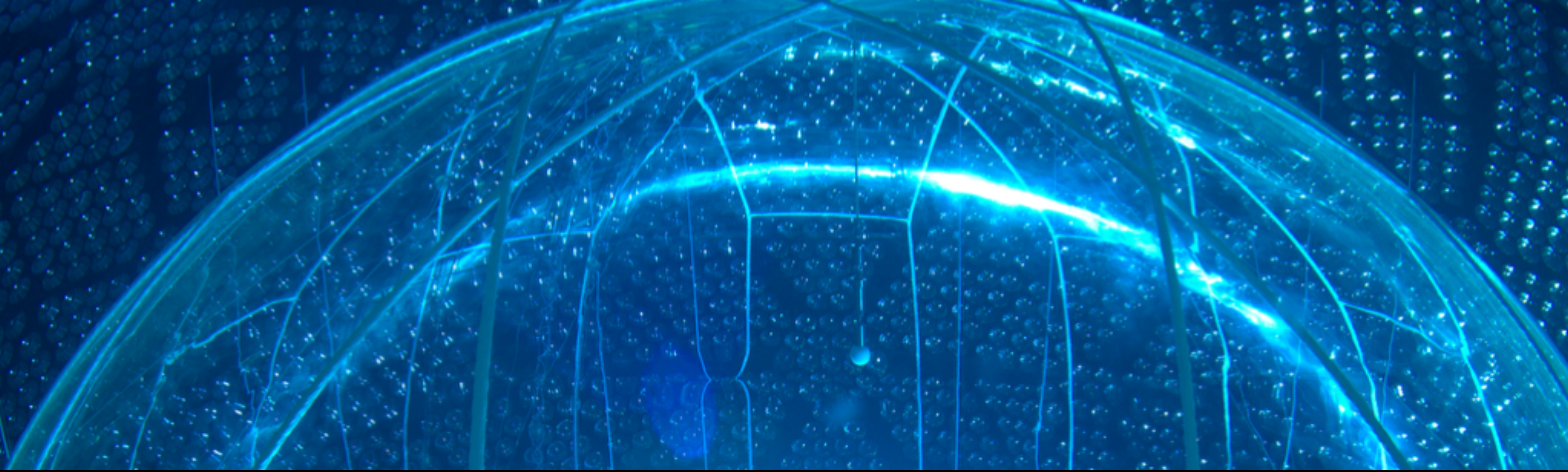


The SNO+ Experiment

Nuno Barros
on behalf of the SNO+ Collaboration

Penn
University of Pennsylvania

SNO+

Rencontres du Vietnam: Neutrinos
Qui Nhon, Vietnam, July 2017

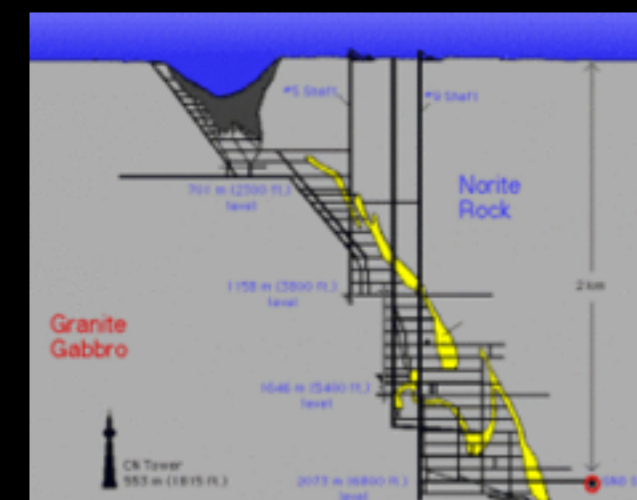
The SNO+ Collaboration

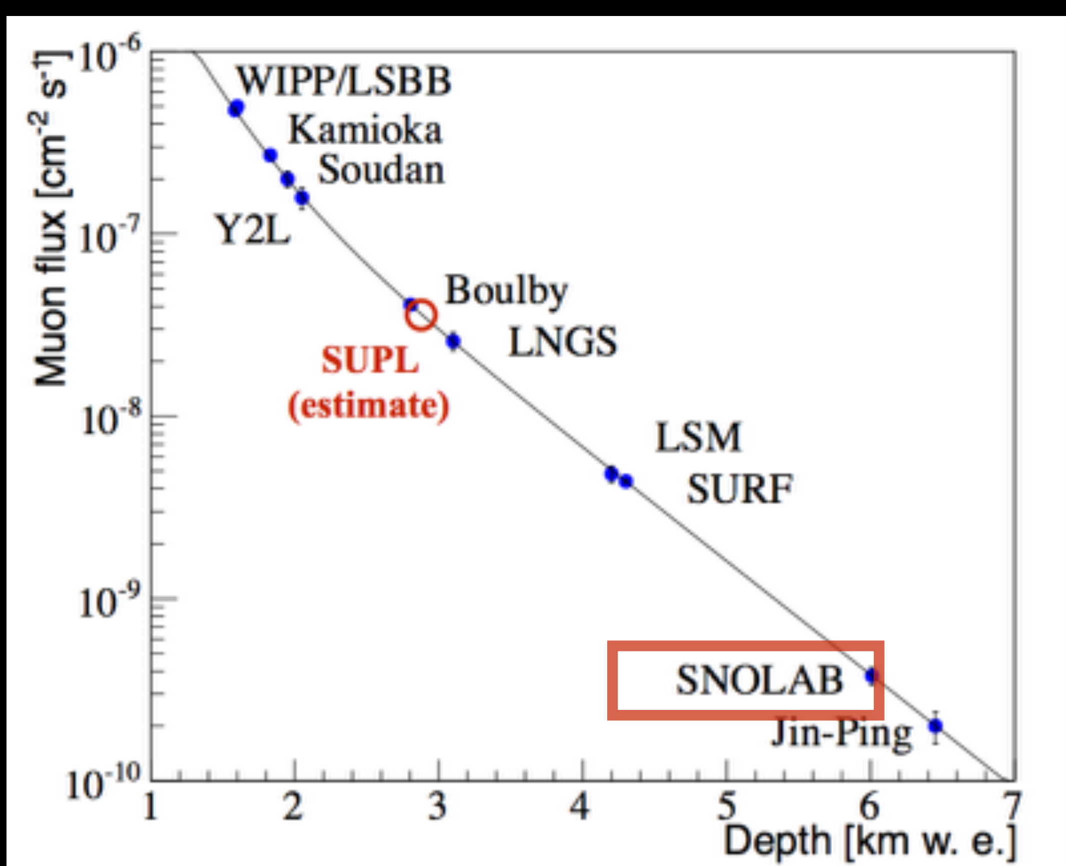
120 members
23 institutions
5 countries

- University of Alberta
- Armstrong Atlantic State University
- University of California, Berkeley/ LBNL
- Boston University
- Brookhaven National Laboratory
- University of Chicago
- University of California, Davis
- Technical University of Dresden
- Lancaster University
- Laurentian University
- LIP (Lisbon and Coimbra)
- University of Liverpool
- Universidad Nacional Autonoma de Mexico
- University of North Carolina
- Norwich University
- University of Oxford
- University of Pennsylania
- Queen's University
- Queen Mary University of London
- SNOLAB
- University of Sussex
- TRIUMF
- University of Washington

SNOLAB Facility

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

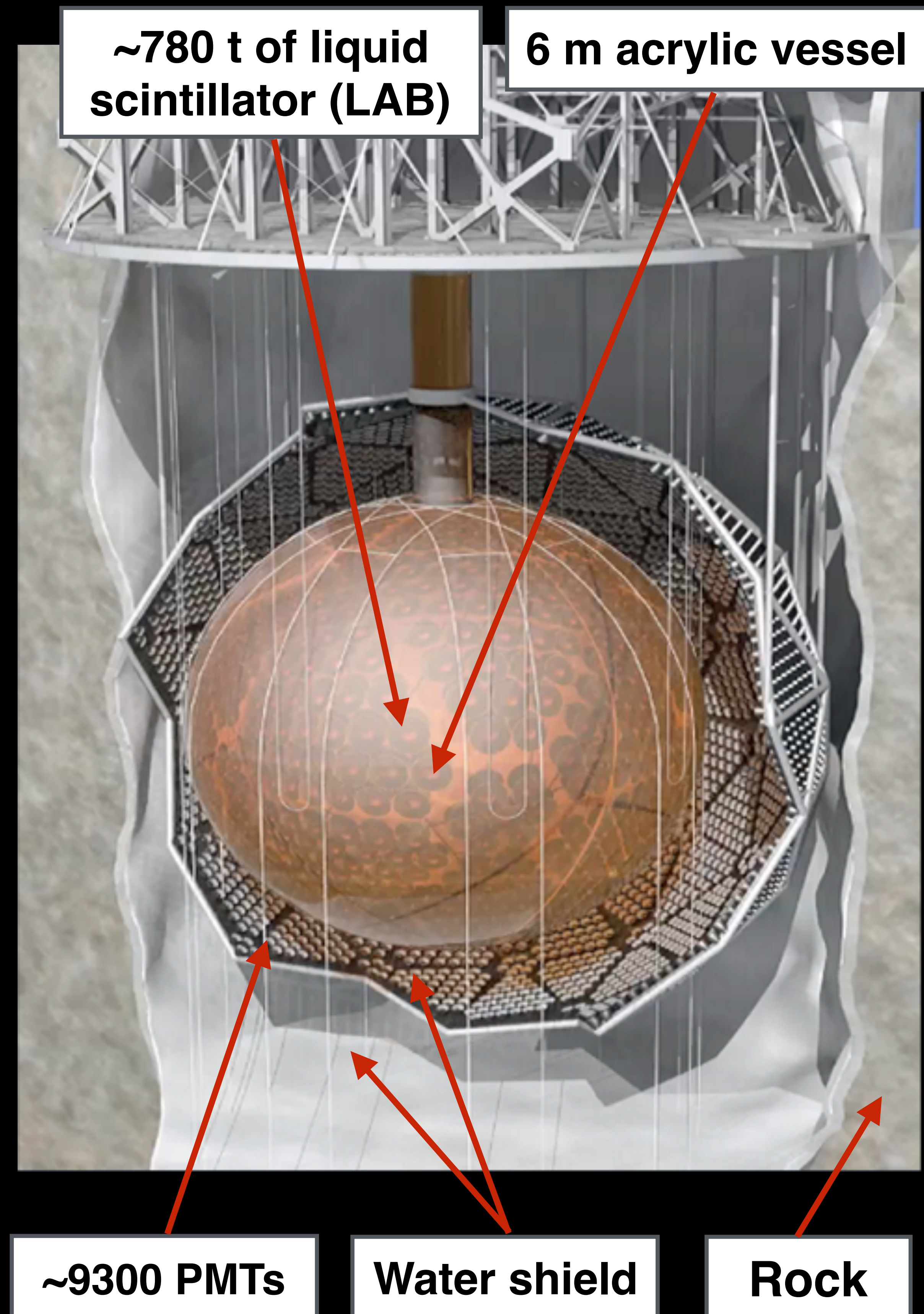




SNO+

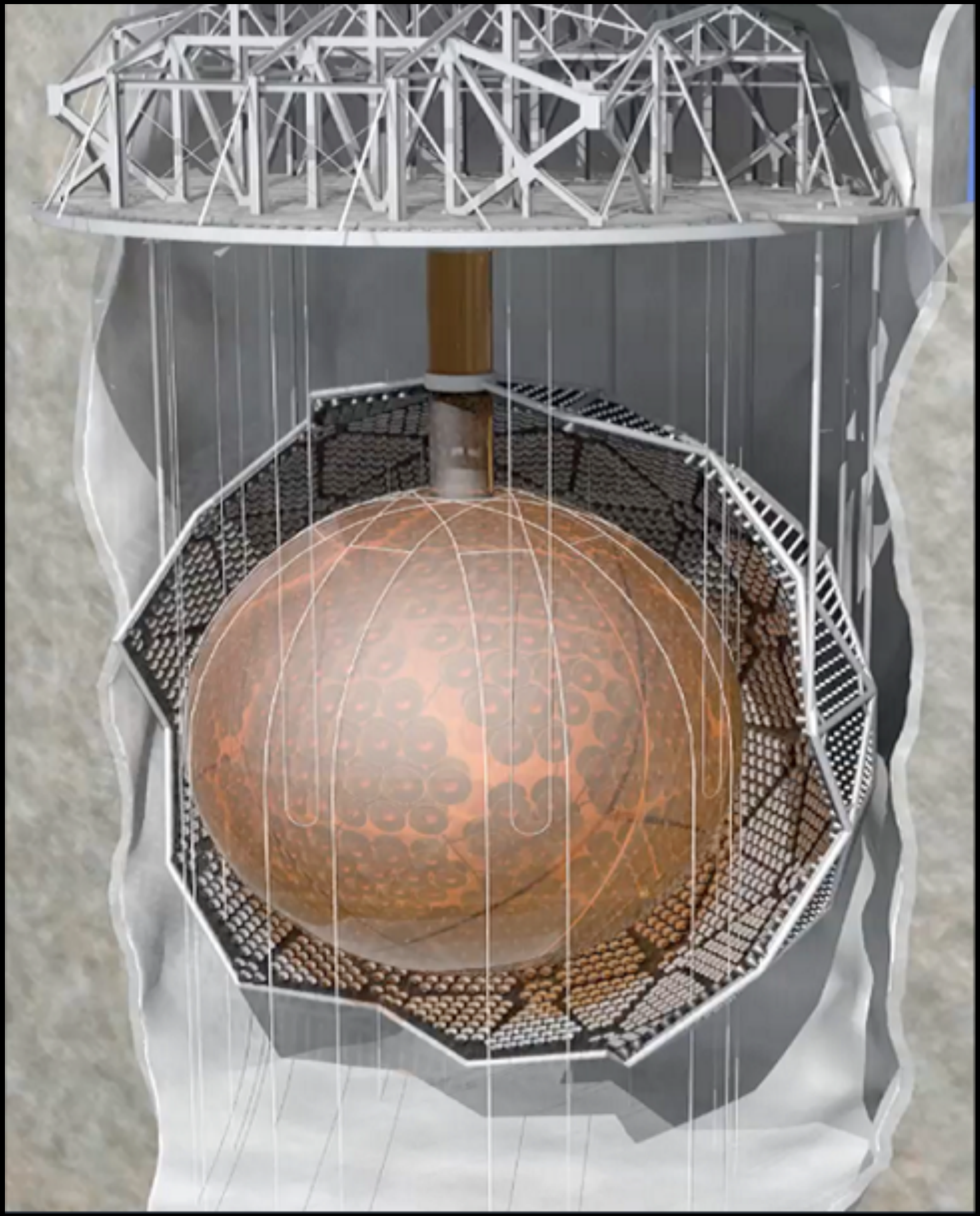
The SNO+Detector

- 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



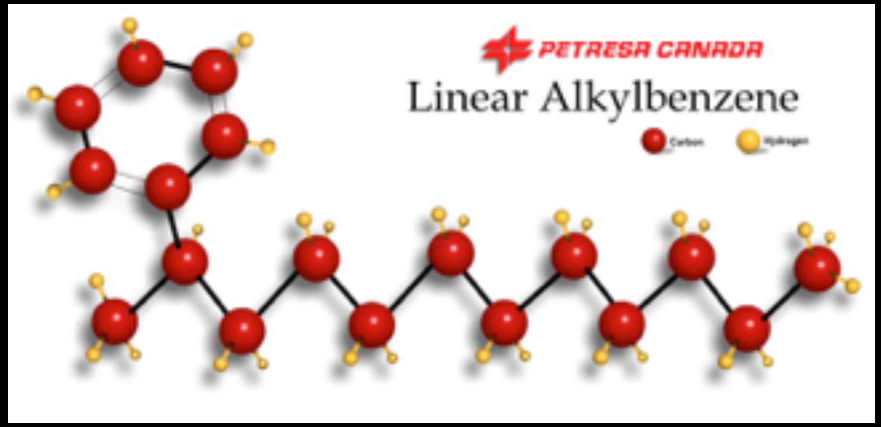
Detector Upgrades

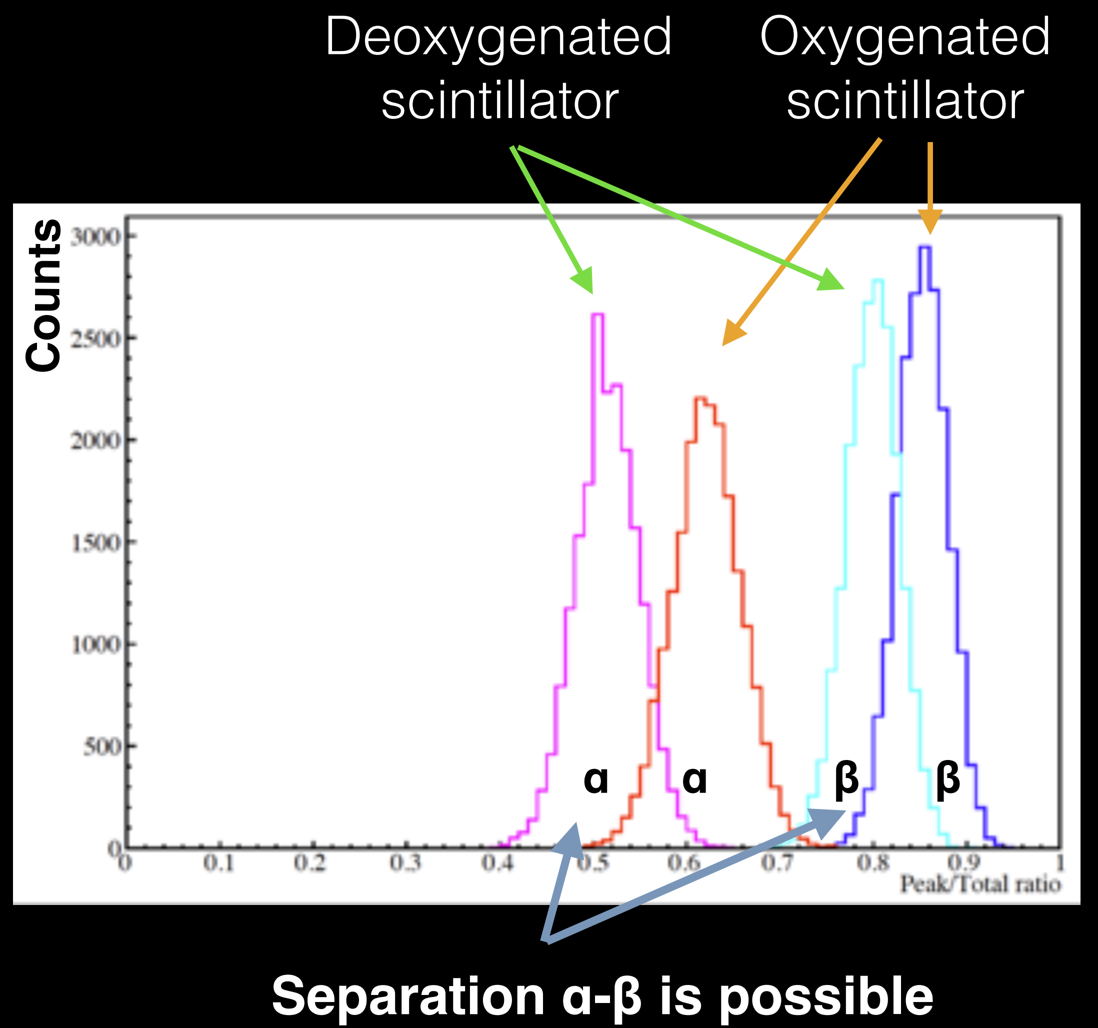
- Upgrades to reflect new objectives
- Replace heavy water with liquid scintillator
  - Load with ^{130}Te for 0νββ search
- Hold-down ropes
  - Compensate for lower density of scintillator
- Upgraded electronics
  - Handle higher event rates (> 1 kHz)
- Repaired PMTs
  - Maximize coverage
- New calibration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



Detection principle

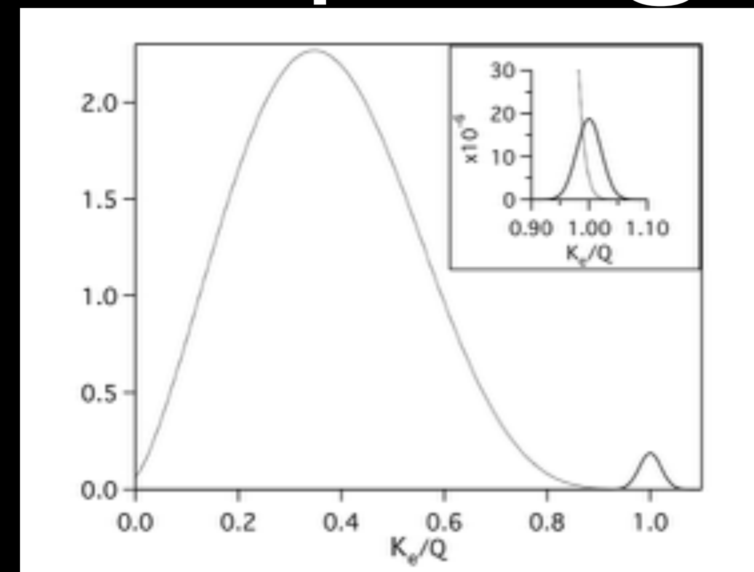
- Organic Scintillator (LAB+PPO) produces light when excited by charged particles
    - ~10000 photons/MeV
    - Few hundred detected by PMTs
    - ~20 m attenuation length
- Calorimetric measurement + pulse shape
    - Event energy from number of photons
    - Even position from photon time-of-flight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

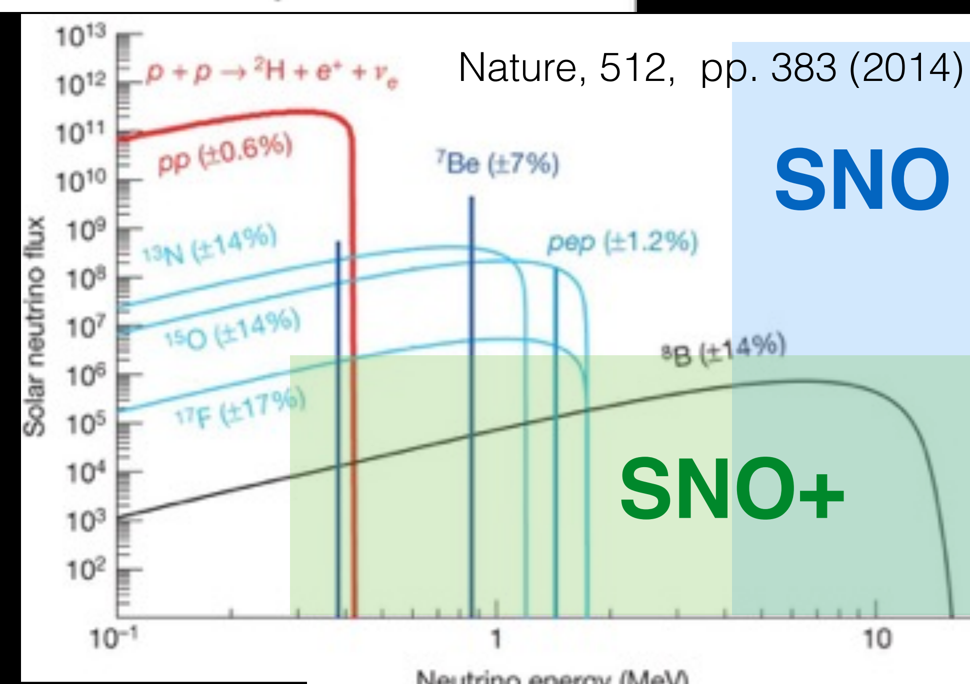


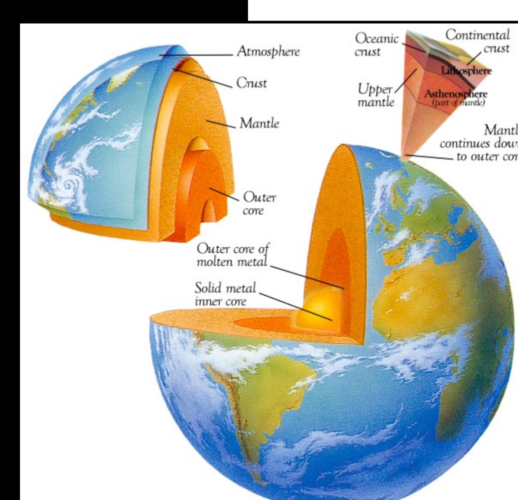


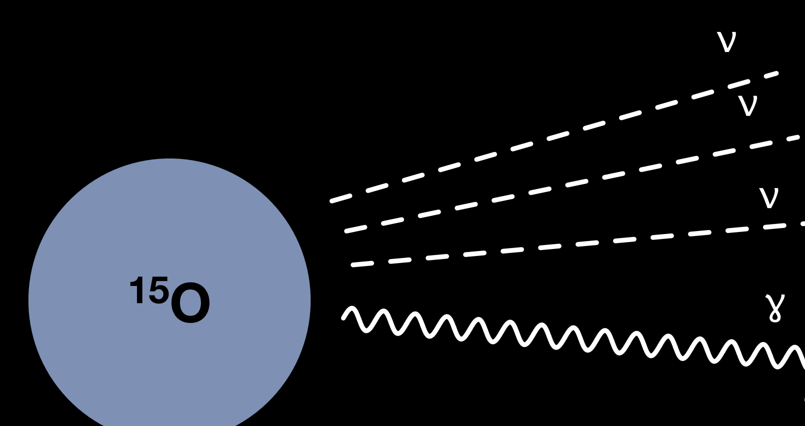
SNO+ physics program

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



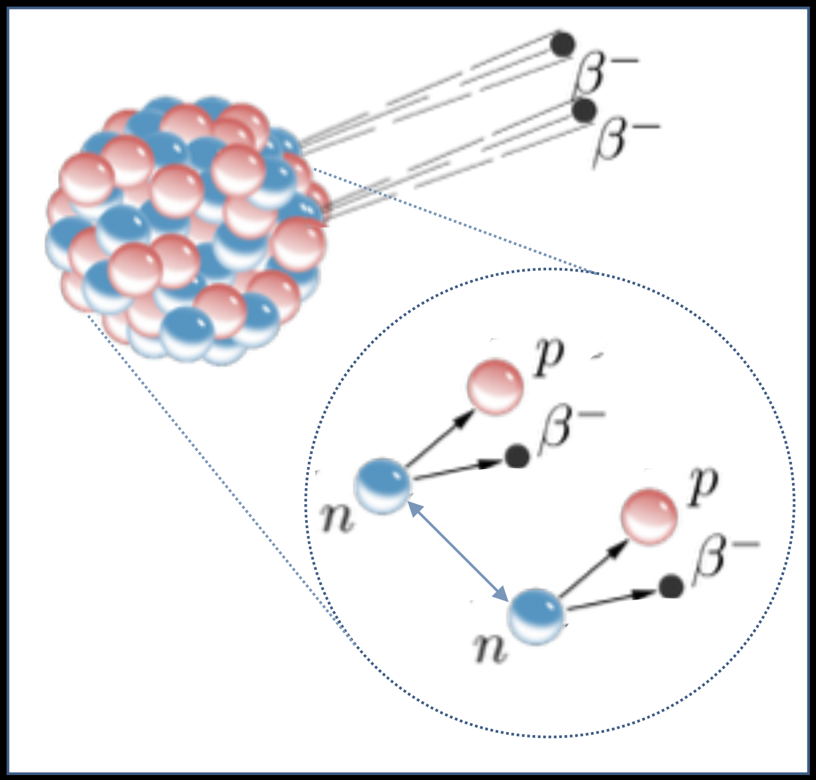






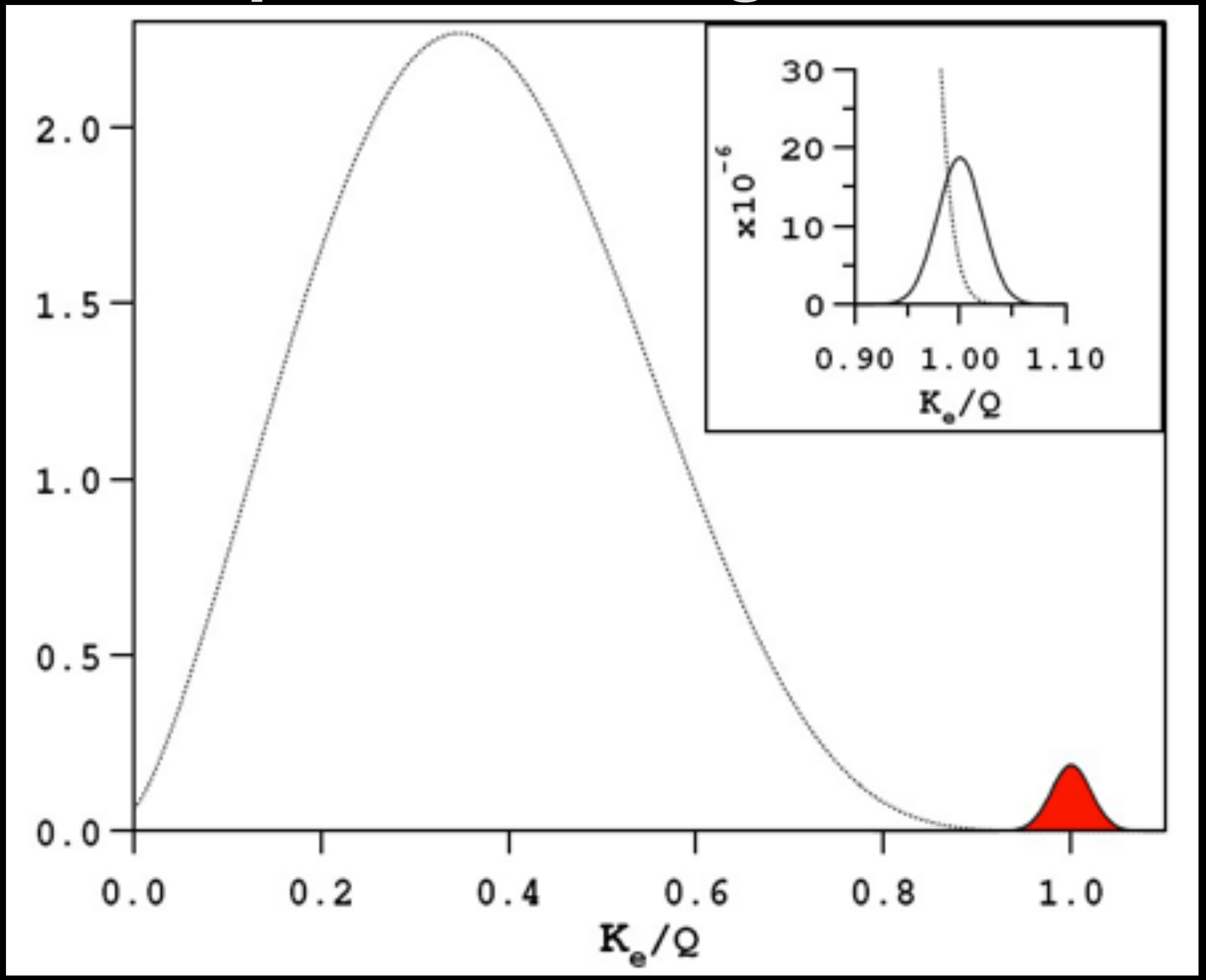
0νββ decay

Neutrino-less double beta decay



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

Experimental signature



If observed:

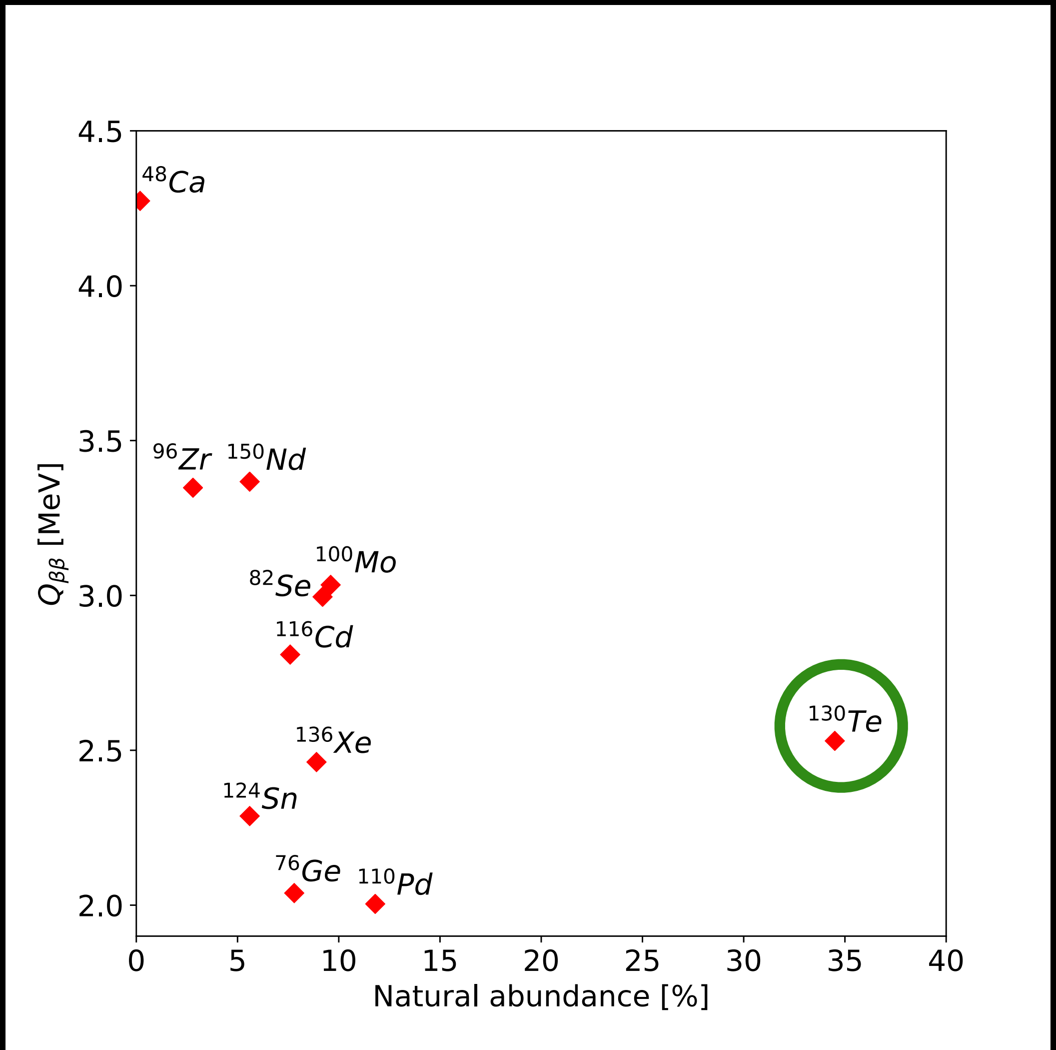
- Neutrinos are Majorana particles
- Lepton number violation: ΔL = 2
- Input on absolute ν mass scale and hierarchy

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+

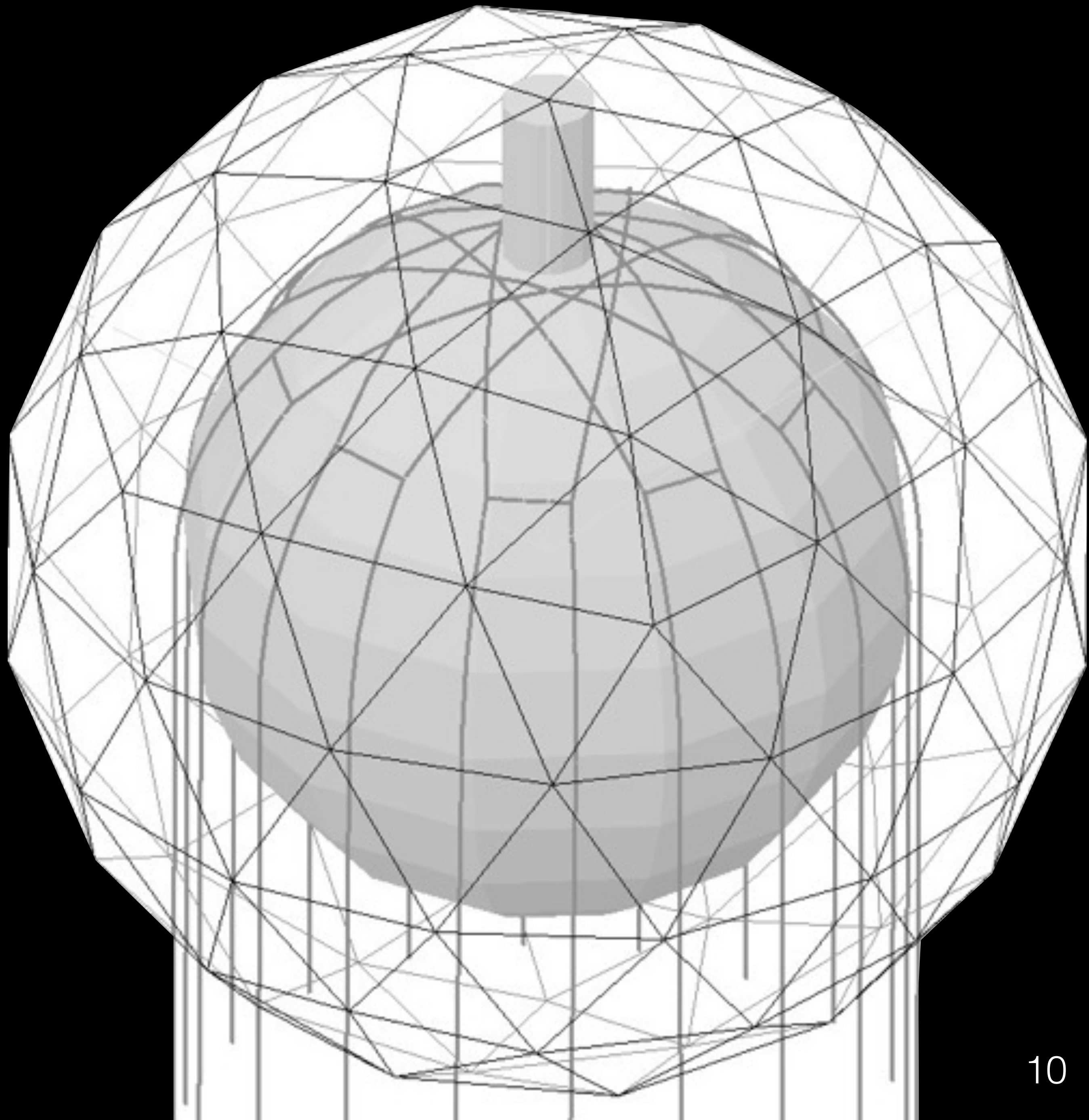
- **Load the scintillator with Te**
- **Double beta decay isotope: ^{130}Te**
    - Long 2νββ half-life: ~ 7×10^{20} years
    - High Q-value : ~2.5 MeV
    - High natural abundance: ~30%
    - No absorption lines in PMT sensitive region
    - Scalable: by increasing loading
- **Loading method: Te acid + butanediol (TeBD)**
    - Initially loading 0.5% (funding secured)
        - ~1330 kg of ^{130}Te
    - Good optics: transparent, low scattering



SNO+ advantages

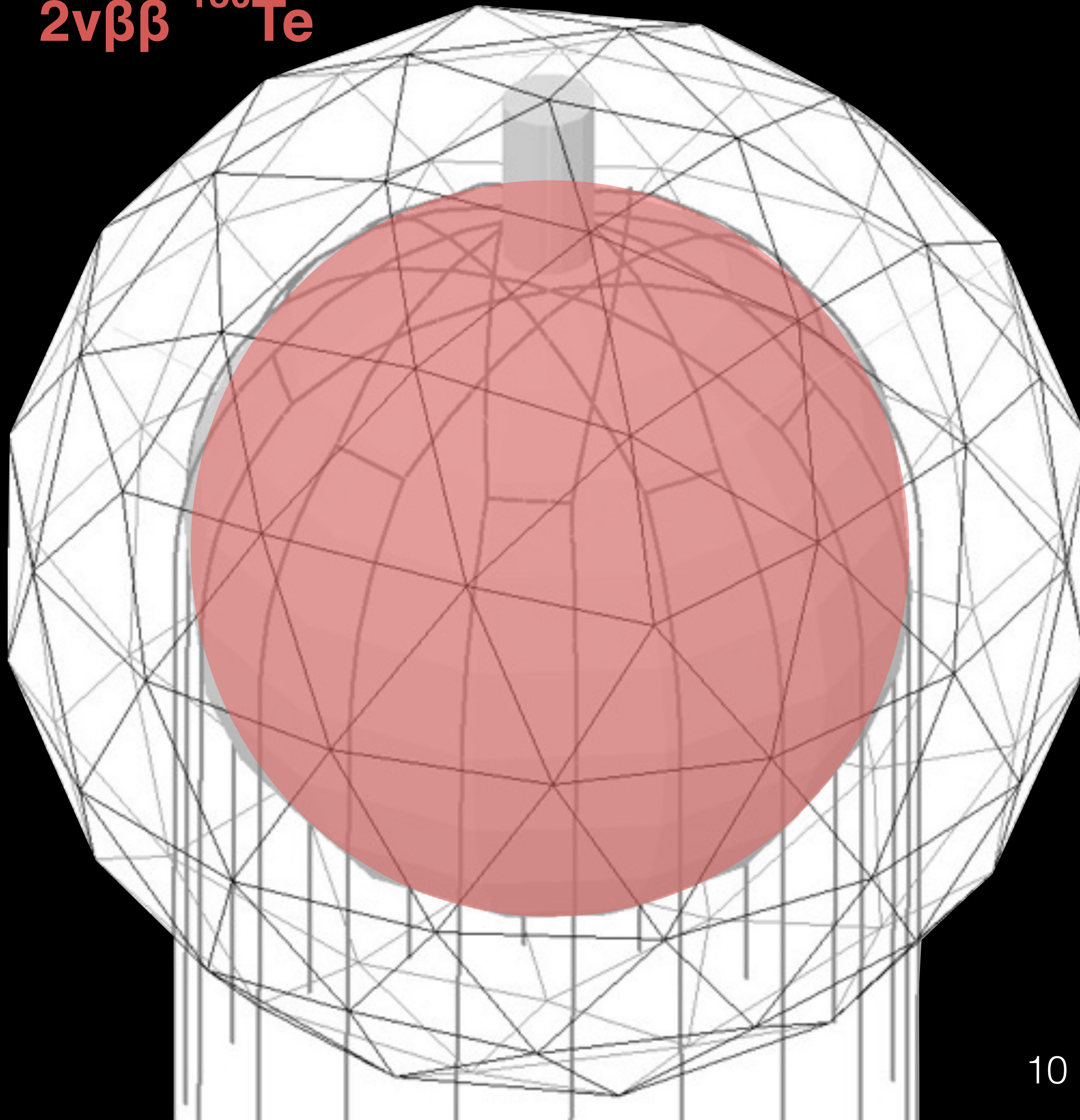
- Scalable loading
- Low backgrounds
    - External shielding
    - Scintillator self-shielding
    - LAB purification

SNO+ 0νββ backgrounds



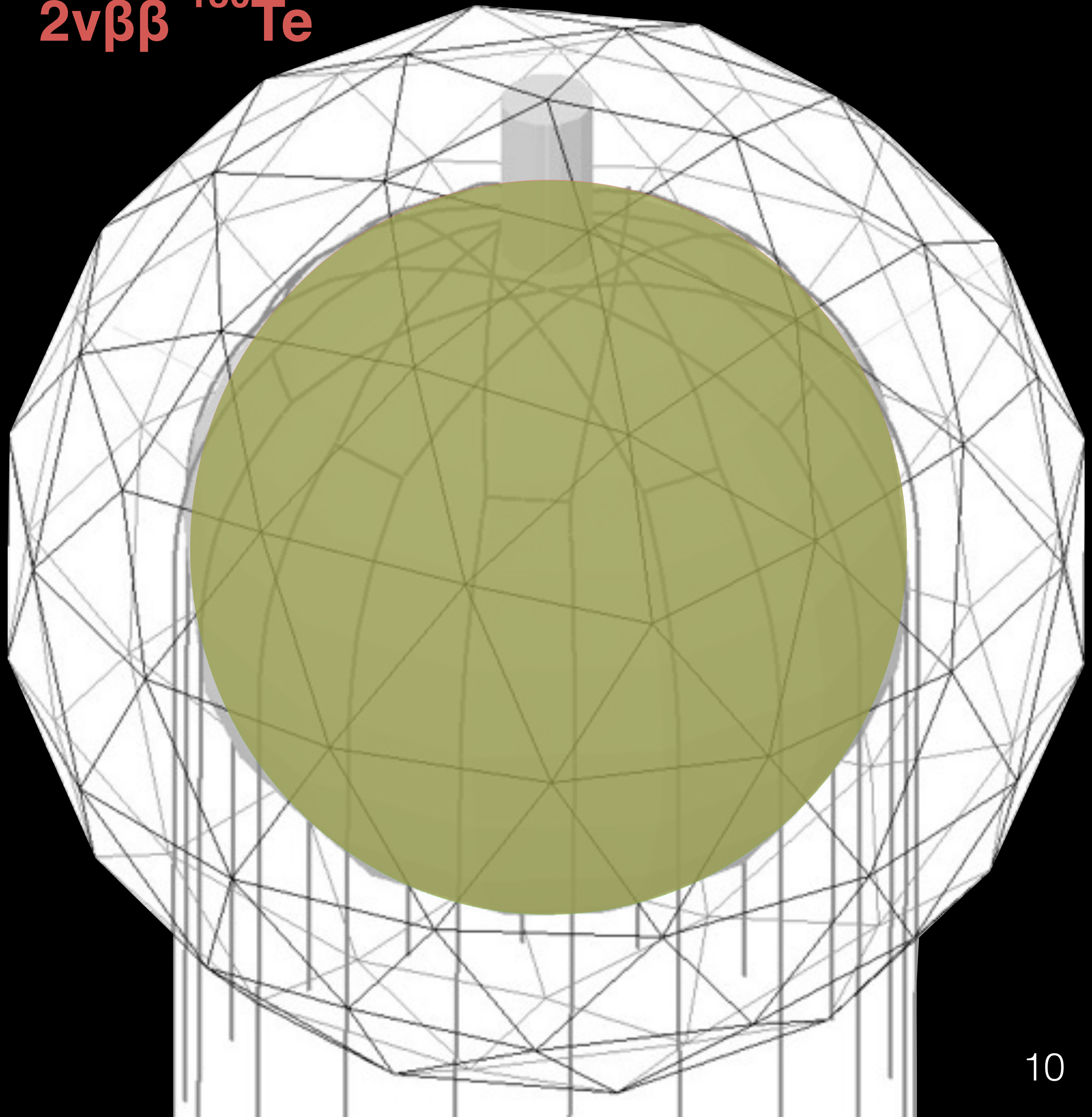
SNO+ 0νββ backgrounds

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



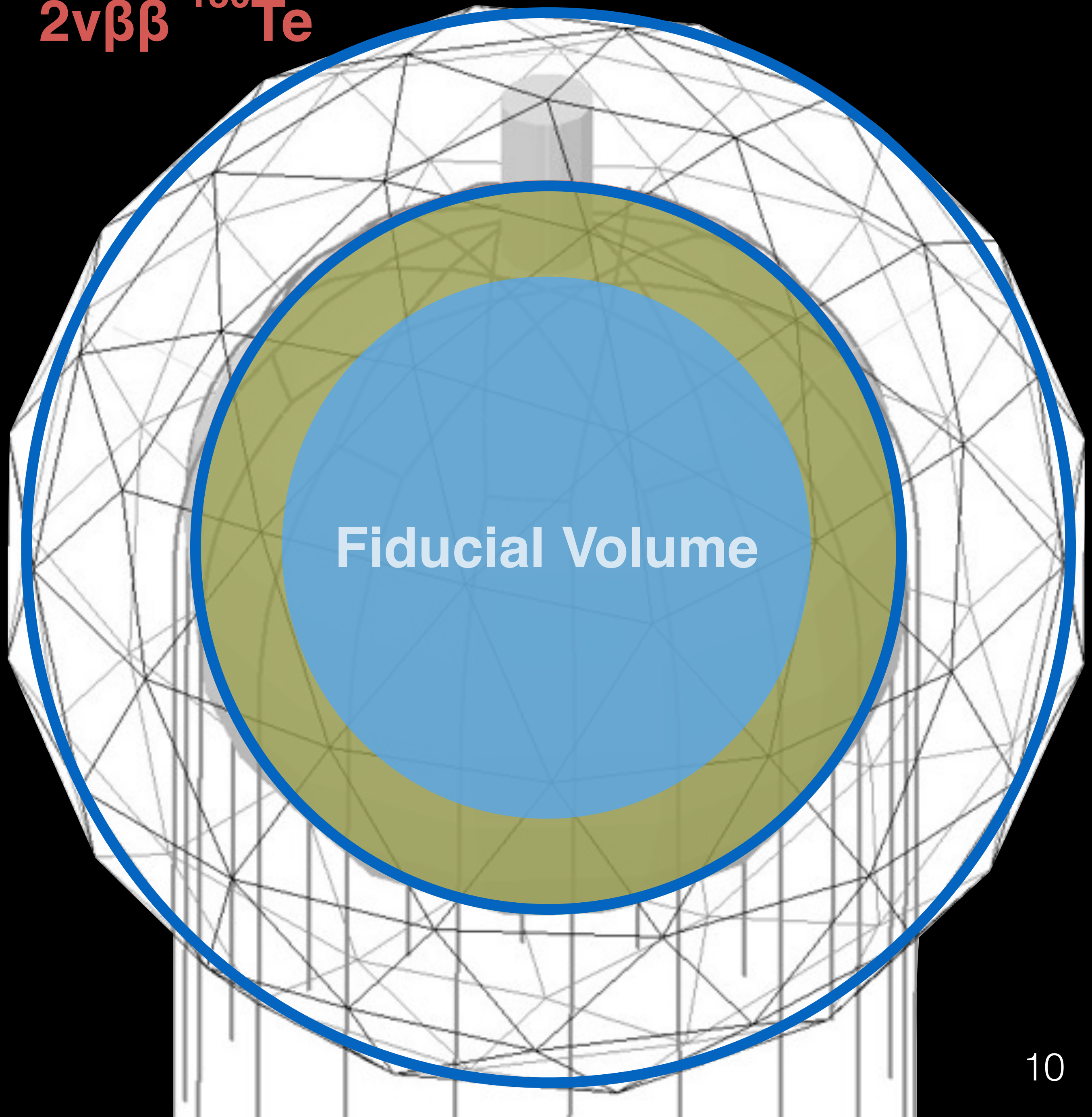
SNO+ 0νββ backgrounds

- **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**

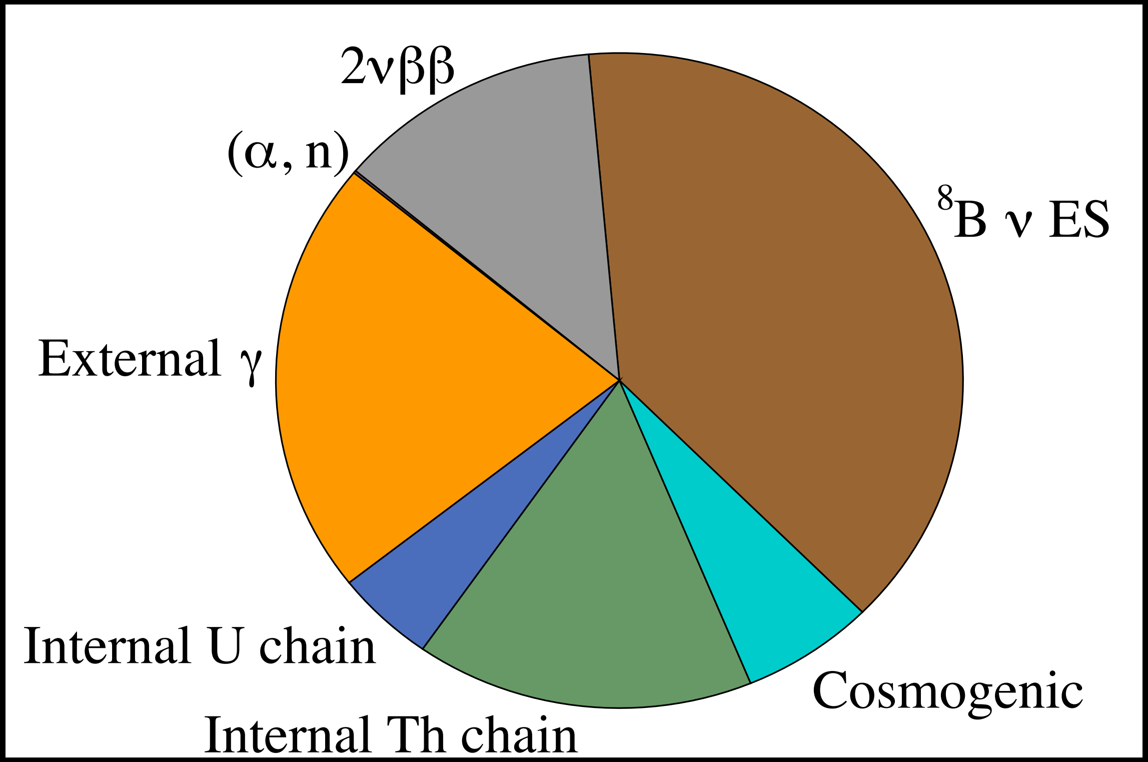


SNO+ 0νββ backgrounds

- **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)

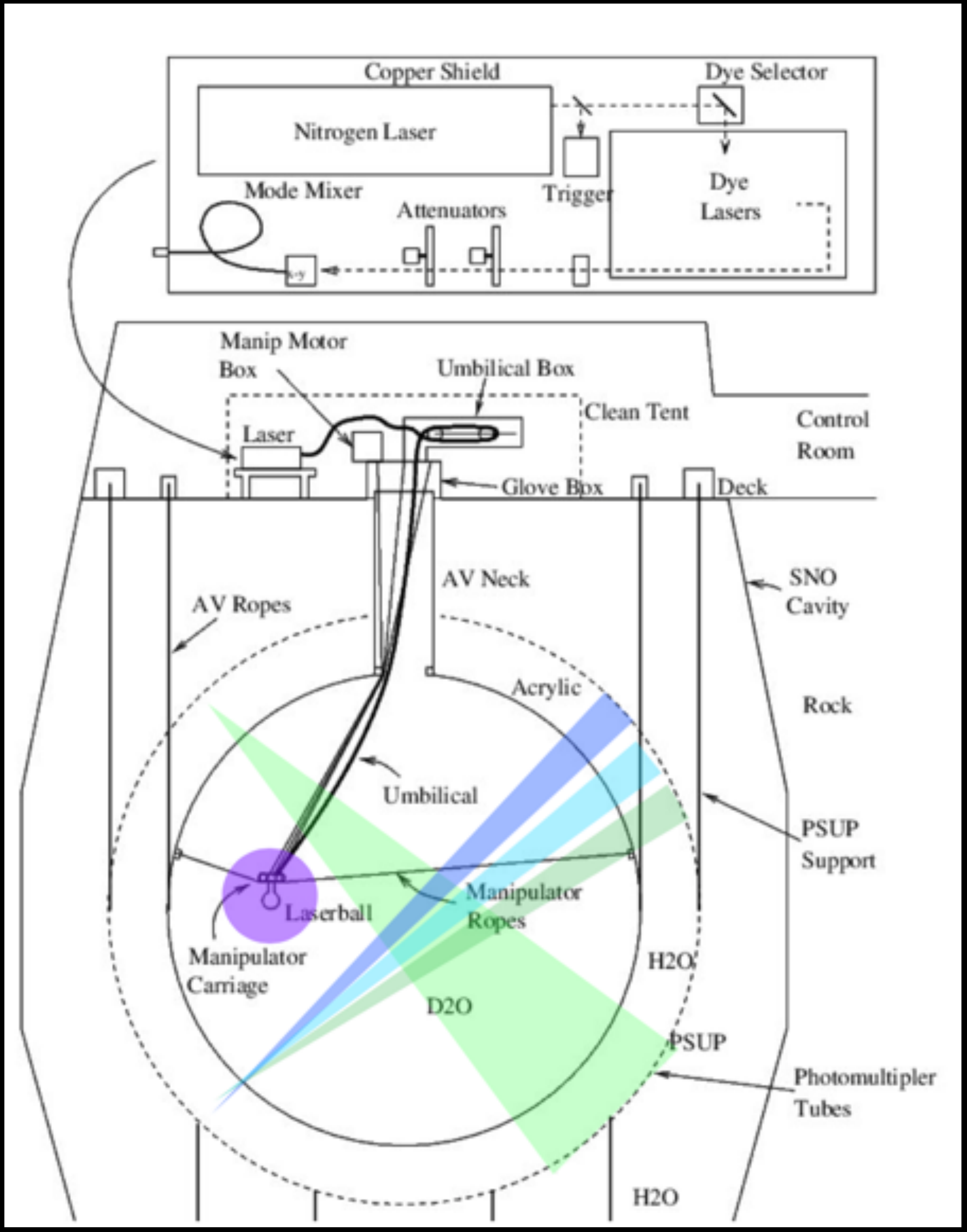
(α, n)

- Thermal neutron capture
- Delayed coincidence

Detector calibration

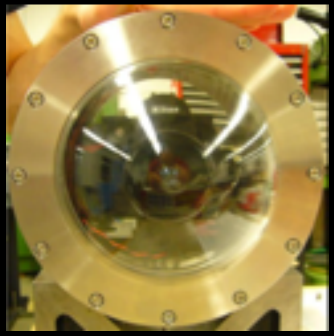
Multiple calibration systems in place

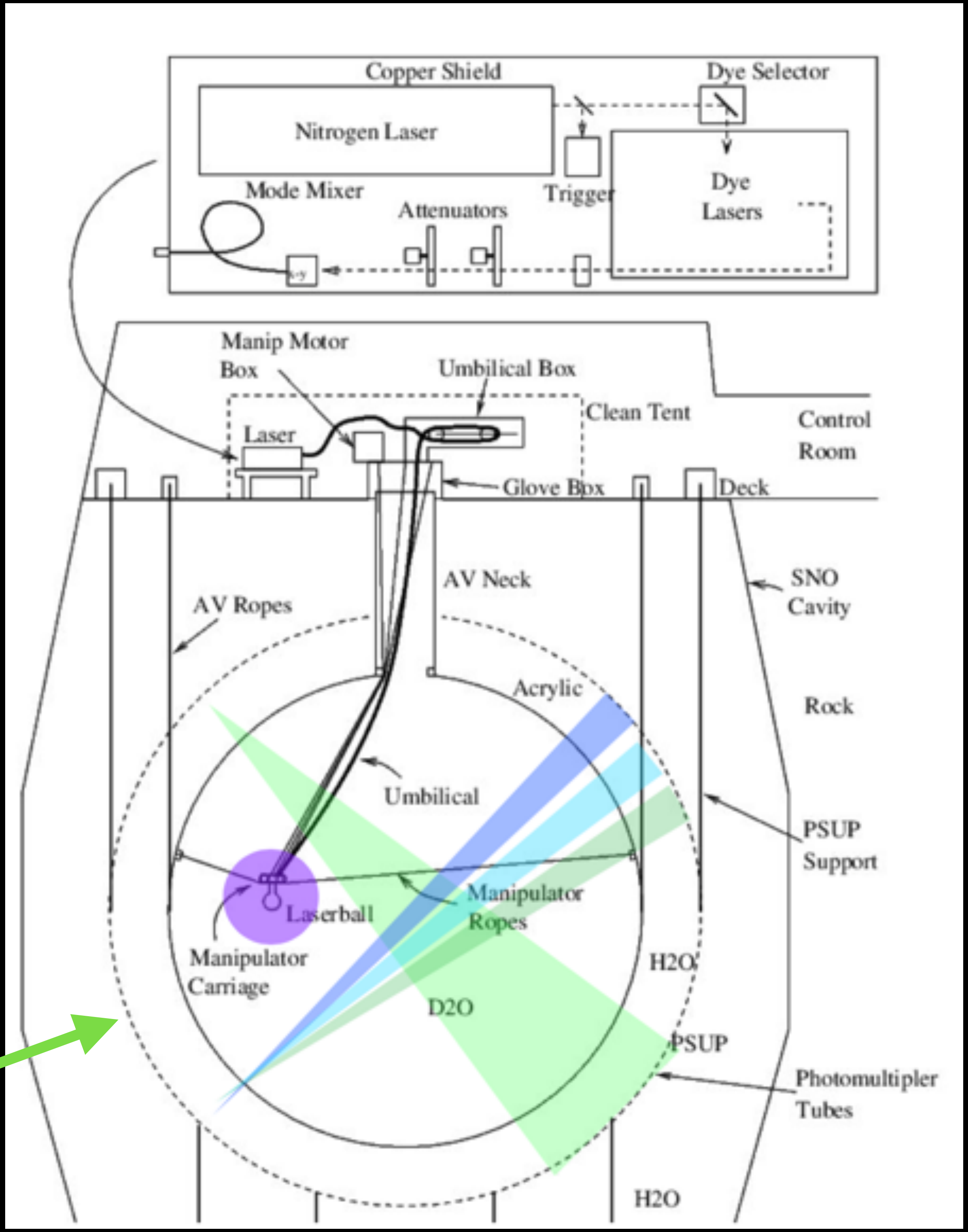
- “Laserball” : light diffuser
  - Optical parameters of the detector
  - Attenuation, angular response of PMTs
- Deployed radioactive sources
  - Various sources for different purposes
  - Tagged sources for known energies
  - Energy scale and resolution
  - Collection efficiency



Detector calibration

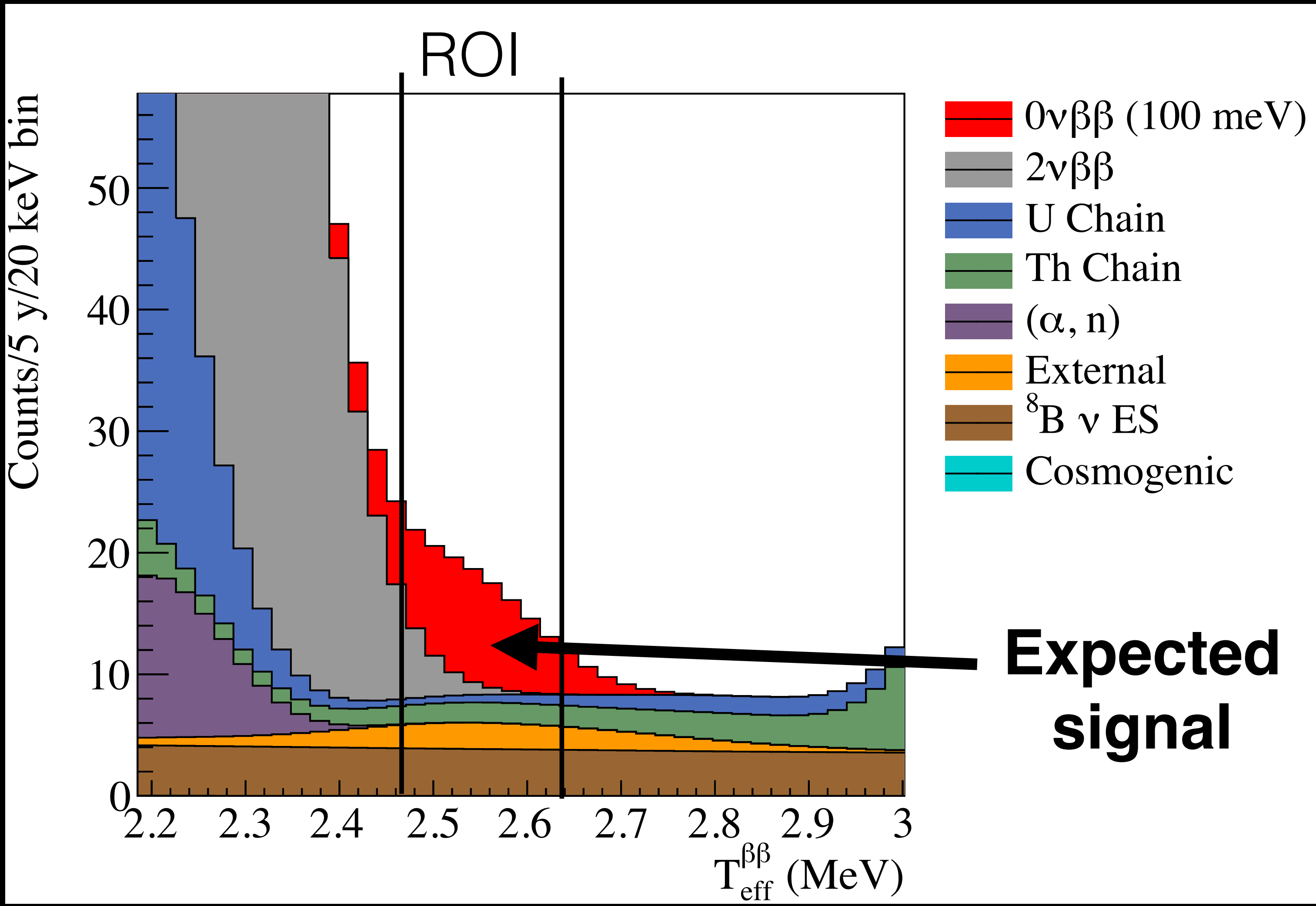
- **Internal calibration system [JINST 10, P03002 (2015)]**
  - Optical fibers mounted in PMT structure
  - Uses fast LEDs and fibers for multiple measurements:
    - timing
    - gain
    - scattering
    - late light
  - Continuous monitoring of stability
  - No source insertion
- **Underwater cameras**
  - Improve resolution in source position





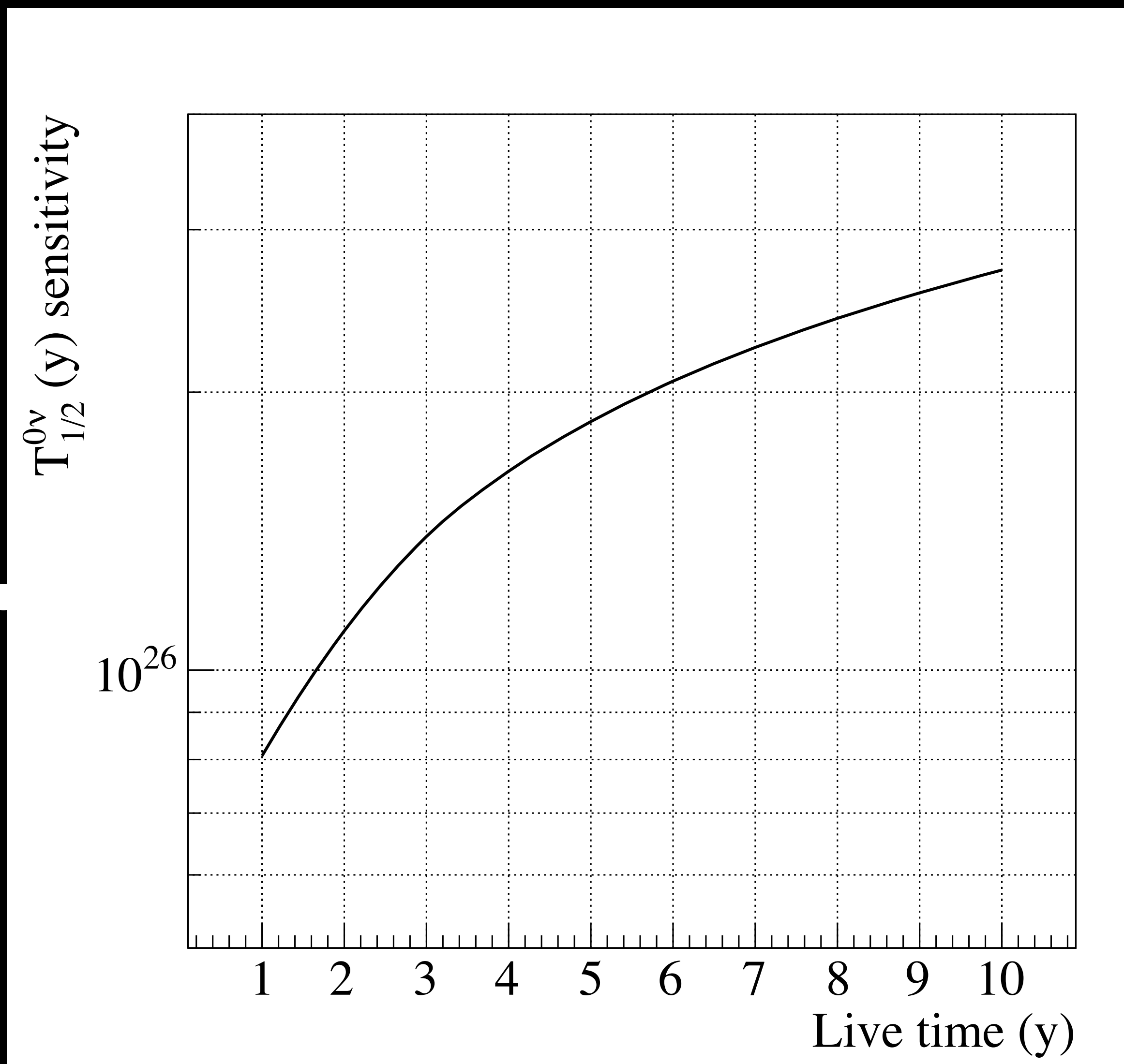
SNO+ 0νββ spectrum

- 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}

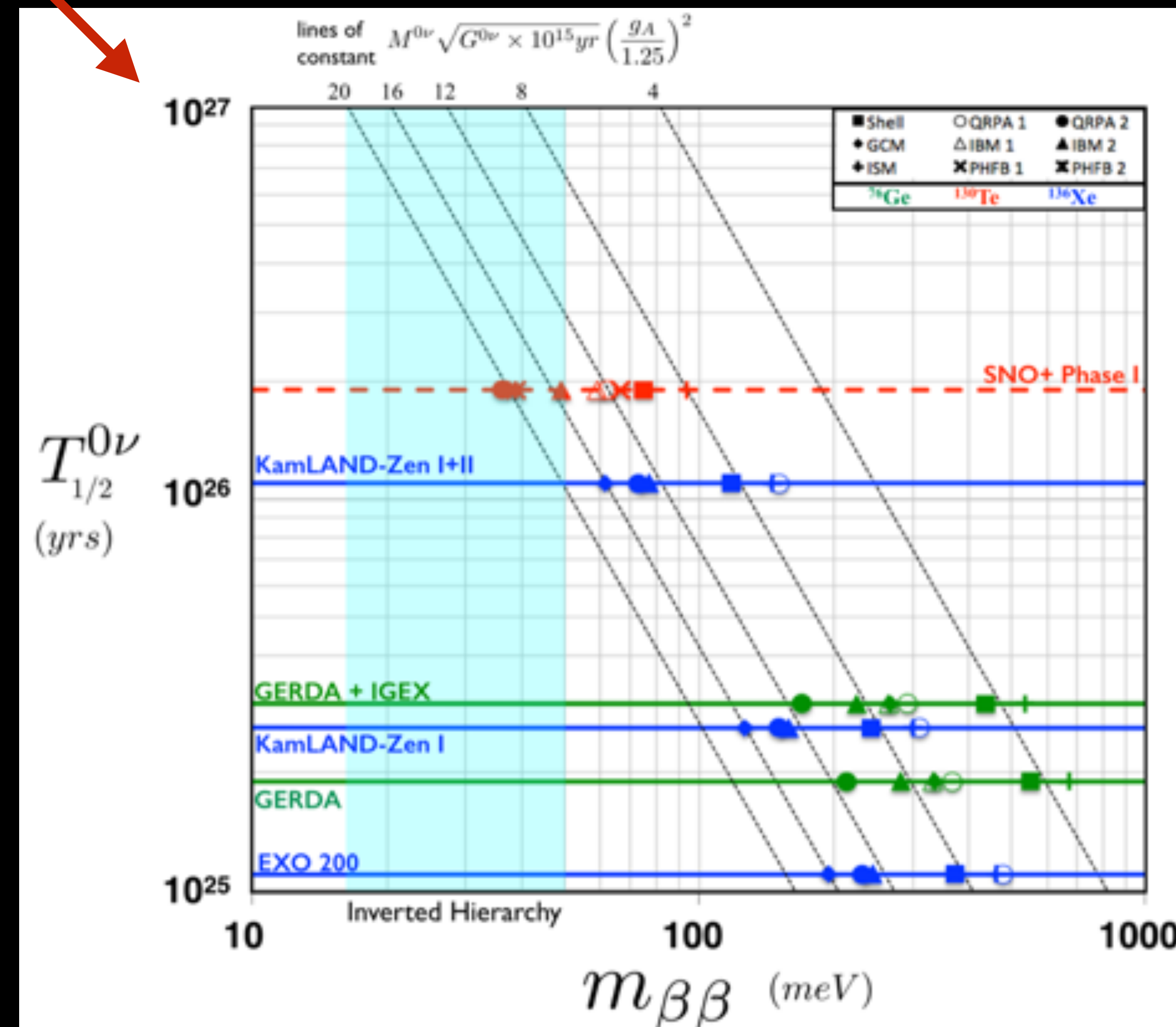


- Expected spectrum after 5 year run
  - $m_{\beta\beta}$ = 100 meV
  - 0.5% Te loading (~1330 kg 130Te)

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

Water Phase	Scintillator Phase	^{130}Te loaded Scintillator Phase
NOW	late 2017	late 2018

Nucleon Decay

$0\nu\beta\beta$

Solar Neutrinos*

Geo-neutrinos

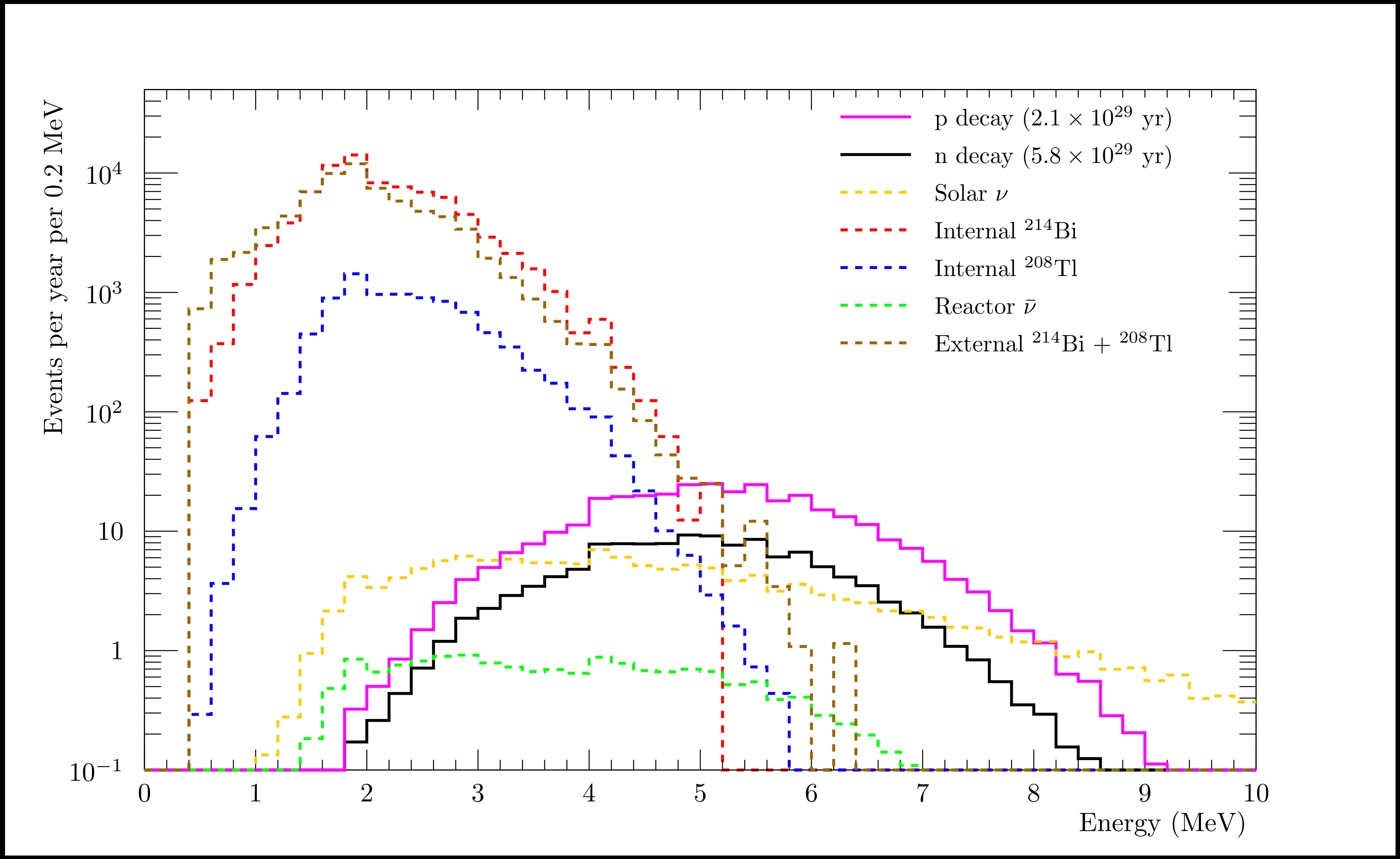
Reactor Neutrinos

Supernova Neutrinos

Background Studies

* low energy solar neutrinos after Te-loaded phase

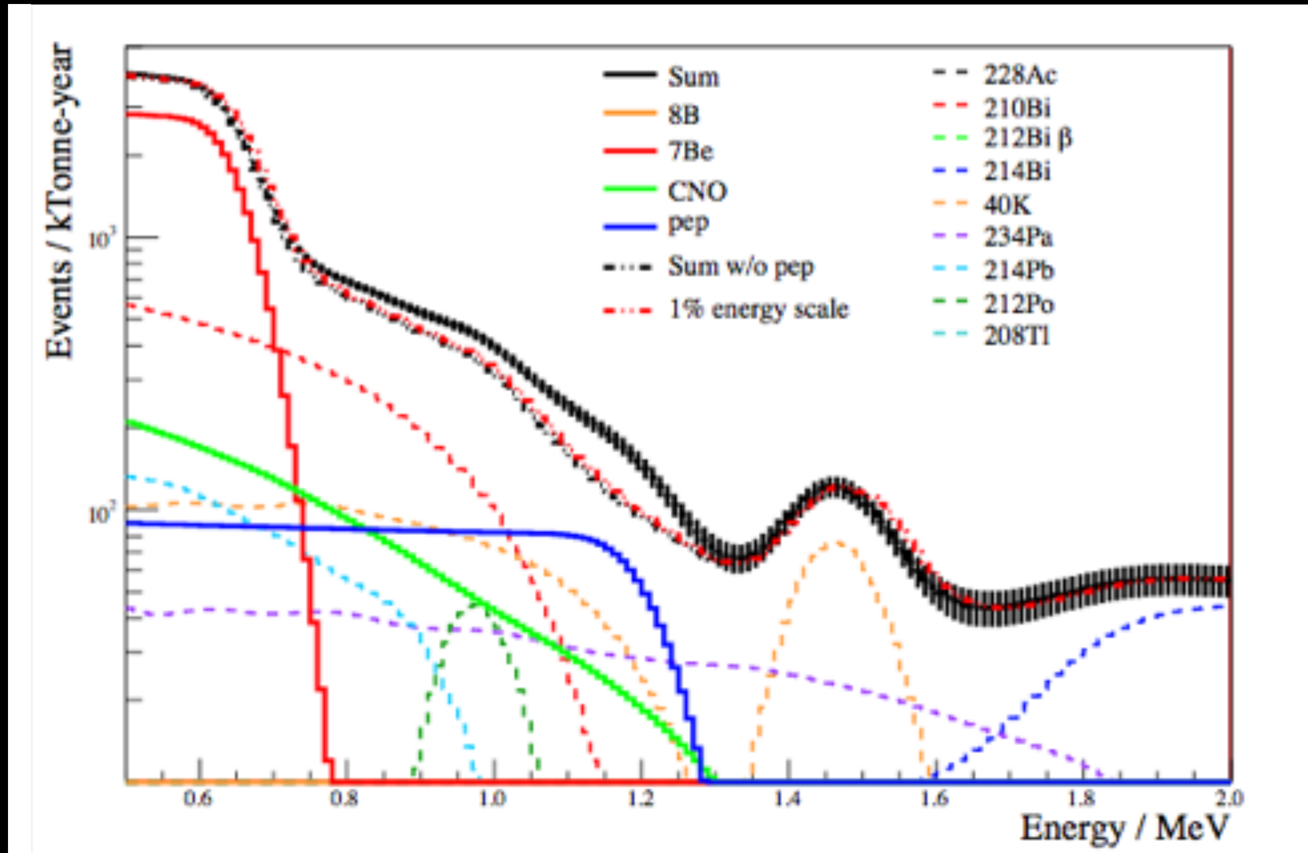
Nucleon decay

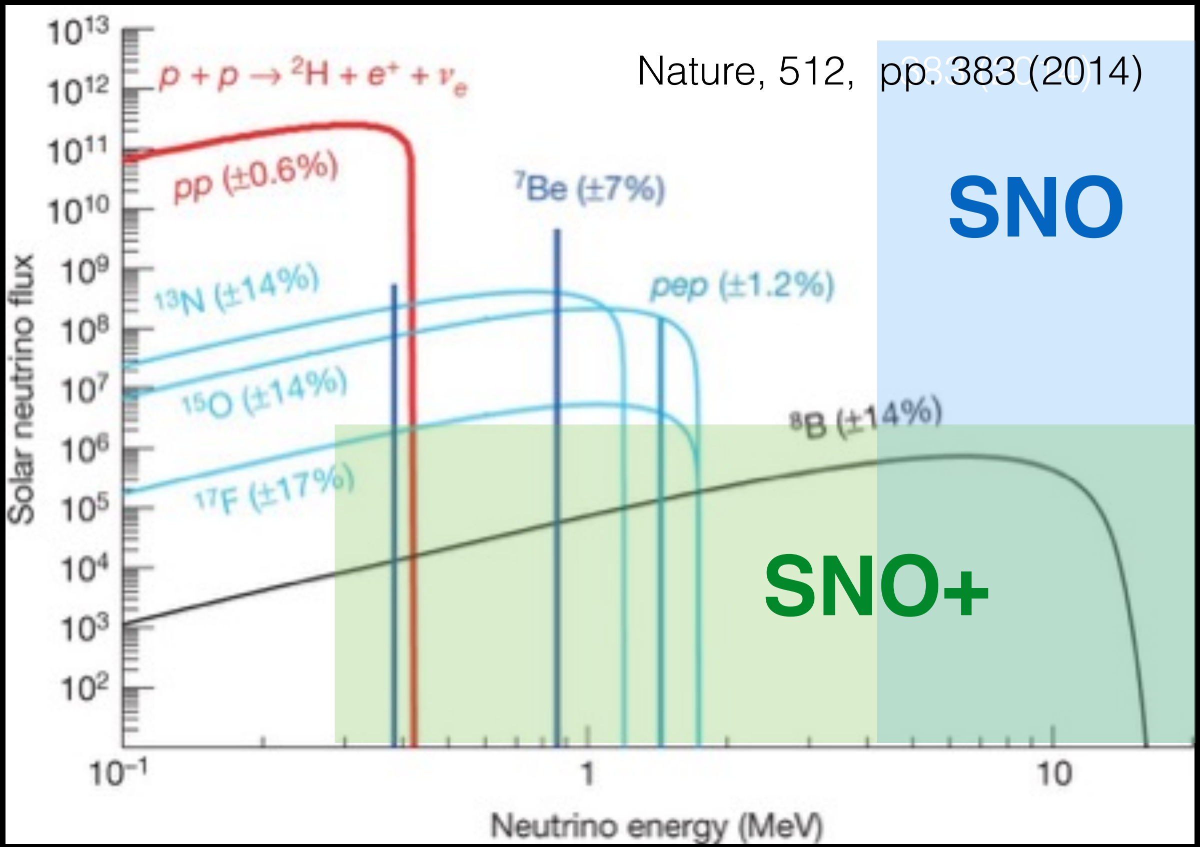


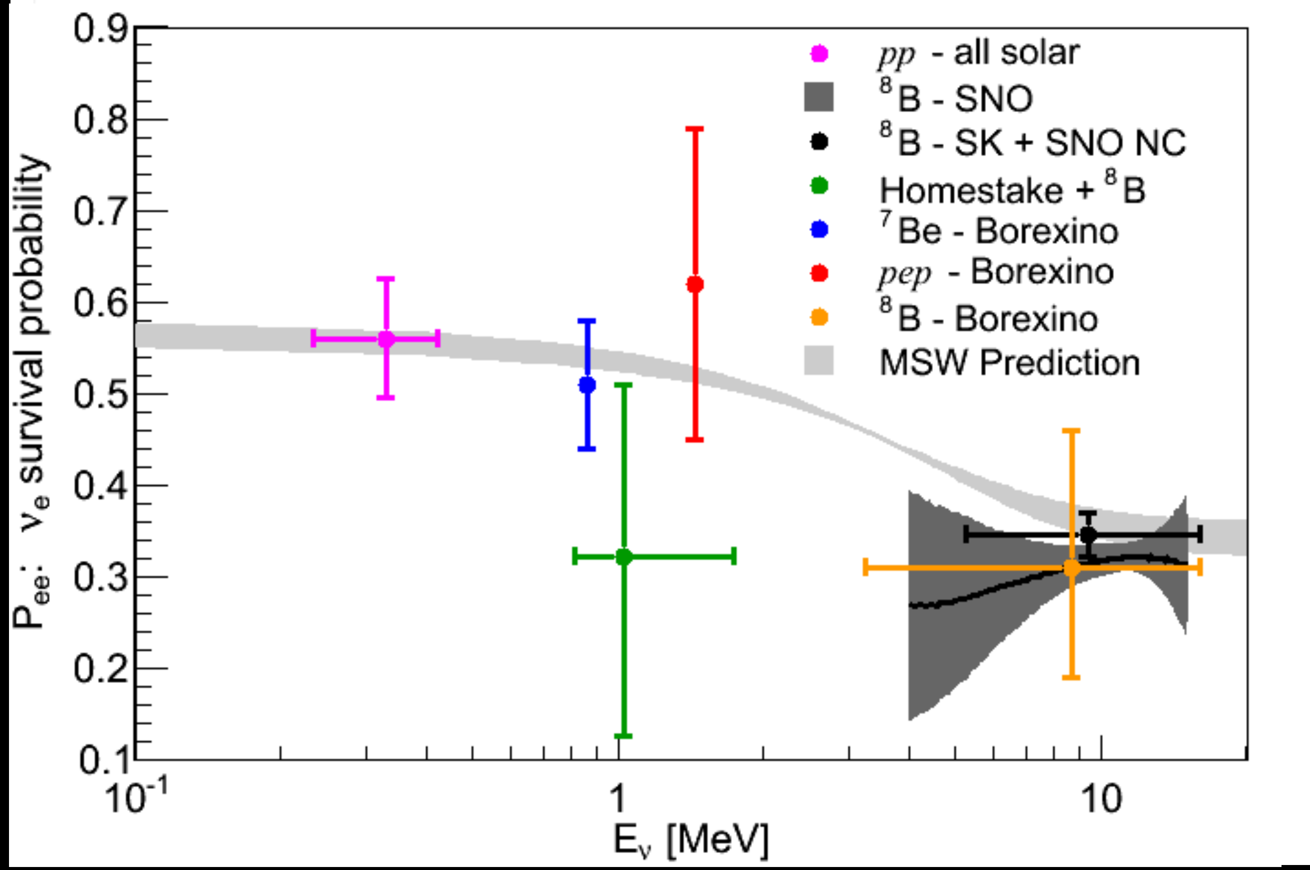
- Look for invisible decay modes
  - $^{16}O \longrightarrow {}^{15}O^*$ or $^{15}N^*$ + ~5 MeV ɣ
- Sensitivity
  - $\tau_n = 1.2\text{x}10^{30}$ years (current limit [KamLAND] : $5.8\text{x}10^{29}$)
  - $\tau_p = 1.4\text{x}10^{30}$ years (current limit [SNO] : $2.1\text{x}10^{29}$)

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

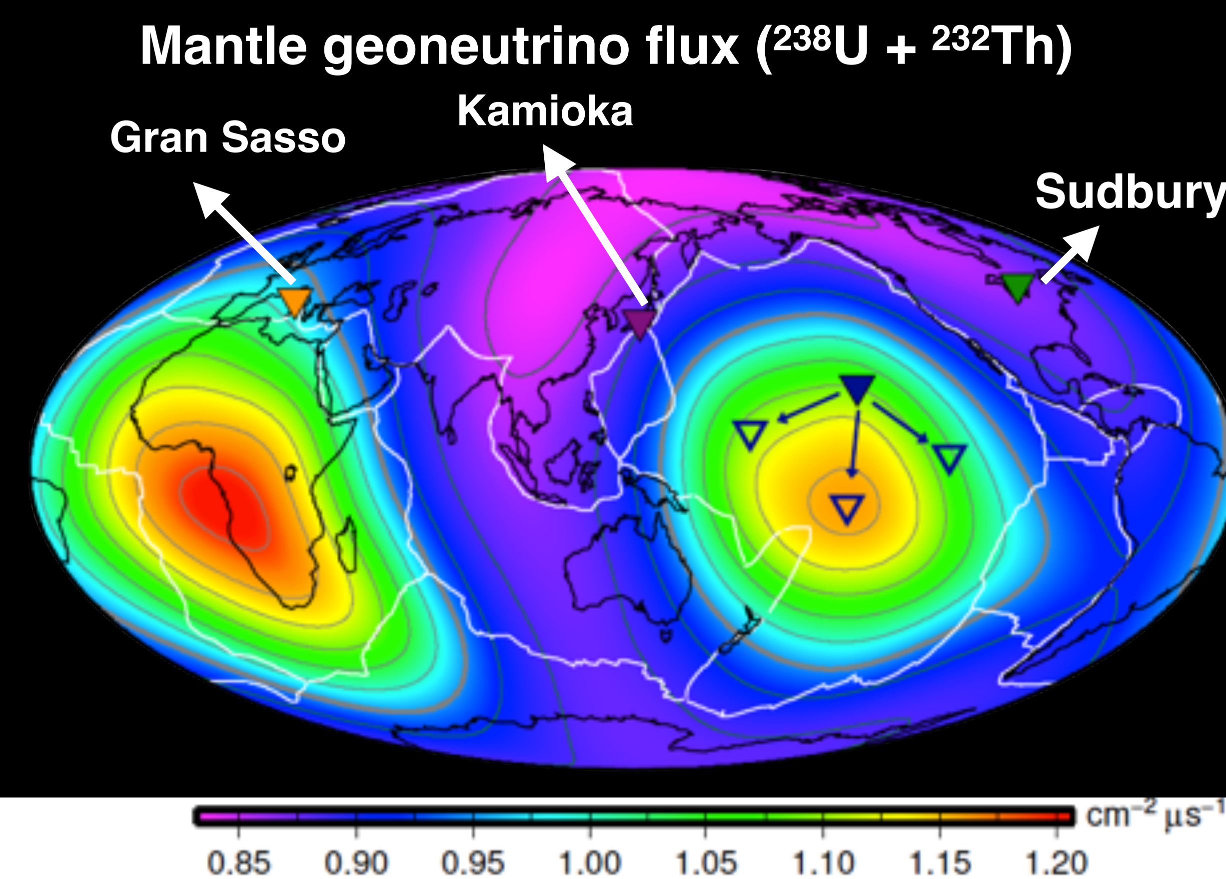


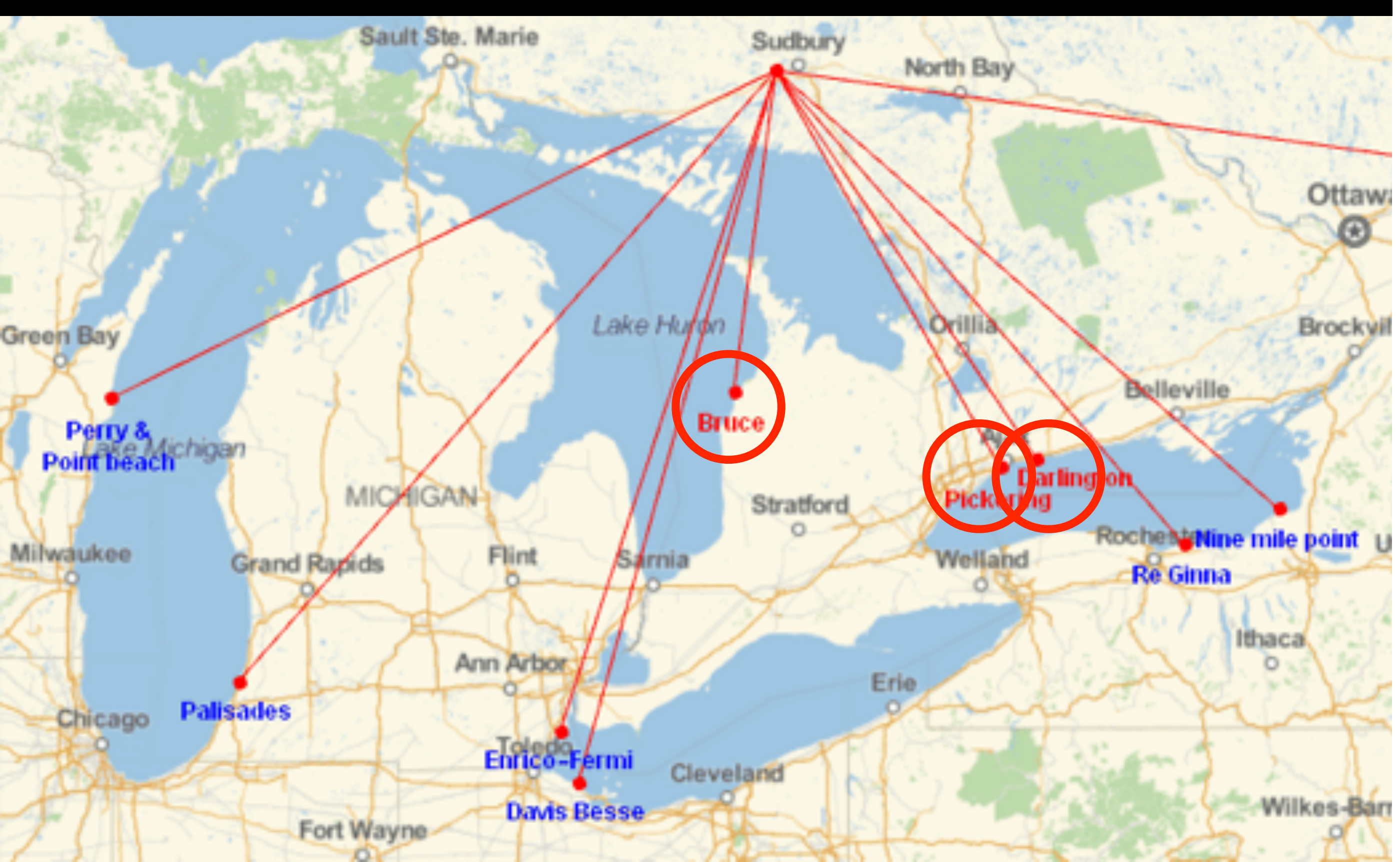


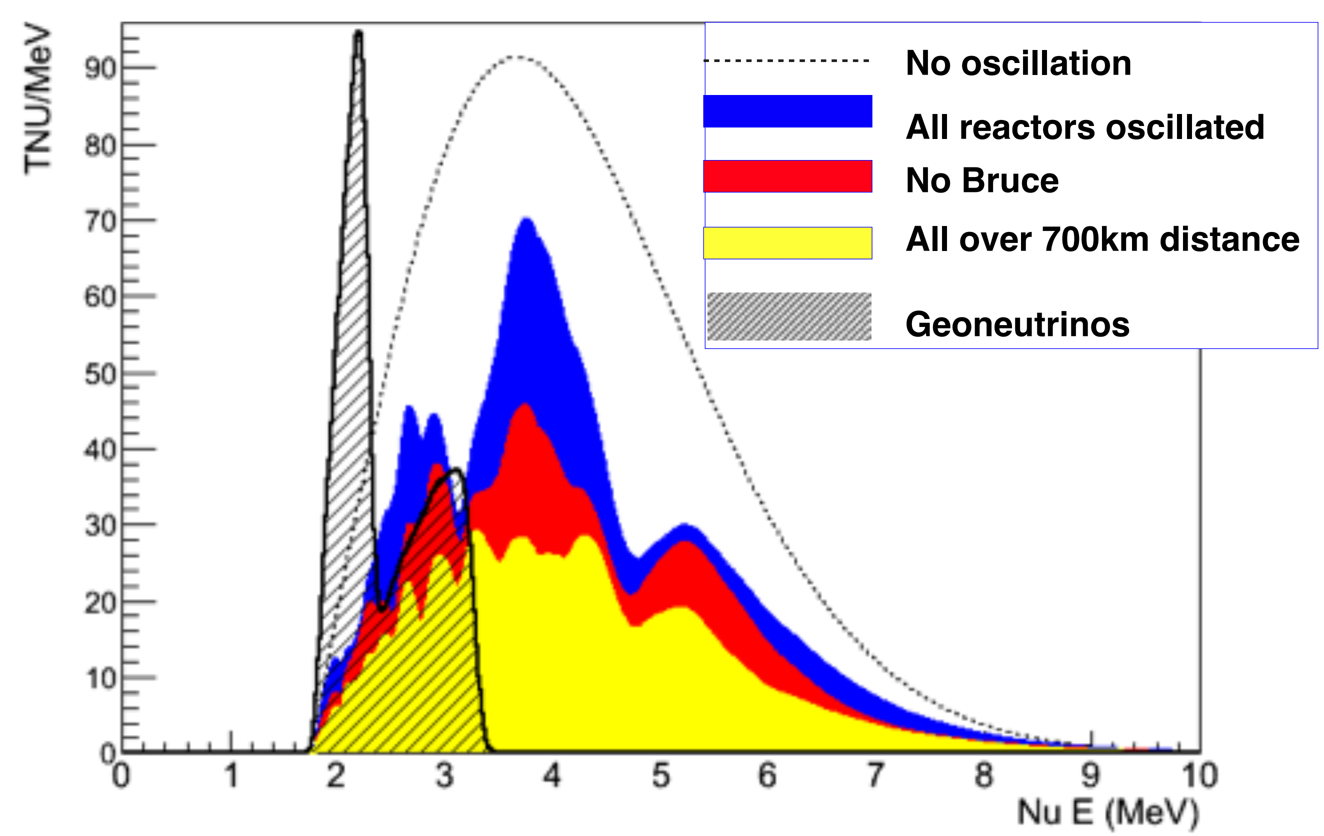


Reactor and geo-neutrinos

- 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

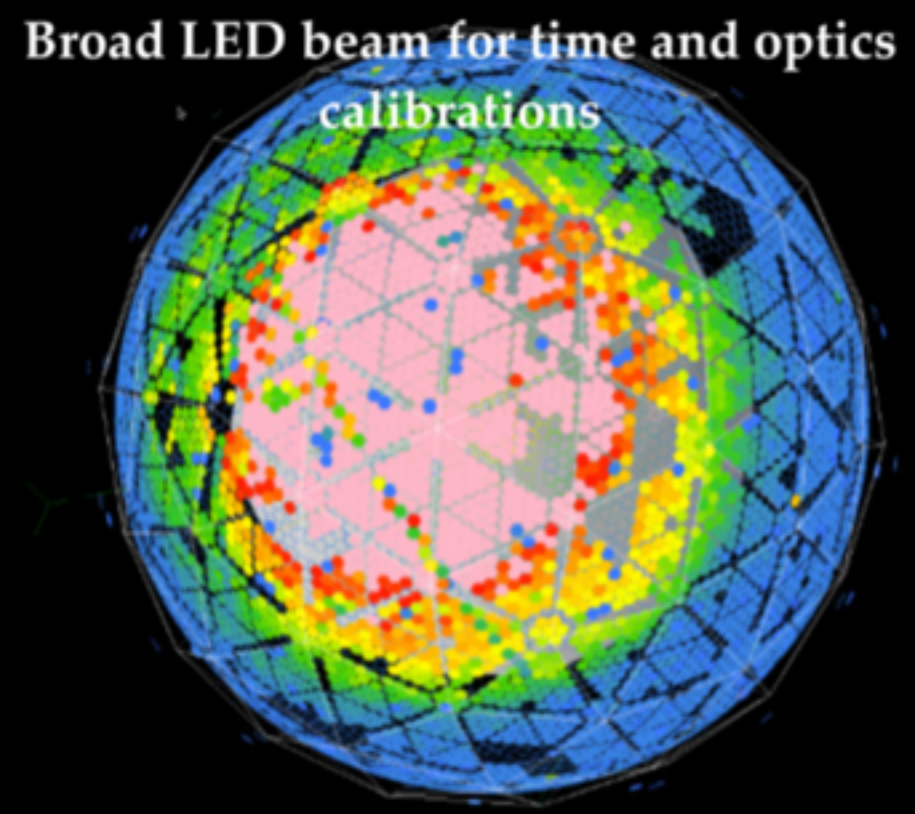


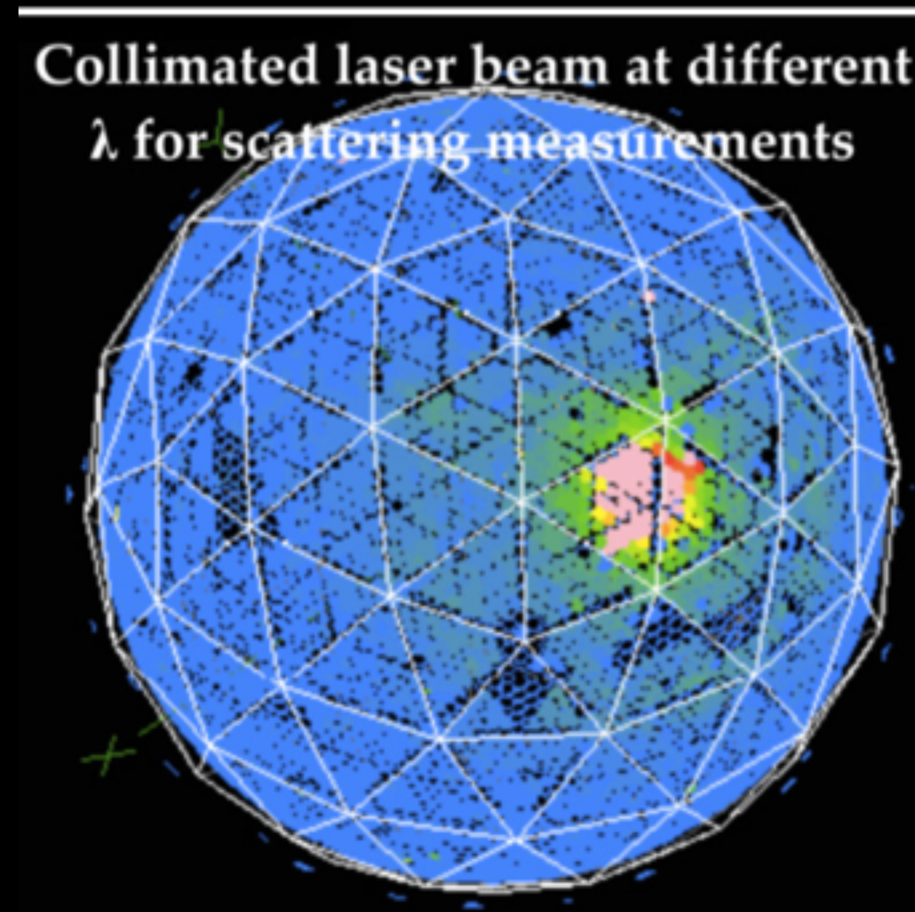




Current Status

- Repaired leaks in cavity
- Replaced repaired PMTs
- Commissioning of internal calibration systems (LED/laser)
- Commissioning of electronics upgrades with high event rates
- Commissioning of DAQ system





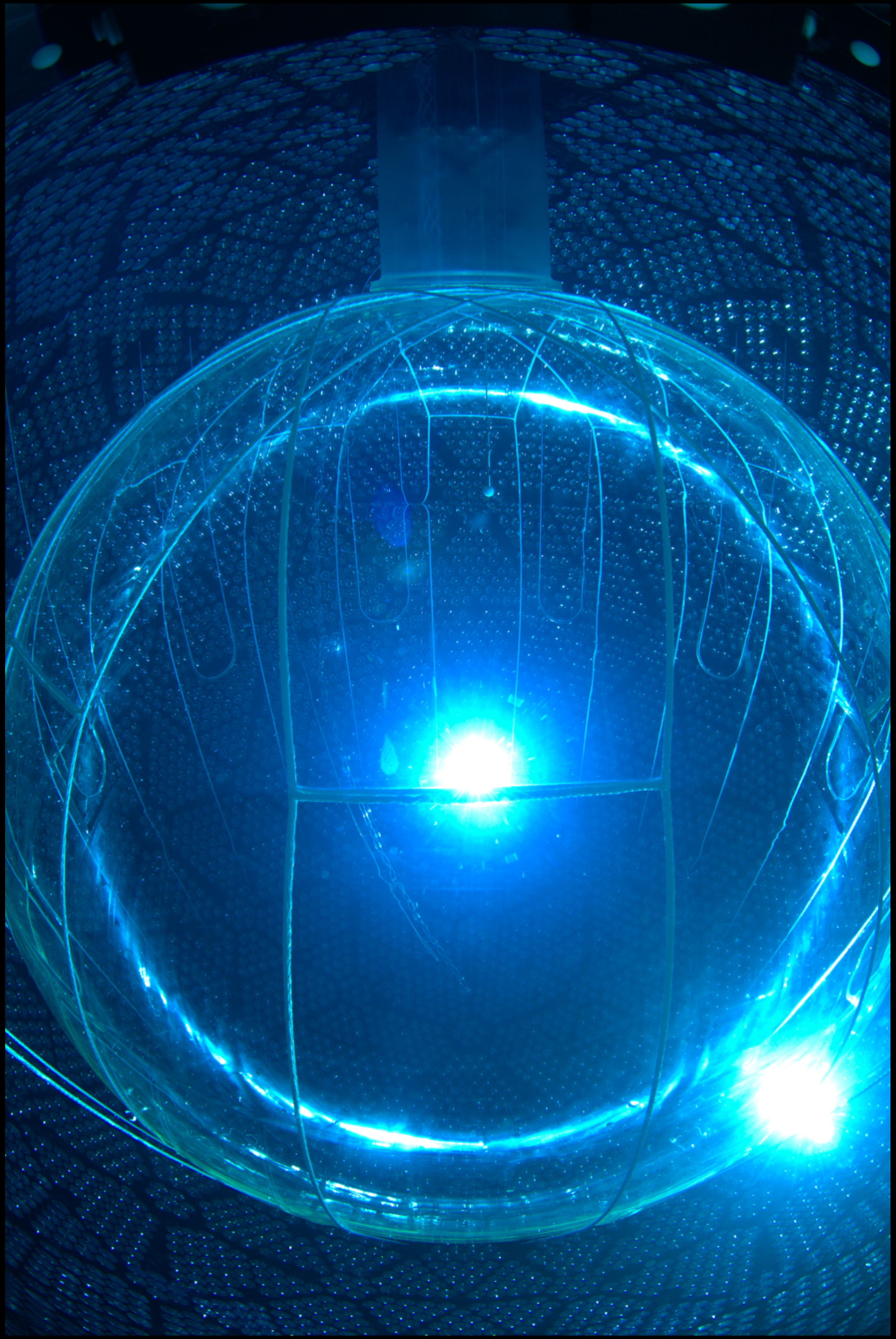
Current Status

- Scintillator purification plant installed and being commissioned
- Started LAB shipments underground
- TeA stored underground
- Started construction of Te purification plant

Scintillator purification plant underground

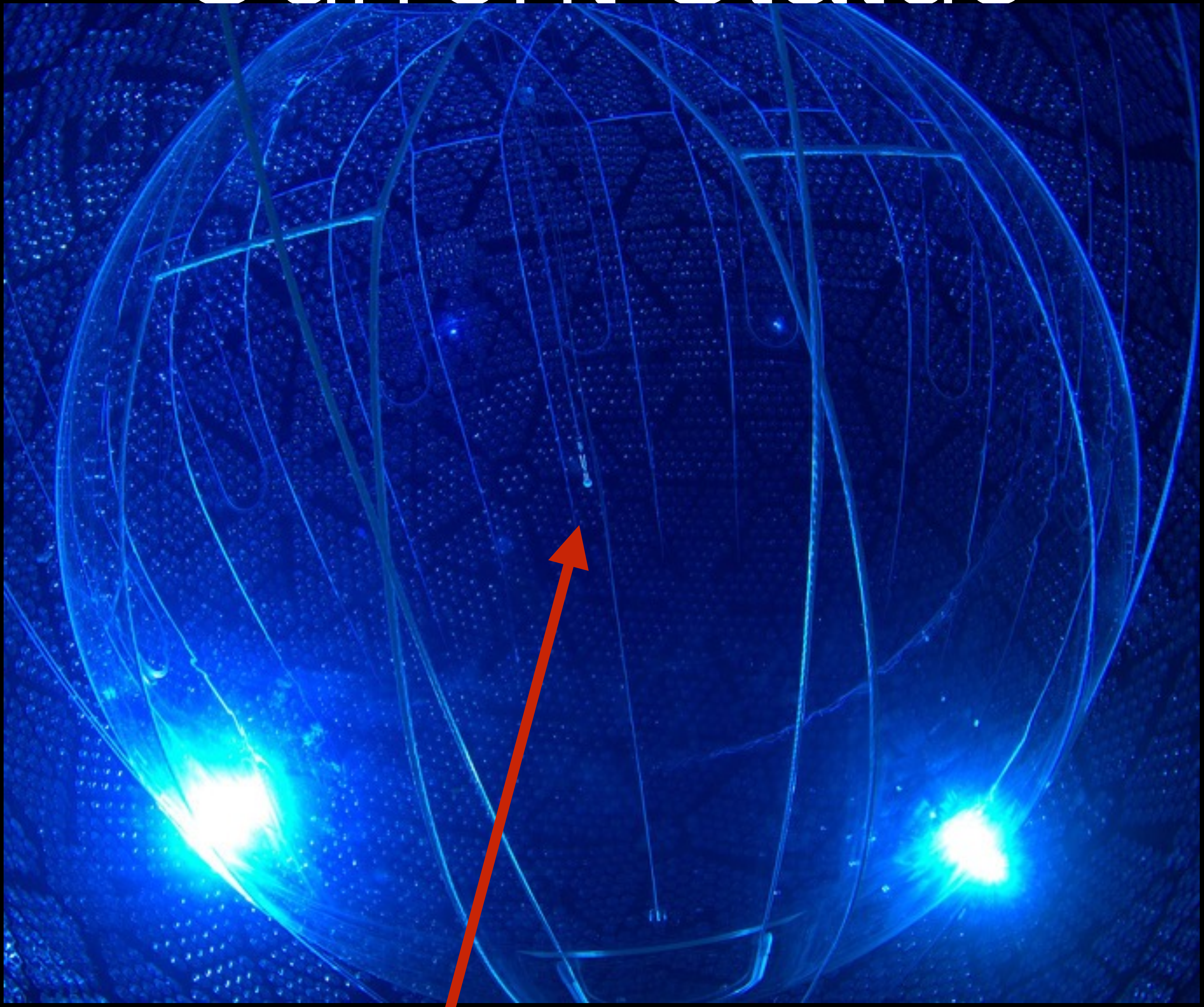
Current Status

- Detector filled with water
- Laser and ^{16}N source calibrations
- Water phase data taking has begun
- Commissioning of upgrades ongoing
- Blind data taking since May



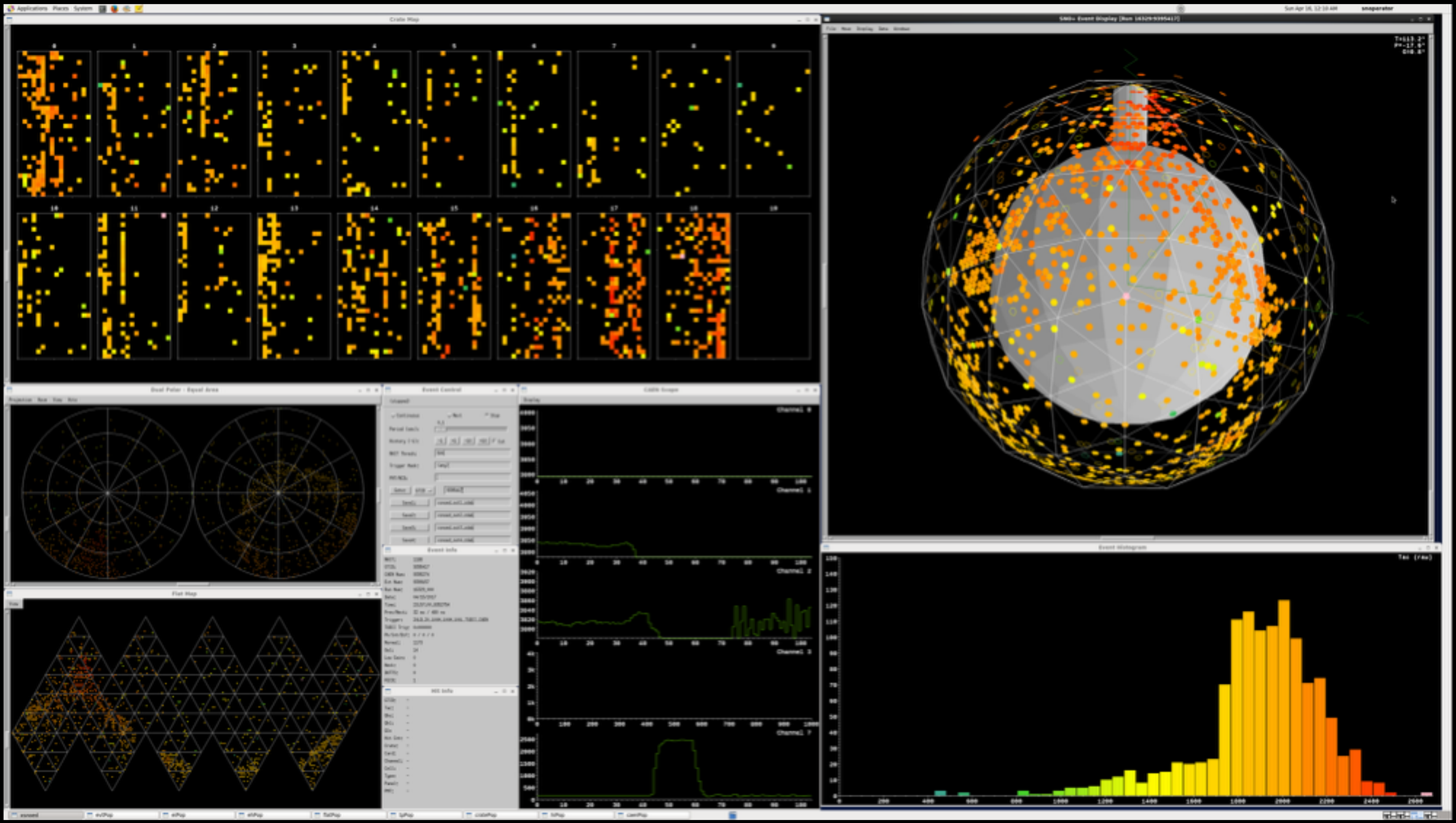
Detector filled with water

Current Status



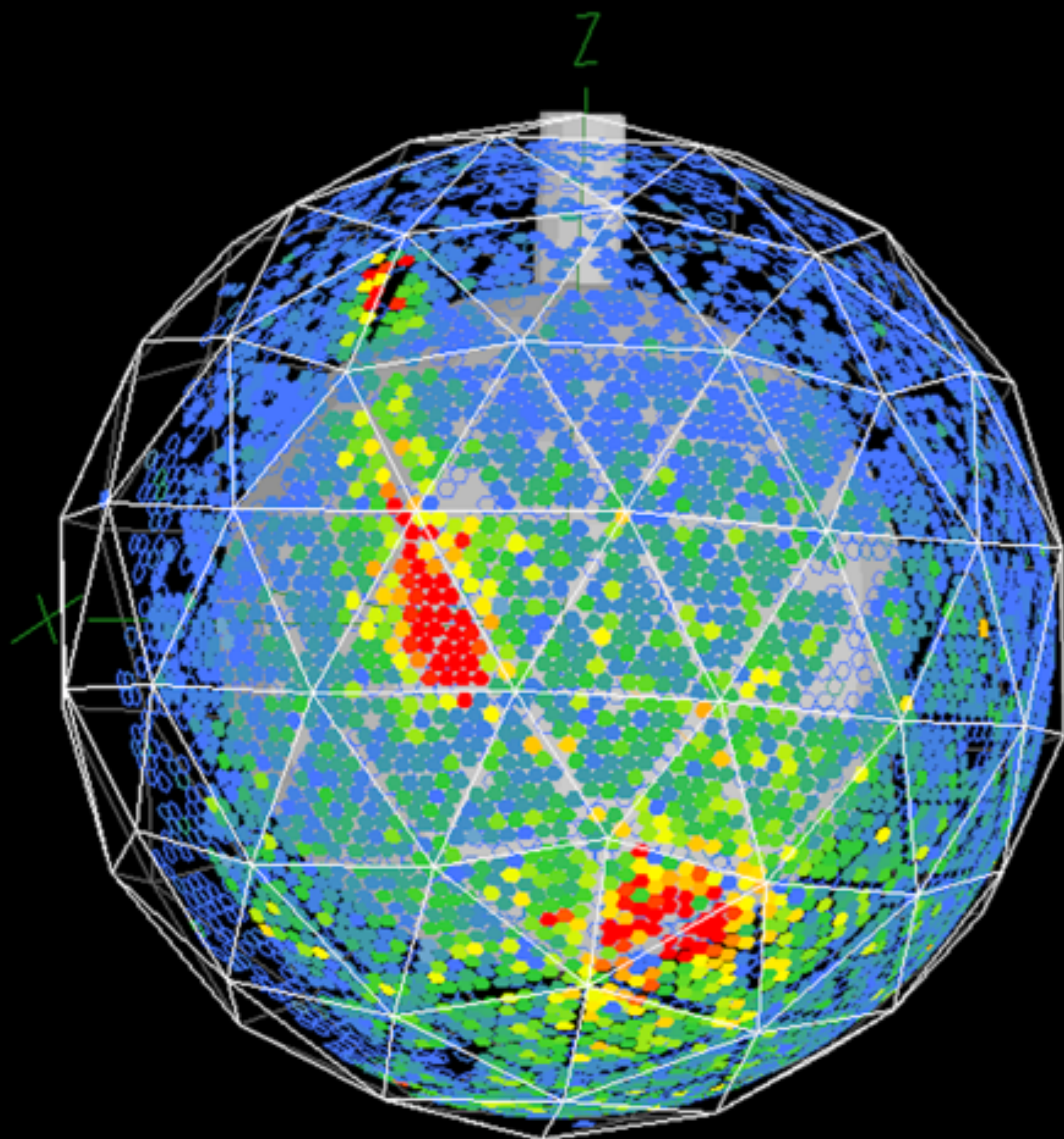
Camera picture while lowering optical calibration source ("laserball")

First water data

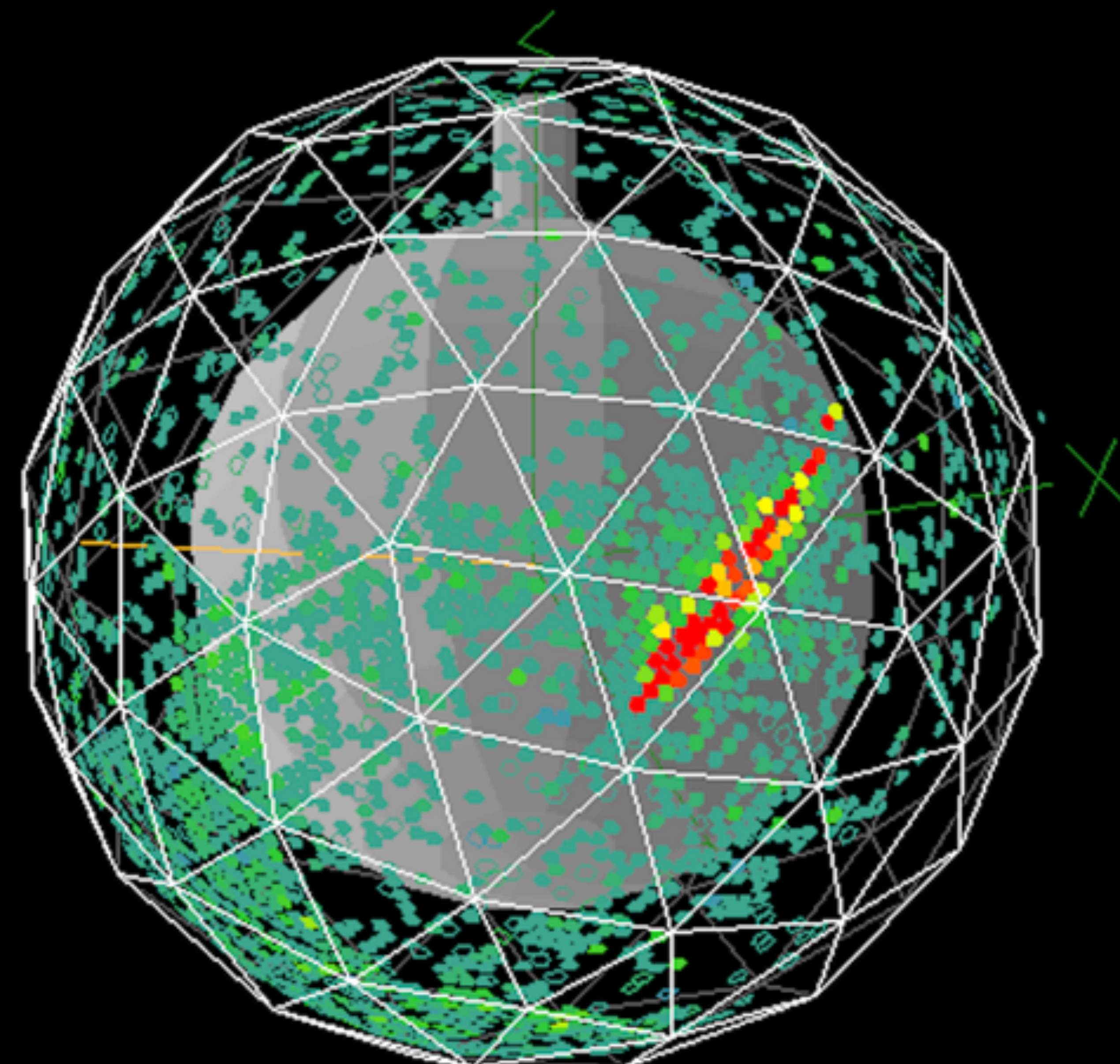


Muon candidate

First water data

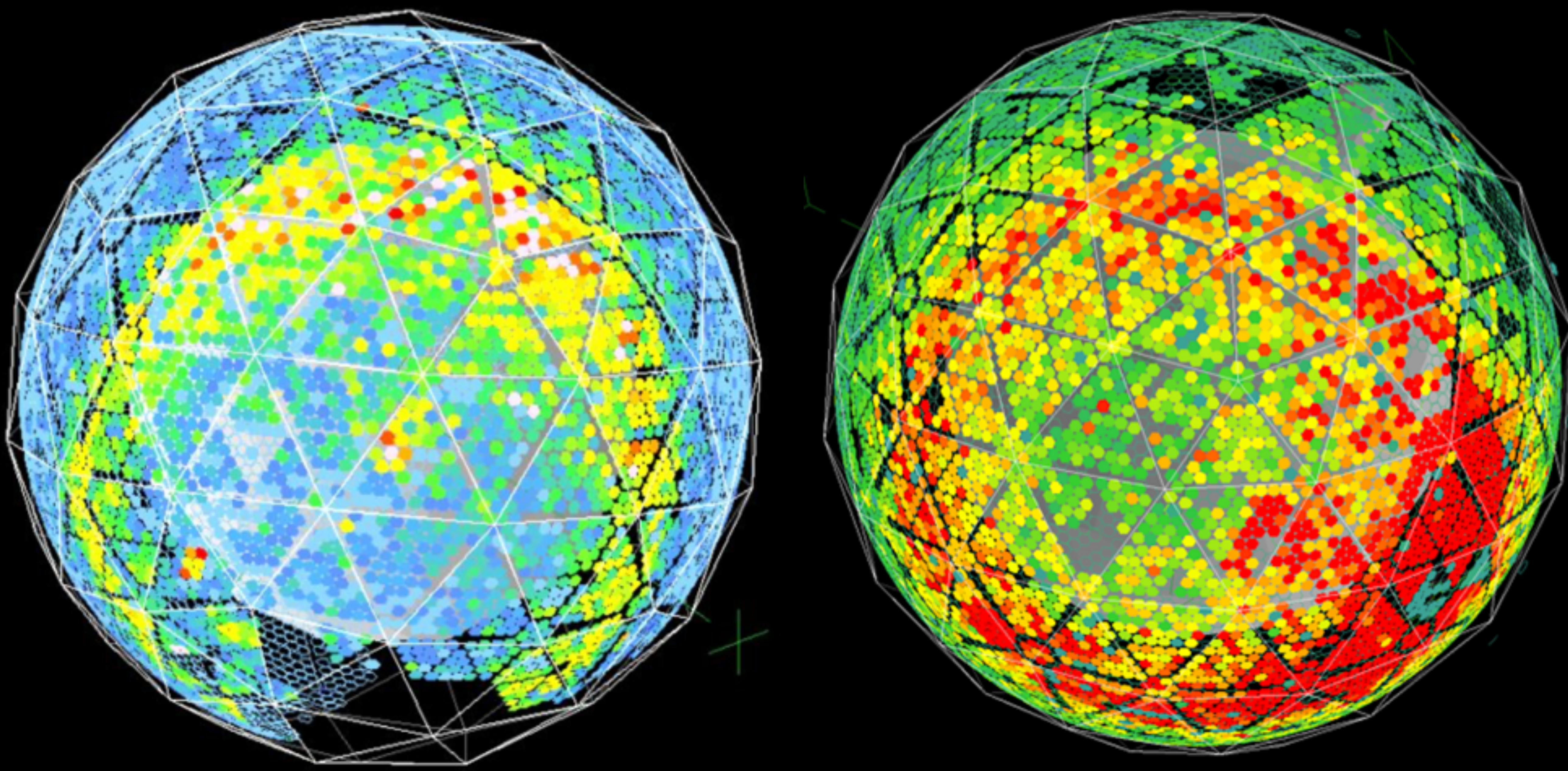


Double Muon candidate



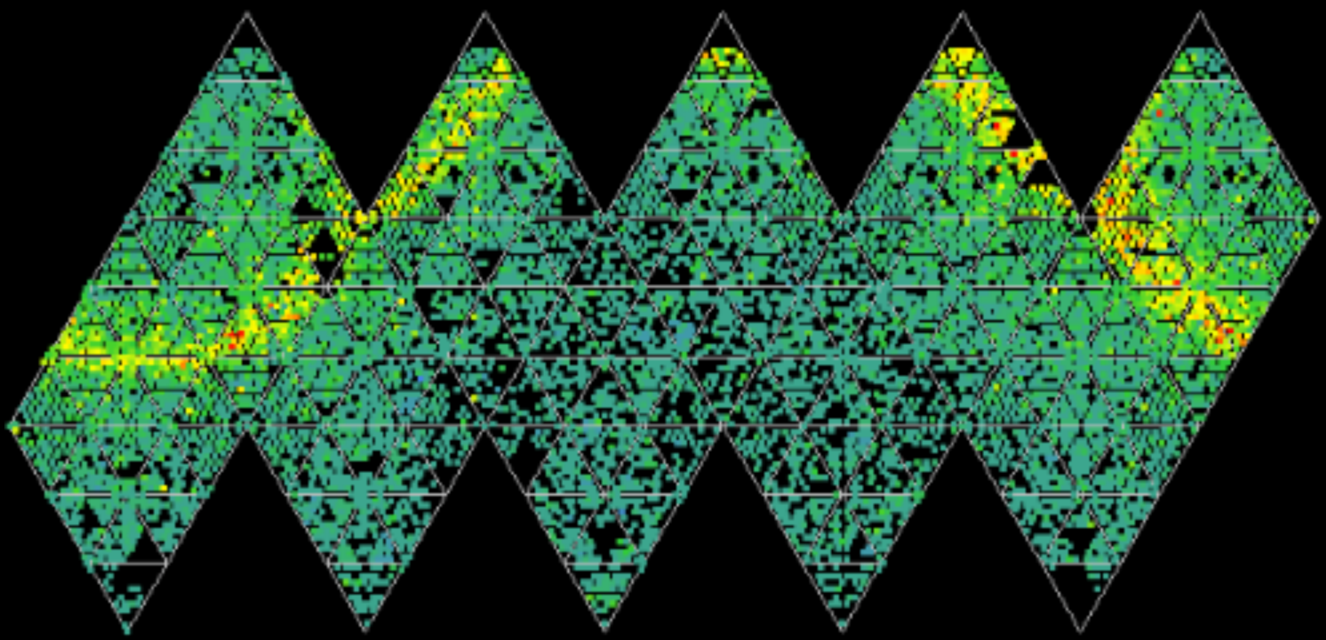
“Grazing” Muon candidate

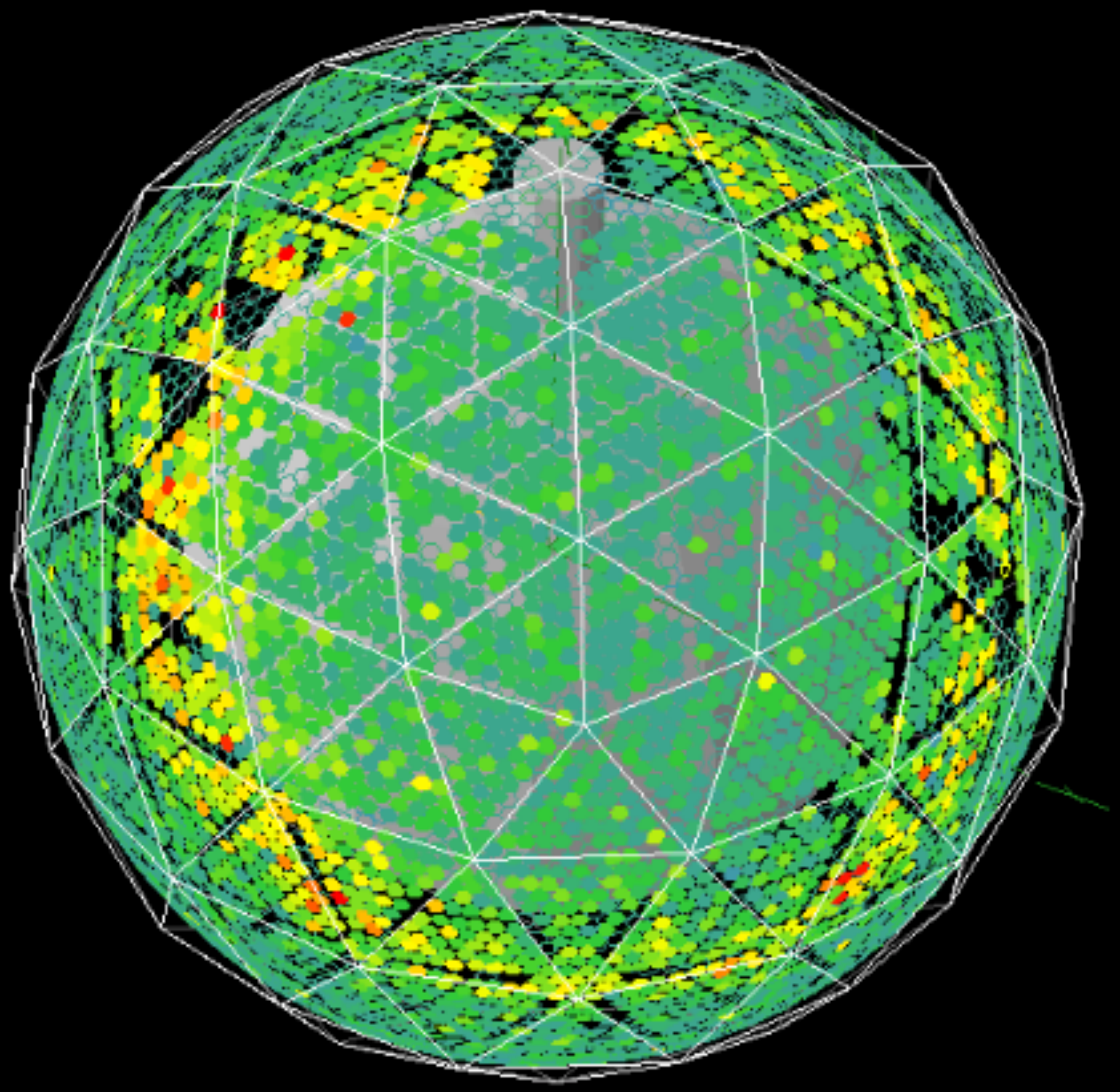
First water data



Muon candidates

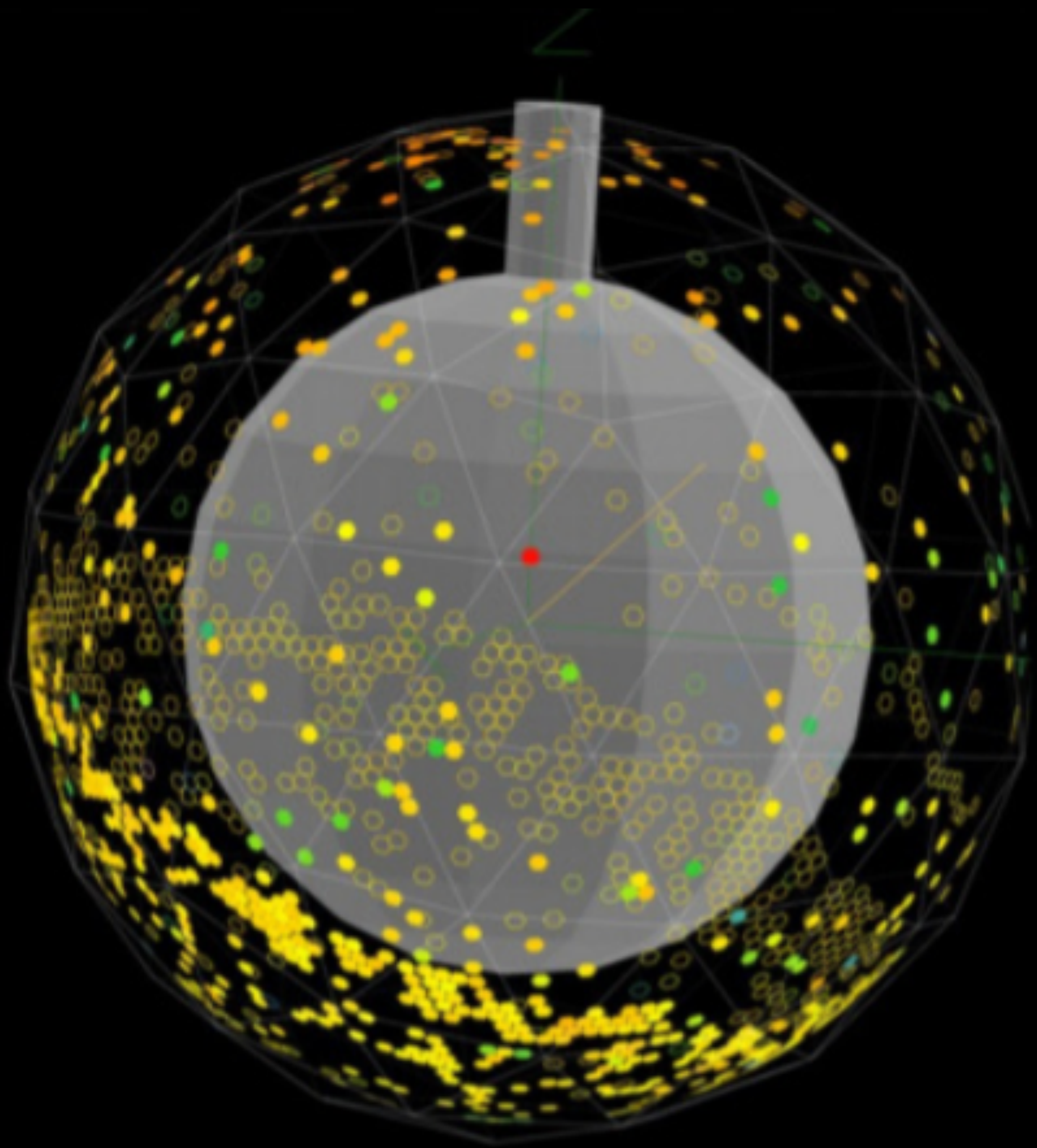
First water data





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+ is a large liquid scintillator detector with broad physics program
    - $0\nu\beta\beta$ is the primary goal
- The detector is currently filled with water and taking data
- Scintillator purification system is being commissioned
- Tellurium systems under construction
- Neutrinoless double beta decay phase will begin in late 2018
- Water results coming soon