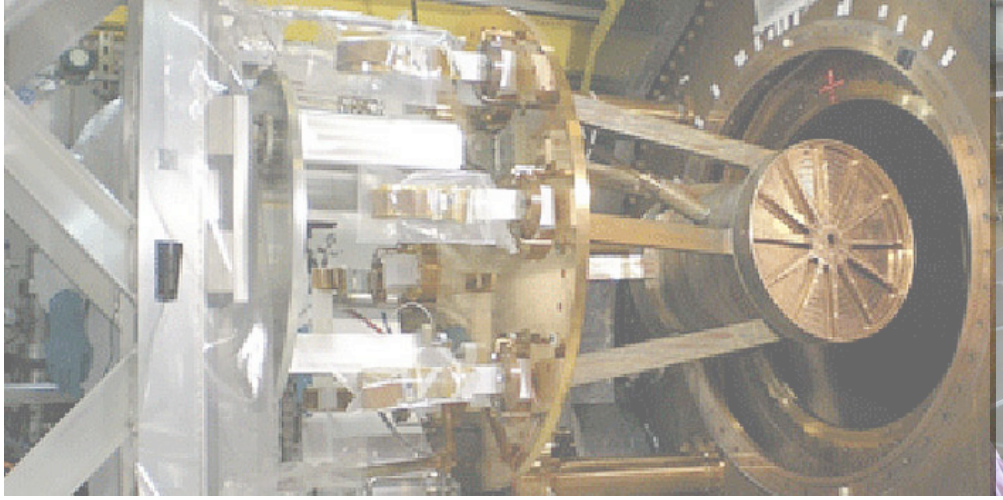
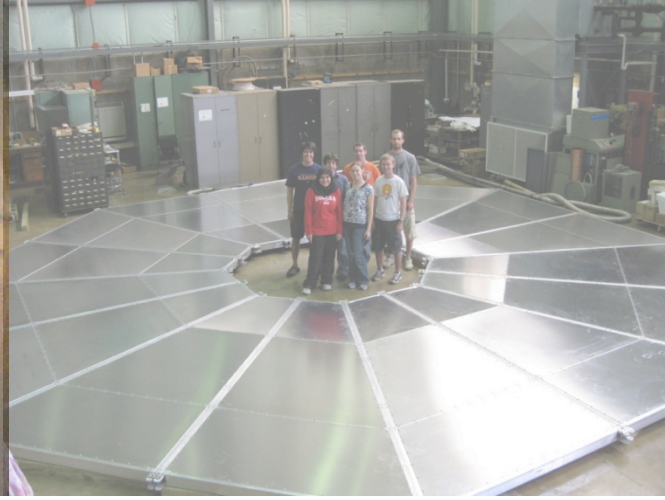
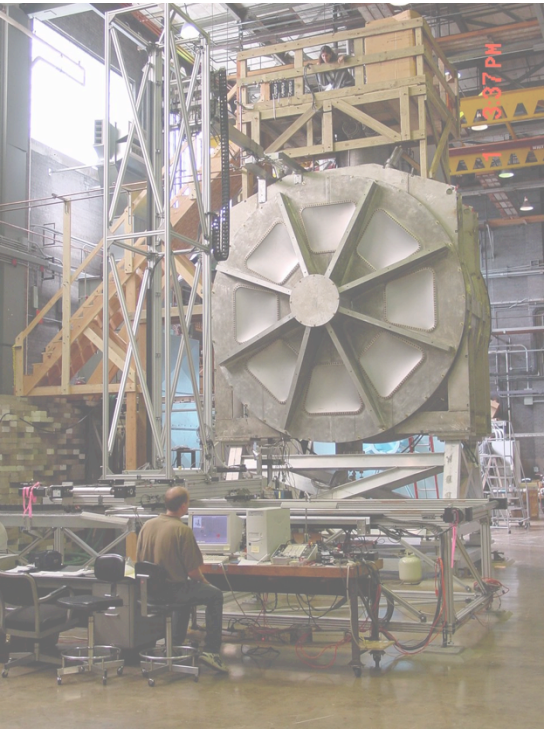




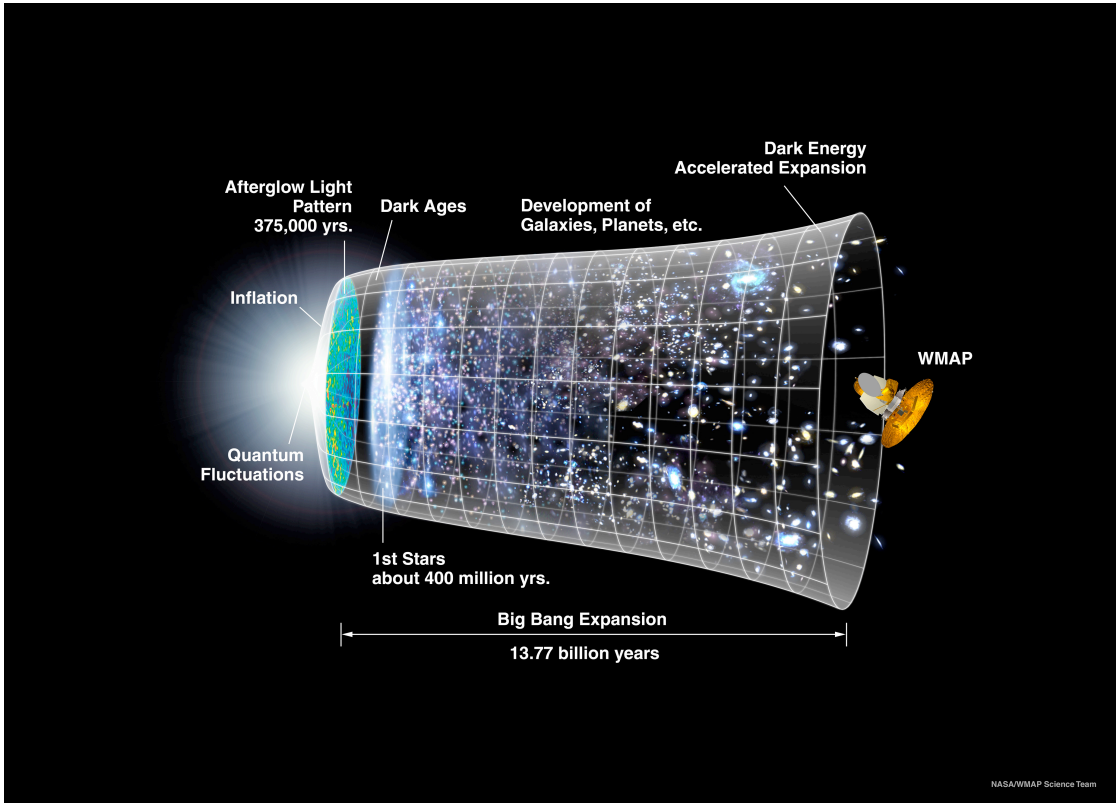
Fundamental Symmetry and Neutrino Physics



Liang Yang

Physics 403

Do we understand the Universe we live in?



Standard Cosmological Model

Standard Model of Particle Physic

Standard Models are incomplete...

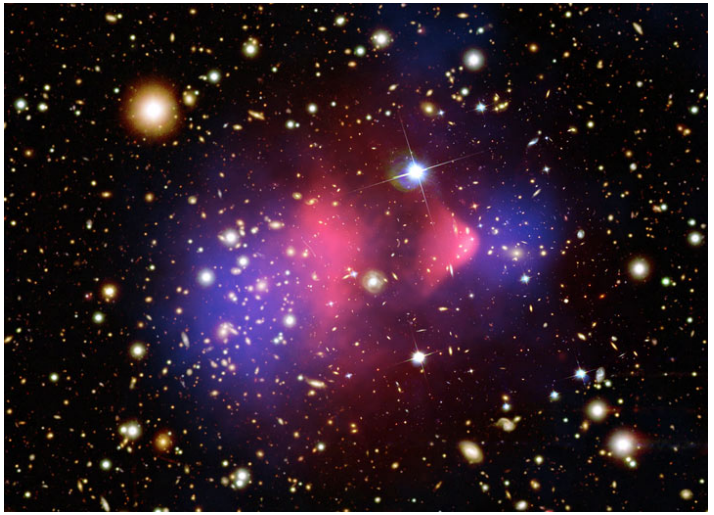
- What's the origin of matter – antimatter asymmetry in today's Universe?

- 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

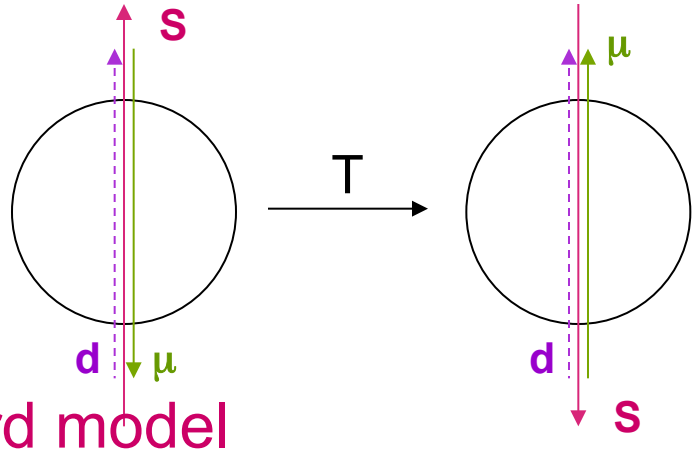
- **LHC: direct search for new particles**
  - Discovery of Higgs!
  - Hints of New Physics?

- **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

Physics: Neutron Electric Dipole Moment

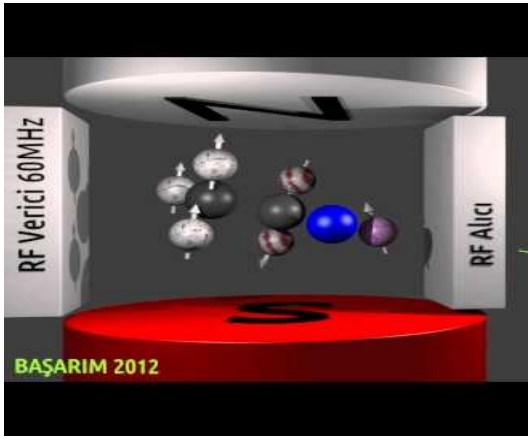
- Neutron has spin **S** (1/2)
  - has magnetic moment, μ
  - electric dipole moment, **d**?
    - violates time reversal symmetry



- Time reversal is violated in standard model
  - we think CPT is conserved
  - CP (T) violation observed in K^0, B^0 decays
  - T violation observed in K^0 decays
  - *origin unknown!*
- Theories beyond standard model predict CP violation
  - e.g. supersymmetry (SUSY): $\mathbf{d}_n \neq 0$
- Most intriguing aspect – CP violation required to give observed baryon asymmetry in universe
  - must be some difference between interactions of, say, protons & antiprotons

nEDM Measurement

- Measure precession frequency of neutron (magnetic) moment
  - almost like undergraduate nuclear magnetic resonance experiment



  - precession frequency depends on magnetic moment, magnetic field

$$f = 2\mu_B B / h$$

  - add electric field E (parallel or anti-parallel to B)

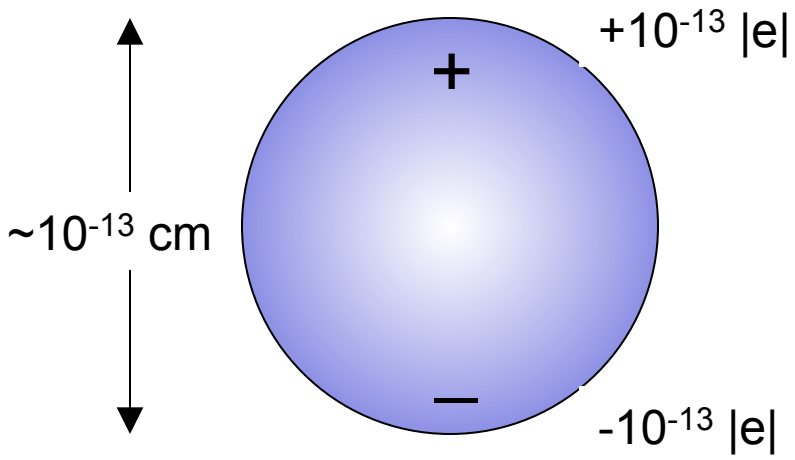
$$f = 2\left(\mu_n B \pm d_n E\right) / h$$

  - Can isolate small $d_n E$ piece by subtracting precession frequencies

$$f_{\uparrow\uparrow} - f_{\uparrow\downarrow} = 4 d_n E / h$$

How Small is Small?

- Current limit on neutron EDM is ~ 10^{-26} e·cm
- Equivalent of 10^{-13} electron charge at neutron N and S poles

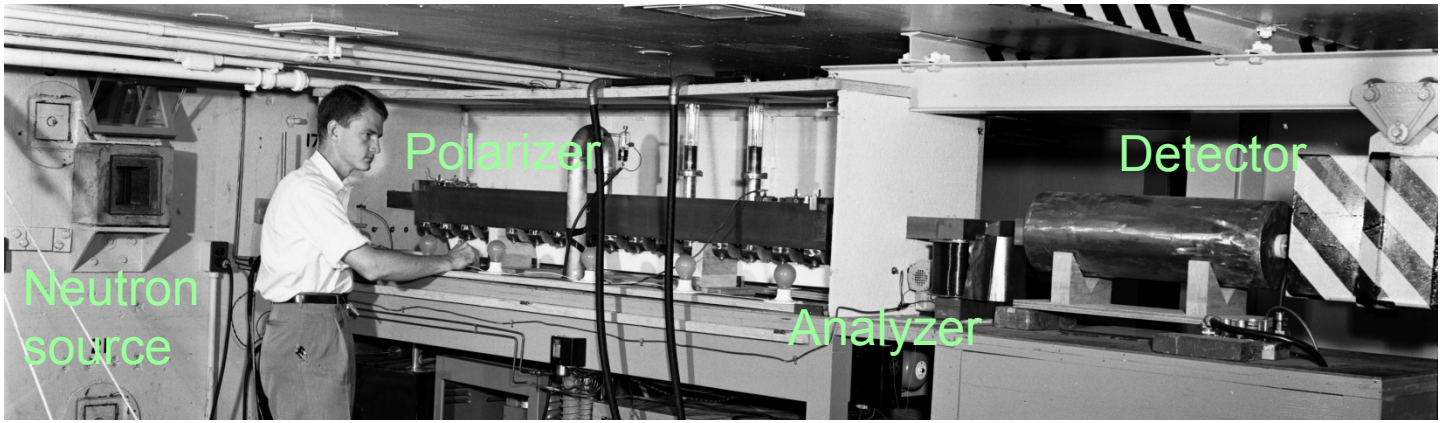


How Does One Trap Neutrons?

- Slow them down! "Ultracold Neutrons" (UCN)
- With kinetic energy of 100 neV (T ~ 1 mK), UCN behave like waves trapped by total internal reflection
  - deBroglie wavelength ~ 1 μm: sample many nuclei on reflection
  - Only certain materials work for walls, e.g., ^{58}Ni, deuterated polystyrene

Experimental Method

- Use "Ramsey Oscillatory Field" measurement
  - First implemented in neutron EDM measurement by James Smith (former UIUC Physics Department)



Jim Smith, ca. 1950

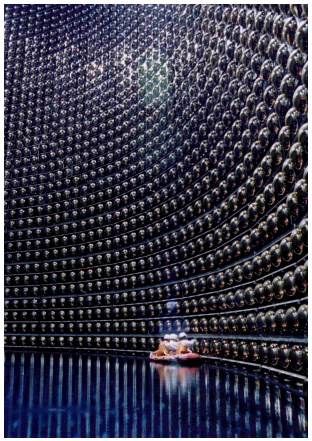
J. H. Smith, E. M. Purcell & N. F. Ramsey, Phys. Rev. **108** (1957) 120.

1. Polarize neutrons
2. Allow them to precess in combined E and B fields for time T
3. Analyze neutron polarization (measure transmission)
4. Reverse E (or B), go to 1.

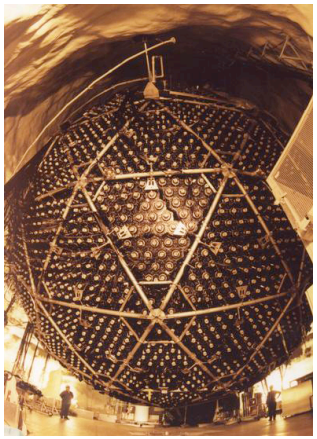
New Measurement: First Phase

- Institut Laue-Langevin, Grenoble
- Currently world's most intense source of ultracold neutrons
- Nuclear physics (ultra-cold neutrons) ⊕ Atomic physics (magnetometers) → Particle/Astrophysics
  - Physics beyond the standard model
  - Baryon asymmetry of the universe

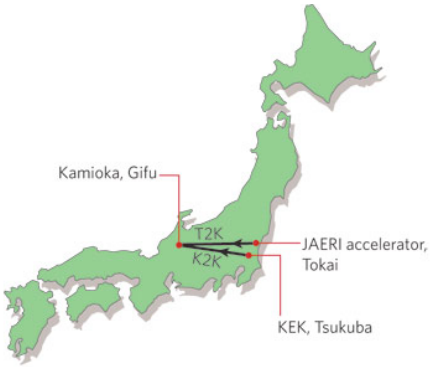
Neutrino Oscillation and Neutrino Mass



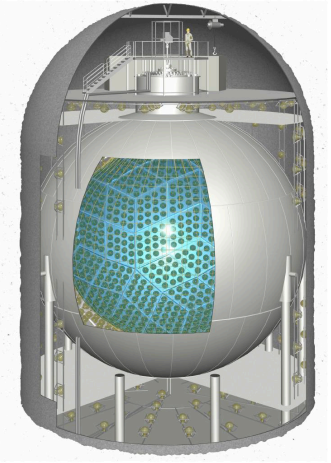
Super-K



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

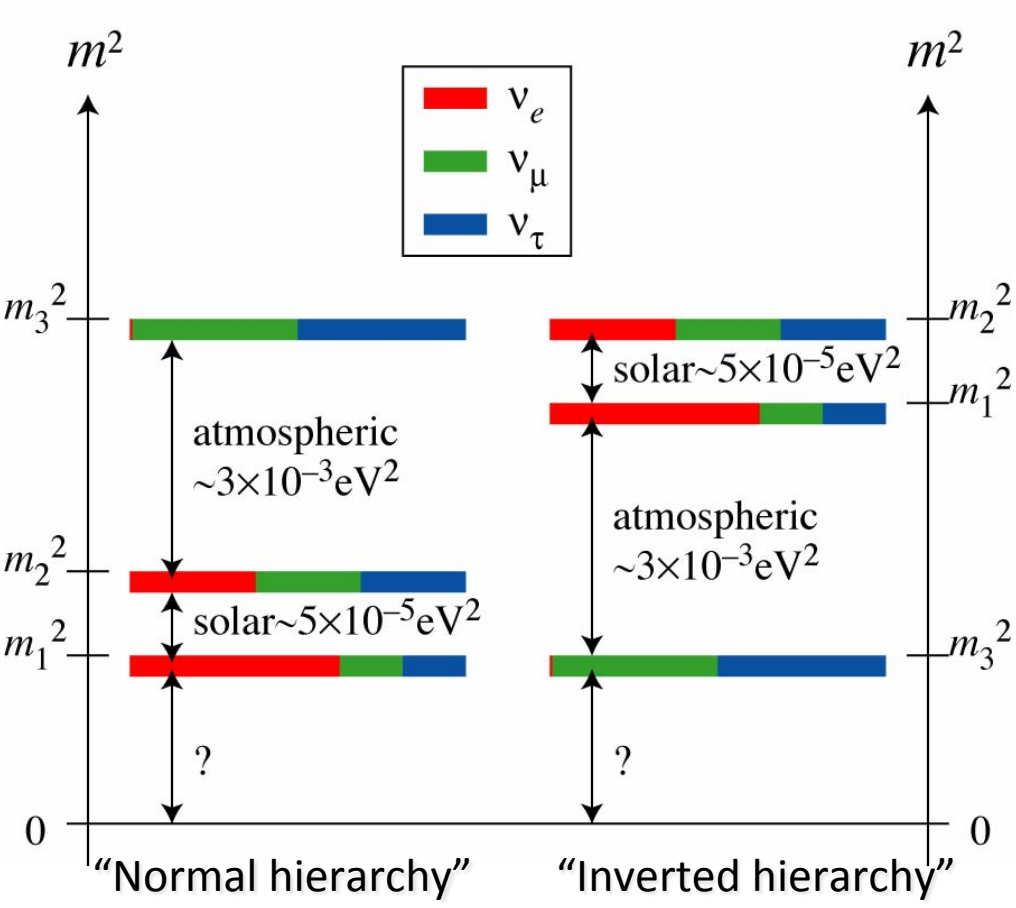
Neutrinos have Mass

The first evidence of physics beyond the Standard Model!

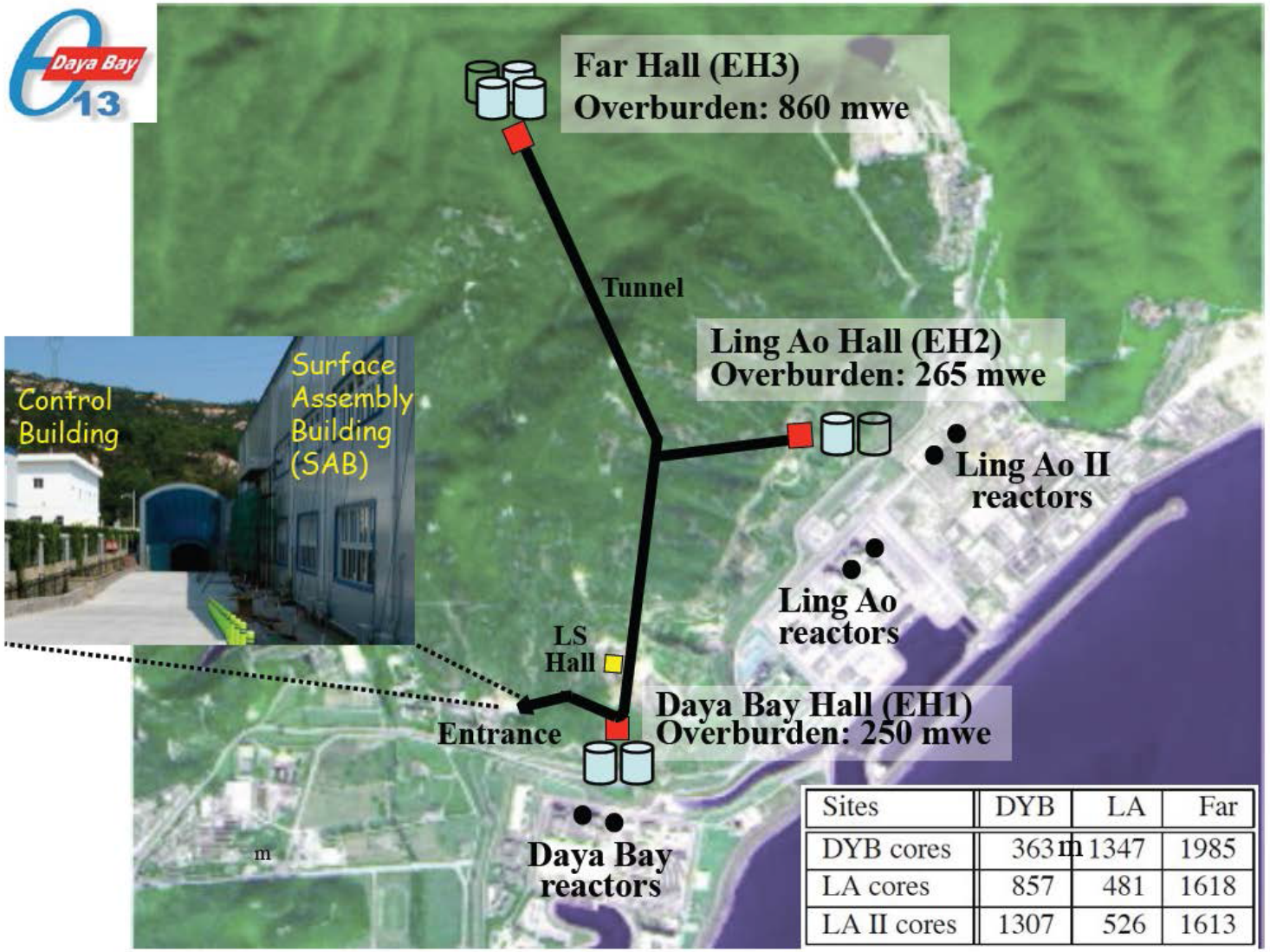
Unknown Properties of Neutrinos

Major Questions in Neutrino Physics

- Majorana particle, (i.e. its own antiparticle)
- Absolute mass scale of neutrinos.
- Mass hierarchy
- Mixing Angle Theta-13 (measured !)
- CP violation phase
- Anomalies (Sterile neutrinos?)

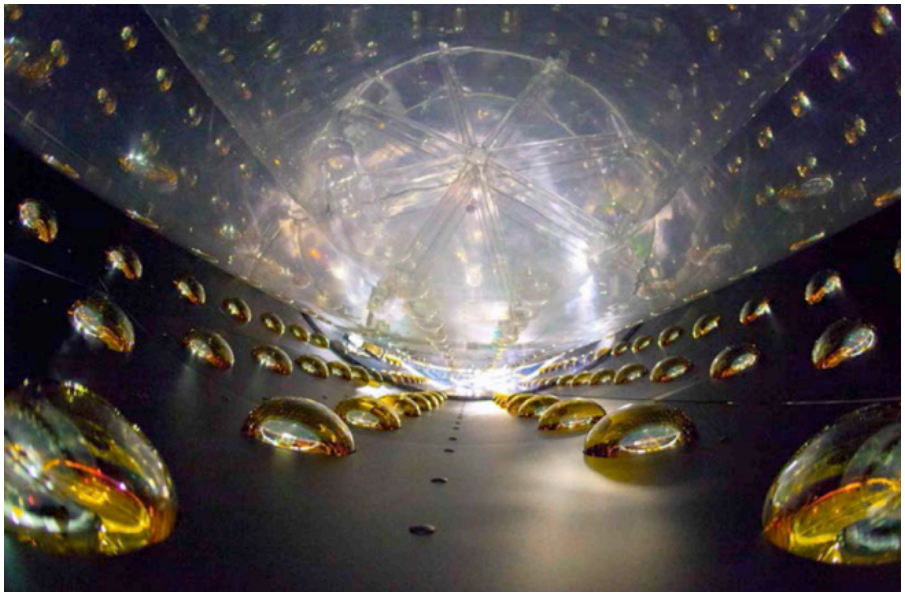


Eight Identical detectors in three underground sites connected by tunnels

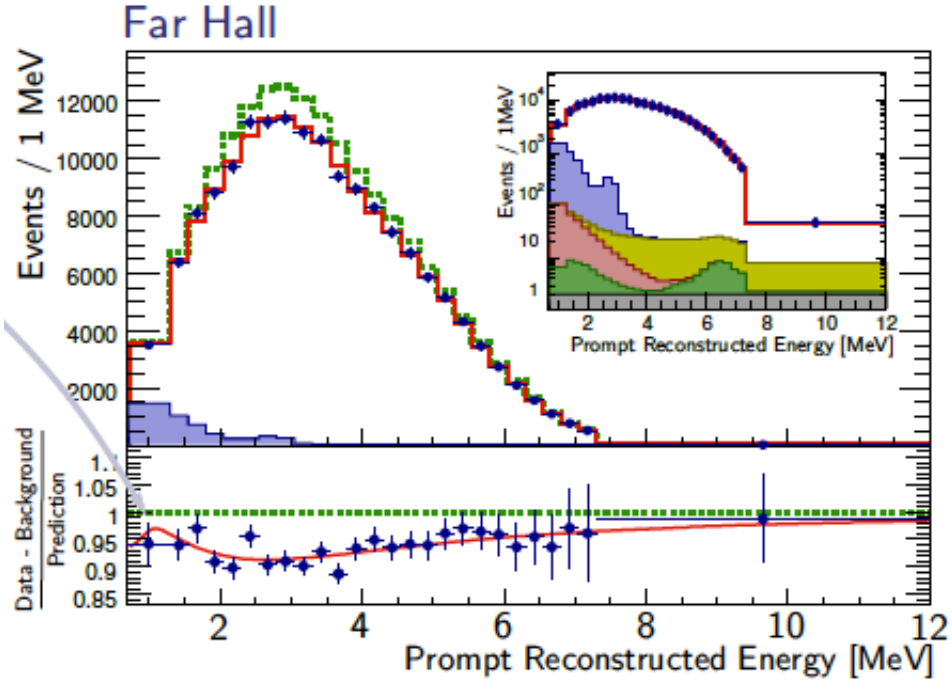


Sites	DYB	LA	Far
DYB cores	363 m	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

Daya Bay Experiment Measured the Last Mixing Angle θ_{13} (2012)



Daya Bay Antineutrino Detector



$\sin^2 2\theta_{13} = 0.090 + 0.008 - 0.009$

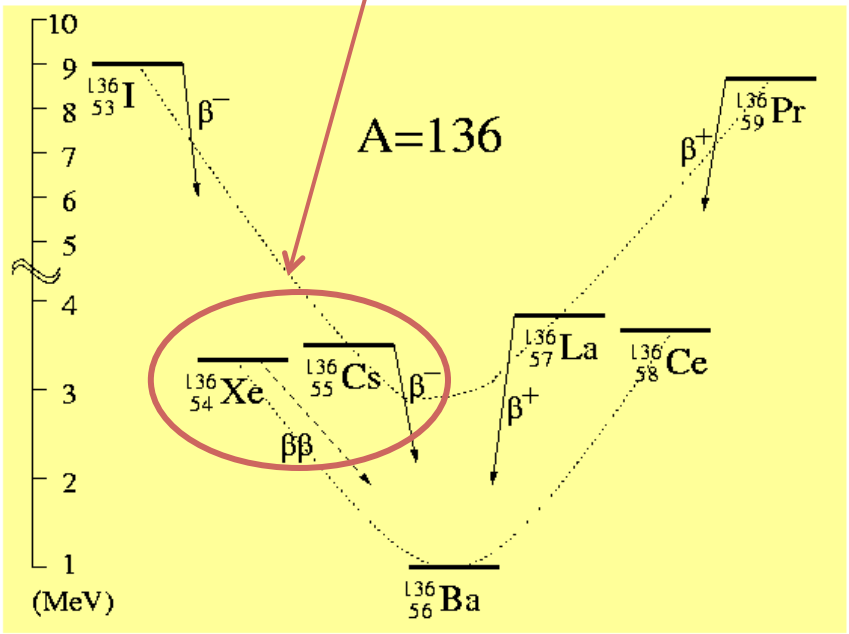
Most precise measurement of θ_{13} (Aug. 2013)

S. Jetter, NuFACT 2013

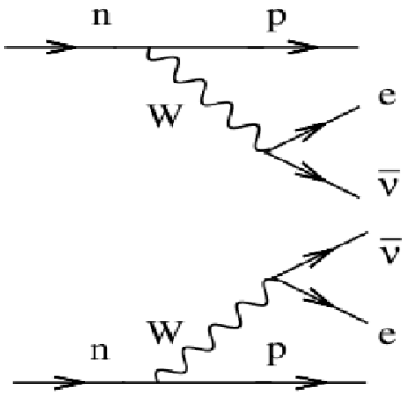
Next step: Improve measurement precision, search for sterile neutrino and Mass Hierarchy

Double Beta Decay

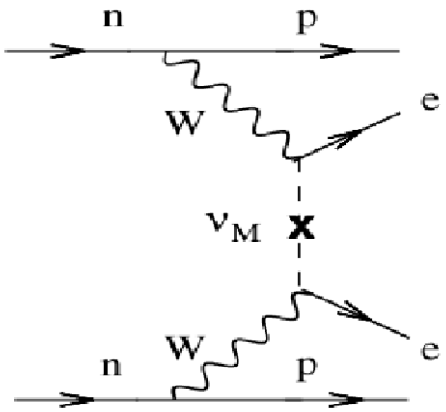
Observable if single beta decay is forbidden



Two neutrino double beta decay



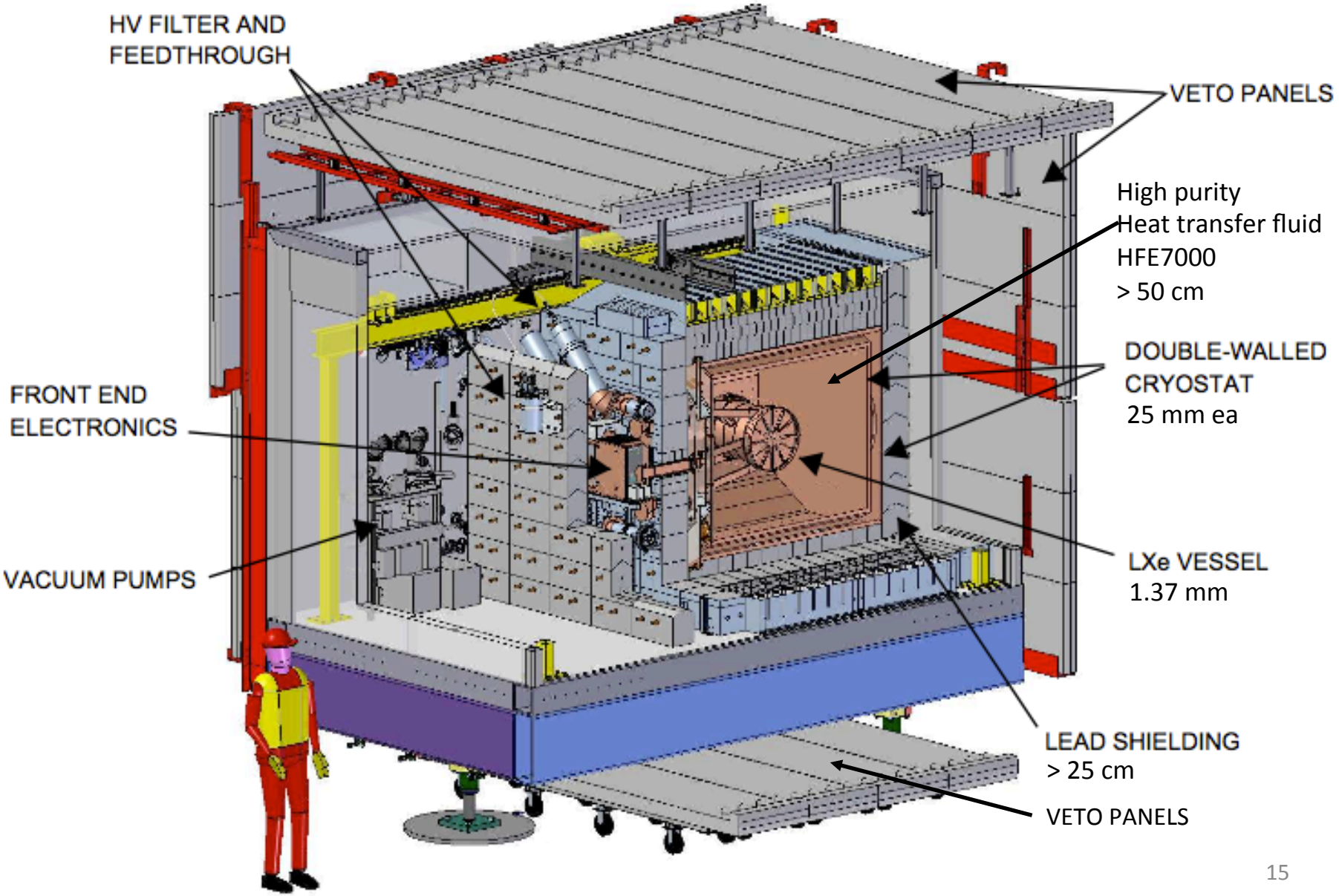
Neutrinoless double beta decay



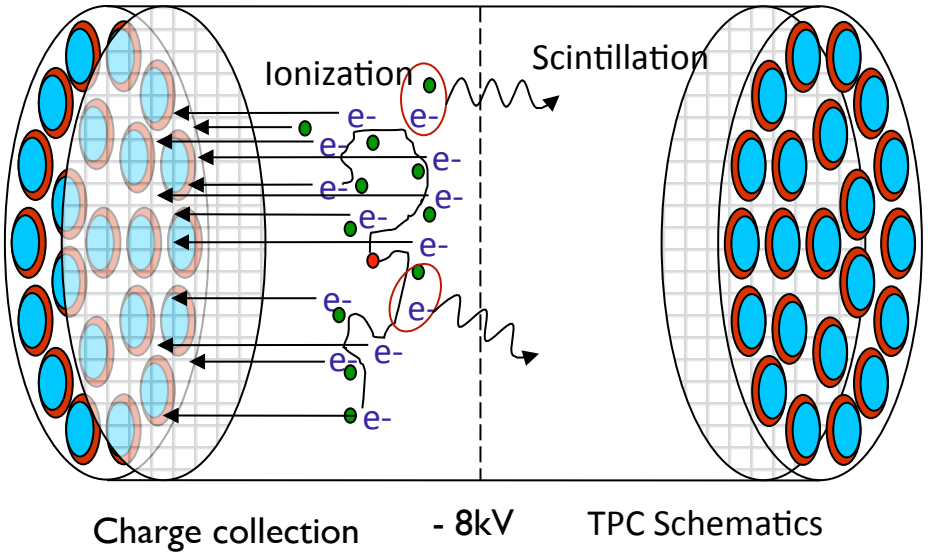
Observation of $0\nu\beta\beta$:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

The EXO-200 Detector

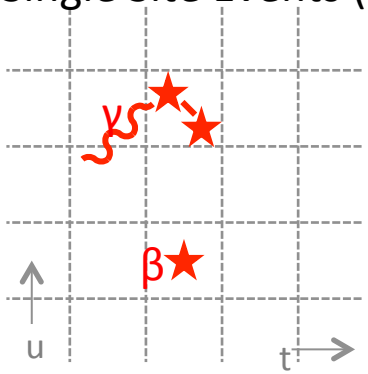


Liquid Xenon Time Projection Chamber

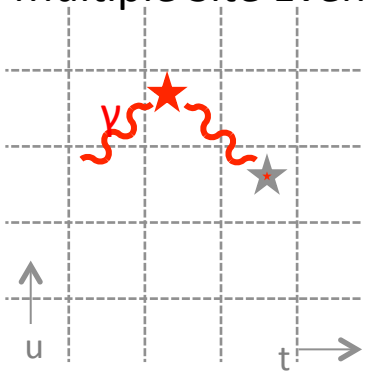


The EXO-200 time projection chamber uses both scintillation and ionization signals to fully reconstruct energy depositions inside liquid xenon

Single Site Events (SS)

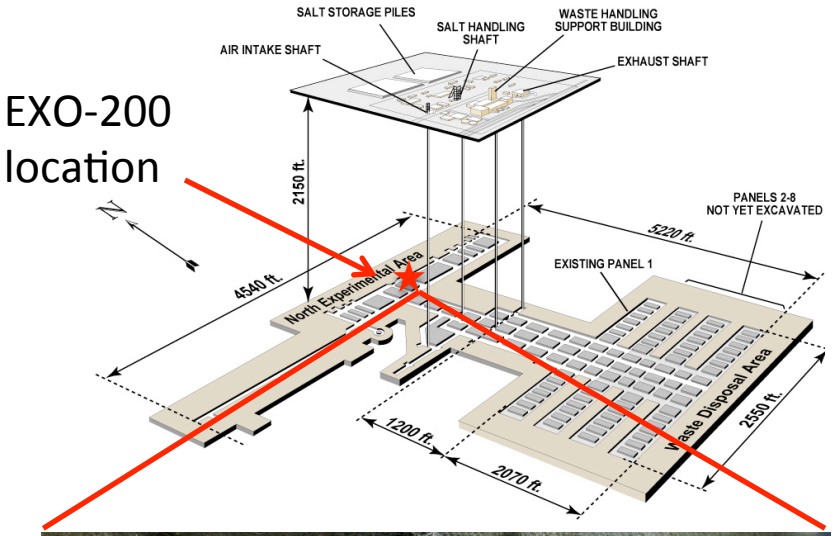


Multiple Site Events (MS)



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

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

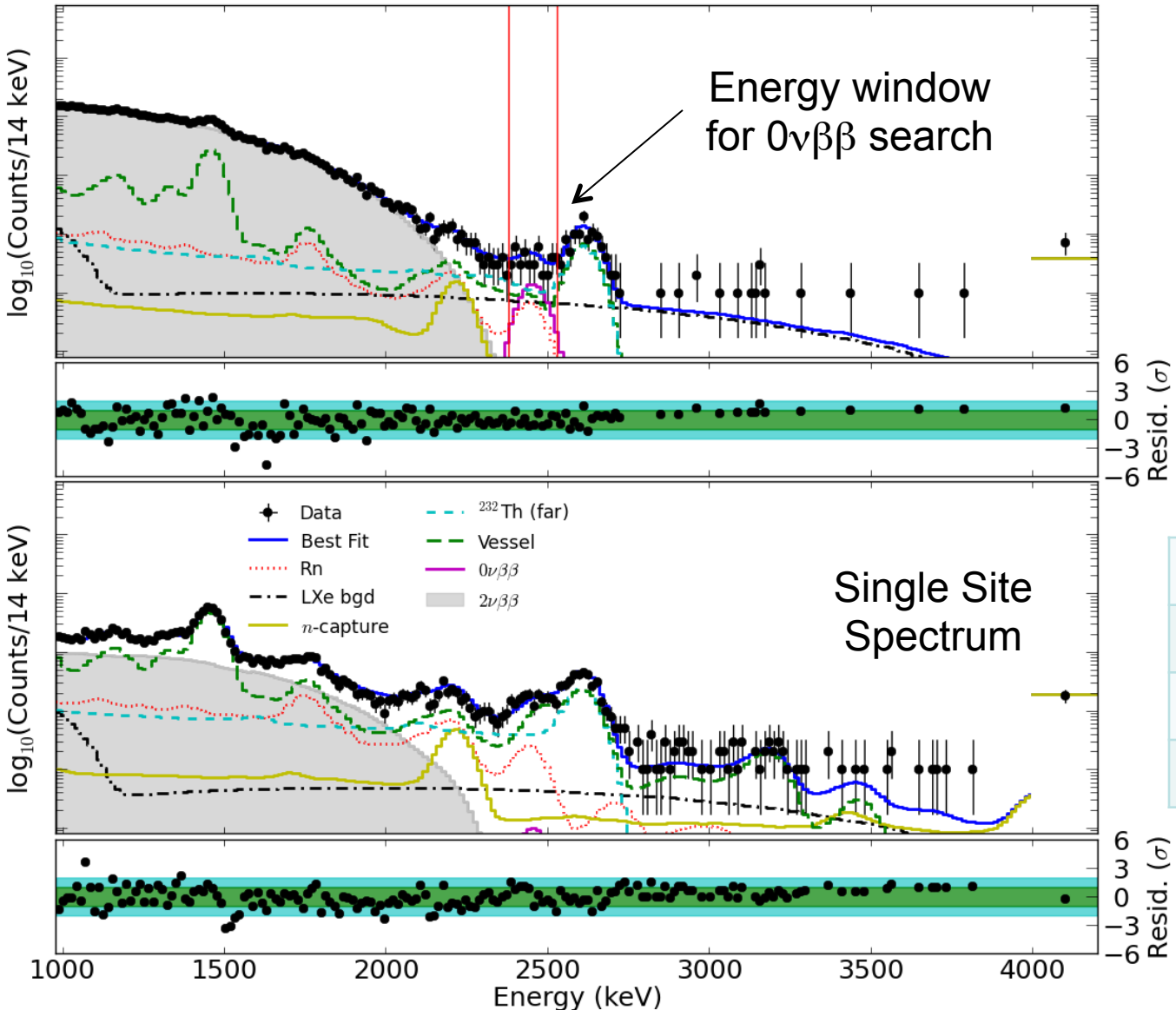
$$U \sim 0.048\, ppm$$

$$Th \sim 0.25\, ppm$$

$$K \sim 480\, ppm$$

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

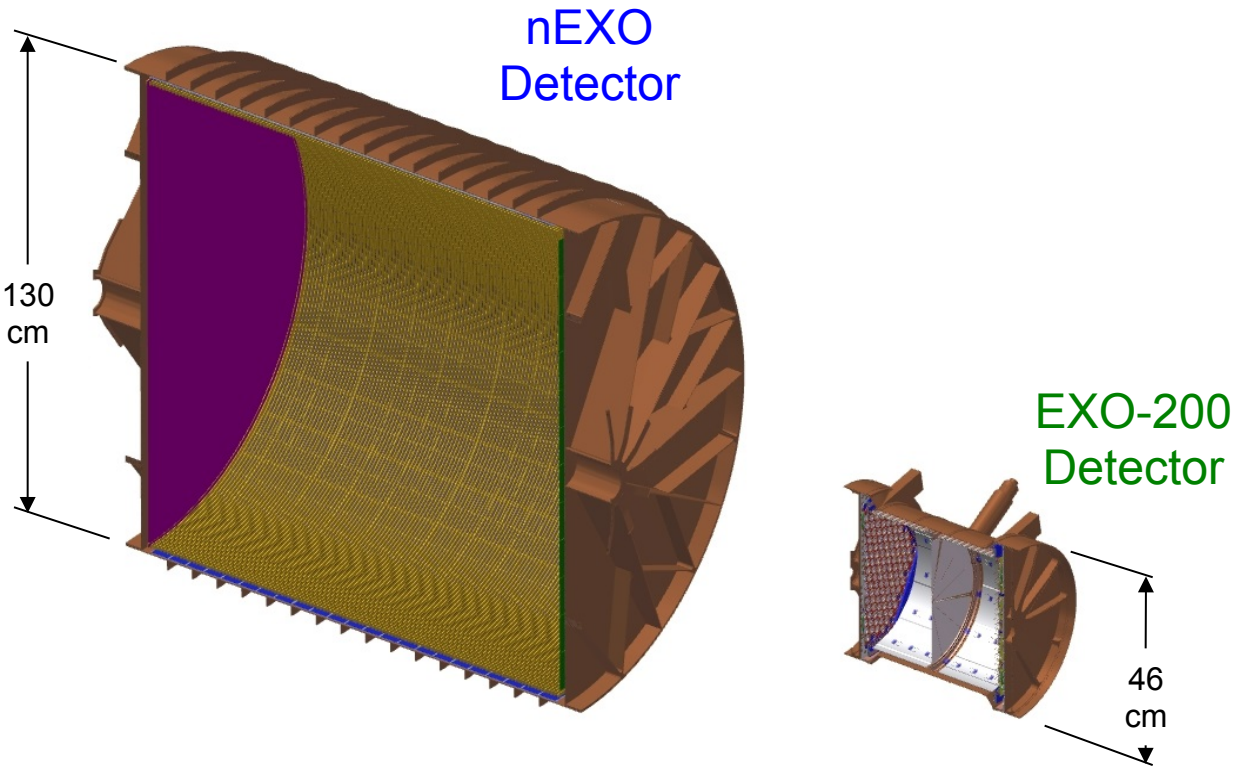
Background events from the fit

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

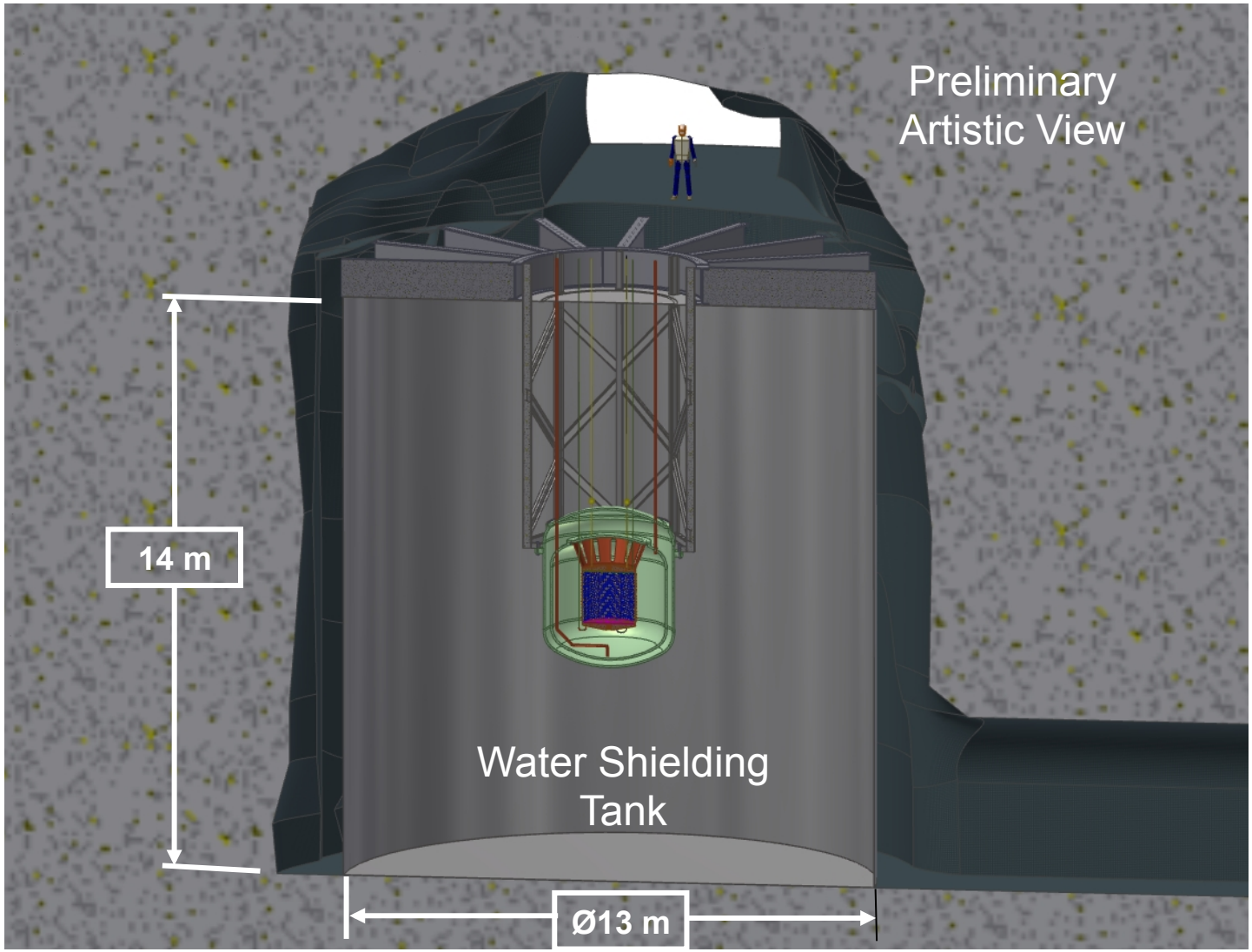
Background index: $(1.7\pm0.2)\cdot10^{-3}$ keV^{-1} kg^{-1} yr^{-1}

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

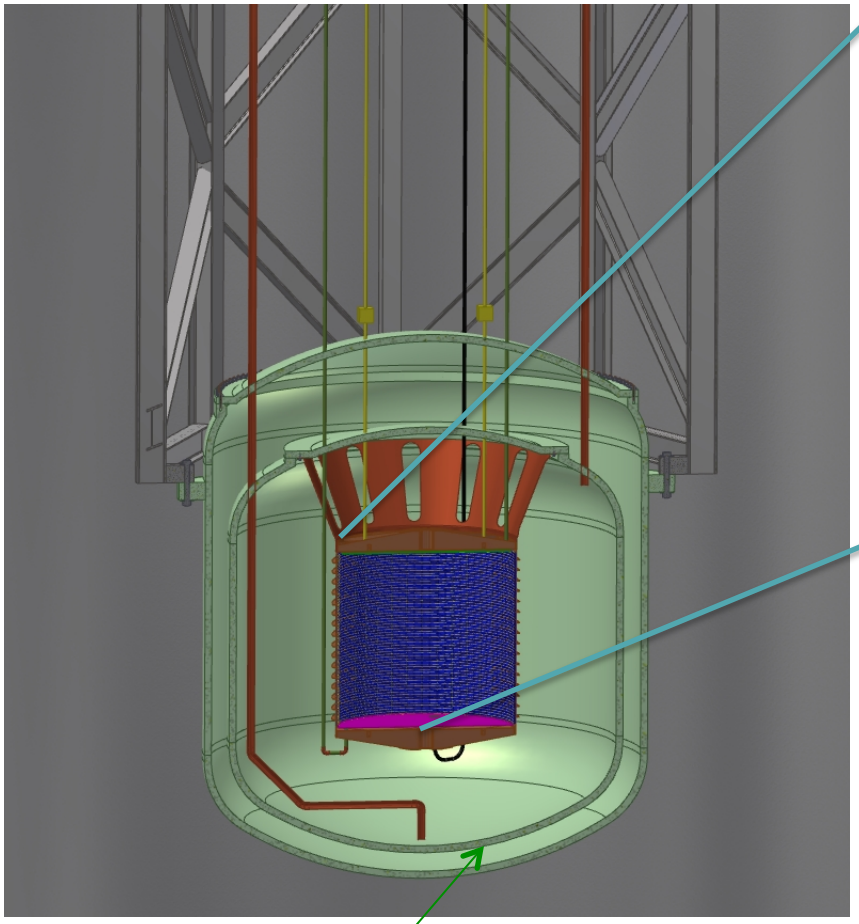


nEXO in the SNOlab Cryopit

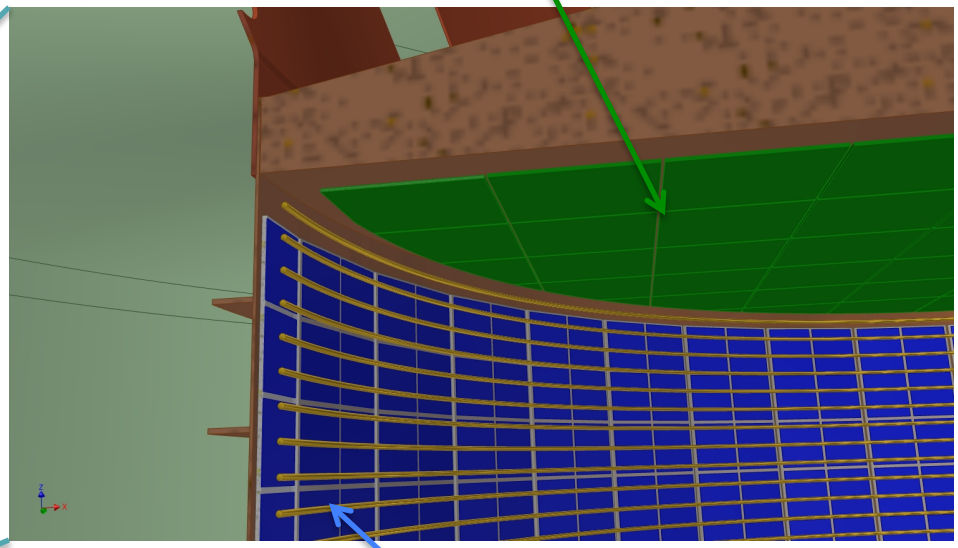


6,000 m.w.e. depth sufficient to shield cosmogenic background.

Preliminary Artistic View of nEXO TPC



Carbon Fiber Cryostat



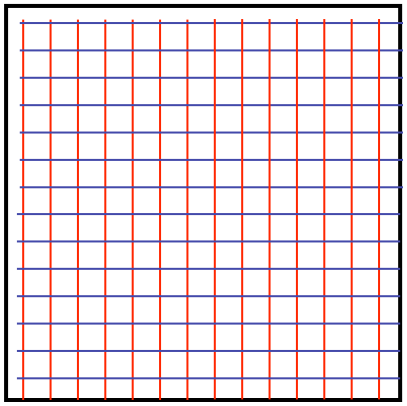
Charge Readout Tiles

Silicon Photomultipliers (SiPMs)

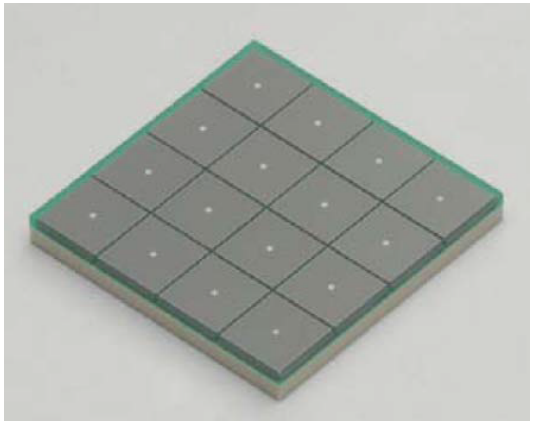
Baseline concept: (Improved TPC design).

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

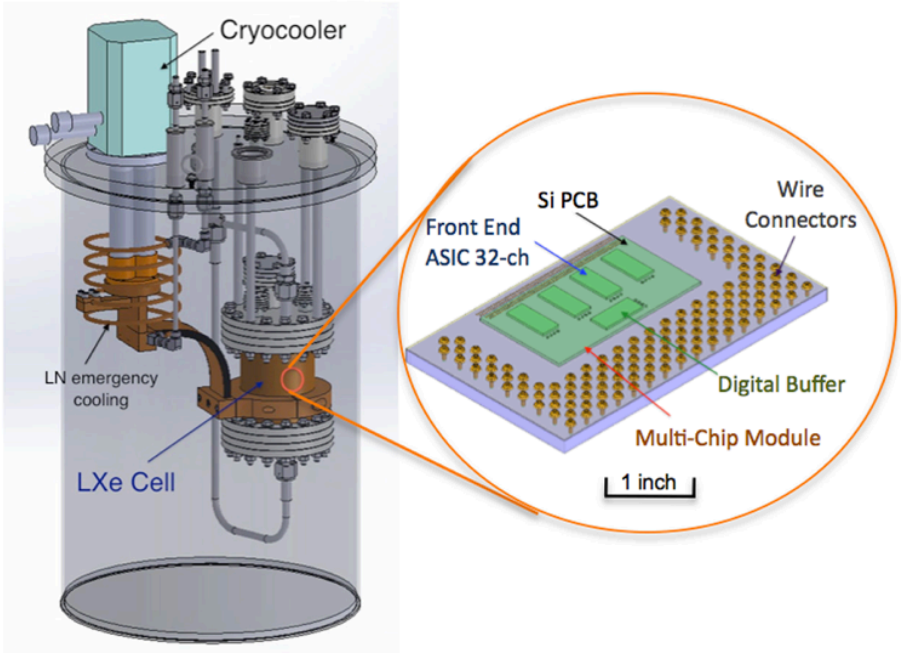
nEXO Front End Electronics



Charge readout tile concept



UV sensitive SiPM under development

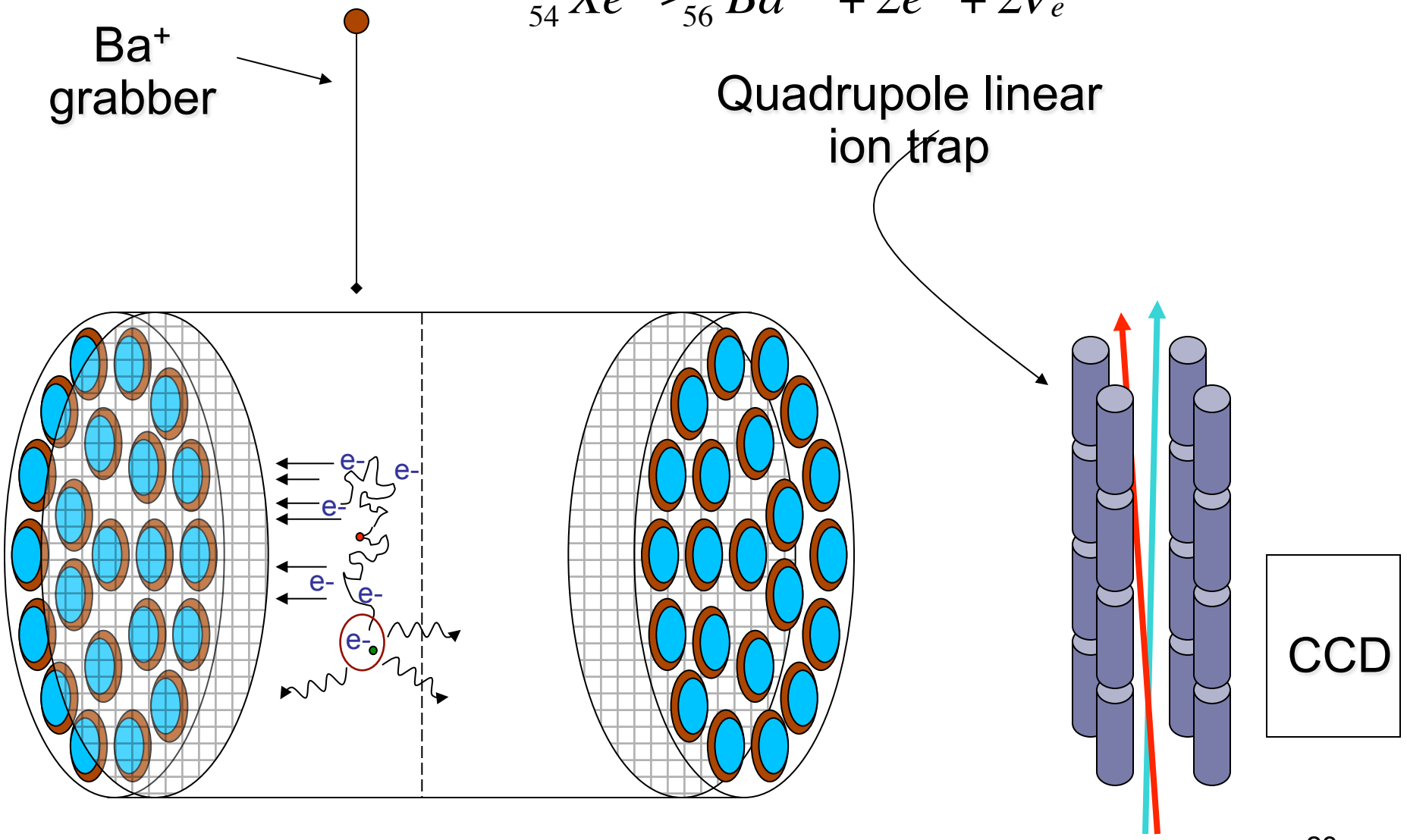


nEXO Cold Electronics Test Apparatus

- 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.

Extracting Ba^+ and Detecting in Ion Trap

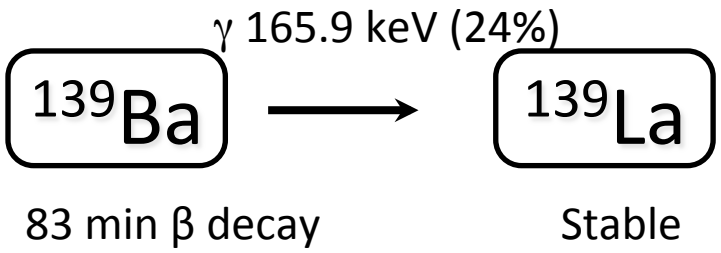
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^- + 2\bar{\nu}_e$$



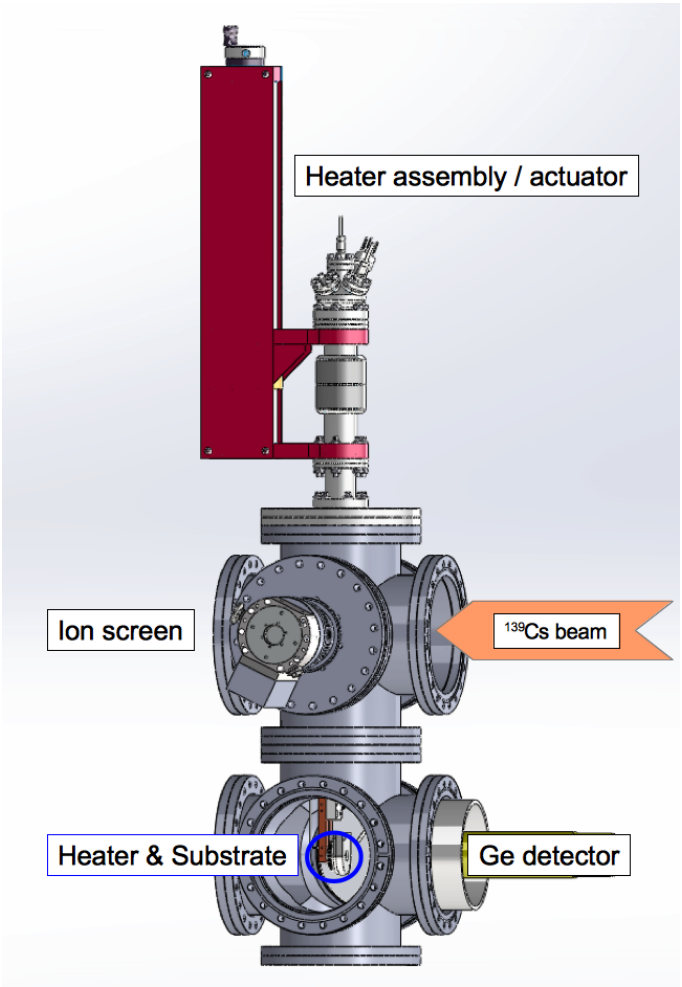
Study Barium Ion Transport

How to study the movement of a single Ba ion?

Using radioactive ion beam — CARIBU beam at Argonne Lab can provide a nice radioactive beam of ^{139}Ba



- Illinois group is building an apparatus to first study surface desorption of Ba ions
- Ionization and trap loading will be studied later
- Beamtime approved for 2015



Ba ion surface desorption test apparatus

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…