Neutrino Physics

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Contents

1 Neutrinos in Particle Physics
   Where do they come from?
   Why are they so weird?

2 What do they look like? How can we detect them?

3 What are the fundamental physical properties of neutrinos that we can measure?

4 The big unknowns to be solved

5 Messengers of Cosmos
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Neutrinos in Particle Physics
Standard Model of Particles

**Particles**

| Quarks       | Electric Charge | Electric Charge |
|--------------|-----------------|-----------------|
| Bottom       | -1/3            | 2/3             |
| Strange      | -1/3            | 2/3             |
| Down         | -1/3            | 2/3             |

**Forces**

- **Strong**
  - Gluons (8)
  - Quarks
  - Mesons
  - Baryons
  - Nuclei

- **Electromagnetic**
  - Photon
  - Atoms
  - Light
  - Chemistry
  - Electronics

- **Gravitational**
  - Graviton?
  - Solar system
  - Galaxies
  - Black holes

- **Weak**
  - Bosons (W, Z)
  - Neutron decay
  - Beta radioactivity
  - Neutrino interactions
  - Burning of the sun

*The particle drawings are simple artistic representations*
Neutrinos in the Standard Model

- **3 types** of neutrinos (although extra sterile neutrinos beyond the SM could exist)
- They are electrically **neutral** particles
- Much **lighter** than their charged leptonic partners
- **Very weak interaction** with matter
- Together with photons, they are the most **abundant** elementary particles in the Universe
Antiparticles

For each particle, there is an associated antiparticle with the same mass and opposite charge.

Antiparticles are produced in natural processes (as radioactive decays) and particle accelerators.

Neutrinos could be their own antiparticles.

Equals amounts of particles and antiparticles were created after the Big Bang.

- Where are the antiparticles?
- Why are we made of matter?

- Dirac neutrinos: particle ≠ antiparticle
- Majorana neutrinos: particle = antiparticle
Symmetries

- **Charge Conjugation (C)**: transformation of a particle into its antiparticle
- **Parity (P)**: transformation of left to right (world in a mirror)
- **Time Reversal (T)**: running backwards in time

- **CP Symmetry**: It was thought that CP was a valid symmetry however the observation of neutral kaon decays proved that CP is not conserved in weak interactions
  - Could it be also violated for neutrinos?

- **CPT Symmetry**: conserved in the SM transformations
Left-handed neutrinos

- In the Standard Model, there are **not right-handed** ($\nu_R$) neutrinos
  - Neutrinos are left-handed ($\nu_L$)
  - Antineutrinos are right-handed ($\bar{\nu}_R$)

**Neutrinos have negative helicity**

Helicity: Projection of the spin in the direction of the linear momentum
CP symmetry in neutrinos

- In the weak interactions:
  - P symmetry is not conserved
  - C symmetry is not conserved
  - CP seems to be conserved

- \( \nu_R \) and \( \bar{\nu}_L \) may not exist at all
- May exist but with much larger mass
- Are unaffected by the weak nuclear force

M. Strassler 2013
Weak interaction

- **Magnitudes:**
  - Neutrinos produced by the Sun (are pretty low energy ~MeV) travel (on average) $1.5 \times 10^{16}$ m in lead before interacting.
  - Neutrinos produced by accelerators (~1000 times more energetic ~GeV) travel (on average) $1.5 \times 10^{12}$ m in lead before interacting.
  - For comparison, a proton ~GeV travels 10 cm in lead!!

- Neutrinos only interact with *members of their own family* (electron, muon or tau).
- The identification of the partner charged particle allows us to know the type (flavor) of the neutrino.
Number of neutrino types

- There are 3 types of neutrinos (families) in the SM

\[ \Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{\text{had}} - 3\Gamma_l \]
\[ \Gamma_{\text{inv}} = N_\nu \cdot \Gamma_\nu \]

K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014)

Number \( N = 2.984 \pm 0.008 \) (Standard Model fits to LEP data)

Number \( N = 2.92 \pm 0.05 \) (Direct measurement of invisible Z width)
# Neutrino sources

| Neutrino Sources | Neutrino Flux | Energy Range | Distance |
|------------------|---------------|--------------|----------|
| The Sun          | $\phi_\nu \sim 65$ billion /cm$^2$ s | $E \sim$ MeV | $L \sim 10^8$ km |
| Atmosphere       | $\phi_\nu \sim 10^{-2} - 10^{-9}$ /GeV cm$^2$ sr s | $E \sim$ GeV-TeV | $L \sim 10 - 10^4$ km |
| Earth            | $\phi_\nu \sim 10^6$ /cm$^2$ s | $E \sim$ MeV | $L \sim 10 - 10^3$ km |
| Supernovae       | $\phi_\nu \sim$ several billions in 10 sec | $E \sim$ MeV | $L \sim kpc- Mpc$ |
| Big Bang         | $\phi_\nu \sim 300$ /cm$^3$ | $E \leq$ meV | $L \sim Mpc$ |
| Cosmic accelerators | $\phi_\nu \sim 10^{-2} - 10^{-9}$ /GeV cm$^2$ sr s | $E \sim$ TeV-PeV | $L \sim kpc- Mpc$ |
| Nuclear reactors | $\phi_\nu \sim 2 \times 10^{20}$ /s GW$_{th}$ | $E \sim$ MeV | $L \sim 1-100$ km |
| Particle accelerators | $\phi_\nu \sim$ several billions in 10 sec | $E \sim$ GeV | $L \sim 100-1000$ km |
Neutrino energies and fluxes
How were they discovered?

- Pauli proposed the existence of neutrinos in 1930 as a \textit{desperate remedy} to solve the beta radioactivity “problem”

- In a \textbf{two-body emission}, the \textbf{electron energy} has a \textit{fixed value} (energy conservation)

- The beta radioactivity presents an \textit{anomaly}

- Pauli: “There is a neutral particle able to cross all detectors without leaving any trace and carrying all the missing energy”

- In 1934 \textbf{Fermi} builds a new theory to explain the beta decay and names the new particle “neutrino”
The neutrino discovery (1956)

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Savannah River reactor (US)

\[ ^{235}U + n_{th} \rightarrow X + Y \rightarrow \beta^- - decay \]

Neutrino production in the nuclear reactor cores

Neutrino detection in 1 m³ liquid scintillator (~3 v/h)

Neutrino detection in 1 m³ liquid scintillator (~3 v/h)

Cowan  Reines

Nobel Prize in Physics in 1995
Next discoveries

• 1962: $\nu_\mu$ observed in Brookhaven (US)
  • First accelerator neutrino experiment
  • Discovery of a second type of neutrino (muon)

• Much later, in 2000, the third type of neutrino $\nu_\tau$ (tau) was discovered by the DONUT experiment at Fermilab (US)
Neutrino from accelerators

- It is possible to create an **intense beam of neutrinos** from an **intense beam of protons**

**Advantages:**
- the beam can be *switched on and off* to know when we have neutrinos and when not (signal over background events)
- the neutrino energy can be selected (within a certain range)

**Disadvantages:**
- the neutrino beam is not pure (several types of neutrinos are produced)
- the flux is not very large
- it is expensive!
**Discovery of neutral currents at CERN**

- **1973**: discovery of the weak neutral currents in the Gargamelle bubble chamber at CERN
- **Leptonic NC** (interaction of a neutrino with an electron) y **hadronic NC** (neutrino scattered from a hadron).
  - This was a significant step toward the unification of electromagnetism and the weak force into the electroweak force. The result led to the discovery of the W and Z bosons, which carry the weak force.

\[ \nu + N \rightarrow \nu + X \]
Why are neutrinos so special?

• They are the only **neutral** fermions

• Their **mass**: (value, origin) Why are they much lighter than the other particles?

• Their **nature**: (Dirac, Majorana)? They could be their own antiparticles

• They mix flavors (**oscillation**)

• They are really **hard to detect** (only interact very weakly with matter)

• They could **violate the CP symmetry** (matter-antimatter asymmetry in the Universe)

• They are **extremely abundant** in the Universe

• They are **Cosmic messengers**
In the Standard Model, neutrino do not have mass…
… however neutrinos have a long history of unexpected surprises …
What do neutrinos look like?
Neutrino interactions in the SM

- **CC interactions**: exchange of $W$
  - The lepton in the final state determines if it is a neutrino or antineutrino and its flavor

- **NC interactions**: exchange of $Z^0$

- **The total lepton number is conserved** in the weak interactions observed experimentally:

\[ L = L_e + L_\mu + L_\tau \]

| \( L_e \) | \( L_\mu \) | \( L_\tau \) |
|---|---|---|
| \( (\nu_e, e^-) \) | +1 | 0 | 0 |
| \( (\nu_\mu, \mu^-) \) | 0 | +1 | 0 |
| \( (\nu_\tau, \tau^-) \) | 0 | 0 | +1 |

| \( L_e \) | \( L_\mu \) | \( L_\tau \) |
|---|---|---|
| \( (\nu_e^c, e^+) \) | -1 | 0 | 0 |
| \( (\nu_\mu^c, \mu^+) \) | 0 | -1 | 0 |
| \( (\nu_\tau^c, \tau^+) \) | 0 | 0 | -1 |
Neutrino traps
(I) Big detectors

- Filled with water or liquid scintillators (~kton)
- Surrounded by photosensors to detect the light produced by the neutrino interactions

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo
Neutrino traps
(II) Underground laboratories

Underground detectors installed in the most deepest mines to be protected from the cosmic rays continuously traversing the Earth
Pictures of real neutrinos

1) Neutrinos in CMS
2) Neutral currents at CERN
3) Cerenkov rings
4) PMTs hits in liquid scintillators
5) Tracks in T2K, OPERA, ICARUS
6) Ultra-energetic neutrinos
Neutrinos en CMS → INVISIBLES

CMS Experiment at LHC, CERN
Data recorded: Mon Aug 2 05:02:51 2010 CEST
Run/Event: 142132/92434735

e⁻
\( p_T = 63.7 \text{ GeV} \)

\( \mu^+ \)
\( p_T = 48.8 \text{ GeV} \)

MET
49.9 GeV
Neutrinos en CMS → INVISIBLES
Weak neutral currents

- First candidate to leptonic neutral current process in the Gargamelle experiment at CERN (bubble chamber)
  \[ \nu_\mu \, e^- \rightarrow \nu_\mu \, e^- \]
- Significant step in the knowledge of the electroweak force and the SM structure
Cerenkov rings

\[ p_\mu = 603 \text{ MeV} \]

\[ p_e = 492 \text{ MeV} \]
Neutrinos in liquid scintillators

Prompt signal
\[ E = 3.20 \text{ MeV} \]
\[ \Delta T = 111 \text{ } \mu\text{s} \]
\[ \Delta R = 34 \text{ cm} \]

Delayed signal
\[ E = 2.22 \text{ MeV} \]
Neutrinos in T2K ND

- Tracks of charged particles produced by a neutrino interaction in the T2K near detector
Neutrinos in OPERA

• Detector specially designed to detect the interaction of tau neutrinos
Neutrinos in LAr detectors

$\nu_\mu$ CC event detected by ICARUS from the CNGS beam

CCQE event: $\nu_\mu \, n \rightarrow \mu \, p$
Very high energy neutrinos

cascade

track

double signal

$\nu_e$

$\nu_\mu$

$\nu_\tau$
Physical quantities
Observables and fundamental quantities

❖ **Mass**: almost null

- No direct measurement. Only upper limits from lab experiments and cosmological observations
- We know that the mass is not zero because neutrinos oscillate

❖ **Charge**: null

- Experimental limits derived from the neutrino magnetic moment limit ($<10^{-12} \, q_e$ for $\nu_e$; $<10^{-4} \, q_e$ for $\nu_\tau$)
- Experimental limits from astrophysical measurements ($<10^{-13}$-$10^{-15} \, q_e$)

❖ **Spin** (intrinsic angular momentum): $\frac{1}{2}$

- Measured with angular distributions in scattering or decay processes
Particle Data Group 2018

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98, 030001 (2018)

| Mass $m < 2$ eV  | (tritium decay) |
|------------------|-----------------|
| Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% | (reactor) |
| Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV | (solar) |
| Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% | (accelerator) |
| Magnetic moment $\mu < 0.29 \times 10^{-10} \mu_B$, CL = 90% | (reactor) |

- **Best experimental limits:**
  - **Electron neutrino mass**
    - $^3$H $\rightarrow ^3$He + e$^- + \nu_e$ MAINZ $m(\nu_e) < 2.2$ eV
  - **Muon neutrino mass**
    - $\pi^+ \rightarrow \mu^+ + \nu_\mu$ PSI $m(\nu_\mu) < 170$ keV
  - **Tau neutrino mass**
    - $\tau \rightarrow 5\pi + \nu_\tau$ LEP $m(\nu_\tau) < 18.2$ MeV

*Points without error bars are upper limits*
**Measurement of the neutrino mass**

**KATRIN:** goal $m_\nu < 0.2$ eV (90% CL)

Search for a distortion in the shape of the beta spectrum in the endpoint energy region

$$N(E_e) \propto p_e E_e (E_0 - E_e) \sqrt{(E_0 - E_e)^2 - m_\nu^2 c^4}$$

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

$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$
Double beta decay experiments

- Double beta decay with neutrinos ($2\nu\beta\beta$)
  - Observed in more than 10 isotopes

- Neutrinoless double beta decay ($0\nu\beta\beta$)
  - Violates the total lepton number conservation
  - It requires Majorana neutrino mass
  - Measurement: Effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$
  - Still unobserved

\[
\frac{1}{T_{1/2}} = G |M|^2 \langle m_{\beta\beta} \rangle^2
\]

\[
m_{\beta\beta} = \sum_i U_{ei}^2 \cdot m_{\nu_i}
\]

Maria Goeppert-Mayer
Nobel Prize in Physics in 1963
Neutrino mass from cosmology

- Neutrinos are very abundant. Their mass contribute to the energy density of the Universe

- The presence and interactions of neutrinos in the Universe must be incorporated to the astrophysical and cosmological models

- Precision cosmology measurements can constrain the sum of neutrino masses ($\sum m_\nu$) and the effective number of neutrinos ($N_{\text{eff}}$)

- Best combined limits:
  
  \[ \sum m_\nu \leq 0.23 \text{ eV (95\% CL)} \]
  
  Planck TT + low P + lensing + ext (BAO + JLA + $H_0$)
  
  \[ N_{\text{eff}} = 3.04 \pm 0.18 \]
  
  Planck TT, TE, EE + lowP + BAO

A&A 594, A13 (2016)
Solar neutrinos

Homestake Mine
South Dakota

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \]

Tank of 375 m³ de C₂Cl₄

37Ar extraction station

Prediction (J. Bahcall): 1 Ar atom per day
Measurement (R. Davis): 1/3 of prediction!!

2/3 of neutrinos are missing!!

The discrepancy would go without explanation for more than 30 years (1968-2001)

R. Davis Jr.
Nobel Prize in 2002
Atmospheric neutrinos

Kamiokande and IMB detected atmospheric neutrinos in the 80’s

- **Expected:** 2 times more $\nu_\mu$ than $\nu_e$
  \[ 2\nu_\mu \sim \nu_e \]

- **Found:**
  \[ \nu_\mu \sim \nu_e \]

*Where are the neutrinos going?*
Quantum interference phenomenon in which a neutrino of a certain flavor is transformed into a neutrino of a different flavor.

This phenomenon is only possible if neutrinos have different masses.
Oscillations and waves

- Fundamental particles can sometimes behave like waves
- When two waves of same frequency are moving with the same speed in the same direction superimpose on each other
- When the waves have slightly different frequencies, the resulting wave exhibits interference (“beats”):
  - Sometimes the component waves add together
  - Sometimes they cancel each other
Combination of 3 waves

- In the SM neutrinos are 3 distinct particles but when they propagate they are a combination of 3 different “waves” (1,2,3)
- As a neutrino travels through space, the waves combine in different ways depending on the distance the neutrino has travelled and its energy

During the journey the combination between 1, 2 and 3 might change:
- Sometimes the combination might look like a $\nu_\mu$
- Then later, the waves might combine to look like a $\nu_\tau$
Detection of neutrino oscillations

- Weak interaction produces neutrinos of a certain flavor
- We know which kind of neutrino is by detecting its associated particle

Production

- Neutrinos travel a distance and mix

Propagation

- Neutrinos interact in the detector
- We know which kind of neutrino is by detecting its associated particle
- Comparison of observations with predictions (theory) or expectations coming from measurements at short distances (no osc.)

Detection

Oscillation Probability

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2 \left( \frac{\Delta m^2 \cdot L}{4 \cdot E_\nu} \right) \]

For 3 neutrinos:
- 2 values of \( \Delta m^2 \) (\( \Delta m^2_{21}, \Delta m^2_{32} \))
- 3 values of \( \theta \) (\( \theta_{12}, \theta_{23}, \theta_{13} \))
The discovery of neutrino oscillations (1998): Super-Kamiokande (Japan)
Solution of the solar problem: SNO (Canada)

Neutrinos from the Sun are produced in the solar core. Both electron neutrinos alone and all three types of neutrinos together give signals in the heavy water tank.
Solar neutrino anomaly solved (2001)

- **SNO**: 1000 ton heavy water (D\(_2\)O) in the Sudbury mine (Canada)
- Able to measure *all types of neutrinos* from the Sun
- Reaction sensitive to all types of neutrinos (NC)
  \[ n_x + d \rightarrow p + n + n_x \]
- Reaction only sensitive to electron neutrinos (CC)
  \[ n_e + d \rightarrow p + p + e^- \]
- In case of no oscillations: \( \Phi_{NC} = \Phi_{CC} \)
- If neutrinos oscillate: \( \Phi_{NC} \neq \Phi_{C} \)

Result: \( \Phi_{CC} / \Phi_{NC} = 0.301 \pm 0.033 \)

\( \Phi_{NC} \) in agreement with SSM

Part of \( n_e \) converted into \( n_\mu \) and/or \( n_\tau \)

*Only \( n_e \) are emitted from the Sun by fusion reactions*
Neutrinos have mass!!

- Evidence that the **Standard Model of Particles is not complete**
- Can this observation open the door to new Physics beyond the SM?
Reactor neutrino oscillations

KAMLAND (2002)
Long-baseline (~180 km)
• Confirmation of solar neutrino oscillations
• Disappearance of $\bar{\nu}_e$

Double Chooz, Daya Bay, RENO (2011-)
Short-baseline (~1km)
• Measurement of a new type of oscillations
• Disappearance of $\bar{\nu}_e$
Accelerator neutrino oscillations

- **K2K (2004)**: first measurement of oscillations in accelerators
- **MINOS (2006)**: confirmation of atmospheric neutrino oscillations
- **OPERA (2010)**: measurement of the $\nu_T$ appearance in a $\nu_\mu$ beam
- **T2K (2011-), NOvA (2015-)**: measurement of the $\nu_e$ appearance in a $\nu_\mu$ beam
## Observed oscillations

| Experiment                           | Mode          | Neutrino source | Measured parameters |
|--------------------------------------|---------------|-----------------|---------------------|
| IMB, Kamiokande, SK, K2K, MINOS, T2K, NOvA | $\nu_\mu \rightarrow \nu_\mu$ | Atmosphere / Accelerators | $|\Delta m^2_{32}|$ $\theta_{23}$ |
| T2K, MINOS, NOvA                      | $\nu_\mu \rightarrow \nu_e$ | Accelerators     | $\theta_{13}$       |
| Double Chooz, Daya Bay, RENO           | $\bar{\nu}_e \rightarrow \bar{\nu}_e$ | Reactors         | $\theta_{13}$       |
| Homestake, GNO, GALLEX, SAGE, SK, SNO, Borexino, KamLAND | $\nu_e \rightarrow \nu_e$ | Sun / Reactors | $\Delta m^2_{21}$ $\theta_{12}$ |
| OPERA                                 | $\nu_\mu \rightarrow \nu_\tau$ | Accelerators     |                     |
Neutrino oscillation measurements

• Mixing angles and mass differences:

| parameter                  | best fit ± 1σ     |
|----------------------------|-------------------|
| $\Delta m^2_{21}$ [10$^{-5}$eV$^2$] | 7.55±0.20         |
| $|\Delta m^2_{31}|$ [10$^{-3}$eV$^2$] (NO) | 2.50±0.03         |
| $|\Delta m^2_{31}|$ [10$^{-3}$eV$^2$] (IO) | 2.42±0.03         |
| $\sin^2 \theta_{12}/10^{-1}$ | 3.20±0.20         |
| $\sin^2 \theta_{23}/10^{-1}$ (NO) | 5.47±0.20         |
| $\sin^2 \theta_{23}/10^{-1}$ (IO) | 5.51±0.18         |
| $\sin^2 \theta_{13}/10^{-2}$ (NO) | 2.160±0.083       |
| $\sin^2 \theta_{13}/10^{-2}$ (IO) | 2.220±0.076       |

• But still unknown:
  • **Mass hierarchy** (sign of $\Delta m^2_{32}$)?
  • $\theta_{23}$ octant
  • **CP violation** phase

P.F. de Salas et al., Phys. Lett. B782 (2018) 633-640
Global Fit Valencia Group
Big questions to be answered
• Neutrino **masses**: value, origin…

• **Type** of particle: Dirac or Majorana

• **Relation** with the other particles

• Are there **more than 3** neutrinos?

• Do neutrino interactions violate the **CP symmetry**?
The neutrino mass

Direct measurements: \( m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2 \)

Tritium beta decay experiments:
- Troitsk & Mainz: \( m < 2 \text{ eV} \) (95% CL)
- KATRIN (goal): \( m < 0.2 \text{ eV} \) (90% CL)

Neutrinoless double beta decay:
- If measured, neutrinos are Majorana particles
- GERDA, EXO, CUORICINO, KamLAND-Zen, NEMO-3: \( m_{\beta\beta} < 0.1-0.4 \text{ eV} \) (90% CL)
- Future ton scale experiments: \( m_{\beta\beta} < 10 \text{ meV} \)

Indirect measurements (Cosmology):
- \( \sum m_\nu < 0.23 \text{ eV} \) (Planck TT+lowP+lensing+ext.)
- \( N_{\text{eff}} = 4 \) excluded at > 99%CL
- \( N_{\text{eff}} = 3.15 \pm 0.23 \) (Planck TT+lowP+BAO)
Neutrino nature

• Neutrinos do not have electric charge
  • They could be their own antiparticles (Majorana)

• How to know it?
  • Search for rare processes: neutinoless double beta decay
  • There are currently many experiments looking for this process

• If neutrinos are Majorana particles, this could naturally explain why they are much lighter than any charged fermion and…

• this could explain the matter-antimatter asymmetry in the Universe:
  ⇒ LEPTOGENESIS
Relation with the other particles

- Relation with the **Higgs** boson?

- Relation with **quarks**?

- Relation with the other **leptons**: why are neutrinos much lighter?
Anomalies: a forth neutrino?

- Positive signal of LSND and MiniBooNE ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - Observed oscillation not compatible with 3 neutrinos (different frequency):
    $m_4 >> m_3, m_2, m_1$
  - Not confirmed by KARMEN & ICARUS
- Gallium experiments
  - $\nu_e$ deficit observed from intense radioactive neutrino sources ($^{51}$Cr & $^{37}$Ar)
- Very short-baseline reactor experiments
  - $\bar{\nu}_e$ deficit at short distances (few meters from reactors)
More than 3 neutrinos?

Sterile neutrinos ($\nu_s$):

- Do not interact weakly with other particles
- They only feel the gravitational force
- They can mix with active neutrinos
- Possibilities:

$$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e \quad \text{Or} \quad \nu_e \rightarrow \nu_s$$

Could they be related with dark matter?
• Is $m_3 > m_2$ or $m_2 > m_3$? (mass hierarchy)

• Is there **CP violation** in the leptonic sector? Is there any difference between **neutrinos and antineutrinos**?

• If CP violation draws a clear **distinction between matter and antimatter**, then CP violation may be what caused our Universe to be matter-dominated!

• **Experimental requirements to measure CP:**
  
  • Very intense neutrino beams (increase of the accelerators power)
  
  • Giant detectors (~100 kton)
The path to DUNE

Single Phase

DUNE 35-t
@Fermilab (2015)

protoDUNE SP @CERN:
300 ton (2016-2019)

DUNE SP @SURF: 10 kton

Dual Phase

WA105 3x1x1 m³
@CERN: 4.2 ton
(2016-2017)

protoDUNE DP @CERN:
300 ton (2016-2019)

DUNE DP @SURF: 10 kton
The CERN Neutrino Platform

• Approved by the CERN Council in 2014 to develop in the next 5 years a unique R&D and test facility of detectors, beams and components for future neutrino experiments

• A new test area (~53000 m²) has been built (EHN1 extension) with charged particle beams capability: available since 2017

• Projects (2015-2019):
  • NP01 (WA104/ICARUS): detector refurbishment before being shipped to FNAL for the SBN program
  • NP02 (WA105/protoDUNE-DP): construction and operation of a 6 x 6 x 6 m³ double phase liquid argon TPC (300 ton)
  • NP04 (protoDUNE-SP): 300 ton single-phase LAr TPC
  • …
LAr ProtoDUNE@CERN

Construction, installation and operation of single- and dual-phase large scale prototypes ➤ input to final DUNE FD designs

Data taking by end 2018
3x1x1 m³ LAr TPC (CERN- Bldg. 182)
First tracks and light in the 3x1x1

- 3x1x1 m³ demonstrator: the biggest dual-phase detector built until now
  - Installed during 2016, filled with LAr beg. 2017, data taking Jun-Nov 2017
  - Successful in proving the dual-phase concept at the 4 ton scale
CERN Neutrino Platform

protoDUNE-SP

protoDUNE-DP
Cryostats built at CERN

WA105/protoDUNE-DP

protoDUNE-SP
Inside protoDUNE-DP
Inside protoDUNE-SP

protoDUNE-SP

protoDUNE-DP

TO BE CONTINUED…
Cosmic messengers
News from far away...
SN1987A

Large Magellanic Cloud

60,000 l.y.

160,000 light-years

23 February 1987
The explosion was visible to the naked eye
SN1987A: 1\textsuperscript{st} detection of extragalactic neutrinos

• $10^{58}$ neutrinos were emitted from the Supernova 1987A 160,000 years ago

• About $5 \times 10^{17}$ crossed the Kamiokande detector

• 10 neutrinos detected!!

Koshiba

Nobel Prize in Physics 2002
Origin and detection of HE neutrinos

Origin of HE neutrinos

- WIMP decay products?
- HE neutrinos are the decay sub-products of the **annihilation** of WIMPs which may concentrate in astrophysical objects

\[ \chi + \chi \rightarrow q\bar{q}, \ldots \rightarrow X + \nu\bar{\nu} \]

Detection of HE neutrinos

- Astrophysical objects
- HE neutrinos appear as the sub-product of interactions of **accelerated protons** or nuclei with matter or radiation

\[ p + A/\gamma \rightarrow \pi^\pm + \ldots \]
\[ \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) + \ldots \]
\[ \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \nu_\mu (\bar{\nu}_\mu) + \ldots \]

- An array of photomultiplier tubes detect the Cerenkov light from charged particles produced by neutrino interactions
- The Cerenkov cone needs to be reconstructed to determine the energy and direction of the muon

- \( \nu_\mu \) are well suited for high energy detection (since its cross-section and muon range increase with energy) although \( \nu_e \) and \( \nu_\tau \) can also be detected
IceCube
South Pole Neutrino Observatory

IceCube Laboratory
Data from every sensor is collected here and sent by satellite to the IceCube data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

1450 m

IceTop

50 m

86 strings

DeepCore

1450 m

IceCube

2450 m

2820 m

bedrock

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation–managed research facility

Eiffel Tower 324 m
Very HE neutrinos observed in IceCube

• IceCube has detected **82 very high energy neutrino events** in **6 years of data taking**. This is a solid evidence of astrophysical neutrinos from a cosmic source.

• The astrophysical neutrinos observed so far do not allow us to identify any individual source

• Neutrino flux in the energy range of 30 to 2000 TeV and isotropic arrival directions

• More data are needed to understand the source of this astrophysical flux

• Data taking is in progress
Other proposals in Europe

- **KM3NeT**: 1 km$^3$ second-generation neutrino telescope in the Mediterranean Sea
- 3 installation sites located in Toulon (France), Sicily (Italy) and Pylos (Greece)
- ANTARES was the first undersea neutrino telescope: 12 lines (885 PMTs) providing an excellent angular resolution.
Neutrinos from the Big Bang

A cosmic neutrino background is expected (~330 neutrinos per cm$^3$)

Still not directly detected...

The SM neutrinos cannot explain dark matter but they could be the key to understanding the matter-antimatter asymmetry in the Universe
Wrap up

• Neutrinos are **special among elementary particles**
  ▶ Their masses are extremely small (the exact value is unknown)
  ▶ They interact very weakly with matter
  ▶ They mix flavors (oscillation)
  ▶ They could be their own antiparticle

• Neutrinos are **extremely abundant** in the Universe
  ▶ They carry crucial information about the phenomena in the Cosmos

• Neutrinos could explain the **excess of matter in the Universe**

Neutrinos still have surprises for us!
GRACIAS

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