
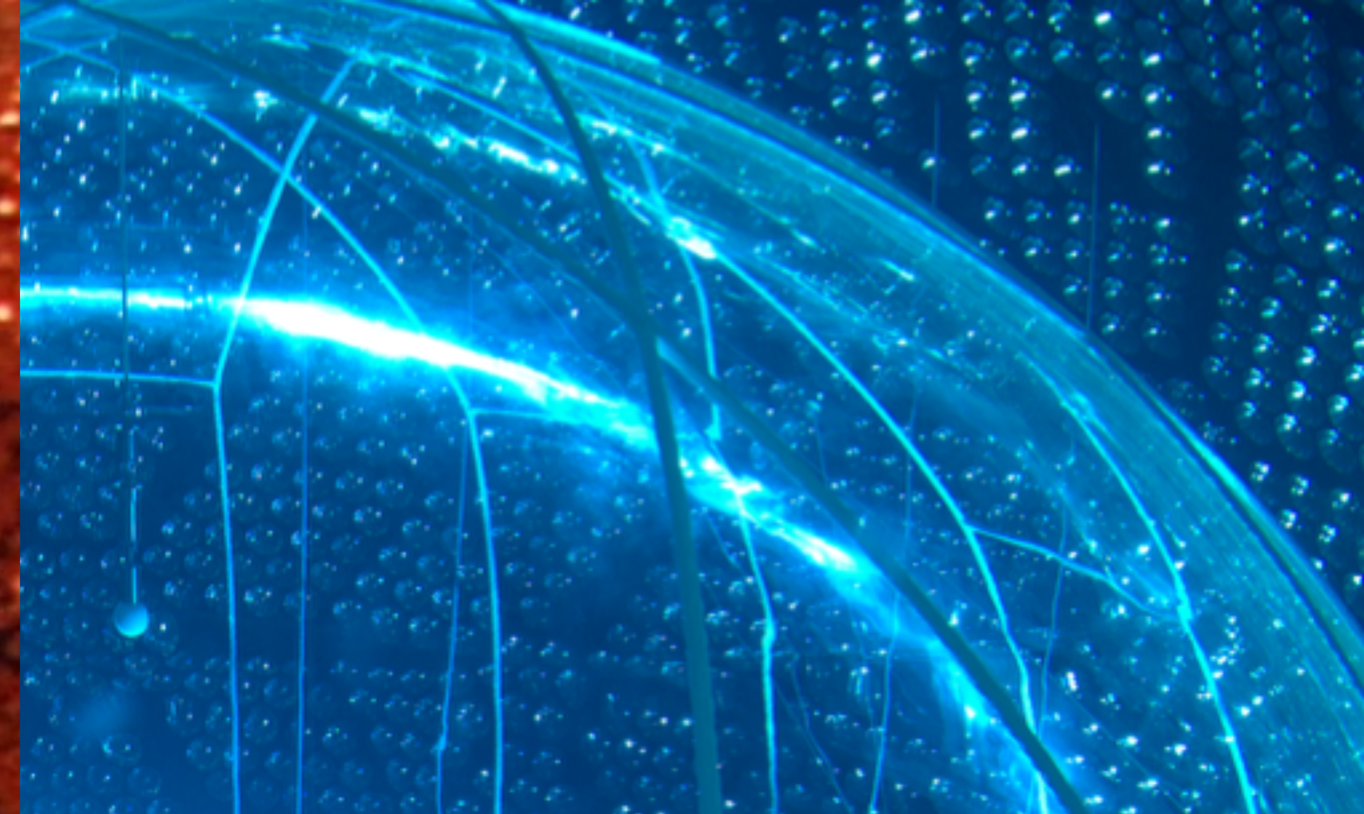

Status of SNO and SNO+

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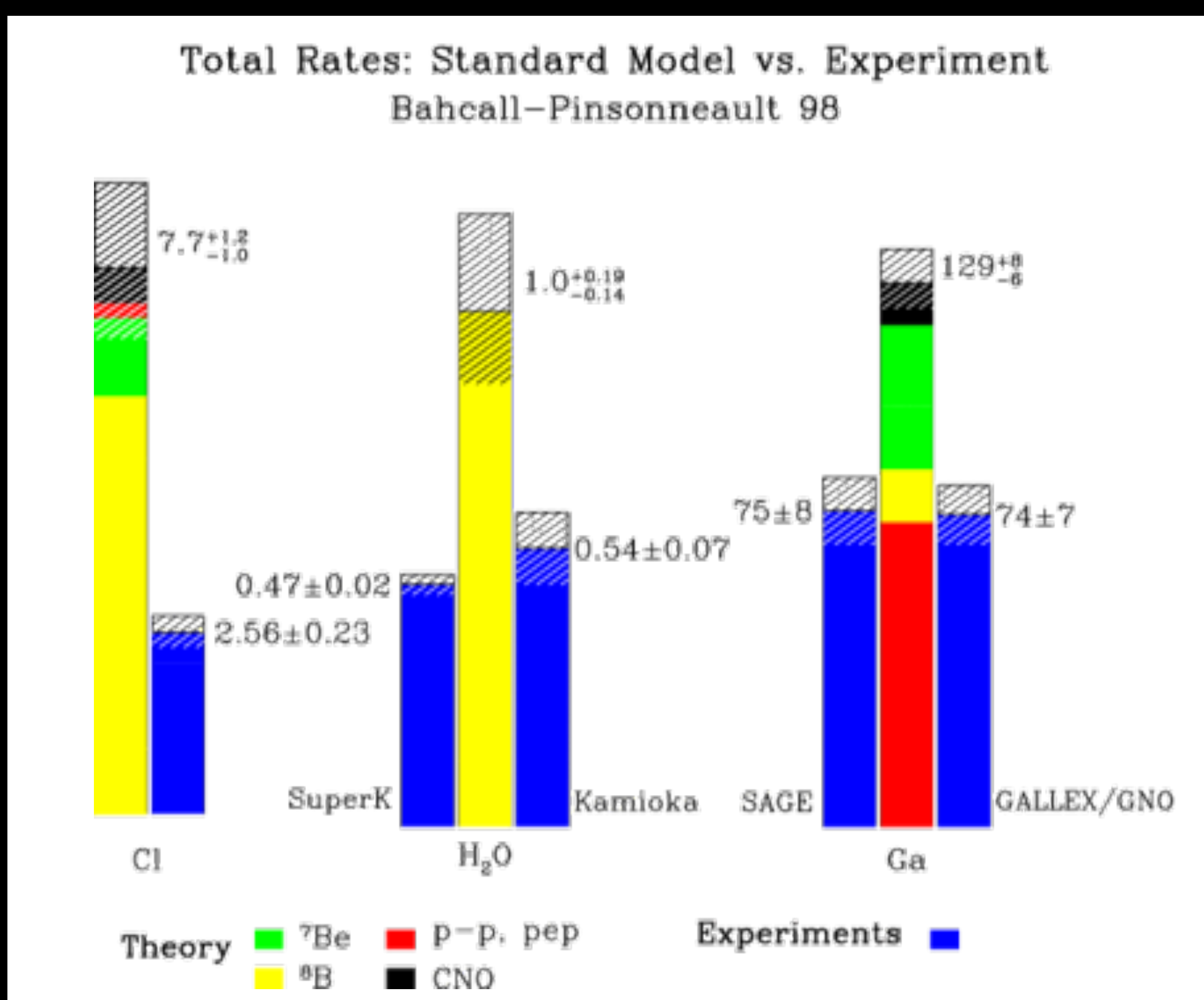
GDR@LPNHE
November 2017

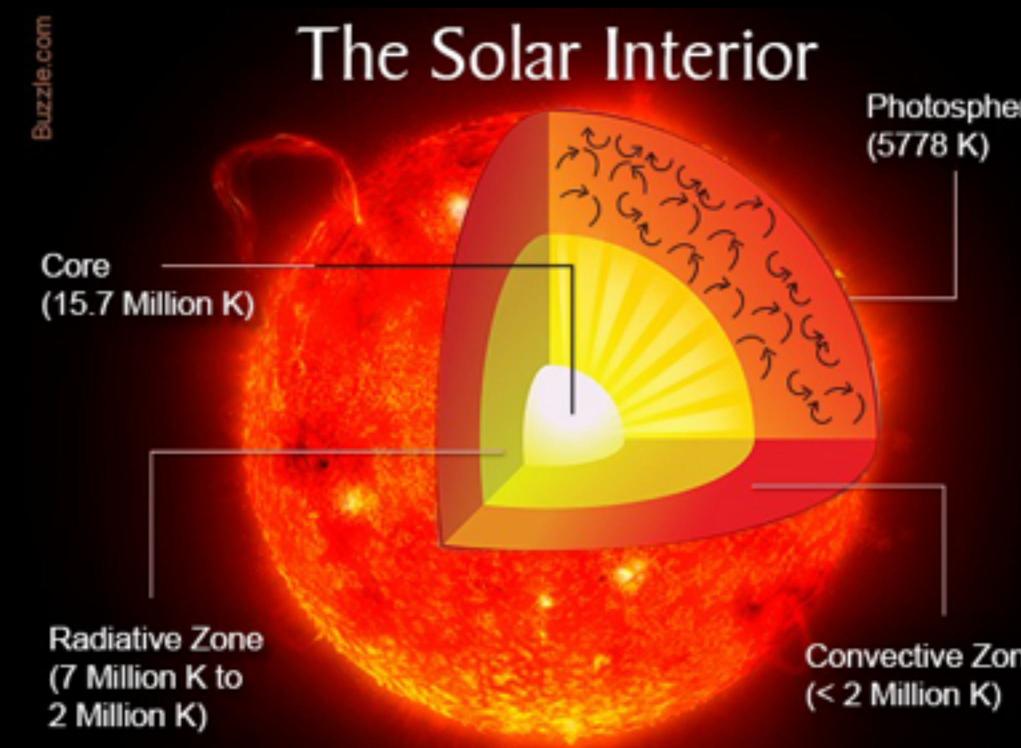
Outline

- SNO
    - Introduction
    - The detector
    - Solar neutrino results
- The path forward
    - New SNO analyses
- SNO+
    - The detector and its upgrades
    - Physics program
    - Status and schedule

A question as old as the Sun

- Nuclear fusion reactions recognized early on as the only viable source of stellar energy production
- Hans Bethe (1930's): first solar model based on nuclear reactions
- John Bahcall: increasingly detailed solar model calculations of the solar neutrino fluxes, since the 60's





- Ray Davis@Homestake: pioneering radiochemical measurements of solar neutrino captures on chlorine.
- Measured flux consistently 1/3 of Bahcall's predictions

SNO Detector

1000 tons of **heavy water**

loaded with NaCl in phase 2

contained in an **acrylic vessel (AV)** 12 m diameter

shielded by 7 kt ultra-pure water

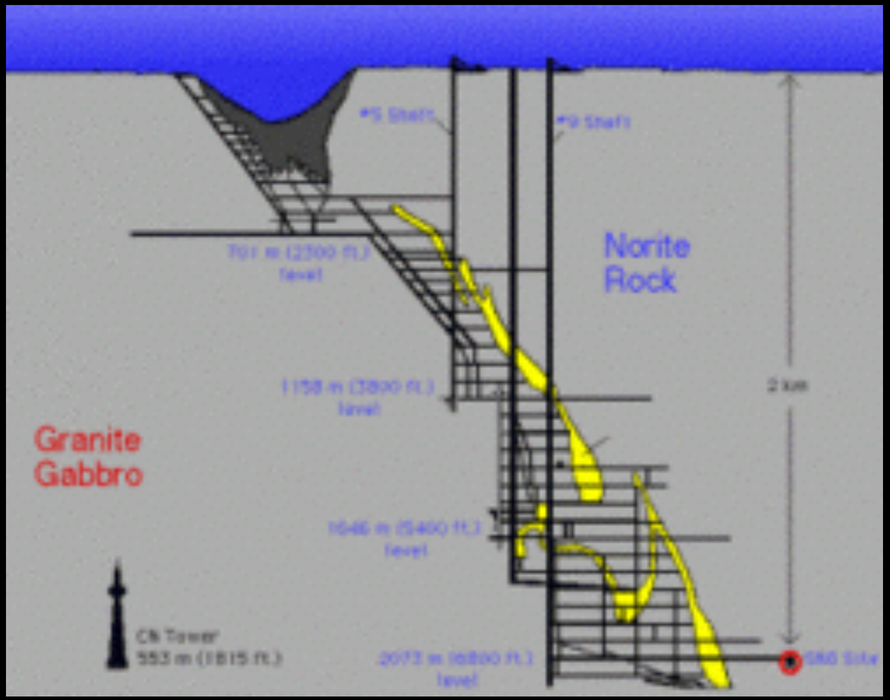
viewed by ~ **9500 PMTs** (8”) mounted on 17 m diam. structure

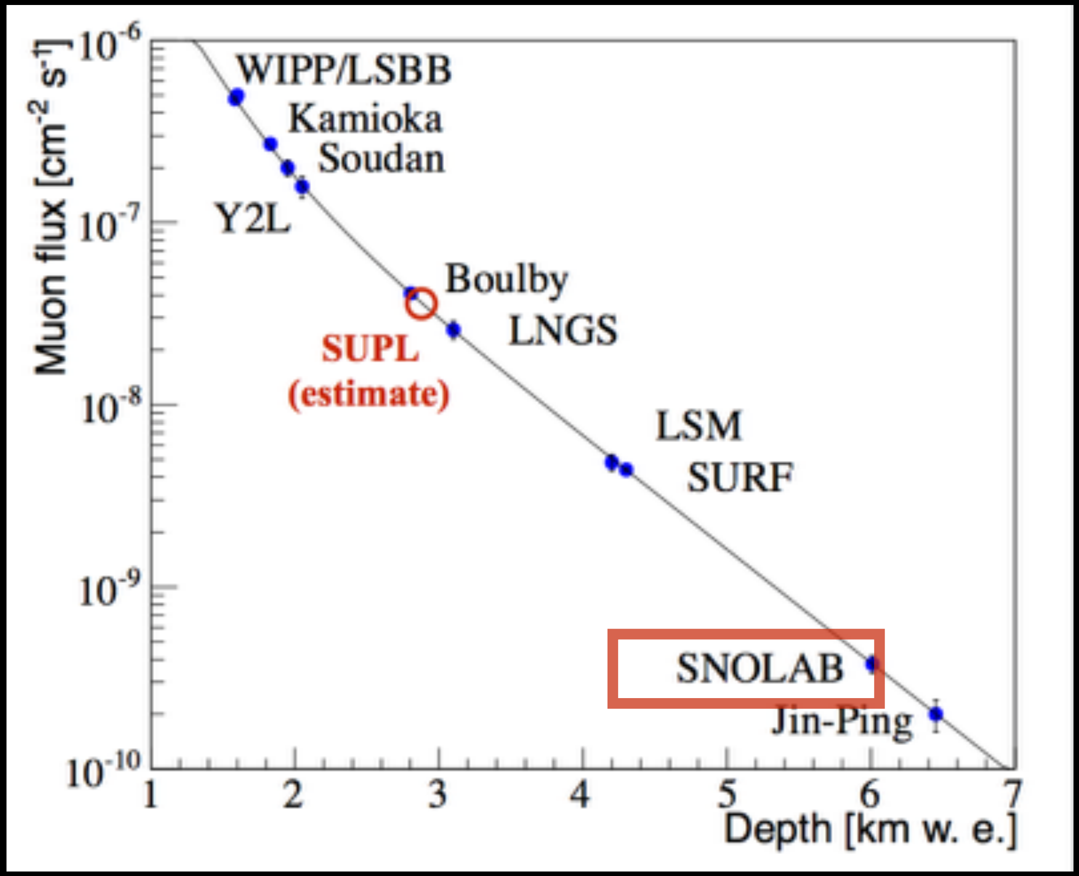
calibration systems

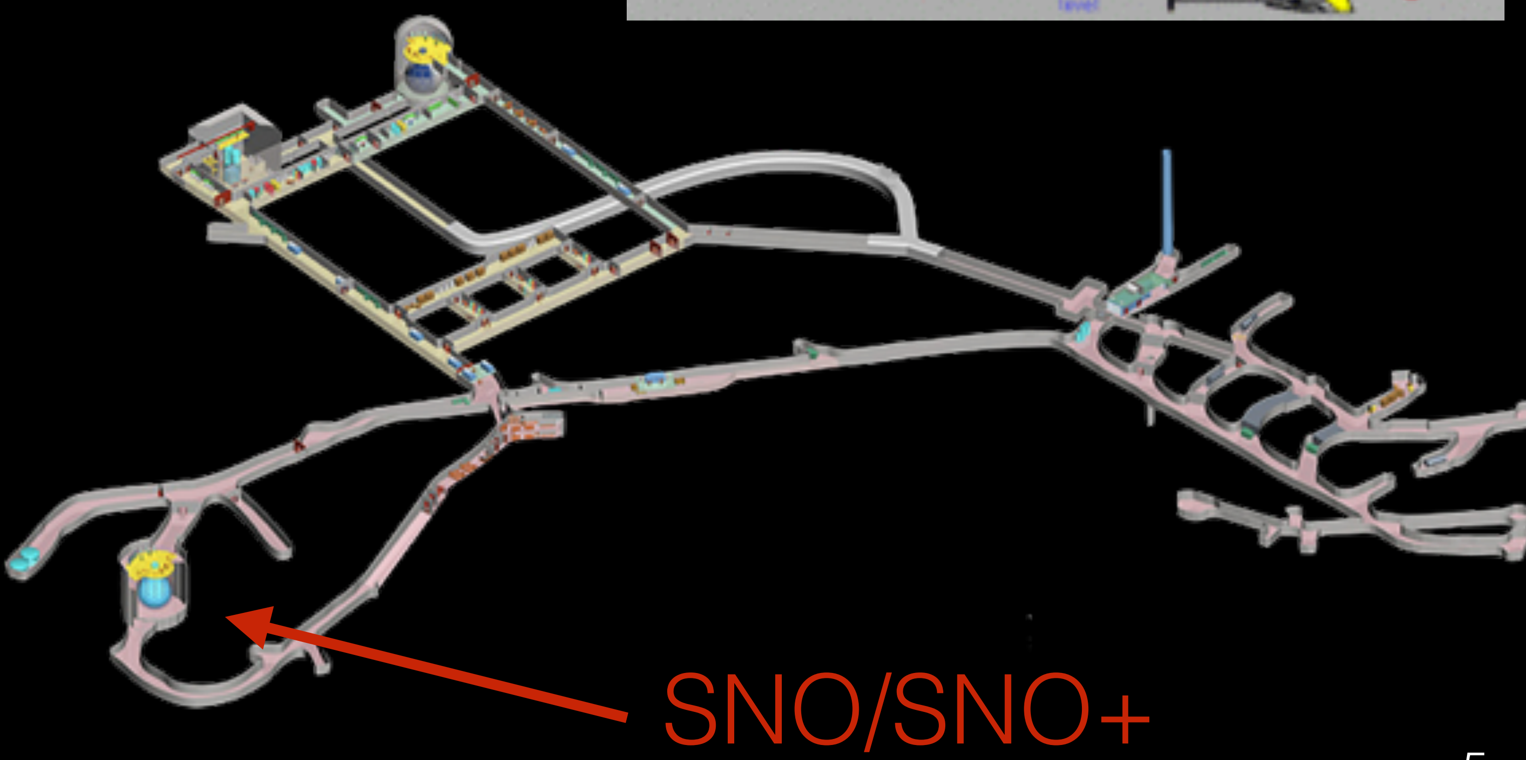
electronics and DAQ

SNOLAB Facility

- Located in Creighton Mine, Sudbury, Canada
- ~2070 m overburden (6000 m.w.e.)
- **μ rate: 0.28 μ d^{-1} m^{-2}**







Reactions on deuterium

$$\nu_e + d \Rightarrow p + p + e^-$$

Charged Current reaction

W boson exchange

Only electron neutrinos

Detect electron in final state

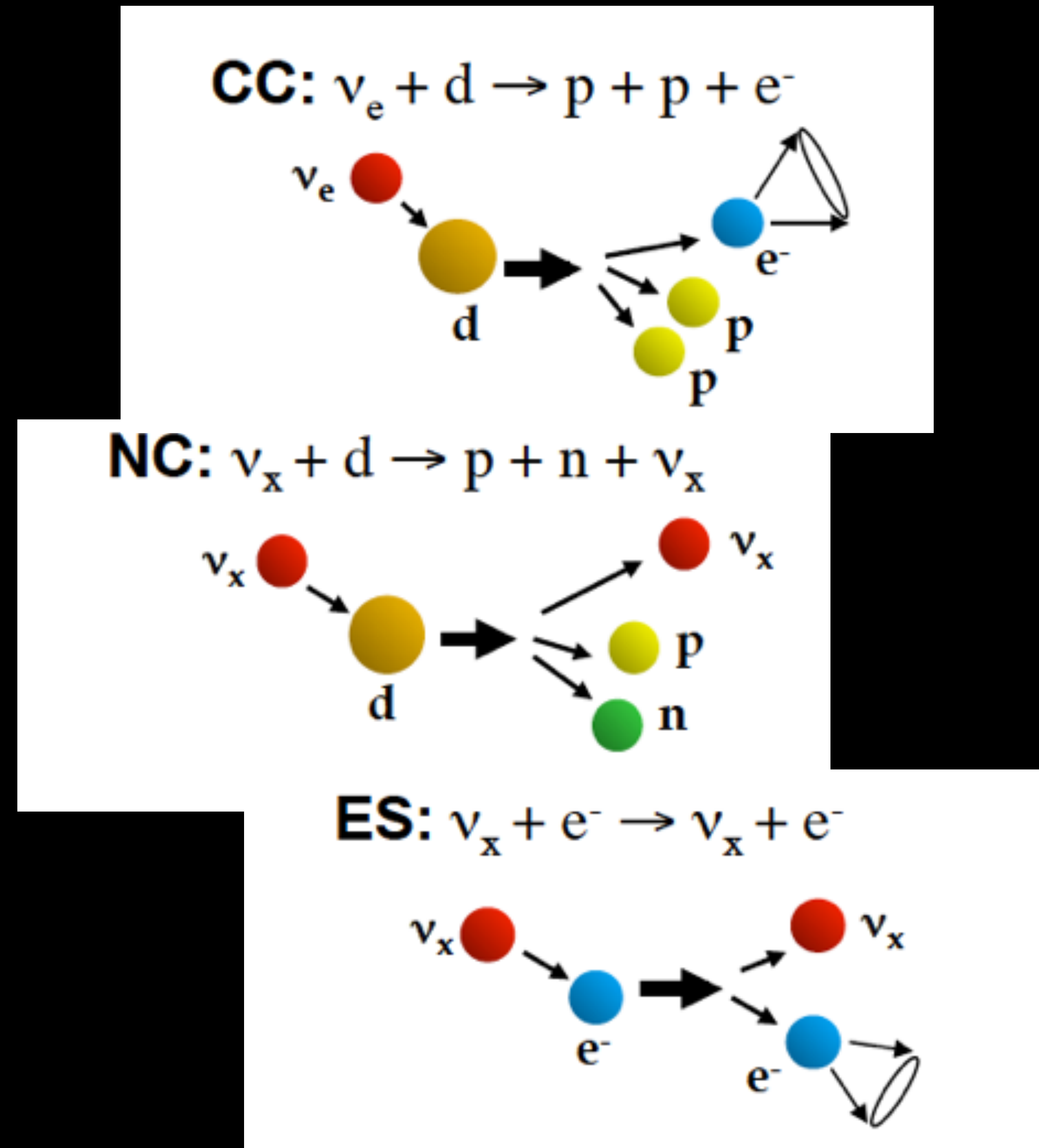
$$\nu_x + d \Rightarrow p + n + \nu_x$$

Neutral Current reaction

Z boson exchange

All neutrino flavors

Detect neutron in final state



also: $\nu_x + e^- \rightarrow \nu_x + e^-$

Elastic Scattering reaction

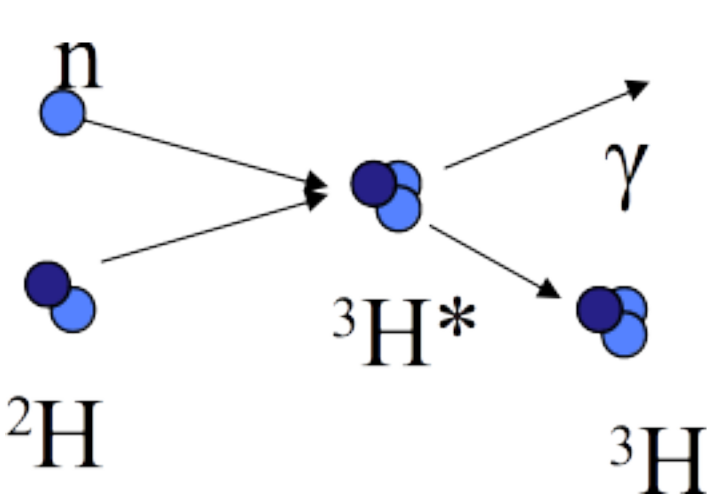
Directional, lower statistics

Less sensitive to ν_μ, ν_τ

The 3 phases of SNO

Phase I (D_2O)

Nov. 99 - May 2001

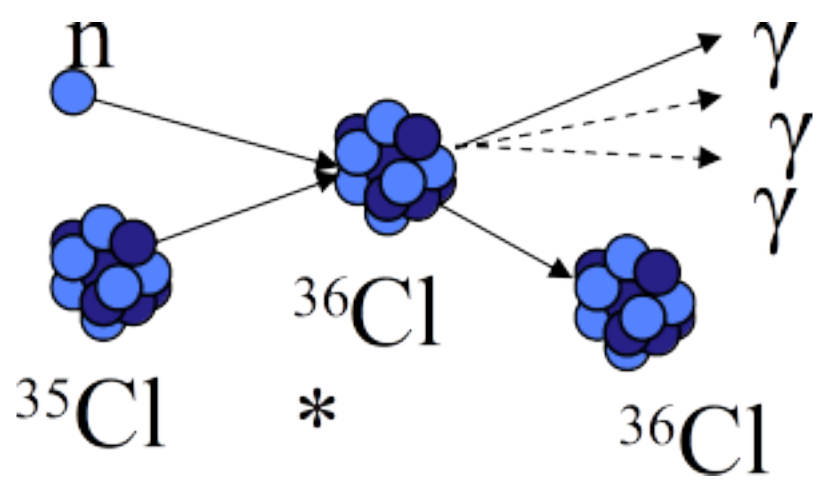


neutrons captured by deuterons

$E(\gamma) = 6.25$ MeV

Phase II (salt)

July 2001 - Sept. 2003

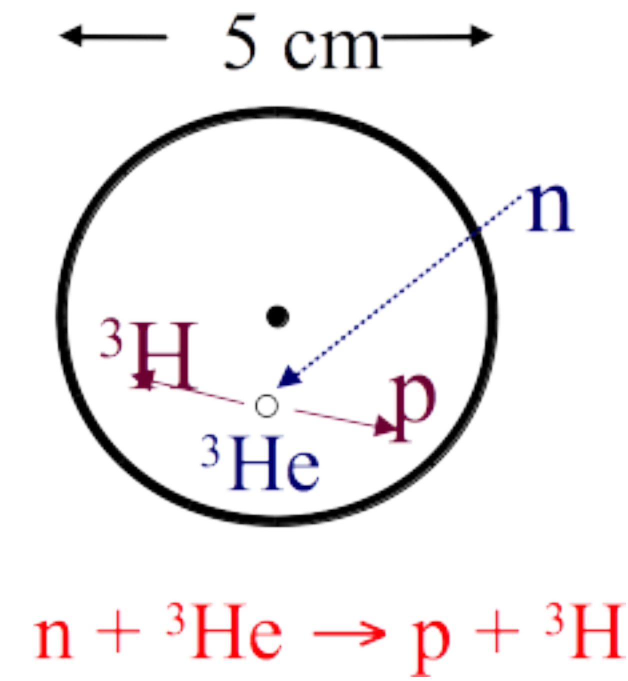


neutrons captured by chlorine

$\Sigma(E(\gamma)) = 8.6$ MeV

Phase III (NCD)

Nov. 2004 - Dec. 2006



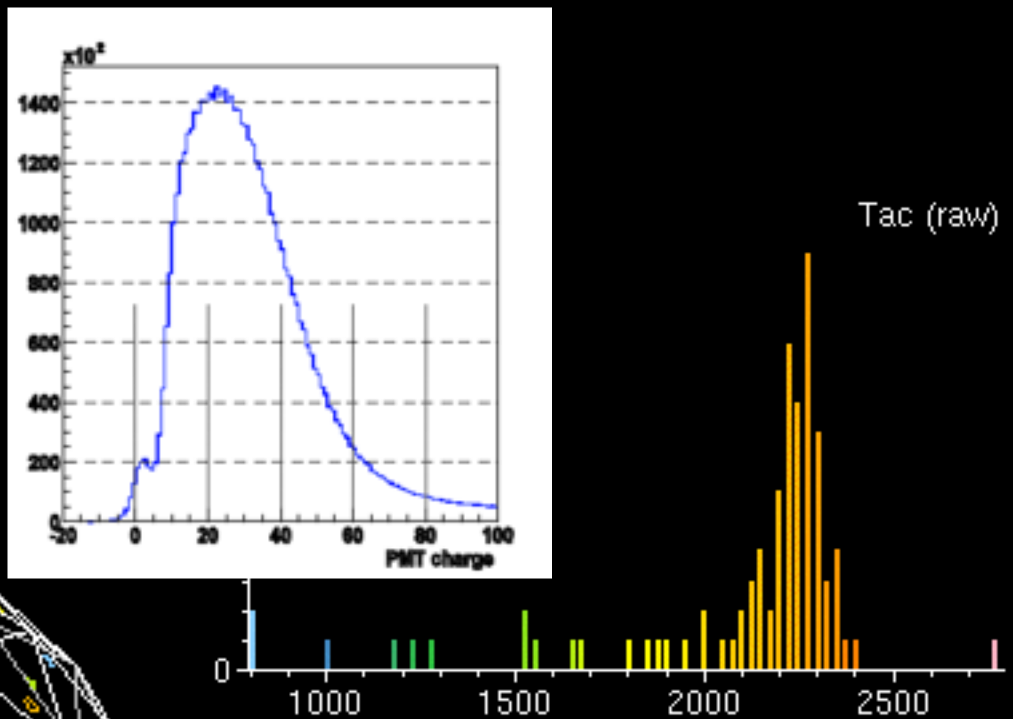
neutrons captured by ^3He

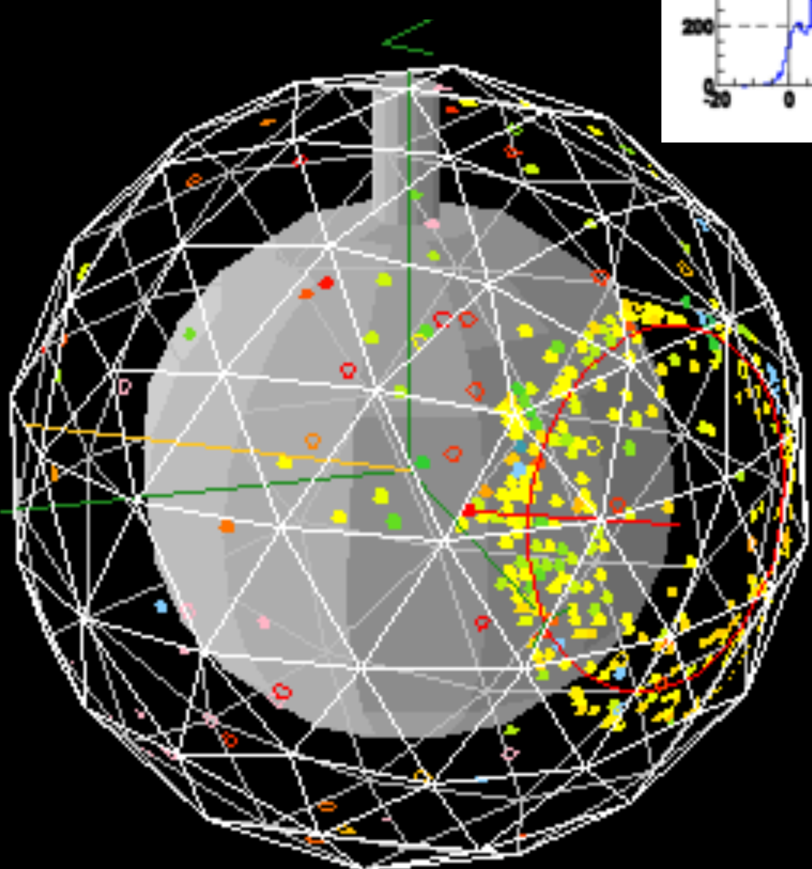
array of 40 proportional counters

Experimental Observables

Hit PMTs:

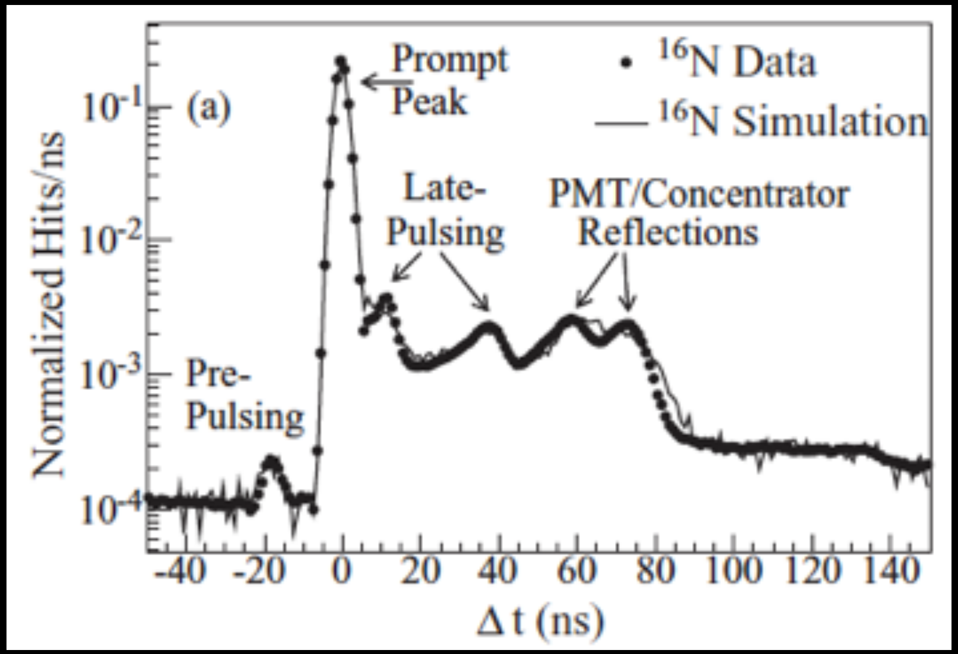
- position
- time
- charge





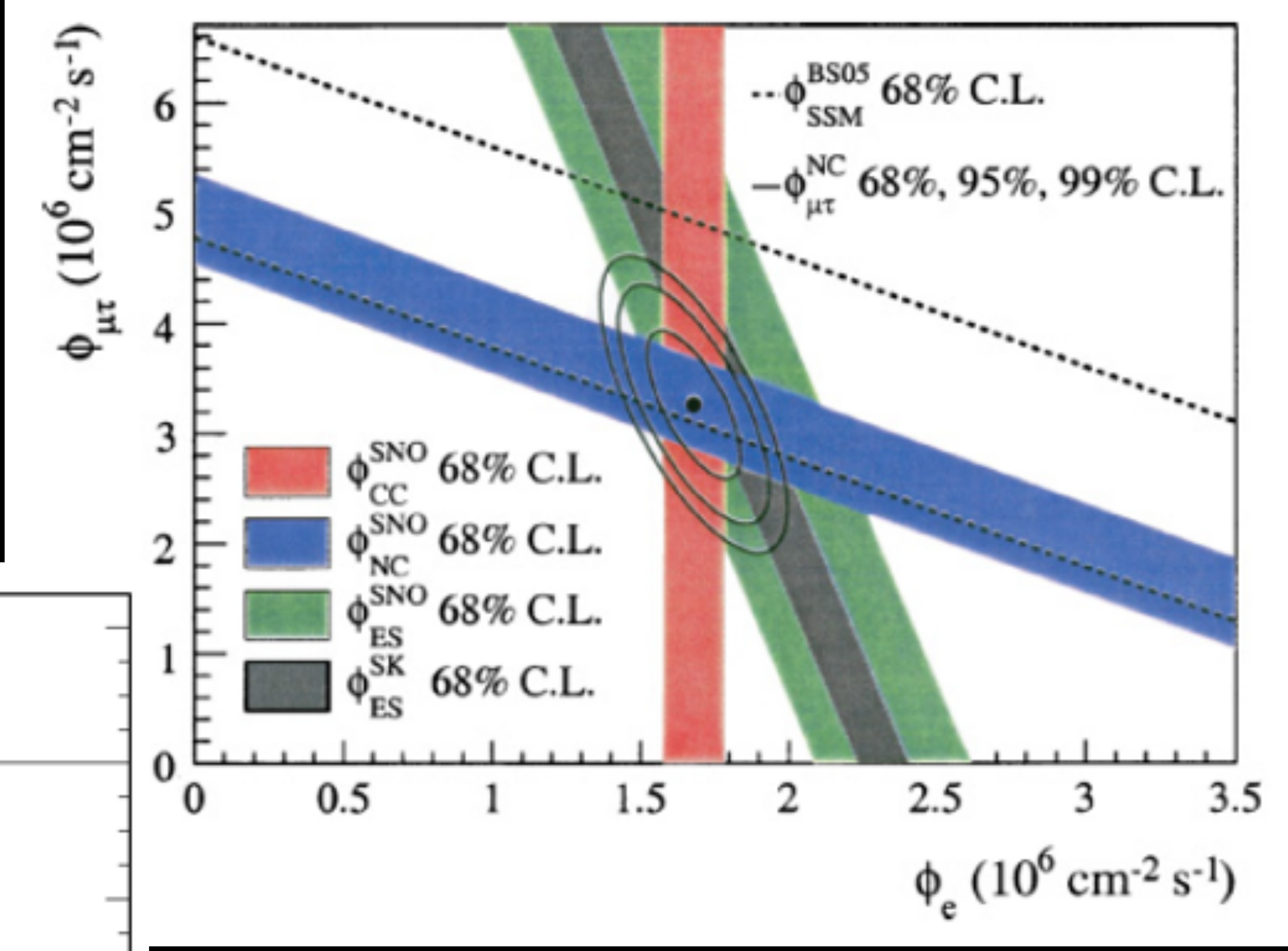
From these we calculate:

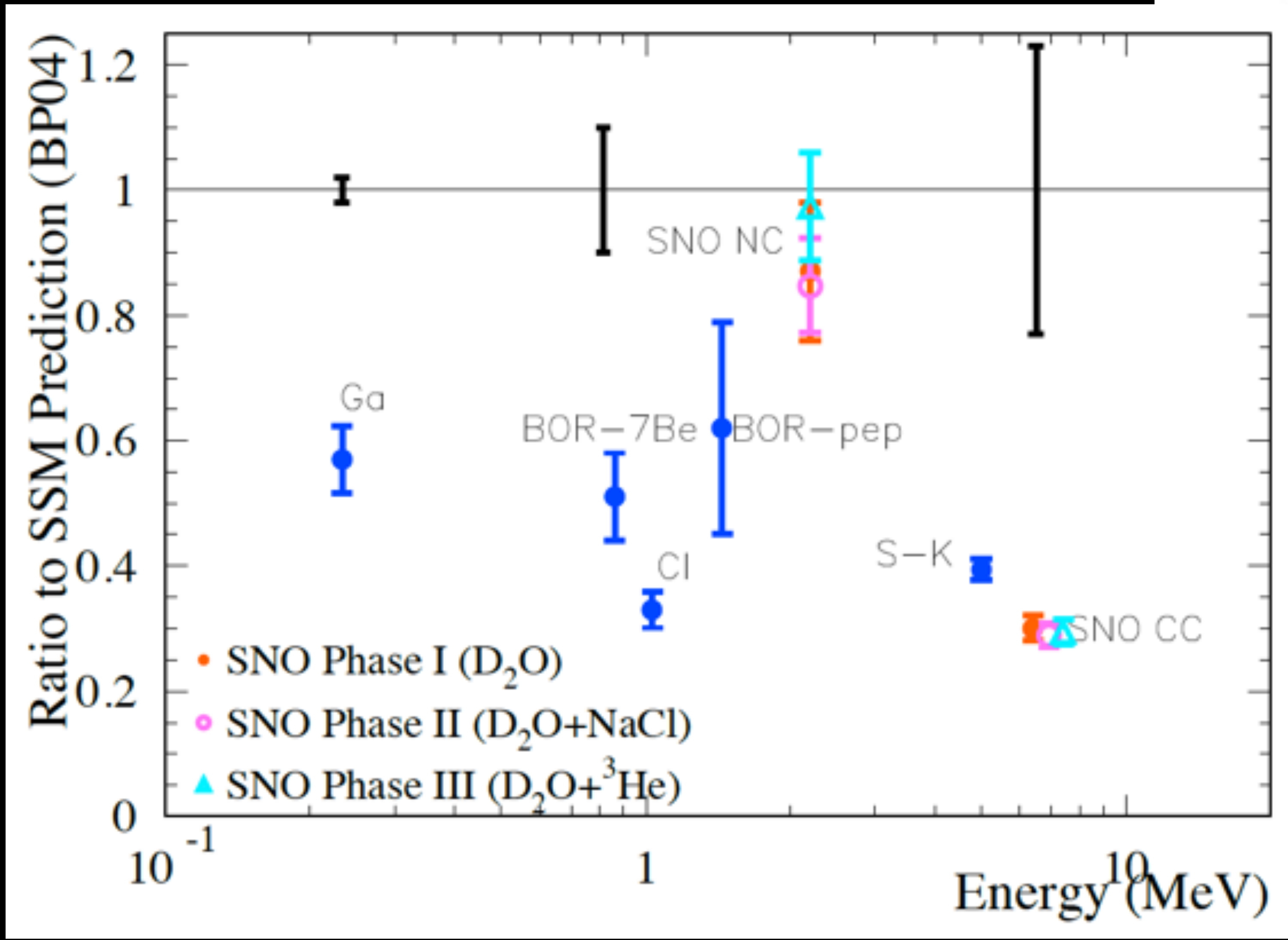
- event position
- direction
- energy
- isotropy



Used extensive calibrations to tune response models and determine systematics

Solar Neutrino Problem, solved!

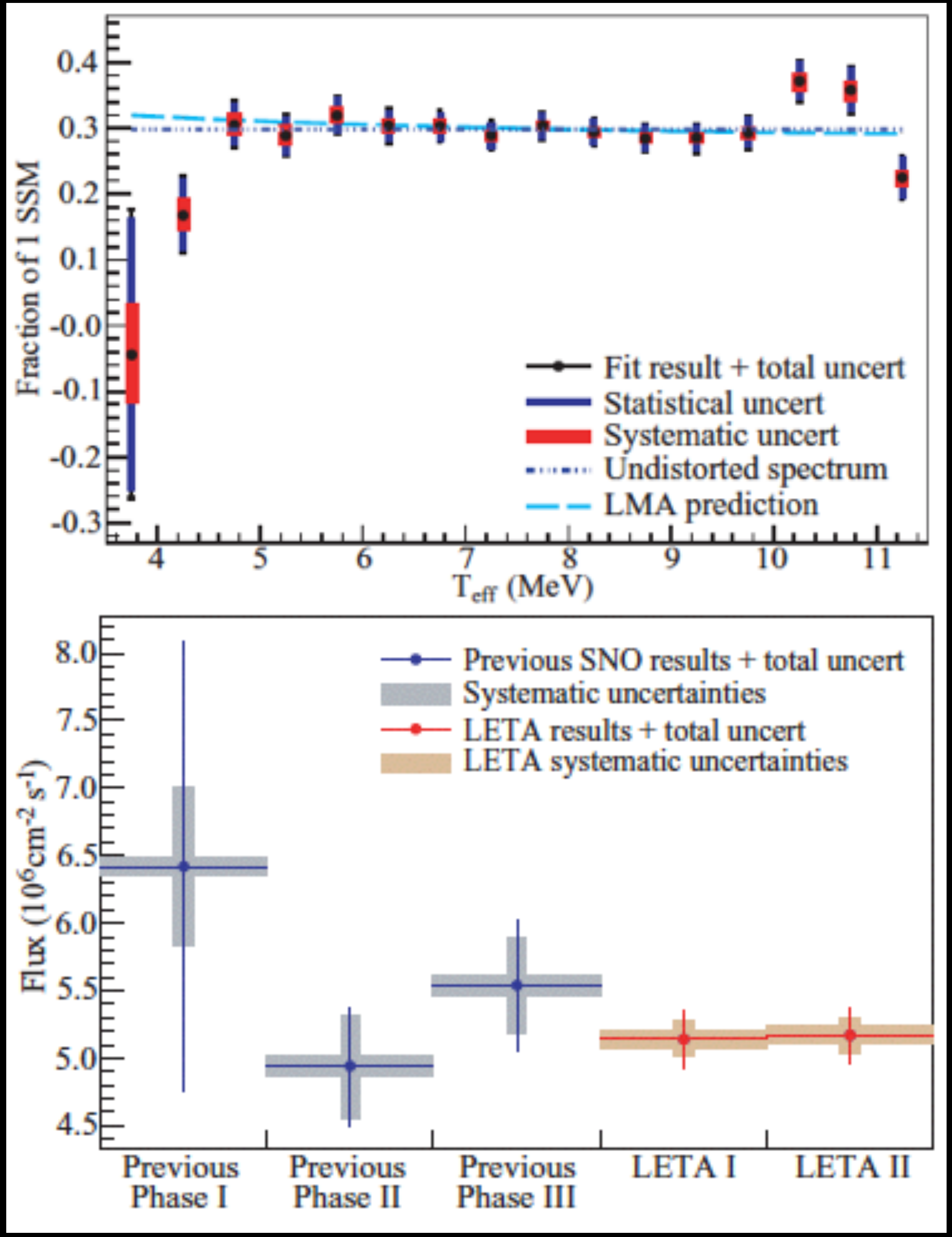




1) ν_e is 1/3 of all ν: neutrinos change flavour!
2) measurement in all flavours confirms solar model

Precision Analyses

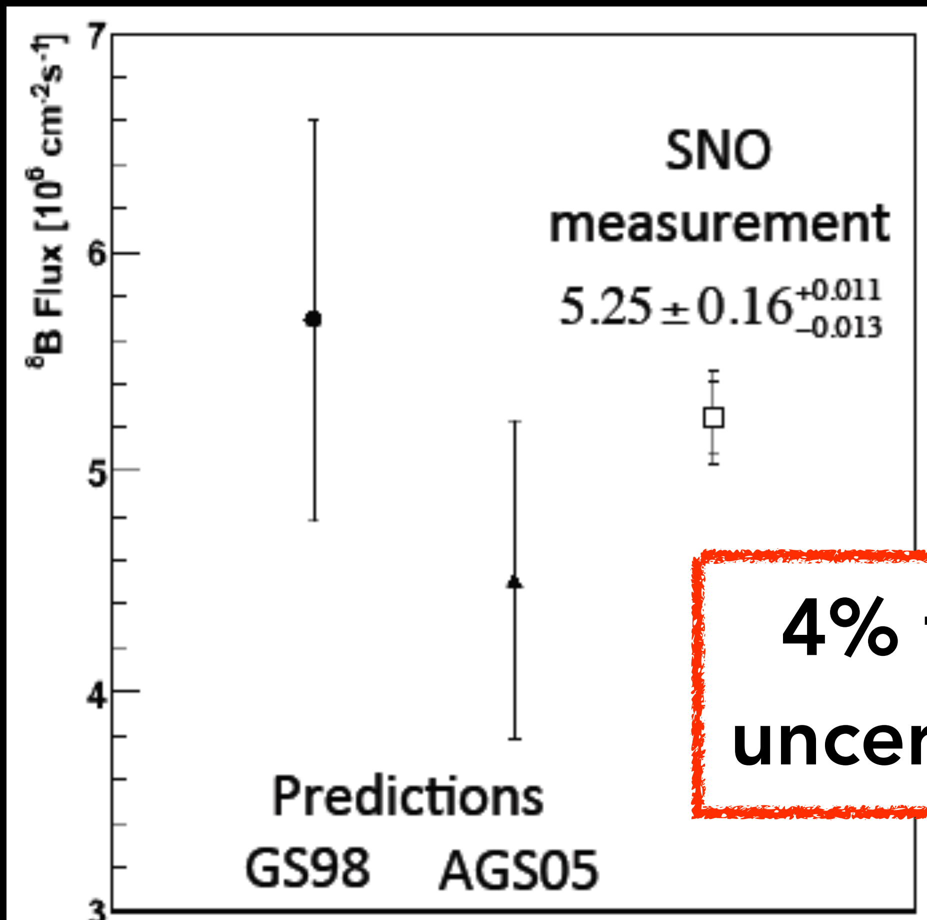
- Combine all phases in a single fit with less observables
  - Account for different responses of each phase
  - Correlated systematics
- Lowered threshold down to 3.5 MeV
  - Improved reconstruction, better background estimates
- Fit in neutrino energy space



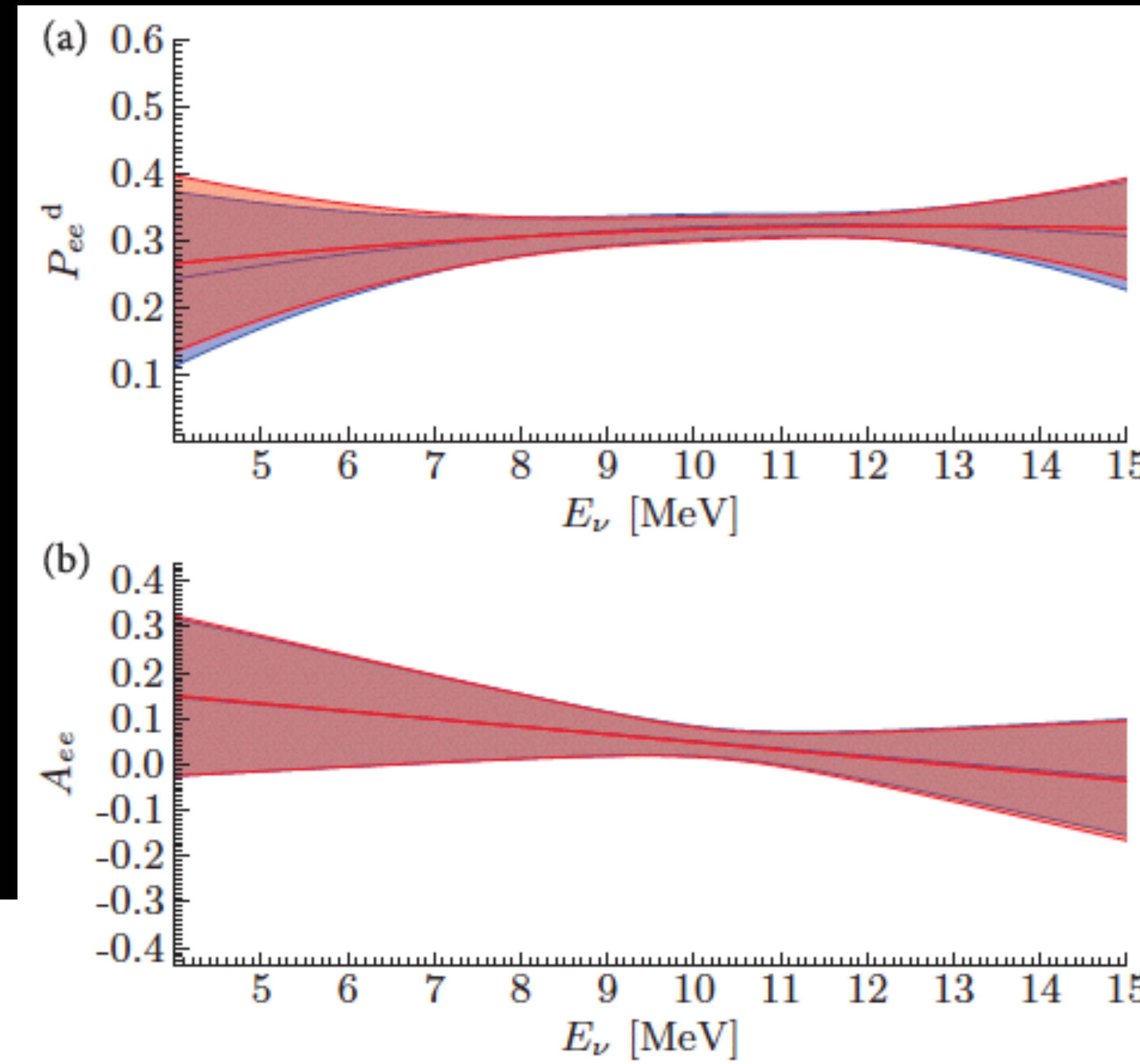
$$\Phi_{^8\mathrm{B}}^{\mathrm{binned}} = 5.140^{+0.160}_{-0.158}(\mathrm{stat})^{+0.132}_{-0.117}(\mathrm{syst}) \times 10^6 \mathrm{cm}^{-2} s^{-1}$$

$$\Phi_{^8\mathrm{B}}^{\mathrm{kernel}} = 5.171^{+0.159}_{-0.158}(\mathrm{stat})^{+0.132}_{-0.114}(\mathrm{syst}) \times 10^6 \mathrm{cm}^{-2} s^{-1}$$

Combination all phases



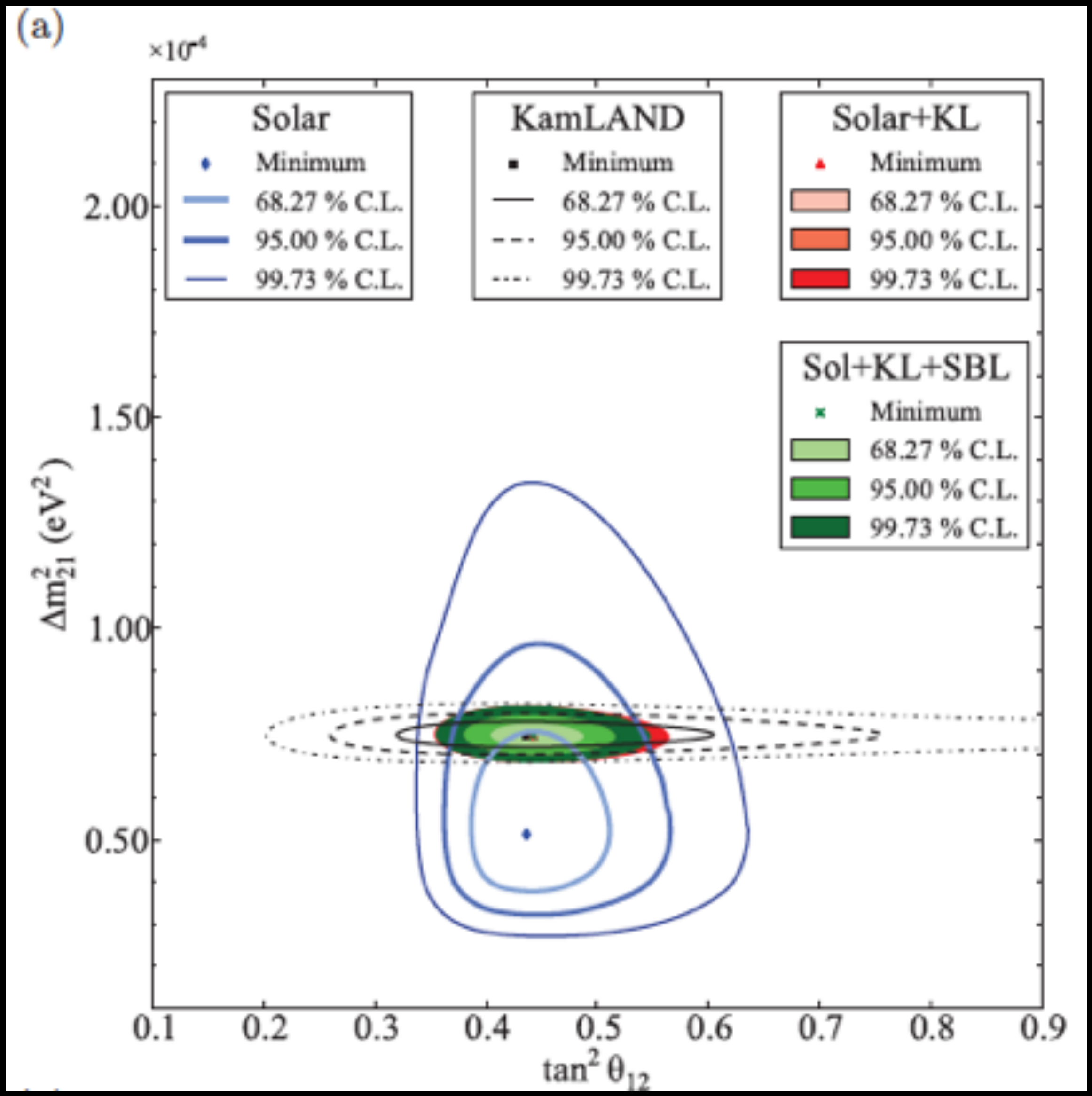
4% total uncertainty

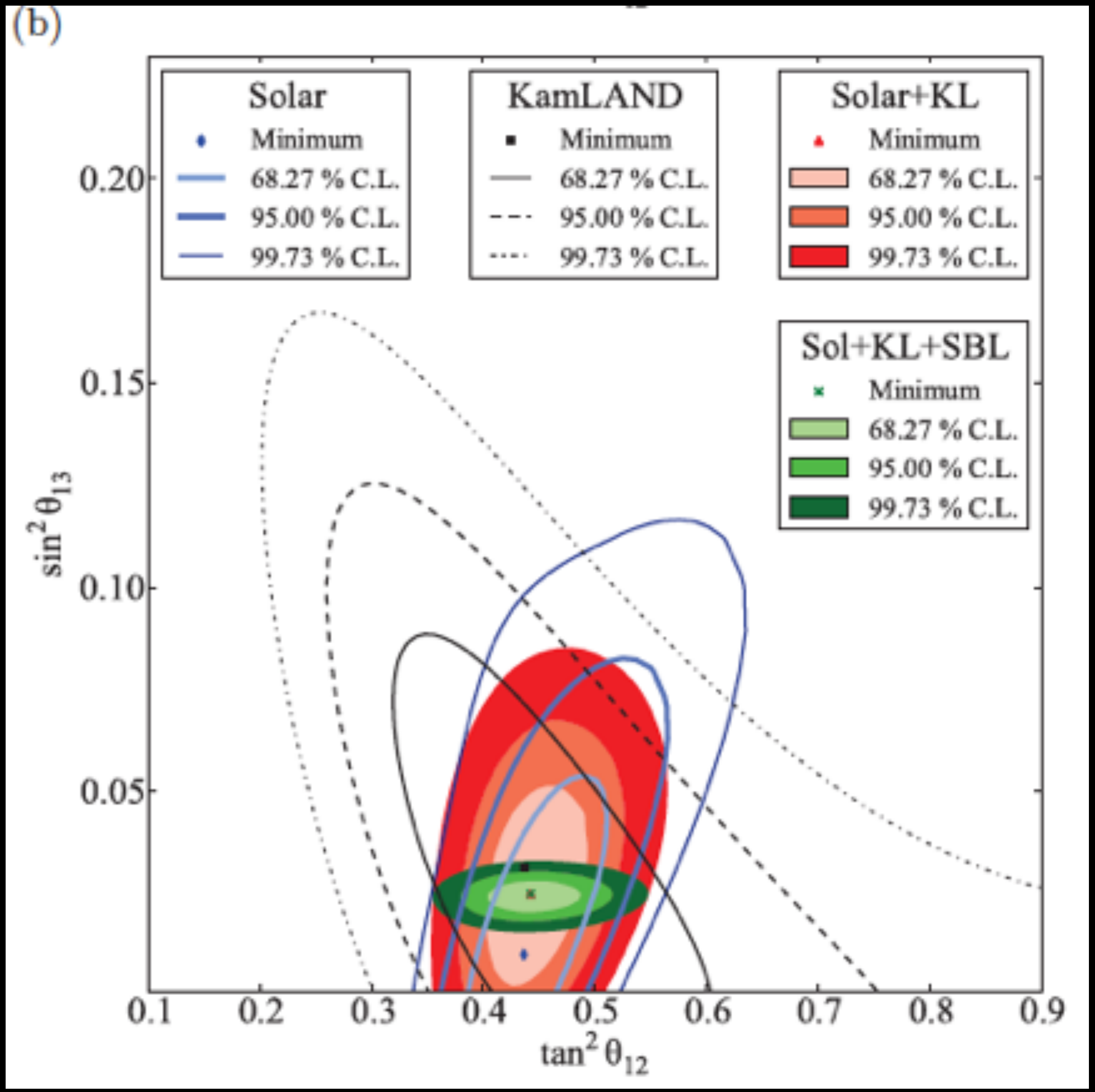


	Best fit	Stat.	Systematic uncertainty			
			Basic	D/N	MC	Total
Φ_B	5.25	±0.16	$^{+0.11}_{-0.12}$	±0.01	$^{+0.01}_{-0.03}$	$^{+0.11}_{-0.13}$
c_0	0.317	±0.016	$^{+0.008}_{-0.010}$	±0.002	$^{+0.002}_{-0.001}$	±0.009
c_1	0.0039	$^{+0.0065}_{-0.0067}$	$^{+0.0047}_{-0.0038}$	$^{+0.0012}_{-0.0018}$	$^{+0.0004}_{-0.0008}$	±0.0045
c_2	-0.0010	±0.0029	$^{+0.0013}_{-0.0016}$	$^{+0.0002}_{-0.0003}$	$^{+0.0004}_{-0.0002}$	$^{+0.0014}_{-0.0016}$
a_0	0.046	±0.031	$^{+0.007}_{-0.005}$	±0.012	$^{+0.002}_{-0.003}$	$^{+0.014}_{-0.013}$
a_1	-0.016	±0.025	$^{+0.003}_{-0.006}$	±0.009	±0.002	$^{+0.010}_{-0.011}$

Consistent with LMA
(including MSW effect)

Neutrino oscillations





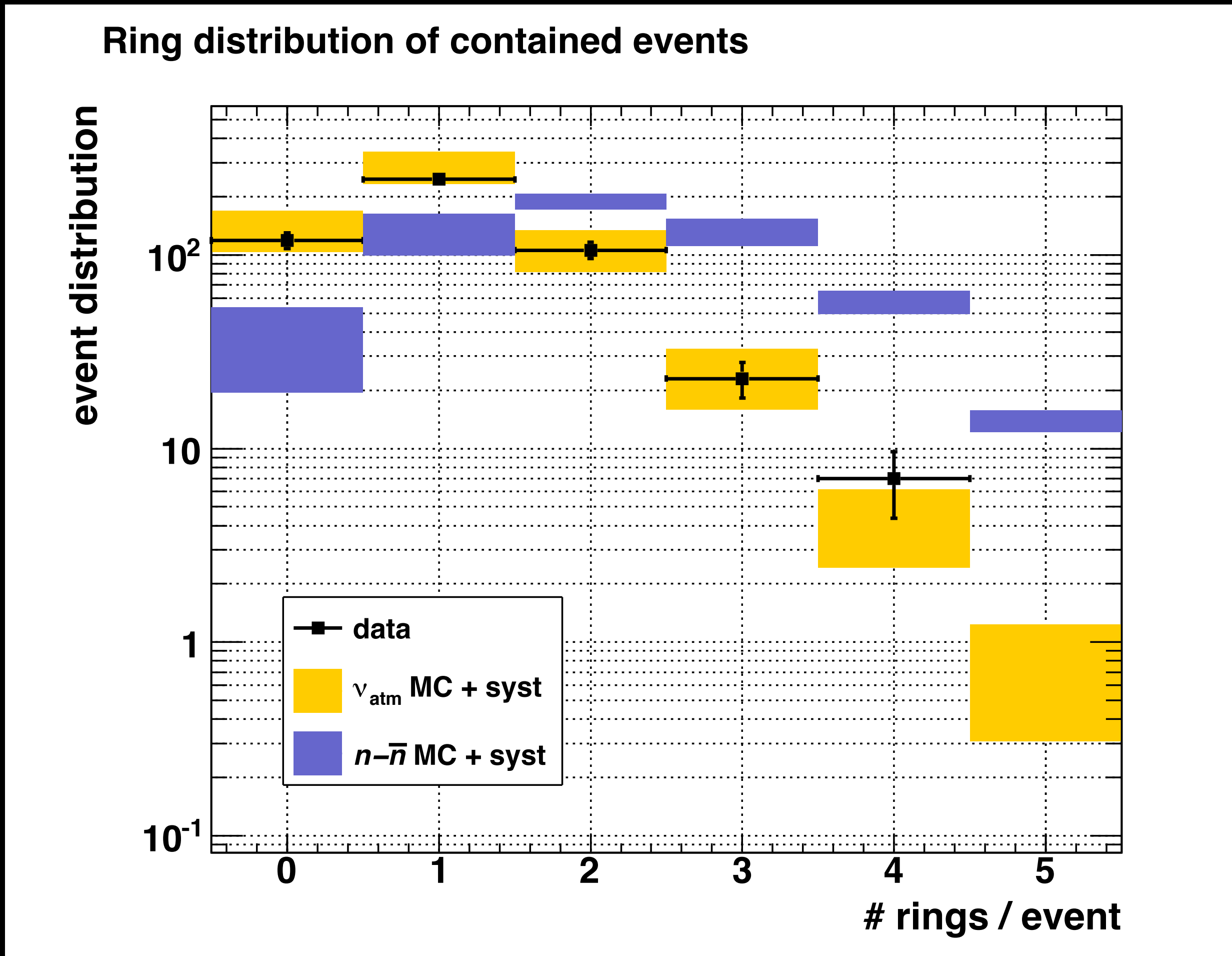
- SNO results crucial to good precision on θ_{12}
- Complementary with KamLAND's Δm^2_{12} sensitivity
- Tension led to early hints of non-zero θ_{13} , SBL experiments (Daya Bay, Reno, Double-Chooz, and also T2K, Minos) then measured it

Looking towards the future

- SNO data
  - Analysis group reactivated in 2016
  - Several analyses ongoing:
    - **n/n-bar oscillations**
    - **HeP solar neutrinos**
    - Neutrino lifetime
    - Lorentz invariance
    - Atmospheric neutrinos
- SNO detector
  - Refurbish, upgrade and fill with scintillator —> SNO+

n/n-bar oscillations

- Fresh off the press (Phys. Rev. D 96, 092005 – 20 November 2017)
    - First result of n/n-bar oscillations in deuteron target
    - Looking for multiple rings
        - In SNO n/n-bar has a signature of 200 MeV - 1.9 GeV
        - Atmospherics are the major background



$$\tau_{n\bar{n}} > 1.18 \times 10^{31} \text{yr (90\% C.L.)}$$

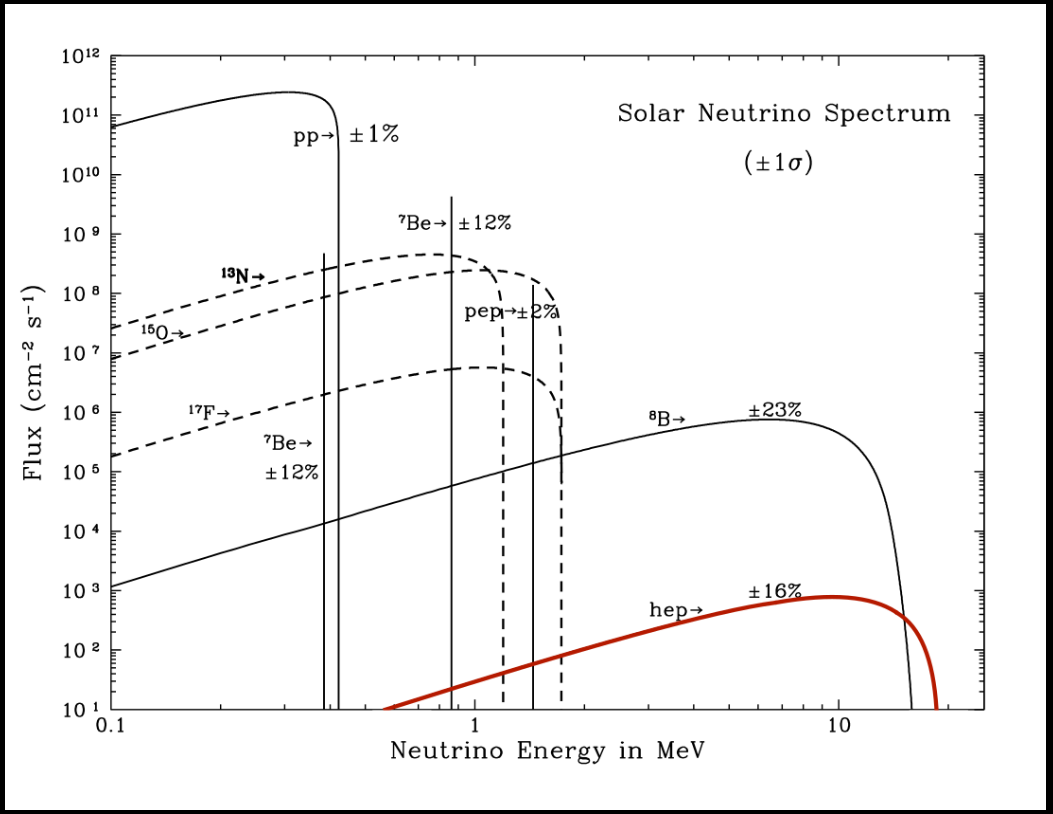
HeP neutrino search on full SNO dataset

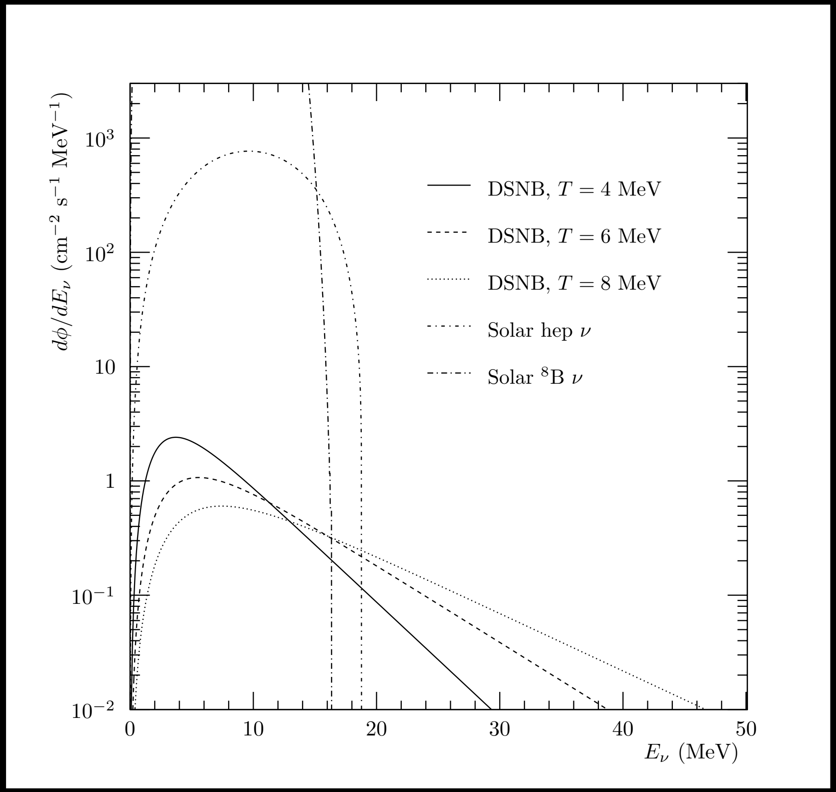
- SNO still has the current best limit (phase I data only)

$$\Phi_{hep} < 2.3 \times 10^4 cm^{-2} s^{-1}$$

$$\Phi_{hep}^{SSM} = 7.93 \pm 1.23 \times 10^3 cm^{-2} s^{-1}$$

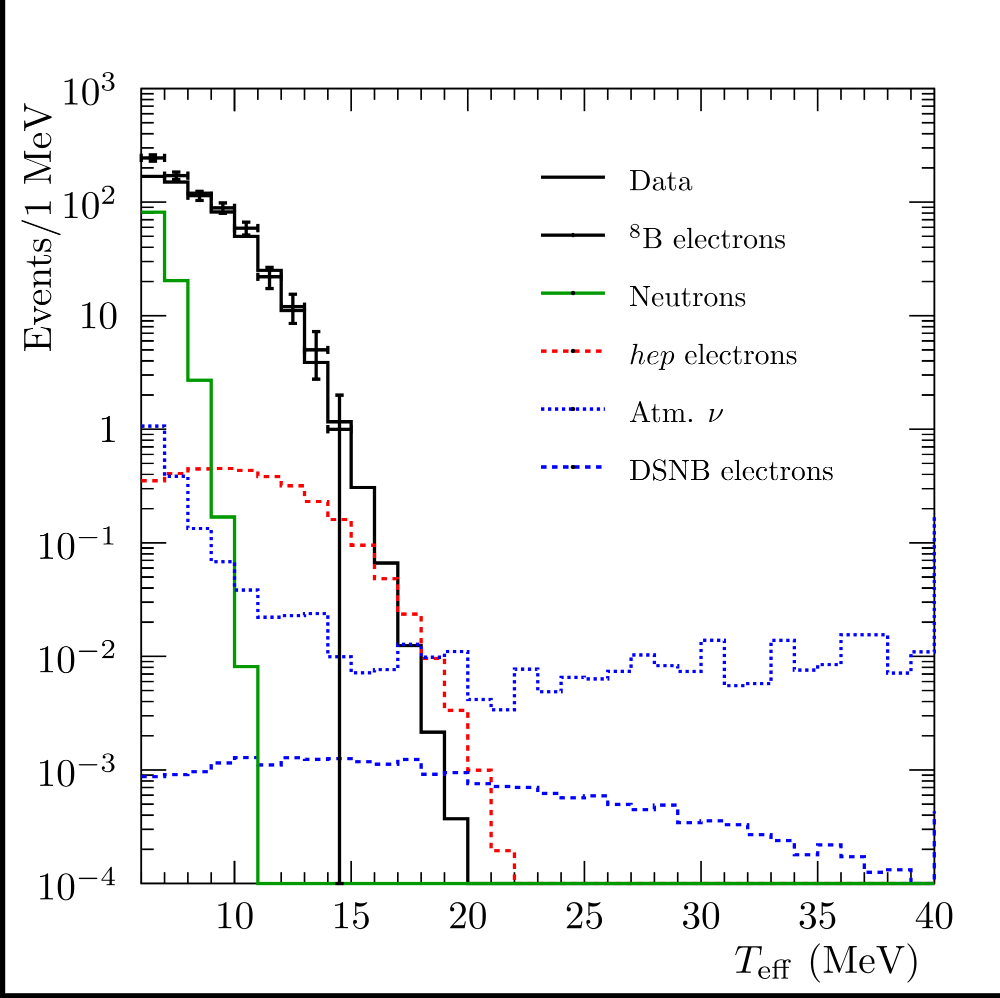
- Signal: CC and ES electrons
  - Enhanced sensitivity due to CC
- Backgrounds: DSNB (fitted), atmospherics, ^{8}B ν





Status of hep search on full dataset

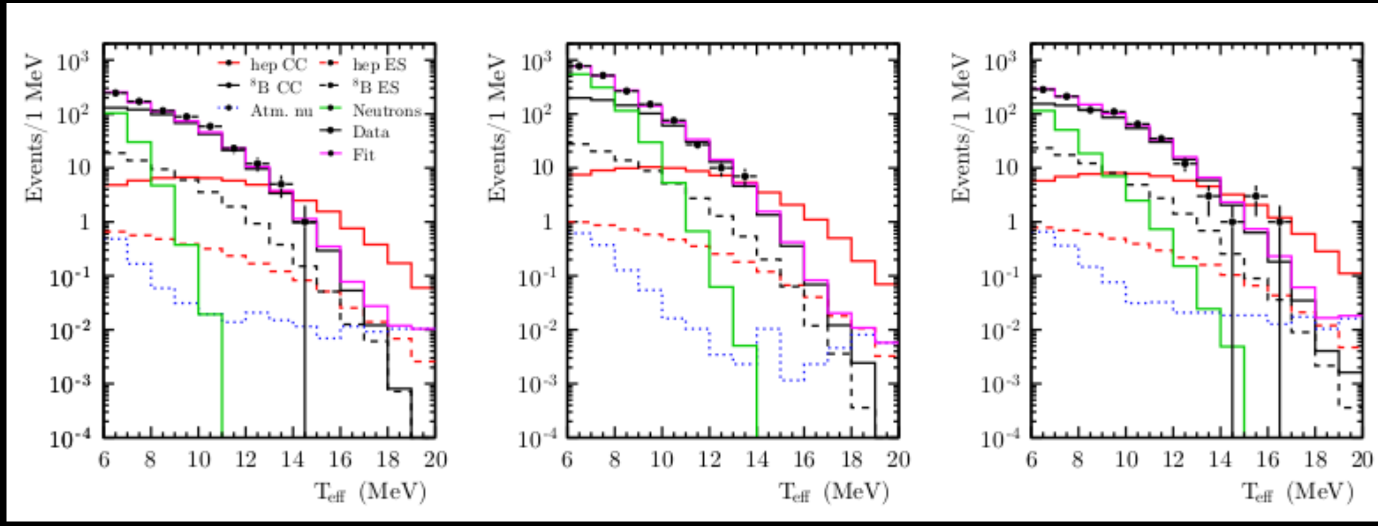
- Sensitivity puts us within range of SSM prediction
- Improvements to maximize sensitivity:
  - Quality cuts (FV, instrumental cuts)
  - atmospheric backgrounds (replace Nuance by Genie)
  - Introduce 8B combined fit
- Blinded analysis complete (1/3 dataset)
  - Undergoing internal review to unblind and fit full data



$$\Phi_{hep}^{\text{1/3 data}} < 1.90 \times 10^4 cm^{-2} s^{-1} \text{ (90\% C.L.)}$$

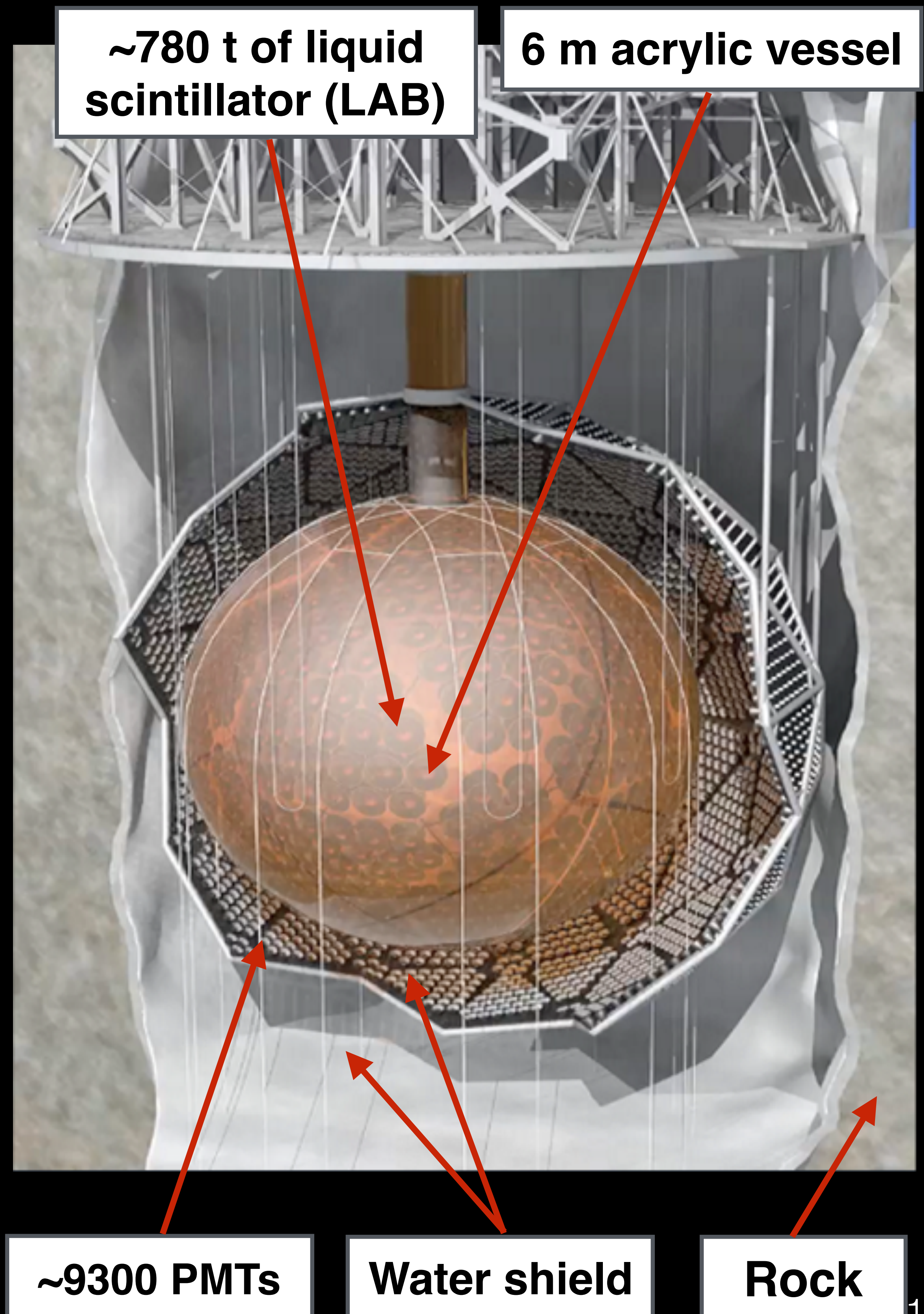
$$\langle \Phi_{hep}^{\text{full data}} \rangle < 9.21 \times 10^3 \text{ cm}^{-2} \text{ s}^{-1}$$

$$(1.15 \times \text{BSB05(OP) SSM})$$



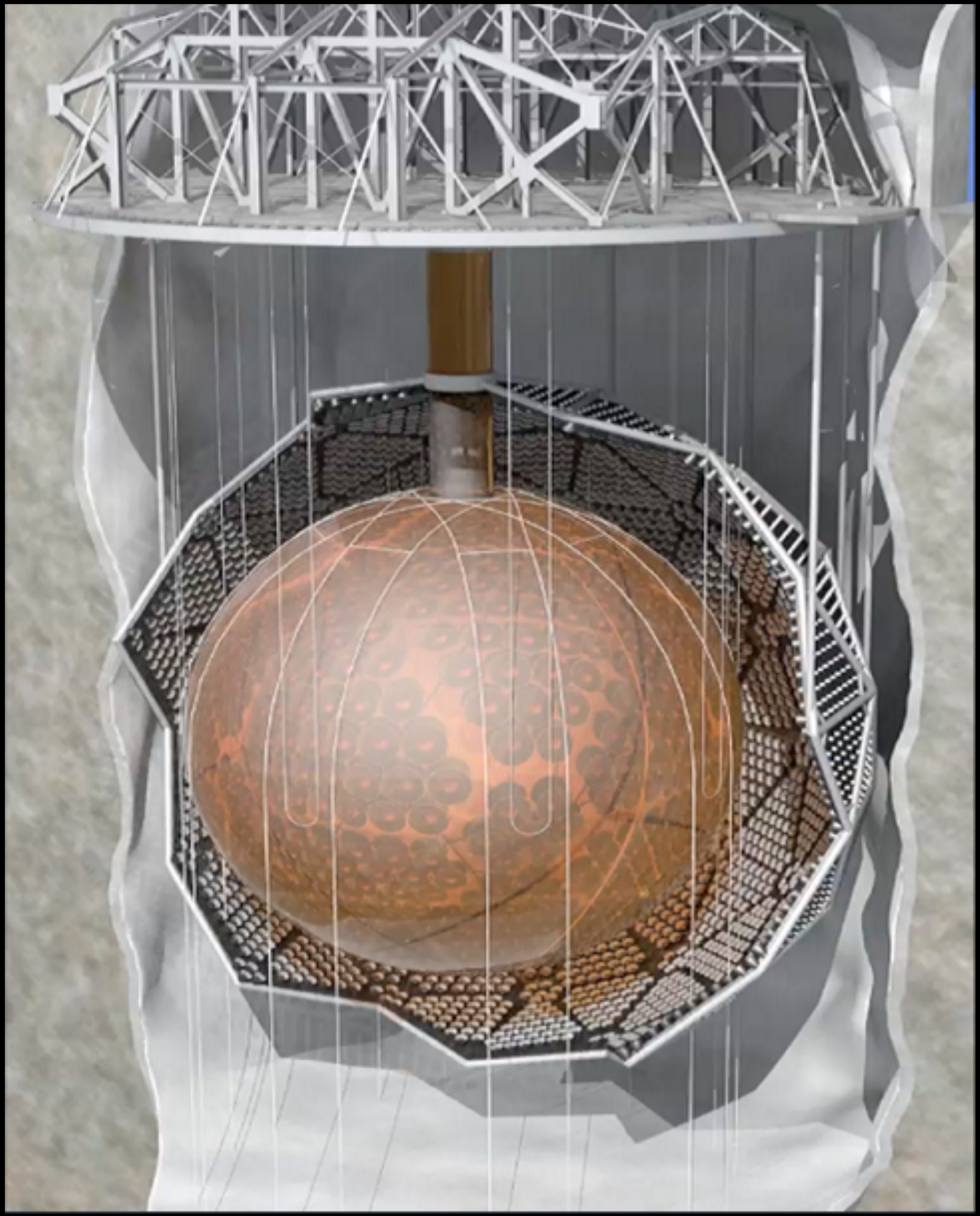
The SNO+Detector

- SNO+ = successor to Sudbury Neutrino Observatory (SNO)
  - Replace heavy water with liquid scintillator
- Support structure holding ~9300 PMTs
  - ~50% coverage with concentrators
- ~63 muons/day in the detector
- Class-2000 clean room
- Target volume in 6 m radius acrylic vessel
- 7000 t ultra pure water shielding
  - 1700 t internal
  - 5300 t external



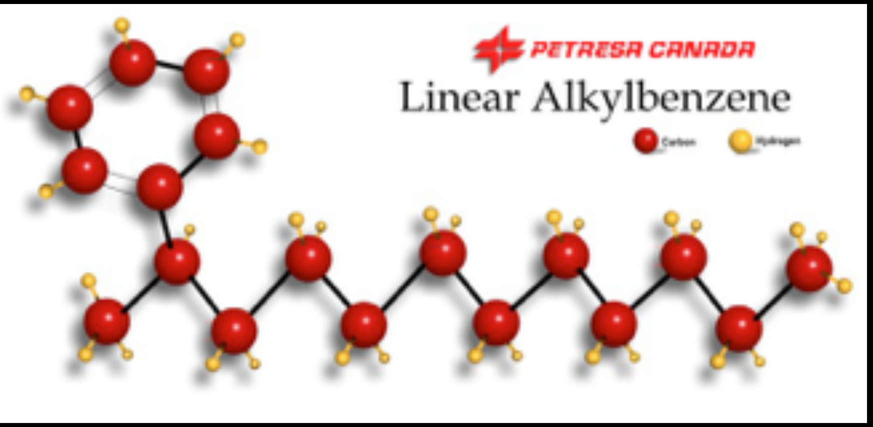
Detector Upgrades

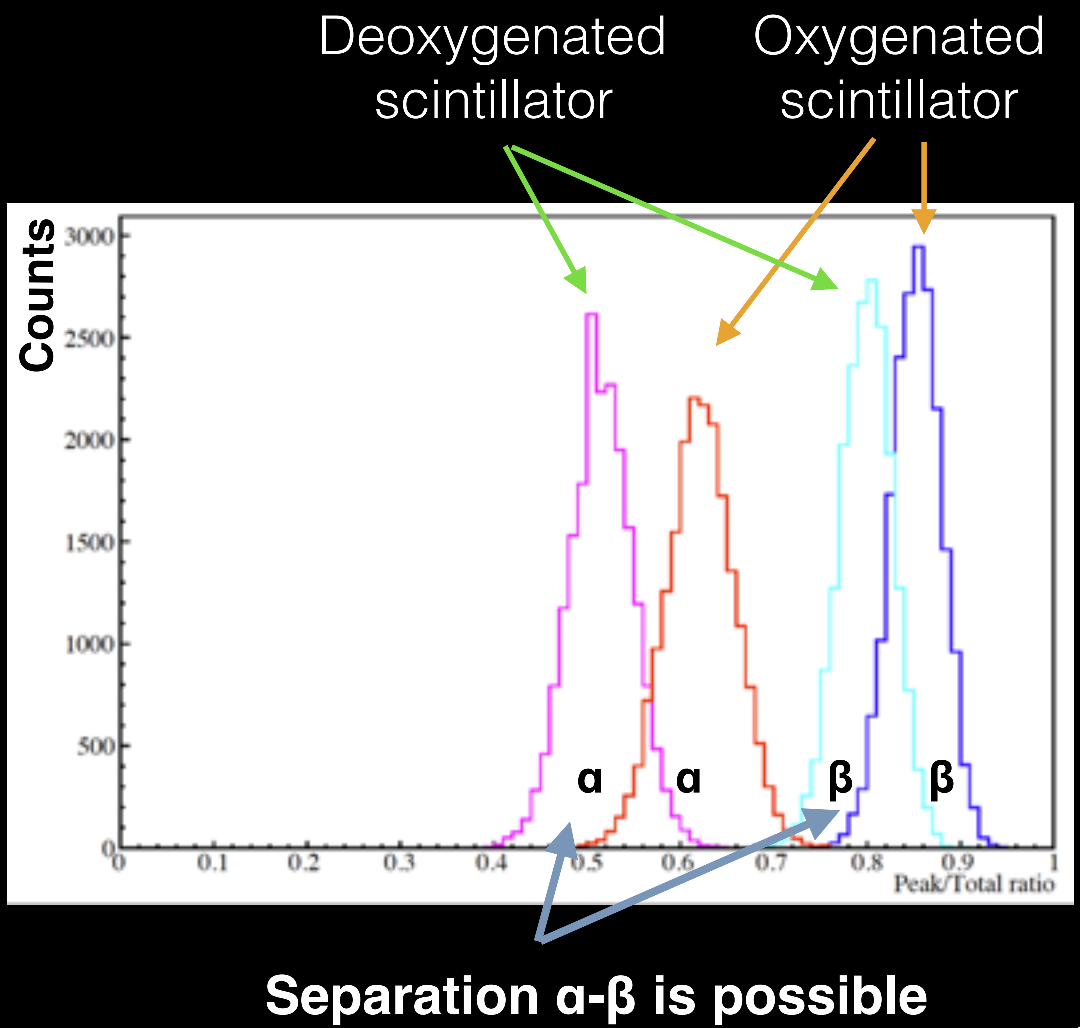
- Replace heavy water with liquid scintillator
  - Load with ^{130}Te for $0\nu\beta\beta$ search
- Hold-down ropes
  - Compensate for lower density of scintillator
- Upgraded electronics
  - Handle higher event rates (> 1 kHz)
- Repaired PMTs
  - Maximize coverage
- New calibration system
  - Minimize source deployment



Detection principle

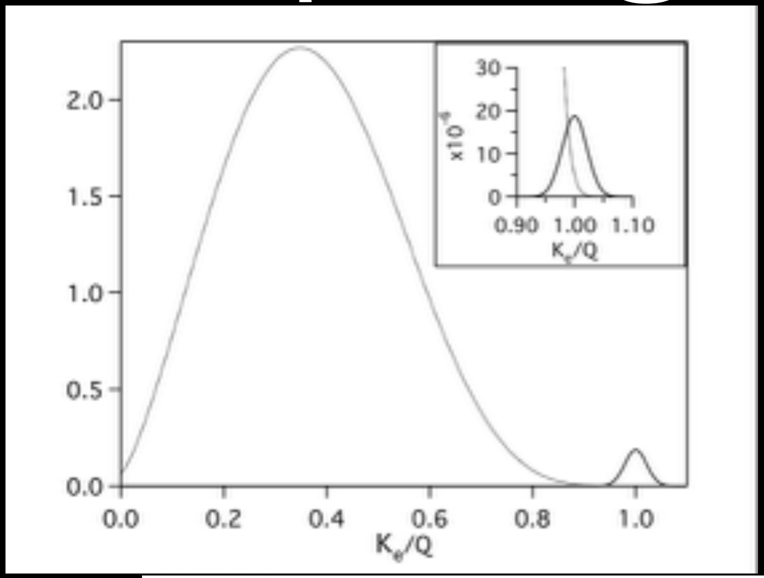
- Organic Scintillator (LAB+PPO) produces light when excited by charged particles
    - ~10000 photons/MeV
    - Few hundred detected by PMTs
    - ~20 m attenuation length
- Calorimetric measurement + pulse shape
    - Event energy from number of photons
    - Even position from photon time-of-flight
- α-β separation through decay-time
    - Background tagging by coincidence techniques

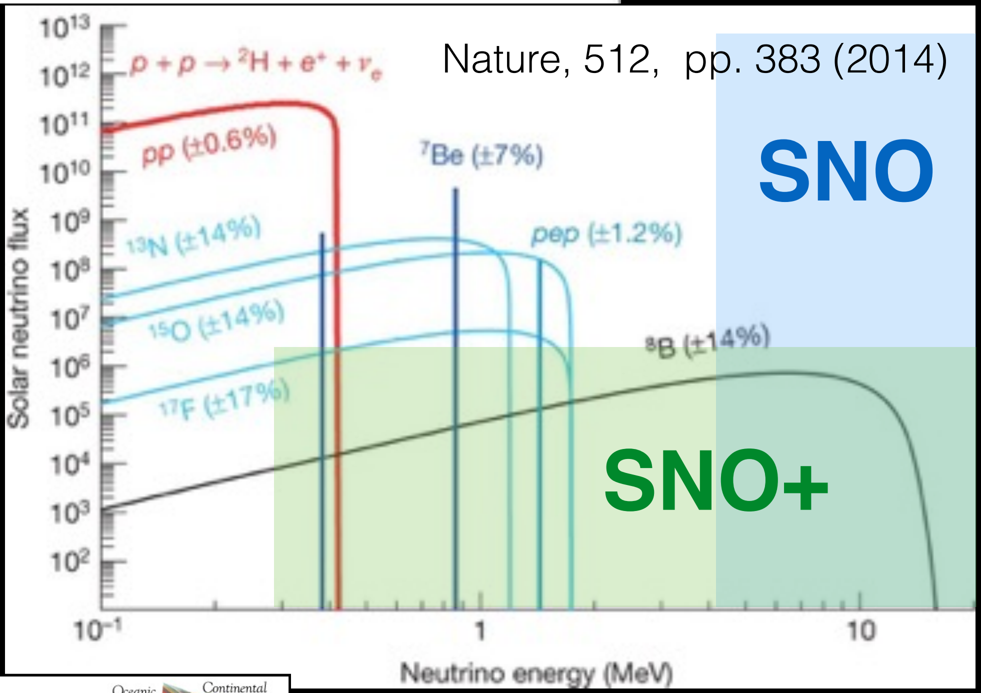


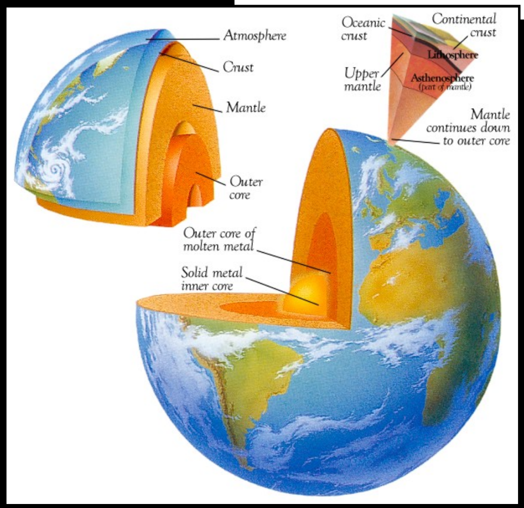


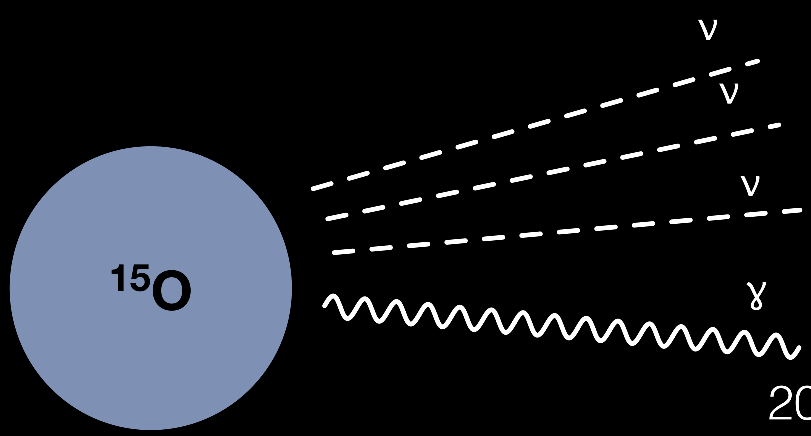
SNO+ physics program

- Main objective:
  - **Search for 0νββ in ^{130}Te**
- Other topics of interest
  - Solar neutrinos
  - Nucleon decay
  - Supernova neutrinos
  - Reactor neutrinos
  - Geo-neutrinos



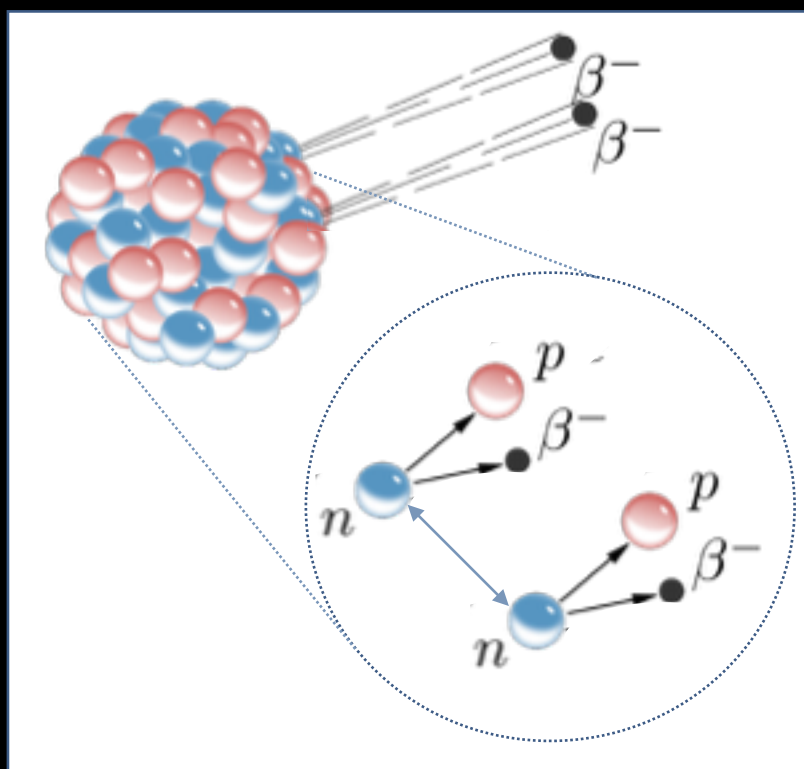






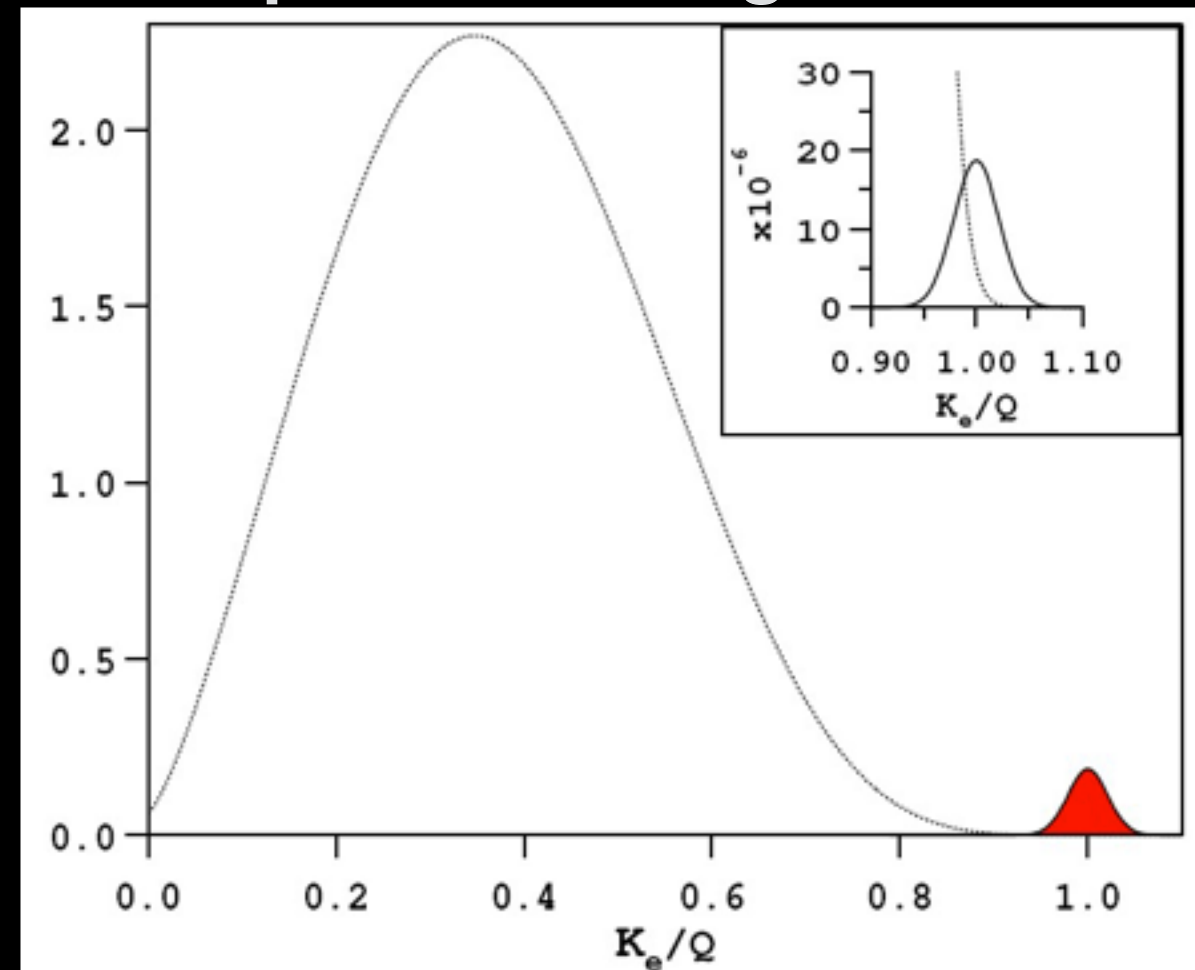
0νββ decay

Neutrino-less double beta decay



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

Experimental signature



If observed:

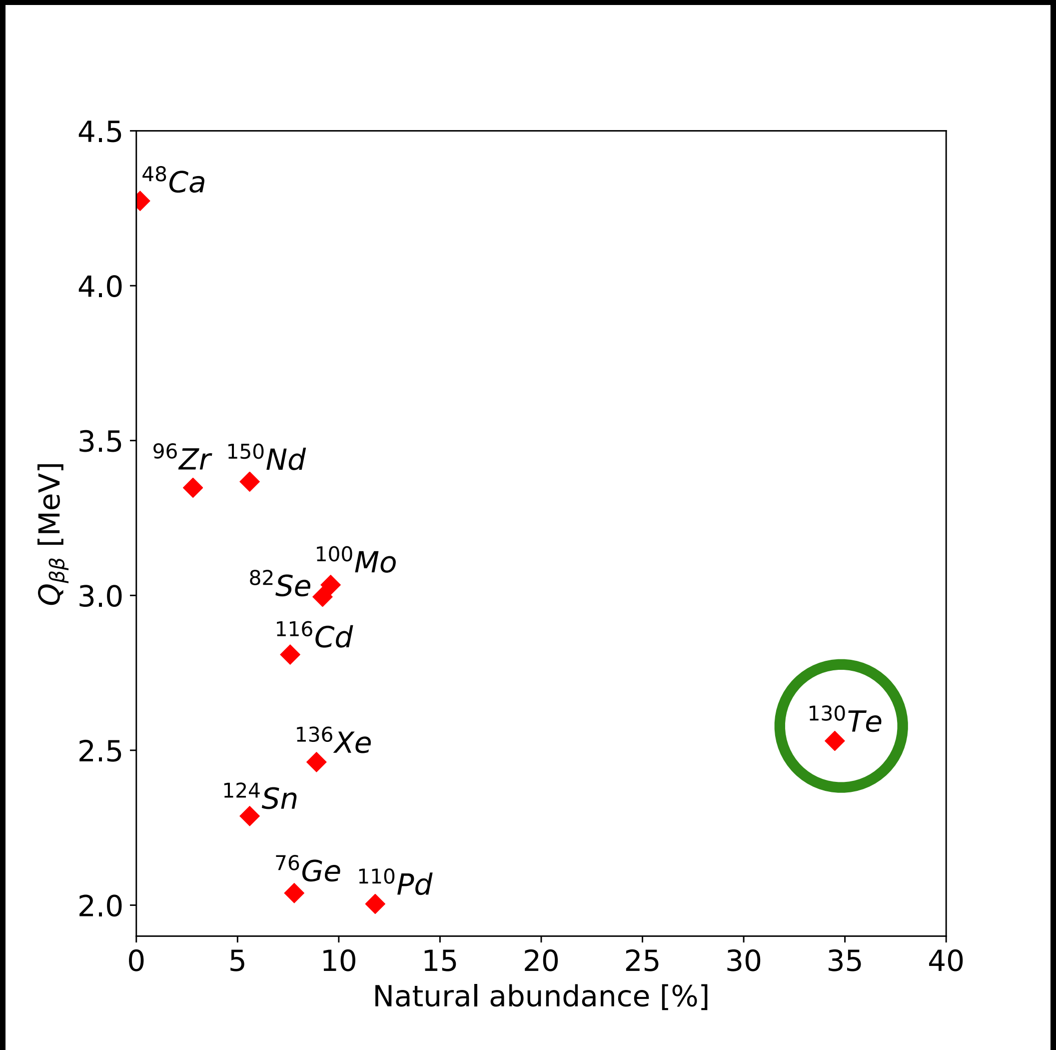
- Neutrinos are Majorana particles
- Lepton number violation: $\Delta L = 2$
- Input on absolute ν mass scale and hierarchy

Approach:

- Search for peak in energy spectrum at end of 2νββ spectrum
- Aim for low background, good energy resolution and large isotope mass

0νββ decay with SNO+

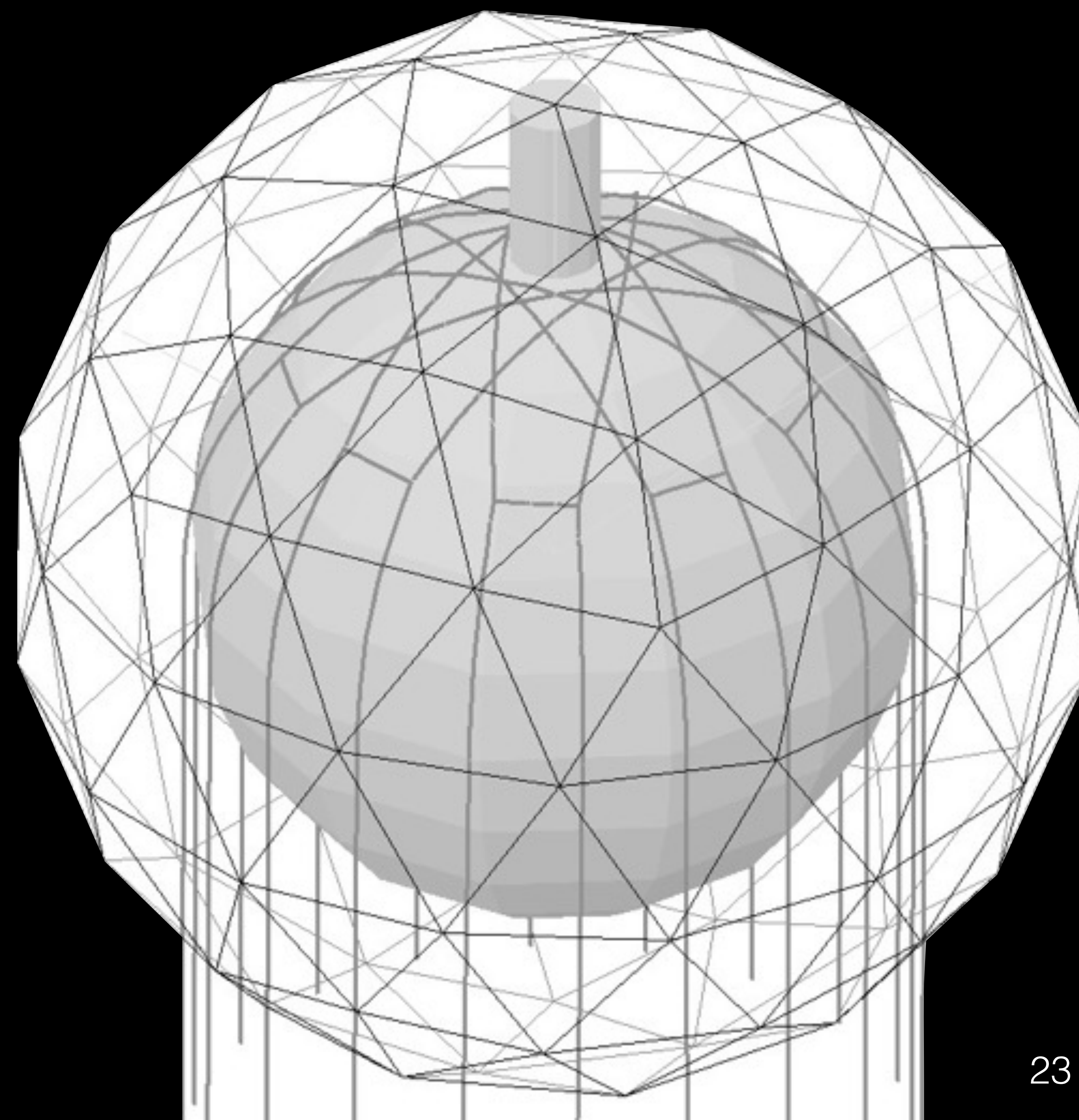
- **Load the scintillator with Te**
- **Double beta decay isotope: ^{130}Te**
  - Long 2νββ half-life: ~ 7x10^{20} years
  - High Q-value : ~2.5 MeV
  - High natural abundance: ~30%
  - No absorption lines in PMT sensitive region
  - Scalable: by increasing loading
- **Loading method: Te acid + butanediol (TeBD)**
  - Initially loading 0.5% (funding secured)
    - ~1330 kg of ^{130}Te
  - Good optics: transparent, low scattering



SNO+ advantages

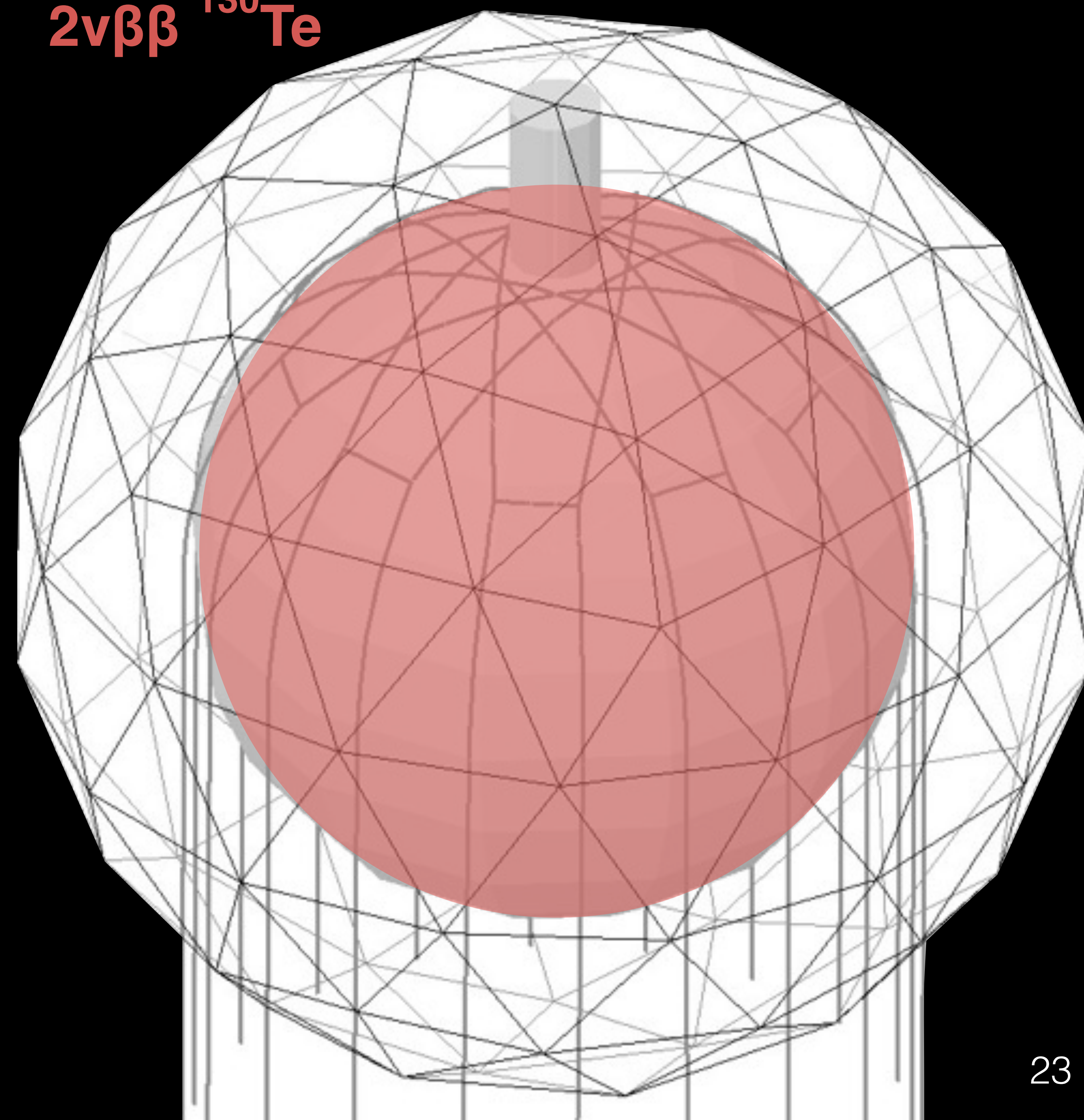
- Scalable loading
- Low backgrounds
  - External shielding
  - Scintillator self-shielding
  - LAB purification

SNO+ 0νββ backgrounds



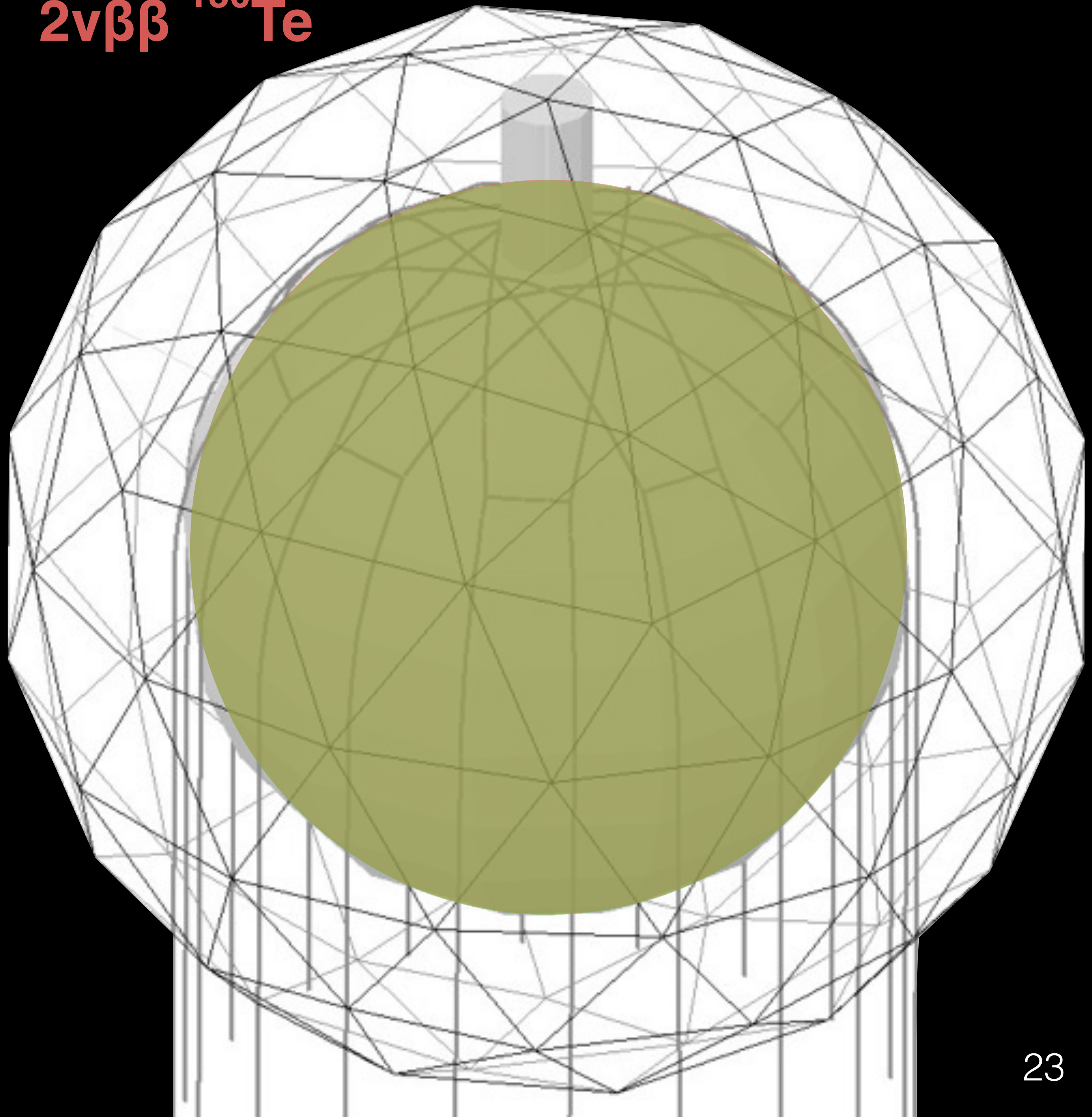
SNO+ 0νββ backgrounds

- **Irreducible:**
  - **^{8}B solar neutrinos**
  - **2νββ ^{130}Te**



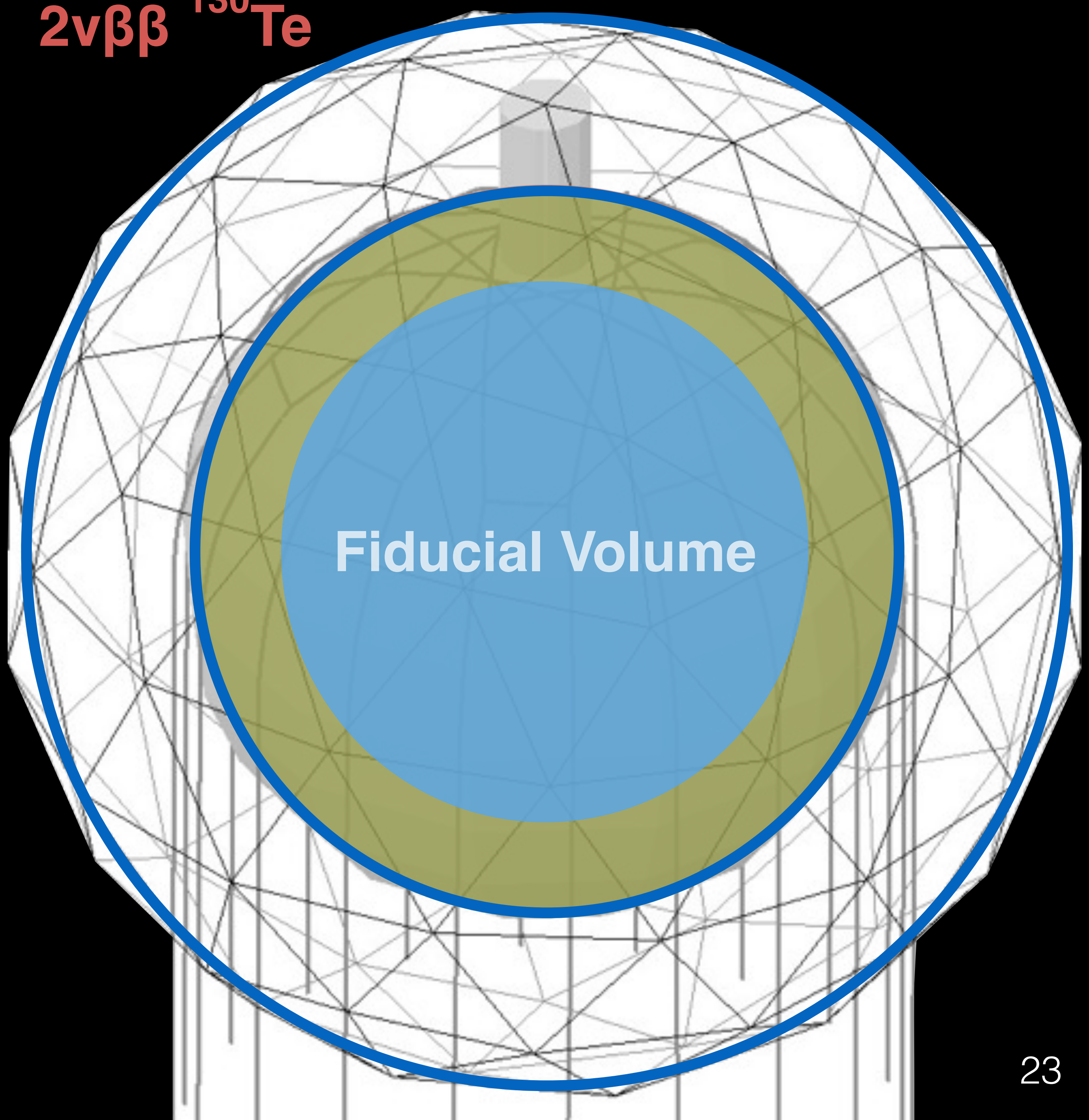
SNO+ 0νββ backgrounds

- **Internal backgrounds:**
  - **Cosmogenic**
    - **^{60}Co, ^{131}I, ^{110m}Ag, ^{124}Sb, ^{11}C**
  - **Scintillator cocktail**
    - **^{238}U, ^{232}Th, ^{210}Po, ^{14}C**
  - **Thermal neutrons**
    - **Capture on H**
- **Irreducible:**
  - **^{8}B solar neutrinos**
  - **2νββ ^{130}Te**

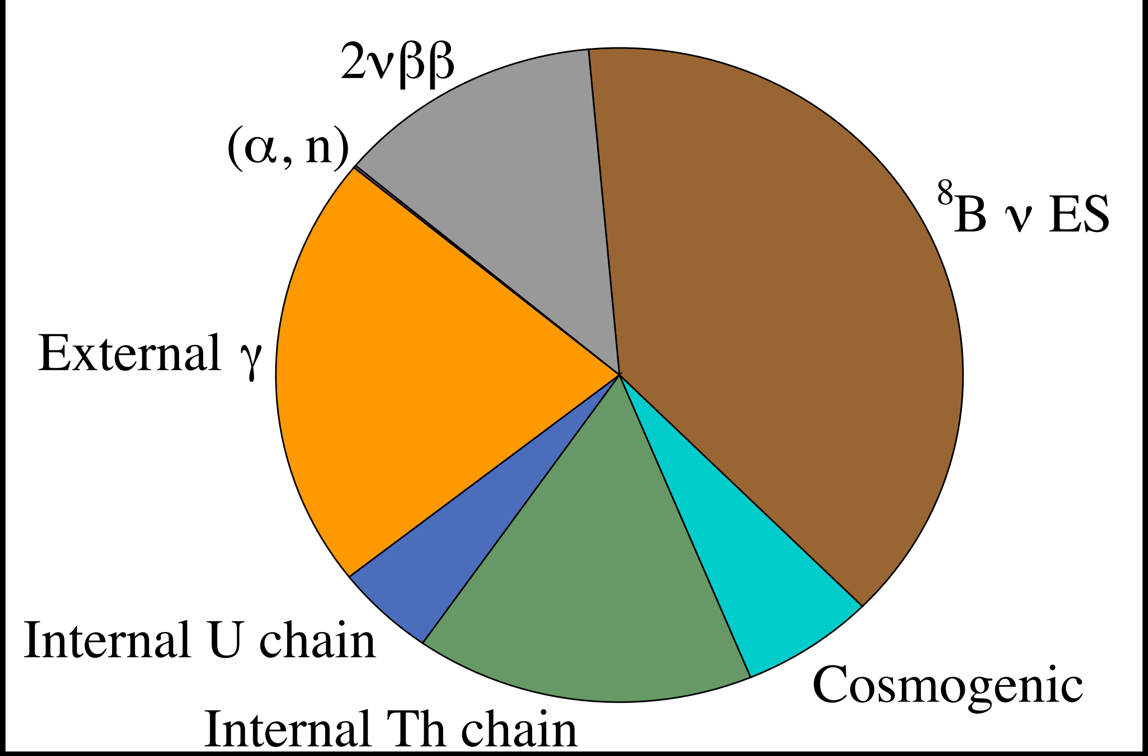


SNO+ 0νββ backgrounds

- **Internal backgrounds:**
  - **Cosmogenic**
    - **^{60}Co, ^{131}I, ^{110m}Ag, ^{124}Sb, ^{11}C**
  - **Scintillator cocktail**
    - **^{238}U, ^{232}Th, ^{210}Po, ^{14}C**
  - **Thermal neutrons**
    - **Capture on H**
- **External backgrounds:**
  - **Acrylic vessel (AV)**
    - **Radon daughters (^{210}Pb, ^{210}Bi, ^{210}Po)**
  - **AV, PMTs, H_2O, Ropes**
    - **^{214}Bi and ^{208}Tl**
- **Irreducible:**
  - **^{8}B solar neutrinos**
  - **2νββ ^{130}Te**



SNO+ background model



13 events/year in FV and ROI

^{8}B solar ν ES

- Mostly flat spectrum in ROI

External ɣ's

- From AV, ropes, water, PMTs
- FV cut at 3.5 m (20%)
- PMT timing

2νββ decay from ^{130}Te

- Asymmetric ROI

Internal U/Th

- ^{214}BiPo, ^{212}BiPo
- Delayed coincidence

Cosmogenic activated isotopes

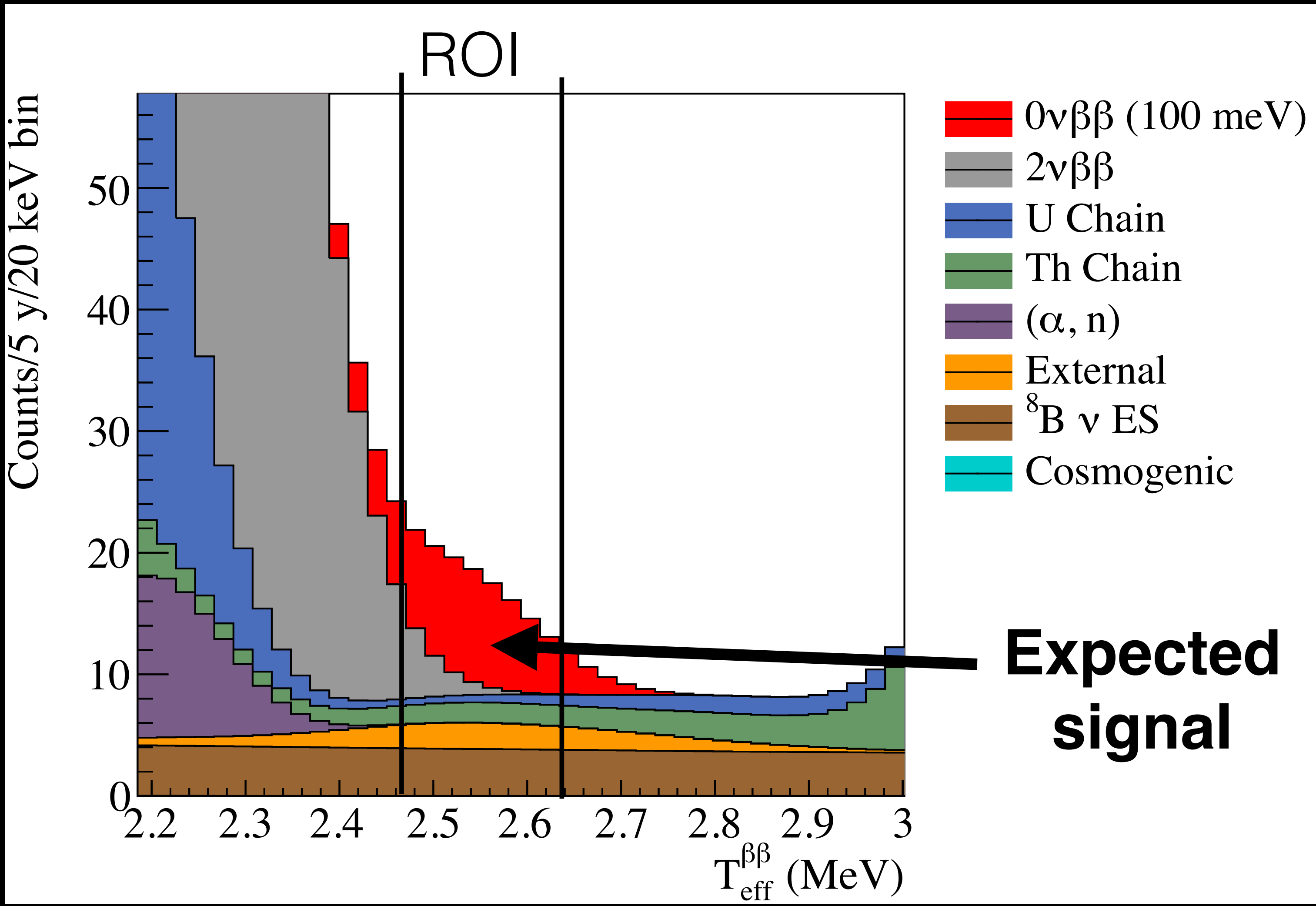
- ^{60}C, ^{110m}Ag, ^{88}Y, ^{22}Na,…
- Purification, cooldown (Te already underground)

(α, n)

- Thermal neutron capture
- Delayed coincidence

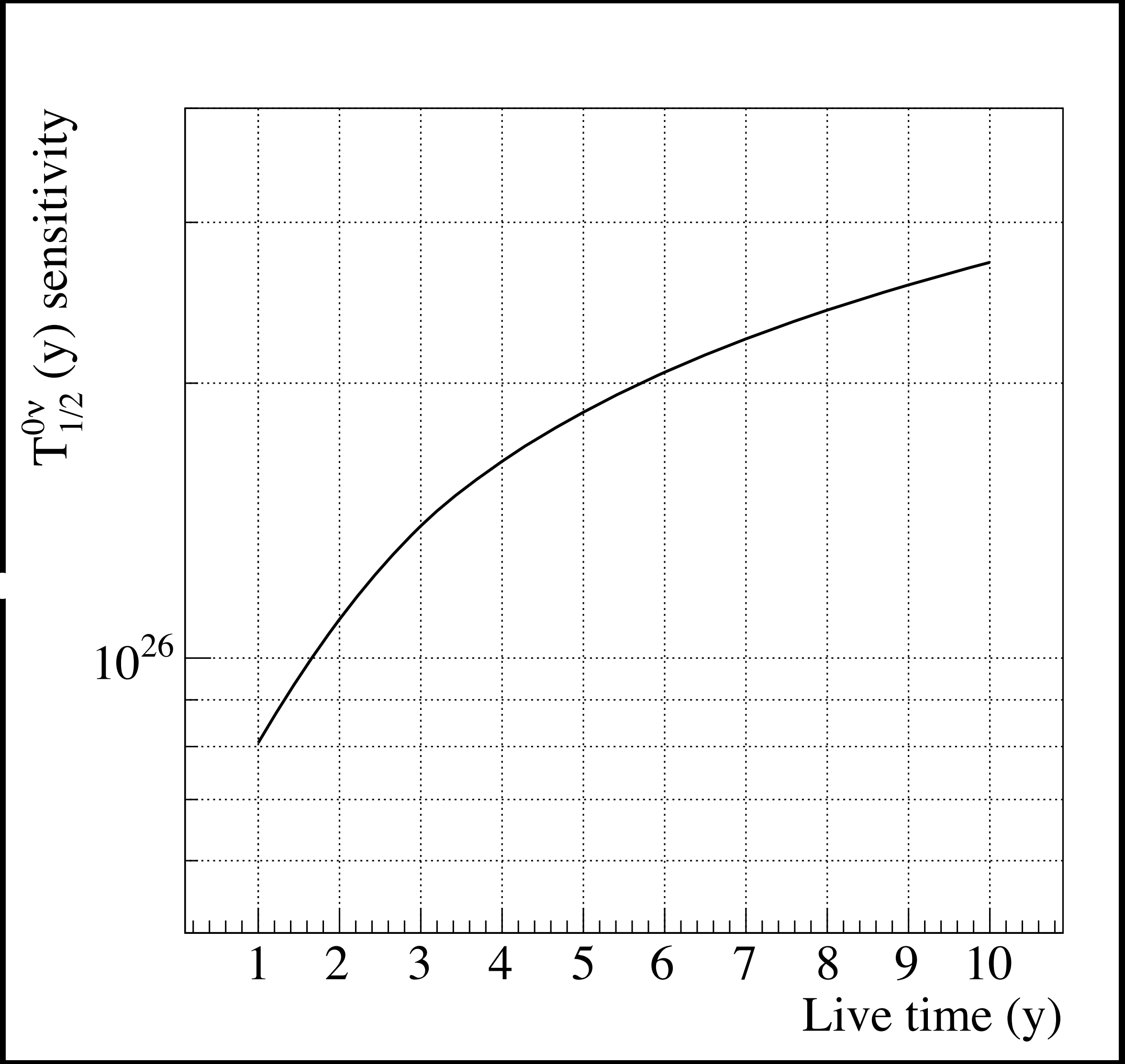
SNO+ 0νββ spectrum

- Details
  - LAB+PPO (2g/L)+bisMSB(15mg/L)
  - FV 3.5 m (20%)
  - > 99.99% rejection ^{214}BiPo
  - 98% rejection ^{212}BiPo
  - 390 hits/MeV
- **Assumptions**
  - NME = 4.03 (IBM-2)
  - gA = 1.269
  - G = 3.69×10^{-14} y^{-1}

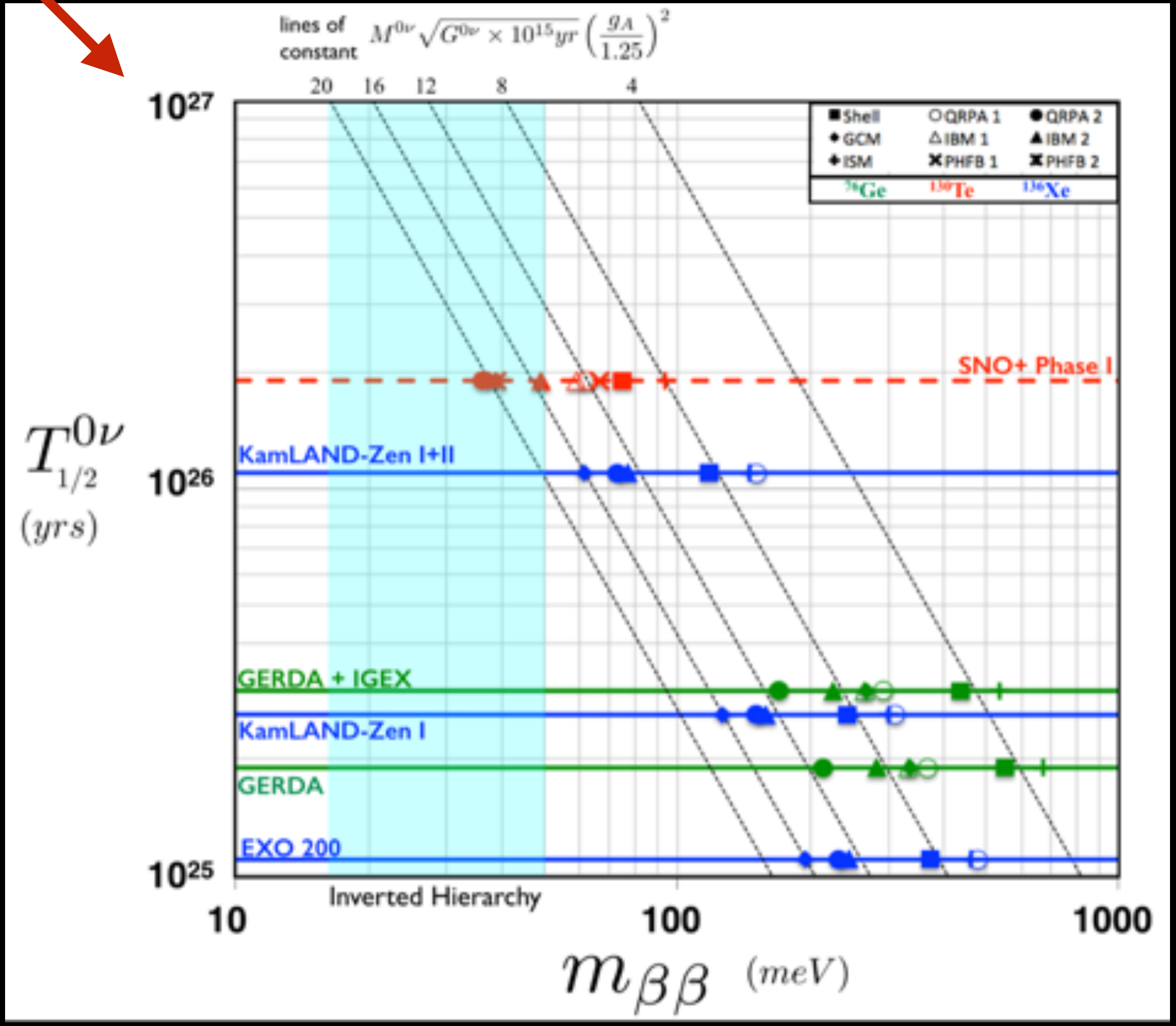


- Expected spectrum after 5 year run
  - $m_{\beta\beta}$ = 100 meV
  - 0.5% Te loading (~1330 kg 130Te)

SNO+ sensitivity

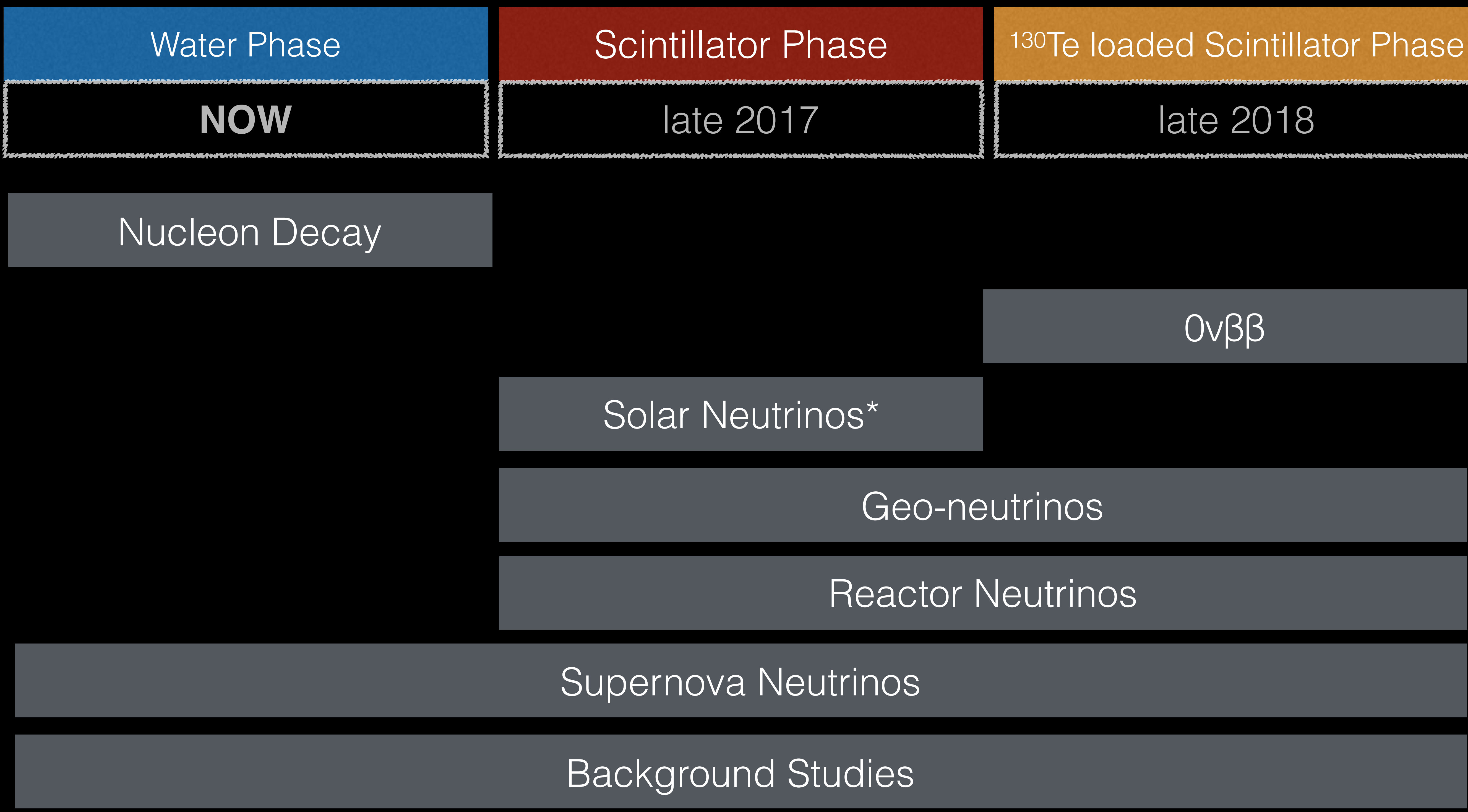


phase II goal



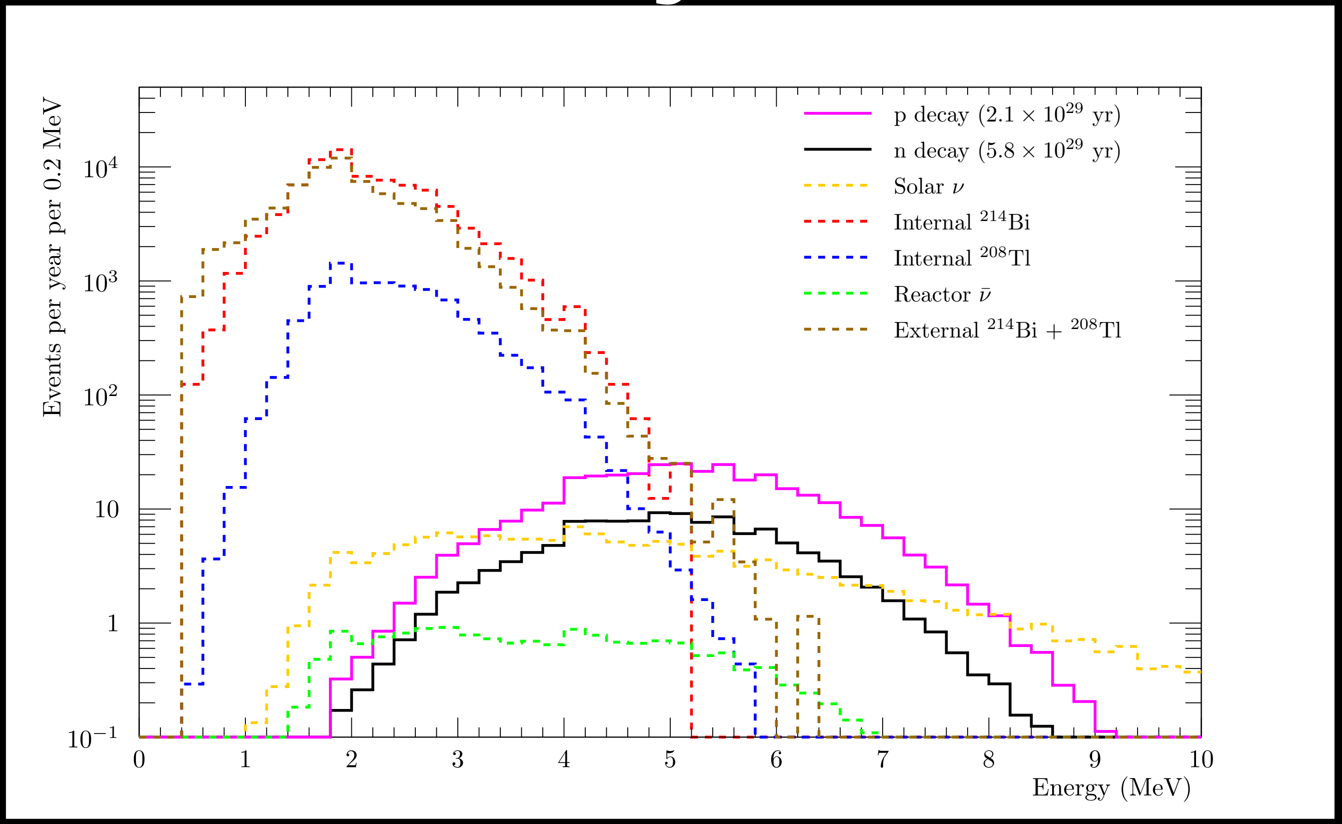
	1 year	5 years
$T_{1/2}$ [10^{26} y]	0.80	1.96
$m_{\beta\beta}$ [meV]	75.2	47.1

Other physics goals



* low energy solar neutrinos after Te-loaded phase

Nucleon decay



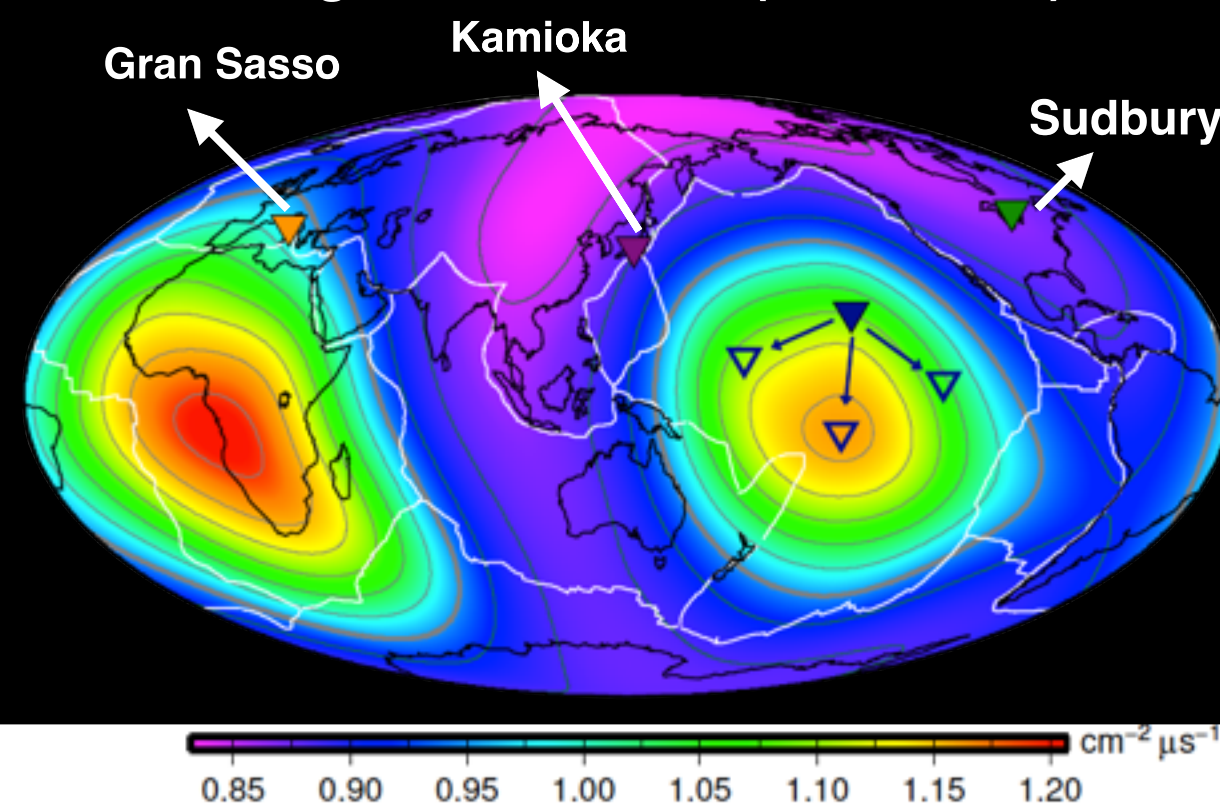
- Look for invisible decay modes
  - n —> ν ν ν
  - p —> ν ν ν
- Leaves unstable nuclei
  - ^{16}O —> ^{15}O* —> ~ 6 MeV ɣ
  - ^{15}N* —> ~6 MeV ɣ

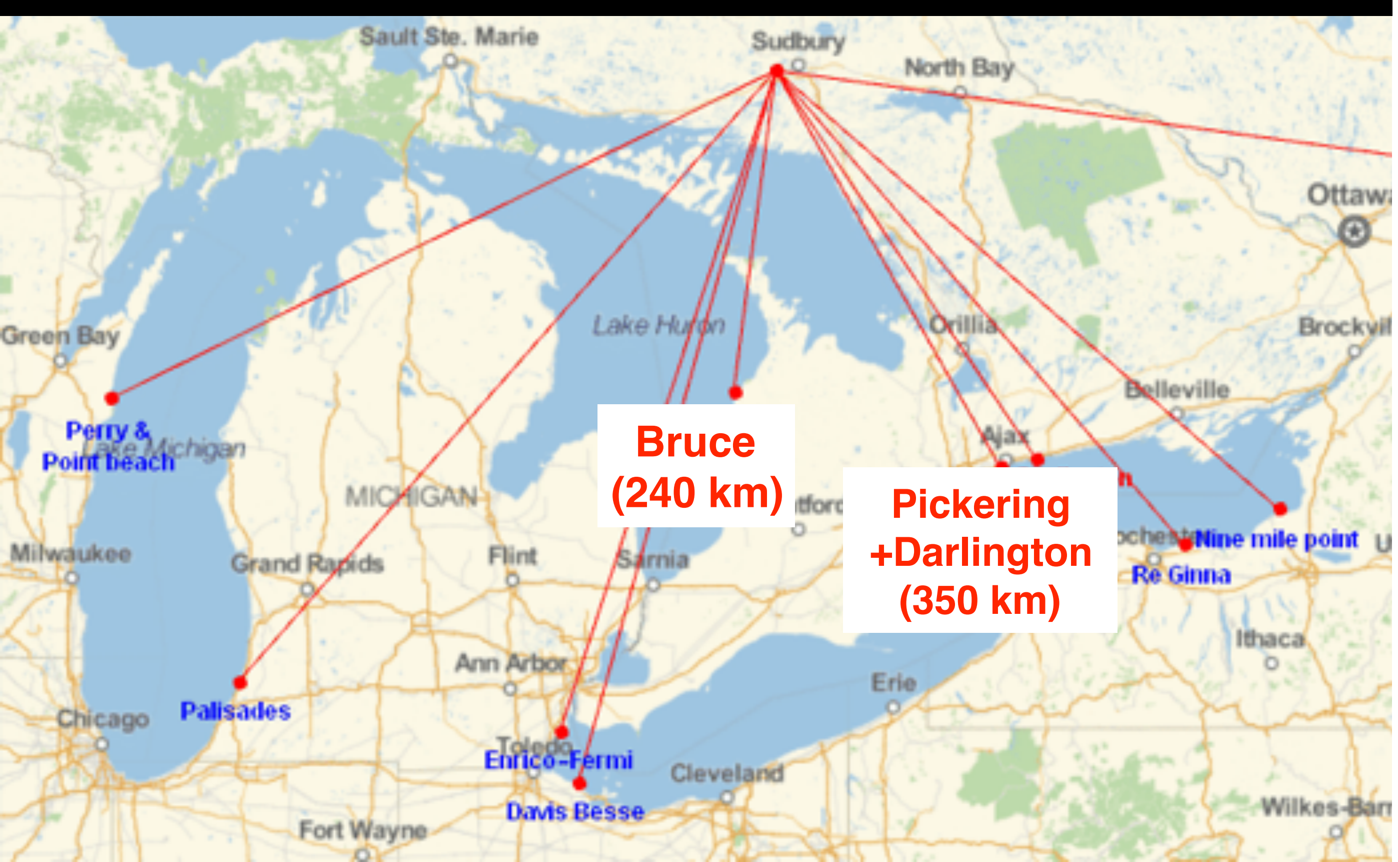
decay signature

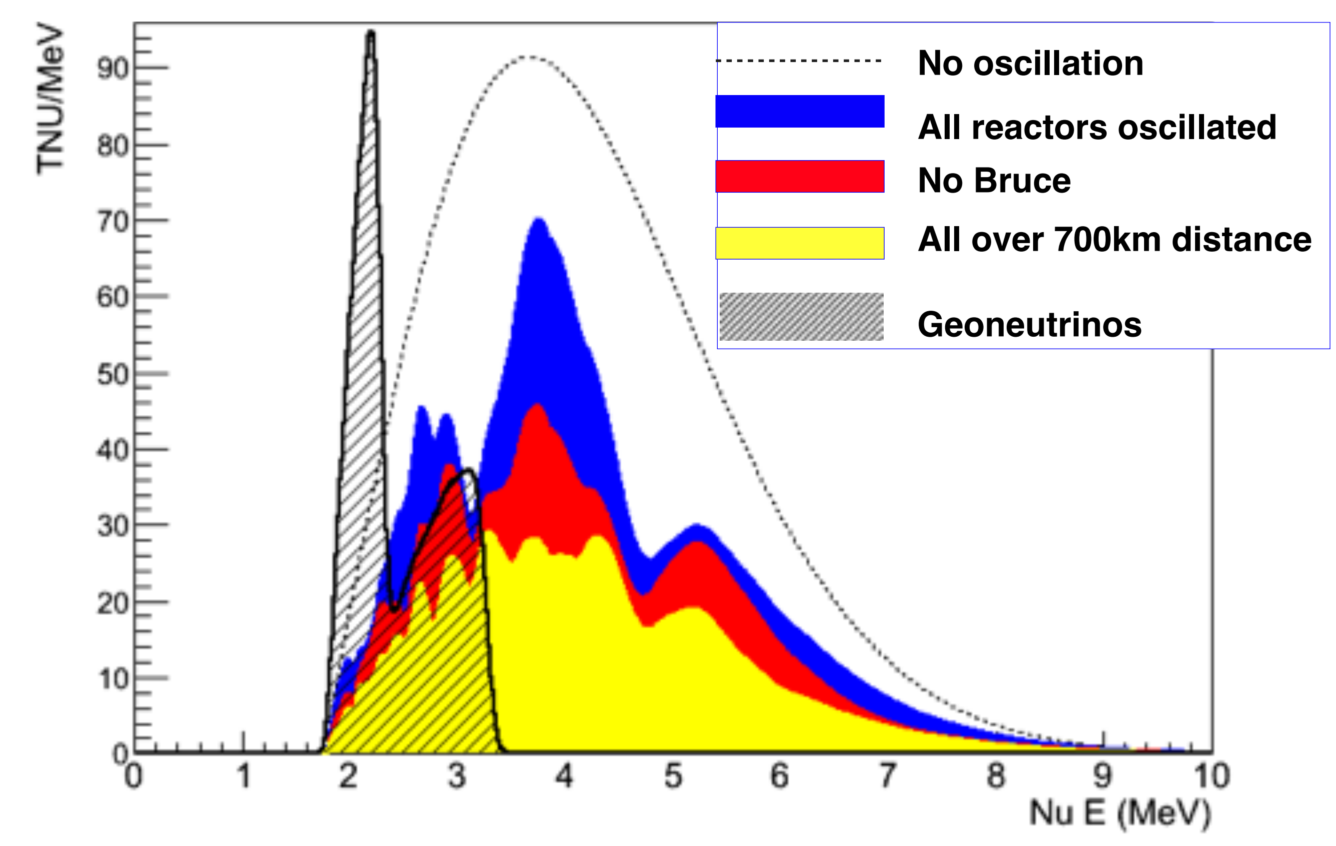
- Sensitivity after 3 months of data taking:
  - τ_n < 1.2×10^{30} years (current limit [KamLAND] : 5.8×10^{29})
  - τ_p < 1.4×10^{30} years (current limit [SNO] : 2.1×10^{29})

Reactor and geo-neutrinos

- **Detection through inverse beta decay**
  - Delayed coincidence e^+ annihilation and n capture
- **Geo**
  - U, Th and K in Earth's crust and mantle
  - Investigate origin of the heat produced within Earth
- **Reactor**
  - 3 nearby reactors dominate flux
  - Precision probe of neutrino oscillations

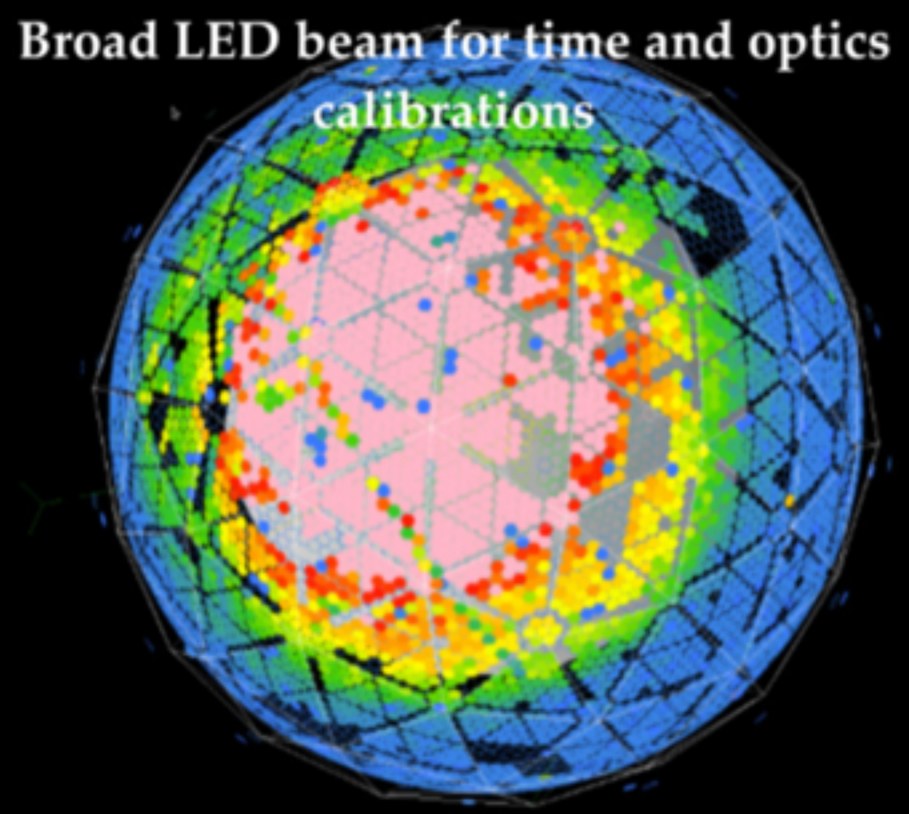


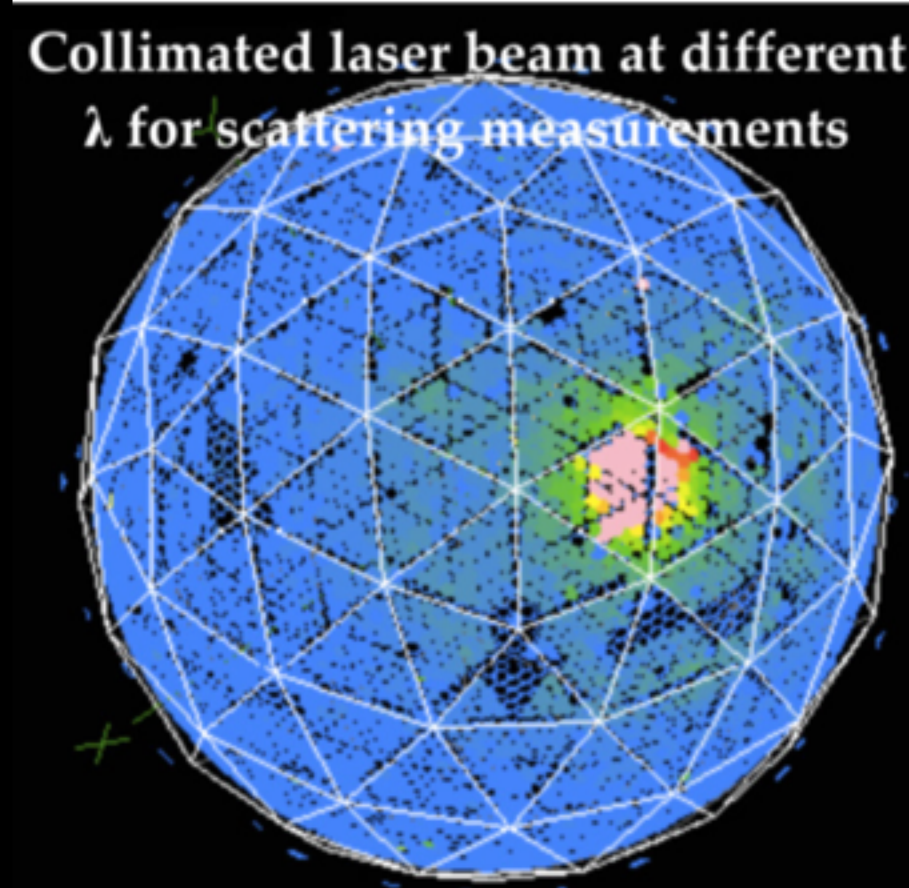




Current Status

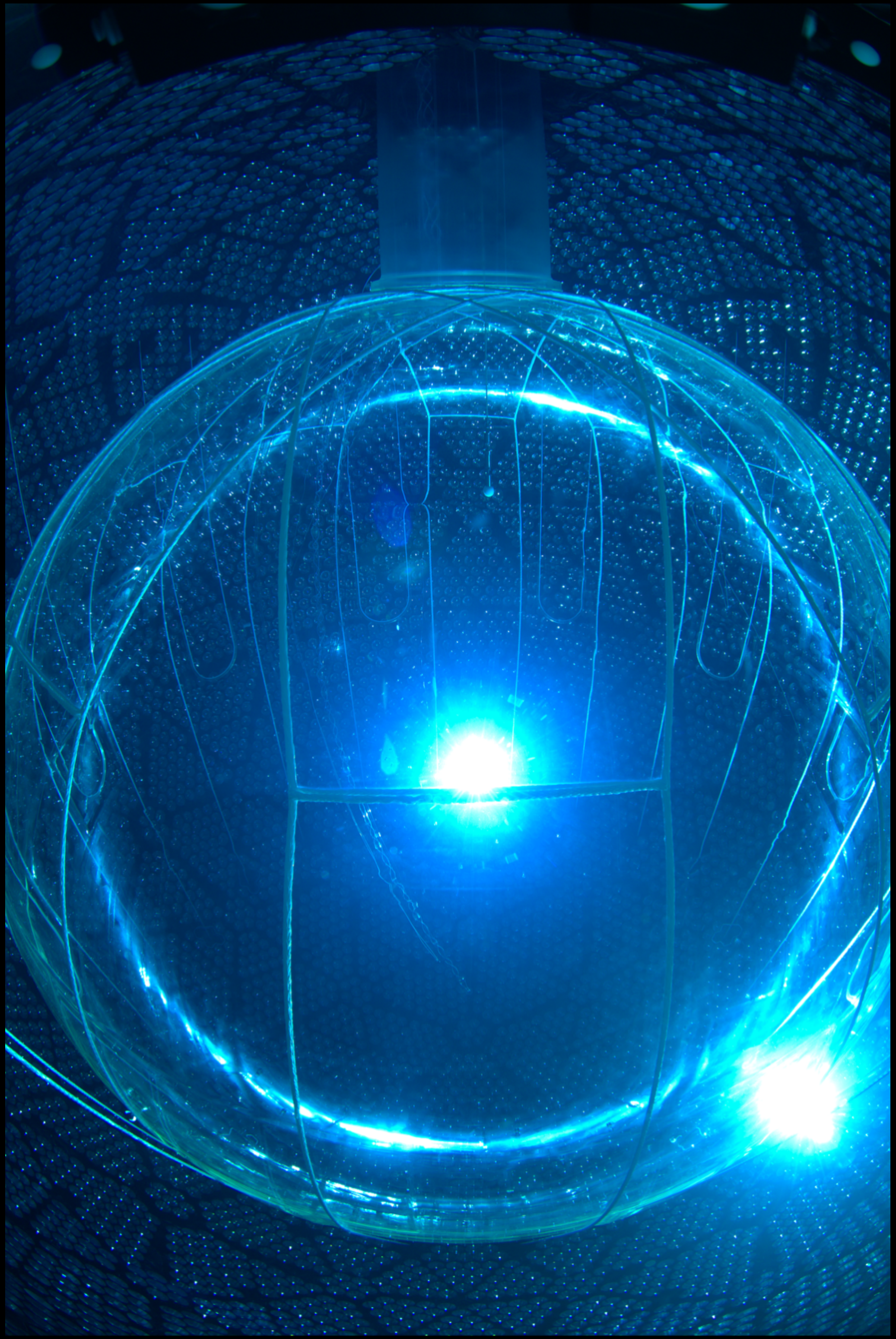
- A very active year:
  - Repaired leaks in cavity
  - Replaced repaired PMTs
  - Commissioned of internal calibration systems (LED/laser)
  - Commissioned electronics upgrades with high event rates
  - Commissioned of DAQ system





Current Status

- Detector filled with water
  - Taking low threshold data
- Laser and ^{16}N source calibrations ongoing (literally now!)
- Reached exposure goal for nucleon decay
  - Blind data taking since May



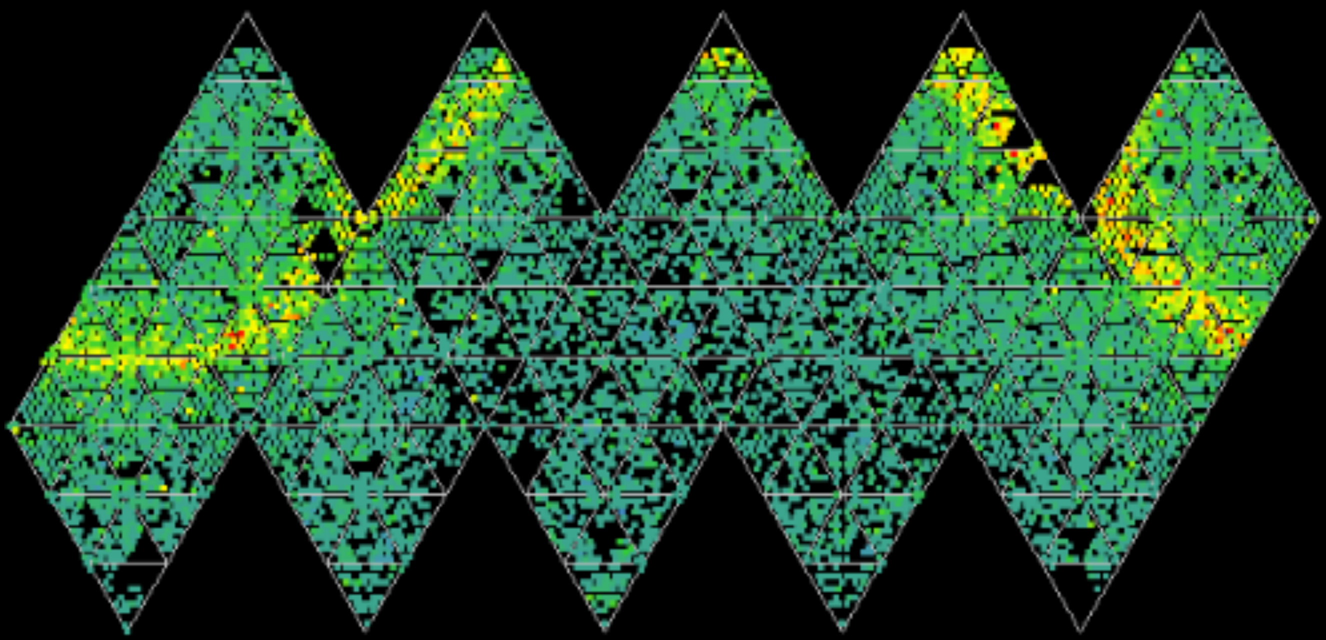
Detector filled with water

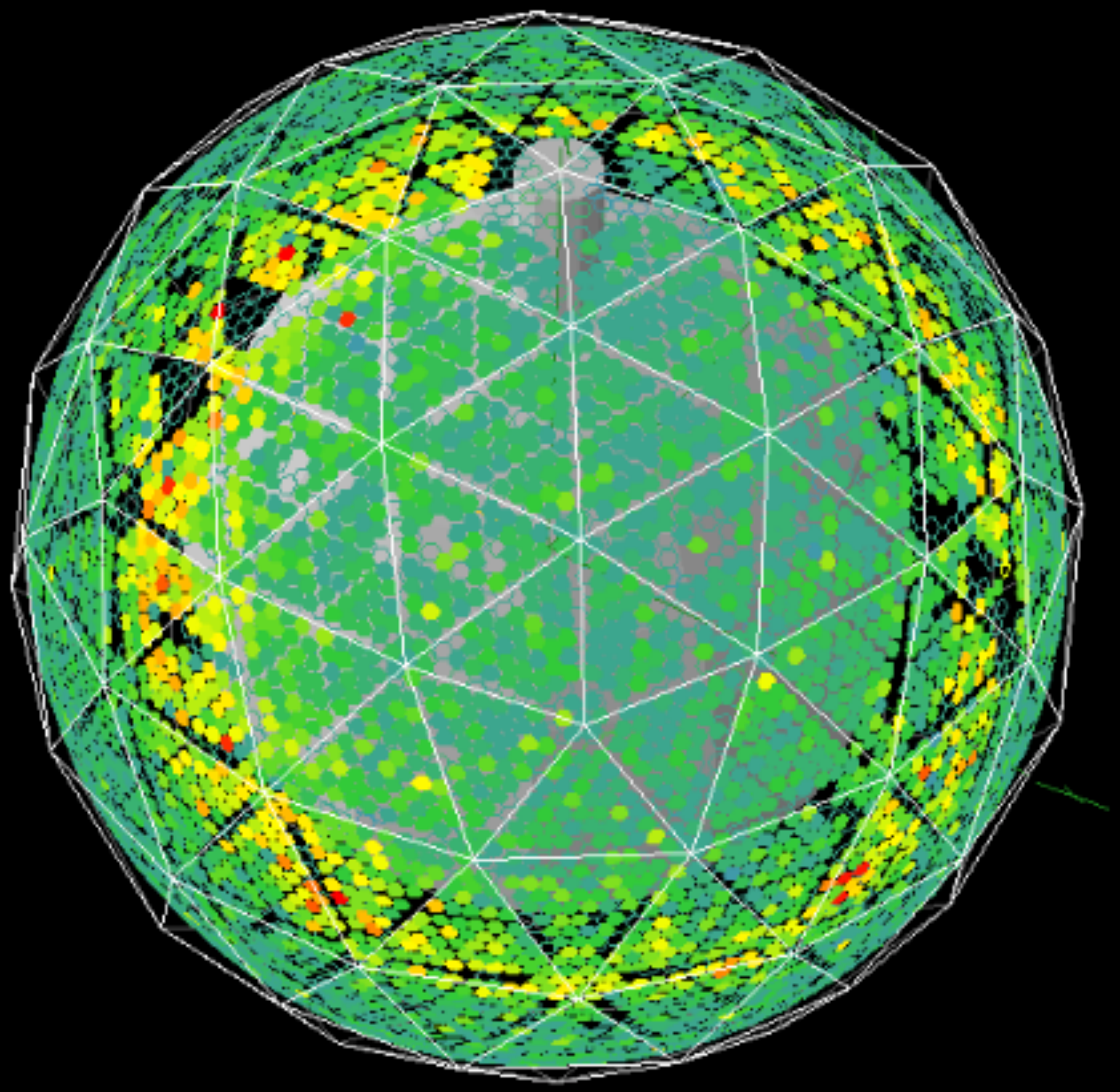
Current Status

- Scintillator purification plant installed and being commissioned
- LAB shipments going underground
- TeA stored underground to cool off
- Currently undergoing construction of Te purification plant

Scintillator purification plant underground

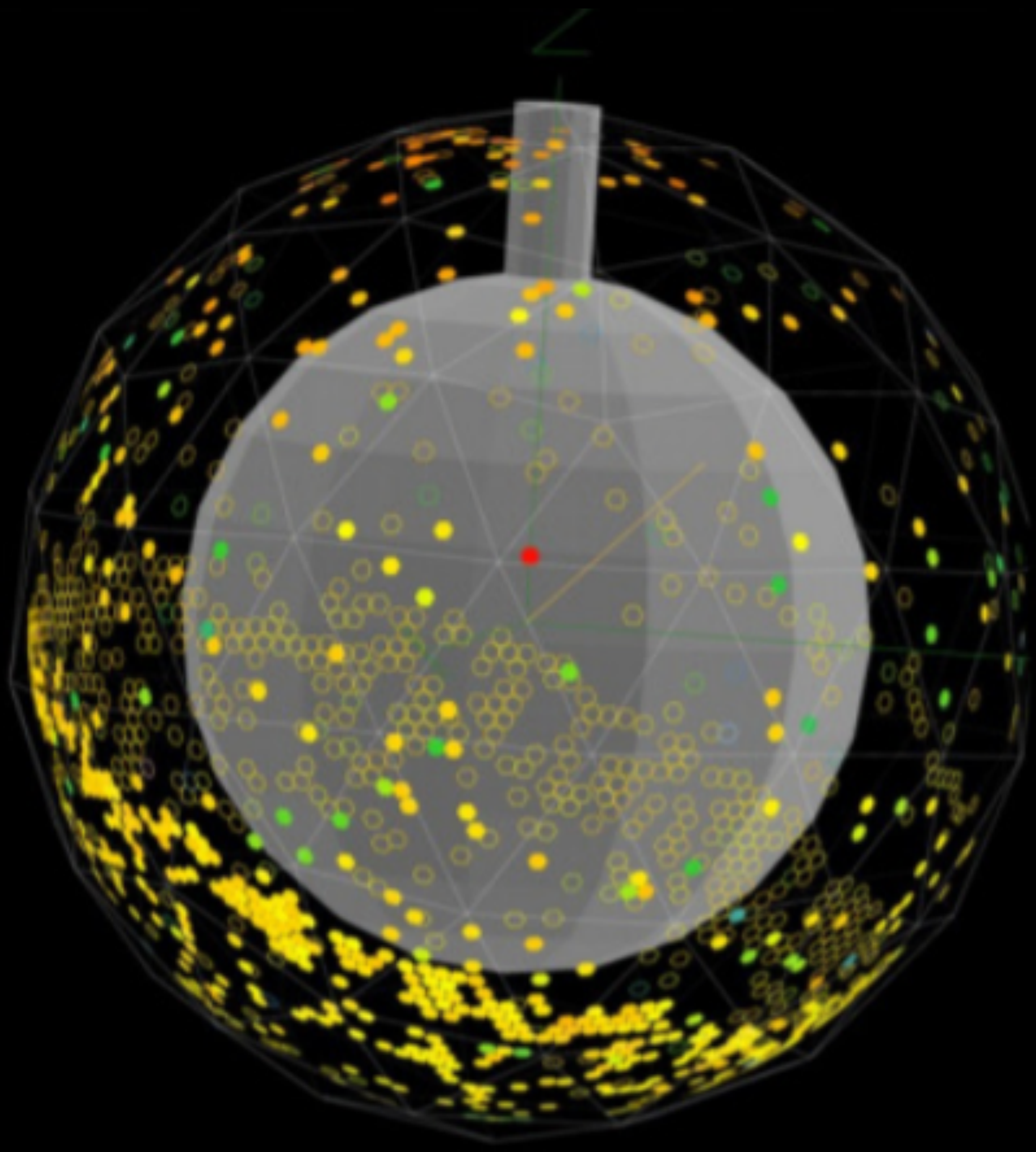
First water data





Atmospheric neutrino candidate event, upward going, no OWLs, large number of hits (Feb 2017)

First water data



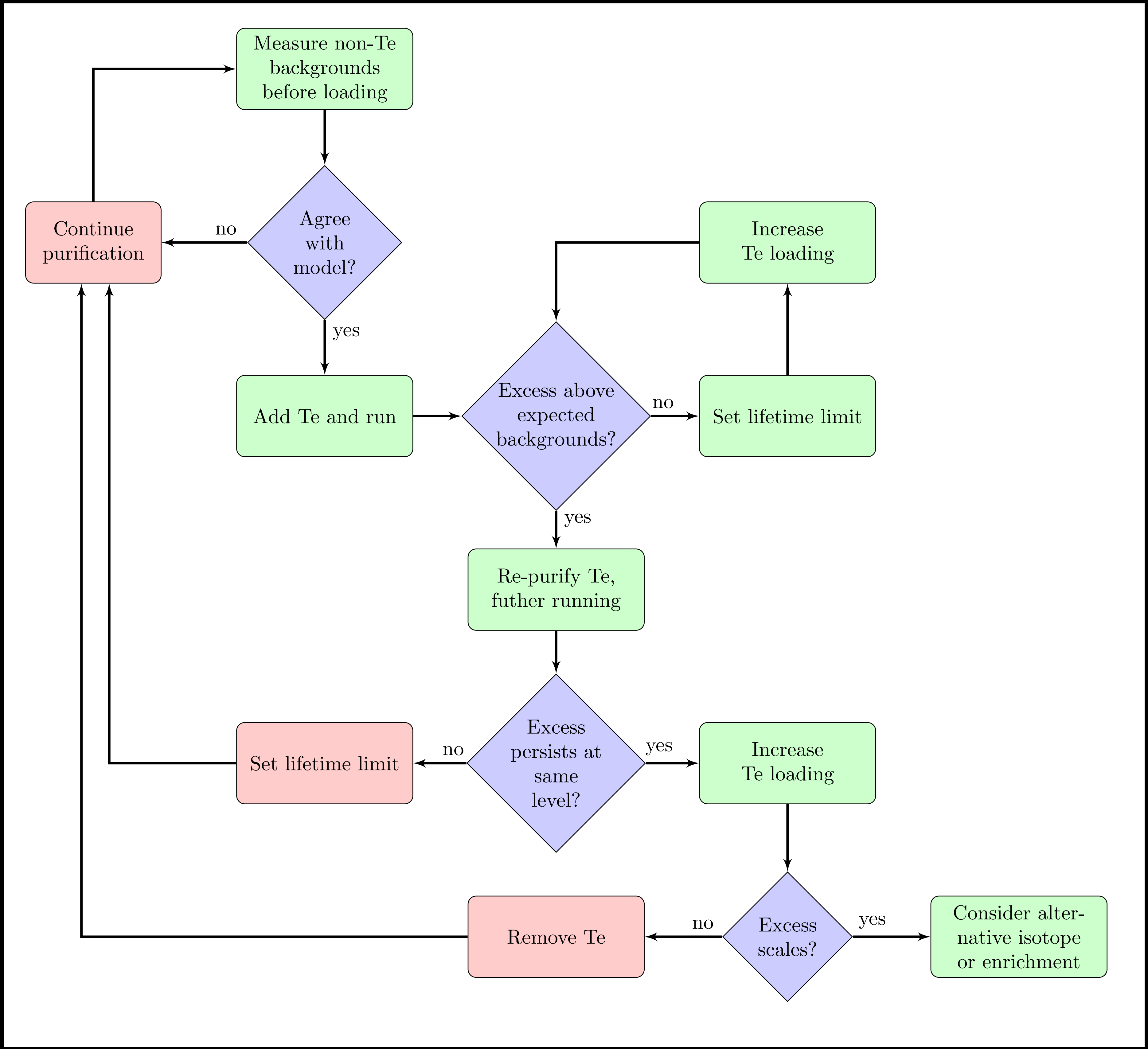
Downward going atmospheric neutrino candidate event, no OWLs, large number of hits

Conclusion

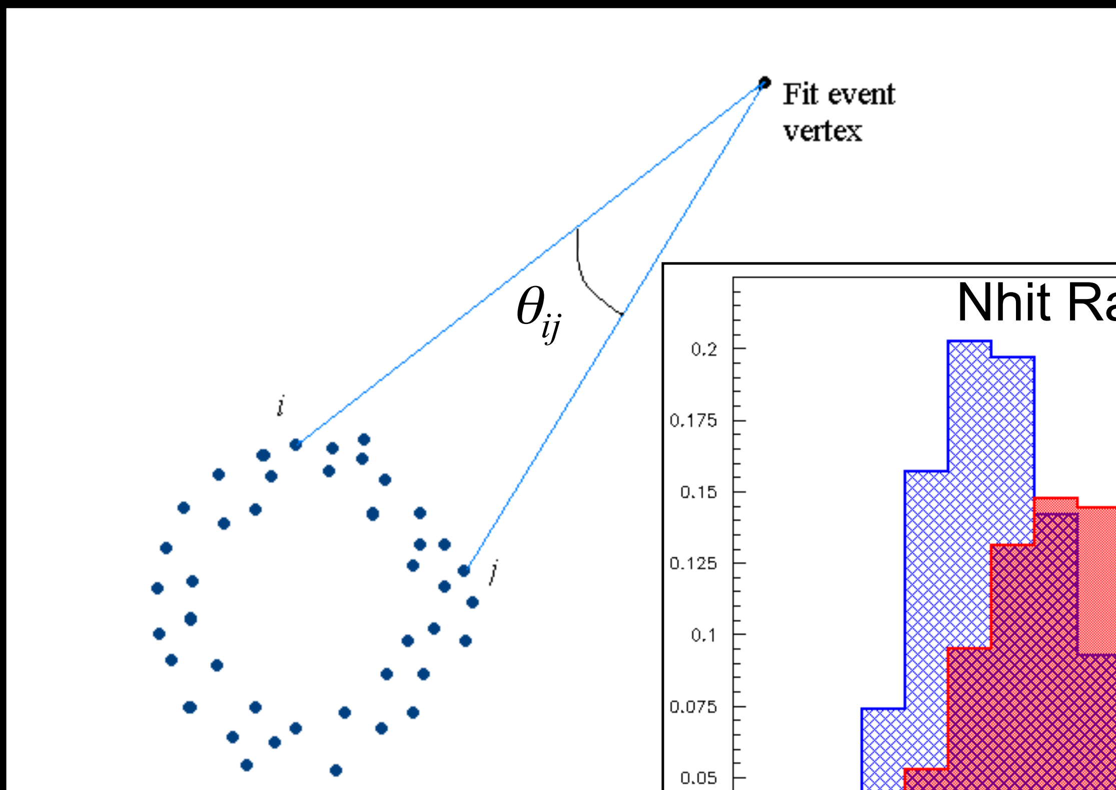
- SNO was instrumental to solve the solar neutrino problem
  - Now pursuing several non 8B analyses with its dataset
  - Motivating sensitivity for HeP neutrino detection
- SNO+ reuses SNO detector with liquid scintillator detector
  - Broad physics program
  - $0\nu\beta\beta$ is the primary goal
- The detector is currently filled with water and taking data
  - Nucleon decay search primary physics objective
- Scintillator purification system is being commissioned
- Tellurium systems under construction
- Neutrinoless double beta decay phase will begin in late 2018
- Water-phase results coming soon

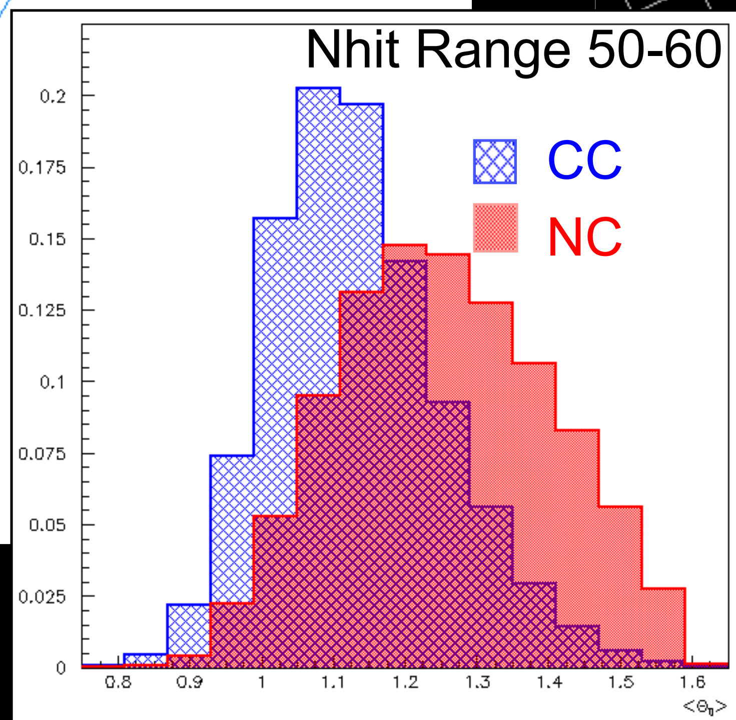
backup

What if we see a bump?



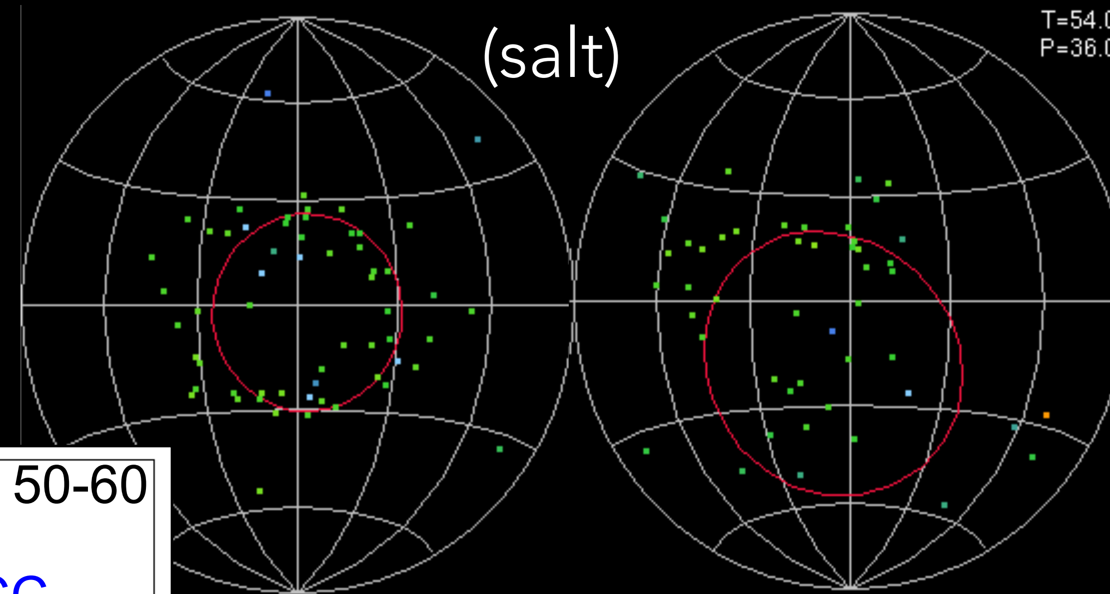
Isotropy





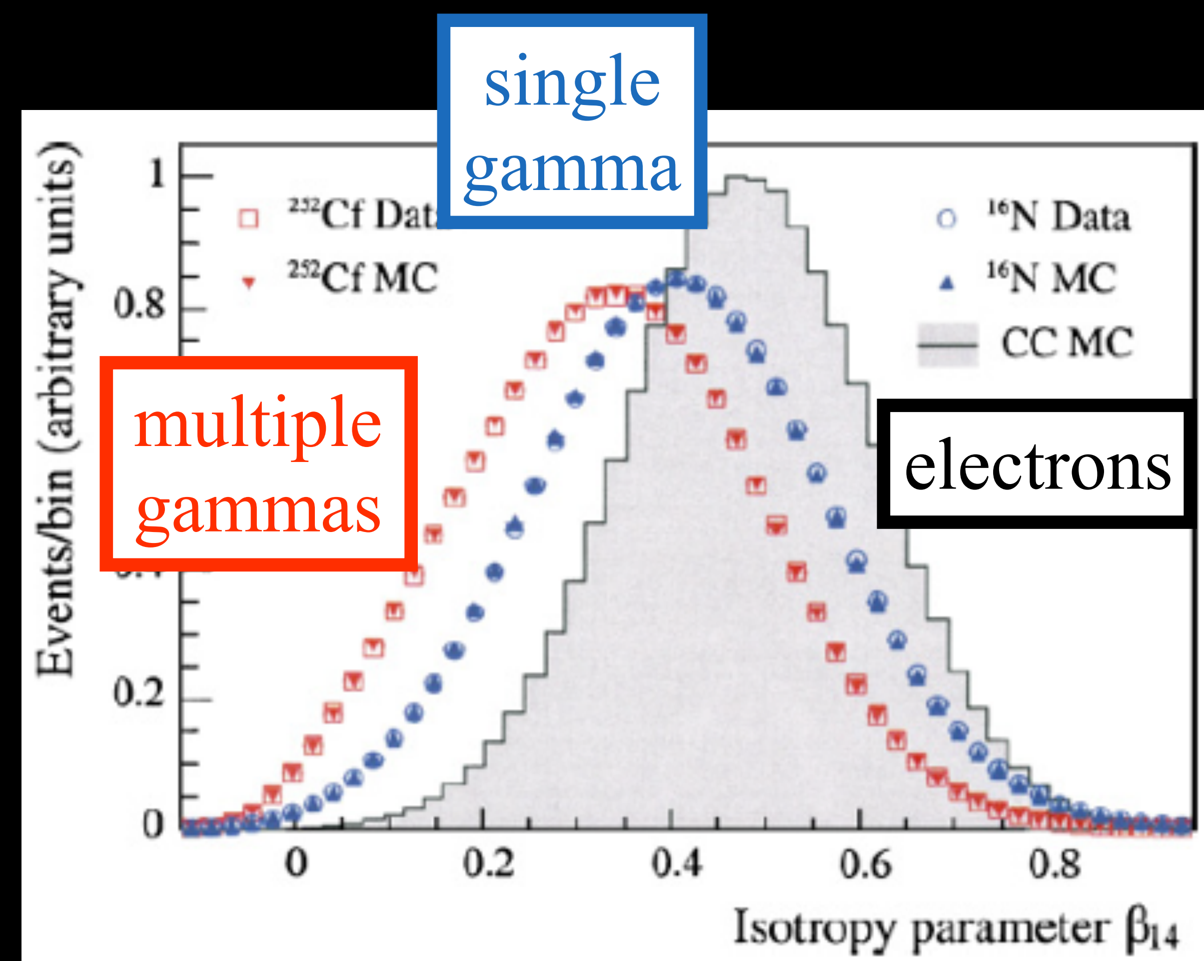
<θij> average
over all PMT pairs

Electron Neutron
(salt)



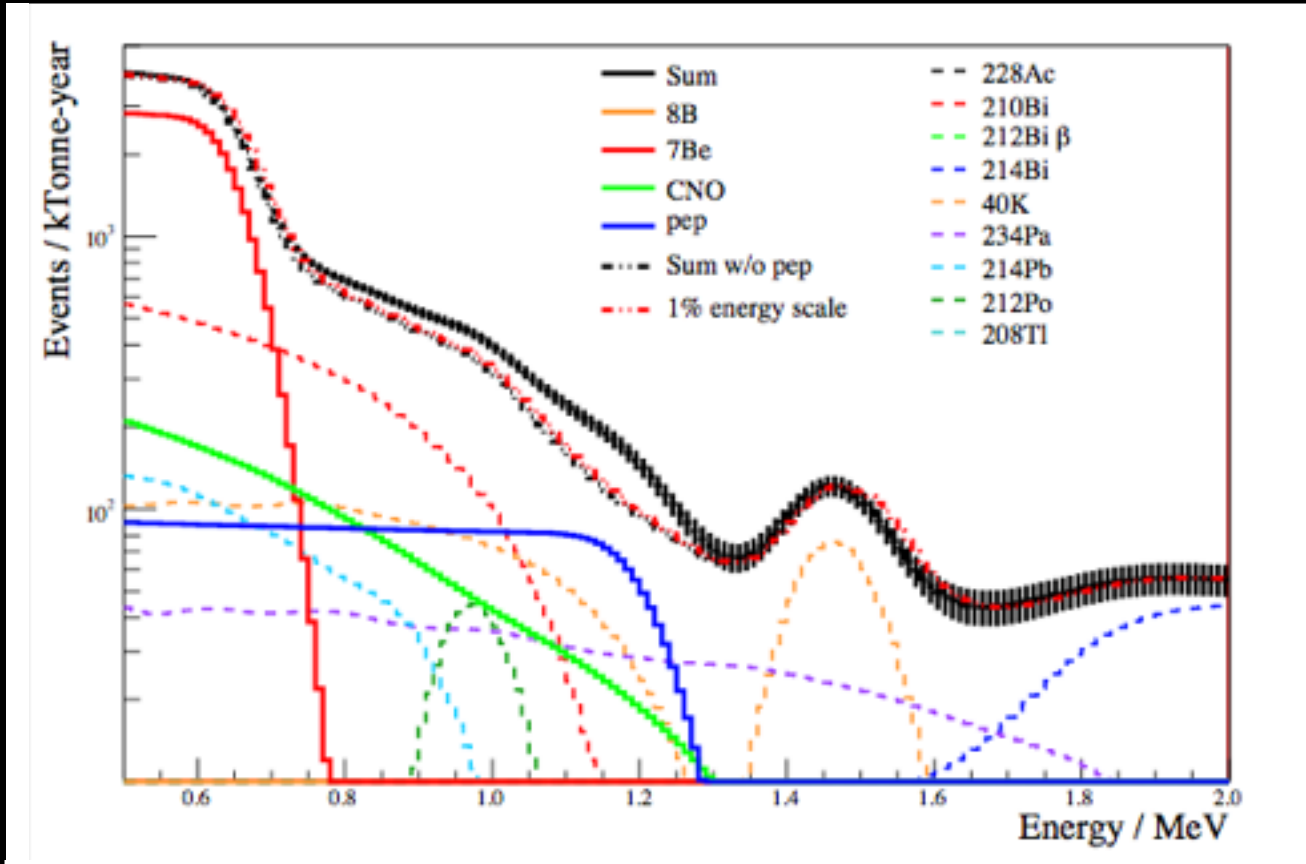
$$\beta_l \approx \left\langle P_l\left(\cos\theta_{ij}\right)\right\rangle_{i\neq j}$$

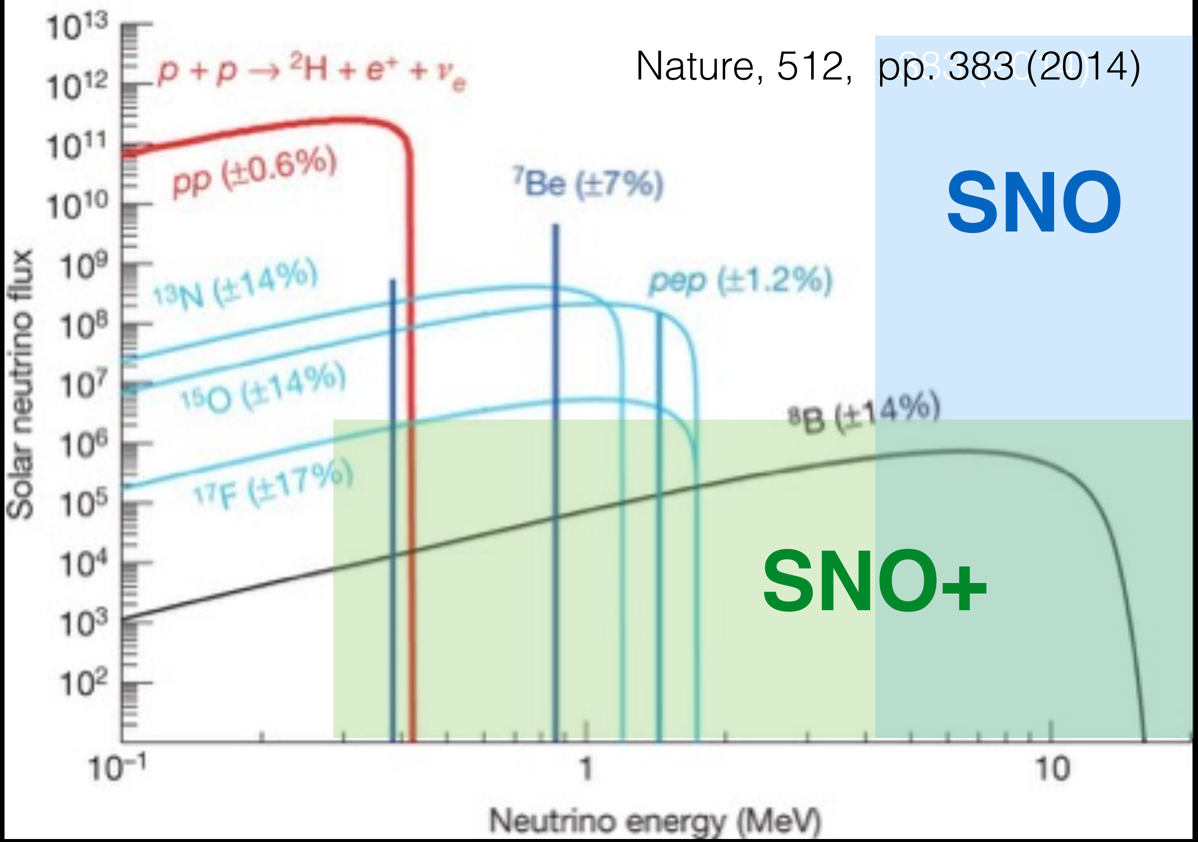
P_l = l_{th} order Legendre polynomial
best separation found with $\beta_{14} = \beta_1 + 4\beta_4$

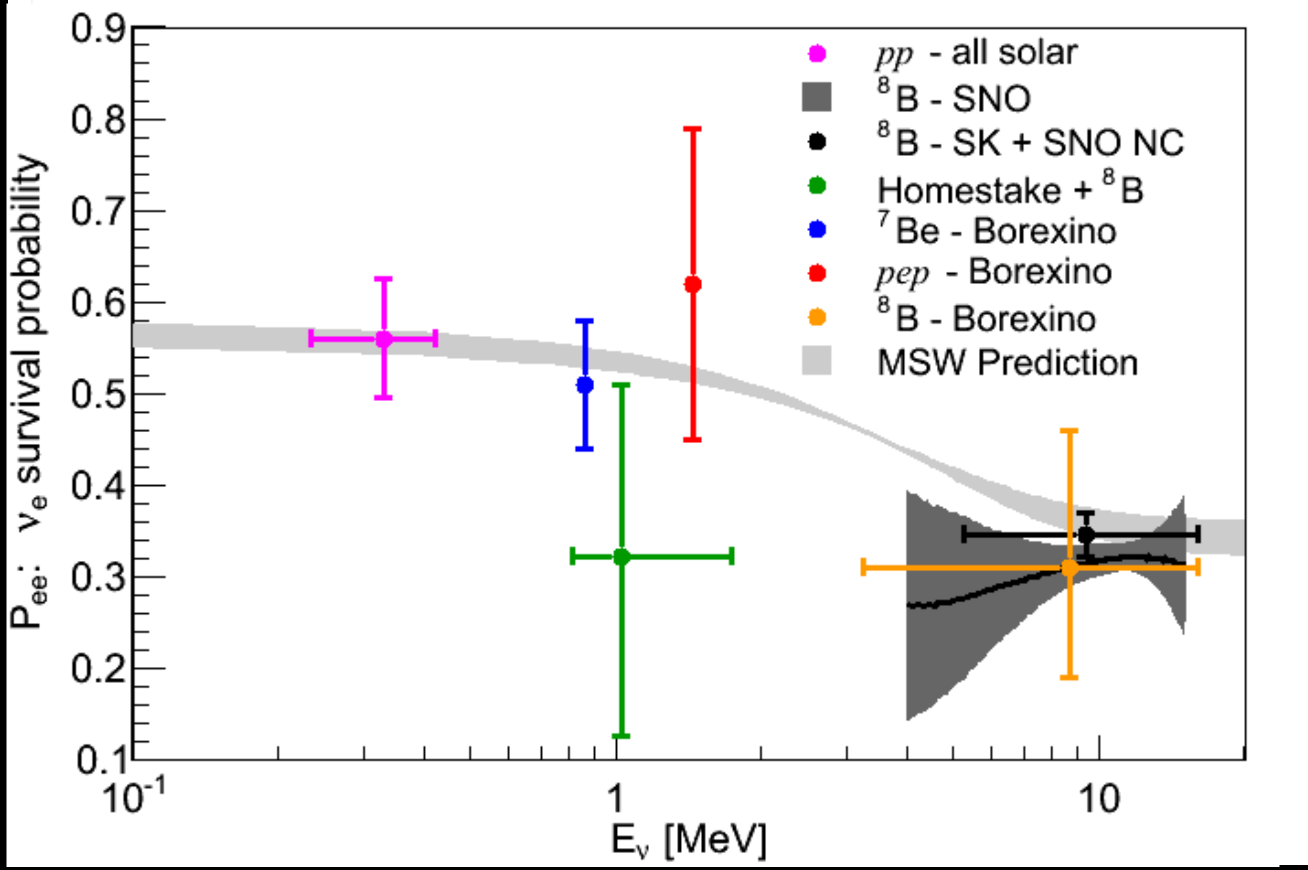


Solar Neutrinos

- Solar neutrinos probe astrophysics and elementary particle physics models:
  - Solar metallicity (CNO)
  - Neutrino oscillations (pep)
- SNO+ solar neutrino goal: pep/CNO solar neutrino measurement
  - Low ^{11}C background thanks to depth (100 times lower than Borexino)
  - Low energy threshold thanks to LAB







Neutrino decay lifetime

- Look for distortion of oscillation spectrum at higher solar ν energies
  - Benefits from analysis being performed in ν energy space