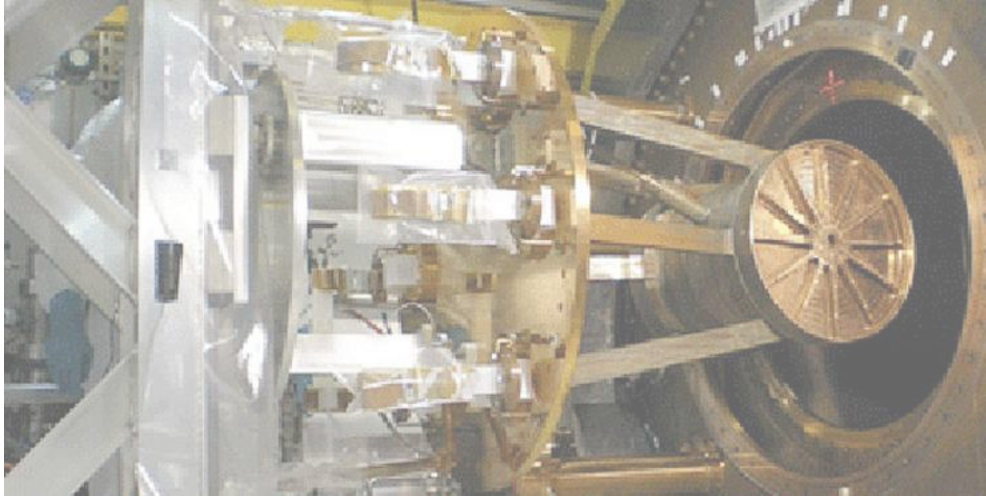
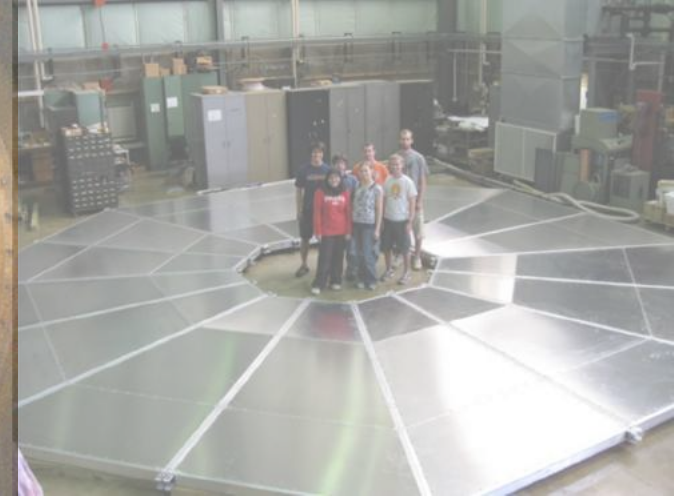




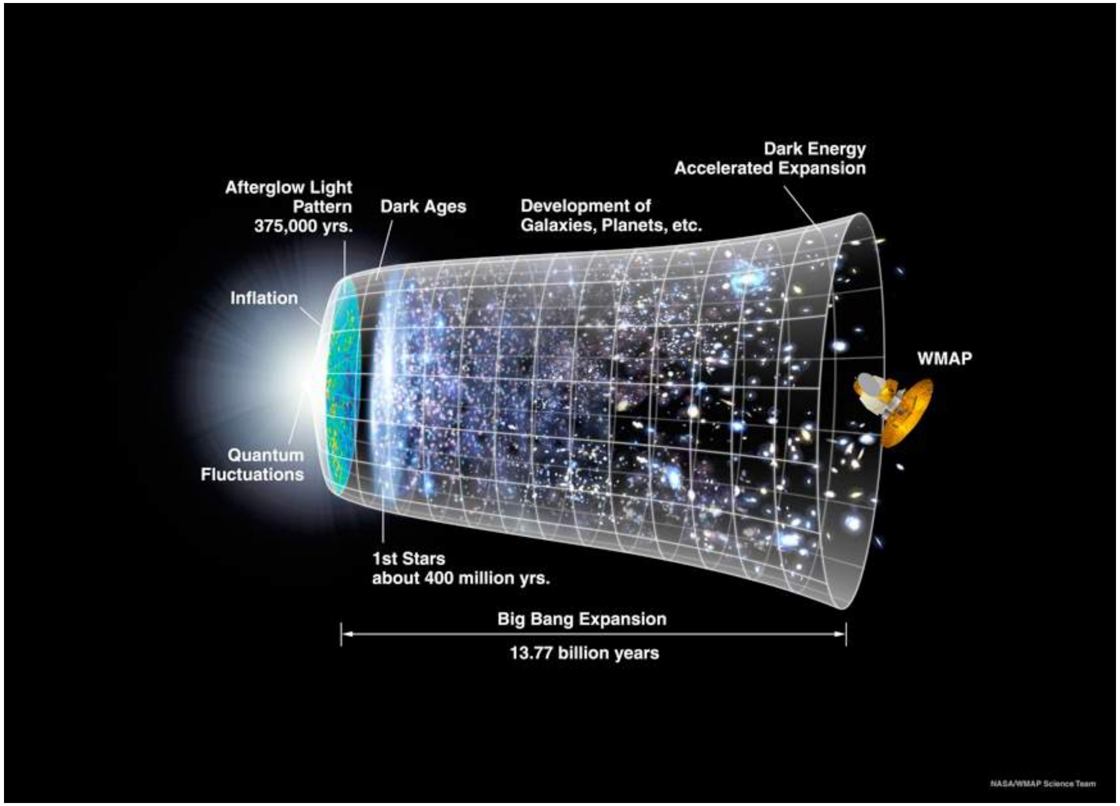
Fundamental Symmetry and Neutrino Physics

Liang Yang

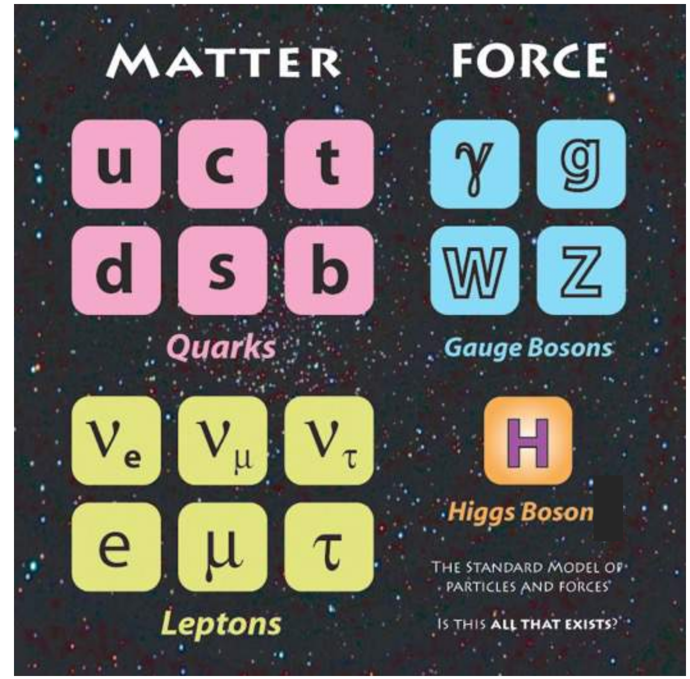
Physics 403

Nov. 16, 2021

Do we understand the Universe we live in?



Standard Cosmological Model

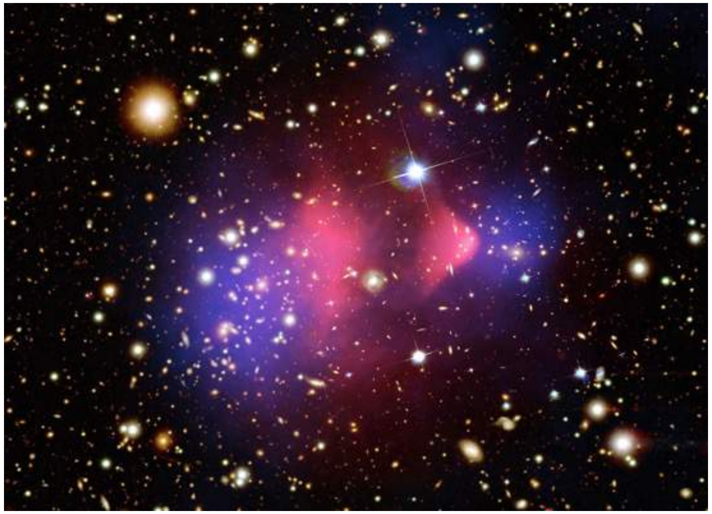


Standard Model of
Particle Physic

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

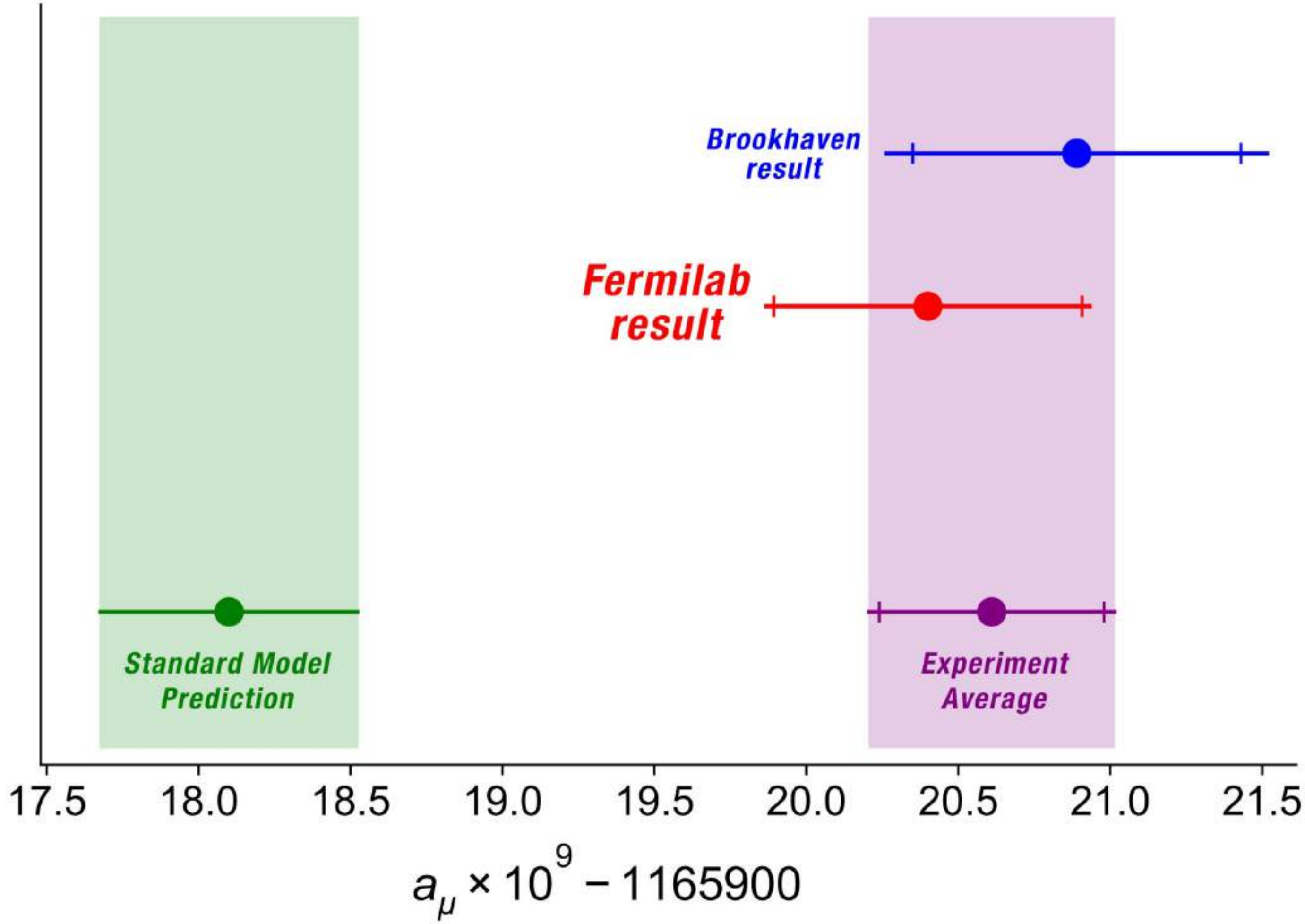
In Search of "New" Standard Model

- **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

Fermilab Muon g-2 result – new physics?

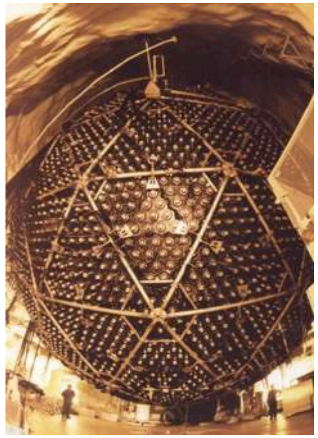


Theory: g-fac.: 2.00233183620(86) anomalous mag. moment: 0.00116591810(43)

Experiment: g-fac.: 2.00233184122(82), anomalous mag. moment: 0.00116592061(41)

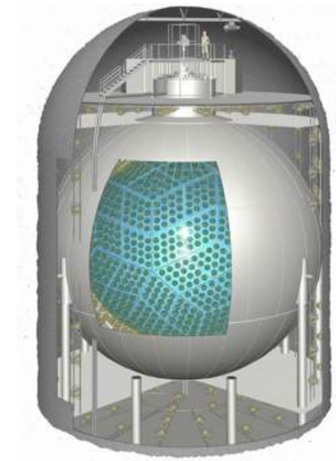
Neutrino Oscillation and Neutrino Mass

Super-K



SNO

K2K



KamLand

Super-K: atmospheric ν_μ neutrino oscillation

SNO: solar ν_e flavor transformation

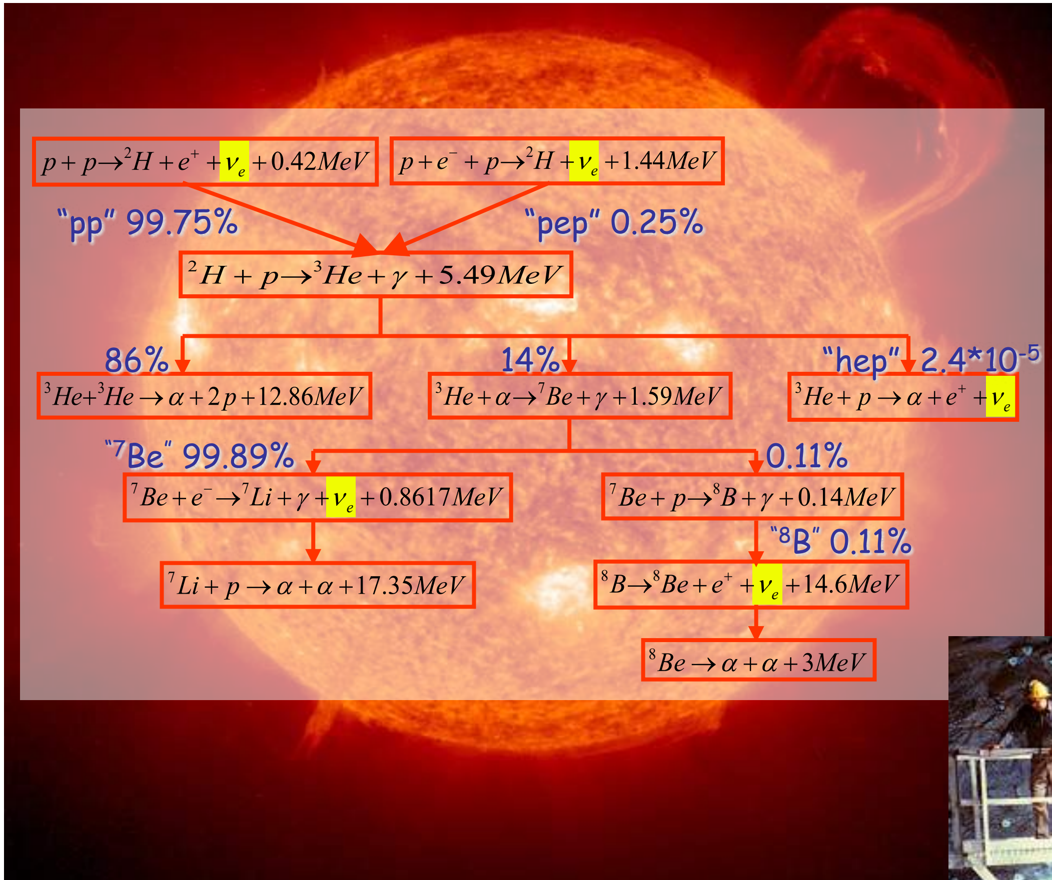
K2K: accelerator ν_μ oscillation

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 :

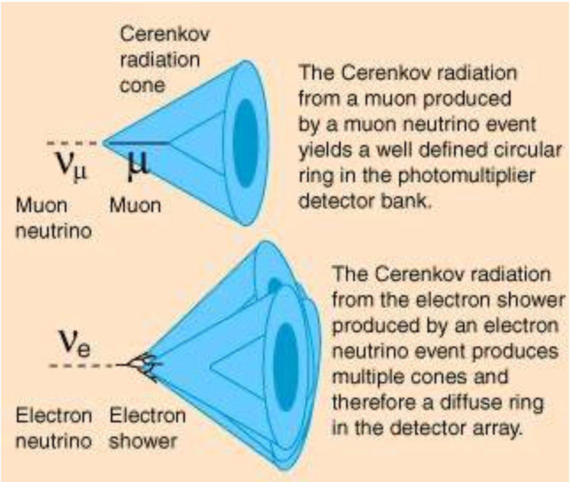
Produced at only 15 atoms per month !

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 !

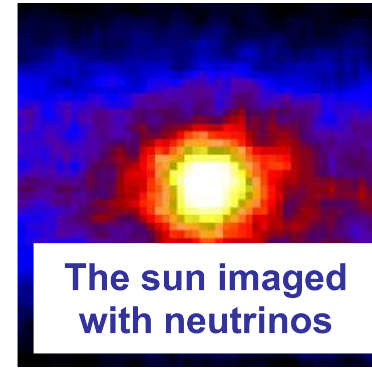
The plot thickens – some good fortune …

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



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.

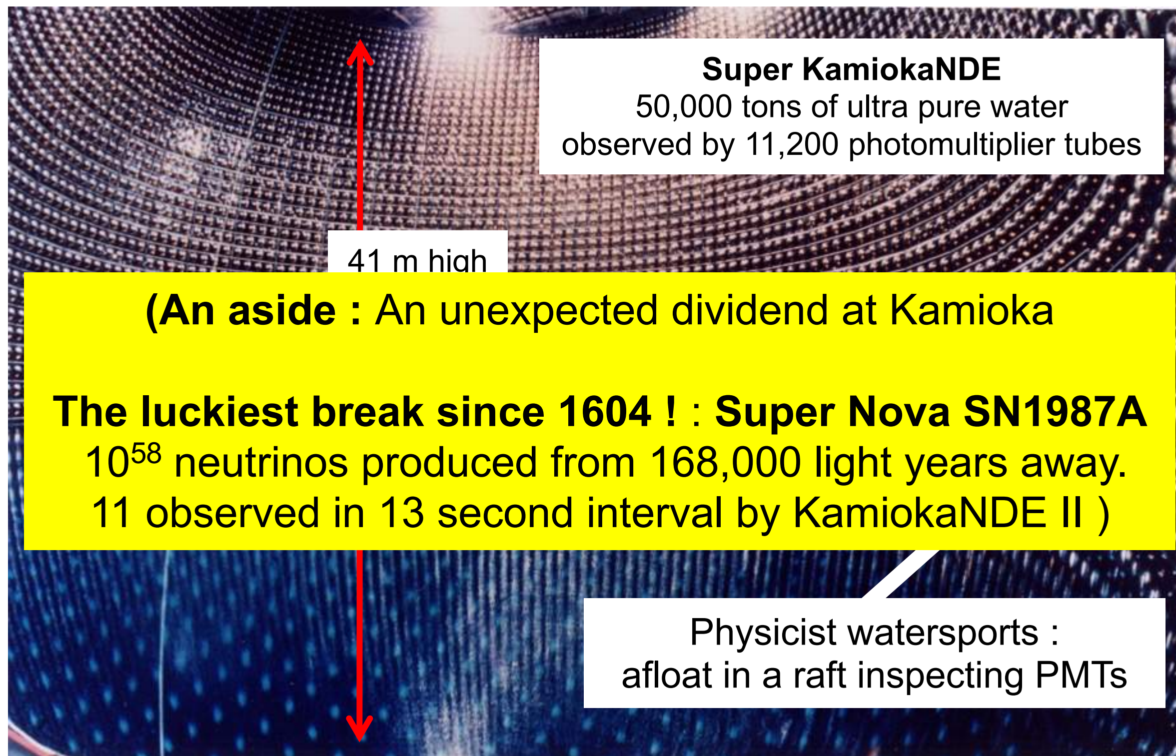
(led by M. Koshiba, also a 2002 Nobelist)


The sun imaged with neutrinos

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

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

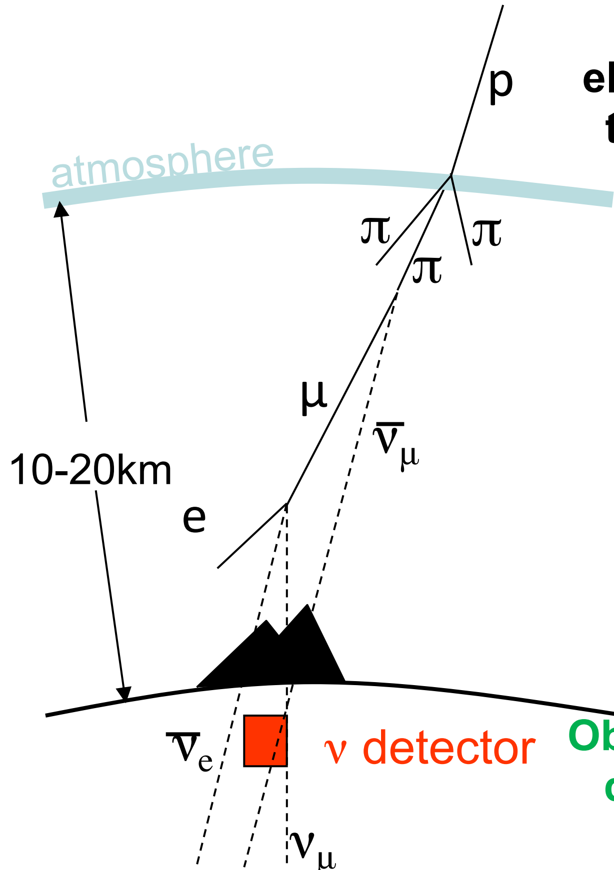


(An aside : An unexpected dividend at Kamioka

The luckiest break since 1604 ! : **Super Nova SN1987A**
10^{58} neutrinos produced from 168,000 light years away.
11 observed in 13 second interval by KamiokaNDE II)

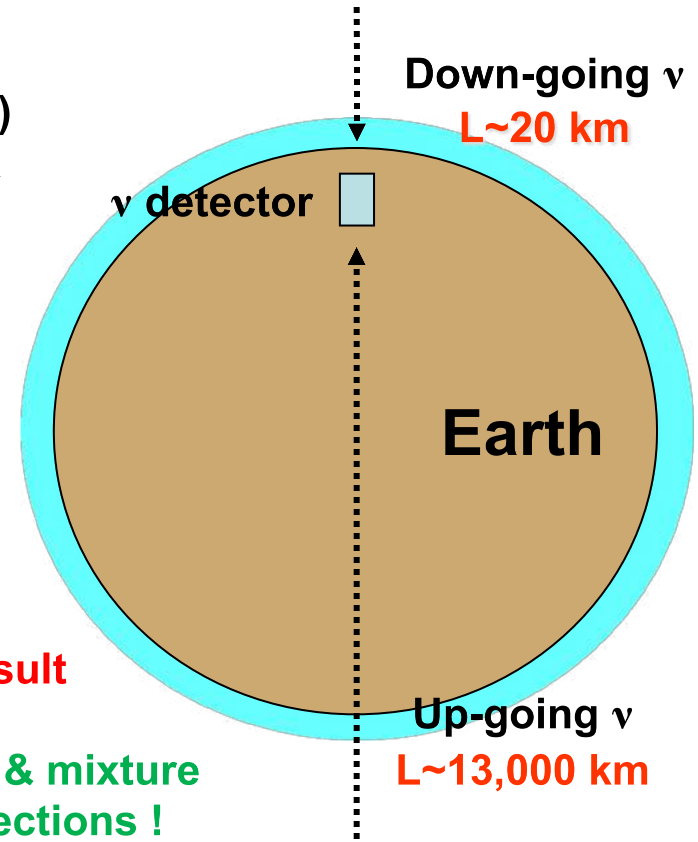
Atmospheric Neutrino

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.)



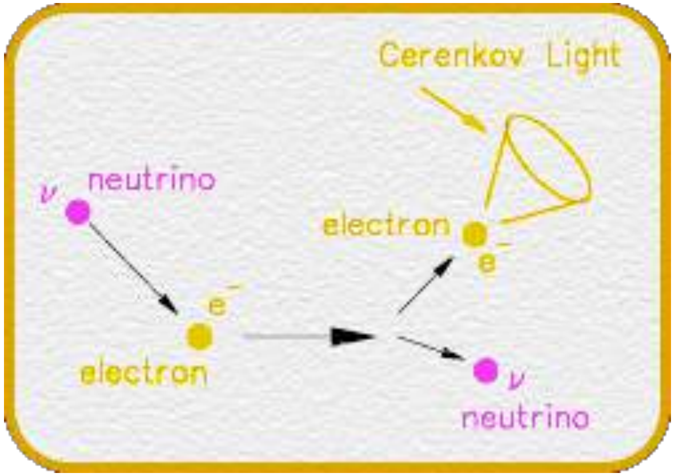
Stunning Result

Observed neutrino rates & mixture differed for the two directions !

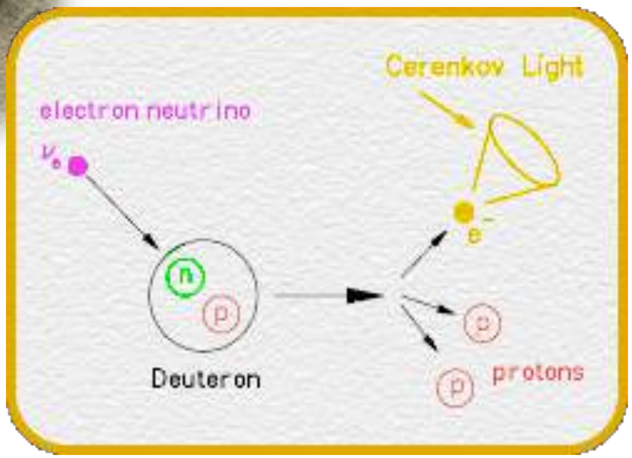
Were flavors changing in transit ?

SNO

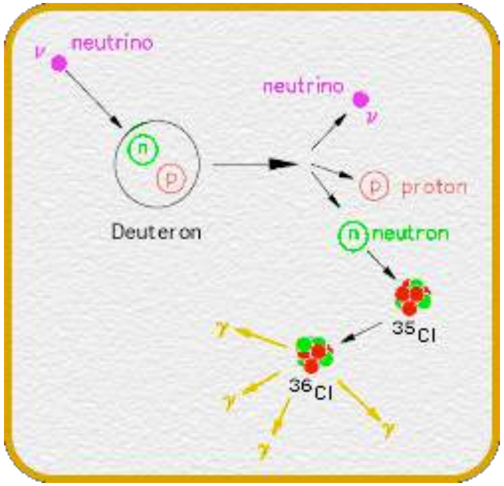
2002 Sudbury Neutrino Observatory



Electron Scattering



Charge Current

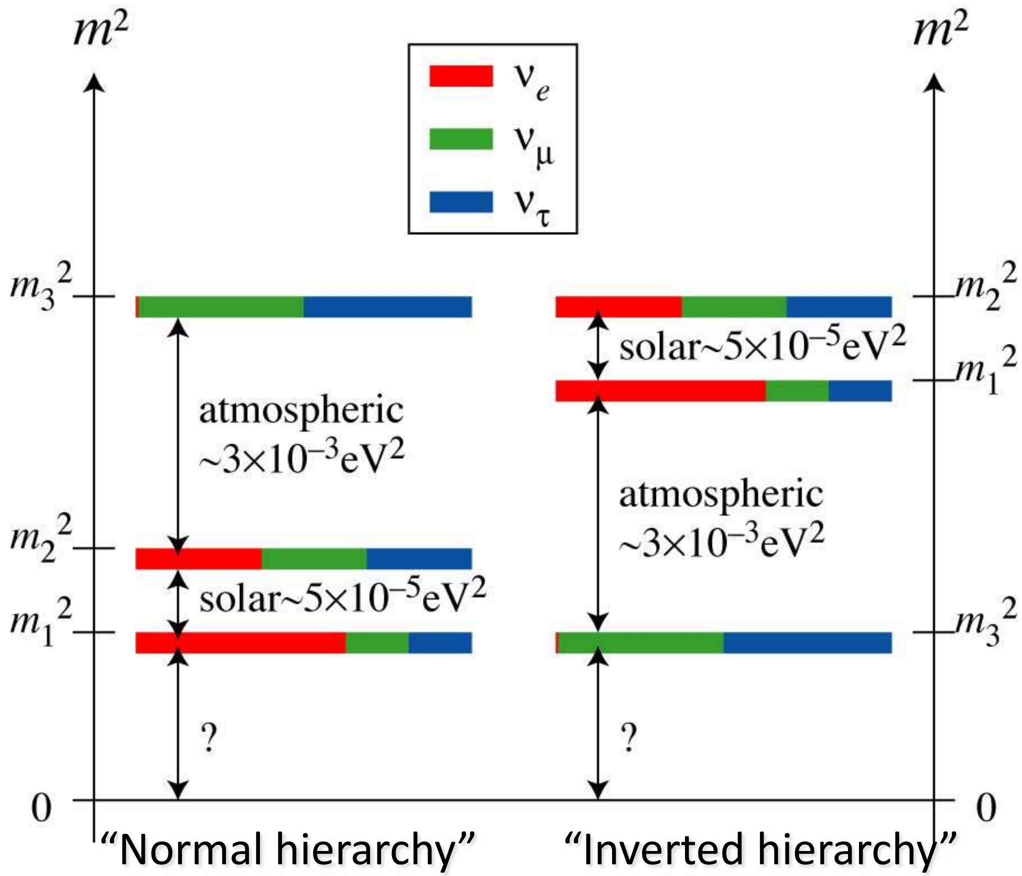


Neutral Current

Unknown Properties of Neutrinos

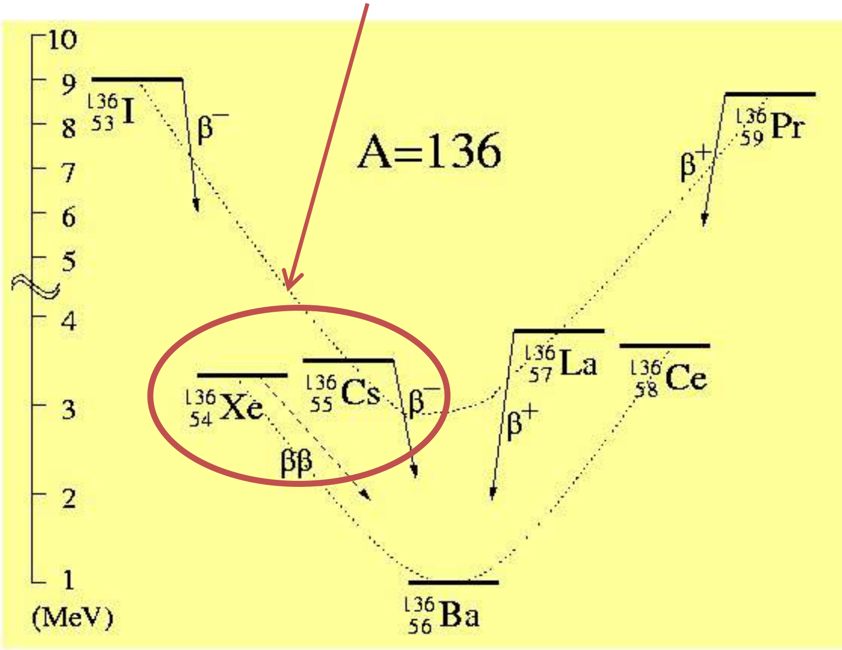
Major Questions in Neutrino Physics

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

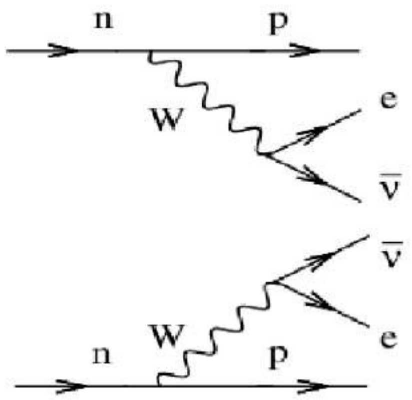


Double Beta Decay

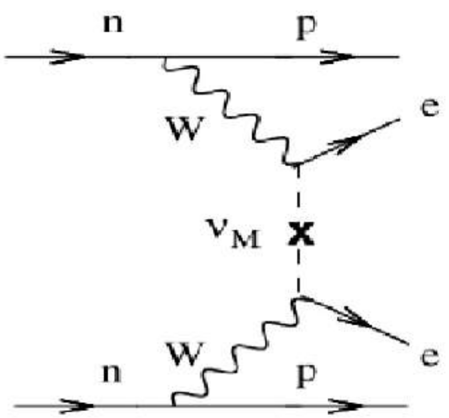
Observable if single beta decay is forbidden



Two neutrino double beta decay



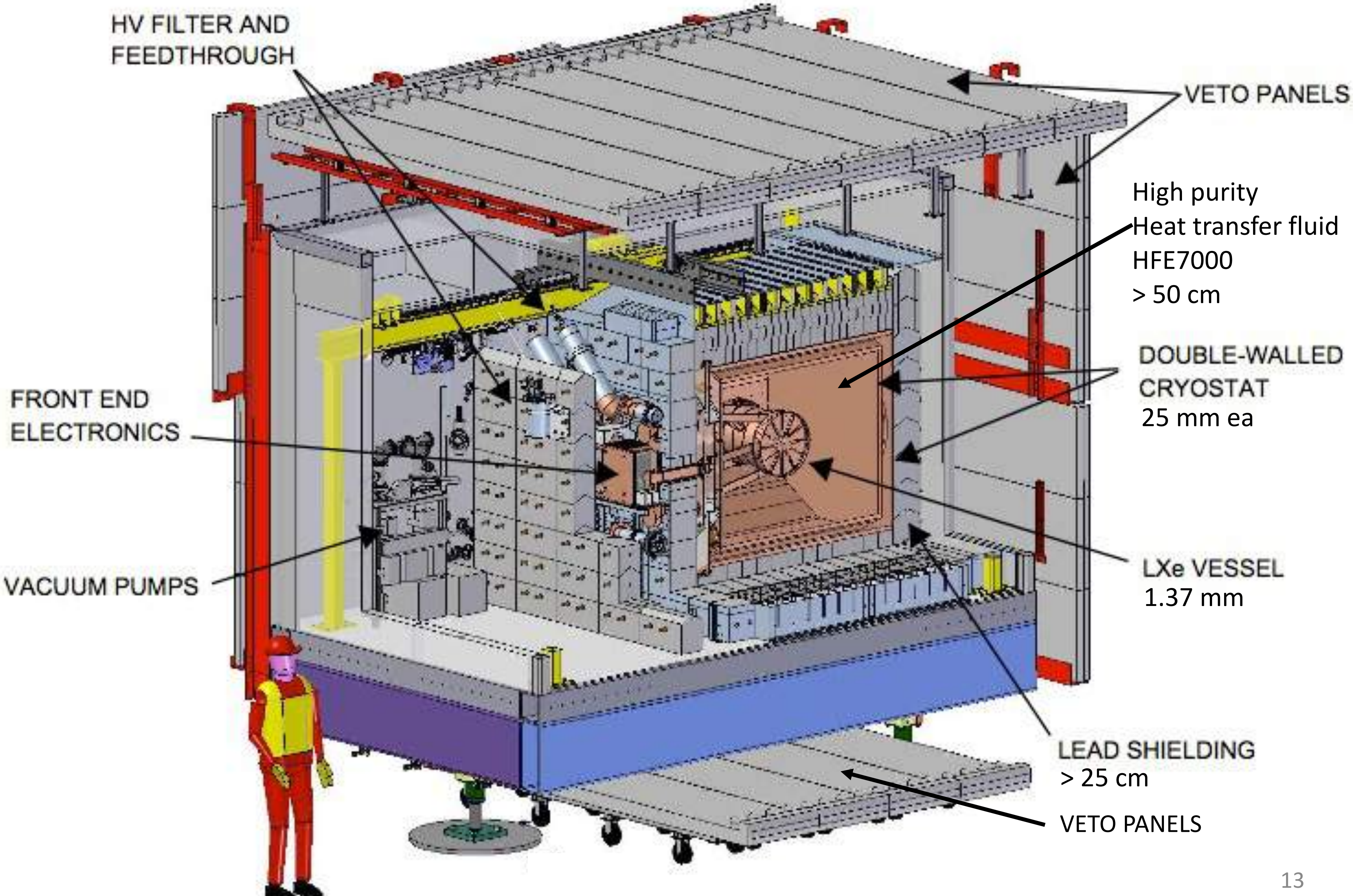
Neutrinoless double beta decay



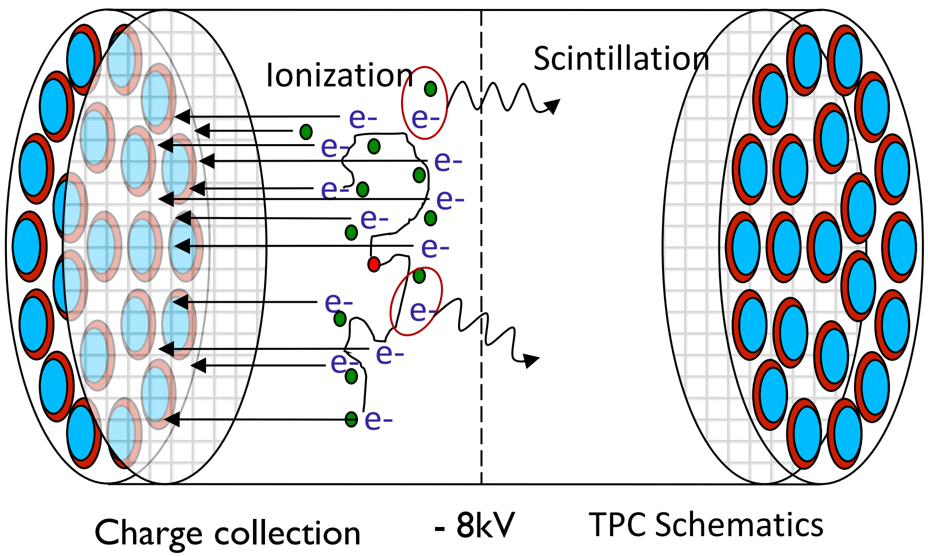
Observation of $0\nu\beta\beta$:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

The EXO-200 Detector

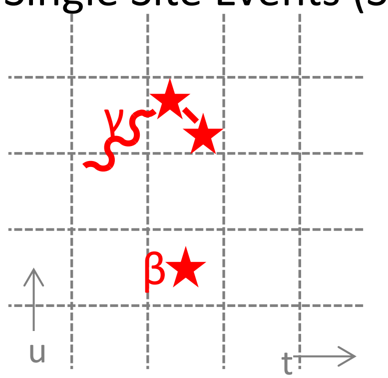


Liquid Xenon Time Projection Chamber

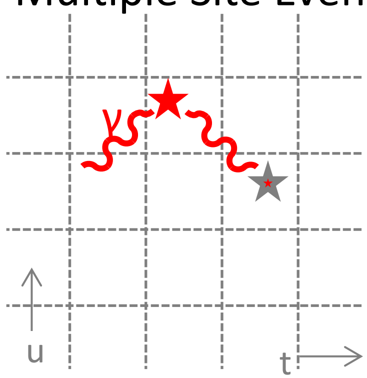


The EXO-200 time projection chamber uses both scintillation and ionization signals to fully reconstruct energy depositions inside liquid xenon

Single Site Events (SS)



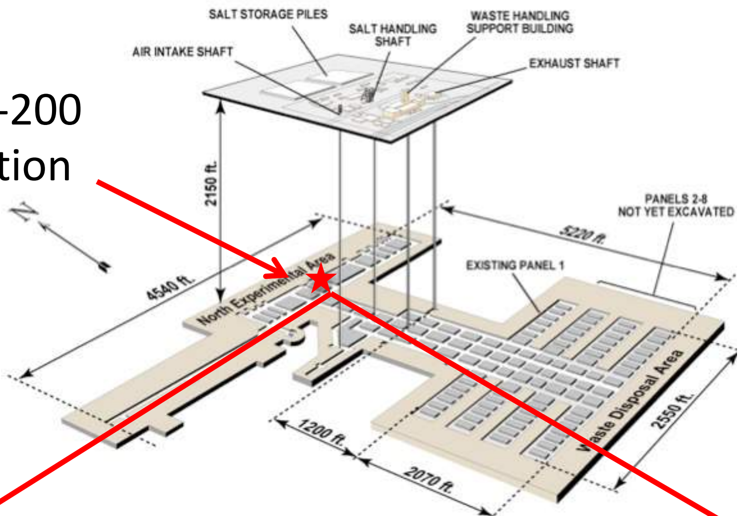
Multiple Site Events (MS)



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

EXO-200 installation site: WIPP

EXO-200 location



- 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

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

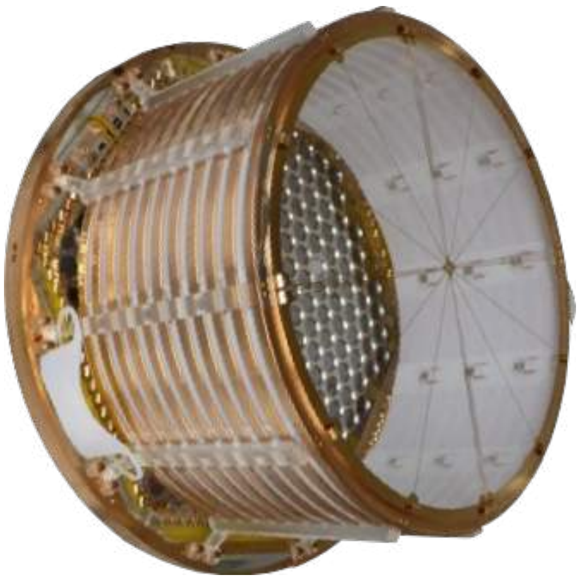
$$U \sim 0.048 \, ppm$$

$$Th \sim 0.25 \, ppm$$

$$K \sim 480 \, ppm$$

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

EXO-200 0νββ Results



EXO-200 TPC

- EXO-200 uses liquid xenon time projection chamber (TPC) to search for 0νββ of ^{136}Xe
- Successful operation from 2011 – 2018 with total ^{136}Xe isotope exposure of 234.1 kg·yr.
- Experimental sensitivities continue to exceed statistics due to improvements in hardware and analysis.
- Setting one of the strongest limits on this rare decay.

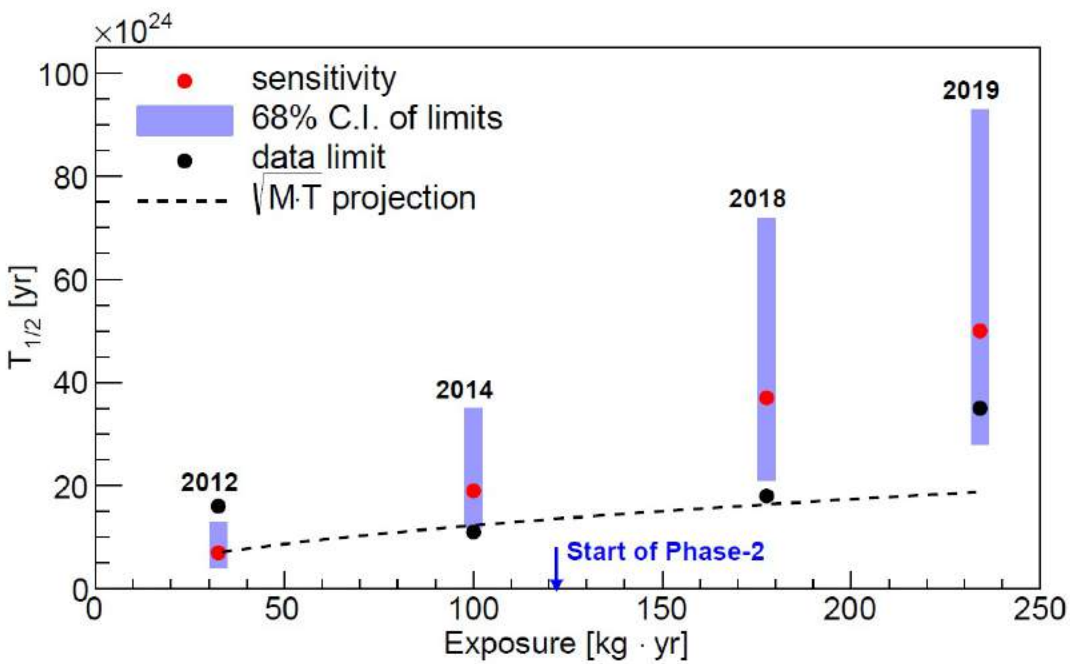
Combined Phase I + II:

Limit $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)

$\langle m_{\beta\beta} \rangle < (93 – 286)$ meV

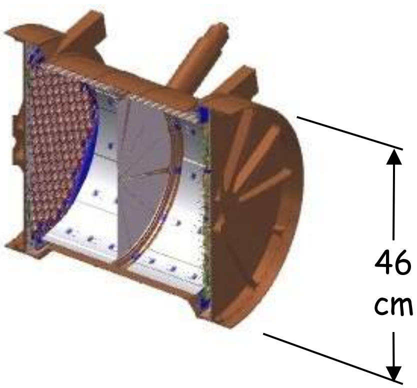
Sensitivity 5.0×10^{25} yr

2012: Phys. Rev. Lett. 109, 032505
2014: Nature 510, 229-234
2018: Phys. Rev. Lett. 120, 072701
2019: Phys. Rev. Lett. 123, 161802

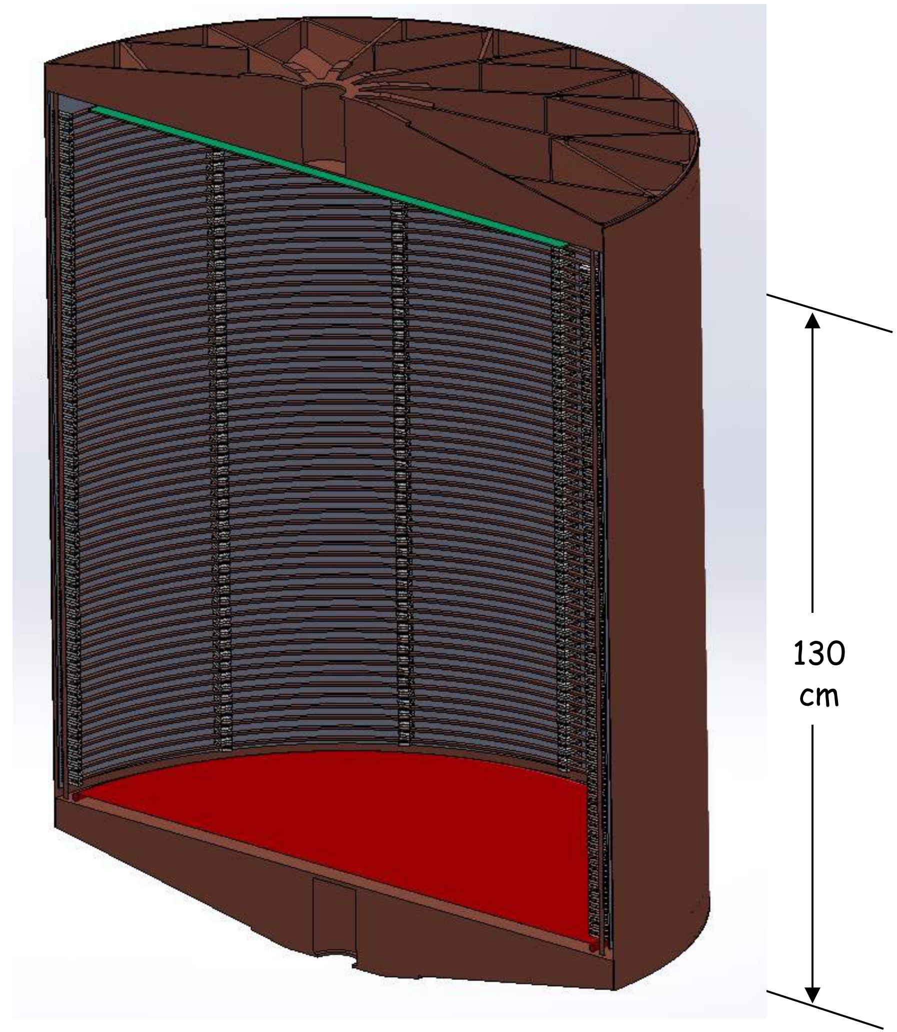


From EXO-200 to nEXO

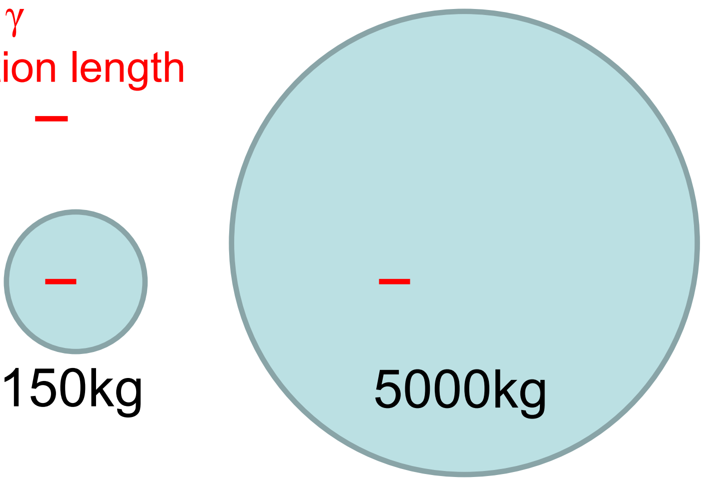
EXO-200 as a technology demonstrator



nEXO: a 5000 kg enriched LXe TPC



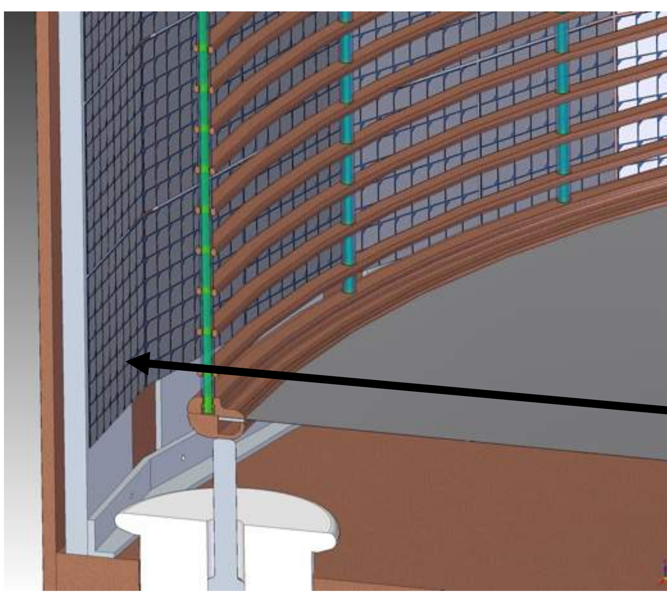
2.5MeV γ
attenuation length
8.5cm = –

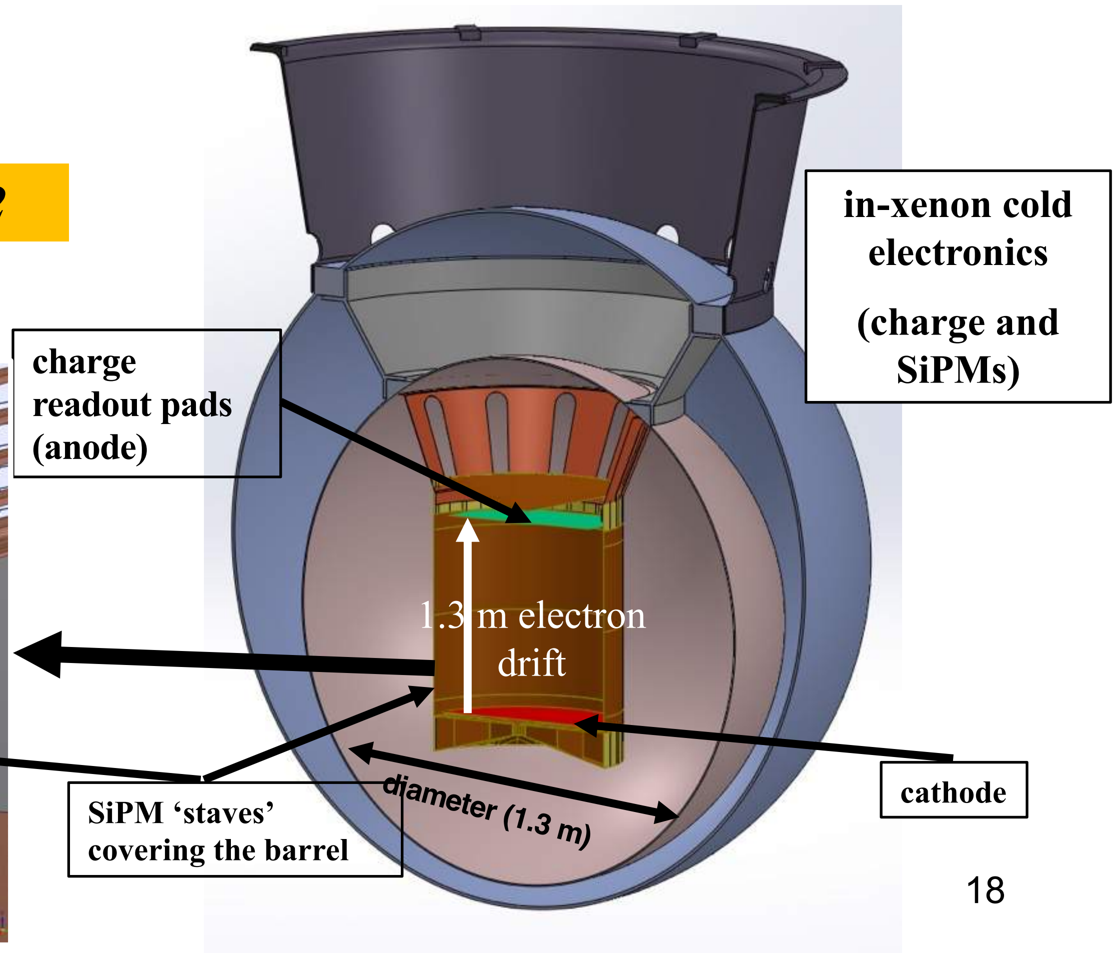


Pre-Conceptual Design of nEXO

- 5 tones of single phase LXe TPC.
- Ionization charge collected by anode.
- 178nm lights detected by ~4 m^2 SiPM array behind field shaping rings.
- Combining light and charge to enhance the energy resolution.

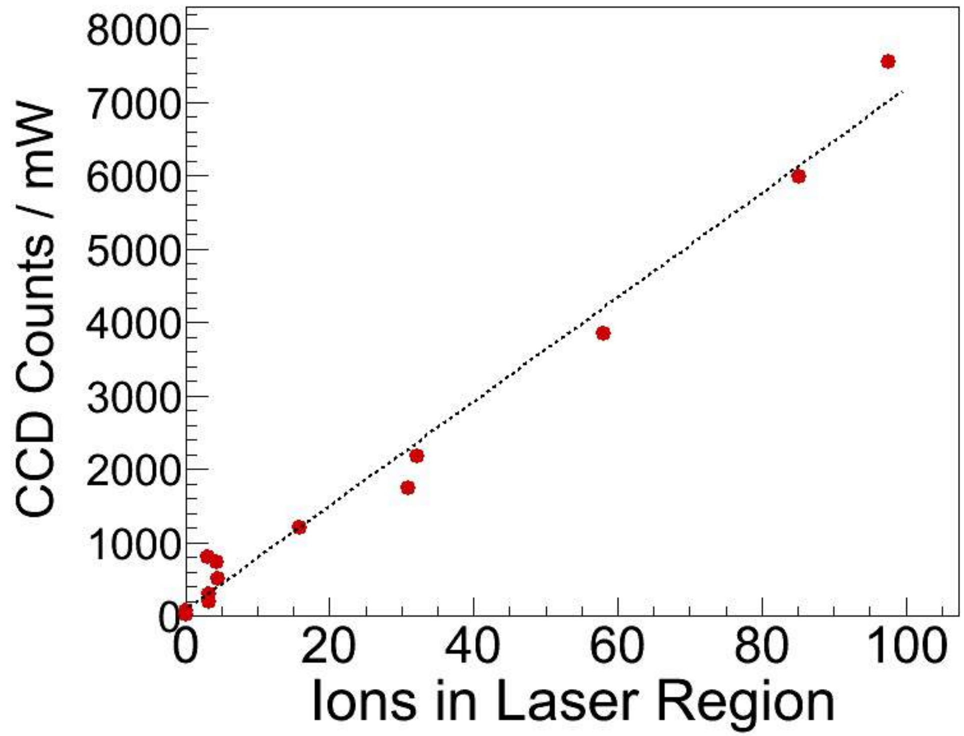
nEXO pre-CDR, arXiv:1805.11142



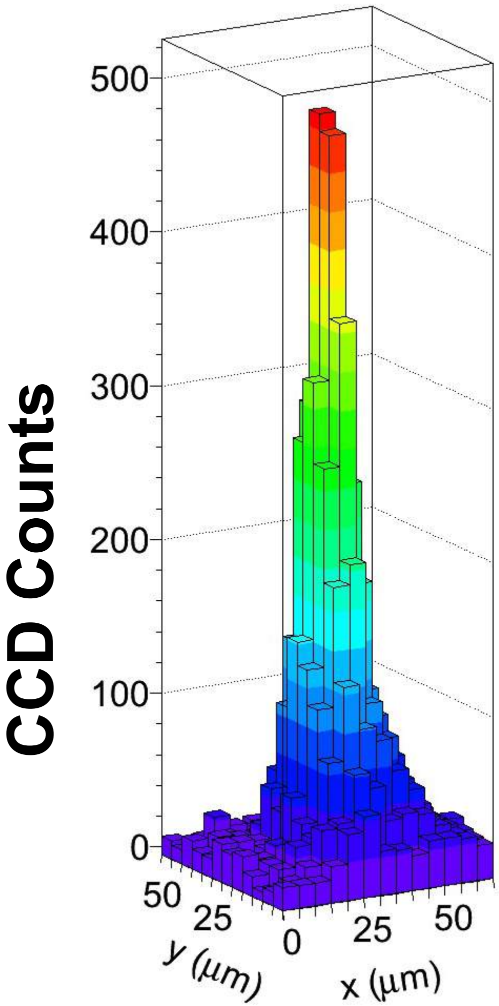


Tagging ββ decay daughter Ba

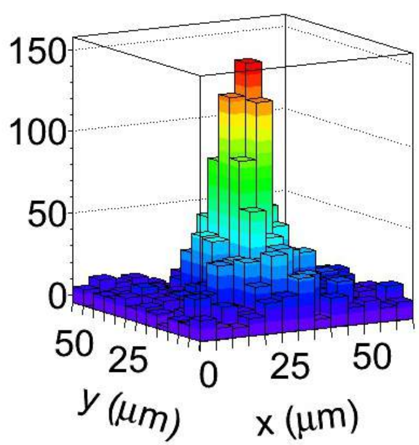
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$



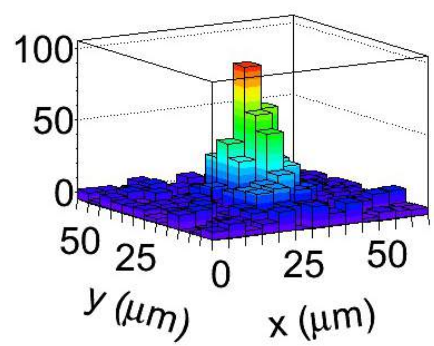
≤ 58-atom



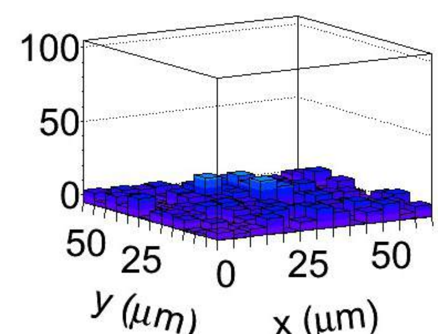
≤ 15-atom



≤ 4-atom

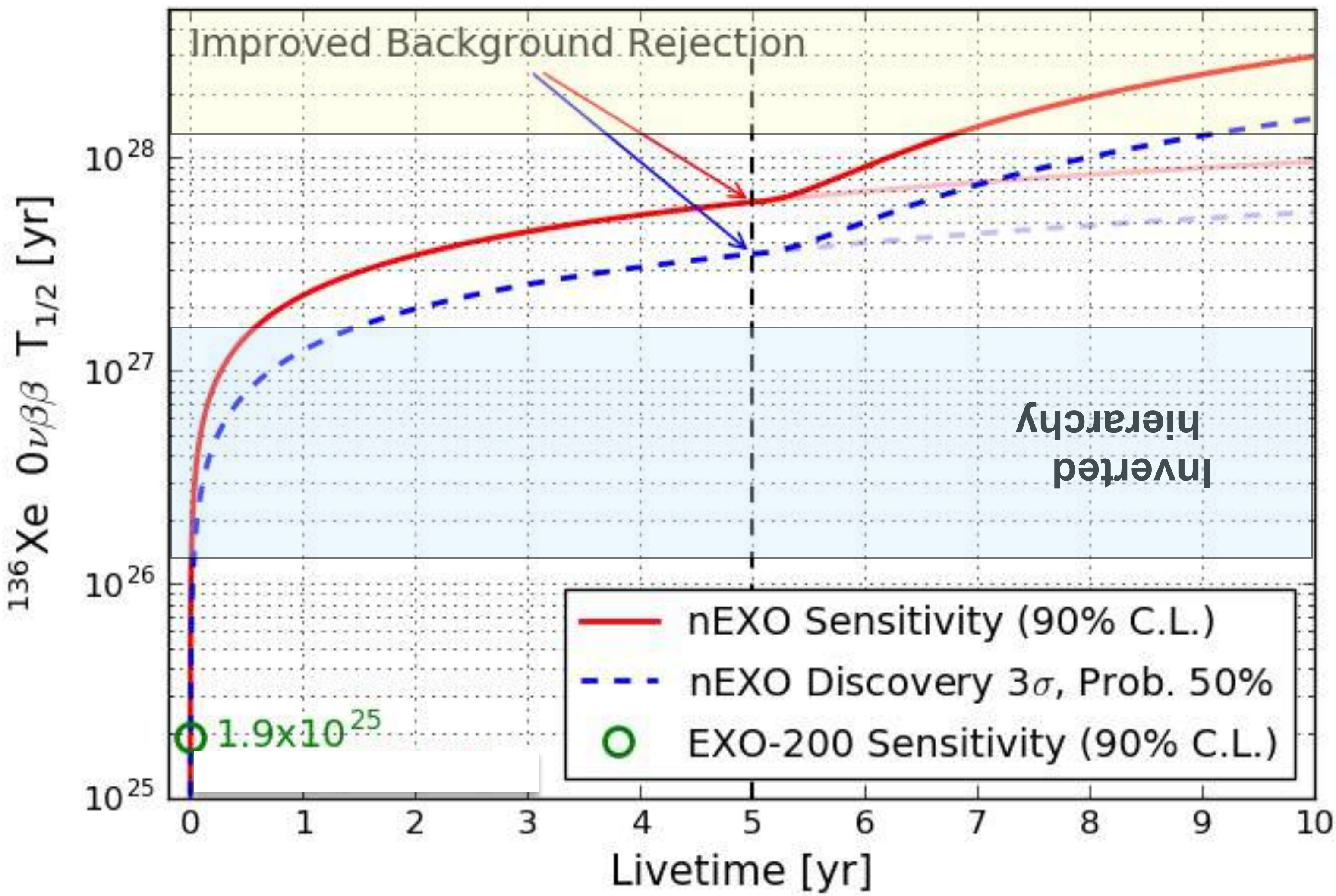


0-atom



C. Chambers et al., Nature, **569**, 203–207 (2019)

nEXO Sensitivity (with Ba tagging)



Normal hierarchy

GCM: Rodriguez, Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503

[nEXO Sensitivity Paper: arXiv:1710.05075](https://arxiv.org/abs/1710.05075)

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…