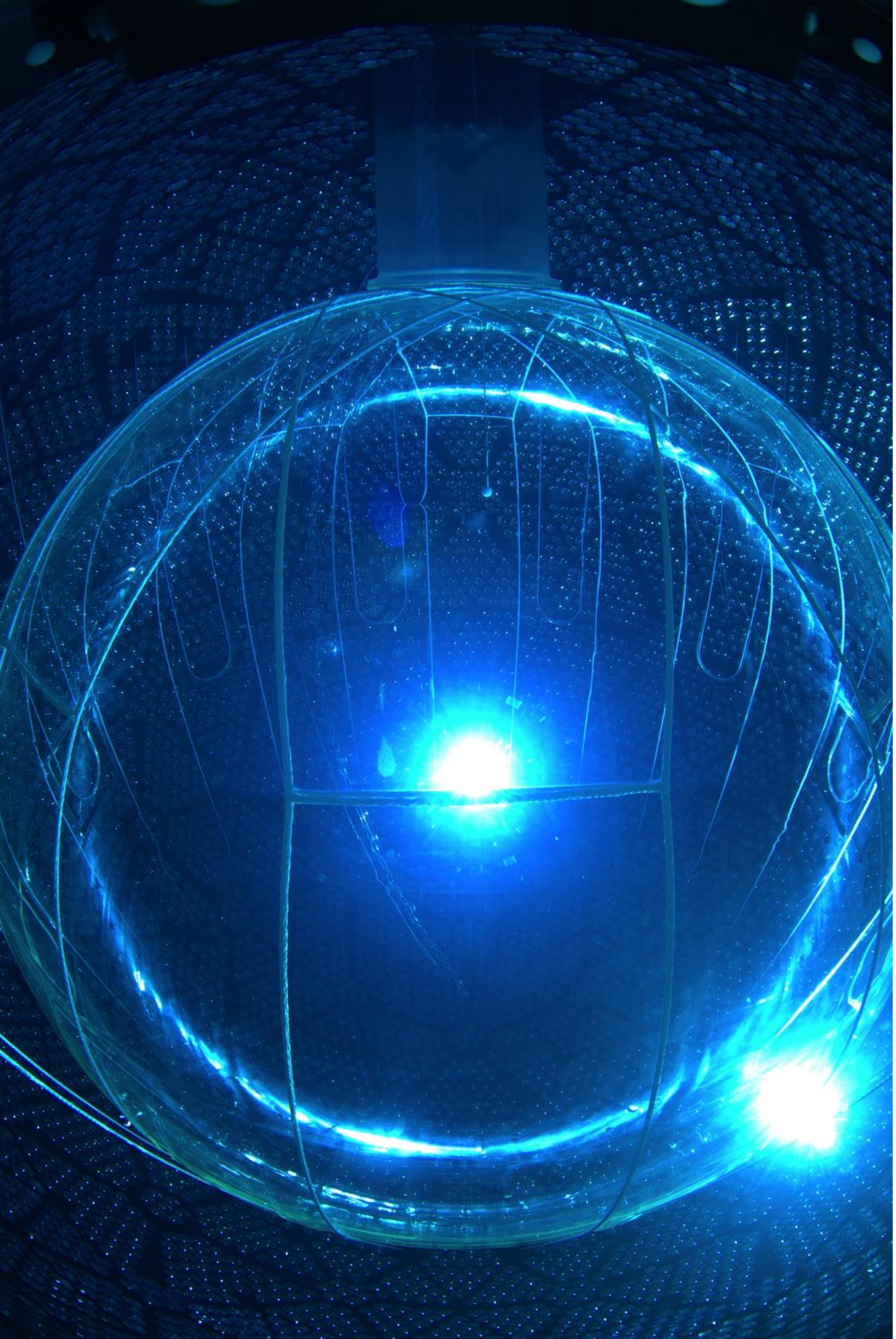
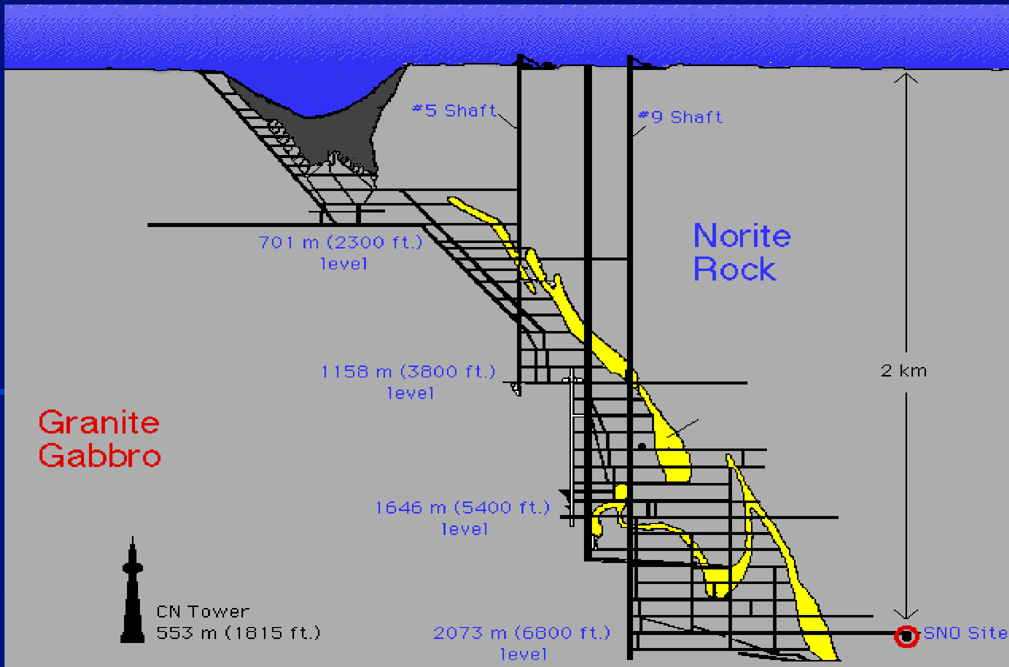


SNO+

Overview for Summer Students

Mark Chen
Queen's University

May 16, 2021



SNO+

~~1000 tonnes D_2O~~ → 780 tonnes liquid scintillator

12 m diameter Acrylic Vessel

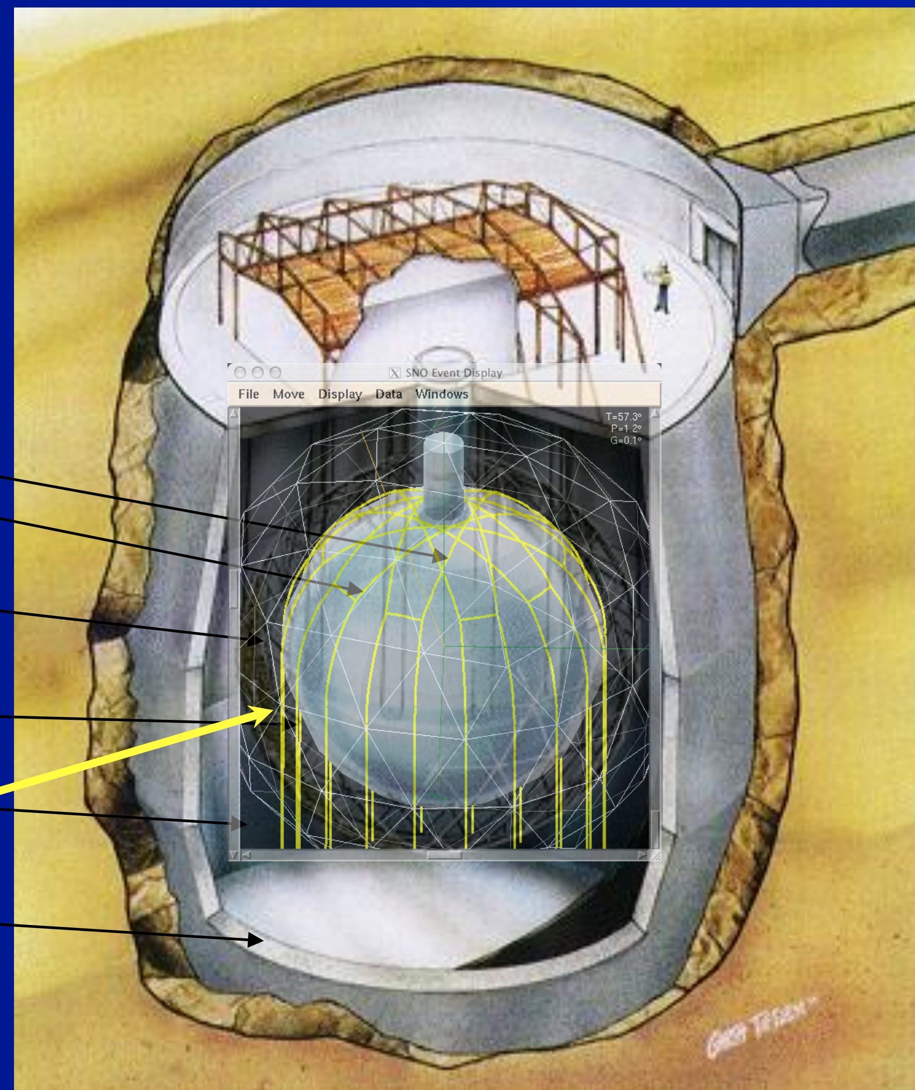
18 m diameter support structure; 9500 PMTs (~50% photocathode coverage)

1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

Urylon liner radon barrier

hold-down rope net

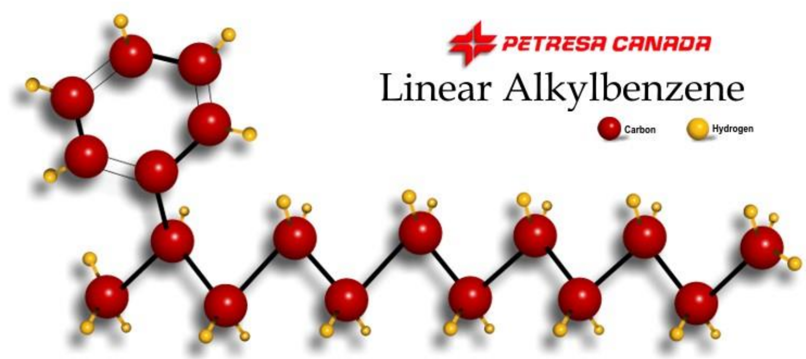


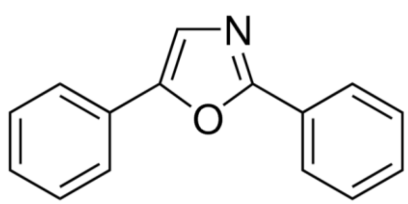
depth: 2092 m (~6010 m.w.e.) ~70 muons/day

Liquid Scintillator for Neutrino Detection

- >50 times light output compared to water Cherenkov
- organic liquids can be made very radio-pure (e.g. Borexino)
  - U, Th, K are insoluble in the scintillator
- *enables neutrino physics program down to <1 MeV energy*

- SNO+ identified linear alkylbenzene as an excellent solvent for liquid scintillator neutrino detectors
  - long light attenuation length
  - compatible with acrylic
  - safe
  - lower cost

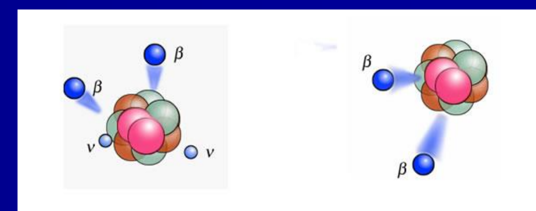




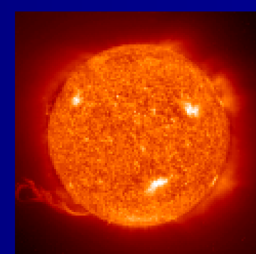
PPO fluor 2 g/L

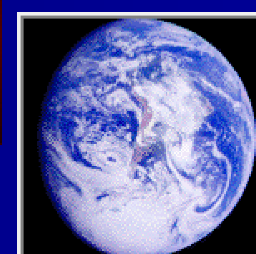
SNO+ Physics Program

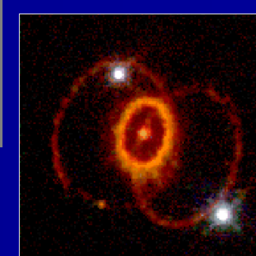
- search for neutrinoless double beta decay



- neutrino physics
  - –solar neutrinos
  - –geo antineutrinos
  - –reactor antineutrinos
  - –supernova neutrinos



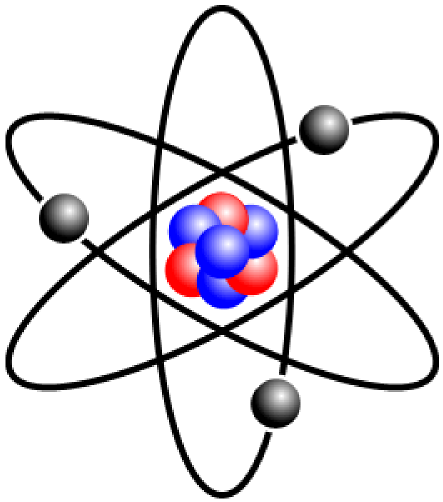




SNO+ Physics Goals

How Does SNO+ Detect Neutrinos?

- neutrinos must first interact to produce a detectable charged particle
- possible targets in ordinary matter:
  - electrons
  - atomic nuclei
    - composed of nucleons (protons and neutrons)
      - composed of quarks



- neutrinos only undergo the weak interaction

CC: $n_l + X \rightarrow l^- + Y$

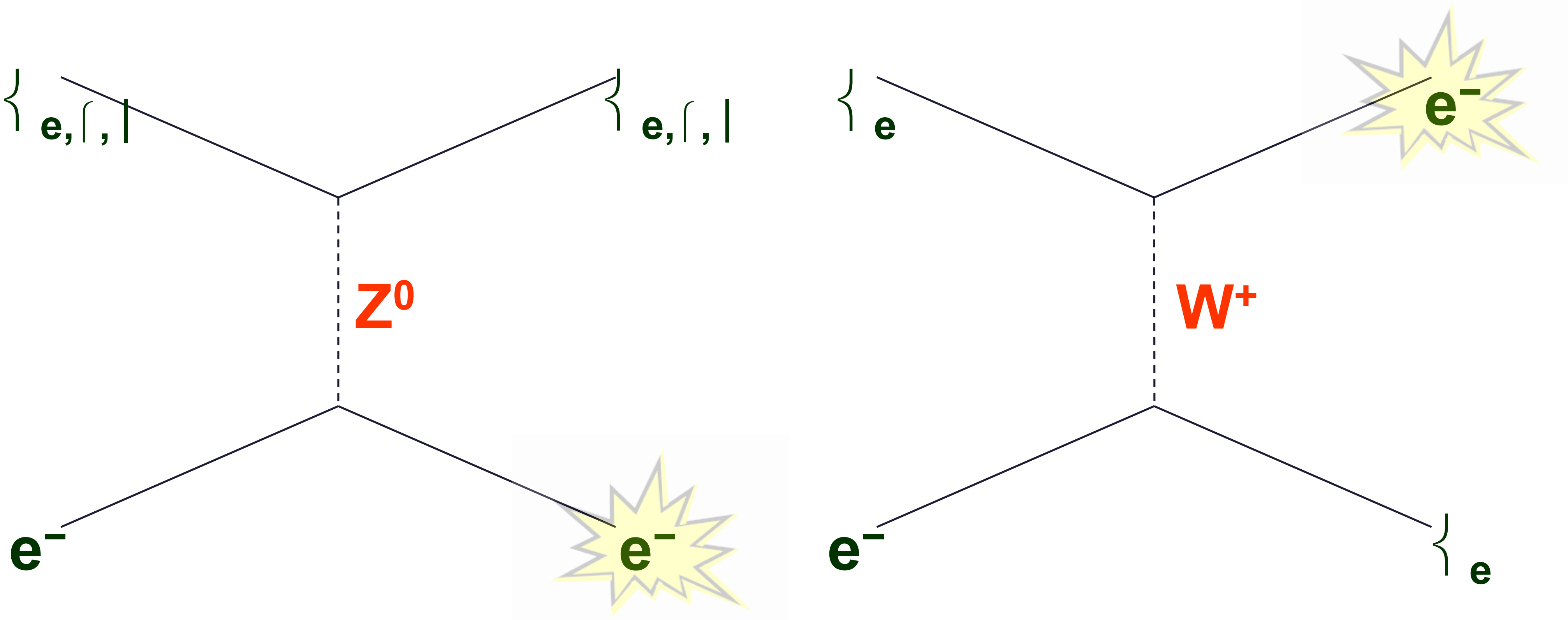
NC: $n_x + X \rightarrow n_x + X$

Y has +1 charge compared to X

Neutrino-Electron Scattering

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

recoiling electrons make scintillation light

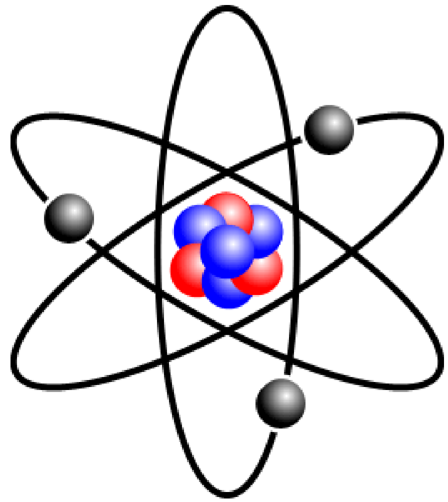


Neutral-Current scattering

Charged-Current Scattering

How Does SNO+ Detect Antineutrinos?

- antineutrinos must first interact to produce a detectable charged particle
- possible targets in ordinary matter:
  - electrons
  - atomic nuclei
    - composed of nucleons (protons and neutrons)
      - composed of quarks



- antineutrinos only undergo the weak interaction

CC: $\bar{\nu}_e + X \rightarrow e^+ + Y$

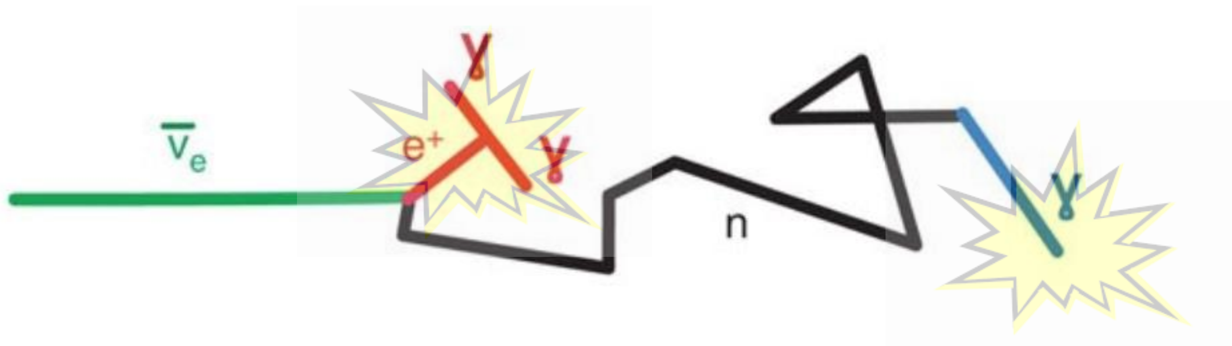
NC: $\bar{\nu}_x + e^- \rightarrow e^- + \bar{\nu}_x$

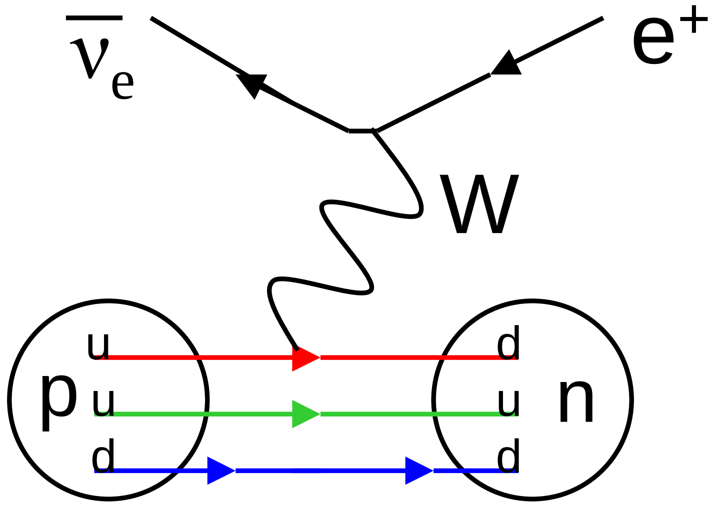
Y has –1 charge compared to X

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

Inverse Beta Decay (on protons)

- charged-current weak interaction of anti-electron neutrinos on protons
  - this is how neutrinos were first detected by Reines and Cowan





- the positron makes a prompt scintillation signal
- the neutron takes ~0.2 ms to bounce around and then get captured (by a proton)
  - releasing a 2.2 MeV gamma ray that makes a delayed signal

The inverse beta decay **delayed coincidence signal** is very distinctive in a liquid scintillator detector which has lots of hydrogen (protons) in the organic molecule.

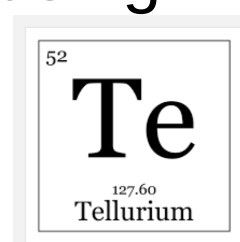
SNO+

Neutrino Physics at Lower Energy

- study solar neutrinos at lower energies than SNO
- detect geo antineutrinos – Earth's "neutrino glow" produced by natural radioactivity in the crust and mantle
- measure antineutrino oscillations from nearby nuclear reactors (Bruce, Pickering, Darlington)
- supernova neutrino watch

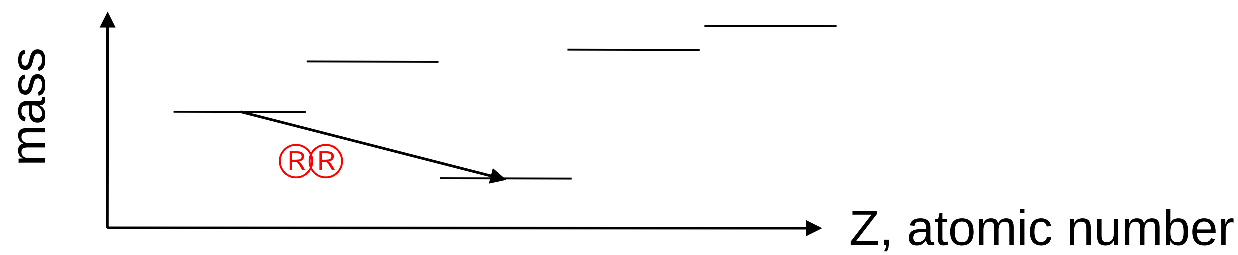
- probe the <u>matter-antimatter nature</u> of neutrinos using tellurium dissolved in the liquid scintillator

  → search for neutrinoless double beta decay

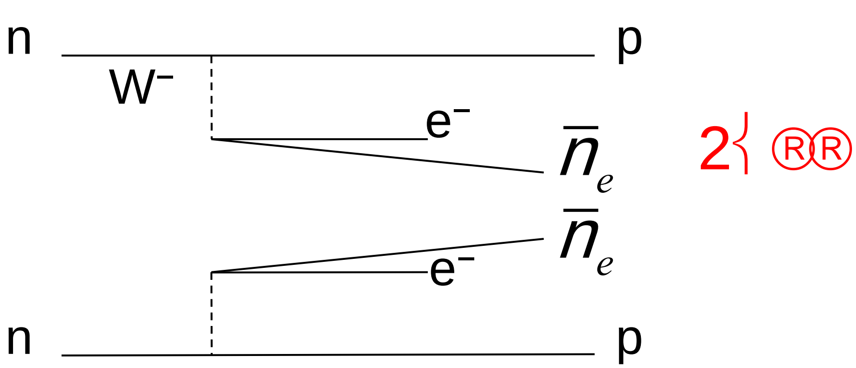


Double Beta Decay

- some even-even nuclei cannot ® decay but can undergo double beta decay, a very rare second-order weak process
  - e.g. ^{130}Te has half-life 8.2×10^{20} years



- this process occurs and has been observed
  two-neutrino double beta decay



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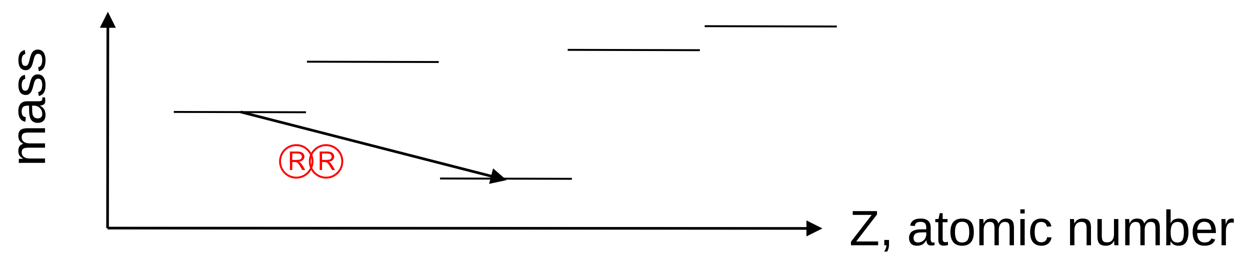
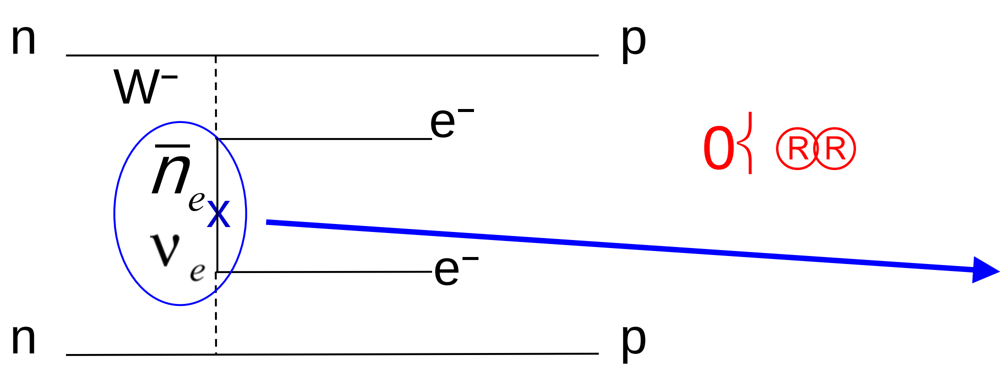


- can this (beyond the Standard Model) process occur?
  neutrinoless double beta decay



requires neutrinos to be their own antiparticle − i.e. Majorana fermions as opposed to Dirac fermions

Standard Model Leptons

chiral gauge theory

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \qquad \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \qquad \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \qquad\qquad e_R \mu_R \tau_R$$

mass is the Yukawa coupling to the Higgs

$$-\frac{y_e v}{\sqrt{2}}\,\overline{e_L}\,e_R - \frac{y_\mu v}{\sqrt{2}}\,\overline{\mu_L}\,\mu_R - \frac{y_\tau v}{\sqrt{2}}\,\overline{\tau_L}\,\tau_R + \text{h.c.}.$$

$$m_e = \frac{y_e v}{\sqrt{2}}, \quad m_\mu = \frac{y_\mu v}{\sqrt{2}}, \quad m_\tau = \frac{y_\tau v}{\sqrt{2}}.$$

and neutrinos have zero mass

Neutrino Mass is Physics Beyond the Standard Model

Dirac

$$yH\,\bar{\nu}_R \nu_L \rightarrow m_D\,\bar{\nu}_R \nu_L \quad + \text{h.c.}$$

why is the Yukawa coupling so small?
implies new global U(1) symmetry?!
what's going on with the right-handed fields?
– they would be sterile (don't interact)

Majorana

neutrinos are their own antiparticles

$$m_M \bar{\nu}_L^C \nu_L$$

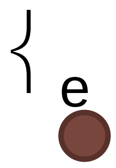
"talk to a different Higgs"
small mass could be "natural"

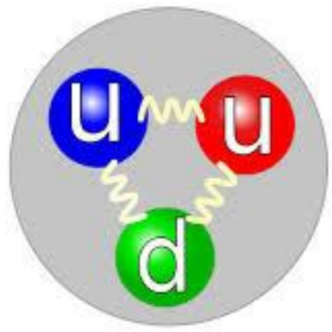
or both

$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L^C \end{pmatrix} \begin{pmatrix} m & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_R^C \\ N_R \end{pmatrix}$$

Are Neutrinos Majorana Fermions?

- they carry no electromagnetic charge, no QCD colour, no moments, no other quantum number
- other than *lepton number*…but what is that?





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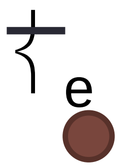
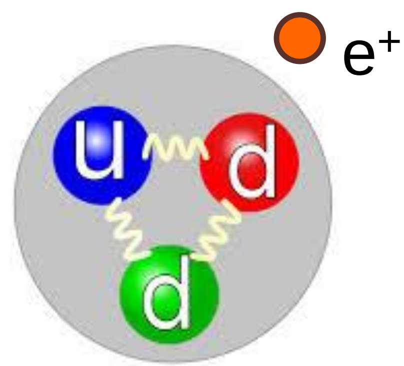




Why does this only happen for the “anti”-neutrino? Does the proton know it was an anti-lepton?

$$\bar{n}_e + p \rightarrow e^+ + n$$

Answer: Chirality and the Weak Interaction

- the weak interaction distinguishes between left and right chirality and that's why $\bar{n}_e + p \rightarrow e^+ + n$

- does the weak interaction additionally distinguish between lepton number L = 1 and L = –1? Or is that just redundant?

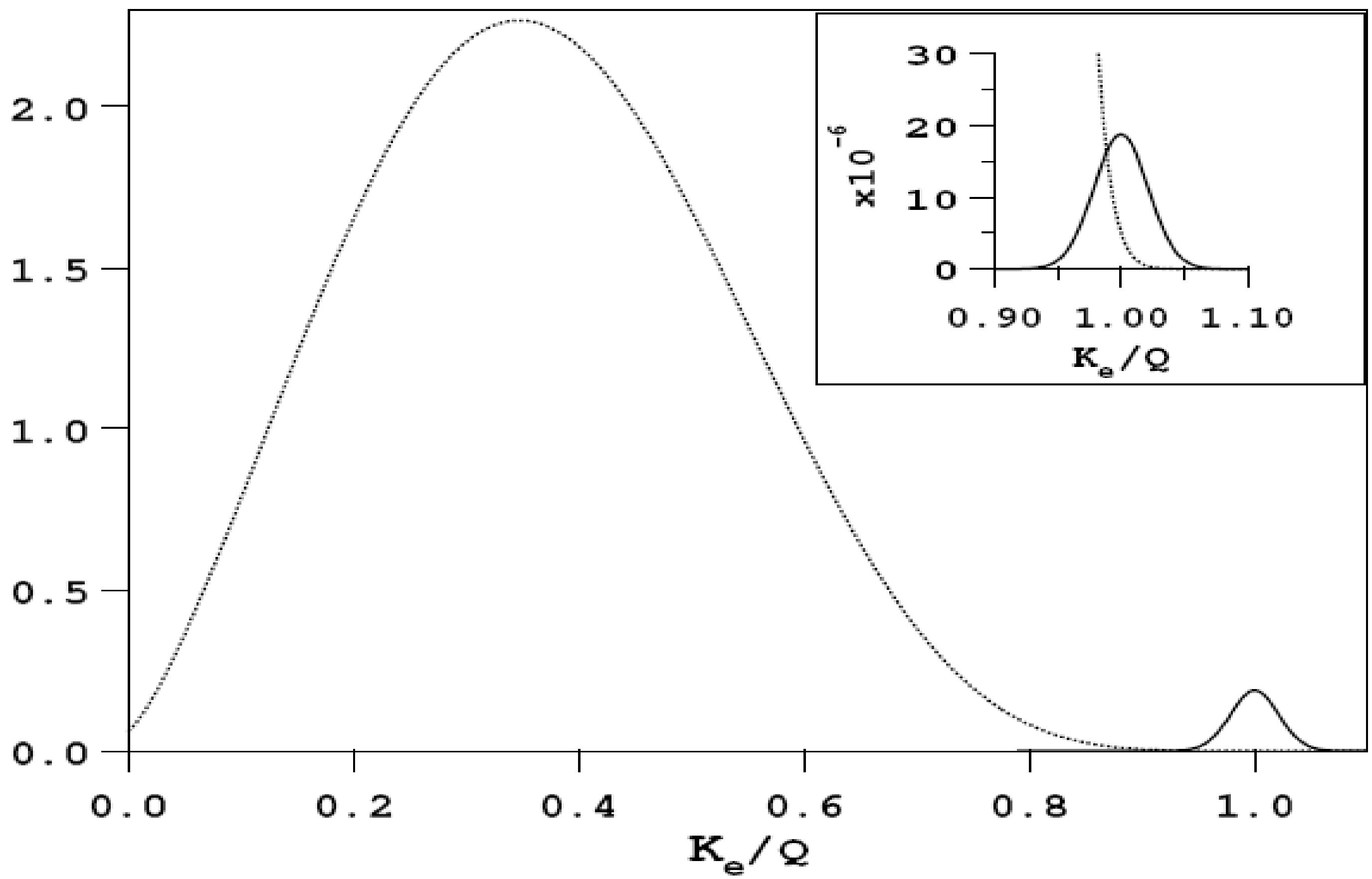
- *if* lepton number *is* meaningful, then particles and antiparticles are <u>fundamentally</u> different – neutrinos and antineutrinos carry a "global U(1) weak hypercharge associated with lepton number"

- *but if* one discards lepton number as a meaningful quantity (lepton number is *ad hoc* so <u>get rid of it</u>) then neutrinos are Majorana fermions…FACT!

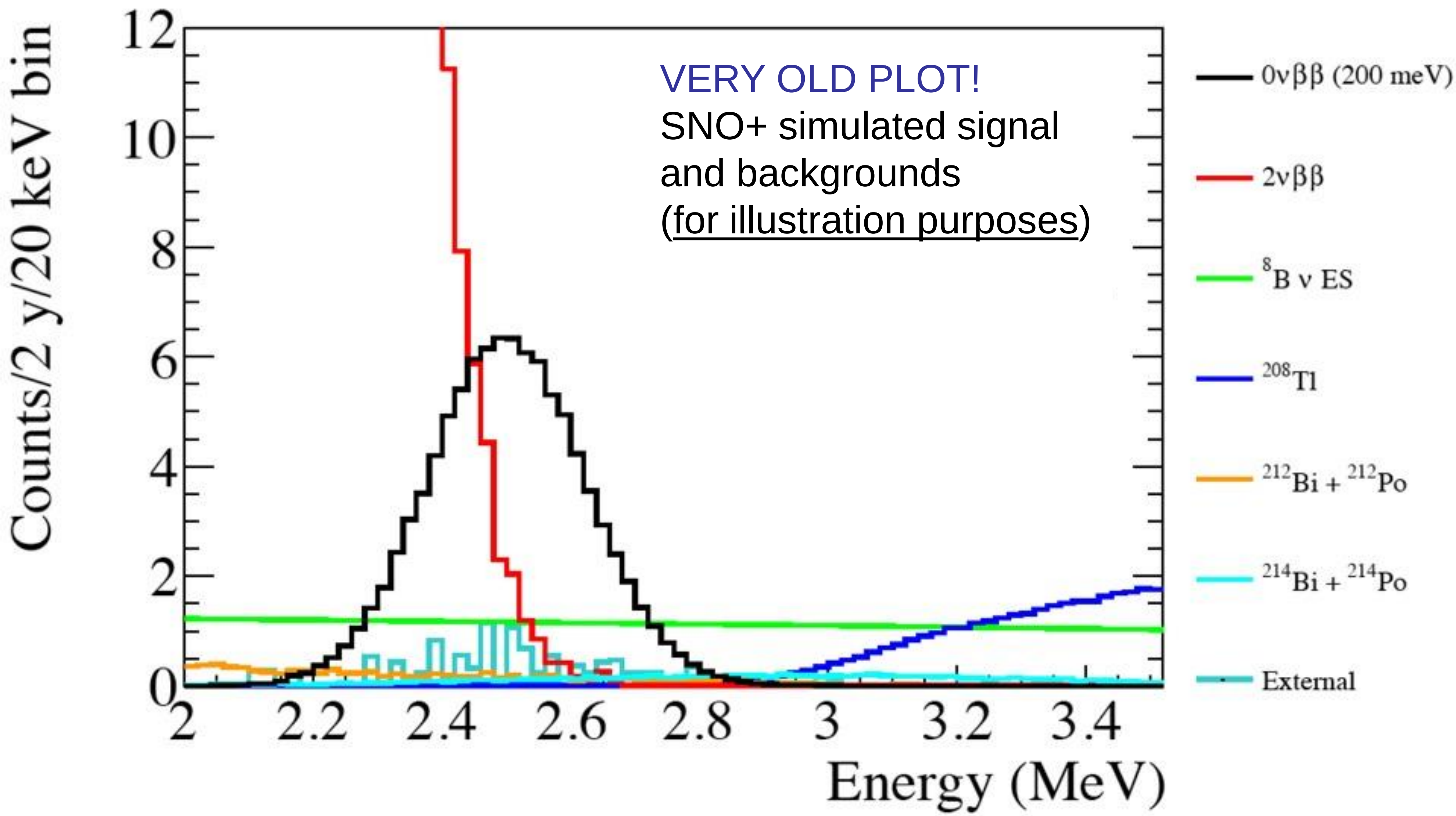
Neutrinoless double beta decay would be a ***lepton number violating*** process $\Delta L = 2$

How to Search for 0νββ?

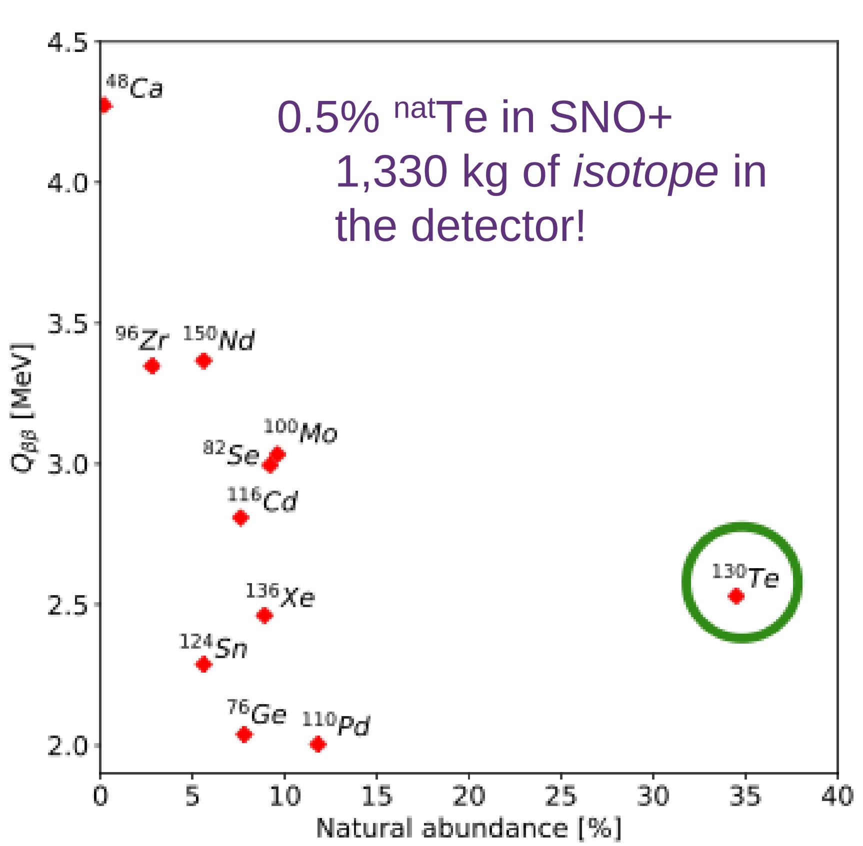
- look at sum of energy of both electrons (calorimetry)
- search for a peak at the double beta endpoint



Simulated SNO+ Neutrinoless Double Beta Decay Signal – Early ^{130}Te Study



Tellurium for Double Beta Decay



Large natural isotopic abundance 34% for ^{130}Te

tonne-scale for ^{130}Te:

cost is $1.5 million

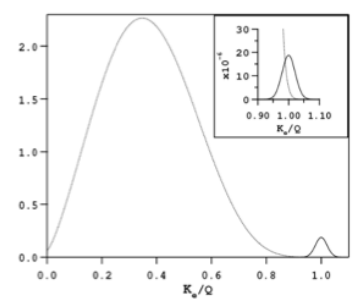
compare to O($100 million) for tonne-scale of enriched isotope

potential to increase loading from 0.5% to 3-5% ($15 million cost)

Background suppression in the 0νββ ROI (Q=2.53 MeV),

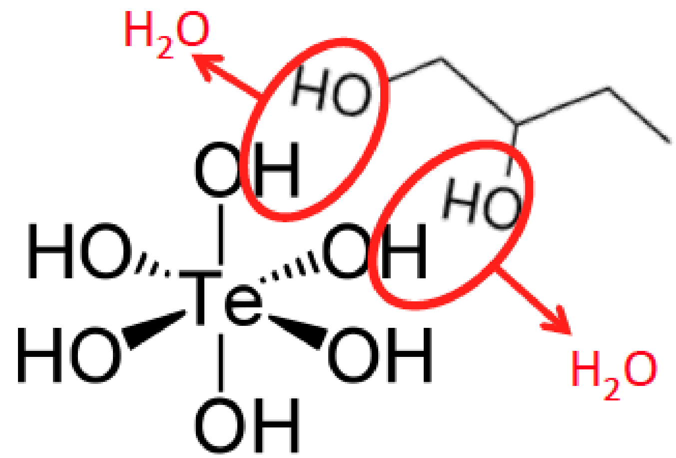
U, Th backgrounds can be tagged and rejected by suppression factors >5,000 (e.g. ^{214}Bi-^{214}Po coincidence)

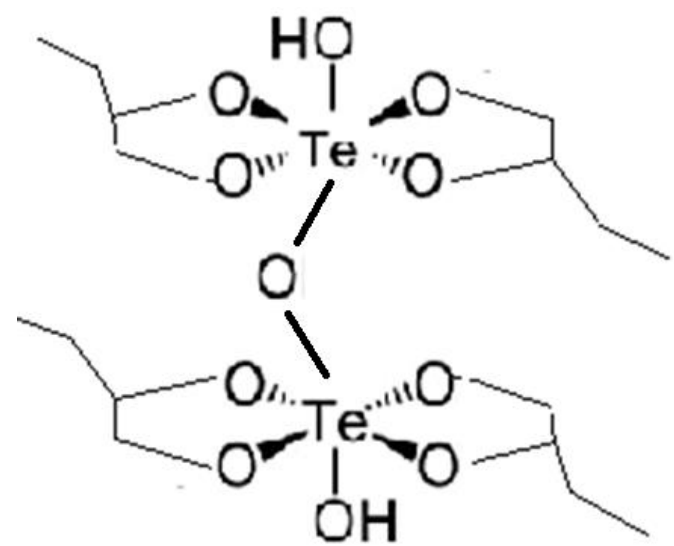
^{130}Te and ^{136}Xe have the smallest 2νββ/0νββ ratio



Synthesis

- React the telluric acid with butanediol to produce an LAB soluble product
- Mix aqueous telluric acid with 1,2 butanediol, heat, apply vacuum and sparge until water is removed
  - Dehydration reactions are reversible, so water removal is important
  - Reaction temperature 70-80°C, not less than 60°C or more than ~110°C
  - BD:TeA molar ratio of 3.0
- Novel approach
  - "Our own" CAS number

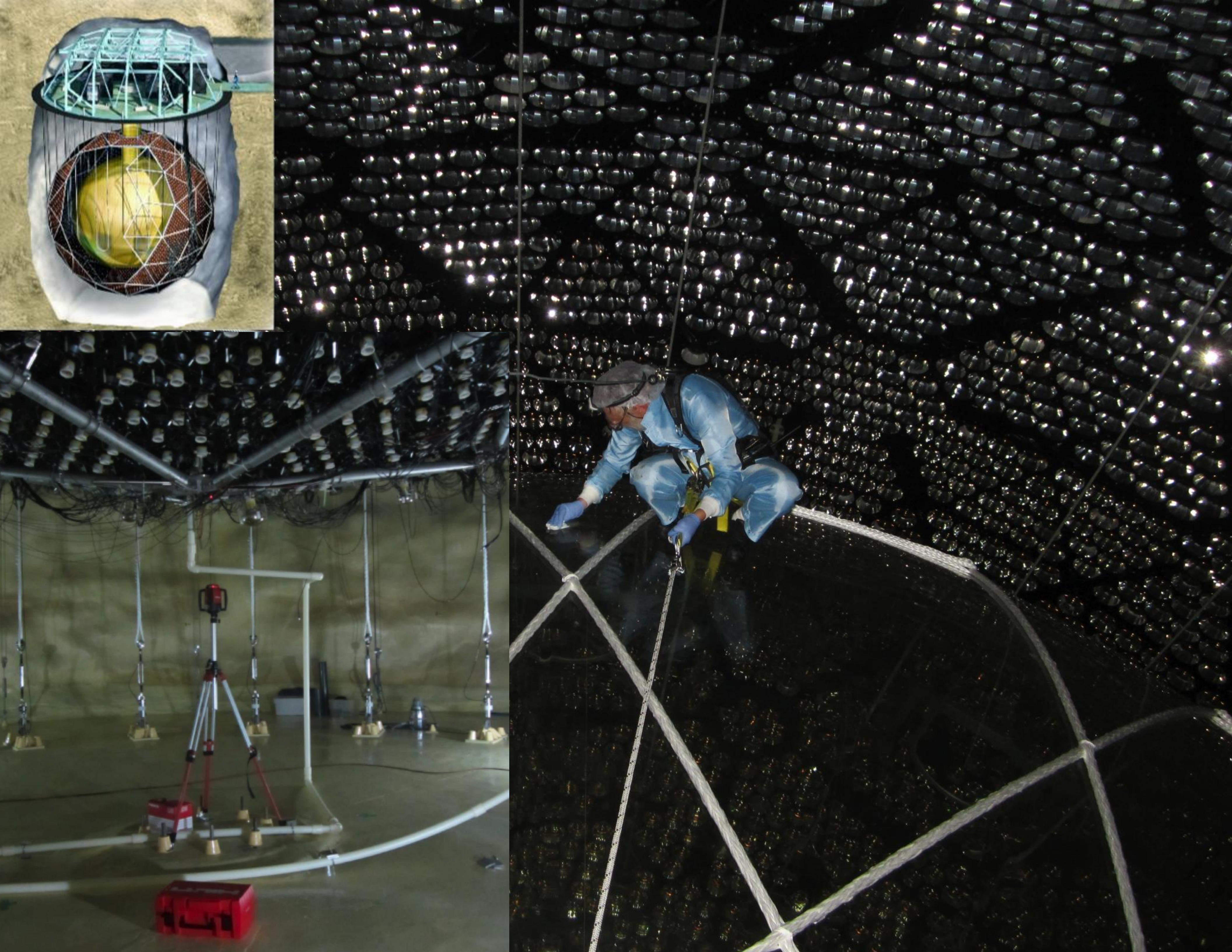


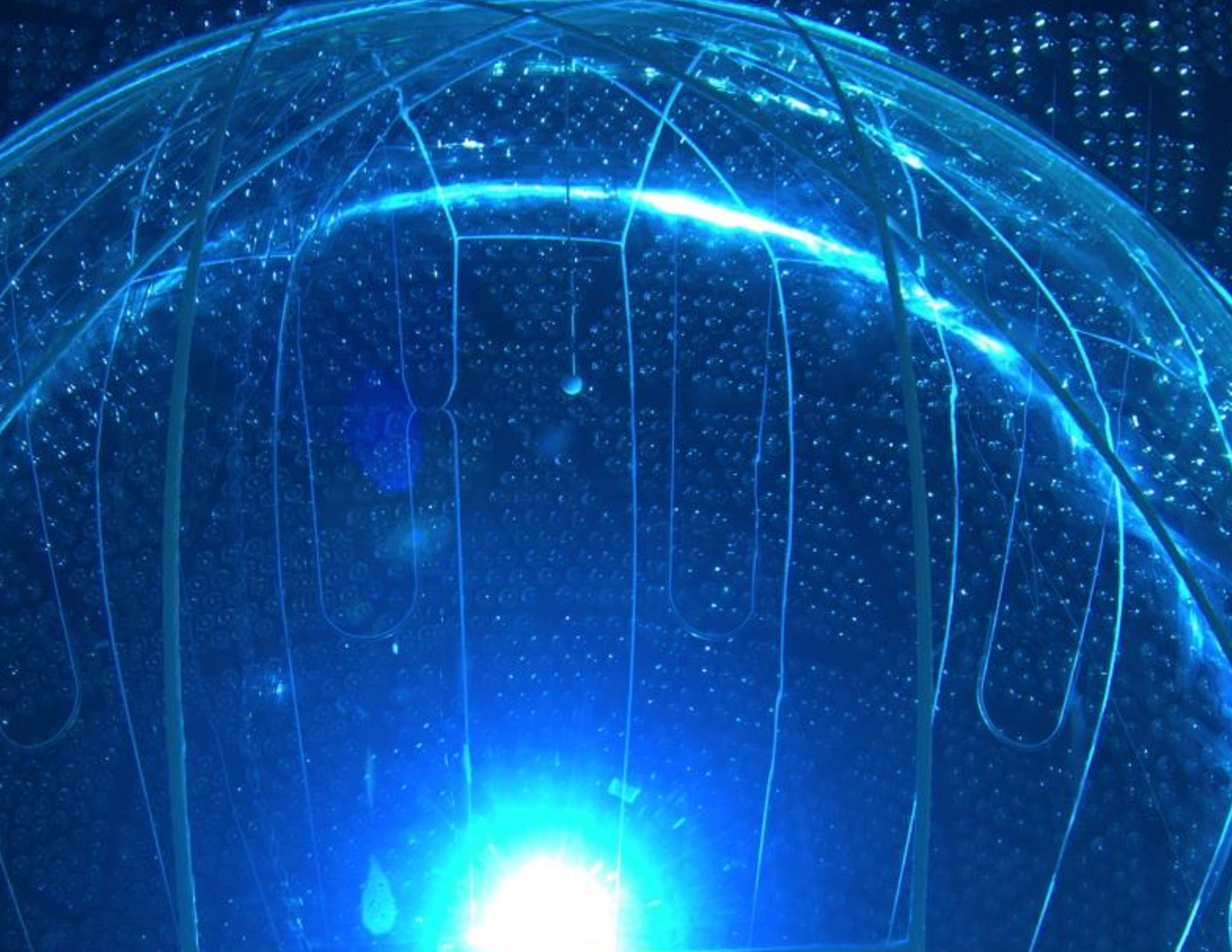


CAS # 2173121-84-9
"Tellurium, 1,2-butanediol hydroxy oxo complexes"

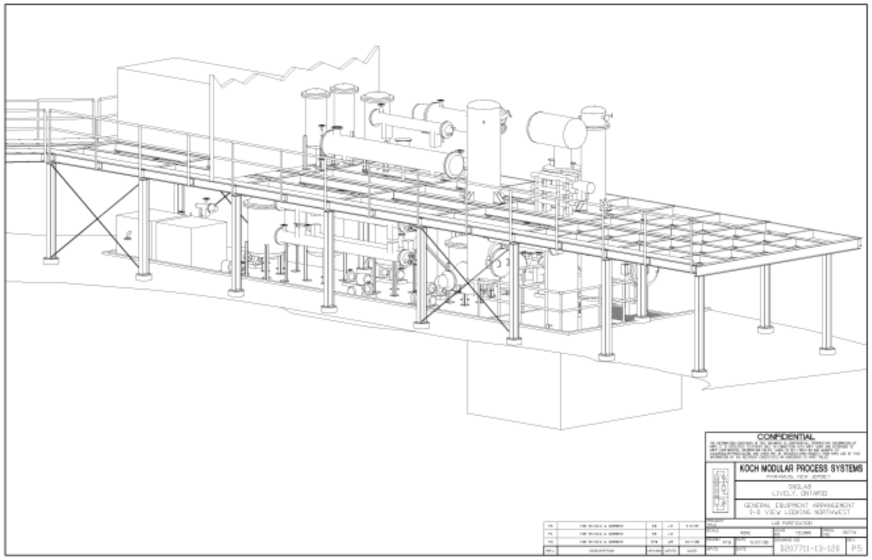
TELLURIC ACID PURIFICATION

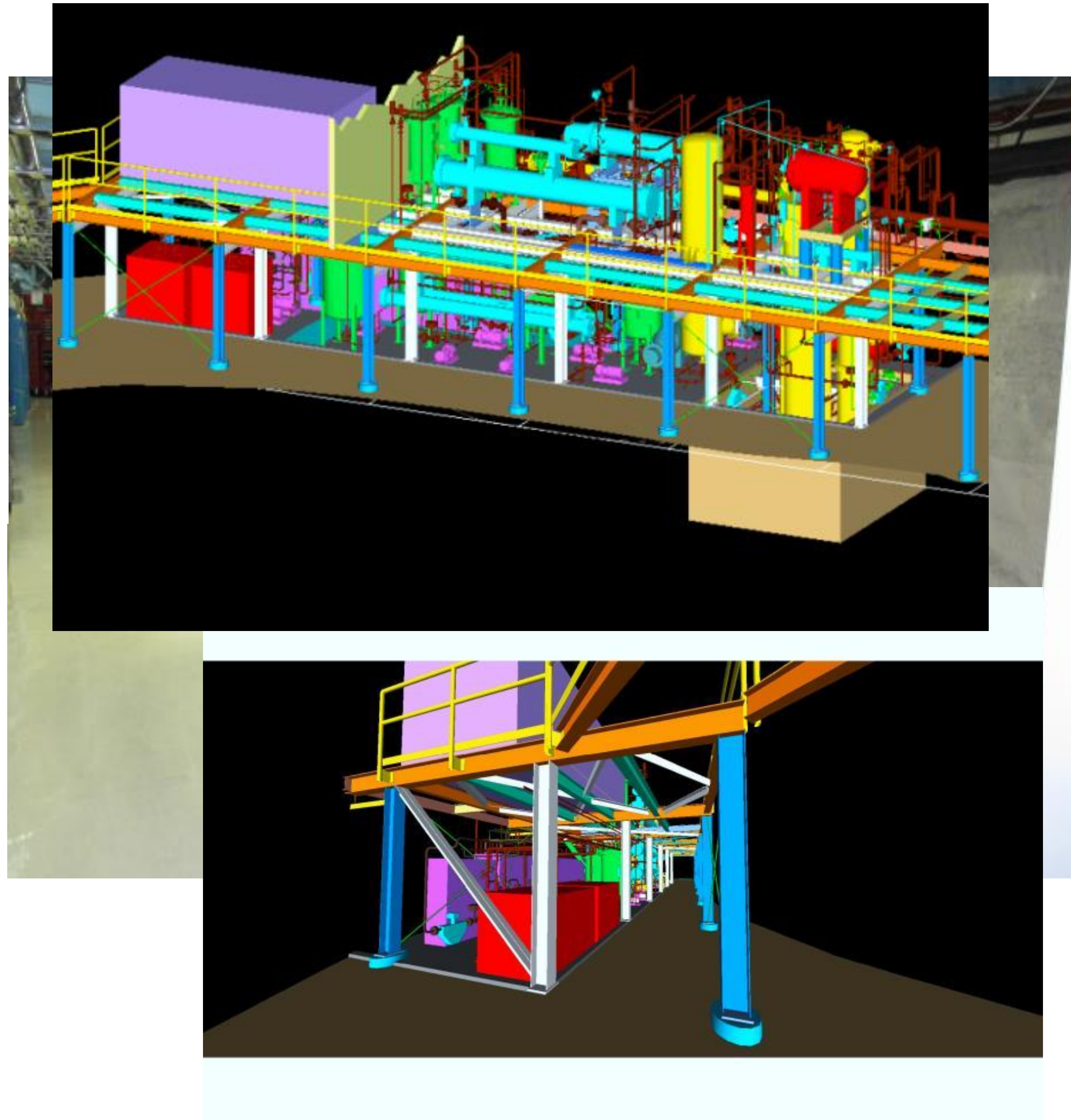
TE-DIOL SYNTHESIS





Liquid Scintillator Purification Plant





- utility plumbing (cooling water, compressed air, vent, boiloff nitrogen)
- process control, wiring, instrumentation, electrical
- firewalls, fire detection and suppression


SCINTILLATOR
SCINTILLATOR 1042
E-101

SNO+ Current Status

- 2016: Water fill of Cavity and Acrylic Vessel
- May 2017: start of water "Physics" data taking

- October 2018: started liquid scintillator operations
- July 2019: initial fill of 20 tonnes | commissioning of scintillator purification plant
- January-March 2020:
  - most scintillator plant and fill problems resolved
  - scintillator fill progressing well (at last!) – *PAUSED by COVID-19*
  - partial fill (~50% filled or ~365 tonnes)
  - "quiet" data – partial fill physics
- October 2020-March 2021: resumption of fill
- bulk AV fill completed March 27th, 2021!!

- 2019: Tellurium-loading plants built and installed
  - commissioning the plants underway – *delayed by COVID-19* – now completed
  - next step: test batch and commissioning the process
  - loading tellurium in the detector, then double beta decay search begins mid-end of next year

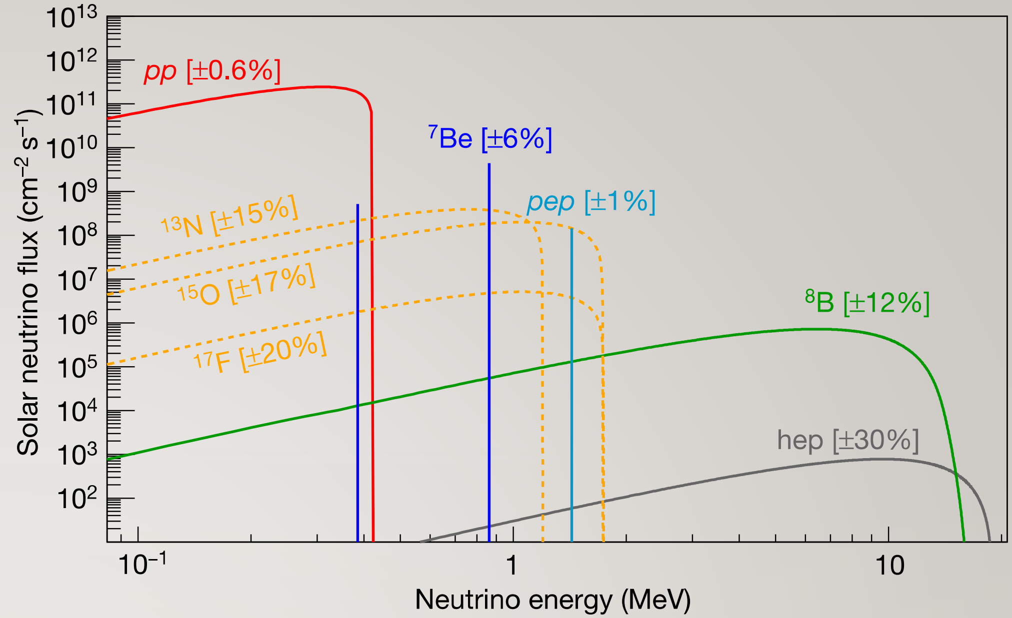
SNO+ Current Activities

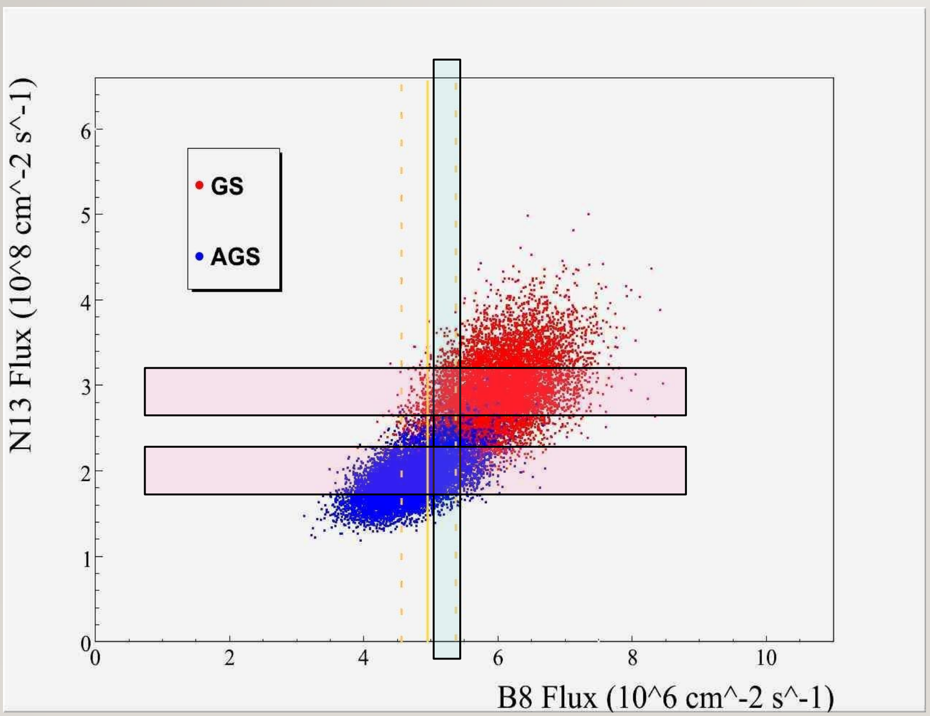
- analyze data from full AV fill
- measure backgrounds
- physics analysis – multiple topics!
- plan and execute calibration procedure and campaign
- ongoing scintillator plant operations (recirculation) on the AV
- Te cocktail chemistry
- prepare for Te process operations

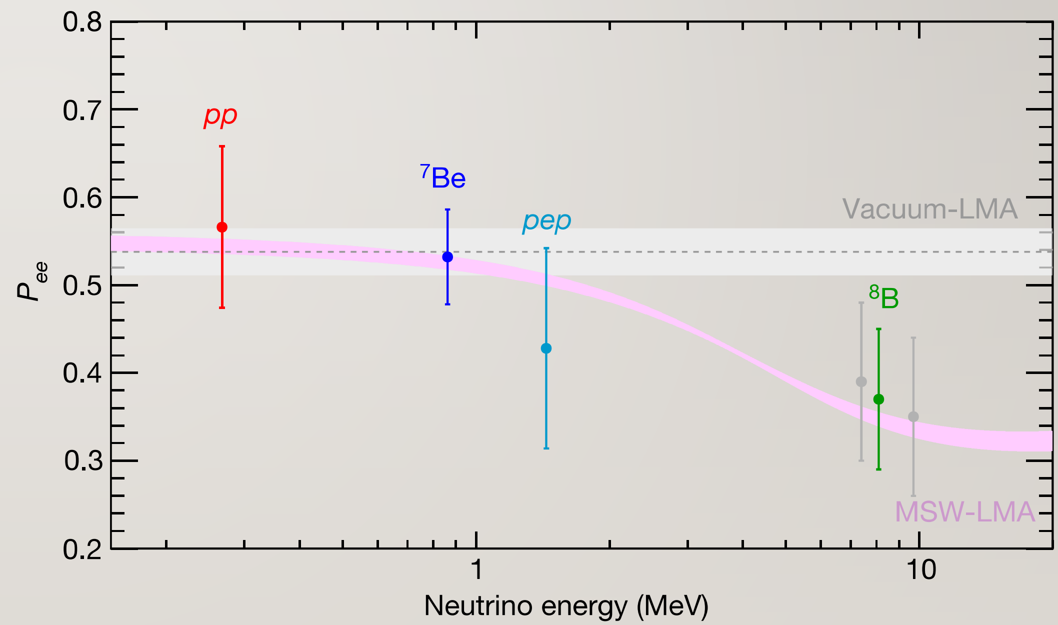
Backup Slides

SOLAR NEUTRINOS

- pep and CNO solar neutrinos
- low energy ^{8}B solar neutrinos





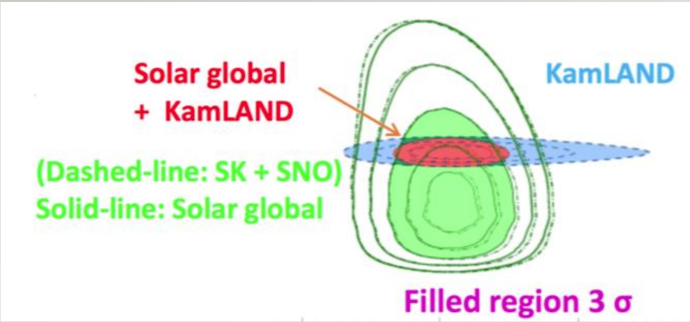


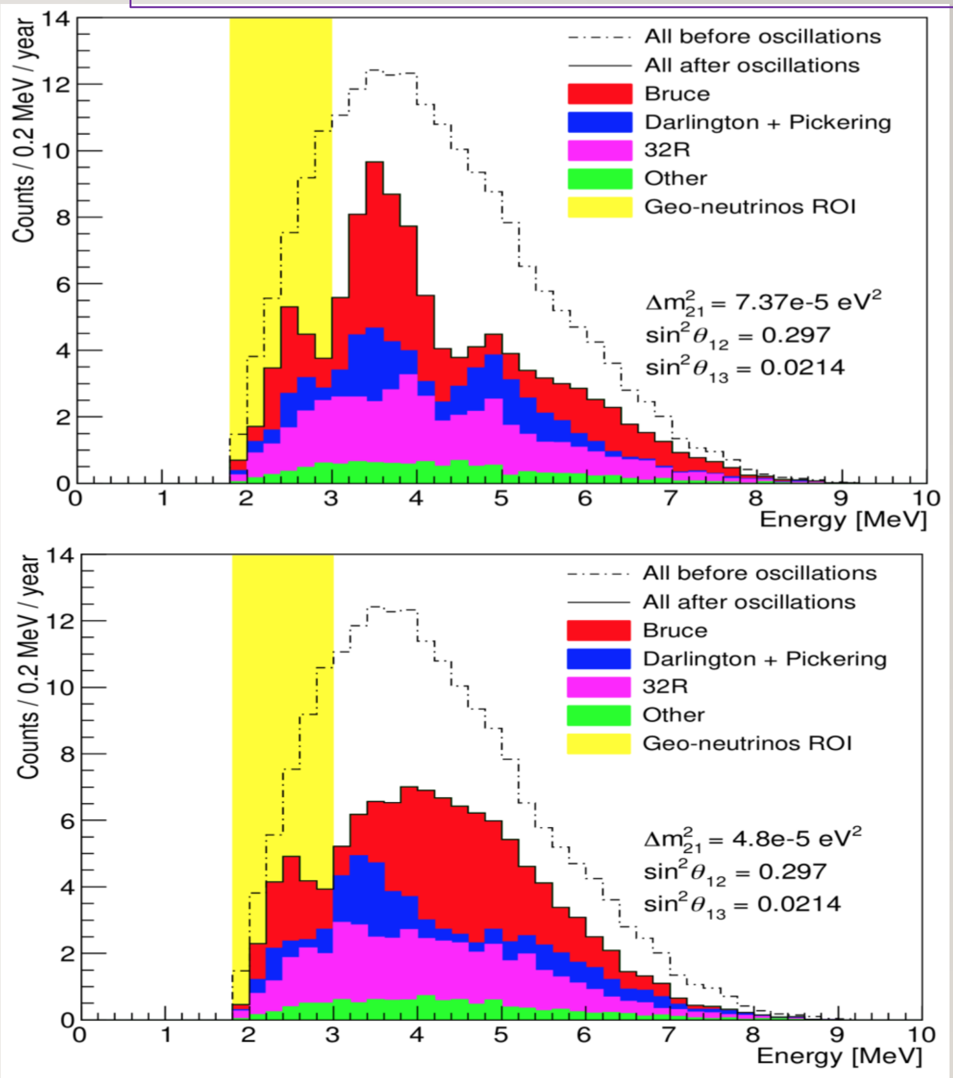
solar neutrino survival probability

solar metallicity with CNO neutrinos

ANTINEUTRINOS – GEO AND REACTOR

$\pm 0.7 \times 10^{-5}$ eV^2 precision possible with 6-months of SNO+ data





Geo Neutrinos in SNO+