There's SNO place like Home:

The SNO+ Project

S. Biller, Oxford University

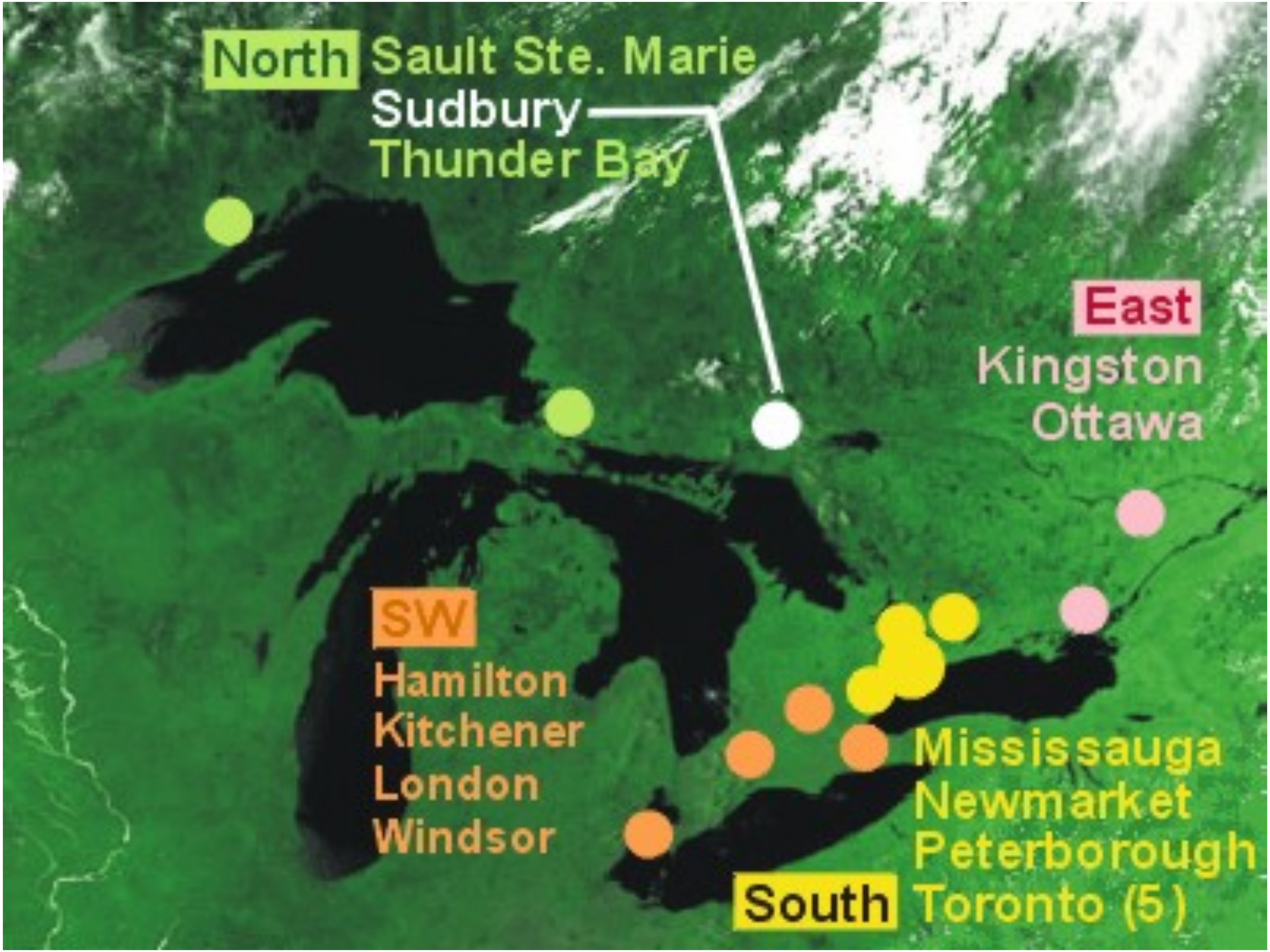
VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

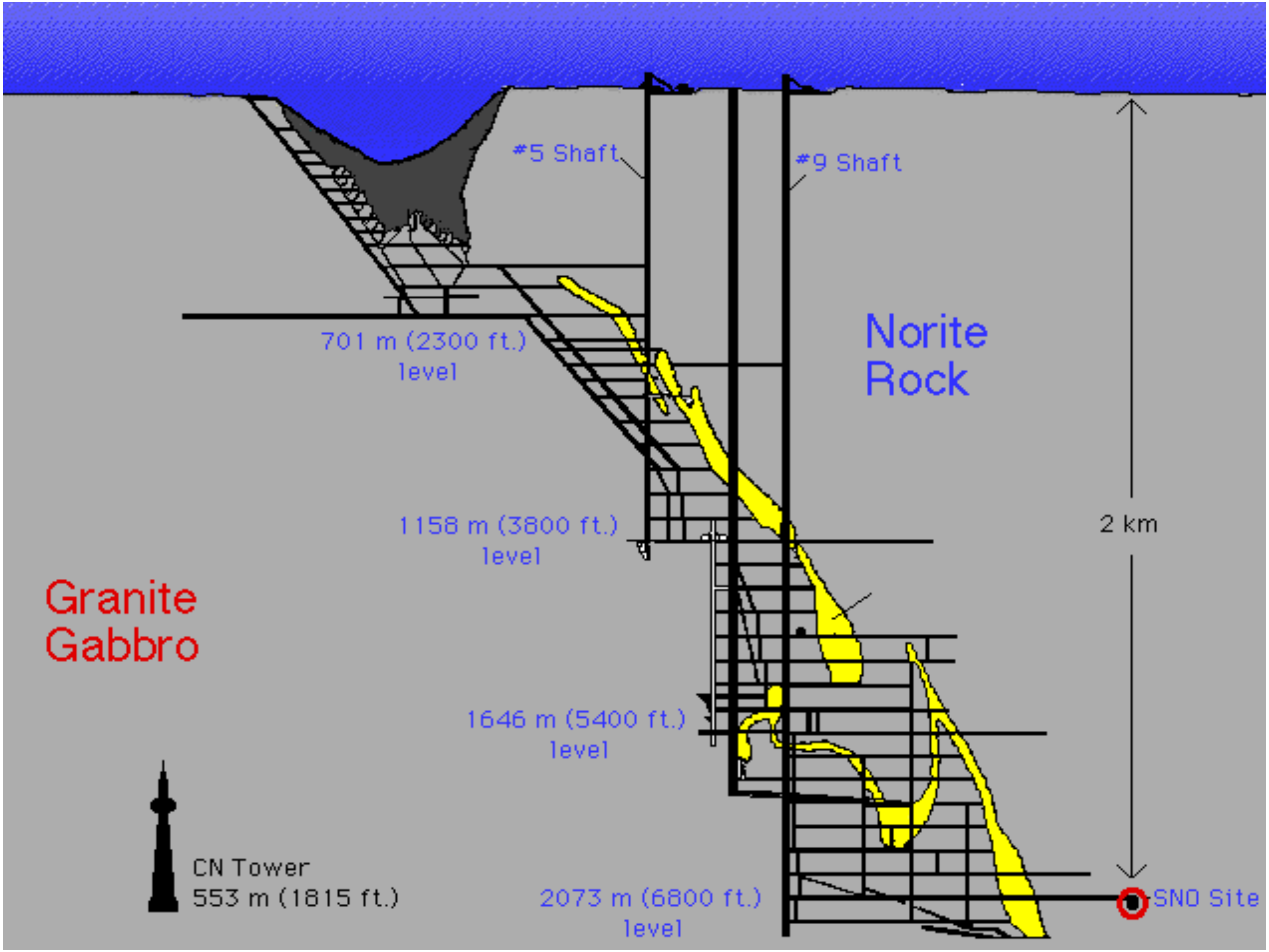
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \to \nu + p + n$ and the charged-current reaction $\nu_e + d \to e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

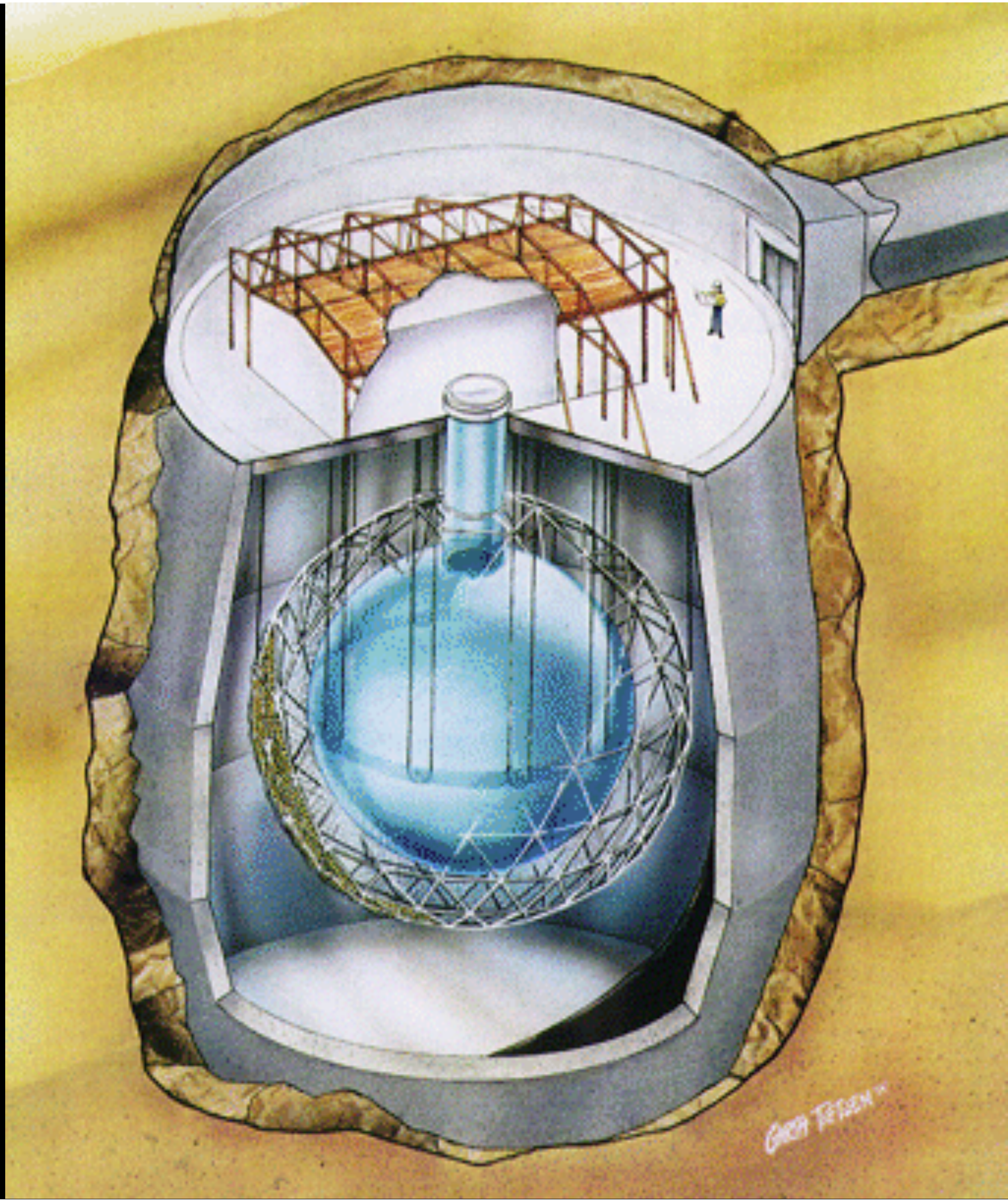

North
Sault Ste. Marie
Sudbury
Thunder Bay
East
Kingston
Ottawa
SW
Hamilton
Kitchener
London
Windsor
Mississauga
Newmarket
Peterborough
South
Toronto (5)

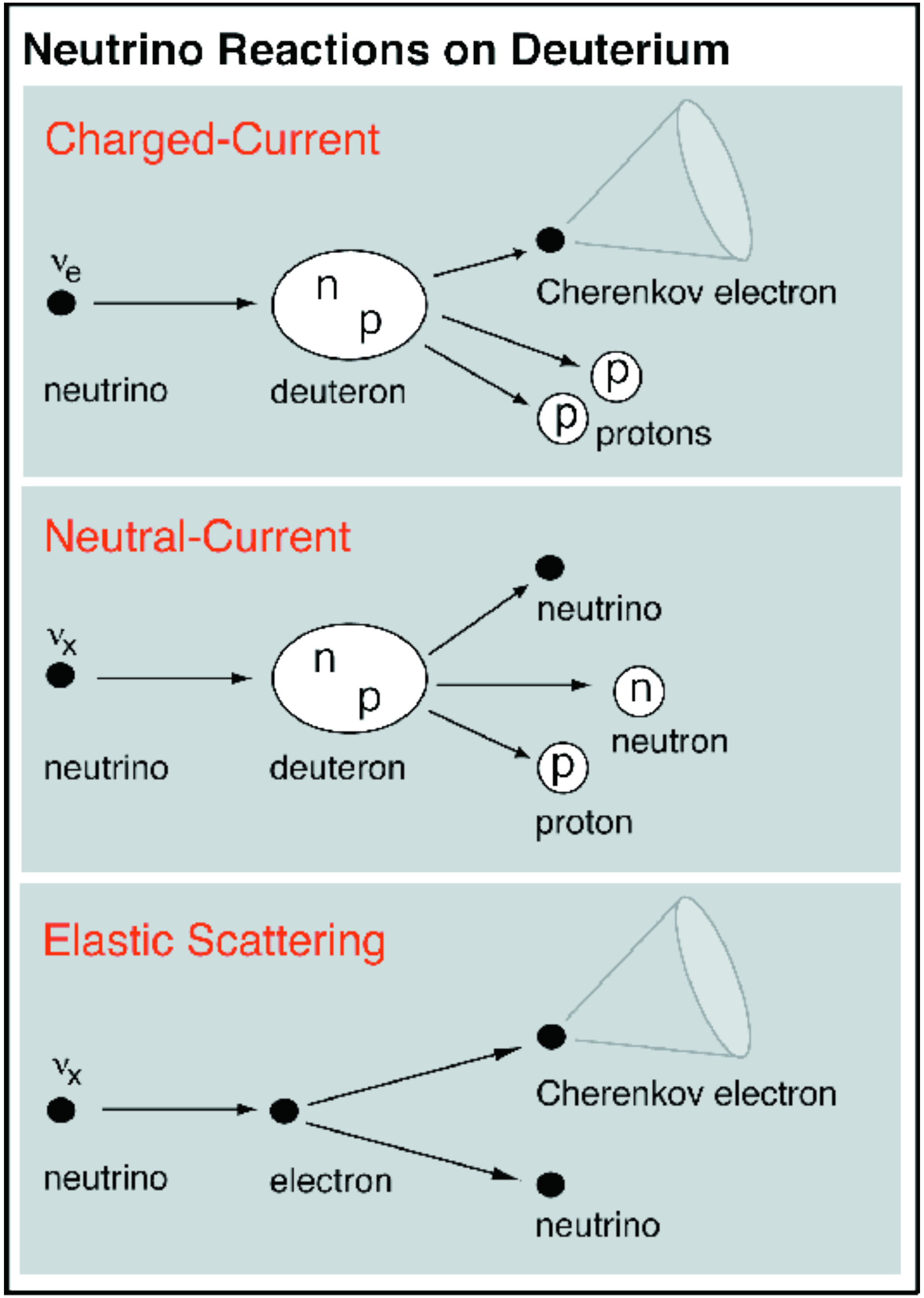
Coffee


MEATBIRD
BEACH
TOWN OF WALDEN


#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
2 km
Granite Gabbro
1646 m (5400 ft.) level
CN Tower 553 m (1815 ft.)
2073 m (6800 ft.) level
SNO Site


Dr. SNO





Neutrino Reactions on Deuterium
Charged-Current
ν_e
neutrino
n
p
deuteron
Cherenkov electron
p
p
protons
Neutral-Current
ν_x
neutrino
n
p
deuteron
neutrino
n
neutron
p
proton
Elastic Scattering
ν_x
neutrino
electron
Cherenkov electron
neutrino

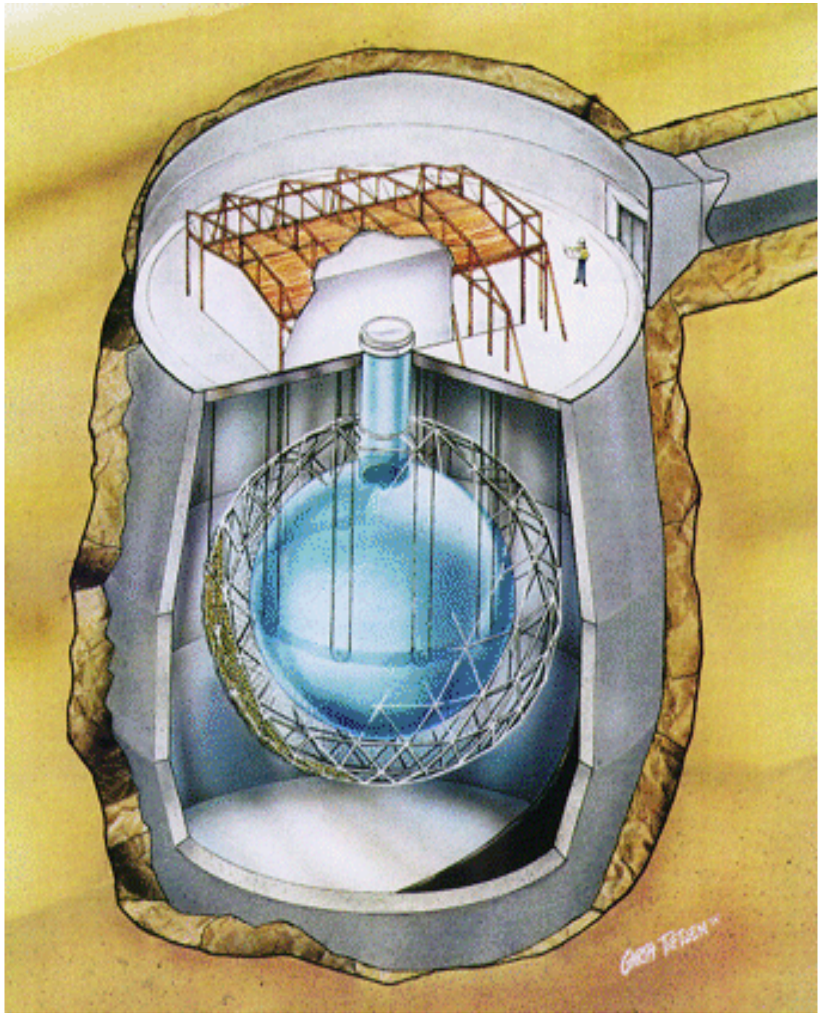
14:00 GMT, 28 November, 2006

Detector high voltage was ramped down as SNO ceased operation

R.I.P.

SNO+

Replace 1000 tonnes of ultrapure D_2O with 800 tonnes of ultrapure scintillator



(so, technically, should be "SNO-")

Physics with Liquid Scintillator

- **Neutrinoless double beta decay**
  → ***various*** isotopes possible !
- **Low energy solar neutrinos**
  → pep, CNO, ^{8}B and potentially ^{7}Be & pp !!
- **Geo-neutrinos** → unmatched
- **240 km baseline reactor neutrino oscillation**
  → Δm^2 resolution comparable to KamLAND !
- **Supernova neutrinos** → major player
- **"Invisible" modes of nucleon decay**
  → unique sensitivity with initial water data !

The SNO+ Collaboration

Queen's University
Laurentian University
University of Alberta
TRIUMF
SNOLAB

University of Pennsylvania
University of Washington
Black Hills State University
Armstrong Atlantic University
University of North Carolina
Brookhaven National Lab

Oxford University
Sussex University
Leeds University
Liverpool University
Sheffield University
QMUL

LIP Lisbon

TU Dresden

Current UK SNO+ Involvement

Oxford University:

Steve Biller, **Nick Jelley**, **Armin Reichold**, Phil Jones, Ian Coulter & Ken Clark*

(UK Spokesperson & Head of Event Reconstruction)

Sussex University:

Elisabeth Falk, **Jeff Hartnell** (Head of Data Flow), **Simon Peeters** (Head of Calibration),

Shak Fernandes, James Sinclair, Gwen Lefeuvre

Leeds University:

Stella Bradbury, **Joachim Rose**

Queen Mary University of London:

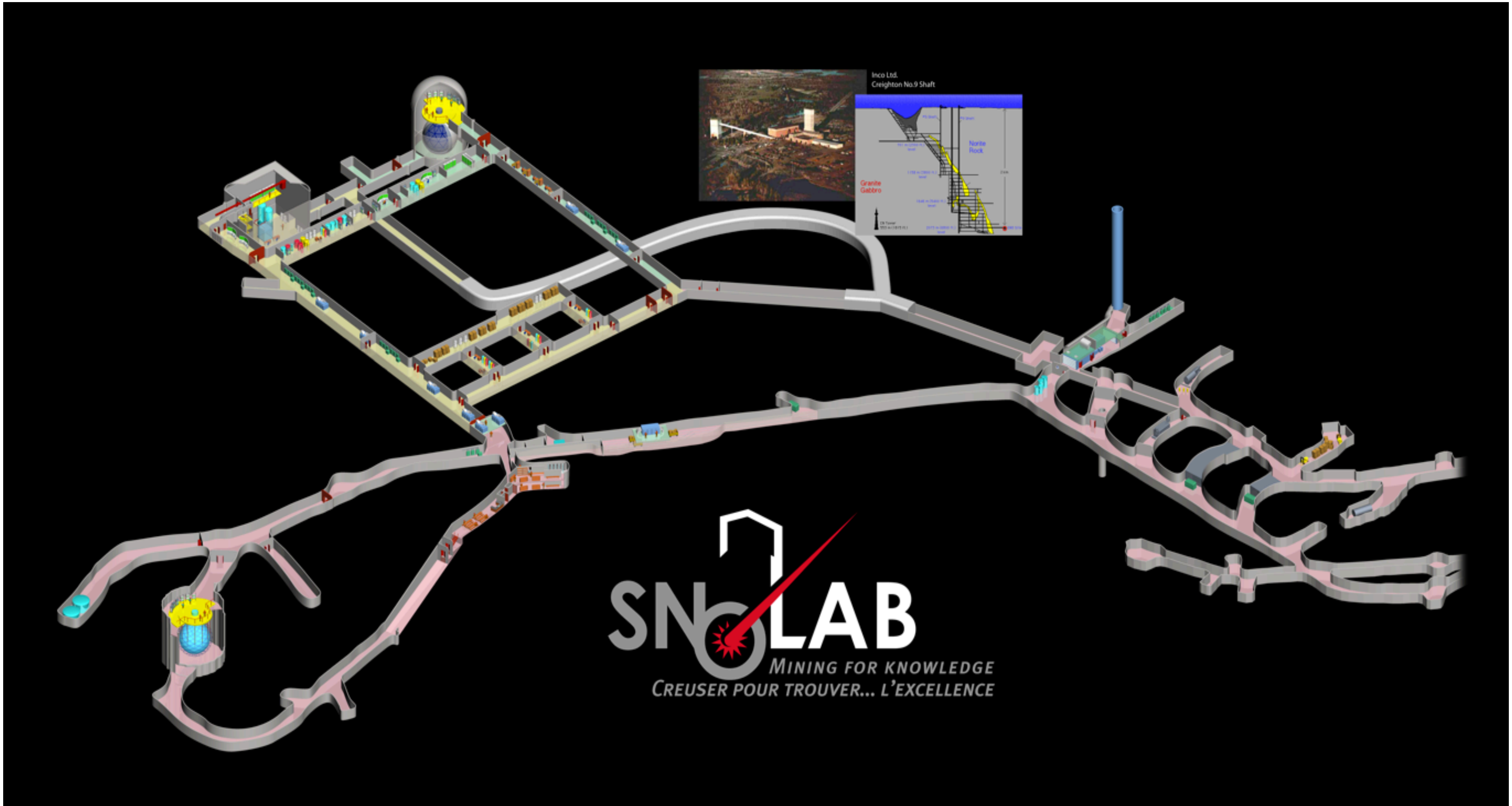
Jeanne Wilson
(Analysis Coordinator)

Liverpool University

Neil McCauley

University of Sheffield

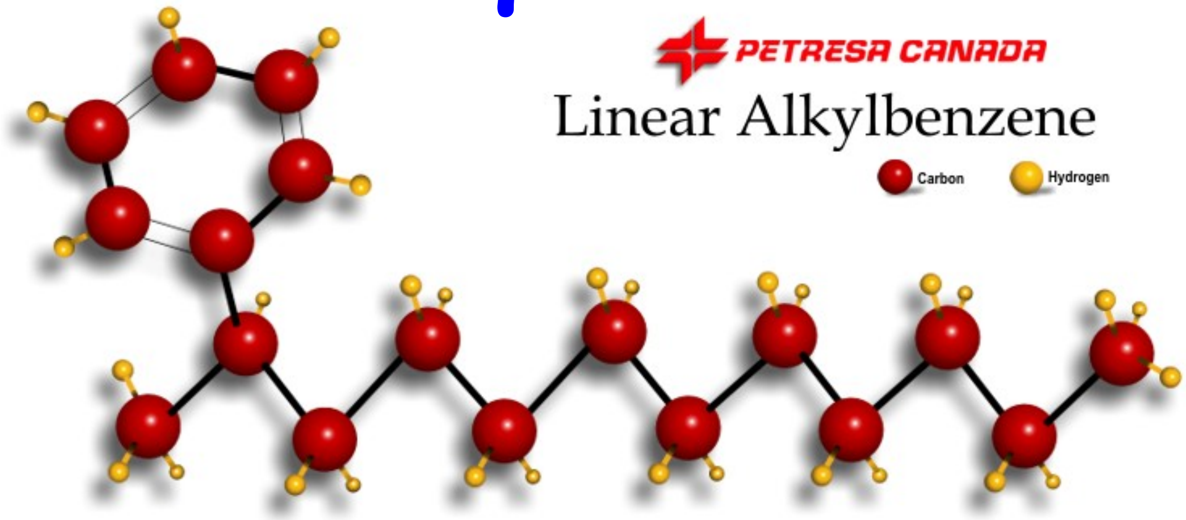
John McMillan



Now part of larger SNOLAB major underground science facility.

Nigel Smith is the new director.

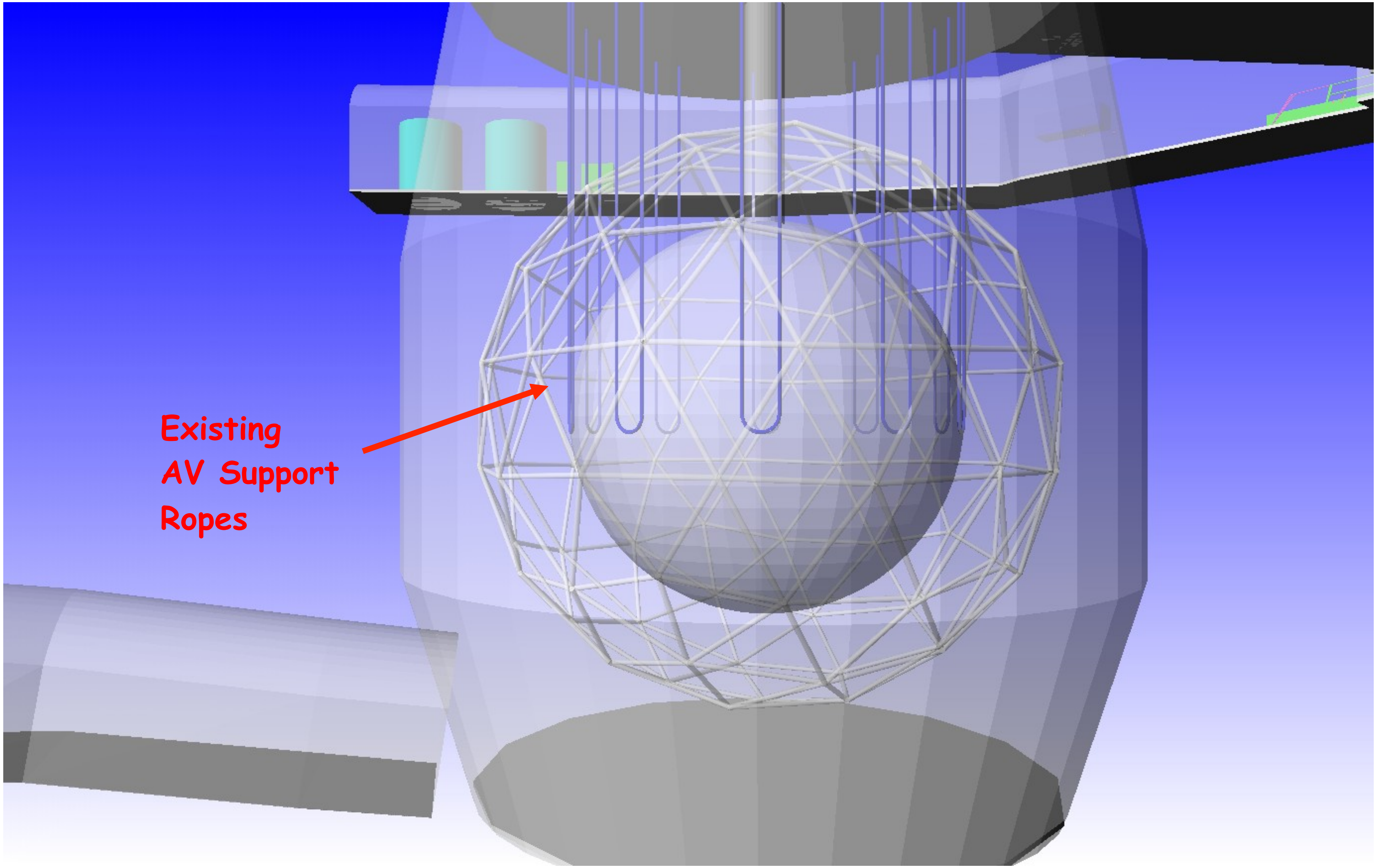
SNO+ Liquid Scintillator



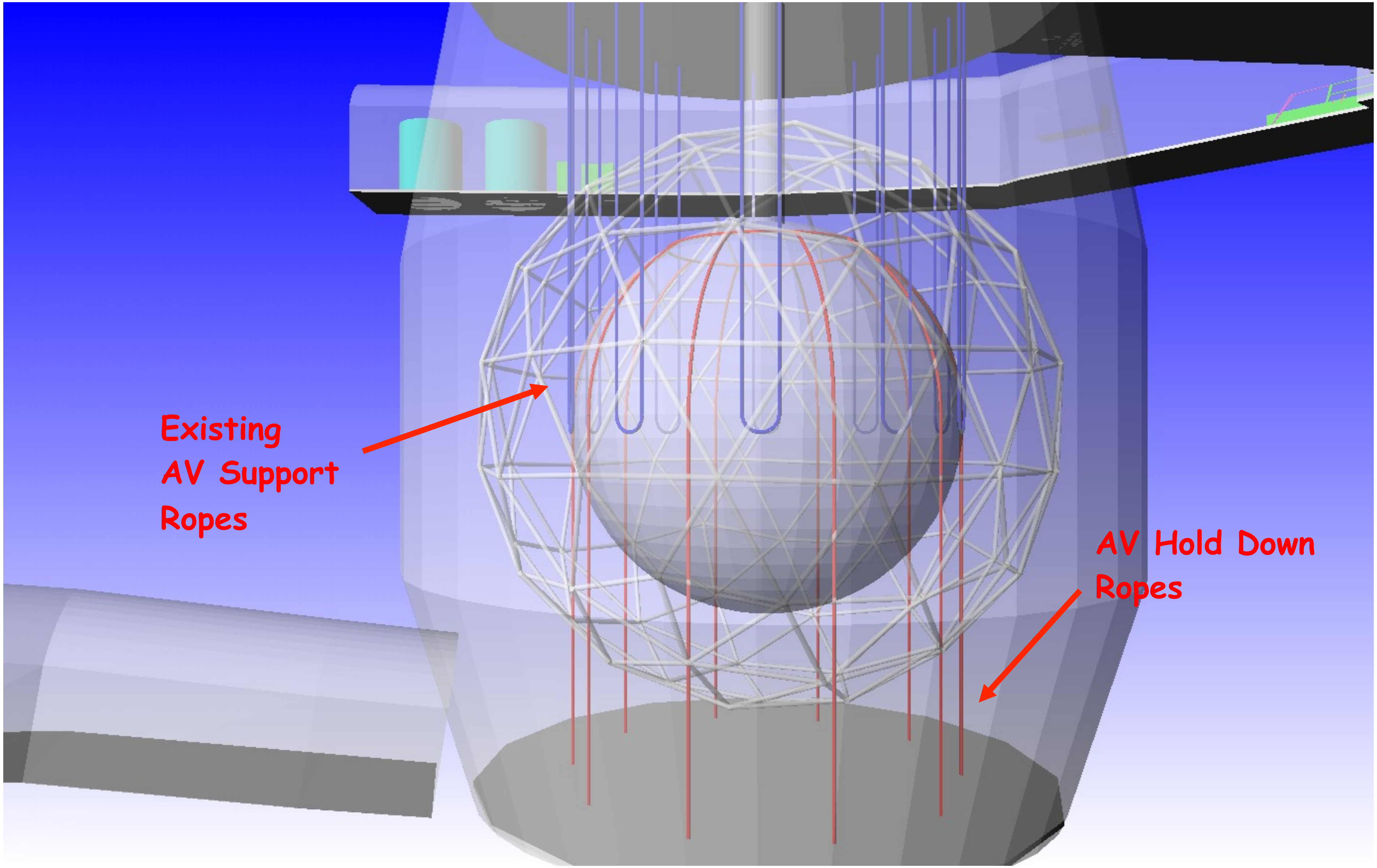
- compatible with acrylic, undiluted
- high light yield
- pure (light attenuation length in excess of 20 m at 420 nm)
- low cost
- high flash point 130°C safe
- low toxicity safe
- smallest scattering of all scintillating solvents investigated
- density r = 0.86 g/cm^3
- metal-loading compatible

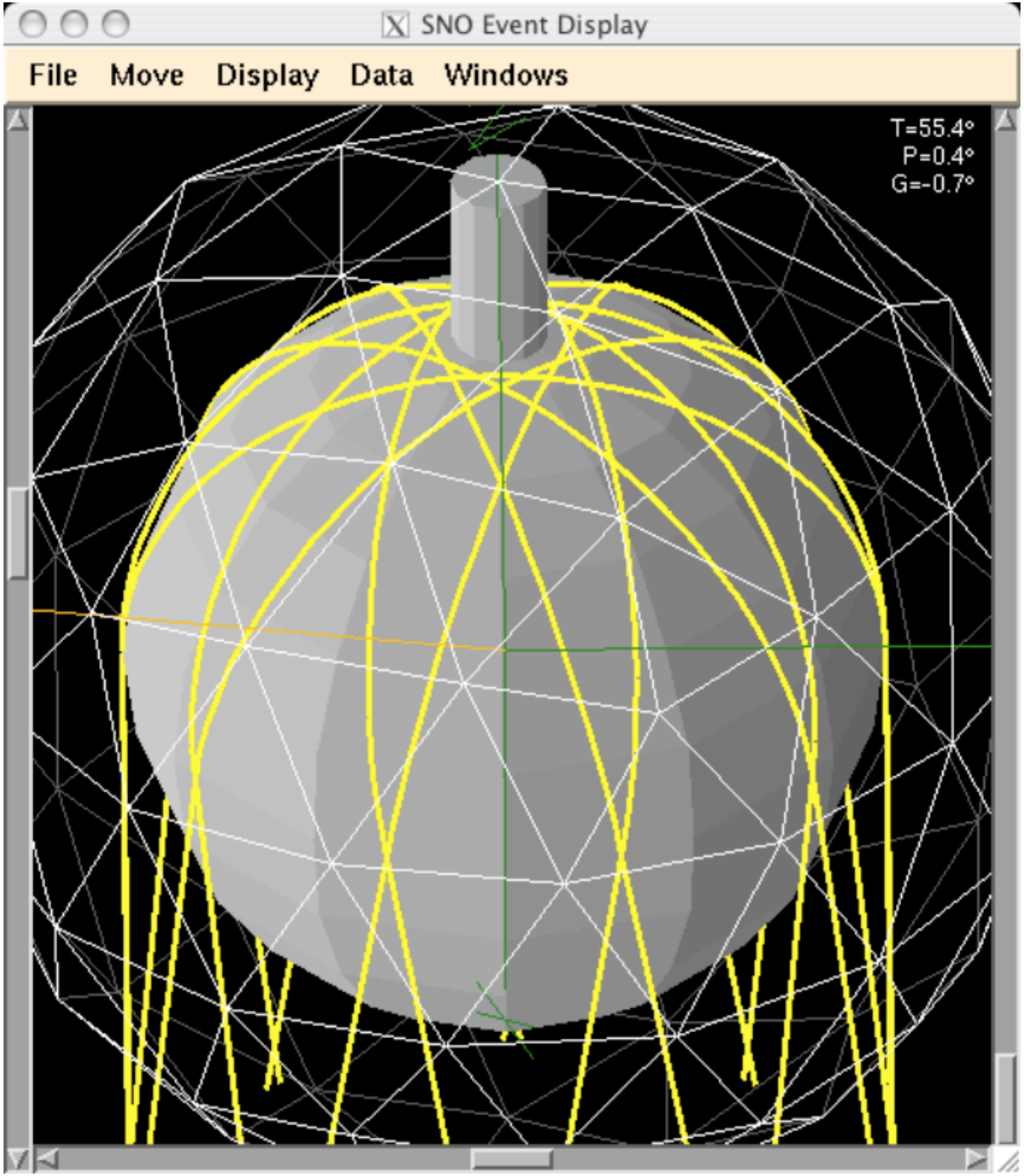
Daya Bay and Hanohano plan to use LAB; others LENS, Double CHOOZ, LENA, NOnA considering

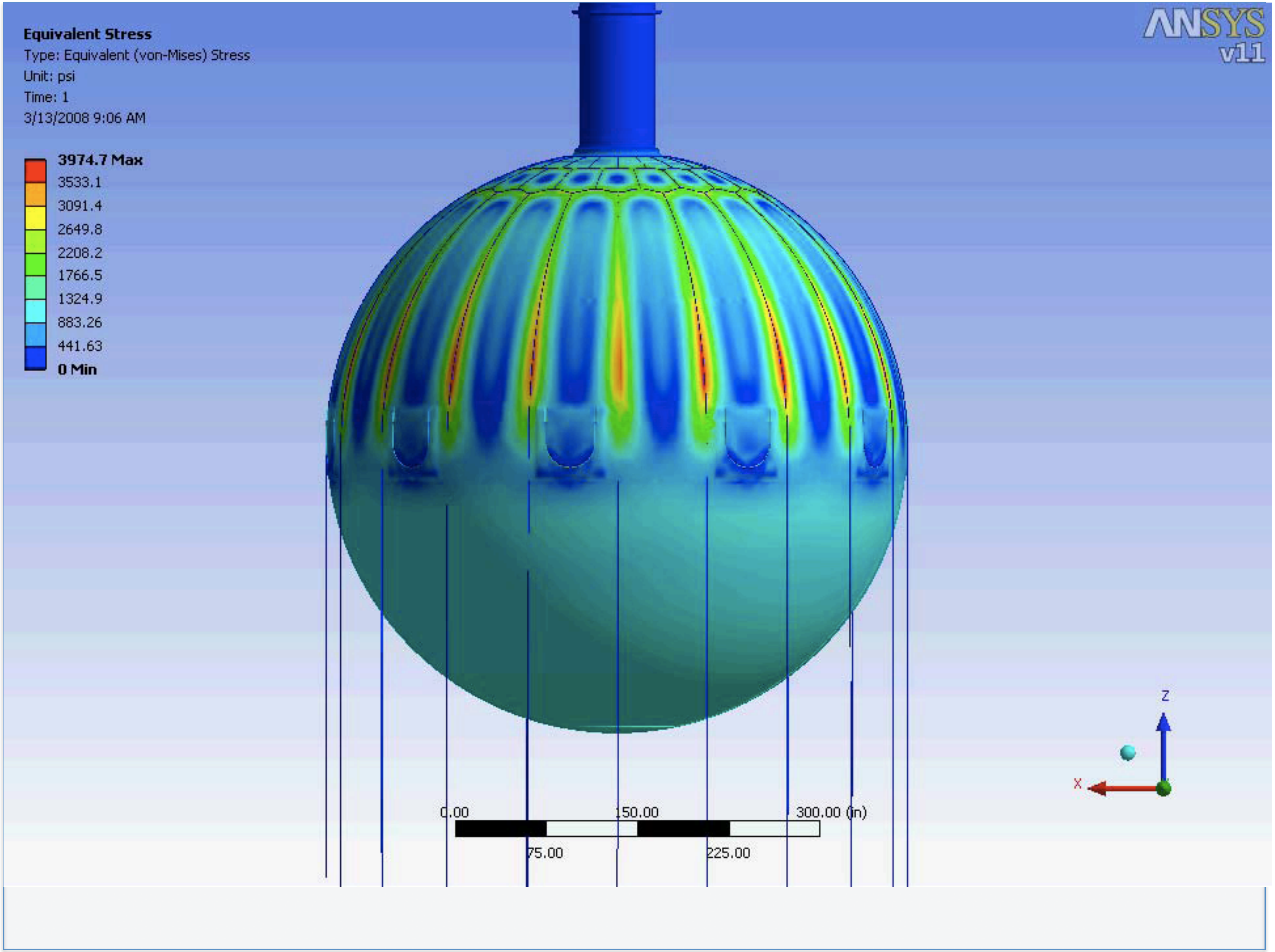
SNO+ AV Hold Down

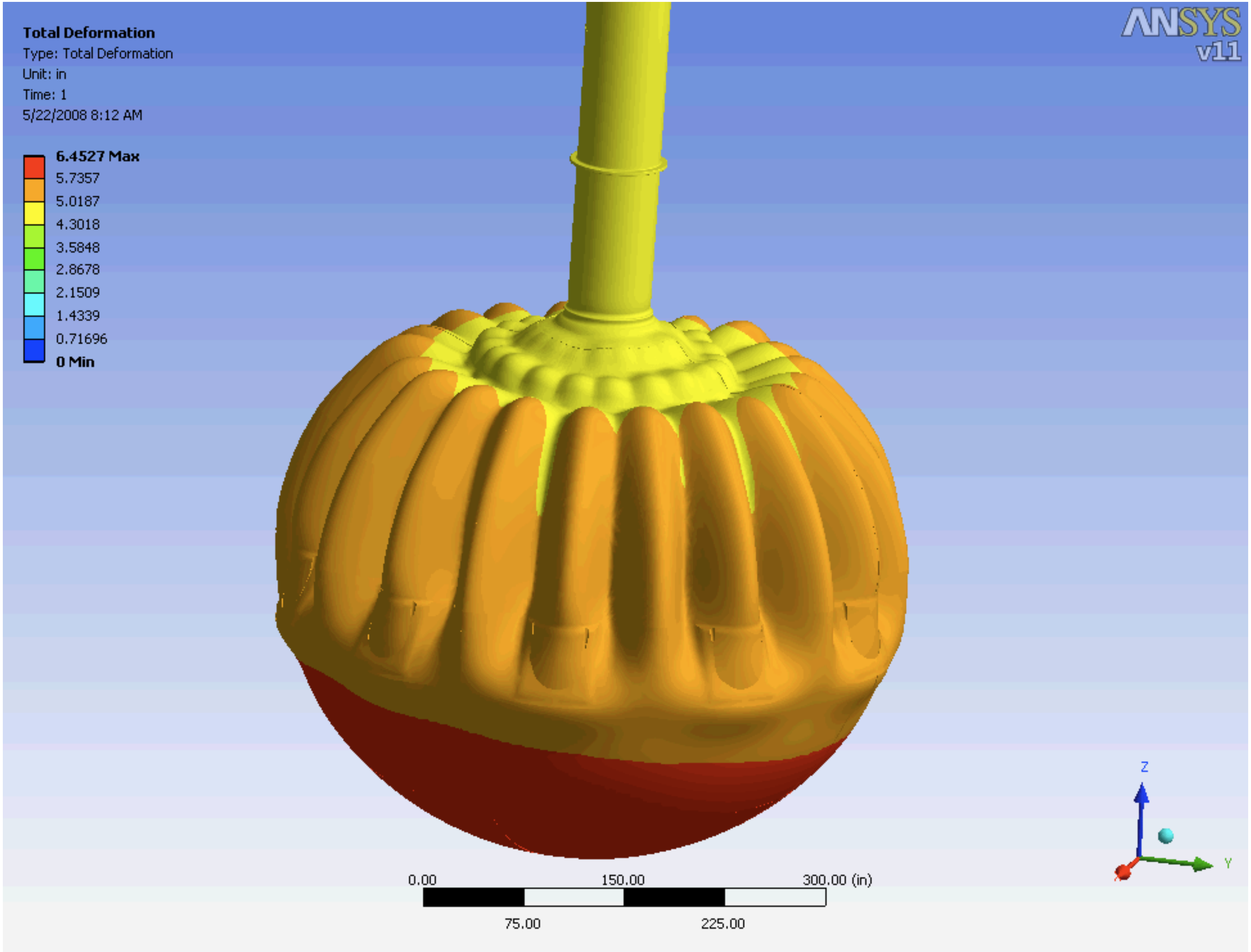


SNO+ AV Hold Down




SNO Event Display
File
Move
Display
Data
Windows
T=55.4°
P=0.4°
G=-0.7°

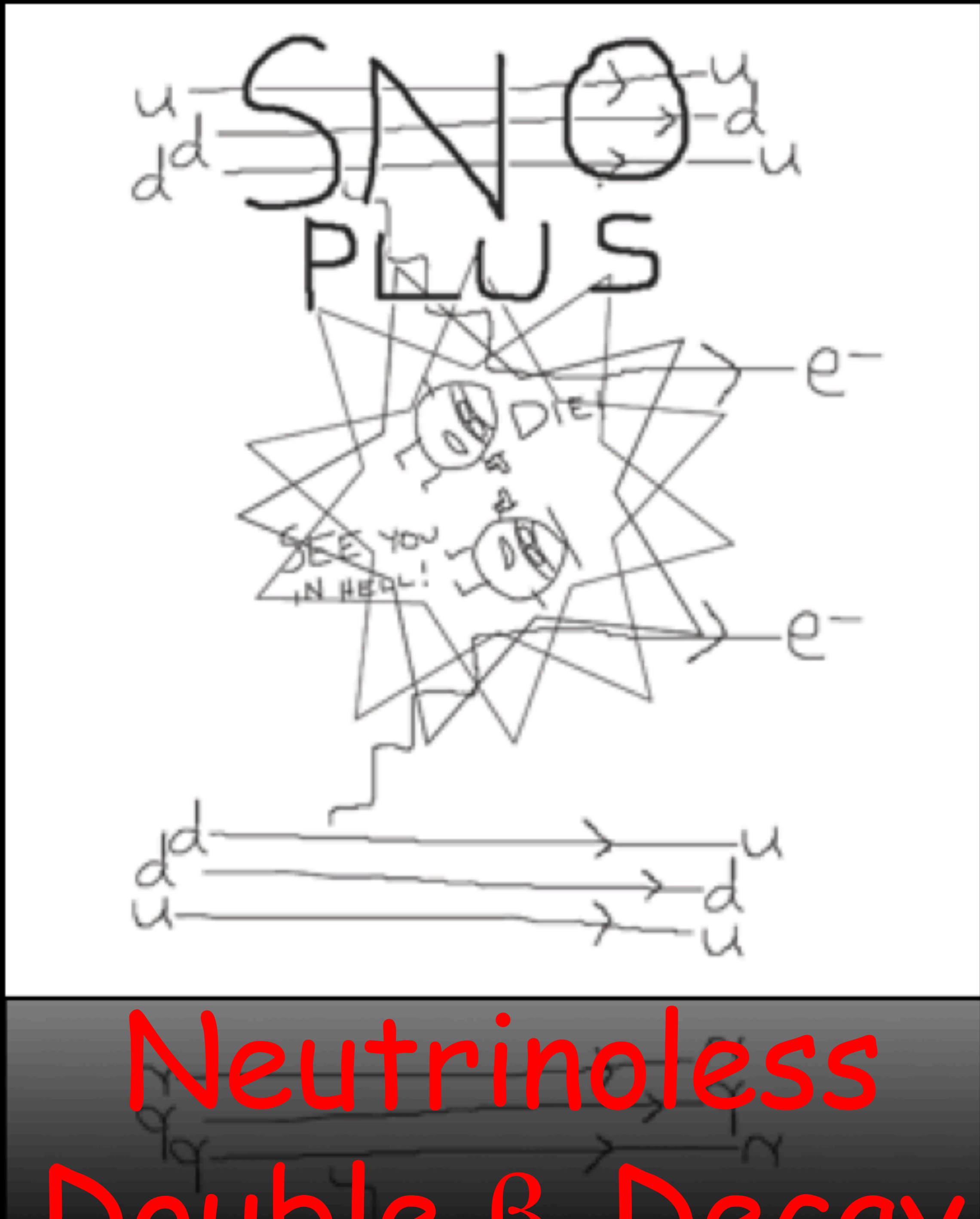

Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
3/13/2008 9:06 AM
3974.7 Max
3533.1
3091.4
2649.8
2208.2
1766.5
1324.9
883.26
441.63
0 Min
ANSYS
v11
0.00
150.00
300.00 (in)
75.00
225.00
Z
X


Total Deformation
Type: Total Deformation
Unit: in
Time: 1
5/22/2008 8:12 AM
6.4527 Max
5.7357
5.0187
4.3018
3.5848
2.8678
2.1509
1.4339
0.71696
0 Min
ANSYS
v11
0.00
150.00
300.00 (in)
75.00
225.00
Z
Y


• Electronics refurbishment
• Improved cover-gas system
• New glovebox
• Repair of liner
• Re-sanding of acrylic vessel
• Overhaul of software design
• New calibration systems
• New purification systems
• Replacement of pipes
•
•
•
•

SNO+

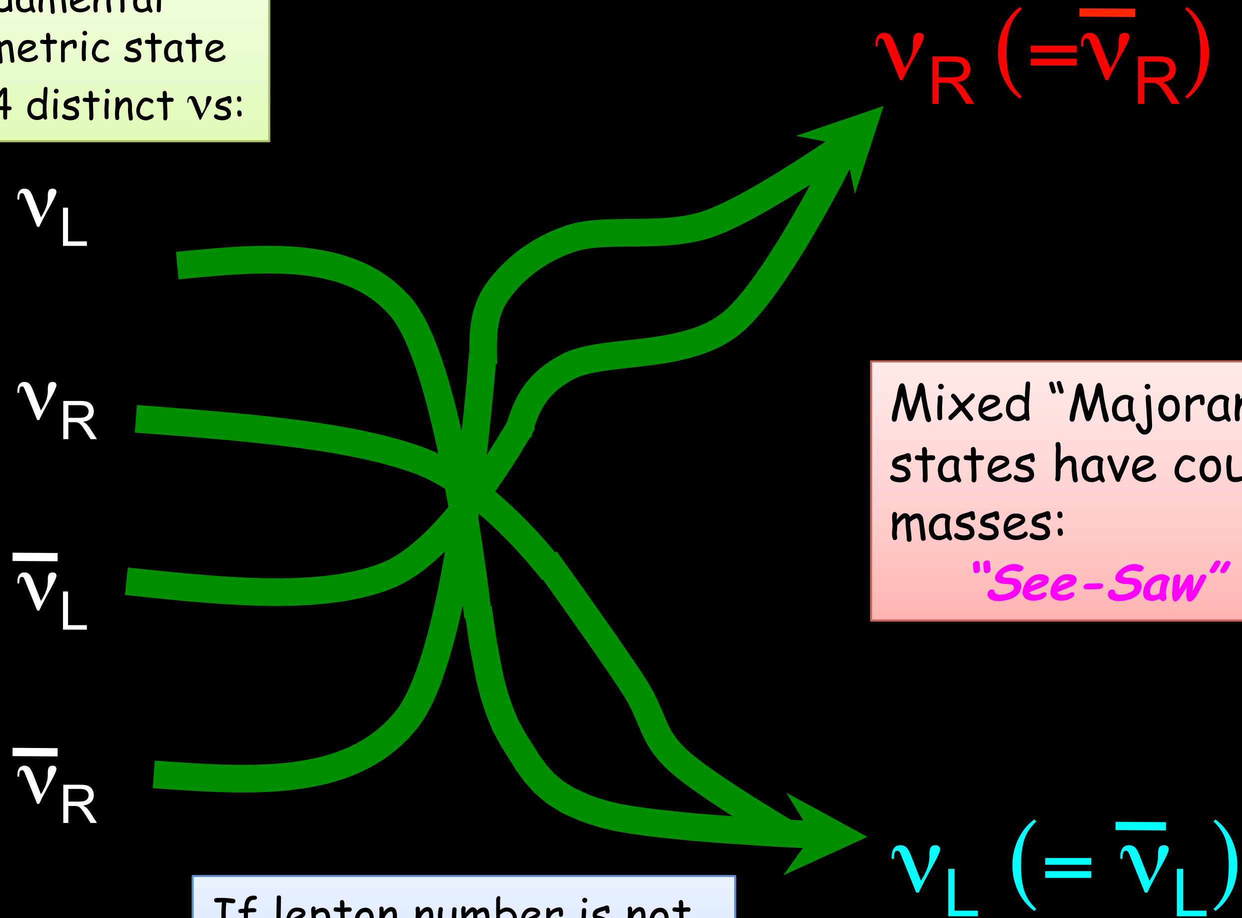
A Diverse Instrument for Neutrino Research within the SNOLAB Underground facility



Neutrinoless Double β-Decay

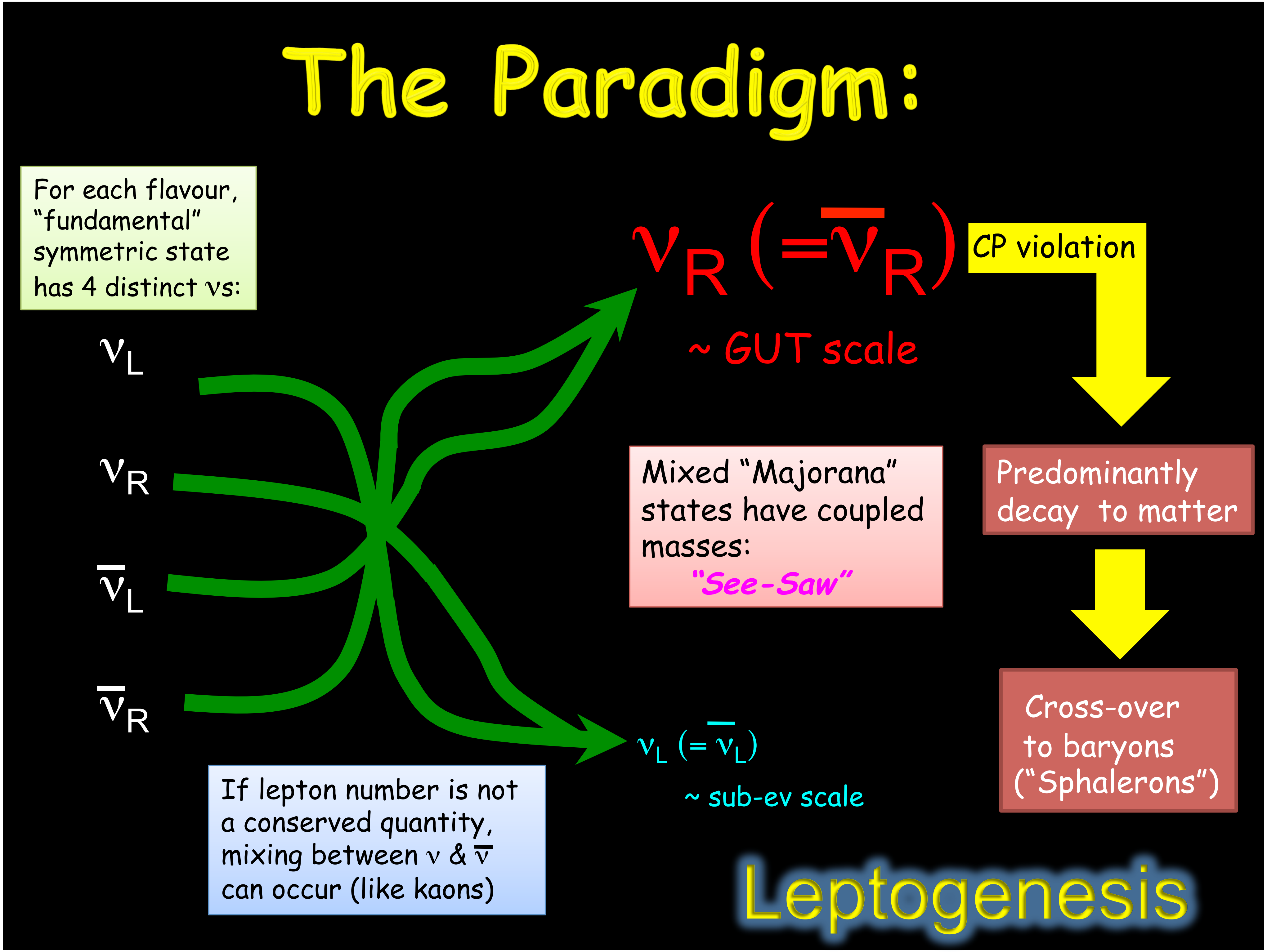
The Paradigm:

For each flavour, "fundamental" symmetric state has 4 distinct νs:



Mixed "Majorana" states have coupled masses:
"See-Saw"

If lepton number is not a conserved quantity, mixing between ν & $\bar{\nu}$ can occur (like kaons)


The Paradigm:
For each flavour, "fundamental" symmetric state has 4 distinct νs:
ν_L
ν_R
$\bar{\nu}_L$
$\bar{\nu}_R$
ν_R (= $\bar{\nu}_R$)
~ GUT scale
CP violation
Mixed "Majorana" states have coupled masses:
"See-Saw"
Predominantly decay to matter
Cross-over to baryons ("Sphalerons")
ν_L (= $\bar{\nu}_L$)
~ sub-ev scale
If lepton number is not a conserved quantity, mixing between ν & $\bar{\nu}$ can occur (like kaons)
Leptogenesis

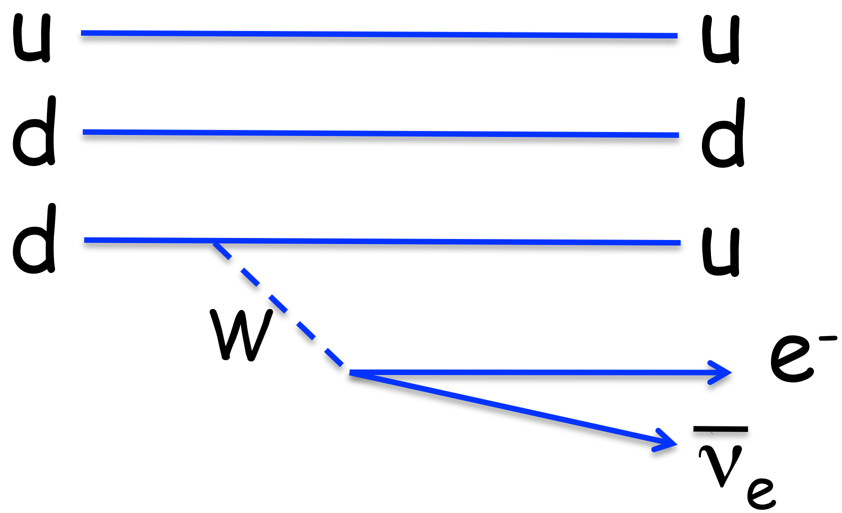
Reasons To Try ~~Marijuana~~ Majorana:

- Seesaw mechanism with GUT-scale Majorana neutrino could explain scale of observed neutrino masses
- Coupled with CP violation, would be a key feature of Leptogenesis
- Would provide an extremely sensitive probe of the absolute neutrino mass

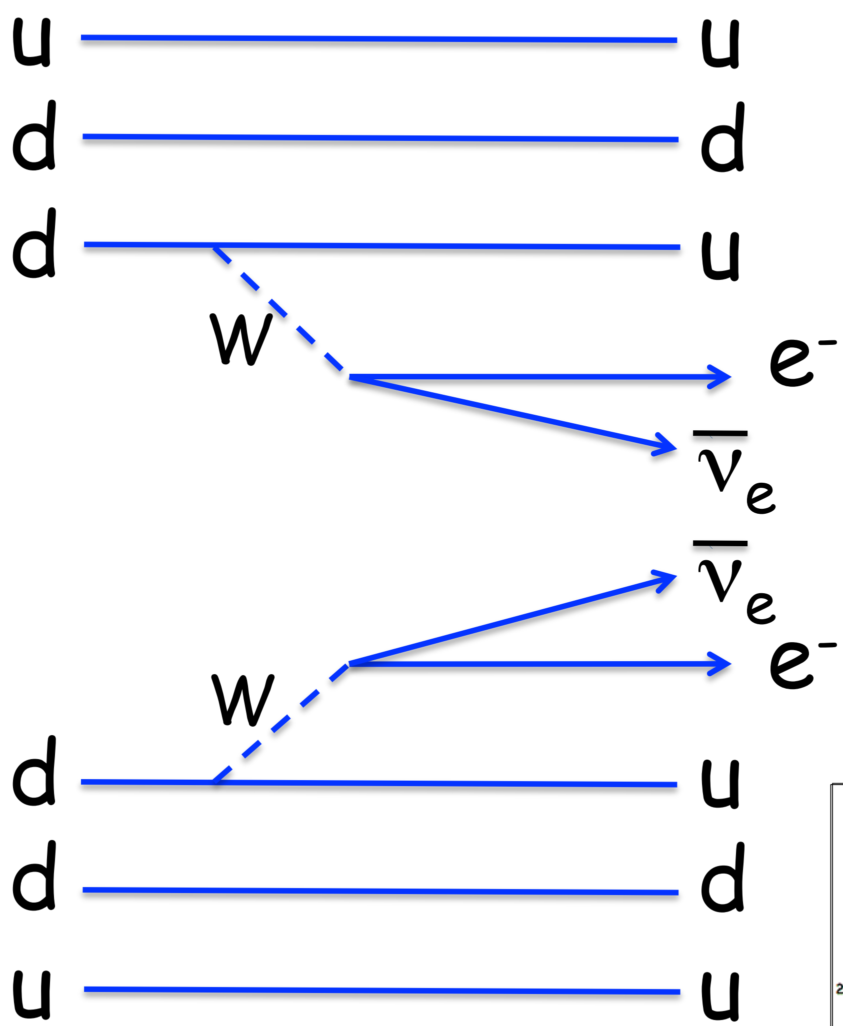
The <u>**ONLY**</u> Potentially Viable Approach Known is

Neutrinoless Double β Decay

Single Beta Decay

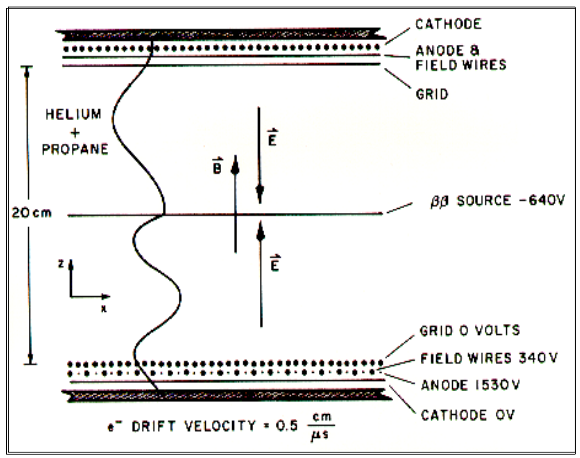


Double Beta Decay



Maria Goeppert-Mayer
1935

Elliott, Hahn & Moe
1988 (^{82}Se)

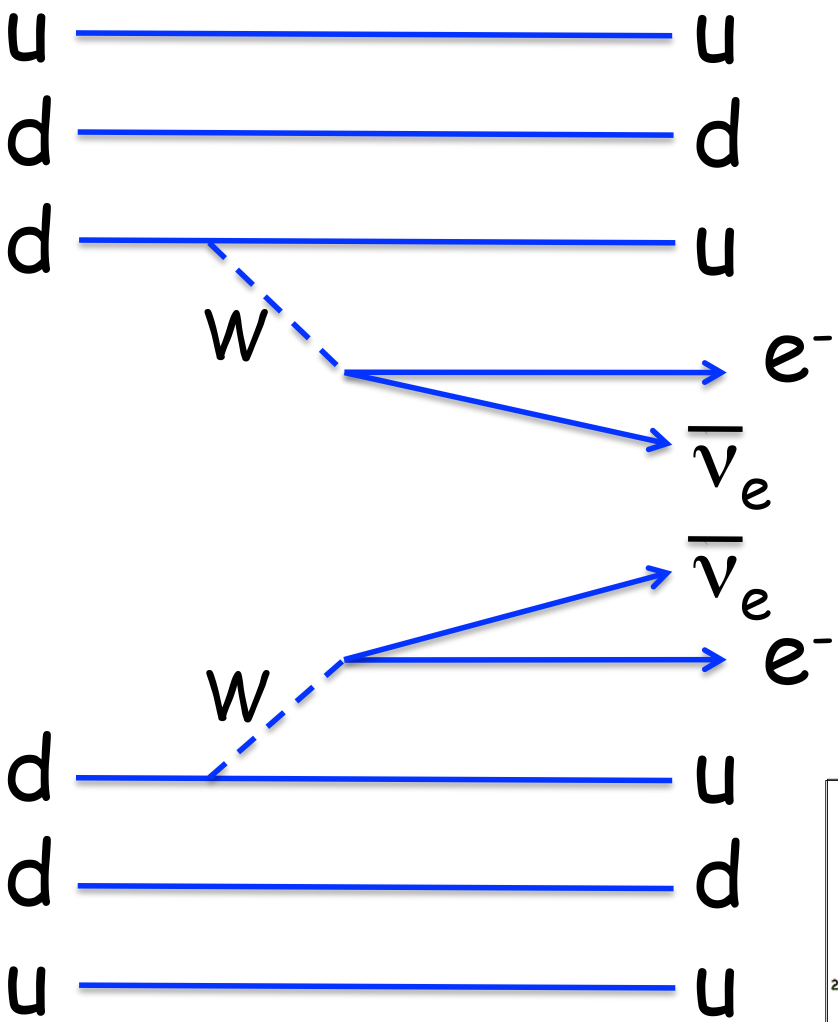


Double Beta Decay

Ettore Majorana
1937

However, if $\overline{\nu}_e$ could somehow change into ν_e ...

Wendell Furry
1939



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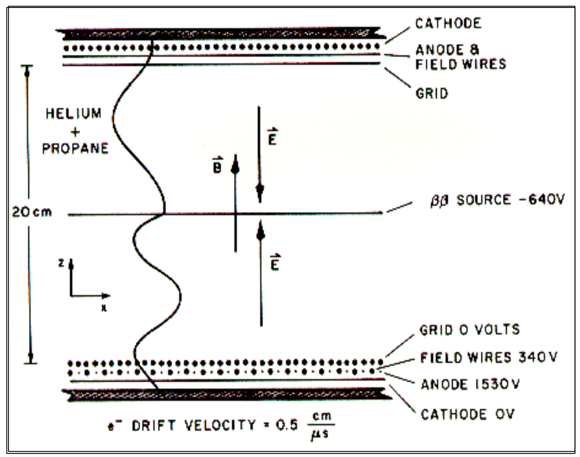
1988 (^{82}Se)



Double Beta Decay

Ettore Majorana
1937

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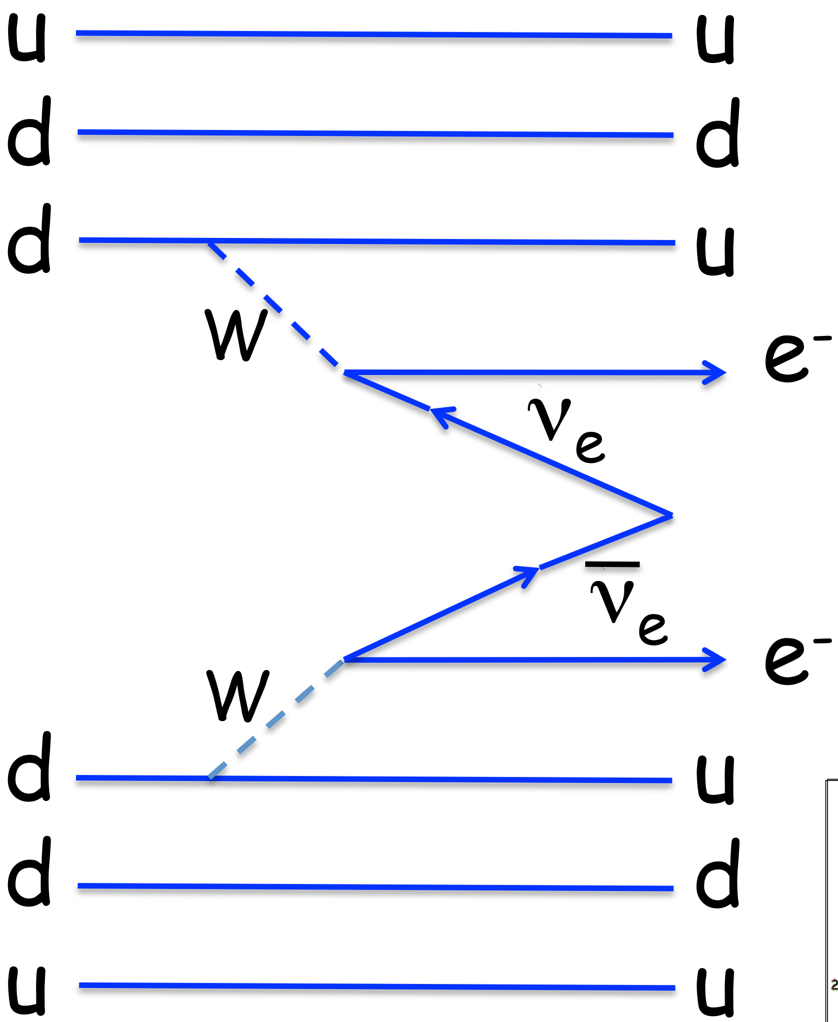

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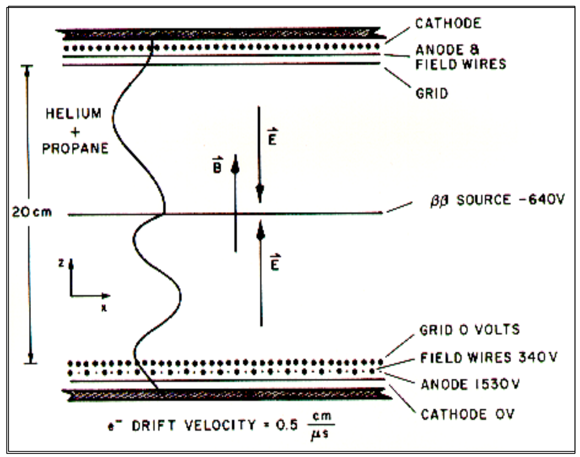

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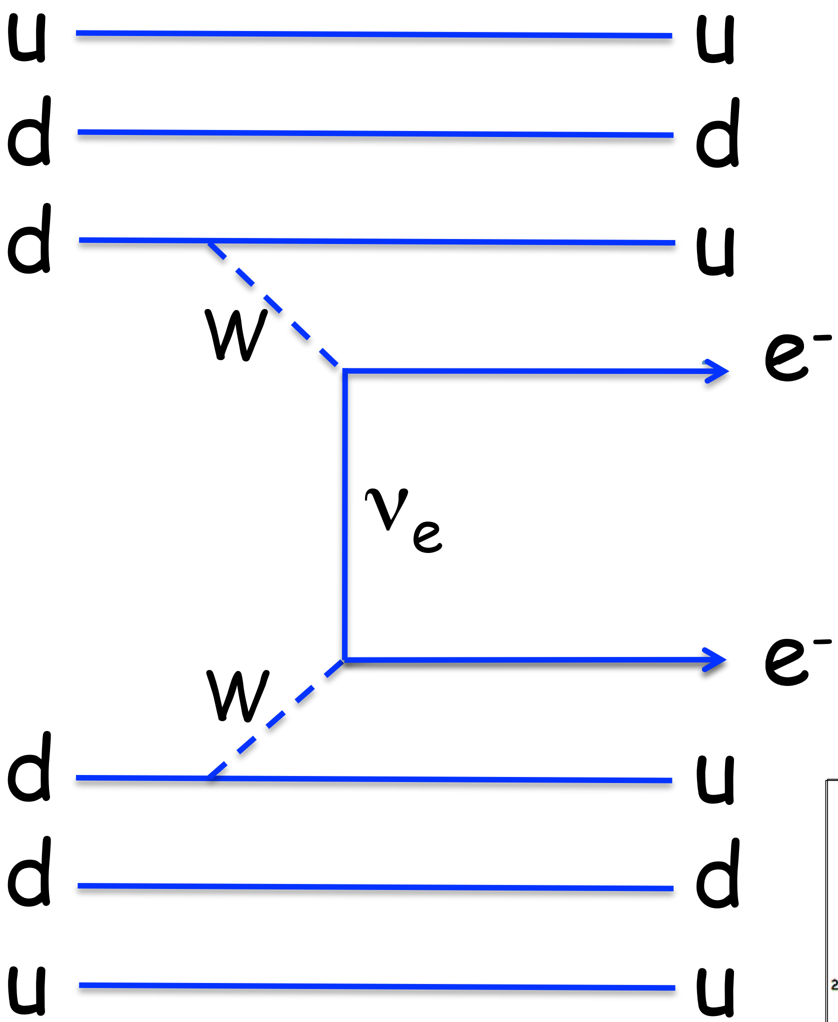
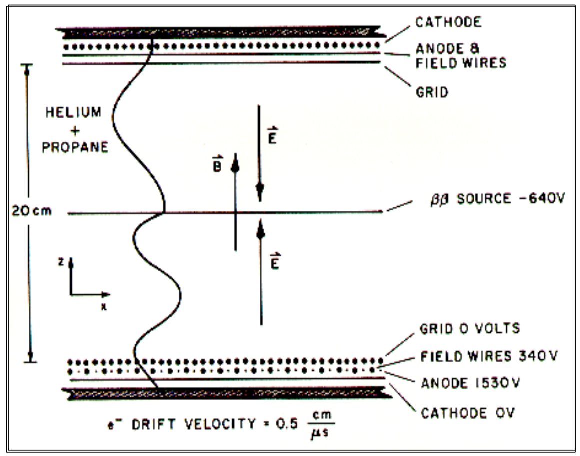
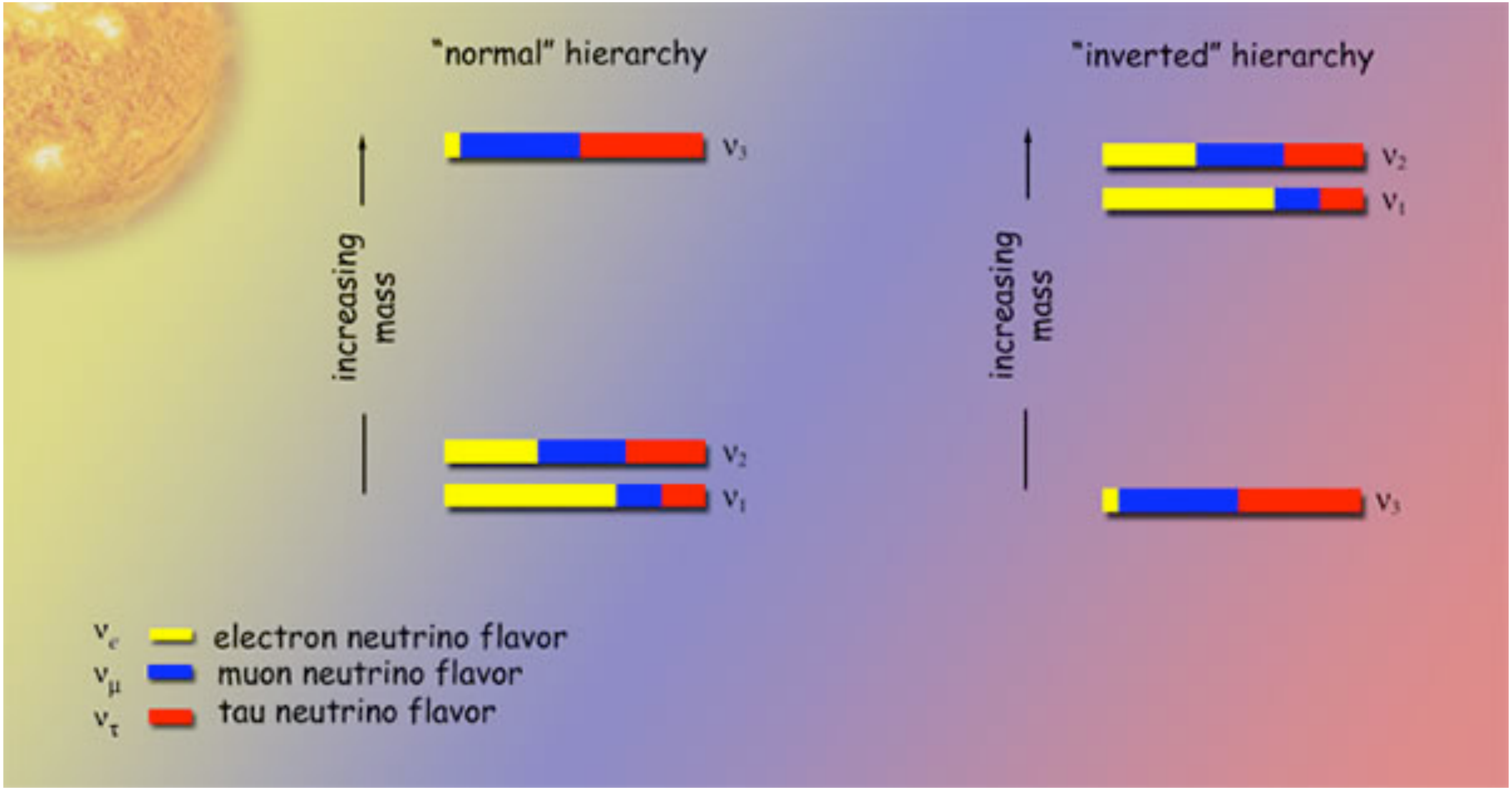


Maria Goeppert-Mayer
1935

Wendell Furry
1939

Elliott, Hahn & Moe
1988 (^{82}Se)





$$\Gamma^{0\nu} = G^{0\nu}(E0,Z) \left| M^{0\nu}{}_{GT} - (g_V/g_A)^2 M^{0\nu}{}_F \right|^2 \langle m_\nu \rangle^2$$

Exactly calculable phase integral

Nuclear matrix elements (not so exactly calculable)

Effective neutrino mass $= \Sigma m_i U^2{}_{ei}$

So,

$$\langle m_\nu \rangle_{\text{bound}} \propto \Gamma_{\text{bound}}^{\frac{1}{2}} \qquad \Gamma_{\text{bound}} \propto 1/\sigma_{\text{detection}}$$

<u>Signal Dominated Regime</u>

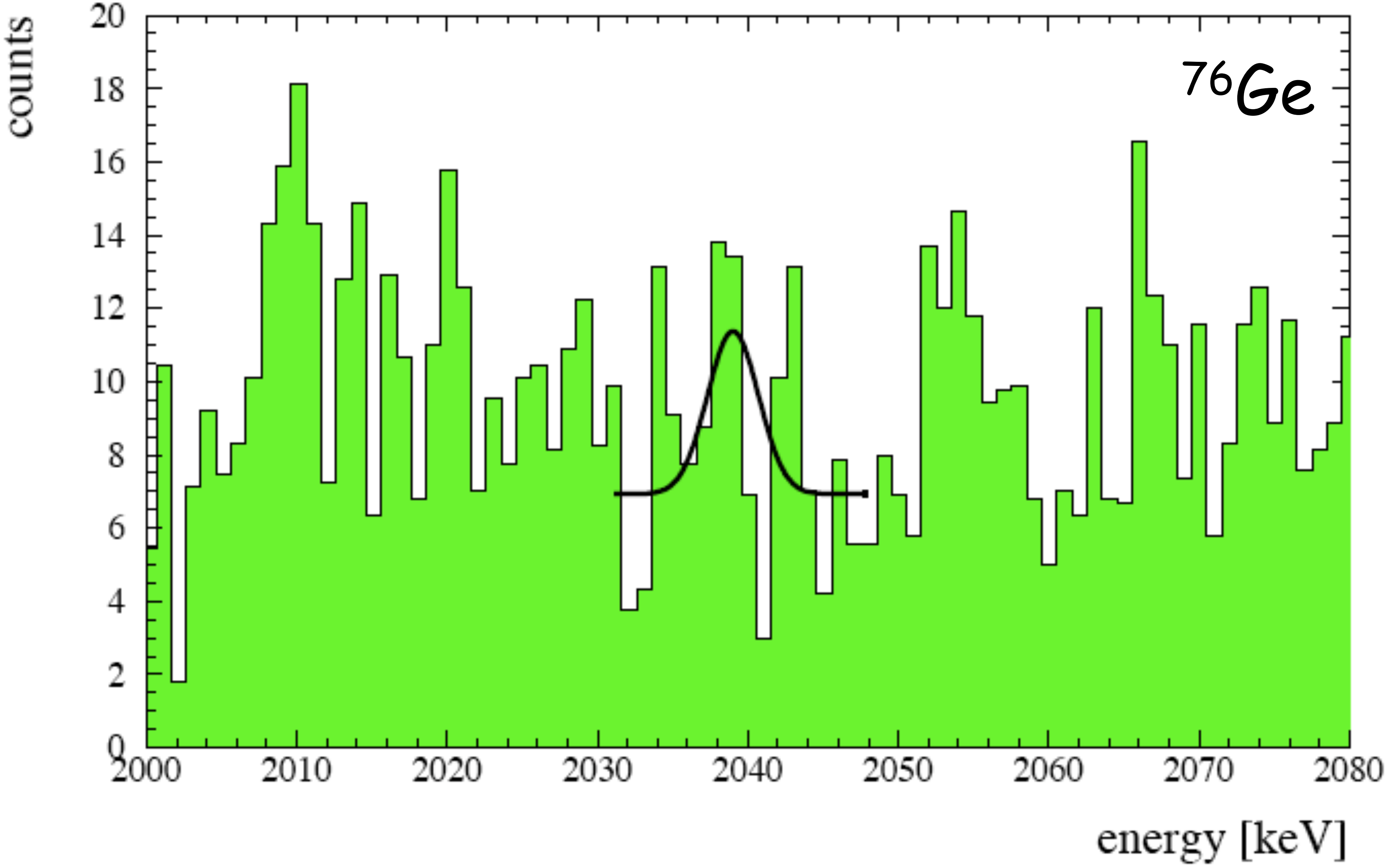
$$\sigma \propto (S)^{\frac{1}{2}} \approx (MT)^{\frac{1}{2}}$$

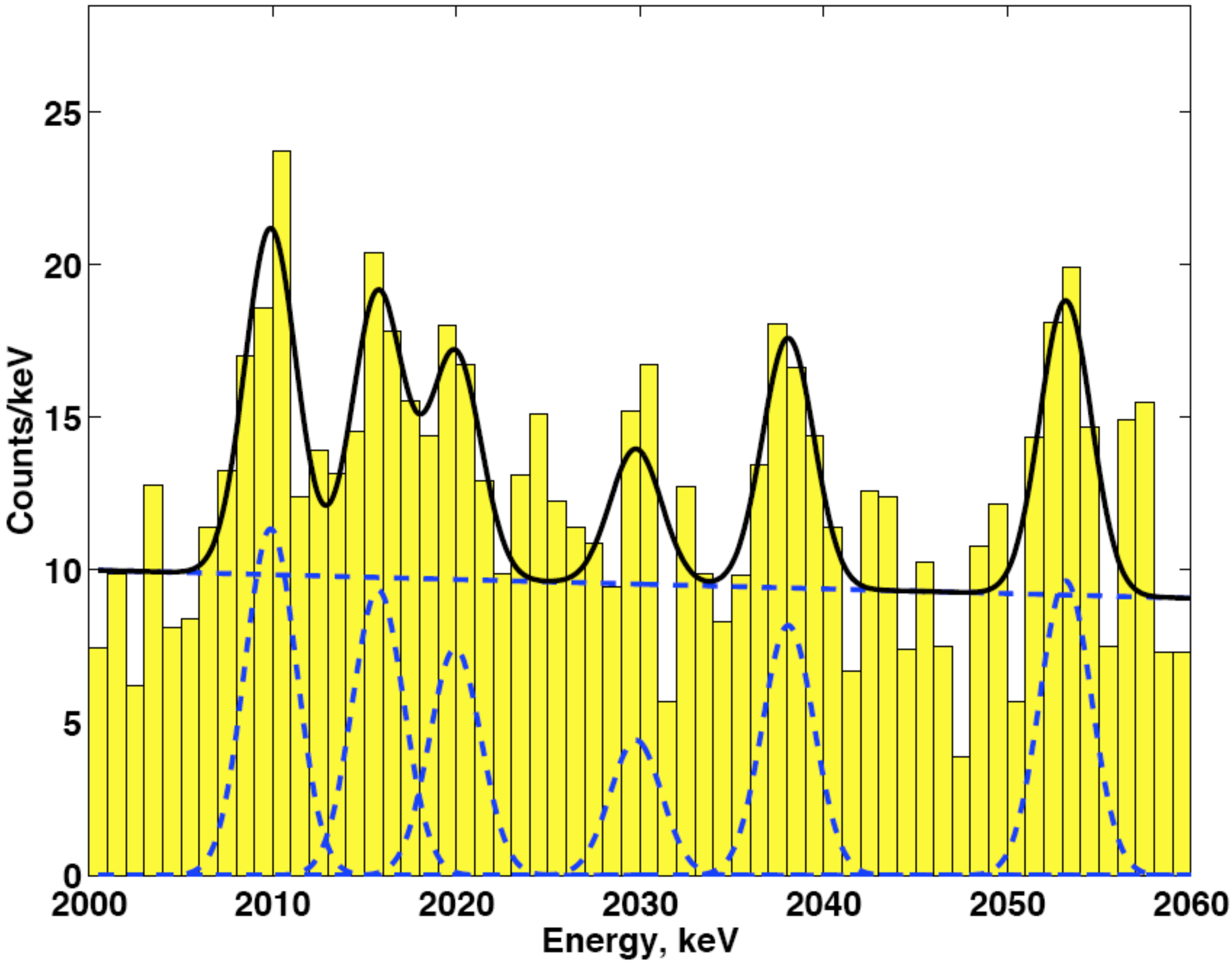
M: target mass, T: counting time

$$\langle m_\nu \rangle_{\text{bound}} \propto \left(\frac{1}{MT}\right)^{1/4}$$

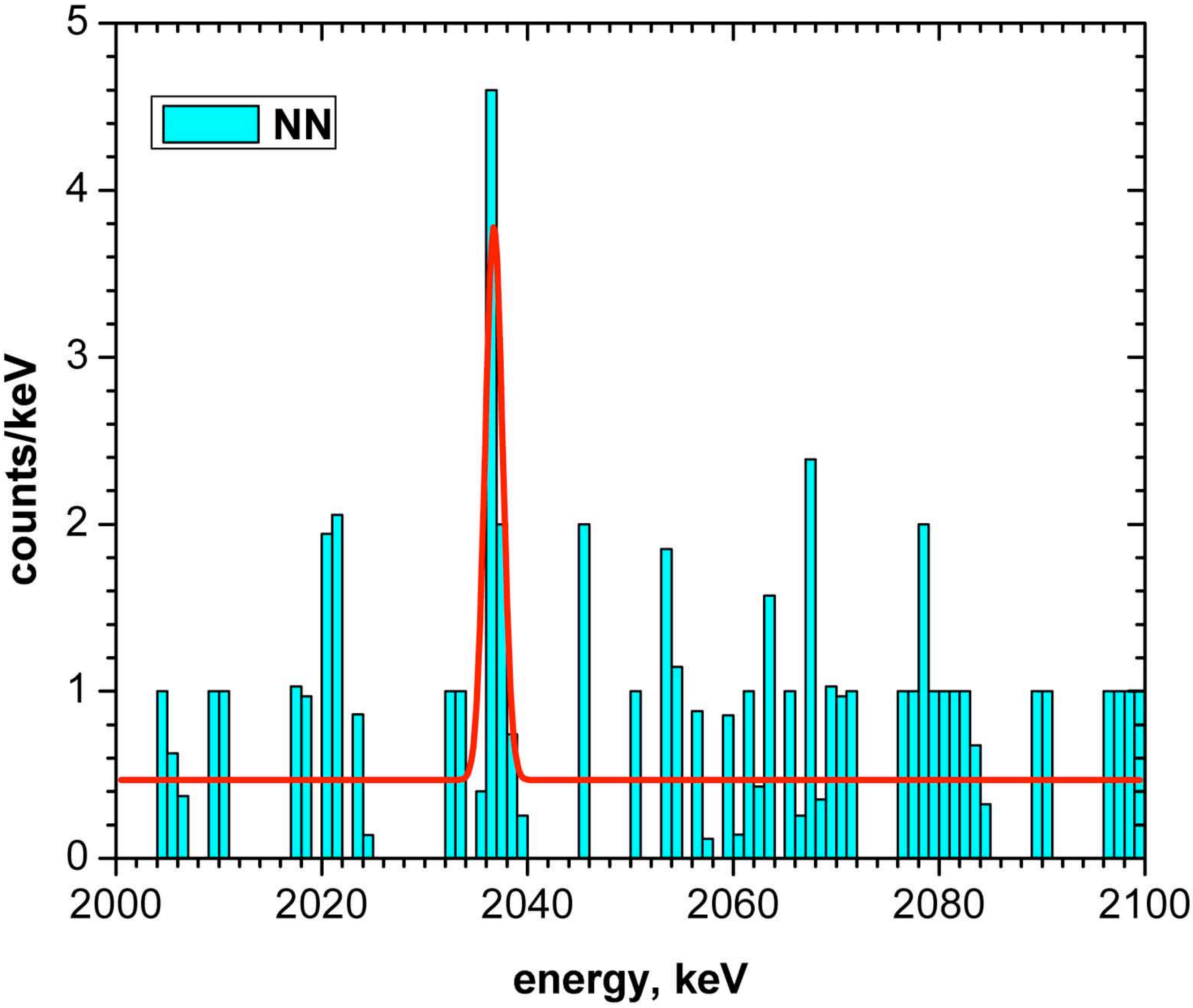
Ouch!

H.V. KLAPDOR-KLEINGROTHAUS et al., 2001





Counts/keV
Energy, keV
0
5
10
15
20
25
2000
2010
2020
2030
2040
2050
2060



NN
counts/keV
energy, keV
0
1
2
3
4
5
2000
2020
2040
2060
2080
2100

Overview of Experiments

Name	Nucleus	Mass*	Method	Location
Operational & recently completed experiments				
CUORICINO	Te-130	11 kg	bolometric	LNGS
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM
Construction funding				
CUORE	Te-130	200 kg	bolometric	LNGS
EXO-200	Xe-136	160 kg	liquid TPC	WIPP
GERDA I/II	Ge-76	35 kg	ionization	LNGS
SNO+	Nd-150	56 kg	scintillation	SNOlab
Substantial R&D funding / prototyping				
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka
Majorana	Ge-76	26 kg	ionization	SUSL
NEXT	Xe-136	80 kg	gas TPC	Canfranc
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM
R&D and/or conceptual design				
CARVEL	Ca-48	tbd	scintillation	Solotvina
COBRA	Cd-116, Te-130	tbd	ionization	LNGS
DCBA	Nd-150	tbd	drift chamber	Kamioka
EXO gas	Xe-136	tbd	gas TPC	SNOlab
MOON	Mo-100	tbd	tracking	Oto
Other decay modes				
TGV	Cd-106		ionization	LSM

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

S. Schönert, TAUP 2009

SNO+ Double Beta Decay

- A liquid scintillator detector has poor energy resolution... but HUGE quantities of isotope (high statistics) and low backgrounds help compensate

- Large, homogeneous liquid detector leads to well-defined background model
  - fewer types of material near fiducial volume
  - meters of self-shielding

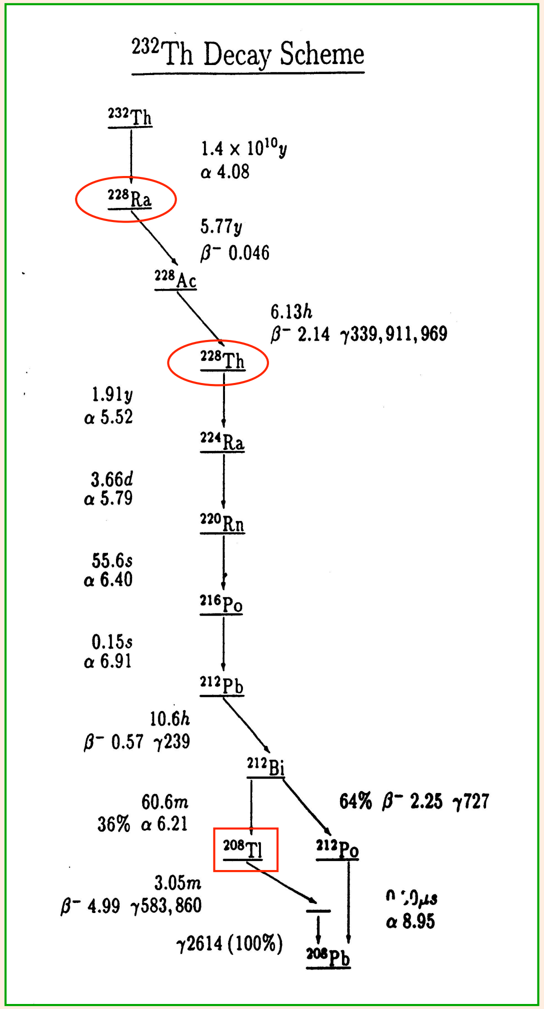
- “Source in”/“Source out” capability to test backgrounds, improve purification, etc.

- Interesting new technique with a rapid timescale that could perhaps be pushed even further

^{150}Nd

(5% natural abundance)

Loaded by carboxylate technique developed at Brookhaven



Radio-purification goals:

< 10^{-17} g ^{228}Ra/^{228}Th per g scintillator

demonstated by Borexino & KamLAND

^{228}Th and ^{228}Ra in 10 tonnes of 10% Nd (in form of $NdCl_3$ salt) down to

< 10^{-14} g ^{232}Th/g Nd

A reduction of >10^6 relative to raw salt measurement!!!

Purification/Assay Programme:

1.LAB

Organic liquids are known to be very low in Th. Vacuum distillation will improve the purity even further and this has been successfully demonstrated by both Borexino and Kamland. Our purification systems are being designed and manufactured by the same company as Borexino. The fact that both Kamland and Borexino see low levels of Th ($\sim 10^{-17}$ g Th/g scintillator) demonstrates that this can be achieved.

2. PPO

PPO will be dissolved in an LAB concentrate and distilled using the same equipment as the LAB. Again, the distillation process will "remove" Th from the PPO solution, whilst leaving the PPO in solution. This is the same technique used by Borexino.

3. Nd salt

The $NdCl_3$ solution will be mixed with $BaCl_2$ and $(NH_4)_2SO_4$ will be added to co-precipitate any Ra with $BaSO_4$. The precipitate is simply filtered out of the solution.

To remove Th, Hydrous Zirconium Oxide (HZrO) is added to the solution. The HZrO co-precipitates with any Th and removed by filtering the supernatant solution. This is very similar to the final part of the secondary concentration stage of the HTiO assay process in SNO.

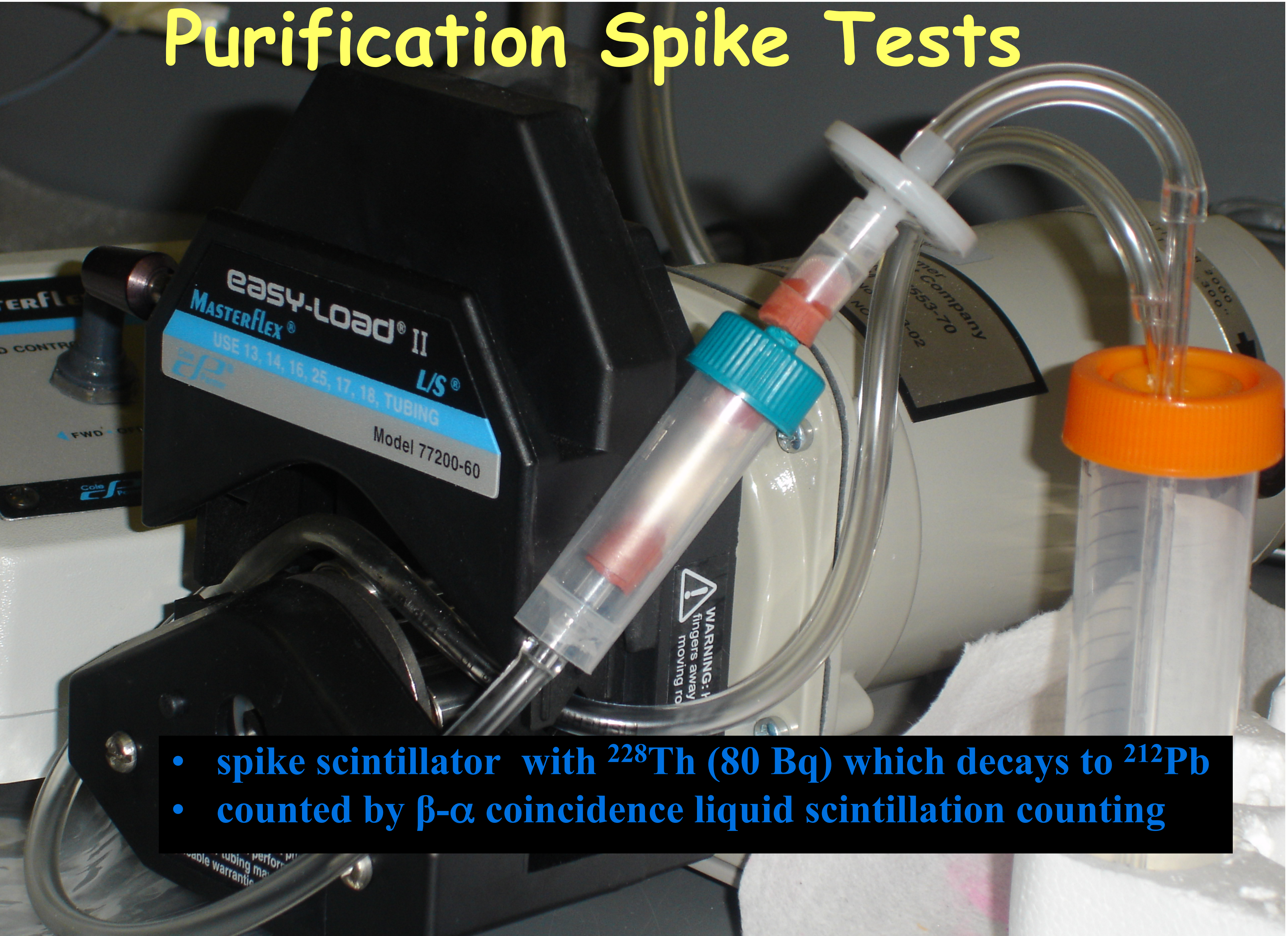
Each pass gives a factor of 1000 reduction in Th and Ra, so with 2 passes we would ostensibly get the required factor of 10^6 reduction and our desired level of 10^{-17} g Th/g scintillator.

Experience from SNO indicates we can achieve this.

How clean are your pipes?
How tight is your system?

BNL have also been working on their **"chemistry 101"** method. This is a self scavenging technique and relies upon the fact that Th is more soluble when compared with Nd at certain pH values. The salt is dissolved in (ultra pure) water at a controlled pH. The pH is then adjusted to a pre-determined level, at which "all" of the Th is separated.

Purification Spike Tests



- spike scintillator with ^{228}Th (80 Bq) which decays to ^{212}Pb
- counted by β-α coincidence liquid scintillation counting

Spike Test Results: Extraction Efficiencies of Th and Ra in 10% $NdCl_3$ using HZrO and $BaSO_4$

Purification method	Adsorbent Conc	Extraction efficiency	
		228Th	226Ra
	0.1 mg/g Zr	<5%	<10%
	0.44 mg/g Zr	99.06±0.22%	30.7±5.7%
HZrO mixed-in	**0.82 mg/g Zr**	**99.89±0.02%**	30.1±9.0%
BaSO4 mixed-in	1.0 mg/g Ba	9.5±4.7%	63.4±1.9%
	0.49 mg/g Ba	20.4±4.4%	97.2±0.2%
BaSO4 co-precipitation	**1.39 mg/g Ba**	62.8±2.3%	**99.89±0.03%**

factor of 1000 purification per pass achieved for both Th and Ra!

4. TMHA

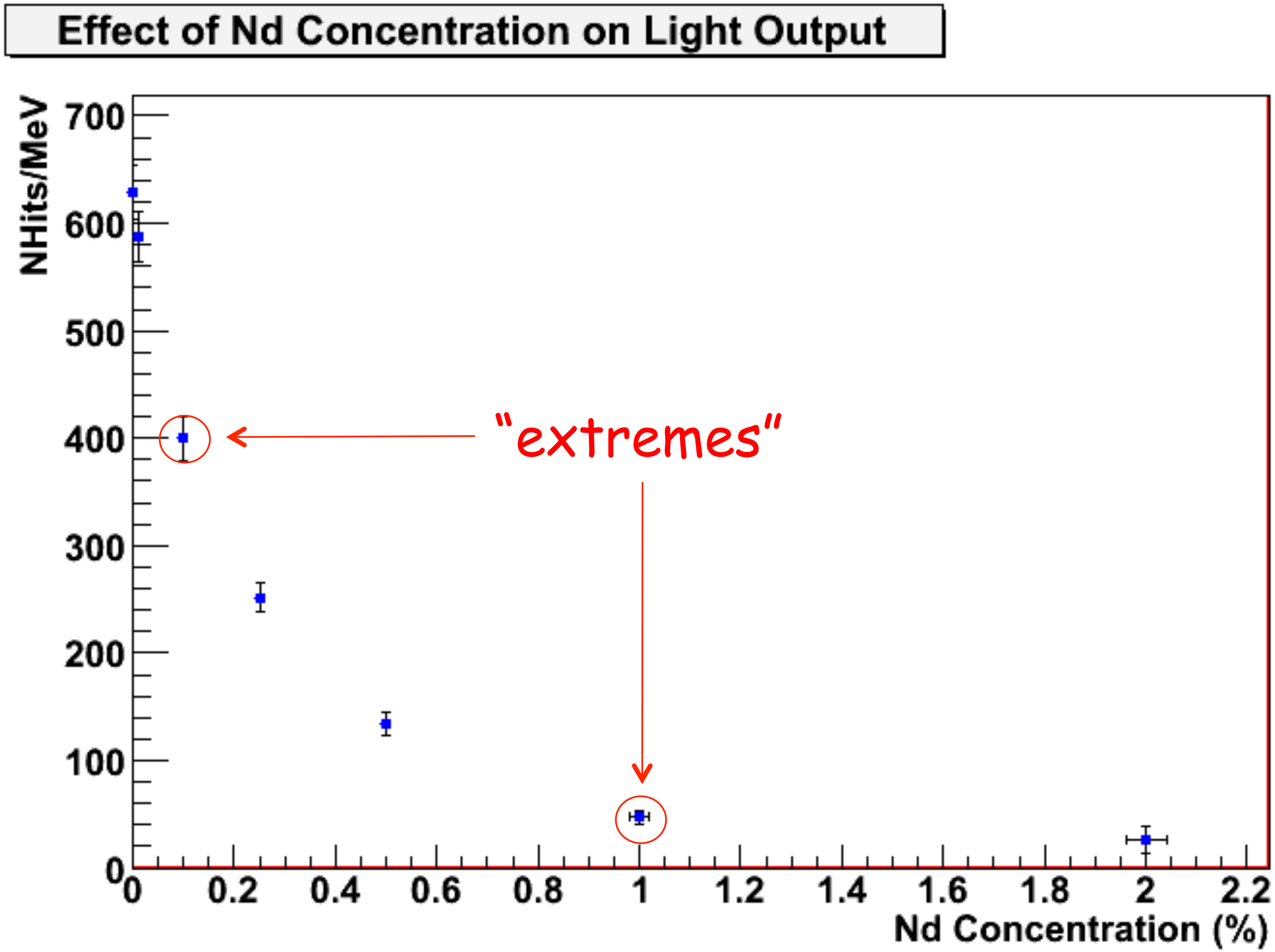
(Used in the Nd loading process) will be purified by distillation.

5. In-situ analysis

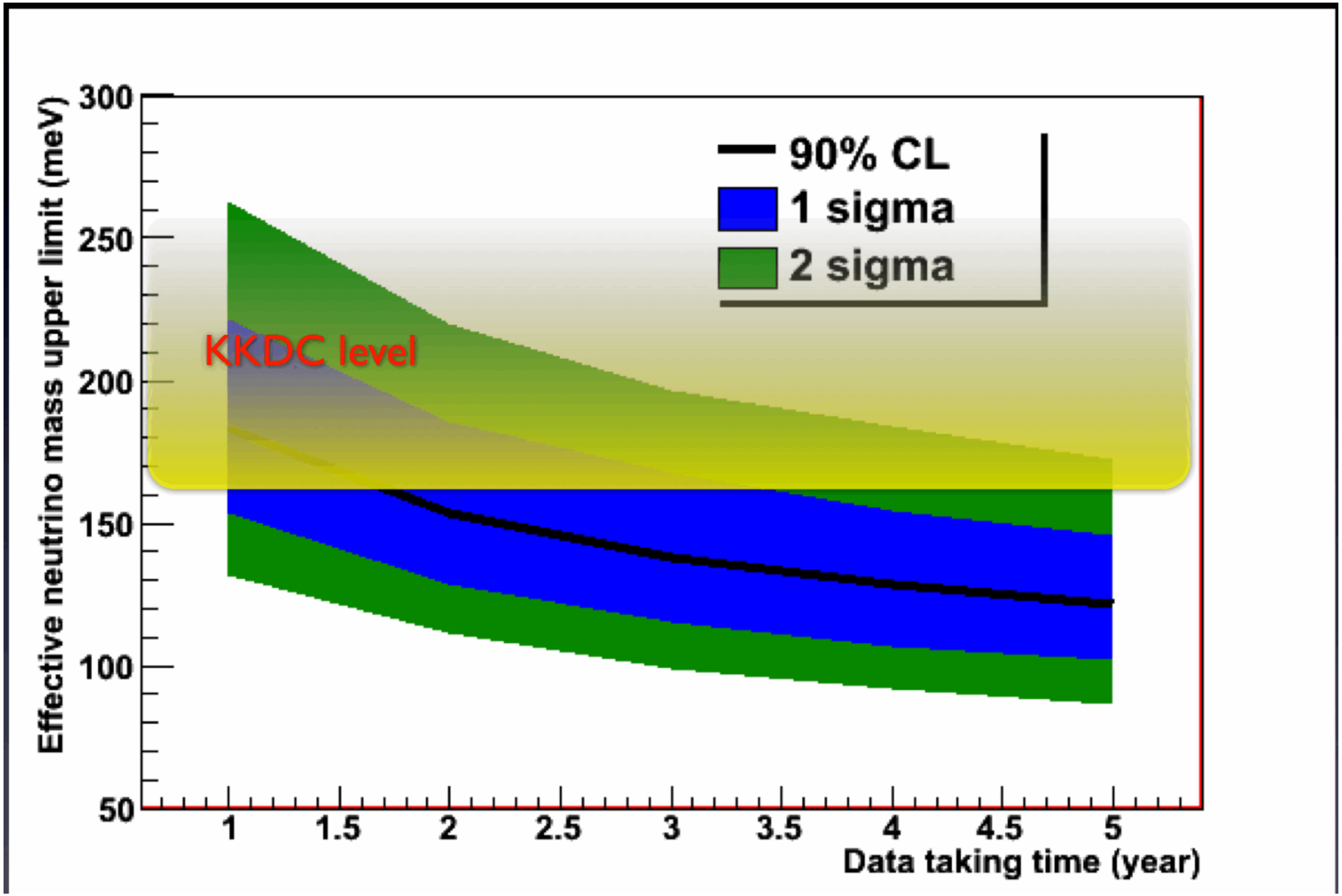
As with SNO, we plan an *in-situ* analyses of the backgrounds in the scintillator. We will search for the Bi-Po coincidences in both chains (300 ns half life). Also of interest will be to search for the 3 min Bi-Tl coincidence on the "other side of the branch". This may be possible as we can distinguish betas from alphas with our scintillator timing. Other approaches are also being explored.

etc., etc.,…

Light Output and Concentration



0.1% Natural Nd in SNO+

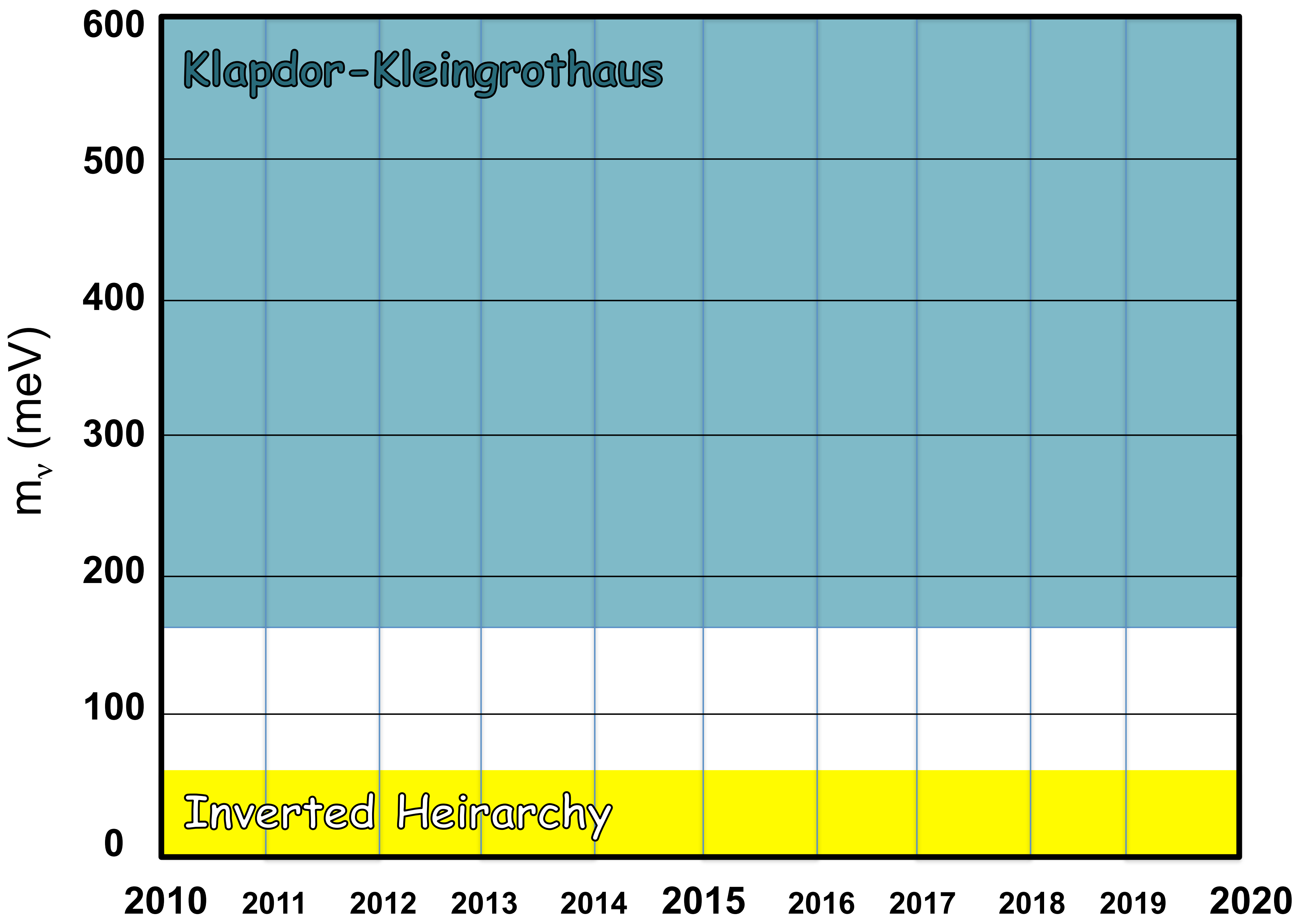


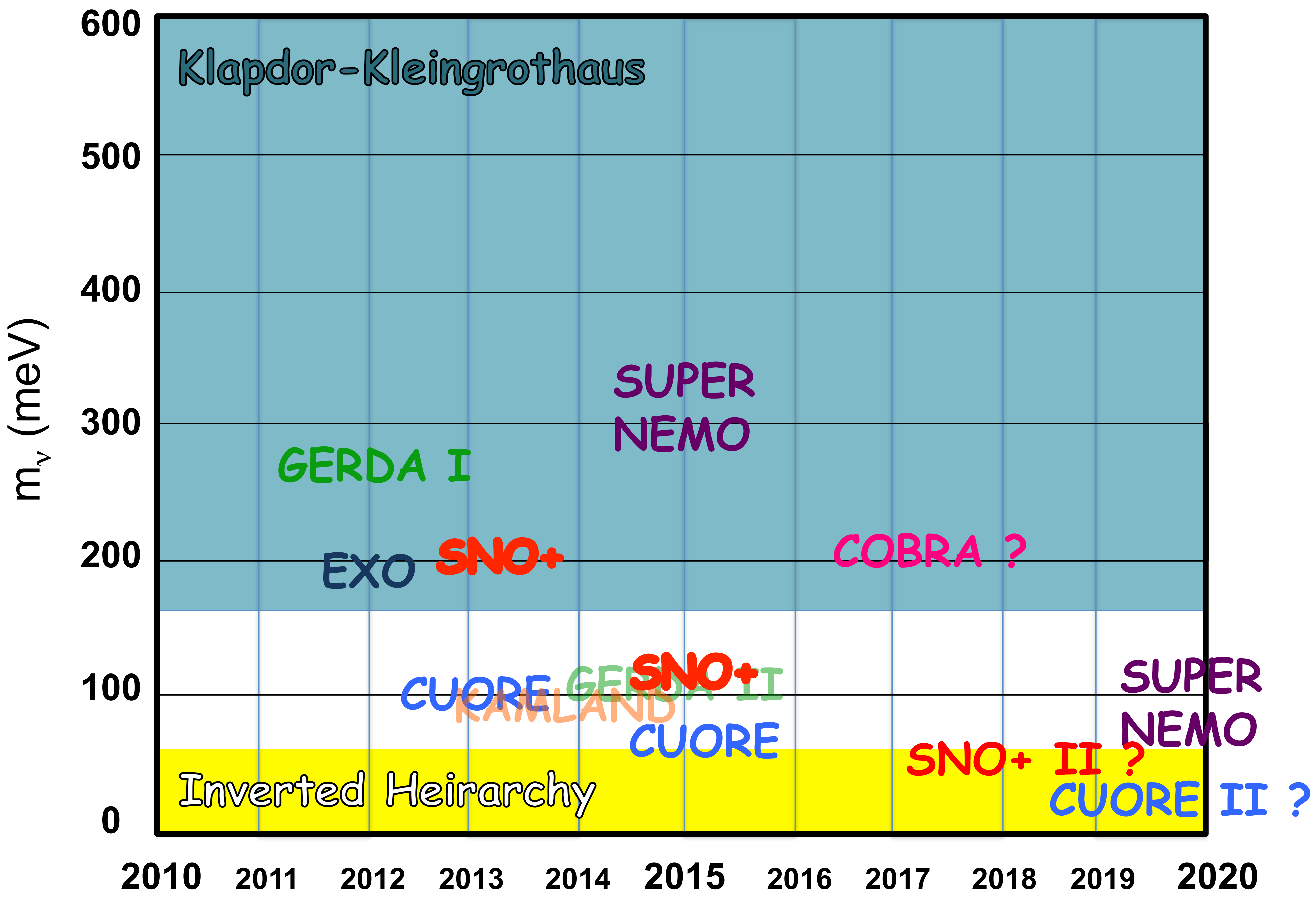
How do you firmly establish whether a possible signal is actually $0\nu2\beta$?

Two methods: **1) Redundancy**

2) Redundancy

Different isotopes with signals predicted at different energies, with different backgrounds, and different signal rates that scale correctly with the corresponding matrix elements.


Klapdor-Kleingrothaus
Inverted Heirarchy
m_ν (meV)
600
500
400
300
200
100
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020



600
500
400
300
200
100
0
m_ν (meV)
Klapdor-Kleingrothaus
SUPER NEMO
GERDA I
EXO
SNO+
COBRA ?
CUORE
KAMLAND
GERDA II
SNO+
CUORE
SUPER NEMO
SNO+ II ?
CUORE II ?
Inverted Heirarchy
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

Towards SNO++

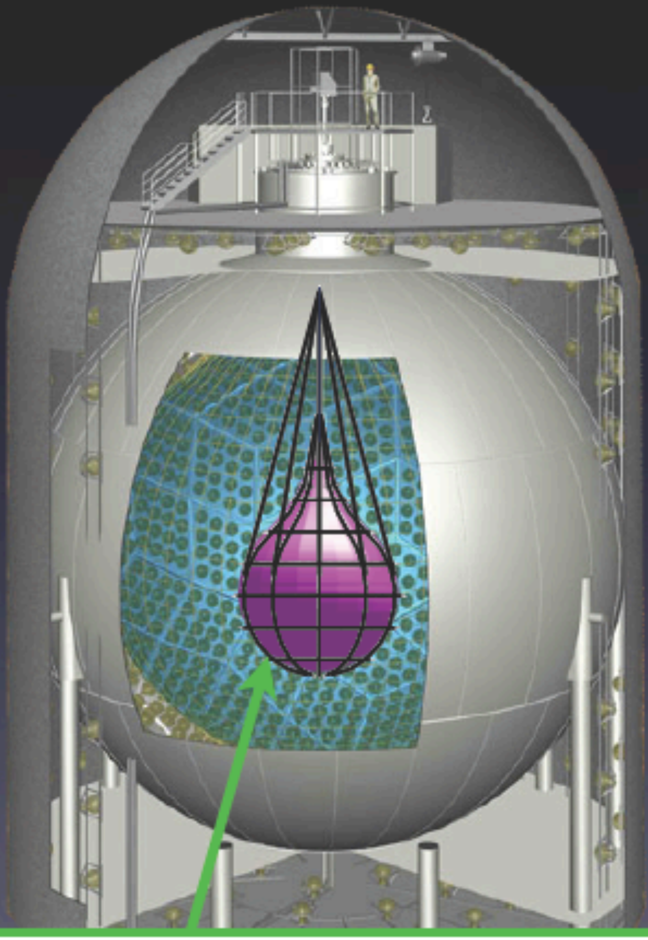
^{150}Nd enrichment

Nanoparticles

Rik Brydson (ParticlesCIC, Leeds)
Alison Crossley, Kerstin Jurkschat (Oxford)
Peter Dobson (Begbroke Science Park, Oxford)

Other Isotopes

KamLAND-Zen



^{136}Xe 400 kg loaded LS
in mini-balloon, R=1.7m

^{136}Xe 400 kg:

- 2.7 wt% dissolved into LS
- easy handling/ enrichment (90%)
- longer 2ν beta decay life time
- $T^{2\nu} > 10^{22}$ years (cf: ~$10^{19\text{-}20}$)

KamLAND exists:

- ultra pure environment (U/Th~10^{-17} g/g)
- LS techniques
- Balloon experience
- LS Density control techniques
- Reactor/Geo neutrino

^{96}Zr

UNDER INVESTIGATION

$Q_{\beta\beta}$ = 3.35 MeV (versus 3.37 MeV for ^{150}Nd)

0ν Matrix Element ~ comparable to ^{150}Nd

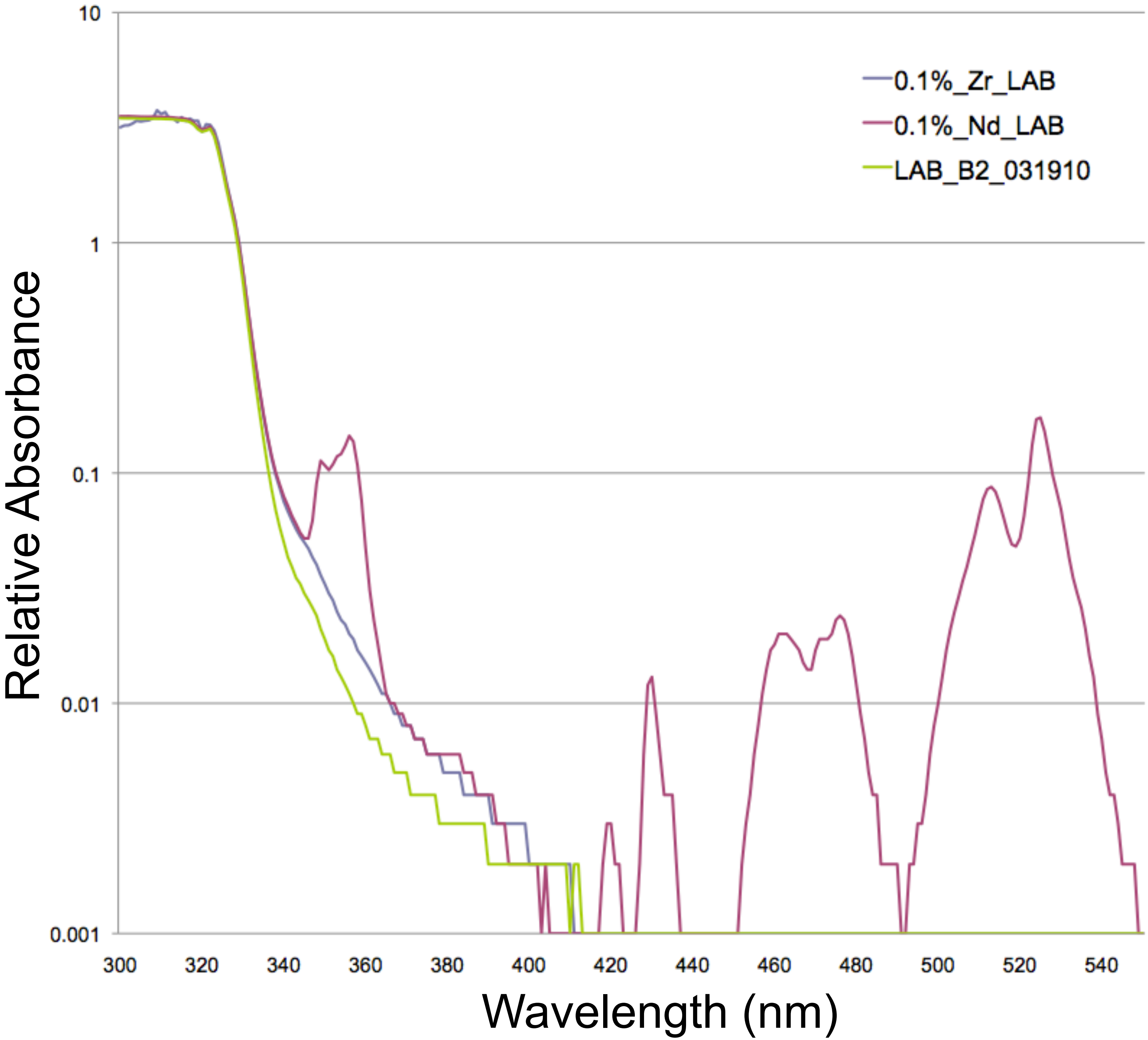
0ν Phase Space factor ~ 3.5 times worse than ^{150}Nd −

Natural Abundance = 2.8% (half that of ^{150}Nd) −

2ν Lifetime = 2.3×10^{19}yr (2.5 times longer than ^{150}Nd) +

Can also be loaded into LAB by similar process
(so far, 6 month stability established with up to 3%)

More optically transparent than Nd +



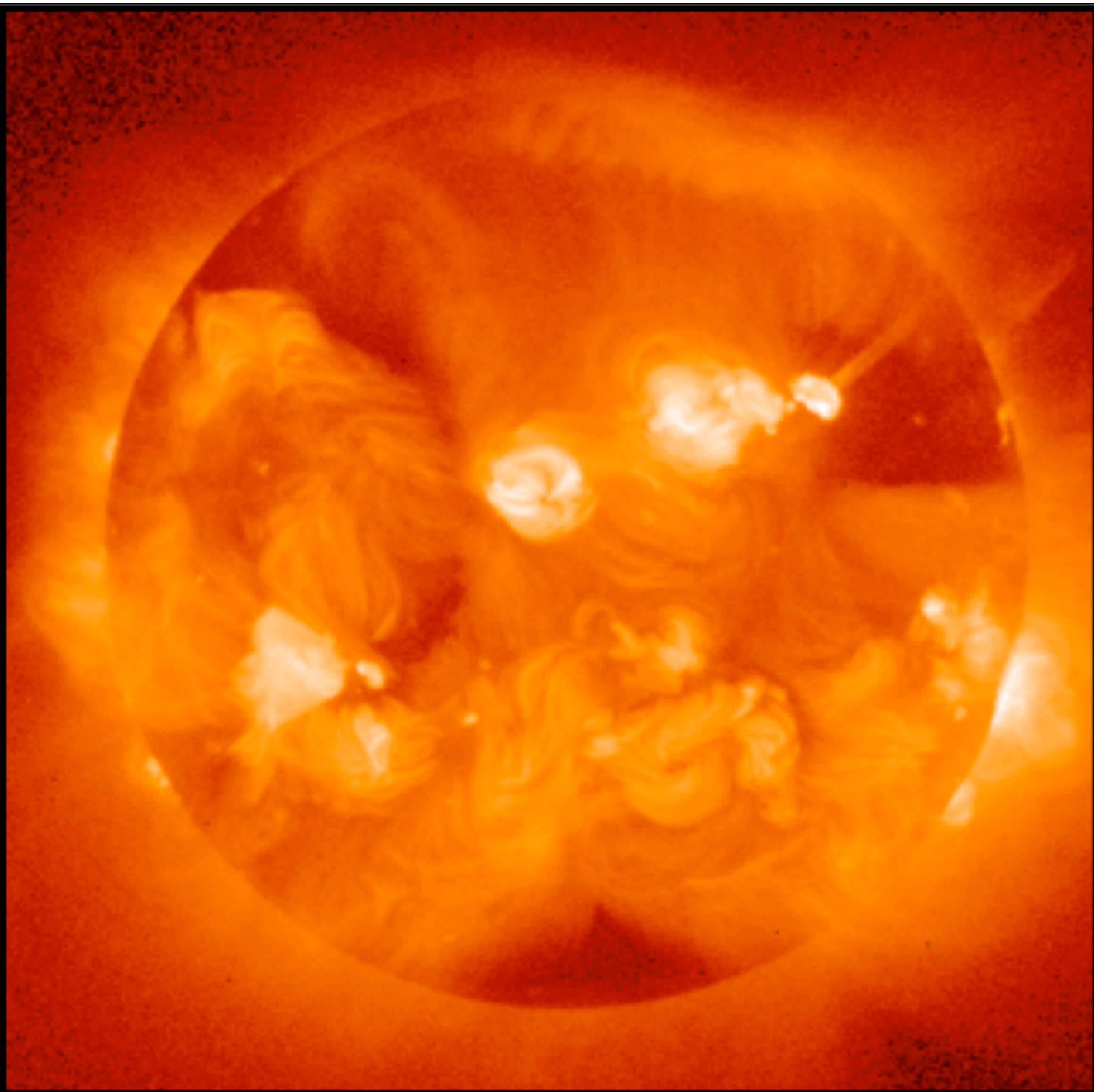
Relative Absorbance
Wavelength (nm)
0.1%_Zr_LAB
0.1%_Nd_LAB
LAB_B2_031910
10
1
0.1
0.01
0.001
300
320
340
360
380
400
420
440
460
480
500
520
540

Inherent background radioactivity levels ?

Purification ?

Removal from scintillator ?

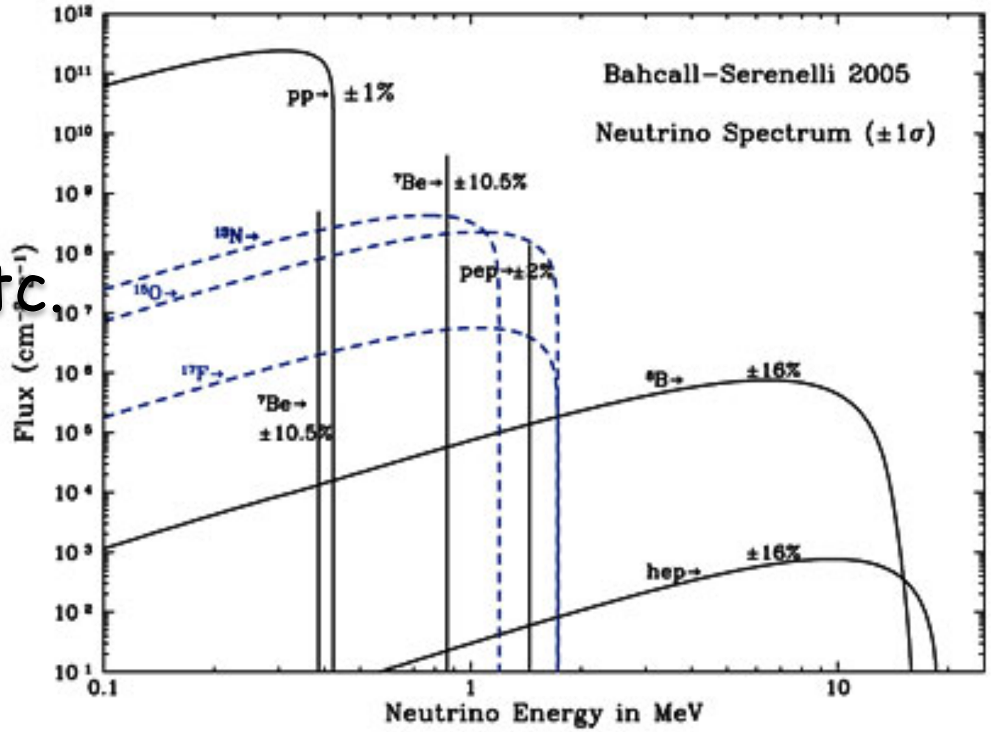
UNDER INVESTIGATION



Low Energy Solar Neutrinos

Solar Neutrinos

Detail MSW transition
(neutrino-matter couplings),
Solar Composition Problem, etc.



p-p Solar Fusion Chain

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

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,p$ ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$ ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow \alpha + \alpha$ ${}^{8}B \rightarrow 2\,\alpha + e^{+} + \nu_e$

CNO Cycle

${}^{12}C + p \rightarrow {}^{13}N + \gamma$ ${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$

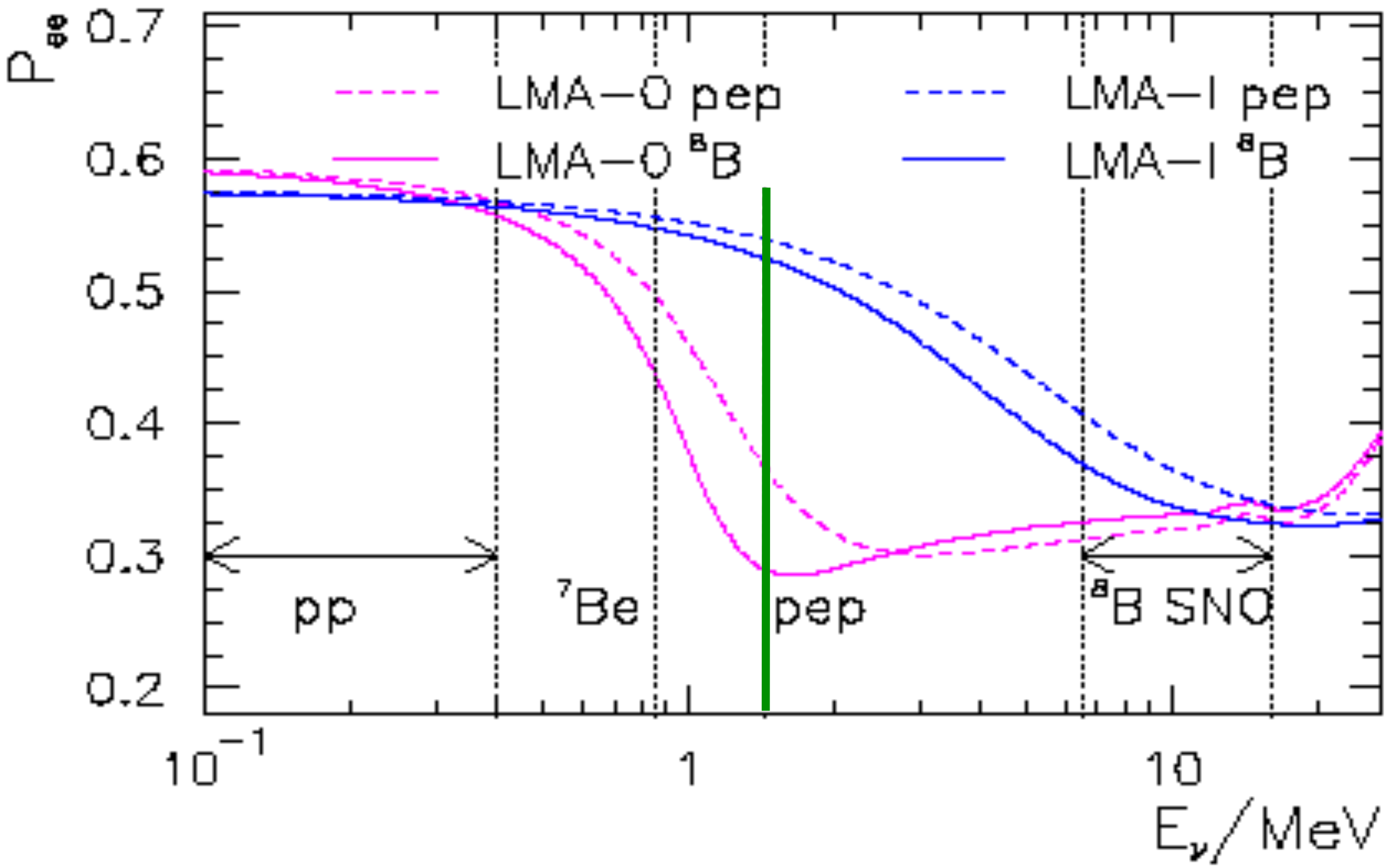
${}^{13}C + p \rightarrow {}^{14}N + \gamma$

${}^{14}N + p \rightarrow {}^{15}O + \gamma$ ${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$

${}^{15}N + p \rightarrow {}^{12}C + \alpha$

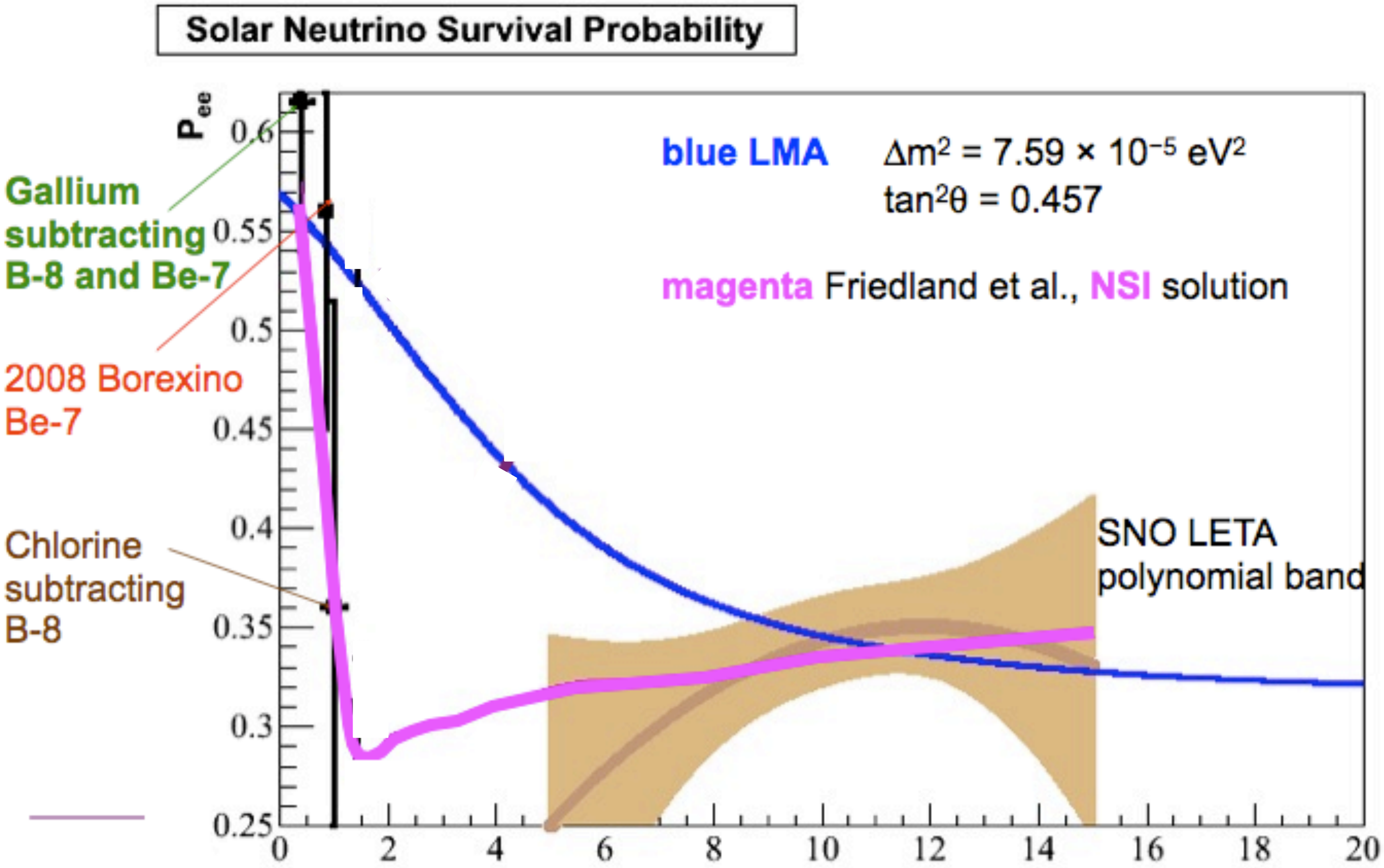
pep Solar Neutrinos

• pep ν directly tests solar luminosity constraint & probes MSW in sensitive 1.4 MeV regime to test for non-standard interactions:

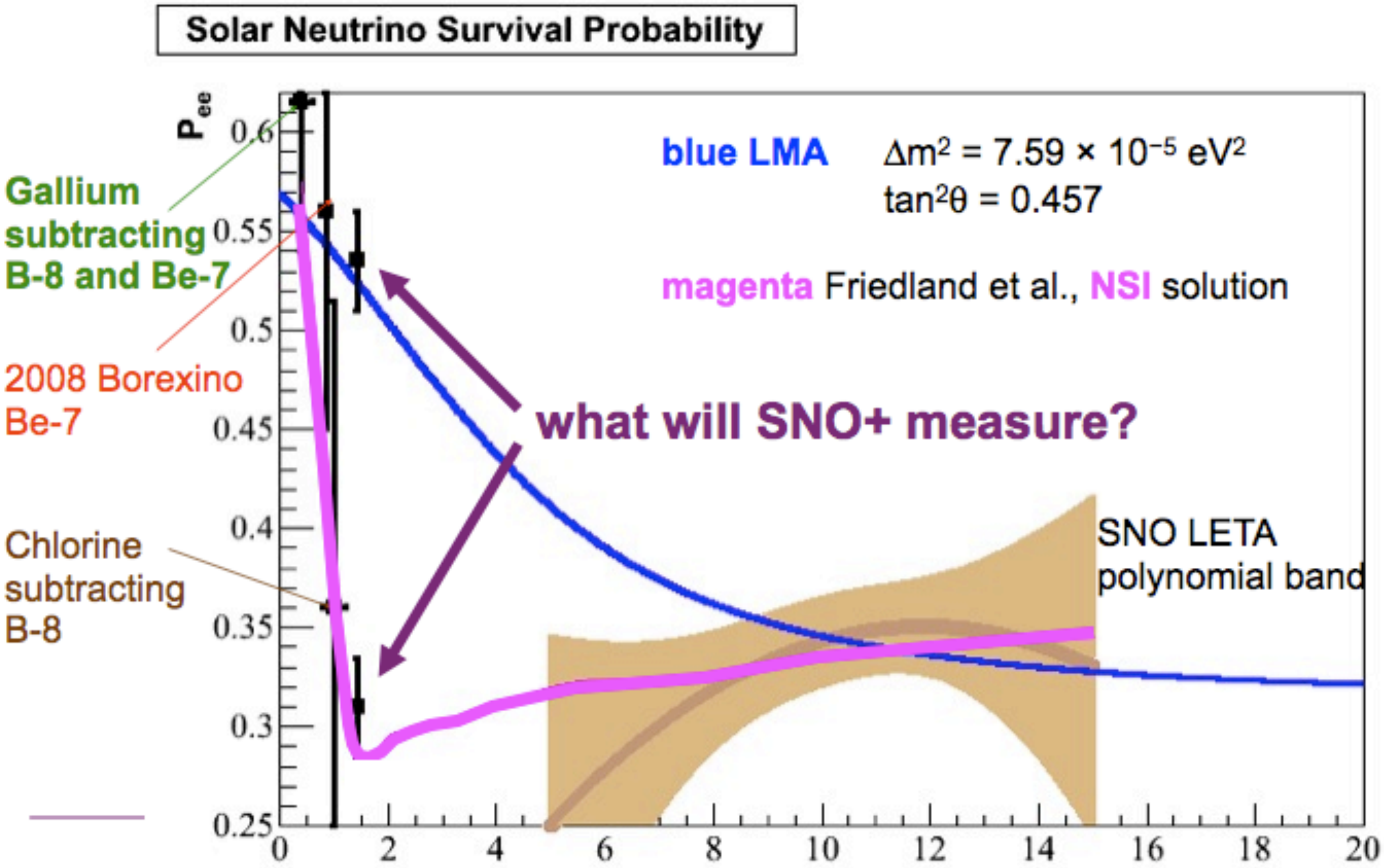


Friedland et al., Phys. Lett. B, **594**, (2004)

Survival Probability for Solar Neutrinos: All Experimental Data Distilled



Survival Probability for Solar Neutrinos: All Experimental Data Distilled



pep Solar Neutrinos

Also sensitive to θ_{13} - complementary to long baseline and reactor experiments: (hypothetical 5% stat. 3% syst. 1.5% SSM measurement has discriminating power for θ_{13})

LETA paper 2009:
LETA joint-phase fit
+ Phase III
+ all solar expts
+ KamLAND

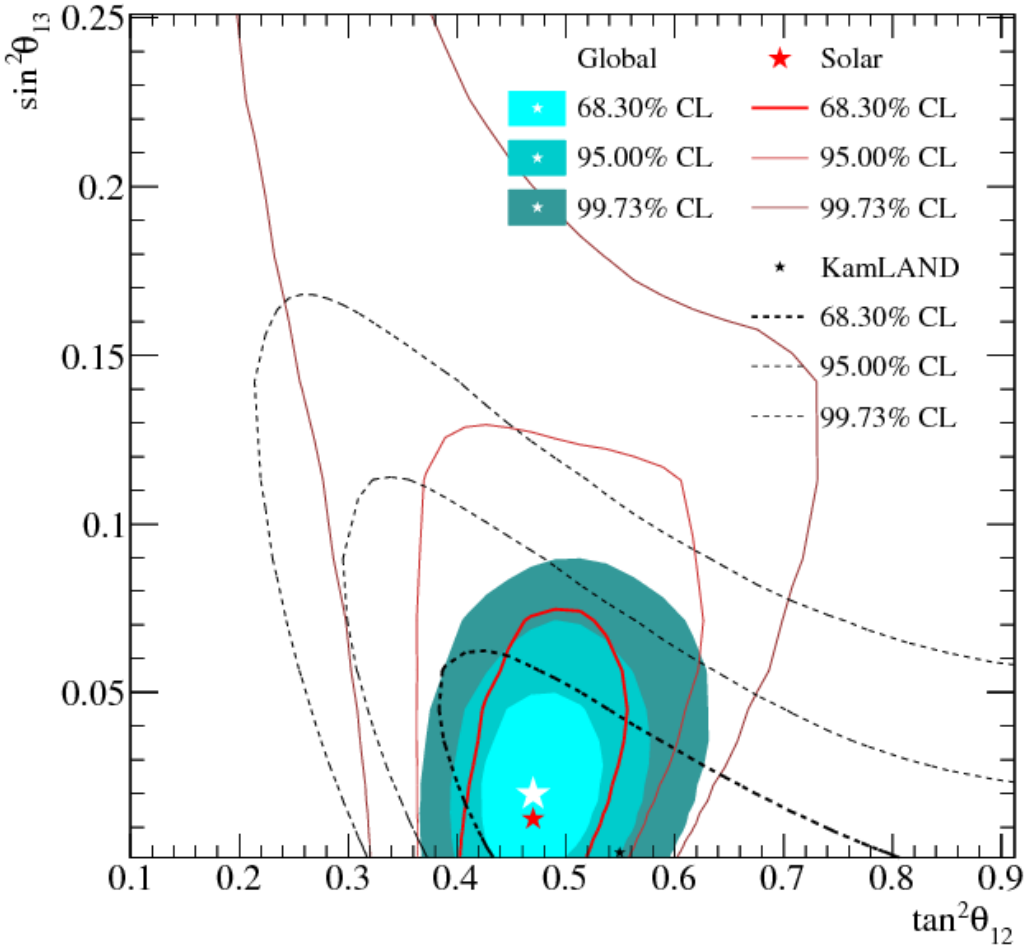
3-flavor analysis:

Best-fit:

$\sin^2\theta_{13}$ = 2.00 +2.09 -1.63 x10^{-2}

$\Rightarrow$

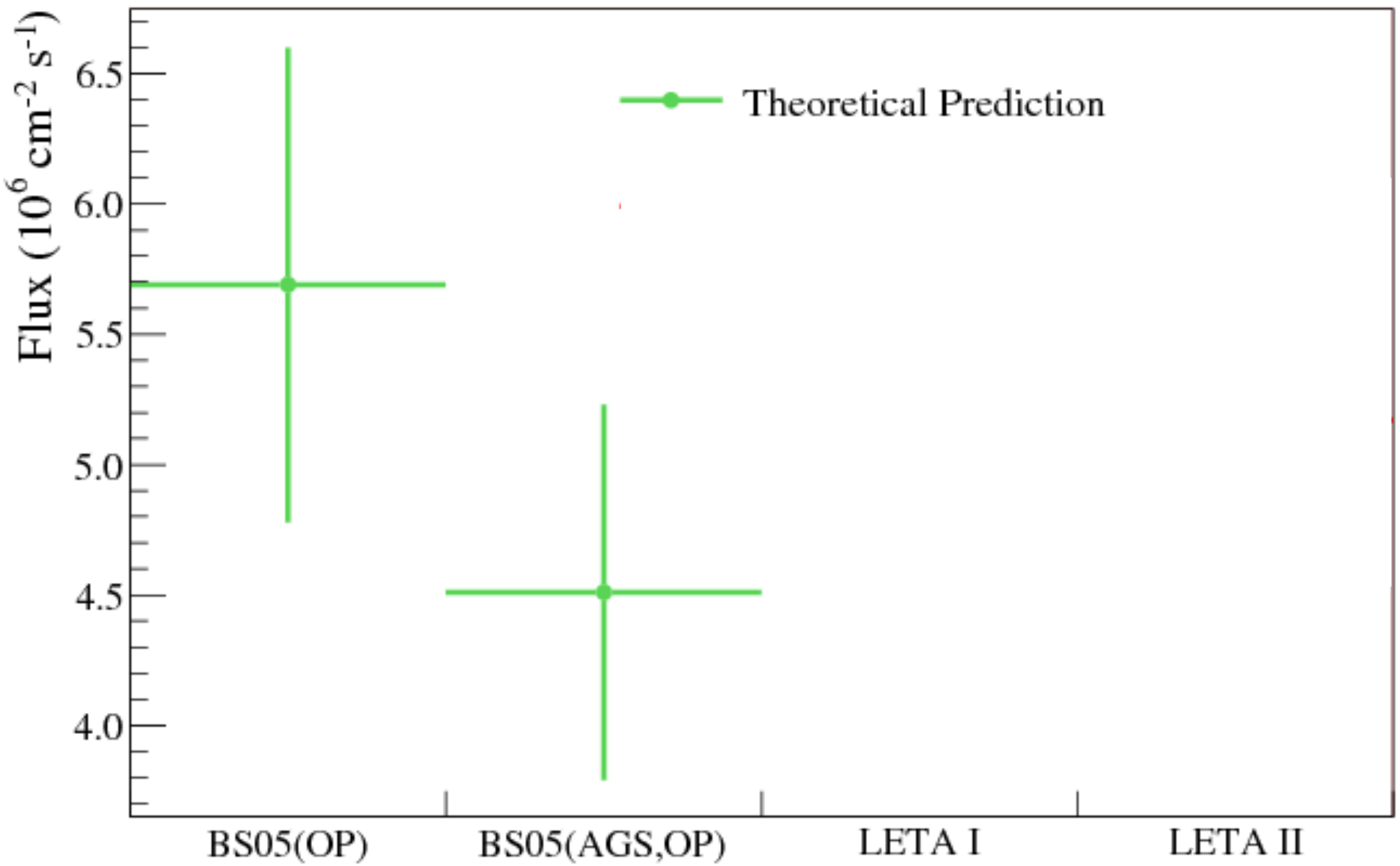
$\sin^2\theta_{13}$ < 0.057 (95% C.L.)



CNO Solar Neutrinos

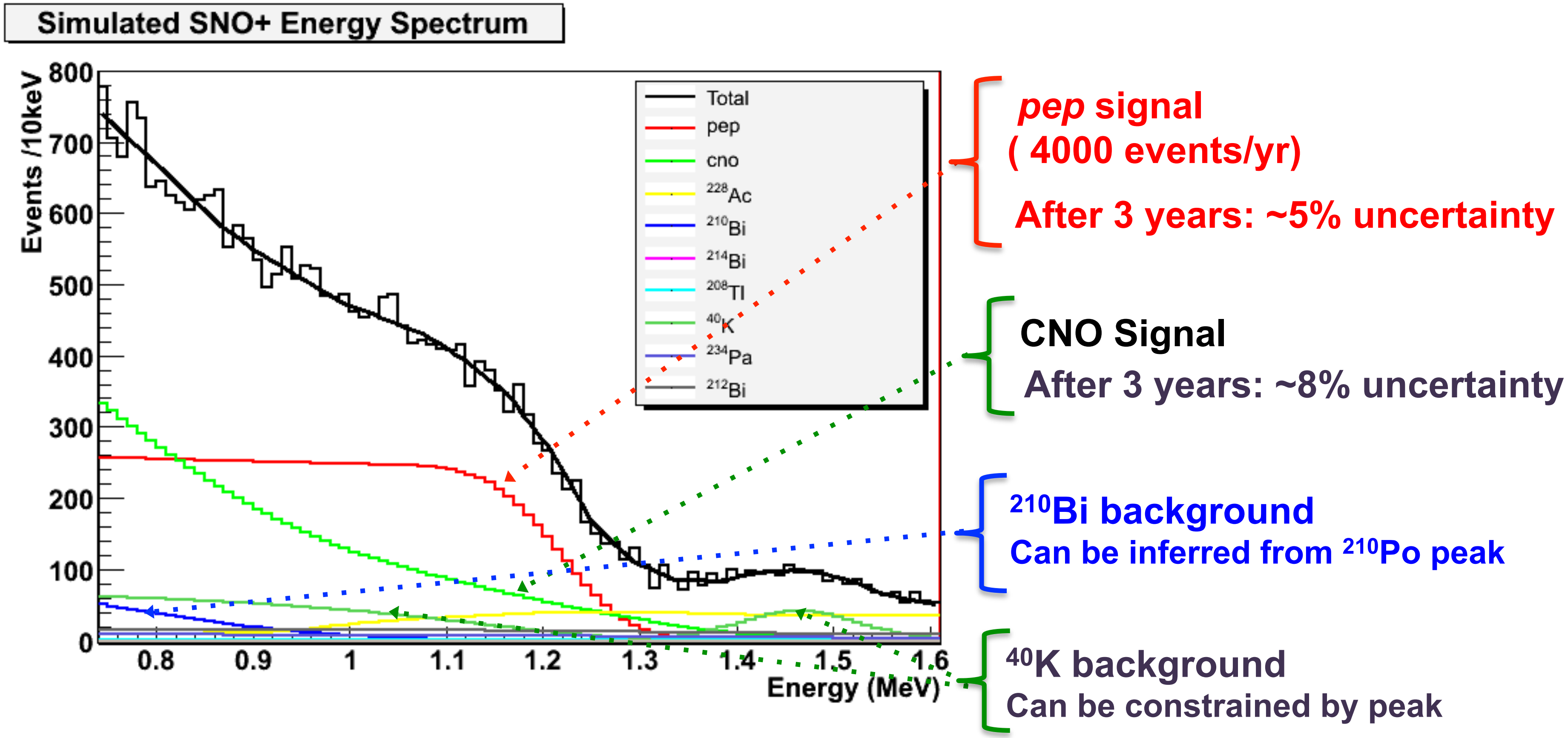
• CNO ν gives information on age of Globular Clusters and also aims to solve "Solar Composition Problem" (contradictions with helioseismology)

(Pena-Garay & Serenelli, arXiv:0811.2424)



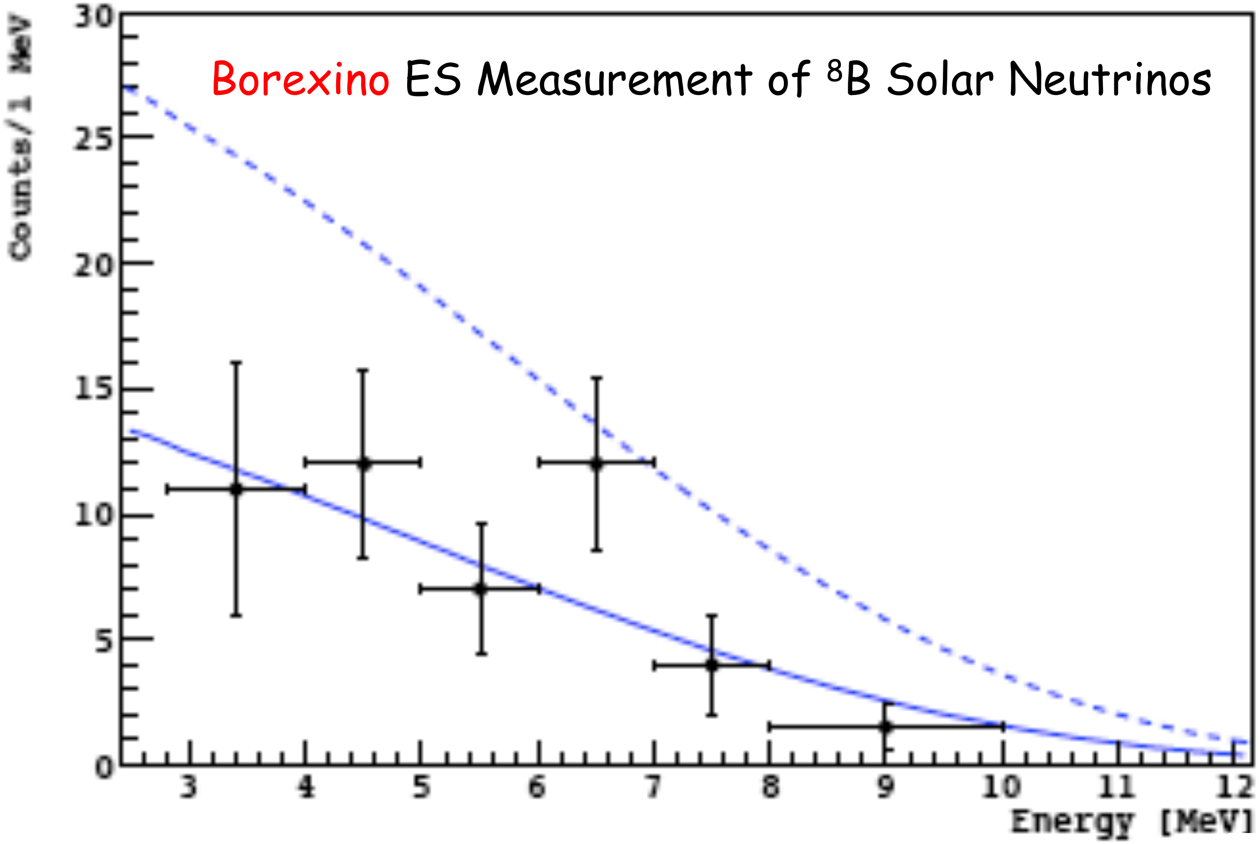
J. N. Bahcall, A. M. Serenelli, and S. Basu, AstroPhys. J. **621**, L85 (2005)

SNOLAB depth of 6000 mwe gives a muon flux 800 times less than KamLAND and virtually eliminates background from ^{11}C, making SNO+ uniquely sensitive for a precision measurement.

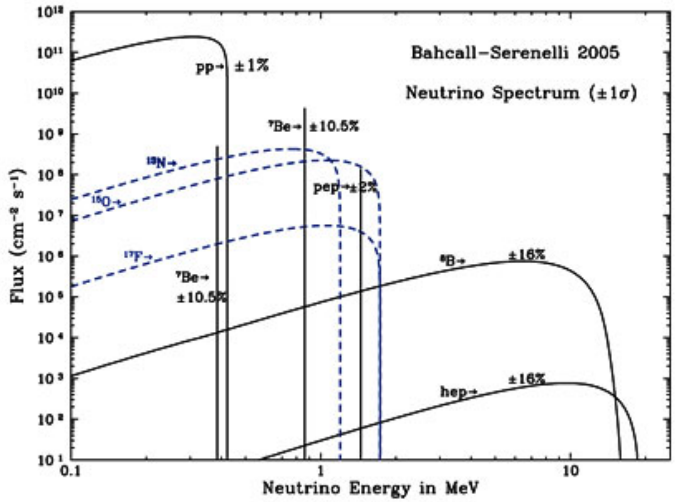


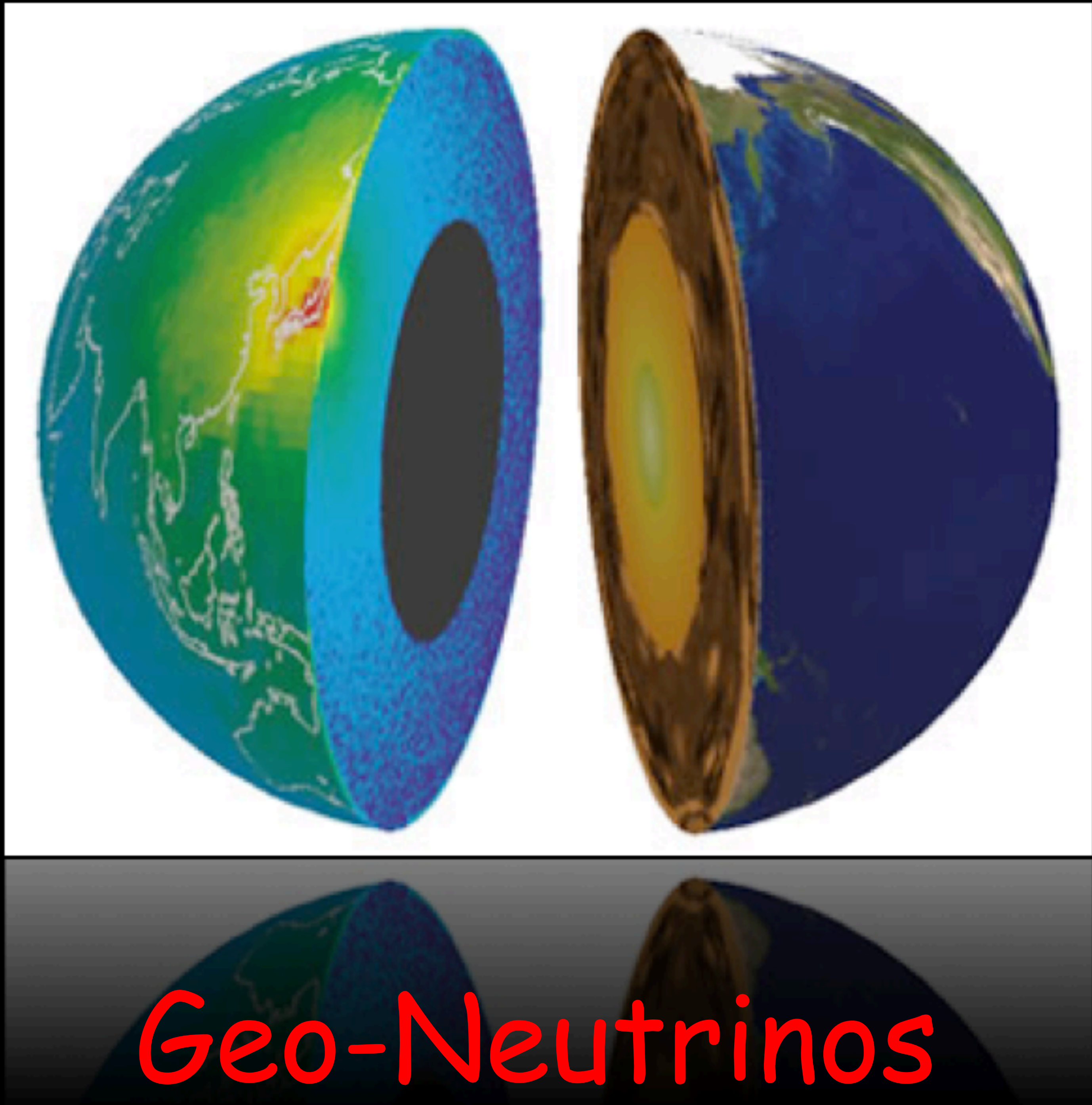
3600 *pep* events/(kton·year), for electron recoils >0.8 MeV

^{210}Bi (U), ^{40}K are most important for solar studies.
Borexino has demonstrated similar levels of backgrounds.



Plus, can also measure ^{8}B neutrinos below SNO energy and hopefully also ^{7}Be and maybe even pp to provide a truly comprehensive and definitive solar neutrino study!



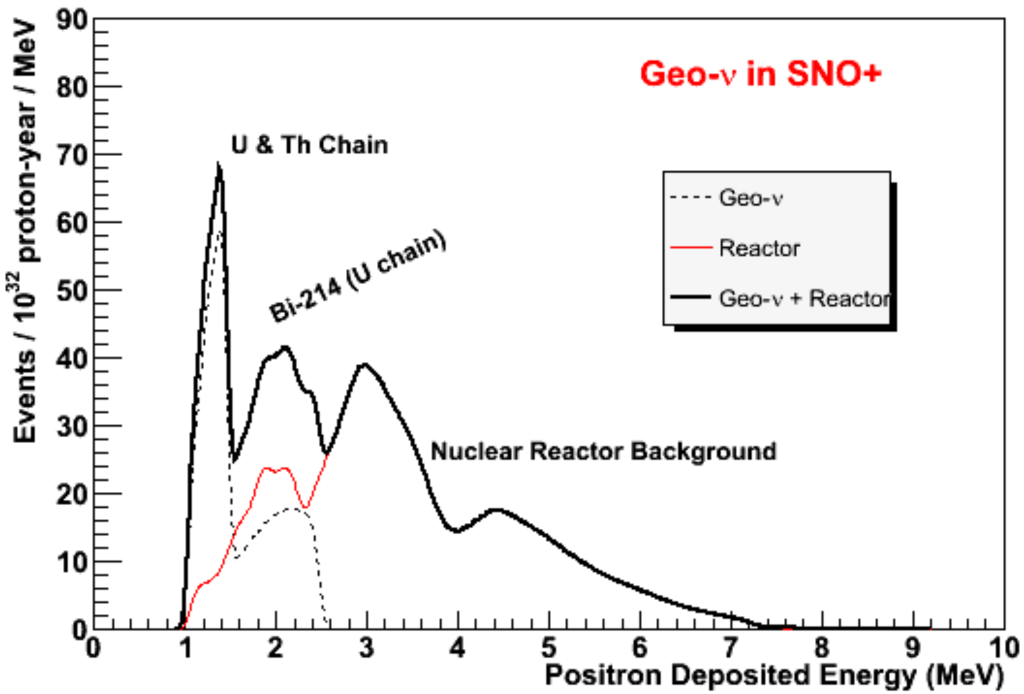


Geo-Neutrinos

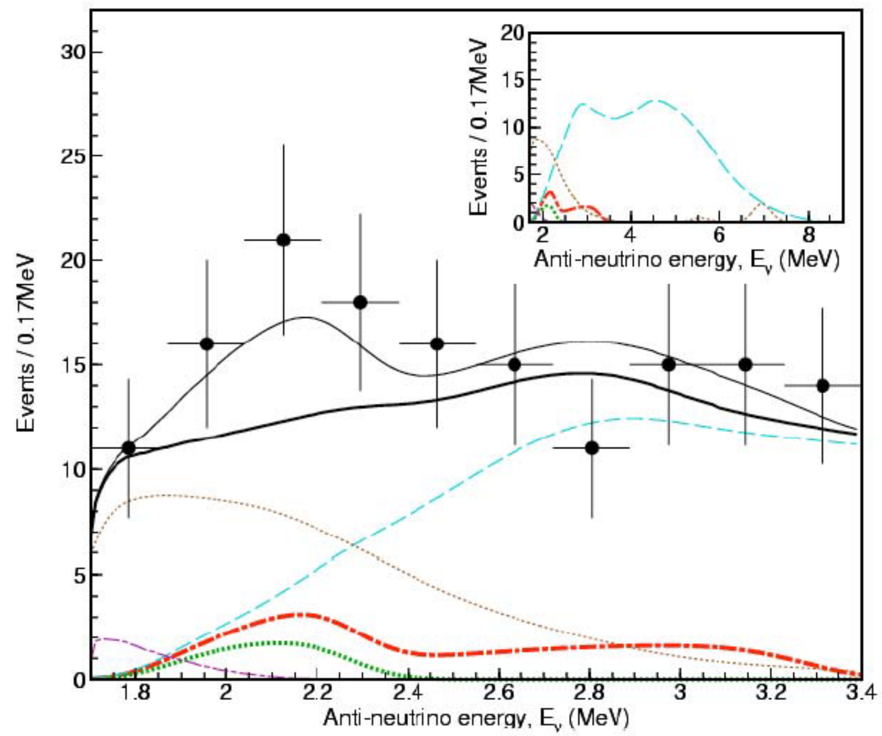
Geo-Neutrino Signal

antineutrino events $\bar{\nu}_e + p \rightarrow e^+ + n$:

- KamLAND: 33 events per year (1000 tons CH_2) / 142 events reactor
- SNO+: 44 events per year (1000 tons CH_2) / 38 events reactor



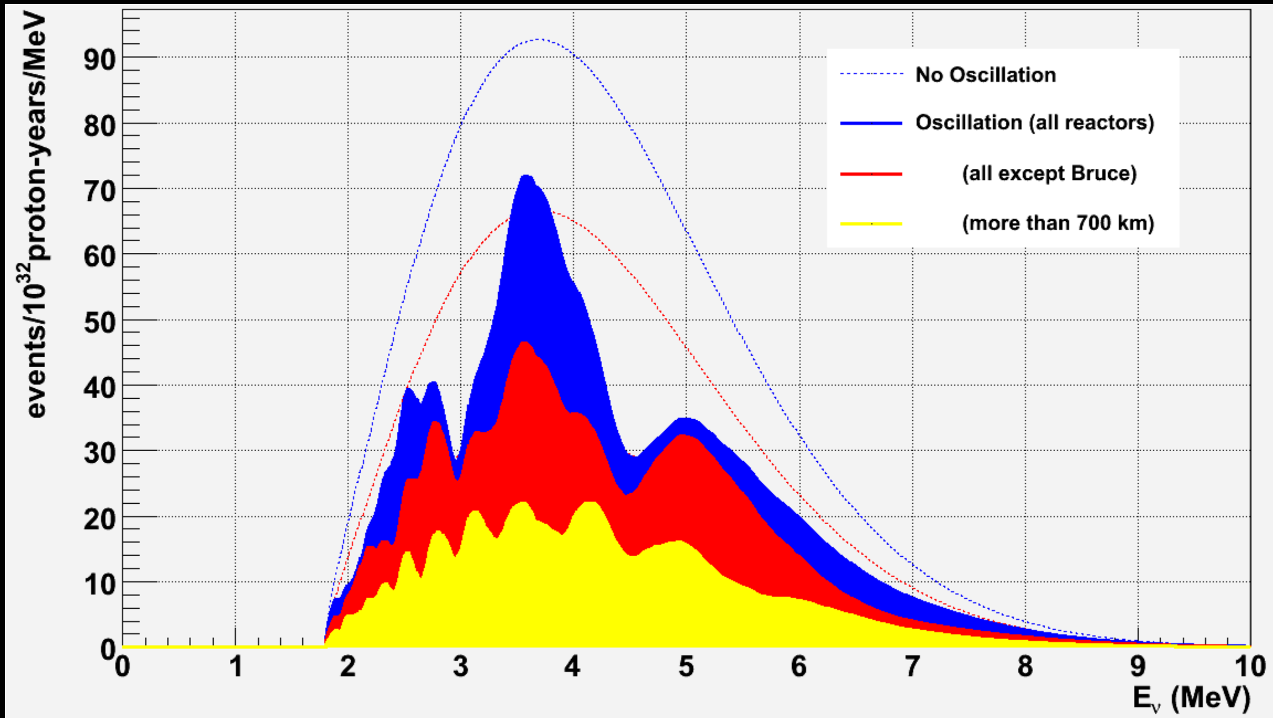
SNO+ geo-neutrinos and reactor background



KamLAND geo-neutrino detection…July 28, 2005 in Nature

Reactor Neutrinos

Reactors Contribution to the Spectrum



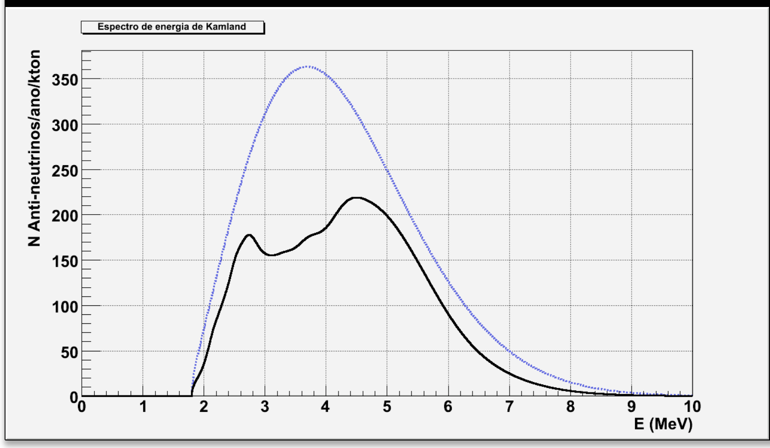
• Bruce reactor will contribute mainly to the central peak.

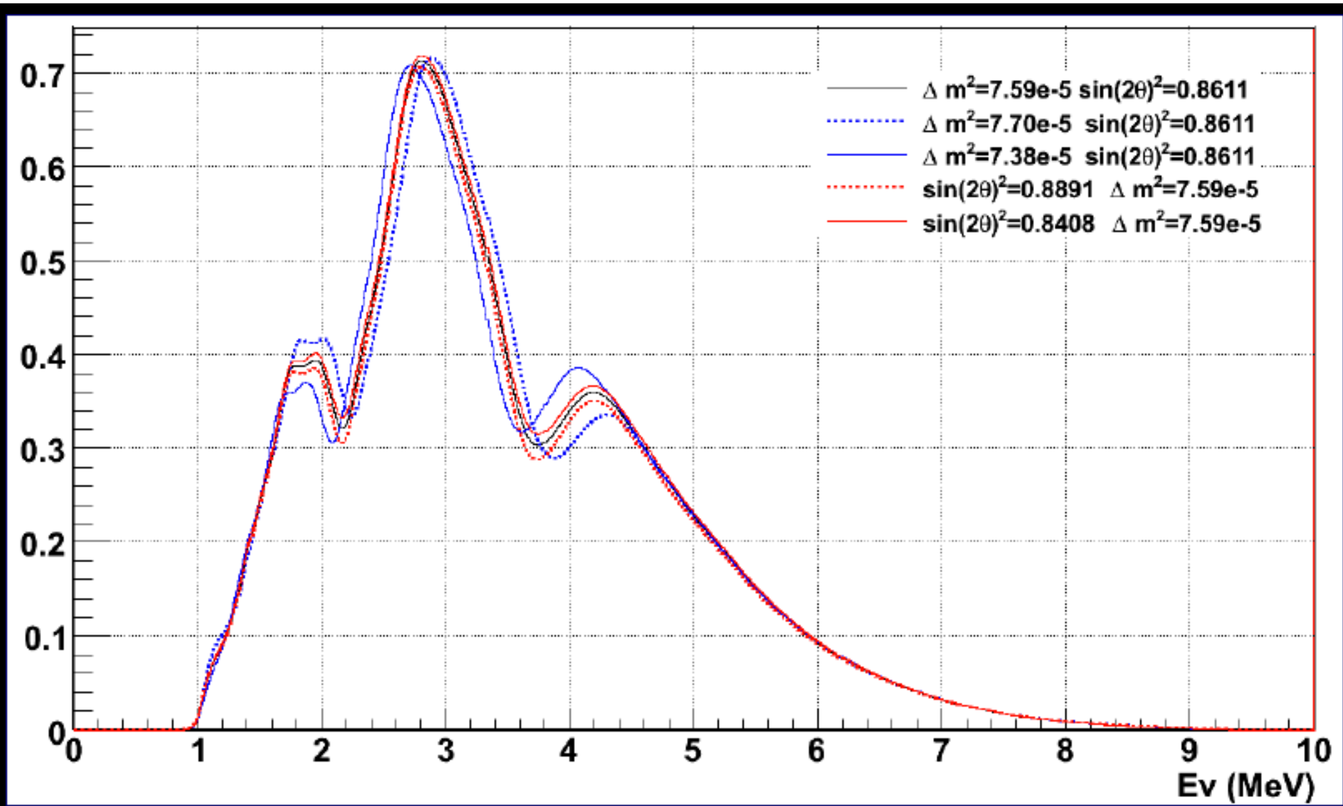
• We can take advantage from any “shut-off” period

→ L/E Analysis

Main Reactors (distances smaller than 700km to the detector)

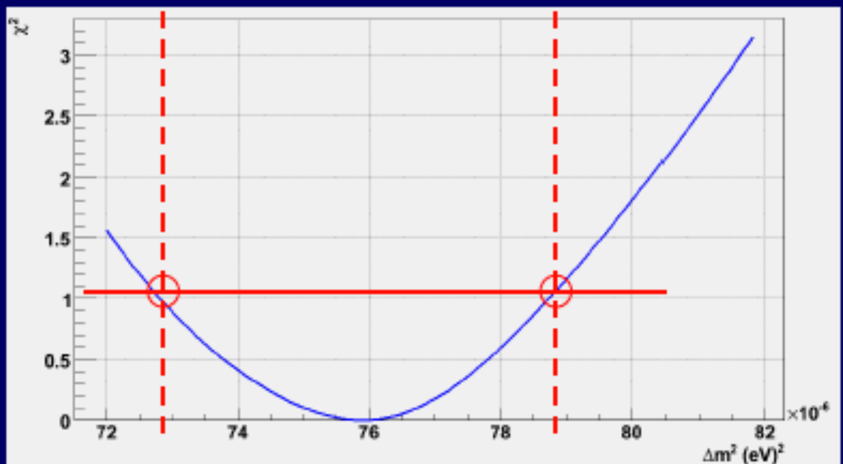
Reactor	d (km)	Th. Power (GW)
Bruce	281	10,32
Pickering	330	6,192
Darlington	340	10,572
R.E. Ginna	455	1,41
James A. Fitzpatrick	488	2,34
Nine Mile Point	488	5,07
Perry	530	3,1615
Enrico Fermi	559	3,255
Kewaunee	568	1,509
Davis-Besse	588	2,531
Point Beach	589	2,91
Palisades	617	2,34
Gentily	648	1,914
Beaver Valley	657	4,929
Donald C. Cook	685	3,06





- Study for Δm^2

Chi^2 test applied to the visible energy spectrum with a varying Δm^2 around 7.59e-5 eV^2 and a fixed value of $\sin(2\Theta)^2$=0.8611 (plot for 6% resolution).



Resolution	-1σ	+1σ
6%	7.27e-5	7.88e-5
3%	7.32e-5	7.82e-5

6% : $\Delta m_{12}^2 = 7.59_{-0.32}^{+0.29} \times 10^{-5} (eV)^2$

3% : $\Delta m_{12}^2 = 7.59_{-0.27}^{+0.23} \times 10^{-5} (eV)^2$

Relative Diference in errors ~20%

(life-time=1x10[32]proton-year, approx 1.8 years for the calculations)

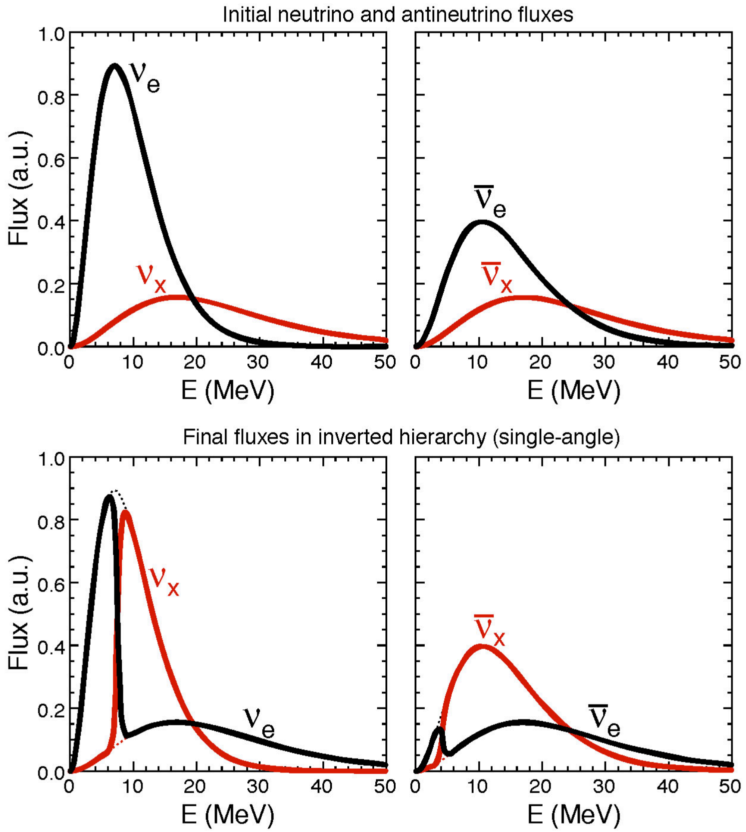
SuperNova Neutrinos

$\bar{\nu}_e + p \longrightarrow e^+ + n$	**Sensitive to electron anti-neutrinos; Threshold energy = 1.8 MeV; Positron energy ~ tens of MeV; Coincidence with n capture on hydrogen (~ms);**
$\bar{\nu}_e + {}^{12}C \longrightarrow {}^{12}B + e^+$ $\quad \hookrightarrow \bar{\nu}_e + {}^{12}C + e^-$	**Sensitive to electron anti-neutrinos; Threshold energy = 14.4 MeV; Coincidence with ^{12}C: $t_{1/2}$ = 20.2ms, (endpoint 13.4 MeV)**
$\nu_e + {}^{12}C \longrightarrow {}^{12}N + e^-$ $\quad \hookrightarrow \nu_e + {}^{12}C + e^+$	**Sensitive to electron neutrinos; Threshold energy = 17.3 MeV; Coincidence with ^{12}N: $t_{1/2}$ = 11ms, (endpoint 16.3 MeV)**
$\nu_x + {}^{12}C \longrightarrow {}^{12}C^* + \nu_x$ $\quad \hookrightarrow {}^{12}C + \gamma$ (15.1 MeV)	**Sensitive to any flavour neutrino; Distinctive mono-energetic gamma**
$\nu_x + p \longrightarrow \nu_x + p$	**Sensitive to any flavour neutrinos; Low KE (sub-MeV), not well-defined signature. Possible detection from rates near threshold**
$\nu_x + e^- \longrightarrow \nu_x + e^-$	**Principally sensitive to electron neutrinos; Cherenkov signal would also be seen in H2O (with directional information)**

$\tan^2\theta_{13}$	$\bar{\nu}_e\ p \rightarrow e^+\ n$ nominal	$\bar{\nu}_e\ p \rightarrow e^+\ n$ +earth effect	$\bar{\nu}_e\ ^{12}C \rightarrow {}^{12}B\ e^+$ nominal	$\bar{\nu}_e\ ^{12}C \rightarrow {}^{12}B\ e^+$ +earth effect	$\nu_e\ ^{12}C \rightarrow {}^{12}N\ e^-$ nominal	$\nu_e\ ^{12}C \rightarrow {}^{12}N\ e^-$ +earth effect
10^{-6}	463 (463)	487 (487)	56 (56)	45 (45)	25 (25)	27 (27)
$>10^{-3}$	463 (644)	487 (644)	80 (56)	80 (45)	25 (51)	27 (51)
no osc	383		2.6		13	

$\nu_x\ p \longrightarrow \nu_x\ p$	$\nu_x\ ^{12}C \longrightarrow {}^{12}C^*\ \nu_x$
676	44

KamLAND predictions from Bandyopadhyay *et. al*, hep-ph/0312315



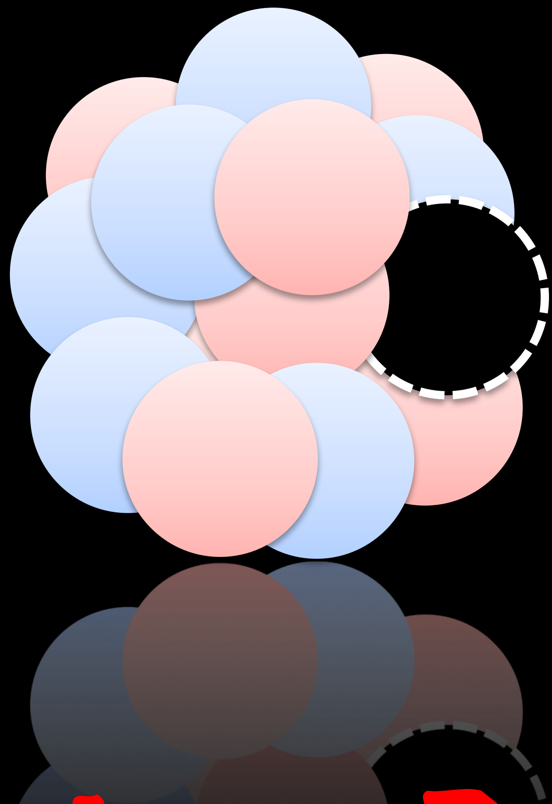
Initial flux at r~10 km

Final flux at r~200 km after collective **n-n** interactions

Anti-neutrinos undergo flavour swap

High- energy neutrinos undergo flavour swap, but low energy neutrinos don't (spectral split)

(Lisi @ TAUP 07)



Nucleon Decay

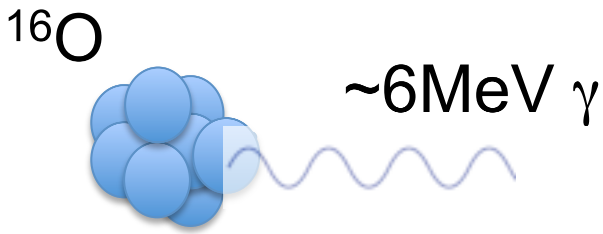
"Invisible" Modes of Nucleon Decay

→ modes where negligible visible energy from by-products is deposited in the detector

For example: $n \rightarrow 3\nu$

- Violates (B-L)   (interesting for matter/antimatter asymmetry)
- Models can be constructed where this is primary mode!!
  {Mohapatra & Perez-Lorenzana, Phys Rev D67, 075015 (2003)}

How?



6 or 7 MeV nuclear γ emitted about 45% of the time

In SNO, this would have contaminated NC signal
(de-excitation following n capture on tritium or Cl)

Compare D_2O and salt data: $\tau_{inv} > 2.3 \times 10^{29}$ years

Phys. Rev. Lett. 92 (2004) 102004 **arXiv:hep-ex/0310030**

Best current bound from KamLAND: $\tau_{inv} > 5.8 \times 10^{29}$ years
(Araki et al., PRL, 96, 2006)

However, with H_2O in SNO detector, we expect virtually

zero background around 6 MeV, aside from solar ν ES !

We need to take H_2O data when commissioning and filling for SNO+ detector anyway. With just 1 month of H_2O data we would expect to achieve a sensitivity of:

$$\tau_{inv} > 2 \times 10^{30} \text{ years}$$

Order of magnitude improvement on current bound may be possible with just 3 months of data !!!

Schedule

&

Status

First Data in 2012

Rough Order or Running:

H_2O ~ couple months — nucleon decay

Pure Scintillator ~ several months — initial solar study

Nd-loaded Scintillator ~ few years — Phase I $\beta\beta$

Pure Scintillator ~ few years — detailed solar study

Follow-on Phase ~ ? — Phase II $\beta\beta$? Other ?

geo-neutrinos

reactor neutrinos

live for supernova running

UK Status:

Alpha-4 rated in last Prioritisation Exercise

Bridging funds provided by STFC for next 2 years

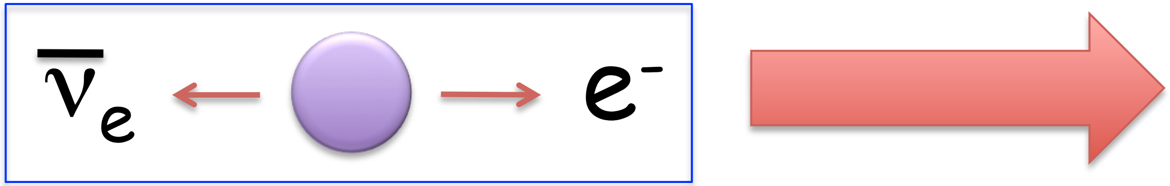
Will apply for continued ("proper") support in 2012
(travel, postdocs, academic time... but not much else)

➡ **Significant support leveraged from Canadians!**

High UK Impact;
Significant Scientific Output;
Preserves Substantial Scientific Diversity;
Capitalises on Previous Investments;
Extremely Modest Cost to STFC

First Attempt:

Produce neutrinos at the lowest possible energy, then physically boost to frame of reversed helicity



Lowest known Q value for beta decay: **^{115}In → ^{115}Sn(3/2+)**

Q = 155 eV !!

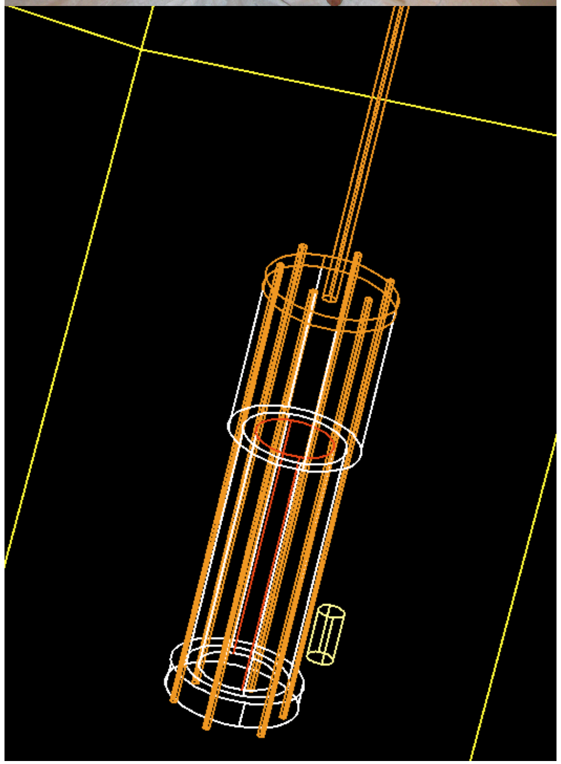
Br = 10^{-4}

$$\gamma \sim \frac{100\ \text{eV}}{0.1\ \text{eV}} = 10^3$$

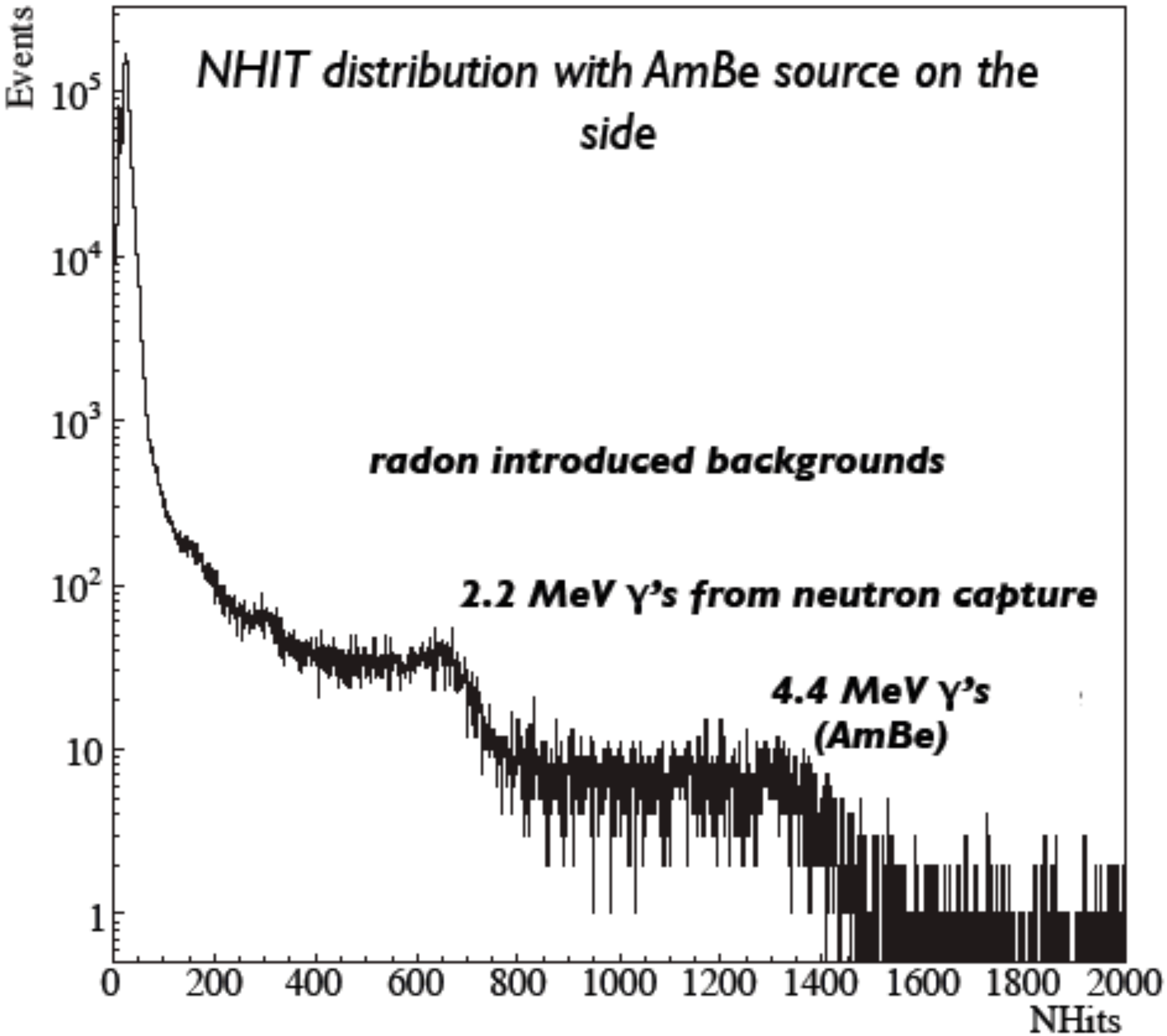
$E(^{115}\text{In}) \sim 100$ TeV

$\sigma \sim 10^{-47}\ \text{cm}^2/\text{eV}$

Easier ways to earn a living !!!



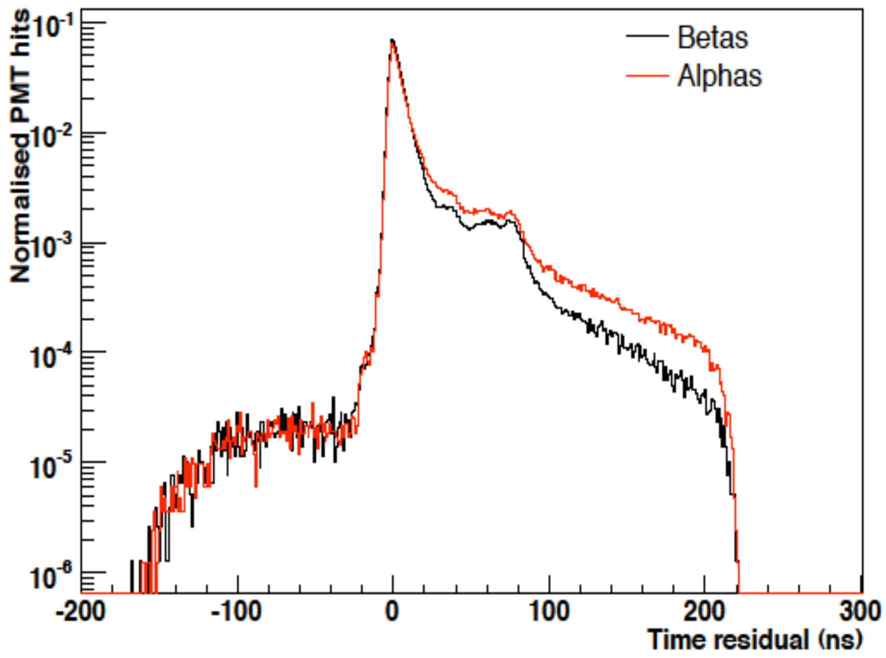
Scintillator “bucket” with source deployed in H2O-filled SNO detector

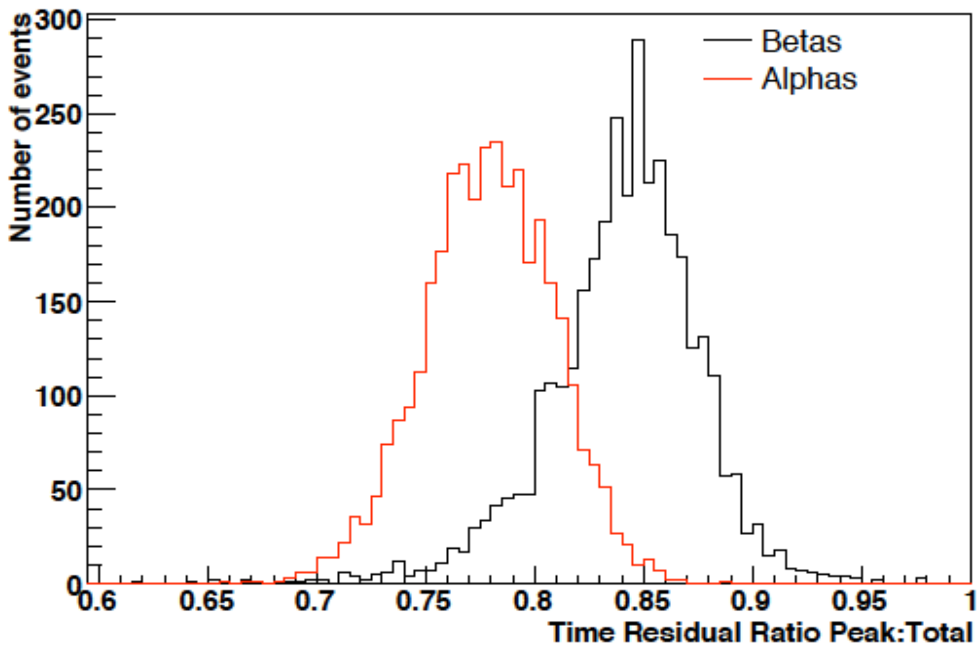


450 observed photons per MeV

Resolution of 5% at 1 MeV

Electron/alpha separation





SASQUATCH COMPANION
Version 1.00

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User Manual
Programmer Manual
SNOMAN Companion
Code

Getting started

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Tutorials
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Verification

Technical

Coding Standards
Update Documentation

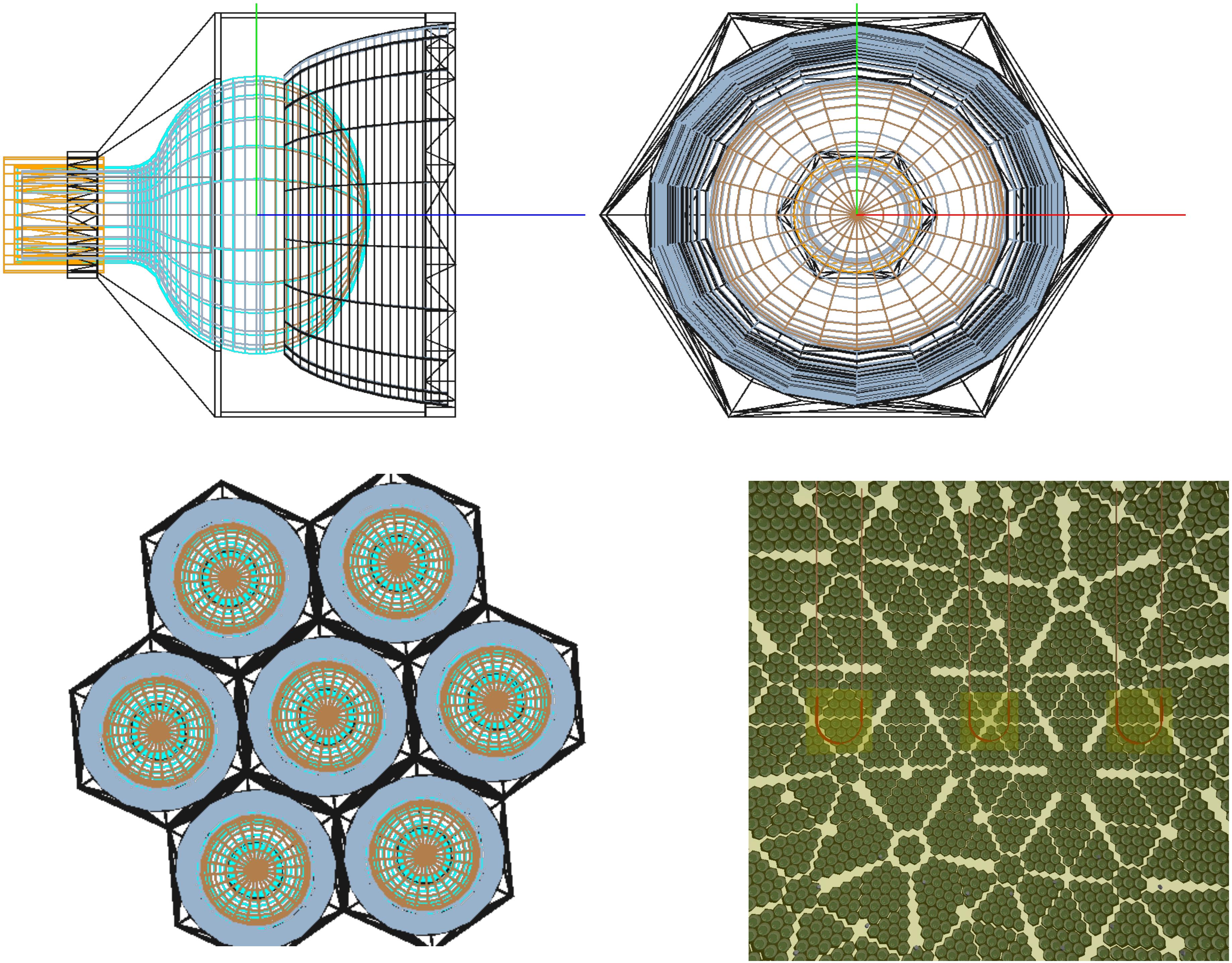
SASQUATCH COMPANION

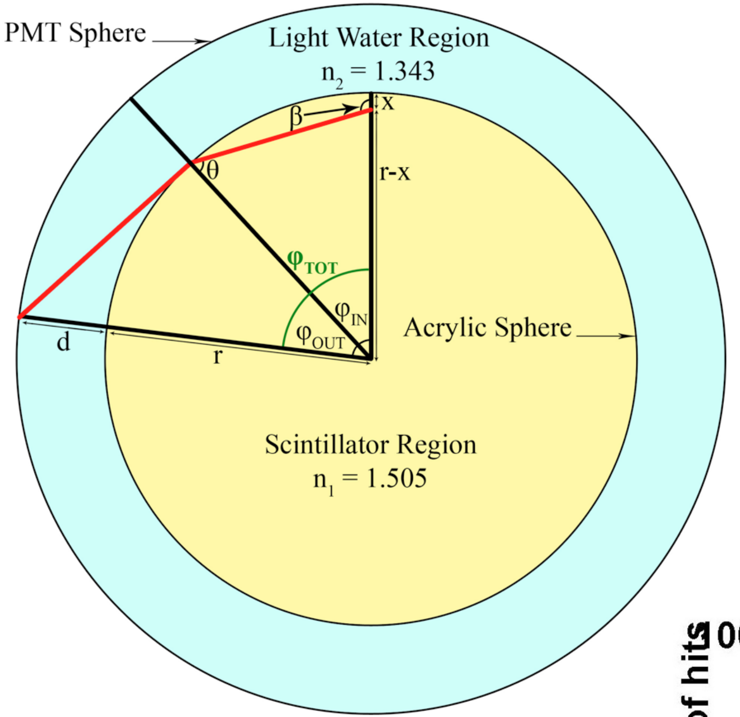
Code Version 1.00

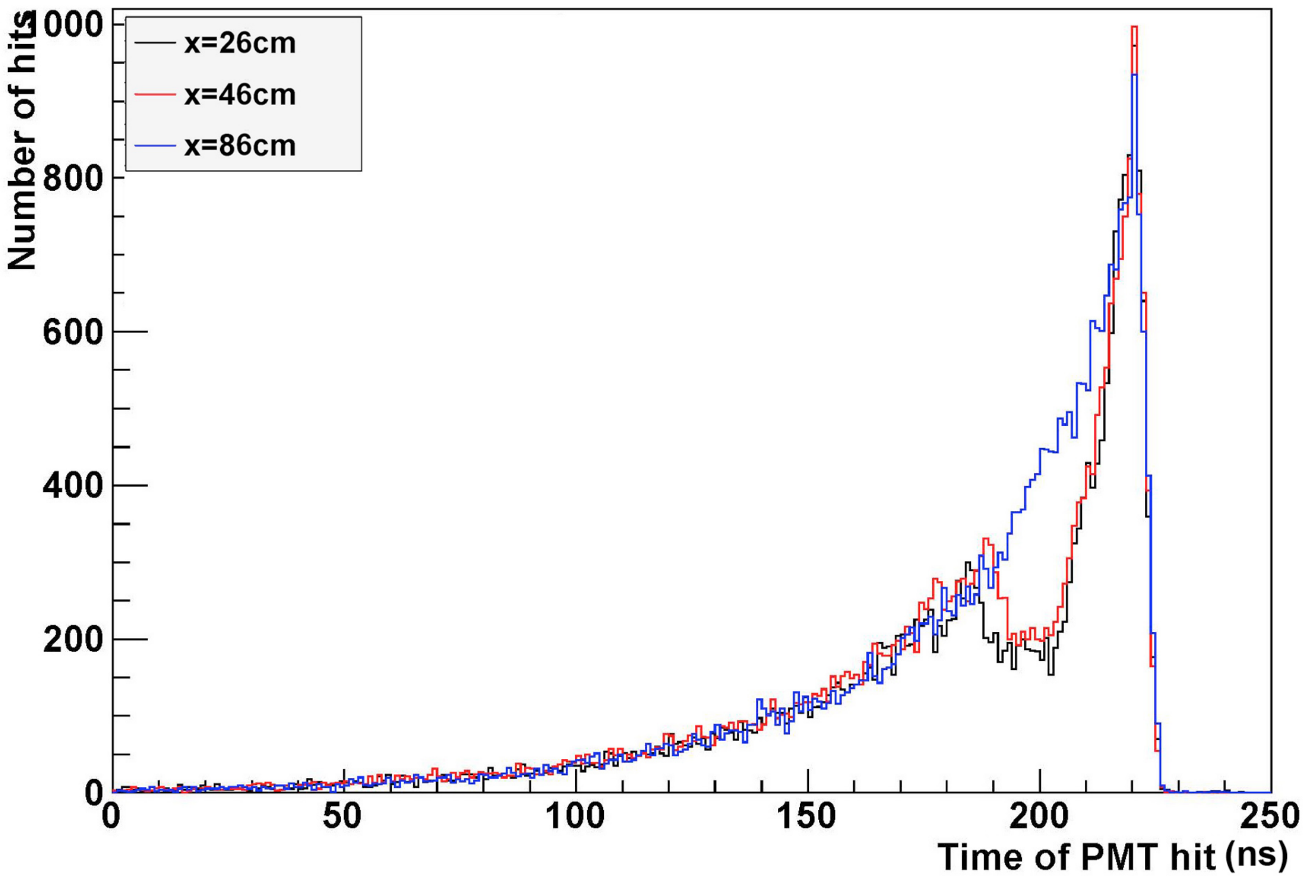
Welcome to the SASQUATCH Companion, a guide to the SNO+ simulation and analysis software which represents an unholy union between the SNOMAN and RAT codes (a truly abominable SNOMAN!). Together with the User Manual and the Programmer Manual , this should hopefully tell you all you ever wanted to know about SASQUATCH but were afraid to ask! Please send any comments, suggestions or complaints to Steve Biller.

Last updated: 16 October 2009

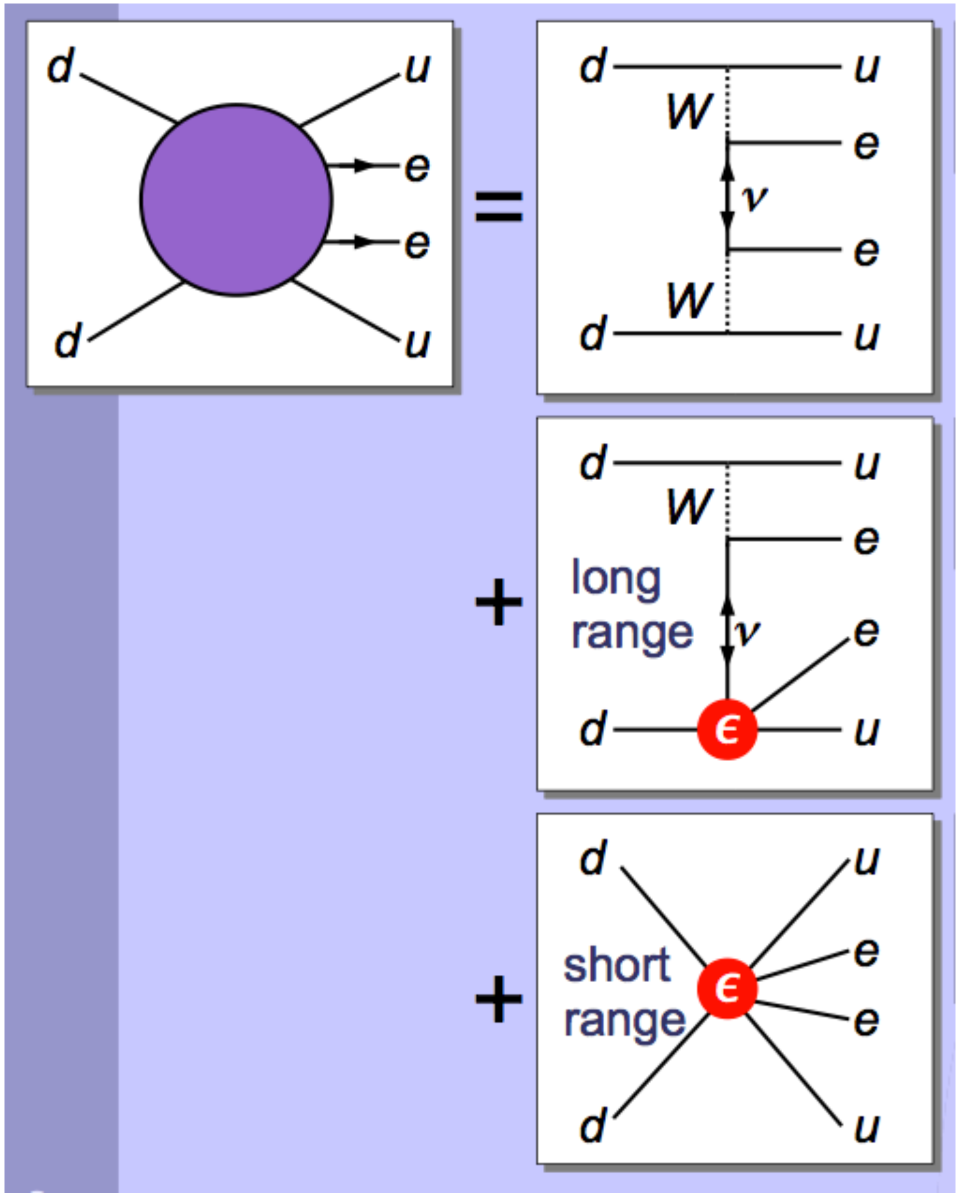
Search for: [ ] Find | find all words (AND)

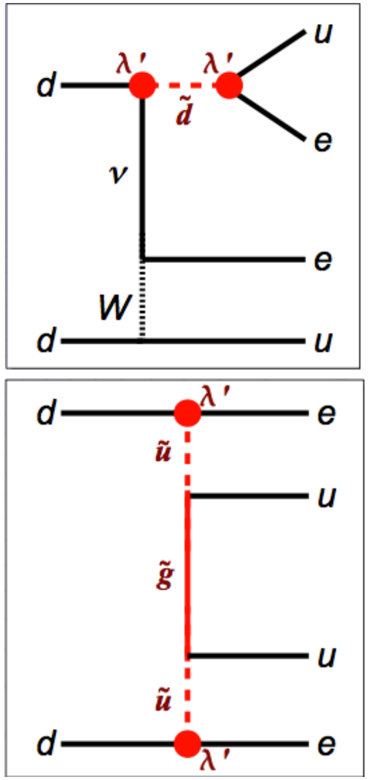



PMT Sphere
Light Water Region
n_2 = 1.343
x
β
r-x
θ
φ_{TOT}
φ_{IN}
φ_{OUT}
Acrylic Sphere
d
r
Scintillator Region
n_1 = 1.505

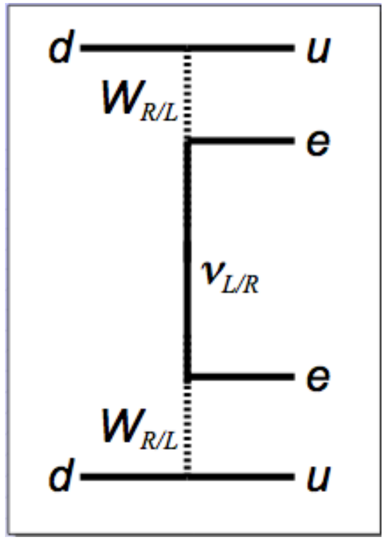

Number of hits
x=26cm
x=46cm
x=86cm
1000
800
600
400
200
0
0
50
100
150
200
250
Time of PMT hit (ns)

Which Mechanism?

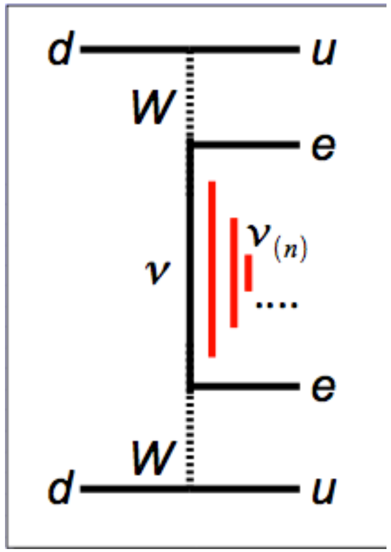




SUSY Models



RH Currents



Extra Dimensions

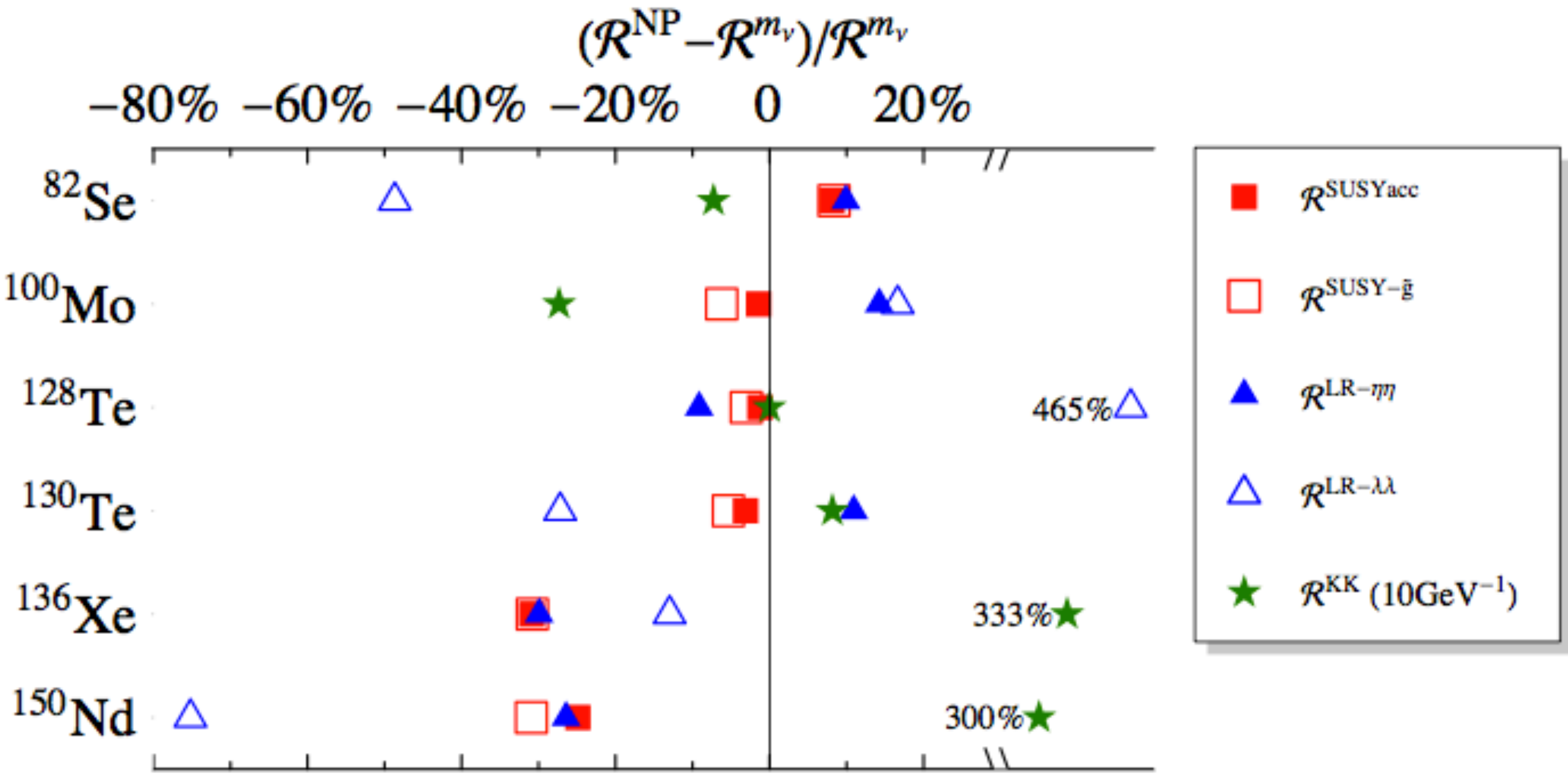


FIG. 1: Relative deviations of half life ratios $\mathcal{R}^{NP}(^{A}X)$, normalized to the half-life of ^{76}Ge, compared to the ratio in the mass mechanism $\mathcal{R}^{m_\nu}(^{A}X)$.

Deppisch & Päs, 2007

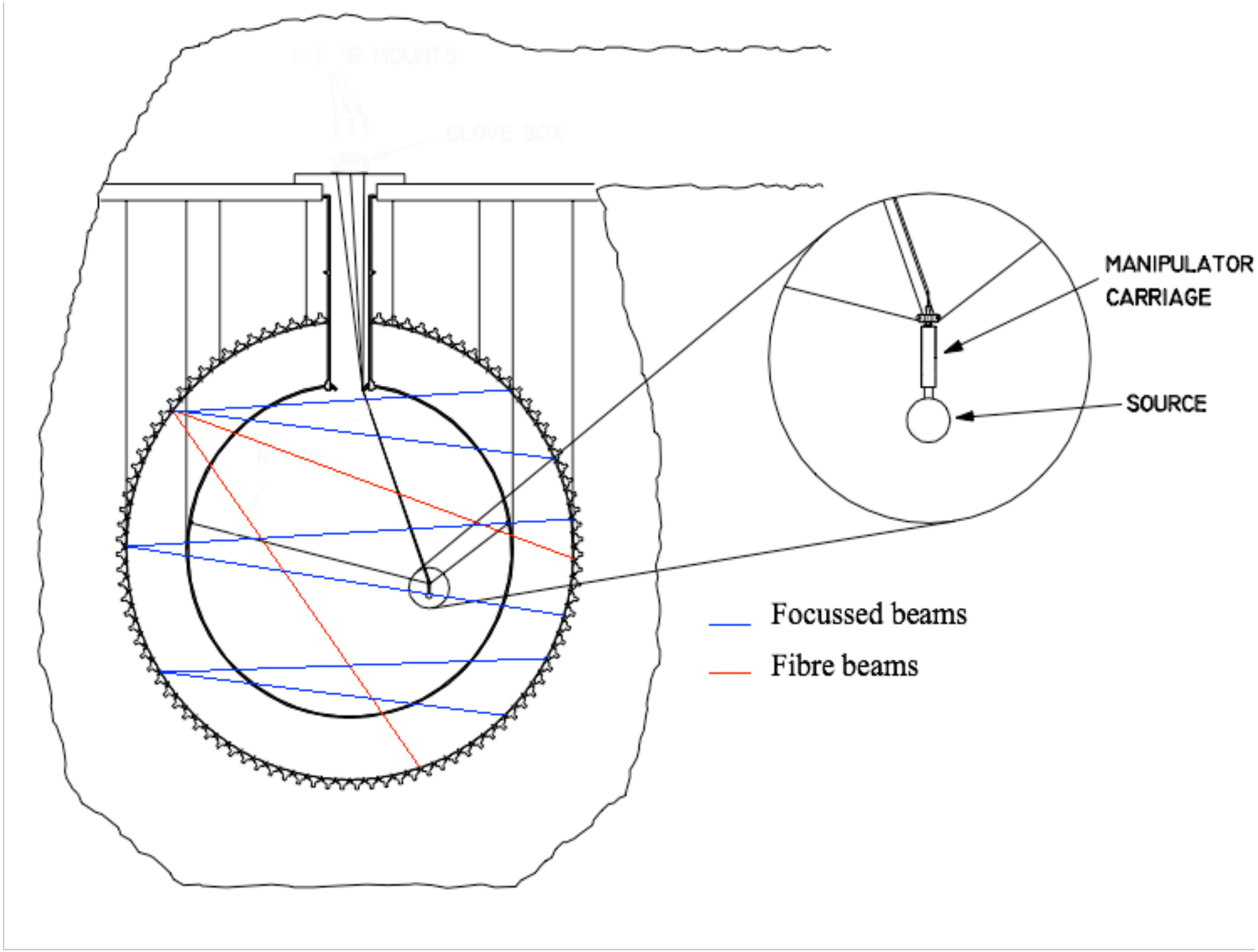
see also Gehman & Elliott, 2007

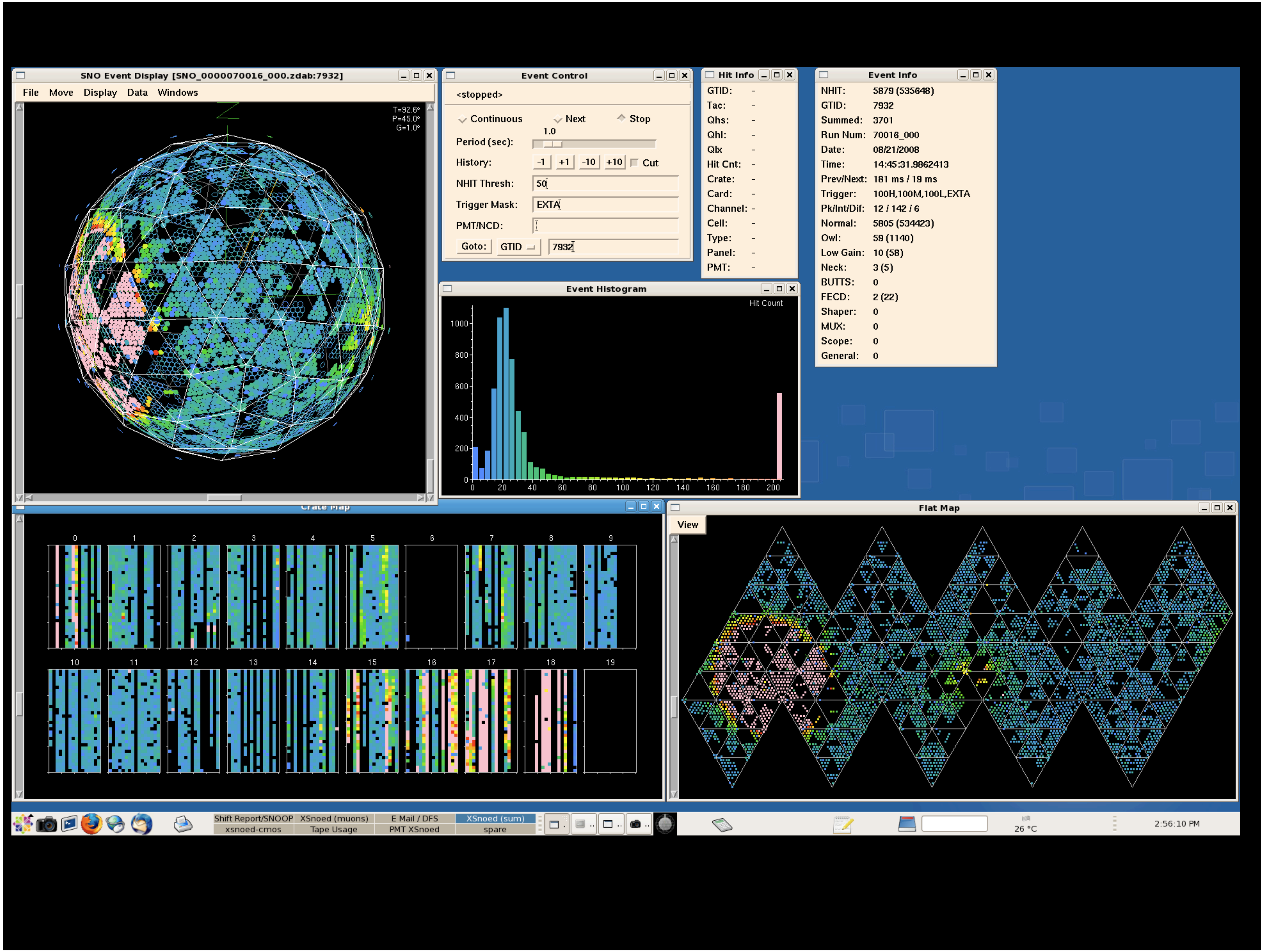
OUTLOOK:

By 2015, neutrino masses above ~100 meV will either be firmly established or firmly ruled out based on multiple experiments (including SNO+) using different isotopes.

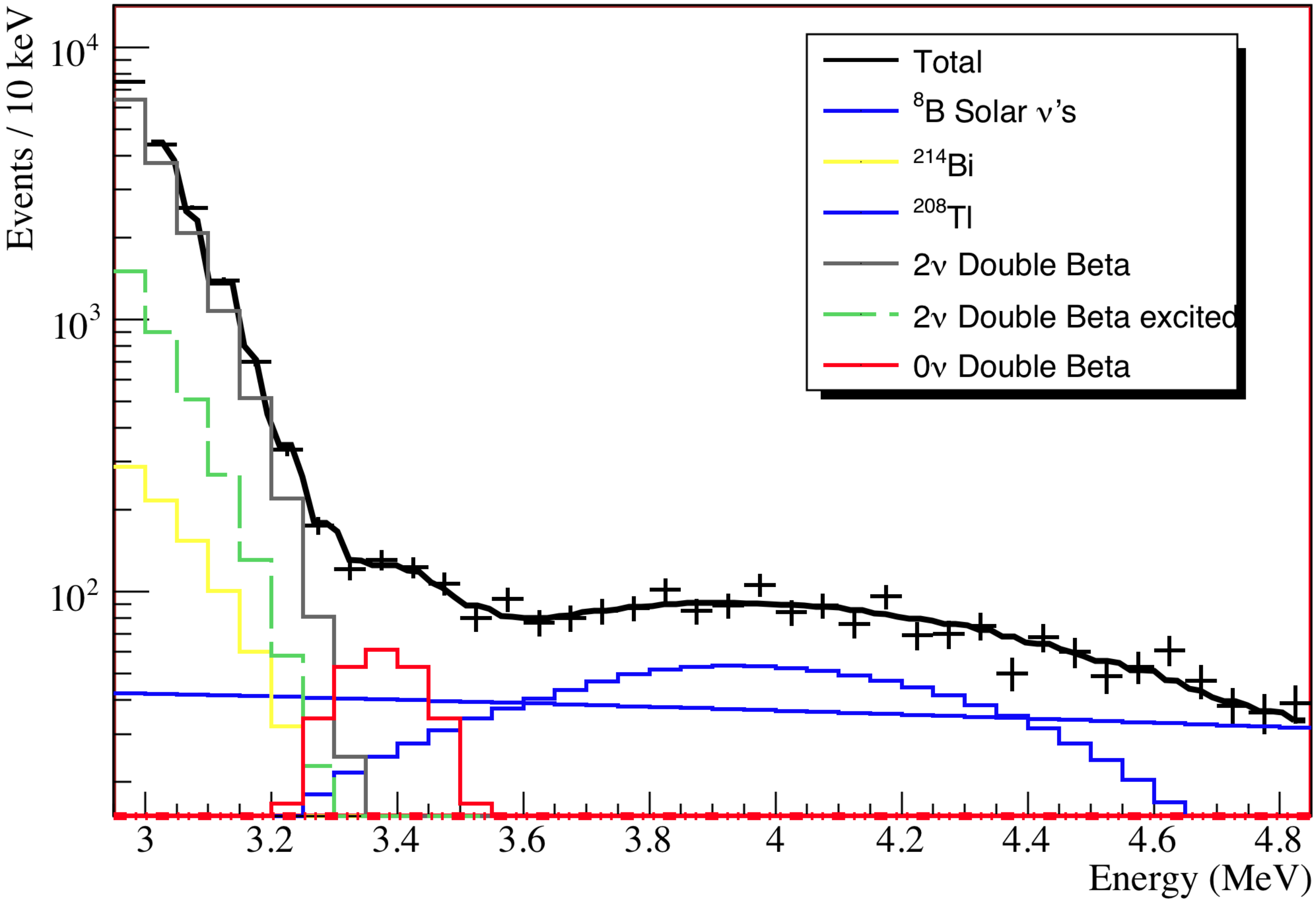
If established, first constraints on several physics mechanisms will likely be made using ratio of lifetimes in these different isotopes.

If ruled out, all experiments will have to push to larger masses/enrichment to properly test inverted hierarchy. First experiments here might be running by ~2018.


MANIPULATOR
CARRIAGE
SOURCE
Focussed beams
Fibre beams

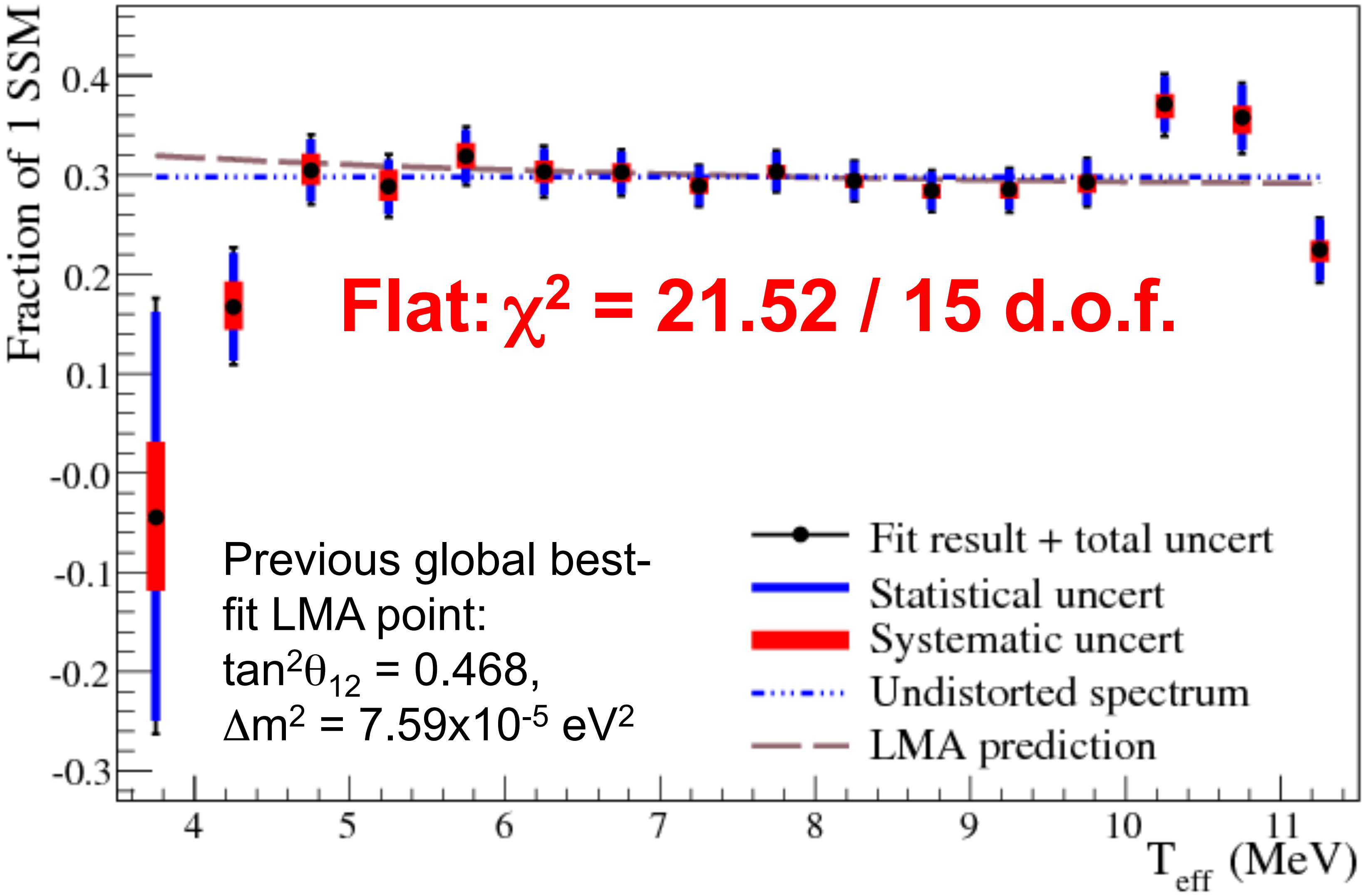

SNO Event Display [SNO_0000070016_000.zdab:7932]
File Move Display Data Windows
T=92.6°
P=45.0°
G=1.0°
Event Control
<stopped>
Continuous
Next
Stop
1.0
Period (sec):
History:
-1
+1
-10
+10
Cut
NHIT Thresh:
50
Trigger Mask:
EXTA
PMT/NCD:
Goto:
GTID
7932
Hit Info
GTID: -
Tac: -
Qhs: -
Qhl: -
Qlx -
Hit Cnt: -
Crate: -
Card: -
Channel: -
Cell: -
Type: -
Panel: -
PMT: -
Event Info
NHIT: 5879 (535648)
GTID: 7932
Summed: 3701
Run Num: 70016_000
Date: 08/21/2008
Time: 14:45:31.9862413
Prev/Next: 181 ms / 19 ms
Trigger: 100H,100M,100L,EXTA
Pk/Int/Dif: 12 / 142 / 6
Normal: 5805 (534423)
Owl: 59 (1140)
Low Gain: 10 (58)
Neck: 3 (5)
BUTTS: 0
FECD: 2 (22)
Shaper: 0
MUX: 0
Scope: 0
General: 0
Event Histogram
Hit Count
1000
800
600
400
200
0
0 20 40 60 80 100 120 140 160 180 200
Crate Map
0 1 2 3 4 5 6 7 8 9
10 11 12 13 14 15 16 17 18 19
Flat Map
View
Shift Report/SNOOP
XSnoed (muons)
E Mail / DFS
XSnoed (sum)
xsnoed-cmos
Tape Usage
PMT XSnoed
spare
26 °C
2:56:10 PM

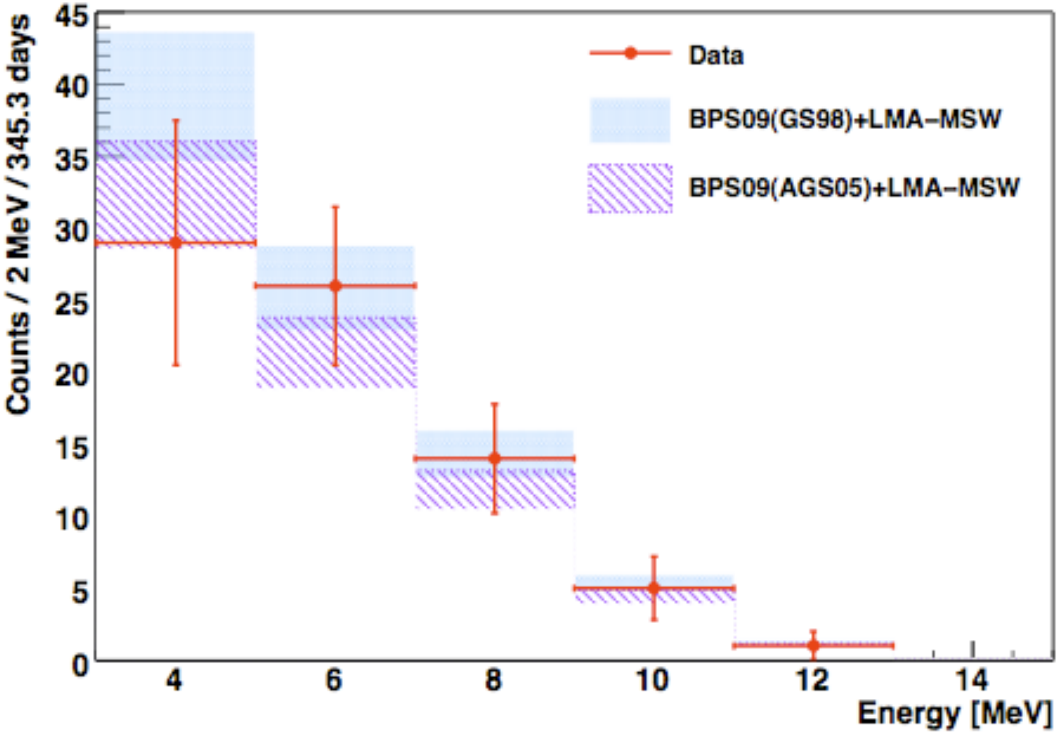
3 Years of data, m_ν=350meV, U/Th = 10^{-17} g/g
0.1% natural Nd loading, IBM-2 matrix elements



SNO CC Recoil-Electron Spectrum

Phys. Rev. C 81, 055504 (2010), **arXiv:0910.2984**





Borexino

- 300tonnes
- 2200 PMTs
- 3500mwe

Phys.Rev.Lett.101:091302,2008

arXiv:0805.3843v2