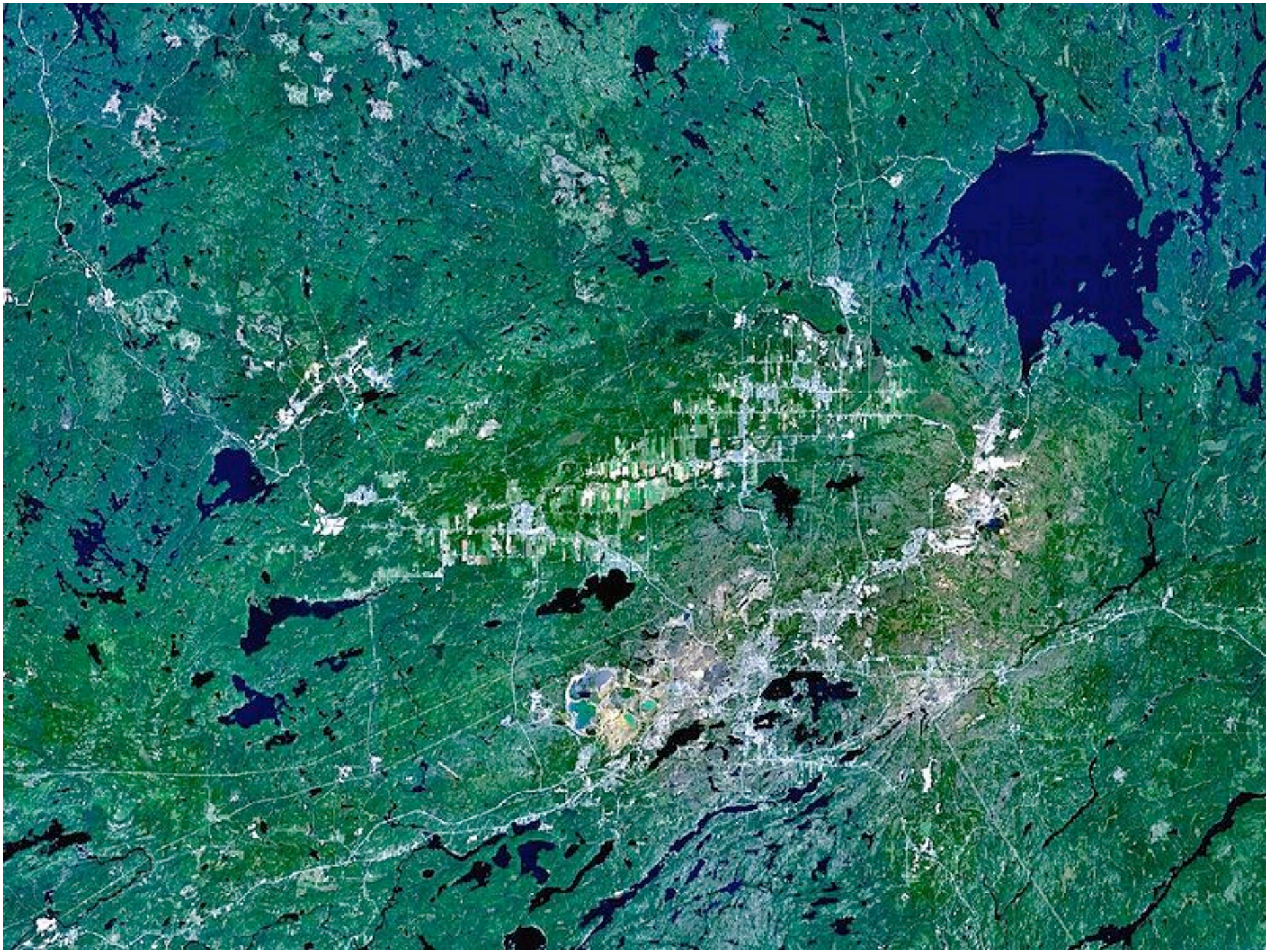
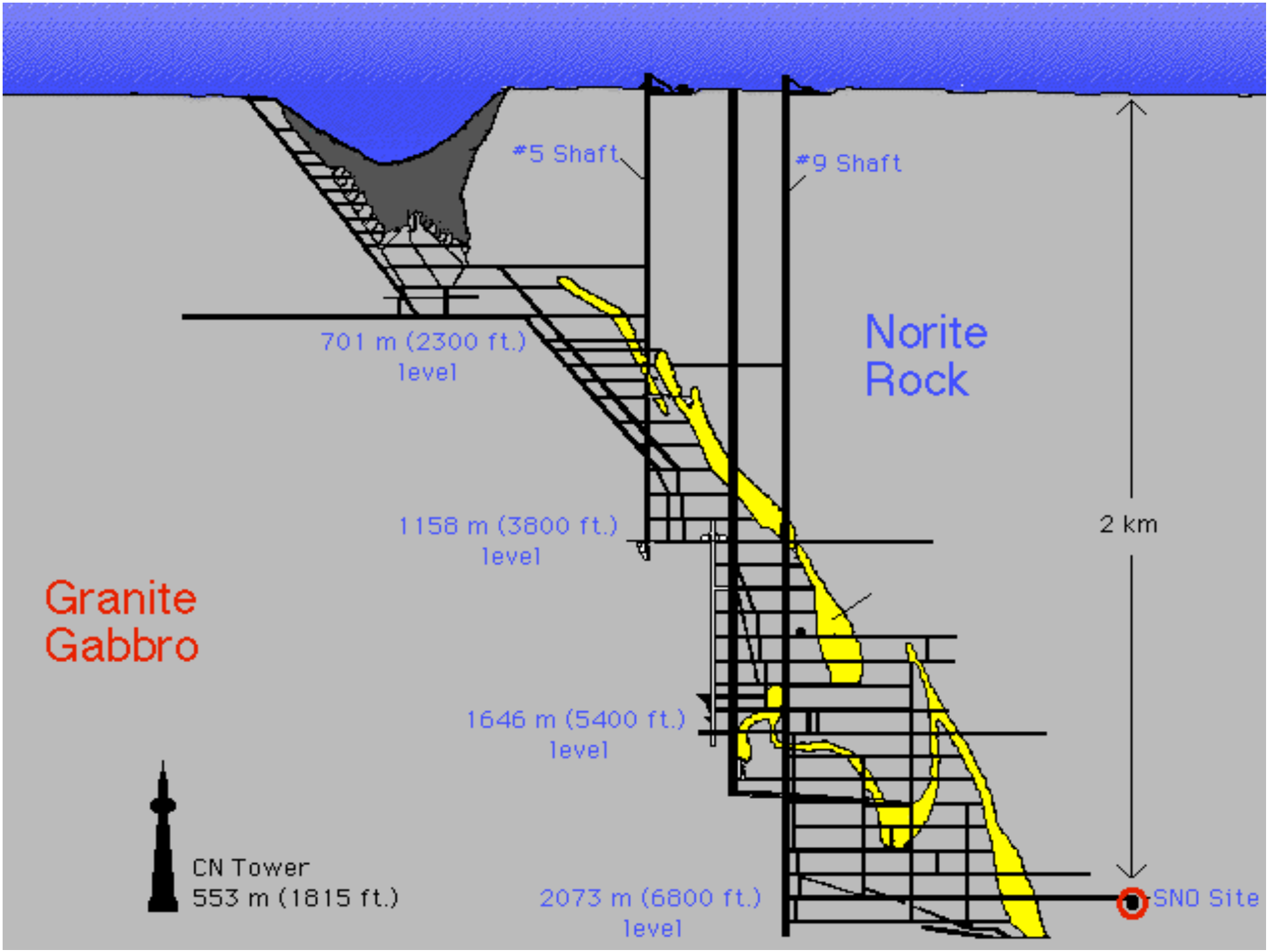
Neutrino Physics in Sudbury

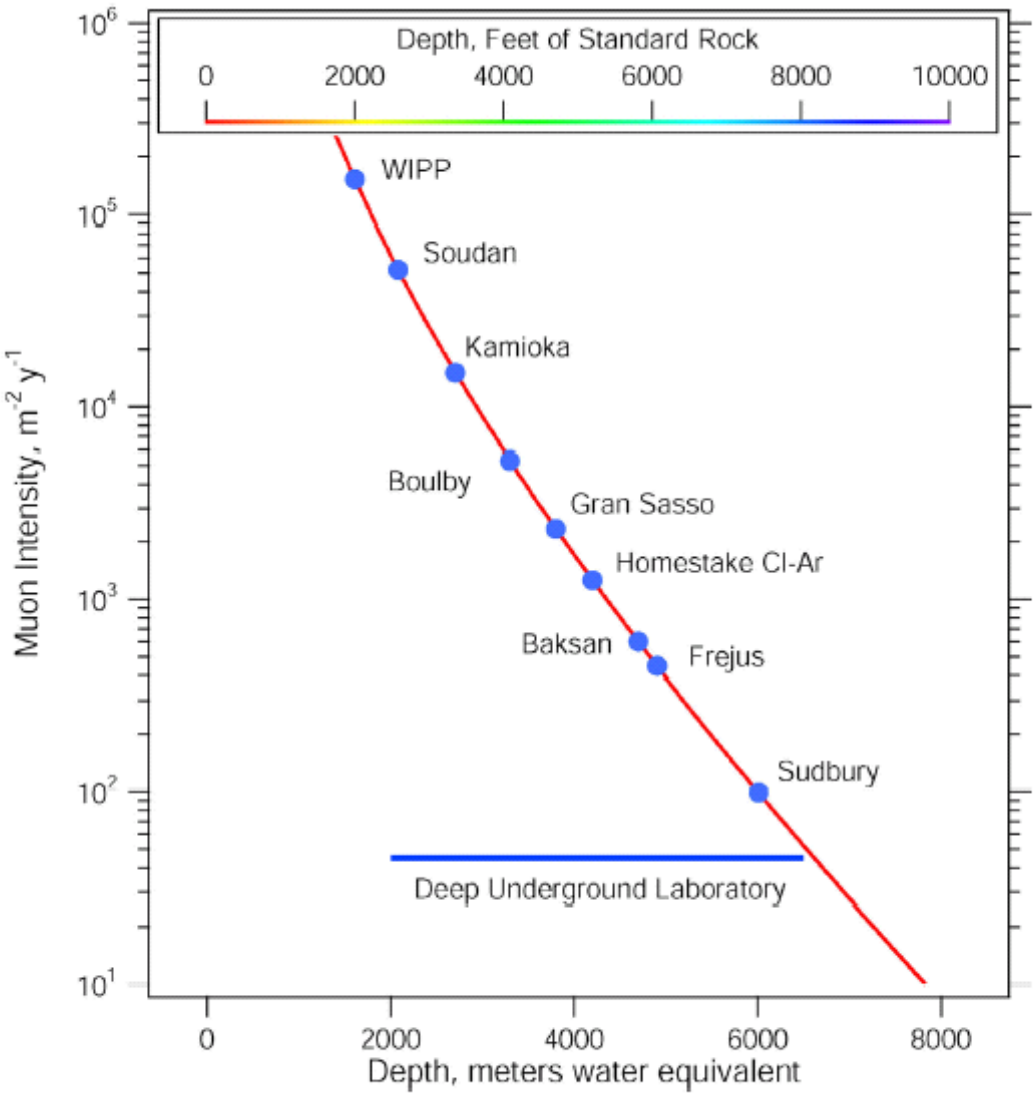
Jeanne Wilson

QMUL, 12th March 2010

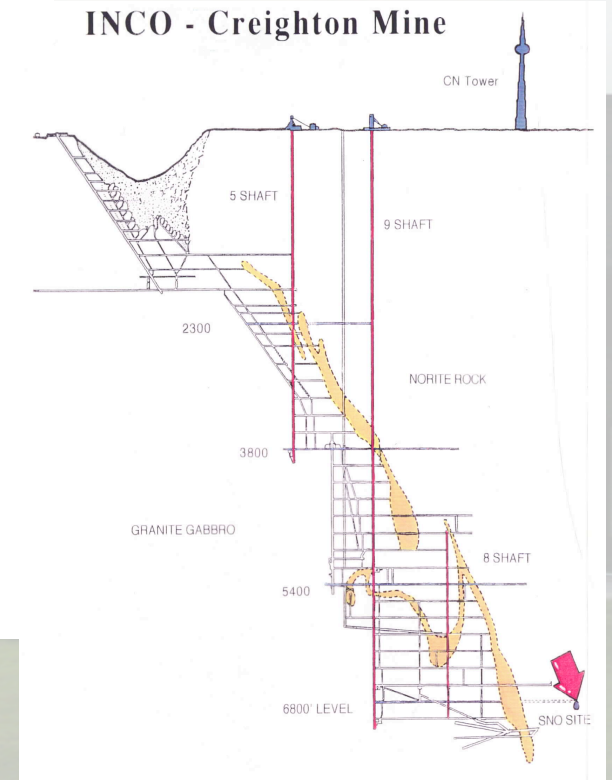
- Why Sudbury?
- The Sudbury Neutrino Observatory
  - Motivation
  - Physics Goals
  - Detector design
  - Challenges
  - Most recent result – low energy threshold analysis (LETA)
- From SNO to SNO+
  - New physics goals
  - New challenges
  - UK work
  - Current status



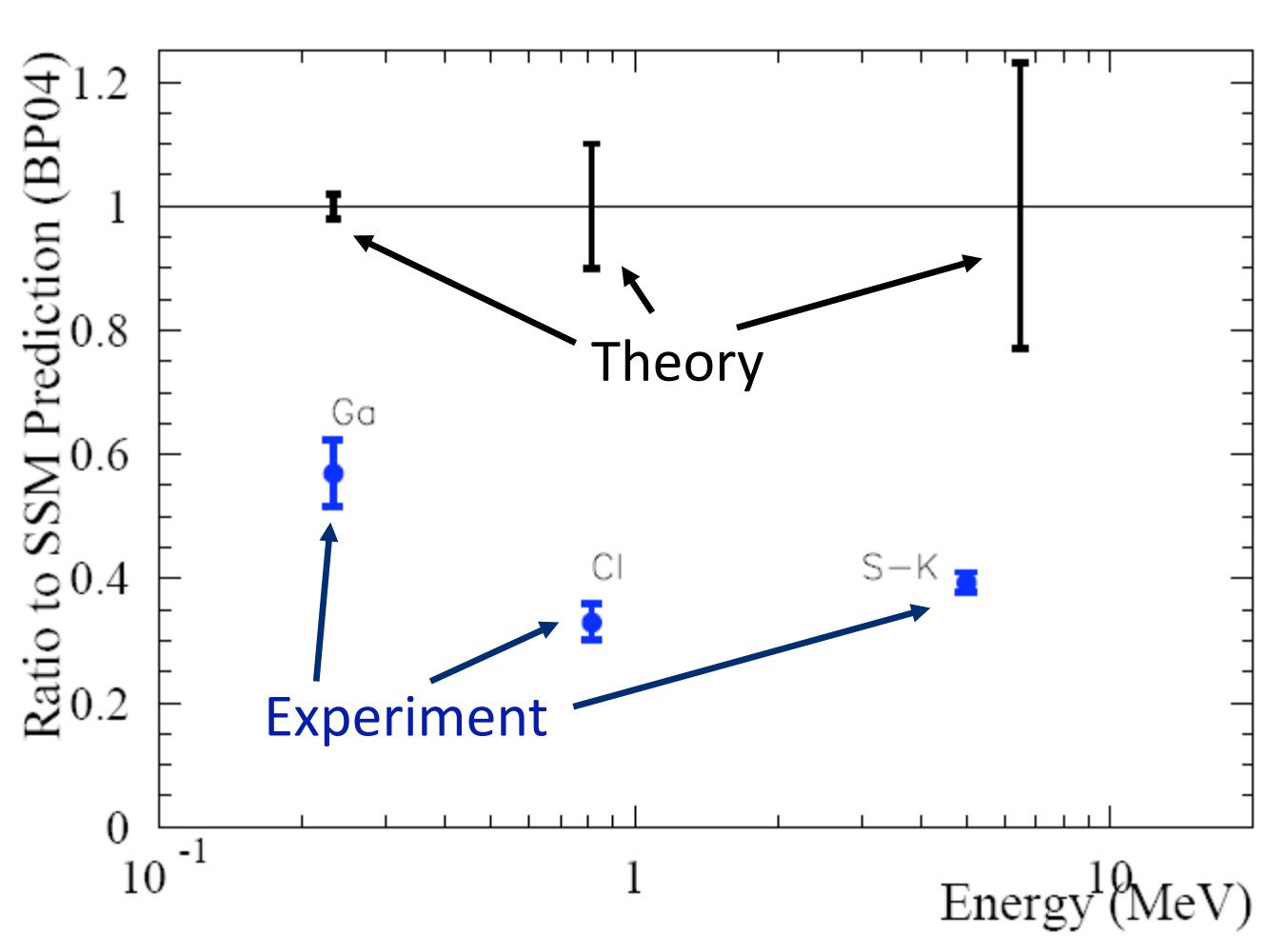

#5 Shaft
#9 Shaft
Norite
Rock
701 m (2300 ft.)
level
1158 m (3800 ft.)
level
2 km
Granite
Gabbro
1646 m (5400 ft.)
level
CN Tower
553 m (1815 ft.)
2073 m (6800 ft.)
level
SNO Site


Depth, Feet of Standard Rock
0
2000
4000
6000
8000
10000
WIPP
Soudan
Kamioka
Boulby
Gran Sasso
Homestake Cl-Ar
Baksan
Frejus
Sudbury
Deep Underground Laboratory
Muon Intensity, m-2 y-1
10^6
10^5
10^4
10^3
10^2
10^1
0
2000
4000
6000
8000
Depth, meters water equivalent

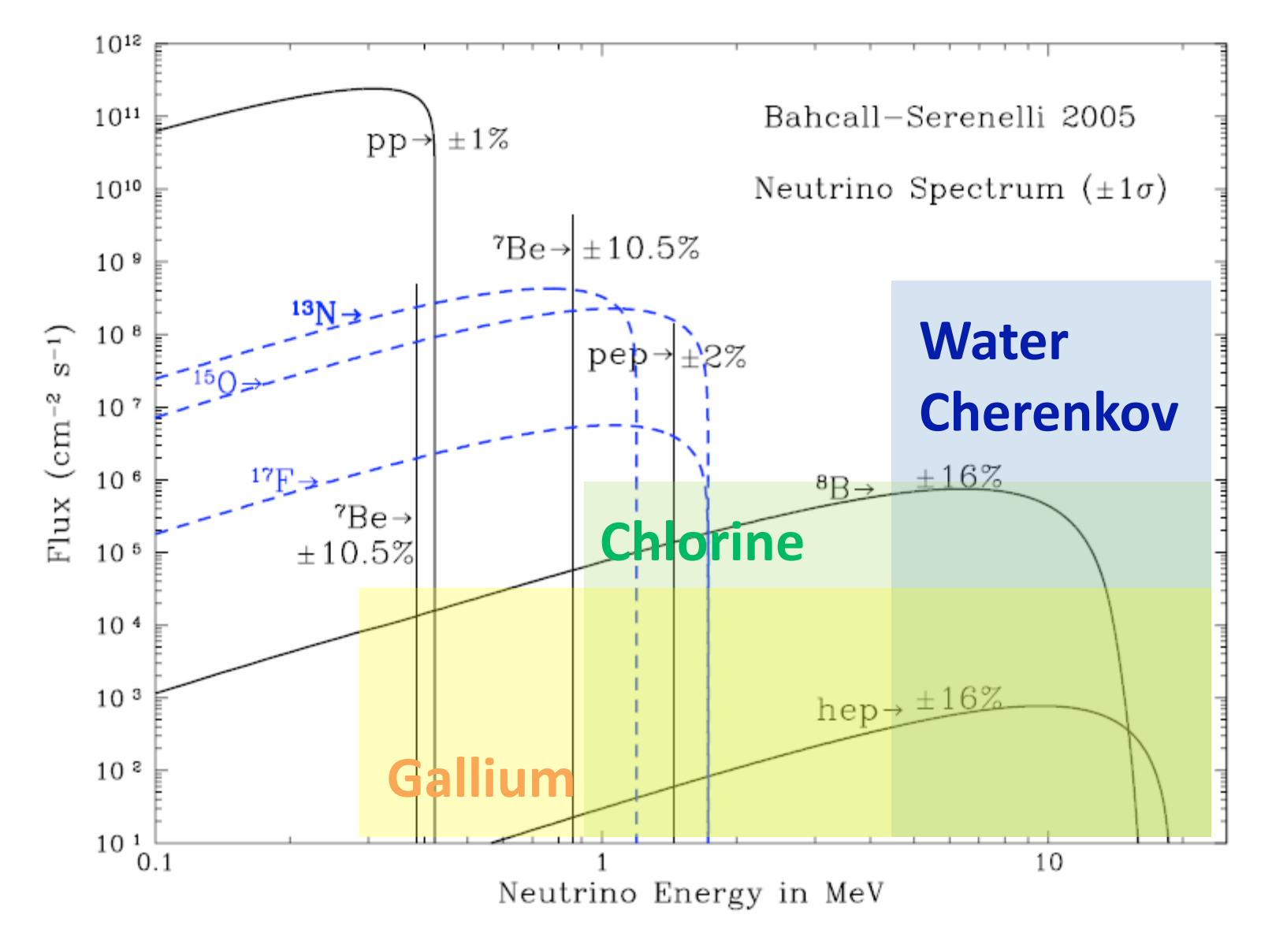

Creighton Mine
World's Deepest Continuous Shaft
Flat Overburden


INCO - Creighton Mine
CN Tower
5 SHAFT
9 SHAFT
2300
NORITE ROCK
3800
GRANITE GABBRO
8 SHAFT
5400
6800' LEVEL
SNO SITE

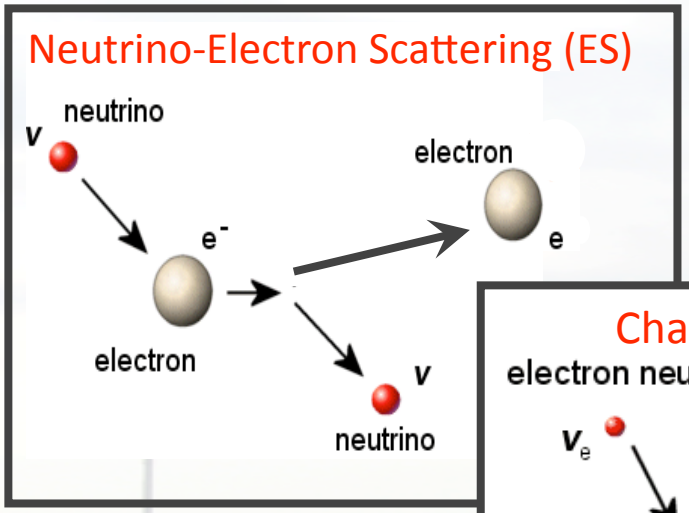
Solar Neutrino Problem



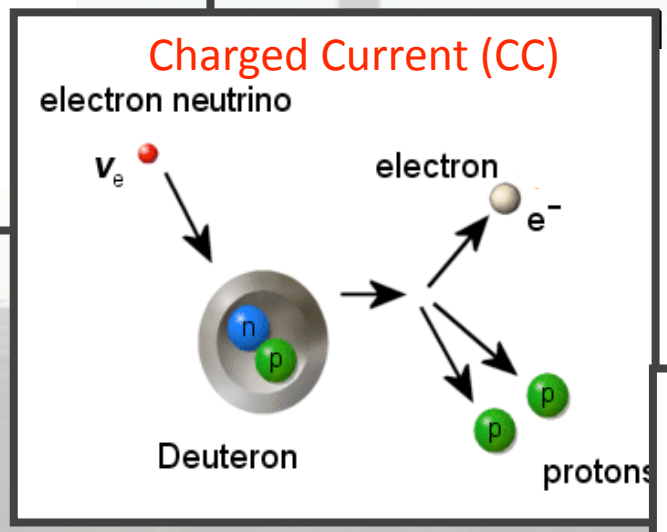
Solar Neutrinos



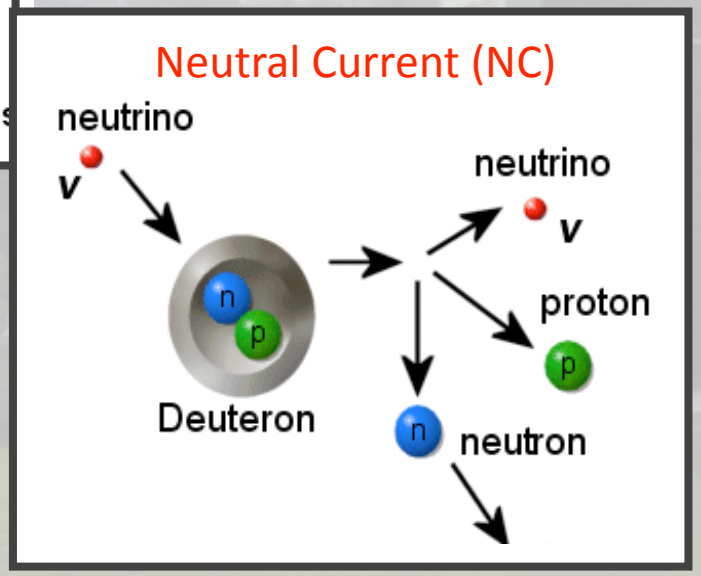
The Answer: Heavy Water



1. Elastic Scattering
Primarily sensitive to ν_e
Measures ν direction



2. Charged Current
Sensitive only to ν_e
Measures ν energy



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

The Sudbury Neutrino Observatory

3 phases:

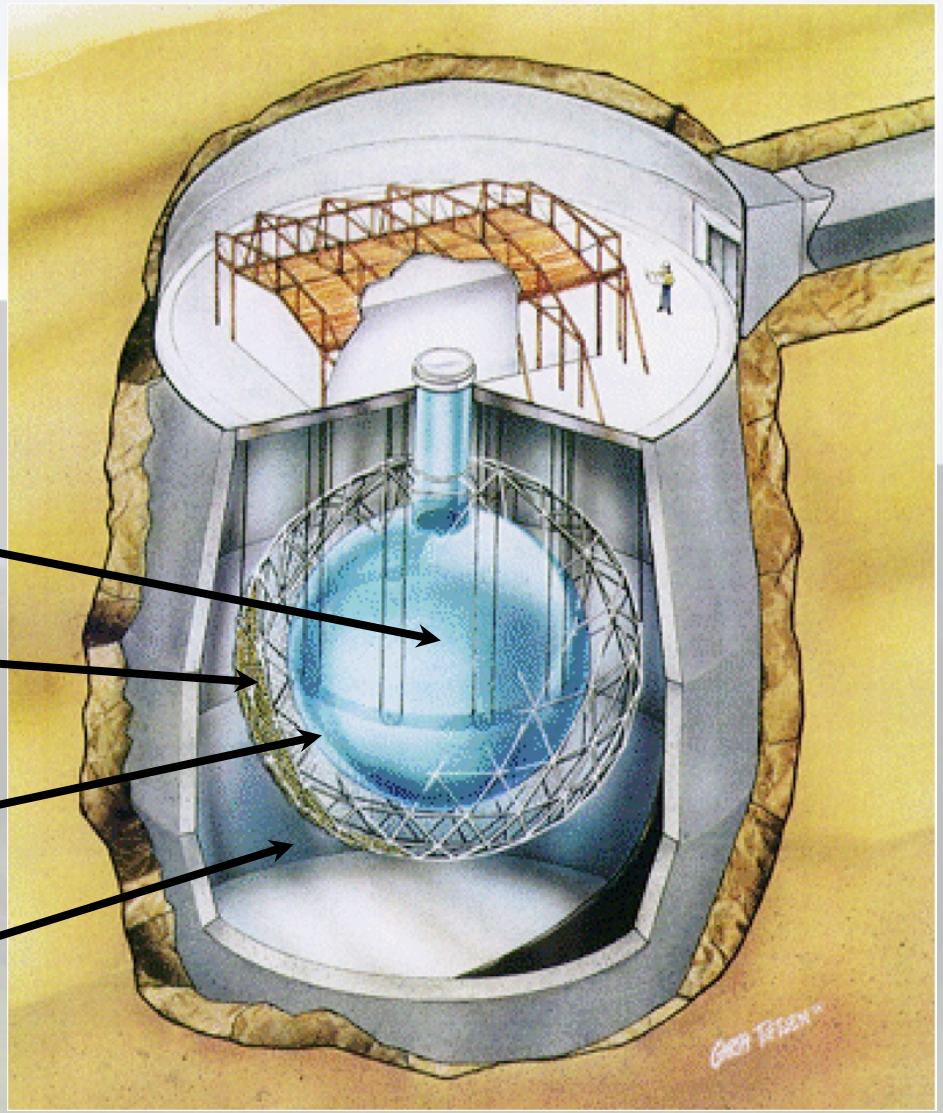
1. Pure D_2O
2. D_2O + NaCl
3. D_2O + ^3He proportional counters

1000 tonnes D_2O

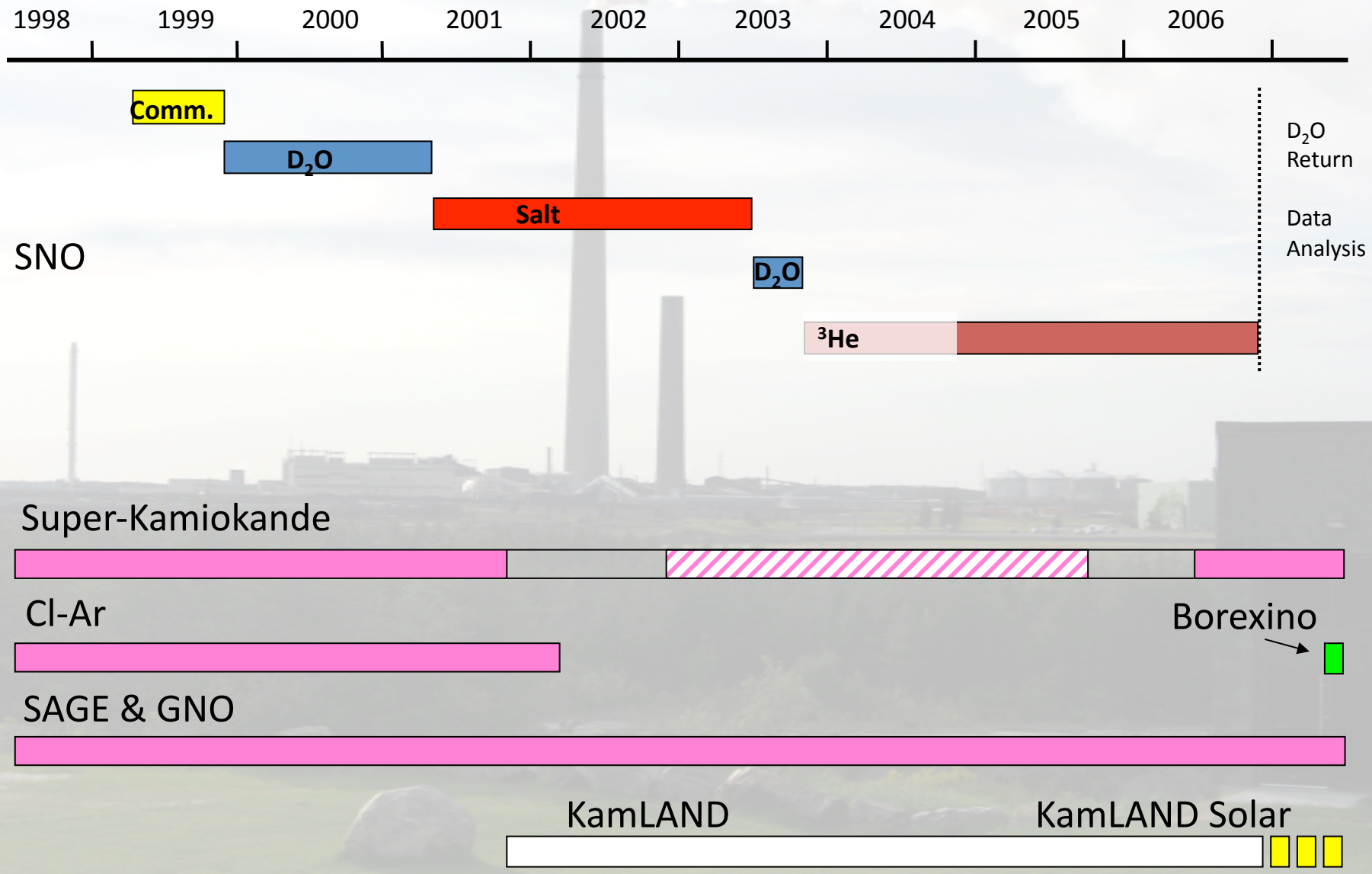
Support structure for 9500 PMTS
54% coverage

12 m diameter acrylic vessel

7000 tonnes H_2O shielding



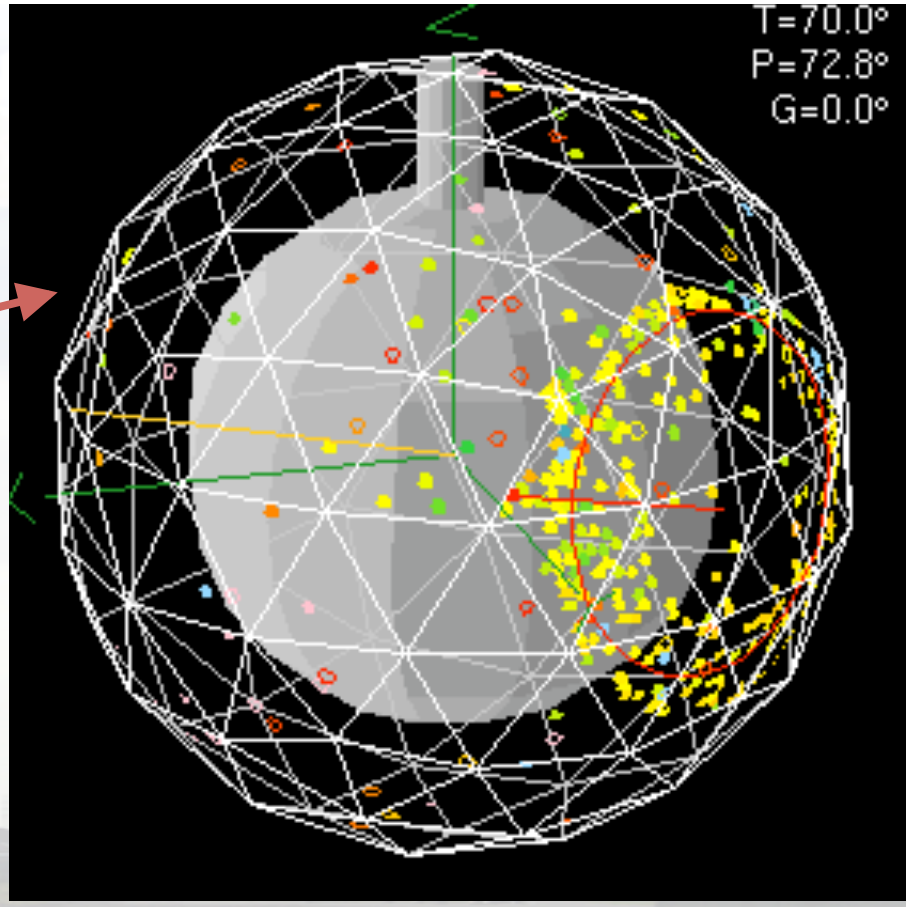
Solar Neutrino Program

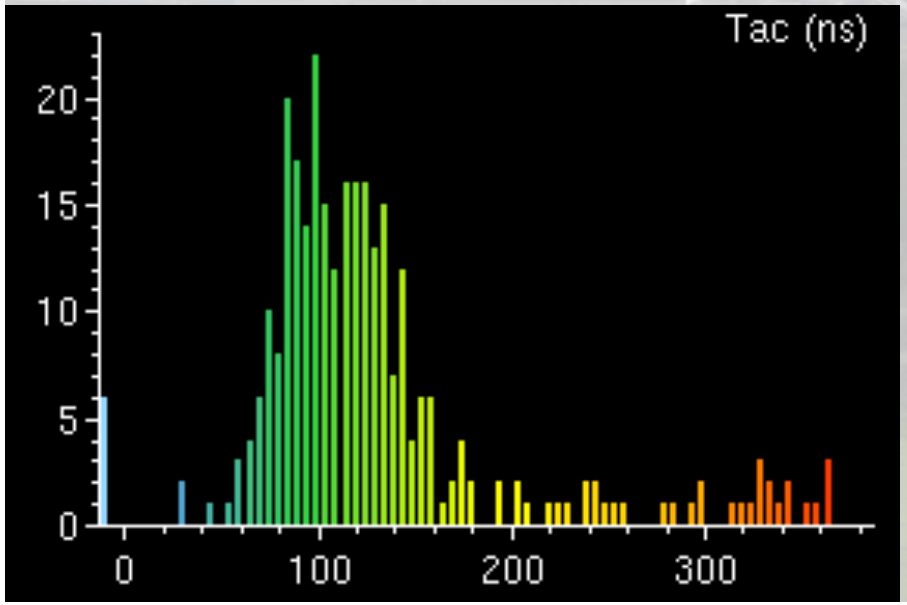


What We Measure

PMT Measurements

-position
-charge
-time

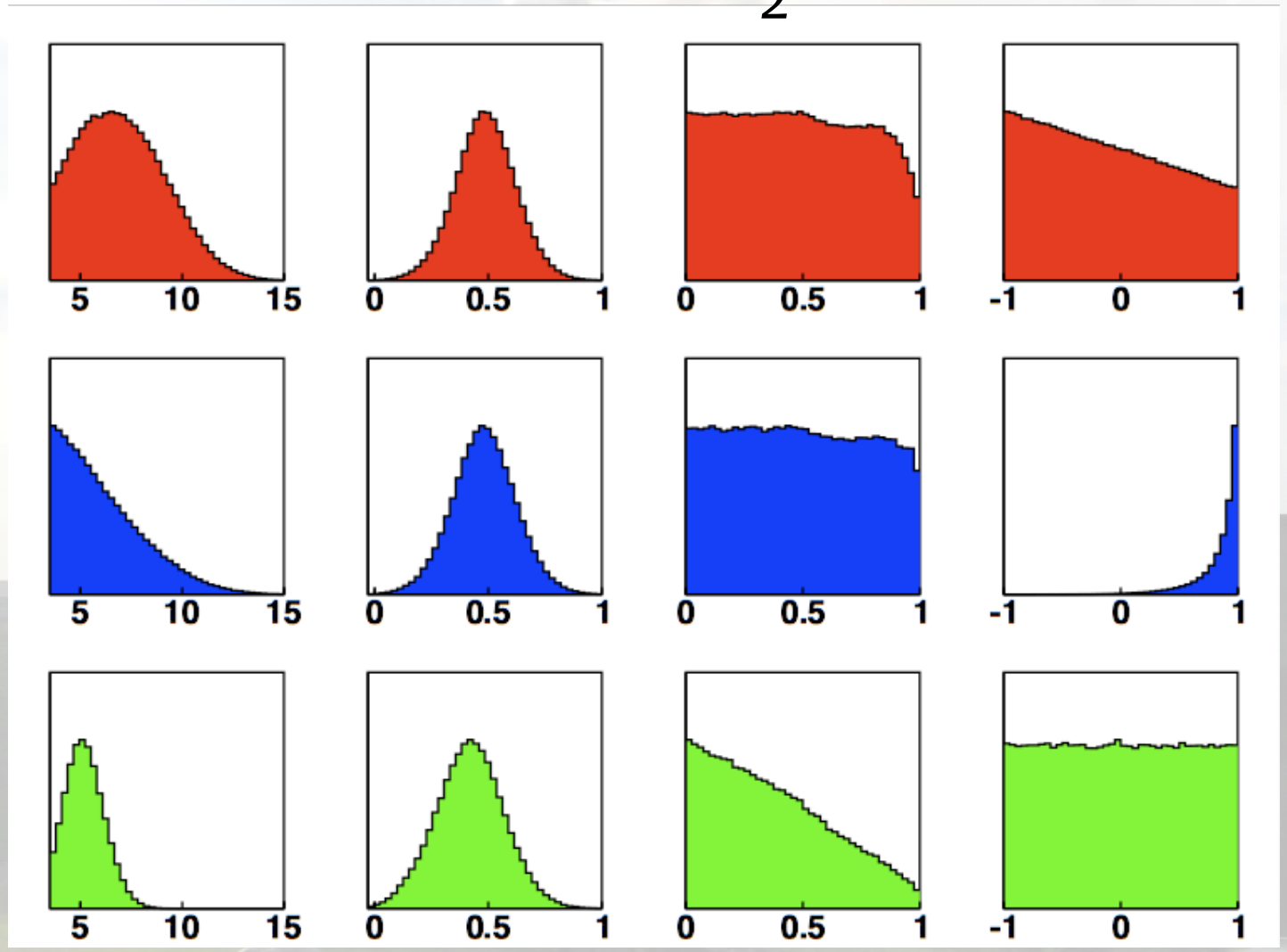




Reconstructed Event

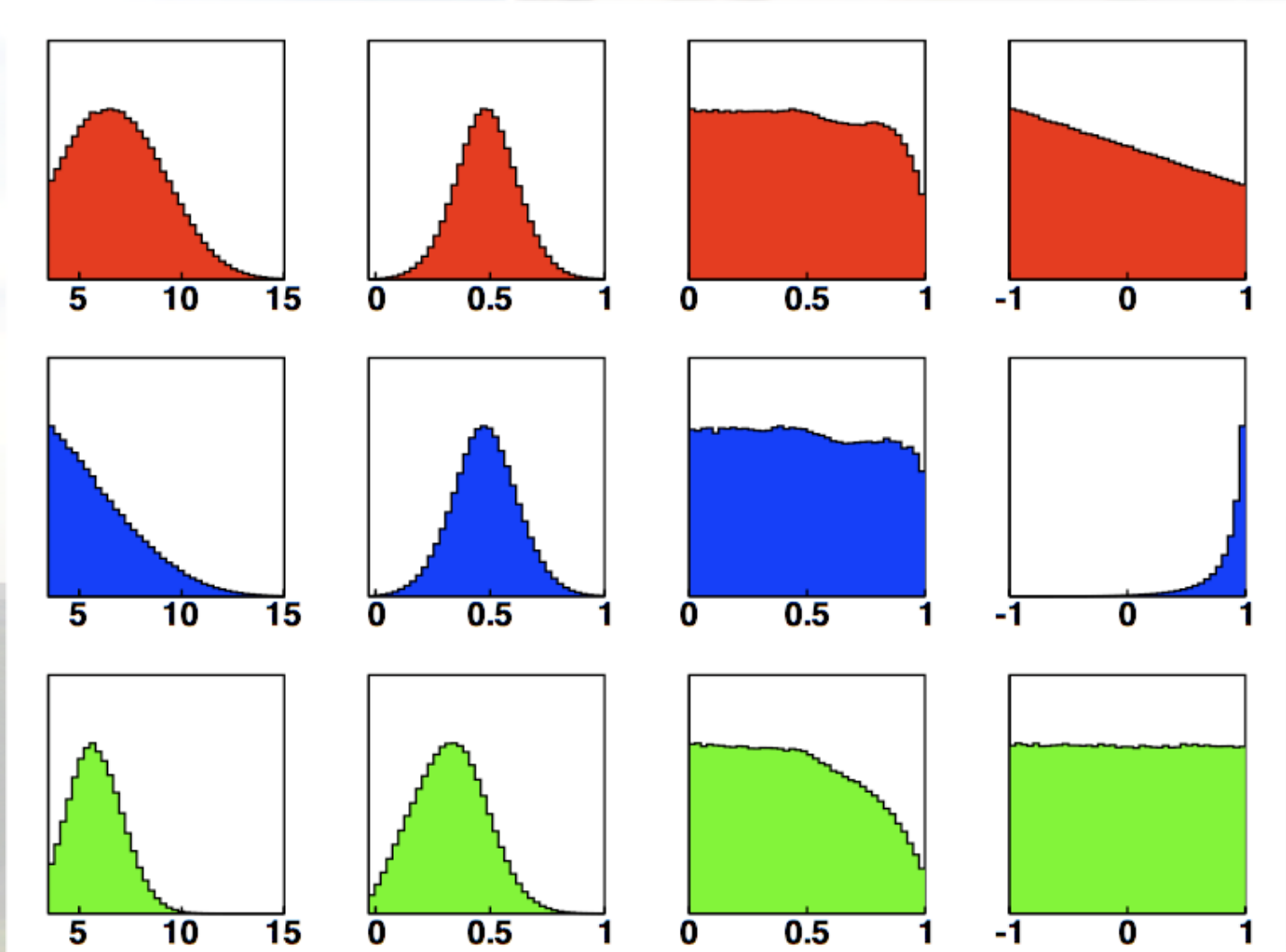
-event vertex
-event direction
-energy
-isotropy

Phase 1: D_2O



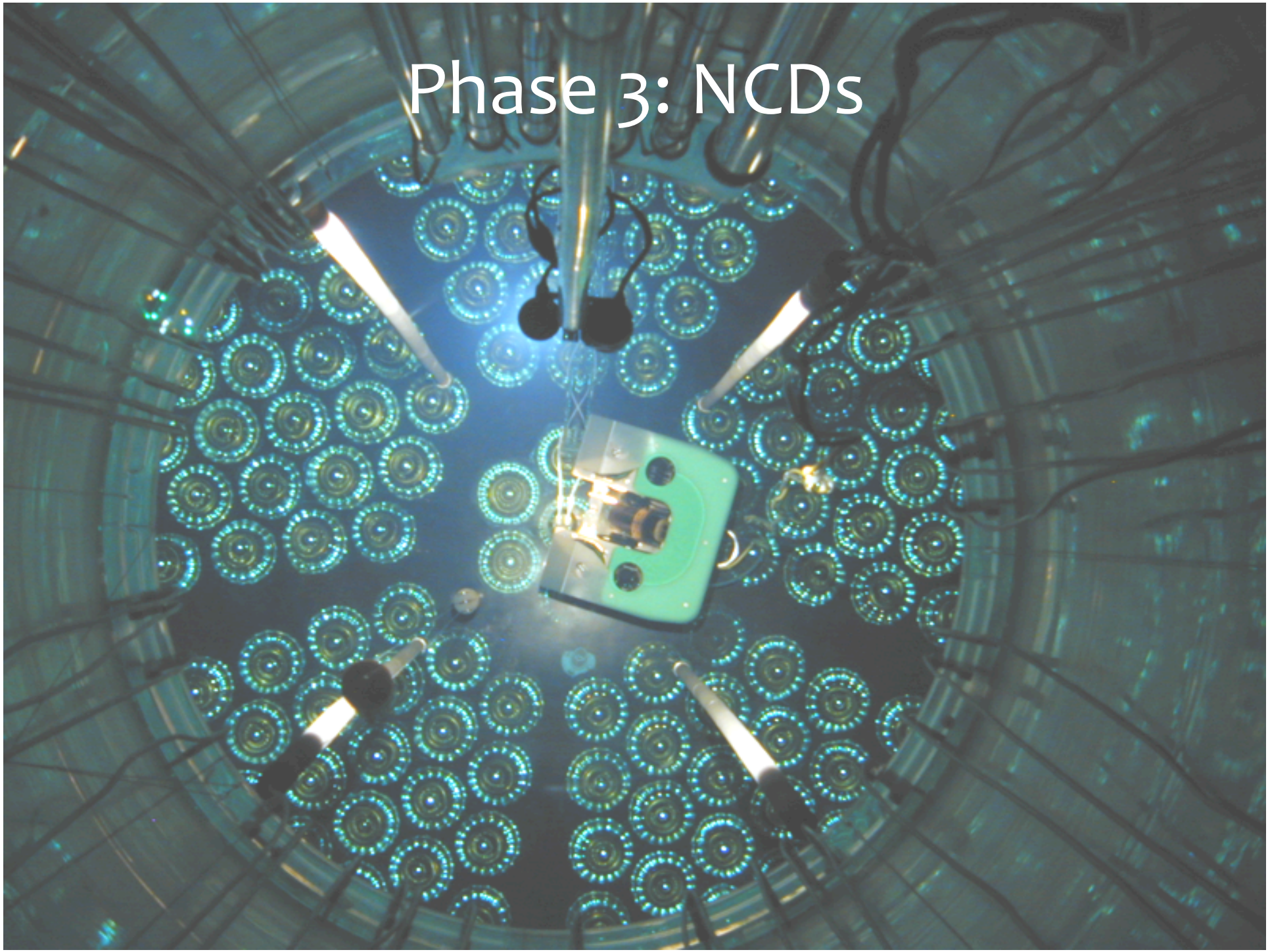
Energy	Isotropy	Position	Direction
T_{eff}	β_{14}	$R^3 = R_{fit}^3/R_{AV}^3$	$\cos(\theta_\Theta)$

Phase 2: Salt

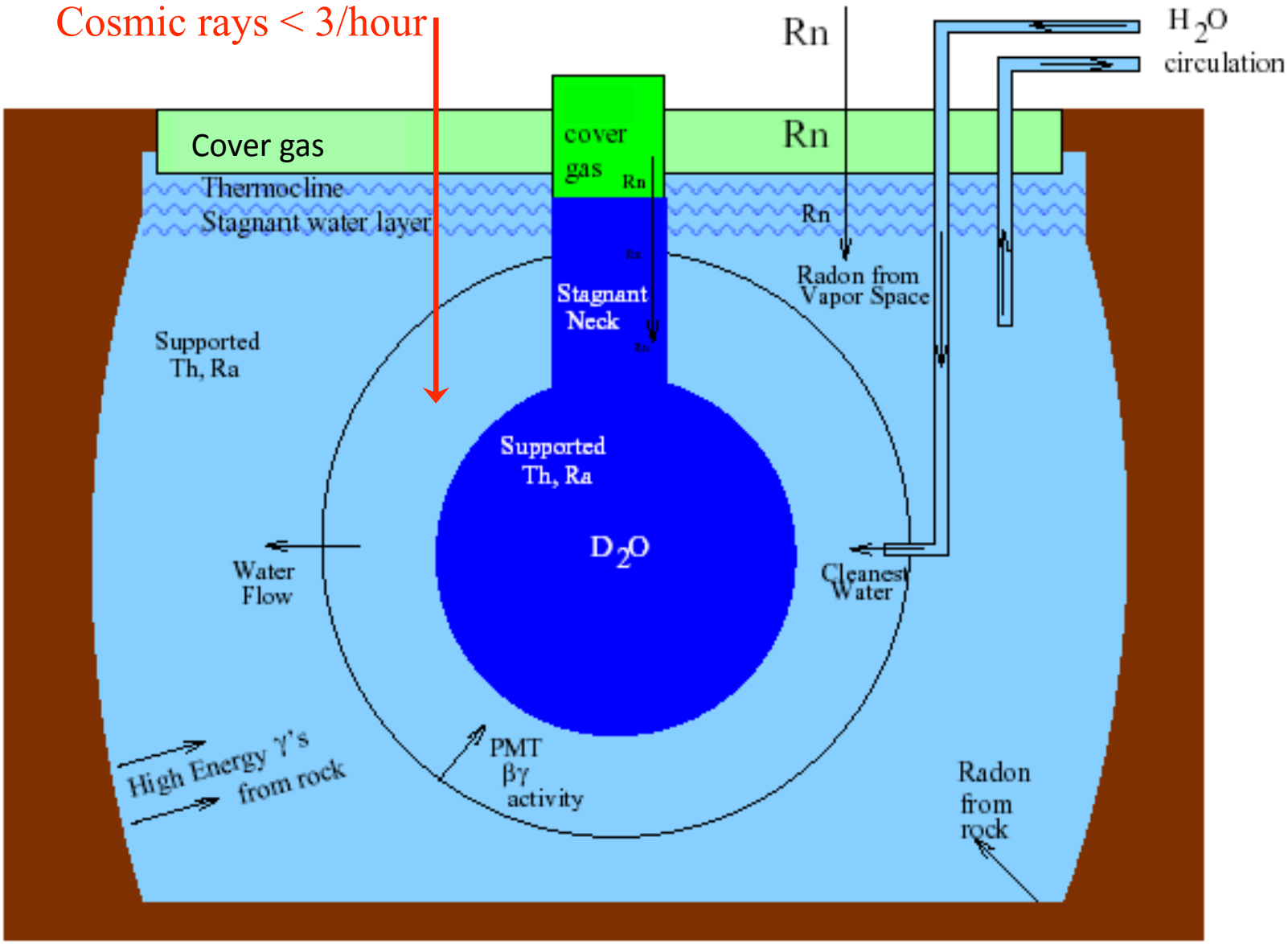


Energy	Isotropy	Position	Direction
T_{eff}	β_{14}	$R^3 = R_{fit}^3/R_{AV}^3$	$\cos(\theta_\Theta)$

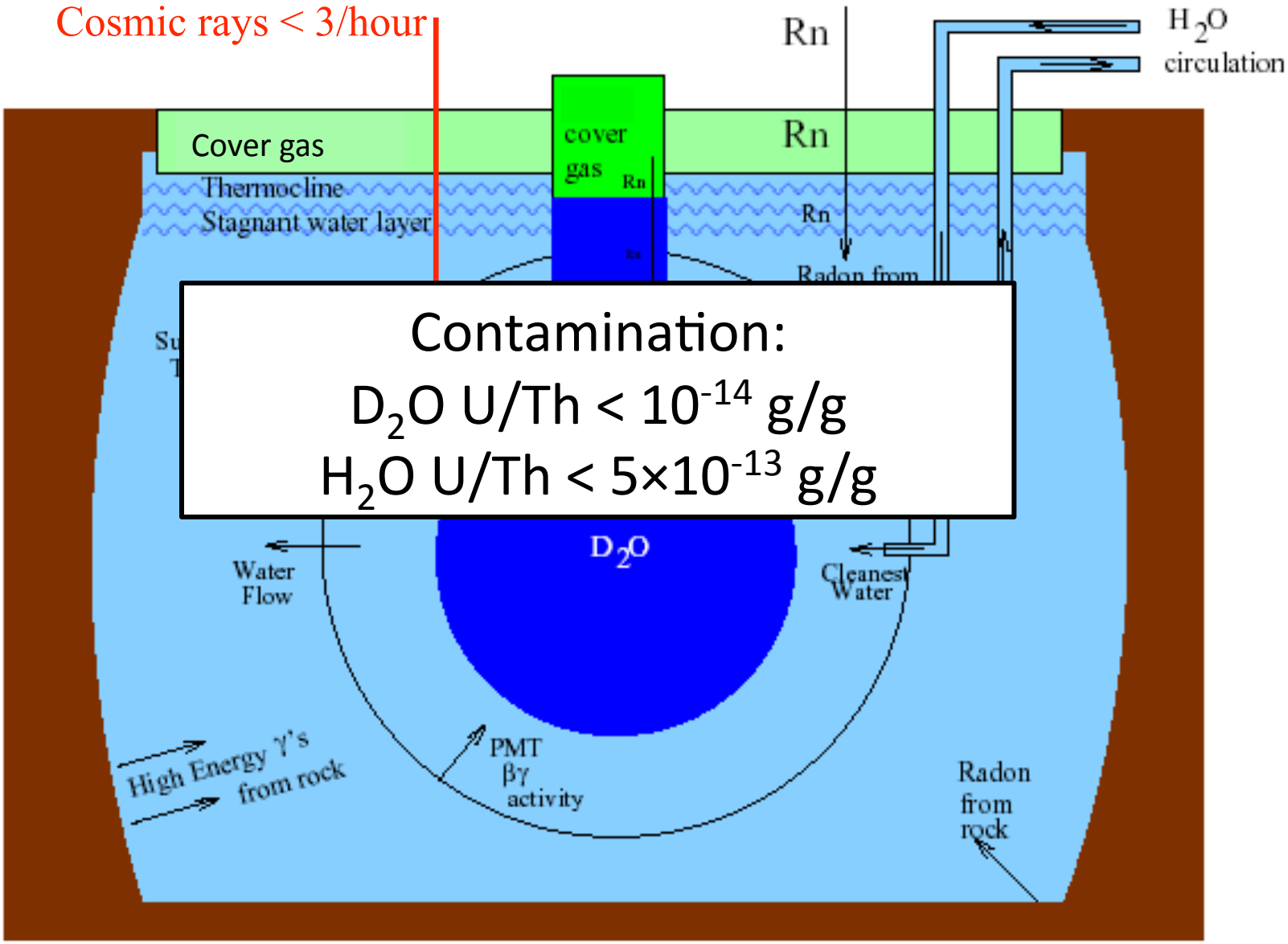
Phase 3: NCDs



Challenges: Radioactive Backgrounds



Achievements: Radioactive Backgrounds

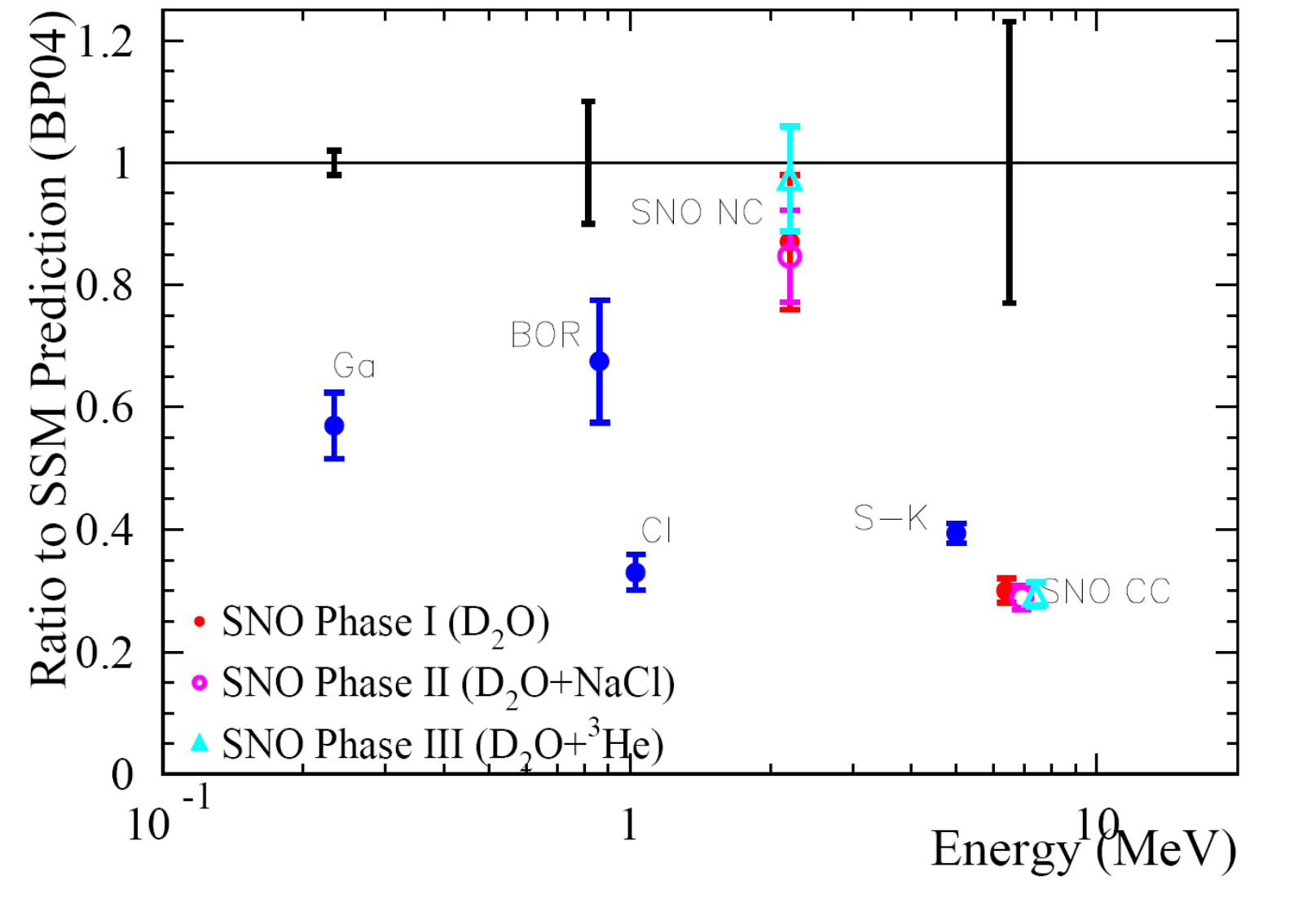


Contamination:

D_2O U/Th < 10^{-14} g/g

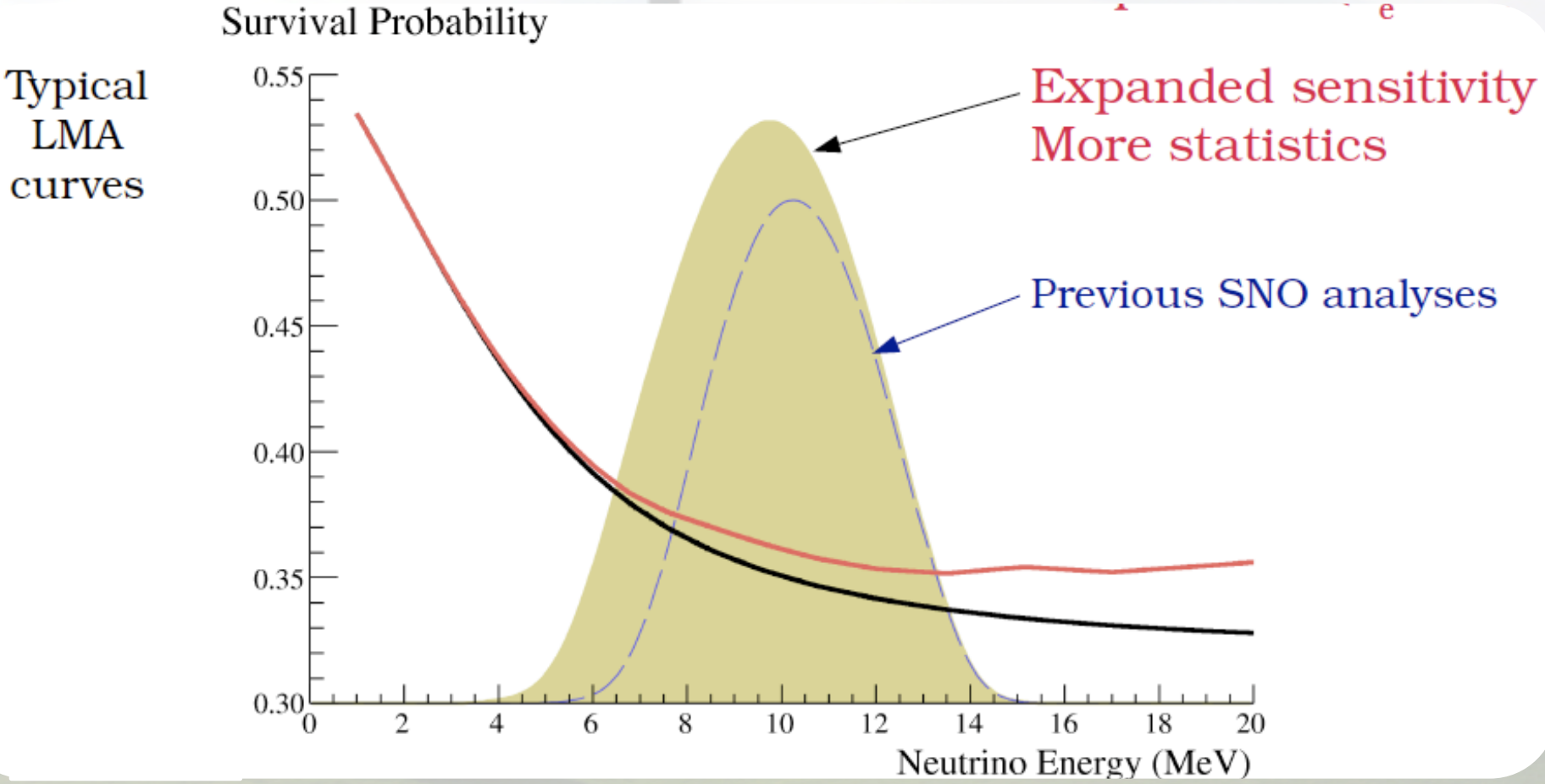
H_2O U/Th < 5×10^{-13} g/g

Solar Flux results



3.5 MeV Analysis Threshold

arXiv:0910.2984 [nucl-ex]

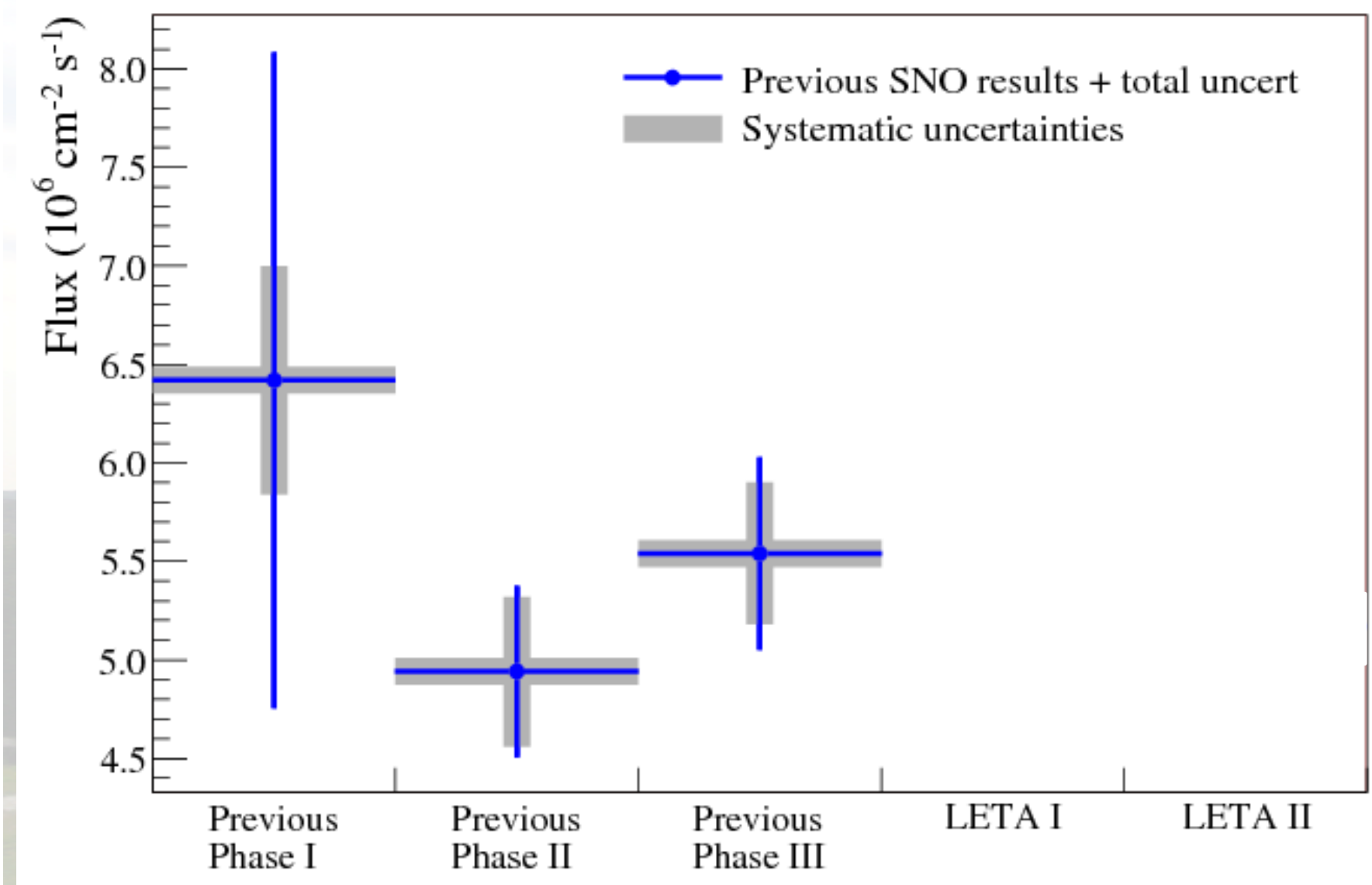


CC statistics

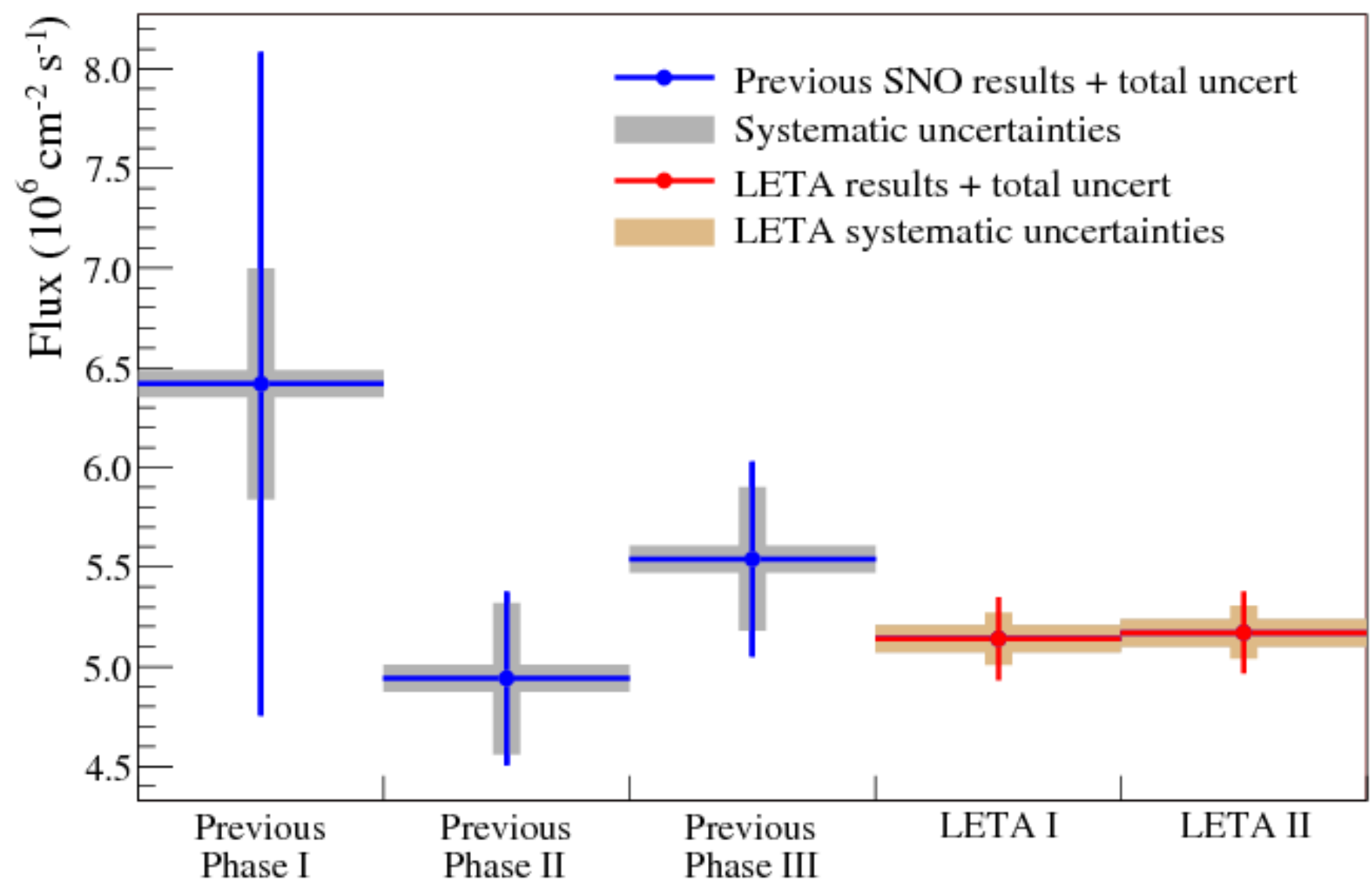
Analysis Improvements:

1. Lower threshold to 3.5MeV
2. Combine 2 phases in a joint-phase fit
3. Reduce backgrounds
4. Improve MC simulation
5. Reduce systematic uncertainties
6. Create PMT β-γ PDF directly from data
7. Improved Signal Extraction approach
8. Improved oscillation analysis

^{8}B Flux Result

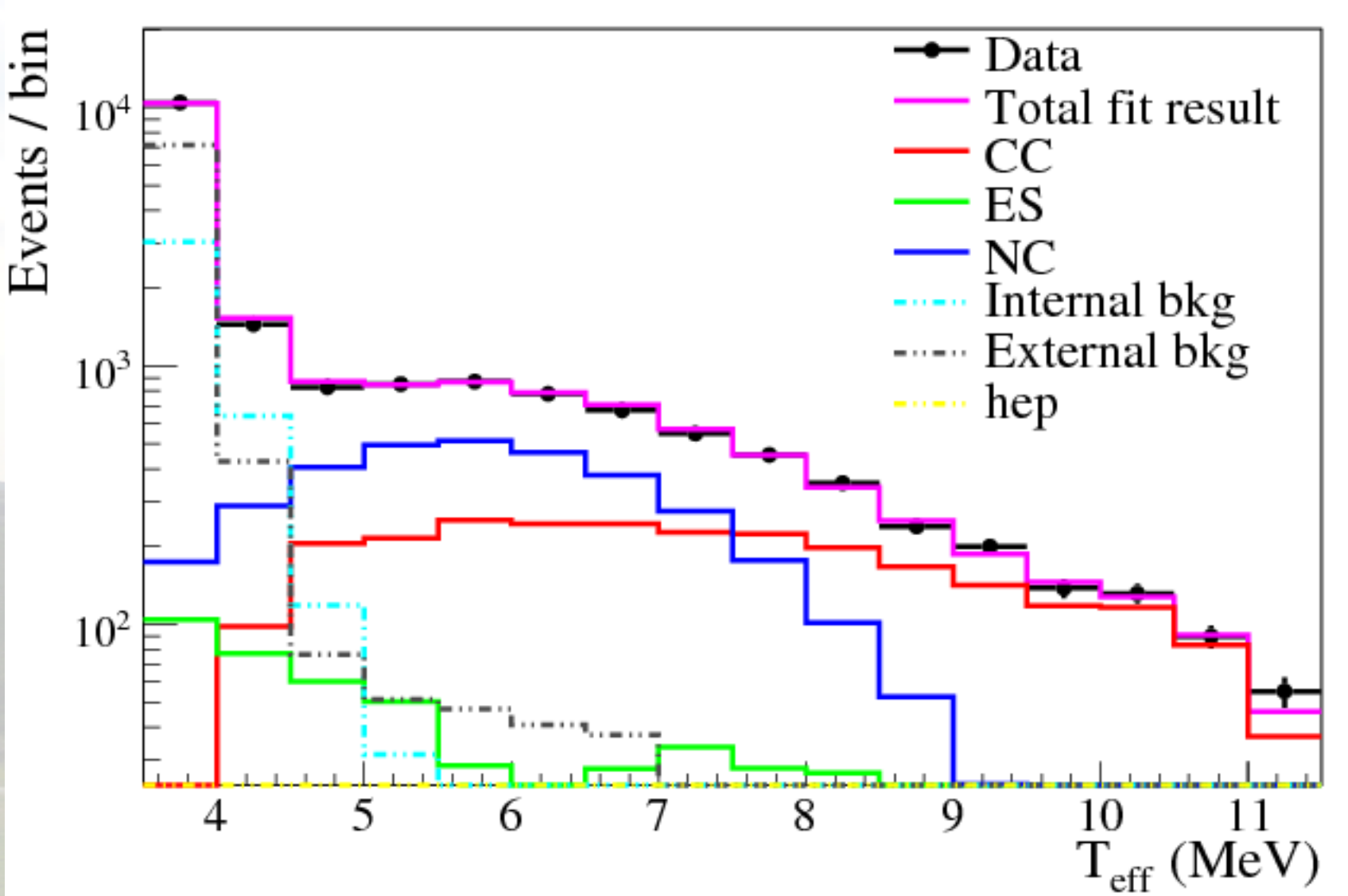


^{8}B Flux Result

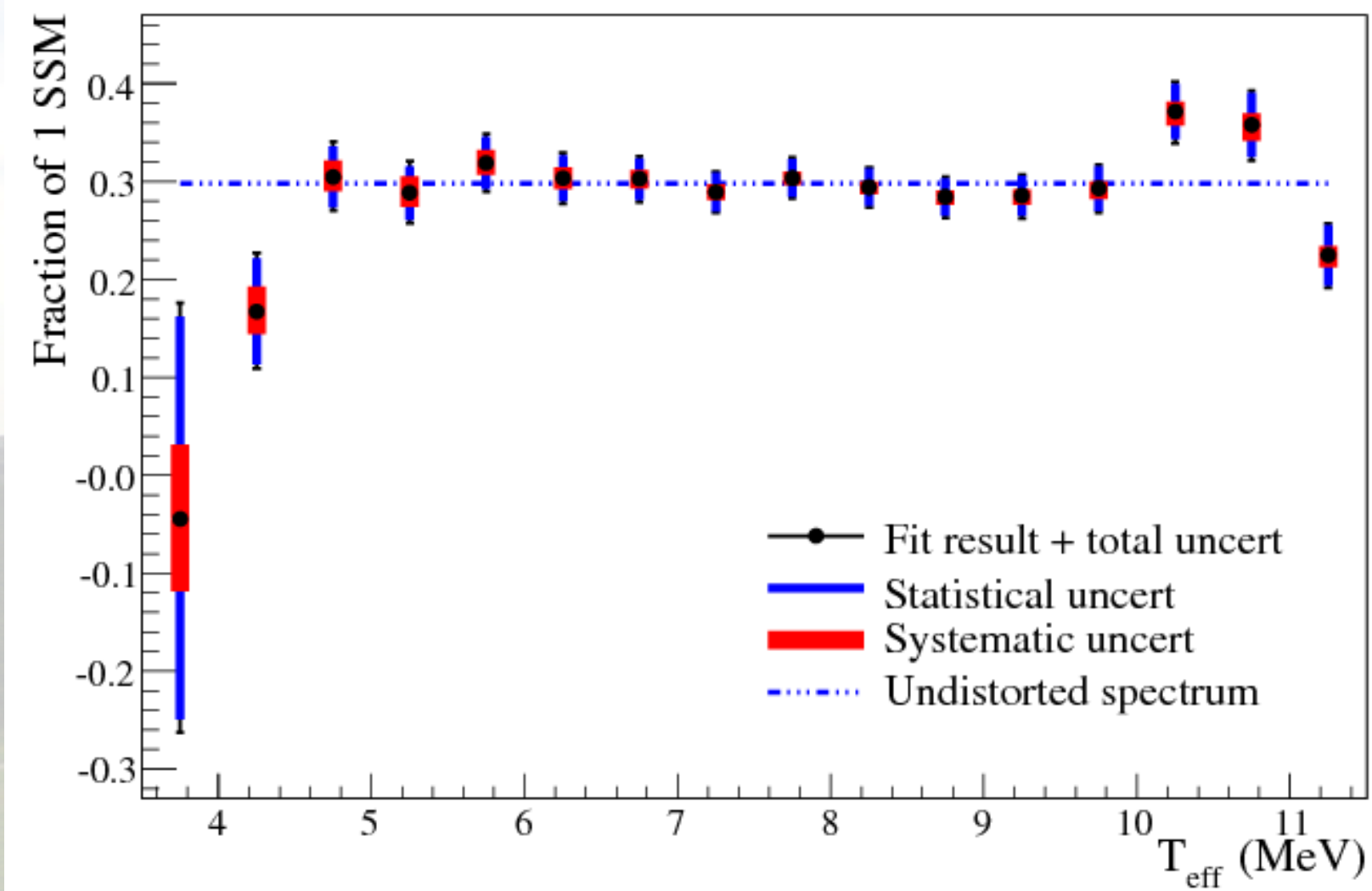


$\chi^2 = 13.6 / 16$

Fit Result



CC Recoil-Electron Spectrum



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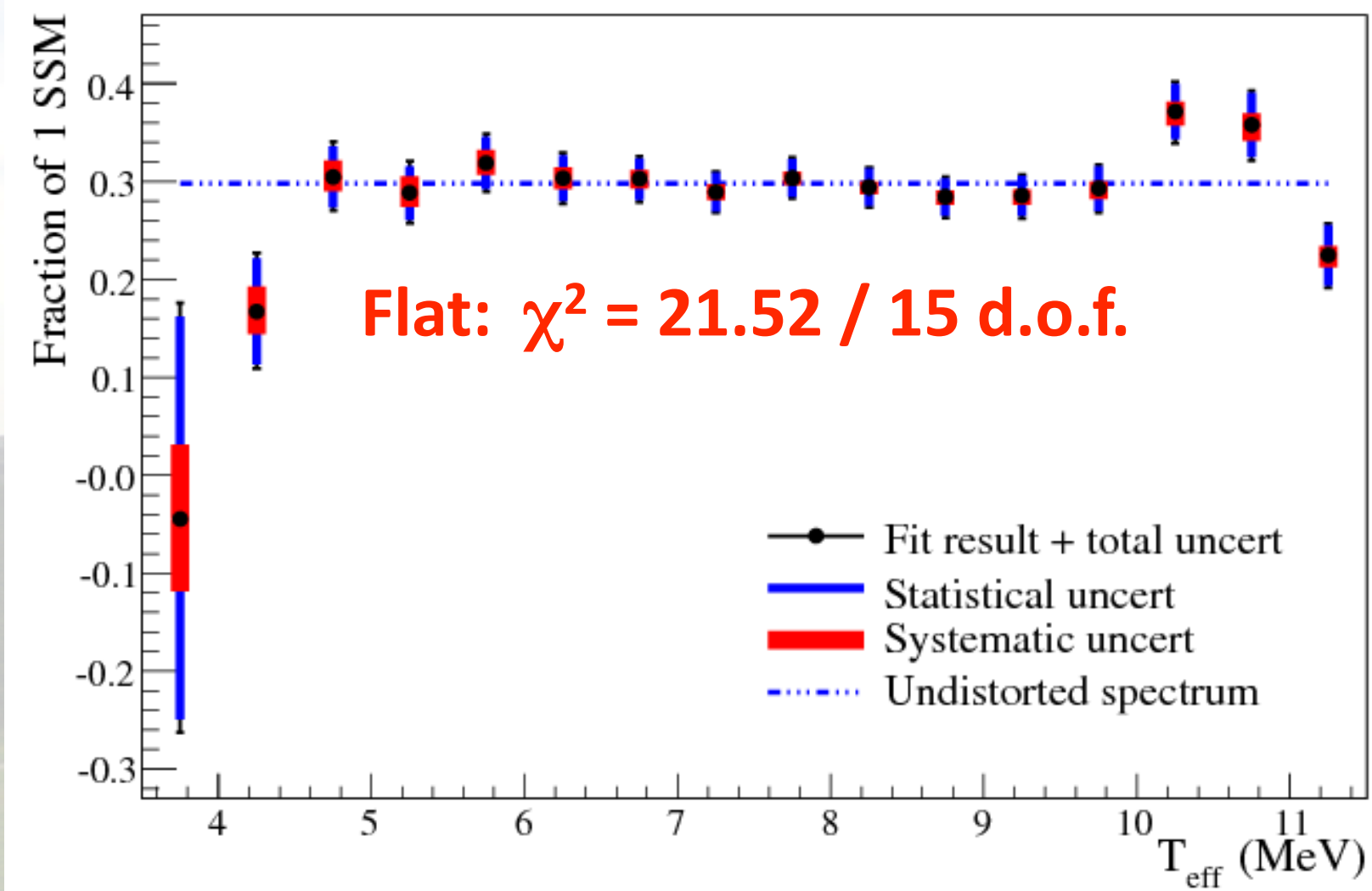

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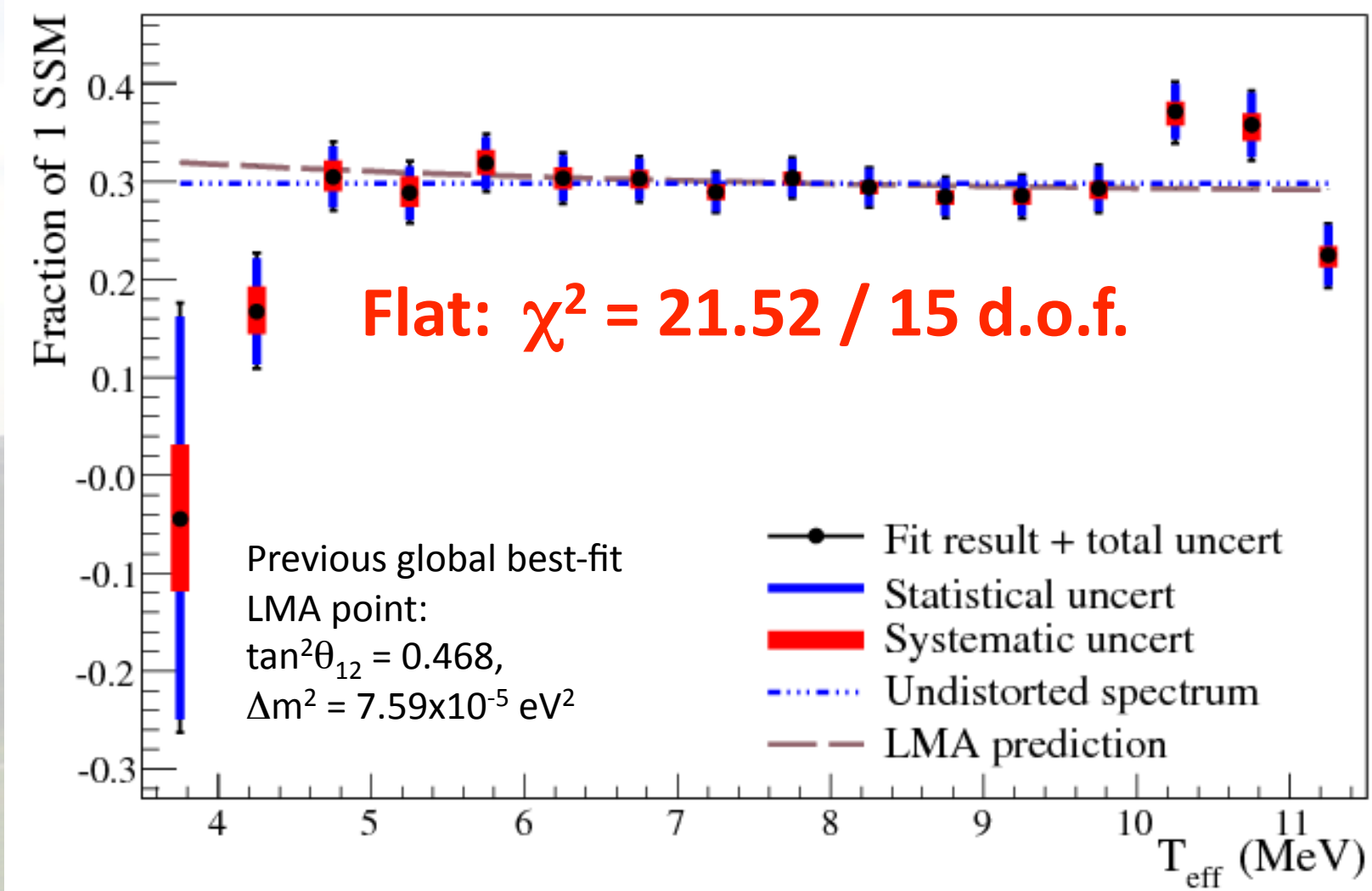
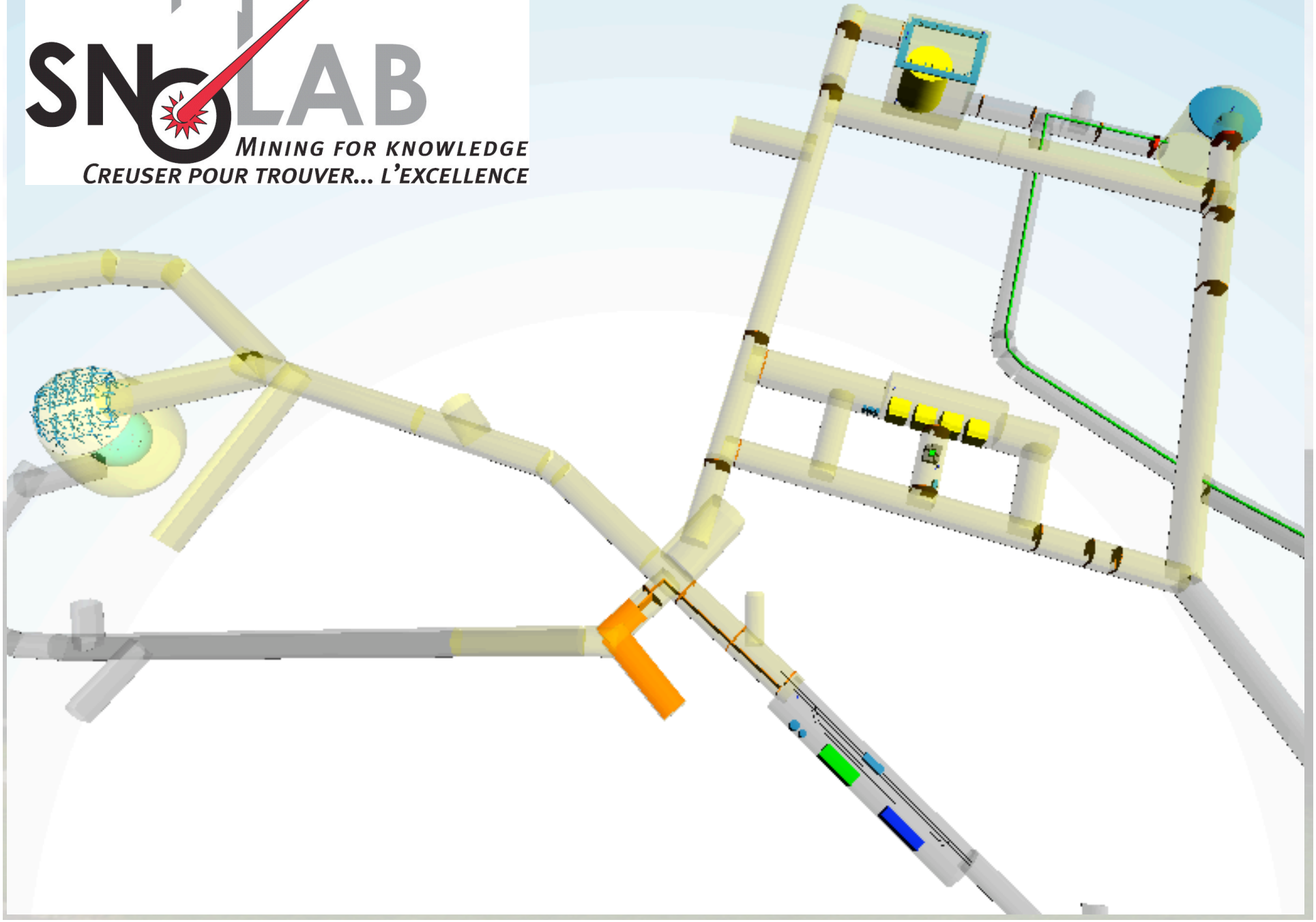


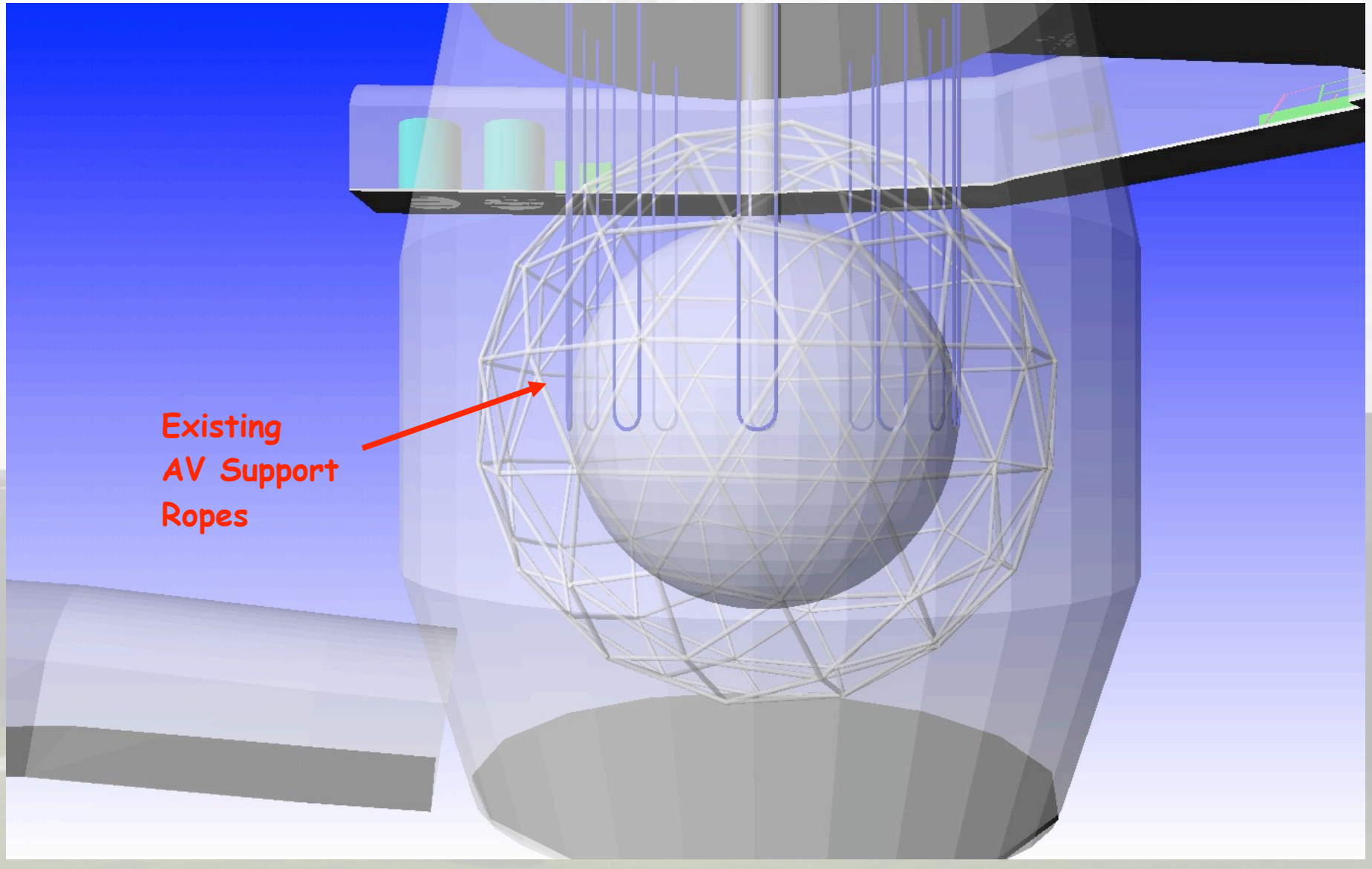
SNOLAB

MINING FOR KNOWLEDGE

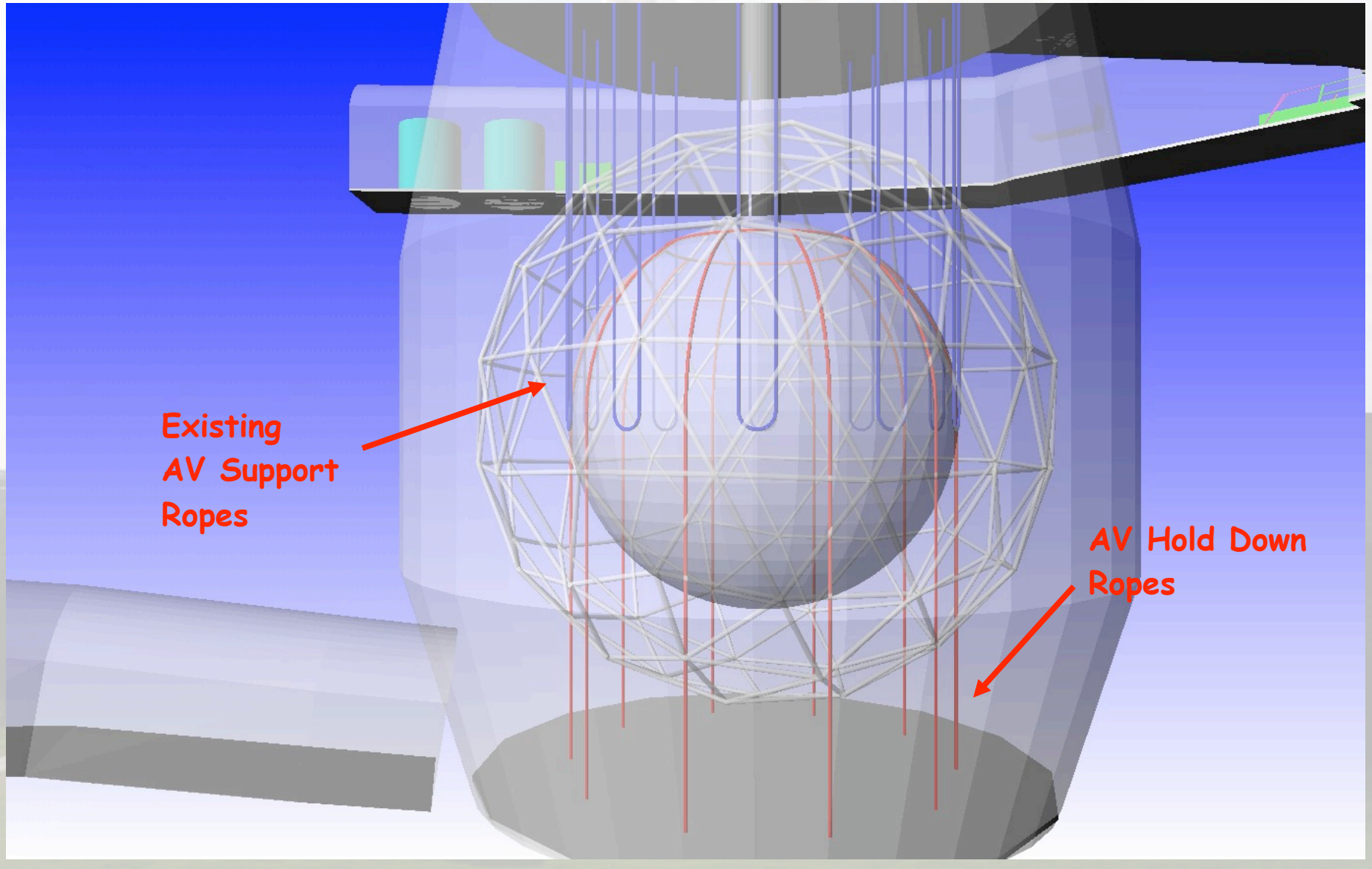
CREUSER POUR TROUVER... L'EXCELLENCE



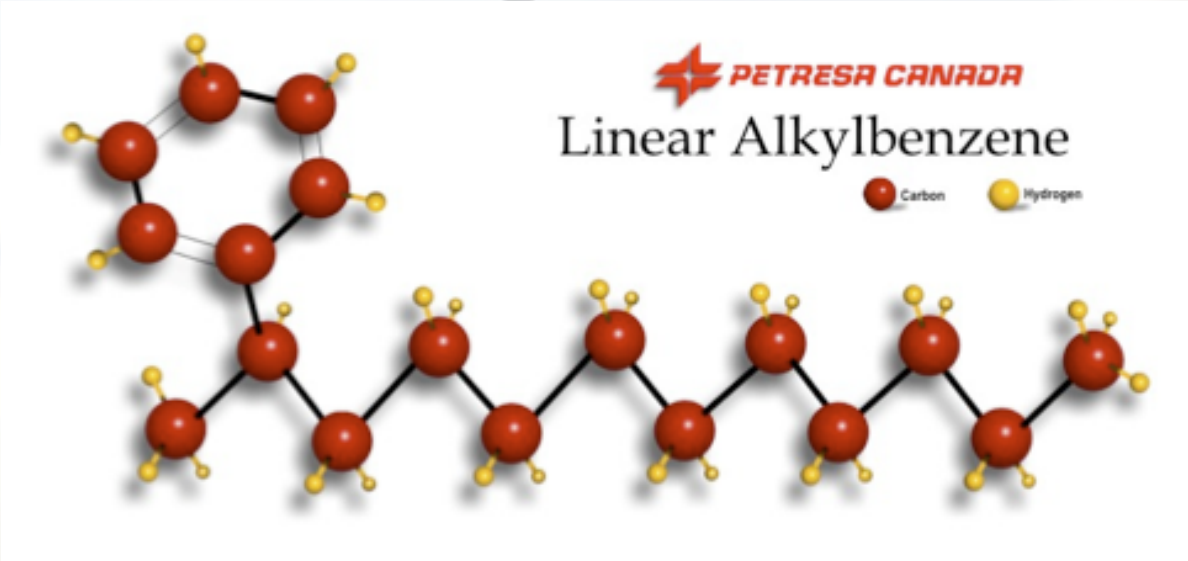
SNO…



...To SNO+



SNO+ Liquid scintillator



- Cheap
- Safe
- Compatible with SNO acrylic
- + PPO fluor ➡
- Good light yield: ~400 PMT hits / MeV

Physics goals

- Pep solar neutrinos
- Neutrino-less double beta decay of ^{150}Nd
- Reactor neutrinos
- Geo-neutrinos
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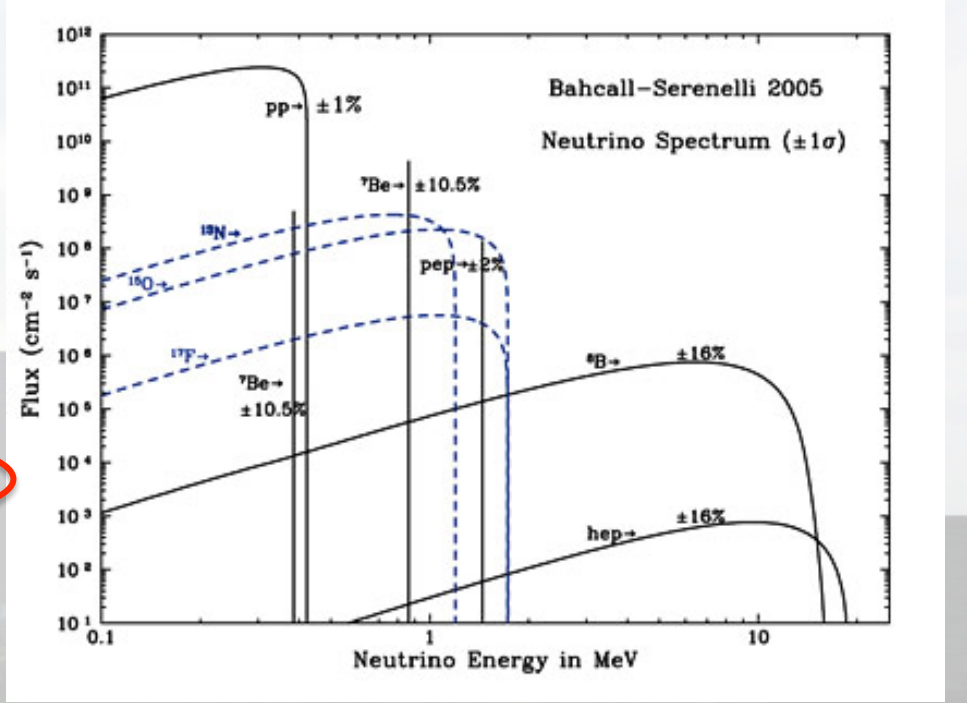
Low Energy Solar Neutrinos

- complete our understanding of neutrinos from the Sun

  pep, CNO, ^{7}Be, pp



p-p Solar Fusion Chain

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

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

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

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

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

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

CNO Cycle

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

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

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

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

Why *pep* Solar Neutrinos?

SSM pep flux:

uncertainty ±1.5%

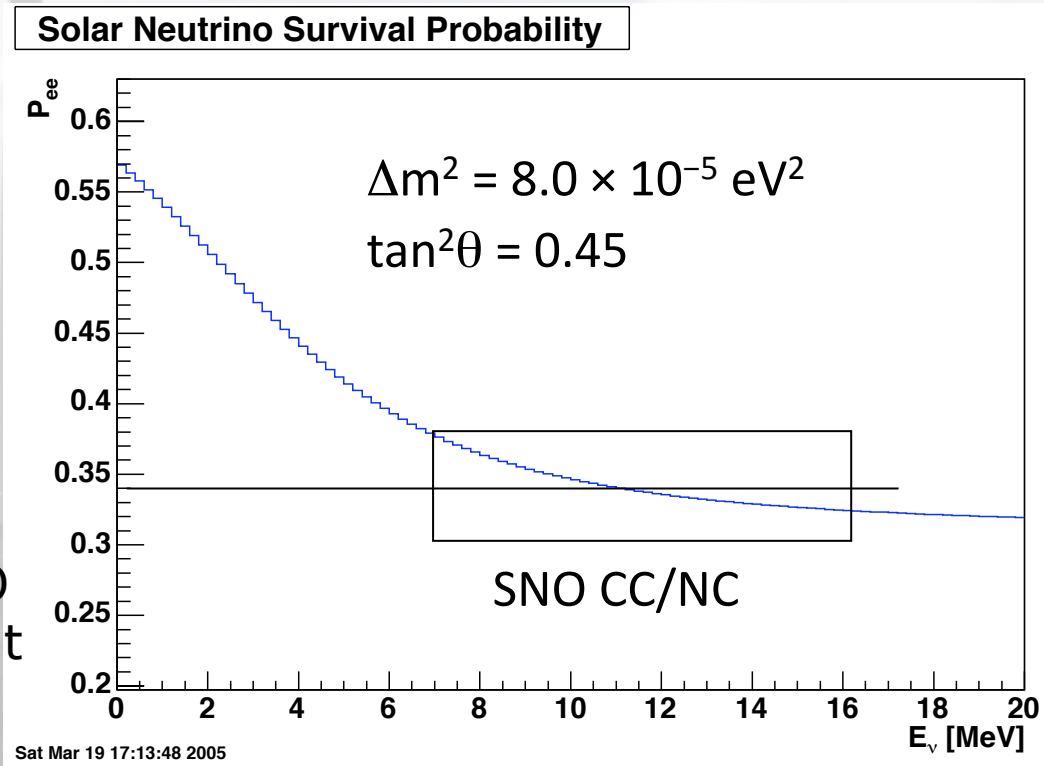
known source

known cross section (ν-e scattering)

→ measuring the rate gives the survival probability

→ **precision test**

for neutrino physics with low energy solar neutrinos, have to achieve precision similar to SNO or better…it's no longer sufficient to just detect the neutrinos



pep solar neutrinos:

E_ν = 1.44 MeV

…are at the right energy to search for new physics

observing the rise confirms MSW and our understanding of solar neutrinos

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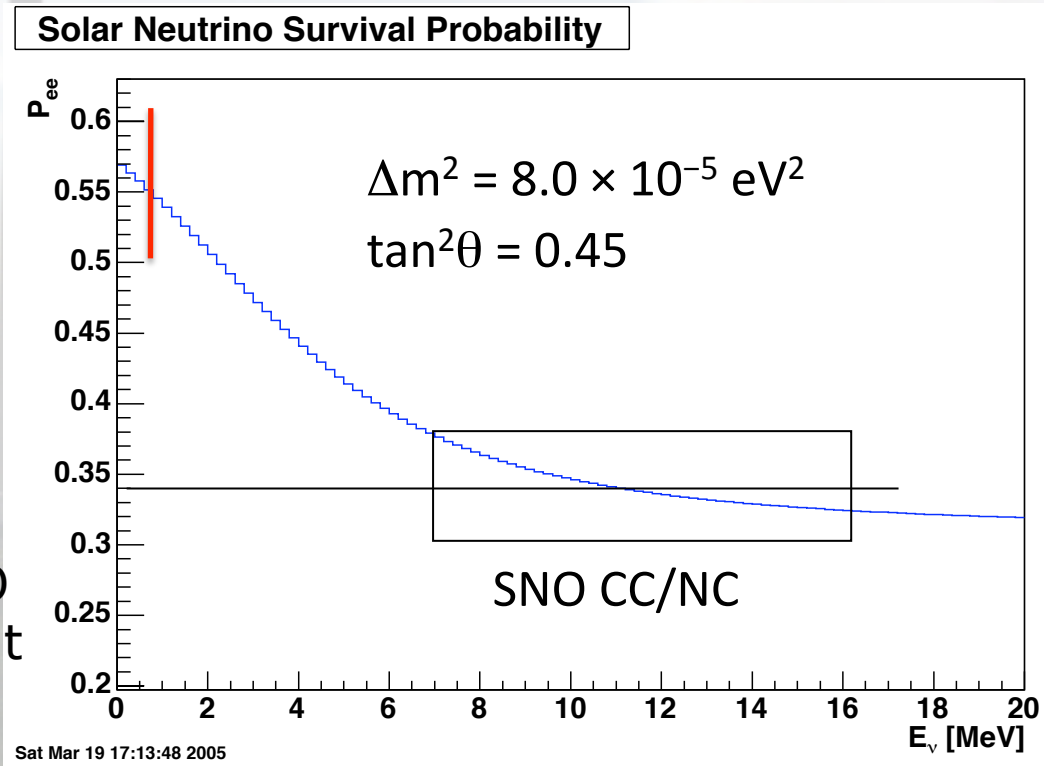

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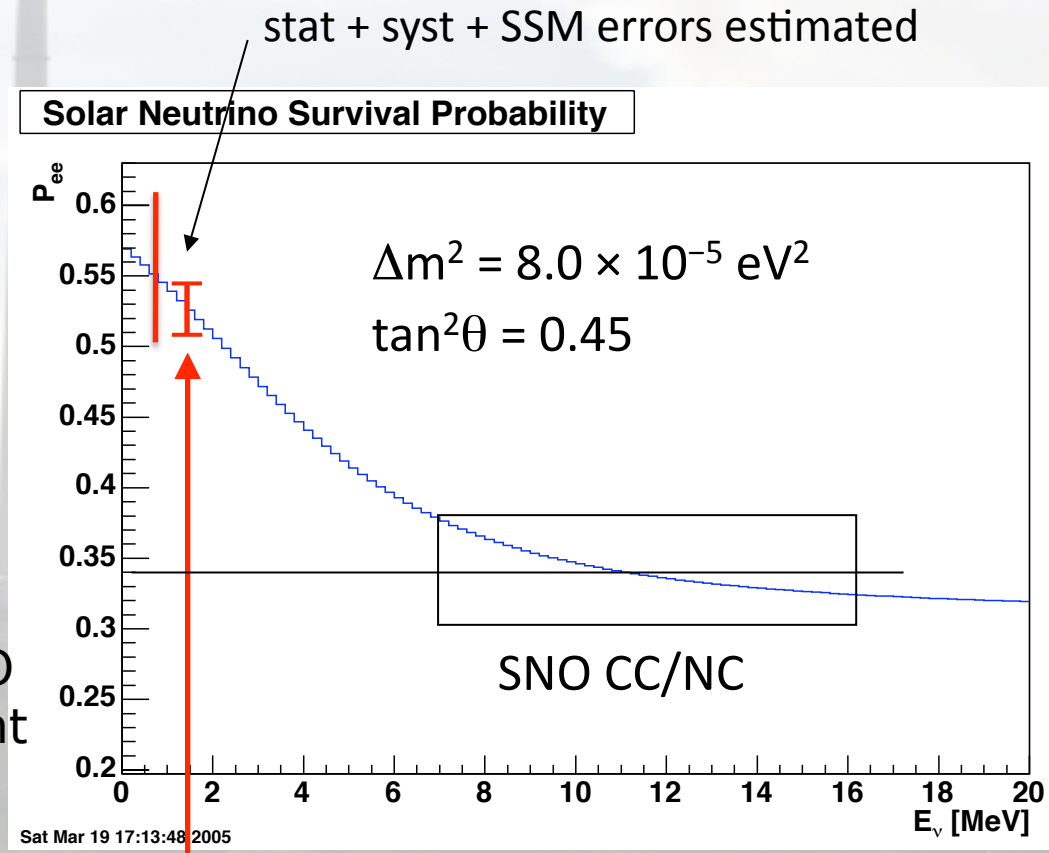

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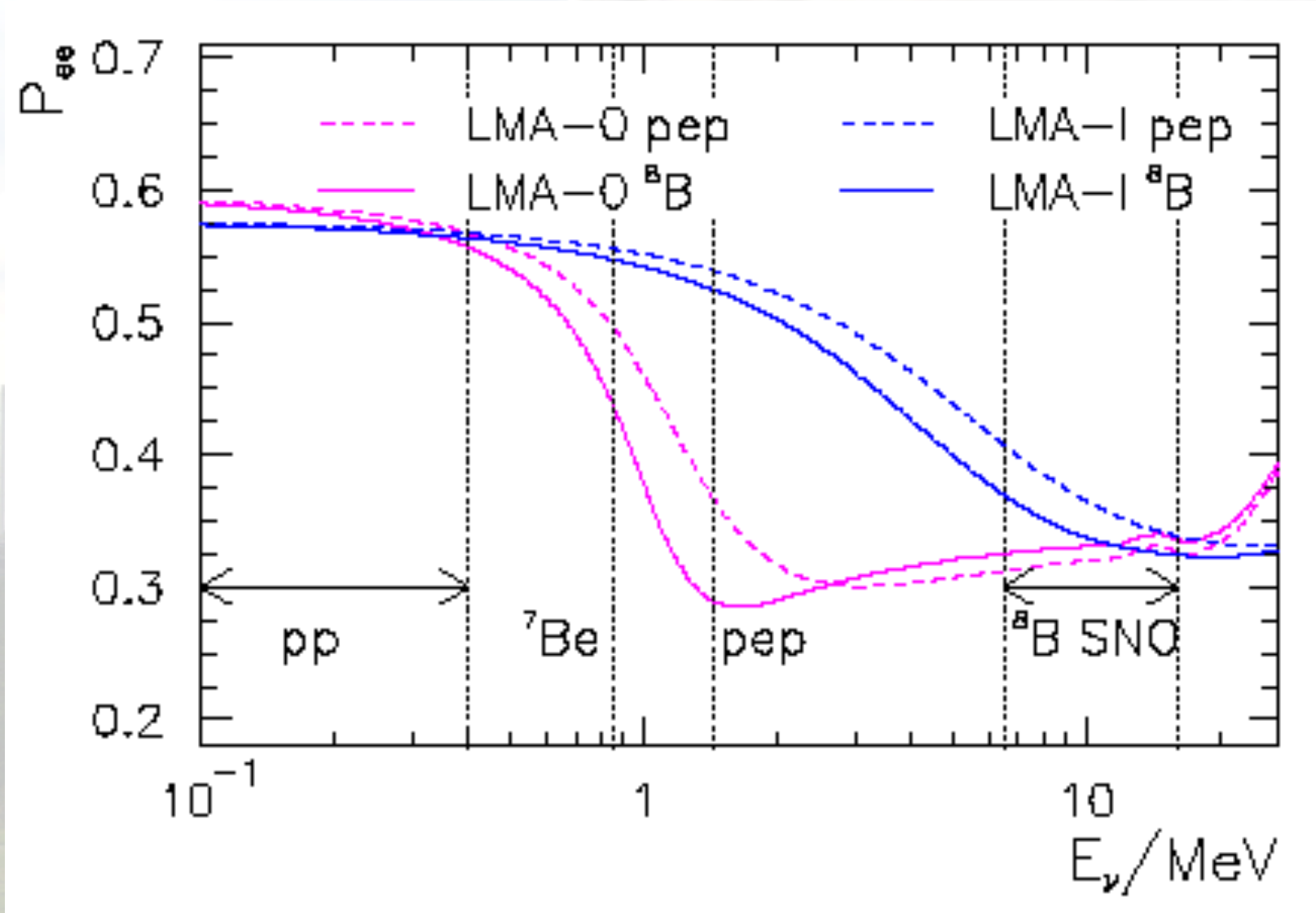


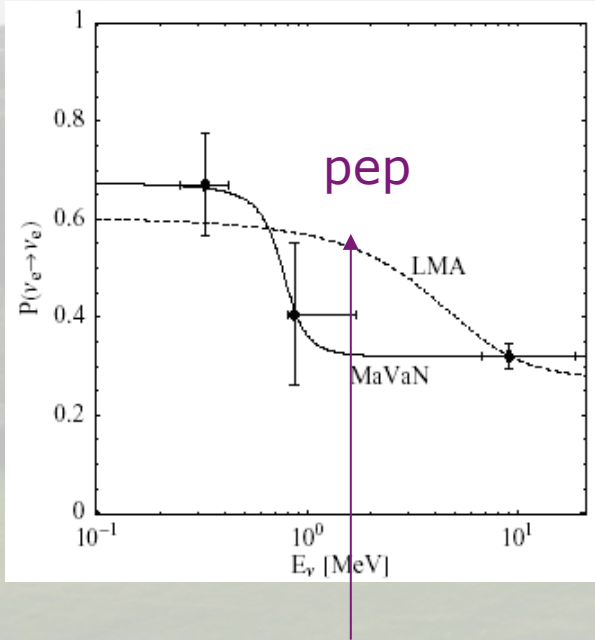
Peña-Garay, Phys. Lett. B, **594**, 347, (2004)

Mass-Varying Neutrinos

- cosmological connection: mass scale of neutrinos and the mass scale of dark energy are similar
- postulating a scalar field and neutrino coupling results in neutrinos whose mass varies with the background field (e.g. of other neutrinos)

- solar neutrinos affected?
- *pep ν: a* sensitive probe

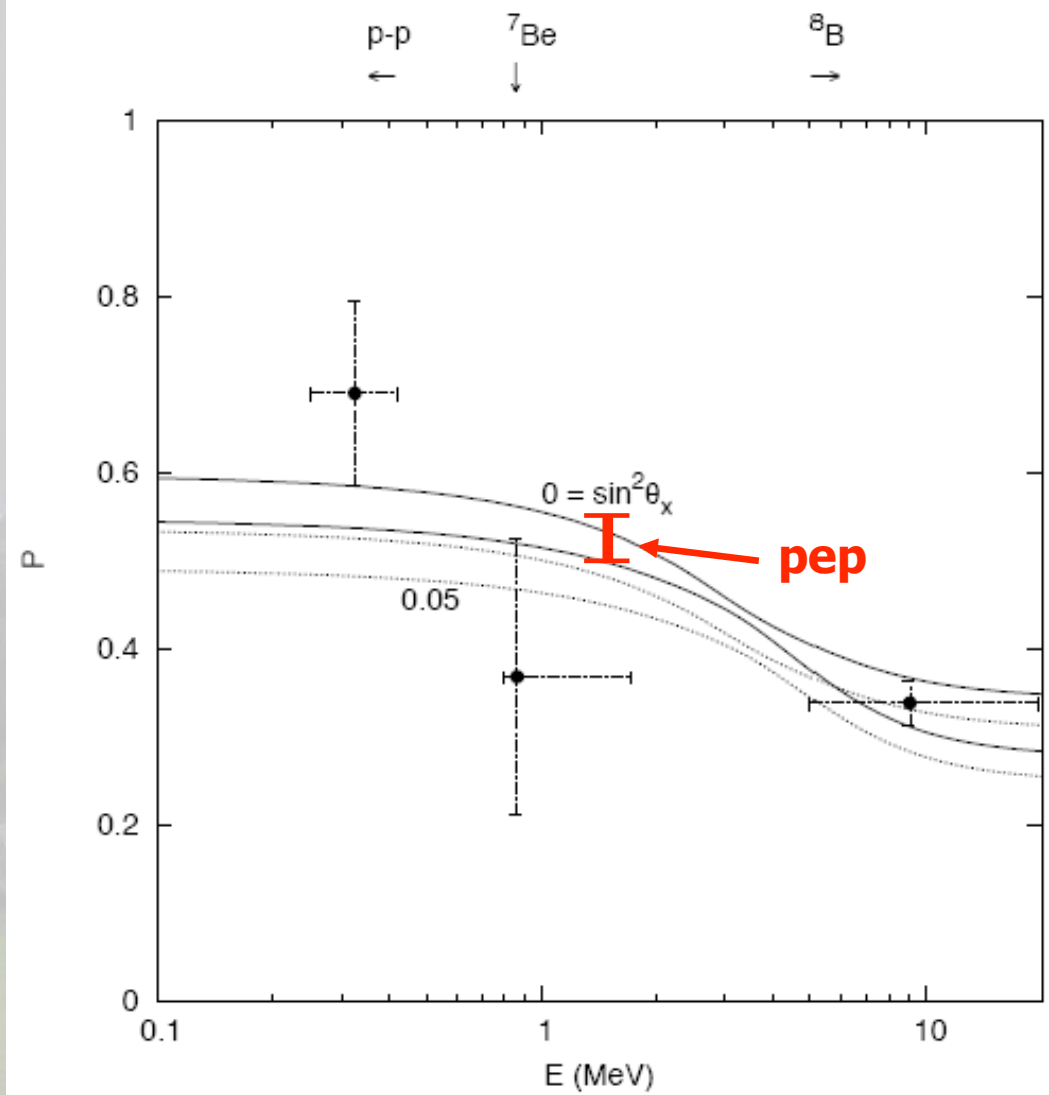
Fardon, Nelson, Weiner, hep-ph/0309800



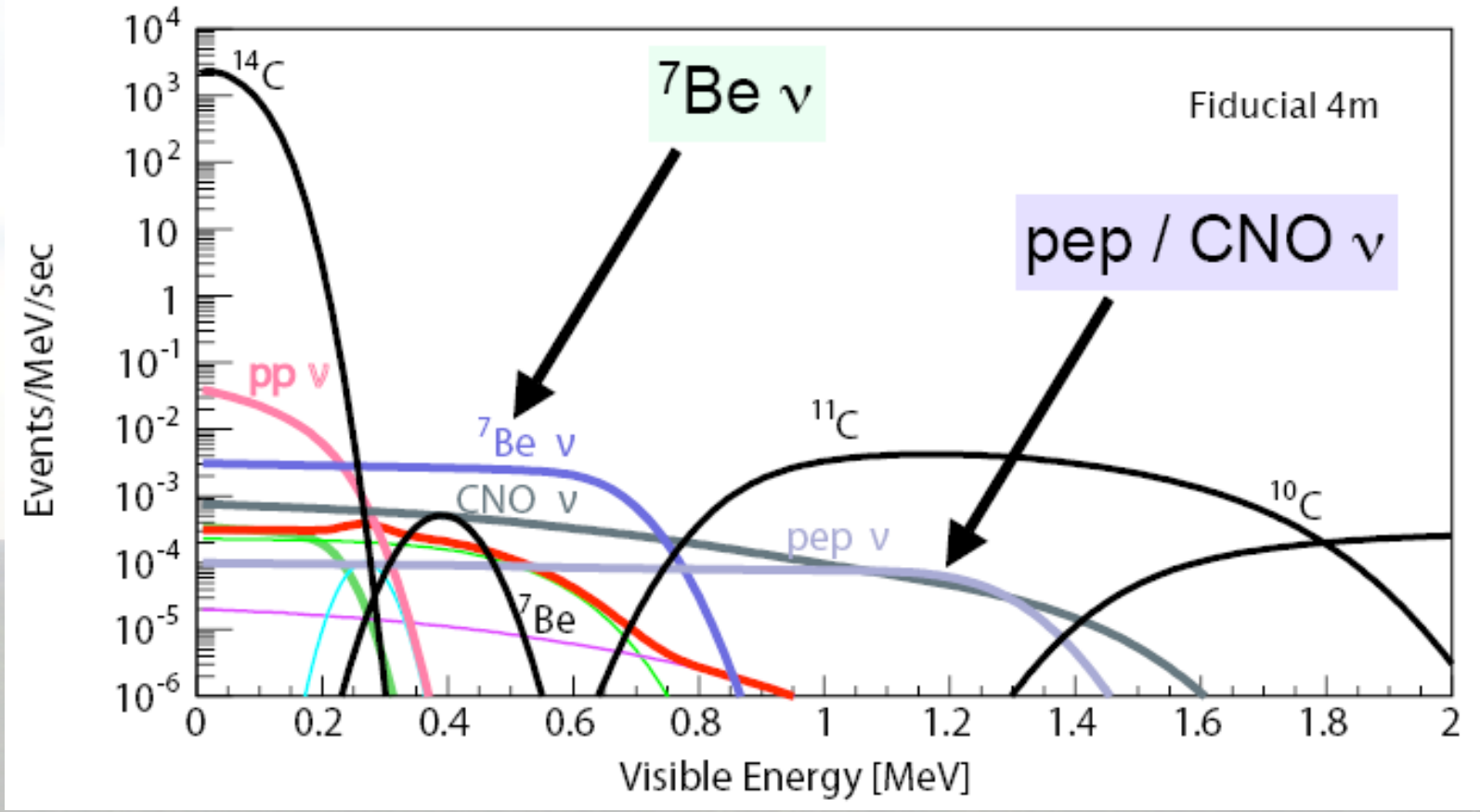
Barger, Huber, Marfatia, hep-ph/0502196

pep ν and θ_{13}

- solar neutrinos are complementary to long baseline and reactor experiments for θ_{13}
- hypothetical 5% stat. 3% syst. 1.5% SSM measurement
- has discriminating power for θ_{13}

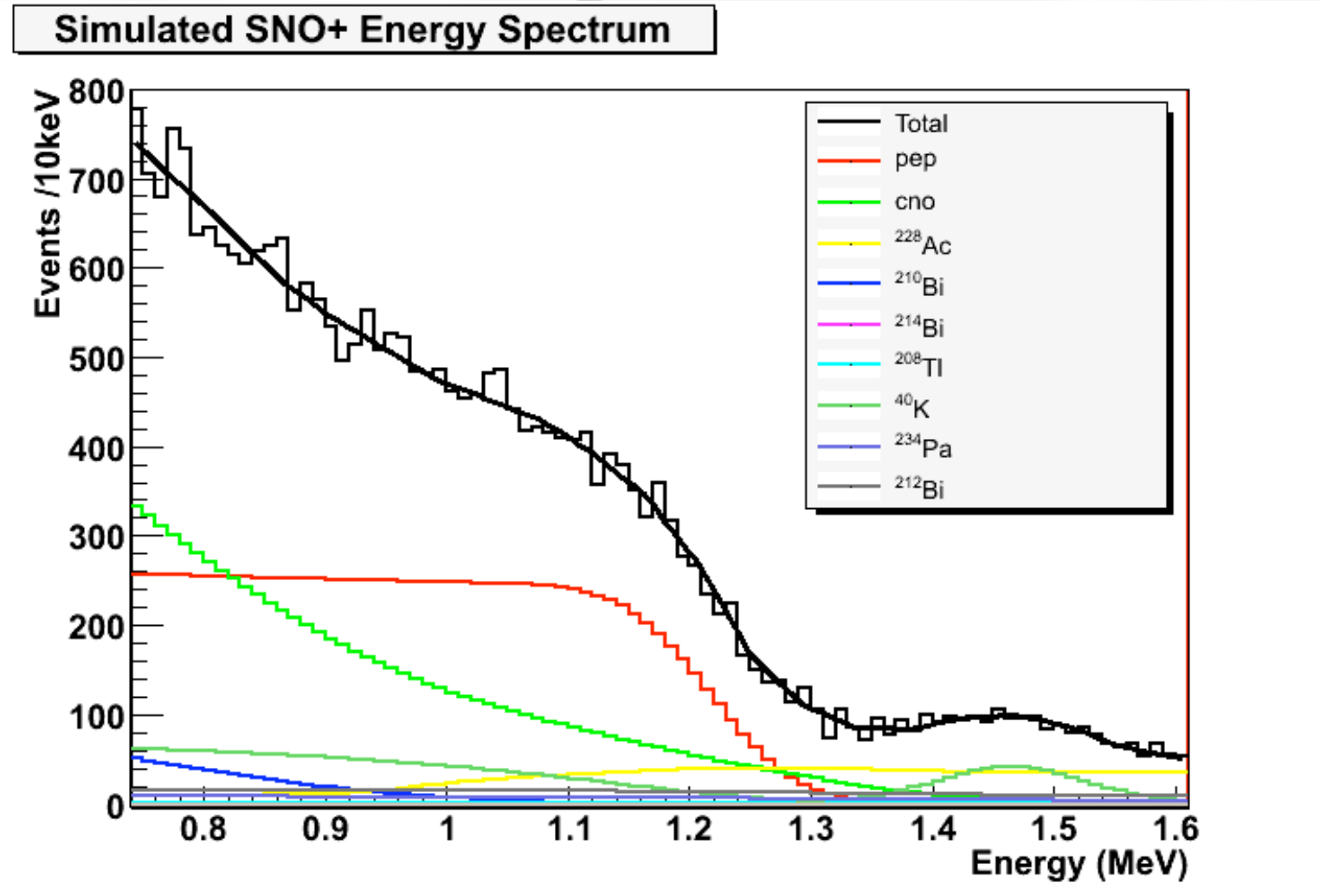


Why don't others measure pep?



- SNO+ at 6000mwe
- Muon flux factor 800 less than KamLAND (factor 100 less than Borexino)

SNO+ *pep* Solar Neutrino Signal



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

Physics goals

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- Neutrino-less double beta decay of ^{150}Nd
- Reactor neutrinos
- Geo-neutrinos
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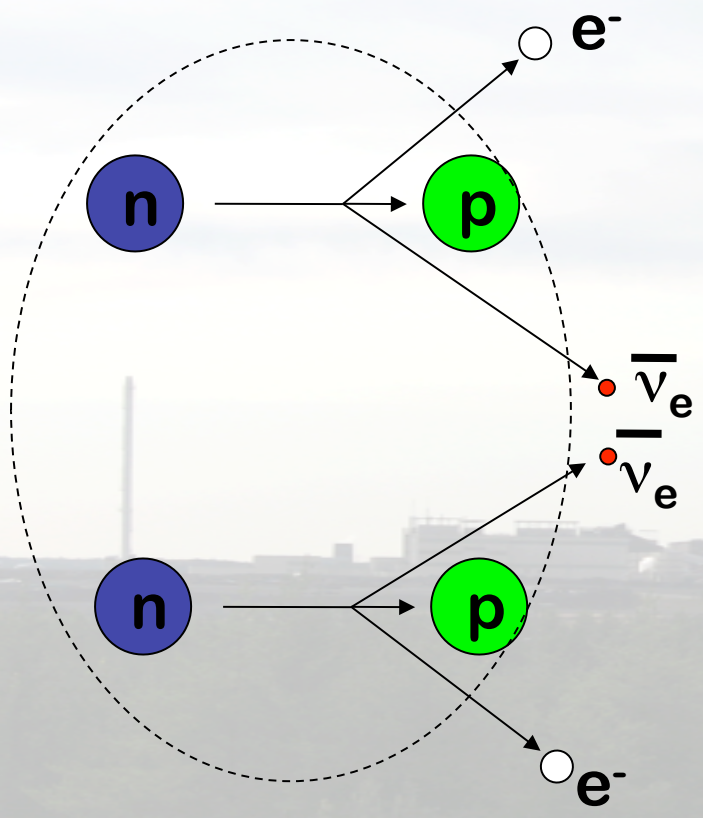
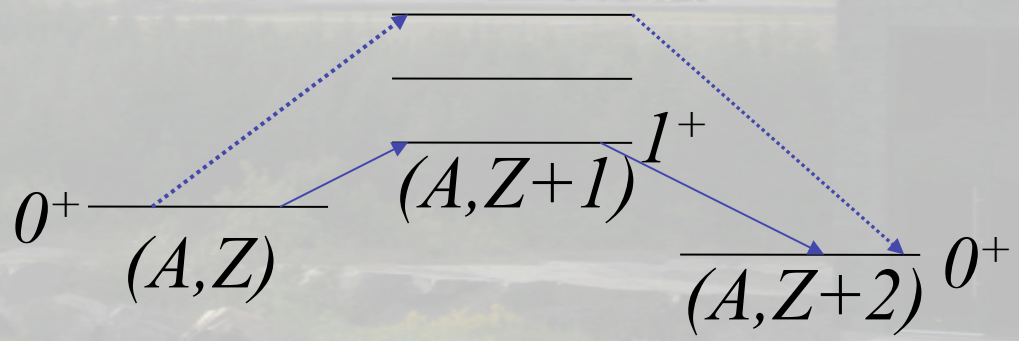
Double Beta Decay ($2\nu\beta\beta$)

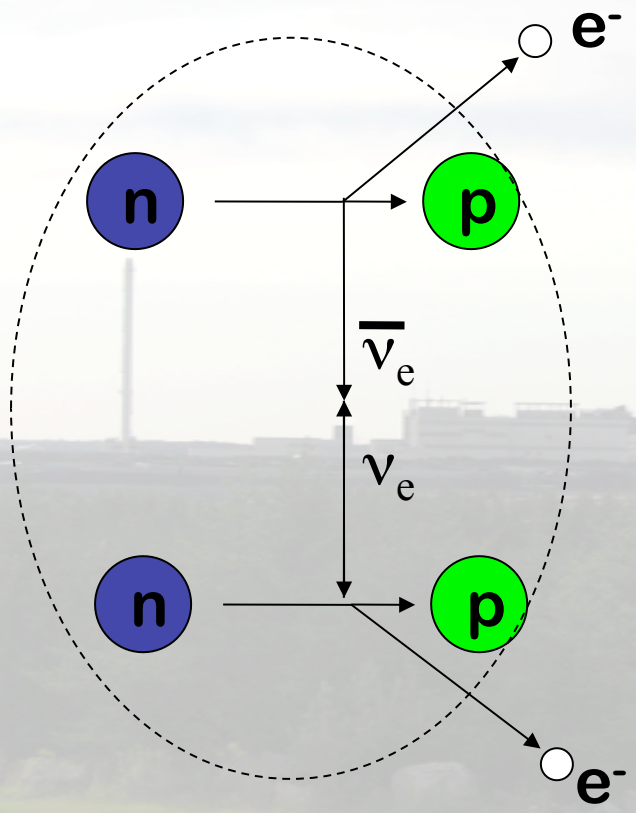


$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e$



Only 35 isotopes known in nature

Neutrinoless mode ($0\nu\beta\beta$)

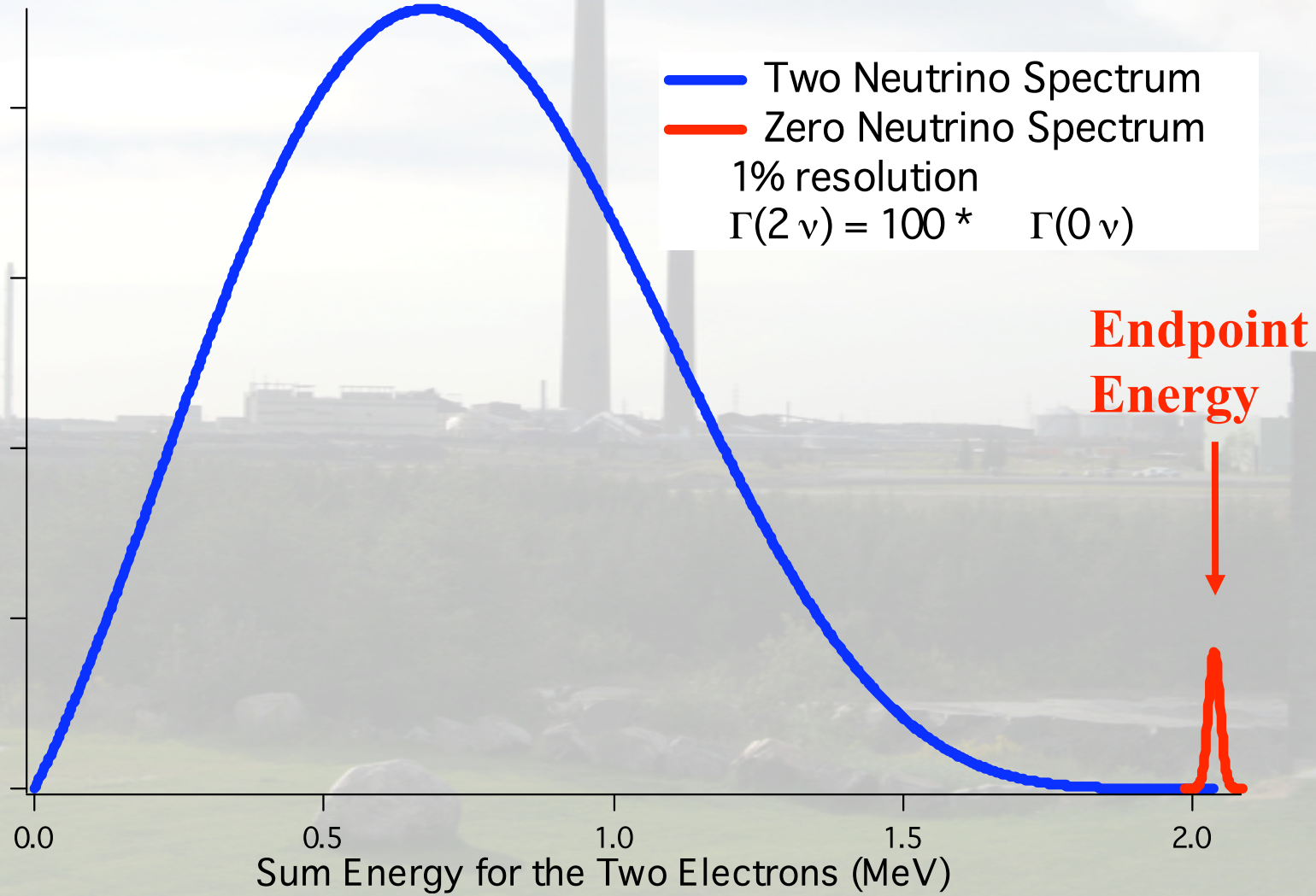


$$\Delta L = 2$$

$$(A,Z) \rightarrow (A,Z+2) + 2\ e^-$$

- Can only occur for Majorana neutrinos
- Rate proportional to absolute neutrino mass scale

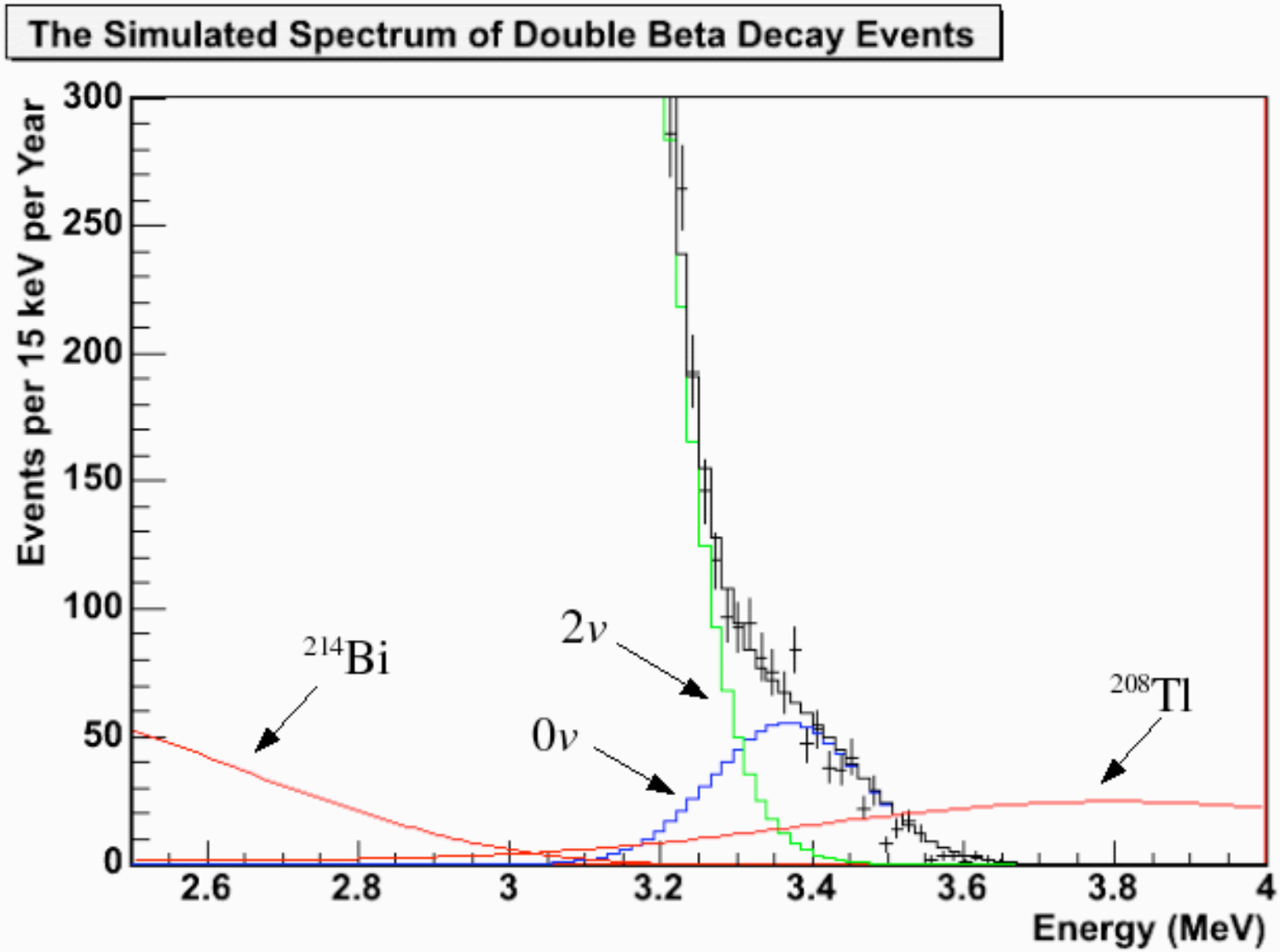
ββ Decay


Two Neutrino Spectrum
Zero Neutrino Spectrum
1% resolution
Γ(2 ν) = 100 * Γ(0 ν)
Endpoint Energy
0.0
0.5
1.0
1.5
2.0
Sum Energy for the Two Electrons (MeV)

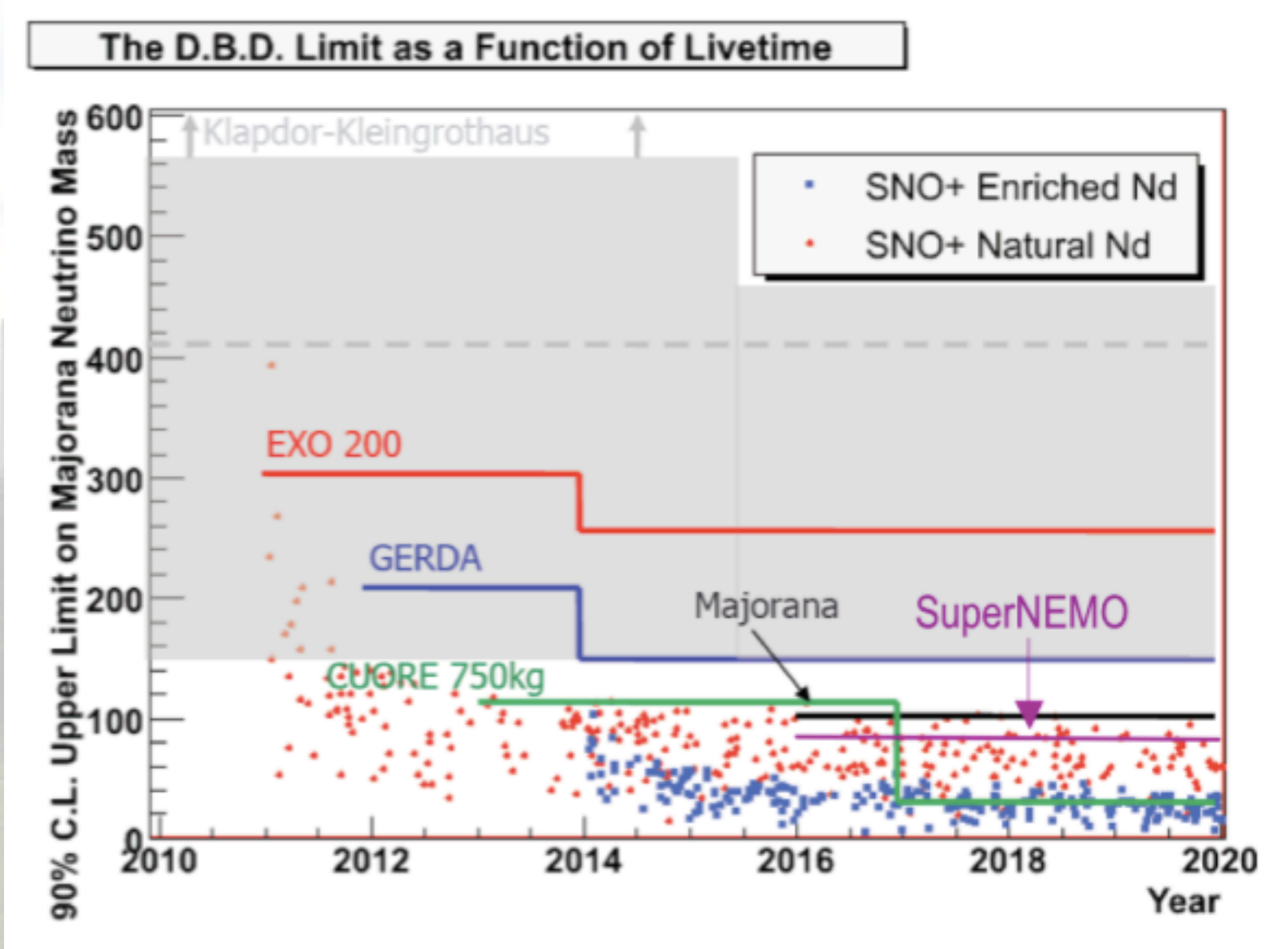
SNO+ Double Beta Decay

- ^{150}Nd
  - Q = 3.37MeV
  - large phase space, fast rate
  - 5.6% natural abundance, enrichment possible
- Large, homogeneous liquid detector leads to well-defined background model
- Source in–source out capability
- Poor energy resolution but high statistics

0νββ in SNO+

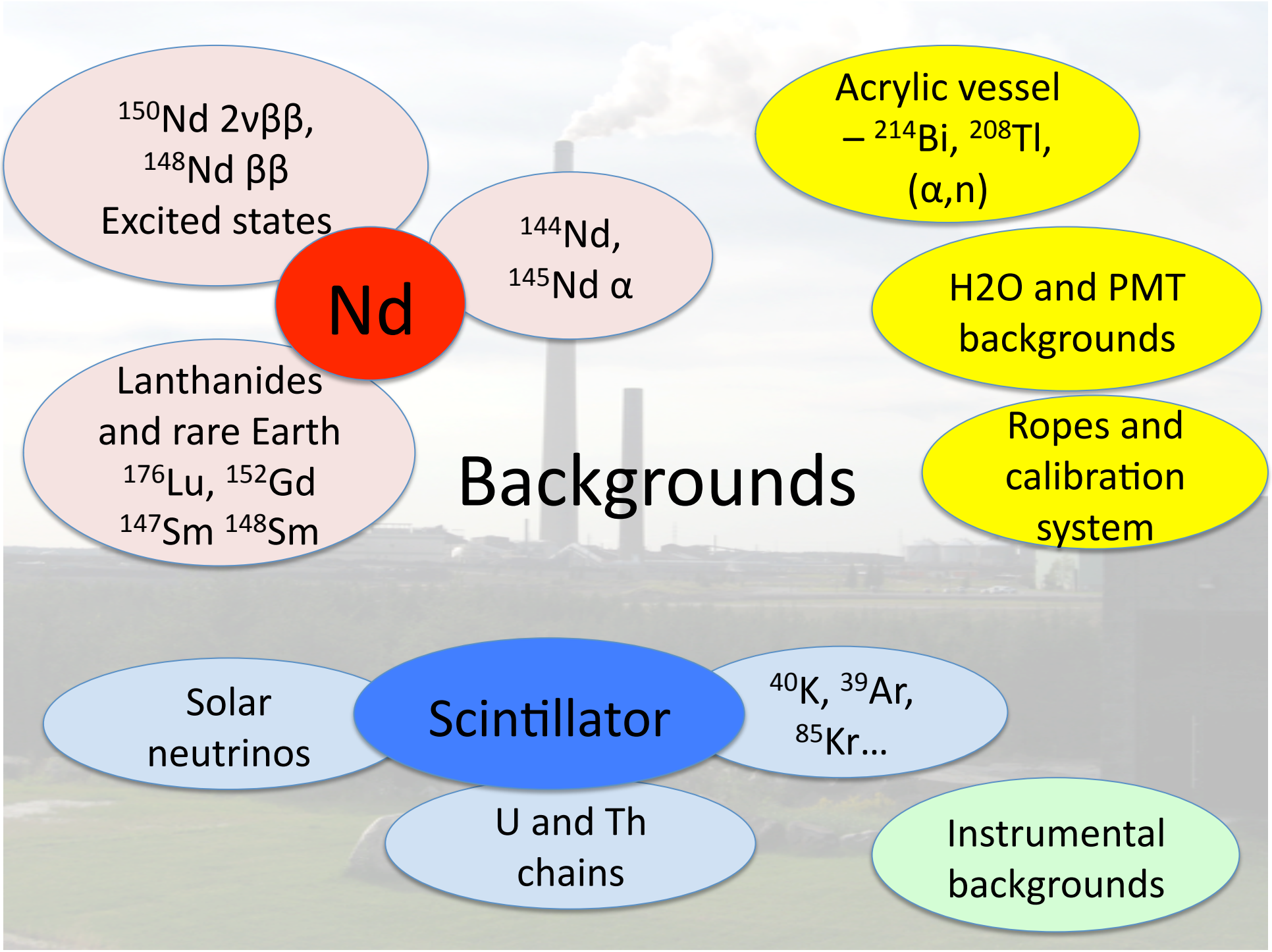

The Simulated Spectrum of Double Beta Decay Events
Events per 15 keV per Year
300
250
200
150
100
50
0
2.6
2.8
3
3.2
3.4
3.6
3.8
4
Energy (MeV)
214Bi
2ν
0ν
208Tl

SNO+ sensitivity



Future sensitivity

- Nd enrichment is difficult
  - AVLIS – French facility not available ☹
  - Single Photon Atomic Sorting: Isotope Separation with Maxwell's Demon **arXiv:1001.0944**
- Different isotopes
  - ^{96}Zr, ^{100}Mo
- Nanoparticles
  - Different absorption characteristics – higher loading


^{150}Nd 2νββ,
^{148}Nd ββ
Excited states
^{144}Nd,
^{145}Nd α
Nd
Lanthanides
and rare Earth
^{176}Lu, ^{152}Gd
^{147}Sm ^{148}Sm
Acrylic vessel
– ^{214}Bi, ^{208}Tl,
(α,n)
H2O and PMT
backgrounds
Ropes and
calibration
system
Backgrounds
Solar
neutrinos
Scintillator
^{40}K, ^{39}Ar,
^{85}Kr…
U and Th
chains
Instrumental
backgrounds

Pure source of Nd

Source	Sample mass (g)	Name of supplier	Stated purity (%)	Date counted	^{138}La (μg La/g Nd)	^{176}Lu (μg Lu/g Nd)	^{40}K (μg K/g Nd)
$NdCl_3$	1811.3	Hefa	~99	080225	513 ± 32	3.4 ± 0.3	6.3 ± 1.1
Nd_2O_3	1794.7	Alfa	99.9	080319	21 ± 3	8.5 ± 1.4	14.0 ± 1.2
Nd_2O_3	24.80	Stanford	>99.95	080930	0 ± 19	0 ± 230	25 ± 6
Nd_2O_3	24.13	Stanford	>99.95	080827	0 ± 25	0 ± 460	18 ± 6
Nd_2O_3	65.53	Stanford	Not given	080922	175 ± 42	0 ± 1700	12 ± 5
Nd_2O_3	73.90	Stanford	Not given	080926	240 ± 40	0 ± 1500	4.5 ± 3.0
Nd_2O_3	359.2	Nanoproducts	99.9	091015	61 ± 14	0.07 ± 0.08	9.5 ± 2.4
Nd_2O_3	997.8	Metall	99.999	091117	< 0.24	0.15 ± 0.01	0.39 ± 0.22
Tolerable					0.5	0.1	~0.08

Source	Sample mass (g)	Name of supplier	Stated purity (%)	Date counted	^{227}Ac (μBq/g Nd)	^{214}Bi (μBq/g Nd)	^{212}Bi (μBq/g Nd)
$NdCl_3$	1811.3	Hefa	~99	080225	193 ± 20	19.7 ± 3.9	189 ± 10
Nd_2O_3	1794.7	Alfa	99.9	080319	873 ± 47	17.0 ± 1.9	75 ± 5
Nd_2O_3	24.80	Stanford	>99.95	080930	1900 ± 100	0 ± 23	330 ± 60
Nd_2O_3	24.13	Stanford	>99.95	080827	2300 ± 100	9 ± 30	210 ± 50
Nd_2O_3	65.53	Stanford	Not given	080922	41000 ± 2500	250 ± 50	200 ± 50
Nd_2O_3	73.90	Stanford	Not given	080926	41000 ± 2500	40 ± 30	125 ± 40
Nd_2O_3	359.2	Nanoproducts	99.9	091015	120 ± 20	195 ± 16	570 ± 30
Nd_2O_3	997.8	Metall	99.999	091117	< 1.2	0.43 ± 0.56	3.4 ± 0.9
Tolerable					2.7	0.21	3.4×10^{-5}

Removing the U/Th

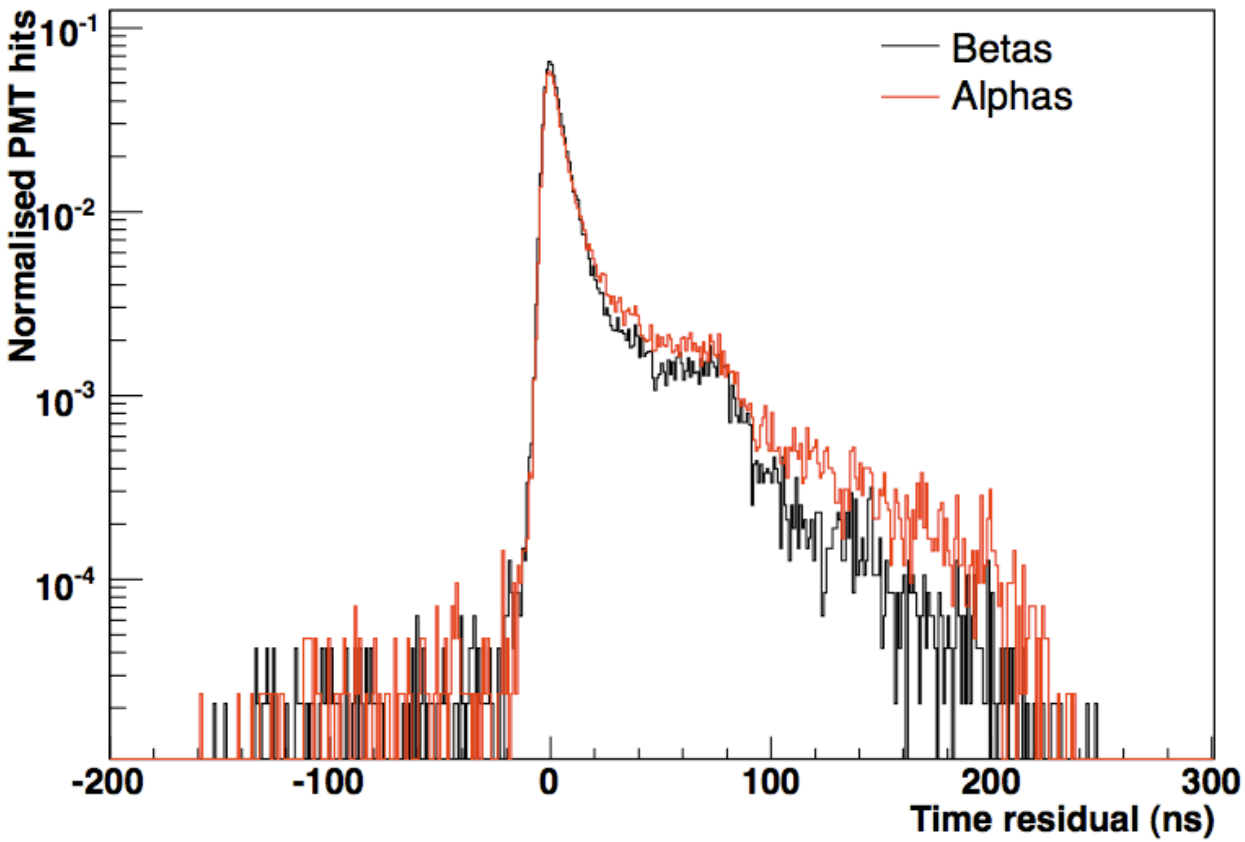
- $NdCl_3$ salt + BaCl + $(NH_4)2SO_4$
  - co-precipitate any Ra with BaSo4
- + HZrO
  - co-precipitate Th
  - reduction factor of 1000/pass
  - 2 passes gives 10^6 reduction and desired scintillator level of 10^{-17}gTh/gLAB.

Or … Self scavenging

- Th is more soluble than Nd at certain pH levels
- Dissolve salt in ultra-pure water at controlled pH
- Adjust pH – Th is removed (95 - 100%), Nd remains
- Can incorporate in existing Nd-LS production scheme

Alpha discrimination

- Alphas highly quenched – factor ~10
- More late light due to different excitation mode of scintillator by heavier particles

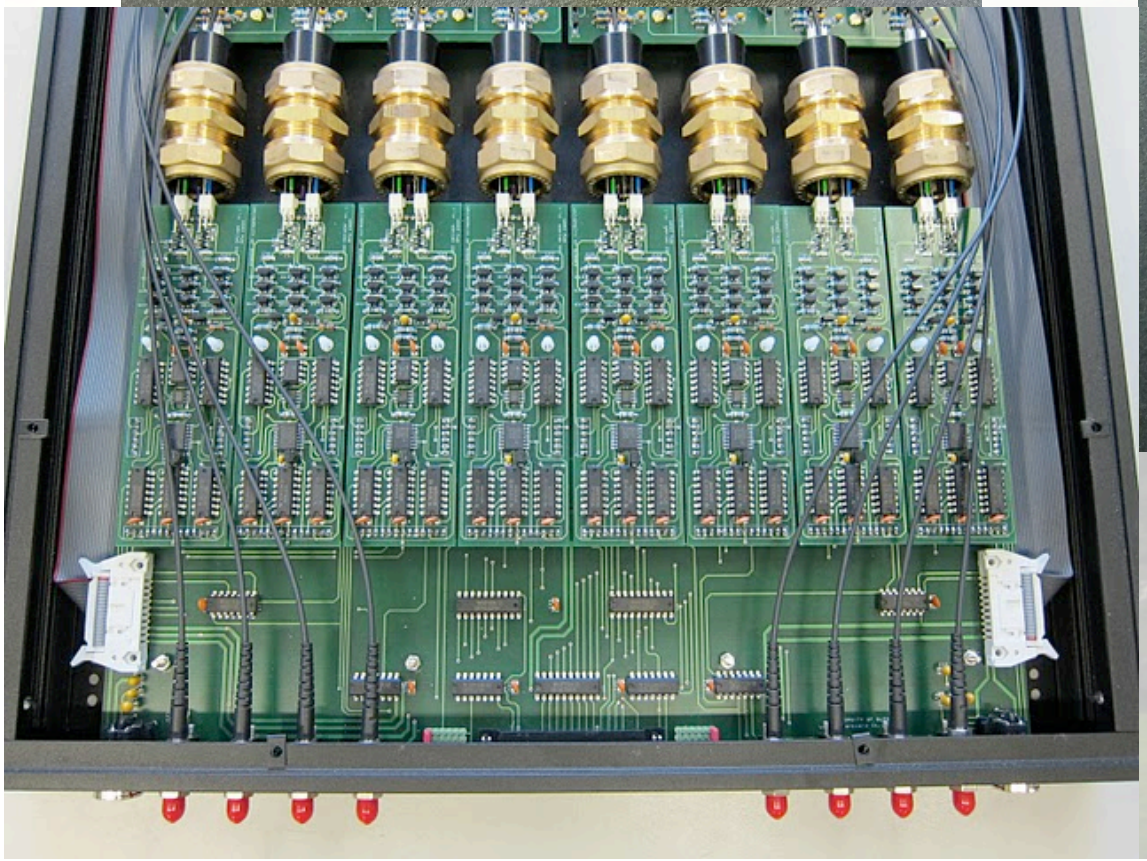


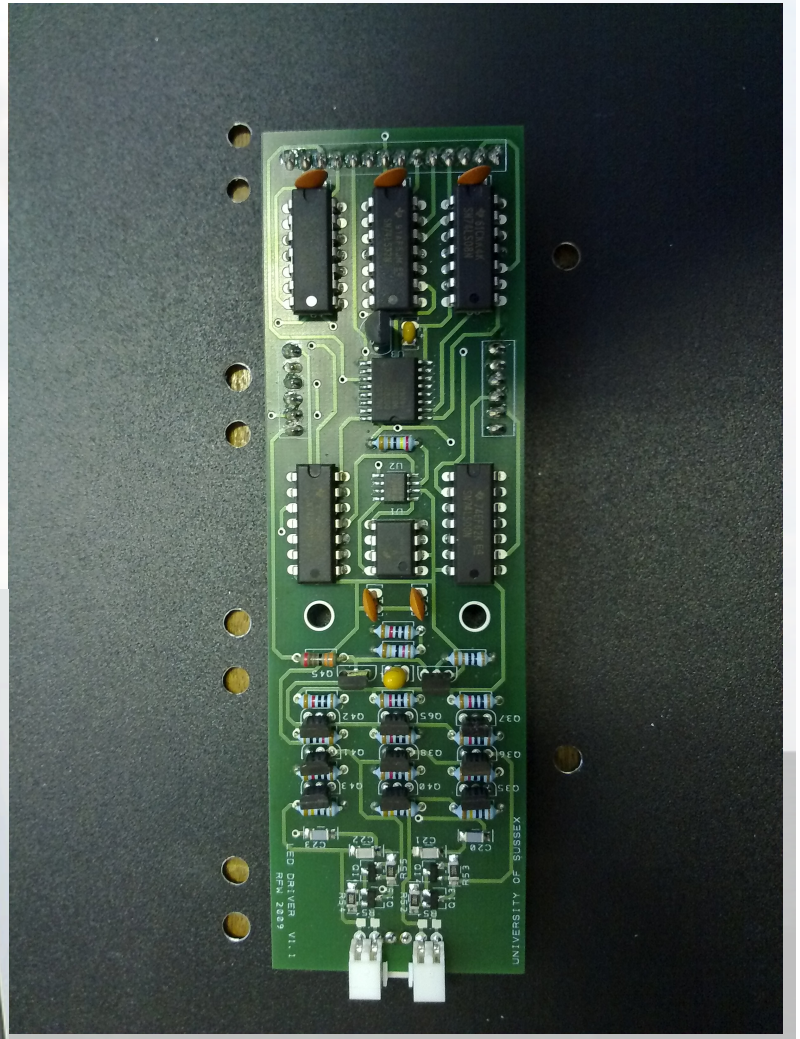
Pile-up rejection

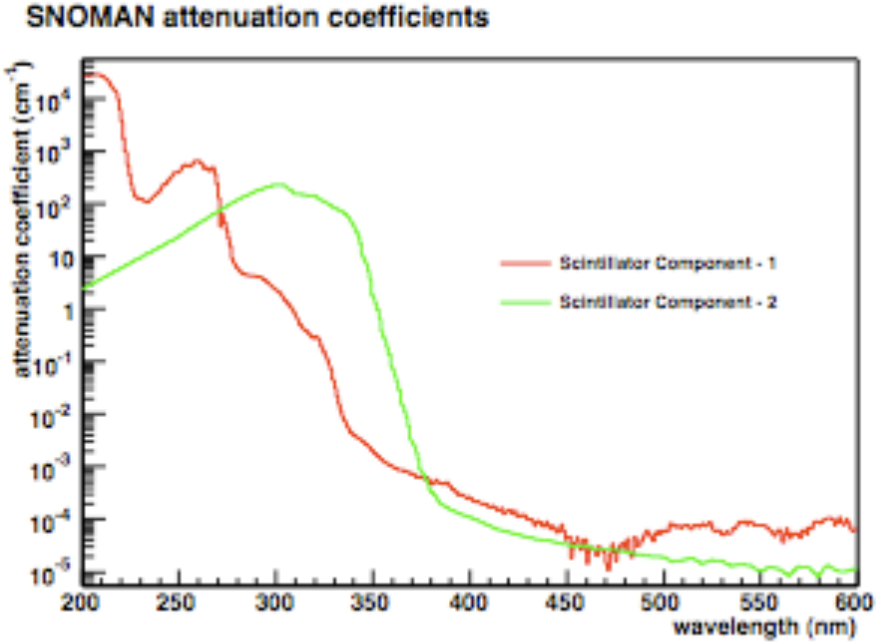
- Low energy backgrounds in coincidence with $2\nu\beta\beta$ could move event into $0\nu\beta\beta$ window
- Rejection criteria
  - Timing
  - Hit isotropy
  - Goodness of fit – single vs multiple vertex fitter

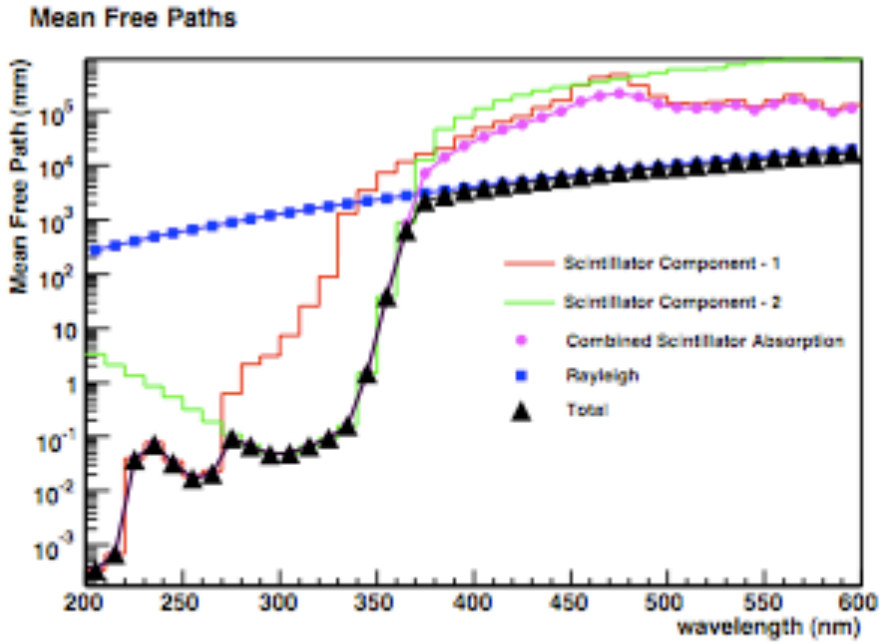
Calibration - ELLIE

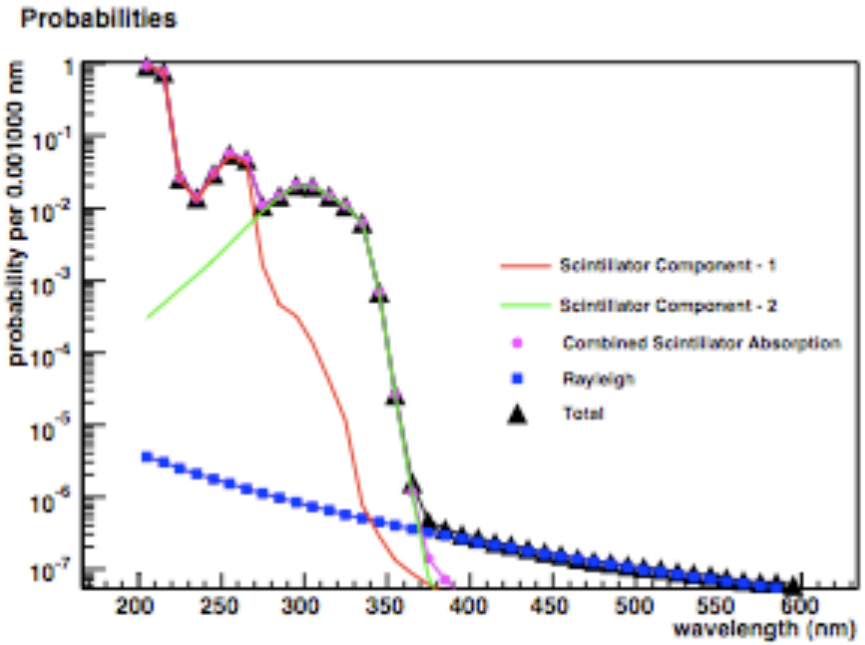
- **E**mbedded **L**ED **L**ight **I**njection **E**ntity
  - Timing calibration of PMTs
  - PMT response
  - Attenuation length
  - DAQ test (Supernova response)
  - Test for coincidence signals
- 91 light injection points on PMT support structure
- ~500nm, fast pulses, ~12 degree opening angle

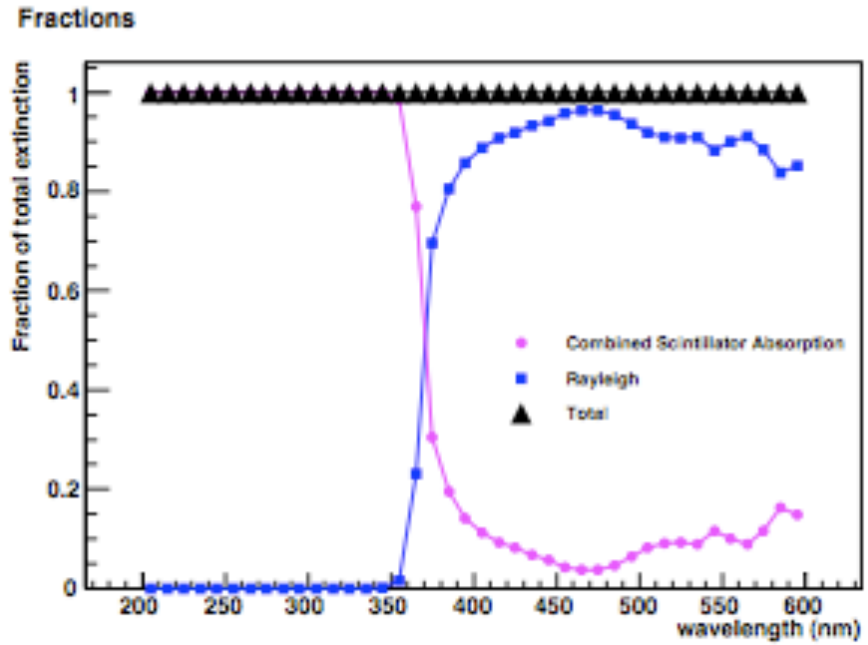



UNIVERSITY OF SUSSEX
LED DRIVER V1.1
RFK 2009


SNOMAN attenuation coefficients
attenuation coefficient (cm^{-1})
wavelength (nm)
Scintillator Component - 1
Scintillator Component - 2


Mean Free Paths
Mean Free Path (mm)
wavelength (nm)
Scintillator Component - 1
Scintillator Component - 2
Combined Scintillator Absorption
Rayleigh
Total

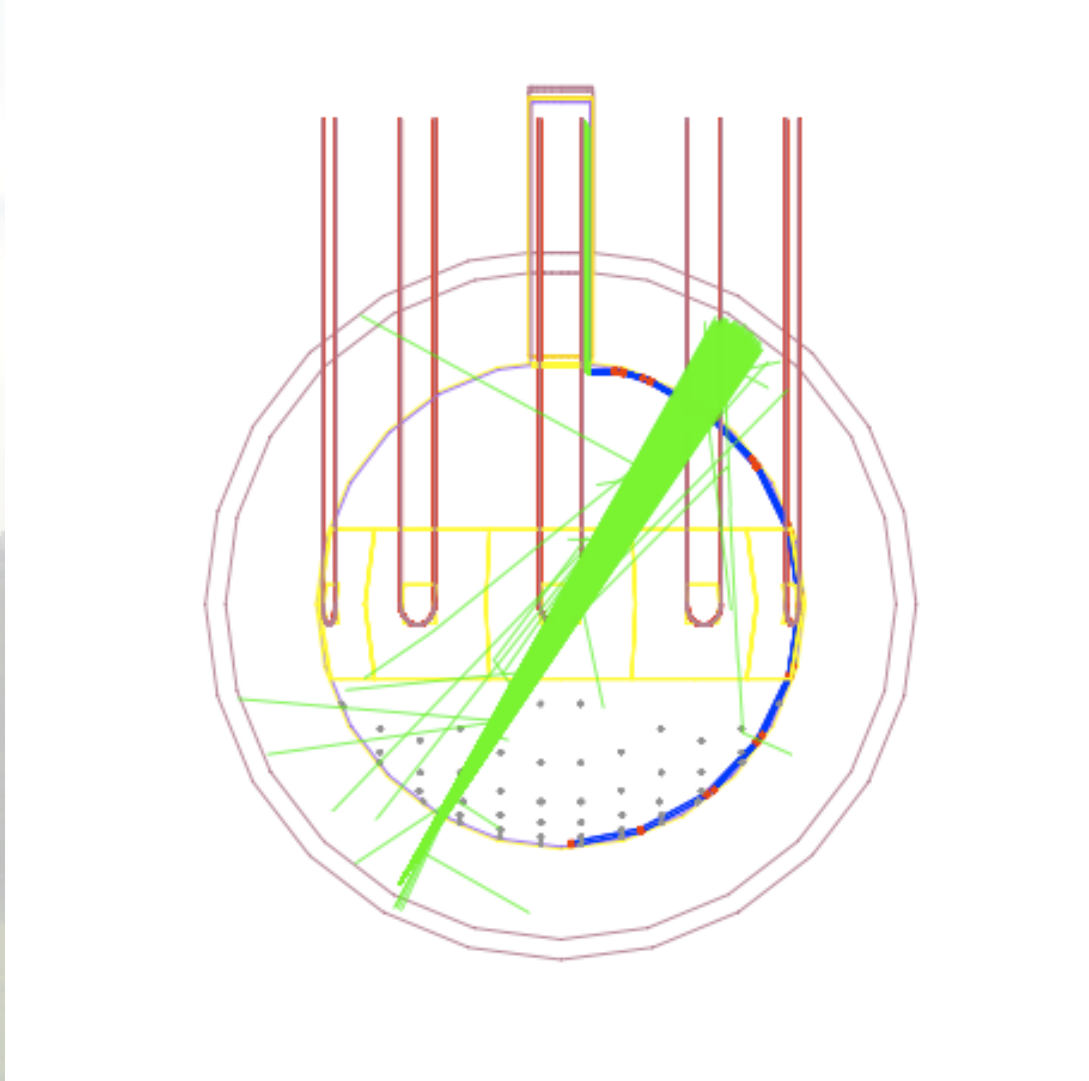

Probabilities
probability per 0.001000 nm
wavelength (nm)
Scintillator Component - 1
Scintillator Component - 2
Combined Scintillator Absorption
Rayleigh
Total

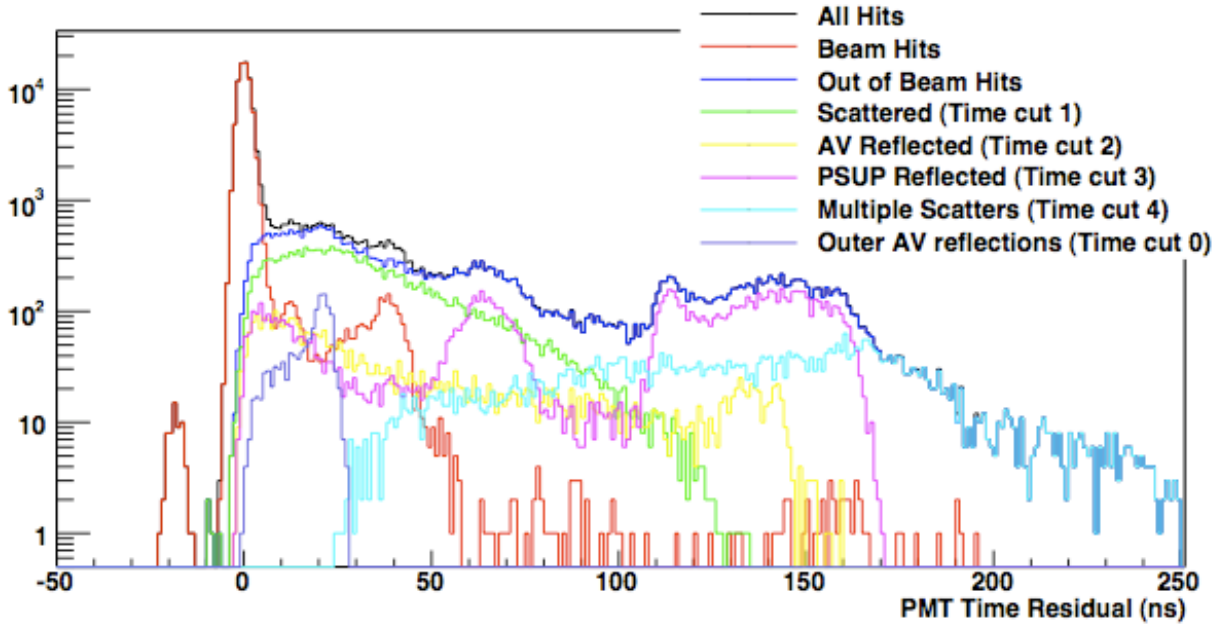

Fractions
Fraction of total extinction
wavelength (nm)
Combined Scintillator Absorption
Rayleigh
Total

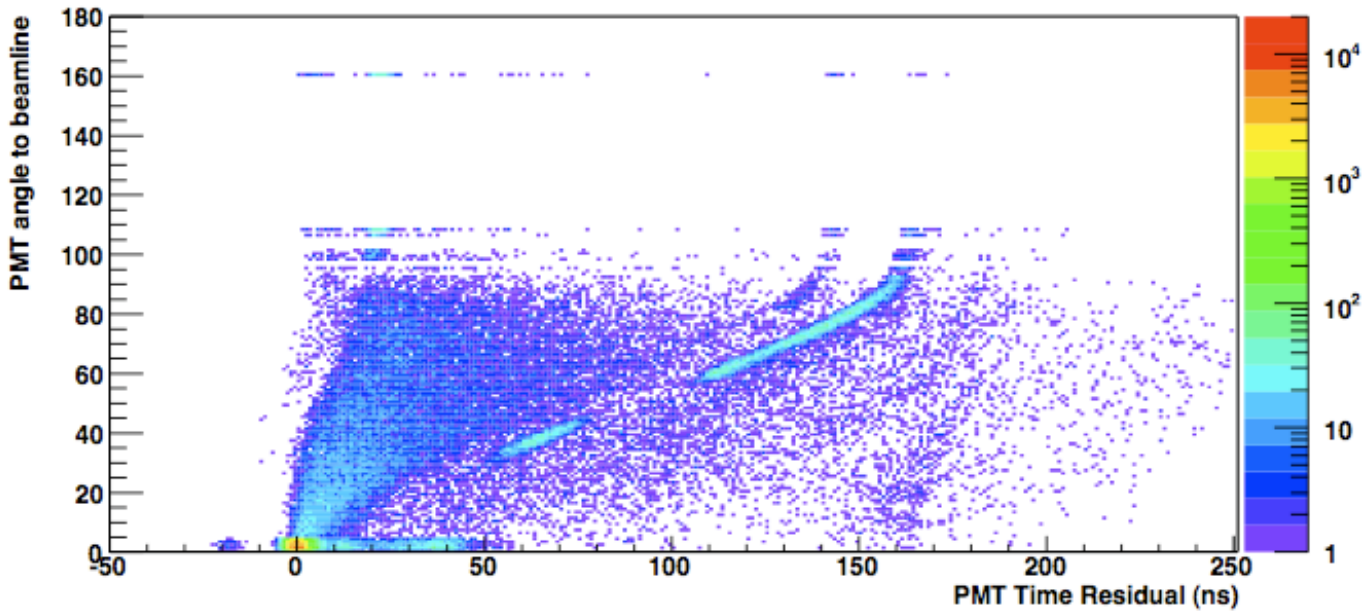
Calibration - SMELLIE

- **S**cattering **M**odule of ELLIE
  - 6 beams of ~6 degree opening angle
  - Sample different path lengths and detector regions
  - Range of wavelengths (350nm – 550nm)
- Feedback to assess light level
  - Attenuation measurement

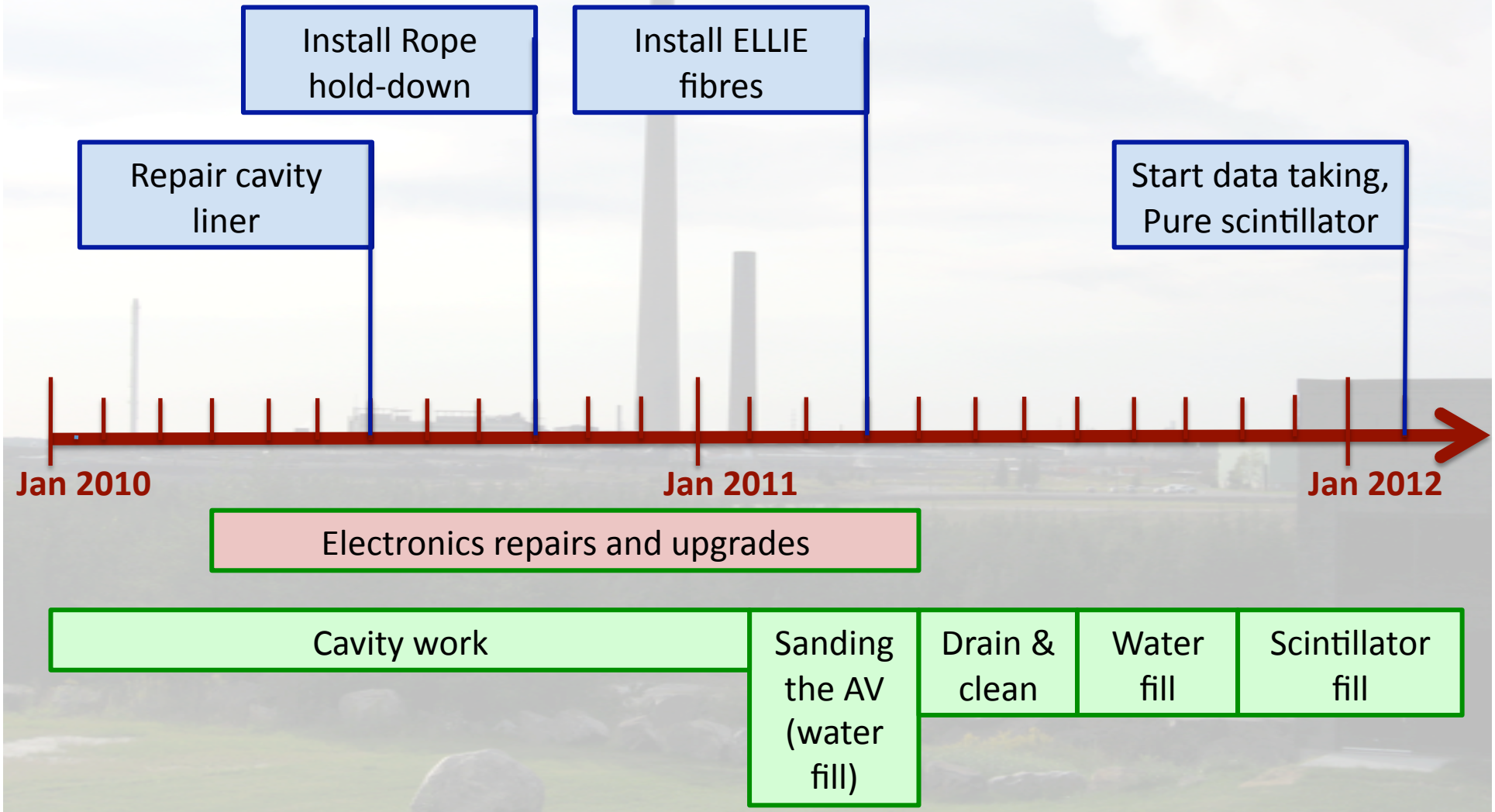
Calibration – SMELLIE




All Hits
Beam Hits
Out of Beam Hits
Scattered (Time cut 1)
AV Reflected (Time cut 2)
PSUP Reflected (Time cut 3)
Multiple Scatters (Time cut 4)
Outer AV reflections (Time cut 0)
PMT Time Residual (ns)


PMT angle to beamline
PMT Time Residual (ns)

Timescale


Install Rope hold-down
Install ELLIE fibres
Repair cavity liner
Start data taking, Pure scintillator
Jan 2010
Jan 2011
Jan 2012
Electronics repairs and upgrades
Cavity work
Sanding the AV (water fill)
Drain & clean
Water fill
Scintillator fill

Summary

- Sudbury is a great venue for low background physics
- SNO hugely successful, still publishing results
- SNOLAB major new underground facility
- SNO+ aims to make a timely double beta decay search and precision solar neutrino measurements + lots of other physics/ astrophysics