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LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
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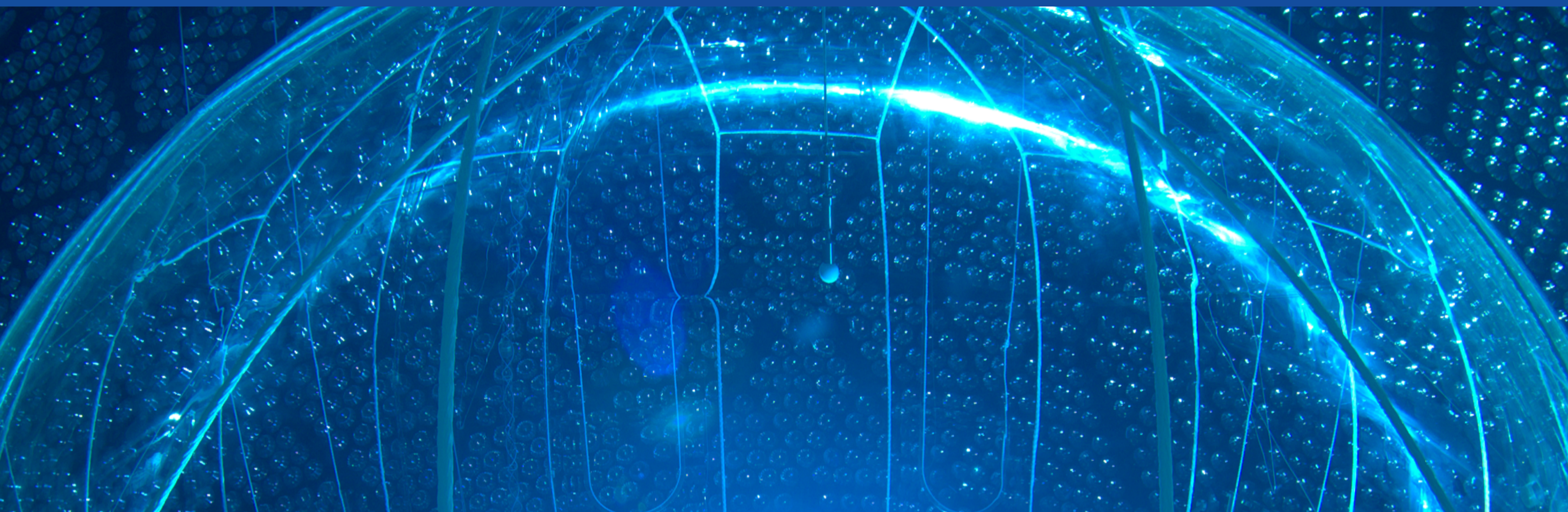
Neutrinos: oscillations, mass and how to measure them

Nuno Barros, LIP/UC



Mini-School on Particle and Astroparticle Physics - May 9th, 2022

Neutrinos, a desperate hypothesis to solve beta decay

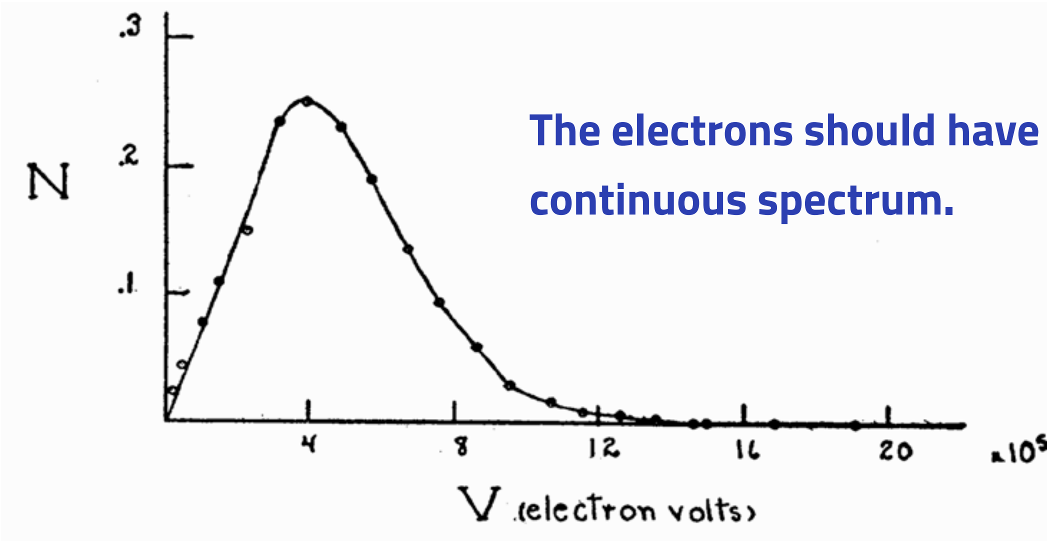
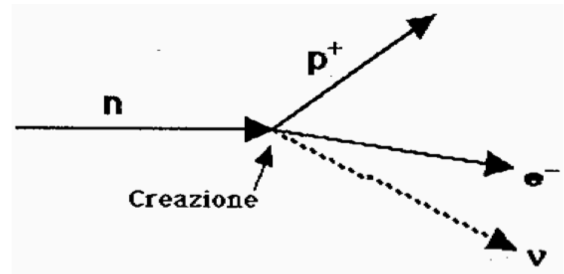


FIG. 5. Energy distribution curve of the beta-rays.

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



Pauli

"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)

Fermi

neū · trï'nō : small neutral object

Neutrinos as the window into the Universe

A rather unique particle…

- Have no charge - do not participate in electromagnetism
  - **Could be their own anti-particles**

- Are the **second most abundant** particle in the visible universe
  - After photons

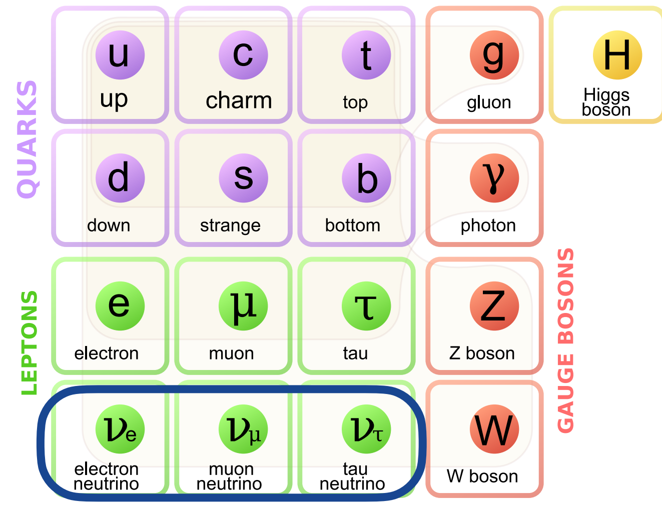
- Come in three flavours
  - Paired with the corresponding charged leptons

- Are very light
  - For a long time thought to be massless

- Interact very weakly
  - Only participate in the weak interaction

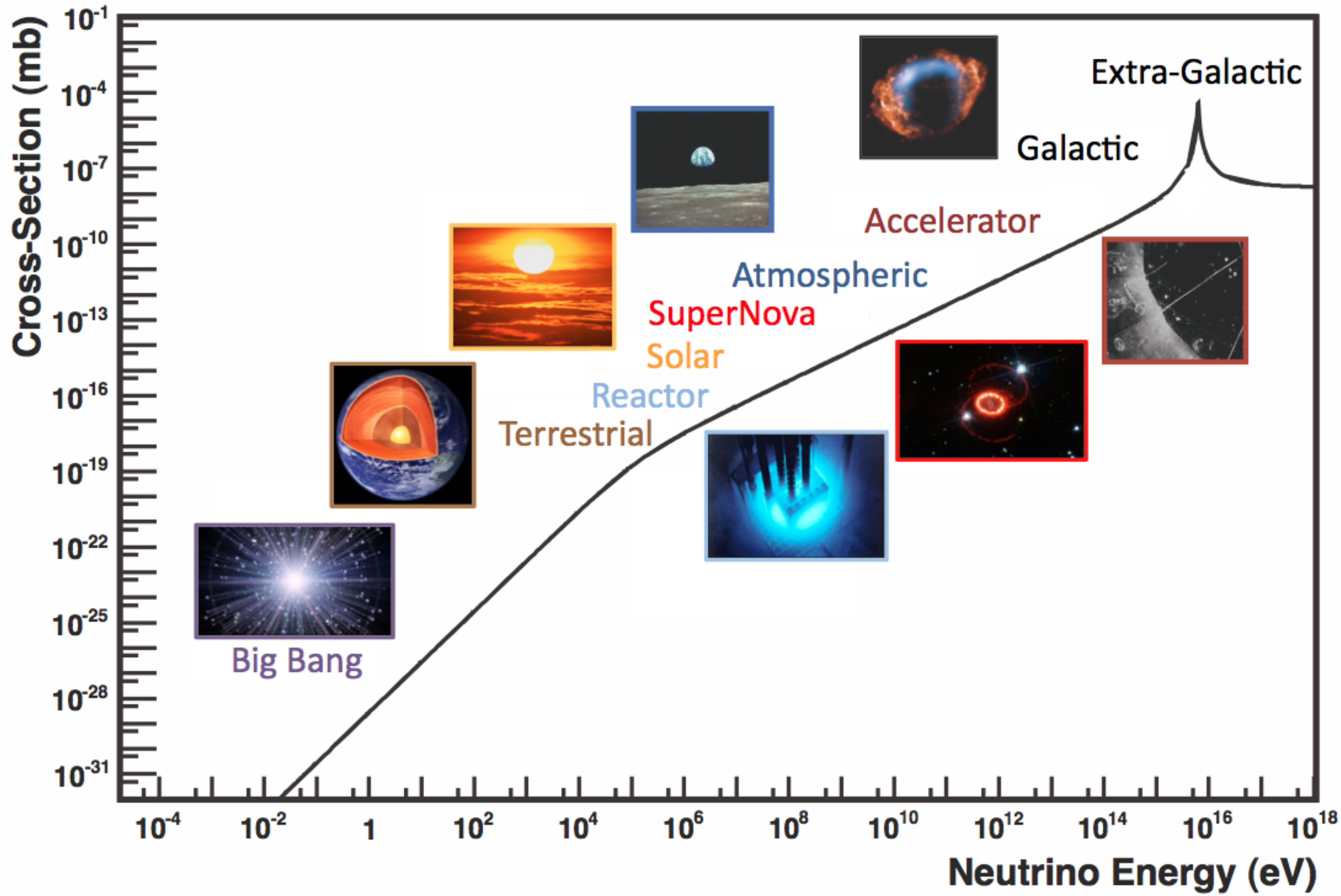
- They change flavour
  - Neutrino oscillations imply massive neutrinos

The table of known elementary particles



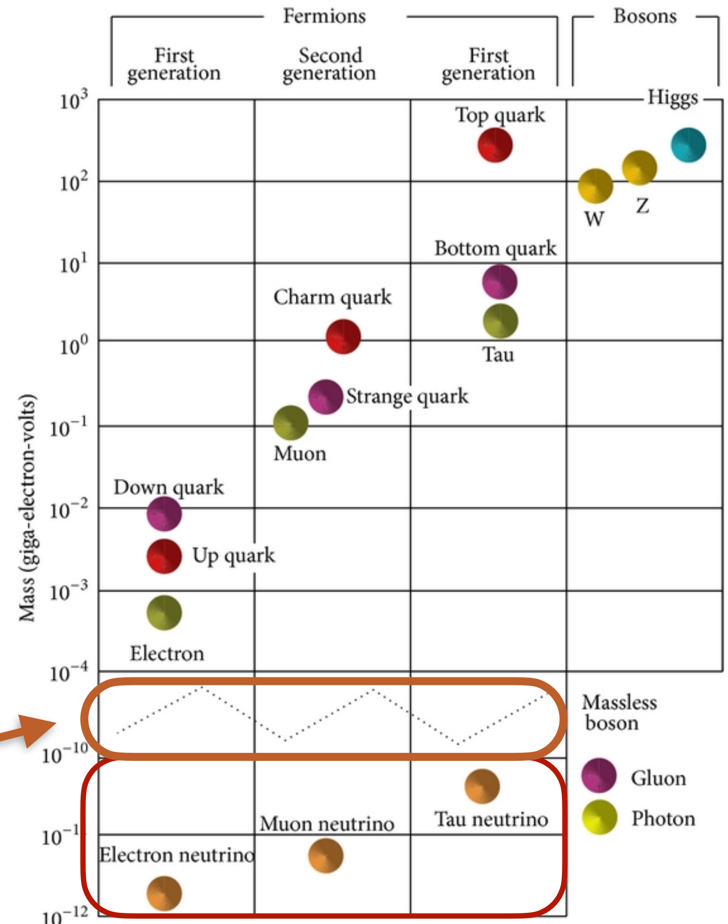
Where do neutrinos come from?

...everywhere, every energy, every time!



Neutrinos have mass

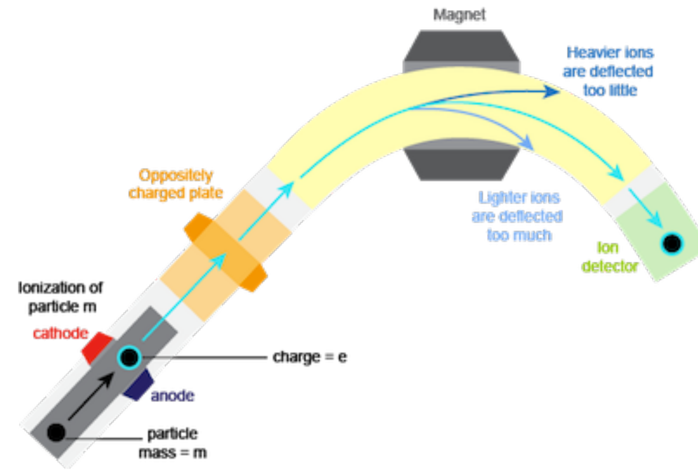
- ν masses are much smaller than other particles
- Other particles get mass because they are
  “slowed down” by the Higgs field.
- **Neutrino masses are so small, perhaps they get mass some other way?**



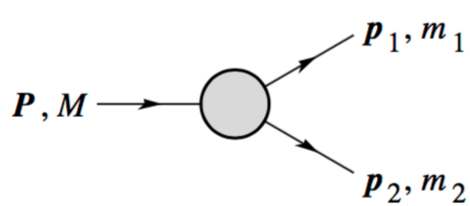
“the desert” (6 orders of magnitude long)

Why so small?

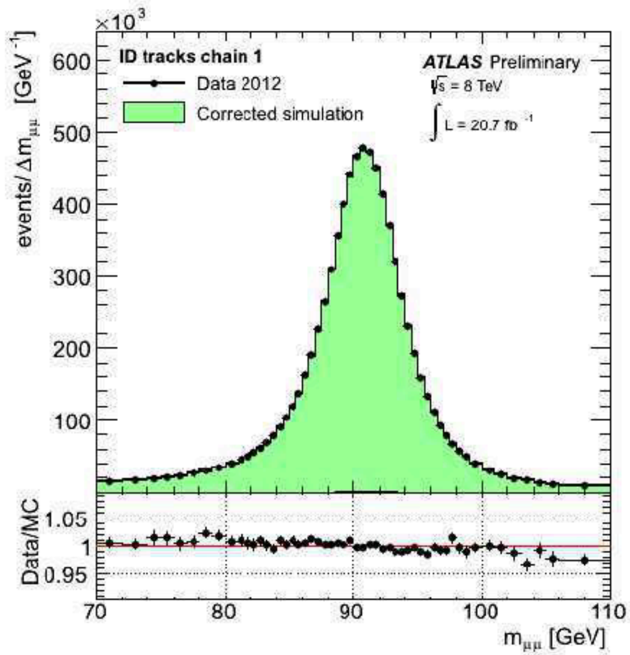
Neutrino mass is hard to measure



- Neutrinos are massless in the Standard Model
- 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 into others ✗
- **Use quantum interference to probe neutrino mass** ✓



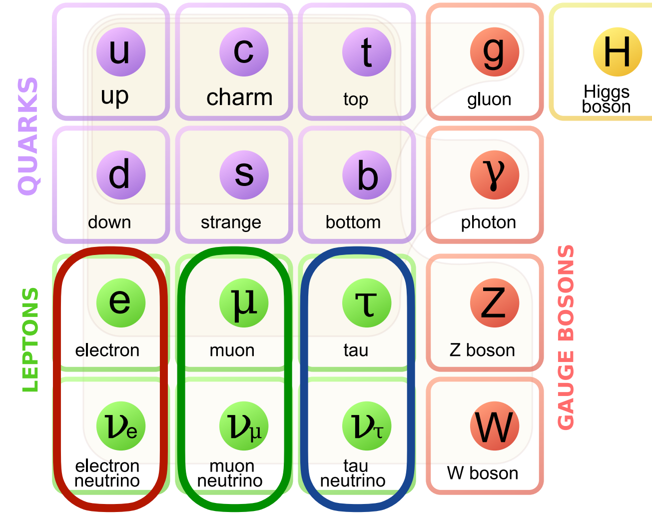
$$M^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$



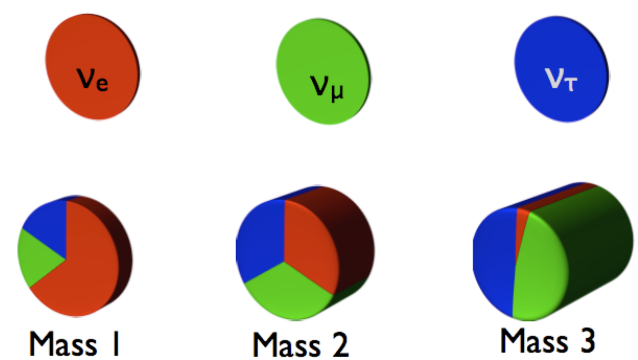
Neutrino states

Weak flavour states vs mass states

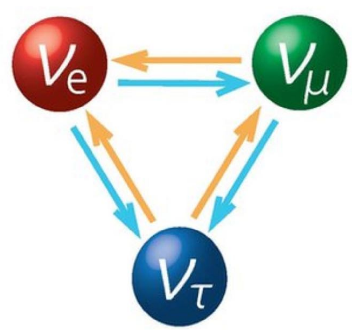
- **Neutrinos come in three “flavours”**
  - According to the lepton they produce when they have weak CC interactions



- **Neutrinos also come in three mass states**
  - But these states are not the same!!



- **If these masses are non-zero, flavour can change when neutrinos propagate!**
  - **Neutrino Oscillations!**



Neutrino Oscillations

Short introduction with two flavours

- The weak flavour eigenstates (ν_e, ν_μ) are different from the mass eigenstates (ν_1, ν_2)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- The weak states are mixtures of the mass states:

$$|\nu_\mu> = -sin\theta|\nu_1> + cos\theta|\nu_2>$$

$$|\nu_\mu(t)> = -sin\theta\ (|\nu_1> e^{-iE_1 t}) + cos\theta\ (|\nu_2> e^{-iE_2 t})$$

- This leads to an **oscillation probability**

$$P_{\text{oscillation}}(\nu_\mu \longrightarrow \nu_e) = \left|\langle \nu_e | \nu_\mu(t) \rangle\right|^2 = \sin^2 2\theta_{12} \sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right)$$

Fundamental oscillation parameters:

- θ : Magnitude of oscillation
- Δm^2 : period

Experimental parameters:

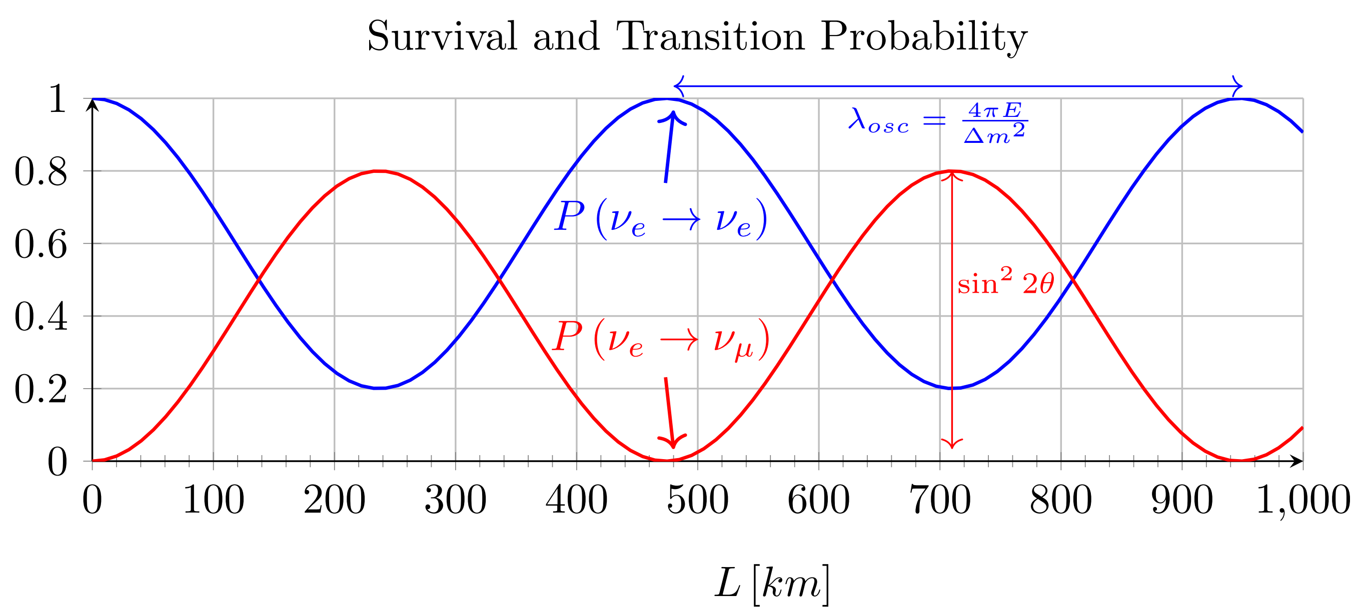
- L : Distance from source to detector
- E : Neutrino energy

Neutrino Oscillations

How to plan a neutrino oscillation experiment

$$P_{\text{oscillation}}\left(\nu_\mu \longrightarrow \nu_e\right) = \left|\left\langle \nu_e | \nu_\mu(t) \right\rangle\right|^2 = \sin^2 2\theta_{12} \sin^2\left(1.27\,\Delta m^2_{21} \frac{L}{E}\right)$$

- Choose **L** and **E** adequate to the ranges of Δm^2 of interest
- Get a suitable neutrino source (accelerator, reactor, the Sun...)
- Collect (a lot of) data and "see" neutrinos **appearing** and **disappearing**



Neutrino Oscillations

...now in three flavours!

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

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12}-s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12}-s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12}-s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12}-s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{bmatrix} 0.82\pm0.01 & 0.54\pm0.02 & 0.15\pm0.03 \\ 0.35\pm0.06 & 0.70\pm0.06 & 0.62\pm0.06 \\ 0.44\pm0.06 & 0.45\pm0.06 & 0.77\pm0.06\end{bmatrix}$$

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

$$P\left(\nu_\alpha \longrightarrow \nu_\beta\right) \neq P\left(\overline{\nu}_\alpha \longrightarrow \overline{\nu}_\beta\right)$$

- **Neutrino oscillations are consistent with being mass driven**

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

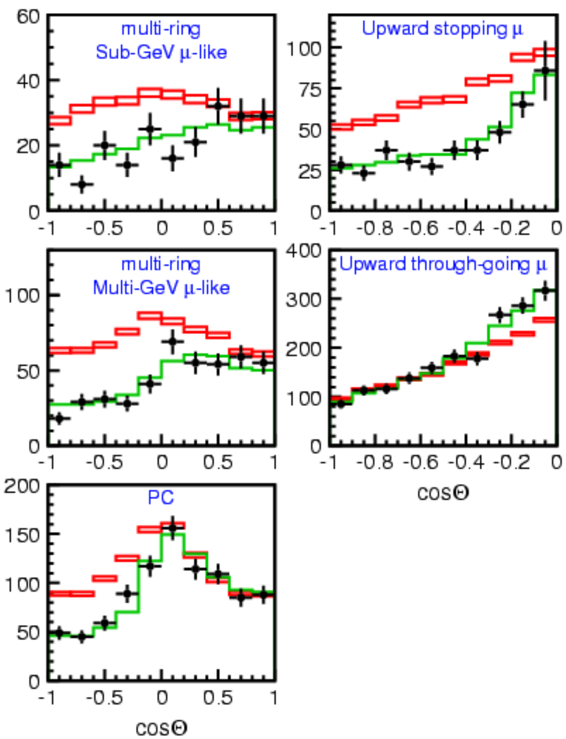
CP violating term (third line)

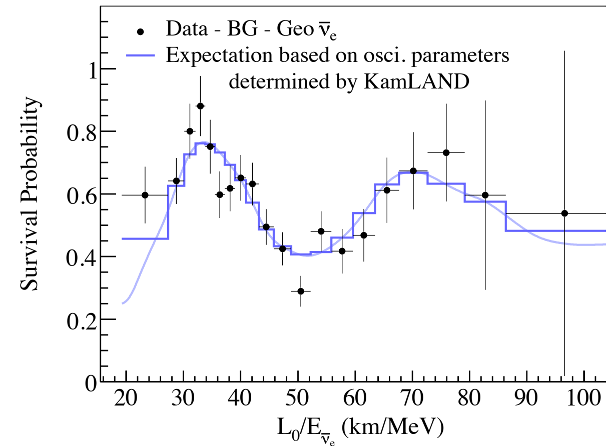
Matter term (last line)

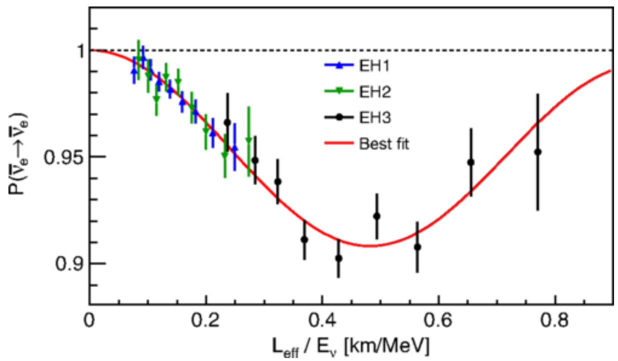
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

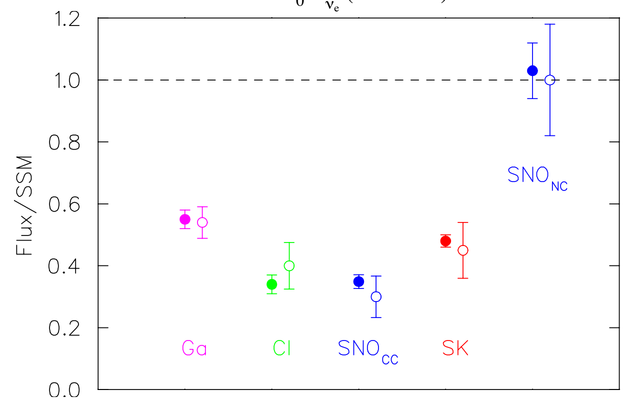
Neutrino Mass and Oscillations

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

LBL reactor + Solar

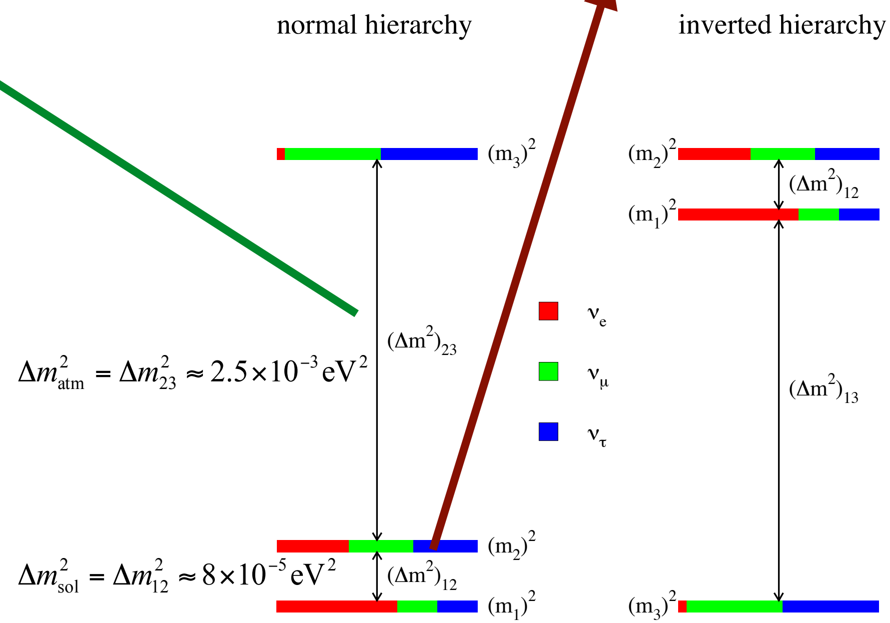
What have we learned in the last ~20 years

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

Accelerator and Atmospheric | **SBL reactor** | **Solar + LBL reactor**

	VALUE
$\lvert\Delta m^2_{32}\rvert$	2.52±0.04 E-03 (eV^2)
Δm^2_{21}	7.40±0.21 E-05 (eV^2)
$\sin^2\theta_{12}$	0.31±0.01
$\sin^2\theta_{23}$	$0.56^{+0.02}_{-0.12}$
$\sin^2\theta_{13}$	0.022±0.0007
δ_{CP}	$(-0.4\pm0.09)\pi$?

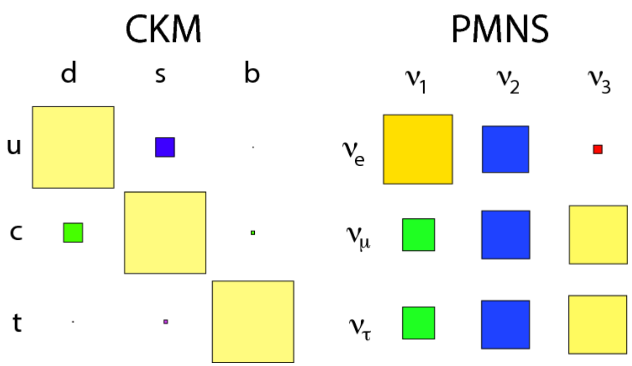
NuFit Results

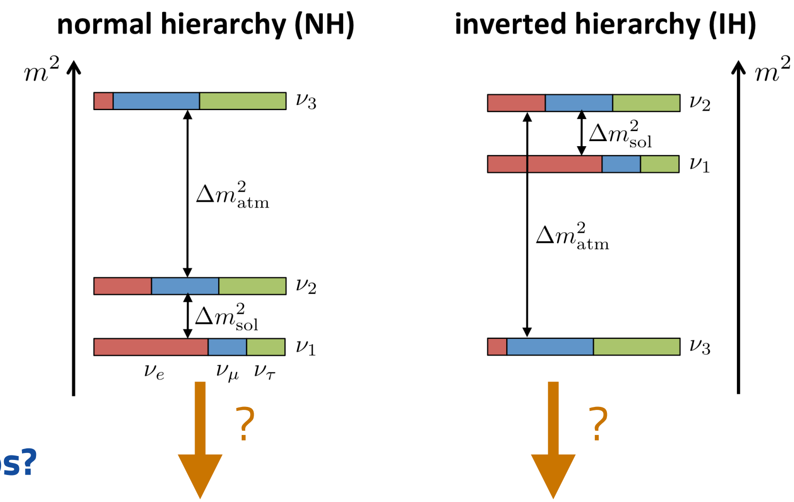


What haven't we learned yet about neutrinos

Many questions waiting for answers!

- **Do neutrinos and antineutrinos oscillate in the same way?**
  - Do they violate the CP symmetry?
- **What is the ordering of their masses?**
- **What are the precise values of the neutrino mixing parameters?**
  - Why are these parameters so different from the quarks?





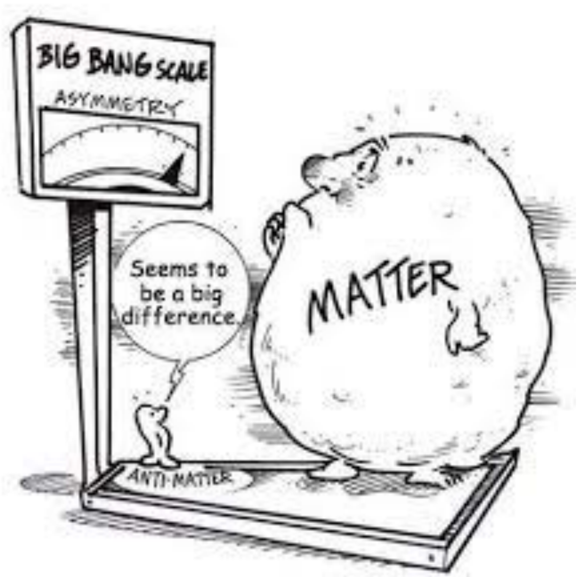
- **What is the absolute mass of the neutrinos?**
- **Are neutrinos Majorana or Dirac particles?**
  - Are neutrinos their own antiparticles?

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

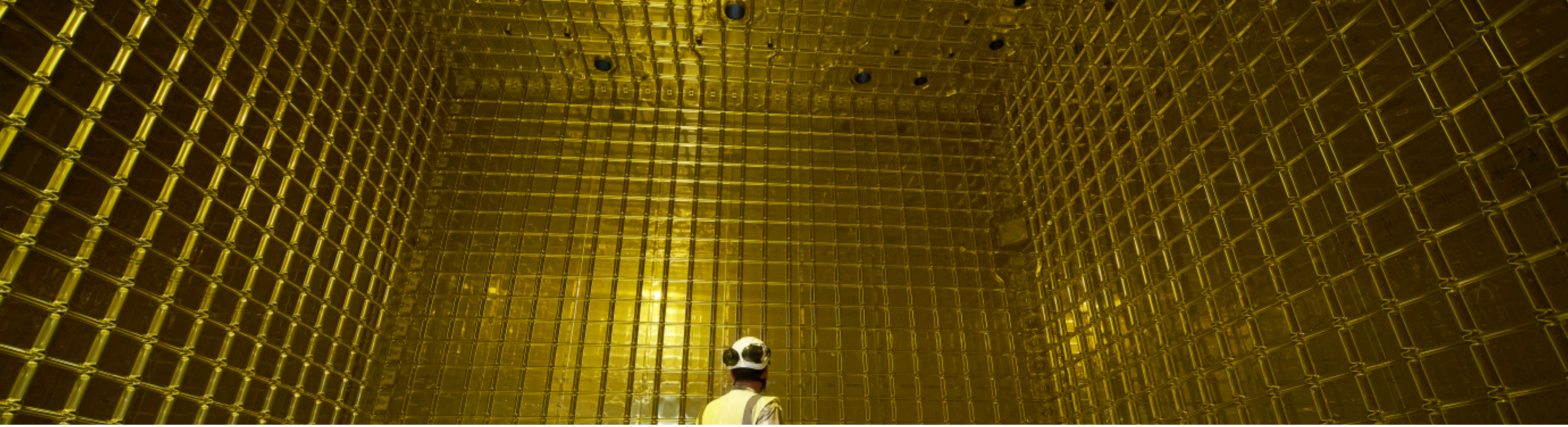
SNO+

Why do we care?

Where is all the antimatter?



- Physics laws need to be slightly different for particles and antiparticles
- The asymmetry in the quark sector **cannot** explain the difference
- **An asymmetry in the lepton sector could solve the mystery**
  - Heavy neutrinos produced in the Big Bang (**Majorana particles**)
  - They decay into light particles
  - Due to **CP violation**, they have a preference to decay into particles, instead of anti-particles



The future of Neutrino Oscillations

CP Violation and Mass Hierarchy with the DUNE Experiment

DUNE - Testing the ν model

- **We currently have a model that has several parameters**
  - But the data that it explains is rather limited

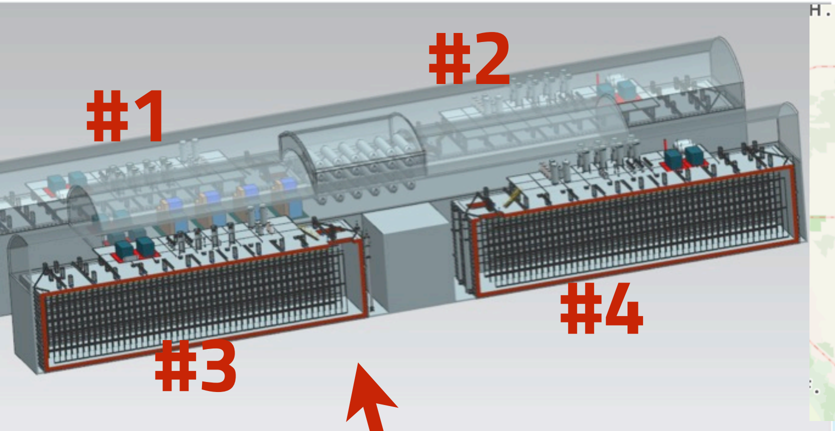
- **What predictions from the model can we check?**
  - L/E (or just L, or just E) oscillation behaviour
  - Universality of the parameters (Δm^2, θ)
  - **CP violation if δ is non-zero**

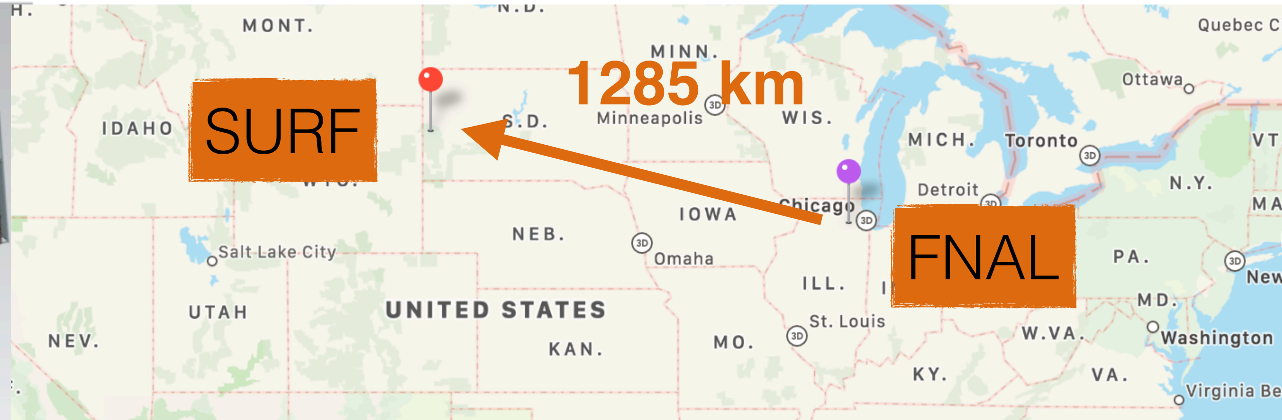
- Neutrino oscillations give us a natural "interferometer"
  - **Anything that distinguishes flavours (or mass states) alters the pattern**

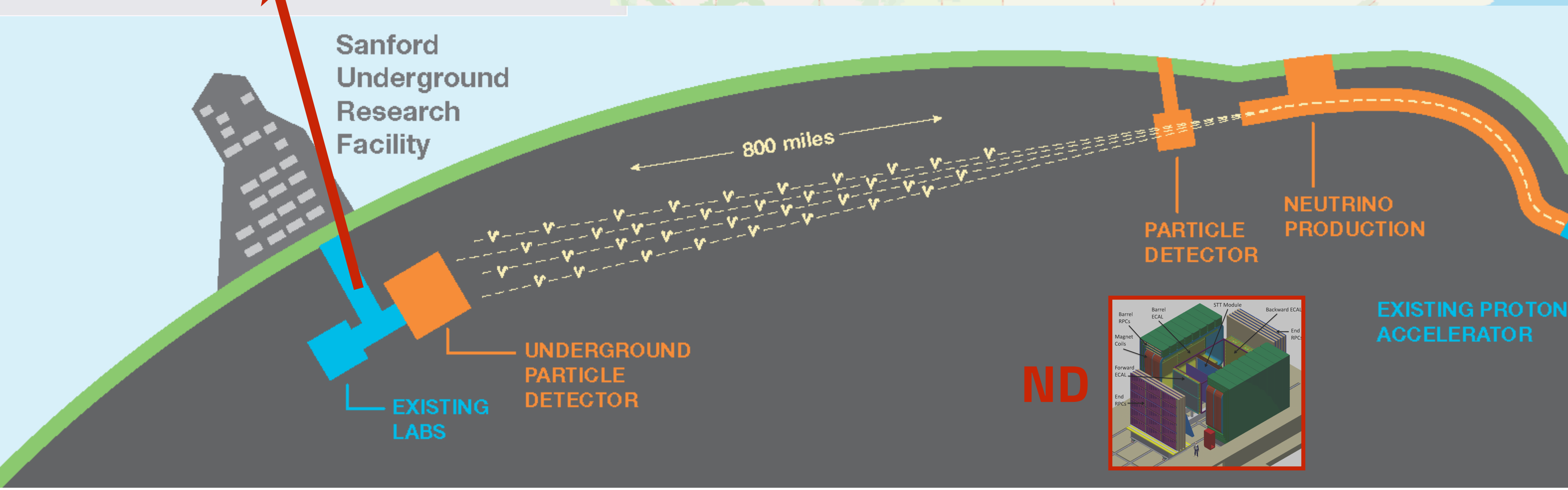
Searching for CP violation with the DUNE Experiment

...amongst other things

DEEP UNDERGROUND NEUTRINO EXPERIMENT

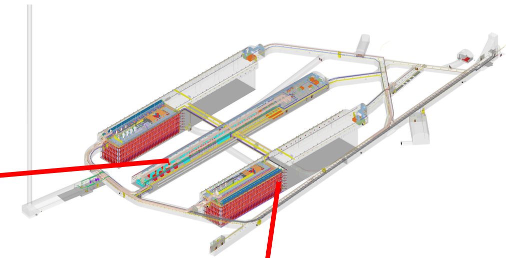


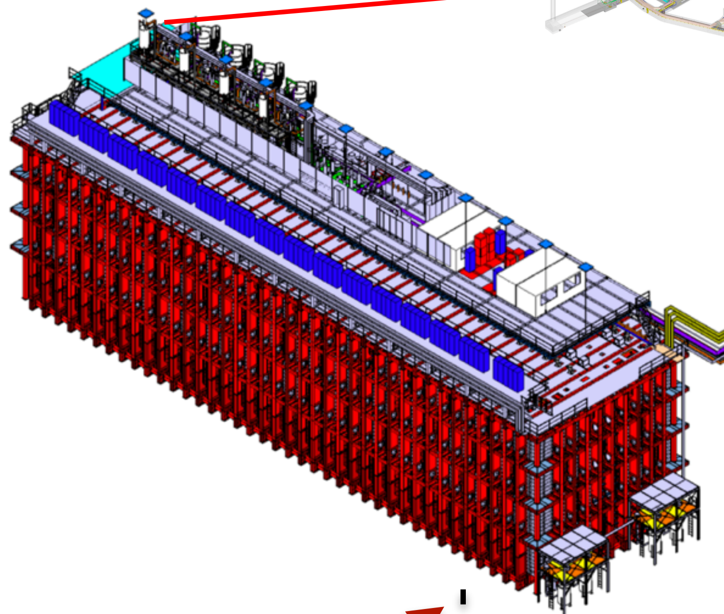




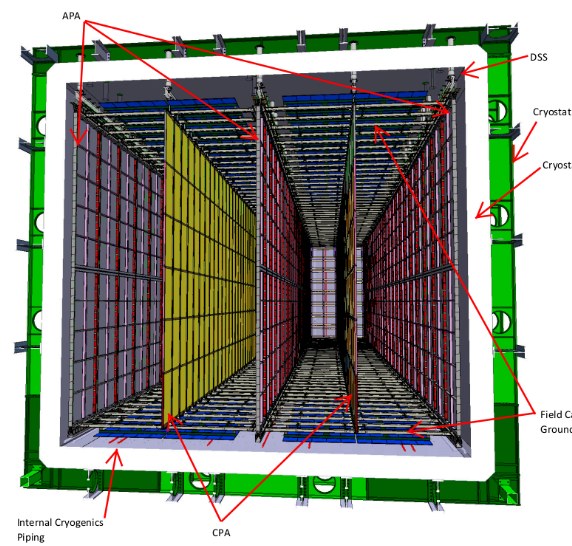
DUNE detectors

- 5 main caverns
  - 4 detector + 1 support
    - Support : Cryogenics and DAQ
- Detectors based on LArTPC technologies
  - Same cryostat
    - 62 m x 19 m x 18 m
      - 17 kt total LAr mass (70 kt total)
      - 10 kt fiducial LAr mass (40 kt total)
- E = 500 V/cm
  - Cathode voltage : -180 kV
- 150 APAs per detector module
  - 384 000 channels
  - Continuous digitisation of ~ms waveforms



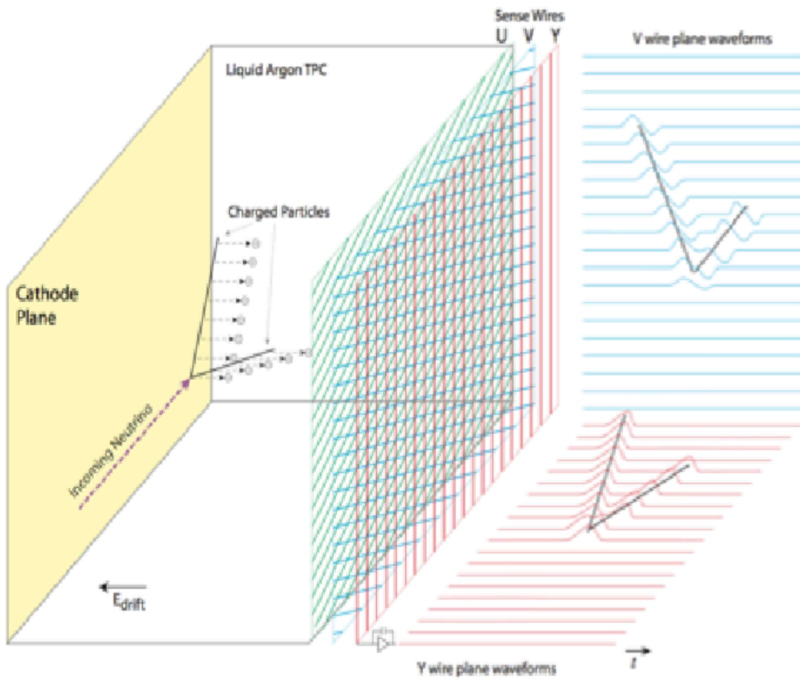


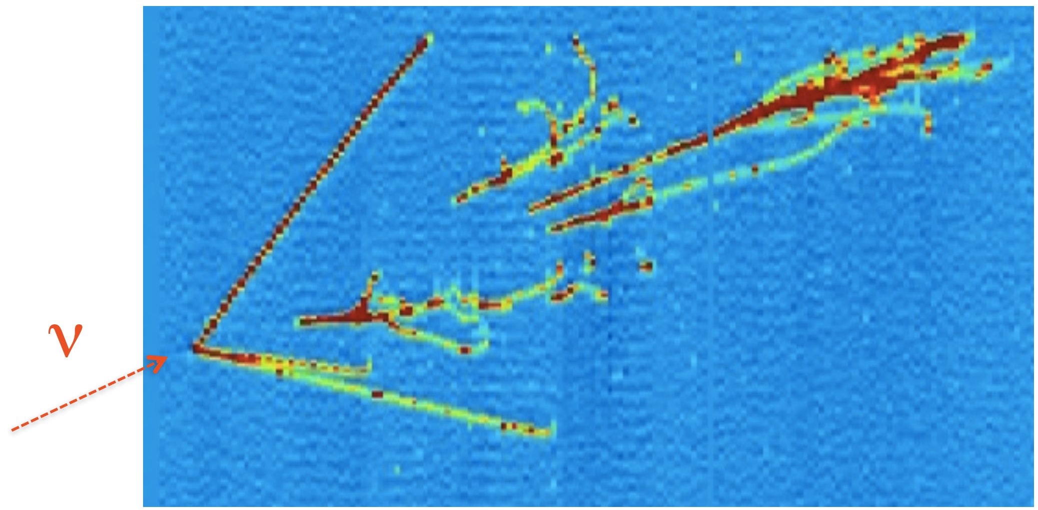
A tall physicist

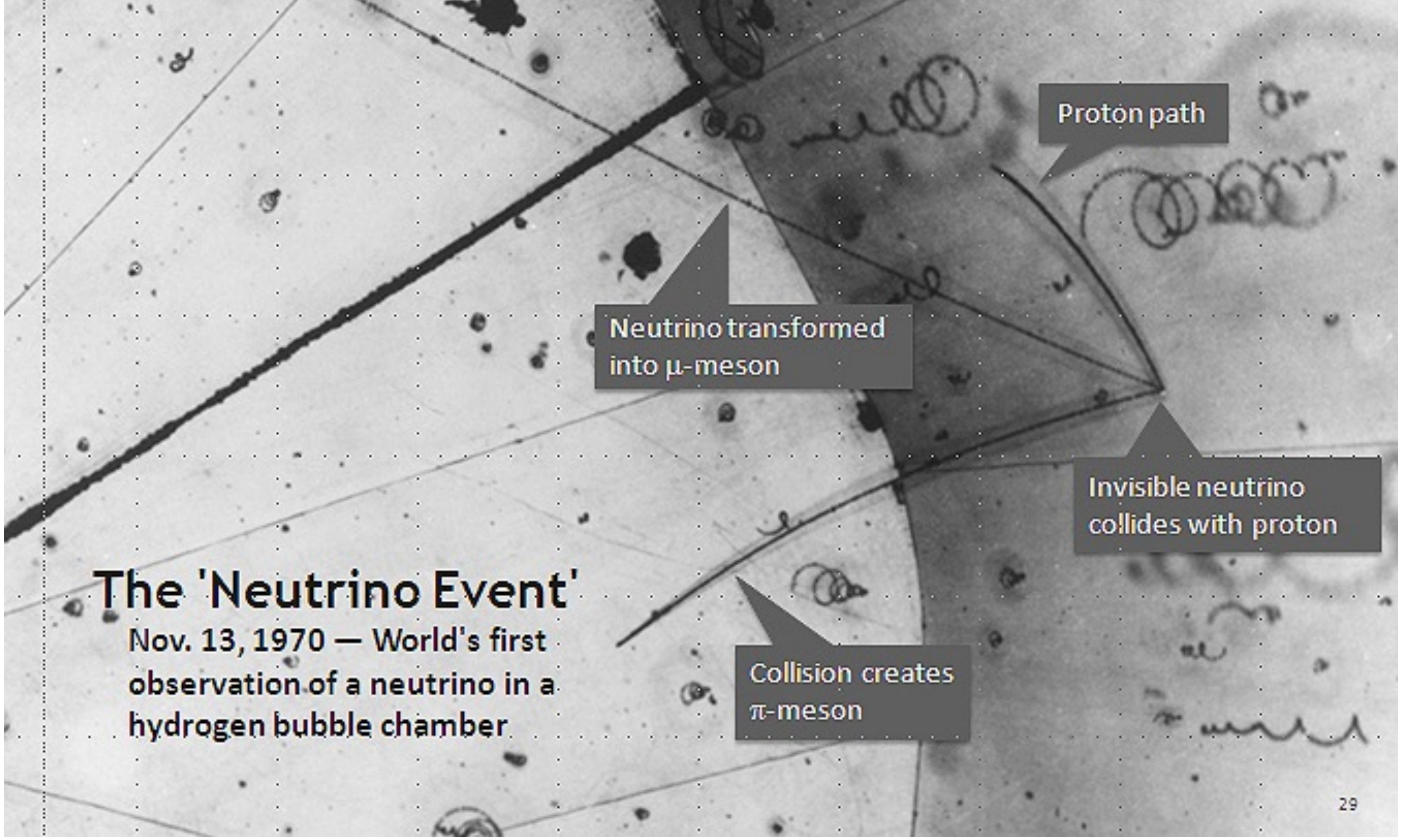


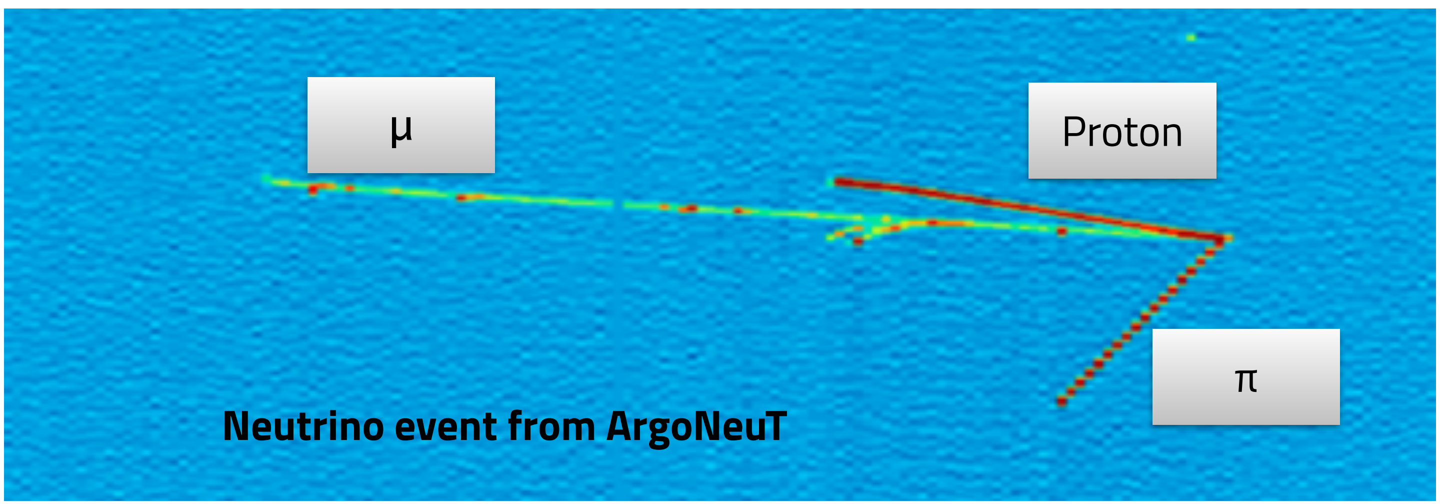
DUNE Far Detector: LAr TPCs

- 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)



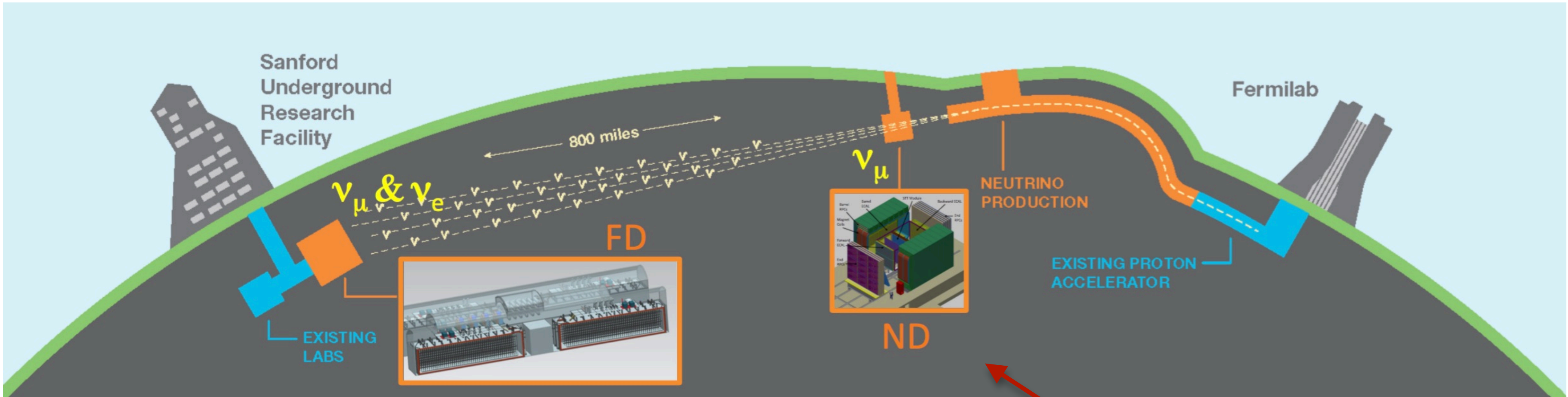



Proton path
Neutrino transformed into μ-meson
Invisible neutrino collides with proton
The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber
Collision creates π-meson
29

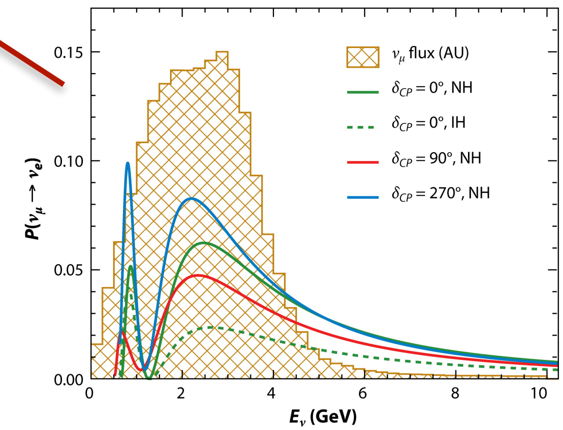

μ
Proton
π
Neutrino event from ArgoNeuT

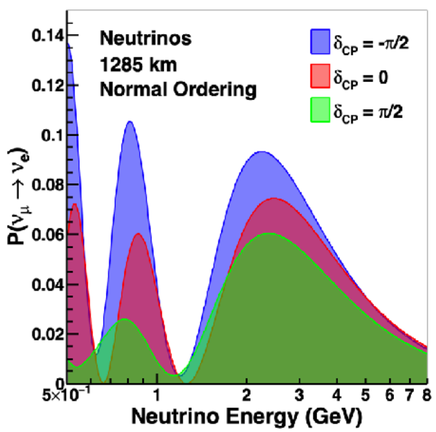
Long Baseline Oscillations

LBL physics with a neutrino beam...



- **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

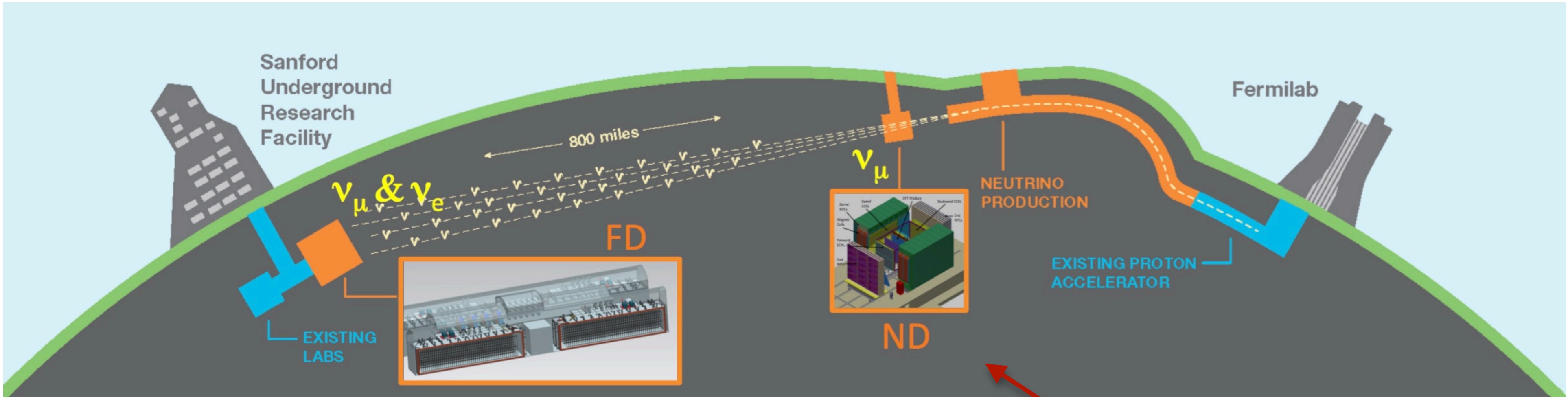




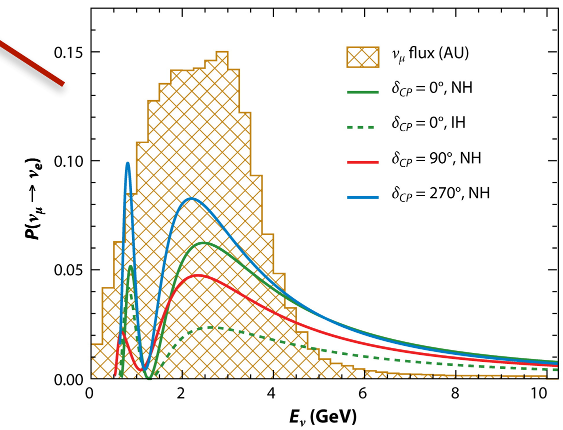
Probe of neutrino oscillations (with matter effects) and mass hierarchy

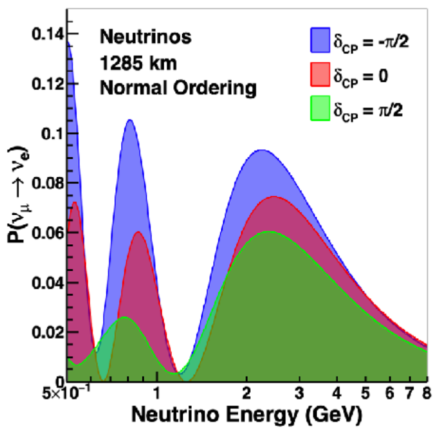
Long Baseline Oscillations

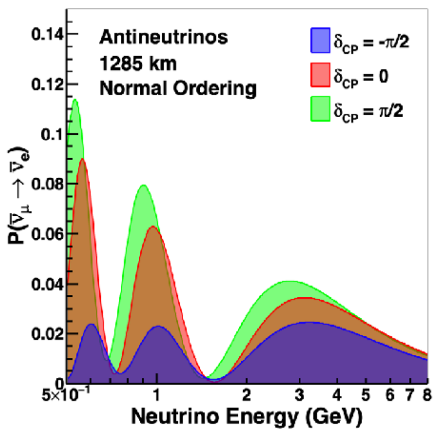
...and then repeat for antineutrinos



- **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





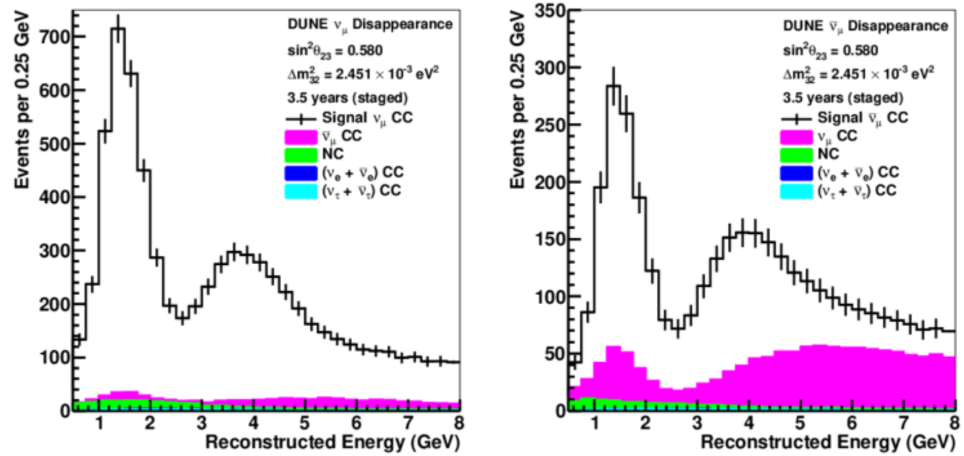


Physics of DUNE

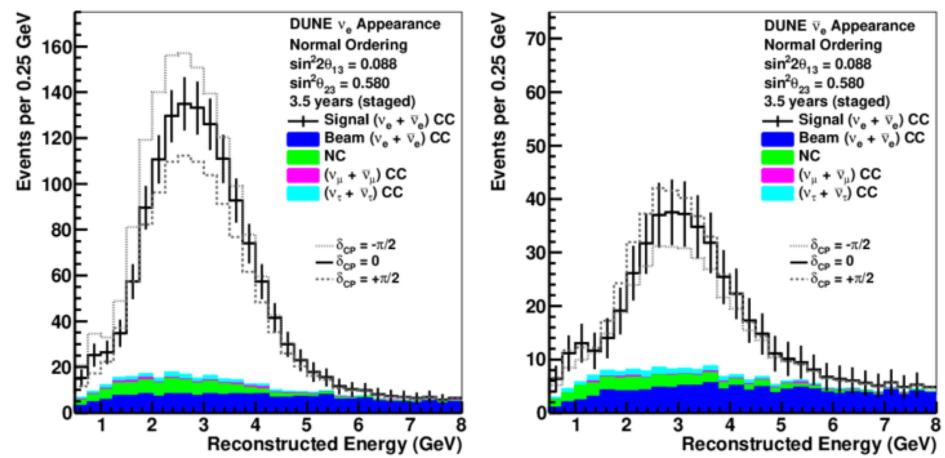
Oscillation analysis strategy

- Determine MH, δ_{CP} , θ_{23} octant, test 3-flavor paradigm and search for BSM effects (eg. NSI) **in a single experiment**
- Long baseline: matter effects are large (~40%)
- **Wide-band beam:**
  - ν_μ disappearance and ν_e appearance over range of energies
- MH and δ_{CP} effects are **separable**

(anti-)ν_μ disappearance



(anti-)ν_e appearance



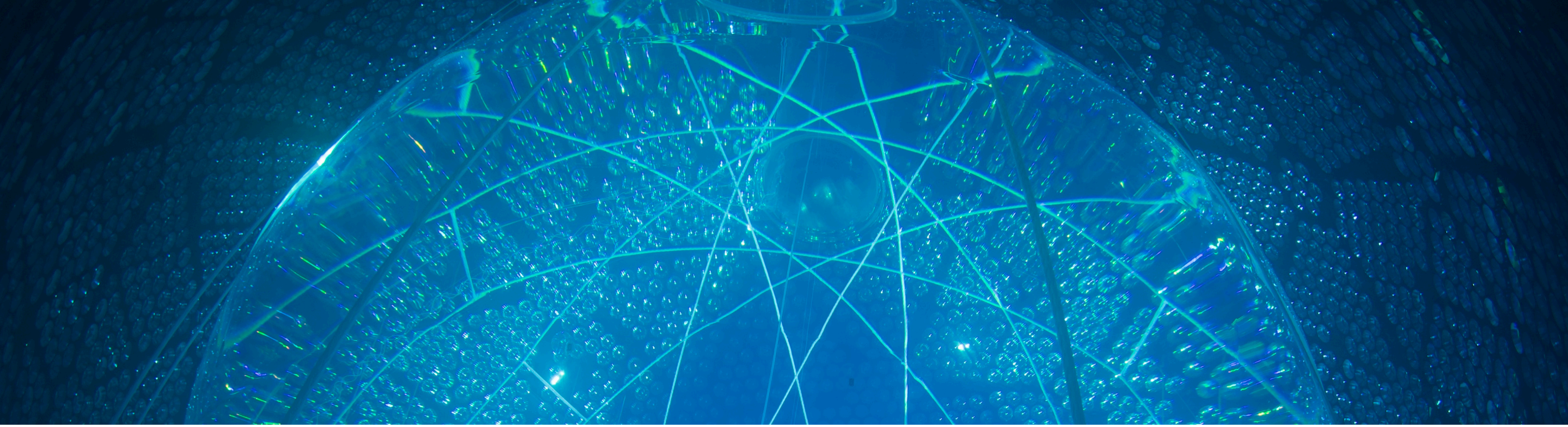
DUNE Physics Program

From MeV to GeV

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

E~O(few GeV)

E~O(10 MeV)

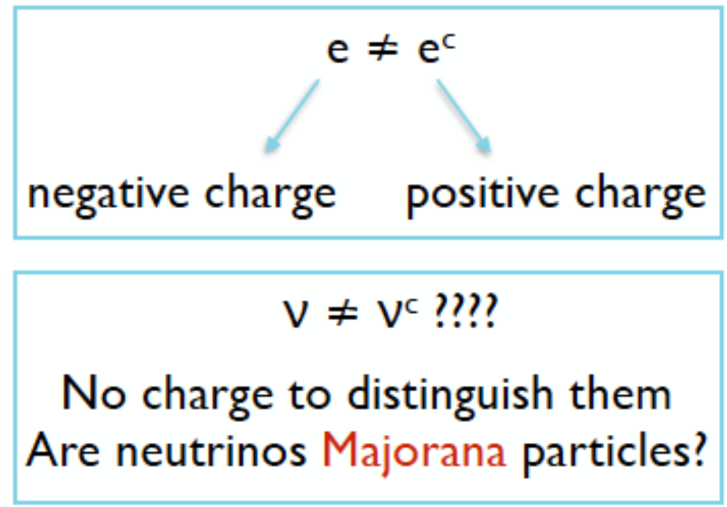


The Nature of the Neutrino

Lepton Number Violation with the SNO+ Experiment

Are neutrinos Dirac or Majorana fermions?

- Except for neutrinos, all fundamental 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**



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

Double beta decay

- If simple β- or β+-decay is forbidden on energetic grounds a nucleus can decay through a double beta mode:

$$^{106}_{48}Cd \longrightarrow ^{106}_{46} Pd + 2e^{+} + 2\nu_e$$

- The probability for a decay is very small, the mean lifetime of a nucleus is much larger than the age of the universe ($\tau_U \sim 1.4\times10^{10}$ y)

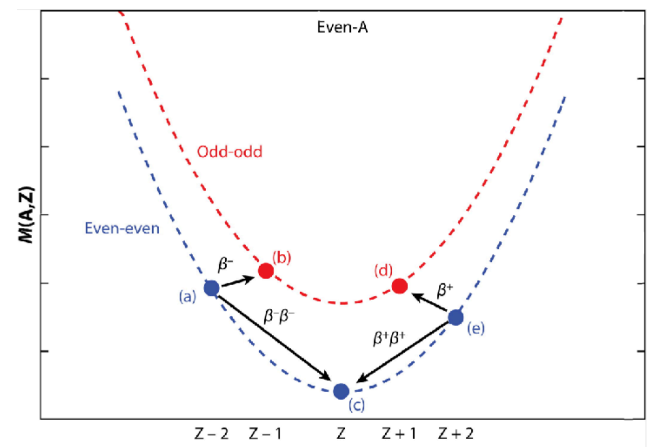
$$\tau_{2\nu} \approx 10^{20} y$$

- This is indeed a very rare process (as for instance proton decay, which was not yet observed)

- Nonetheless - **if one uses a large amount of nuclei**, the process can be observed experimentally
  - DBD can happen for 35 natural isotopes (**observed in 11**)

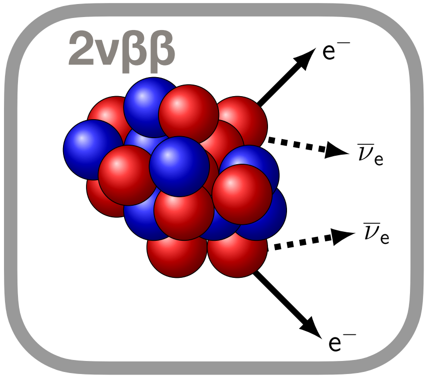
$$^{A}_{Z-2}X \longrightarrow ^{A}_{Z}Y + 2e^{-} + 2\overline{\nu}_e$$

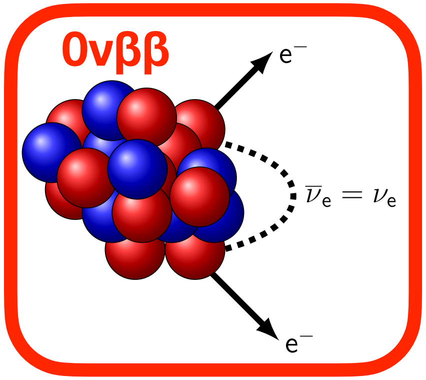
mass parabola of isobars with even A



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

Neutrinoless double beta decay (0νββ)





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

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}\left|M\right|^2 \left|\frac{m^{\nu}_{\beta\beta}}{m_e}\right|$$

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

$$m^{\nu}_{\beta\beta} = \left|U_{e1}\right|^2 m_1 + \left|U_{e2}e^{i\alpha_1}\right|^2 m_2 + \left|U_{e3}e^{i(\alpha_2+\delta)}\right|^2 m_3$$

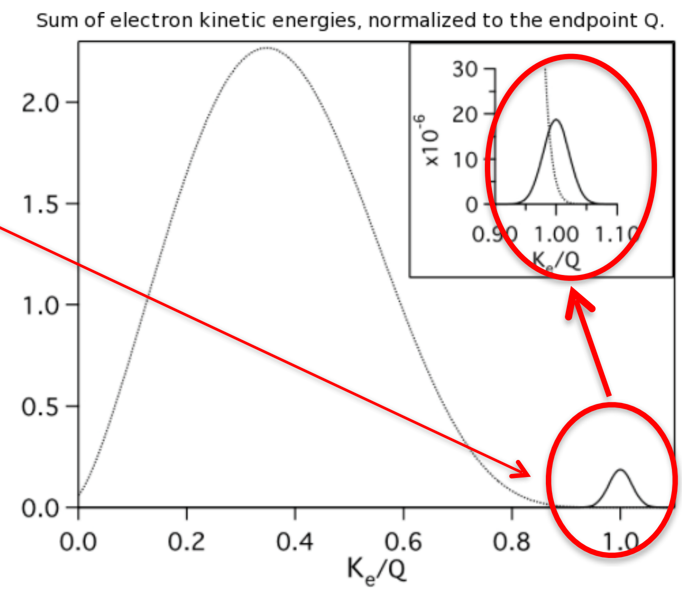
$$= c^2_{12}c^2_{13}m_1 + s^2_{12}c^2_{13}e^{2i\alpha_1}m_2 + s^2_{13}e^{2i(\alpha_2+\delta)}m_3$$

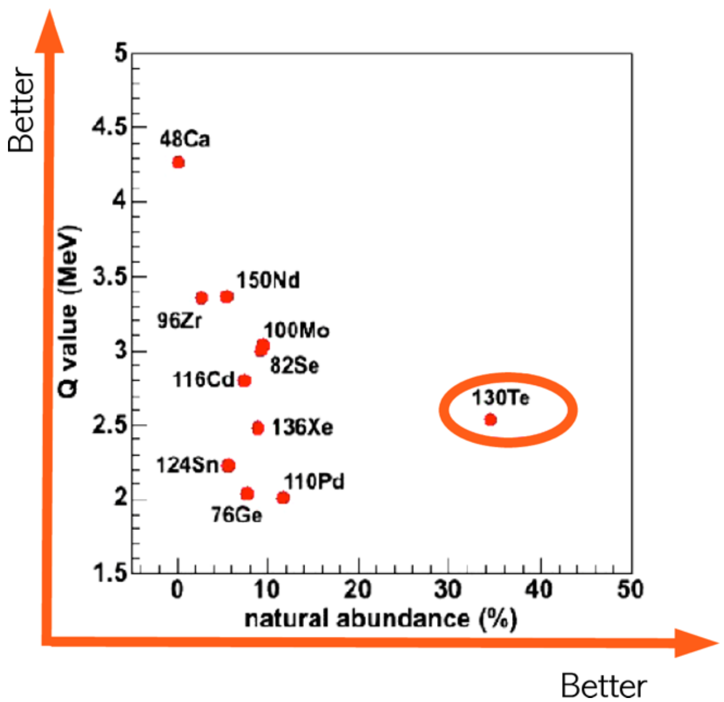
Remember: Oscillations can only tell us mass differences

Searching for 0νββ

Looking for one very particular needle in a pile of needles!

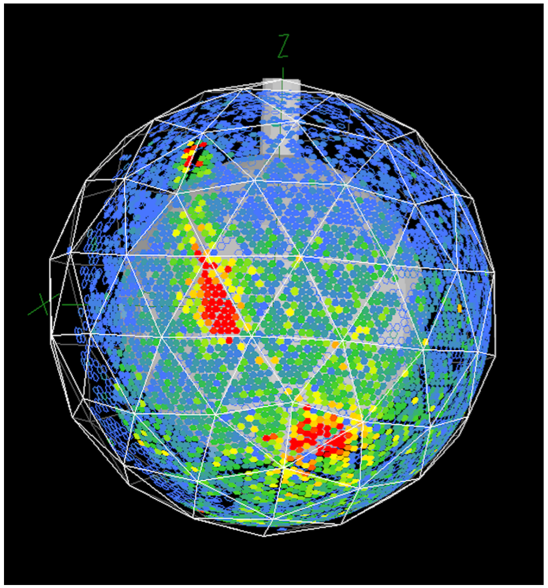
- **Method**
  - Search for a peak in the energy spectrum (sum of the two electrons)
  - Acquire data for a long time and with high quantities of isotope

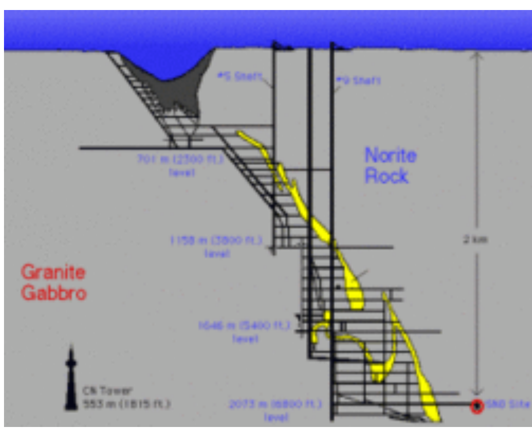




- **Choice of isotope**
  - Natural abundance, energy
- **Low backgrounds**
  - Underground location
  - Low radioactivity

The SNO+ Experiment





780 tons of **liquid scintillator**

new calibration systems

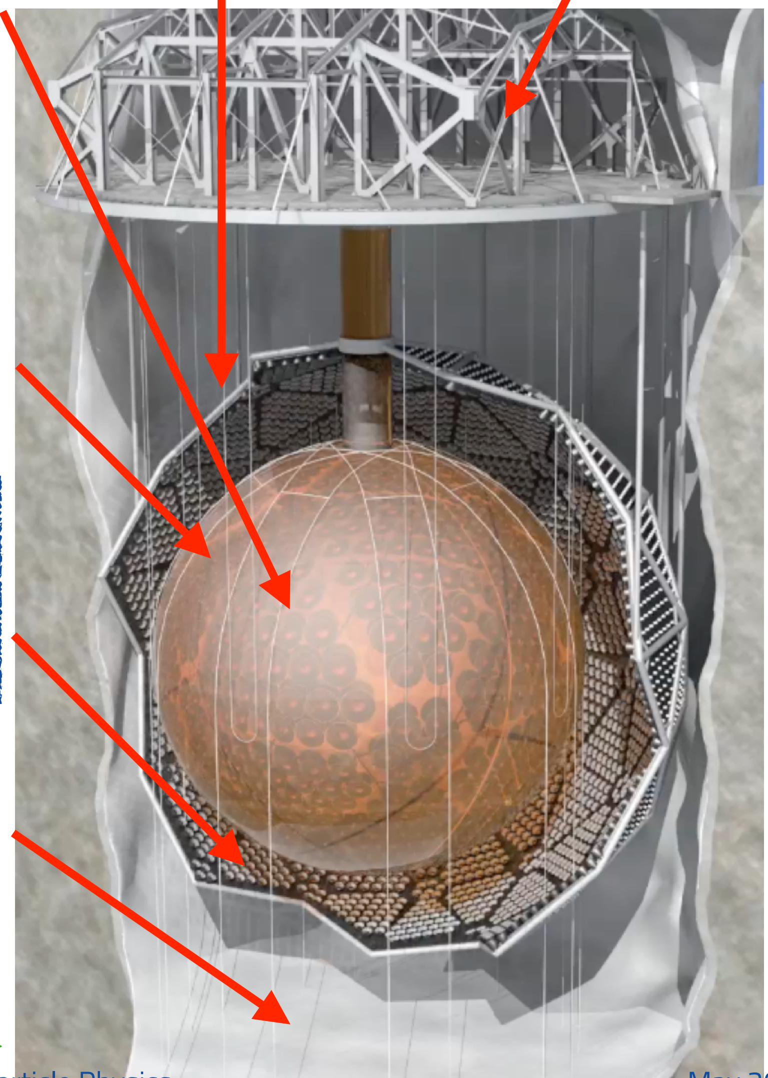
DAQ

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

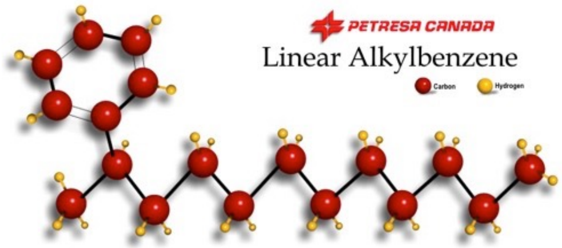
contained in an acrylic vessel (AV) 12 m diameter

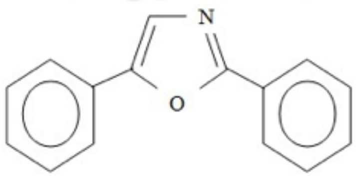
viewed by ~ 9300 PMTs (8″) mounted on 17 m diam. structure

shielded by 7 kt ultra-pure water



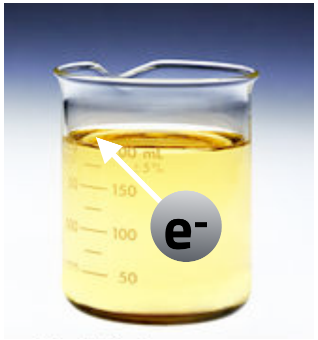
Scintillation detectors



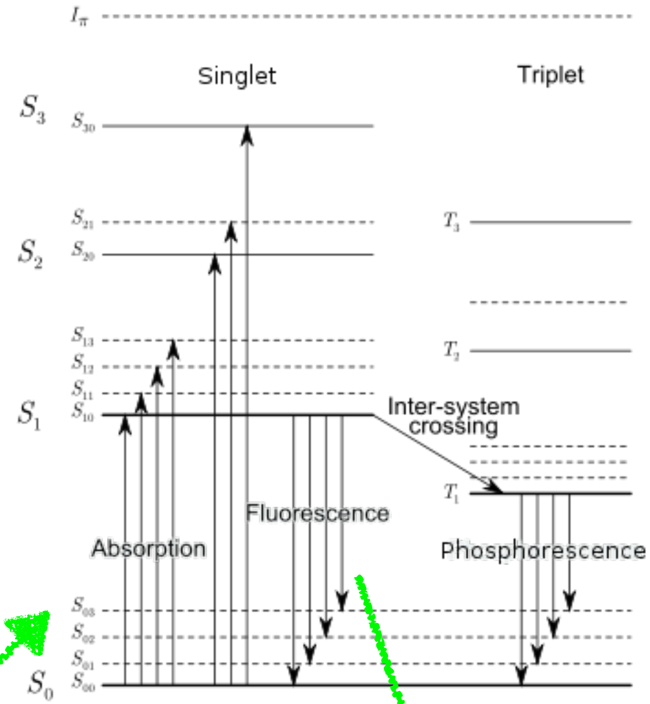


LAB +

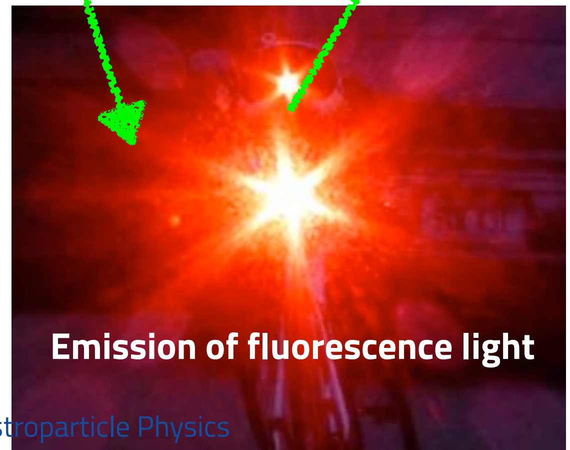
2g/l PPO



Charged particle excites scintillator molecules



Detected by photomultipliers

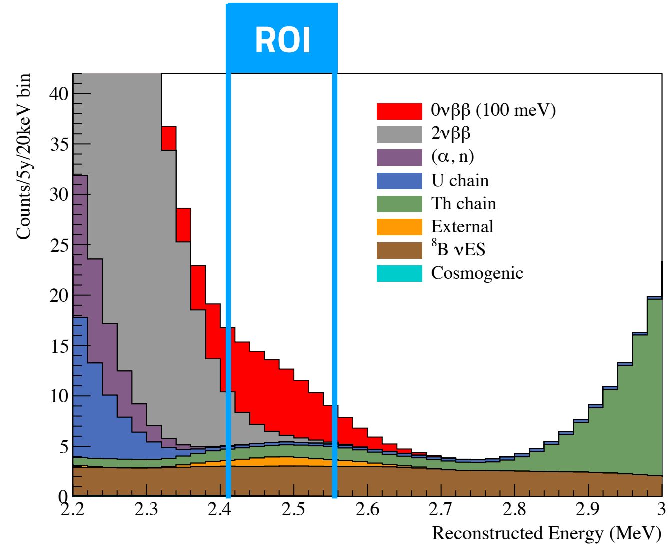


Emission of fluorescence light

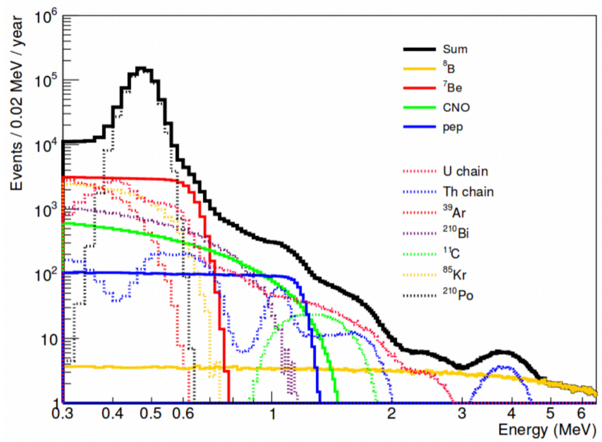
SNO+ physics program

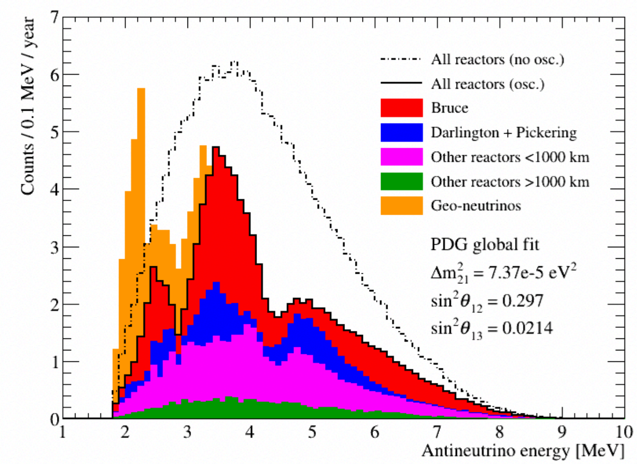
…780 ton scale low background calorimeter

- Main objective:
  - **Search for 0νββ in ^{130}Te**

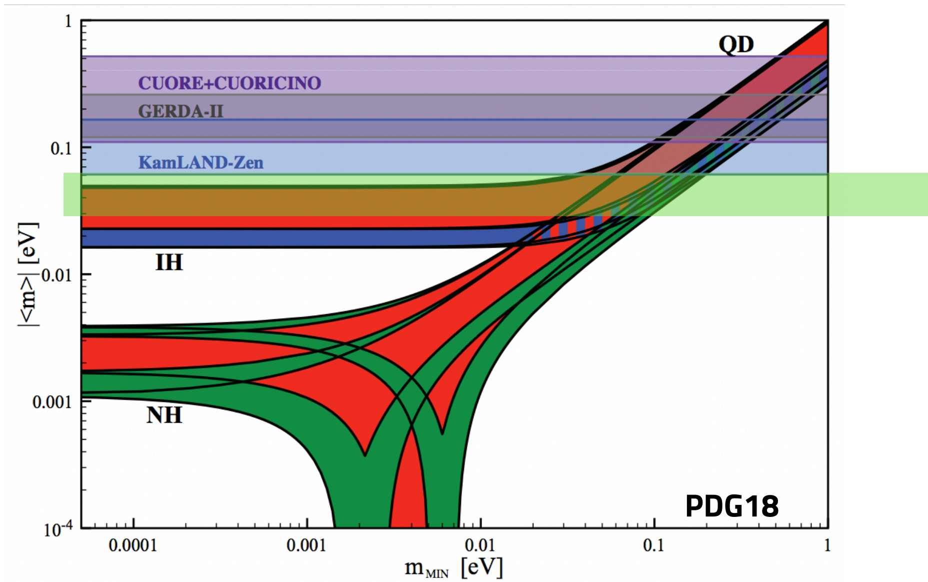


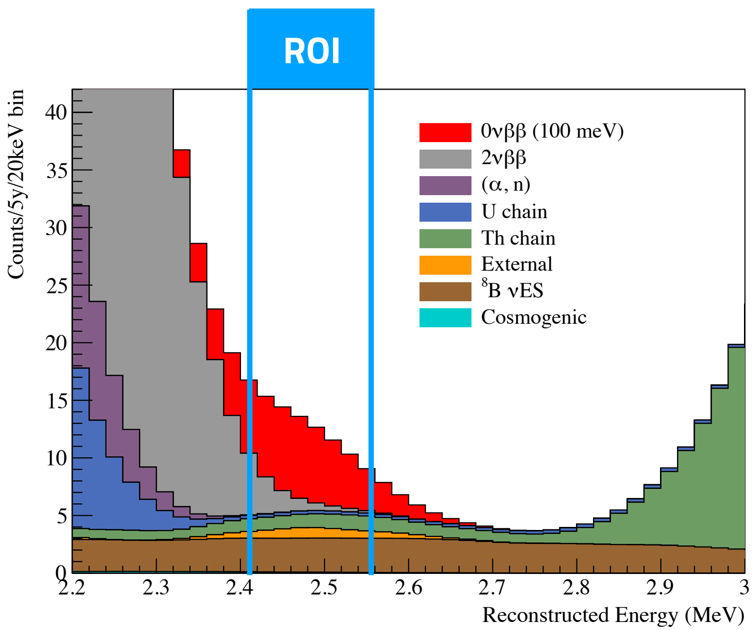
- Other topics of interest
  - **Solar neutrinos**
  - Nucleon decay
  - Supernova neutrinos
  - **Reactor and geo-antineutrinos**





SNO+ 0νββ sensitivity

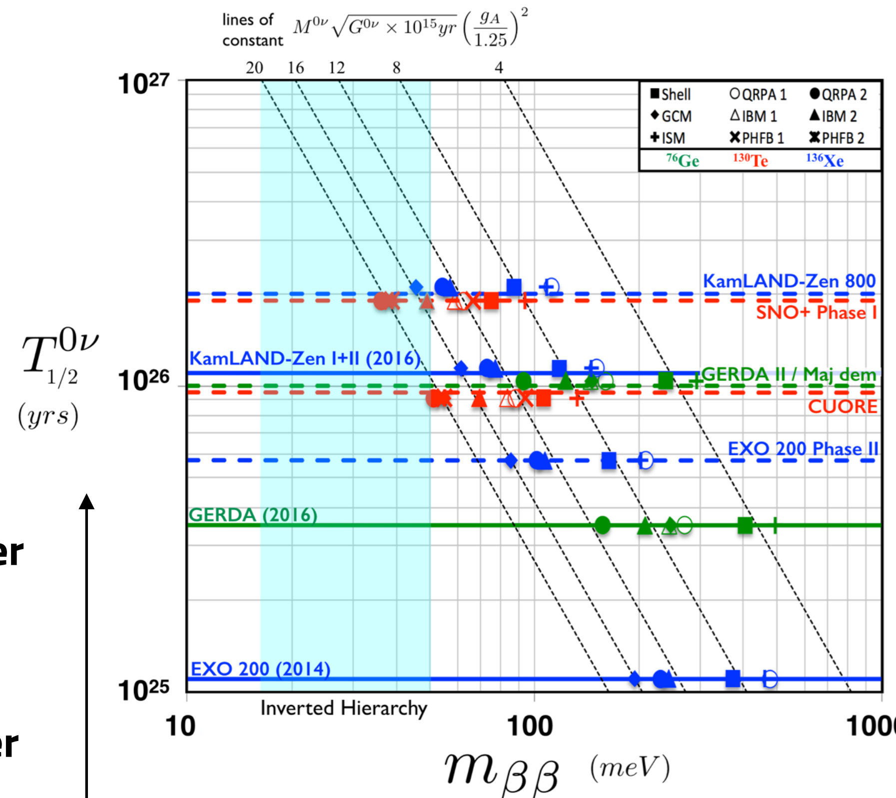




SNO+ Expectation after 5 years data taking:

$T_{1/2} > 2.1 \times 10^{26}$ years

37 meV $< m_{\beta\beta} <$ 89 meV

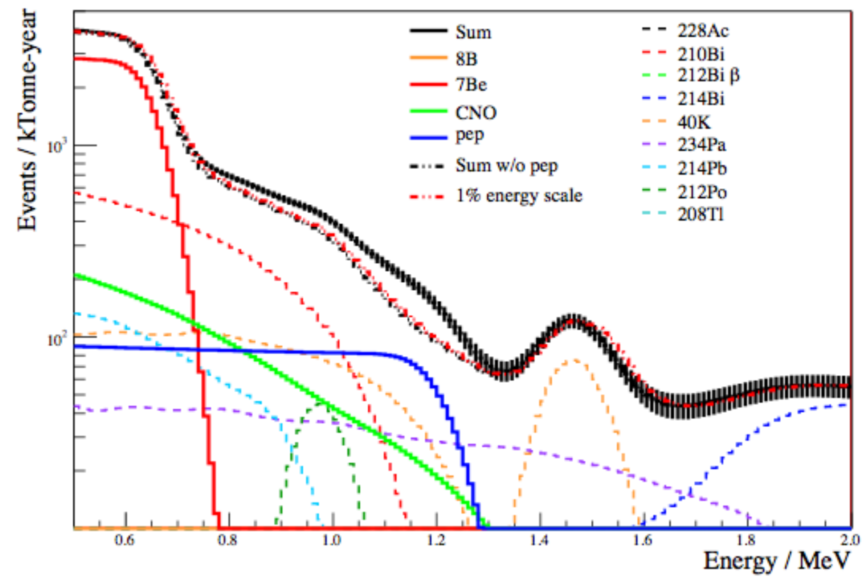


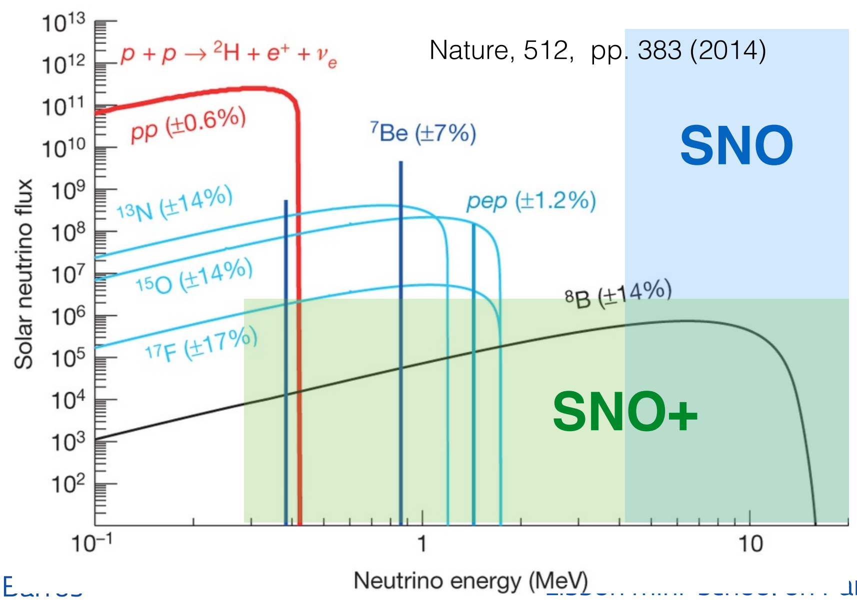
Higher $T_{1/2}$ is better

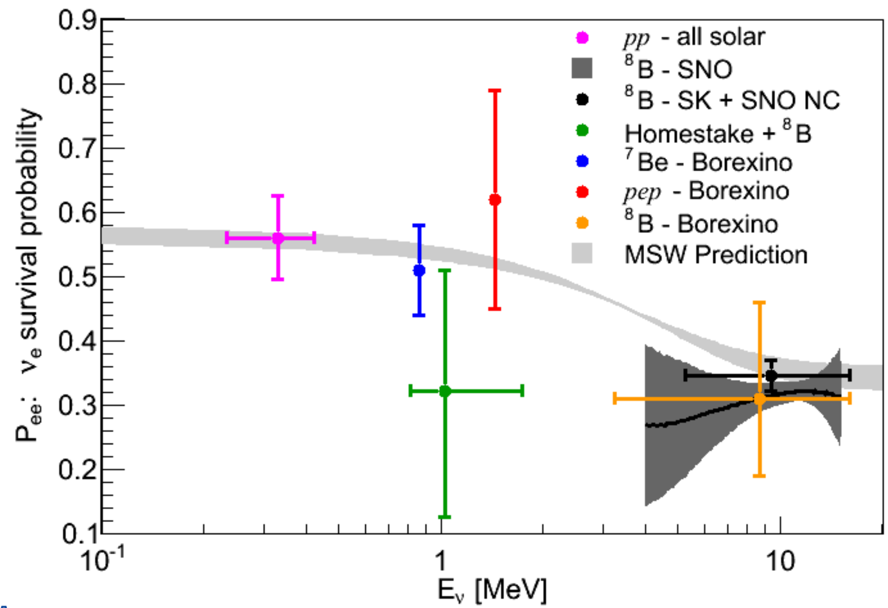
Lower $m_{\beta\beta}$ is better

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 competition)

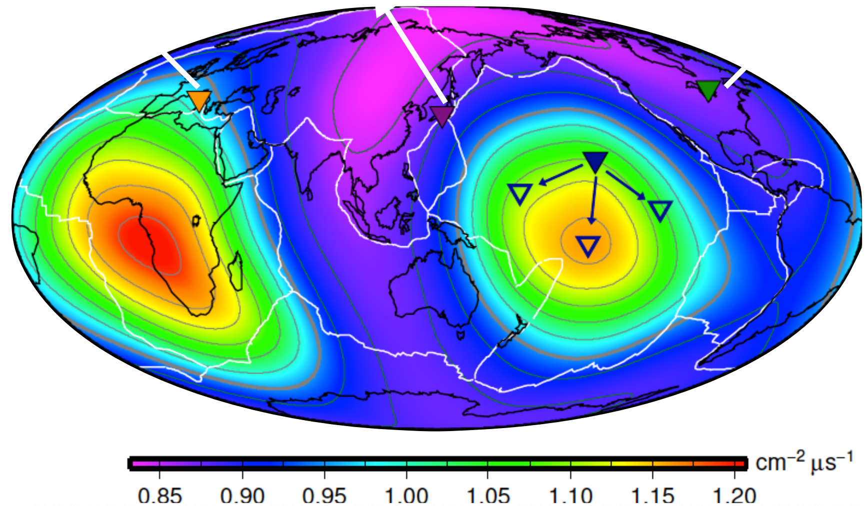


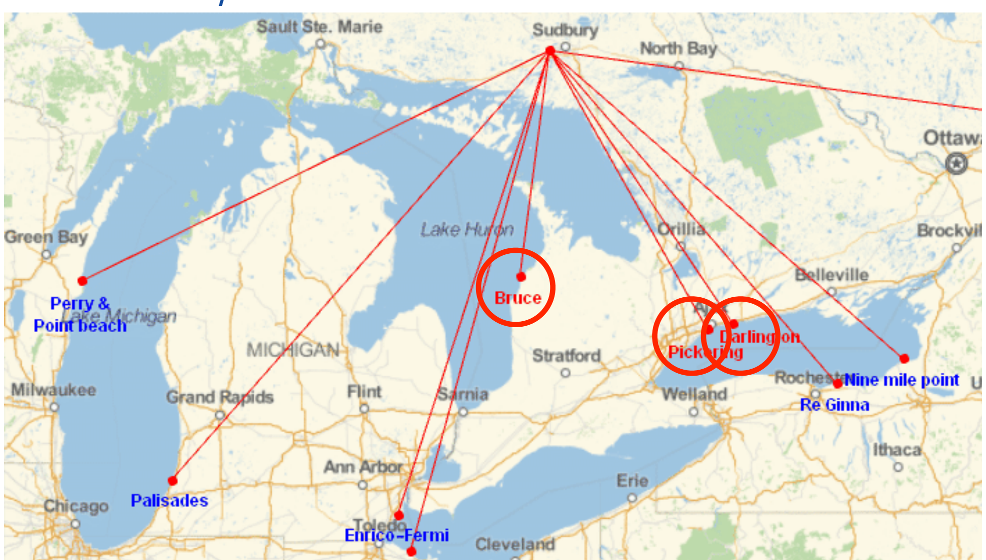


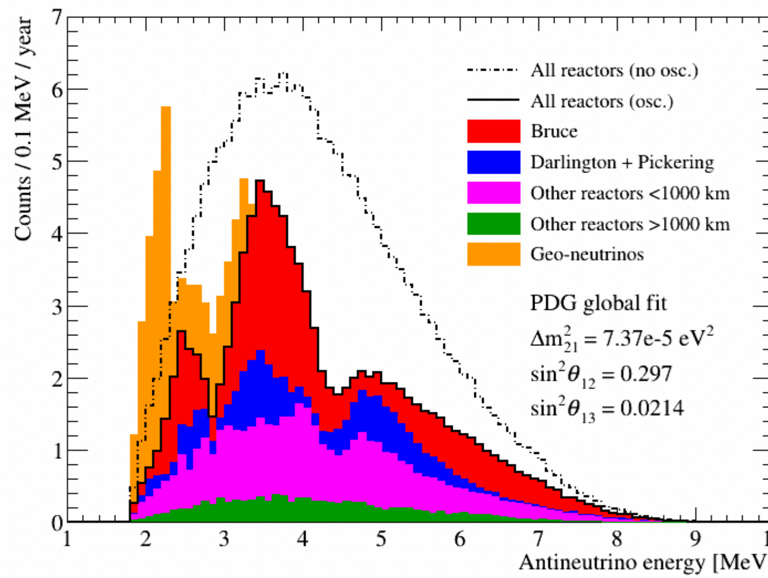


Reactor and geo-antineutrinos

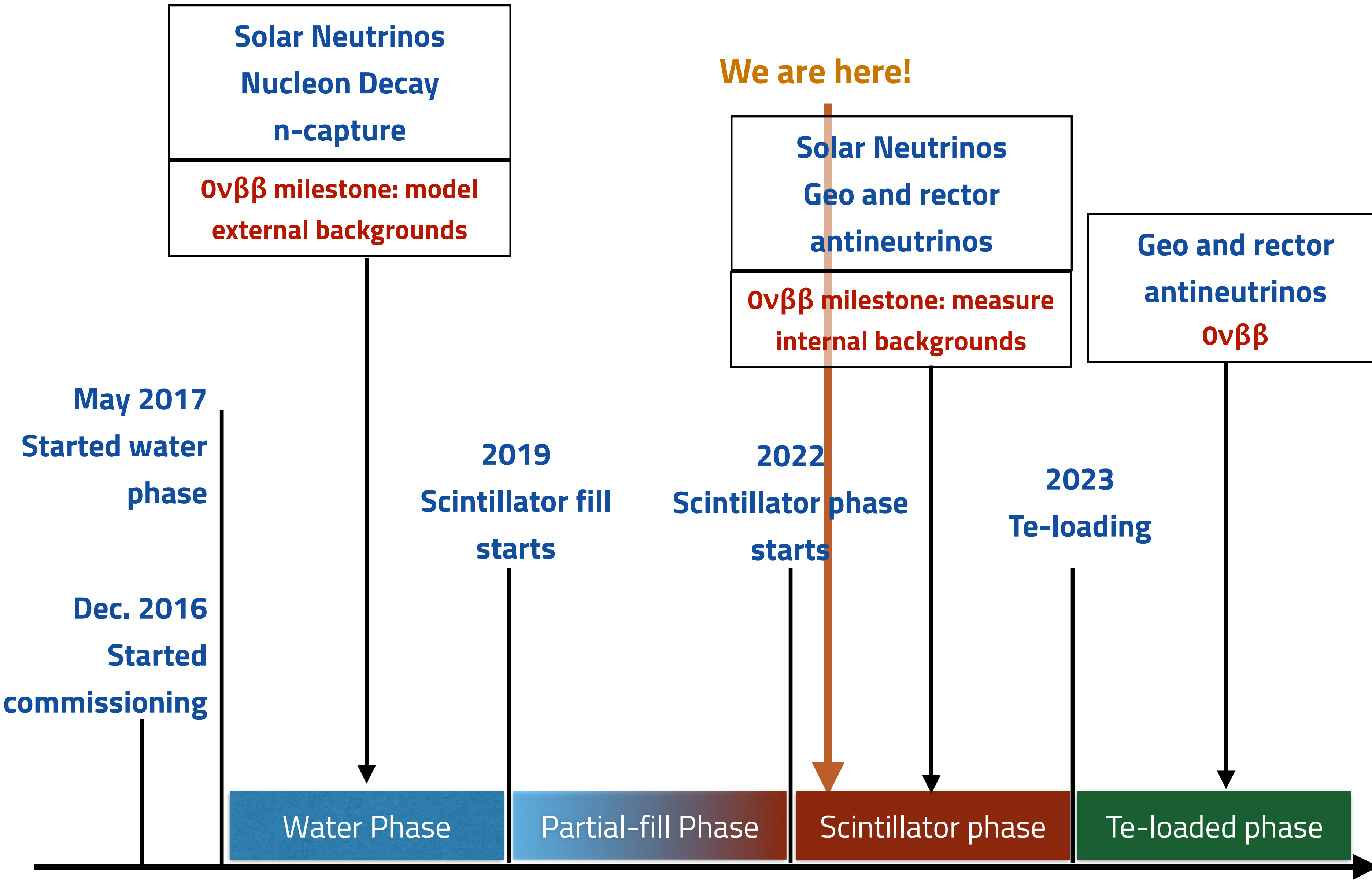
- Detection through inverse beta decay
  - Delayed coincidence e^+ annihilation and n capture
- **Geo**
  - U, Th and K in Earth's crust and mantle
  - **Investigate origin of the heat produced within Earth**
- **Reactor**
  - 3 nearby reactors dominate flux







SNO+ timeline

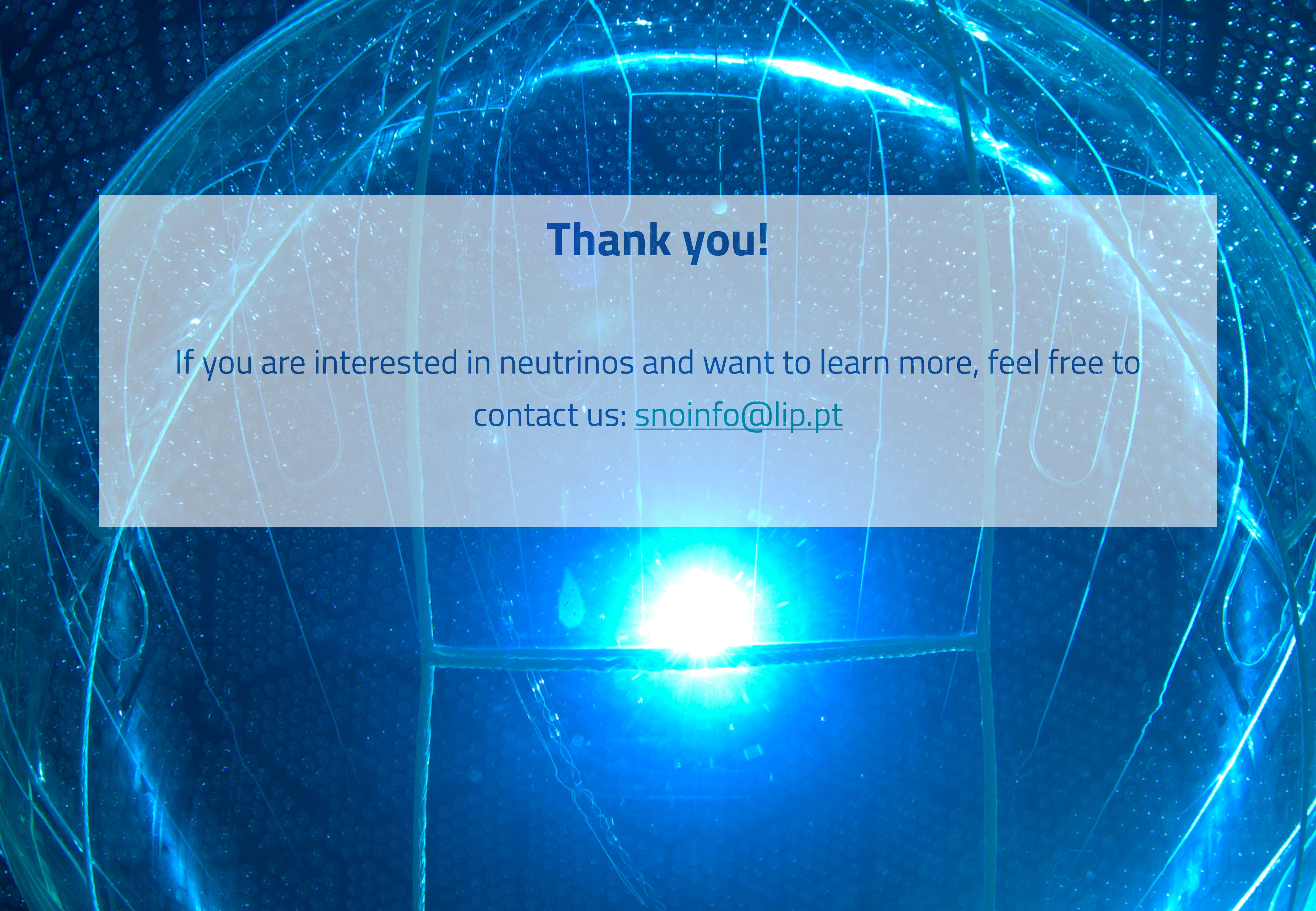


Summary

- **In the last decades 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



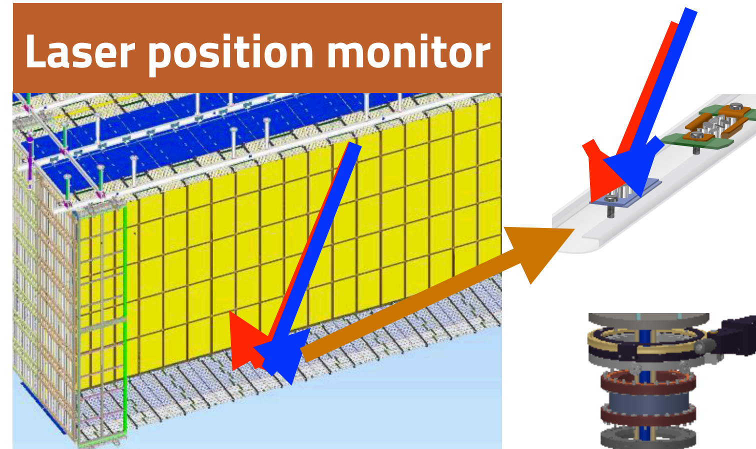
Thank you!

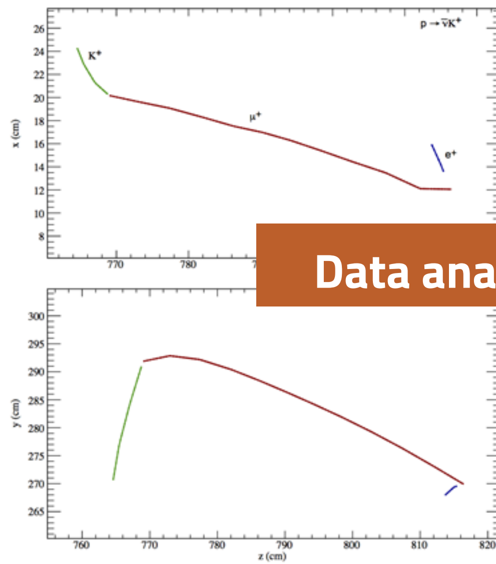
If you are interested in neutrinos and want to learn more, feel free to contact us: snoinfo@lip.pt

Neutrino activities (DUNE edition)

- **Detector calibration**
  - Hardware design (laser, n-source)
  - Analysis of calibration data
- **DAQ**
  - Electronics design
  - Data quality
- **Data analysis**
  - Cosmic rays
  - Beam data

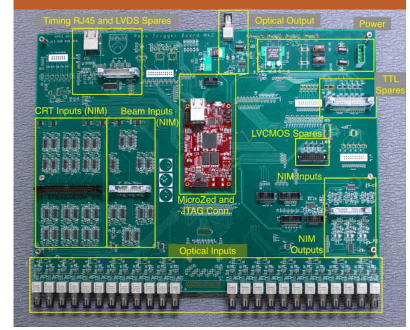
Laser position monitor

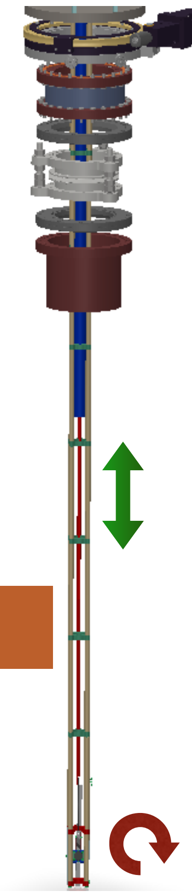


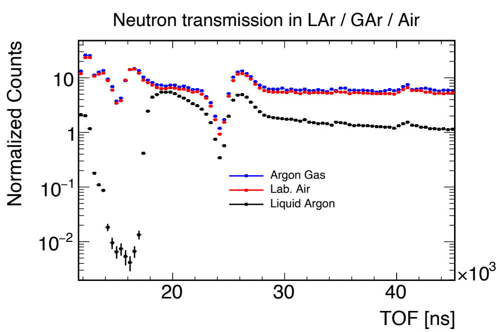


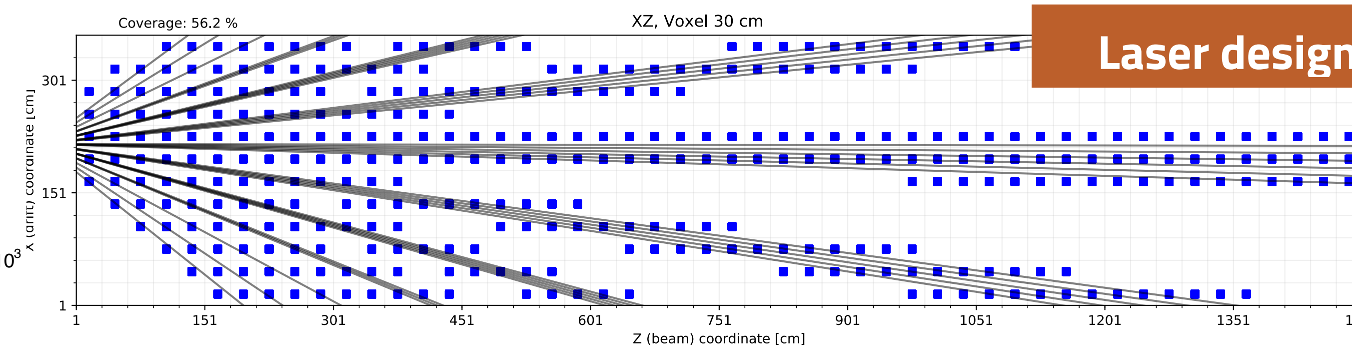
Data analysis

Cal/DAQ









Laser design

Neutrino activities at LIP (SNO+ edition)

- **Detector calibration**
  - With Optical and radioactive sources
- **Background events**
  - Data quality
- **Data analysis**
  - Cosmic muons in SNO+
  - Solar neutrinos
  - **Reactor anti-neutrinos**
  - **Neutrinoless double beta decay**
  - Nucleon decay searchers