CIPANP 2018

Neutrino Mass and Neutrino Mixing parallel session

Search for neutrinoless double-beta decay with SNO+

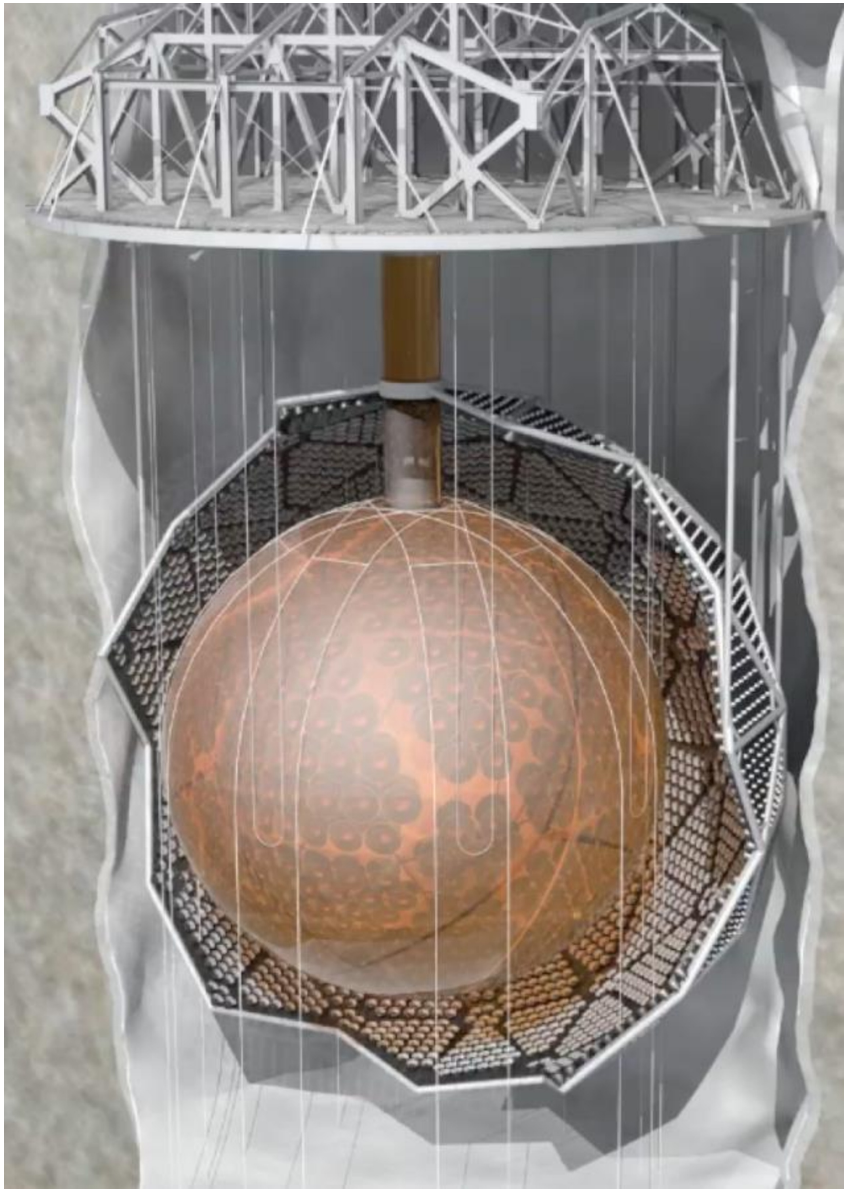
Vincent Fischer

University of California at Davis

May 29, 2018

Overview of SNO+

- **SNO+** is a large liquid scintillator detector located in **SNOLAB, Canada**
- Successor to SNO (Sudbury Neutrino Observatory)
- ~ 780 tonnes of **tellurium-loaded** liquid scintillator
- Main goal: Look for the **neutrinoless double-beta decay** process
- Other physics goals: Solar, supernovae and reactor neutrinos, geoneutrinos, nucleon decay
- **Three phases**:
  - Water phase
  - Scintillator phase
  - Te-loaded scintillator phase



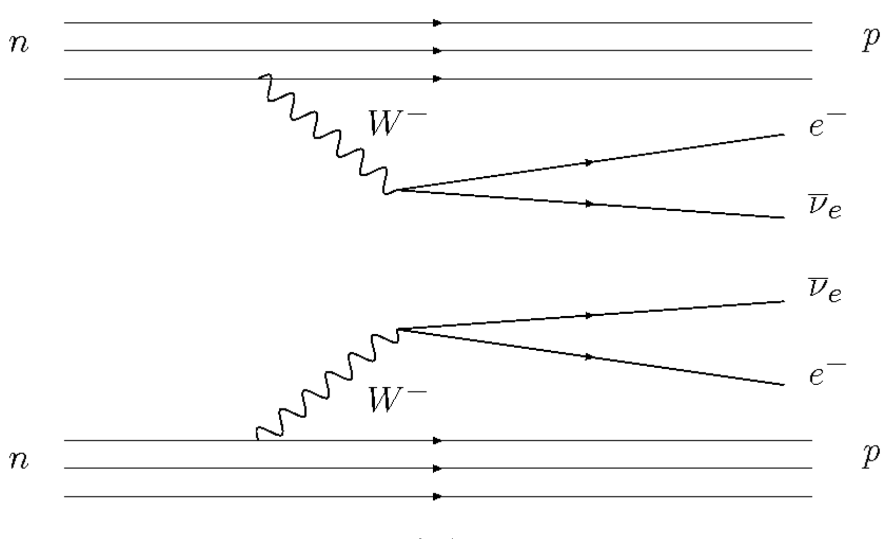
The SNO+ collaboration

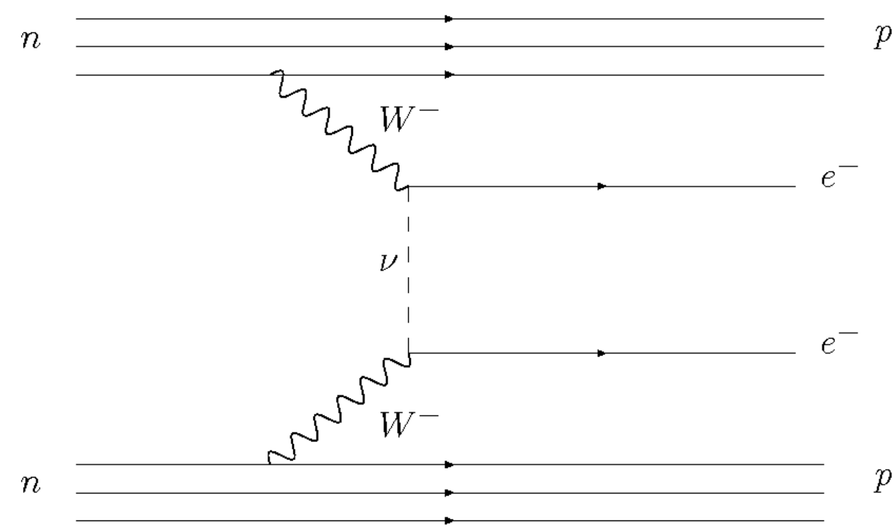
~150 collaborators, 24 institutes, 6 countries, 1 detector

University of Alberta
Armstrong Atlantic State University
University of California Berkeley / Berkeley National Lab
Boston University
Brookhaven National Lab
University of Chicago
University of California Davis
T.U. Dresden
Lancaster University
Laurentian University
LIP Lisbon

University of Liverpool
National Autonomous University of Mexico
University of North Carolina
Norwich University
SNOLAB
University of Oxford
University of Pennsylvania
Queen's University
Queen Mary University of London
University of Sussex
TRIUMF
University of Washington

Double-beta decay process



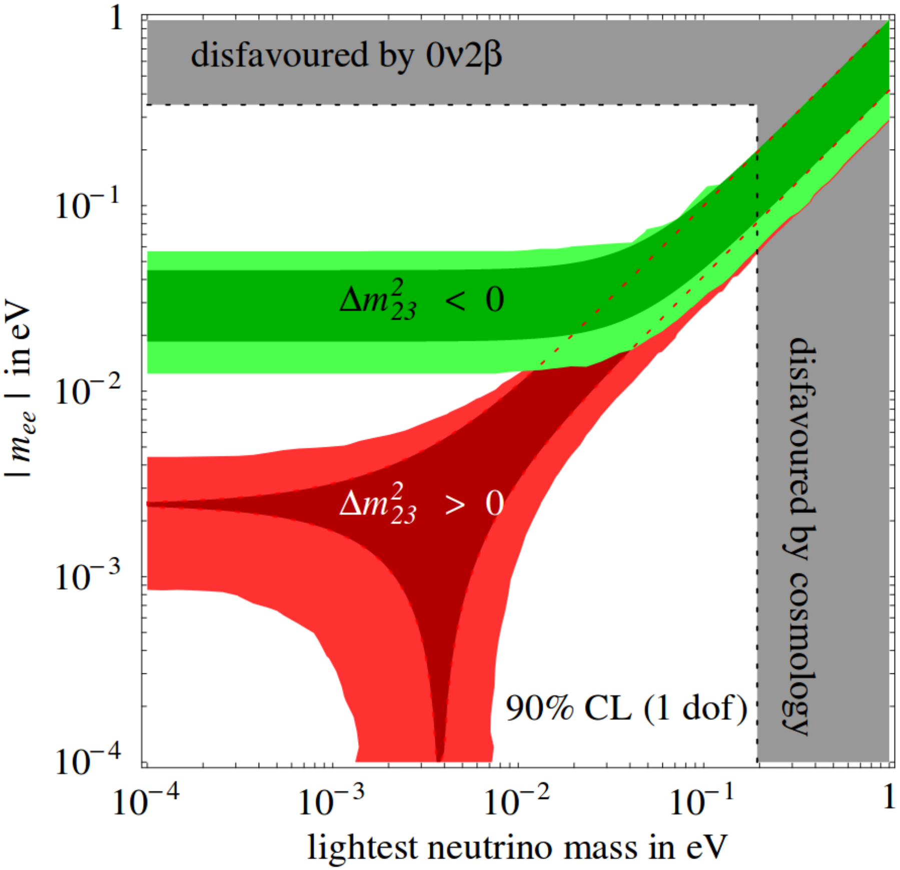


- **2-neutrino double-beta decay**
  - Allowed by the Standard Model
  - **Conserves** lepton number
  - Occurs when beta decay is forbidden
  - Observed for 11 isotopes – $T_{1/2} \sim 10^{18} - 10^{24}$ years

- **Neutrinoless double-beta decay**
  - **Violates** lepton number conservation
  - Can occur if neutrinos are **Majorana** particles
  - Hunted after by numerous experiments

Double-beta decay rates and sensitivity

Nucl.Phys. B637 (2002) 345-377



- Rate of double-beta decay:

  $$\text{Rate} \sim (T^{0\nu}_{1/2})^{-1} = G^{0\nu}\,|M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2/m_e^{\,2}$$

  with:
  $T^{0\nu}_{1/2}$ = half-life
  $G^{0\nu}$ = Phase space factor
  $|M^{0\nu}|^2$ = Nuclear matrix element
  $m_{\beta\beta}$ = Effective neutrino mass
  m_e = Lightest neutrino mass

  And $\langle m_{\beta\beta}\rangle = |\sum_i U_{ei}^{\,2}.m_i|$ (i=1..3)

- Recent mass hierarchy results are favoring a normal hierarchy
- Inverted hierarchy domain hasn't been probed yet

Double-beta decay signature

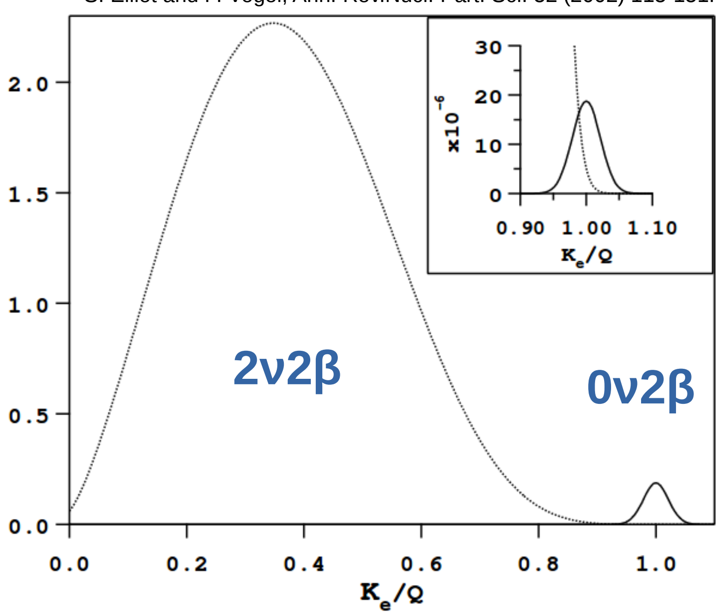
- **2 main approaches** are currently used by the community:

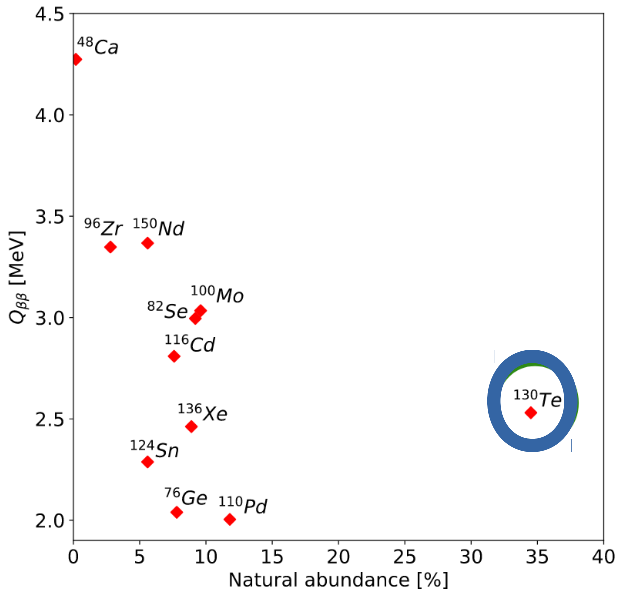
- High energy resolution
- Distinctive energy signature
- Small detectors
  → **Lower decay rates but distinct signature**

- Lower energy resolution
- Well-understood backgrounds
- Large detectors
  → **Higher decay rates but more subject to backgrounds**

The SNO+ approach

S. Elliot and P. Vogel, Ann. Rev.Nucl. Part. Sci. 52 (2002) 115-151.





Te has a long 2ν2β half-life (~7 x 10^{20} years) and a large natural abundance

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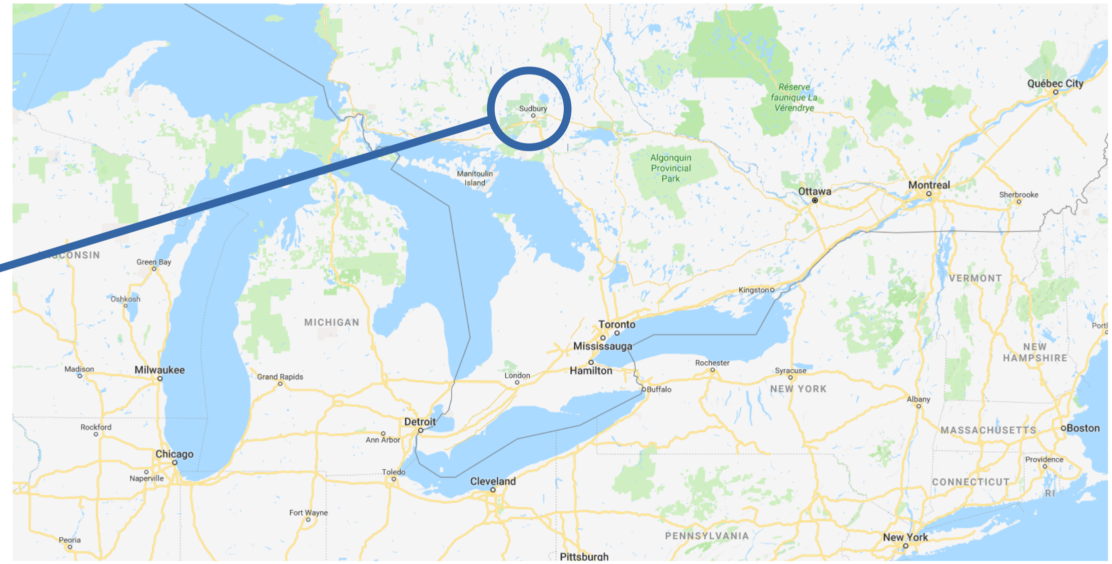
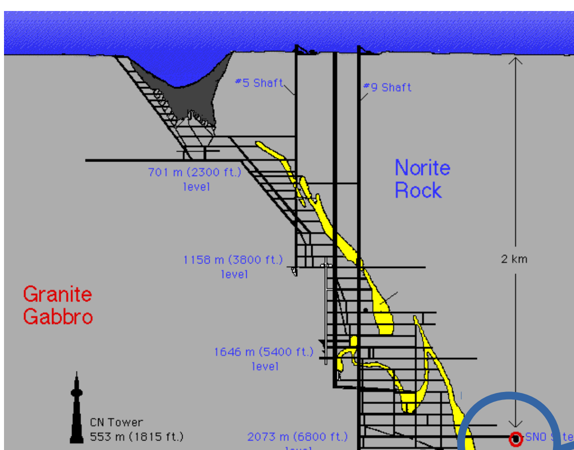
SNO+ at SNOLAB

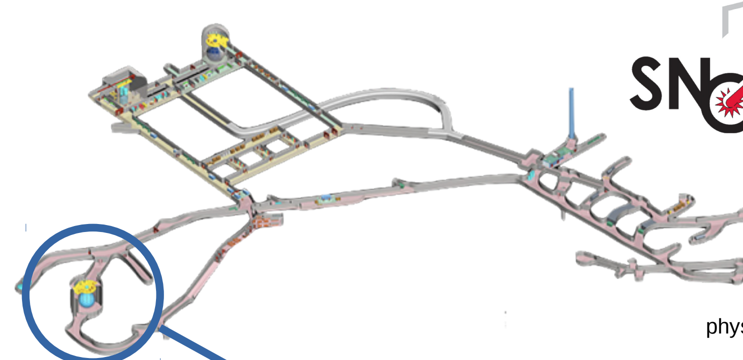
SNO+

SNOLAB is located **2 km underground** in the Creighton mine in Sudbury, Ontario





sno.phy.queensu.ca

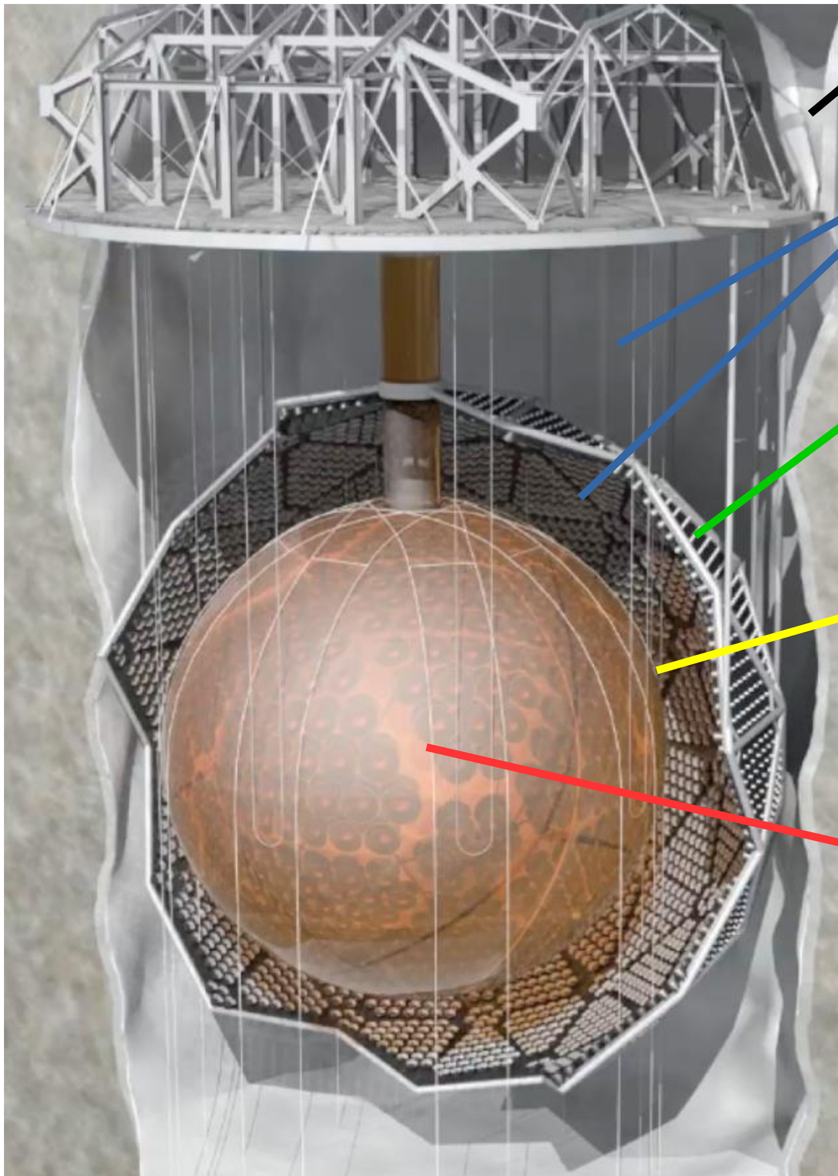


SNOLAB

physics.ualberta.ca

SNO+

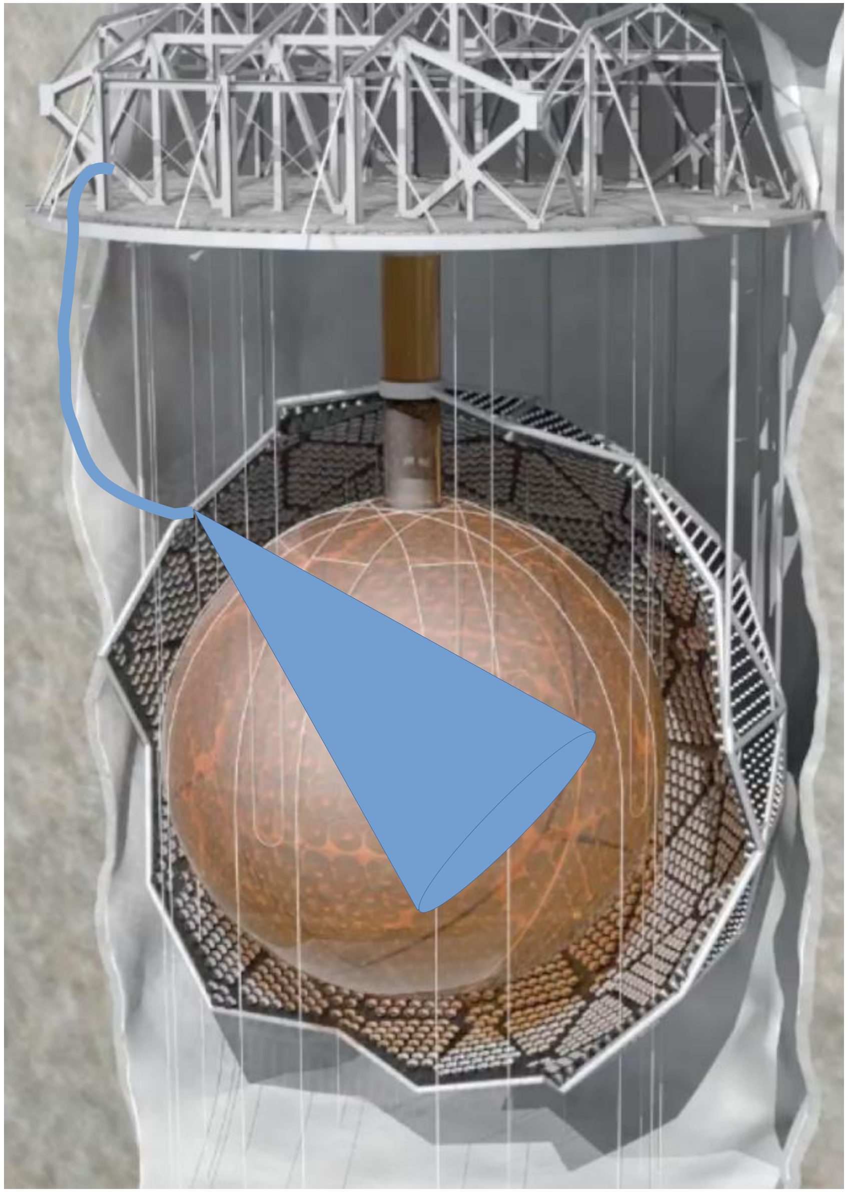
The SNO+ detector



- ~ **6000 m.w.e. rock overburden**
- **Inner and outer shielding**:
  - Pure water
  - 7000 tonnes in total
- **Support structure**:
  - Diameter ~ 18 meters
  - Holds **~9300 PMTs → 54% coverage**
- **Acrylic vessel**:
  - Diameter ~ 12 meters
  - Thickness ~ 5 cm
- **Target volume**:
  - Water phase: **Pure water**
  - Scintillator phase: **LAB*** (+ 2g/L PPO**)
  - Tellurium phase: **+ 1330 kg ^{130}Te**
- New hold down rope system, new calibration systems, new DAQ and readout systems

*LAB: Linear Alkyl Benzene
**PPO: 2,5-diphenyloxazole (fluor)

Calibrating SNO+



Light calibration

In-situ measurement of:
- **PMT responses and efficiencies**
- **Water/scintillator properties**

Optical fibers
- System of fixed fibers coupled to LEDs/lasers
- 106 different locations
- Different wavelengths

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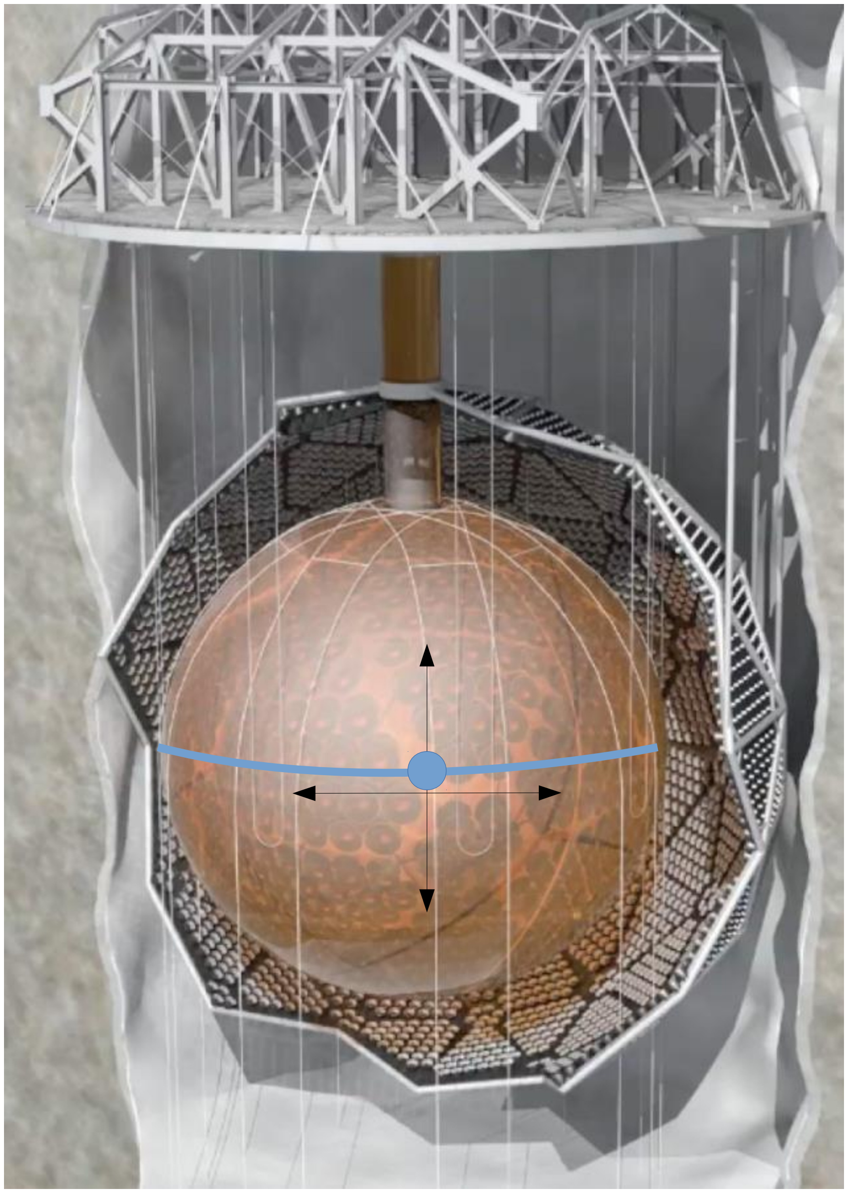
Calibrating SNO+

SNO+



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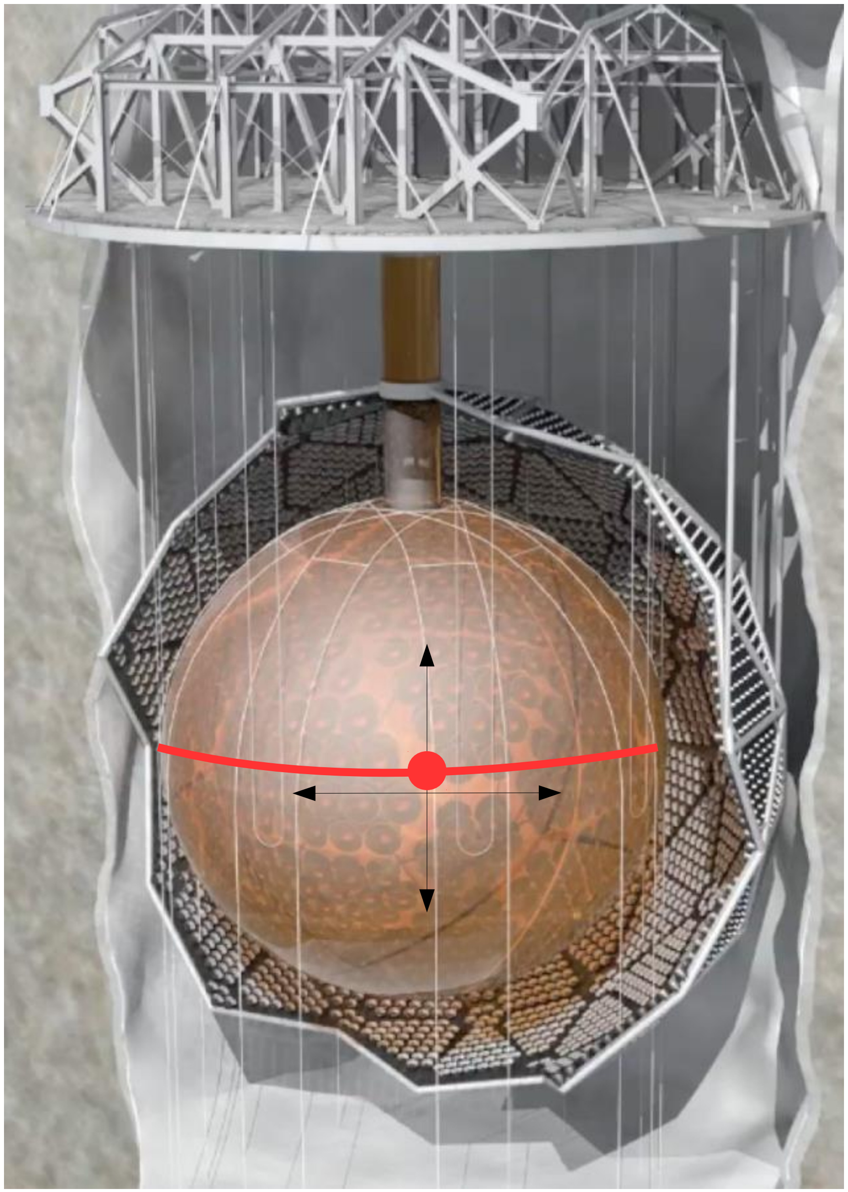
Laserball and underwater cameras
- Deployed diffusing sphere
- 40 different locations, several dyes
- Position pinpointed by cameras
- Deployable Cherenkov source

Calibrating SNO+



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Radioactive source calibration

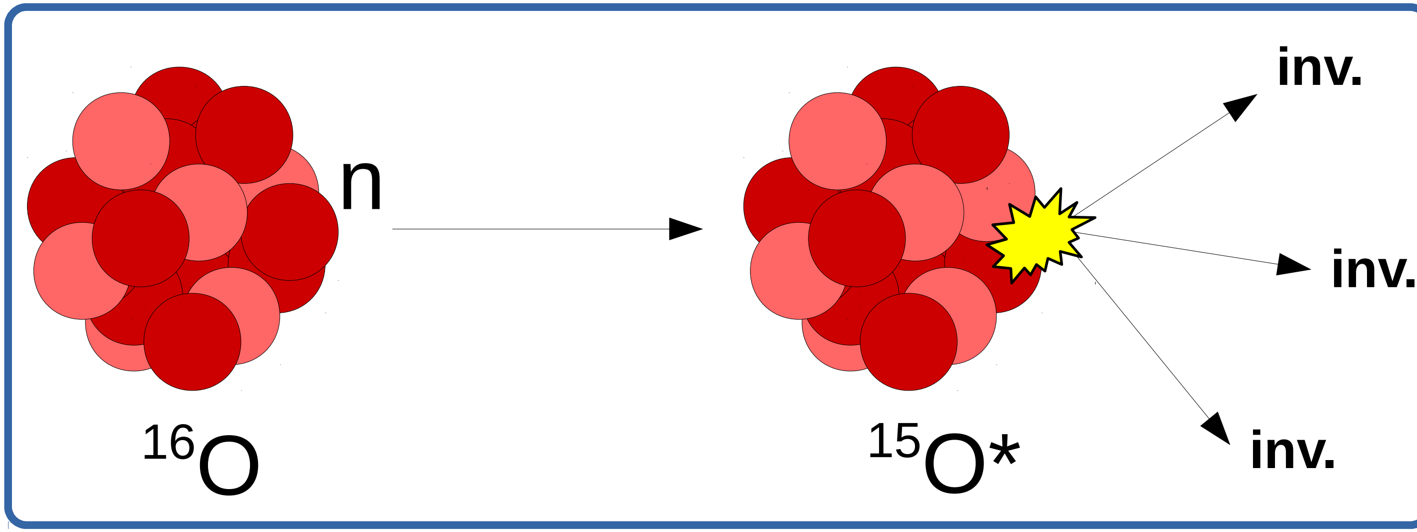
Measurement of efficiencies and systematics associated to energy and position reconstruction

- Sources deployable throughout the detector
- Various gamma and neutrons sources

Several calibration systems (light and sources) successfully deployed during the water phase !

Invisible nucleon decay

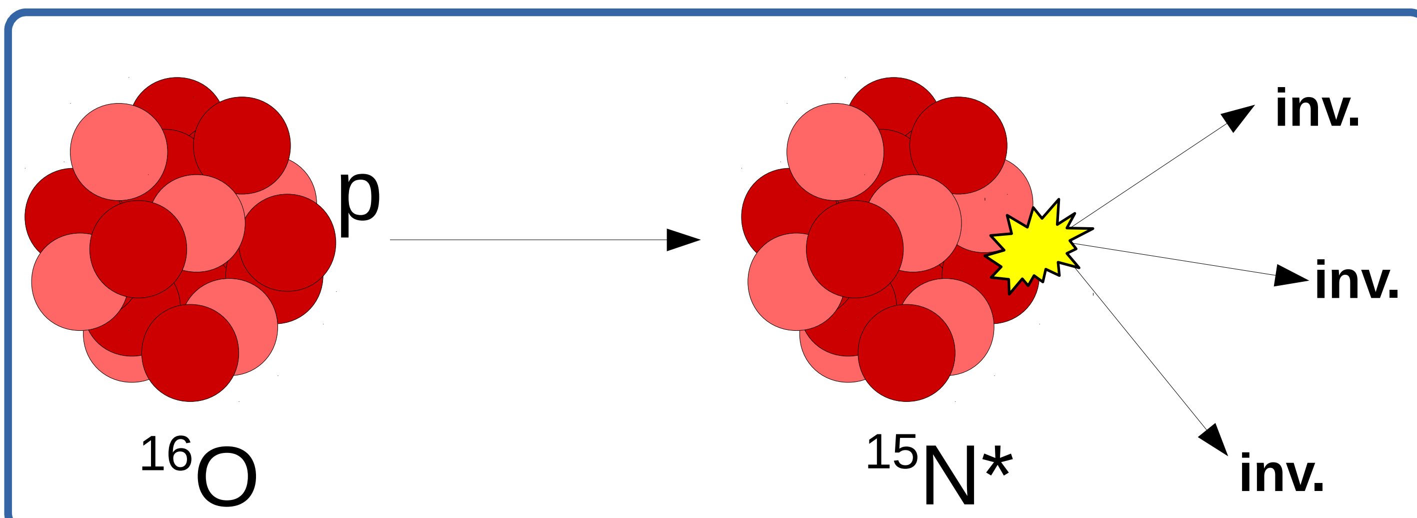
Phys. Rev. C 48, 1442



neutron → invisible
(e.g. n → 3ν)

De-excitation gammas:

- 6.32 MeV (41%)
- 7.01 MeV (4%)



proton → invisible

De-excitation gammas:

- 6.18 MeV (44%)
- 7.03 MeV (2%)

SNO+ Water phase - Sensitivity

Adv.High Energy Phys. 2016 (2016) 6194250

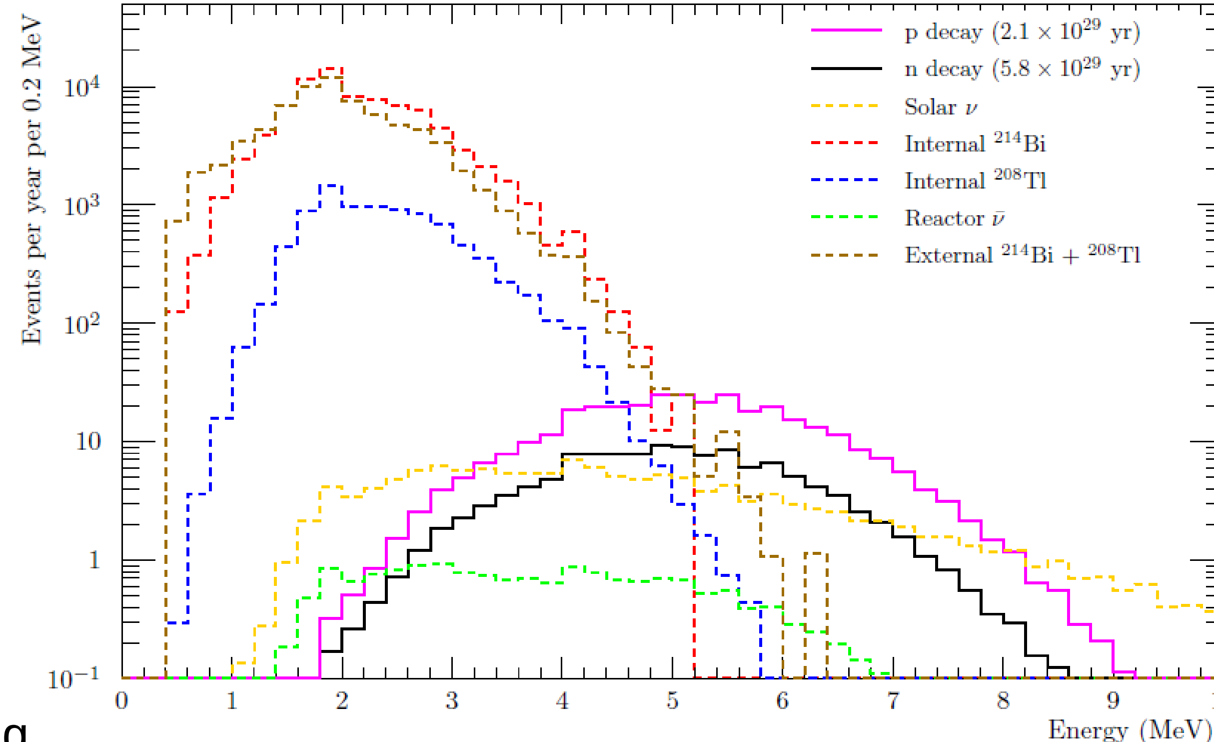
Invisible nucleon decay lifetime:

2.4 x 10^{32} efficiency livetime

$$\tau > \frac{N_{nucleons} \times \epsilon \times f_T}{S_{90\%}}$$

expected signal events

30 background counts in ROI expected after 6 months of data taking



Water phase backgrounds and signals (fiducial and solar cut)

90% CL expected limits

τ_n > 1.2 x 10^{30} years (best limit from KamLAND is 5.8 x 10^{29} years)

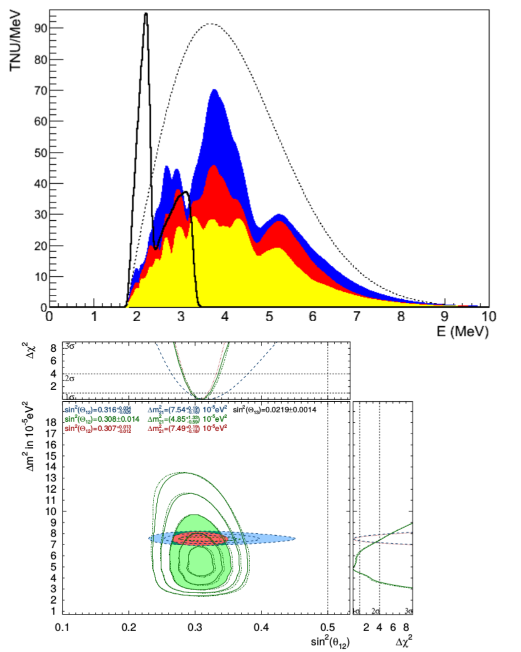
τ_p > 1.4 x 10^{30} years (best limit from SNO is 2.1 x 10^{29} years)

PRL, vol. 92, no. 10, Article ID 102004, 2004

PRL, vol. 96, no. 10, Article ID 101802, 2006

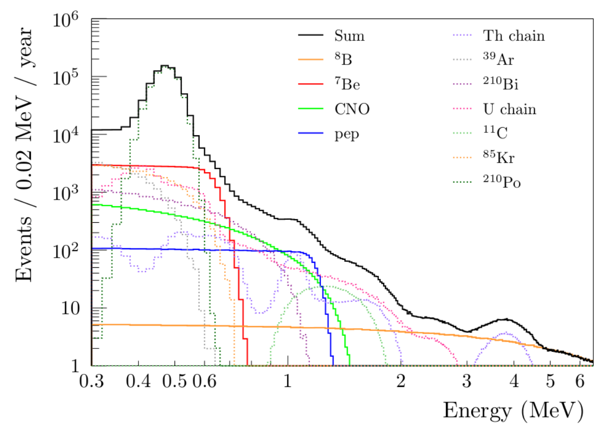
SNO+ Scintillator phase - Physics

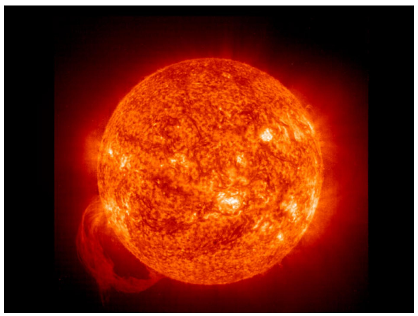
Reactor antineutrinos



Phys.Rev. D94 (2016) no.5, 052010

Solar neutrinos

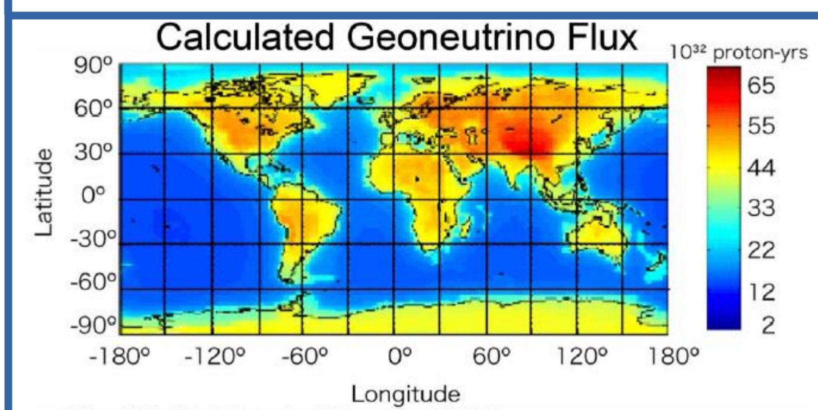




National Geographics

Broad range of neutrino physics!

Geoneutrinos



G. Fiorentini, M. Lissia, F. Mantovani, and R. Vannucci, hep-ph/0401085

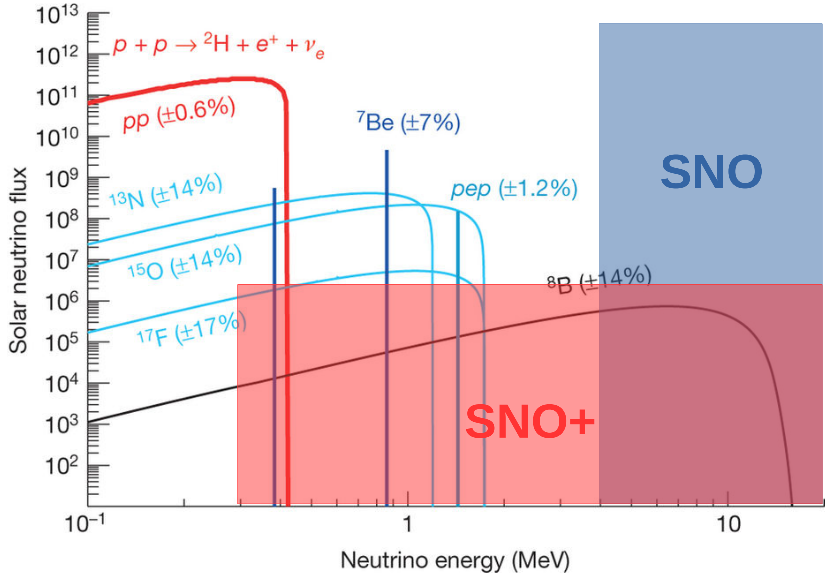
Supernova neutrinos

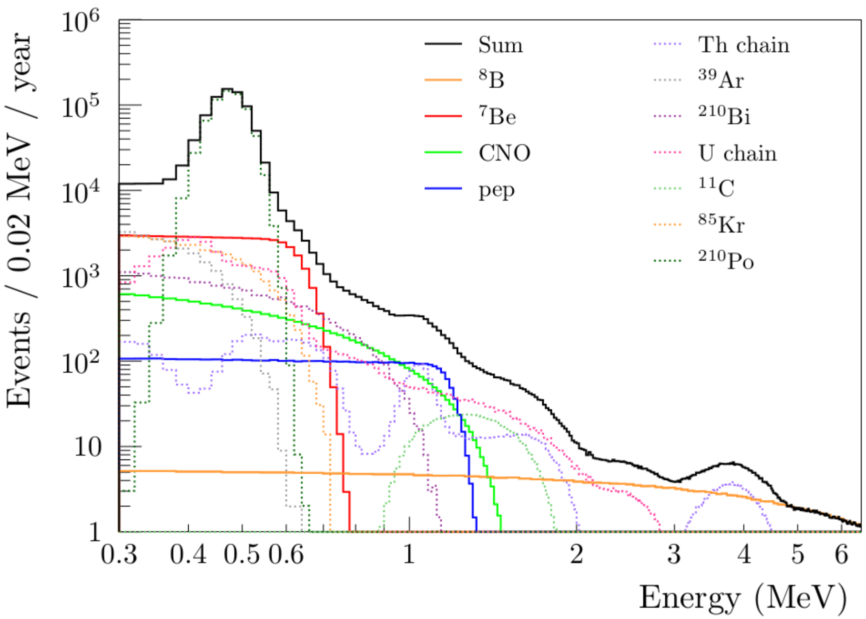
Wikipedia.com

SNO+ Scintillator phase - Solar neutrinos

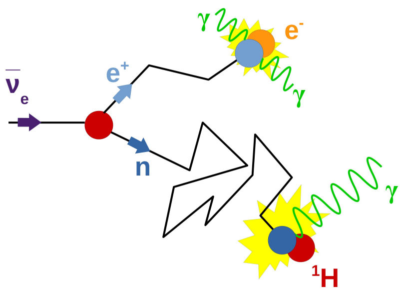
- **Lower threshold** makes SNO+ sensitive to a wider range of solar neutrinos
- SNO+ aims at measuring both **CNO and pep neutrinos**
  - Study **solar metallicity**
  - Study **neutrino oscillations** and matter effects
- Requires **very low levels of contamination** (Borexino levels)
- SNOLAB's rock overburden is a **major advantage** to limit the amount of cosmogenic backgrounds

Nature, 512, pp. 383 (2014)

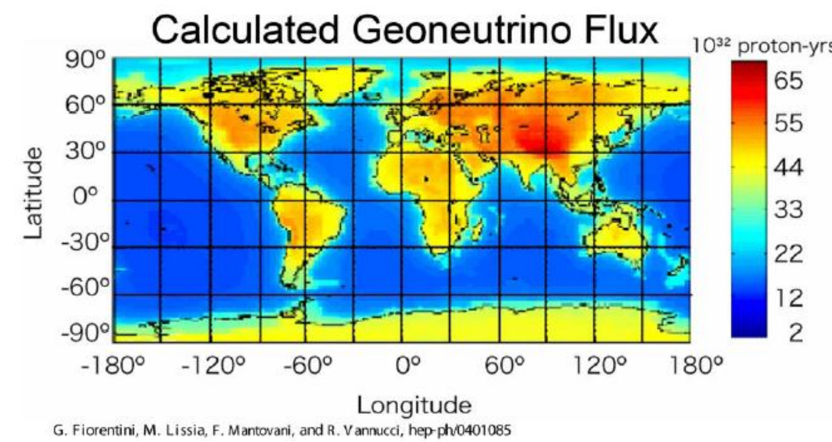




SNO+ Scintillator phase - Reactor and geoneutrinos

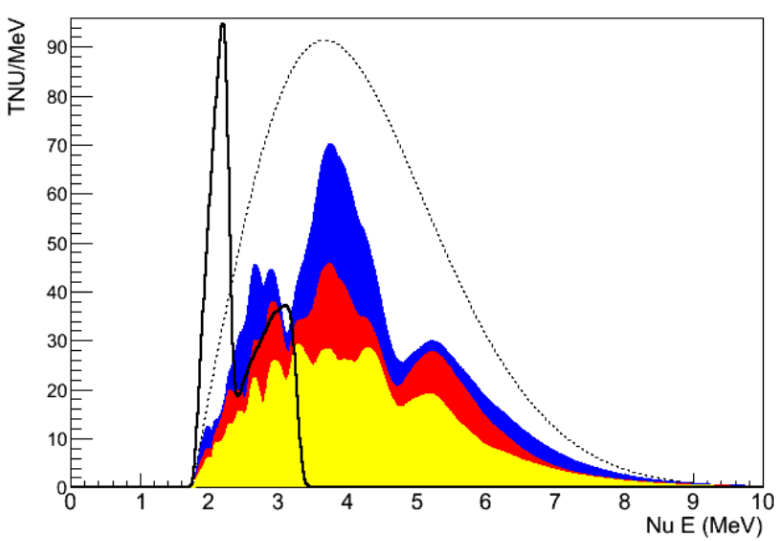


Antineutrinos detected through **Inverse Beta Decay** on H
→ Coincidence (e^+,n)

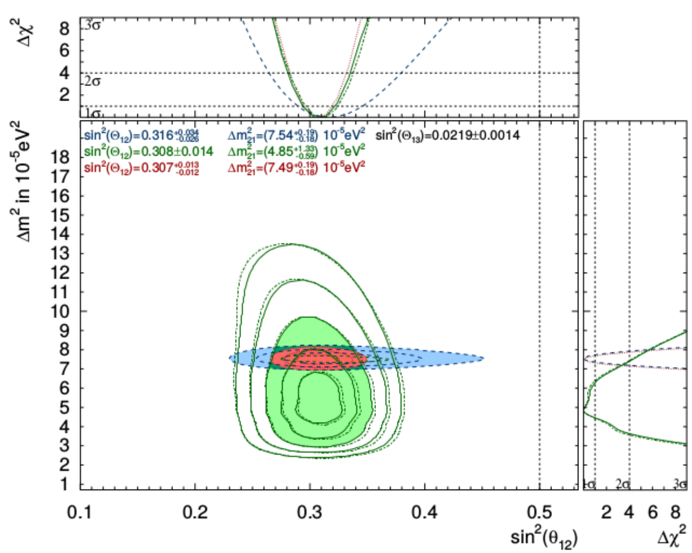


- **A few tens of geoneutrinos** expected per year

- **About 100 reactor neutrinos** expected per year
- Mostly from local reactors
- New measurement of Δm_{12}^2 could help understand the solar-reactor tension (~1.5σ)



Phys.Rev. D94 (2016) no.5, 052010



SNO+ Scintillator phase - Filling and purification

- LAB shipped from CEPSA BECANCOUR, Quebec to SNOLAB
- Stored aboveground and shipped underground in railcars
- Purification takes place underground in a **dedicated plant**:
  - Multi-stage distillation
  - Metal scavenging
  - Water extraction
  - N_2 gas stripping

    → **Commissioning ongoing**

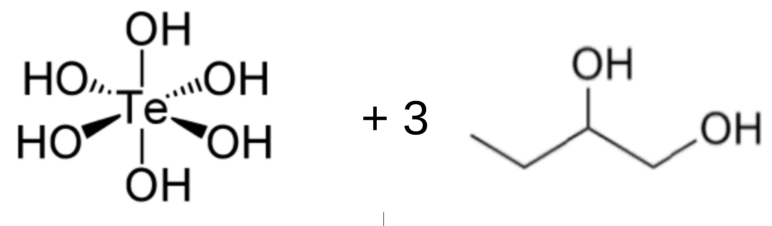
Target levels (g/g)

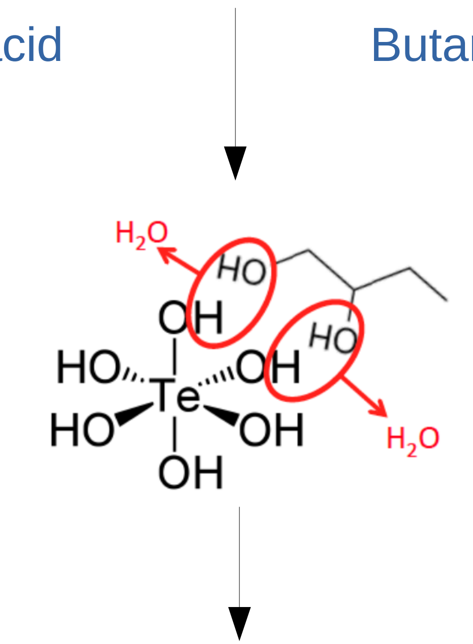
U: $< 10^{-17}$
Th: $< 10^{-18}$
Kr: $< 10^{-25}$
K: $< 10^{-18}$
Ar: $< 10^{-24}$

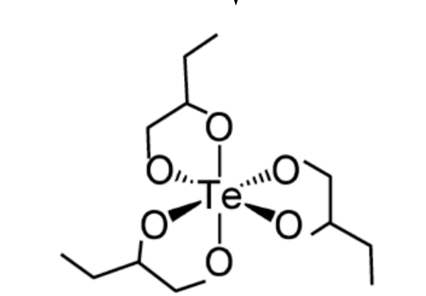
Detector filling with LAB planned over the summer

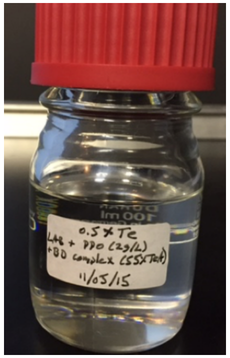
SNO+ Tellurium Phase

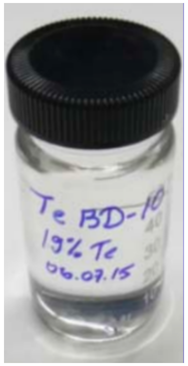
- **Tellurium phase** expected after understanding the backgrounds and detector response during the scintillator phase
- Initial Te loading → **0.5% ^{nat}Te by weight**
  (1300 kg ^{130}Te)
- Tellurium has to be loaded in LAB using an organo-metallic complex (Te acid) and a solvent (butanediol)
- **Mixture**:
  - LAB → Liquid scintillator
  - PPO → Fluor (2 g/L)
  - Bis-MSB → Wavelength shifter (15 mg/L)
  - Te-ButaneDiol → Tellurium complex
- **Advantages**:
  - High light yield (~400 p.e./MeV) achieved even at higher Te-loadings
  - Long attenuation length
  - No intrinsic UV absorption lines
  - Good α/β time discrimination





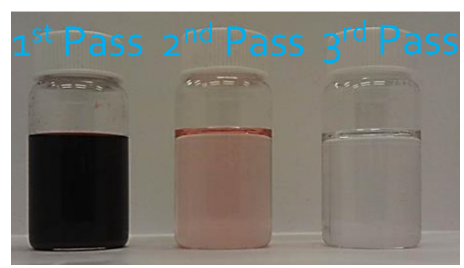




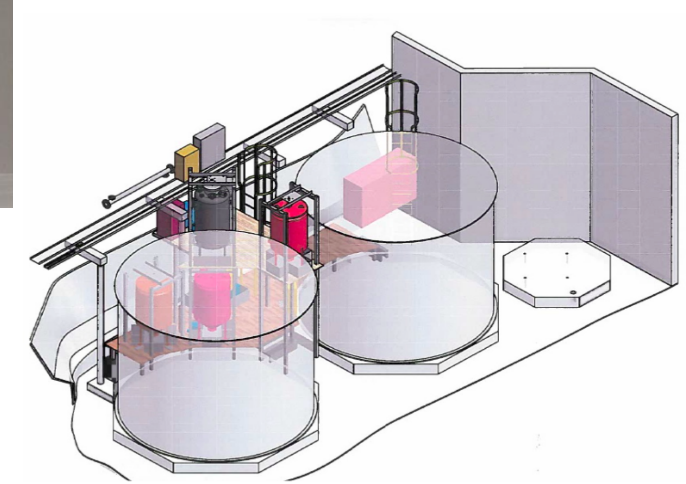


SNO+ Tellurium phase - Loading

- Tellurium acid has been underground for more than 3 years to “cool down” after exposure to cosmics
- **Dedicated “Te plant”**:
  - Filter insoluble contaminations
  - Use of nitric acid to crystallize and precipitate Te acid in order to drain soluble contaminations
- Purification also removes metals created upon cosmic activation on Te (^{60}Co, ^{110m}Ag, ^{88}Y, etc..)
- **Dedicated “Diol plant”** to mix purified Te acid and butanediol



Purification of a cobalt-spiked Te solution



Target levels

U: < 1.3 x10^{-15} (3 x 10^{-8} Bq/kg)
Th: < 5 x 10^{-16} (1.2 x 10^{-9} Bq/kg)

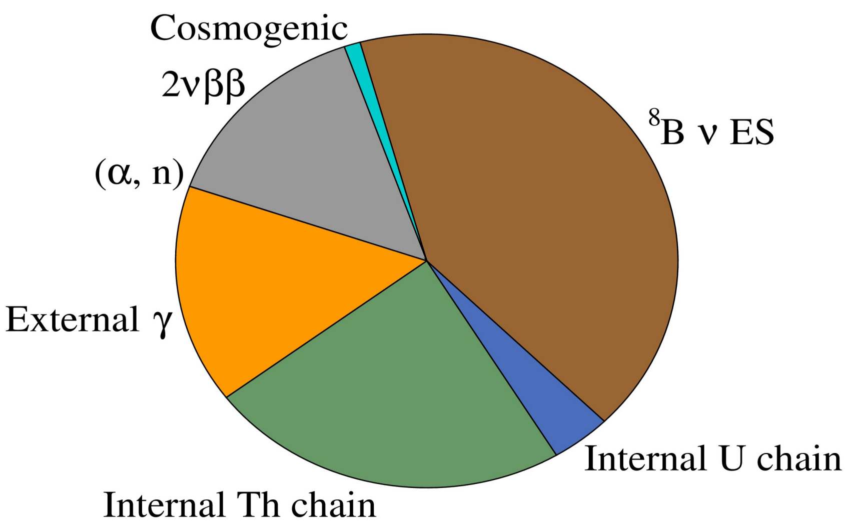
→ > 10^{4} contamination reduction from raw Te

Underground cooling and purification reduce cosmogenics

SNO+ Tellurium phase - Expected signal and backgrounds

SNO+ background estimation

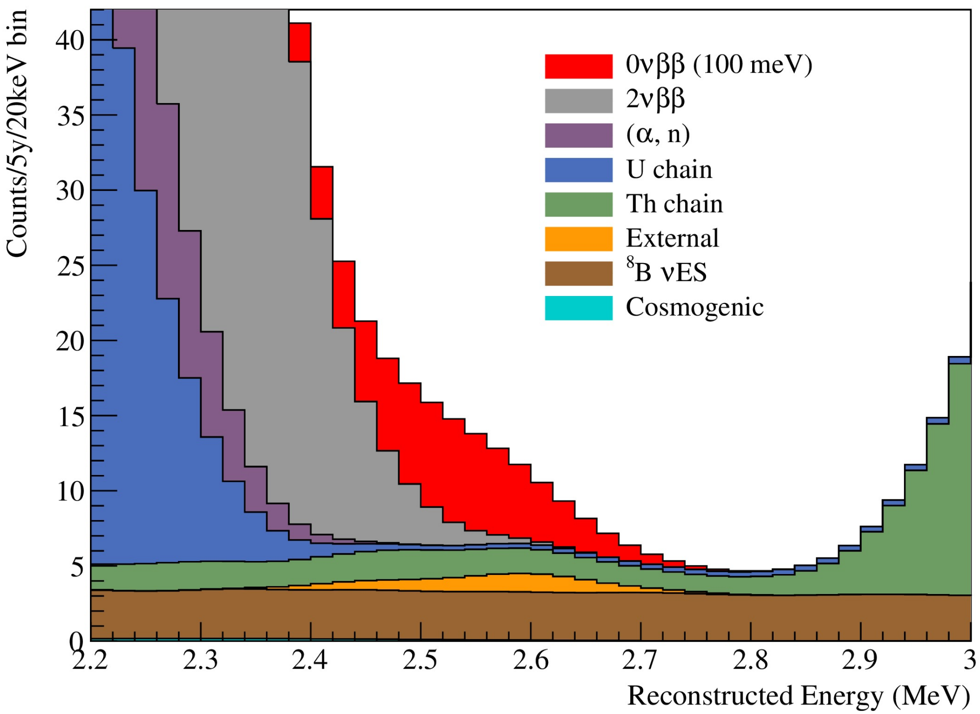
ROI: 2.49 - 2.65 MeV [-0.5σ - 1.5σ]
Counts/Year: 12.4



- ^{8}B solar: Flat ES spectrum
- Internal U/Th: BiPo coincidences
- External gamma: From PMTs, water, etc..
- (α,n): Coincidence upon neutron capture
- 2ν2β
- Cosmogenics: Te activation

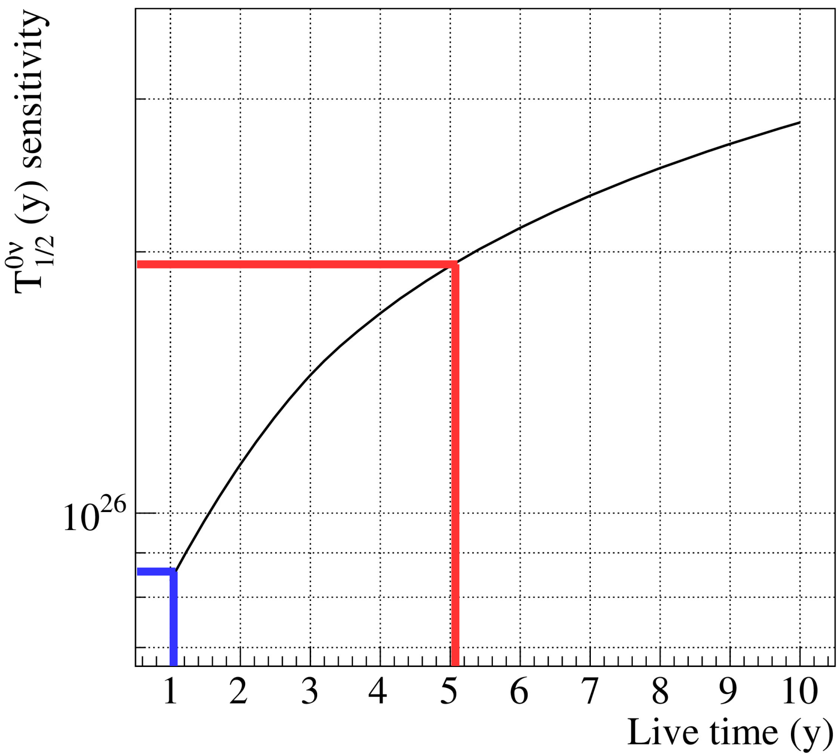
13 events per year in ROI

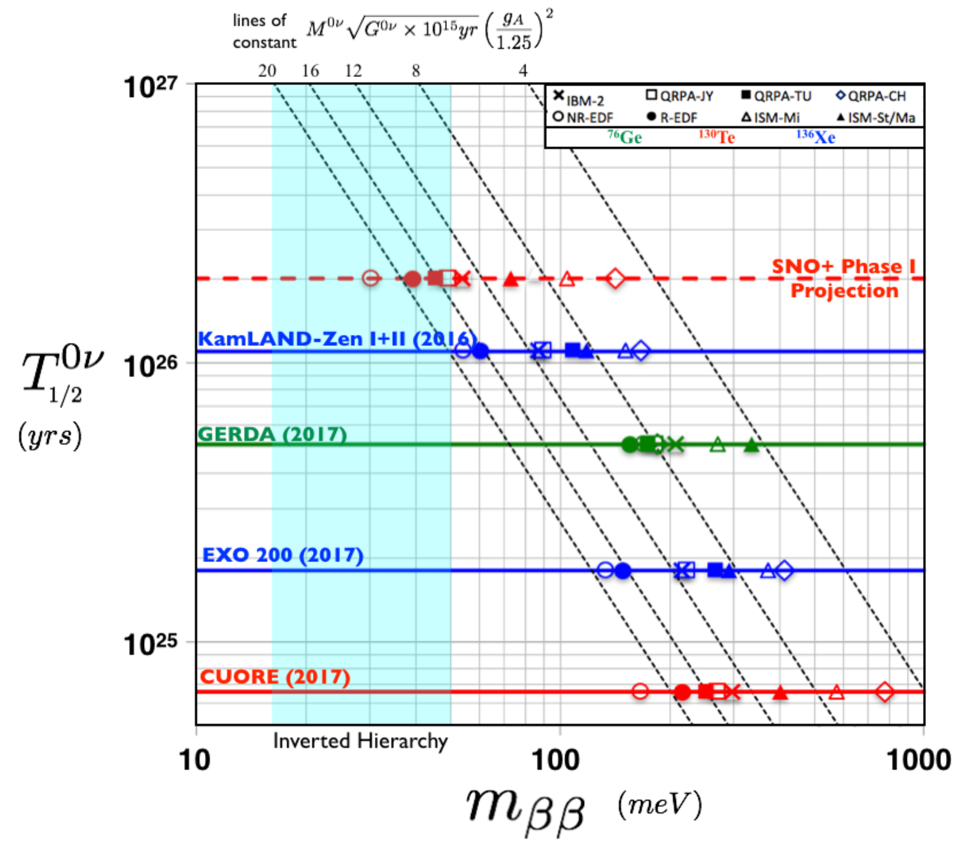
SNO+ expected energy spectrum



- 5 years of data taking
- $M_{\beta\beta}$ = 100 meV
- Nominal 0.5% Te-loading

SNO+ Tellurium phase - Sensitivity





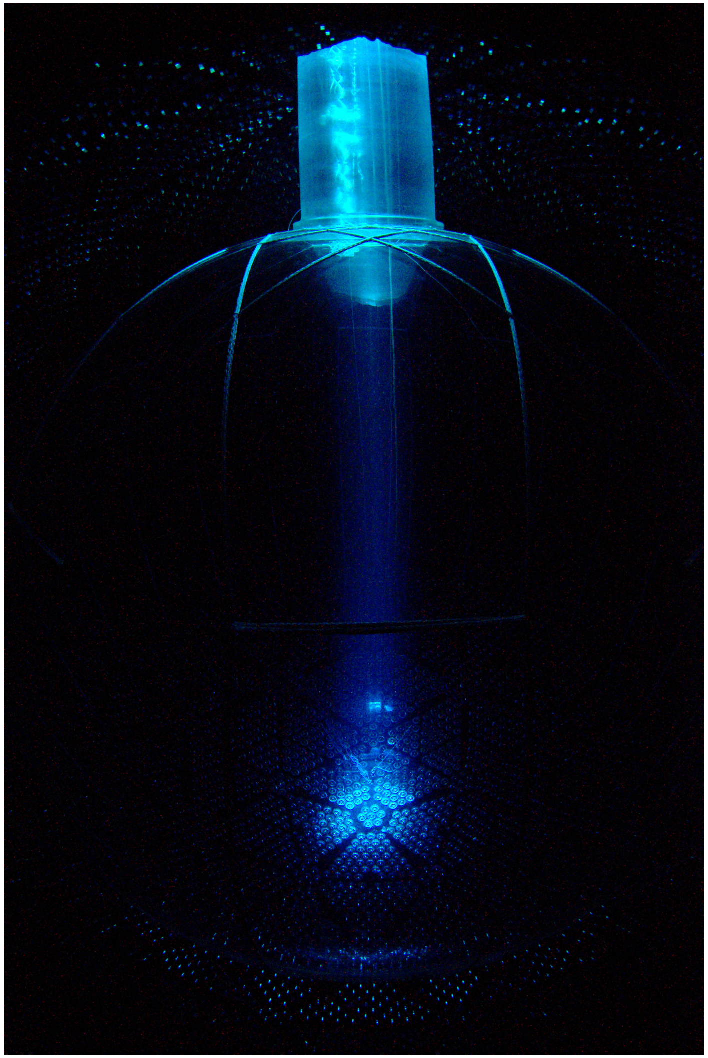
After 1 year: $T_{1/2}^{0\nu}$ **> 0.8 x 10^{26} years**
$m_{\beta\beta}$ < 75.2 meV

After 5 years: $T_{1/2}^{0\nu}$ **> 1.9 x 10^{26} years**
$M_{\beta\beta}$ < 50.6 meV

A possible Phase II with a higher Te loading would aim at reaching a limit > 10^{27} years

Conclusion and take-home message

- **SNO+** is a large liquid scintillator detector with a **broad range of physics goals**
- SNO+ is currently **taking data in its water phase** and will set limits on nucleon decay processes
- Scintillator fill will **start in the summer**
- SNO+ with scintillator will be sensitive to solar, reactor and geoneutrinos and will measure the intrinsic backgrounds for the Te phase
- **Te-loading expected in 2019**



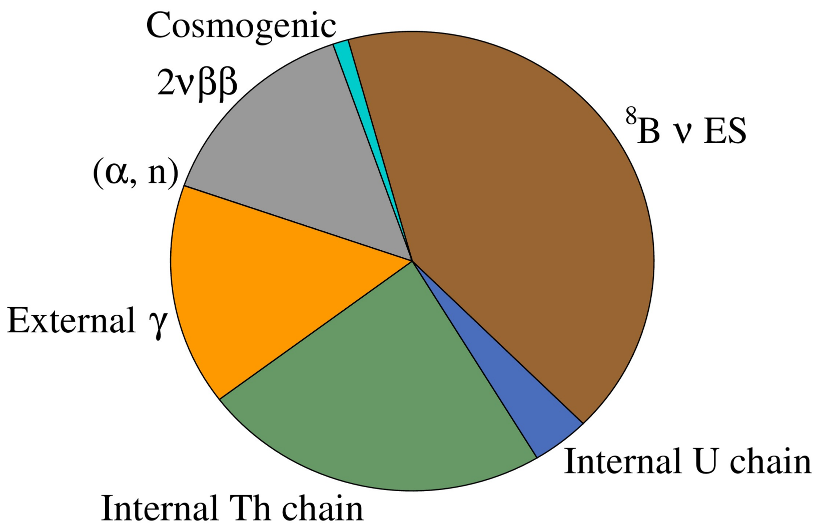
THANK YOU FOR YOUR ATTENTION

BACK-UP

Background model details

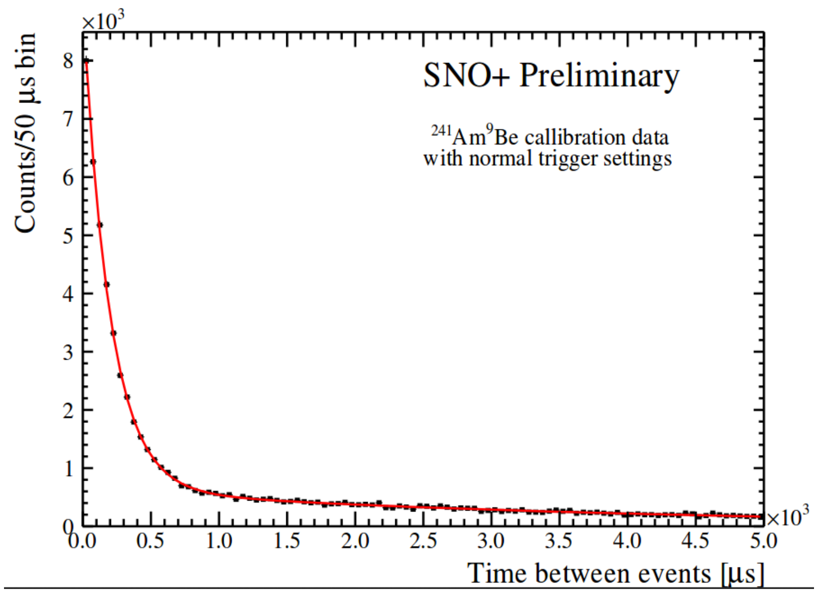
- LS mixture: LAB + PPO (2 g/L) + bis-MSB(15 mg/L) + ^{nat}Te(0.5% loading)
- Fiducial Volume = 3.5 m
- 100% rejection of ^{214}BiPo
- 98% rejection of ^{212}BiPo
- 390 PMT hits/MeV
- ROI = [2.49 –2.65] MeV

ROI: 2.49 - 2.65 MeV [-0.5σ - 1.5σ]
Counts/Year: 12.4

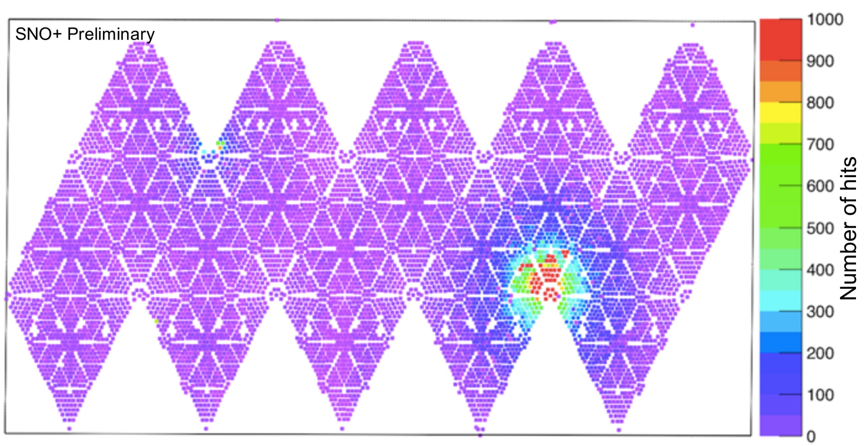


Water phase calibration

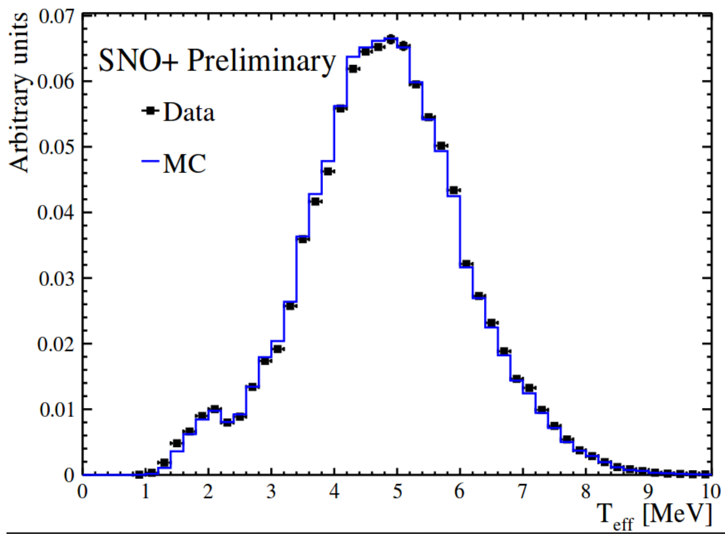
AmBe coincidence ΔT

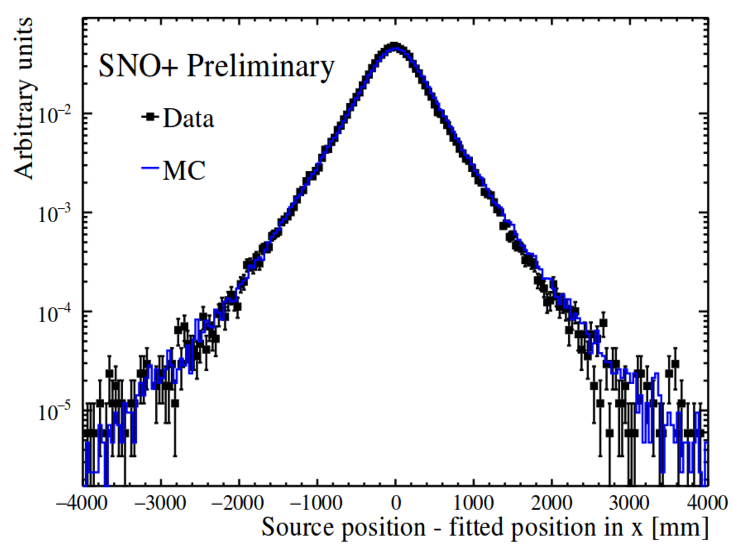


Light injection through optical fiber



^{16}N energy and position reconstruction





Phase 1 – Solar results