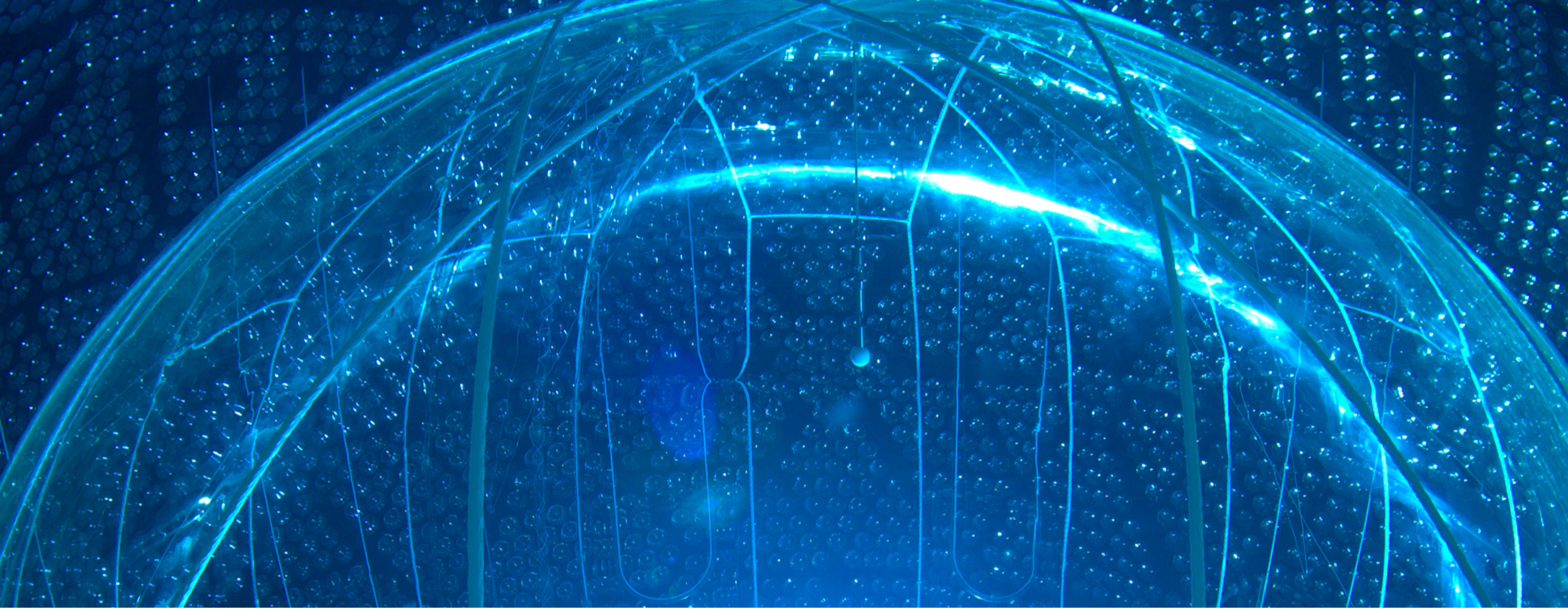


Neutrinos, no-neutrinos and antineutrinos

Nuno Barros (LIP)

V mini-school on Particle and Astroparticle Physics

Neutrinos, a desperate hypothesis to solve beta decay

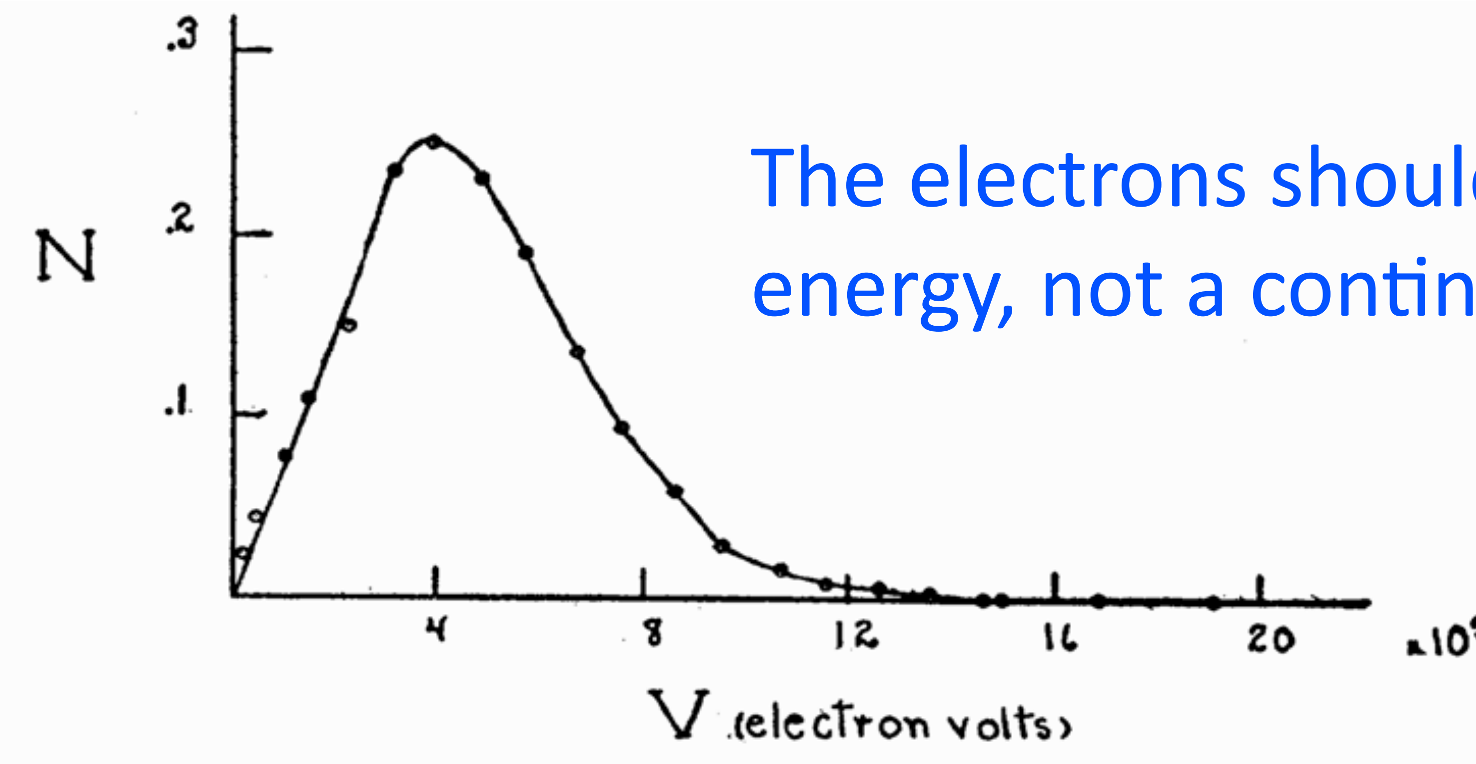
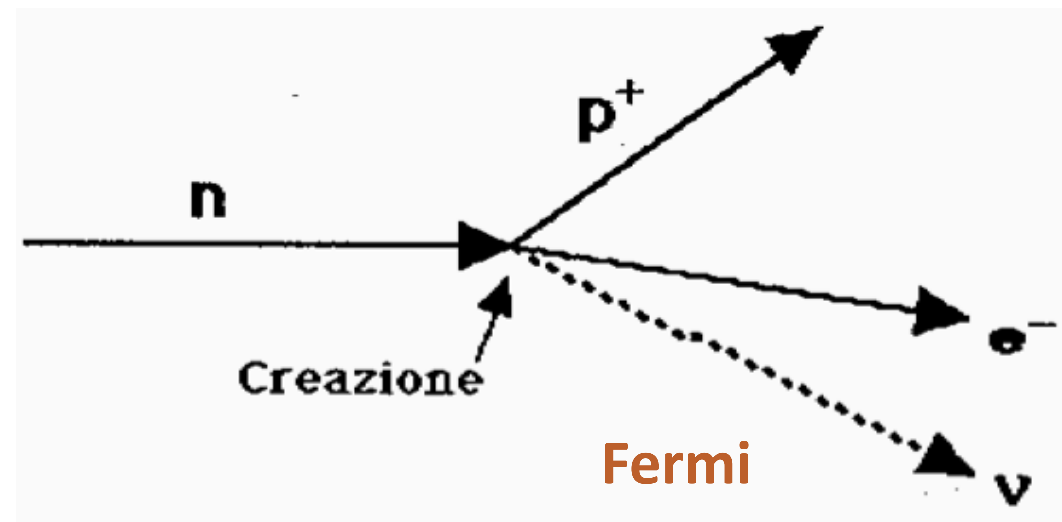


FIG. 5. Energy distribution curve of the beta-rays.

The electrons should have a single energy, not a continuous spectrum.



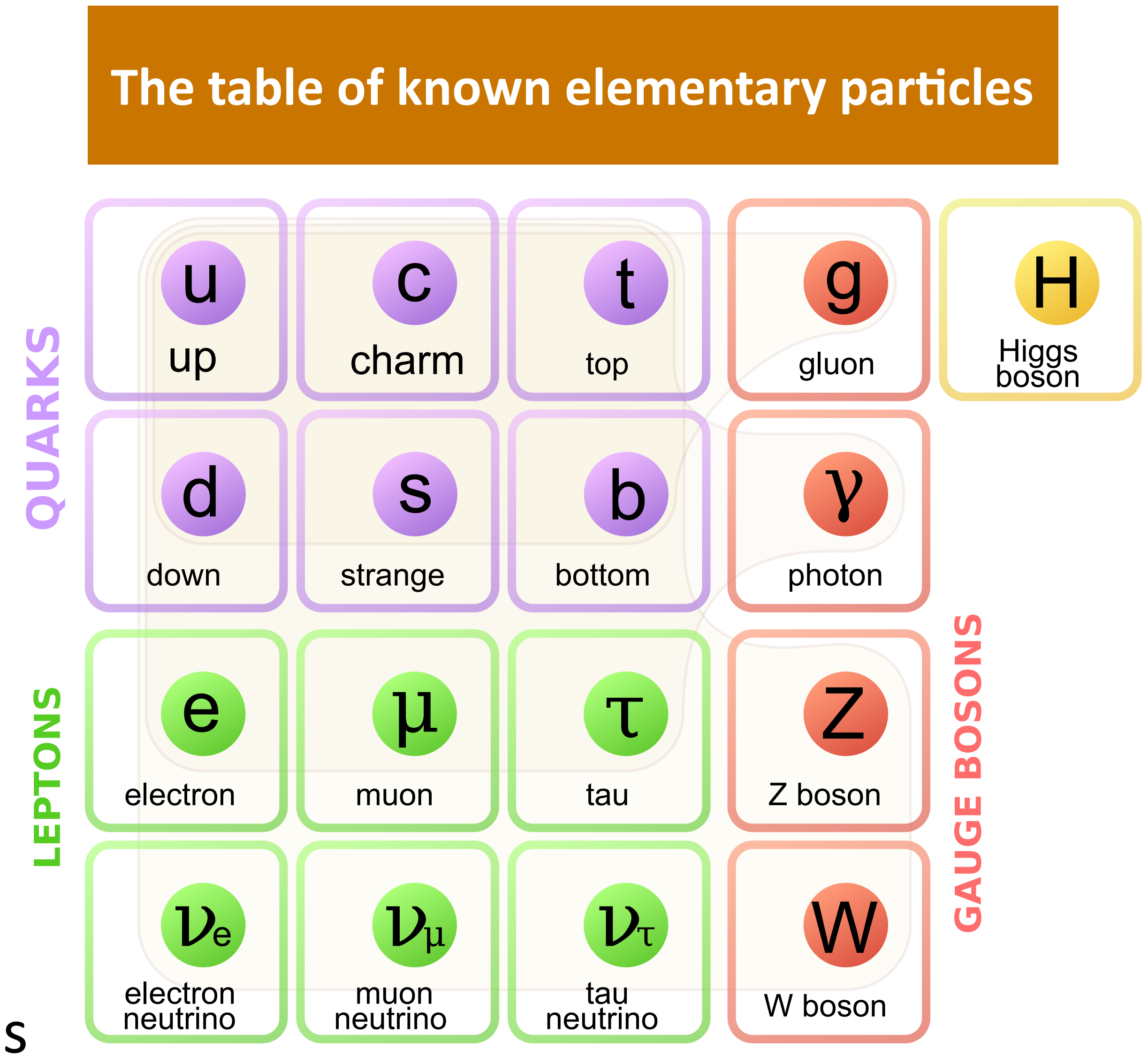
Pauli

Fermi

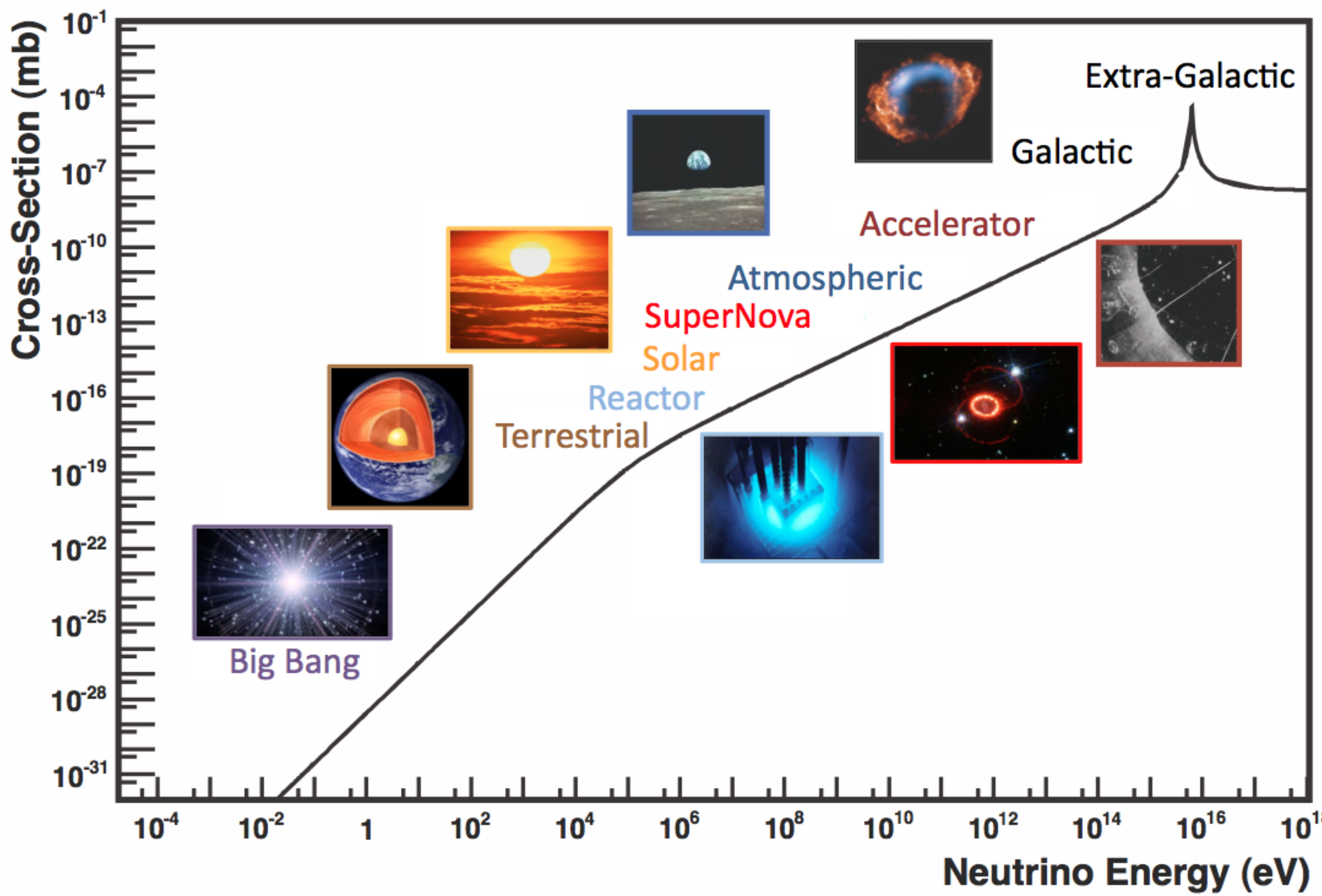
"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."
— Wolfgang Pauli (1930)

What do we know about neutrinos?

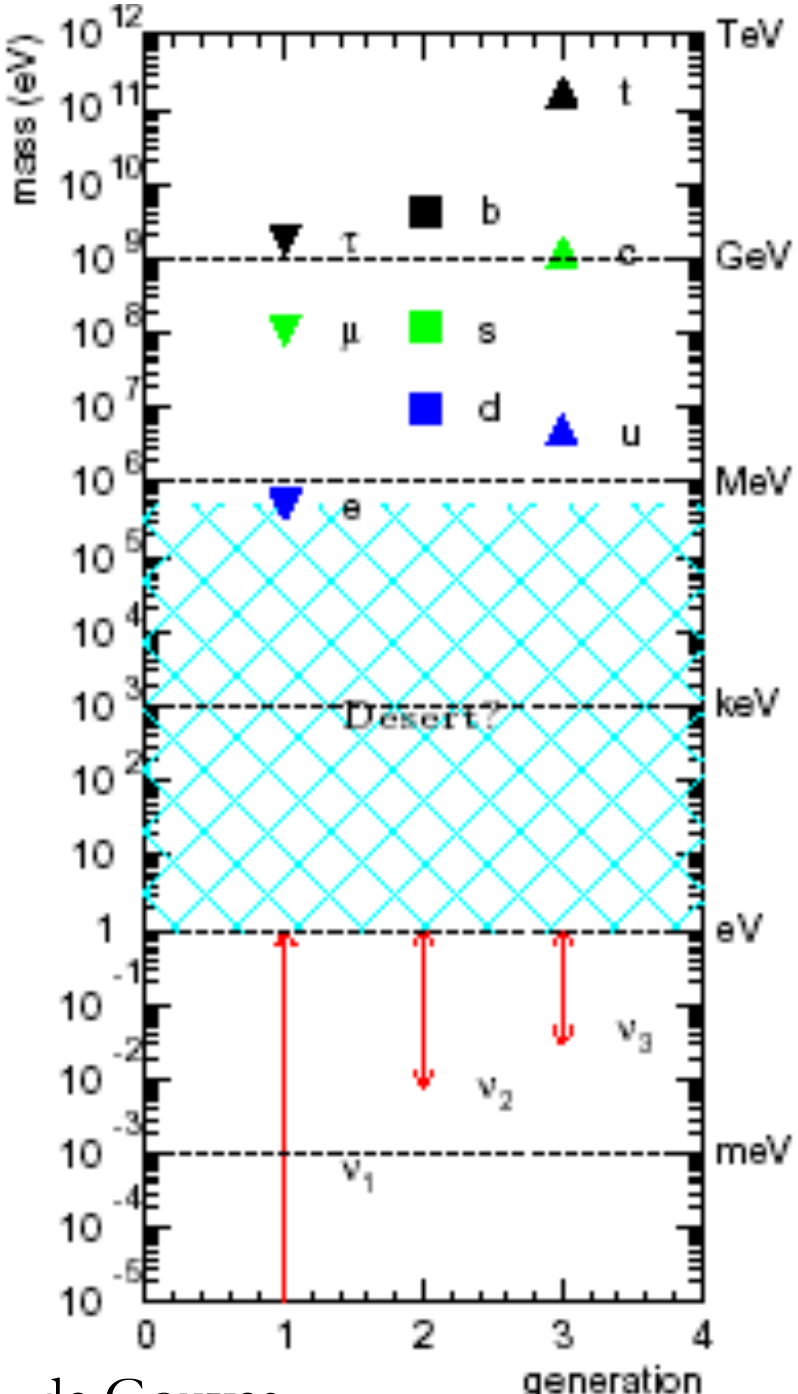
- Have no charge - do not participate in electromagnetism
  - Could be their own anti-particles
- Come in three flavors
- Are very light
  - Thought to be massless
  - Neutrino oscillations imply massive neutrinos
- Interact very weakly
- Neutrinos (ν) are always left-handed and anti-neutrinos ($\bar{\nu}$) are always right-handed



Where neutrinos come from?



Neutrinos have mass



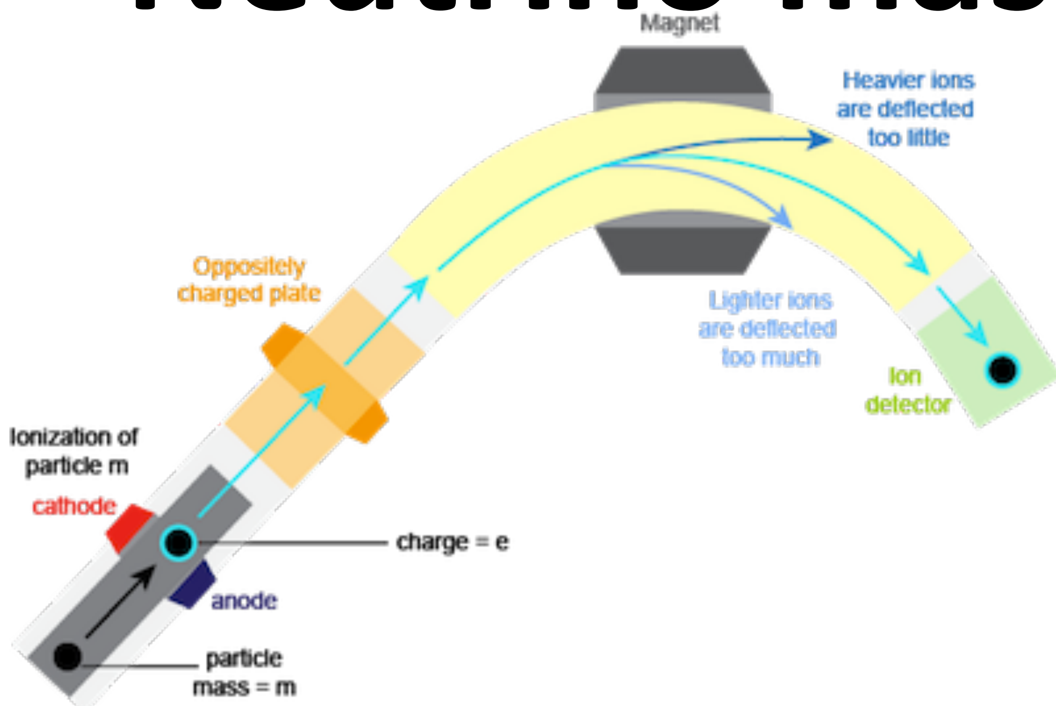
ν masses are much smaller than other particles

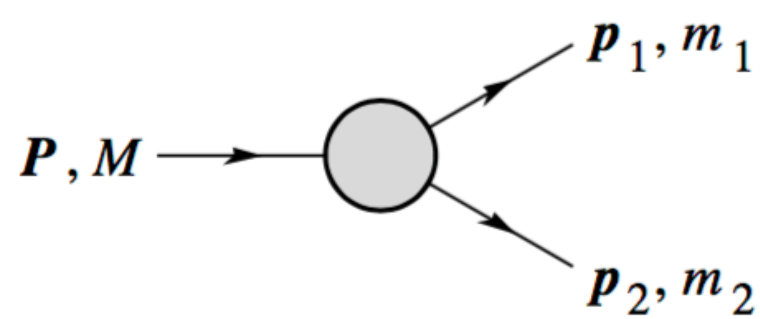
Other particles get mass because they are "slowed down" by the Higgs field.

Neutrino masses are so small, perhaps they get mass some other way?

A. de Gouvea

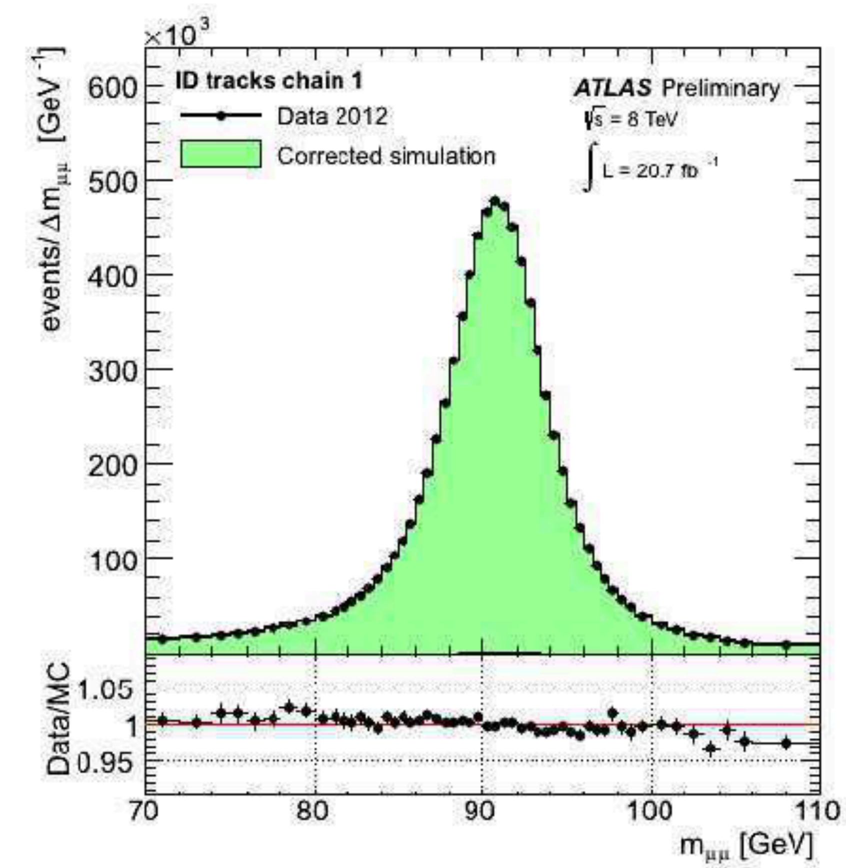
Neutrino mass is hard to measure



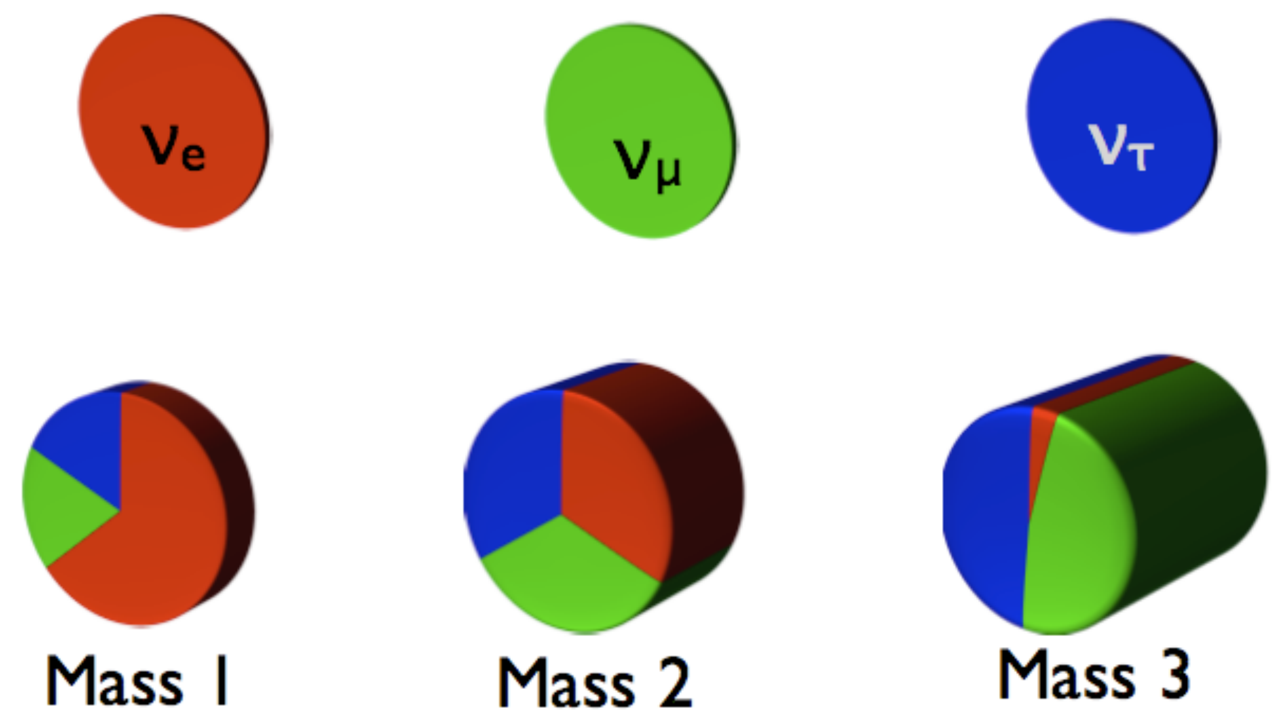


$$M^2=(E_1+E_2)^2-(\vec{p}_1+\vec{p}_2)^2$$

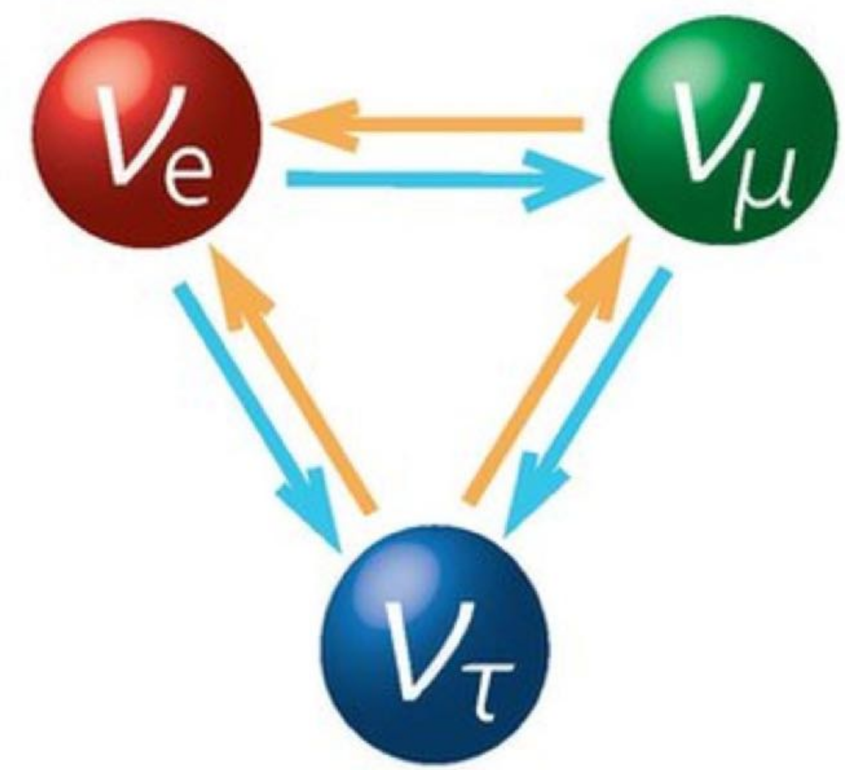
- Usual techniques don't work…
- Measure their track curvature in a magnetic field
  - neutrinos are neutral, not affected by EM fields ✗
- Measure energy and momentum of daughter particles ?
  - Neutrinos are the lightest particles, don't decay in others ✗
- Use quantum interference to probe neutrino mass ✓



Neutrino states



- Neutrinos come in three “flavors”
  - According to the lepton they produce when they have weak CC interactions
- Neutrinos come in three masses
  - But these states are not the same!!
- If the masses are non-zero, flavor can change when neutrinos propagate!



Neutrino oscillations

- Consistent with being mass driven

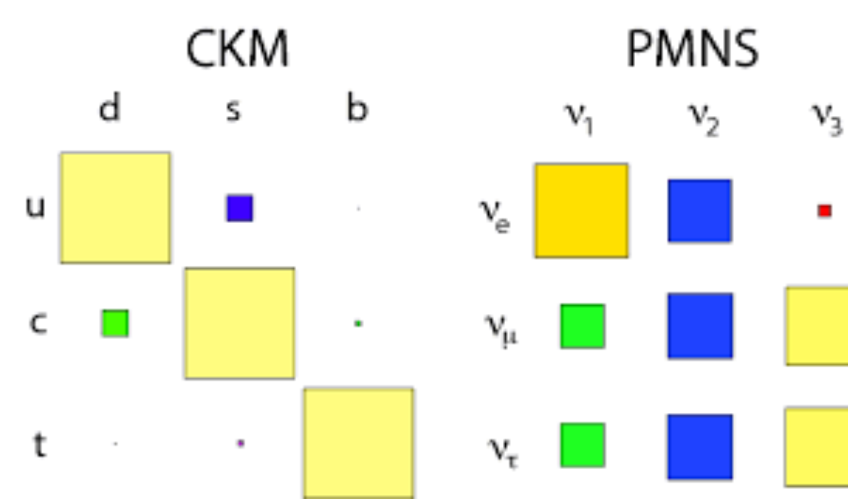
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{bmatrix} 0.82 \pm 0.01 & 0.54 \pm 0.02 & 0.15 \pm 0.03 \\ 0.35 \pm 0.06 & 0.70 \pm 0.06 & 0.62 \pm 0.06 \\ 0.44 \pm 0.06 & 0.45 \pm 0.06 & 0.77 \pm 0.06 \end{bmatrix}$$

- Neutrinos are parametrized by 3 masses (**m_1, m_2, m_3**), 3 angles (**θ_{12},θ_{13},θ_{23}**) and an extra complex phase $e^{i\delta}$

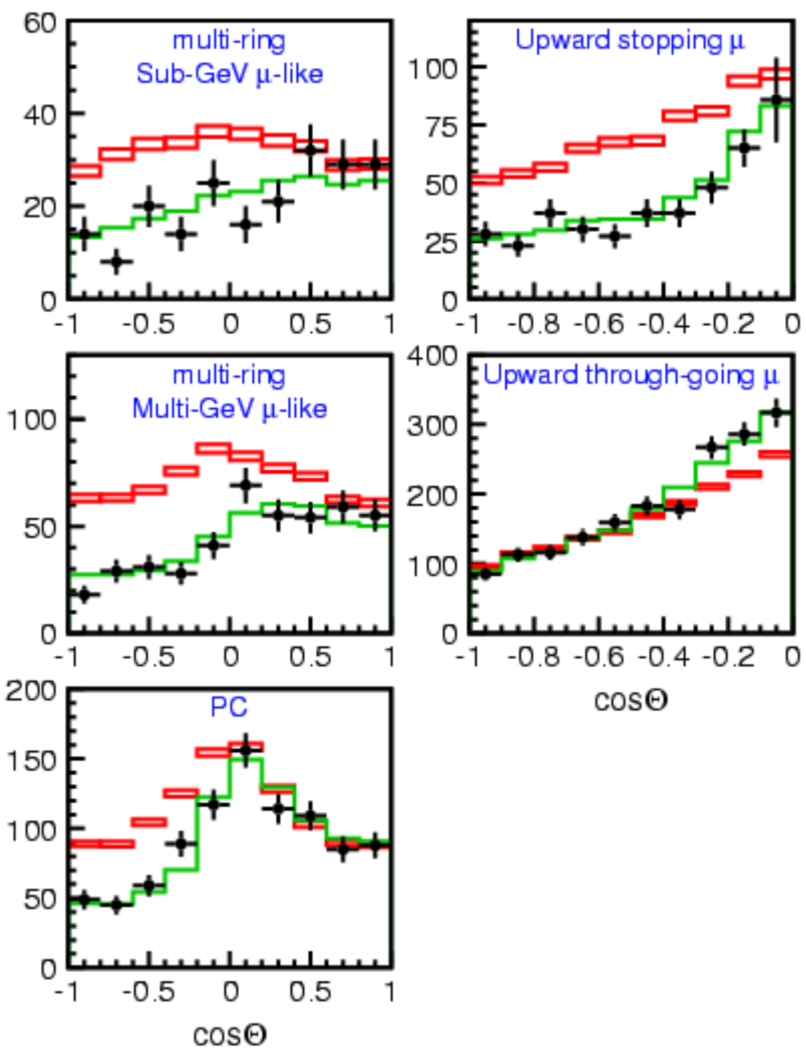
- The phase $e^{i\delta}$ is responsible for matter/anti-matter asymmetry (CP violation)

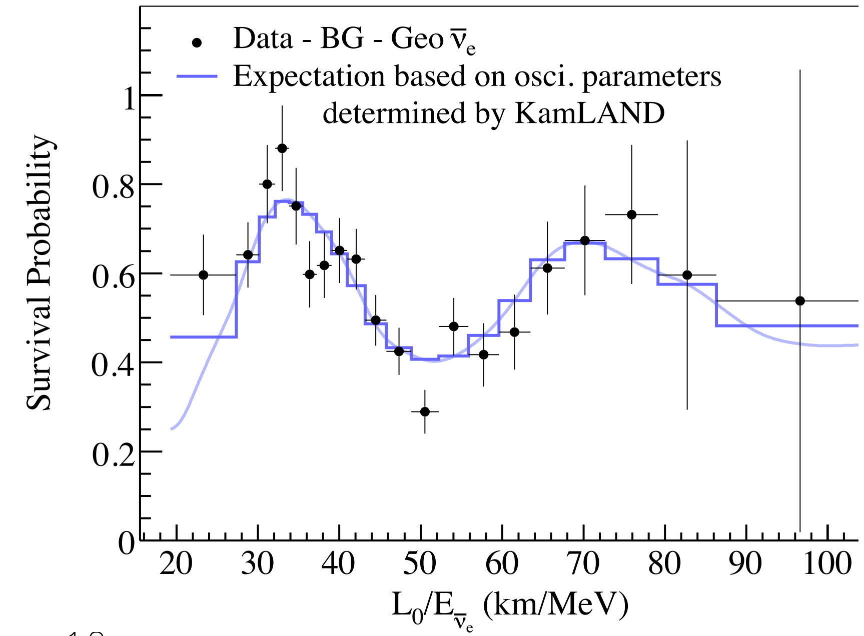
$$P\left(\nu_\mu \rightarrow \nu_e\right) \neq P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$$

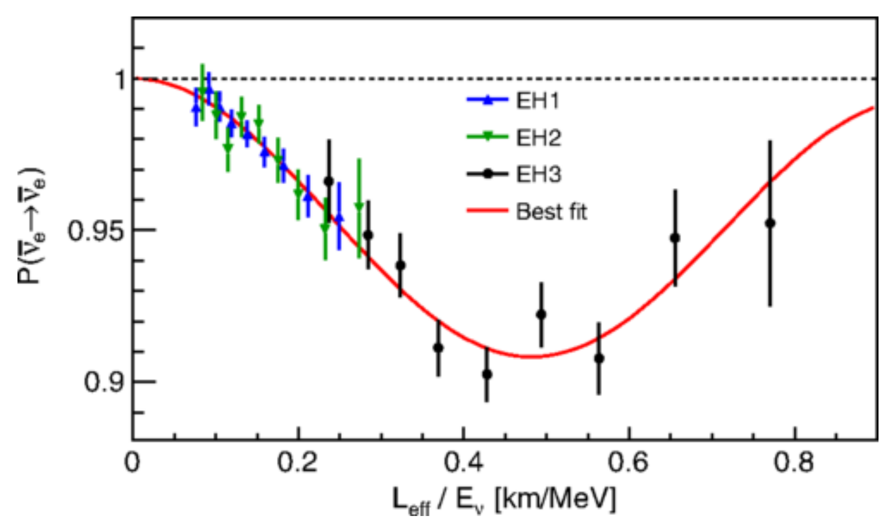
-

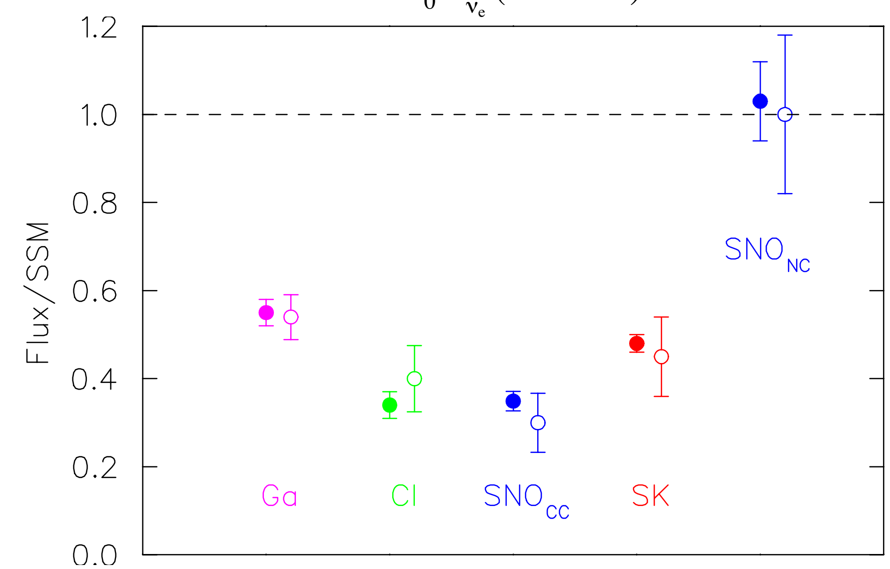


What have we learned in the last ~20 years









$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Accelerator and Atmospheric

SBL reactor

Solar + LBL reactor

What have we learned in the last ~20 years

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

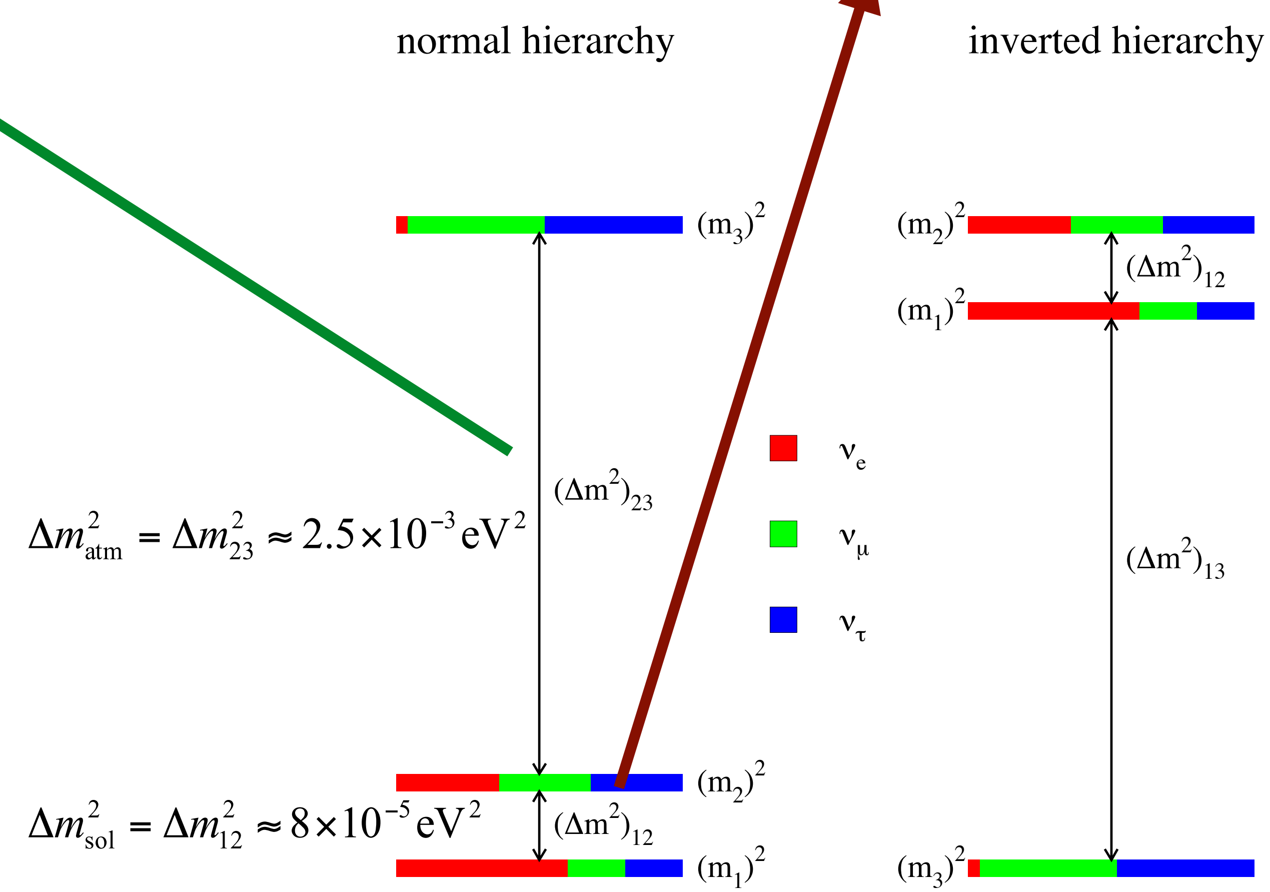
Accelerator and Atmospheric

SBL reactor

Solar + LBL reactor

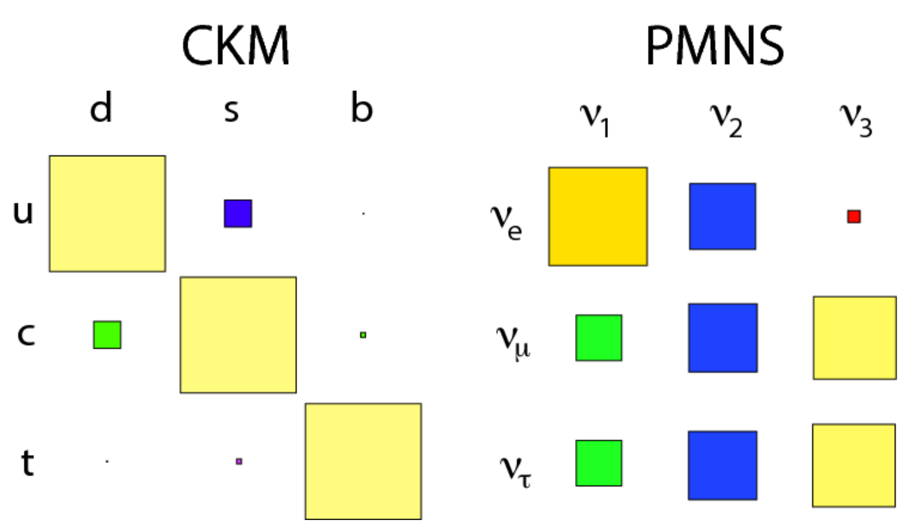
	VALUE
$\lvert\Delta m^2_{32}\rvert$	2.52±0.04 E-03 (eV²)
Δm^2_{21}	7.40±0.21 E-05 (eV²)
$\sin^2\theta_{12}$	0.31±0.01
$\sin^2\theta_{23}$	$0.56^{+0.02}_{-0.12}$
$\sin^2\theta_{13}$	0.022±0.0007
δ_{CP}	(-0.4±0.09)π ?

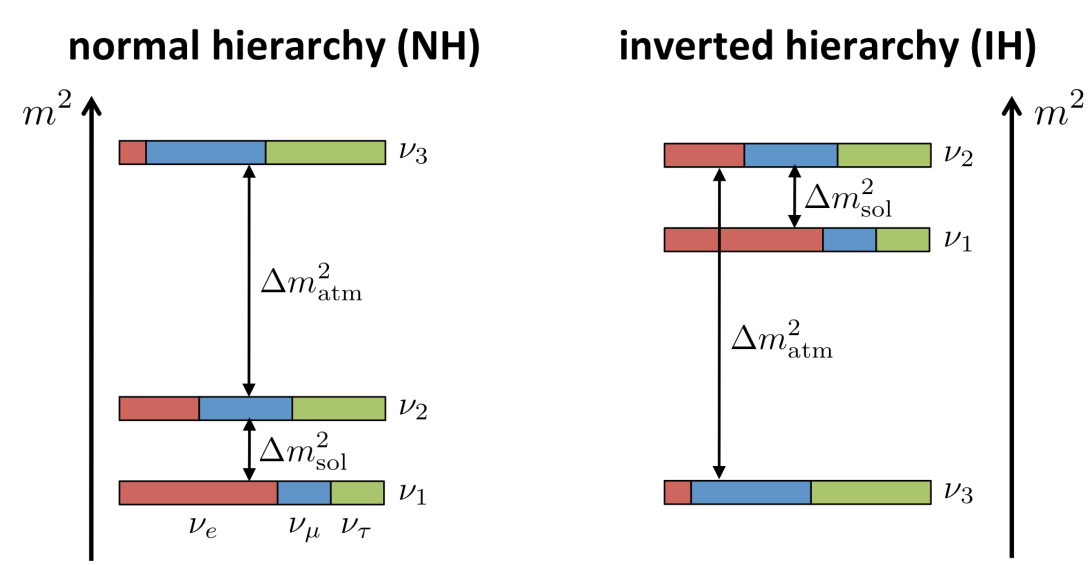
NuFit Results



What haven't we learned yet about neutrinos

- Is there CP violation in the lepton sector?
- Which mass hierarchy is correct?
- What are the precise values of the neutrino mixing parameters?





DUNE

- What is the absolute mass scale?
- Are neutrinos Majorana or Dirac particles?

SNO+

Neutrinos and antineutrinos

CP violation in DUNE

3-flavor Survival Probablity

$$P\left(\nu_\mu \to \nu_e\right) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Delta_{31}$$
$$+ 8C_{13}^2 S_{12} S_{13} S_{23} \left(C_{12} C_{13} \cos\delta - S_{12} S_{13} S_{23}\right) \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$
$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$
$$+ 4S_{12}^2 C_{13}^2 \left(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right) \sin^2\Delta_{21}$$
$$- 8C_{13}^2 S_{13}^2 S_{23}^2 \left(1 - 2S_{13}^2\right) \frac{aL}{4E_\nu} \cos\Delta_{32} \sin\Delta_{31}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

CP violating term tells us if $P\left(\nu_\mu \to \nu_e\right) \neq P\left(\overline{\nu}_\mu \to \overline{\nu}_e\right)$

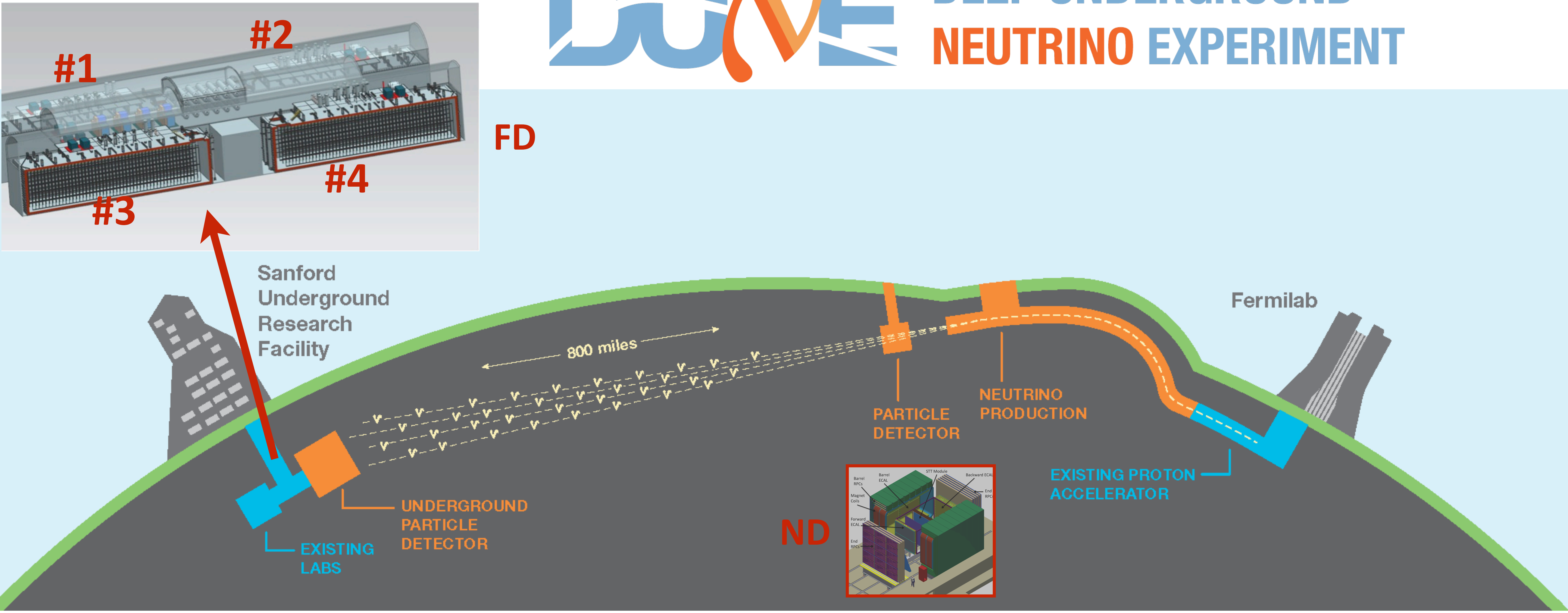
Matter term depends on sign of $m_3^2 - m_1^2$

DUNE - Testing the ν model

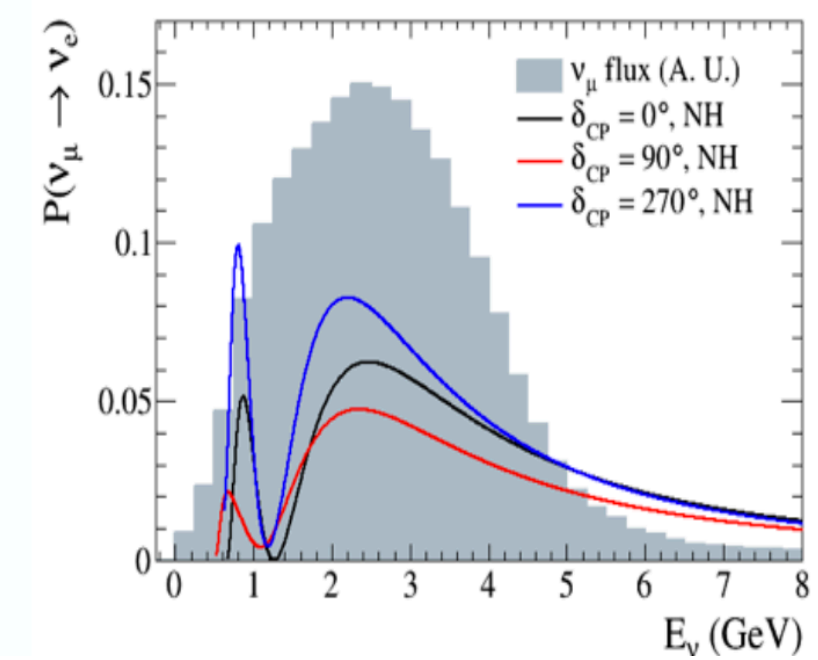
- **We currently have a model that has several parameters**
  - But the data that it explains is rather limited
- **What predictions from the model can we check?**
  - L/E (or just L, or just E) oscillation behavior
  - Universality of the parameters (Δm^2, θ)
  - **CP violation if δ is non-zero**

- Neutrino oscillations give is a natural "interferometer"
  - **Anything that distinguishes flavors (or mass states) alters the pattern**

DEEP UNDERGROUND NEUTRINO EXPERIMENT



- **Long baseline high purity beam of muon neutrinos**
  - **Neutrino energy ~2 GeV**
  - Four identical cryostats filled with 10 kT of LAr
  - LAr TPC technology to be used in at least 3 detectors
    - Although the specific implementation (single phase, dual phase) is not set for all cryostats



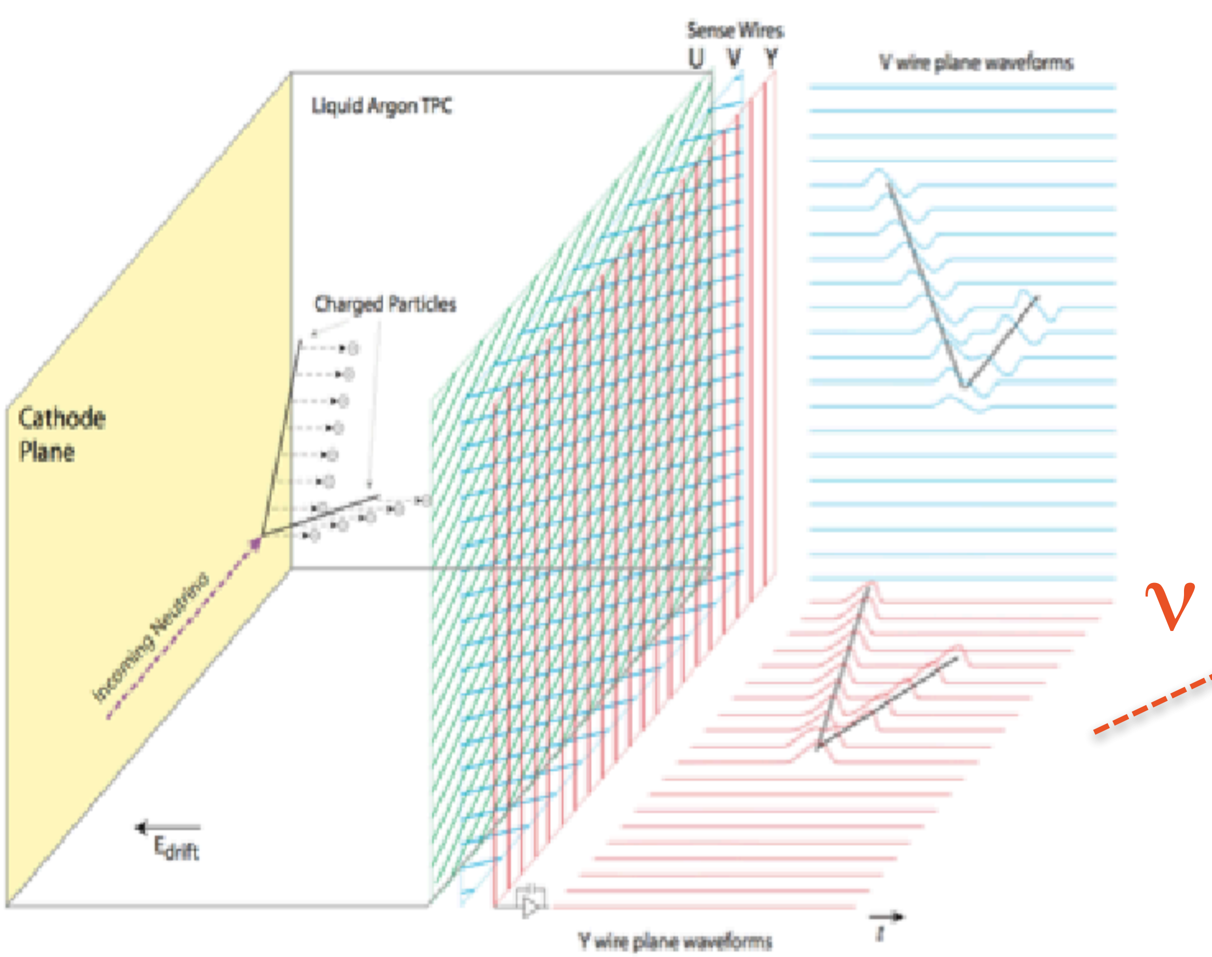
DUNE Far Detector: LAr TPCs

LAr TPC provides:

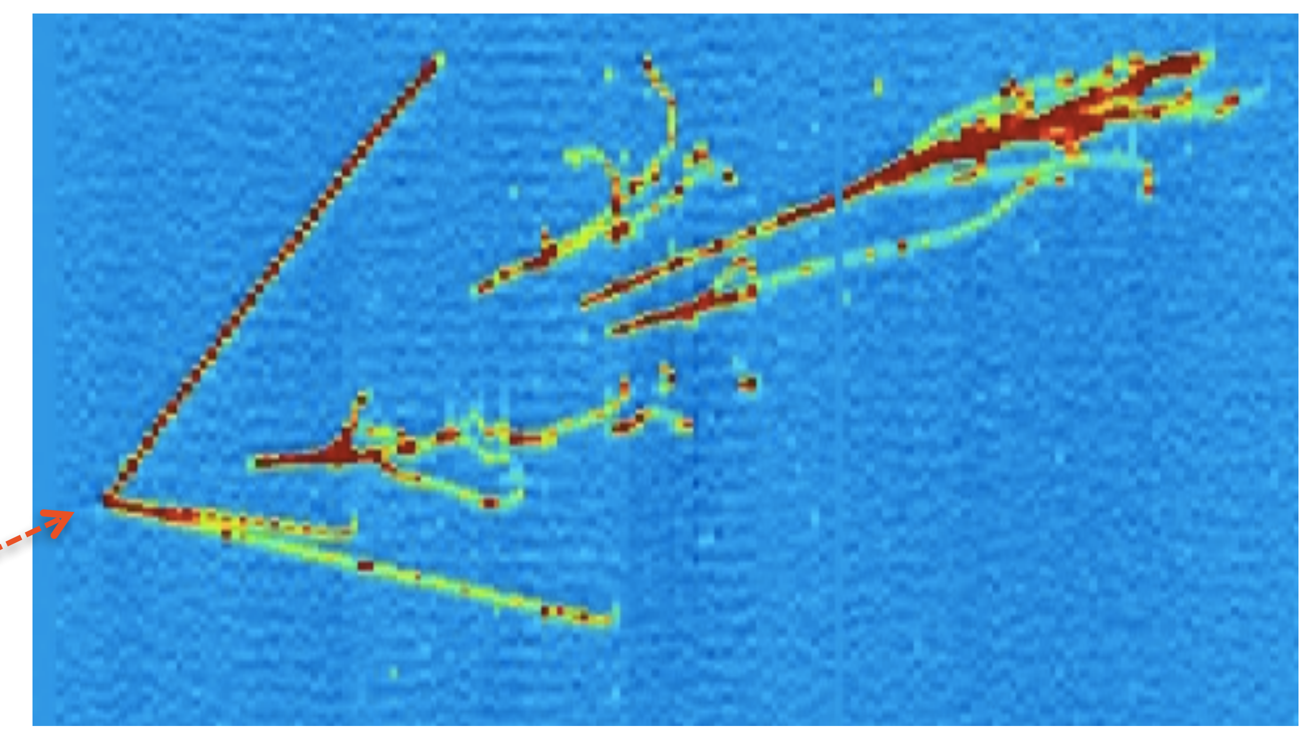
- Excellent 3D imaging
  - few mm resolution over large volume
- Excellent energy measurement
  - Fully active calorimeter
- Allows particle ID by dE/dx, range, event topology

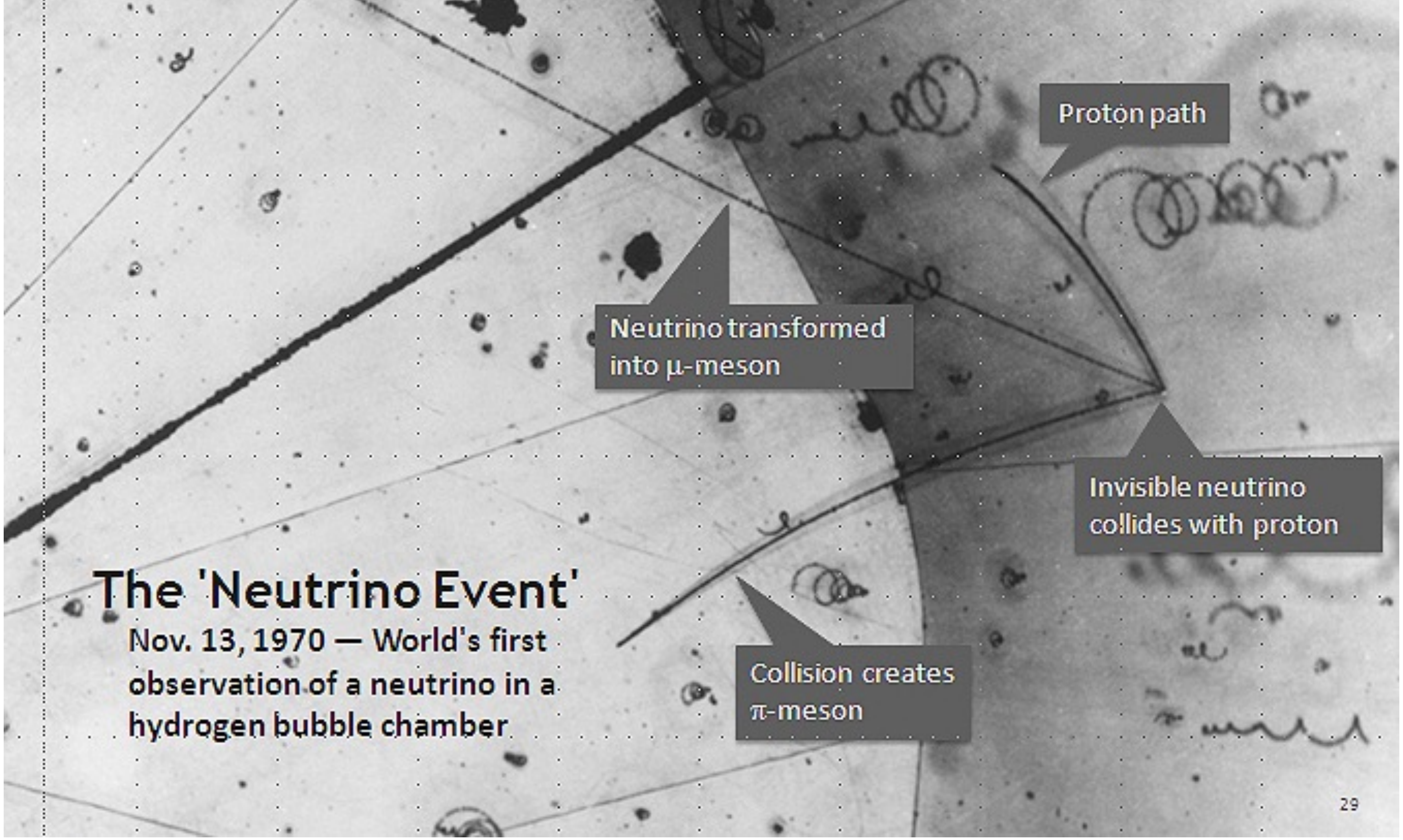
Major (and exciting) challenges

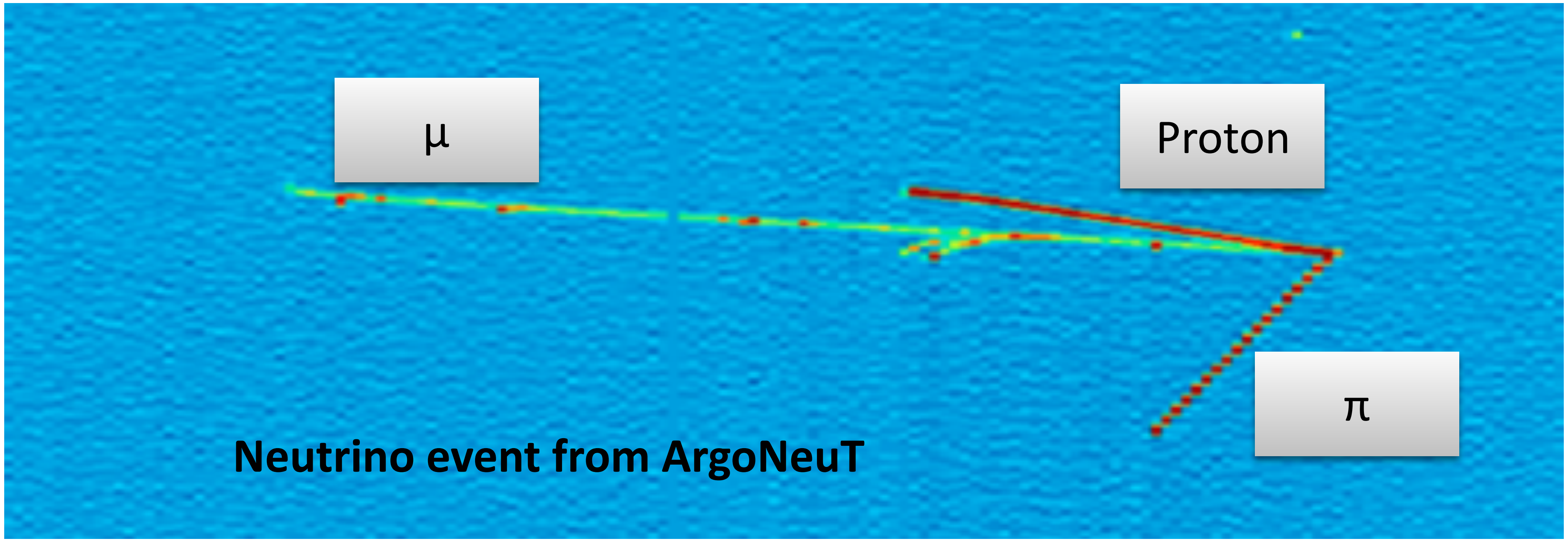
- Scaling technology to very large detector volumes
- Event reconstruction and classification – recent success in using Convolutional Visual Networks (CVNs) for event classification (ResNet in TensorFlow)



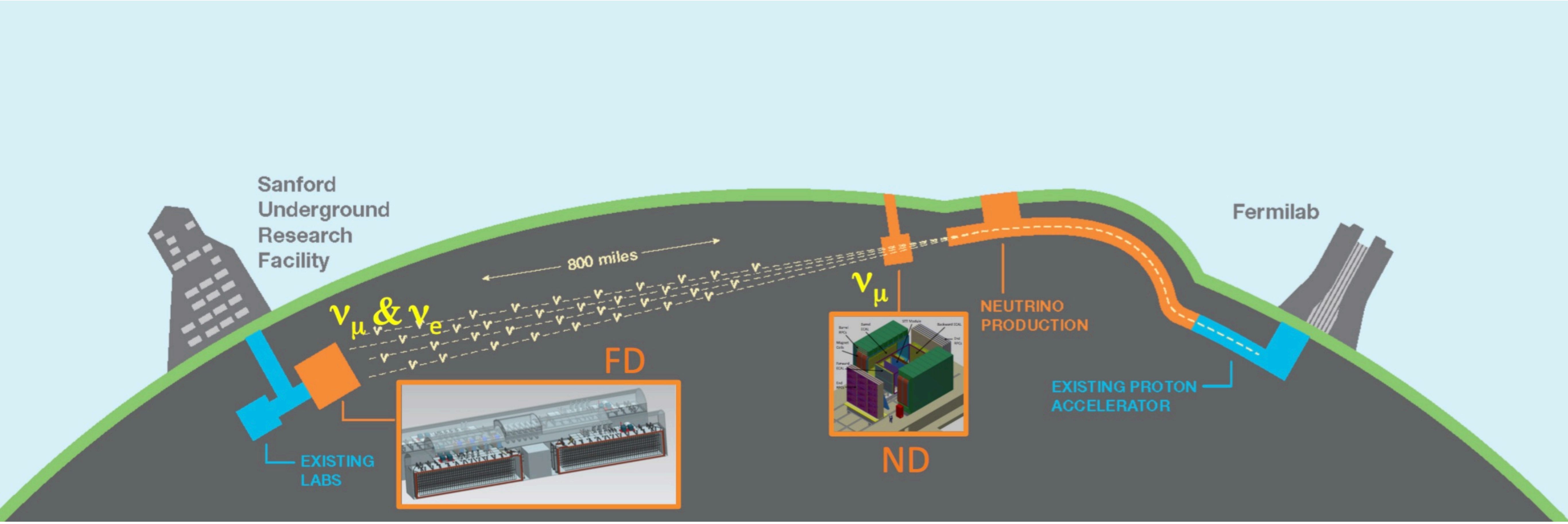
ν




Proton path
Neutrino transformed into μ-meson
Invisible neutrino collides with proton
The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber
Collision creates π-meson
29


μ
Proton
π
Neutrino event from ArgoNeuT

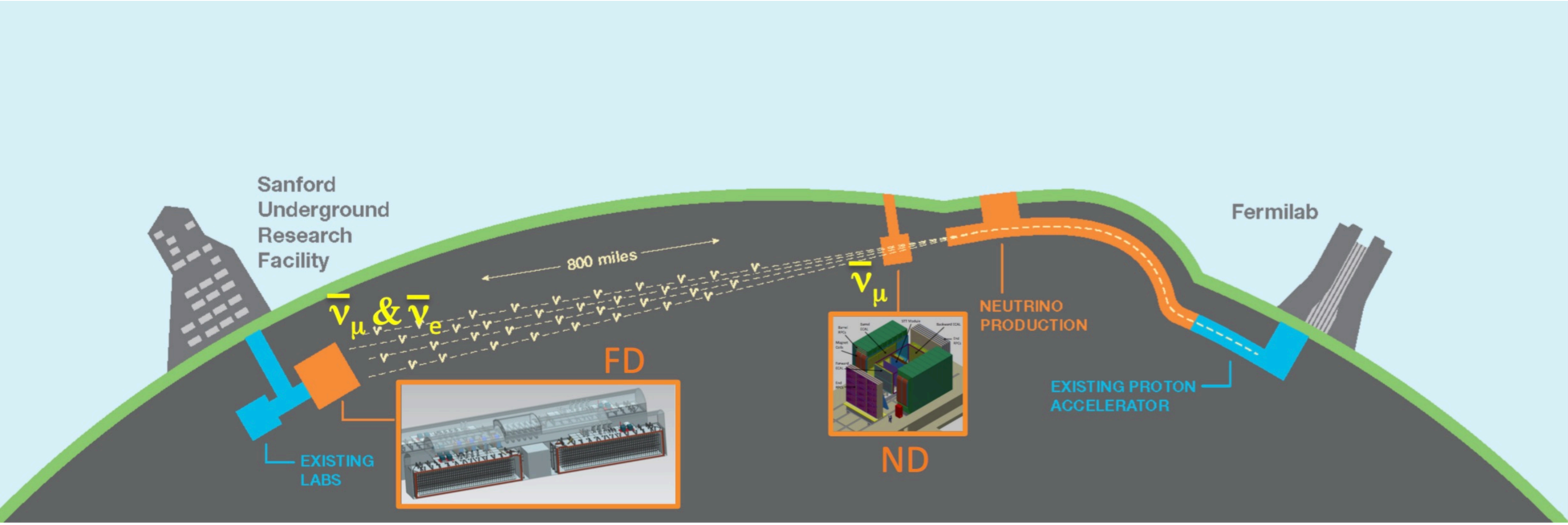
Long Baseline Oscillations



- **Measure neutrino spectra at 1300 km in a wide band beam**
  - Near detector at Fermilab: measurement of ν_μ unoscillated beam
  - Far detector at SURF: measure oscillated ν_μ and ν_e

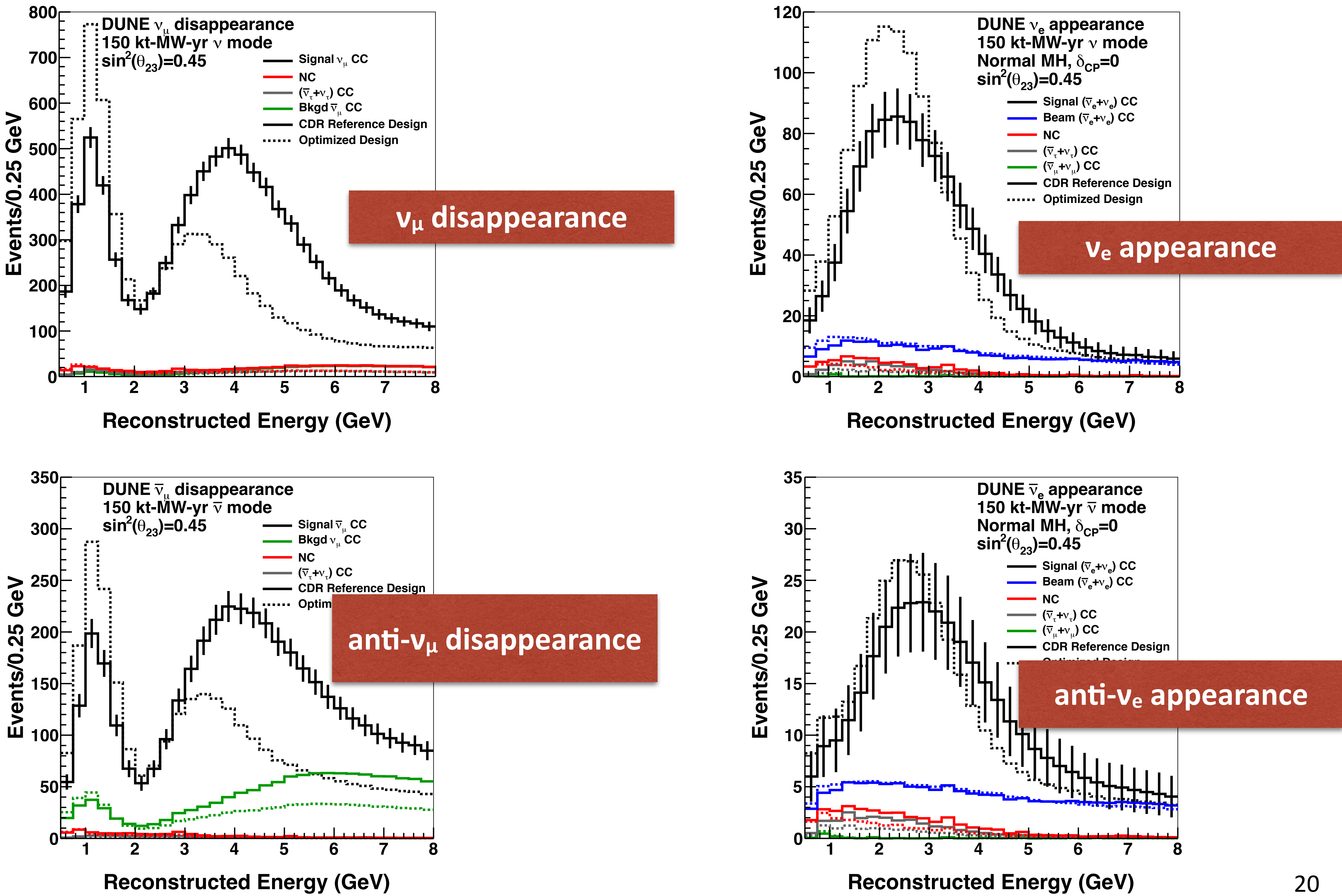
Long Baseline Oscillations

…and then repeat for antineutrinos



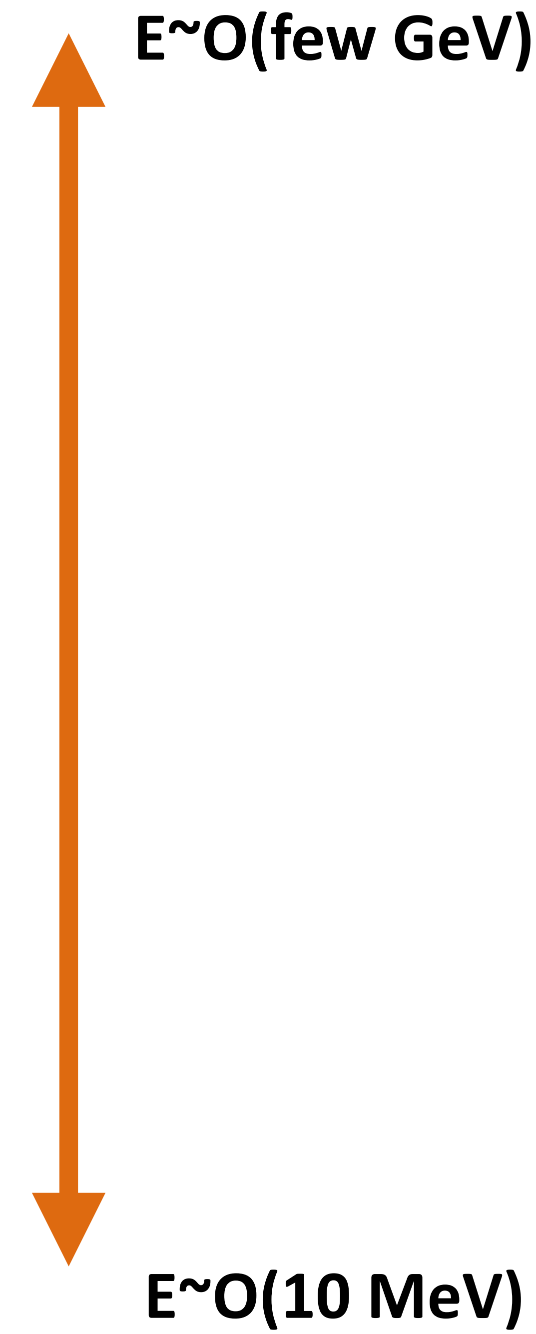
- **Measure antineutrino spectra at 1300 km in a wide band beam**
  - Compare oscillations of neutrinos and antineutrinos
  - Direct probe of CP violation in the neutrino sector

Neutrino Oscillation Physics



DUNE Physics Program

- **Neutrino Oscillation Physics**
  - High sensitivity potential for leptonic CP violation
  - Identify the neutrino mass hierarchy
  - Precision oscillation physics and test of 3-flavor oscillations
- **Proton Decay**
  - Target SUSY-favored mode $p \longrightarrow K^+ \nu$
- **SN burst physics and astrophysics**
  - Galactic core collapse supernova, unique sensitivity to ν_e
- **Atmospheric Neutrinos**
- **Solar neutrinos (similar approach as SN)**
- **Neutrino Interaction Physics (Near Detector)**

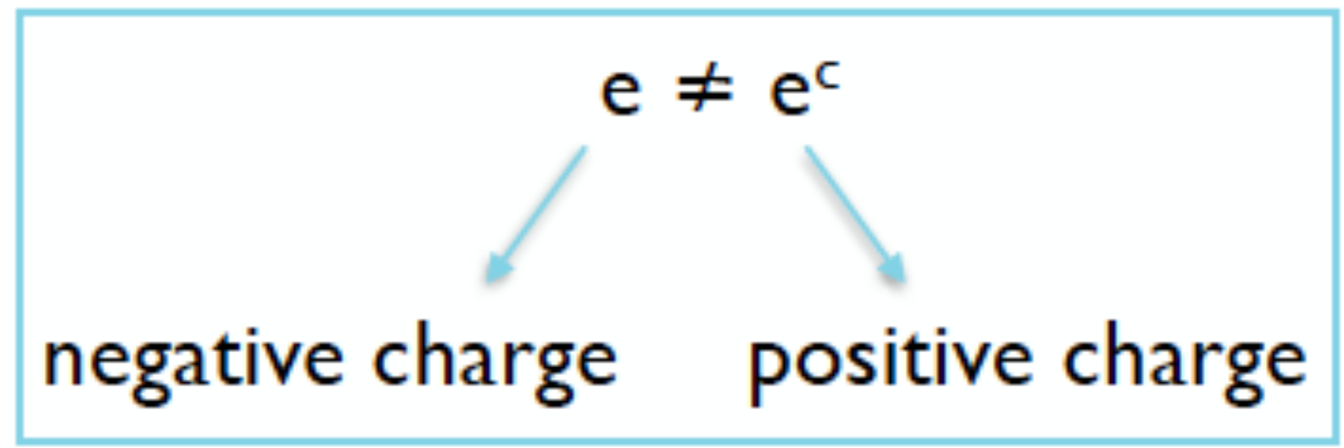


No-neutrinos

Lepton Number Violation in SNO+

Are neutrinos Dirac or Majorana fermions?

- Except for neutrinos, all fermions of the standard model are electrically charged
- Thus, there is a distinction between particle and antiparticle
- For neutrinos, this is not obvious - particles could be identical to antiparticles, with only chirality/helicity distinguishing them



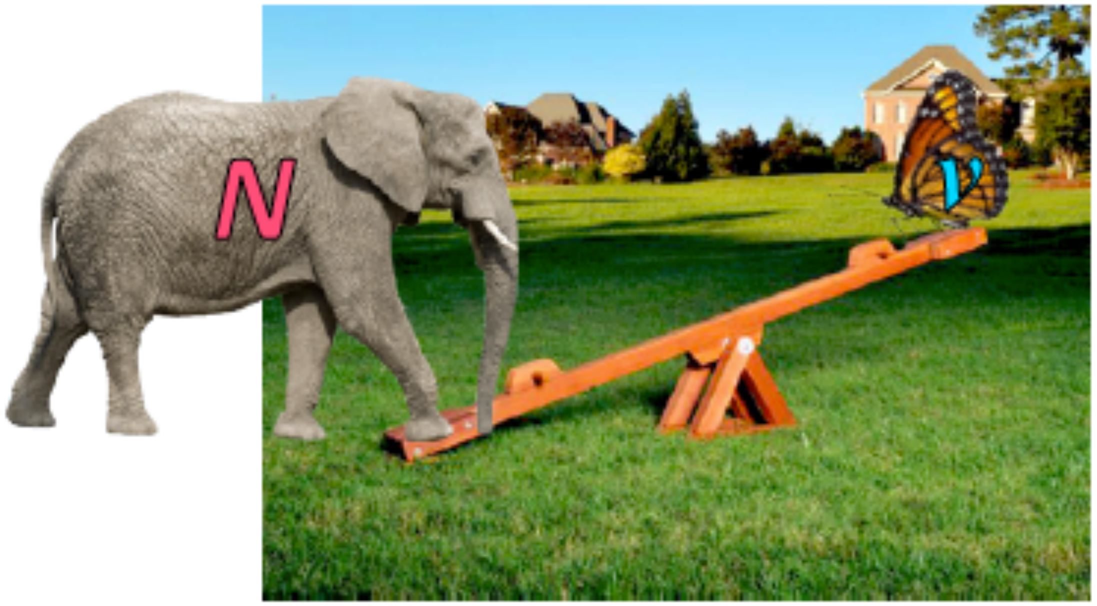
$\nu \neq \nu^c$????

No charge to distinguish them
Are neutrinos Majorana particles?

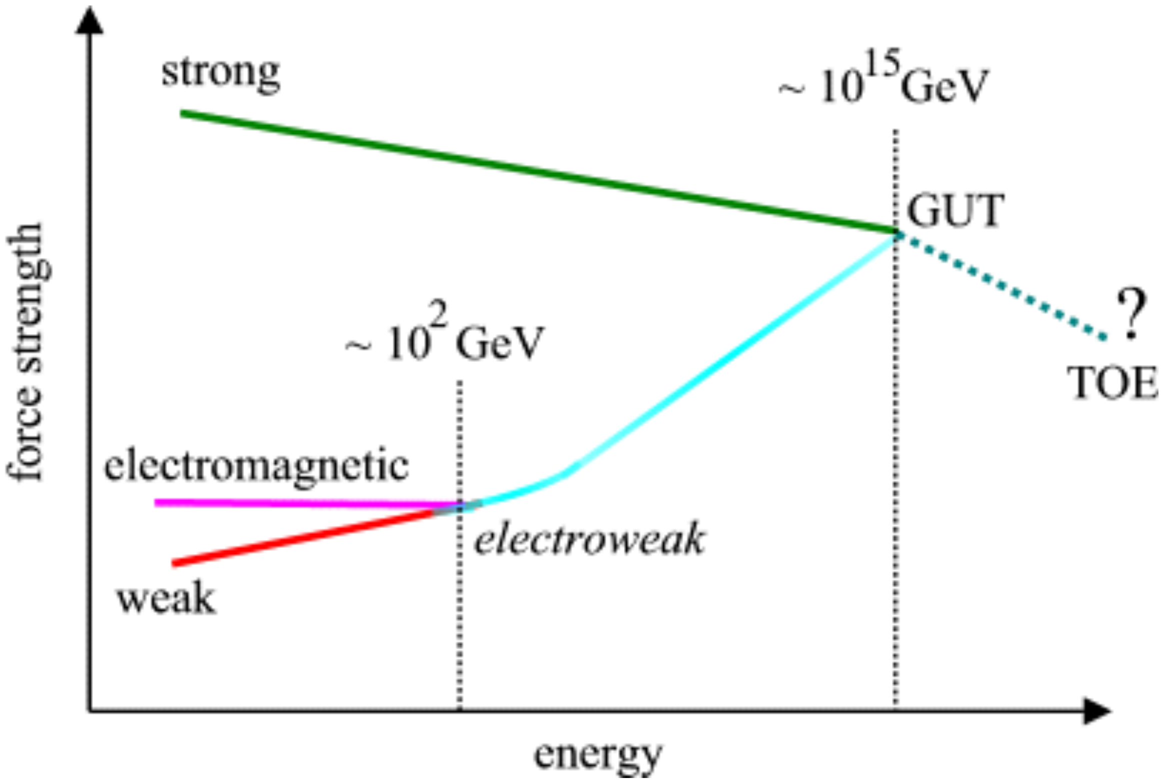
Long-standing question:
Neutrinoless double-beta decay experiments (SNO+, …) looking to answer this

Massive Majorana neutrinos

$m_\nu \cdot m_N \approx m_D^2$

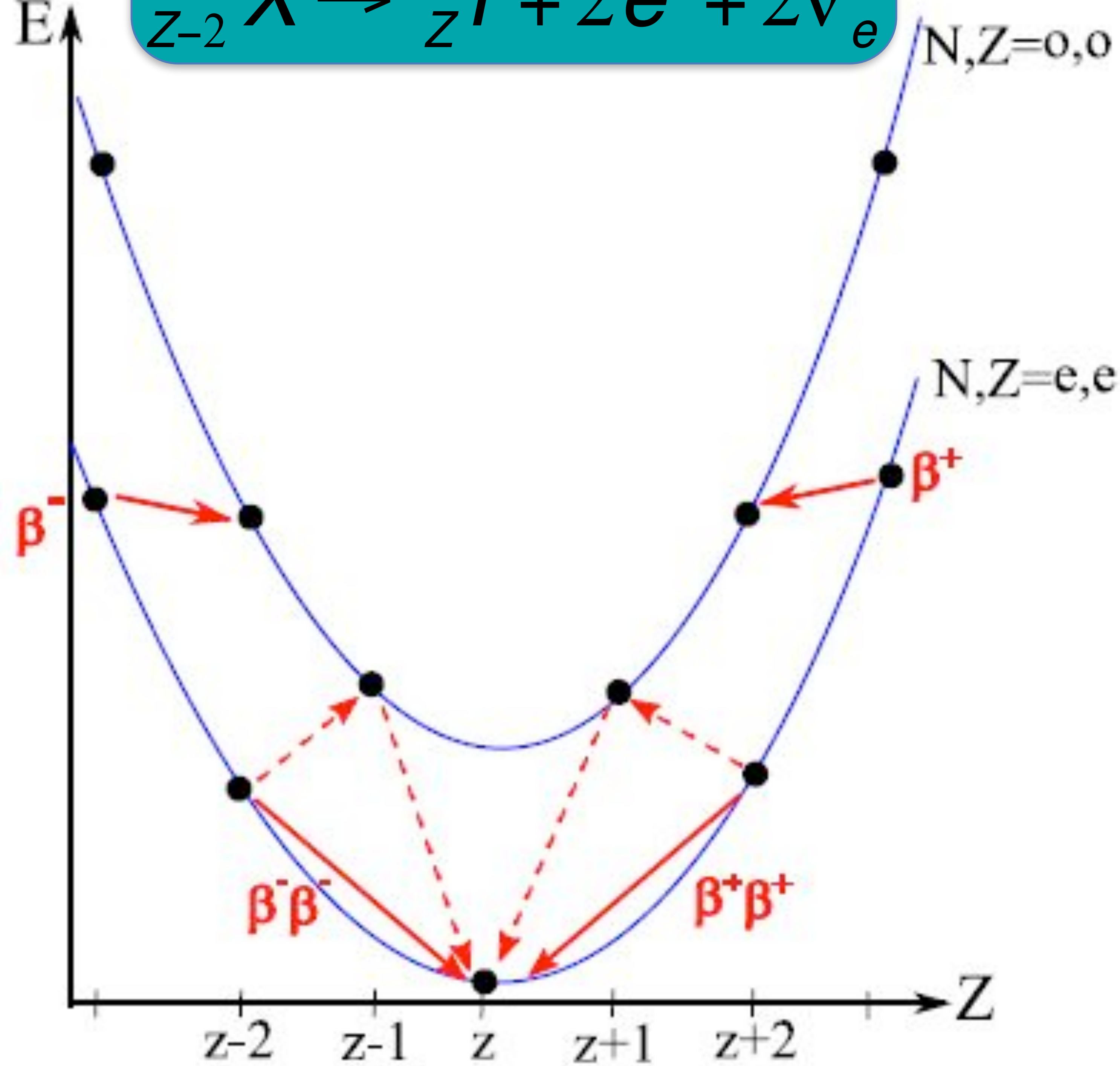


- **IF** Heavy Majorana neutrinos exist, a "see-saw" mechanism can explain the smallness of masses
  - Dirac term m_D ~ 100 GeV (scale of W, Z, Higgs bosons)
  - If m_N ~10^{14} – 10^{15} GeV (GUT scale)
  - Then m_ν ~ 0.01 - 0.1 eV (expected from oscillations/limits)
    - **Coincidence?**



Double Beta Decay

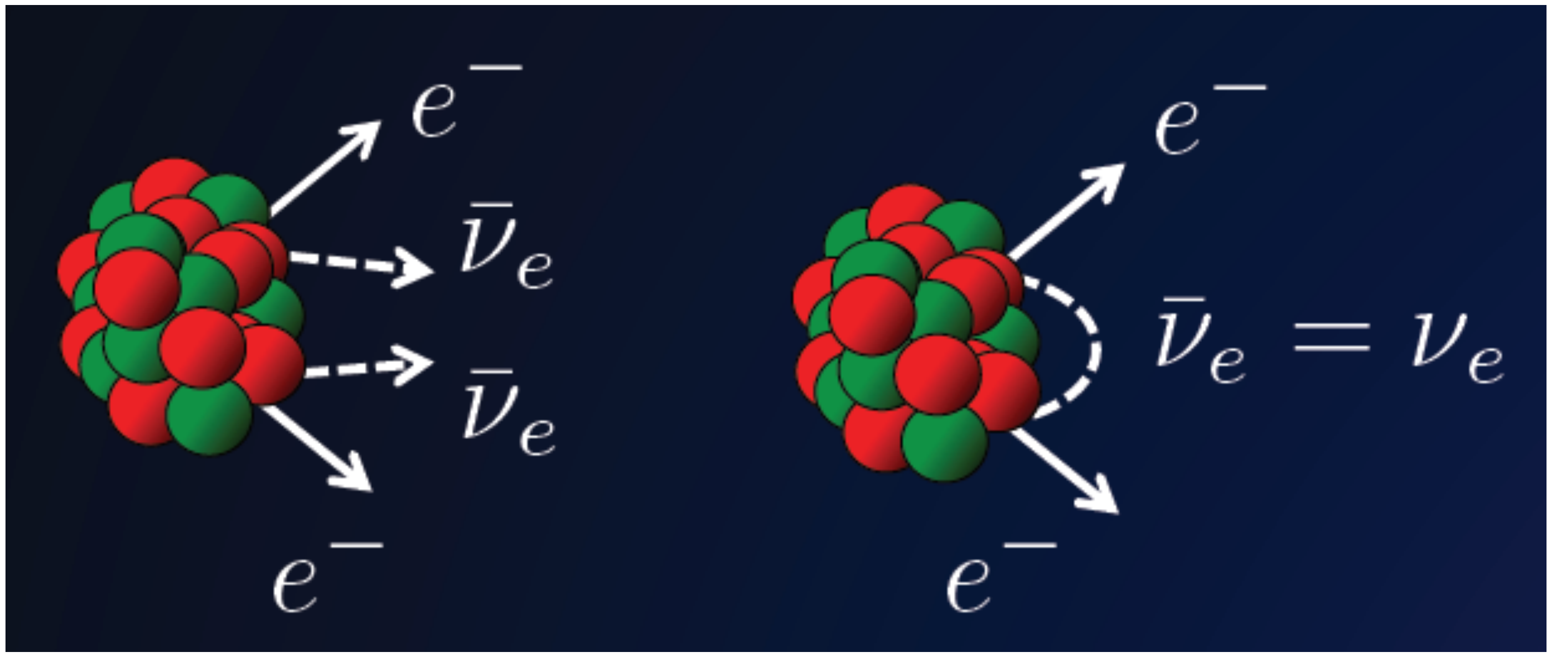
$$ {}^{A}_{Z-2}X \rightarrow {}^{A}_{Z}Y + 2e^{-} + 2\bar{\nu}_{e} $$



- Very rare nuclear decay
  - When normal beta decay is not energetically possible
  - DBD can happen for 35 natural isotopes (observed in 11)

Typical $T_{1/2} \sim 10^{18}$ - 10^{21} yr

Neutrinoless double beta decay (0νββ)



- Only happens if neutrinos are of Majorana type
- Half-life depends on the neutrino mass

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}\,|\mathcal{M}|^2 \left|\frac{m_{ee}^{\nu}}{m_e}\right|$$

Half-life

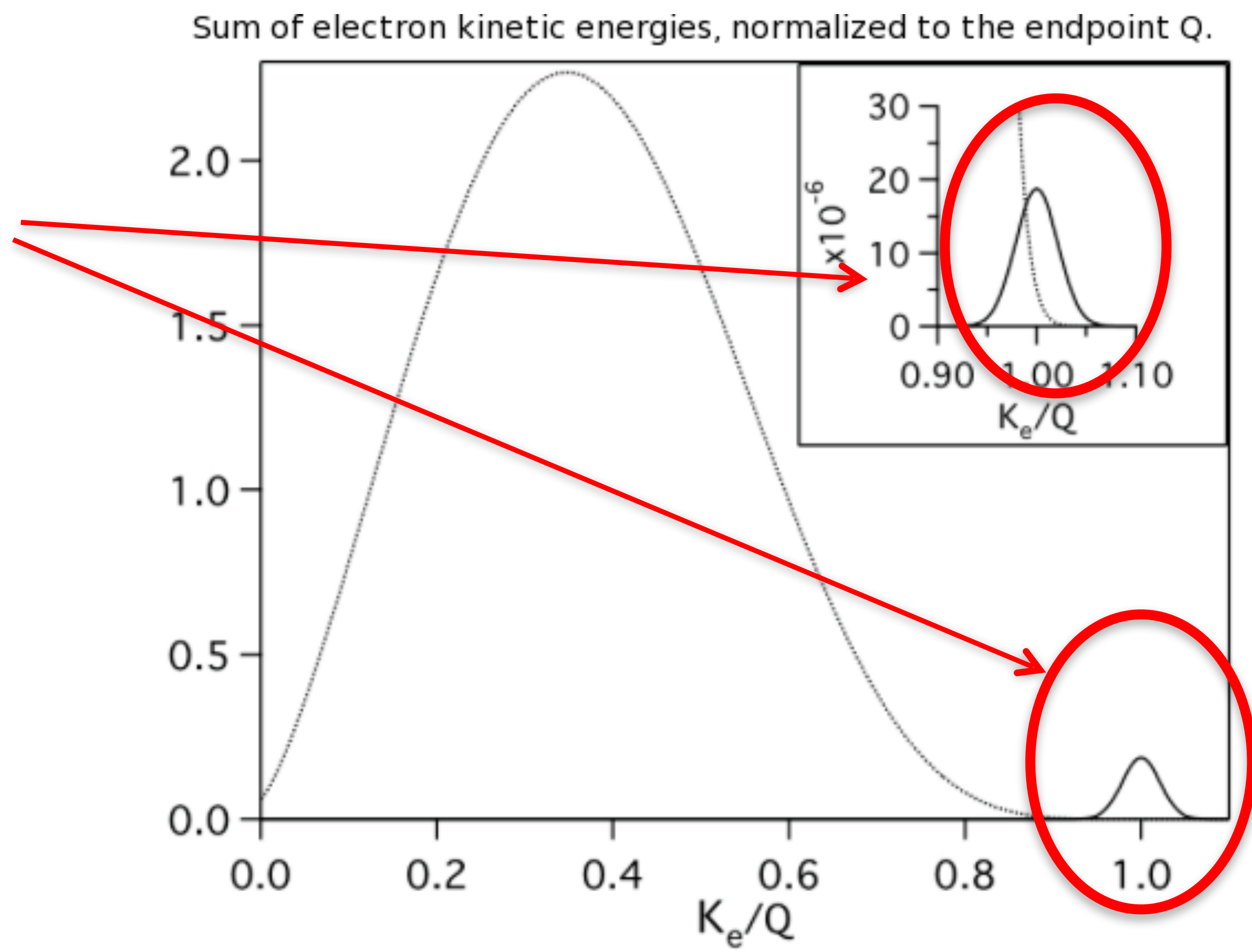
Nuclear Physics terms

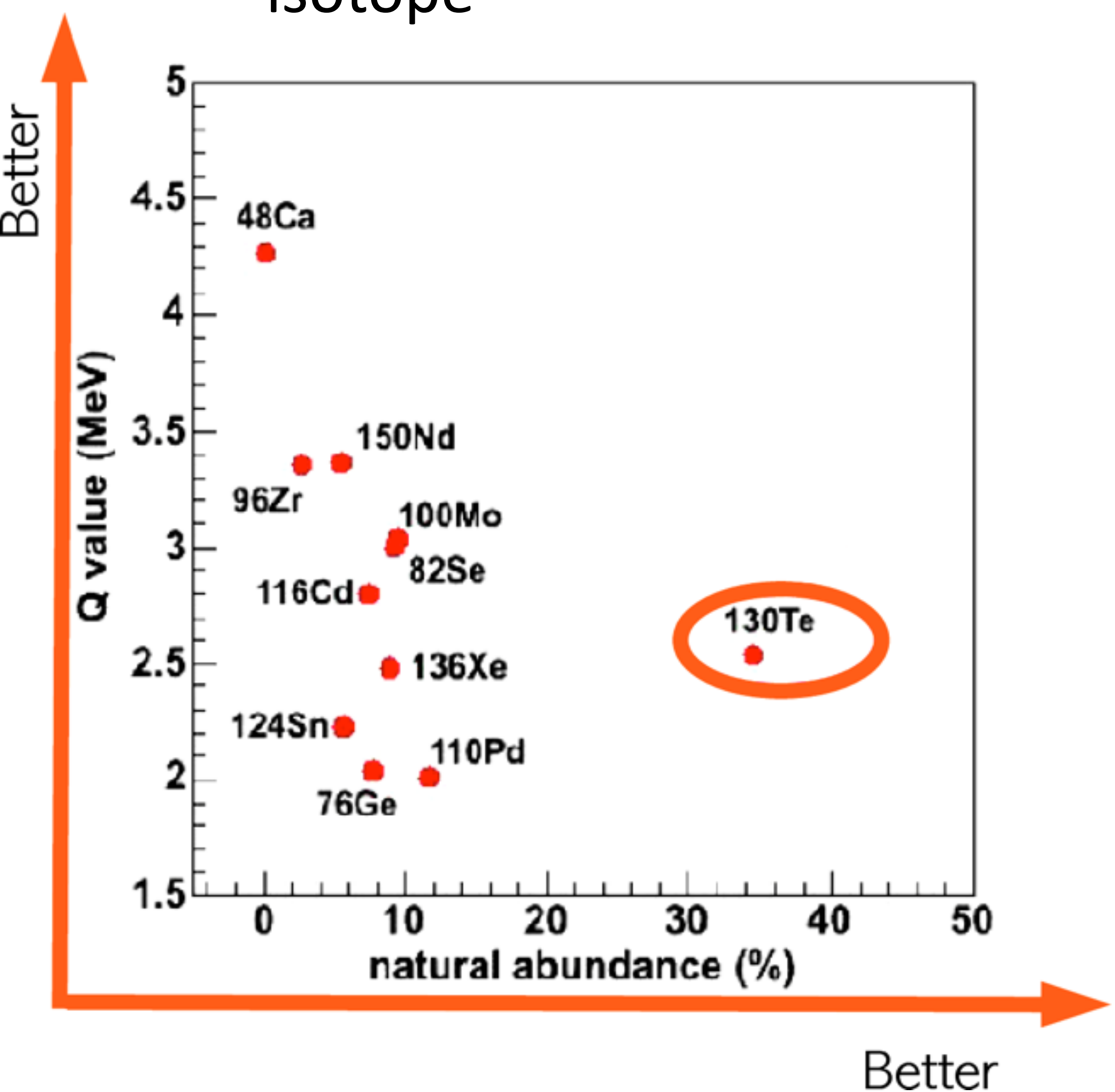
Particle Physics term
Effective Majorana mass
Depends on masses m_1, m_2, m_3
also on neutrino mixing parameters

$$m_{ee}^{\nu} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3 s_{13}^2 e^{2i(\alpha_3+\delta)}$$

Searching for 0νββ

- Method
  - Search for a peak in the energy spectrum (sum of the two electrons)
  - Acquire data for a long time and with high quantities of isotope





- **Choice of isotope**
  - **Natural abundance, energy**
- **Low backgrounds**
  - **Underground location**
  - **Low radioactivity**

SNO+ detector

780 tons of **liquid scintillator**

new calibration systems

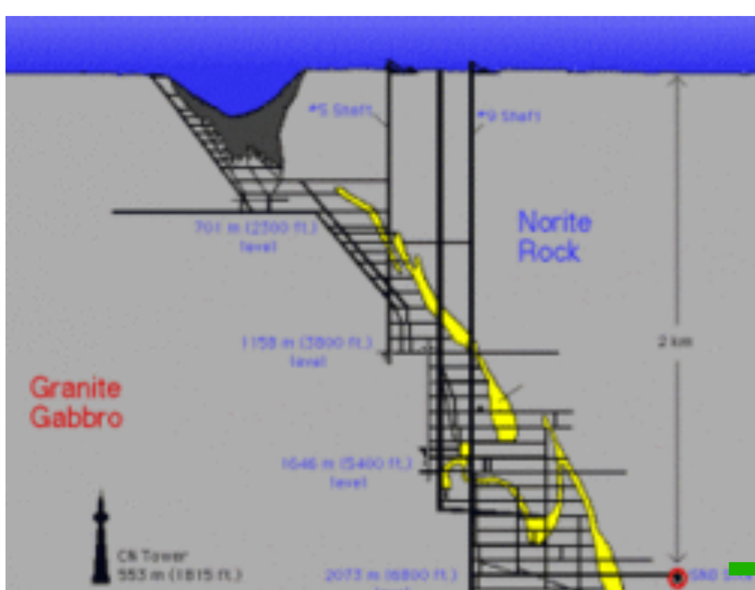
new DAQ and readout cards

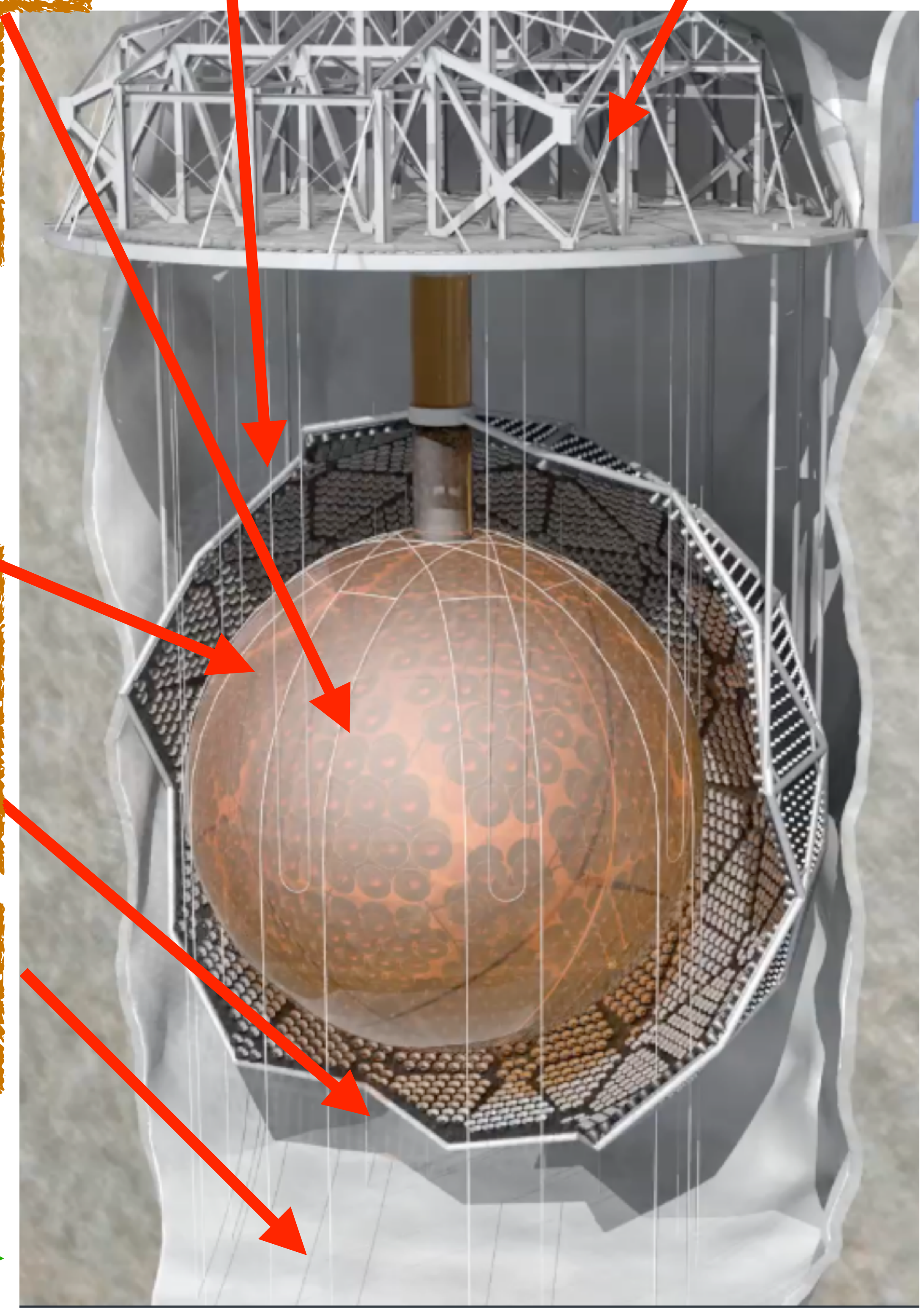
loaded with **double-beta decay isotope** (^{130}Te)

contained in an acrylic vessel (AV) 12 m diameter

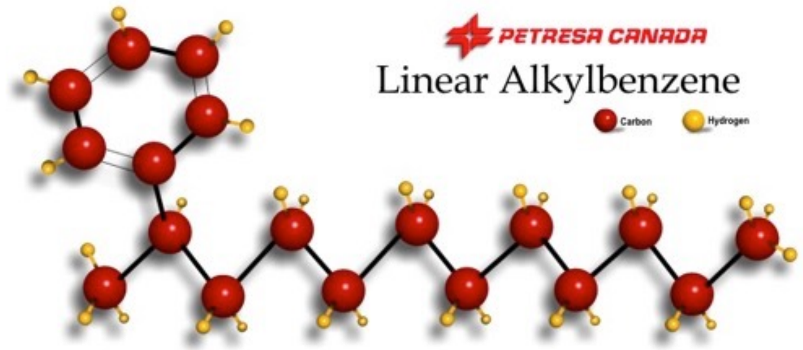
viewed by ~ 9300 PMTs (8'') mounted on 17 m diam. structure

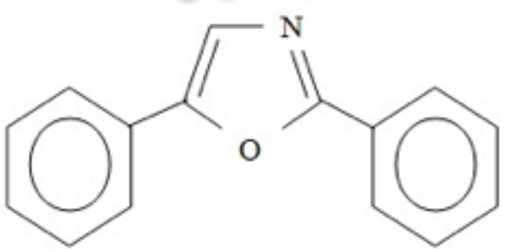
shielded by 7 kt ultra-pure water



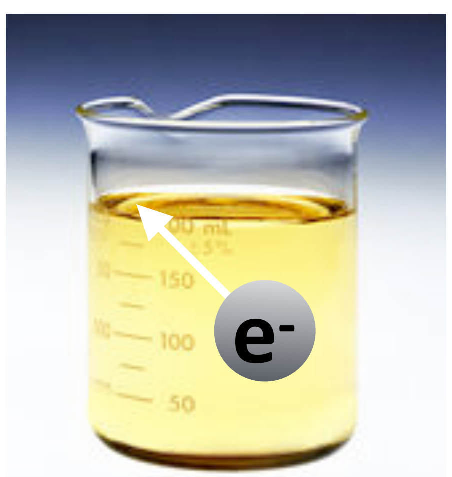


Scintillation detectors

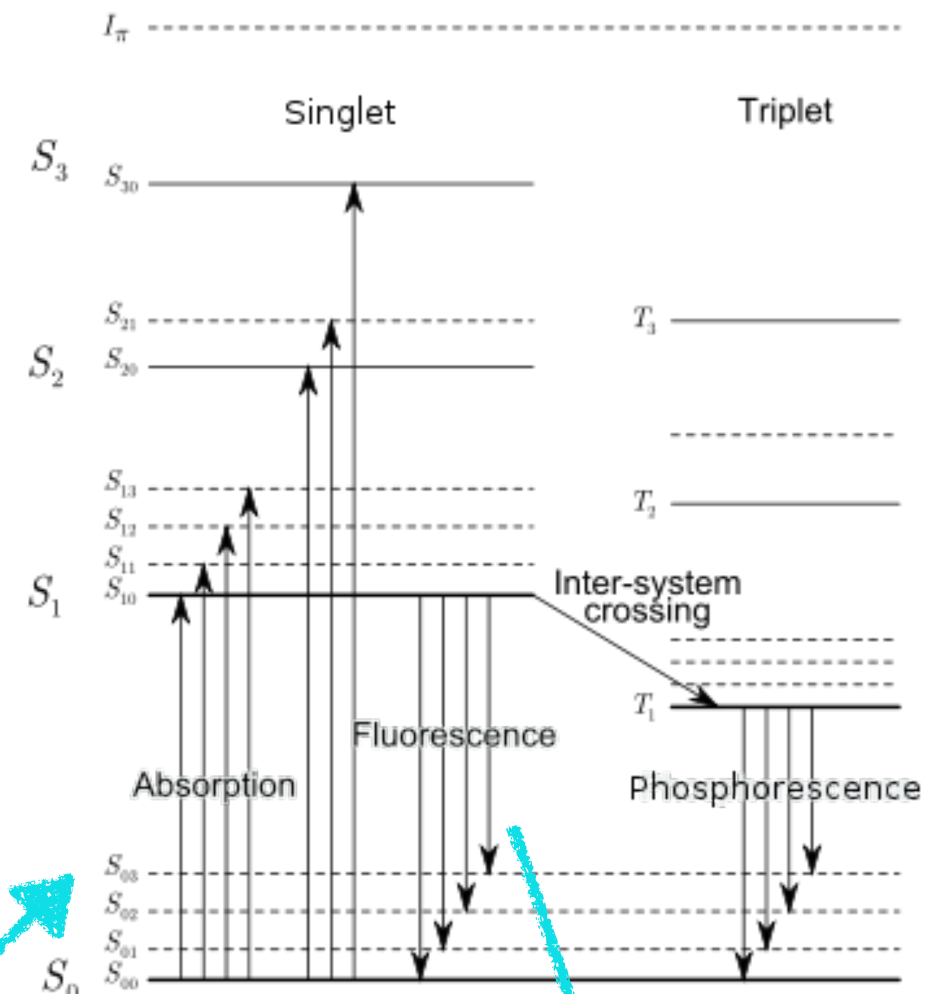




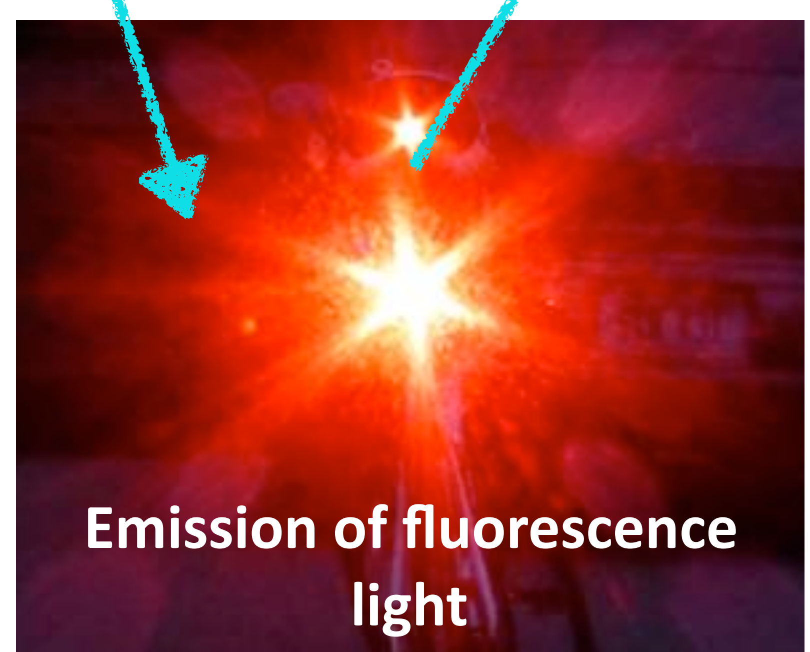
LAB + 2g/l PPO



Charged particle excites scintillator molecules



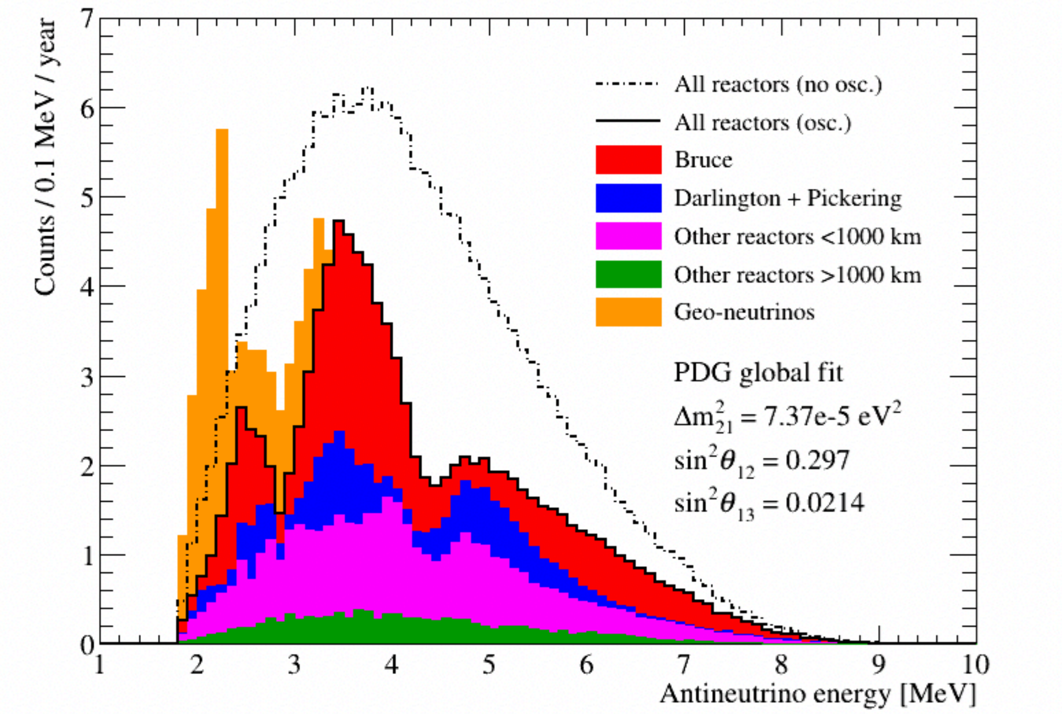
Detected by photomultiplier

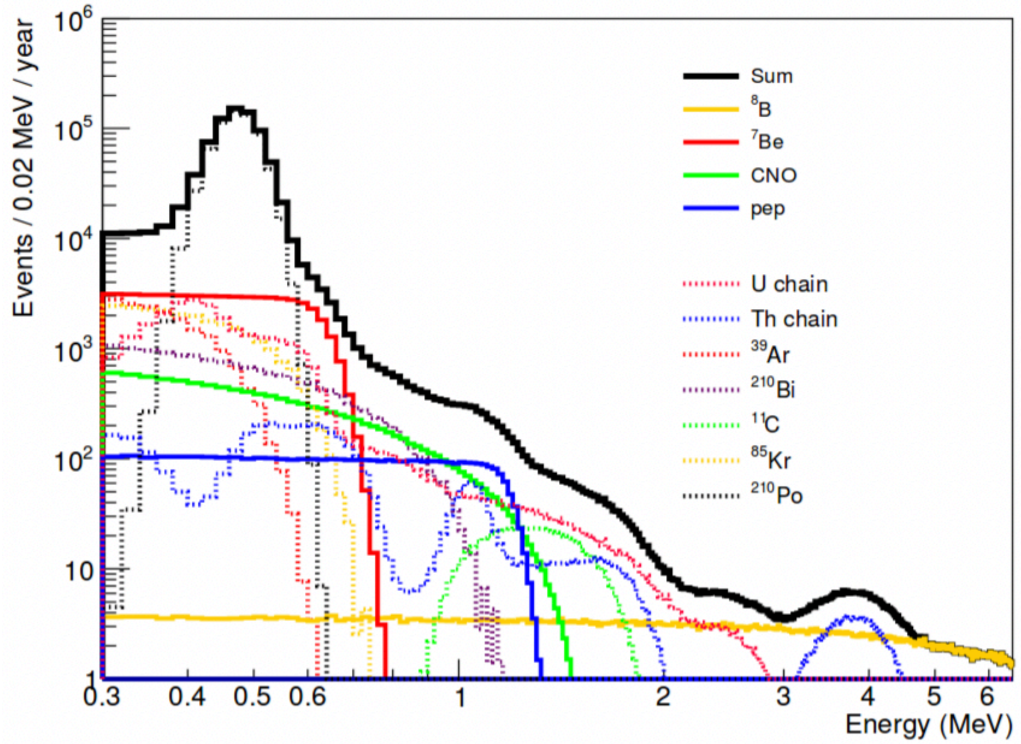


SNO+ physics program

…780 ton scale low background calorimeter

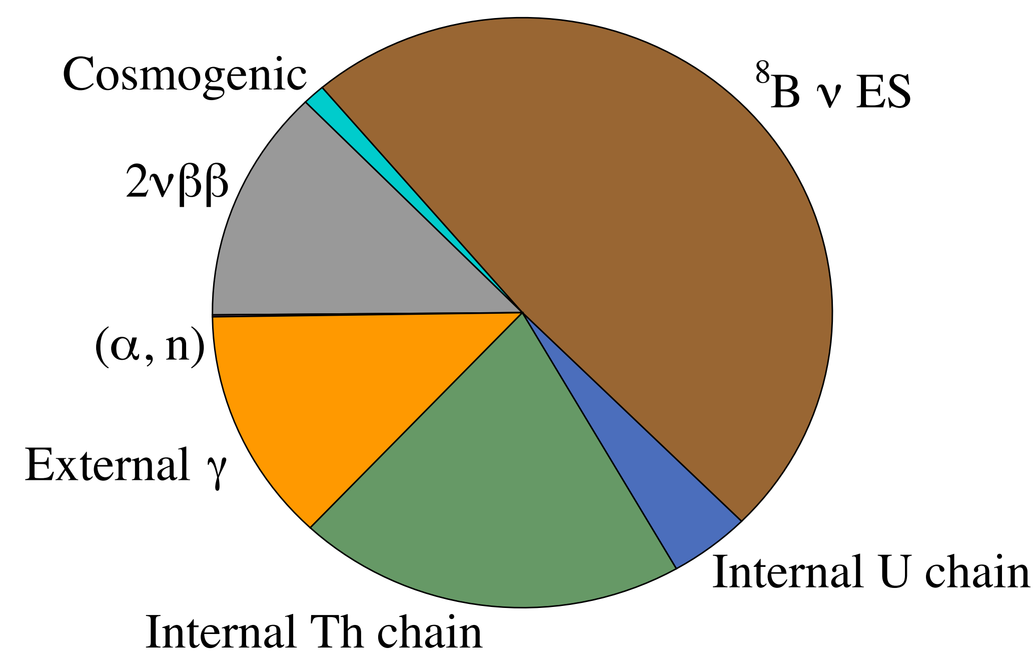
- Main objective:
  - **Search for 0νββ in ^{130}Te**
- Other topics of interest
  - Solar neutrinos
  - Nucleon decay
  - Supernova neutrinos
  - Reactor and geo-antineutrinos





SNO+ background model for 0νββ

ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47



^{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, cool down (Te already underground)

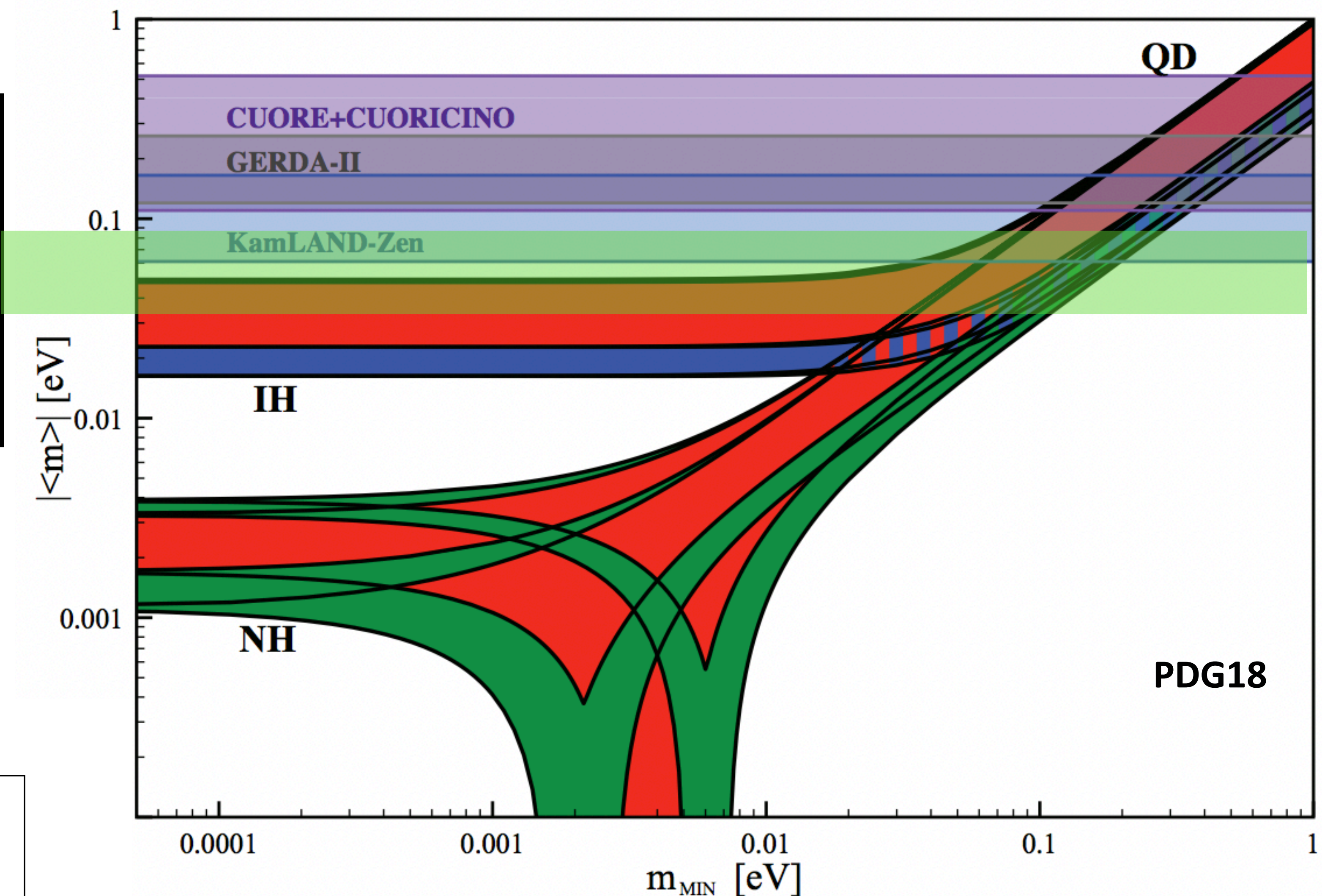
(α, n)

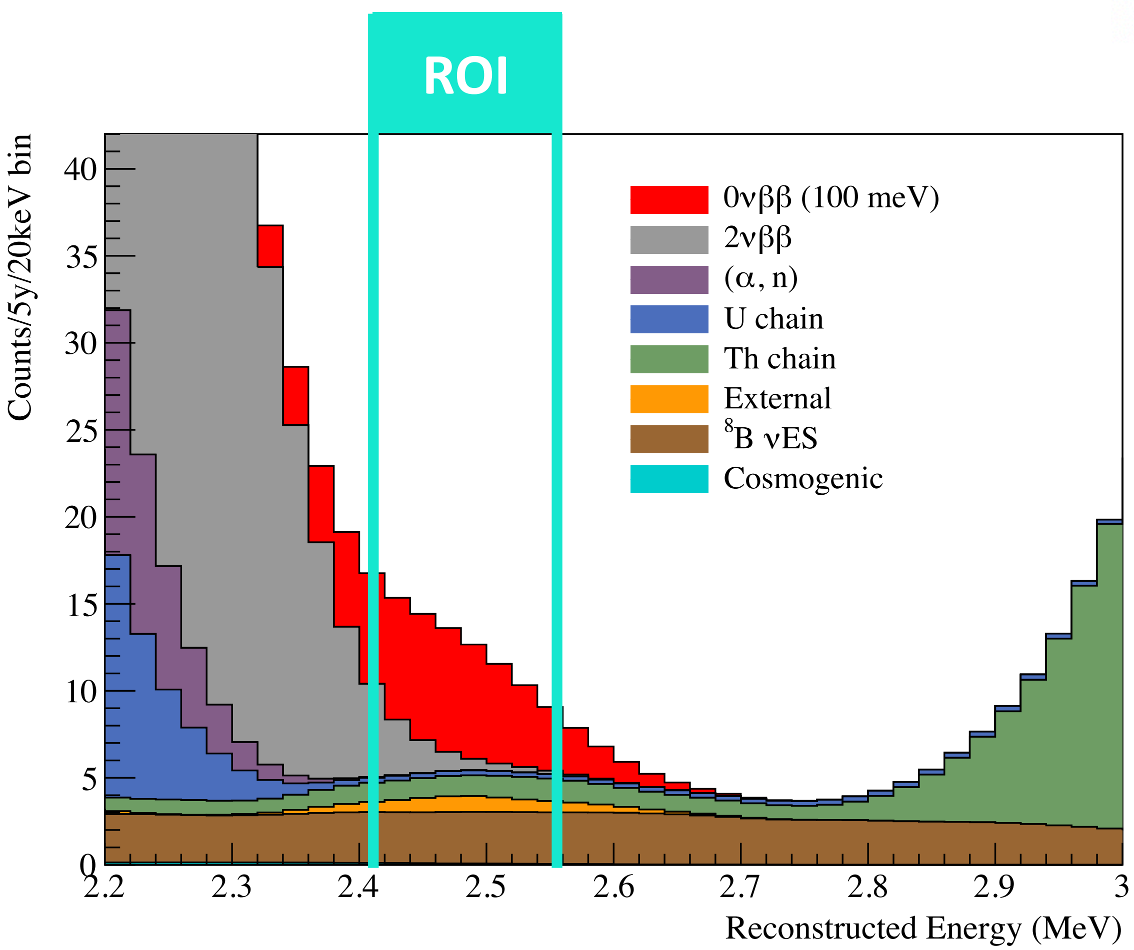
- Thermal neutron capture
- Delayed coincidence

SNO+ 0νββ sensitivity

SNO+ Expectation after 5 years data taking:

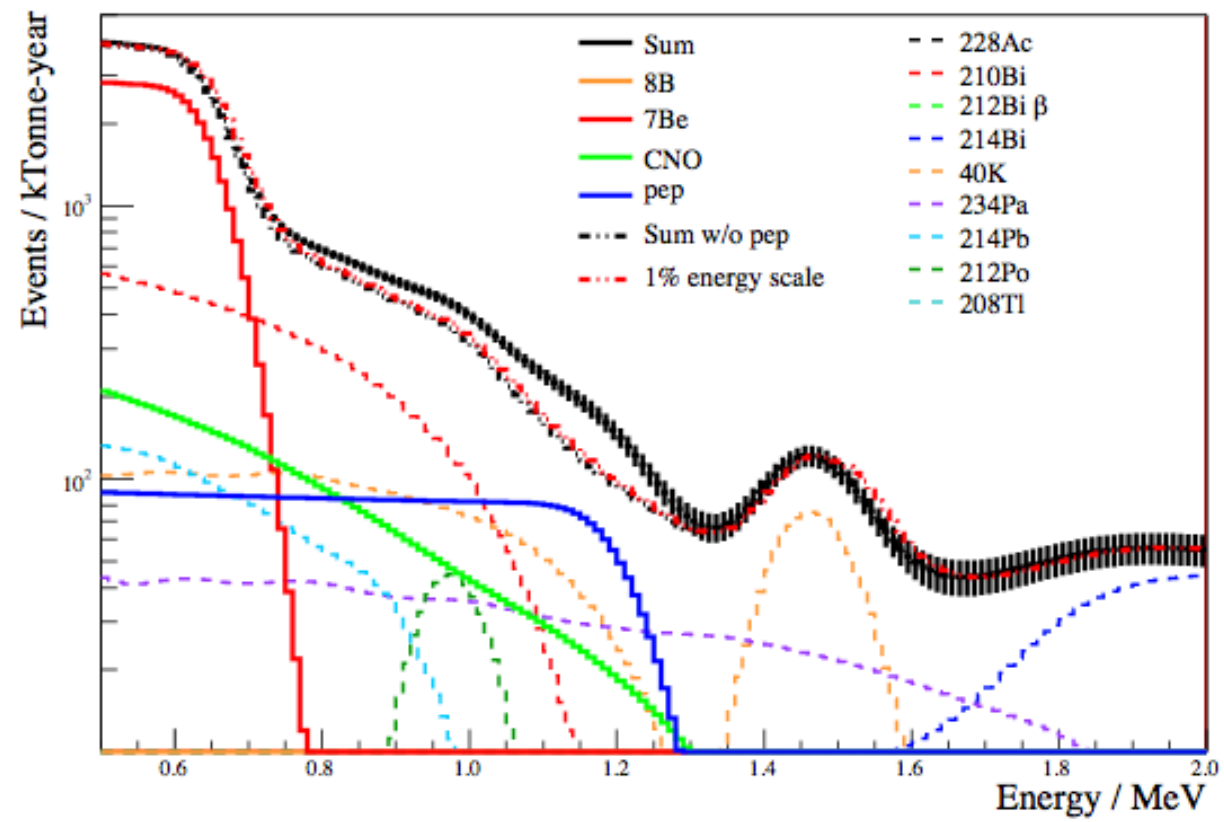
T1/2 > 2.1x10^26 years
37 meV < $m_{\beta\beta}$ < 89 meV

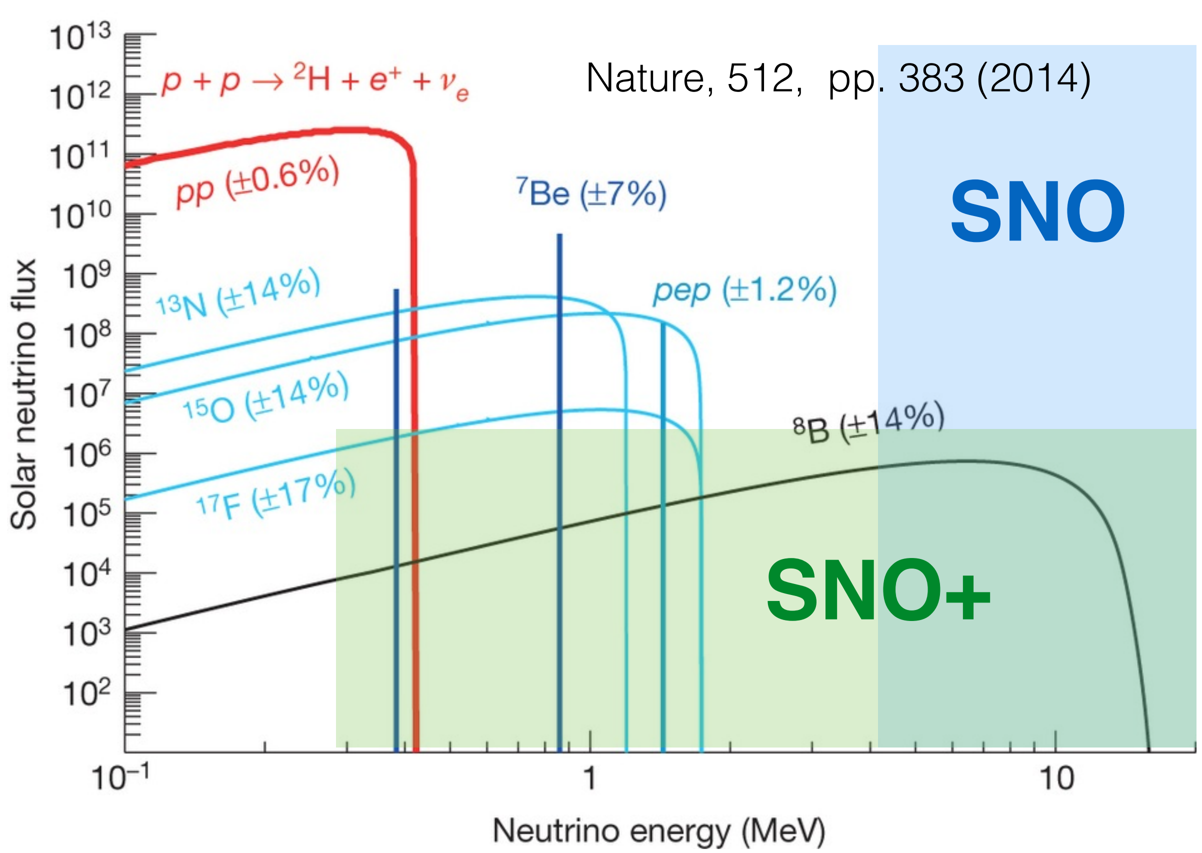


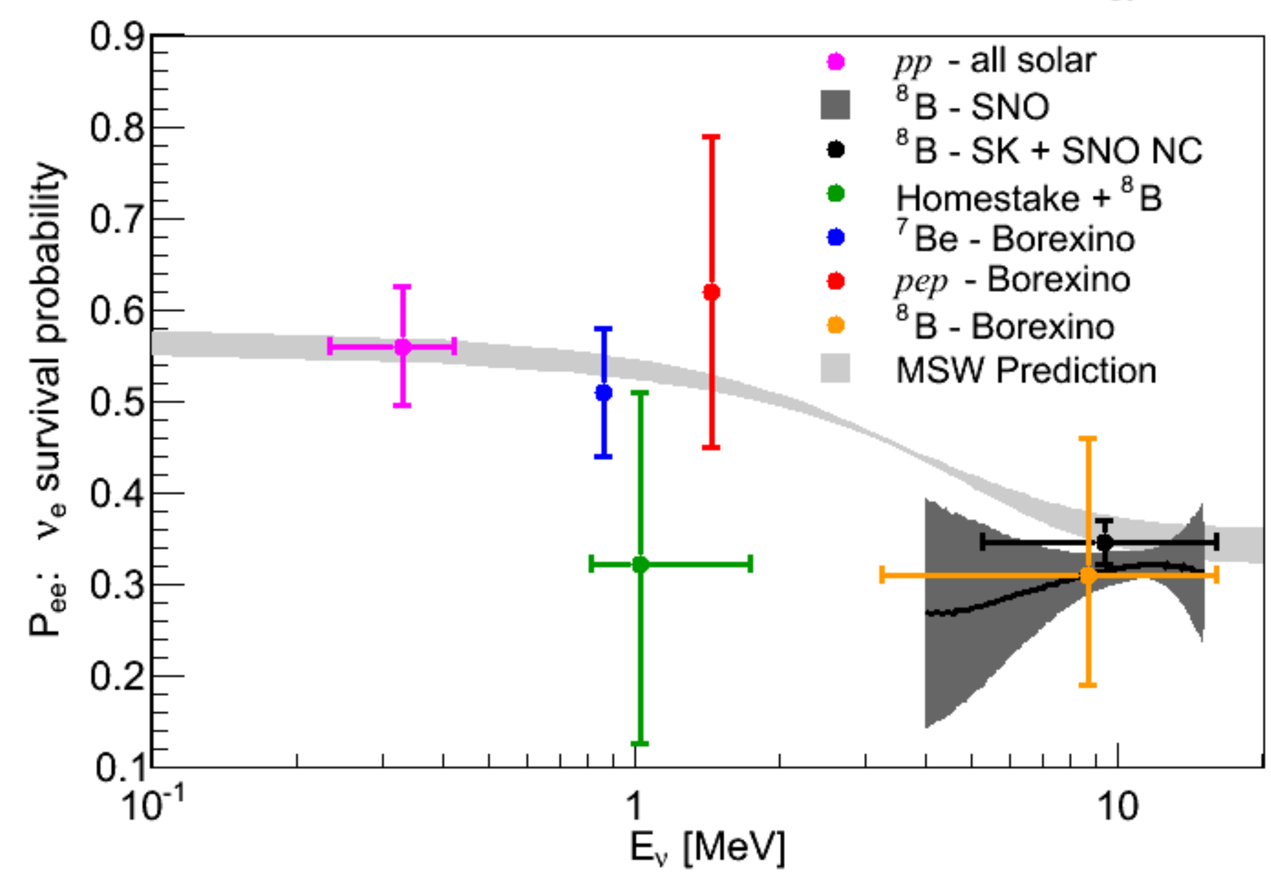


Solar Neutrinos

- **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

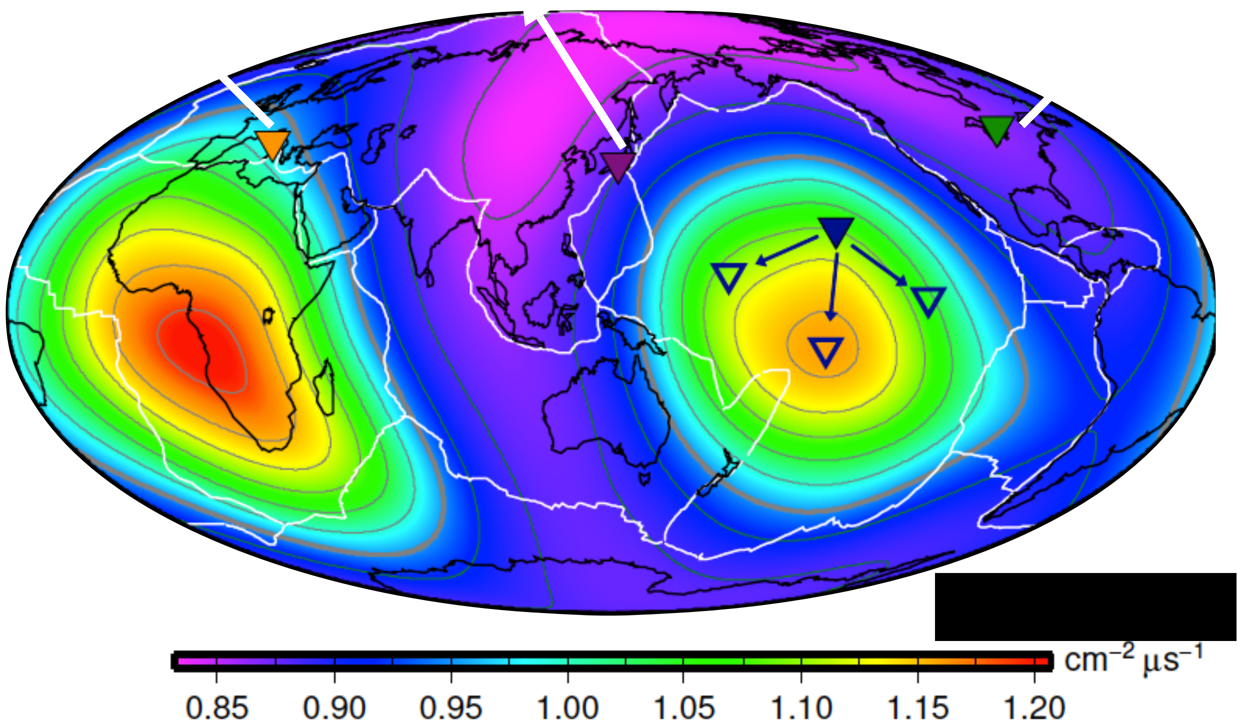


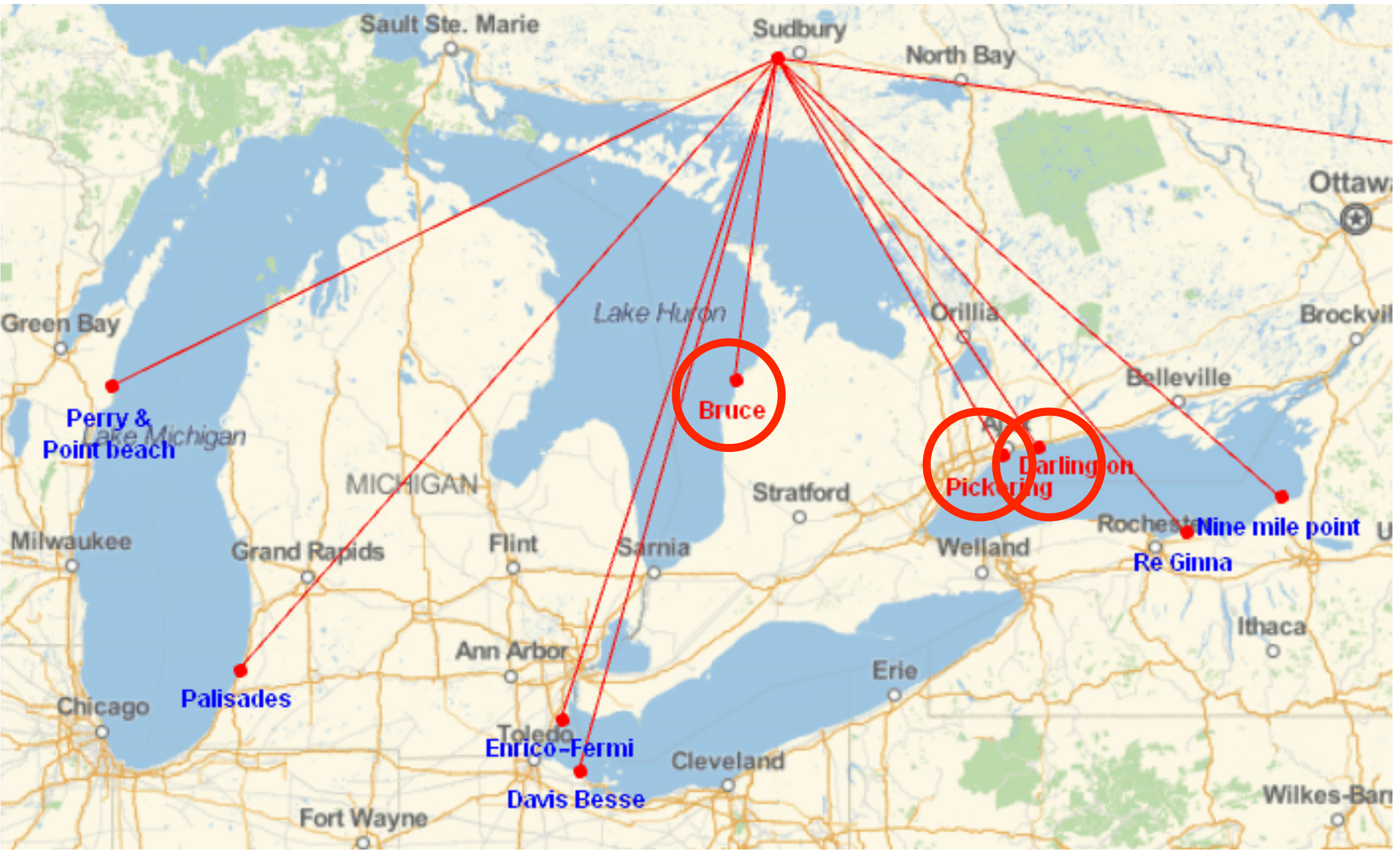


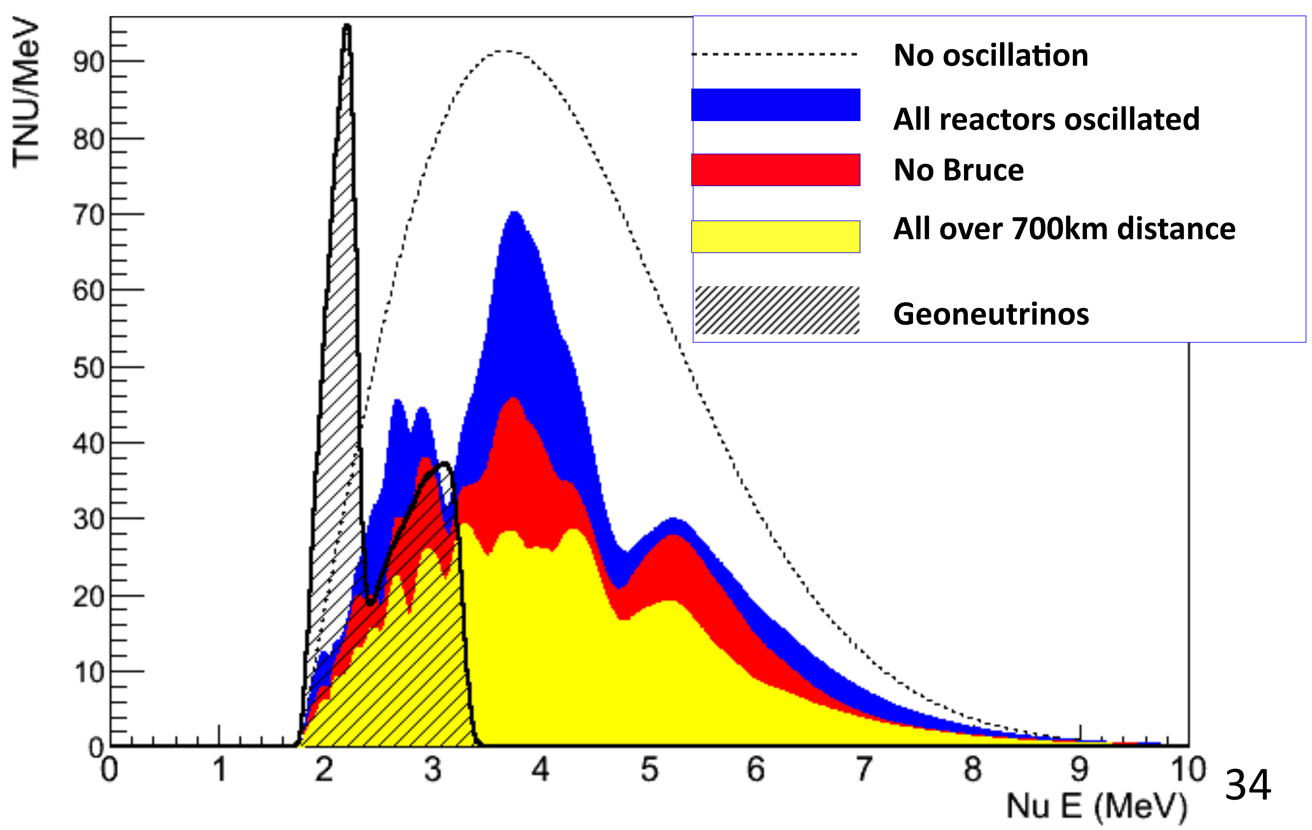


Reactor and geo-antineutrinos

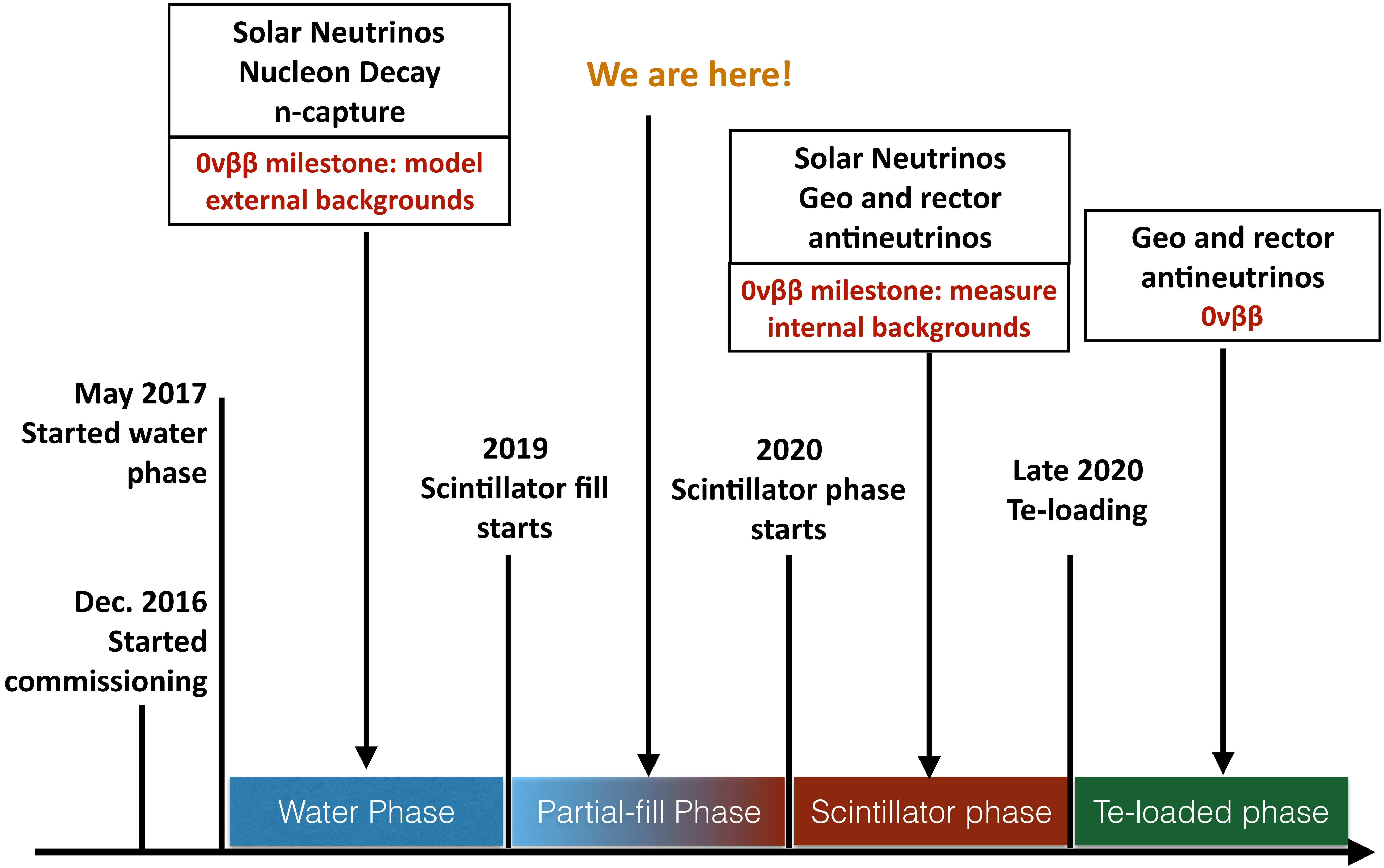
- Detection through inverse beta decay
  - Delayed coincidence e^+ annihilation and n capture
- **Geo**
  - U, Th and K in Earth's crust and mantle
  - Investigate origin of the heat produced within Earth
- **Reactor**
  - 3 nearby reactors dominate flux
  - Precision probe of neutrino oscillations



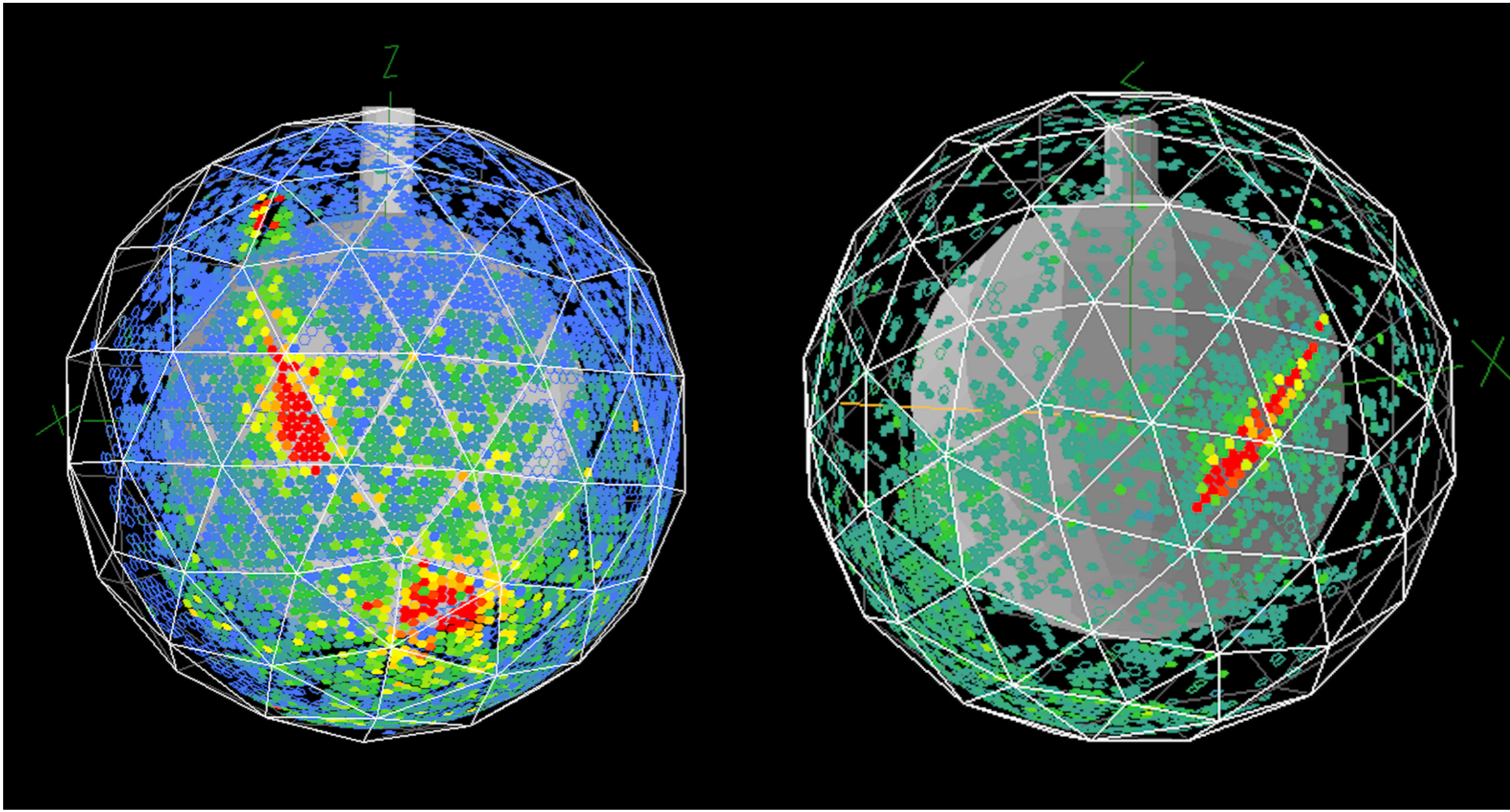




SNO+ timeline



First water data



Double Muon candidate **“Grazing” Muon candidate**

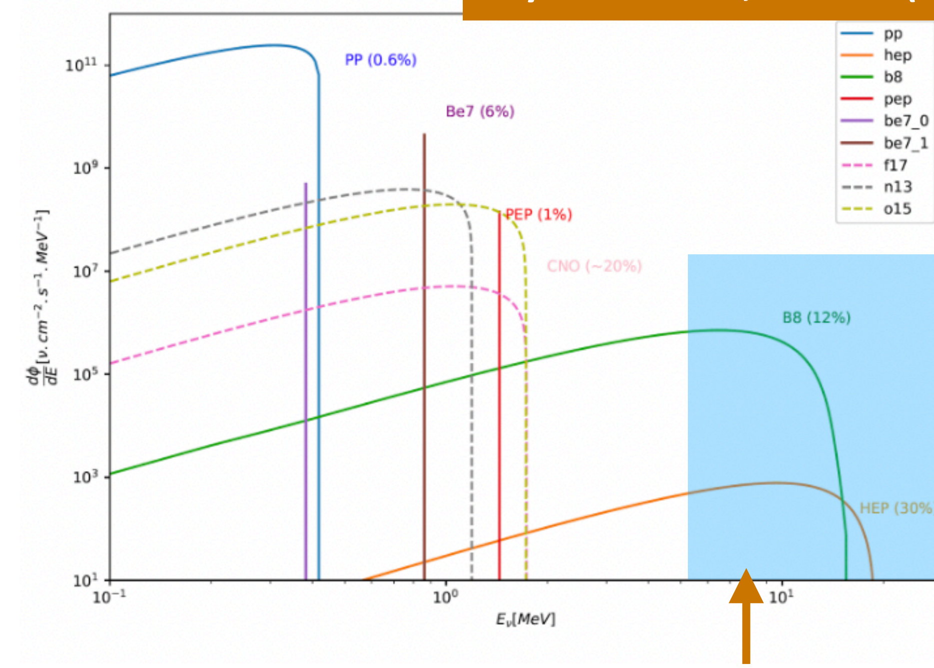
Solar neutrino measurement

- Measured 8B flux
  - Use only direction to Sun (energy)
  - Results compatible with existing measurements

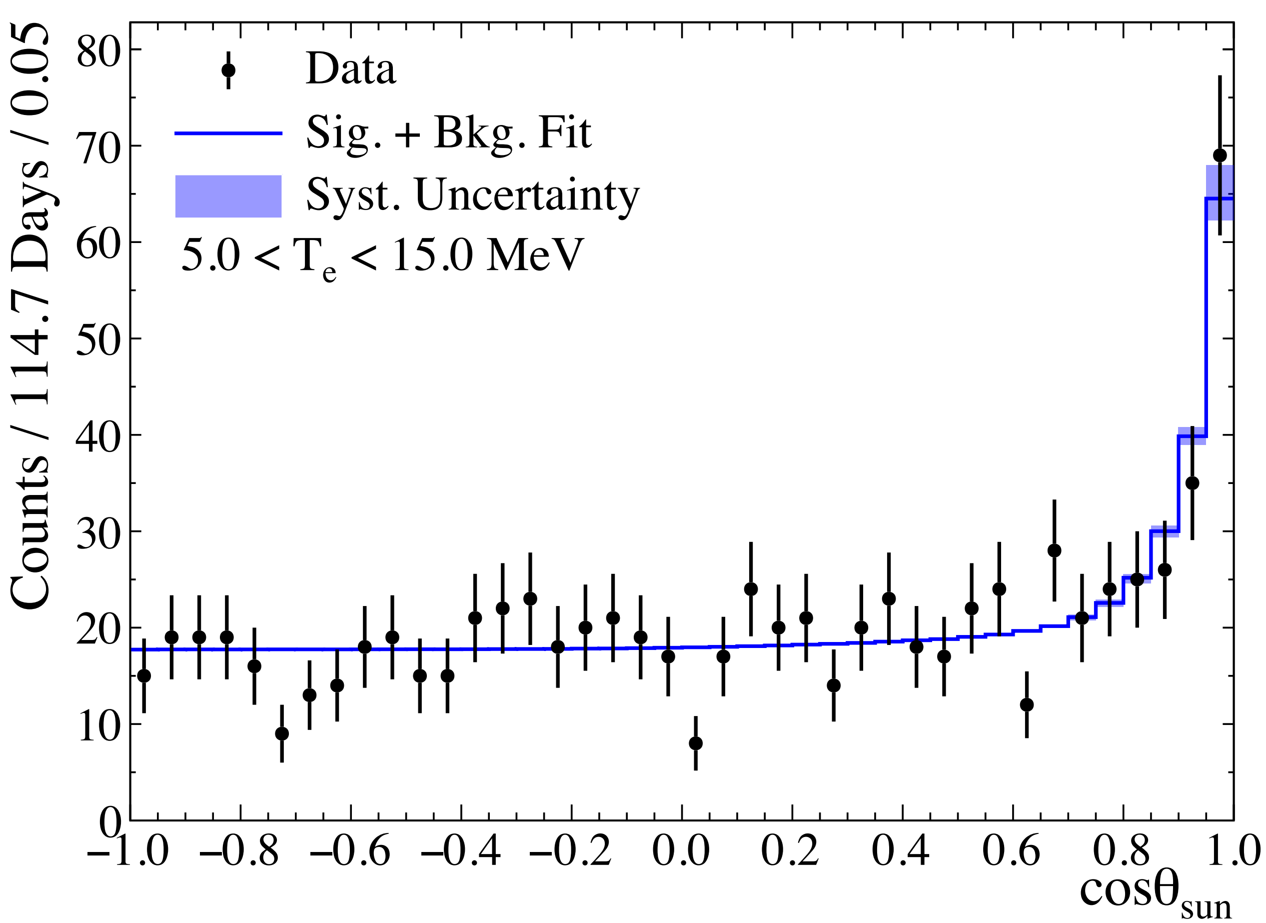
SNO+ (This work): $\Phi_{^8\text{B}} = 5.95^{+0.75}_{-0.71}(\text{stat.})^{+0.28}_{-0.30}(\text{syst.}) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$

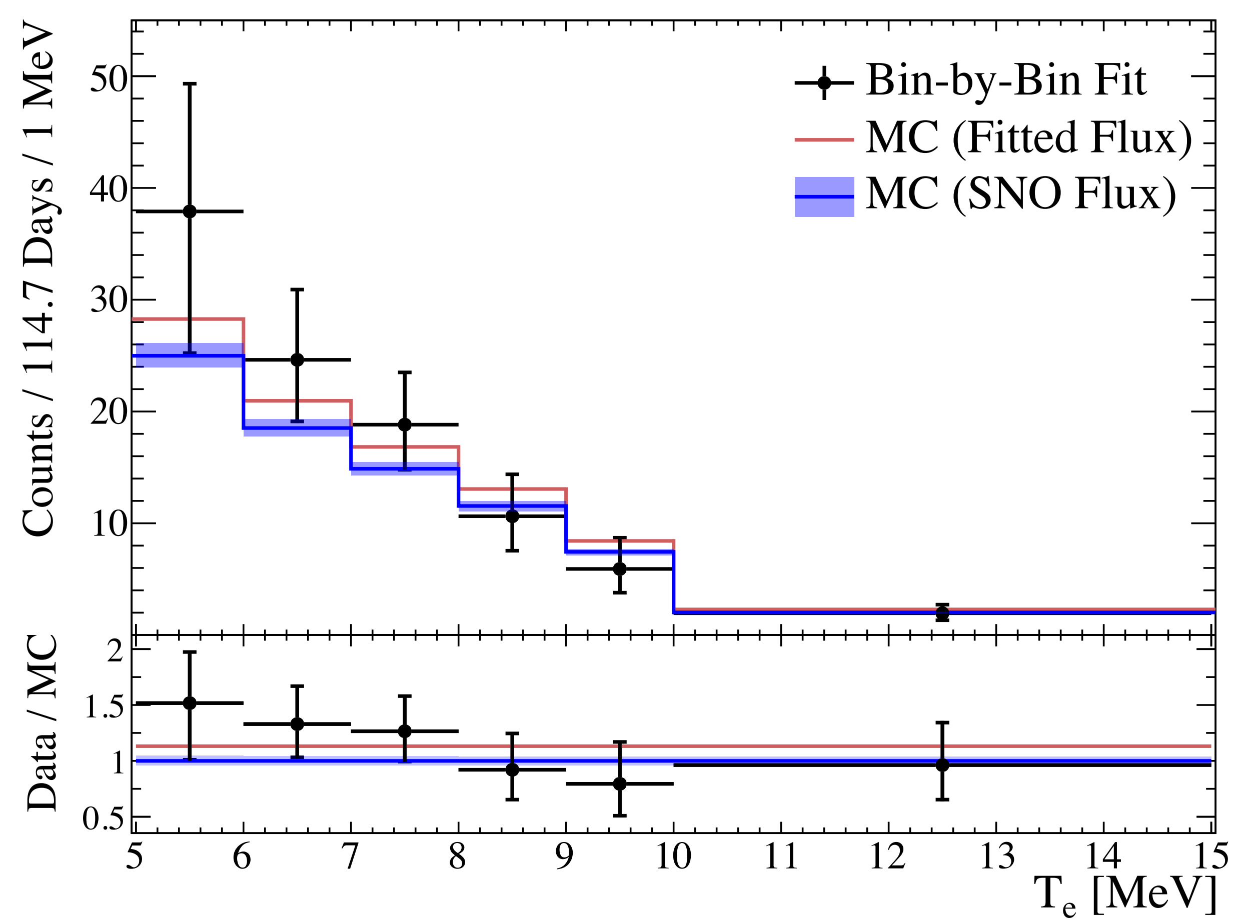
SNO: $\Phi_{^8\text{B}} = (5.25 \pm 0.16(\text{stat.})^{+0.11}_{-0.13}(\text{syst.})) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$

Phys. Rev. D 99, 012012 (2019)



SNO+ sensitive region





Summary

- **In the last 20 years a lot was learned about neutrinos**
    - They oscillate (and we know how)
    - They are massive (but we don't know how much)
- **Much more is still unknown**
  - Are neutrinos their own antiparticles?
  - What is the absolute mass scale?
  - What is the CP violation phase?
  - What is the mass hierarchy?
- **A whole zoo of experiments are trying to address these questions**
  - A rich field of opportunities is in place