Neutrino physics overview

Cloé Girard-Carillo

enigmass+ Workshop
13th October 2025

An extremely biased

Neutrino physics ~~overview~~ talk

Mountain

French cuisine

Physicists' drawing skills

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LPSC GRENOBLE | MODANE

What was the first hint for the existence of neutrinos?

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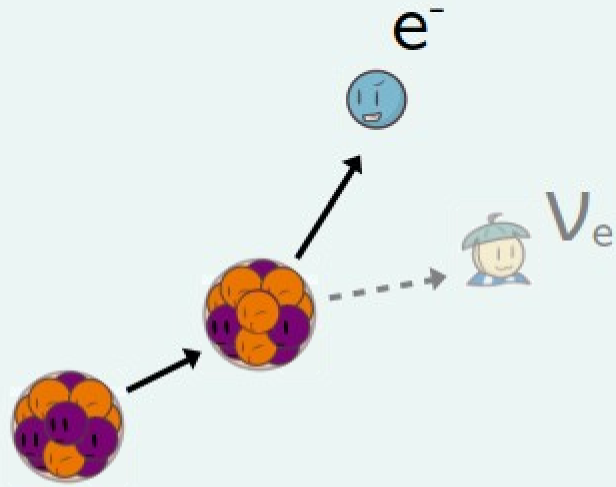
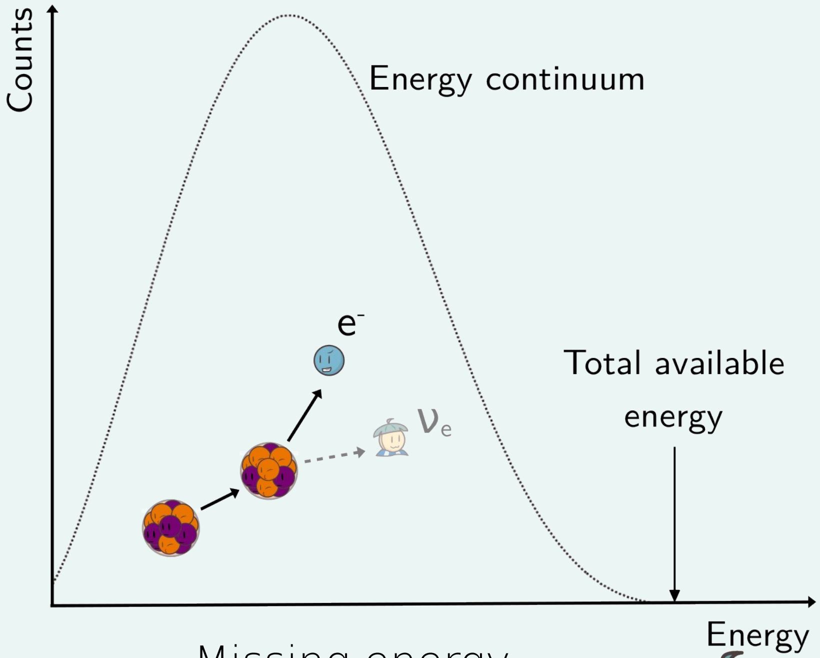


A bit of history

The discovery of neutrino

H.Becquerel (1896):
Discovery of radioactivity
1900: **β decay**

Lise Meitner (1911):
Beta energy spectrum
Only electron observed
Non conservation of total energy



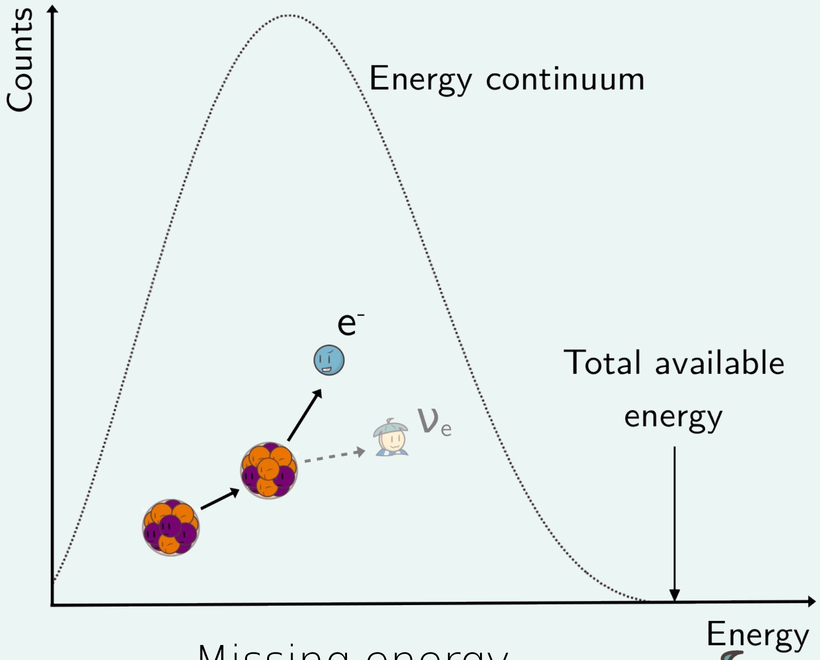
Missing energy

A bit of history

The discovery of neutrino

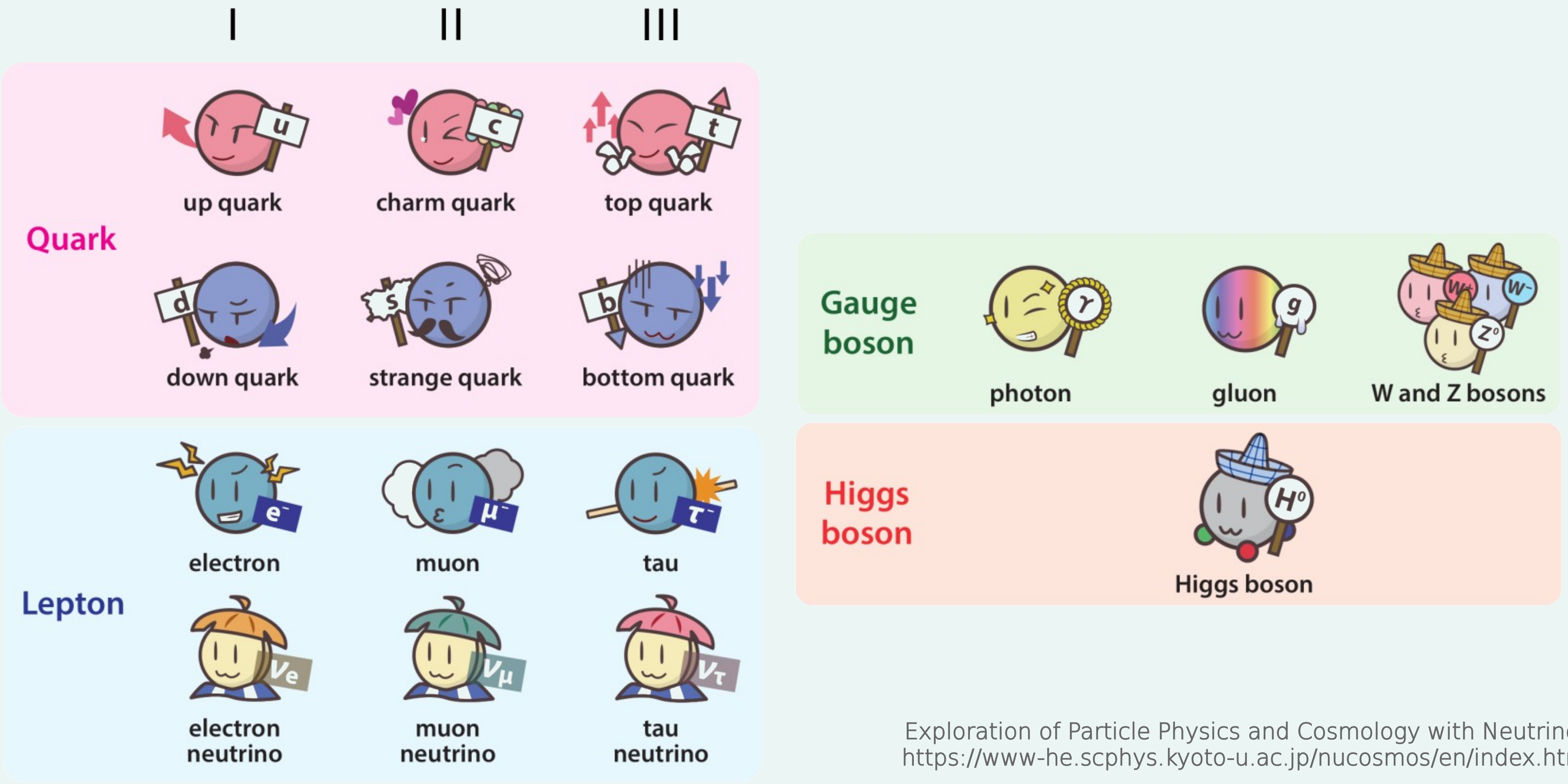
W.Pauli (1930):
Solution to conserve total energy
"**Neutrino**": small interaction probability, neutral, spin 1/2, small or null mass

E.Fermi (1934):
Effective theory
Foundation stone of weak interaction



Missing energy

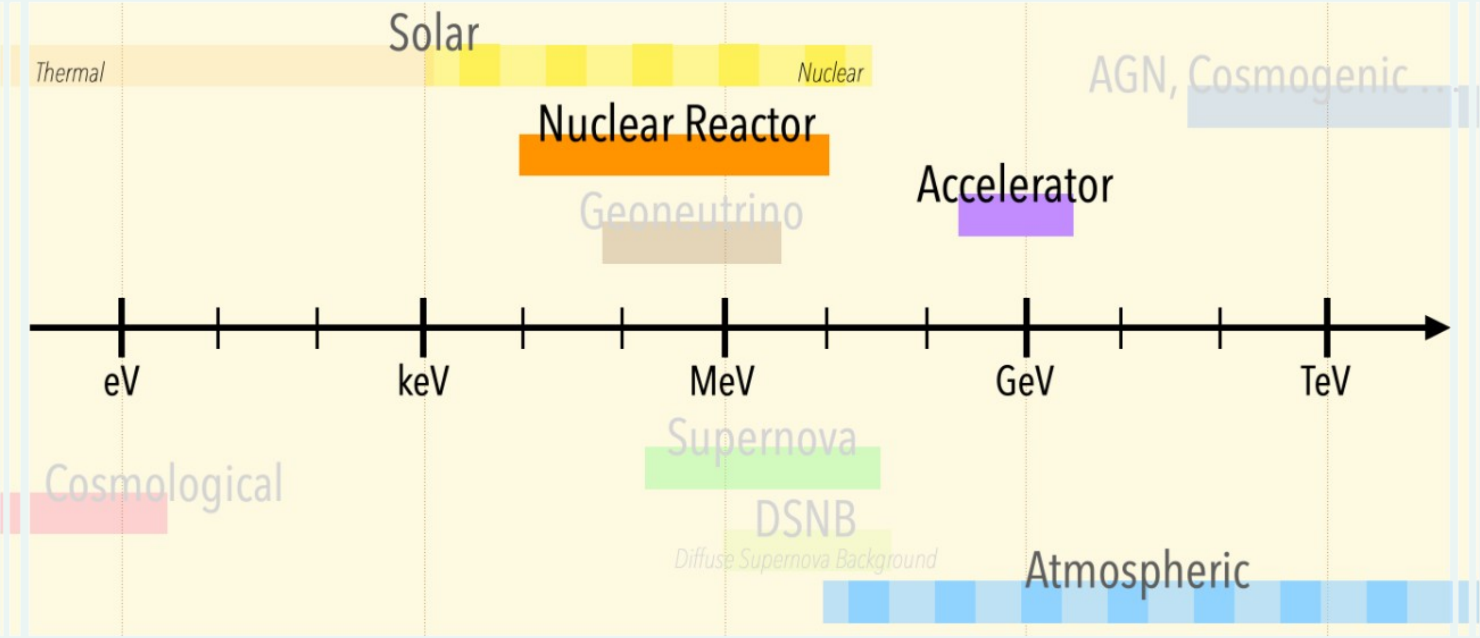
The Standard Model of Particle Physics



Exploration of Particle Physics and Cosmology with Neutrinos
https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/index.html

Where can we find those neutrinos?

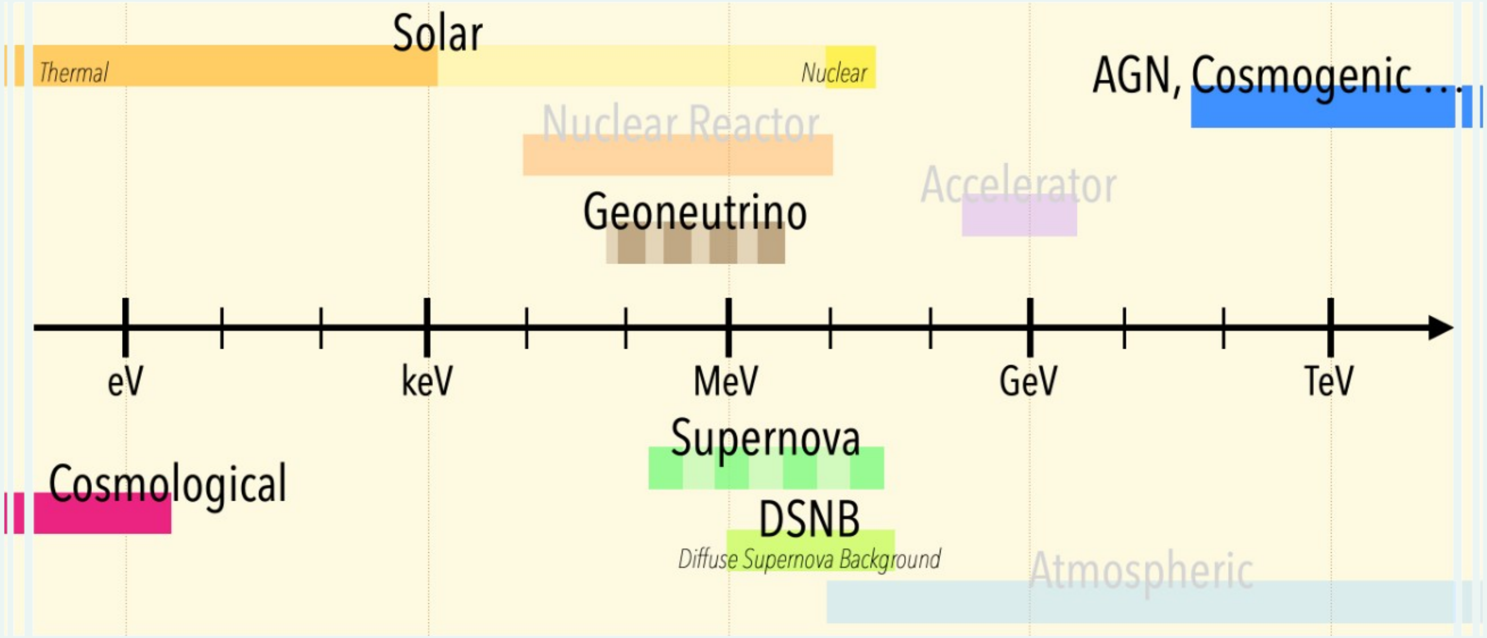
Neutrino sources – mastered sources



Credit: Emile Lavaut

- Solar → high fluxes ~ 10^{10} $cm^{-2}s^{-1}$
- Atmospheric neutrinos → wide range of energy
- Reactor and accelerator → on/off, choose distance to detector & energy of neutrinos

Neutrino sources – as messengers



Credit: Emile Lavaut

From un-seen (or rarely seen) sources or processes:

- Cosmological (Big-Bang, neutrino nature, leptogenesis...) or Cosmogenic (Black-Holes, Galactic Center...)
- Supernova (SN), Diffuse Supernova Background (SN distribution...) or Sun (hep, thermal...)

Open questions in neutrino physics

Most likely will be answered within next 10–15 year by oscillation experiments

- ongoing (T2K, NOνA, IceCube, KM3NeT)
- planned (JUNO, DUNE, Hyper-K)

Might be answered in the foreseeable future

- Absolute neutrino mass scale can be directly probed by measuring the end point of the β-decay spectrum (tritium β-decay, KATRIN bound $m_\nu \leq 0.45$ eV 90% CL, Project-8 aim to reach 0.04 eV)
- Cosmological observables set an indirect upper limit on sum of neutrino masses < 0.12 eV (Planck) and < 0.072 eV (DESI), already disfavor the inverted mass ordering.

Much harder to answer definitively

1. What is neutrino mass ordering (NMO)? Normal or inverted?
2. In which octant is the atmospheric mixing angle?
3. Is there a leptonic CP violation?
4. What is the absolute neutrino mass scale?
5. Are there other species of (sterile) neutrinos?
6. How do neutrinos get mass ? Is it Dirac or Majorana?
7. Why neutrino mixing is so different from quark mixing?
8. Do neutrinos decay? What is their lifetime?
9. Do neutrinos have non-standard interactions ?
10. Are neutrinos responsible for the observed baryon asymmetry?
11. Do neutrinos have anything to do with Dark Matter?

From 2503.21212, P. S. Bhupal Dev

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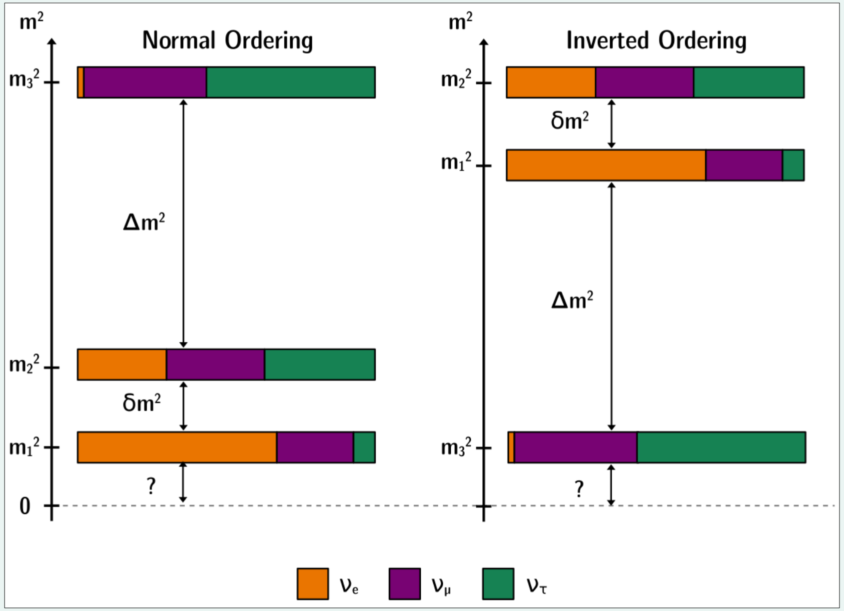
What is neutrino mass ordering (NMO)? Normal or inverted?

Solar neutrinos:

$\Delta m^2_{21} \approx 7.4 \times 10^{-5}\,\mathrm{eV}^2$

Atmospheric neutrinos:

$|\Delta m^2_{31}| \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$



1 heavy state
+
2 light states

2 heavy states
+
1 light state

How we try to determine the ordering?

- Long-baseline accelerator experiments (T2K, NOvA, DUNE)
  → Measuring how neutrinos and antineutrinos oscillate differently while travelling through Earth
  → matter effects enhances or suppresses certain transitions depending on the ordering
- Reactor experiments (JUNO in China, just started taking data)
  → aims to detect subtle interference patterns in the electron antineutrino spectrum depending on MO
- Atmospheric neutrinos (IceCube (Upgrade), ORCA, PINGU)
  → observing neutrinos passing through the Earth at different angles and energies
- Cosmology
  → CMB and large-scale structure data constrain the sum of the neutrino masses (smaller total mass favors normal ordering)

Is there a leptonic CP violation?

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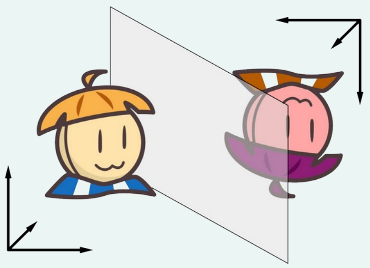
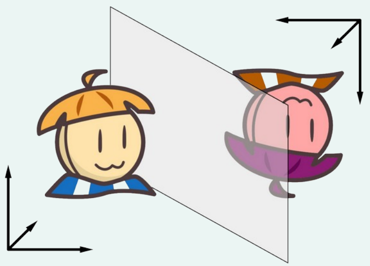


C and P → 2 fundamental symmetries

- C (Charge conjugation): particle ↔ antiparticle
- P (Parity): mirror transformation: inverts spatial coordinates

If a process is CP-symmetric, it should look the same when we replace all particles with their antiparticles and view the system in a mirror

Is there a leptonic CP violation?

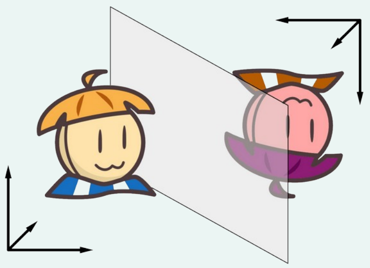


C and P → 2 fundamental symmetries

Why it matters

- one of the necessary conditions (Sakharov conditions) to explain why Universe made mostly of matter (rather than antimatter)
- If CP symmetry were exact, equal amounts of matter and antimatter produced during Big Bang which would have annihilated completely

Is there a leptonic CP violation?



C and P → 2 fundamental symmetries

Why it matters

Where do we observe it?

- Neutral kaons (K^0–anti-K^0 system): discovered in 1964 (Cronin & Fitch)
  → The decay rates of kaons and antikaons differ slightly.
- B mesons (B^0–anti-B^0 system) : observed at BaBar and Belle in 2001.
  → CP violation shows up as an asymmetry in certain decay channels.
- D mesons : evidence found more recently (LHCb)

What's measured so far in SM isn't enough (complexe phase) → neutrinos, EDM

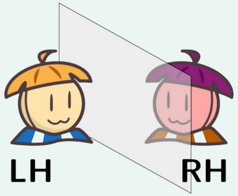
Neutrinos: possible CP violation is being investigated (T2K, NOvA, DUNE).

How do neutrinos get mass ? Is it Dirac or Majorana?

Dirac

Neutrino & antineutrino **distinct** particles
As other fermions: mass → **Higgs** mechanism:

$$\mathcal{L}_{\nu}^{\text{Dirac}} = -\frac{v}{\sqrt{2}}\overline{\nu}_L Y^{\nu} \nu_R + \text{h.c.}$$



→ Need to **extend** the SM with ν_R

Majorana

The neutrino is its **own antiparticle**
Majorana mass term in the Lagrangian

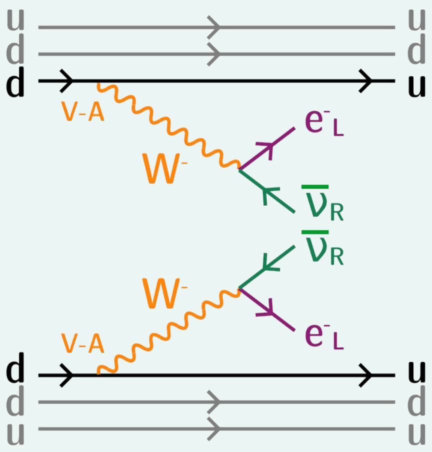
$$\mathcal{L}_{\nu}^{\text{Majorana}} = \frac{1}{2} m_{\nu} \overline{\nu}_{\text{L}}^{c} \nu_{\text{L}} + \text{h.c.}$$

- Lepton Number Violation (**LNV**) ΔL=2
- **Seesaw** mechanisms: smallness of neutrino masses

Probe: Neutrinoless double beta decay (0νββ)

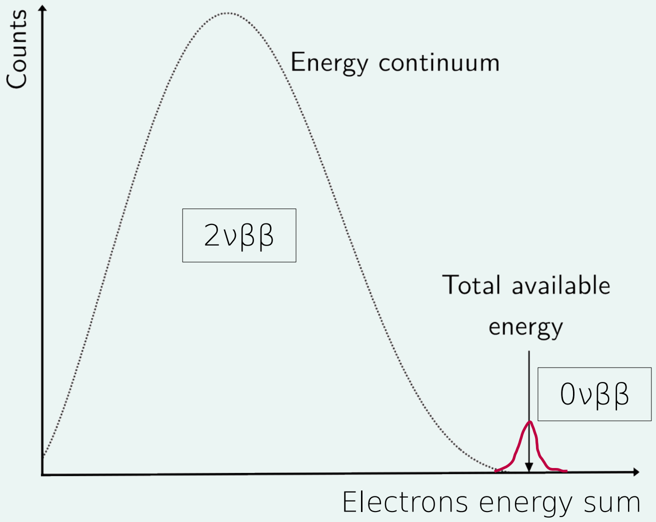
How do neutrinos get mass ? Is it Dirac or Majorana?

2νββ



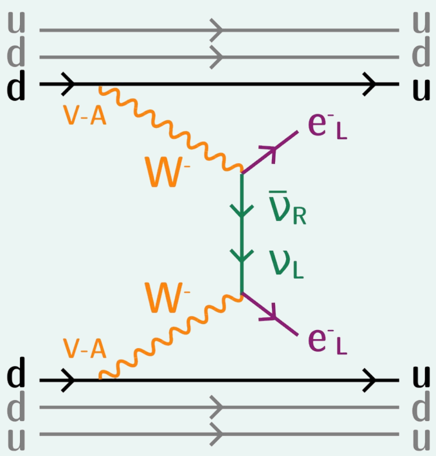
Simple β energetically impossible
2 simultaneous neutron decay
Allowed in SM
One of rarest nuclear decay observed:

$T^{2\nu\beta\beta}_{1/2} \sim 10^{18} - 10^{21}$ years



Majorana particle

0νββ



Forbidden in SM
Only if neutrinos = Majorana particles

$T^{0\nu\beta\beta}_{1/2} > 10^{24} - 10^{26}$ years

Represented for light Majorana neutrino exchange

What is the first thing we want to do to detect rare events?

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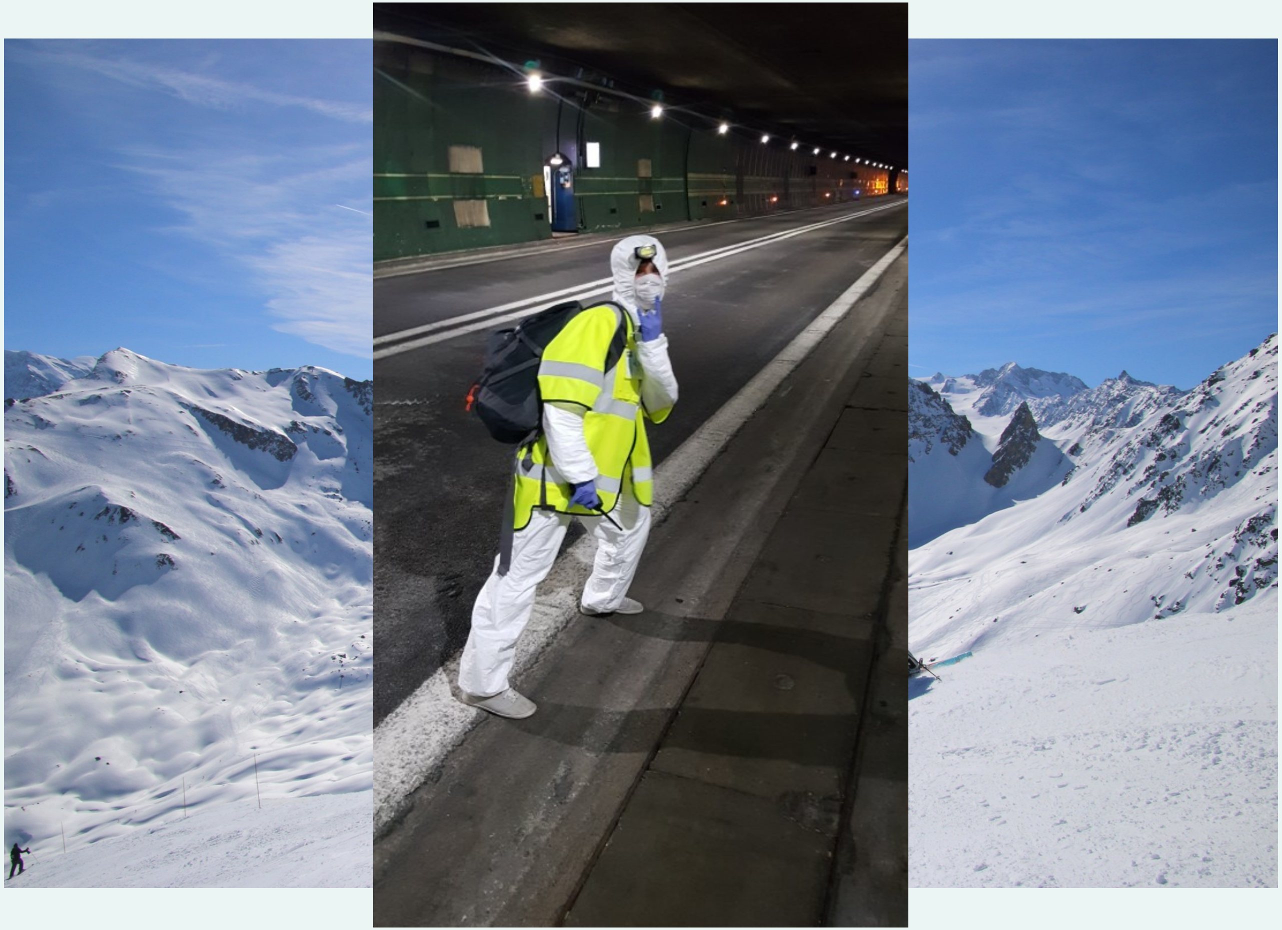

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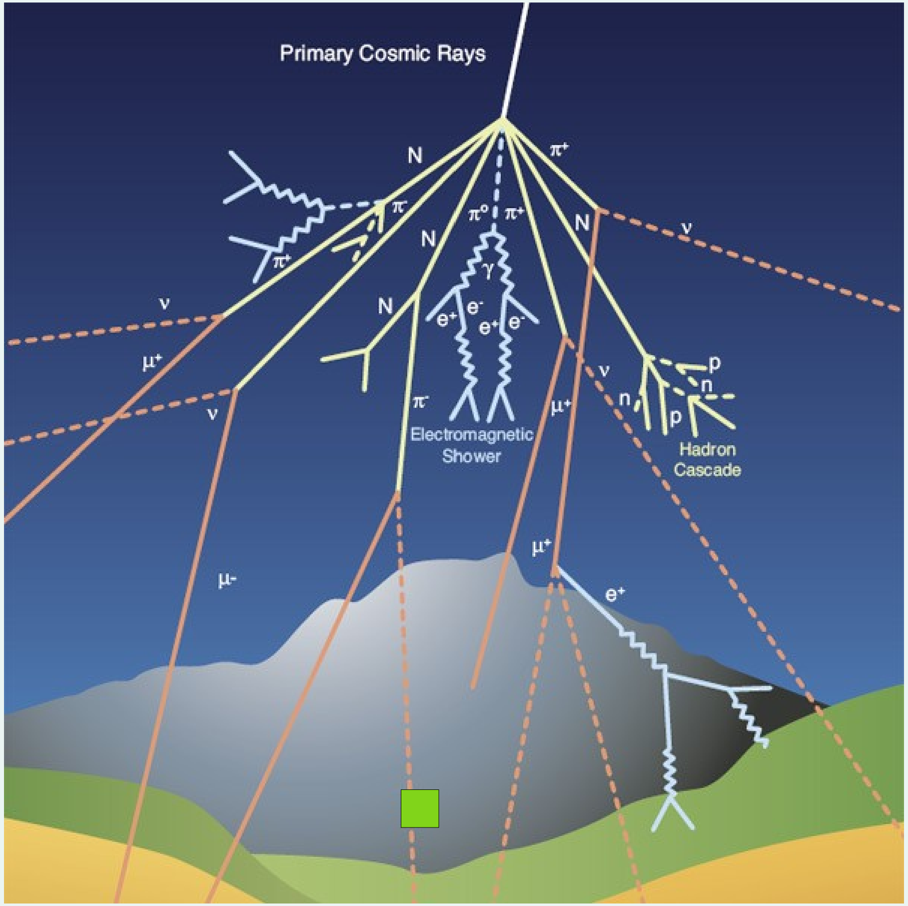

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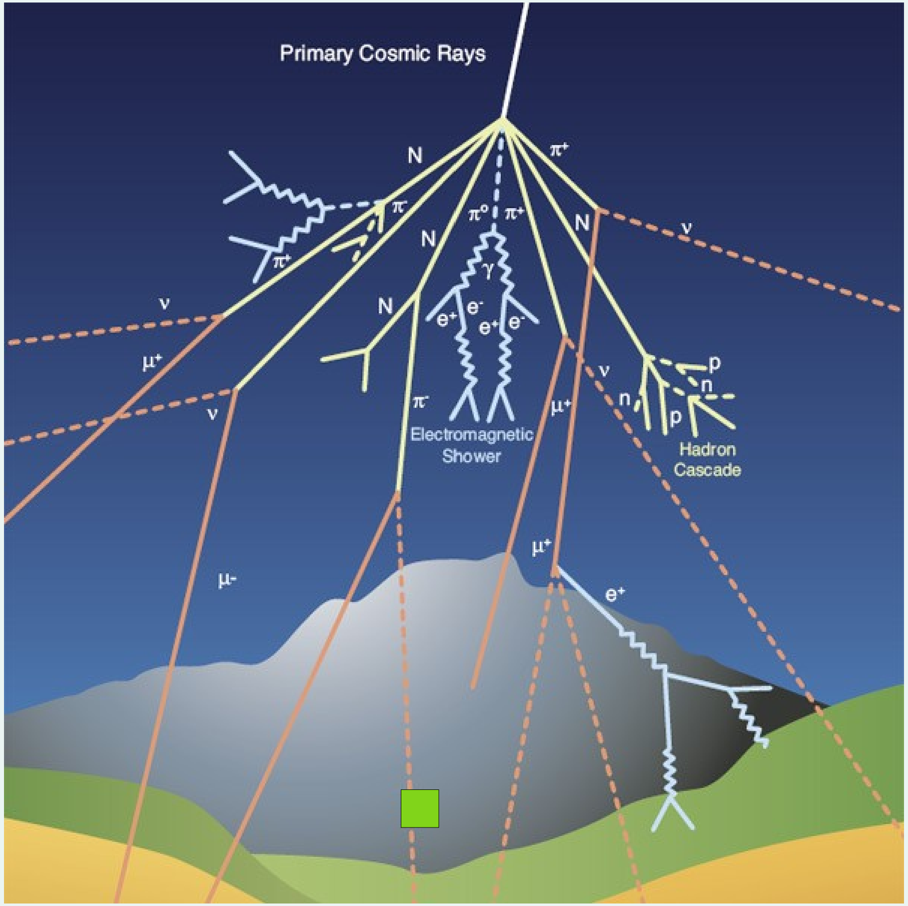

Is
this
sufficient?

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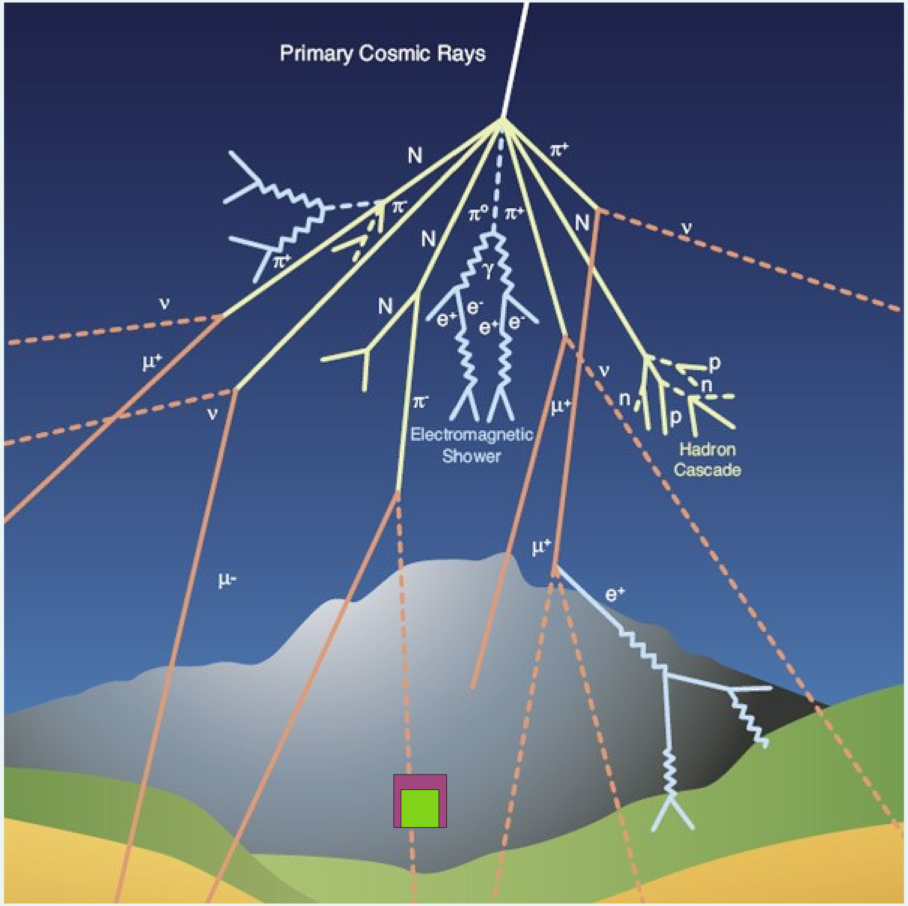

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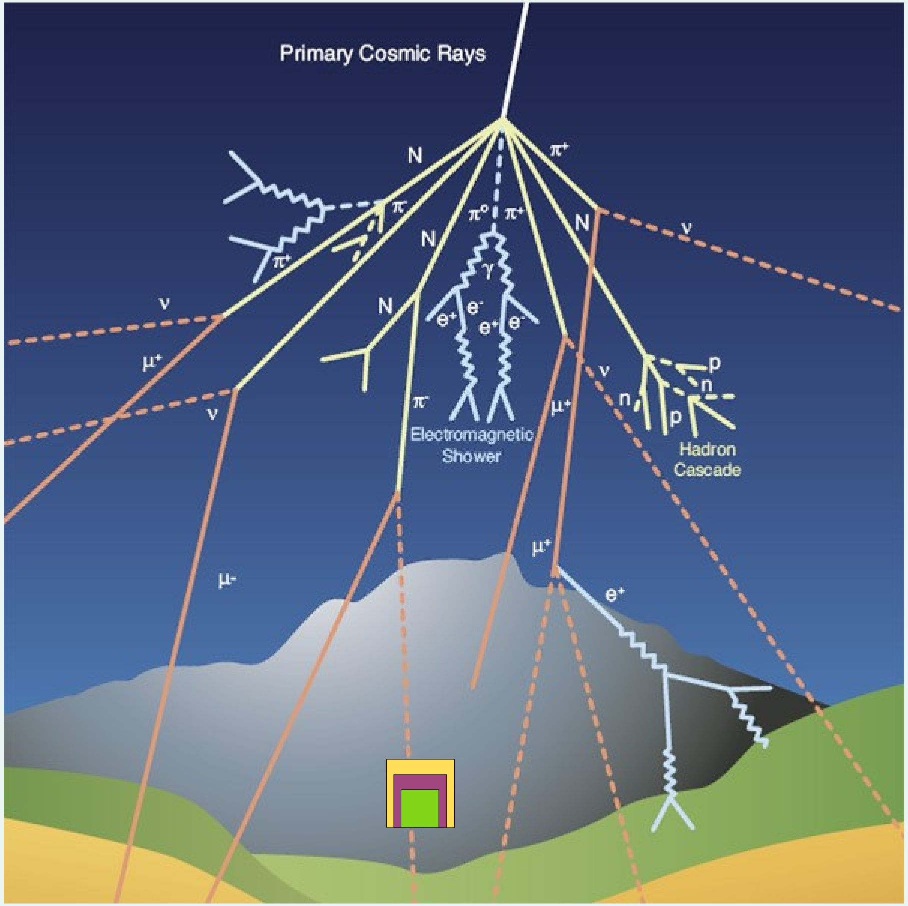

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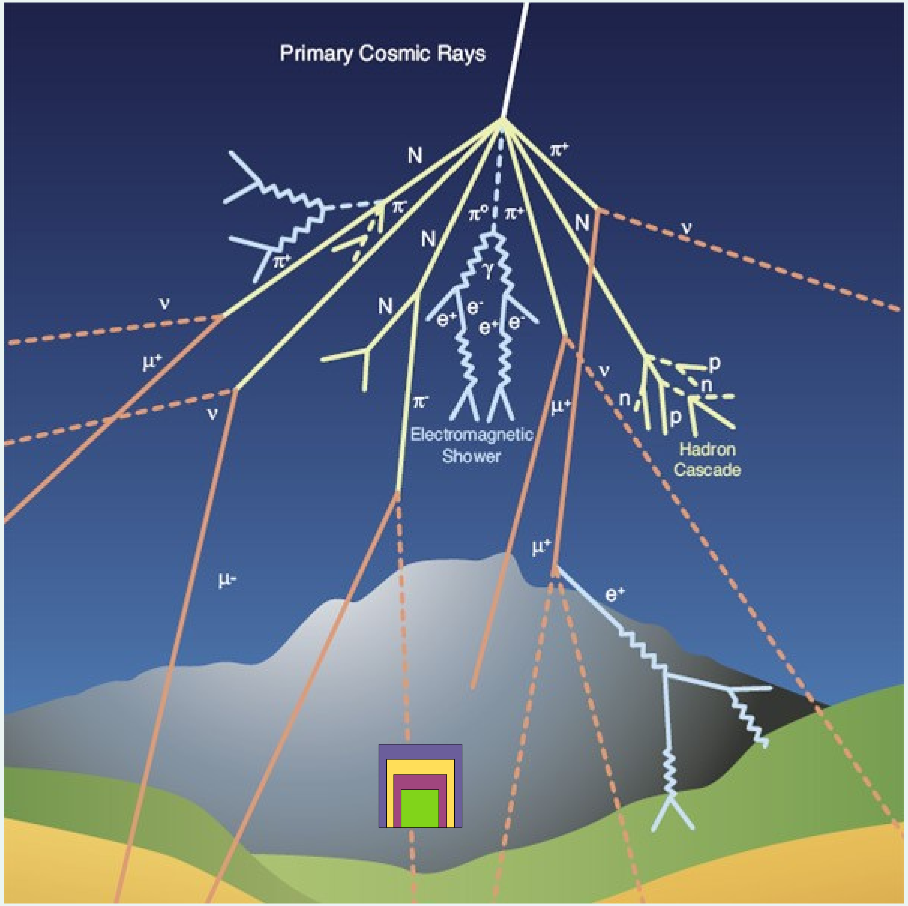

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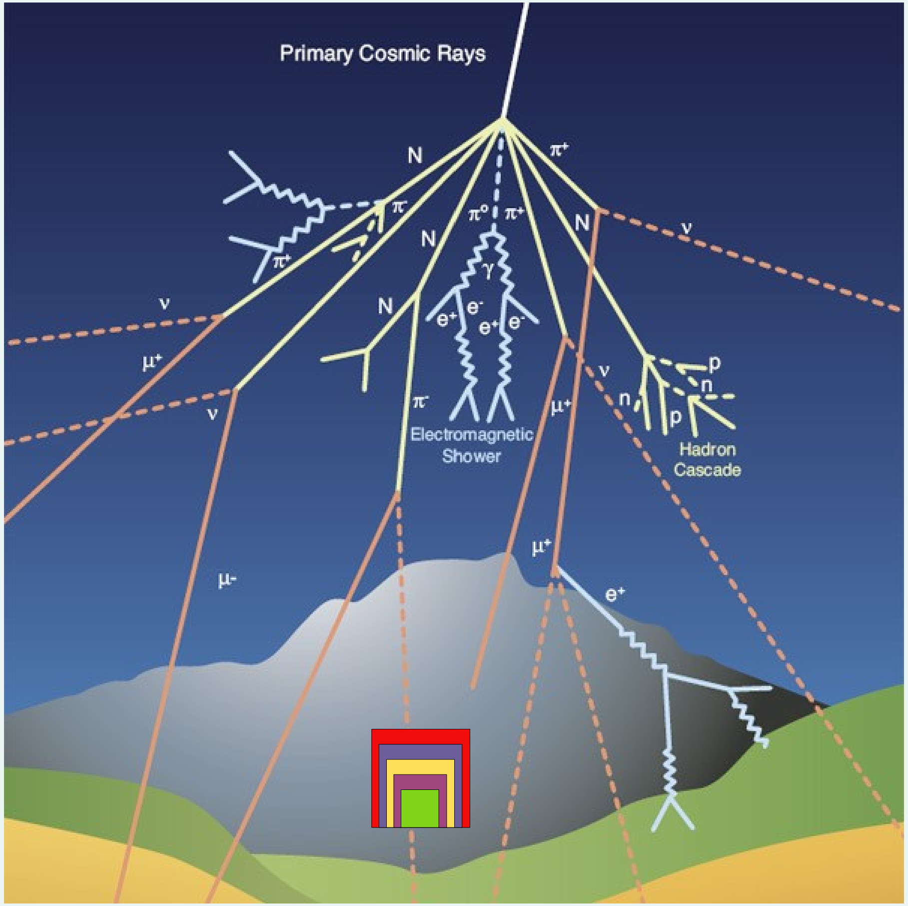

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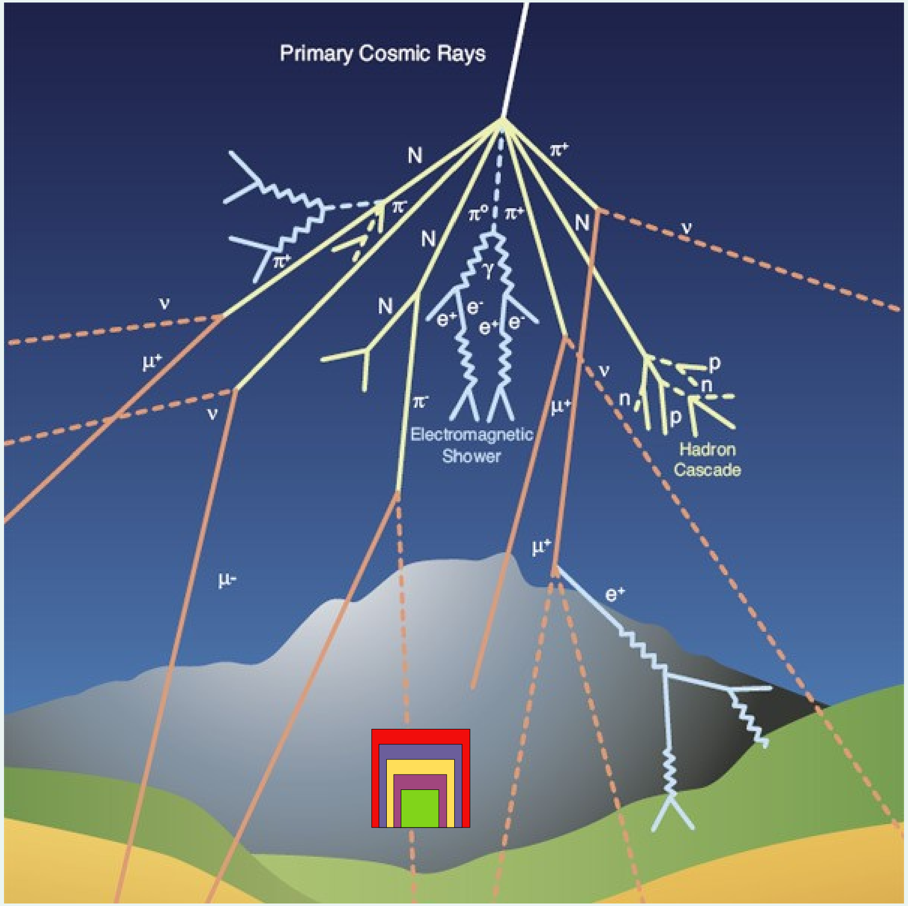

Is
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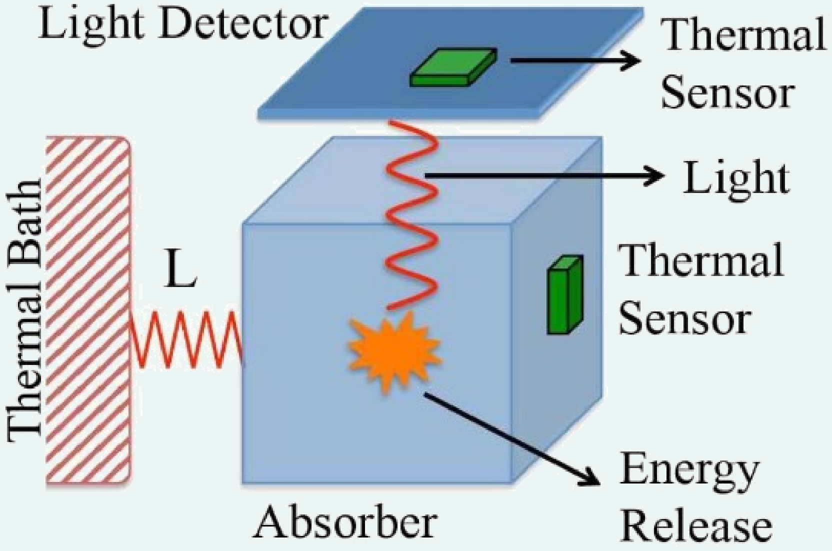
The CUPID experiment

CUPID ^{100}Mo
heat + light
(scintillating bolometer)



CUPID-Mo: best limit on 100Mo at the time
$T_{1/2} > 1.8\times10^{24}$ y

Phys.Rev.Lett. 126(2021)181802 - Eur.Phys.J. C 82,1033(2022)

Bolometer = **calorimeter** measuring **tiny temperature rises** from particle interactions

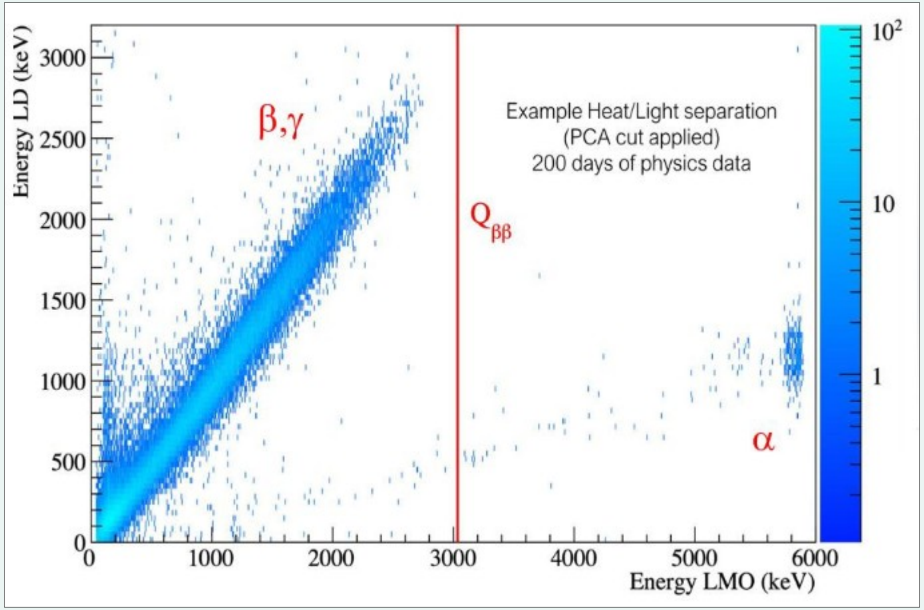
Each CUPID detector is a crystal cooled to **~10 mK** in dilution refrigerator.

When ββ decay occurs inside crystal:

- The 2 emitted electrons deposit their full energy
- Crystal **temperature rises** by only a few microkelvin + **light emission**
  - thermistor (NTD germanium sensor) **convert temperature change into voltage pulse**
  - **Light detectors** detect scintillation light

Gives energy measurement with **extremely high precision** + **PID**

The CUPID experiment



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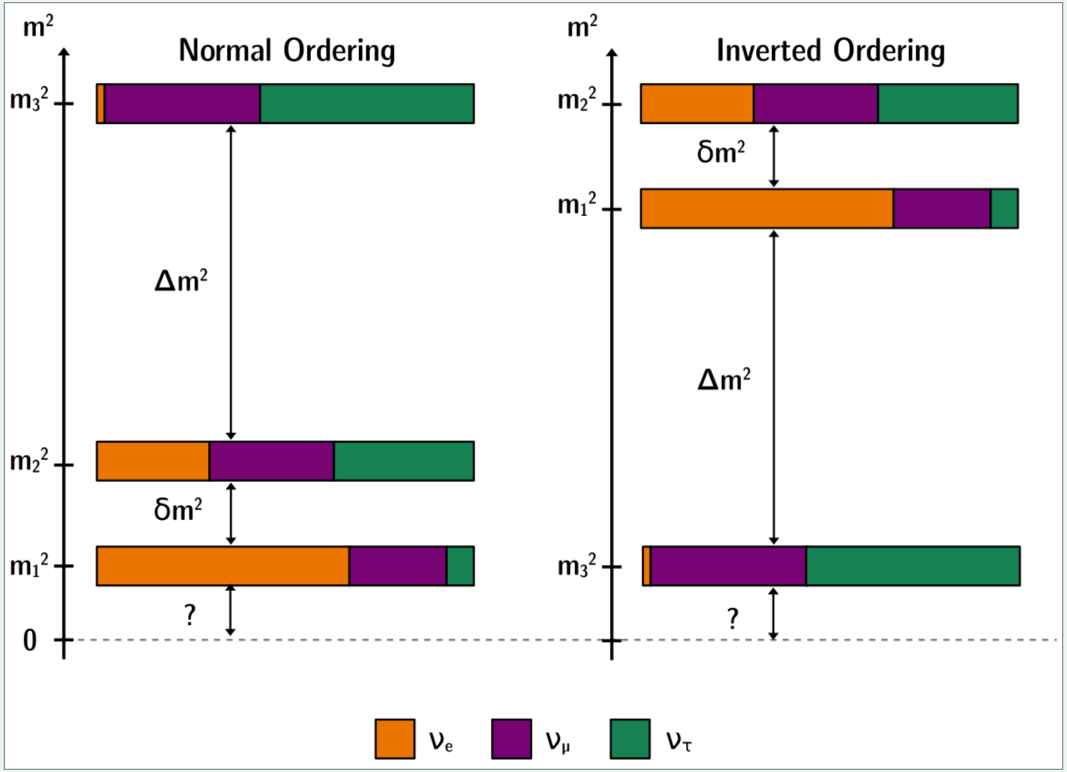
What is the absolute neutrino mass scale?



The KATRIN experiment

The KATRIN experiment

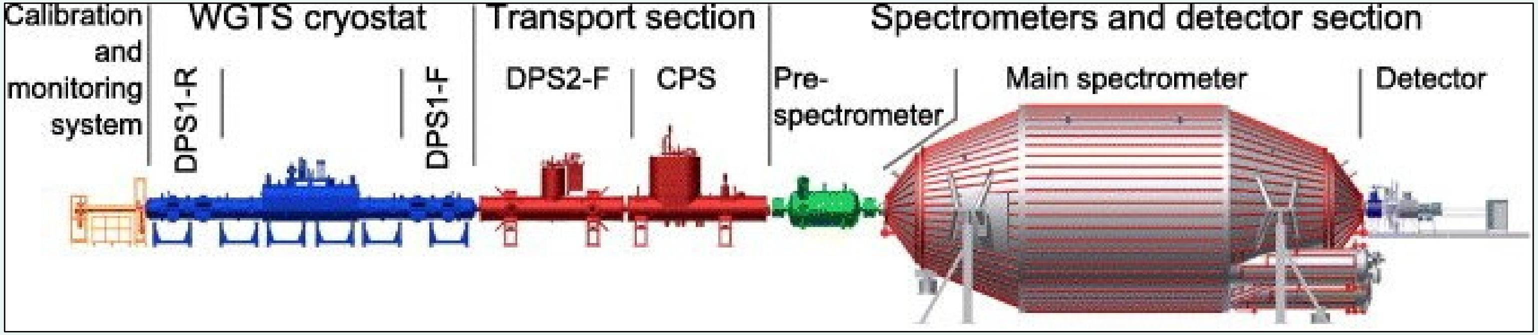
KATRIN

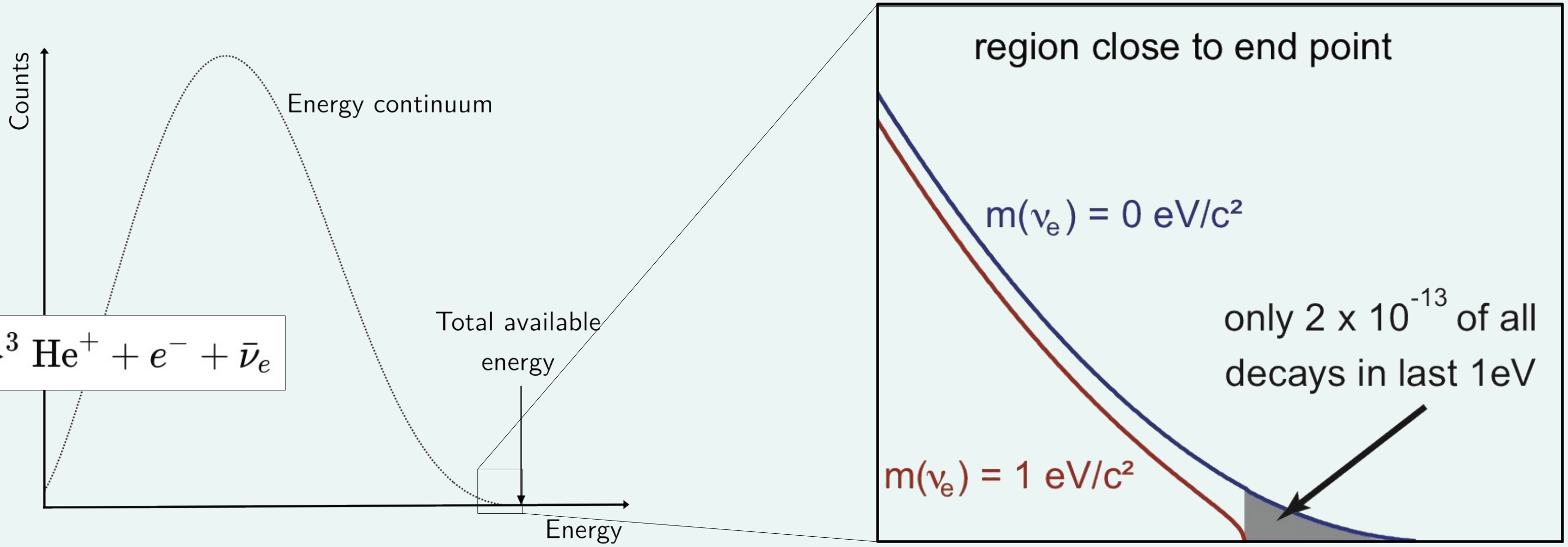
KARLSRUHE TRITIUM NEUTRINO EXPERIMENT

T_2

The KATRIN experiment

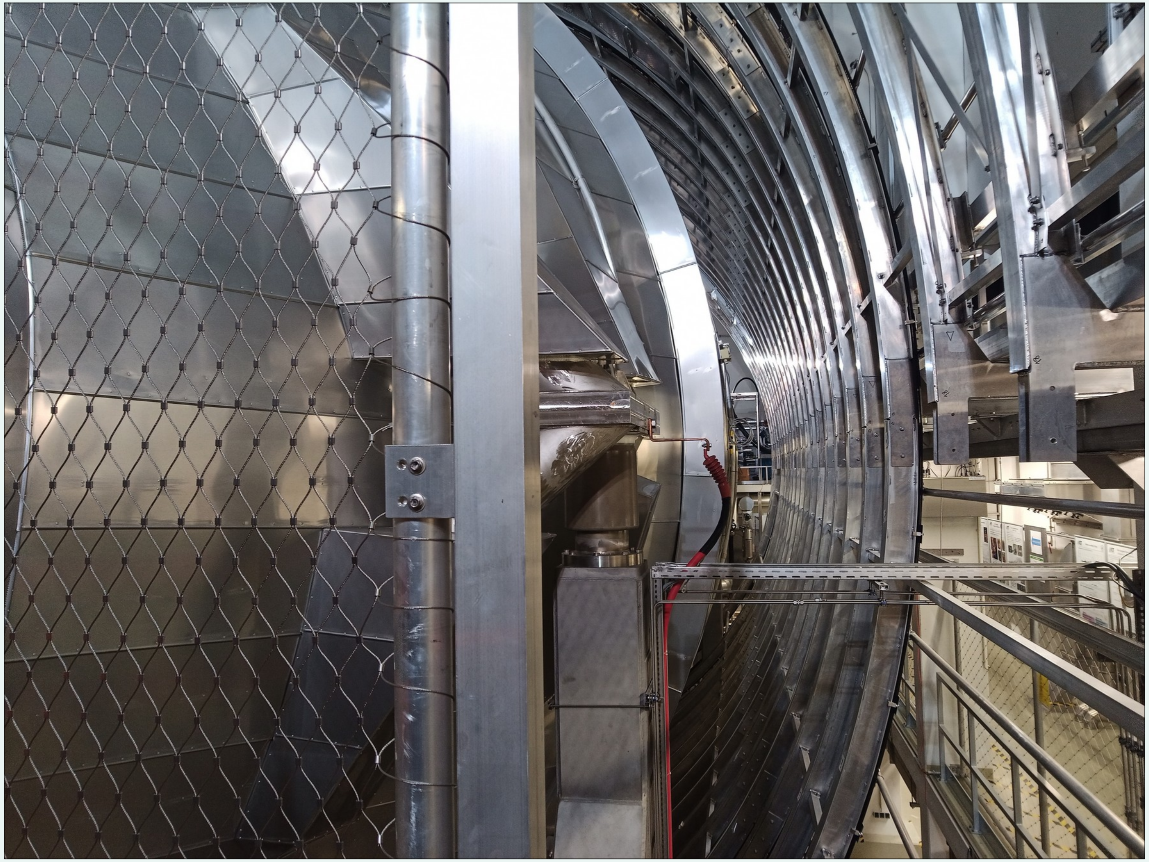
The KATRIN experiment



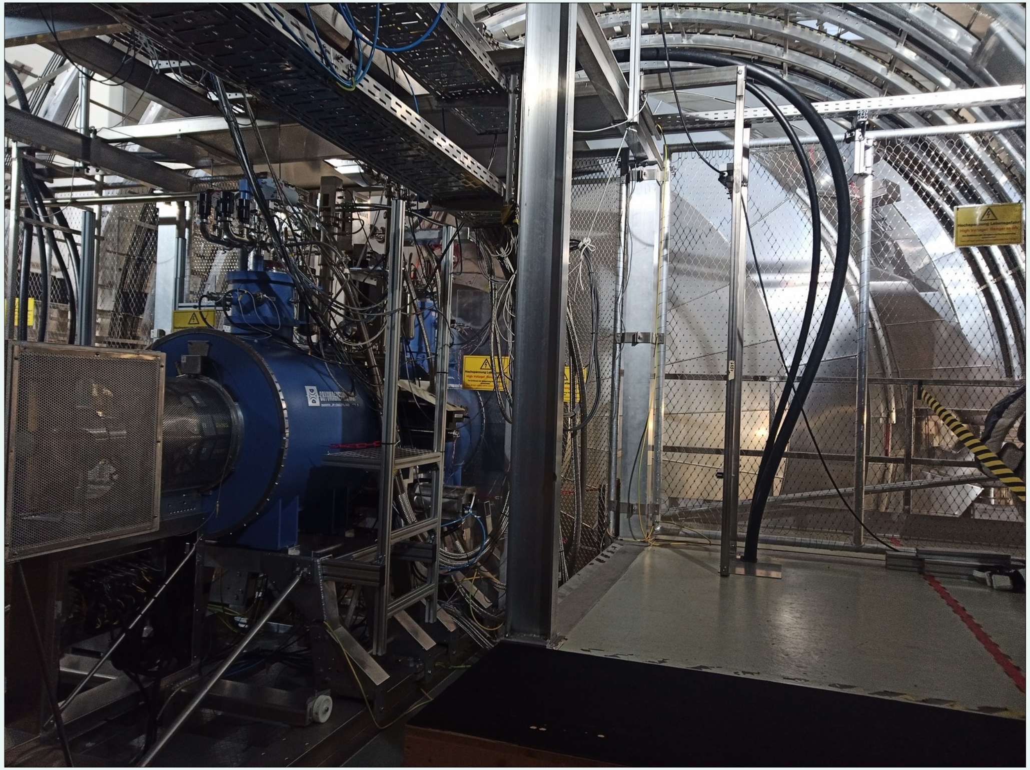


$$^3\mathrm{H} \rightarrow ^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

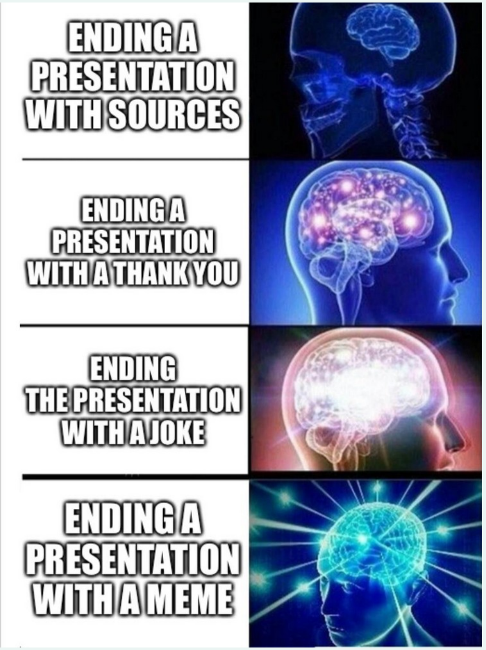
The KATRIN experiment



The KATRIN experiment



Some last important words about neutrino physics...


ENDING A PRESENTATION WITH SOURCES
ENDING A PRESENTATION WITH A THANK YOU
ENDING THE PRESENTATION WITH A JOKE
ENDING A PRESENTATION WITH A MEME

That’s all

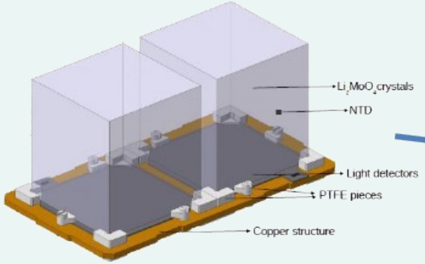
CUPID structure

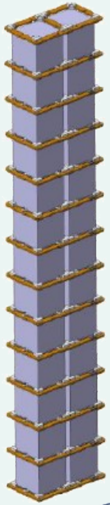
- **CUPID pre-CDR** *arXiv:1907.09376*
- **Upgraded structure** *Eur. Phys. J. C 82, 810 (2022), Eur. Phys. J. C* 85, 737 (2025)
- **TDR under finalization**

- Crystal: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~280 g – enrichment ≥ 95%**
- Thermal sensor: **neutron transmutation doped (NTD) Ge thermistor**
- **Si heater** to stabilize the detector response
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo**
- ~**1.6×10^{27}** ^{100}Mo atoms

Baseline design

Gravity stacked structure





Light detectors

- Ge wafers with NTD sensor and SiO antireflective coating
- Each crystal has top and bottom LD
- No reflective foil

Muon veto for muon induced background suppression