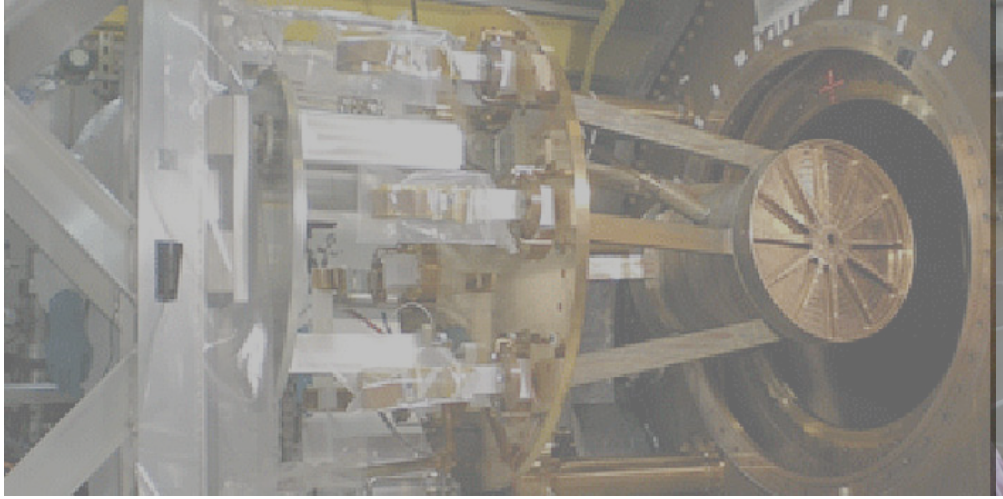
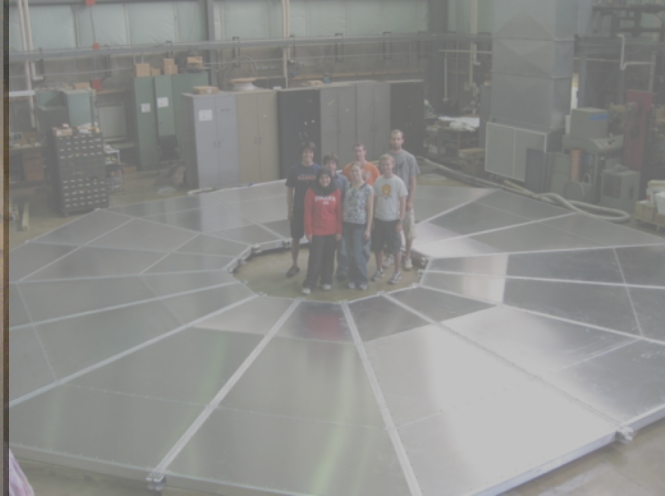
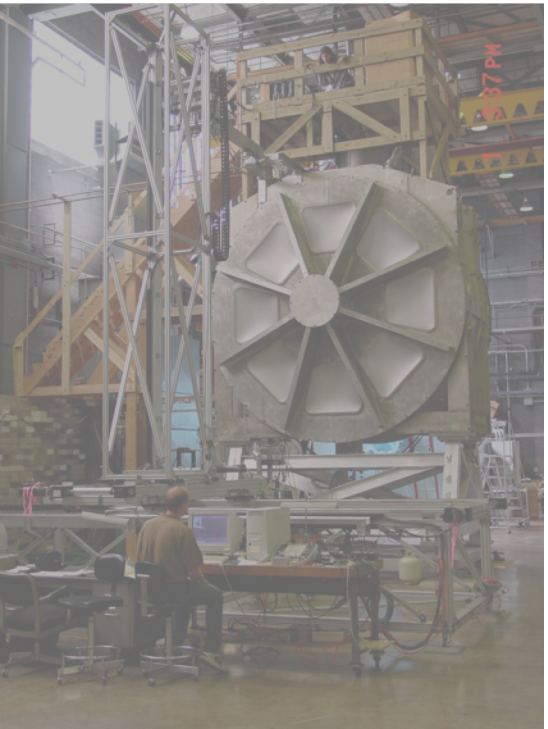




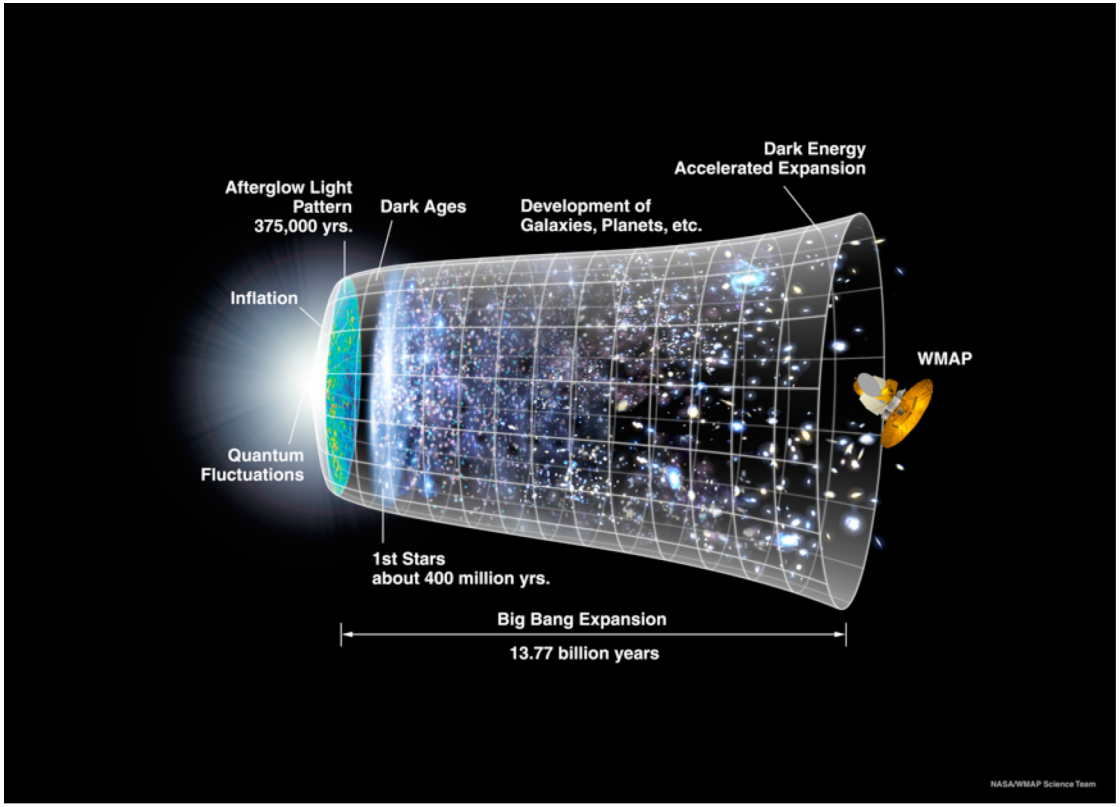
Fundamental Symmetry and Neutrino Physics



Liang Yang

Physics 403

Do we understand the Universe we live in?



Standard Cosmological Model

Standard Model of Particle Physic

Standard Models are incomplete...

- What's the origin of matter – antimatter asymmetry in today's Universe?

- What is dark matter or dark energy?

- What is the nature of gravity?

- Can all forces in nature be unified?

Matter-Antimatter Asymmetry

Dark Matter

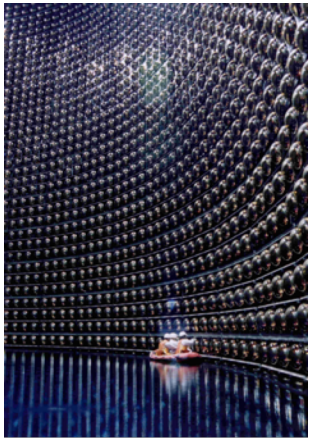
In Search of "New" Standard Model

- **LHC: direct search for new particles**
  - Discovery of Higgs!
  - Hints of New Physics?

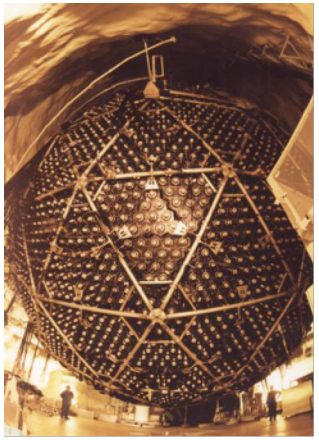
- **Precision measurements:**
  - EDMs of *e, n*, atoms, etc.
  - Weak mixing angle
  - $0\nu\beta\beta$
  - Muon *g*-2
  - Lepton flavor violation
  - π, *K* and *B* decays
  - Unitarity tests

Mostly Nuclear Physics

Neutrino Oscillation and Neutrino Mass

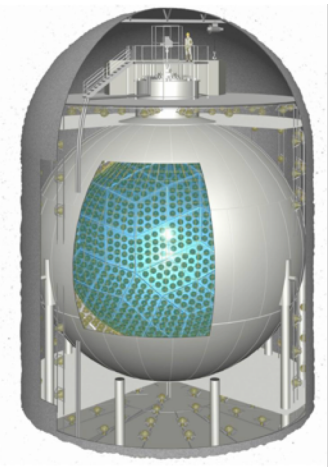


Super-K



SNO

K2K



KamLand

Super-K: atmospheric ν_μ neutrino oscillation

SNO: solar ν_e flavor transformation

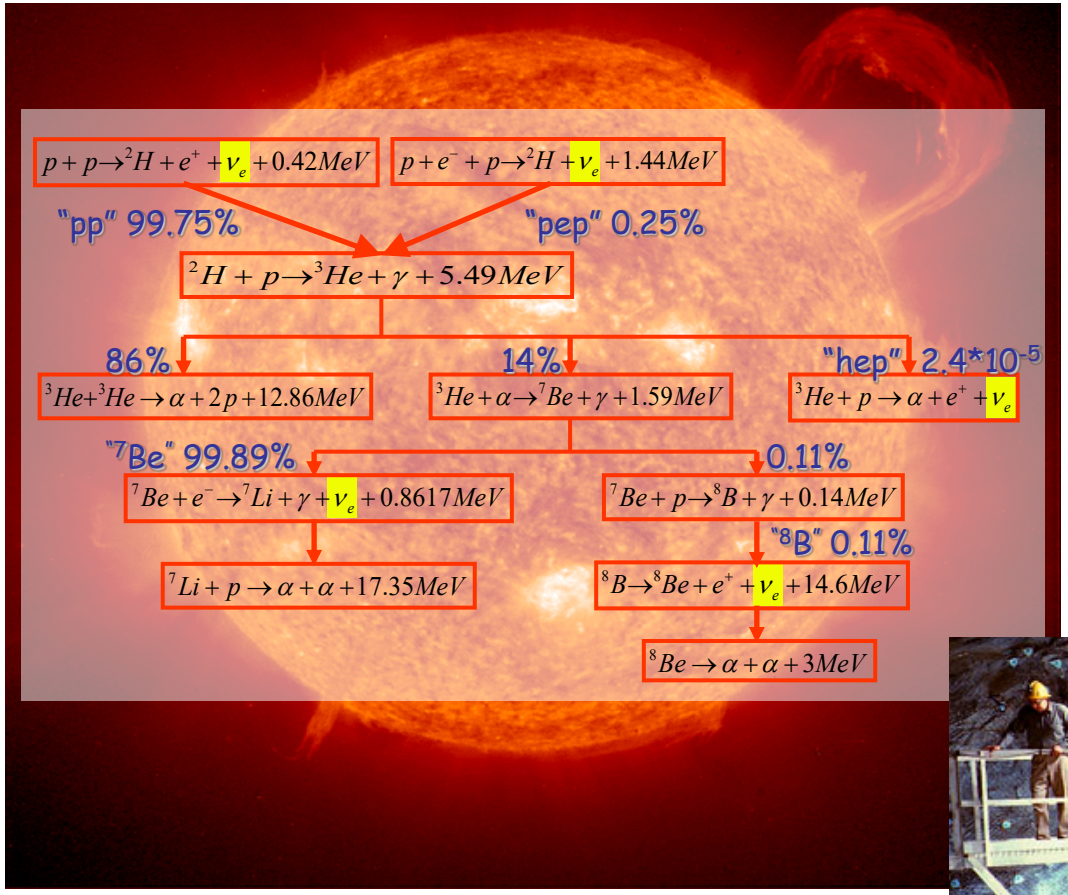
K2K: accelerator ν_μ oscillation

Kamland: reactor $\overline{\nu}_e$ disappearance and oscillation

Neutrinos have Mass

The first evidence of physics beyond the Standard Model!

Our Sun is a copious source of electron type neutrinos …



In a famous experiment 1968
(Nobel prize (2002), Ray Davis)
Observe solar electron-type neutrinos ν_e

Detection in a huge underground vat of cleaning fluid (615 tons) via the reaction
$^{37}Cl + \nu_e = {}^{37}Ar + e^-$

radioactive argon atoms collected periodically and counted :

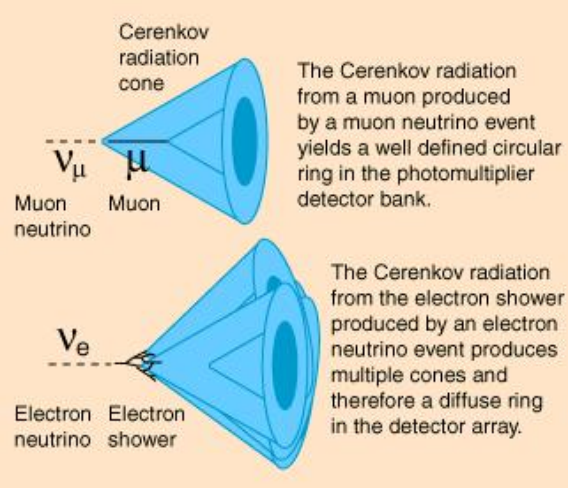
Produced at only 15 atoms per month !

Experiment located 1500m underground
Homestake Gold Mine in SD
3 million times less cosmic ray interactions (bkgrds) due to muons (which are very penetrating particles), compared to the surface.

Far too few (~1/3) solar neutrinos were seen compared to predicted solar production !

The plot thickens – some good fortune …

1983 experiments (for protons decay) also good neutrino detectors … cross check **Homestake**.

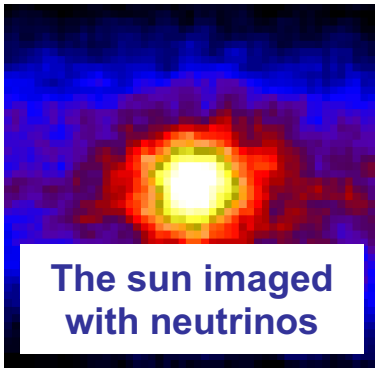


A massive detector, known as "SuperK", clearly observed ν's from the Sun, and confirmed the signal of missing solar ν's.

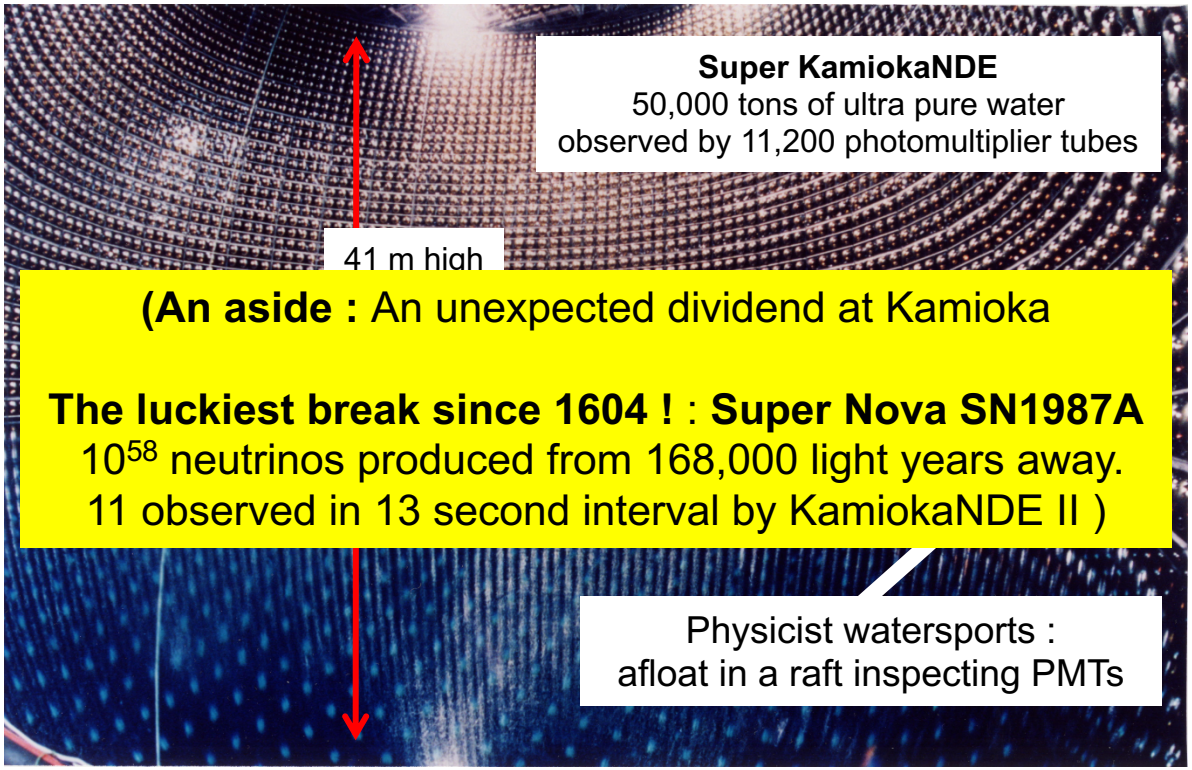
In addition, SuperK was able to observe ν's produced in the upper atmosphere by cosmic rays – "atmospheric ν's", and to tell where they were coming from, leading to a : **Breakthrough Observation in 1998**

In the Kamioka Mine in Japan
- Depth of 1000m
- Water tank (3000 tons for the first one)
- Instrumented to observe light flashes from produced from μ's or e's.

(led by M. Koshiba, also a 2002 Nobelist)

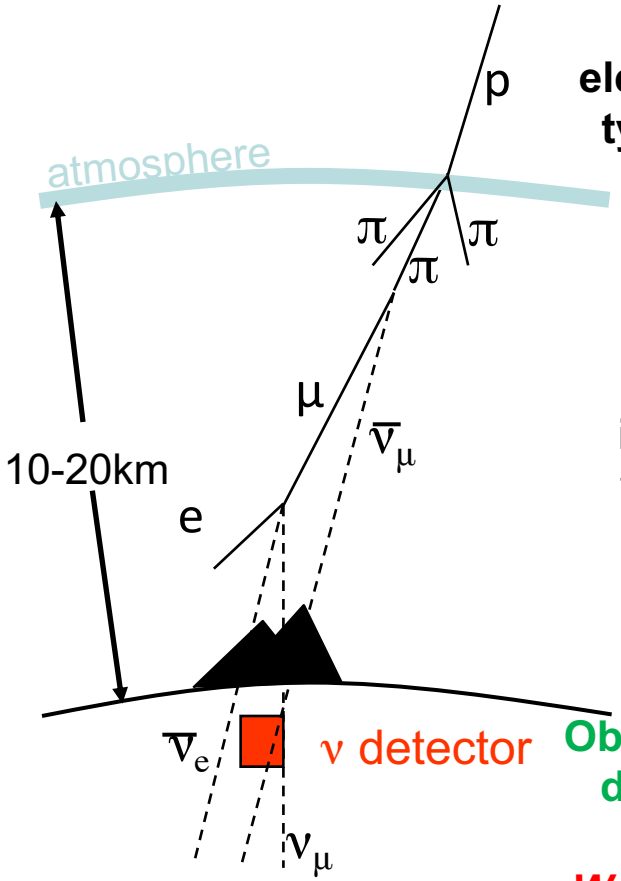


Particles are produced along the ν direction :
For the first time ***directional information***.



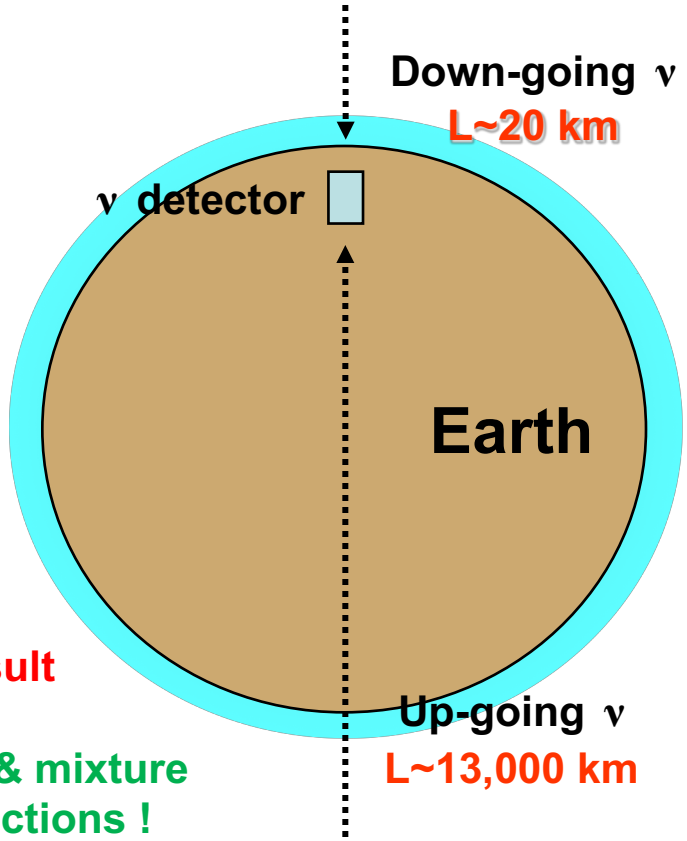
Atmospheric Neutrino

Atmospheric neutrinos originate in cosmic ray "showers"



The **showers** produce **electron, muon (and tau) type neutrinos**, in a mix that can be predicted.

Neutrinos can reach SuperK from *above* or from *below* (the Earth is hardly a barrier at all to a neutrino, after all.)

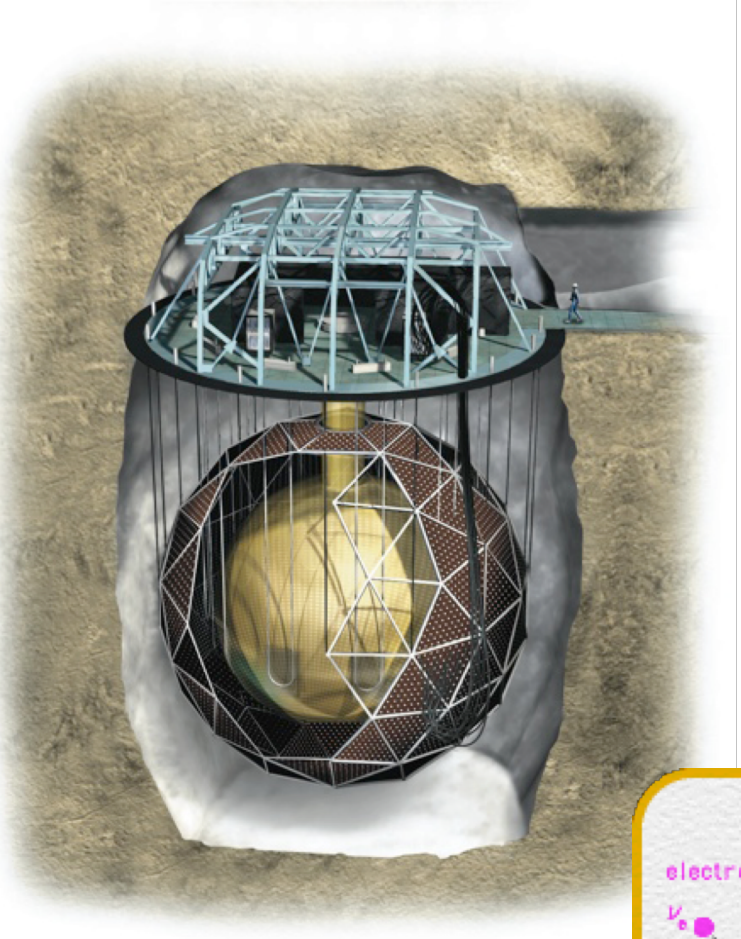


Stunning Result

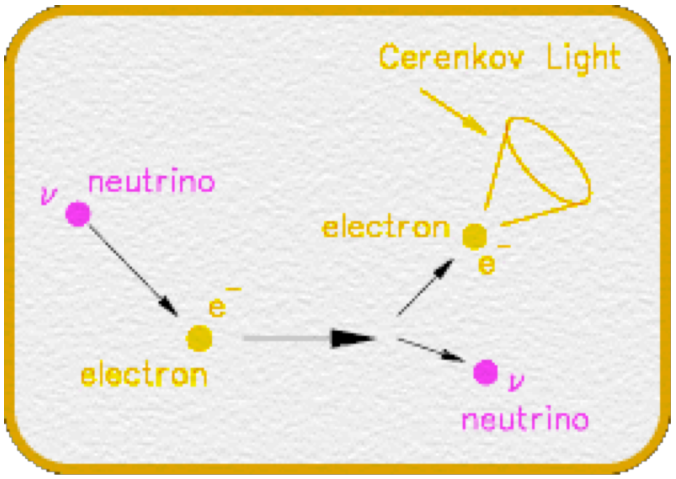
Observed neutrino rates & mixture differed for the two directions !

Were flavors changing in transit ?

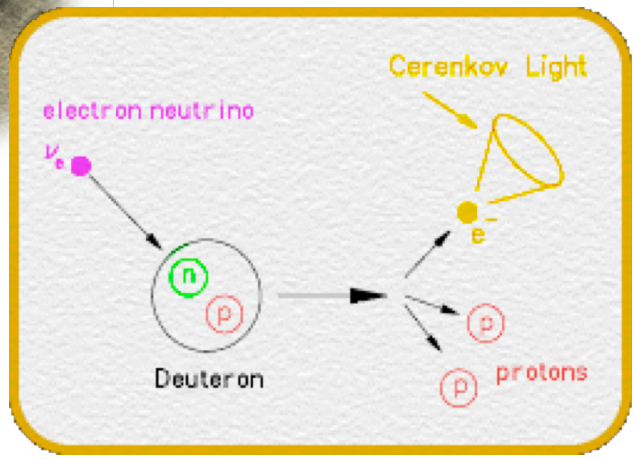
SNO



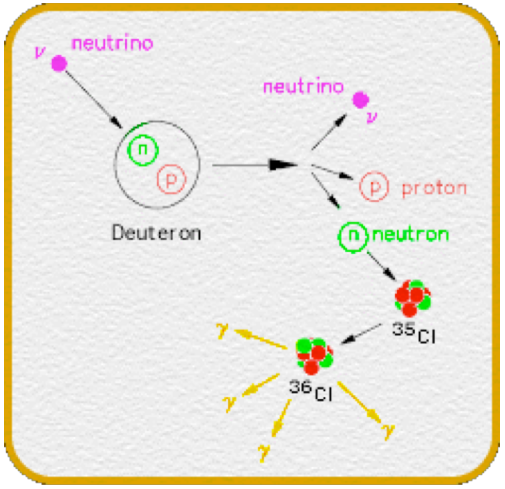
2002 Sudbury Neutrino Observatory



Electron Scattering



Charge Current

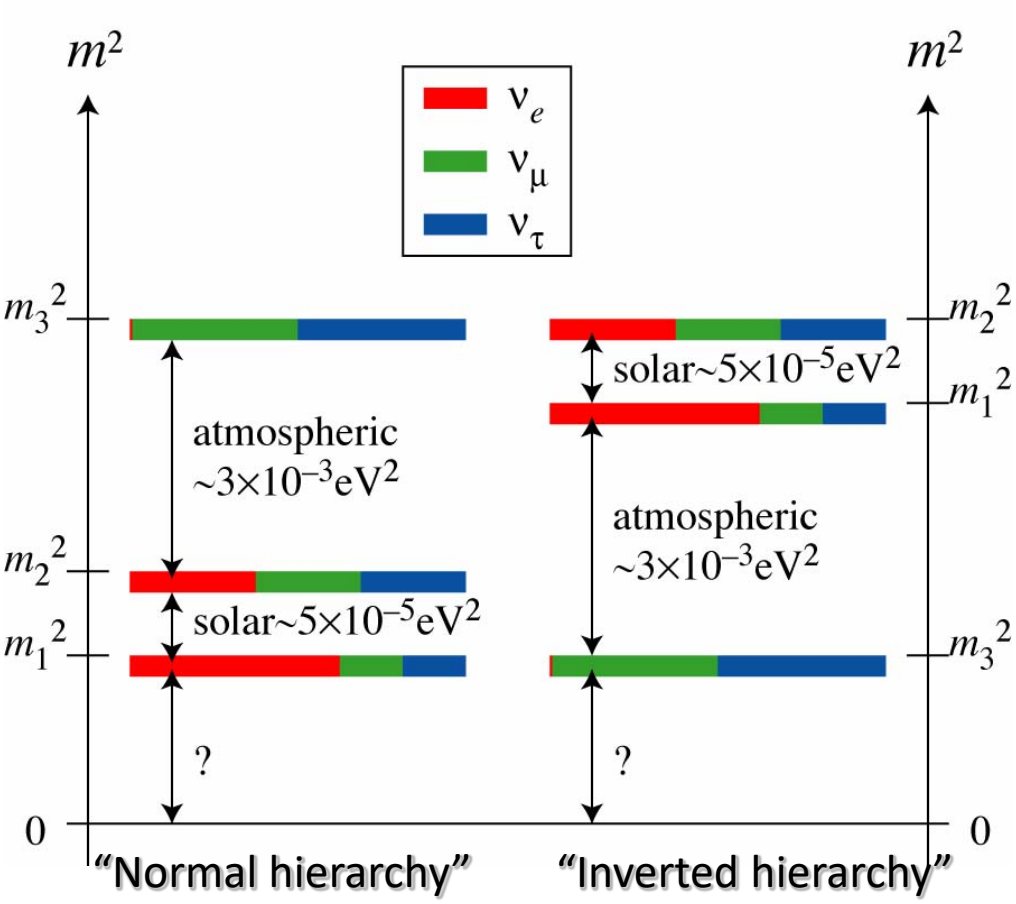


Neutral Current

Unknown Properties of Neutrinos

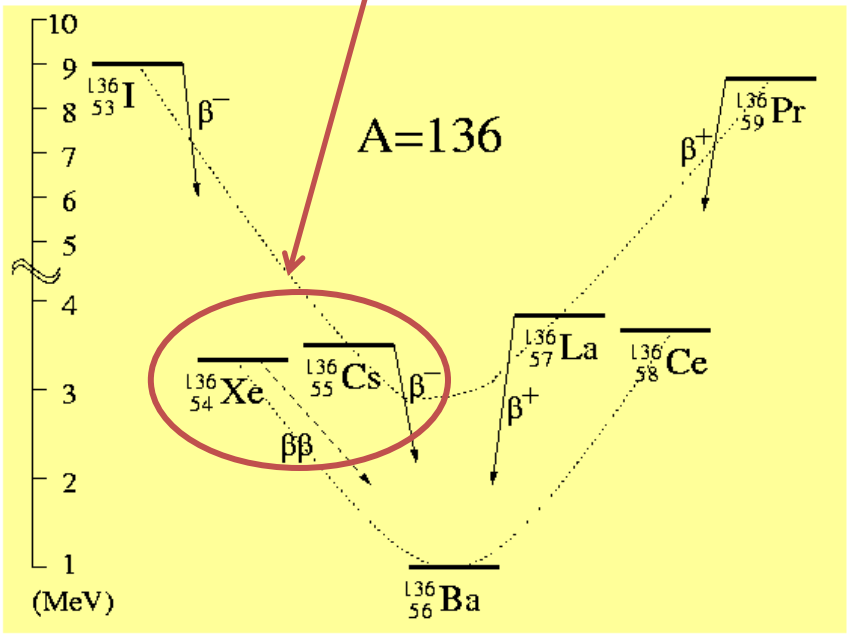
Major Questions in Neutrino Physics

- Majorana particle, (i.e. its own antiparticle)
- Absolute mass scale of neutrinos.
- Mass hierarchy
- CP violation phase
- Anomalies (Sterile neutrinos?)

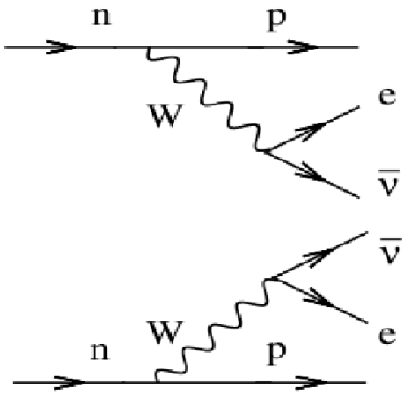


Double Beta Decay

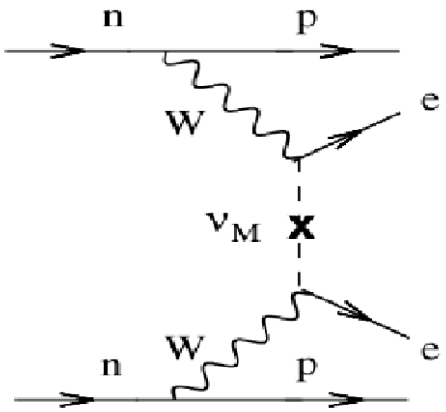
Observable if single beta decay is forbidden



Two neutrino double beta decay



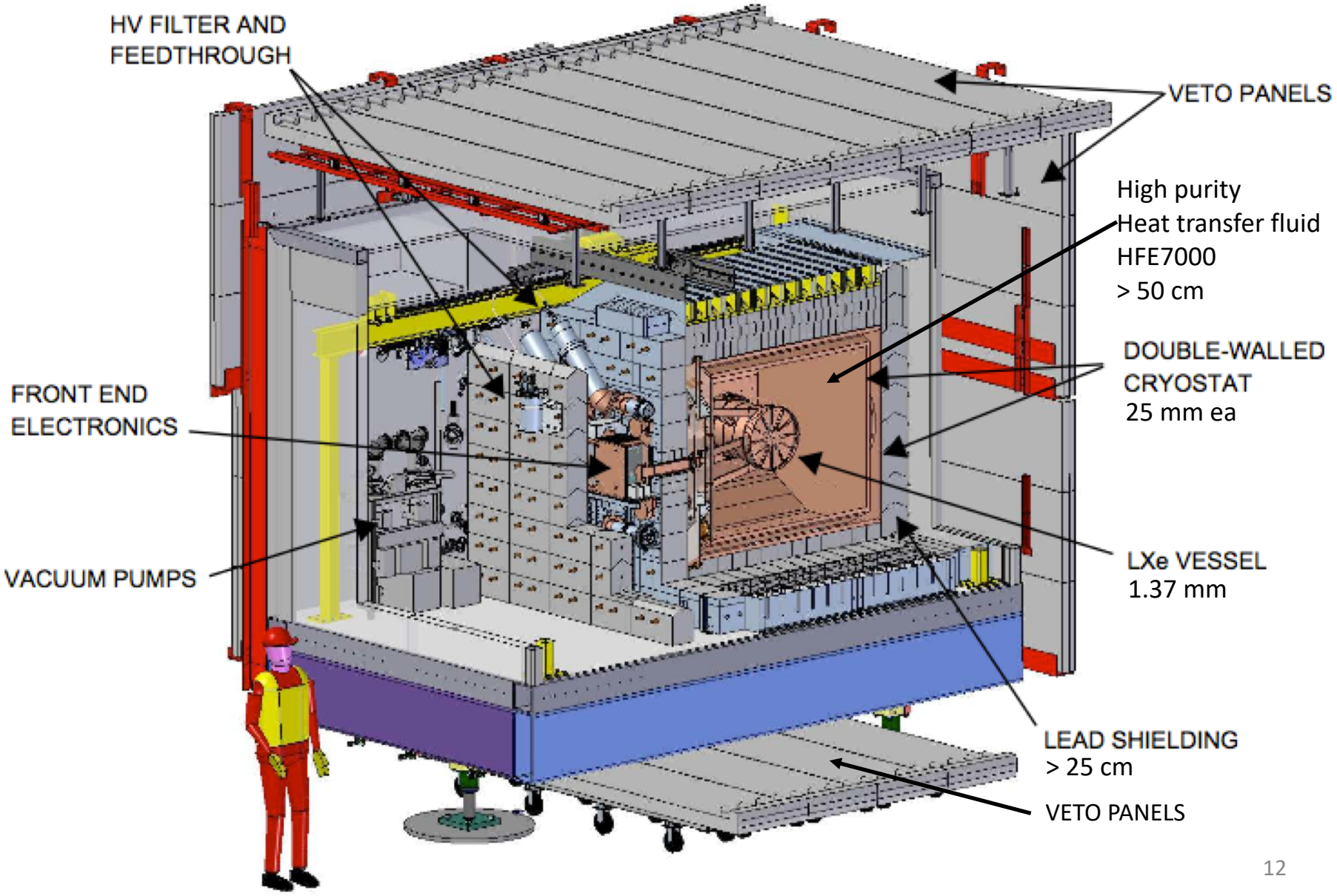
Neutrinoless double beta decay



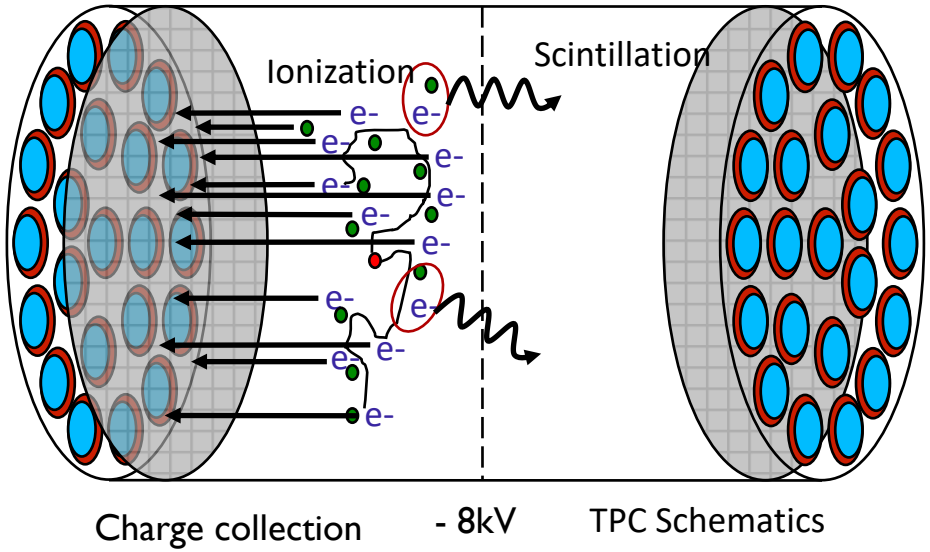
Observation of $0\nu\beta\beta$:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

The EXO-200 Detector

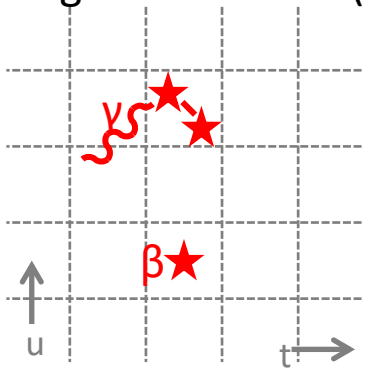


Liquid Xenon Time Projection Chamber

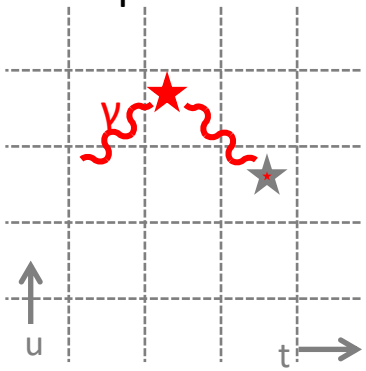


The EXO-200 time projection chamber uses both scintillation and ionization signals to fully reconstruct energy depositions inside liquid xenon

Single Site Events (SS)

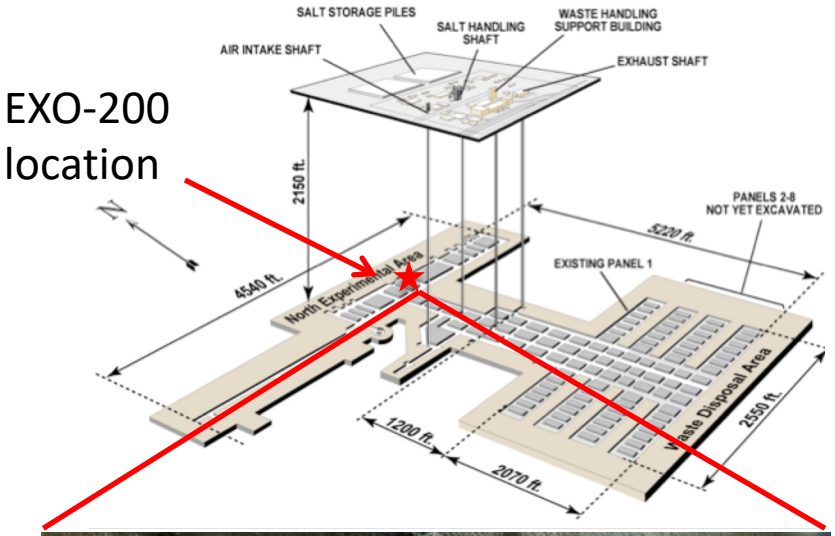


Multiple Site Events (MS)



Event topology is a powerful tool not only for gamma background rejection, but also for signal discovery.

EXO-200 installation site: WIPP



- EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM
- 1600 mwe flat overburden (2150 feet, 650 m)
- U.S. DOE salt mine for low-level radioactive waste storage
- Cleanroom installed on adjustable stands to compensate salt movements.
- Salt "rock" low activity relative to hard-rock mine

$$\Phi_\mu \sim 1.5 \times 10^5\, yr^{-1} m^{-2} sr^{-1}$$

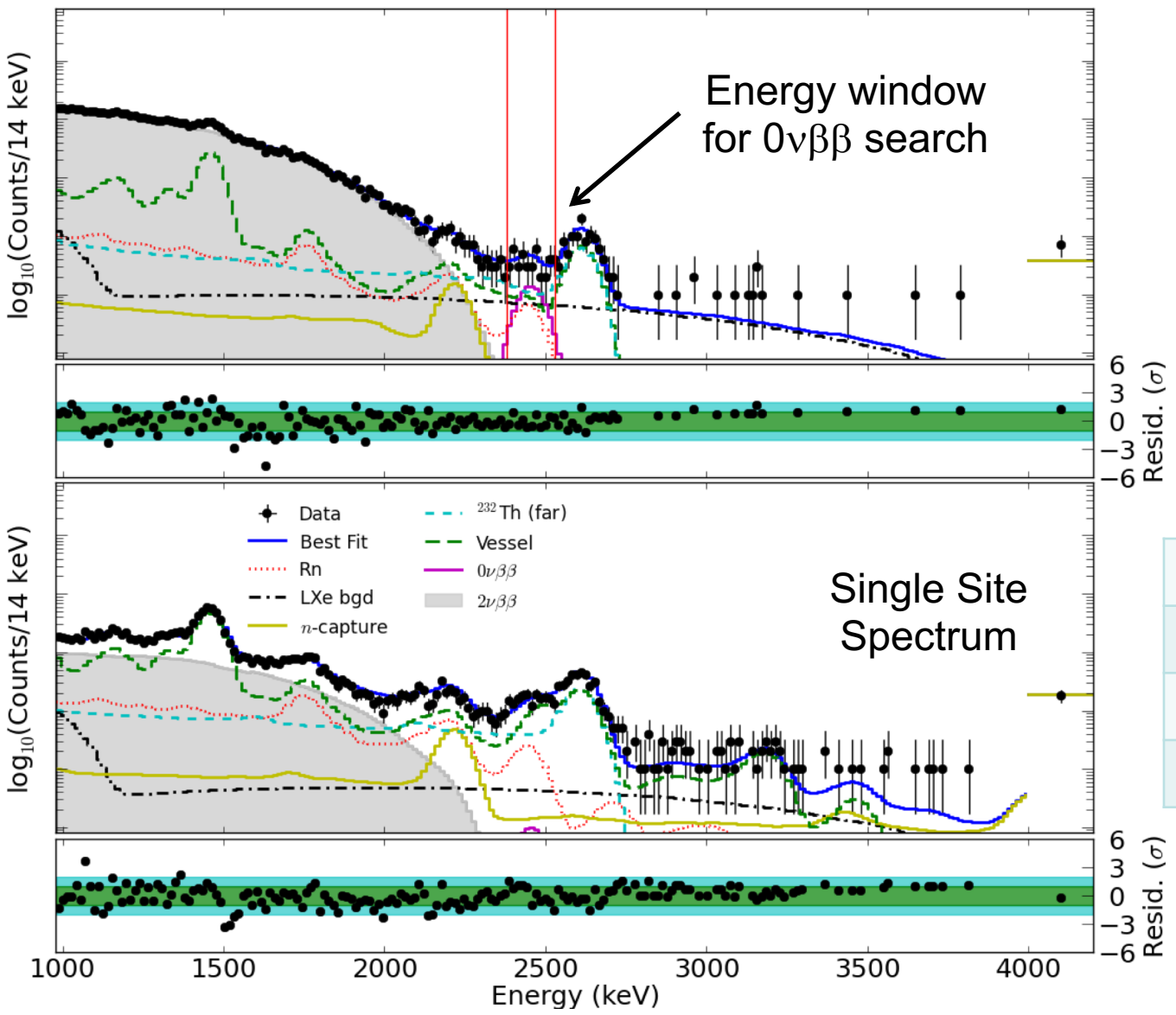
$$U \sim 0.048\, ppm$$

$$Th \sim 0.25\, ppm$$

$$K \sim 480\, ppm$$

Esch et al., arxiv:astro-ph/0408486 (2004)

0νββ Search with First Two Years of Data



^{136}Xe exposure:
99.8 kg yr

Simultaneous fit to energy and standoff dist. for SS and MS

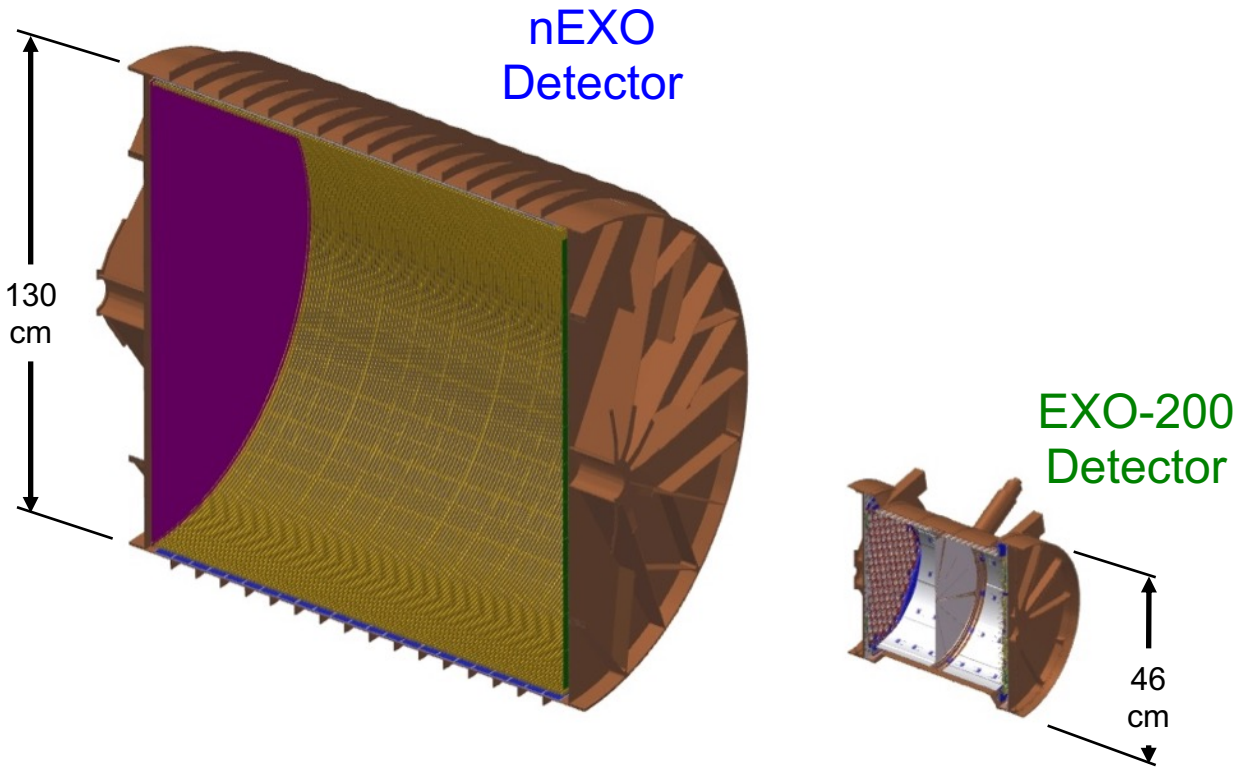
Background events from the fit

^{232}Th	16.0
^{238}U	8.1
^{137}Xe	7.0
Total	31.1

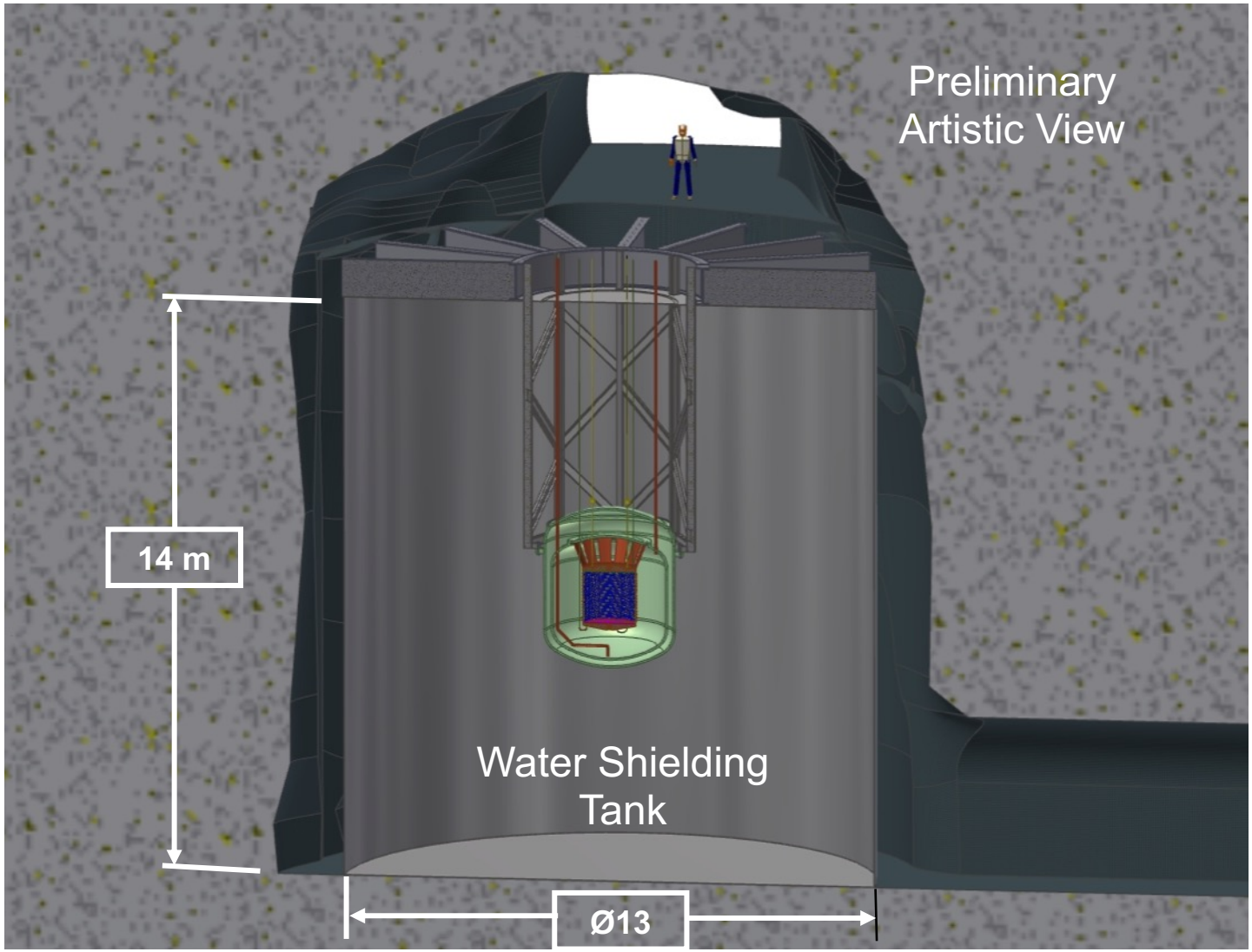
Background index: $(1.7 \pm 0.2) \cdot 10^{-3}$ keV^{-1} kg^{-1} yr^{-1}

nEXO Detector

- 5 tonne LXe TPC “as similar to EXO-200 as possible”, *initially* without Ba-tagging.
- 4.7 tonnes of active ^{enr}Xe (80% or higher), 1.0% (σ) energy resolution.
- Assuming Observed EXO-200 backgrounds minus the Rn in the shield. ββ-scales like the volume, the background like the surface area.
- Provide access ports for a possible later upgrade to Ba tagging

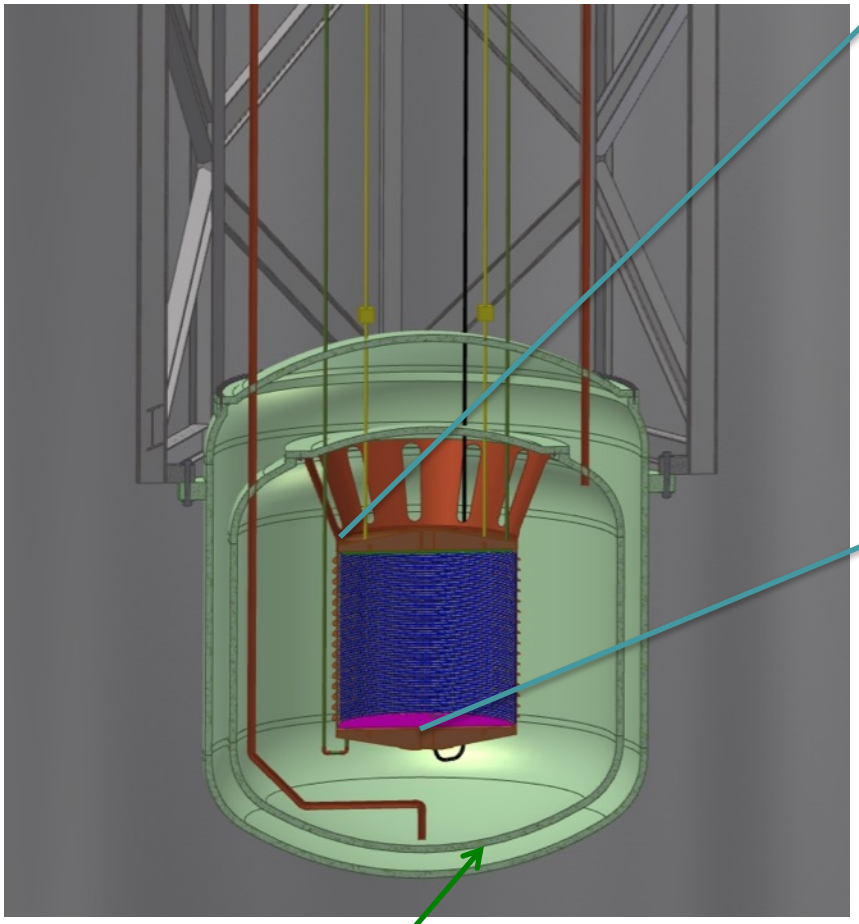


nEXO in the SNOlab Cryopit



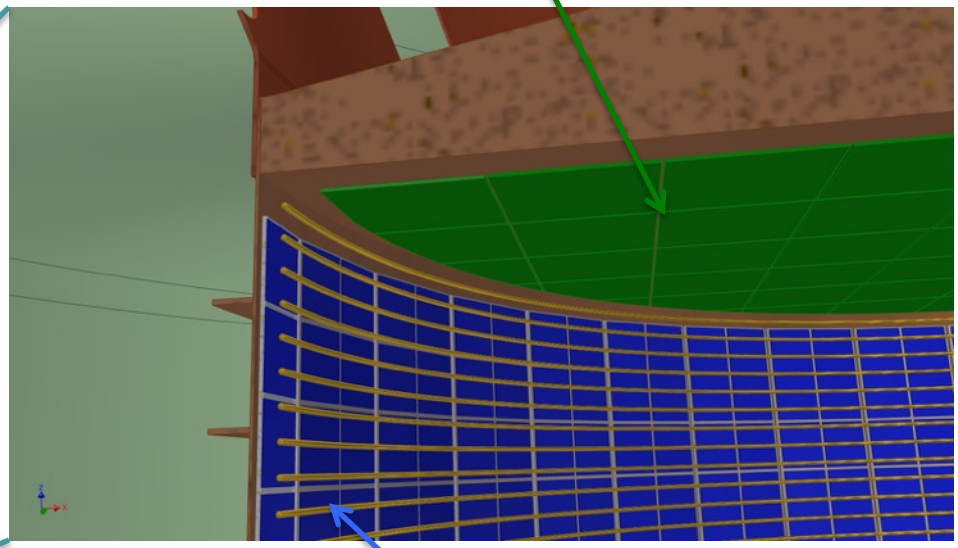
6,000 m.w.e. depth sufficient to shield cosmogenic background.

Preliminary Artistic View of nEXO TPC



Carbon Fiber Cryostat

Charge Readout Tiles

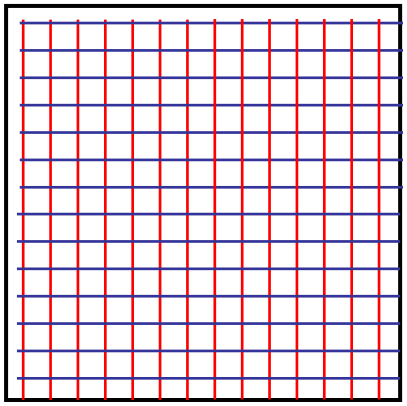


Silicon Photomultipliers (SiPMs)

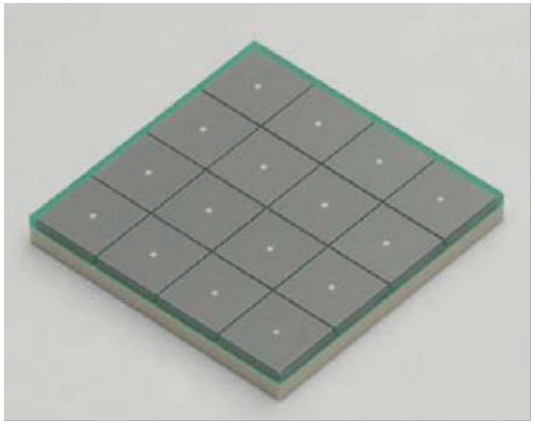
Baseline concept: (Improved TPC design).

- Single drift volume
- Charge collection on the anode plane
- Light collection on the barrel behind field shaping rings

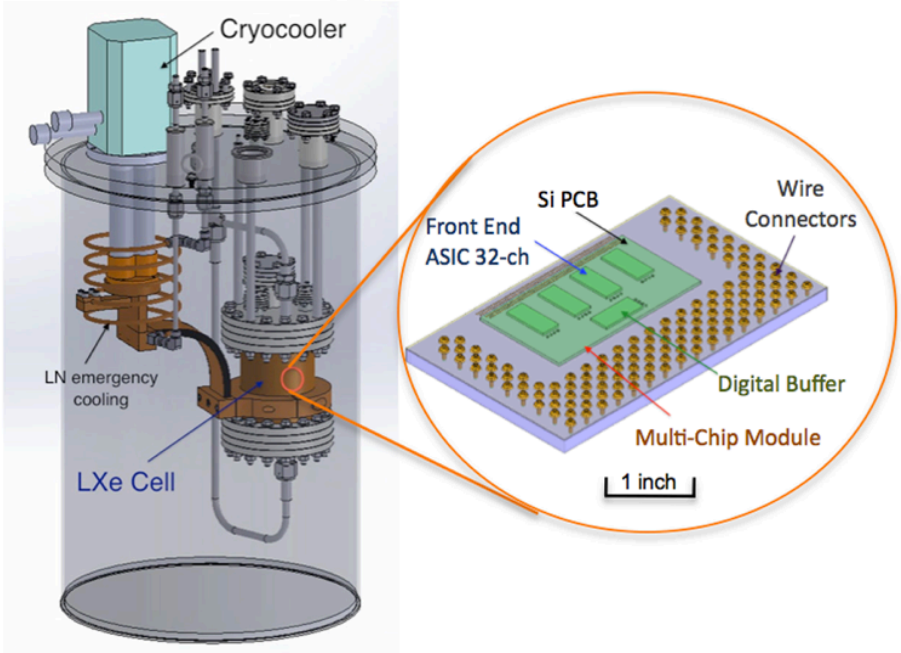
nEXO Front End Electronics



Charge readout tile concept



UV sensitive SiPM under development



nEXO Cold Electronics Test Apparatus

- Low noise, low background cold front end electronics is necessary to reach the experimental sensitivity.
- Illinois group is leading conceptual design and testing of this R&D effort.

What can Neutrino tell us about the Universe?

- What role did neutrino play in the evolution of the universe? (~ 4% mass of the universe, absolute mass scale? Number of species? … double beta decay experiment, tritium decay experiment, sterile neutrino search…)
- Can neutrino be responsible for the matter and anti-matter asymmetry? (CP violation phase? … long baseline neutrino experiment)
- Neutrino might be the best probe deep into the universe (IceCube…)
- Supernovae neutrinos, relic neutrinos…