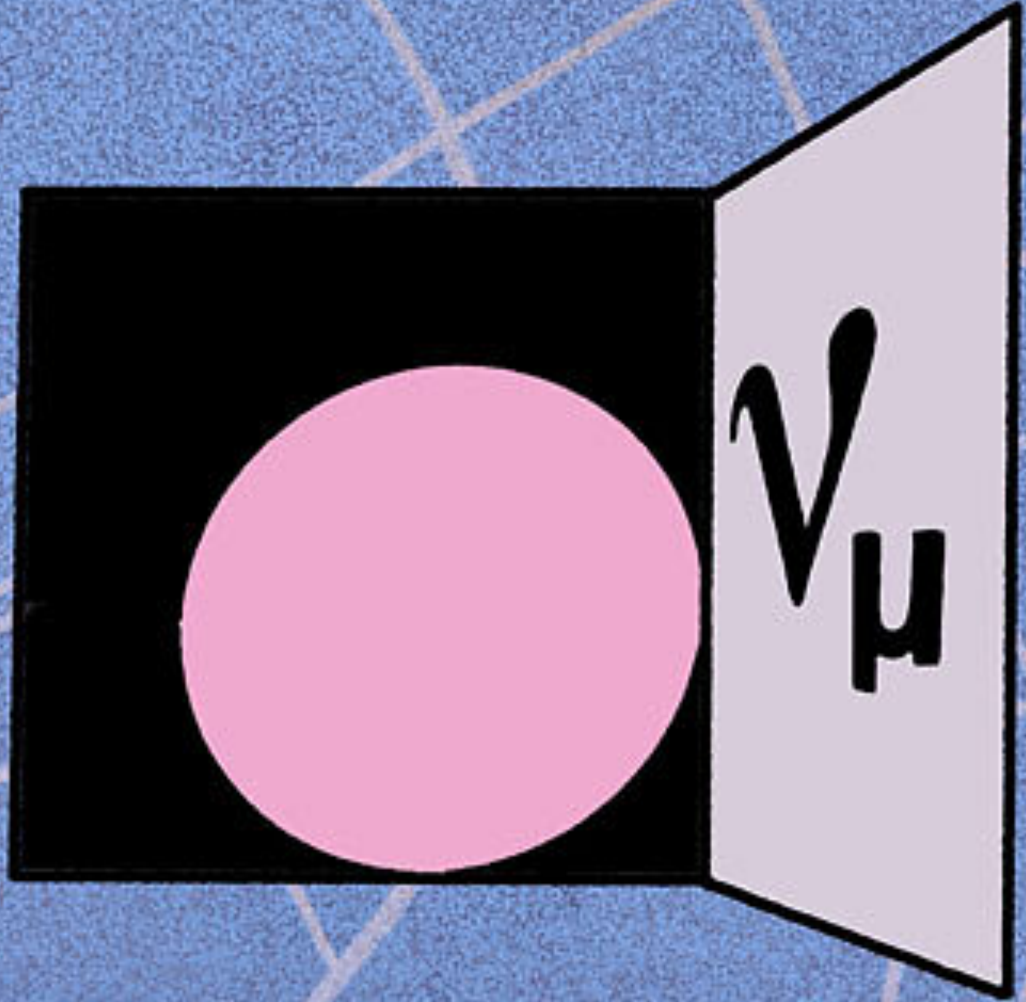
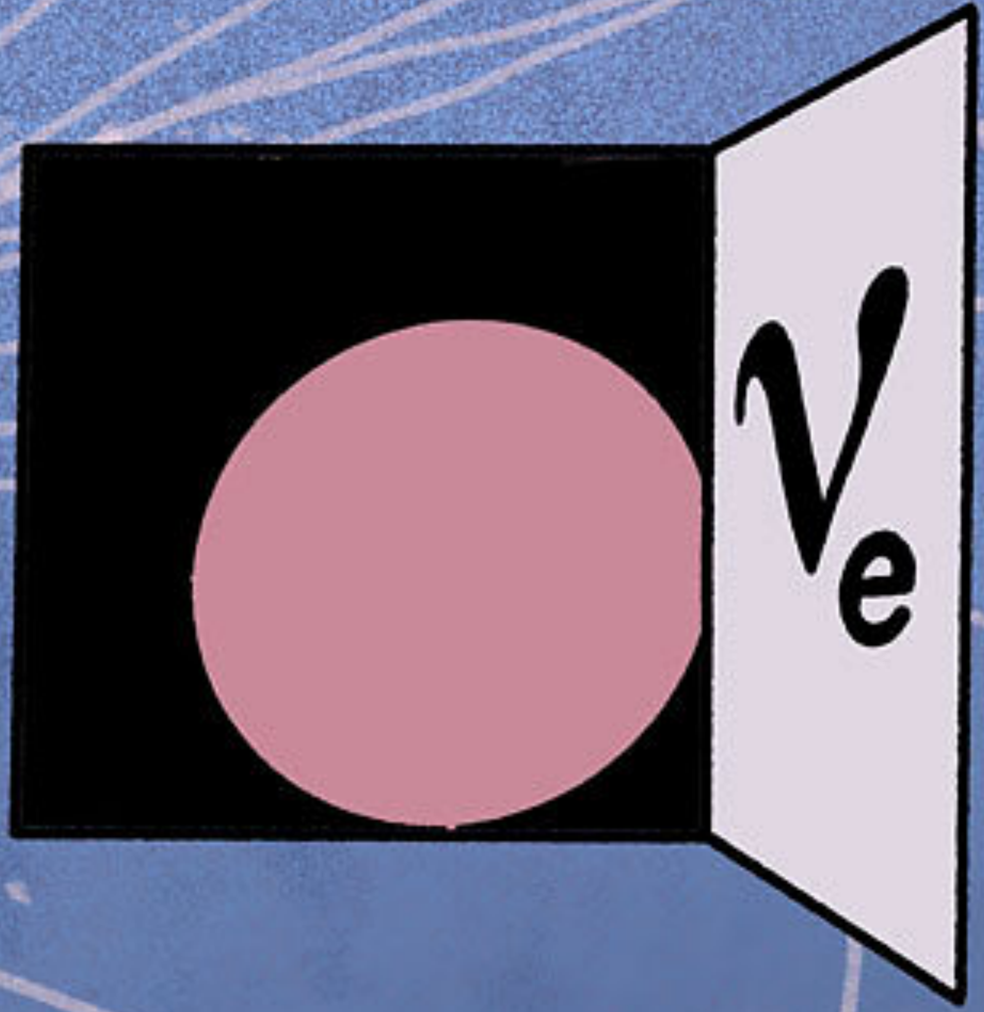
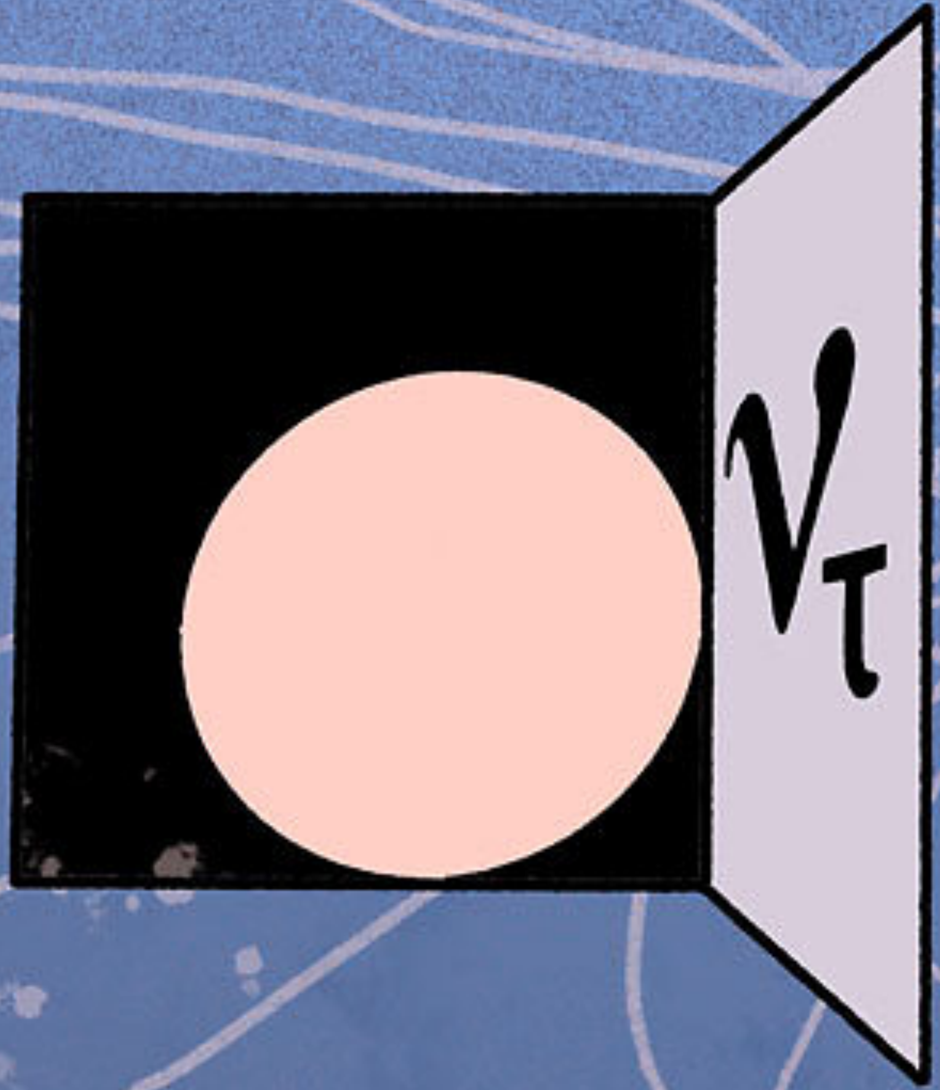
Background image's credit: Symmetry Magazine



Introduction on Neutrinos Physics





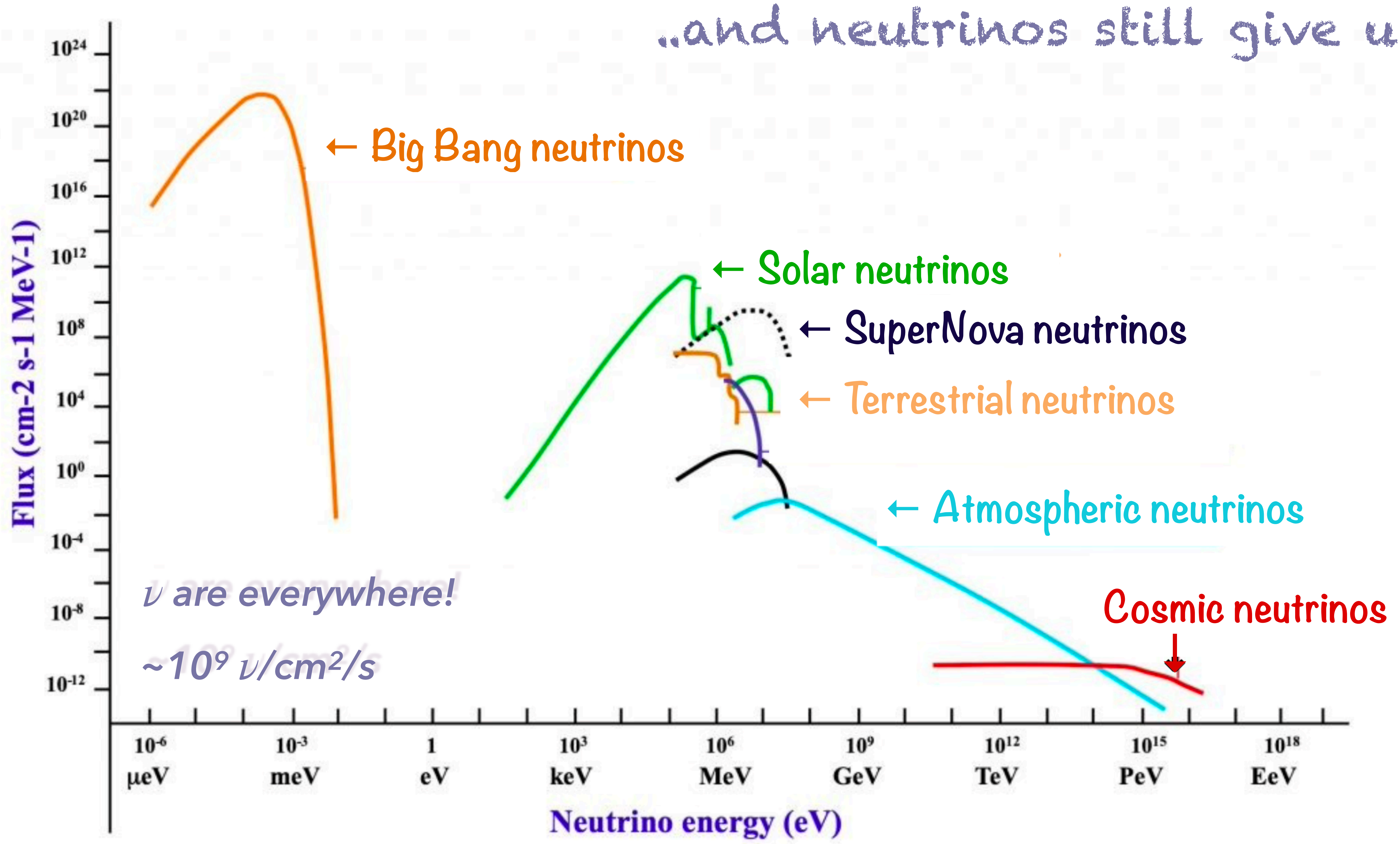
Chiara Lastoria - LPC Caen/CNRS

JRJC 2024 - Saint Jacut-de-la-Mer - 28.11.2023

Outline

- **Brief historical introduction on neutrino physics**
- **Where are we with our current understanding on neutrinos?**
- **A look toward the future!**

It's almost 100 years since they've been postulated
..and neutrinos still give us surprises!

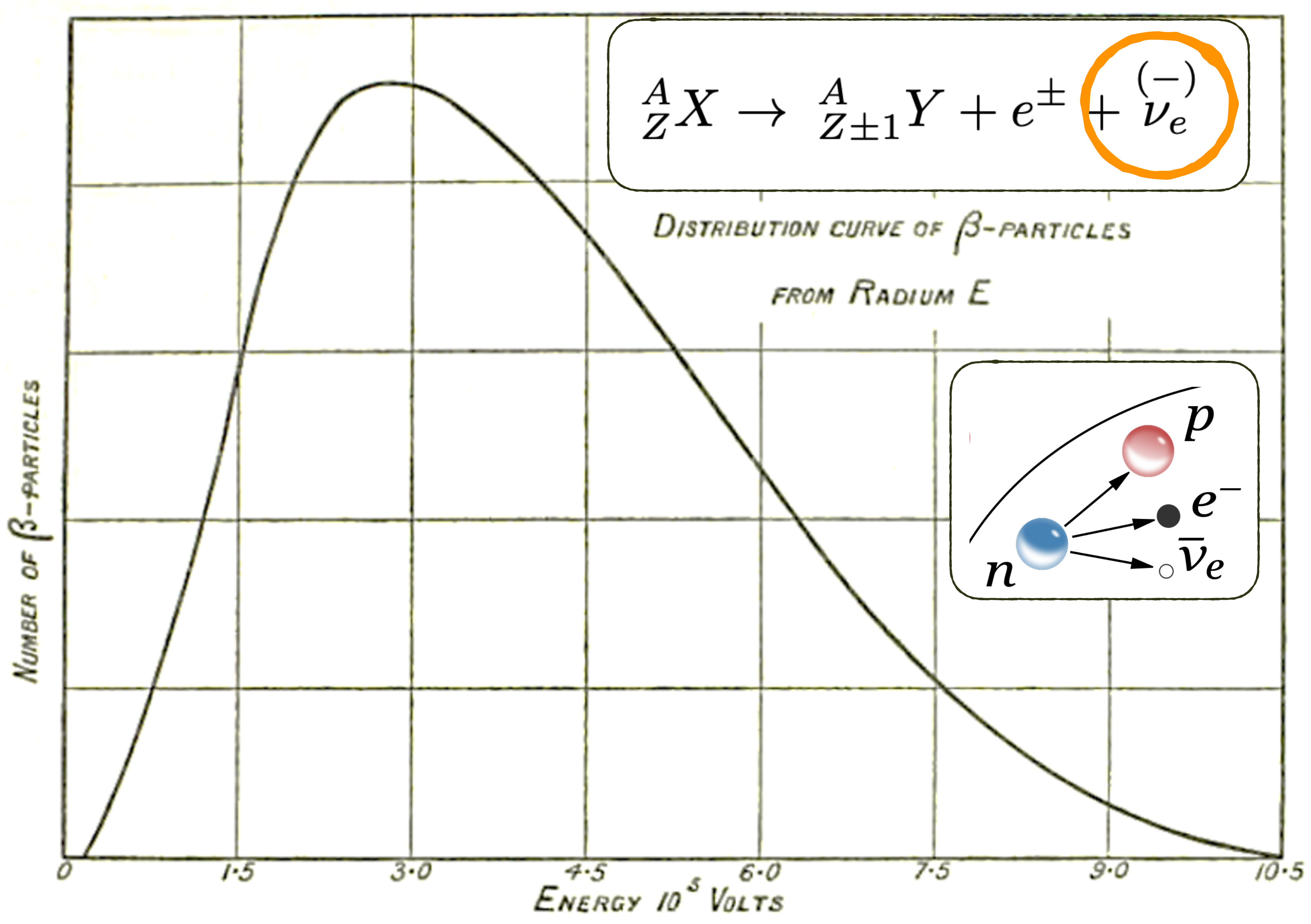


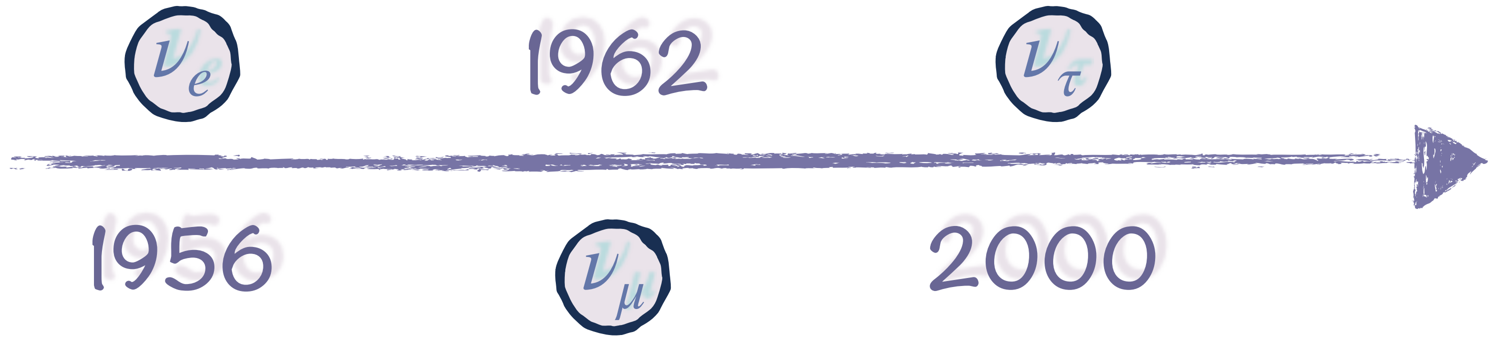
ν are everywhere!

~10^9 ν/cm²/s

Identikit of an introvert cool particle

- A “desperate remedy” postulated by Pauli in 1930
- E. Fermi, theory of weak interaction 1933

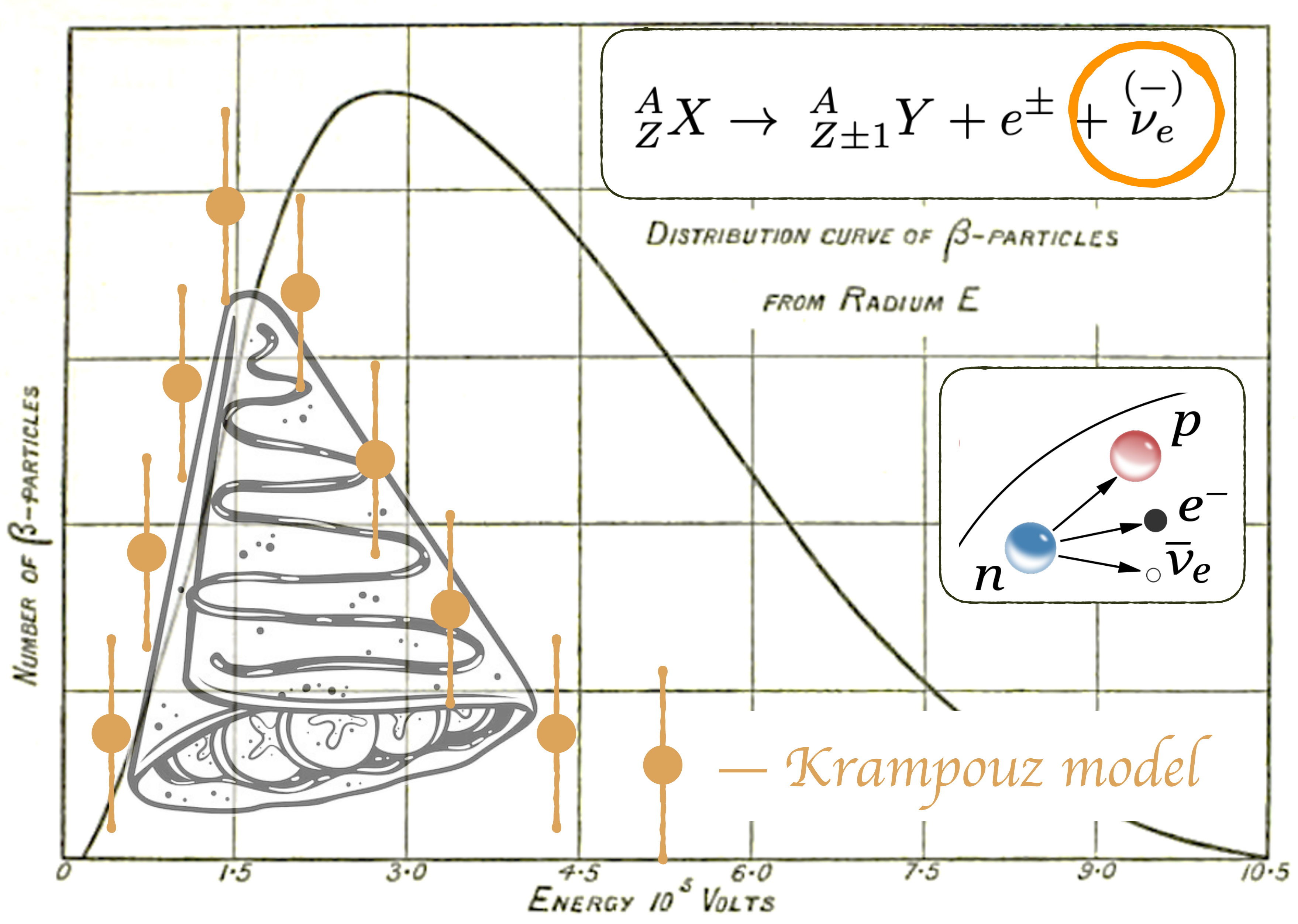


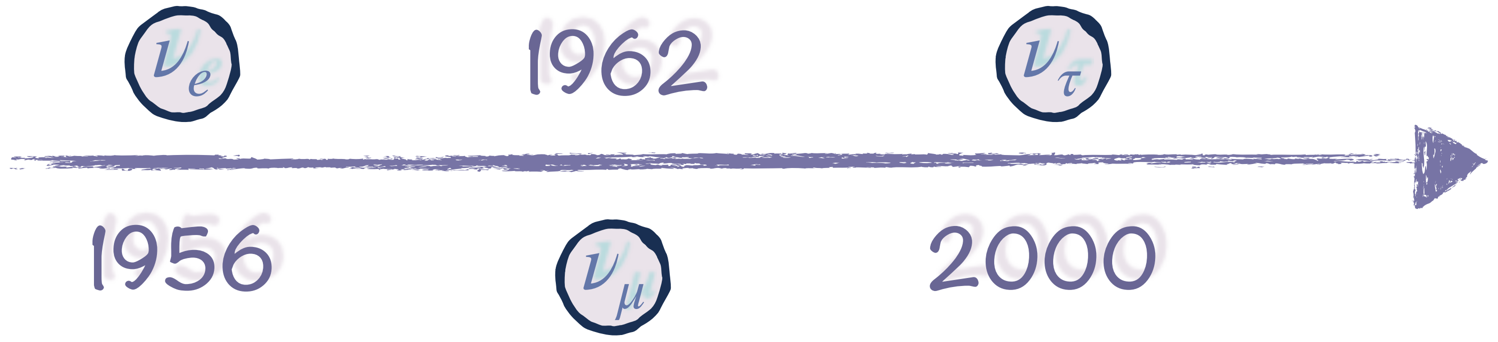


~70 years for discovery of all flavors

Identikit of an introvert cool particle

- A “desperate remedy” postulated by Pauli in 1930
- E. Fermi, theory of weak interaction 1933
- The Krampouz anomaly (1957)
  - ❍ **based on the observation of “sweet” particles**
  - ❍ **Kr, Am, Po, U, Z**



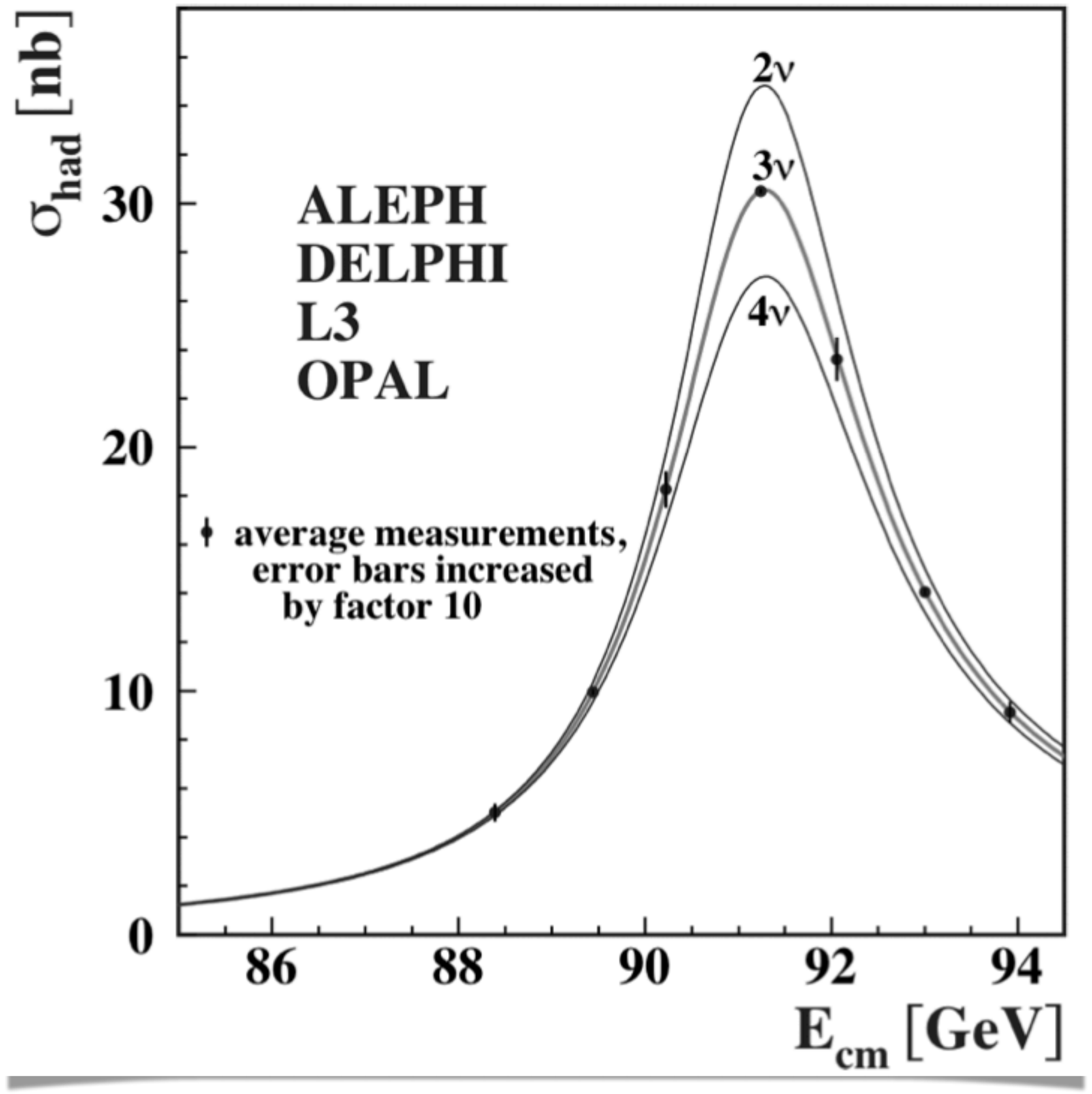


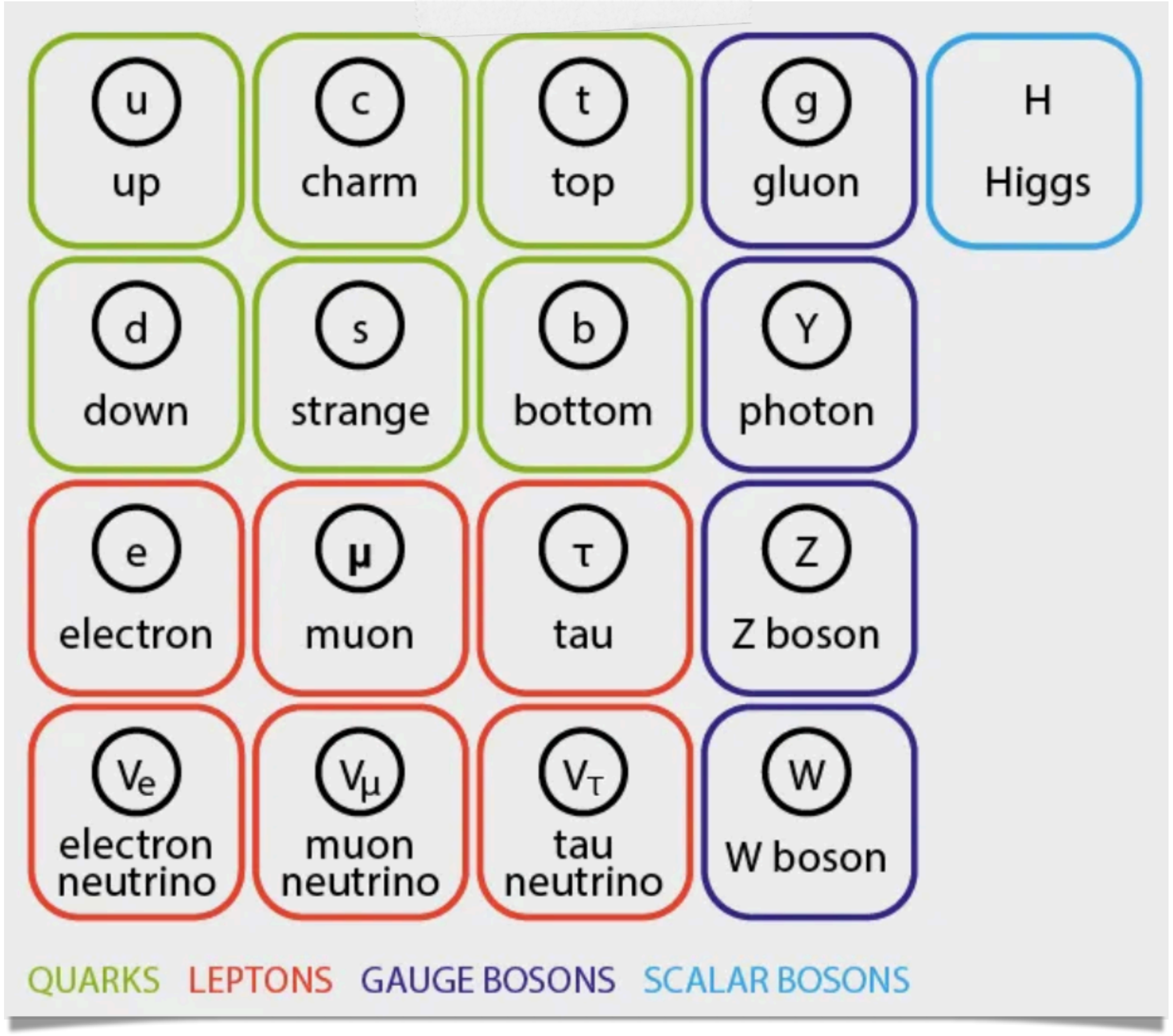
~70 years for discovery of all flavors

Identikit of an introvert cool particle

- A "desperate remedy" postulated by Pauli in 1930
- E. Fermi, theory of weak interaction 1933
- In the Standard Model (SM):
  - ❍ **neutral leptons, massless, weak interactions**
  - ❍ **three families of neutrinos: ν_e, ν_μ, ν_τ**

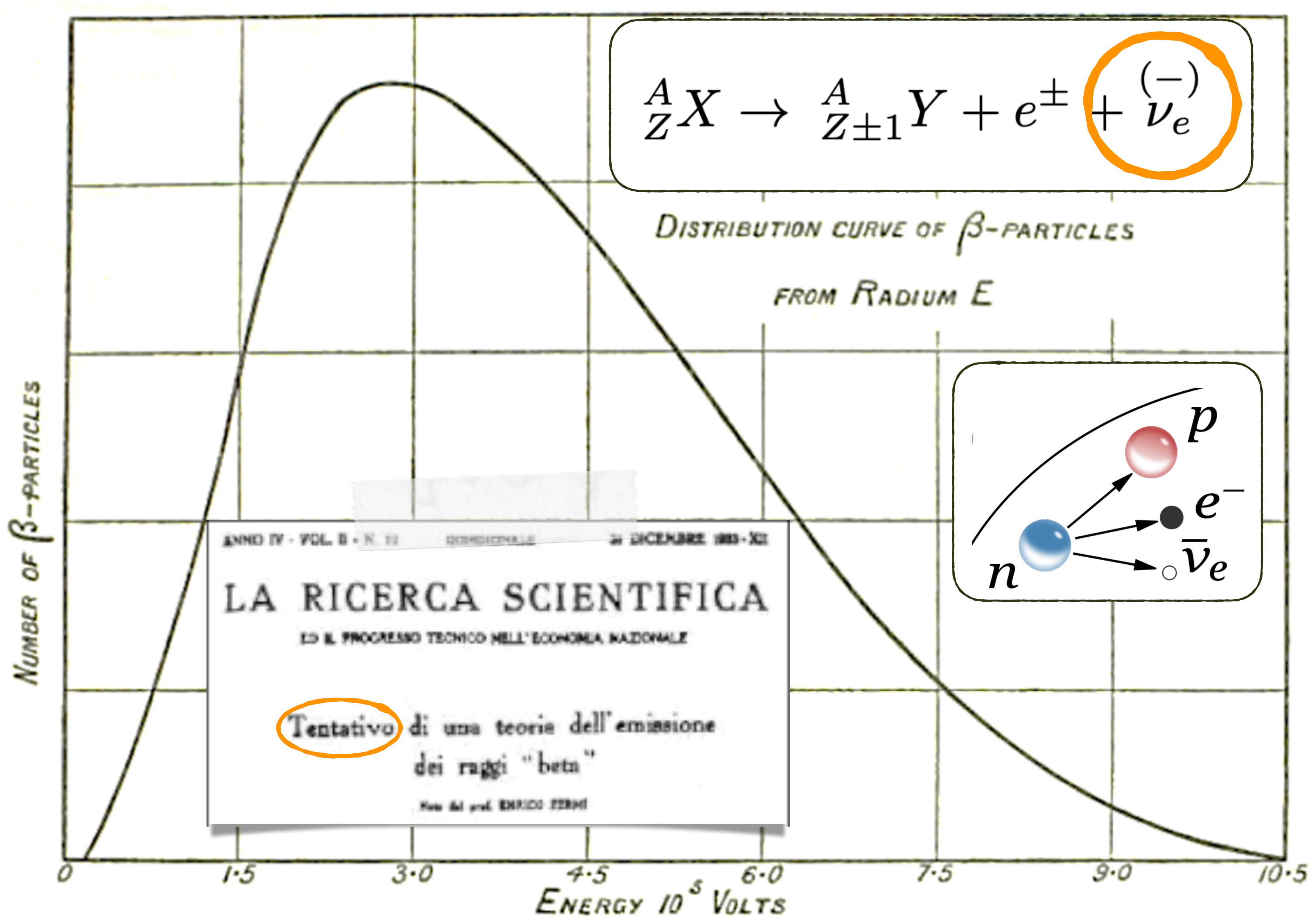
LEP results





u up	c charm	t top	g gluon	H Higgs
d down	s strange	b bottom	γ photon	
e electron	μ muon	τ tau	Z Z boson	
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS LEPTONS GAUGE BOSONS SCALAR BOSONS



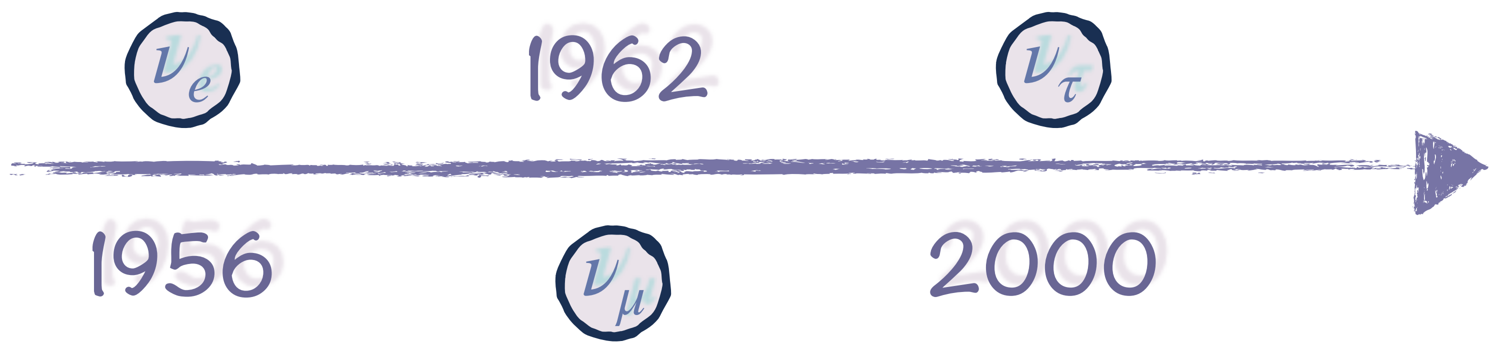
$$^A_ZX \rightarrow {}^{\;\;A}_{Z\pm1}Y + e^{\pm} + \overset{(-)}{\nu_e}$$

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

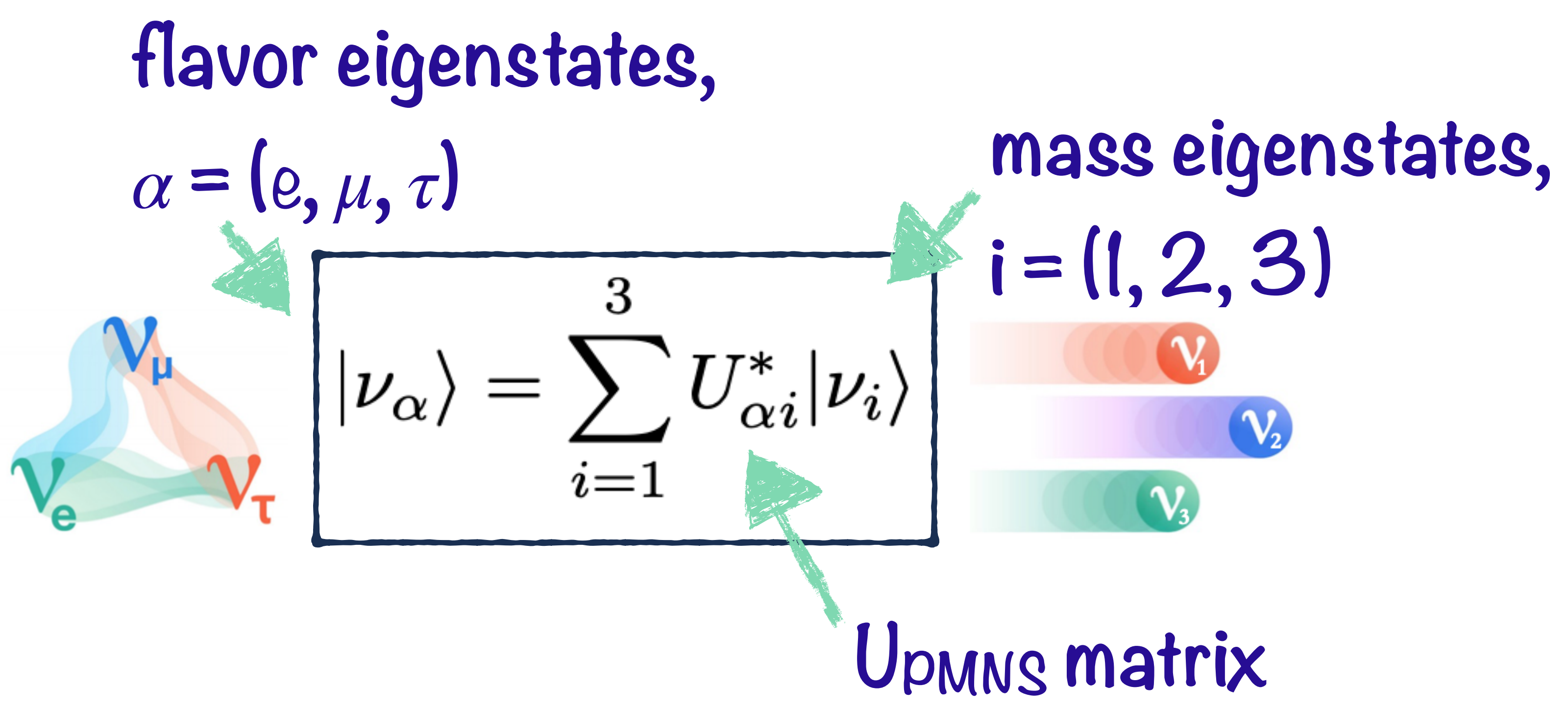
Nota del prof. ENRICO FERMI



~70 years for discovery of all flavors

The neutrino oscillation mechanism

- Only possible if neutrinos have non-zero mass (**first evidence of beyond the SM physics! 😎**)
- For three neutrinos, the mixing is expressed via the **unitary PMNS matrix**
  - ❍ three mixing angles: θ_{12}, θ_{23}, and θ_{13}
  - ❍ two mass splitting: Δm^2_{21} and Δm^2_{31}
  - ❍ one CP violation phase: δ_{CP}



flavor eigenstates,
$\alpha = (e, \mu, \tau)$

mass eigenstates,
i = (1, 2, 3)

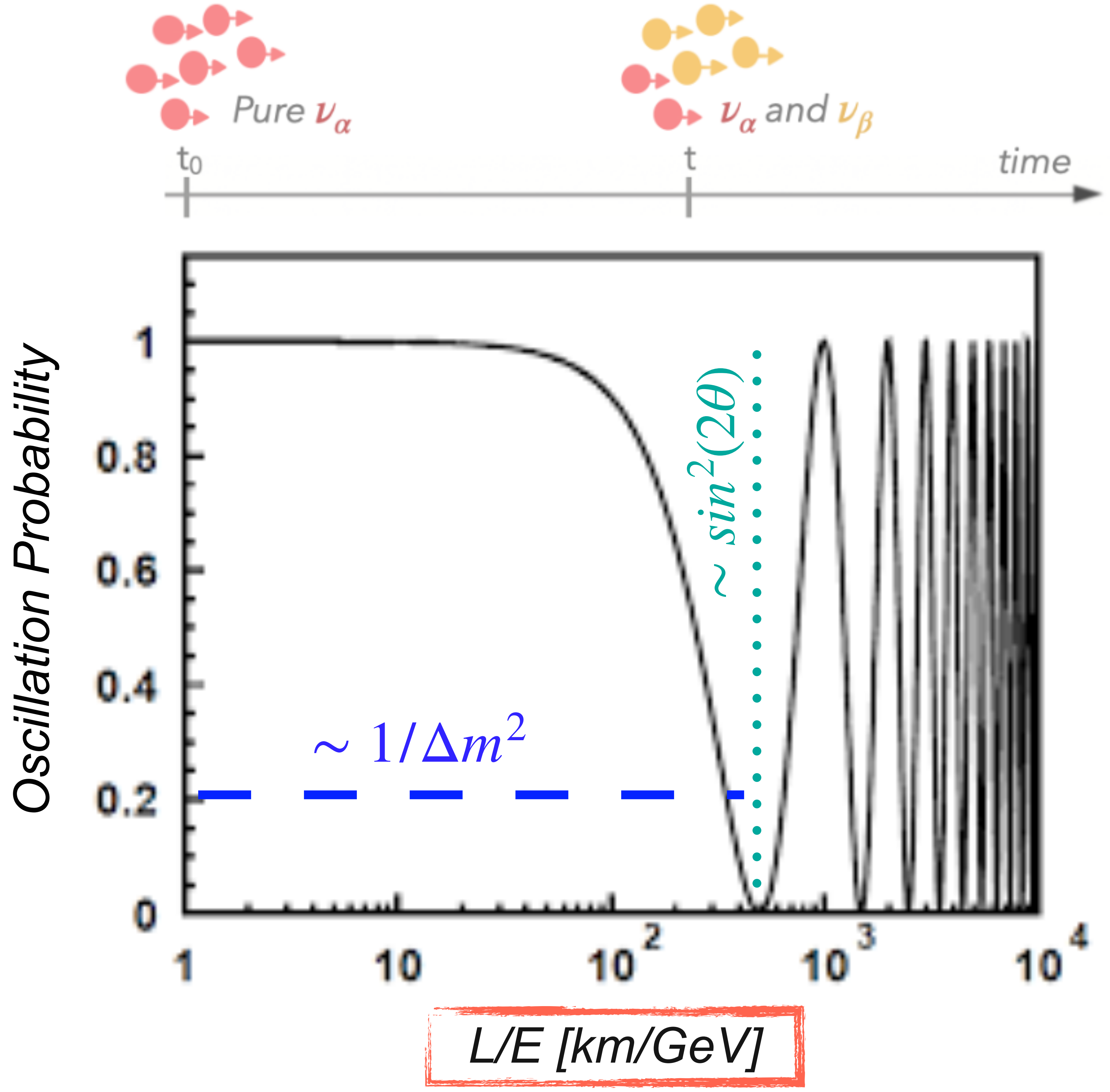
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

U

Oscillation probability:

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

θ = mixing angle, $\Delta m^2 = m_1^2 - m_2^2$, L = baseline, E = energy



The neutrino oscillation mechanism

Contribution of several experiments for a comprehensive measurement of the oscillation parameters

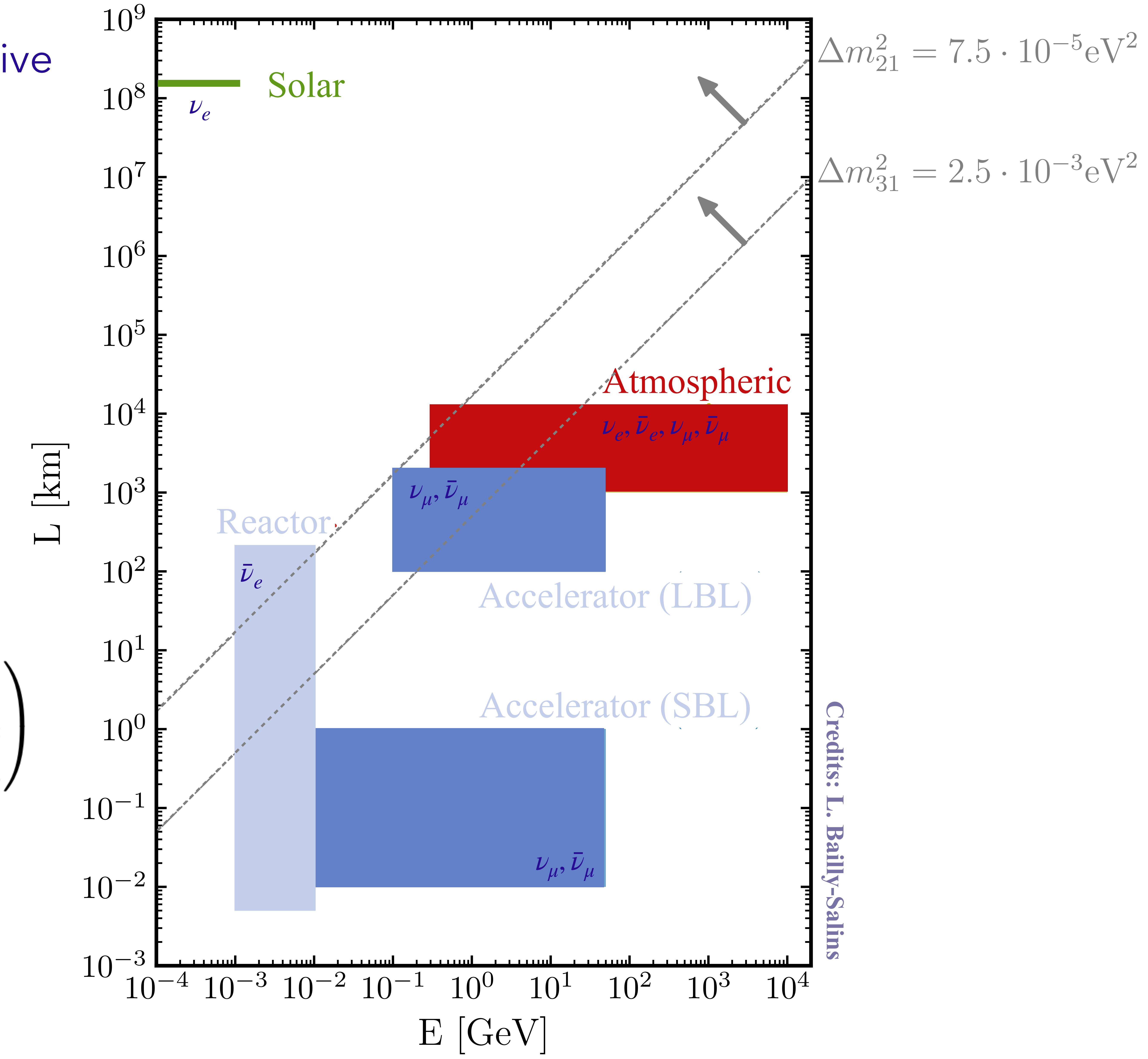
- solar neutrino puzzle
- atmospheric neutrino anomaly

(more in bkp slides)

U_{PMNS} (3x3, unitary)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \overbrace{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}}^{\text{Atmospheric}} \times \overbrace{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}}^{\text{Reactor/Accelerator}} \times \overbrace{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}}^{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

* $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

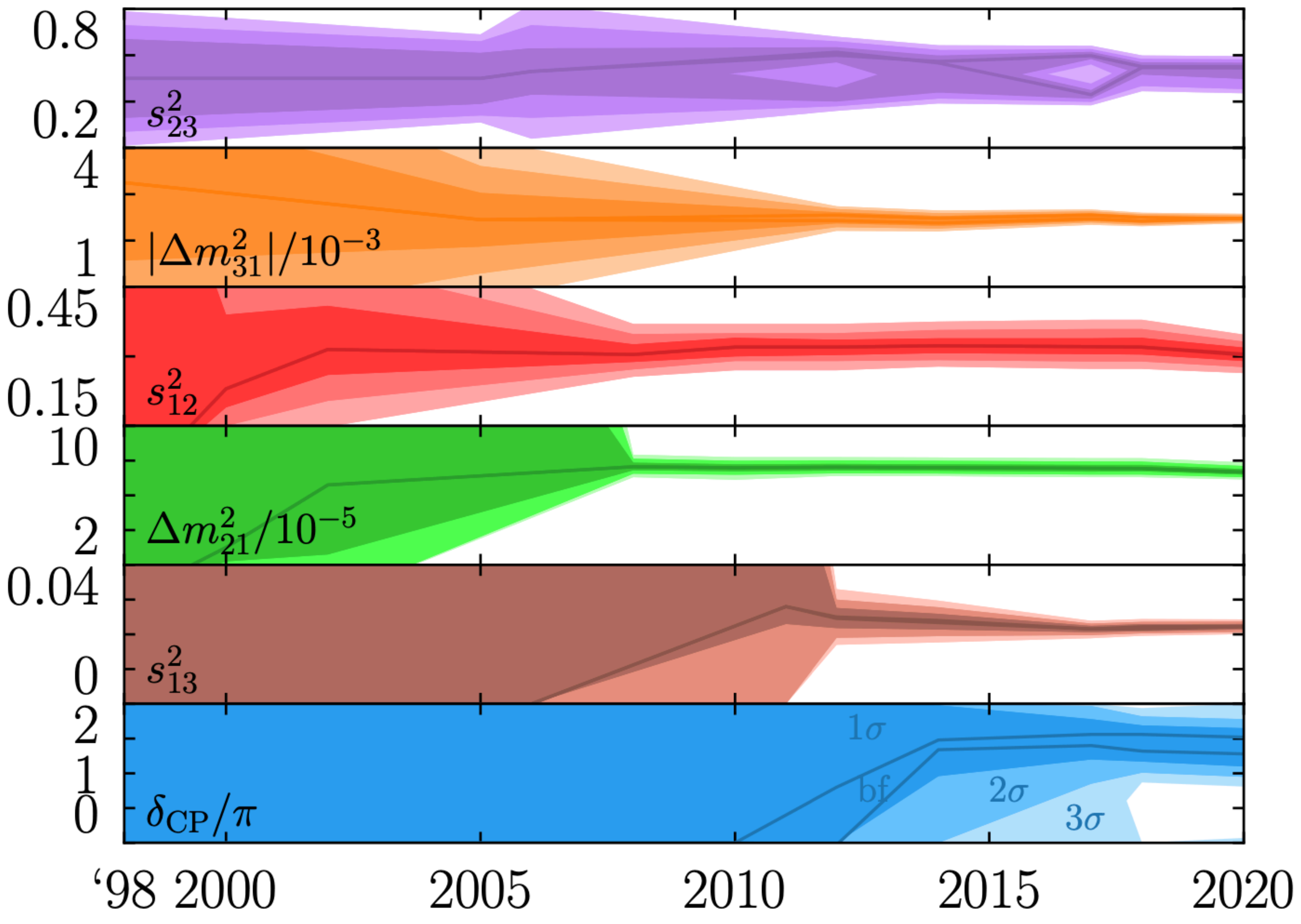


Credits: L. Bailly-Salins

State of the art of oscillation parameters

U_{PMNS} (3x3, unitary)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \overset{\text{Atmospheric}}{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}} \times \overset{\text{Reactor/Accelerator}}{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



1σ uncertainty

3%

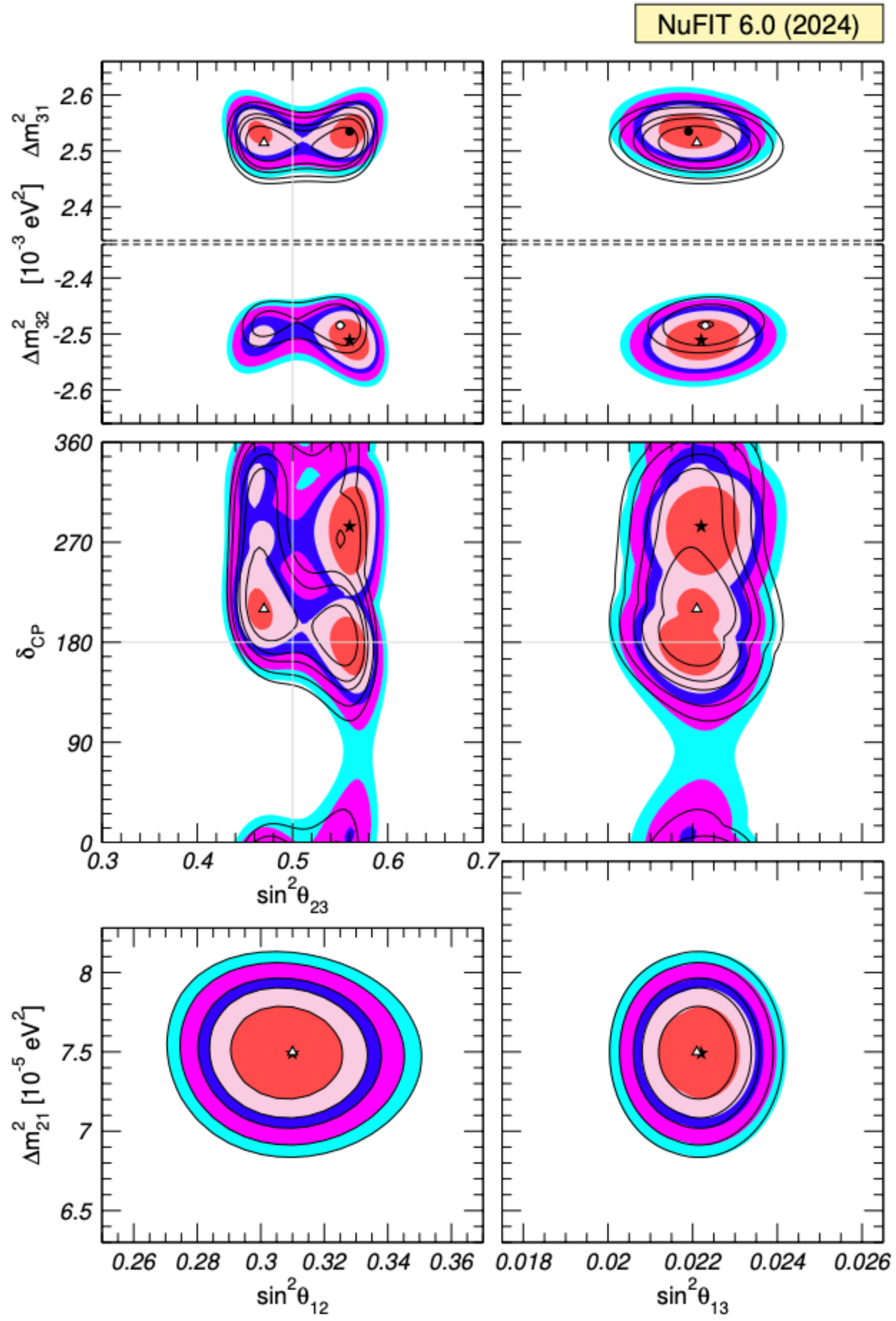
1%

5%

3%

2.5%

15%



Remaining open questions up to today

Which neutrino is the lightest?

- sign of Δm^2_{31} ?

Is ν_3 mostly ν_μ or ν_τ?

- $\theta_{23} < \pi/4$, $\theta_{23} > \pi/4$, or $\theta_{23} = \pi/4$?

Is CP violated in the leptonic sector?

- $\delta_{CP} \neq 0$?

What are their masses?

- direct and indirect measurements

Is the 3ν-flavor paradigm correct?

- is the PMNS unitary?
- do we have sterile neutrinos? if so, how many?

Are neutrinos Dirac/Majorana particles?

Is the 3ν-flavor correct?

- **at short and long baselines**
  - accelerator/reactor experiments (e.g. STEREO)
  - accelerator/atmospheric experiments (e.g. DUNE)

within the 3ν flavor paradigm..

U_{PMNS} matrix

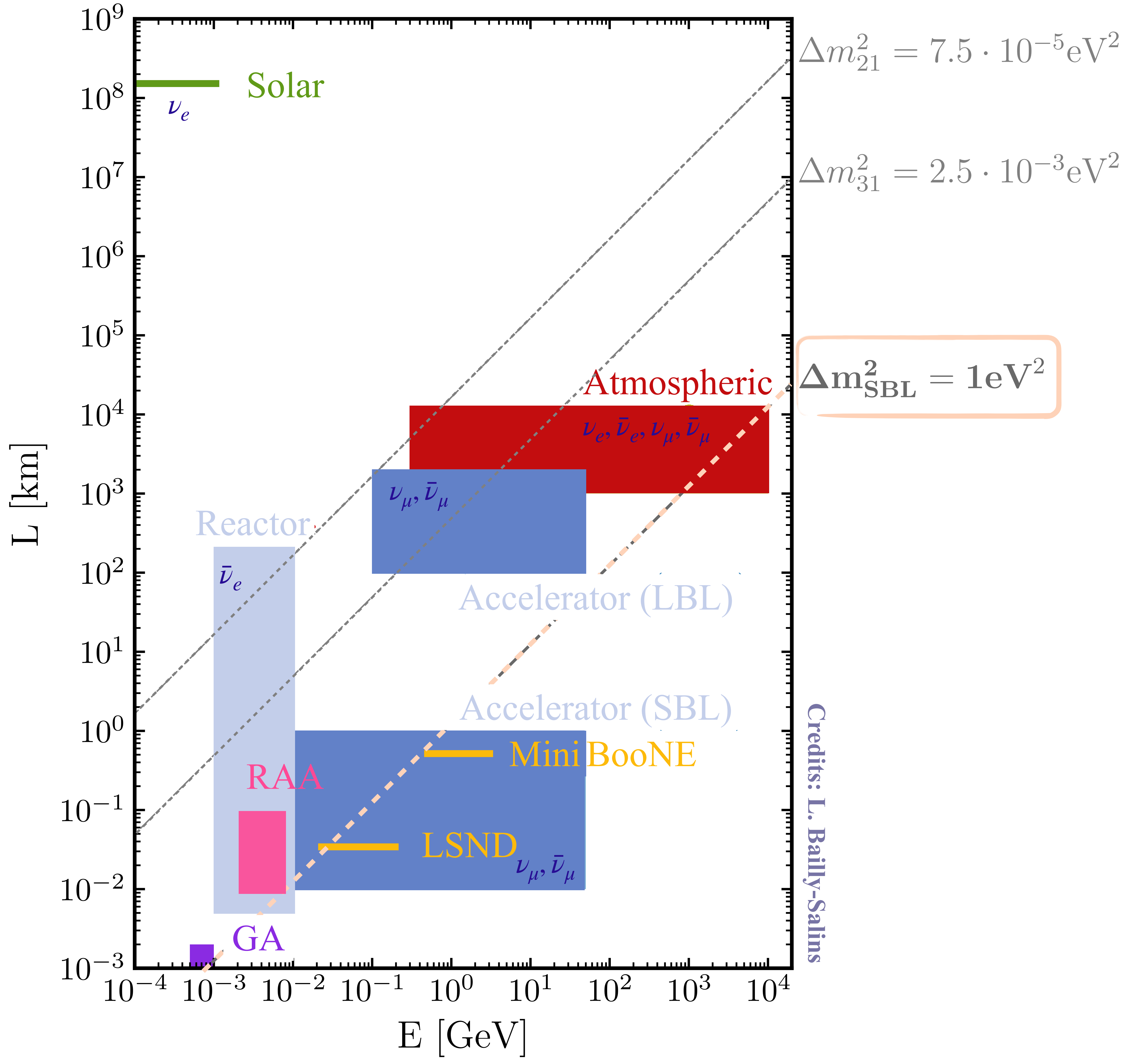
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & ? \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & ? \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & ? \\ ? & ? & ? & ? \end{pmatrix}$$

via oscillation..

more parameters:
$\Delta m^2_{41}, \theta_{14}, \theta_{24}, \theta_{34},$
δ_{14}, δ_{24}

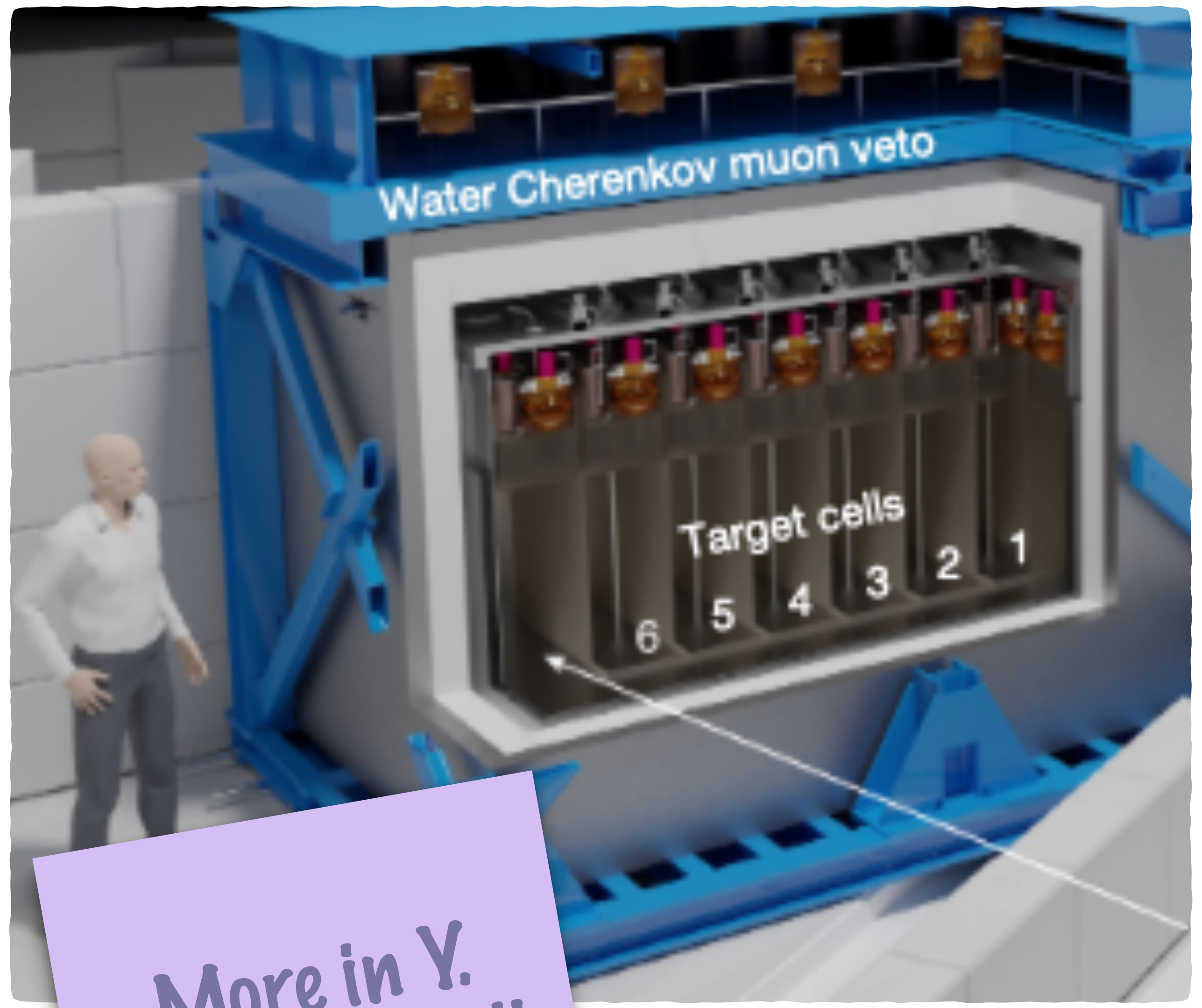
3+1 sterile

..and beyond!

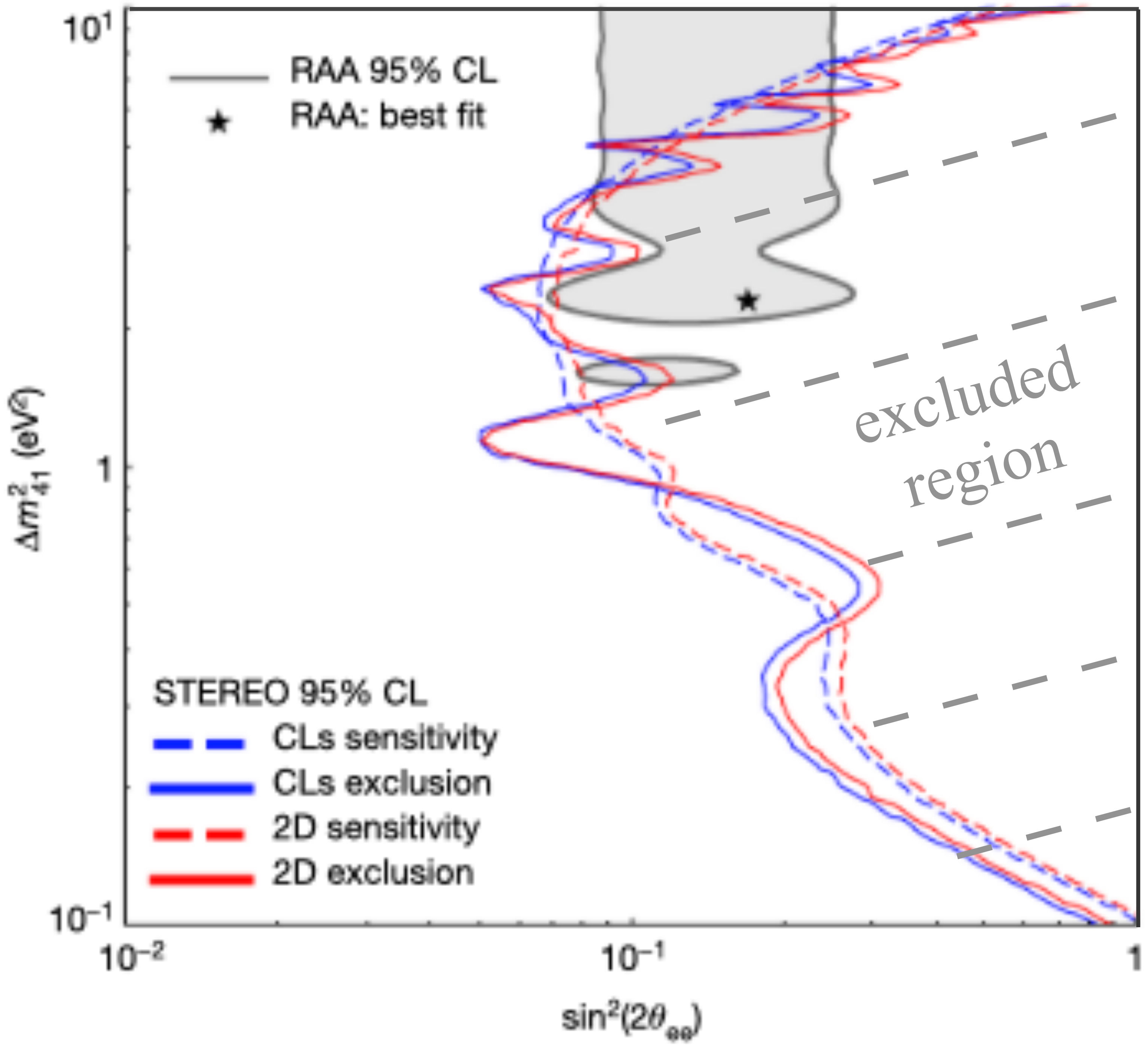


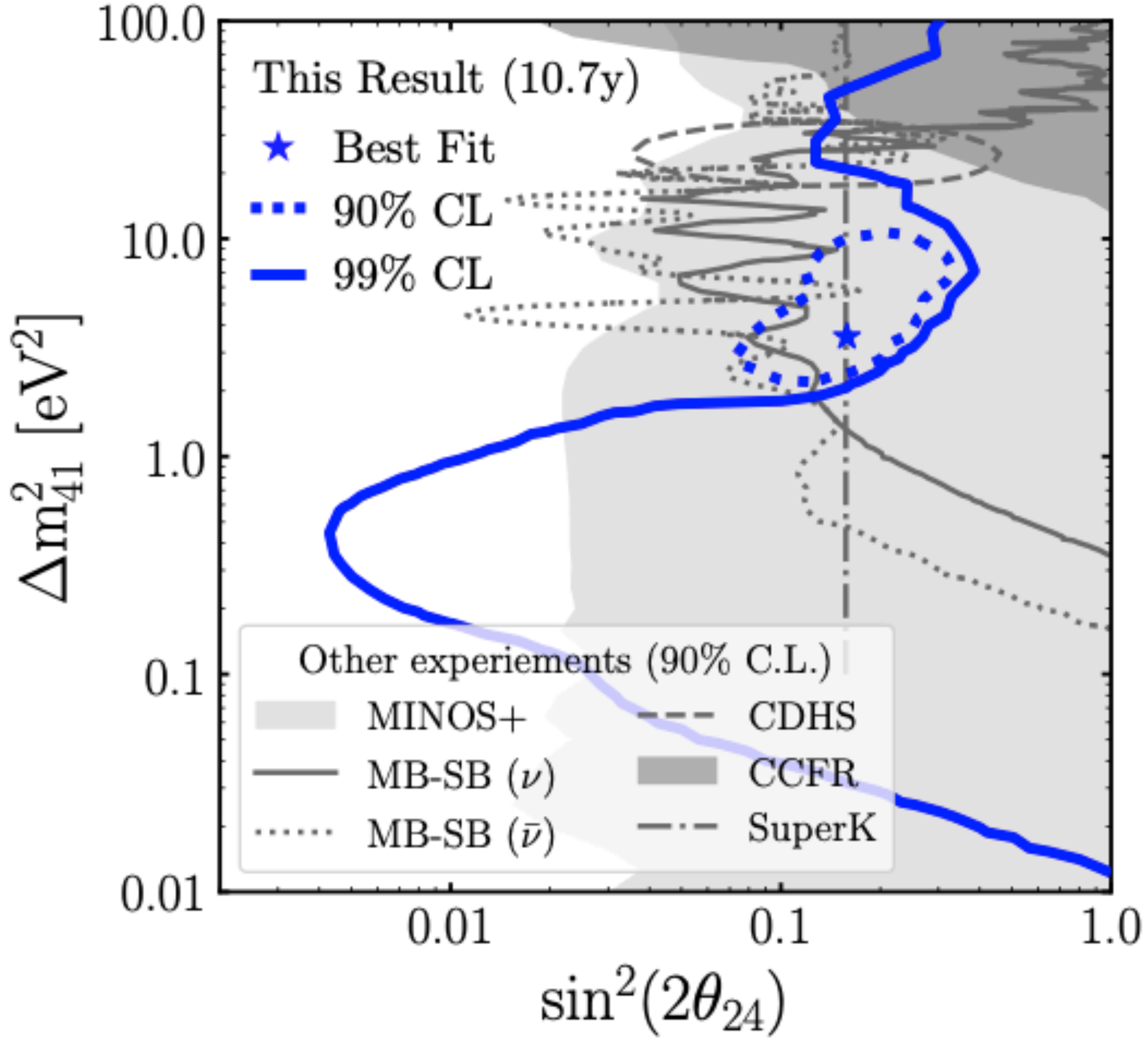
Sterile neutrinos: 3+1 extension

- **STEREO (reactor experiment)**
  - ❍ anti-nue at reactor, very short baseline
  - ❍ rejection of RAA best fit value



More in Y. Querlioz's talk

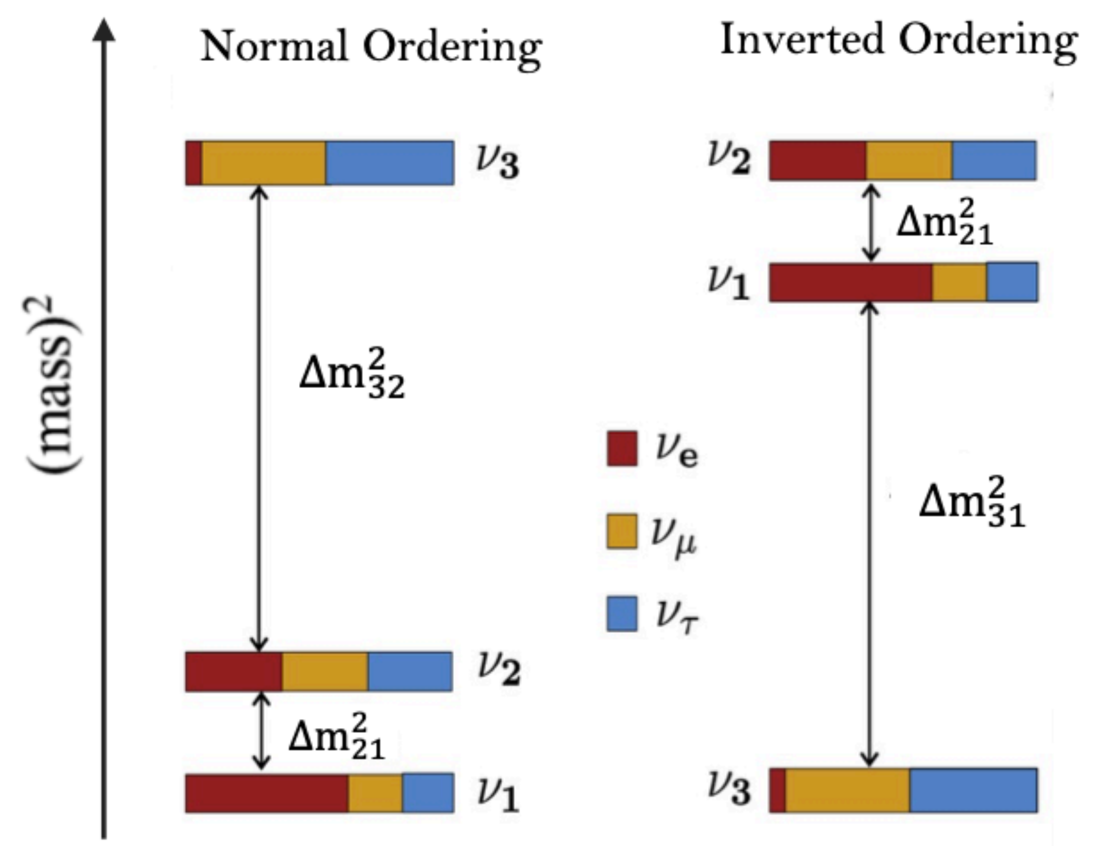




- **IceCube (atmospheric experiment)**
  - ❍ ν_μ spectrum at TeV
  - ❍ absence of sterile neutrino (2.2σ)
- cross-check with other experiments (e.g. KM3NeT) is crucial

Toward a precision era for neutrinos

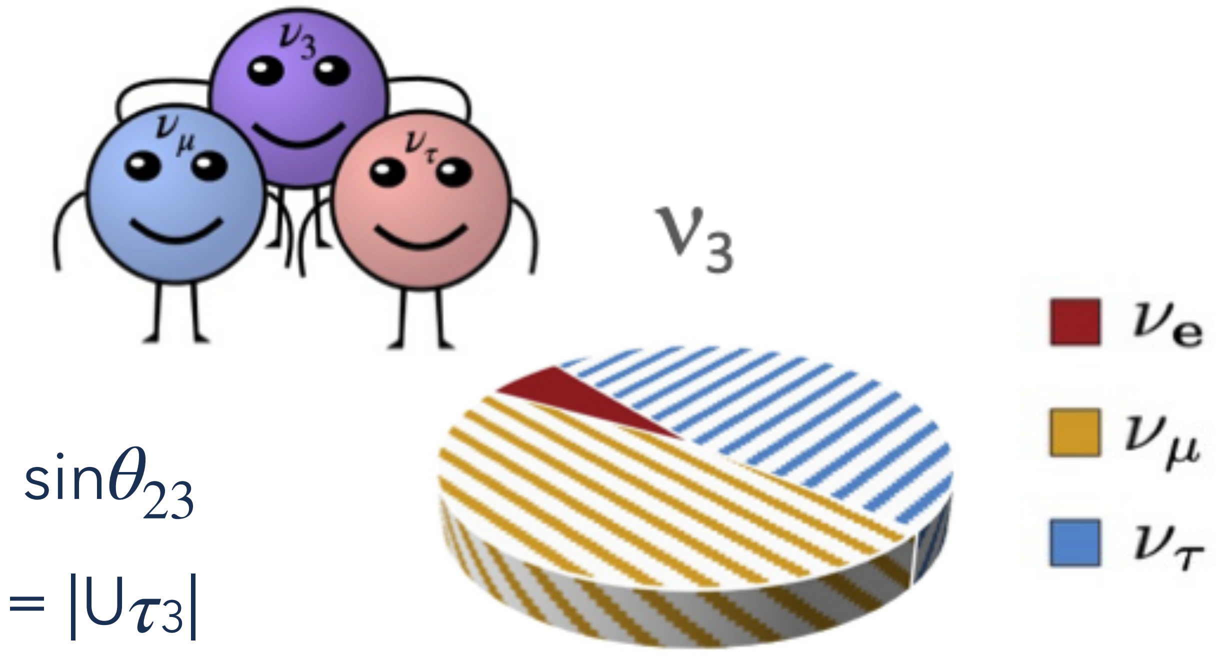
- which neutrino is the lightest? **Neutrino Mass Ordering**
- is ν_3 mostly ν_μ or ν_τ? θ_{23} **octant**
- is the charge-parity (CP) violated in the leptonic sector? δ_{CP} **phase**



we know that:

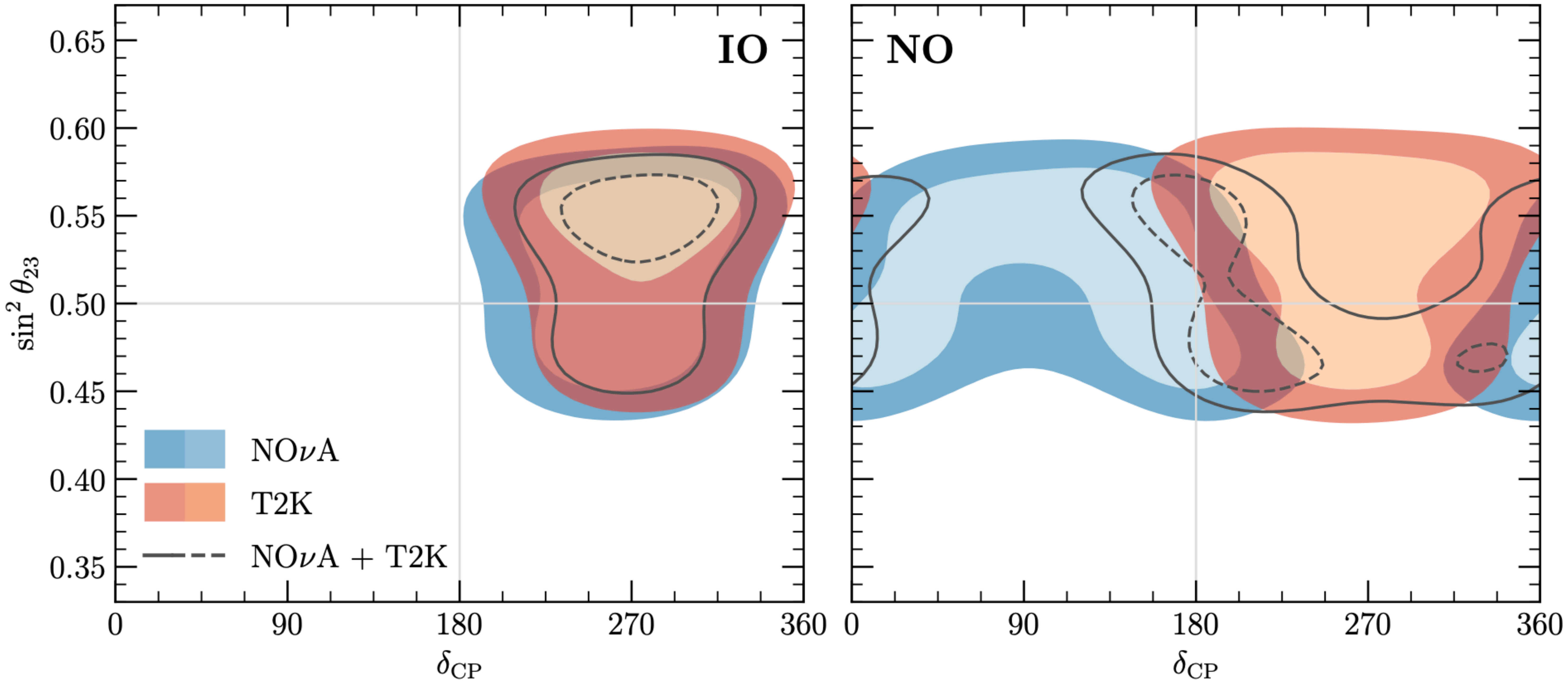
- $m_1^2 < m_2^2$
- $m_2^2 - m_1^2 << |m_3^2 - m_{1,2}^2|$

what about signΔm^2_{31}?



5% precision on sinθ_{23}

if θ_{23}=45°, $|U_{\mu 3}| = |U_{\tau 3}|$



Do neutrinos and anti-neutrinos oscillate differently?

Next-generation for neutrino experiments

- Complementary detection techniques for a better understanding of systematics
  - **unprecedented statistics**
  - **remarkably energy resolution**
  - **excellent background rejection**

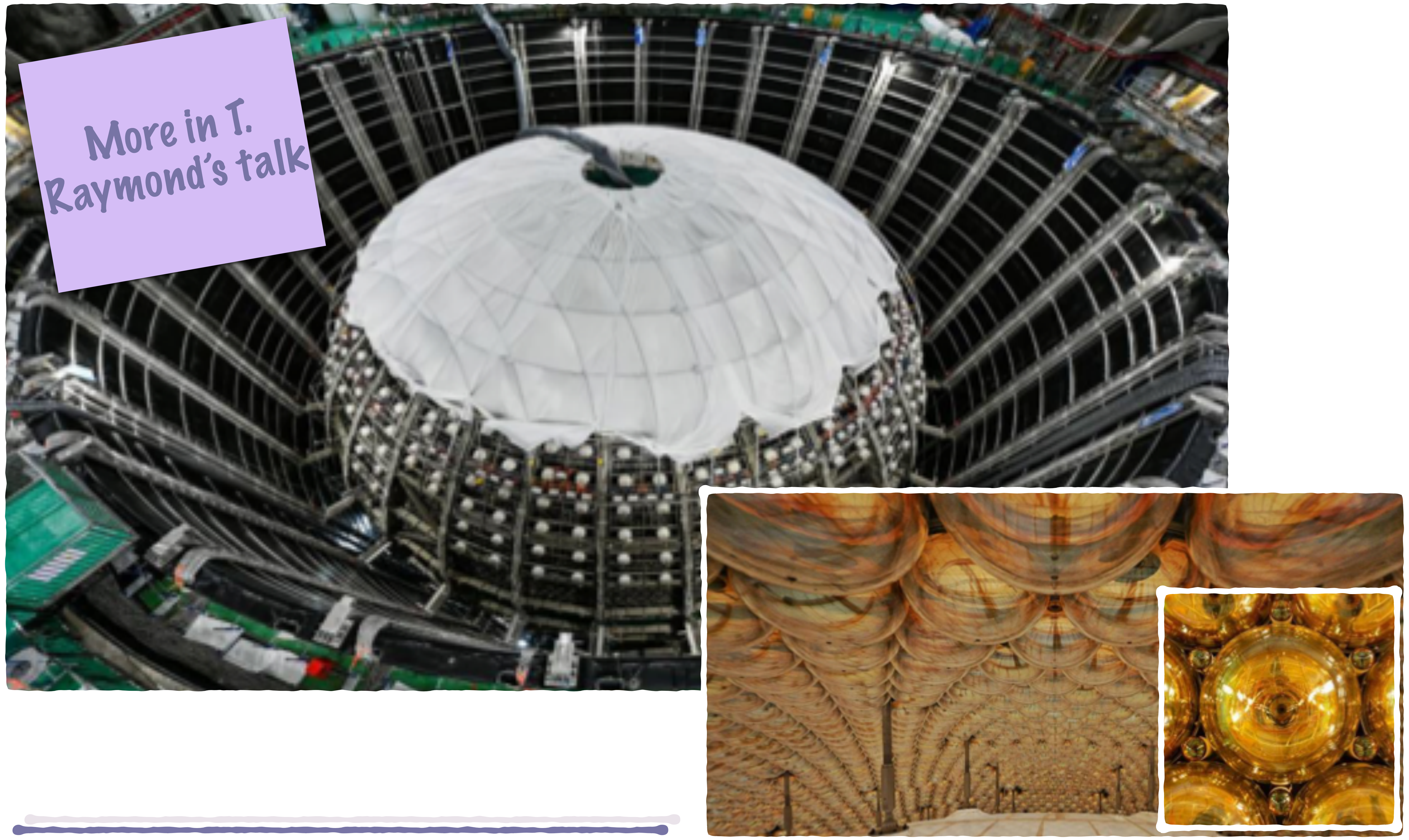
- multi-purpose detectors for MeV to GeV neutrinos
  - reactor neutrinos
  - accelerator neutrinos
  - solar, SN, atmospheric neutrinos

	DUNE	Hyper-K	JUNO
Baseline	1300 km	295 km	53 km
Energy	(0.8 - 6) GeV *	600 MeV	(1-10) MeV
Fiducial Volume	40 kton	190 kton	20 kton
Technology	LAr-TPC	Water Cherenkov	Liquid scintillator
Data taking start	2029	2027	2025

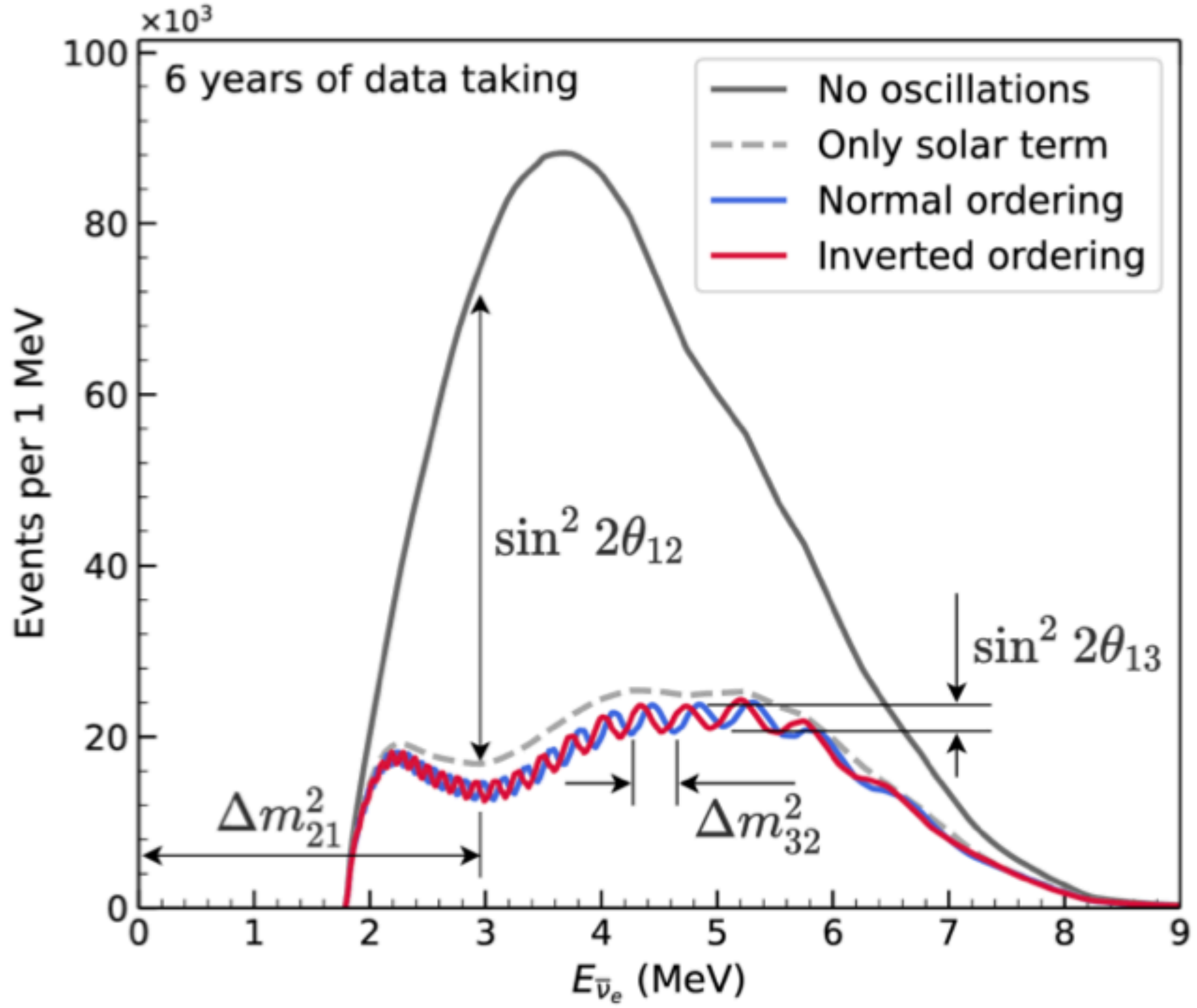
* *most powerful, worldwide*

Jiangmen Underground Neutrino Observatory (JUNO)

- 8 reactors cores, 20-kton liquid scintillator
  - ❍ low background (material screening, clean background)
  - ❍ **remarkable energy resolution (~3% @ 1MeV)**
  - ❍ precise knowledge of reactor spectra



More in T. Raymond's talk

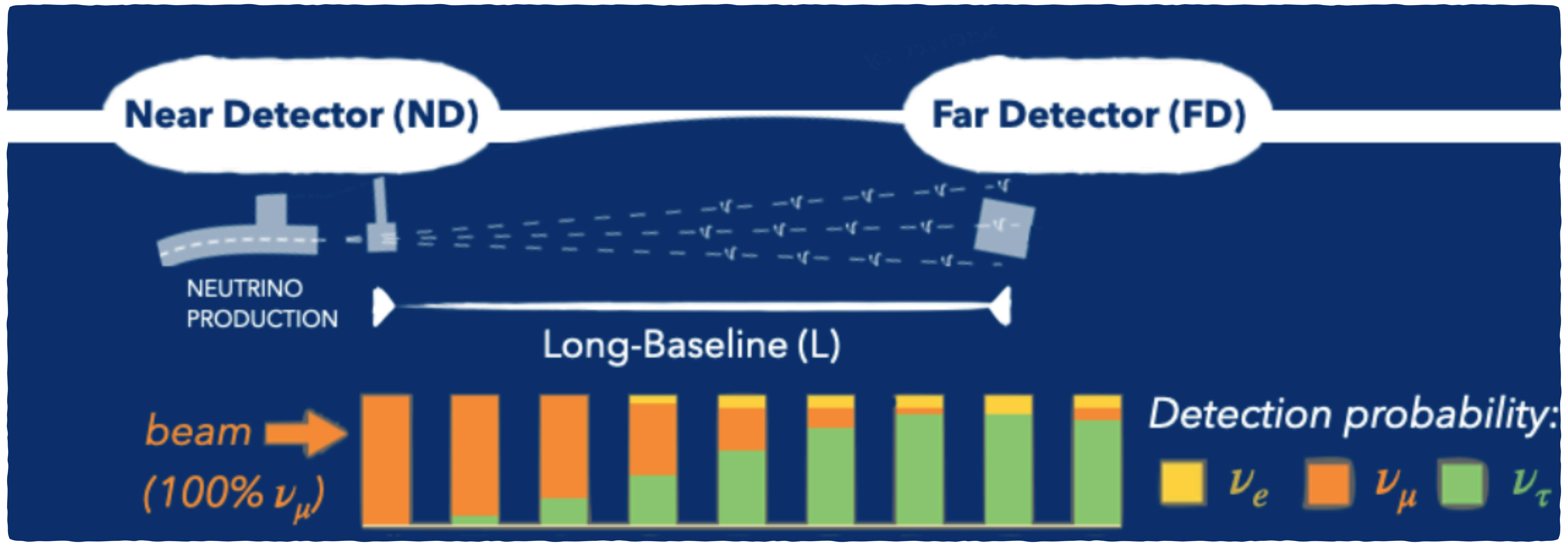


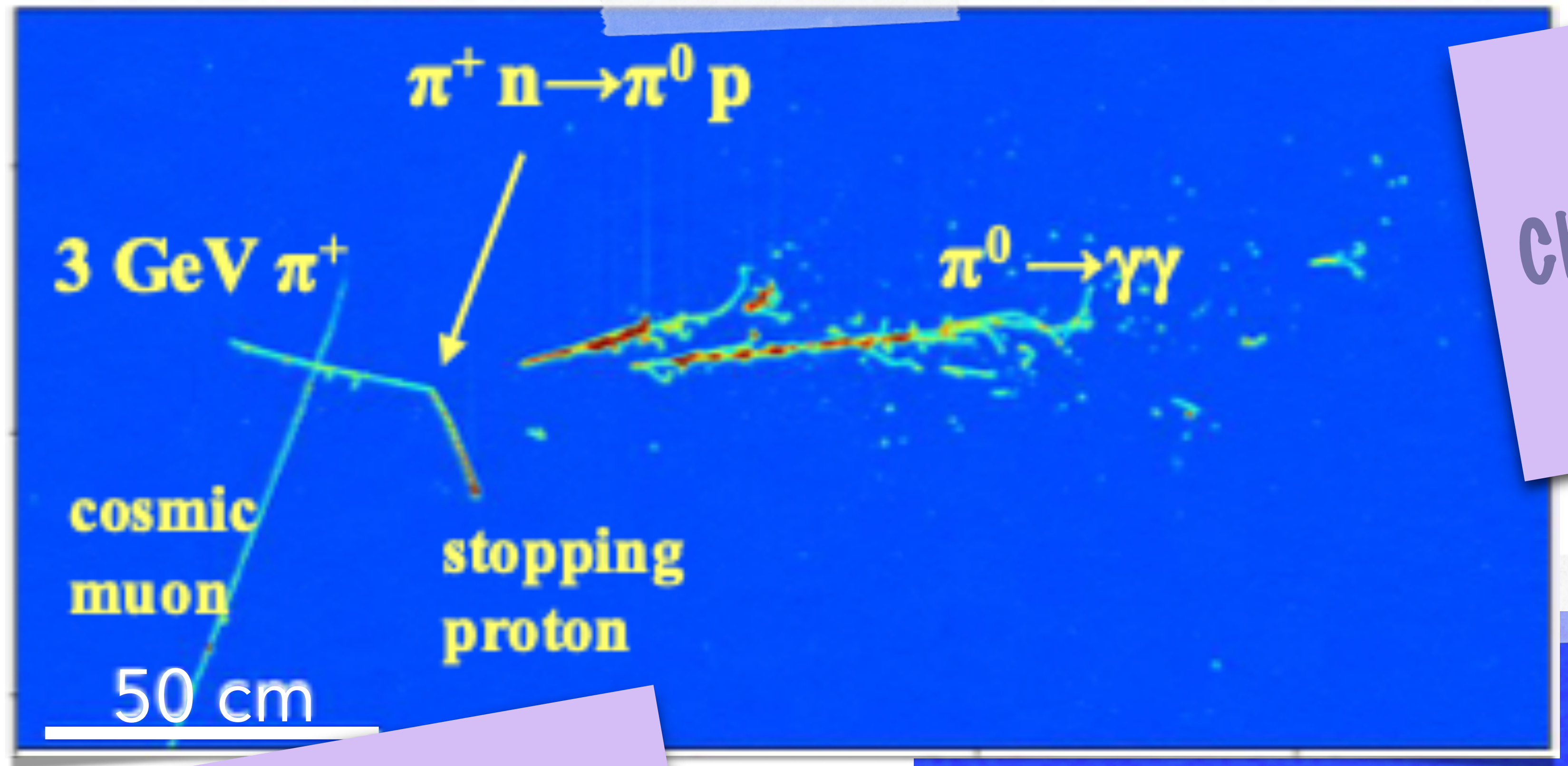
- **best precision on Δm^2_{31}(x10^{-3}eV^2):**

  0.8% (100d)→0.1% (20y)
- 0.3% on Δm^2_{21} (x10^{-5}eV^2), 0.5% on $\sin^2\theta_{21}$
- **Neutrino Mass Ordering determination**
  - ❍ 3σ sensitivity in 6.5y (alone)
  - ❍ 5σ sensitivity in 2y (combined with atmospheric)

Deep Underground Neutrino Experiment (DUNE)

- ND: neutrino flux characterization
  (energy dependence of neutrino cross-section)
- FD: **massive Liquid Argon TPCs** (4x10-kton)
  (remarkable event reconstruction, strong background rejection)
- staged prototype program at CERN for demonstration of technology performance
  - ❍ charged particle beam
  - ❍ cosmic muons

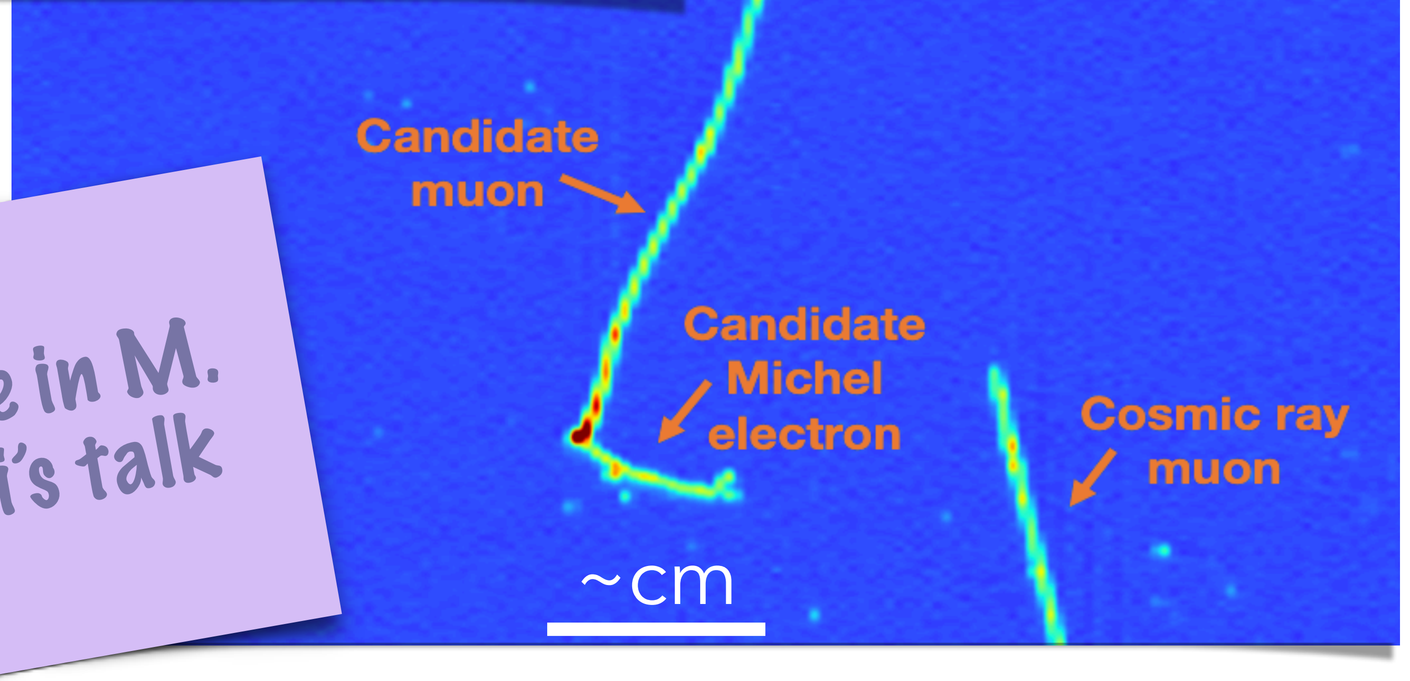




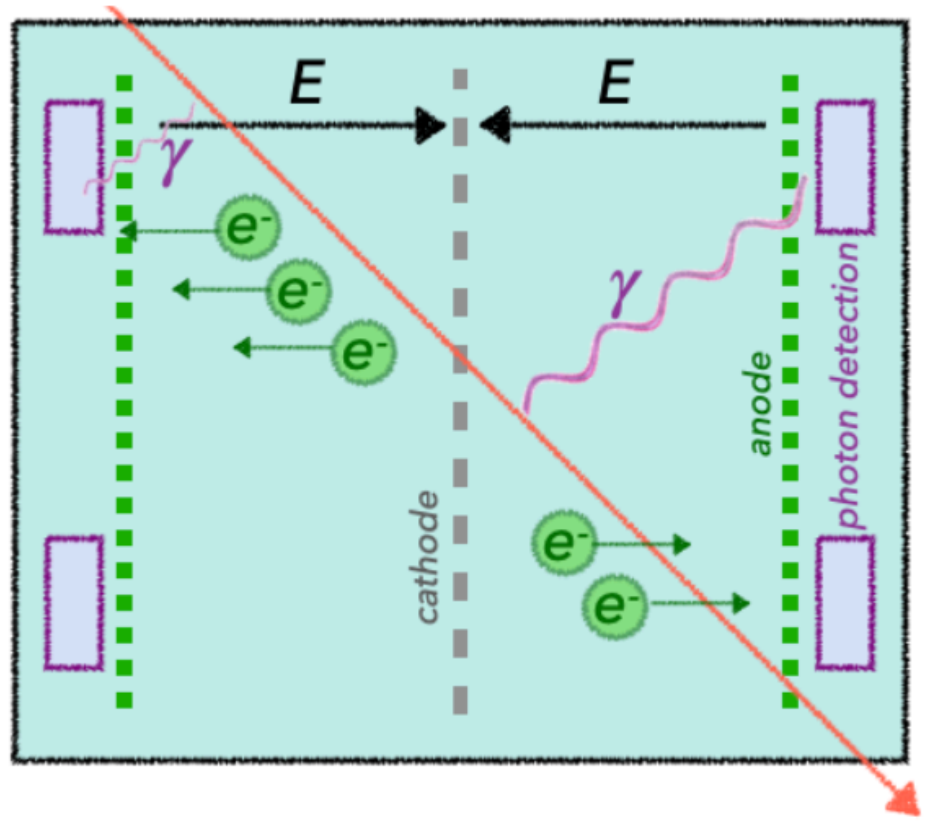
More in I. Cheong Hong's talk

More in E. Laval's talk

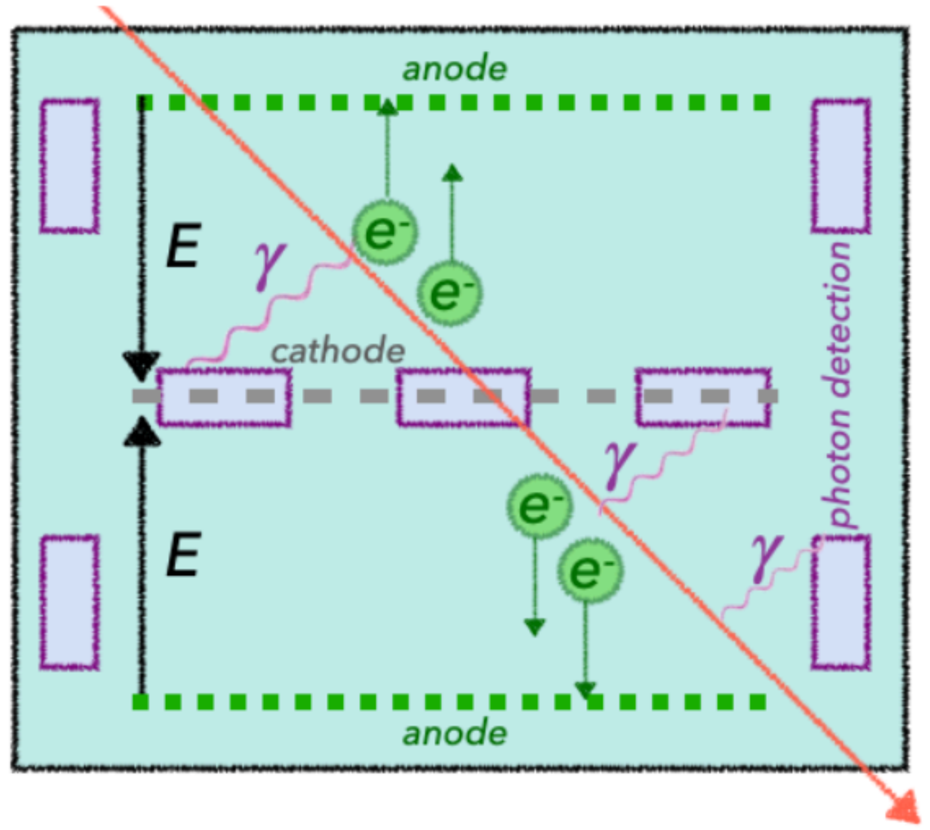
More in M. Galli's talk



Horizontal Drift (or Single-Phase)



Vertical Drift (VD)

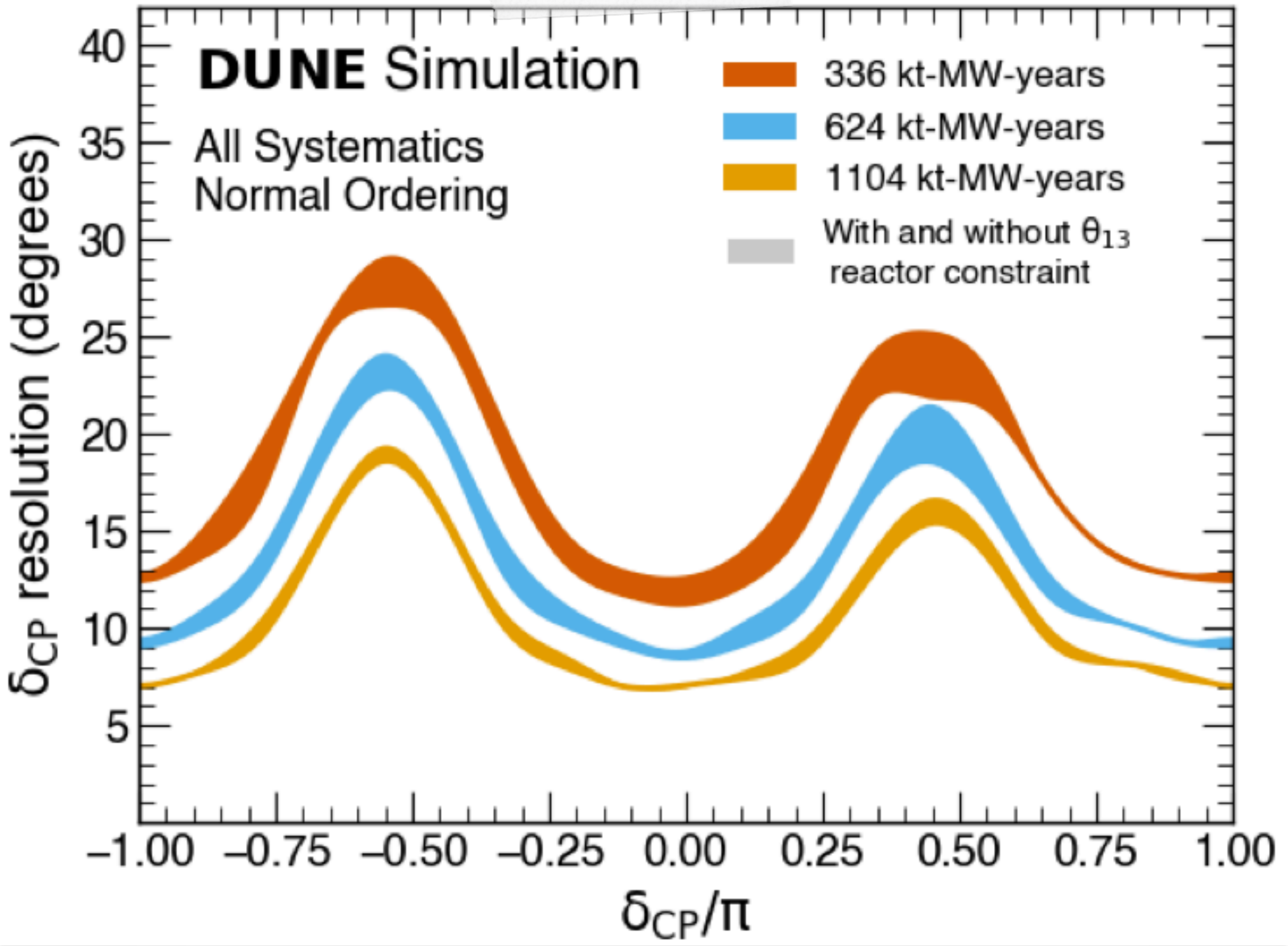


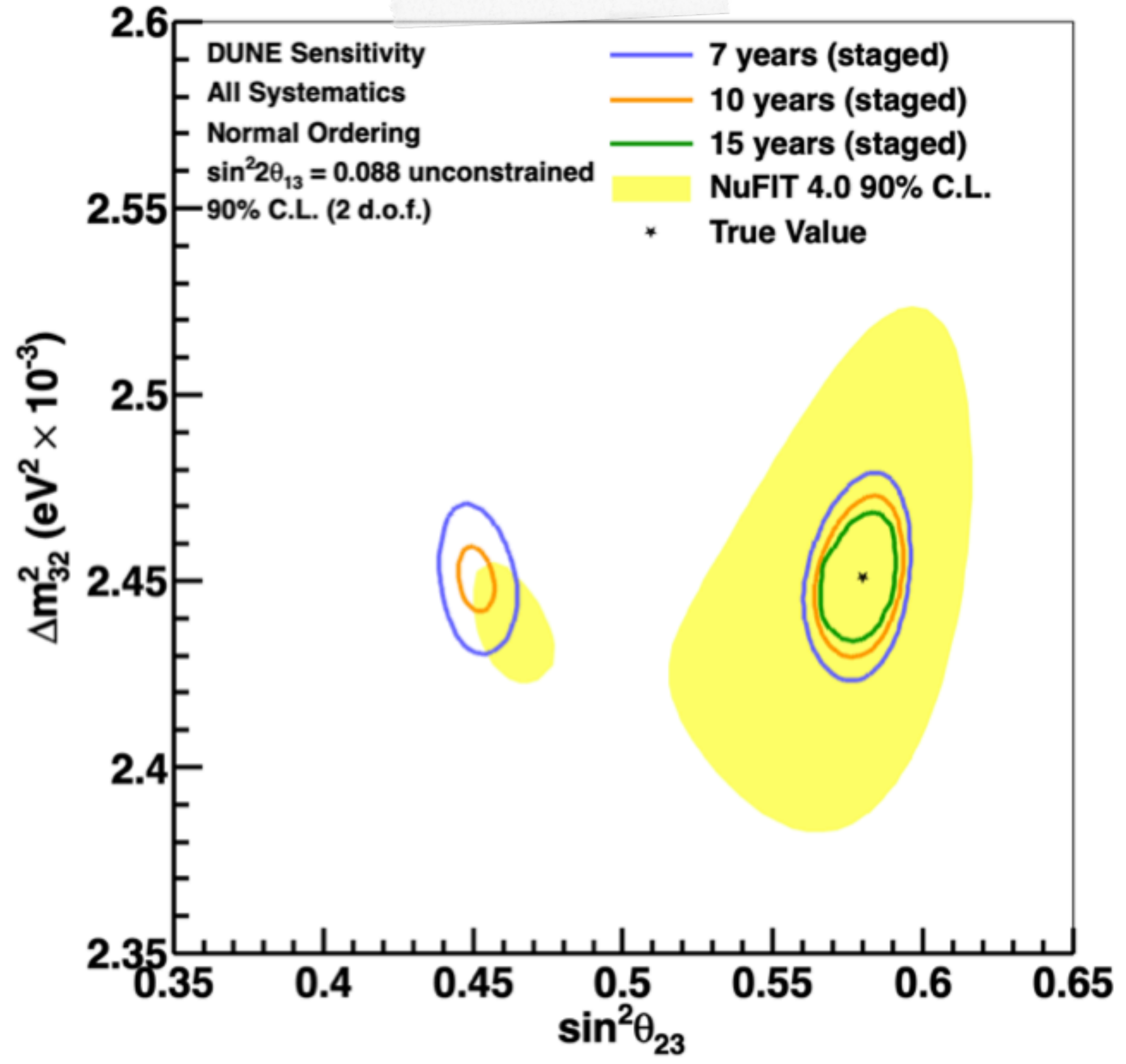
Deep Underground Neutrino Experiment (DUNE)

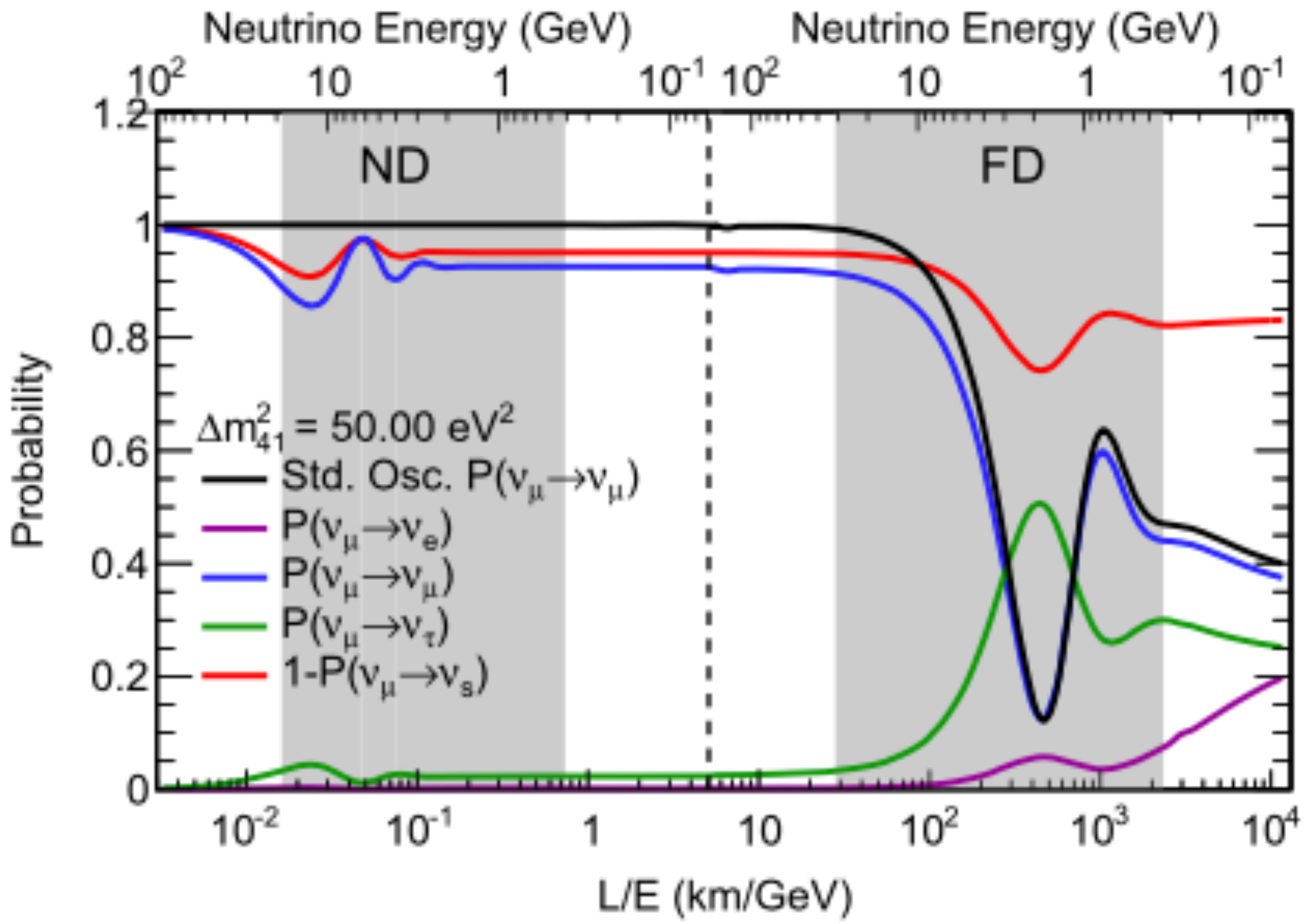
- simultaneous measurement of four channels:

  (ν_μ and $\bar{\nu}_\mu$ disappearance, ν_e and $\bar{\nu}_e$ appearance)
- **CP violation**, ~ 3.5 years for a 3σ sensitivity
- **NMO**, ~ 1 years for a 5σ sensitivity

  (for any value of δ_{CP} phase)
- θ_{23} **octant** discrimination







- no oscillation expected @ND

  (signal possible only from sterile)
- 3+1 model, via oscillation
  - ❍ @FD
  - ❍ atmospheric neutrinos

    (first data available in 2028)

More in C. Sironneau's talk

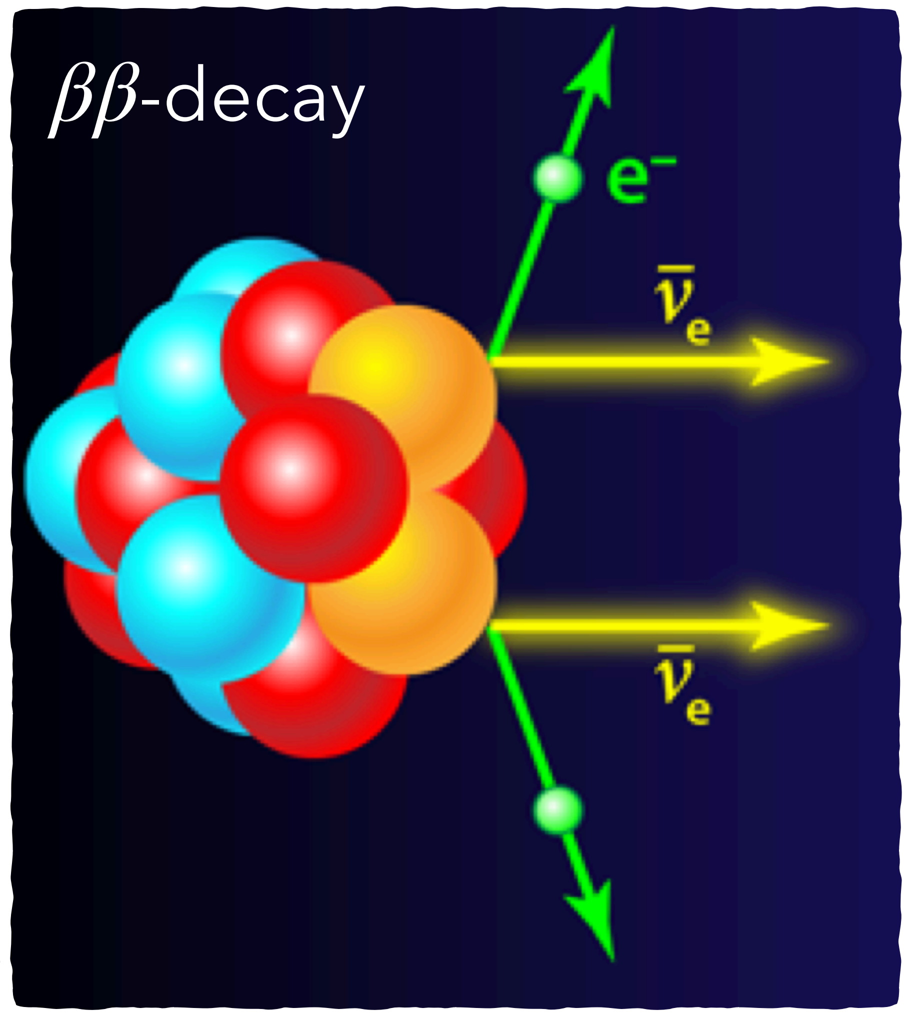
Are neutrinos Dirac or Majorana particles?

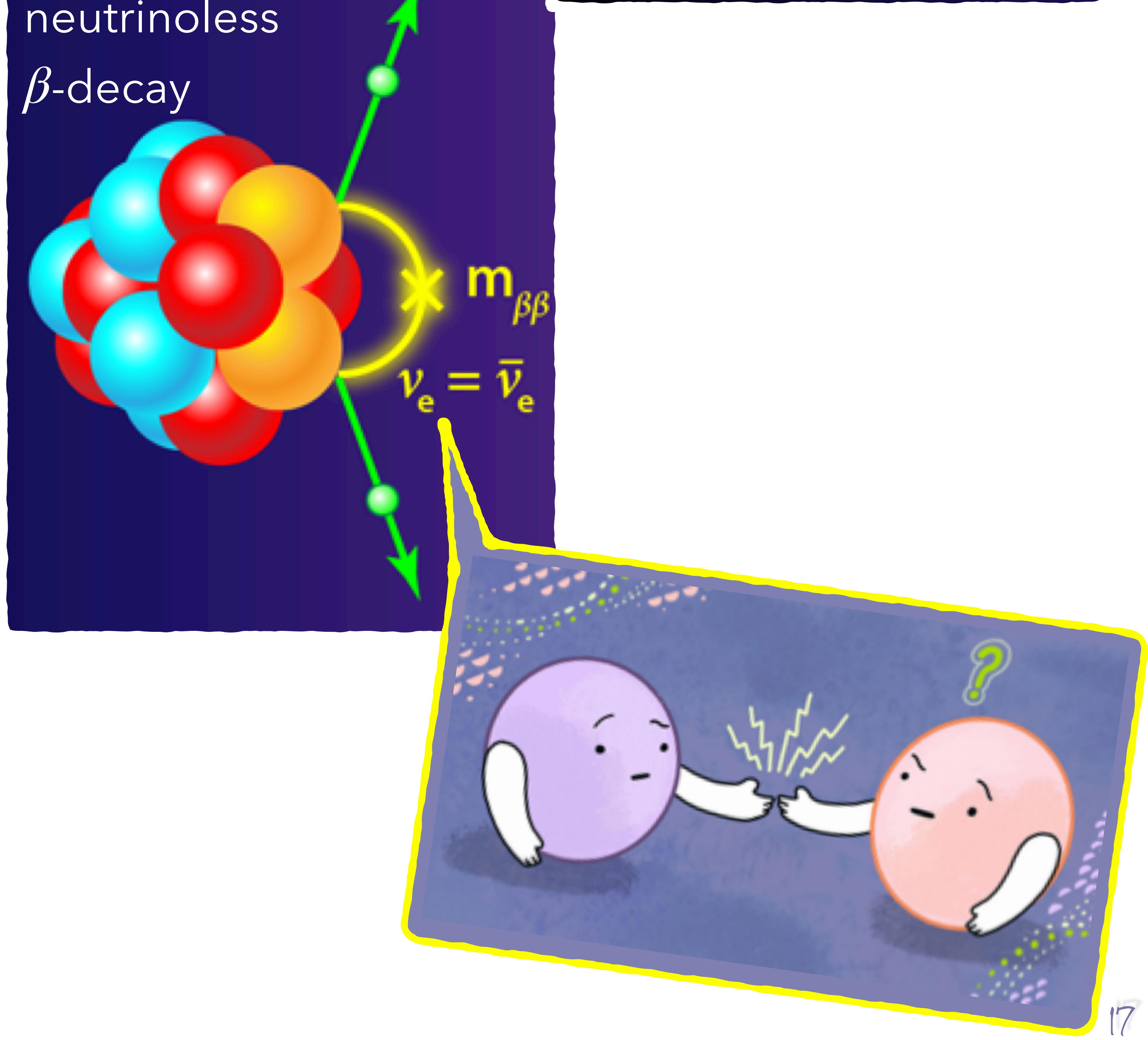
- neutrino is *its own* antiparticle (if Majorana particle)
  - ❍ β-decay, double β-decay with ν emission
  - ❍ ..what if ν are missing?

U_{PMNS} (3x3, unitary)

$$\overset{\text{Atmospheric}}{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}} \times \overset{\text{Reactor/Accelerator}}{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}} \times \overset{\nu\text{-less }\beta\text{-decay}}{\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}}$$

- two additional phases in U_{PMNS}, not affecting the oscillation probabilities
- possible explanation of matter/anti-matter asymmetry

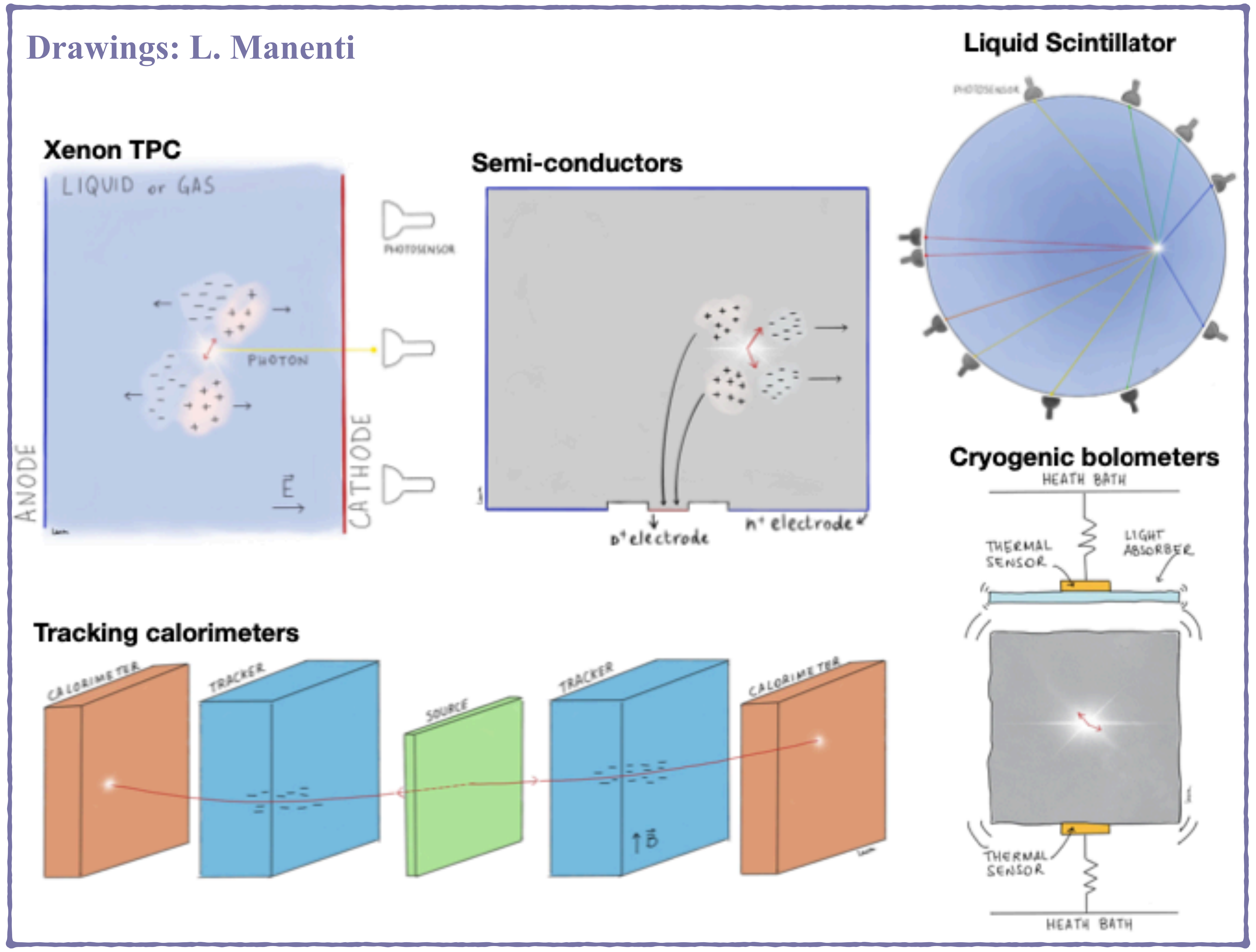




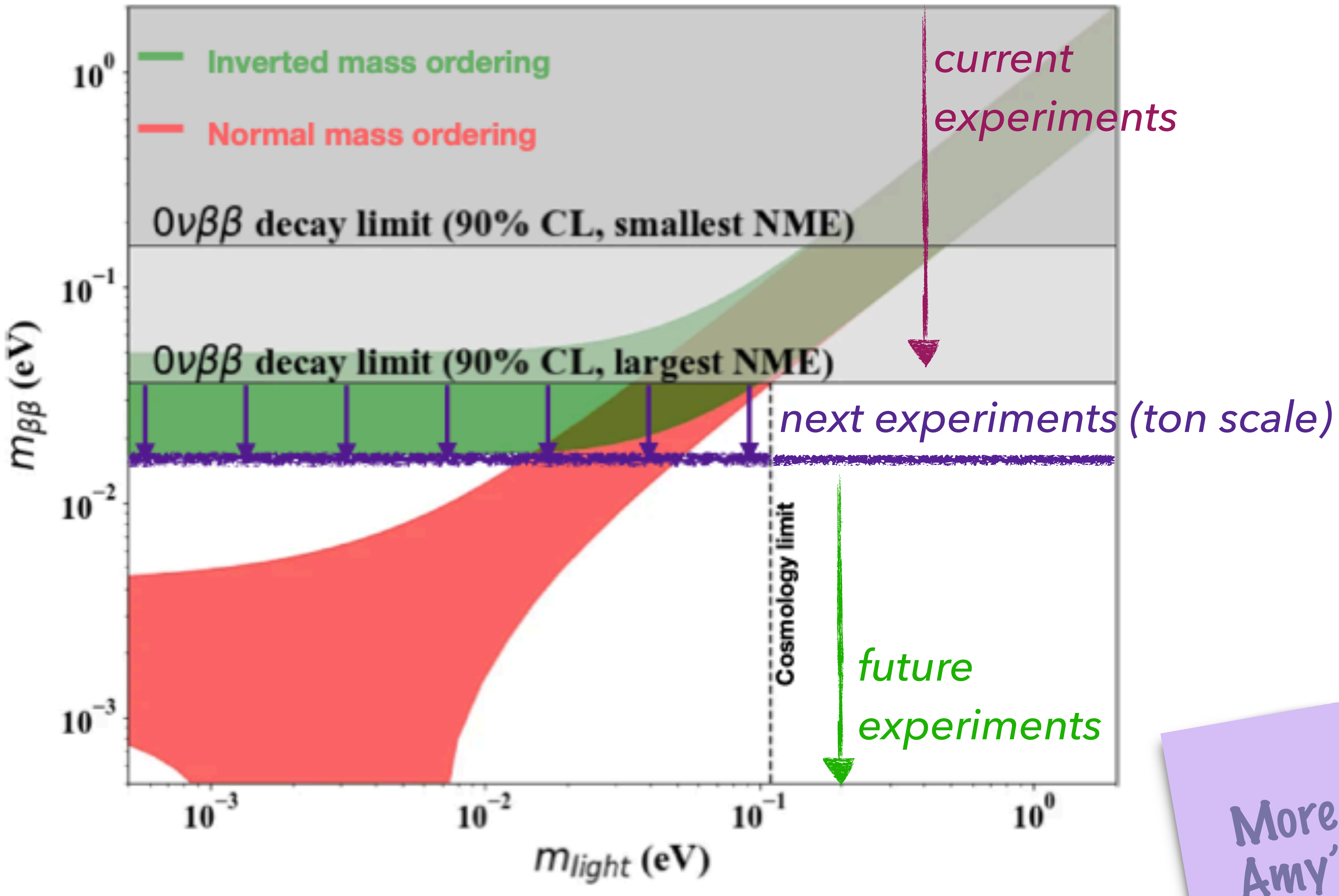
Neutrinoless β-decay

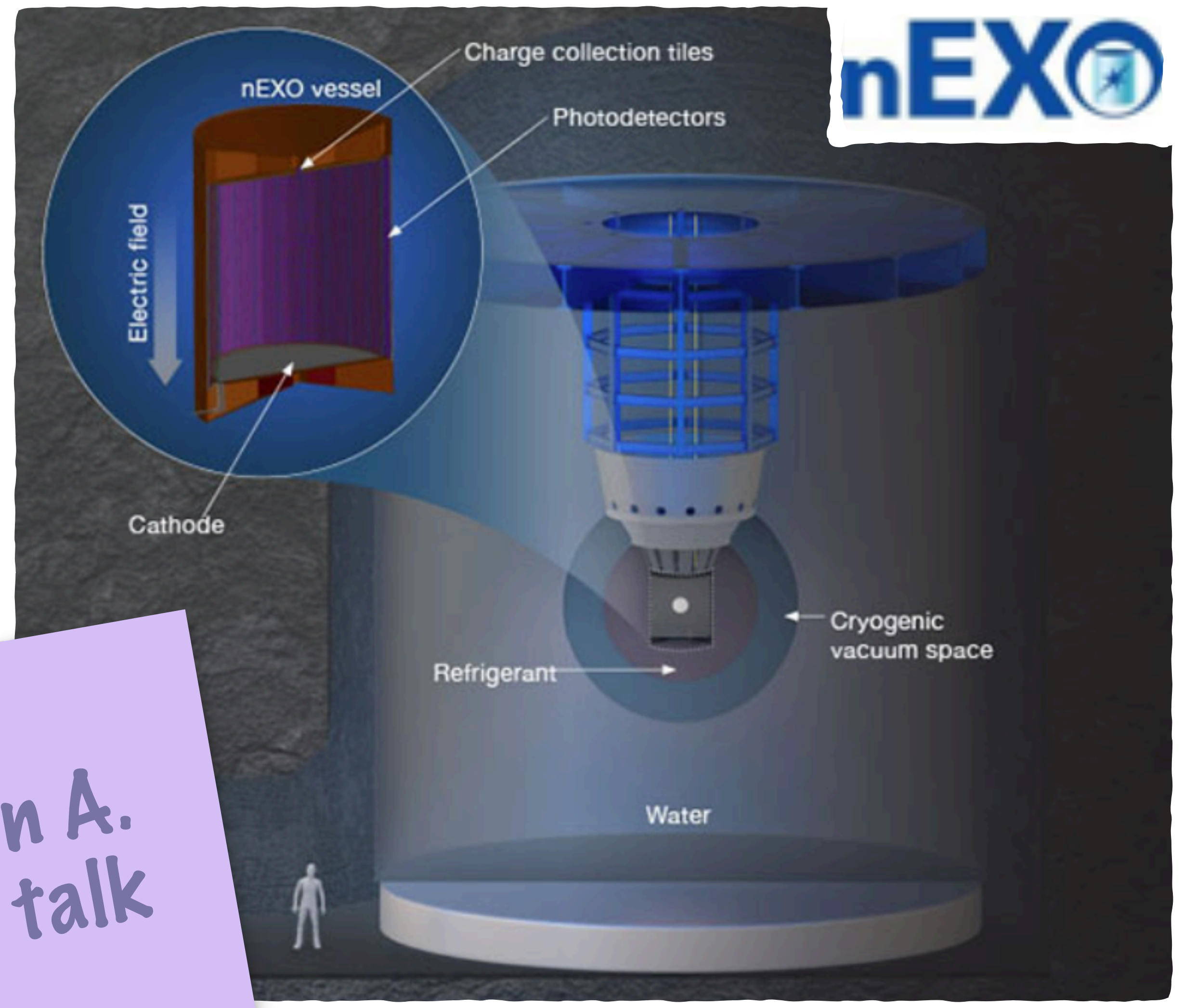
- No ideal detector candidate, several pursued options
  - ❍ best energy resolution
  - ❍ low background
  - ❍ most scalable (while low cost)

Drawings: L. Manenti



* Nuclear Matrix Elements (NME)





- Liquid Xe TPC
  - ❍ 5tons
  - ❍ enriched with Xe^{136} isotope
  - ❍ good background rejection (gamma from Ur and Th chains)

More in A. Amy's talk

Neutrinos are cool...

...and so we are! 😎

Stay tuned for the
~~rest~~
best part
of the conference!

Impact of Nickel Cryostats in the nEXO Detector *Antoine AMY*
17:00 - 17:30

Development of a muon reconstruction algorithm for JUNO using all the sub-detectors *Thomas RAYMOND*
11:00 - 11:30

Refining Sterile Neutrino Exclusion through Joint Analysis: STEREO Phase 2 Reproduction and Analytical Response Modeling
yann querlioz

Sterile Neutrino Search with Atmospherics in DUNE *Camille Sironneau*
14:00 - 14:30

Vertex reconstruction at DUNE experiment *I Cheong Hong*
14:30 - 15:00

Study of Ar^{39} Beta Decays in DUNE's Prototypes *emile lavaut*
15:00 - 15:30

Search of reconstructed Michel-electrons in DUNE *Matteo Galli*
15:30 - 16:00

Extra slides

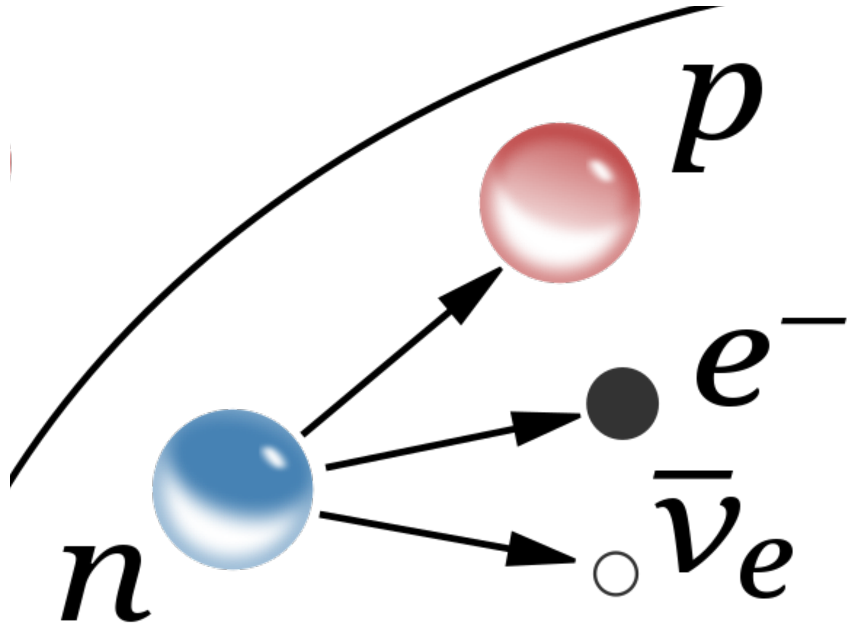
The "desperate remedy" of a new, neutral, massless particle

1896: H. Becquerel, discovery of radioactivity

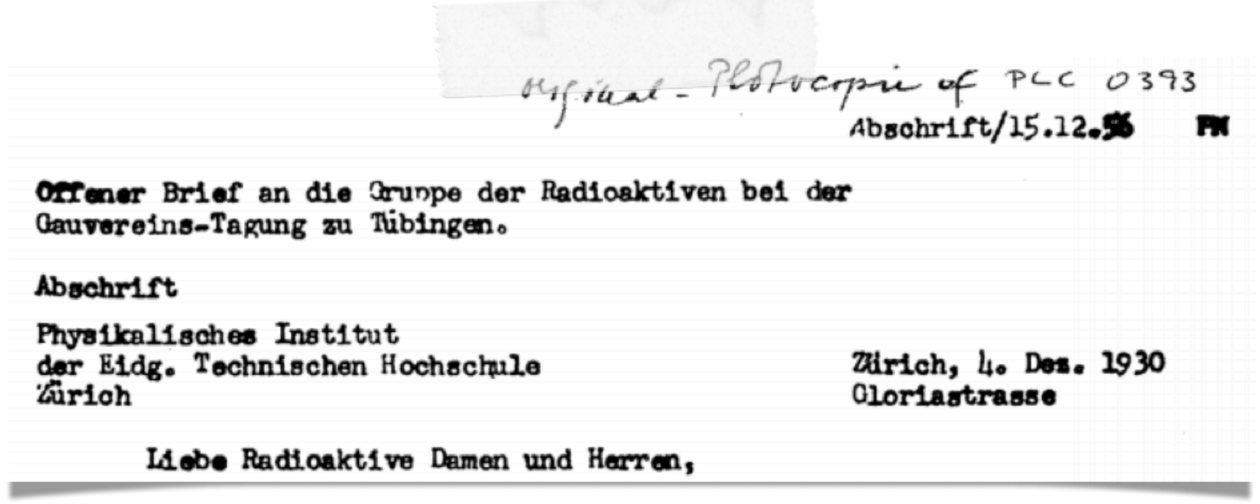
- α and γ, **peak** with a precise energy

1914: J. Chadwick, the beta emission has a **continuous** spectrum

1930: W. Pauli, proposes a **new** particle as a "**desperate remedy**" to energy conservation



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


Original - Photocopie of PLC 0393
Abschrift/15.12.56 PN

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

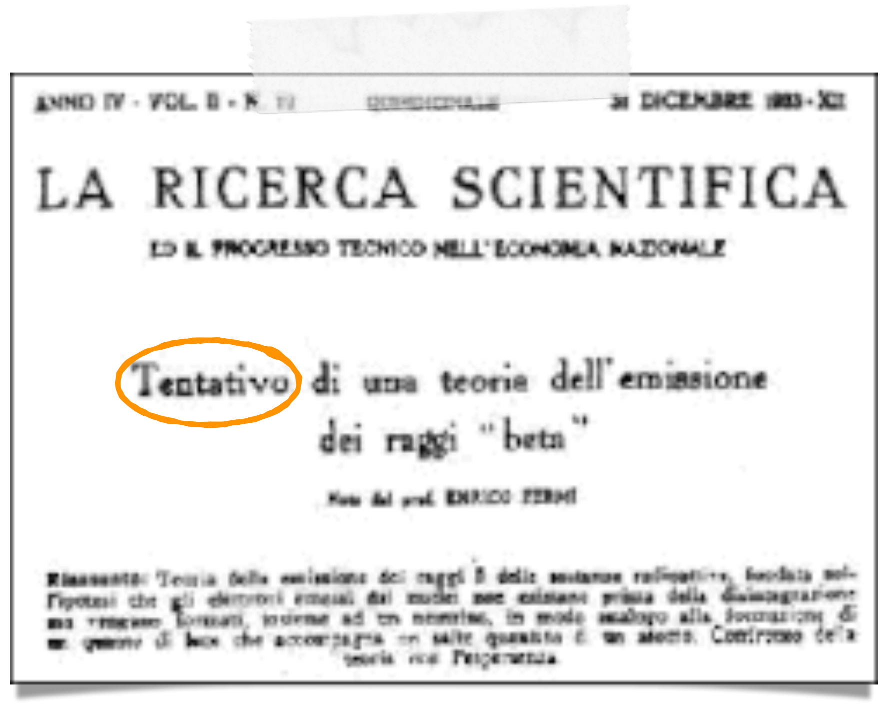
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

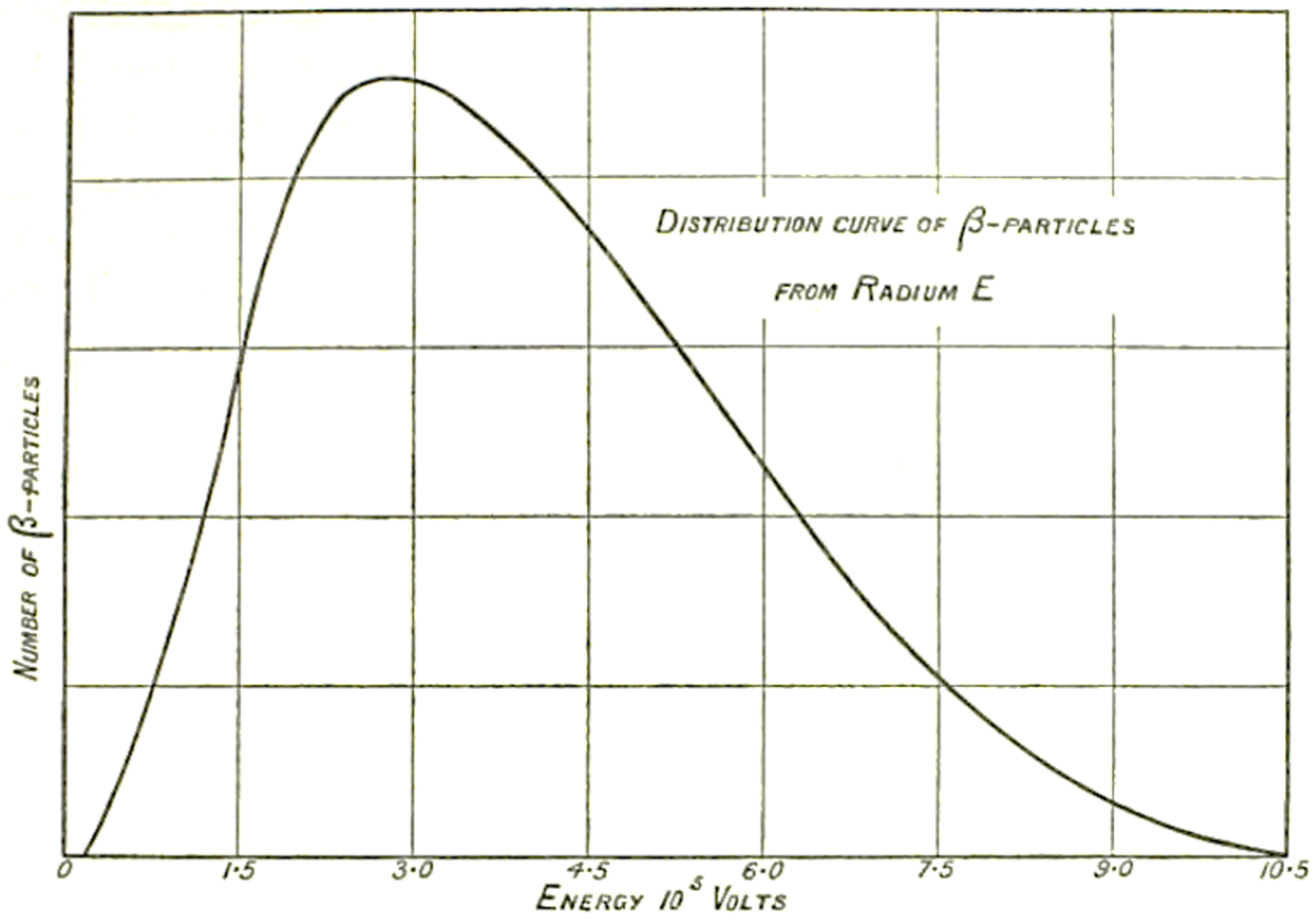
1933: E. Fermi names it **neutrino** and builds the weak interaction theory


LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI



① **1914**: beta decay spectrum

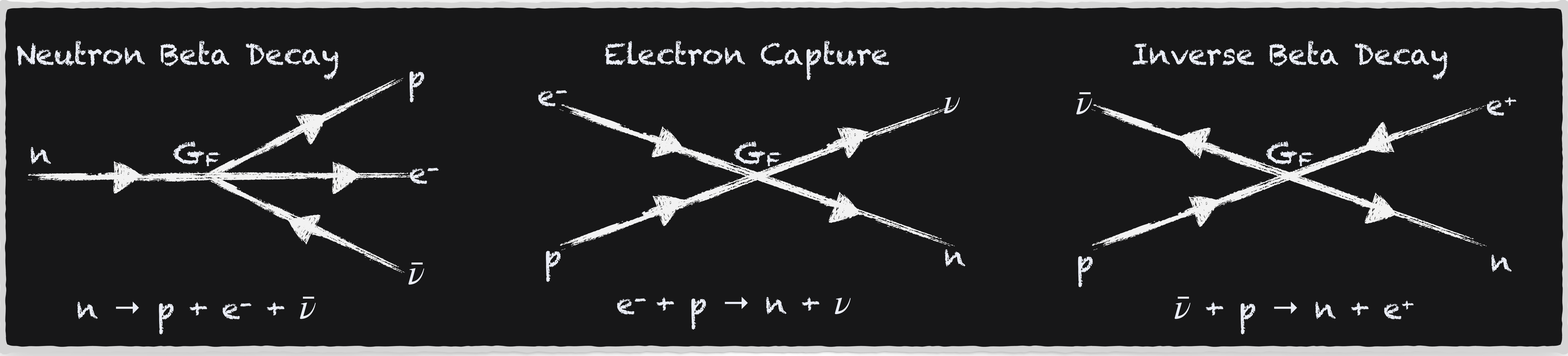
② **1896**: radioactivity

③ **1933**: baptism of the *neutrino*

④ **1930**: the "desperate remedy"

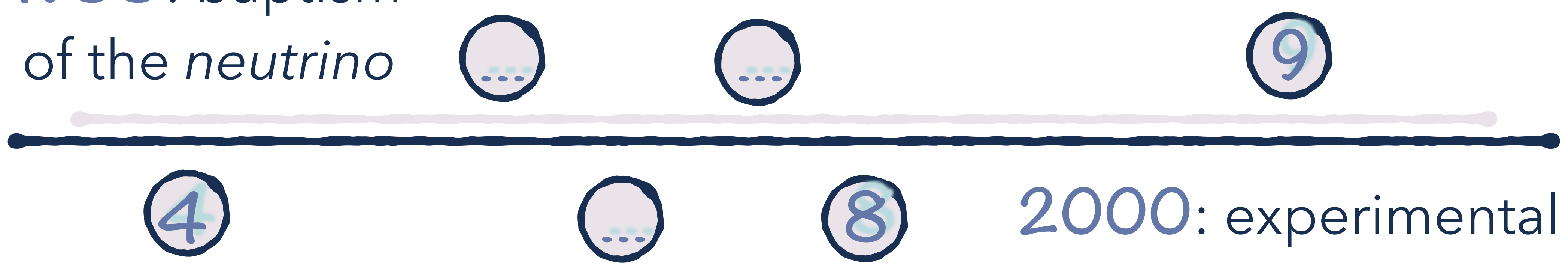
The weak interaction in a nutshell

1933: E. Fermi names it **neutrino** and builds the weak interaction theory



1989, LEP measure the Z boson and concludes that

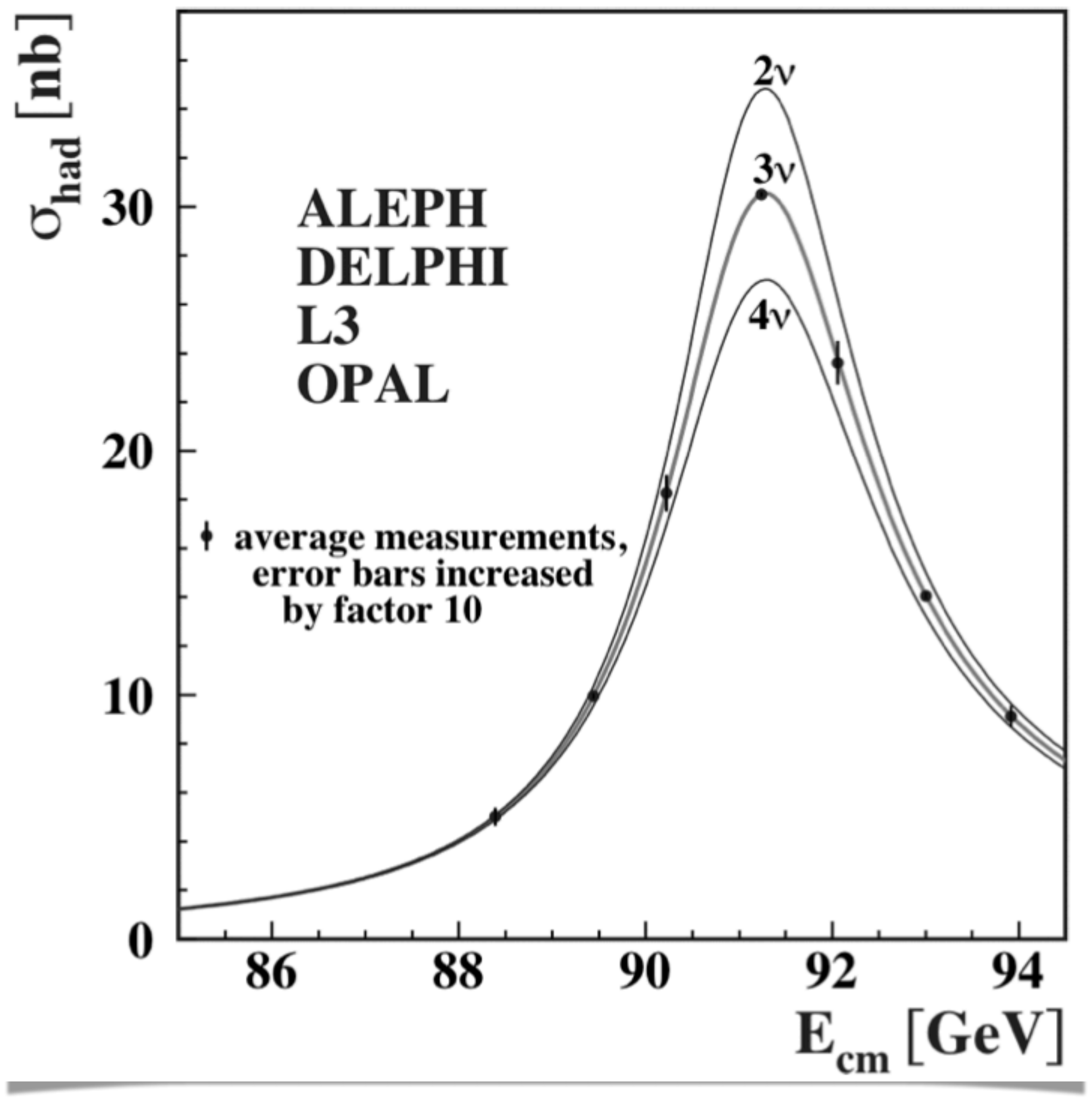
- n. of expected neutrinos compatible with 3: $N_\nu = (2.984 \pm 0.008)$
- light and only left-handed (a.k.a. massless)
- interacting only via weak interactions, via charge-current (CC), exchanging $W^\pm$, or neutral current (NC), exchanging Z^0



1933: baptism of the *neutrino*

2000: experimental observation of 3 ν

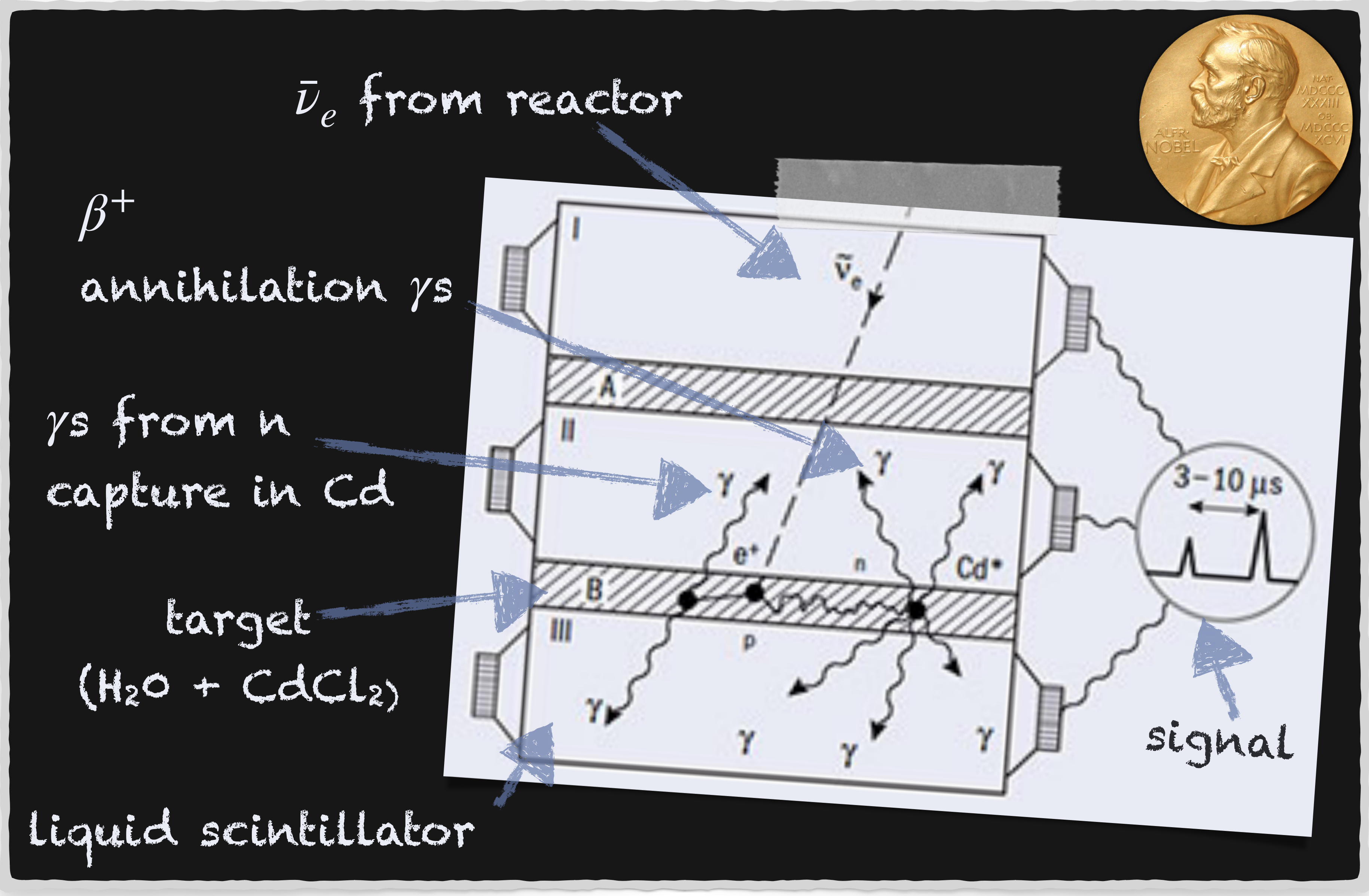
LEP results

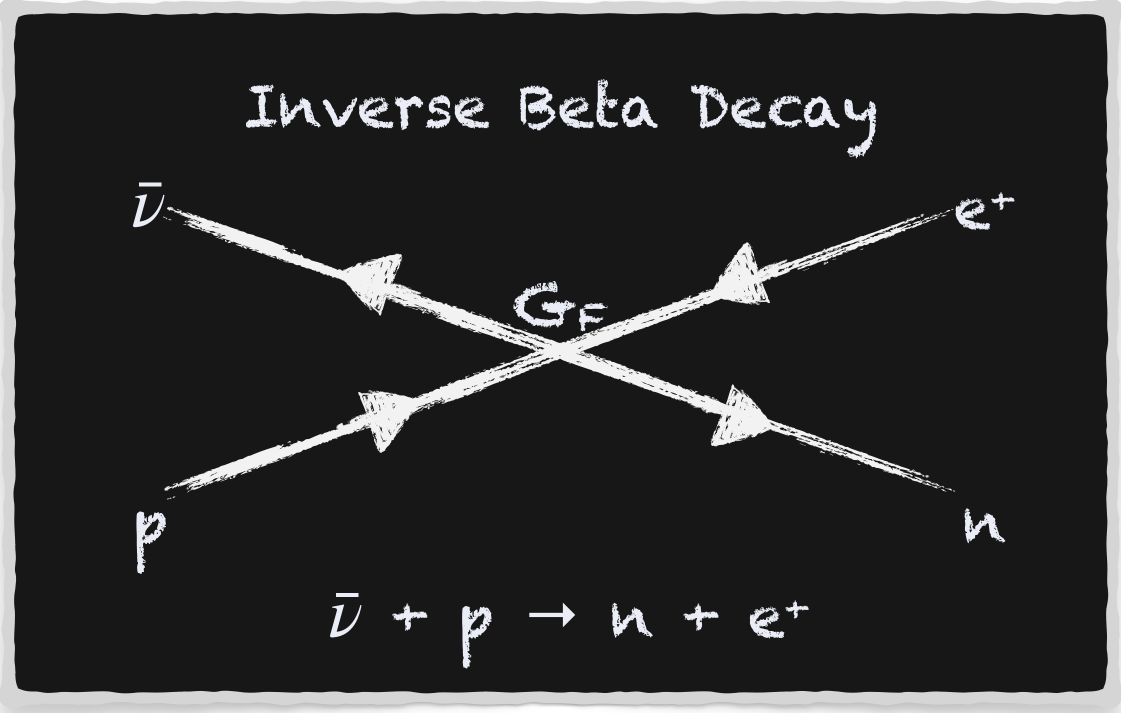


The electron neutrino

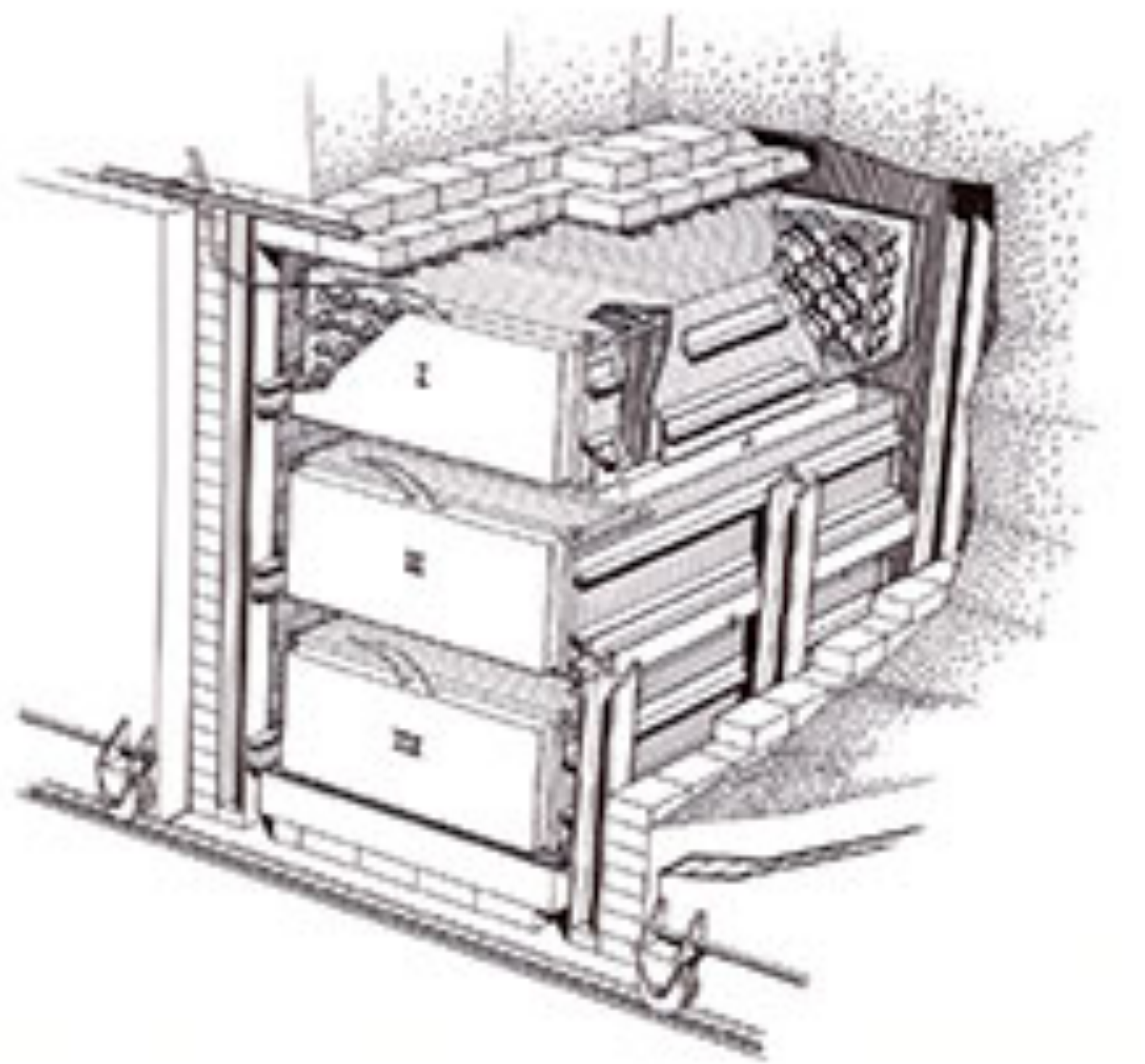
1956: first experimentally $\bar{\nu}_e$ discovery by C. Cowan and R. Reines (*Nobel prize in 1995!*)

- very intense source (reactor @ Savanna River)
- continuous emission, $10^{20}\nu/cm^2/s$
- lots of n and γ bkg
- underground for shielding





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



⑤

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

The muon neutrino

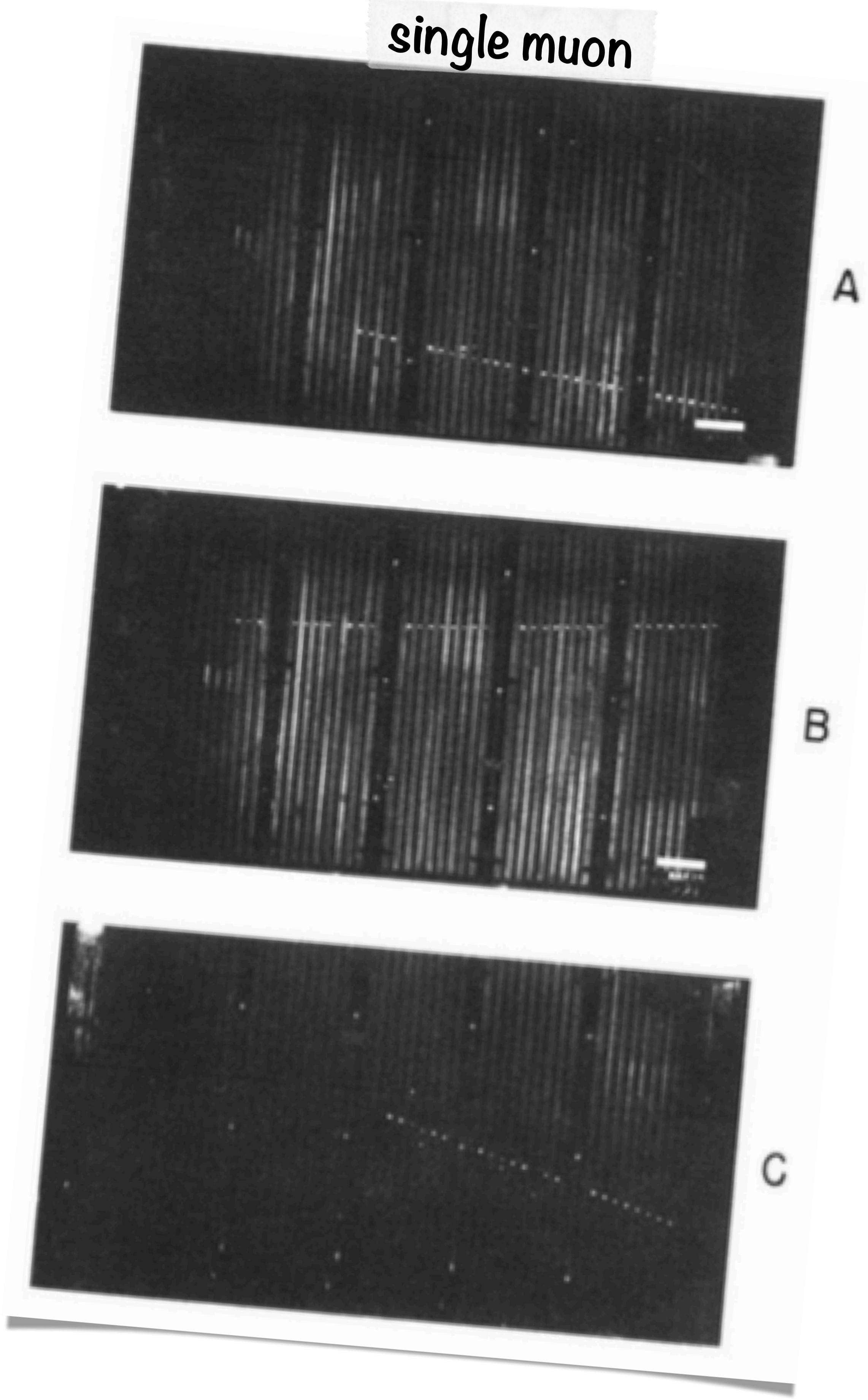
1956: first experimentally $\bar{\nu}_e$ discovery by C. Cowan and R. Reines
(Nobel prize in 1995!)

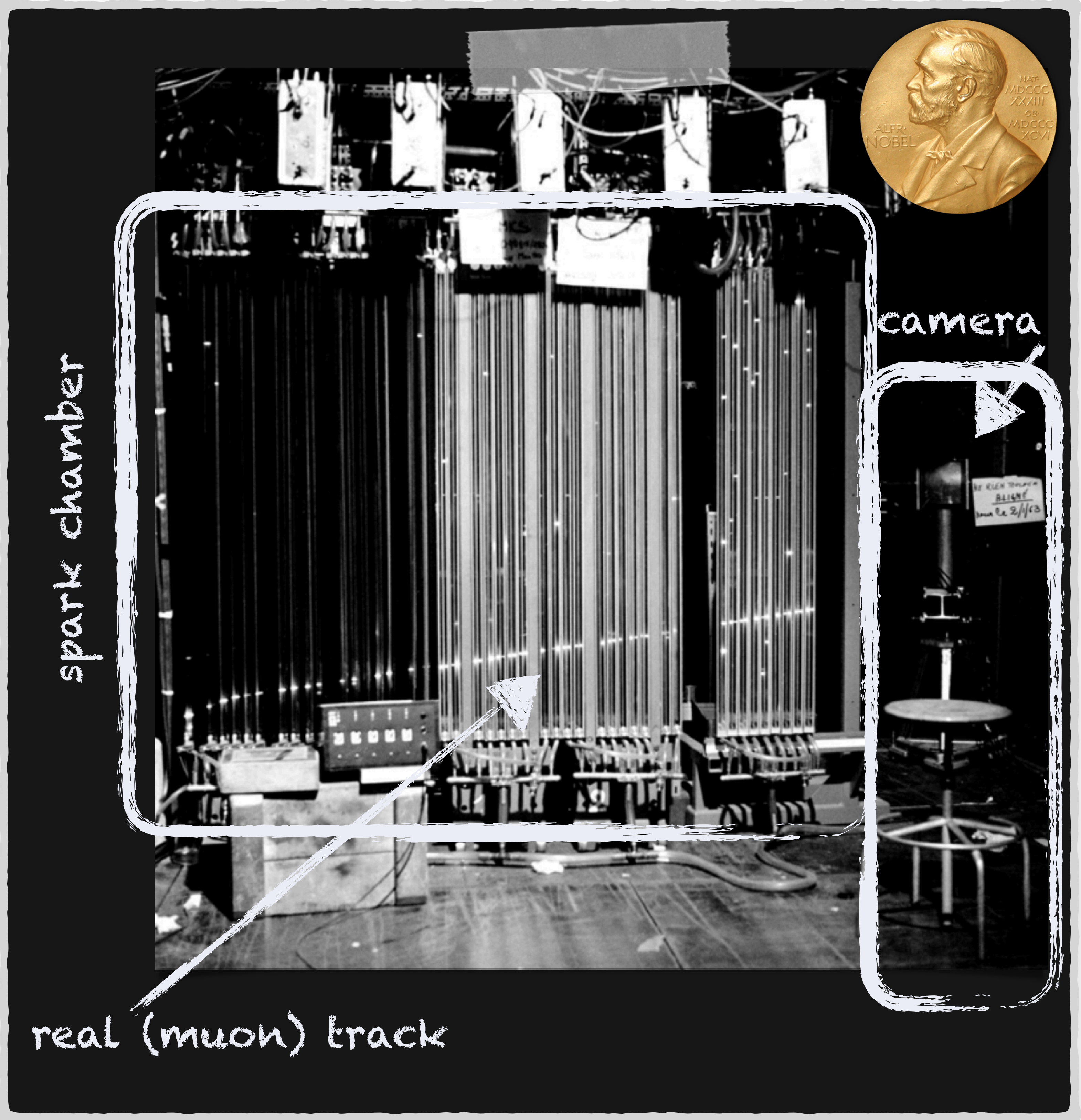
1962: ν_μ discovery by L. M. Lederman et al. @ Brookeven lab
(Nobel prize in 1988!)

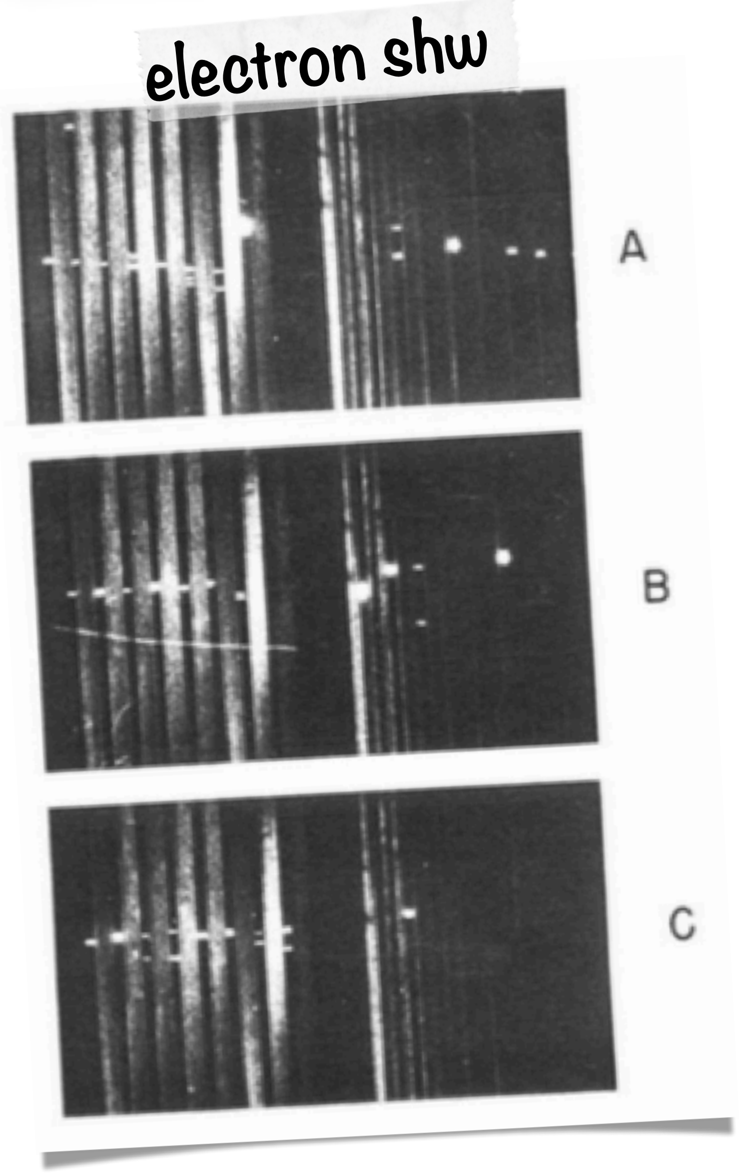
- neutrino from beam
- spark chamber
- using trigger for taking real photographs
- differentiate between electron showers (only 6 events) and muon events (34 single muon events)
  - ν_e are different from ν_μ !

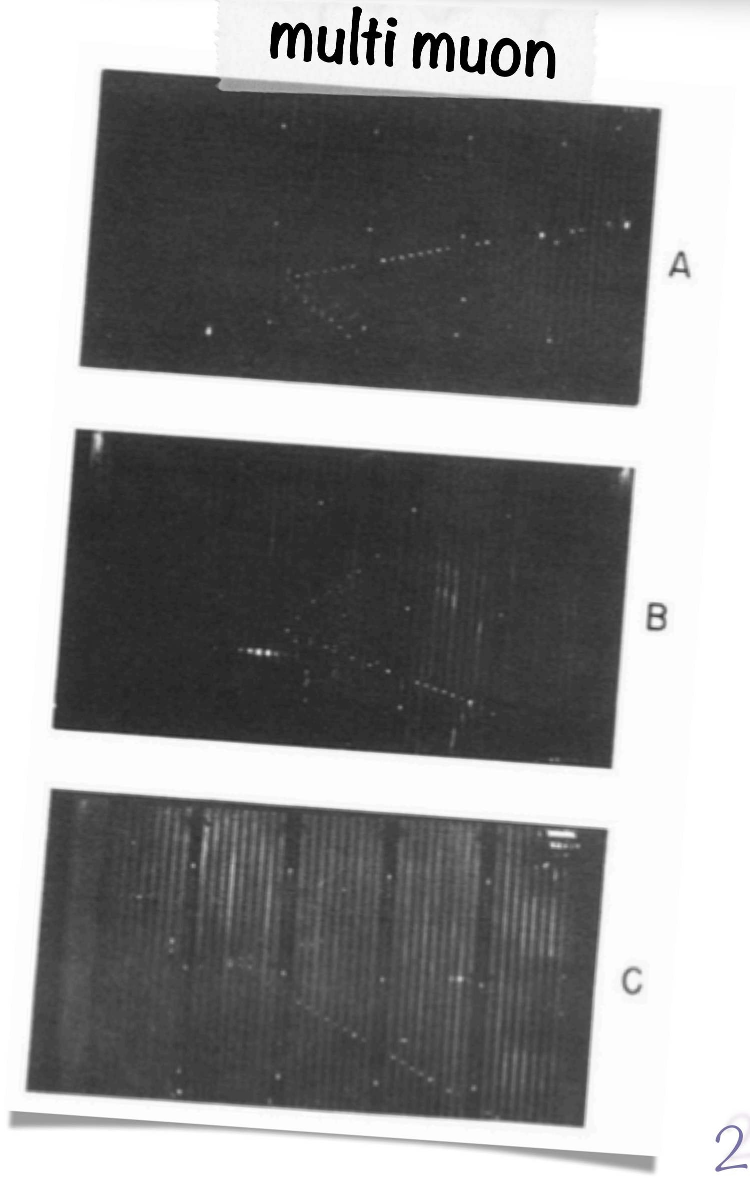
⑤ 1962: ν_μ discovery

⑥









The tau neutrino

1956: first experimentally $\bar{\nu}_e$ discovery by C. Cowan and R. Reines
(*Nobel prize in 1995!*)

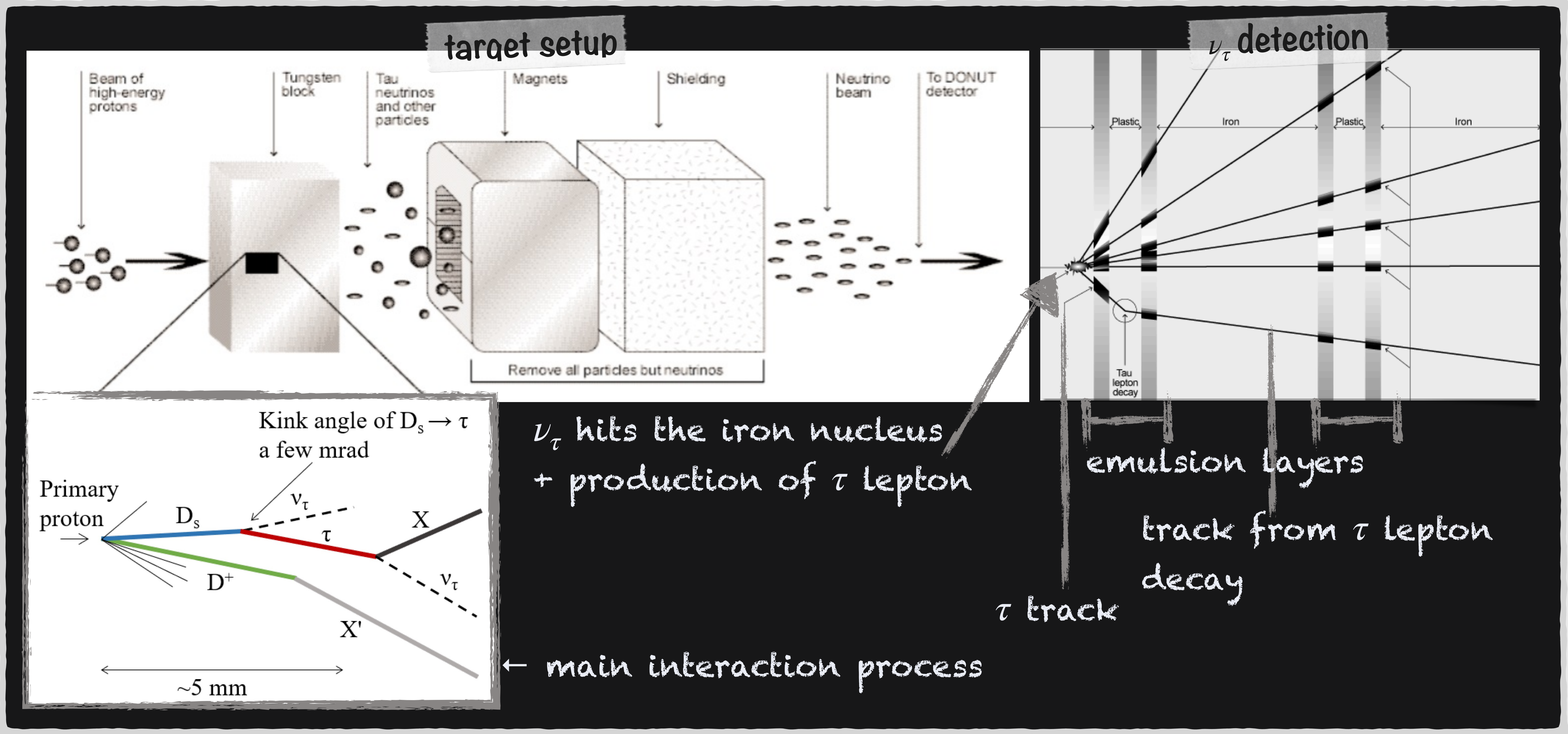
1962: ν_μ discovery by L. M. Lederman et al. @ Brookeven lab
(*Nobel prize in 1988!*)

2000: direct observation of 4 ν_τ events by DONuT experiment

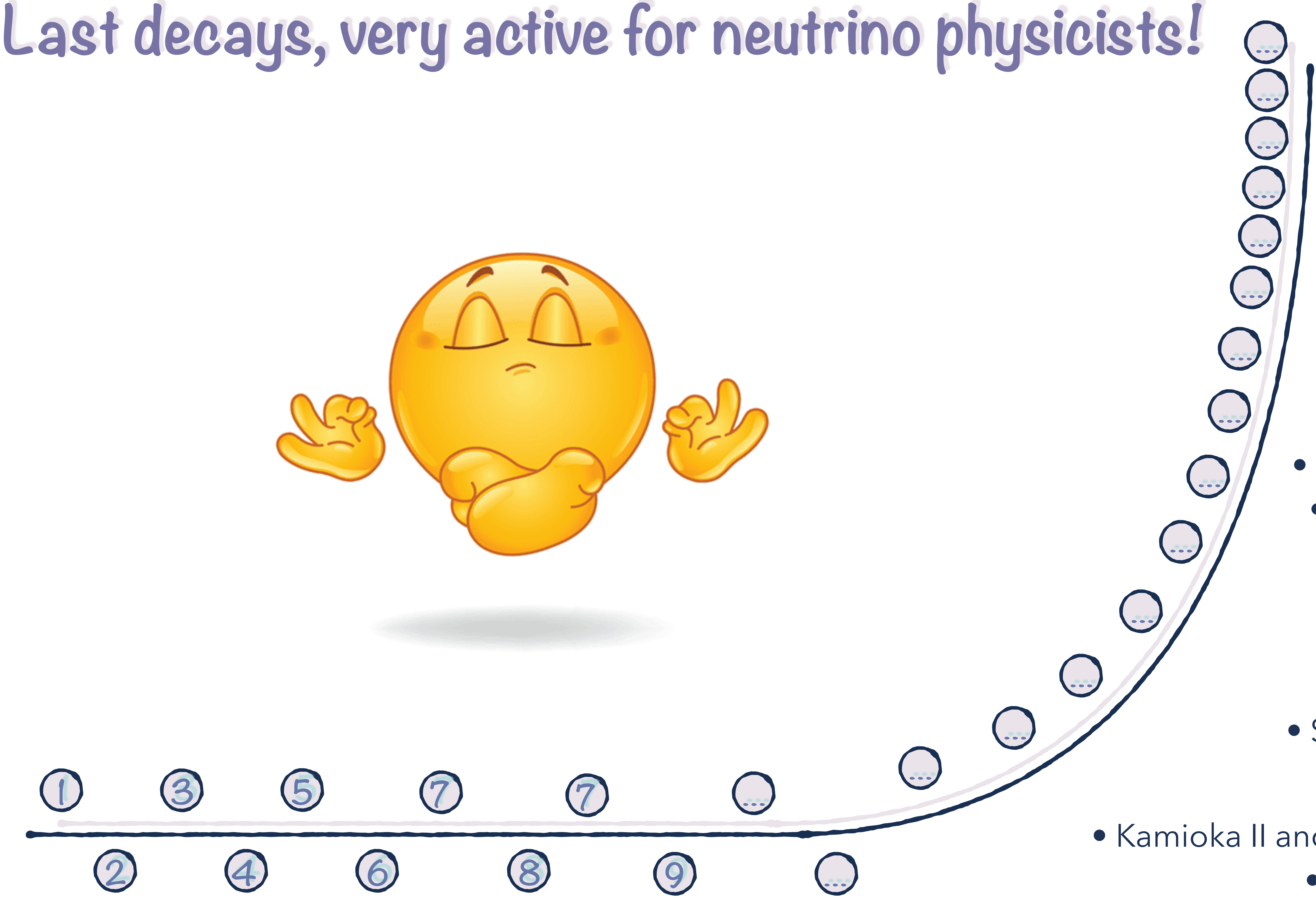
- τ lifetime is extremely short (decay length ~2 mm, fine spatial resolution)
- ν_τ extremely non interacting (very dense detector)

⑤ ⑦

⑥ 2000: ν_τ observation

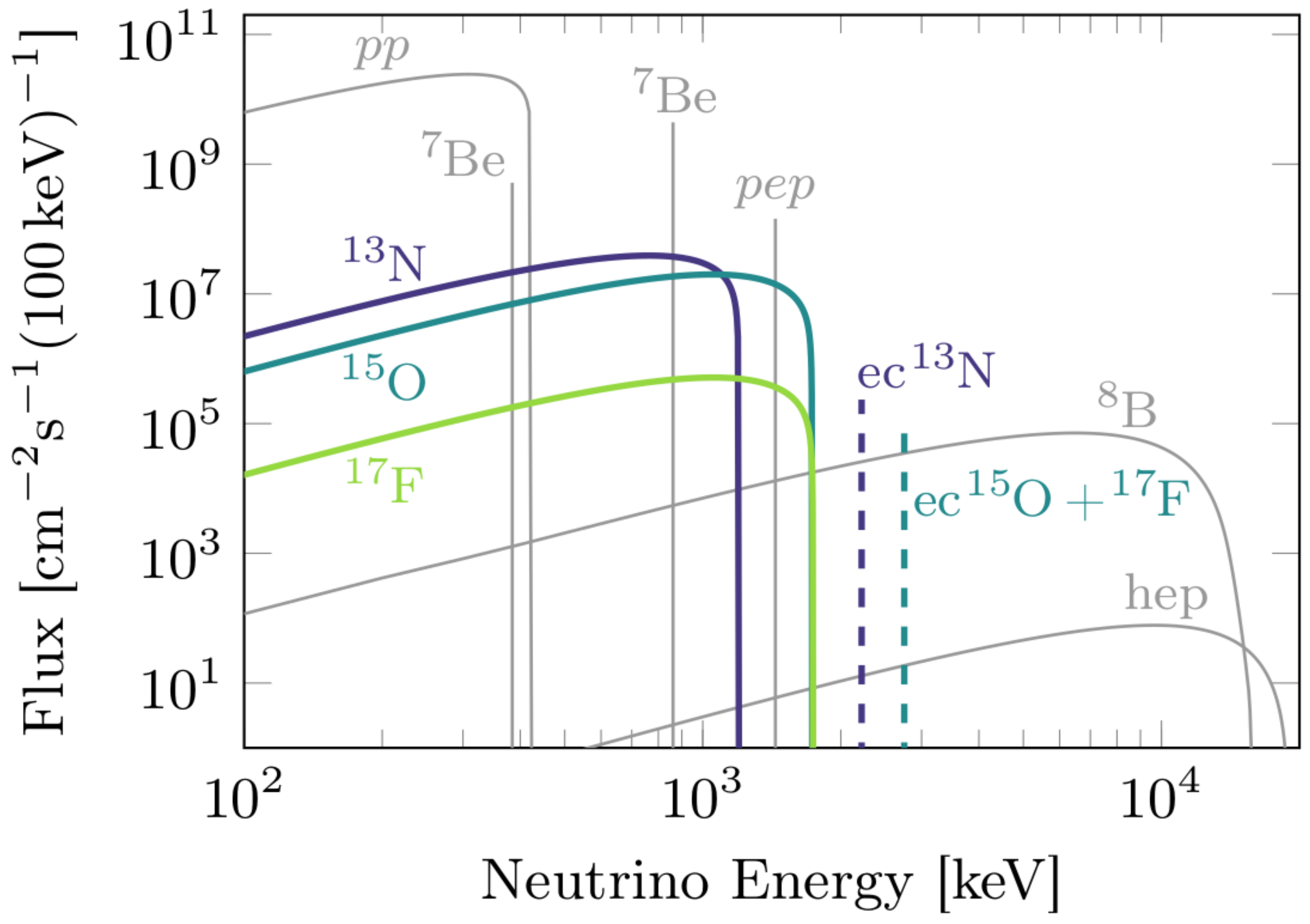


Last decays, very active for neutrino physicists!



- **T2K hints on leptonic CP violation**
- **COHERENT reports first observation of coherent neutrino scattering**
- **IceCUBE observes extragalactic ν**
- T2K observe ν_e appeared from ν_μ
- $\nu_\mu \rightarrow \nu_\tau$ **oscillation** in OPERA
- Daya Bay observe $\bar{\nu}_e$ **disappearence**
- K2K confirms atmospheric oscillations
- KamLAND confirms solar oscillations
- SNO shows solar oscillation to active flavor
- Super K confirms solar deficit and "images" sun
- Super K sees evidence of atmospheric neutrino **oscillations**
- Kamioka II and IMB see **atmospheric neutrino anomaly**
- SAGE and Gallex see the solar deficit
- Kamioka II confirms solar deficit
- **Observation of the solar neutrino puzzle**

The solar neutrino puzzle



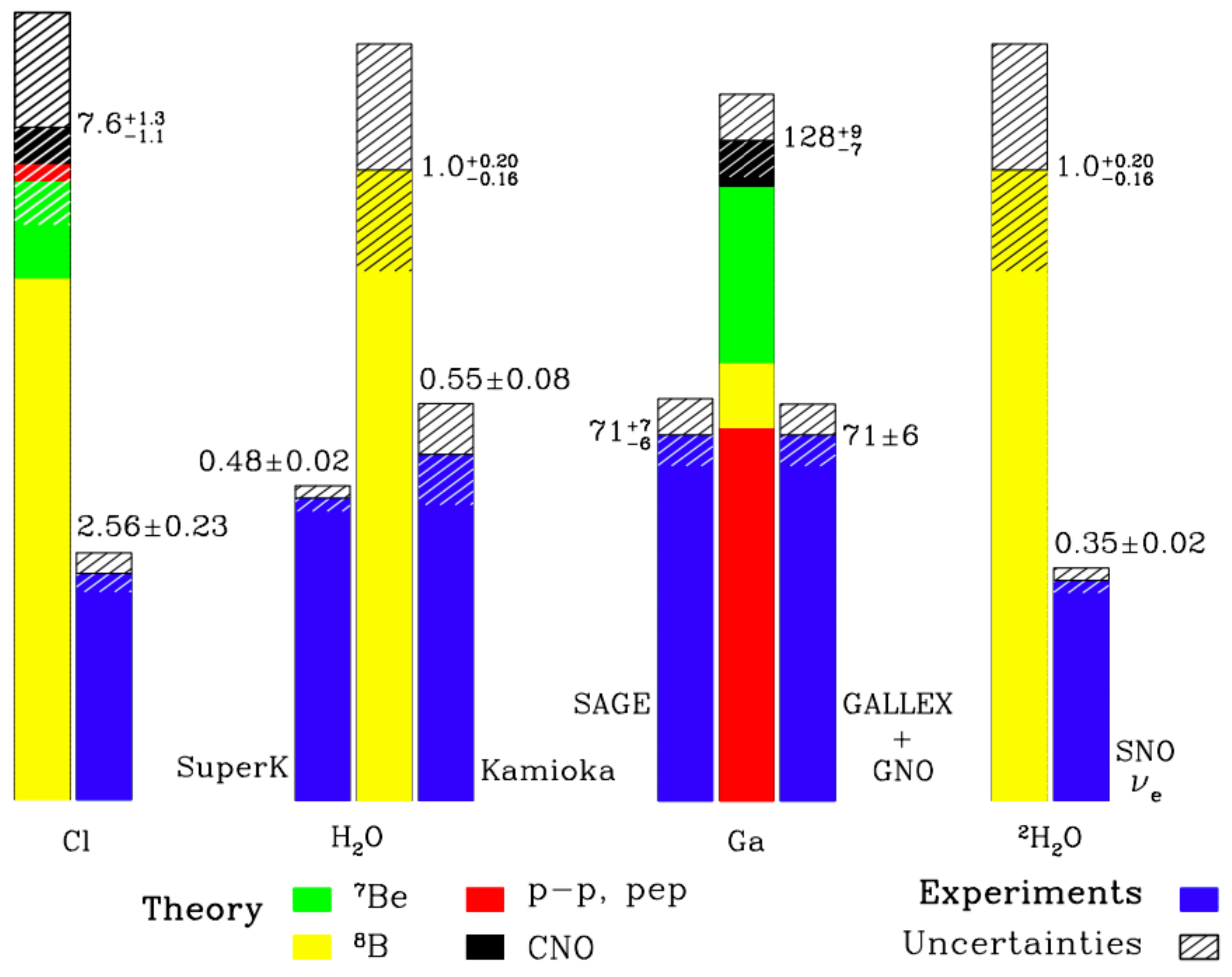
Neutrinos from the Sun: ideal to study the inner structure because they leave bringing all the information related to their production

- thermonuclear reactions (mainly pp chain and CNO cycle)

$$4p + 2e^- \rightarrow {}^4He + 2\nu_e + Q$$

- in data, 50% to 70% of expected neutrinos were missing…

observed ν_e



The solar neutrino puzzle

Neutrinos from the Sun: ideal to study the inner structure because they leave bringing all the information related to their production

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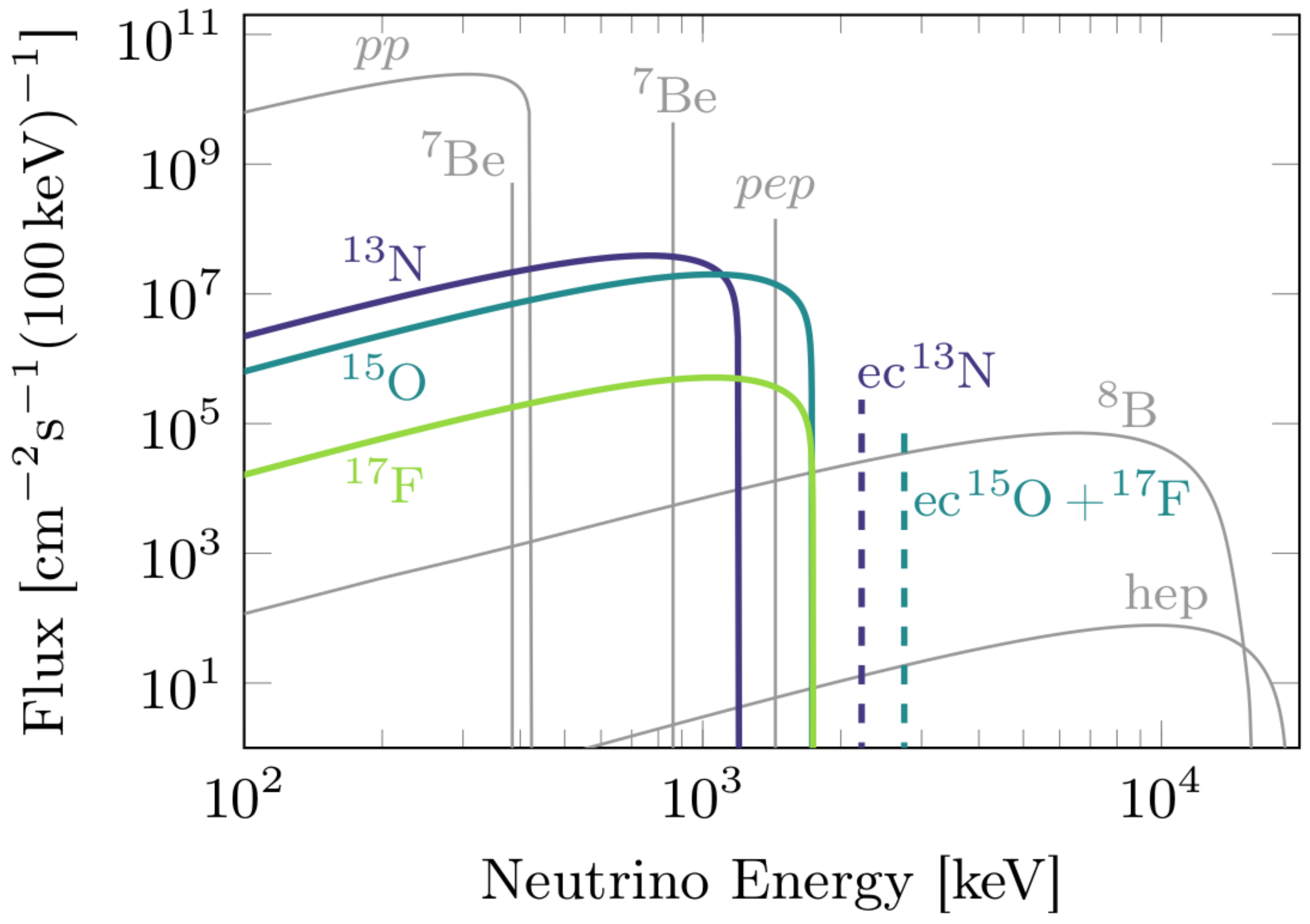
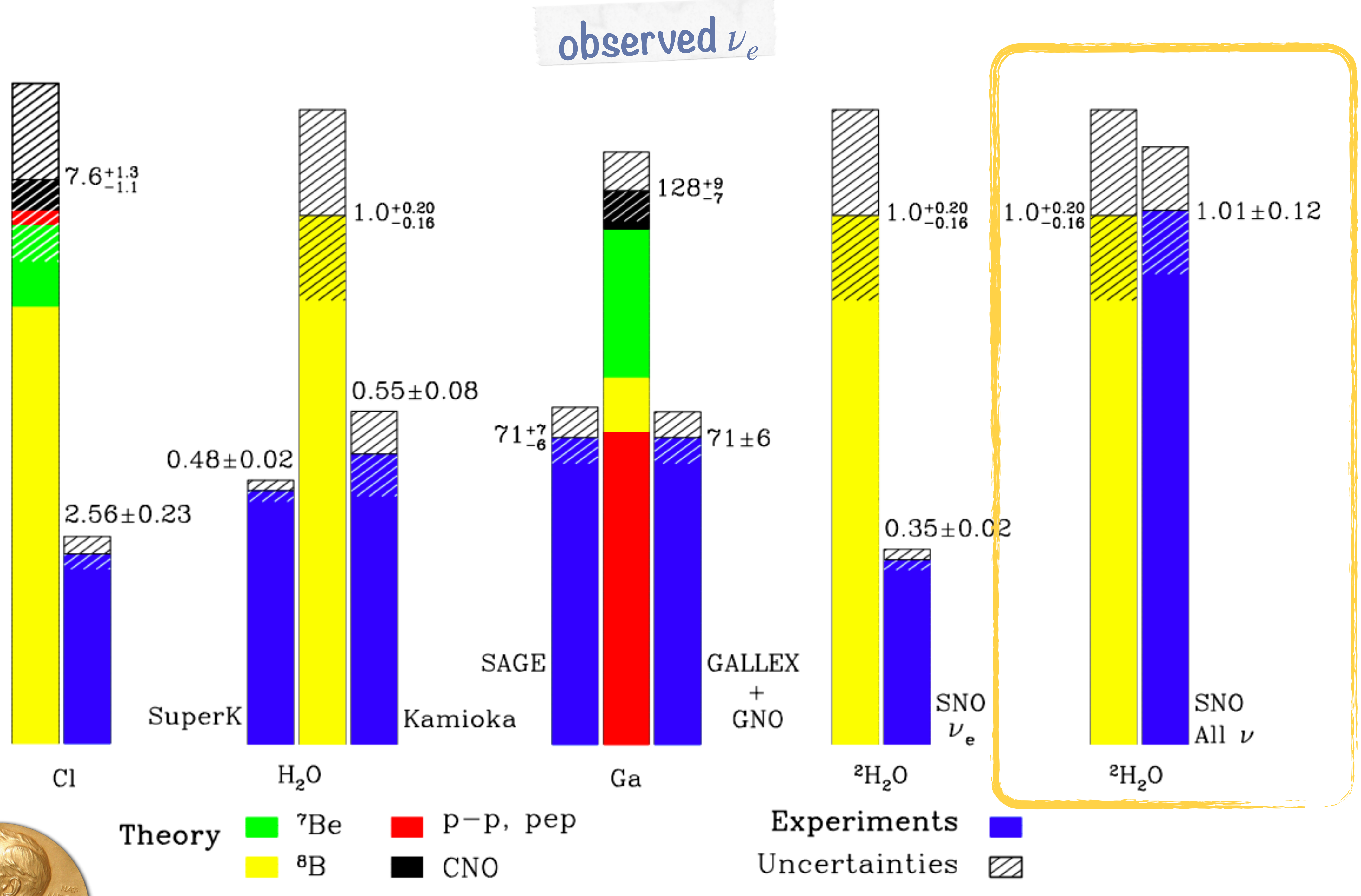


- SNO upgrade: detection of Elastic Scattering (ES) and Neutral current (NC) interactions
  - CC are flavor dependent but ES and NC are not
  - **total flux compatible with Solar Standard Model prediction**
  - ν_e **are 1/3 of the total**, measurement of the ratio:

$$\frac{\Phi(CC)}{\Phi(NC)} = (0.34 \pm 0.023)\,^{+0.029}_{-0.031}$$

(Nobel prize in 2015!)

observed ν_e



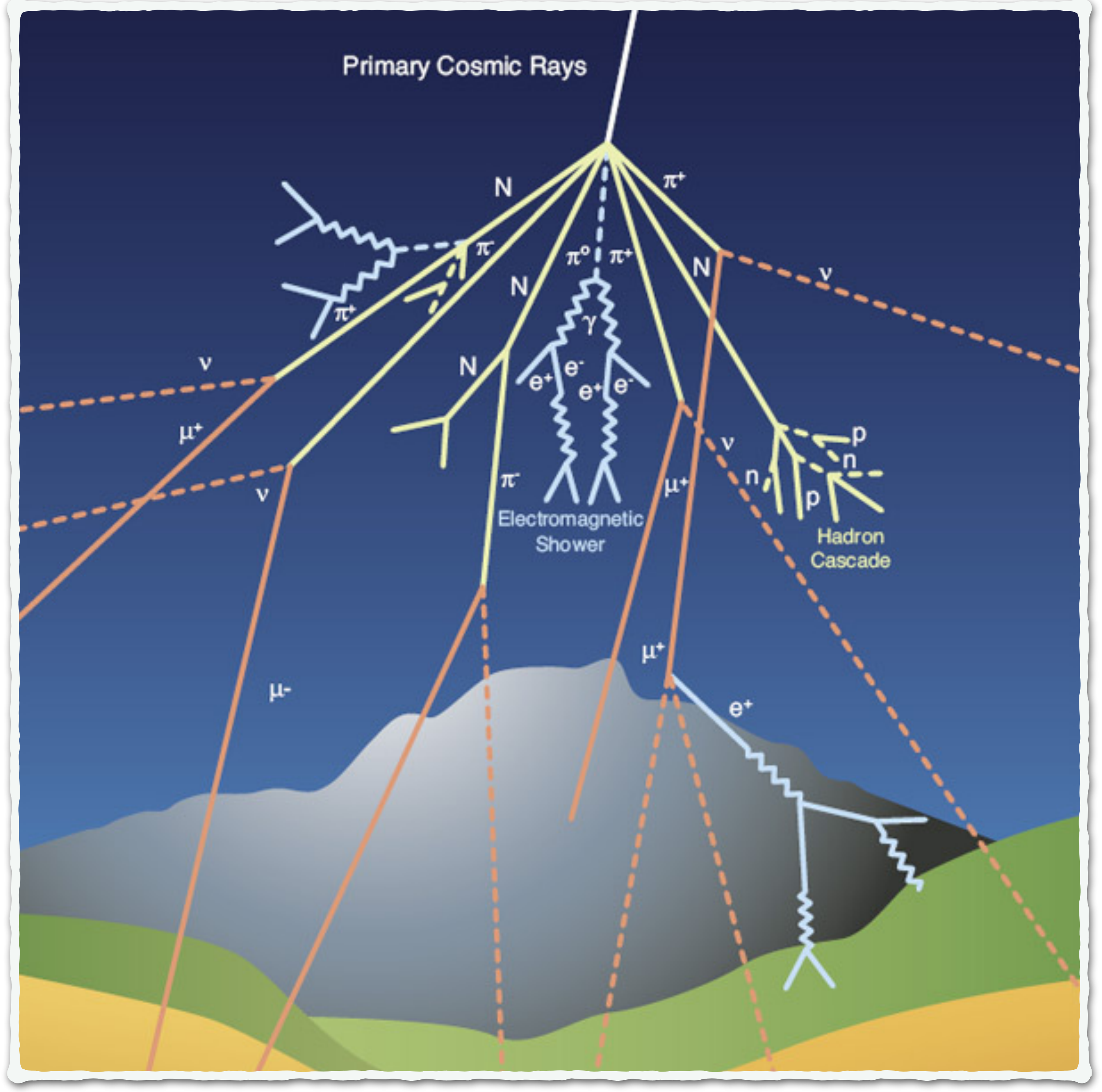
The atmospheric neutrino anomaly

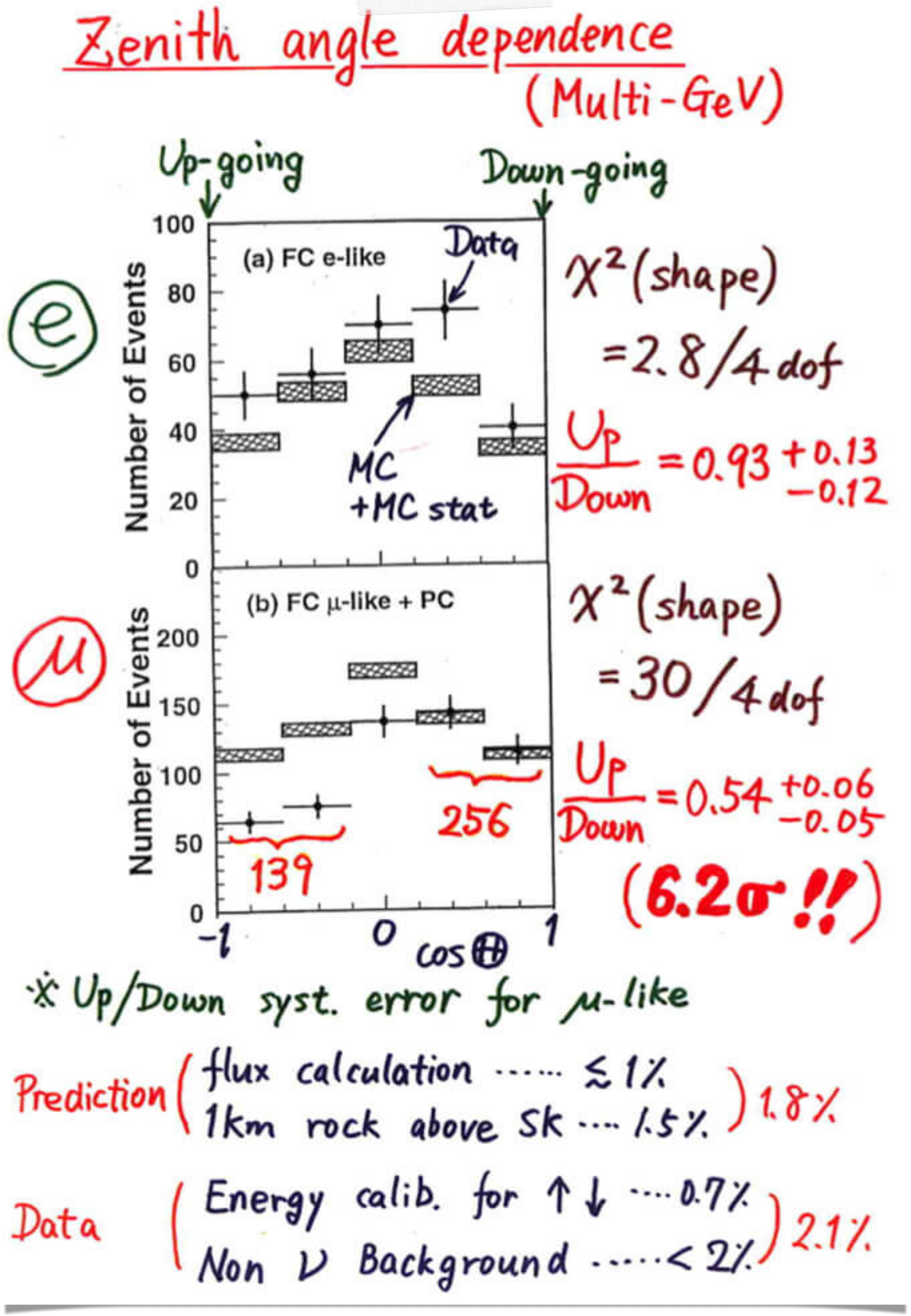
Neutrinos produced in the atmosphere: all muons decay before reaching the ground

- expected ratio of muon neutrino and electron neutrino fluxes

$$\frac{\Phi(\nu_\mu) + \Phi(\bar{\nu}_\mu)}{\Phi(\nu_e) + \Phi(\bar{\nu}_e)} \sim 2$$

- in SuperKamiokande data, only 50% of up-going ν_μ were observed…





※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background ….. < 2%) 2.1%

The neutrino oscillation mechanism

Neutrino flavors are a linear combination of neutrino mass eigenstates

flavor eigenstates,
$\alpha = (e, \mu, \tau)$

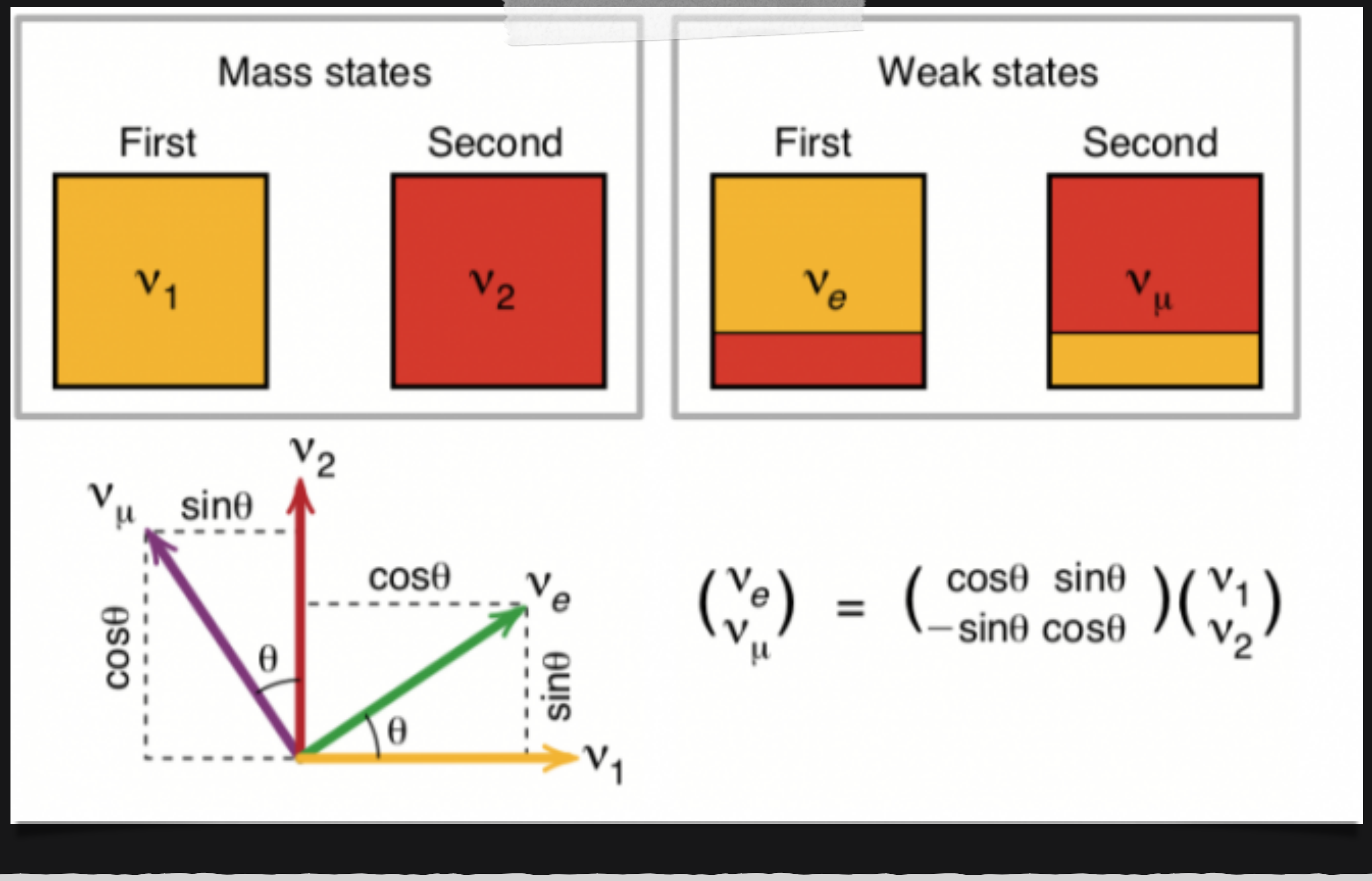
mass eigenstates,
$i = (1, 2, 3)$

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

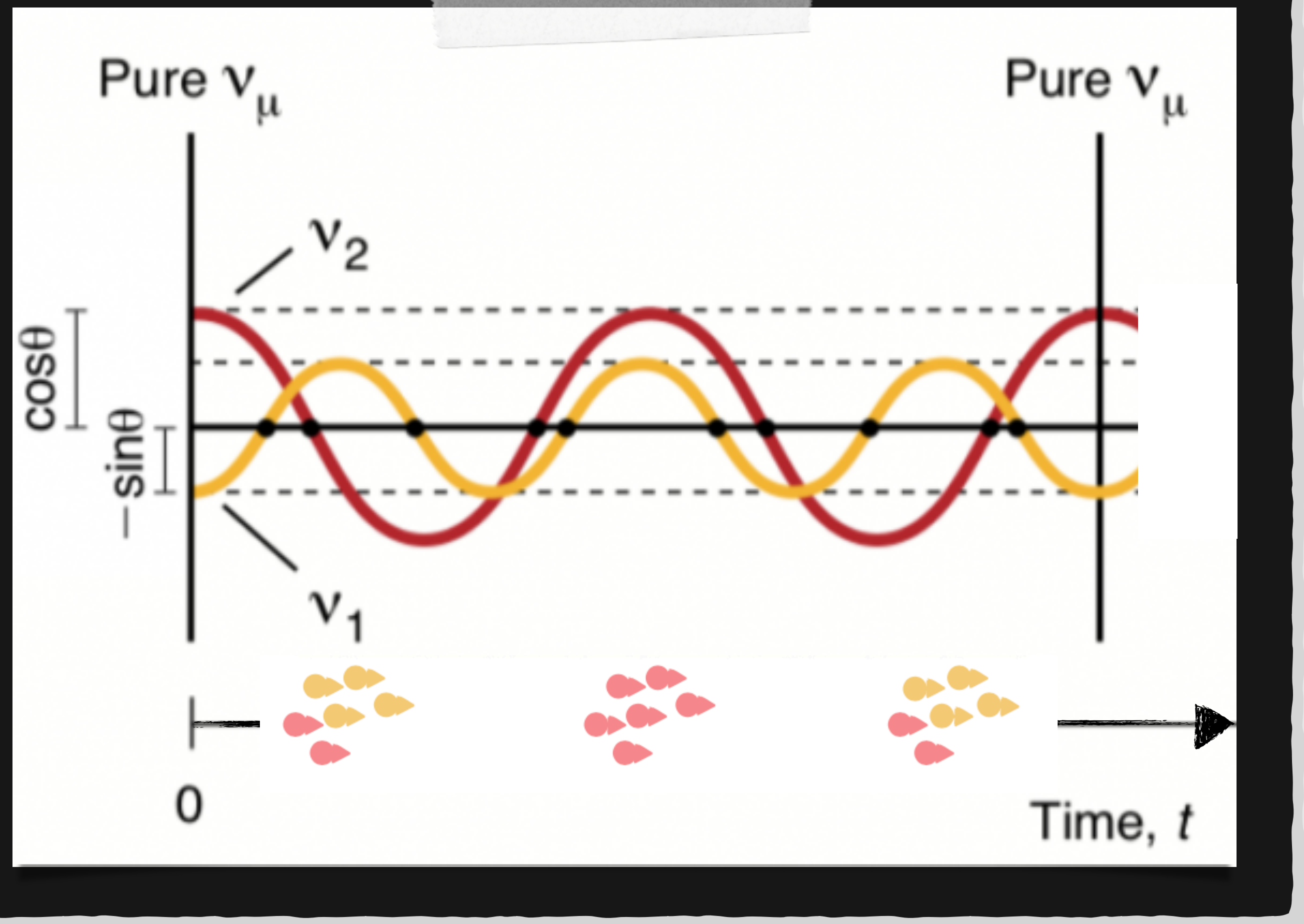
U, PMNS matrix

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

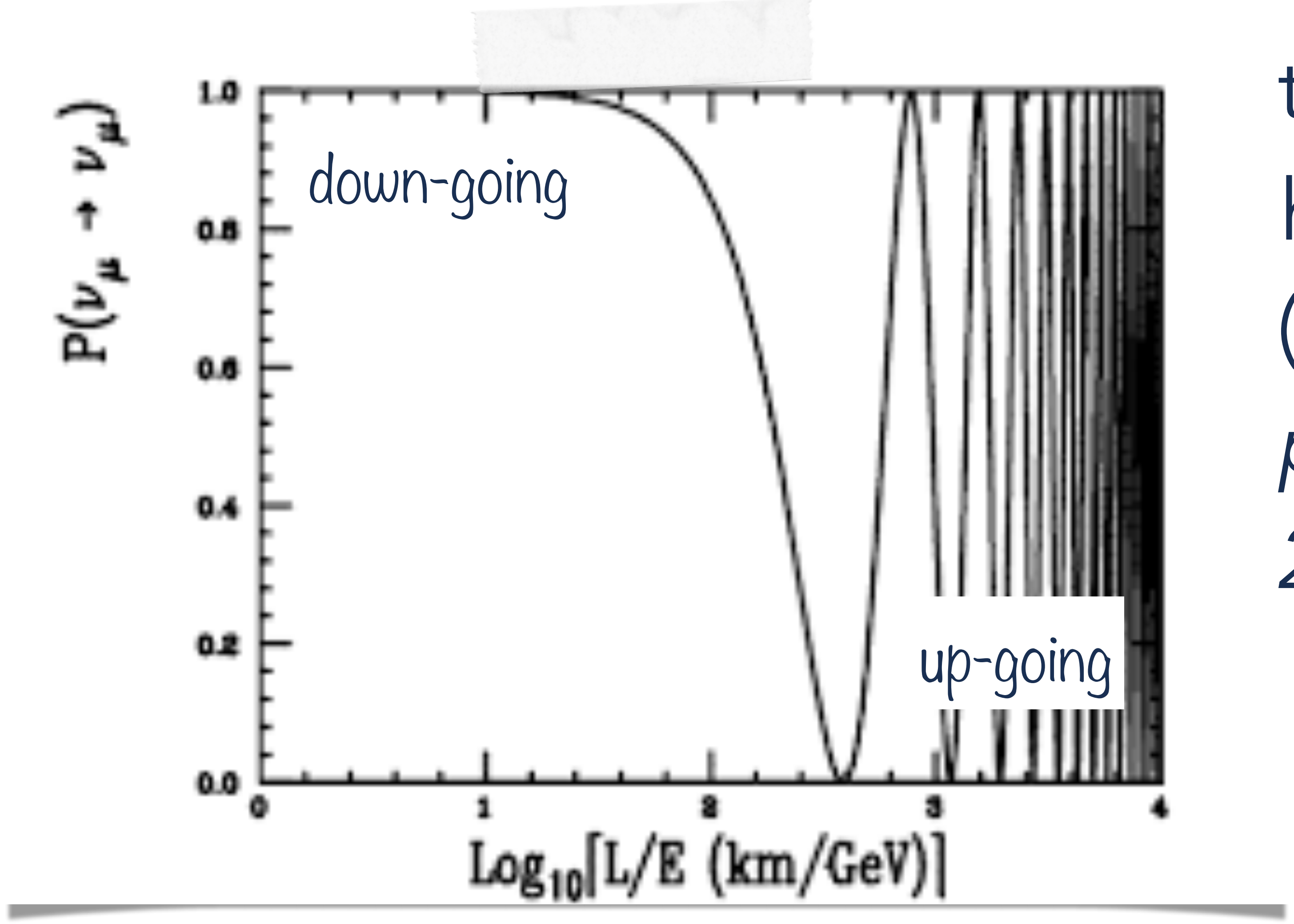
$\Delta m^2 = m_1^2 - m_2^2$, L = baseline, E = energy



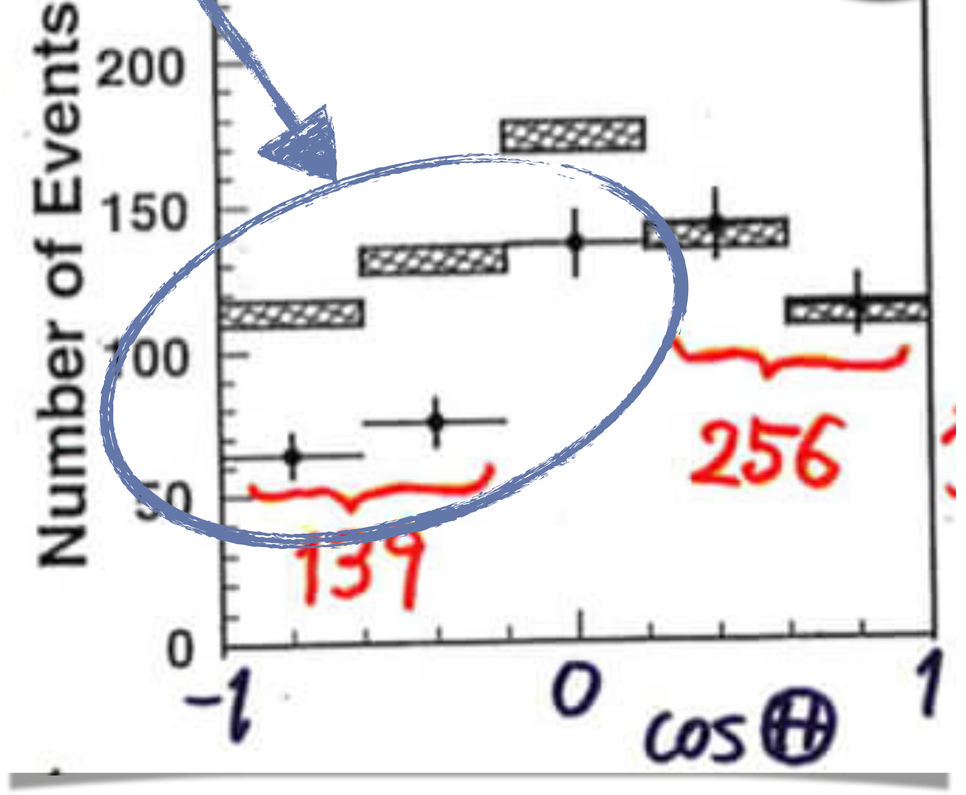
$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$



- the minimum position is determined by the mass splitting (Δm^2)
- the minimum deep is determined by the mixing angle (θ)



the missing up-going ν_μ have oscillated! (*Nobel prize in 2015!*)

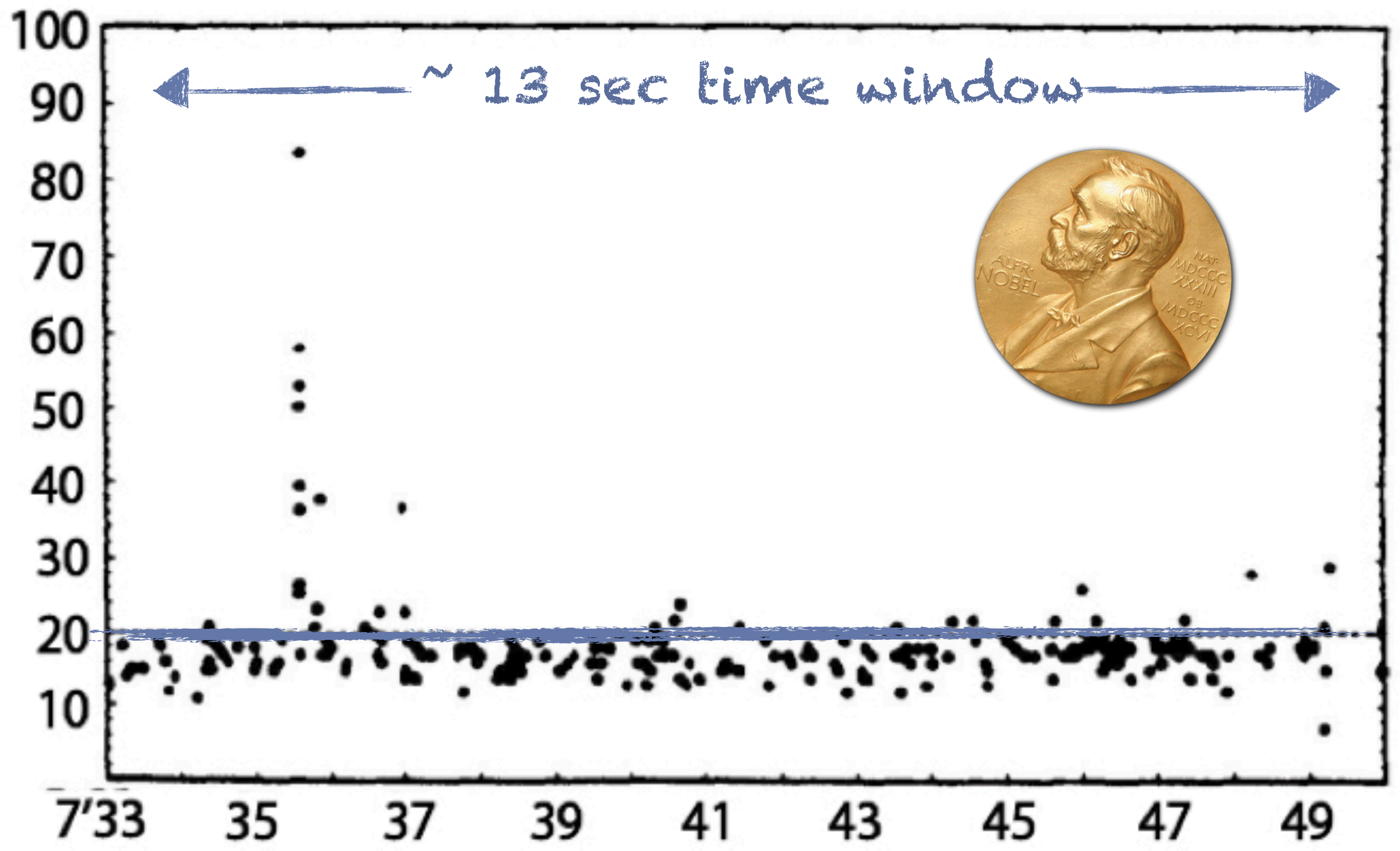


Neutrino astronomy

Neutrinos produced in SN explosion: they carry 99% of the SN energy

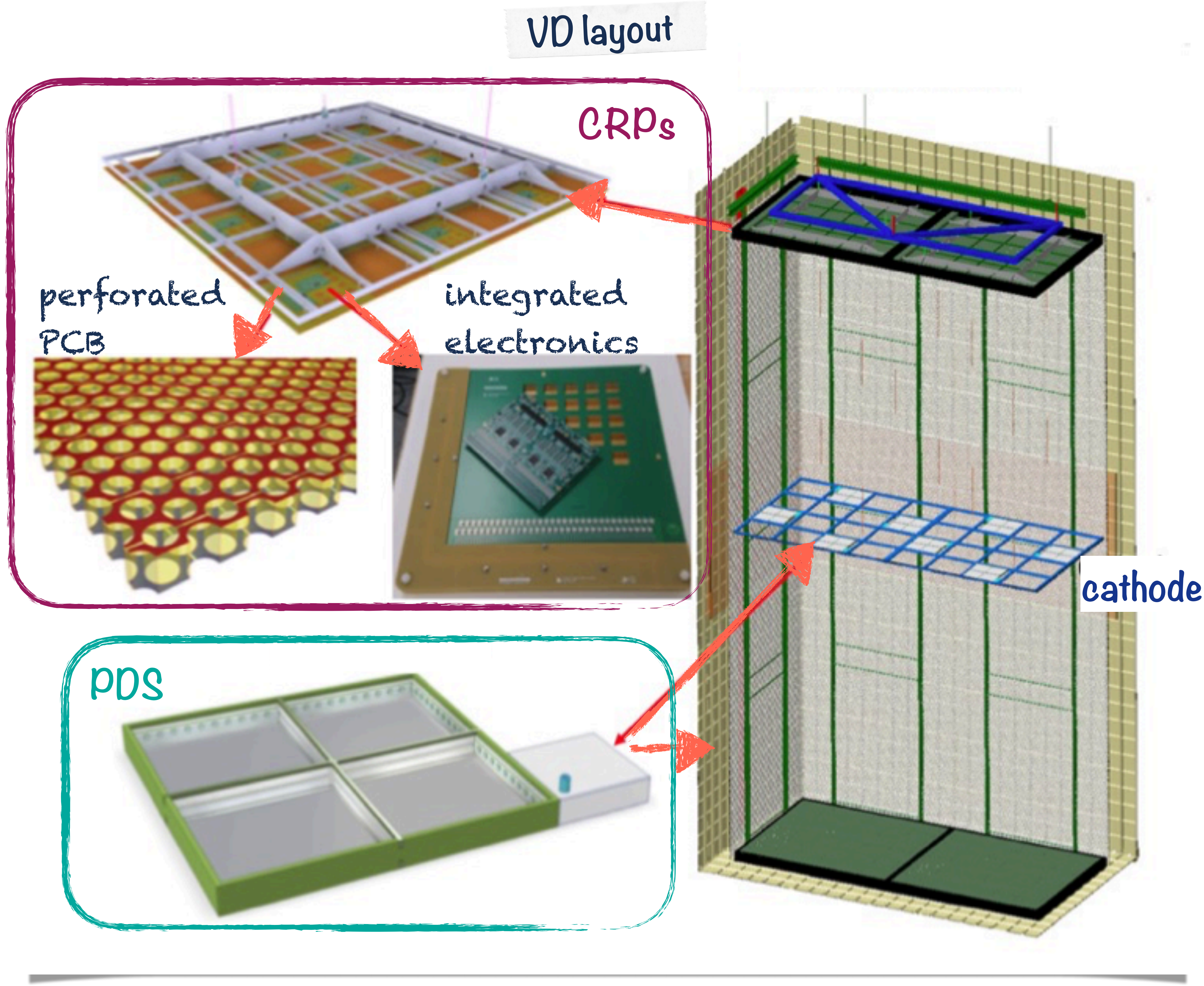
- a SN in the Large Magellan Cloud exploded on Feb. 23rd 1987, 7:33 UTC
  - neutrino signal arrived ~3h before the light signal
  - signal detected by three experiments: 11 events by Kamiokande-II, 8 events by IMB, 5 events by Baksan (*Nobel prize in 2002!*)

SN are expected to explode ~1/century…
so, now, all the experiments are waiting for the next one!



The Vertical Drift configuration

- ProtoDUNE-VD at CERN
- Two main bigger active volume (~6.5m drift each)
  - **Charge Readout Planes** (CRPs)
    - modular structures: two 3x3 m2, in the top and bottom of the TPC
    - perforated PCB strips (optimized orientation and pitch, ~mm precision)
  - **Photon Detection System** (PDS)
    - X-Arapucas*, directly integrated in the cryostat walls and cathode
    - optical fibers to power them and to collect the signal
    - good coverage of active volume



* *Arapuca in Brazilian means "trap", they act as light traps*