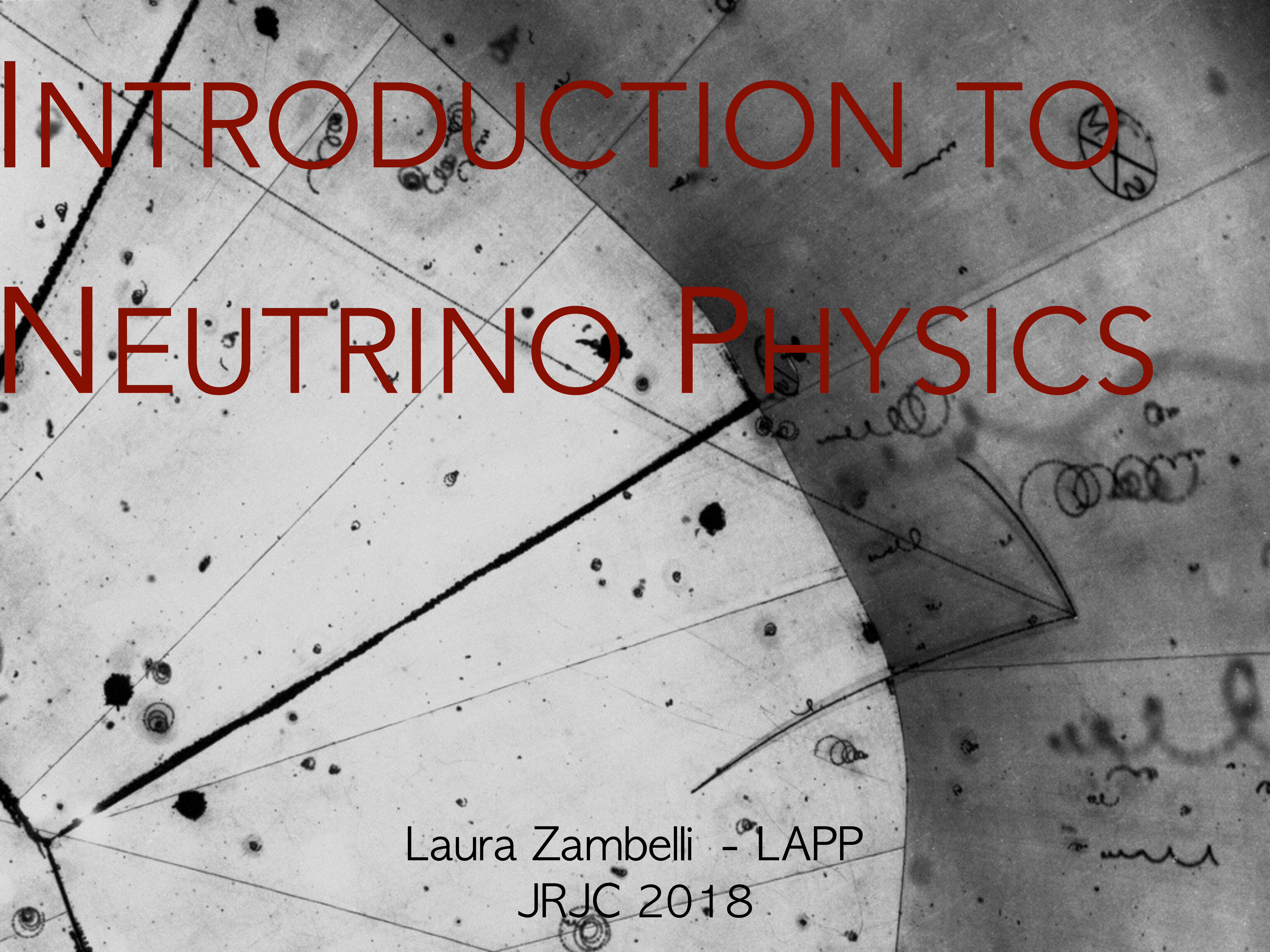
Introduction to Neutrino Physics



Laura Zambelli - LAPP

JRJC 2018

THINGS YOU NEED TO KNOW ABOUT NEUTRINOS

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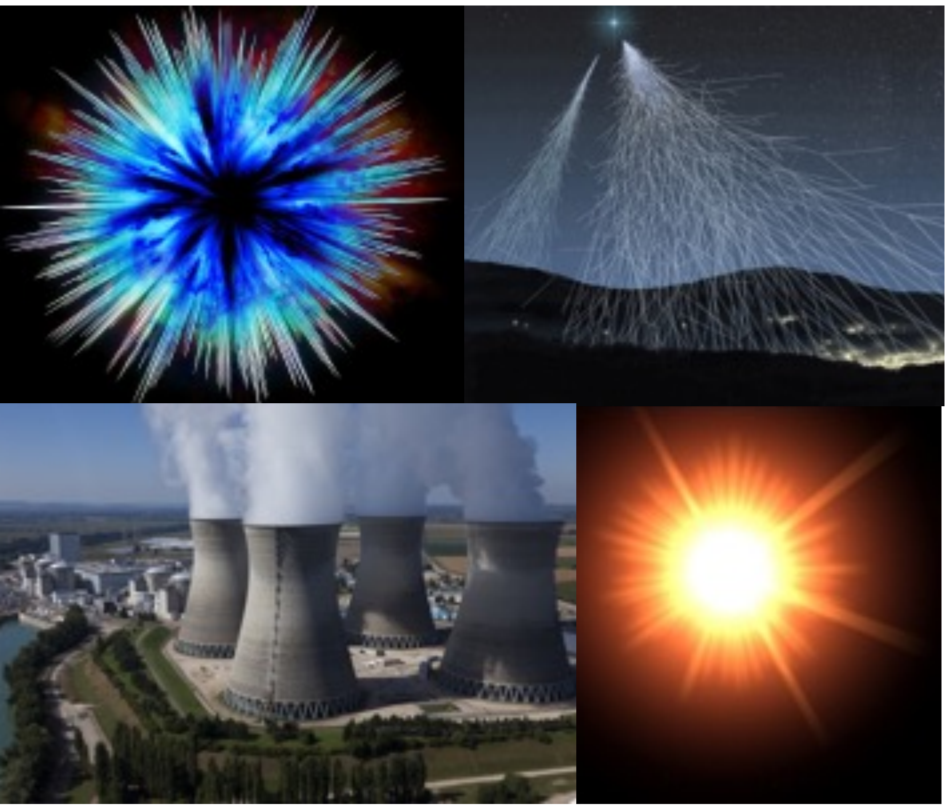
They're everywhere



$\sim 65\times10^{9}\ \nu/\mathrm{cm}^2/\mathrm{s}$

THINGS YOU NEED TO KNOW ABOUT NEUTRINOS

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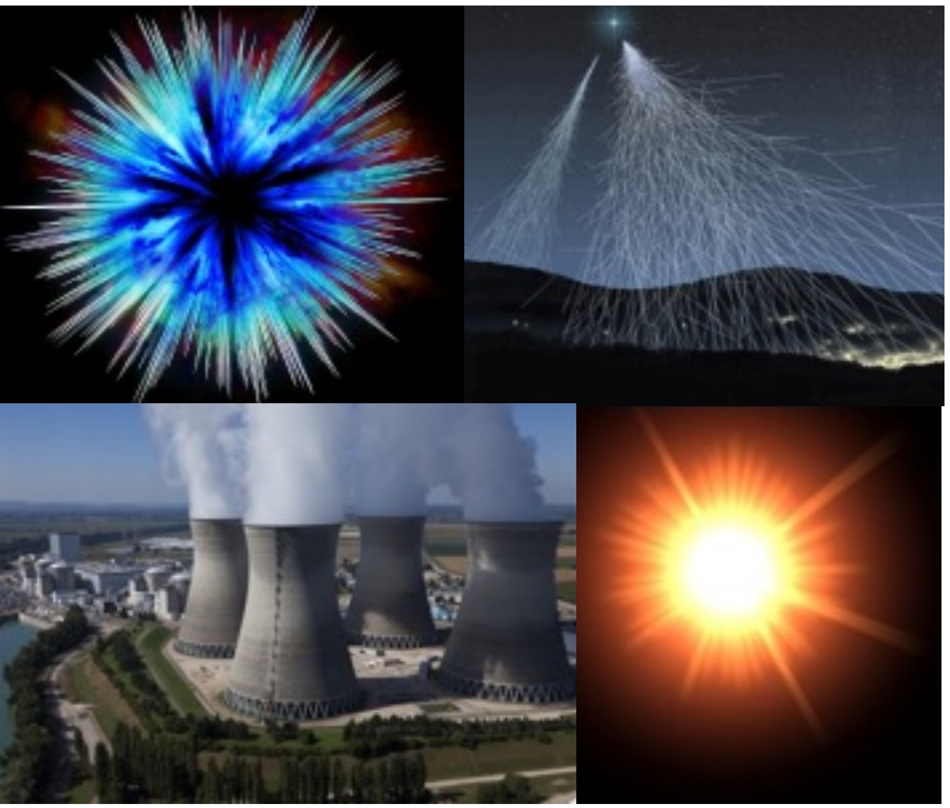

~65×10^{9} $\nu/cm^{2}/s$

They're tiny *(SPOILER)*

At eV scale, or below

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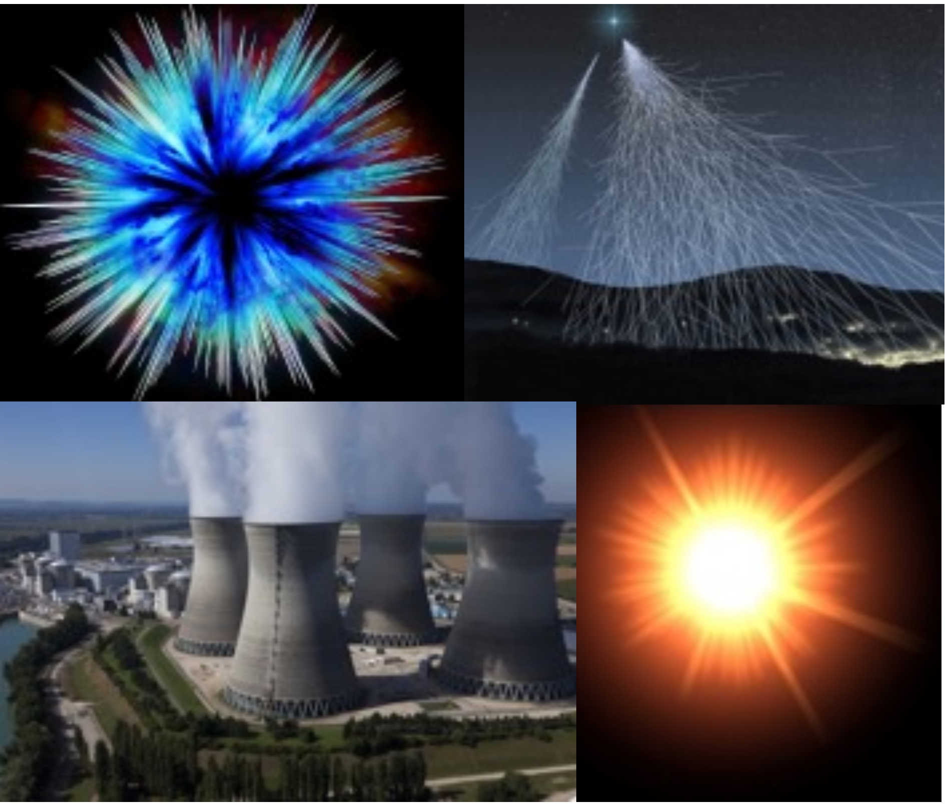


~65×10⁹ ν/cm²/s

They're tiny *(SPOILER)*

At eV scale, or below

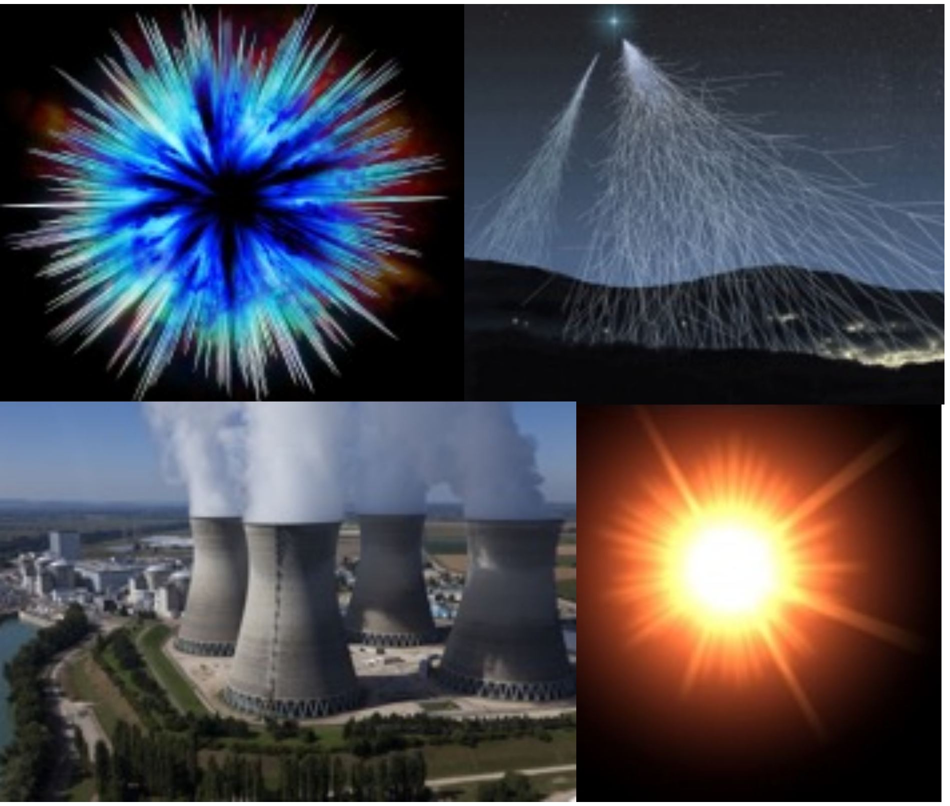
They interact weakly with matter

Quoting Sabrina, yesterday:

> ▸ Neutrinos: weak interaction
> → good luck with that

THINGS YOU NEED TO KNOW ABOUT NEUTRINOS

They're everywhere



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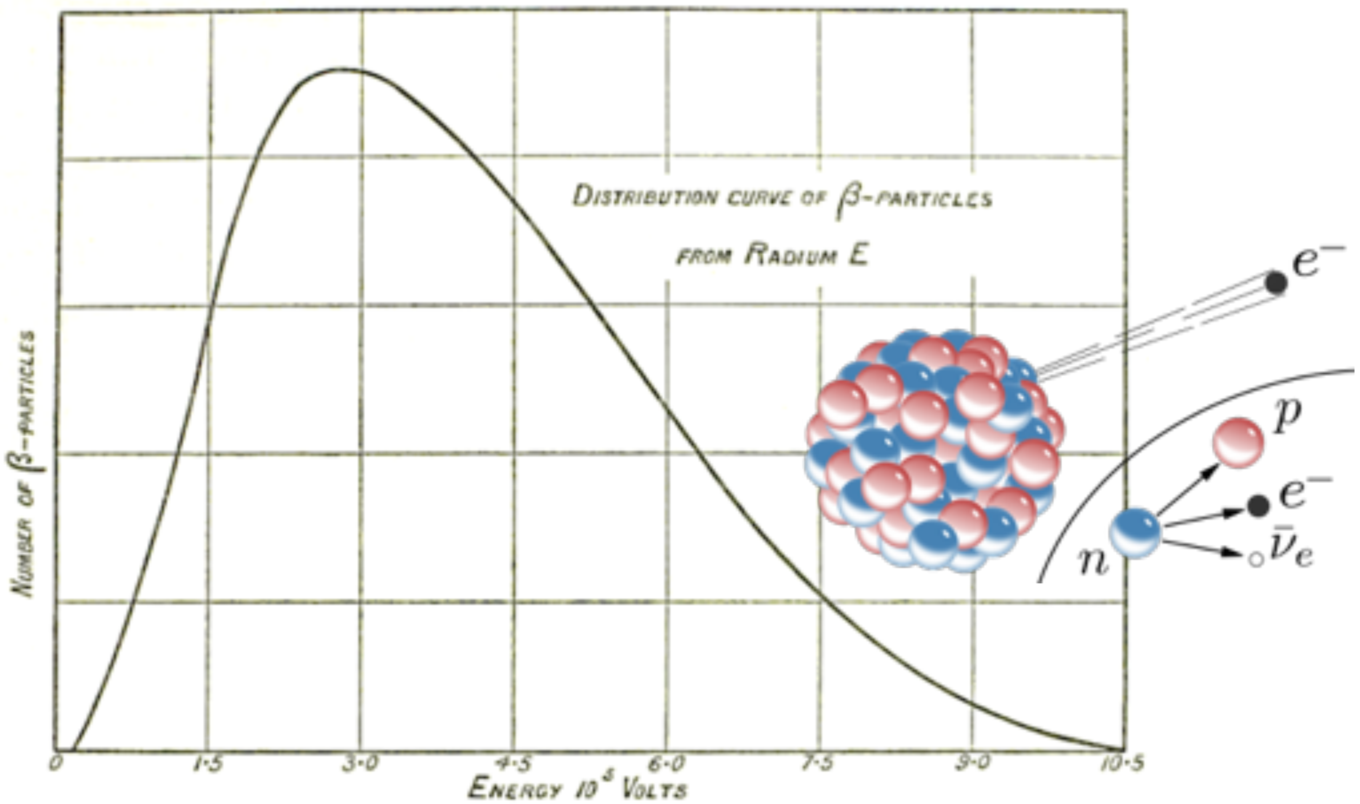
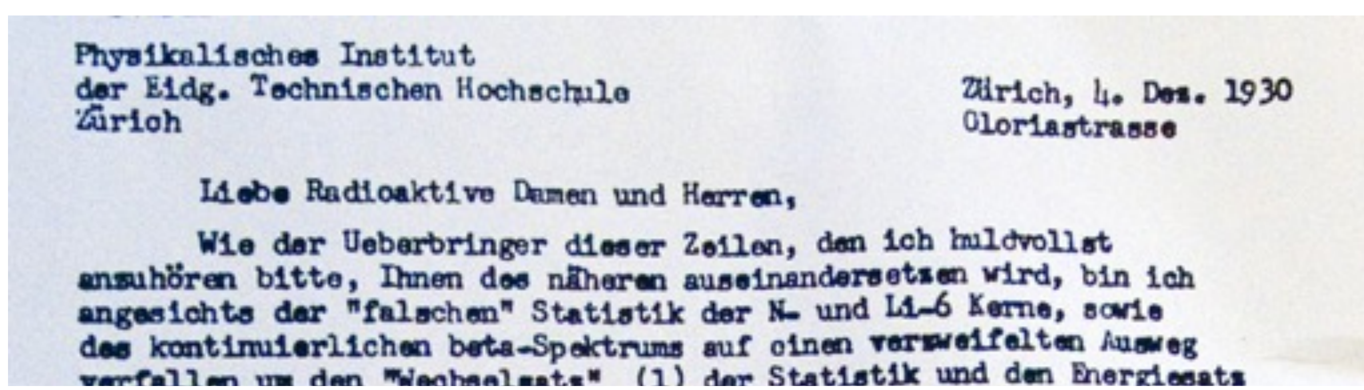
They're cool

Only session
starting at
9:30 !

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. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

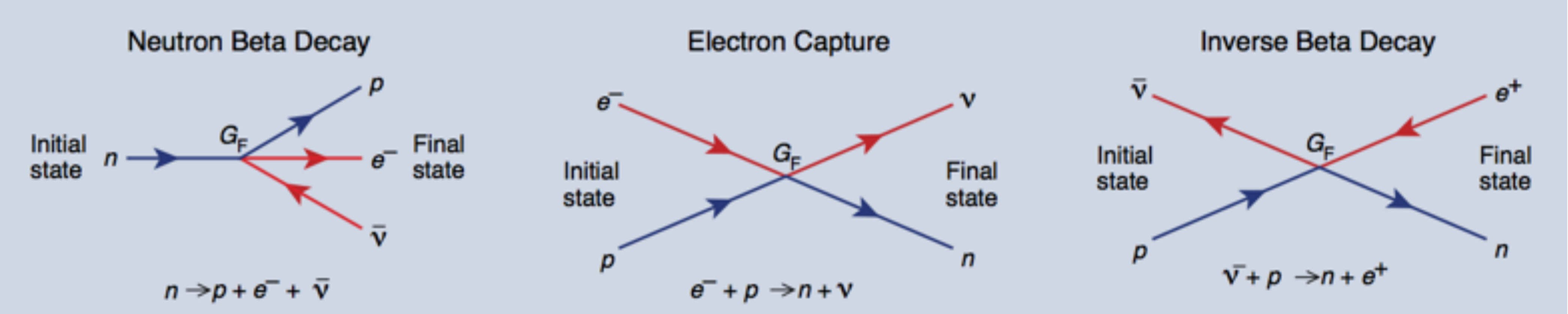
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz

- 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 $\overline{\nu}$e discovery

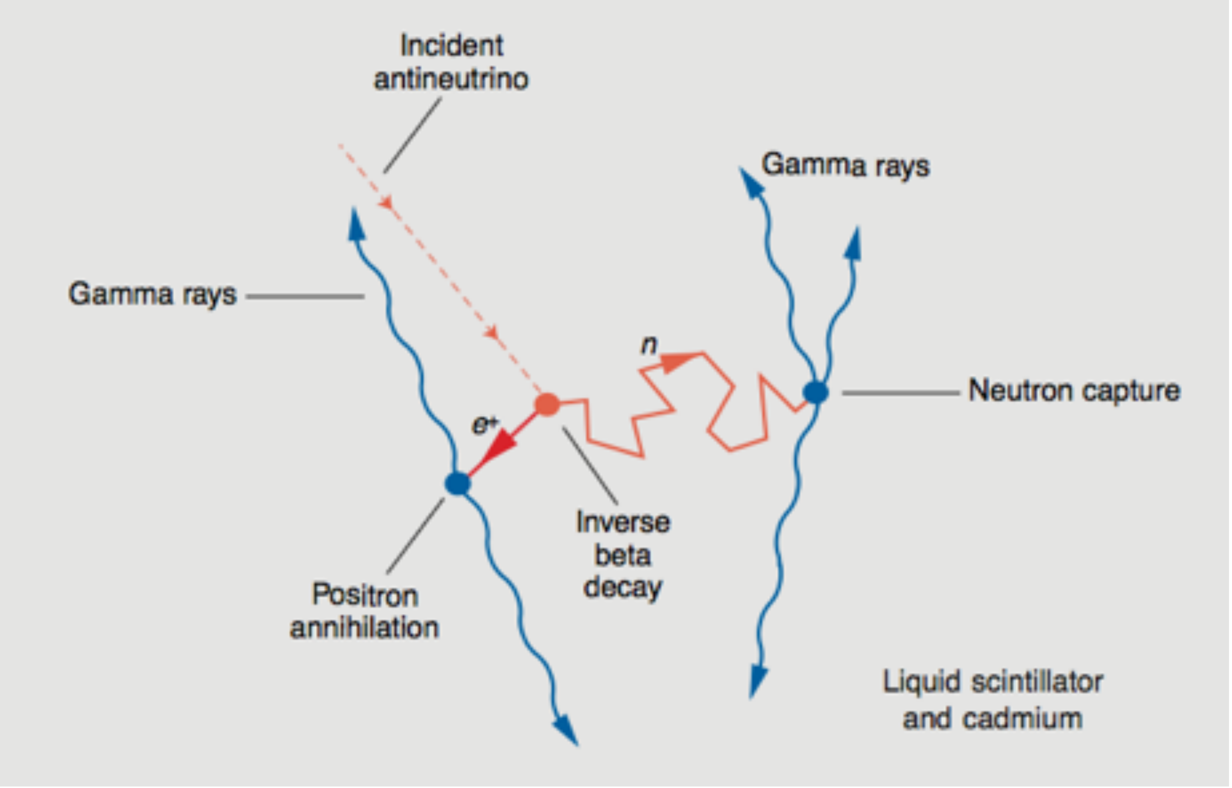
- According to Fermi on β processes, three kinds of reaction are possible:



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

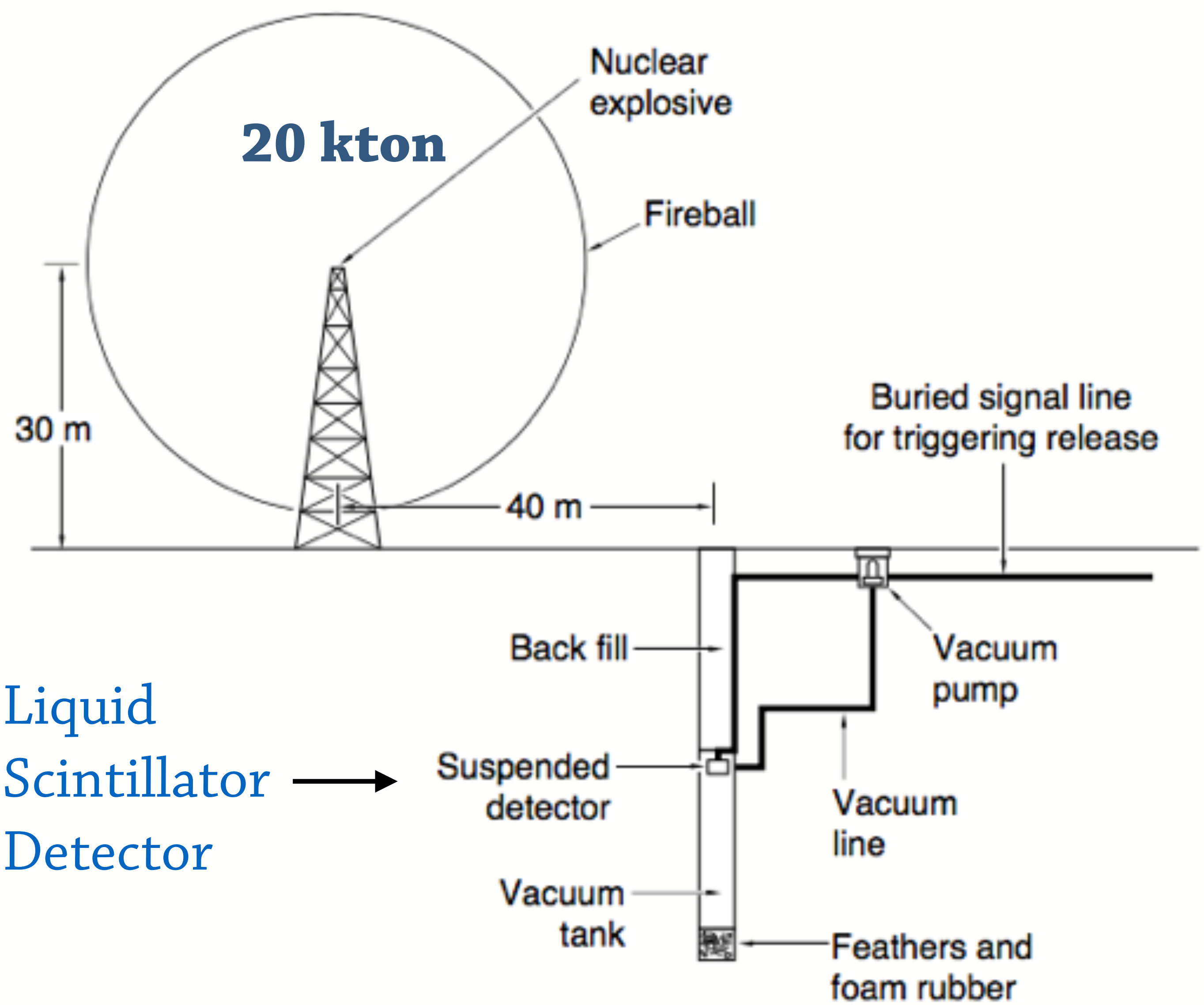
$$\bar{\nu} + p \to n + e^+$$

- 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



Liquid Scintillator Detector →

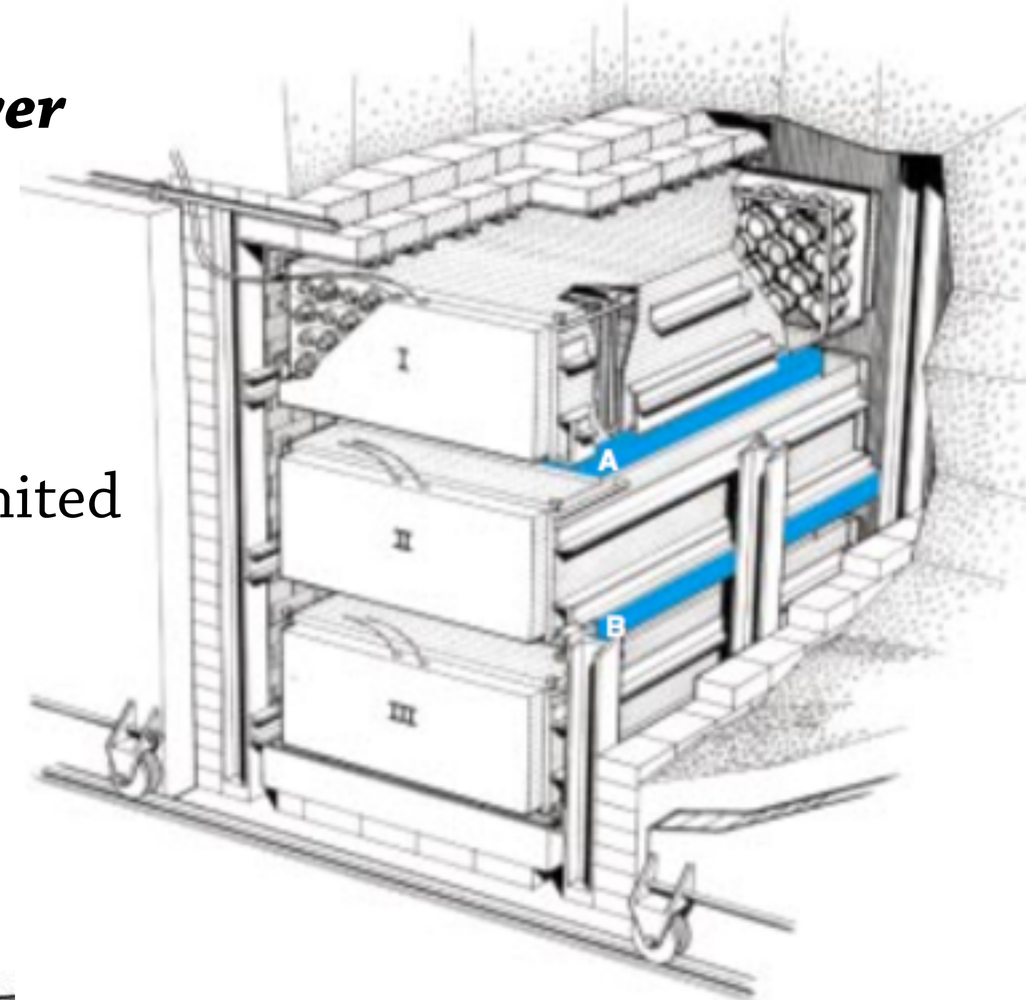
- Very intense source : ~10^{40} ν/s/cm^2
- Short (~2s) : no cosmic background
- But, a lot of neutrons & gammas
- Single use detector

The project was **approved** !

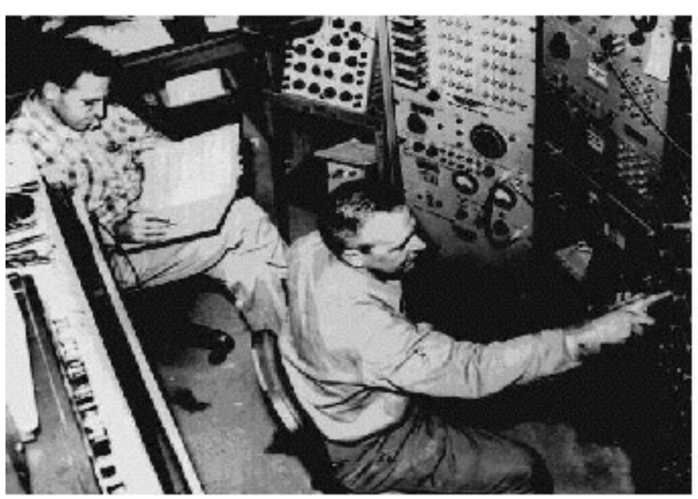
When they had the idea of doping the detector with neutron catcher (giving a better signal discrimination) they **changed their mind**

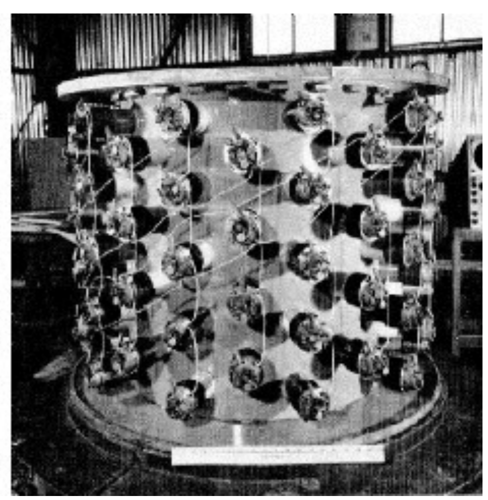
Inverse β and the $\bar{\nu}e$ discovery

Idea 2 : nuclear power plant at Savannah River

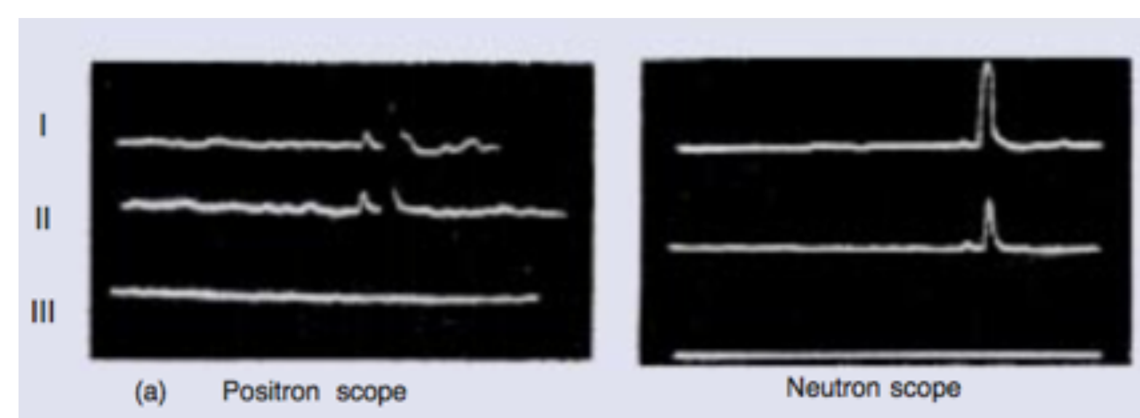


- Intense source ~10^{20} ν/s/cm^2
- Continuous emission
- Also a lot of n & γ background, but can be limited
  Underground, lead shielding, …
- More ethical ?





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

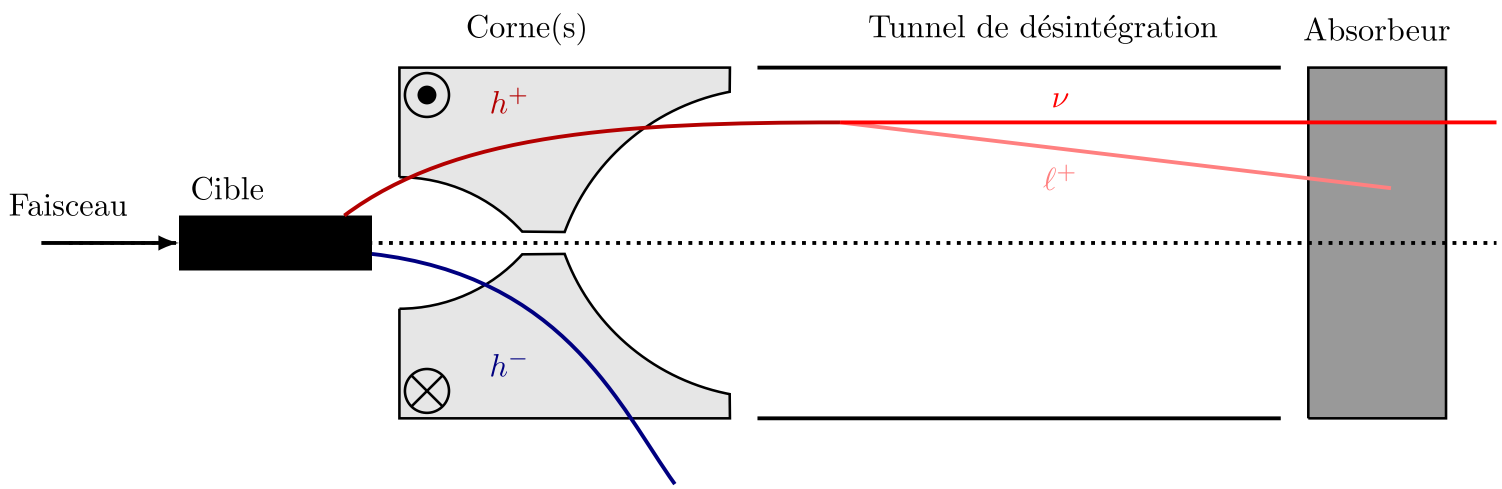


- 1995 Nobel Prize
- Method still used today

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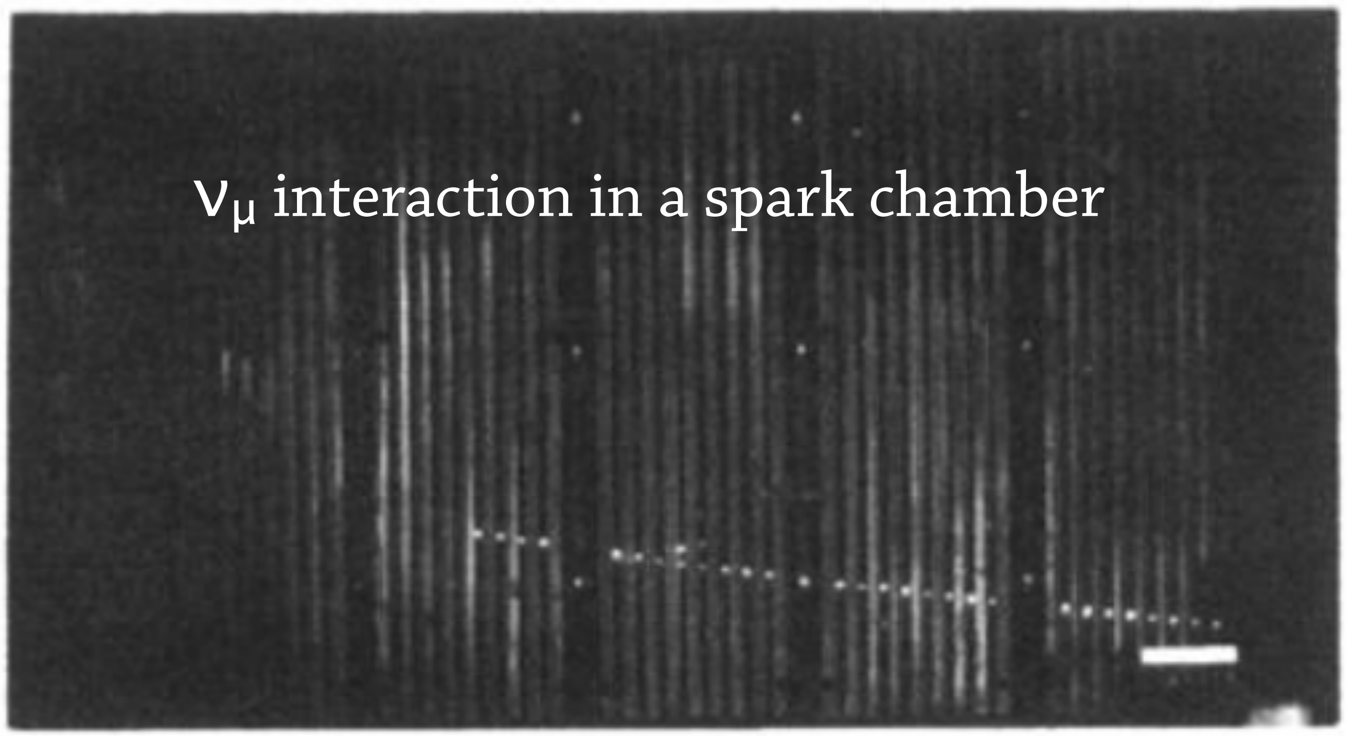
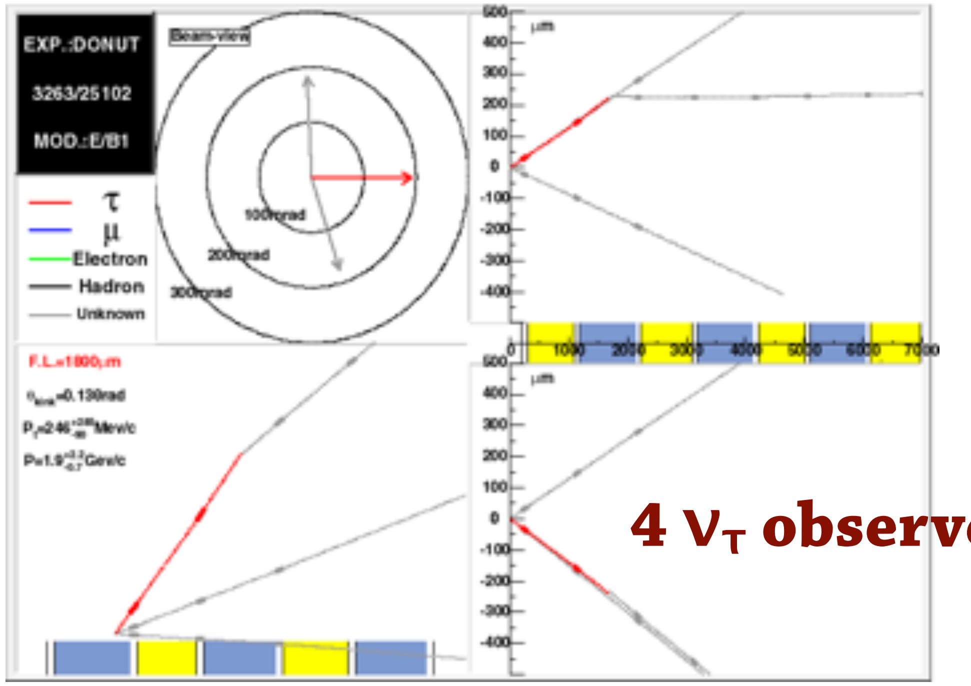
- They found out that they had different kind of ν interactions : **ν_μ discovery** !



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

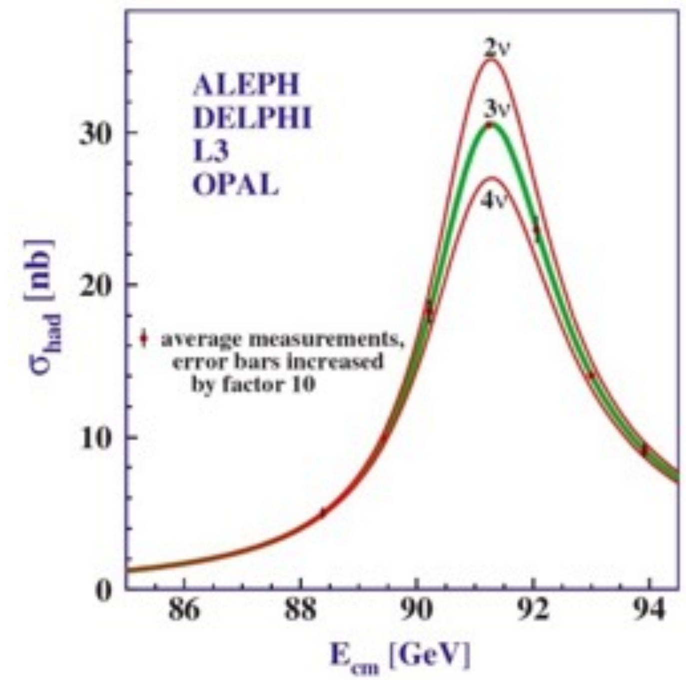


4 ν_τ observed

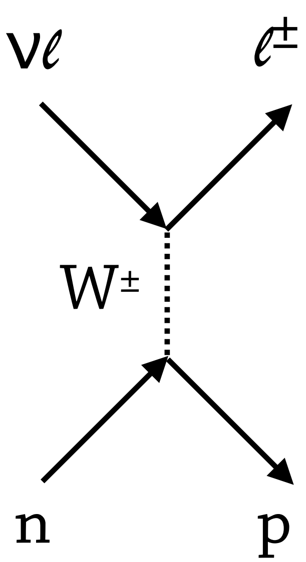
Neutrinos & Standard Model

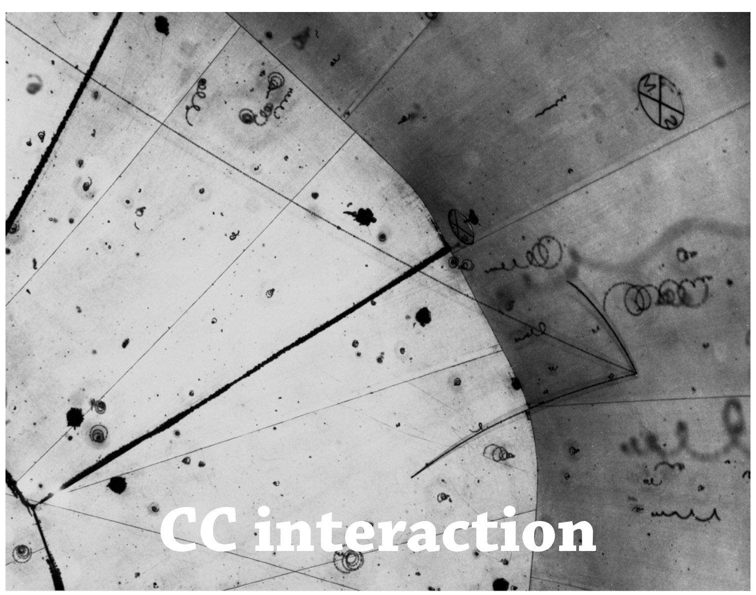
- **Three flavors** of neutrinos (light and active):
  → In 1989, LEP mesures the Z invisible width

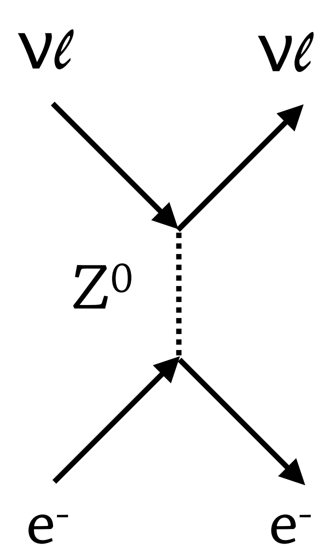
$$N_\nu = 2.984 \pm 0.008$$

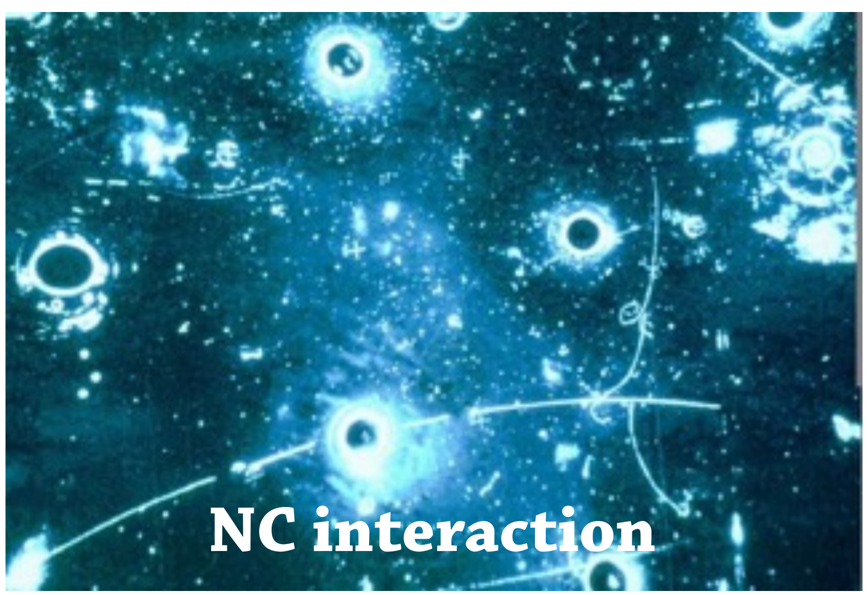


- Only interact through weak interactions
  → **Charged & Neutral current**









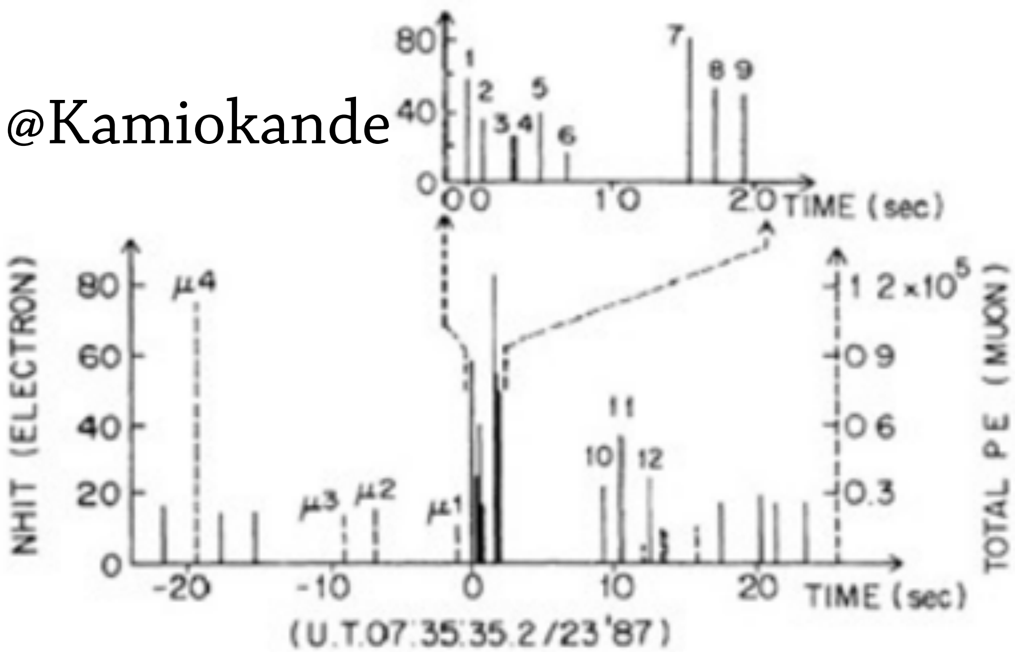
- Only left handed
  → Cannot couple to Higgs field therefore neutrinos are **massless**

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



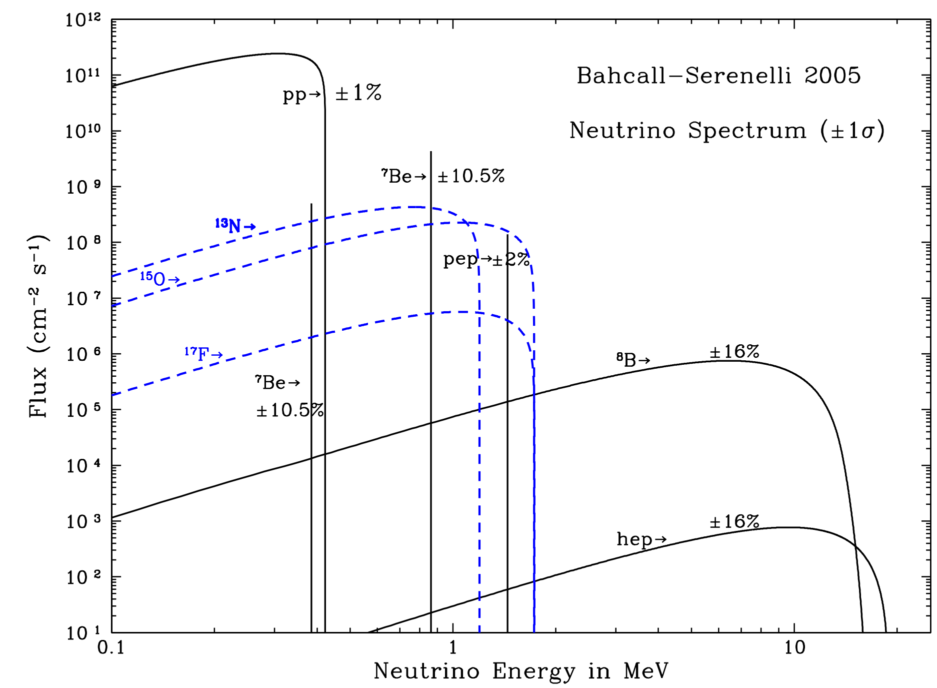
SN1987A

- 99% of the SN energy is released as neutrinos
- 1st case of neutrino astronomy neutrino 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

$$p + atm \rightarrow \pi^+ + \ldots$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

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Solar Neutrinos

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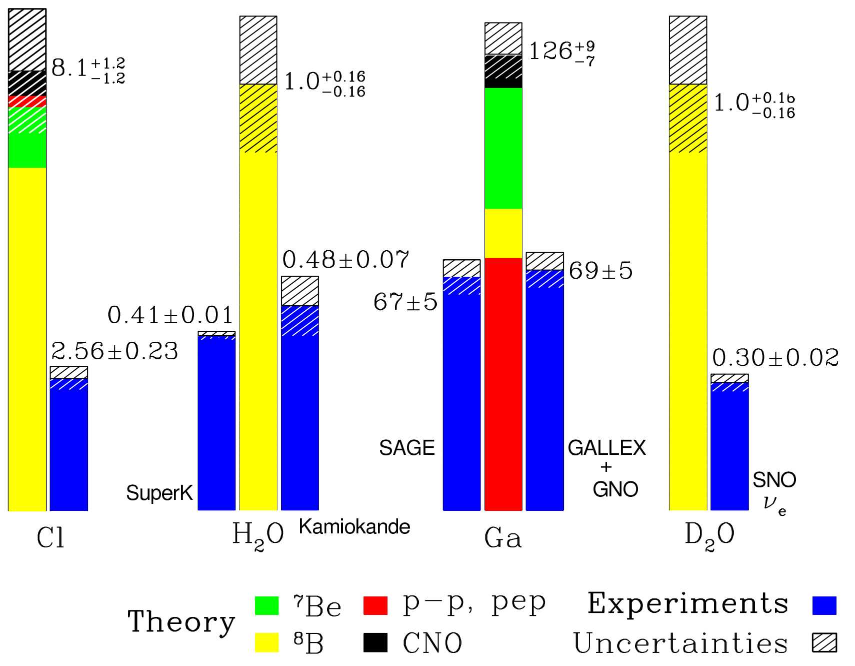
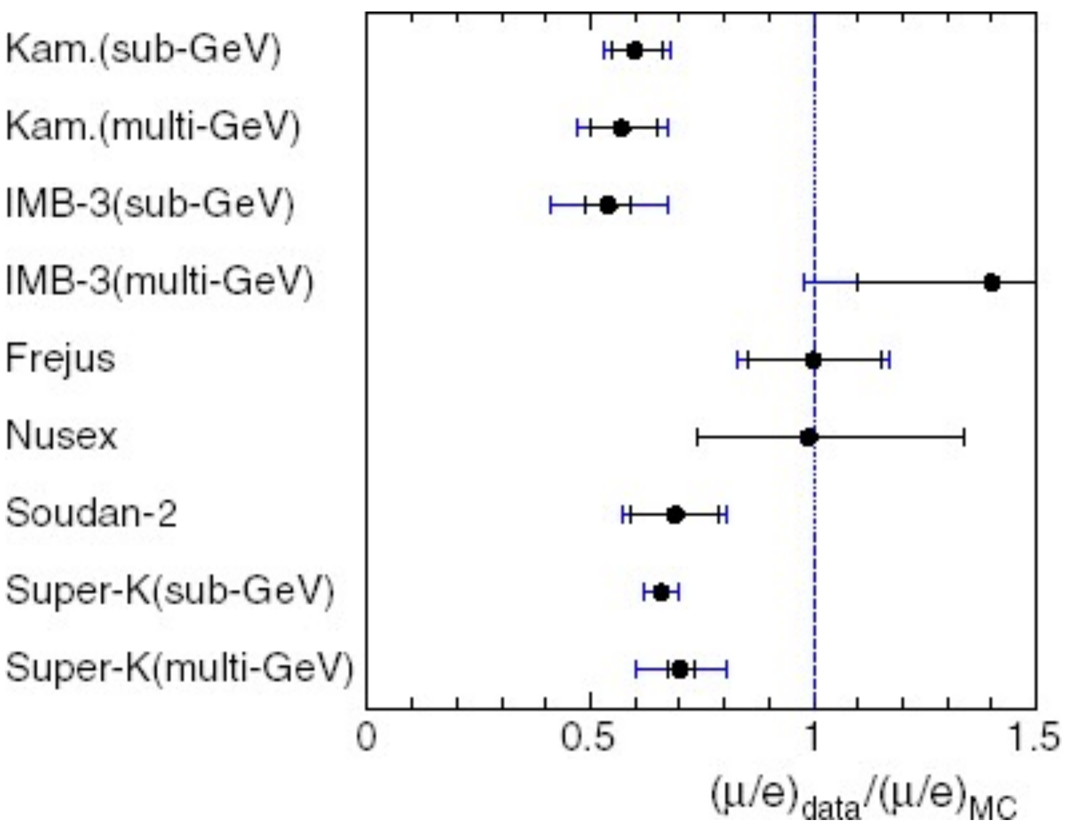
~2/3 of expected ν_e are missing



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 eigenstate are **not superimposed** but **linked** by a 3×3 unitary mixing matrix (the PMNS matrix)

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

$\alpha = (e, \mu, \tau)$:= Flavor states
$i = (1, 2, 3)$:= Mass states
U = PMNS matrix

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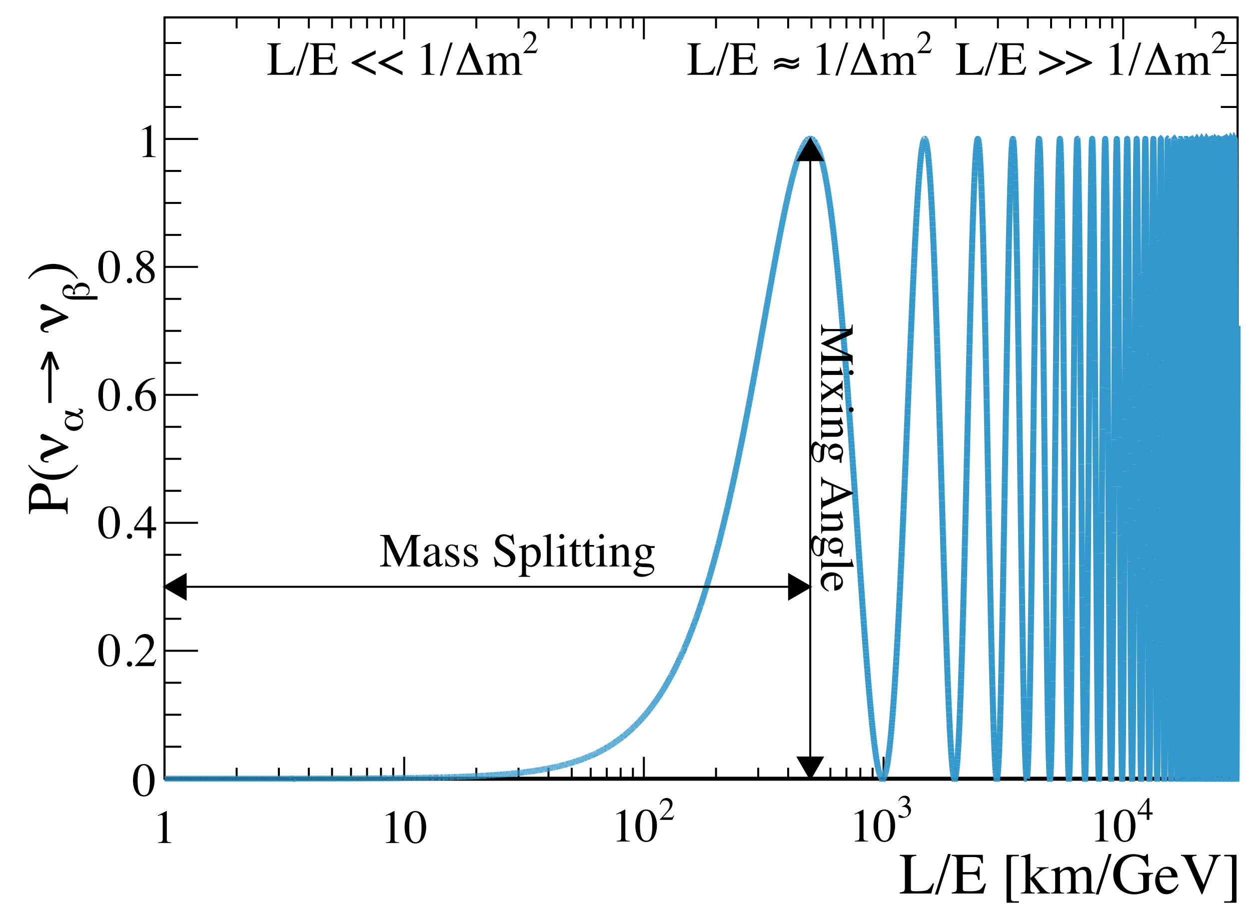
Simplified 2 flavors case

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

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

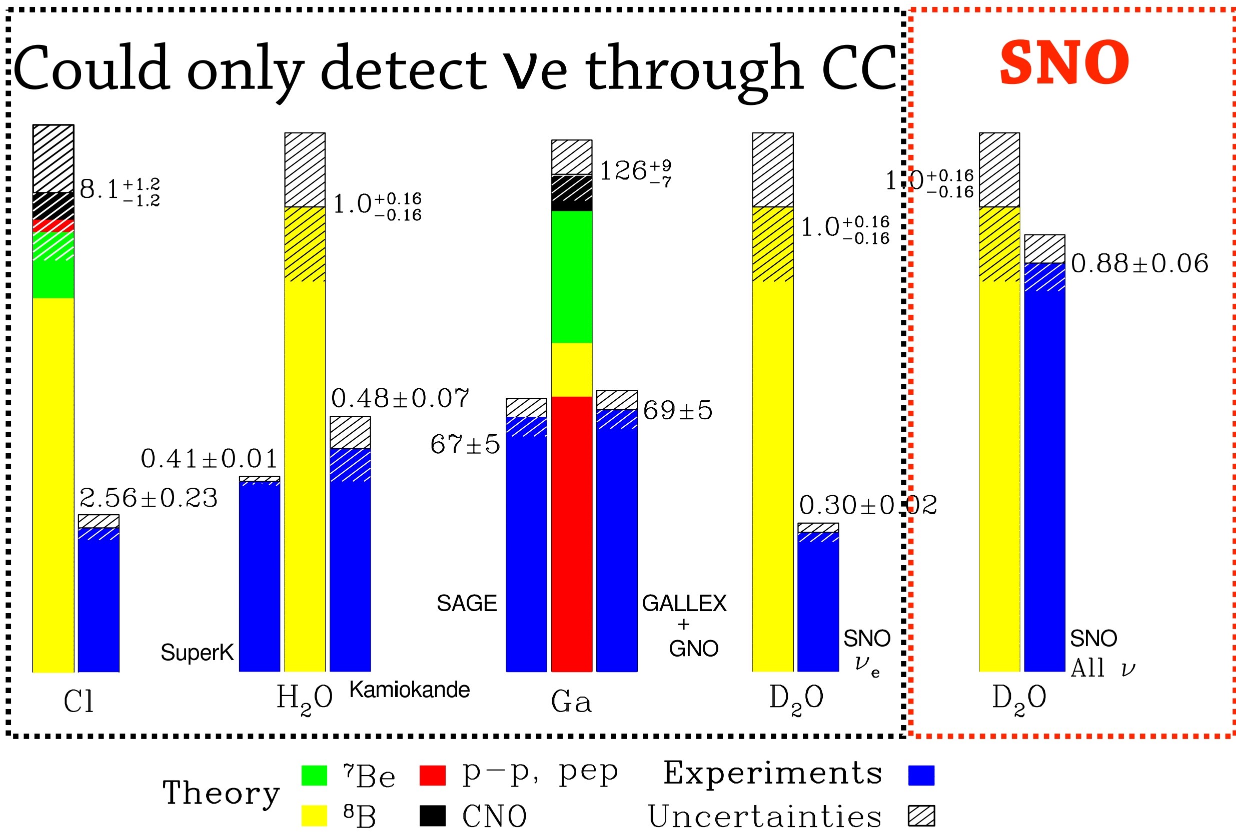
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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



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 :

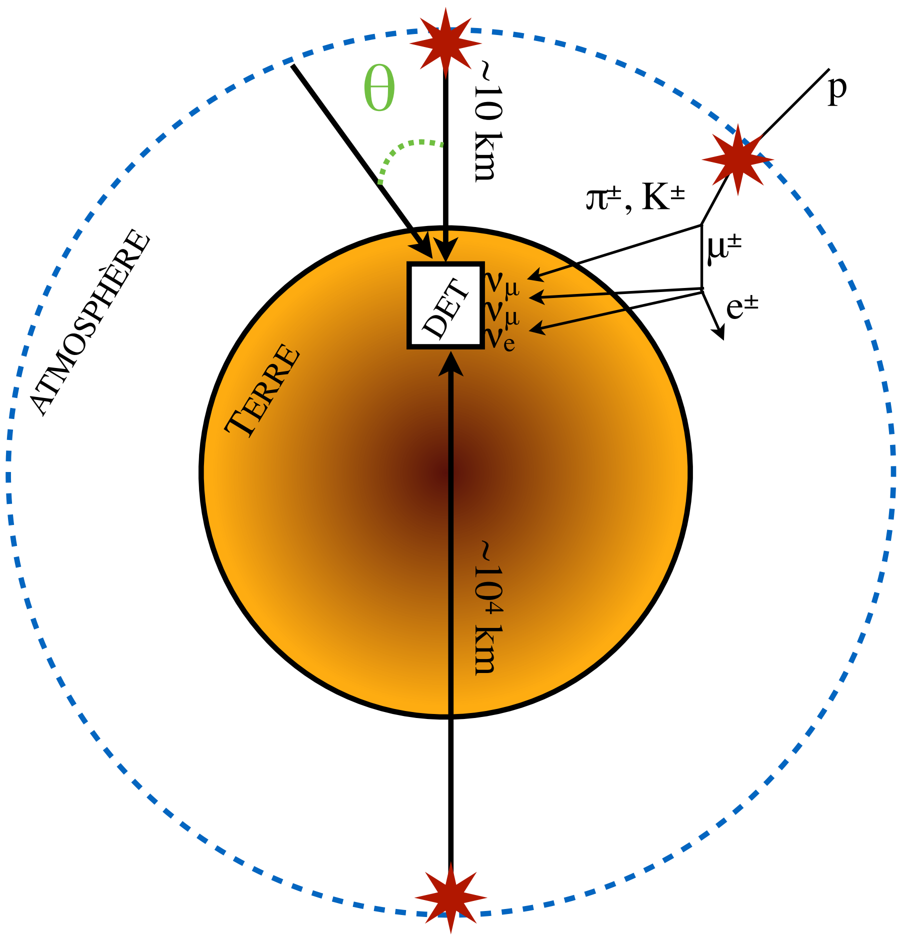
$$\frac{\Phi_{CC}}{\Phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

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

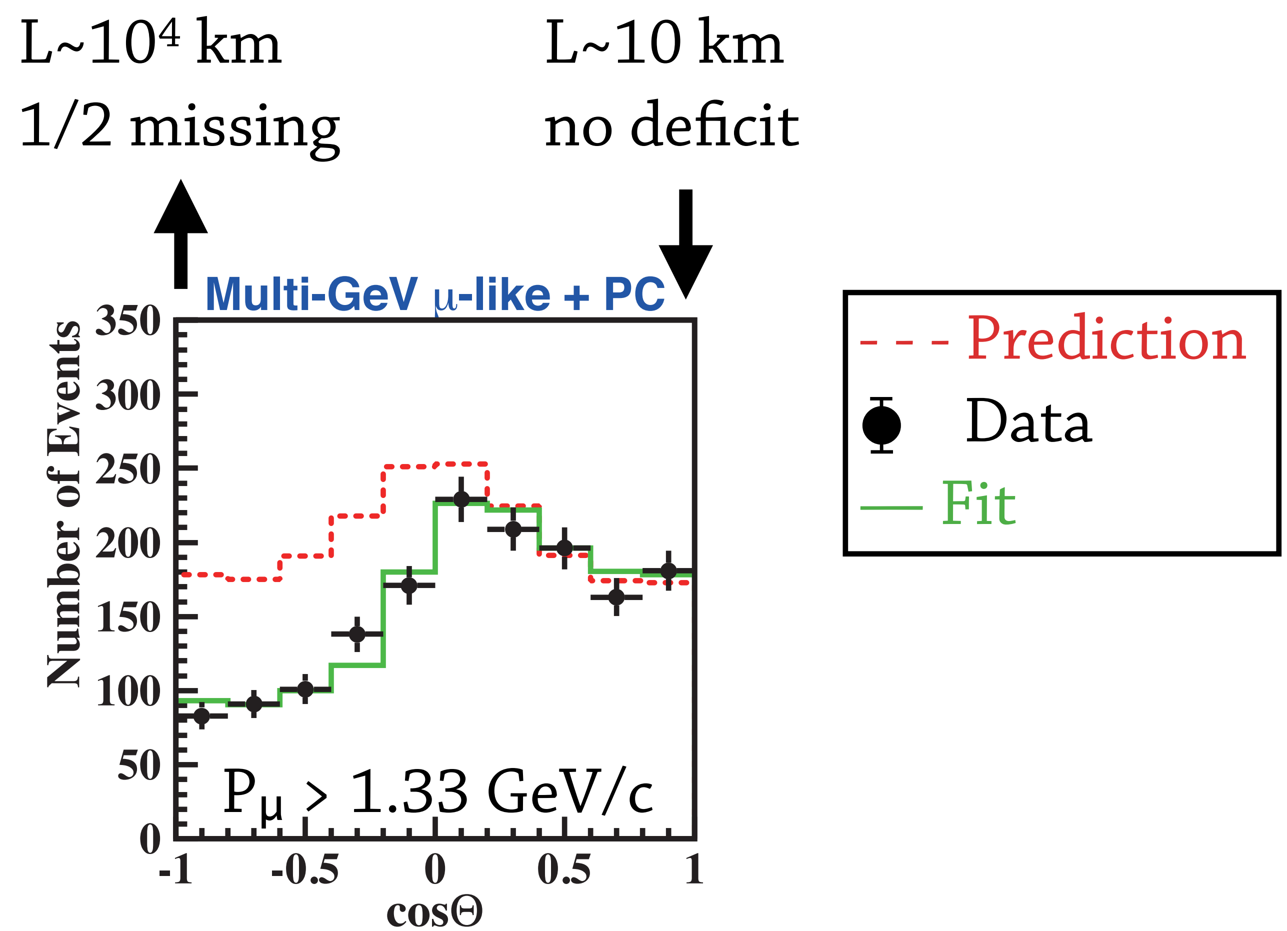
Nobel Prize in 2015 !

ν oscillations : experimental proofs

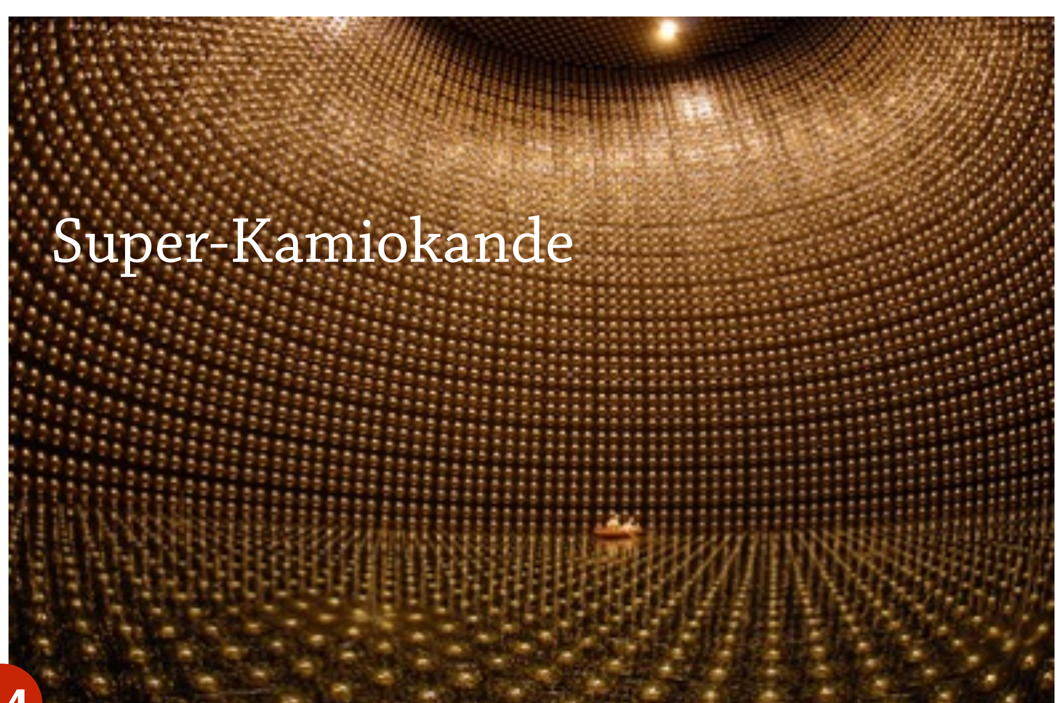
Atmospheric neutrinos



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



↳Atmospheric νμ oscillates into ντ



Nobel Prize in 2015 !

3 flavors oscillations

Atmospheric — Reactor/Accelerator — Solar

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

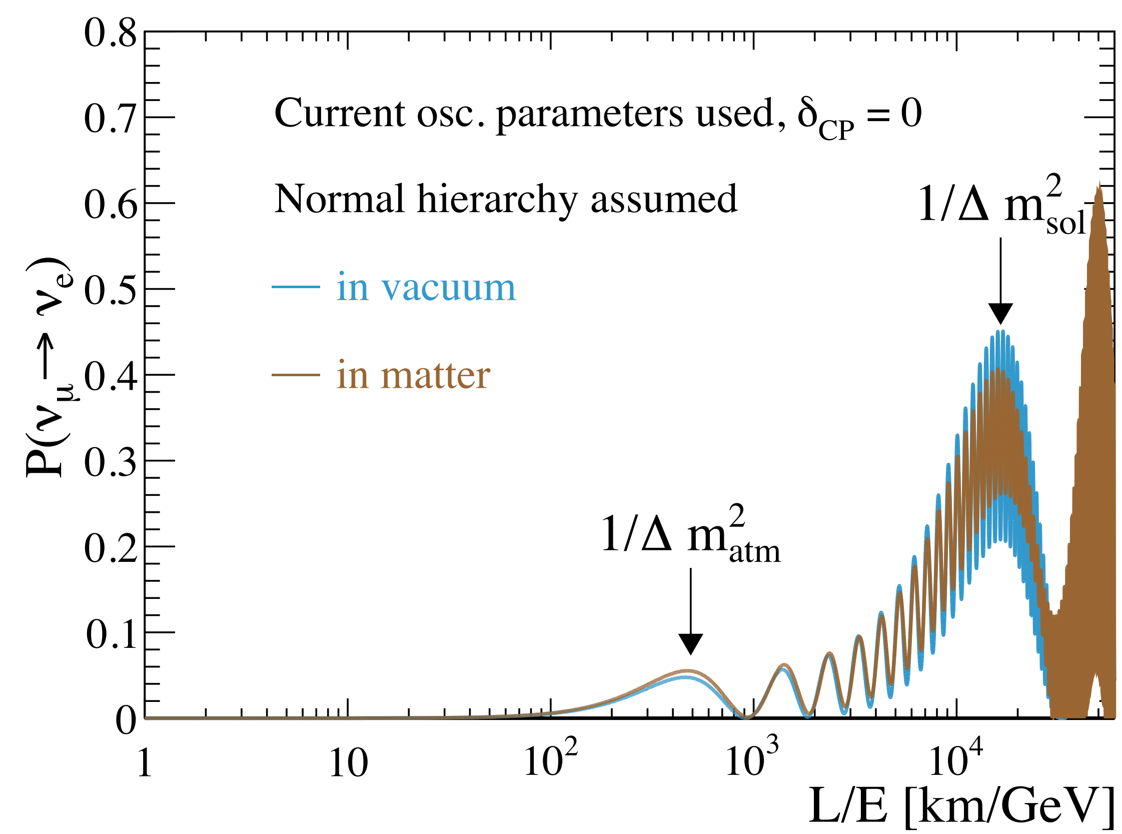
$$s_{ij} = \sin\theta_{ij}$$

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

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

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

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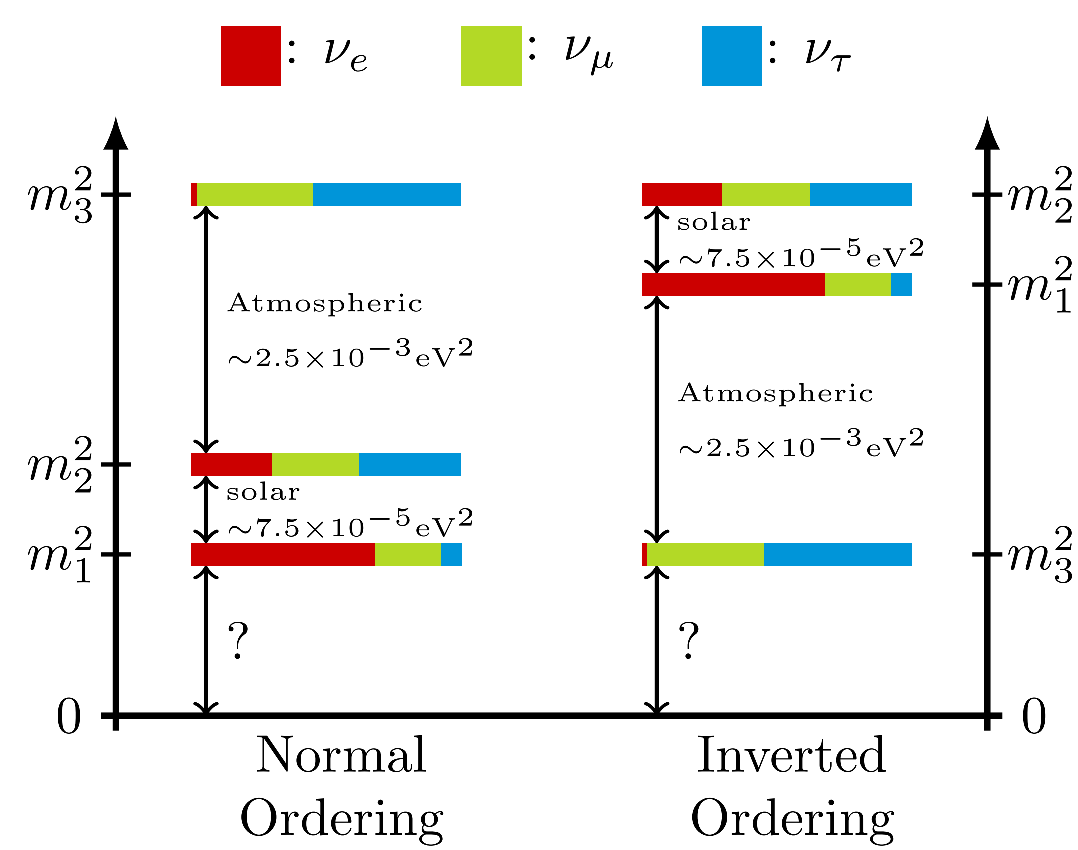
$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

From a global fit of data available on Jan. 2018, at 1σ :

nuFIT 3.2 (2018), nu-fit.org

$$\theta_{12} = 33.62^{+0.78}_{-0.76}$$
$$\theta_{23} = 47.2^{+1.9}_{-3.9}$$
$$\theta_{13} = 8.54^{+0.15}_{-0.15}$$
$$\Delta m^2_{\mathrm{sol}} = \Delta m^2_{21} = 7.40^{+0.21}_{-0.20} \times 10^{-5}\mathrm{eV}^2$$
$$|\Delta m^2_{\mathrm{atm}}| = |\Delta m^2_{3\ell}| = 2.494^{+0.033}_{-0.031} \times 10^{-3}\mathrm{eV}^2$$



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

Reactor source:

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

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

Near detector

At L/E before oscillations

Far detector

At L/E for oscillations

Accelerator source:

CERN

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

T2K, MINOS, NOVA, T2K, DUNE, T2KK

Reactor and Long Baseline experiments

Reactor source:

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

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

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

Near detector

At L/E before oscillations

→

Far detector

At L/E for oscillations

Accelerator source:

- Tunable energy
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T2K, MINOS, NOVA, T2K, DUNE, T2KK

- 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 $\bar{\nu}$ beam
  - ↳ Probe **CP violation** phase

Reactor and Long Baseline experiments

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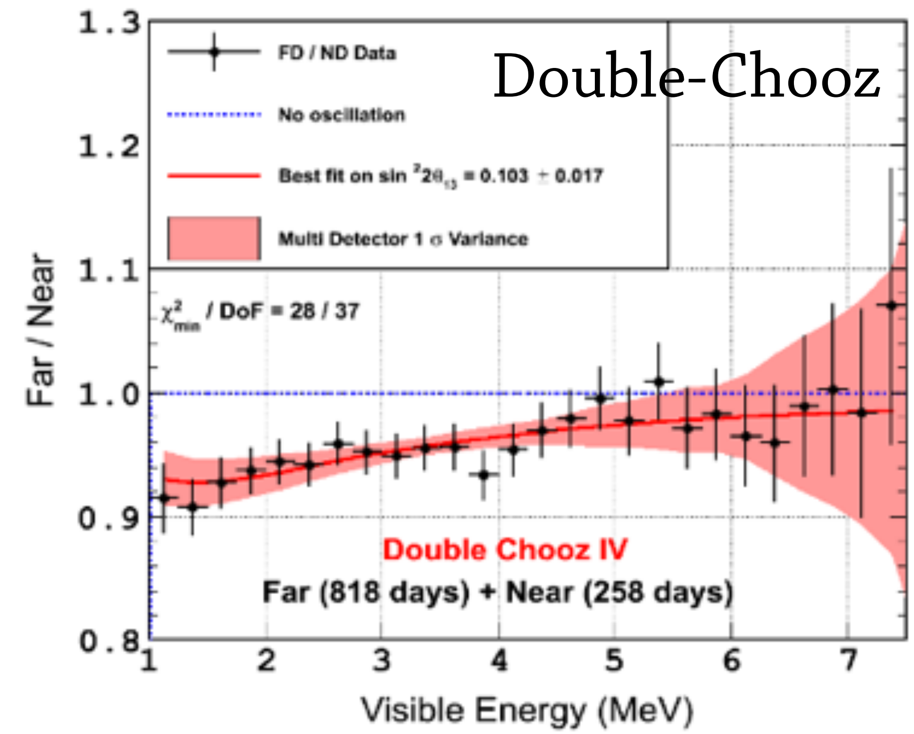

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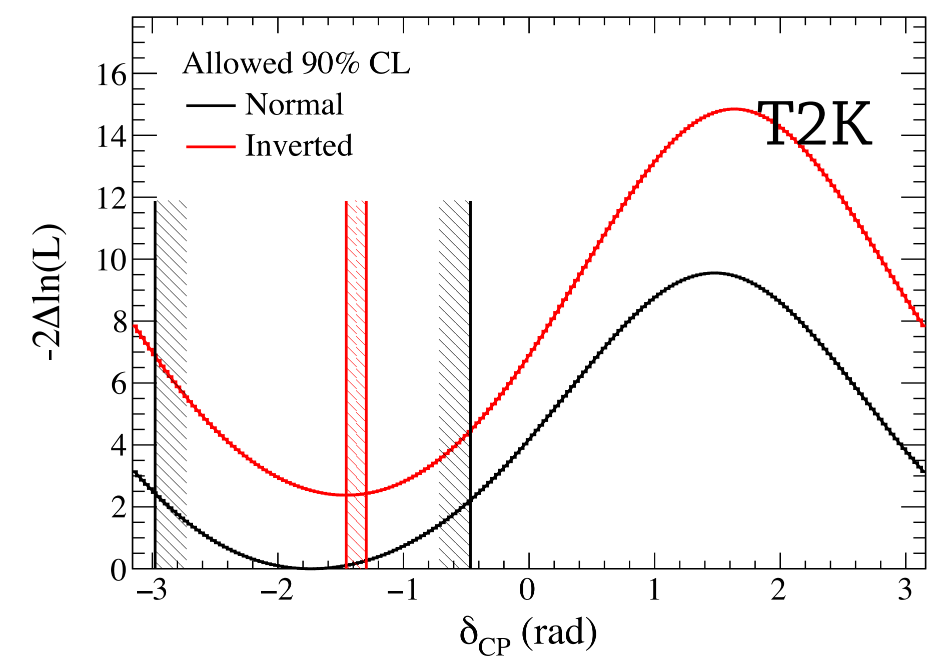


Current LBL experiments weakly prefers NH and max δcp

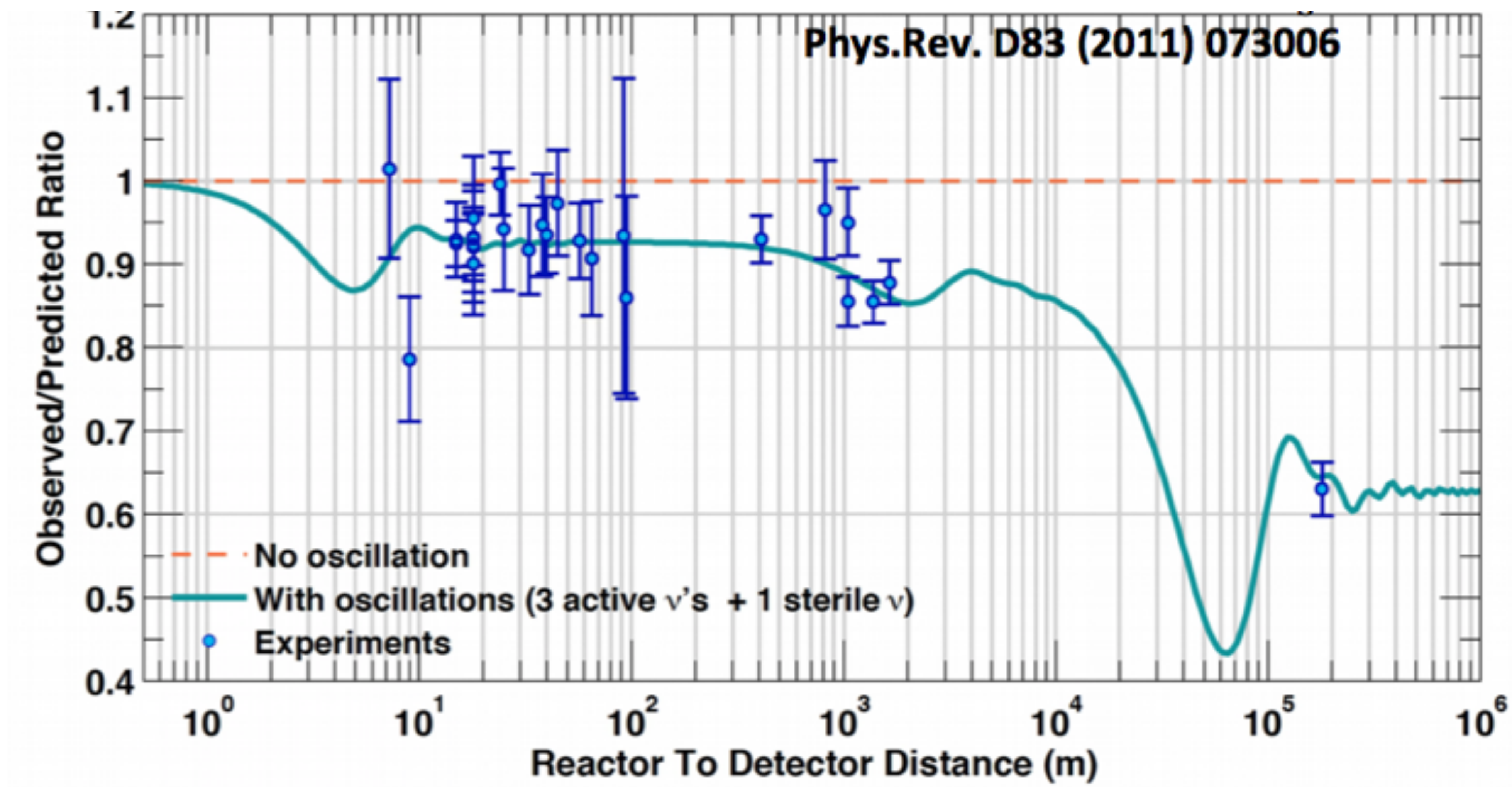
Sterile neutrinos : the return of the anomalies

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

Could be explained by the presence of a **4th neutrino** which would be a **sterile**.

Best fit parameters:

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

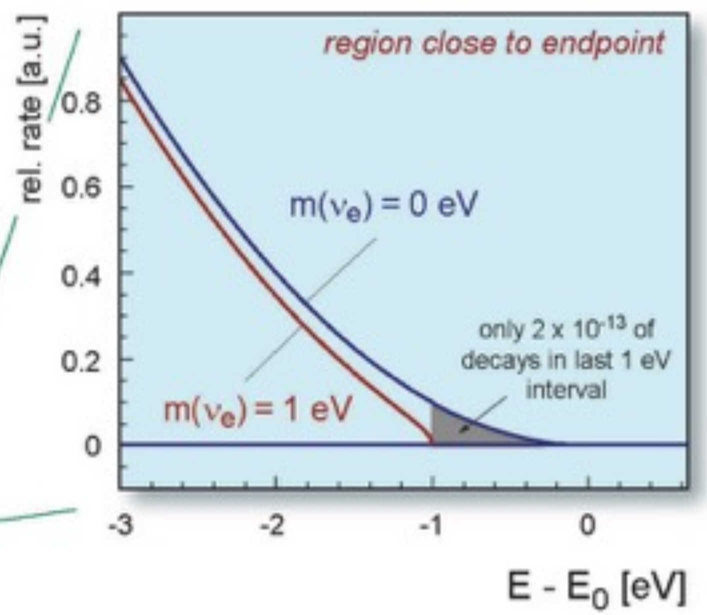


Many **oscillography** experiments ongoing, located few m from a nuclear core

STEREO, SOLID, BAKSAN, …

Neutrino mass : what and how ?

Direct constraints



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

KATRIN, TROITSK

Current limit : $m_{\overline{\nu}e} \leq 2.05$ eV at 95% CL
sensitivity at 0.2 eV

Indirect constraints

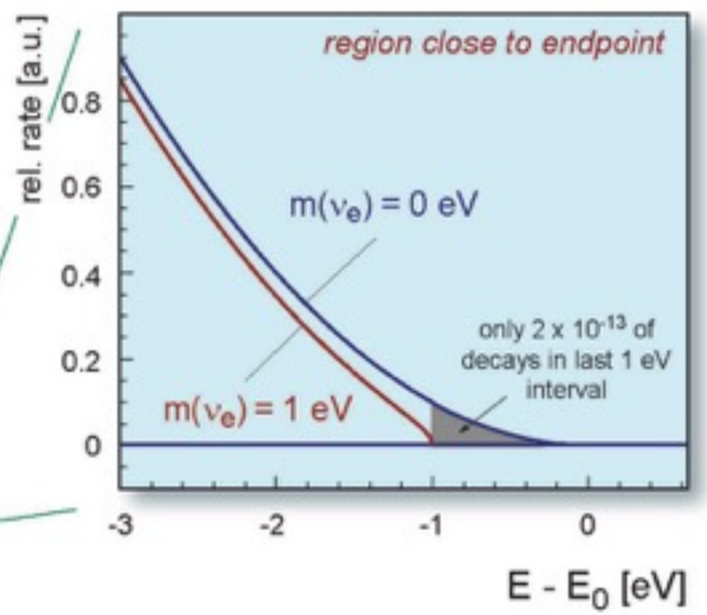
Cosmological observations
(Plank, CMB, SN, ...)

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 : what and how ?

Direct constraints



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↳ rare cases were the e- takes most of the available energy

KATRIN, TROITSK

Current limit : $m_{\bar{\nu}_e} \lesssim$ 2.05 eV at 95% CL
sensitivity at 0.2 eV

Indirect constraints

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

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

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

How do neutrinos get their masses ?

- The **Dirac** way
  Through Higgs coupling
  Need a sterile right handed neutrino
  Why are neutrino so light ?

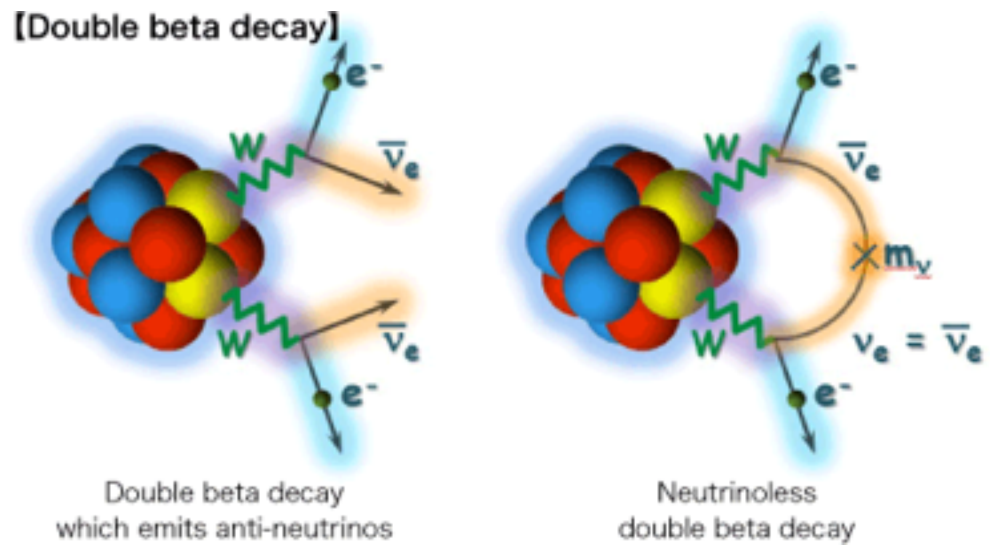
$$\mathcal{L}^D_{mass} = -m_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)$$
$$m_D = \frac{v}{\sqrt{2}}Y_v \leftarrow \sim 10^{-12}$$

- The **Majorana** way
  No distinction between ν and $\bar{\nu}$
  Mass given through seesaw mechanism
  Need massive neutrinos

$$\nu_R = C\bar{\nu}_L^T = \nu_L^C$$
$$m = \frac{m_D^2}{m_R} \quad \begin{matrix}\leftarrow \text{Dirac term} \\ \leftarrow \text{Very big}\end{matrix}$$

Are neutrinos Majorana neutrinos ?

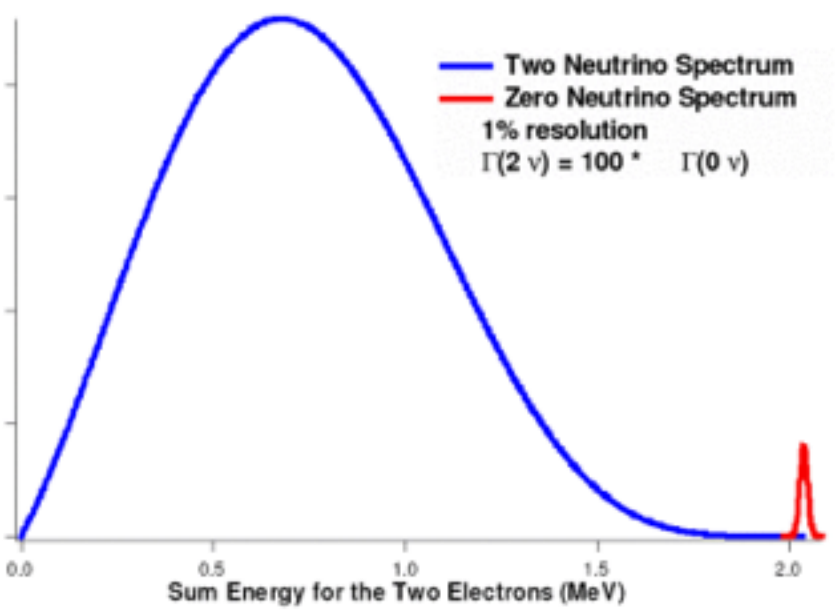
Experimental way : double beta decay with **no** ν emission



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

↳lepton number violated by 2 units

Look at the 2 electrons energy



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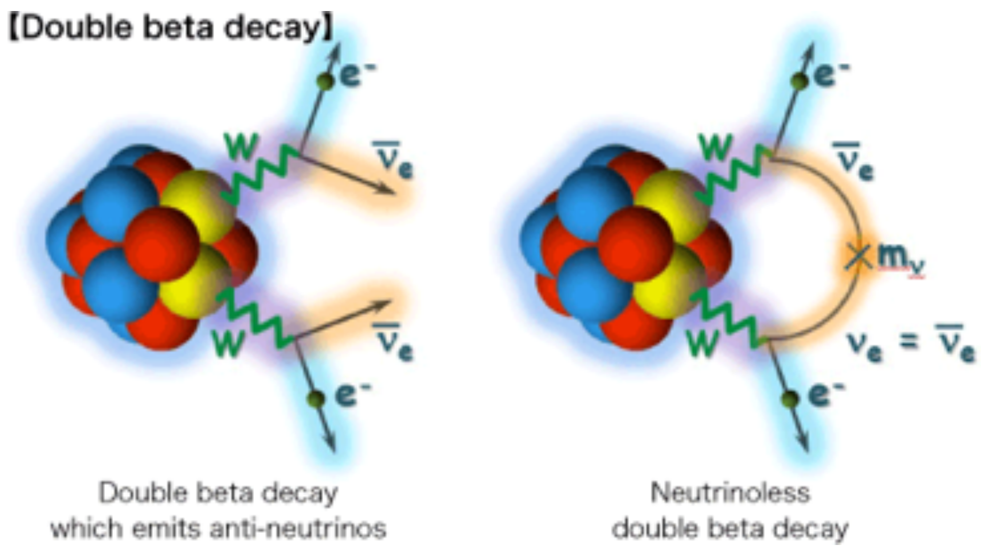

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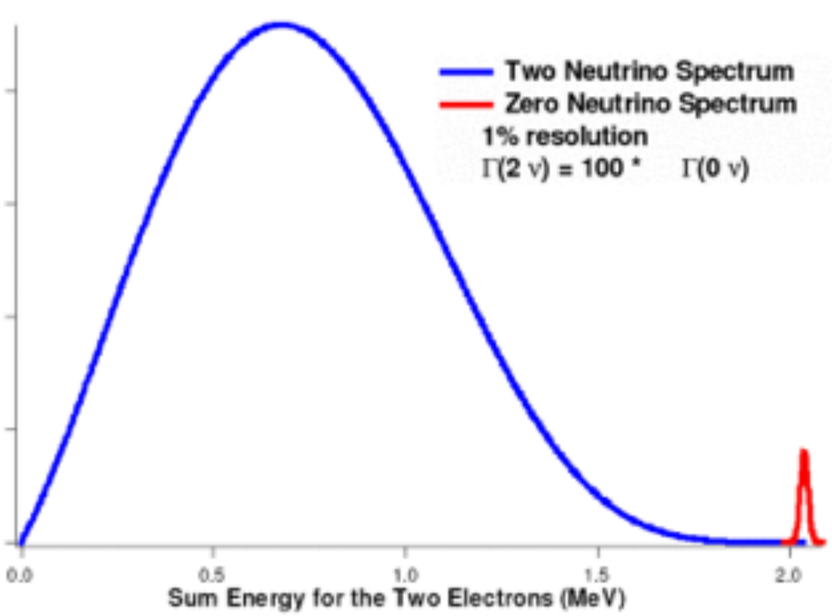
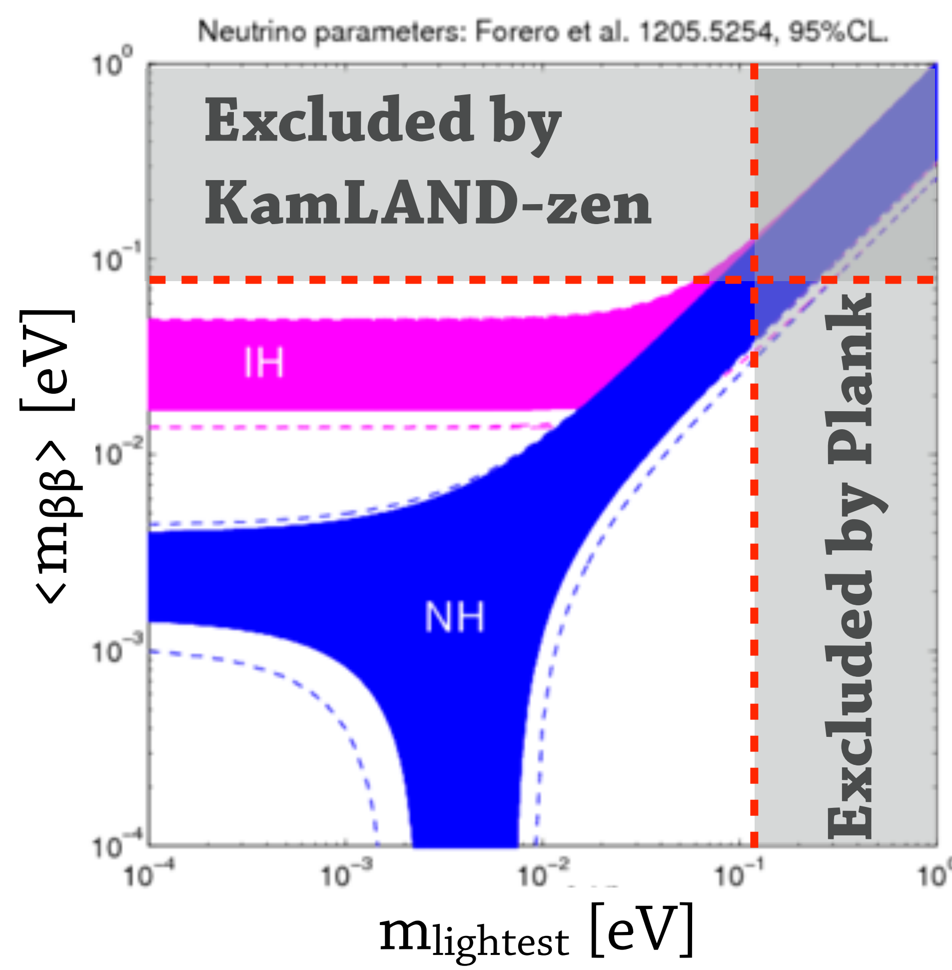
Measured half life depends on:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M^2_{0\nu}|\frac{<m_{\beta\beta}>^2}{m_e^2}$$

phase space — matrix element

Look at the 2 electrons energy

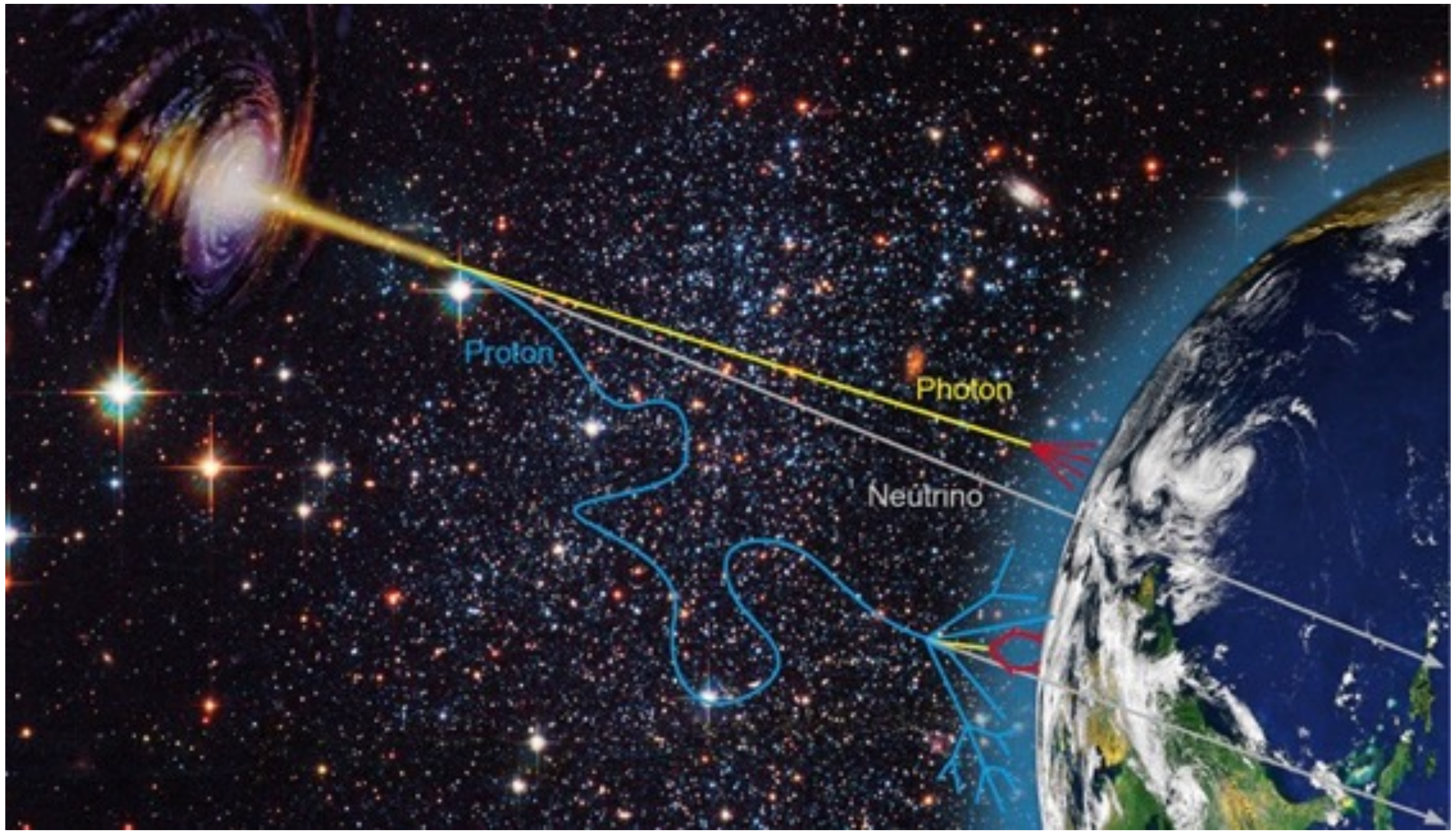




$$< m_{\beta\beta} >= \sum |U_{ei}|^2 m_i$$

- $m_{\beta\beta}$ sensitivity hard to lower
- Current and next generation can probe IH (which seemed disfavored)

Neutrino astronomy : today



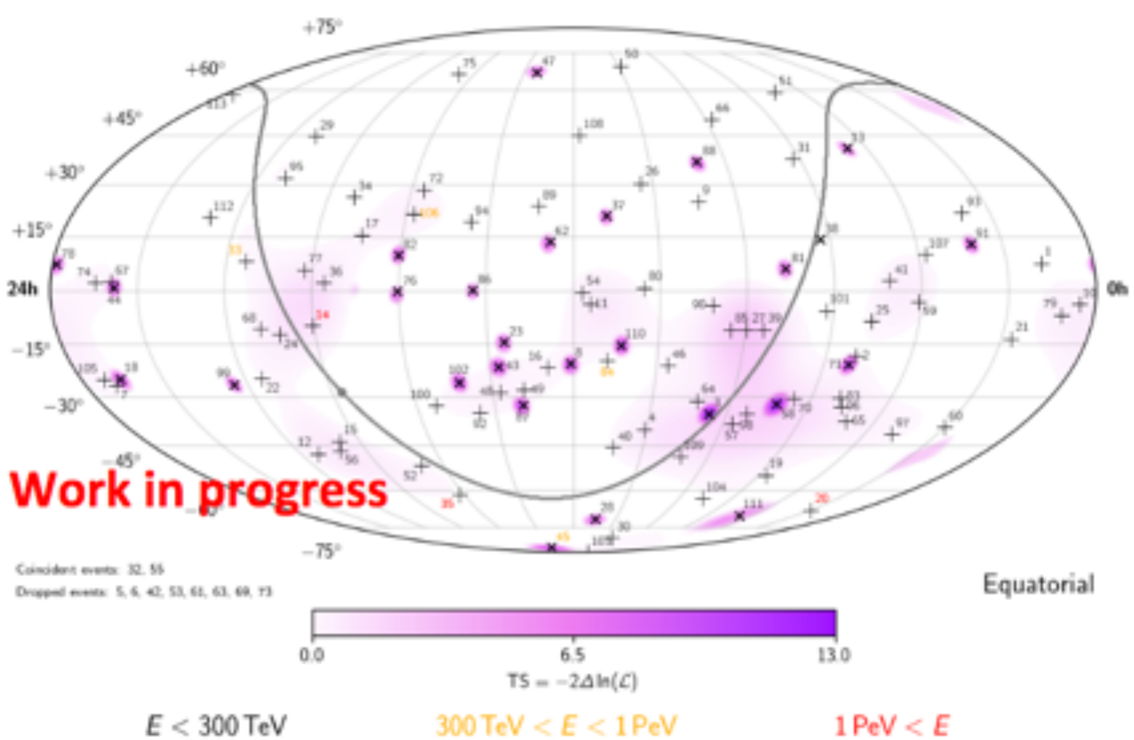
Pros

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

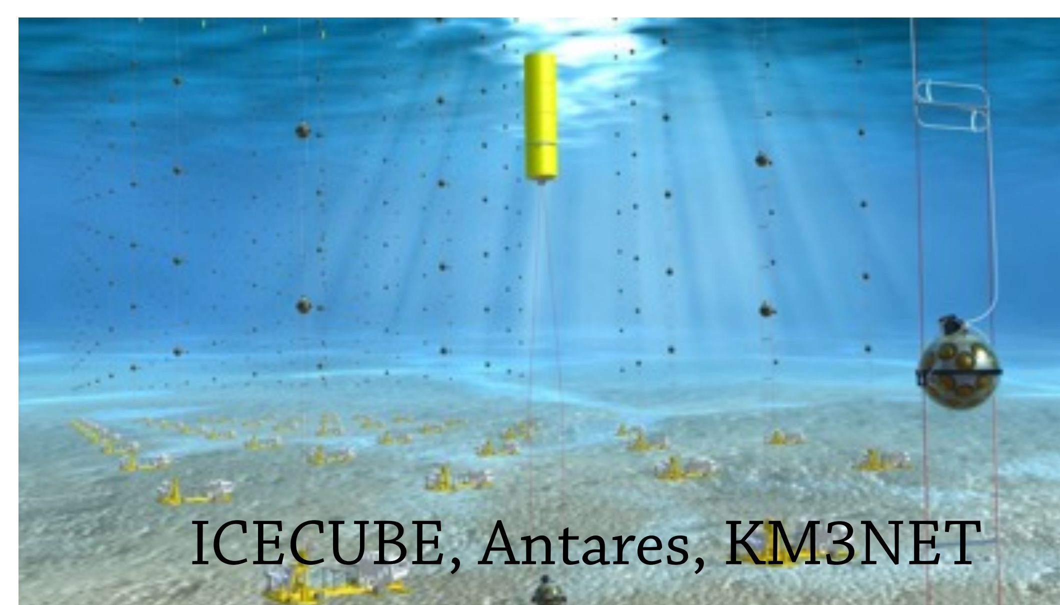
can probe far away objects

Cons

- Low statistics



Large (~km^3) detector underground using sea or ice as target/detector

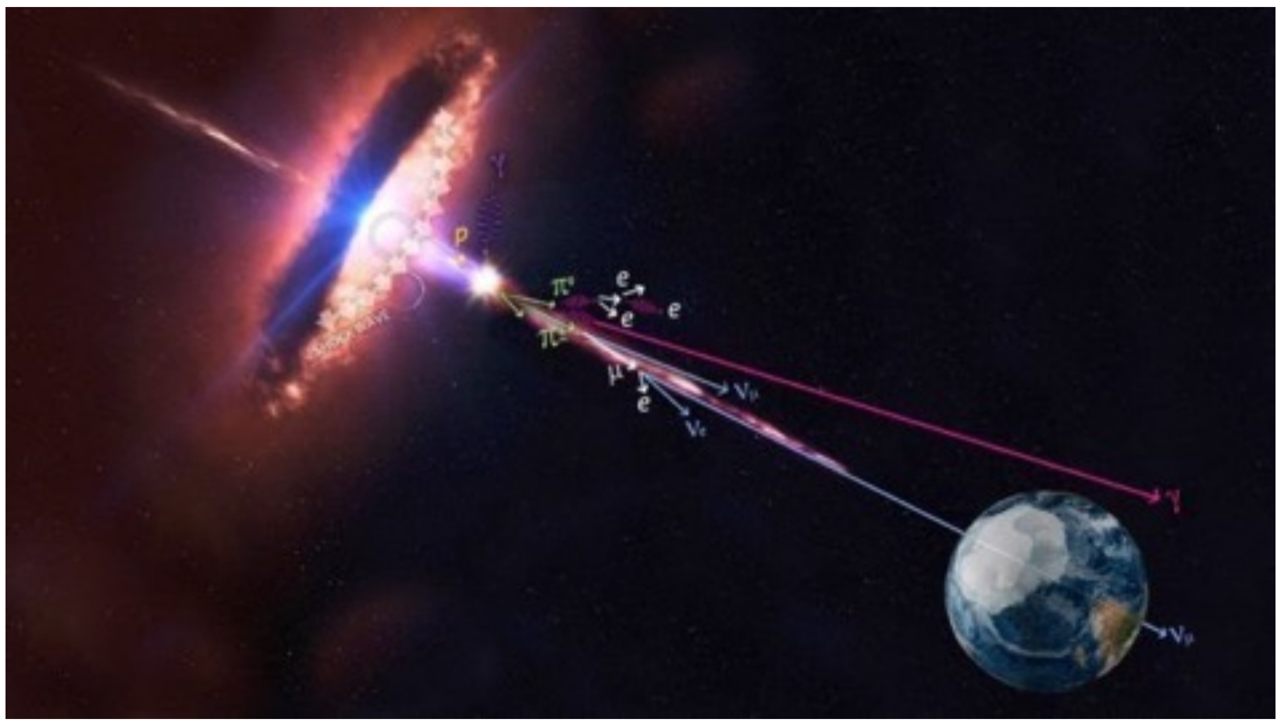


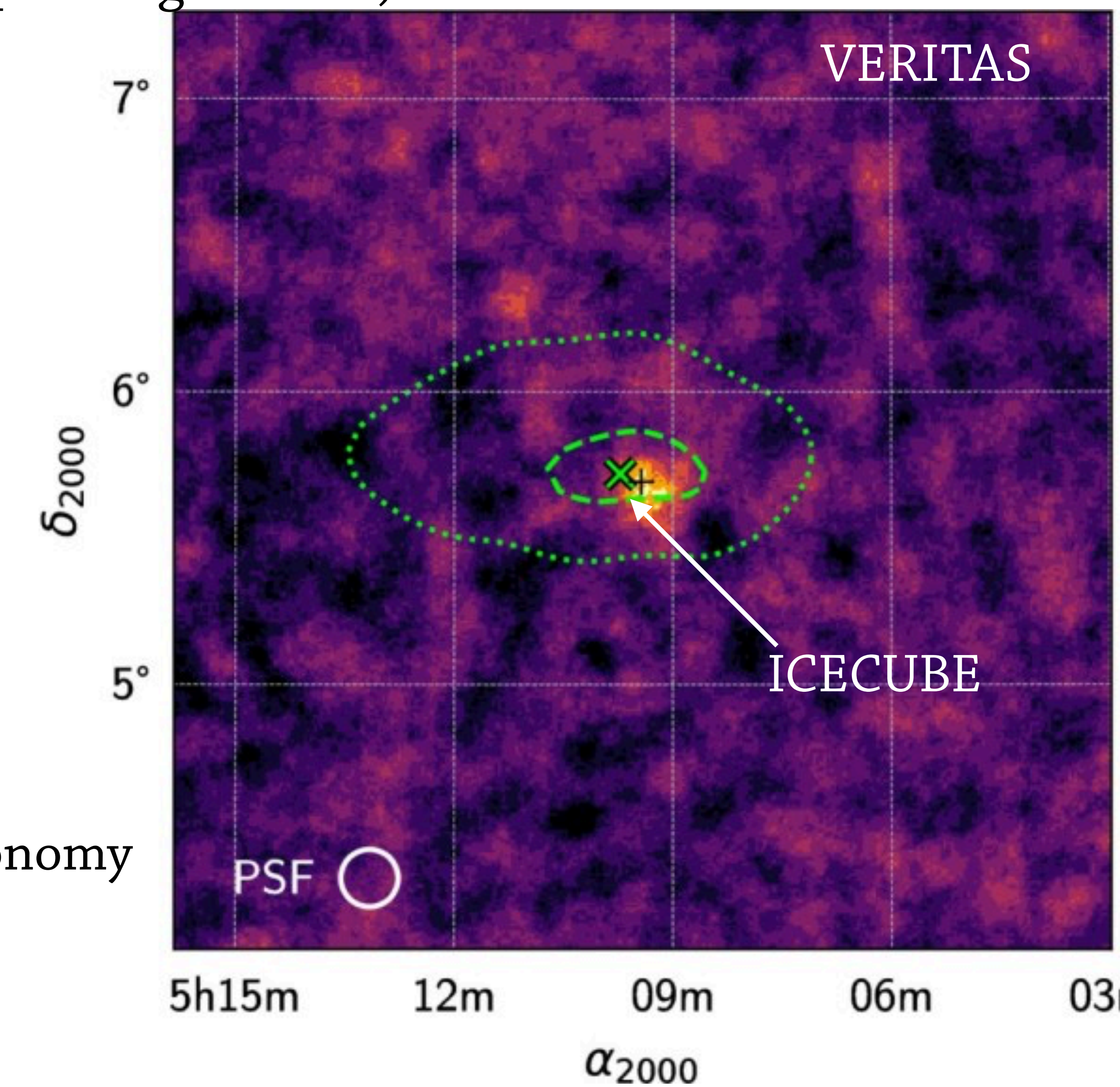
No specific source found yet

Neutrino astronomy : tomorrow

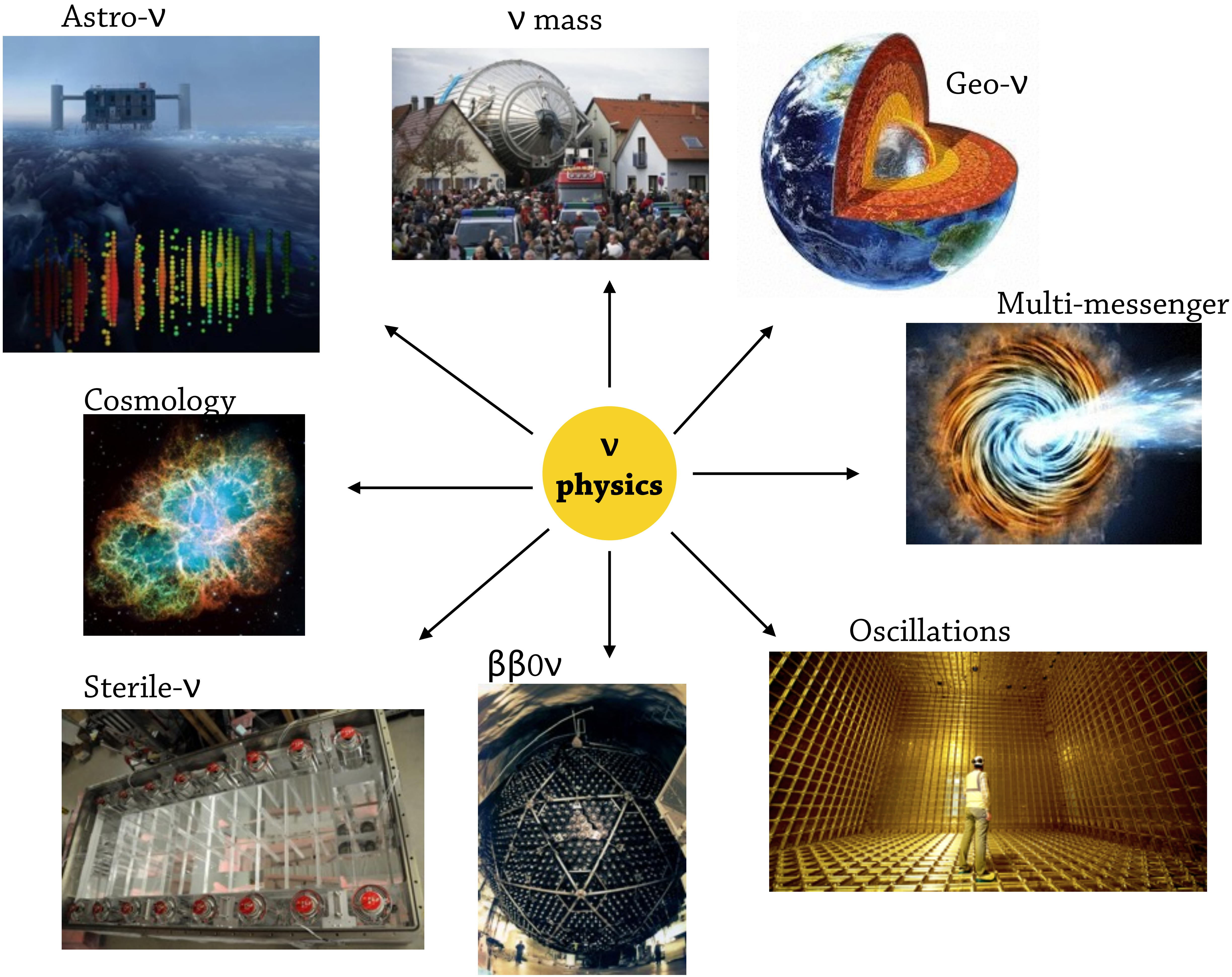
On September 22nd 2017 : **Simultaneous** light & neutrino detection from the TXS 0506+056 blazar

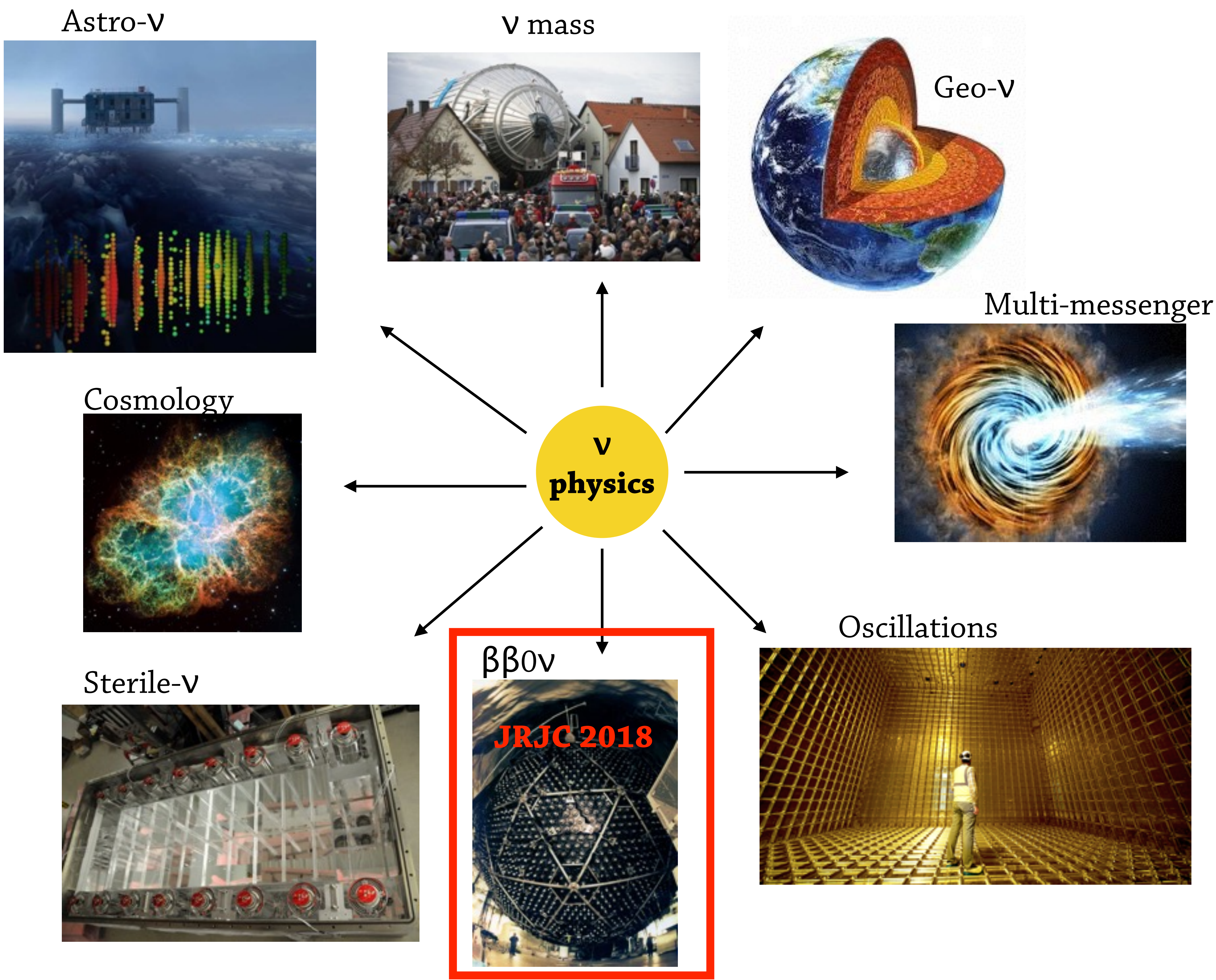
(blazar = Active Galactic Nucleus with one jet pointing to earth)





- 1st case of planned **multi-messenger** astronomy
- Confirmed that blazar emits neutrinos
- Next event with gravitational wave ?


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


Astro-ν
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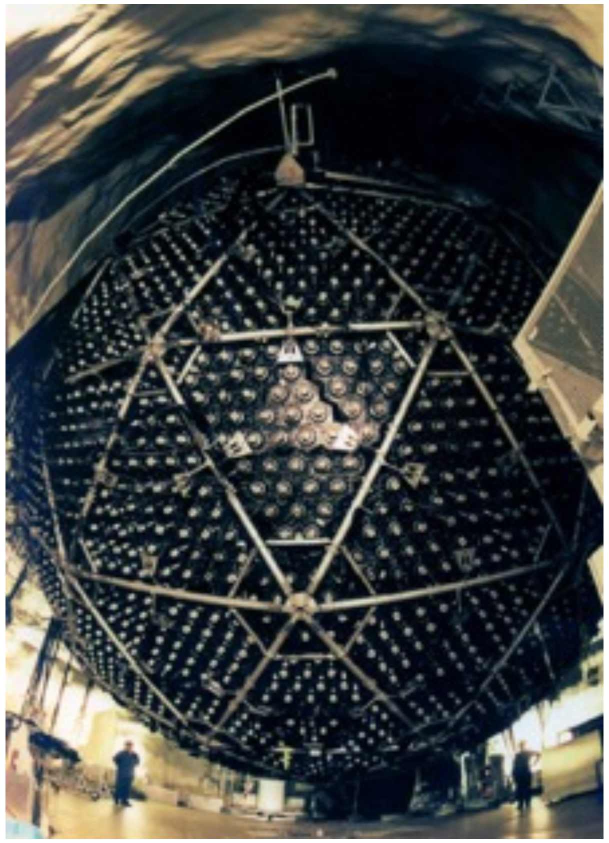
ν
physics
Sterile-ν
ββ0ν
JRJC 2018
Oscillations

ββ0ν experiments

Different Techniques

Liquid Scintillator



SNO+
KamLAND-zen

Bolometers

CUORE
Cupid
Gerda

Tracko-Calo

NEMO-3
SuperNEMO

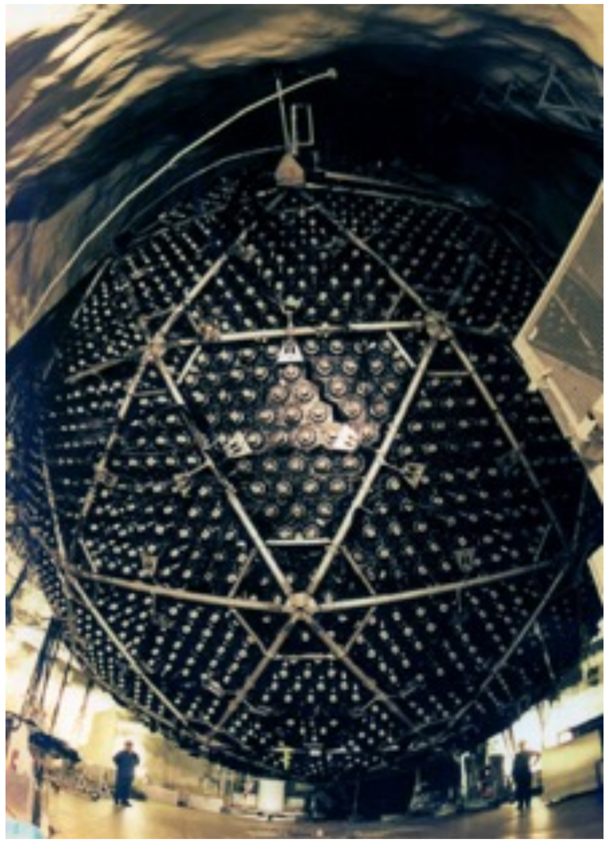
Next ?

NEXT
LiquidO

ββ0ν experiments

Different Techniques

Liquid Scintillator



SNO+
KamLAND-zen

Bolometers

CUORE
Cupid
Gerda

Tracko-Calo

NEMO-3
SuperNEMO
CLOÉ
HICHEM
AXEL

Next ?

NEXT
LiquidO
AXEL