GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Neutrino Physics

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CIEMAT - Basic Research Department
Experimental High Energy Physics Division

High School Teachers Programme (HST)
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CERN

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- Where do they come from?
- Why are they so weird?

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

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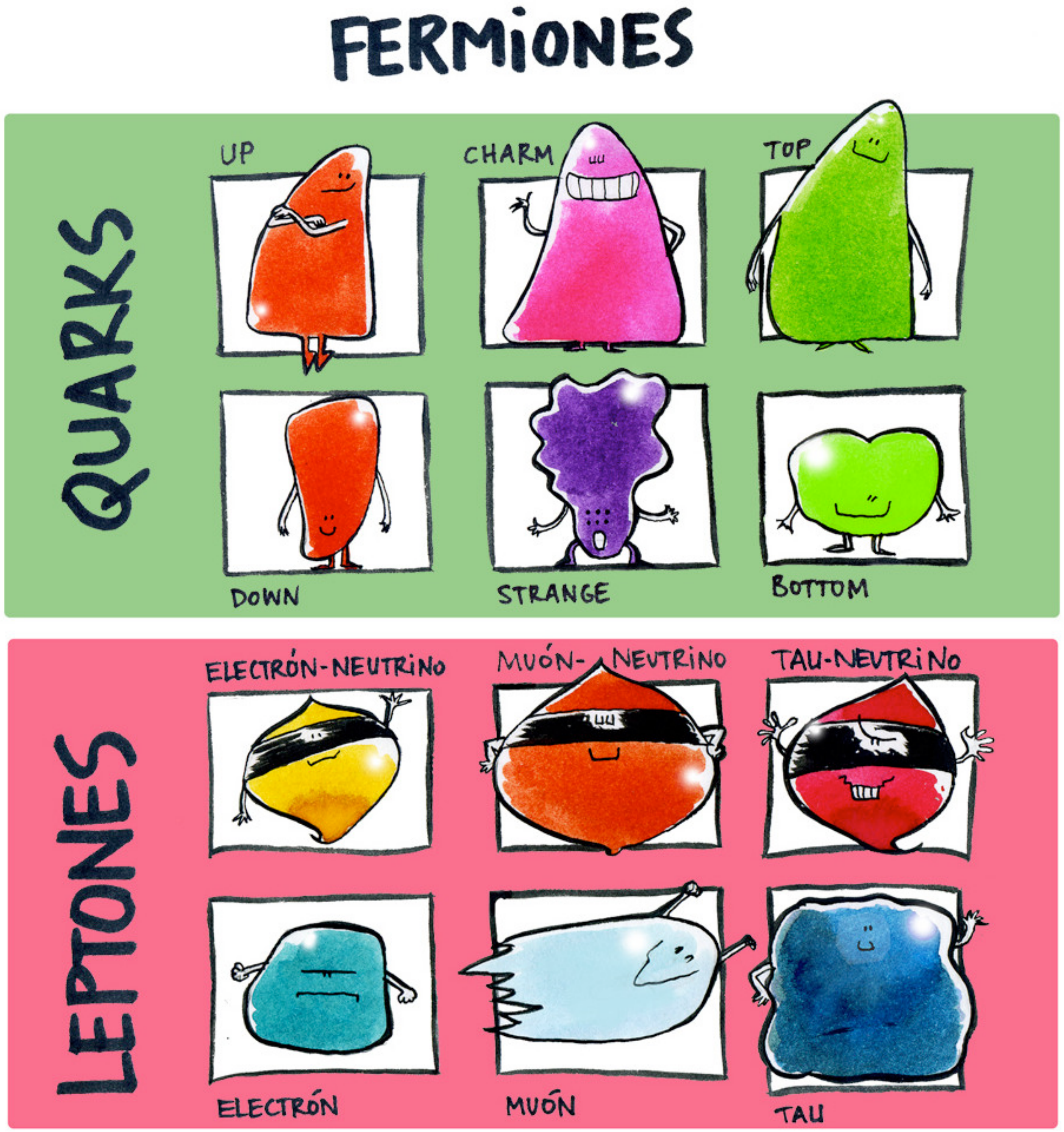

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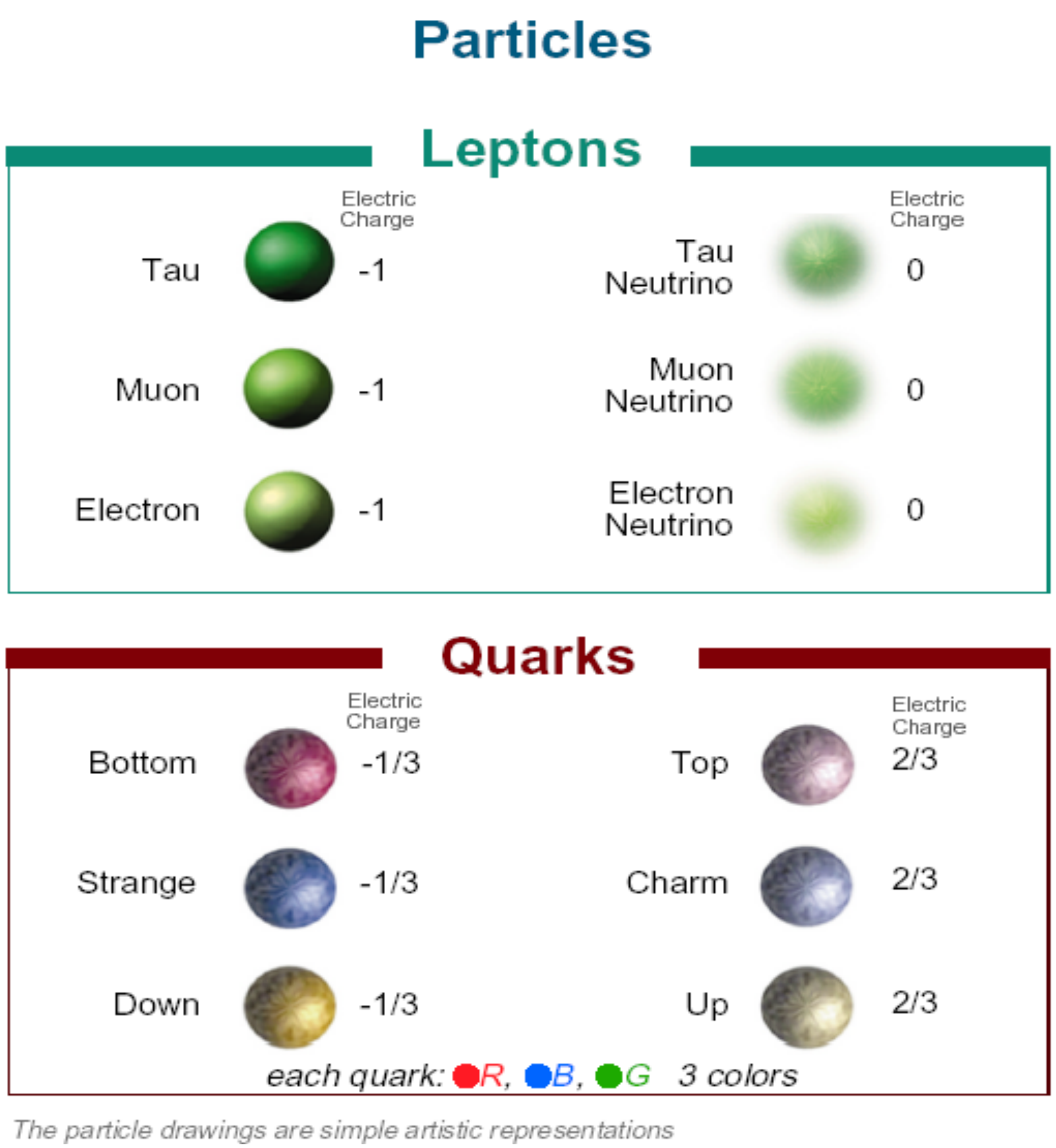
Neutrinos in Particle Physics

Standard Model of Particles

Standard Model of Particles



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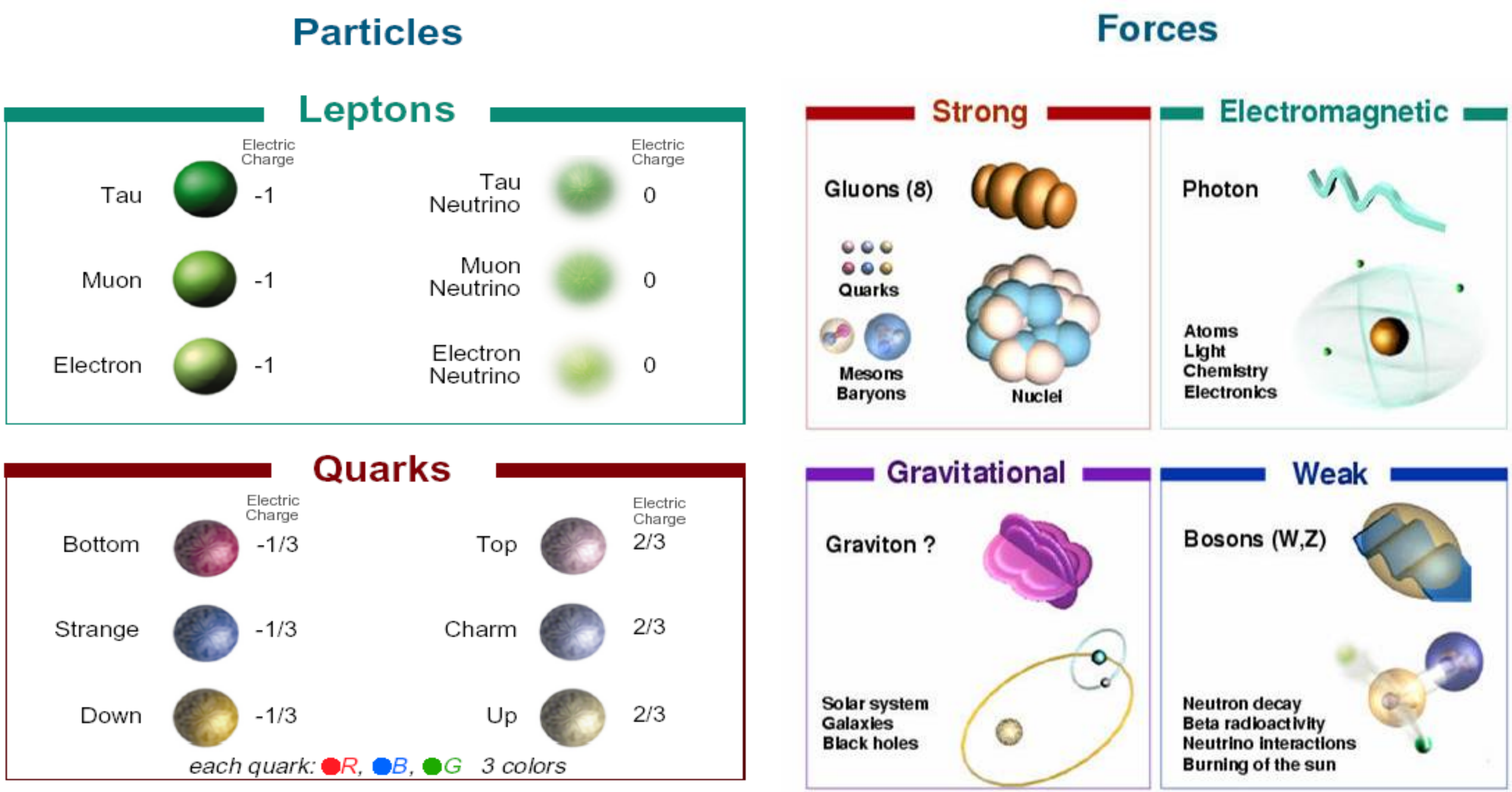
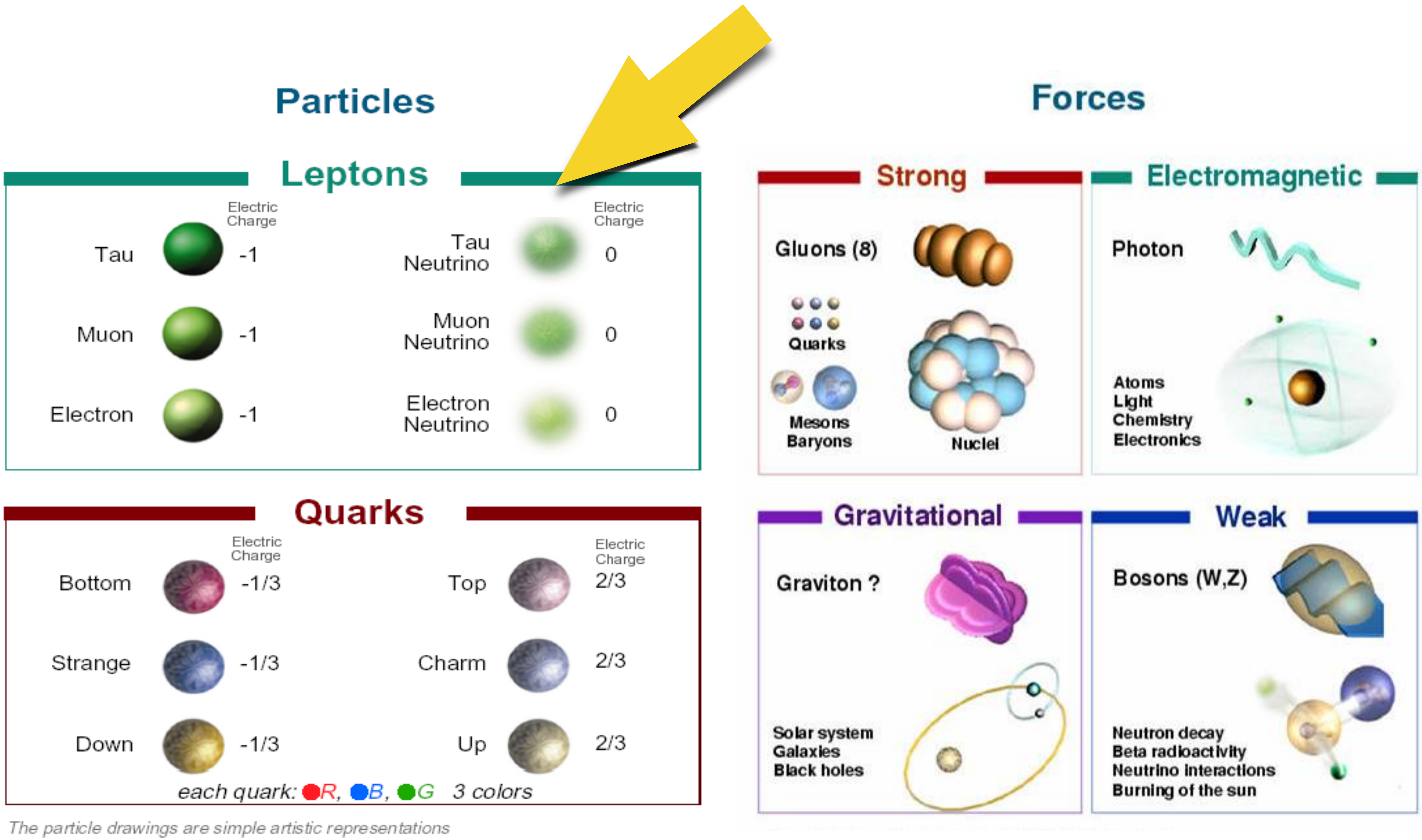


The particle drawings are simple artistic representations

Standard Model of Particles



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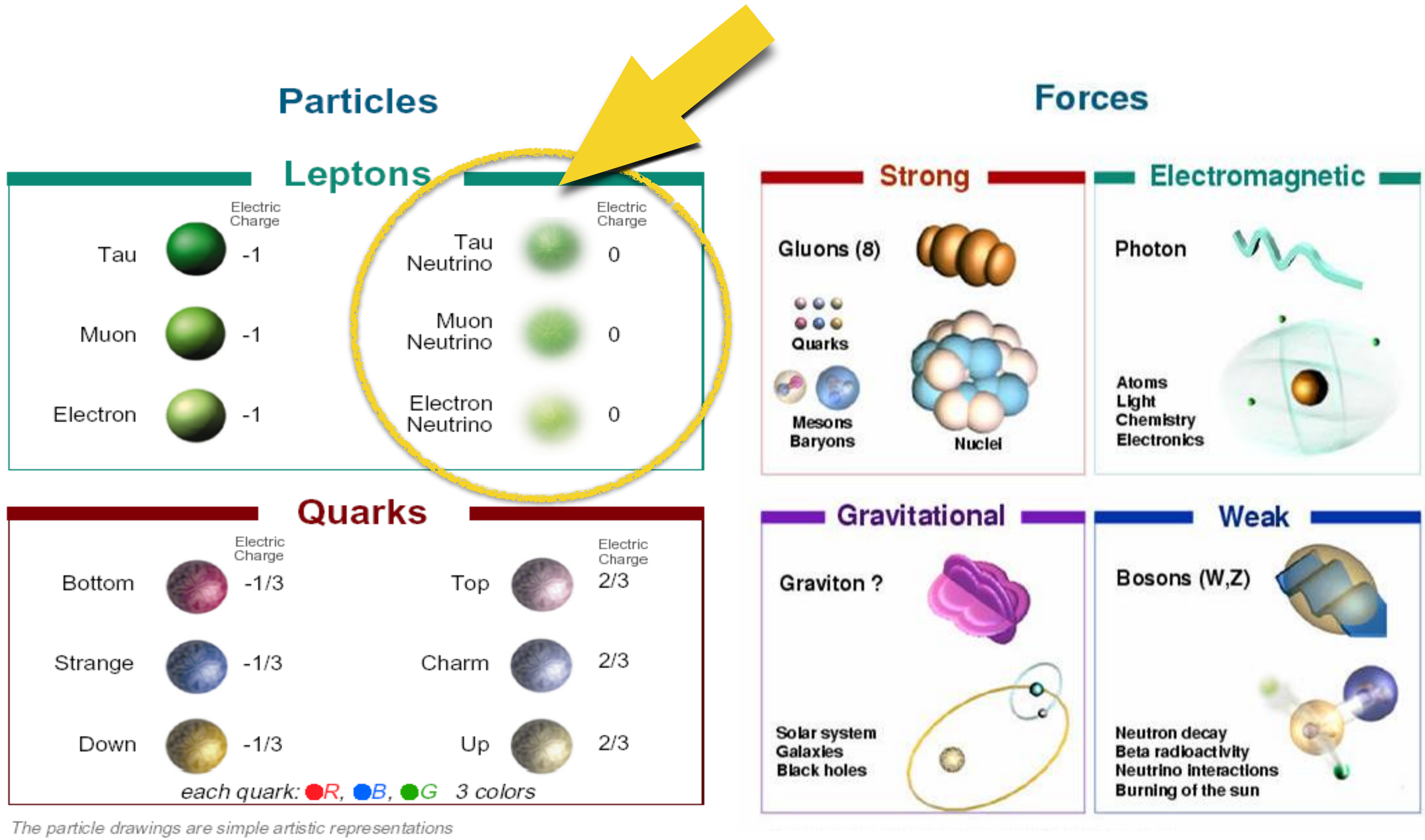
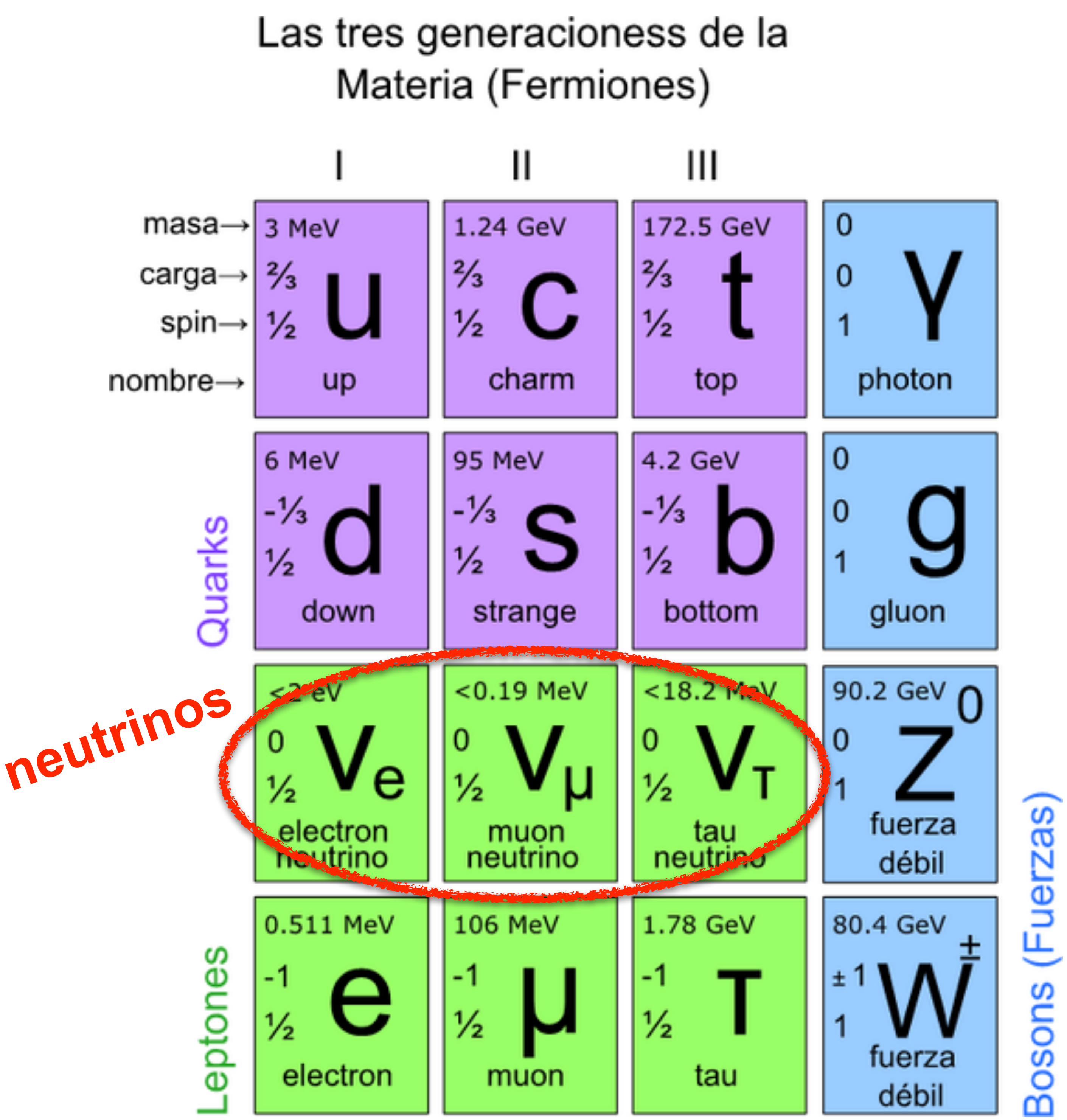
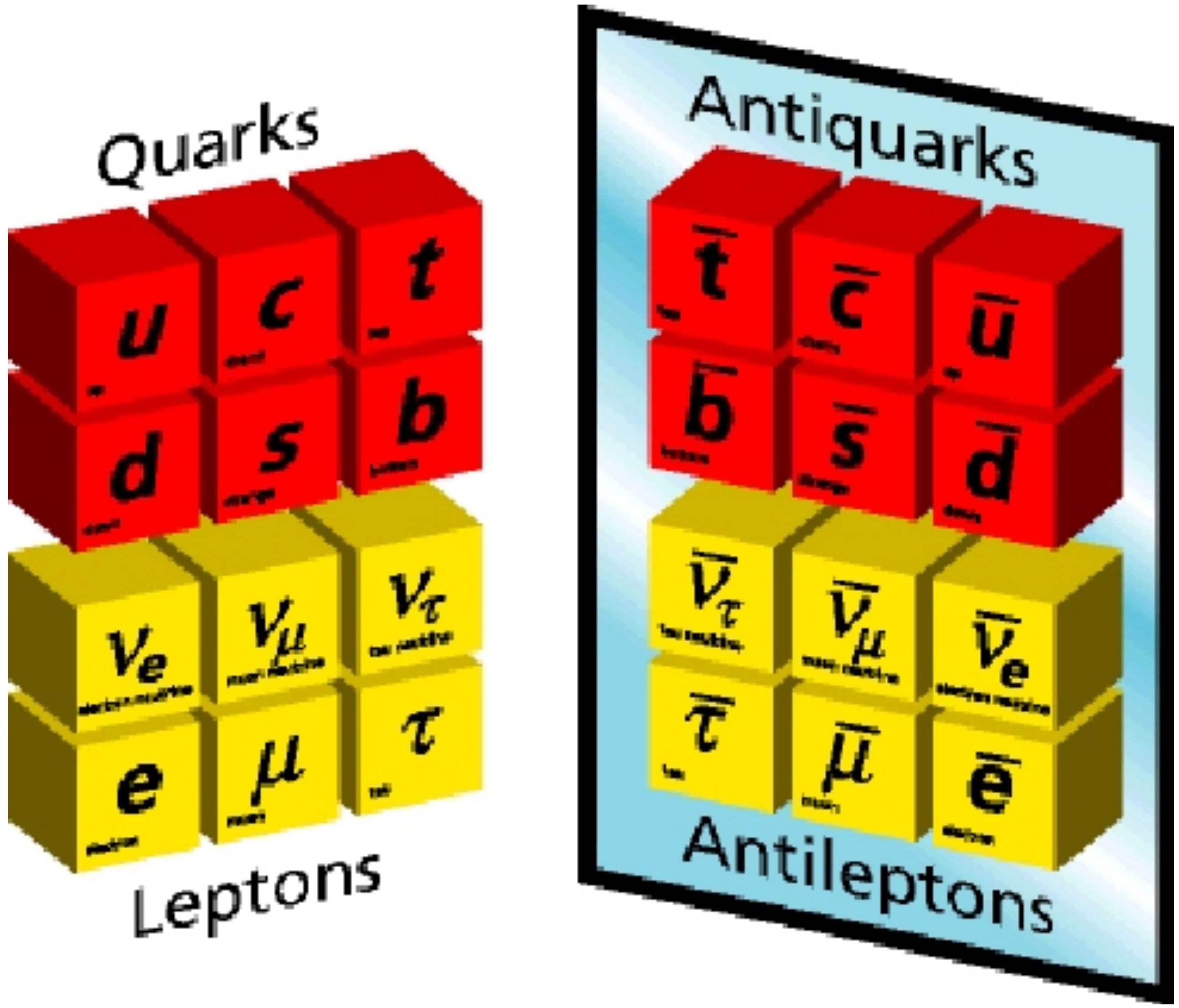


Neutrinos in the Standard Model



- **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

Antiparticles

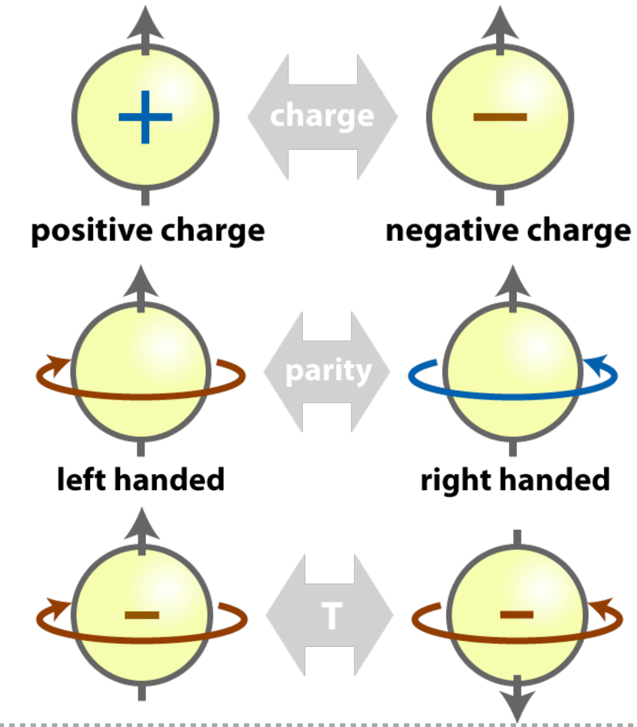


- For each particle, there is an associated **antiparticle** with **the same mass** and **opposite charge**
- Antiparticles are produced in natural processes (as radioactive decays) and particle accelerators
- Neutrinos **could be their own antiparticles**
- Equals amounts of particles and antiparticles were created after the Big Bang
  - Where are the antiparticles?
  - Why are we made of matter?

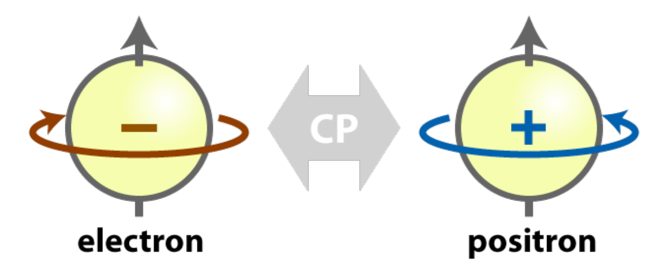
- **Dirac neutrinos**: **particle ≠ antiparticle**
- **Majorana neutrinos**: **particle = antiparticle**

Symmetries

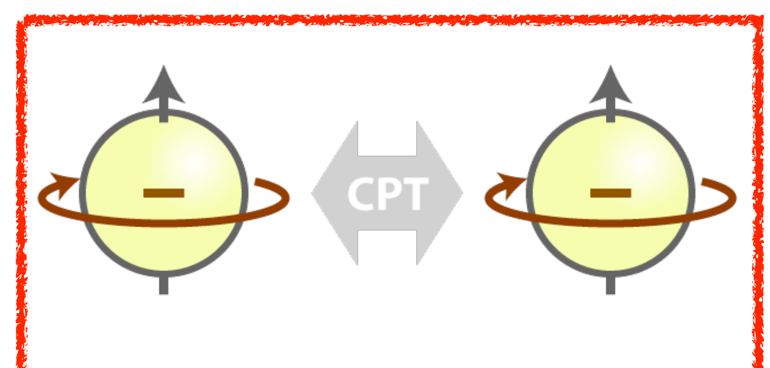
- **Charge Conjugation (C)**: transformation of a particle into its antiparticle
- **Parity (P)**: transformation of left to right (world in a mirror)
- **Time Reversal (T)**: running backwards in time



- **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?

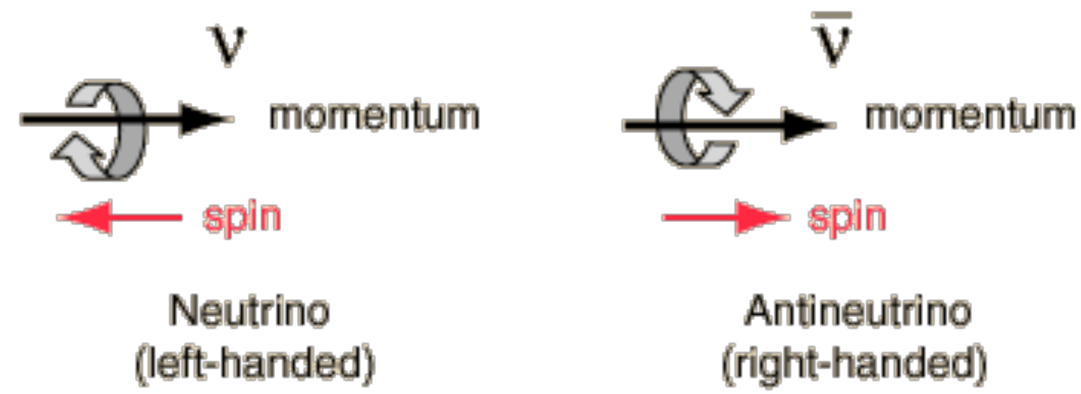


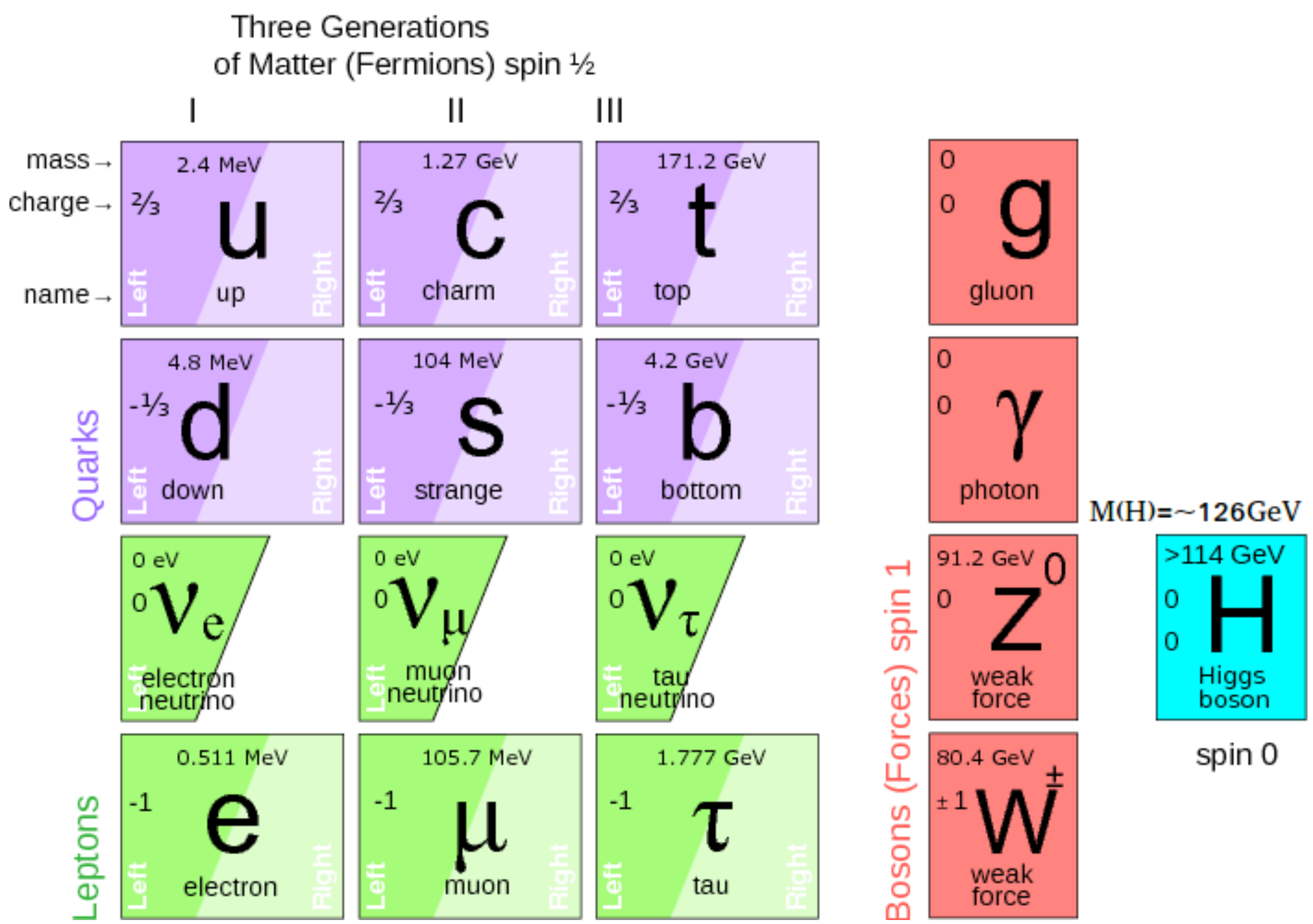
- **CPT Symmetry**: conserved in the SM transformations



Left-handed neutrinos

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

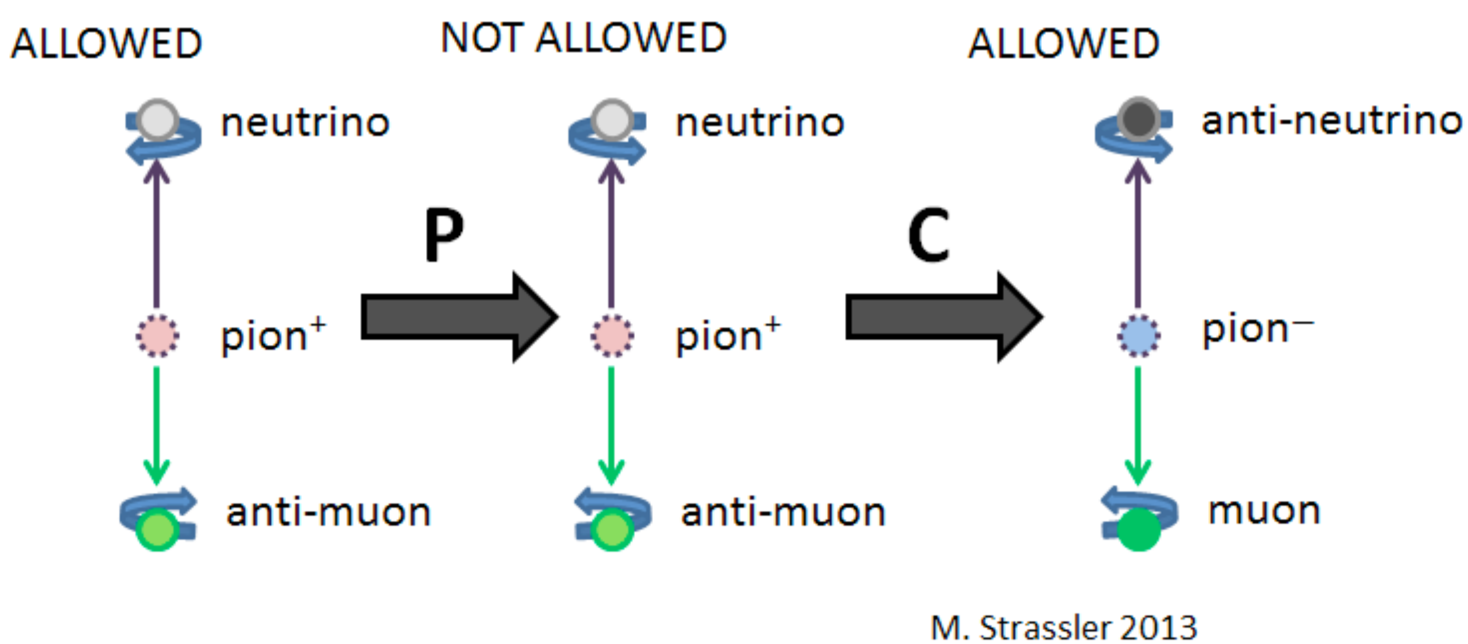


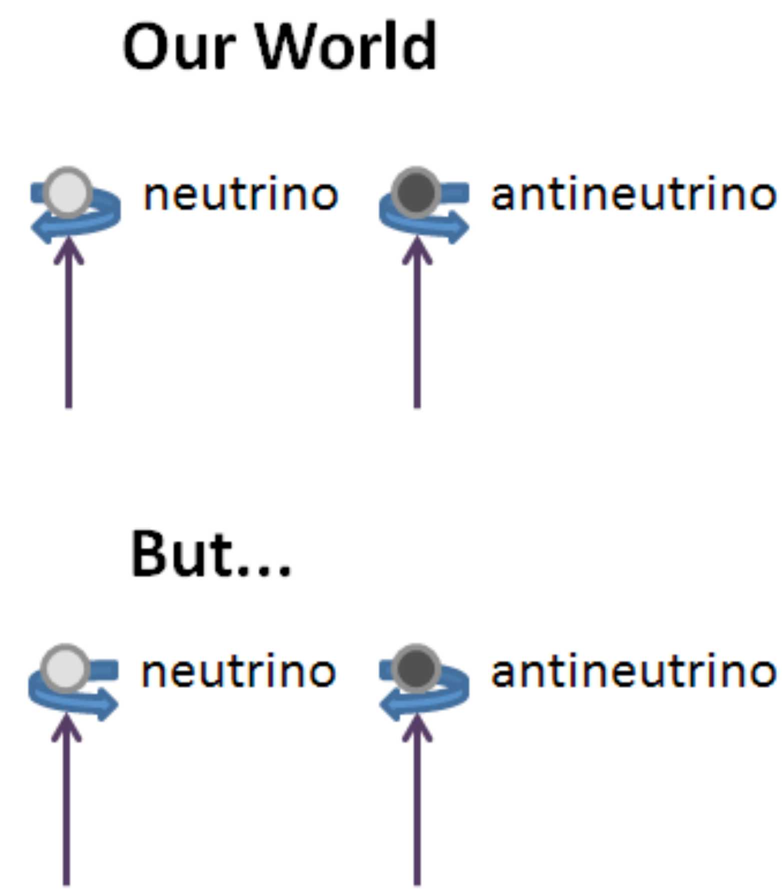


Neutrinos have negative helicity

Helicity: Projection of the spin in the direction of the linear momentum

CP symmetry in neutrinos



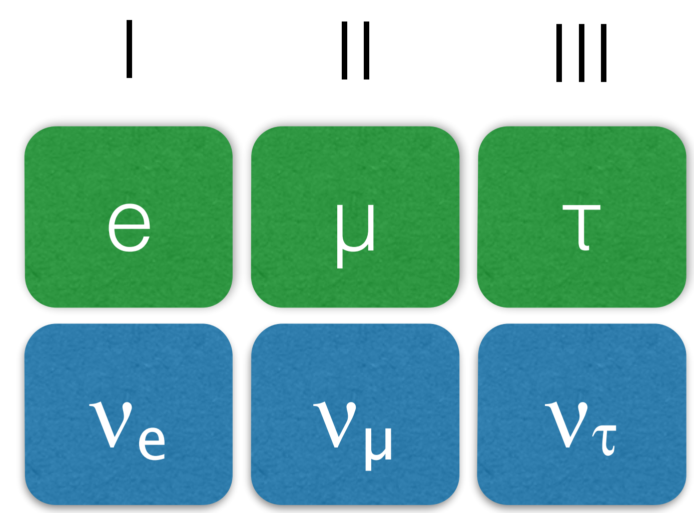


- In the weak interactions:
  - P symmetry is not conserved
  - C symmetry is not conserved
  - CP seems to be conserved

- ν_R and $\overline{\nu}_L$ may not exist at all
- May exist but with much larger mass
- Are unaffected by the weak nuclear force

Weak interaction

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



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I	II	III
e	μ	τ
ν_e	ν_μ	ν_τ

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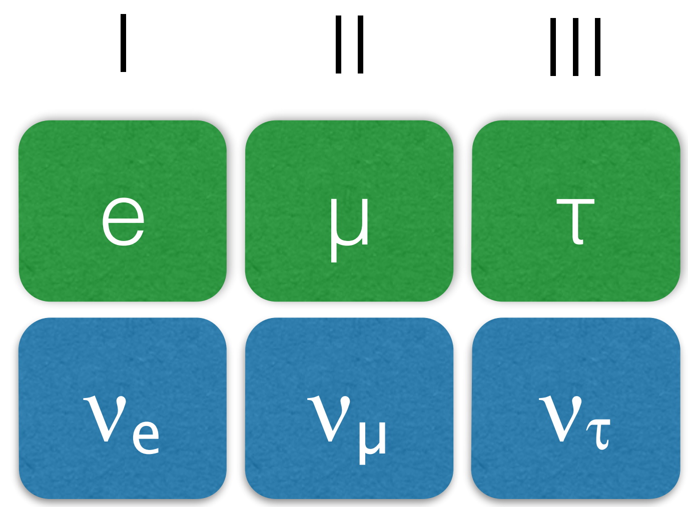

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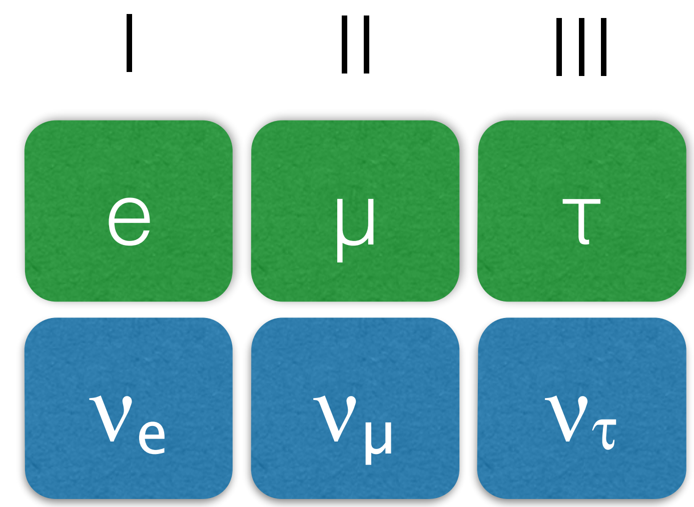

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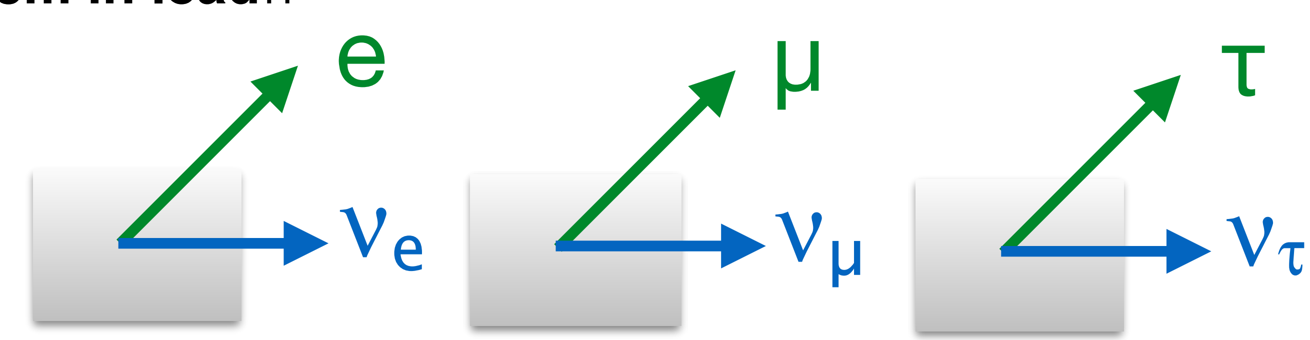

Neutrino appearance

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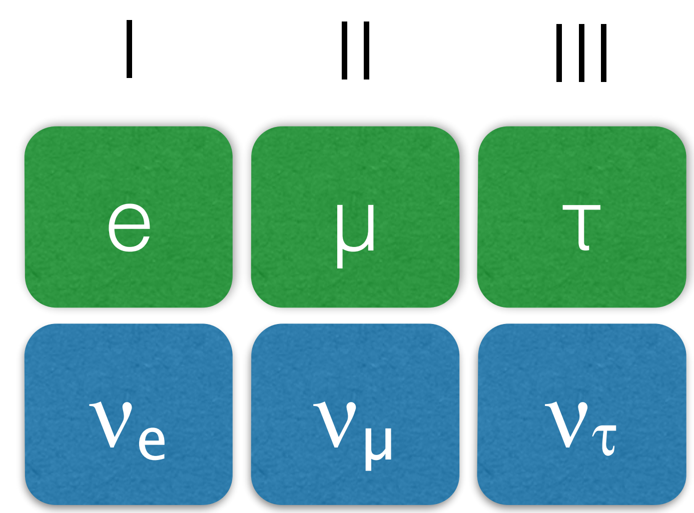

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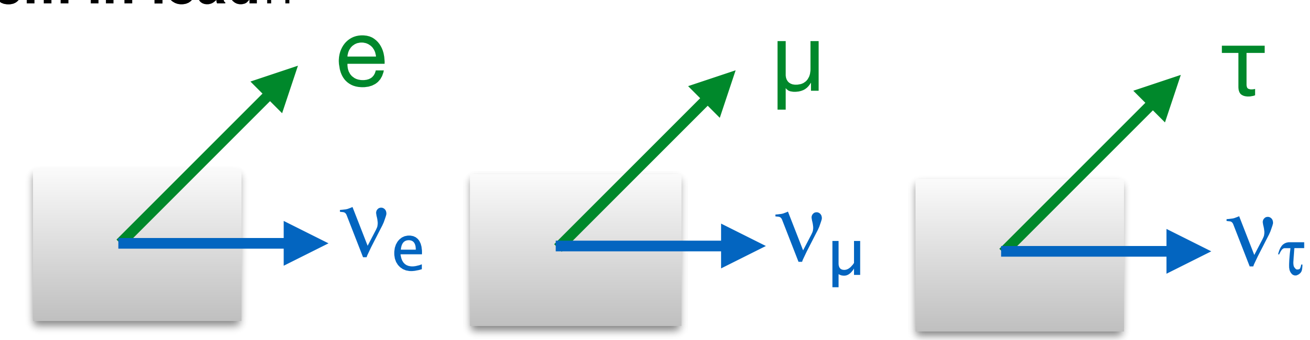

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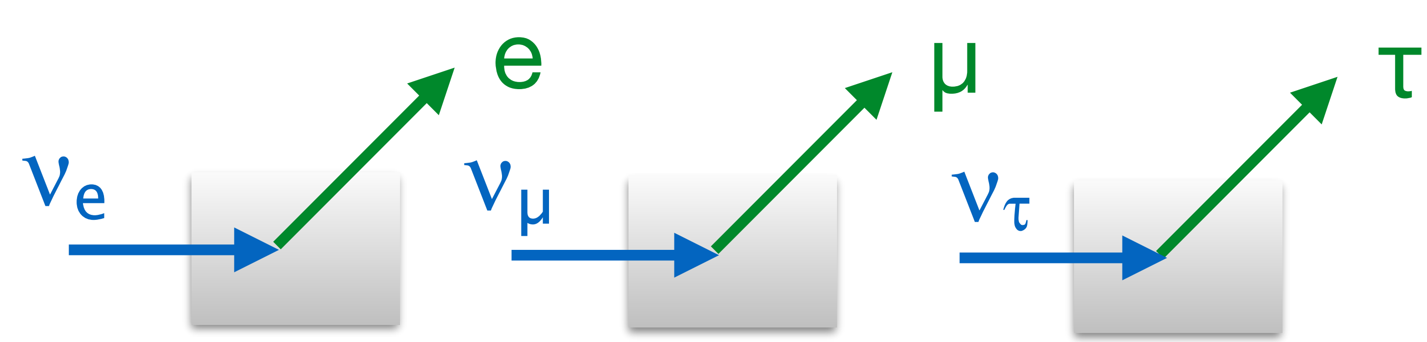
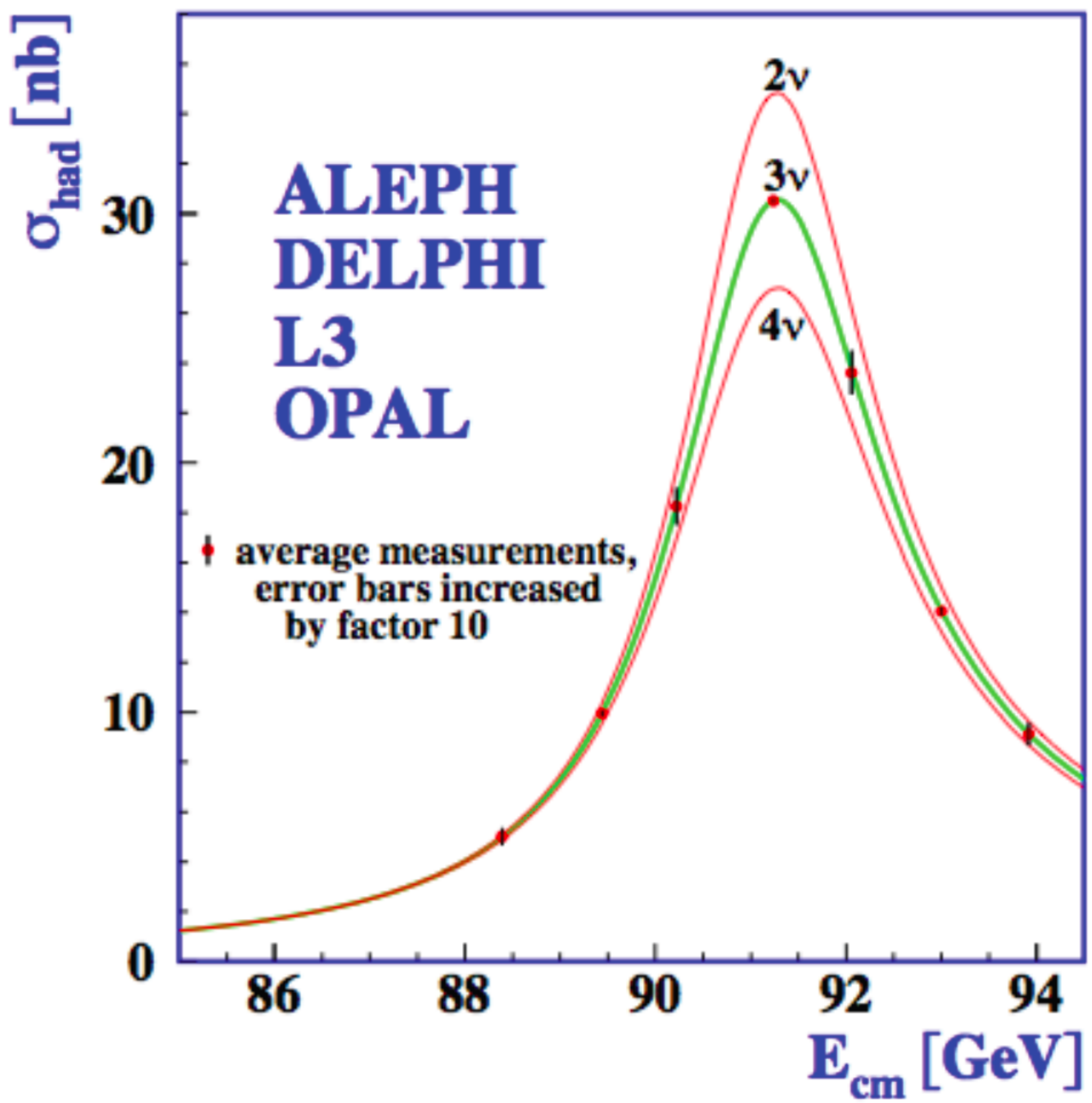


Neutrino disappearance

Number of neutrino types

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



$$\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{\text{had}} - 3\Gamma_l$$

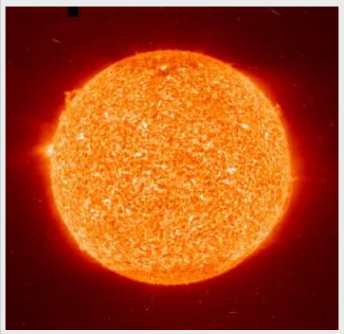
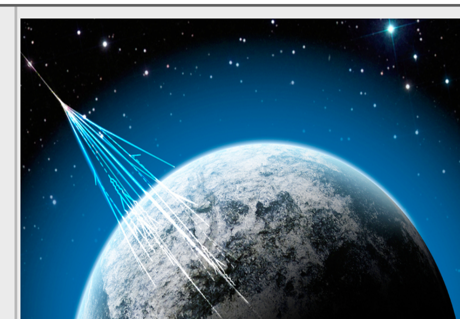
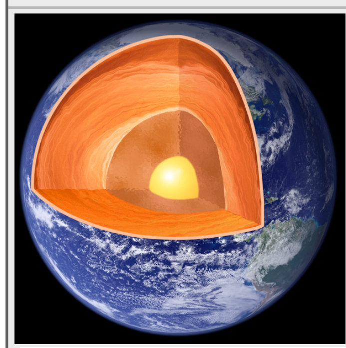
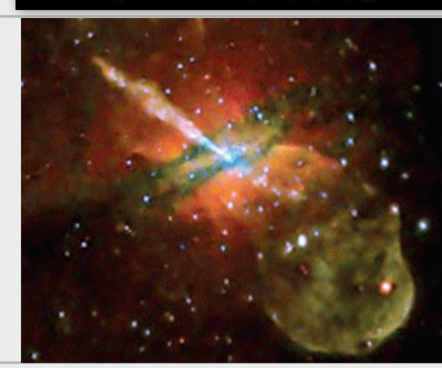
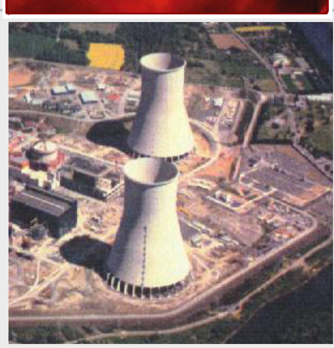
$$\Gamma_{\text{inv}} = N_\nu \cdot \Gamma_\nu$$

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

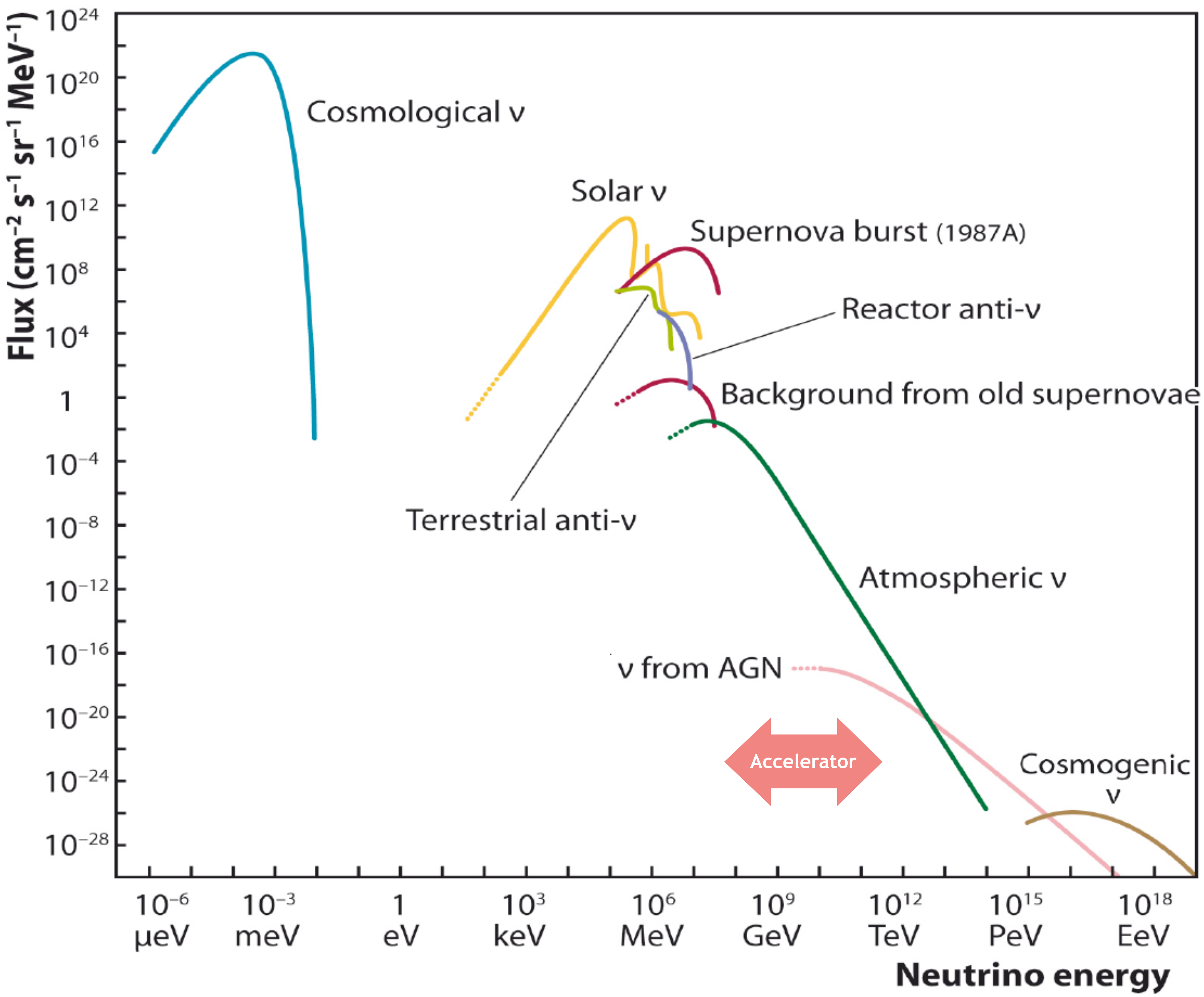
Number N = 2.984 ± 0.008
(Standard Model fits to LEP data)

Number N = 2.92 ± 0.05
(Direct measurement of invisible Z width)

Neutrino sources

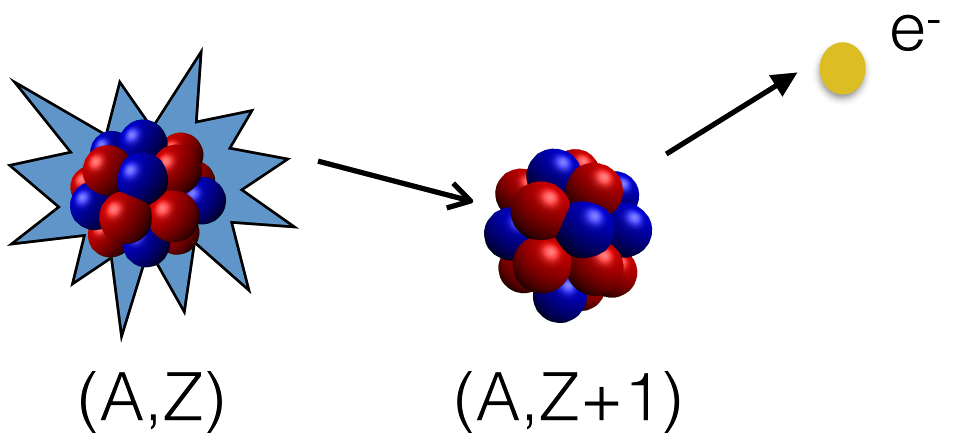
NATURAL		E ~ MeV The Sun L ~ 10^8 km		E ~ GeV-TeV Atmosphere L ~ 10 - 10^4 km
NATURAL		E ~ MeV Earth L ~ 10 - 10^3 km		E ~ MeV Supernovae L ~ kpc- Mpc
NATURAL		E $\lesssim$ meV Big Bang L ~ Mpc		E ~ TeV-PeV Cosmic accelerators L ~ kpc- Mpc
ARTIFICIAL		E ~ MeV Nuclear reactors L ~ 1-100 km		E ~ GeV Particle accelerators L ~ 100-1000 km

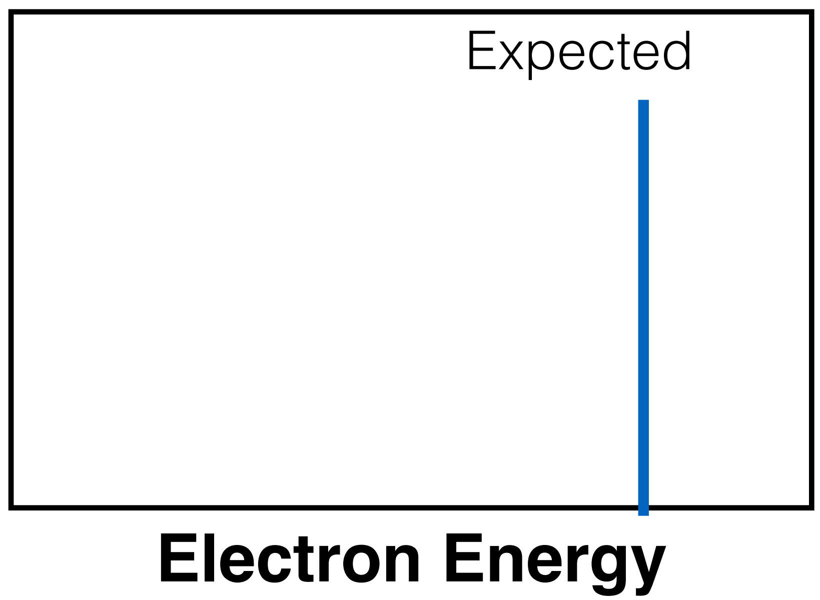
Neutrino energies



How were they discovered?

- Pauli proposed the existence of neutrinos in 1930 as a *desperate remedy* to solve the beta radioactivity “problem”
- In a **two-body emission**, the **electron energy** has a **fixed value** (energy conservation)





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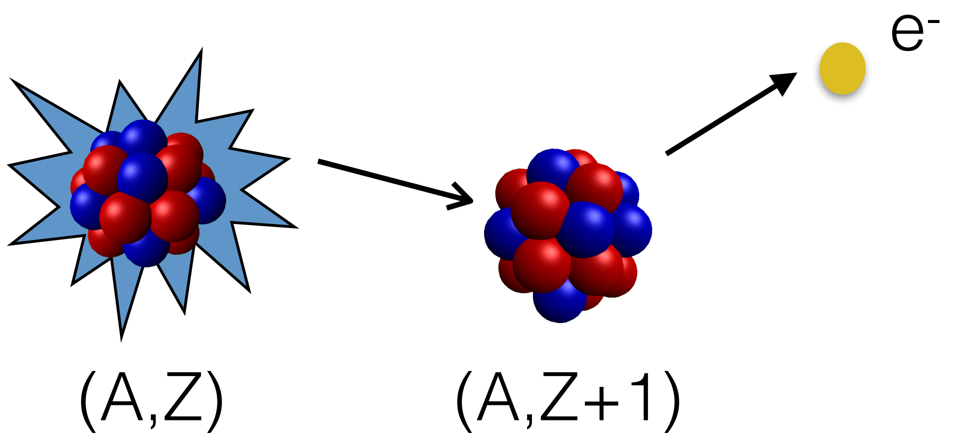

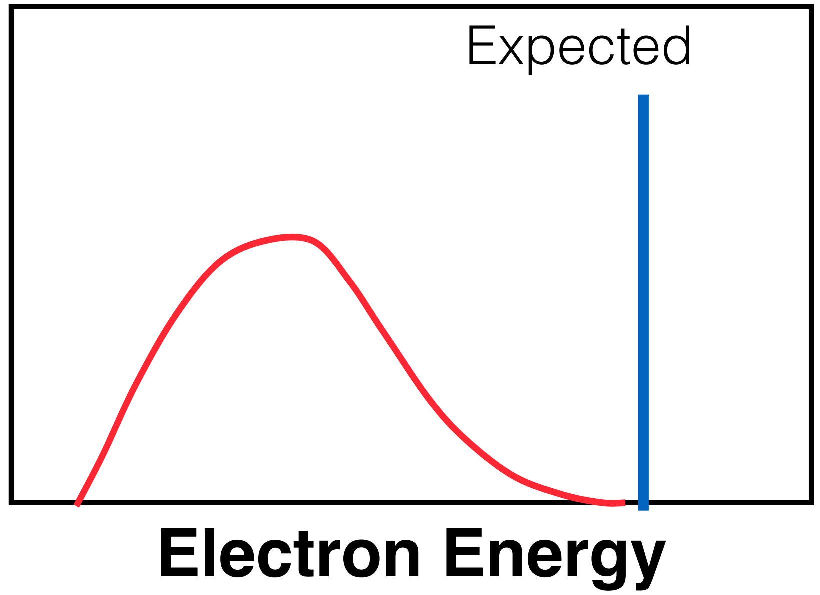

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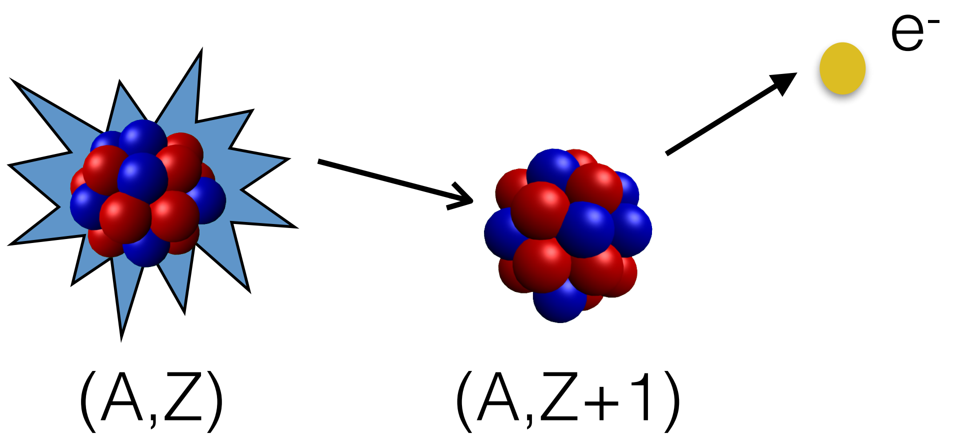

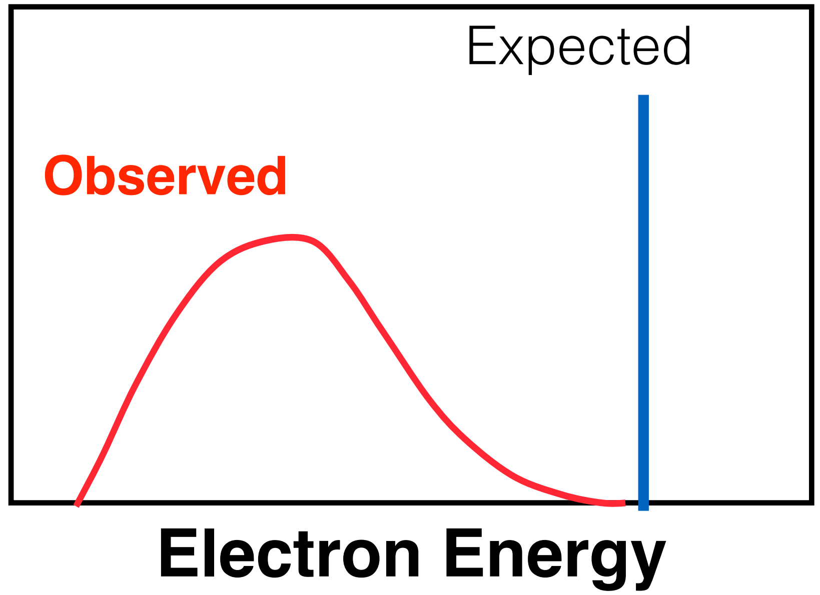

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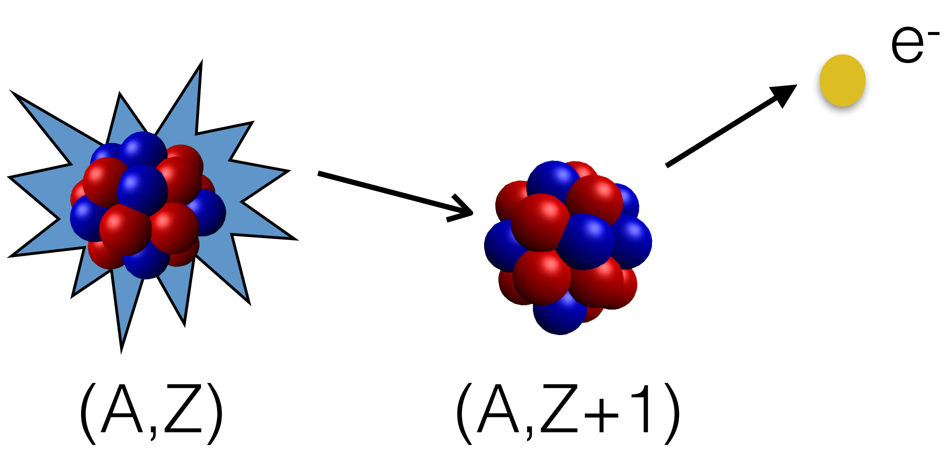

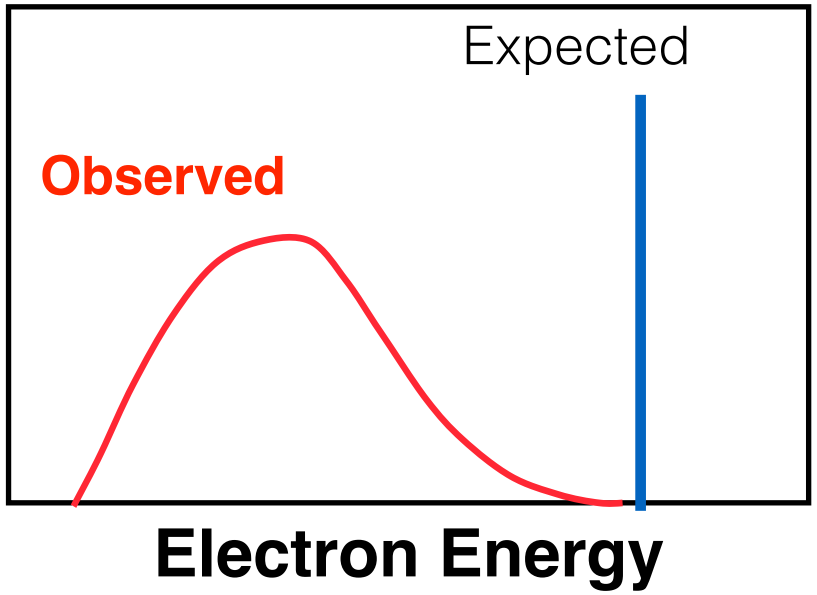

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- **Pauli**: "There is a neutral particle able to cross all detectors without leaving any trace and carrying all the missing energy"
- In 1934 **Fermi** builds a new theory to explain the beta decay and names the new particle "neutrino"

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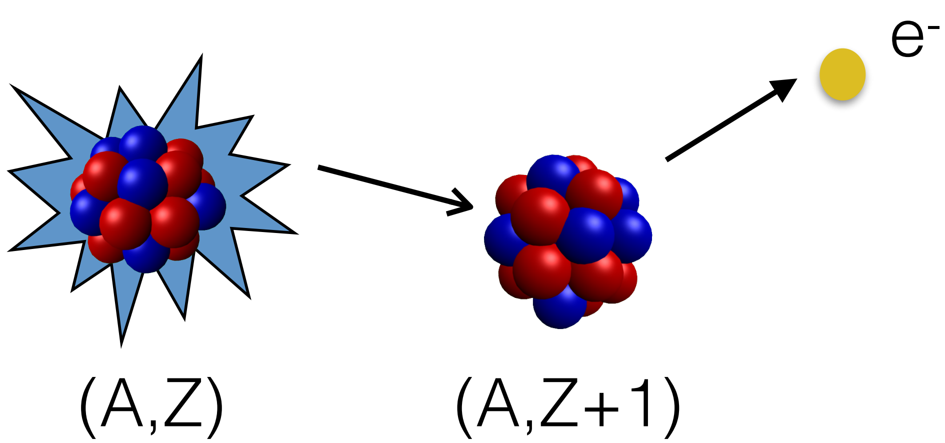

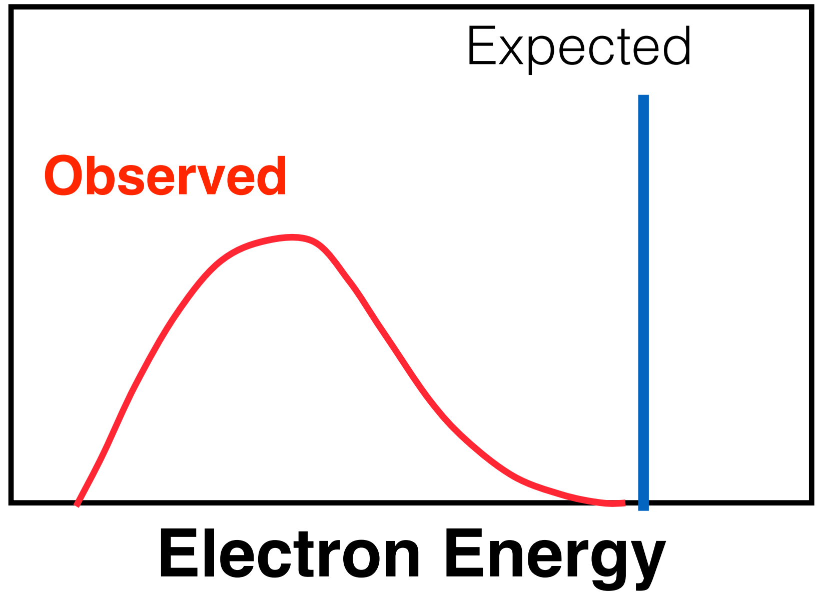

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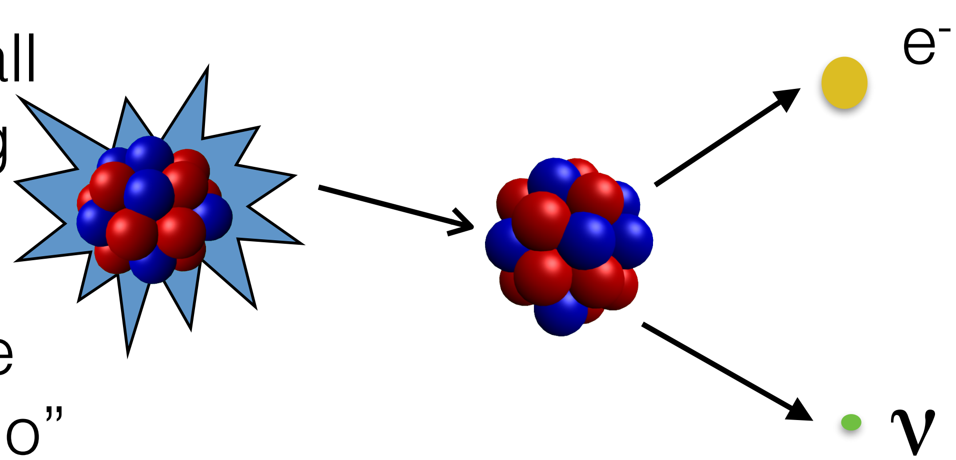

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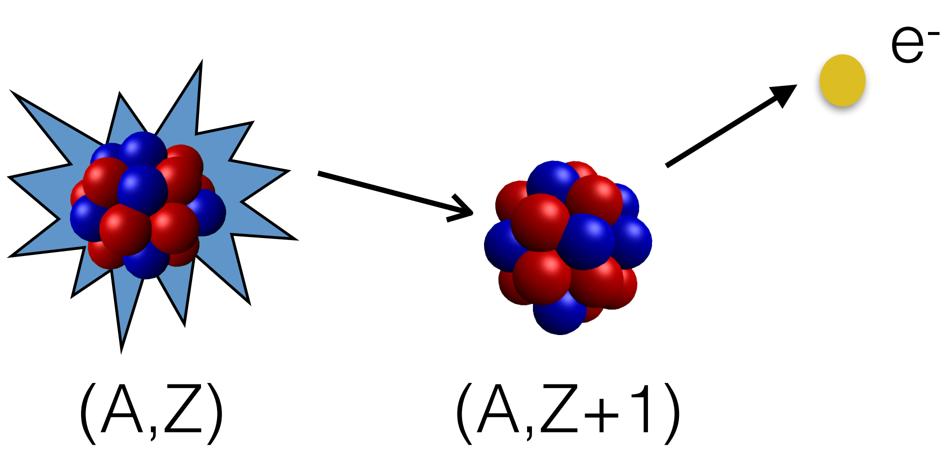

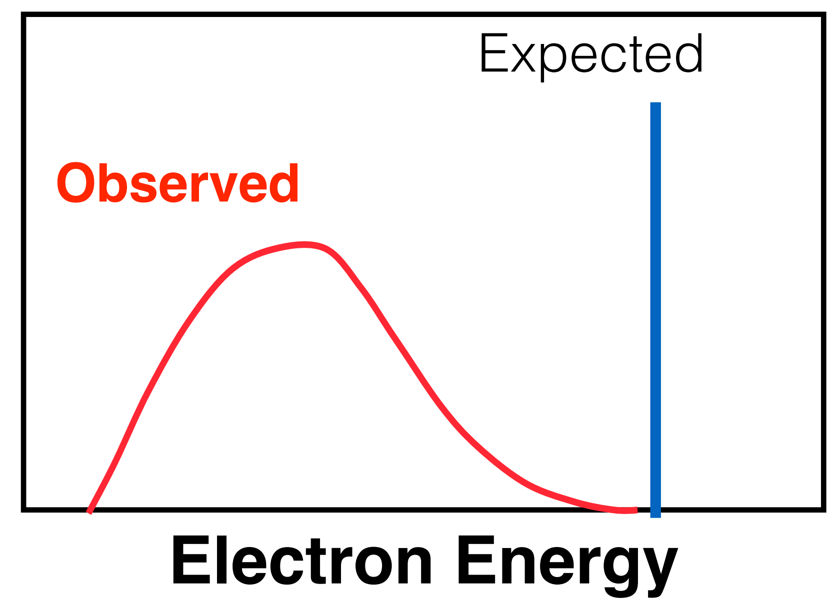

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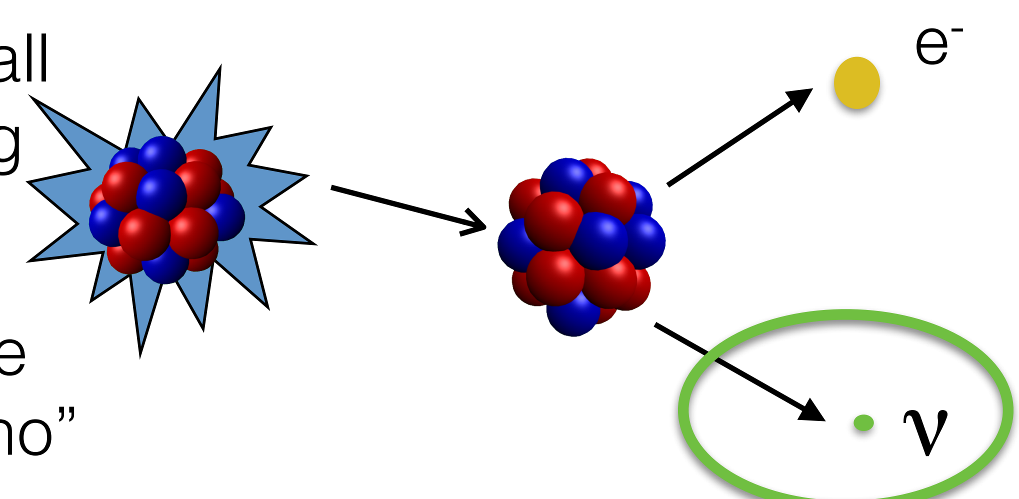


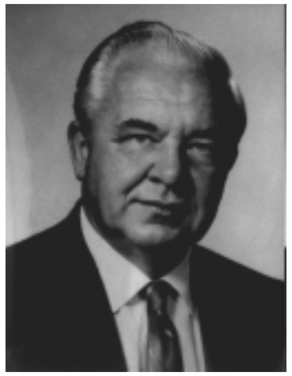
The neutrino discovery (1956)

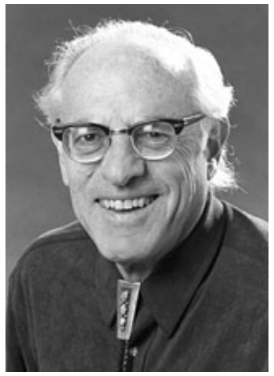
Savannah River reactor (US)

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

Neutrino production in the nuclear reactor cores

Cowan ***Reines***





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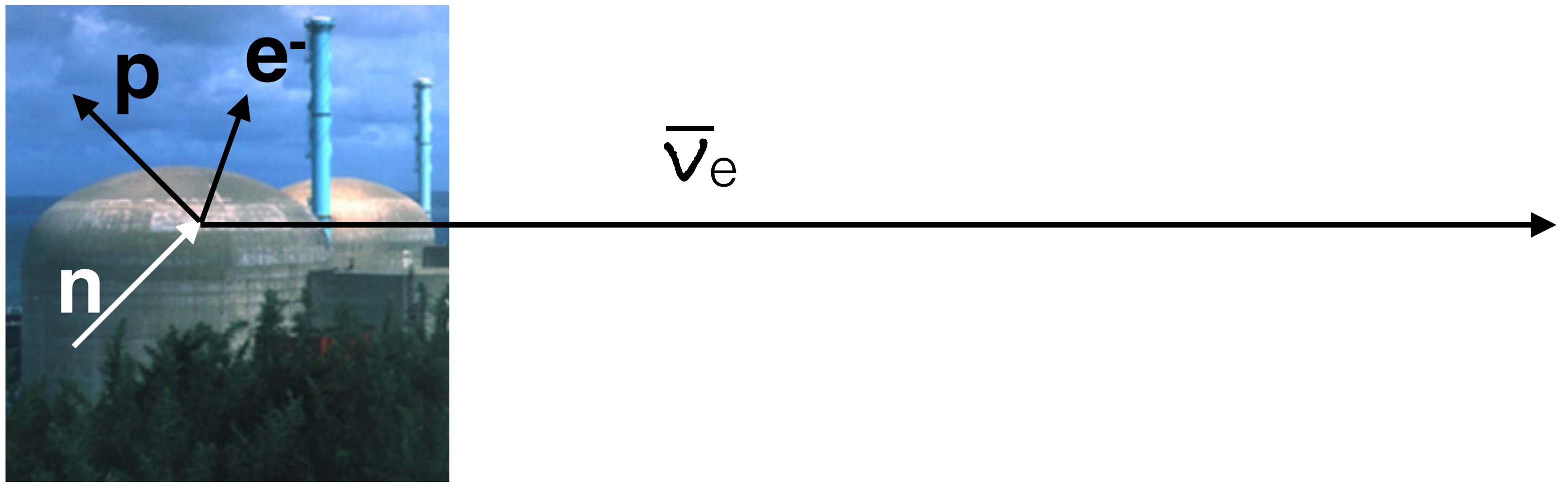

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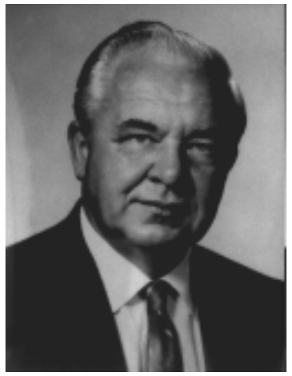

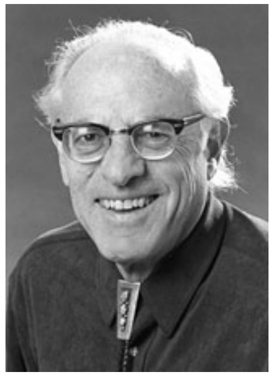

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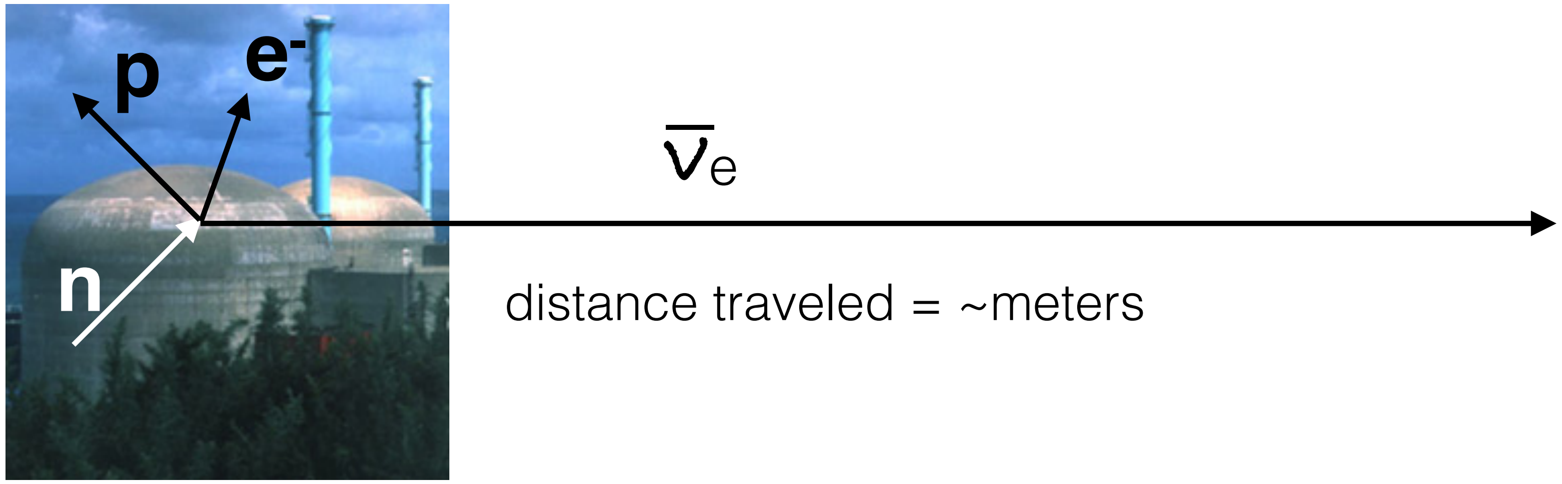

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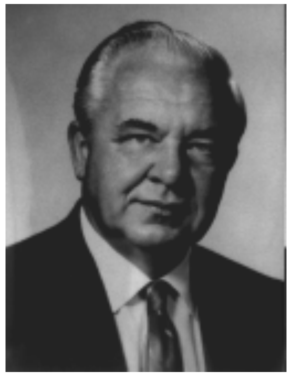

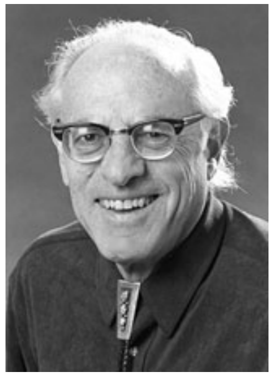

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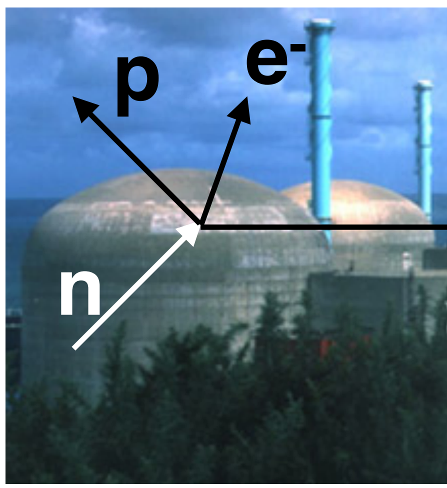
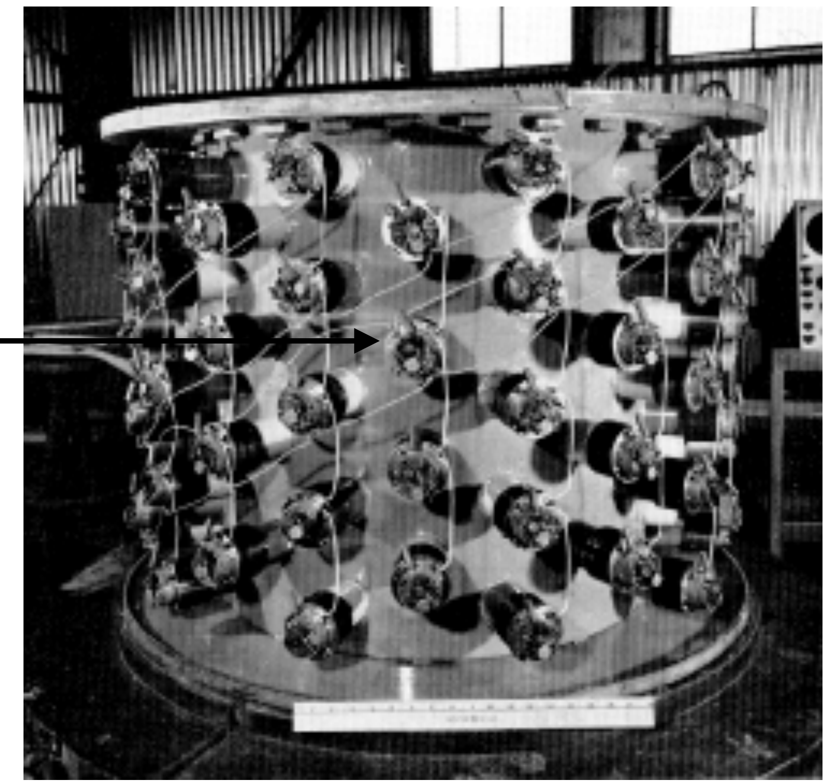


$\bar{\nu}_e$

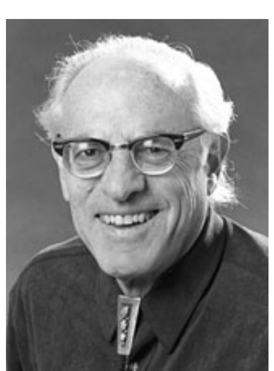
distance traveled = ~meters



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

Neutrino production in the nuclear reactor cores

Cowan ***Reines***



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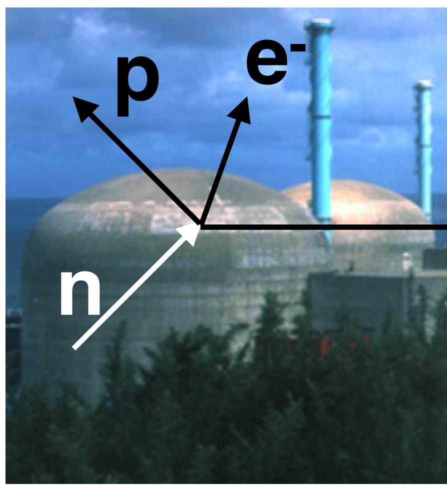

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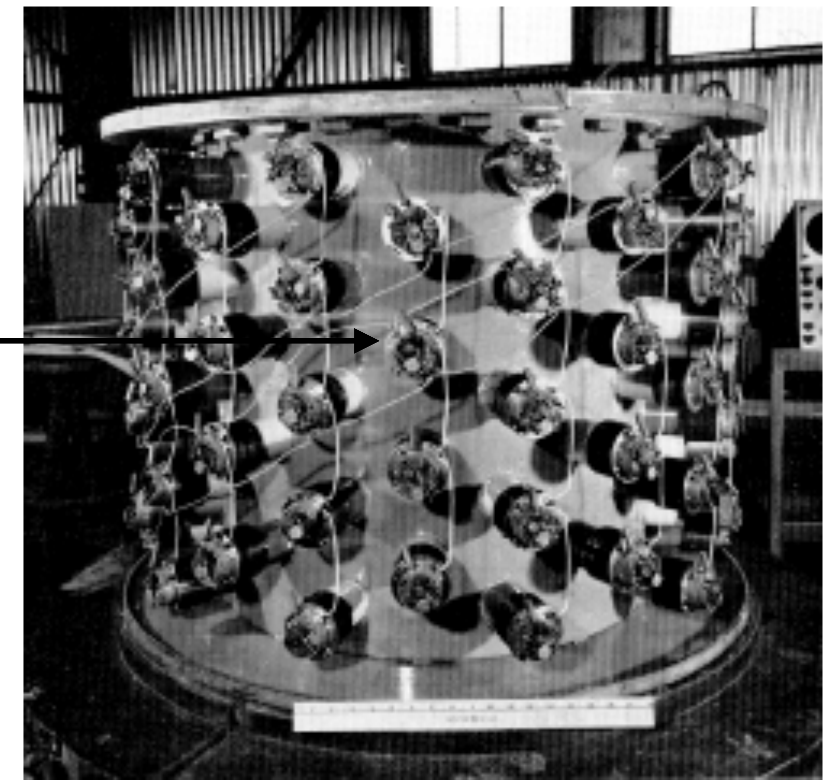

Neutrino detection in 1 m^3 liquid scintillator (~3 ν/h)

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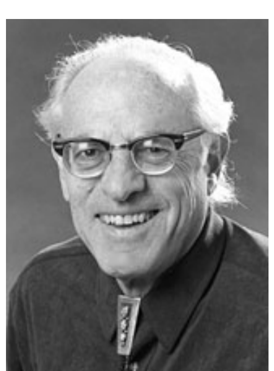

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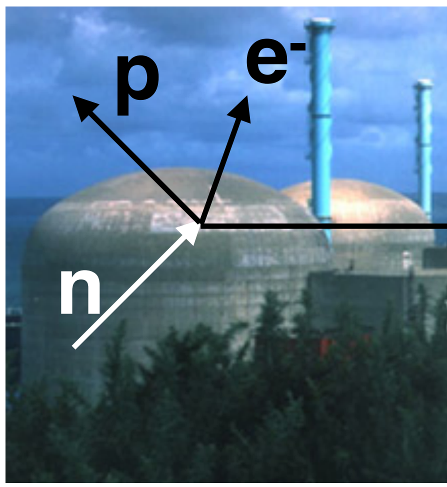

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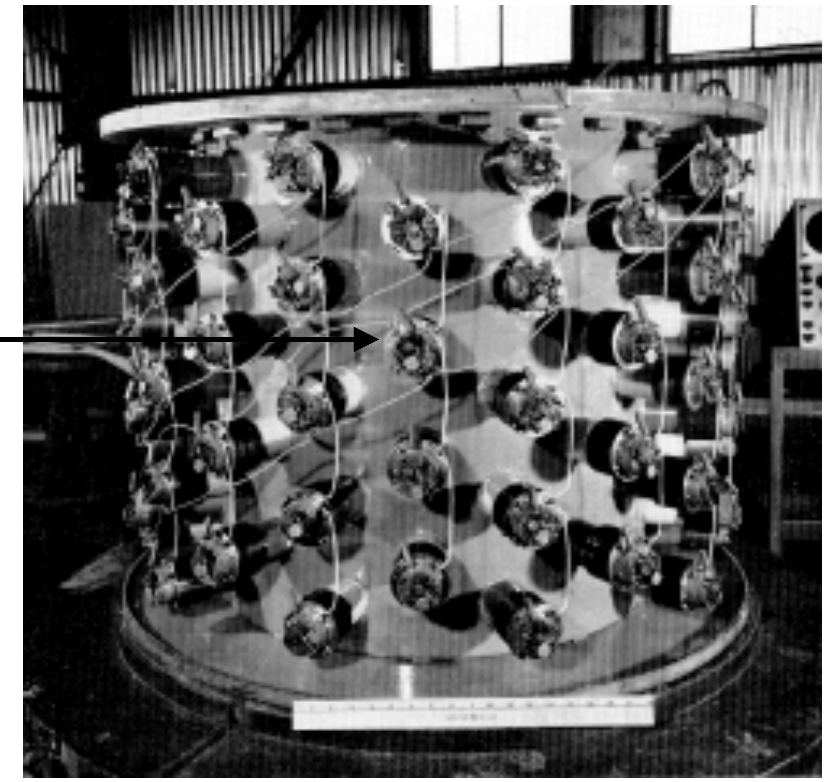

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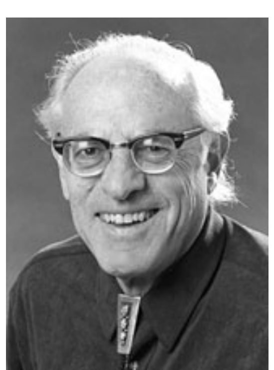

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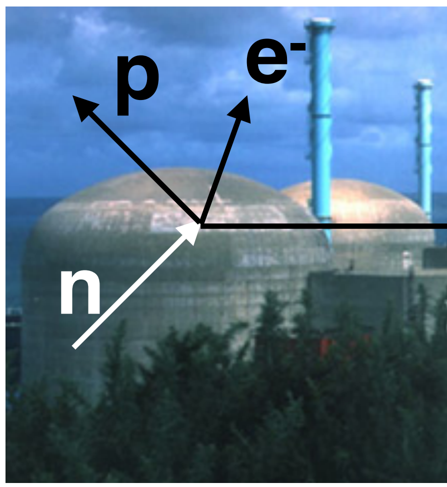

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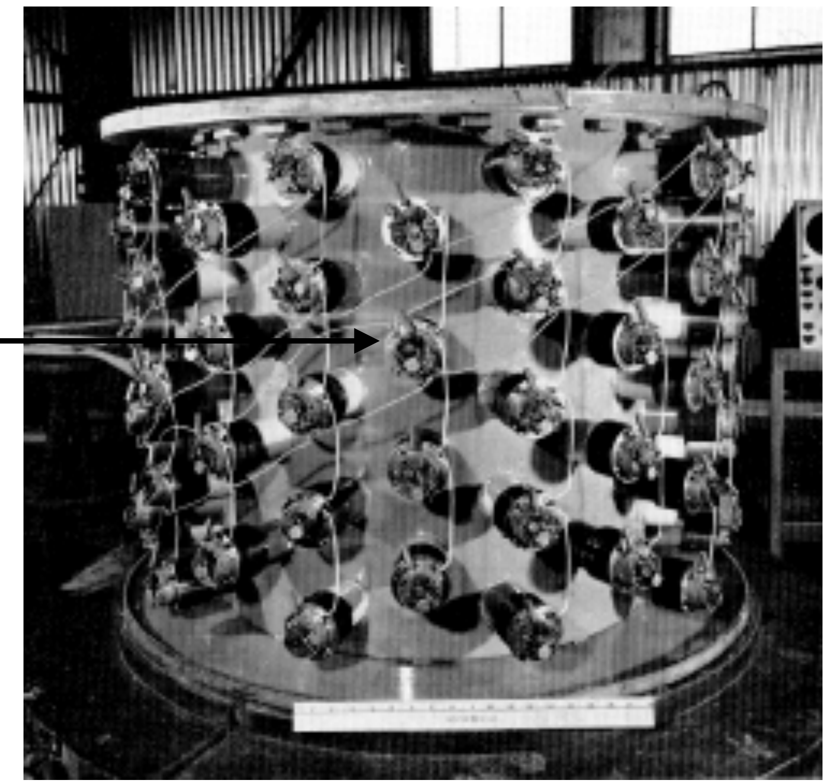

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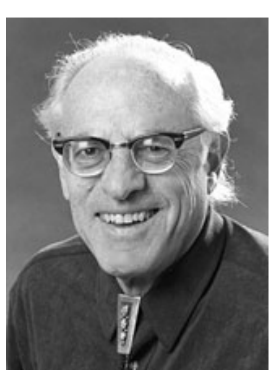

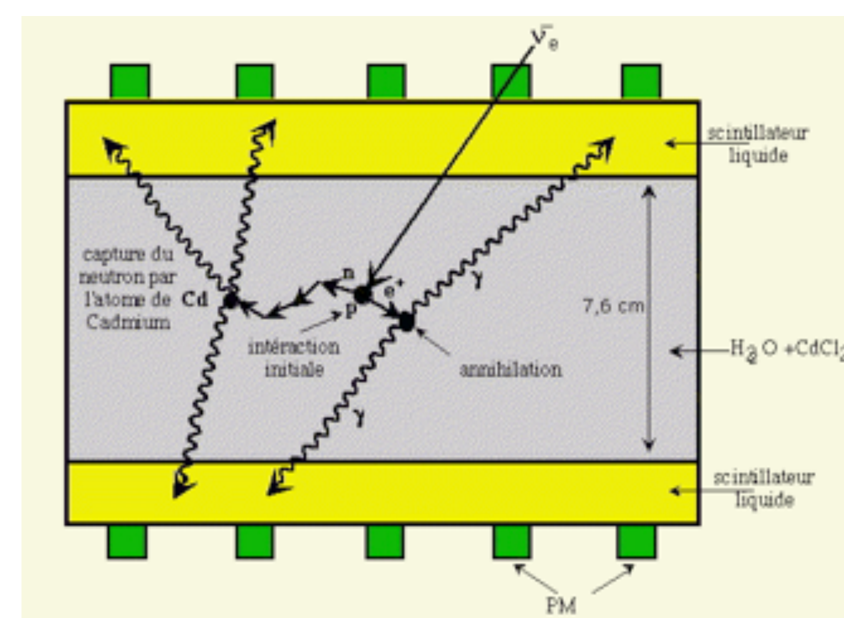

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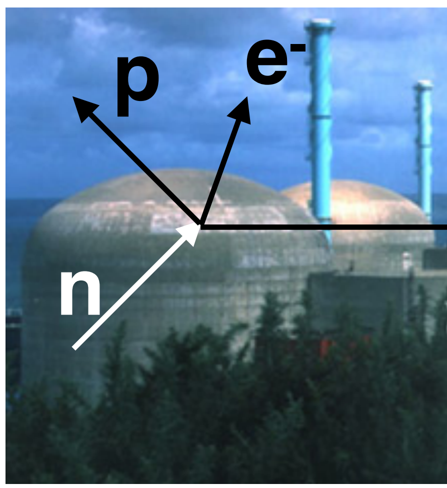

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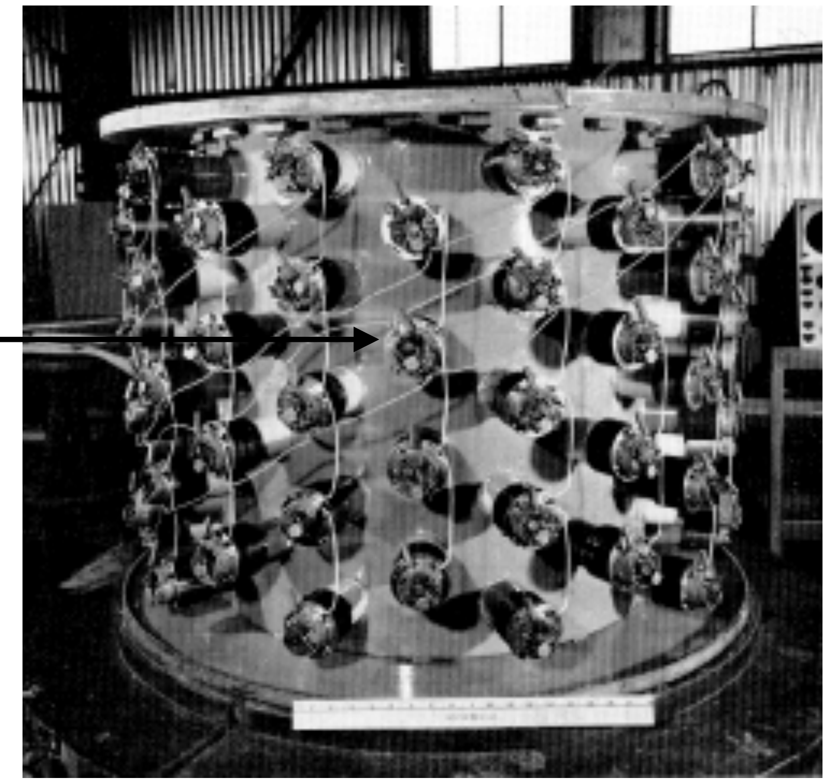

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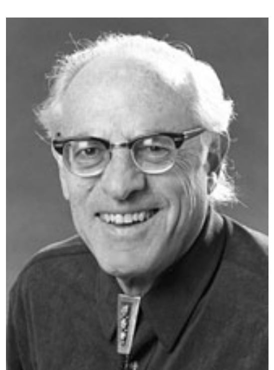

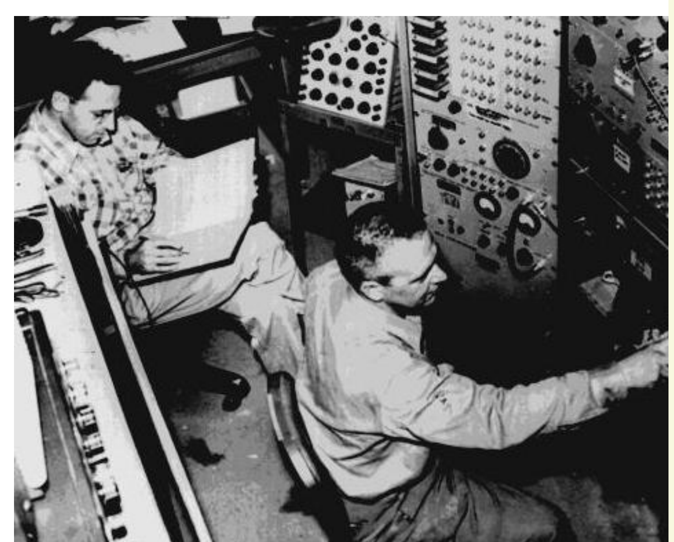

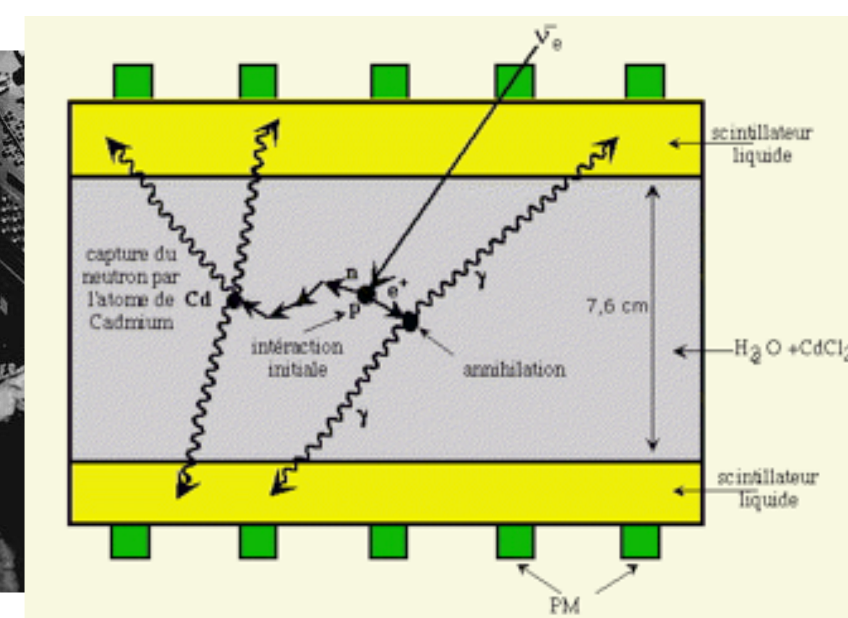

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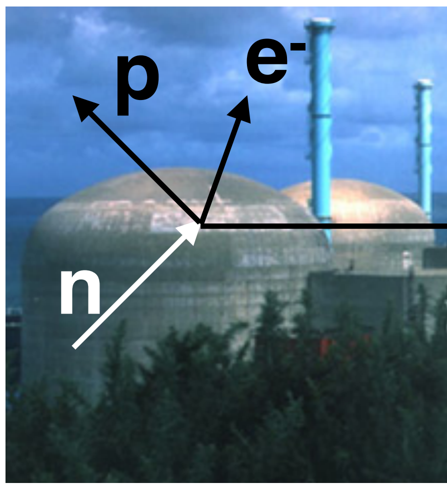

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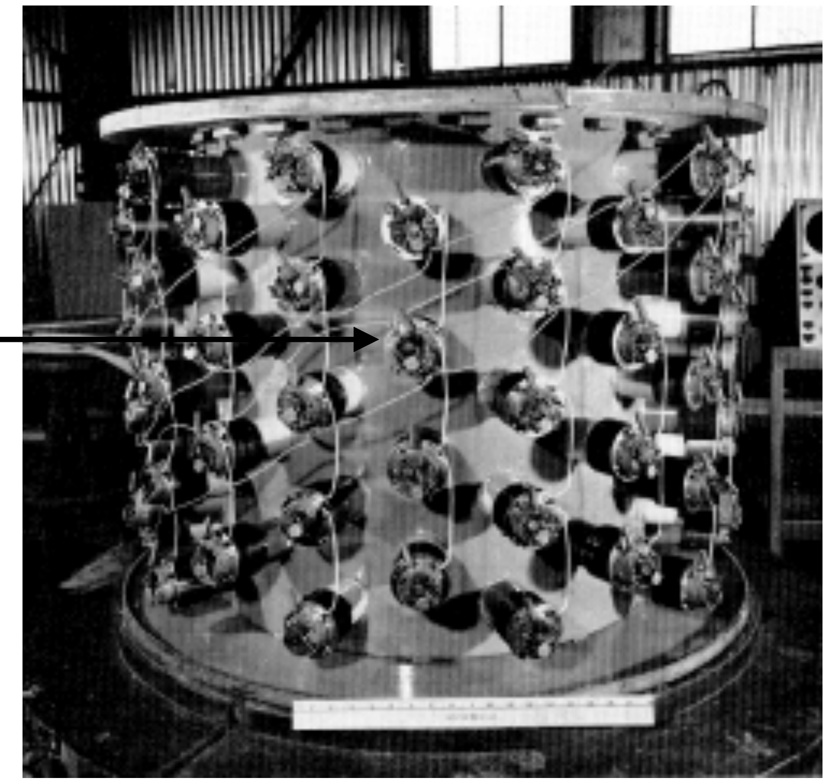

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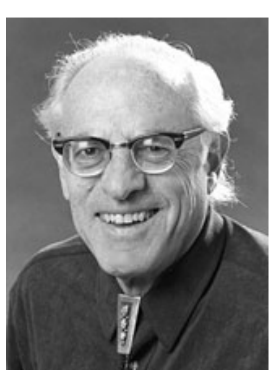
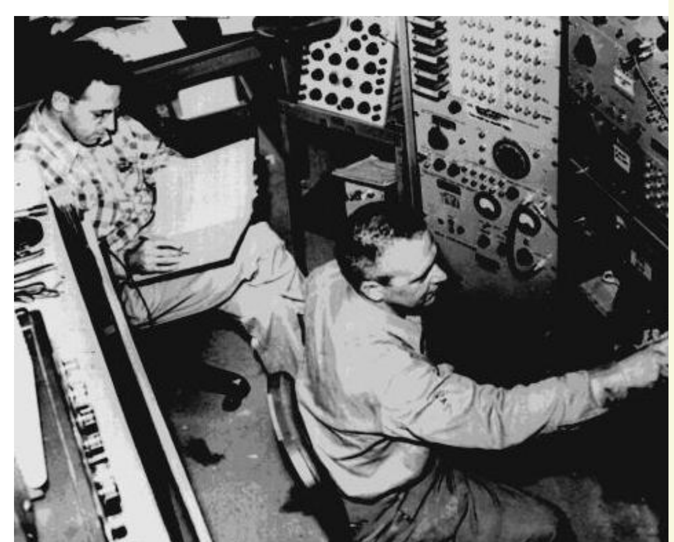
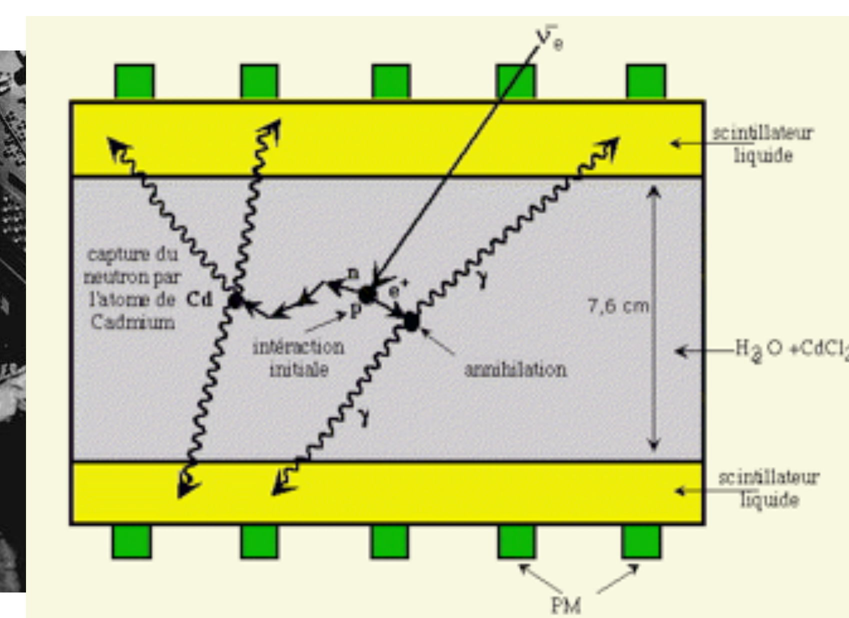


Nobel Prize in Physics in 1995





Next discoveries

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  - Discovery of a *second type of neutrino* (muon)

Lederman

Schwartz

Steinberger

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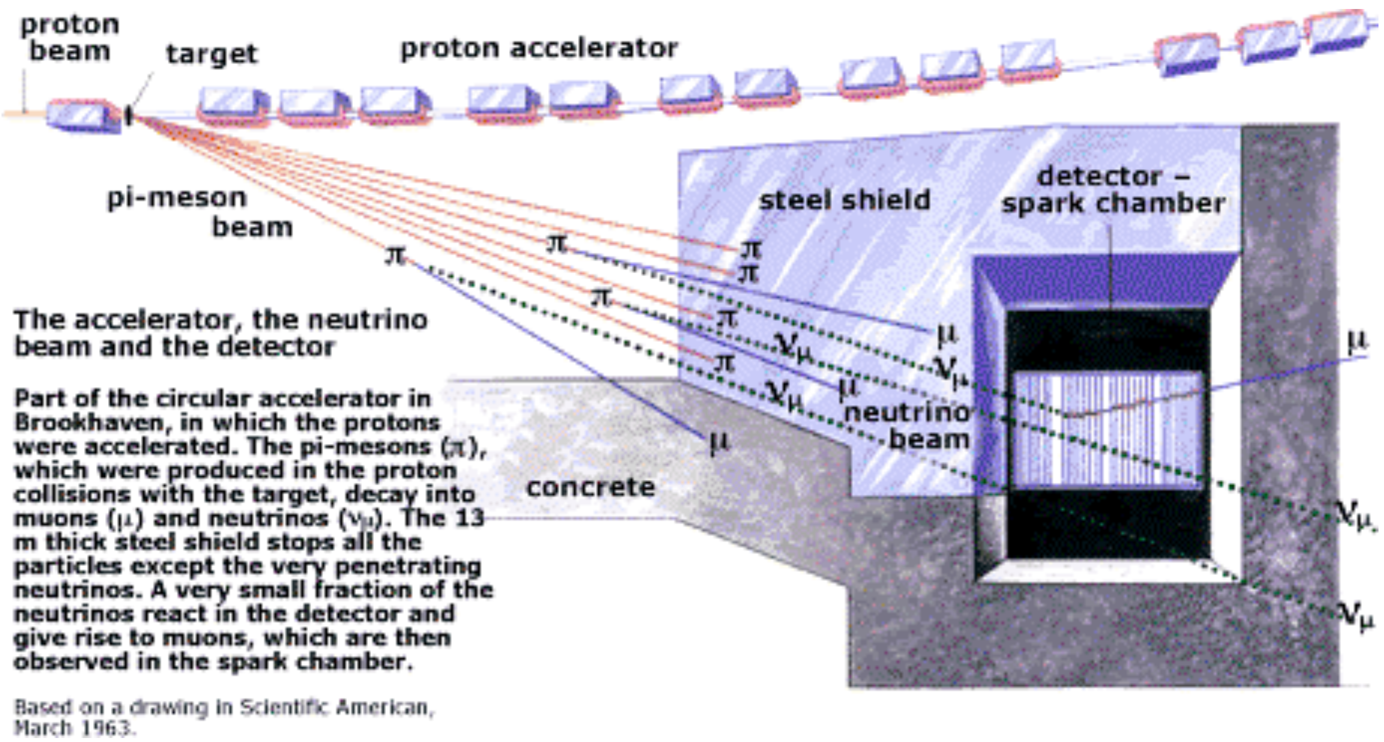

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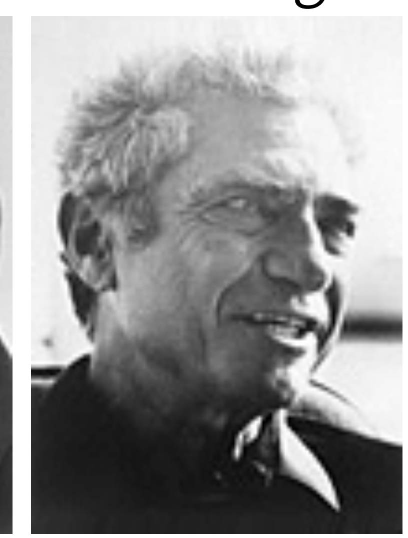

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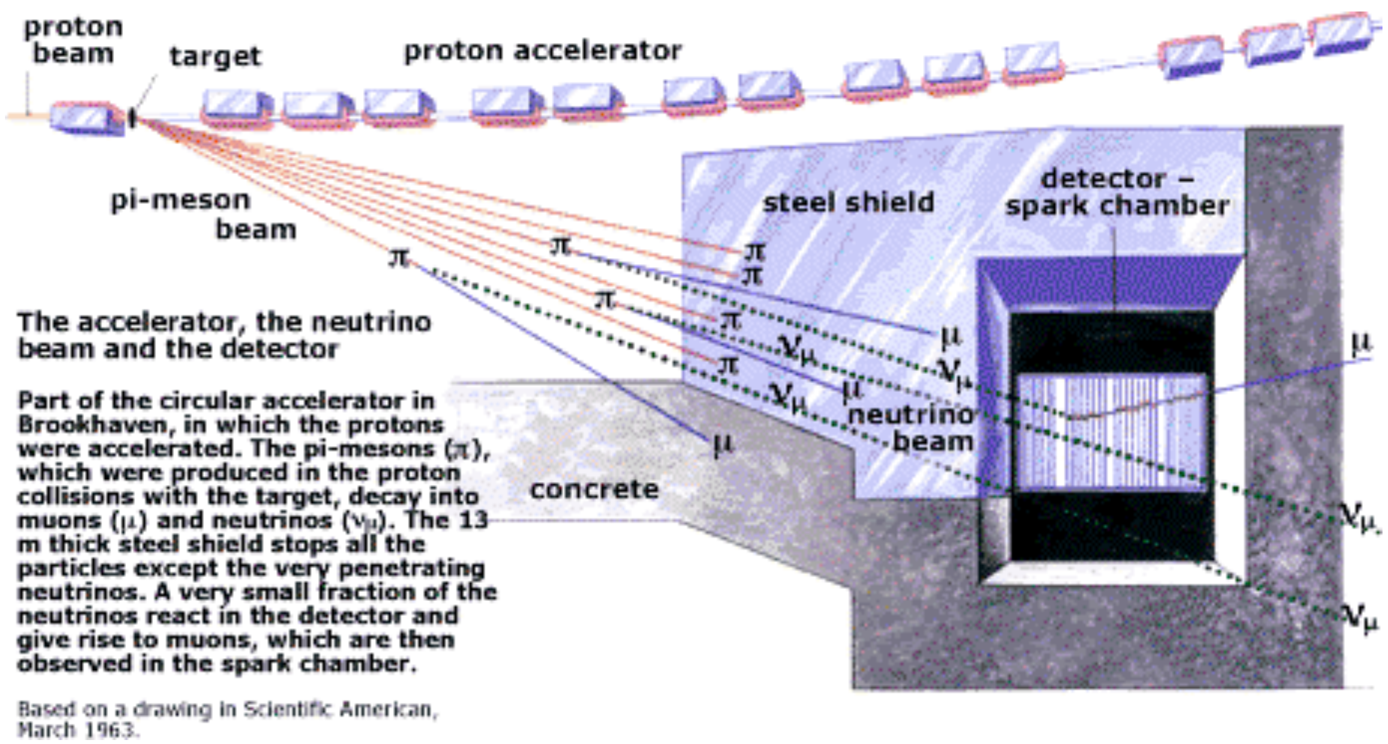

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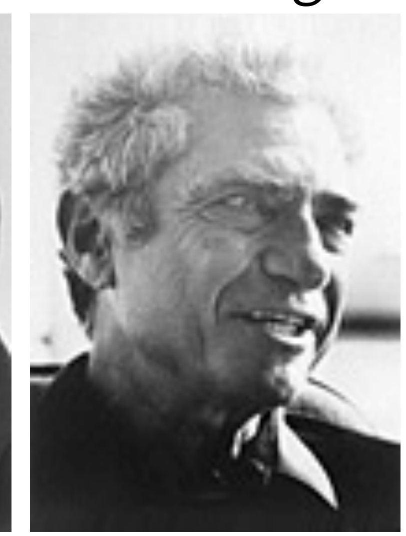

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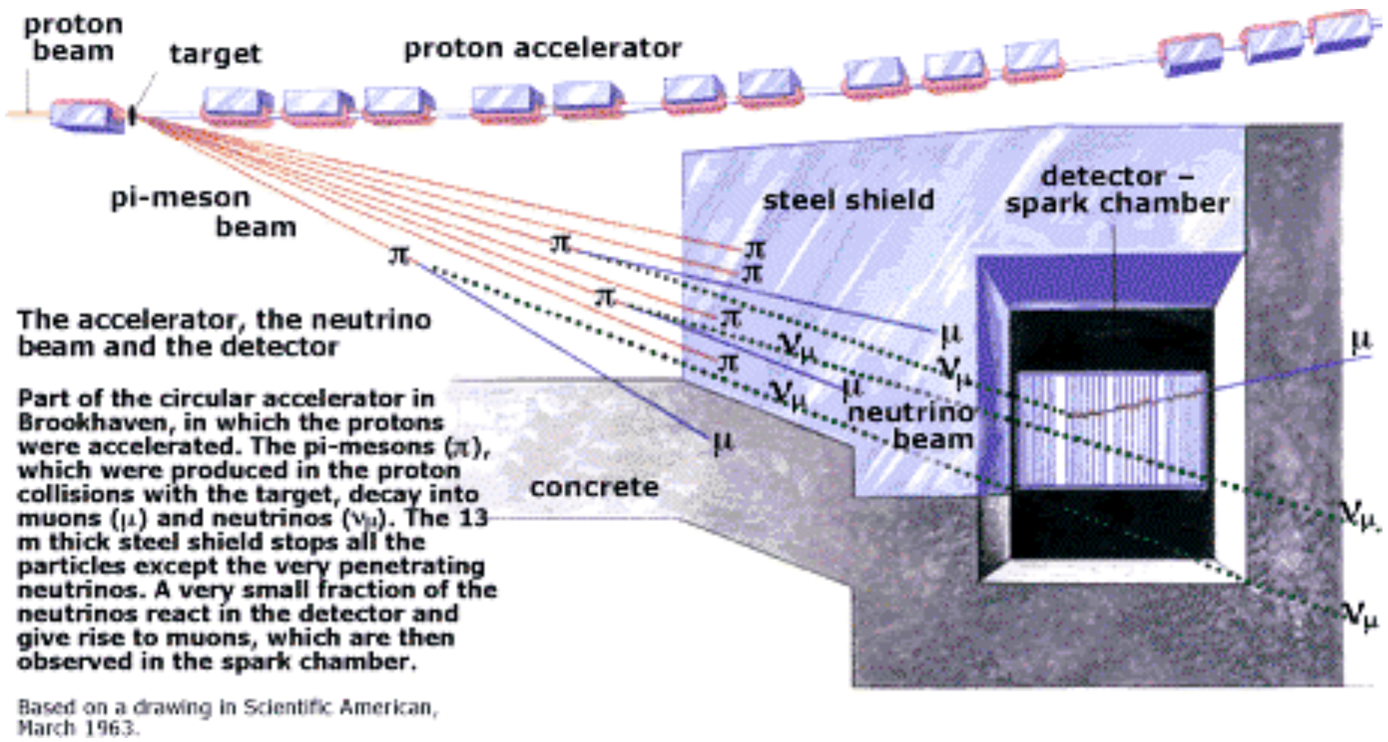

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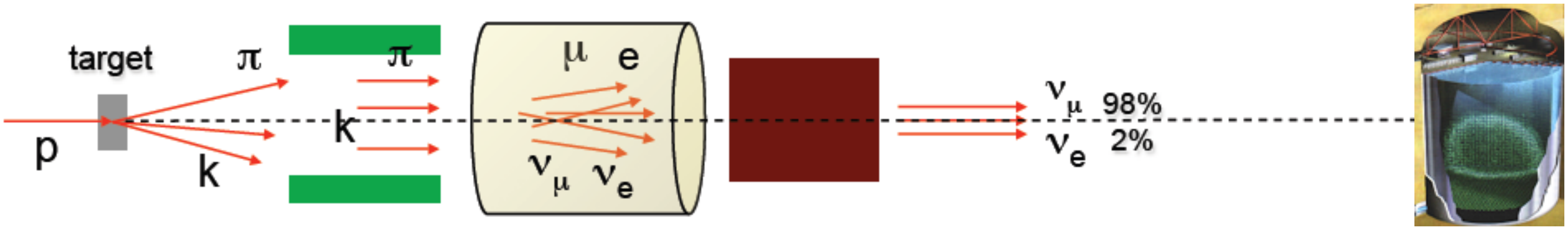
Nobel Prize in Physics in 1988

- Much later, in **2000**, the *third type of neutrino* $\boldsymbol{\nu_\tau}$ (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.

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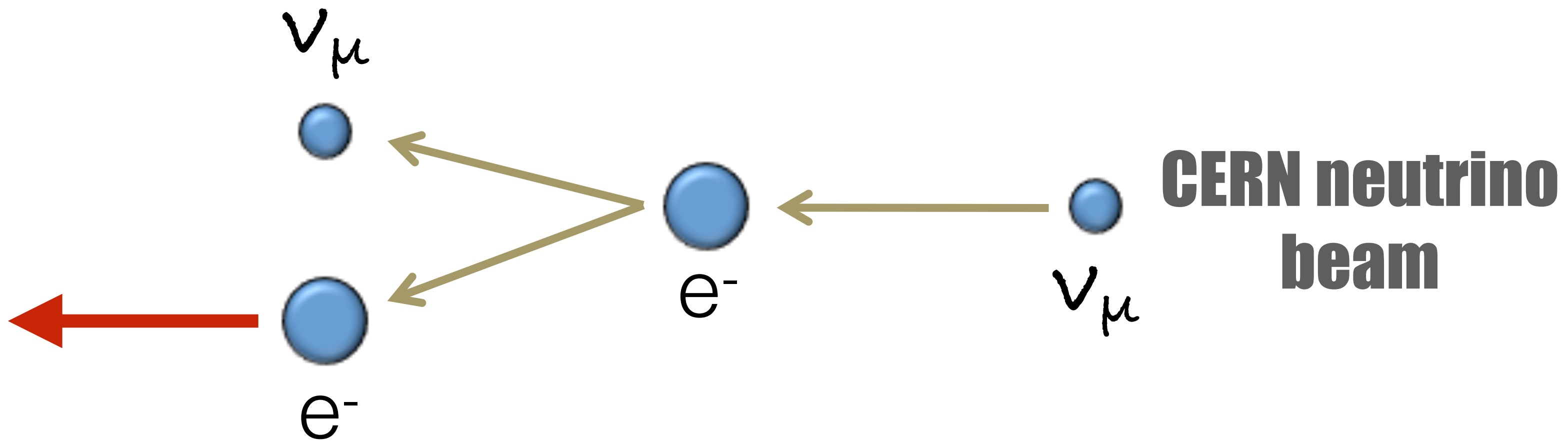

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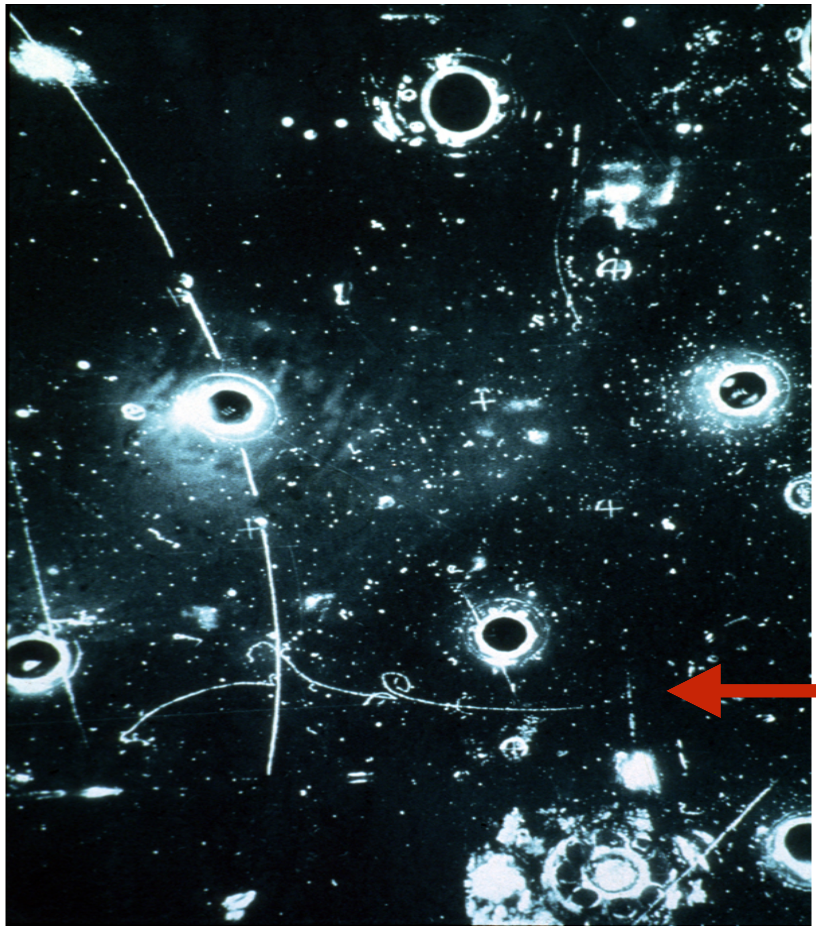

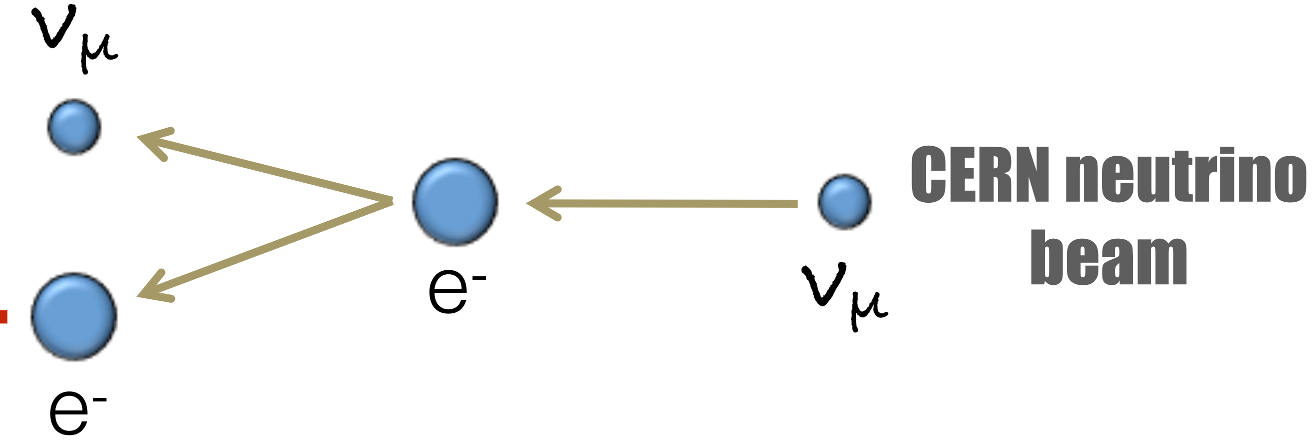

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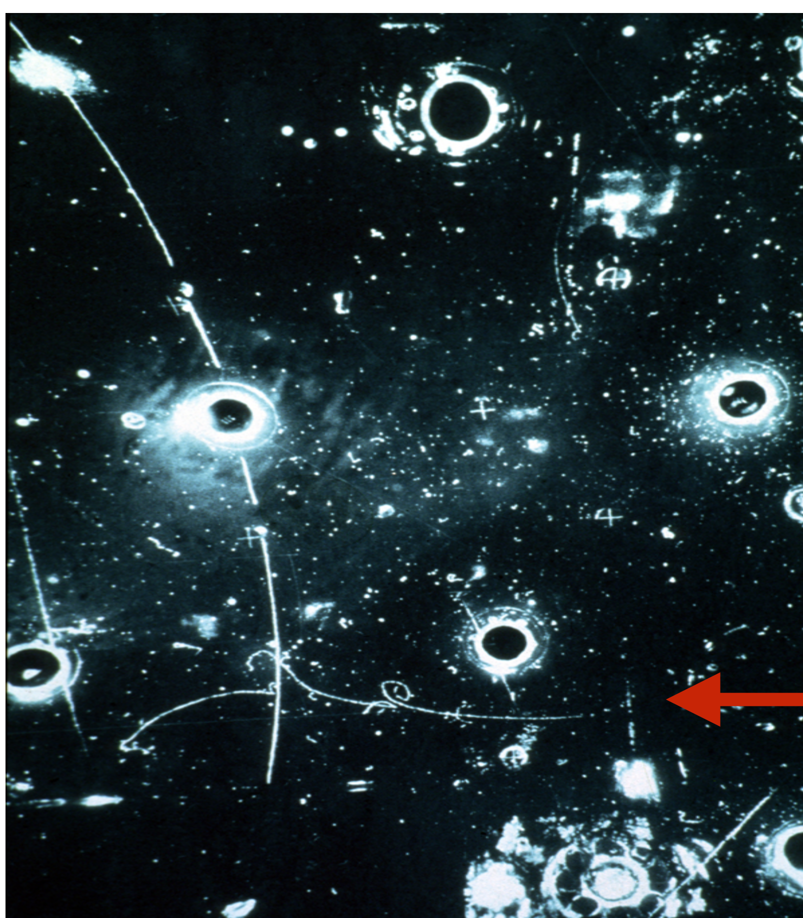
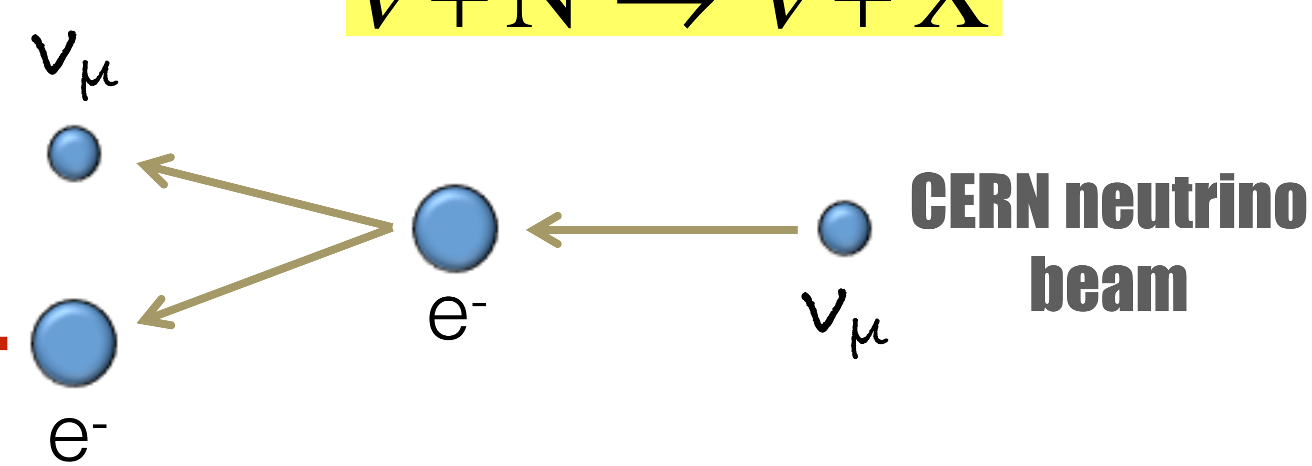
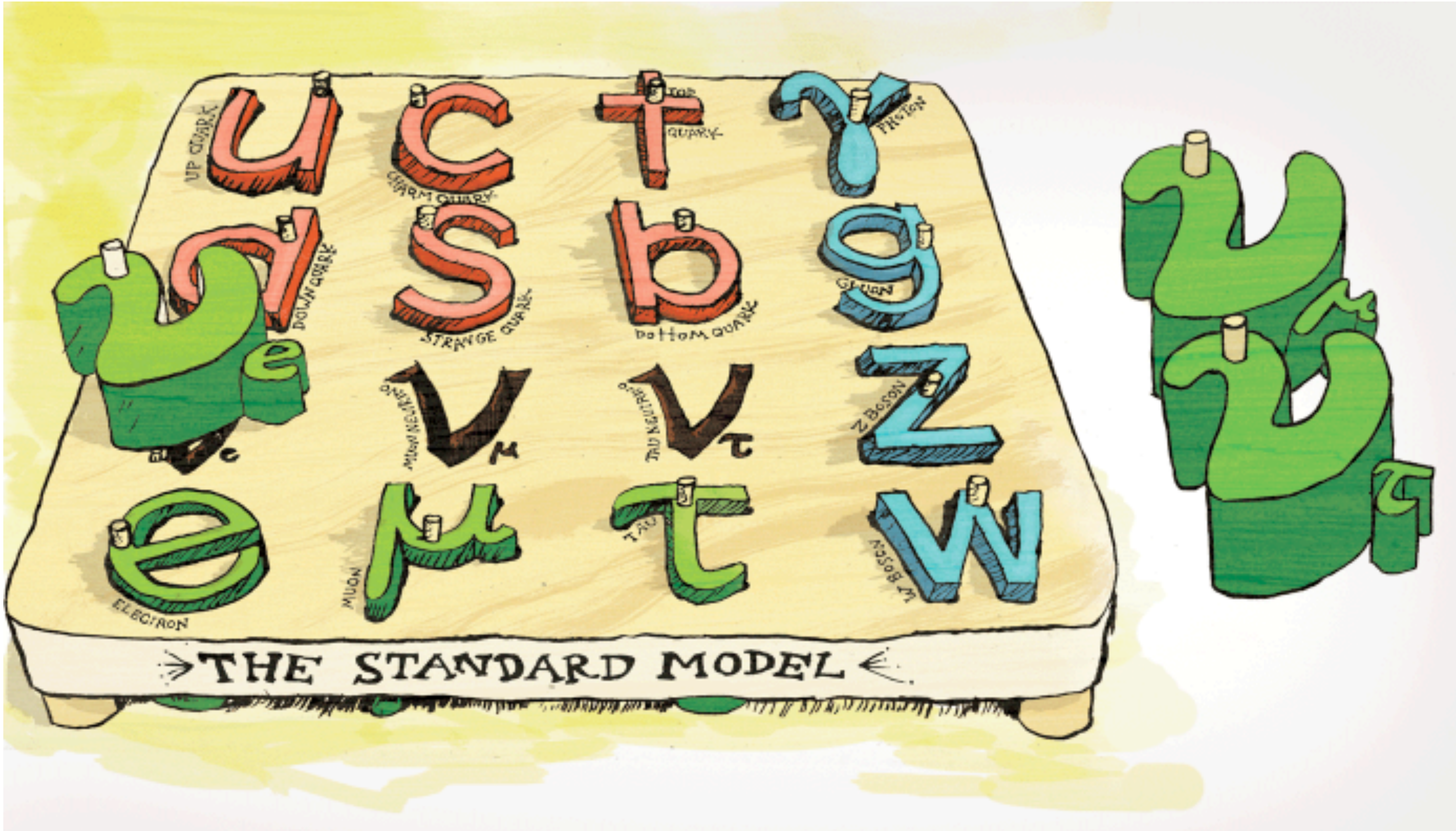


$$\nu + \mathrm{N} \rightarrow \nu + \mathrm{X}$$



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 …

2

What do neutrinos look like?

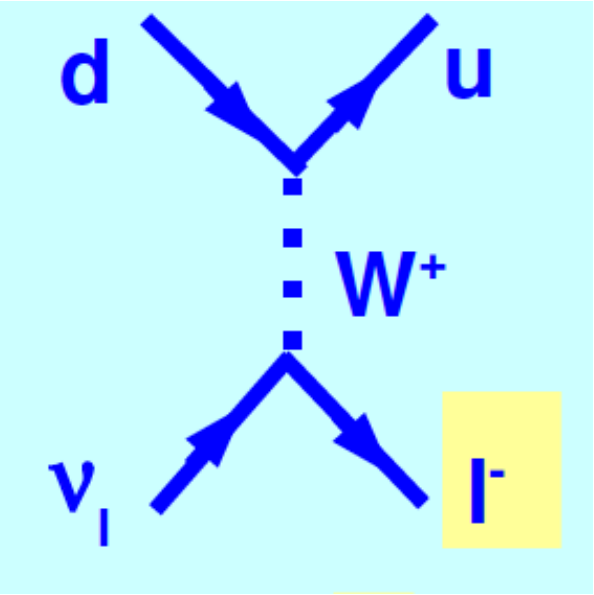
Neutrino interactions in the SM

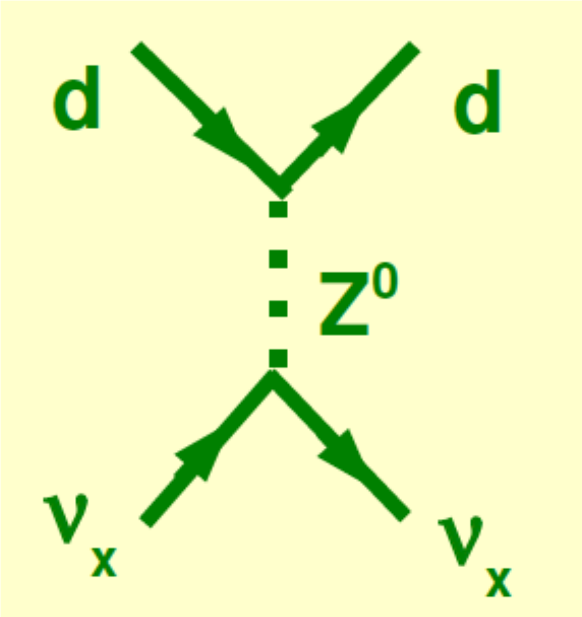
- **CC interactions**: exchange of W
  - The lepton in the final state determines if it is a neutrino or antineutrino and its flavor
- **NC interactions**: exchange of Z^0
- **The total lepton number is conserved** in the weak interactions observed experimentally:

$$L = L_e + L_\mu + L_\tau$$

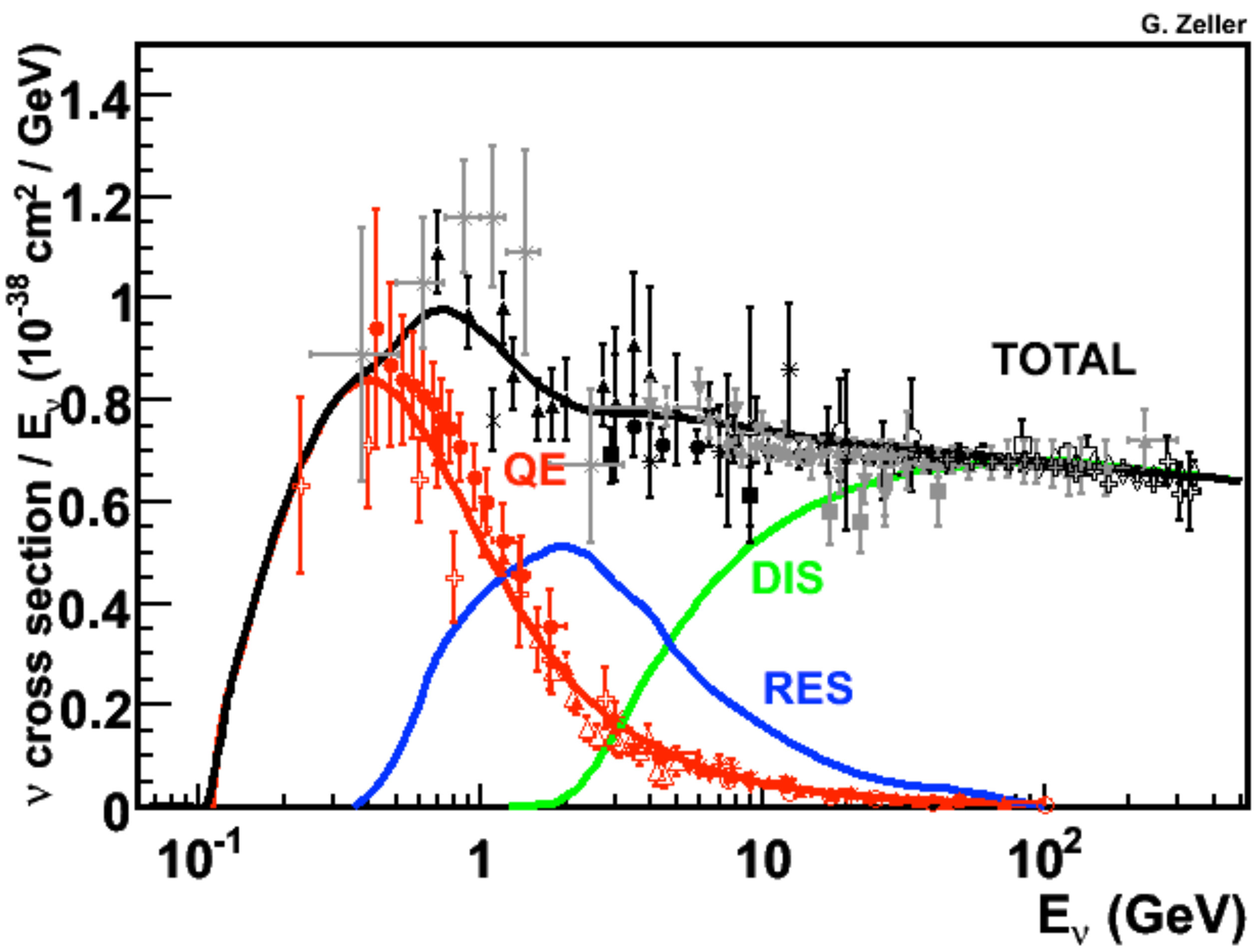
	L_e	L_μ	L_τ
$(\nu_e\,,\,e^-)$	$+1$	0	0
$(\nu_\mu\,,\,\mu^-)$	0	$+1$	0
$(\nu_\tau\,,\,\tau^-)$	0	0	$+1$

	L_e	L_μ	L_τ
$(\nu_e^c\,,\,e^+)$	-1	0	0
$(\nu_\mu^c\,,\,\mu^+)$	0	-1	0
$(\nu_\tau^c\,,\,\tau^+)$	0	0	-1





Neutrino cross sections

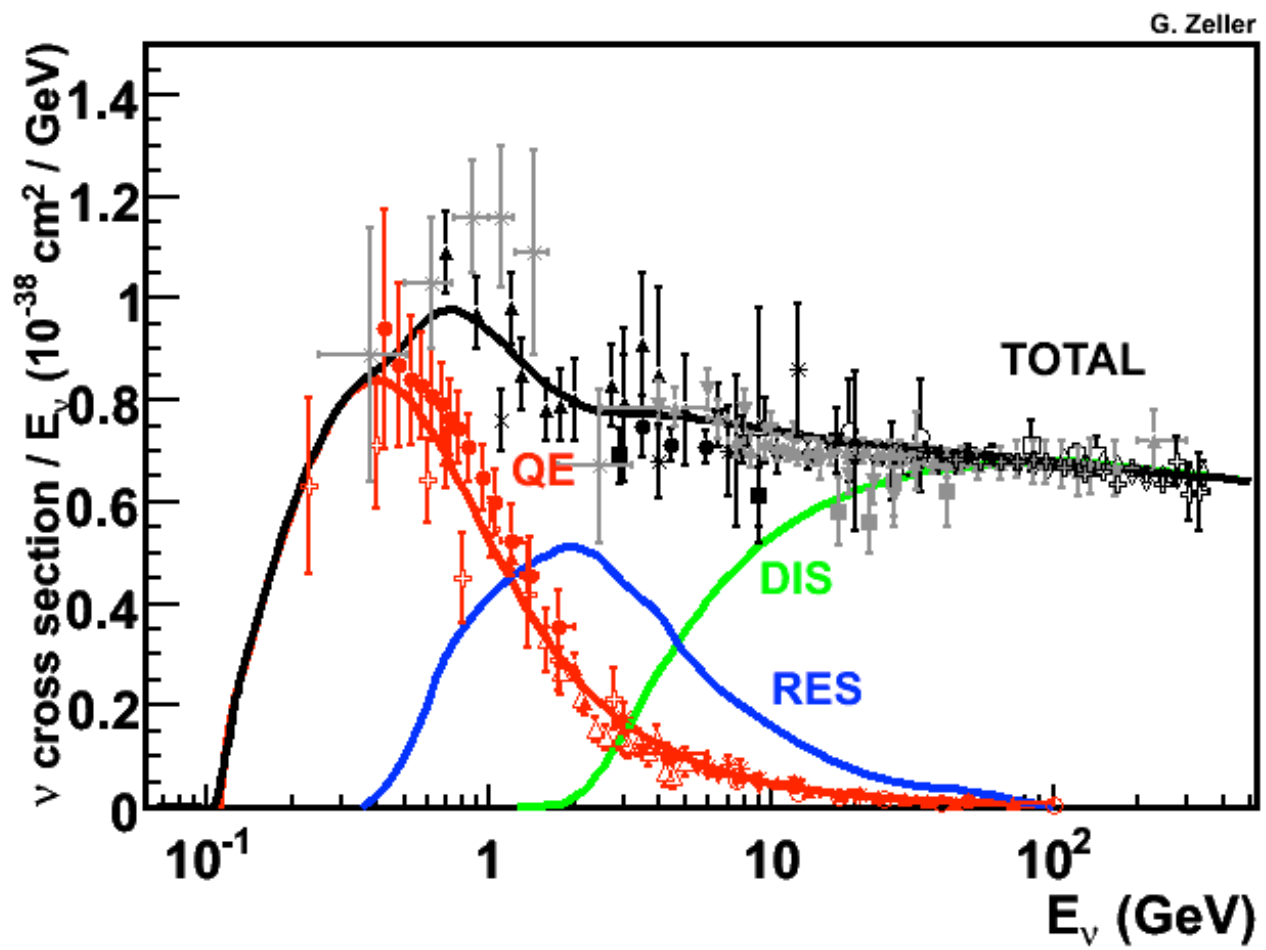


Neutrino cross sections

E_ν < 100 MeV

Solar, SN, reactors

- Inverse beta decay
- CC & NC interactions with nuclei
- Elastic scattering
- σ well known (1% or better)



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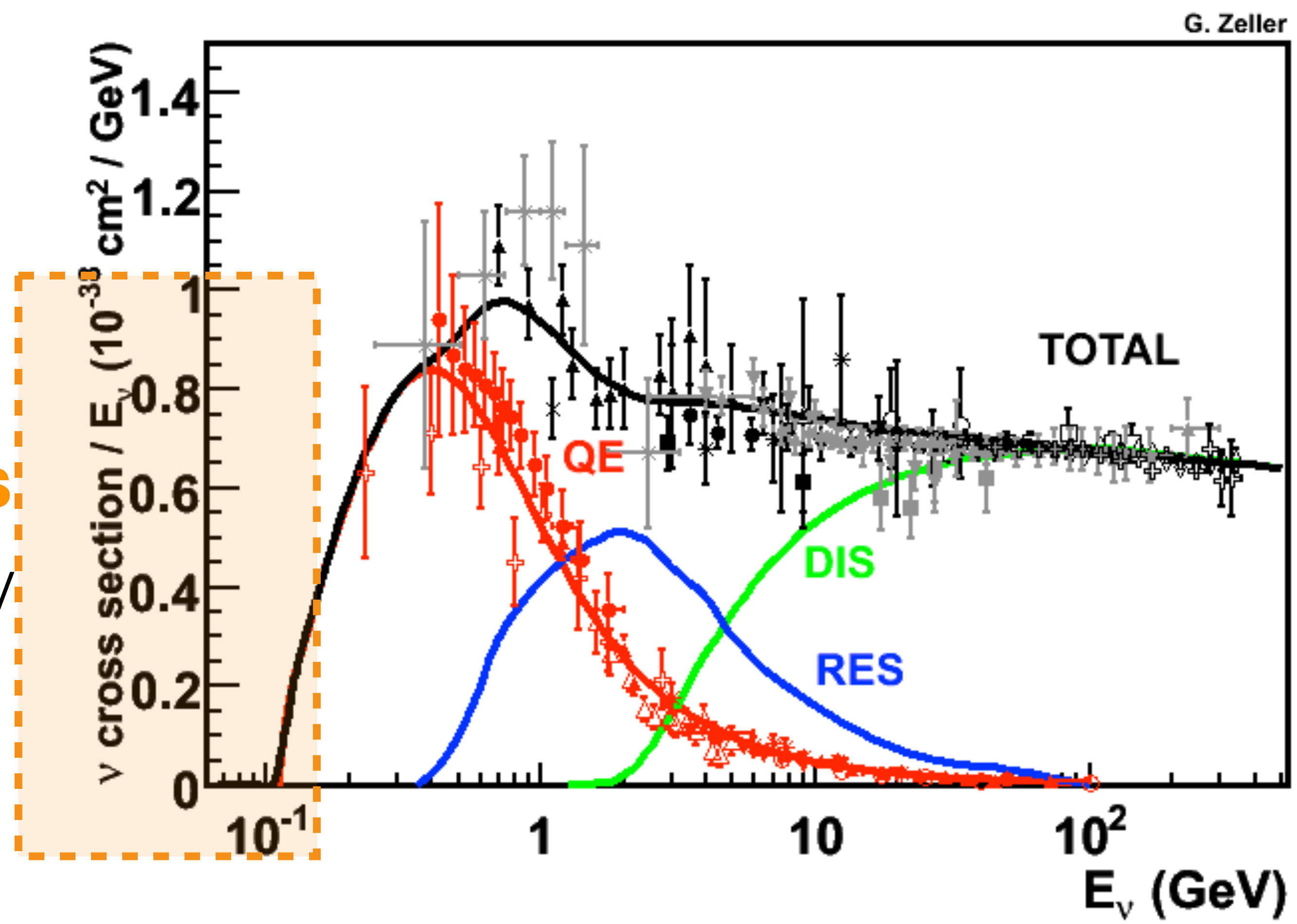

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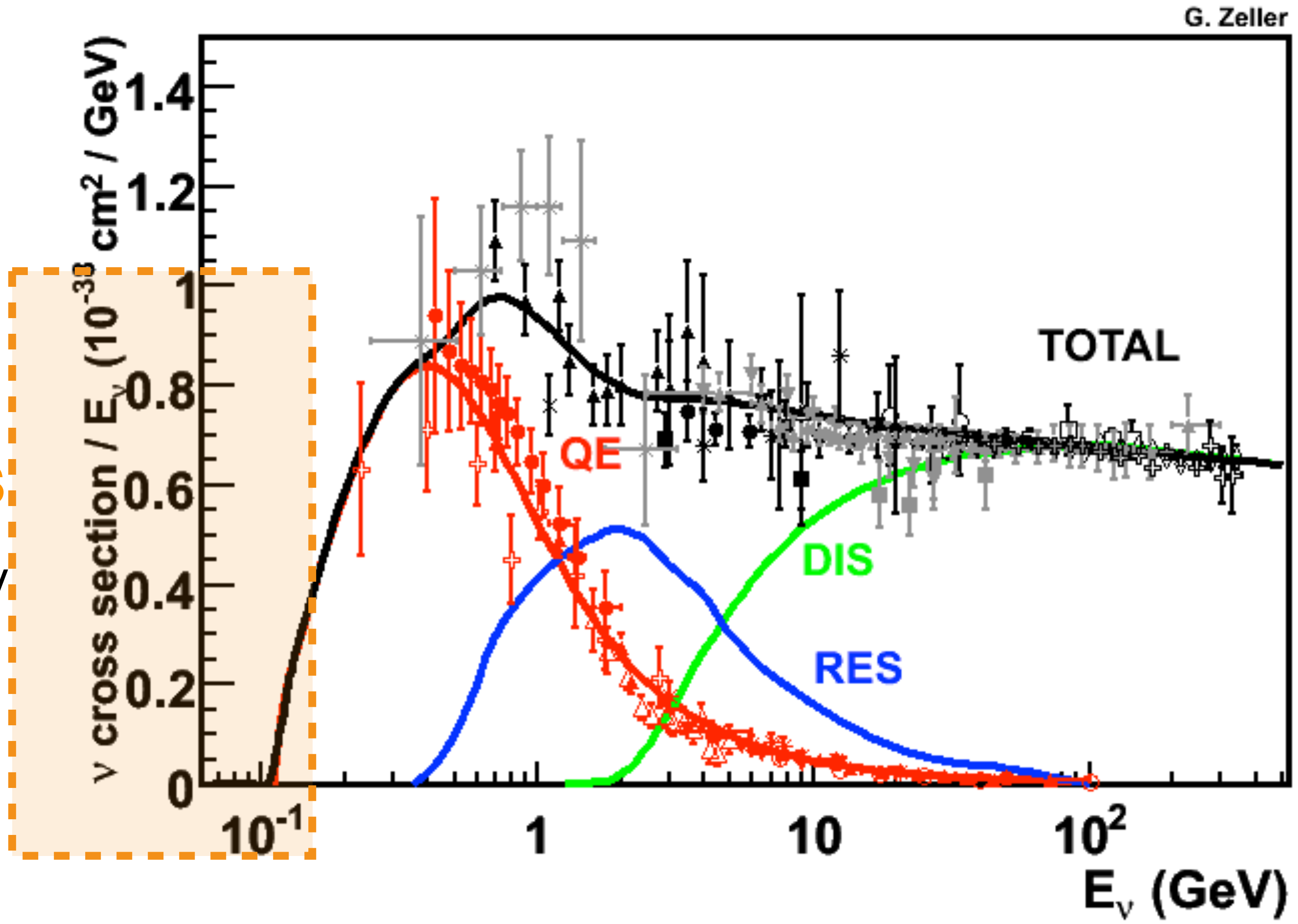

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ν astronomy

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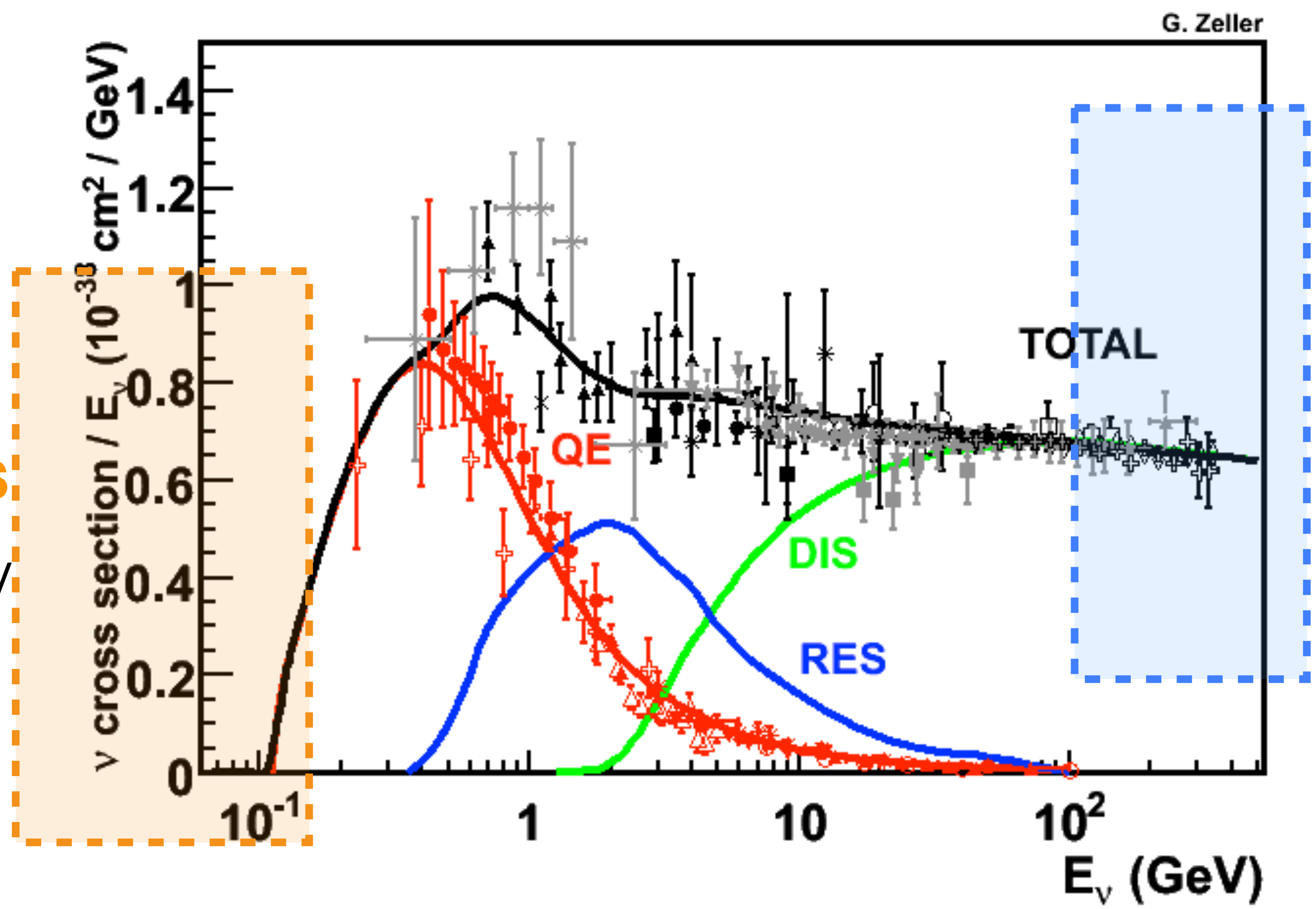

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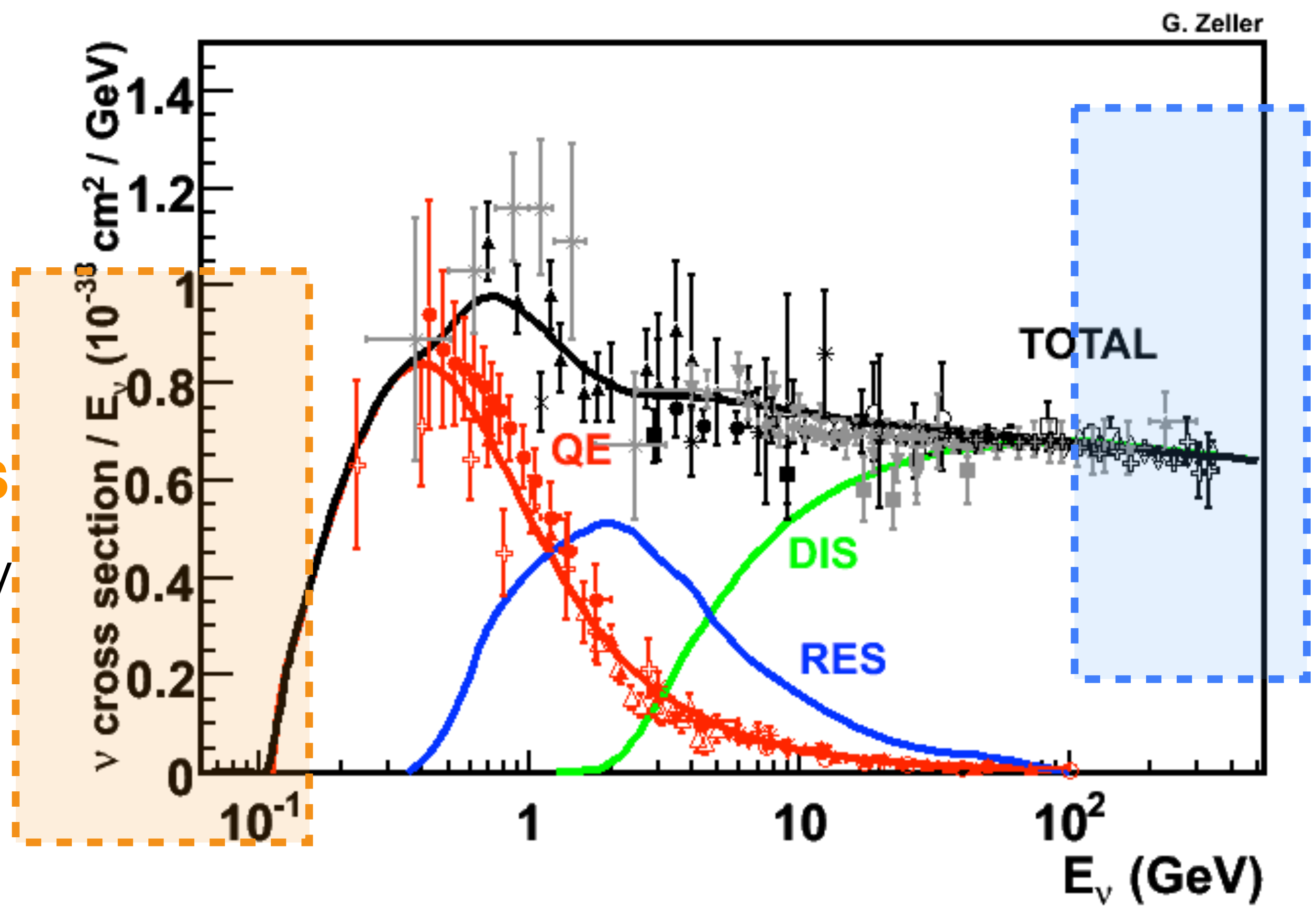

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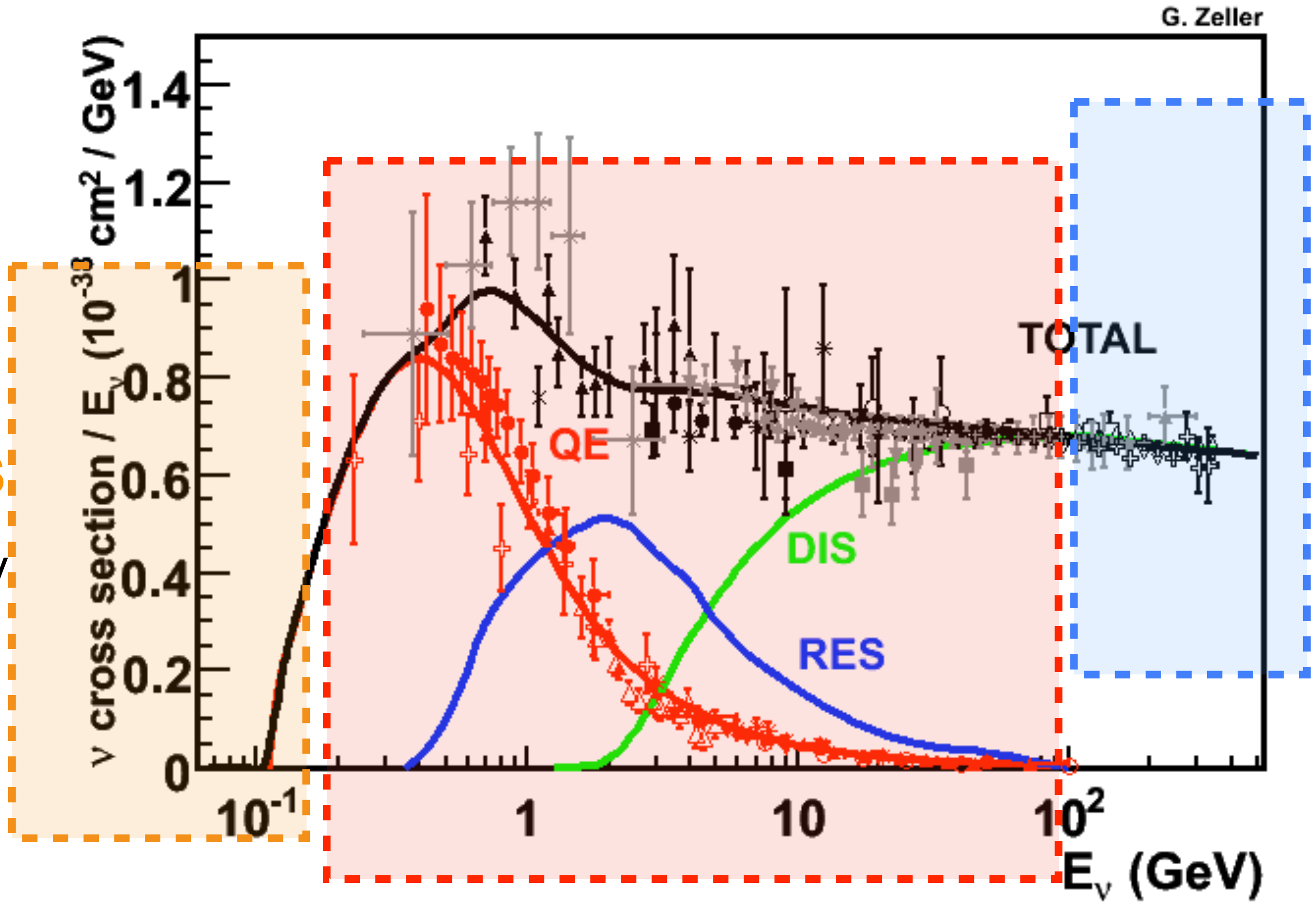

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Neutrino traps
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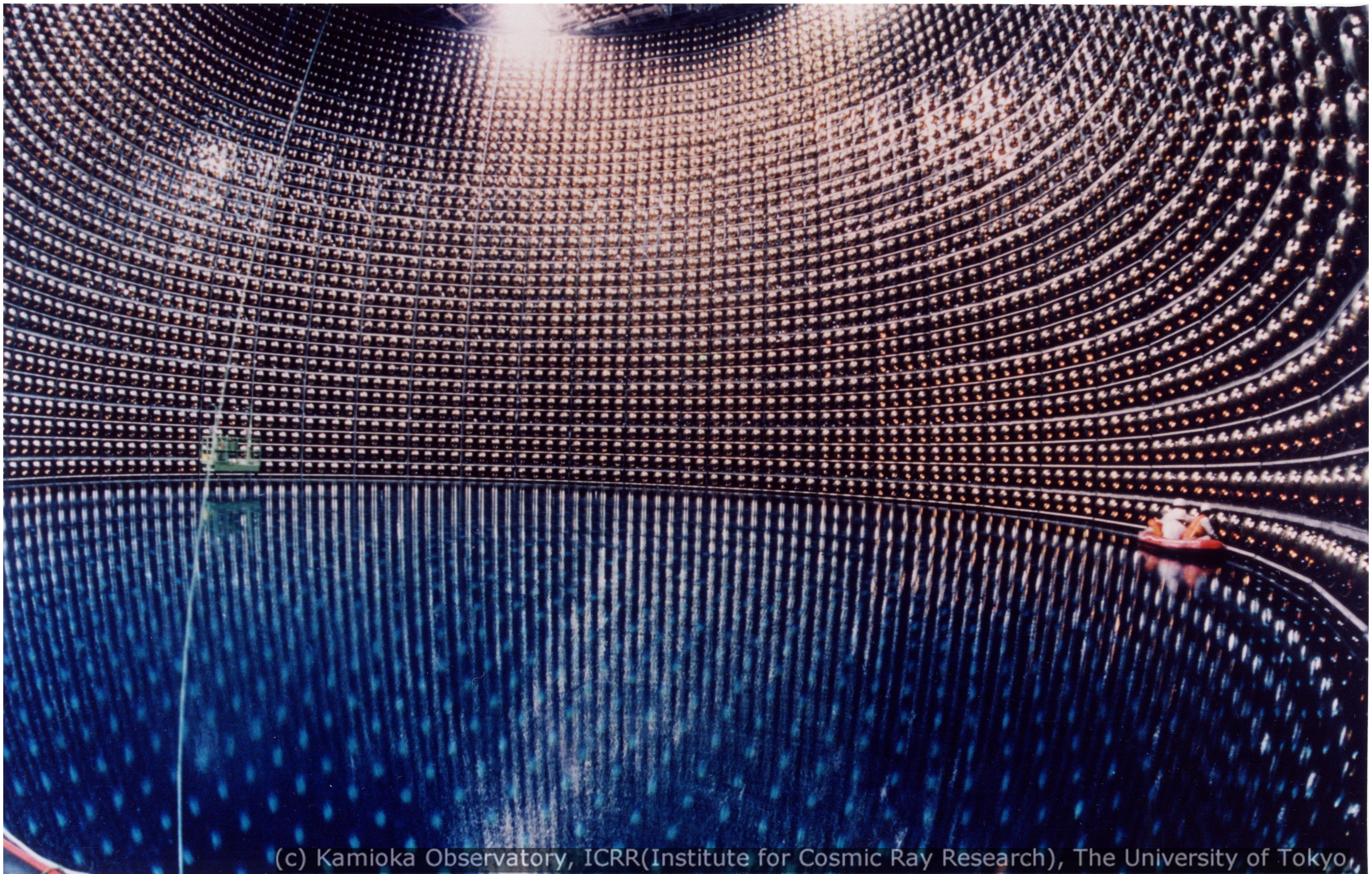

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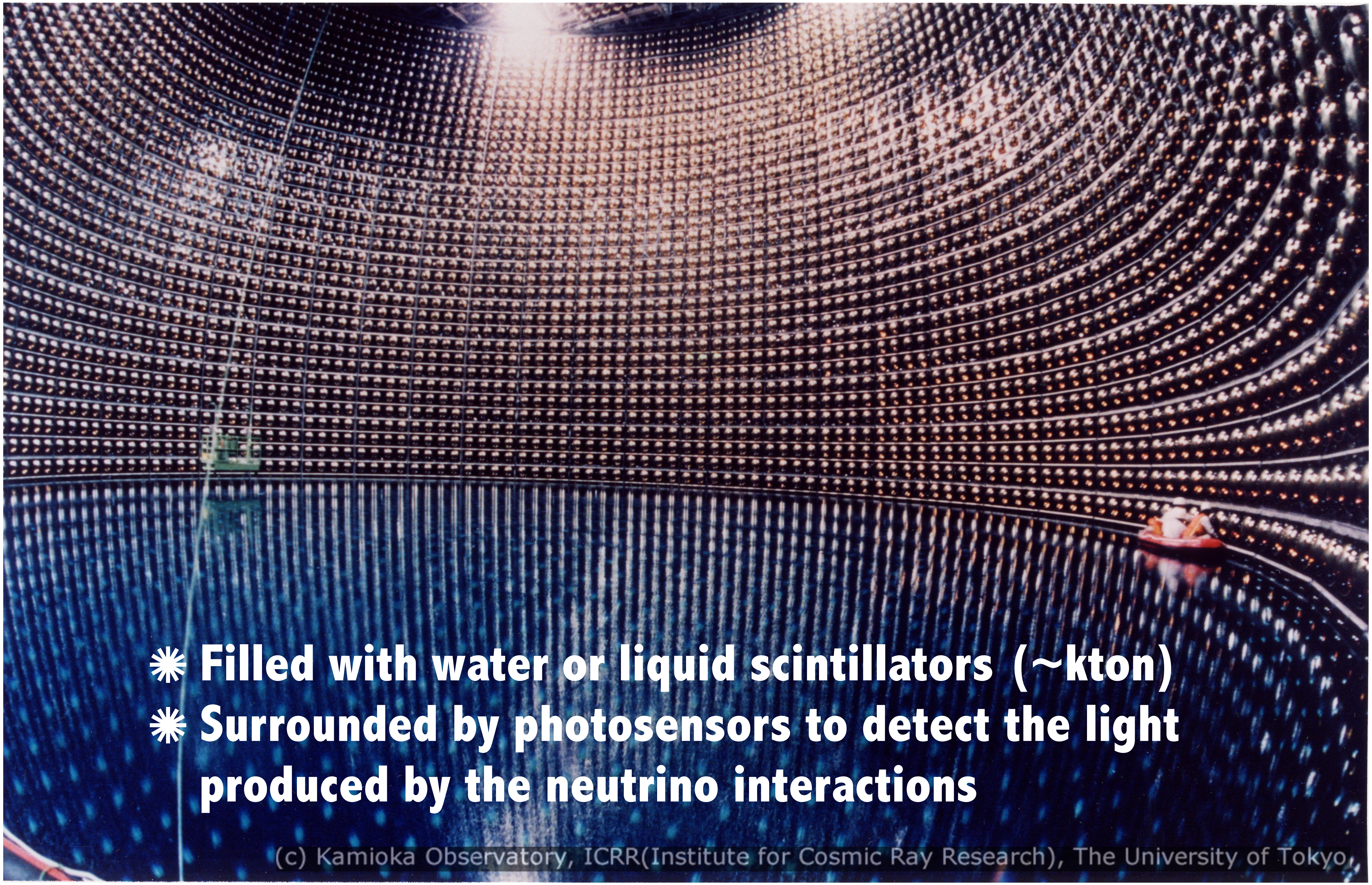
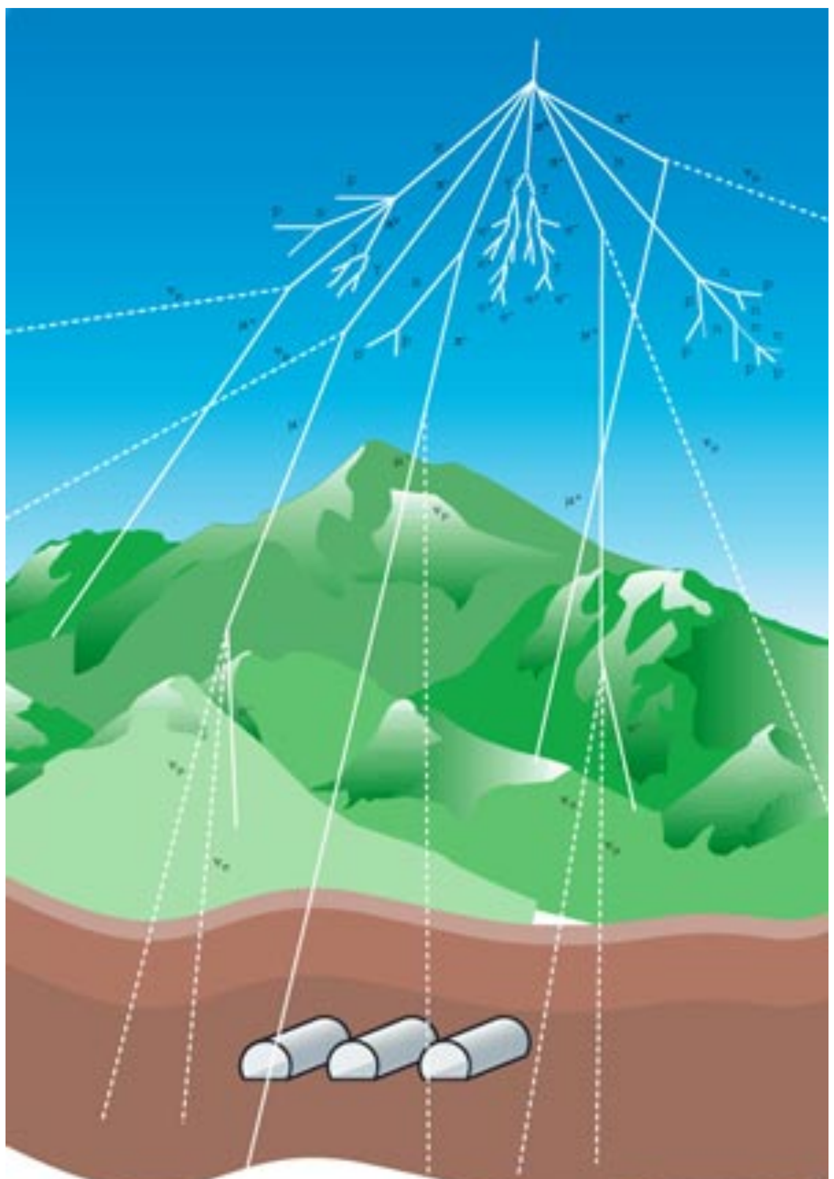
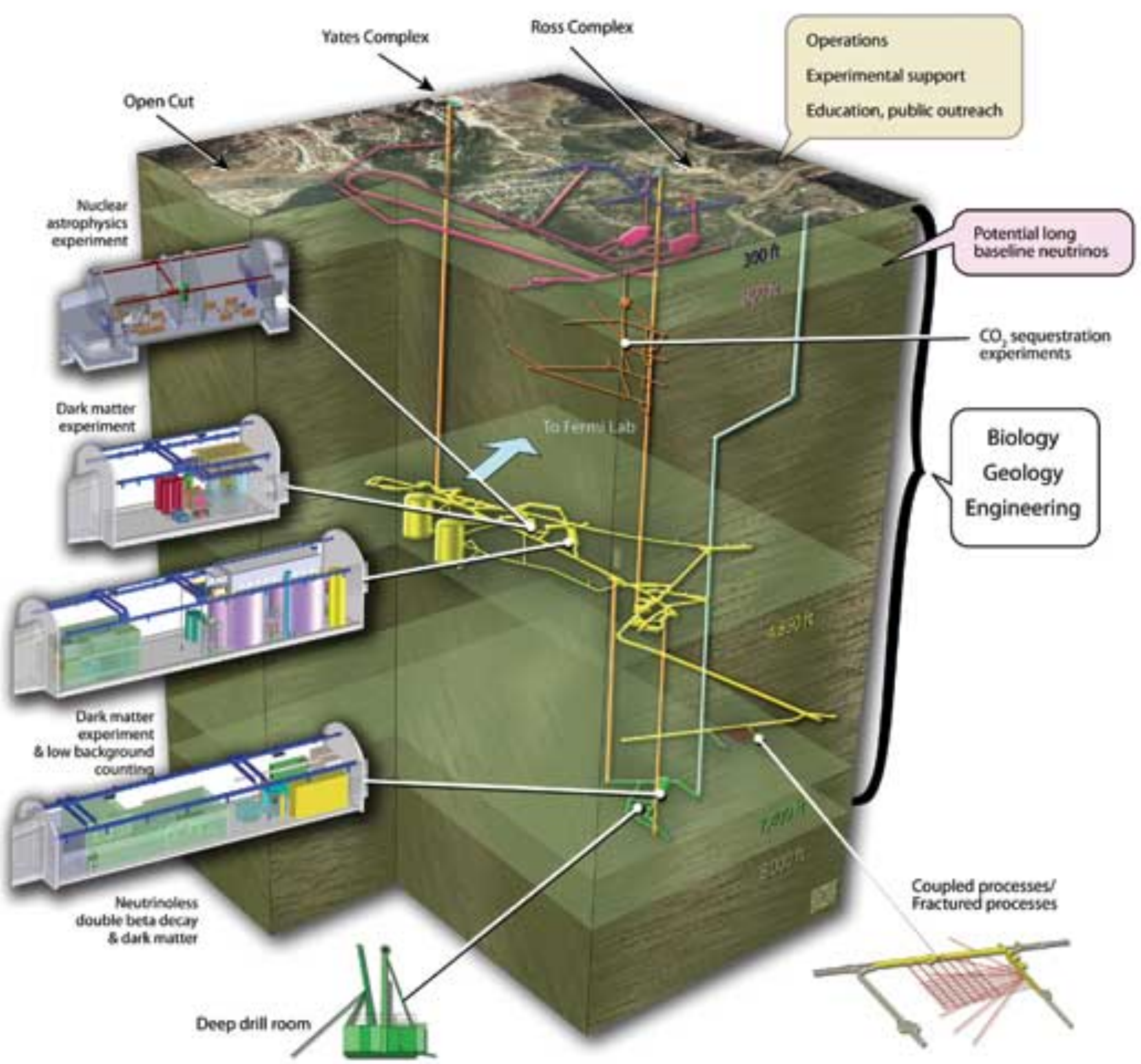


Neutrino traps
(II) Underground laboratories

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





Neutrino detector technologies

- **Bubble and spark chambers**
  - First pictures of neutrinos
- **Radiochemical experiments** (Homestake, GALLEX, SAGE, …)
  - No real time detectors
- **Cerenkov detectors:**
  - Suitable for low rate, low multiplicity, energies below GeV (and around TeV)
- **Tracking calorimeters:**
  - High rate and multiplicity, energies ~GeV and above
- **Unsegmented scintillator calorimeters:**
  - Large light yields at MeV energies
- **Emulsions:**
  - High spatial resolution, direct detection of primary vertex
- **Liquid Argon TPCs:**
  - Potential for large mass with high granularity

Pictures of real neutrinos

1) Neutrinos in CMS

2) Neutral currents at CERN

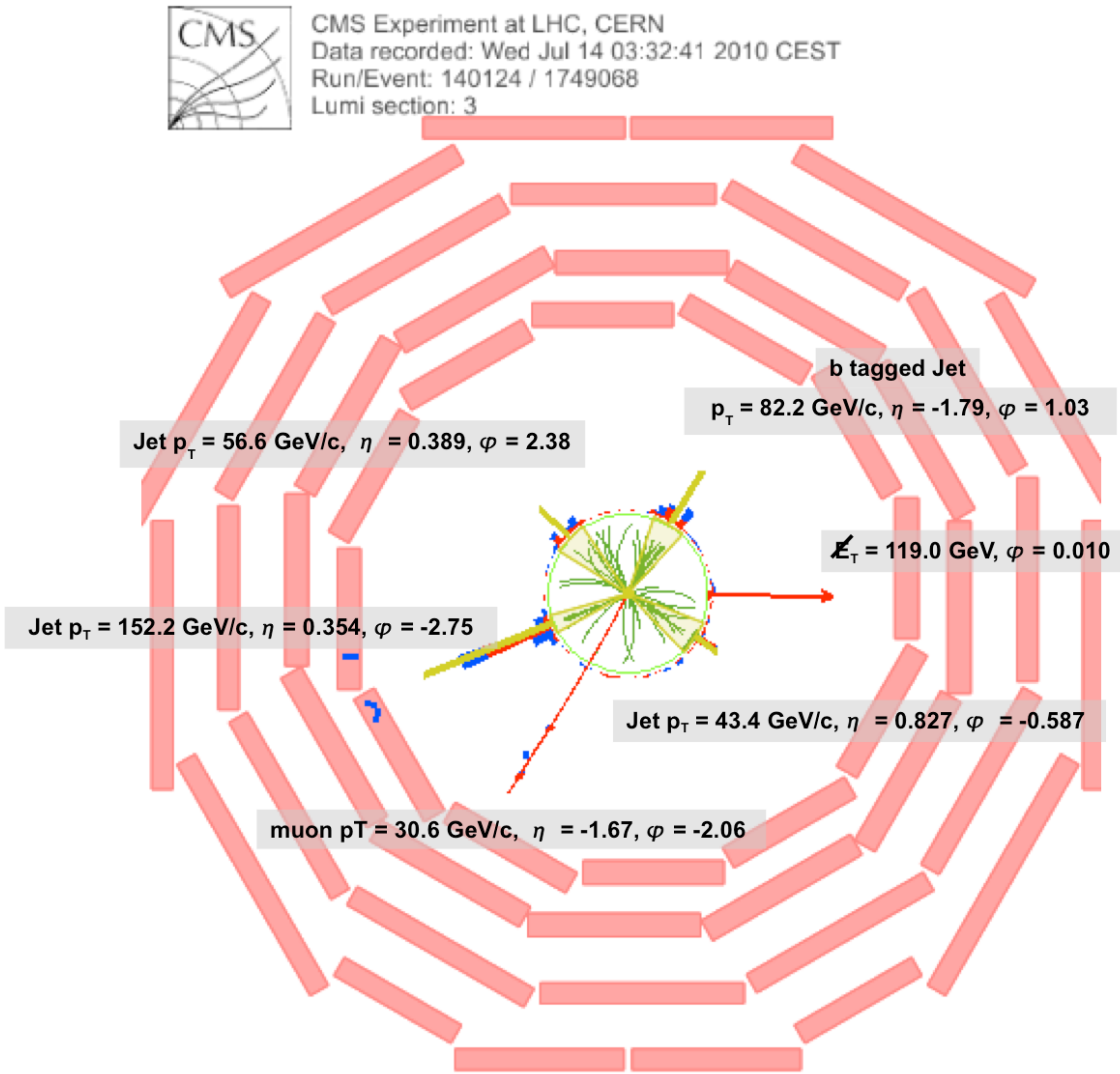
3) Cerenkov rings

4) PMTs hits in liquid scintillators

5) Tracks in T2K, OPERA, ICARUS

6) Ultra-energetic neutrinos

Neutrinos in CMS → INVISIBLES



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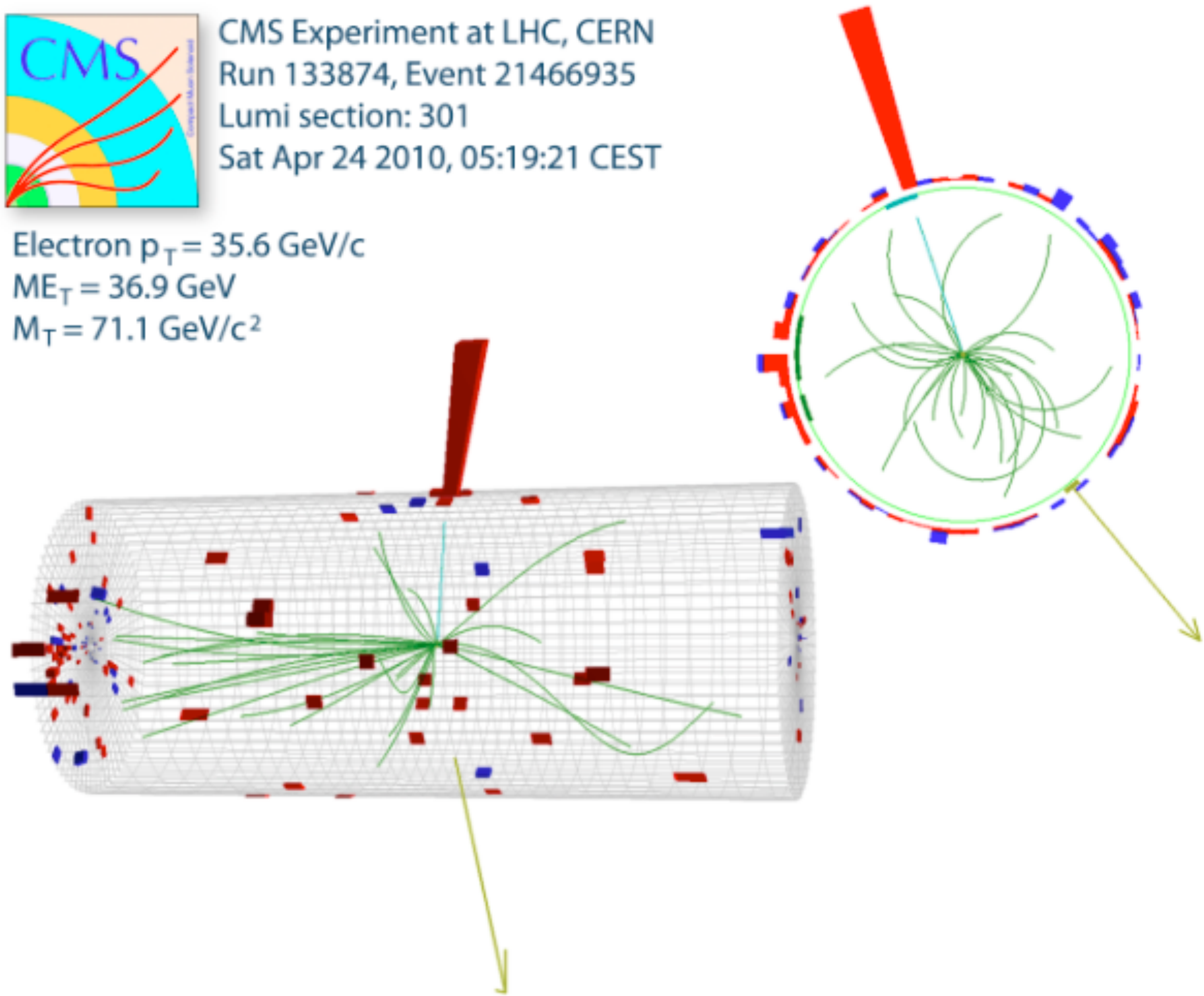
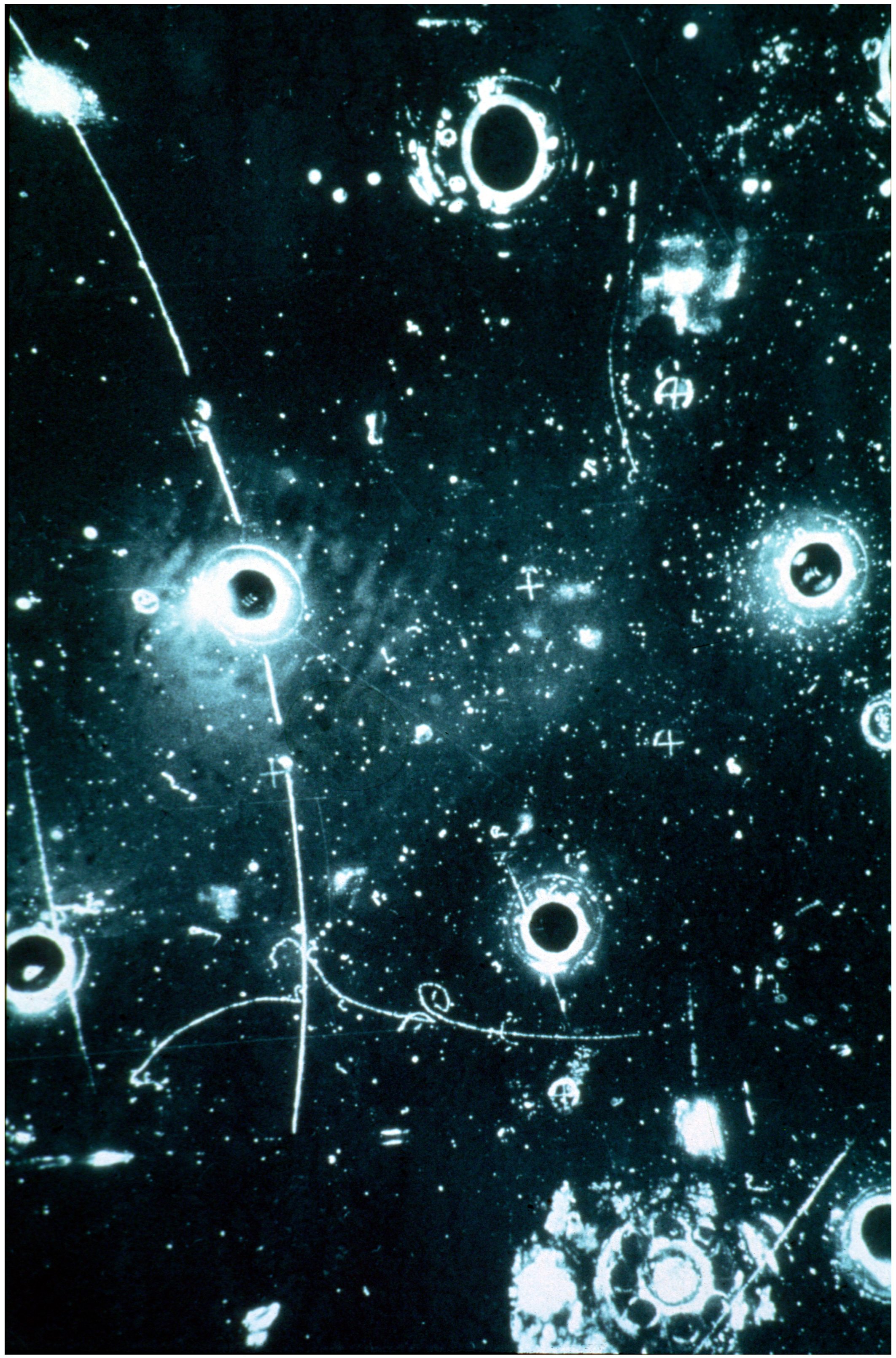


Weak neutral currents

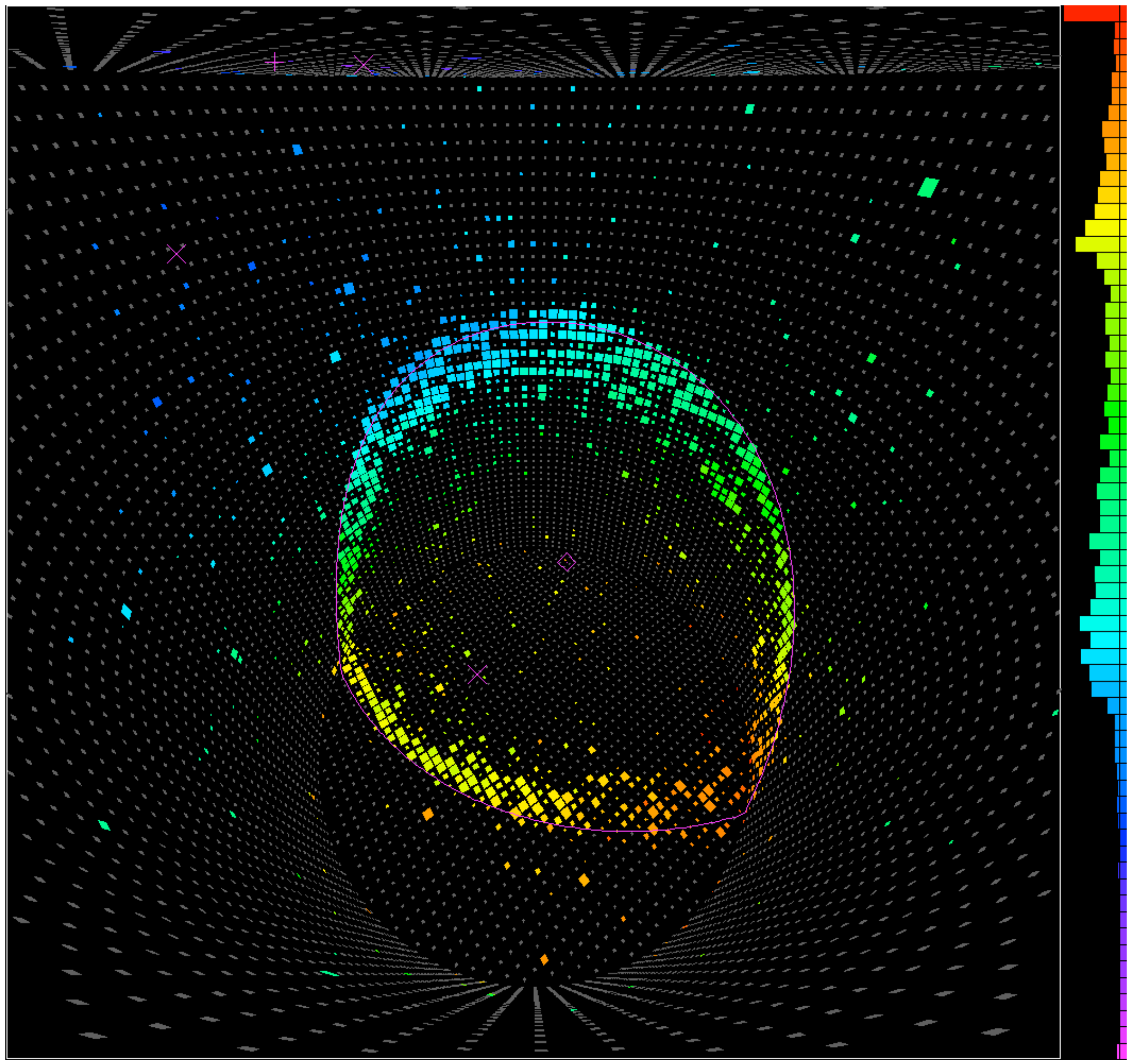


- First candidate to leptonic neutral current process in the Gargamelle experiment at CERN (bubble chamber)

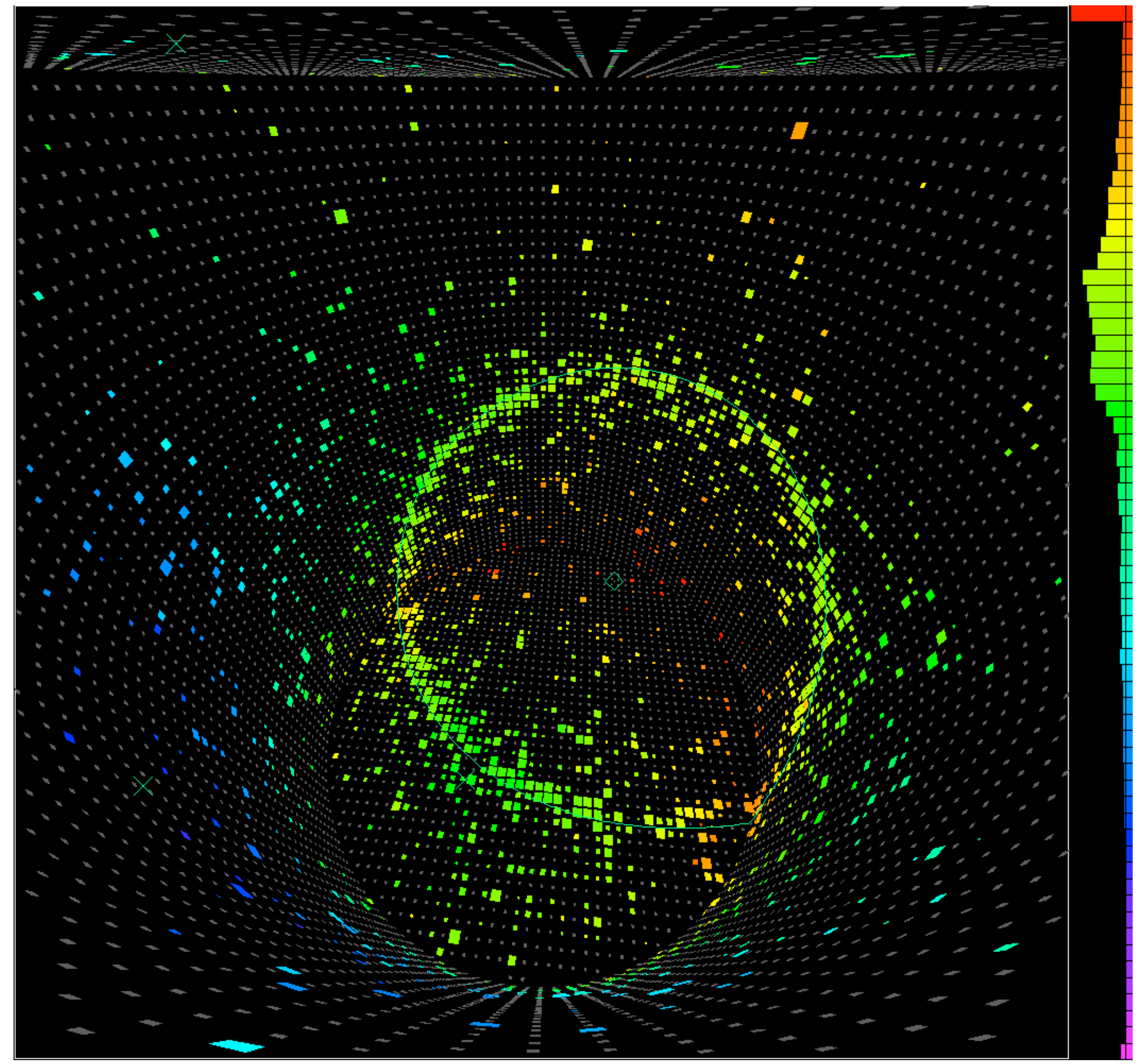
$$\nu_\mu e^- \rightarrow \nu_\mu e^-$$

- Significant step in the knowledge of the electroweak force and the SM structure

Cerenkov rings

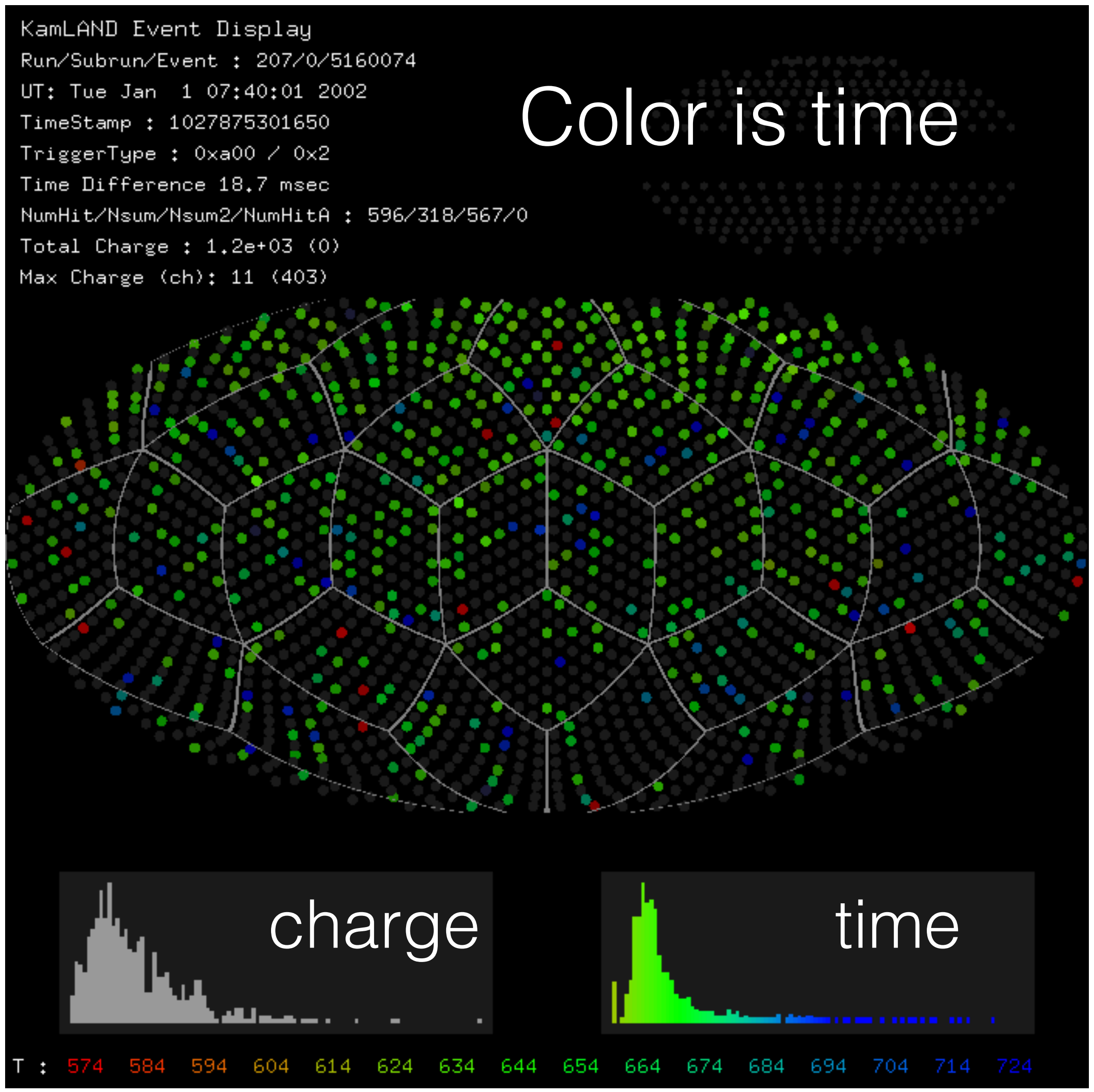


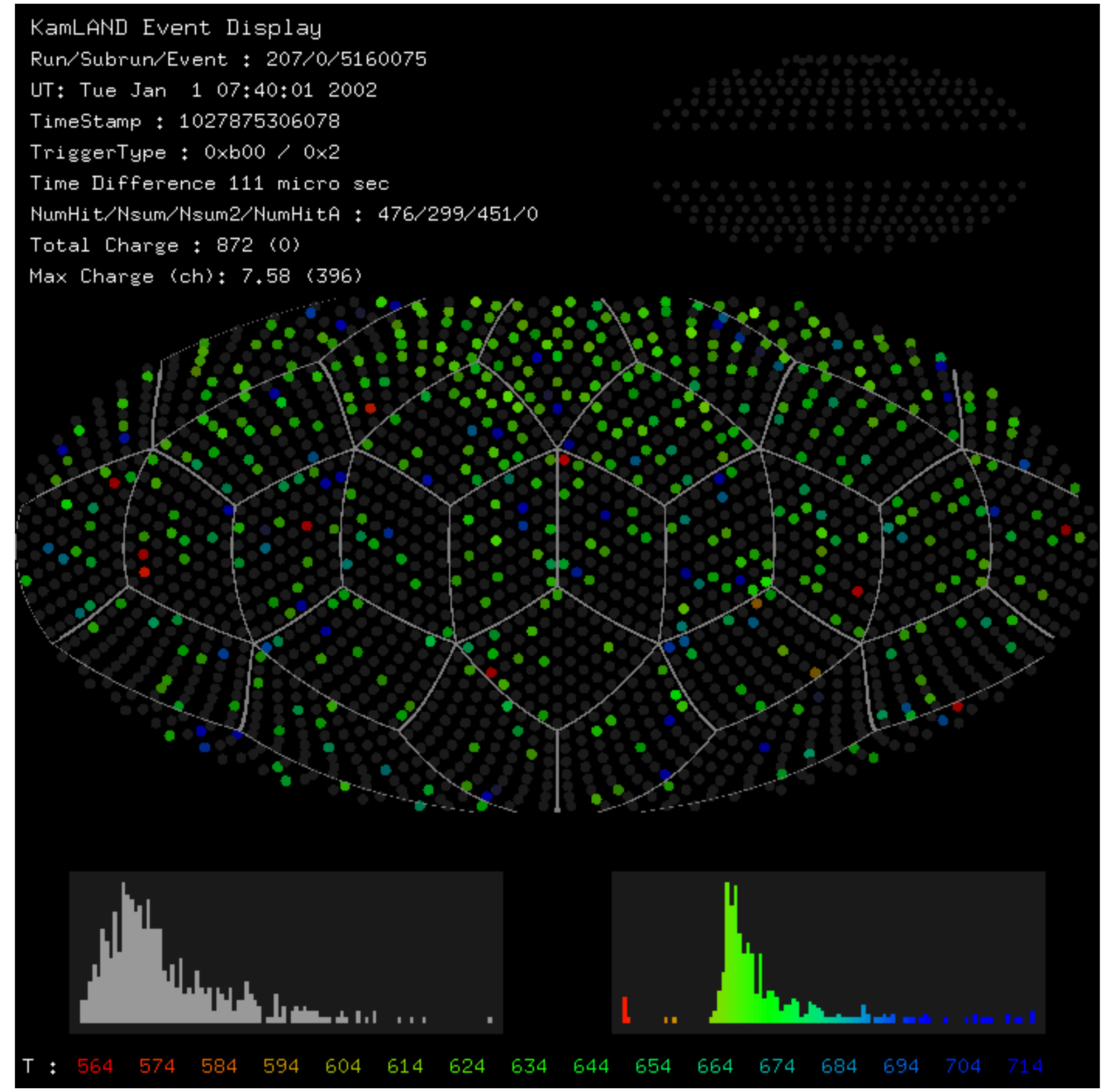
p_μ = 603 MeV



p_e = 492 MeV

Neutrinos in liquid scintillators



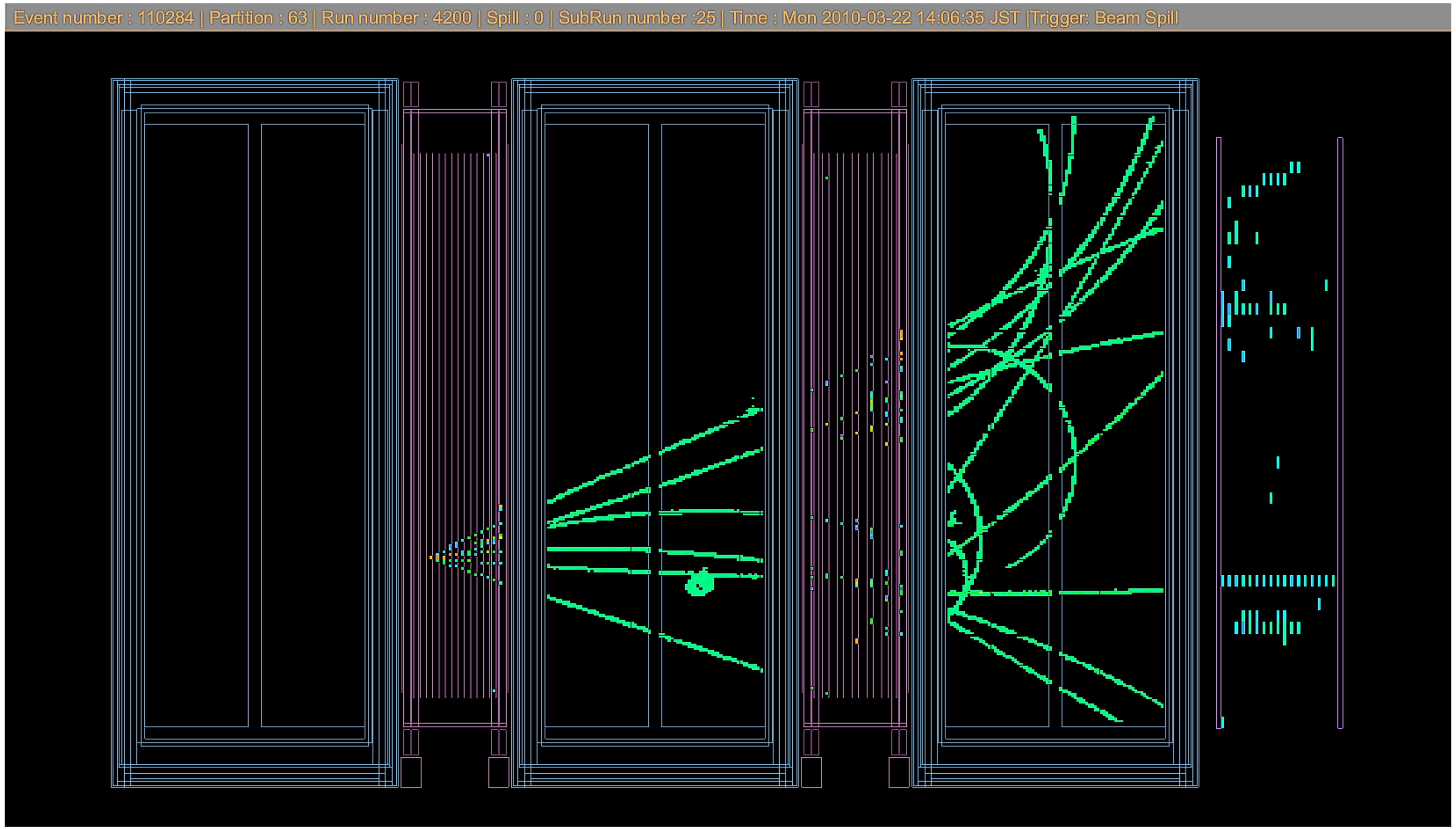


Prompt signal
E = 3.20 MeV

ΔT = 111 μs
ΔR = 34 cm

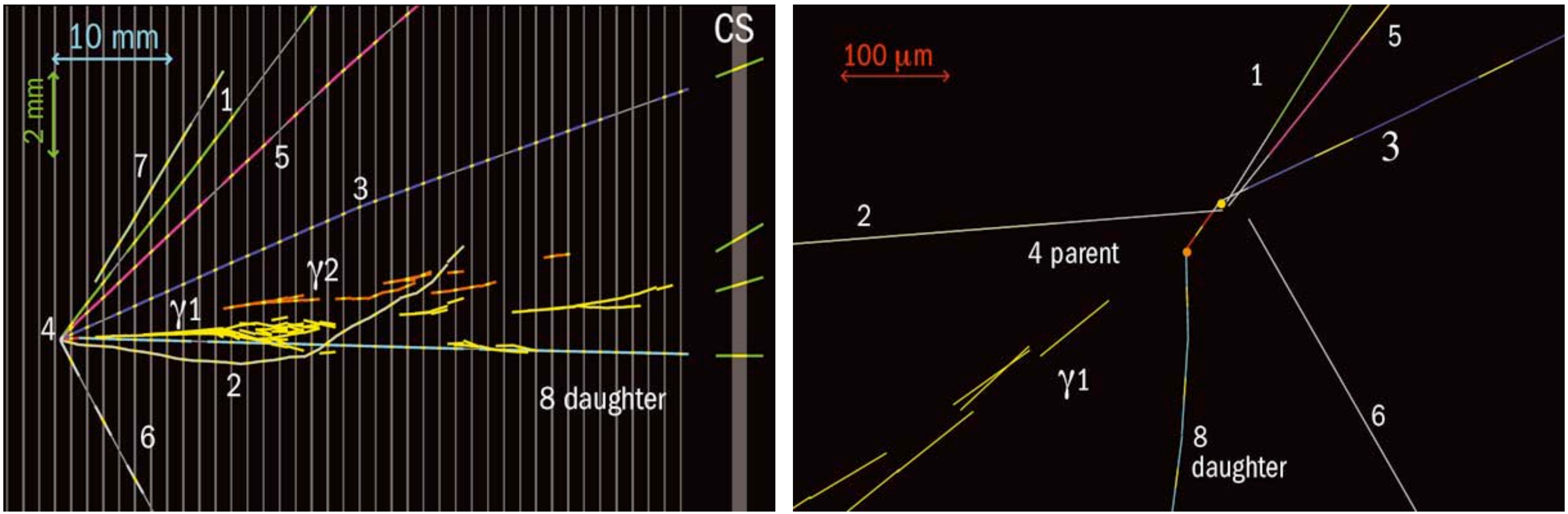
Delayed signal
E = 2.22 MeV

Neutrinos in T2K



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

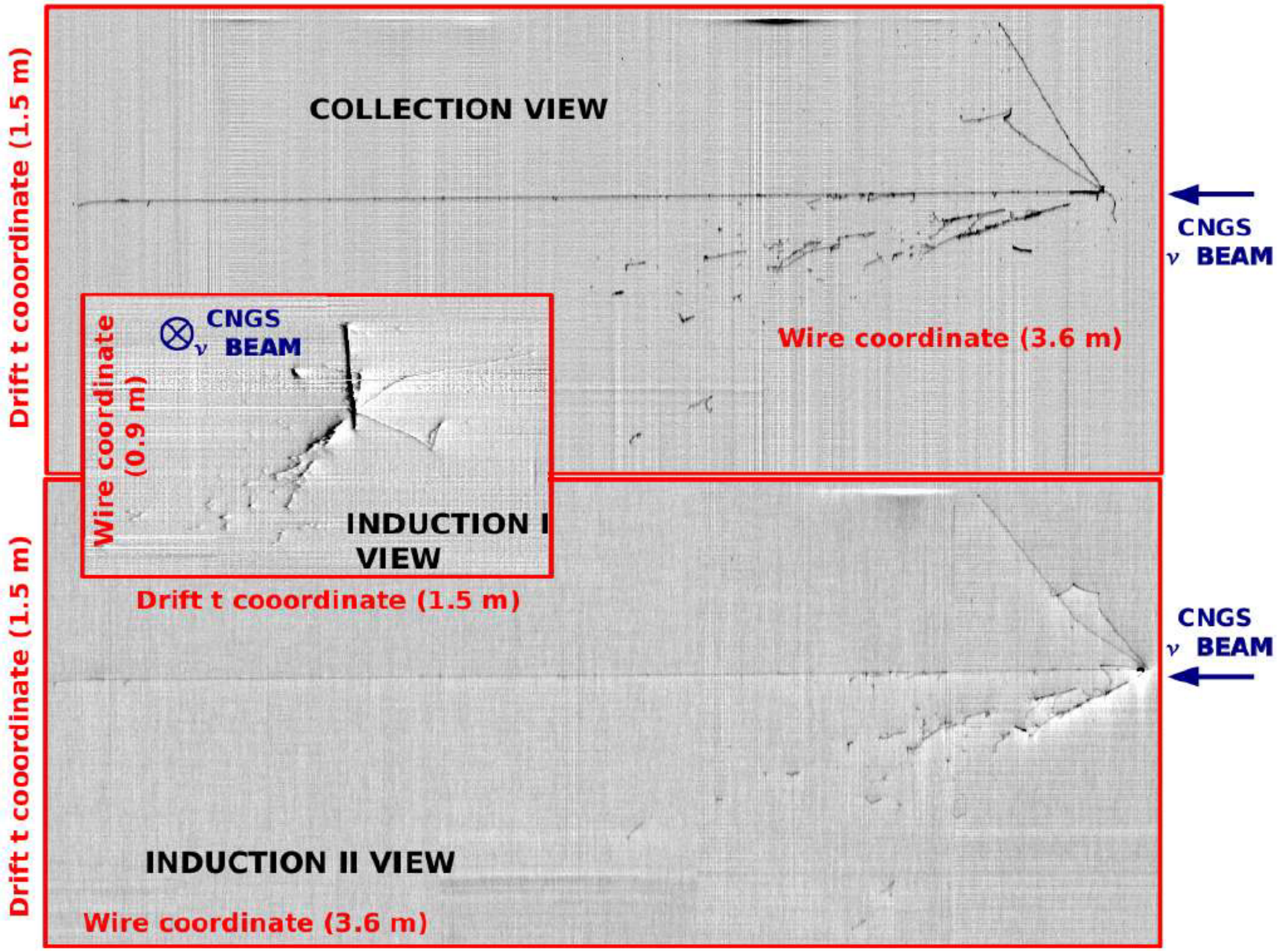
Neutrinos in OPERA

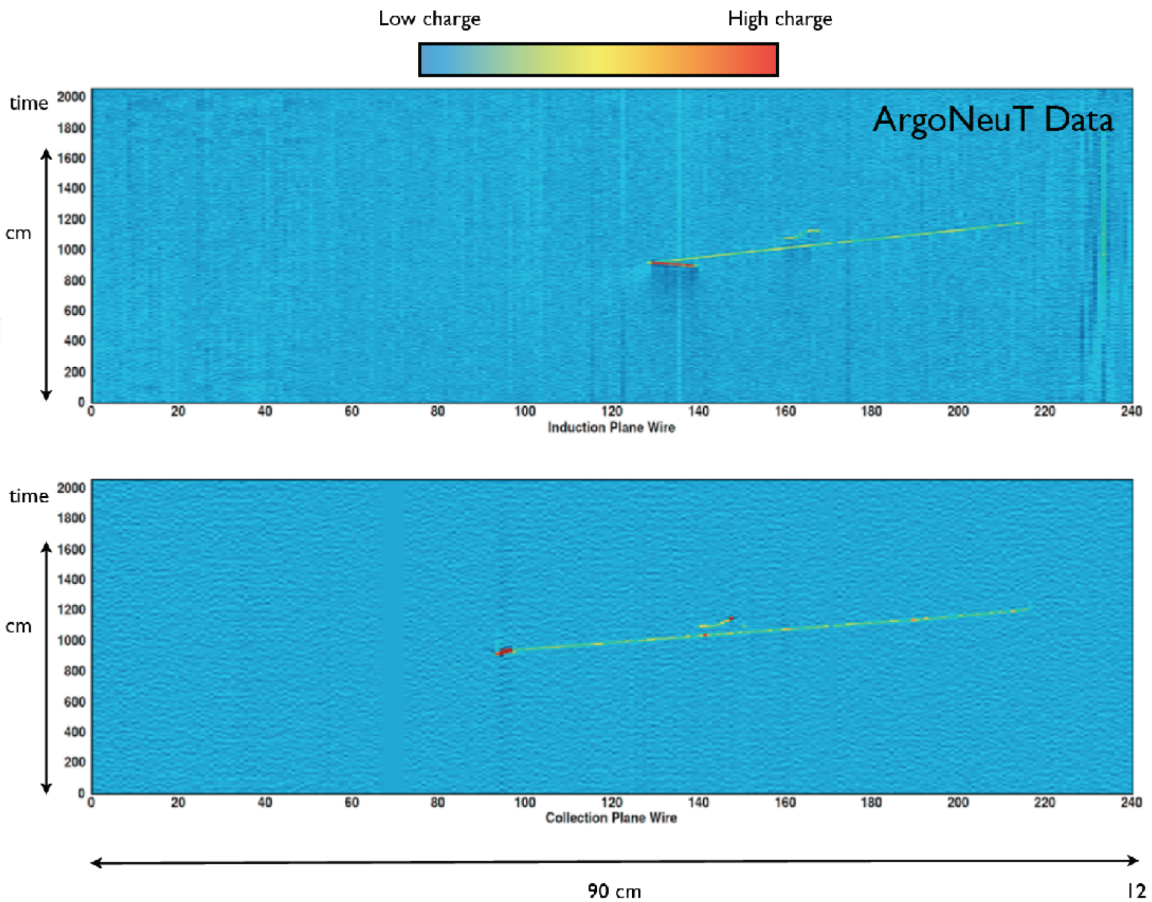


- Detector specially designed to detect the interaction of tau neutrinos

Neutrinos in LAr detectors

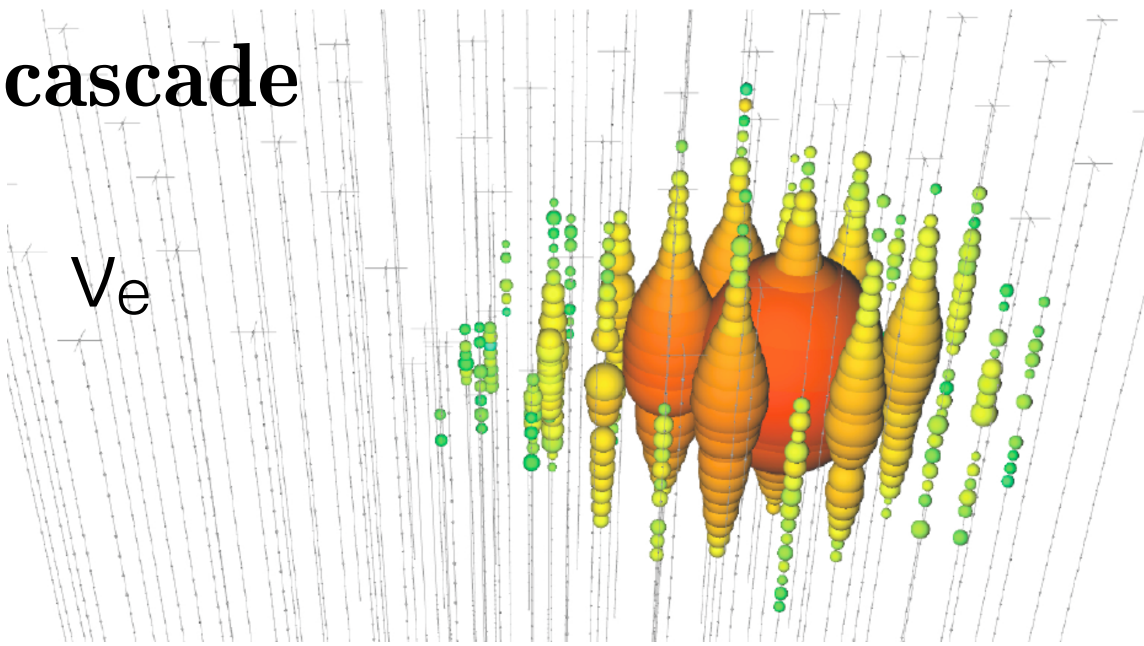
ν_μCC event detected by ICARUS from the CNGS beam

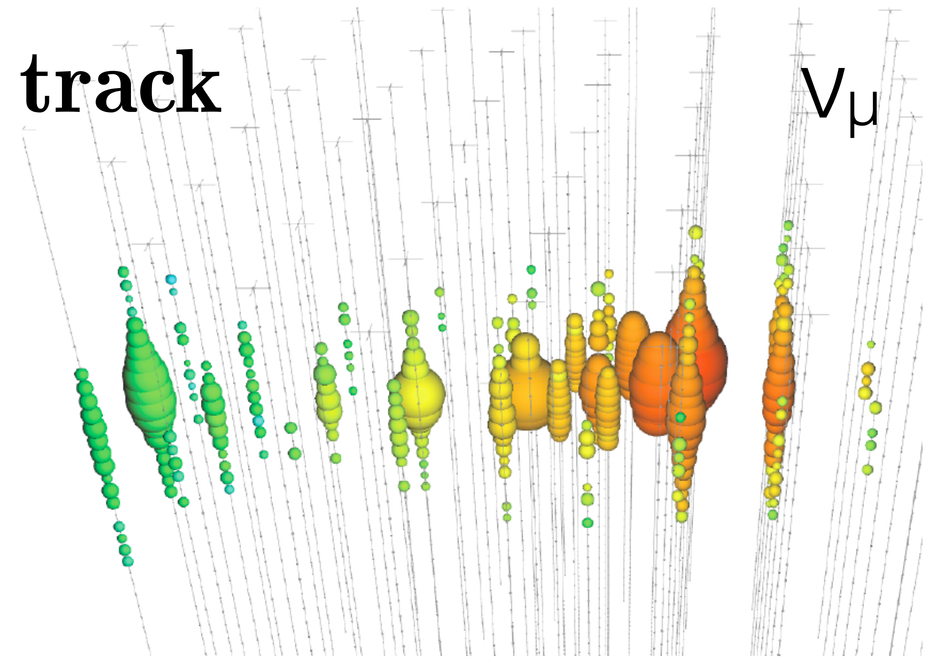


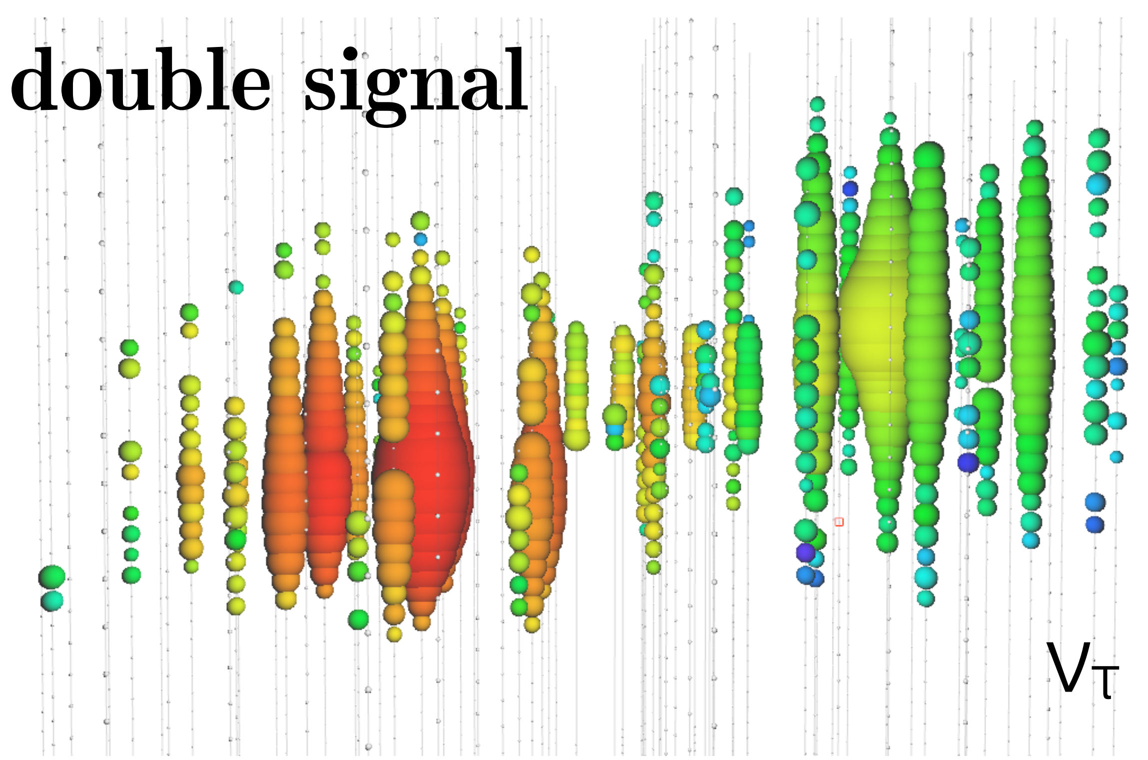


CCQE event: $\nu_\mu\, n \rightarrow \mu\, p$

Very high energy neutrinos







3

Physical quantities

Observables and fundamental quantities

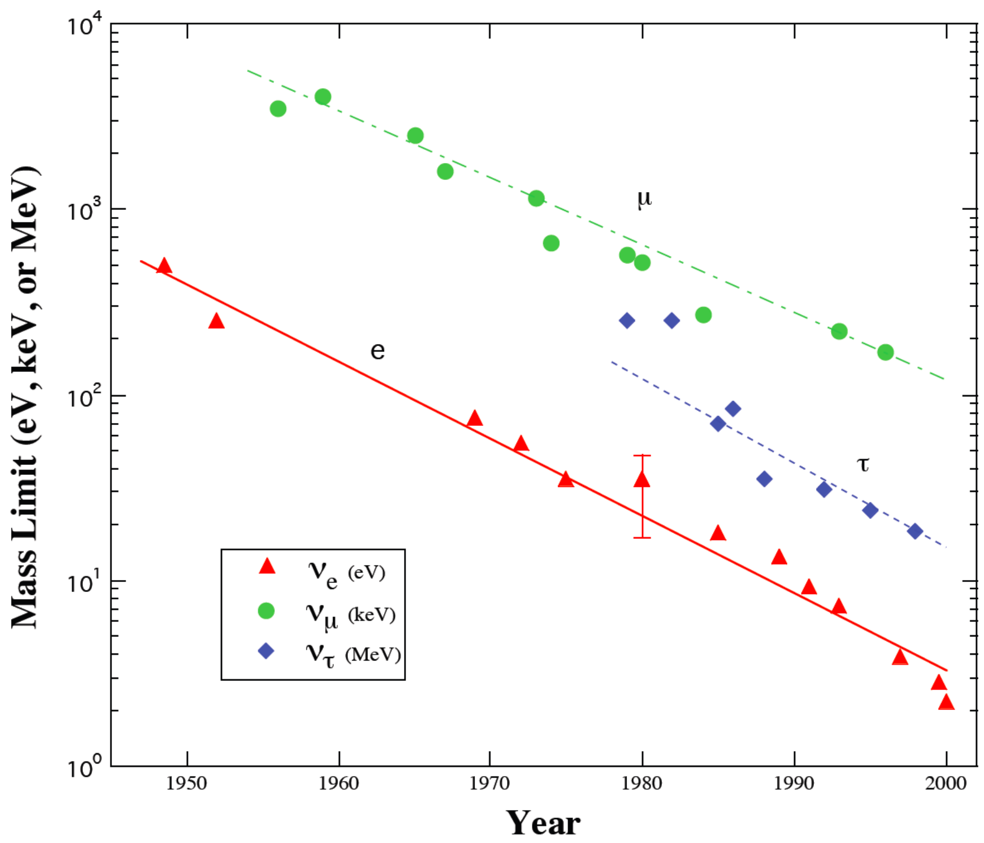
- **Mass**: almost null
  - No direct measurement. Only upper limits from lab experiments and cosmological observations
  - We know that the mass is not zero because neutrinos oscillate
- **Charge**: null
  - Experimental limits derived from the neutrino magnetic moment limit ($<10^{-12}$ q_e for ν_e; $< 10^{-4}$ q_e for ν_τ)
  - Experimental limits from astrophysical measurements ($<10^{-13}$-10^{-15} q_e)
- **Spin** (intrinsic angular momentum): 1/2
  - Measured with angular distributions in scattering or decay processes

PDG 2014

PDG K.A. Olive et al., Chin. Phys. C, 38, 090001 (2014)

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

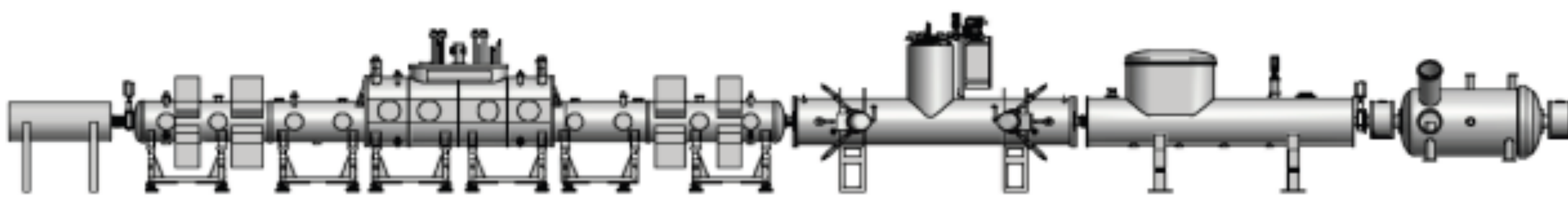
- **Best experimental limits**:
  - Electron neutrino mass
    - $^3H \to {}^3He + e^- + \nu_e$ MAINZ **$m(\nu_e) < 2.2$ eV**
  - Muon neutrino mass
    - $\pi^+ \to \mu^+ \nu_\mu$ PSI **$m(\nu_\mu) < 170$ keV**
  - Tau neutrino mass
    - $\tau \to 5\pi\, \nu_\tau$ LEP **$m(\nu_\tau) < 18.2$ MeV**

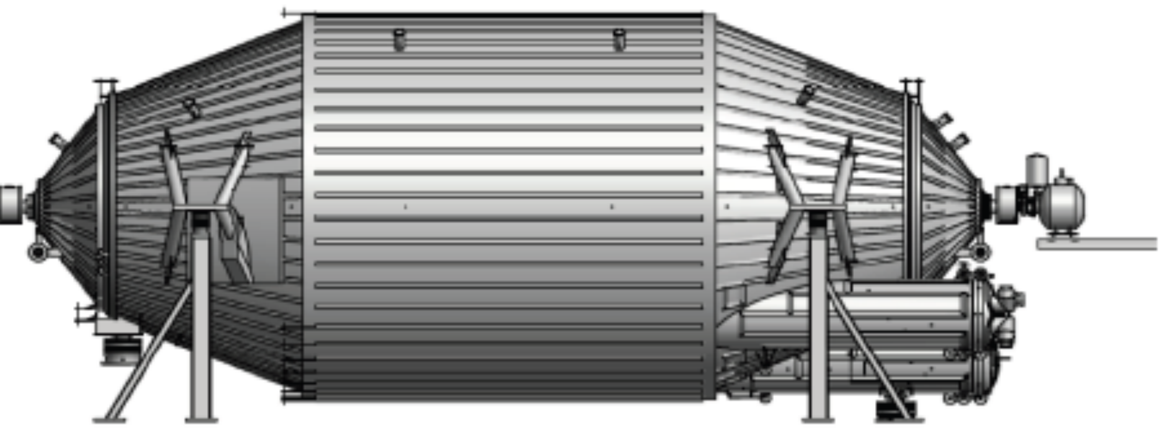


Points without error bars are upper limits

Measurement of the neutrino mass

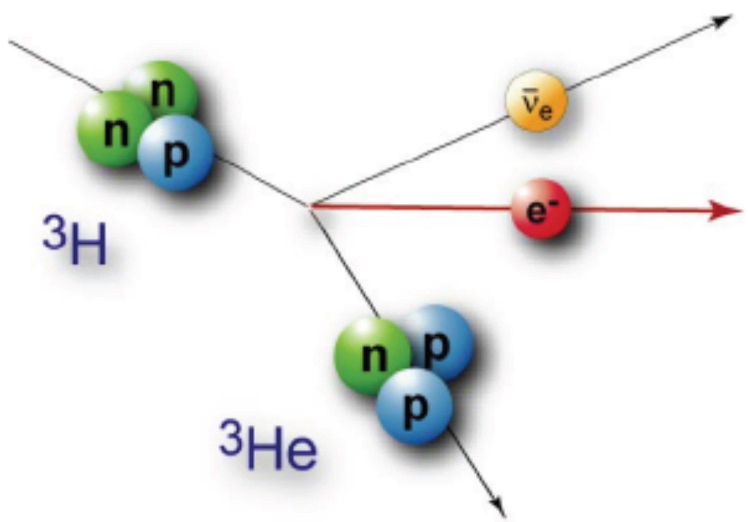
KATRIN: goal $m_\nu < 0.2$ eV (90% CL)





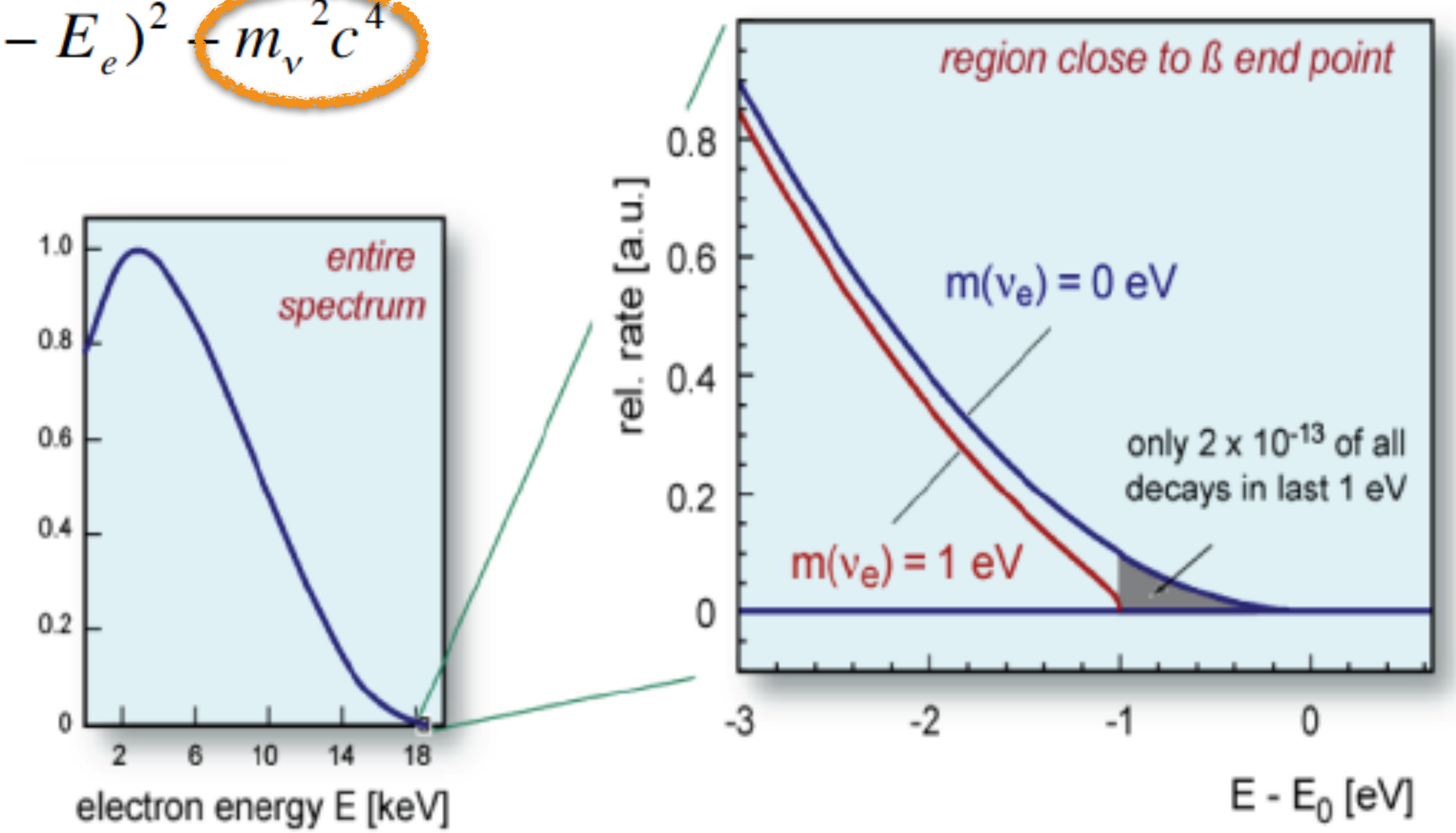
Search for a distortion in the shape of the beta spectrum in the endpoint energy region

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



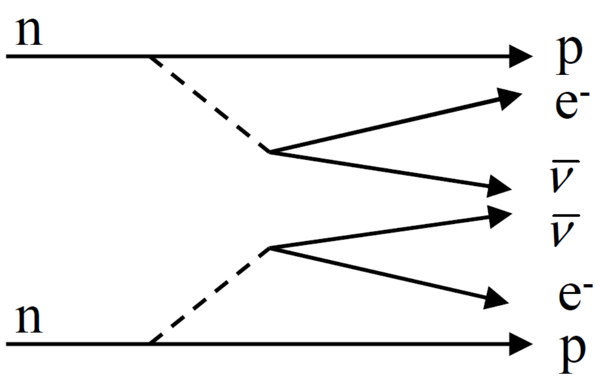
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$



Double beta decay experiments

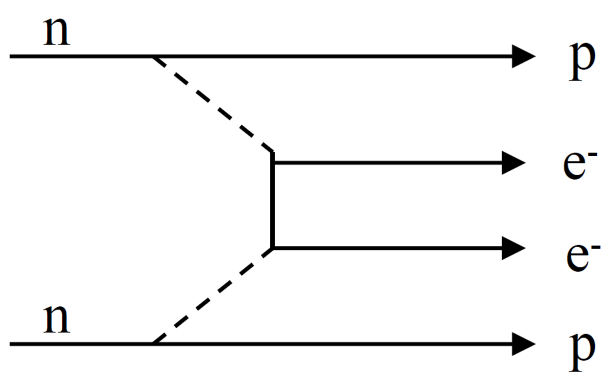
2νββ decay



$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}$

$T_{1/2} \sim 10^{21} y$

0νββ decay



$(Z,A) \rightarrow (Z+2,A) + 2e^-$

$T_{1/2} > 10^{25} y$

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

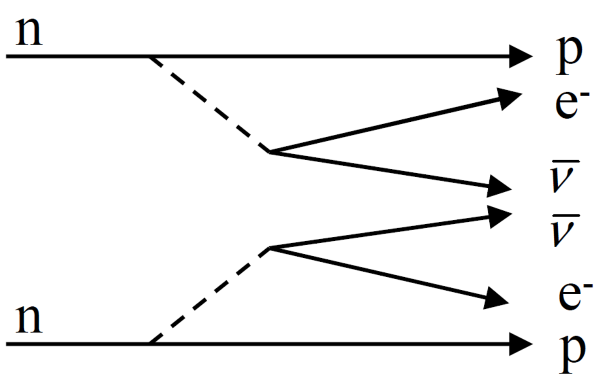
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$$

- **Double beta decay with neutrinos (2νββ)**
  - Observed in more than 10 isotopes
- **Neutrinoless double beta decay (0νββ)**
  - Violates the total lepton number conservation
  - It requires Majorana neutrino mass
  - Measurement: Effective Majorana neutrino mass $<m_{\beta\beta}>$

Maria Goeppert-Mayer

Double beta decay experiments

2νββ decay



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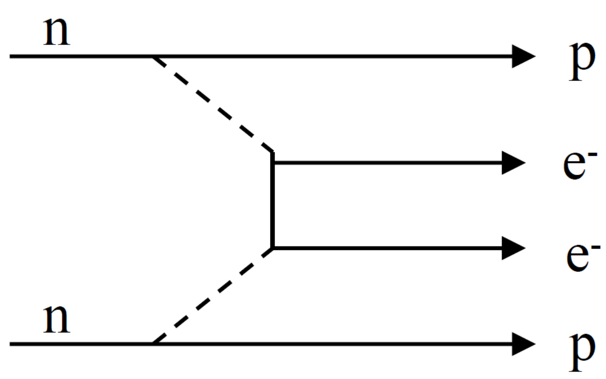

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Maria Goeppert-Mayer

Nobel Prize in Physics in 1963

Current and expected future limits

- 90% CL lower limits on $T^{0\nu}_{1/2}$ and upper bounds on $m_{\beta\beta}$

$\beta\beta^-$ decay	experiment	$T^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [eV]
${}^{48}_{20}\mathrm{Ca} \to {}^{48}_{22}\mathrm{Ti}$	ELEGANT-VI [119]	$> 1.4 \times 10^{22}$	$< 6.6 - 31$
${}^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se}$	Heidelberg-Moscow [224]	$> 1.9 \times 10^{25}$	$< 0.23 - 0.67$
	IGEX [226]	$> 1.6 \times 10^{25}$	$< 0.25 - 0.73$
	GERDA [32]	$> 2.1 \times 10^{25}$	$< 0.22 - 0.64$
${}^{82}_{34}\mathrm{Se} \to {}^{82}_{36}\mathrm{Kr}$	NEMO-3 [120]	$> 1.0 \times 10^{23}$	$< 1.8 - 4.7$
${}^{100}_{42}\mathrm{Mo} \to {}^{100}_{44}\mathrm{Ru}$	NEMO-3 [121]	$> 2.1 \times 10^{25}$	$< 0.32 - 0.88$
${}^{116}_{48}\mathrm{Cd} \to {}^{116}_{50}\mathrm{Sn}$	Solotvina [234]	$> 1.7 \times 10^{23}$	$< 1.5 - 2.5$
${}^{128}_{52}\mathrm{Te} \to {}^{128}_{54}\mathrm{Xe}$	CUORICINO [235]	$> 1.1 \times 10^{23}$	$< 7.2 - 18$
${}^{130}_{52}\mathrm{Te} \to {}^{130}_{54}\mathrm{Xe}$	CUORICINO [236]	$> 2.8 \times 10^{24}$	$< 0.32 - 1.2$
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{56}\mathrm{Ba}$	EXO [239]	$> 1.1 \times 10^{25}$	$< 0.2 - 0.69$
	KamLAND-Zen [241]	$> 1.9 \times 10^{25}$	$< 0.15 - 0.52$
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$	NEMO-3 [243]	$> 2.1 \times 10^{25}$	$< 2.6 - 10$

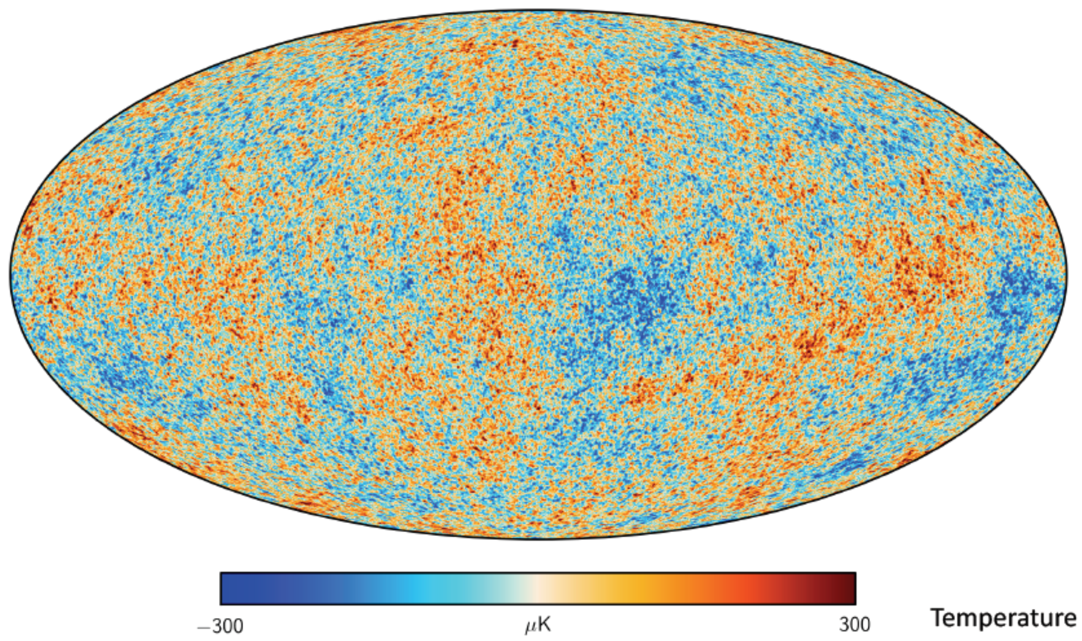
arXiv:1411.4791

- Next generation of experiments between 100 kg and 1 ton with different isotopes and different experimental techniques

- Goal: **$\langle m_{\beta\beta} \rangle \sim 0.01 - 0.1$ eV**

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_{eff})



- Best combined limits:

  $\Sigma m_\nu \leq 0.23$ eV (95% CL)

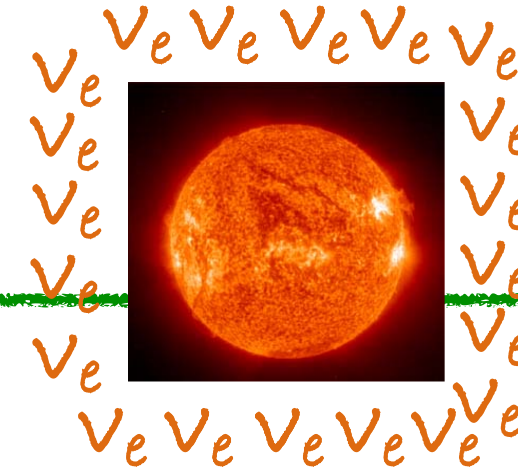
  Planck TT + low P + lensing + ext (BAO + JLA + H_0)

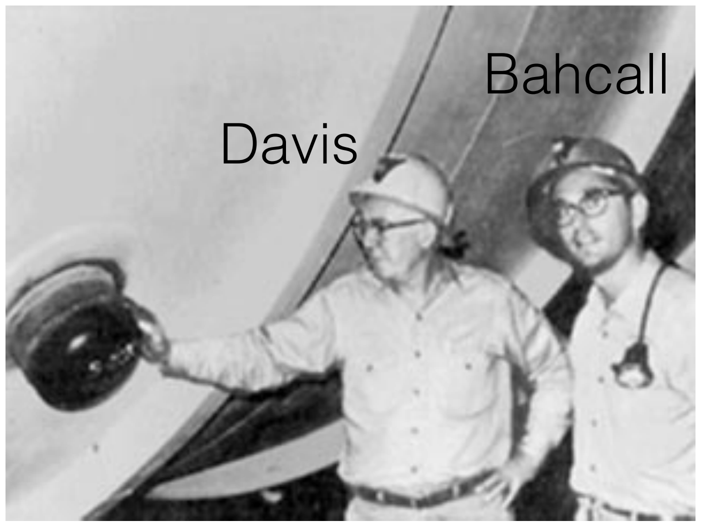
  Neff = 3.04 ± 0.18

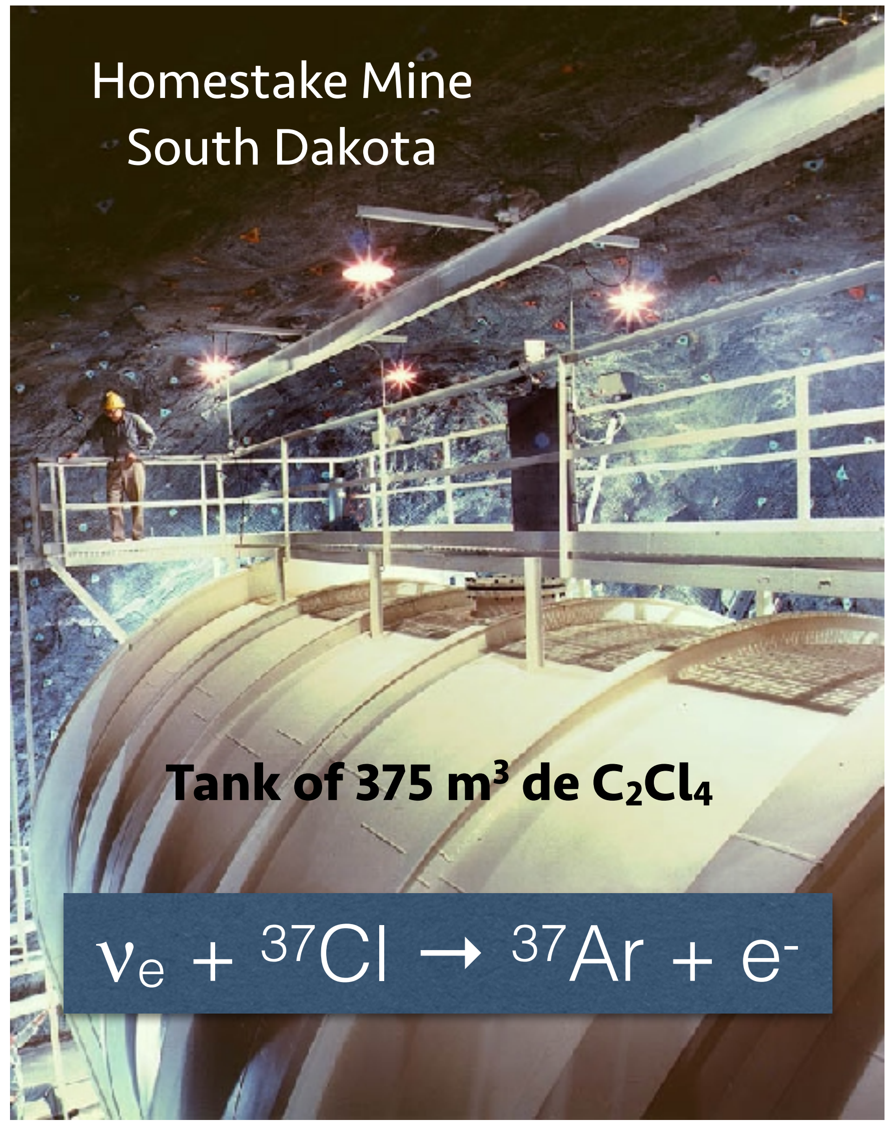
  Planck TT, TE, EE + lowP+ BAO

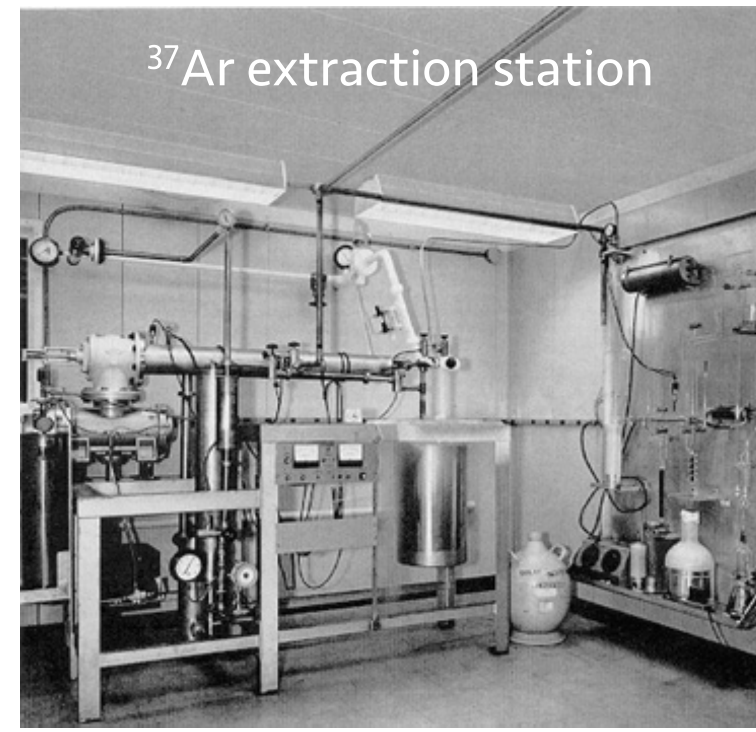
arXiv:1502.01589

Solar neutrinos

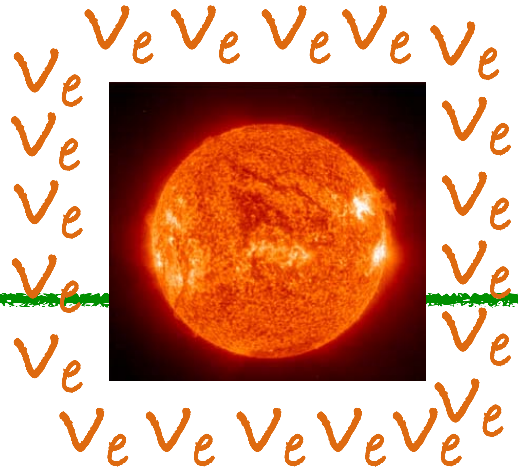


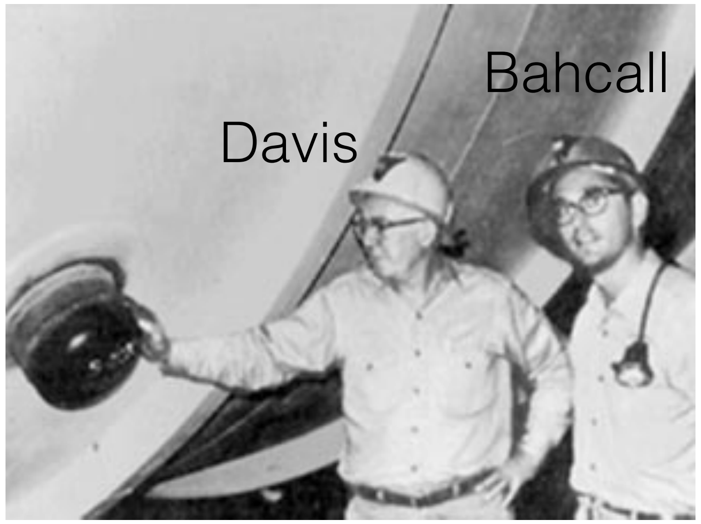


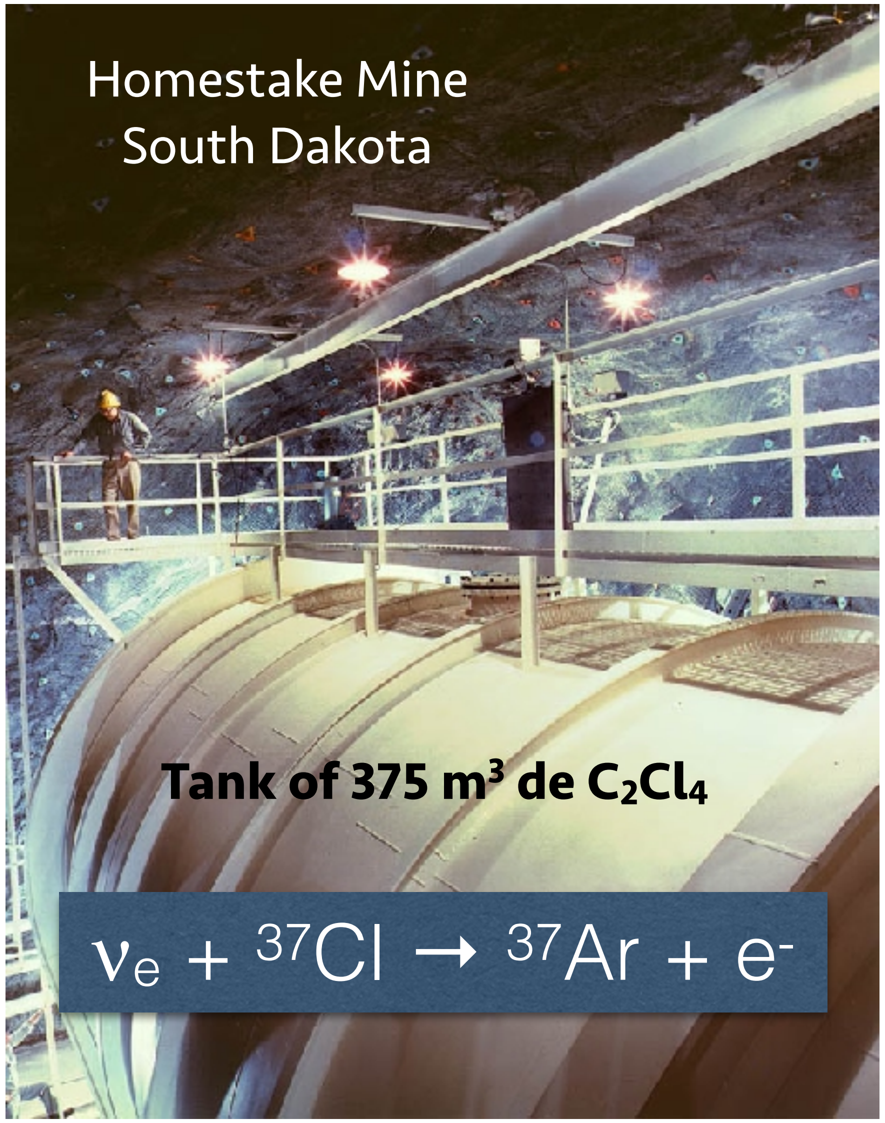


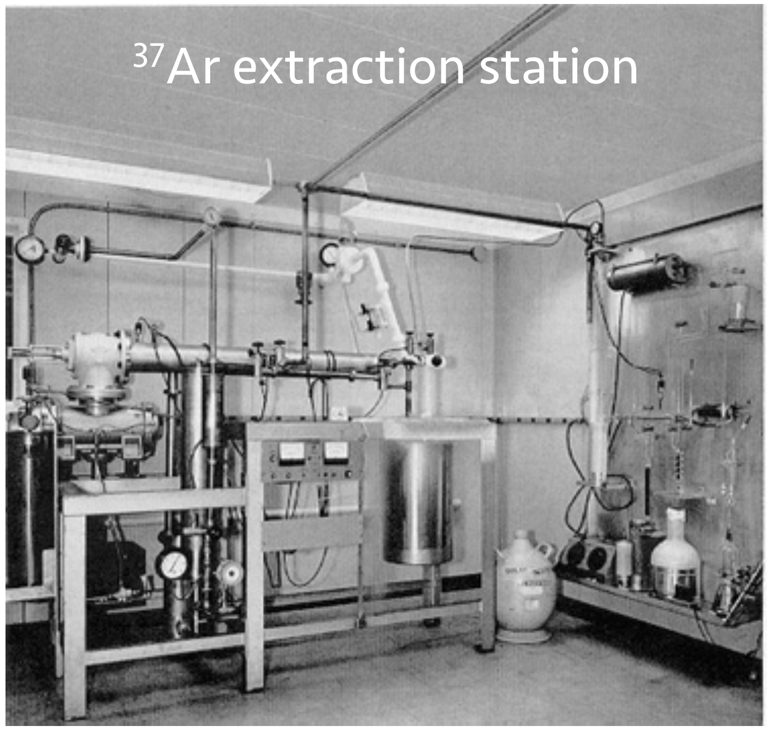


Solar neutrinos



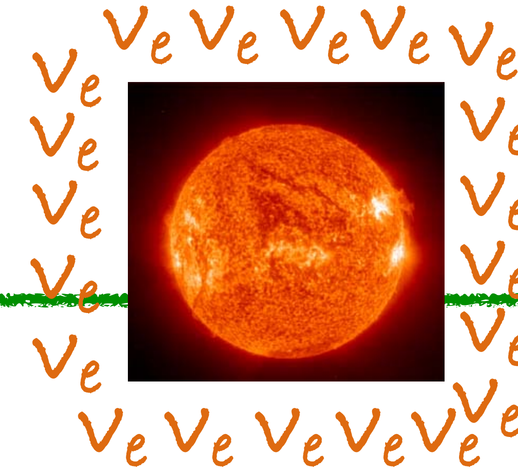


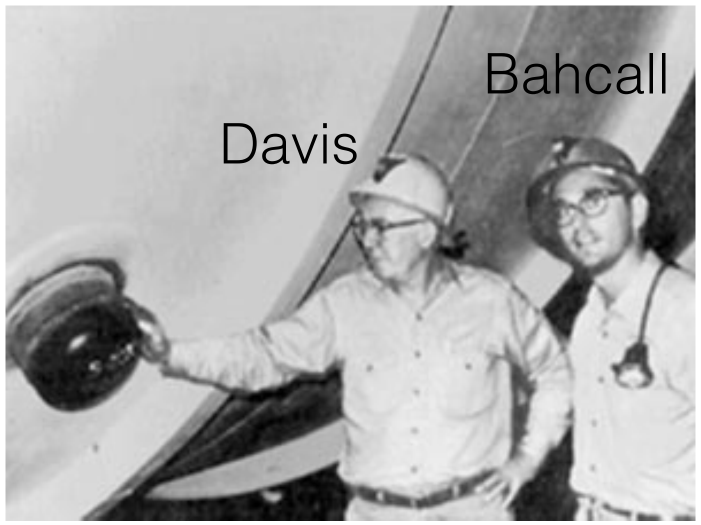


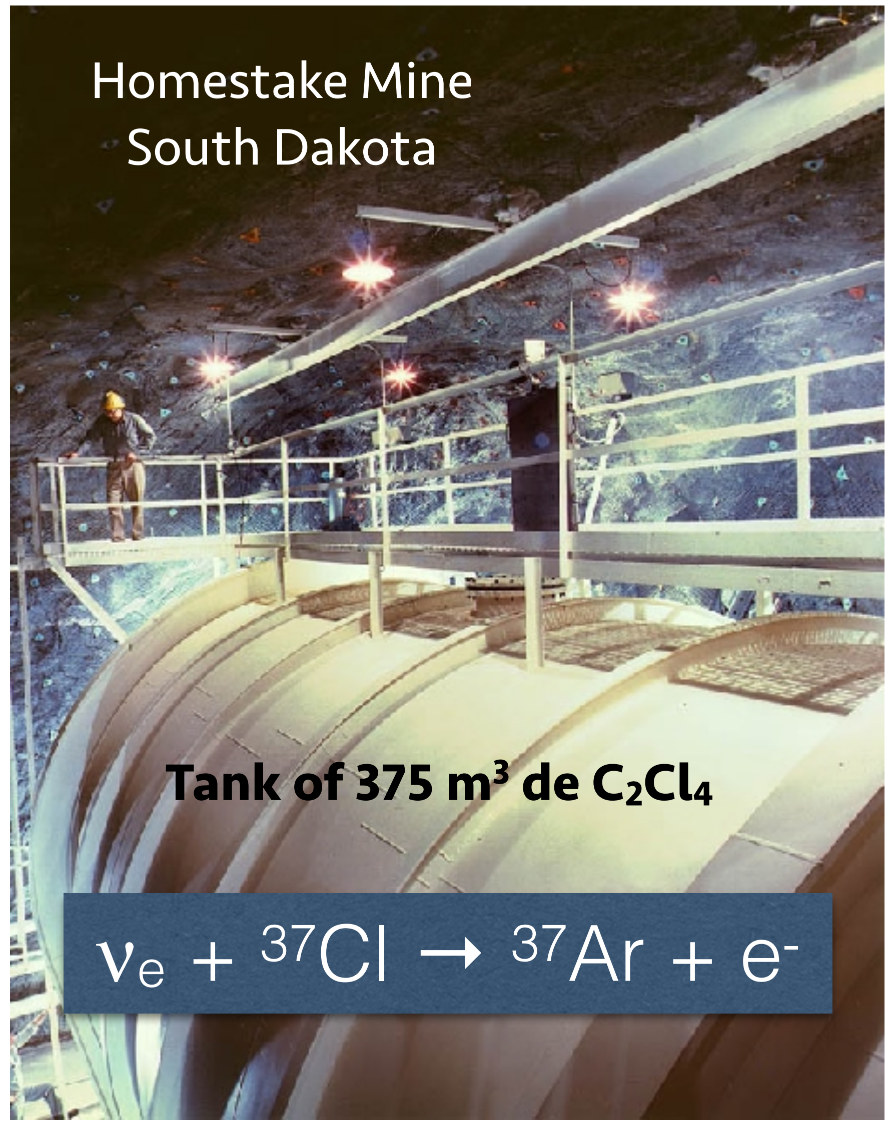


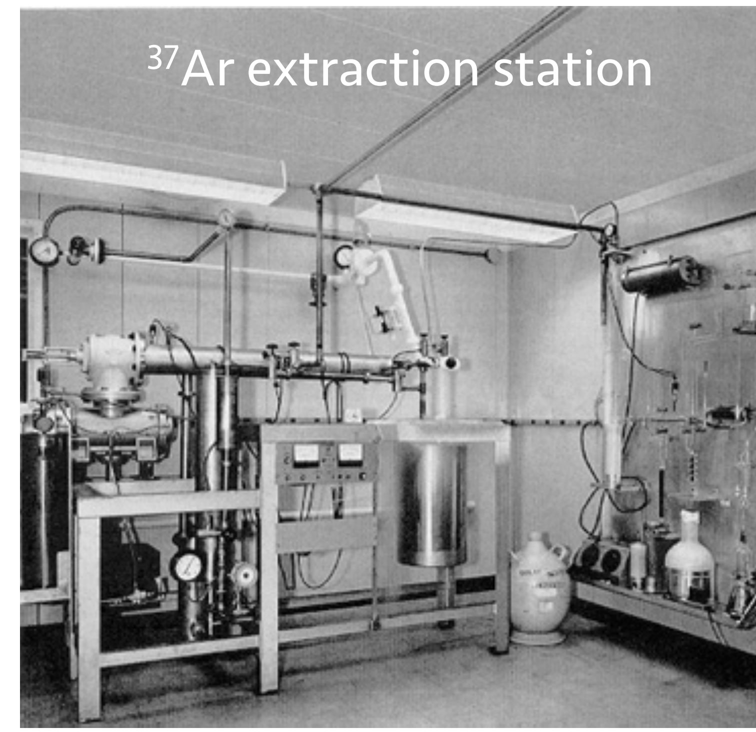
Prediction (J. Bahcall): 1 Ar atom per day

Solar neutrinos



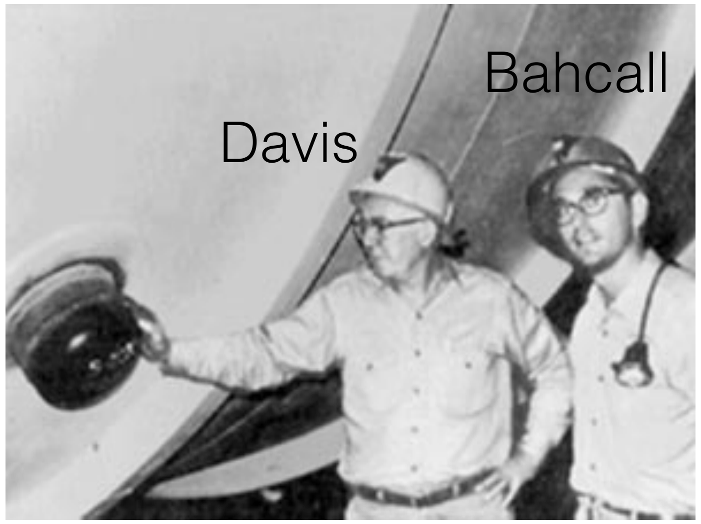


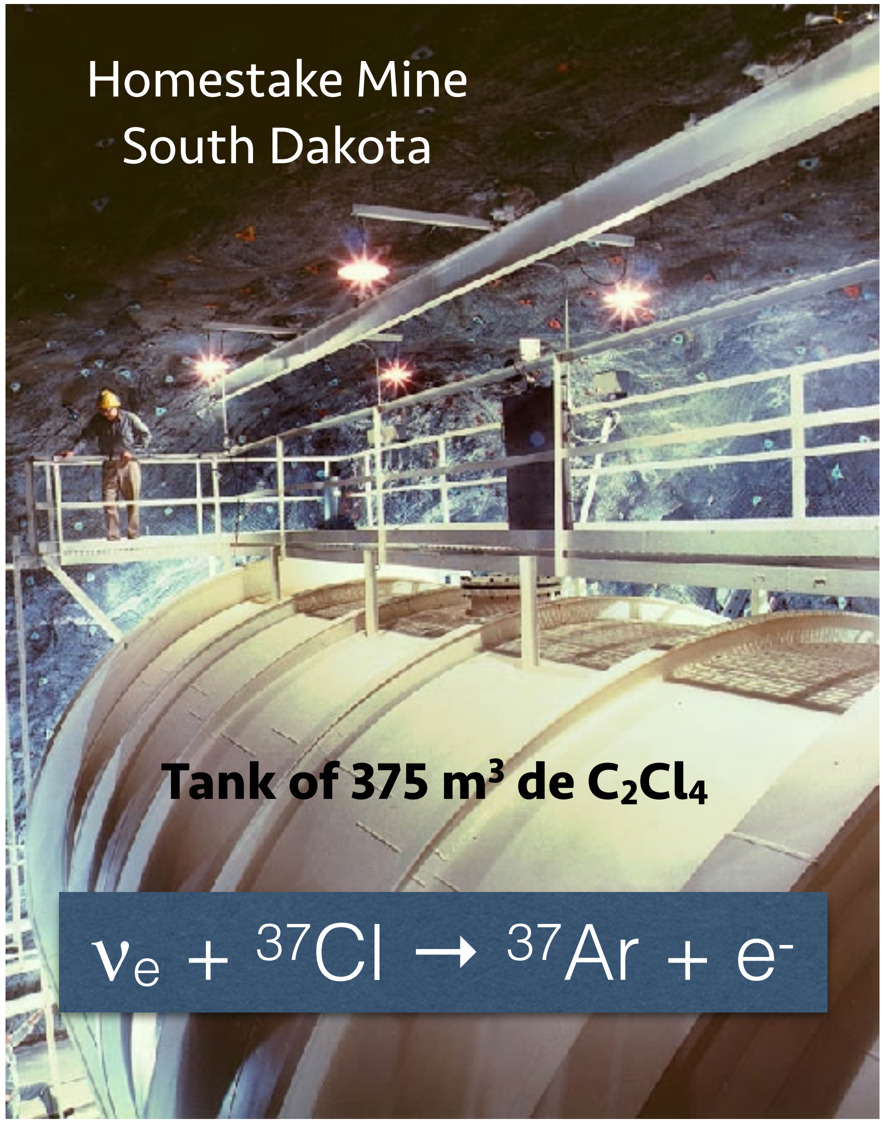


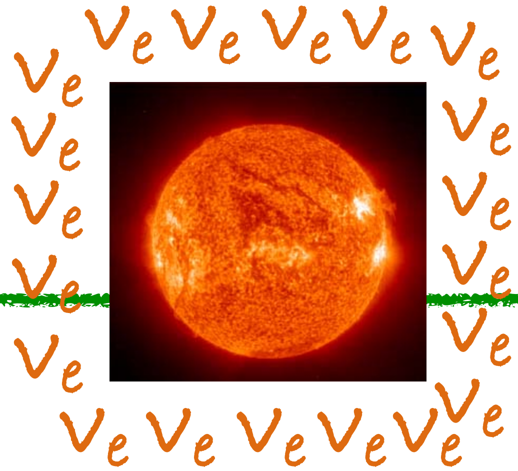


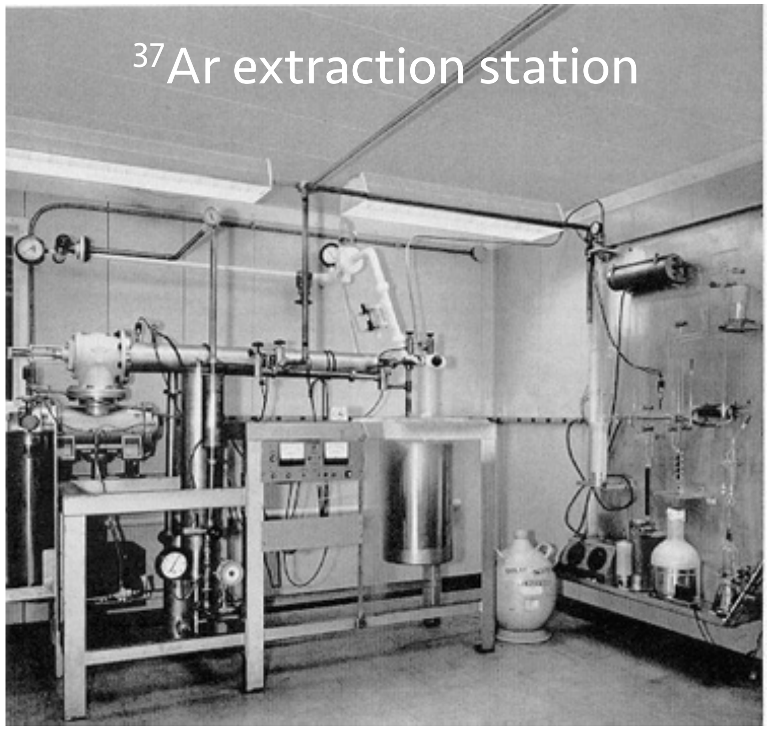
Prediction (J. Bahcall): 1 Ar atom per day
Measurement (R. Davis): 1/3 of prediction!!

Solar neutrinos









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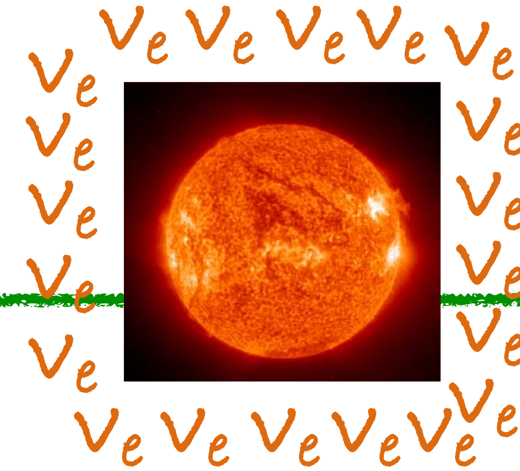
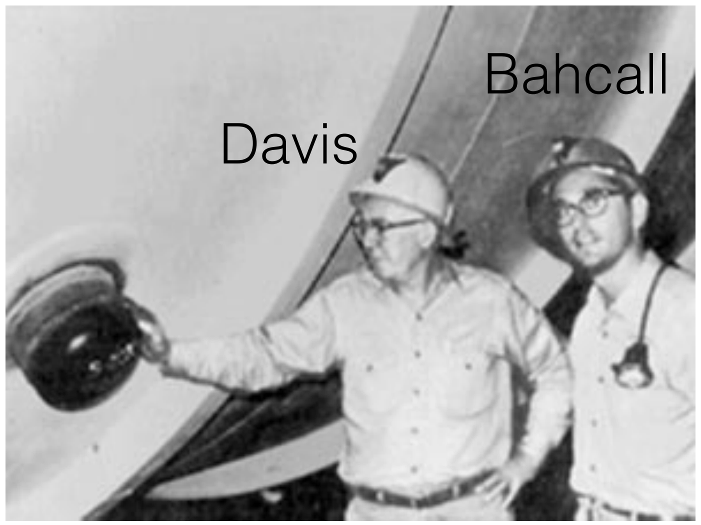
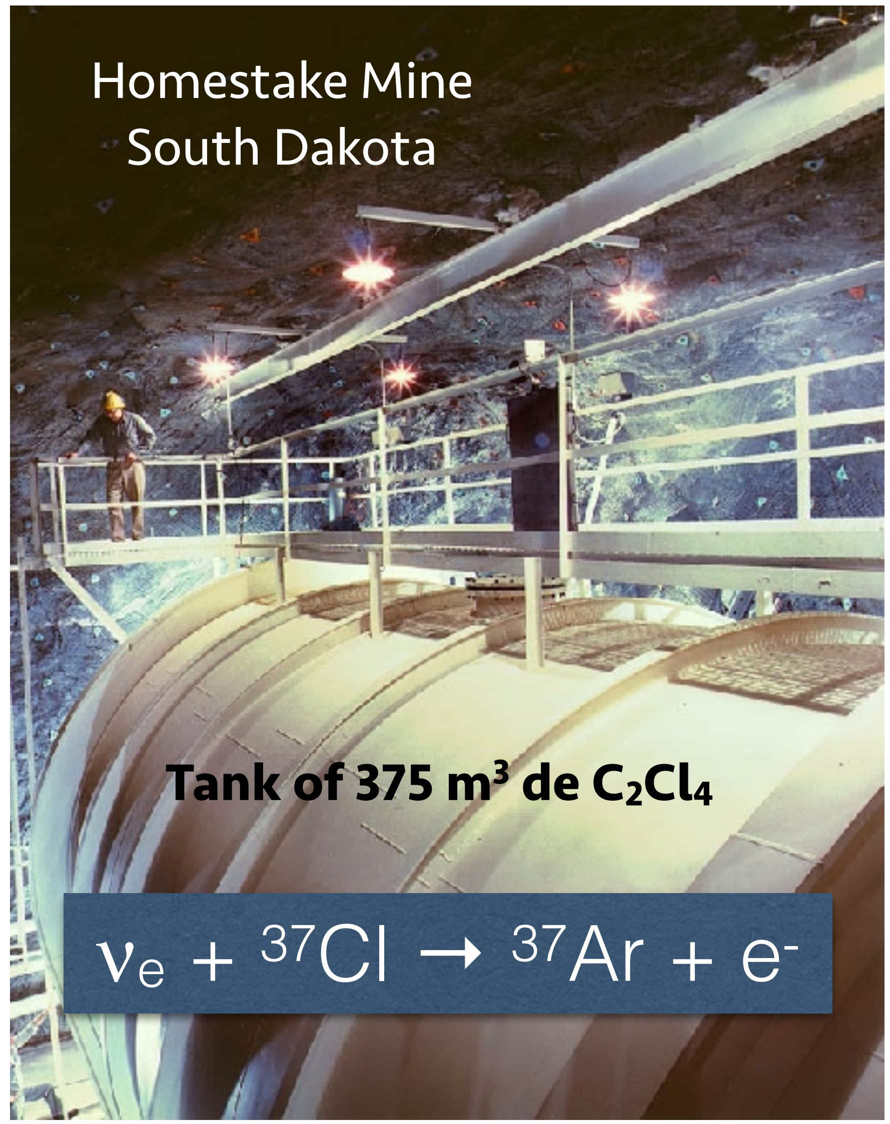
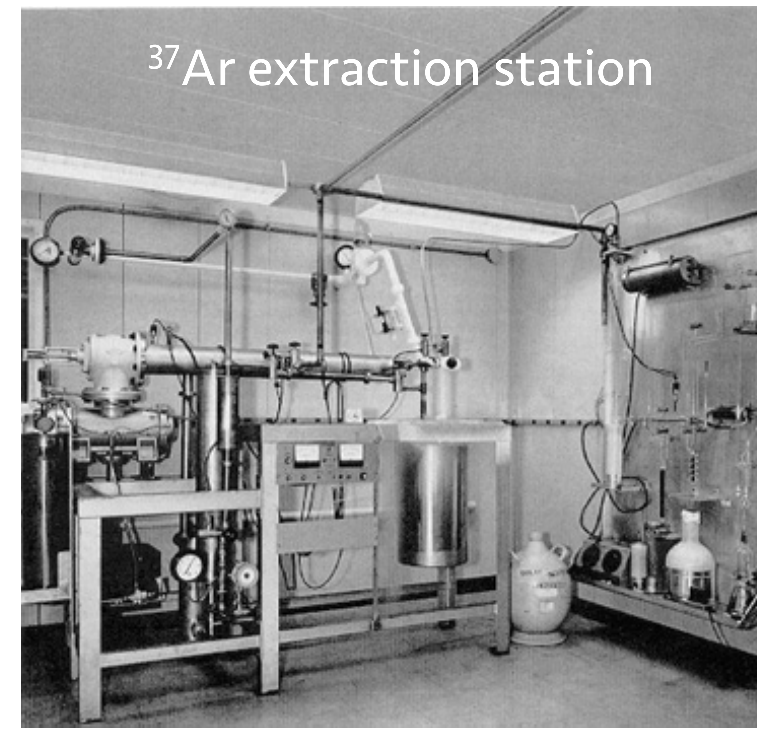
Solar neutrinos









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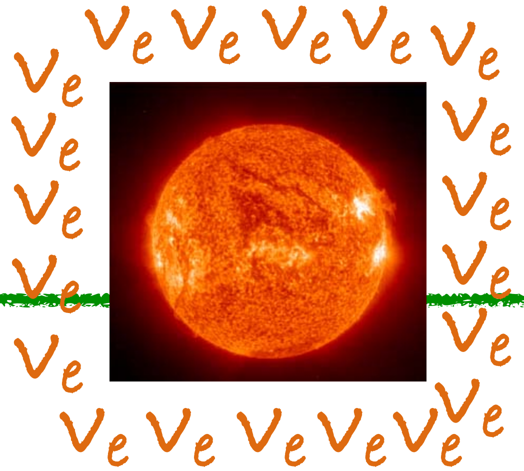
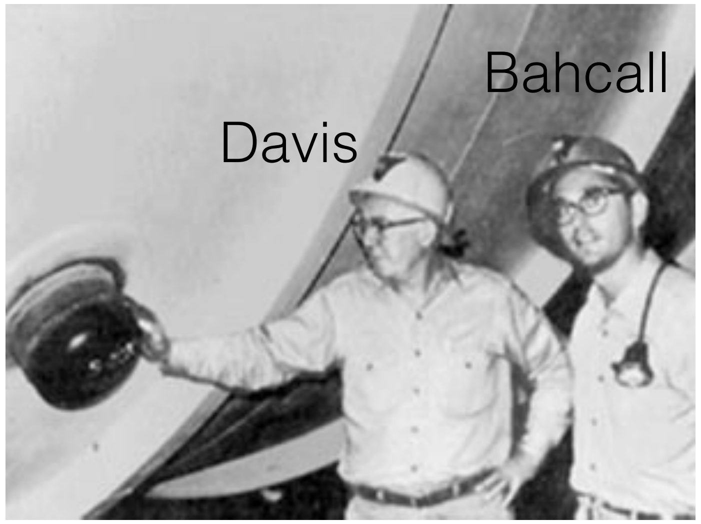
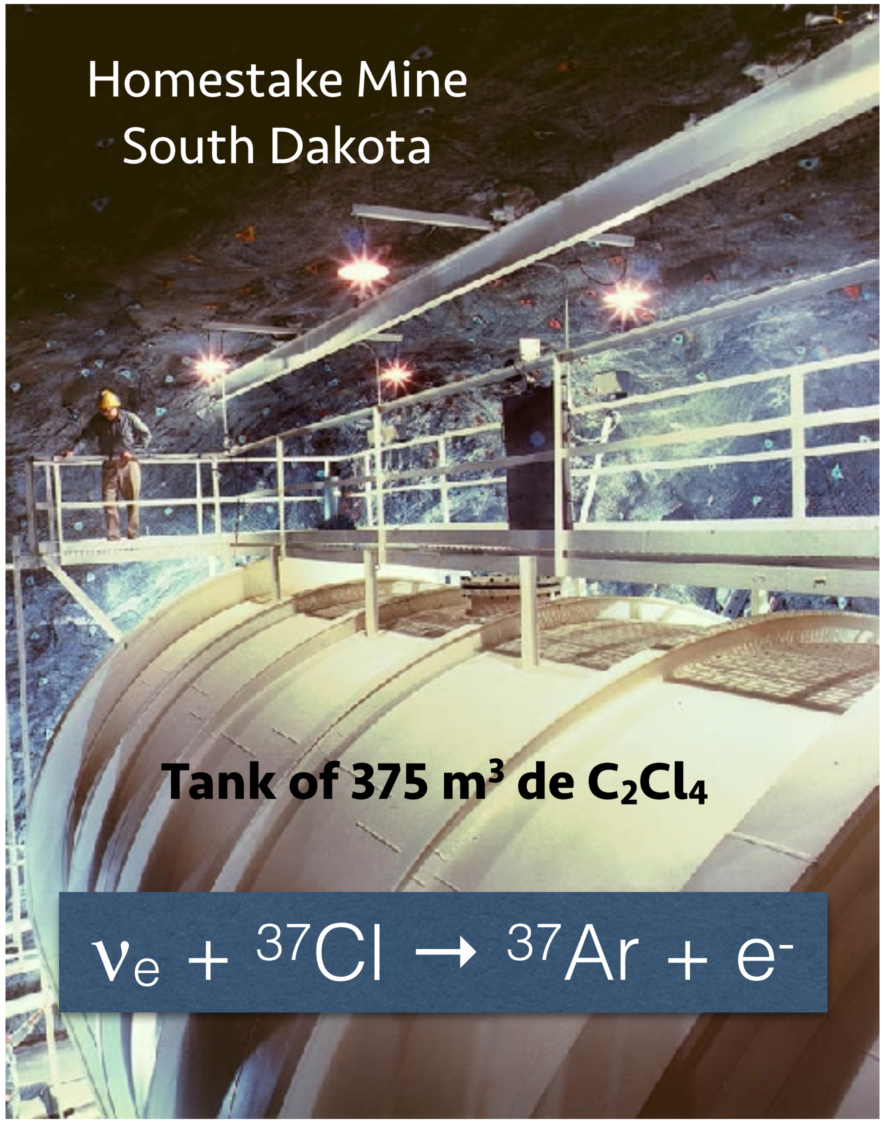
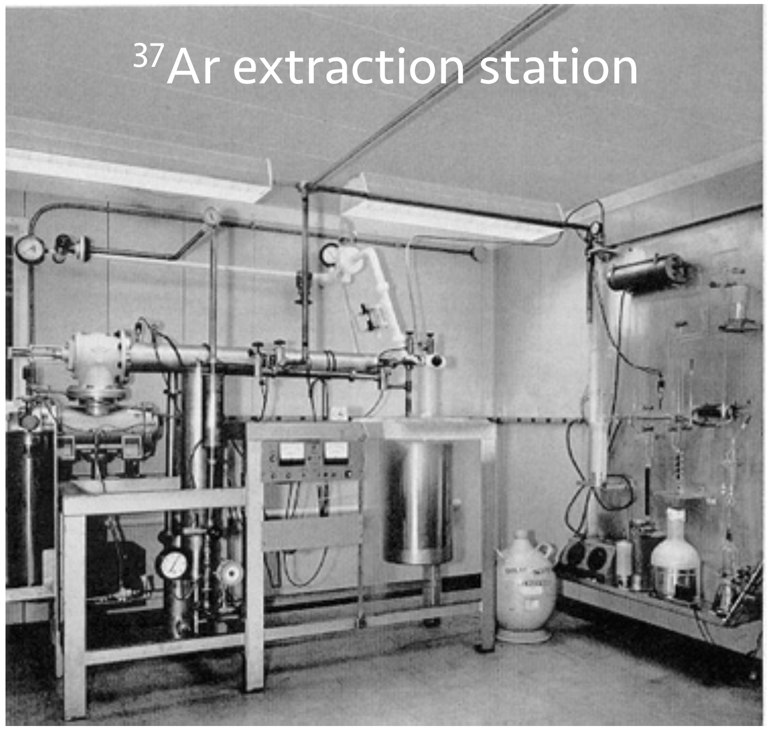
The discrepancy would go without explanation for more than 30 years

Solar neutrinos









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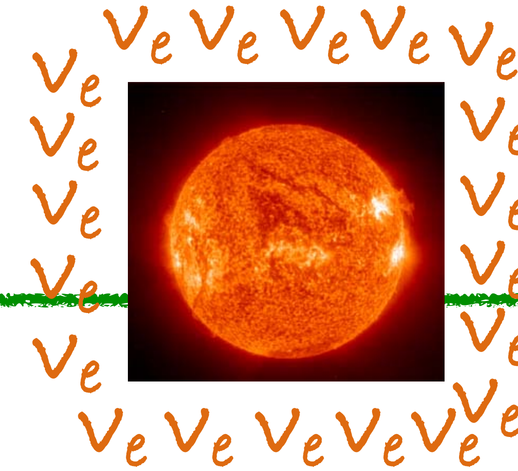
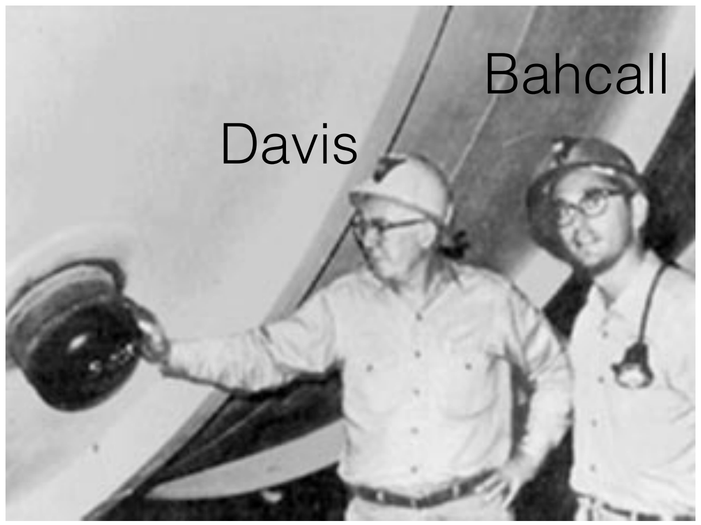
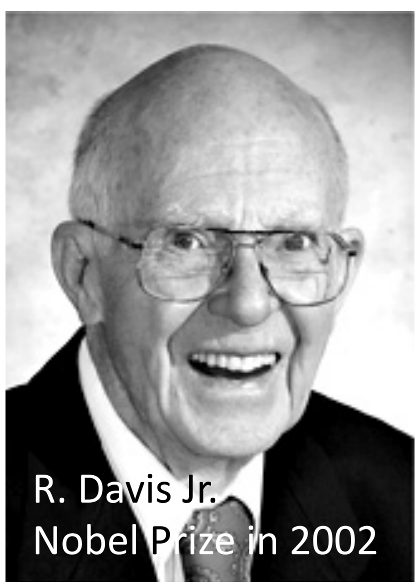
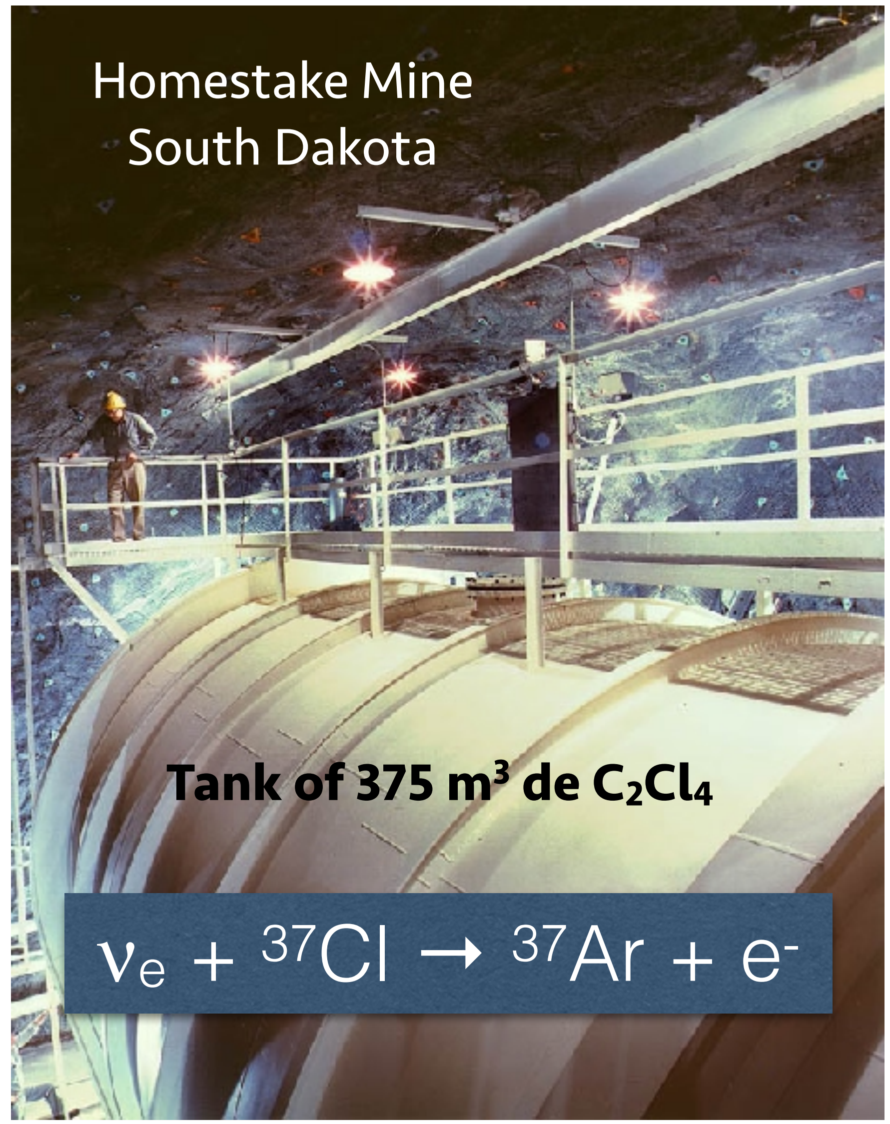
(1968-2001)

Solar neutrinos

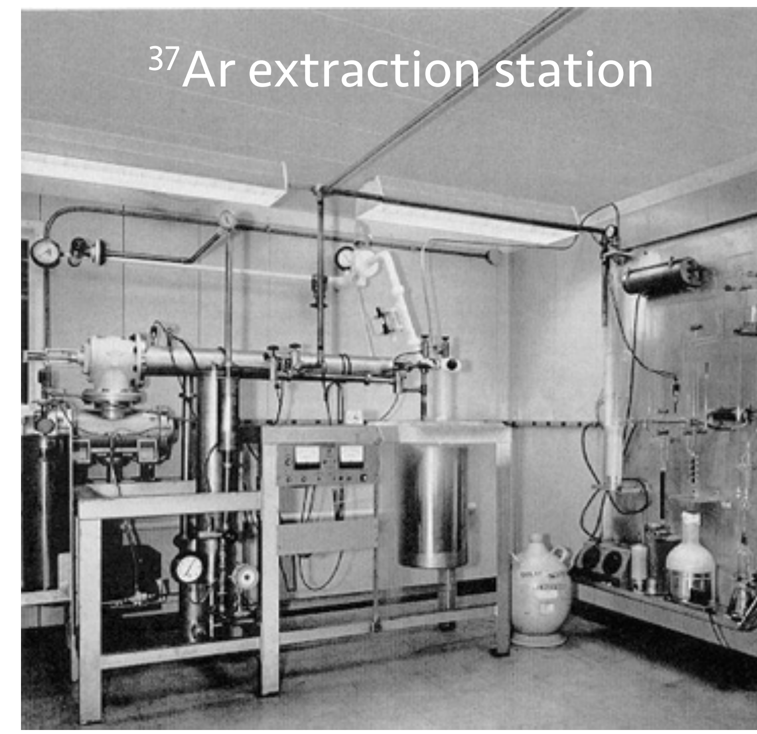








$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$



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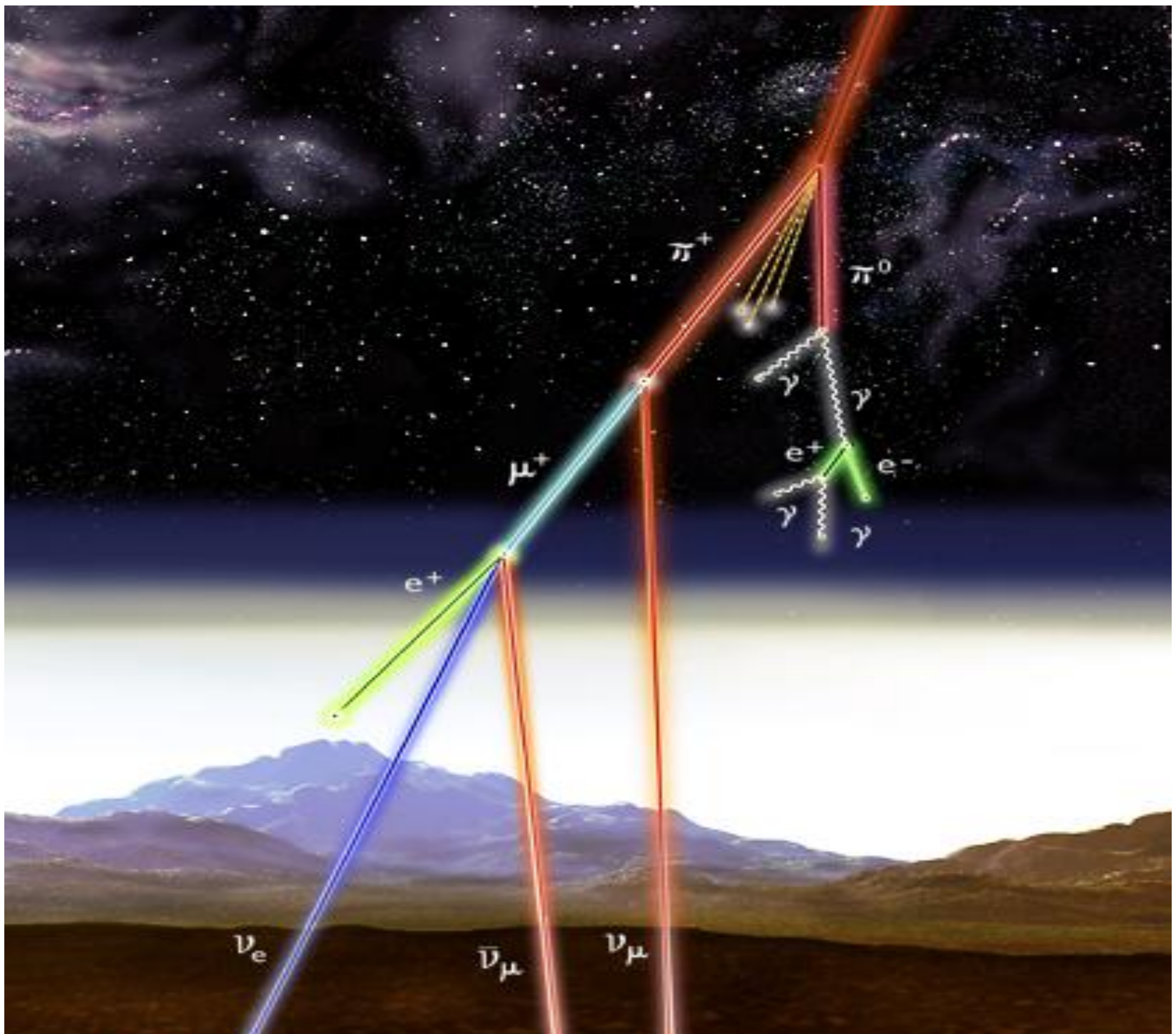
Atmospheric neutrinos

Kamiokande and IMB detected atmospheric neutrinos in the 80's



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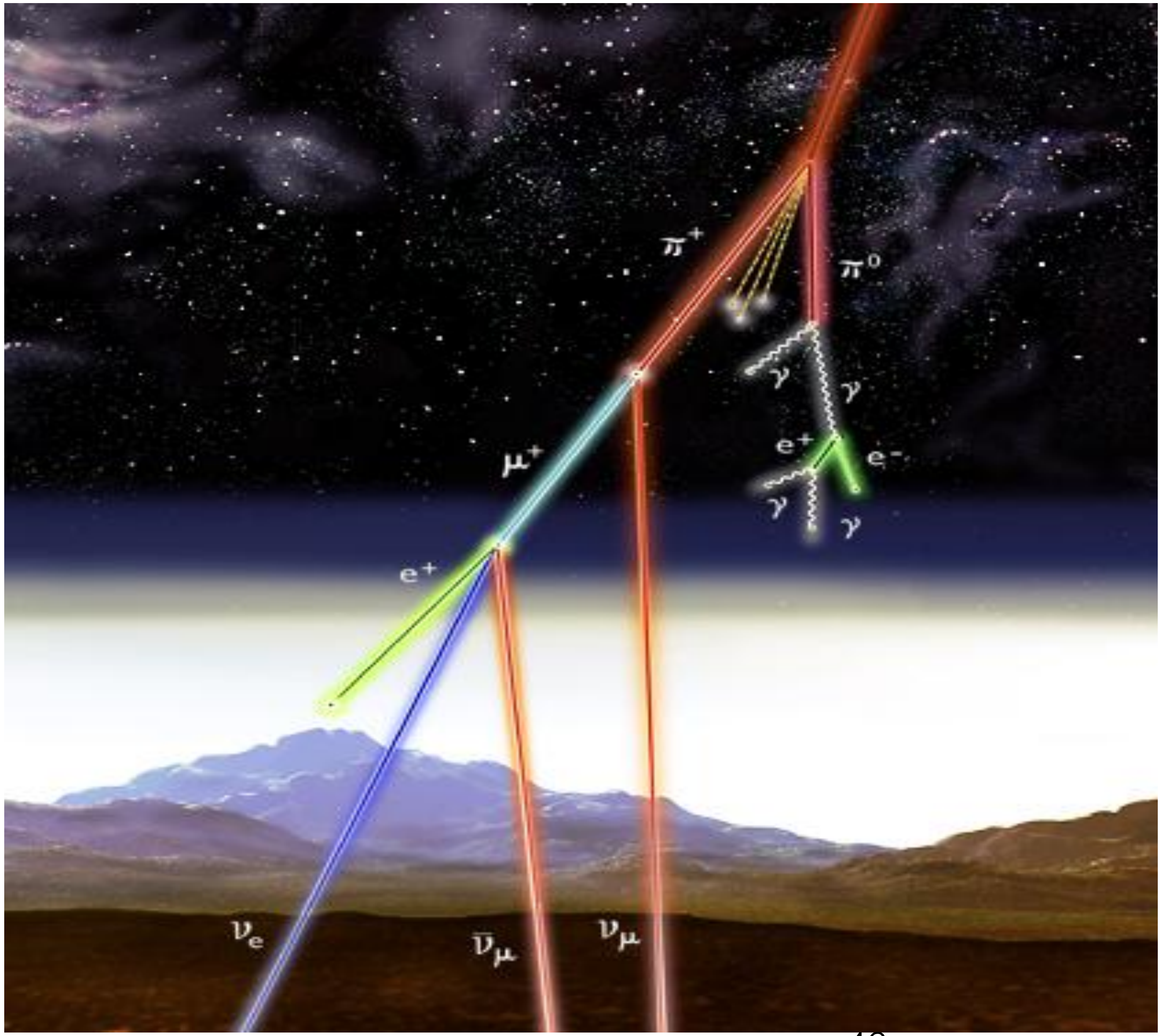
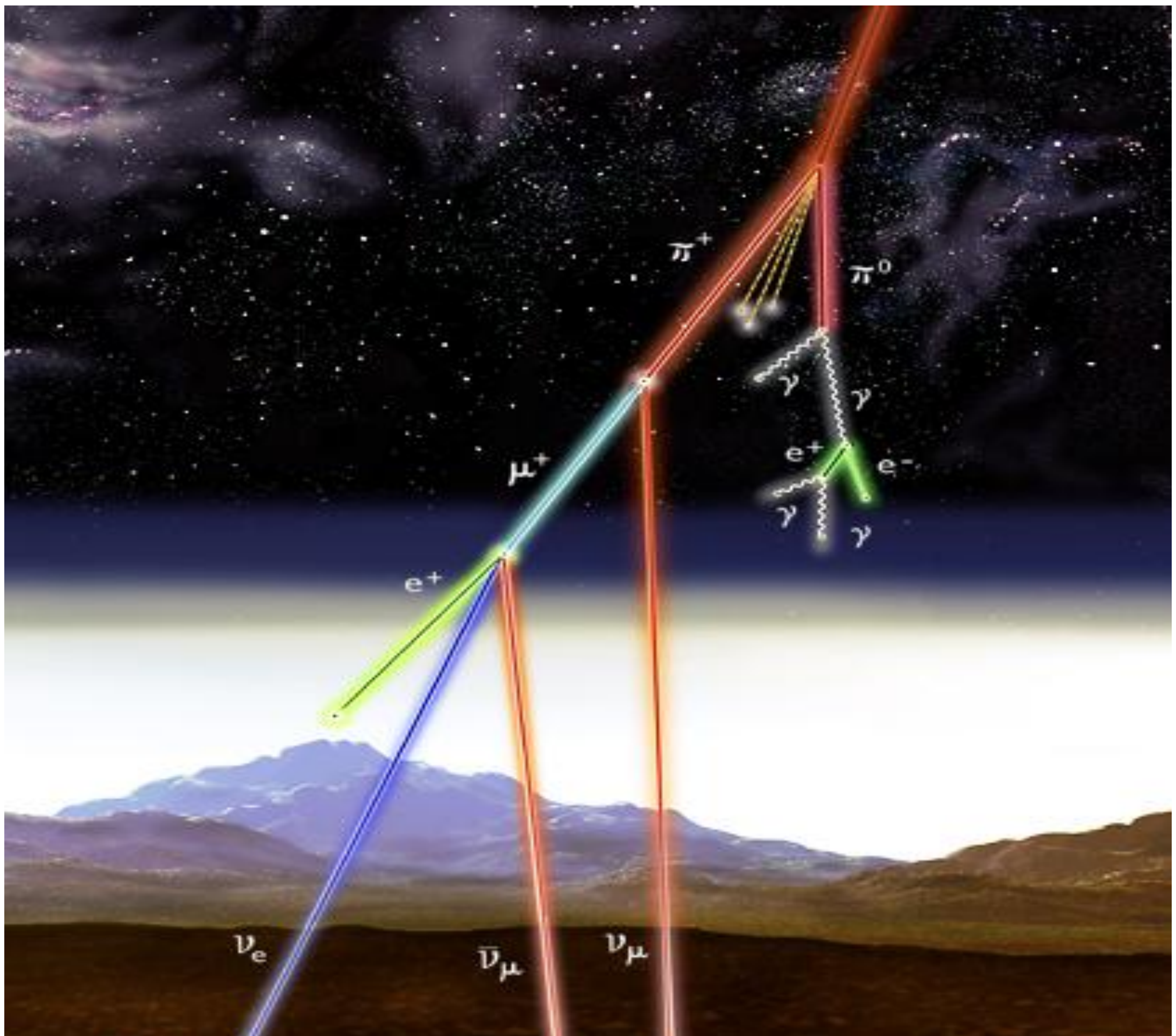


- **Expected:** 2 times more ν_μ than ν_e

Atmospheric neutrinos

Kamiokande and IMB detected atmospheric neutrinos in the 80's



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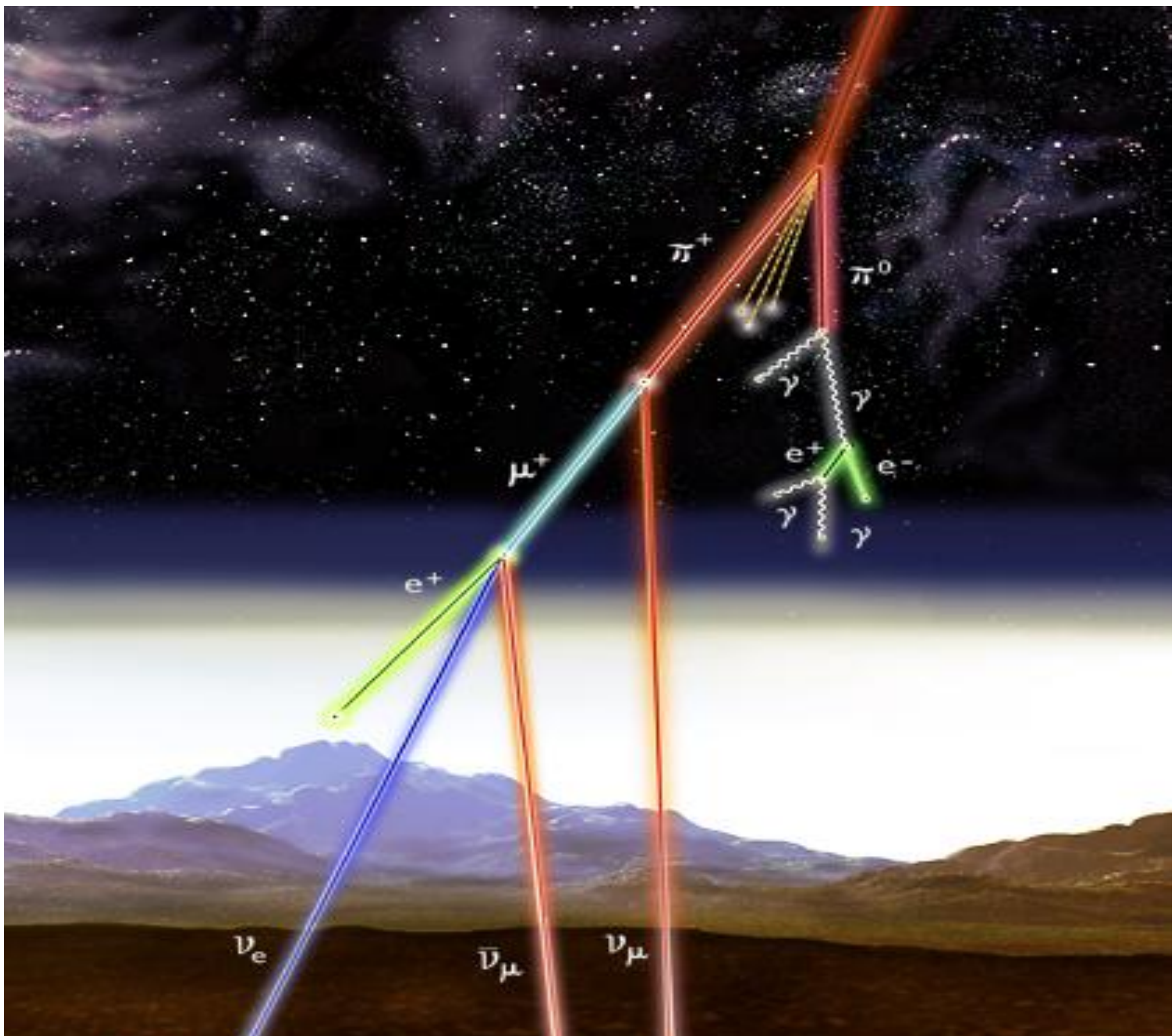

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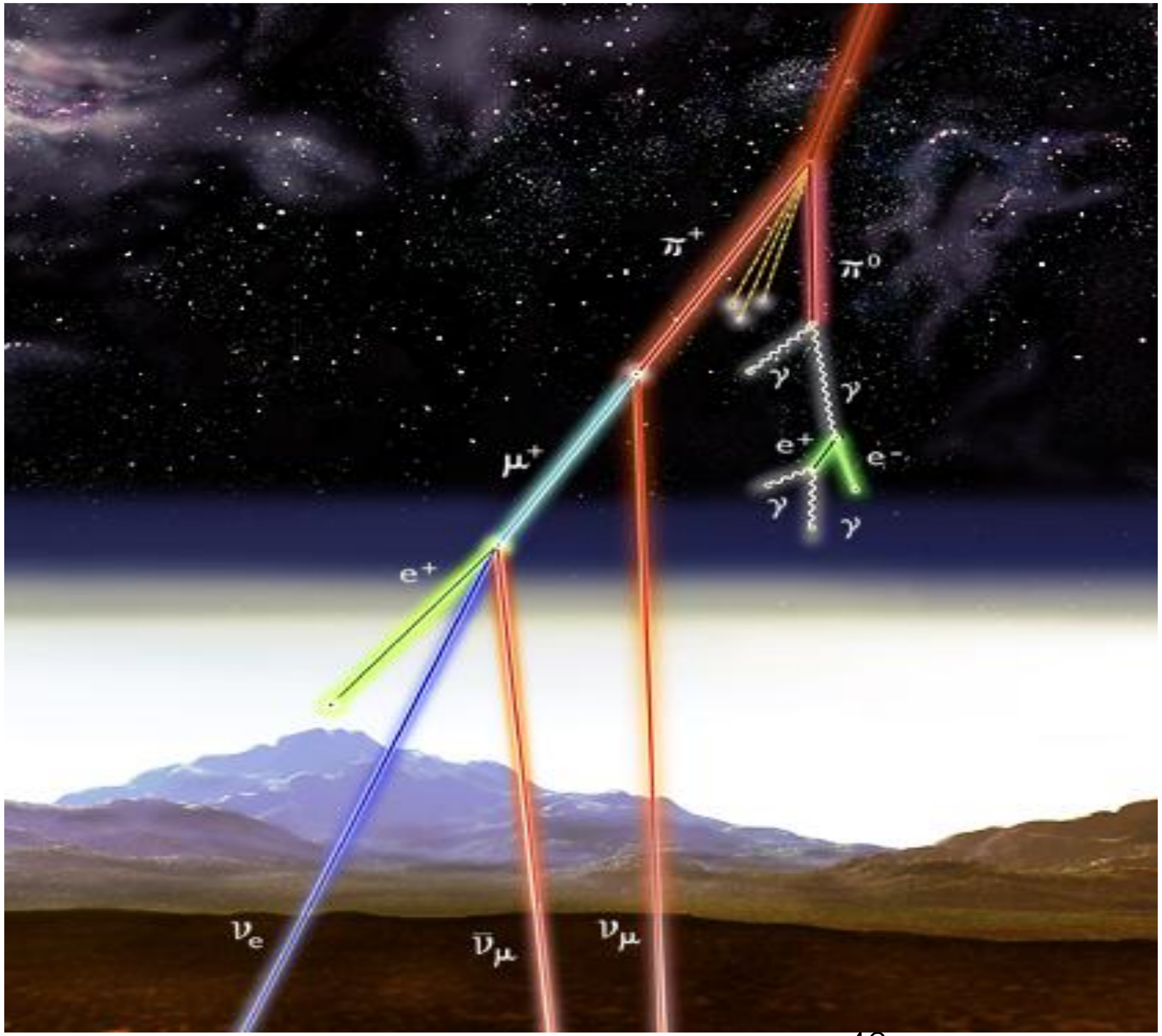

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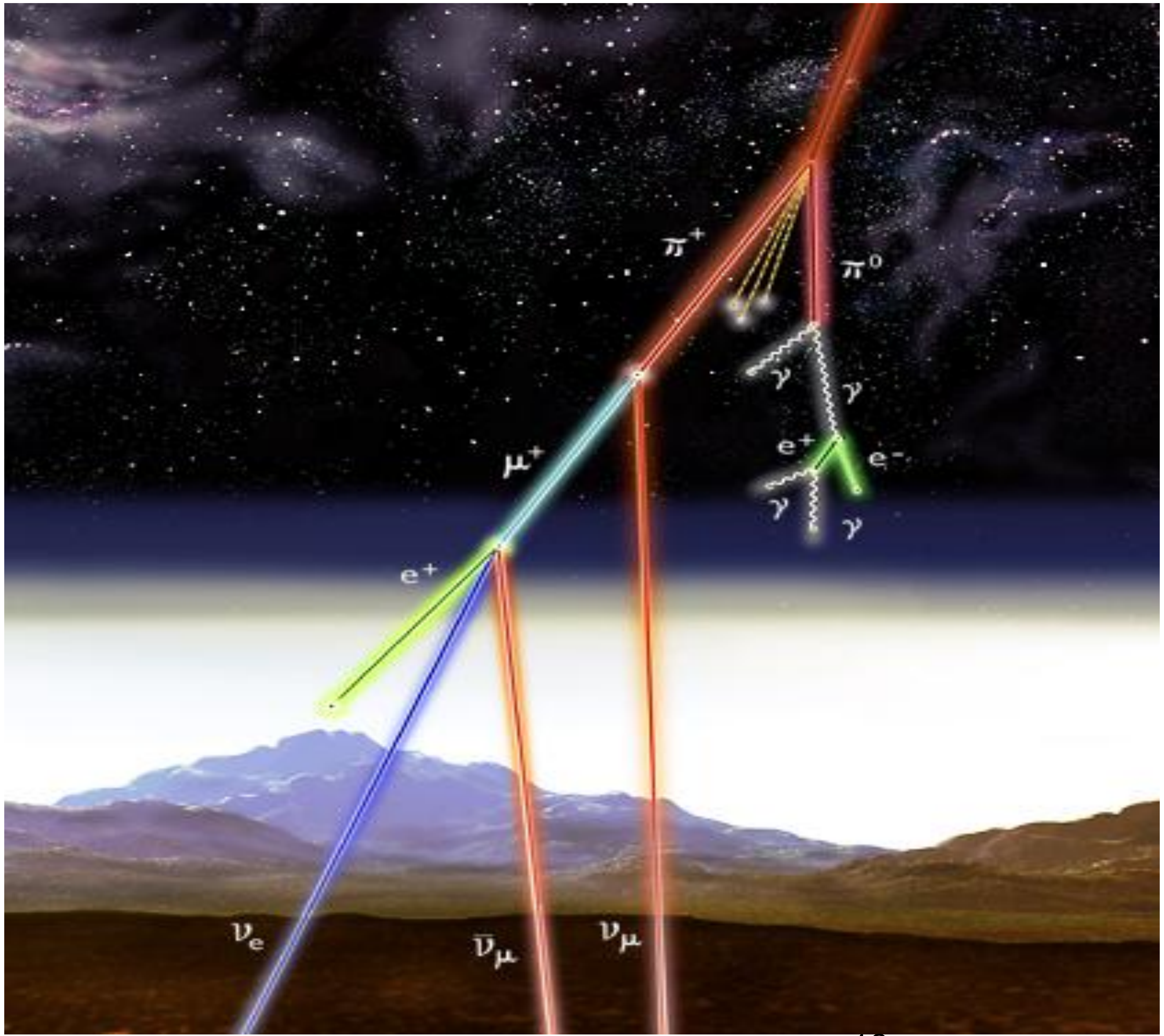

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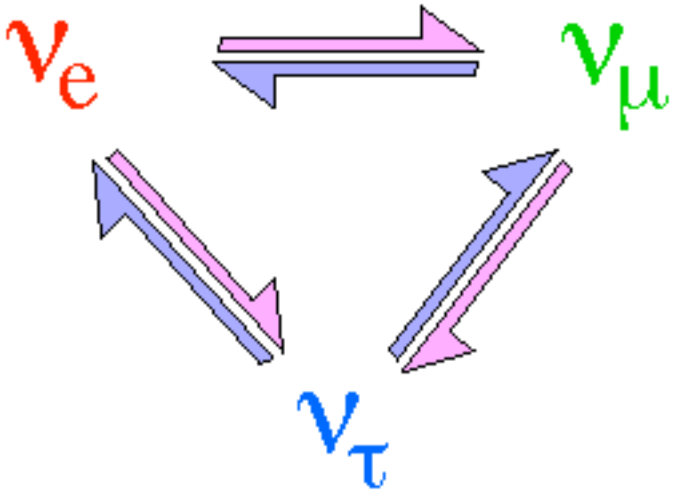
Where are the neutrinos going?

The idea of oscillations

B. Pontecorvo (1957)

Quantum interference phenomenon in which a neutrino of a certain flavor is transformed into a neutrino of a different flavor



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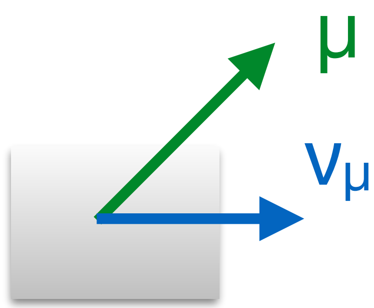

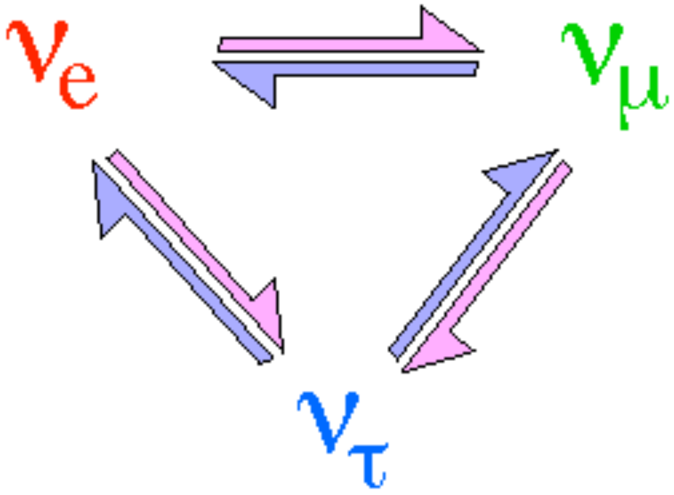

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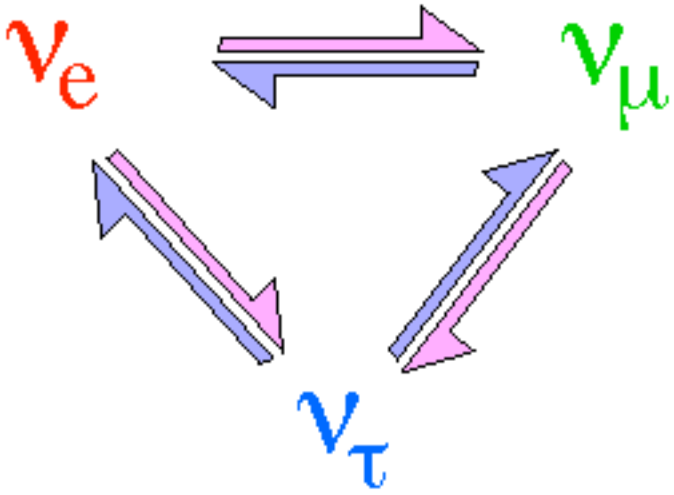

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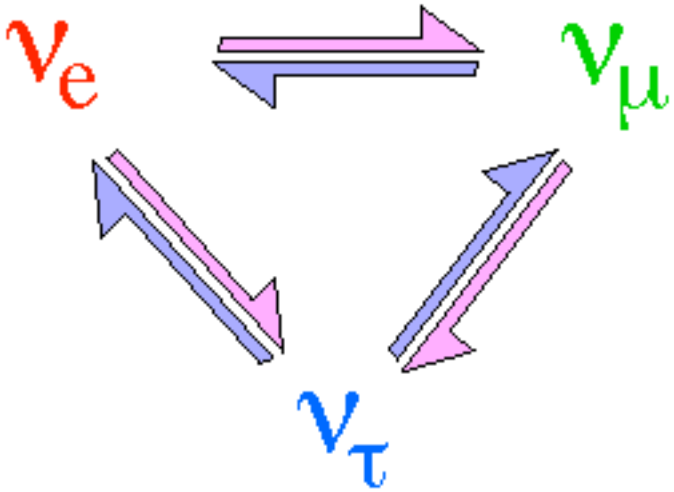

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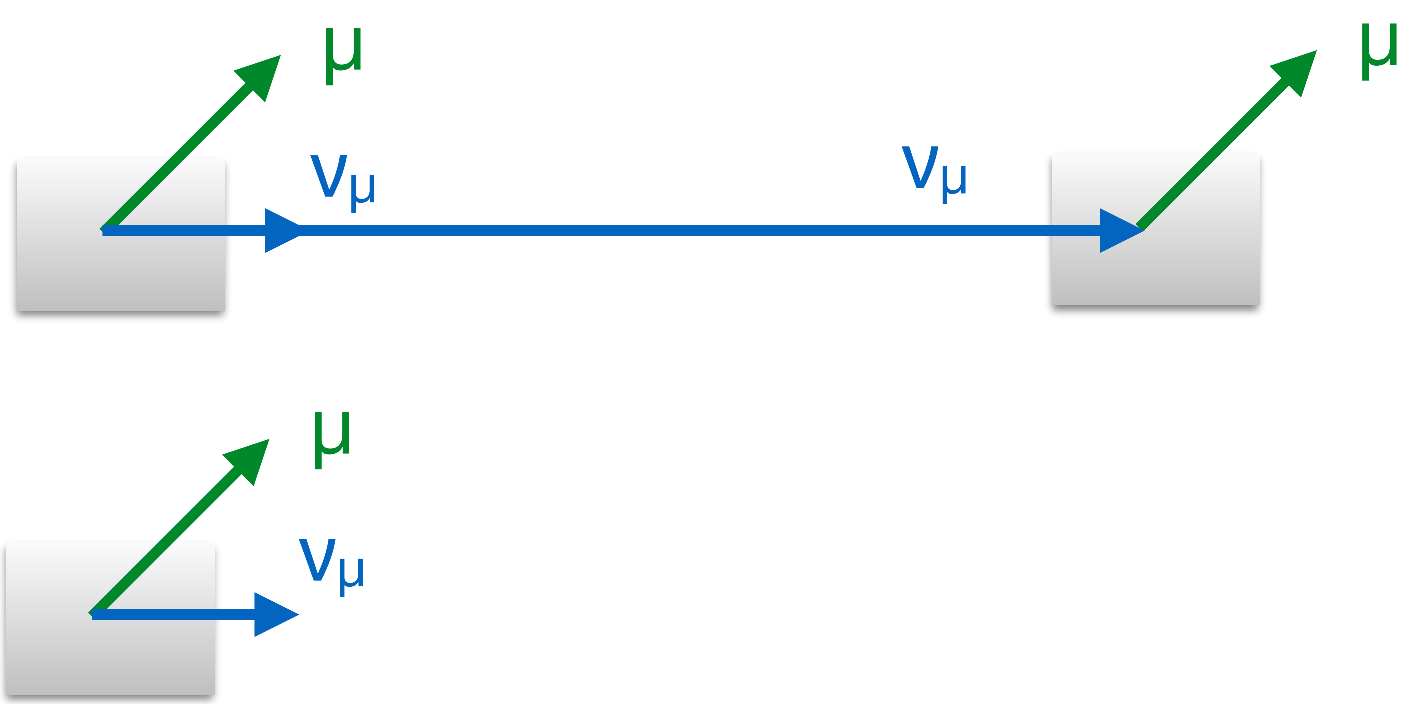

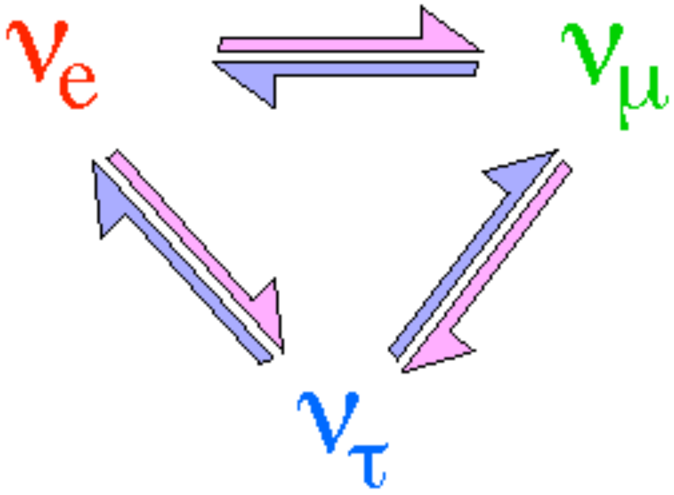

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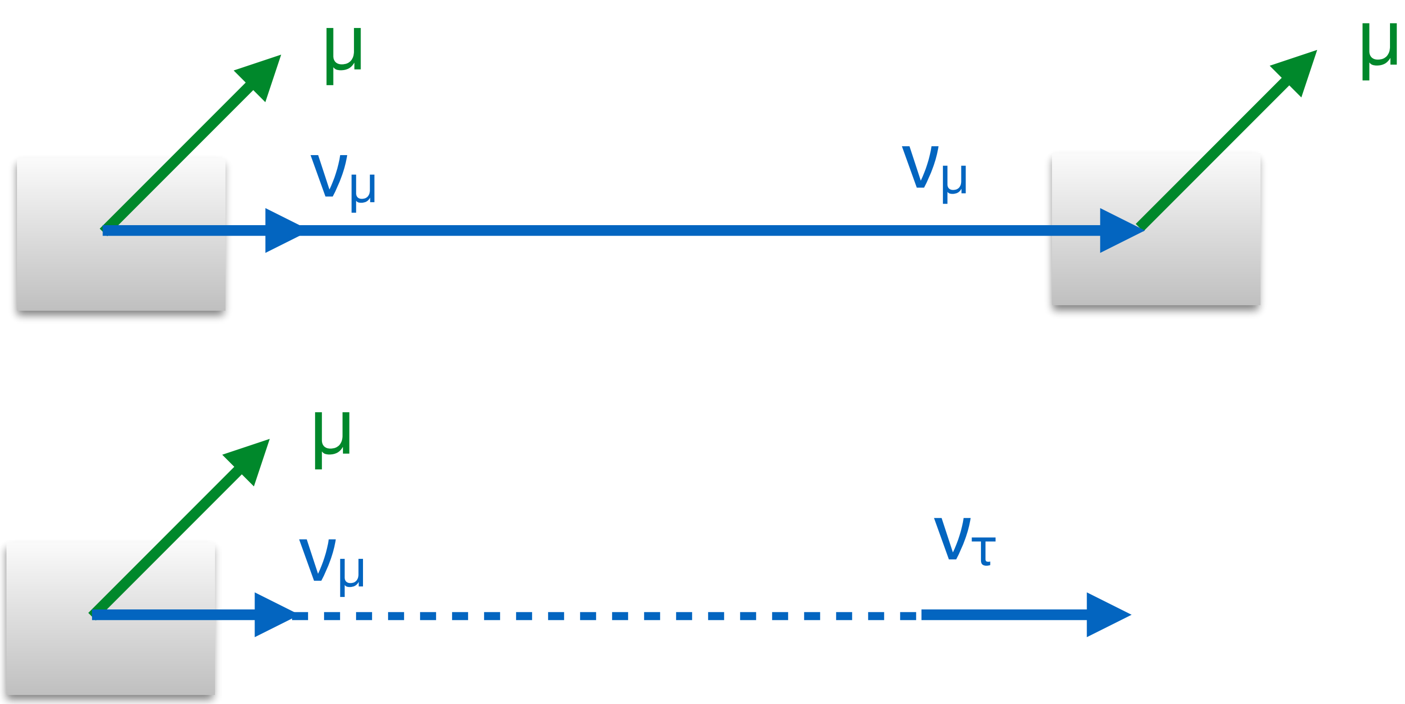

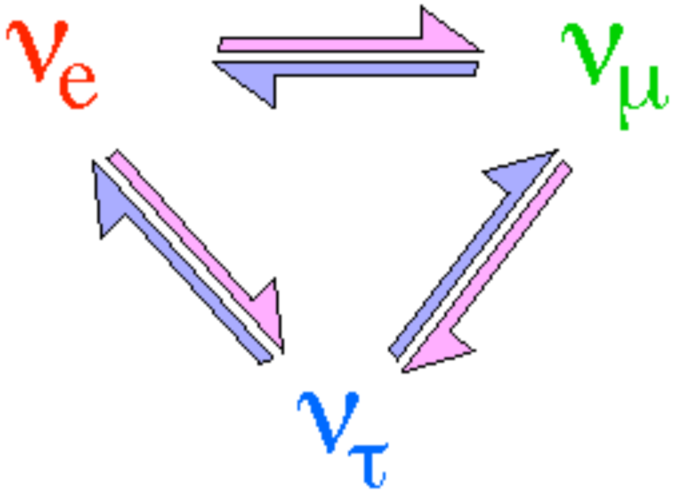

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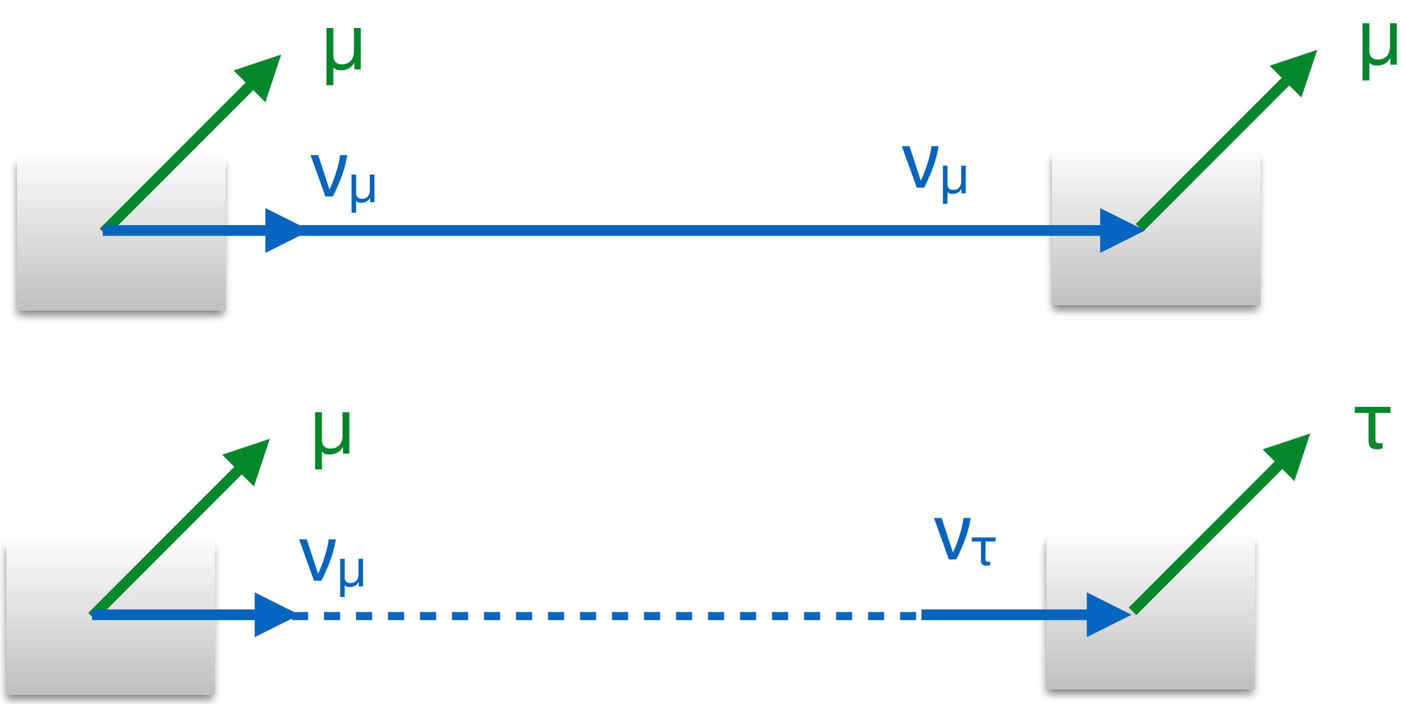

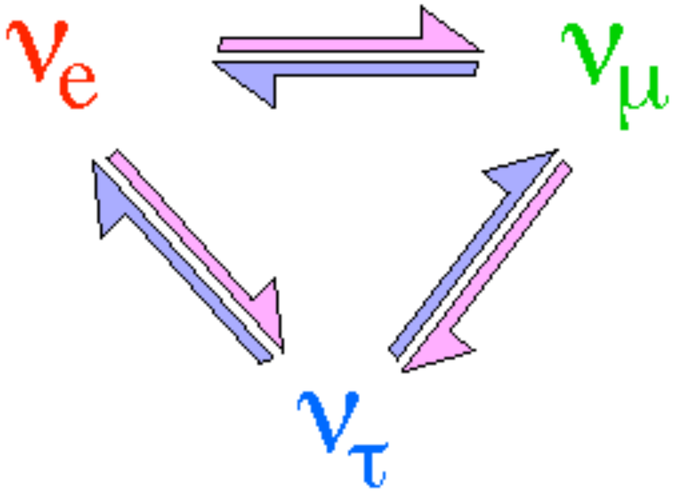

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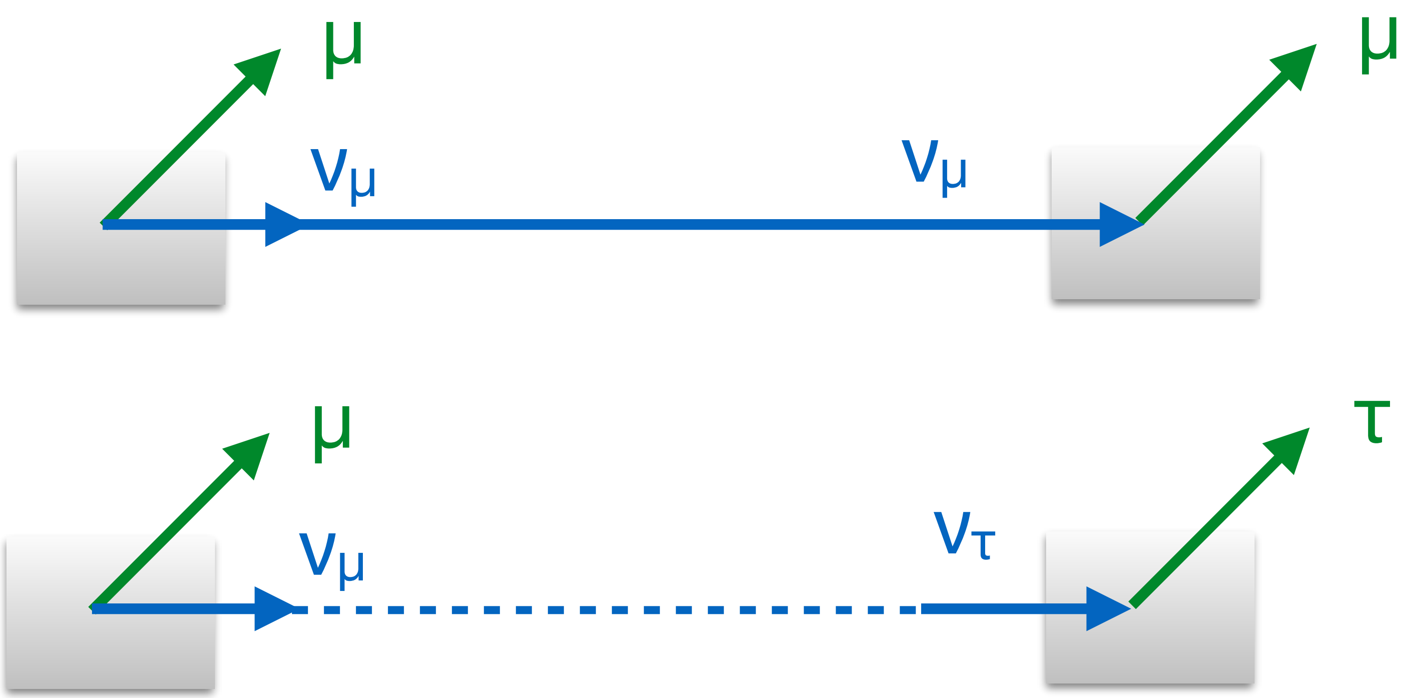

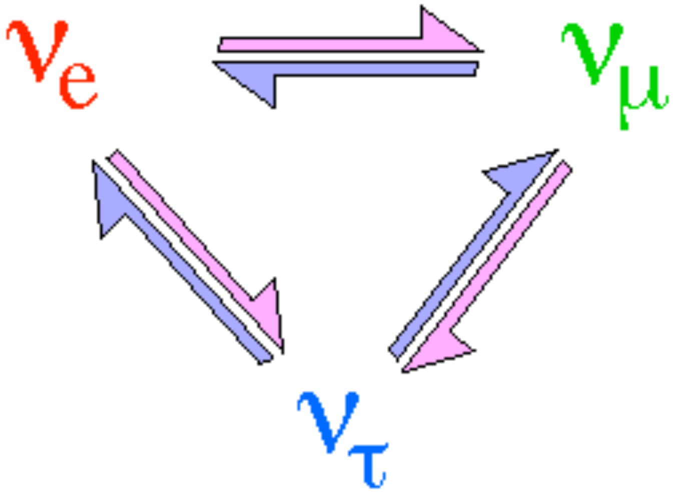

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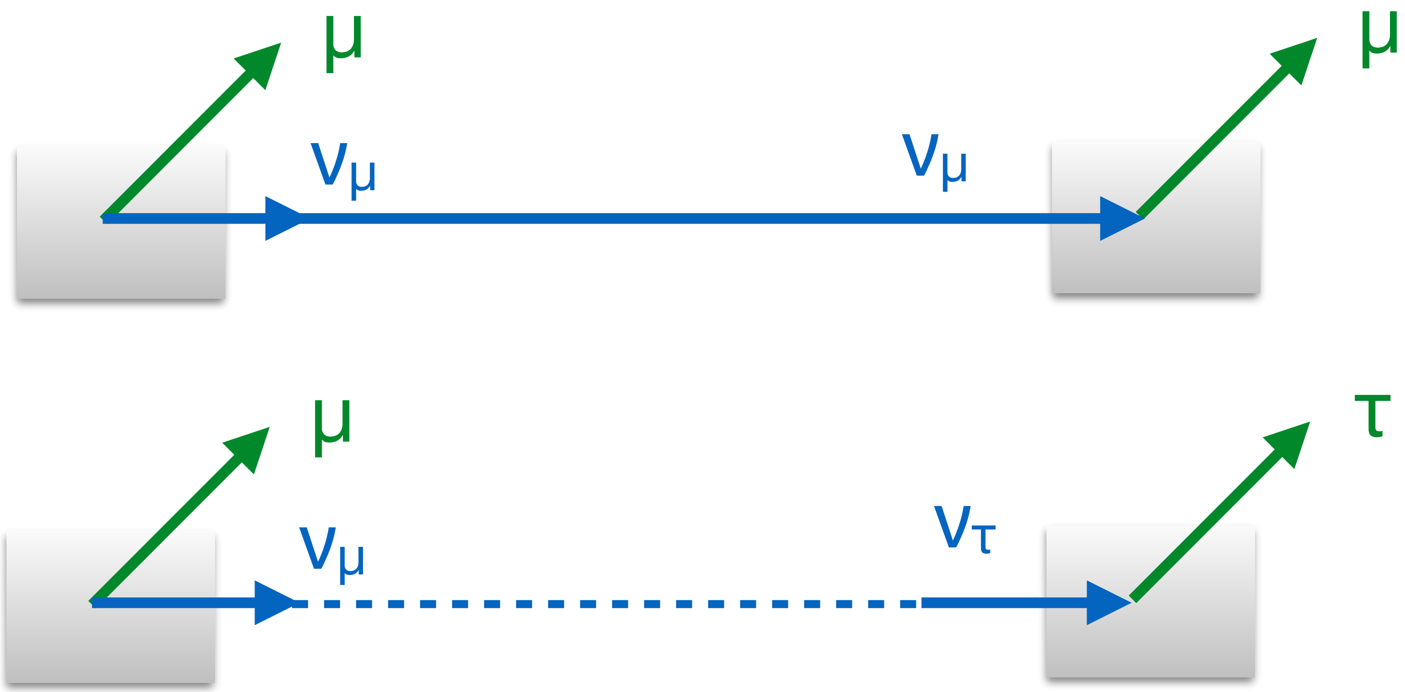

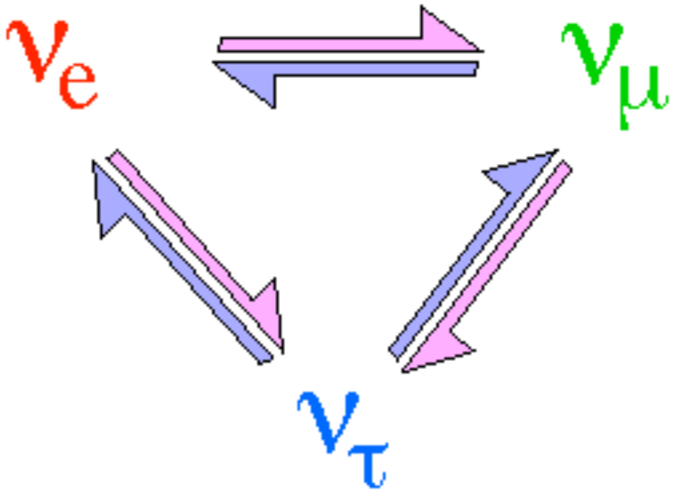

This phenomenon is only possible if neutrinos have different masses

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
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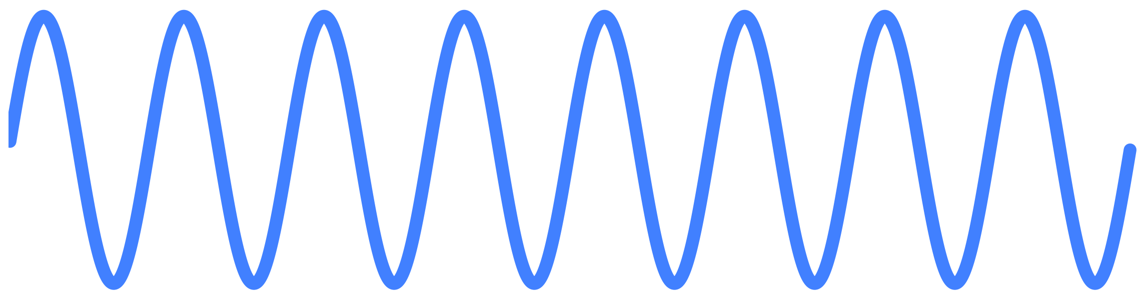

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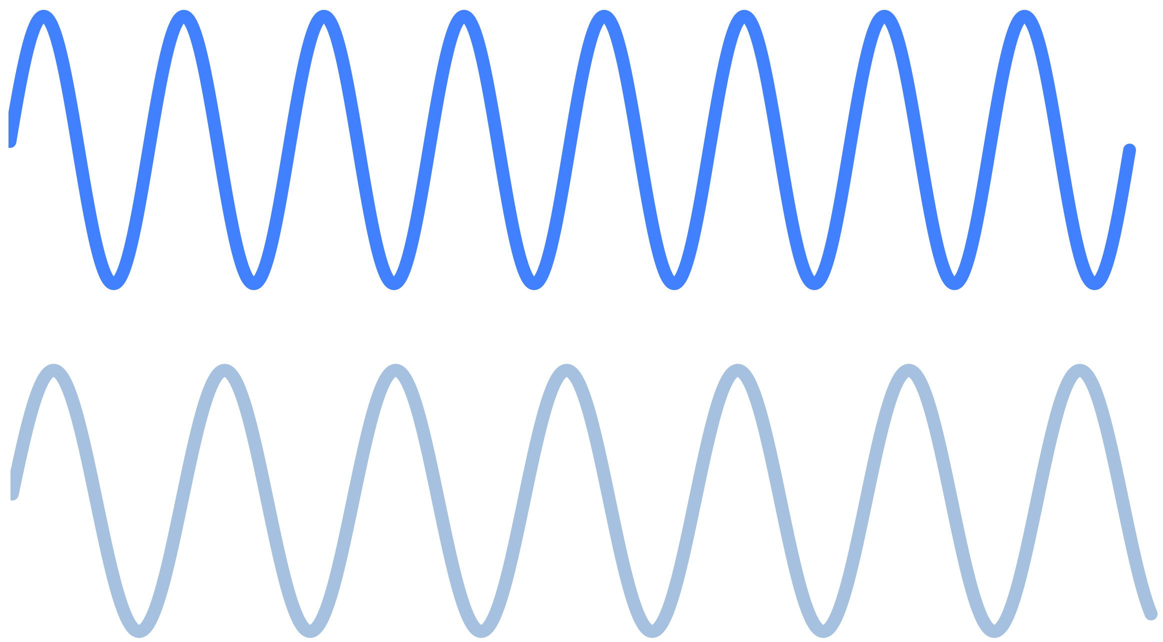

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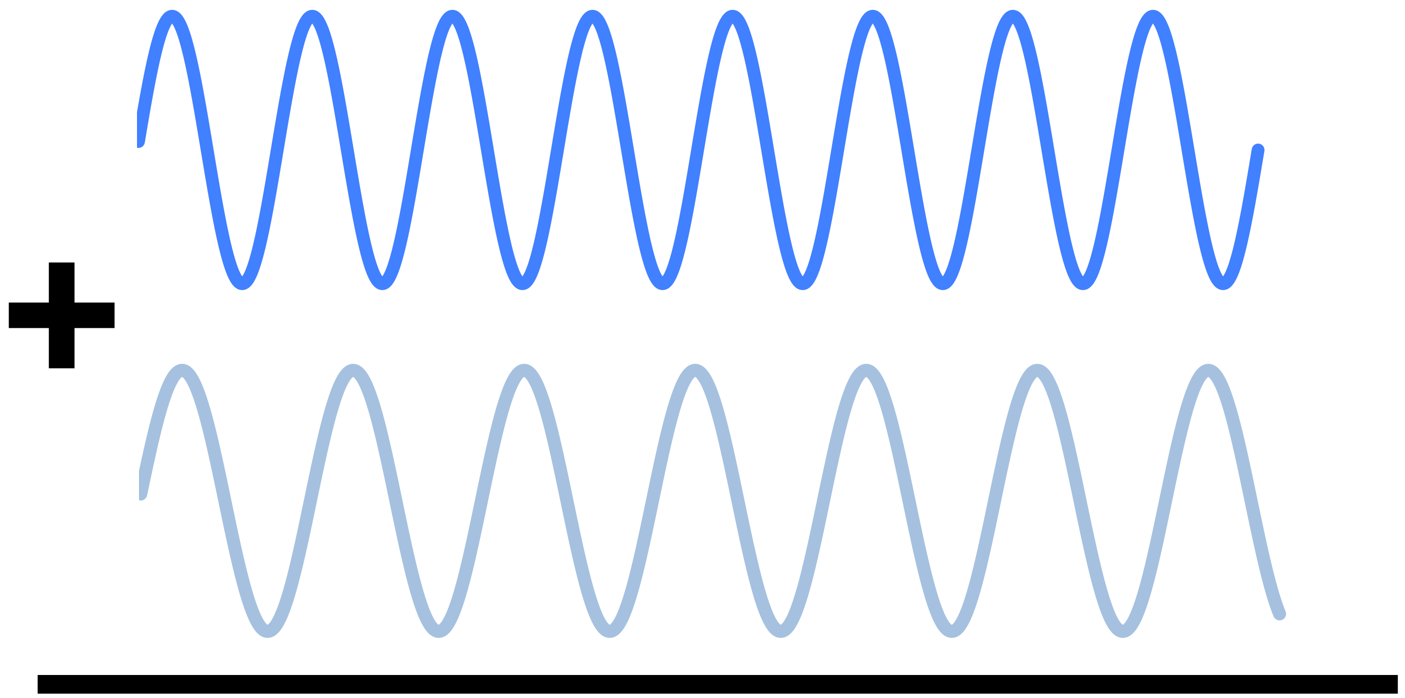

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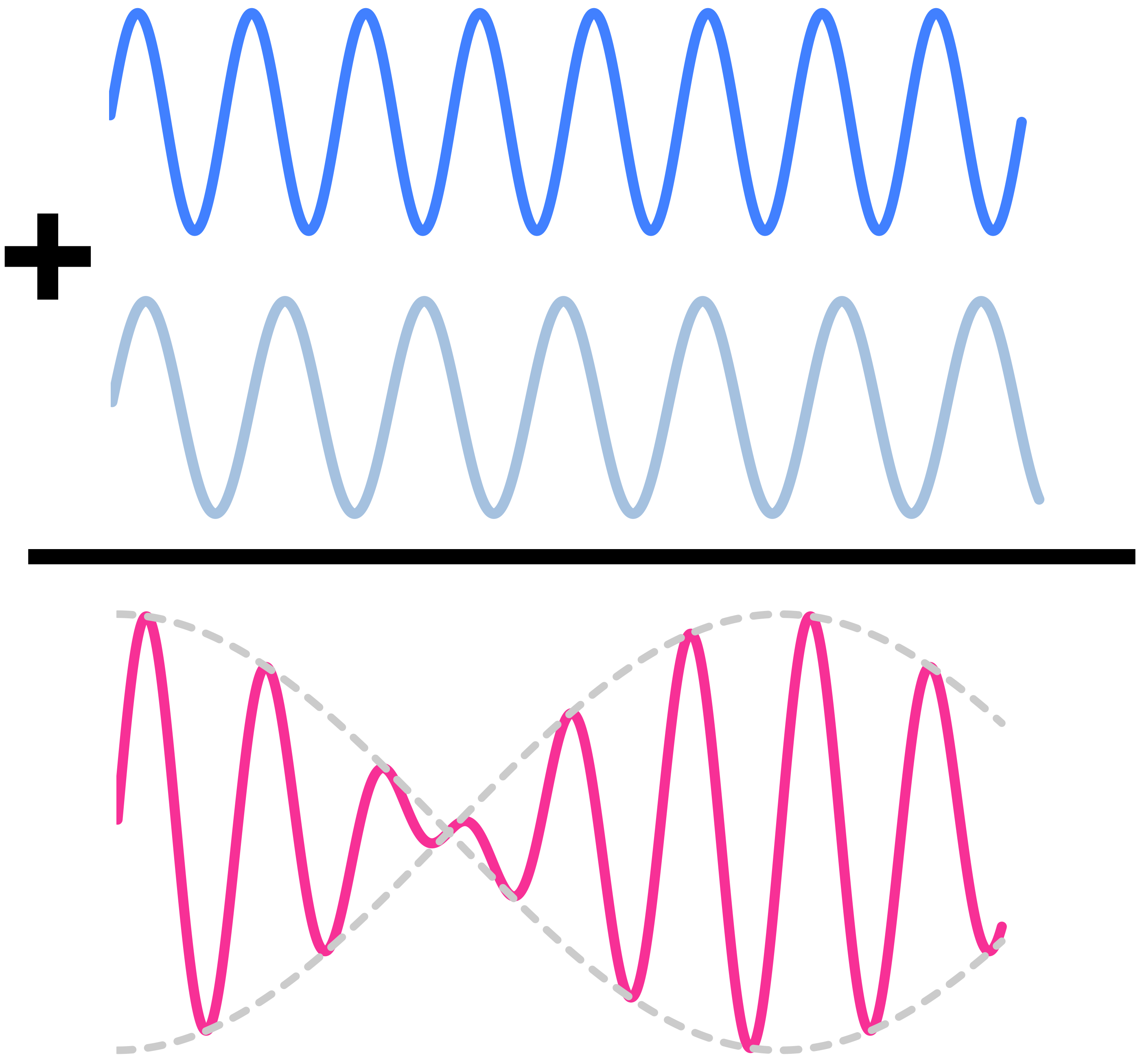

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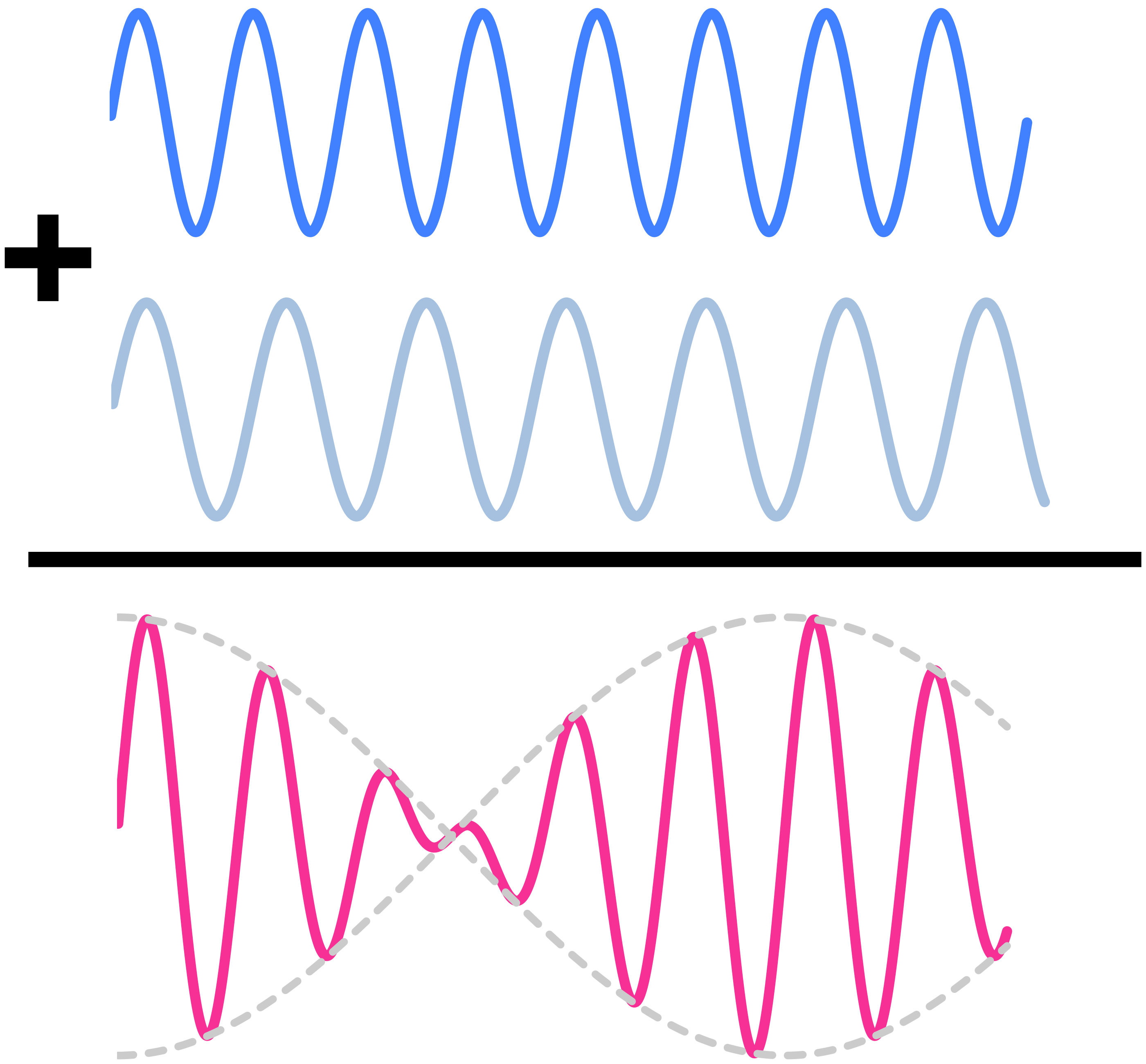
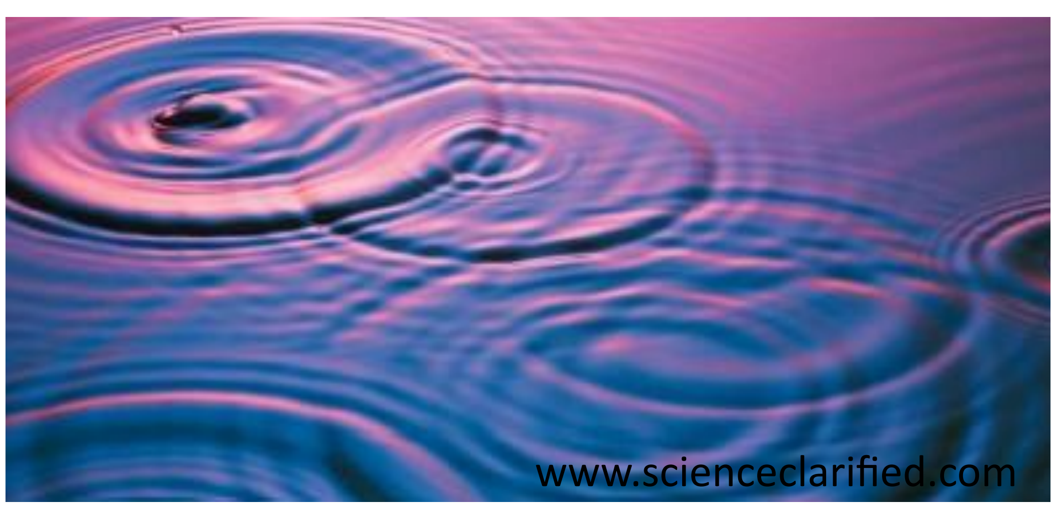
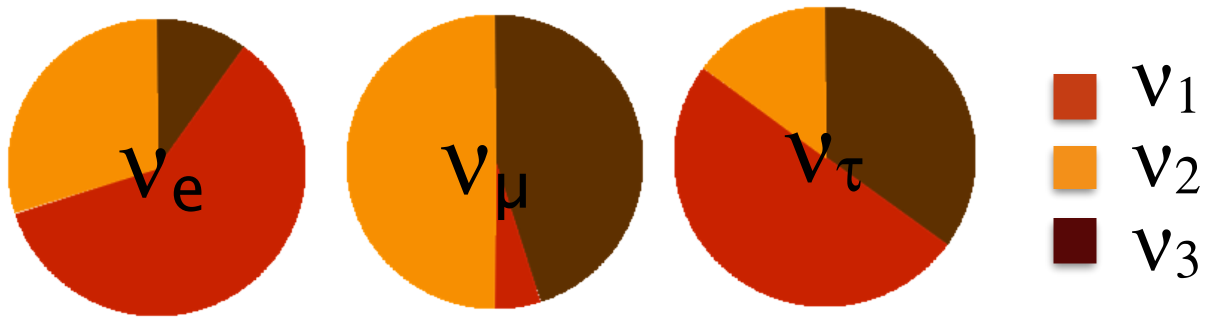


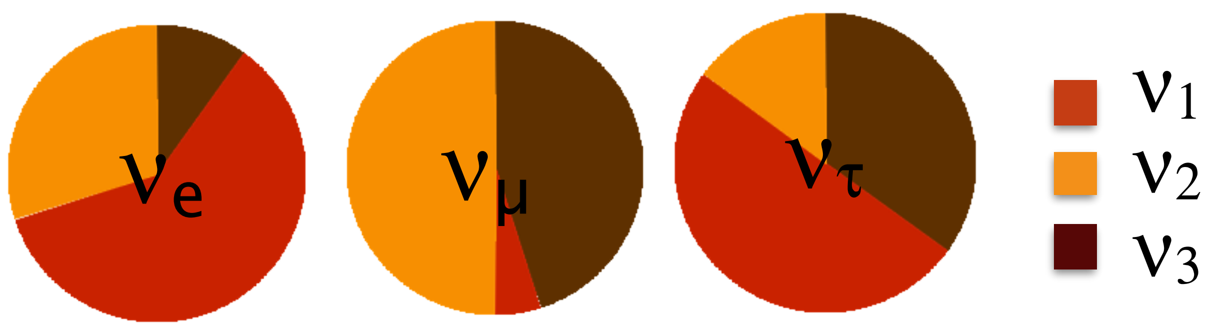


Combination of 3 waves



- 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**

Combination of 3 waves



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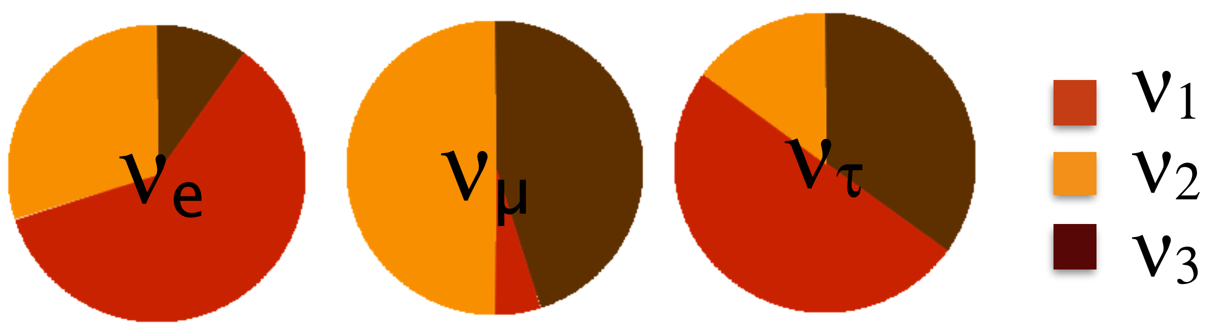

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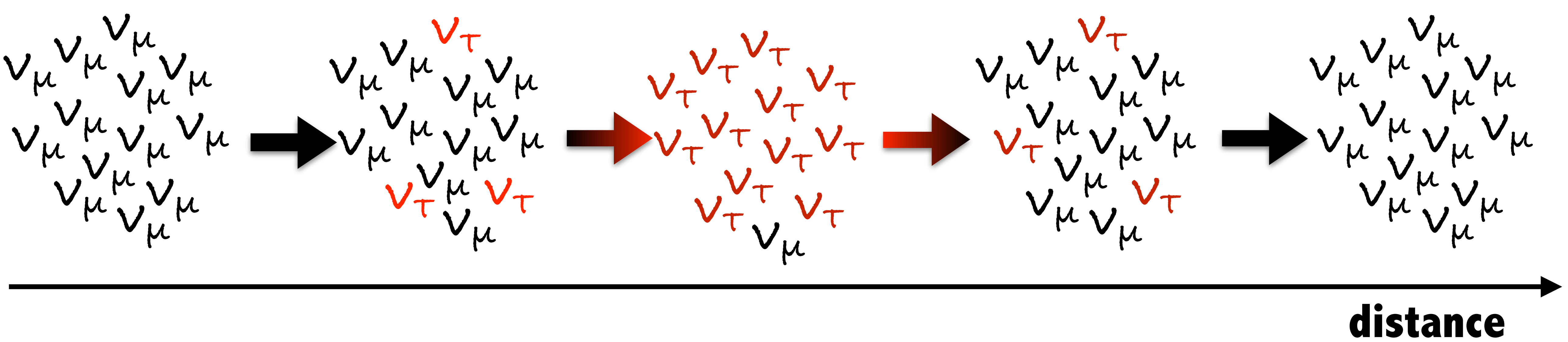

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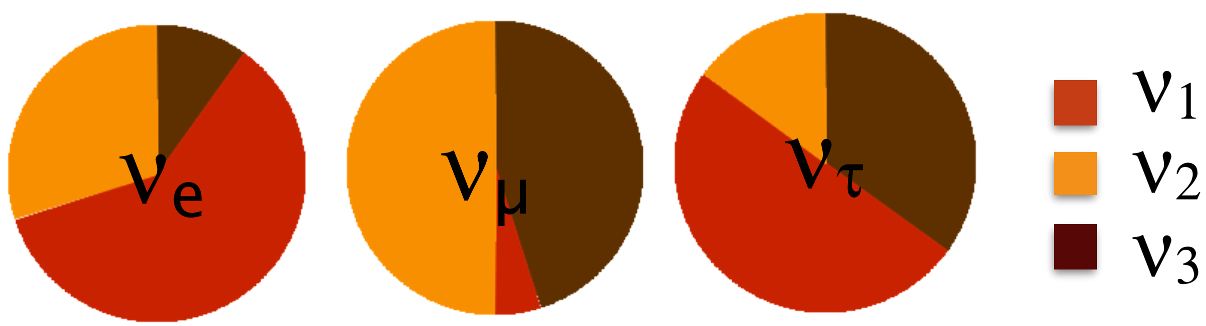

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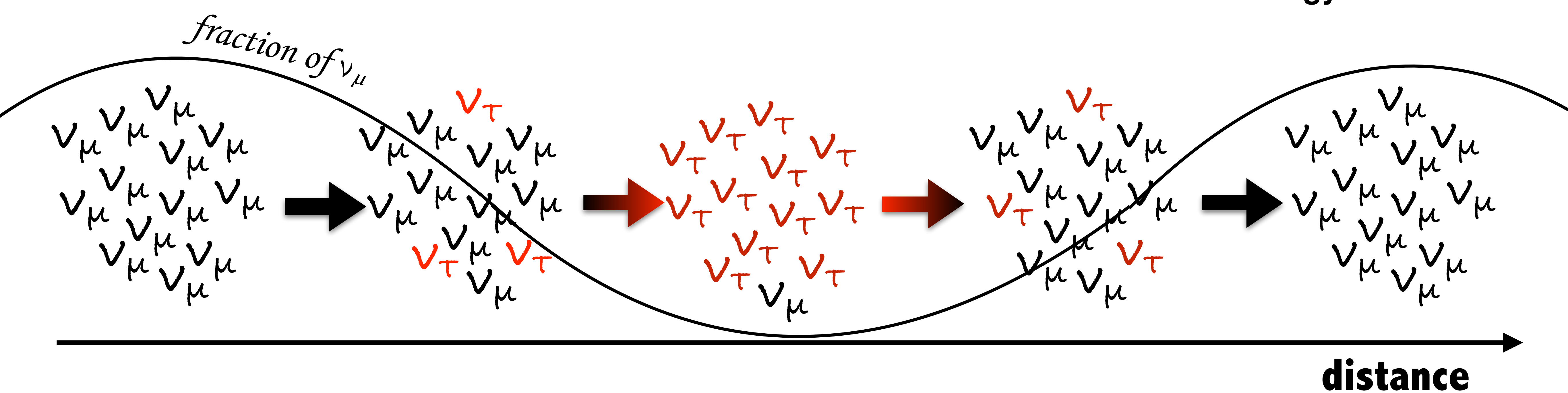

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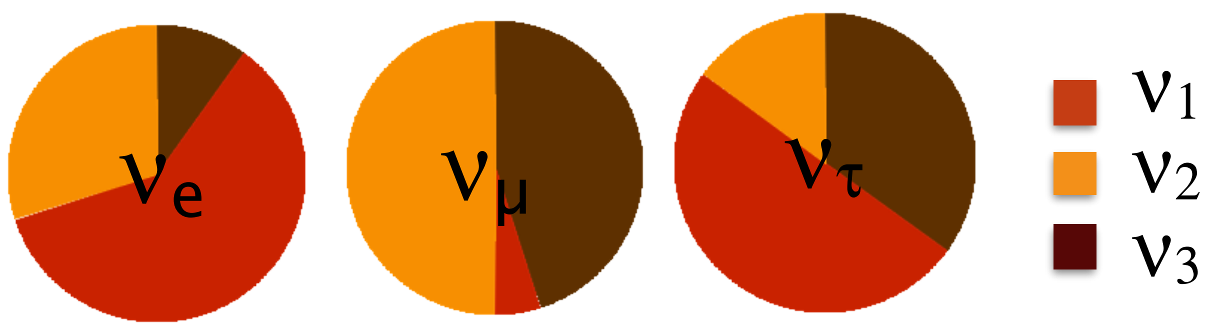

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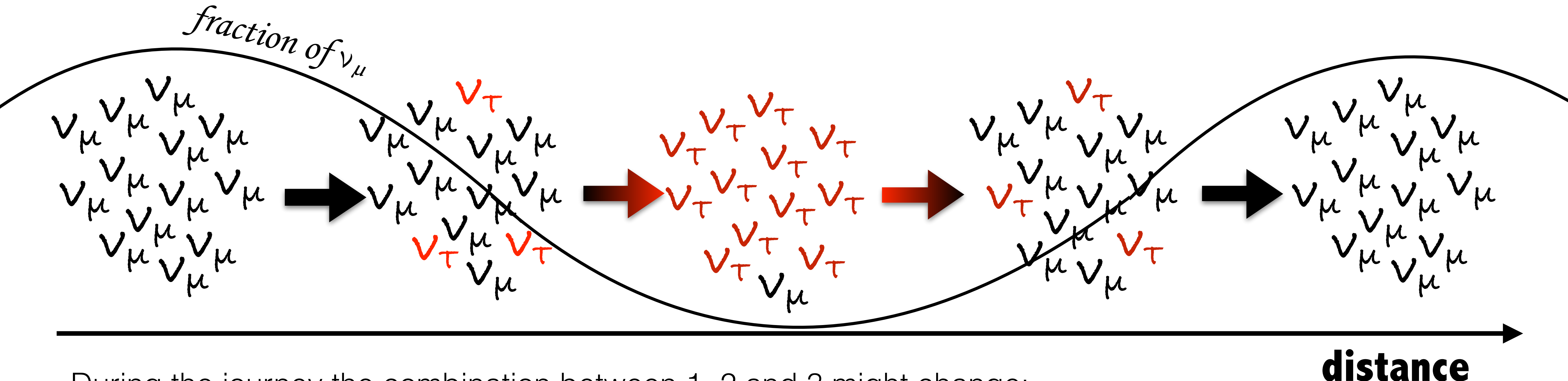
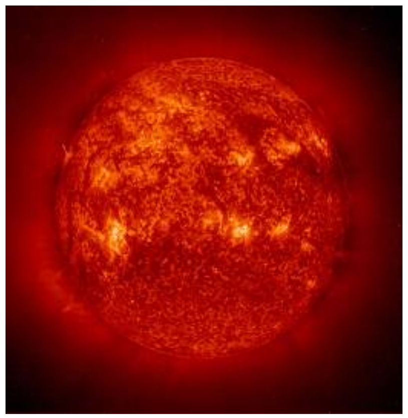


During the journey the combination between 1, 2 and 3 might change:

- Sometimes the combination might look like a ν_μ
- Then later, the waves might combine to look like a ν_τ

Detection of neutrino oscillations



ν_e

E_ν

production

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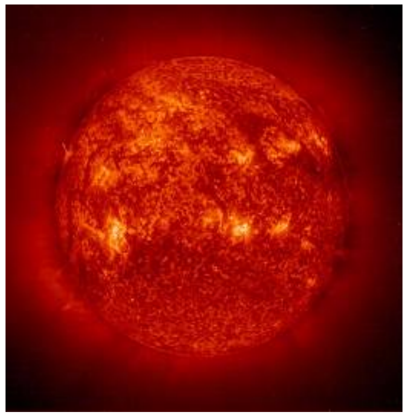

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- Weak interaction produces neutrinos of a certain flavor
- We know which kind of neutrino is by detecting its associated particle

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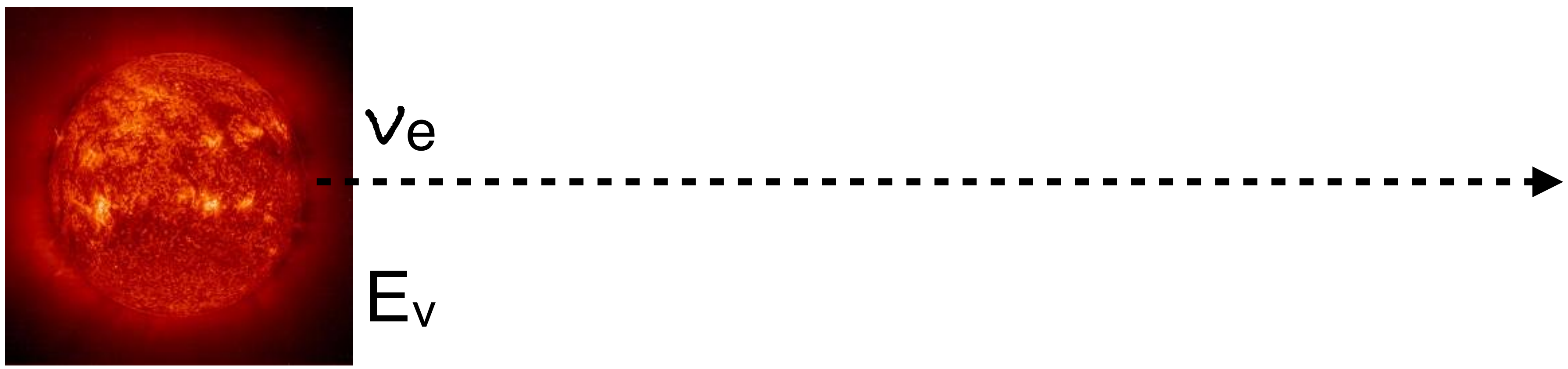

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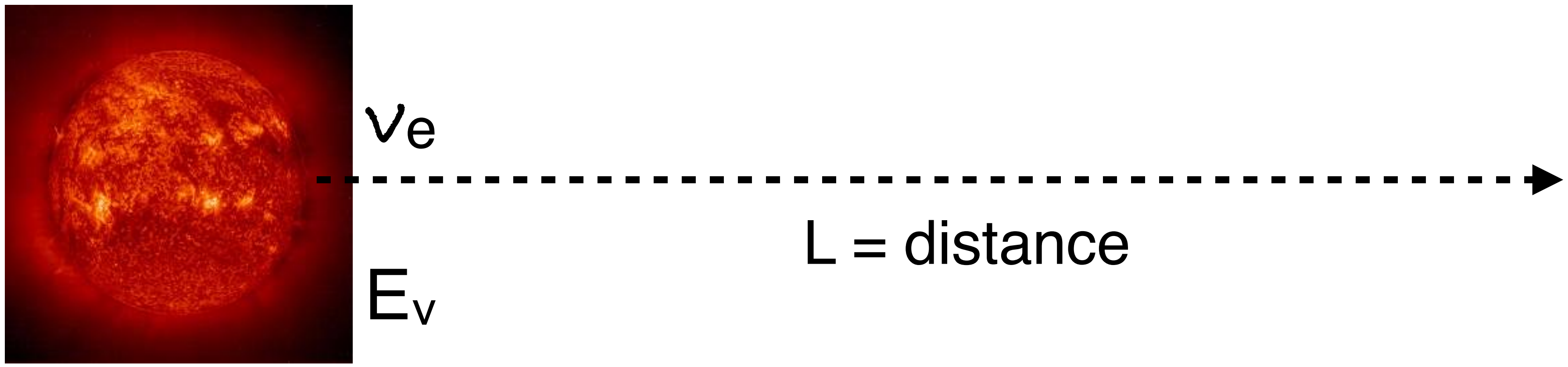

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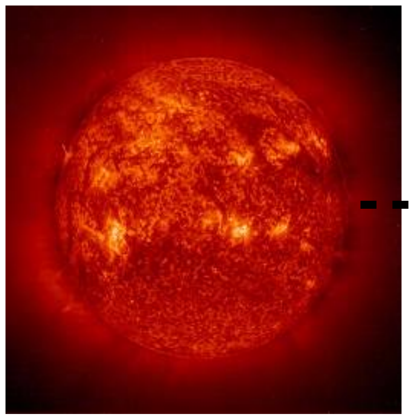

ν_e

L = distance

E_ν

production **propagation**

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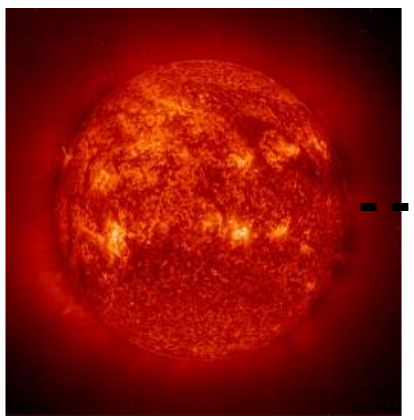

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Neutrinos travel a distance and mix

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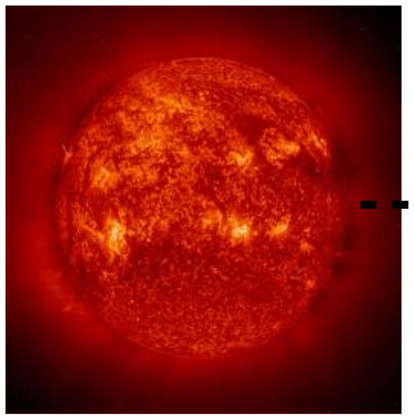

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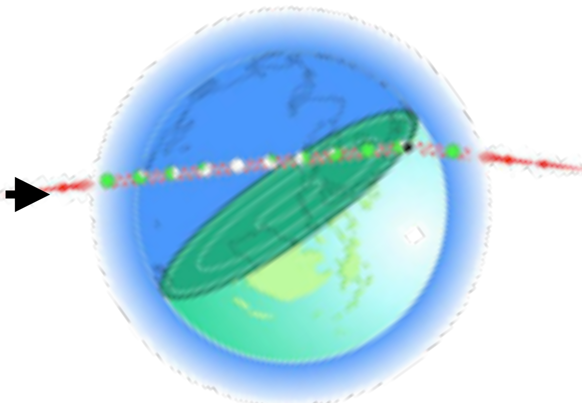

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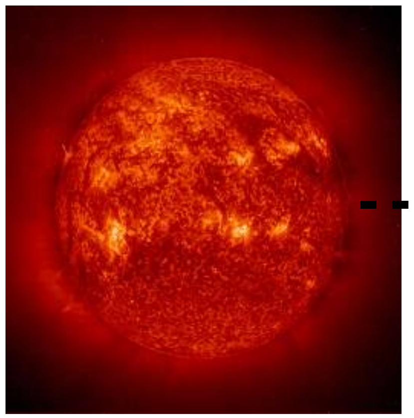

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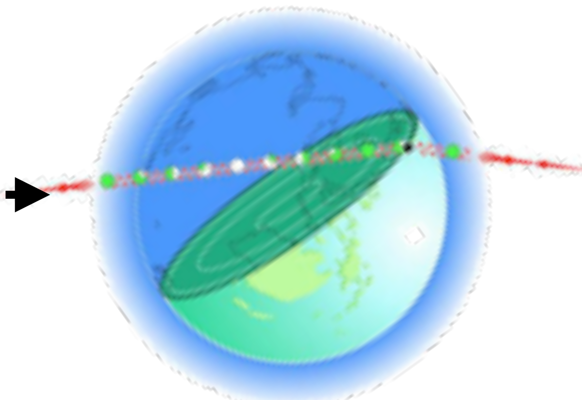

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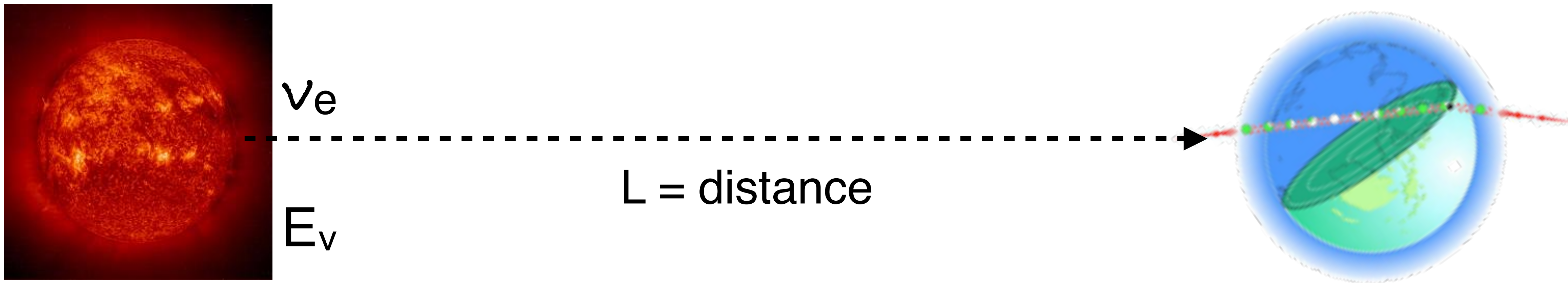

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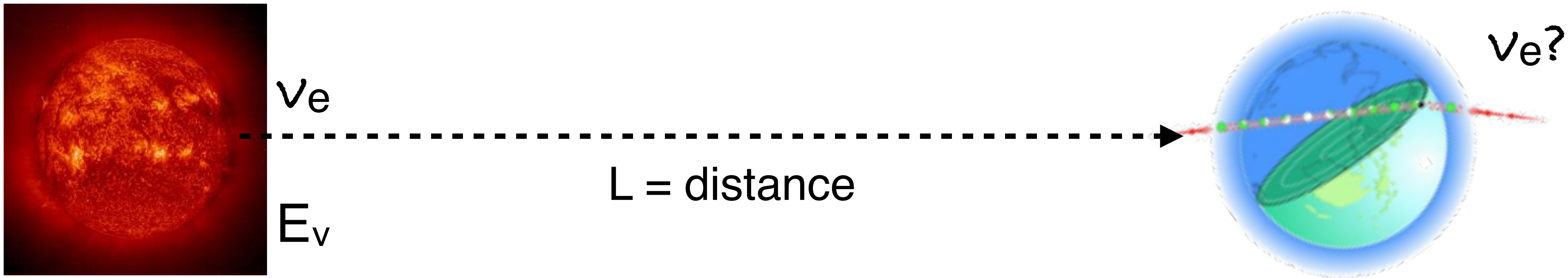

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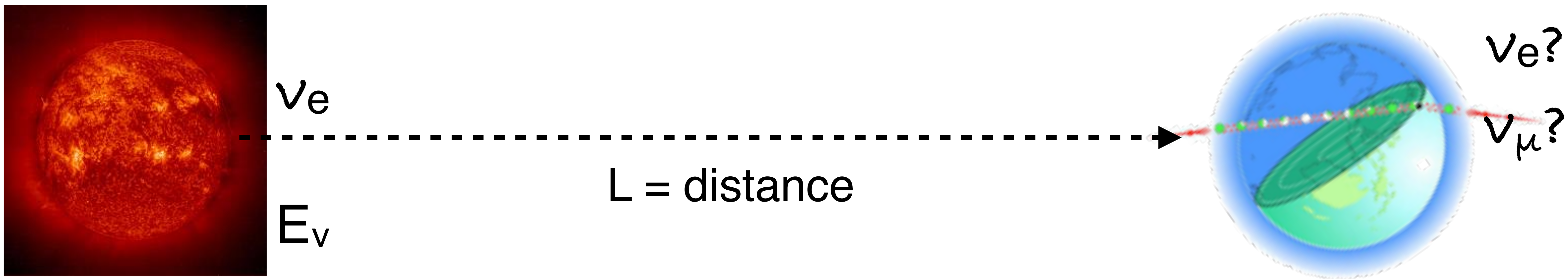

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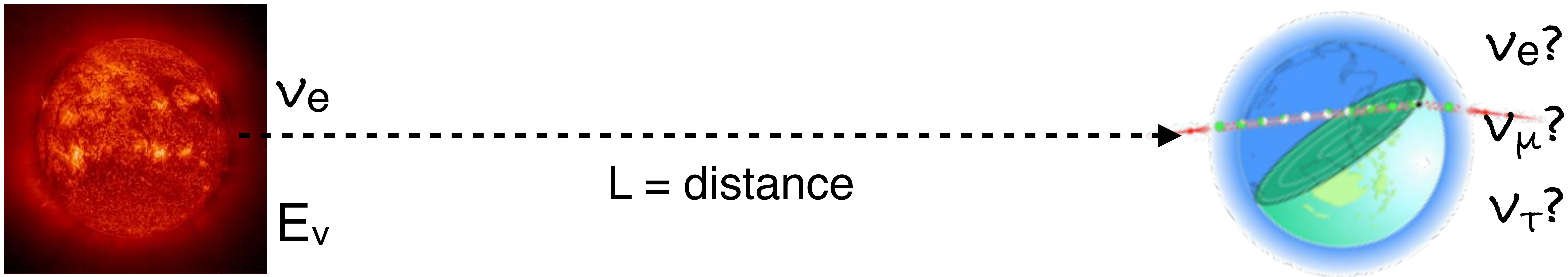

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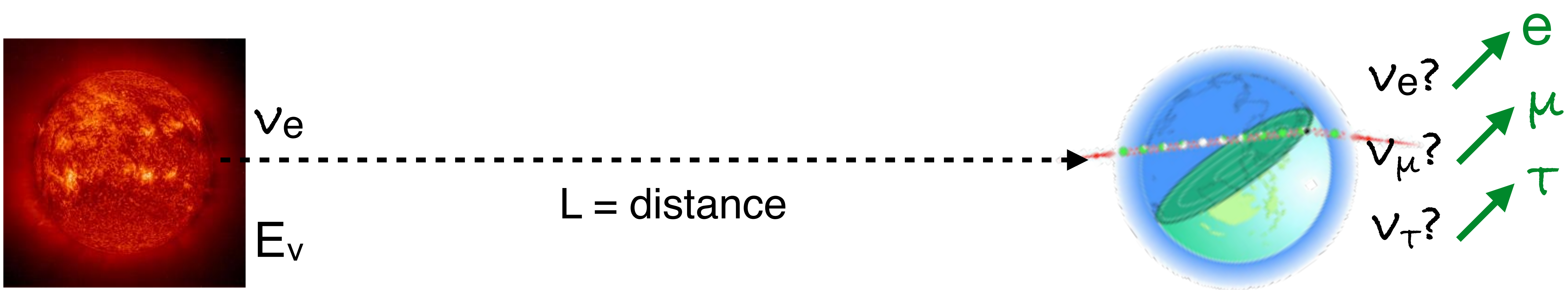

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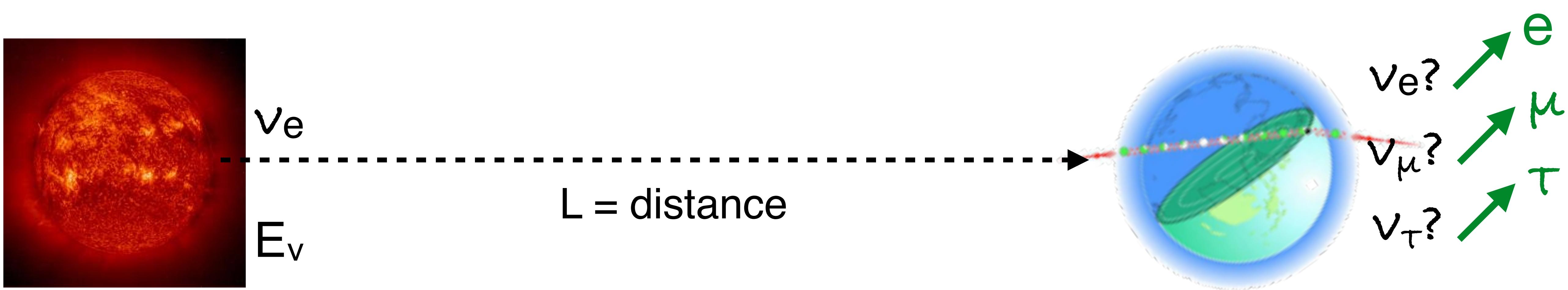

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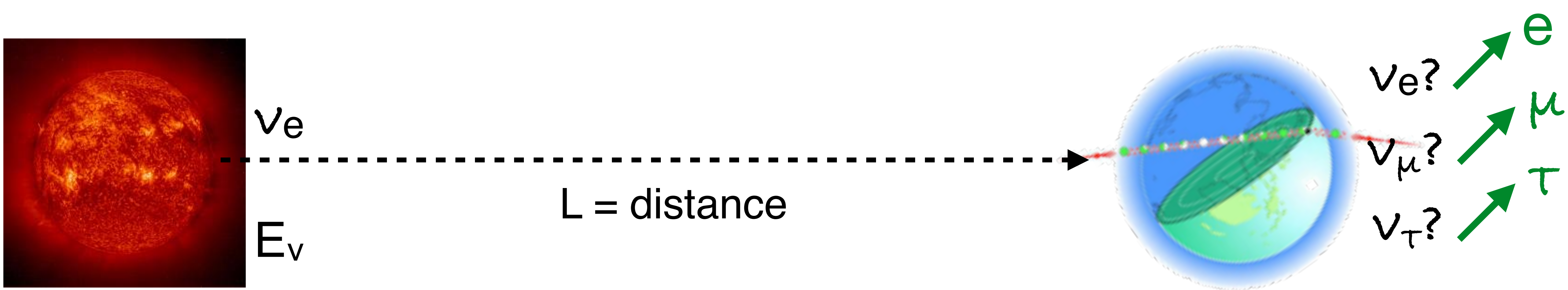

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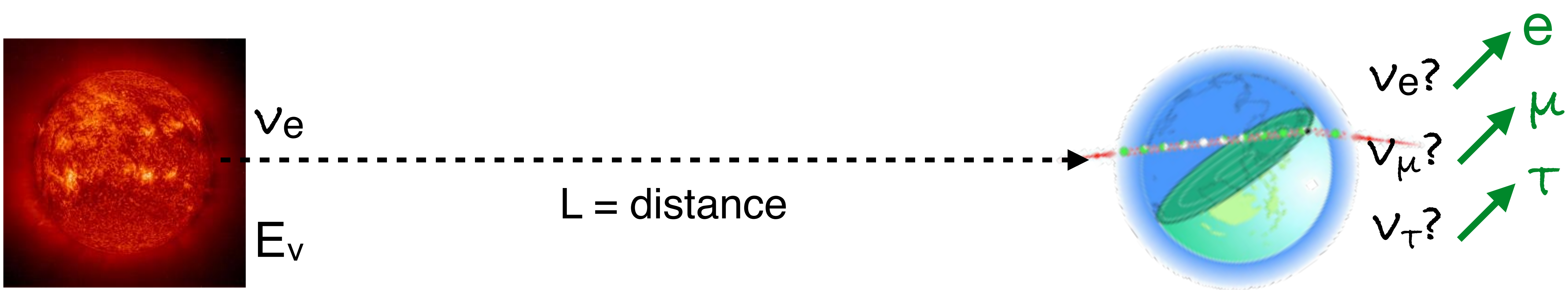

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For 3 neutrinos:

2 values of Δm^2 (Δm^2_{21}, Δm^2_{32})
3 values of θ (θ_{12}, θ_{23}, θ_{13})

detection

- 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.)

Flavor mixing

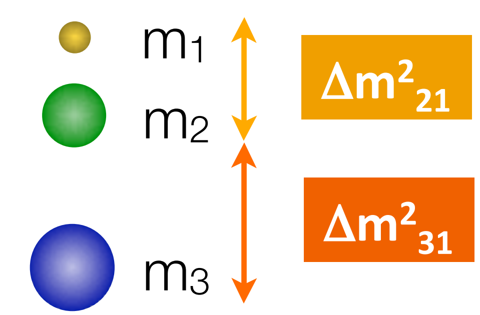
Atmospheric + LBL | Reactors + LBL | Solar + KamLAND

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

θ_{atm} | θ_{13}, δ_{CP} | θ_{solar}

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$



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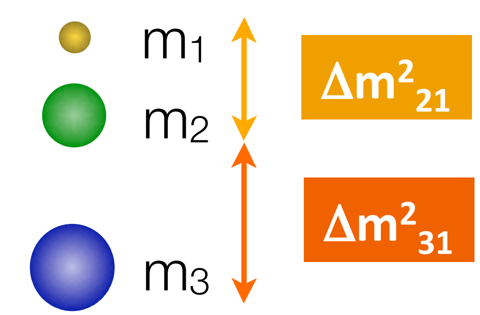

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4 \cdot E_\nu}\right)$$

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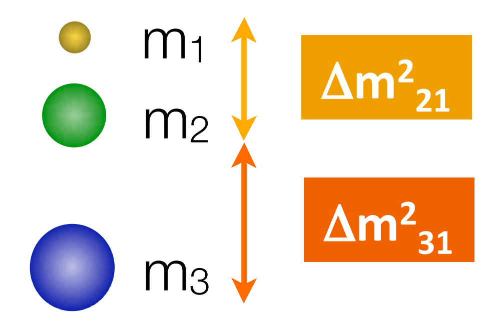

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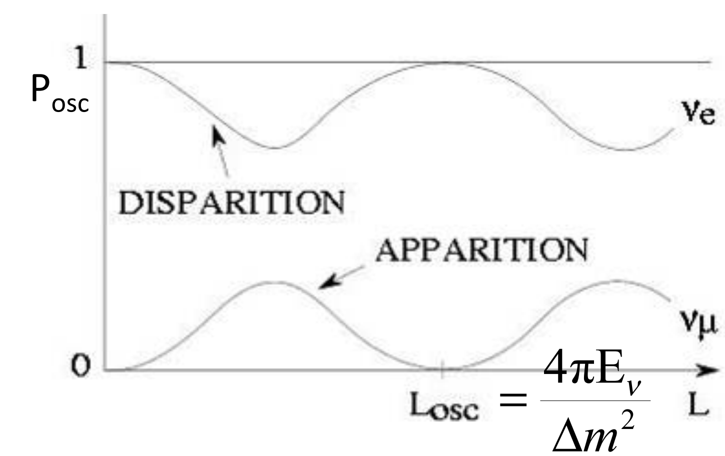

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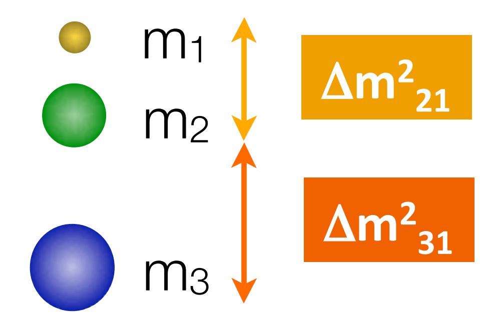

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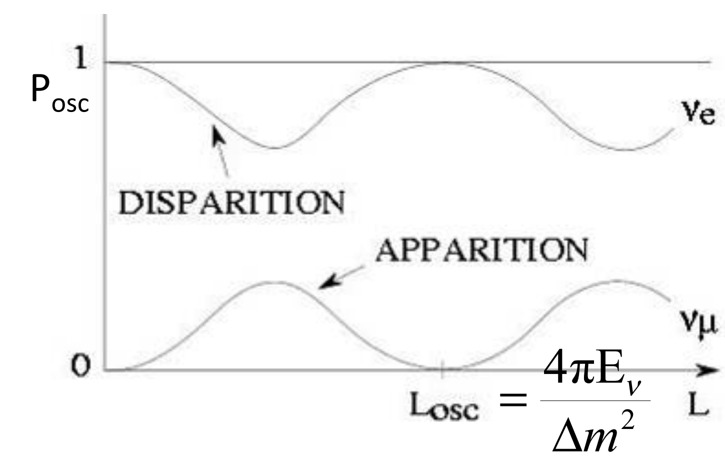

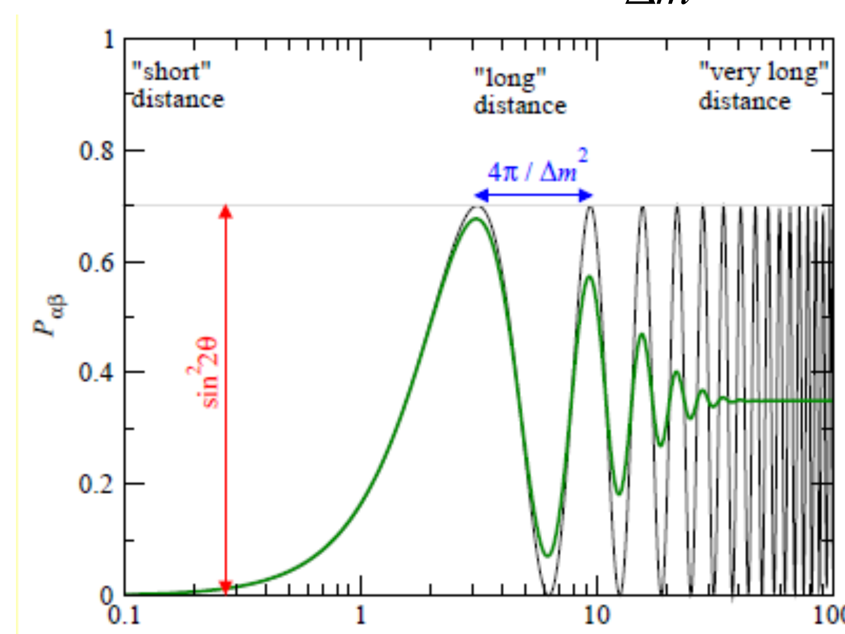

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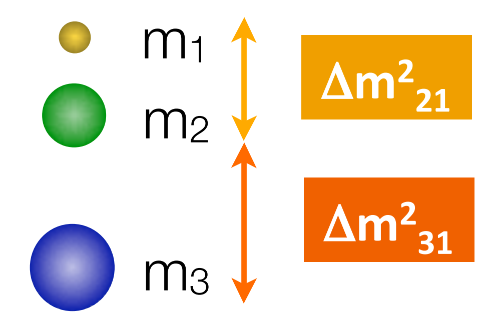

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amplitude

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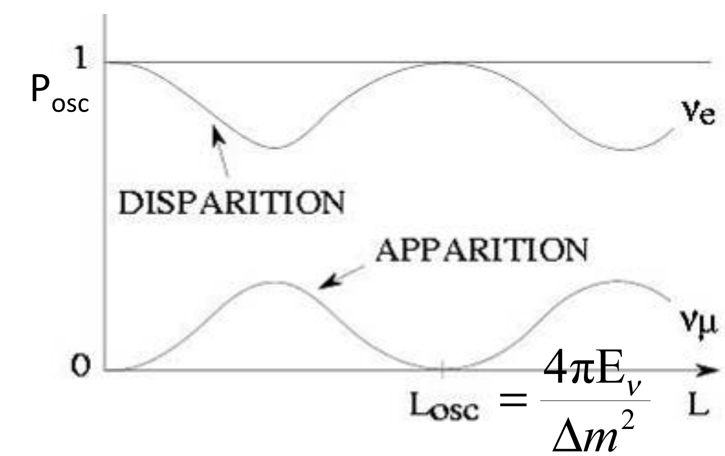

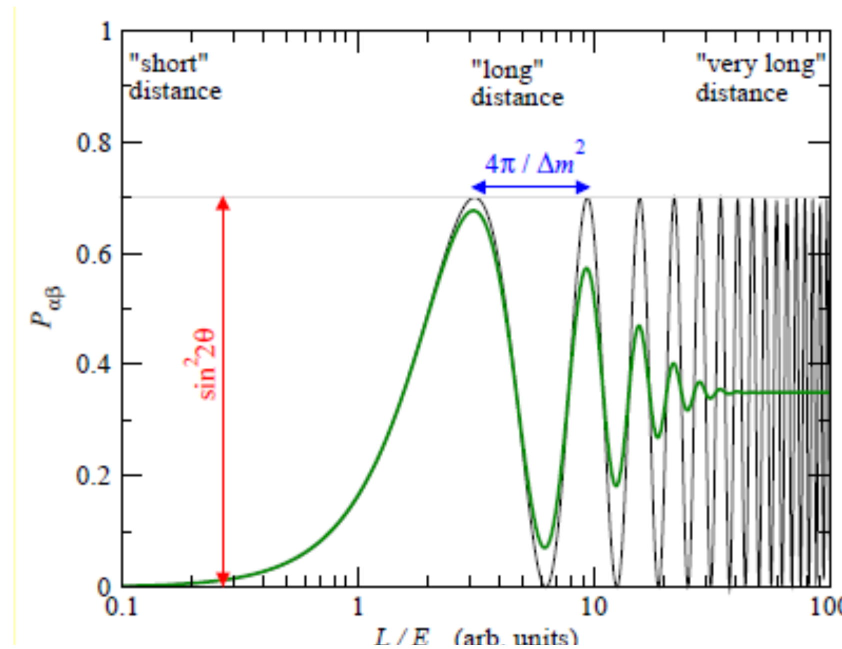

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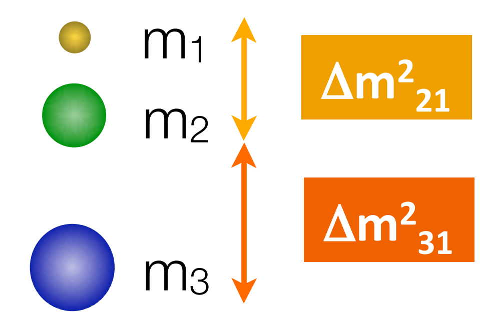

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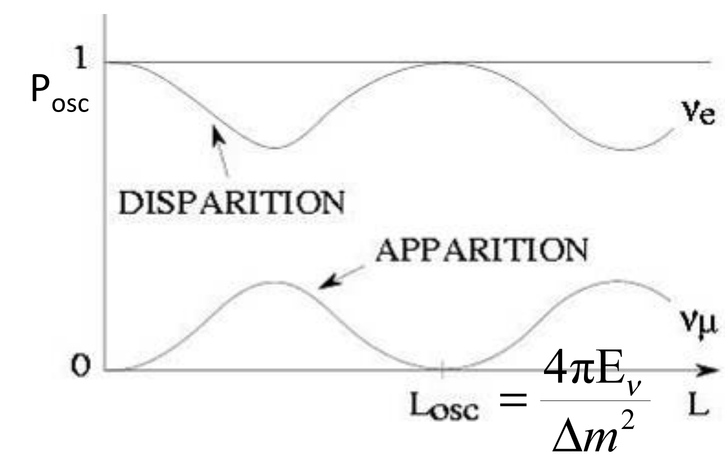

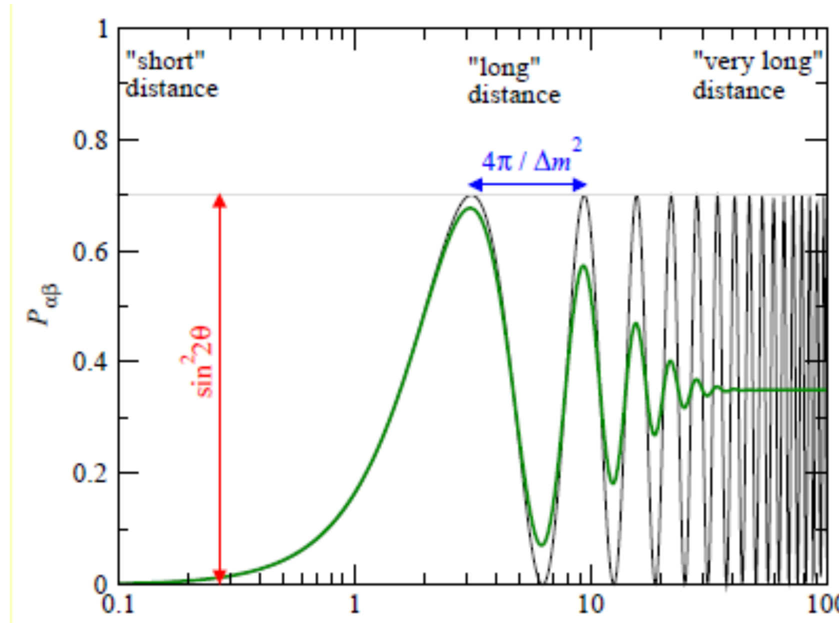

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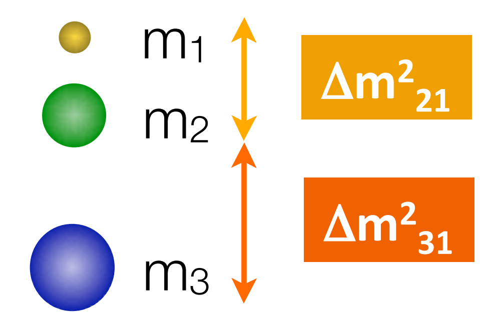

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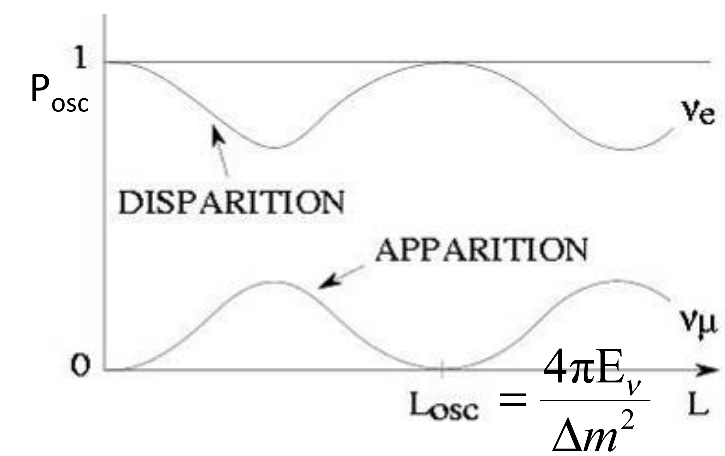

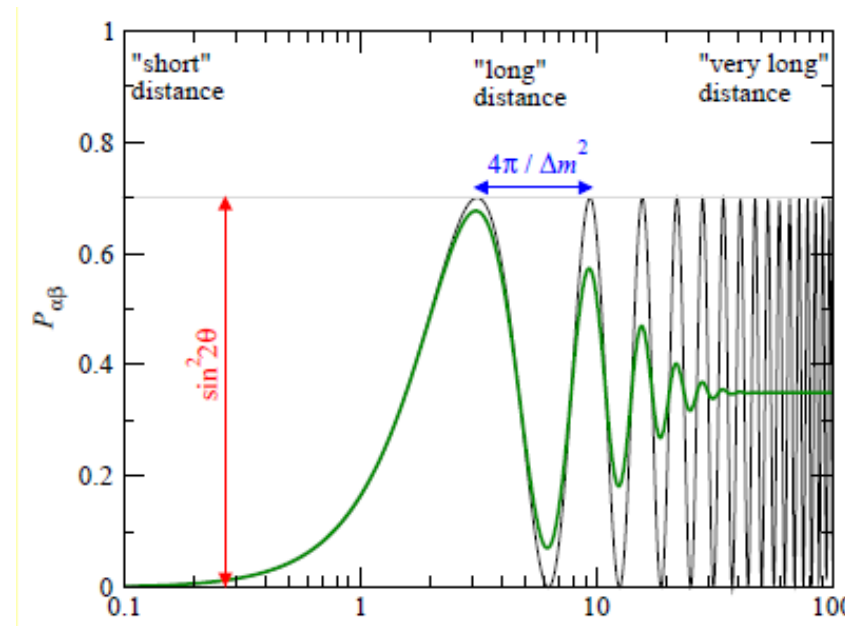

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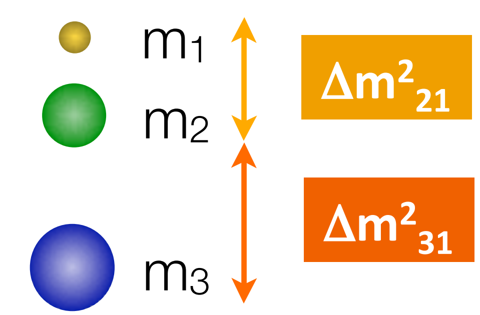

amplitude

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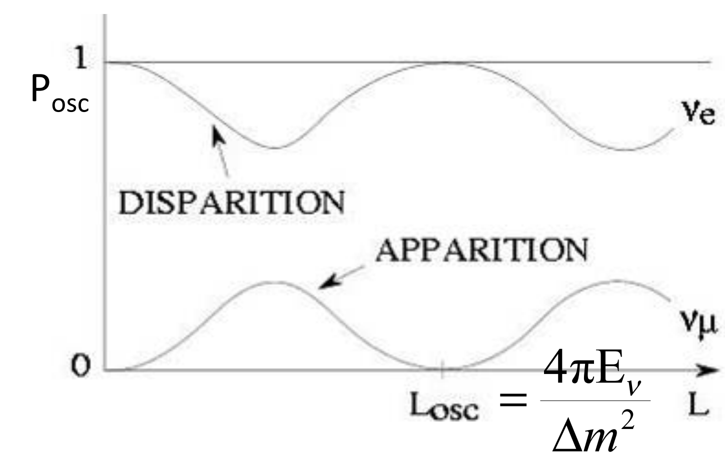

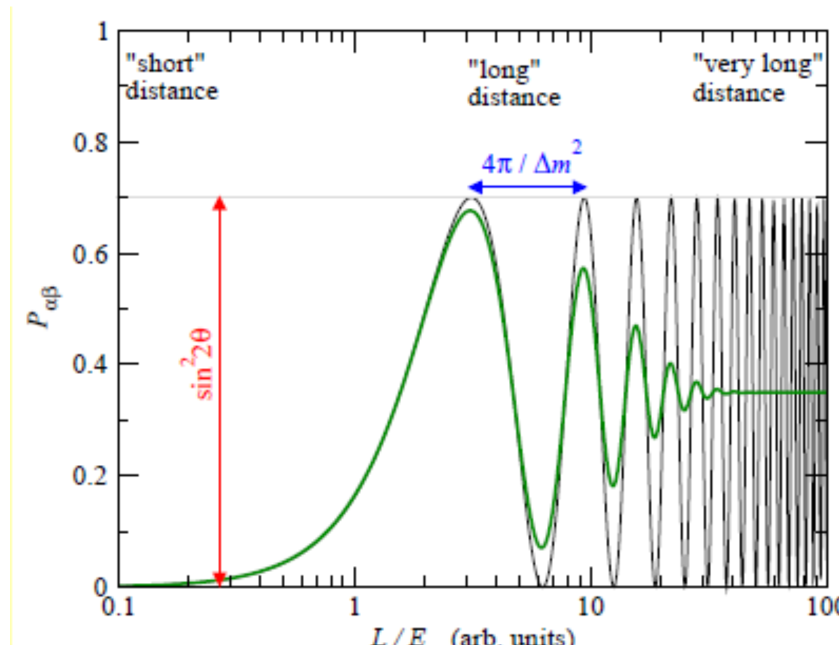

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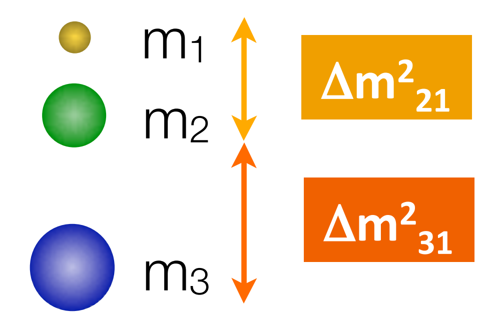

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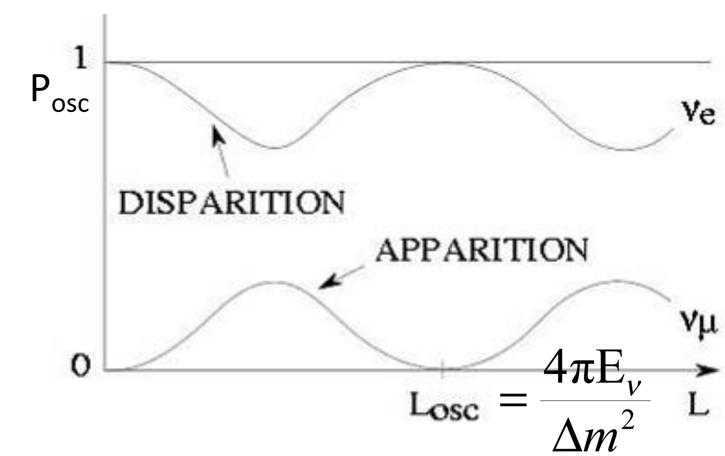

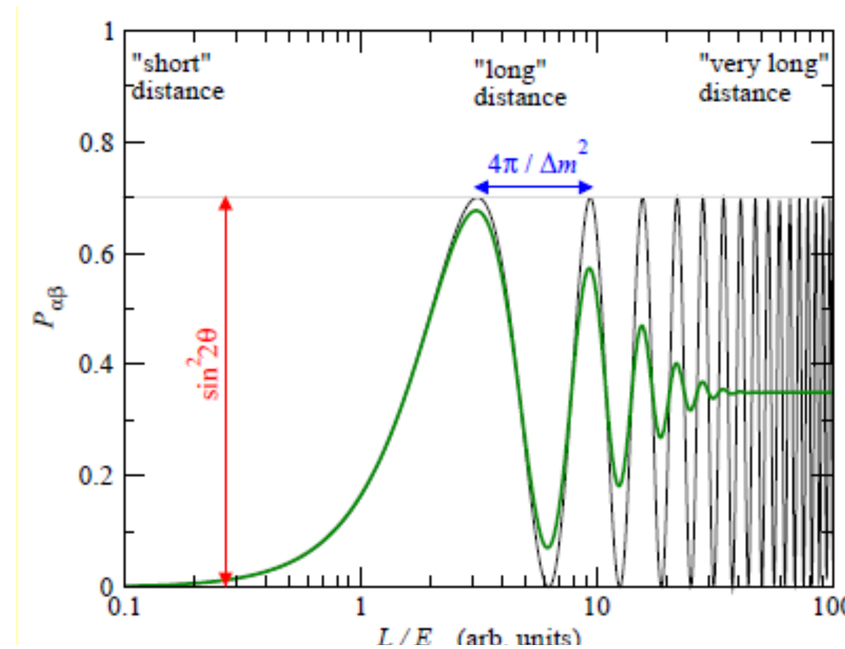

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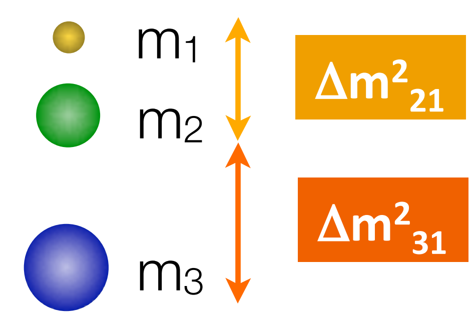

amplitude

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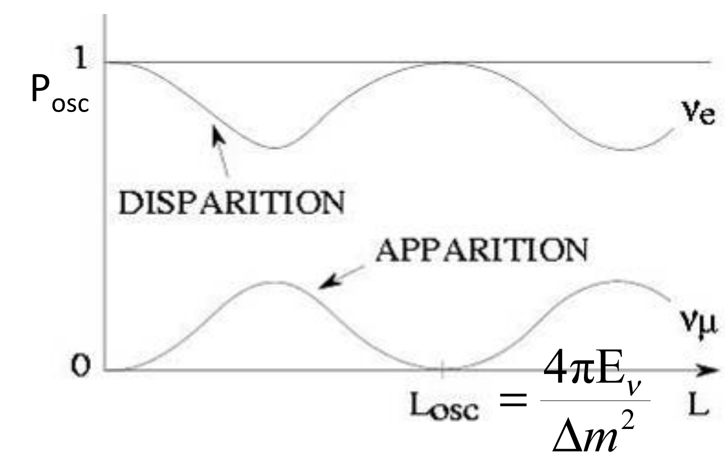

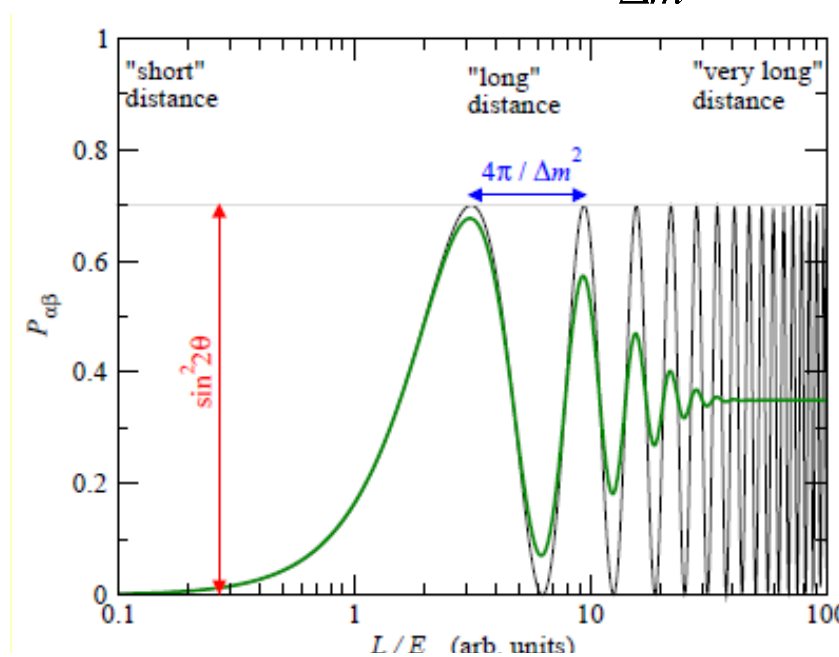

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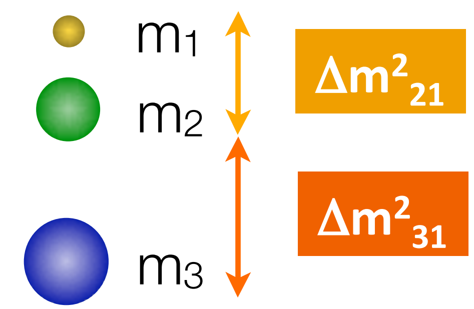

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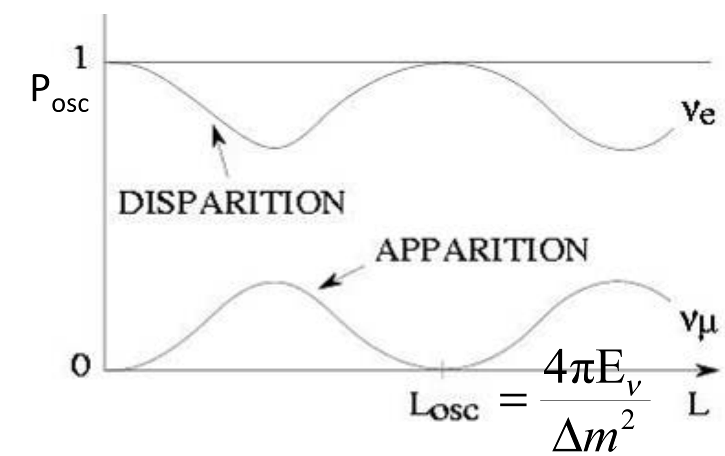

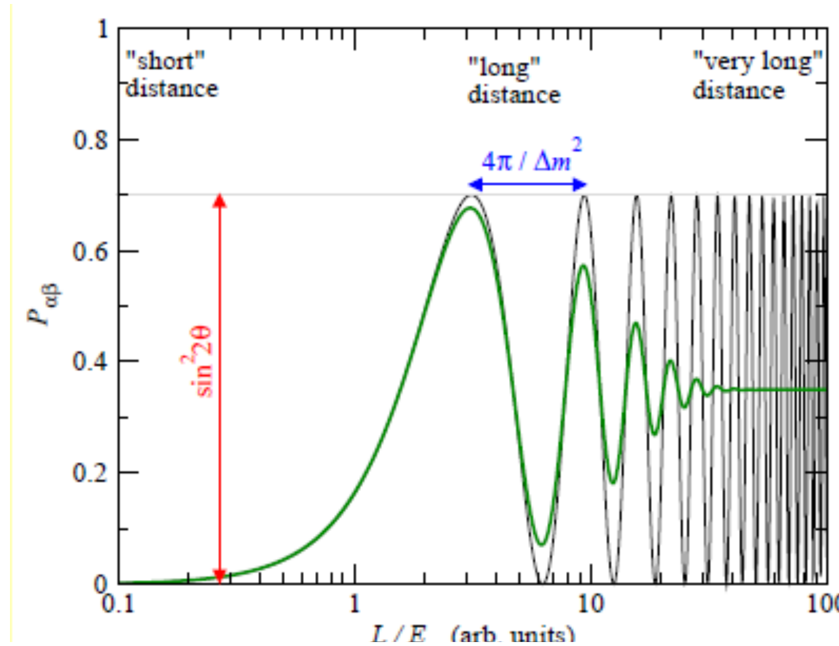

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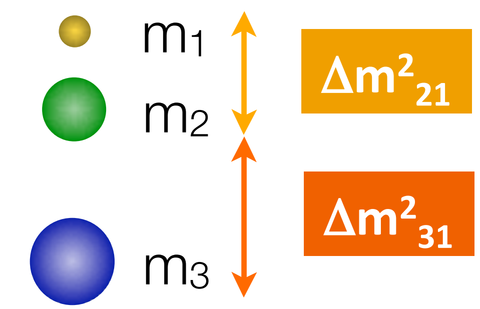

amplitude — frequency

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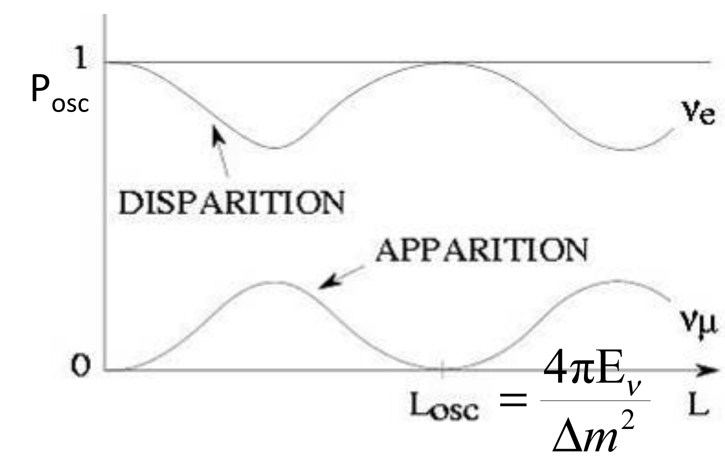
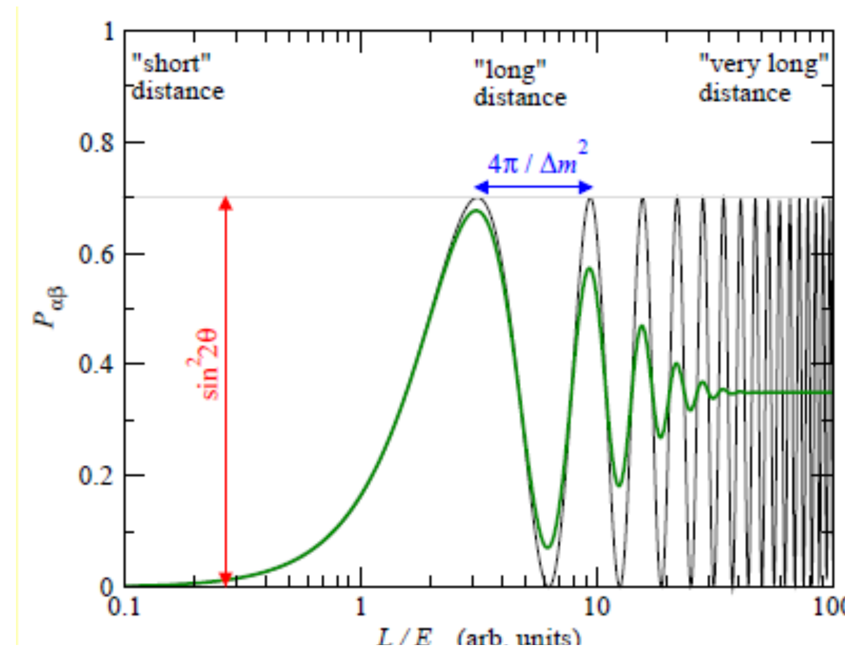
experimental parameters





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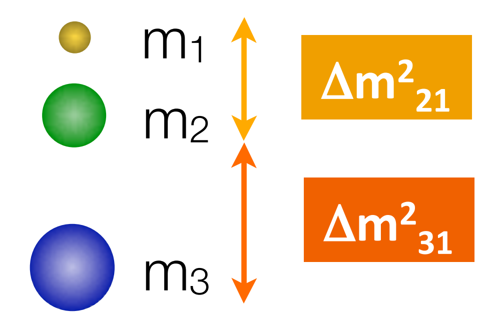

amplitude

frequency

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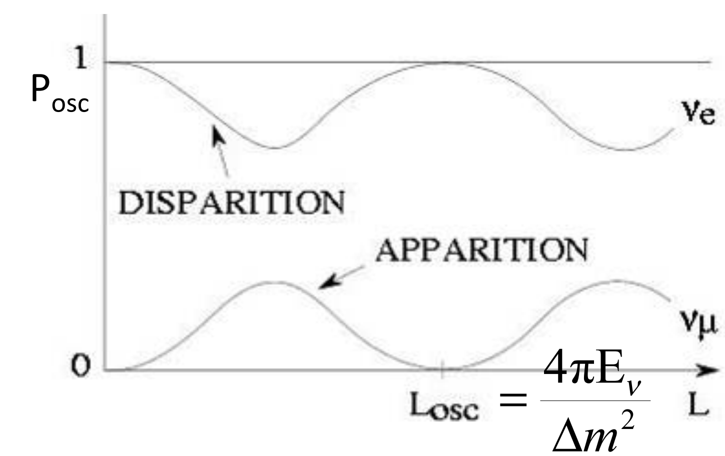
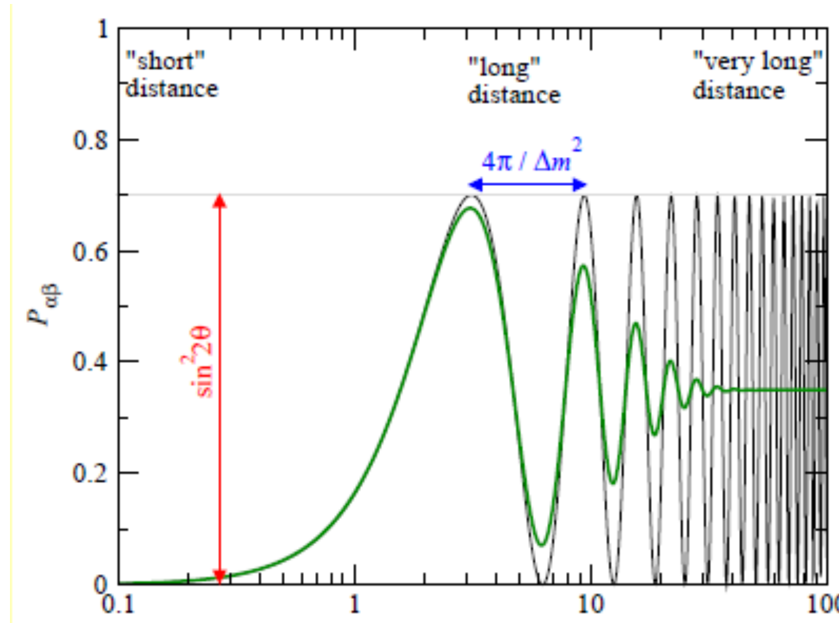
Maximal oscillation:





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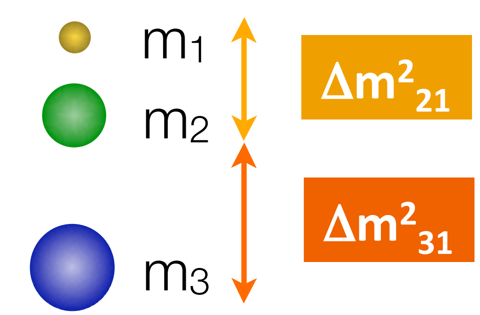

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amplitude   frequency

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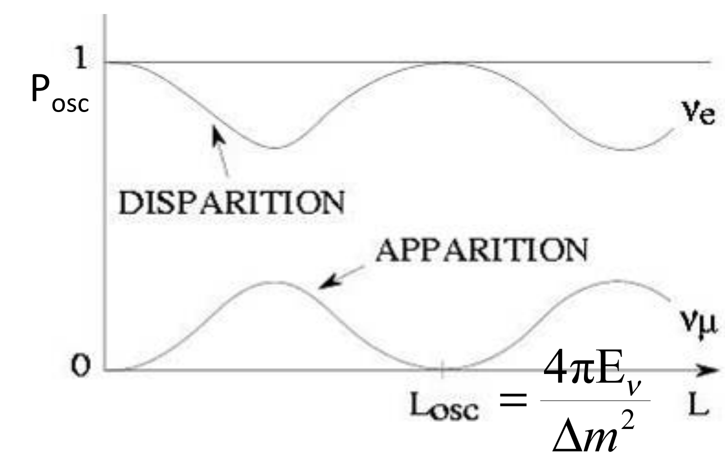
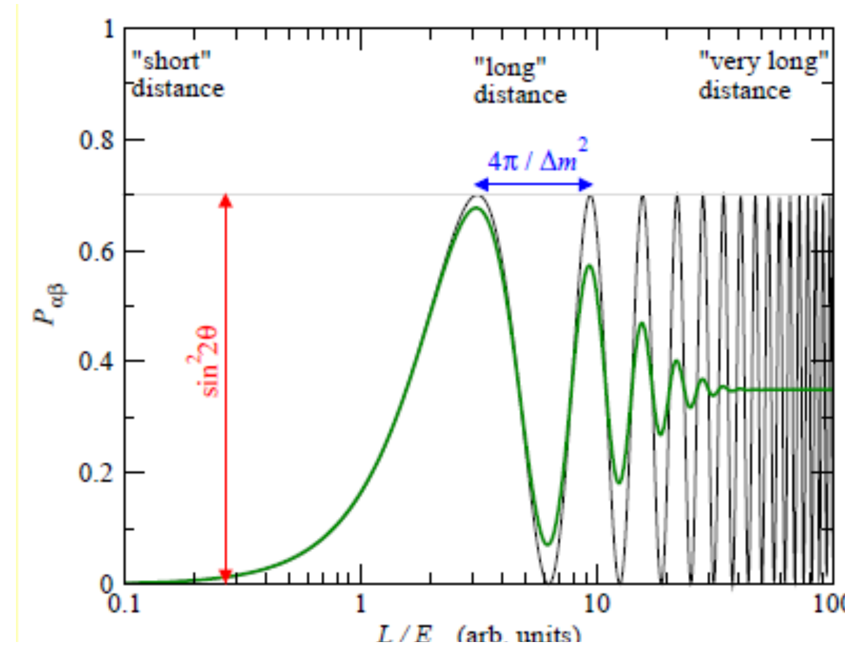
experimental parameters



Maximal oscillation:

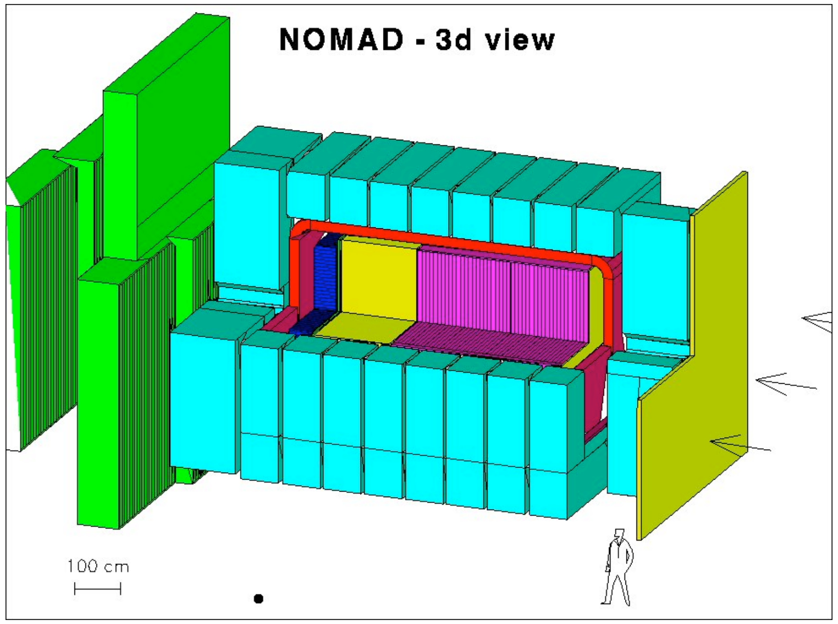
$$\frac{L}{E} = \frac{2\pi}{\Delta m^2_{32}} \approx 500\ \text{km/GeV}$$

$$\frac{L}{E} = \frac{2\pi}{\Delta m^2_{21}} \approx 15000\ \text{km/GeV}$$

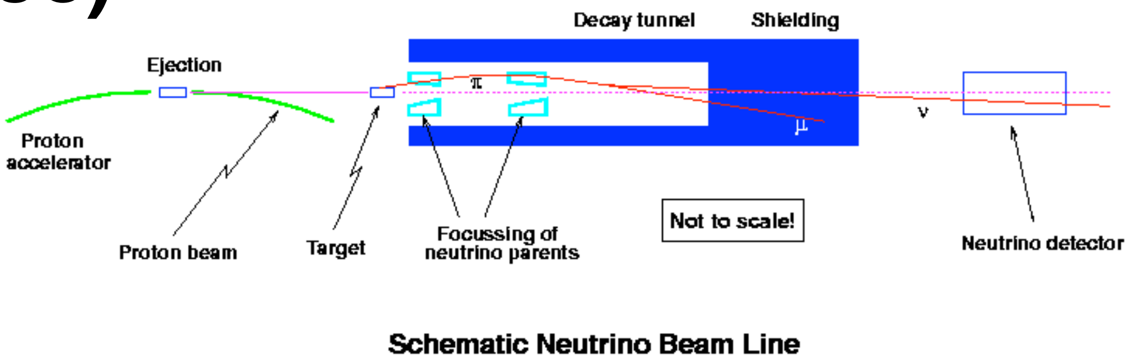


Failed attempts…

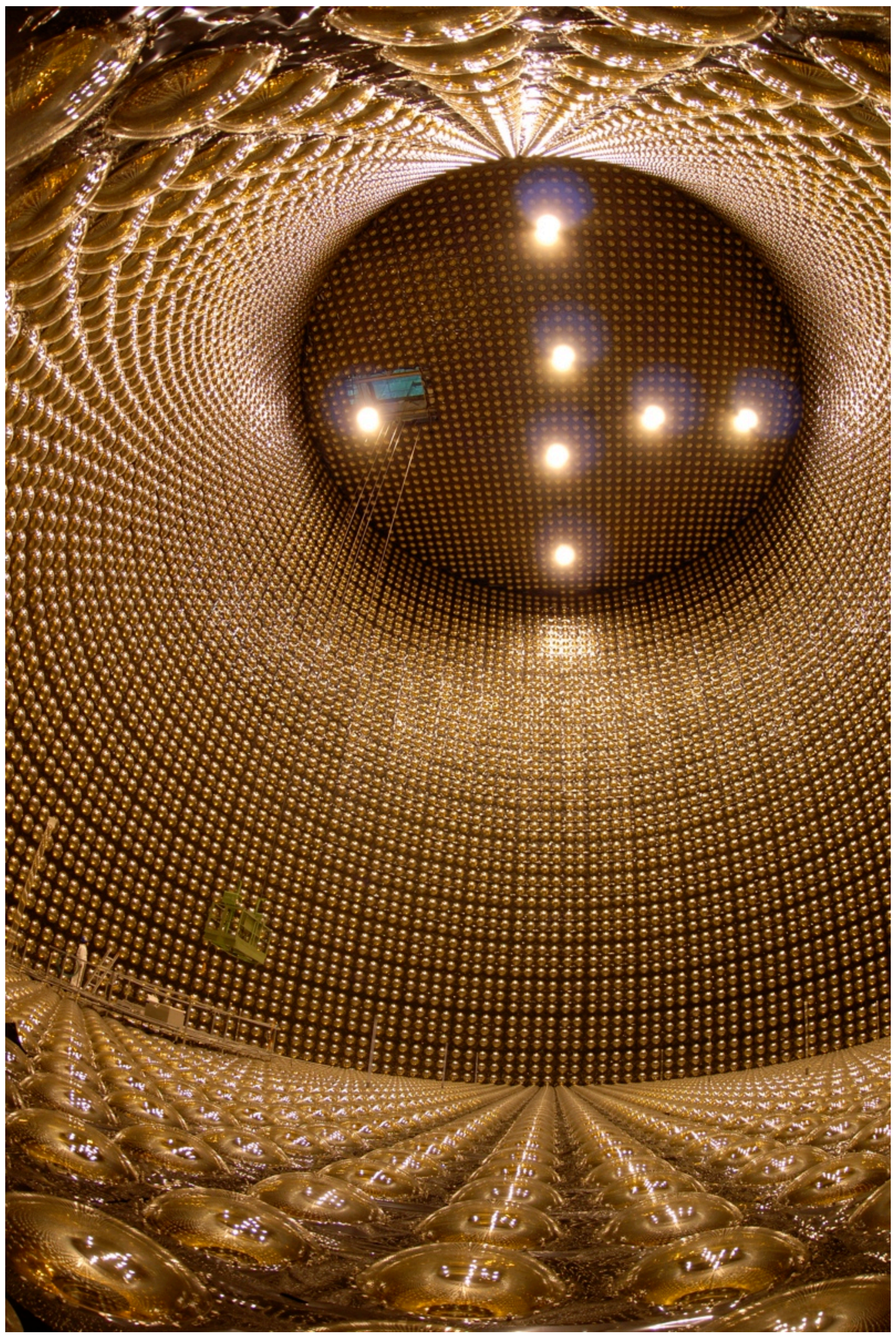
- **Looking for $\bar{\nu}_e \rightarrow \bar{\nu}_?$ (disappearance)**
  - ILL, Goesgen, Bugey, Palo Verde and CHOOZ in reactors
- **Looking for $\nu_\mu \rightarrow \nu_\tau$ (appearance)**
  - CHORUS and NOMAD at CERN (1995-1998)

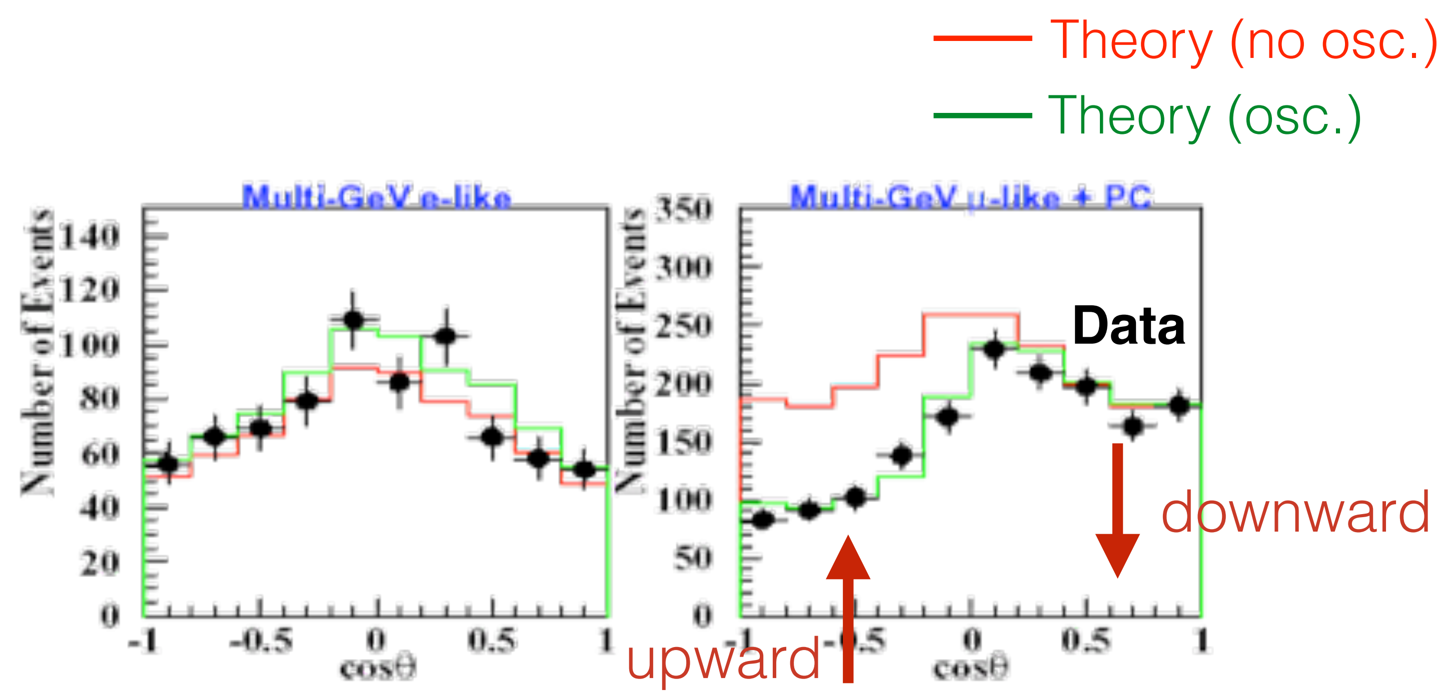


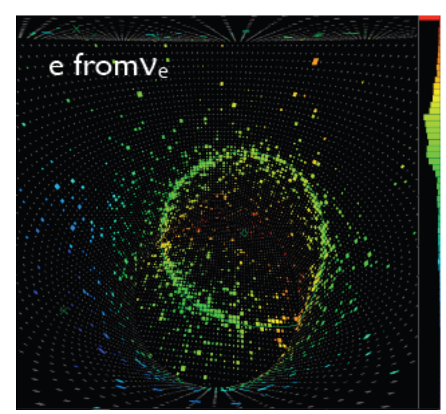
- **Looking for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (appearance)**
  - KARMEN
  - LSND / MiniBooNE (oscillation observed??)



The discovery of neutrino oscillations (1998)







e^-

μ^-

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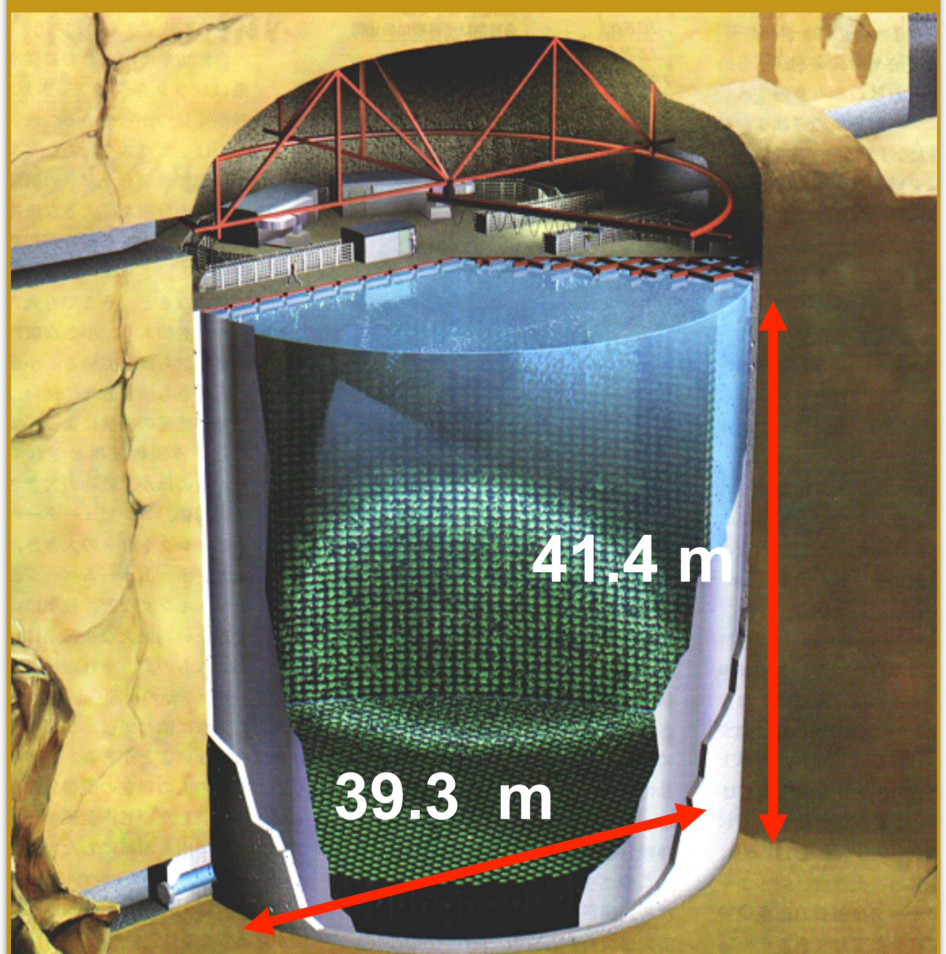
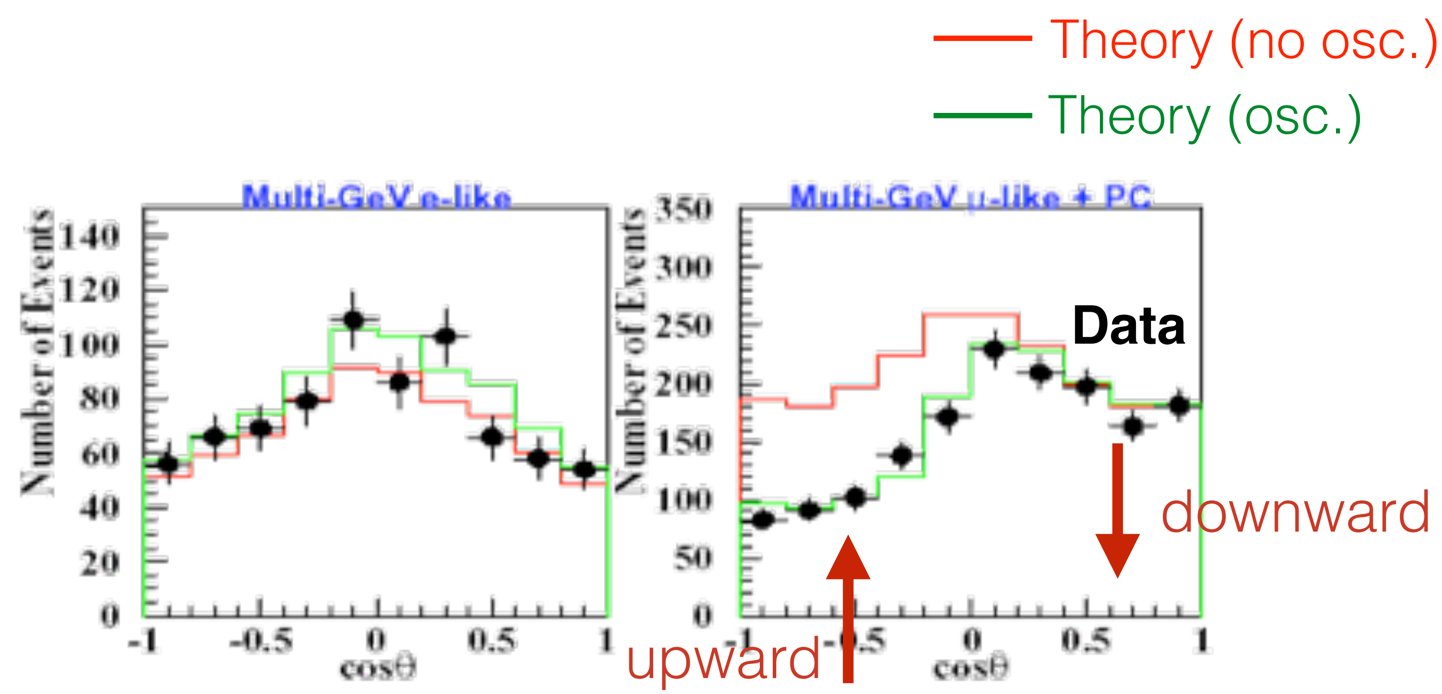
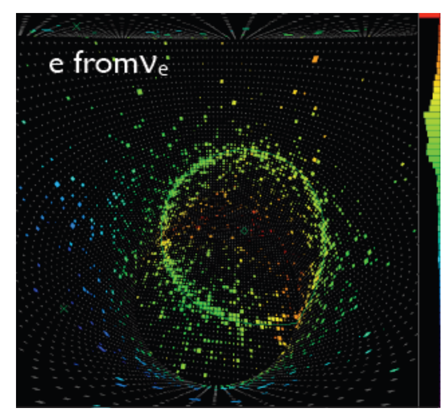


Super-Kamiokande detector in the Kamioka mine (Japan) (50 kton water, 11000 PMTs)





e⁻

μ⁻

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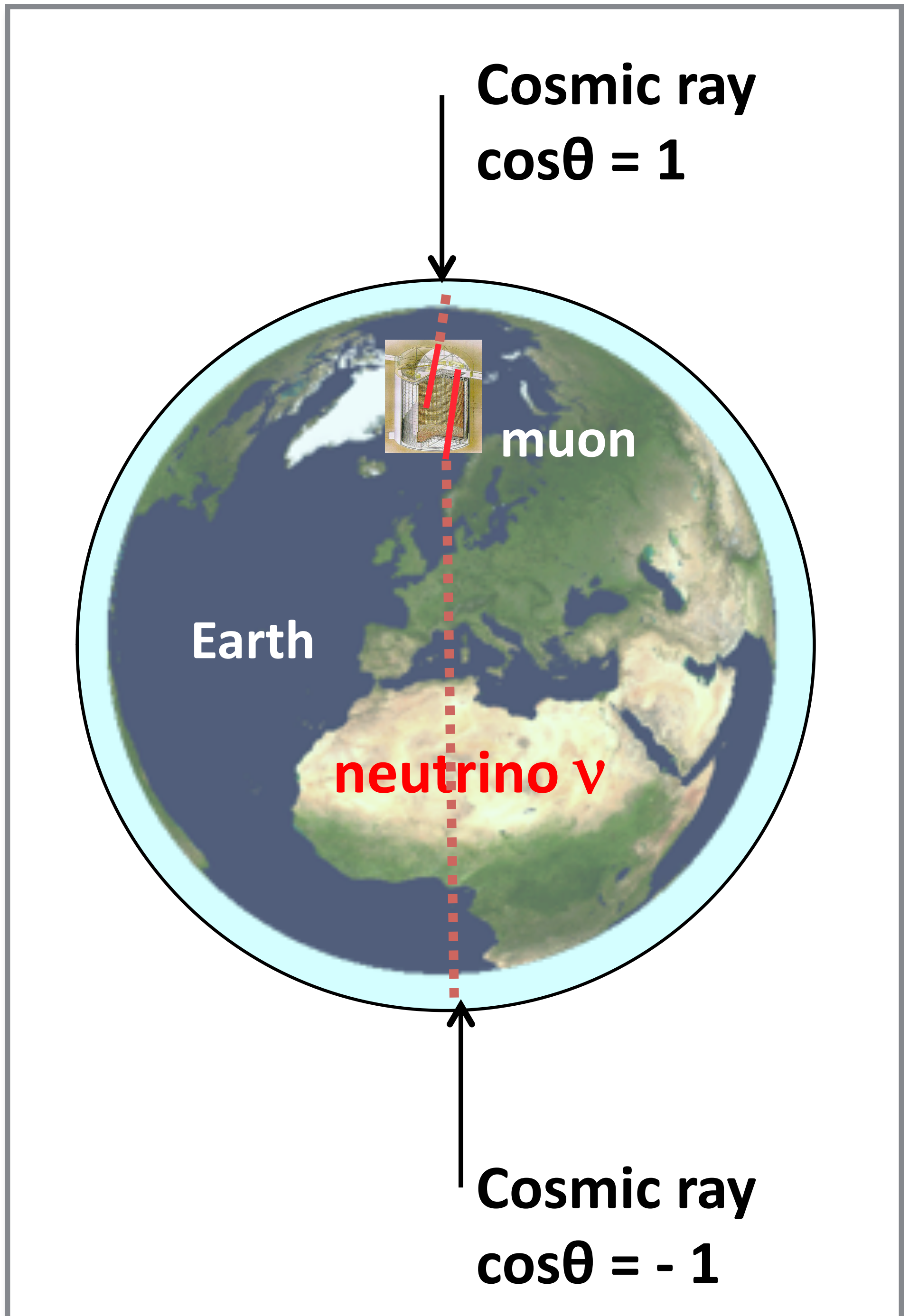

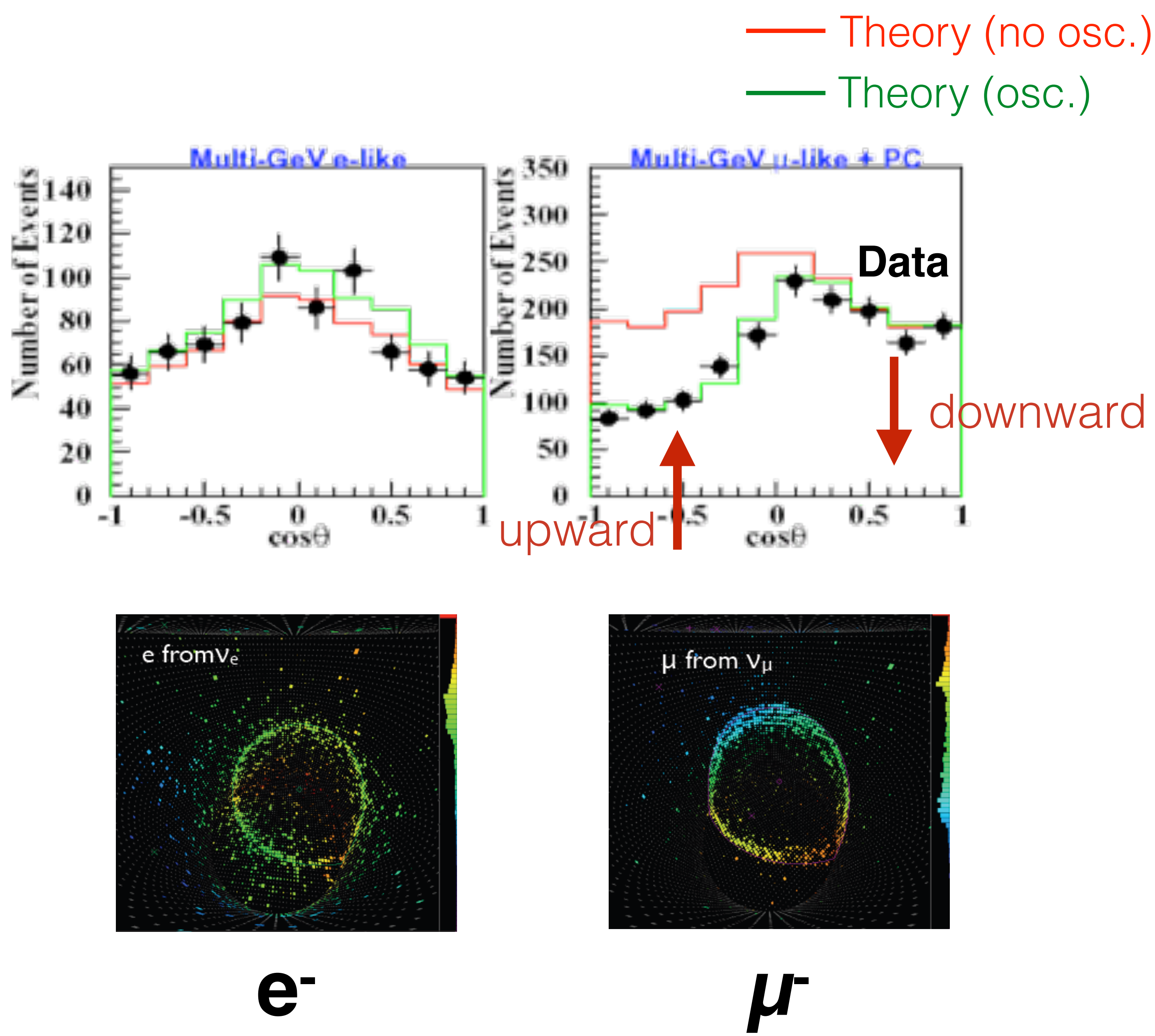

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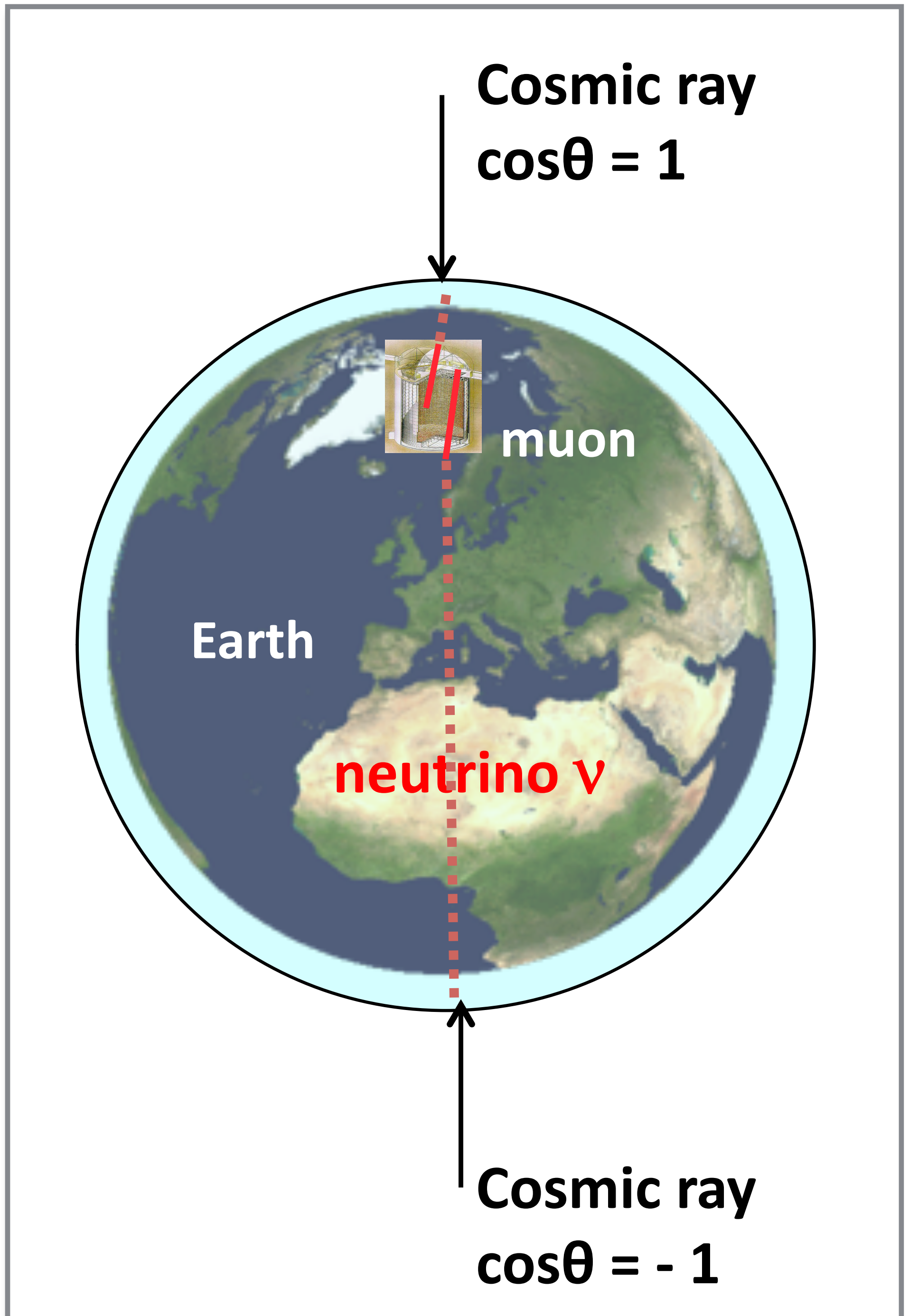

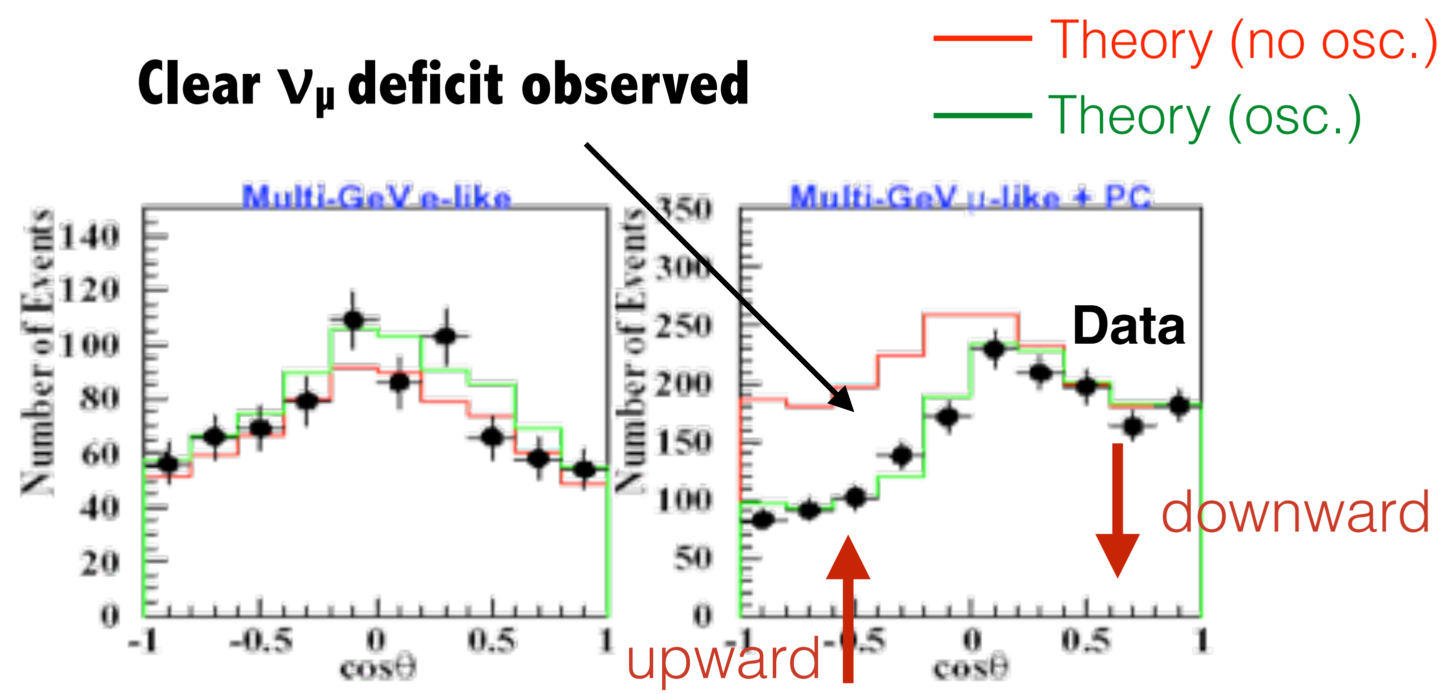

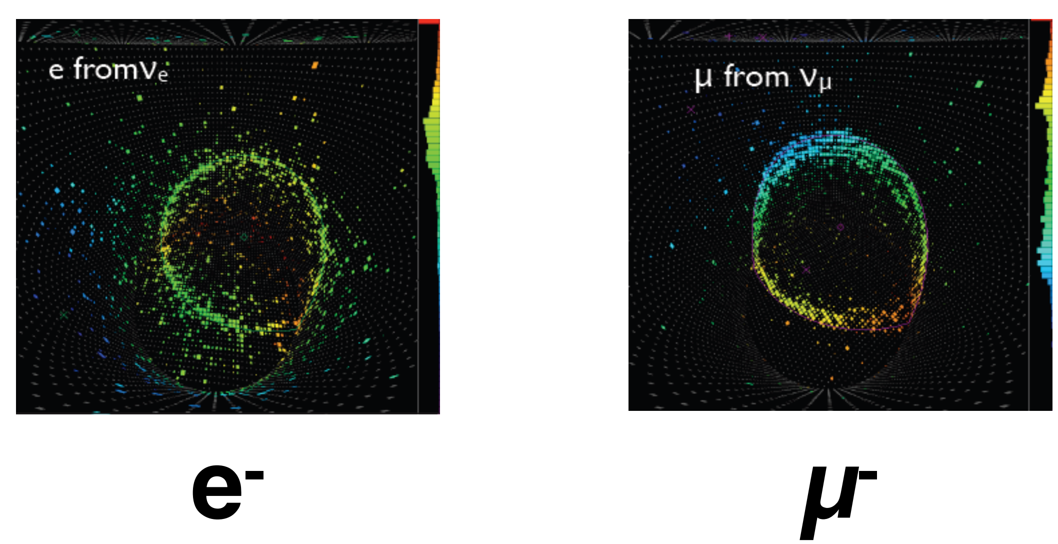

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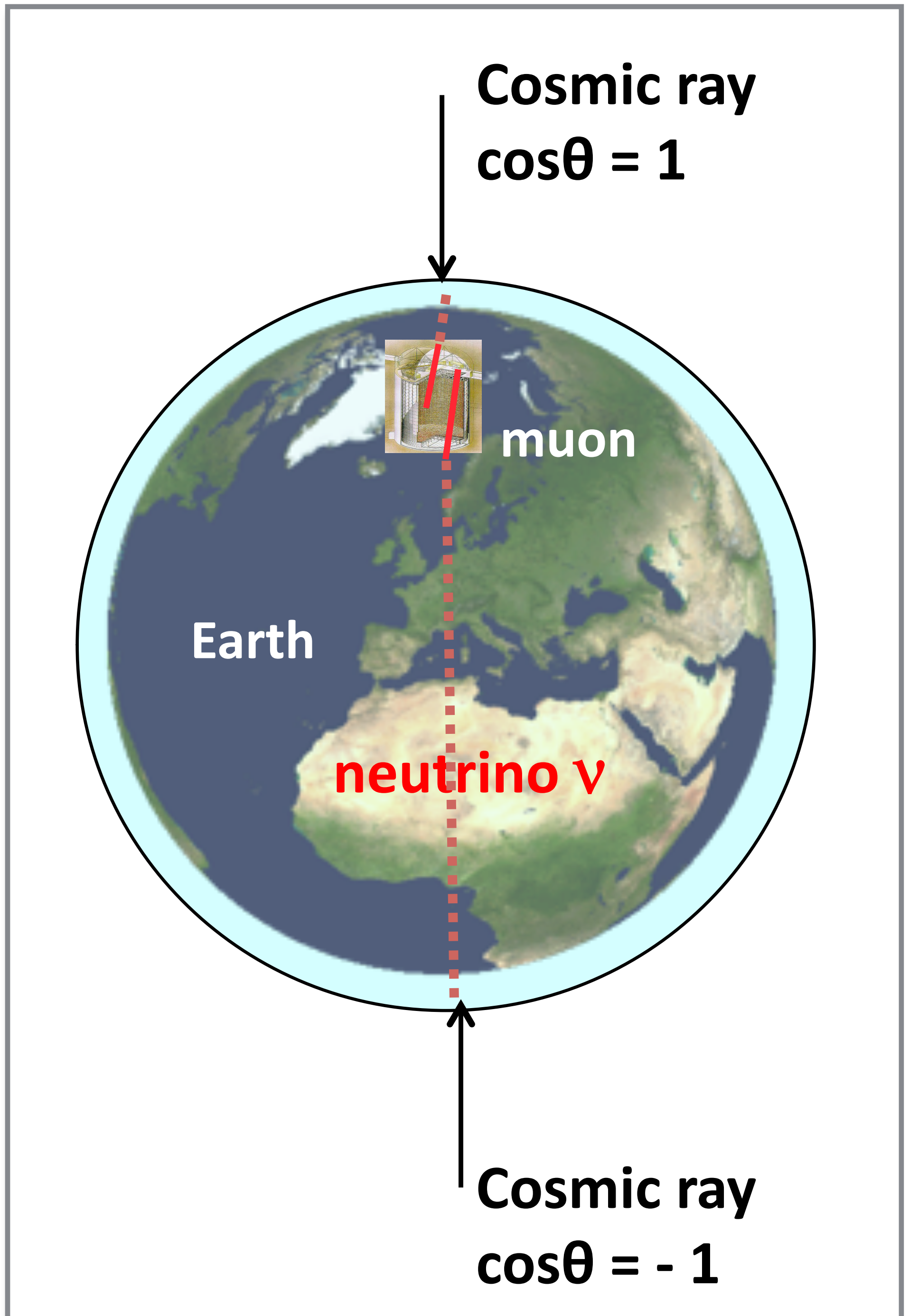
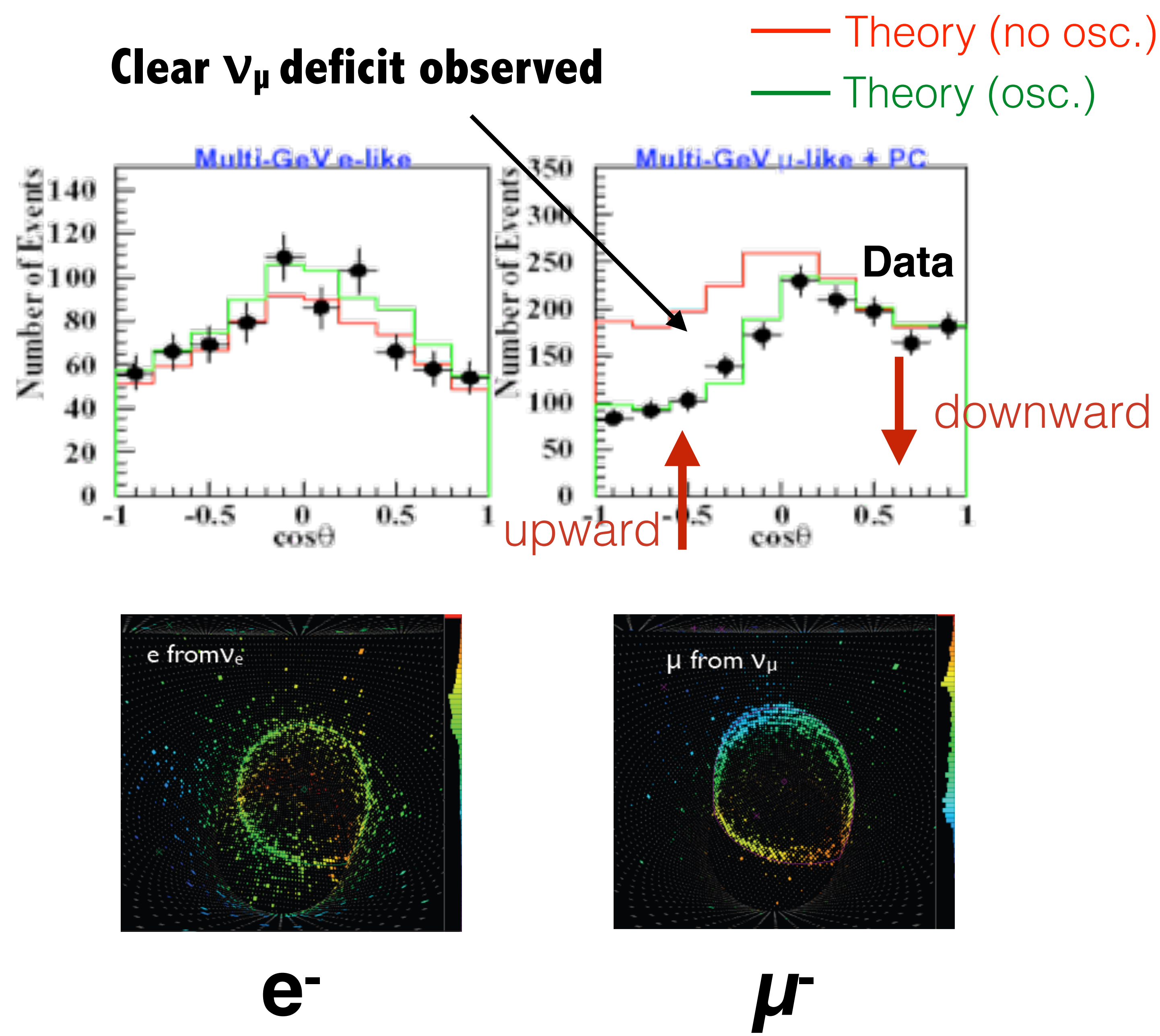
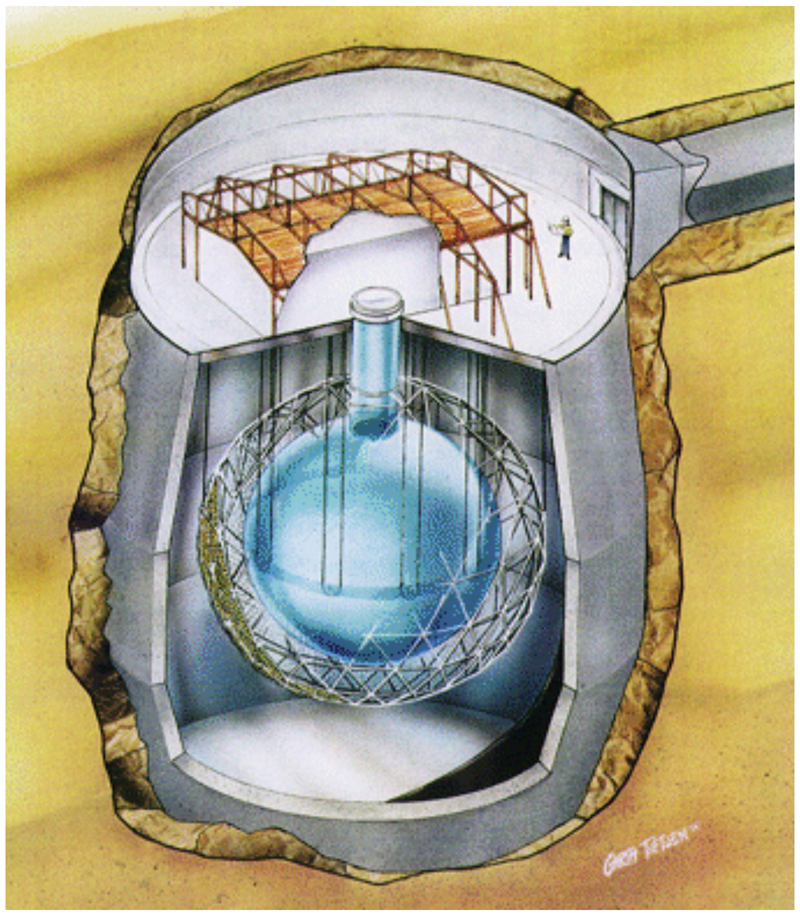




Atmospheric neutrino oscillations

$\nu_\mu \rightarrow \nu_\tau$

Solar neutrino anomaly solved (2001)



- **SNO**: 1000 ton heavy water (D_2O) in the Sudbury mine (Canada)
- Able to measure *all types of neutrinos* from the Sun
- Reaction sensitive to all types of neutrinos (NC)

$$\nu_x + d \Rightarrow p + n + \nu_x$$

- Reaction only sensitive to electron neutrinos (CC)

$$\nu_e + d \Rightarrow p + p + e^-$$

- In case of no oscillations: $\Phi_{NC} = \Phi_{CC}$
- If neutrinos oscillate: $\Phi_{NC} \neq \Phi_{C}$

Only ν_e are emitted from the Sun by fusion reactions

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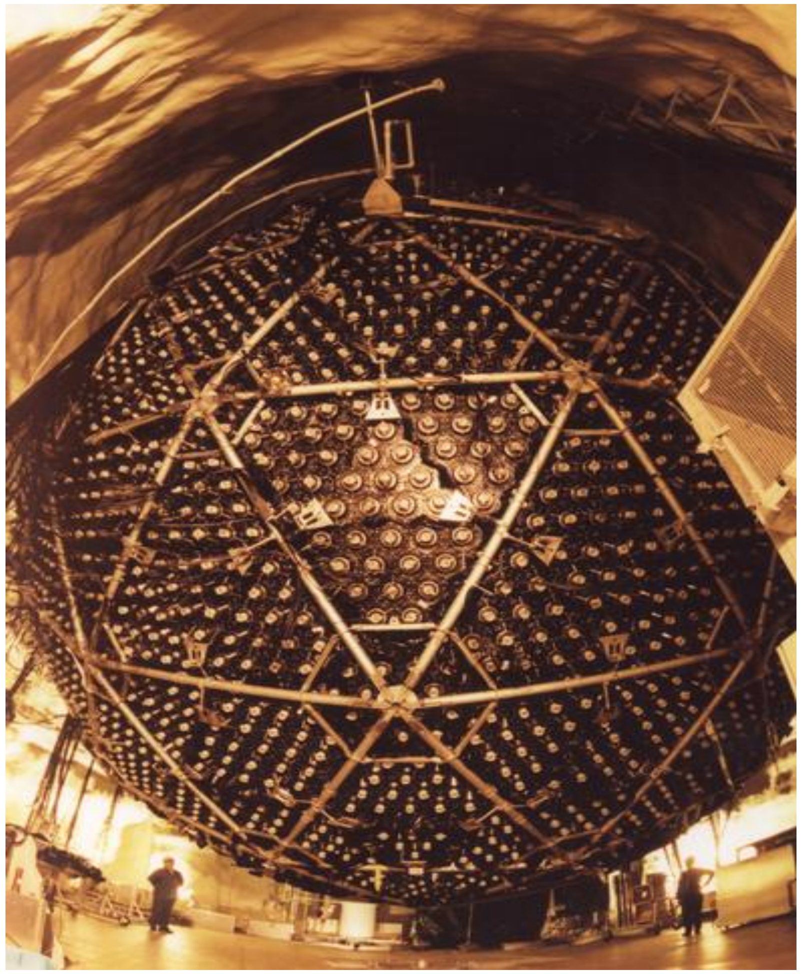

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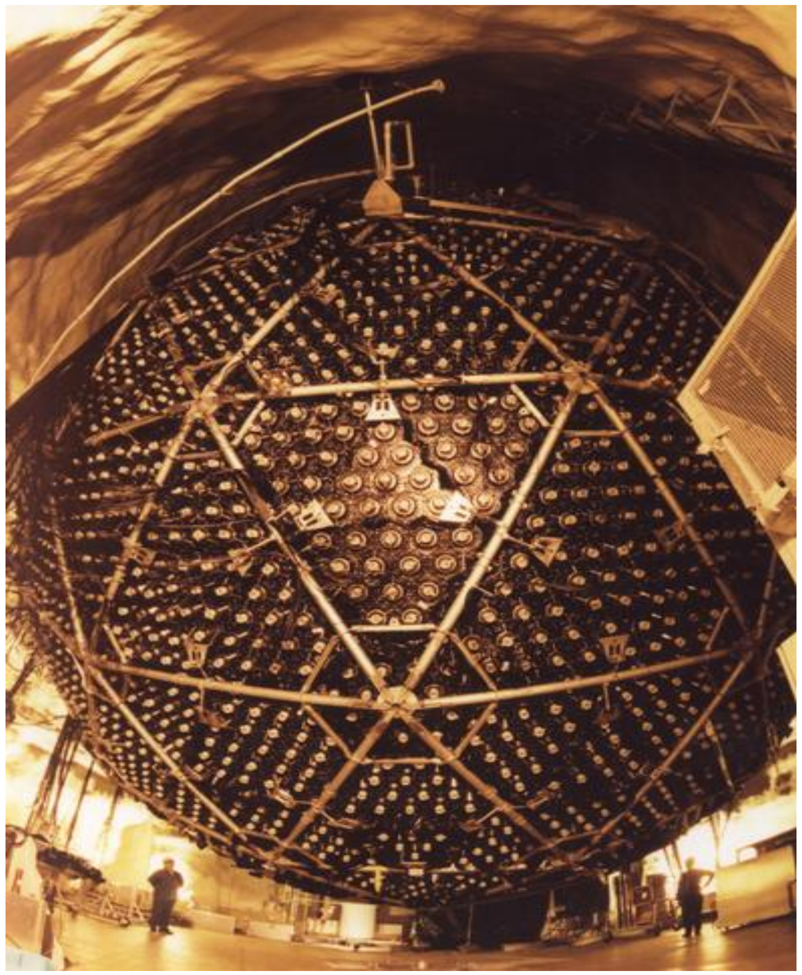

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Result: $\mathbf{\Phi_{CC} / \Phi_{NC} = 0.301 \pm 0.033}$

Φ_{NC} in agreement with SSM

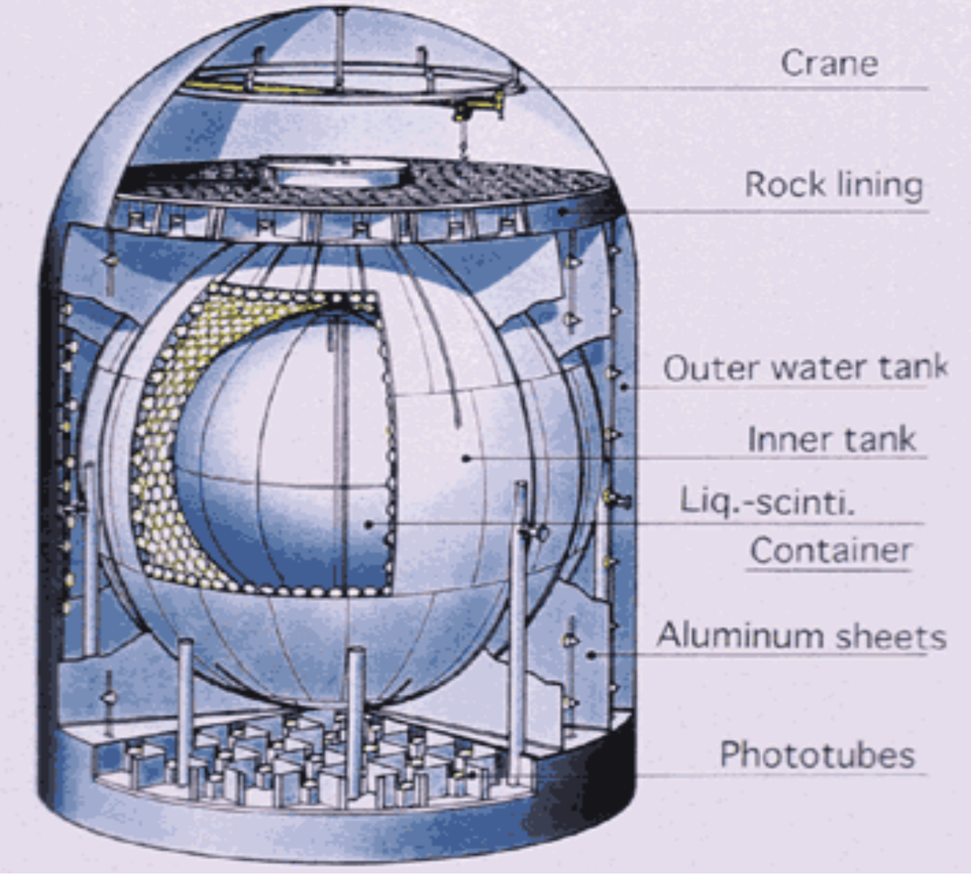
Part of $\boldsymbol{\nu_e}$ **converted into** $\boldsymbol{\nu_\mu}$ **and/or** $\boldsymbol{\nu_\tau}$

Reactor neutrino oscillations

KAMLAND (2002)

Long-baseline (~180 km)

- Confirmation of solar neutrino oscillations
- Disappearance of $\bar{\nu}_e$



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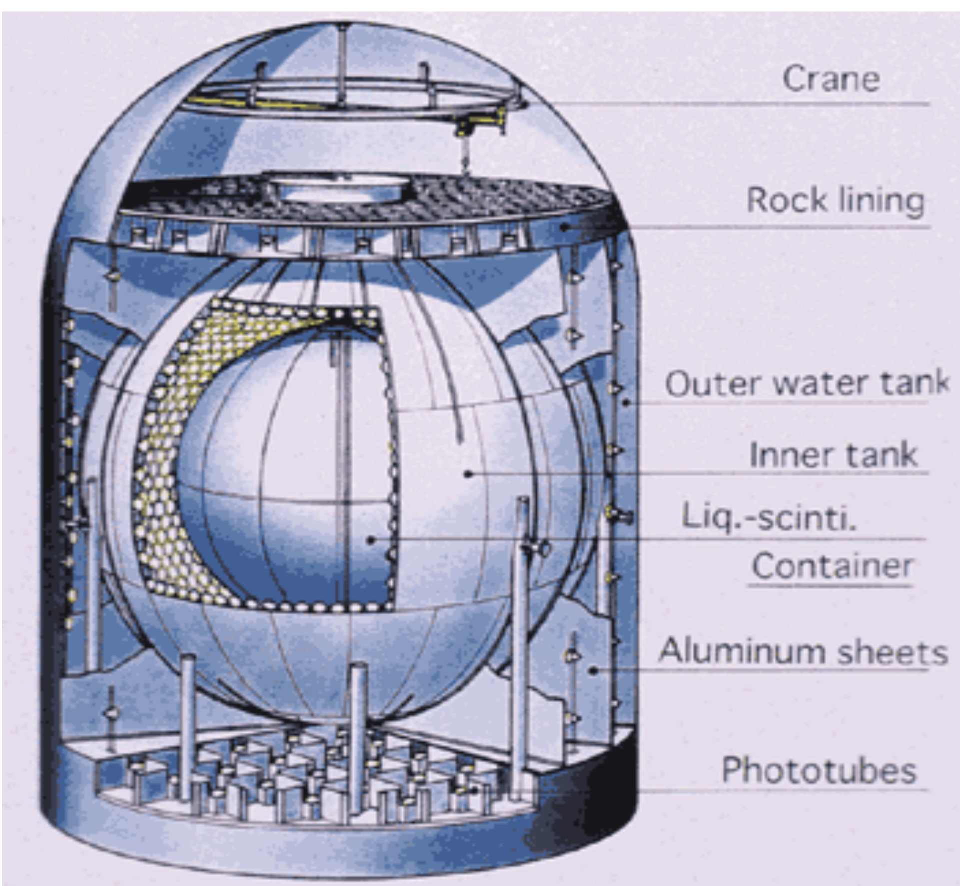

Double Chooz, Daya Bay, RENO (2011-)

Short-baseline (~1km)

- Measurement of a new type of oscillations
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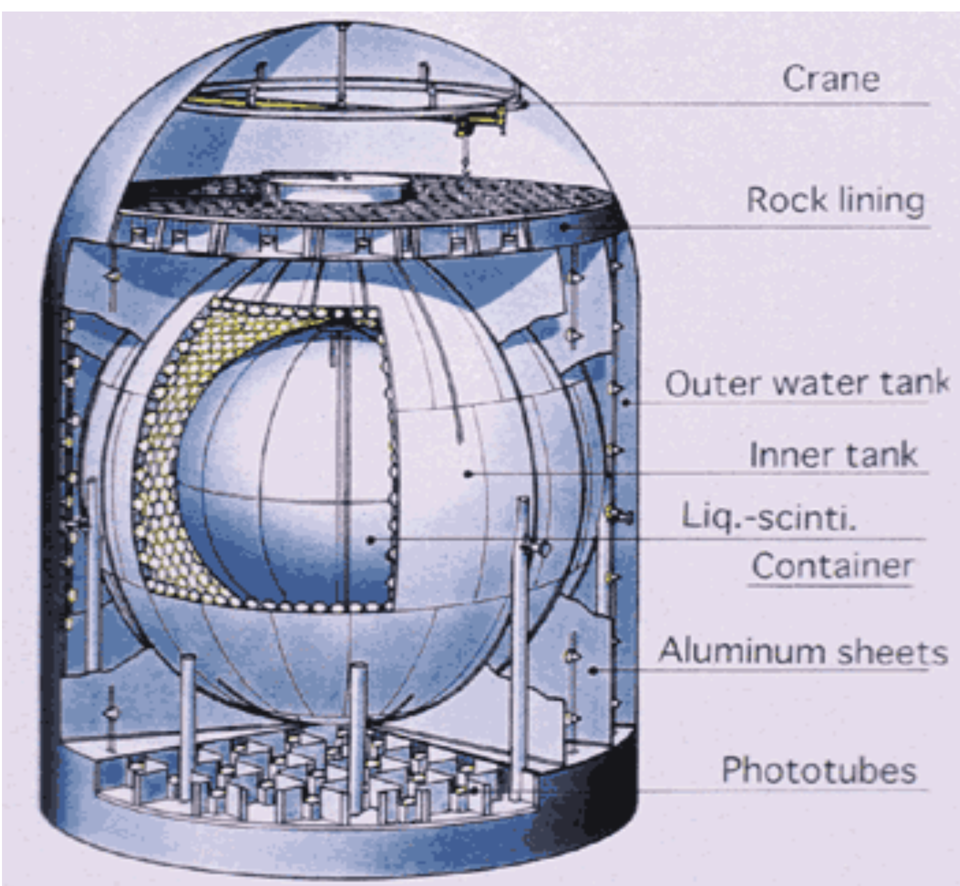

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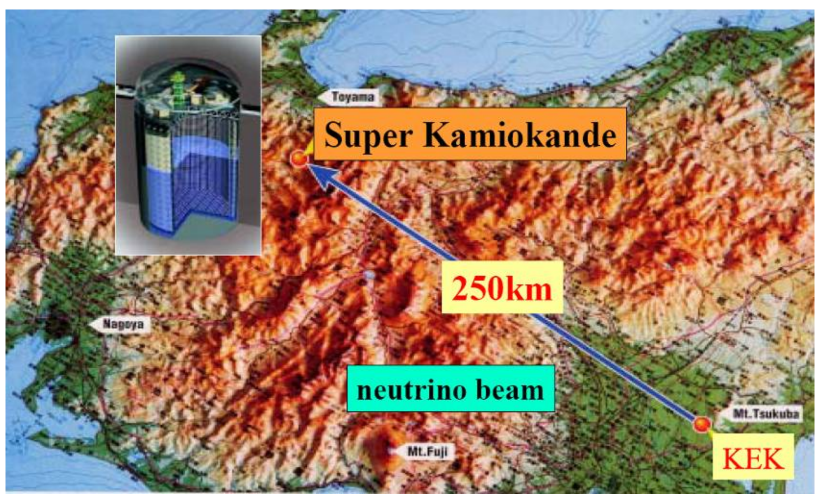

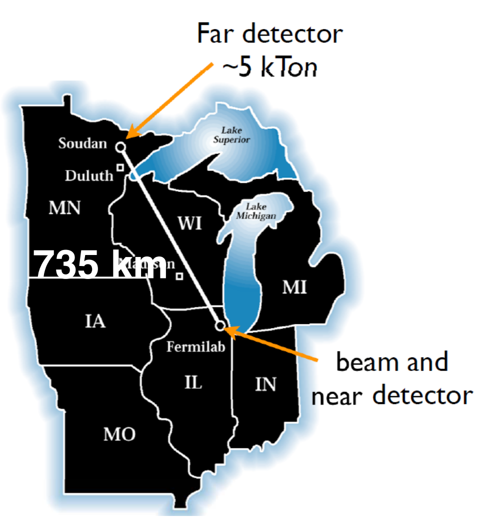

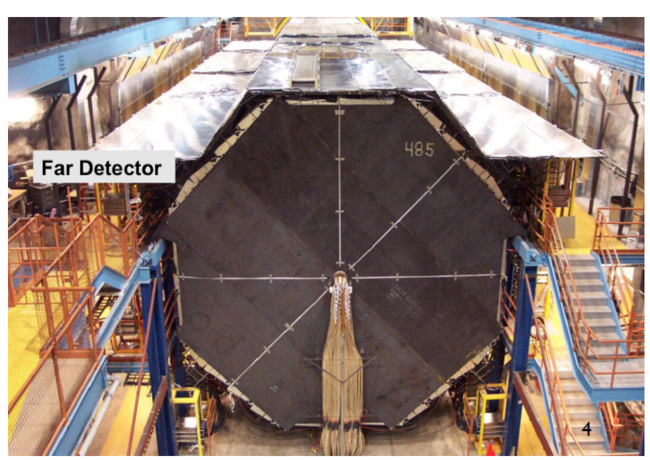

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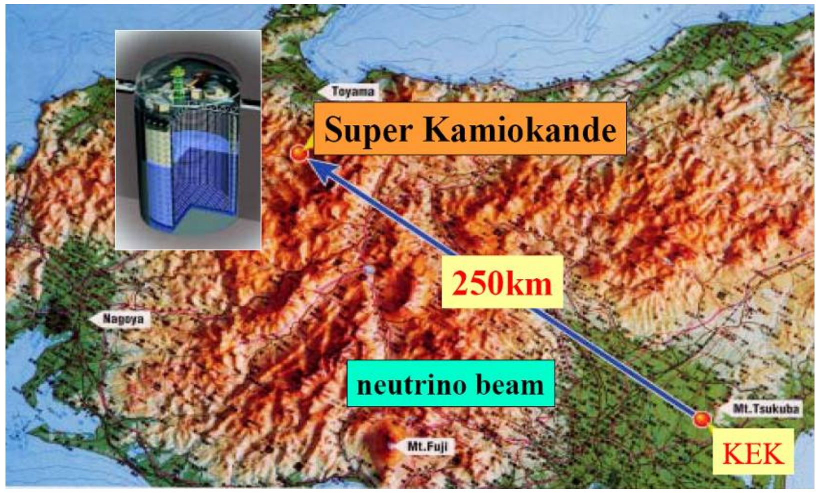

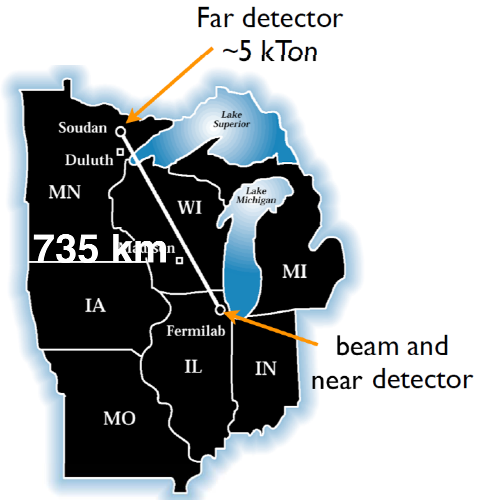

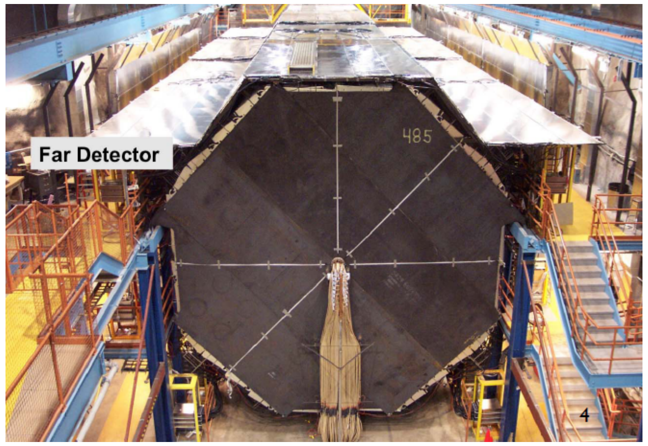

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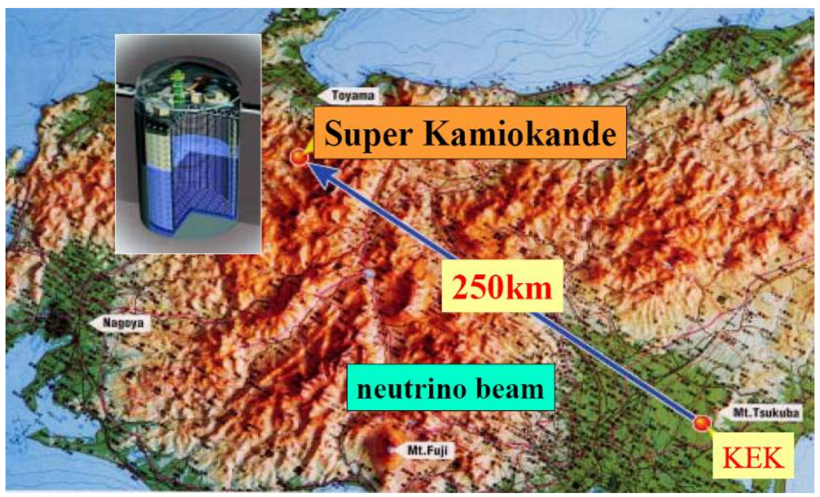

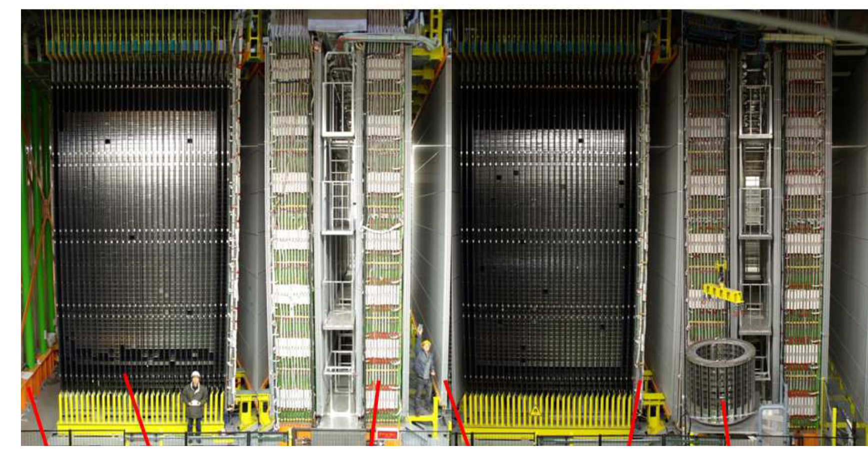

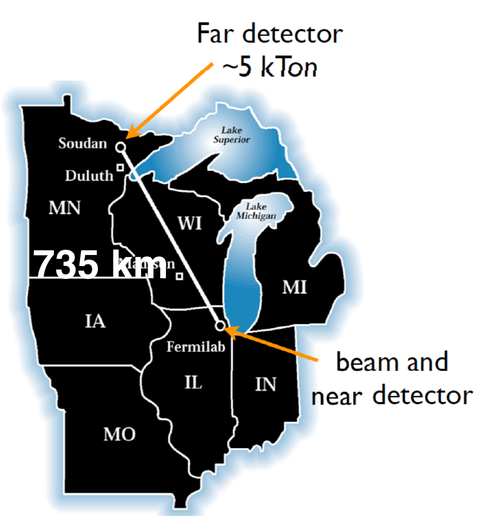

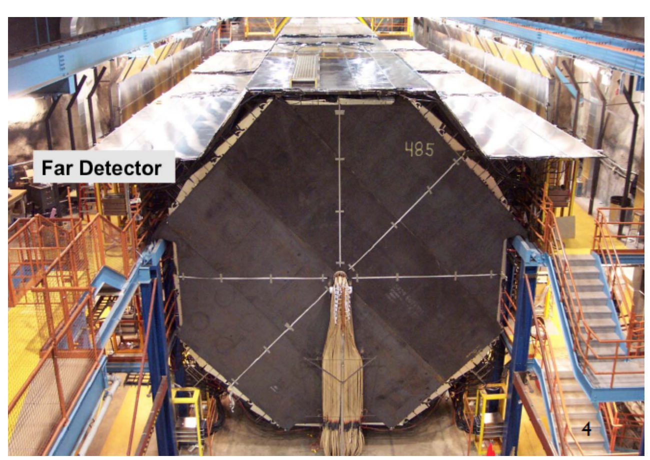

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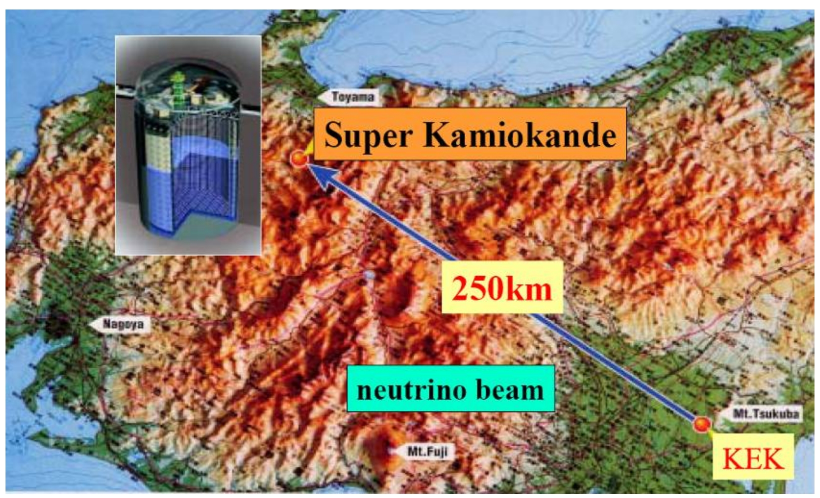

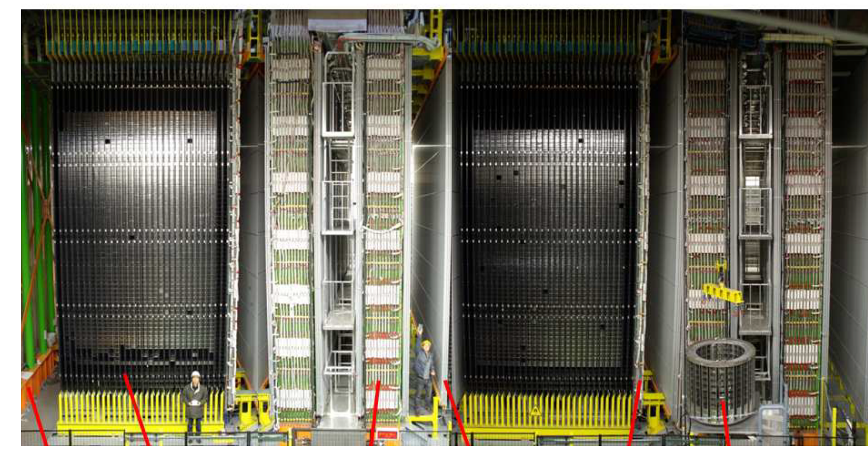

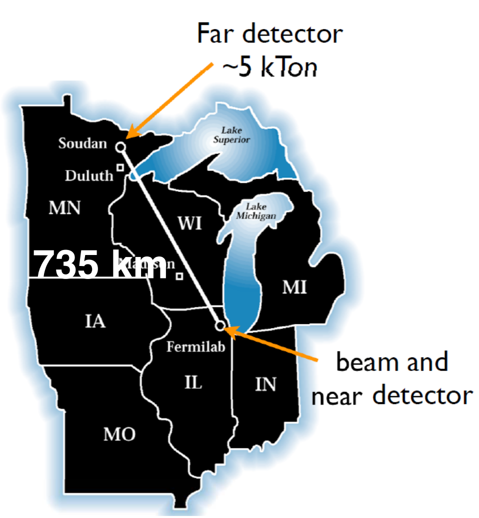

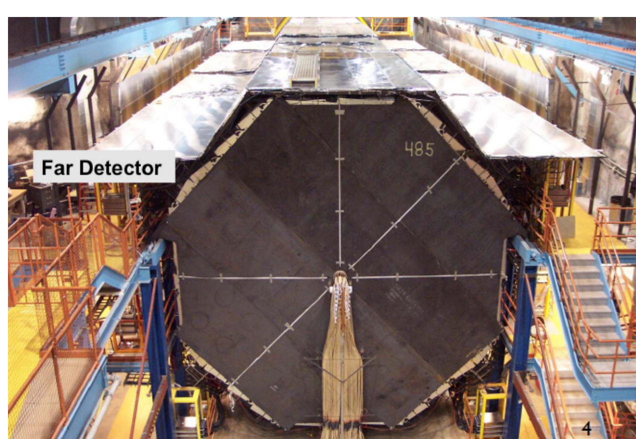

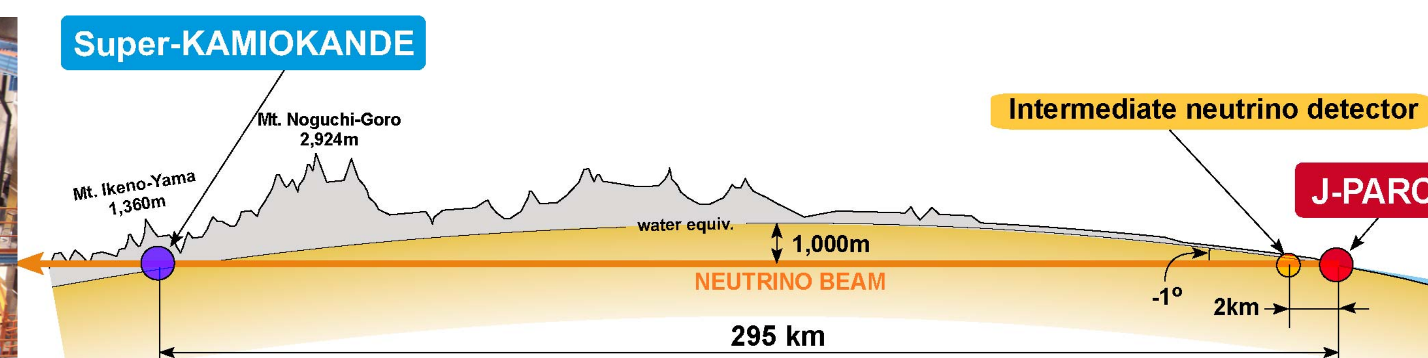

Observed oscillations

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

Neutrino oscillation measurements

- Mixing angles and mass diferences:

Neutrino oscillation measurements

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PDG K.A. Olive et al., Chin. Phys. C, 38, 090001 (2014)

$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$

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[i] The sign of Δm^2_{32} is not known at this time. The range quoted is for the absolute value.

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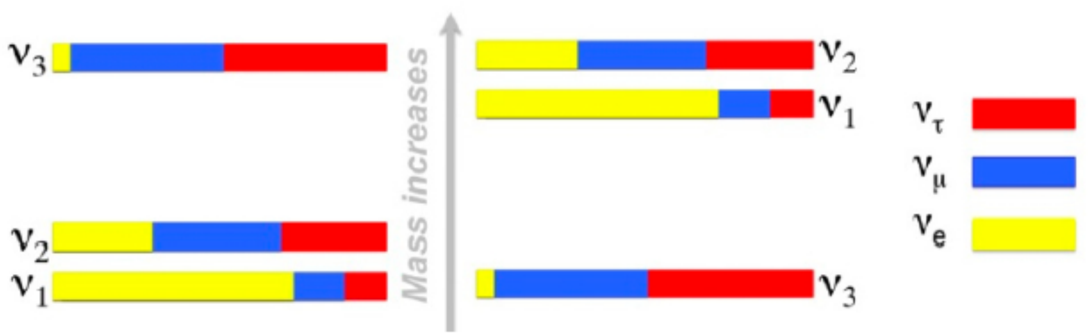

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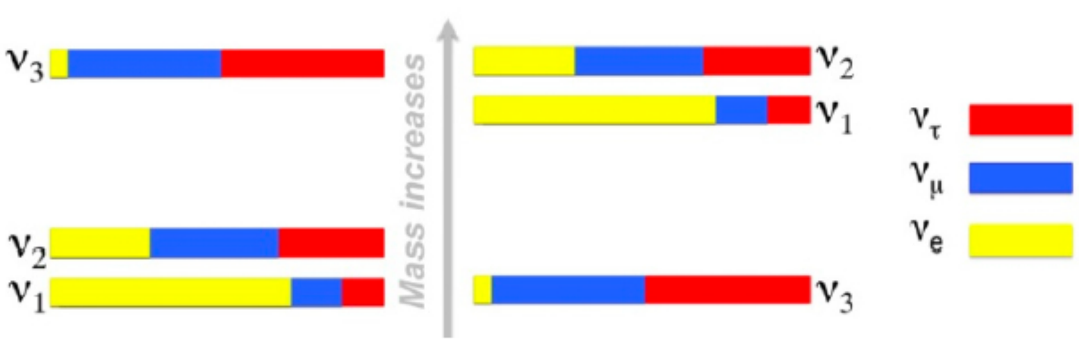

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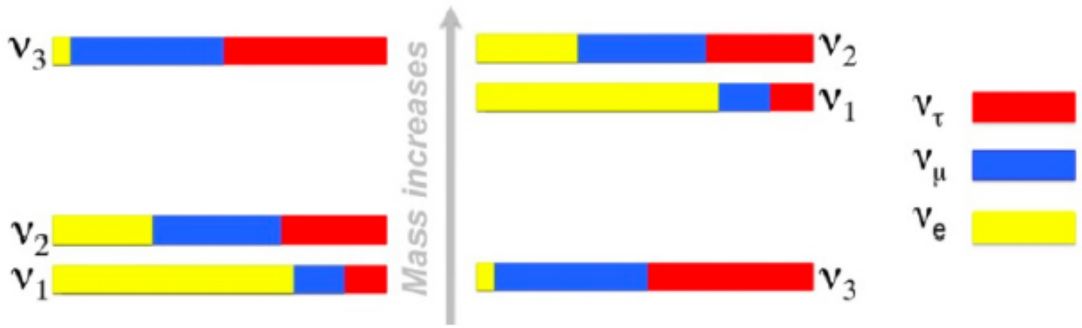
  - θ_{23} octant
  - CP violation phase



4

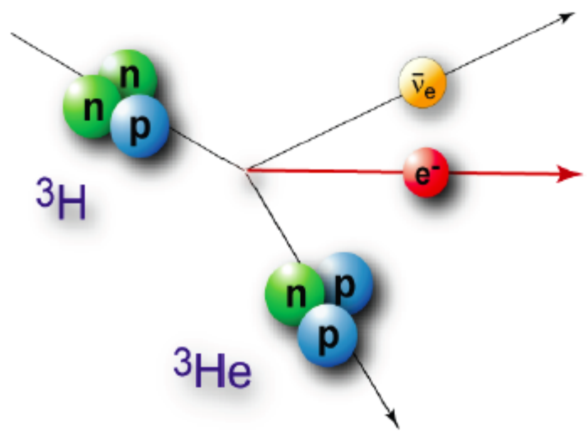
Big questions to be answered

¿?

- Neutrino masses: value, origin…
- Type of particle: Dirac or Majorana
- Relation with the other particles
- Do neutrino interactions violate the CP symmetry?
- Are there more than 3 neutrinos?

The neutrino mass

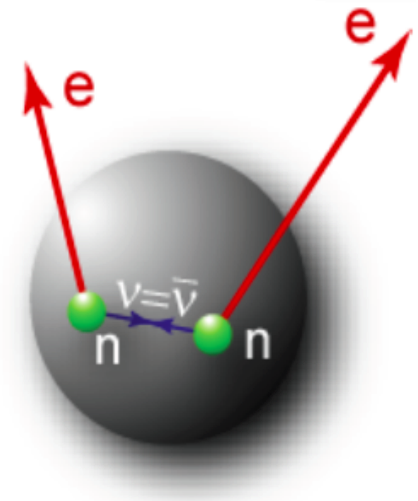
☑ **Direct measurements**: $m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$



Tritium beta decay experiments:

- Troitsk & Mainz: **m < 2 eV (95% CL)**
- KATRIN (goal): m < 0.2 eV (90% CL)

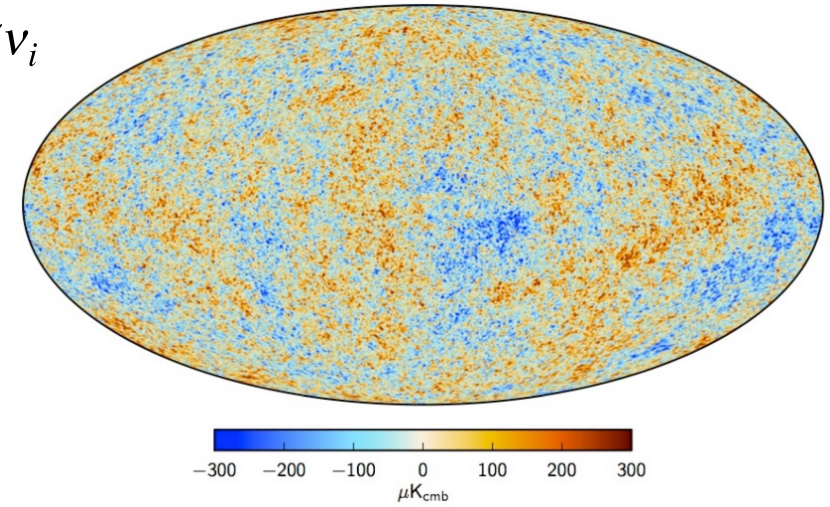
☑ **Neutrinoless double beta decay**: $m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$



- If measured, neutrinos are Majorana particles
- GERDA, EXO, CUORICINO, KamLAND-Zen, NEMO-3: **$m_{\beta\beta}$ < 0.2-0.4 eV (90% CL)**
- Future ton scale experiments: $m_{\beta\beta}$ < 10 meV

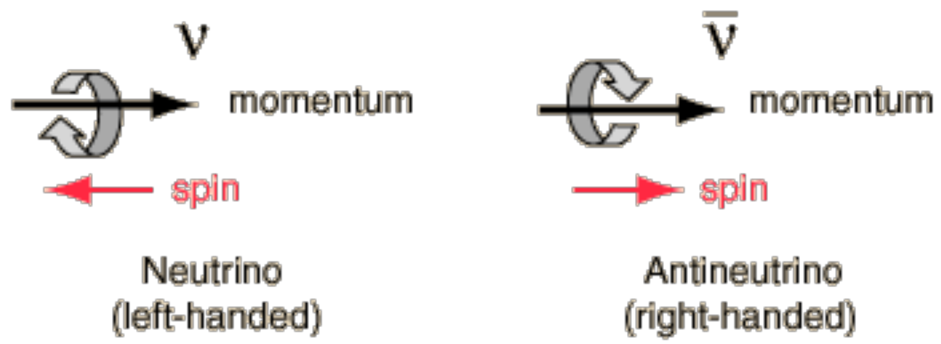
☑ **Indirect measurements (Cosmology)**: $m = \sum_i m_{\nu_i}$

PLANCK 2015 (arXiv:1502.01589)



- **$\sum m_\nu$ < 0.23 eV** (Planck TT+lowP+lensing+ext.)
- N_{eff} = 4 excluded at > 99%CL
- N_{eff} = 3.15 ± 0.23 (Planck TT+lowP+BAO)

Neutrino nature



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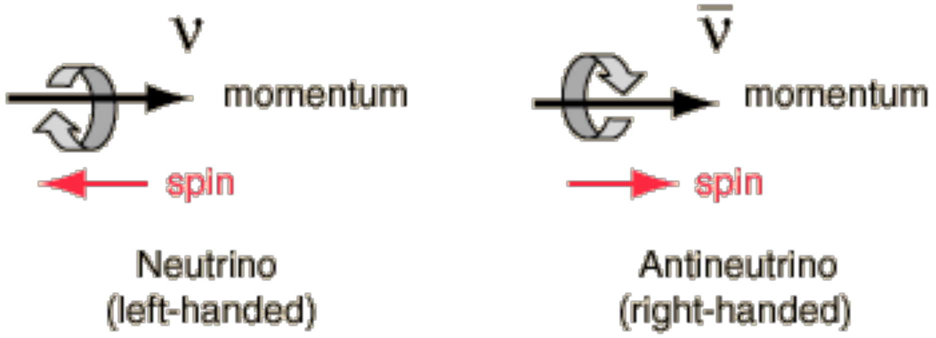

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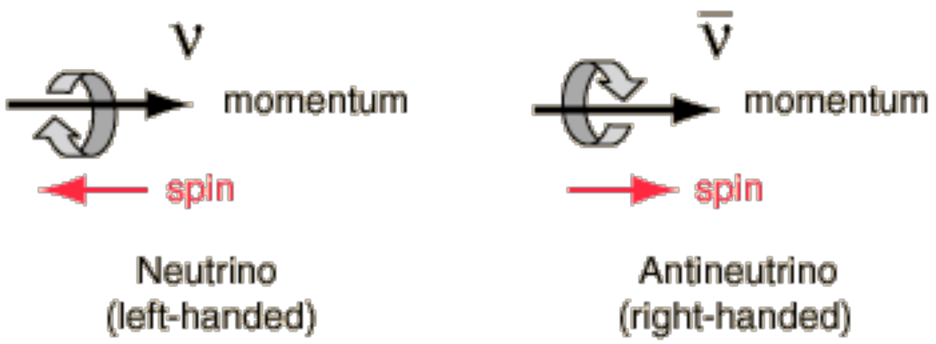

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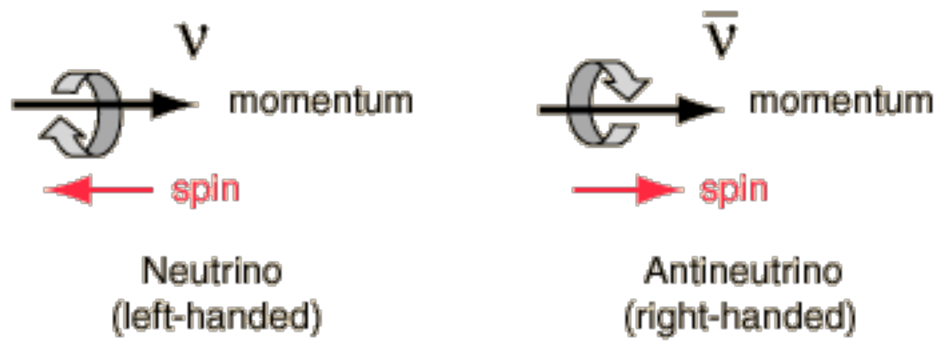

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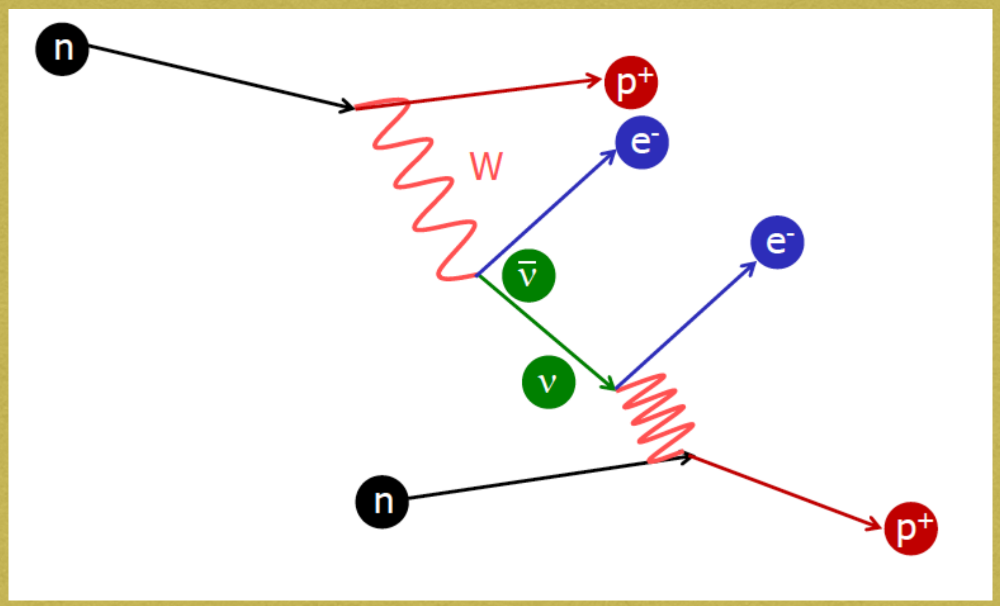

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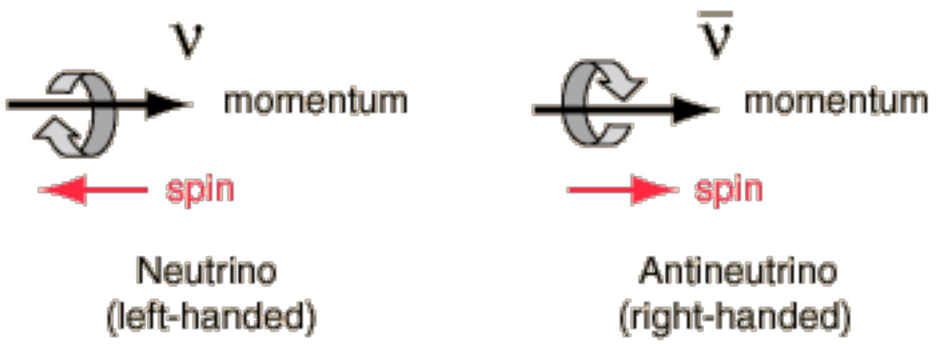

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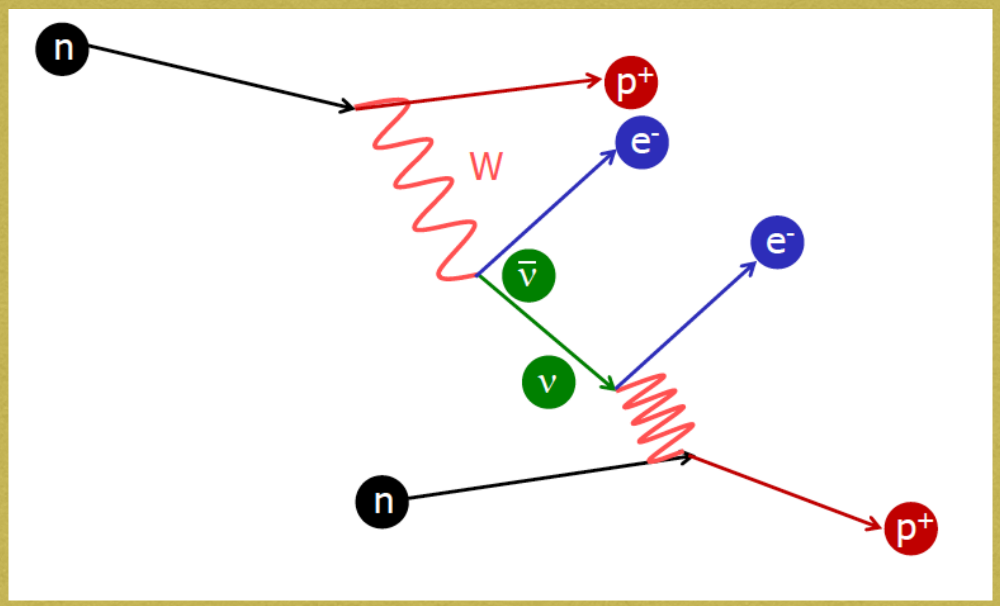

Direct proof of Majorana neutrinos existence

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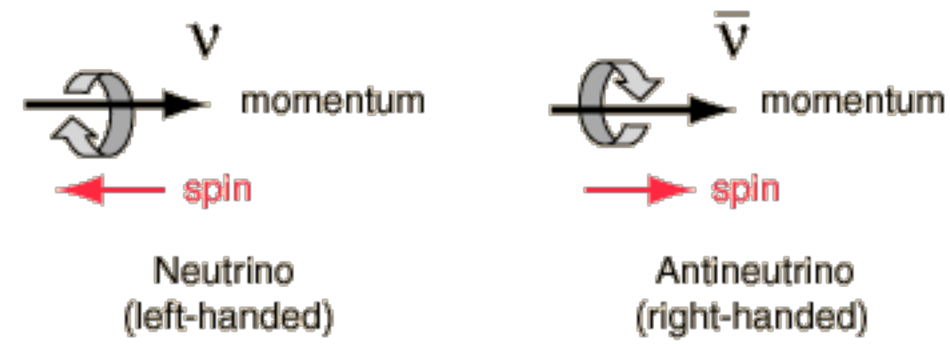

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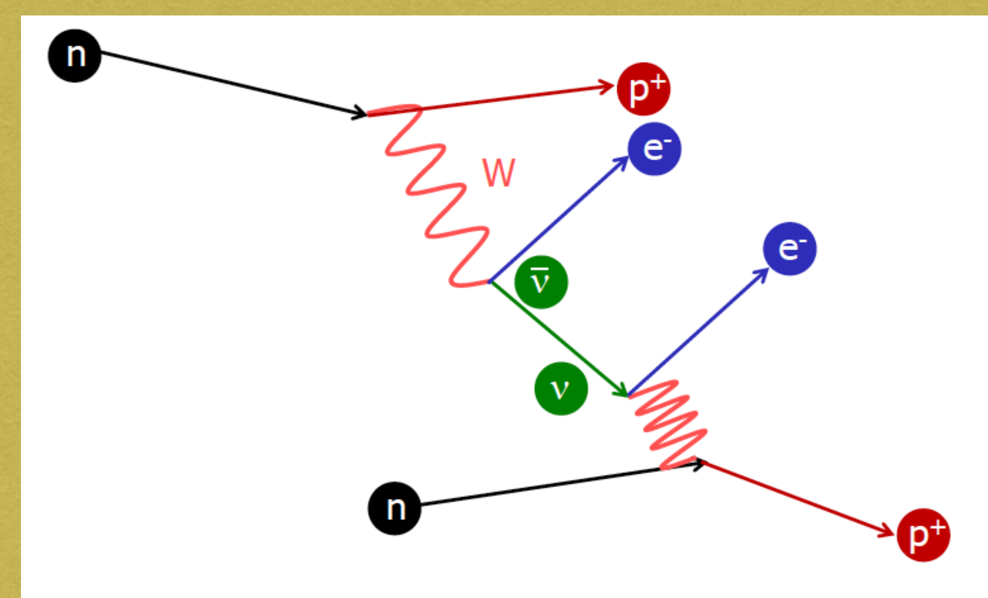

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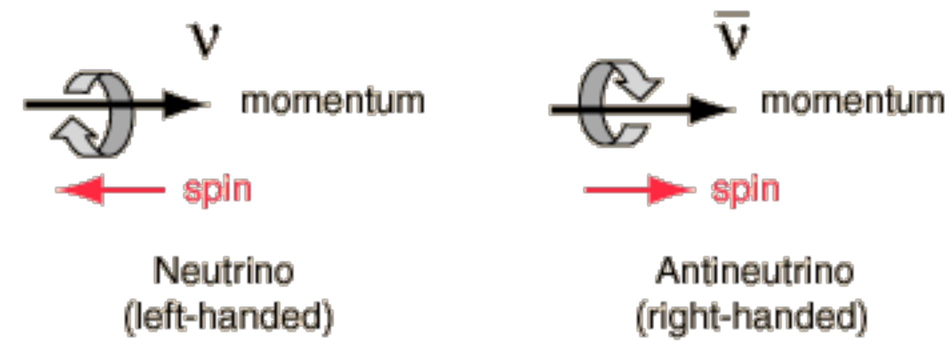
- this could explain the **matter-antimatter asymmetry in the Universe**:

  $\Rightarrow$ **LEPTOGENESIS**



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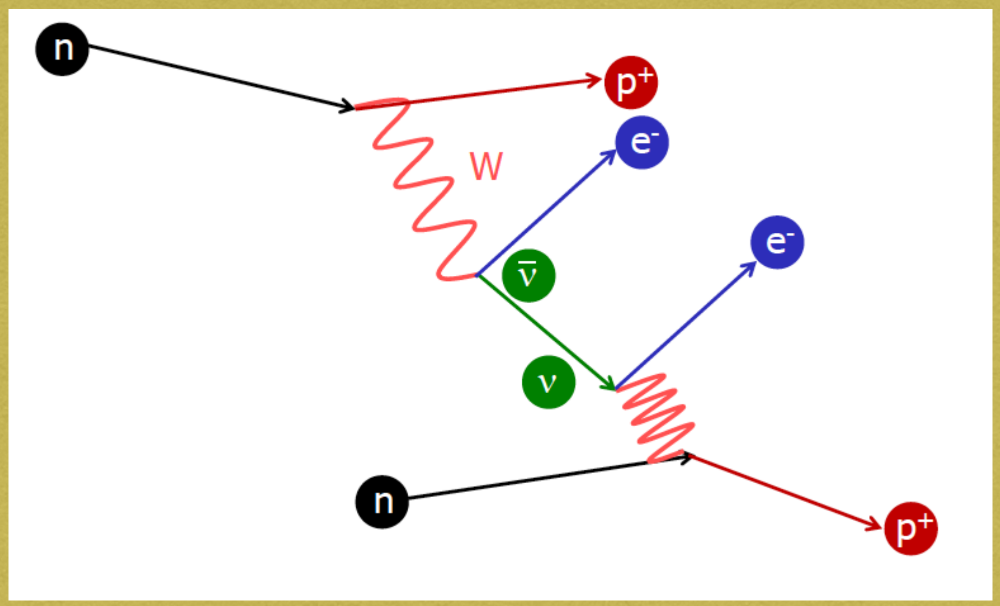

Direct proof of Majorana neutrinos existence

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- Relation with the Higgs boson?

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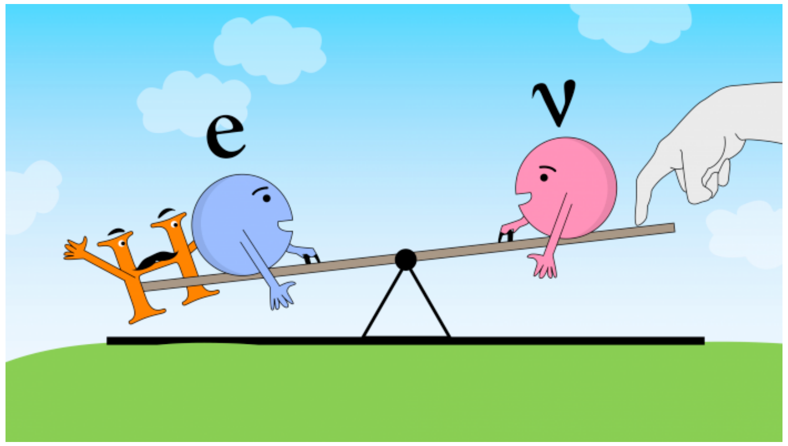

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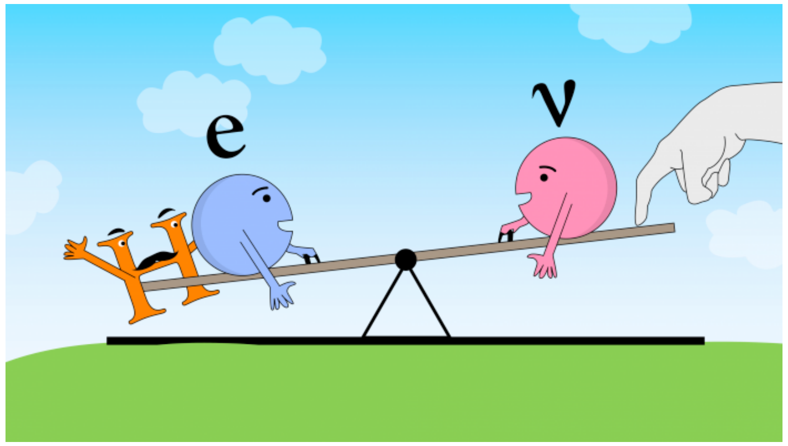

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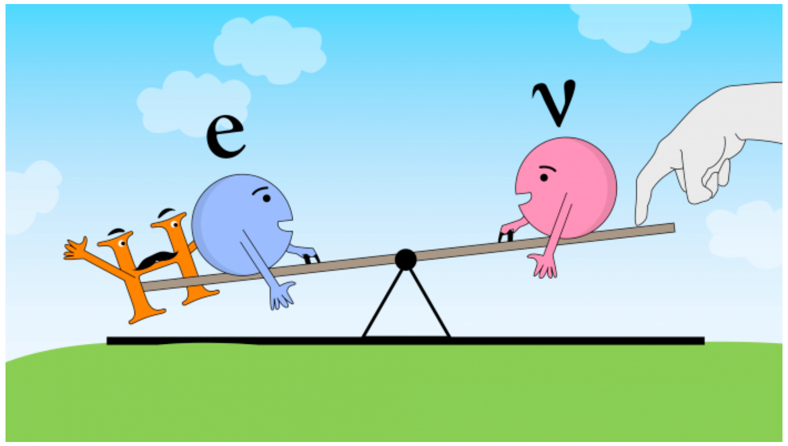

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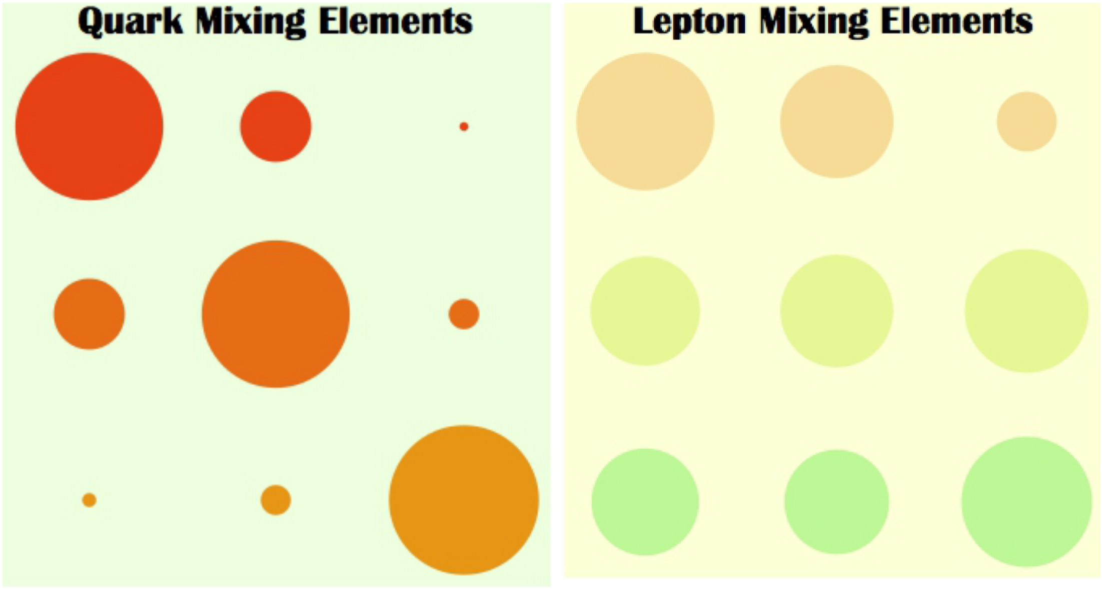

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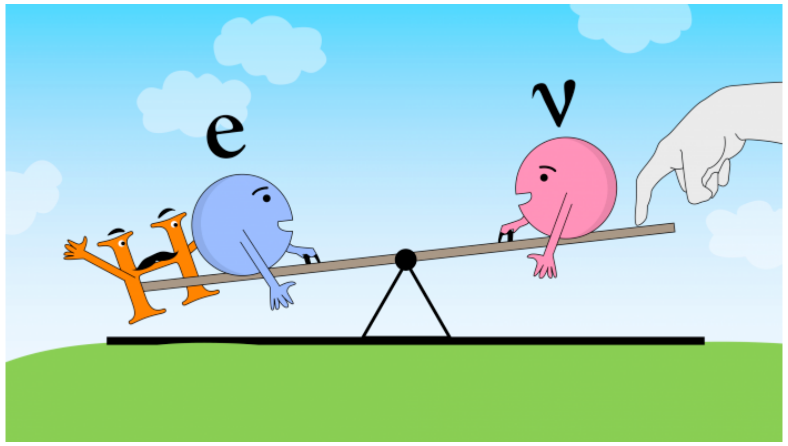

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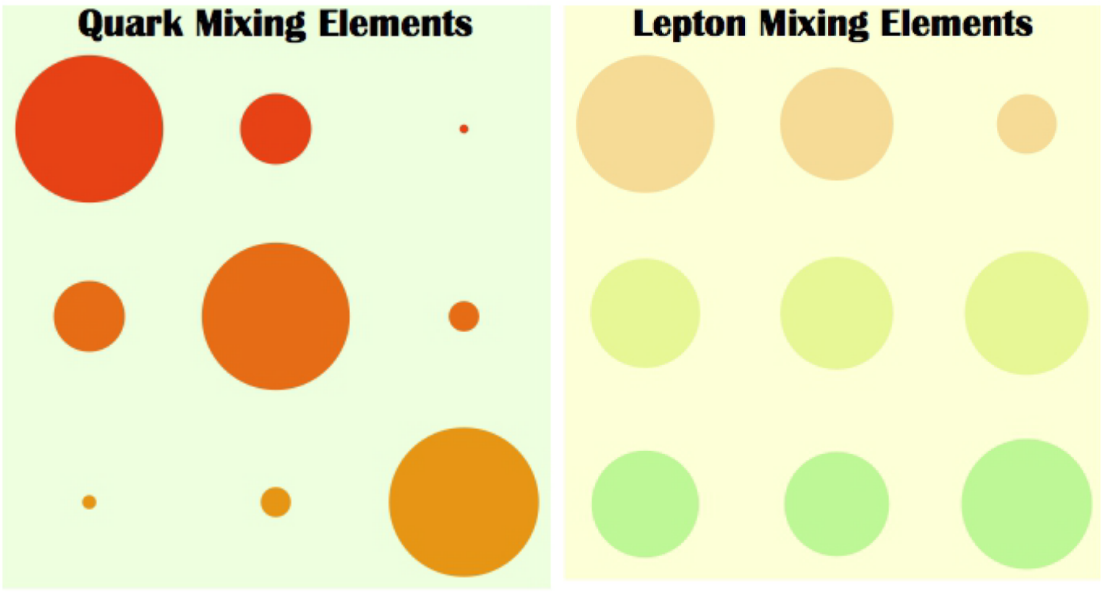

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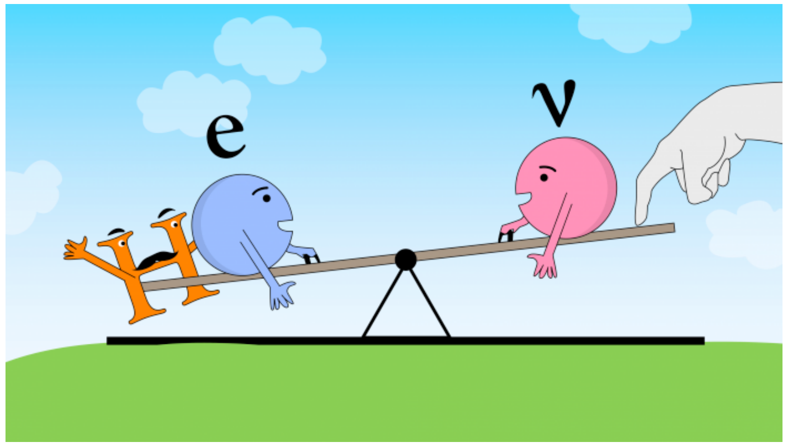

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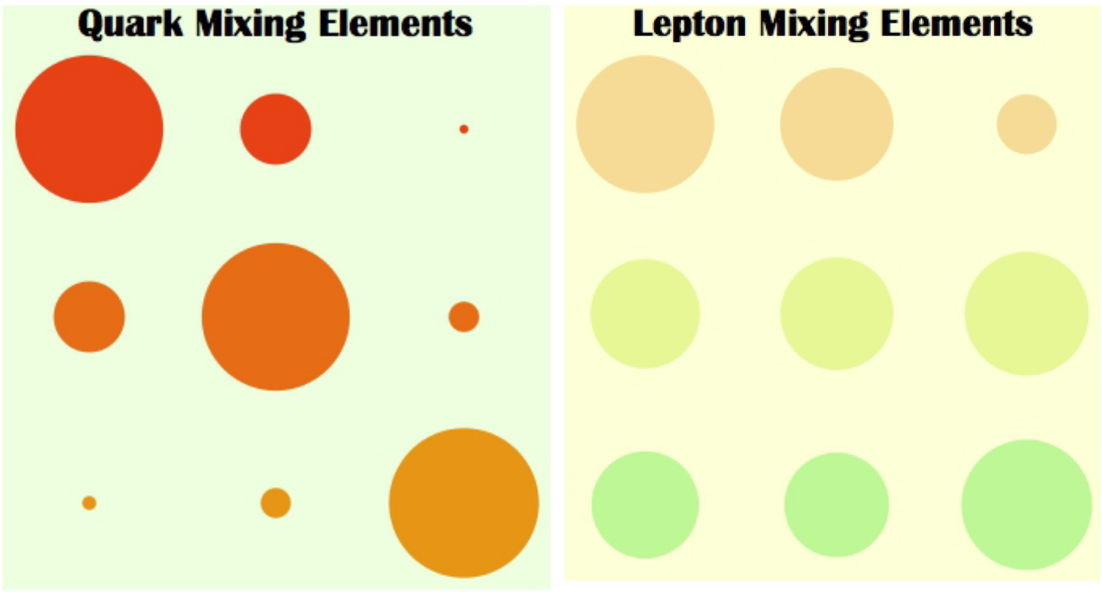

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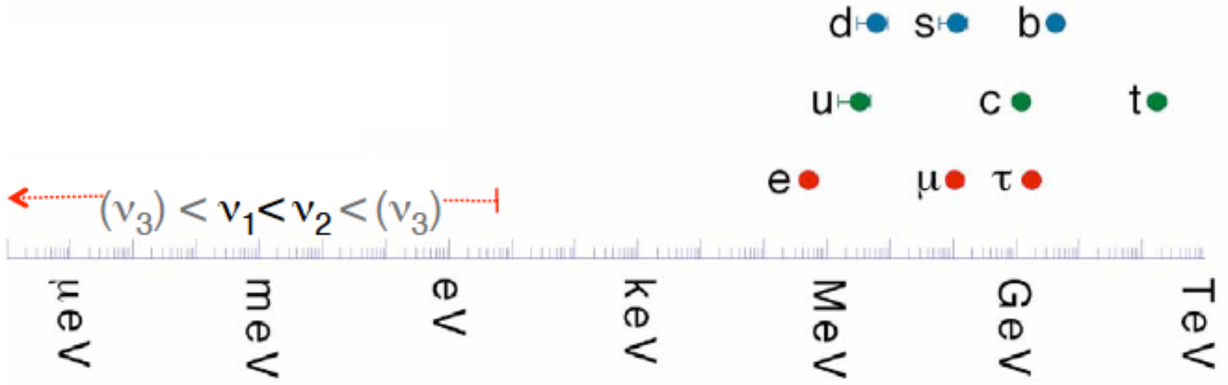

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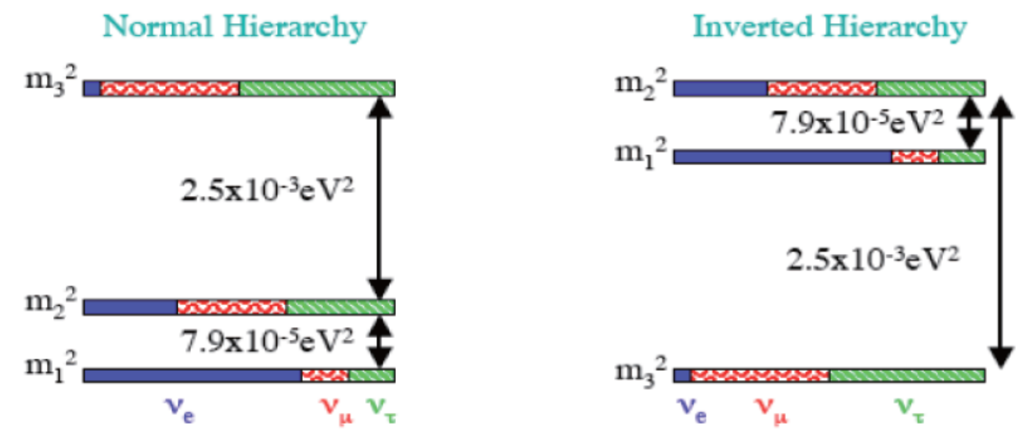

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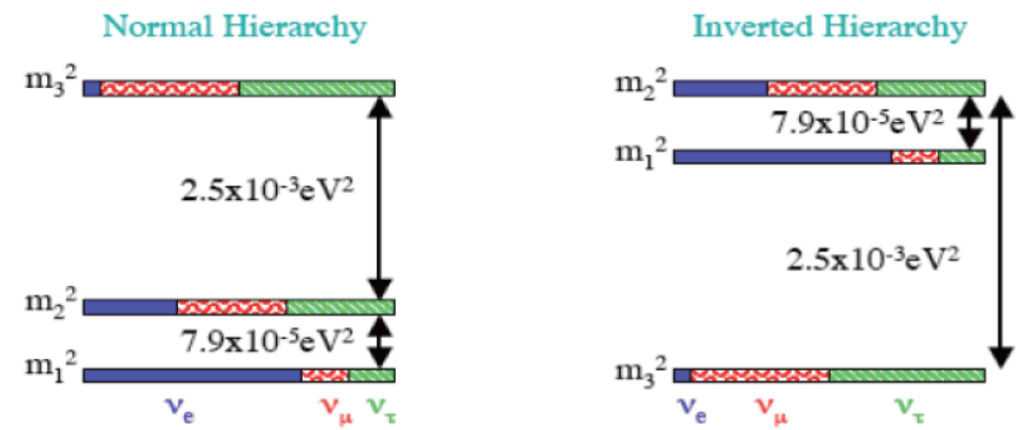

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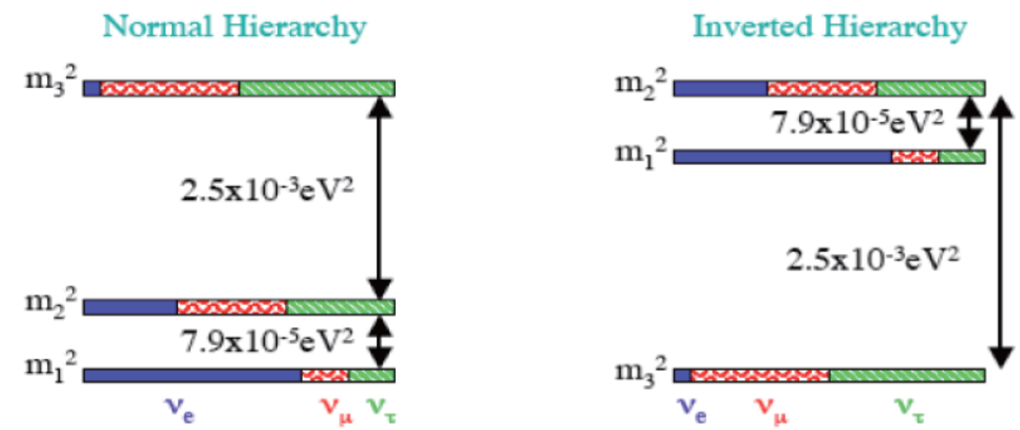

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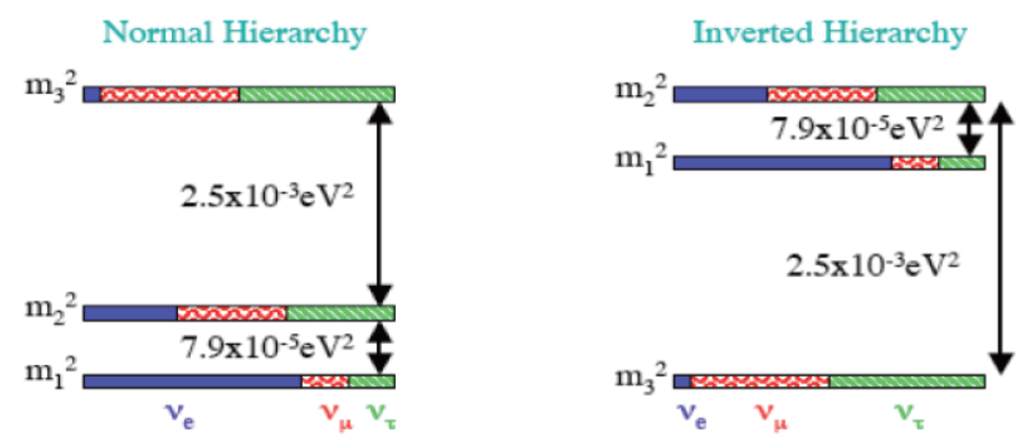

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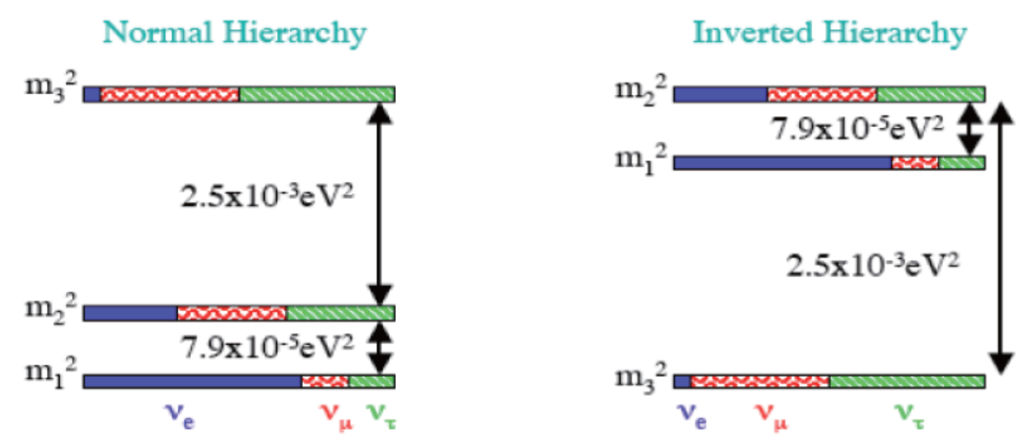

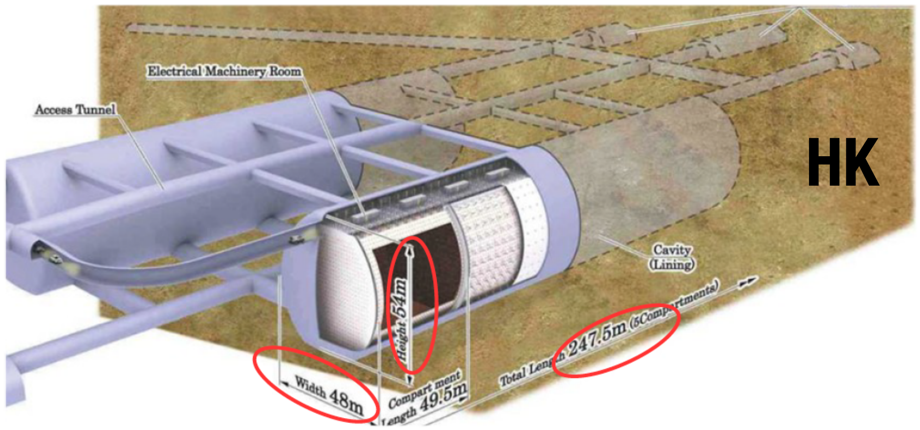

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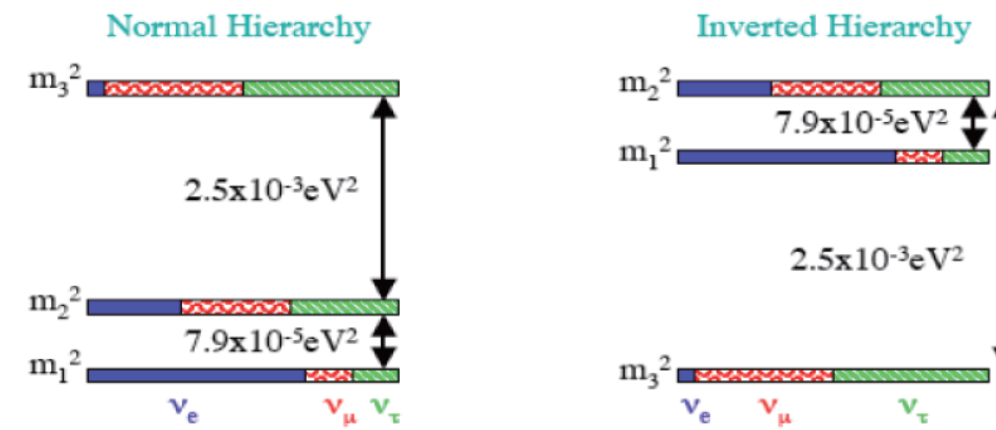

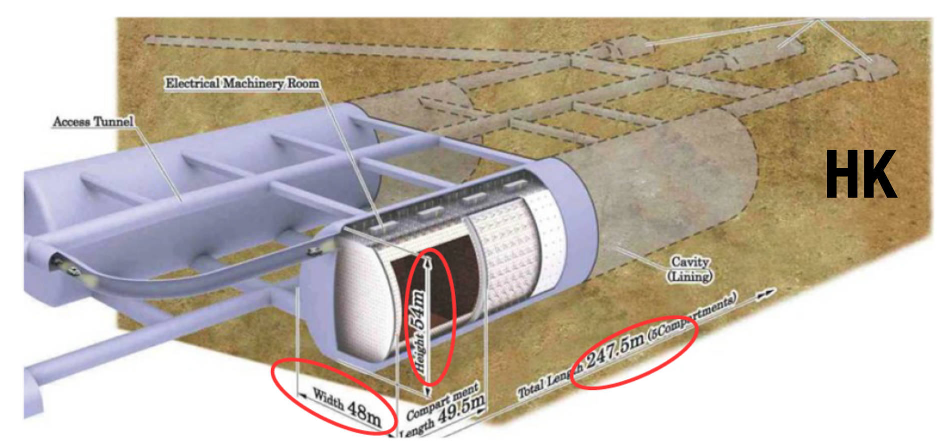

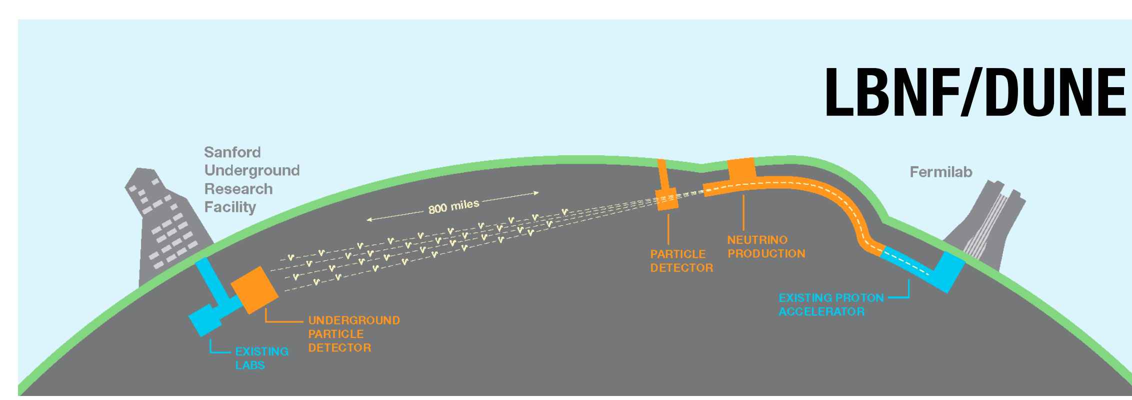

The CERN Neutrino Platform

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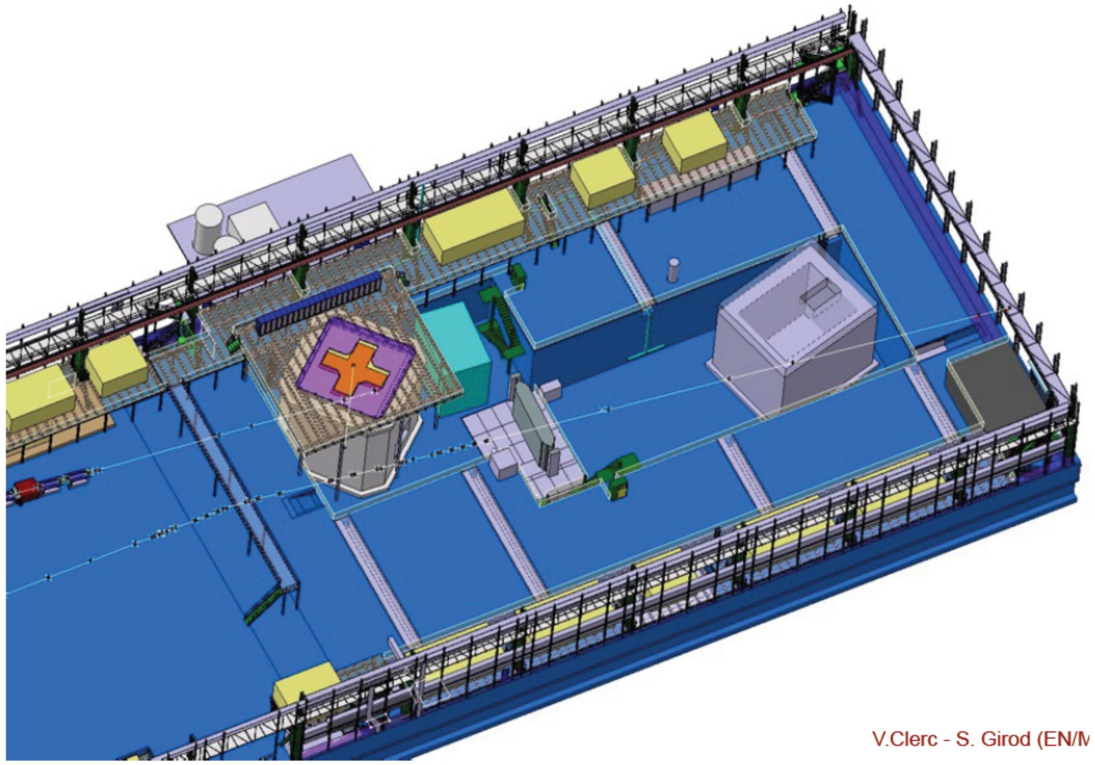

V.Clerc - S. Girod (EN/M

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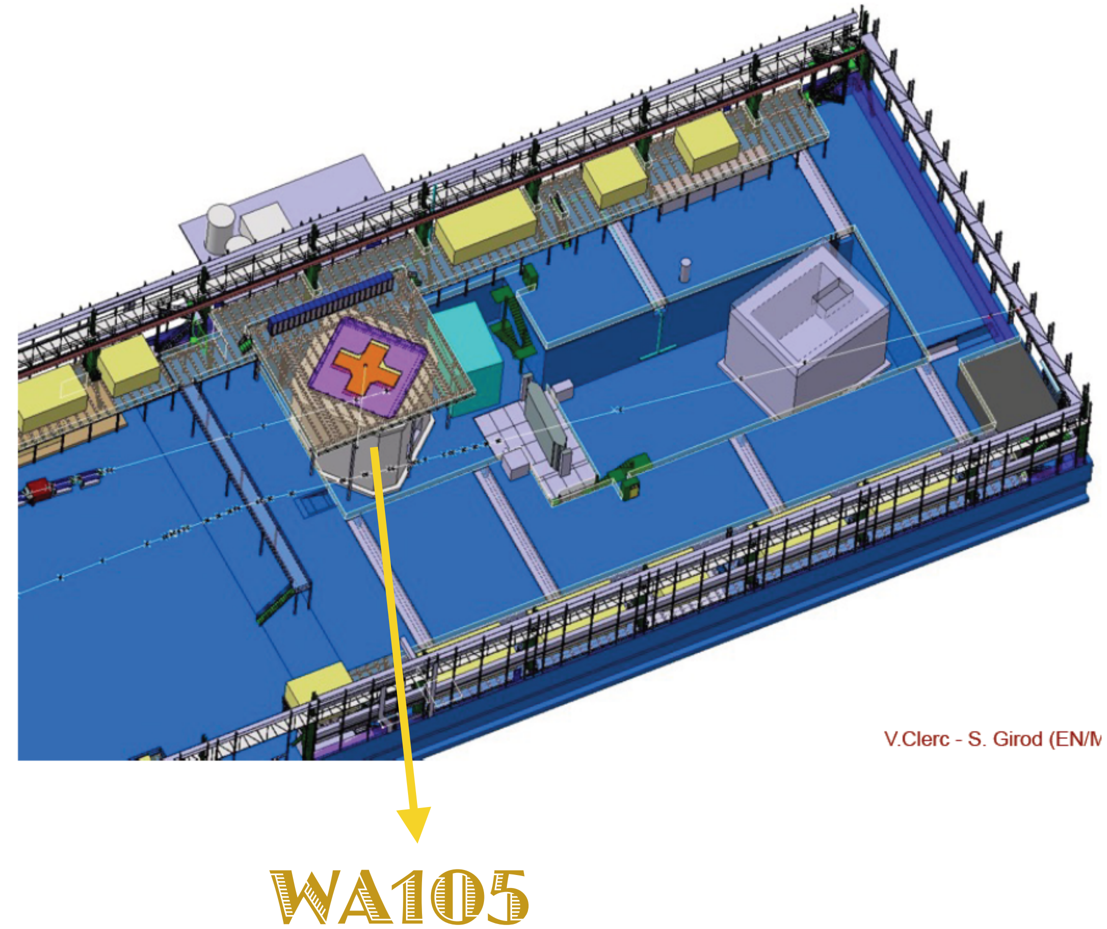

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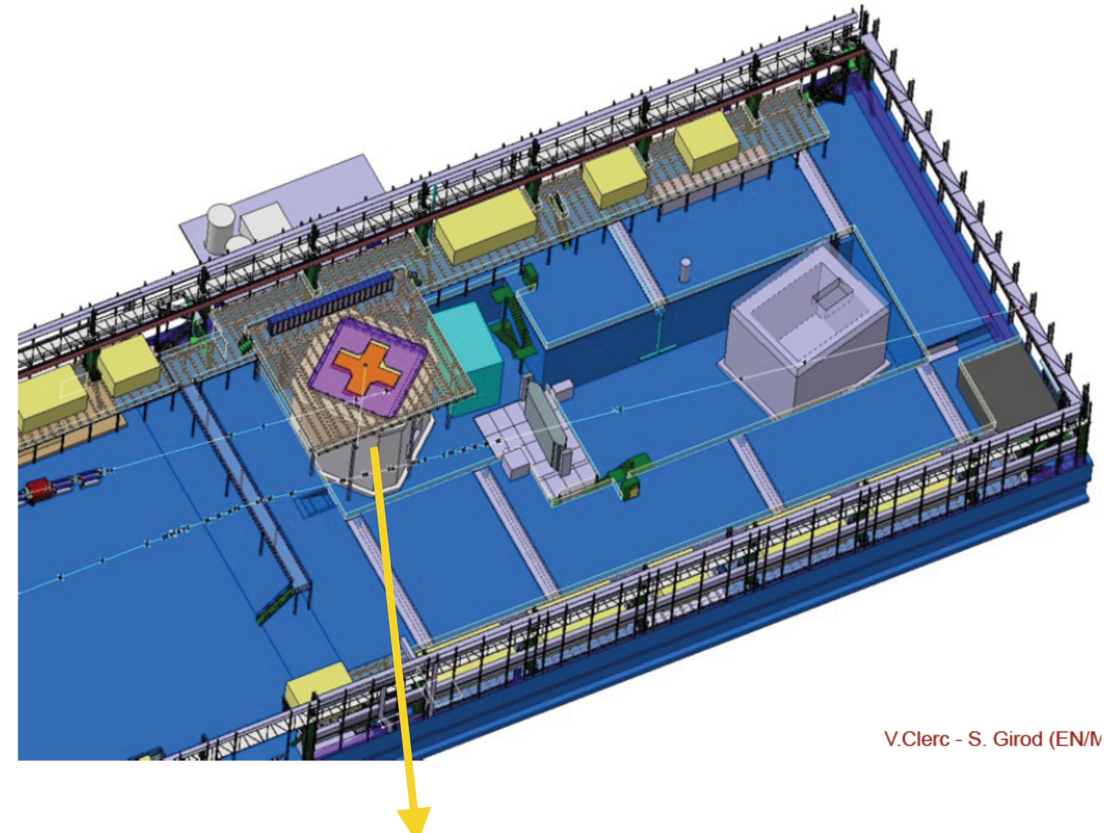

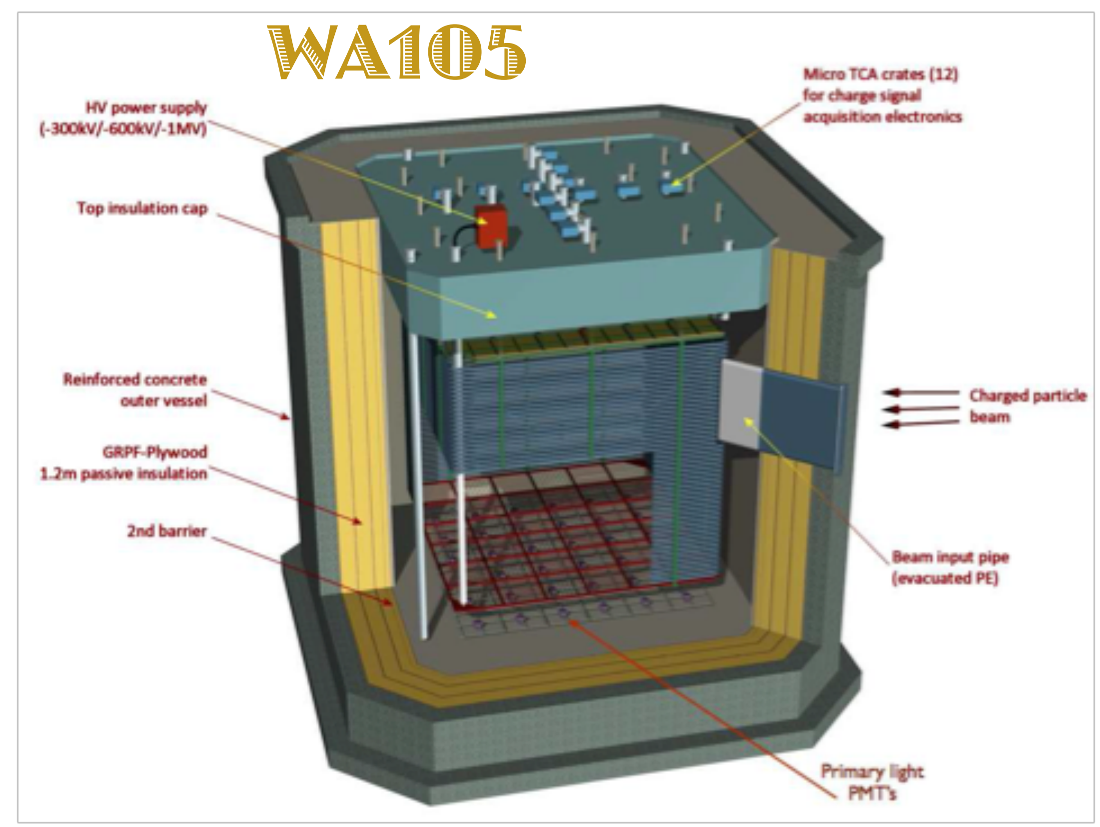

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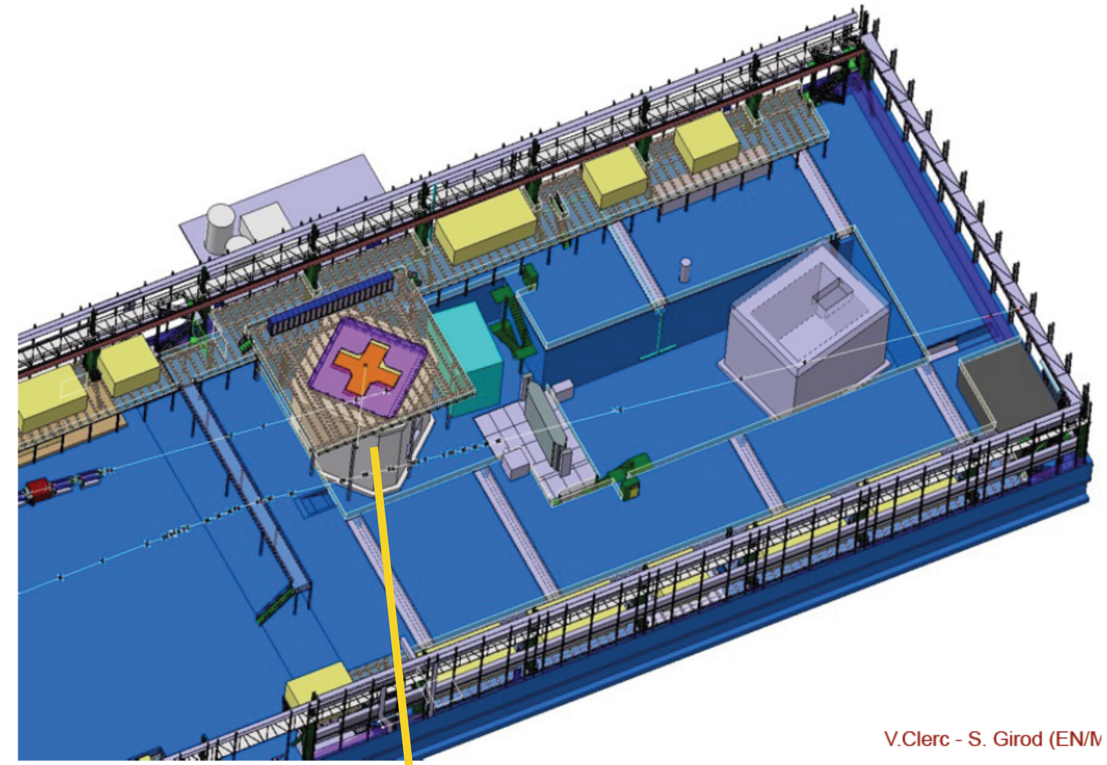
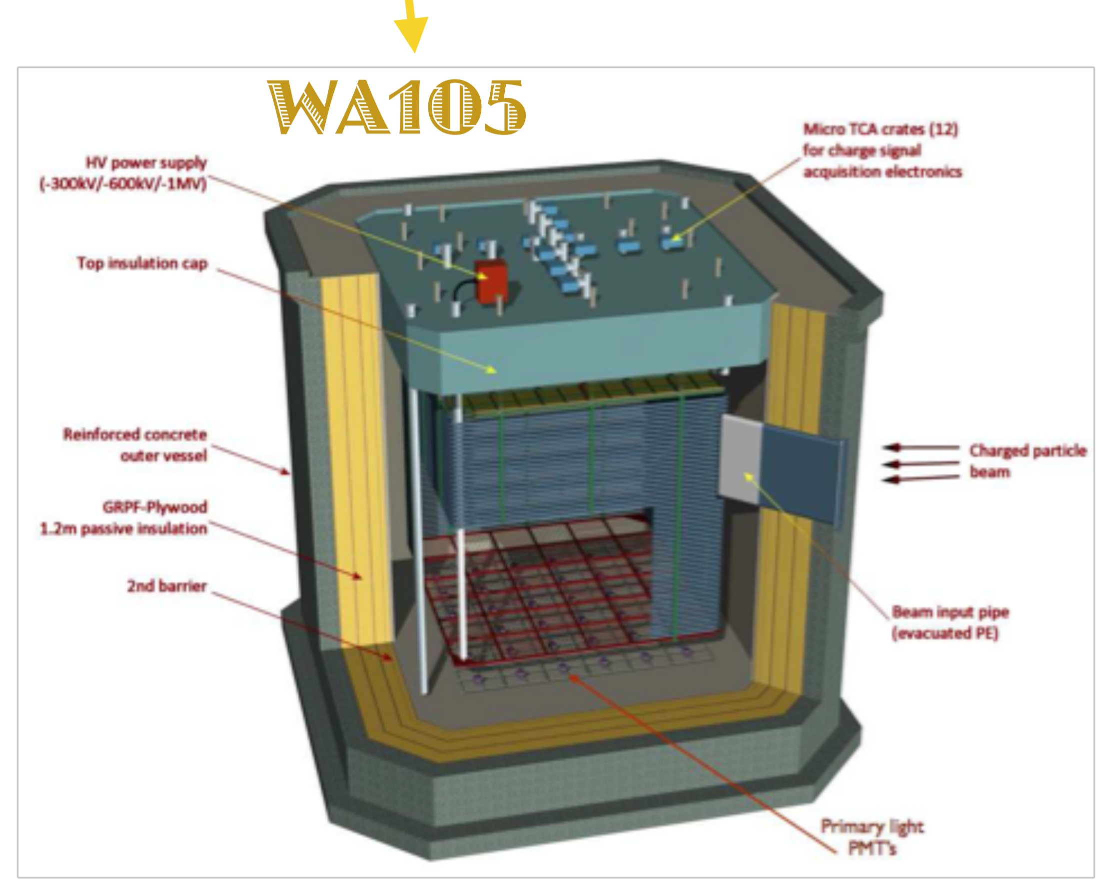
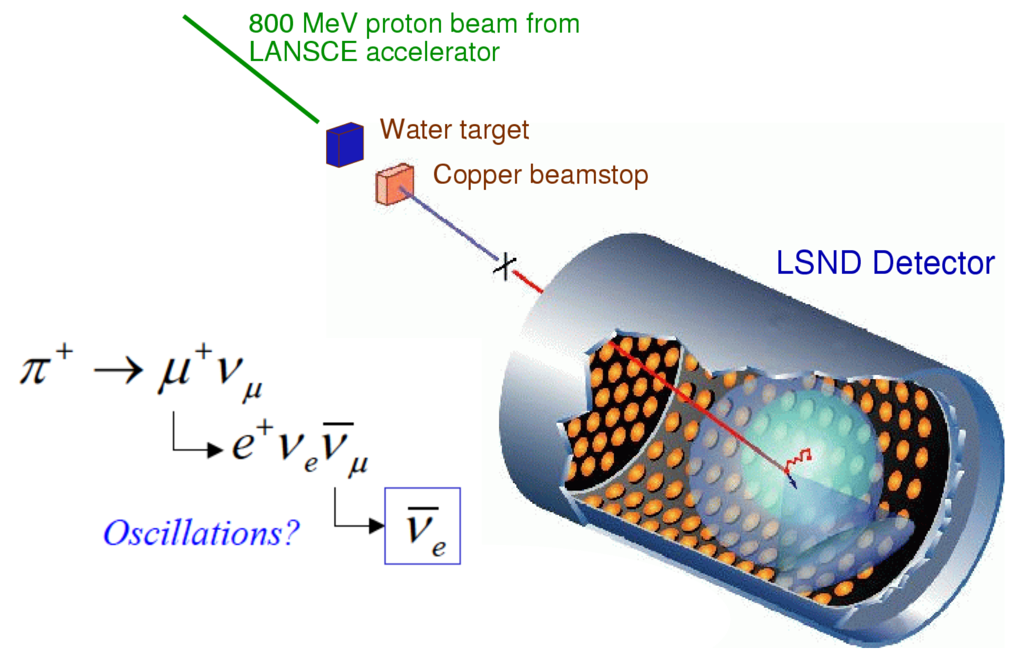
- WA105 (LBNO-DEMO): construction, operation and exposure to charged particles beam of a 6 x 6 x 6 m^3 double phase liquid argon TPC

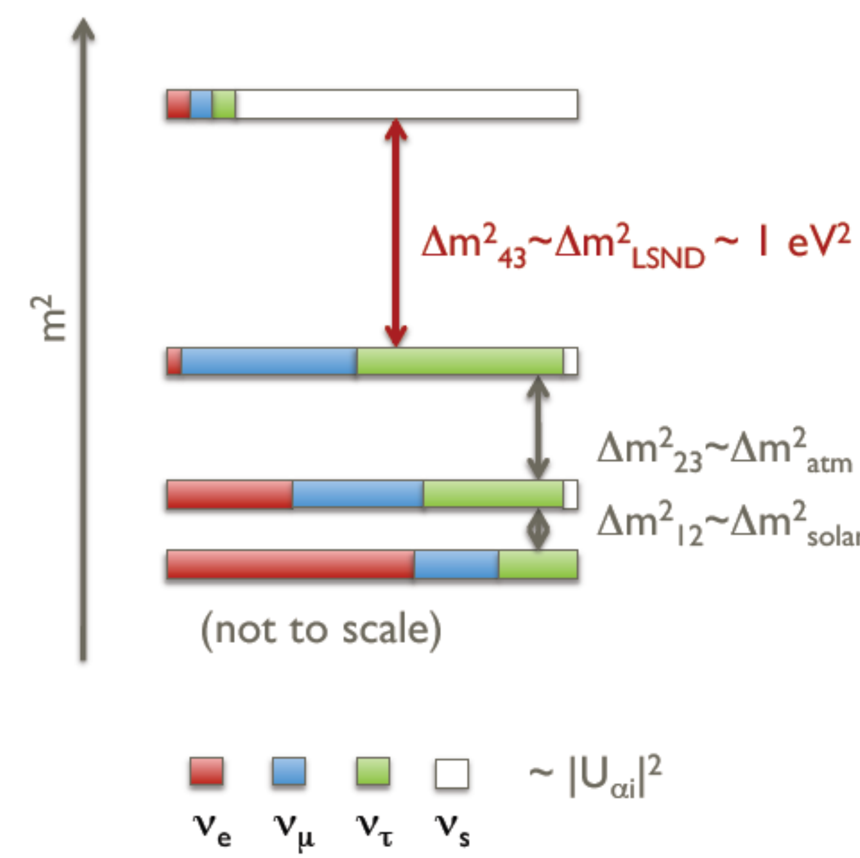




Anomalies: a forth neutrino?

- 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
- Galio experiments
    - ν_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)



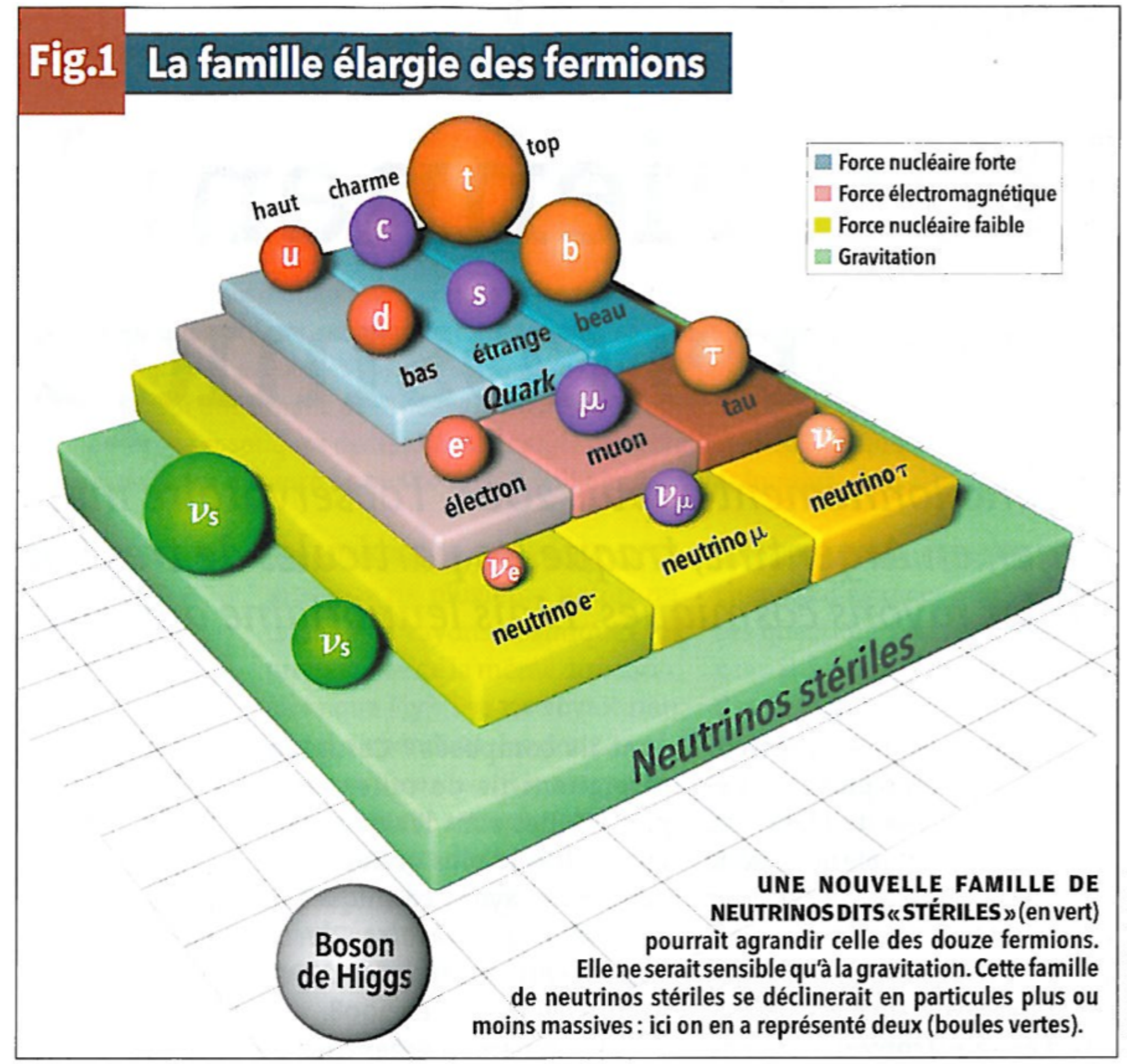


More than 3 neutrinos?

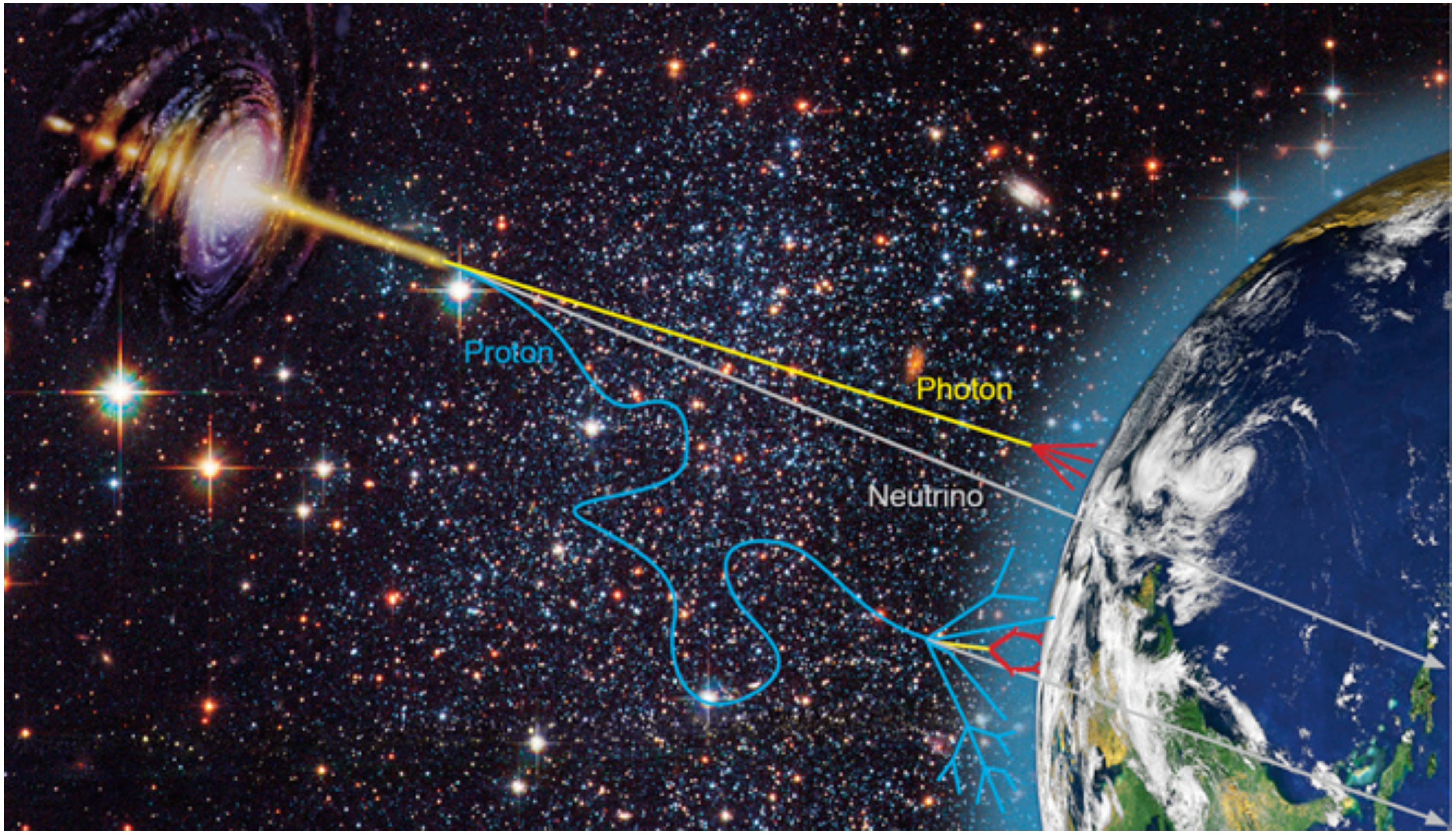
Sterile neutrinos (ν_s):

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

$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ or $\nu_e \rightarrow \nu_s$



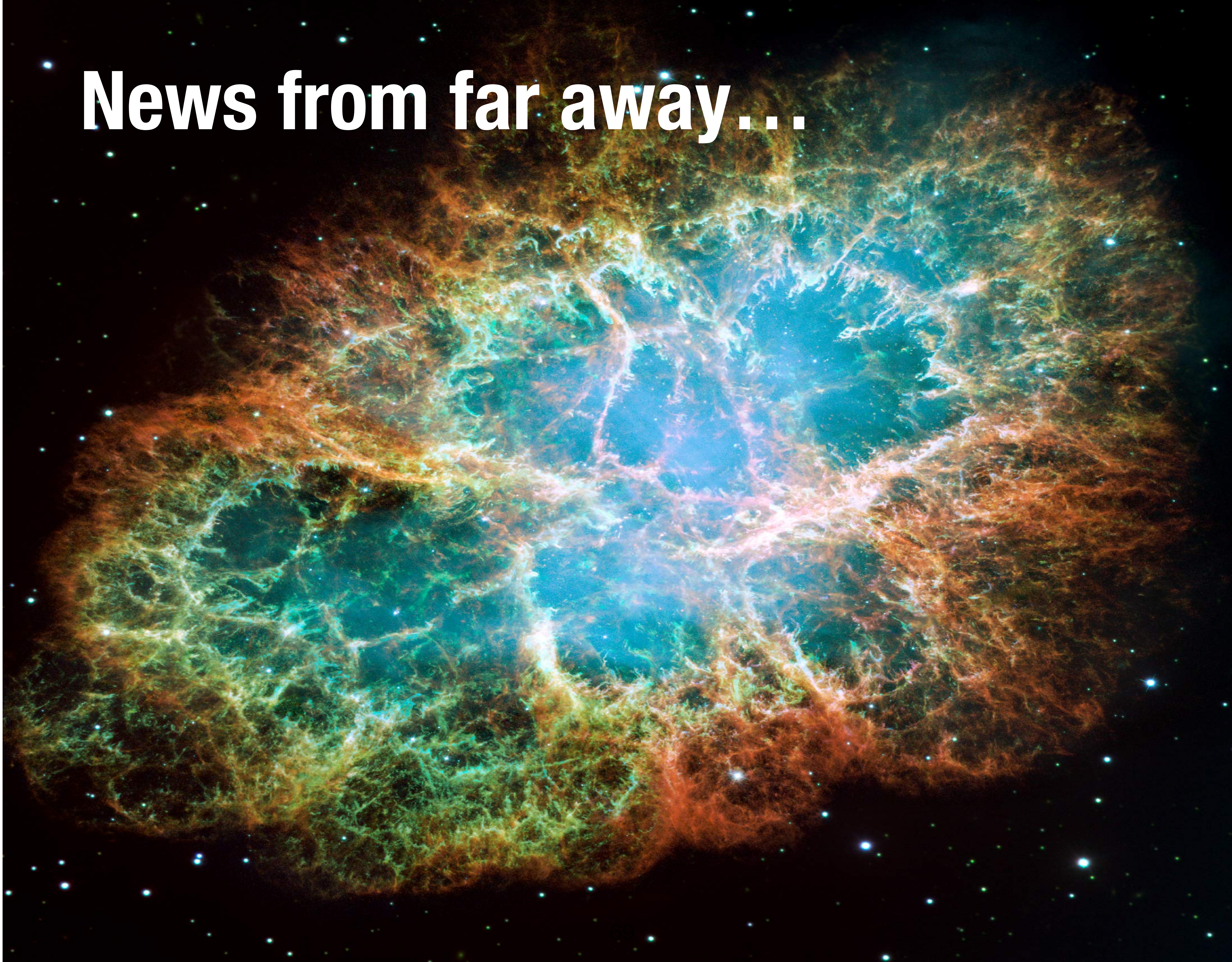
Could they be related with dark matter?



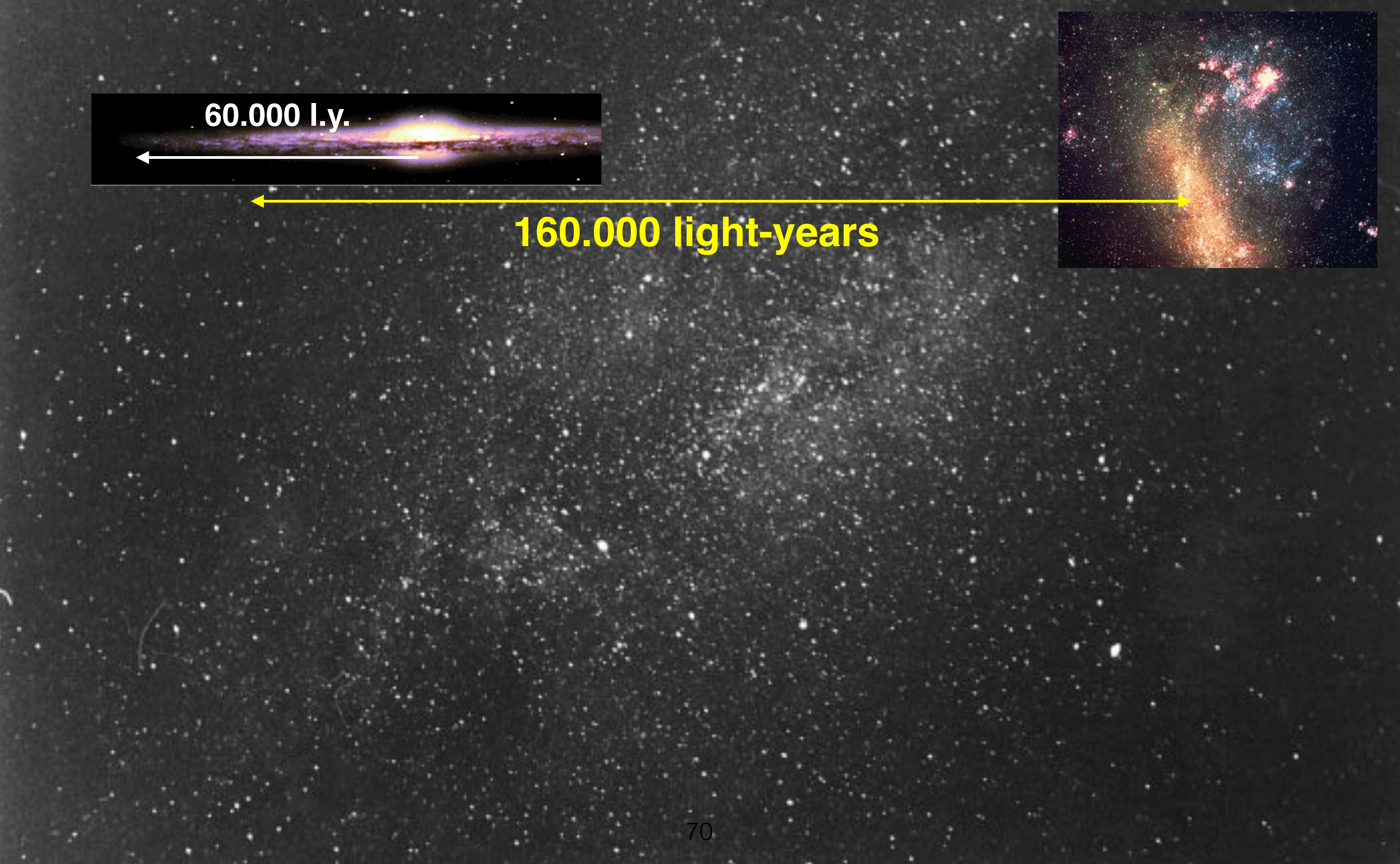
5

Cosmic messengers

News from far away…

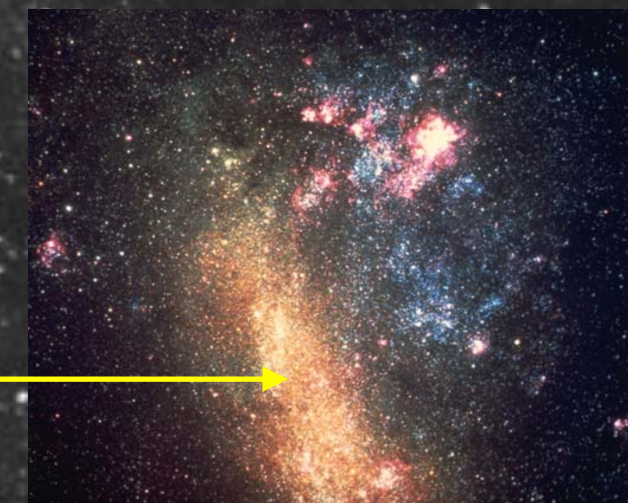


SN1987A

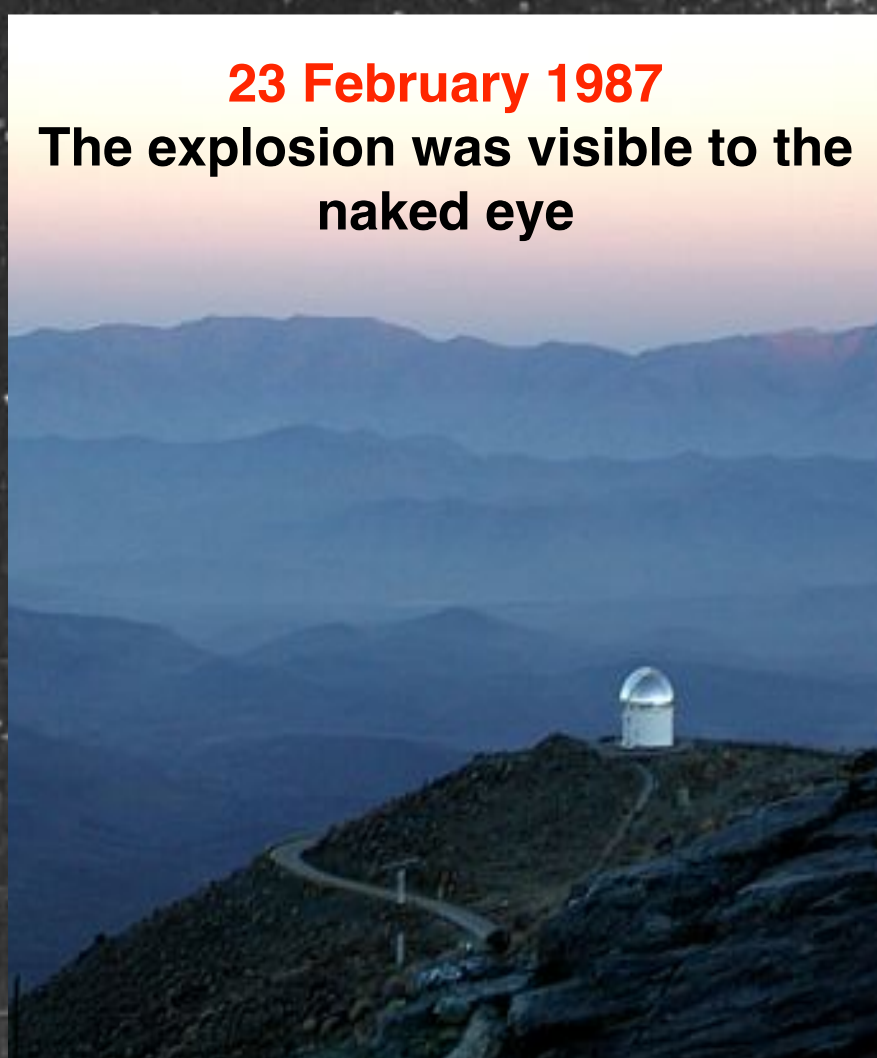


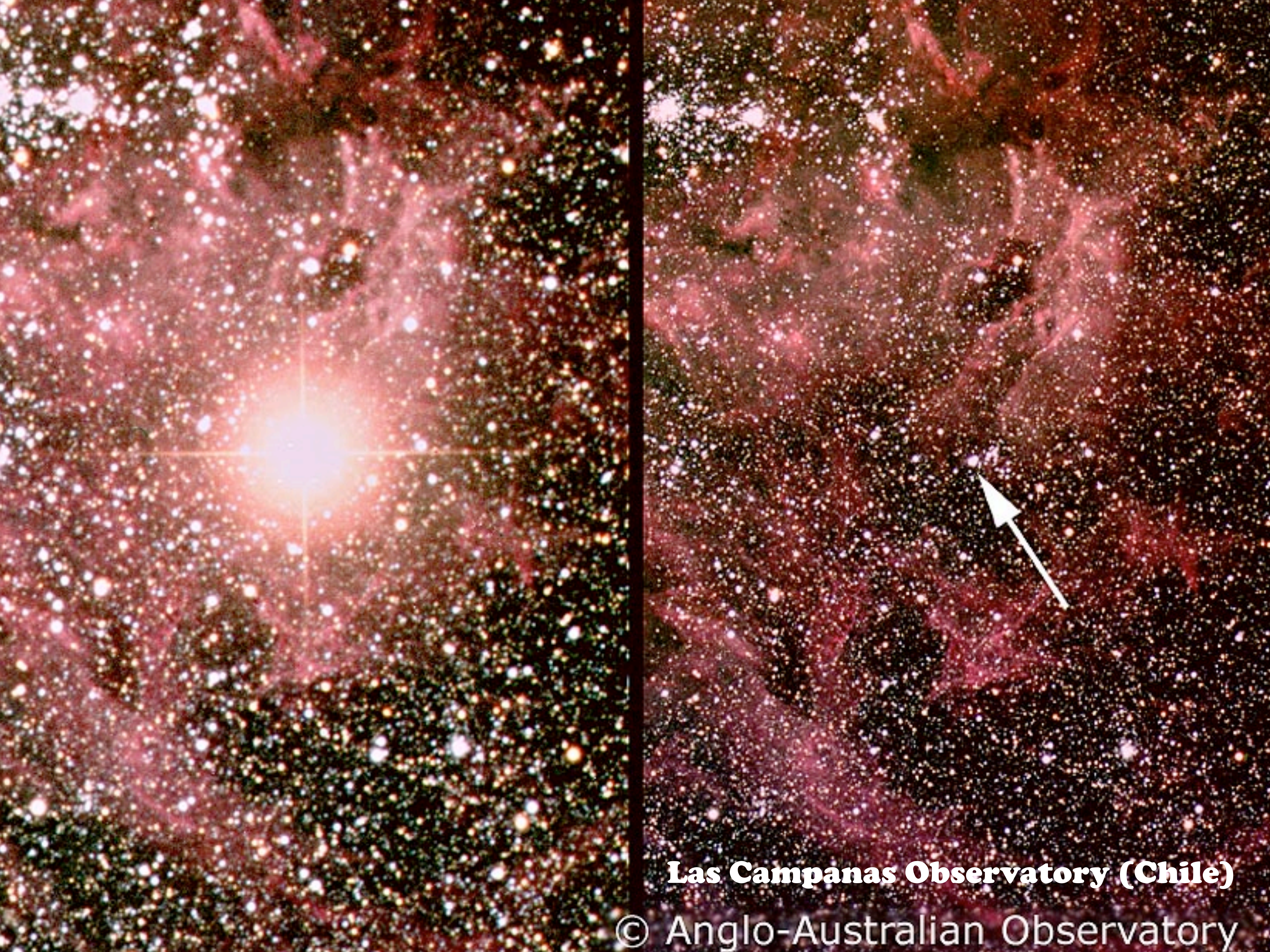
SN1987A

Large Magellanic Cloud



160.000 light-years

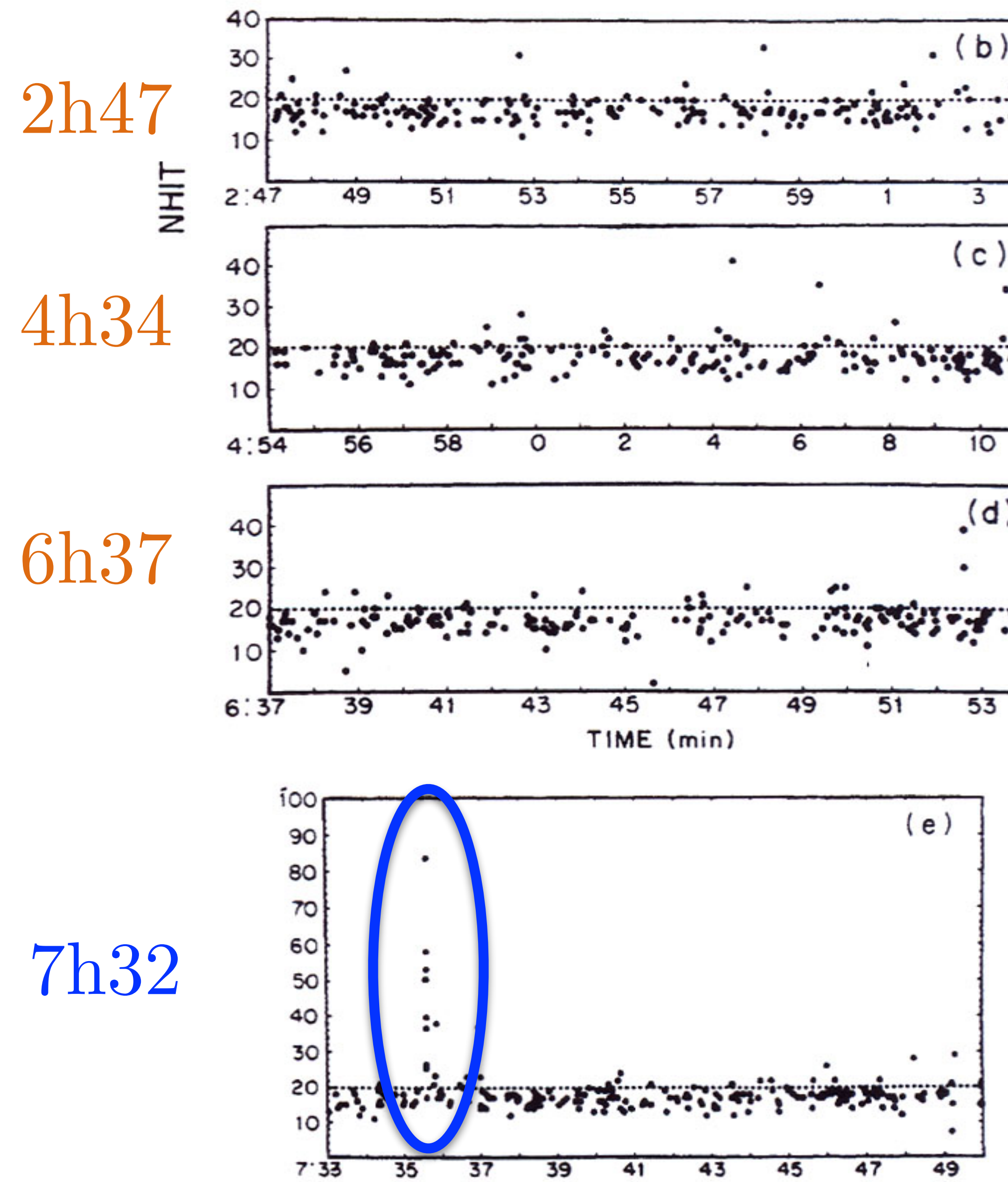


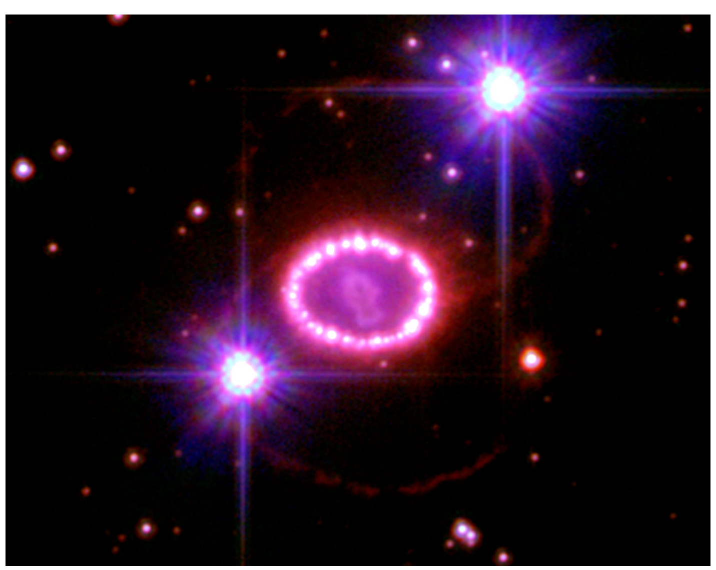

Las Campanas Observatory (Chile)
© Anglo-Australian Observatory

SN1987A: first detection of extragalactic neutrinos

- 10^{58} neutrinos were emitted from the Supernova 1987A 160.000 years ago
- About 5×10^{17} crossed the Kamiokande detector
- **10 neutrinos detected!!**

Kamiokande





Koshiba

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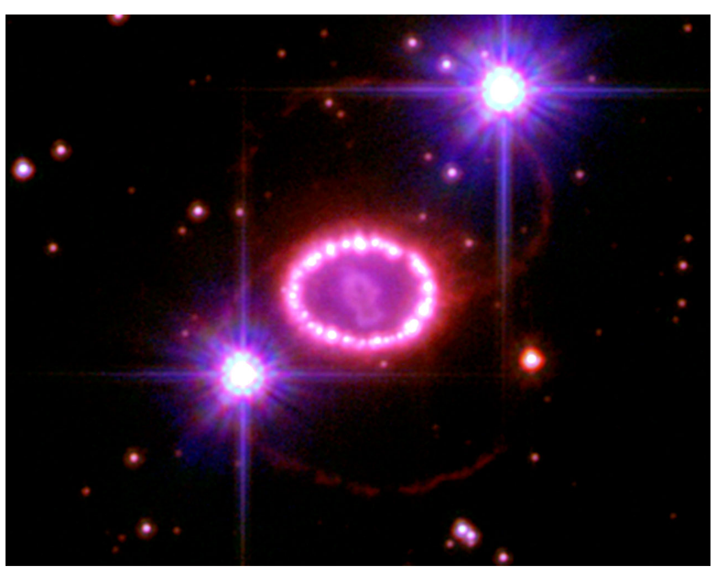
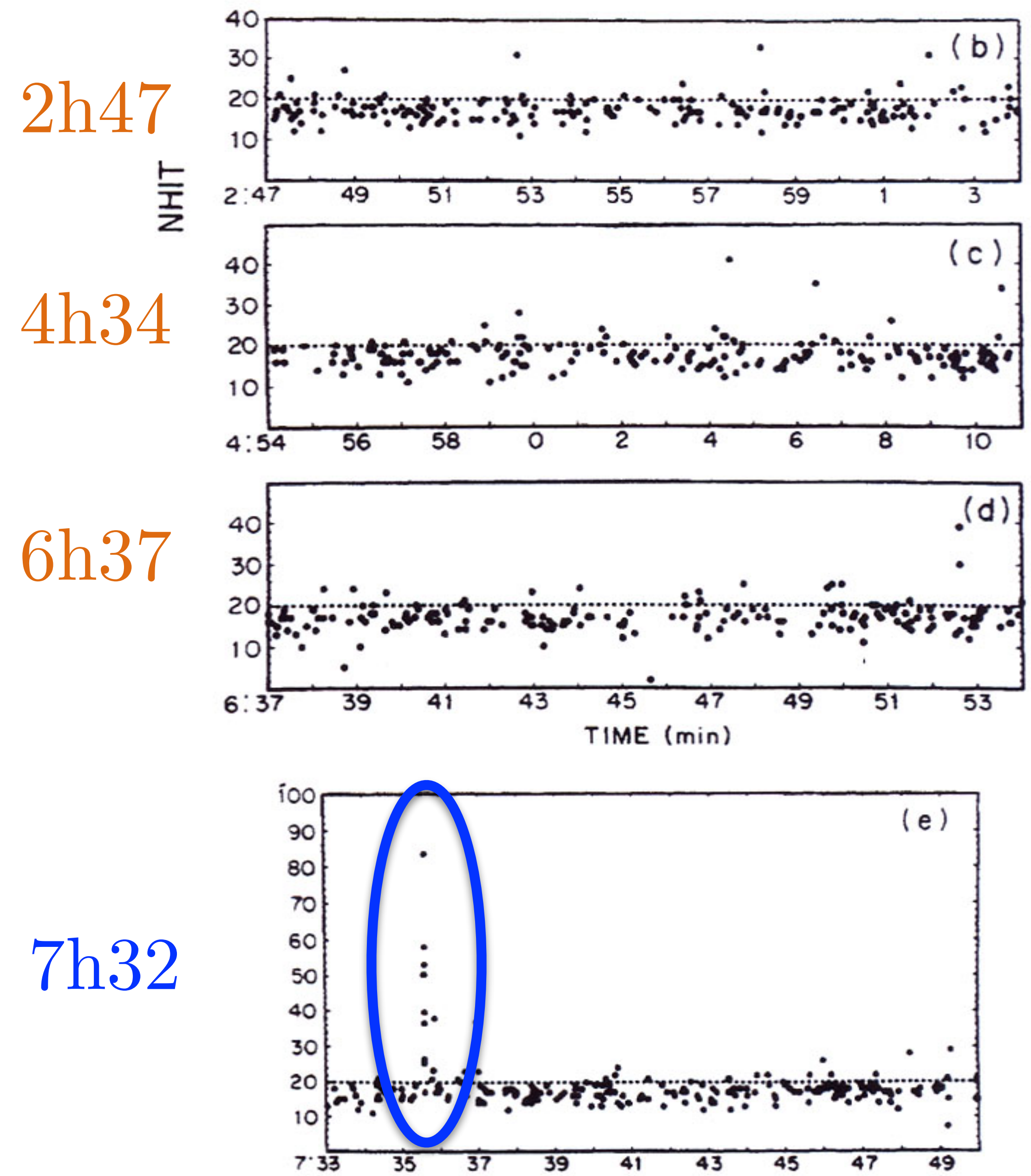


Koshiba

Nobel Prize in Physics 2002

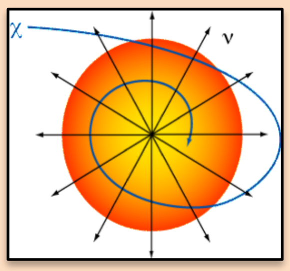
Kamiokande



Origin and detection of HE neutrinos

Origin of HE neutrinos

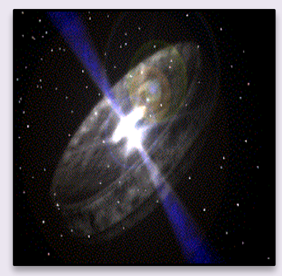
WIMP decay products?



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

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

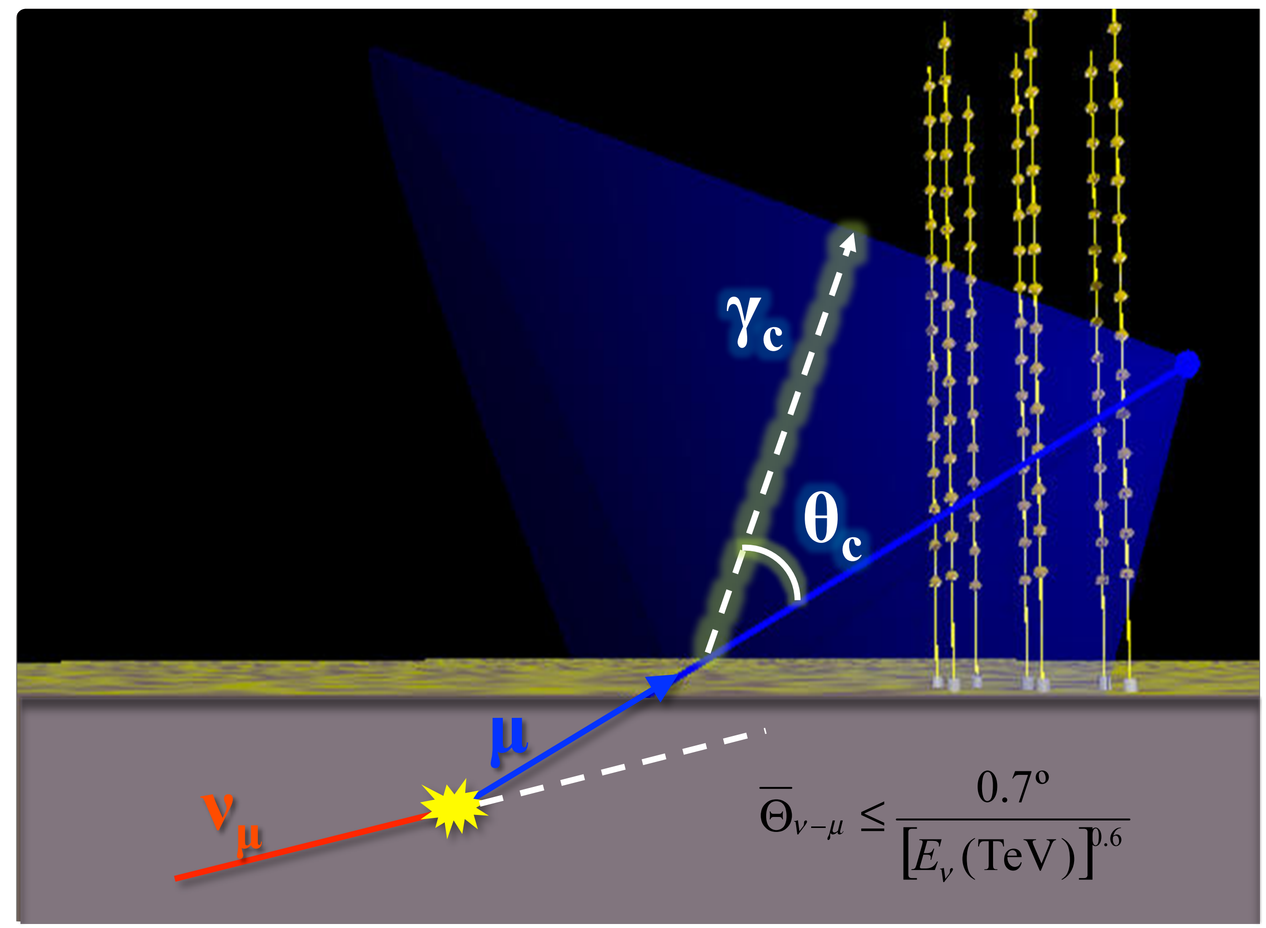
Astrophysical objects



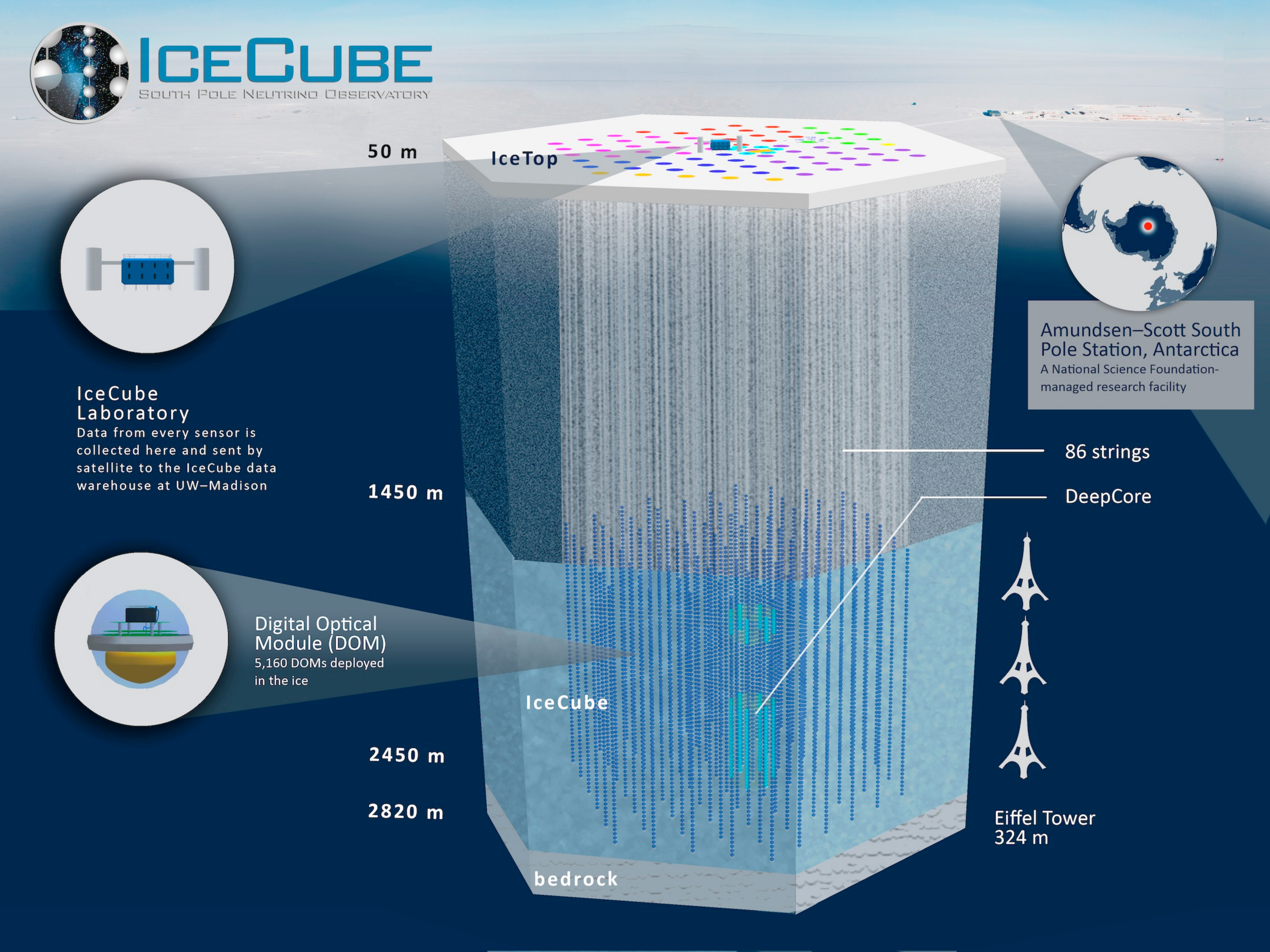
HE neutrinos appear as the sub-product of interactions of **accelerated protons** or nuclei with matter or radiation

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

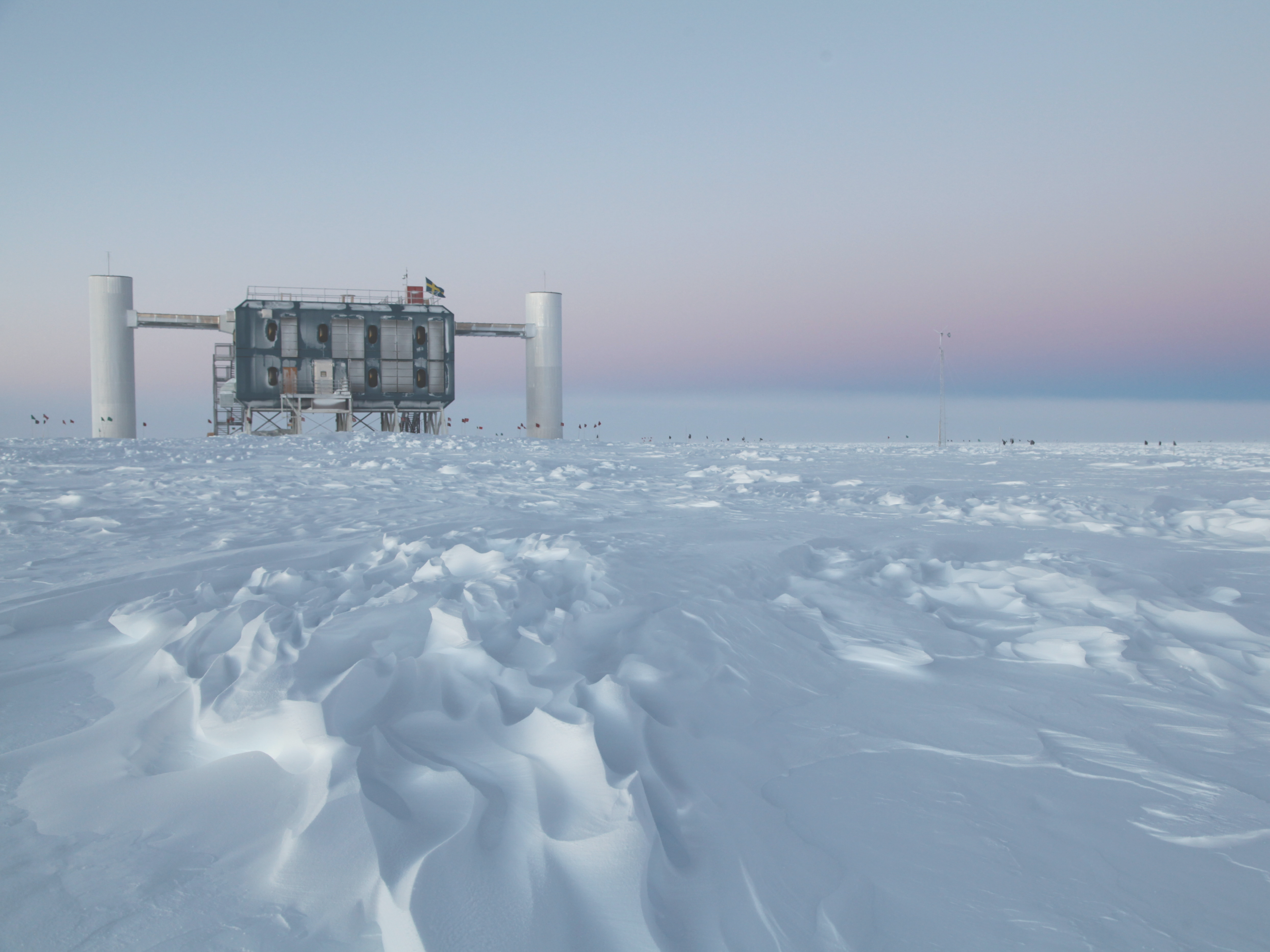
Detection of HE neutrinos

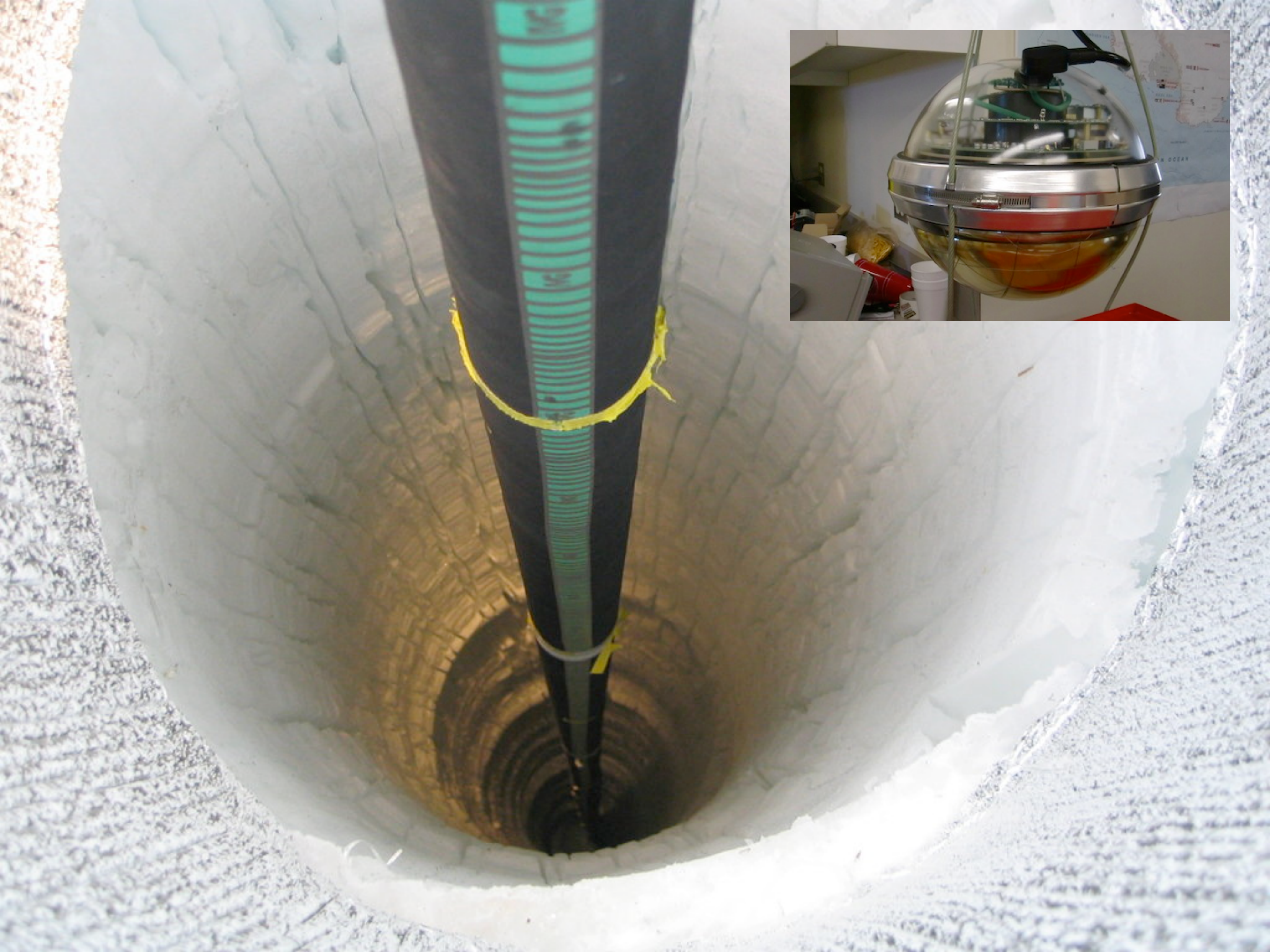


- ν_μ are well suited for high energy detection (since its cross-section and muon range increase with energy) although ν_e and ν_τ can also be detected
- An array of photomultiplier tubes detect the Cerenkov light from charged particles produced by neutrino interactions
- The Cerenkov cone needs to be reconstructed to determine the energy and direction of the muon



IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data from every sensor is collected here and sent by satellite to the IceCube data warehouse at UW–Madison
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube
2450 m
2820 m
bedrock
Eiffel Tower
324 m





Very HE neutrinos observed in IceCube

- IceCube has detected **37 very high energy neutrino events** between May 2010 and May 2013 (5.7σ significance). 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

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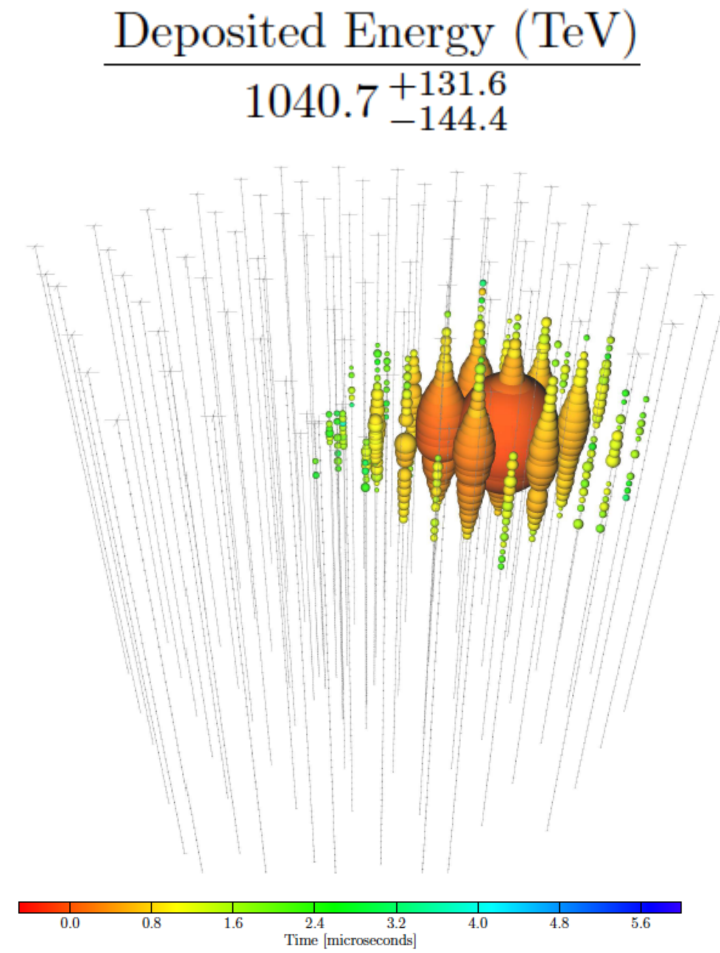

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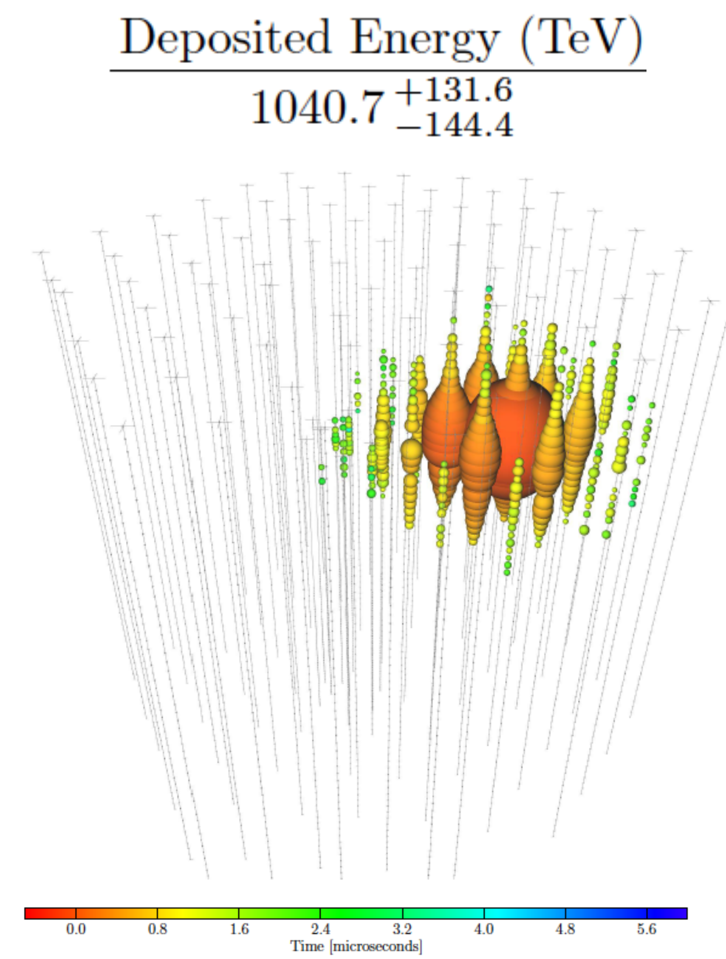
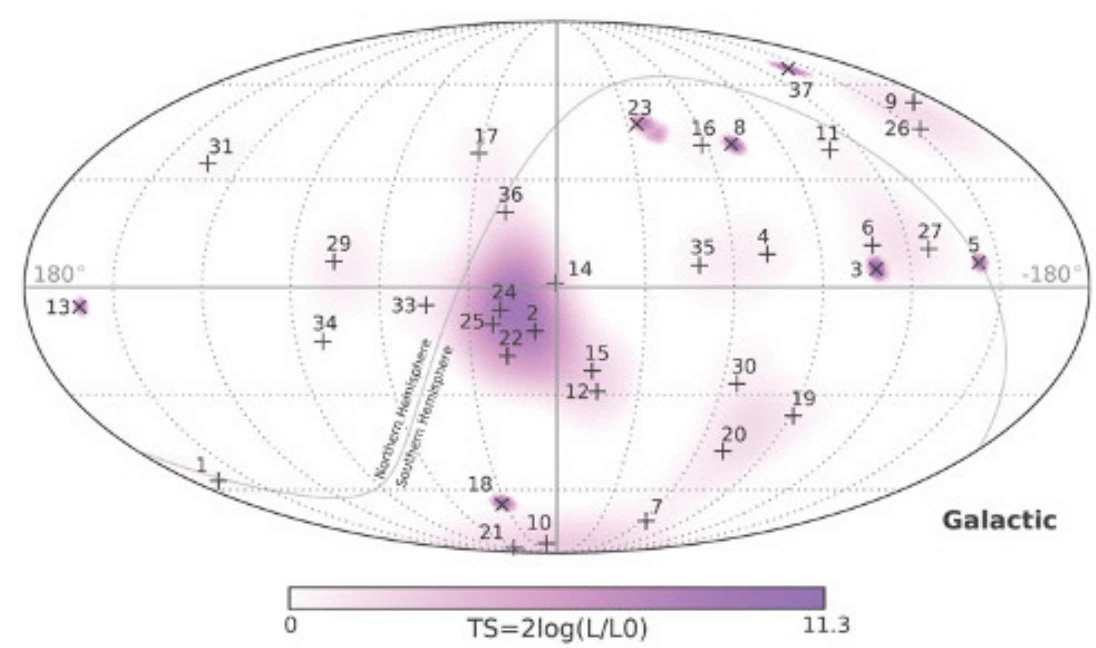
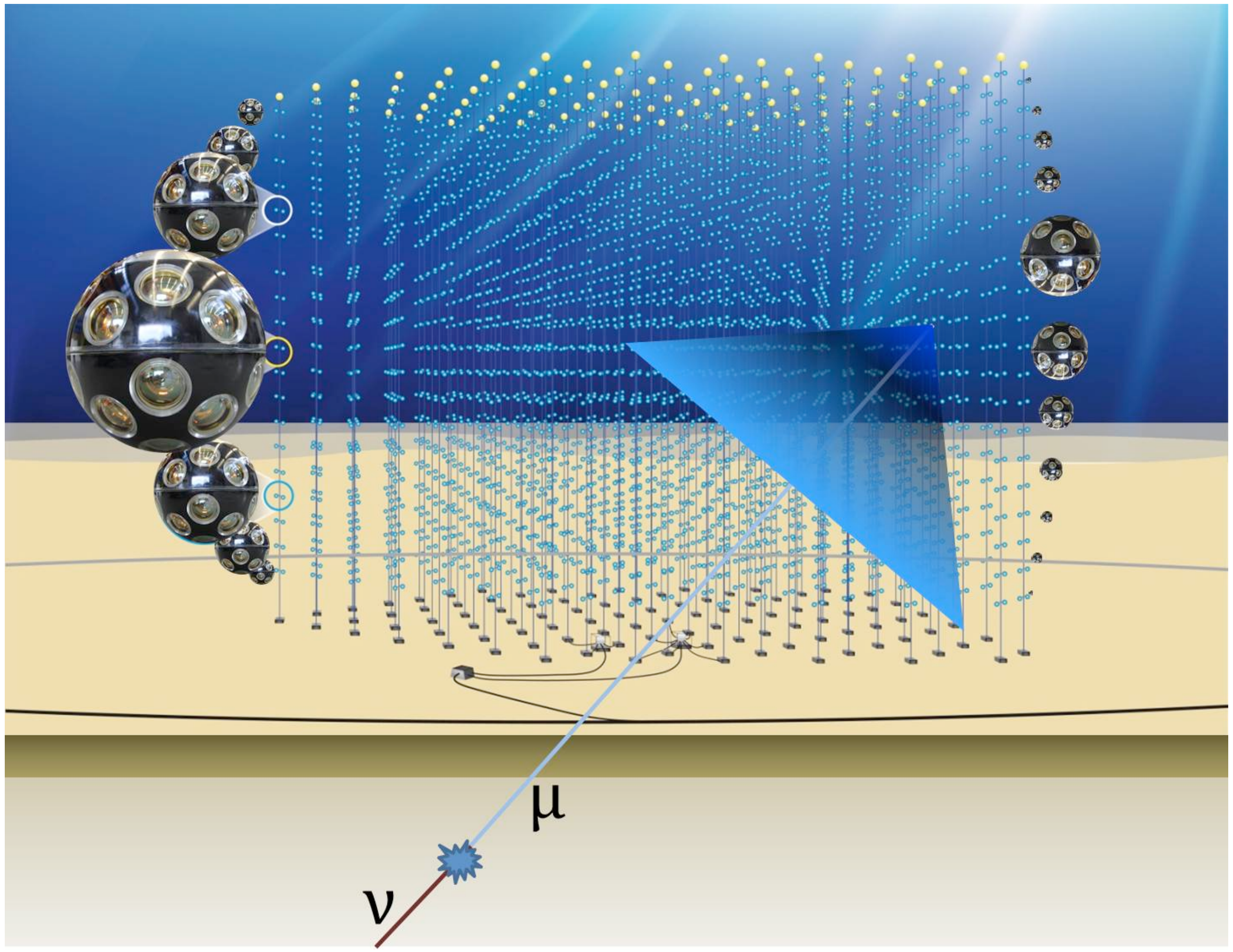
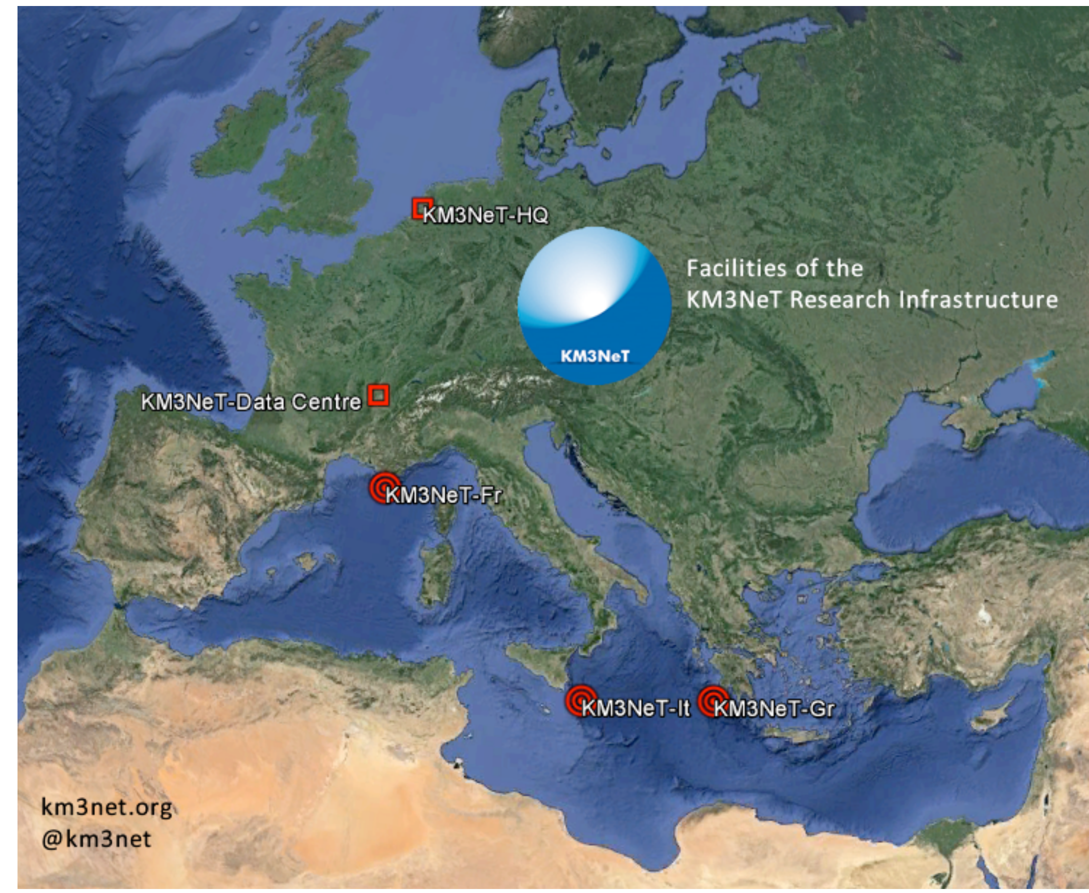




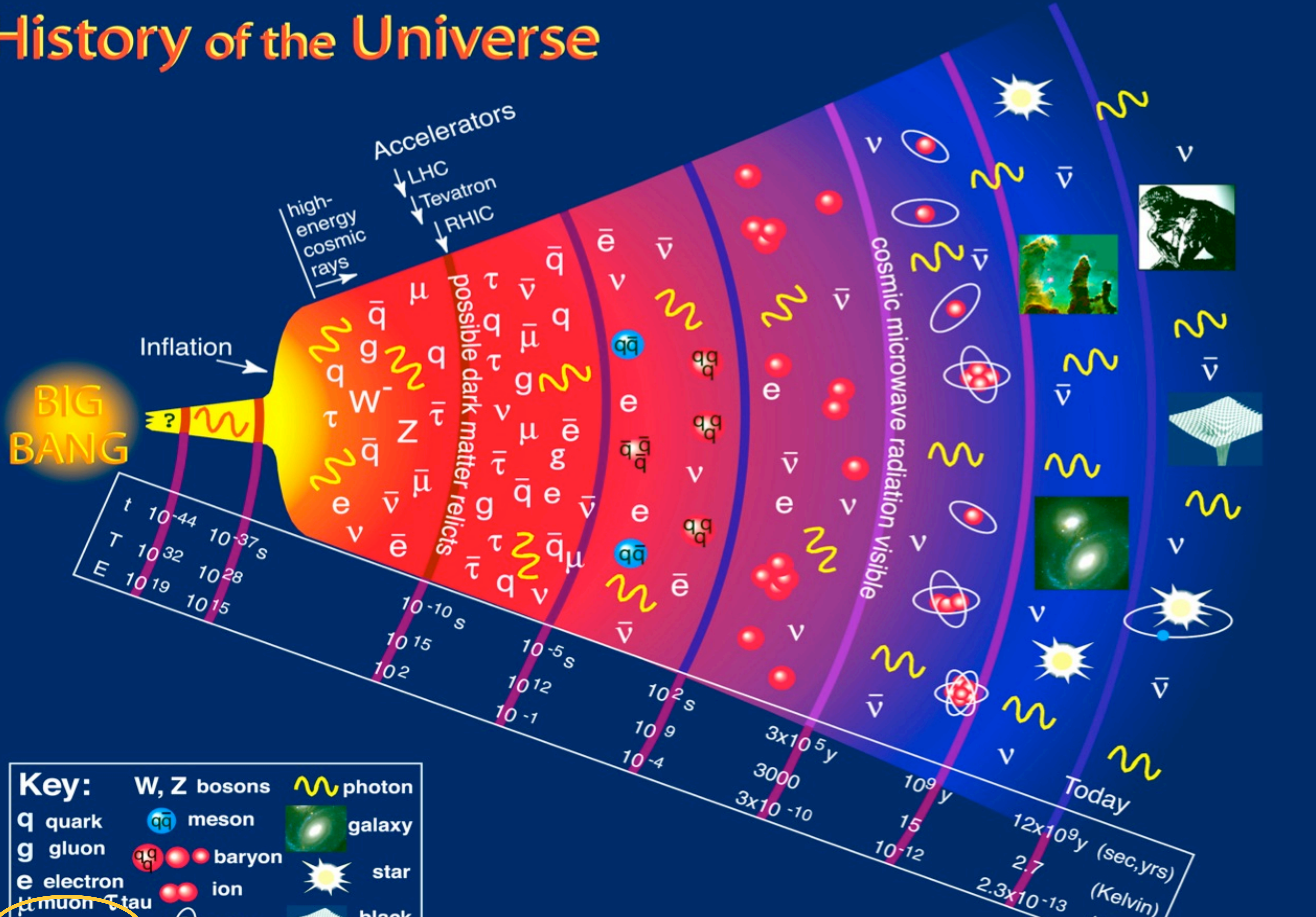
Other proposals in Europe





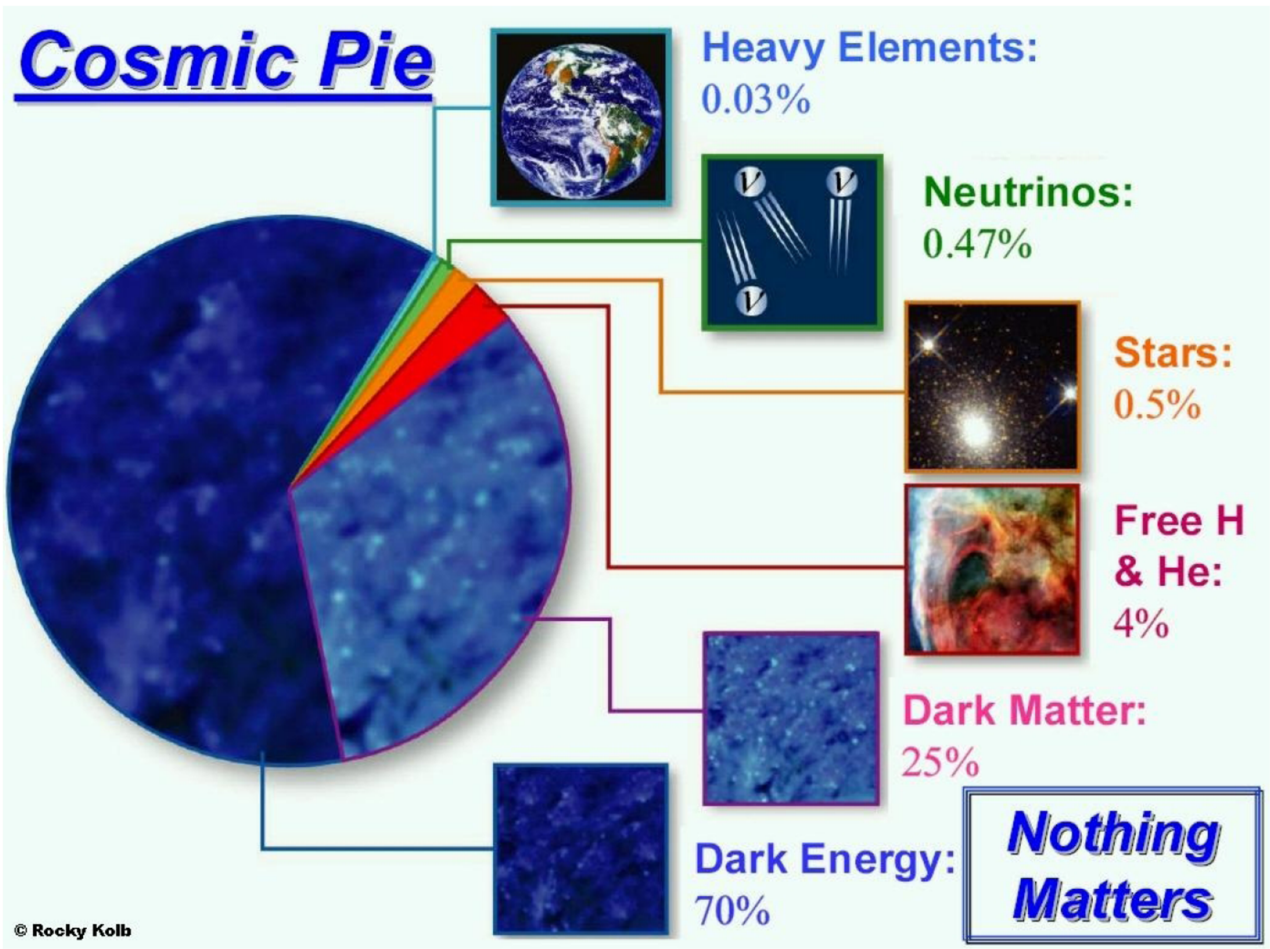
- **KM3NeT:** 1 km^3 second-generation neutrino telescope in the Mediterranean Sea
- 3 installation sites located in Toulon (France), Sicily (Italy) and Pylos (Greece)
- ANTARES was the first undersea neutrino telescope: 12 lines (885 PMTs) providing an excellent angular resolution. Taking data until the end of 2016.

History of the Universe

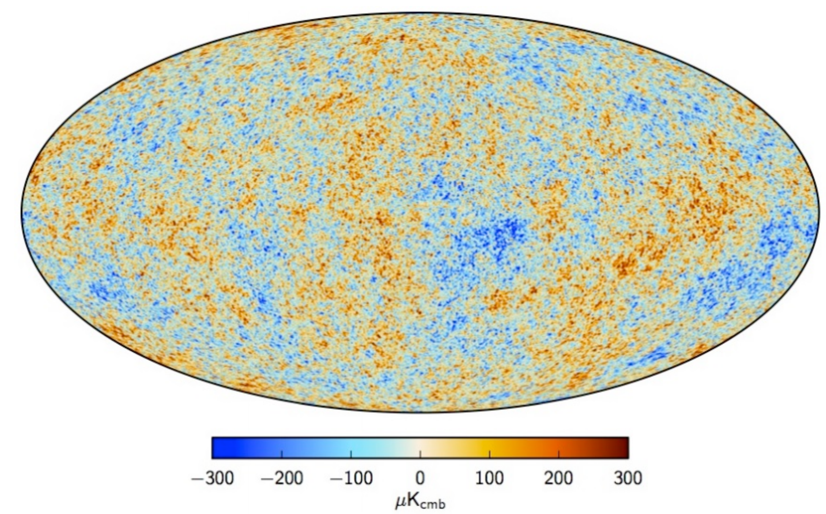


Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Neutrinos from the Big Bang



CMB as seen by PLANCK



- A cosmic neutrino background is expected (~330 neutrinos per cm^3)
- Still not directly detected…

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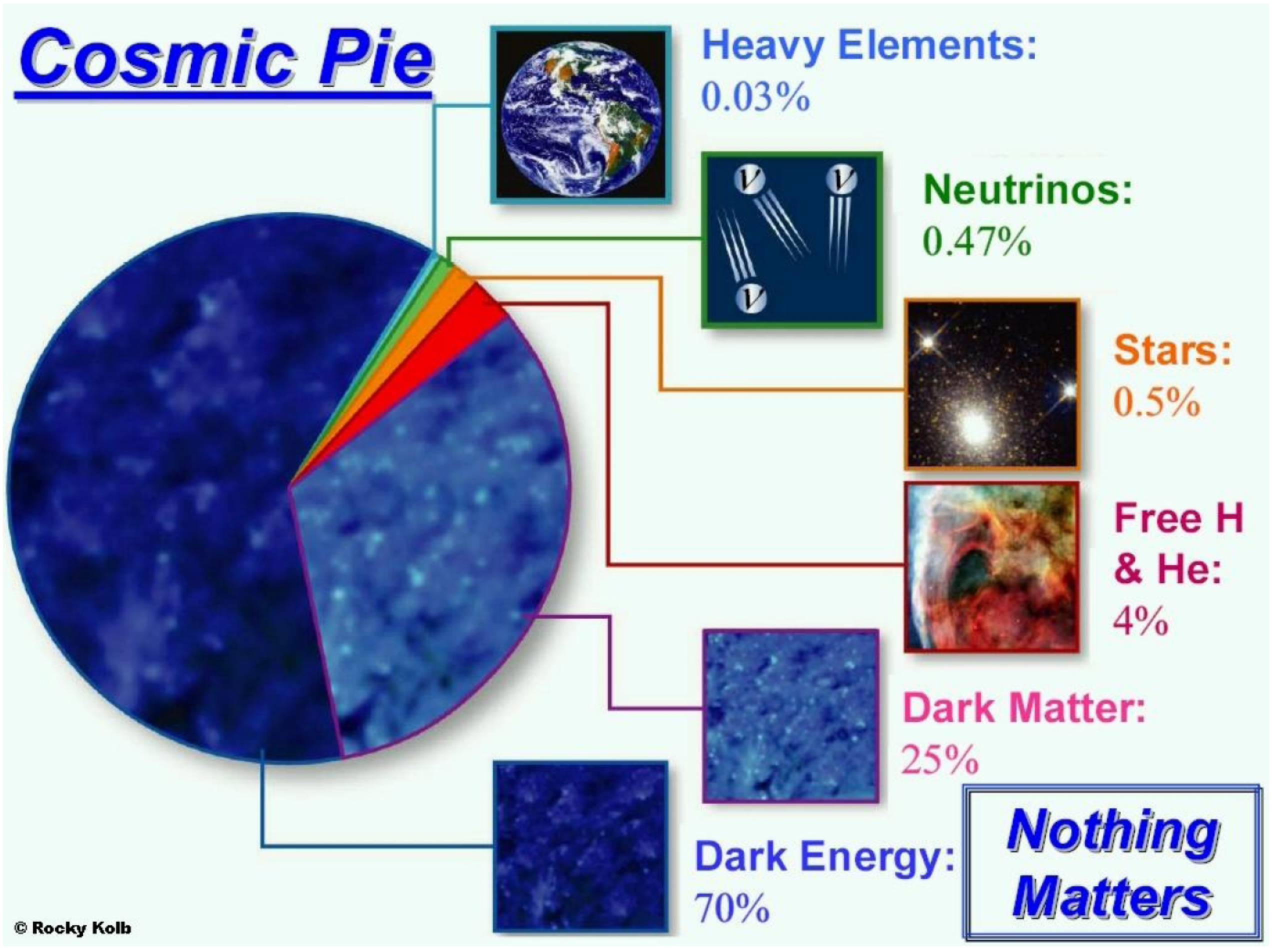

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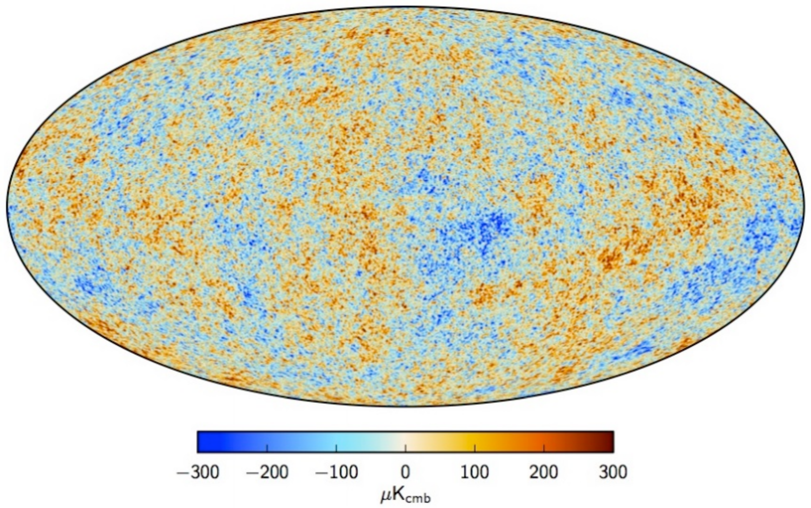

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- Still not directly detected…

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

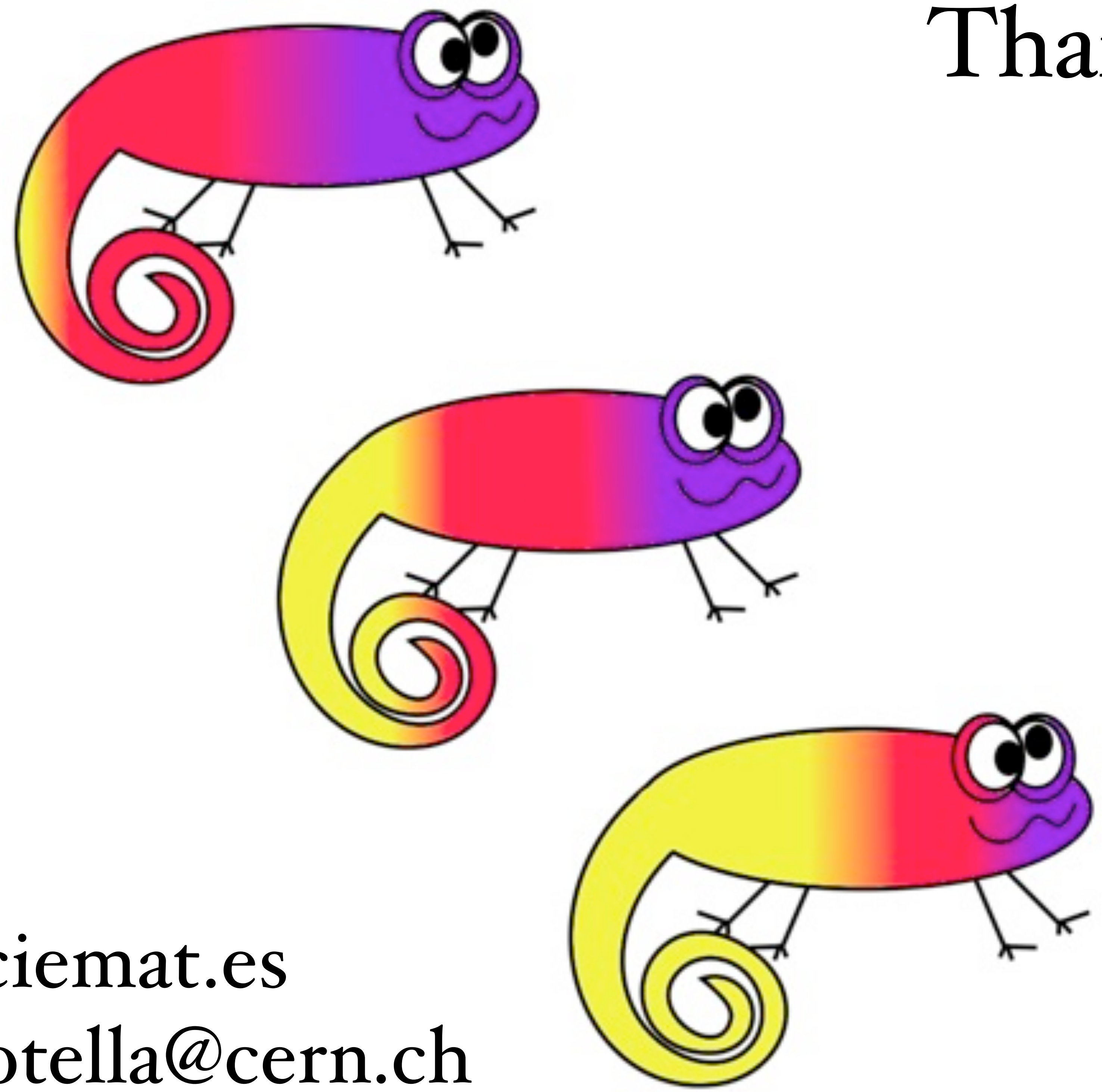
Conclusions

Wrap up

- Neutrinos are **special among elementary particles**
  - Their masses are extremely small (the exact value is unknown)
  - They interact extremely 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!

Thank you!



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