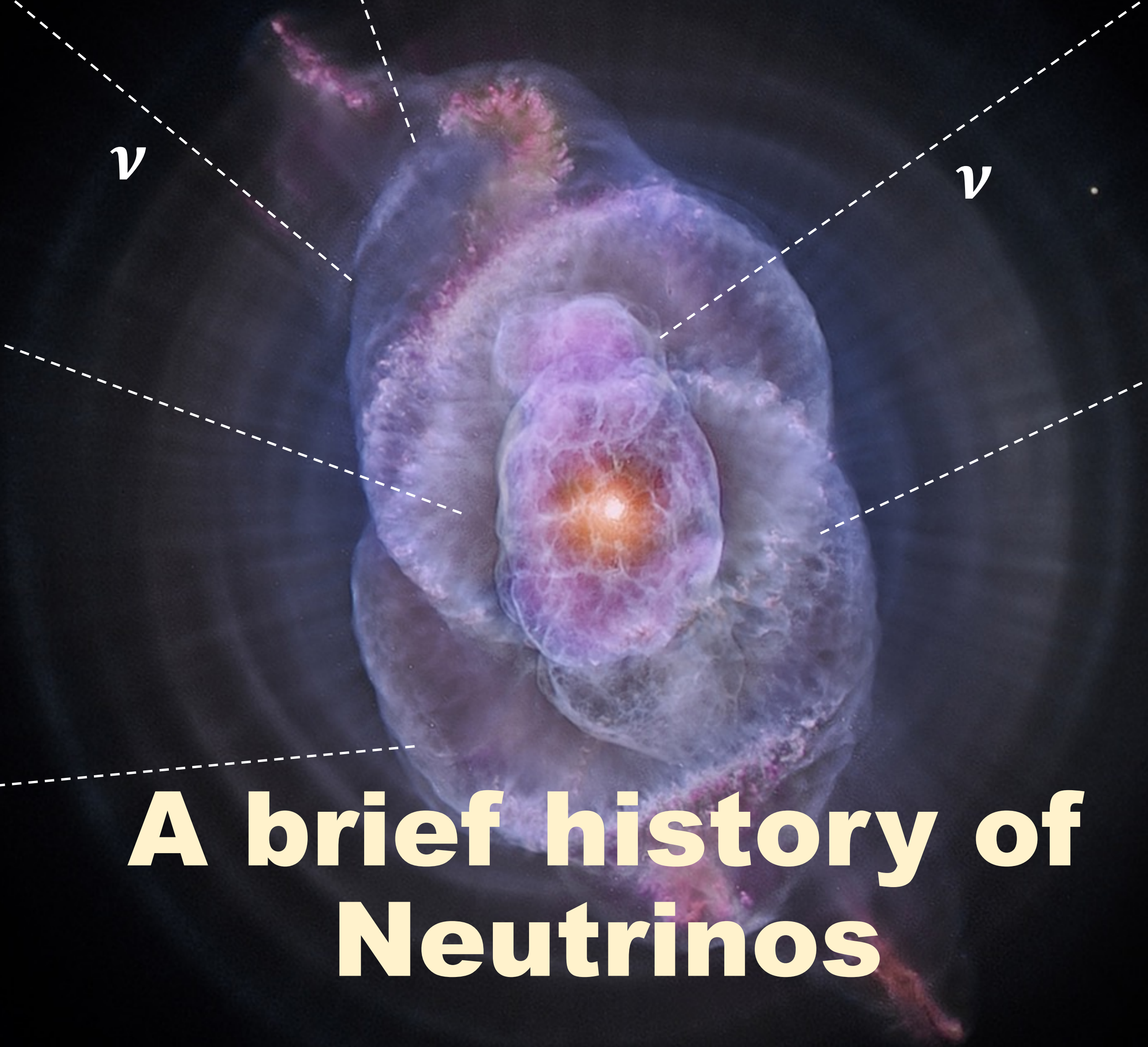


A brief history of Neutrinos

Ana Sofia Inácio, LIP and FCUL, Lisboa

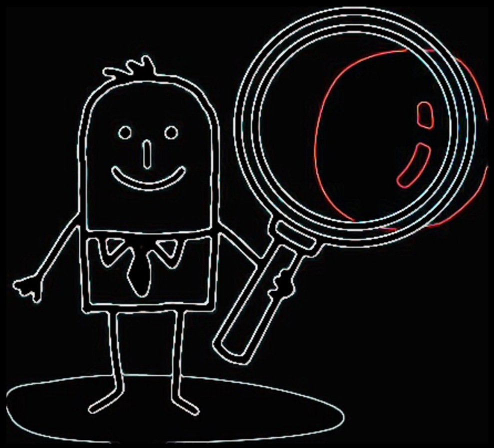
In this talk

Goal #1

- Neutrino properties
  - What we know
  - What we don't know

Goal #2

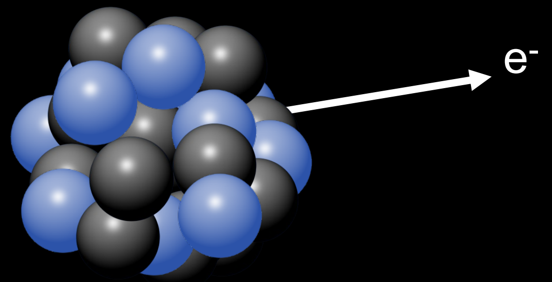
- Large Scale experiments looking for neutrinos
  - SNO+
  - DUNE



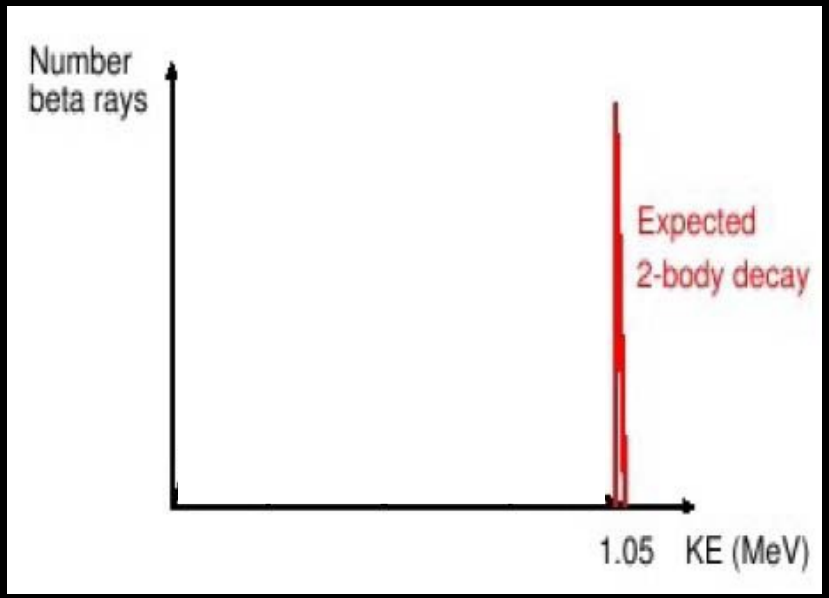
Once upon a time…

(in the 1930s)

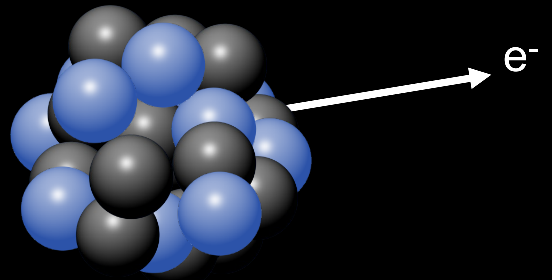
The beta decay problem



- Thought to be a two-body decay, like alpha decay
  - Energy and momentum conservation, electron at a fixed energy

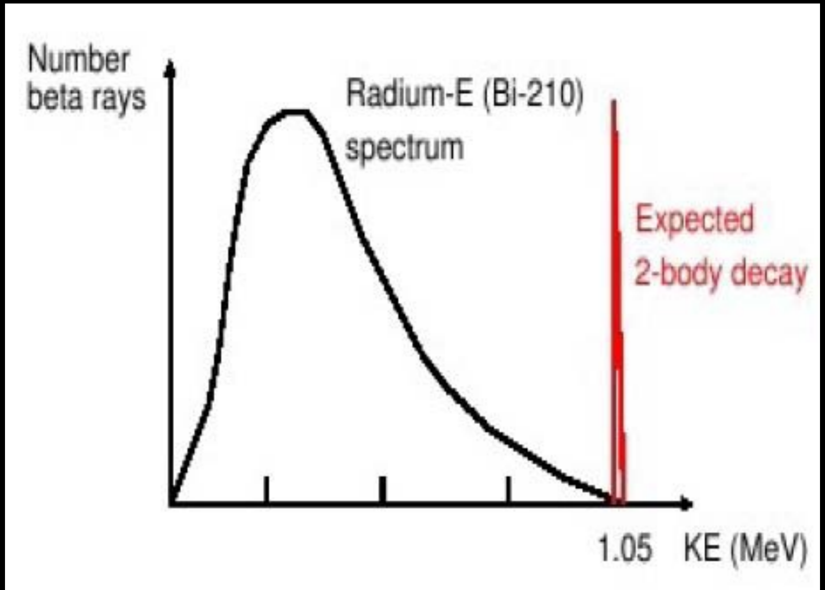


The beta decay problem

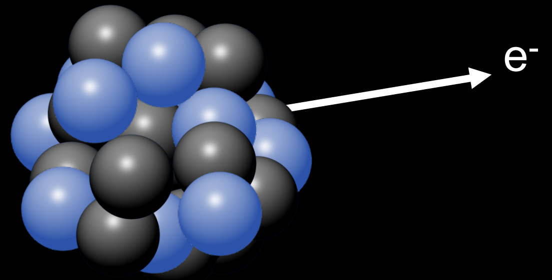


- Thought to be a two-body decay, like alpha decay
  - Energy and momentum conservation, electron at a fixed energy

- Experimental evidence (1920-29): Hahn, Meitner, Chadwick
  - Observed a continuous electron energy spectrum!



The beta decay problem



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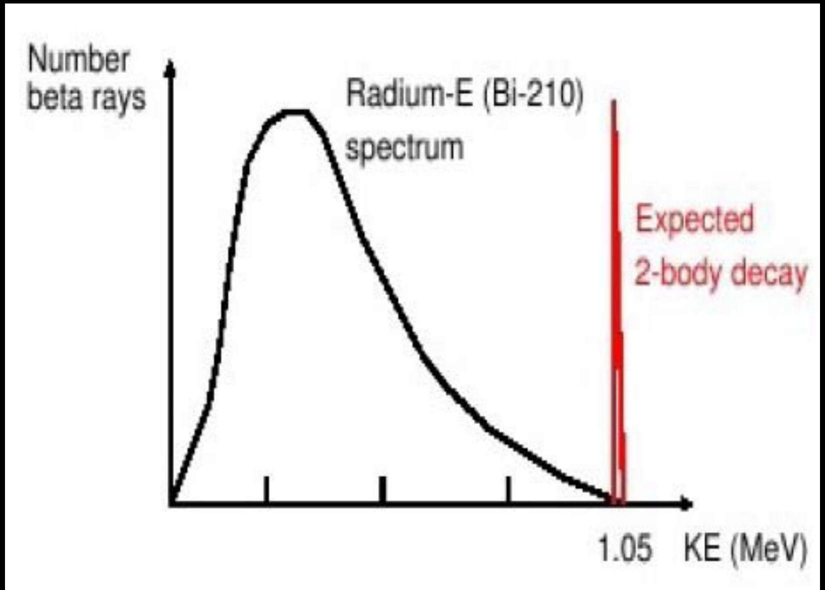
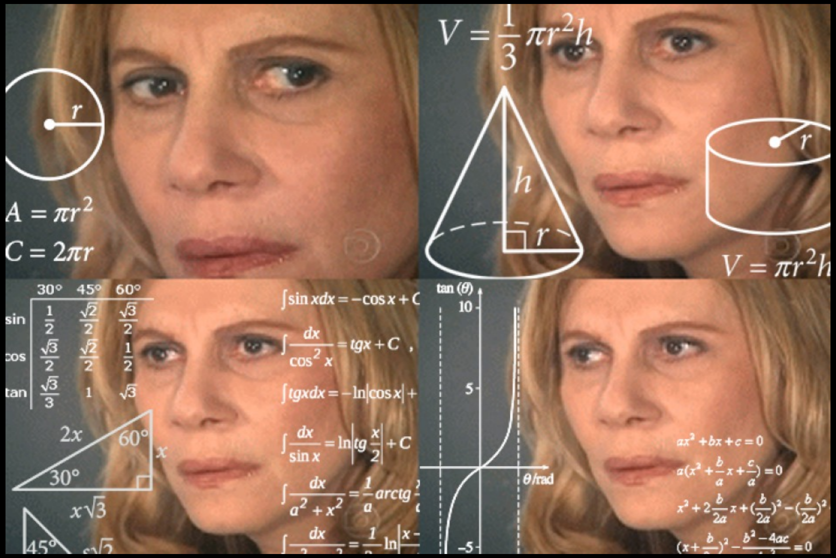


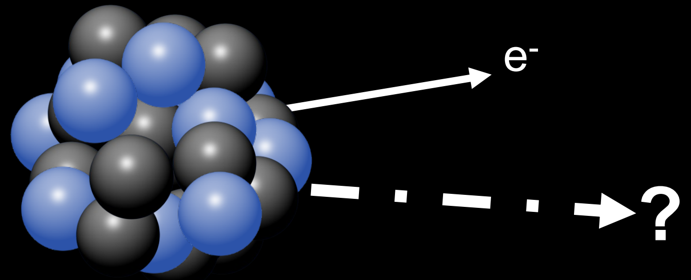


Where did the energy go?

What is happening during the decay?

Is energy conservation a lie??

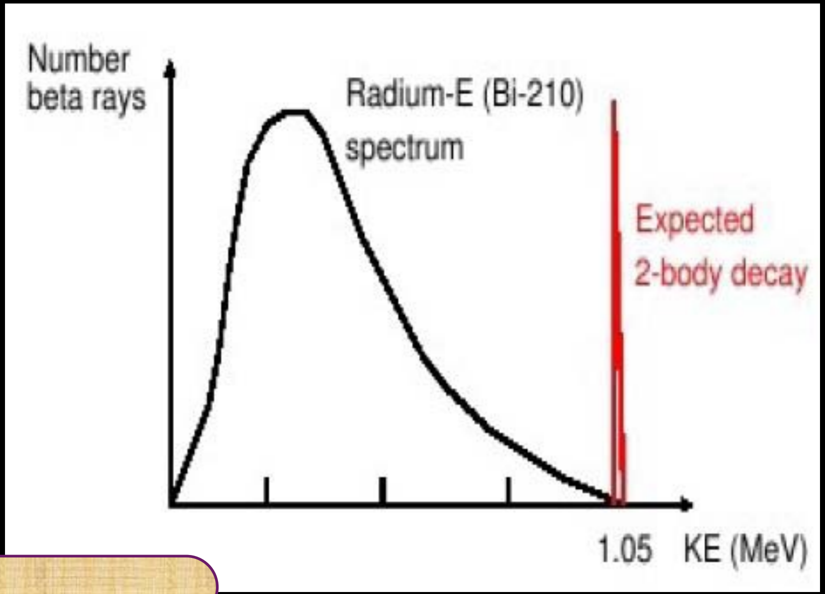
The beta decay problem



- W. Pauli, 1930

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^{-} + ? $$

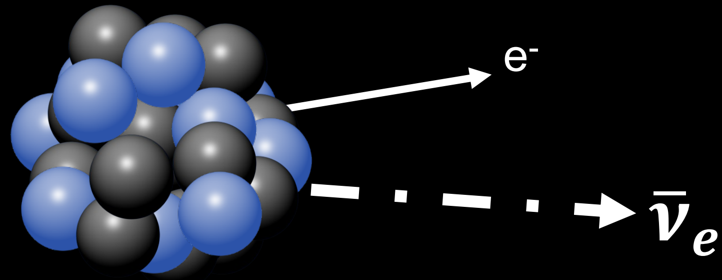
- Pauli hypothesized an undetected particle that he called a "neutron”. The new particle was emitted from the nucleus together with the electron.



Dear Radioactive Ladies and Gentlemen,

[…] I have hit upon a desperate remedy to save the […] law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and […]. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. […]

The beta decay problem



- W. Pauli, 1930

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^{-} + \bar{\nu}_e$$

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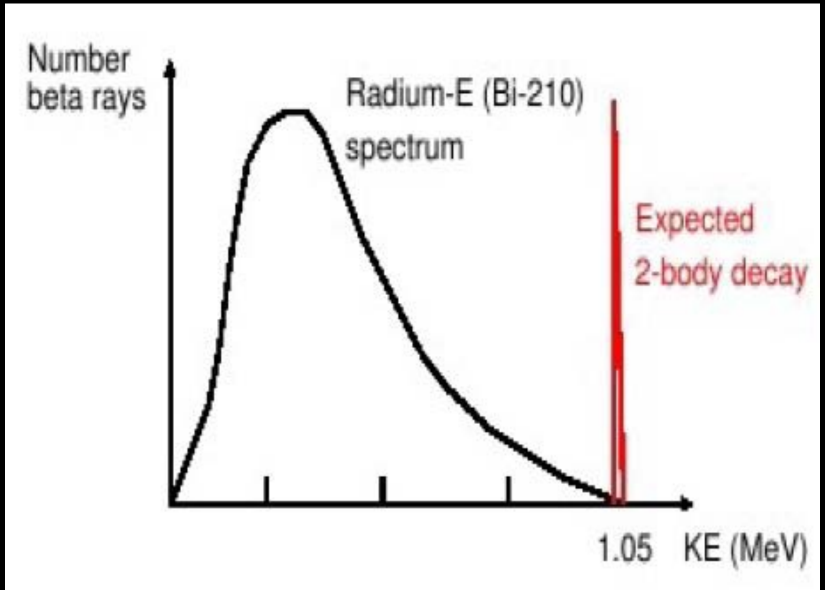
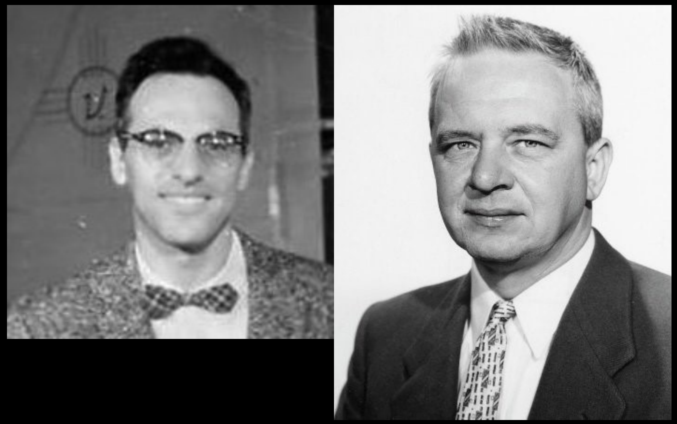


Enrico Fermi gives it the name of **neutrino** (from italian, little neutral one) and includes in his beta decay theory (1934)

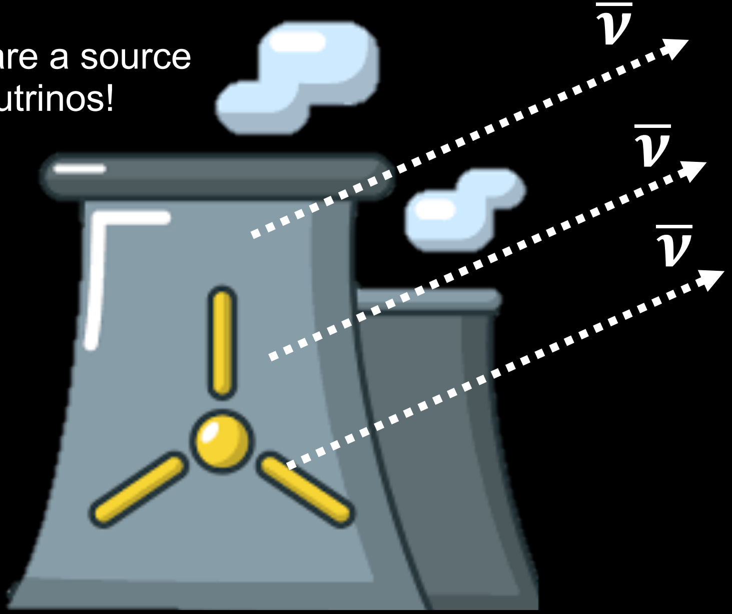

I have done a terrible thing
I have postulated a particle that cannot be detected.
ROFLBOT

However, 50 years later…

F. Reines and C. Cowan



Reactors are a source of (anti)neutrinos!



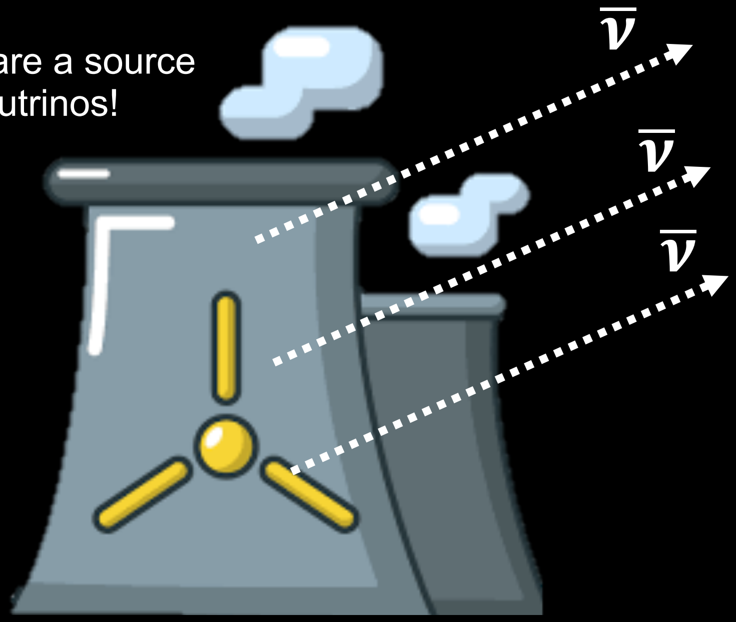
$$\bar{\nu} + p \rightarrow n + e^{+}$$

Detect the positron AND the neutron!

However, 50 years later…

F. Reines and C. Cowan

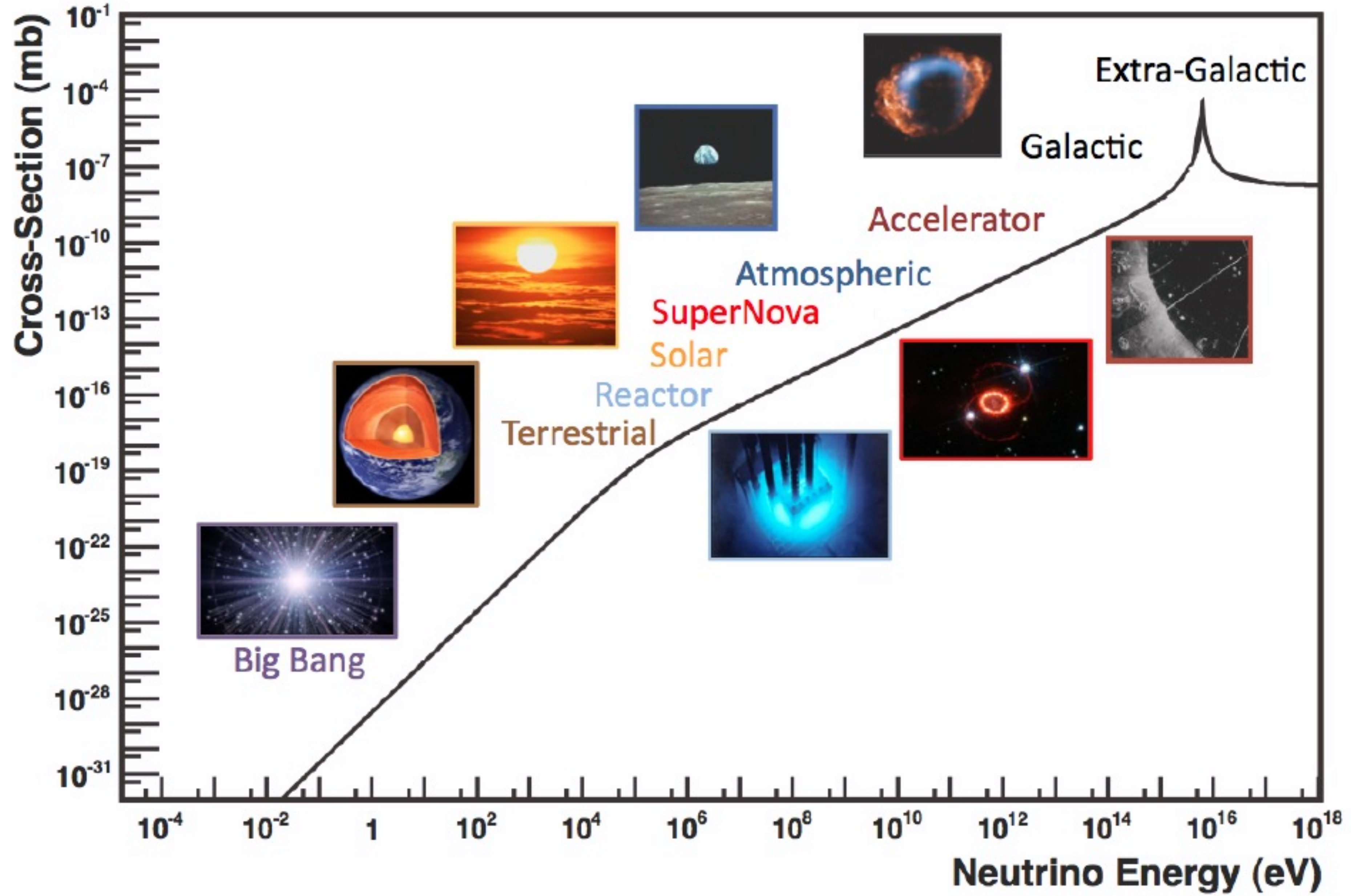
Reactors are a source of (anti)neutrinos!



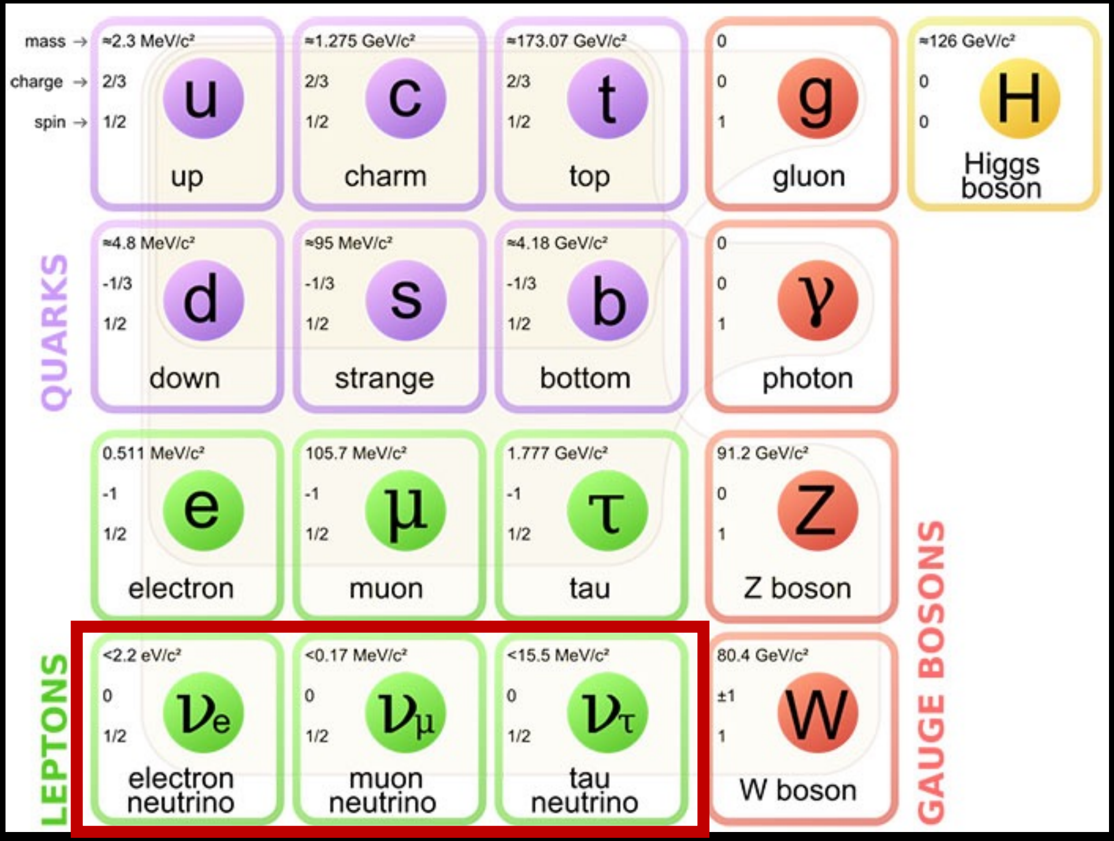
$$\bar{\nu} + p \rightarrow n + e^{+}$$

On June 14, 1956, Reines and Cowan sent a telegram to Pauli:

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters."

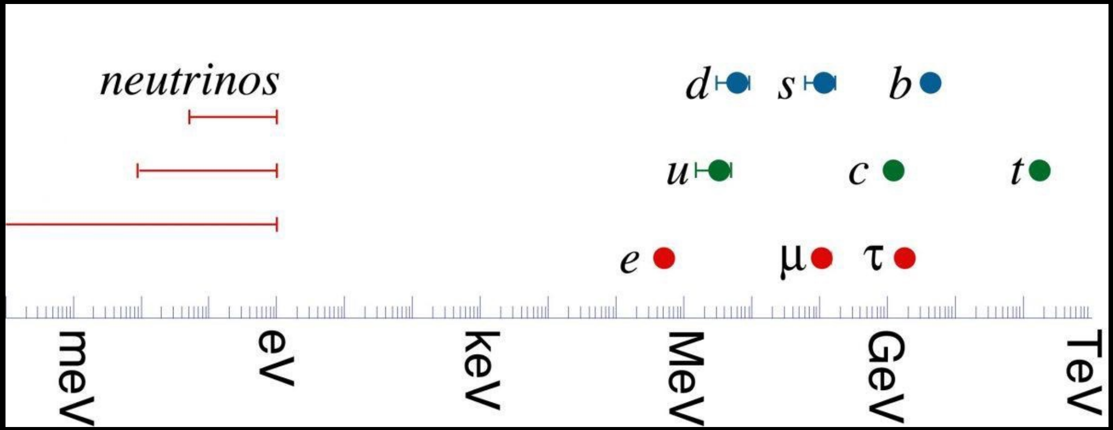

Cross-Section (mb)
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{-31}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
Neutrino Energy (eV)
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang

Neutrinos in the Standard Model

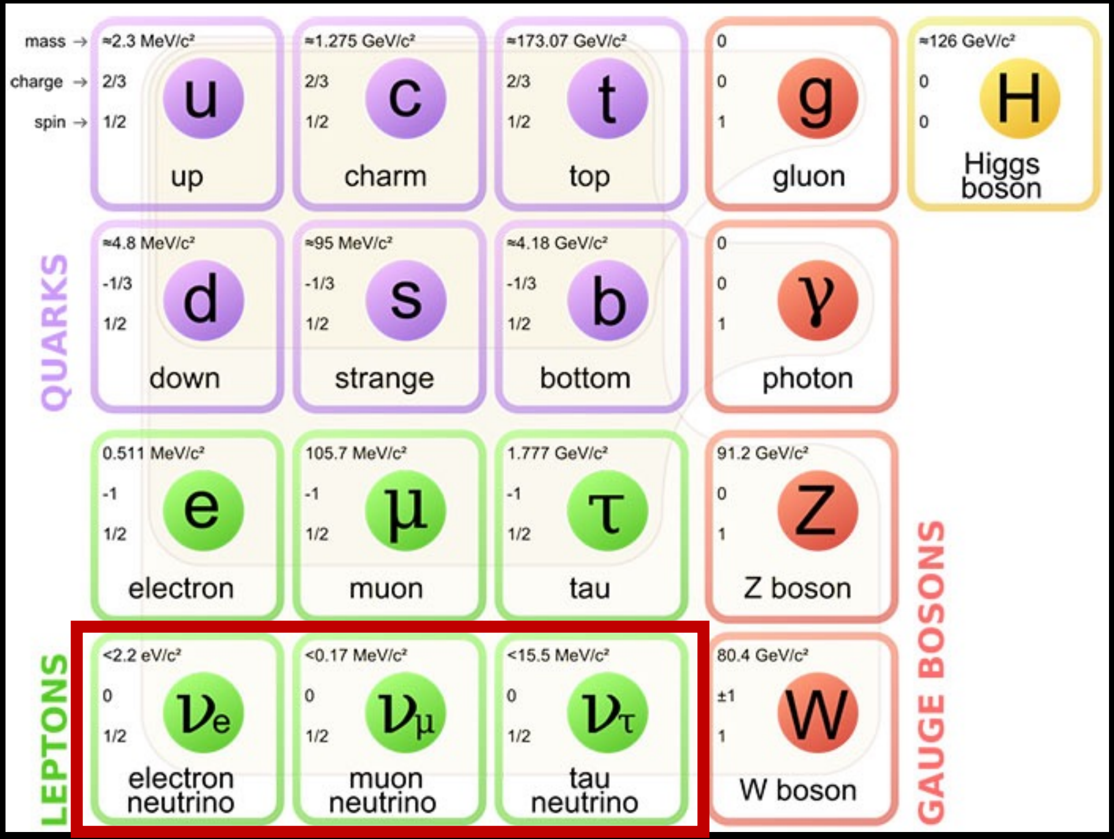


- Neutrinos are:
  - Neutral leptons
  - 3 flavours
  - Spin 1/2
  - Only interact via weak interation (Z and W bosons)

  - The Standard Model does not account for their masses (massless)
  - But we know that they have a very very small mass... (but not the exact value of the mass)



Neutrinos in the Standard Model



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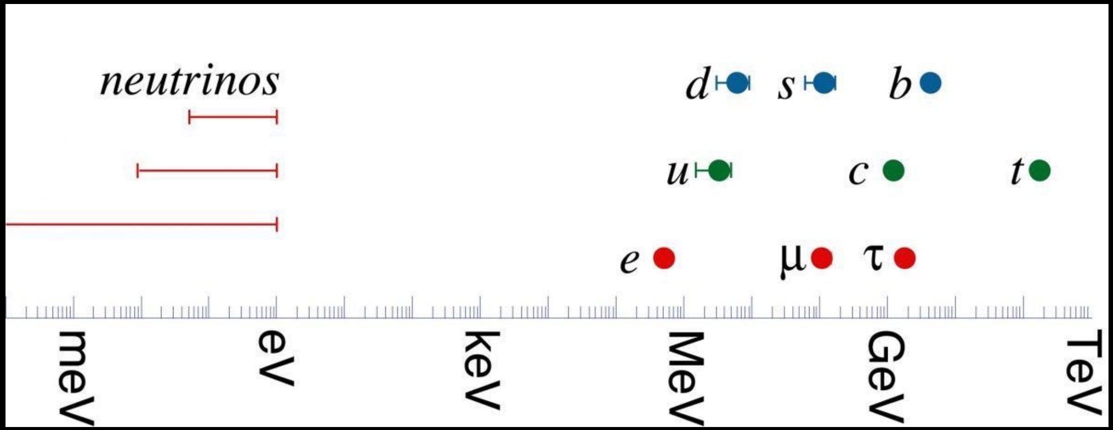
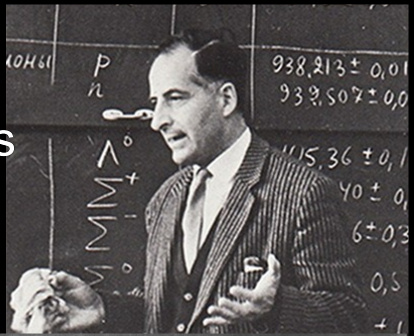


How do we know that neutrinos have non-zero masses?

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



Three flavours of Neutrinos

ν_e ν_μ ν_τ

Courtesy of Sakata Memorial Archival Library

S. Sakata 1911-1970 | Z. Maki 1929-2005 | M. Nakagawa 1932-2001

Neutrinos Oscillate

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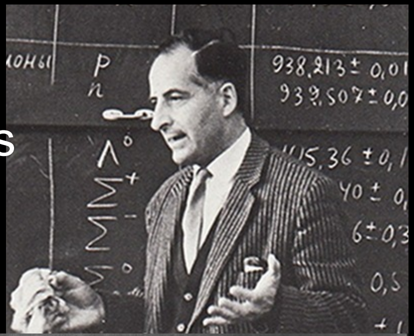
$\nu - \bar{\nu}$ oscillations

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Courtesy of Sakata Memorial Archival Library

Three flavours of Neutrinos

$$\boldsymbol{\nu_e} \qquad \boldsymbol{\nu_\mu} \qquad \boldsymbol{\nu_\tau}$$

Are a linear combination of three neutrino mass states

$$\boldsymbol{\nu_1} \qquad \boldsymbol{\nu_2} \qquad \boldsymbol{\nu_3}$$

$$\boldsymbol{\nu_e} = a\boldsymbol{\nu_1} + b\boldsymbol{\nu_2} + c\boldsymbol{\nu_3}$$
$$\boldsymbol{\nu_\mu} = d\boldsymbol{\nu_1} + e\boldsymbol{\nu_2} + f\boldsymbol{\nu_3}$$
$$\boldsymbol{\nu_\tau} = g\boldsymbol{\nu_1} + h\boldsymbol{\nu_2} + i\boldsymbol{\nu_3}$$

Neutrinos Oscillate

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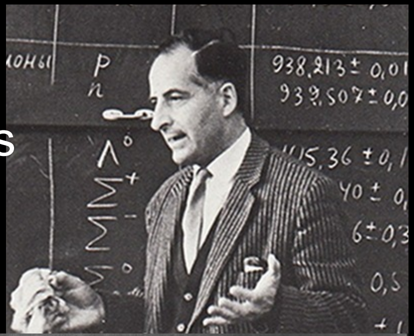


Three flavours of Neutrinos

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

Are a linear combination of three neutrino mass states

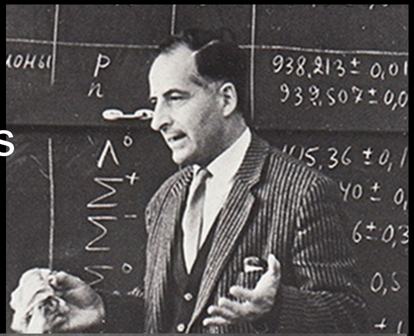
$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The PMNS Matrix

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



Three flavours of Neutrinos

$\nu_e \quad \nu_\mu \quad \nu_\tau$

Are a linear combination of three neutrino mass states

$\nu_1 \quad \nu_2 \quad \nu_3$

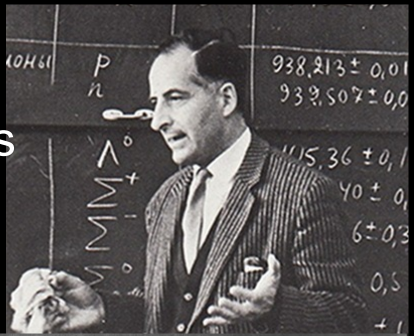
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12}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

The PMNS Matrix

(that looks more like this)

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations



When neutrinos travel, they change from one flavour to the other.

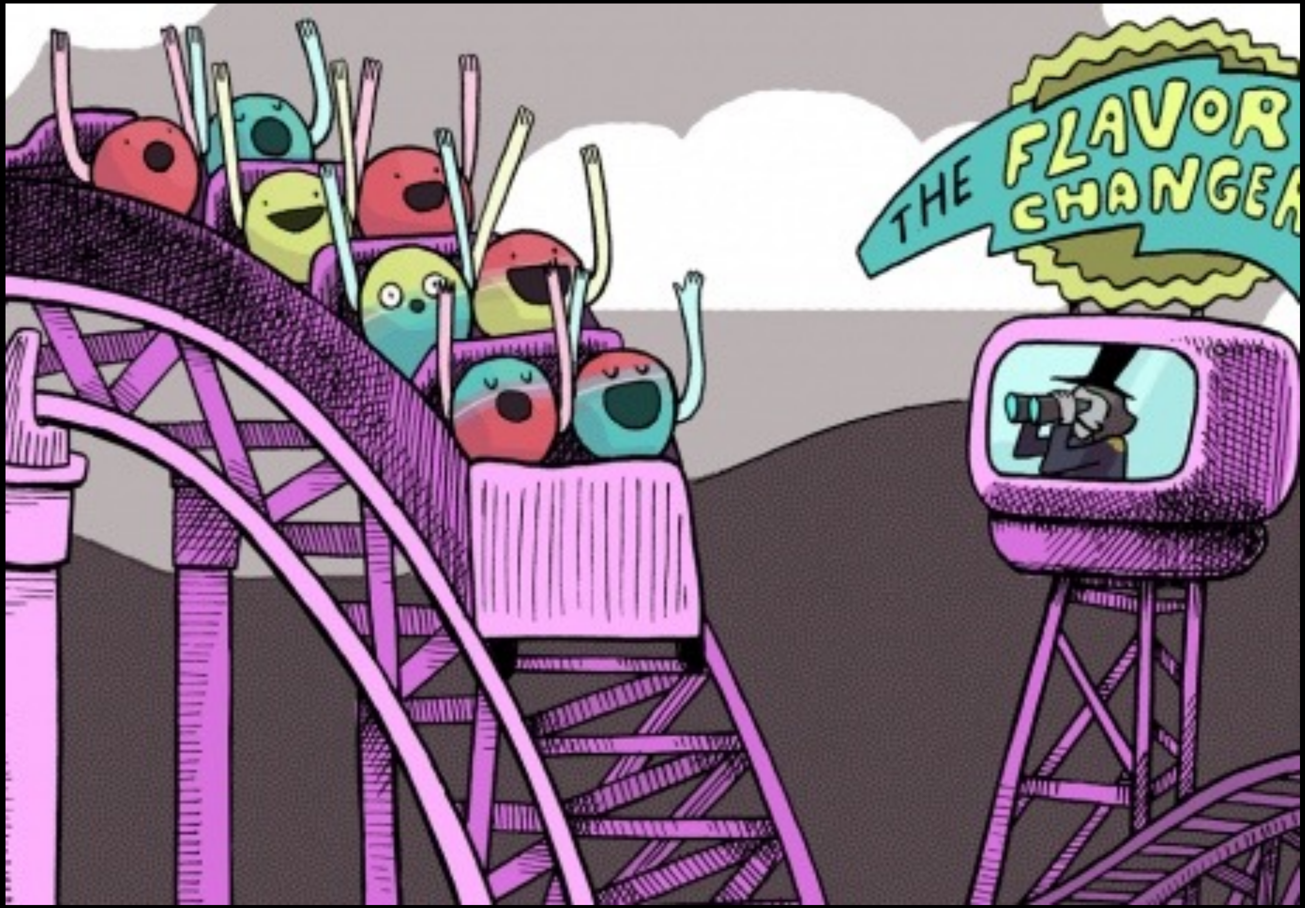
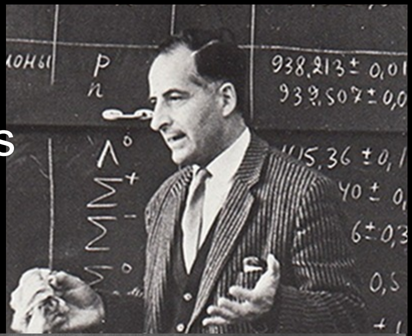


Image from Symmetry Magazine

Neutrinos Oscillate

B. Pontecorvo
$\nu - \bar{\nu}$ oscillations

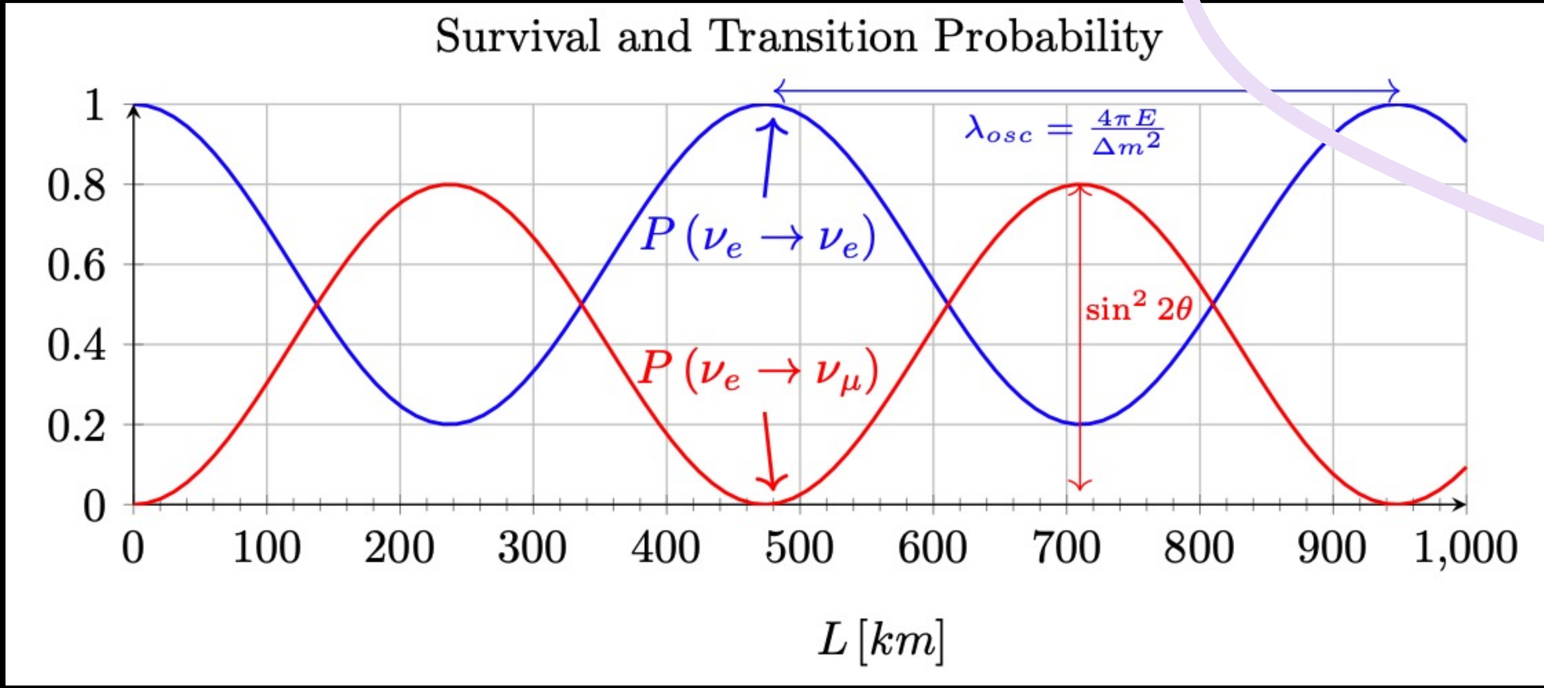


When neutrinos travel, they change from one flavour to the other.

Two neutrino case:

$$P_{oscillation}(\boldsymbol{\nu_e} \rightarrow \boldsymbol{\nu_\mu}) = sin^2 2\theta_{12} sin^2\left(1.27\Delta m^2_{21}[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

$m_2^2 - m_1^2$



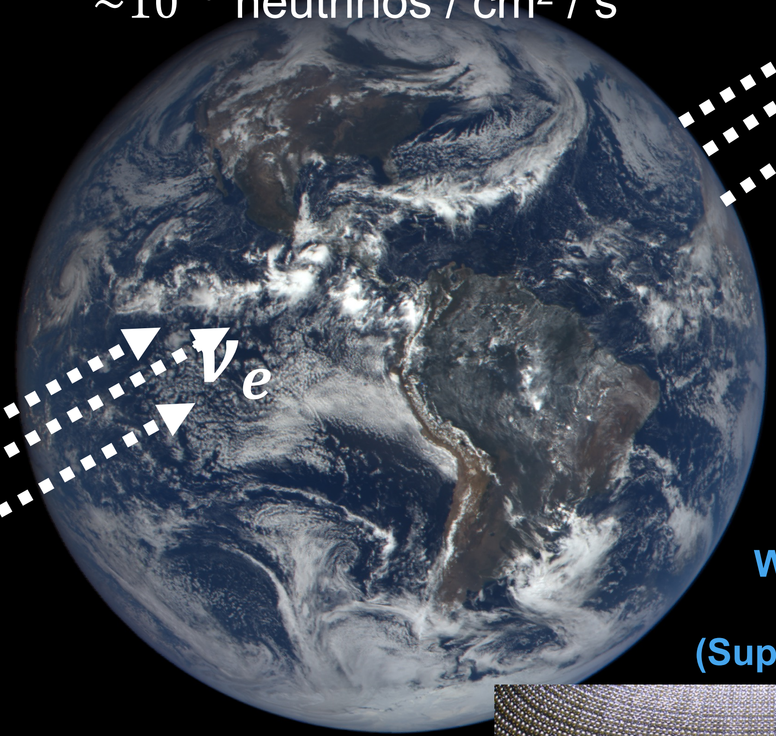
Hummm…
And how do we know that neutrinos oscillate?

From the 1970s to the 2000s, multiple experiments were measuring neutrinos from the Sun.

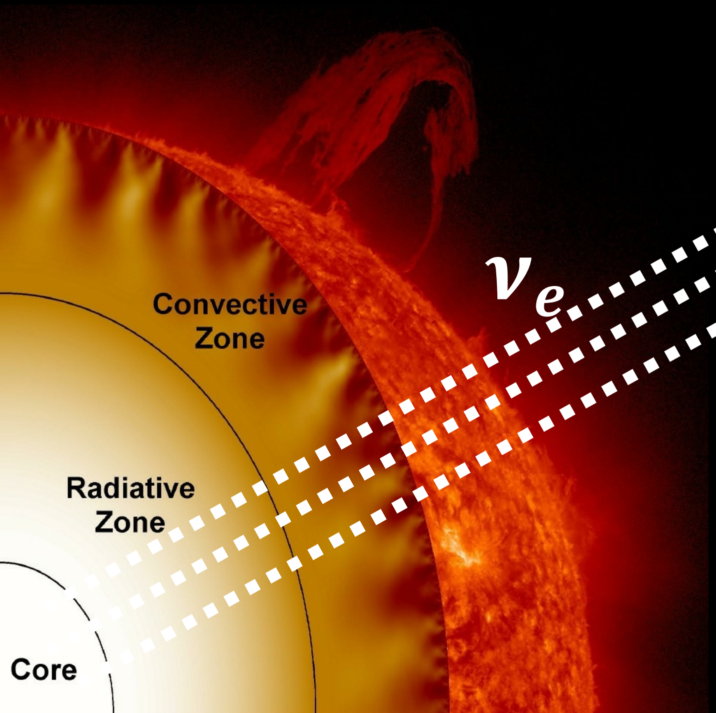
$\sim 10^{10}$ neutrinos / cm^2 / s

A lot of neutrinos, but very small interaction cross-section of $\sim 10^{-44}\ cm^{-2}$

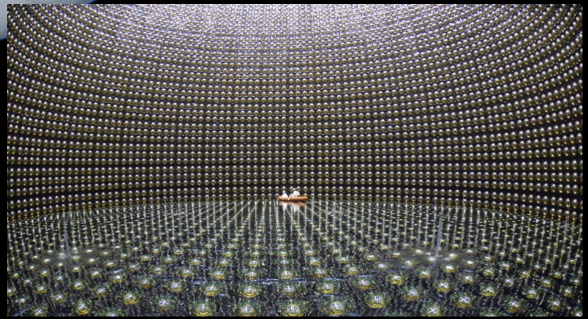
The detectors were placed underground in order to be shielded by rock from cosmic rays.
Muon flux at sea level = 1 / cm^2 / minute



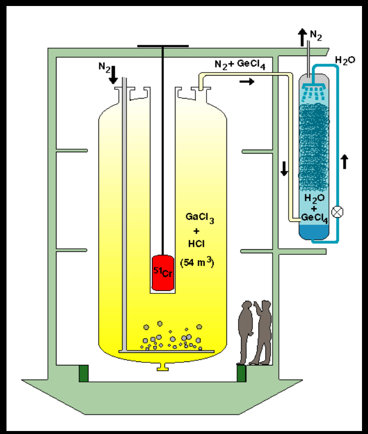
ν_e ν_e ν_e ν_e ν_e ν_e ν_e ν_e



Water Cherenkov Experiments (Super-Kamiokande)



Homestake Experiment (Chlorine)



Gallium Experiments (SAGE, GALLEX, GNO)

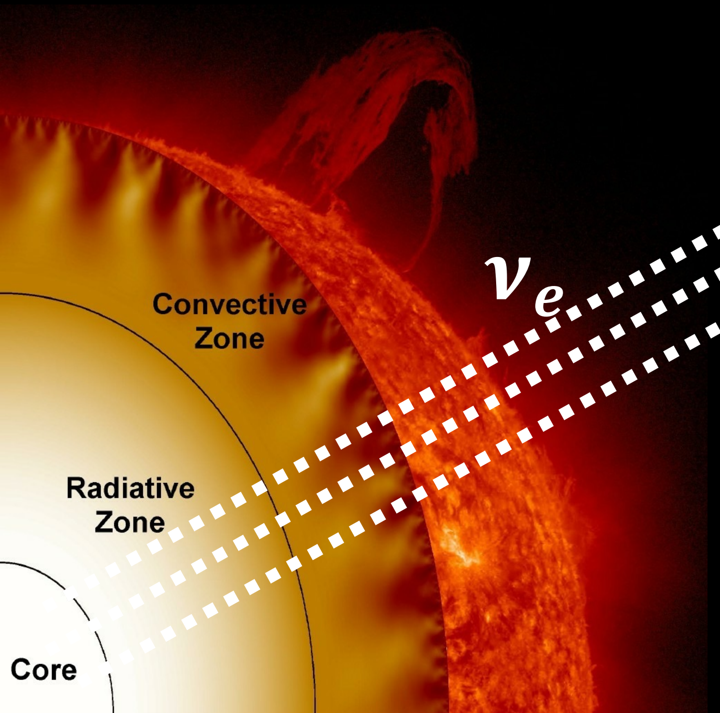
From the 1970s to the 2000s, multiple experiments were measuring neutrinos from the Sun.

$\sim 10^{10}$ neutrinos / cm^2 / s

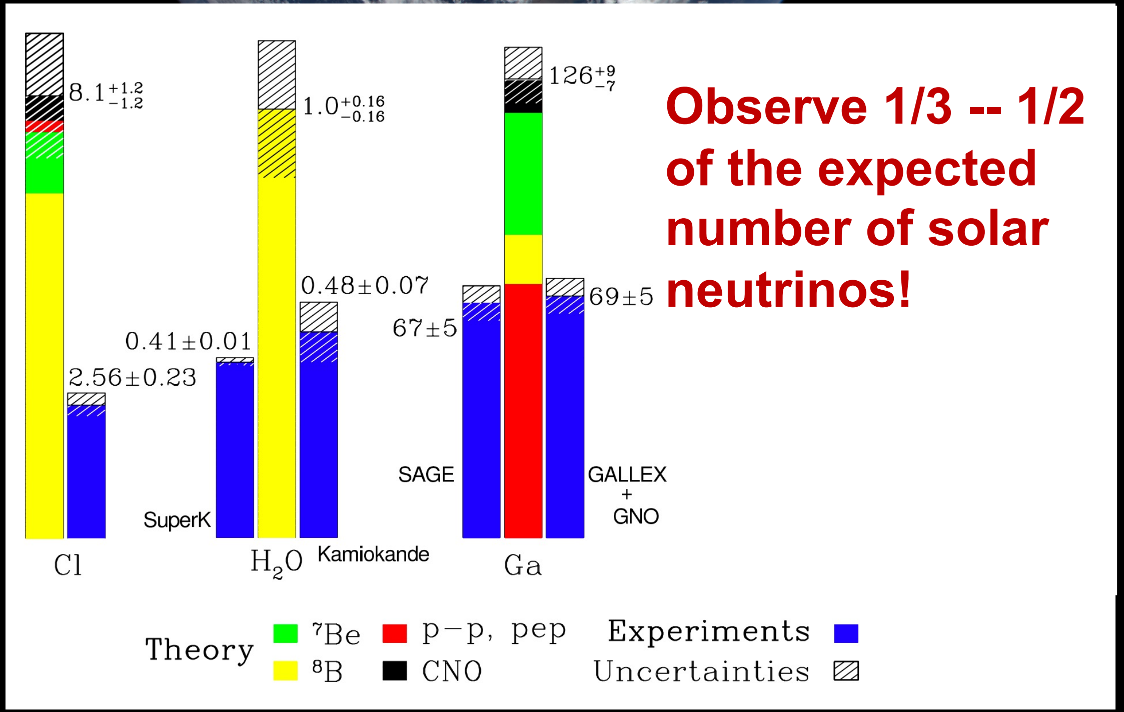
A lot of neutrinos, but very small interaction cross-section of $\sim 10^{-44}\ cm^{-2}$

The detectors were placed underground in order to be shielded by rock from cosmic rays.
Muon flux at sea level = 1 / cm^2 / minute

ν_e ? ? ? ν_e ? ? ν_e



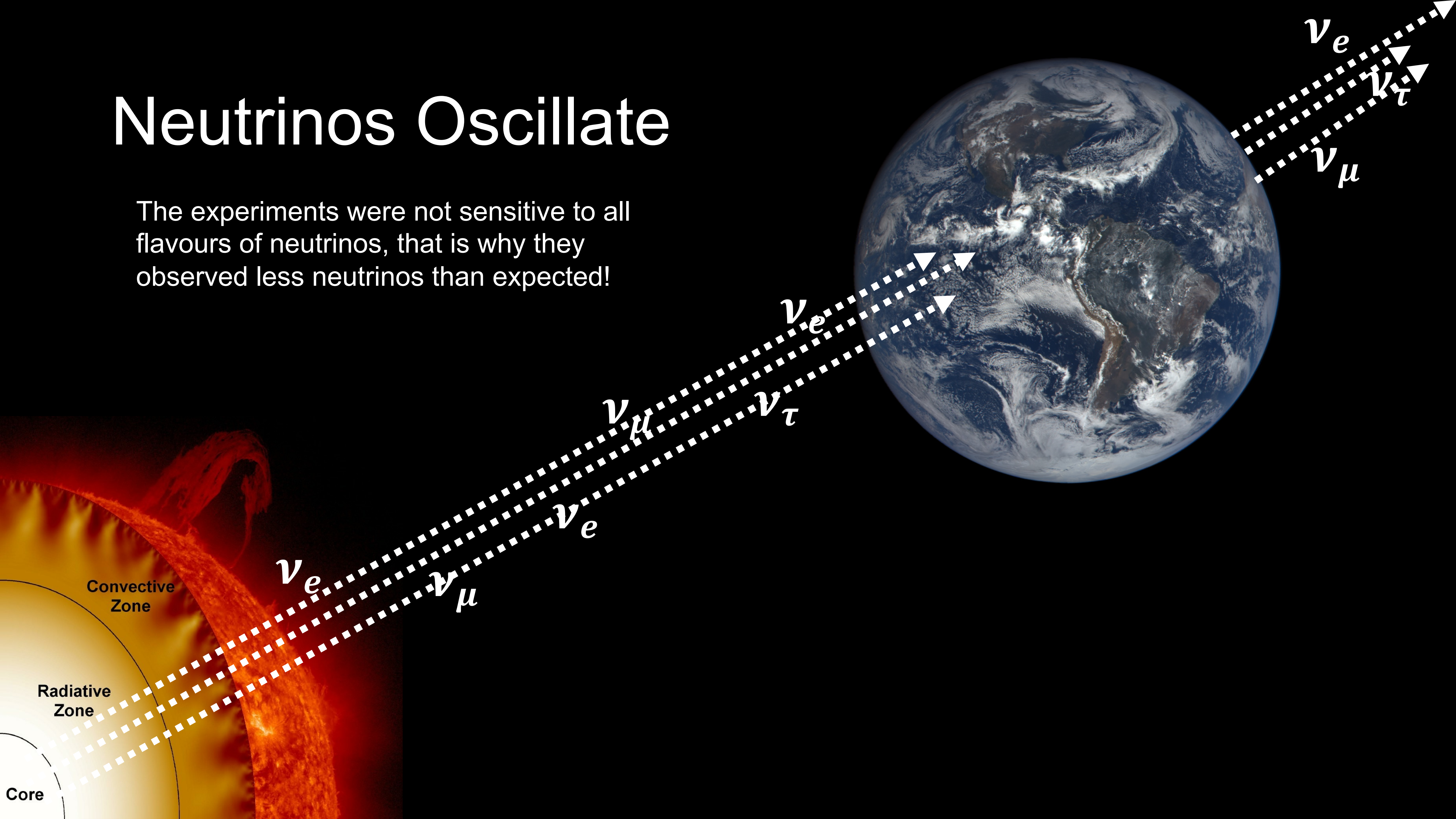
Are we not measuring all the neutrinos from the Sun? What happens to them on the way to Earth?



Observe 1/3 -- 1/2 of the expected number of solar neutrinos!

Neutrinos Oscillate

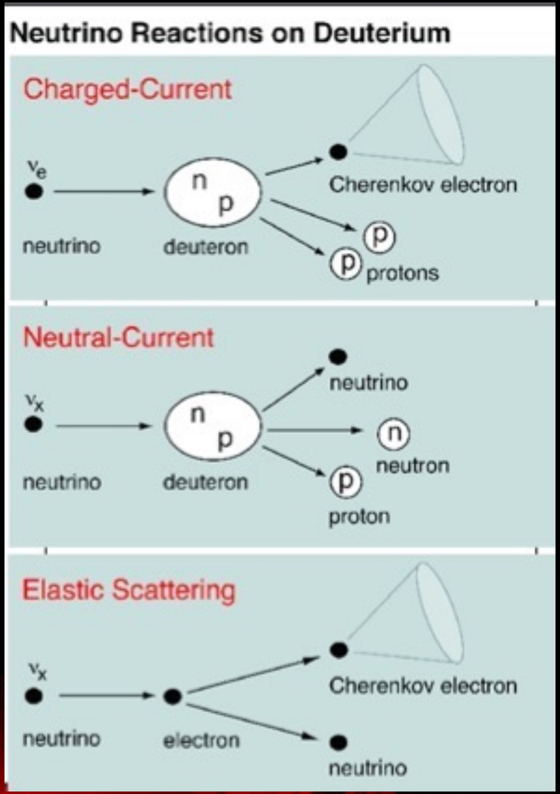
The experiments were not sensitive to all flavours of neutrinos, that is why they observed less neutrinos than expected!

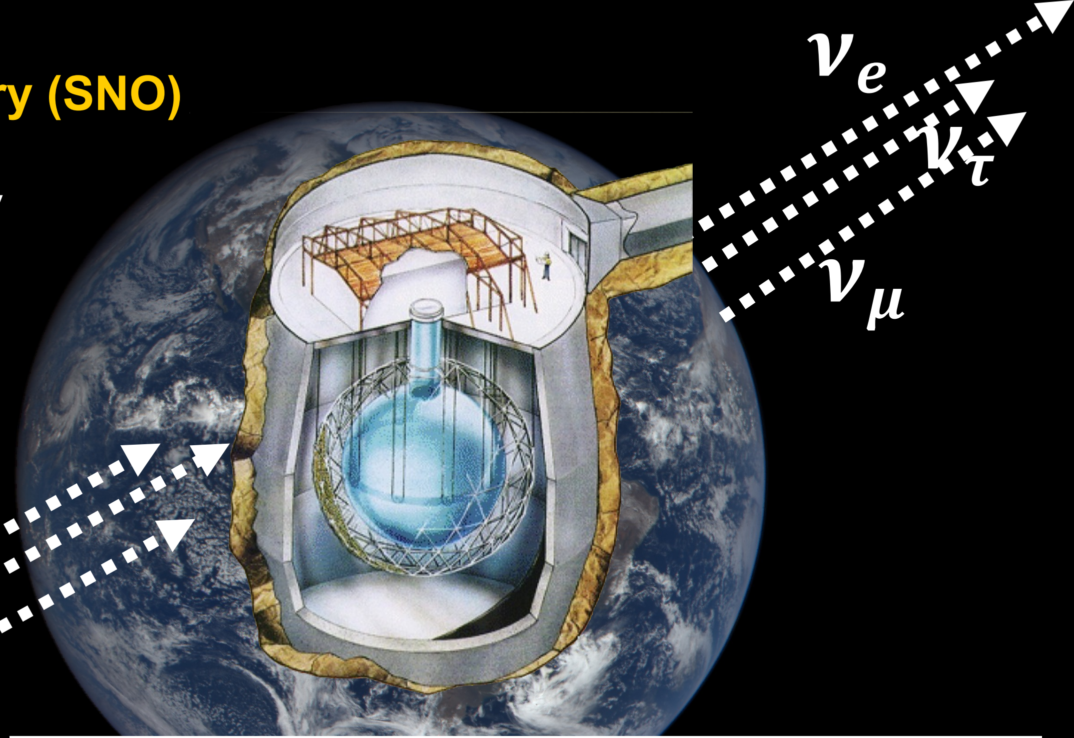


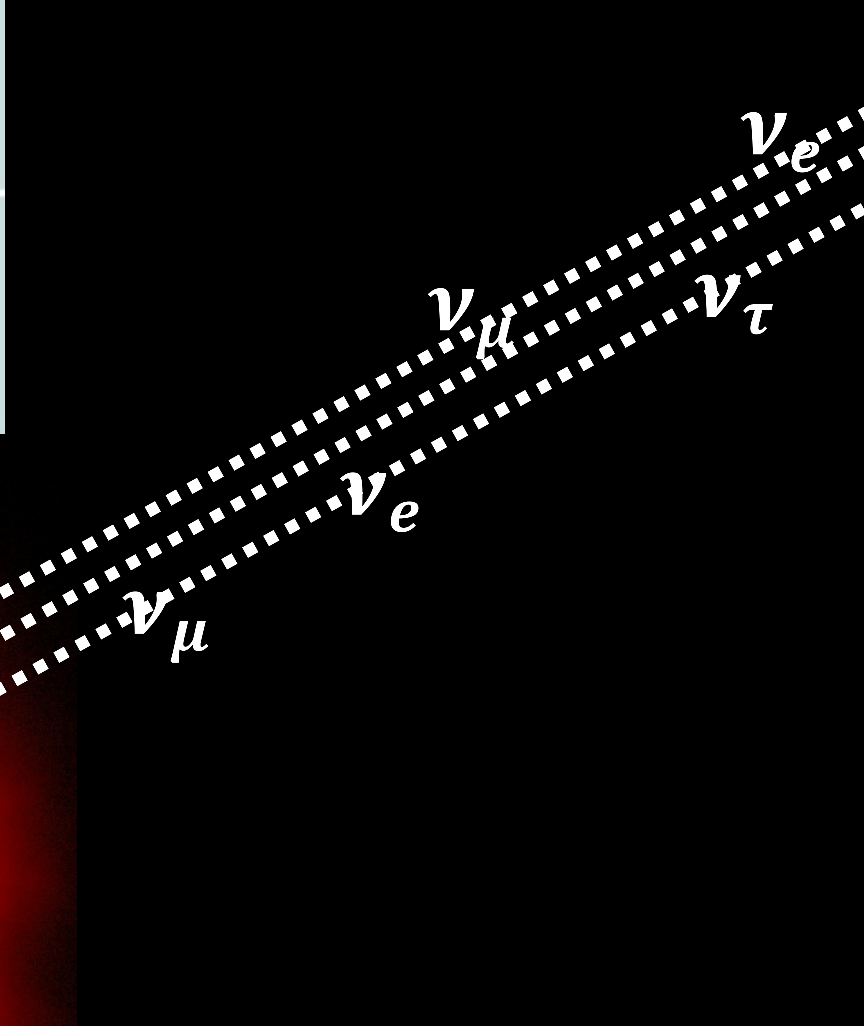
The Sudbury Neutrino Observatory (SNO)

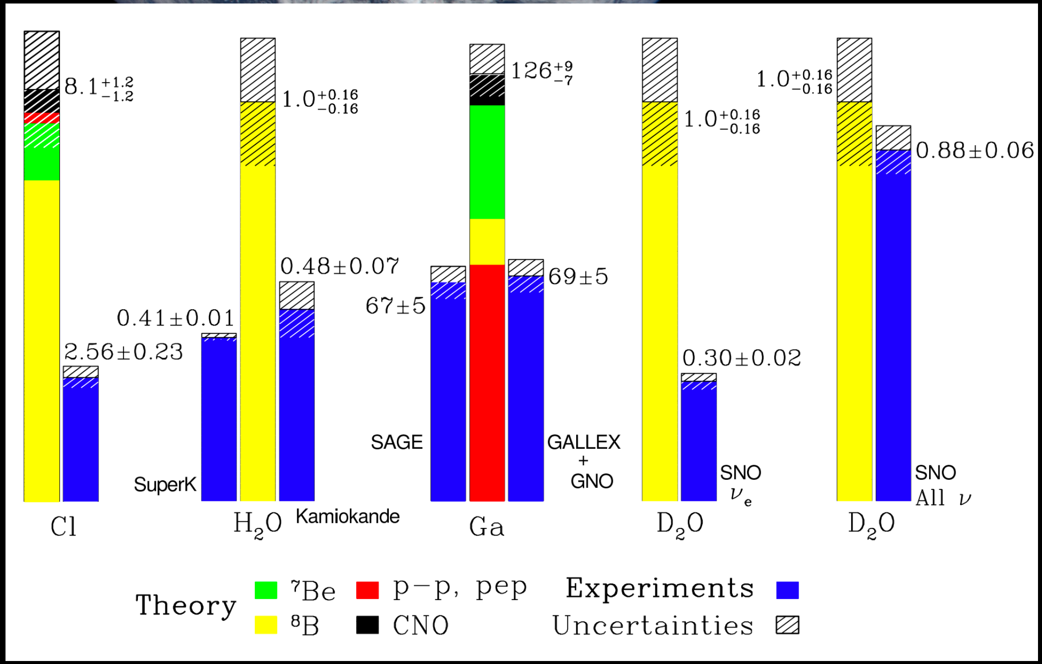
Heavy water (deuterium) Cherenkov detector.

Sensitive to all flavours of neutrinos.









Atmospheric Neutrinos

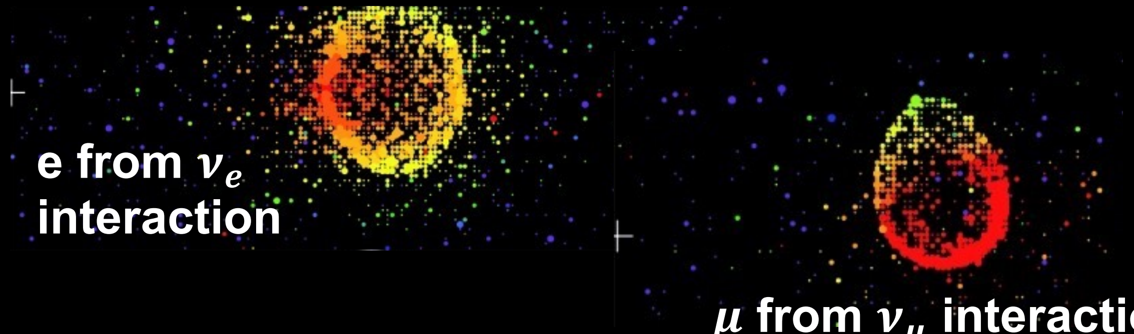
- Produced ~15 kilometers above Earth's surface.

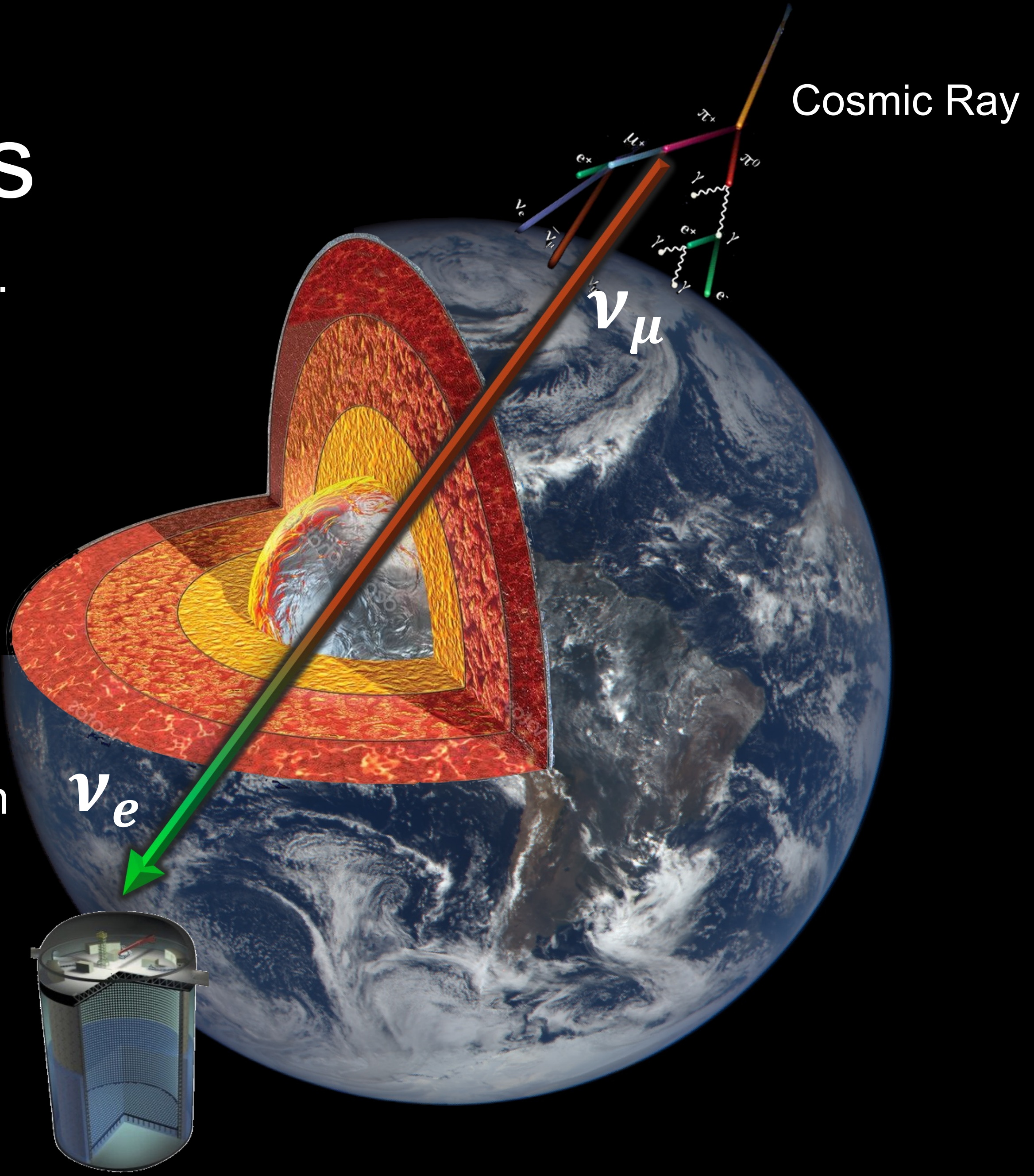
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$

- A different ratio shows that neutrinos oscillated.

- That is what Super-Kamiokande observed when comparing the number of ν_e and ν_μ interactions.

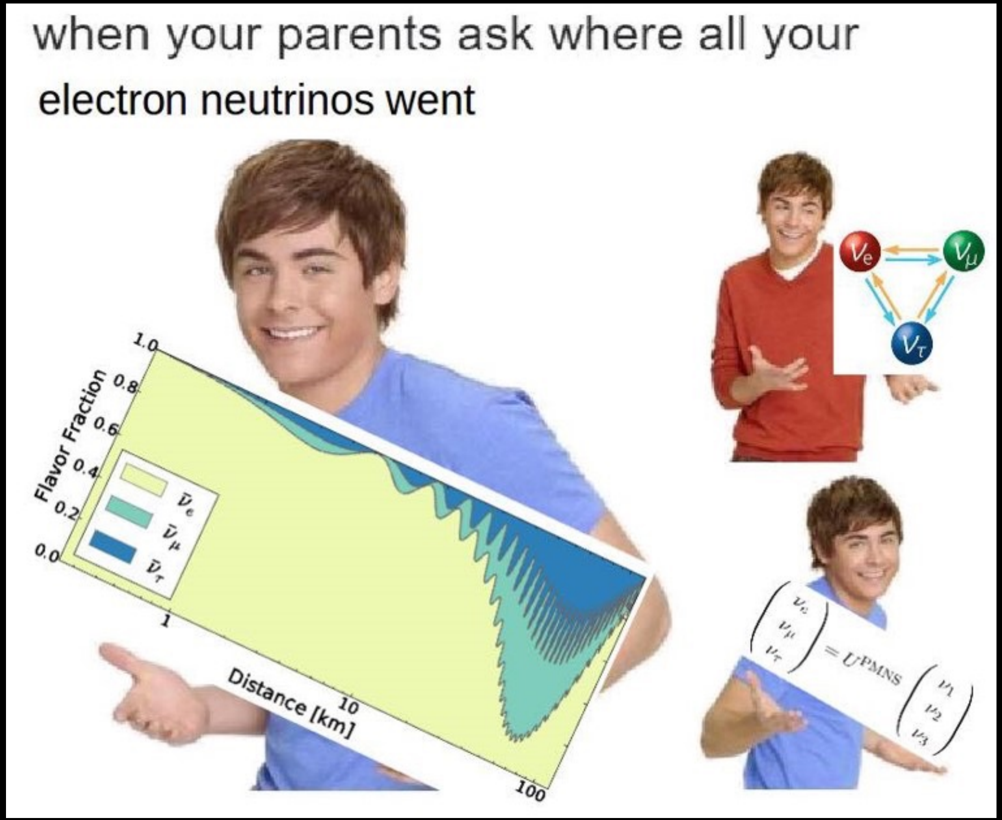




Neutrino Oscillations Discovered!

"...the research group in Canada led by Arthur B. McDonald could demonstrate that the neutrinos from the Sun were not disappearing on their way to Earth. Instead they were captured with a different identity when arriving to the Sudbury Neutrino Observatory."

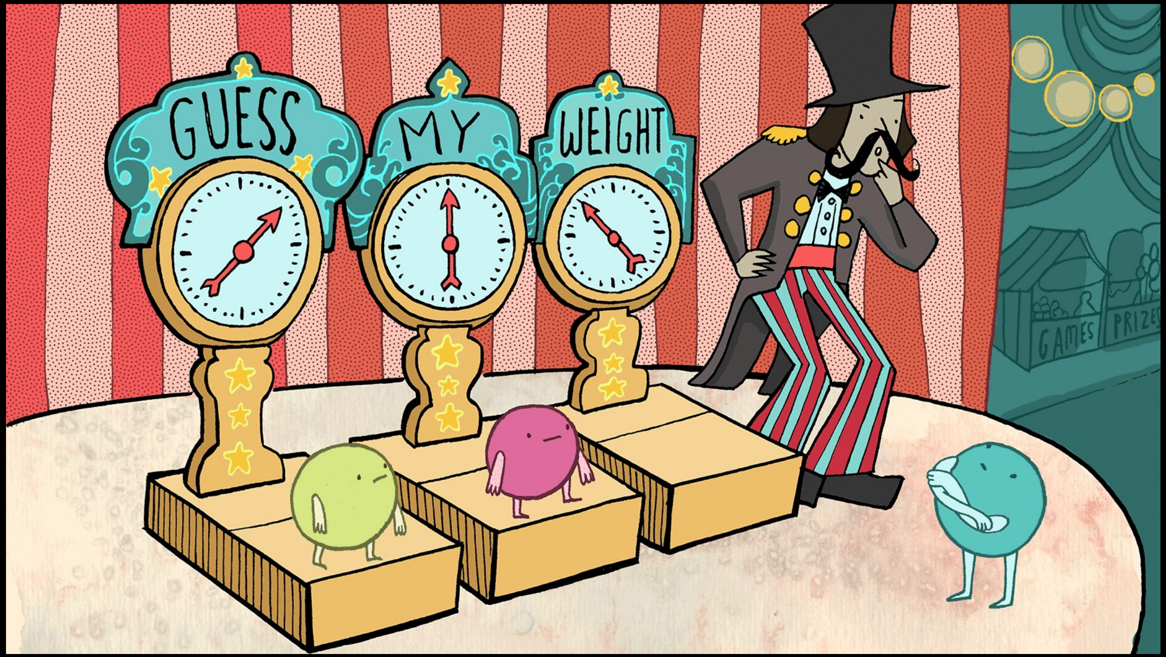
"...Takaaki Kajita presented the discovery that neutrinos from the atmosphere switch between two identities on their way to the Super-Kamiokande detector in Japan."



What are the open questions?

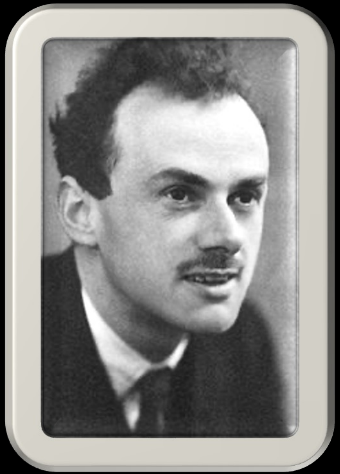
What we don’t know about neutrinos

- What is the value of the mass?



What we don’t know about neutrinos

- What is the value of the mass?
- Where do the masses come from?



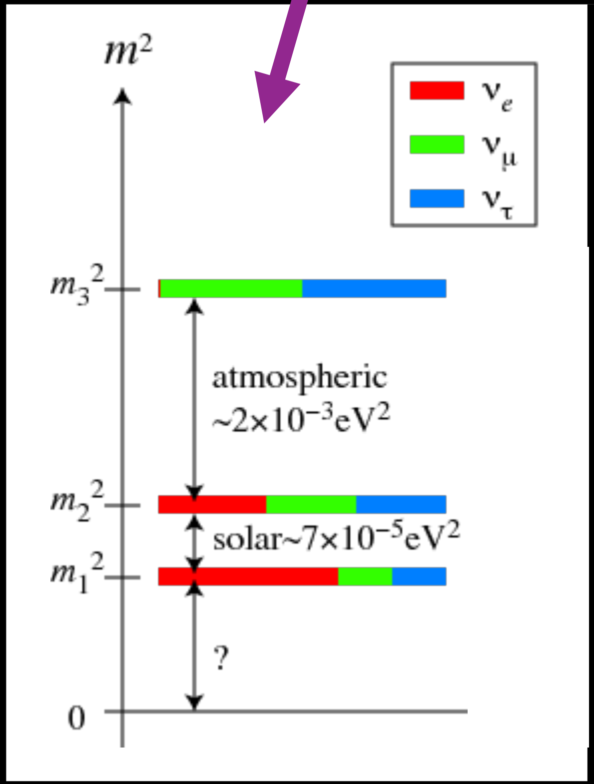
Dirac Neutrinos
Lepton number conservation
Neutrino ≠ anti-neutrino

Majorana Neutrinos
Lepton number violation
Neutrino = anti-neutrino

What we don't know about neutrinos

- What is the value of the mass?
- Where do the masses come from?
- How are the masses ordered?

Solar experiments have fixed the order between m_1 and m_2



What we don't know about neutrinos

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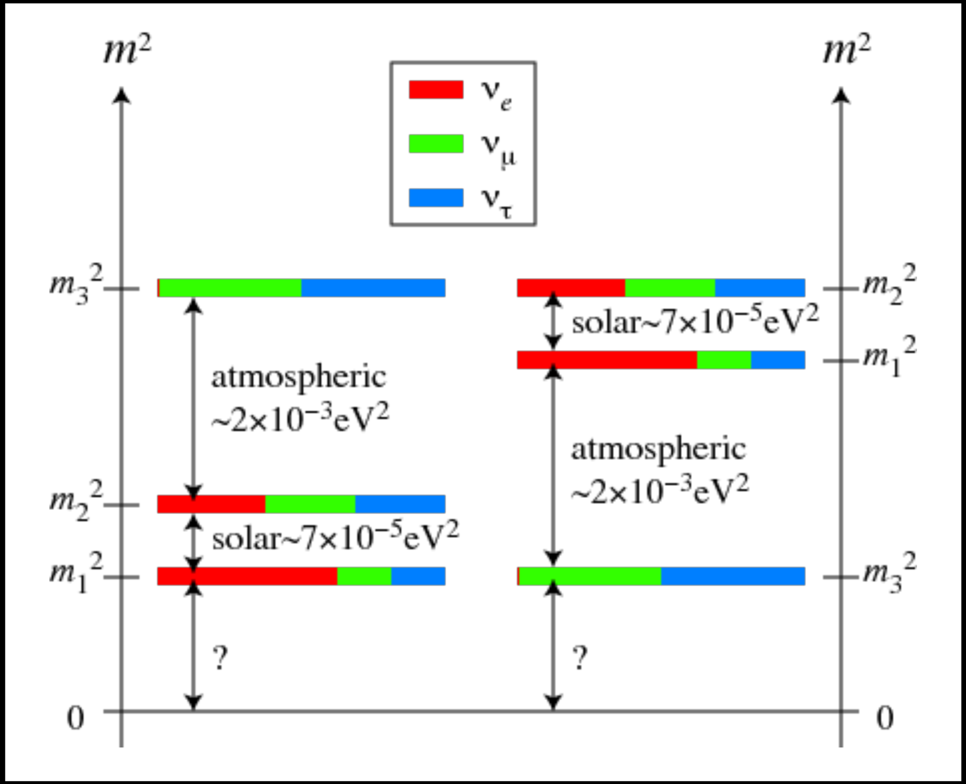
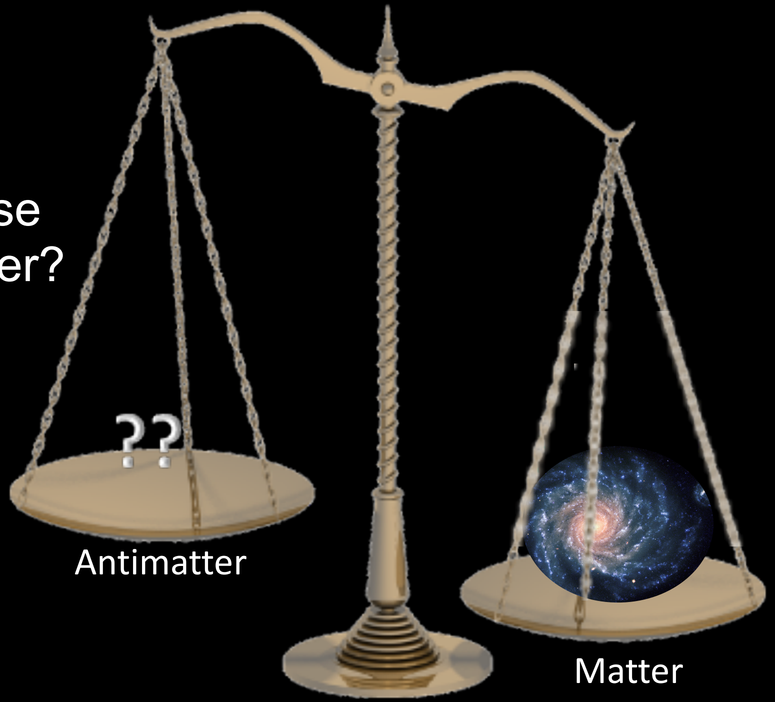


What we don't know about neutrinos

study of differences between neutrino and antineutrino oscillations

- What is the value of the mass?
- Where do the masses come from?
- How are the masses ordered?
- Is there CP violation in the lepton sector?

Why is the Universe only made of matter?



To answer these questions…

Neutrino detection 101

- Neutrinos have a very small interaction probability
  - You need more than 10^{16} neutrinos to observe 1 neutrino/s in 10 m^3 of water
  - *Important:* We don't observe neutrinos directly (weak interaction and no charge), we observe the product of their reactions!!!!!!

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

Neutrino detection 101

- Neutrinos have a very small interaction probability
  - You need more than 10^{16} neutrinos to observe 1 neutrino/s in 10 m^3 of water
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$$\nu_e + e^- \rightarrow \nu_e + e^-$$

- **So how do we study neutrinos?**
  - We need large detectors
  - And large neutrinos fluxes
  - A looooot of time
  - Reduce as much as possible other sources
  of contamination (cosmic radiation for example)

What we don’t know about neutrinos

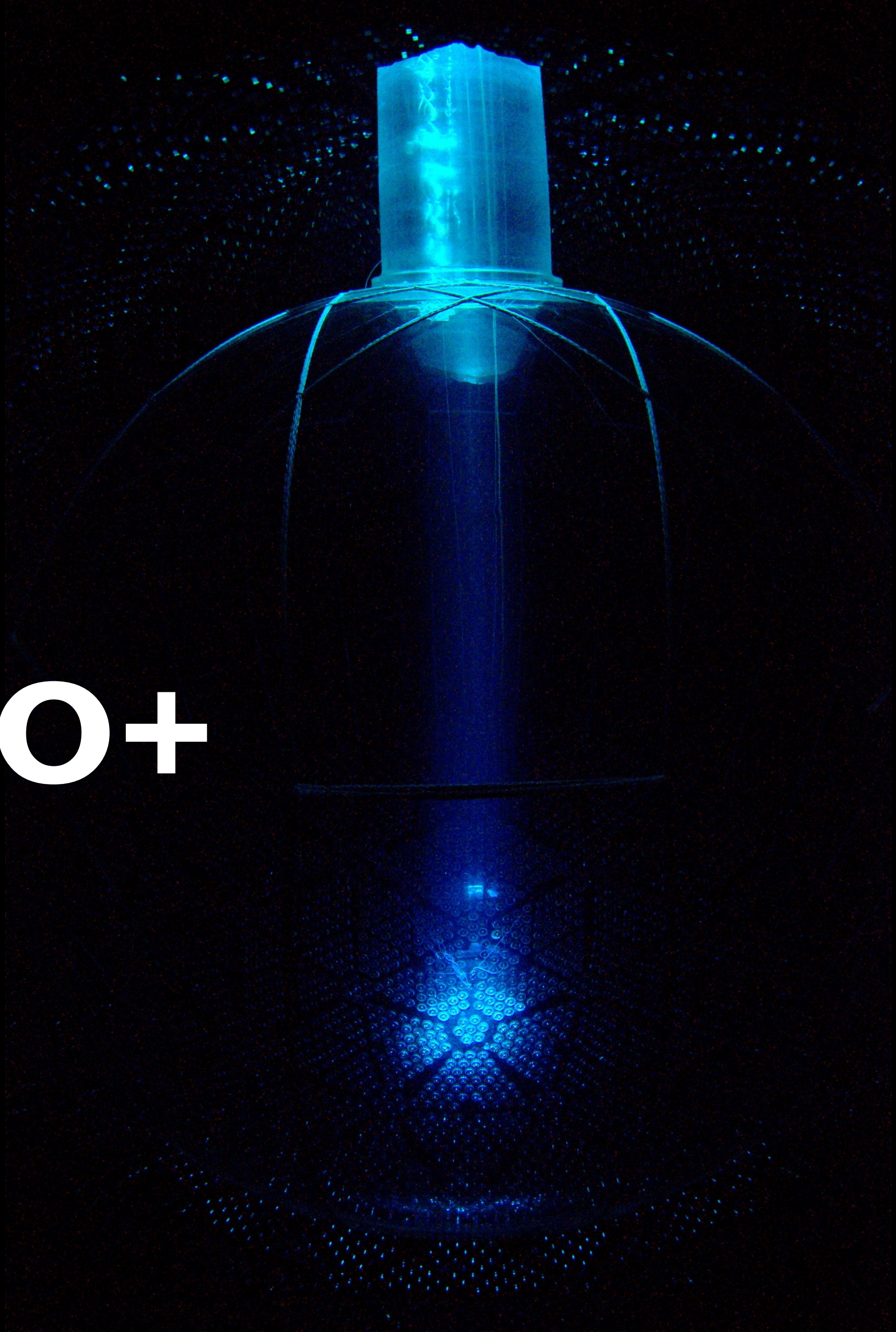
- What is the value of the mass?
- Where do the masses come from?

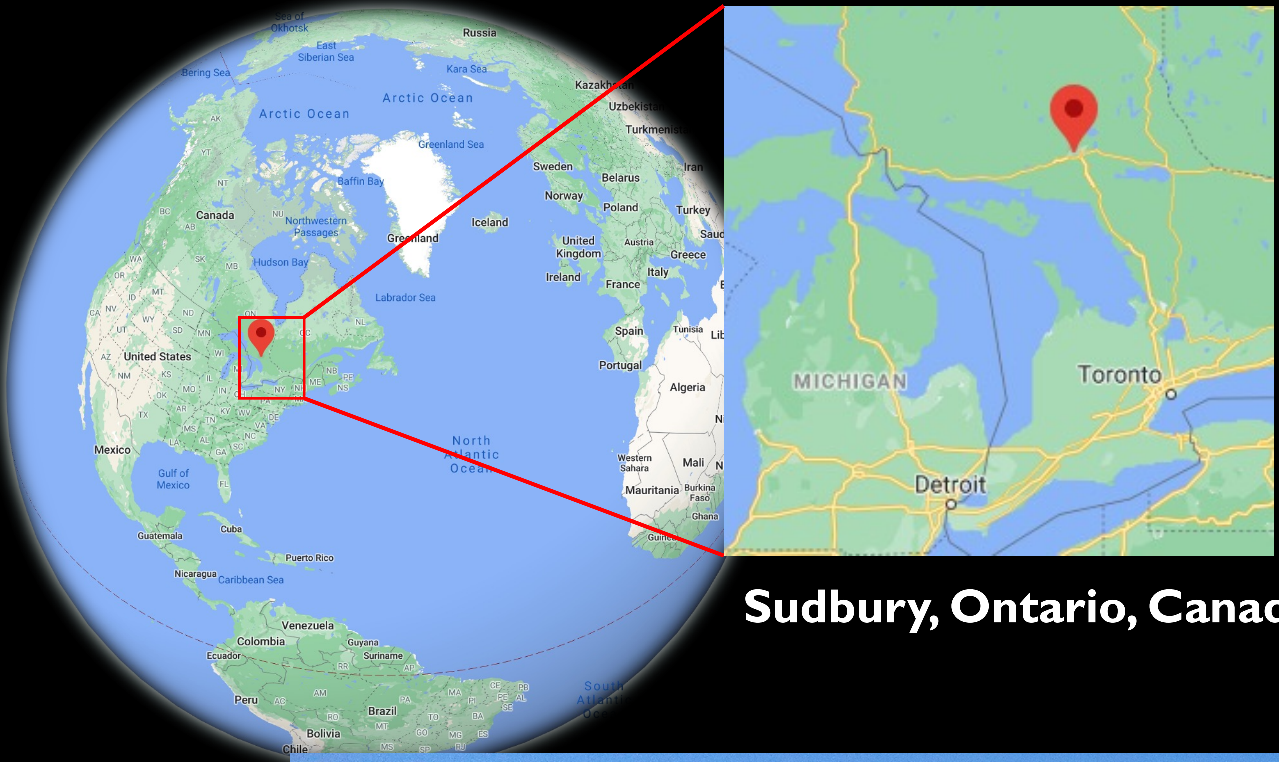
SNO+

- How are the masses ordered?
- Is there CP violation in the lepton sector?

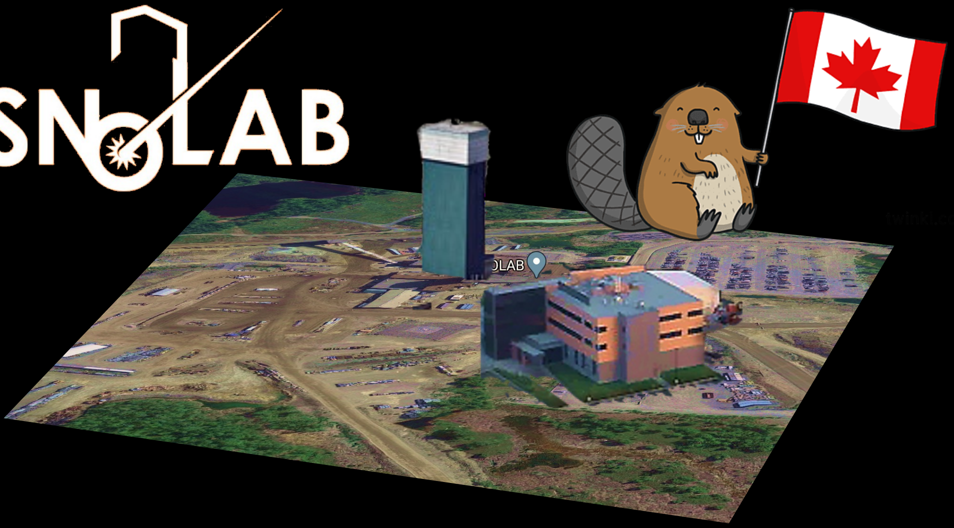
DUNE

SNO+

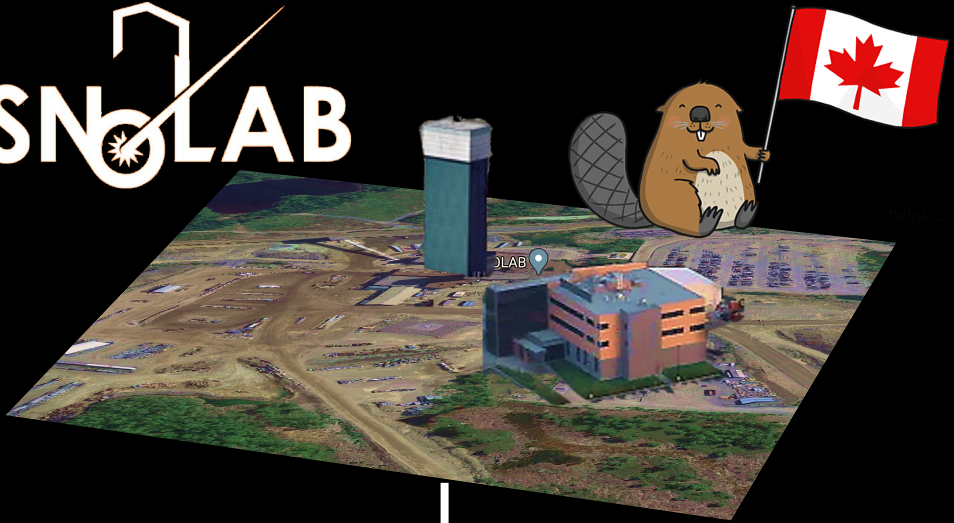




Sudbury, Ontario, Canada

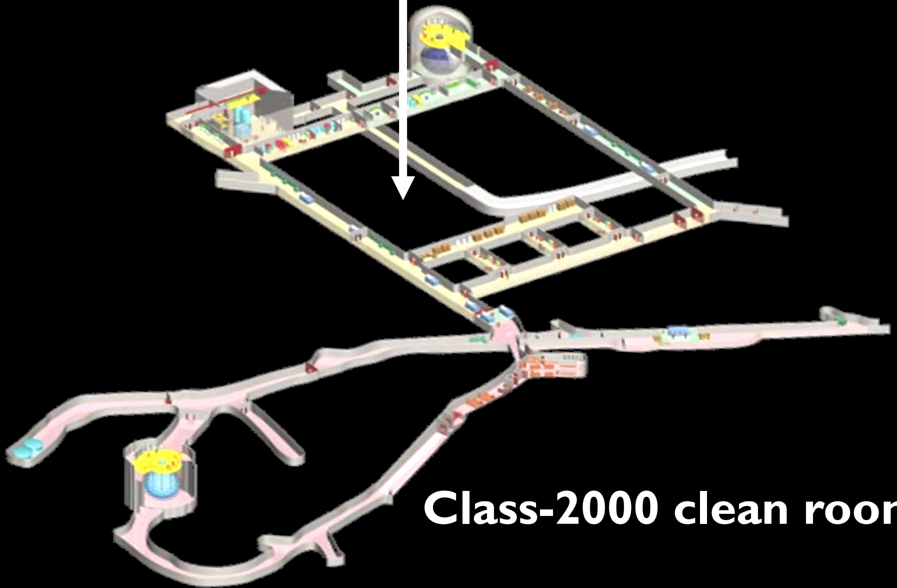


SNOLAB



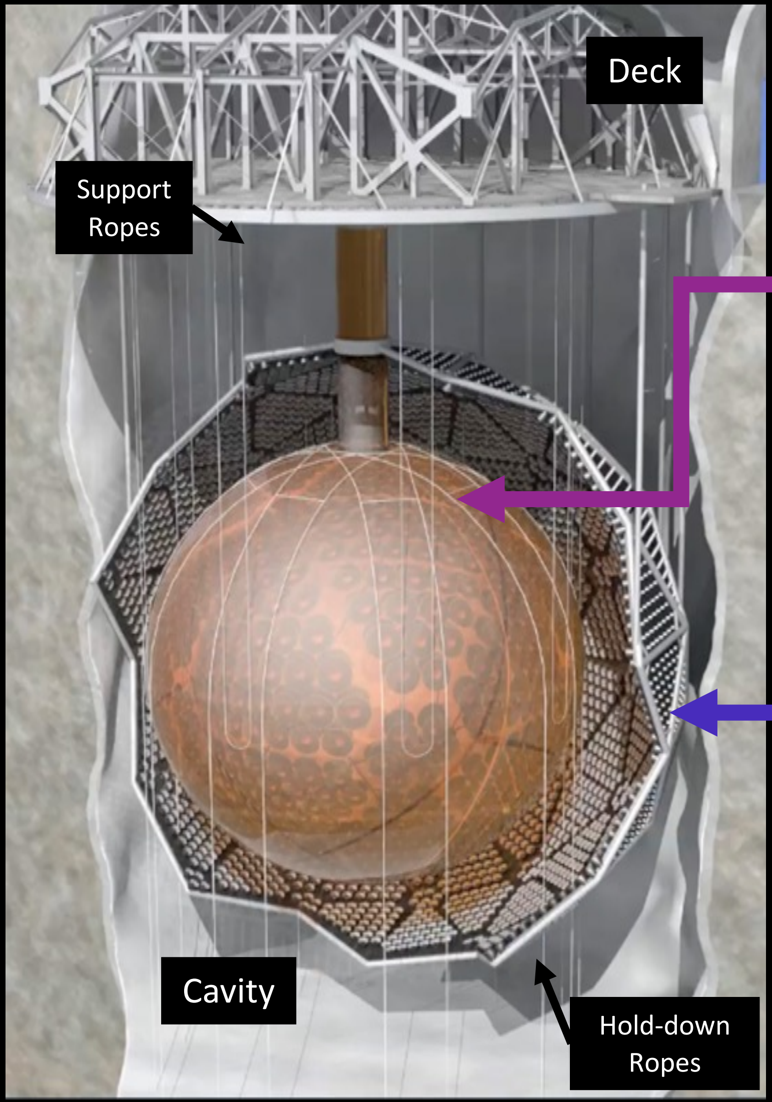
2070m (6000m w.e.)

~ 63 cosmic muons/day



Class-2000 clean room

The SNO+ Detector



At a depth of 2km (rock, ~5900 mwe, ~63 cosmic muons/day)

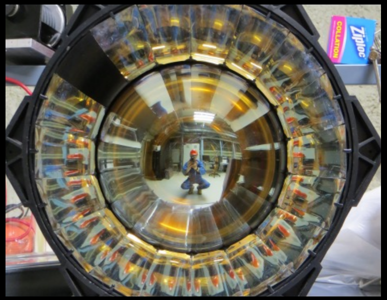
Acrylic Vessel
6 m radius, 5 cm thickness

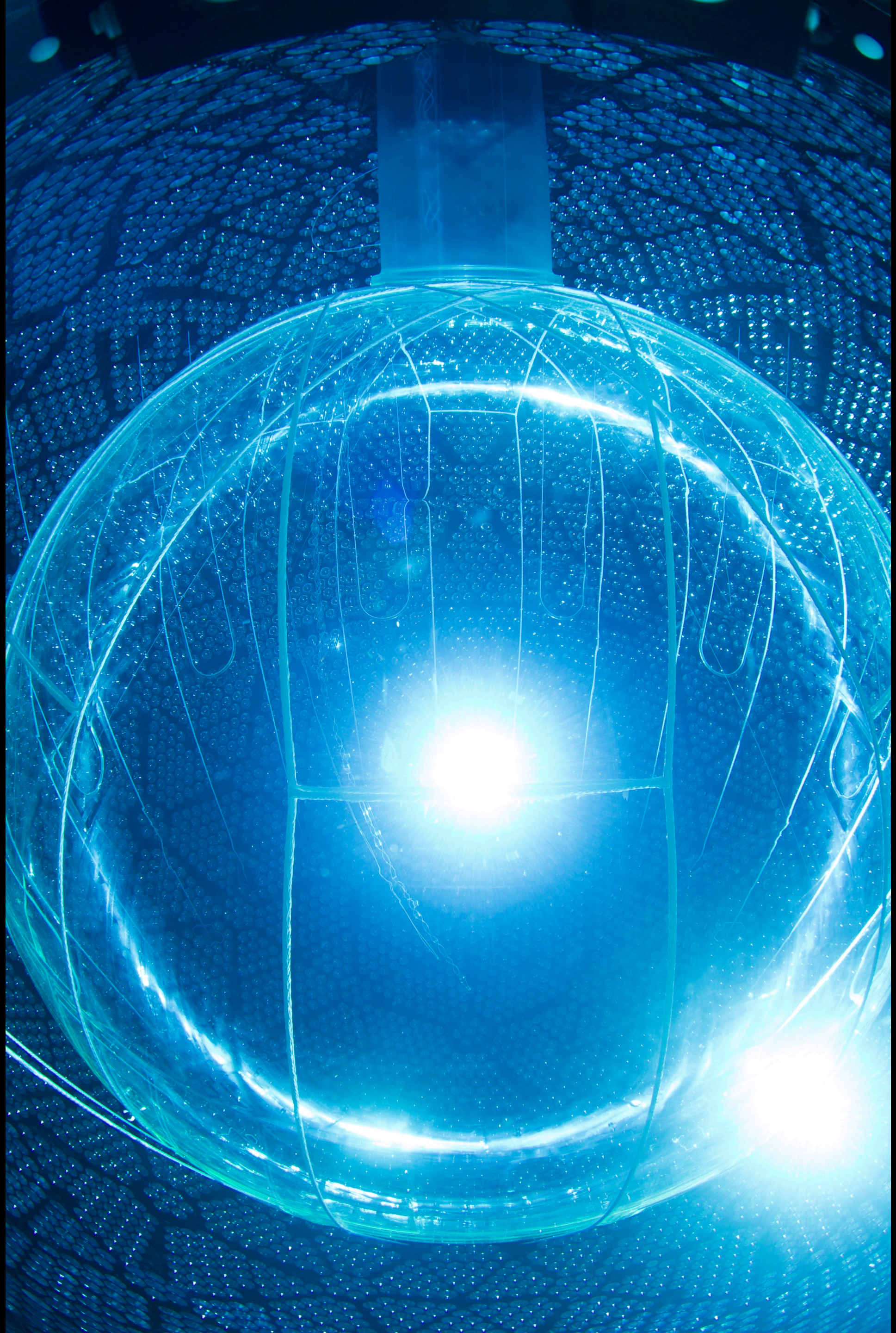
905 tonnes of ultra-pure water

780 tonnes of Liquid Scintillator

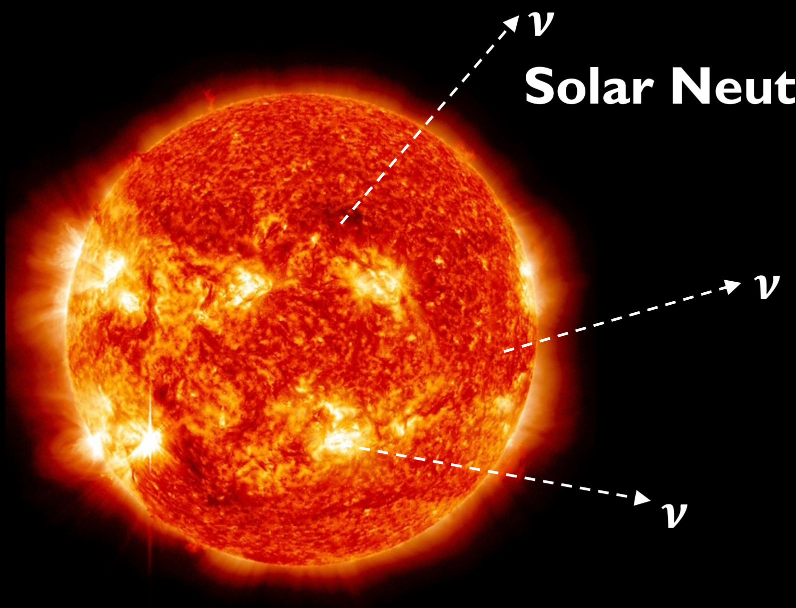
+ 3.9 tonnes of natural Tellurium

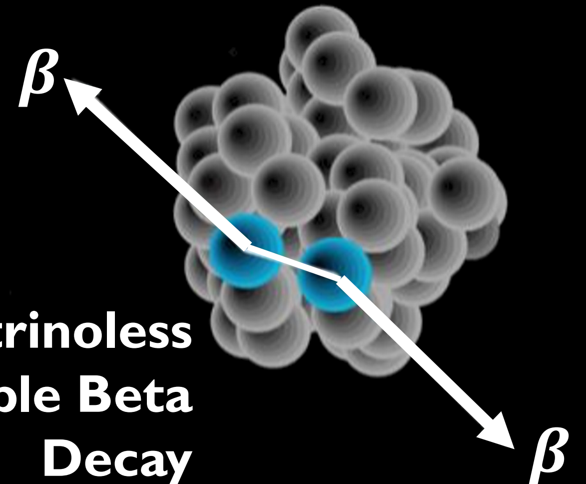
PMT Support Structure
8.9 m radius, holds 9400 PMTs + Concentrators

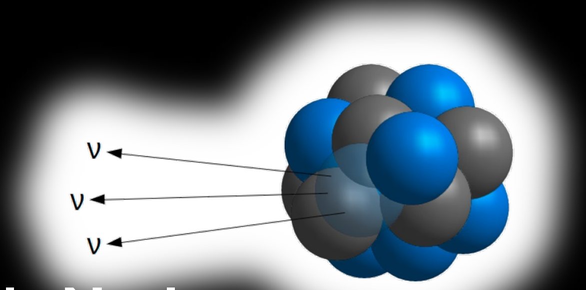


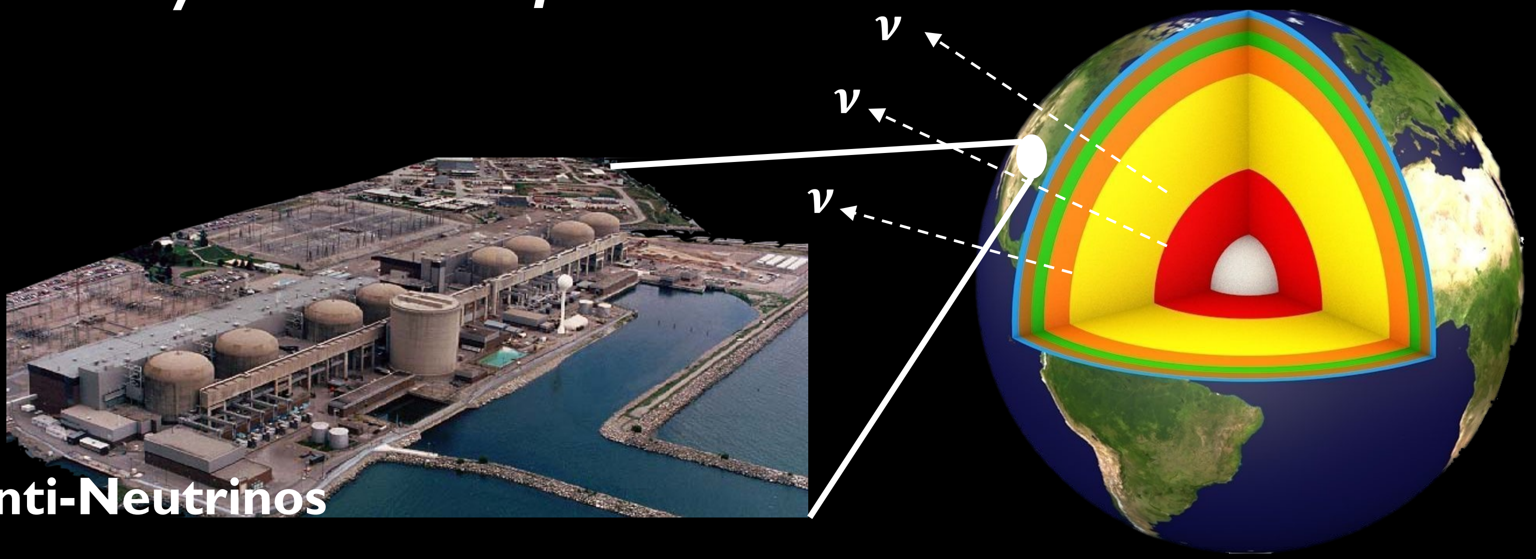


Physics Programme









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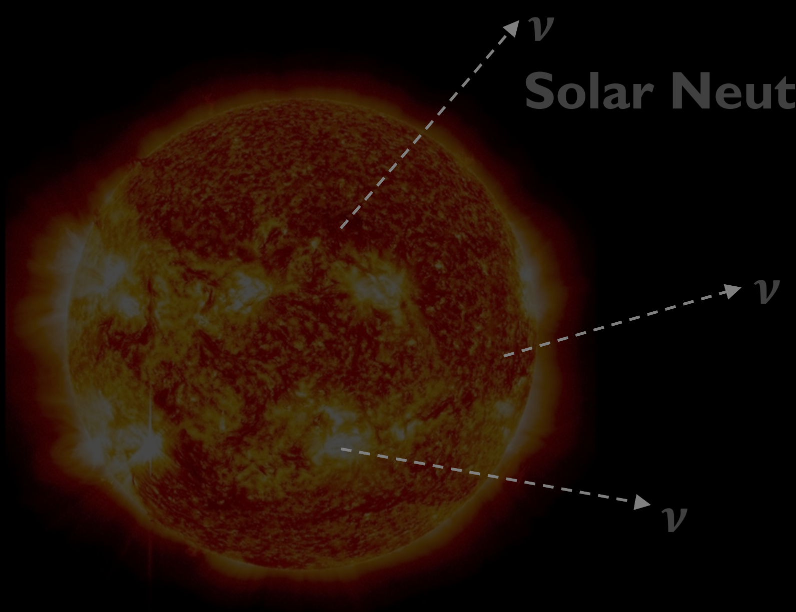
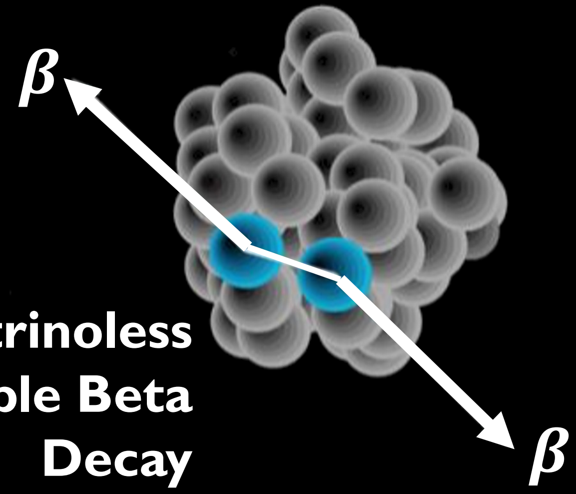
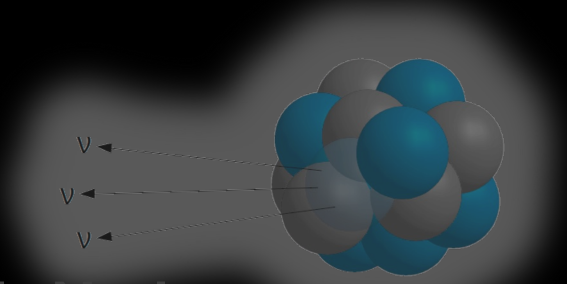


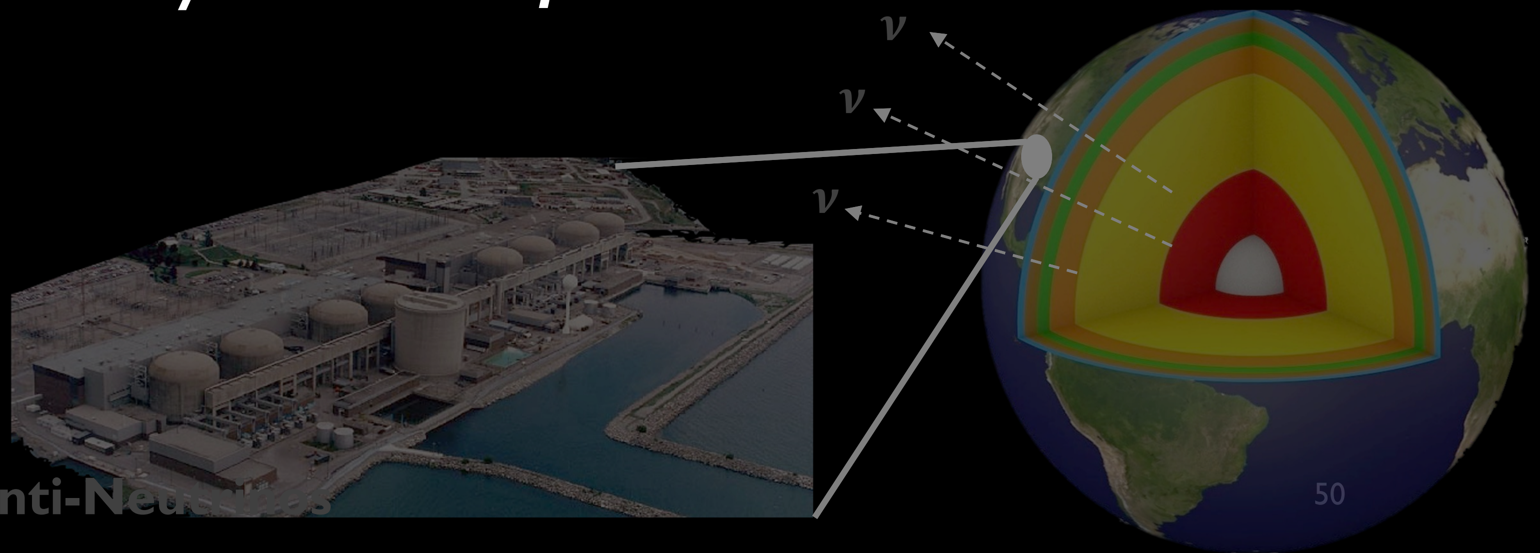
Main Goal



Neutrinoless Double Beta Decay



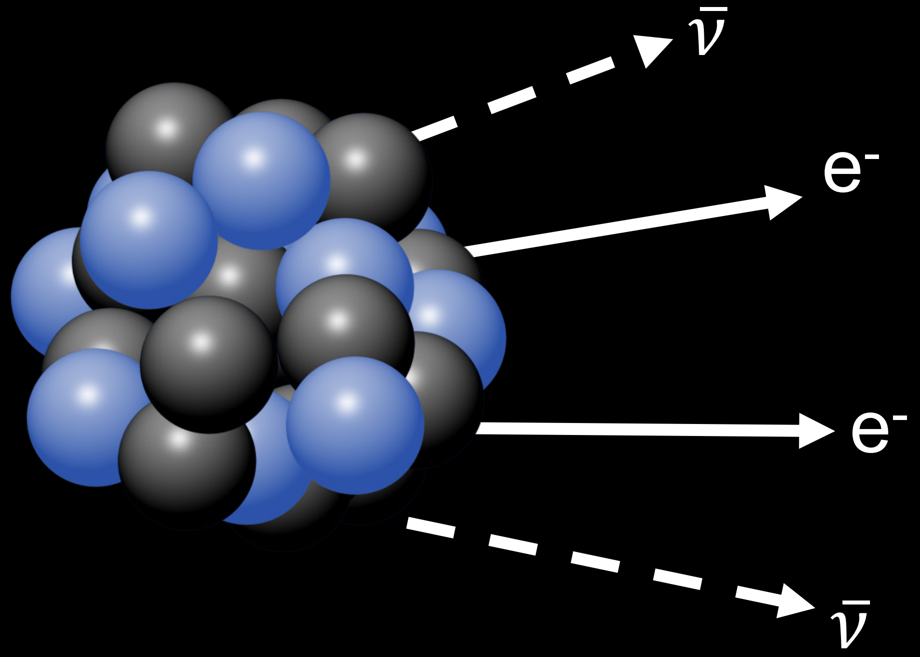
Invisible Nucleon Decay

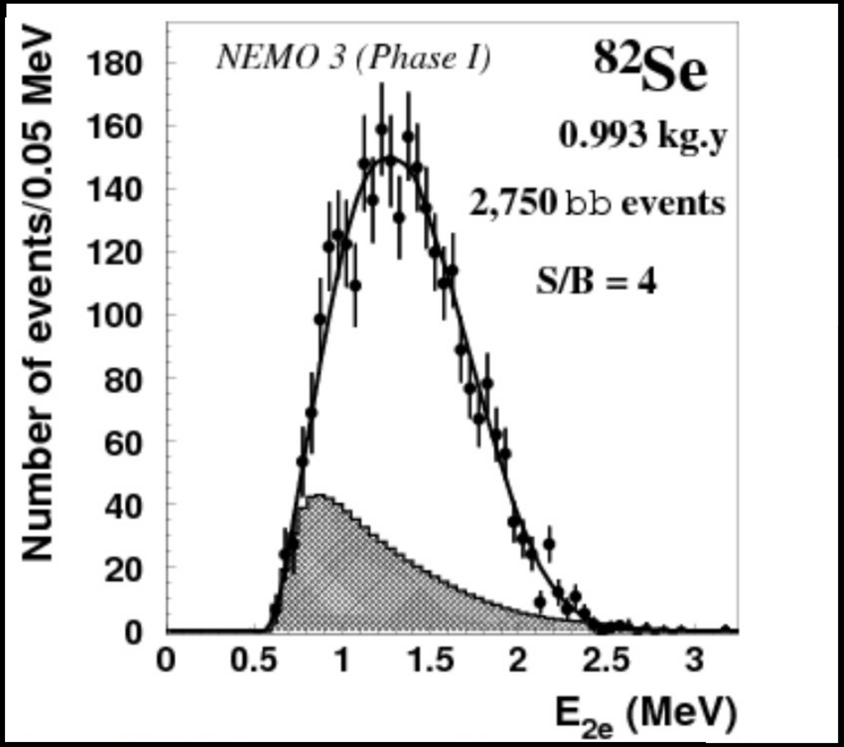


Reactor Anti-Neu...

2ν Double Beta Decay

A rare nuclear decay through which some nuclei reach stability.

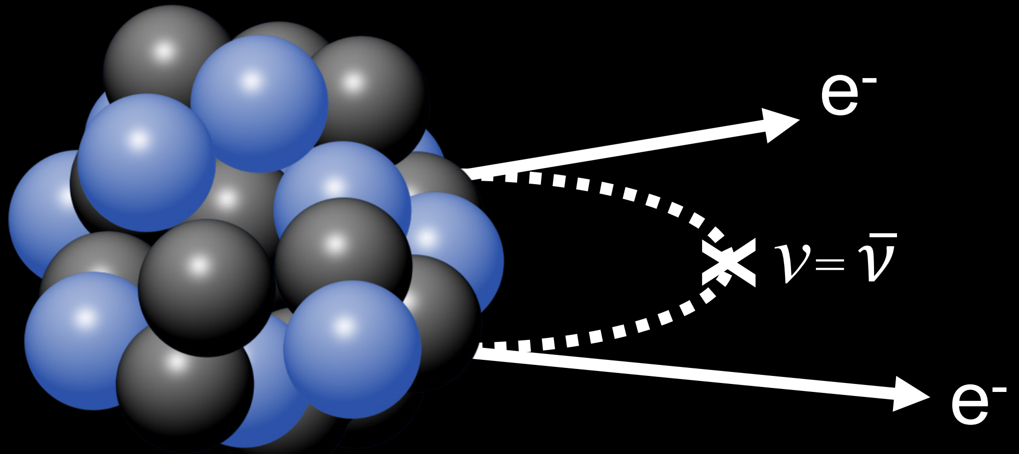


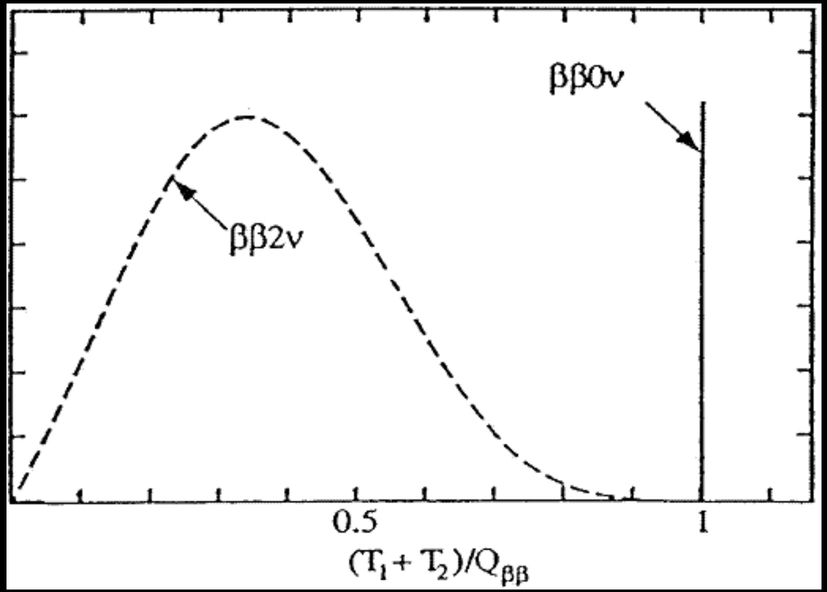


Detected Kinetic Energy of the Two Electrons/Q

- Possible when normal beta decay is not energetically allowed.
- Can happen for 35 natural isotopes. Observed in 11: ^{48}Ca, ^{76}Ge, ^{130}Te, ^{136}Xe...
- Long half-lives between 10^{19} and 10^{24} years.

0ν Double Beta Decay





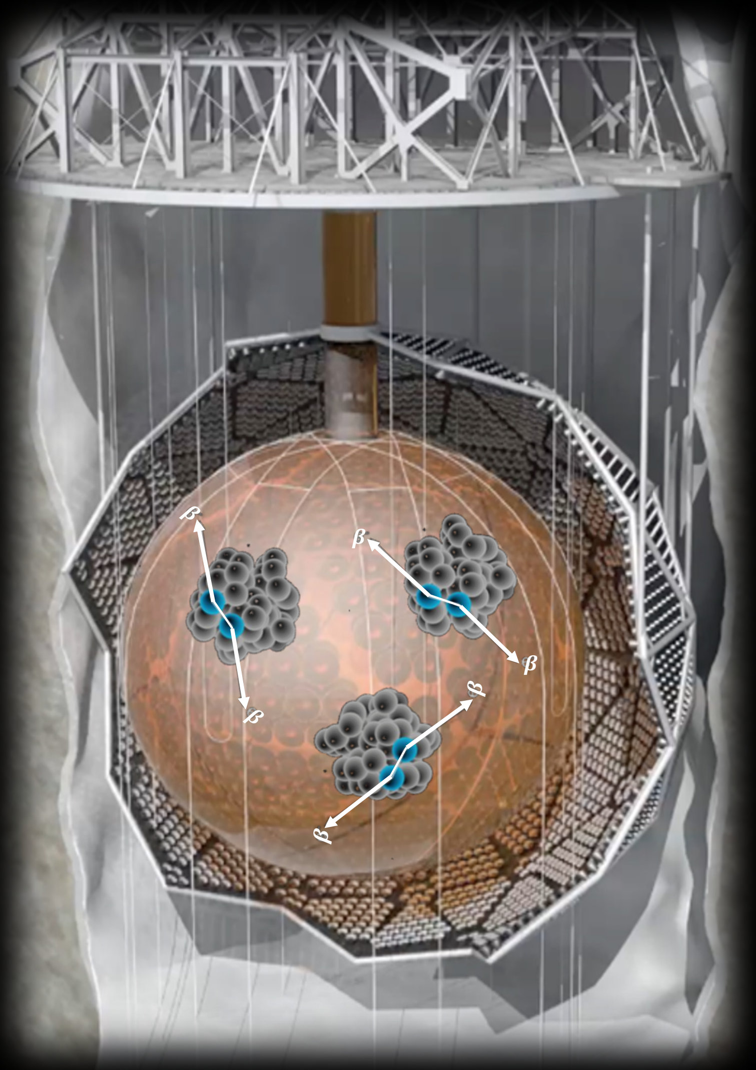
- Possible if neutrinos are Majorana particles (their own anti-particles).
- Violates lepton number conservation.
- Rate depends on the effective electron neutrino Majorana mass.

$$\left[T_{0\nu}^{1/2}\right]^{-1} = G_{0\nu}|\mathcal{M}_{0\nu}|^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

$$m_{\beta\beta} = \left|\sum_{i=1,2,3} e^{i\xi_i}|U_{ei}^2|m_i\right|$$

Neutrinoless Double Beta Decay Search in SNO+

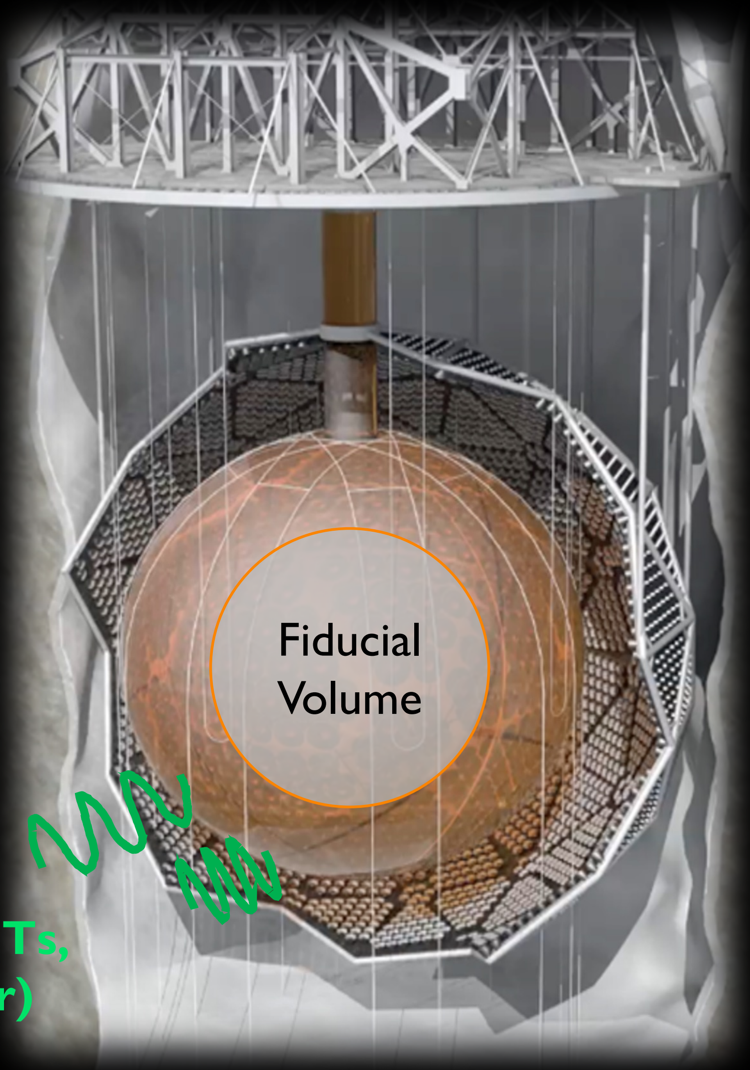
What are the advantages?



Neutrinoless Double Beta Decay Search in SNO+

What are the advantages?

1. Massive detector
   - High statistics
   - Self-shielding from external backgrounds through fiducialization.



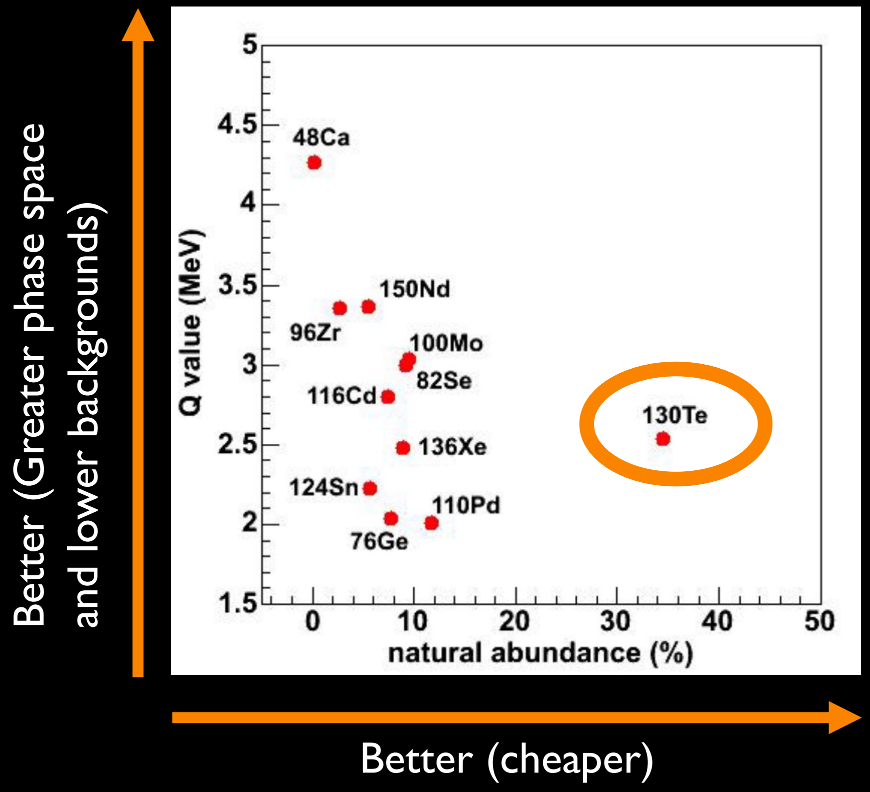
Neutrinoless Double Beta Decay Search in SNO+

What are the advantages?

1. Massive detector
   - High statistics
   - Self-shielding from external backgrounds through fiducialization.
2. $0\nu\beta\beta$ decay candidate: **^{130}Te**
   - Highest natural abundance (34%), no enrichment needed – easily scalable at low cost.
   - Q-value at 2.527 MeV – less background from natural radioactivity
   - Initial phase loading: 0.5% natural Te by weight

   = 1333 kg of ^{130}Te.

Ton-scale!



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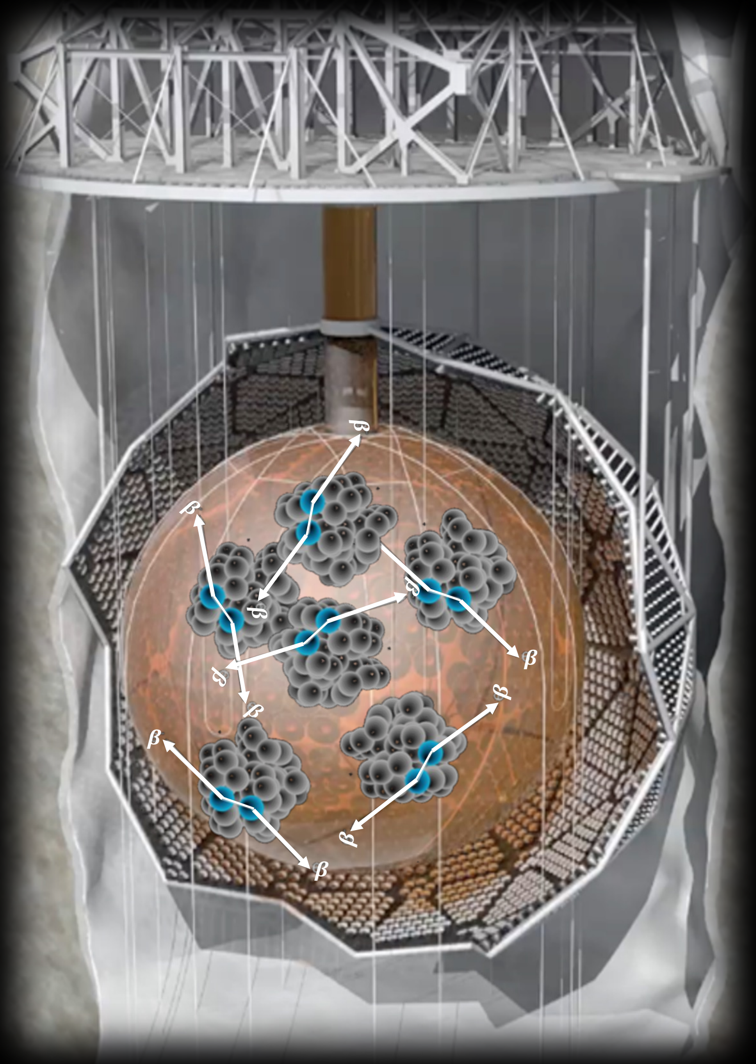
   - Highest natural abundance (34%), no enrichment needed – easily scalable at low cost.
   - Q-value at 2.527 MeV – less background from natural radioactivity
3. Liquid scintillator
   - Can be purified
   - Loading can be scaled



SNO+ Timeline

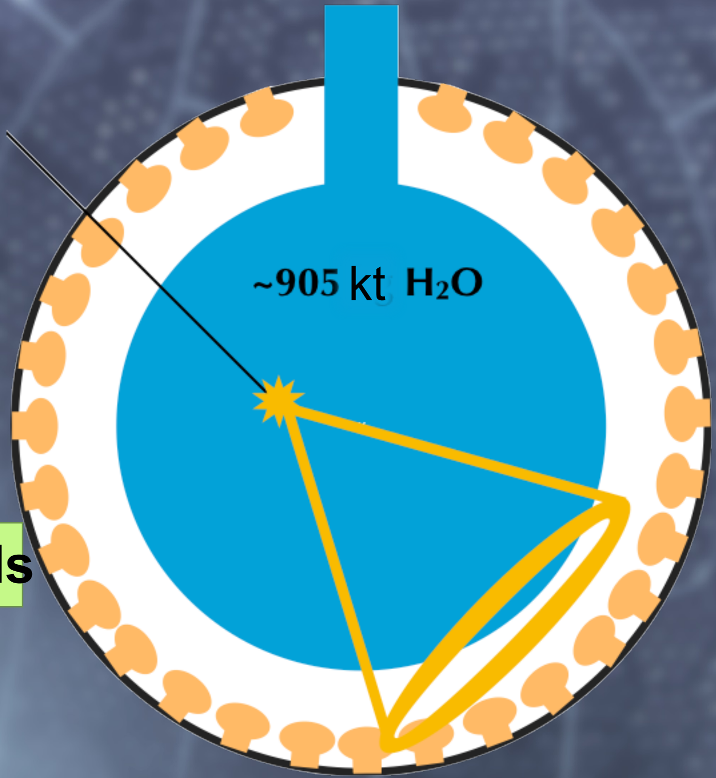
2016 2017

Dec. 2016
Started taking commissioning data

May 2017
Start of the Water Phase

Detector Calibration

Measure External Backgrounds



^8B Solar Neutrinos

Nucleon Decay Searches

Neutron response and Anti-neutrinos

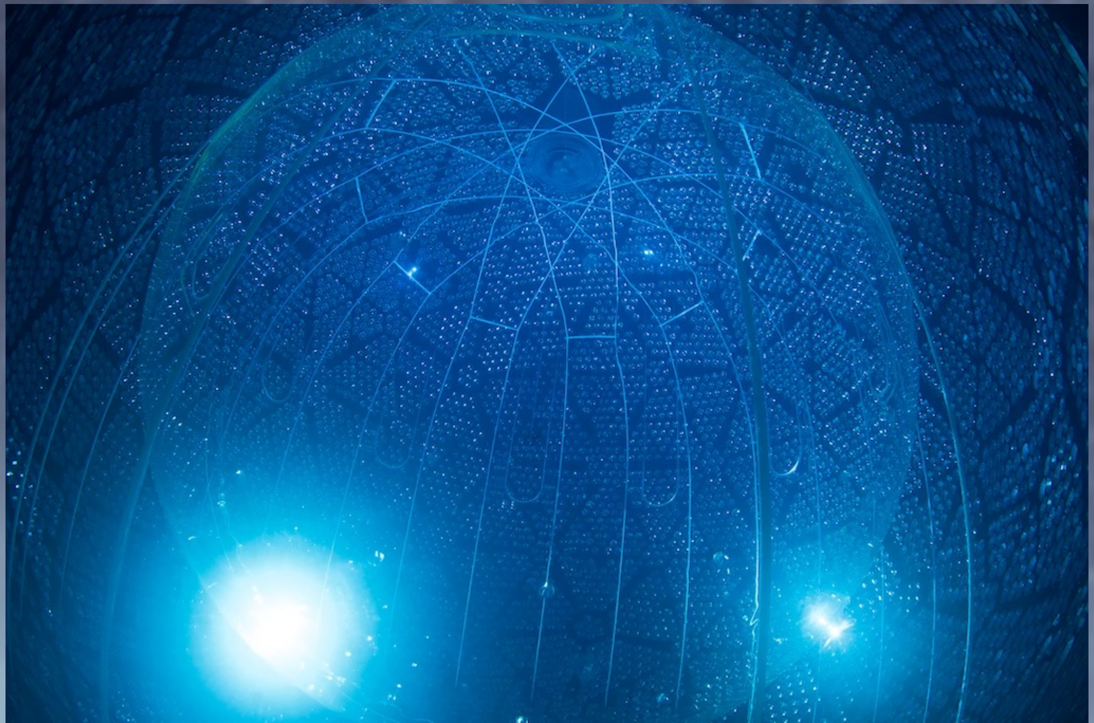
SNO+ Timeline

2016 — Dec. 2016
Started taking
commissioning data

2017 — May 2017
Start of the
Water Phase

2019 — Start of
Scintillator Fill

2021 — End of
Scintillator Fill



SNO+ Timeline

2016 — 2017 — 2019 — 2021

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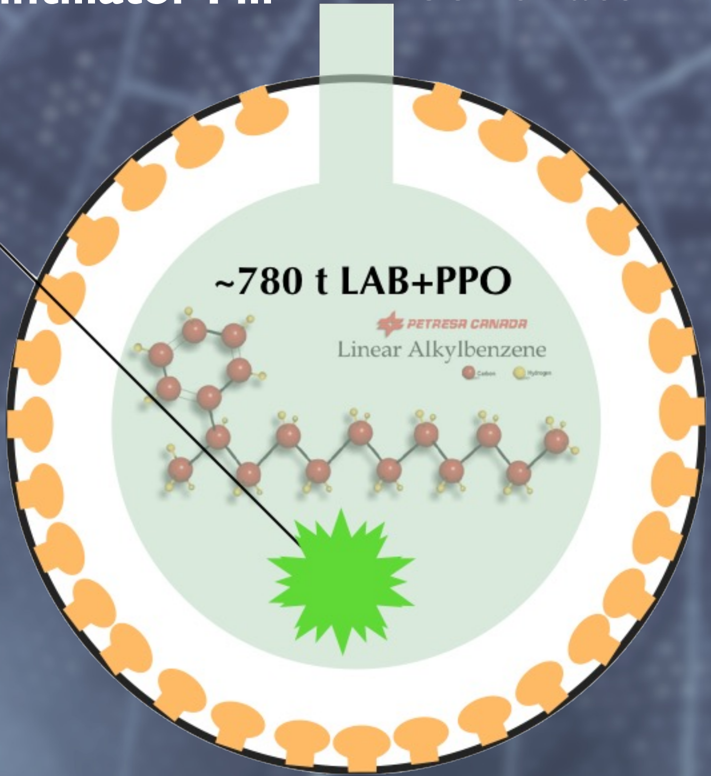


^{8}B + Low Energy Solar Neutrinos

Reactor Anti-neutrinos

Nucleon Decay Searches

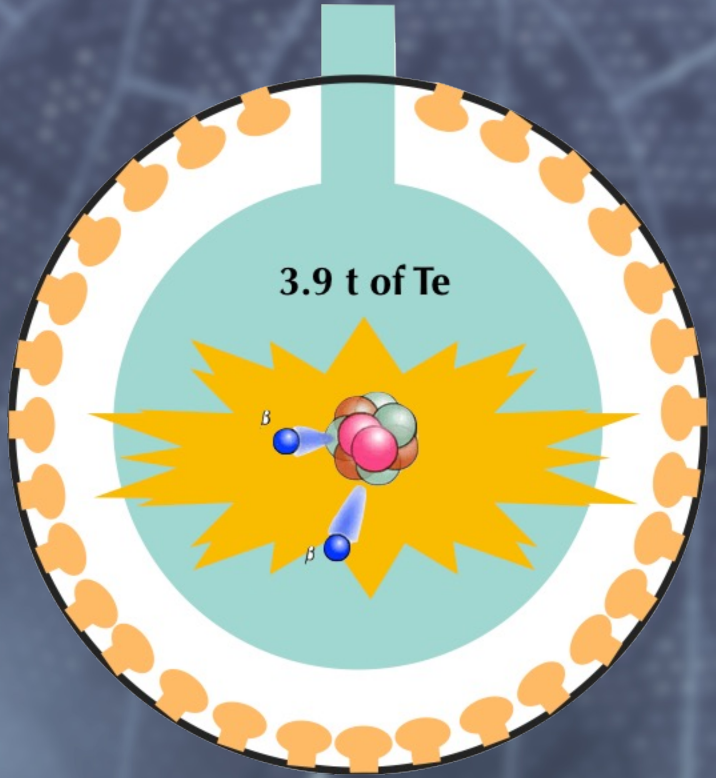
Geo Anti-Neutrinos

Measurement of Internal Backgrounds before adding the Tellurium

Perform a “target out” $\beta\beta$ analysis
→ prepare/test analysis and techniques using real data
→ determine count rate in the ROI in the absence of Tellurium

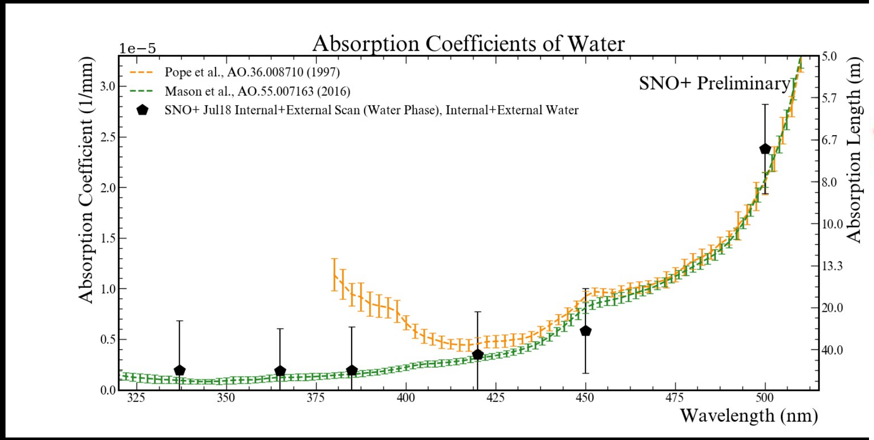
SNO+ Timeline

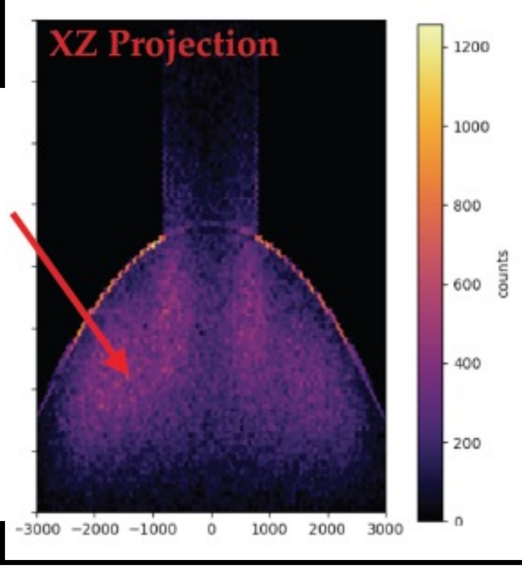
- **2016** — Dec. 2016: Started taking commissioning data
- **2017** — May 2017: Start of the Water Phase
- **2019** — Start of Scintillator Fill
- **2021** — End of Scintillator Fill
- **2024** — Tellurium is added to the scintillator

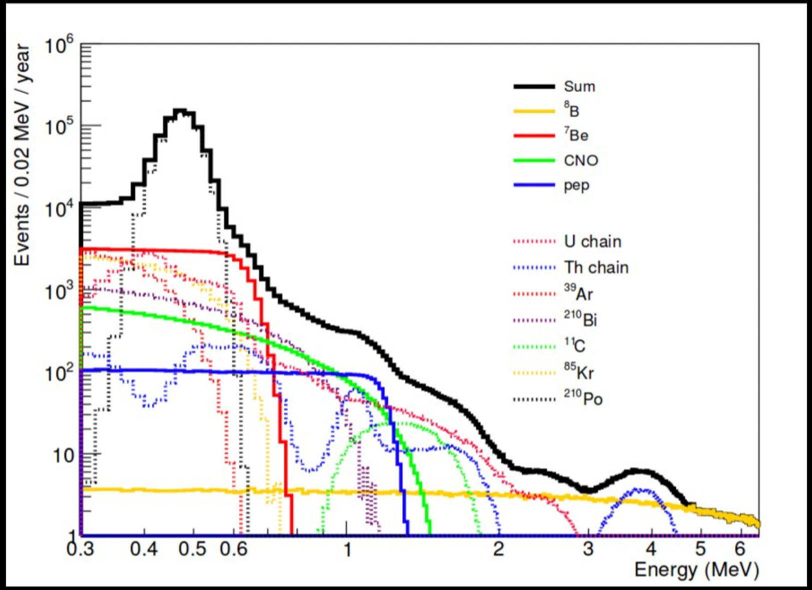


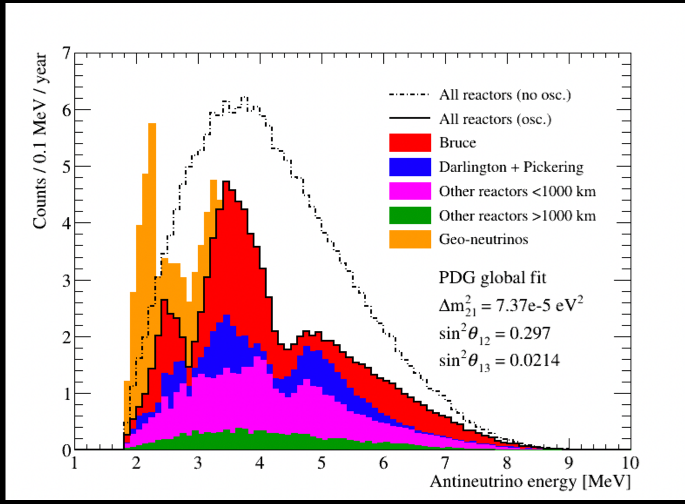
SNO+ Activities @LIP

- **Detector calibration**
  - Optical and Radioactive sources
- **Background events**
  - Water/Scintillator characterisation
- **Data analysis**
  - Cosmic muons in SNO+
  - Solar neutrinos
  - Reactor anti-neutrinos
  - $0\nu\beta\beta$



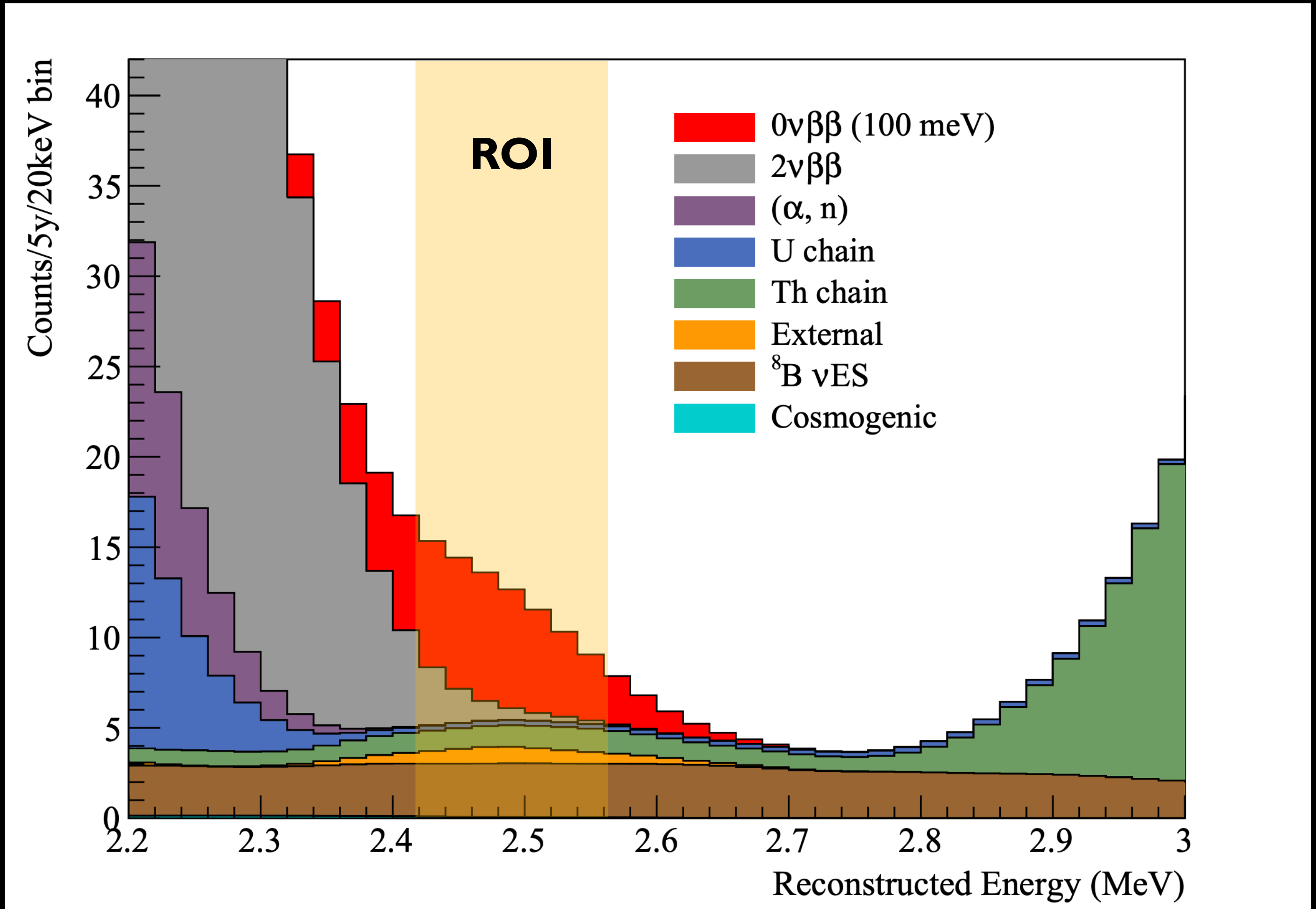






SNO+ Tellurium Phase - Prospects

Expected Energy Spectrum after 5 Years with 0.5% Te loading, Fiducial Volume of 3.3 m radius



Expect 9.47 events / year in the ROI (with our target background levels)

SNO+ Tellurium Phase - Prospects

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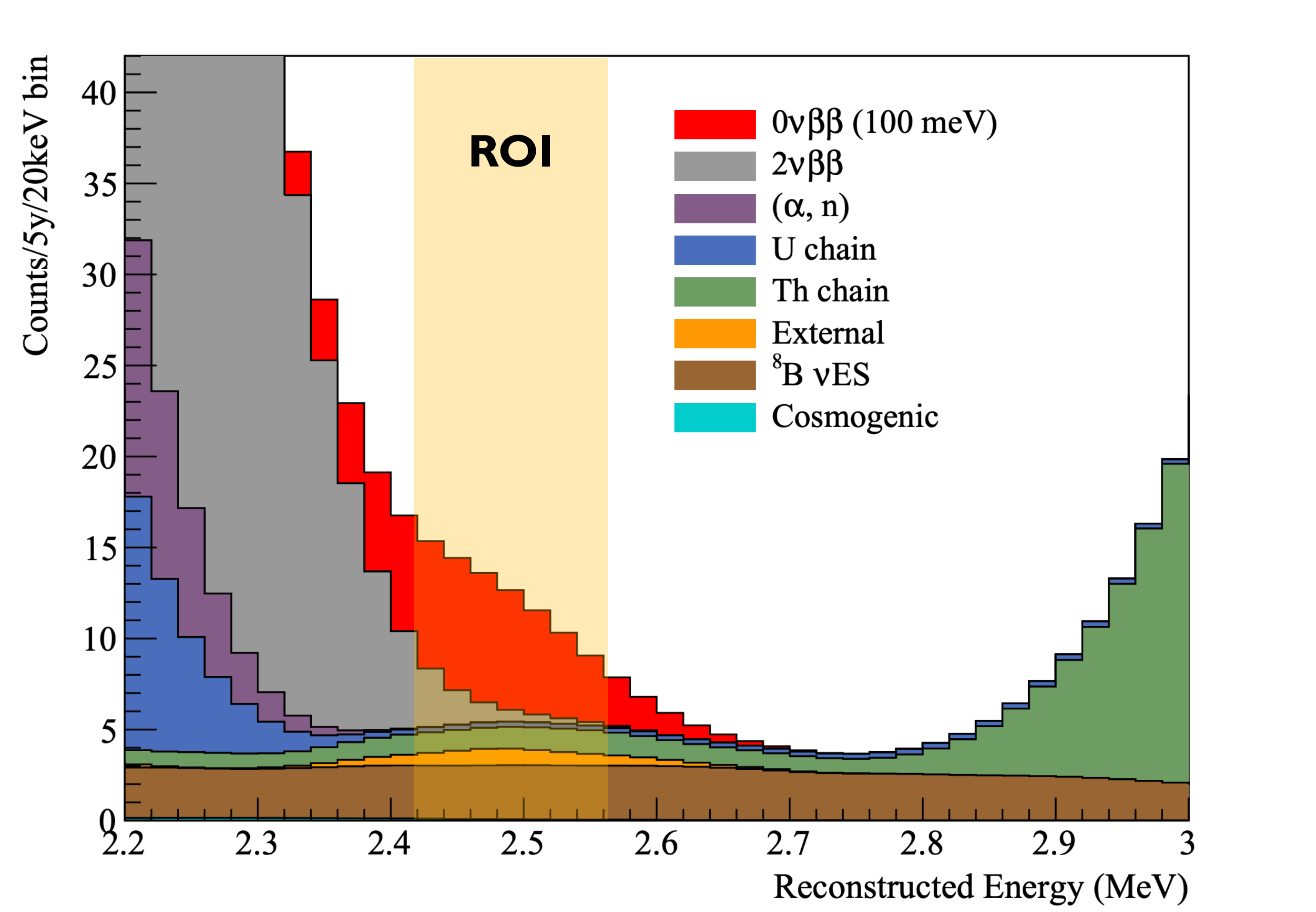


From a simple counting analysis, for 5 years, in an optimized energy ROI and fiducial volume

Expected Half-Life Sensitivity > 2.1×10^{26} years

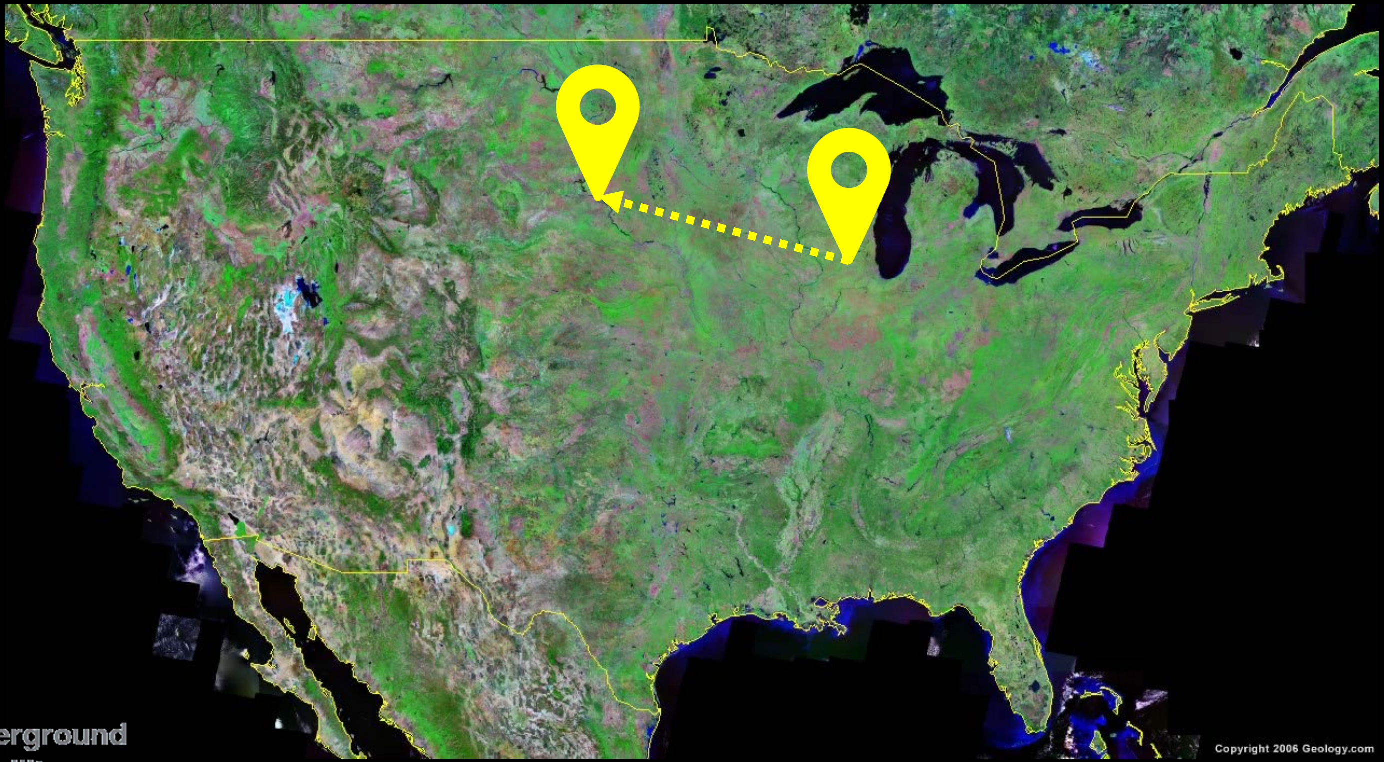
$m_{\beta\beta}$ range 37-89 meV (model dependent)

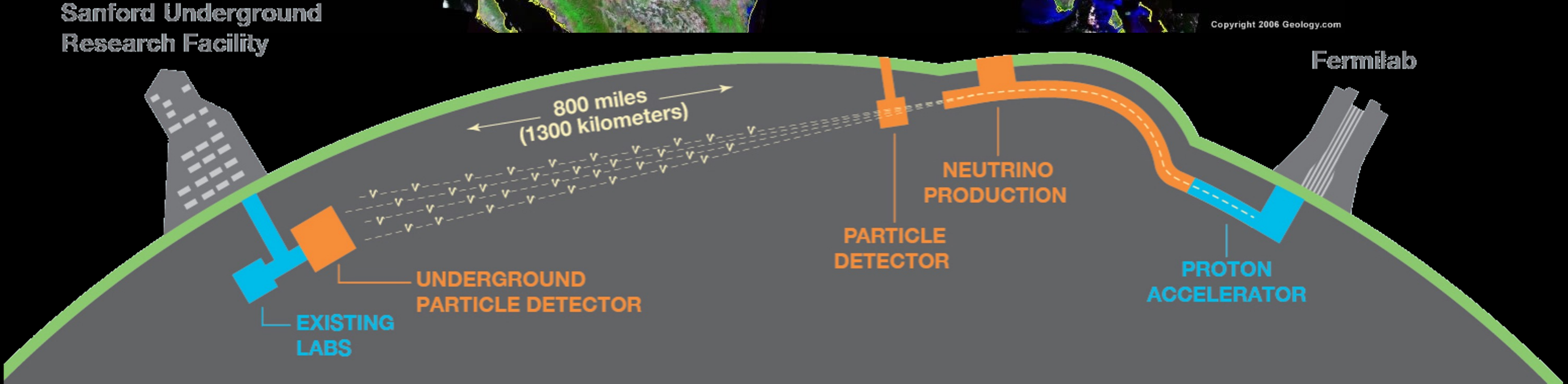

DUNE

Is there CP violation in the lepton sector?

- If neutrino's interactions DO NOT conserve CP, neutrino and antineutrinos oscillations are different!

The Deep Underground Neutrino Experiment





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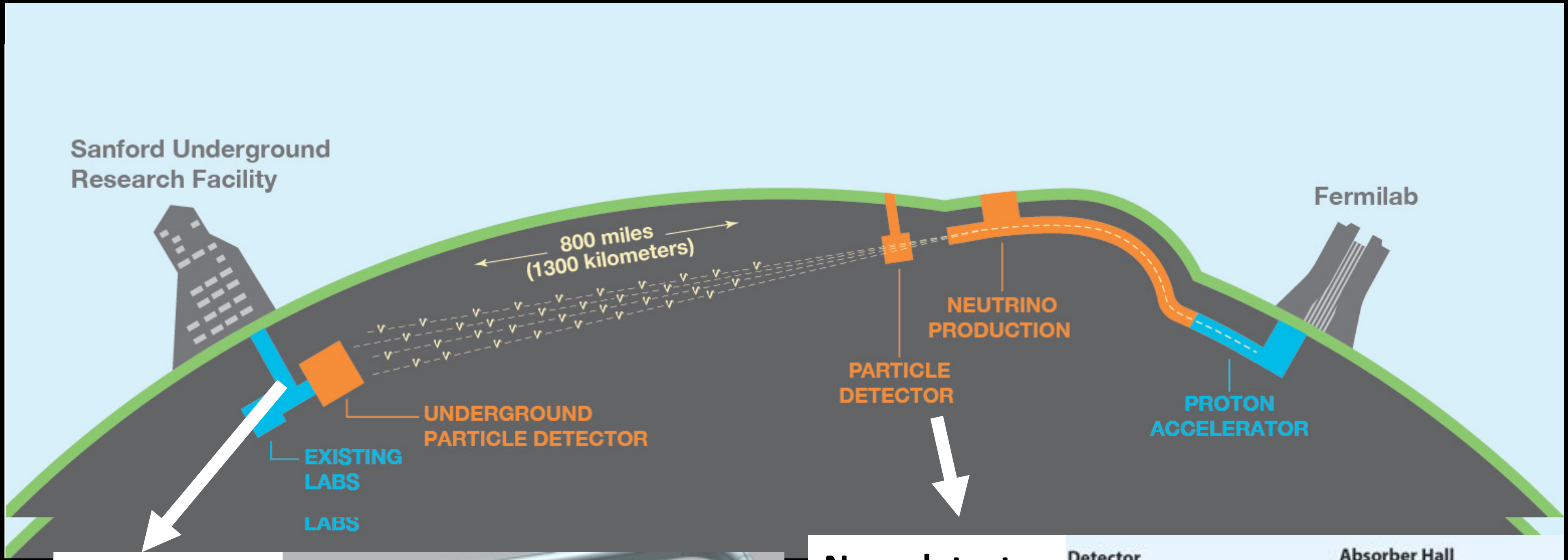

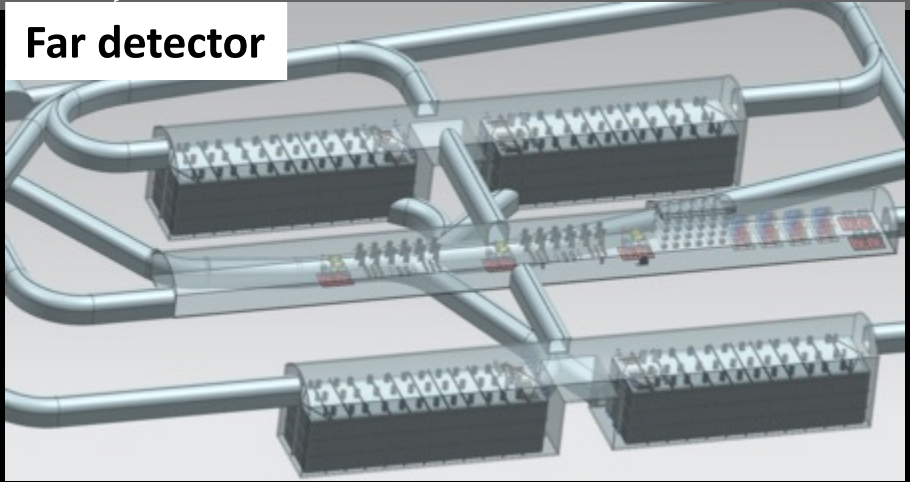

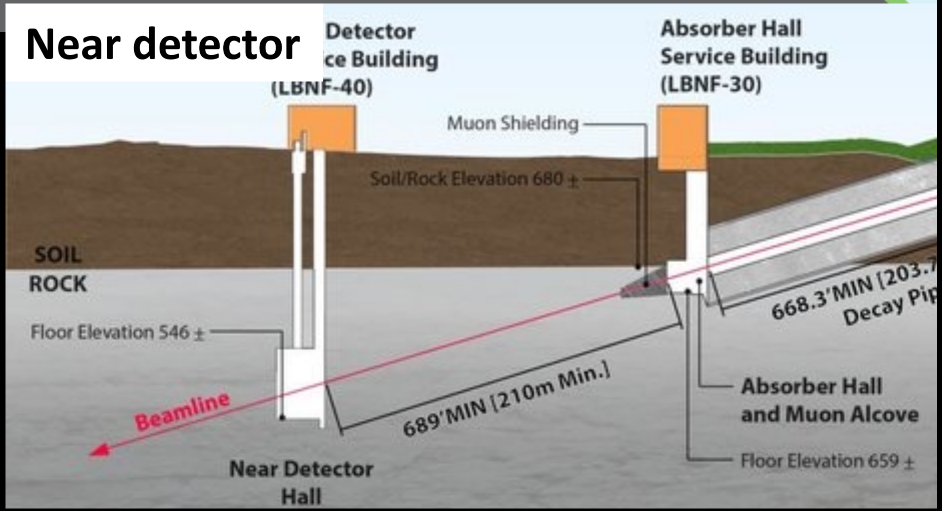

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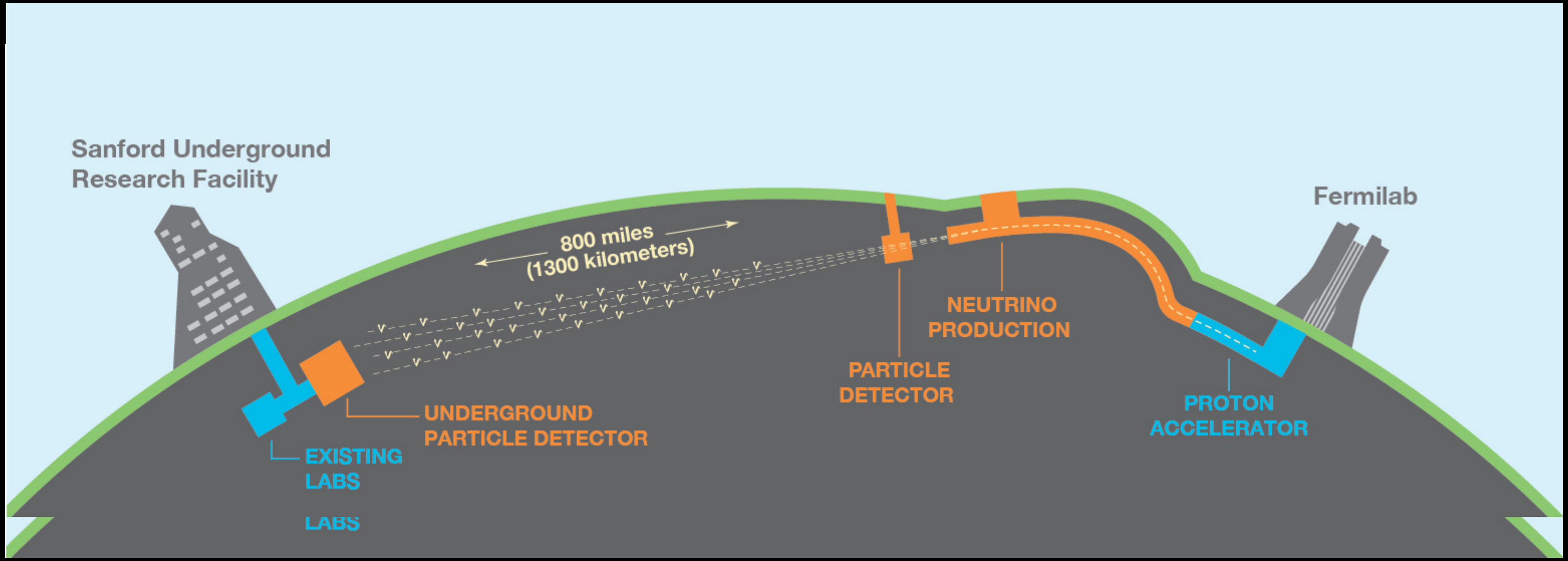


★ **Neutrino Oscillation Physics**
- ◉ High sensitivity for leptonic CP violation
- ◉ Identify the neutrino mass hierarchy
- ◉ Precision oscillation physics

★ **Proton Decay**
- ◉ Target SUSY-favored mode p —> K+ ν ND

★ **SN burst physics and astrophysics**
- ◉ Galactic core collapse supernova
- ◉ unique sensitivity to νe

★ **Atmospheric Neutrinos**

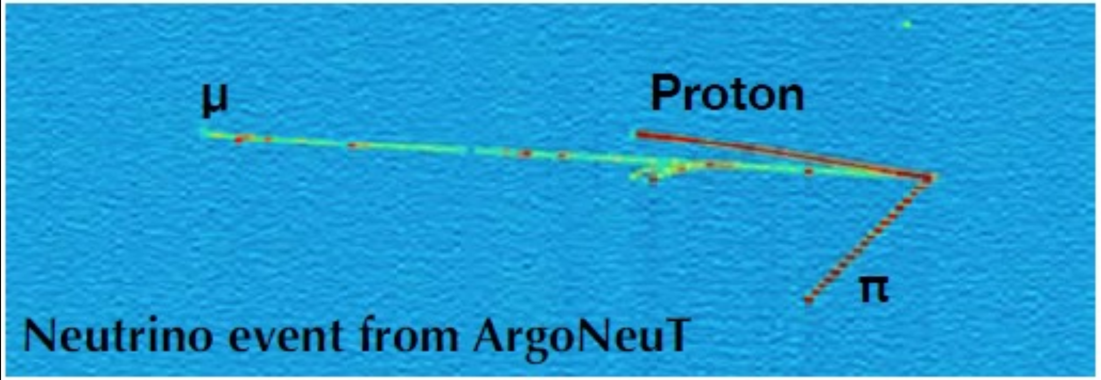
★ **Solar neutrinos (similar approach as SN)**

★ **Neutrino Interaction Physics (Near Detector)**

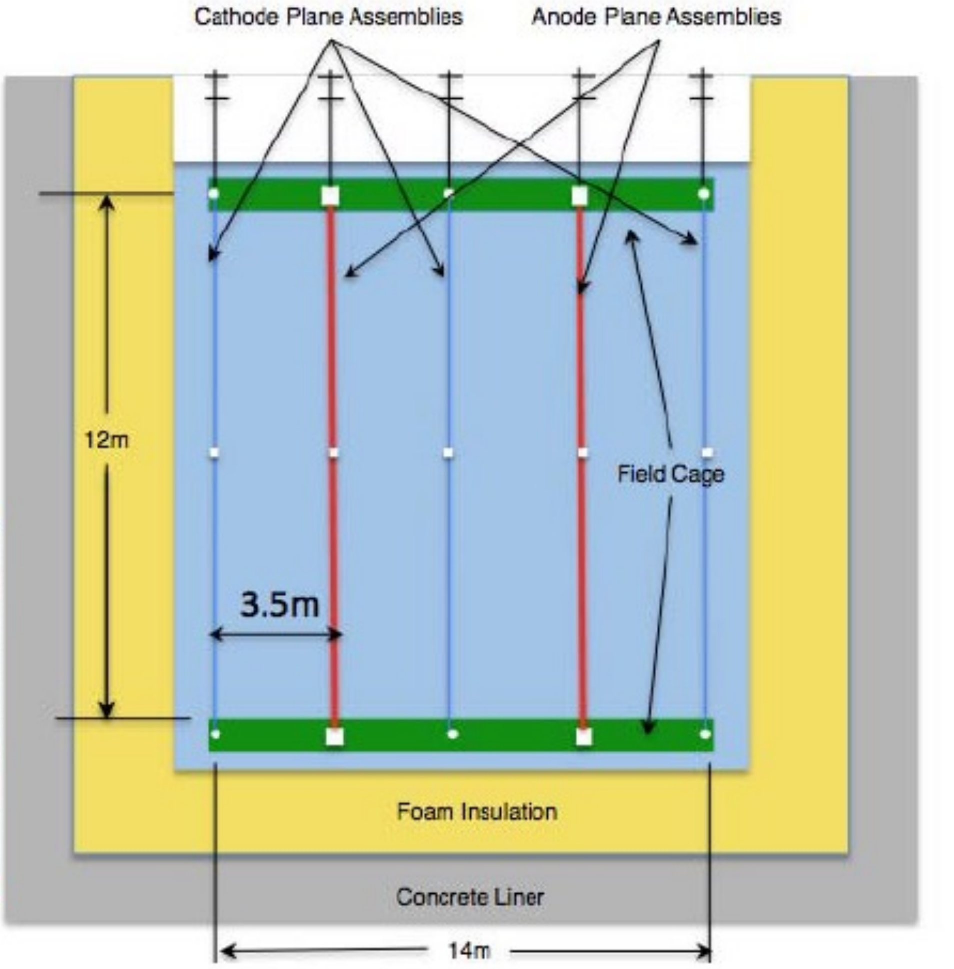
The Deep Underground Neutrino Experiment

** Liquid Argon Time Projection Chambers

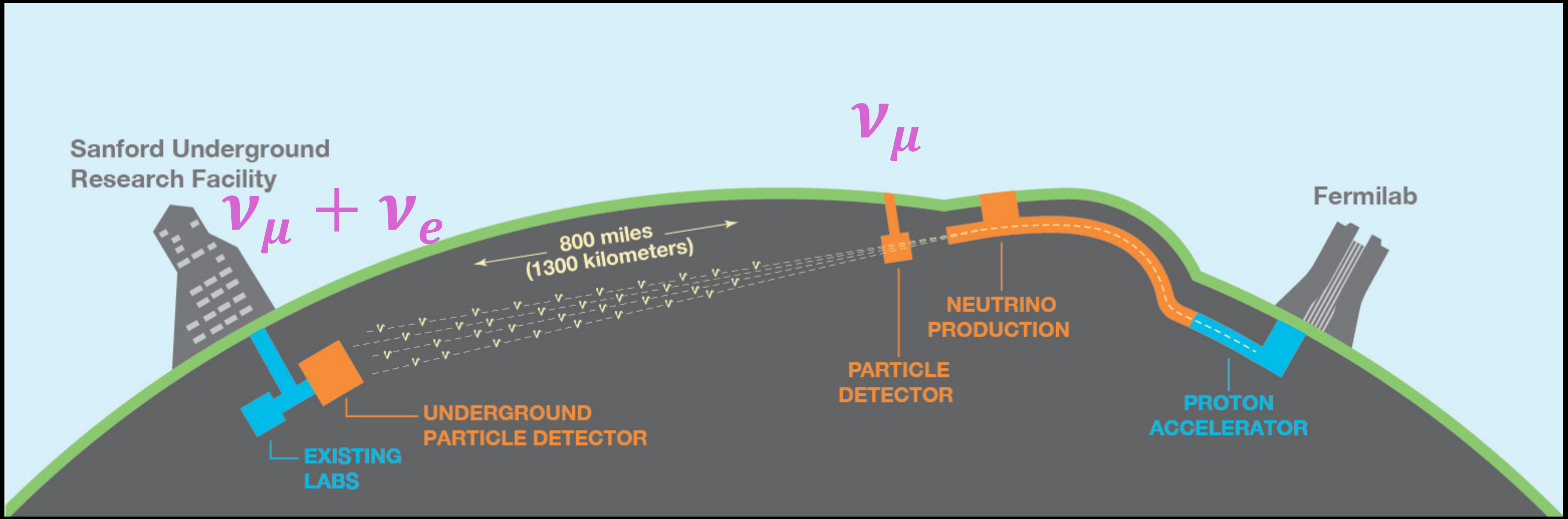
** Full measurement of all particle tracks —> more information than in water Cherenkov detector



Neutrino event from ArgoNeuT



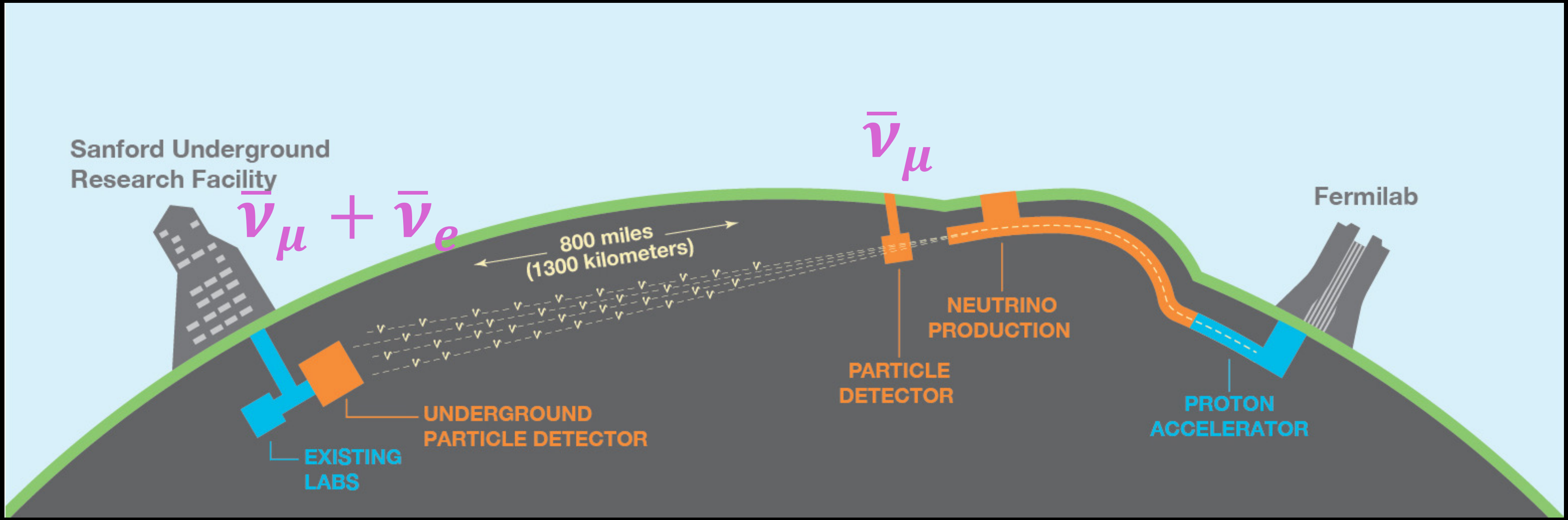
The Deep Underground Neutrino Experiment



Measure a neutrino beam at long distance…

Near detector at Fermilab: measurement of ν_μ unoscillated beam
Far detector at SURF: measure oscillated ν_μ and ν_e

The Deep Underground Neutrino Experiment

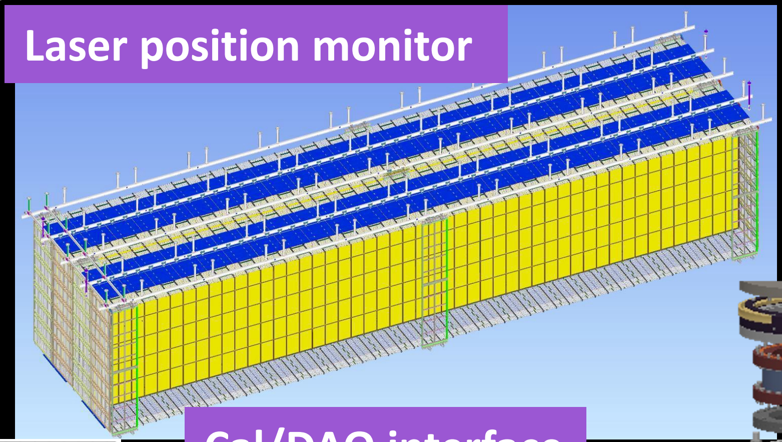


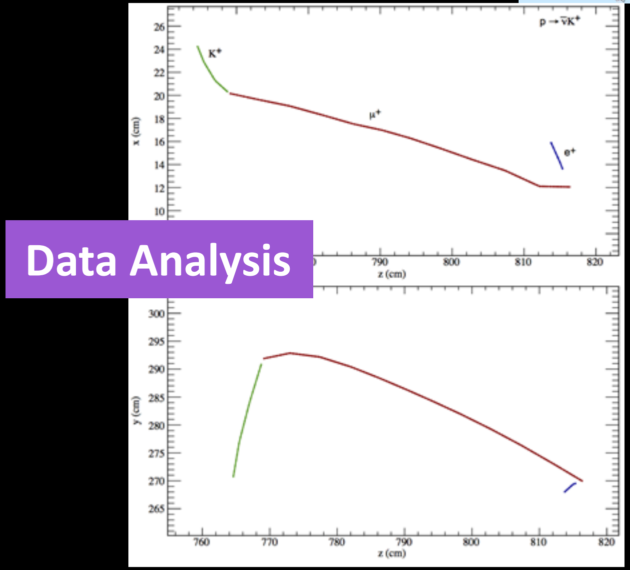
…and then repeat for antineutrinos

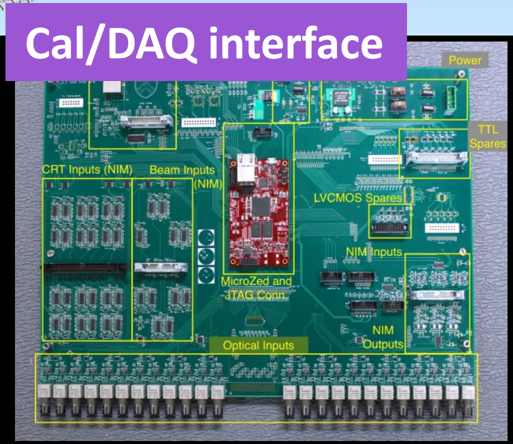
Compare oscillations of neutrinos and antineutrinos
Direct probe of CP violation in the neutrino sector

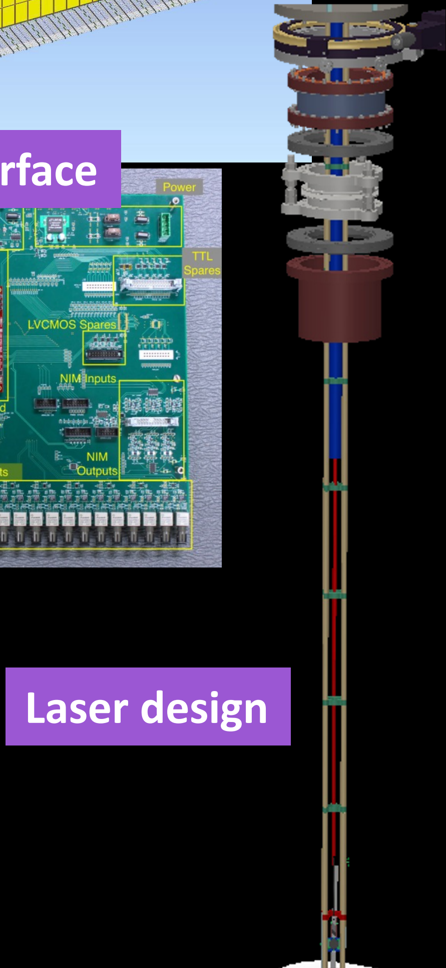
DUNE Activities @LIP

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









Summary

★ They oscillate (and we know how)
★ They are massive (but we don’t know how much)

★ 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