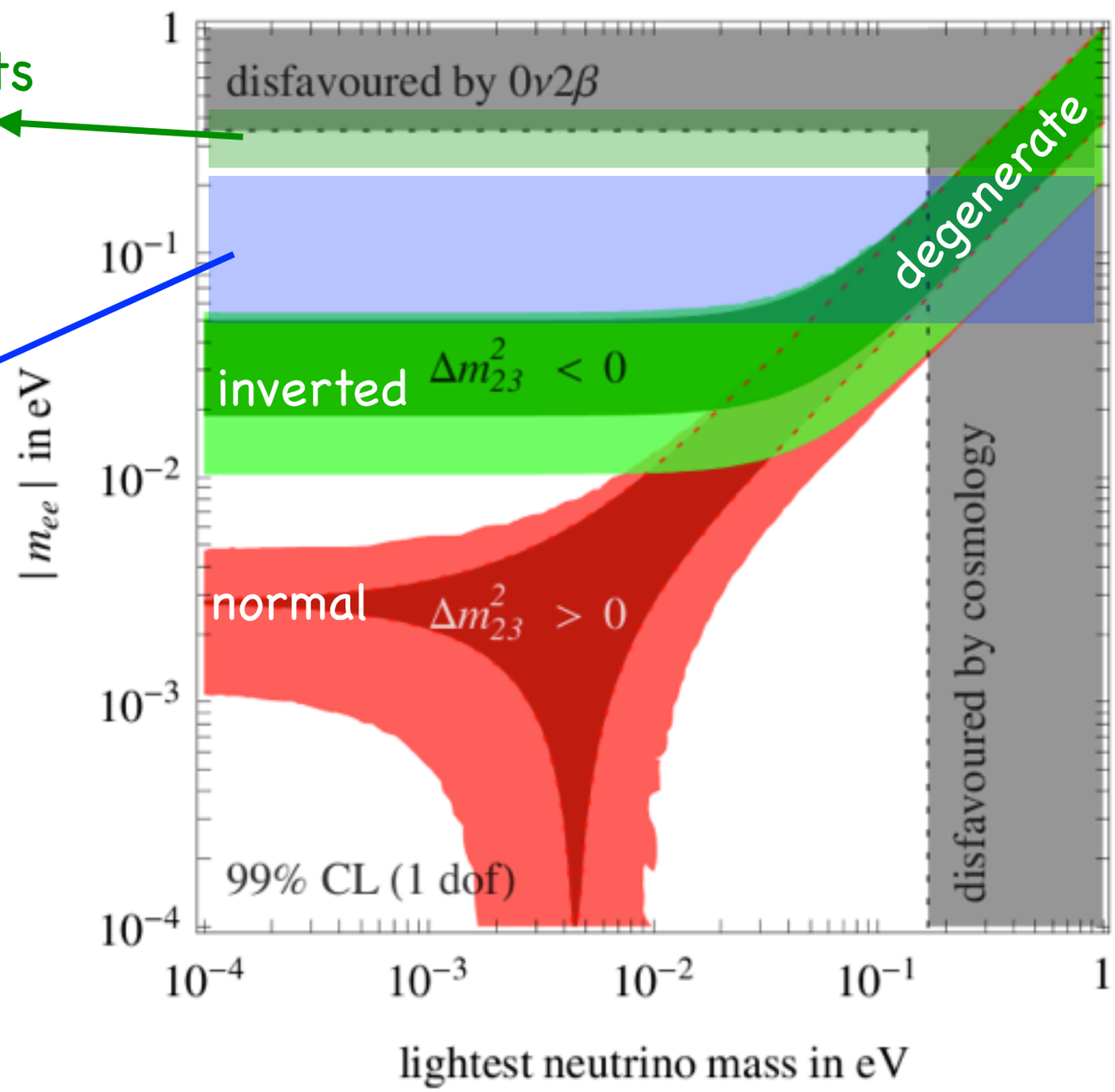
Uses QRPA

Status of the Field

Mass Hierarchy

Current Experiments
NEMO3, Cuoricino,
Gerda-I, SuperNEMO
demonstrator

Future Experiments
CUORE, EXO, GERDA,
SuperNEMO...



Status of the Field

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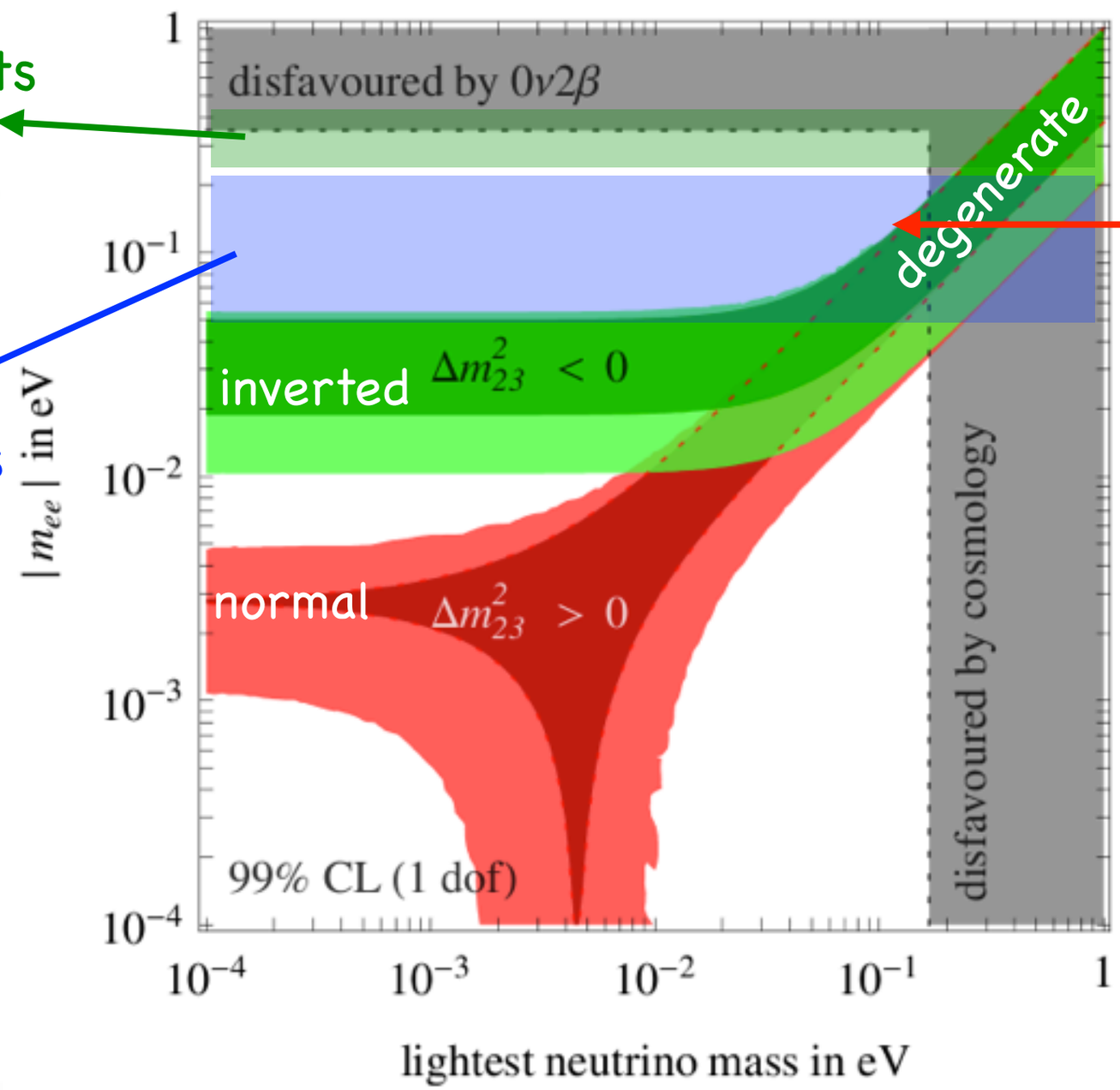


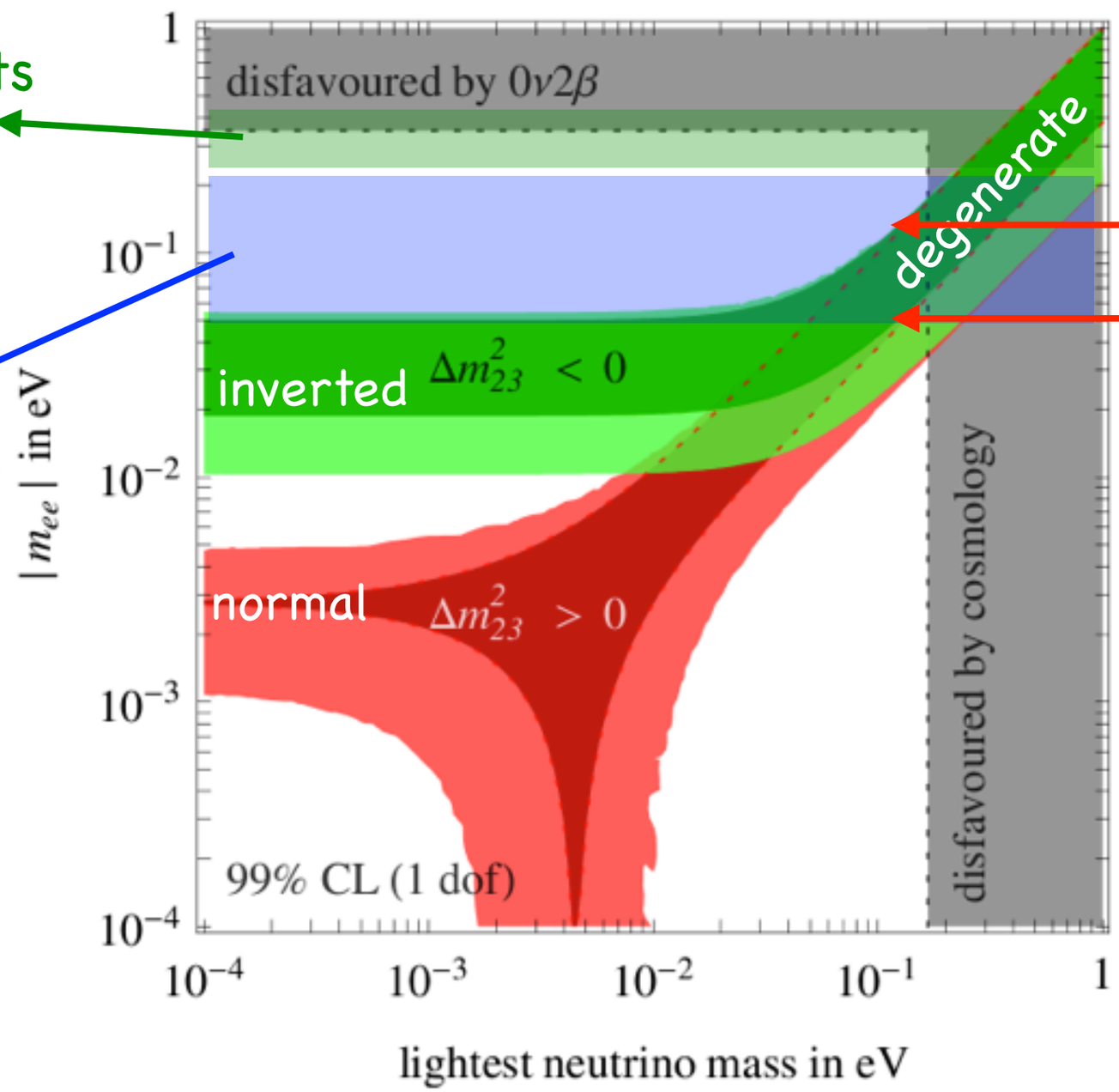
SNO+ stage 1

Status of the Field

Mass Hierarchy

Current Experiments
NEMO3, Cuoricino, Gerda-I, SuperNEMO demonstrator

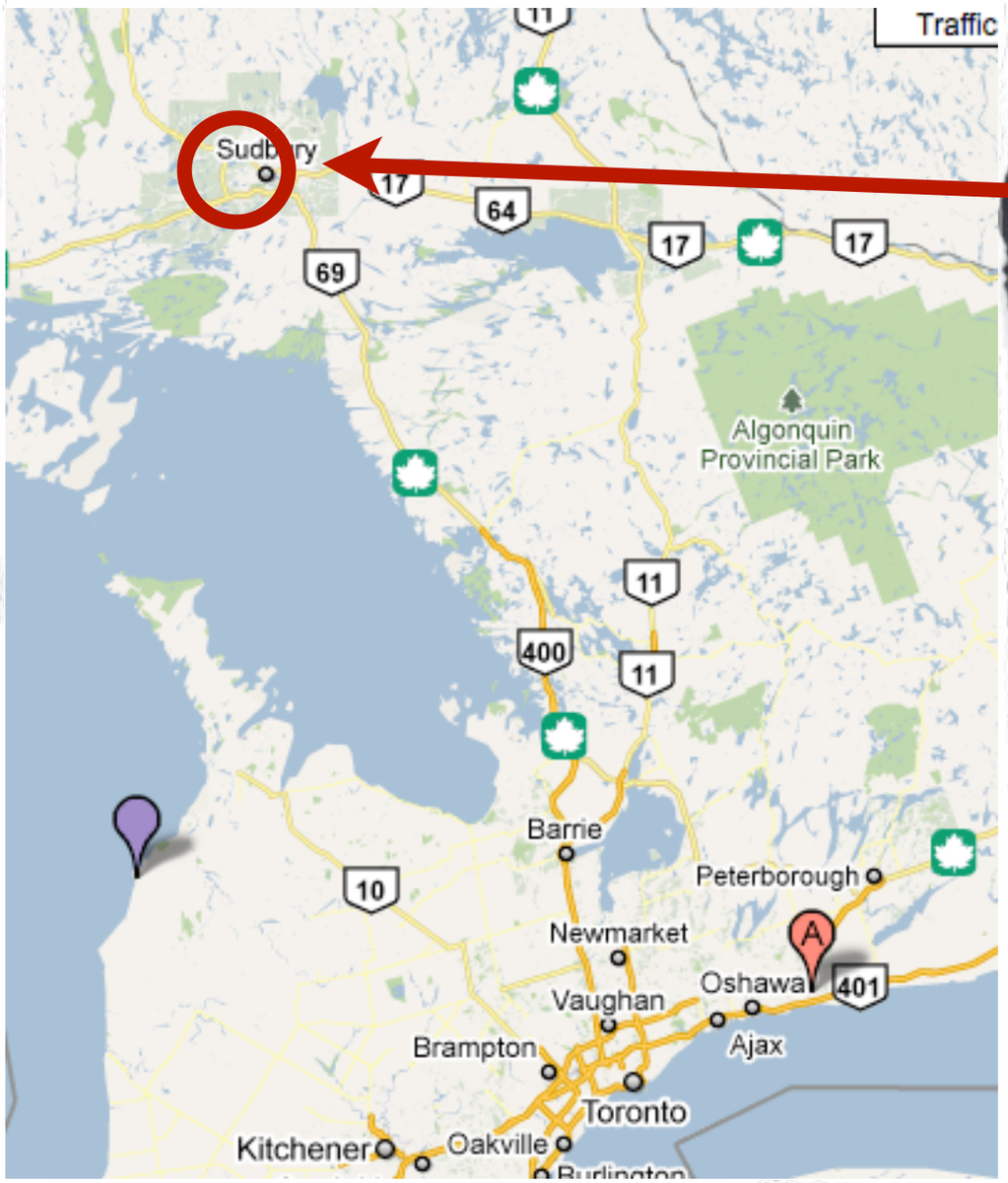
Future Experiments
CUORE, EXO, GERDA, SuperNEMO...



SNO+ stage 1

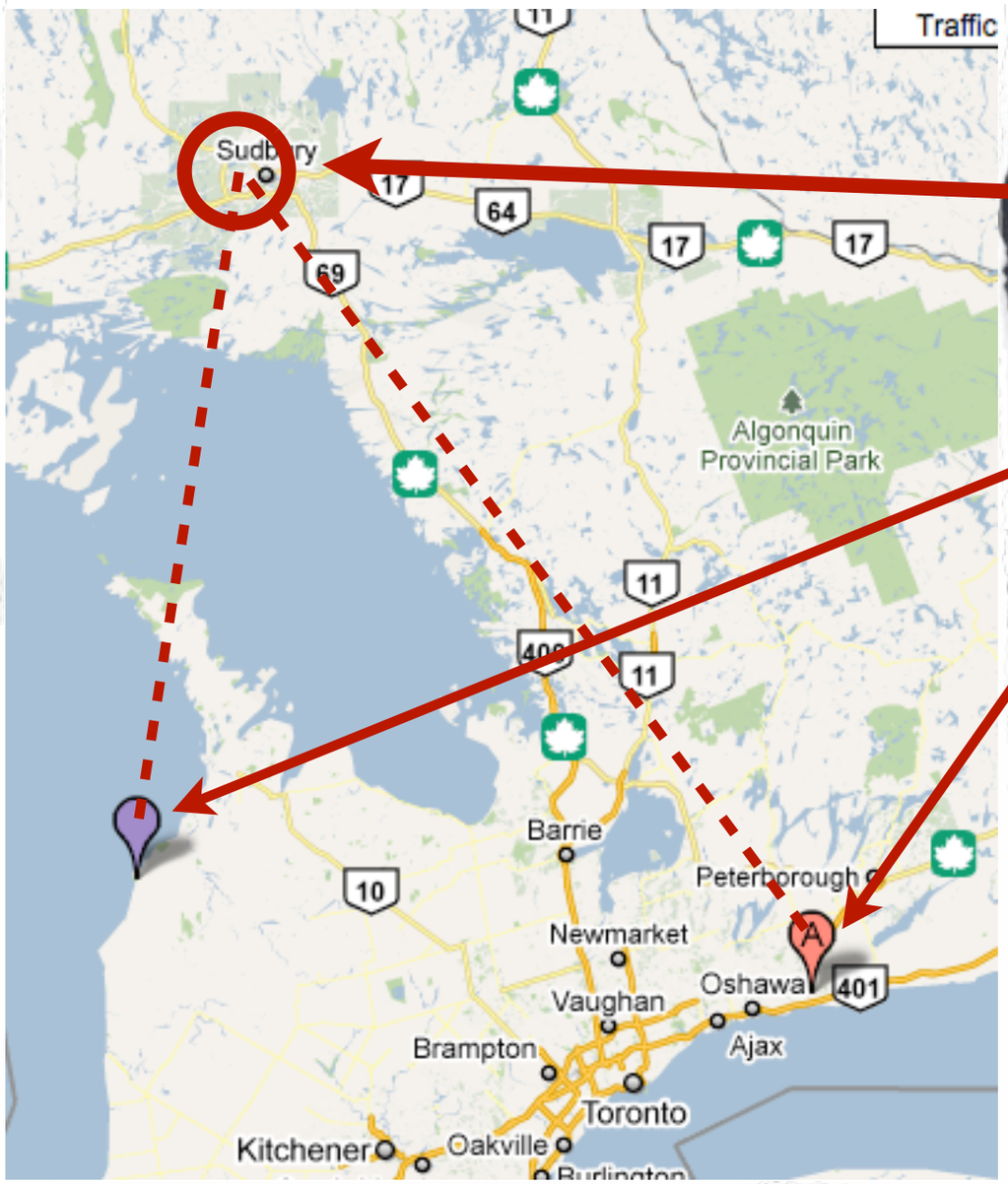
SNO+ stage 2: enriched Nd

Reactor Antineutrinos



SNO+ site

Reactor Antineutrinos

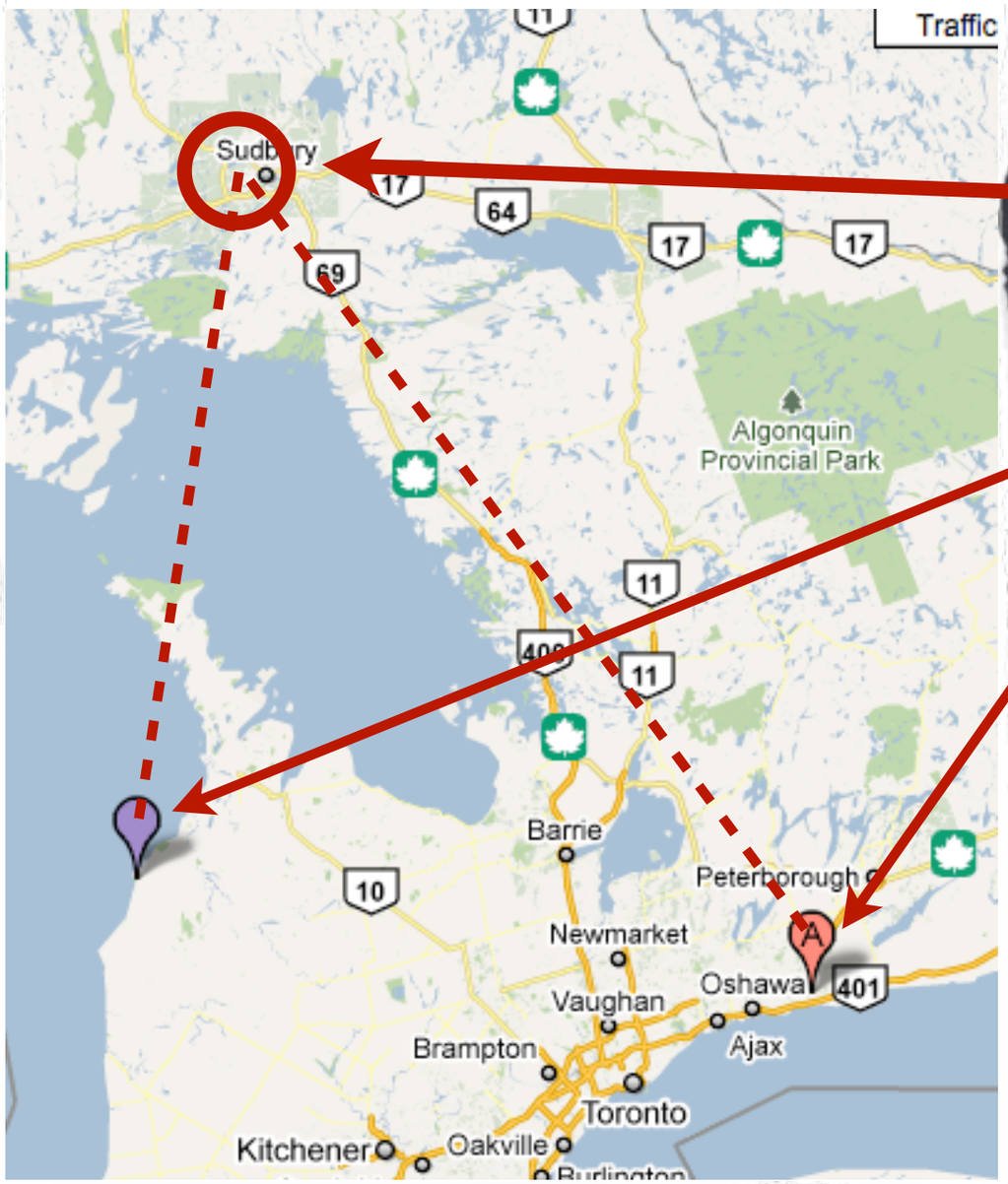


SNO+ site

Two nearby reactors:
- well-defined flux
- similar L

⇒ clear oscillation pattern

Reactor Antineutrinos



SNO+ site

Two nearby reactors:
- well-defined flux
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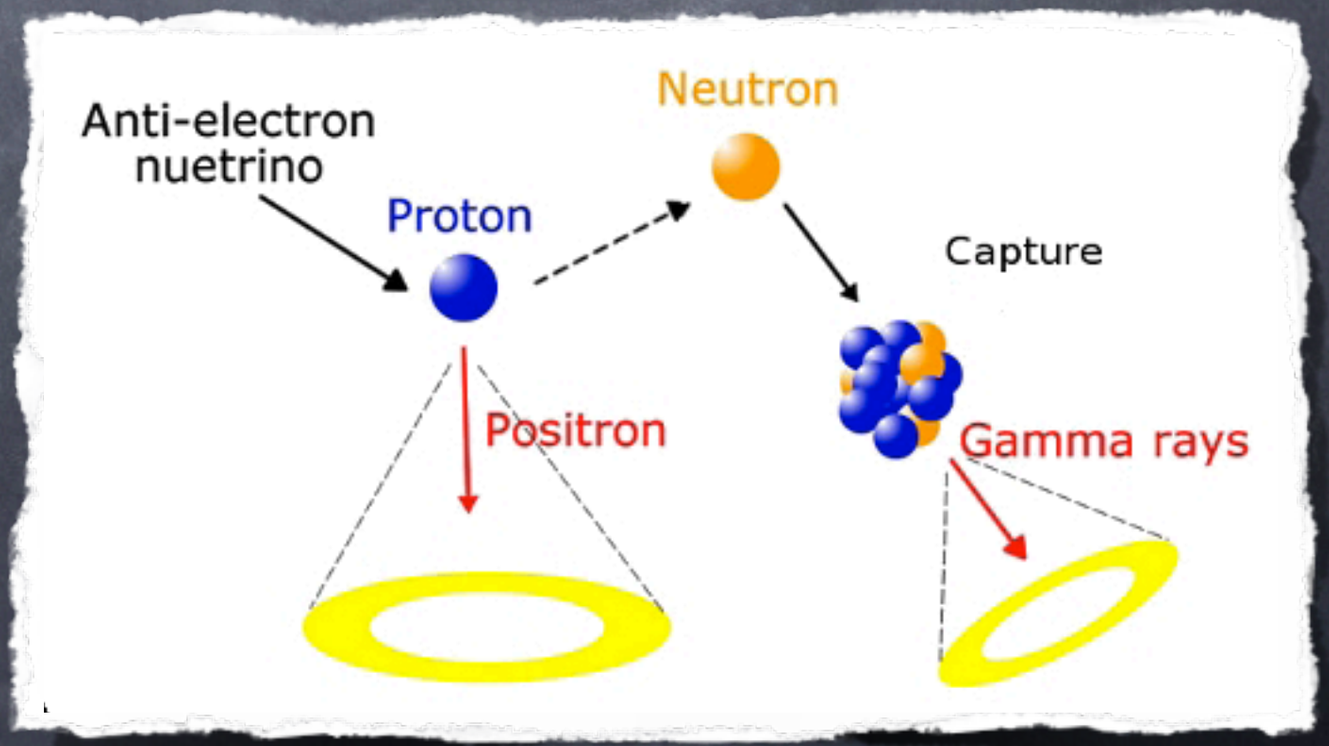
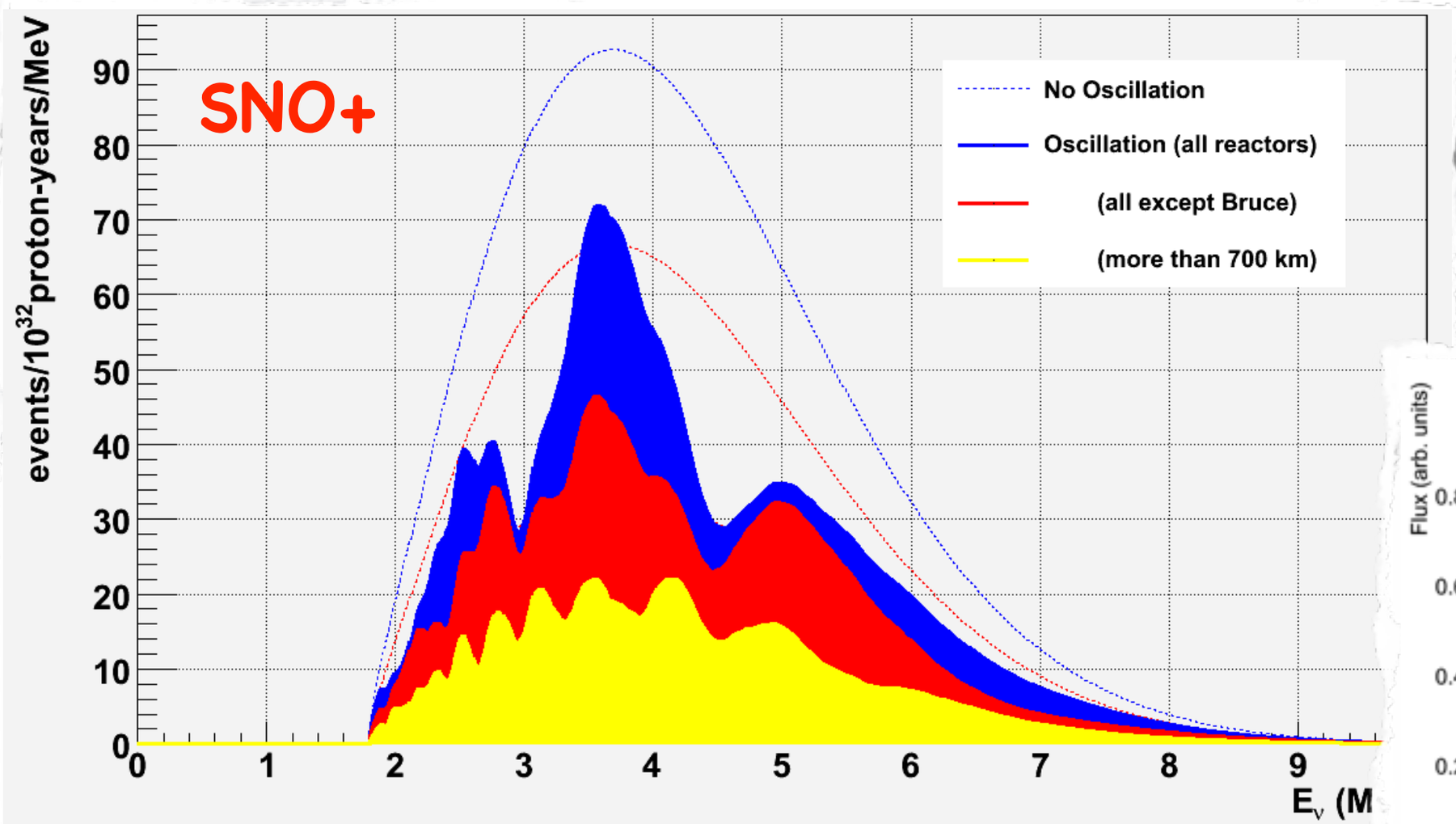
- ⇒ clear oscillation pattern

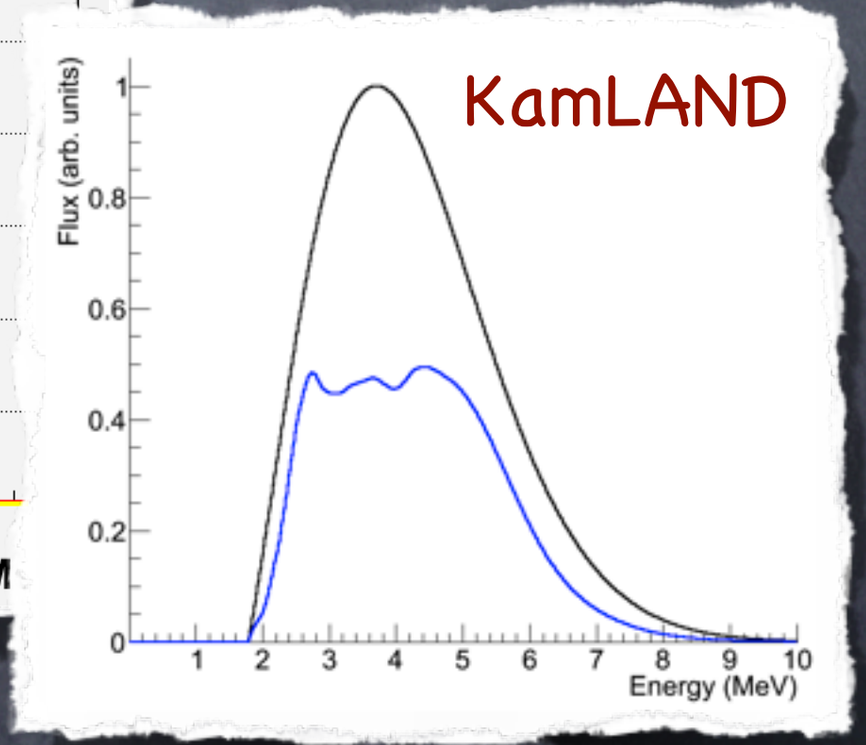


Reactor Antineutrinos

Reactor antineutrino energy spectra



Smaller flux
but
Multiple oscillation minima

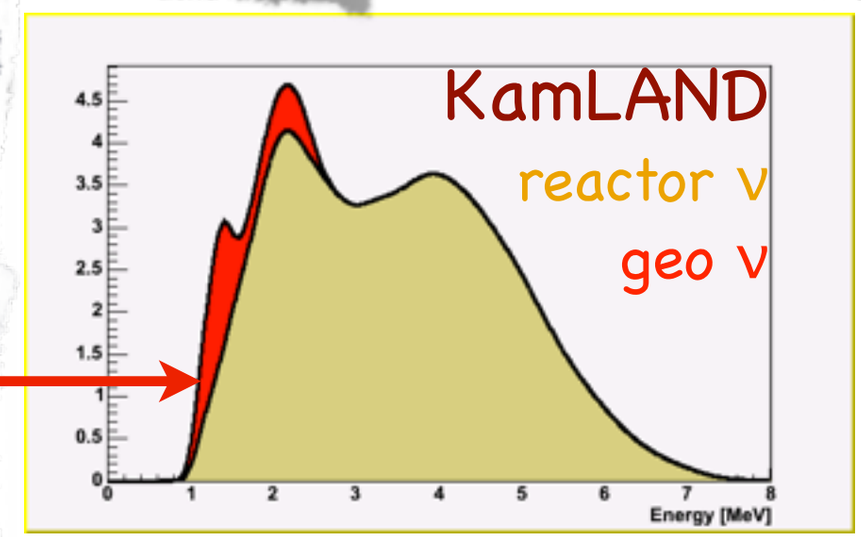


$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \sin^2 \frac{1.27\Delta m^2_{12} L}{E_\nu}$$

Geo Neutrinos

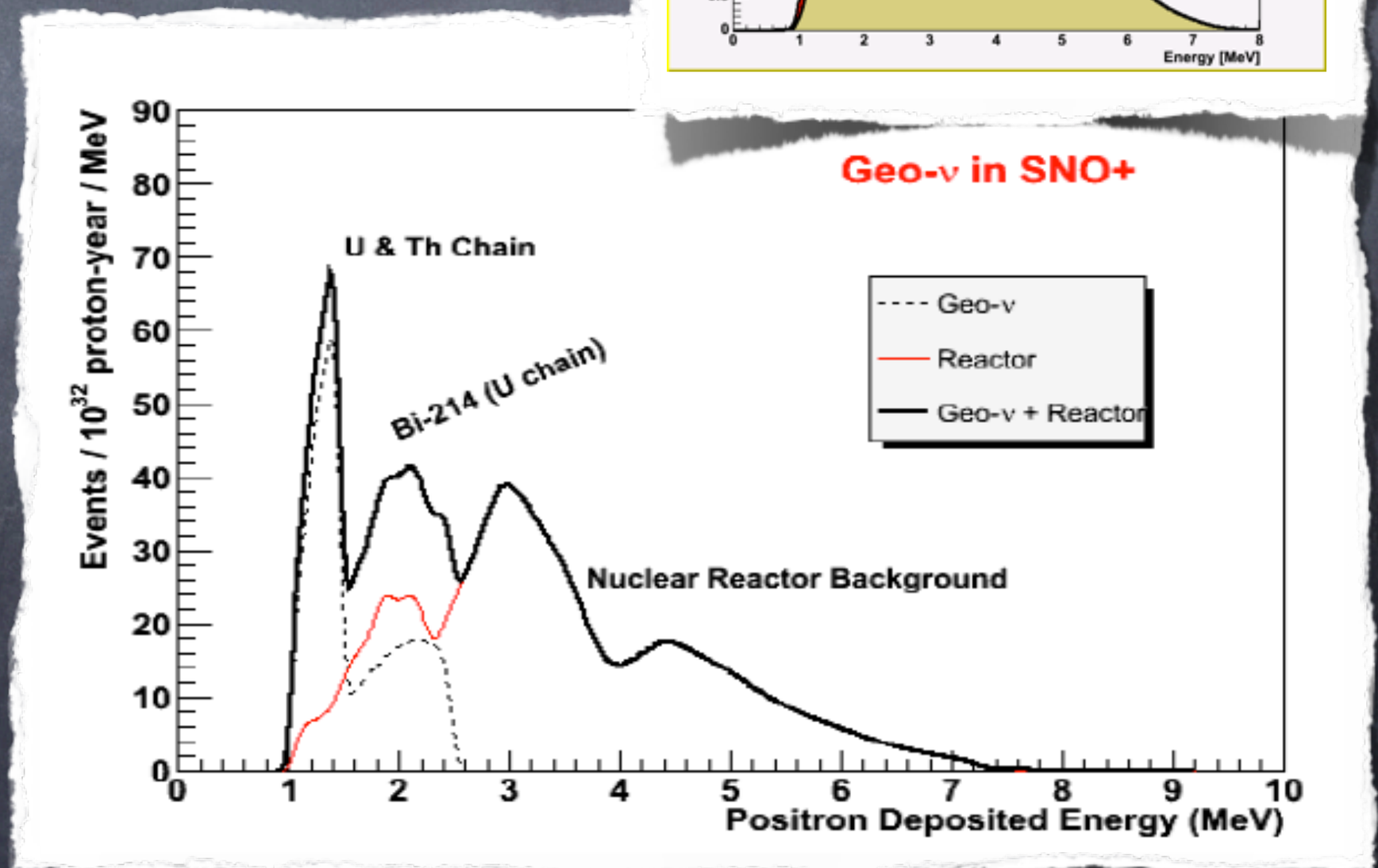
Electron antineutrinos from U, Th, K decay in the Earth

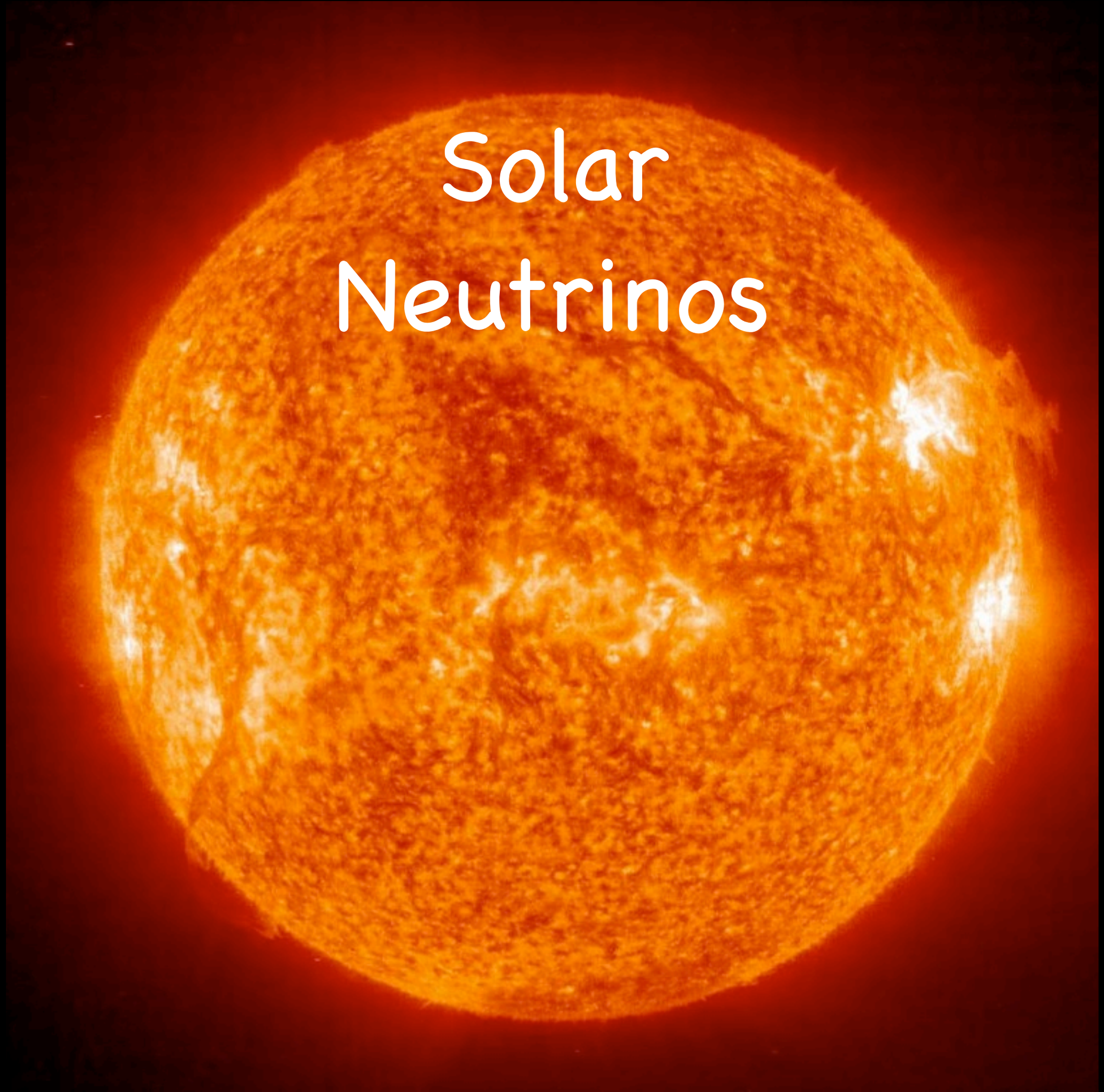
Smaller reactor background than KamLAND



Expect
~20 events / yr

Check models of heat production in the Earth

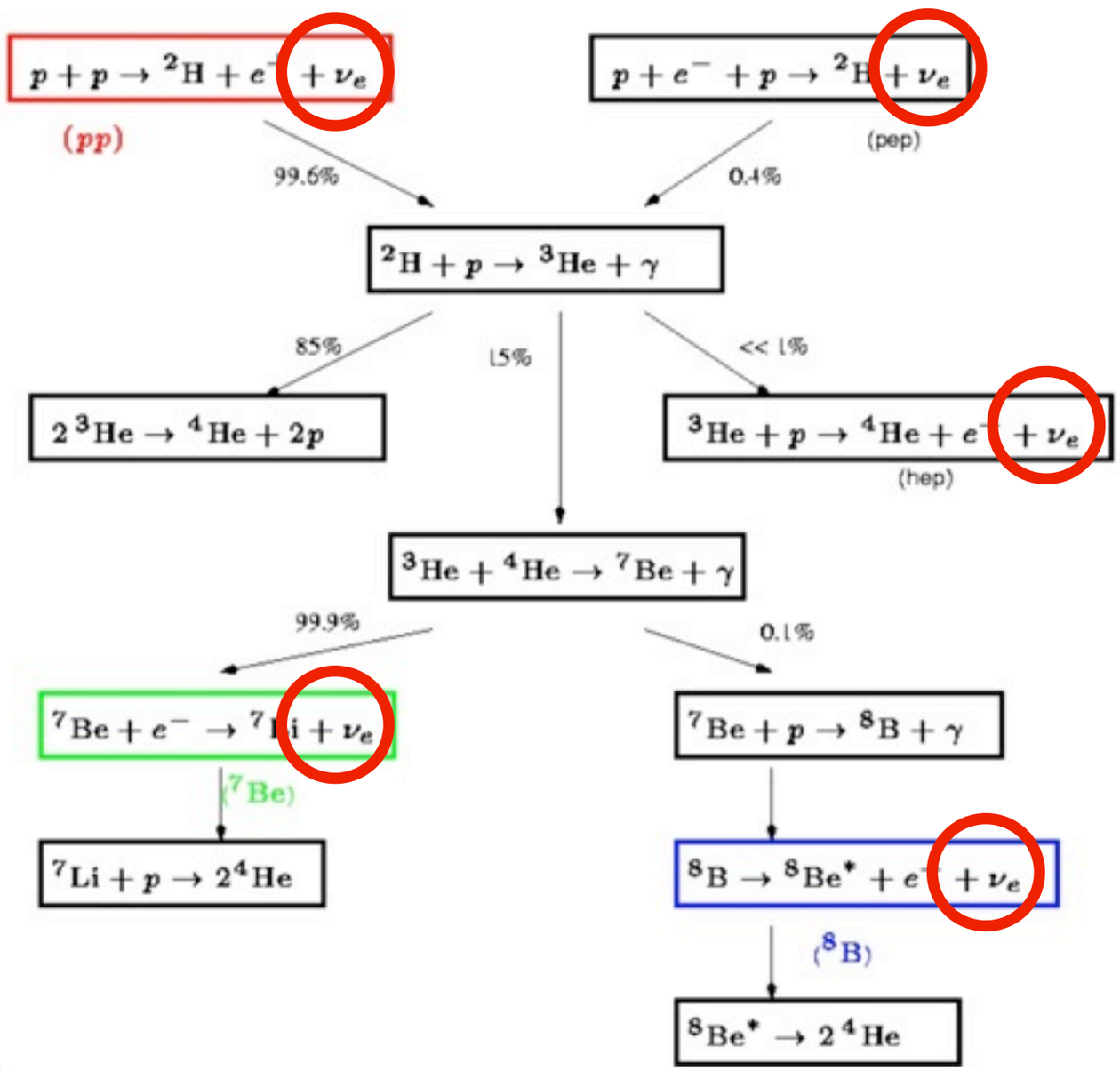




Solar Neutrinos

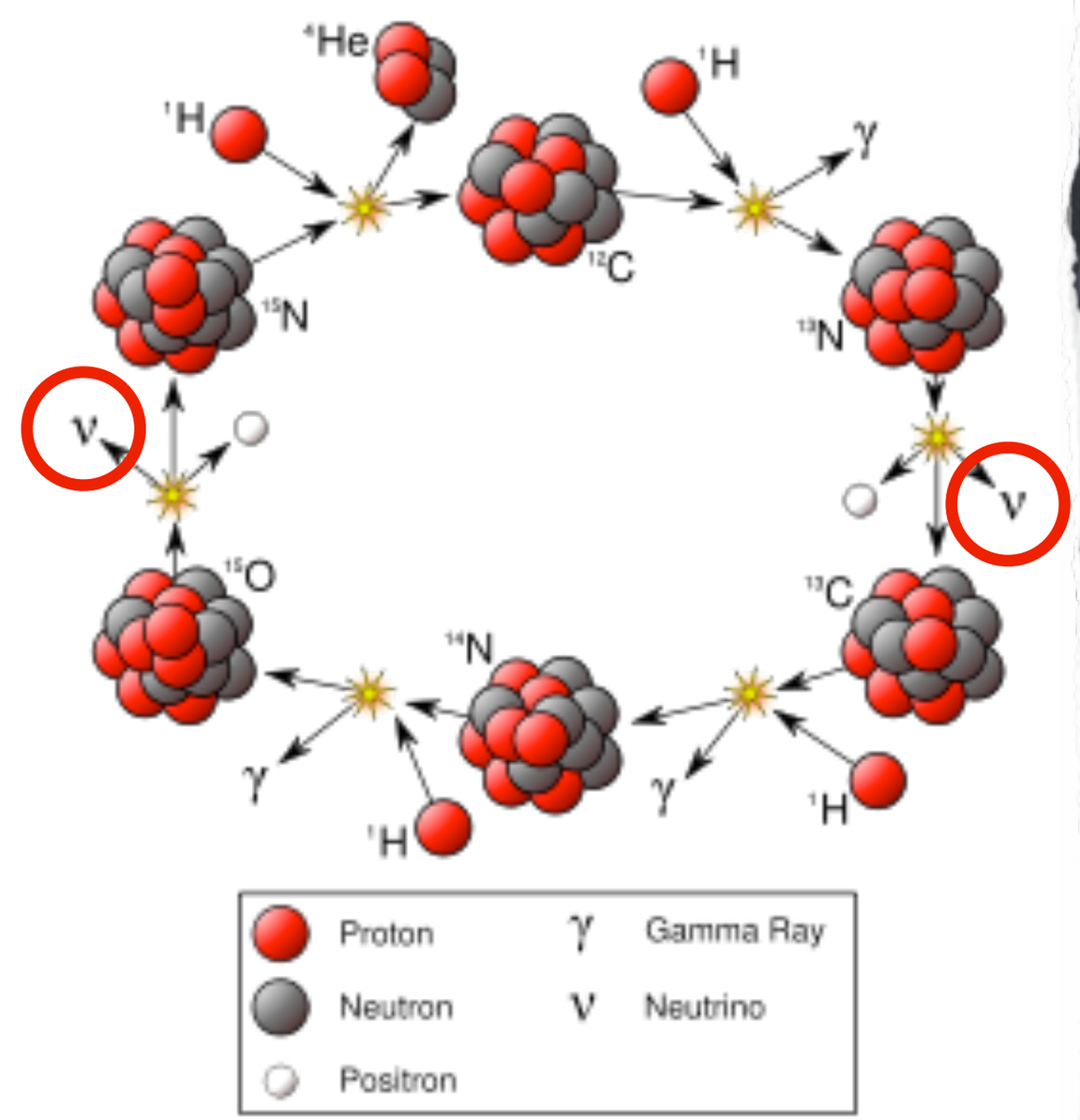
Solar Neutrinos

pp Chain

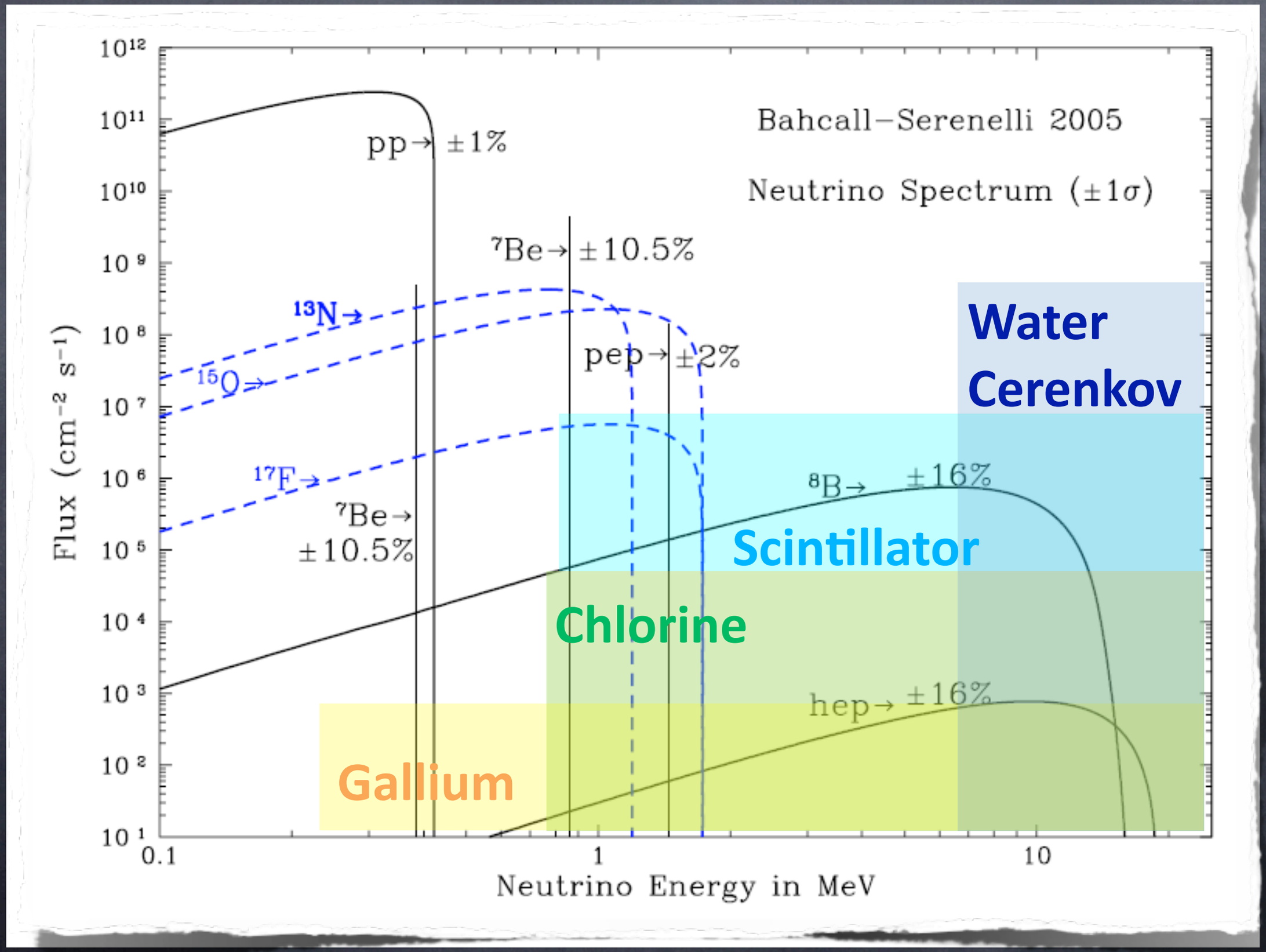


CNO Cycle

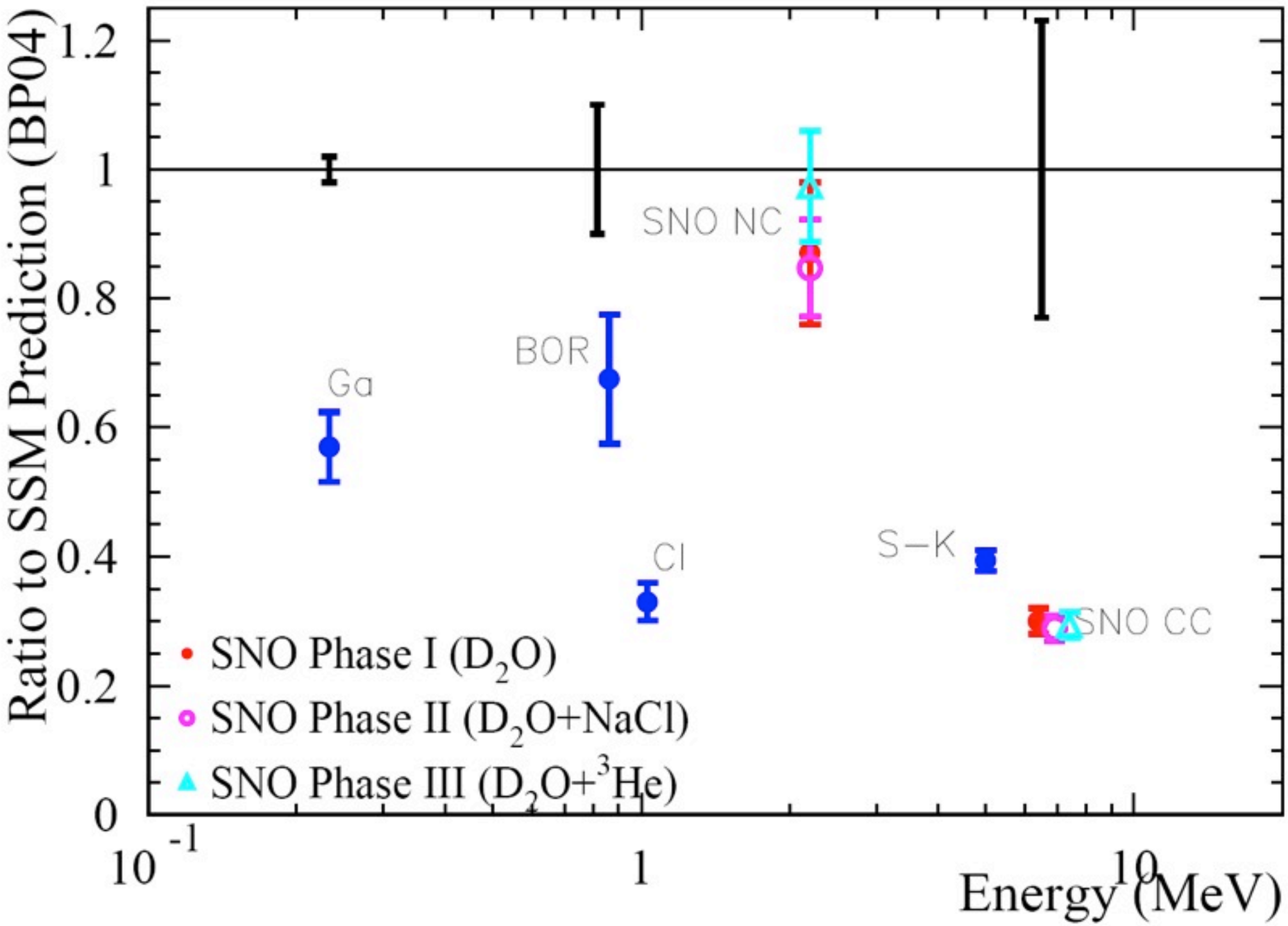
(contributes ~1% of solar energy)



Solar Neutrinos

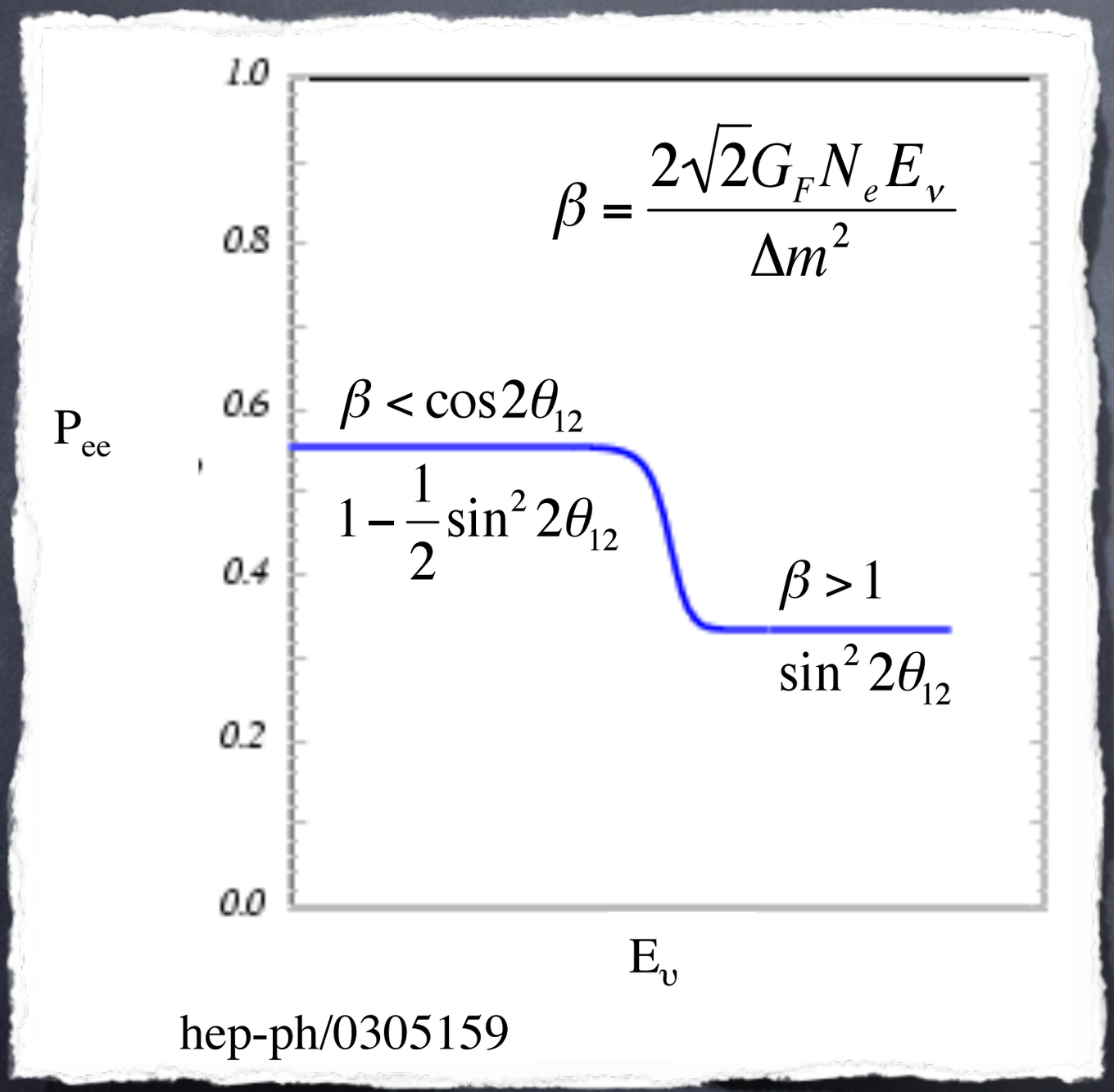


Neutrino Oscillation



What More Can we Learn?

MSW Oscillation



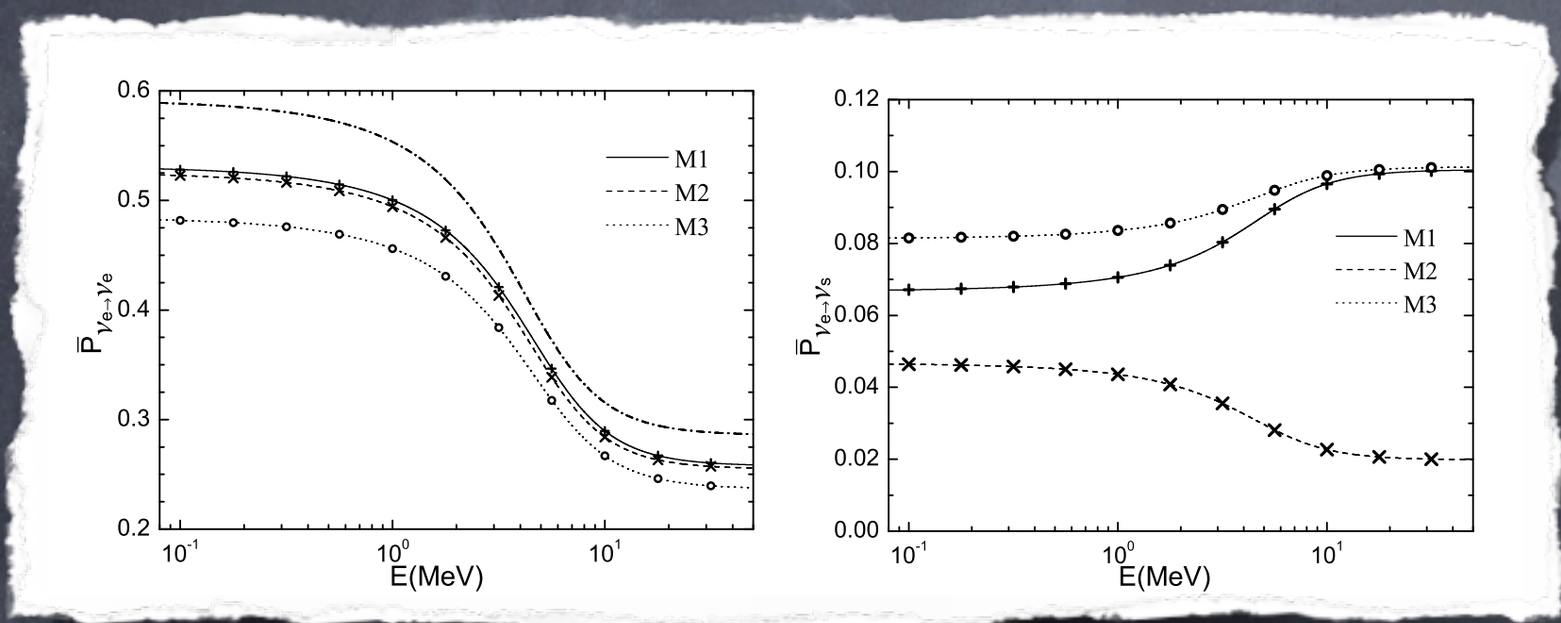
Rise of survival probability at low E_ν as we approach vacuum-average value of $1-(1/2)\sin^2 2\theta$

New Physics

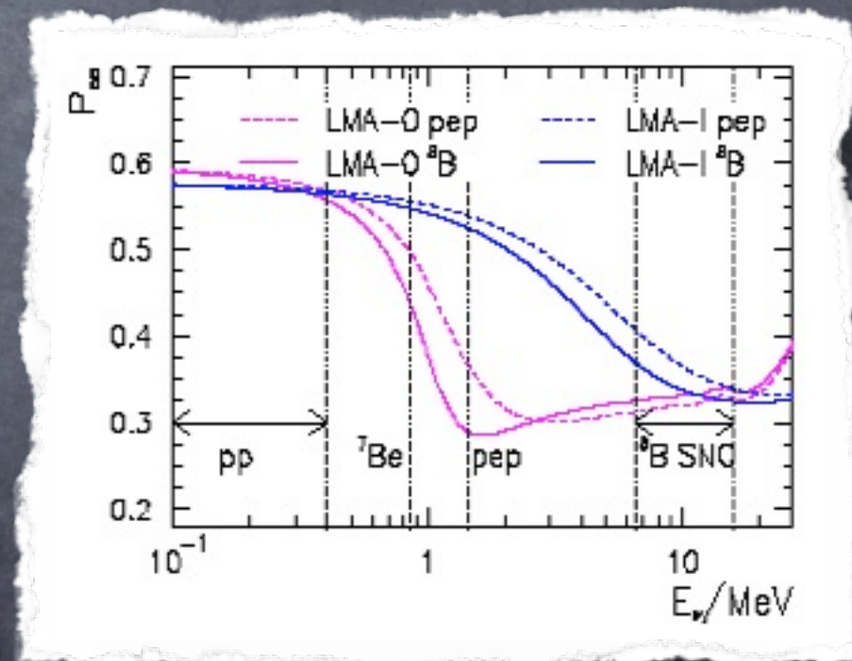
Non-standard effects can alter position/shape of the rise

Sterile Neutrinos

C. Giunti, Y. F. Li PRD80:113007 (2009)



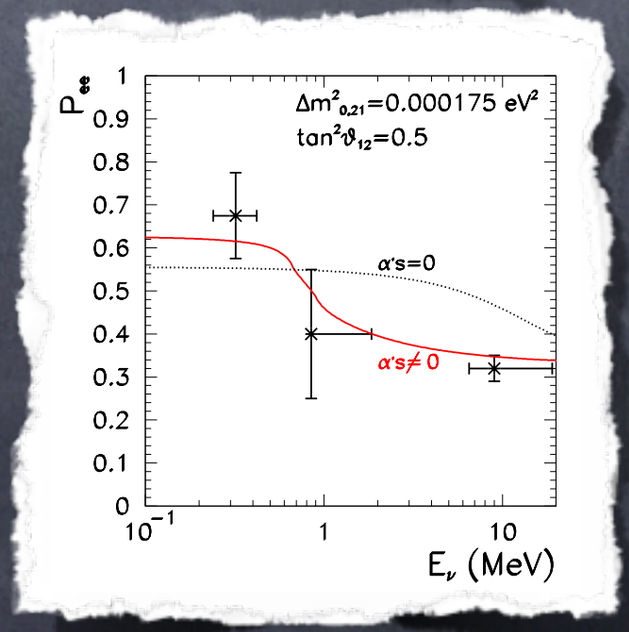
Non-standard interactions (flavour changing NC)



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

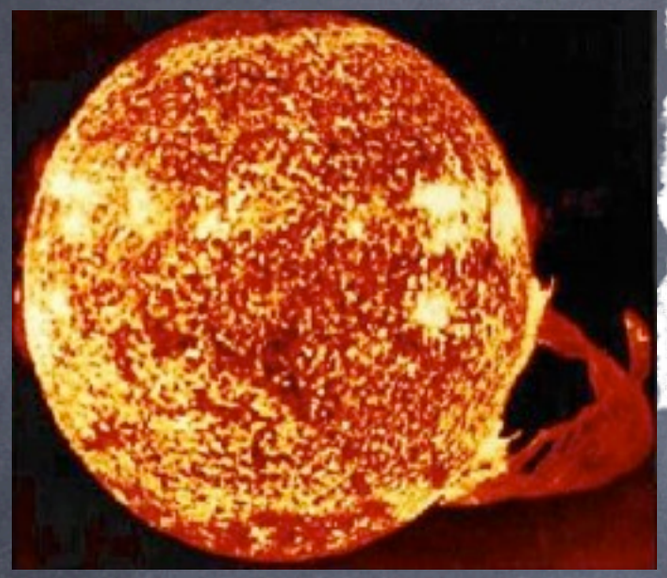
Mass varying neutrinos (MaVaNs)

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



What More Can we Learn?

Understanding the Sun



Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. ---John Bahcall, PR, (1964)

Solar Metallicity:

SSM always agreed beautifully with helioseismology

Modern measurements of surface metallicity are lower

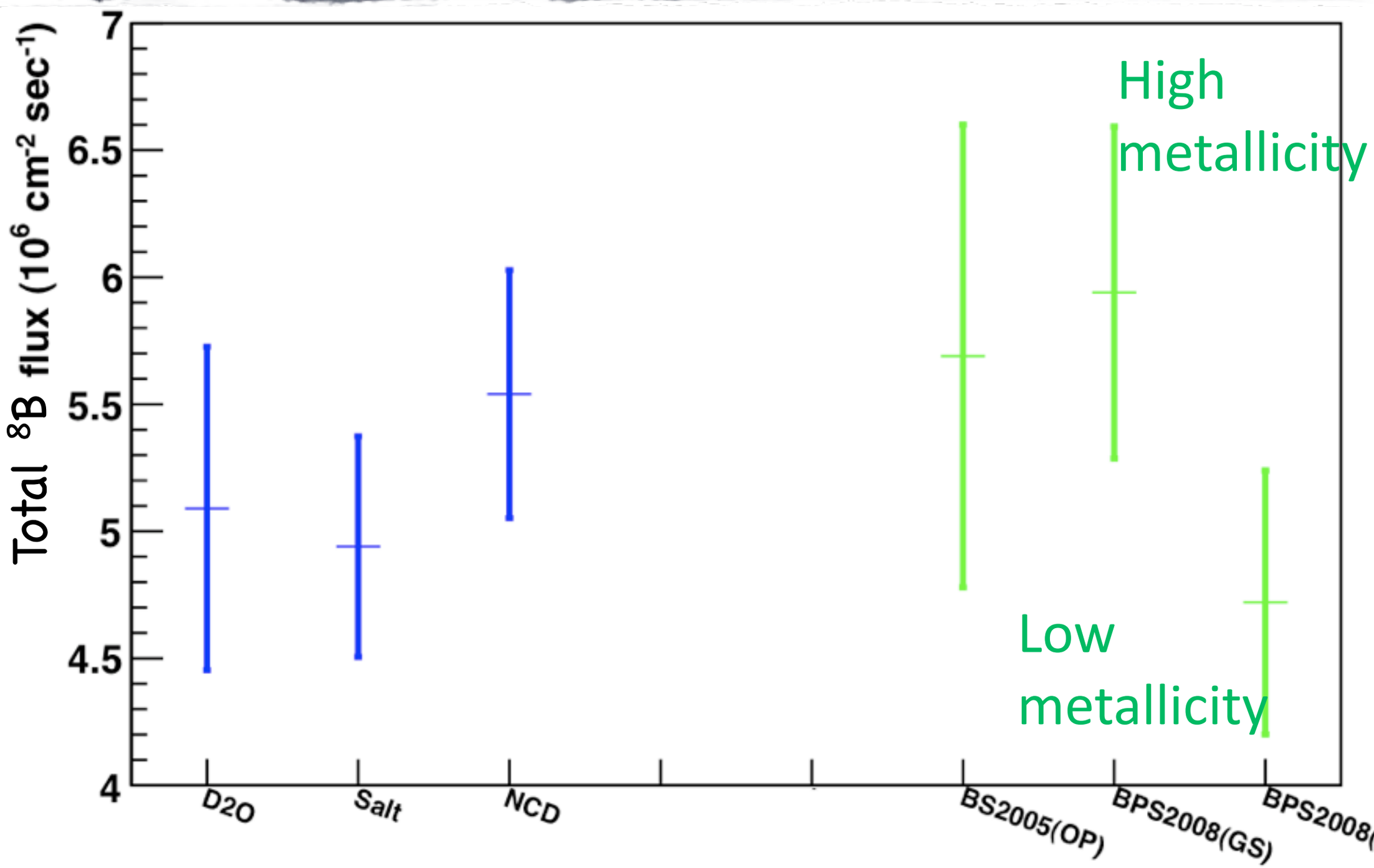
⇒ New disagreement to be resolved

CNO flux tells us core metallicity

More accurate experimental results could pick a SSM

What More Can we Learn?

Understanding the Sun



What More Can we Learn?

Final Mixing Angle: solar vs KamLAND

REACTOR

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.27\Delta m^2_{13} L}{E_\nu} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.27\Delta m^2_{12} L}{E_\nu}$$

SOLAR

$$P(\nu_e \to \nu_e) = \sin^4 \theta_{13} + \cos^4 \theta_{13} P^{2\nu}_{ee}(\theta_m, \Delta_M)$$

$$\Delta_M = \Delta m^2_{12} \sqrt{\zeta}$$

$$P^{2\nu}_{ee}(\theta_m, \Delta_M) = \left(1 - \sin^2 2\theta_m \sin^2 \frac{1.27\Delta_M L}{E_\nu}\right)$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_{12}}{\zeta}$$

$$a = 2\sqrt{2} E_\nu G_F n_e \cos^2 \theta_{13}$$

$$\zeta = \left(\cos 2\theta_{12} - \frac{a}{\Delta m^2_{12}}\right)^2 + \sin^2 2\theta_{12}$$

What More Can we Learn?

Final Mixing Angle: solar vs KamLAND

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$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.27\Delta m^2_{13} L}{E_\nu} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.27\Delta m^2_{12} L}{E_\nu}$$

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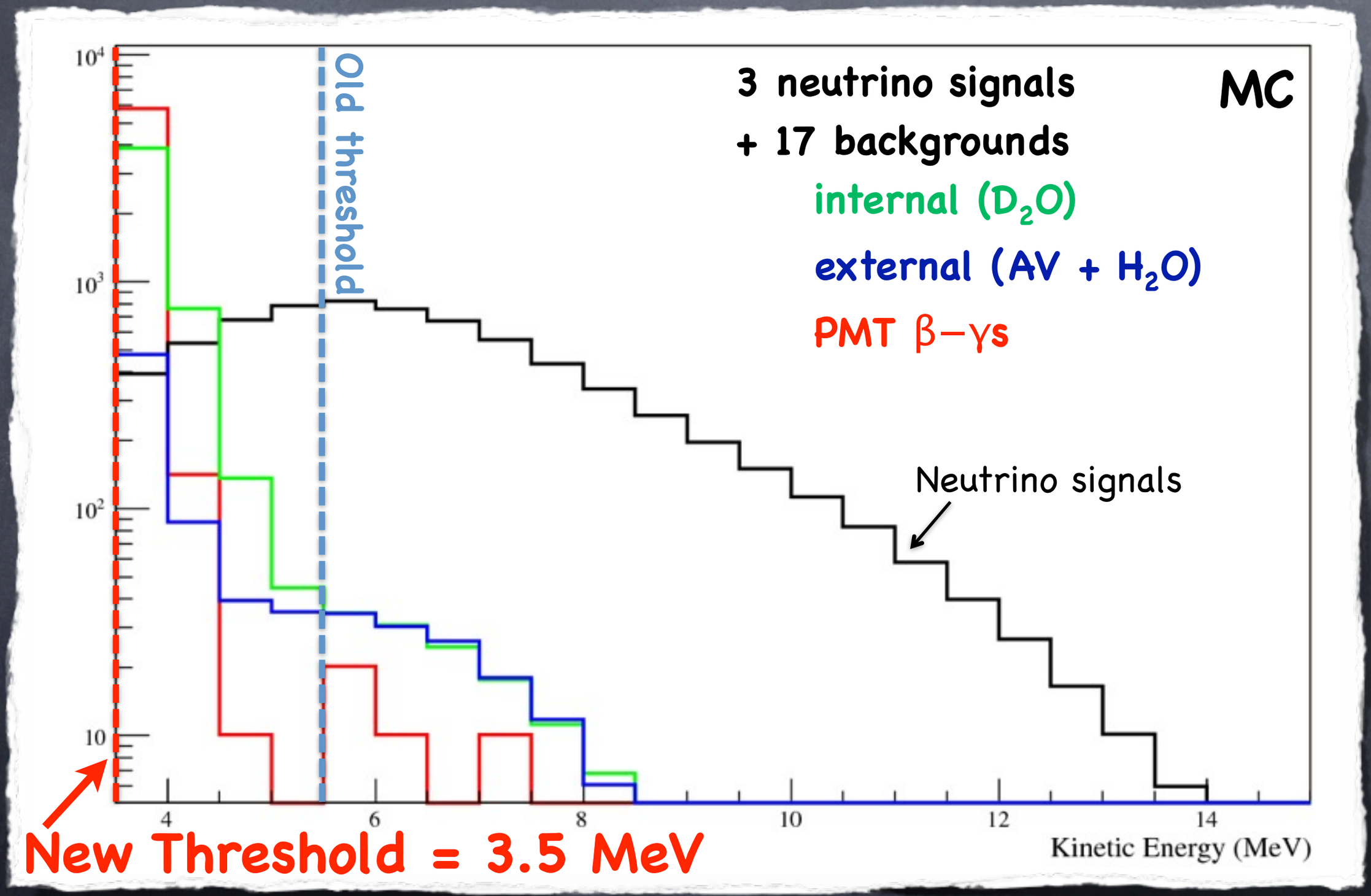
$$\zeta = \left(\cos 2\theta_{12} - \frac{a}{\Delta m^2_{12}}\right)^2 + \sin^2 2\theta_{12}$$

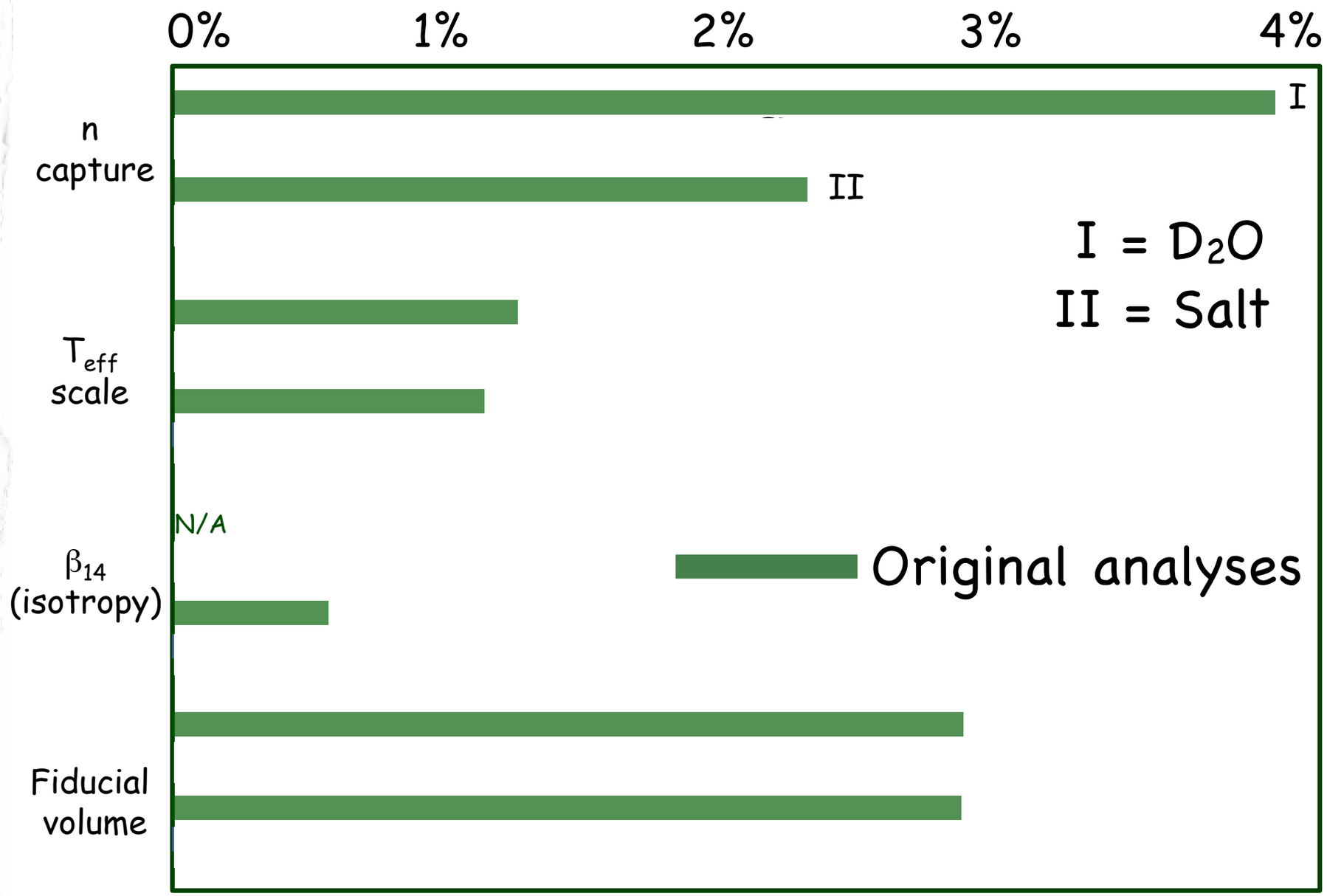
New Analysis: LETA

Low Energy Threshold Analysis



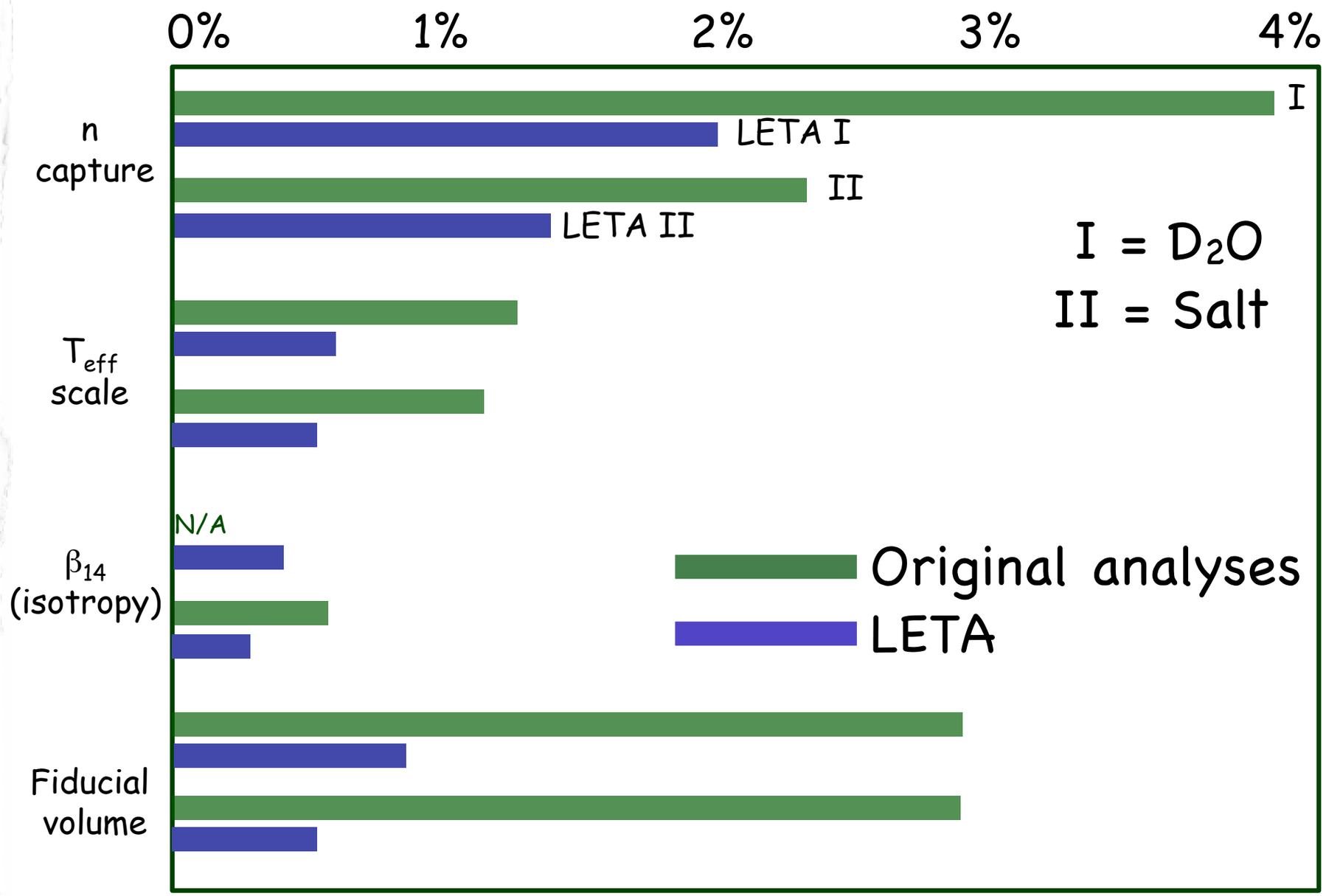
LETA

Reduced Uncertainties

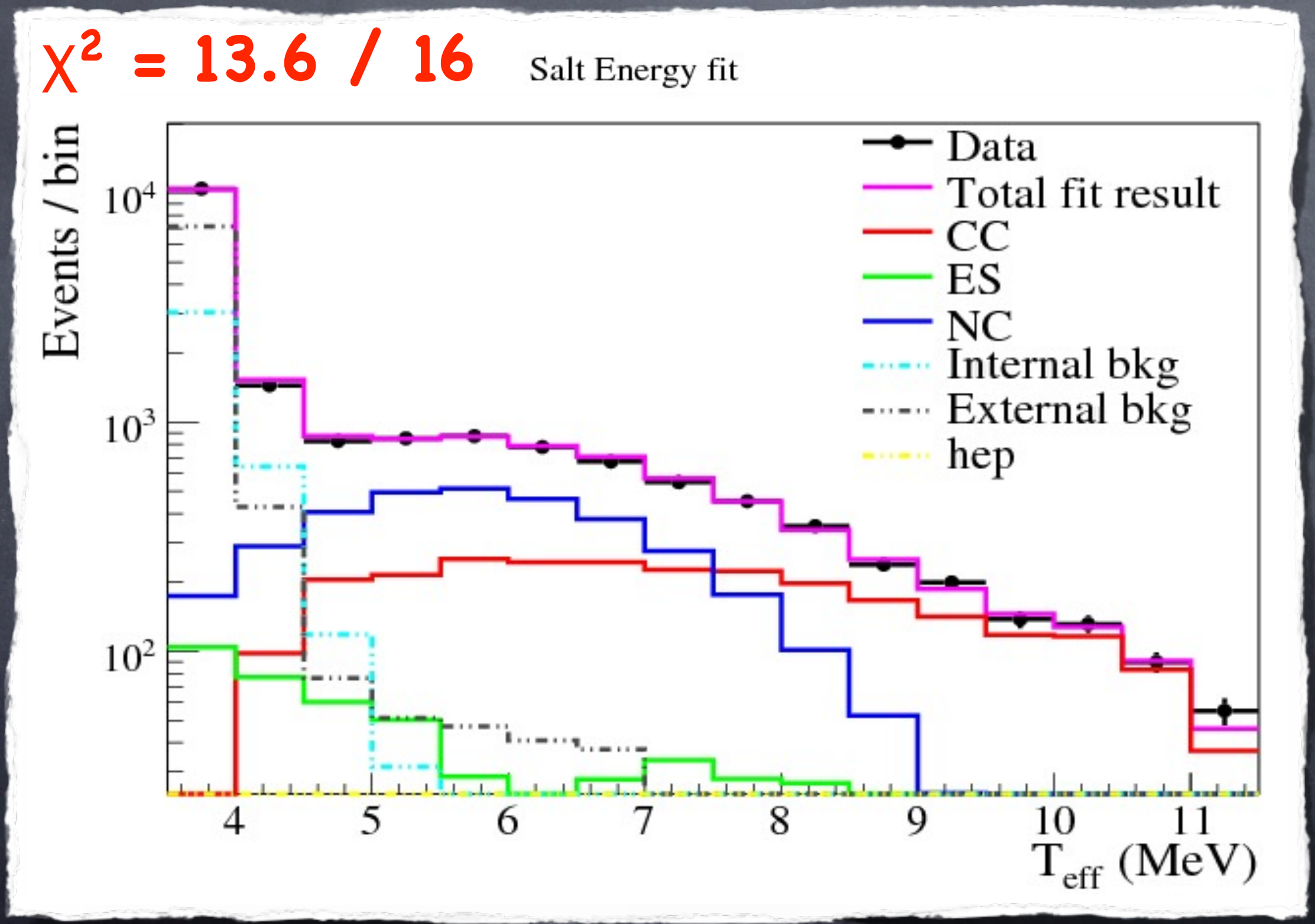


LETA

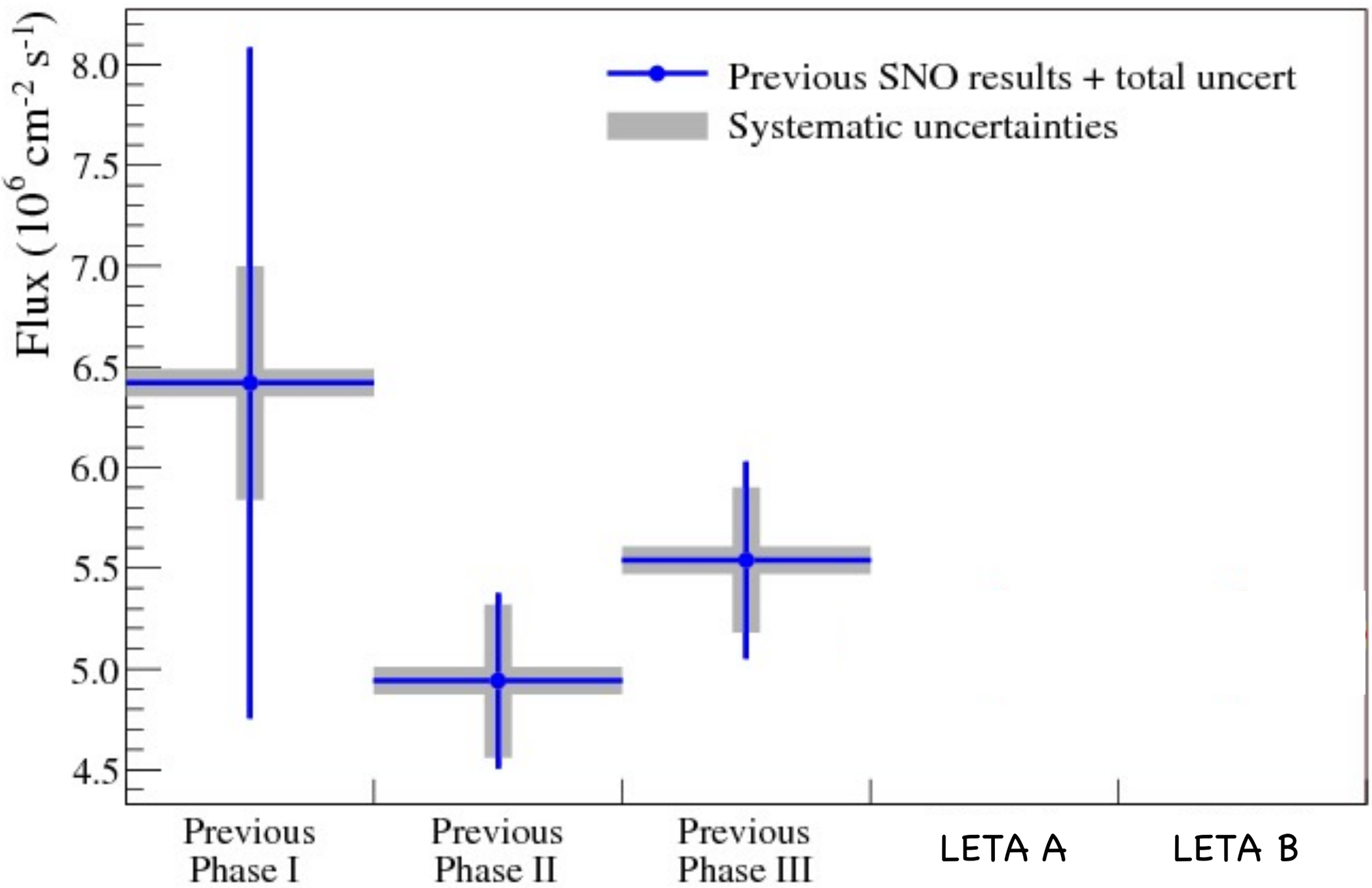
Reduced Uncertainties



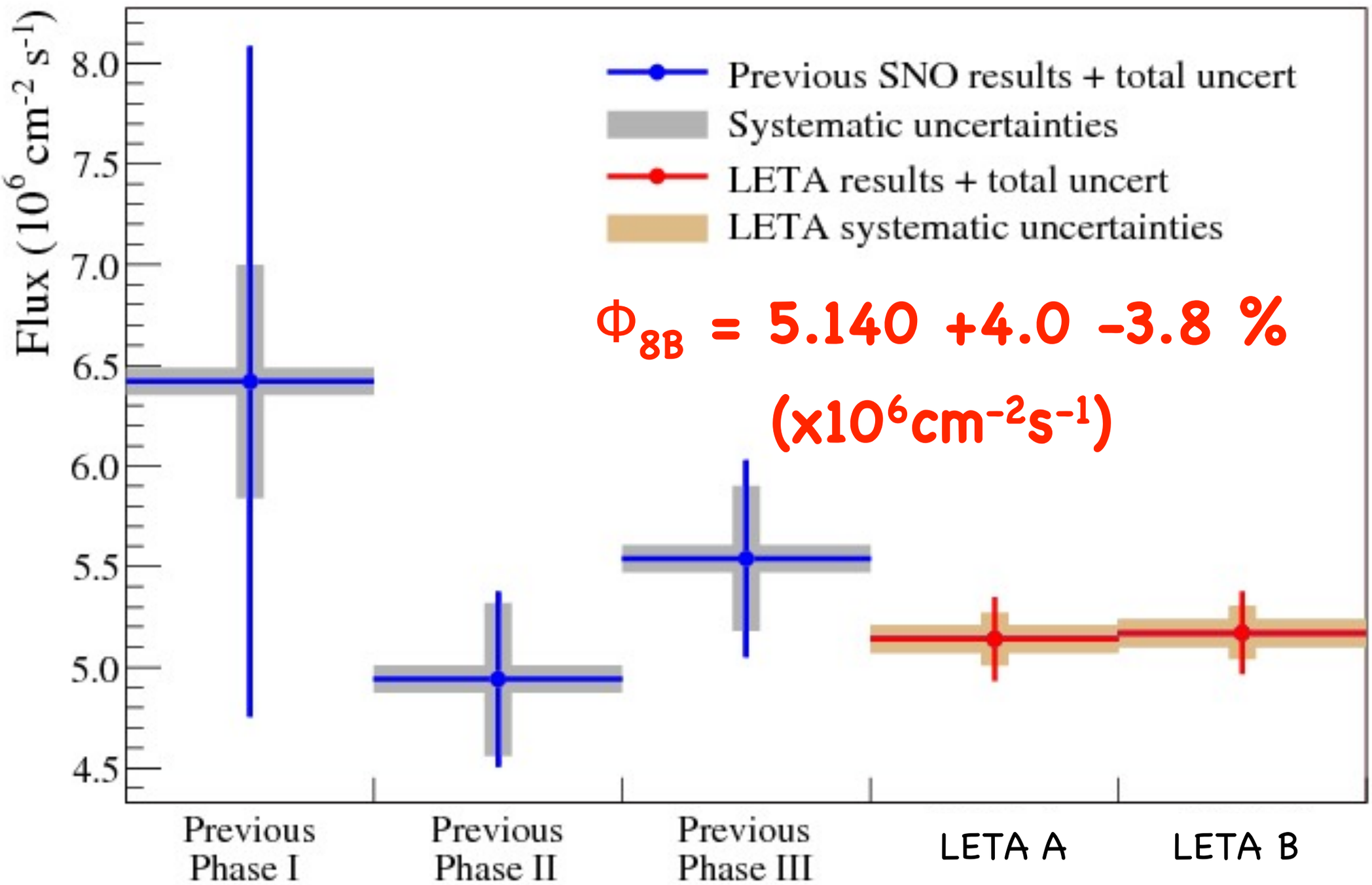
Fit Result


χ^2 = 13.6 / 16
Salt Energy fit
Events / bin
10^4
10^3
10^2
4
5
6
7
8
9
10
11
T_{eff} (MeV)
Data
Total fit result
CC
ES
NC
Internal bkg
External bkg
hep

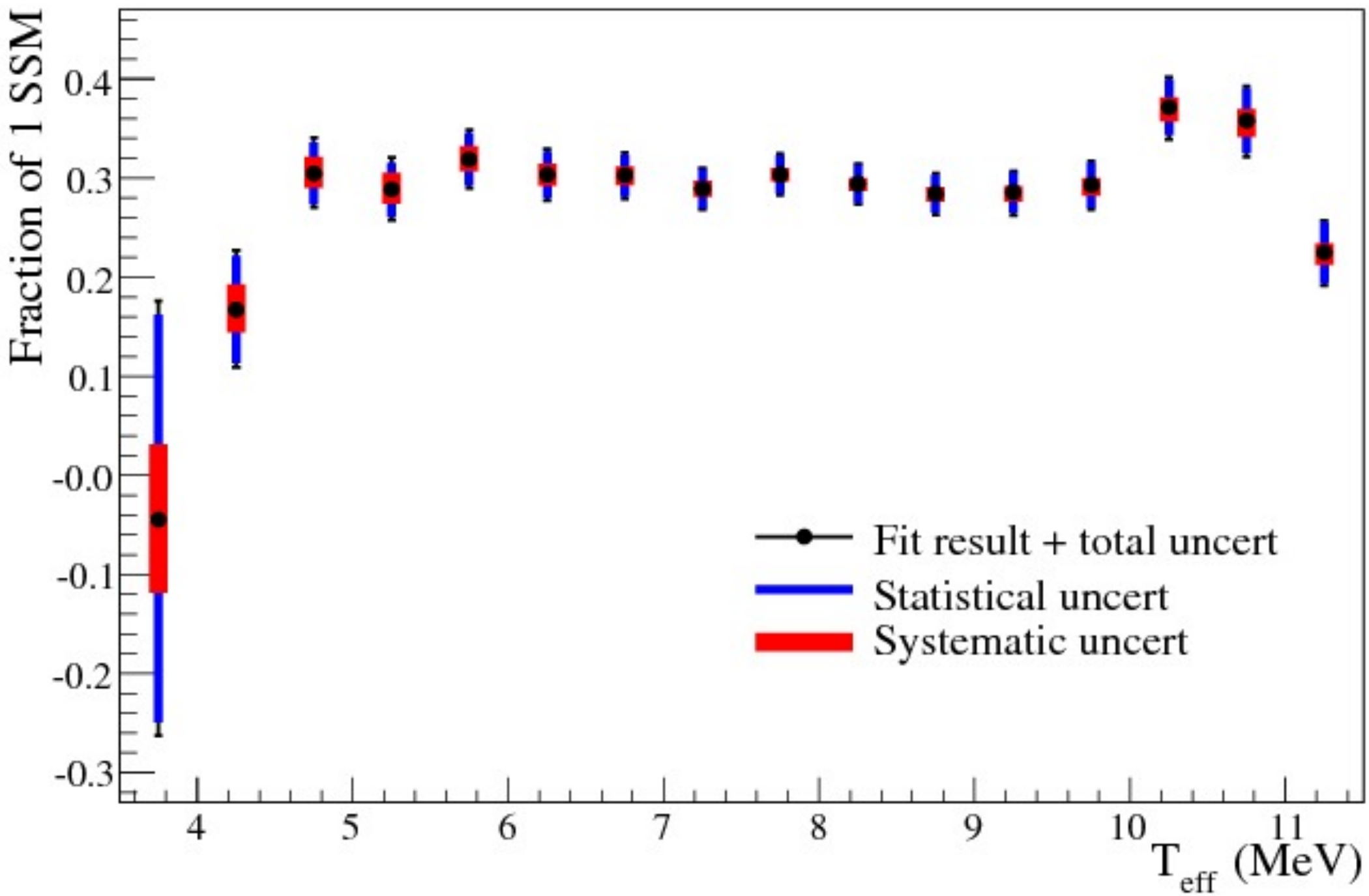
Total ^8B Neutrino Flux: ν_x



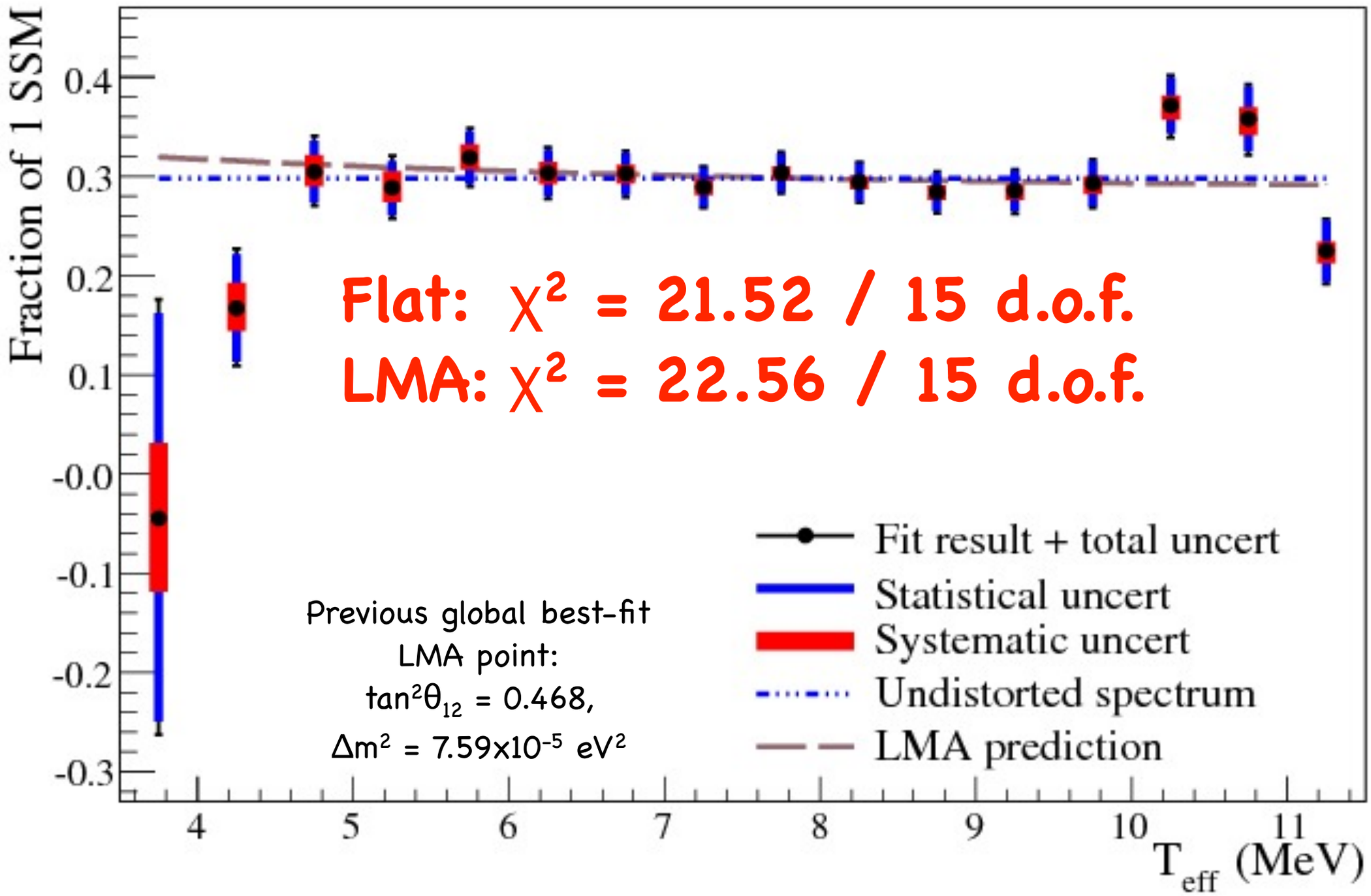
Total ^{8}B Neutrino Flux: ν_x



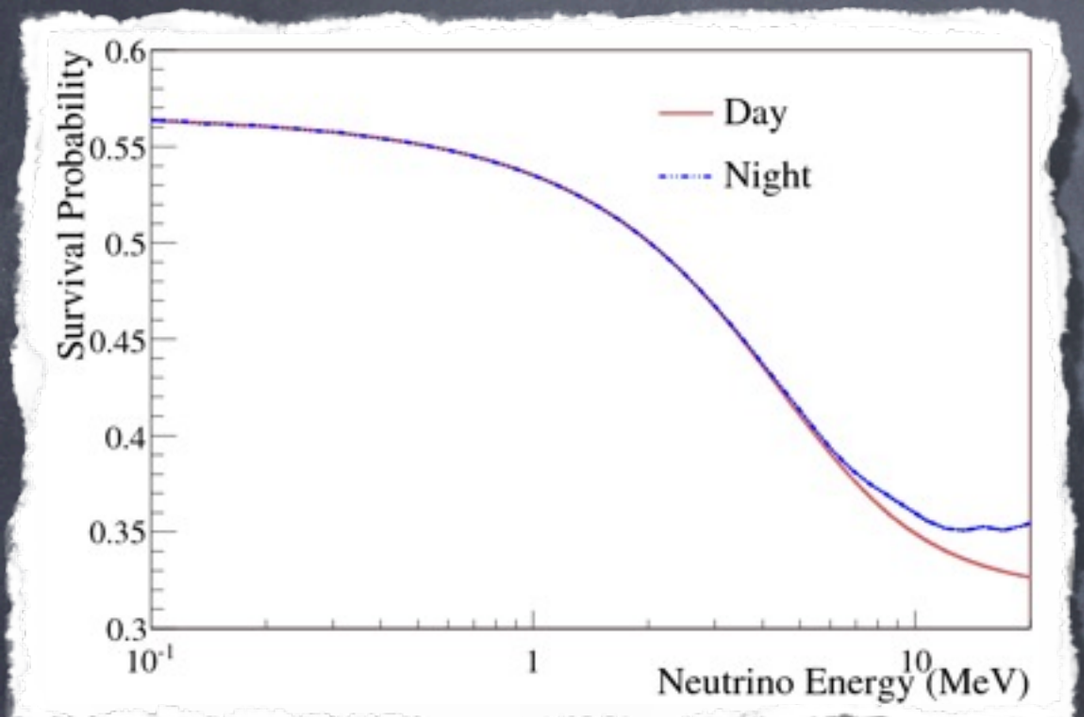
CC Recoil-Electron Spectrum

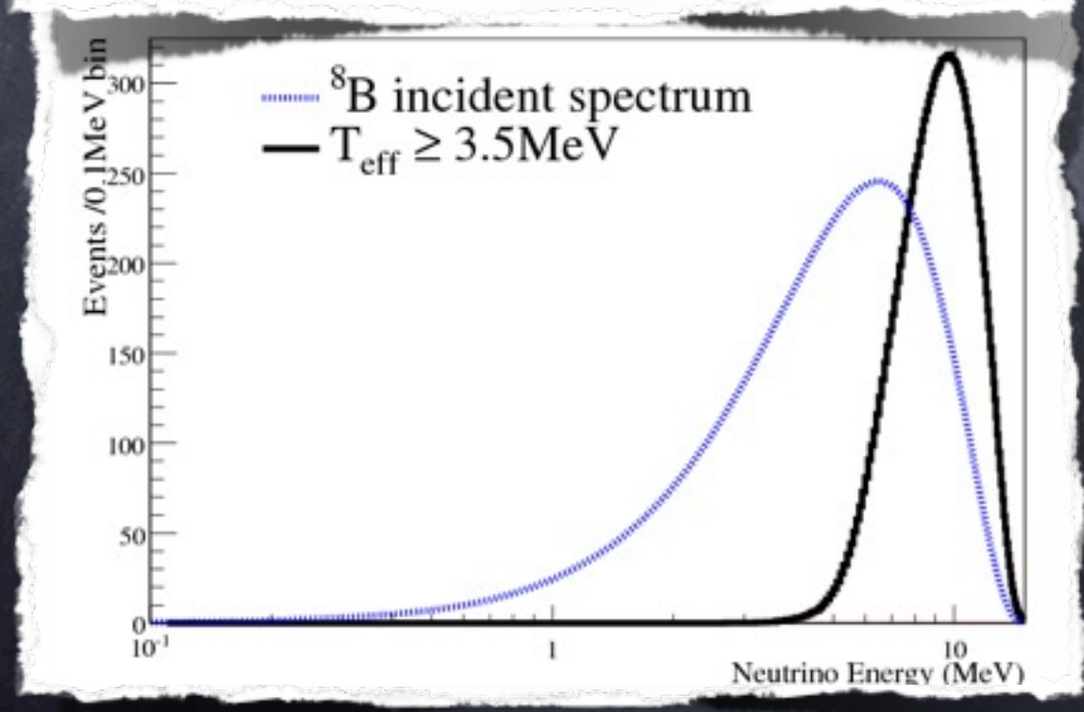


CC Recoil-Electron Spectrum



Direct Fit for Energy-Dependent Survival Probability





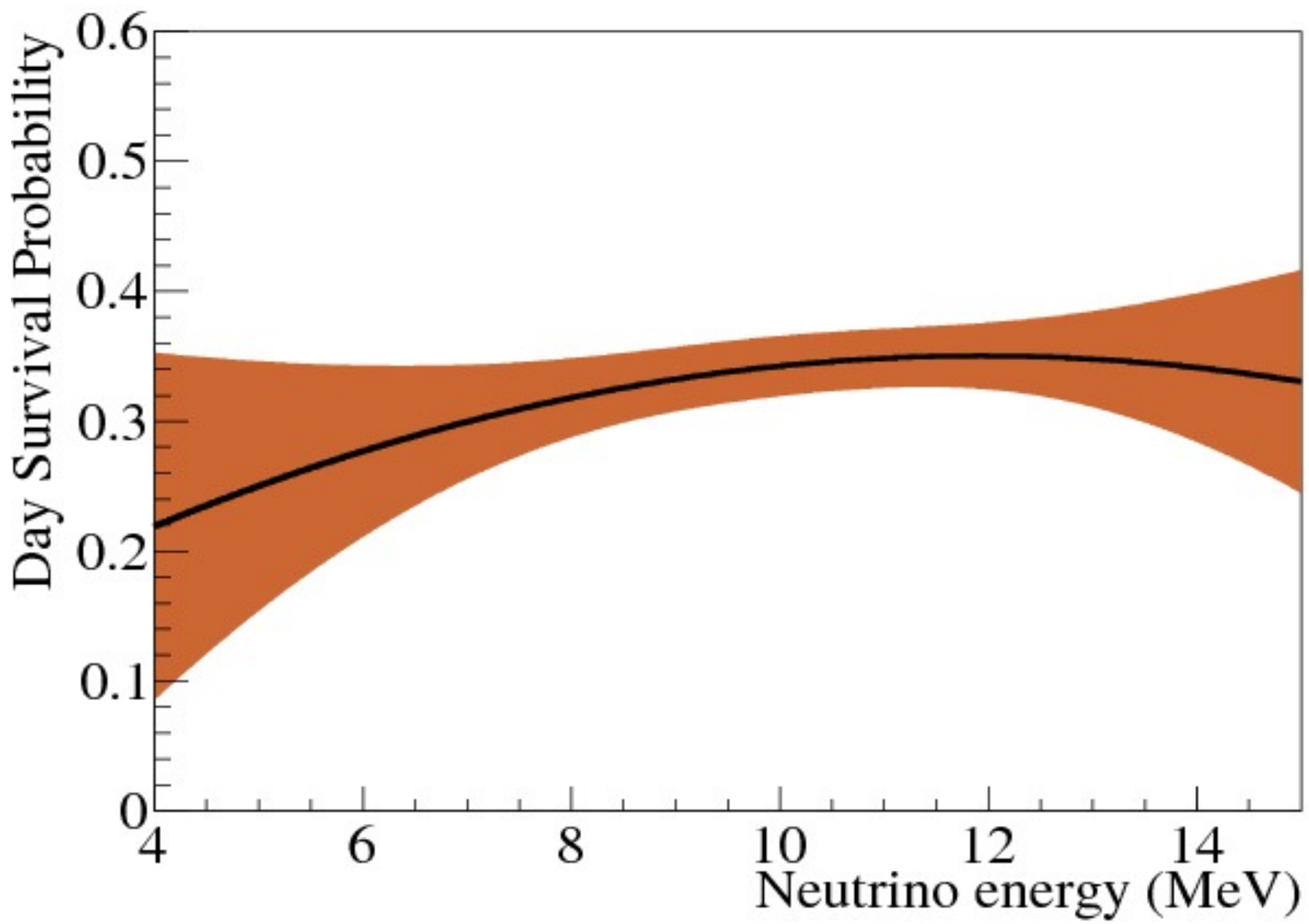
Neutrino signal directly described by 6 parameters:

1. Total ^{8}B neutrino flux

2. Quadratic expansion of ν_e P_{ee} around E_ν = 10 MeV

3. Linear expansion of day/night asymmetry around E_ν = 10 MeV

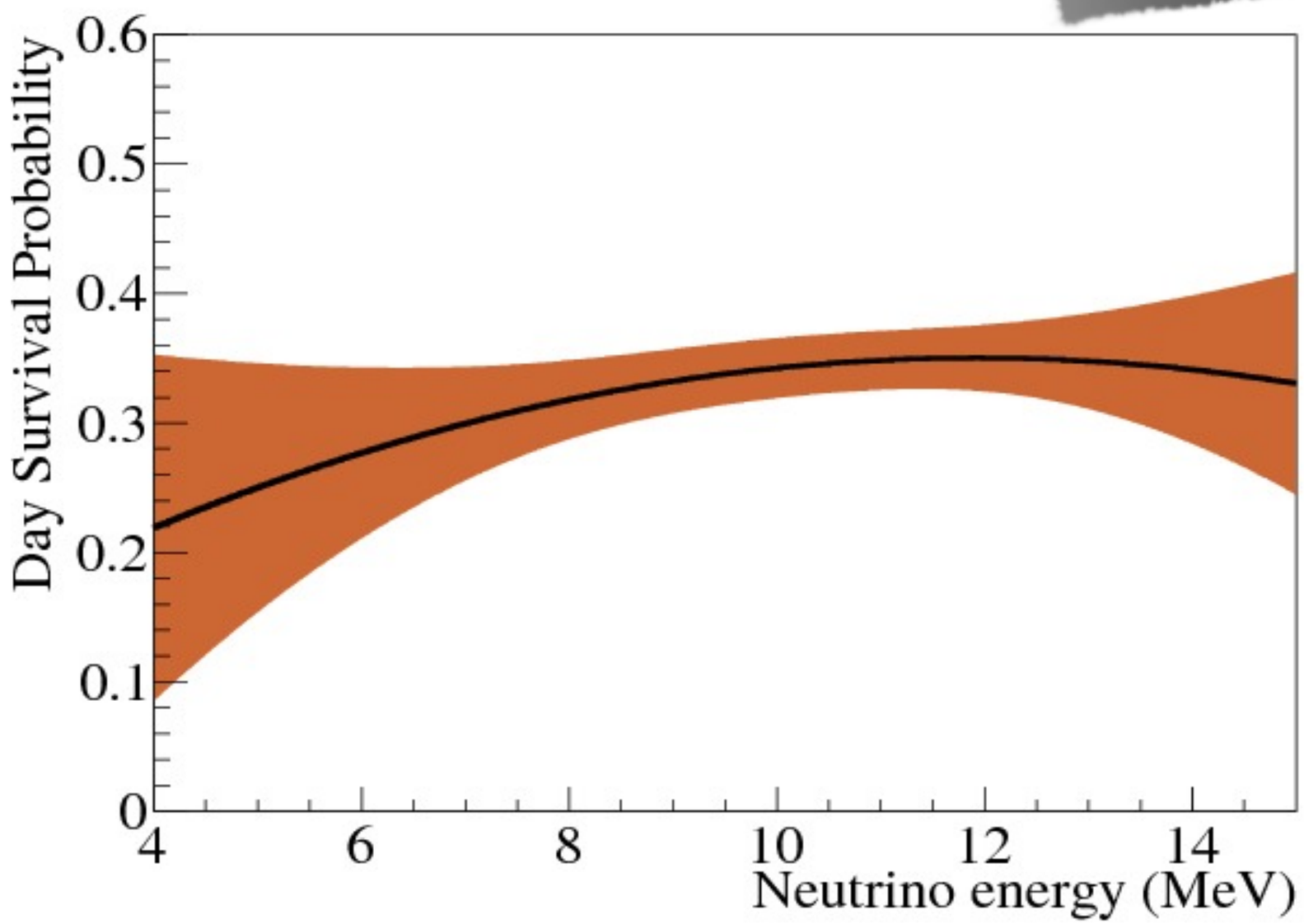
Direct Fit for Energy-Dep P_{ee}



Direct Fit for Energy-Dep P_{ee}

No distortion, no a/s:

$\Delta\chi^2$ = 1.94 / 4 d.o.f.



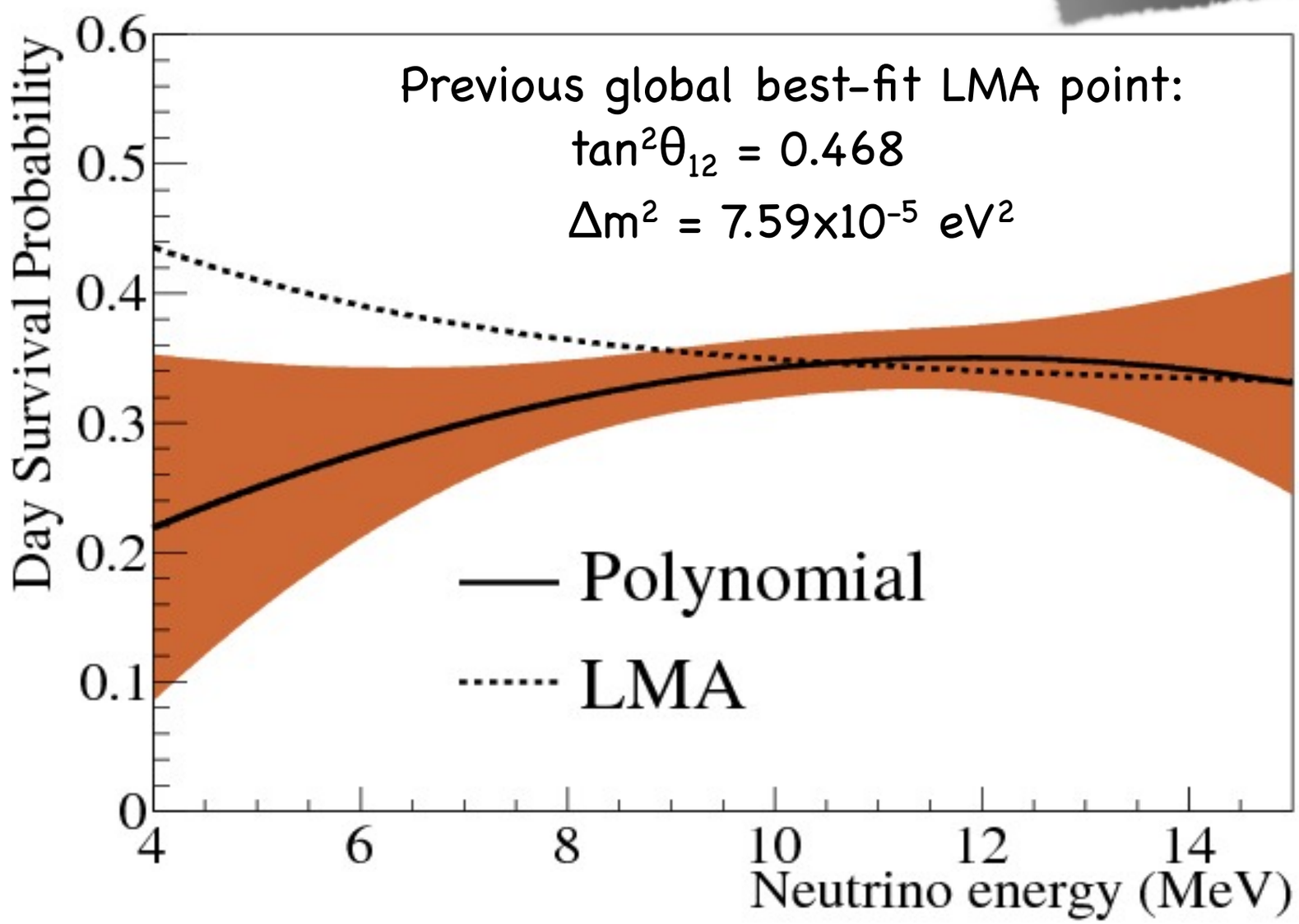
Direct Fit for Energy-Dep P_{ee}

No distortion, no a/s:

$\Delta\chi^2$ = 1.94 / 4 d.o.f.

LMA Prediction:

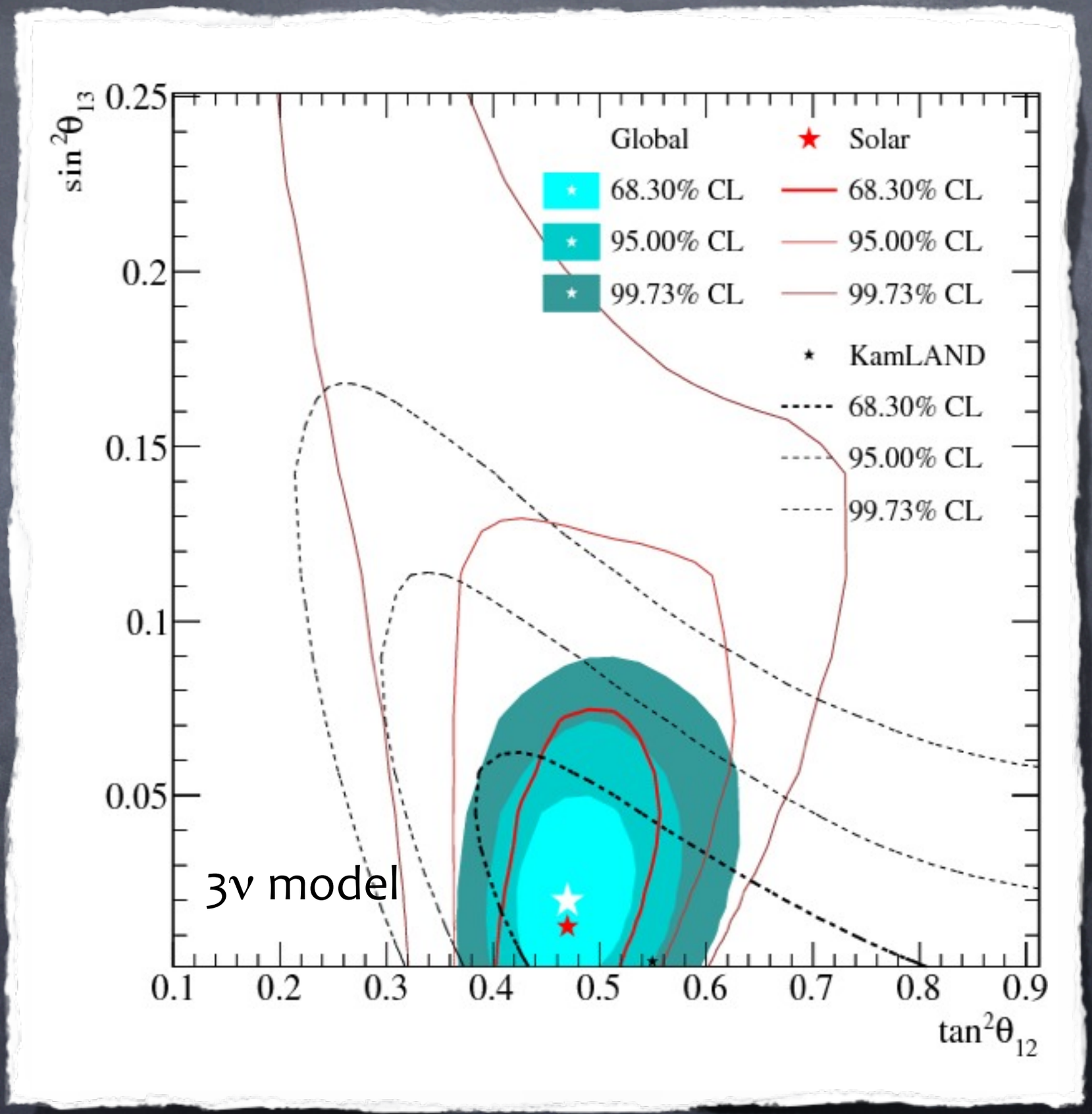
$\Delta\chi^2$ = 3.90 / 4 d.o.f.



Solar + KamLAND: 3 flavour

LETA paper 2010:
LETA joint-phase fit
+ Phase III
+ all Solar expts
+ KamLAND

3 flavour overlay



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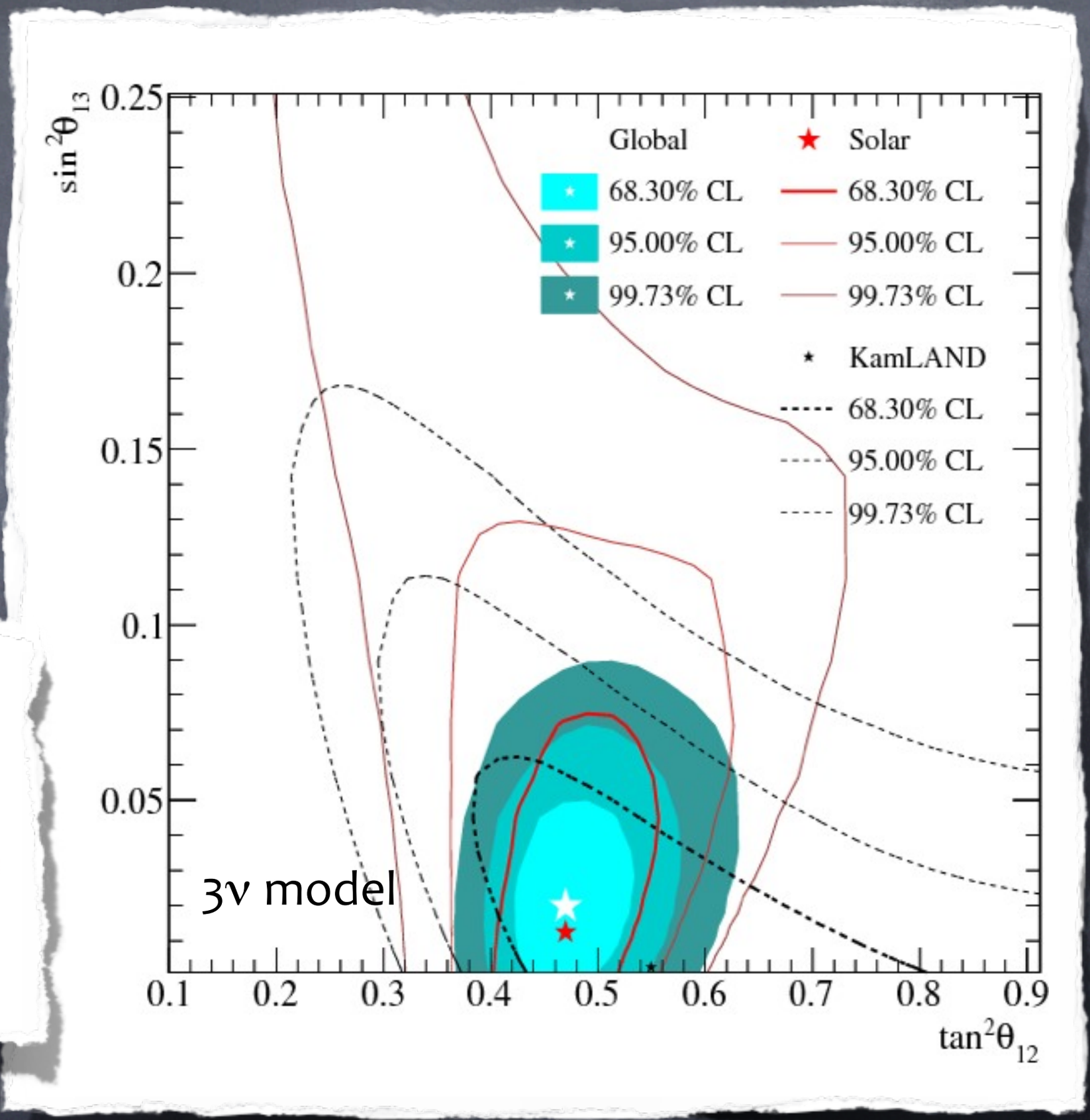


Global 3ν best fit:

$\tan^2\theta_{12} = 0.468\ ^{+0.042}_{-0.033}$

$\sin^2\theta_{13} = 2.00\ ^{+2.09}_{-1.63} \times 10^{-3}$

or

$\sin^2\theta_{13} < 0.057$ (95% CL)

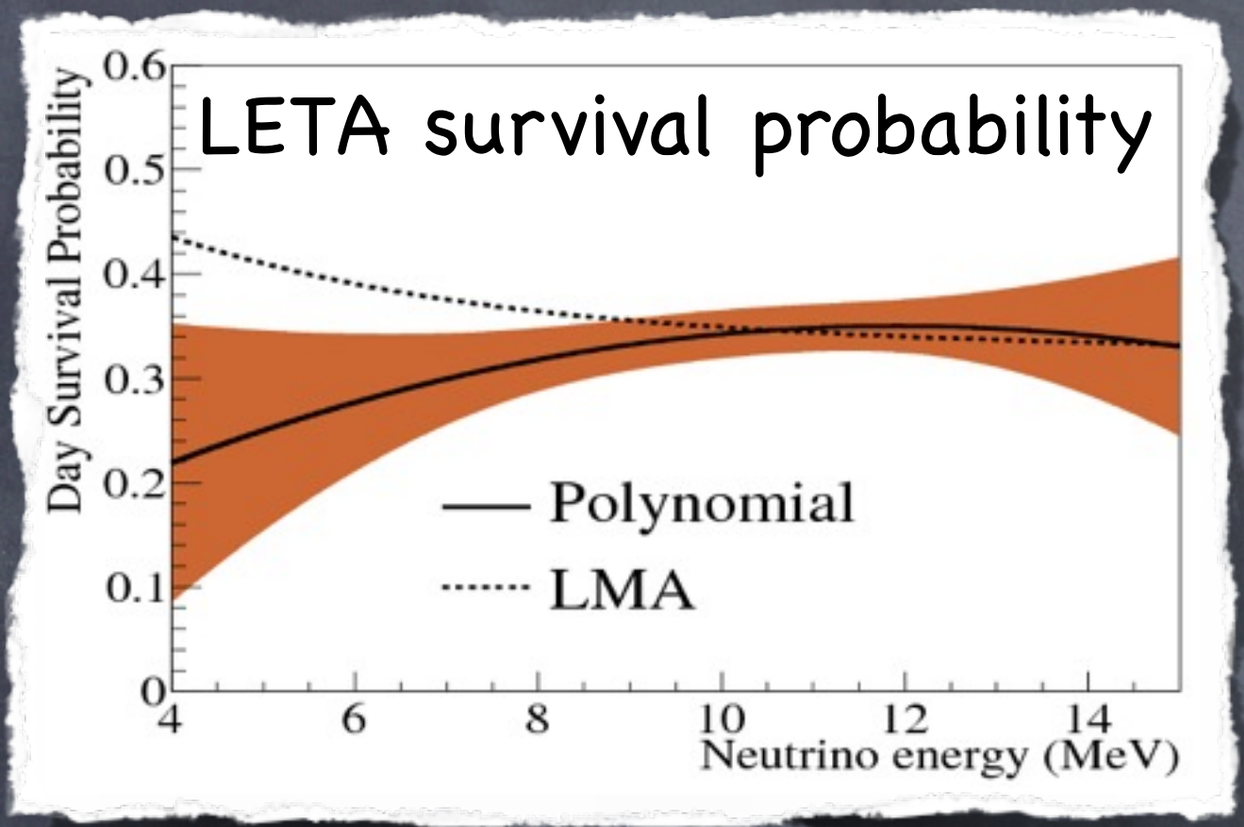
LETA Paper

Published May 2010, Phys. Rev. C

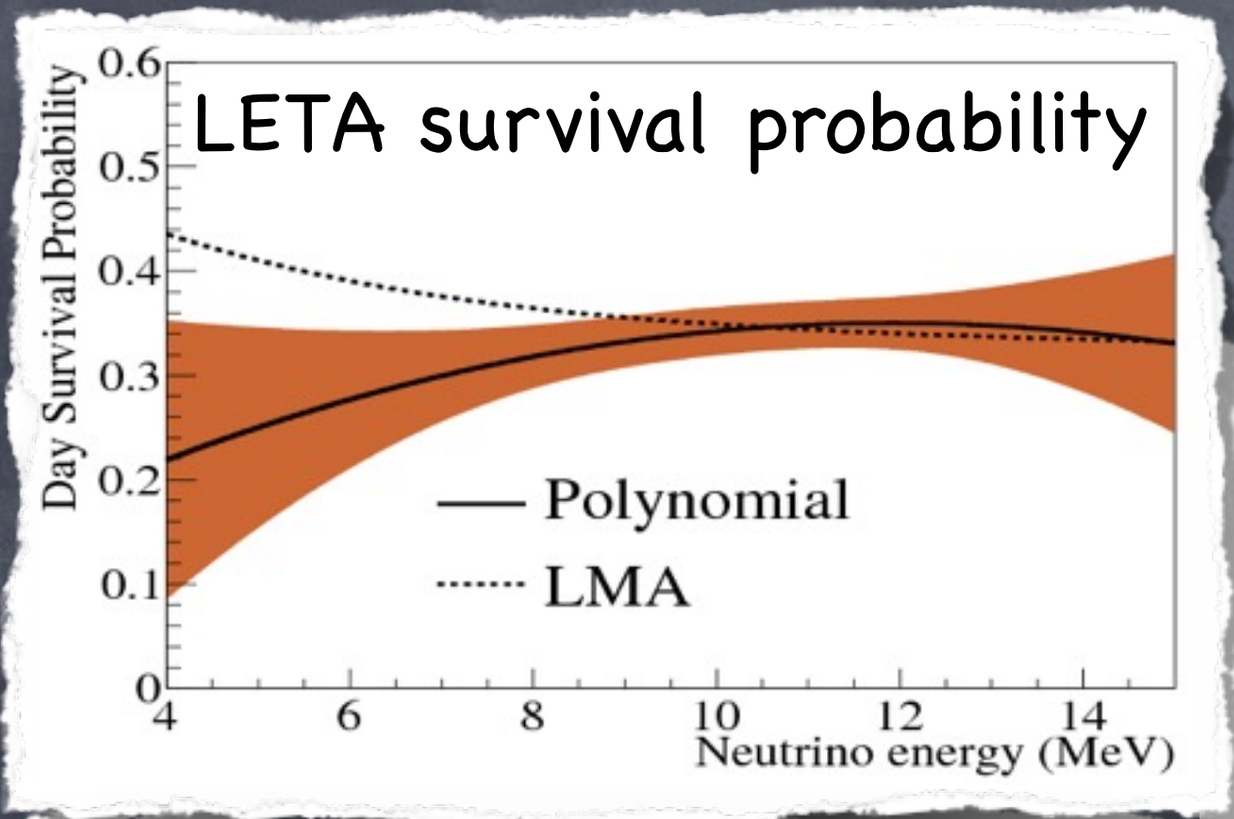
Phys. Rev. C81, 055504 (2010)
arXiv:0910.2984 [nucl-ex]

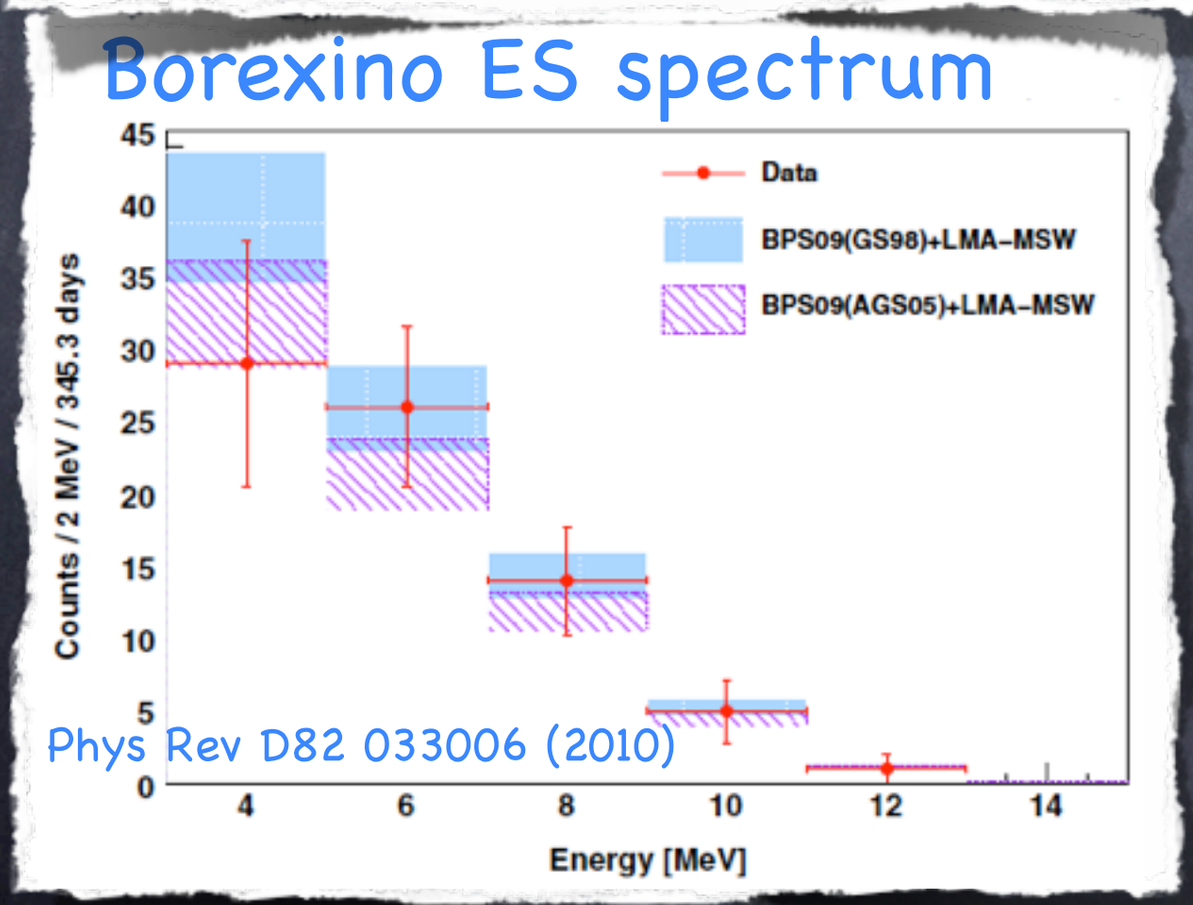
Results announced at the 2009 Neutrino Champagne conference in Reims, France.

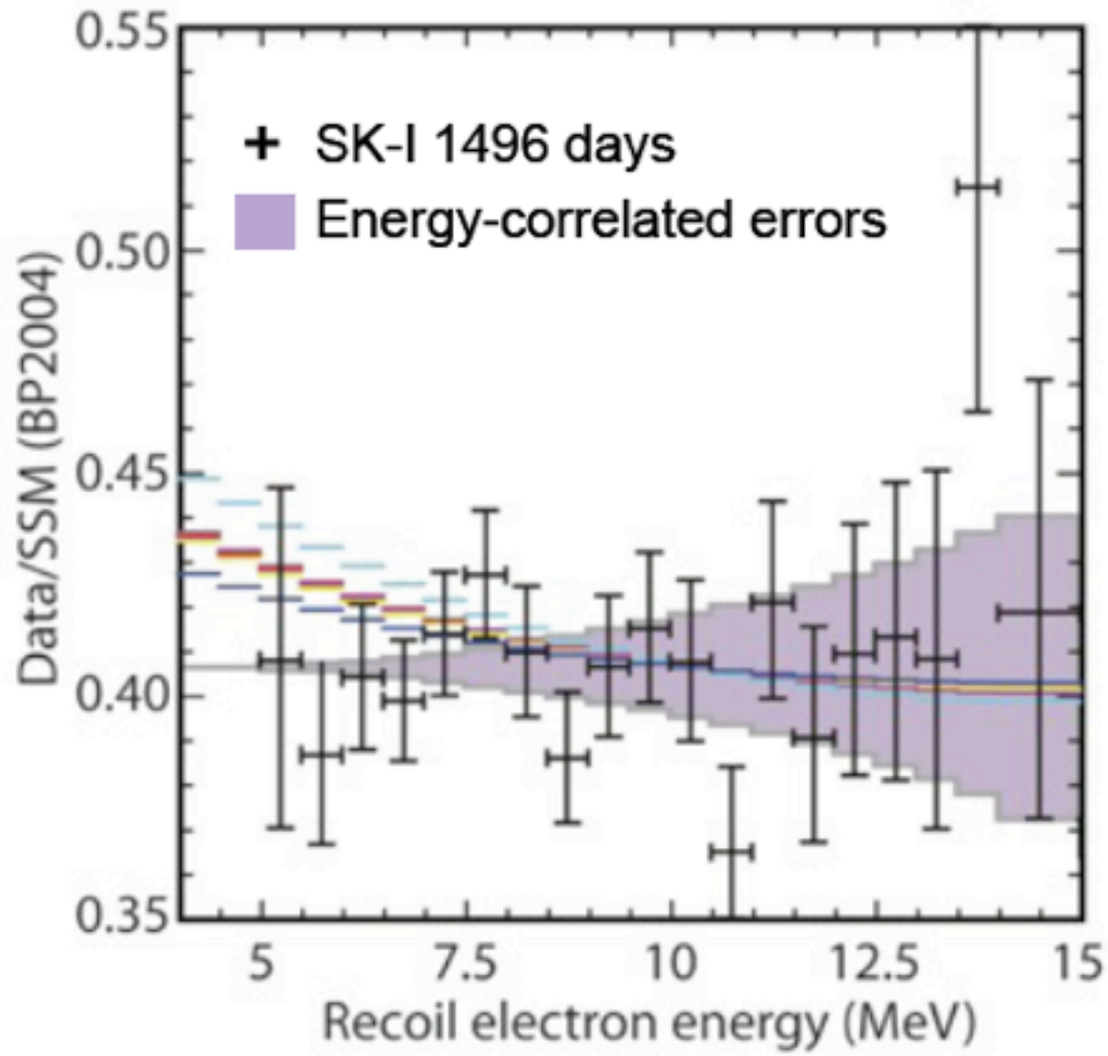
Where do we Stand?



Where do we Stand?

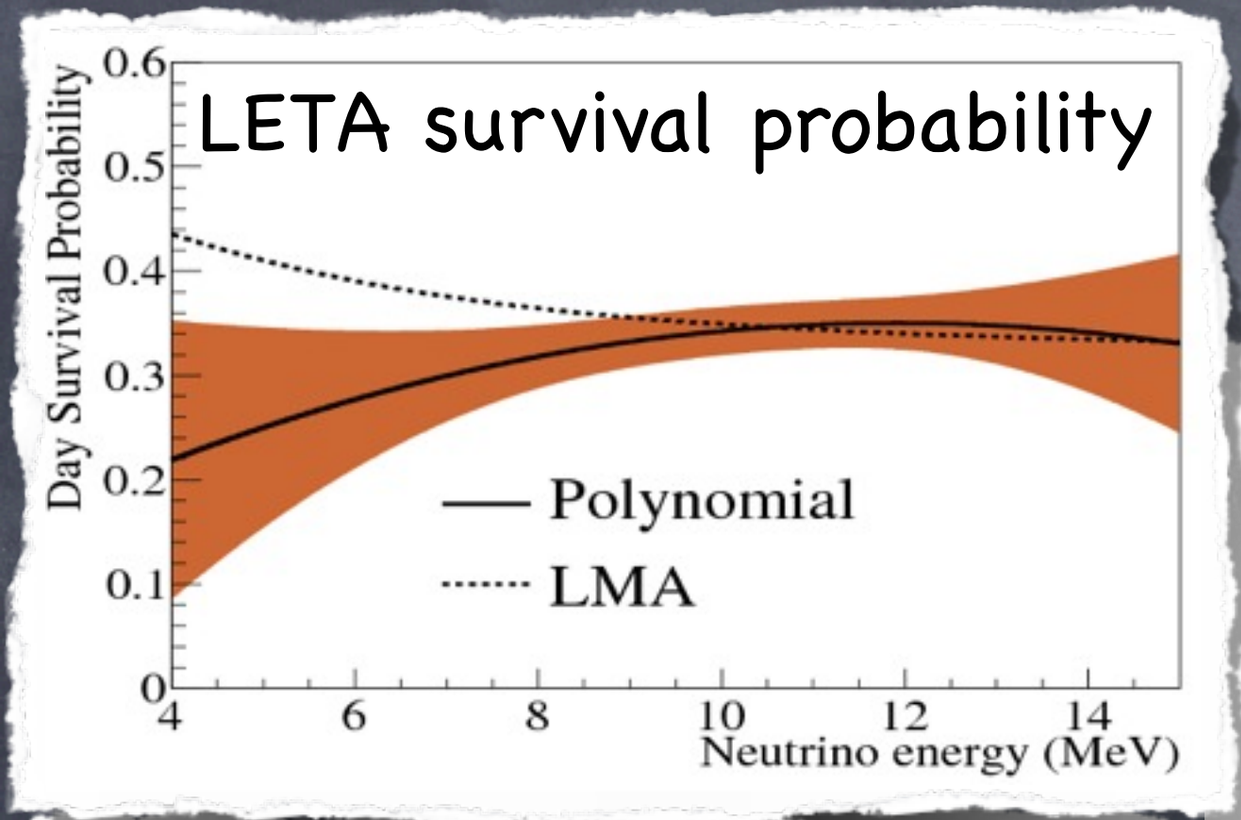




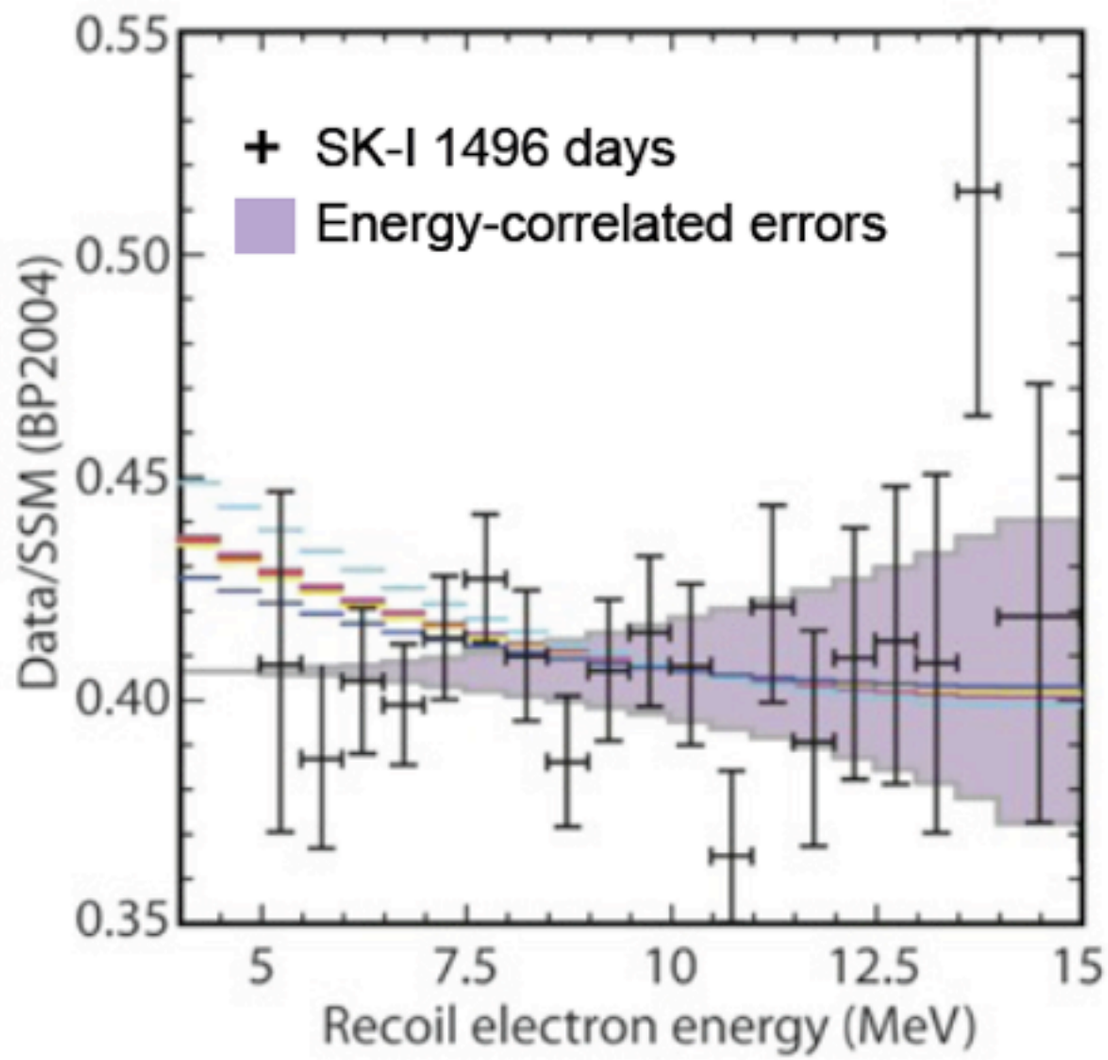


J.L. Raaf, Boston University

Where do we Stand?

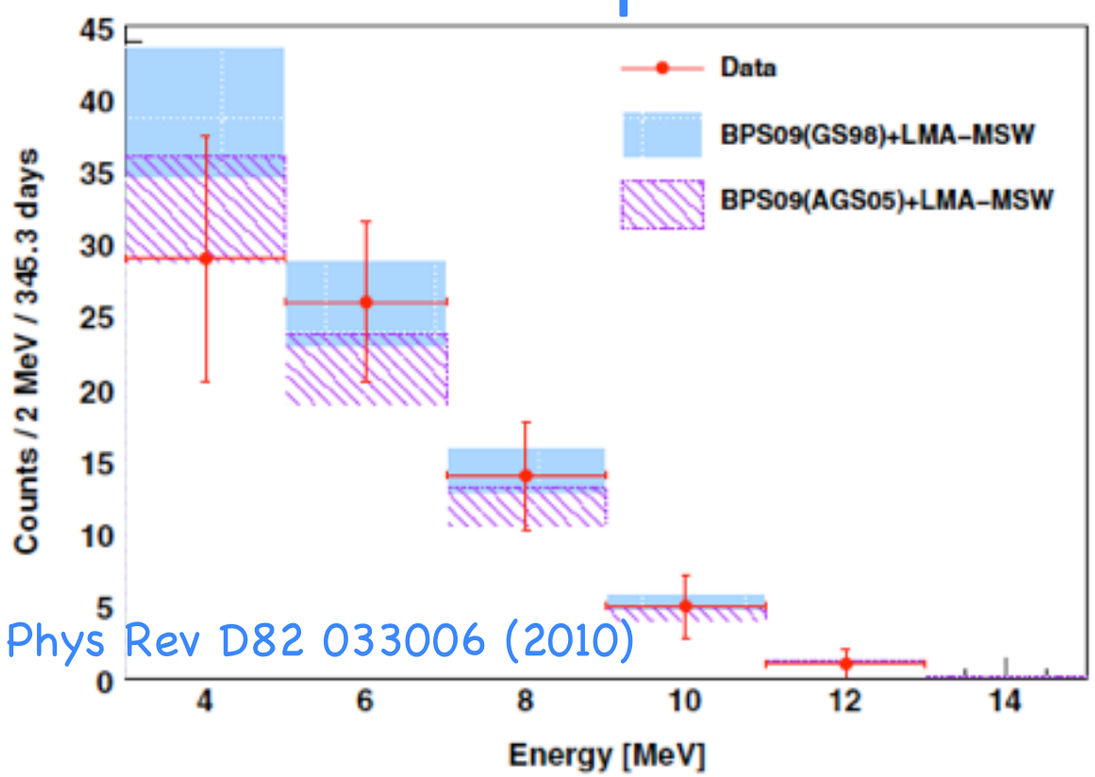


Still to find evidence for MSW rise



J.L. Raaf, Boston University

Borexino ES spectrum



Phys Rev D82 033006 (2010)

Light sterile neutrino: arXiv:1012.5627v1 [hep-ph]
Non-standard MSW dynamics: arXiv 1101.3875 [hep-ph]

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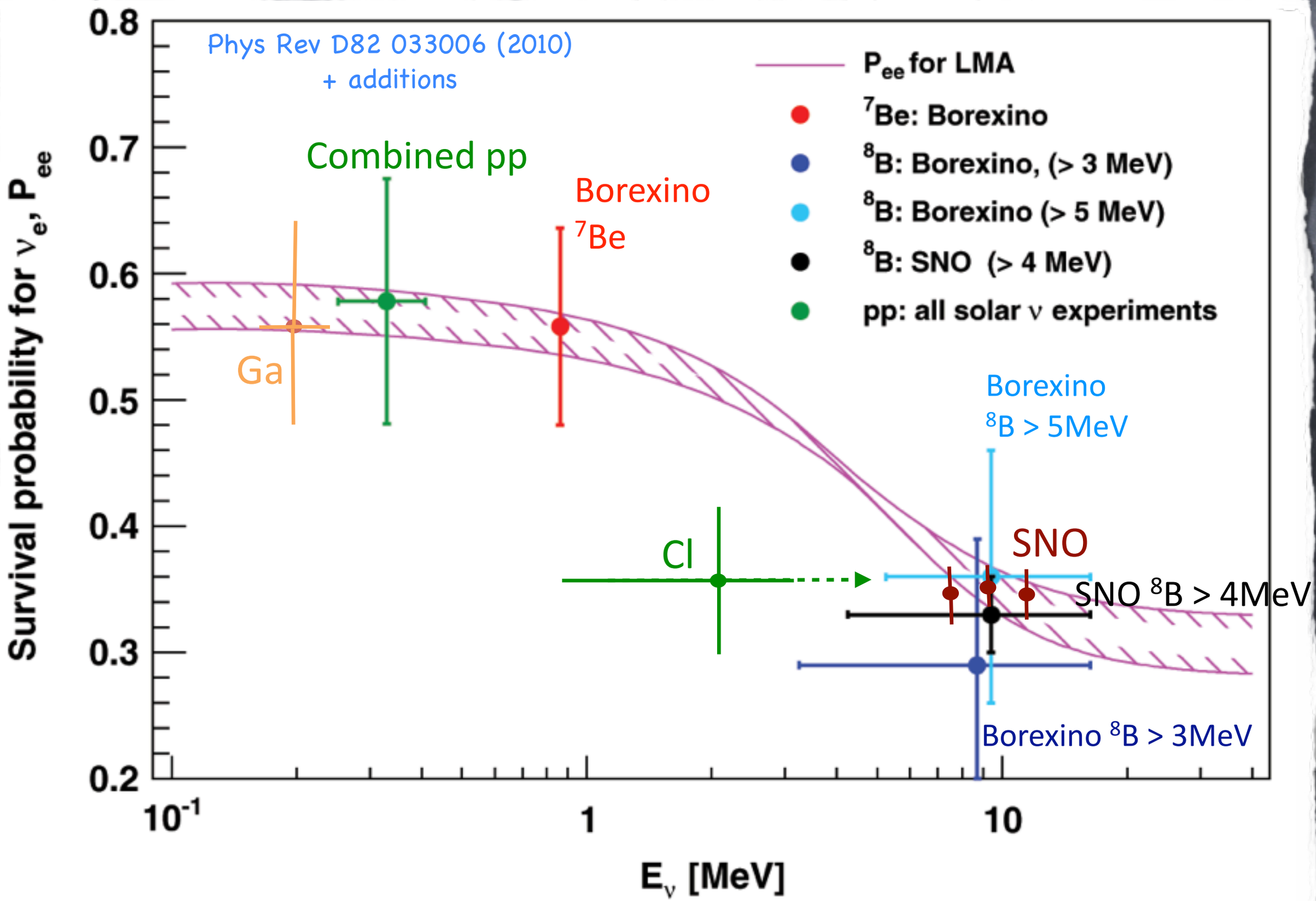

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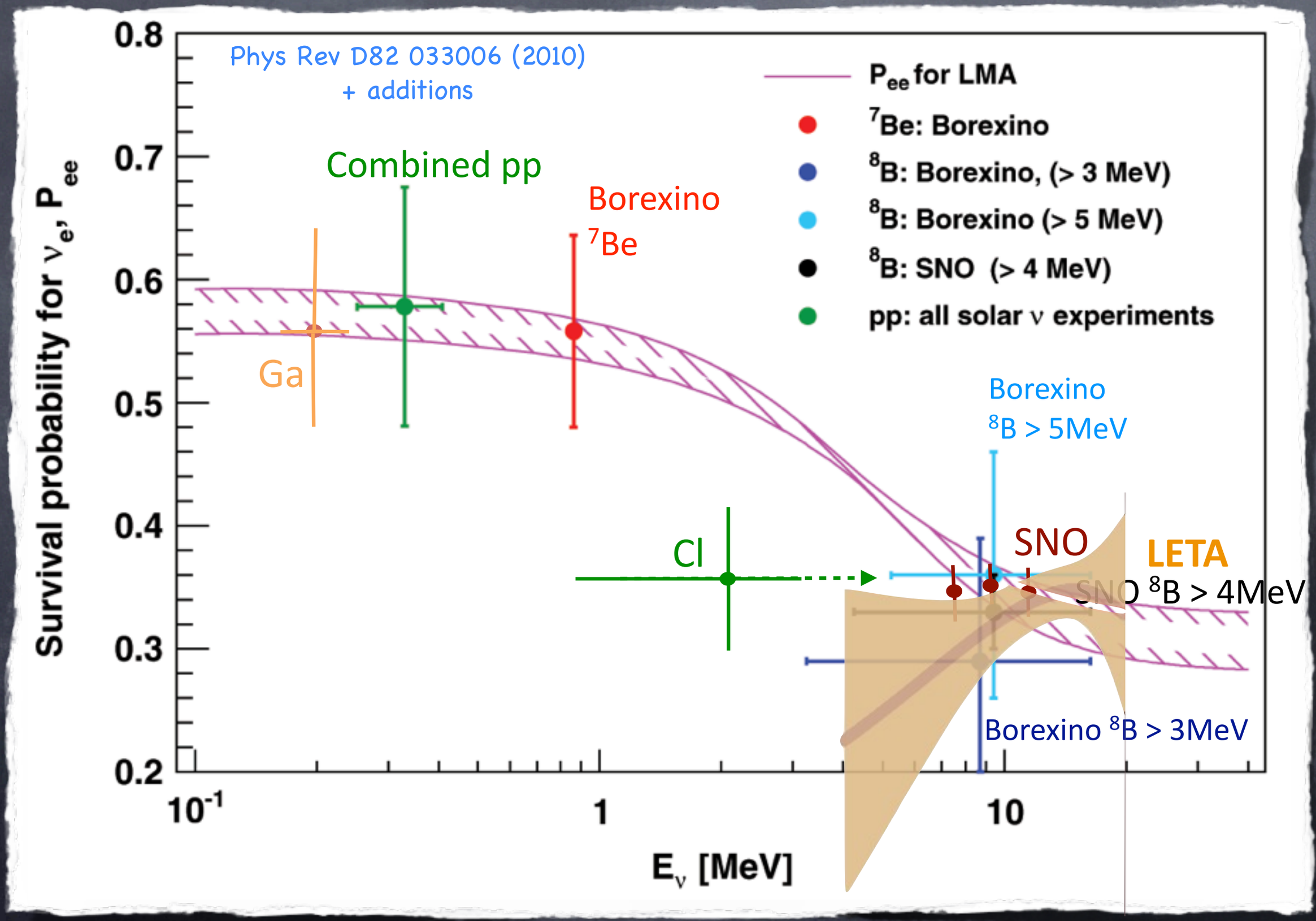
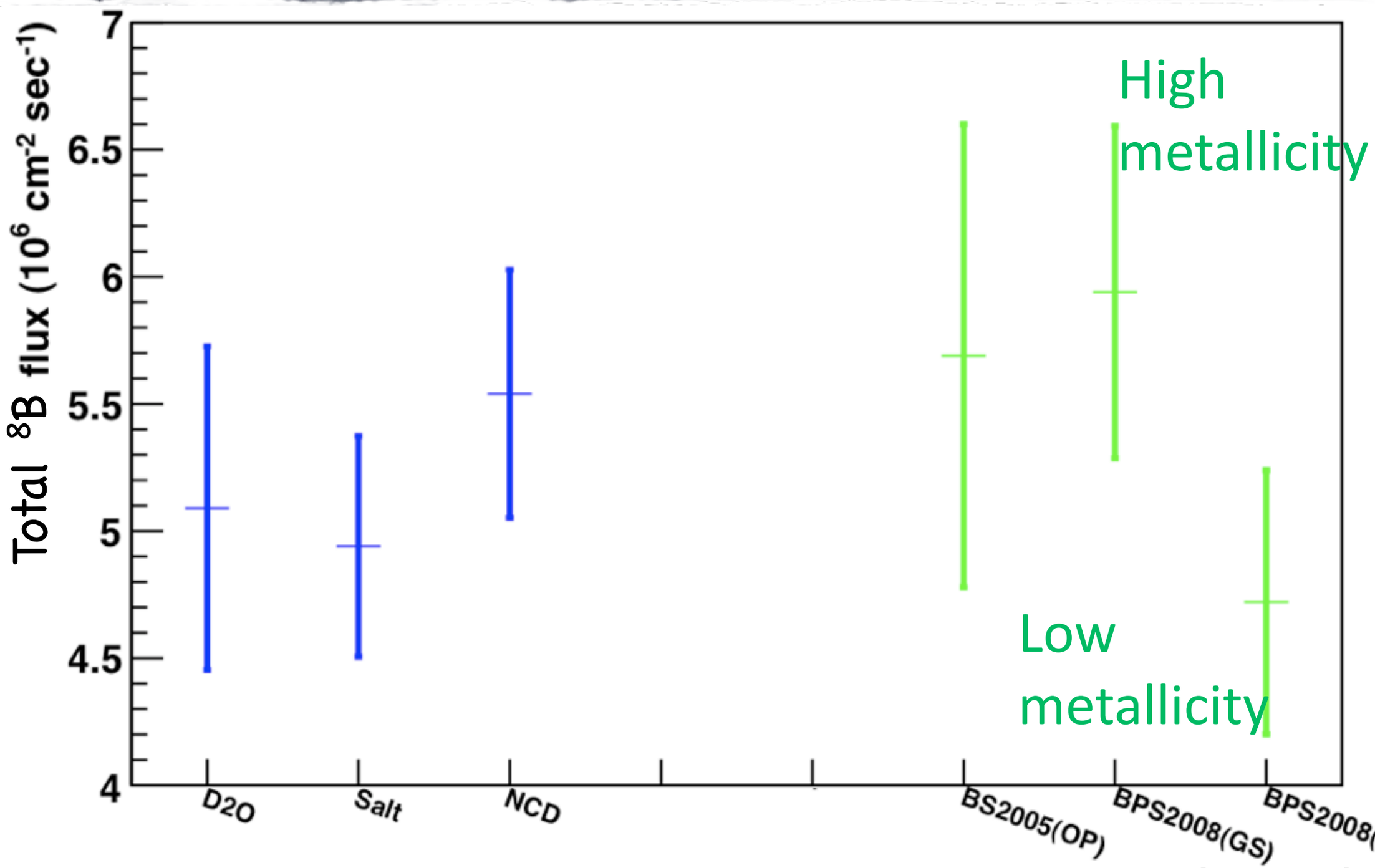


Where Do We Stand?

Understanding the Sun



Effect of mass-loss during early phases of stellar evolution: arXiv: 1103.2620 [astro-ph]

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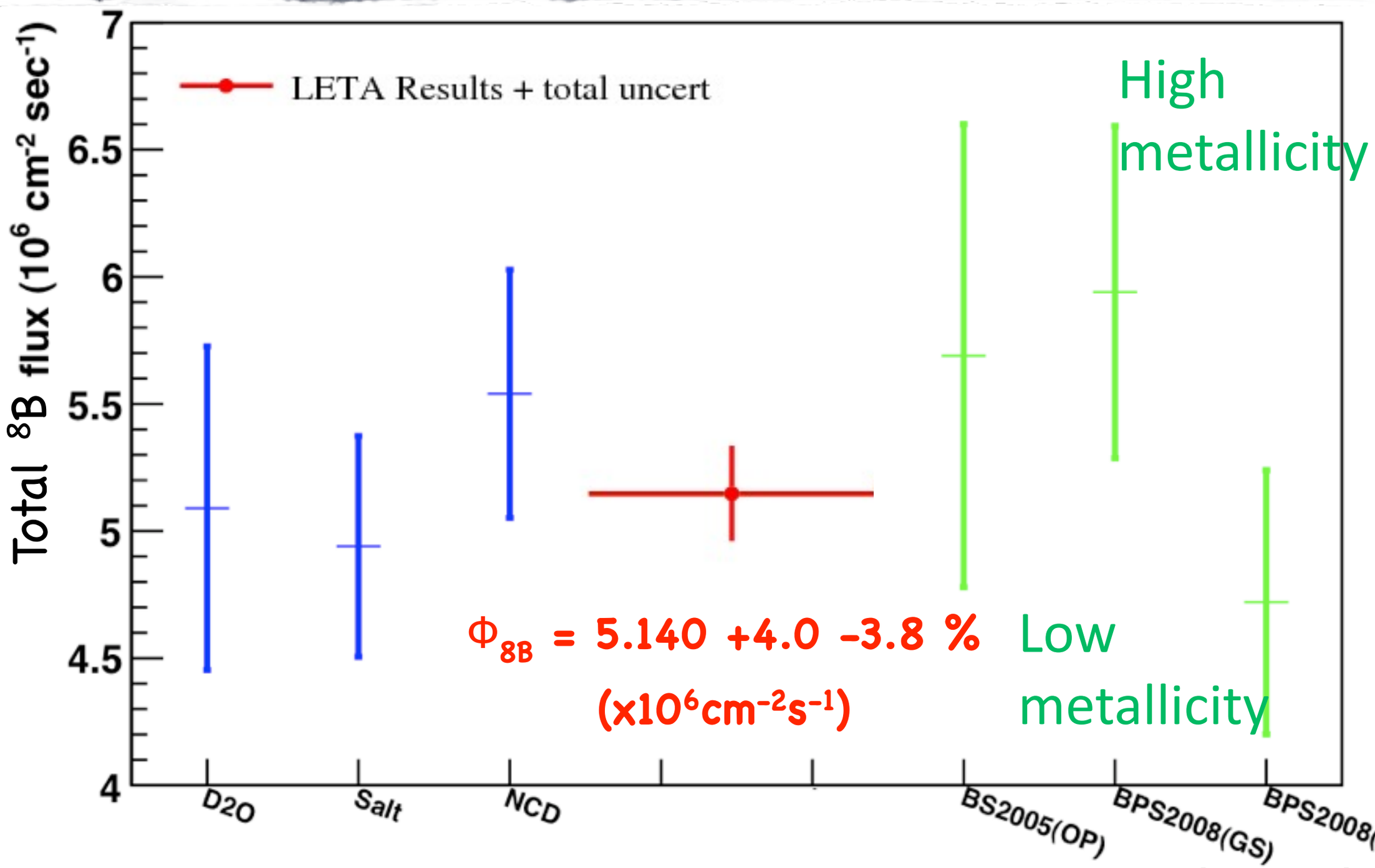

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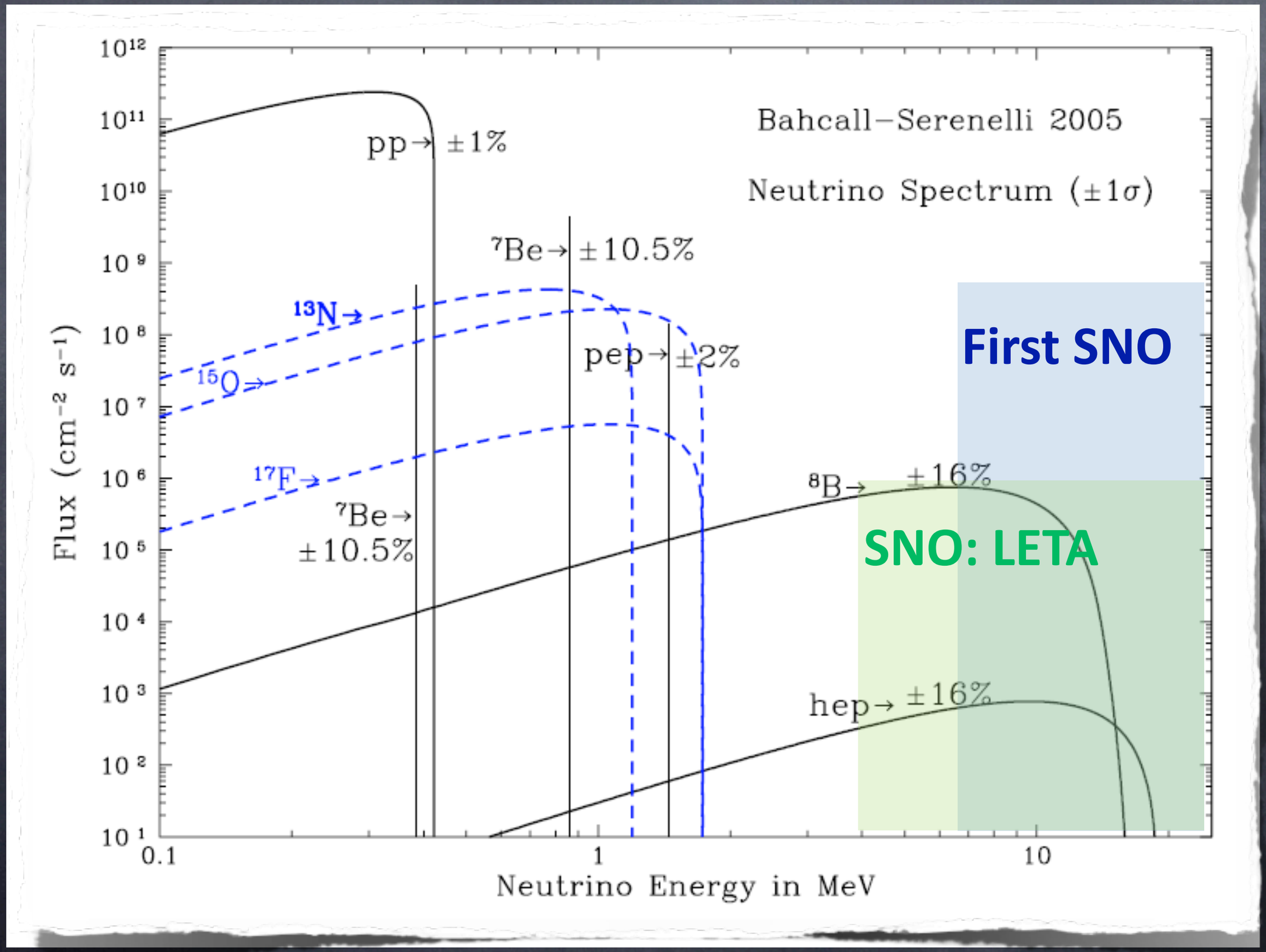
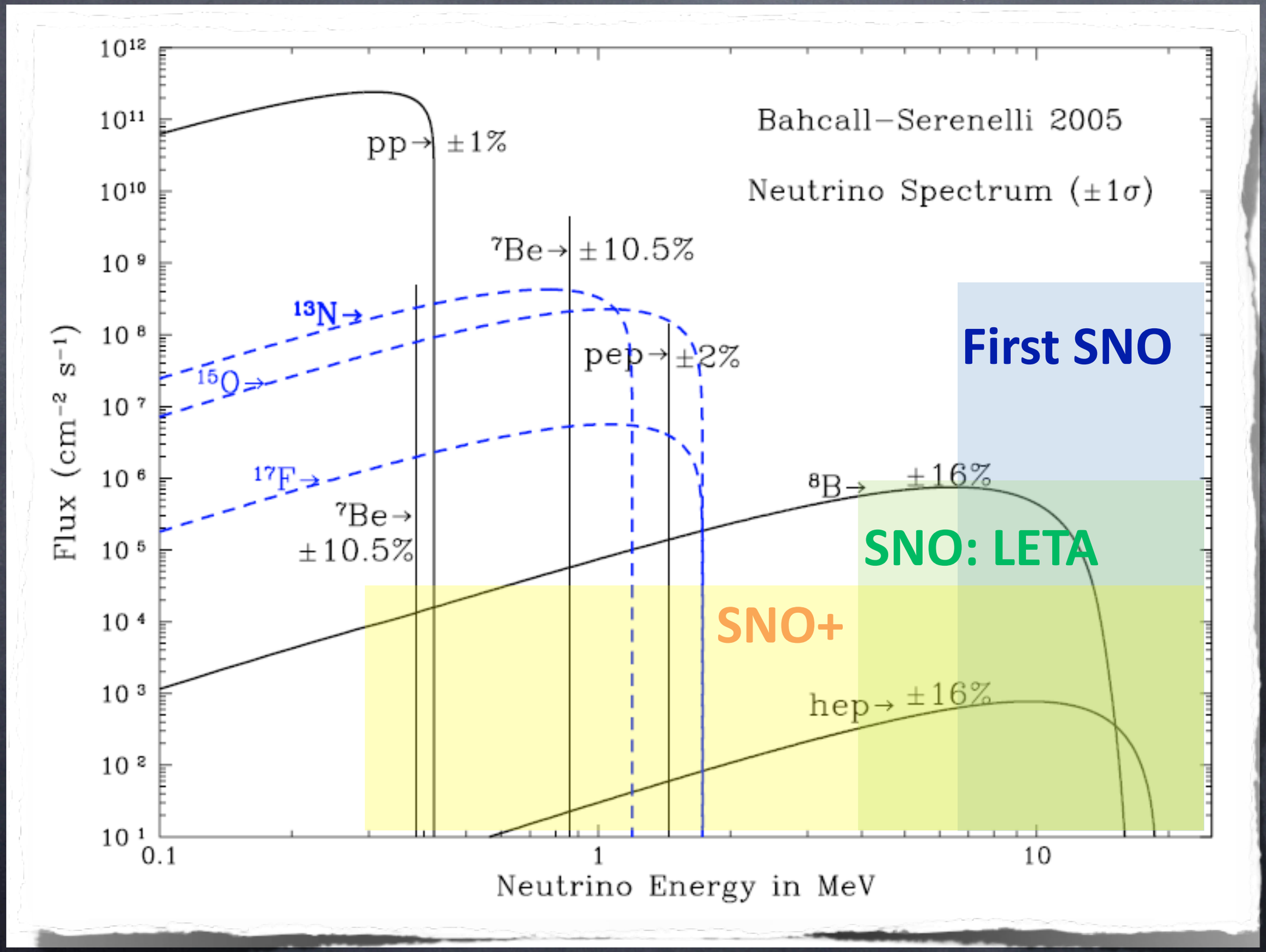
Solar ν Status



SNO+ Solar ν Prospects



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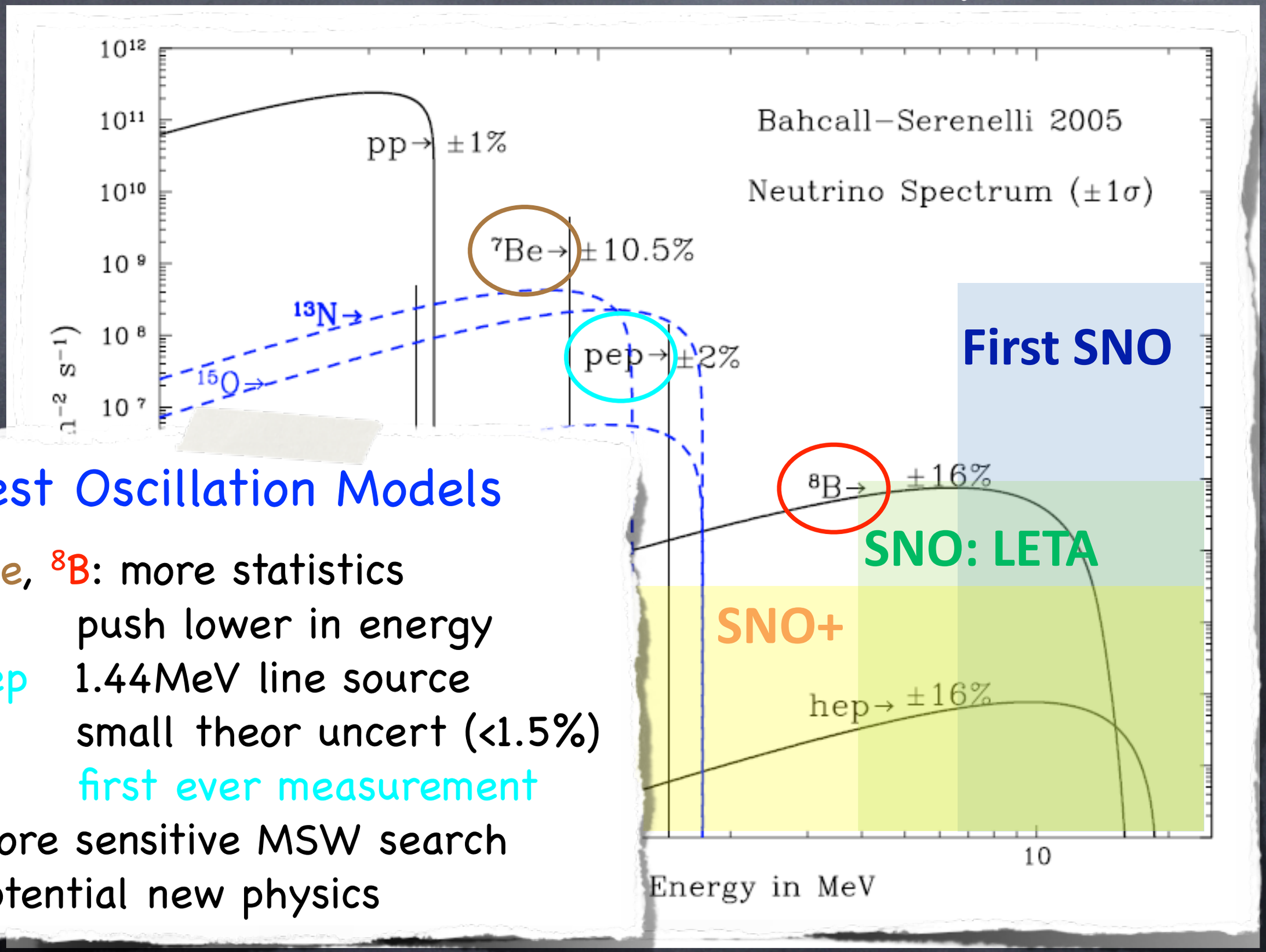


Test Oscillation Models

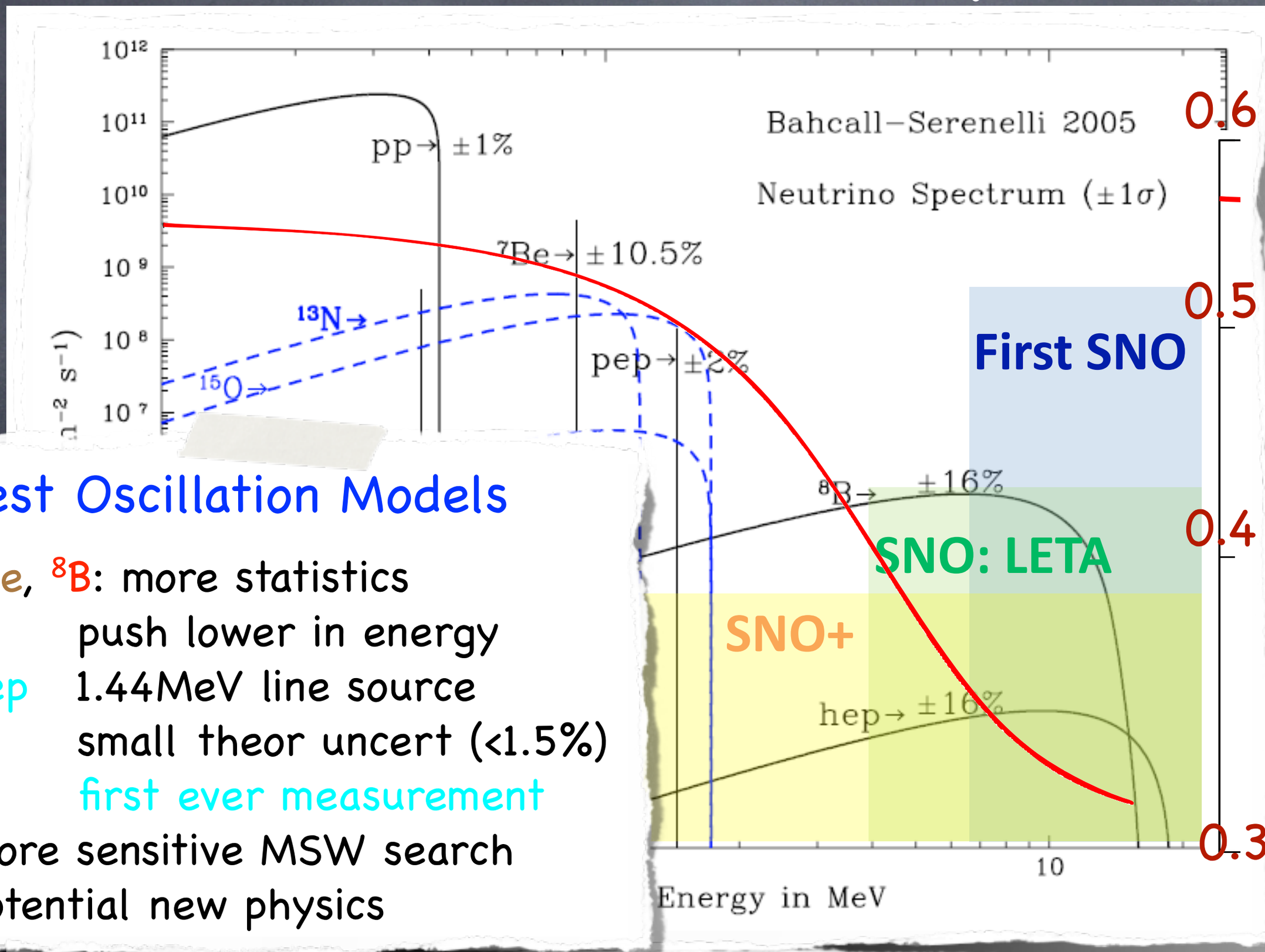
^{7}Be, ^{8}B: more statistics
push lower in energy

pep 1.44MeV line source
small theor uncert (<1.5%)
first ever measurement

More sensitive MSW search

Potential new physics

SNO+ Solar ν Prospects



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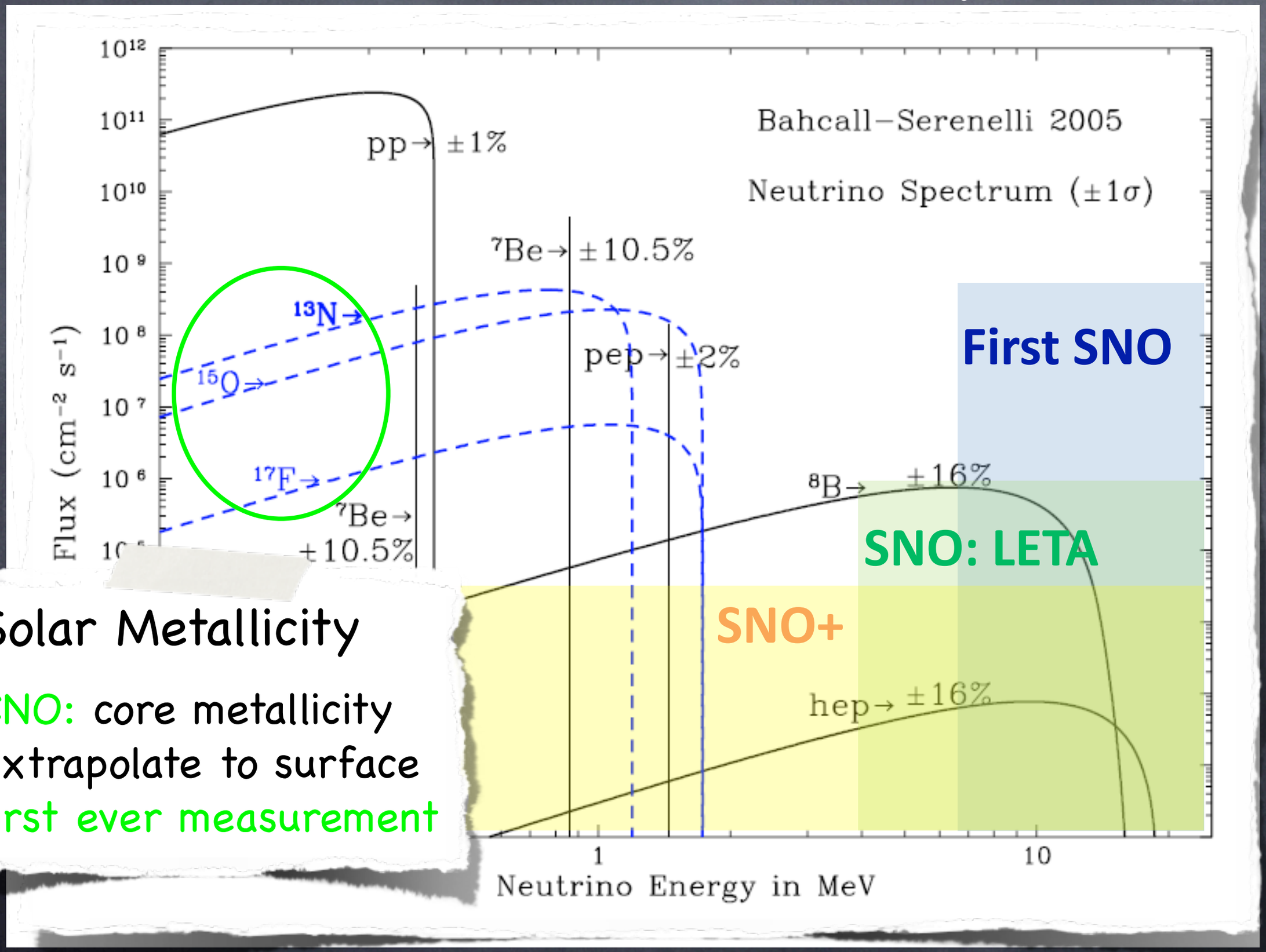


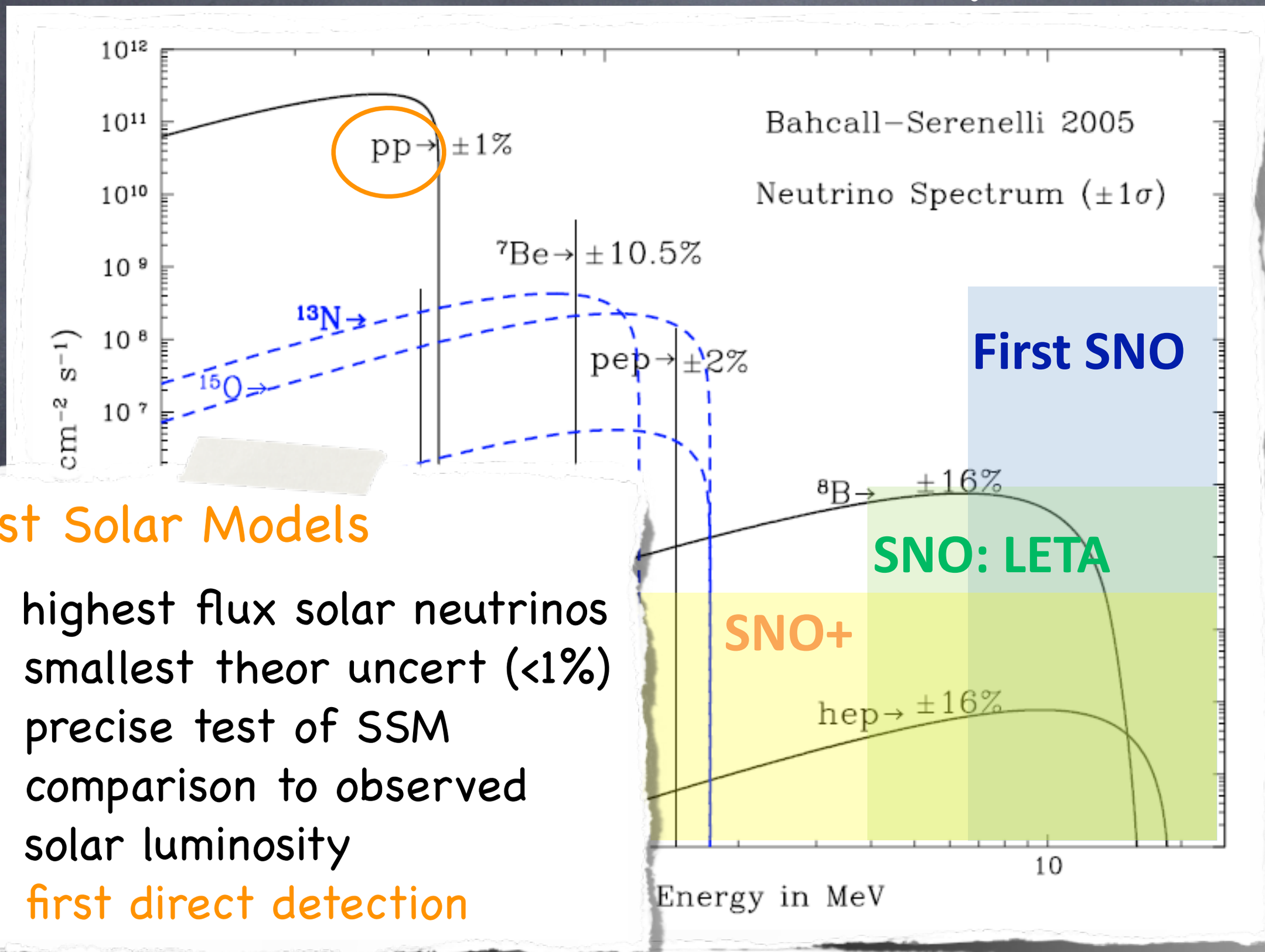
Solar Metallicity

CNO: core metallicity

Extrapolate to surface

first ever measurement

SNO+ Solar ν Prospects



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precise test of SSM
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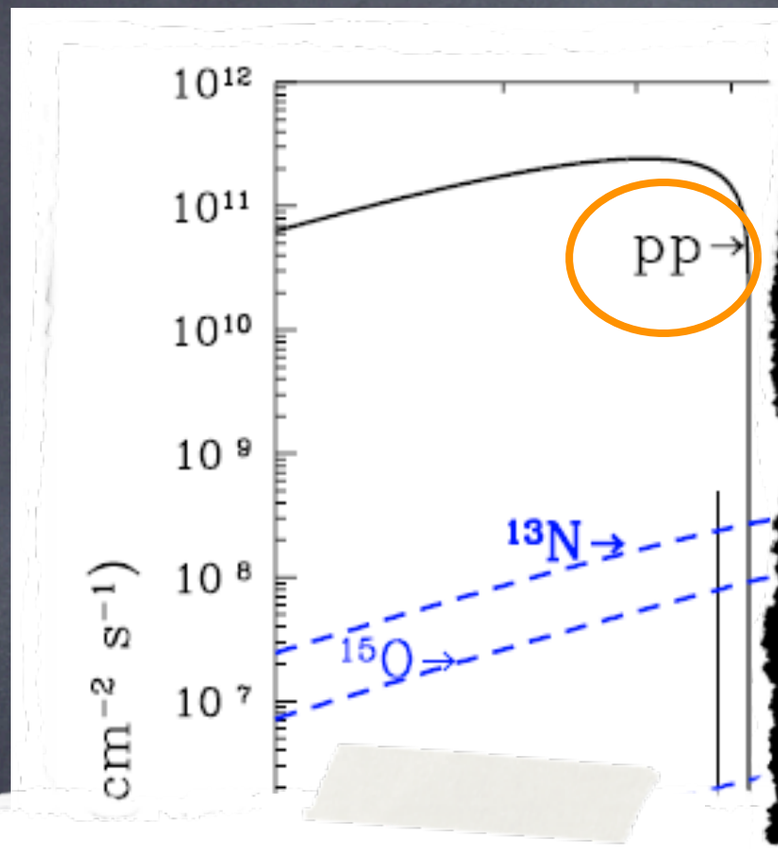

John Bahcall:
"p-p neutrinos are the gold ring of solar neutrino physics and astronomy. Their measurement will constitute a simultaneous and critical test of stellar evolution theory and of neutrino oscillation solutions"

Test Solar Models

pp highest flux solar neutrinos
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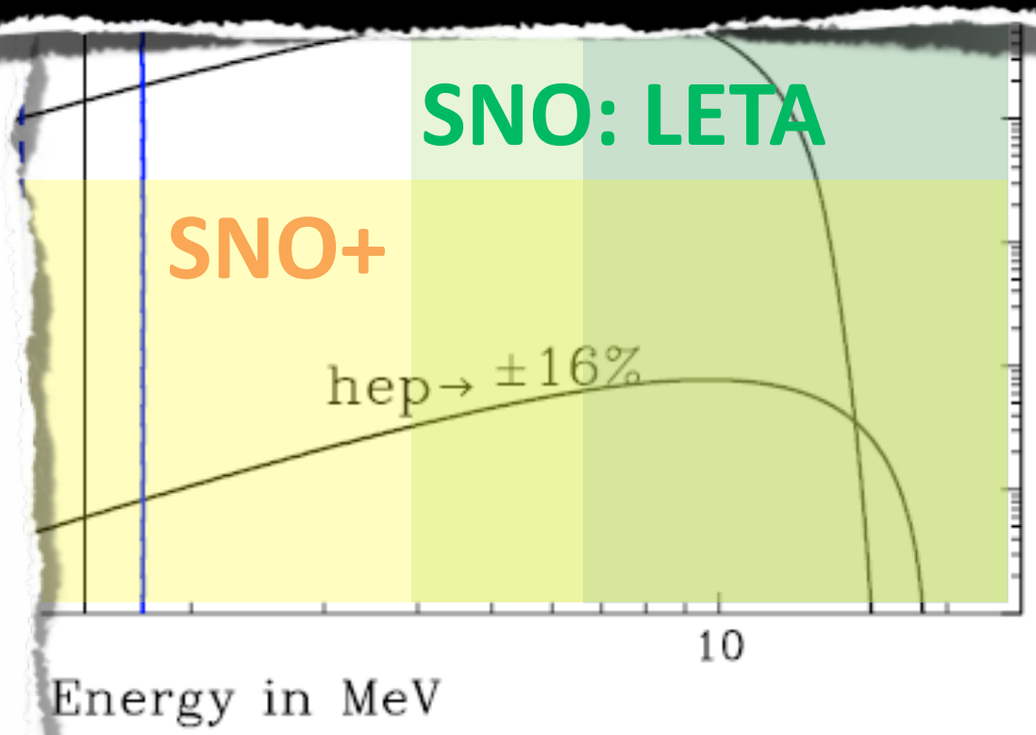
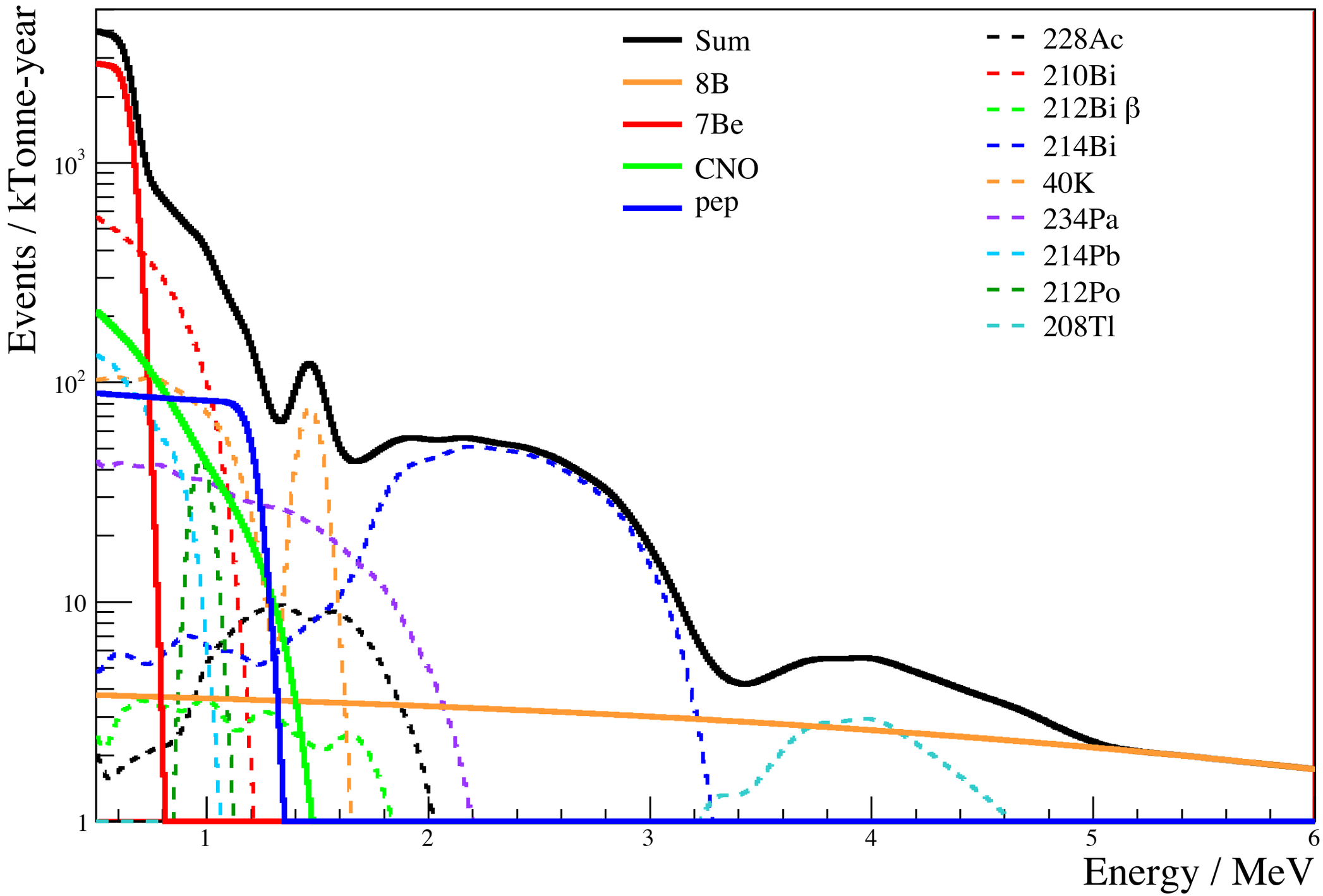
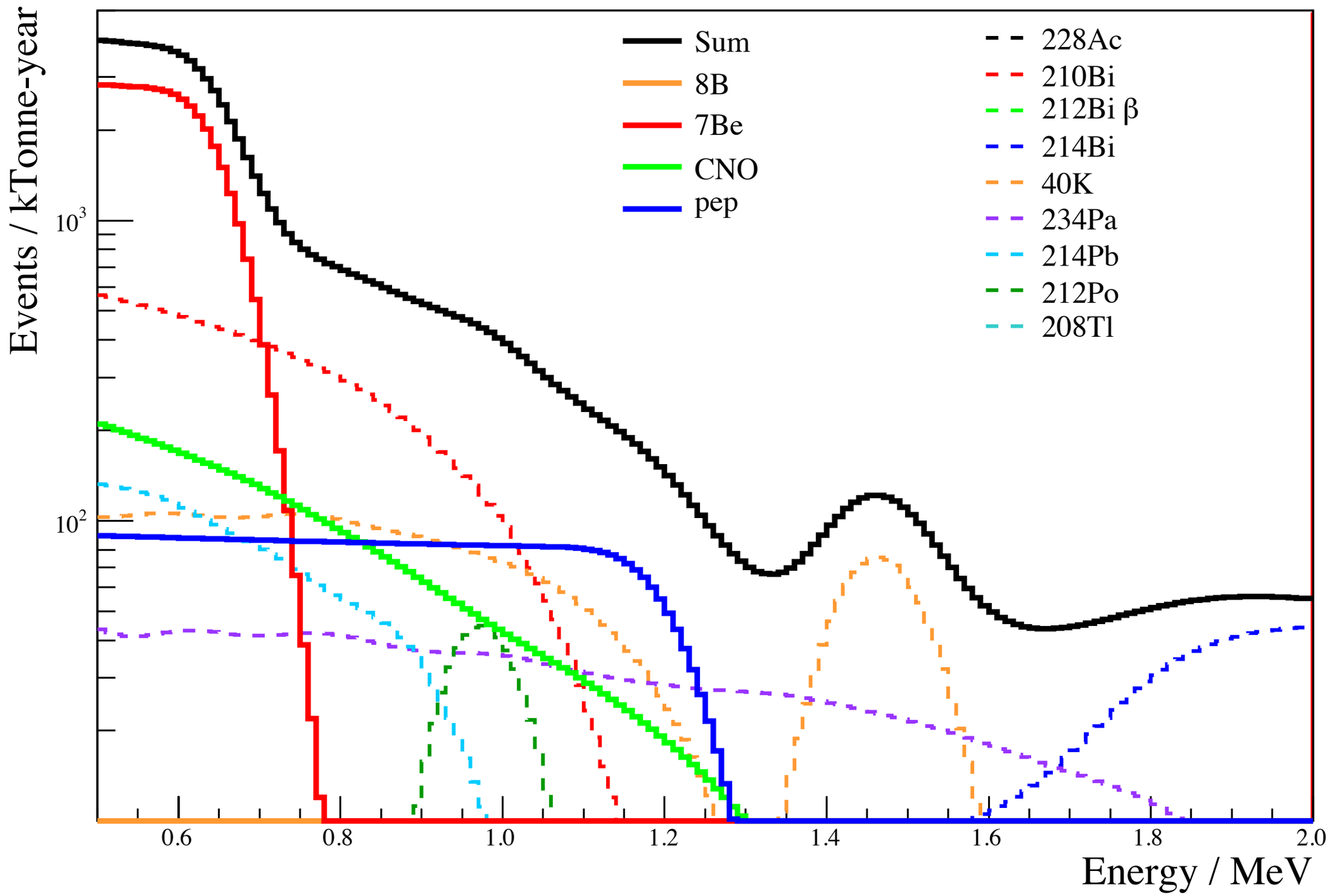
precise test of SSM
comparison to observed solar luminosity
first direct detection



SNO+ Solar ν Signals



SNO+ Low Energy Solar ν



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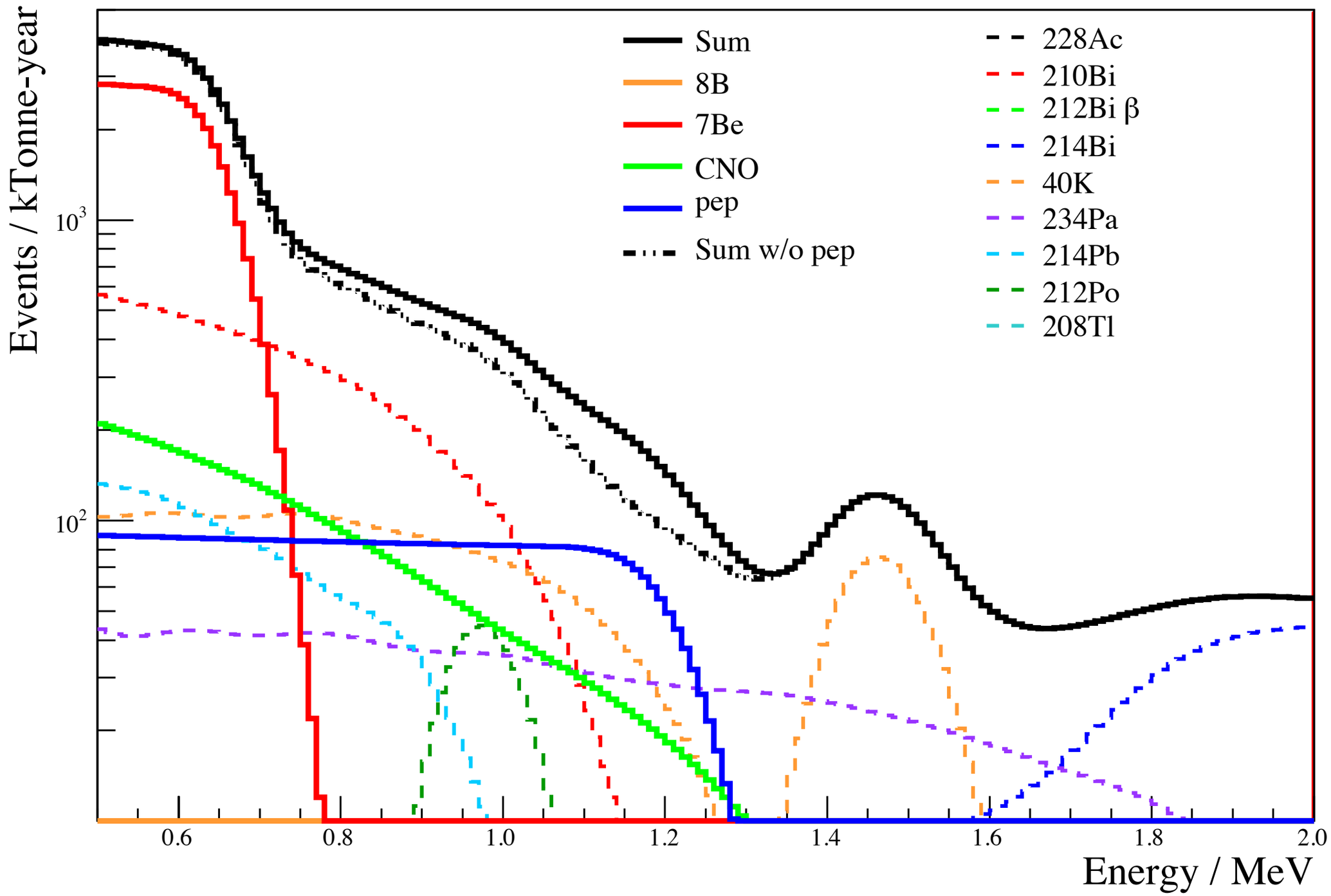

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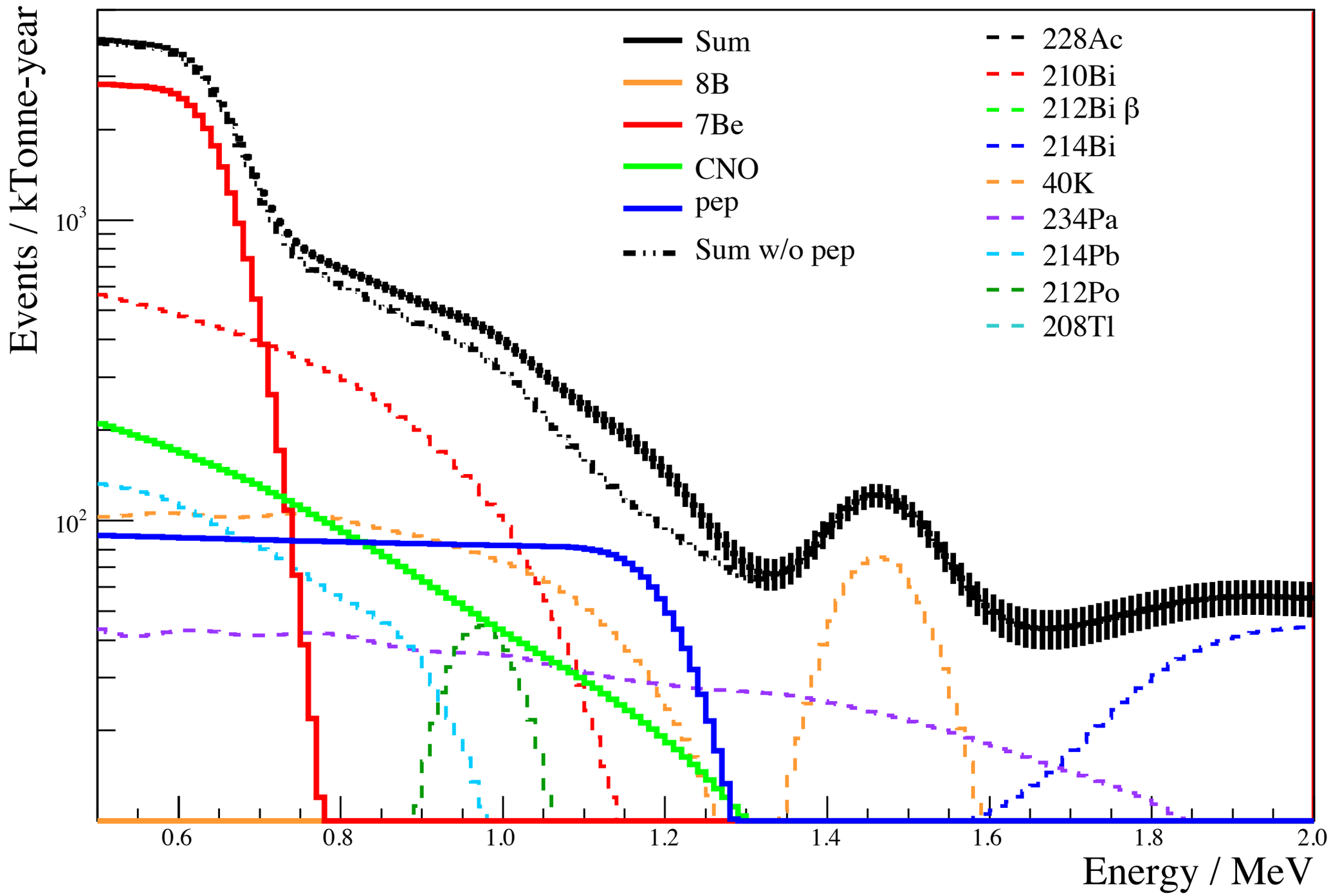

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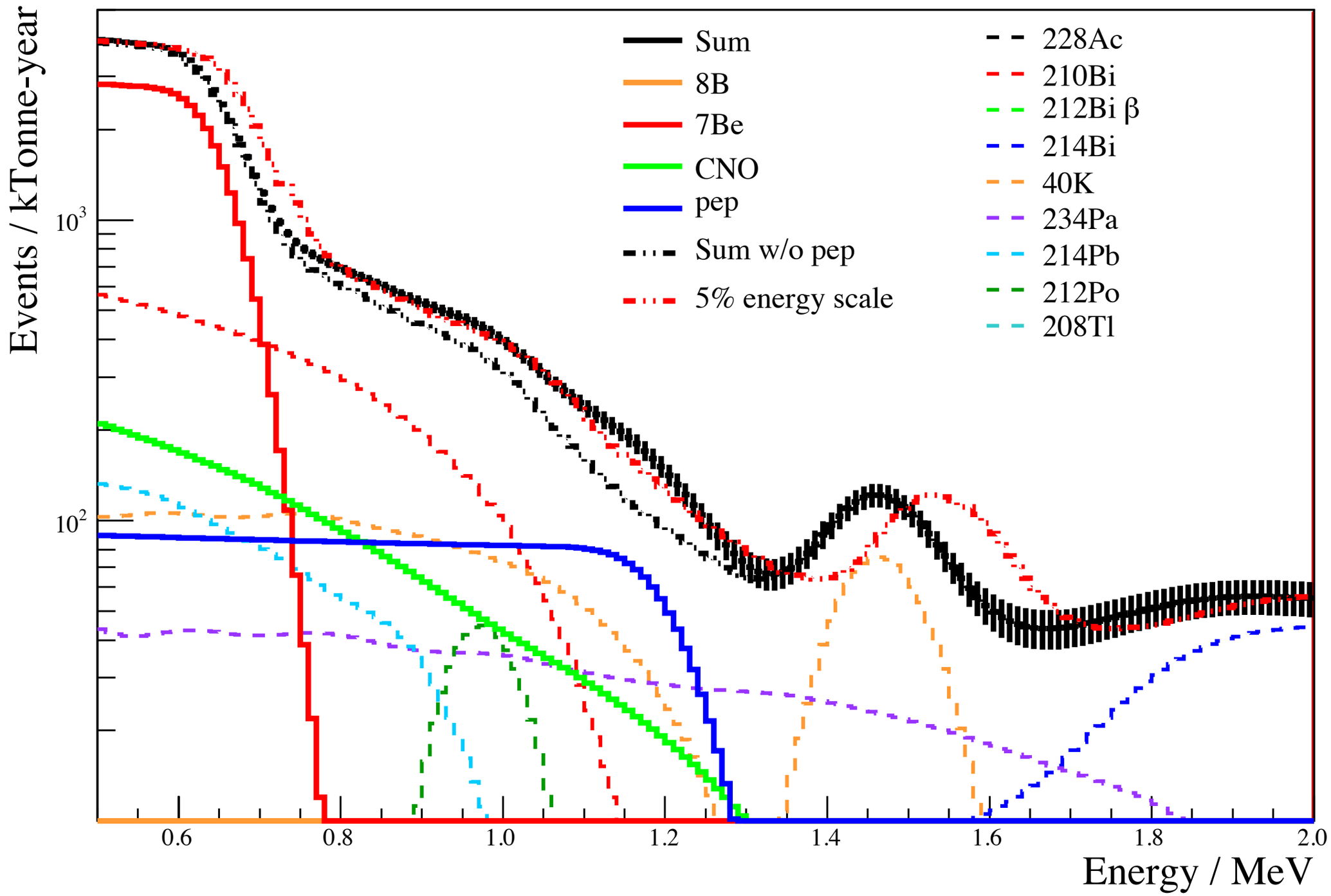

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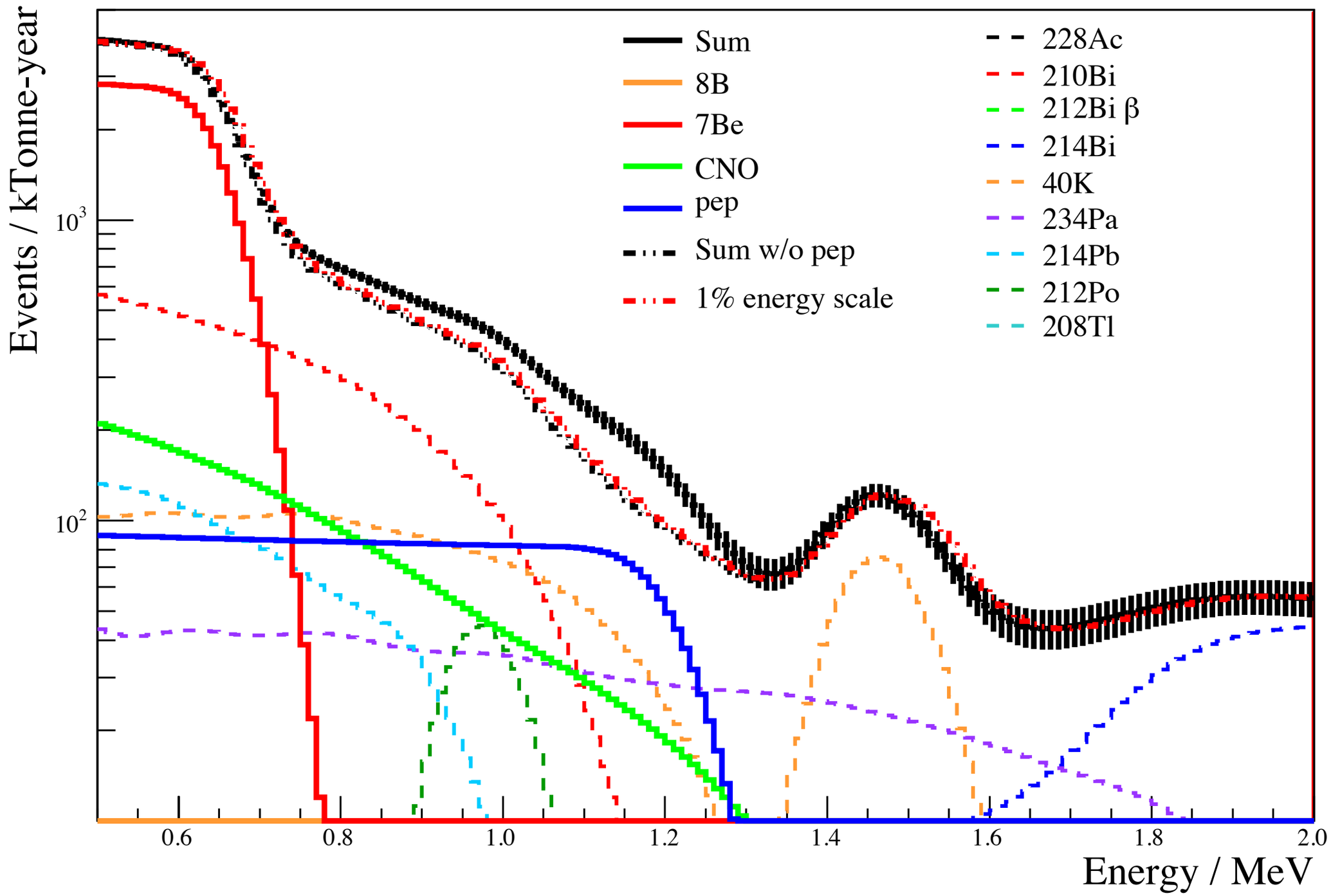

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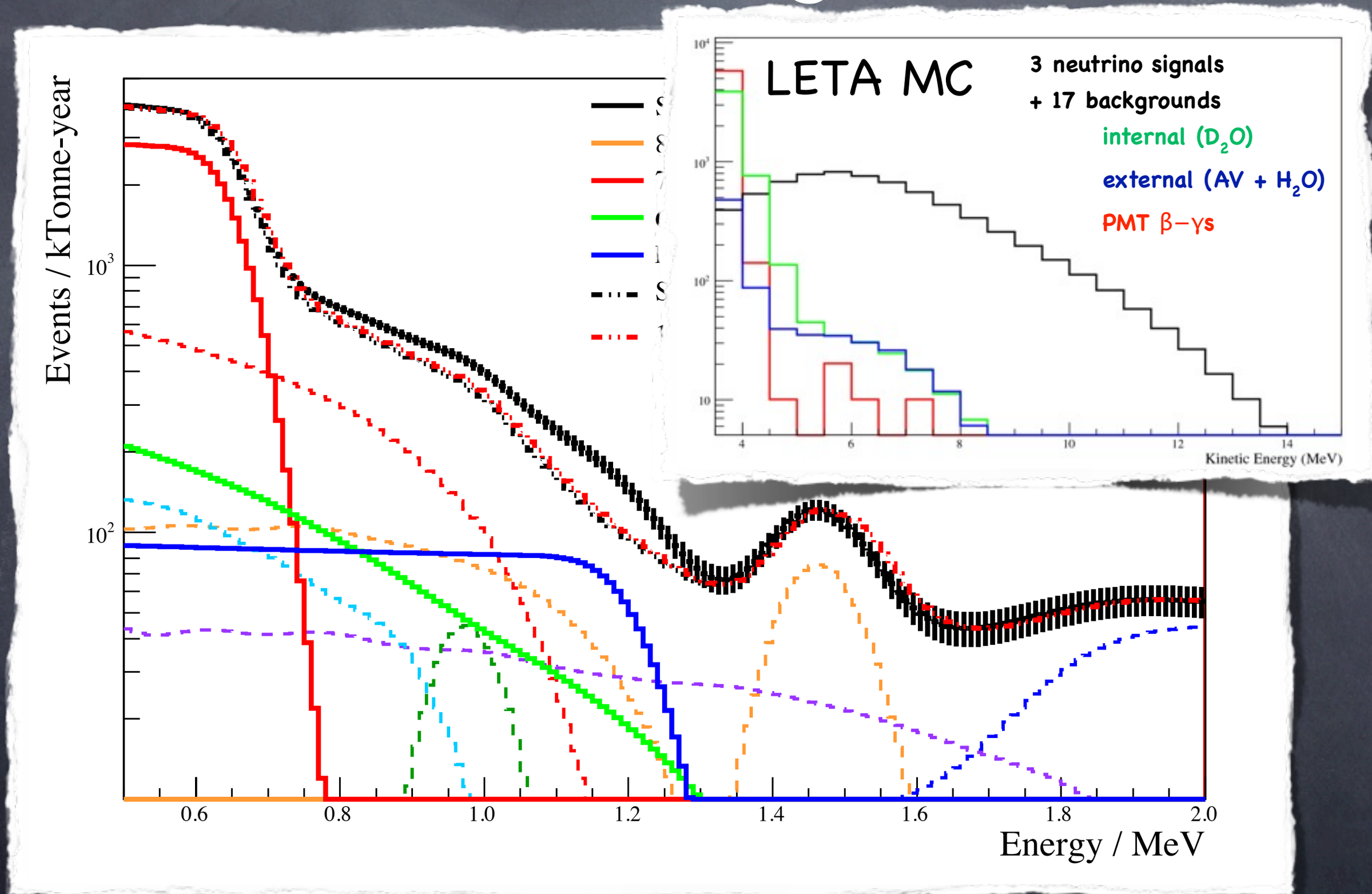

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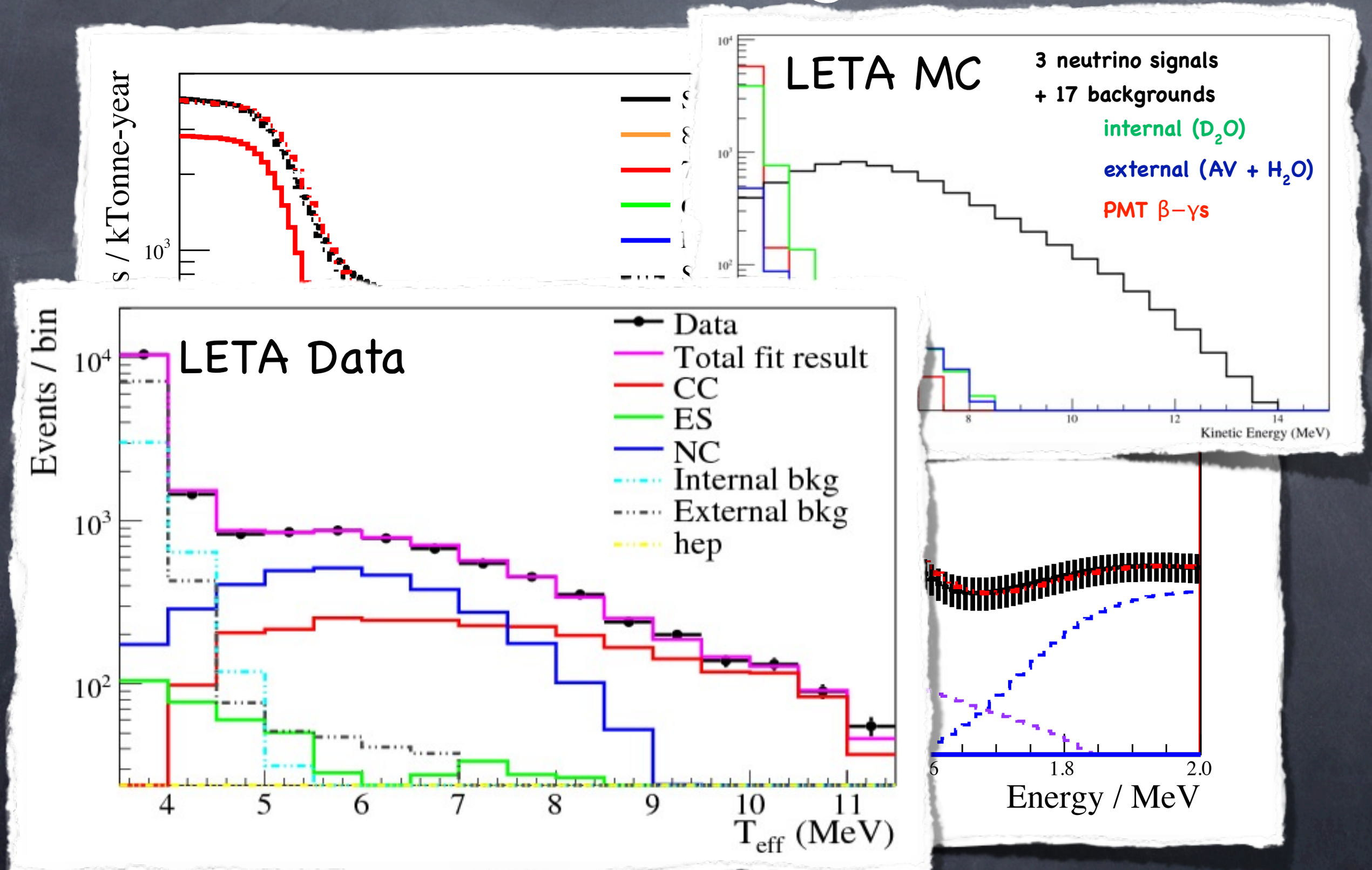
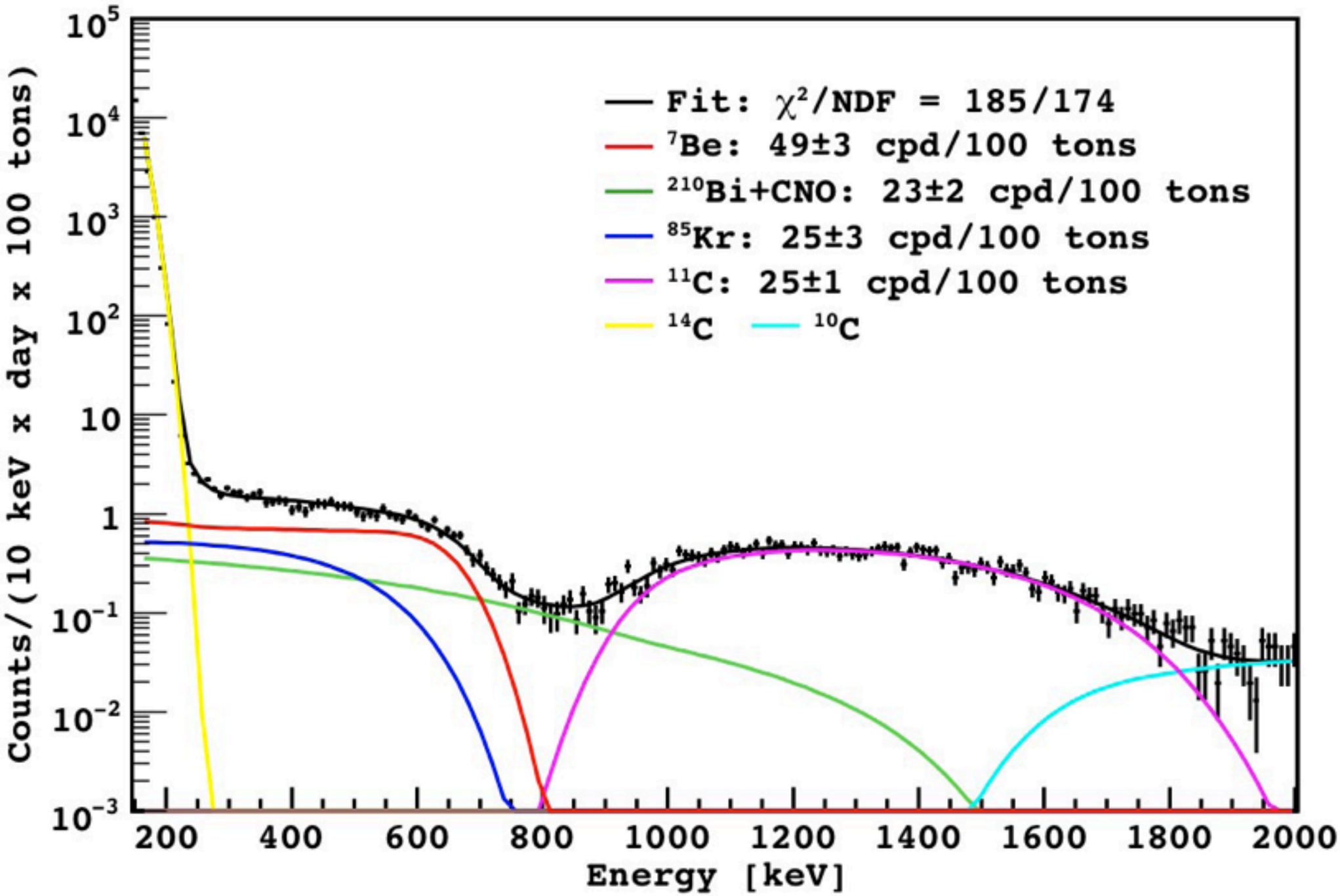
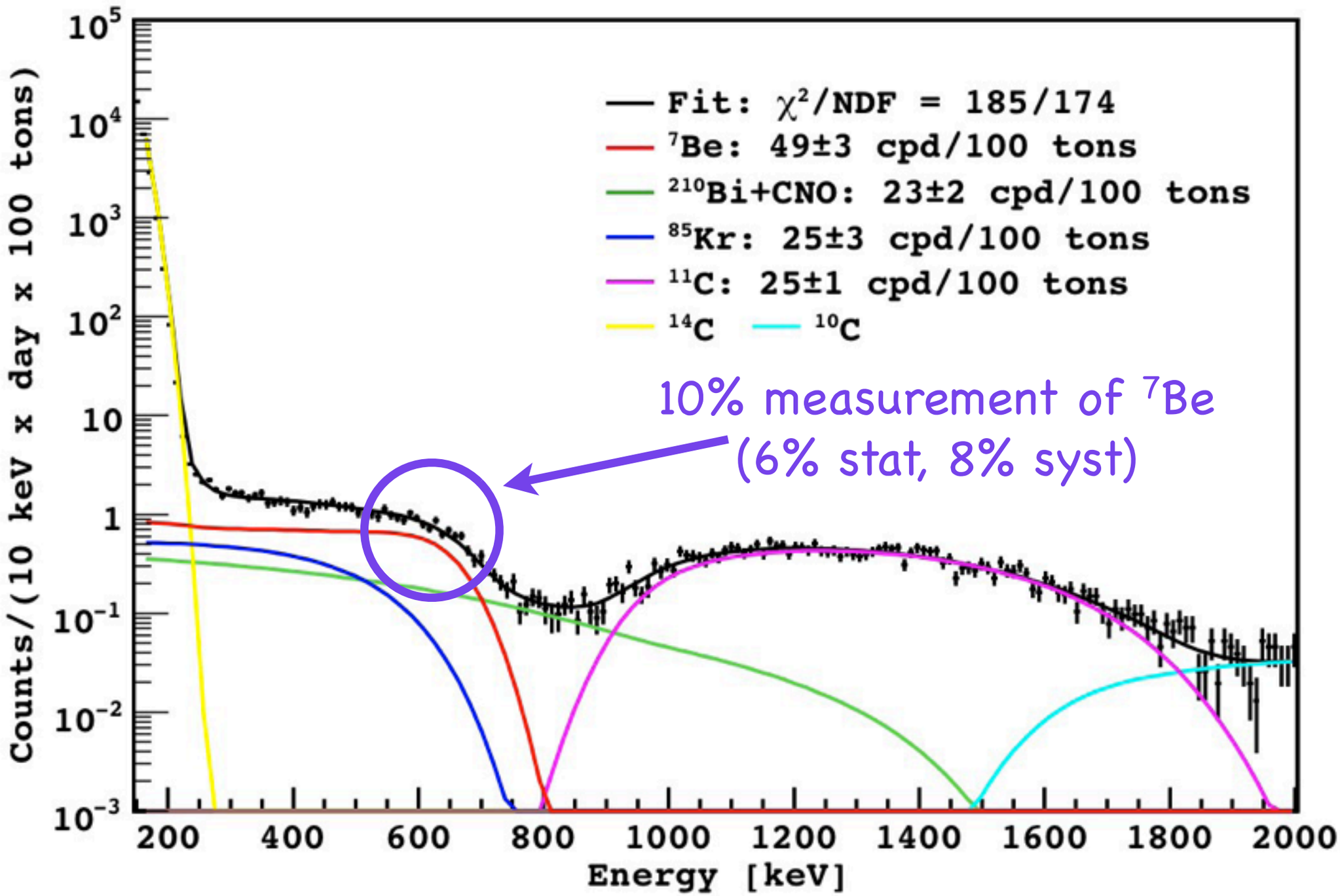


Borexino Low Energy ν



Borexino Collaboration, Phys. Rev. Lett. 101, 091302 (2008)

Borexino Low Energy ν



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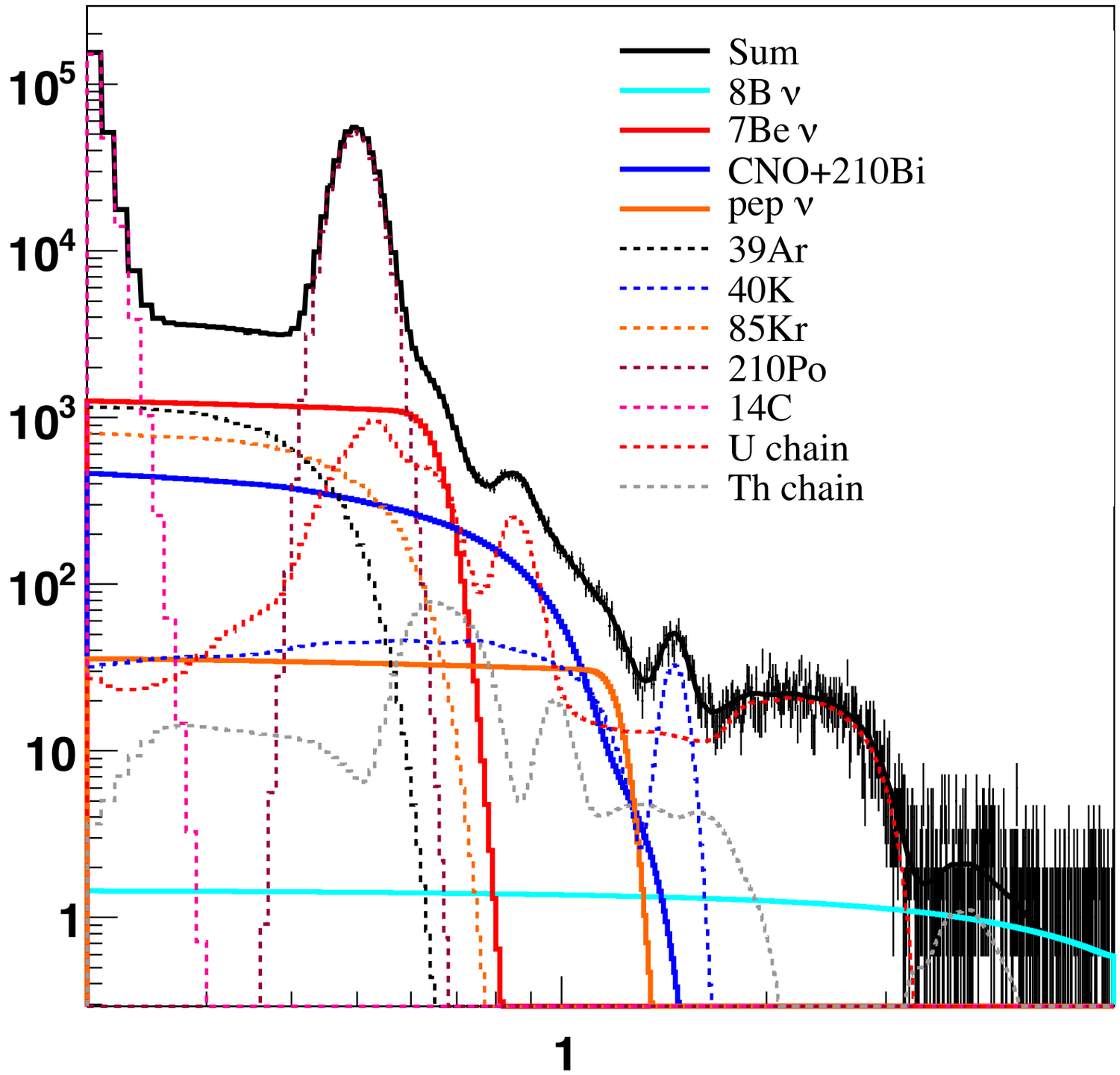
SNO+ Preliminary Studies



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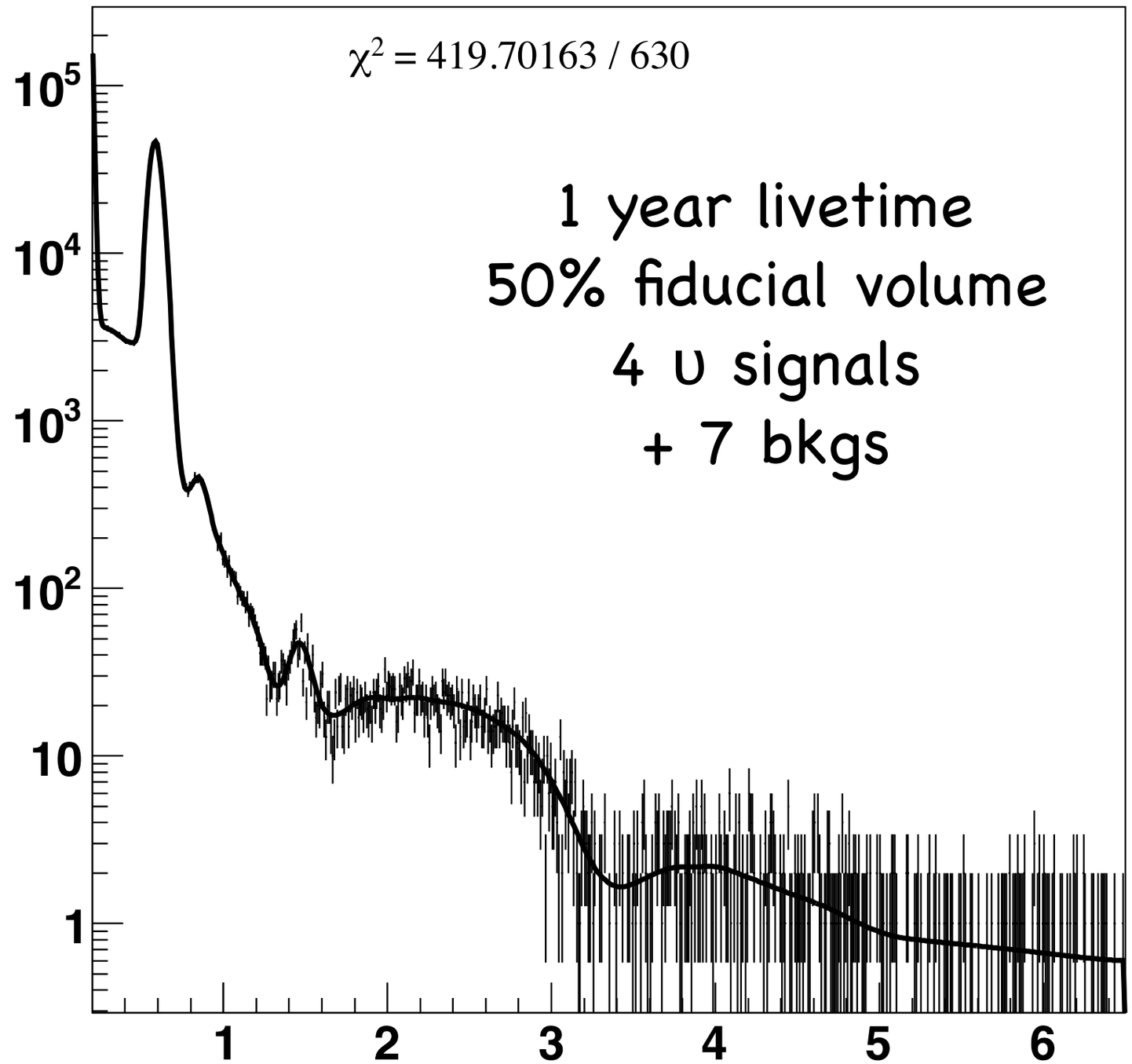

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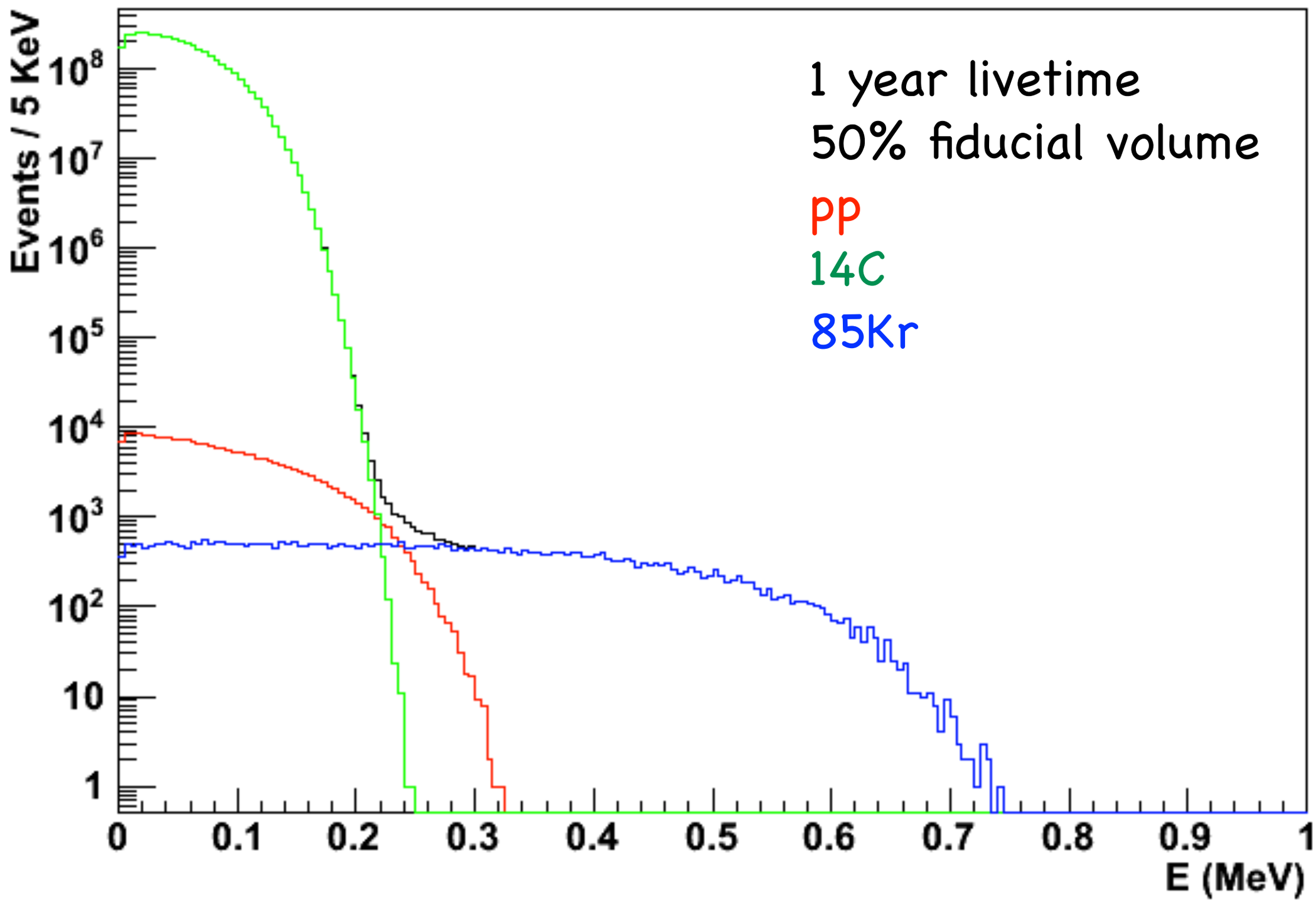
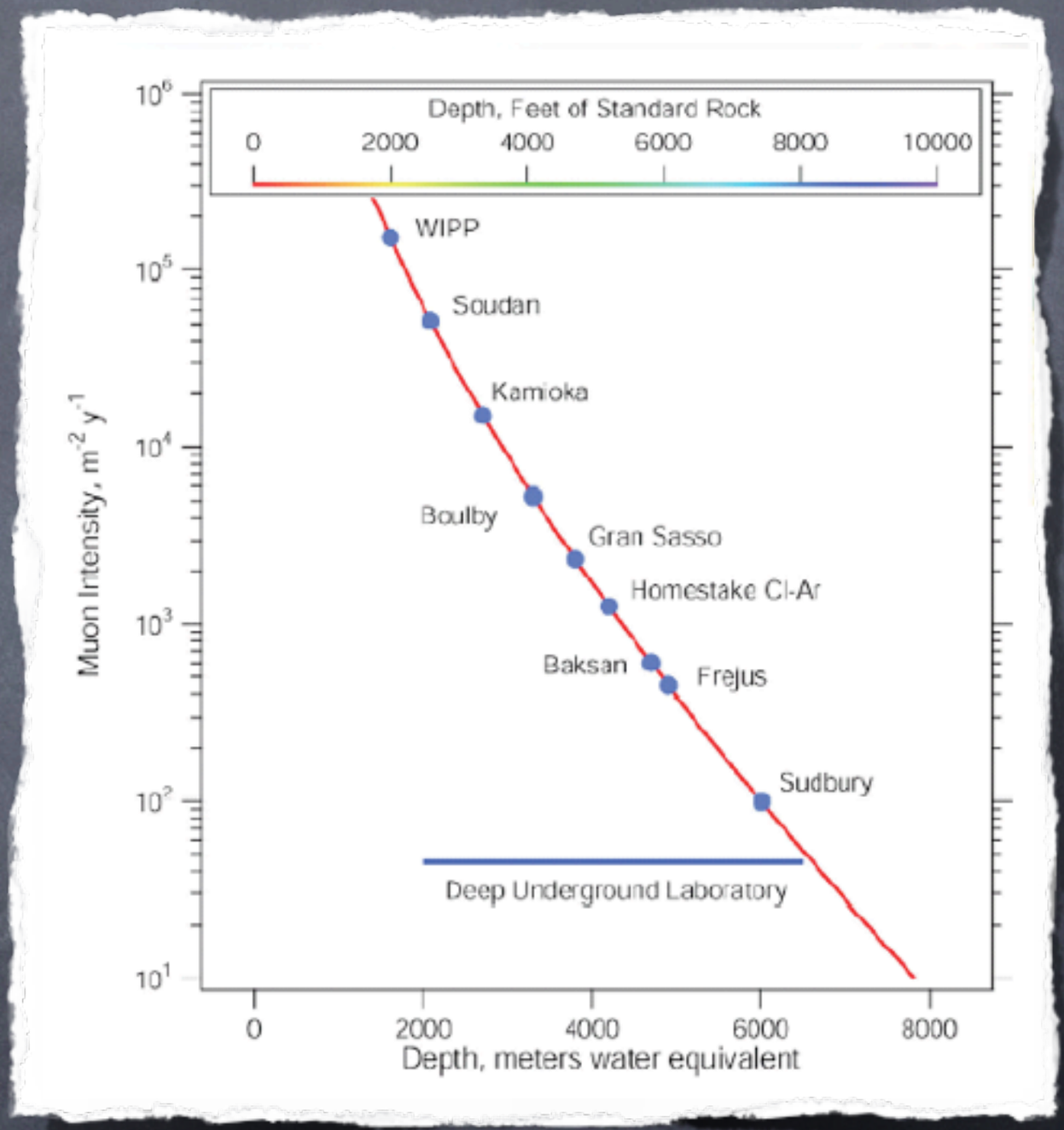


SNO+ Advantages: Depth

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

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



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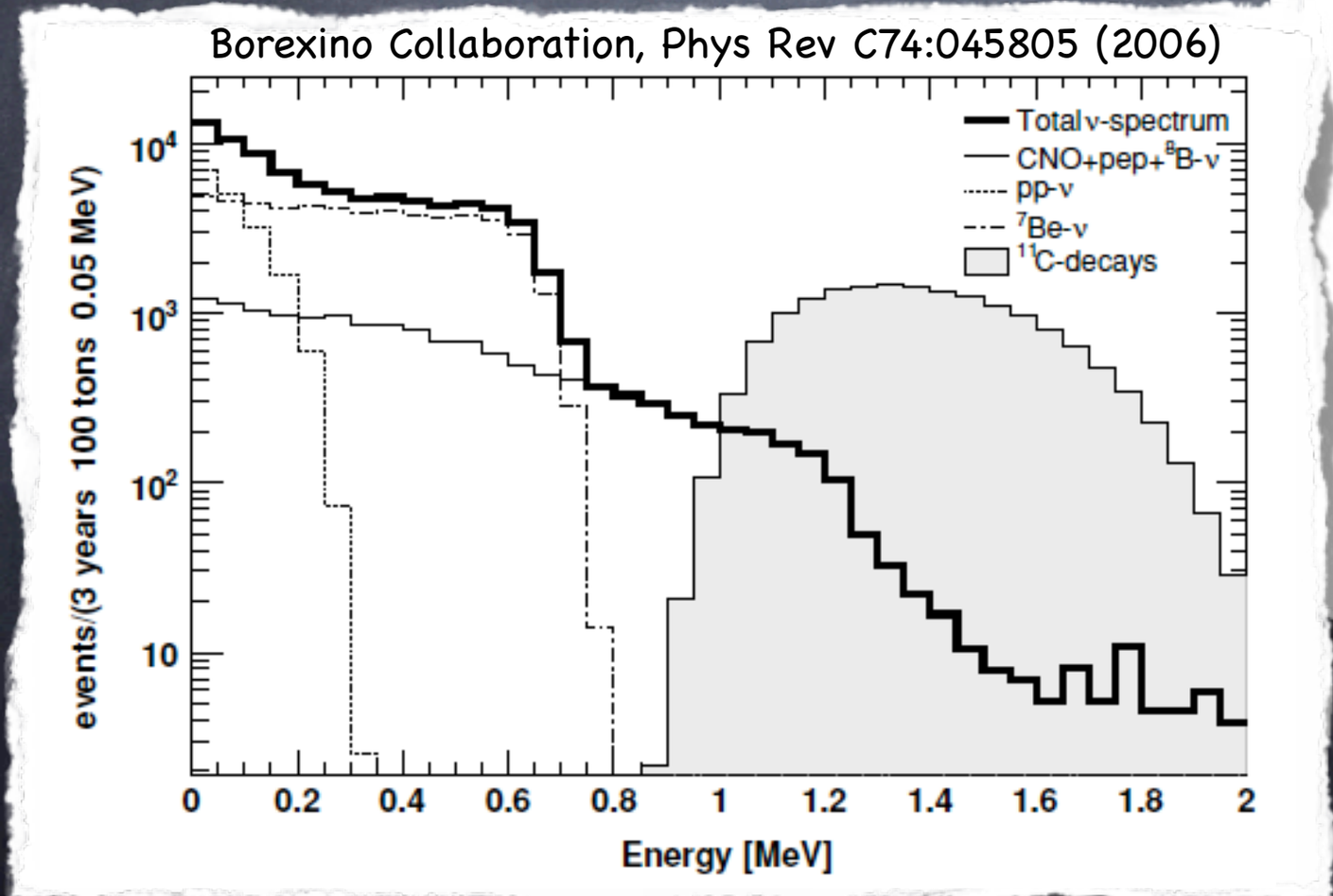

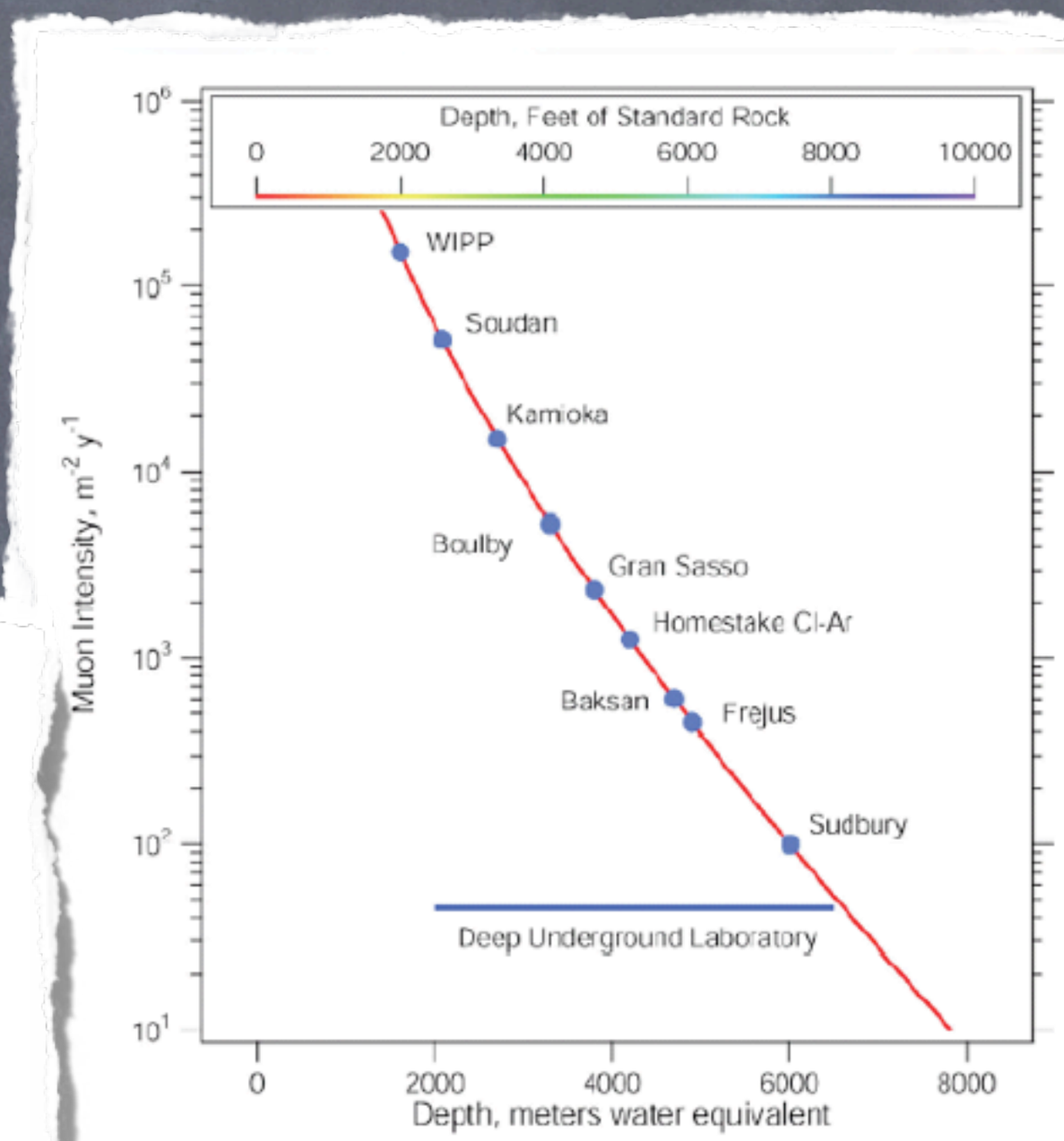

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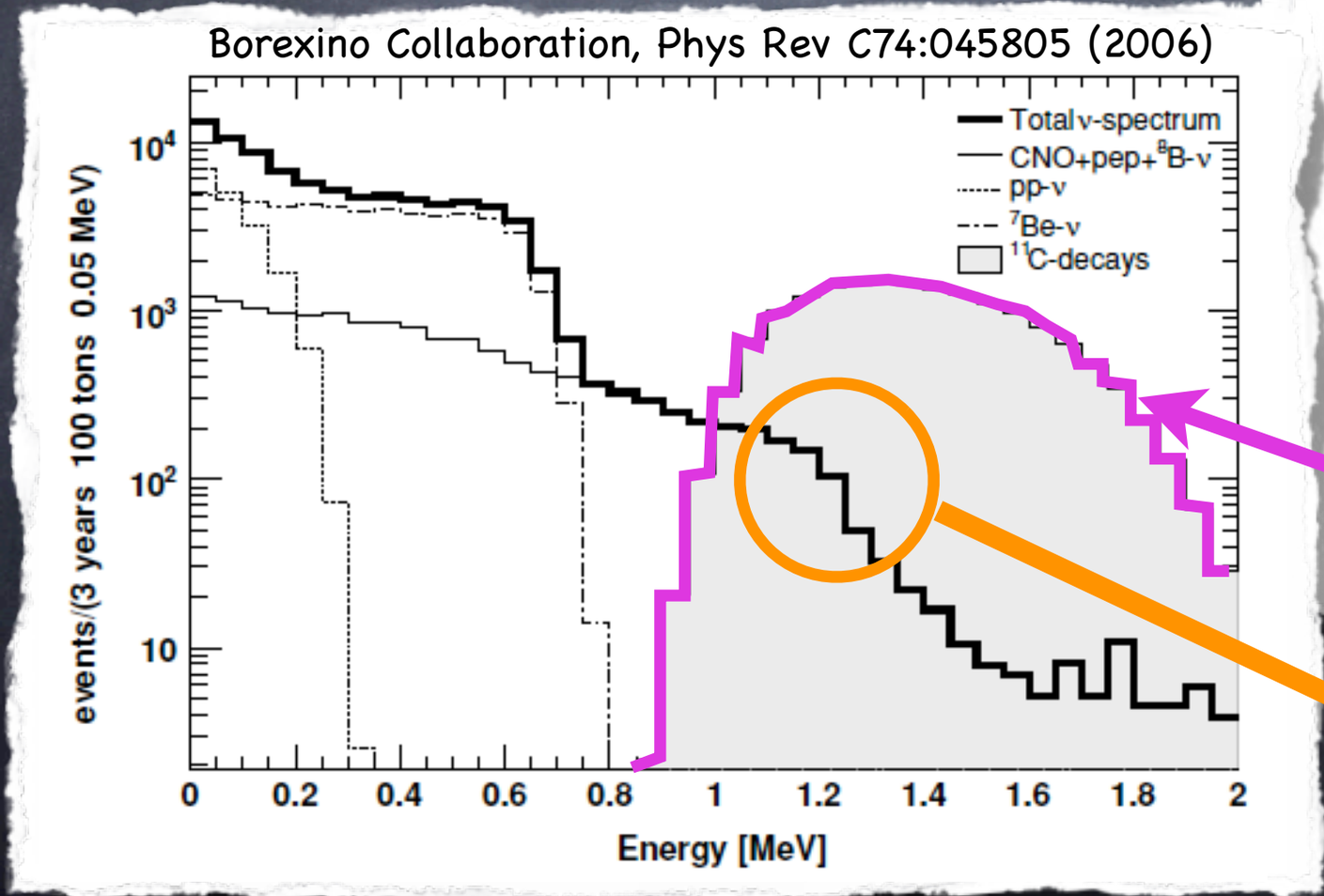
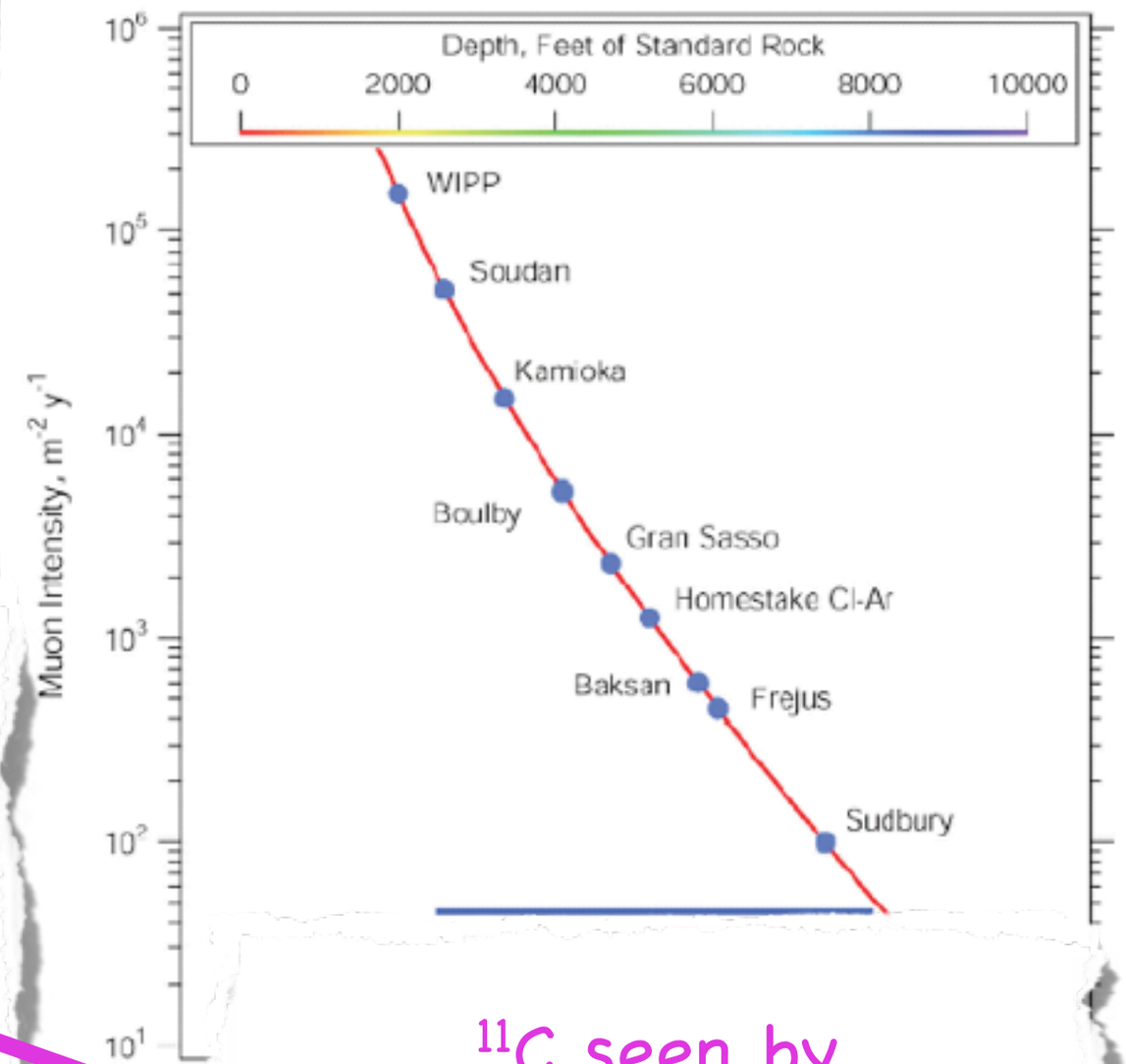
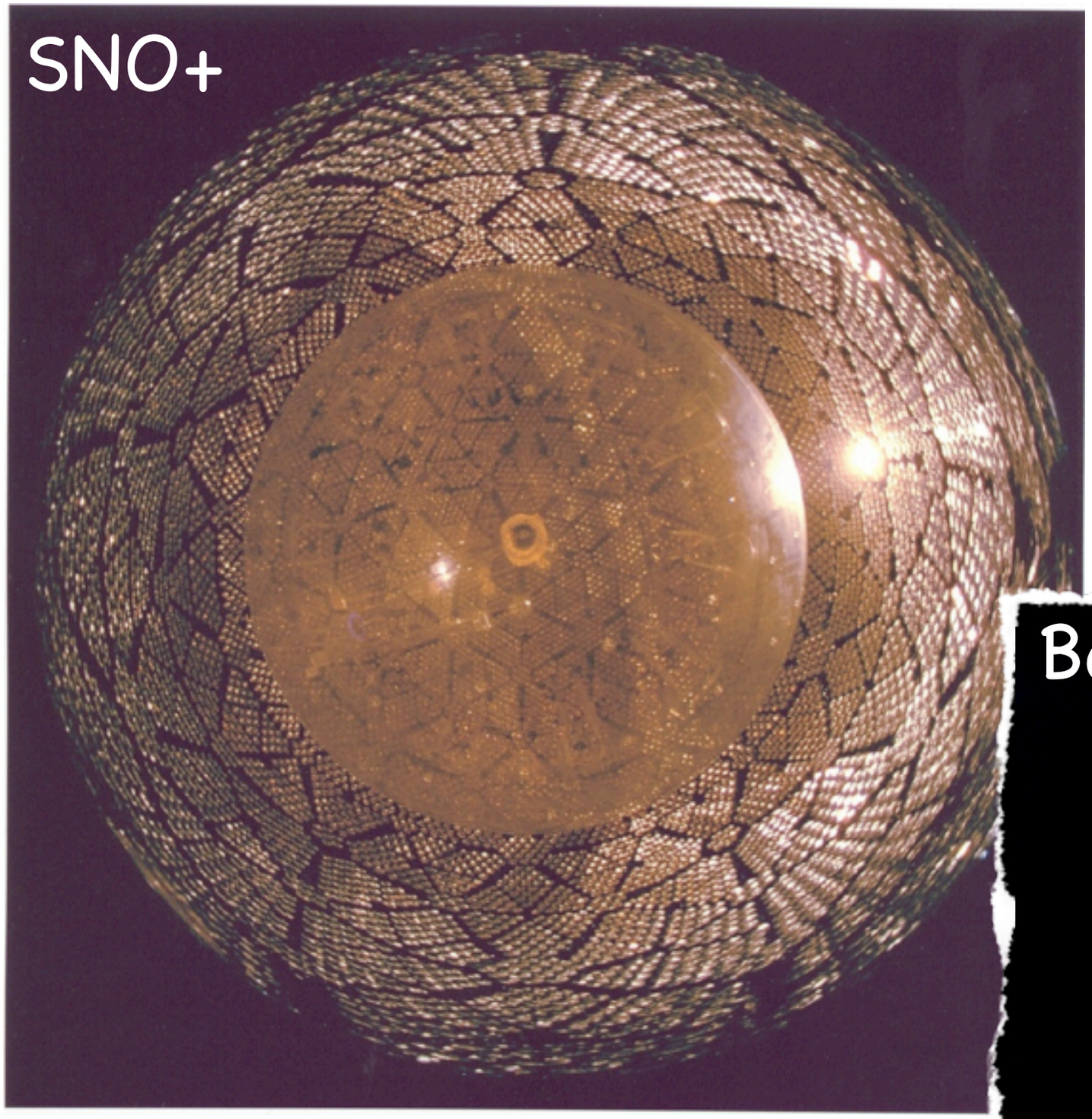




^{11}C seen by Borexino & KamLAND

pep edge

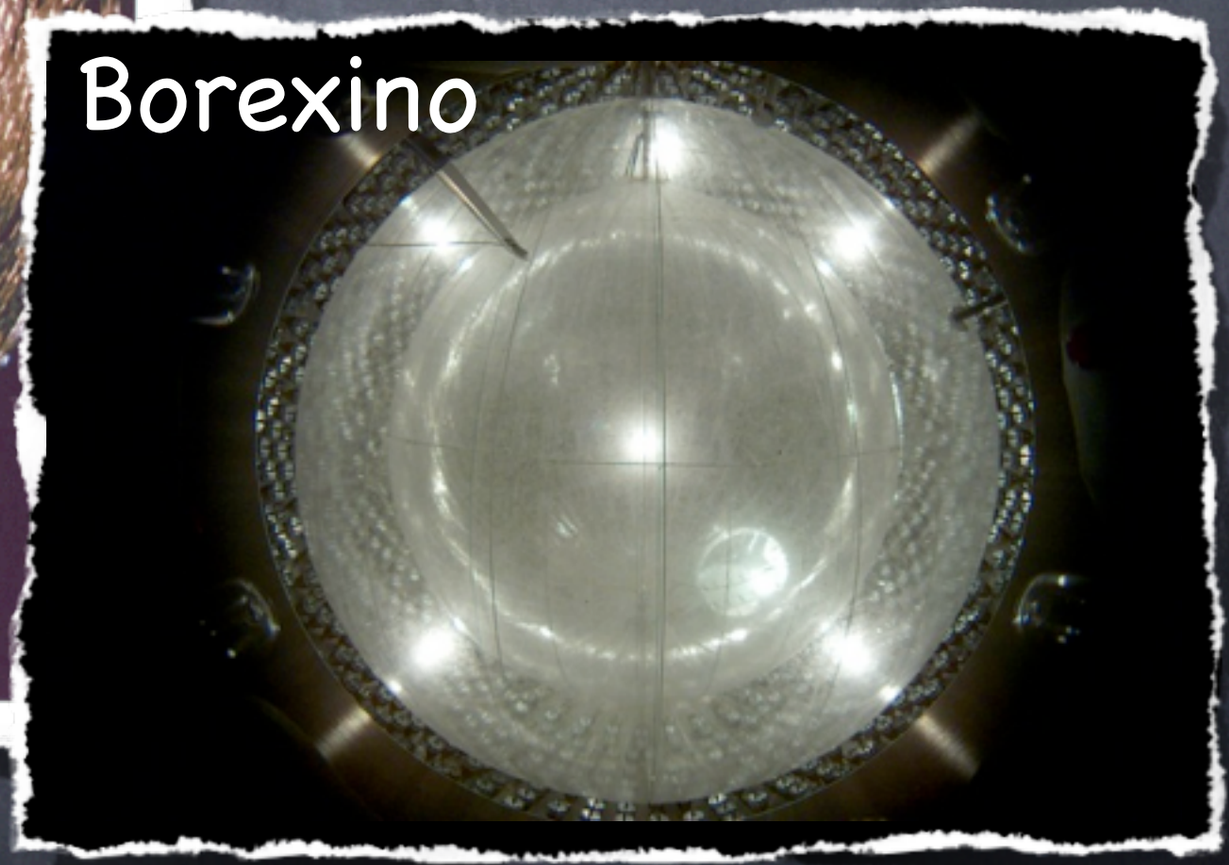
SNO+ Advantages



1. Energy resolution:
~2200 vs ~9500 PMTs

2. Size:
278 vs 780ton scintillator

roughly to scale



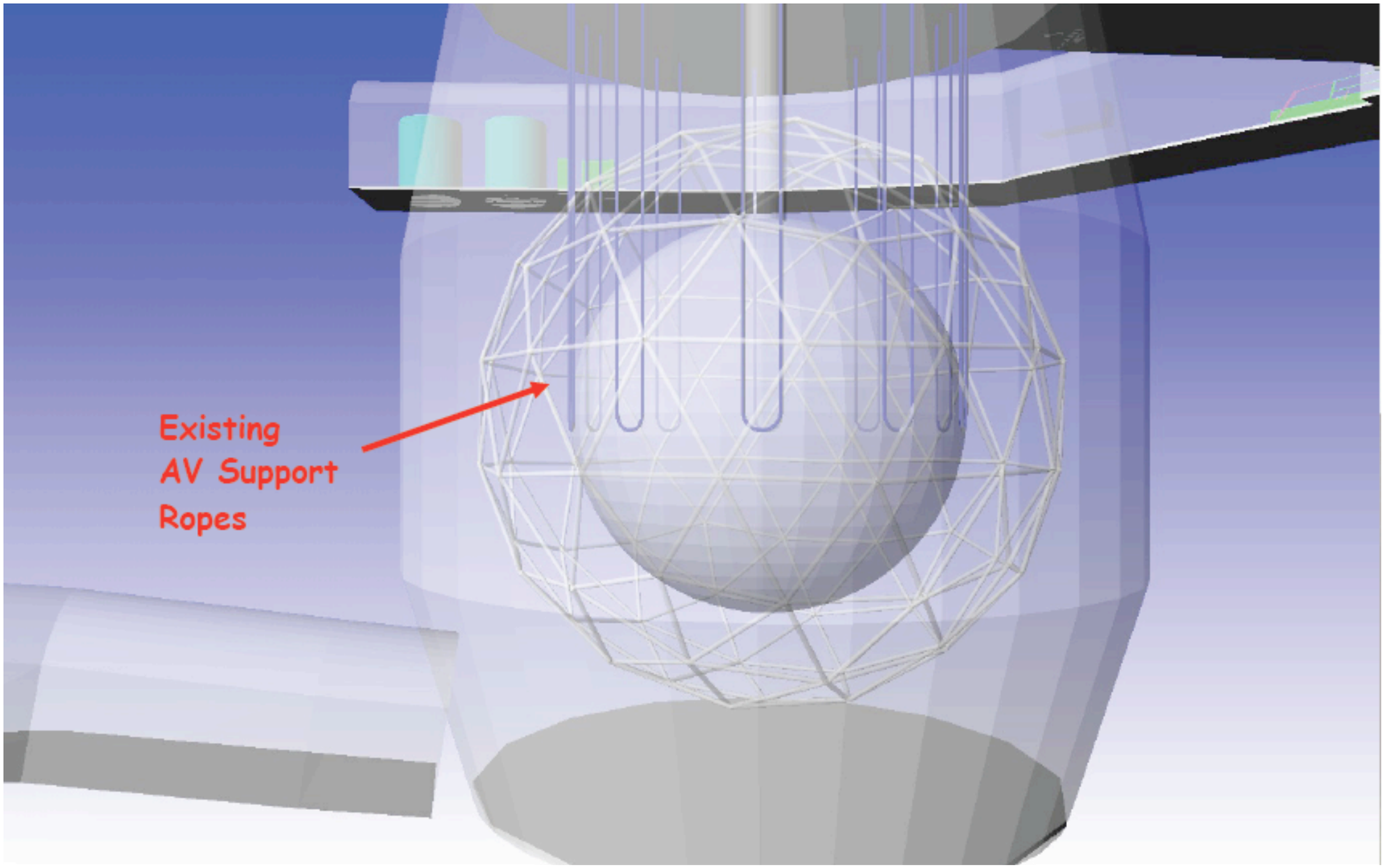
SNO+ Progress

1. Hold-down ropes

2. Electronics upgrades
   - 2.1. Data translation & transmission
   - 2.2. Trigger
   - 2.3. Trigger sum

3. Simulation and Analysis
   - 3.1. Coordination
   - 3.2. Simulation & Verification
   - 3.3. Preparation for Day Zero

Hold-Down Ropes



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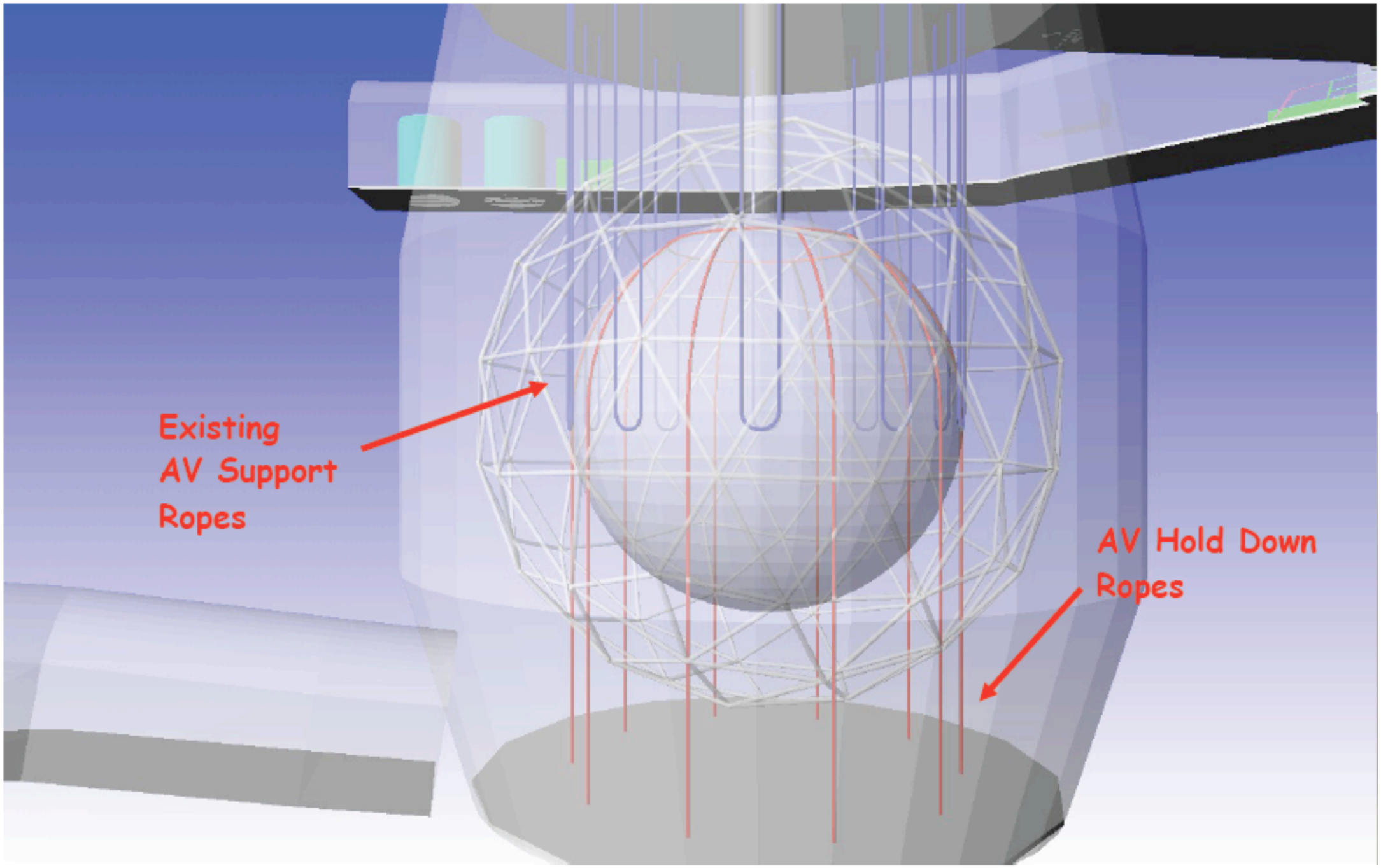

Hold-Down Ropes

Analysis of AV stress and buckling

Material constraints:

- Strength (reduce thickness)
- Radiopurity (ext bkgs)

$\Rightarrow$ tensylon chosen

Hold-Down Ropes

Analysis of AV stress and bu

Material constraints:

Strength (reduce thick

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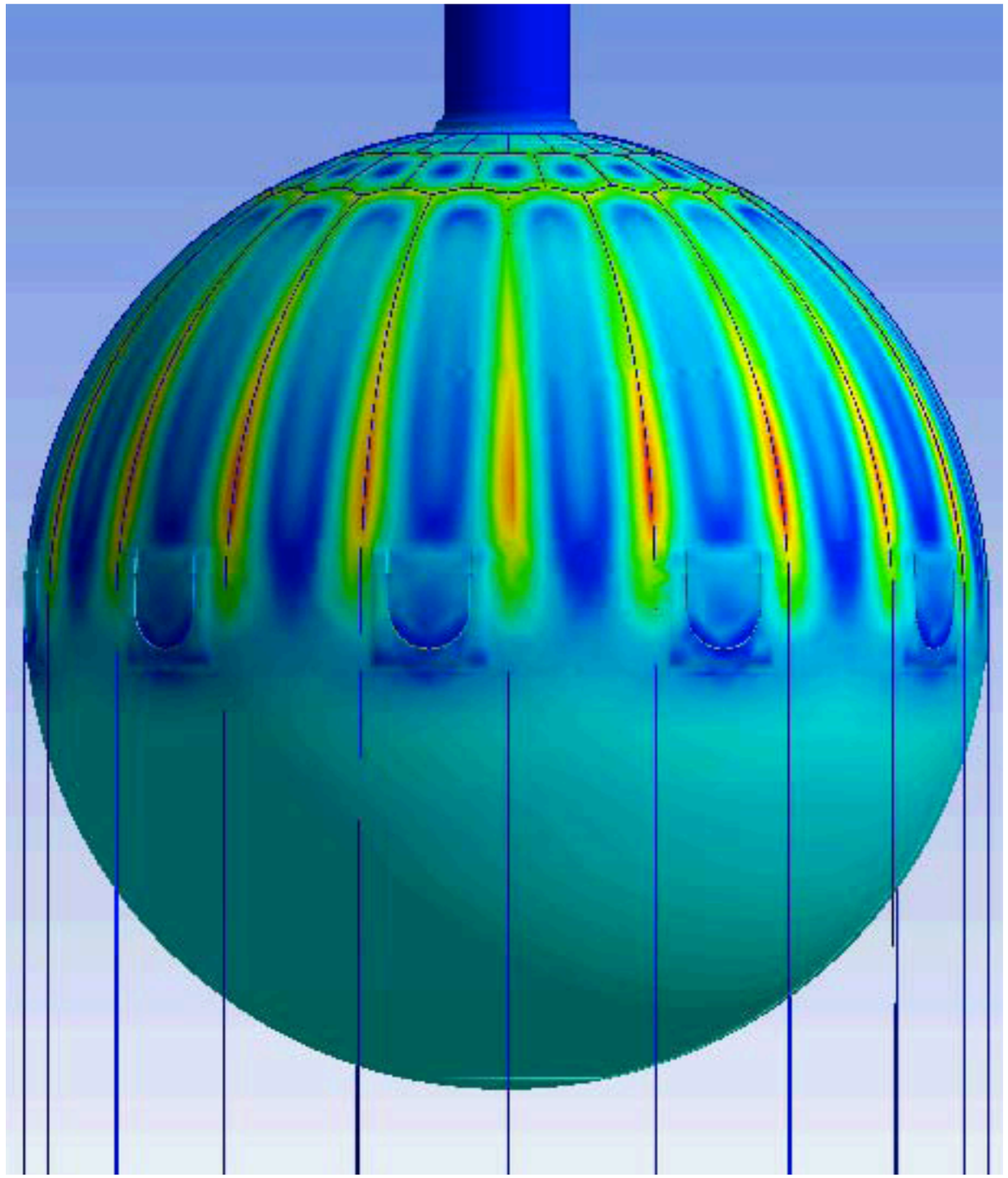
⇒ tensylon chosen



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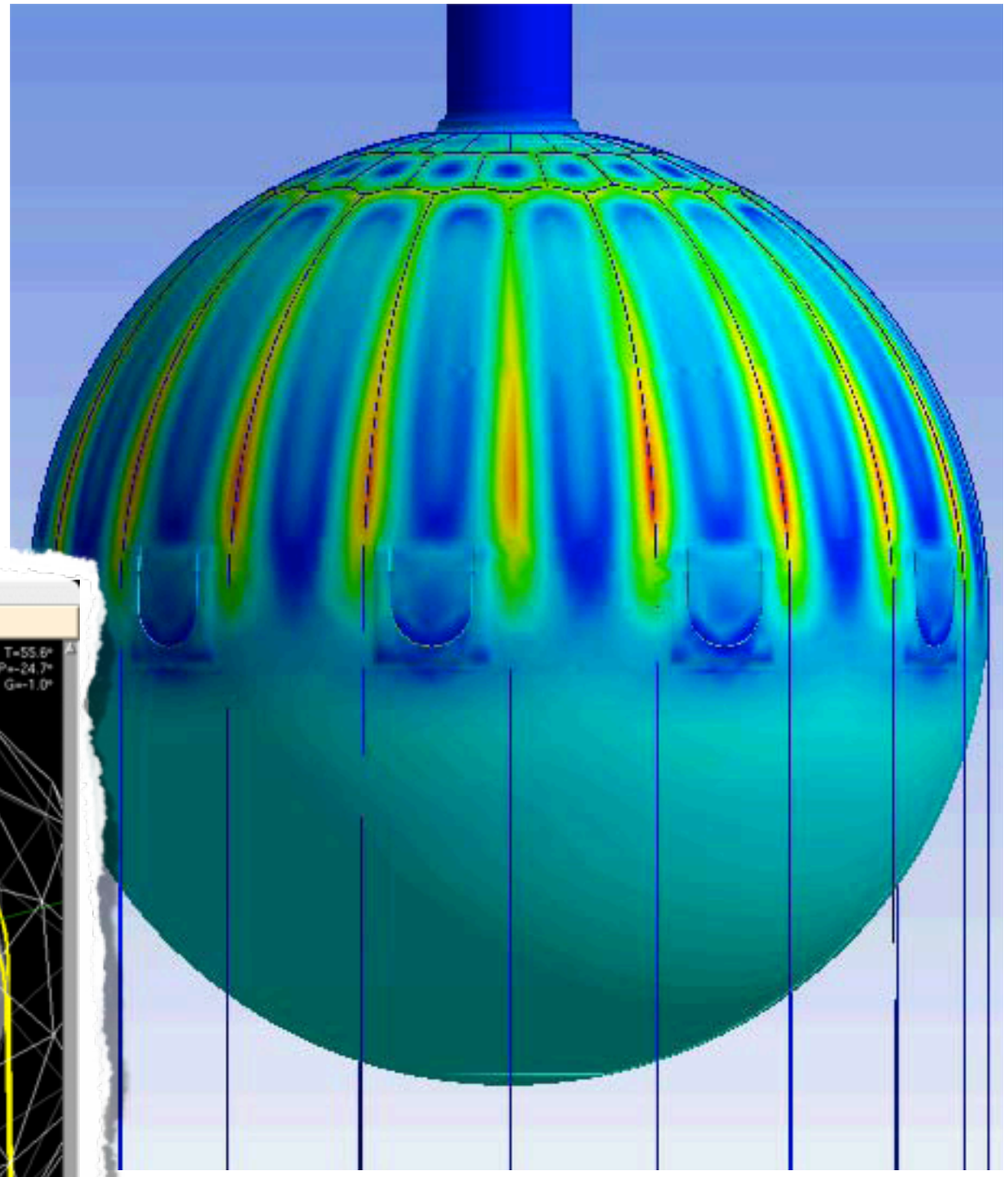

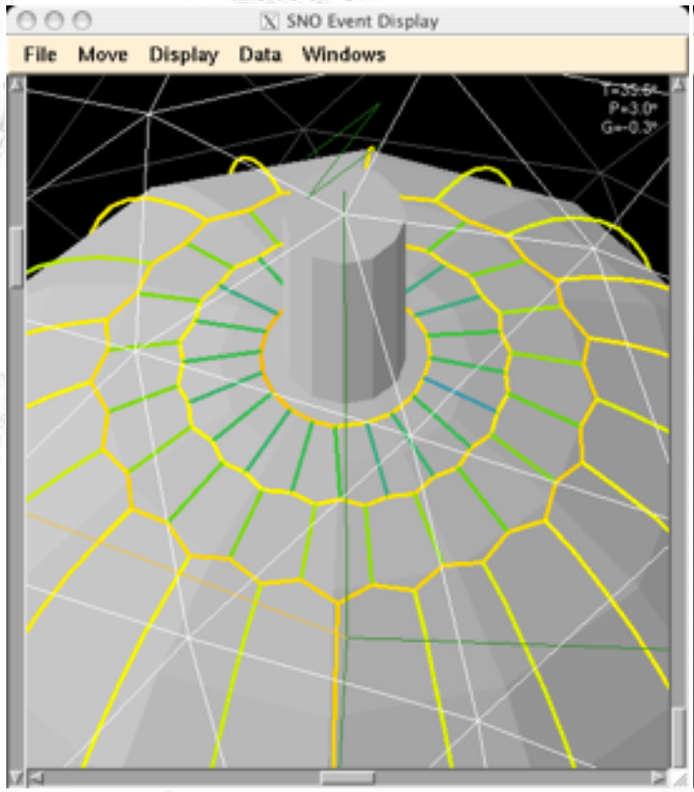

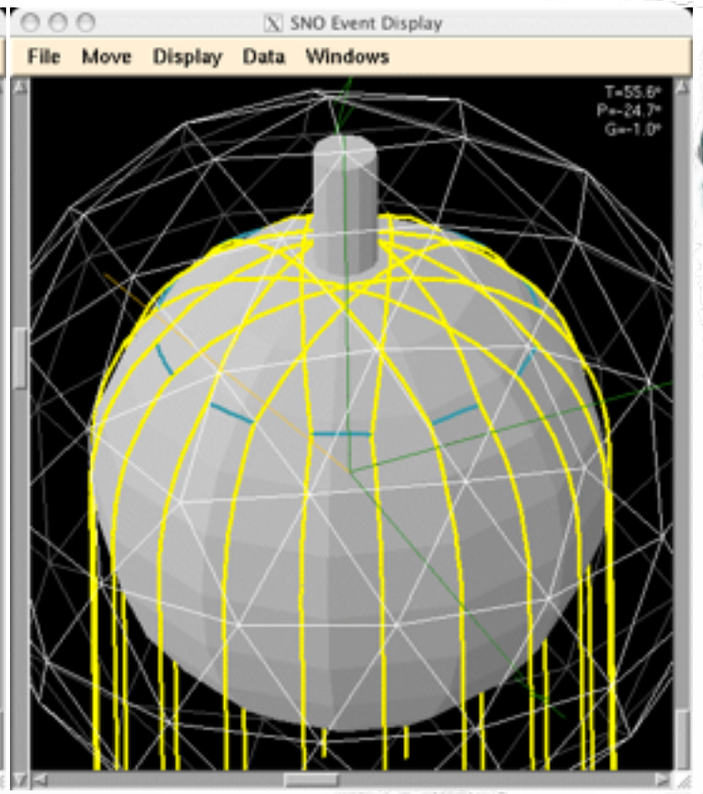

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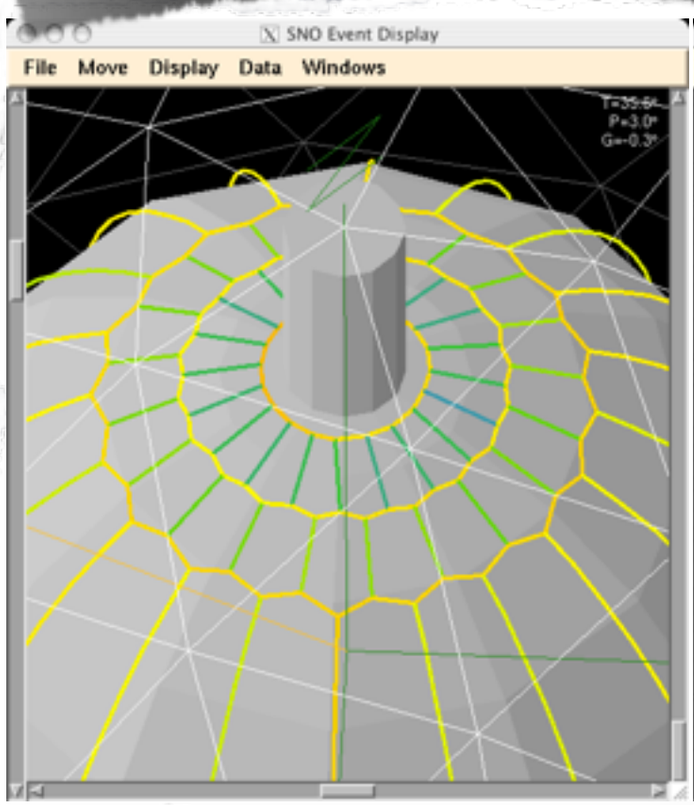

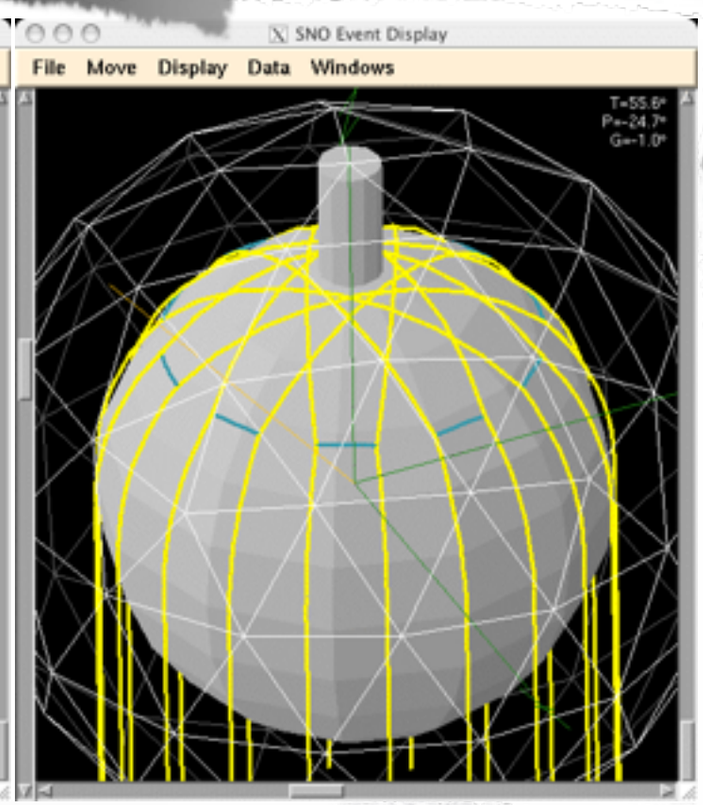

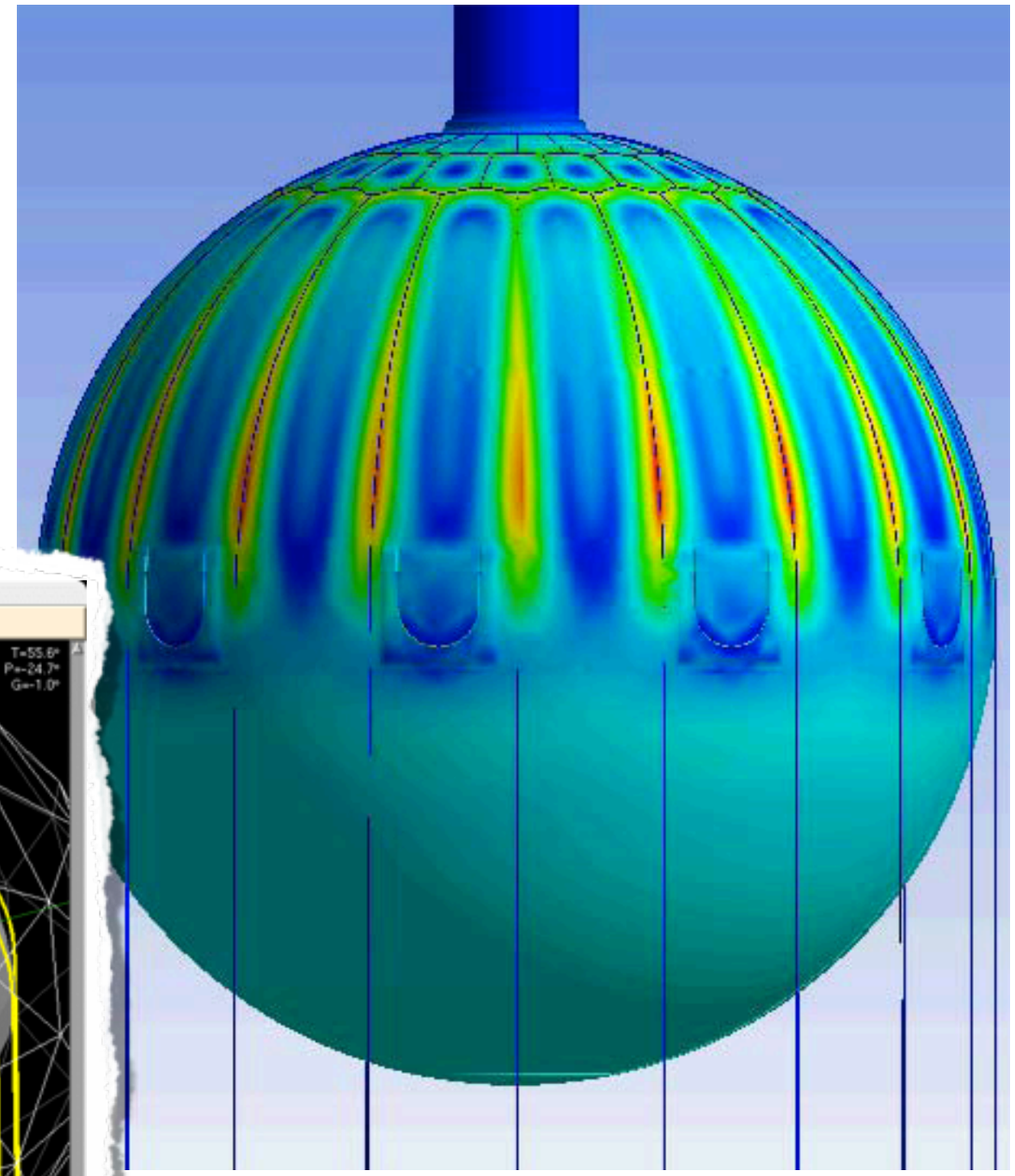

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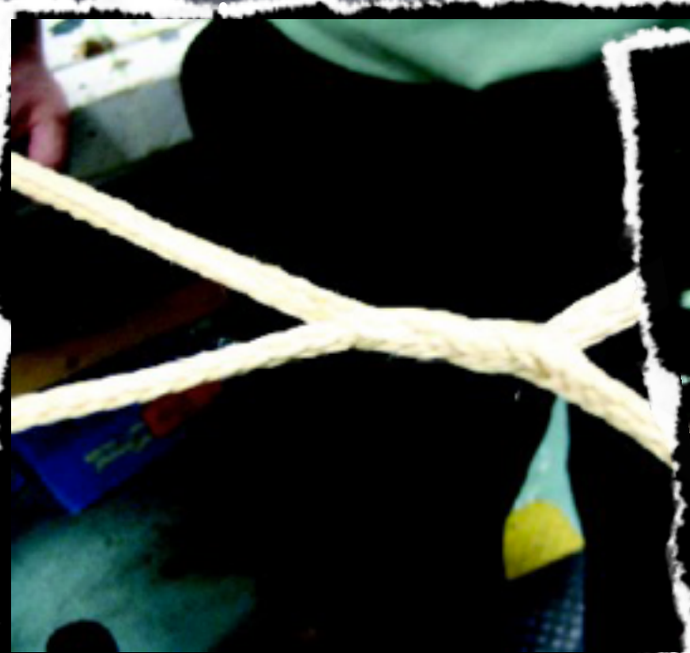
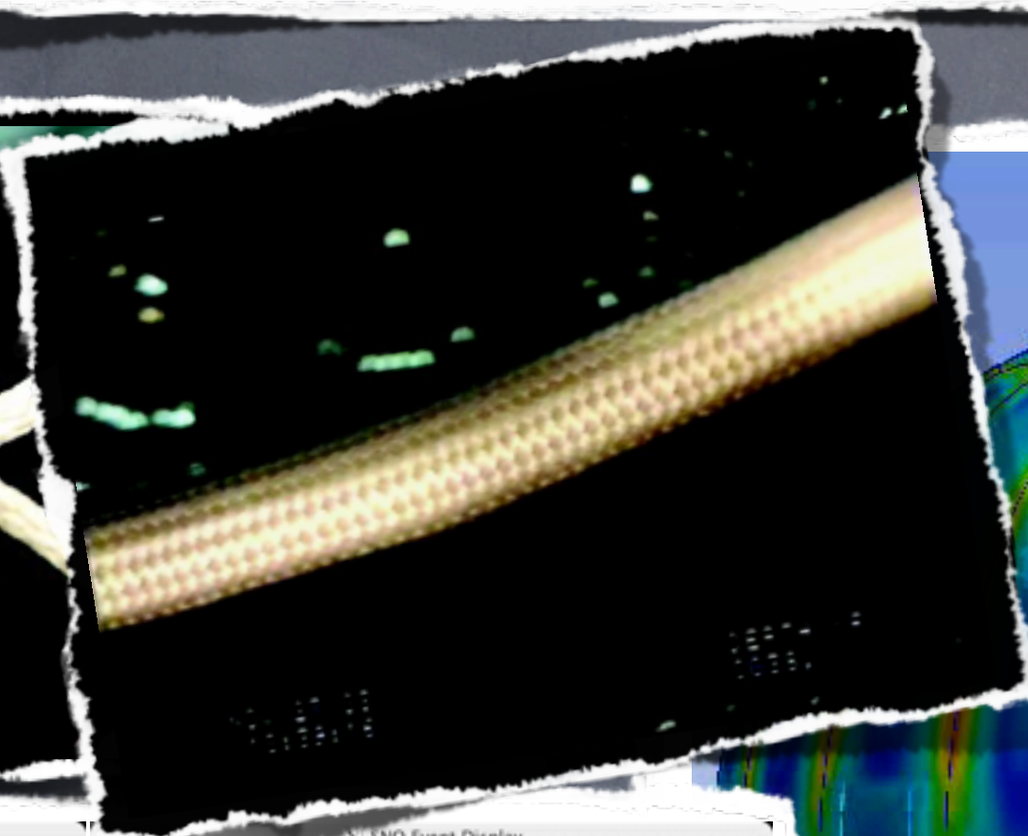
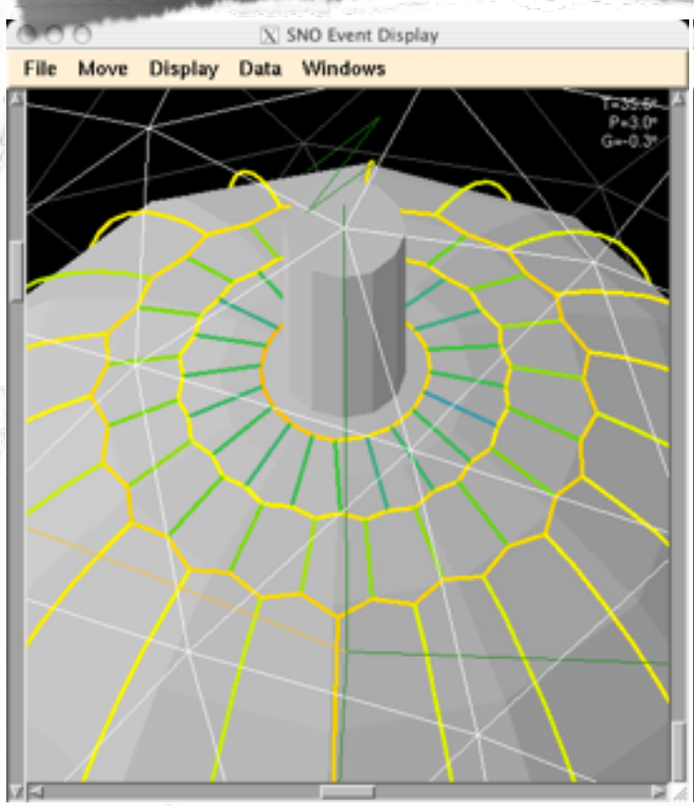
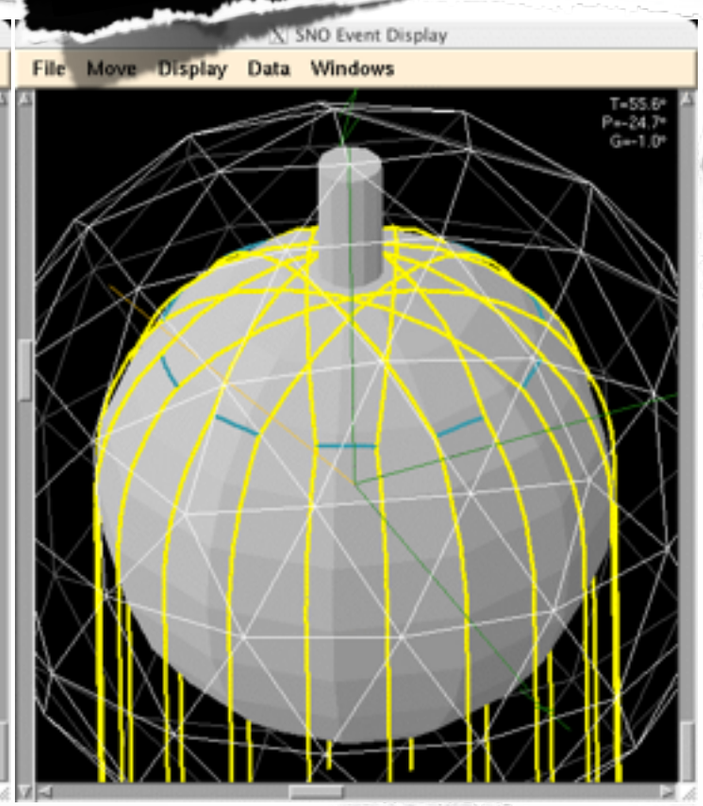
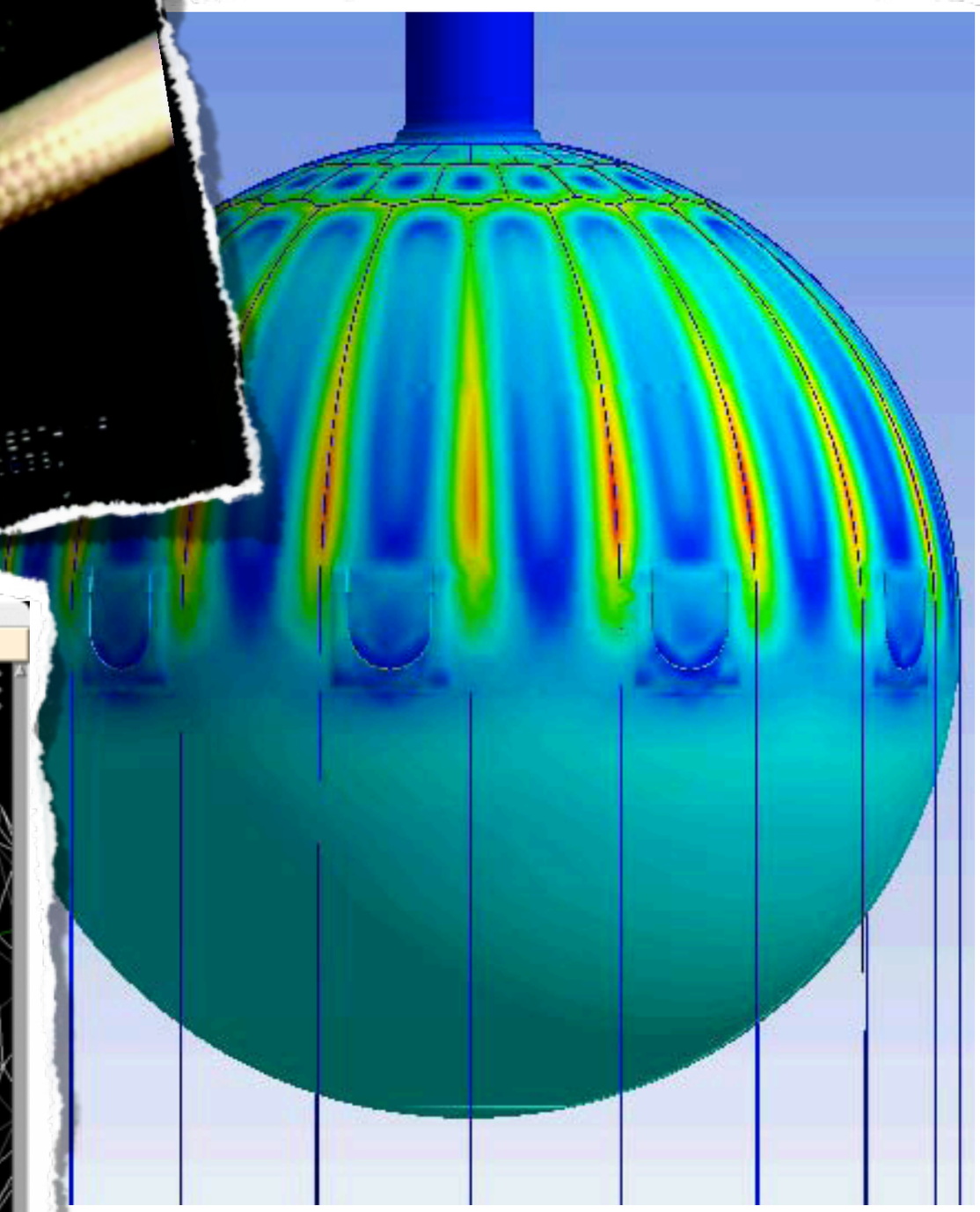










Electronics: Translation

SNO electronics

9728 channels:

- 4 PMTs per daughterboard
- 8 DBs per motherboard
- 16 MBs per crate
- 19 crates

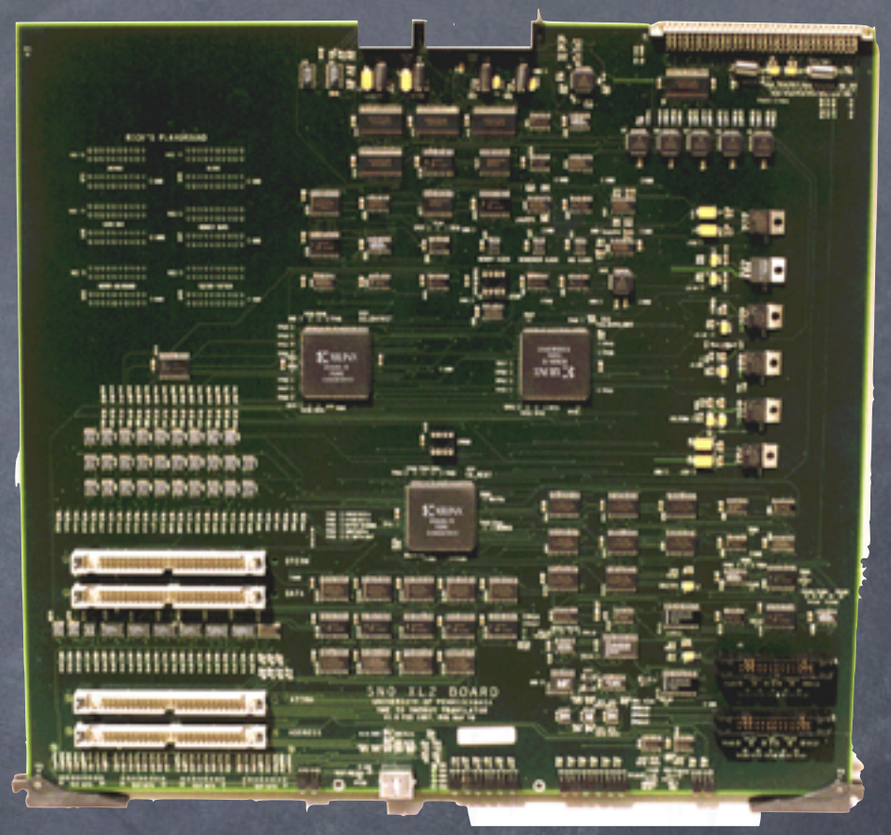
3 charge + 1 time per channel

VME-like "SNOBUS" interface

Single-crate readout

⇒ 2Mbit/s max bandwidth

XL2



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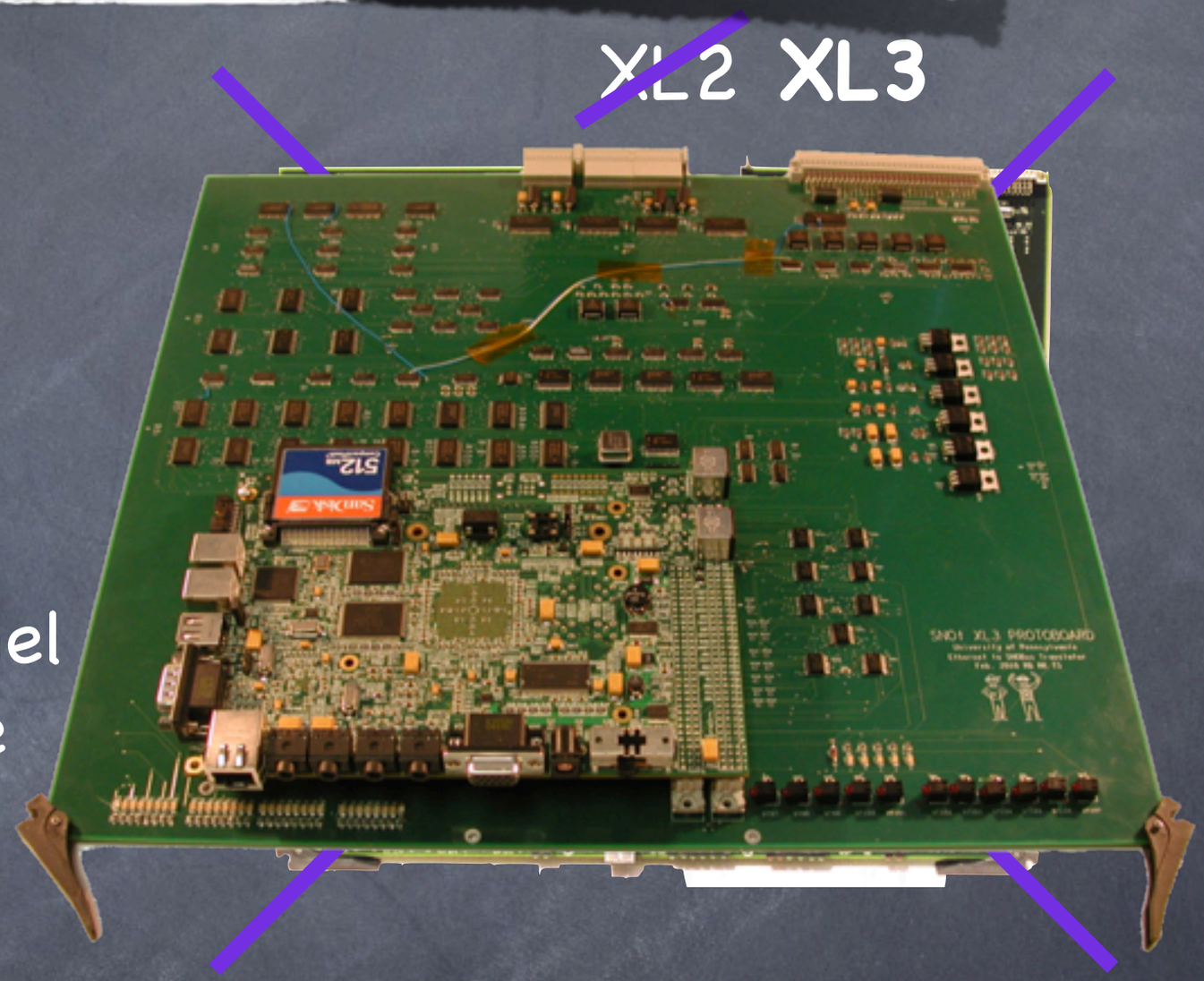

SNO+ electronics

New custom crate-readout cards in each crate

Autonomously push data to central switch

Via TCP/IP - robust, natural combination

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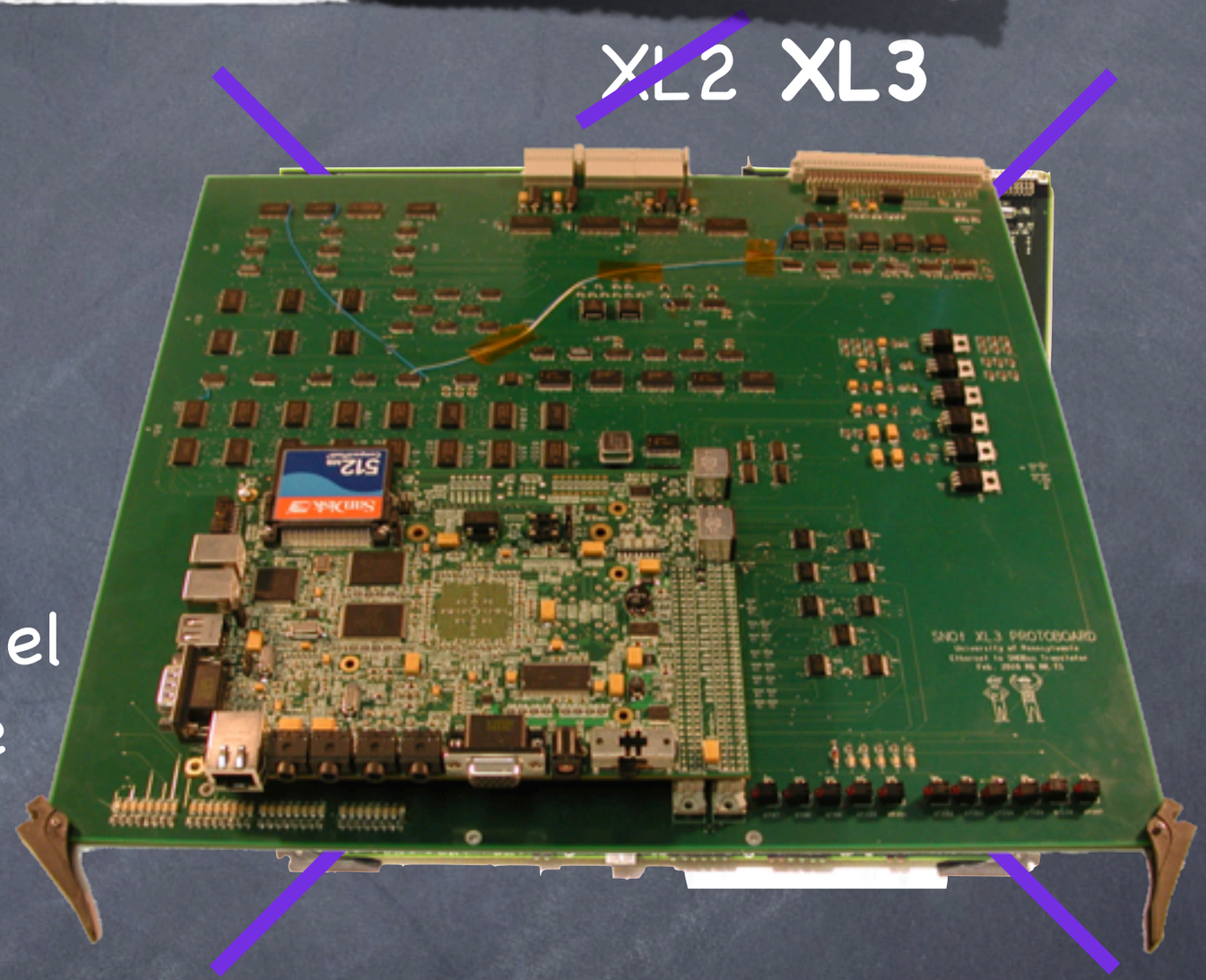
Single-crate readout

⇒ 2Mbit/s max bandwidth



SNO+ electronics

New custom crate-readout cards in each crate

Autonomously push data to central switch

Via TCP/IP - robust, natural combination

New bandwidth 250Mbit/s

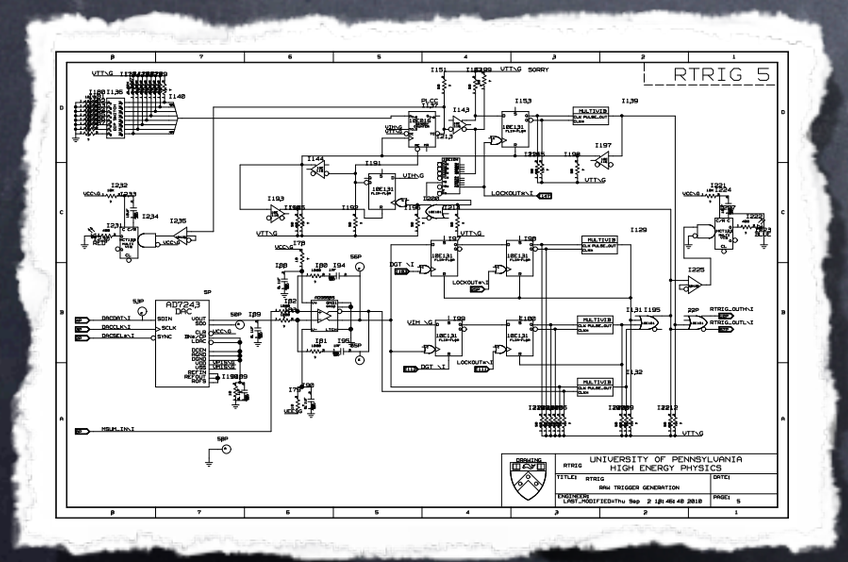
Electronics: Trigger

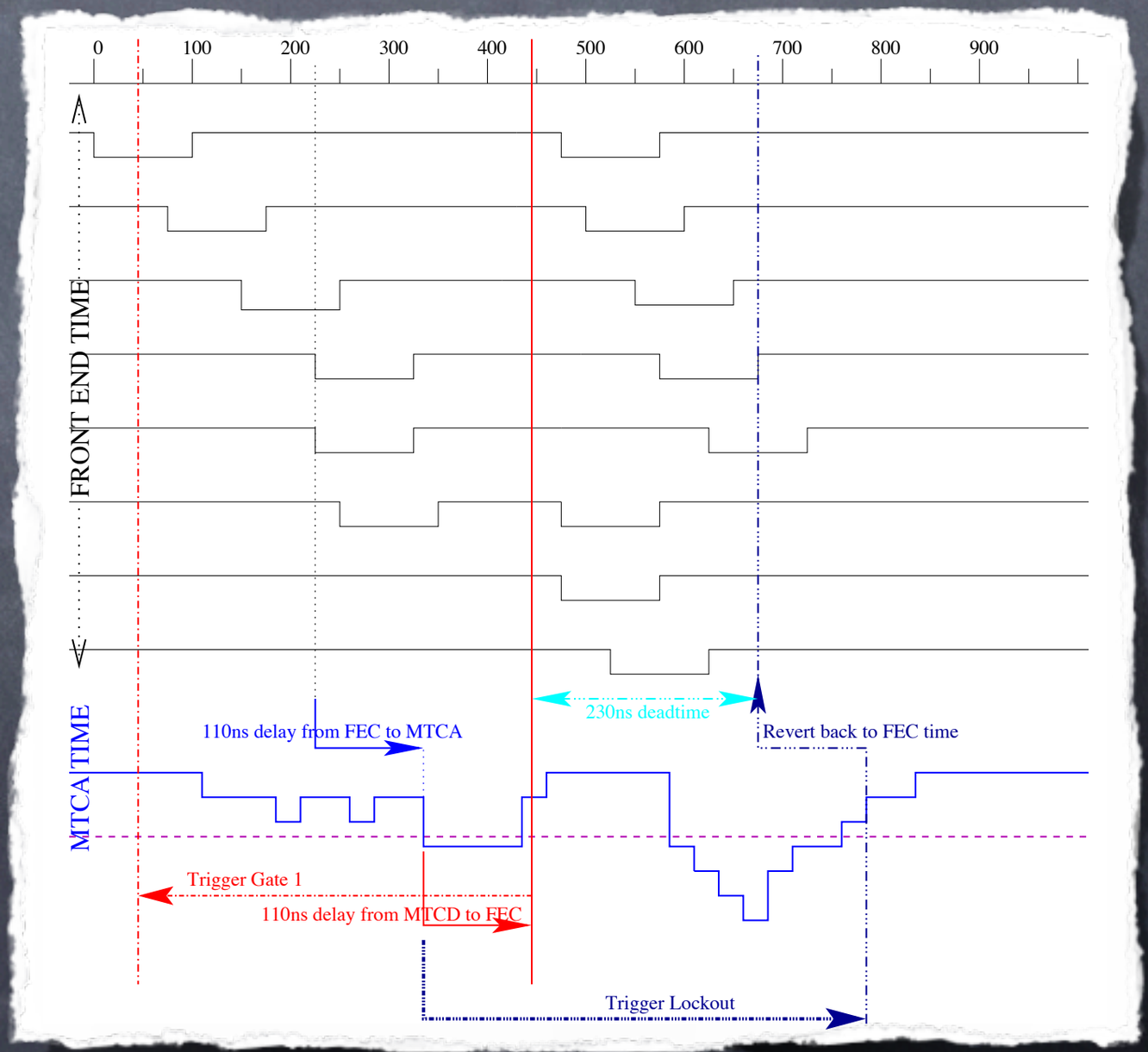
Higher rates / occupancy ⇒ requires new design

Discovered previously unknown deadtime in SNO trigger logic:
⇒ requires new logic

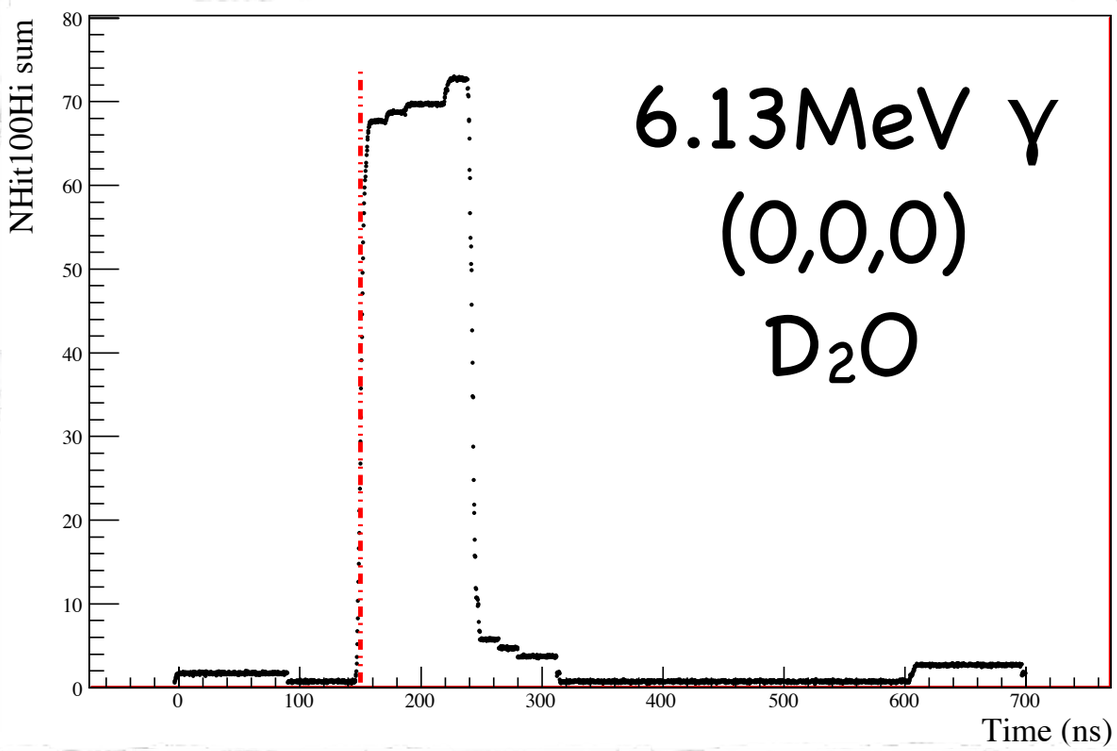
+ Ability to force retriggers

Important for tagging low E bkg coincidence events

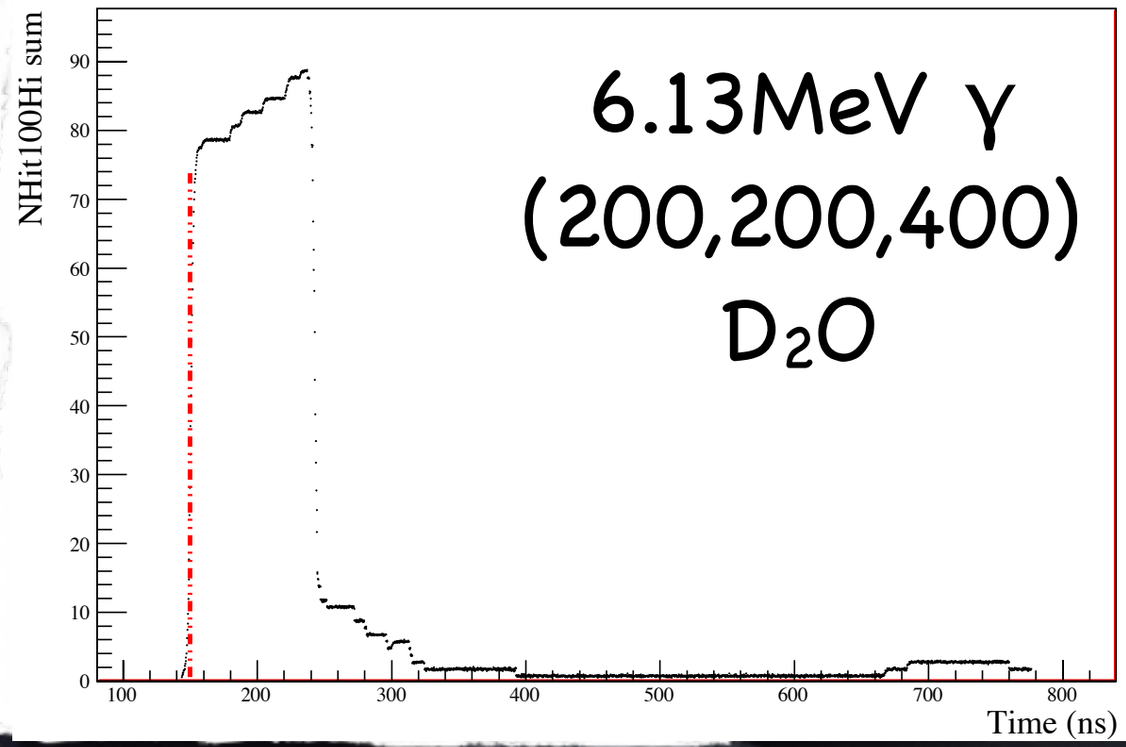


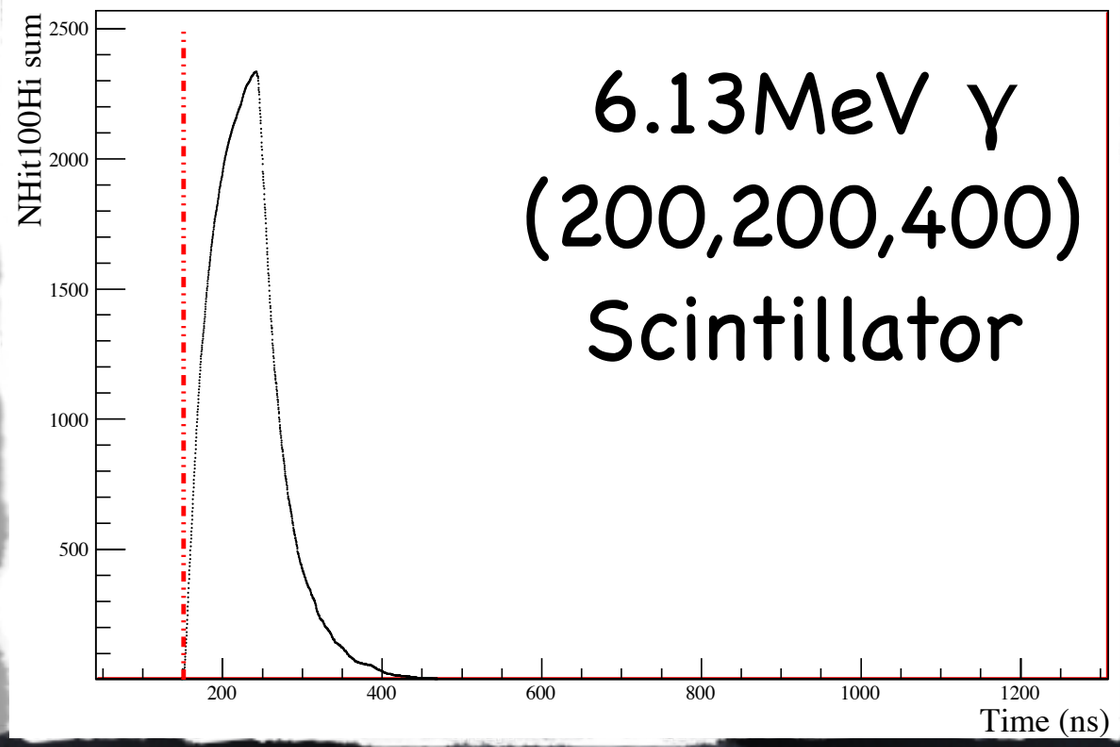


Electronics: Analogue Trigger Sum



SNO:
Analog Measurement Board evaluated trig sum properties:
- integral
- differential at t/h crossing
- peak height

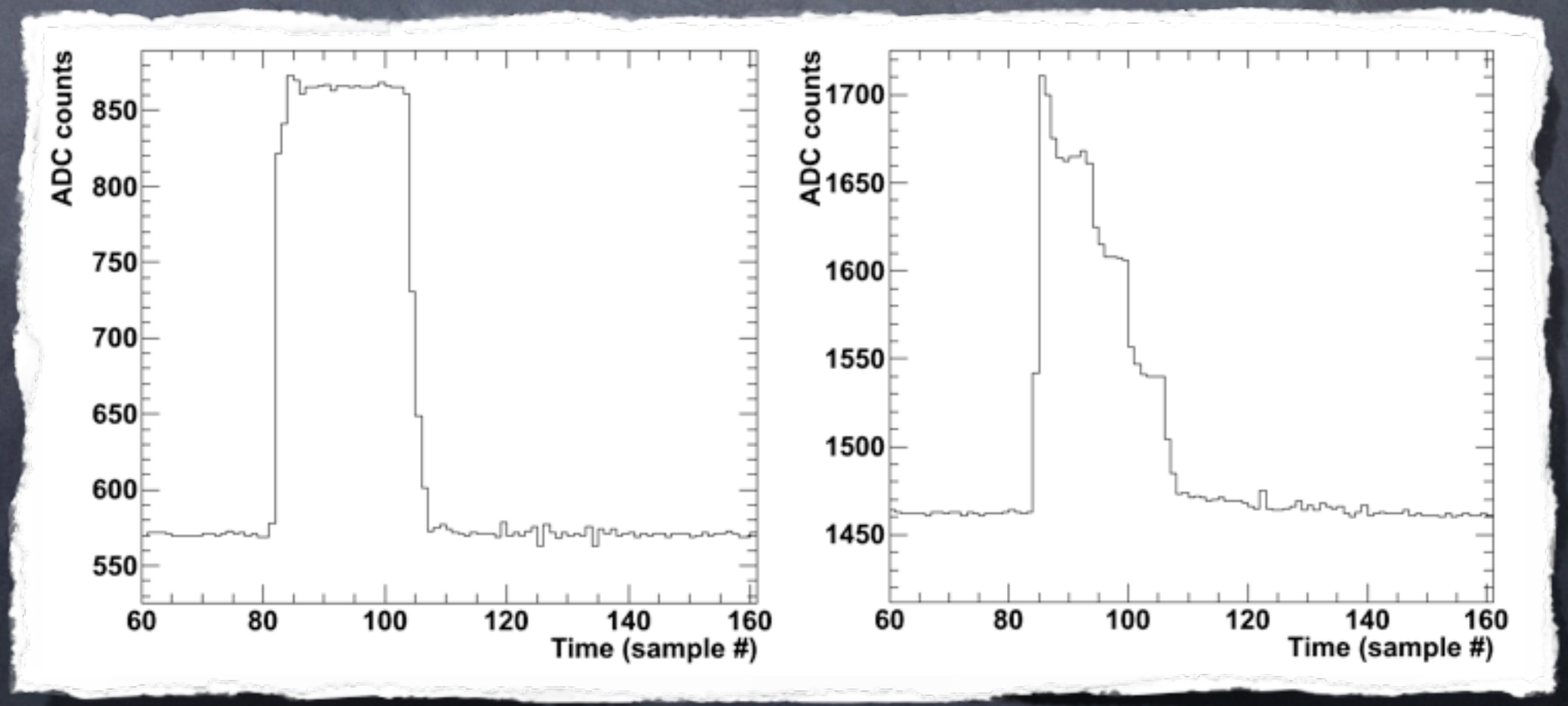




Electronics: Analogue Trigger Sum

CAEN v1720 8-channel
12-bit digitiser

SNO+:
- Fully digitised trigger-sum waveforms
- 250MHz (4ns sample size)
- 110-sample window: include inter-event deadtime



Analysis: Coordination

Existing fortran package (SNOMAN)
vs
New C++ package (RAT)

Jan 2009
First MC meeting

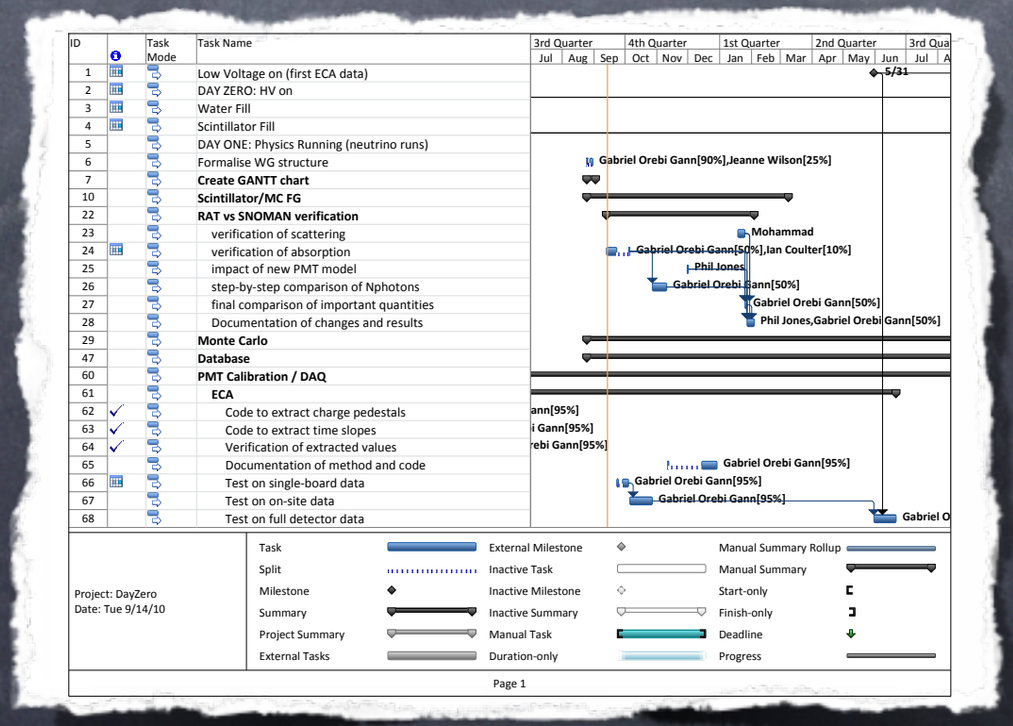
May 2010
First data-processing module

Mid 2011
Expect first data

Major undertaking
Short timescale
Limited manpower
⇒ optimise efforts

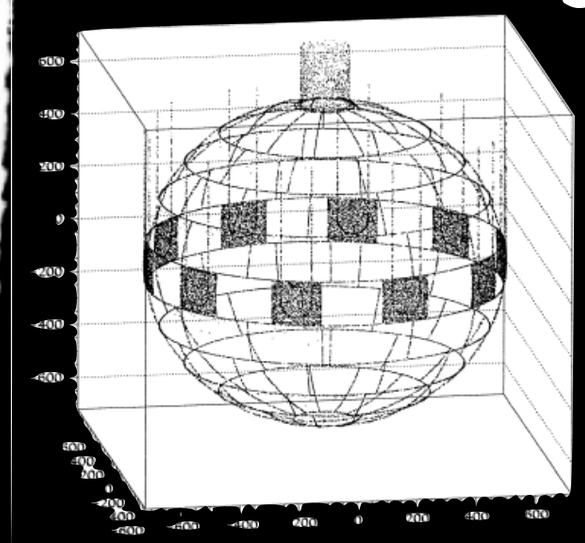
⇒ prioritise goals

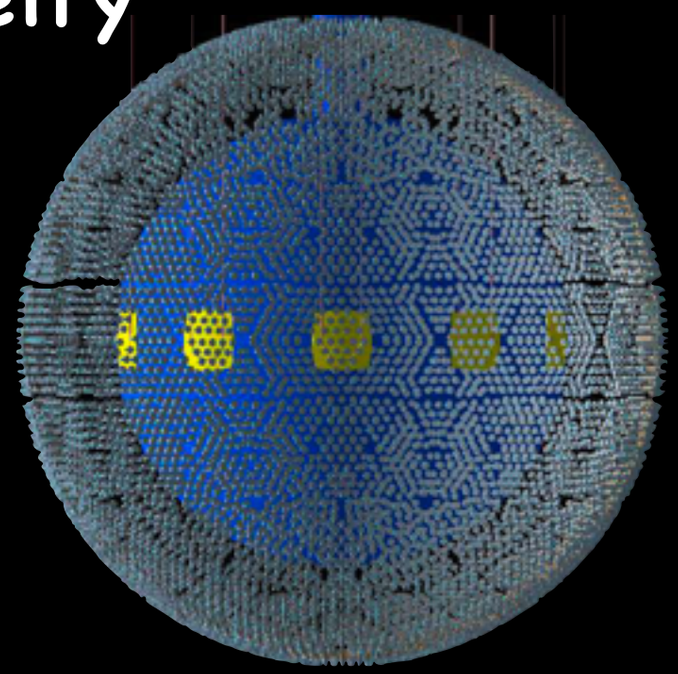
⇒ aim for Day Zero



Analysis: Simulation

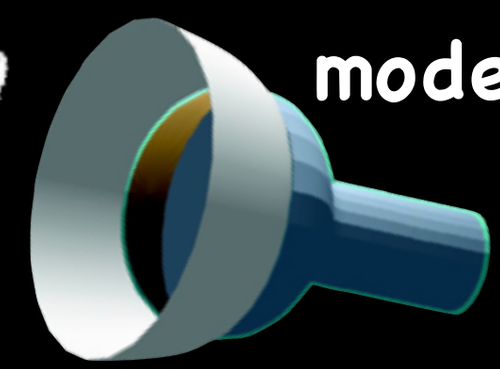
Full detector geometry

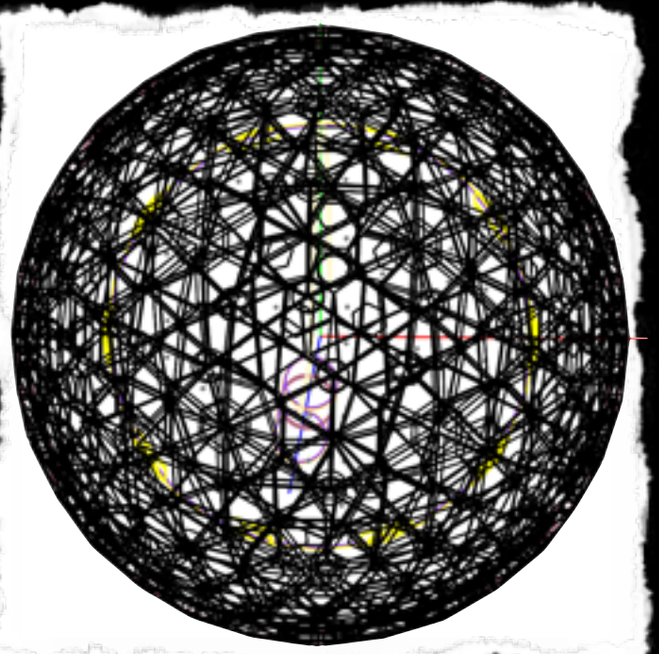


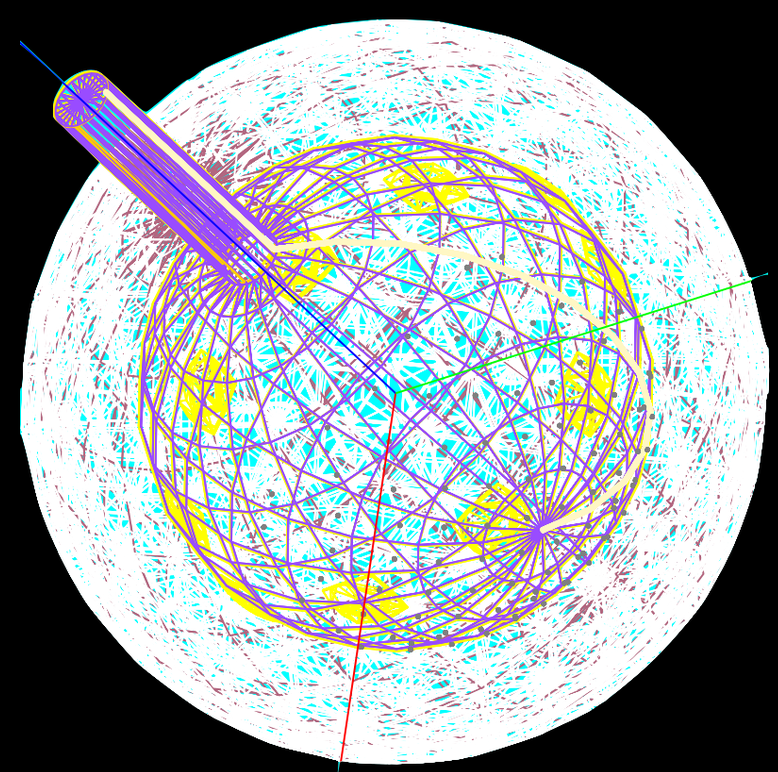


Full optical photon tracking

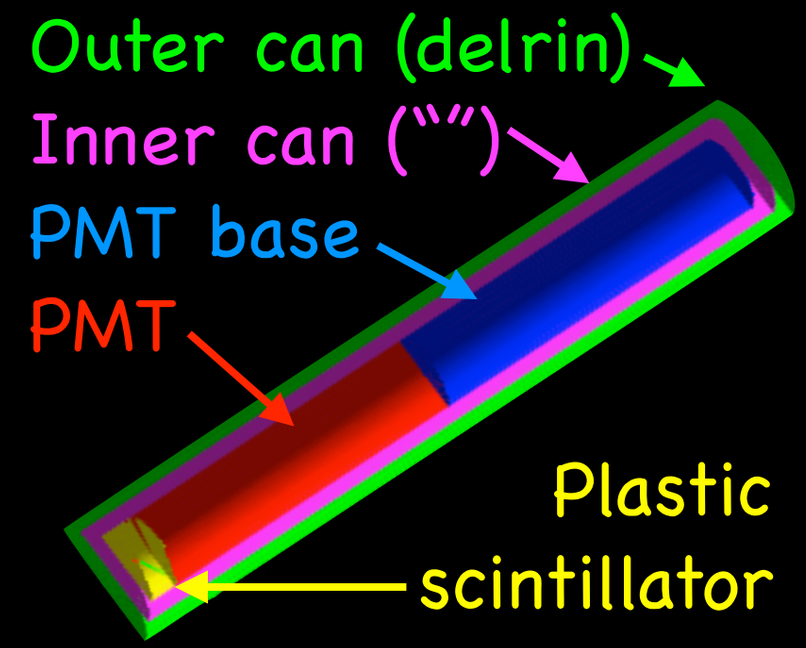
PMT + Concentrator model



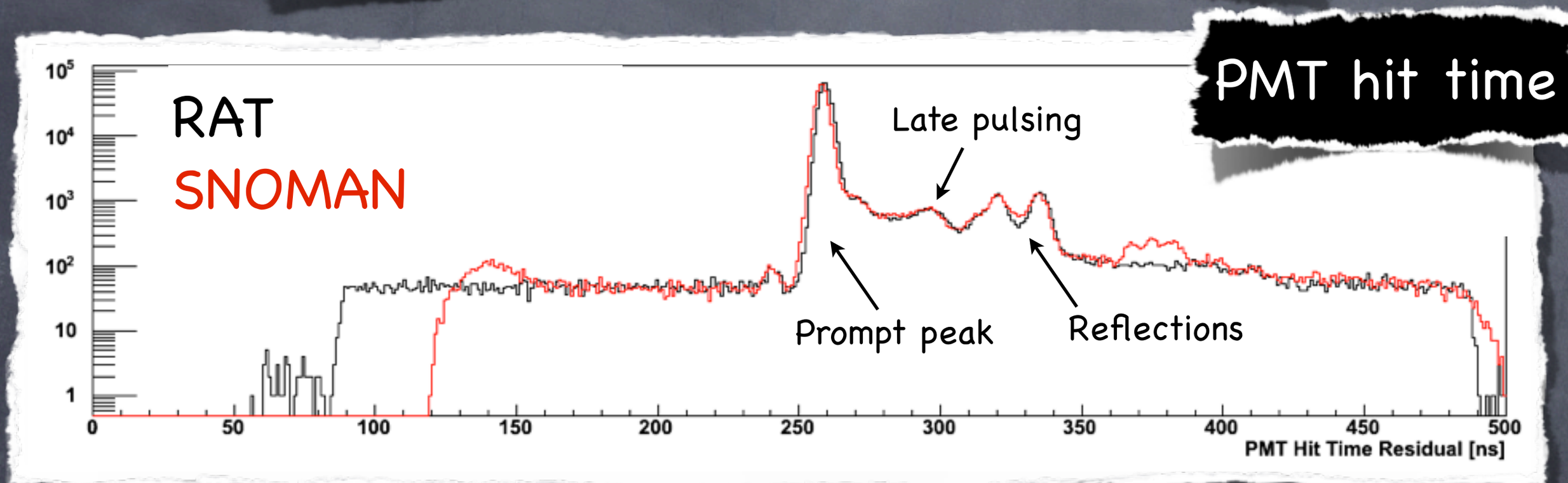


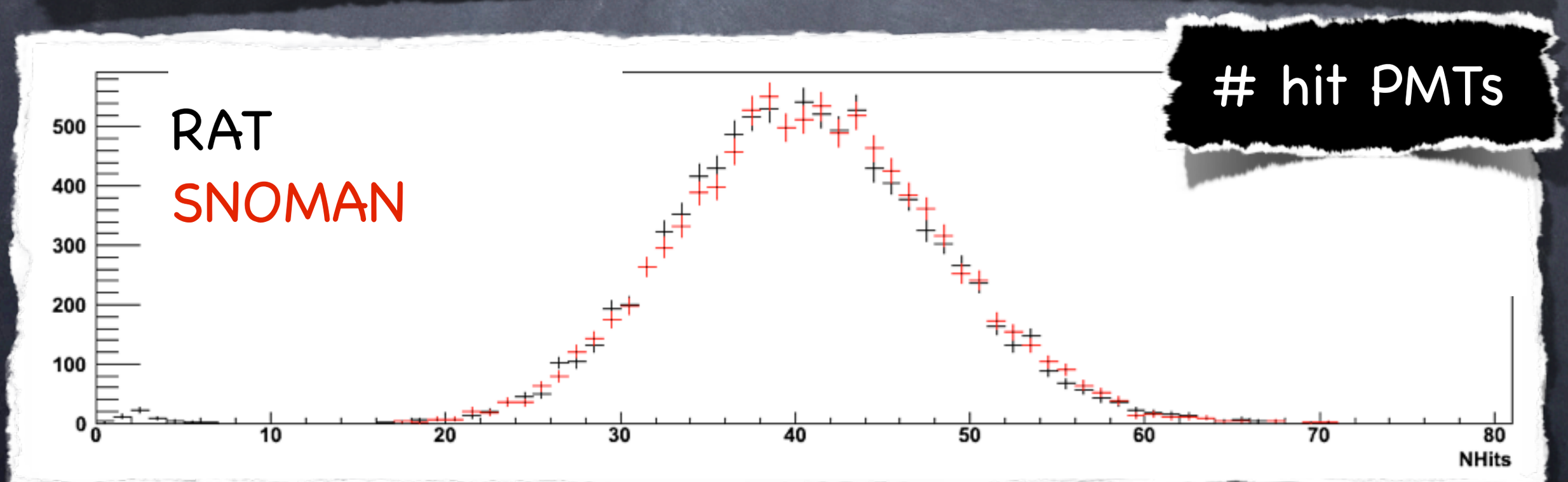


Calibration sources



Analysis: Verification



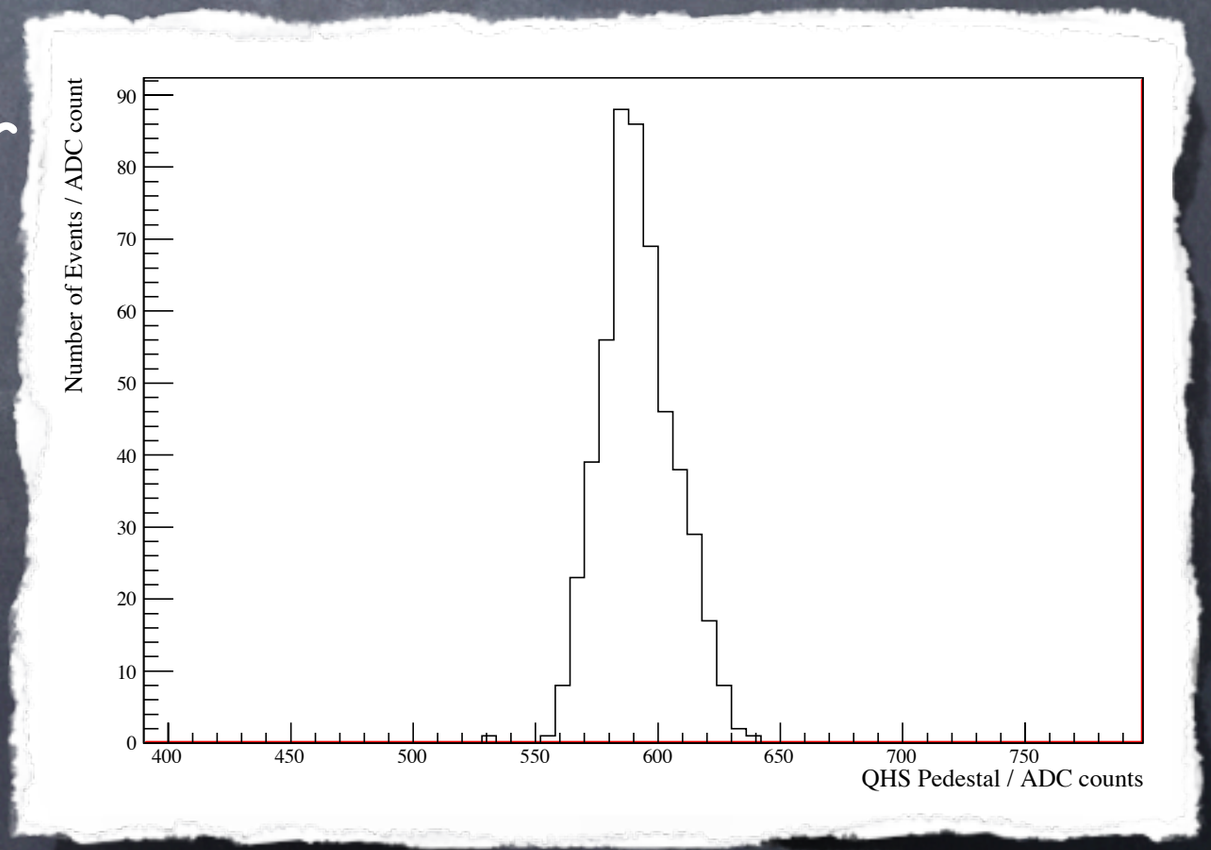


Analysis: Channel Calibrations

- Charge pedestals:
  'zero point' or 'baseline' charge
  i.e. charge measured in absence
  of photon hit

16 storage cells per channel
Use `ped' pulse to force trigger
10 events per cell

for each of:
16 cells * 32 channels *
16 cards * 19 crates
(= 155,648 cells)



Analysis: Channel Calibrations

FIRST SNO+ DATA!

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  Use `ped' pulse to force trigger
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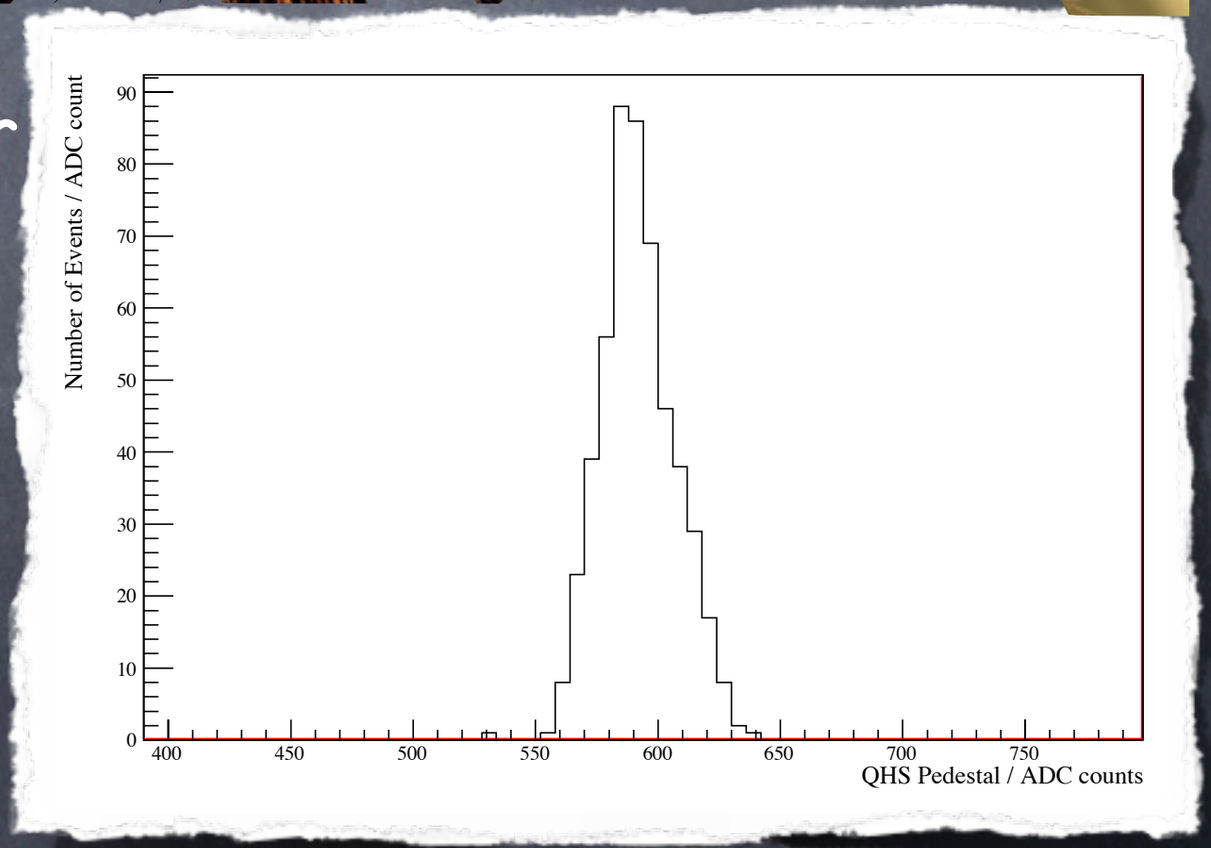

Looking Forward

- SNO+
  - Electronics installed: mid 2011
  - HV on: late 2011
  - Light water fill: late 2011
  - Scintillator fill: mid 2012
  - Solar Phase: Jan 2013
  - $0\nu\beta\beta$ Phase: 2013+

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  - 0νββ Phase: 2013+

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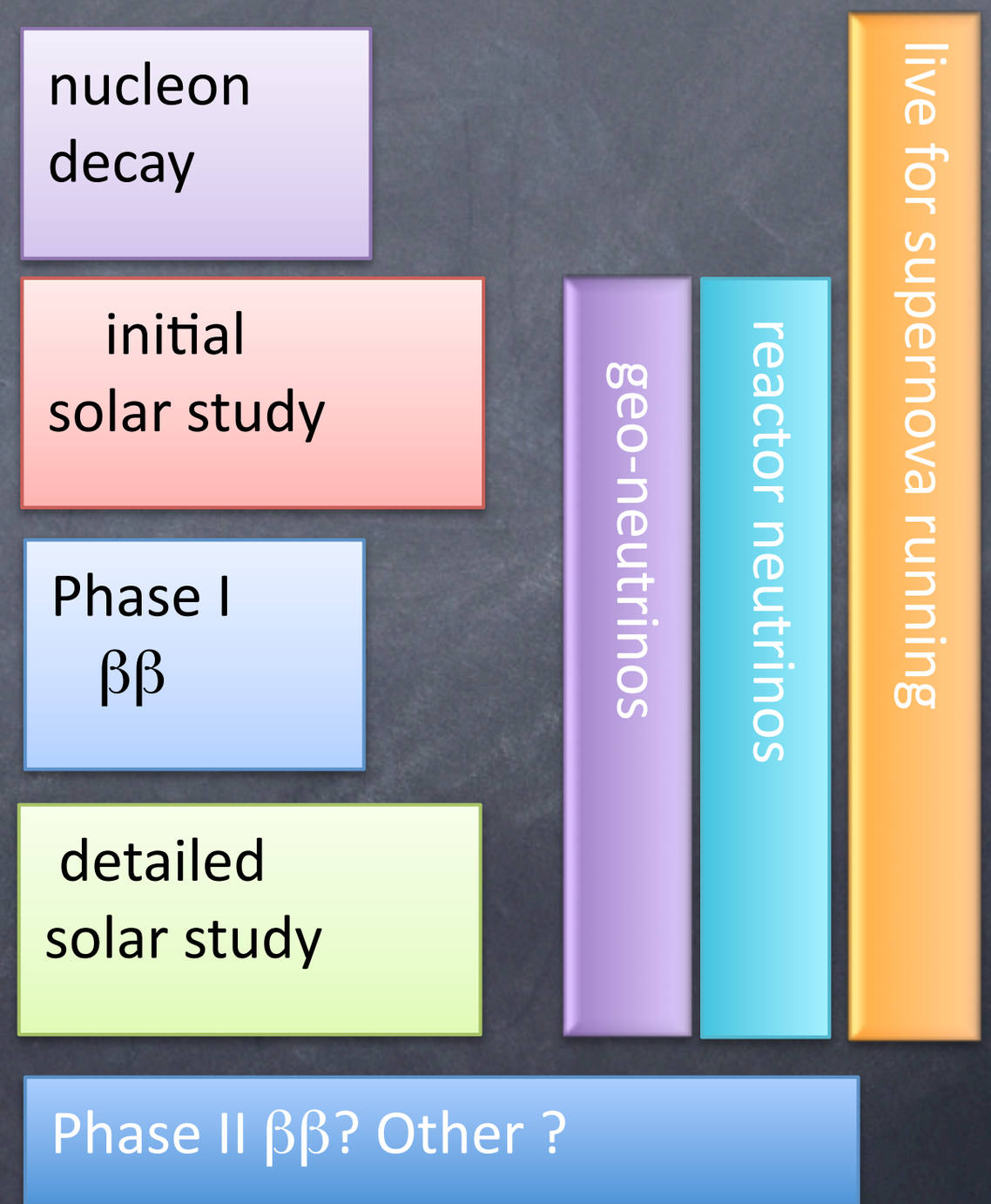
  - Light water fill: late 2011 → Detector calibrations
  - Scintillator fill: mid 2012 → Scintillator calibrations
  - Solar Phase: Jan 2013 → Solar ν Physics!
  - 0νββ Phase: 2013+ → 0νββ Search!

Physics Plan

- SNO+
  - Light Water running (Jan 2012)
  - Scintillator run (Jan 2013)
  - Nd-loaded scintillator (Mid 2013)
  - Pure scintillator (II) (2016?)



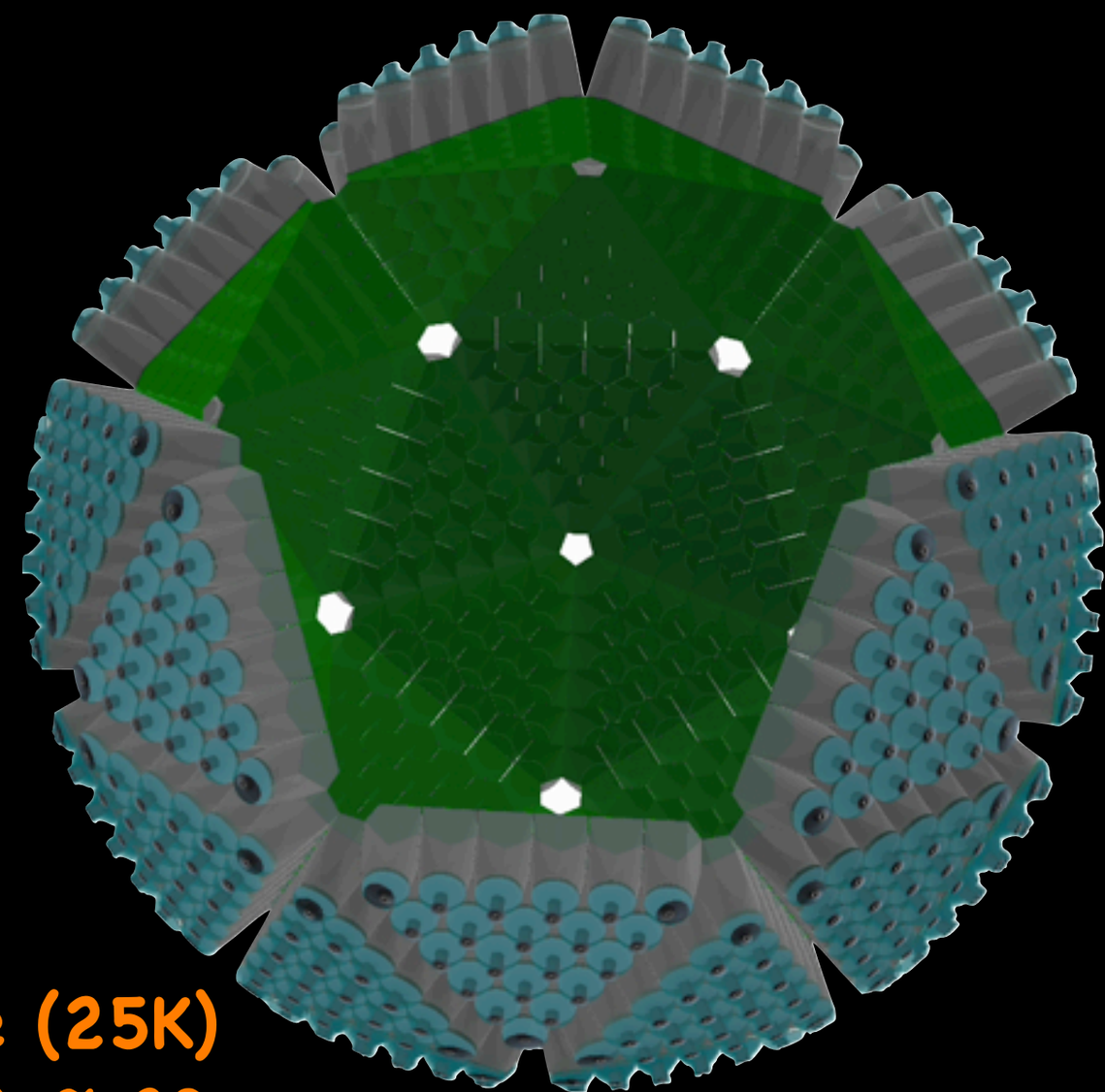
Looking Forward

- Beyond SNO+

CLEAN:

Solar ν + WIMP search

- Liquid noble-gas target
- 50ton (~2m target vol)
- Interchangeable target:



1. Ar (T = 85K)

- A ~ 40 (2* DM rate)
- Self-shielding
- Very cheap
- ^{39}Ar bkg (1 Bq/kg)
  $T_{1/2}$ = 250 yr

2. Ne (25K)

- A ~ 20
- Very clean
- Cheaper than Xe, He

~1% pp measurement

Summary

Summary

SNO+

- Currently being converted from original SNO experiment
- A multi-purpose neutrino experiment
- Broad physics programme

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Solar ν Physics at SNO+

- Insight into νs & the Sun
- Test oscillation theory
- Test solar models
- Potential for exciting new discoveries

Summary

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- A multi-purpose neutrino experiment
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Solar ν Physics at SNO+

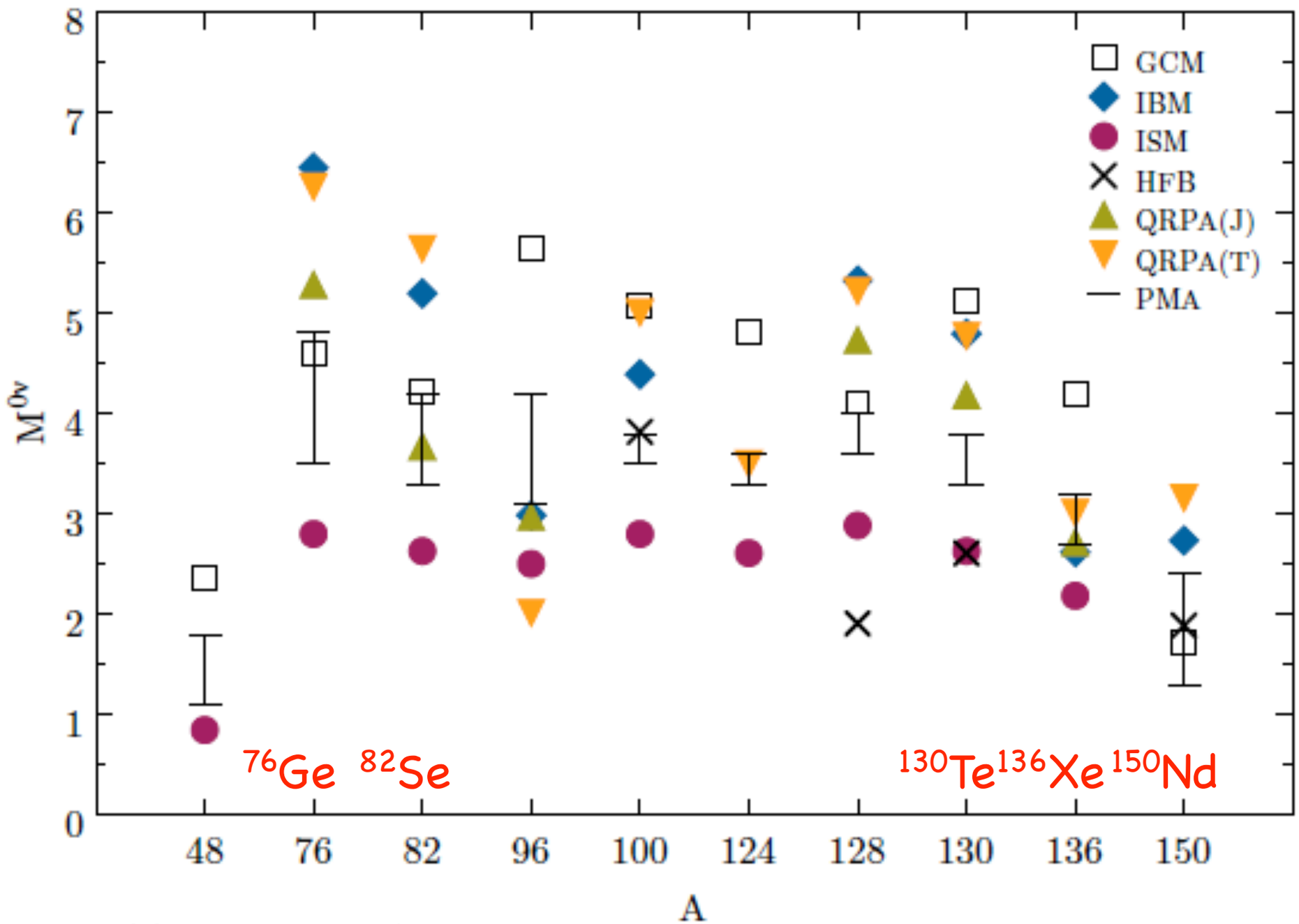
- Insight into νs & the Sun
- Test oscillation theory
- Test solar models
- Potential for exciting new discoveries

Status report

- New hardware commissioned
- Detailed simulation in place
- Focus on readiness for Day Zero (first data!)

Nuclear Matrix Elements

Different techniques can give quite different results for NME values:



Sense and Sensitivity of ββ expts: arxiv/1010.5112

0νββ Experiments

Expt Approach	Pros	Cons
Large self-shielding calorimetry	Self-shielding: low ext bkg Large M, easily scalable Source in / source out caln High detection efficiency	Lower E resn
Xe TPC	Relatively easy to enrich No long-lived r/a isotopes Scintn + ionisation signals	$Q_{\beta\beta}$ ~ 2.46MeV: close to ^{208}Tl, hard to disentangle 2νββ not yet observed
High-resolution calorimetry	Excellent E resn Simple, compact	No tracking Ltd bkg suppression (exc E) Poor self-shielding
Tracko-calo expt	Good bkg rejection	Low detection efficiency Low E resn Very hard to scale

0νββ Experiments

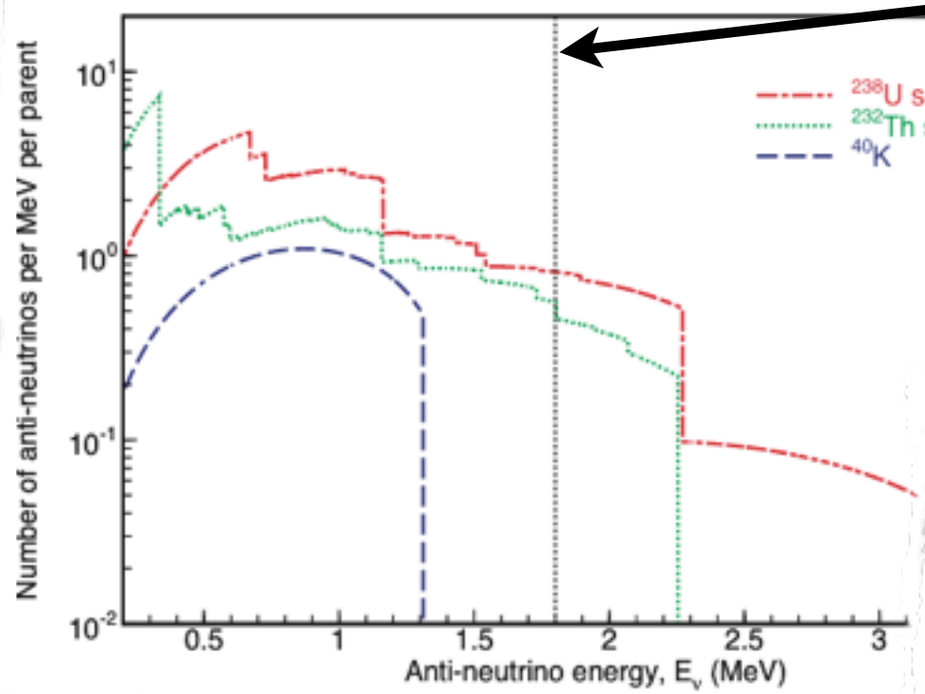
Expt	Isotope	Resn (% at $Q_{\beta\beta}$)	Bkg rate (cts/keV/ton/yr)	Efficiency	Mass (kg)	
SNO+	**^{150}Nd**	**<3.0**	**2.0**	**1.00**	**50**	Large self-shielding calorimetry
KamLAND-Zen	^{136}Xe	4.0	0.5	0.80	400	
NEXT-100	^{136}Xe	1.0	0.2	0.25	100	Xe TPC
EXO-200	^{136}Xe	3.5	2.5	0.40	200	
CUORE	^{130}Te	0.4	50	0.85	200	High-resolution calorimetry
Gerda/ Majorana	^{76}Ge	0.2	3.7	0.85	40	
Super-NEMO	^{82}Se	5.0	0.4	0.25	50	Tracko-calo expt

Sense and Sensitivity of ββ expts: arxiv/1010.5112

Geo Neutrinos

Electron antineutrinos from U, Th, K decay in the Earth

Inverse β decay threshold



Check models of Earth's heat production

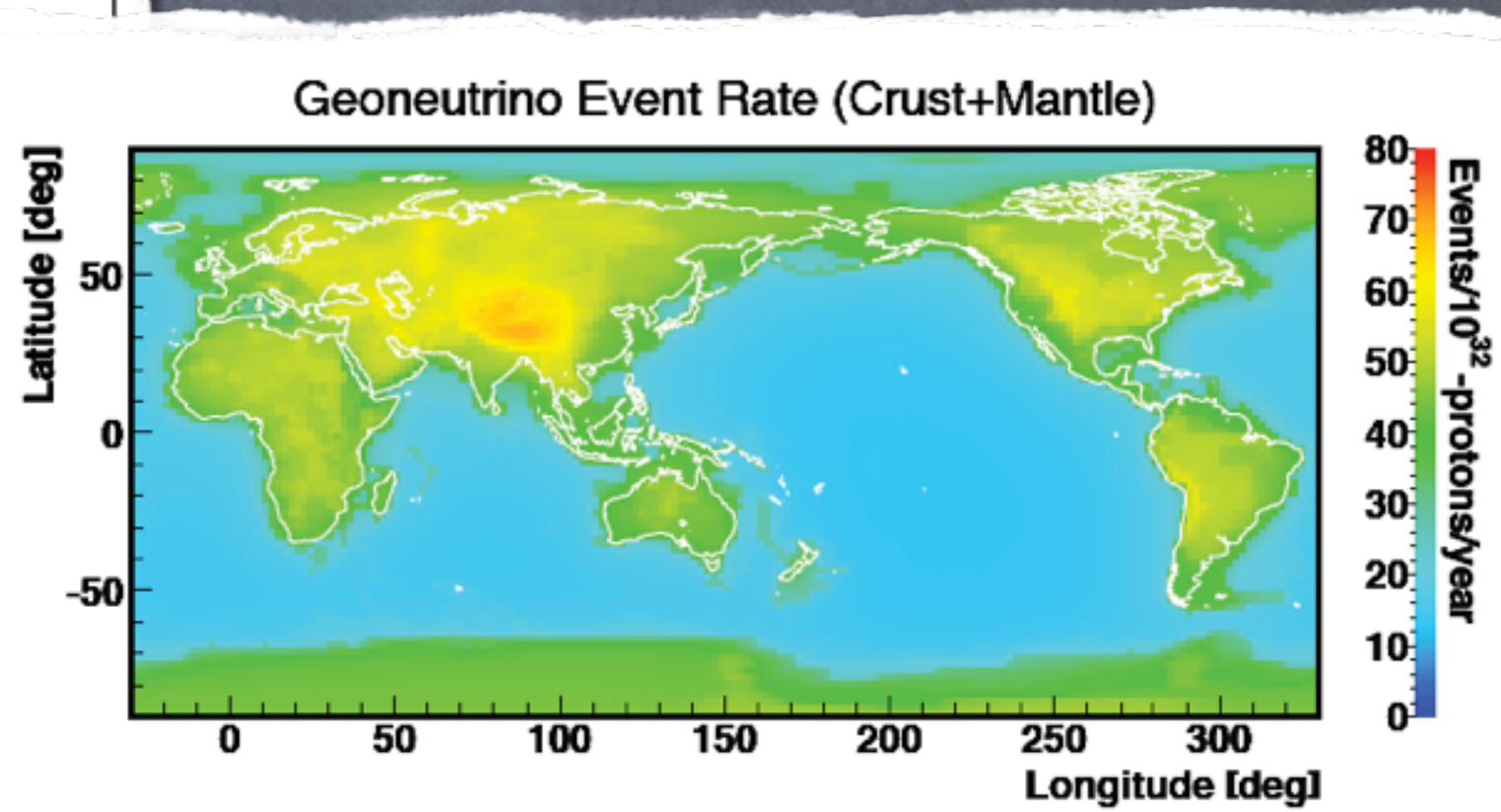


Image: S. Enomoto

N. Tolich,
Neutrino 2010 presentation

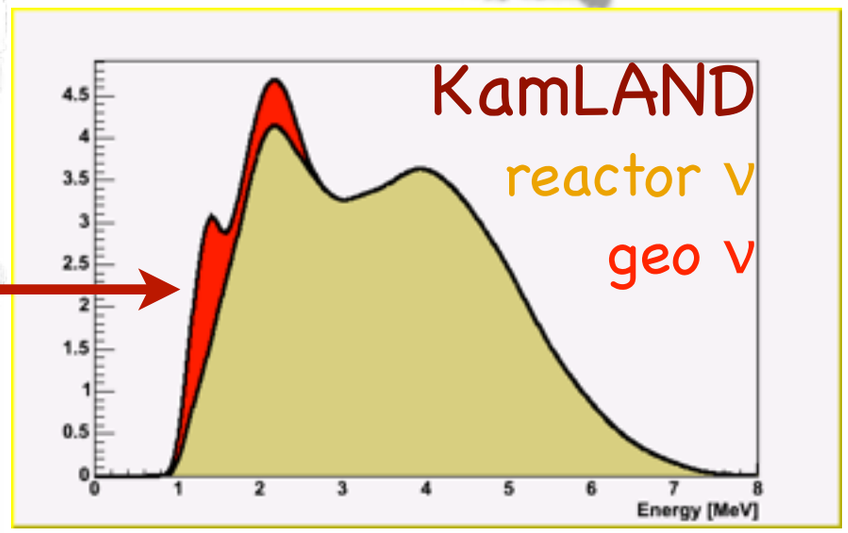
All figures assume Sanshiro Enomoto's model for U, Th content of crust and mantle

Geo Neutrinos: SNO+

~20% mantle contribution

Smaller reactor background than KamLAND

Expect ~20 events / yr



kamLAND:

~500 reactor ν

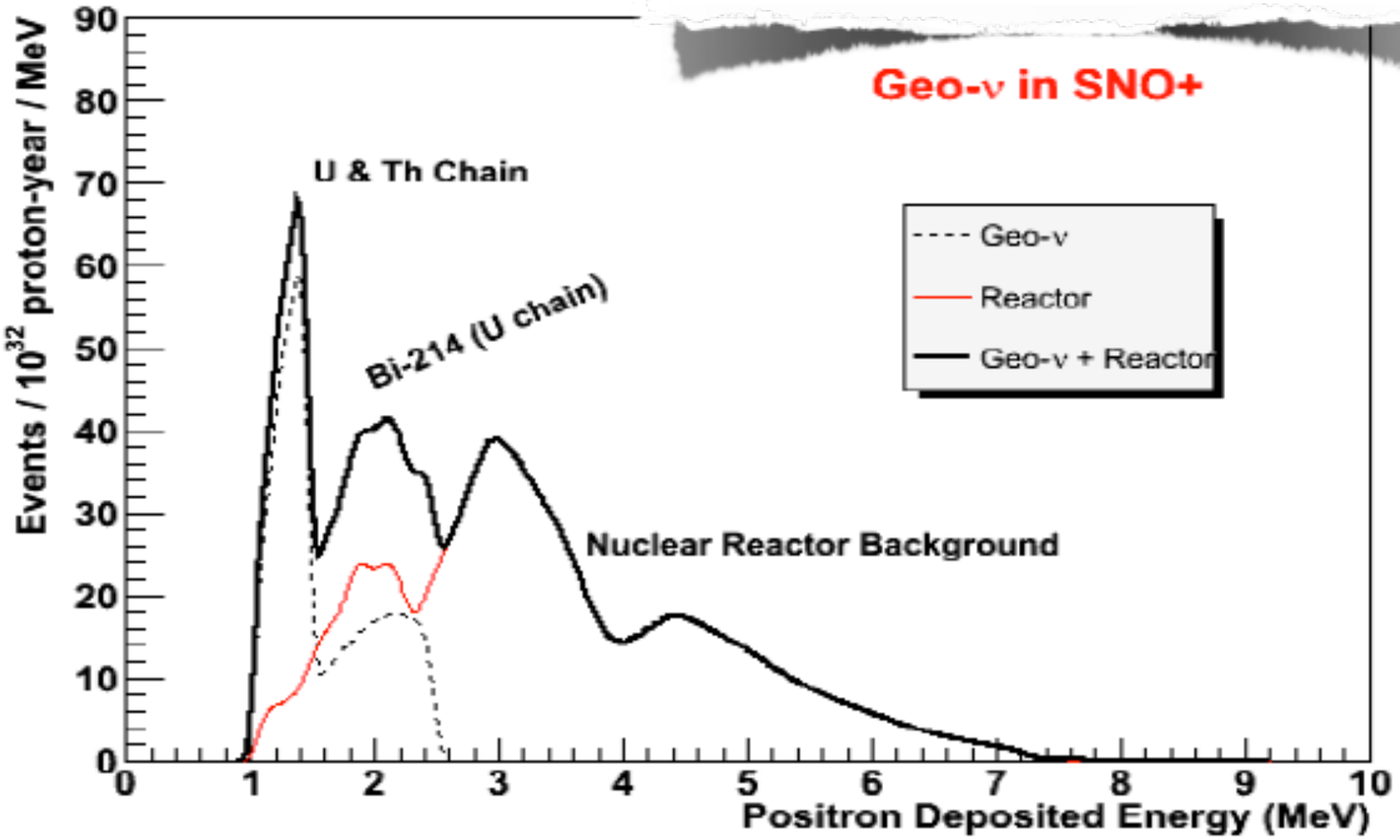
vs

~100 geo ν

⇓

$\Phi_\nu = 4.3 \pm {}^{1.2}_{1.1} *10^6 cm^{-2}s^{-1}$

(K. Inoue, neutrino 2010)

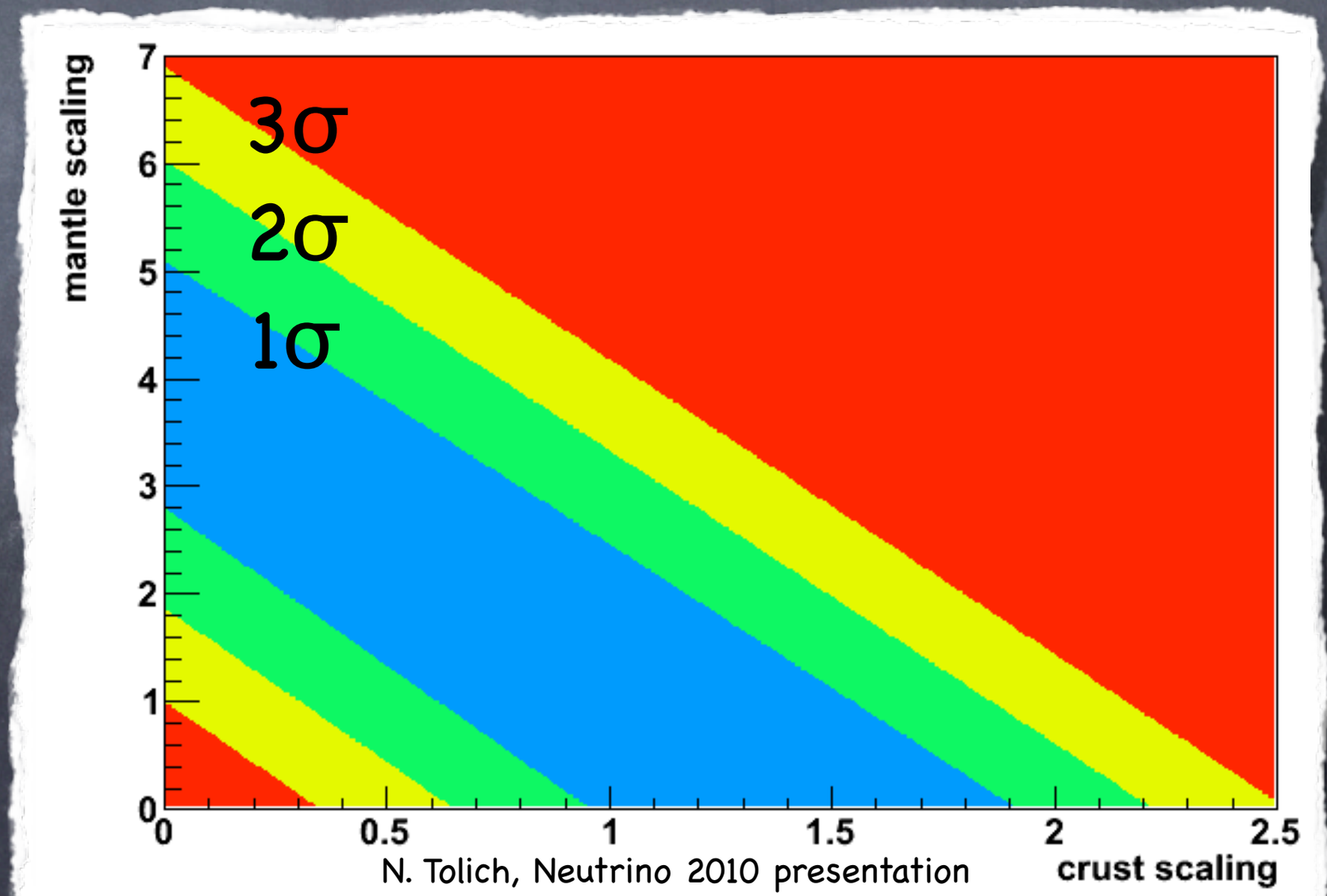


Geo Neutrinos: Status

Flux measurements ($*10^6 cm^{-2}s^{-1}$):

KamLAND (2010): $4.3 \pm {}^{1.2}_{1.1}$ (K. Inoue, neutrino 2010)

Borexino (2010): $7.1 \pm {}^{2.9}_{2.4}$ (Phys. Lett. B 687, 299)



N. Tolich, Neutrino 2010 presentation

(Not inc errors in model, other than mantle/crust scalings)

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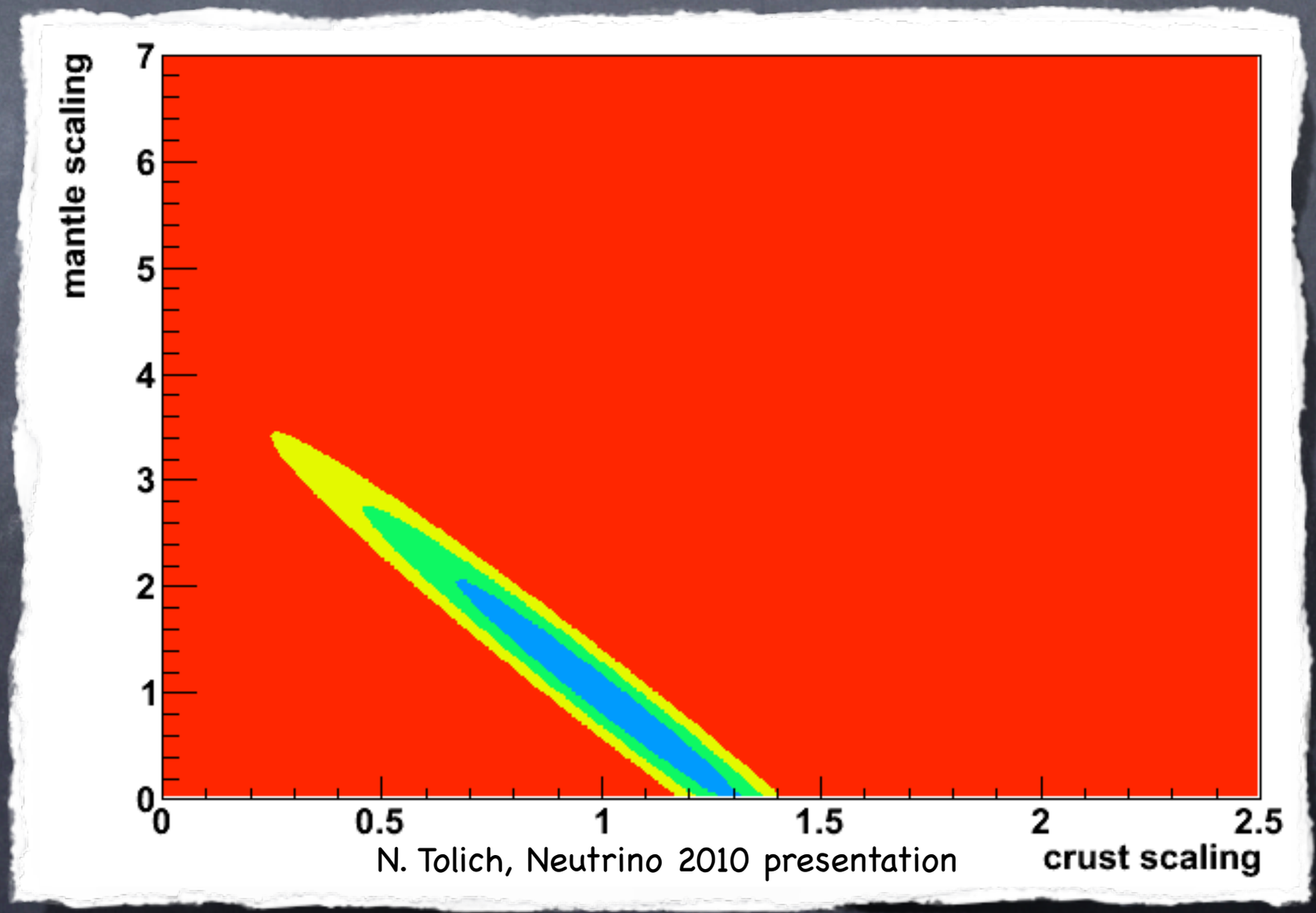
5% measurement at SNO+
+ KamLAND
+ Borexino



N. Tolich, Neutrino 2010 presentation

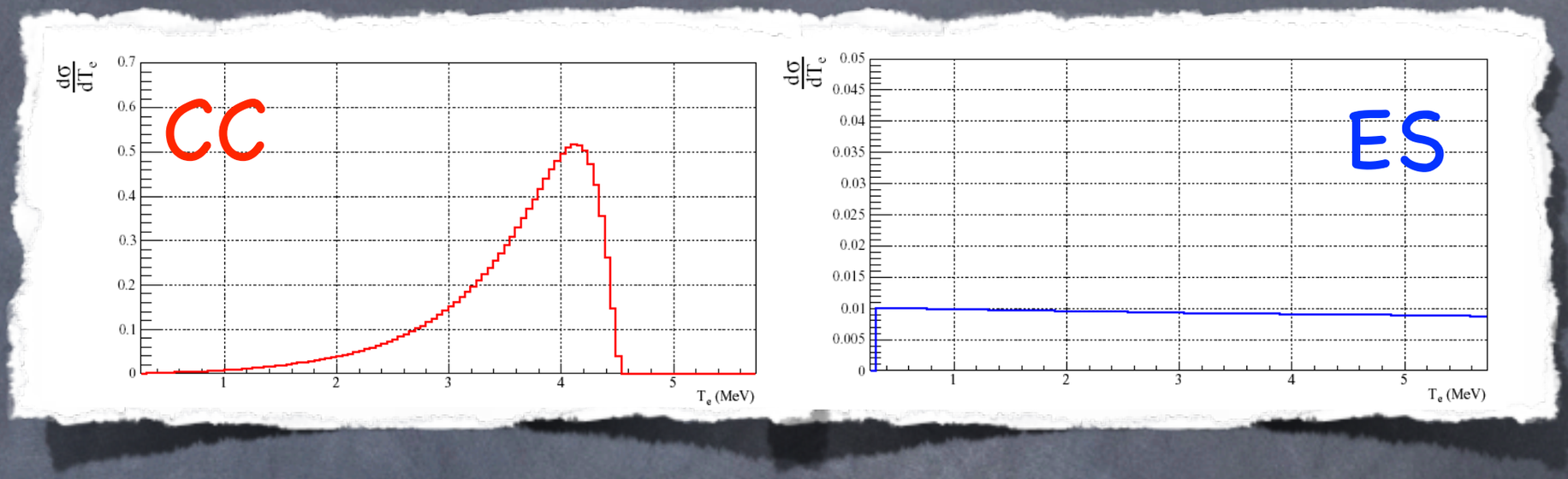
New Analysis: LETA

Low Energy Threshold Analysis

New Analysis: LETA

Low Energy Threshold Analysis

Cross-section for E_ν = 6MeV



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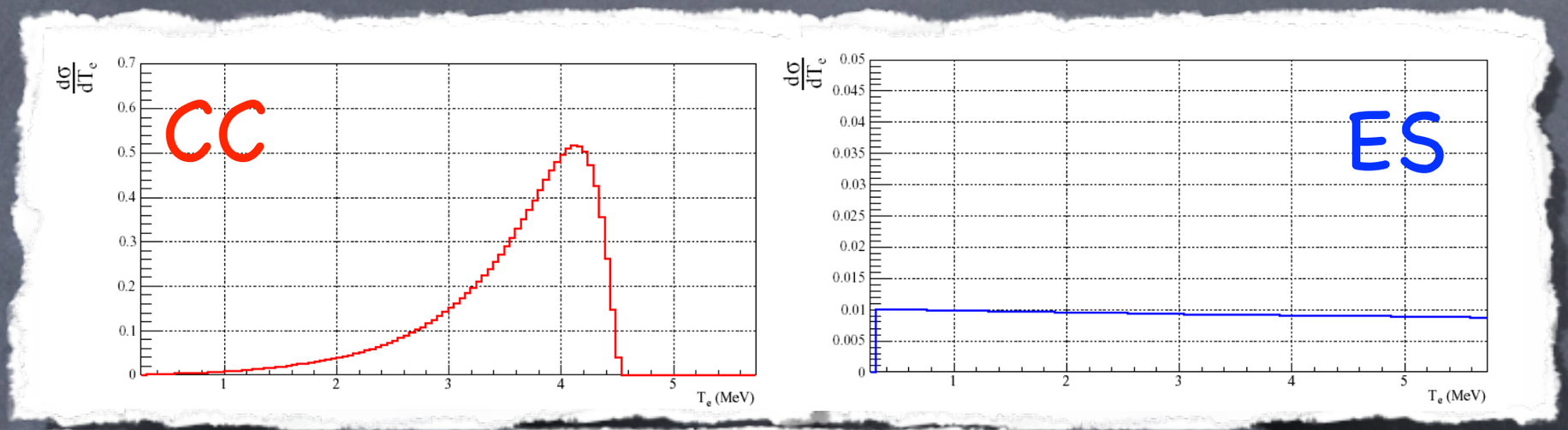
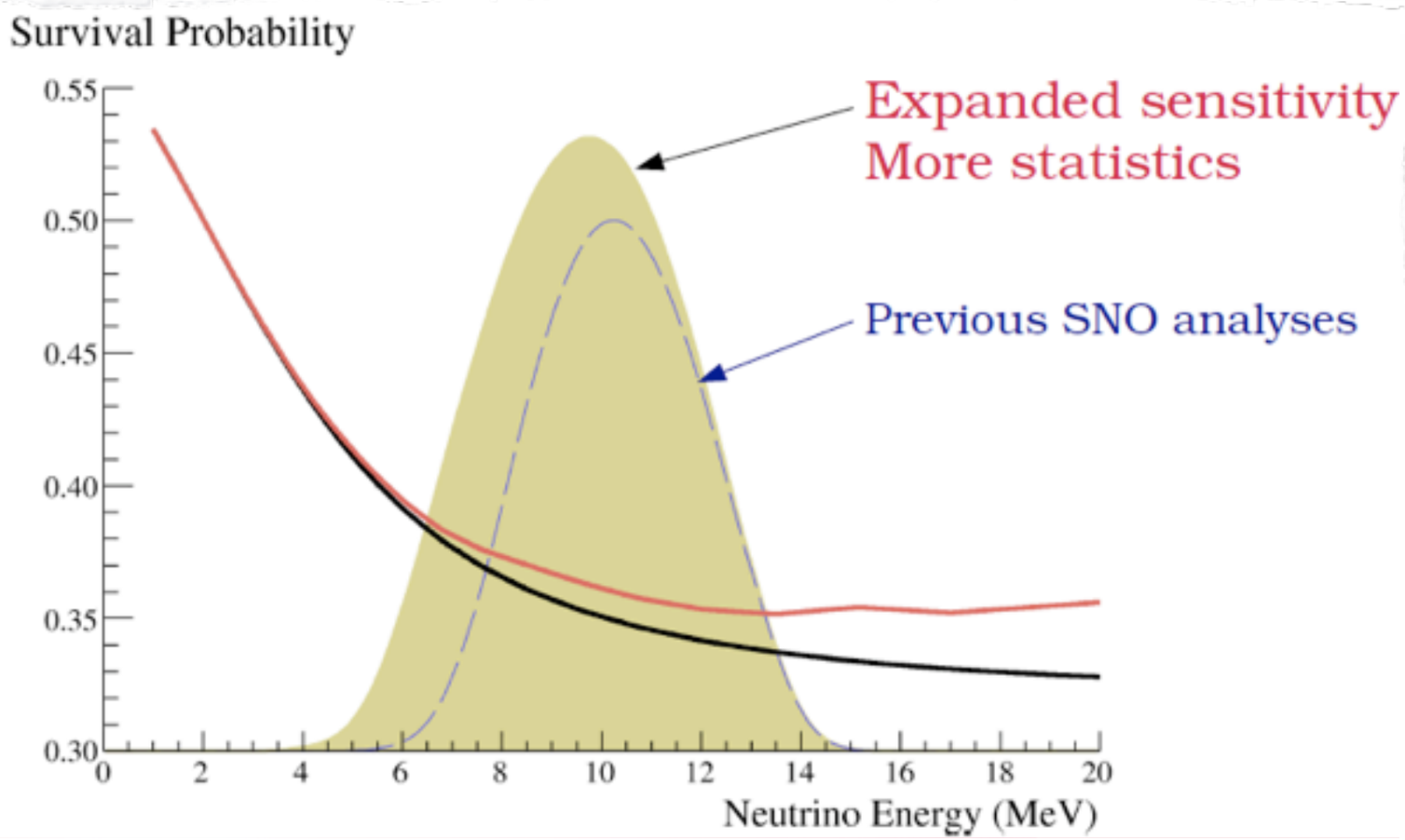


Typical LMA curves



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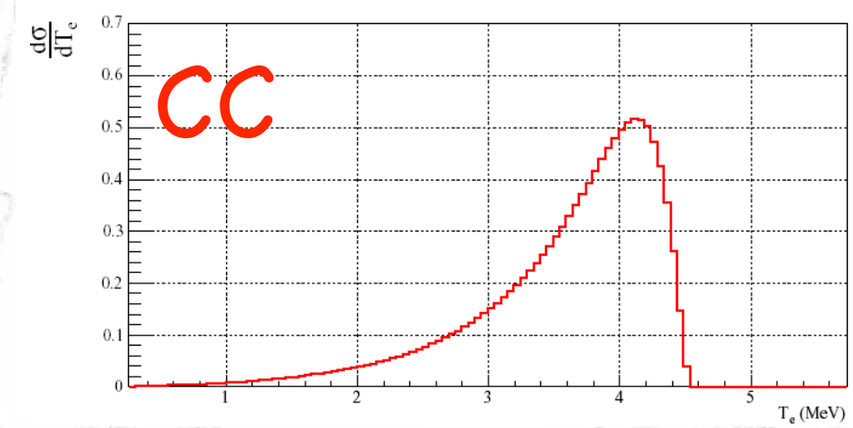
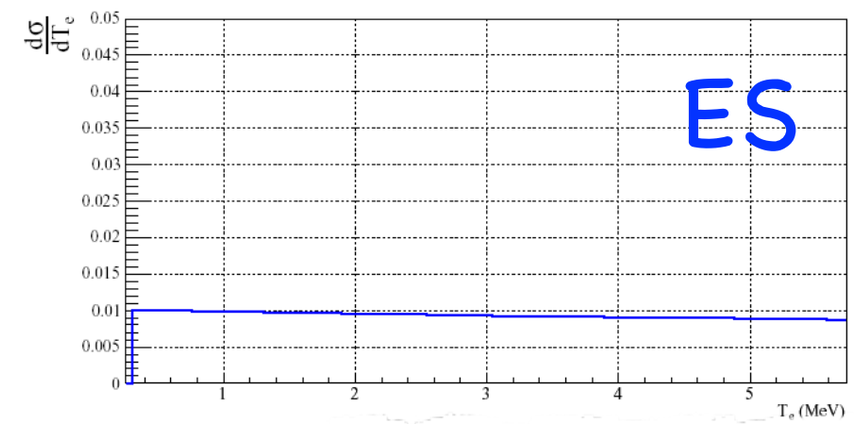
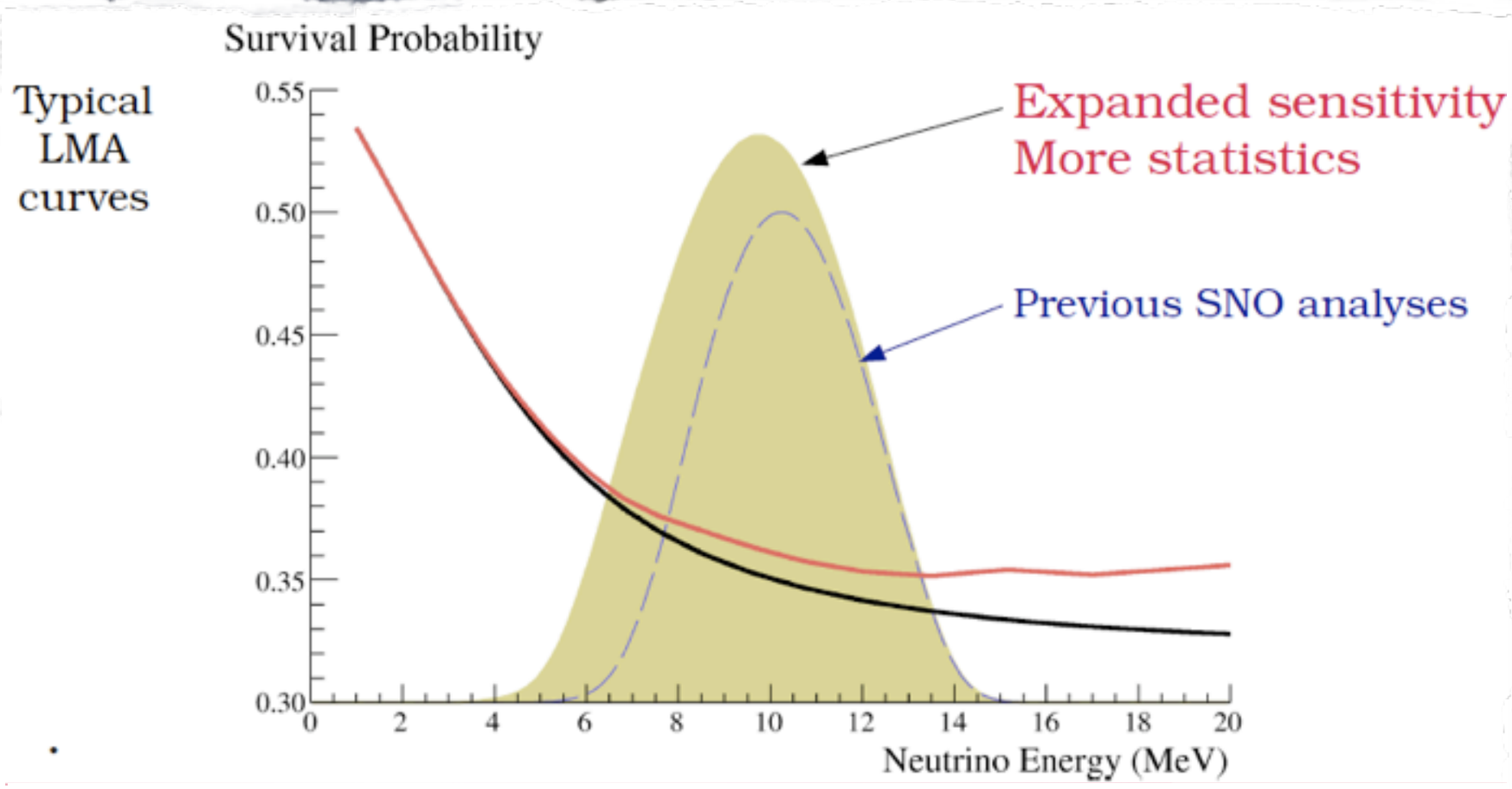
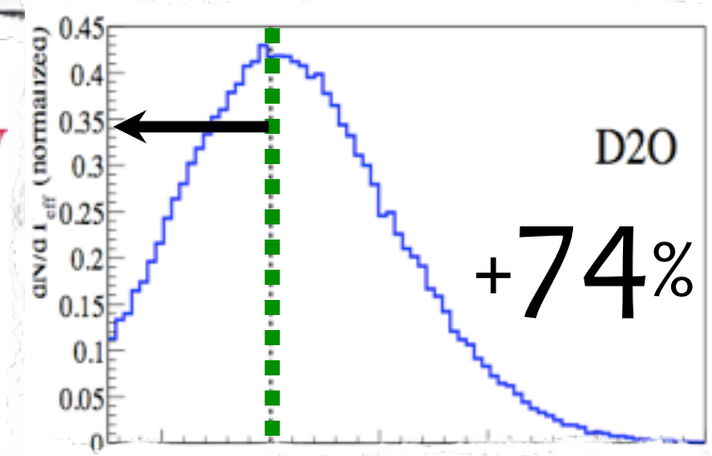
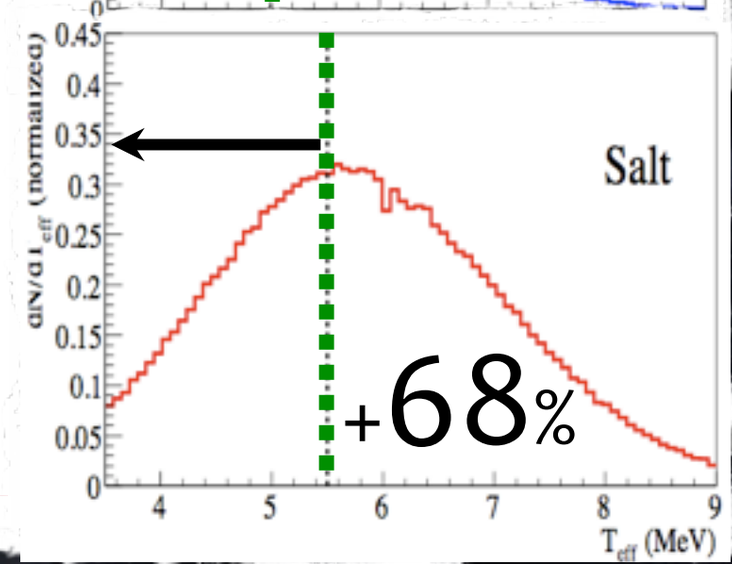




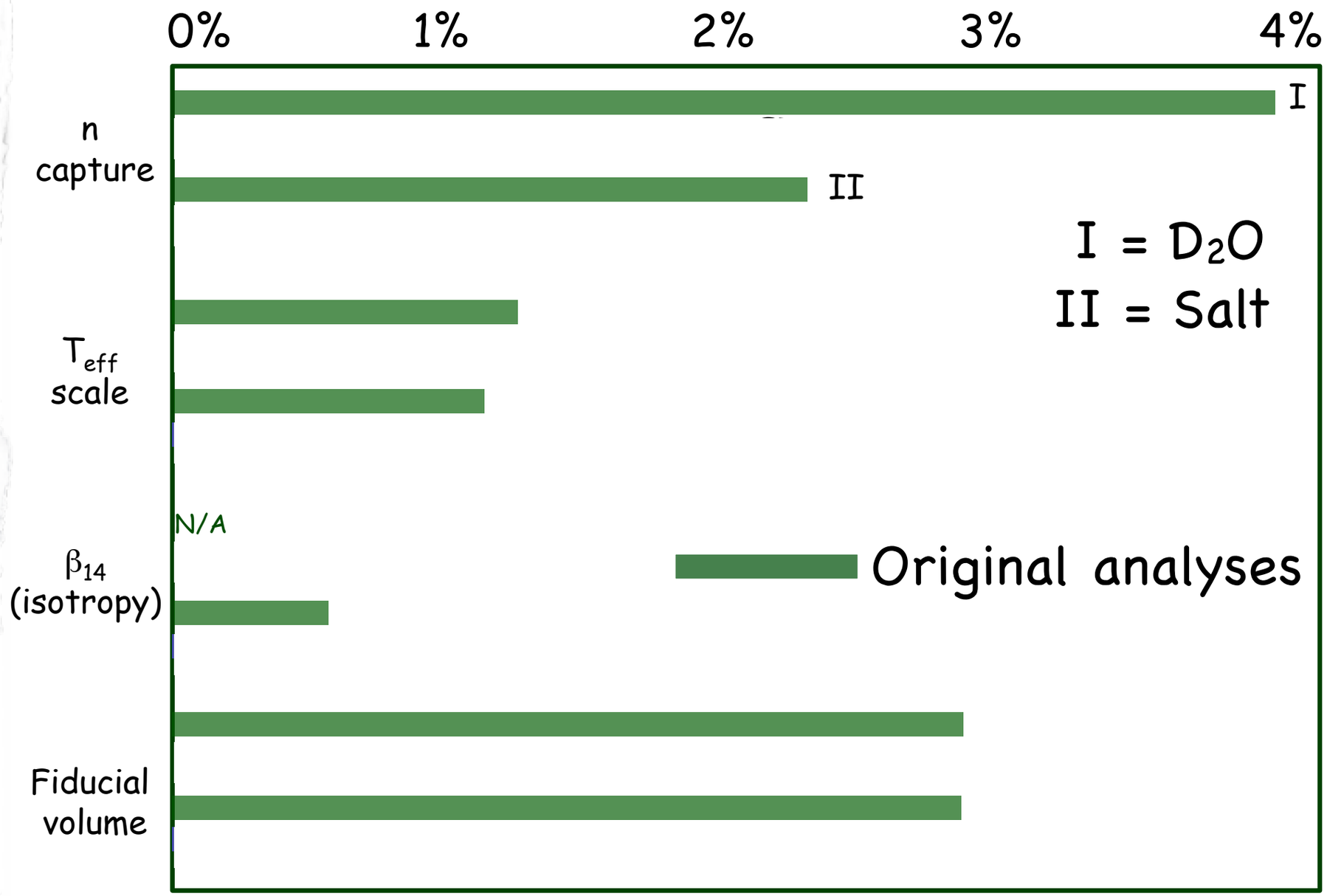






LETA

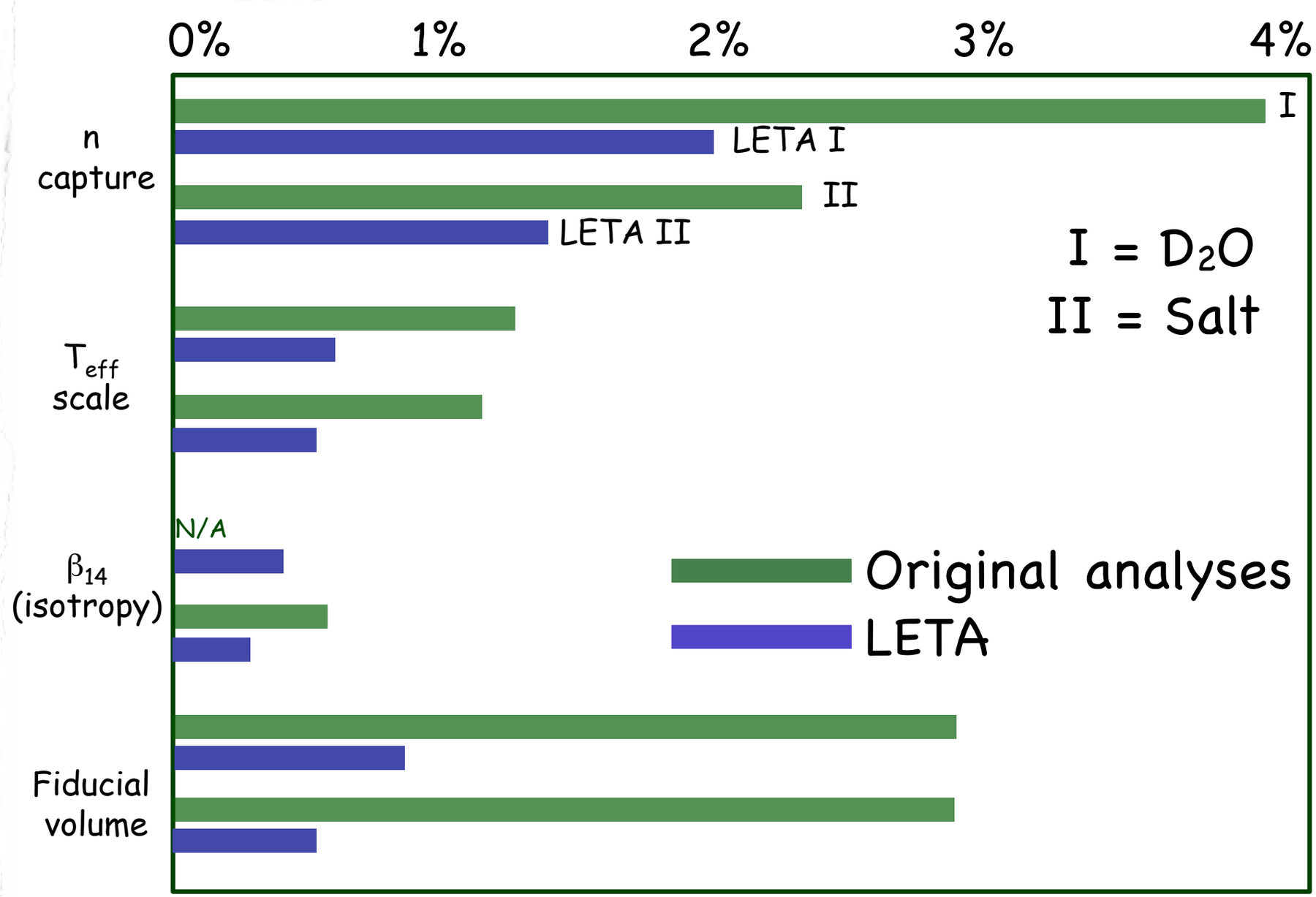
Reduced Uncertainties



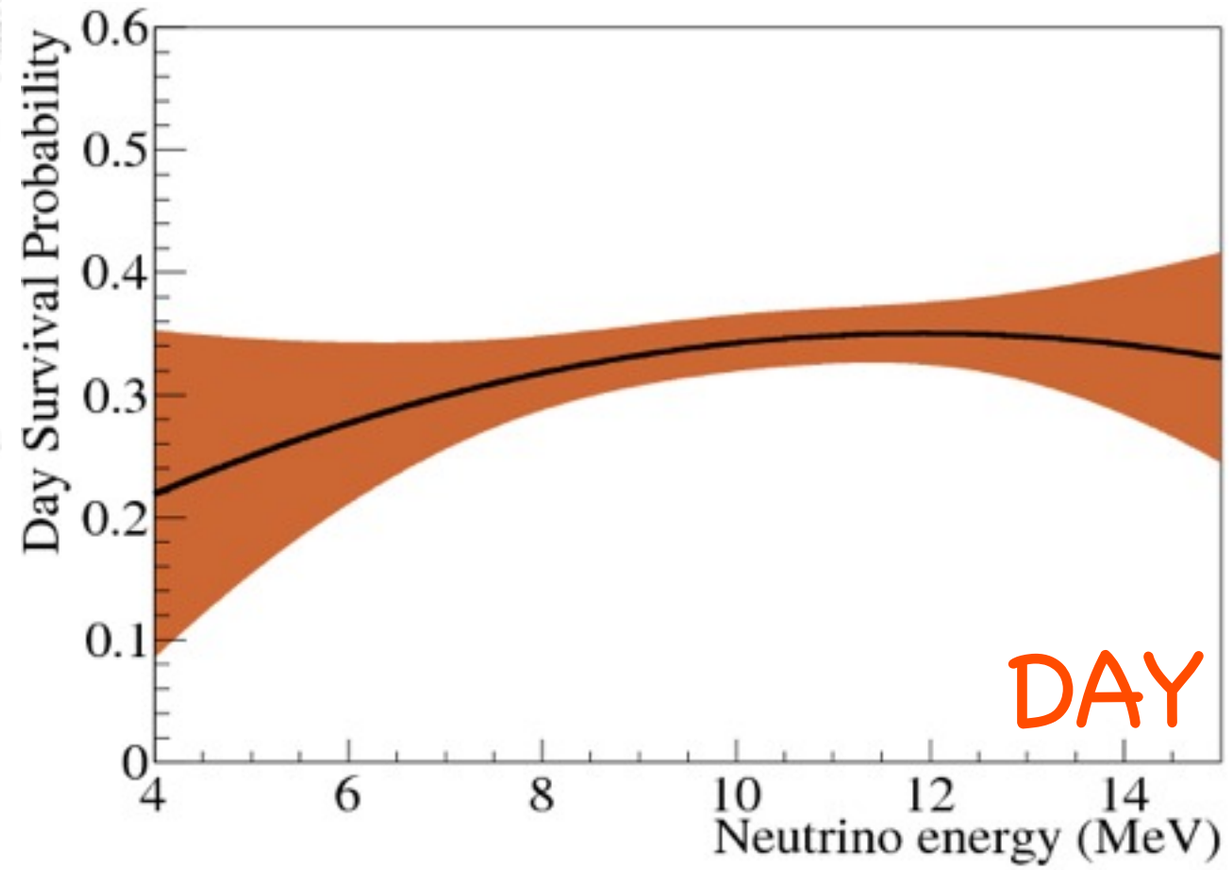
Systematic	Phase	Effect on rate /%			
		NC	CC1	CC12	ES0
Angular resn (+)	I	−0.032	−0.688	−0.075	1.176
Angular resn (−)	I	0.039	0.648	0.128	−1.477
Angular resn (+)	II	−0.058	−0.458	−0.172	3.219
Angular resn (−)	II	0.065	0.298	0.194	−3.488
Axial scale (+)	I	−0.030	0.261	0.128	0.047
Axial scale (−)	I	0.188	−2.377	−0.746	−1.344
Axial scale (+)	II	0.030	−0.366	0.079	−0.037
Axial scale (−)	II	−0.320	−1.981	−0.493	−0.892
Z scale (+)	I				
Z scale (−)	I				
Z scale (+)	II				
Z scale (−)	II				
X offset (+)	I				
X offset (−)	I				
X offset (+)	II				
X offset (−)	II				
Y offset (+)	I				
Y offset (−)	I				
Y offset (+)	II				
Y offset (−)	II				
Z offset (+)	I				
Z offset (−)	I				
Z offset (+)	I				
Z offset (−)	I				
X resn	I				
X resn	II				
Y resn	I				
Y resn	II				
Z resn	I				
Z resn	II				

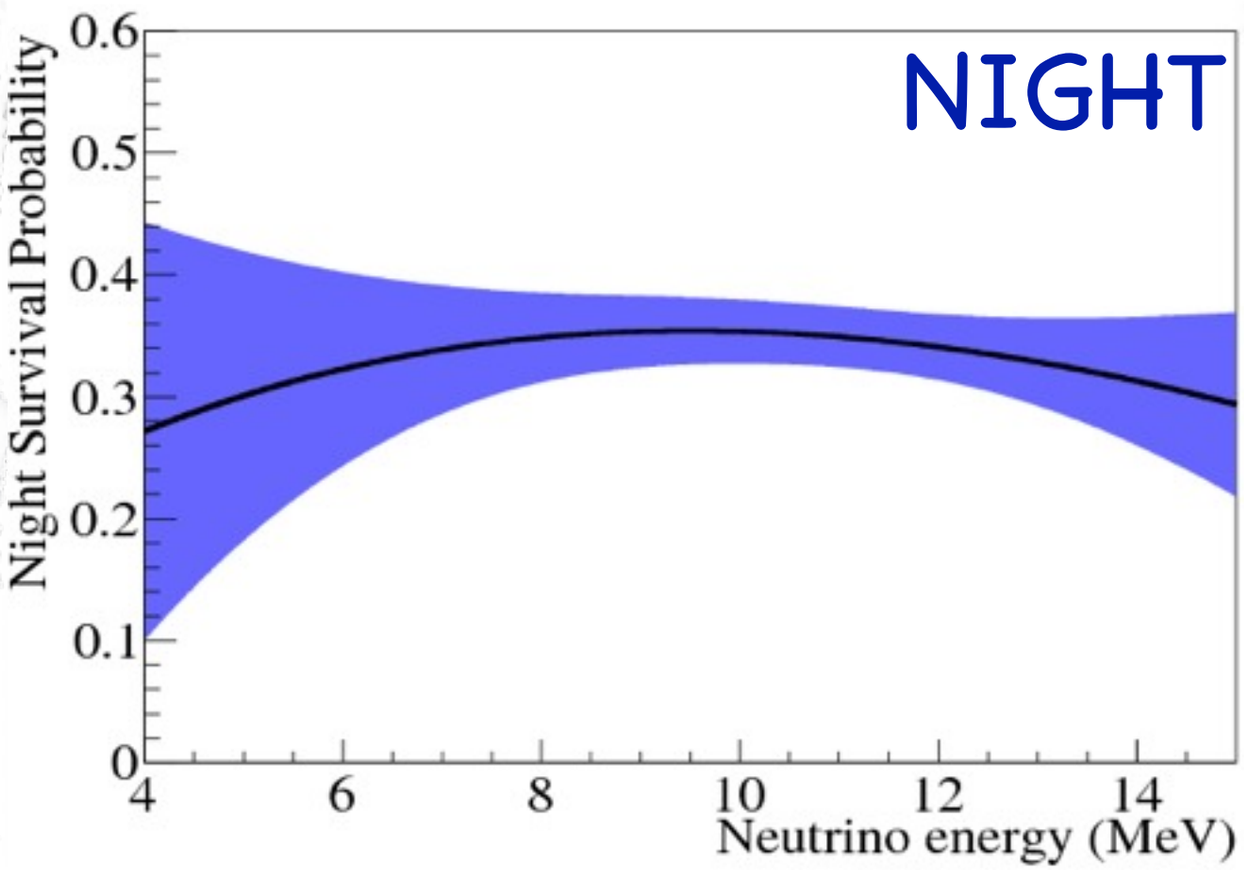
Systematic	Phase	Effect on rate /%			
		NC	CC1	CC12	ES0
T_{eff} scale (+)	I, II	−0.293	−2.037	−2.144	−0.156
T_{eff} scale (−)	I, II	0.137	0.475	0.913	0.035
T_{eff} scale (+)	I	0.030	−0.956	−0.337	−0.148
T_{eff} scale (−)	I	−0.084	1.659	0.652	0.236
T_{eff} scale (+)	II	−0.307	0.317	−1.094	0.105

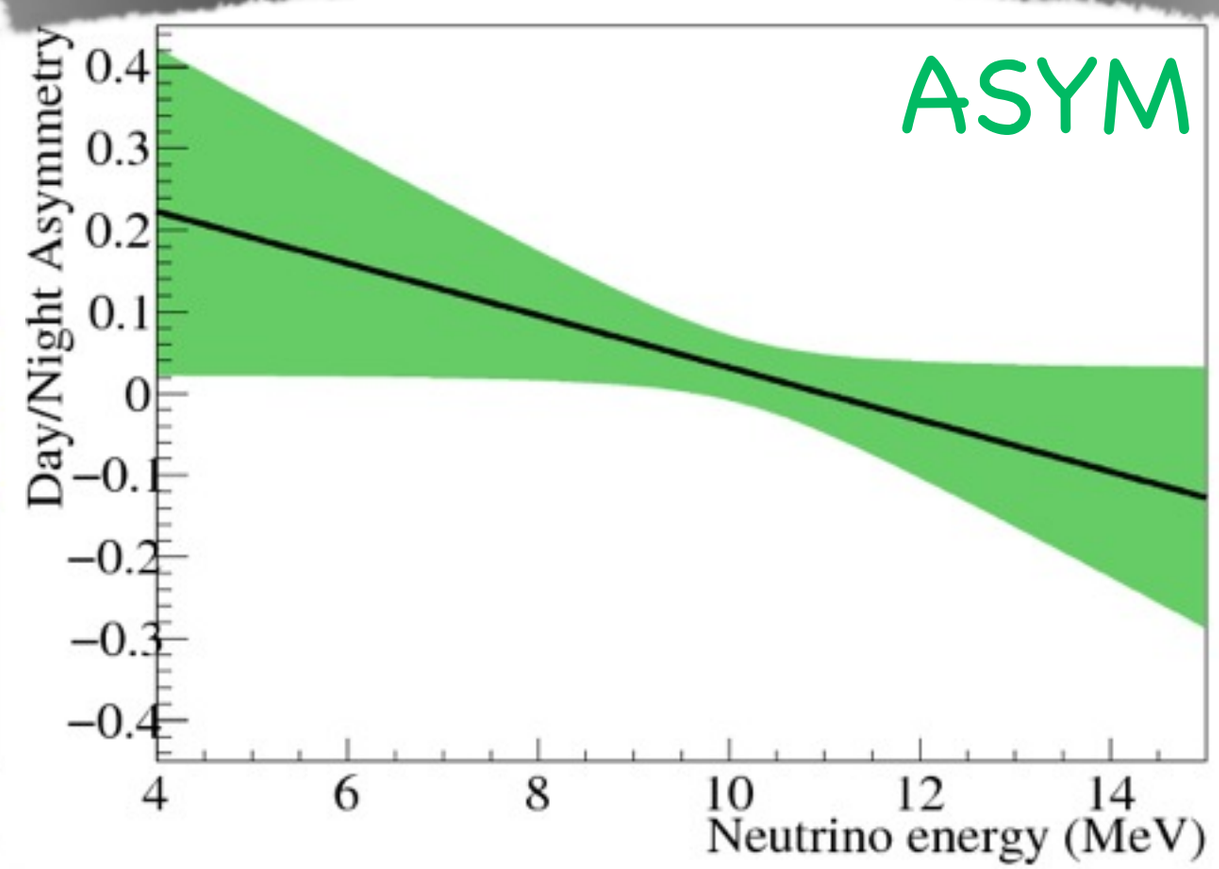
Systematic	Phase	Effect on rate /%			
		NC	CC1	CC12	ES0
Z−dep fid vol (+)	I	0.397	−0.277	−1.735	0.378
Z−dep fid vol (−)	I	−0.230	0.119	1.027	−0.233
Z−dep fid vol (+)	II	−0.698	0.794	−1.144	0.322
Z−dep fid vol (−)	II	0.825	−0.994	1.376	−0.389
Cut acceptance (+)	I, II	−0.357	−0.519	−0.434	−0.451
Cut acceptance (−)	I, II	1.039	1.299	1.136	1.171
Photodisint.n (+)	I, II	−0.180	0.134	−0.002	0.026
Photodisint.n (−)	I, II	0.183	−0.100	0.004	−0.023
neut cap (+)	I	−0.049	−0.797	0.003	−0.074
[illegible]	[illegible]	[illegible]4	0.829	−0.001	0.084
[illegible]	[illegible]	[illegible]6	0.616	−0.001	0.062
[illegible]	[illegible]	[illegible]3	−0.612	0.003	−0.060
[illegible]	[illegible]	[illegible]9	0.040	−0.000	−0.001
[illegible]	[illegible]	[illegible]0	−0.053	0.001	−0.011
[illegible]	[illegible]	[illegible]8	−0.751	0.008	−0.056
[illegible]	[illegible]	[illegible]67	−0.463	0.003	−0.182
[illegible]	[illegible]	[illegible]09	−6.482	−0.003	−1.469
[illegible]	[illegible]	[illegible]2	3.217	0.004	0.821
[illegible]	[illegible]	[illegible]6	−0.814	0.001	−0.196
[illegible]	[illegible]	[illegible]1	−0.328	0.003	0.010
[illegible]	[illegible]	[illegible]3	−2.875	0.003	−0.402
[illegible]	[illegible]	[illegible]	1.746	0.000	0.238
[illegible]	[illegible]	[illegible]3	−2.371	0.002	−0.185
[illegible]	[illegible]	[illegible]4	0.870	−0.000	0.440
[illegible]	[illegible]	[illegible]3	5.674	−0.004	0.774
[illegible]	[illegible]	[illegible]6	−2.113	0.003	−0.203
[illegible]	[illegible]	[illegible]5	0.735	−0.000	0.370
[illegible]	[illegible]	[illegible]1	−1.014	0.003	−0.111
[illegible]	[illegible]	[illegible]2	−2.271	0.002	−0.714
[illegible]	[illegible]	[illegible]2	0.559	0.000	0.509
[illegible]	[illegible]	[illegible]6	4.456	0.029	0.396
[illegible]	[illegible]	[illegible]4	−4.102	−0.027	−0.802
[illegible]	[illegible]	[illegible]5	−1.388	−0.001	−0.008
[illegible]	[illegible]	[illegible]	0.192	0.005	0.060
[illegible]	[illegible]	[illegible]	−1.054	−0.006	0.257
[illegible]	[illegible]	[illegible]	1.394	0.009	−0.459



Direct Fit for Energy-Dep P_{ee}



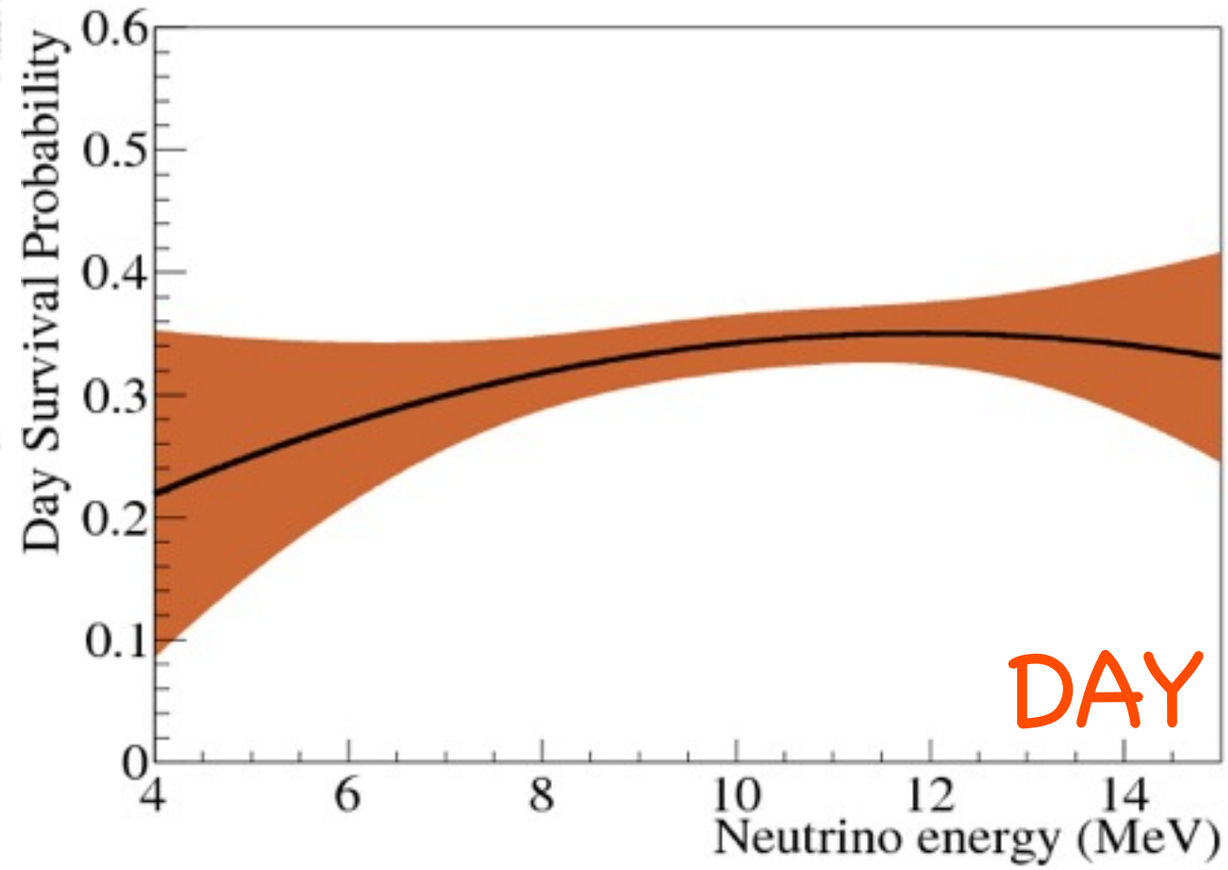


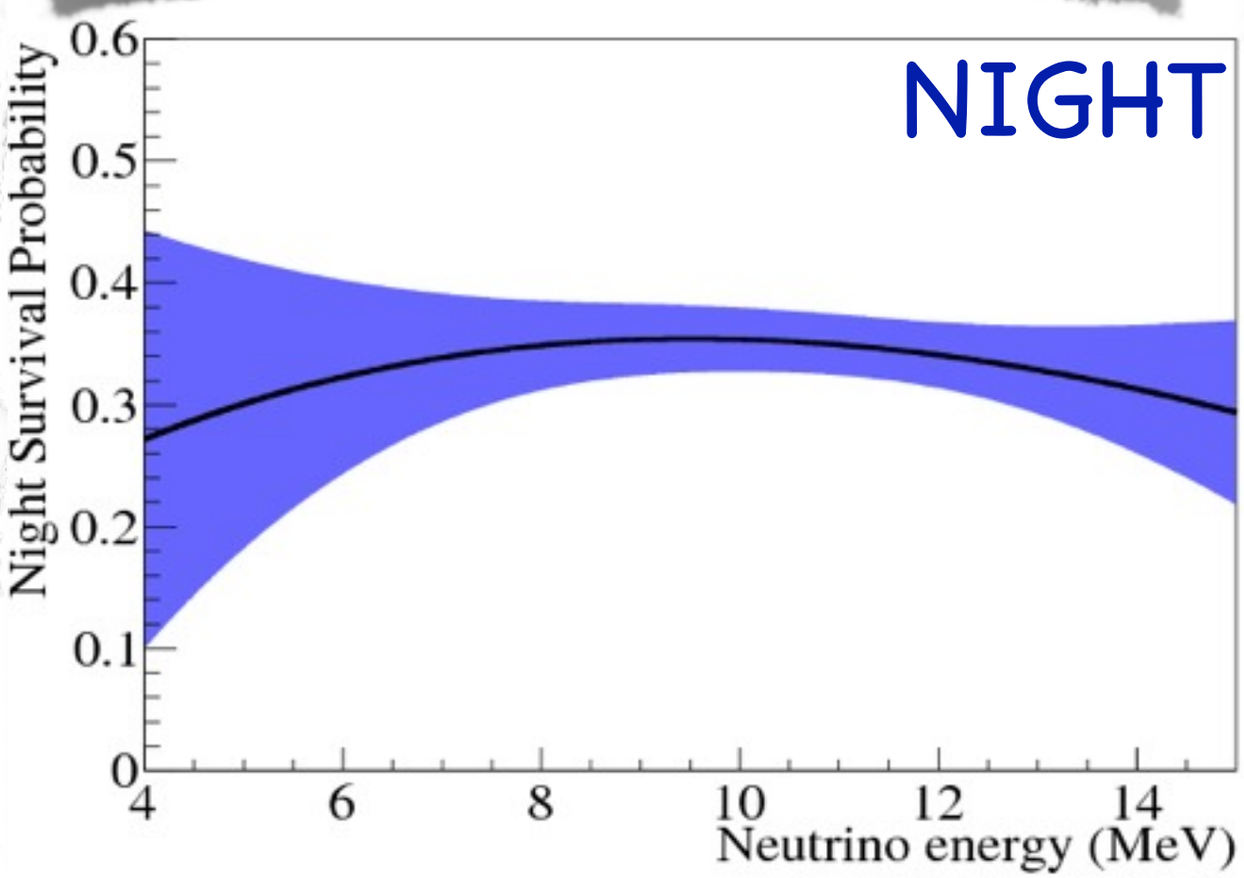


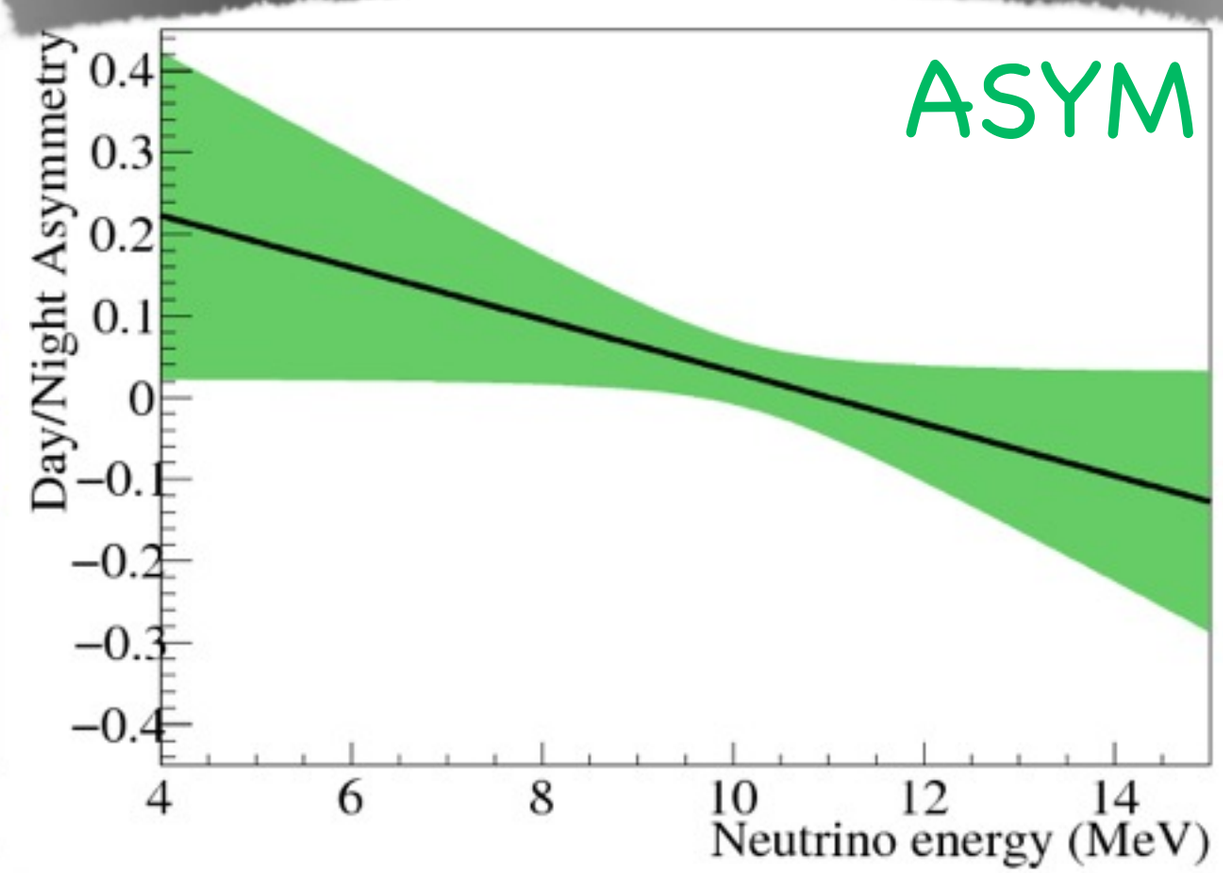
Direct Fit for Energy-Dep P_{ee}

No distortion, no a/s:

$\Delta\chi^2$ **= 1.94 / 4 d.o.f.**







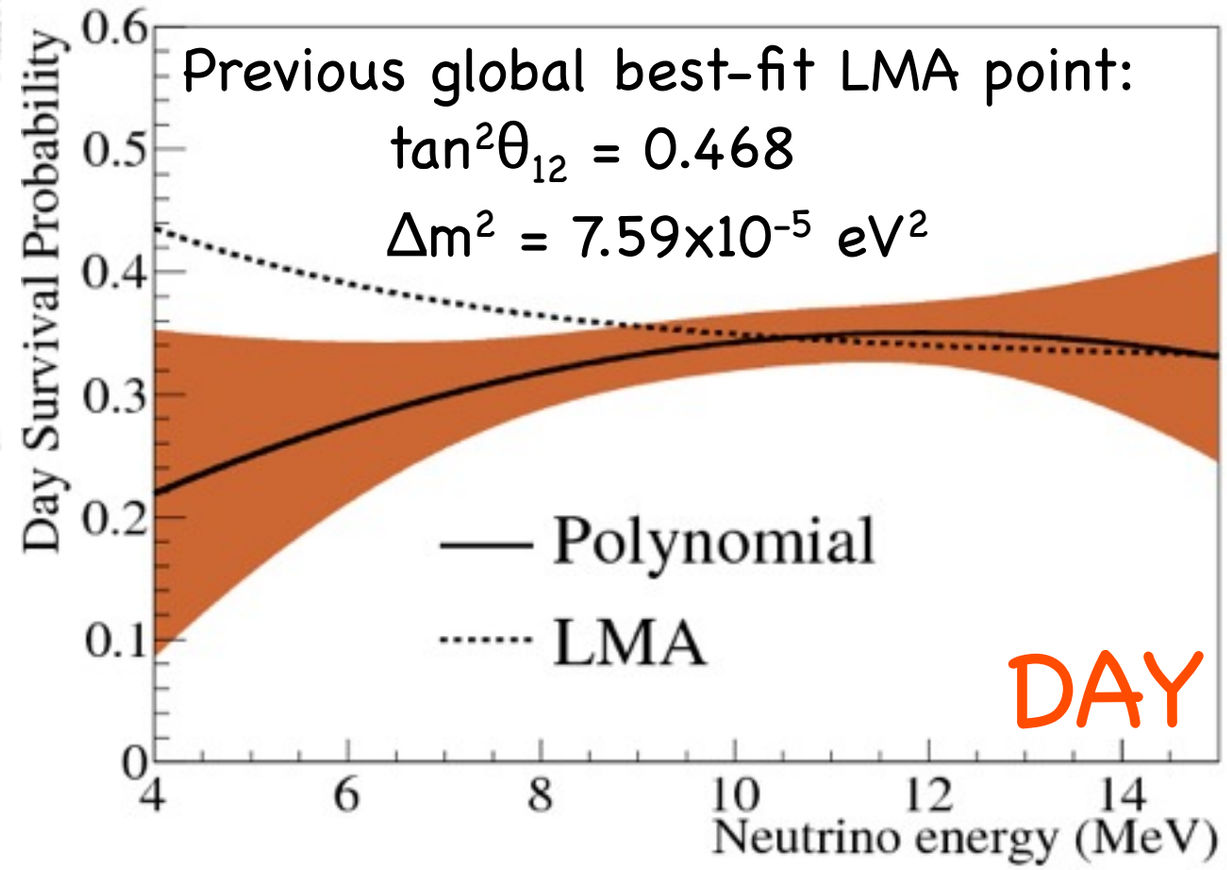
Direct Fit for Energy-Dep P_{ee}

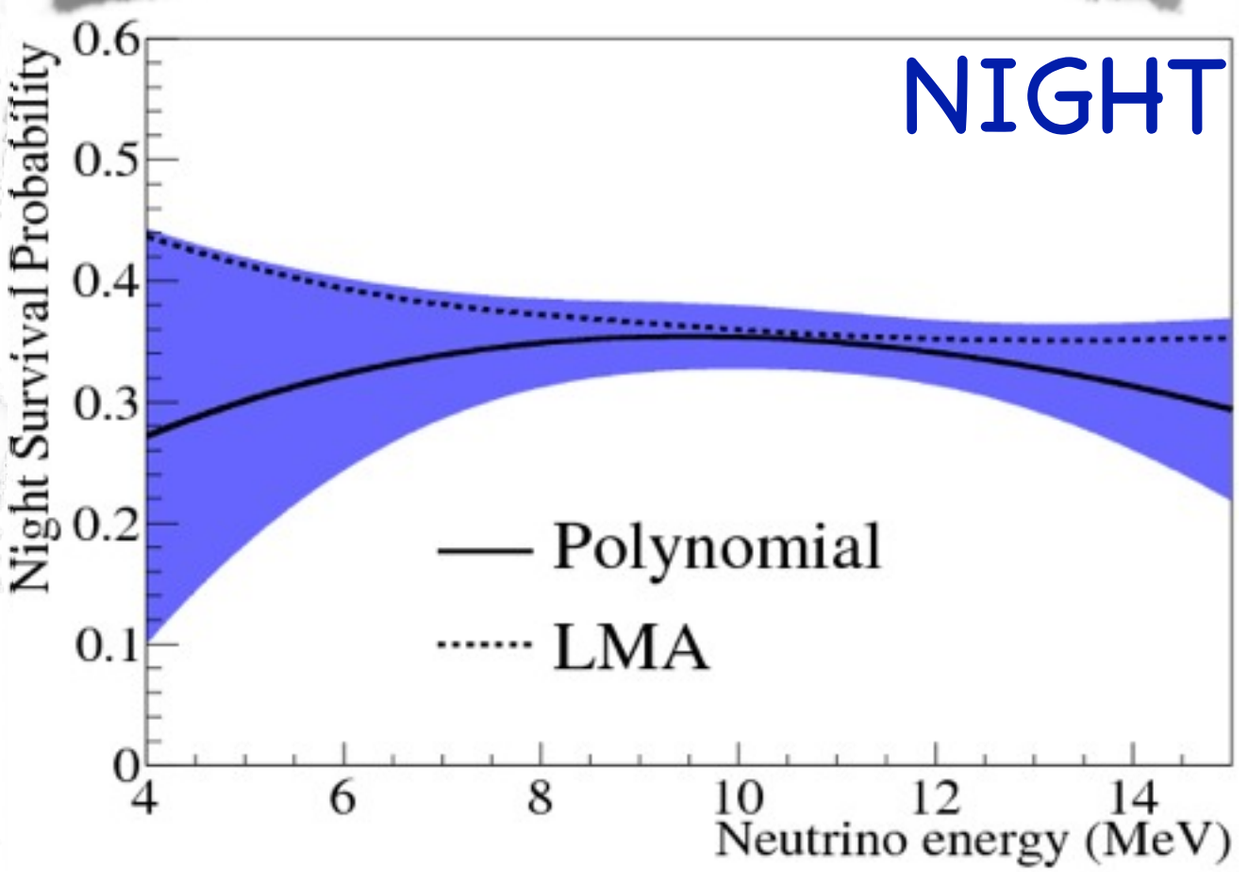
No distortion, no a/s:

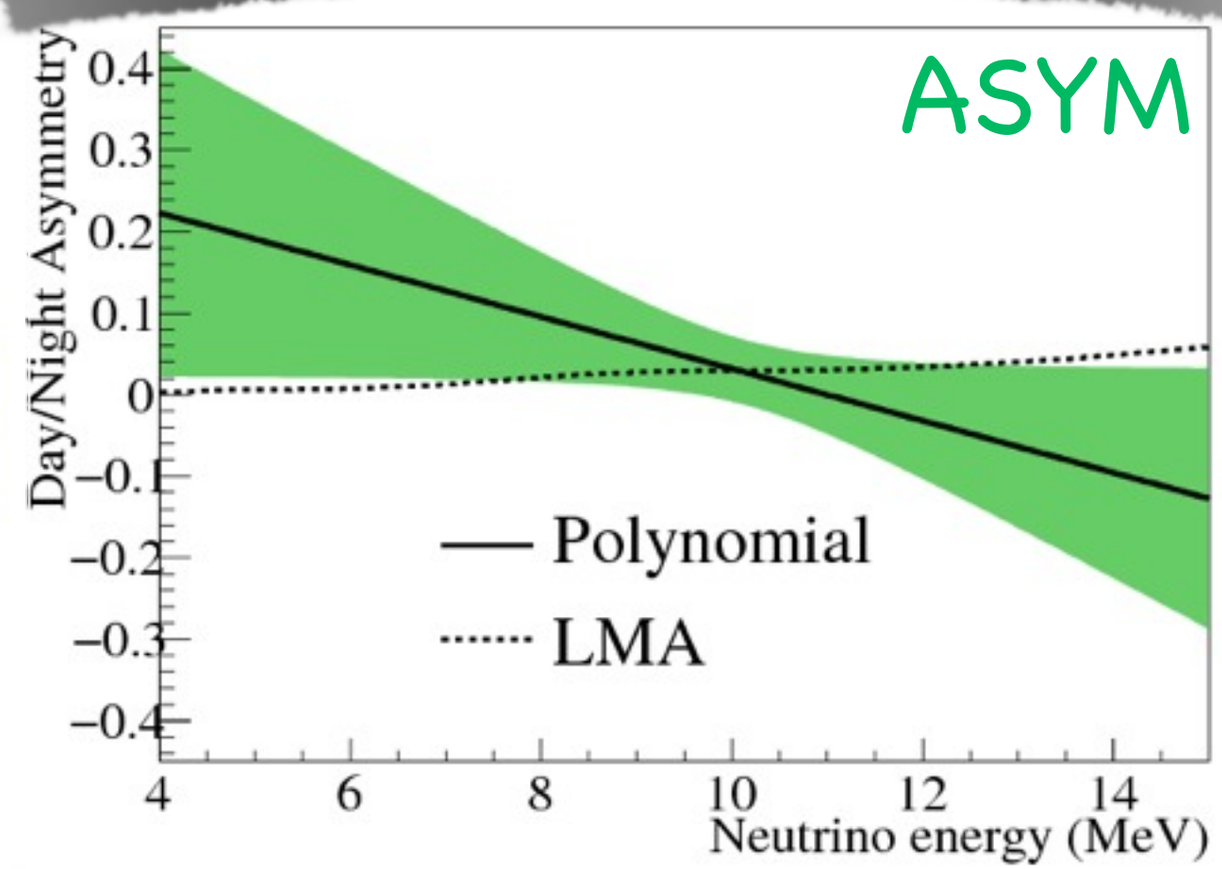
$\Delta\chi^2$ = 1.94 / 4 d.o.f.

LMA Prediction:

$\Delta\chi^2$ = 3.90 / 4 d.o.f.



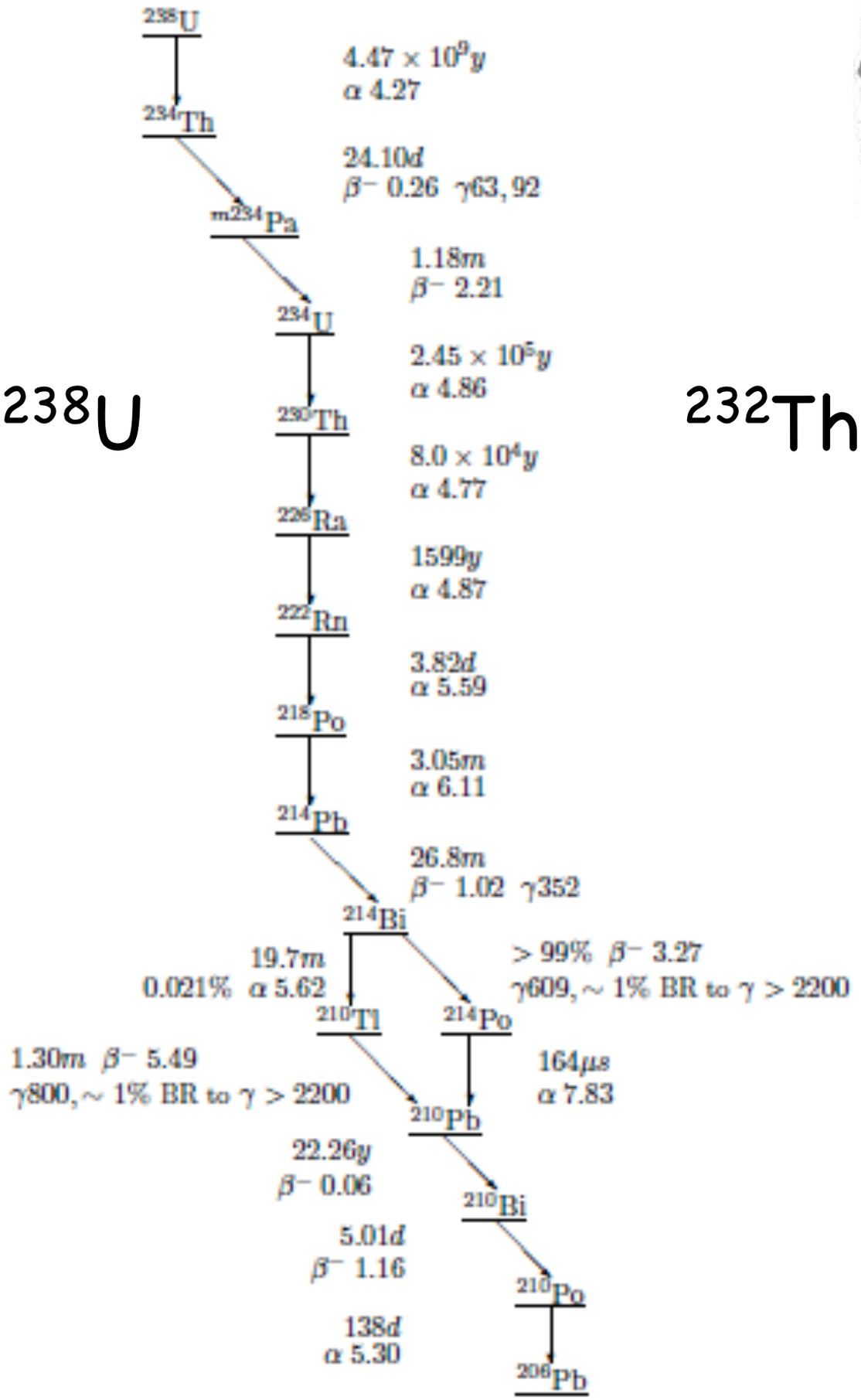
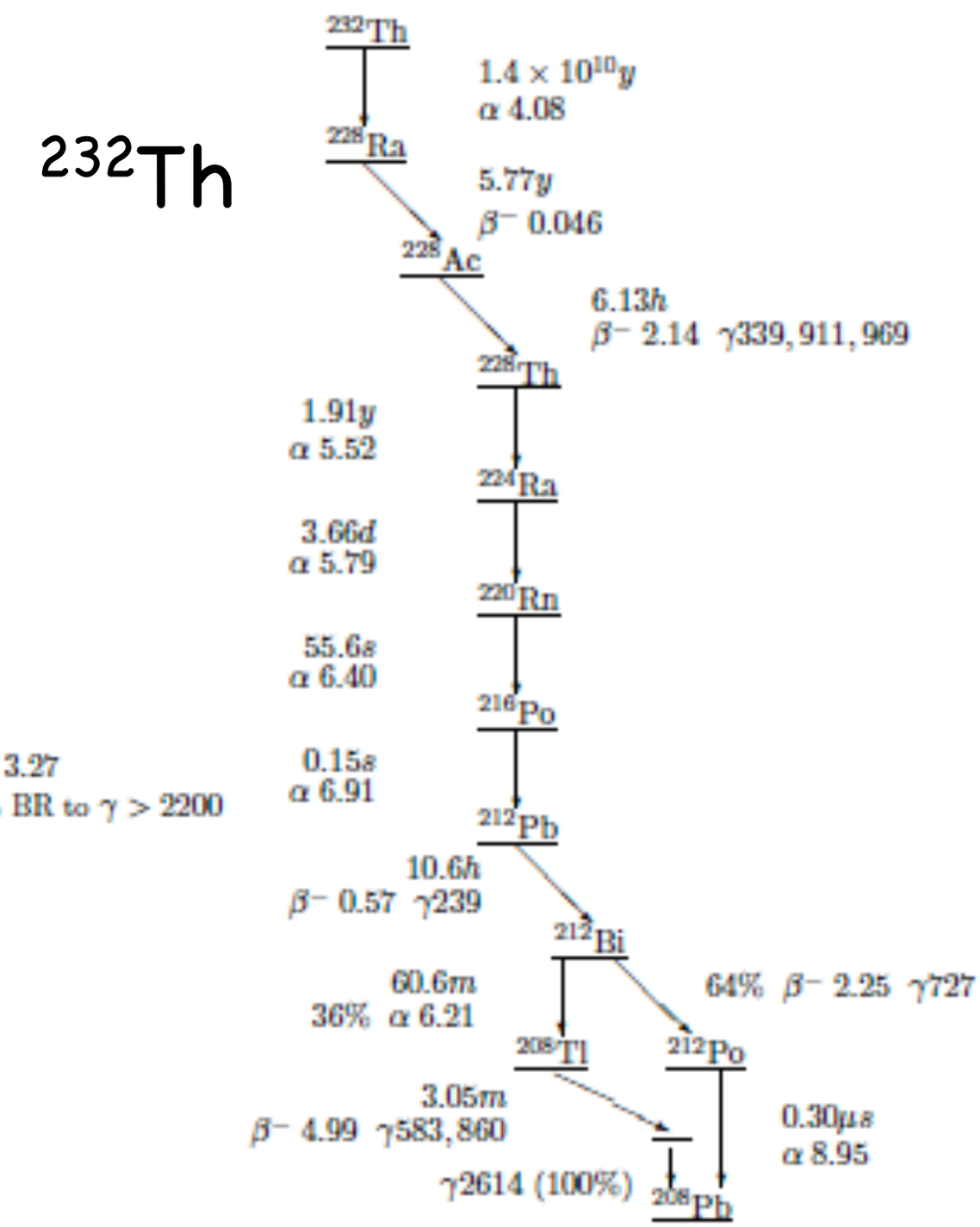




Background

Decay Chains

^{238}U



^{232}Th