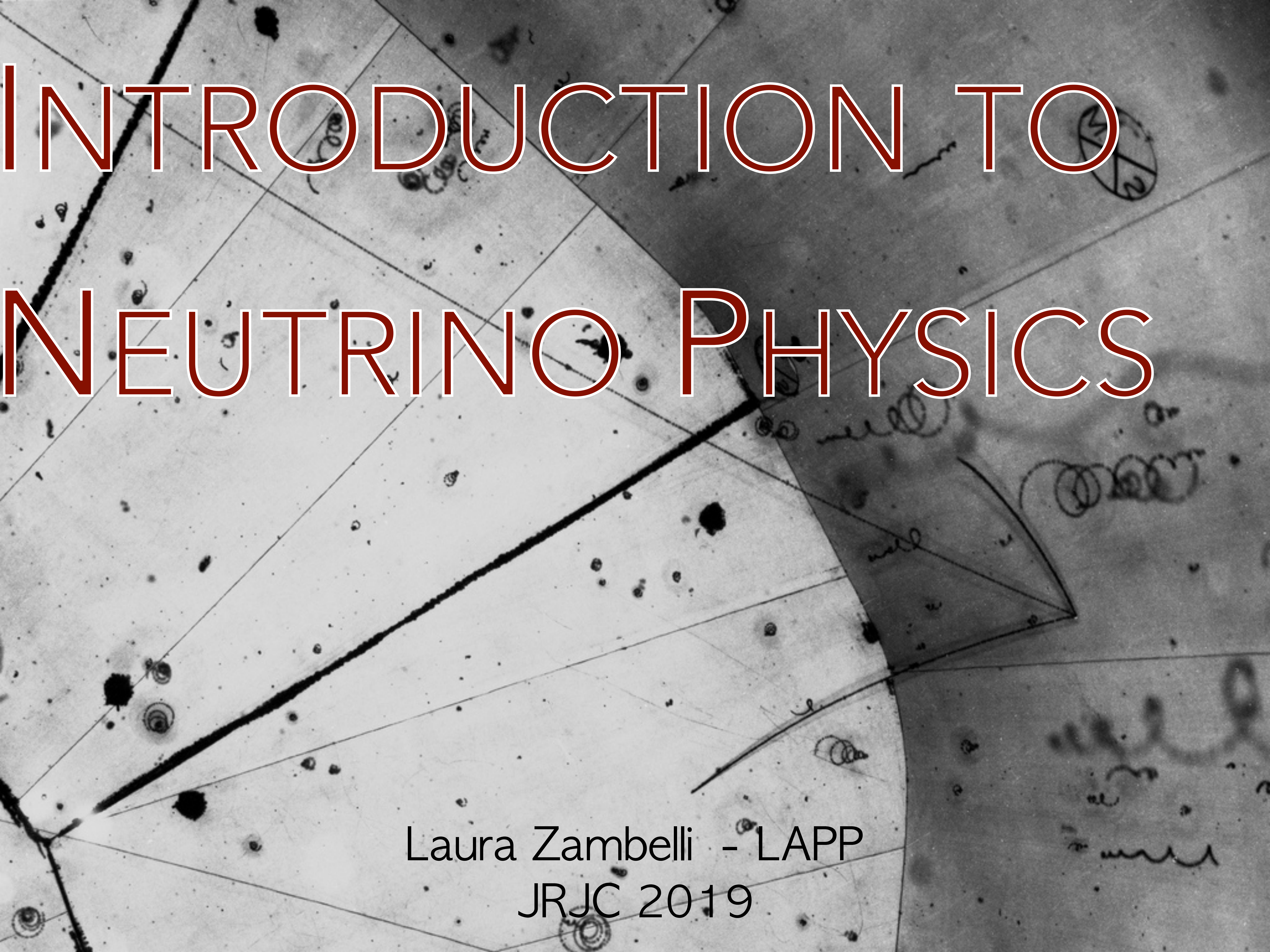
Introduction to Neutrino Physics

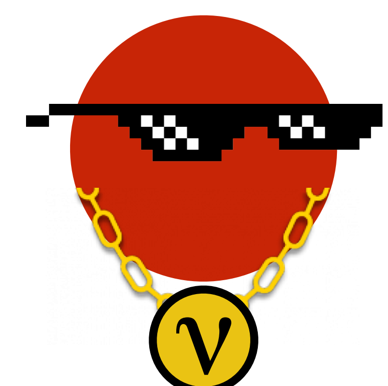


Laura Zambelli - LAPP

JRJC 2019

Introduction to Neutrino Physics

AKA "the particle who gives 0 fuck" by Romain



Laura Zambelli - LAPP

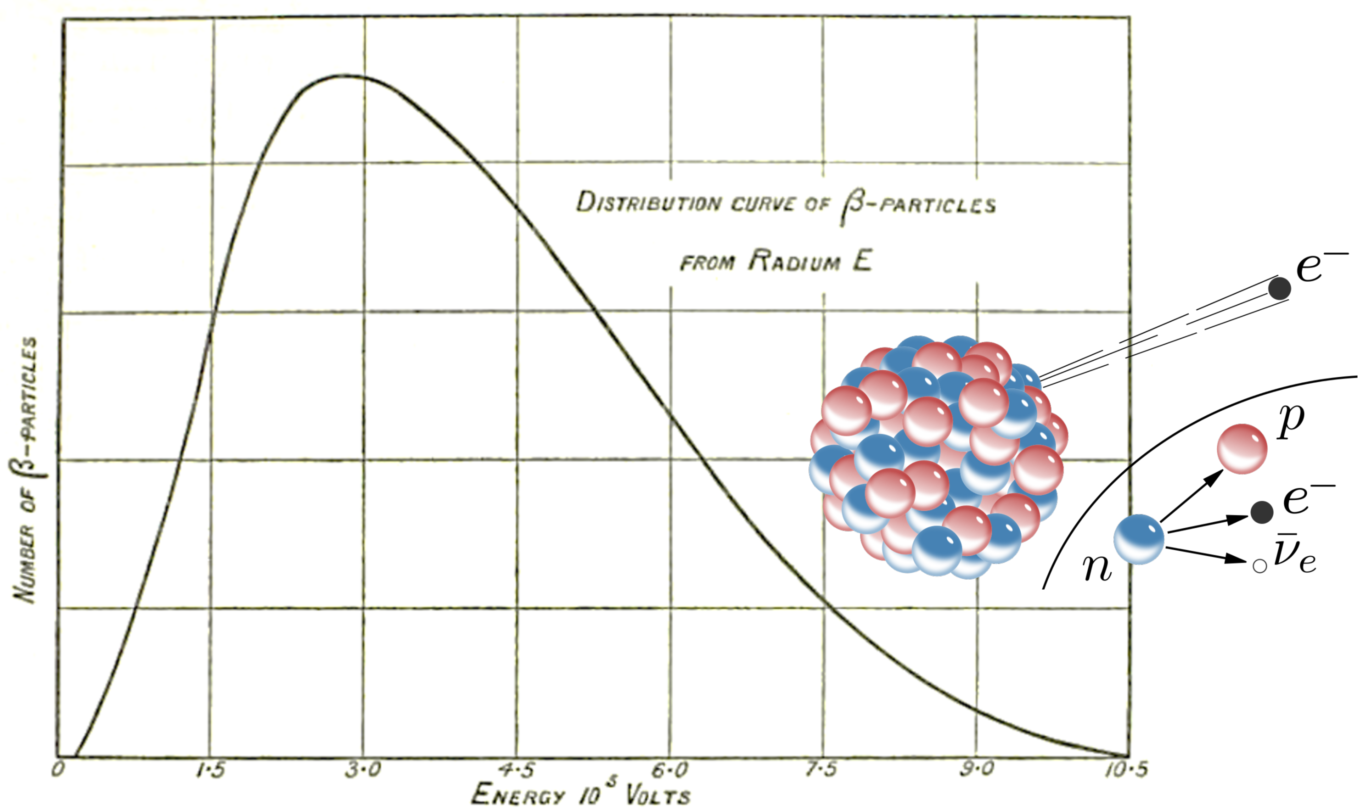
JRJC 2019

IF YOU EVER THOUGHT NEUTRINOS WERE USELESS

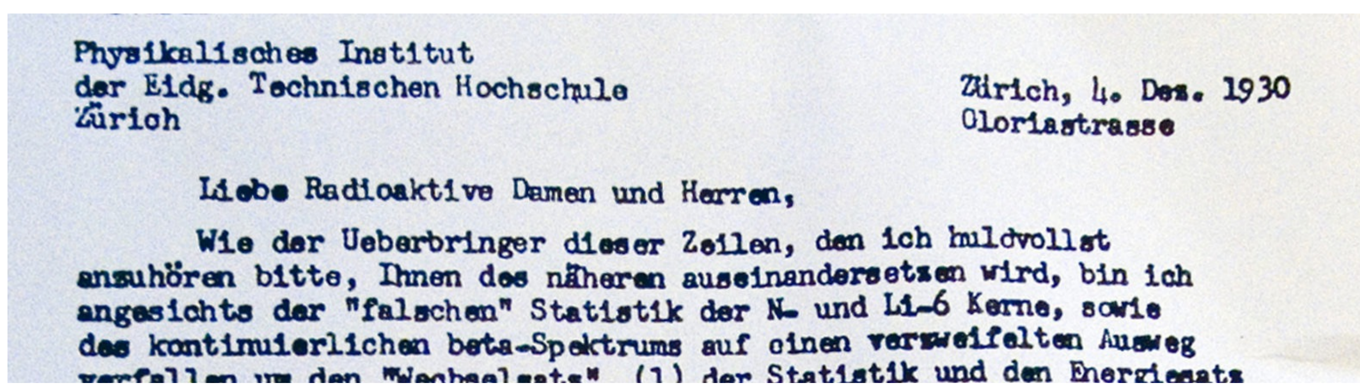
IF YOU EVER THOUGHT NEUTRINOS WERE USELESS

→ JRJC 1912 : No neutrino session to protect them from drowning

β decay and the idea of ν



- As opposed to discrete α and γ spectrum, Chadwick (1914) discovered that β emission is **continuous**
- In order to keep the principle of energy & spin conservation, **Pauli** suggested (1930) a "desperate solution" : β decays would also produce a neutral, spin 1/2 and nearly massless particle



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

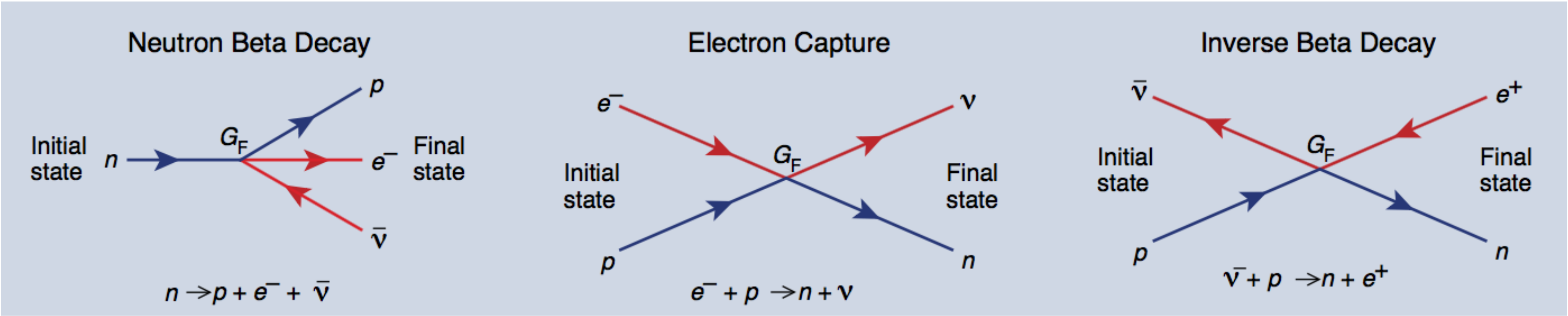
Wie der Ueberbringer dieser Zeilen, den ich huldvollst
anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg

- In 1934, **Fermi** named this particle the **neutrino** (little neutral) and includes it in his weak interaction theory

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z\pm1}Y + e^{\pm} + \overset{(-)}{\nu_e} $$

Inverse β and the $\bar{\nu}$e discovery

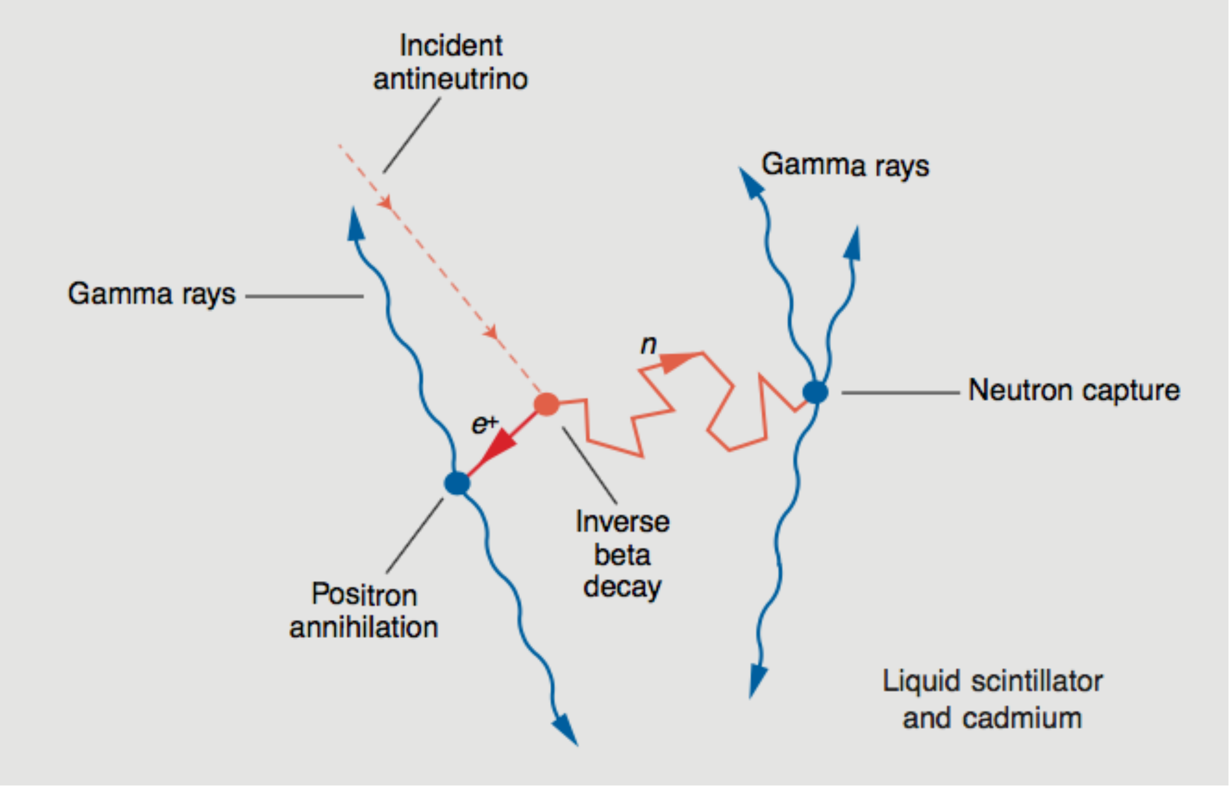
- According to Fermi on β processes, three kinds of reaction are possible:



- In Los Alamos in the 50s, Reines and Cowan aims at discovering the neutrino through **inverse β** reaction:

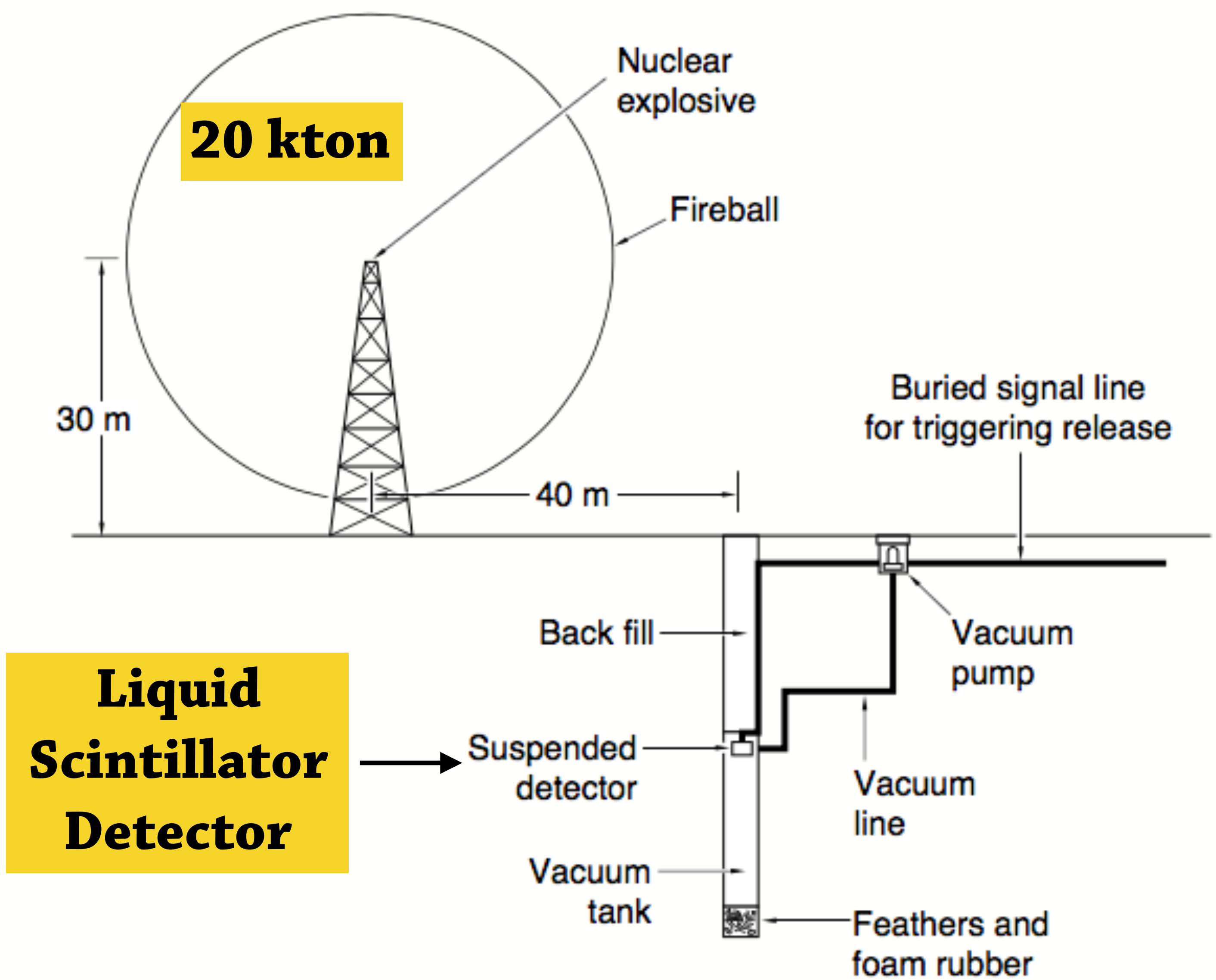
$$\bar{\nu} + p \rightarrow n + e^+$$

- In a liquid scintillator detector, the **positron annihilates** with an electron, producing 2 photons
- By doping the liquid with Cadmium, the **neutron will also by captured**, after having thermalized (few ms after the positron)
- They knew that neutrino was hard to catch, therefore they needed an **intense** ν source



Inverse β and the $\overline{\nu}e$ discovery

Idea 1 : nuclear bomb



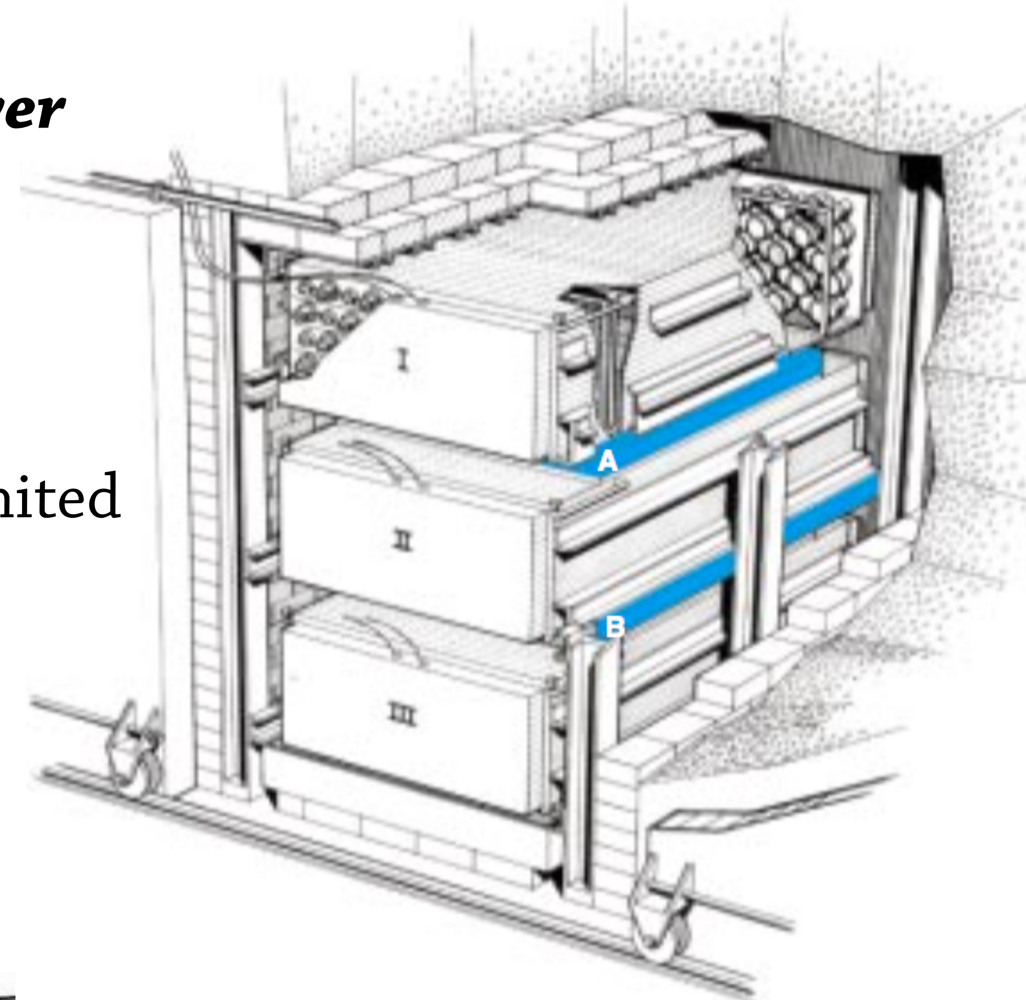
- Very intense source : ~10^{40} ν/s/cm^2
- Short (~2s) : no cosmic background
- But, a lot of neutrons & gammas
- Single use detector

The 'El Monstro' project was **approved** !

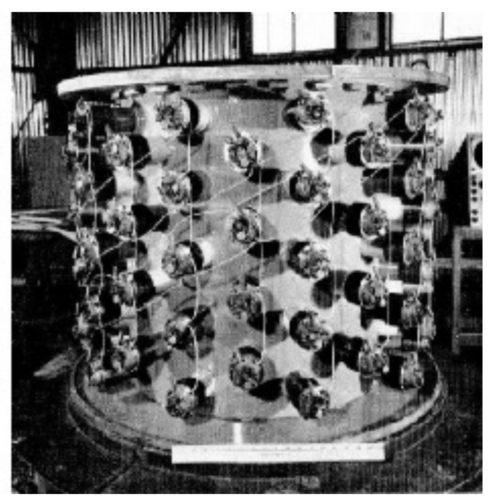
When they had the idea of doping the detector with neutron catcher (giving a better signal discrimination) they **changed their mind**

Inverse β and the $\overline{\nu}e$ discovery

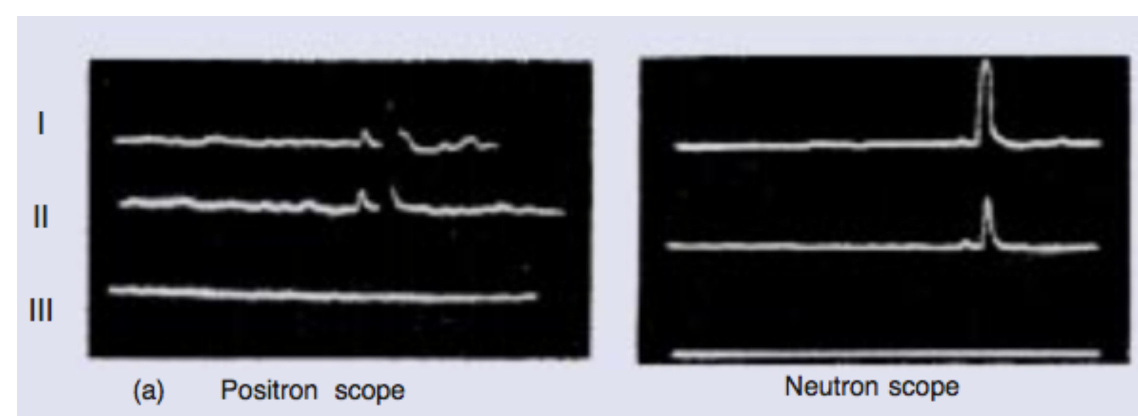
Idea 2 : nuclear power plant at Savannah River



- Intense source ~10^{20} ν/s/cm^2
- Continuous emission
- Also a lot of n & γ background, but can be limited
  Underground, lead shielding, …
- More ethical ?



$\overline{\nu}_e$ discovery in 1956

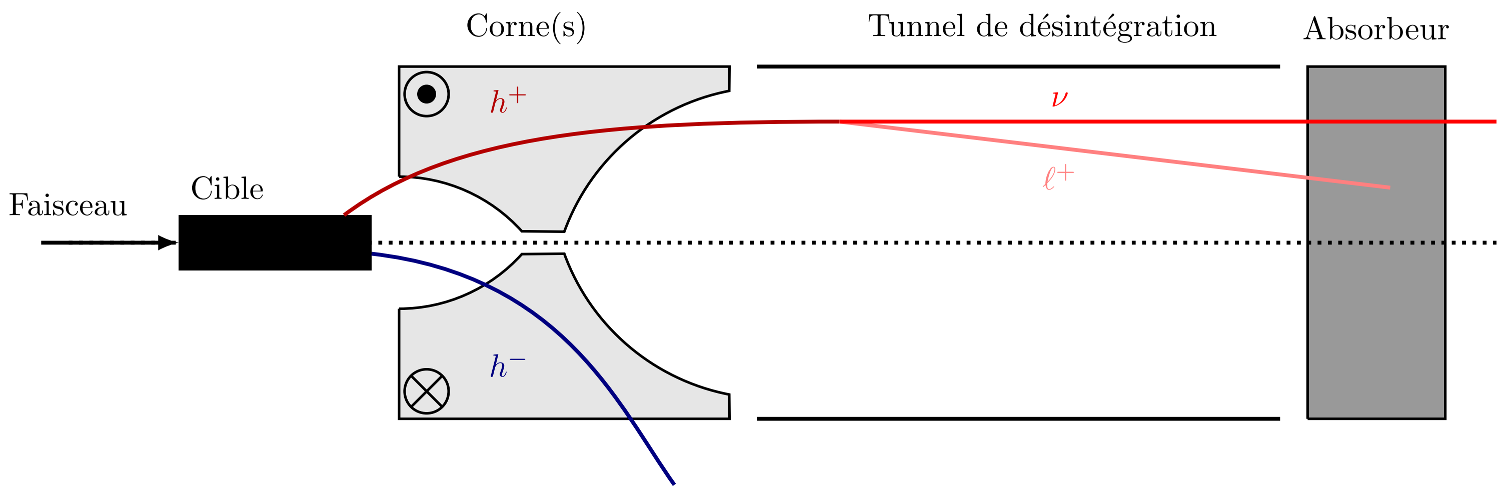


- 1995 Nobel Prize
- Method still used today

ν_μ and ν_τ discoveries

- In 1962, Lederman, Schwartz and Steinberger made the first **accelerator-based neutrino** source

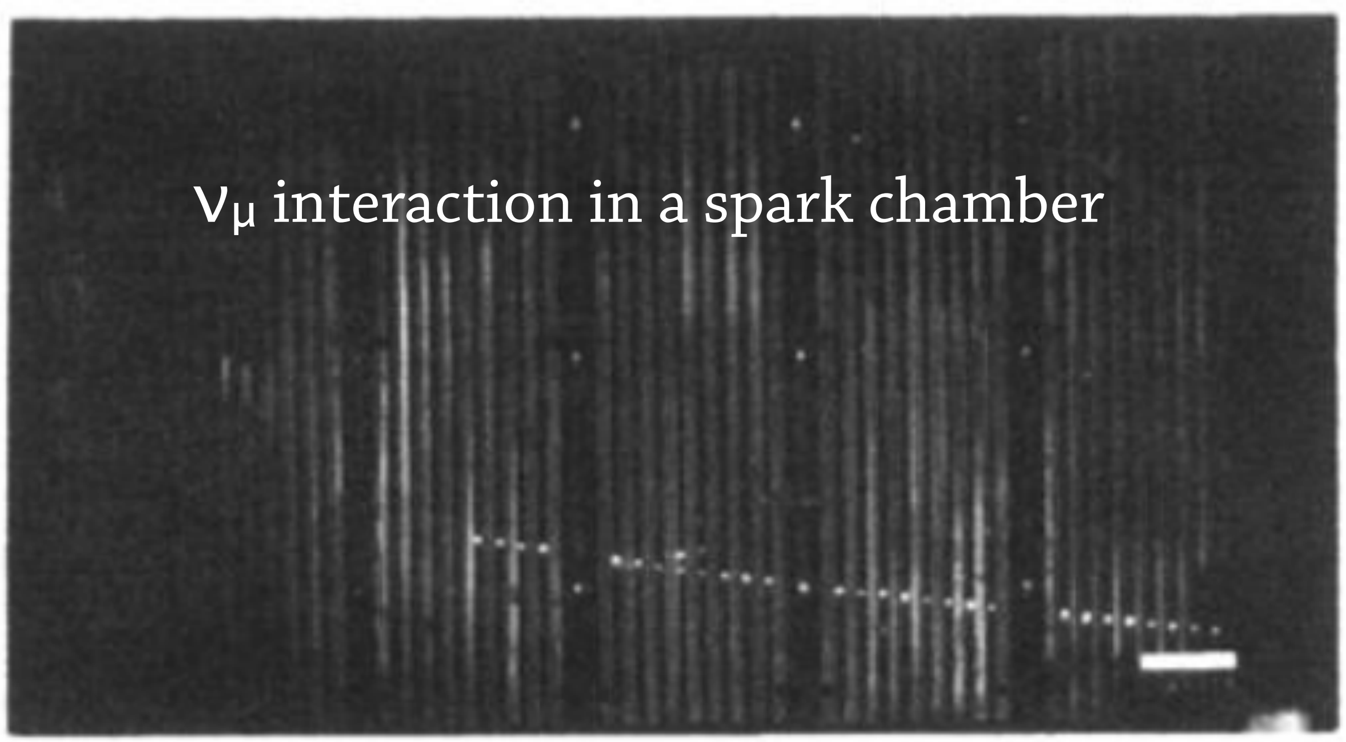
→ Accelerated protons hits a target, $\pi^\pm$ are created and decay into $\mu^\pm + \nu_\mu$



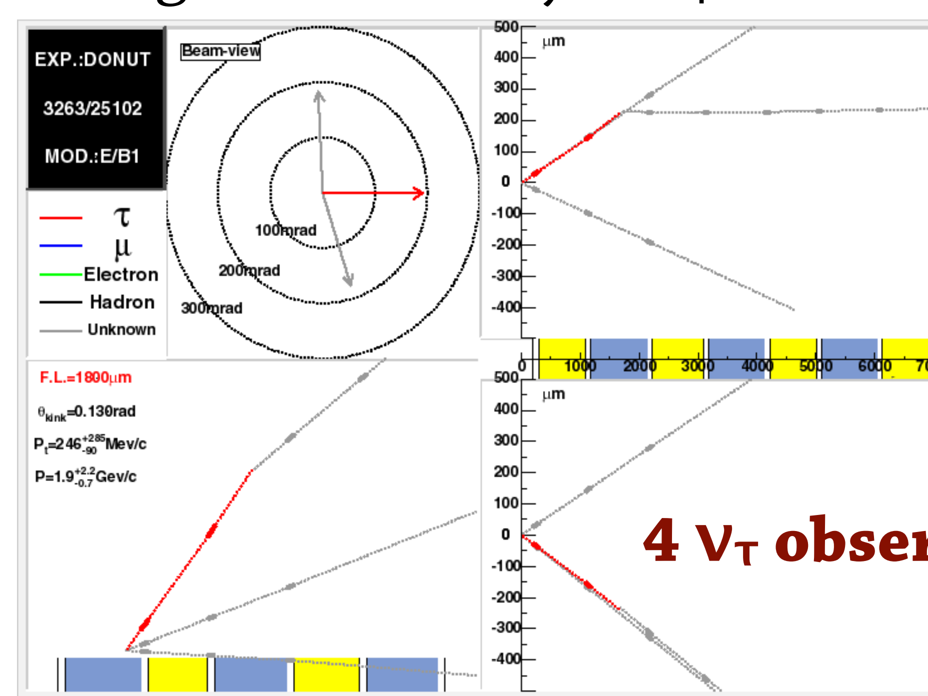
-1988 Nobel Prize

- Method still used today

- They found out that they had different kind of ν interactions : **ν_μ discovery** !



- In 2000, a ν_τ beam was created by producing Ds (same way as ν_μ beam)



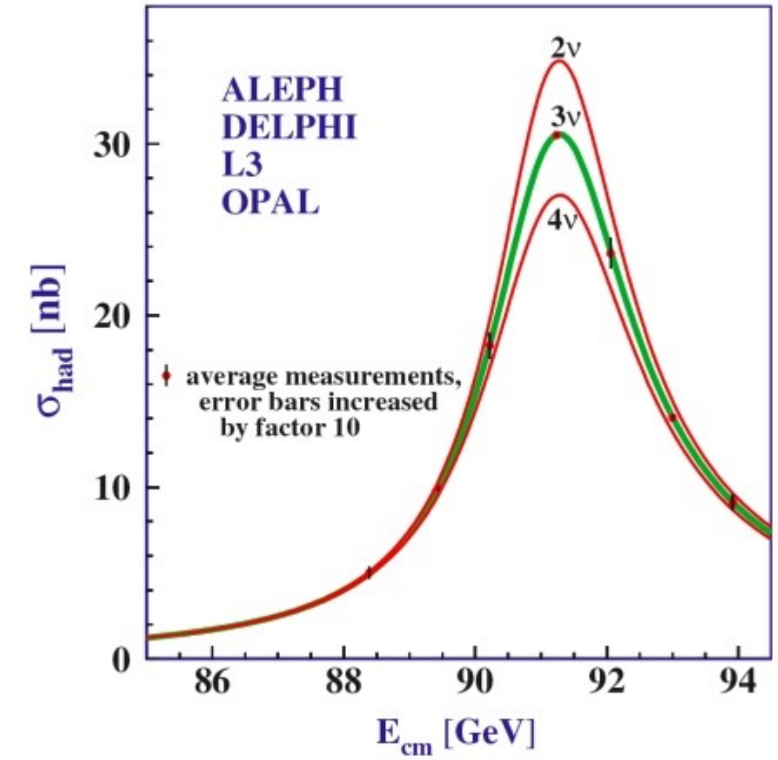
4 ν_τ observed

Neutrinos & Standard Model

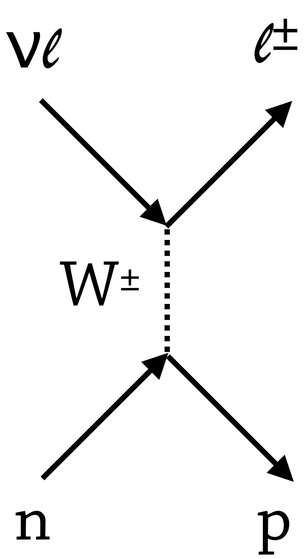
- **Three flavors** of neutrinos (light and active):
  - → In 1989, LEP mesures the Z invisible width

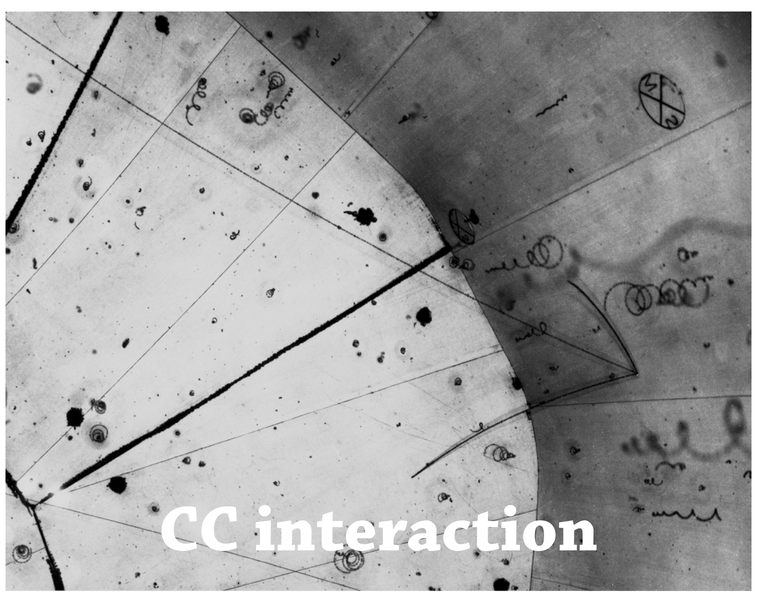
$$N_\nu = 2.984 \pm 0.008$$

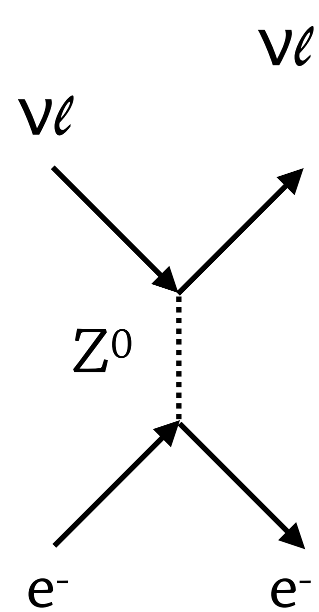
named ν_e, ν_μ, ν_τ

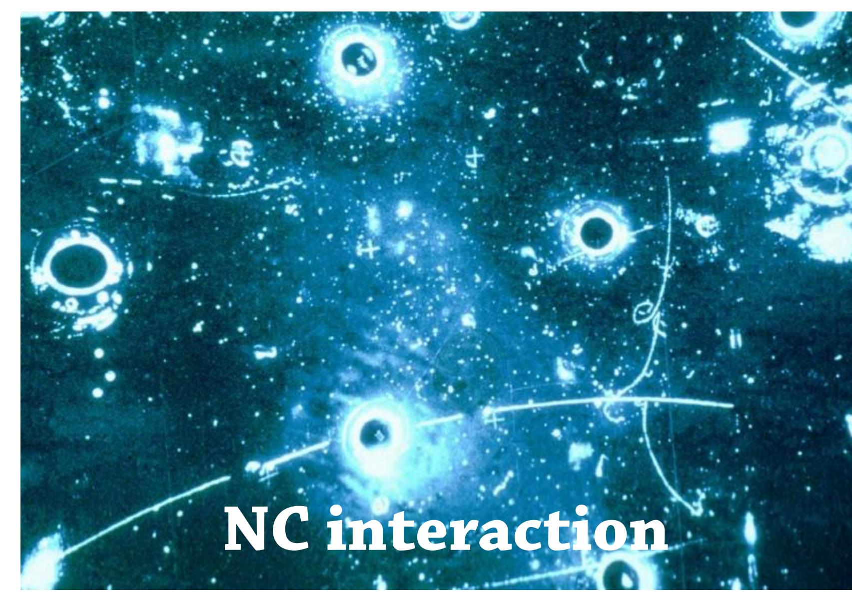


- Only interact through weak interactions
  - → **Charged & Neutral current**









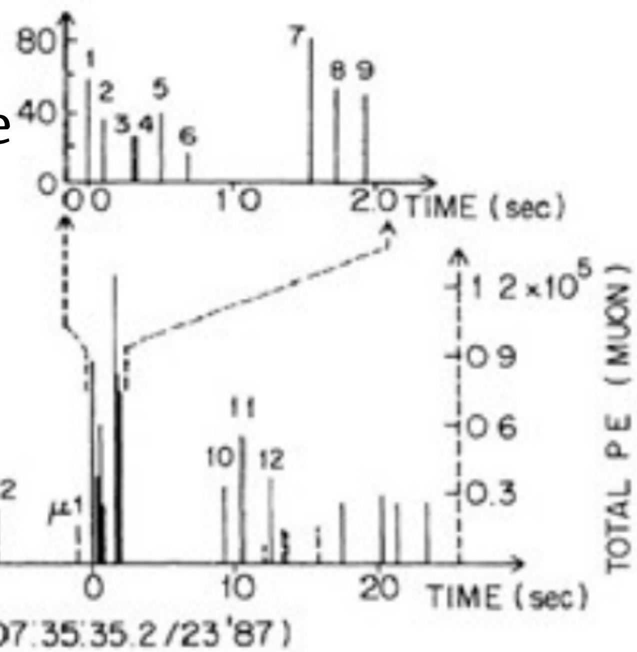
- Only left handed
  - → Cannot couple to Higgs field therefore neutrinos are **massless**

Neutrino Astronomy : Beginning

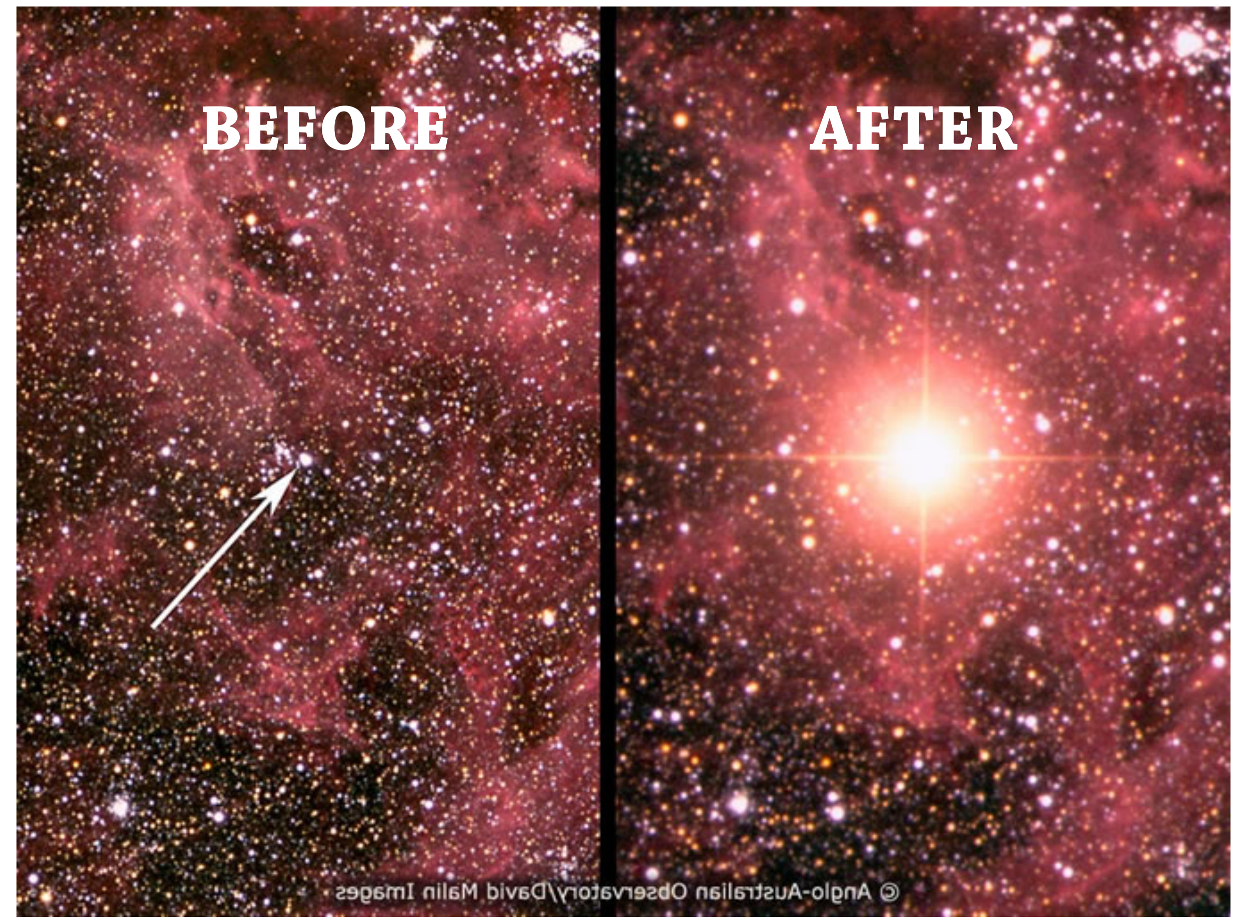
On February 23rd 1987, a supernova exploded in the large magellan cloud (170 000 l.y.)

3h before the light signal, three neutrino detectors observed a large number of events in a very short time (**24 events in 13s**)

@Kamiokande



SN1987A

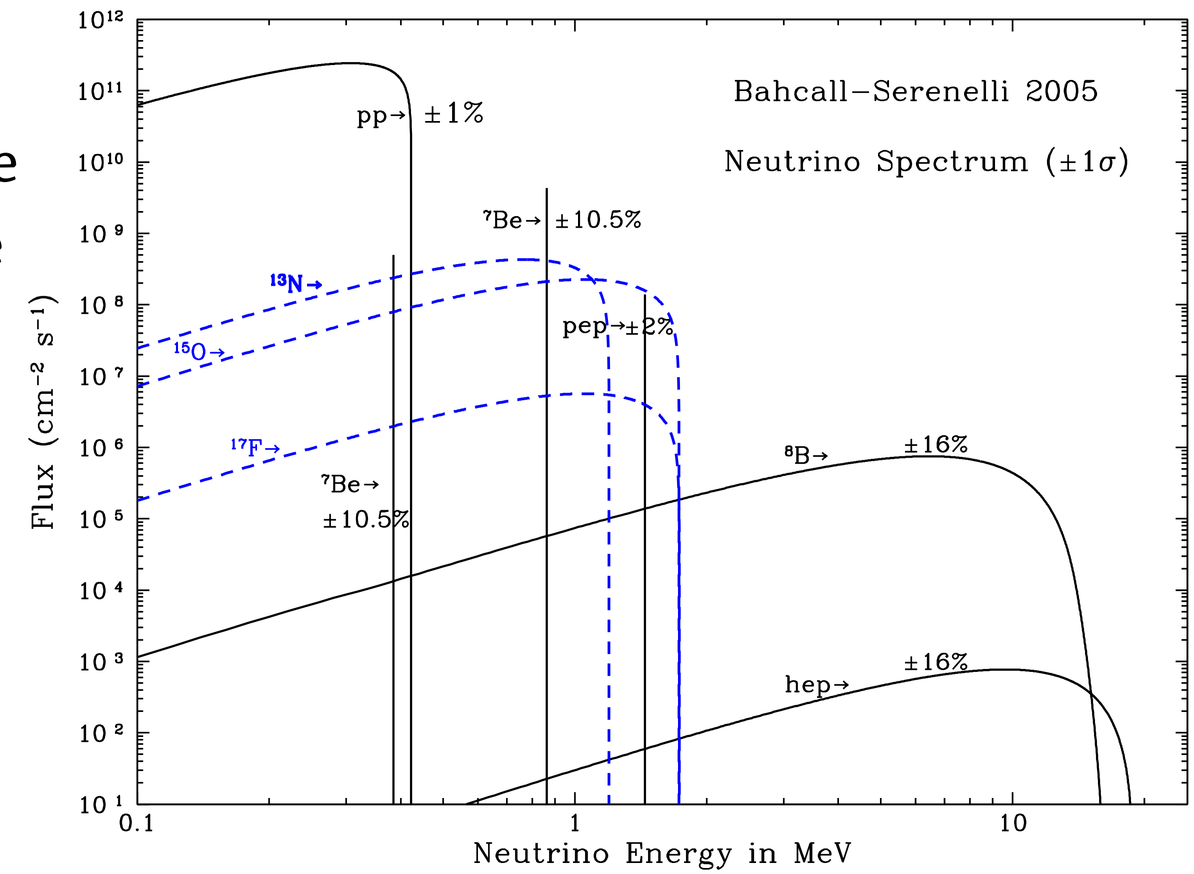


- 99% of the SN energy is released as neutrinos
- 1st case of neutrino astronomy and multi-messenger
- **Nobel Prize for Kamiokande in 2002**
- Never happened again, all ν experiments are still waiting for a new nearby SN

Neutrino Astronomy : Anomalies

Solar Neutrinos

- In order to study the nuclear fusion occurring in the sun, neutrinos are the ideal messenger as they leave the medium instantly
- ν_e flux : ~ 7×10^{10} ν/s/cm^2



Atmospheric neutrinos

- When cosmic rays hits earth, they interact with the atmosphere and produce pions and muons
- In terms of flavors, at ground $N(\nu_\mu)/N(\nu_e) = 2$

$$p + atm \rightarrow \pi^+ + \dots$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

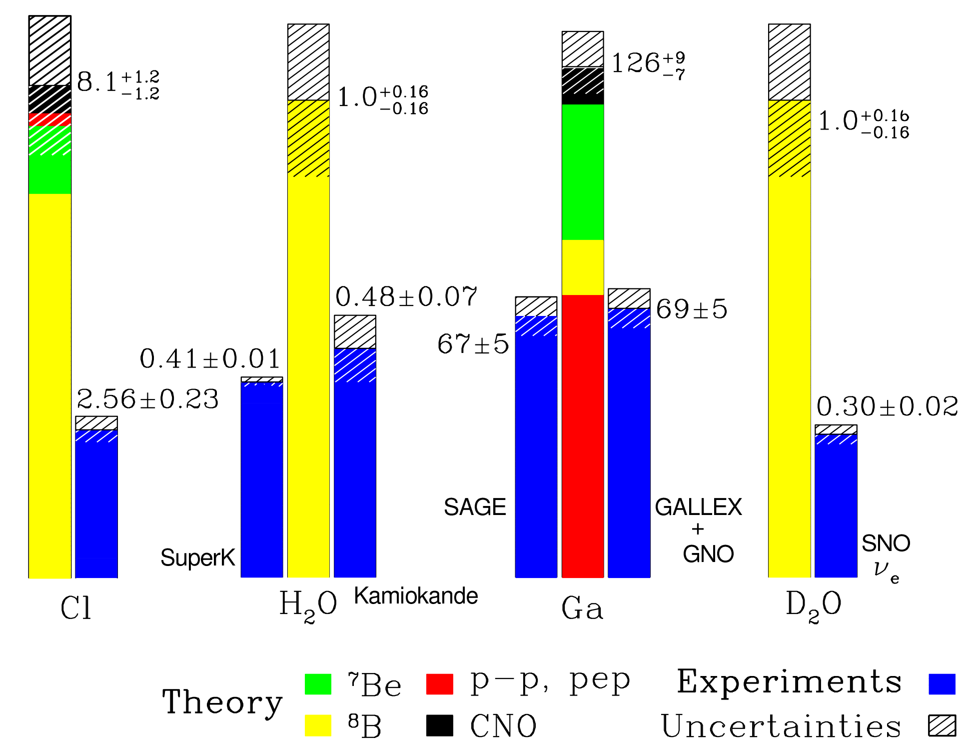
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Neutrino Astronomy : Anomalies

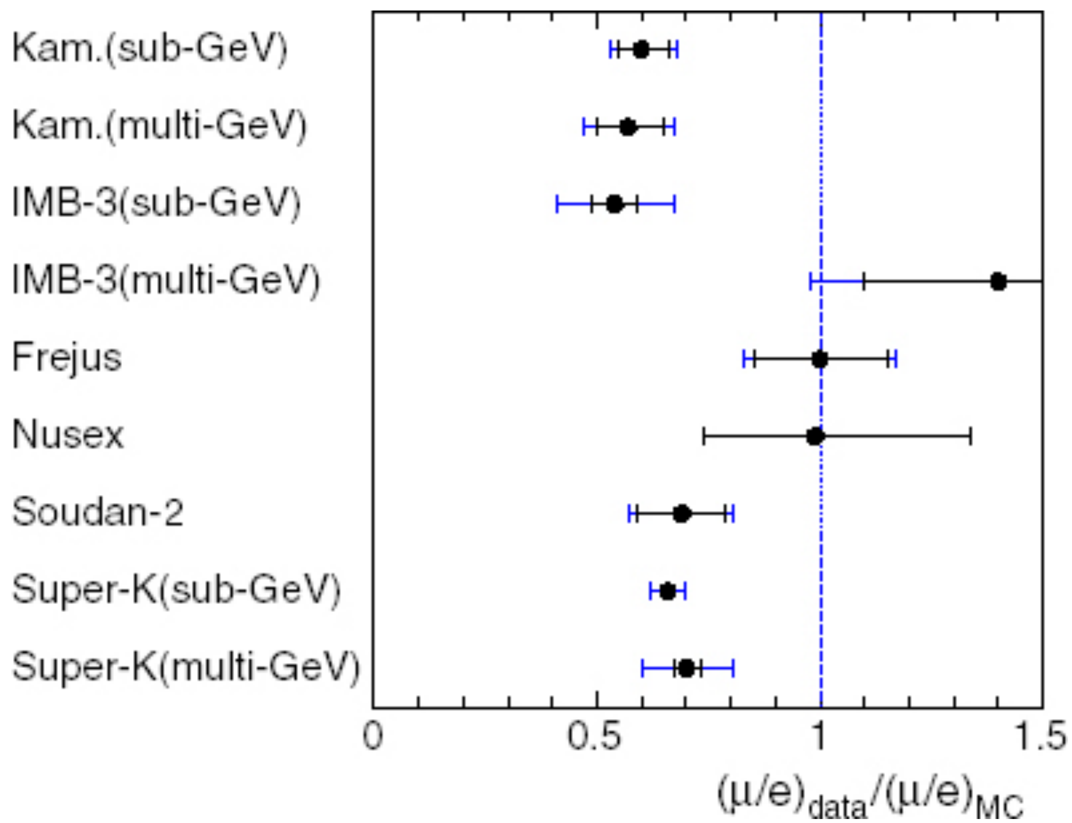
Solar Neutrinos

- In order to study the nuclear fusion occurring in the sun, neutrinos are the ideal messenger as they leave the medium instantly
- ν_e flux : ~ 7×10^{10} ν/s/cm^2

~2/3 of expected ν_e are missing



Atmospheric neutrinos



- When cosmic rays hits earth, they interact with the atmosphere and produce pions and muons
- In terms of flavors, at ground $N(\nu_\mu)/N(\nu_e) = 2$

~1/2 of expected ν_μ are missing

The oscillations can help

- Several hypothesis : ν-decay, ν decoherence, flavor changing neutral currents, oscillations, …
- In 1957, Pontecorvo suggested the $\nu \rightarrow \bar{\nu}$ oscillations
- Principle : Neutrino flavor and mass eigenstates are **not superimposed** but **linked** by a 3×3 unitary mixing matrix (the PMNS matrix)

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$$

α = (e, μ, τ) := Flavor states
i = (1, 2, 3) := Mass states
U = PMNS matrix

The oscillations can help

- Several hypothesis : ν-decay, ν decoherence, flavor changing neutral currents, oscillations, …
- In 1957, Pontecorvo suggested the $\nu \rightarrow \bar{\nu}$ oscillations
- Principle : Neutrino flavor and mass eigenstates are **not superimposed** but **linked** by a 3×3 unitary mixing matrix (the PMNS matrix)

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$$

α = (e, μ, τ) := Flavor states
i = (1, 2, 3) := Mass states
U = PMNS matrix

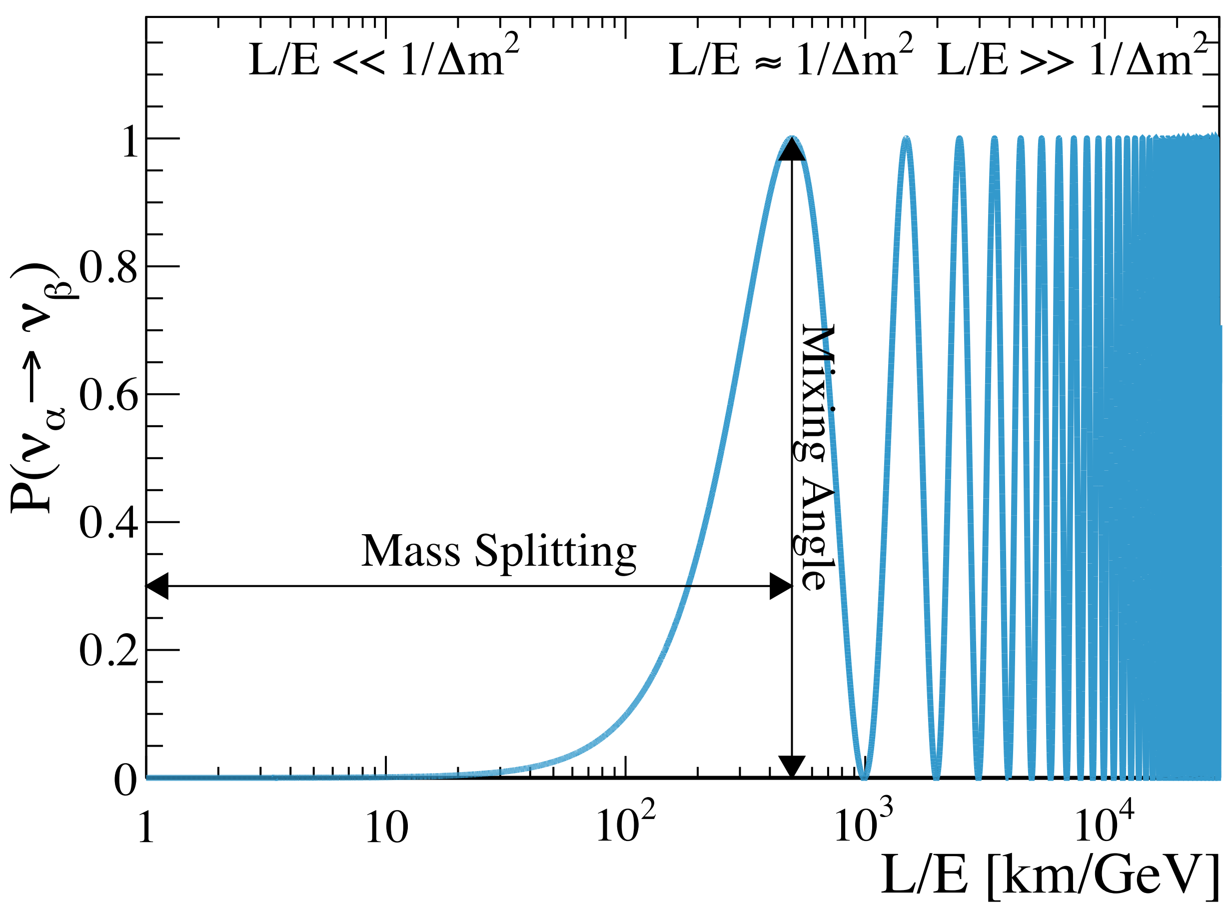
Simplified 2 flavors case

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

With a source ν_α at an energy E, the probability to detect a ν_β at a distance L is :

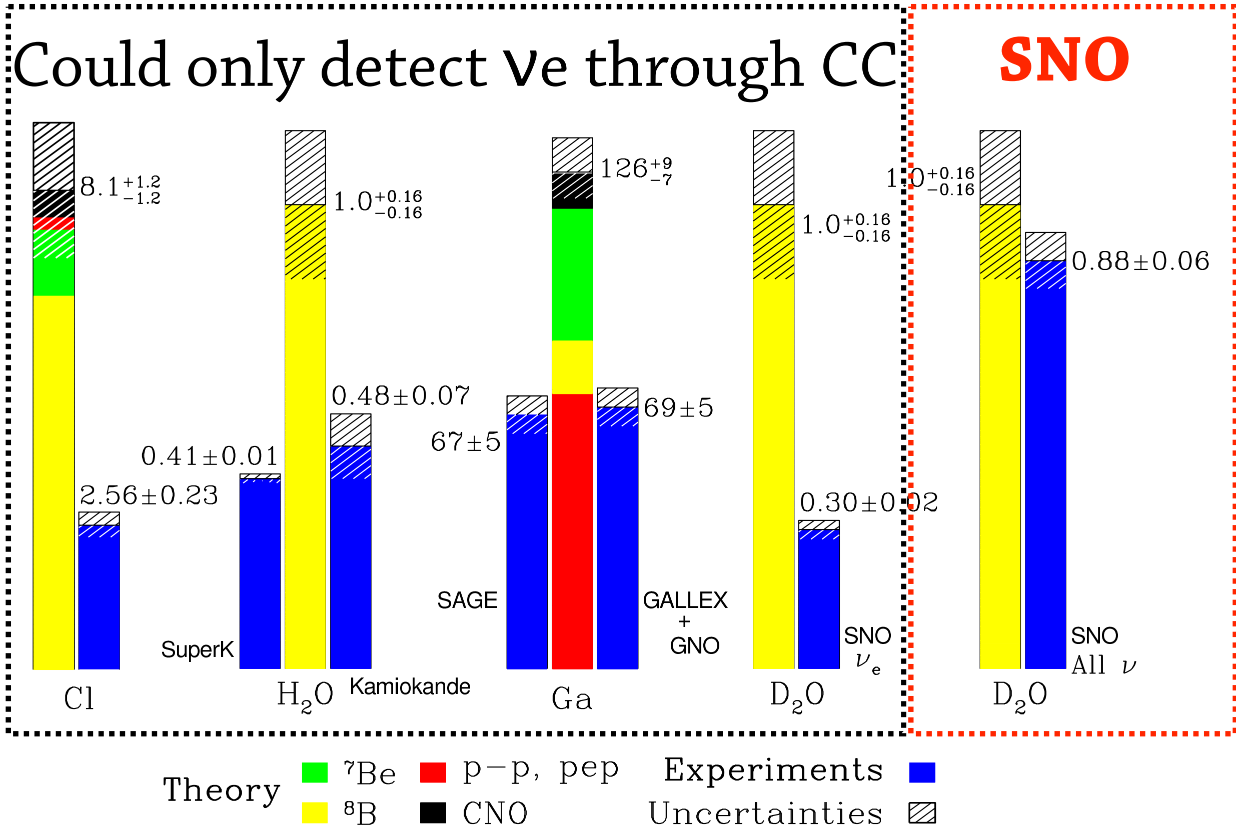
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$\Delta m^2 = m_1^2 - m_2^2$



ν oscillations : experimental proofs

Solar Neutrinos



SNO (1kton of heavy water) was designed to detect solar neutrinos through:

- **CC** interactions $\nu_e + d \rightarrow p + p + e^-$

  ν_e only (ν_μ and ν_τ don't have enough energy)
- **ES** interactions $\nu_x + e^- \rightarrow \nu_x + e^-$

  all flavors
- **NC** interactions $\nu_x + d \rightarrow p + n + \nu_x$

  all flavors

(NC & ES are not sensitive to flavor, and have no energy threshold)

SNO measured the ratio :

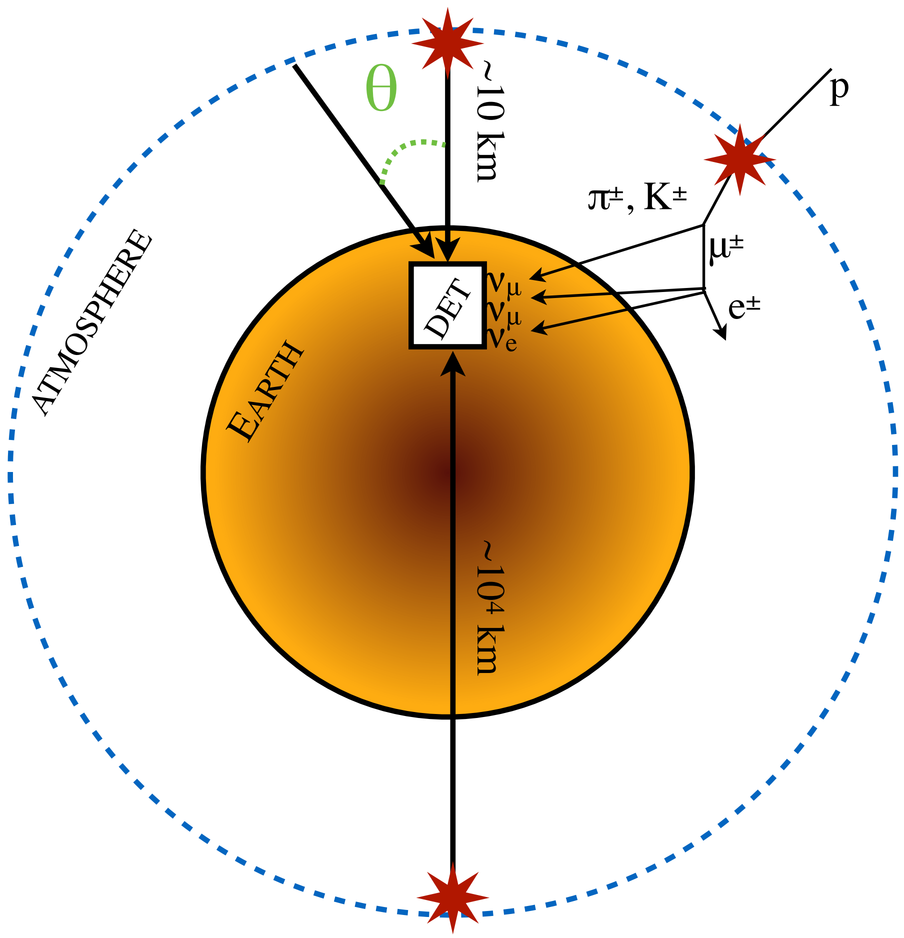
$$\frac{\Phi_{CC}}{\Phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

And showed that the **total** flux of solar neutrino is **compatible** with the solar standard model

Nobel Prize in 2015 !

ν oscillations : experimental proofs

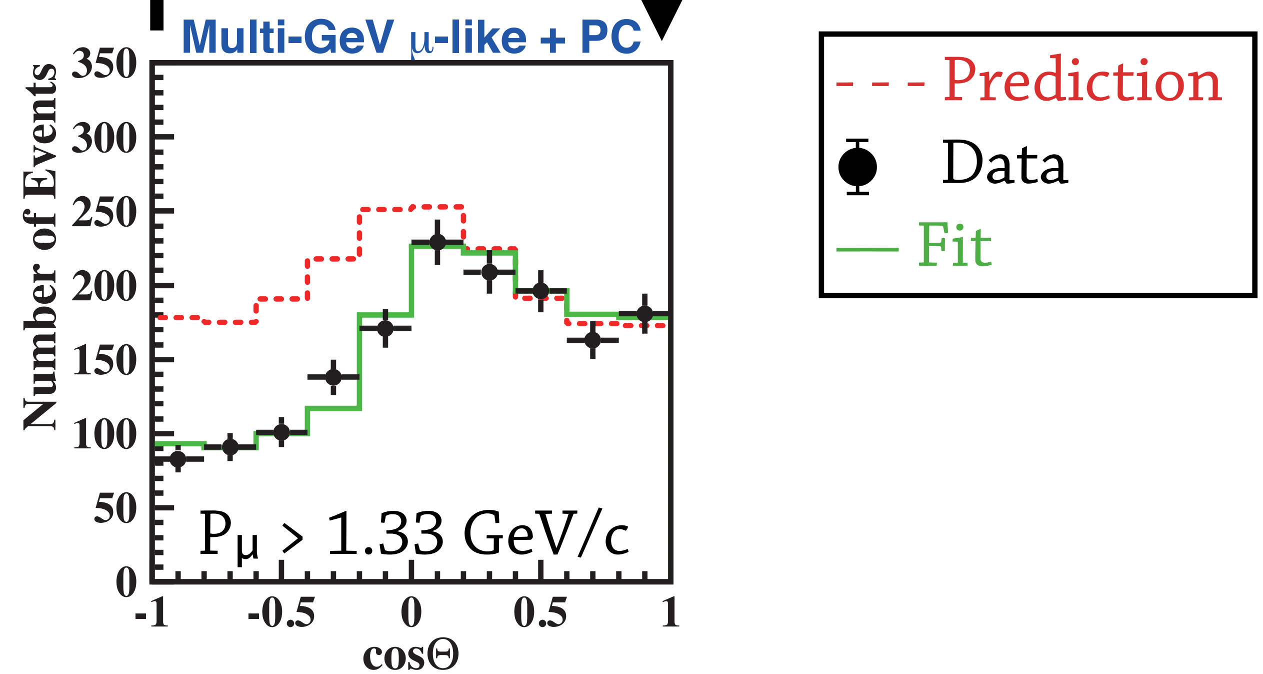
Atmospheric neutrinos



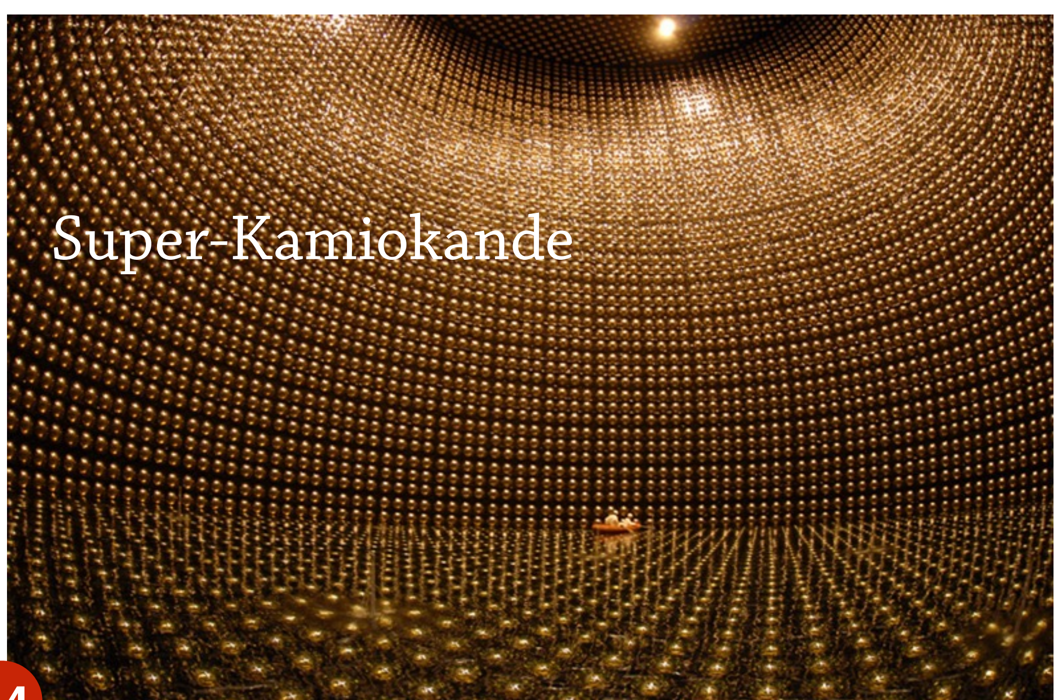
Kamiokande looked at the direction of the atmospheric neutrinos and found out that the ν_μ deficit was **direction dependent** :

L~10^4 km
1/2 missing

L~10 km
no deficit



↳Atmospheric ν_μ oscillates into ν_τ



Nobel Prize in 2015 !

3 flavors oscillations

Atmospheric — Reactor/Accelerator — Solar

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

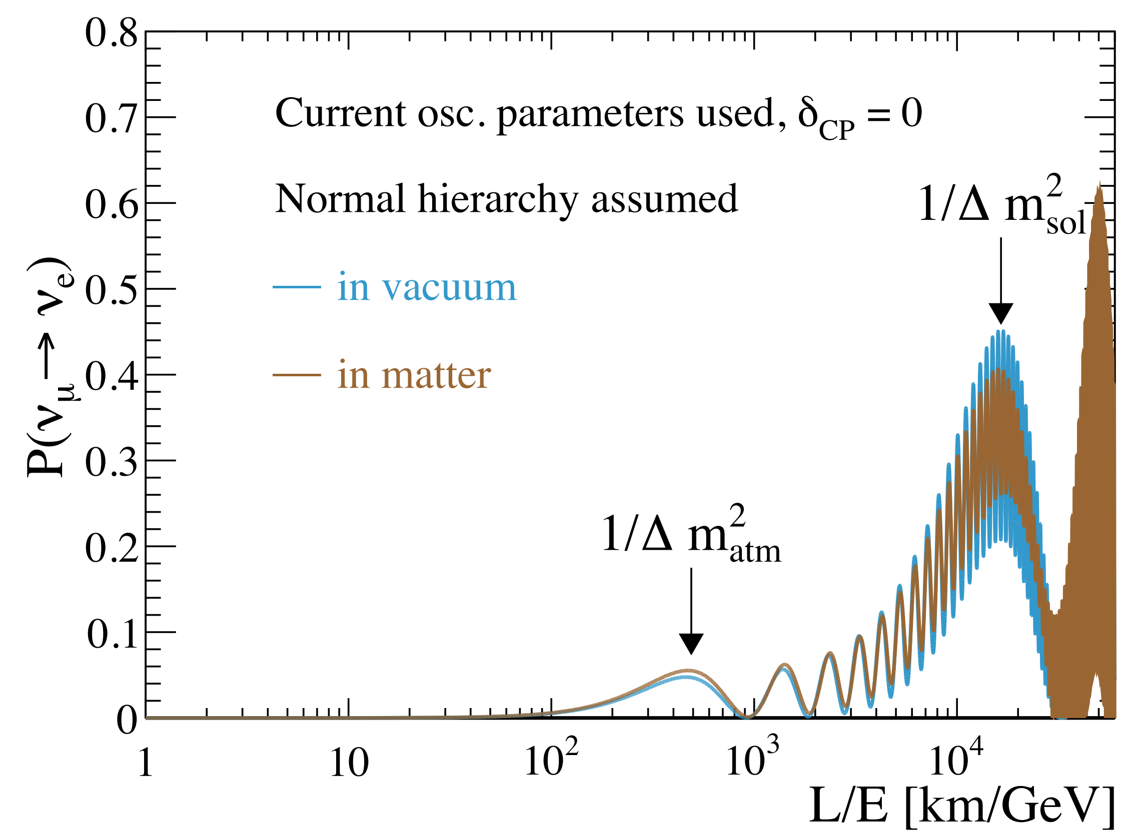
$$s_{ij} = \sin\theta_{ij}$$

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

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

In the 3 ν flavor case, the oscillation phenomena is described by:

- **3** mixing angles: θ_{12}, θ_{23} and θ_{13}
- **2** mass splittings: Δm^2_{sol}, Δm^2_{atm}
- **1** CP violation phase δ
- Oscillation probabilities are modified in matter



NB : ν oscillations proves that neutrinos are **massive**

Current knowledge of oscillation parameters

Atmospheric | Reactor/Accelerator | Solar

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

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

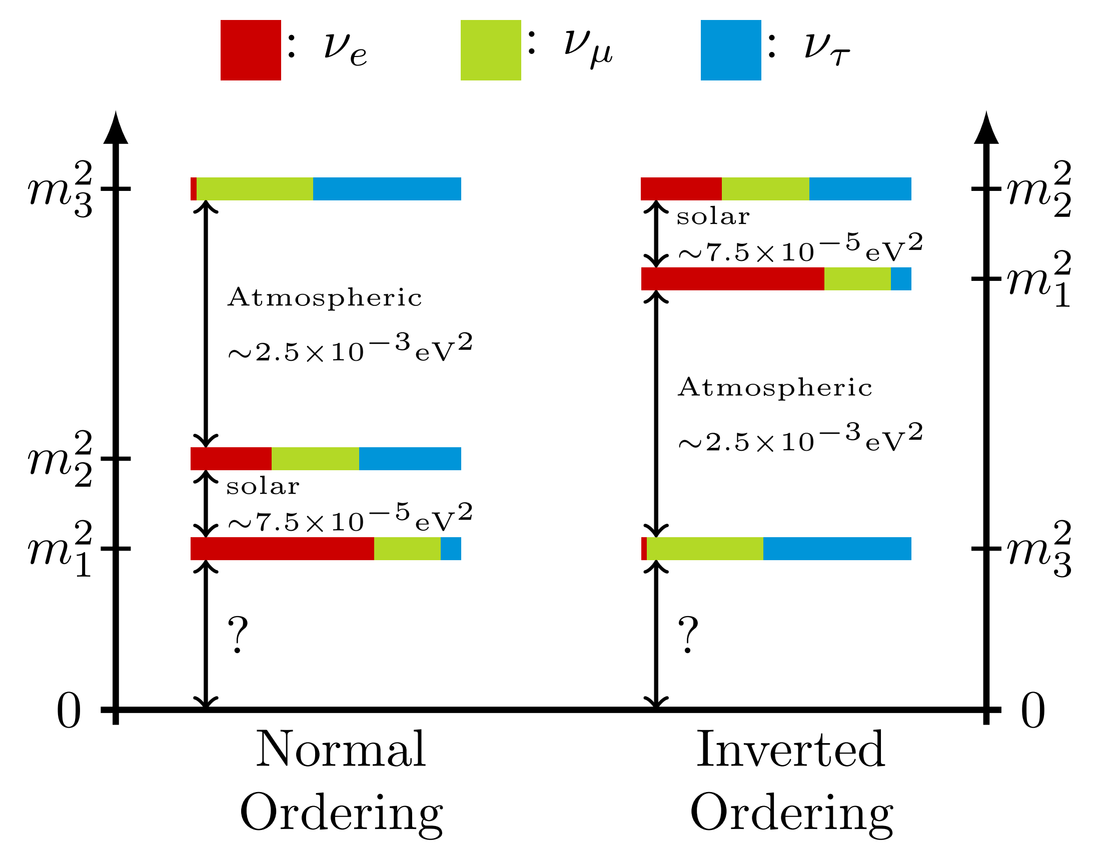
$c_{ij} = \cos\theta_{ij}$

$\Delta m^2_{ij} = m_i^2 - m_j^2$

From a global fit of data available on Jul. 2019, at 1σ :

nuFIT 4.1 (2019), nu-fit.org

$$\theta_{12} = 33.82^{+0.78}_{-0.76}$$
$$\theta_{23} = 48.3^{+1.1}_{-1.9}$$
$$\theta_{13} = 8.61^{+0.13}_{-0.13}$$
$$\Delta m^2_{21} = \Delta m^2_{\rm sol} = 7.39^{+0.21}_{-0.20}\times 10^{-5}{\rm eV}^2$$
$$|\Delta m^2_{31}| \simeq |\Delta m^2_{32}| = |\Delta m^2_{\rm atm}| = 2.523^{+0.032}_{-0.030}\times 10^{-3}{\rm eV}^2$$



Open questions to be answered :

- Is θ_{23} maximal ?
- What is the neutrino mass hierarchy ?
- Is there CP violation in the leptonic sector ?

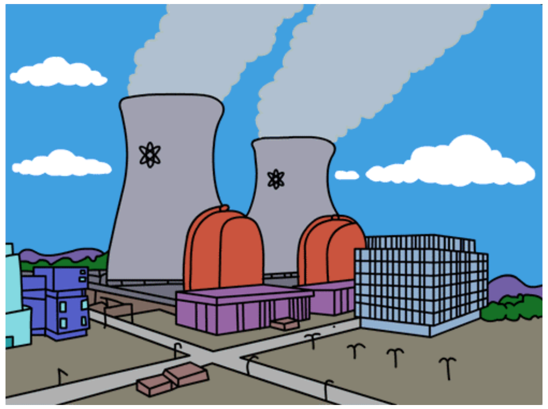
Reactor and Long Baseline experiments

Neutrino source → ***Near detector*** → ***Far detector***

Neutrino source		Near detector		Far detector
	→	At L/E before oscillations	→	At L/E for oscillations

Reactor and Long Baseline experiments

Reactor



- Low energy
- $\overline{\nu}_e$ only
- Flux known at 2-3%

- Can use the 2 flavors probability formula
- Very **clean** measurement : best θ_{13} value
- Sensitivity to mass hierarchy
- But only **disappearance**

(Double)-Chooz, Daya-Bay, RENO, JUNO, …

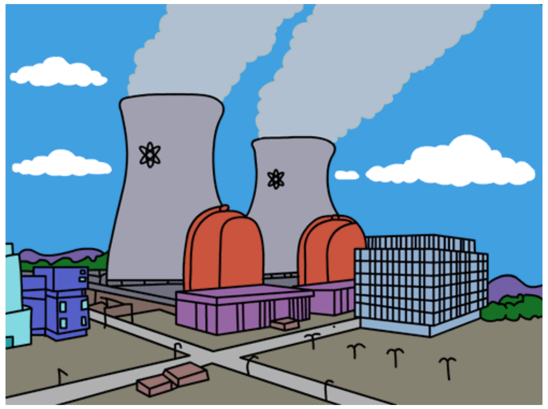
Neutrino source → ***Near detector*** → ***Far detector***

Near detector: At L/E before oscillations

Far detector: At L/E for oscillations

Reactor and Long Baseline experiments

Reactor



- Low energy
- $\overline{\nu}_e$ only
- Flux known at 2-3%

- Can use the 2 flavors probability formula
- Very **clean** measurement : best θ_{13} value
- Sensitivity to mass hierarchy
- But only **disappearance**

(Double)-Chooz, Daya-Bay, RENO, JUNO, ...

Neutrino source → ***Near detector*** → ***Far detector***

Near detector: At L/E before oscillations

Far detector: At L/E for oscillations

Accelerator

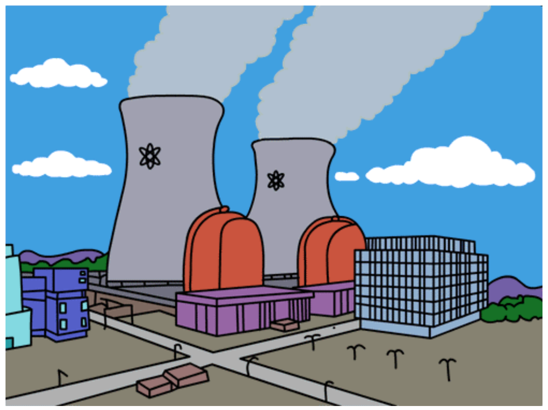
- Tunable energy
- ν_μ or $\overline{\nu}_\mu$ flux
- Flux known at ~10%

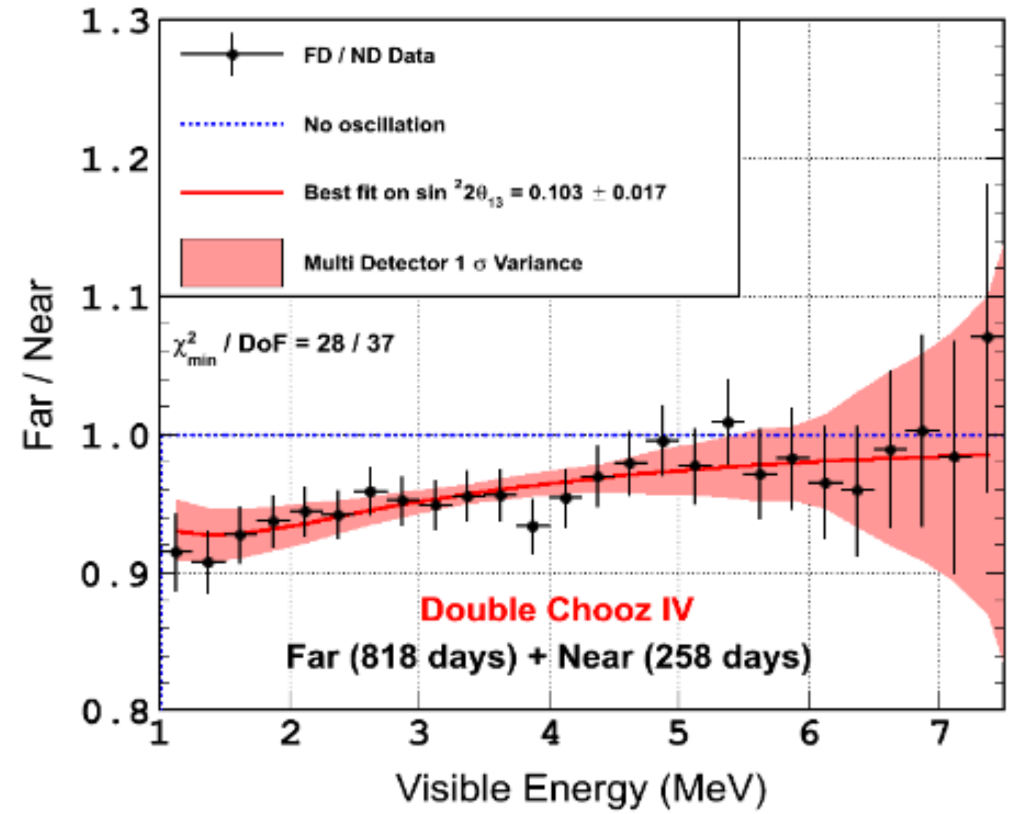
- Measure ν_μ disappearance and ν_e appearance
- Complicated measurement : a lot of **ambiguities**
- Can use matter effect to probe **mass hierarchy**
  ↳ L longer = more effect = less neutrinos
- Can switch from ν beam to $\overline{\nu}$ beam
  ↳ Probe **CP violation** phase

T2K, MINOS, NOVA, T2K, DUNE, T2KK

Reactor and Long Baseline experiments

Reactor





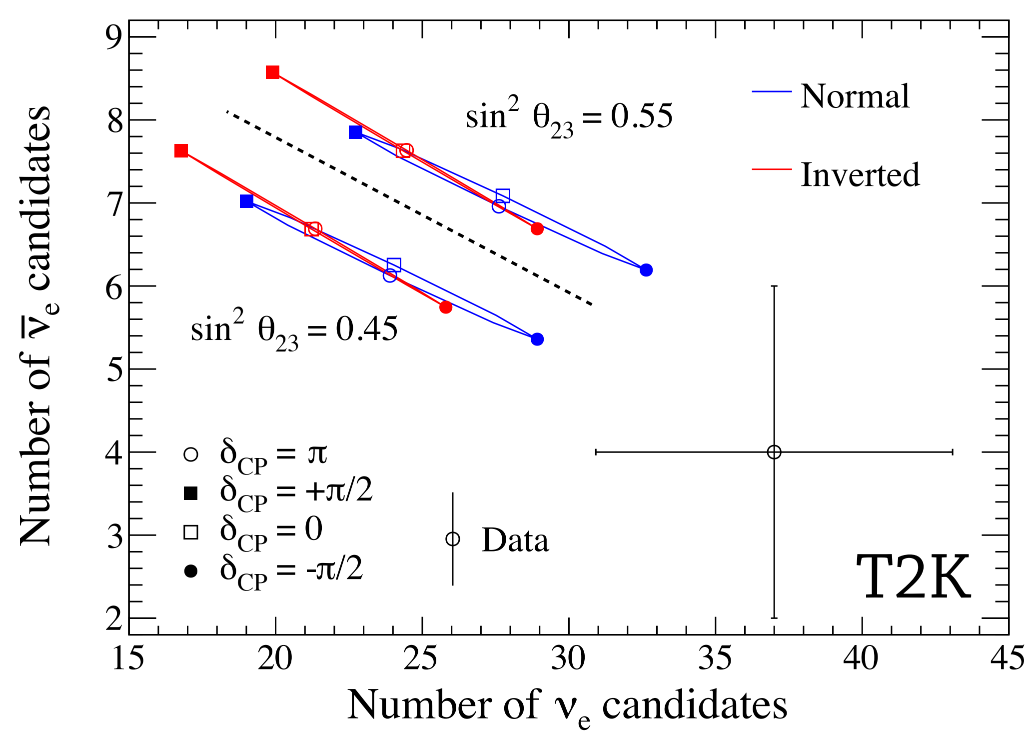
Best measurement of θ_{13} from $\overline{\nu}_e$ disappearance

Neutrino source → ***Near detector*** → ***Far detector***

At L/E before oscillations

At L/E for oscillations

Accelerator



Weakly prefers Normal hierarchy and $\delta_{CP} = -\pi/2$

Solving the oscillation mystery

One need:

- Enhanced effects → detectors placed further away to benefit from matter effects
- More statistics → More intense source, bigger and denser detectors

Solving the oscillation mystery

One need:

- Enhanced effects → detectors placed further away to benefit from matter effects
- More statistics → More intense source, bigger and denser detectors

- Non-funded project -

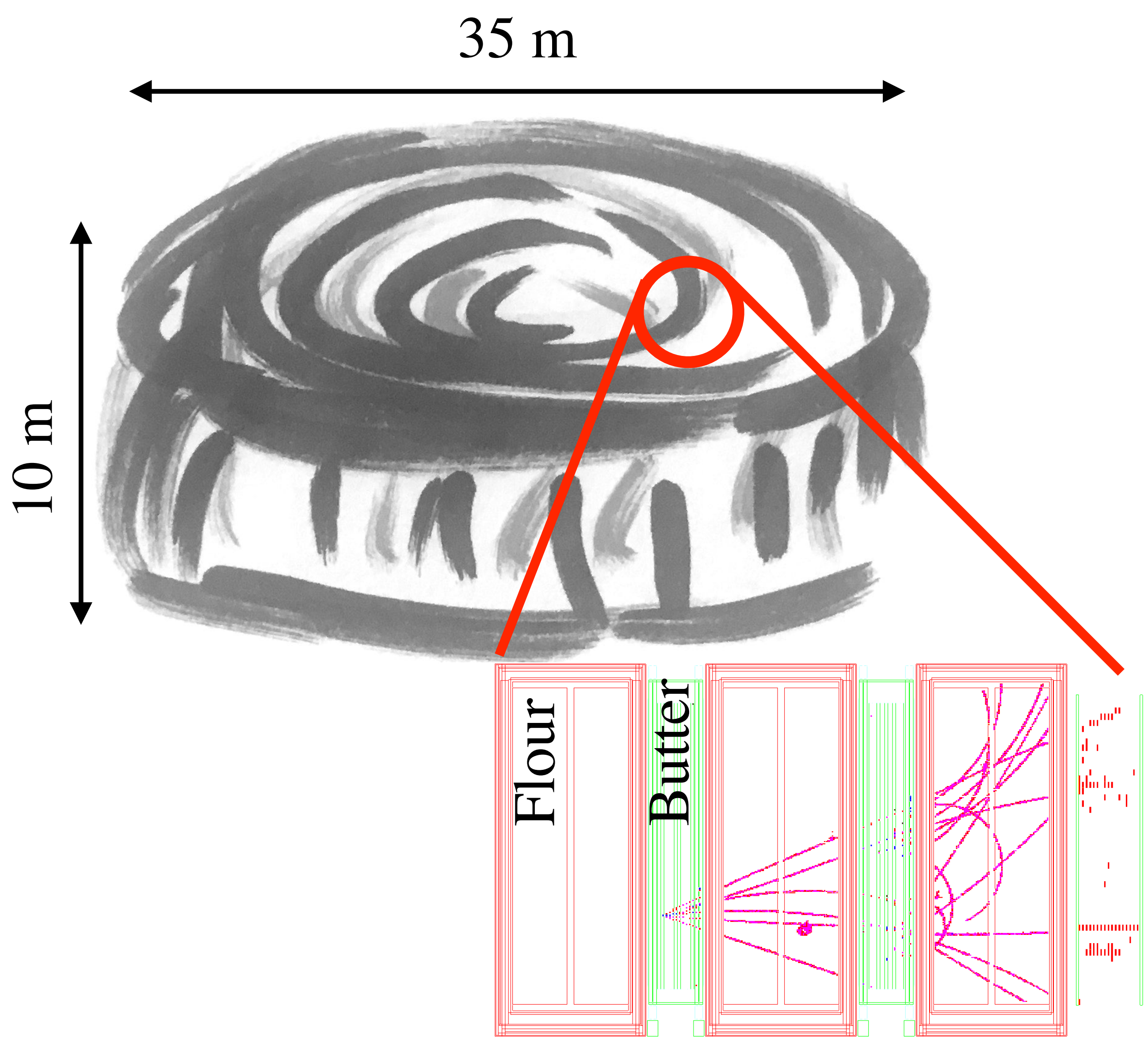


Fig. 2 Schematic view of the KANOE detector

KANOE

Kouign-Amman Neutrino Oscillation Experiment

- Pros -

- 12.5 kt of cooked flour/butter layers
- Excellent spatial & energy resolution

- Cons -

- Too much ν-interaction/s to be sustainable by current electronics
- So dense it could have distorted the space-time continuum
- Shifters could have eaten the detector

Solving the oscillation mystery

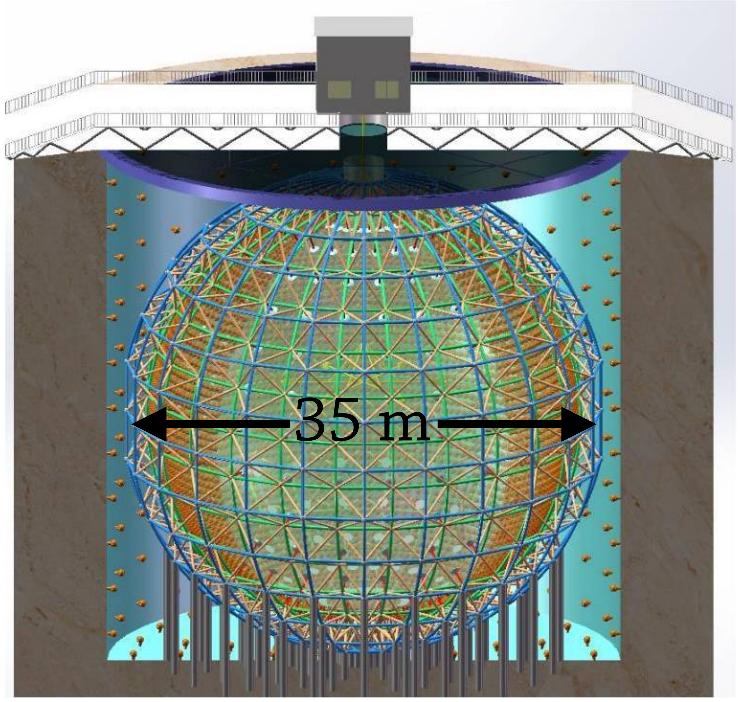
One need:

- Enhanced effects → detectors placed further away to benefit from matter effects
- More statistics → More intense source, bigger and denser detectors

☞ ***Etienne's Talk***

- Future projects -

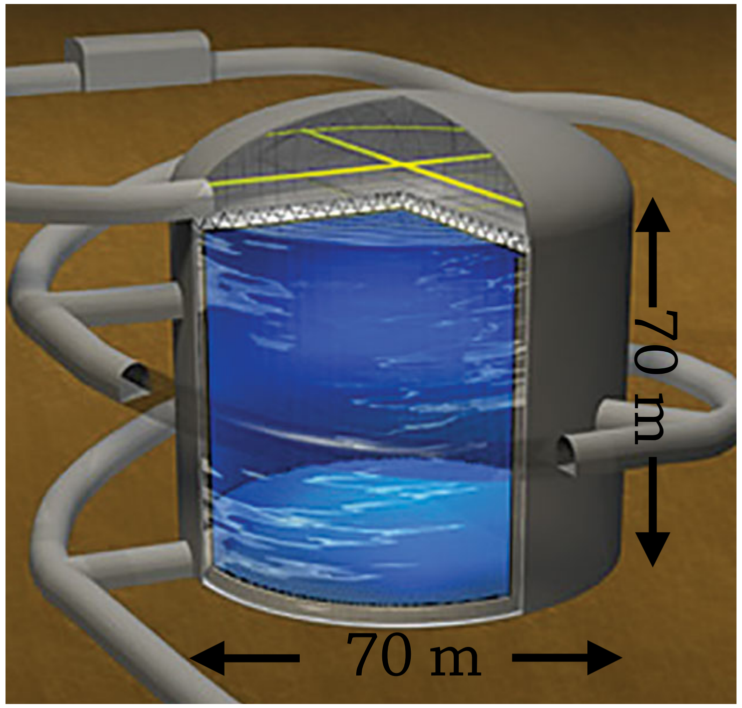
JUNO



- 20 kt liquid scintillator
- IBD technique
- $\bar{\nu}_e$ from reactors
- L ~ 50 km

Mass Hierarchy in 6 y

Hyper-Kamiokande

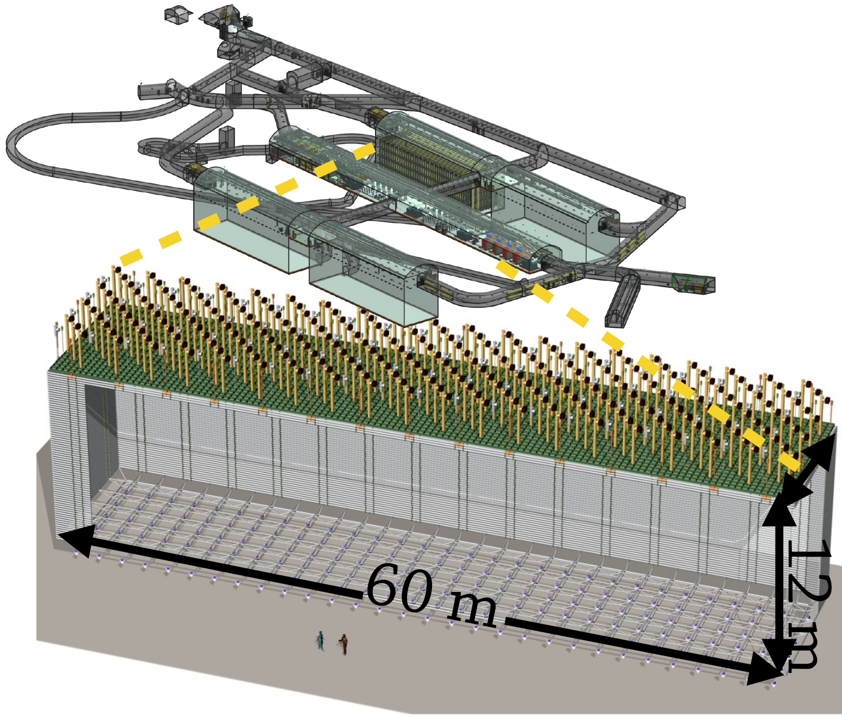


- 190 kt of pure water
- Cherenkov detector
- $\nu_\mu/\bar{\nu}_\mu$ from J-PARC
- L ~ 300 km (and 1100 km?)

Mass Hierarchy in 10 y

$\delta_{cp} \neq 0$ in 10~15 y

DUNE

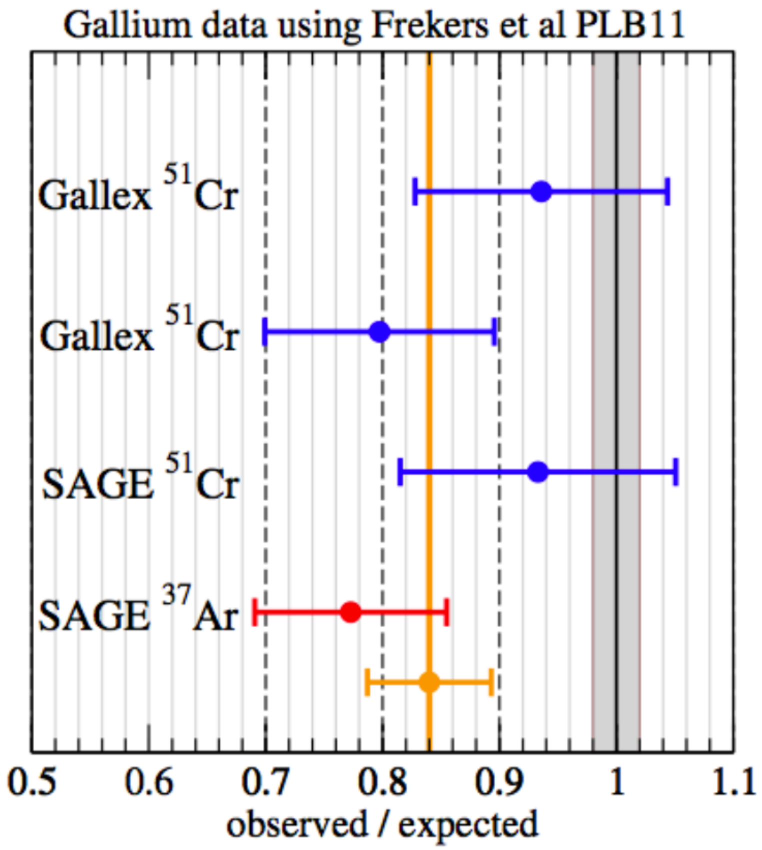


- 40 kt of liquid argon
- TPC detector
- $\nu_\mu/\bar{\nu}_\mu$ from FERMILAB
- L ~ 1300 km

Mass Hierarchy in 7 y

$\delta_{cp} \neq 0$ in 10~15 y

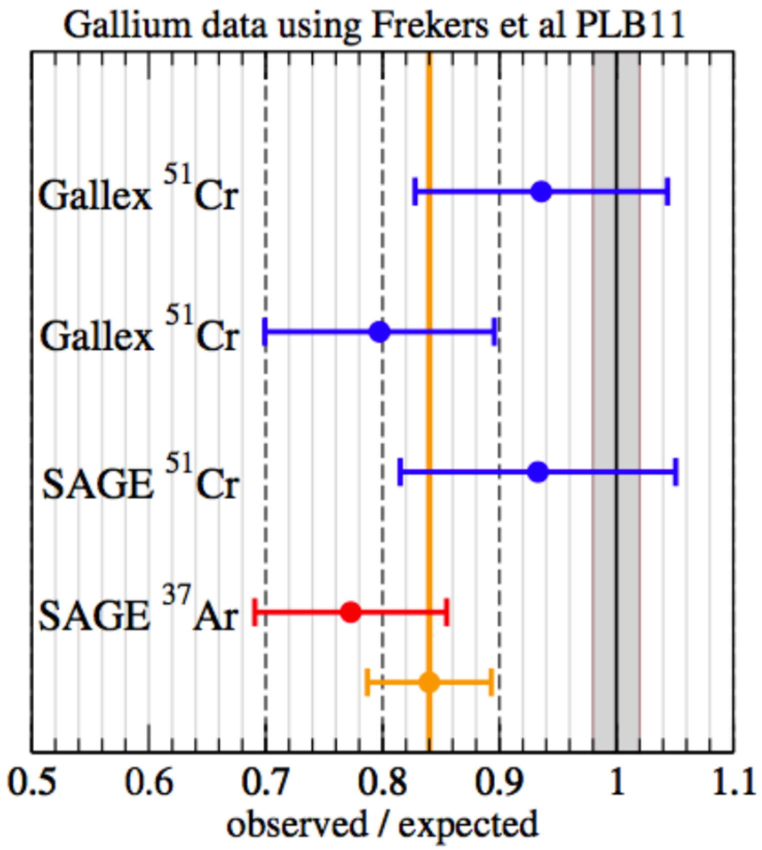
The return of the anomalies



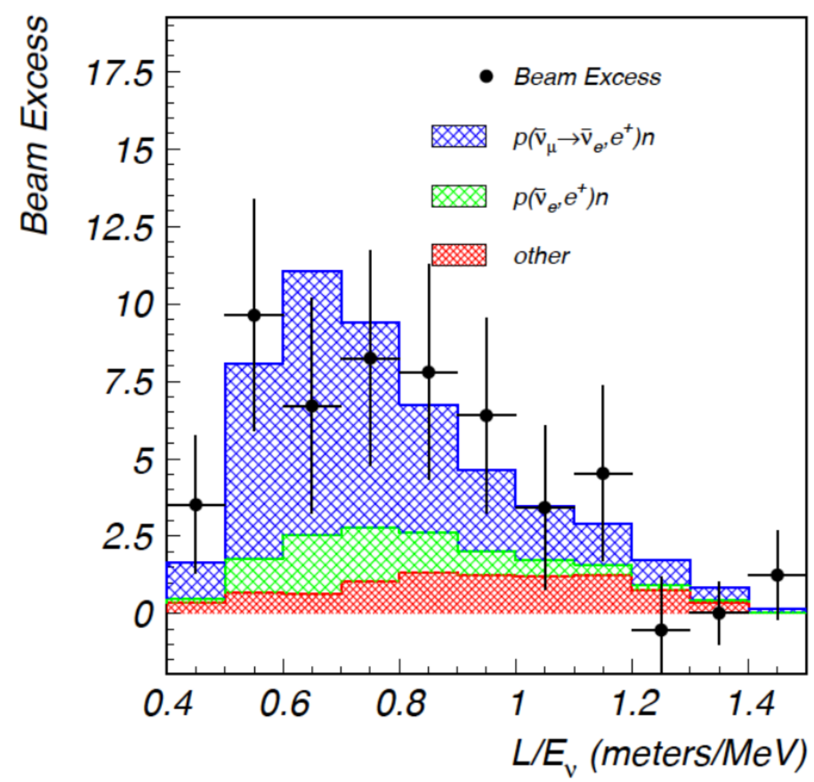
1. 'Gallium Anomaly' :

Calibration of Galium-based experiments with radioactive sources had **a 3σ deficit**

The return of the anomalies

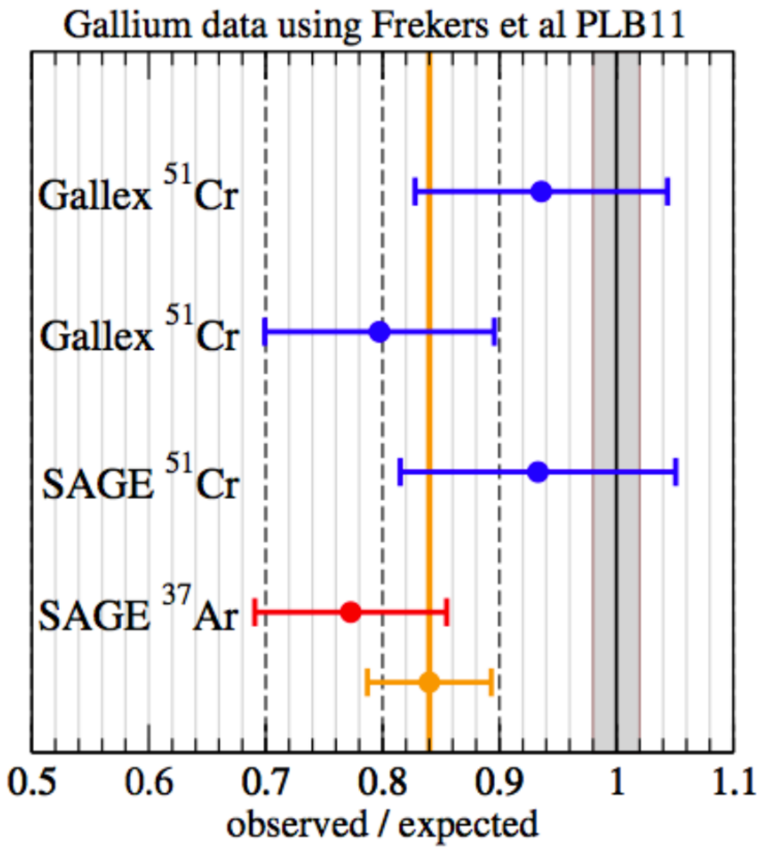


1. 'Gallium Anomaly' :
Calibration of Galium-based experiments with radioactive sources had **a 3σ deficit**

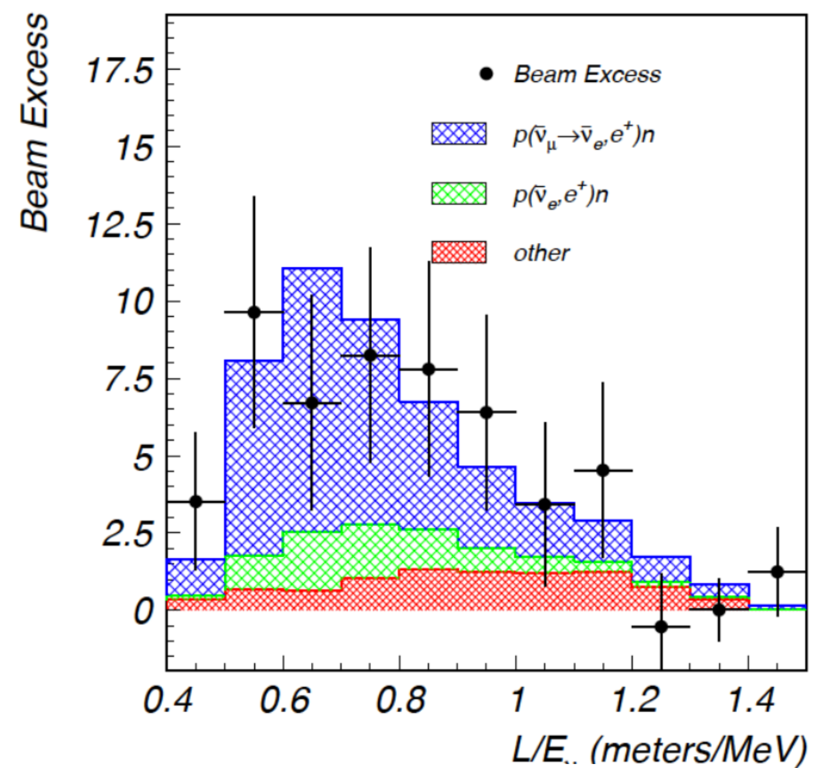


2. $\bar{\nu}_e$ excess seen at small distance in LSND, and confirmed by mini-BooNE (both with same technology). micro-BooNE constructed to resolve this anomaly

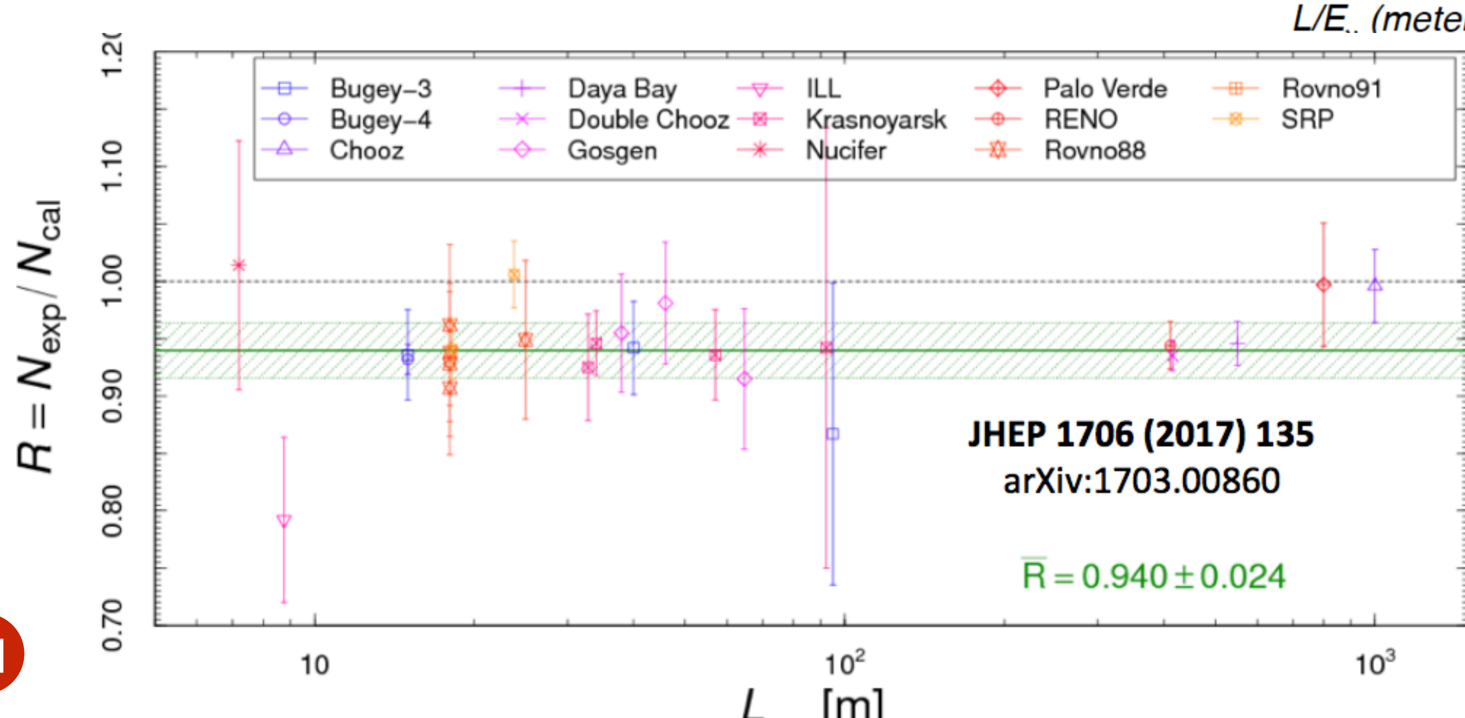
The return of the anomalies



1. 'Gallium Anomaly' :
Calibration of Galium-based experiments with radioactive sources had **a 3σ deficit**



2. $\bar{\nu}_e$ excess seen at small distance in LSND, and confirmed by mini-BooNE (both with same technology). micro-BooNE constructed to resolve this anomaly



3. 'Reactor Anomaly' :
A revised reactor $\bar{\nu}$e flux analysis showed that all past ν experiments had a **~6% deficit** at small distances (3σ)

Solving the anomalies

All these anomalies could be explained by the presence of a **4th neutrino** which would be a **sterile**.

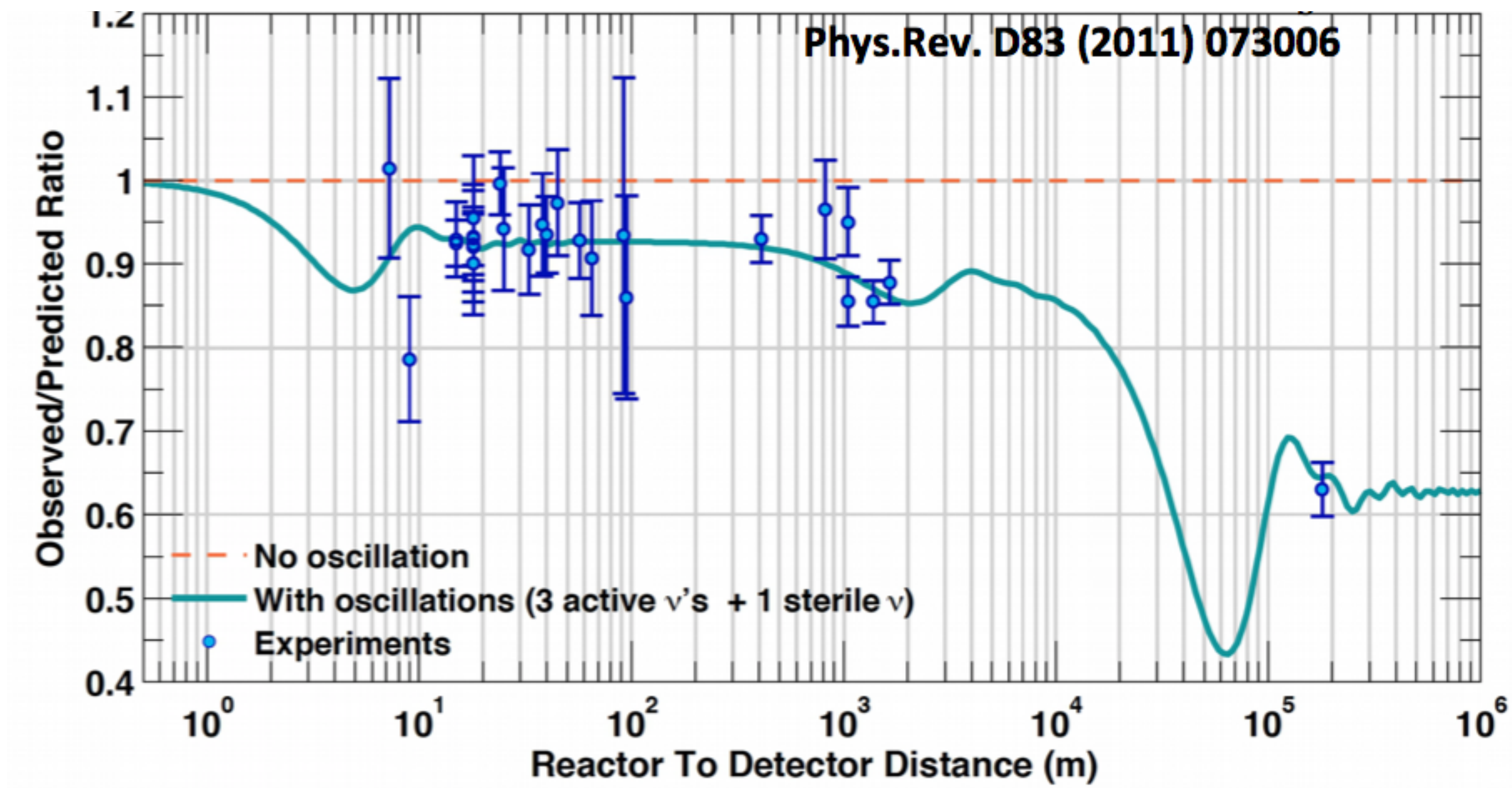
↳ Not even the weak interaction : this neutrino would be invisible

↳ But all 4 neutrinos could oscillate within each others

→ ***New mass splitting and new mixing angle***

Best fit parameters of reactor anomaly:

$\Delta m^2 \sim 2\ eV^2$
$\sin^2(2\theta) \sim 0.15$
$L_{osc} \sim$ few m



Many **oscillography** experiments ongoing, located few m from a nuclear core

☞ ***Loïc's Talk***

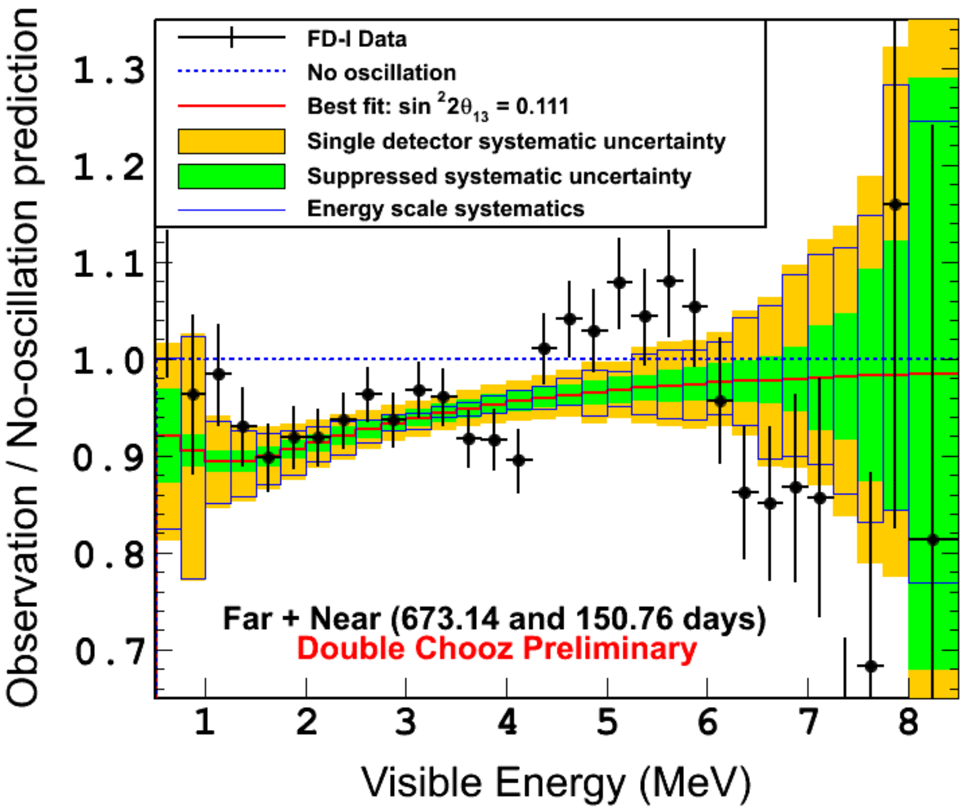
STEREO, SOLID, BAKSAN, …

… But is there an anomaly in the first place ?

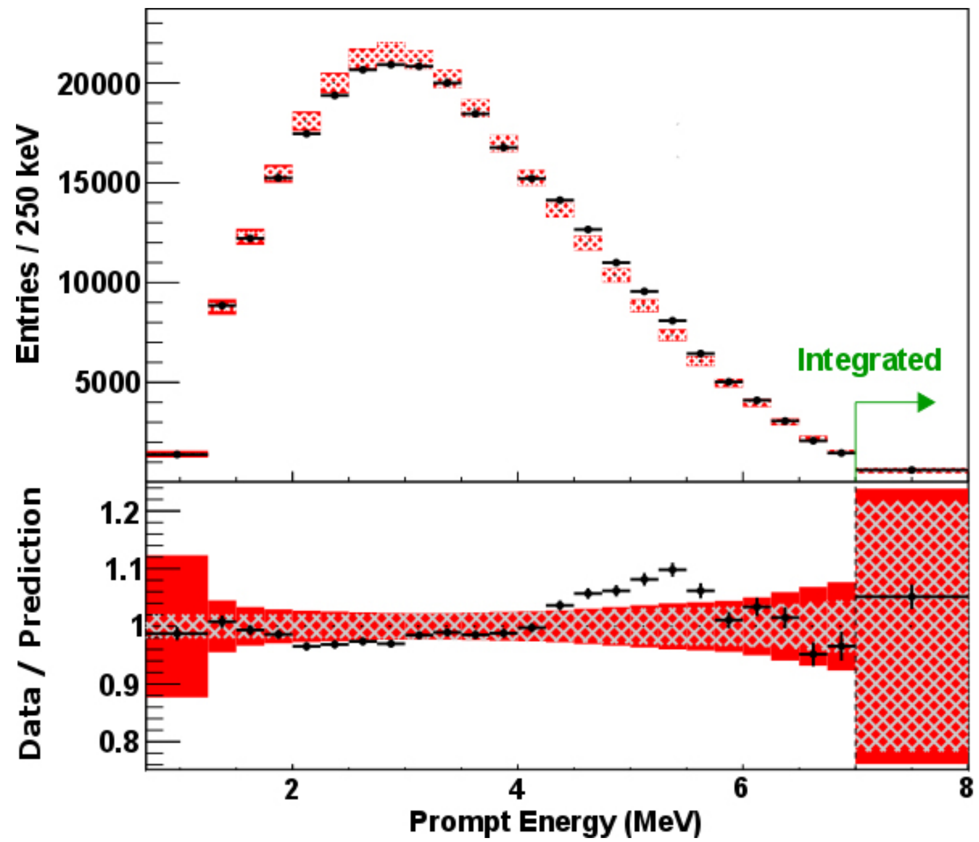
Do we really understand the reactor neutrino flux ?

Many reactor-based experiments have seen the "***5 MeV bump***"

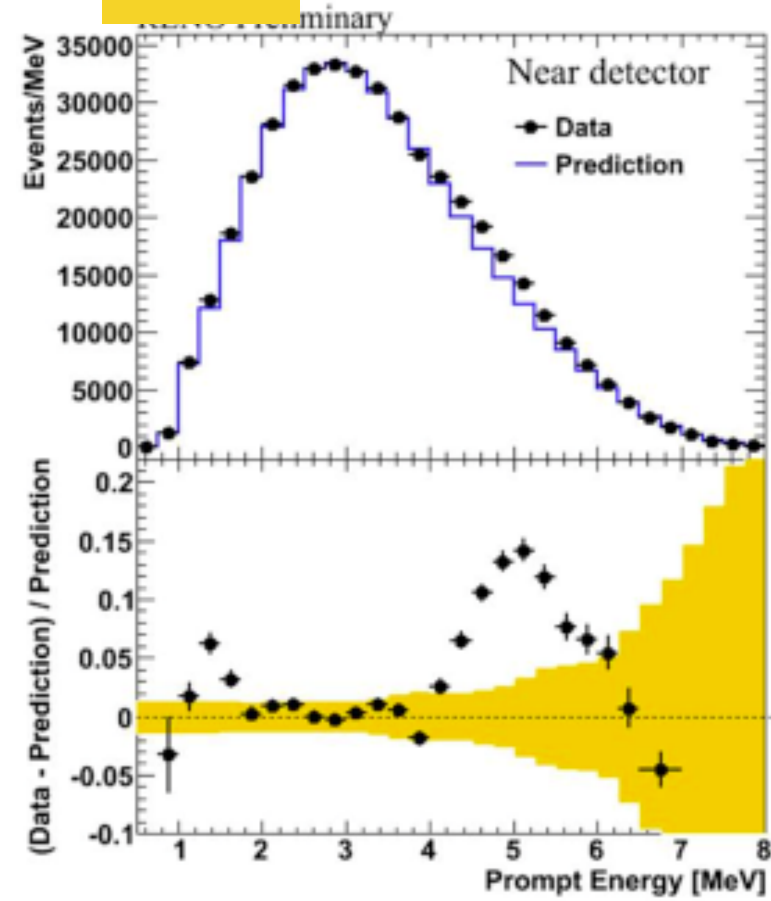
Double Chooz

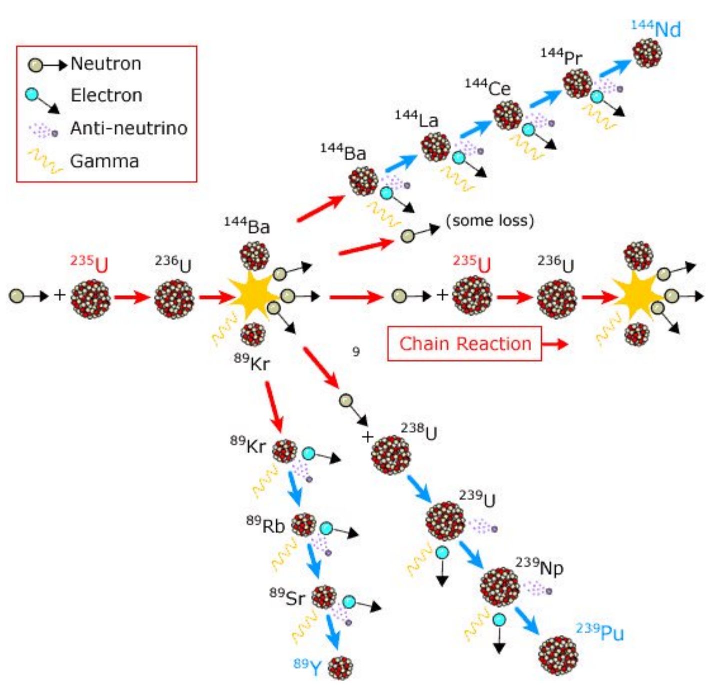


Daya Bay



RENO





Prediction of reactor $\overline{\nu}_e$ flux is ***complicated*** : not all sub-β branches are well known

☞ ***Lorenzo's Talk***

Neutrino mass measurement

Indirect constraints

Cosmological
observations
(Plank, CMB, SN, ...)

→ SN1987a gave the 1st limit:
$m_{\overline{\nu}_e} \leq 5.7$ eV at 95% CL

Current limits :
$\sum m_j \lesssim (0.3 - 1.3)$ eV 95% C.L.

Neutrino mass measurement

Indirect constraints

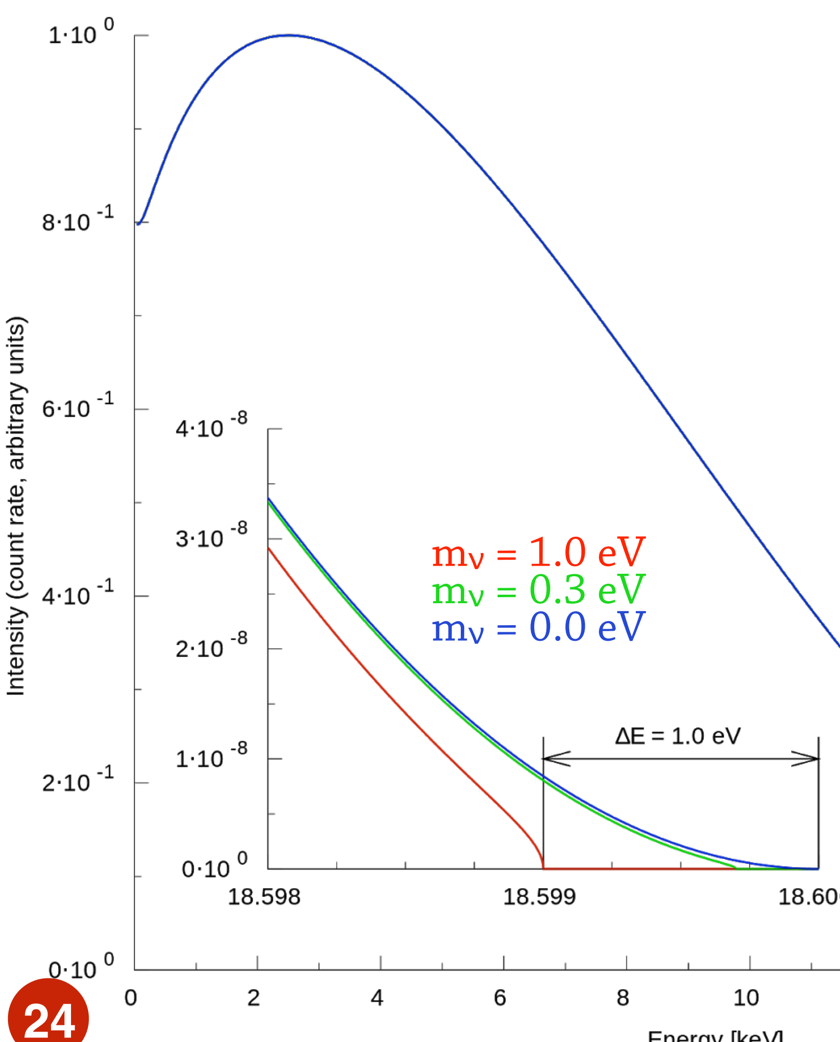
Cosmological
observations
(Plank, CMB, SN, ...)

→ SN1987a gave the 1st limit:
$m_{\bar{\nu}_e} \leq 5.7$ eV at 95% CL

Current limits :
$\Sigma m_j \lesssim (0.3 - 1.3)$ eV 95% C.L.

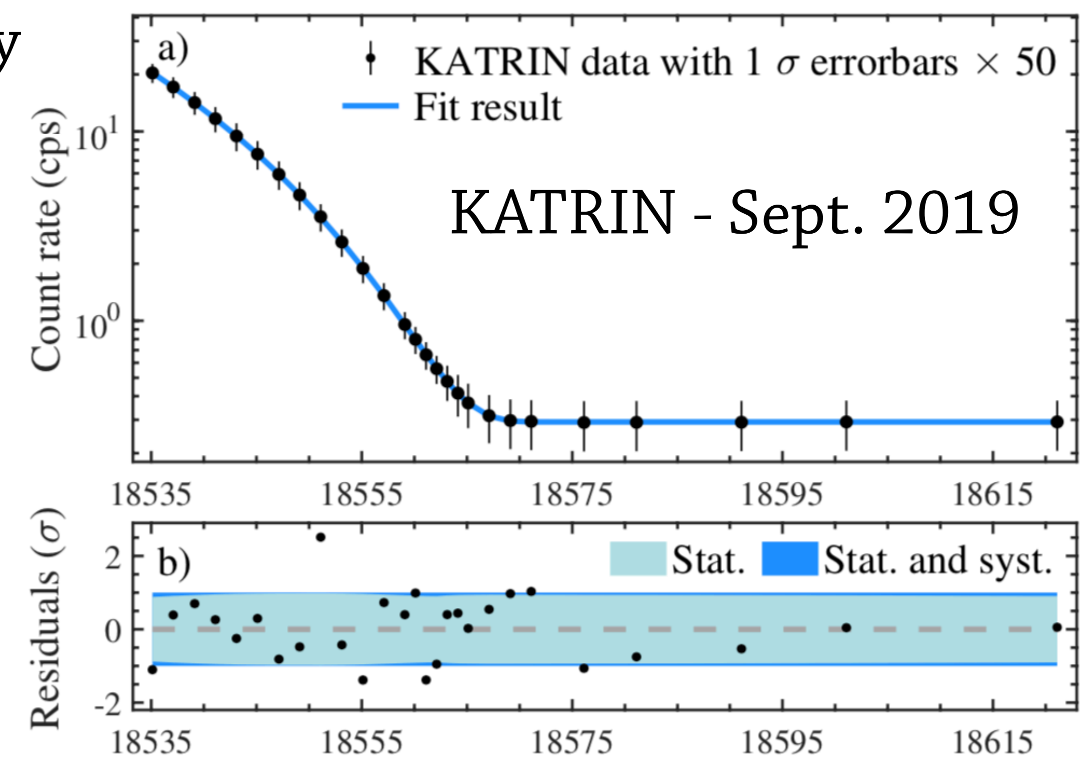
Direct constraints

Look at the **end-point** of the β spectrum
↳ rare cases were the e- takes most of the available energy



KATRIN, TROITSK

Only a fraction
of $2{\times}10^{-13}$ events
in the last eV



Current limit : $m_{\bar{\nu}_e} \leq 1.1$ eV at 90% CL
sensitivity at 0.2 eV

Neutrino mass : how do they get it ?

- The **Dirac** way

  Through Higgs coupling

  Need a sterile right handed neutrino

  Why are neutrino so light ?

$$\mathcal{L}^{D}_{mass} = -m_D(\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R)$$

$$m_D = \frac{v}{\sqrt{2}} Y_v \leftarrow \sim 10^{-12}$$

- The **Majorana** way

  No distinction between ν and $\bar{\nu}$

  Mass given through seesaw mechanism

  Need massive neutrinos

$$\nu_R = C\bar{\nu}_L^T = \nu_L^C$$

$$m = \frac{m_D^2}{m_R} \quad \begin{matrix} \leftarrow \text{Dirac term} \\ \leftarrow \text{Very big} \end{matrix}$$

Neutrino mass : how do they get it ?

- The **Dirac** way

  Through Higgs coupling

  Need a sterile right handed neutrino

  Why are neutrino so light ?

$$\mathcal{L}^D_{mass} = -m_D(\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R)$$

$$m_D = \frac{v}{\sqrt{2}} Y_v \leftarrow \sim 10^{-12}$$

- The **Majorana** way

  No distinction between ν and $\bar{\nu}$

  Mass given through seesaw mechanism

  Need massive neutrinos

$$\nu_R = C\bar{\nu}_L^T = \nu_L^C$$

$$m = \frac{m_D^2}{m_R} \begin{array}{l}\leftarrow \text{Dirac term} \\ \leftarrow \text{Very big}\end{array}$$

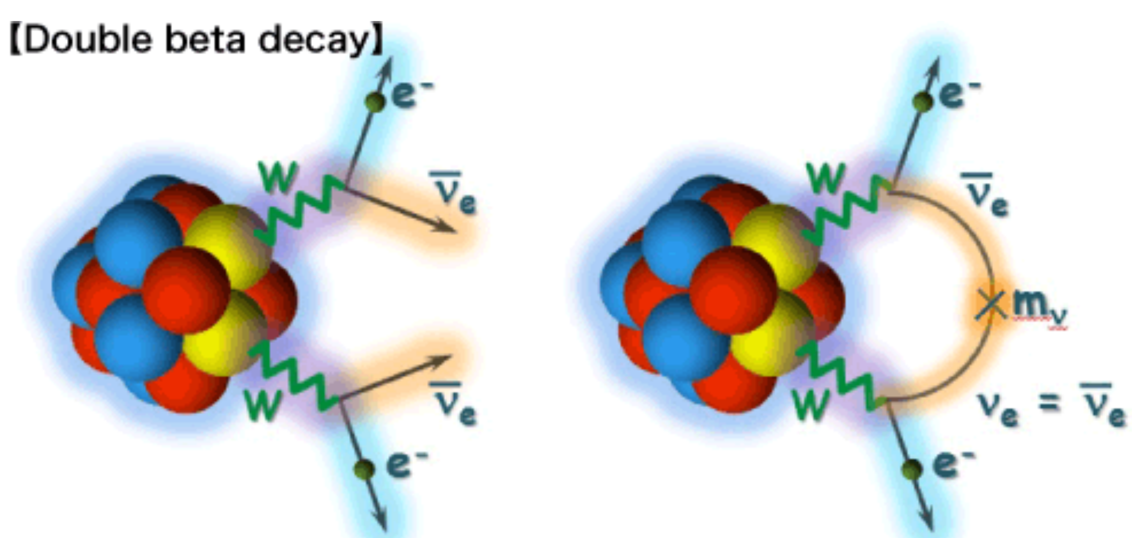
→ ***Only one way to prove that neutrino are Majorana particles :***

Double β decay with **no** neutrino emission

- ββ2ν is very rare (half life ~10^{18} - 10^{24} years)
- ββ0ν is **forbidden** in SM

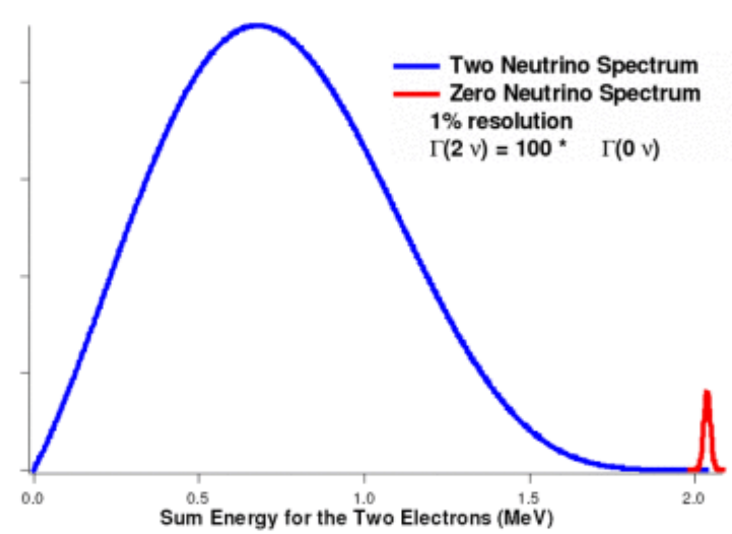
↳lepton number violated by 2 units

SuperNEMO, CUORE, SNO+



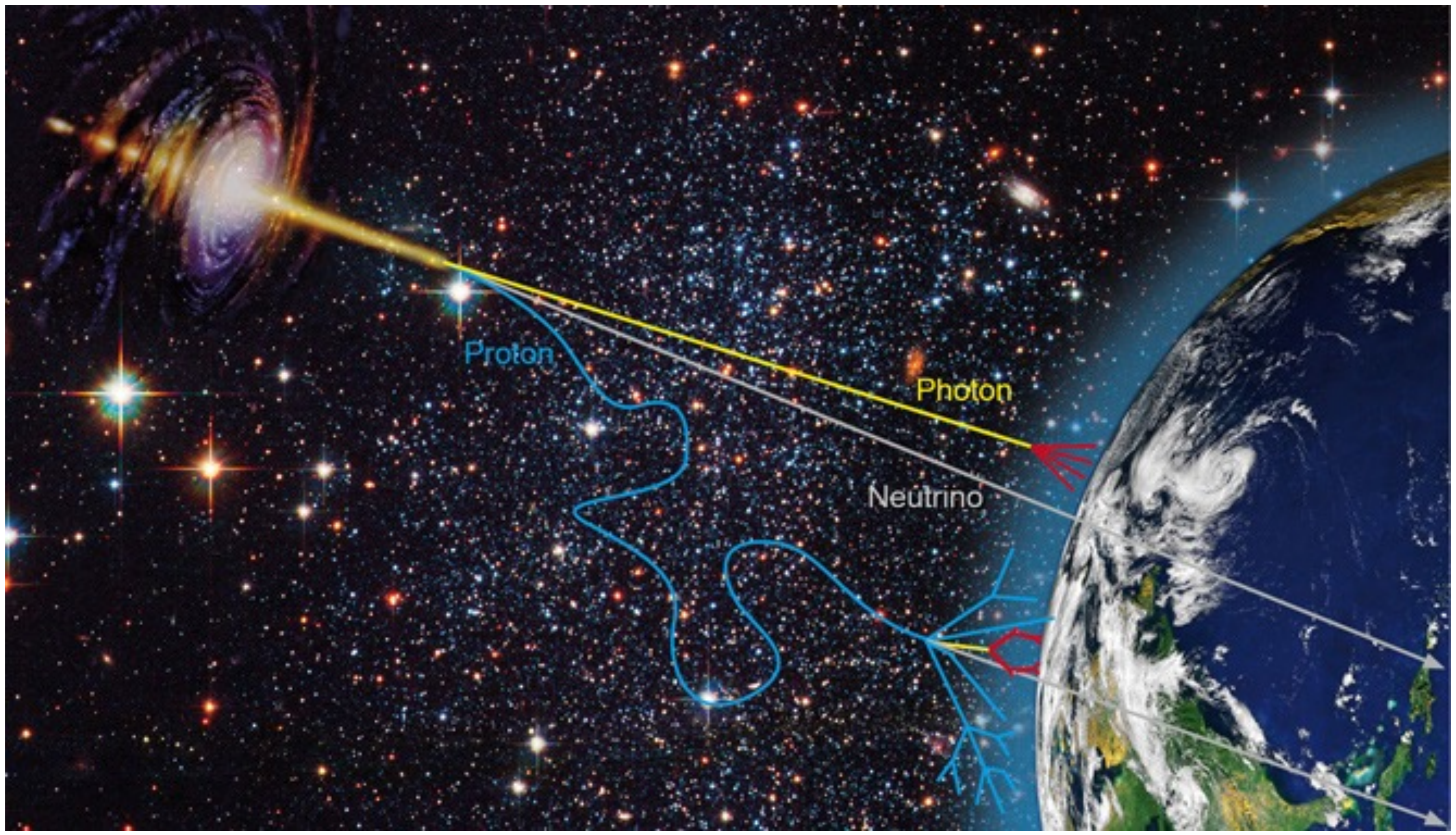
Double beta decay which emits anti-neutrinos

Neutrinoless double beta decay



Very clean experimental signature

Neutrino astronomy : today

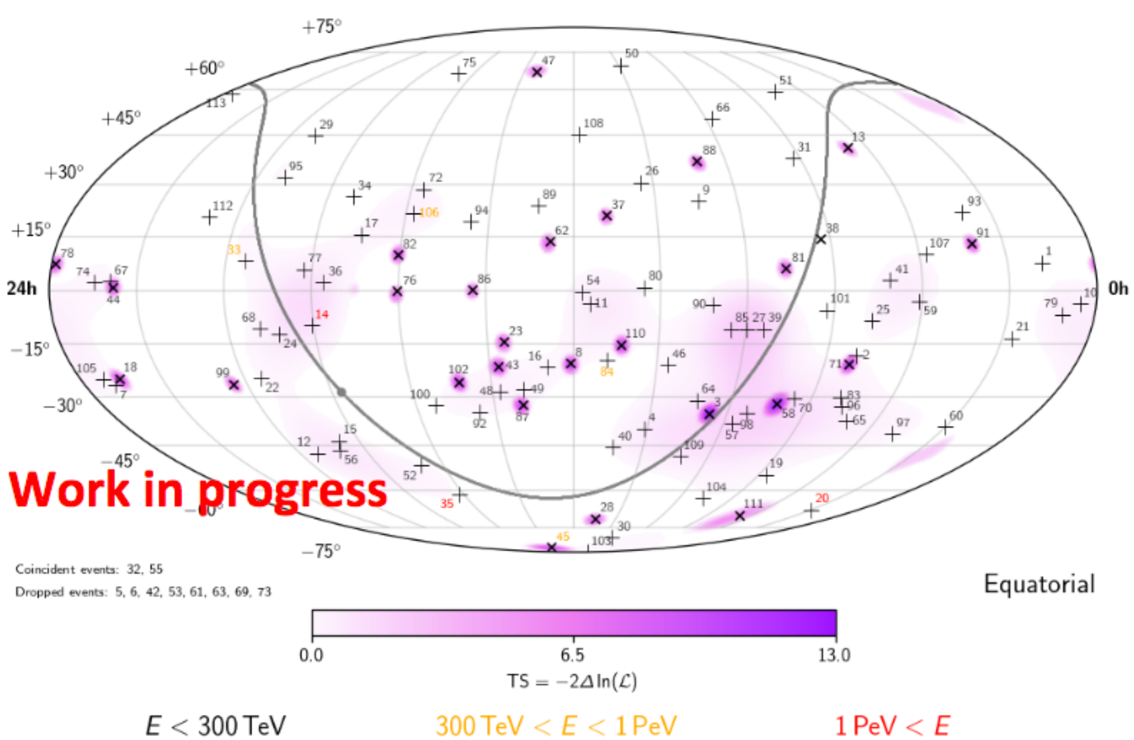


Pros

- Unlike protons & gammas, neutrinos **points to their sources**
- Can probe the inside of the structure
- **No GZK threshold** : can probe far away objects

Cons

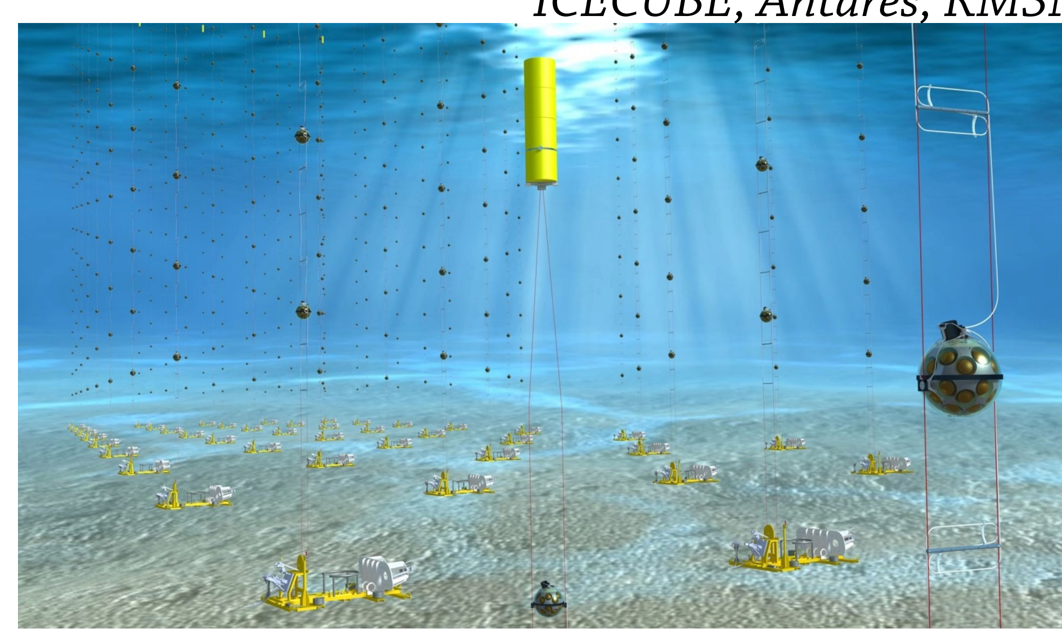
- Low statistics



No specific source found yet

Large (~km³) detector underground using sea or ice as target/detector

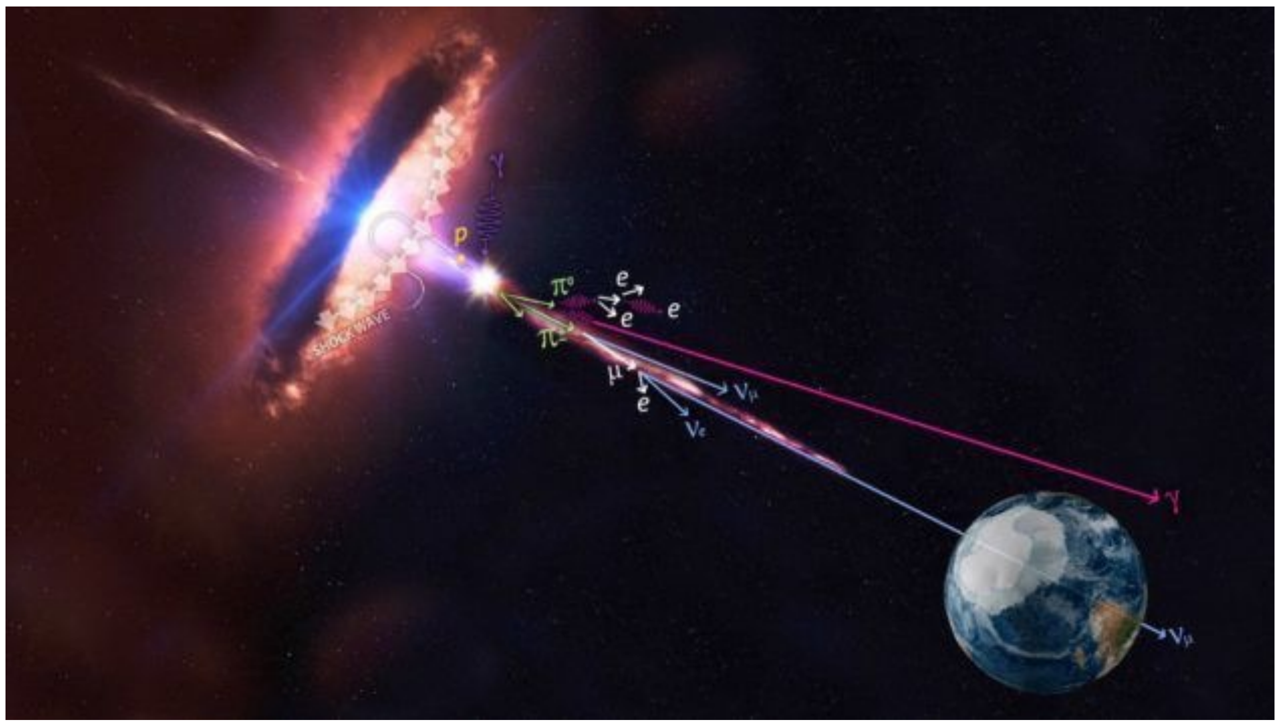
ICECUBE, Antares, KM3NET

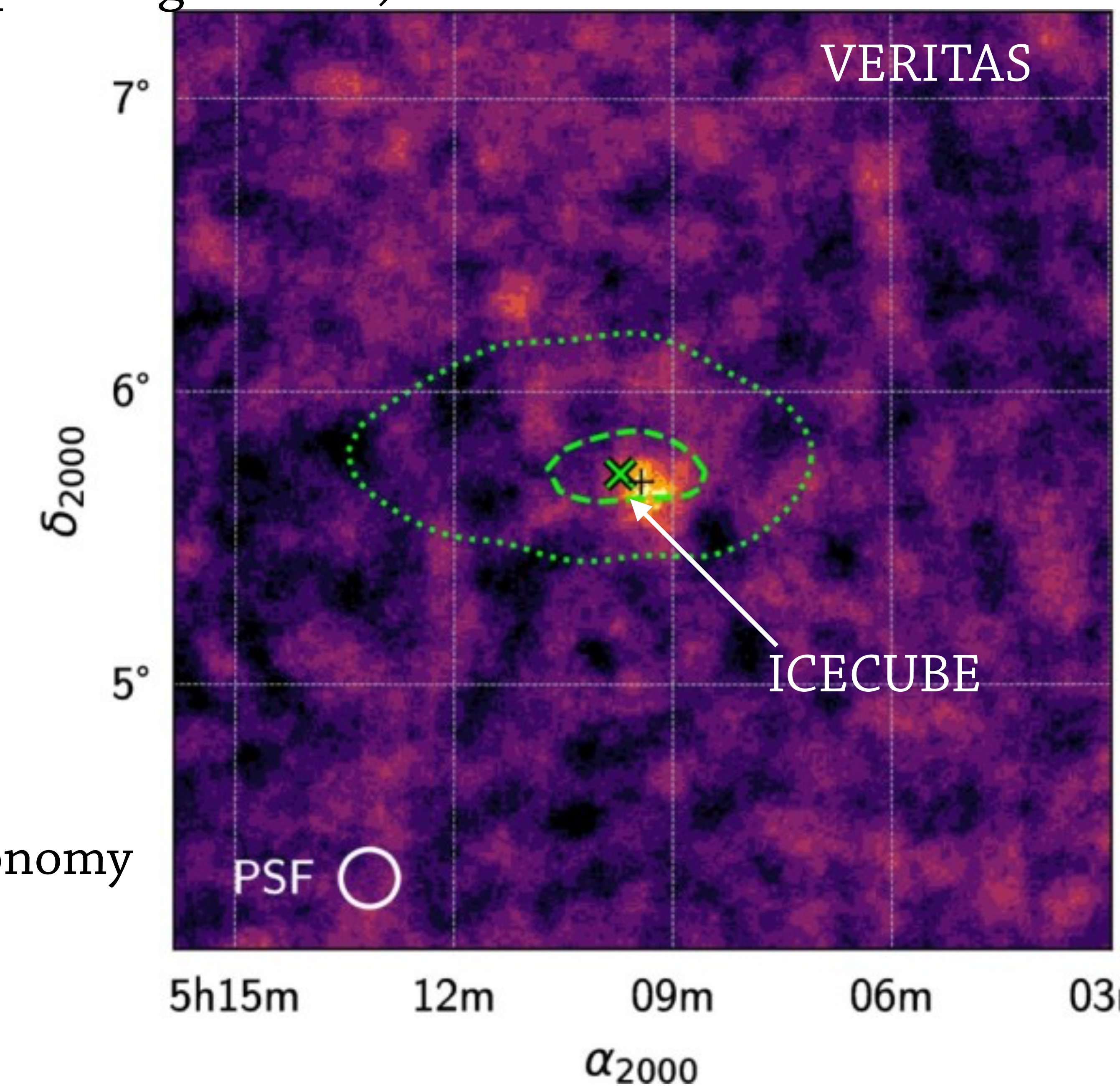


Neutrino astronomy : tomorrow

On September 22nd 2017 : **Simultaneous** light & neutrino detection from the TXS 0506+056 blazar (3σ, E_ν = 290 TeV)

(blazar = Active Galactic Nucleus with one jet pointing to earth)





- 1st case of planned **multi-messenger** astronomy
- Confirmed that blazar emits neutrinos

Summary - Things we are entirely sure about ν

Summary - Things we are entirely sure about ν

- They exist

Summary - Things we are entirely sure about ν

- They exist

- Neutrino physicist are super cool
  ↳ Experimental evidences :

High SWAG density

Bright smile

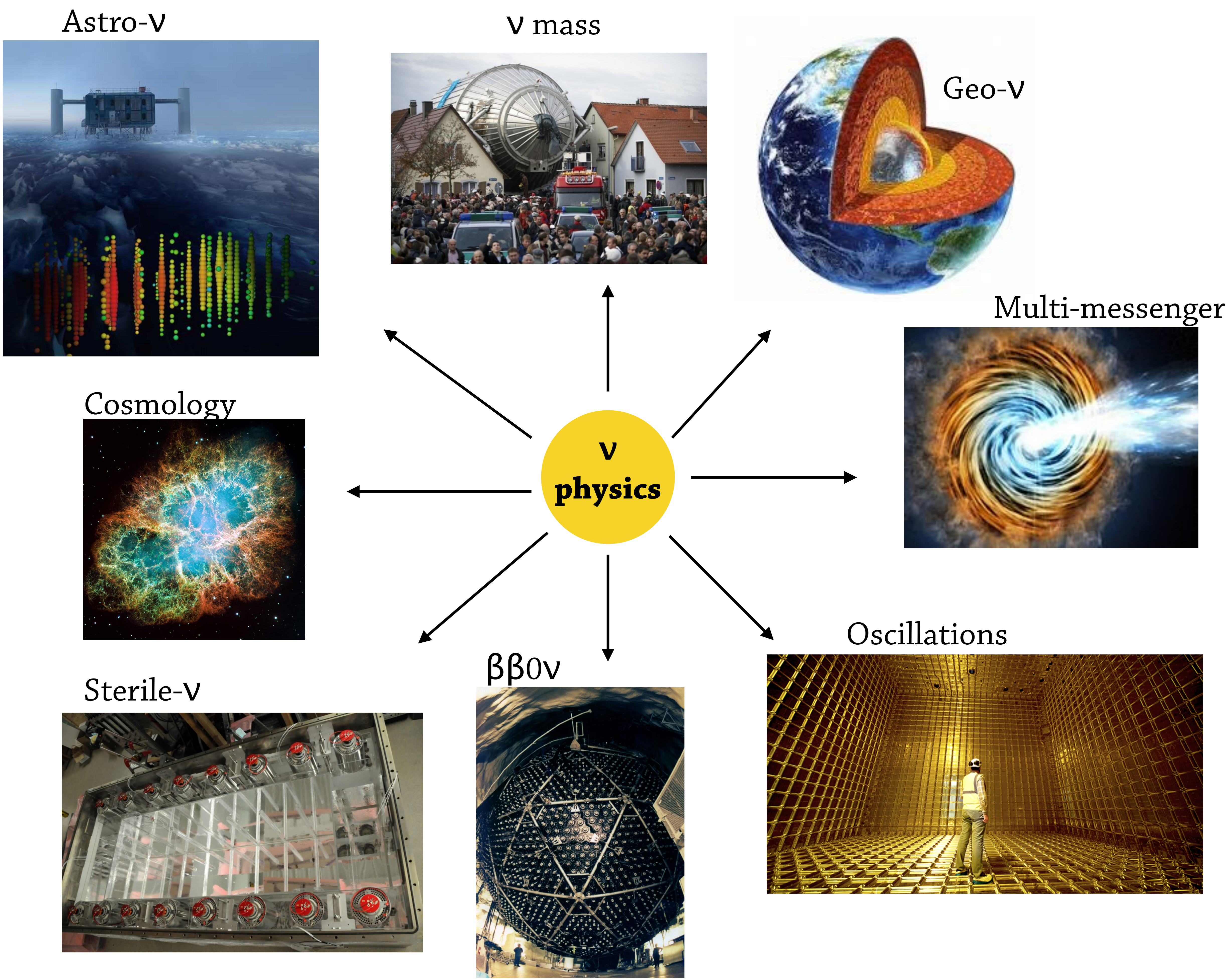
Natural minty breath

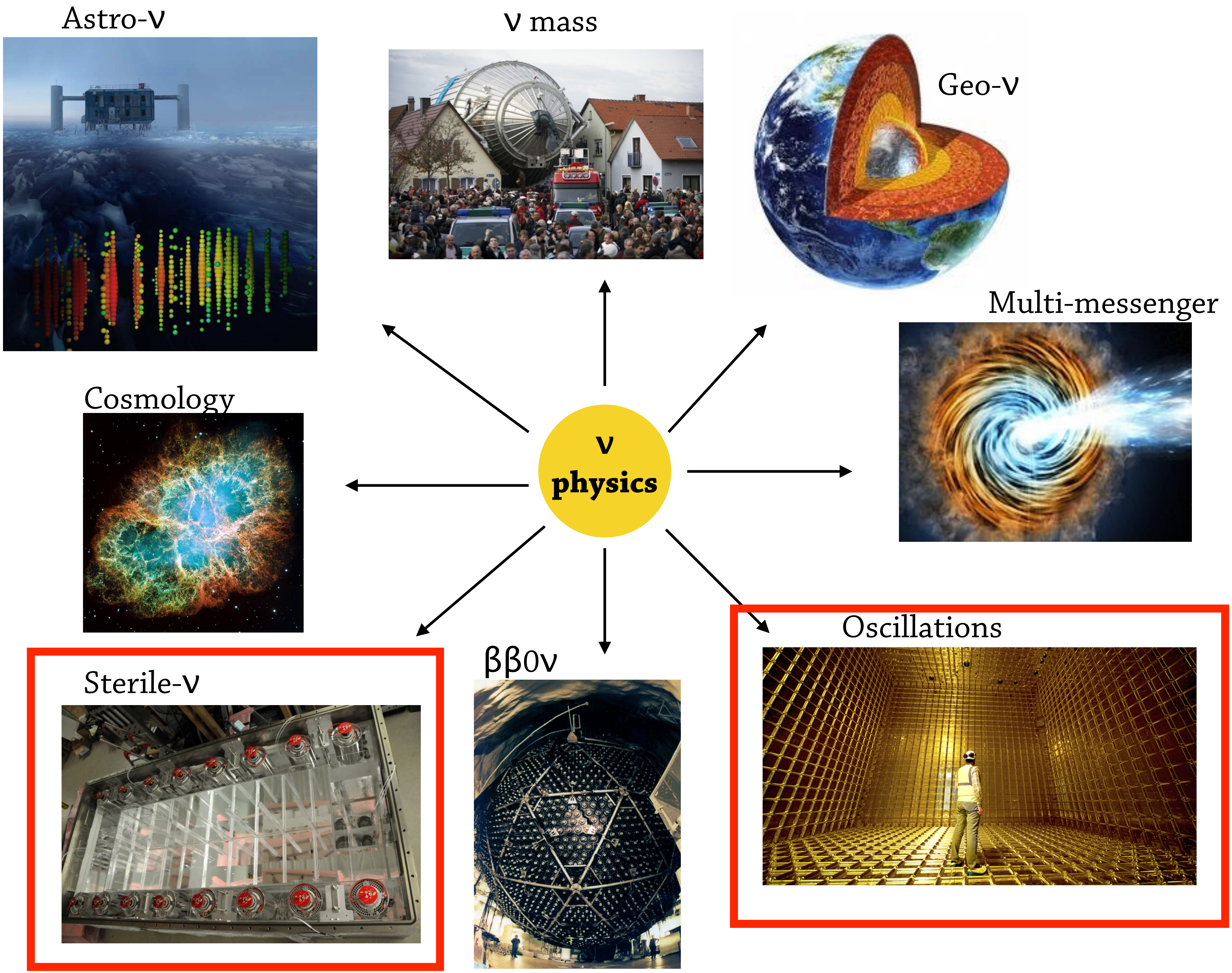
Smart

Fun

Summary - Things we are not yet sure about ν

- How many are they
- How ‘heavy’ they are
- Who’s the heaviest
- Why they are so light
- How they acquired mass
- How precisely they oscillate from one flavor to another
- If neutrino and anti-neutrino behave the same way
- ...


Astro-ν
ν mass
Geo-ν
Multi-messenger
Cosmology
ν
physics
Sterile-ν
ββ0ν
Oscillations


Astro-ν
ν mass
Geo-ν
Multi-messenger
Cosmology
ν
physics
Oscillations
Sterile-ν
ββ0ν