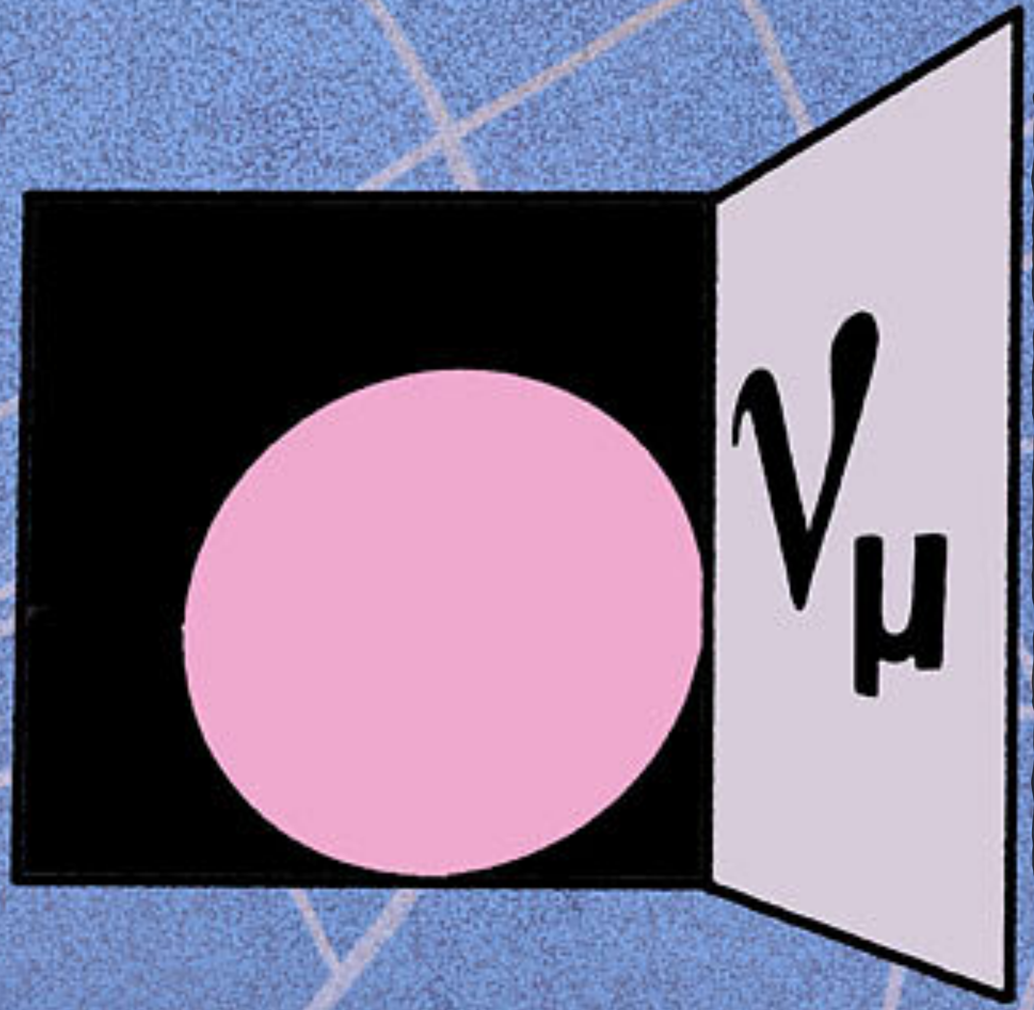
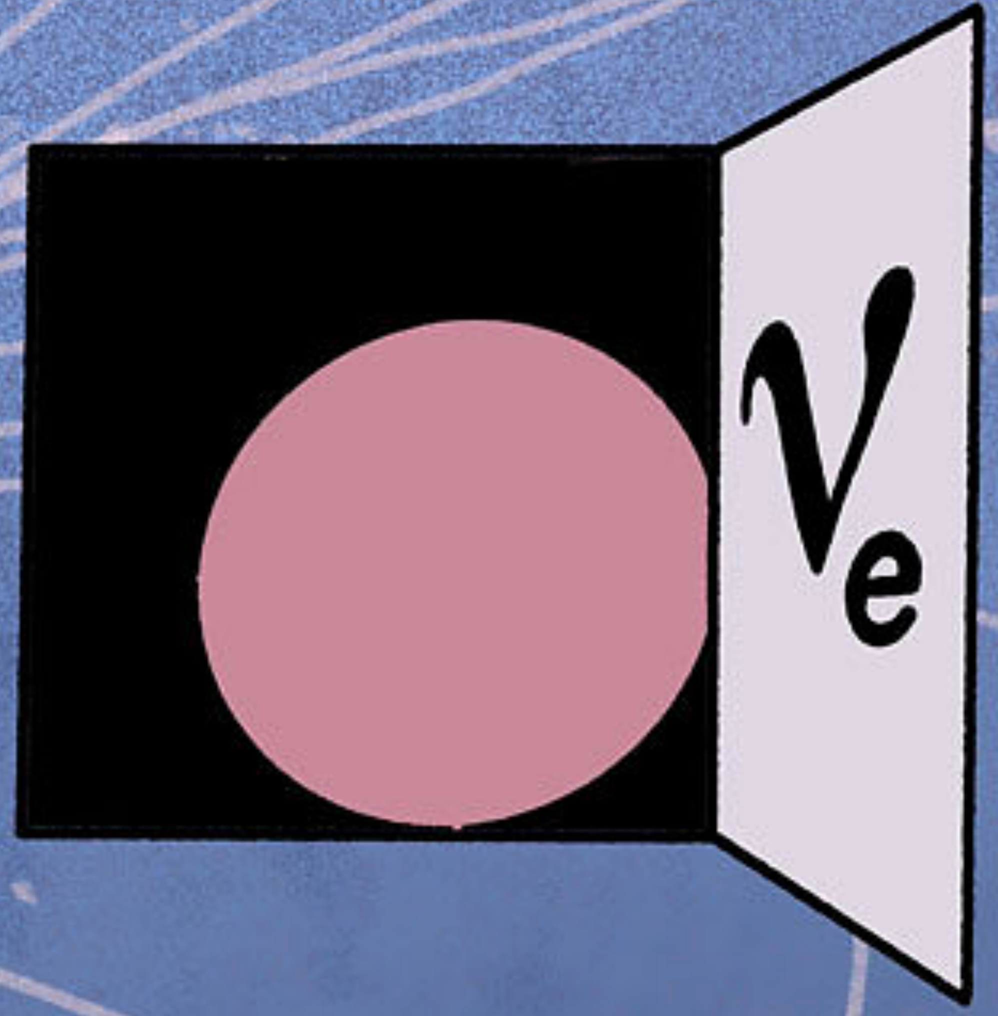
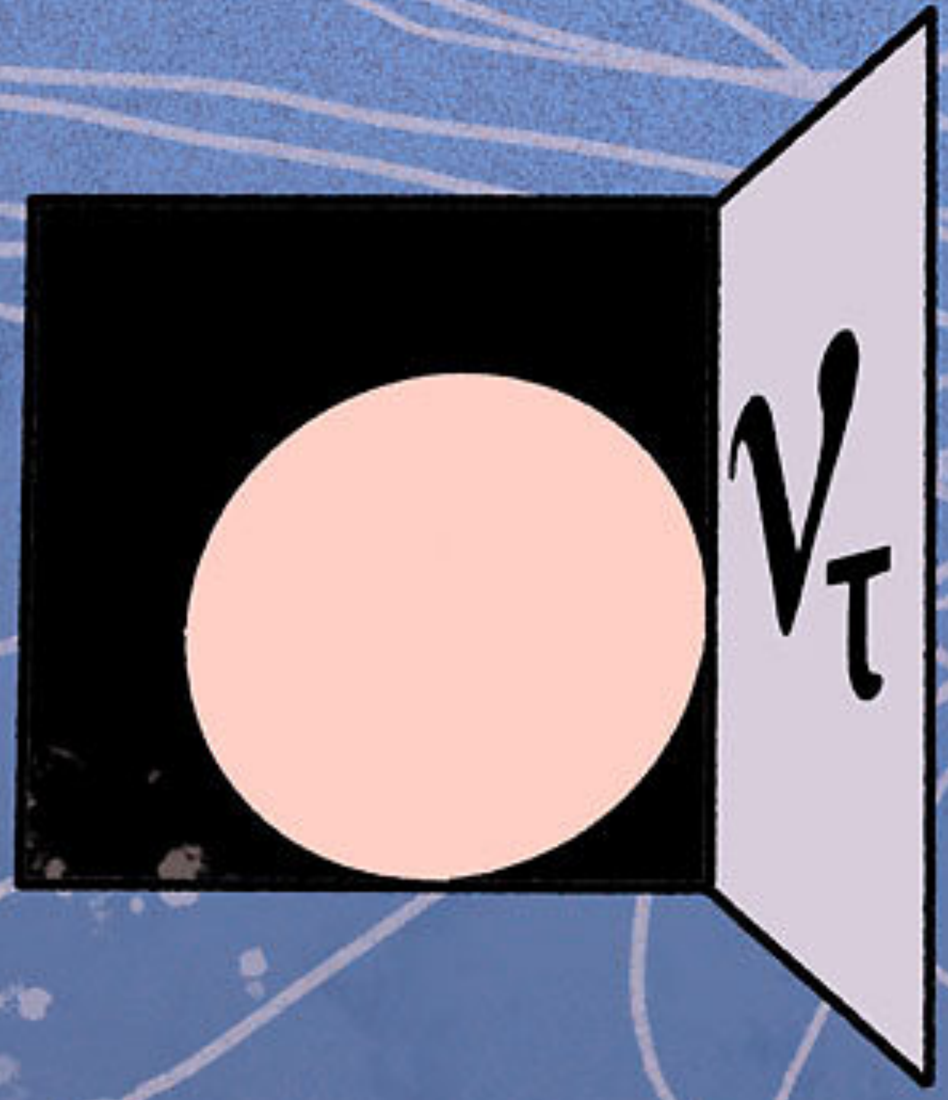
Background image's credit: Symmetry Magazine

Introduction on Neutrinos Physics

(what we think we know about neutrinos and
what we clearly don't know yet..)



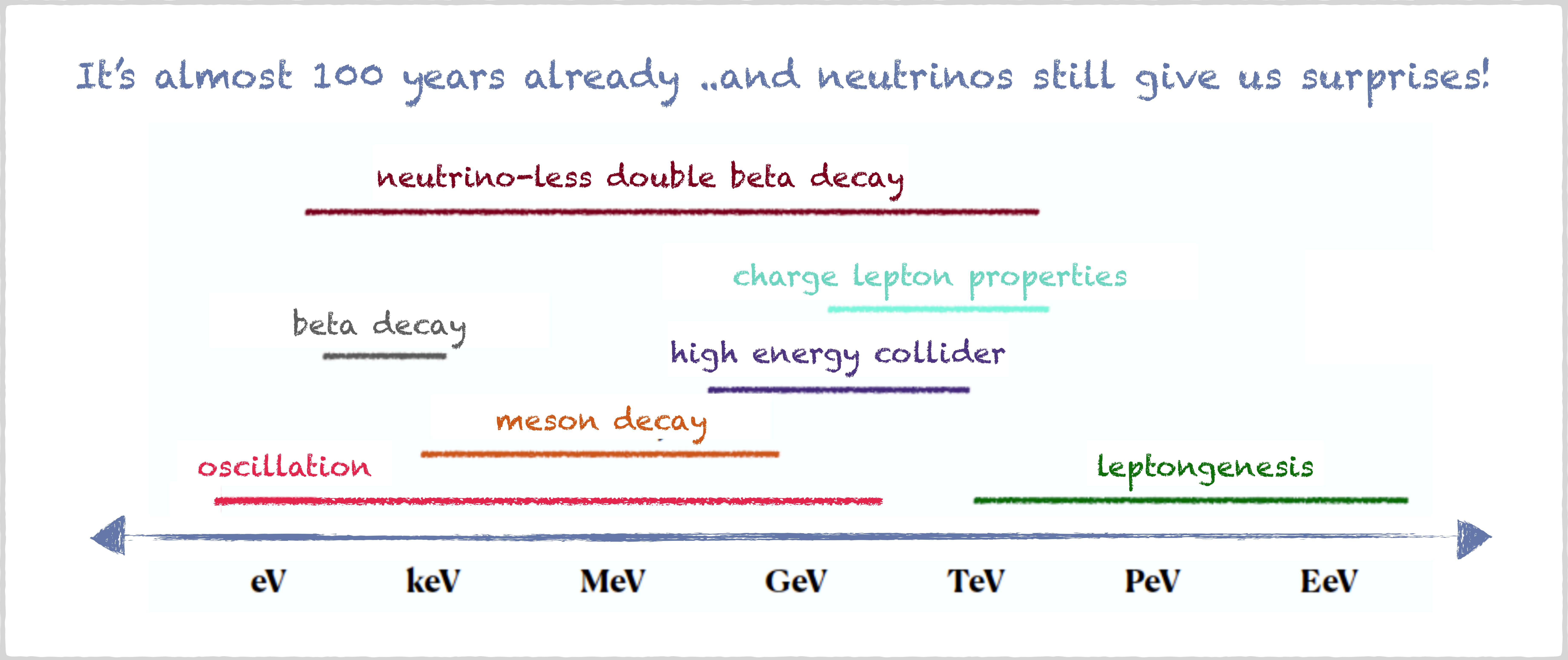




Chiara Lastoria - CNRS/Aix-Marseille Université/CPPM
JRJC Conference 2023 - Saint Jean du Mont - 27.10.2023

Outline

- Historical overview of main milestones in neutrino physics
- Where are we with our current understanding on neutrinos?
- A look toward the future!



Disclaimer:

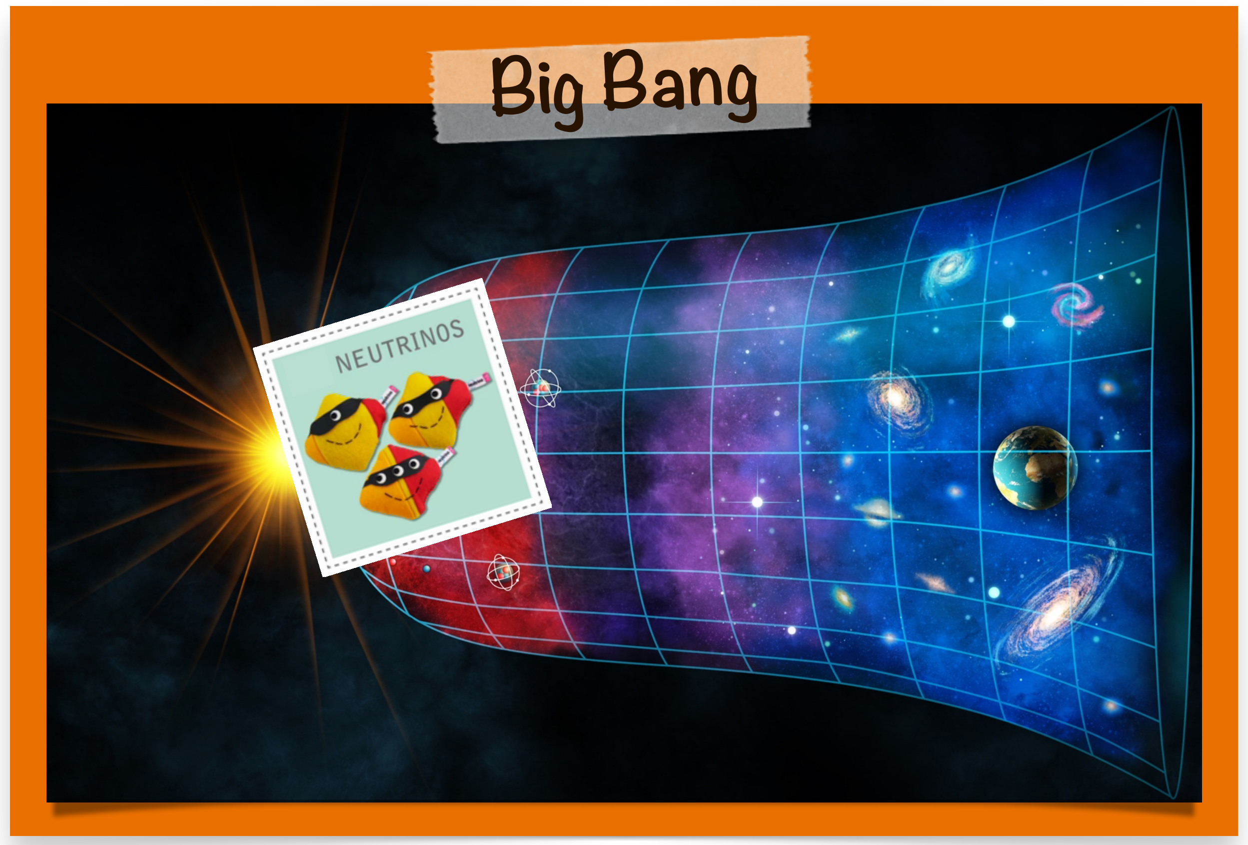
Biased summary around neutrino oscillations:

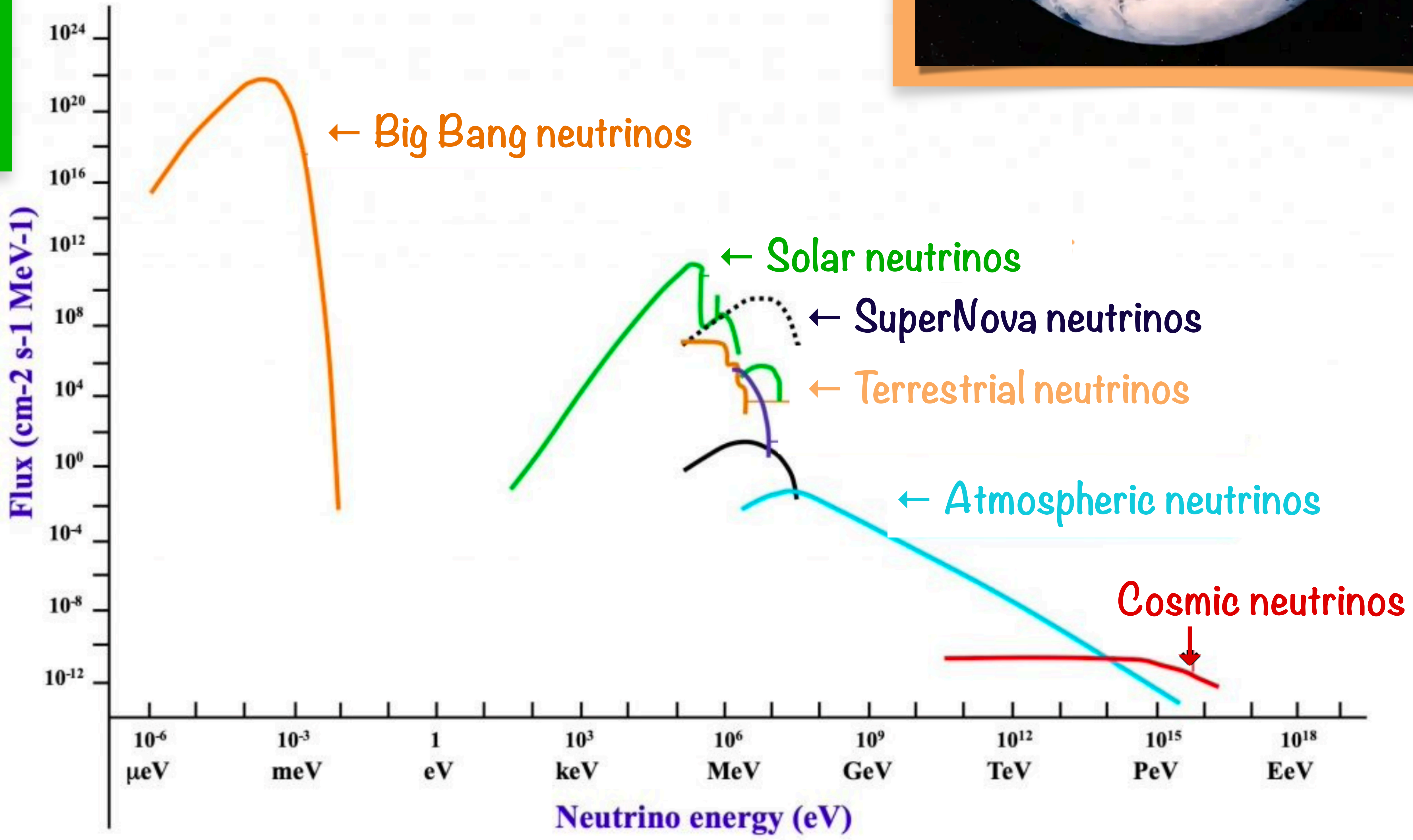
basically, "neutrino oscillation" is us thinking we understood neutrinos, while soon after realizing that we didn't understand anything..

Identikit of an introvert particle

Neutrinos are everywhere!

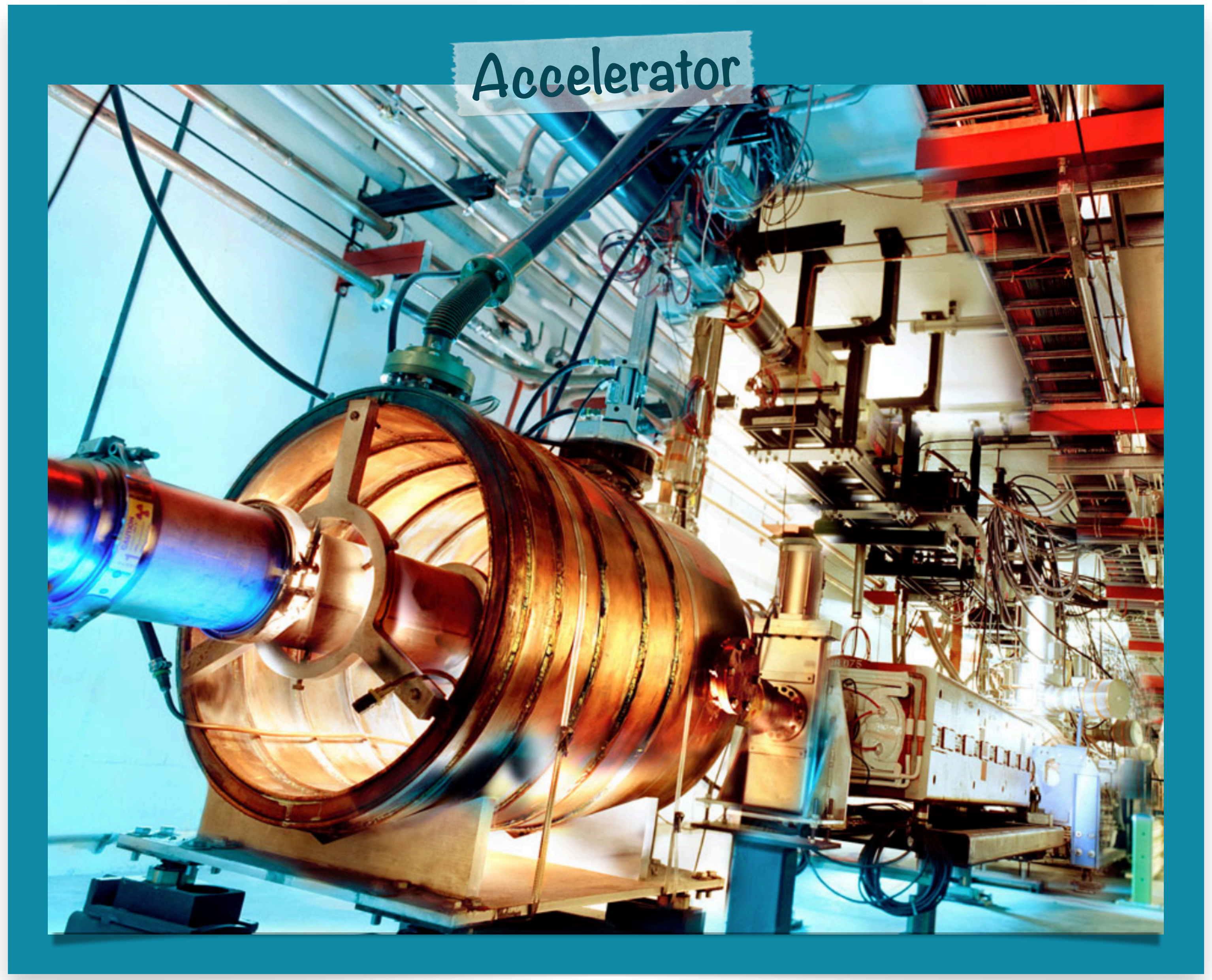
$\sim 10^9\ \nu/\mathrm{cm}^2/\mathrm{s}$

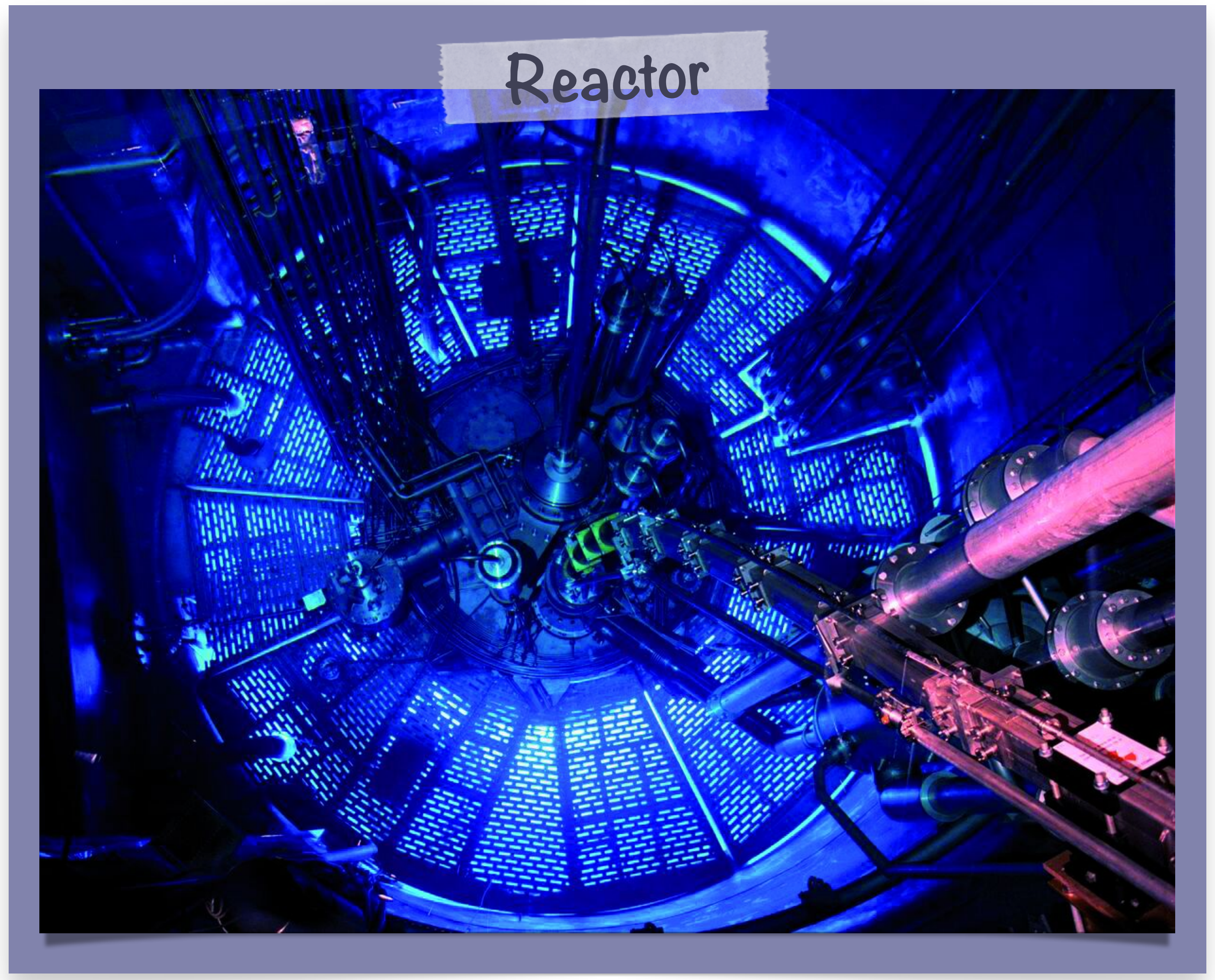


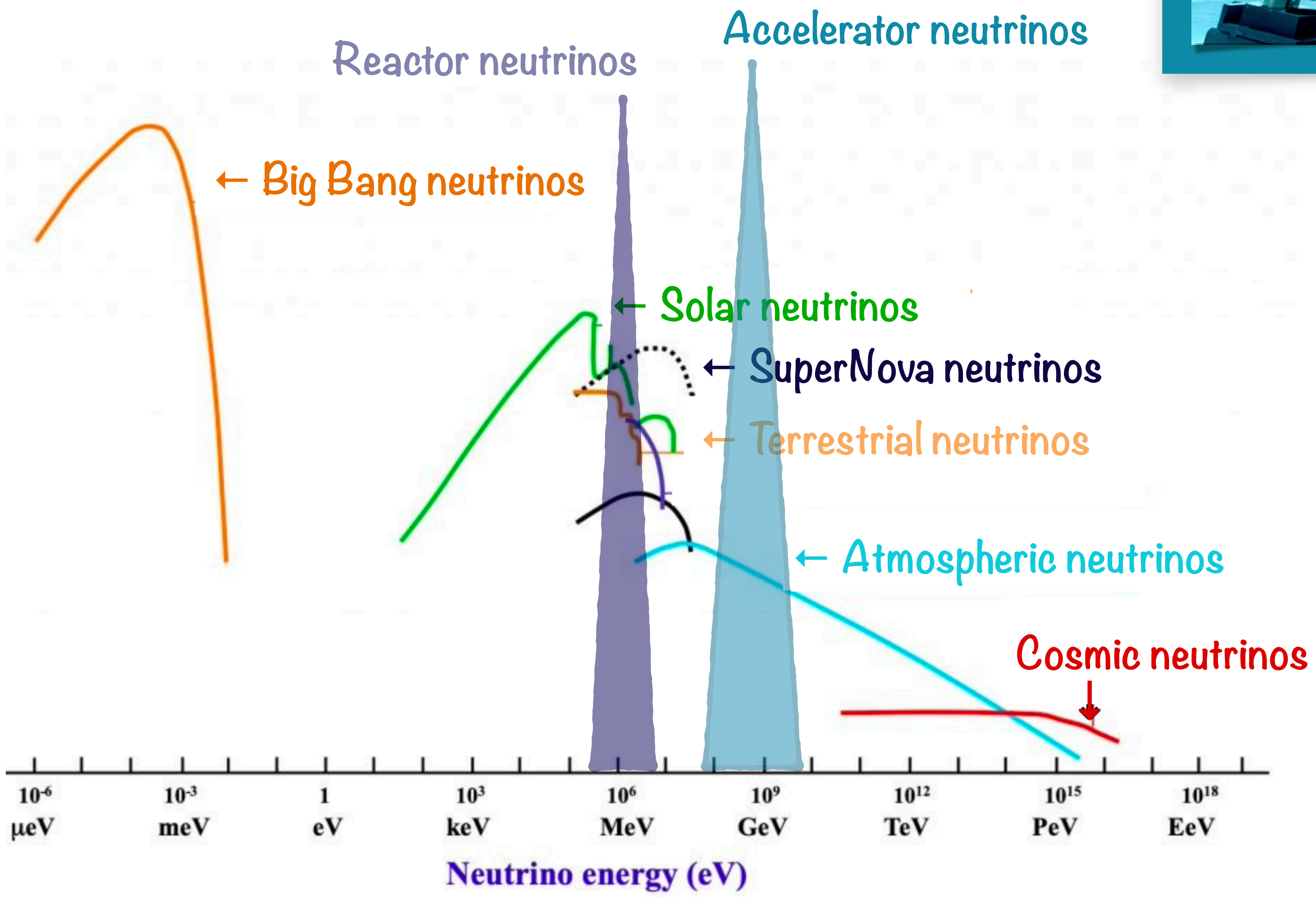


Identikit of an introvert particle

Neutrinos are everywhere! ~10^9 ν/cm^2/s
as well as, they can be artificially produced in reactors and accelerators







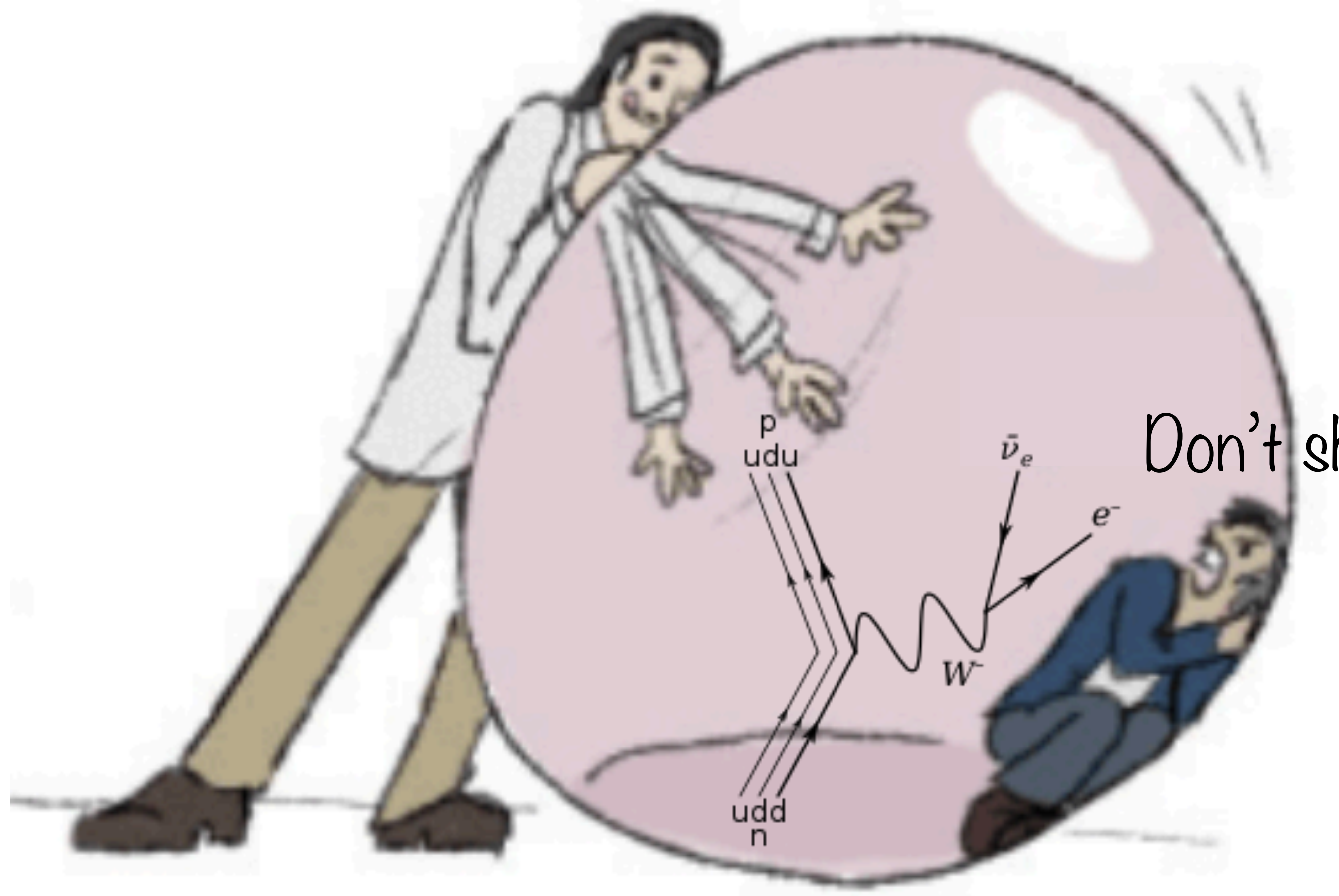
Identikit of an introvert particle

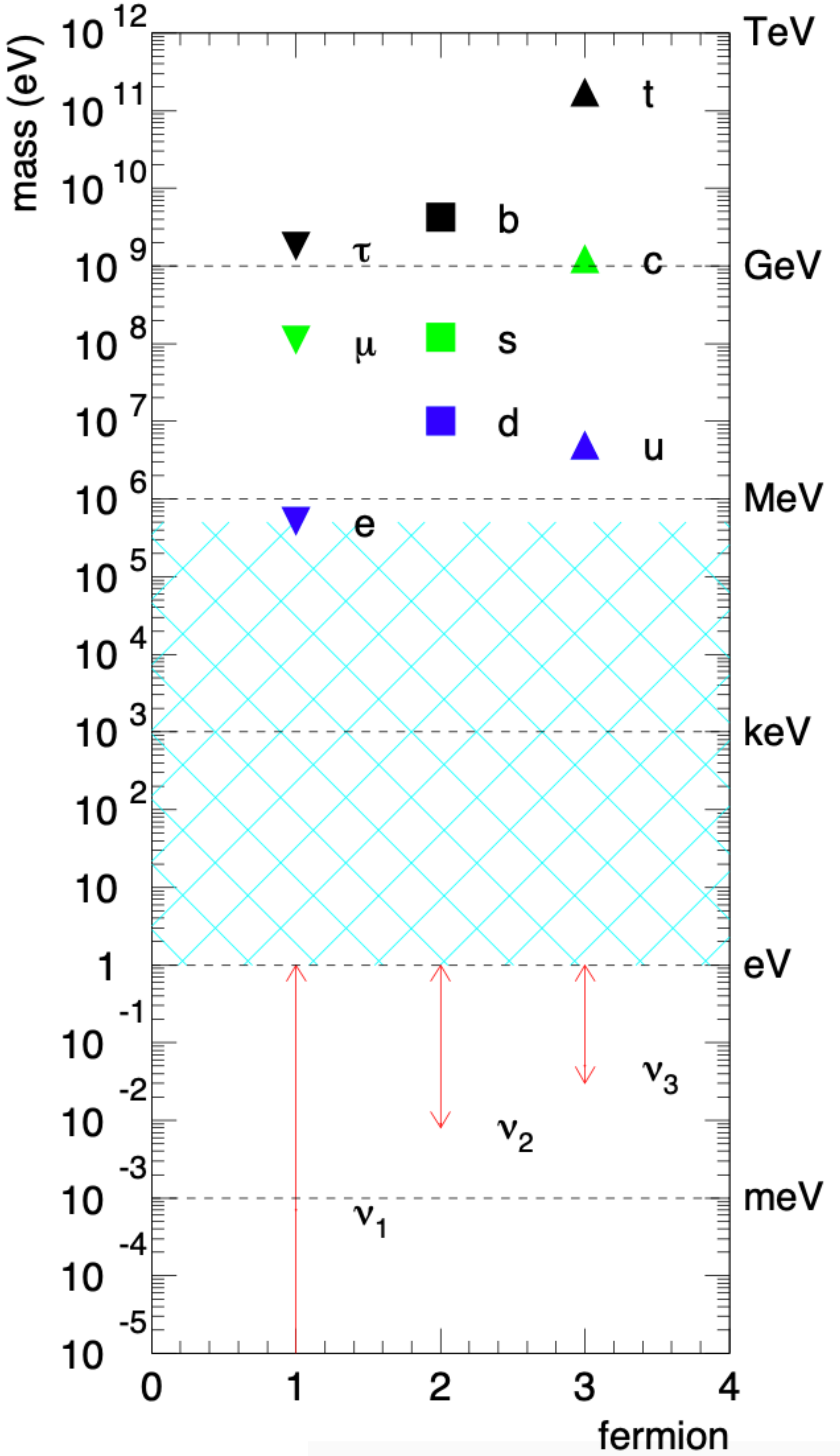
Neutrinos are everywhere! ~10^9 ν/cm^2/s
as well as, they can be artificially produced in reactors and accelerators

BUT

- they have a very small mass (we don't know how small yet..)
- they interact only via weak interactions

Hey ν!
Come out, let's have a beer!





image's credit: "how interact with introverts"

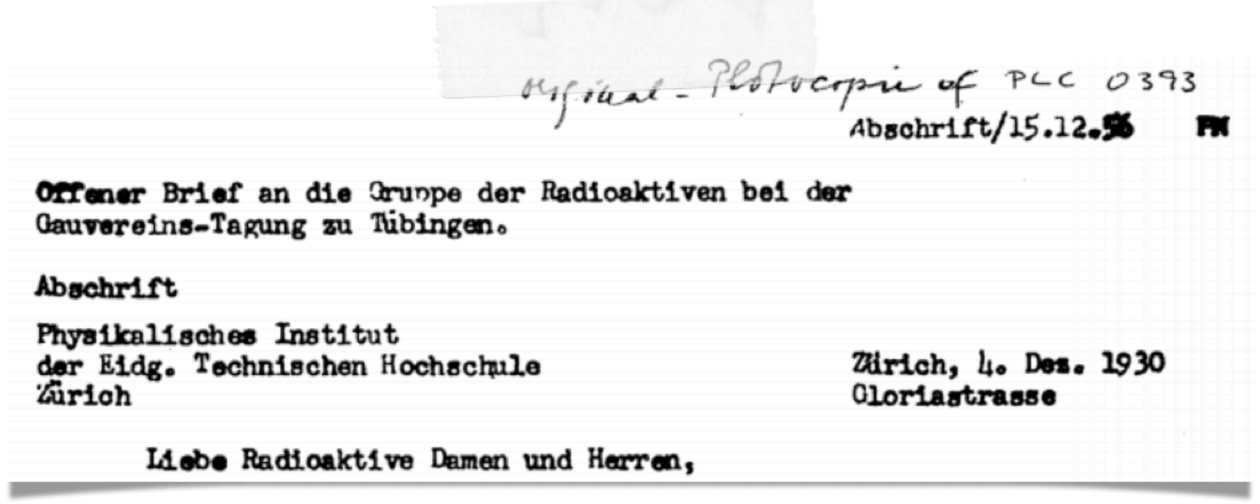
The "desperate remedy" of a new, neutral, massless particle

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


original - Photocopie of PLC 0393
Abschrift/15.12.56 PM

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

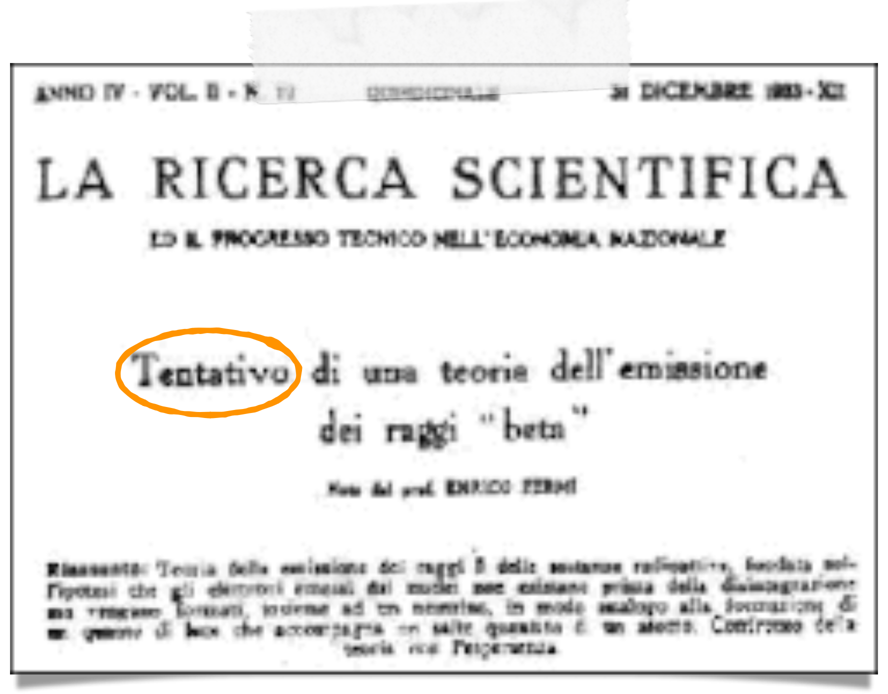
Abschrift

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


ANNO IV - VOL. II - N. 12 — 31 DICEMBRE 1933-XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

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

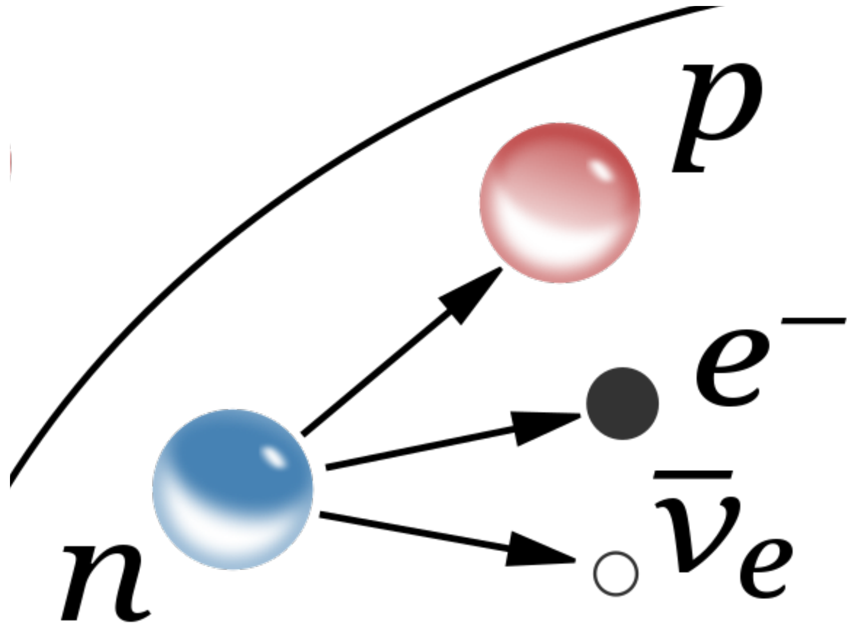
Nota del prof. ENRICO FERMI

(1) **1914**: beta decay spectrum

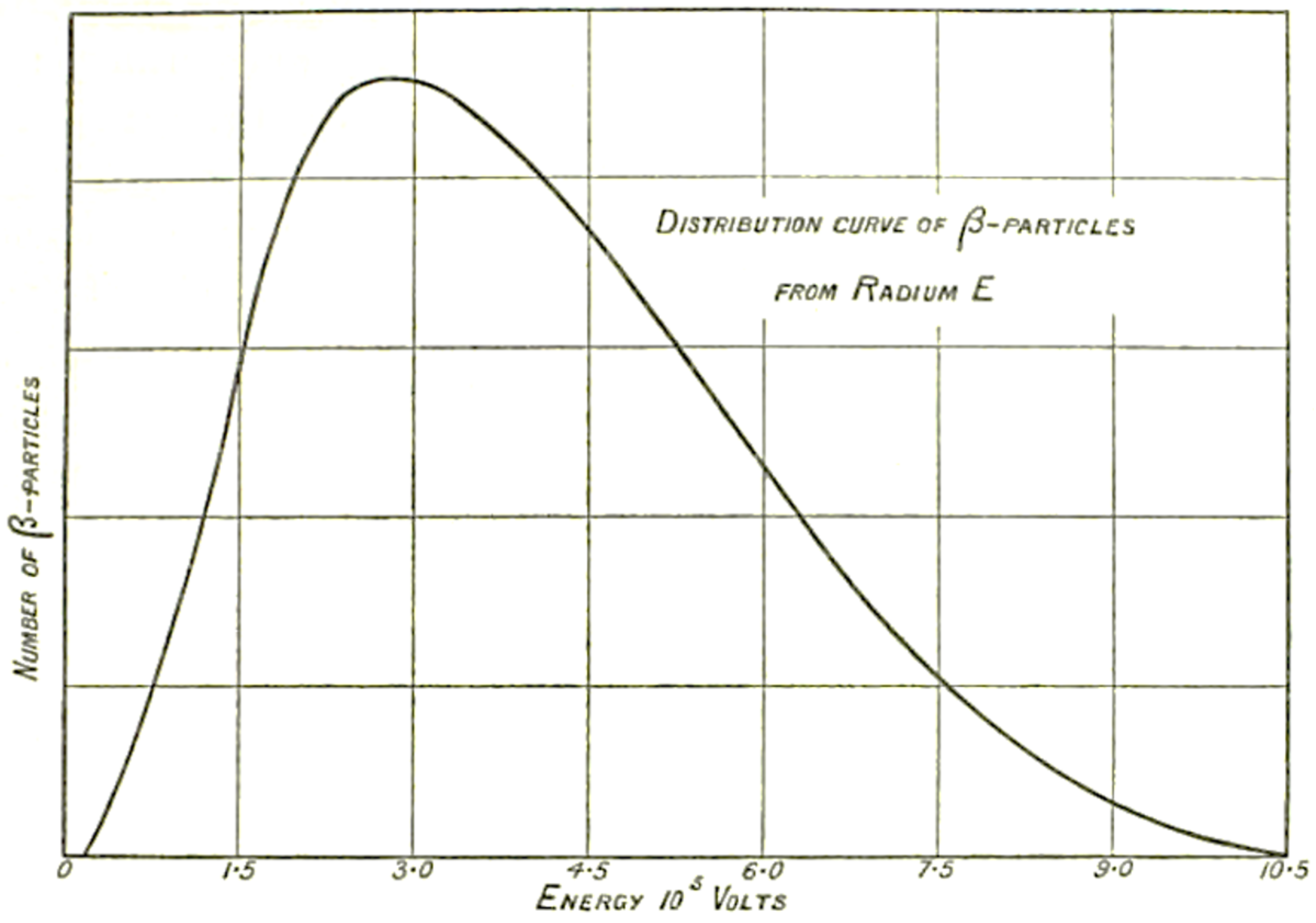
(2) **1896**: radioactivity

(3) **1933**: baptism of the *neutrino*

(4) **1930**: the "desperate remedy"

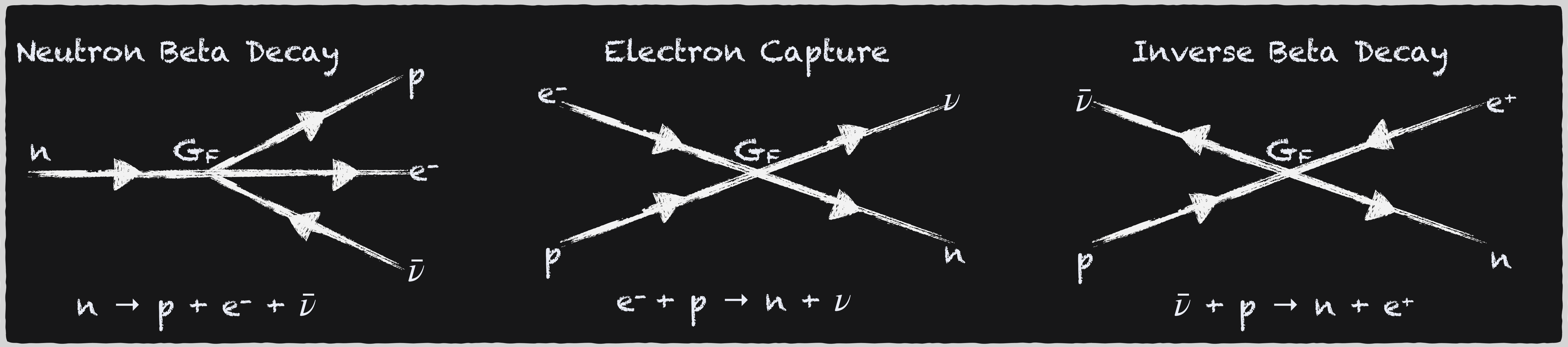


$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z\pm1}Y + e^{\pm} + \overset{(-)}{\nu}_e $$



The weak interaction theory in a nutshell

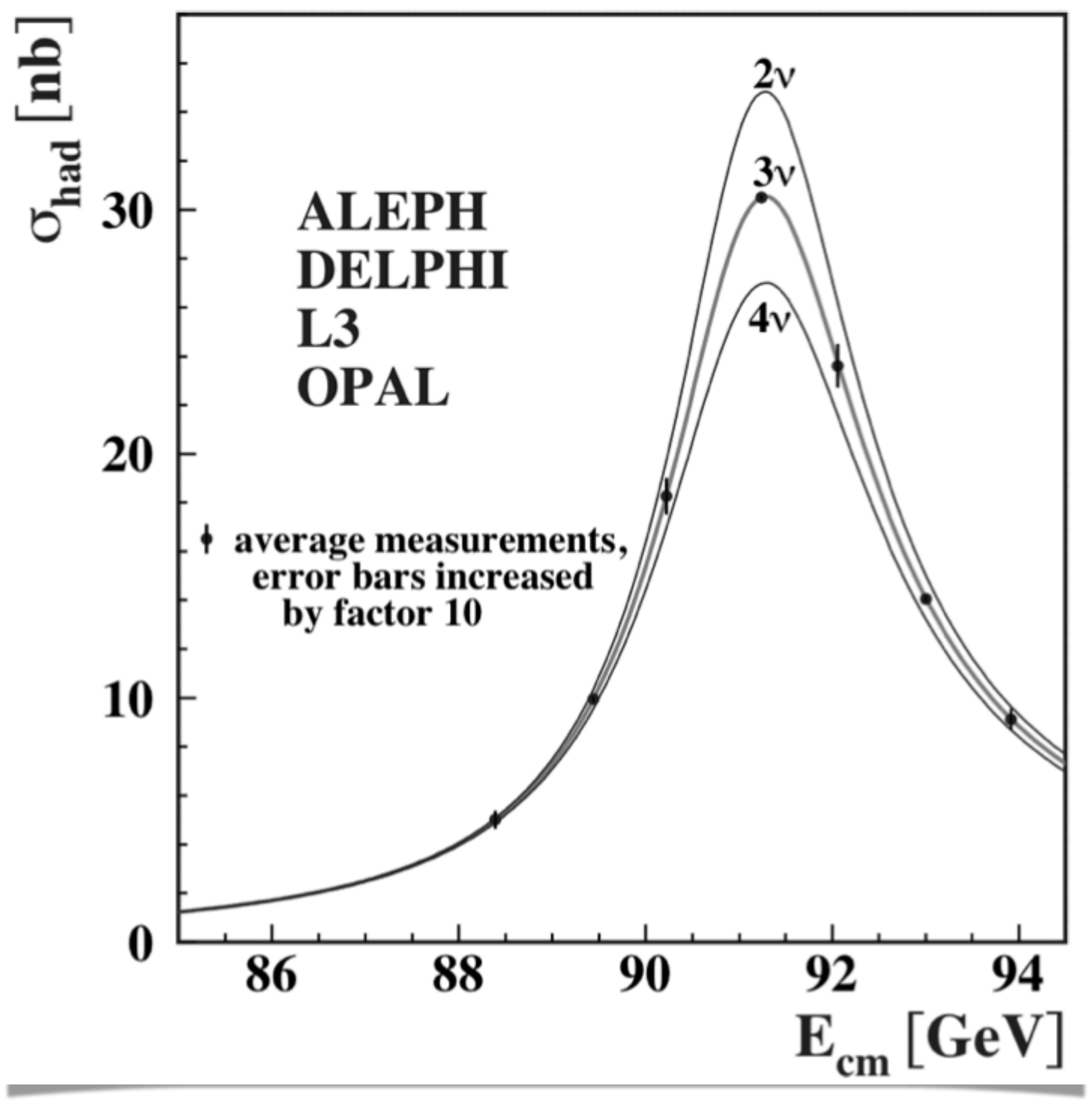
1933: E. Fermi names it **neutrino** and builds the weak interaction theory

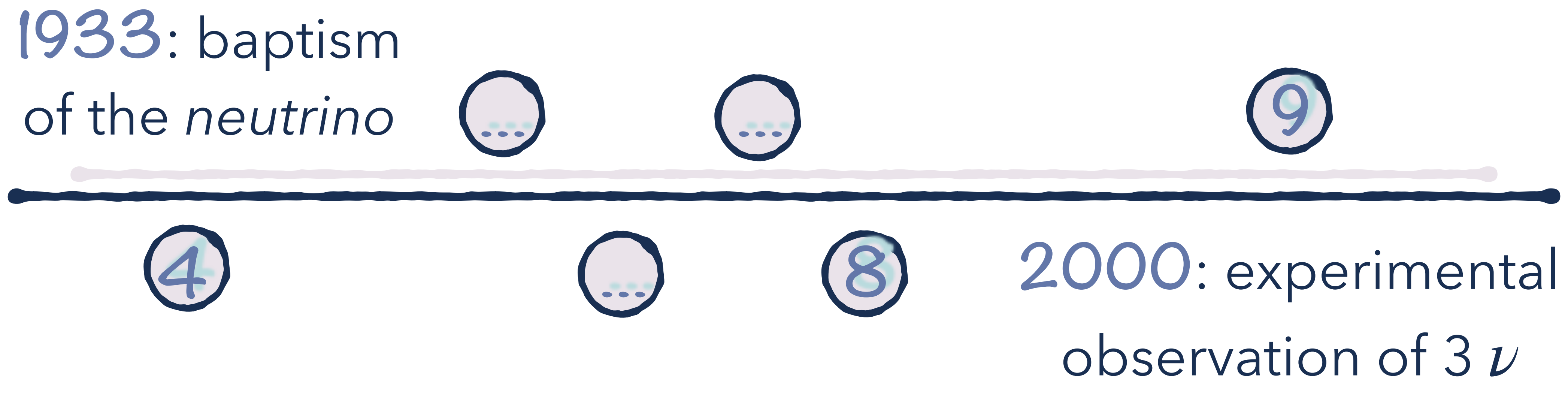


1989, LEP measure the Z boson and concludes that

- 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

LEP results

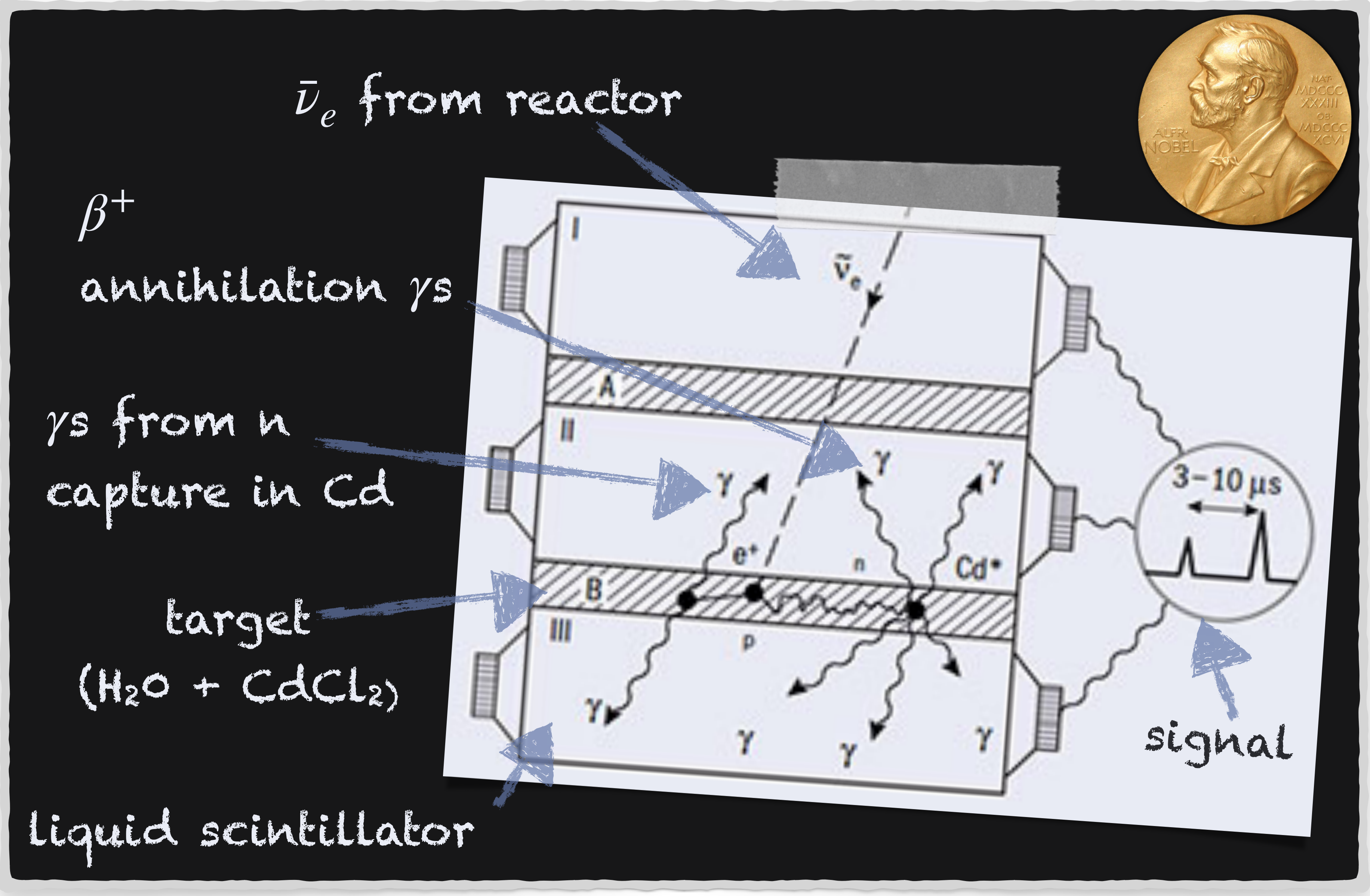


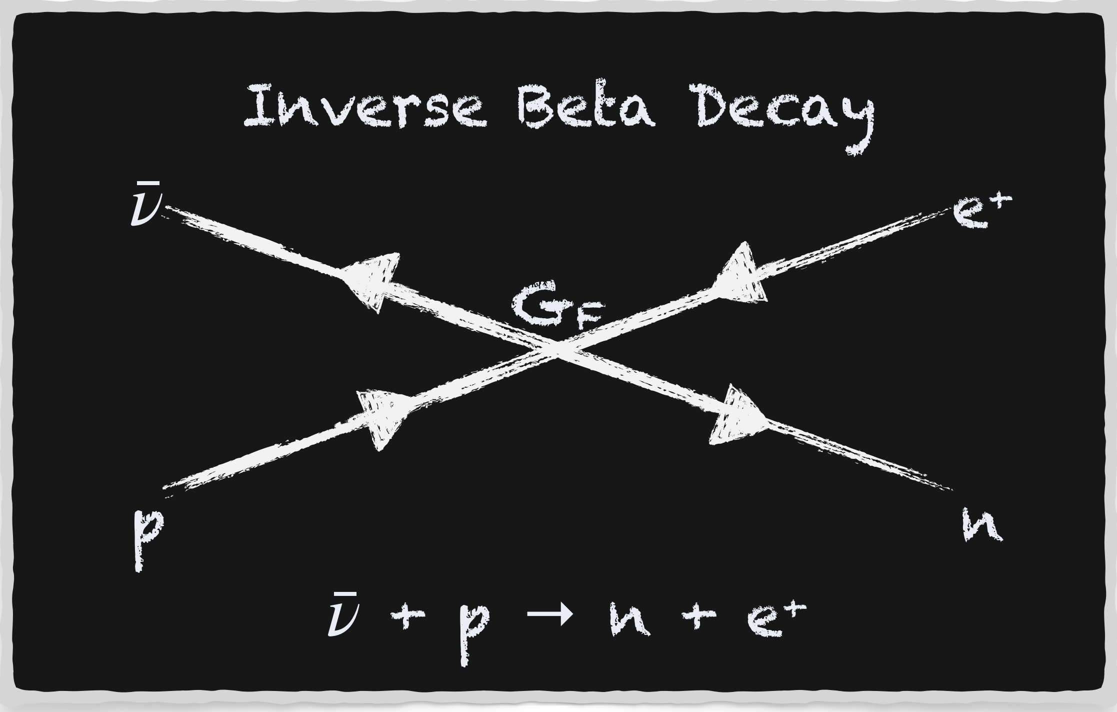


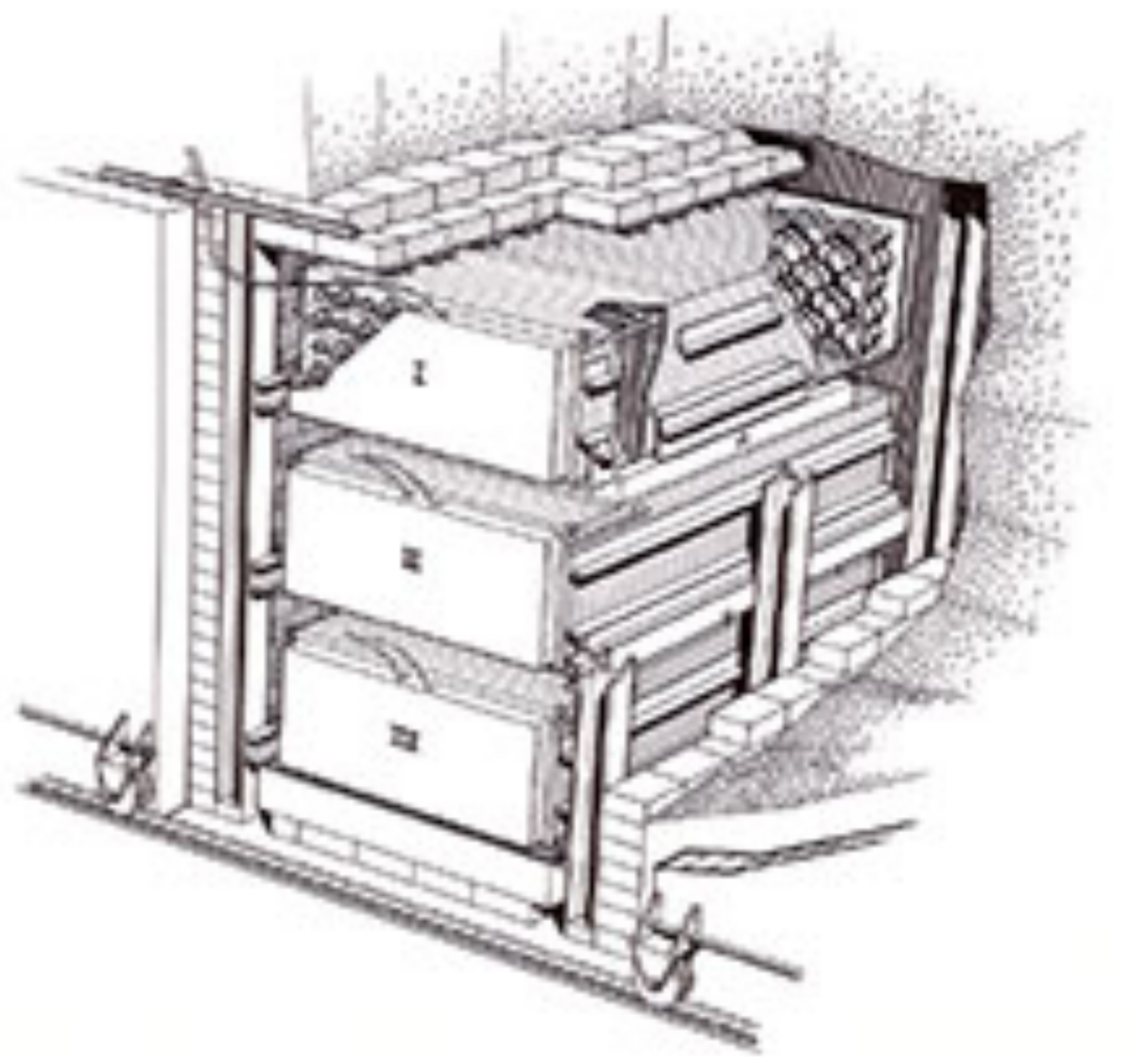
The electron neutrino

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







5

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

The electron neutrino

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

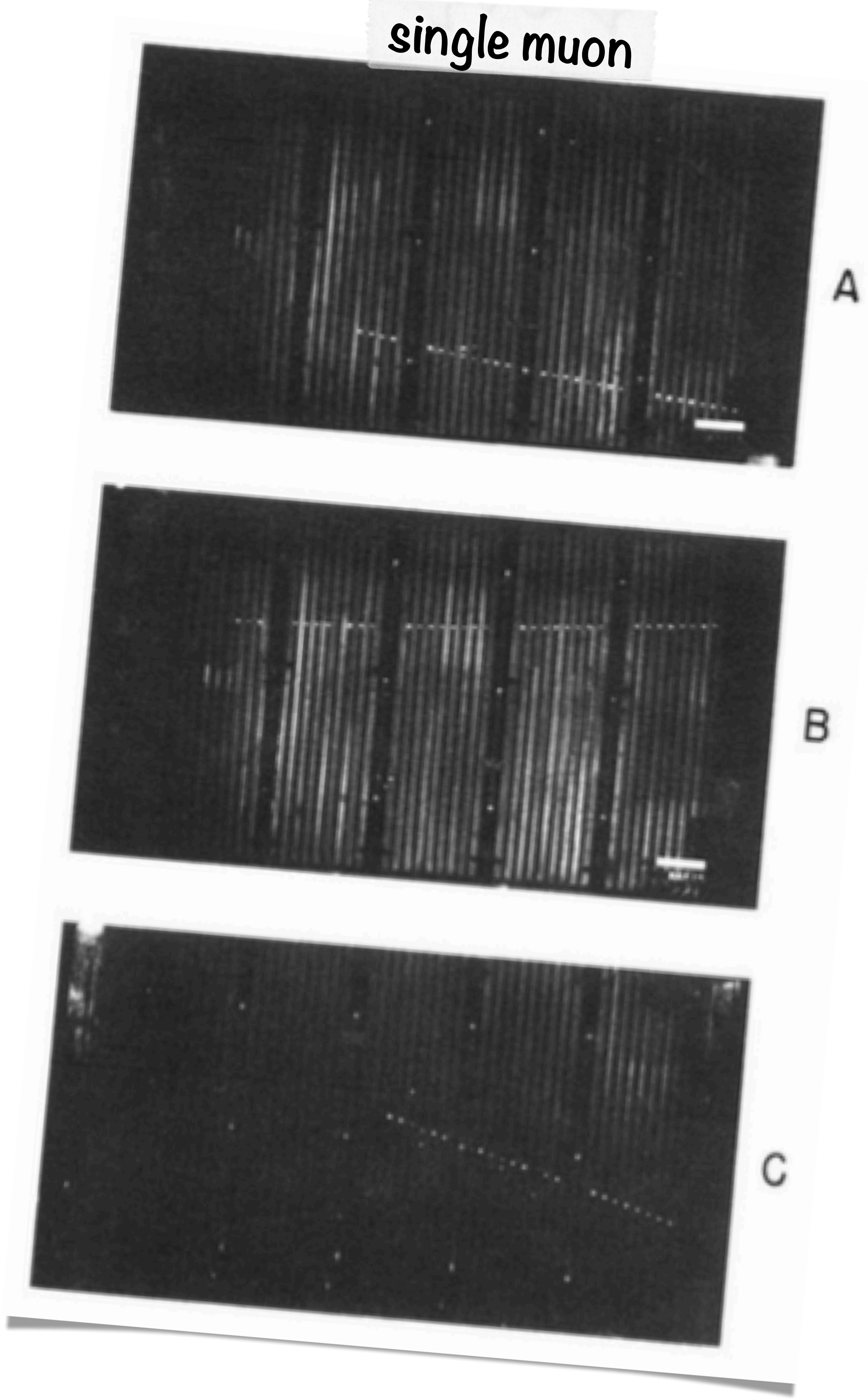
1962: ν_μ discovery by L. M. Lederman et al. @ Brookeven lab
(Nobel prize in 1988!)

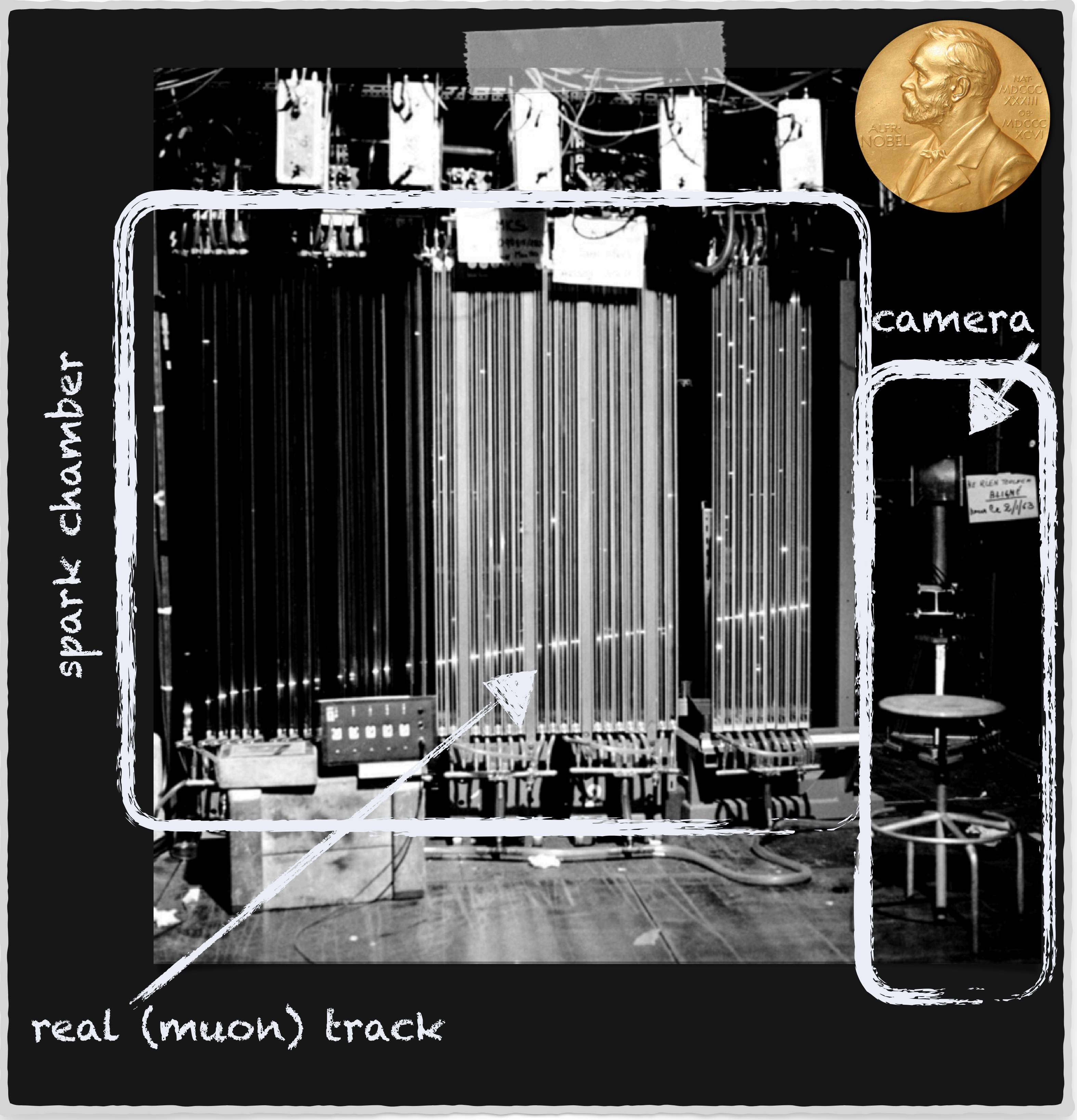
- neutrino from beam
- spark chamber
- using trigger for taking real photographs
- differentiate between electron showers (only 6 events) and muon events (34 single muon events)
  - ν_e are different from ν_μ !

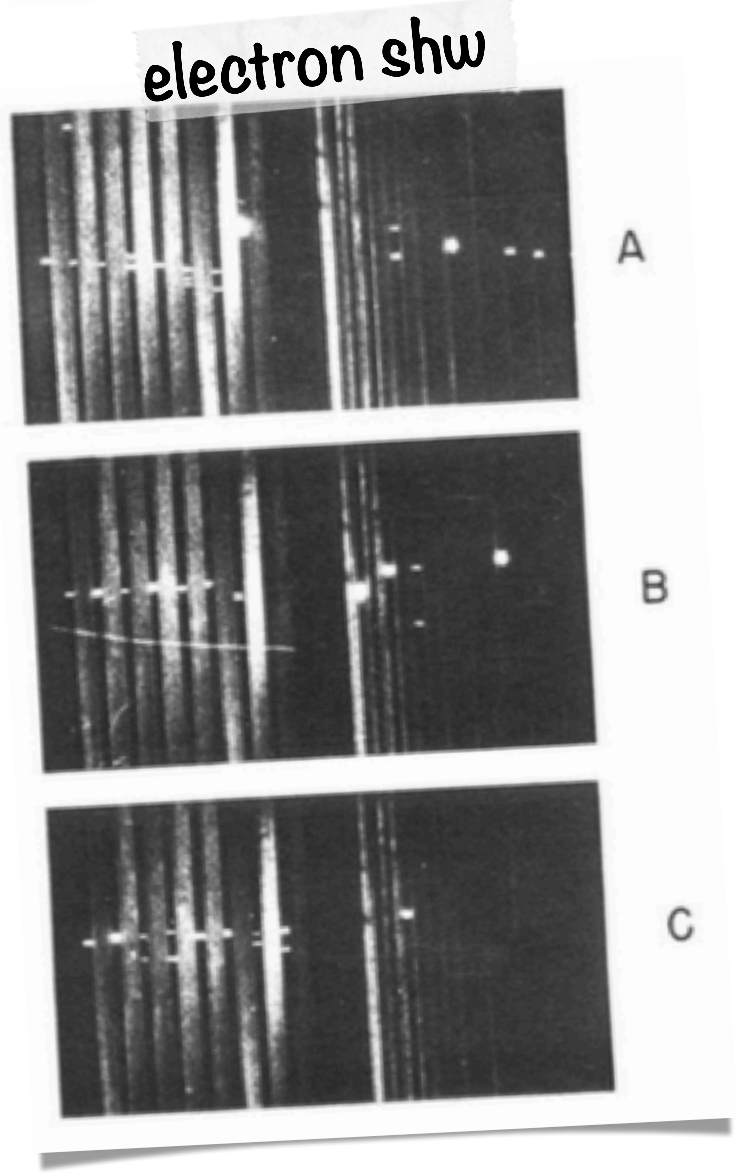
5

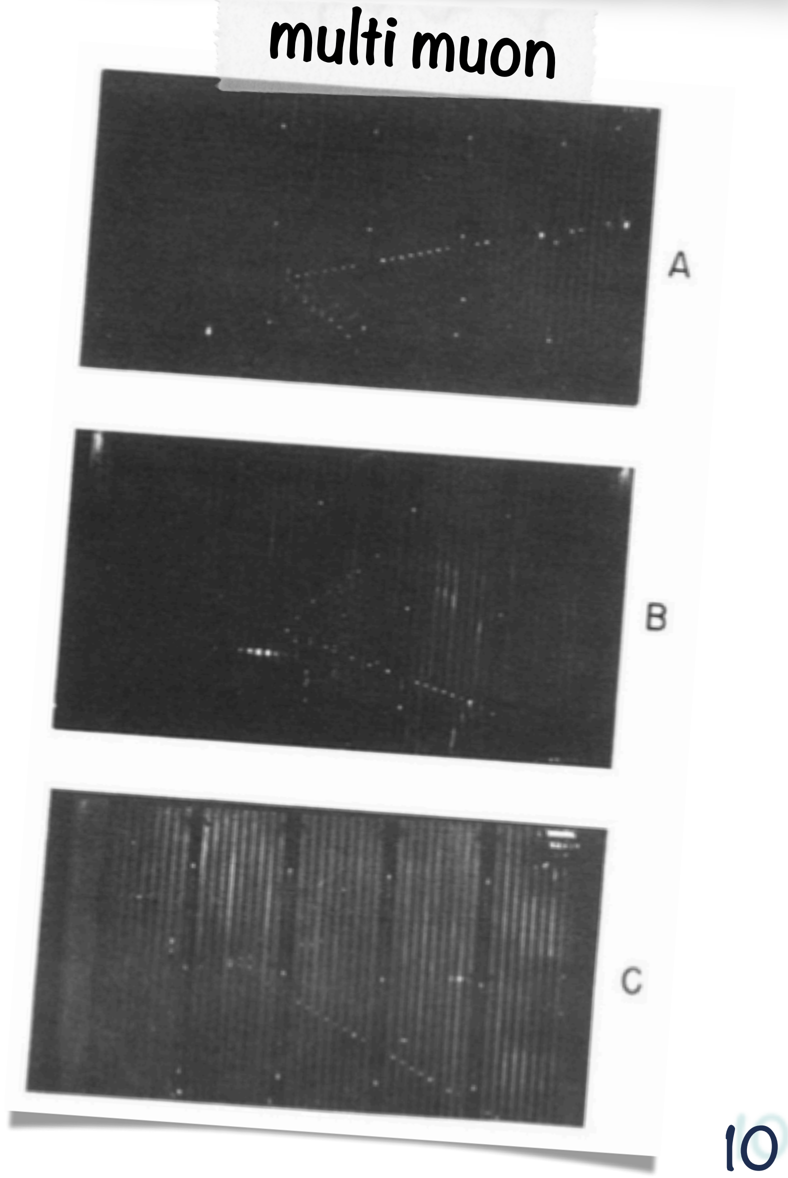
1962: ν_μ discovery

6









The electron neutrino

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(*Nobel prize in 1995!*)

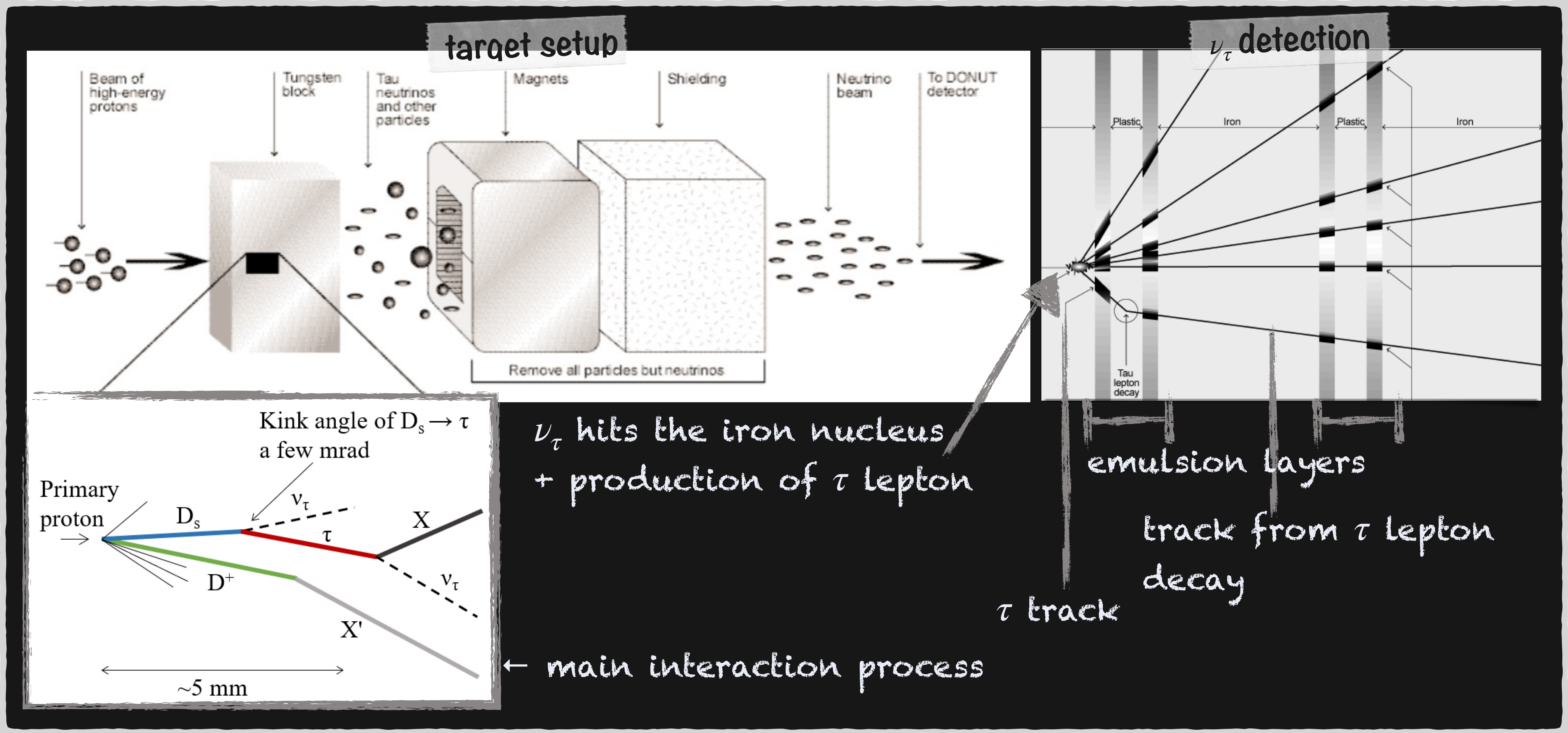
1962: ν_μ discovery by L. M. Lederman et al. @ Brookeven lab
(*Nobel prize in 1988!*)

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 decades, very active for neutrino physicists!

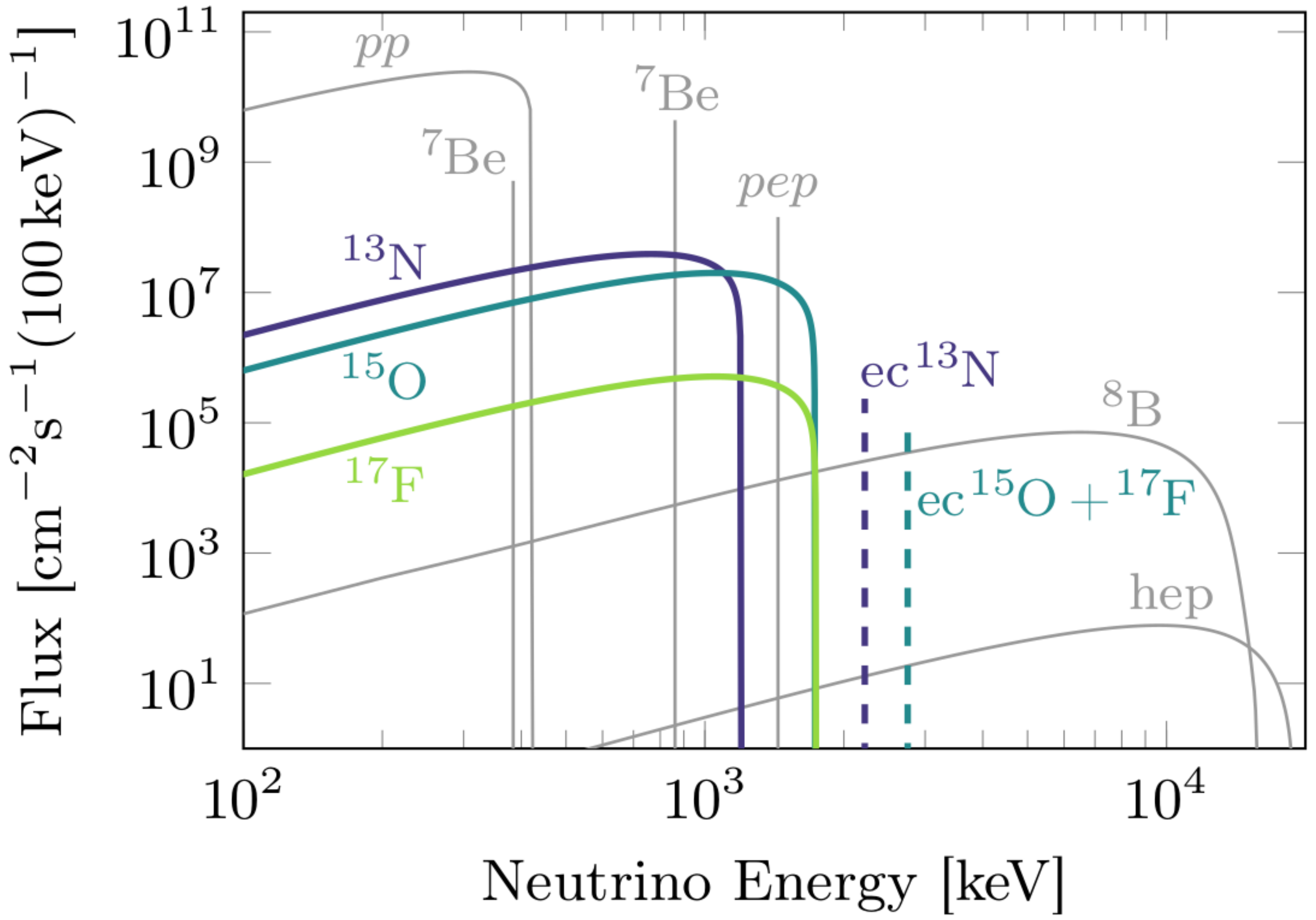
1964~present: stay zen and enjoy it!

- **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

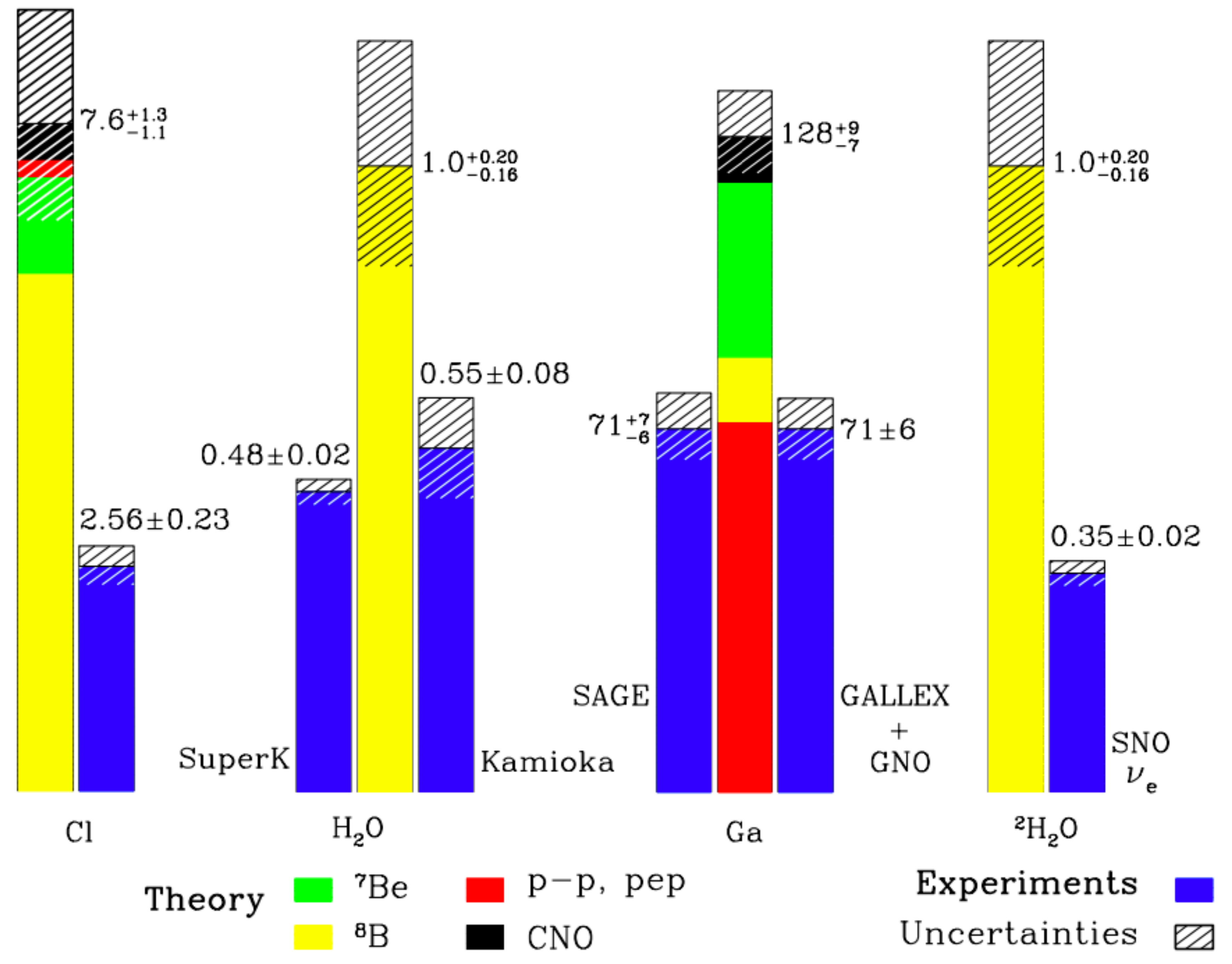
- thermonuclear reactions (mainly pp chain and CNO cycle)



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

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

observed ν_e



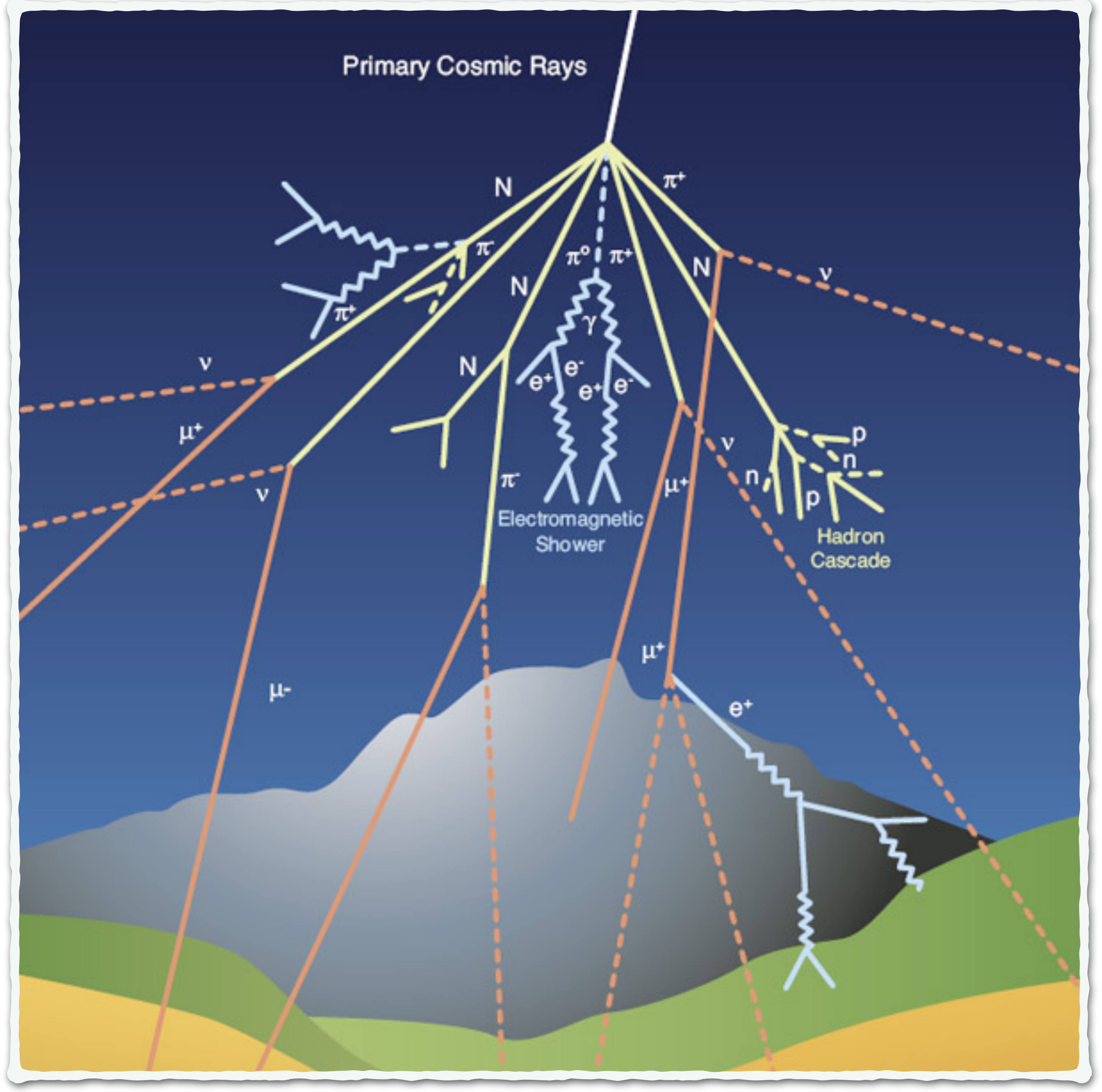
The atmospheric neutrino anomaly

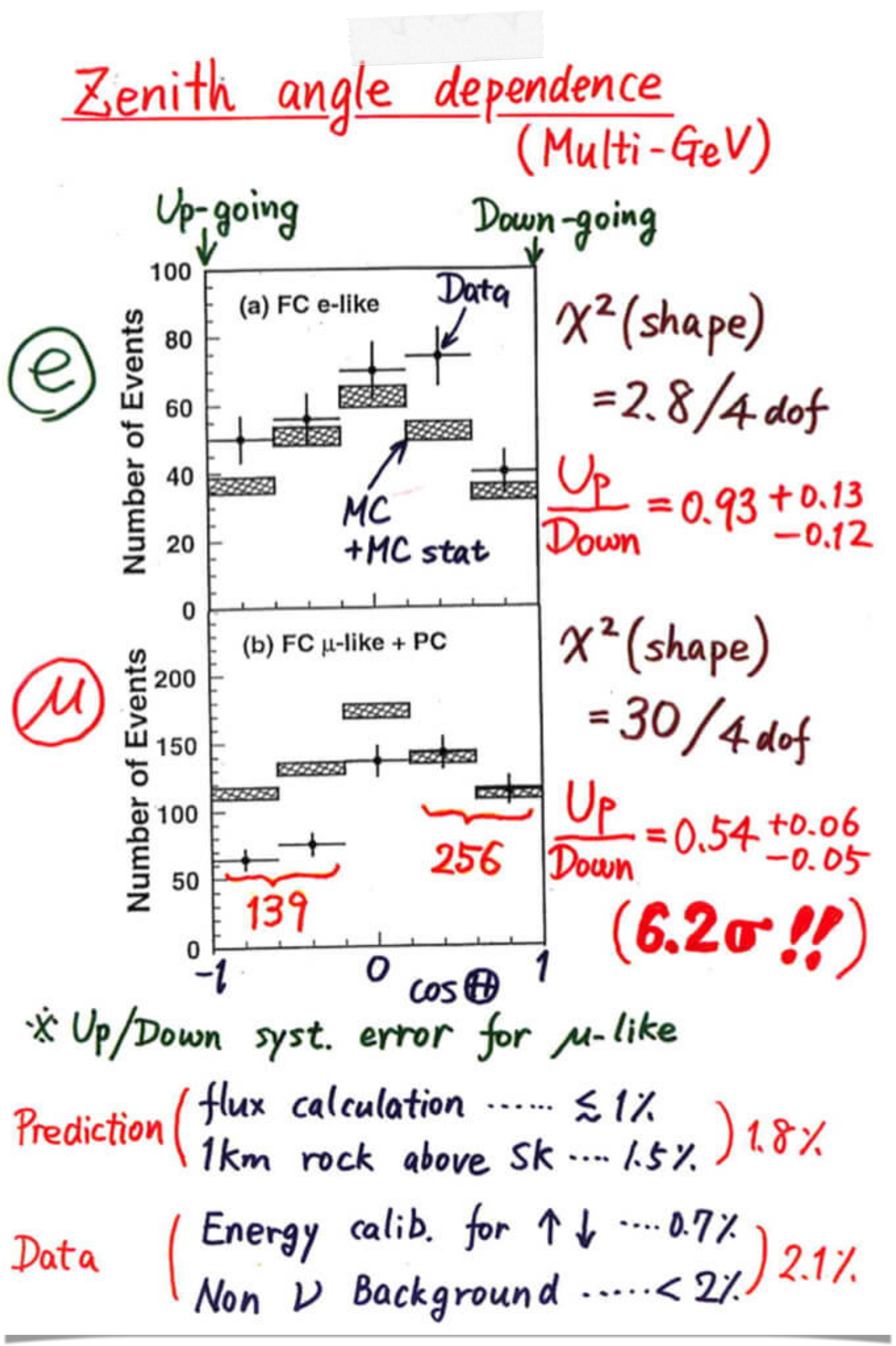
Neutrinos produced in the atmosphere: all muons decay before reaching the ground

- 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…





Neutrino oscillation

Neutrino flavors are a linear combination of neutrino mass eigenstates

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

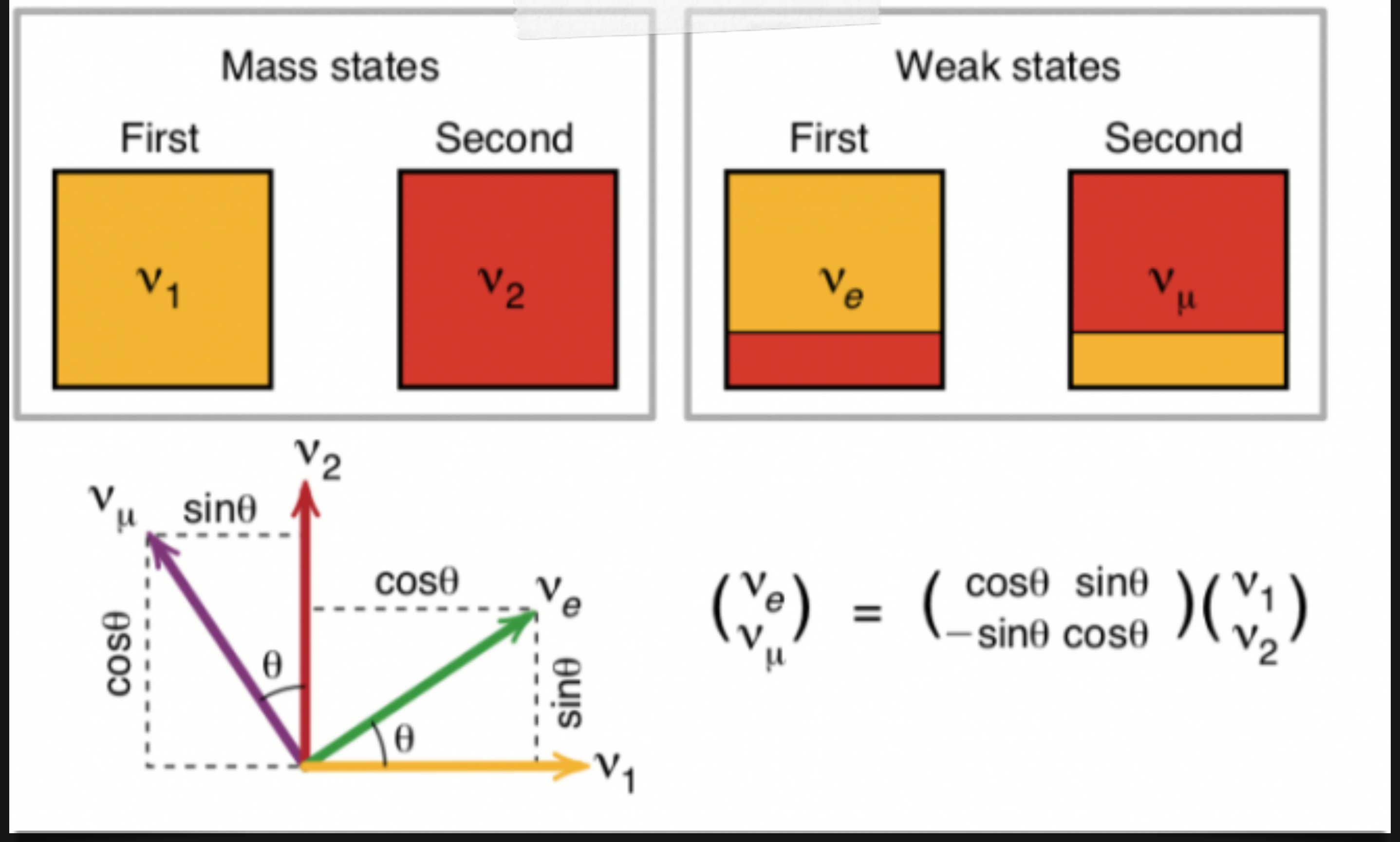
mass eigenstates, $i = (1, 2, 3)$

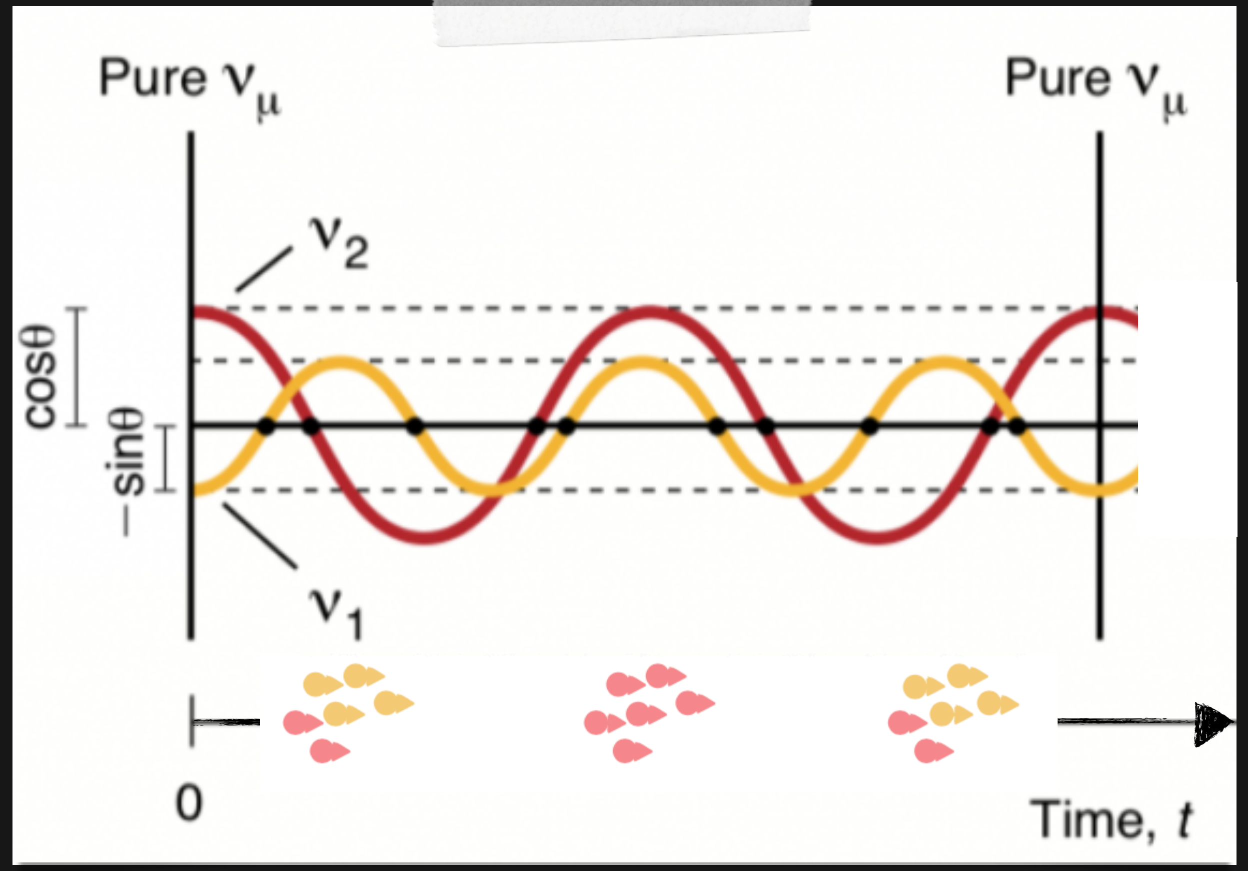
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

U, PMNS matrix

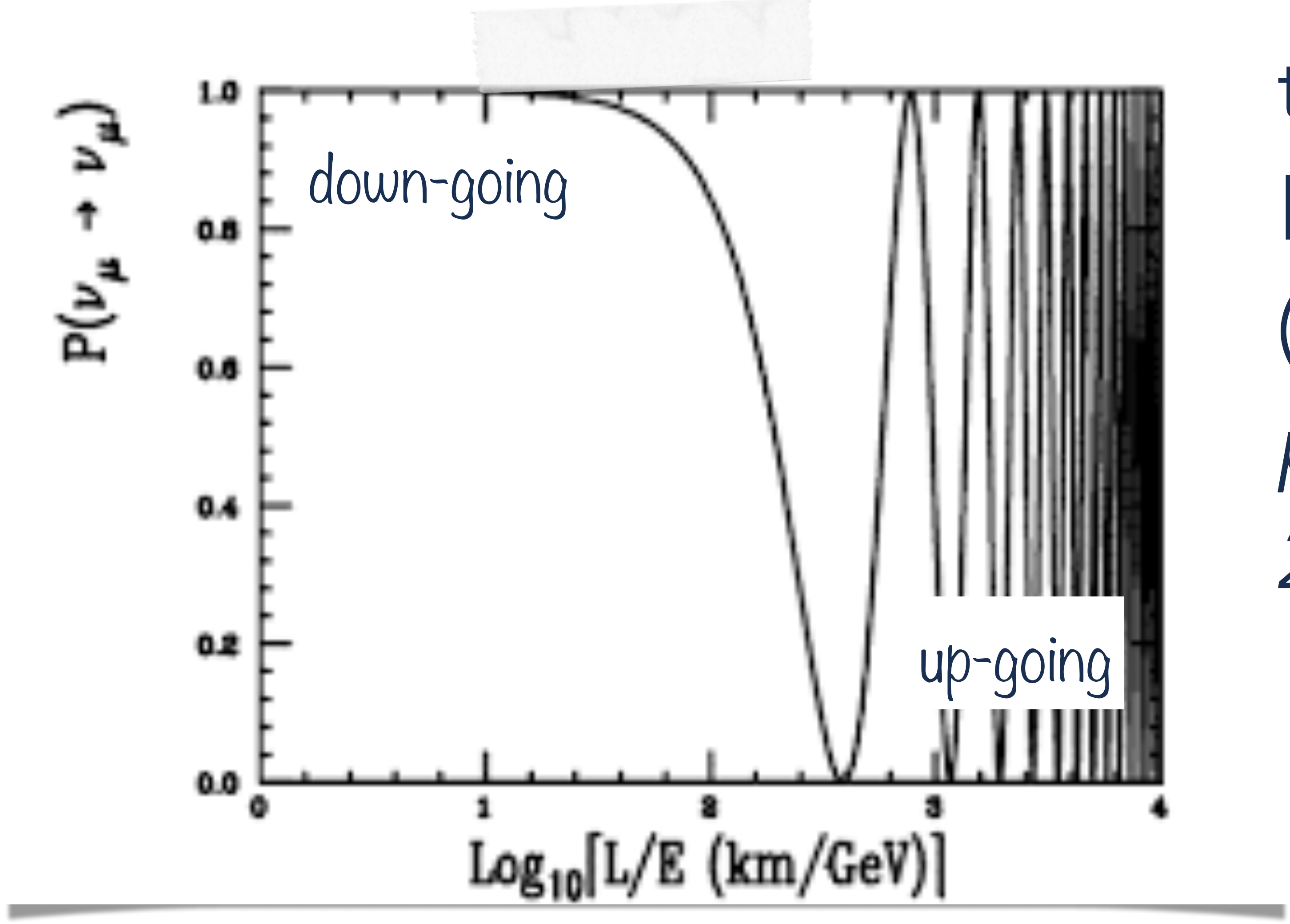
Oscillation probability: $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

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

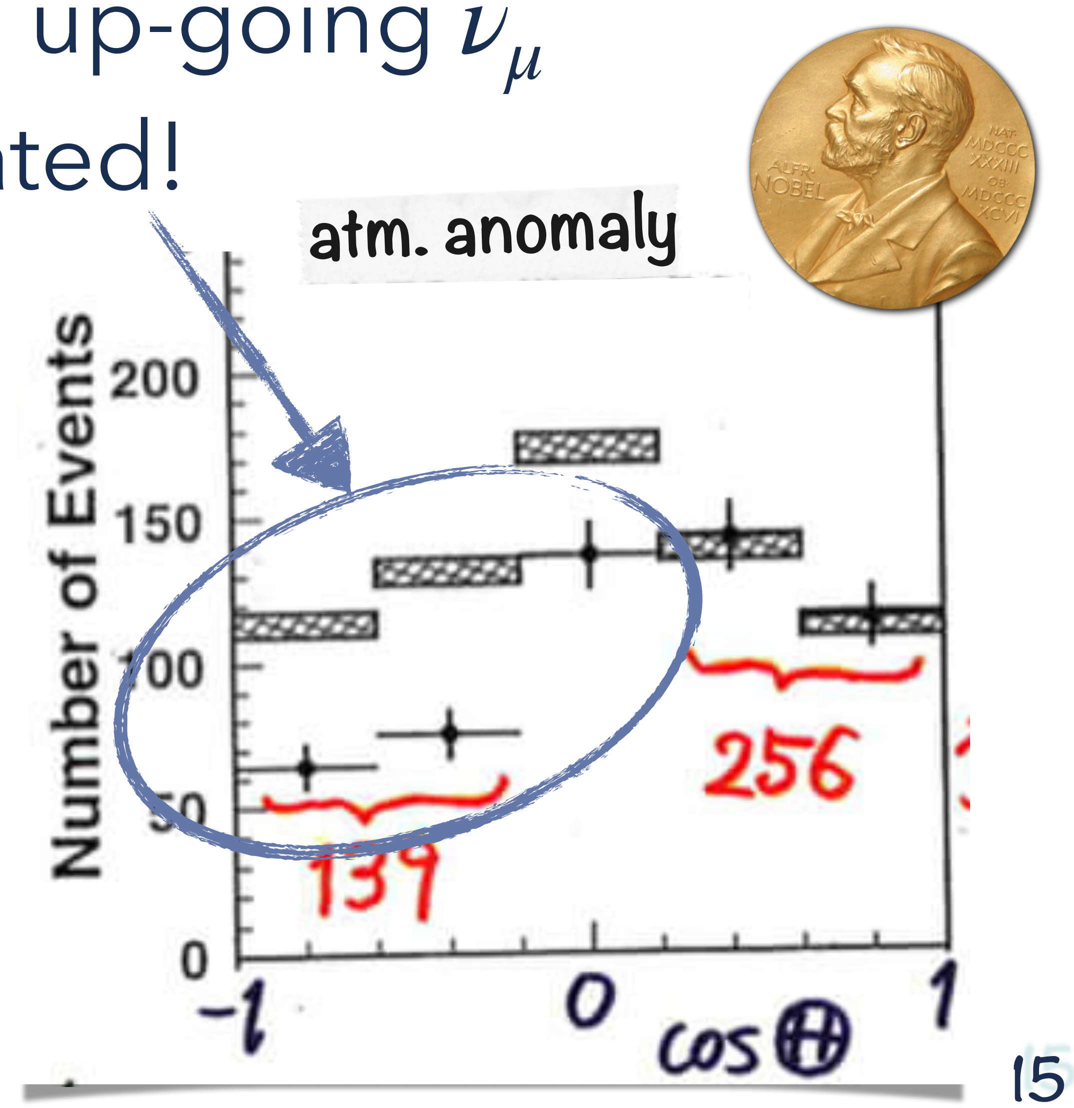




- the minimum position is determined by the mass splitting (Δm²)
- the minimum deep is determined by the mixing angle (θ)



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



Neutrino oscillation

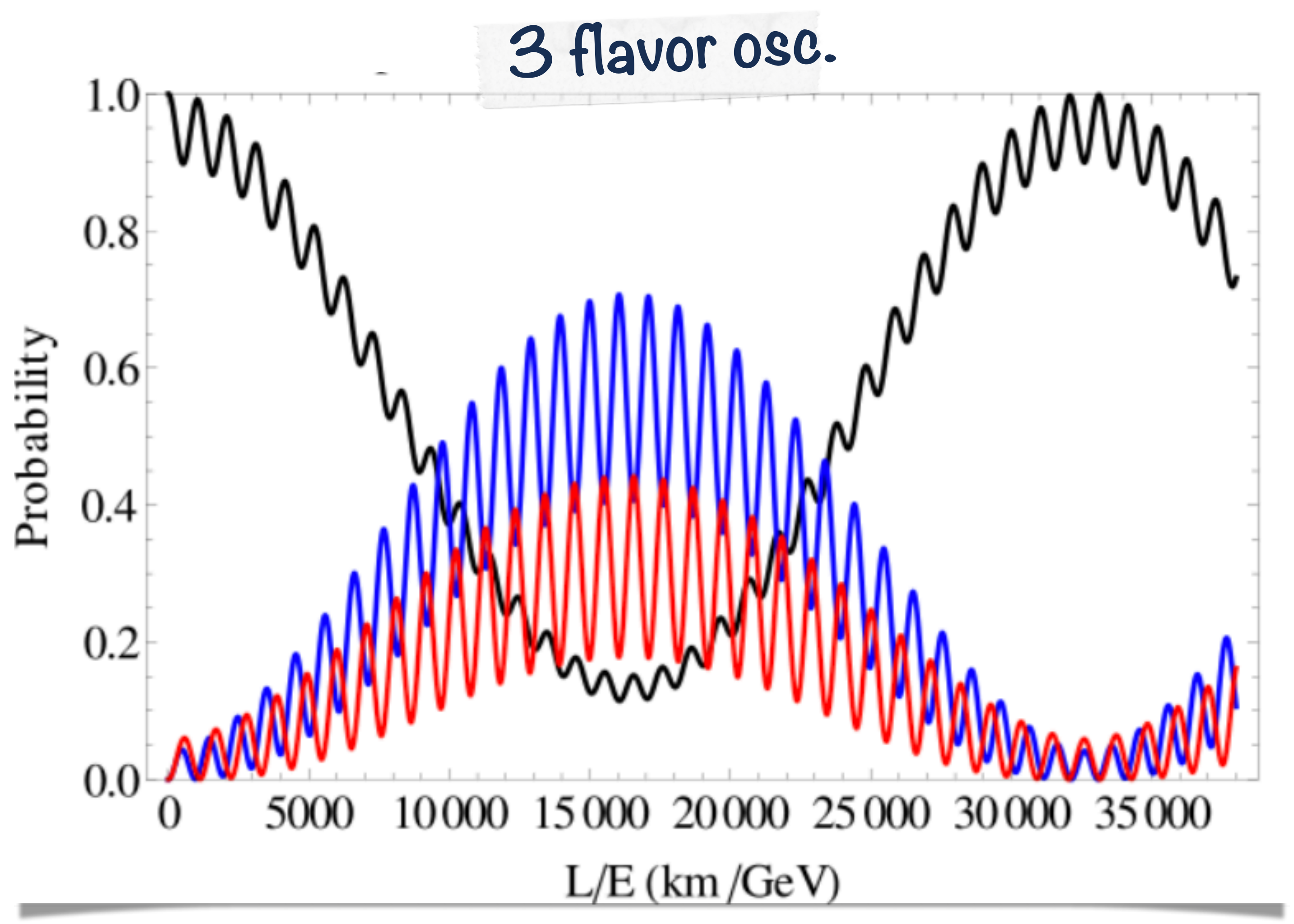
In the case of three neutrinos,

- 3x3 matrix

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

U, PMNS matrix

3 flavor osc.

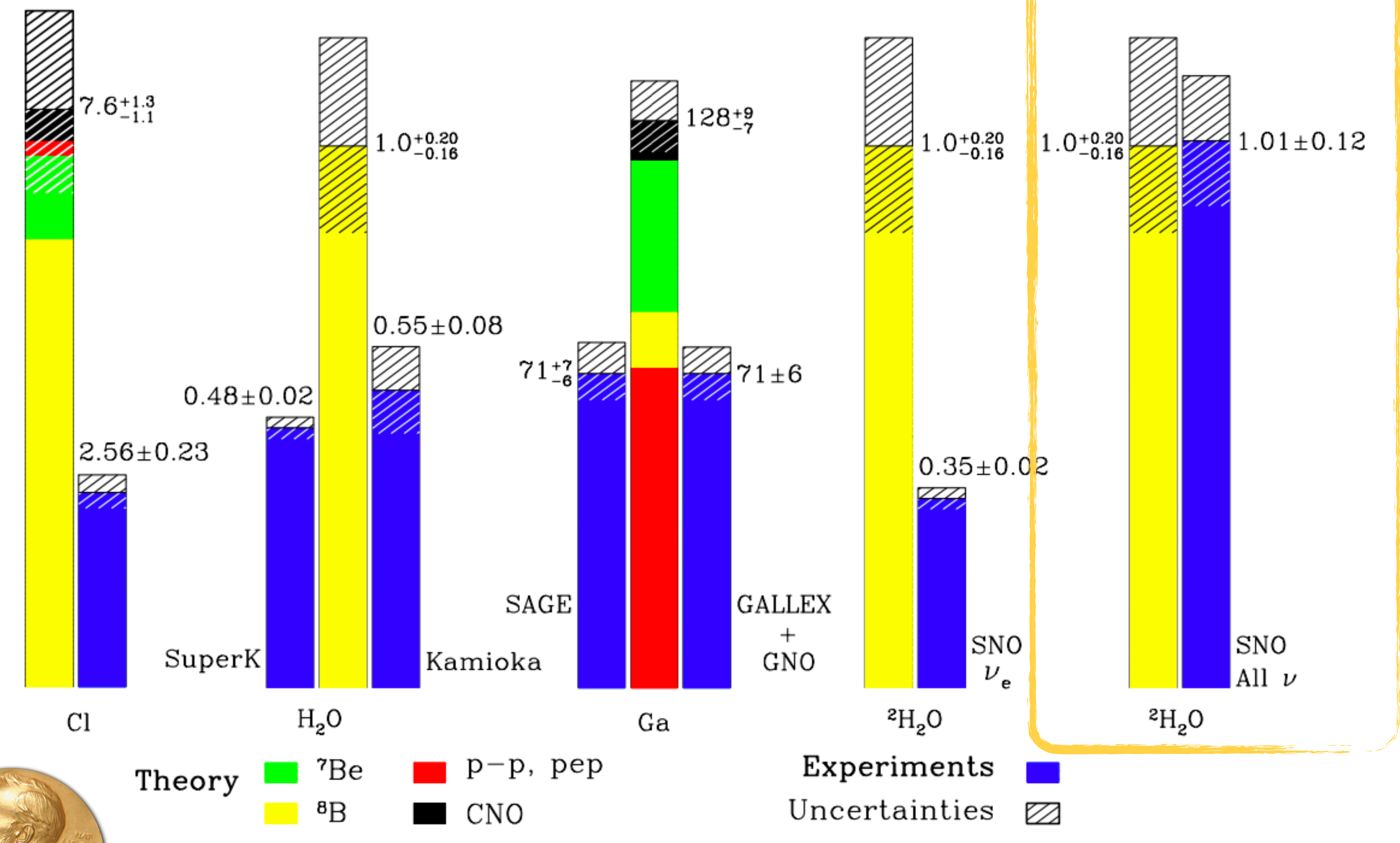


- SNO upgrade: detection of Elastic Scattering (ES) and Neutral current (NC) interactions
  - CC are flavor dependent but ES and NC are not
  - **total flux compatible with Solar Standard Model prediction**
  - ν_e **are 1/3 of the total**, measurement of the ratio:

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

(Nobel prize in 2015!)

solar puzzle



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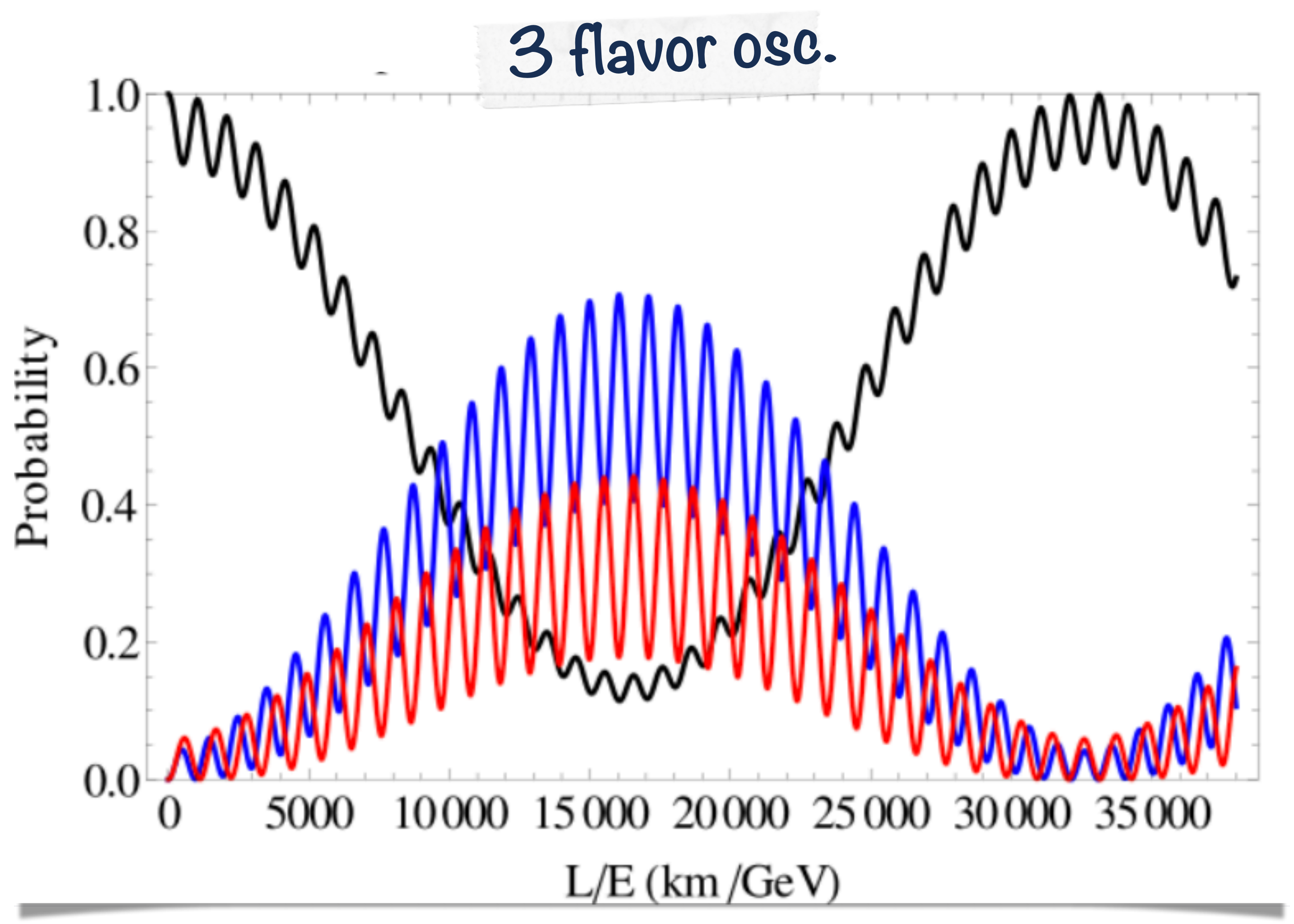


- 3 mixing angles: θ_{12}, θ_{23}, and θ_{13}
  (N.B. measurement of $\theta_{13} \neq 0$ in 2011!)
- 2 mass splitting: Δm^2_{21} and Δm^2_{31}
- 1 CP violation phase: δ_{CP}

The neutrino oscillation is possible only because neutrinos have a non-zero mass!
(first clear evidence of physics beyond the SM! 😎)

parameter	measurement	uncertainty
Δm^2_{21}	$(7.42 \pm 0.21) \times 10^{-5}$ eV^2	3%
Δm^2_{31}	$(2.50 \pm 0.03) \times 10^{-3}$ eV^2	1%
$\sin^2\theta_{12}$	(0.304 ± 0.013)	4%
$\sin^2\theta_{13}$	(0.02220 ± 0.00068)	3%
$\sin^2\theta_{23}$	(0.573 ± 0.023)	5%
sign Δm^2_{13}	+, slightly favored	unknown
δ_{CP}	$(105, 405)^\circ$	unknown

Open questions today

Which neutrino is the lightest?

- $m_1^2 < m_2^2$
- $m_2^2 - m_1^2 << |m_3^2 - m_{1,2}^2|$
- sign of Δm^2_{31} ?

What are their masses?

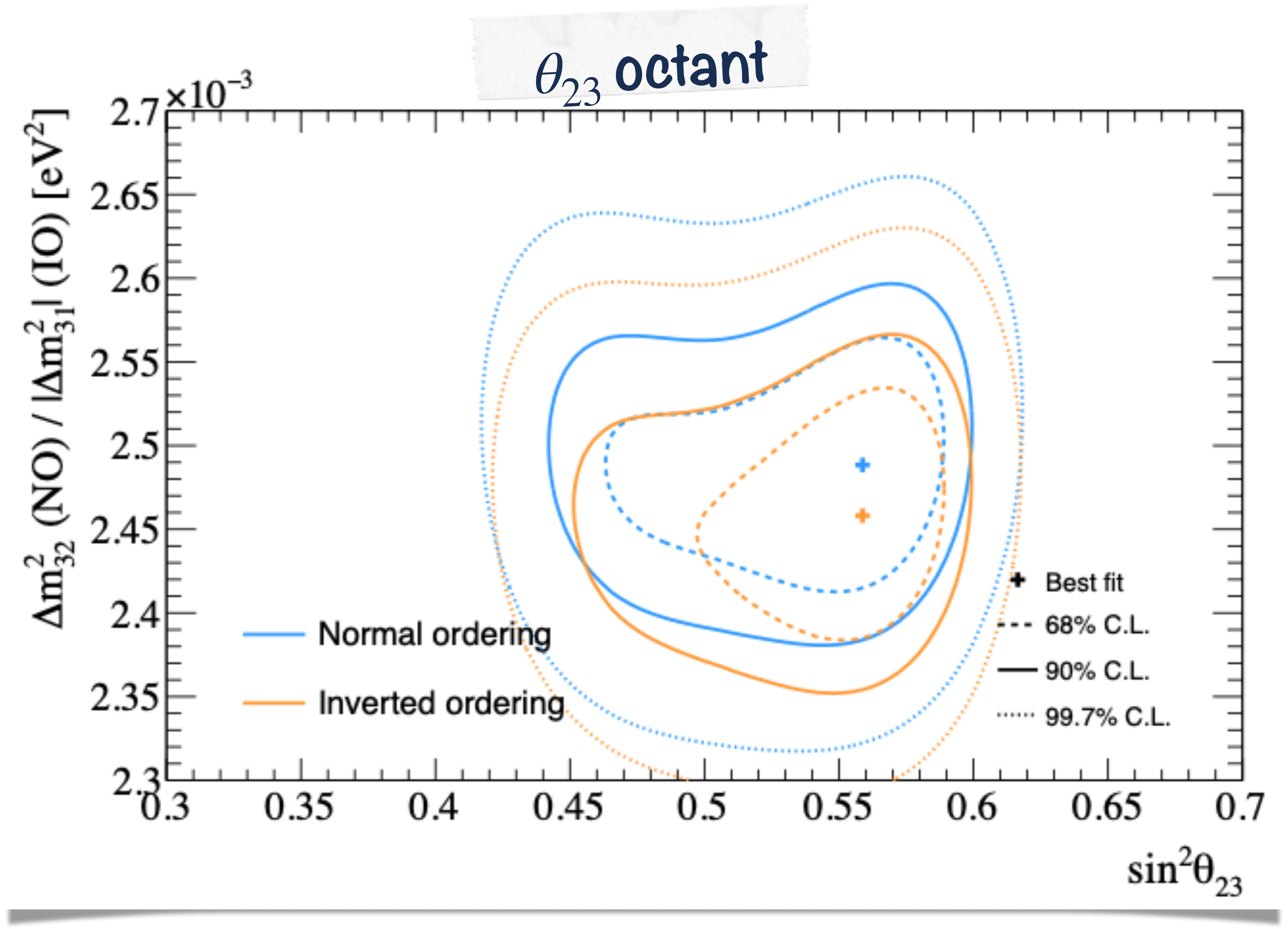
- direct and indirect measurements
- <0.8 eV

Is the PMNS unitary?

- is the three-flavor paradigm correct?
- do we have sterile neutrinos? if so, how many?

Is ν_3 mostly ν_μ or ν_τ?

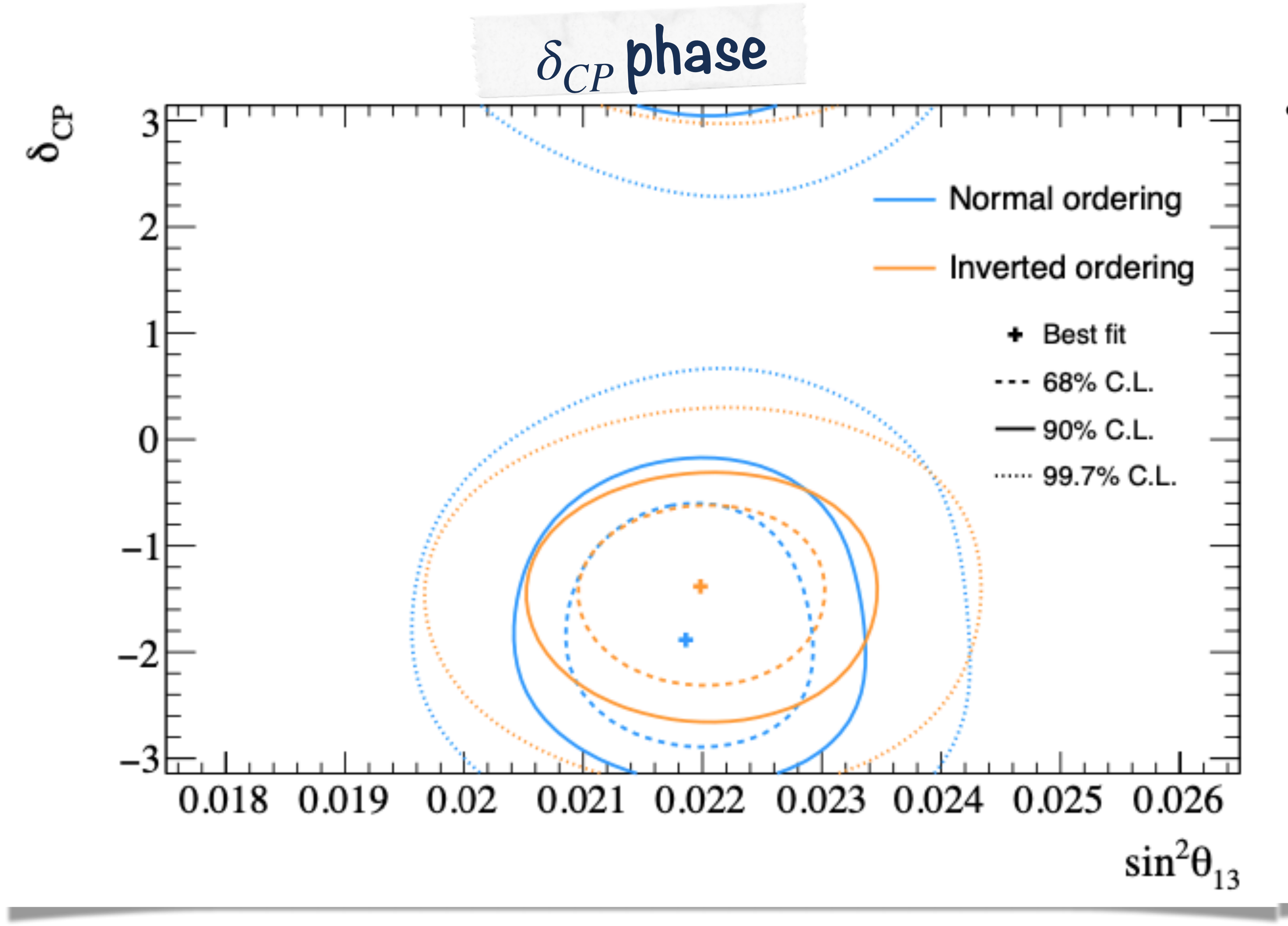
- $\theta_{23} < \pi/4$, $\theta_{23} > \pi/4$, or $\theta_{23} = \pi/4$?

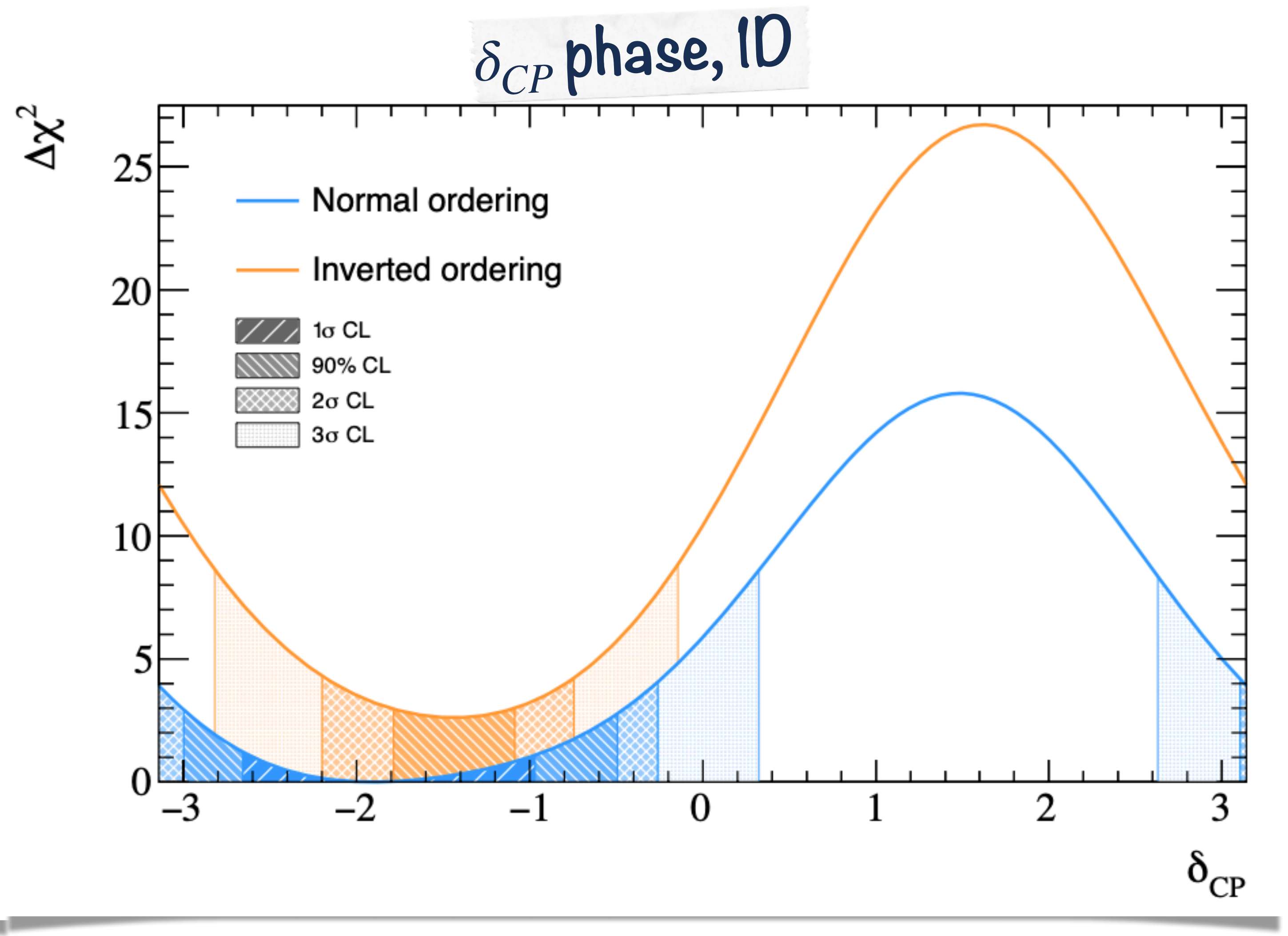


Is CP violated in the leptonic sector?

- $\delta_{CP} \neq 0$?
- first hint by T2K in 2020

  δ_{CP} (90% C.L.) = [-3.00, -0.49] NH,
  [-1.79, -1.09] IH





Next generation neutrino experiments

Long baseline **accelerator** experiments: DUNE and HyperK

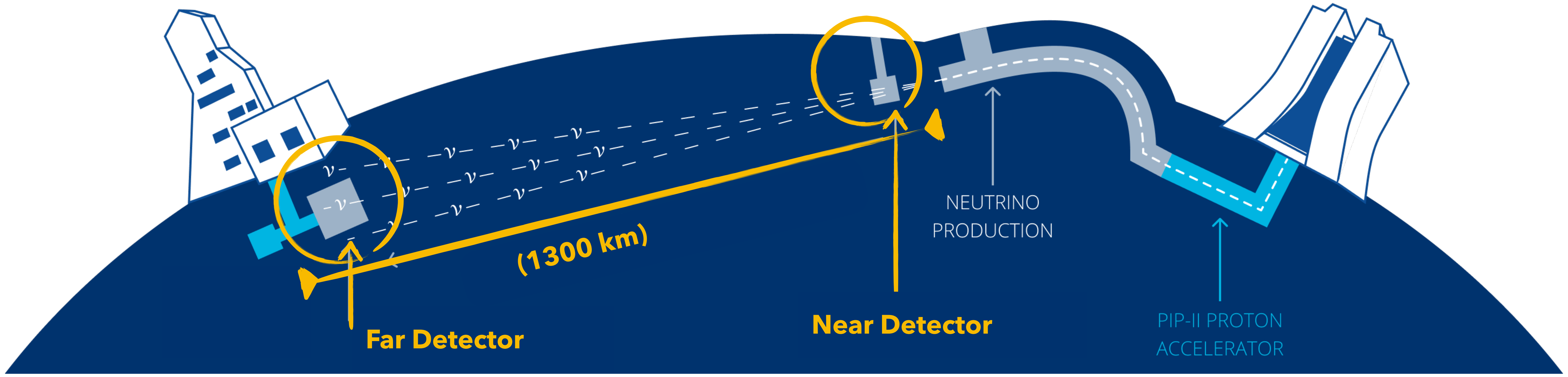
- huge active volume
- good energy resolution

	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	2024

** most powerful, worldwide*

Reactor experiments: JUNO

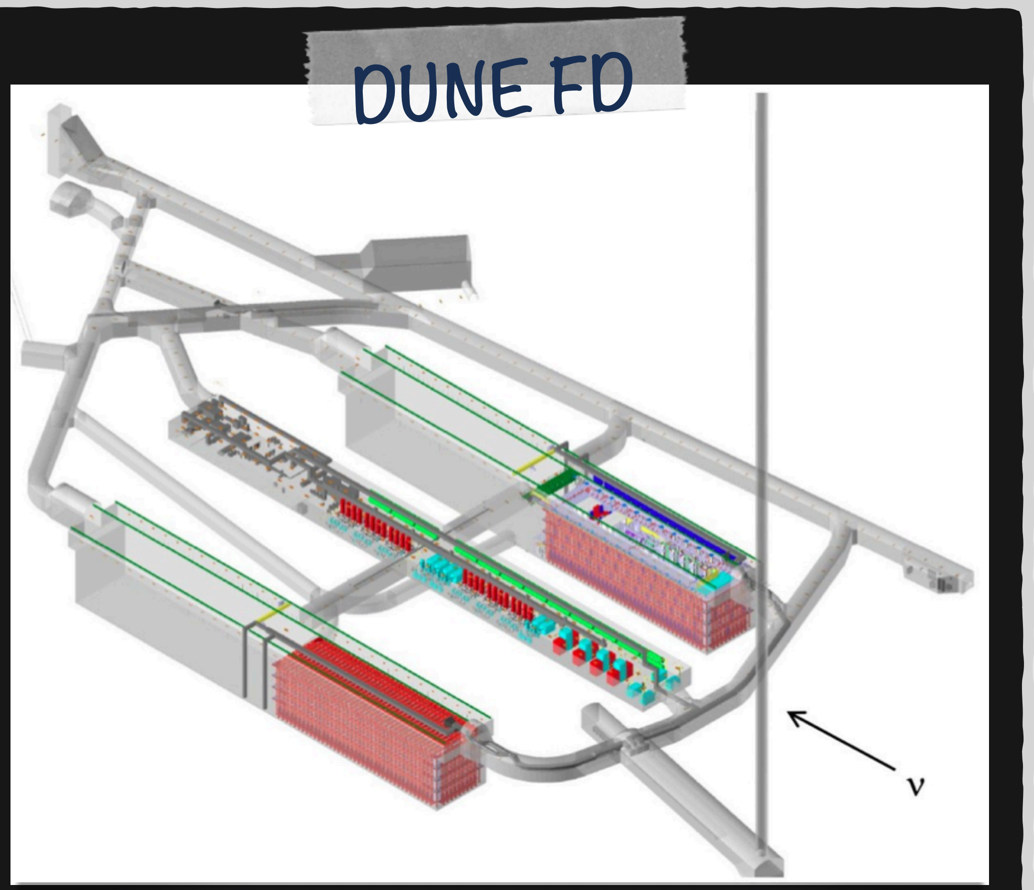
- extremely good energy resolution (3% at 1MeV)

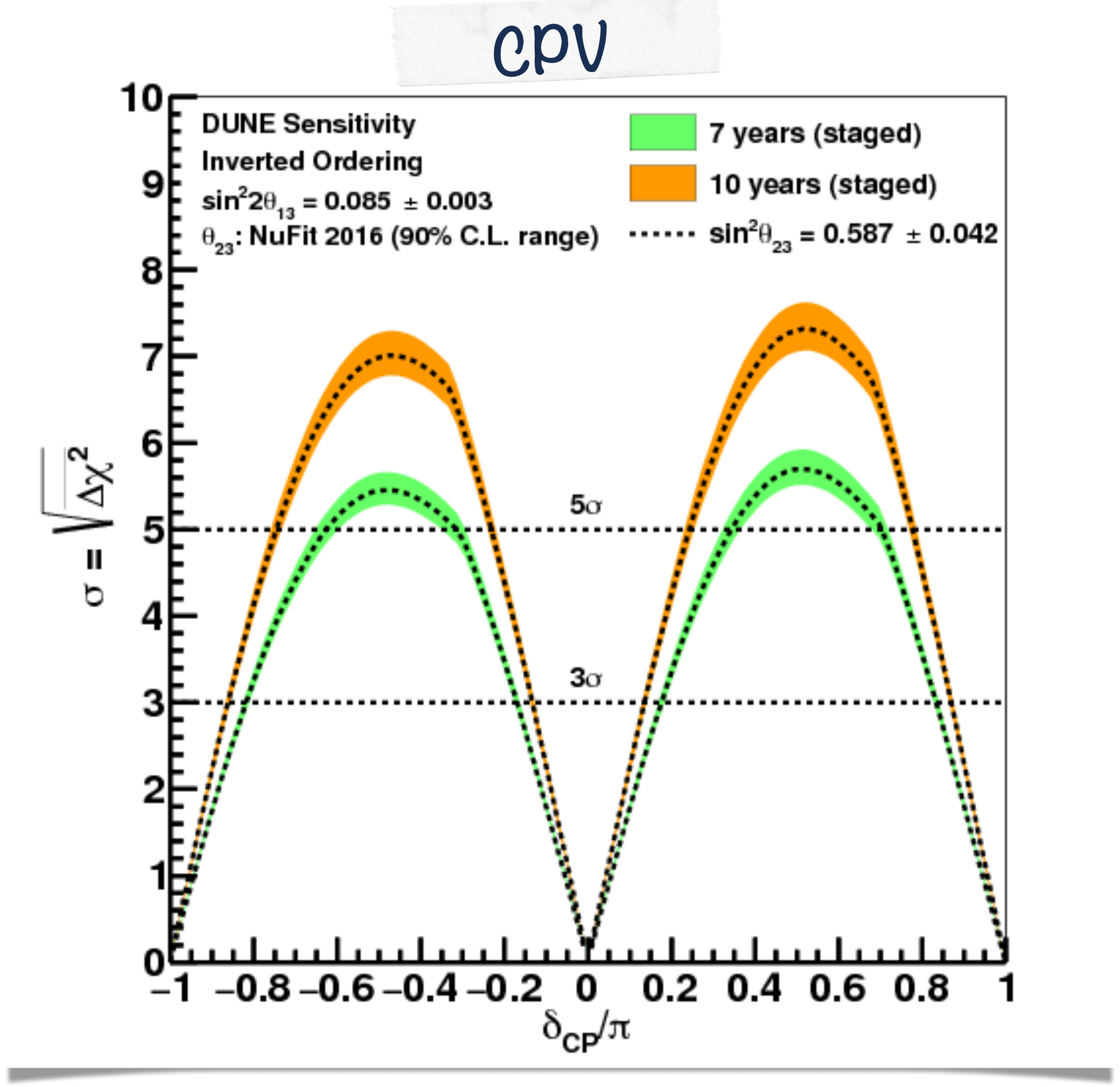


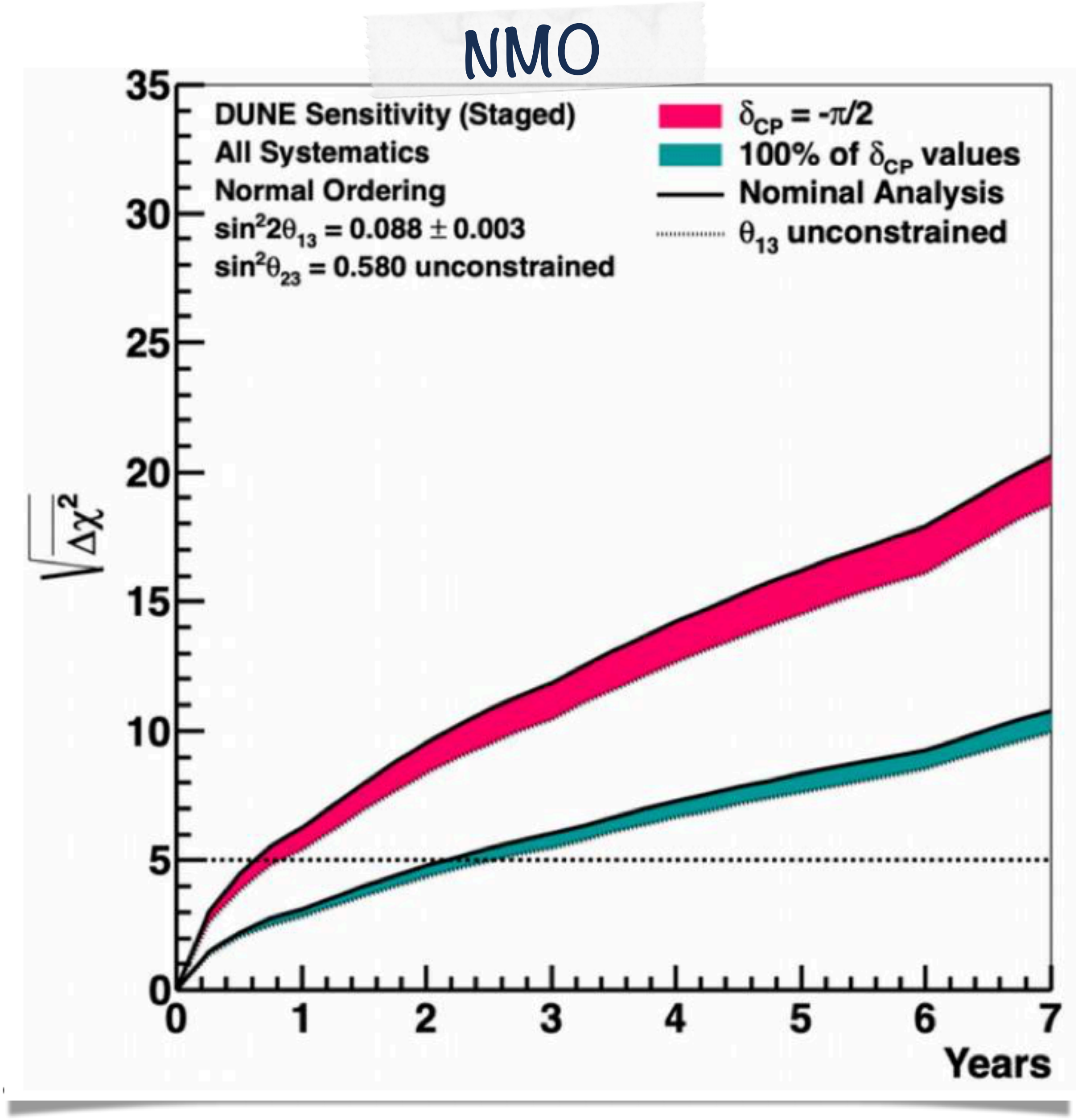
Deep Underground Neutrino Experiment (DUNE)

- Far Detector (FD): **massive target** and **Liquid Argon (LAr) properties**
  - **ν-beam physics (~GeV): δ_{CP}**, neutrino mass ordering (NMO), precise measurement of PMNS matrix elements

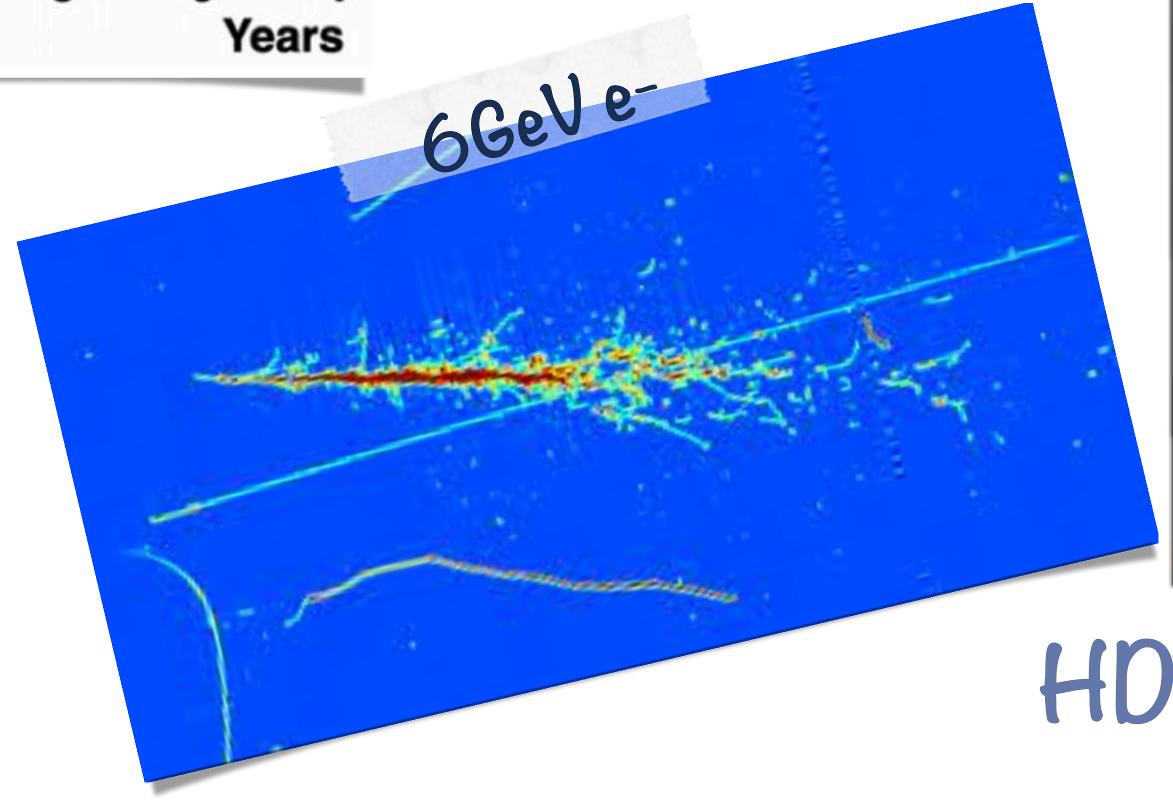
DUNE FD
- 4 modules
- different LAr-TPCs layouts
- 2 decided:
  Horizontal Drift (HD),
  Vertical Drift (VD)

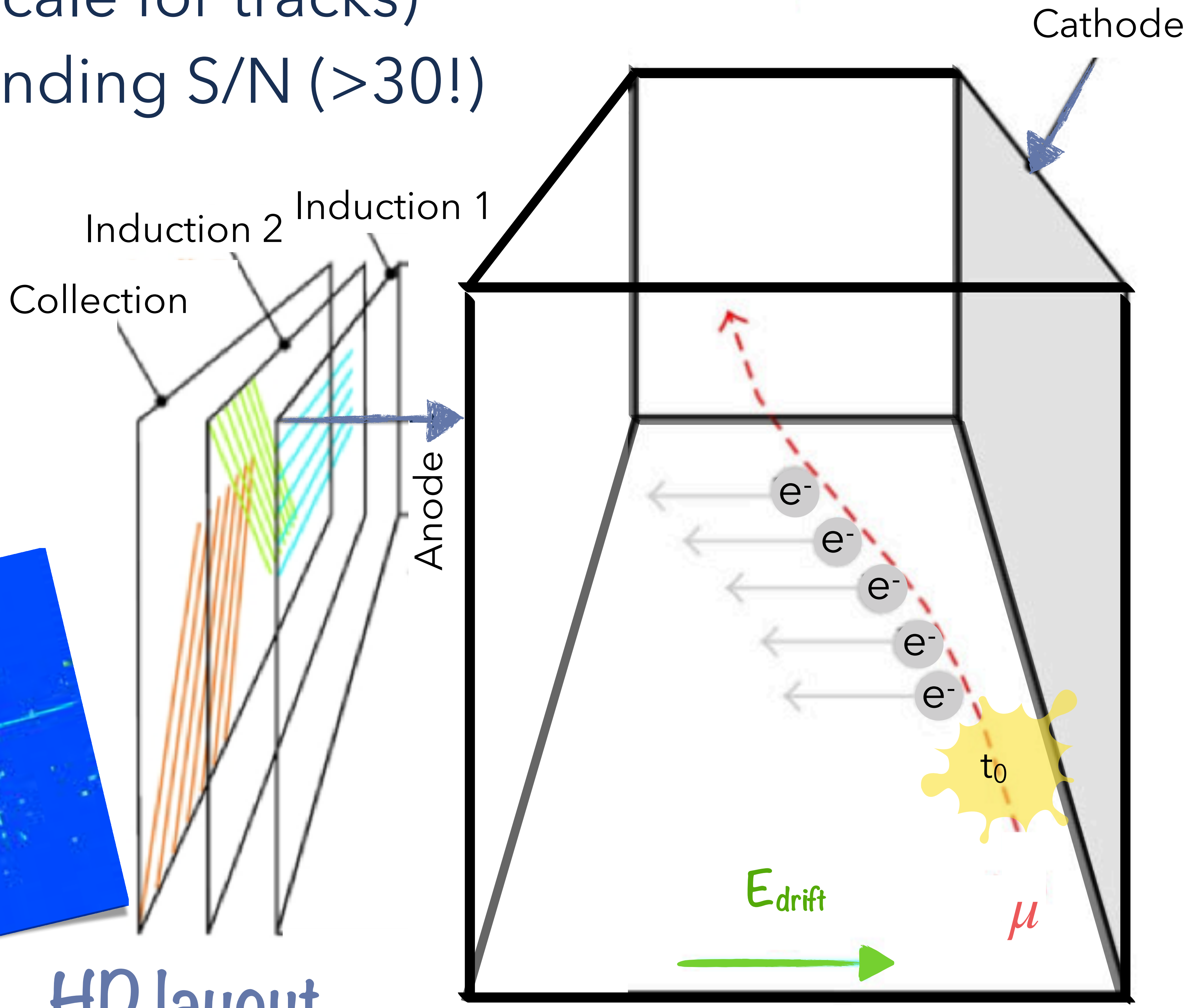






- high precision event reconstruction (mm-scale for tracks)
- outstanding S/N (>30!)





HD layout

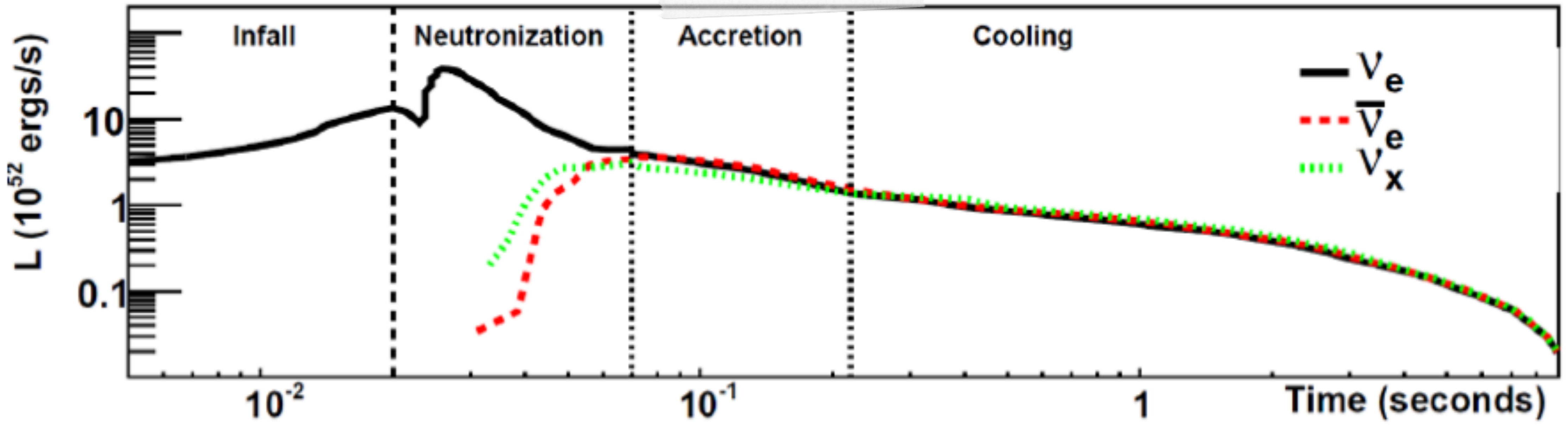
- CP violation, ~ 7 years for a 5σ discovery
- NMO, ~ 1-2 years for a 5σ discovery

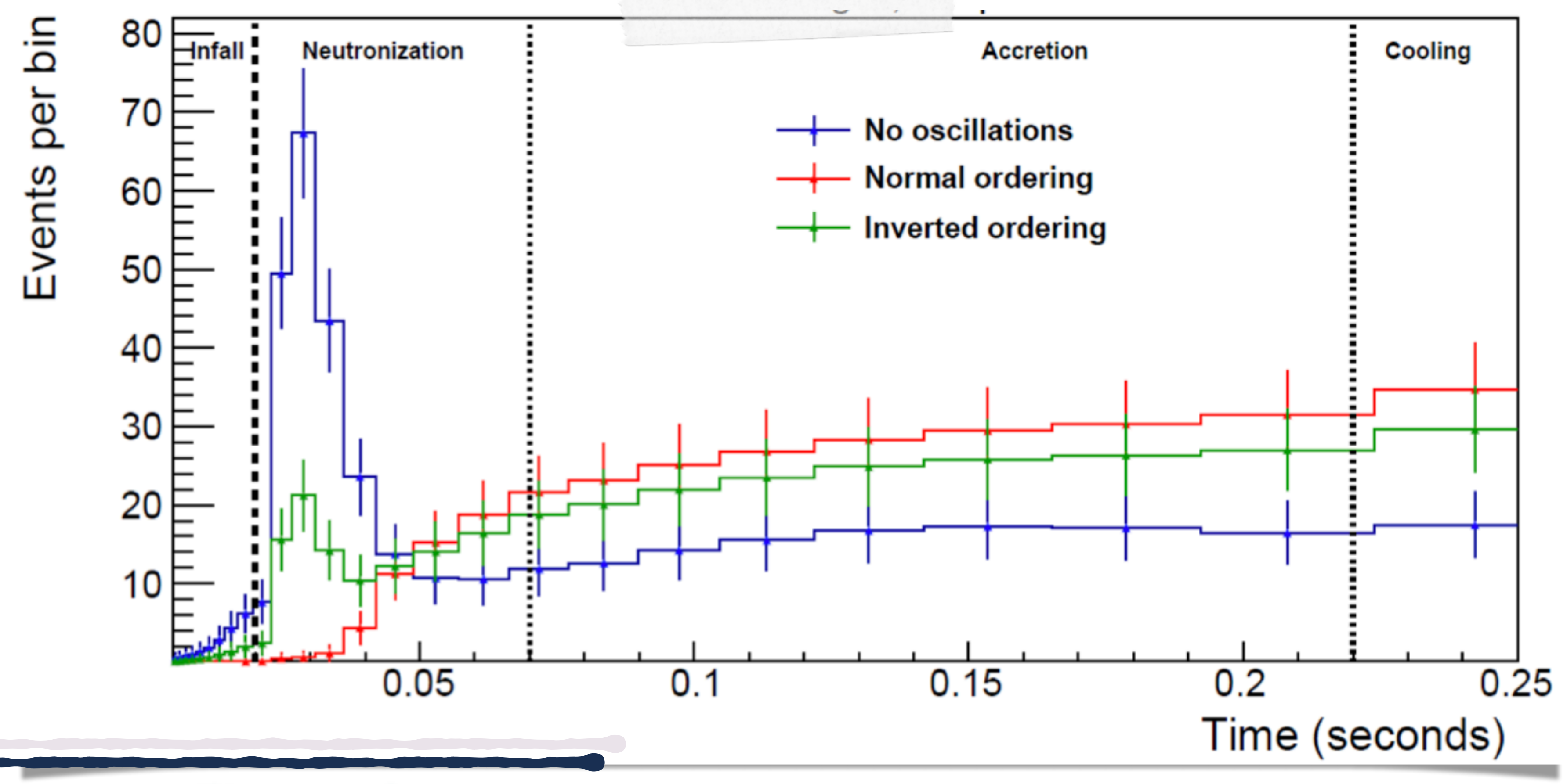
Deep Underground Neutrino Experiment (DUNE)

- Far Detector (FD): **massive target** and **Liquid Argon (LAr) properties**
- **non-beam physics (MeV-GeV range):** proton decays, solar, SuperNovae, atmospheric neutrinos

- profile of the SN flux in the galaxy
- **unique sensitivity to** ν_e

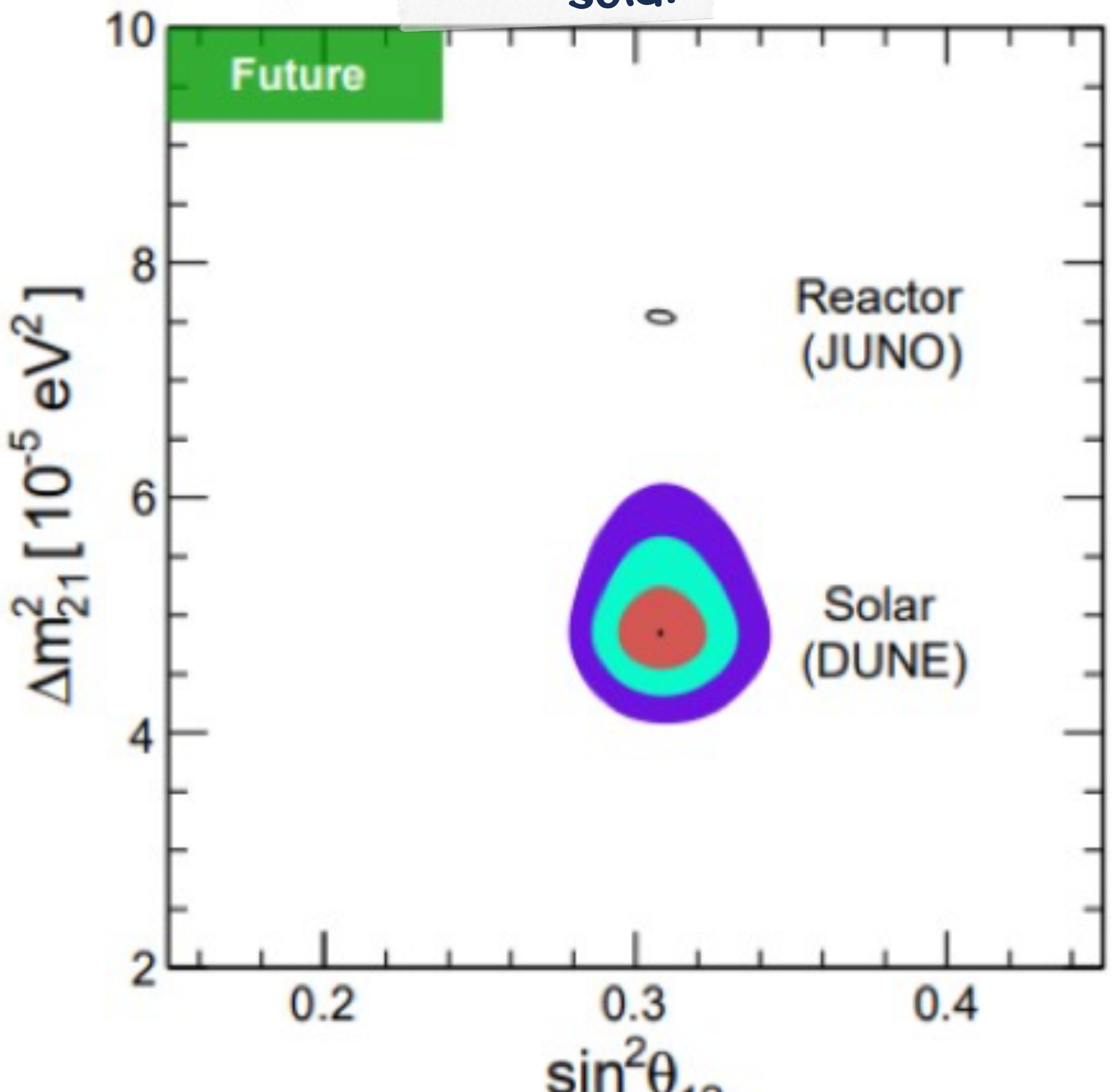
SN





- first measurement of the **solar hep flux**
- solve the existing reactor-solar experiment tension

solar



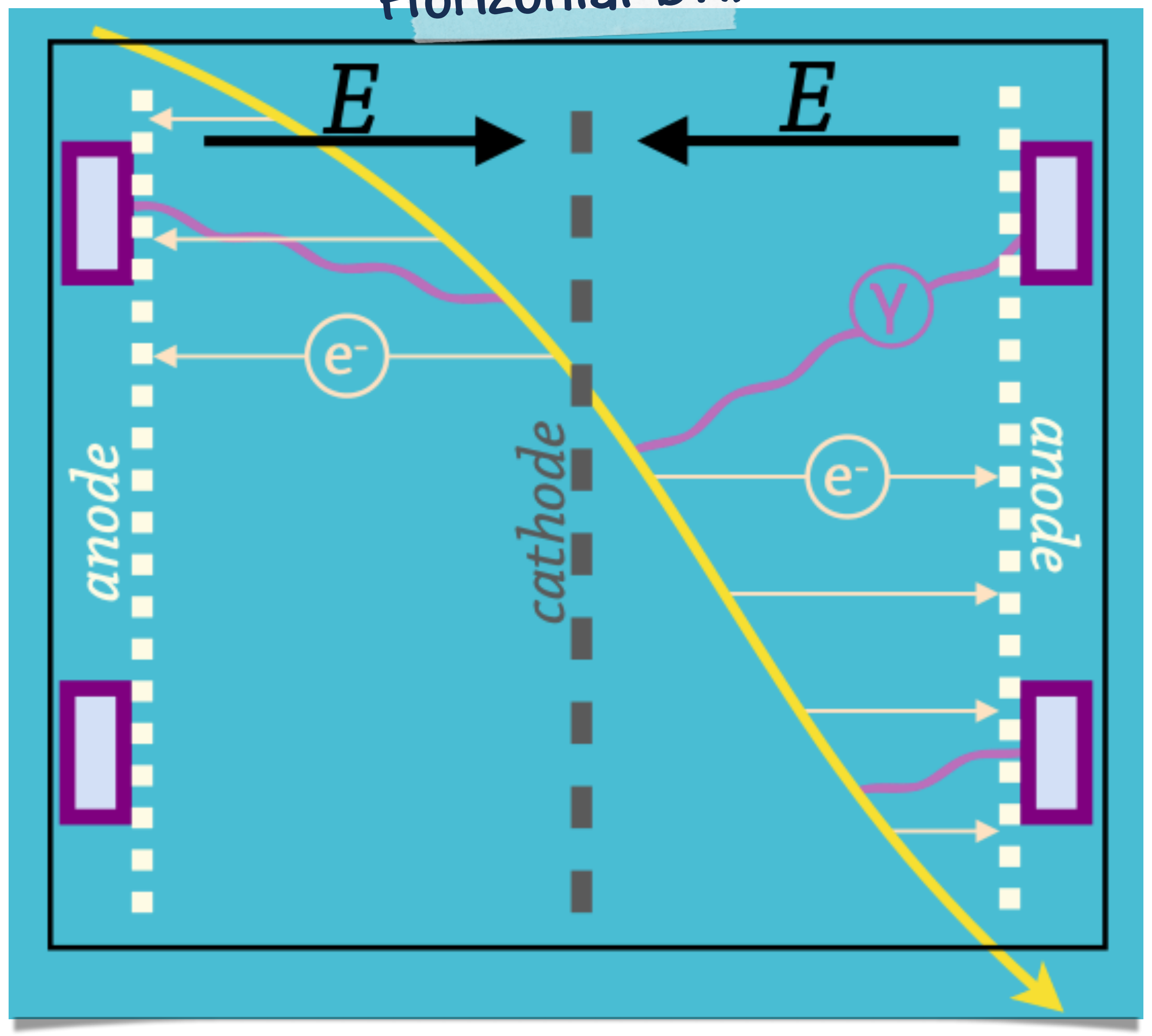
Deep Underground Neutrino Experiment (DUNE)

- since 2016, long R&D program at CERN
- additional requirements for non-beam physics
  - larger active volume
  - stronger background suppression
  - enhanced calorimetry

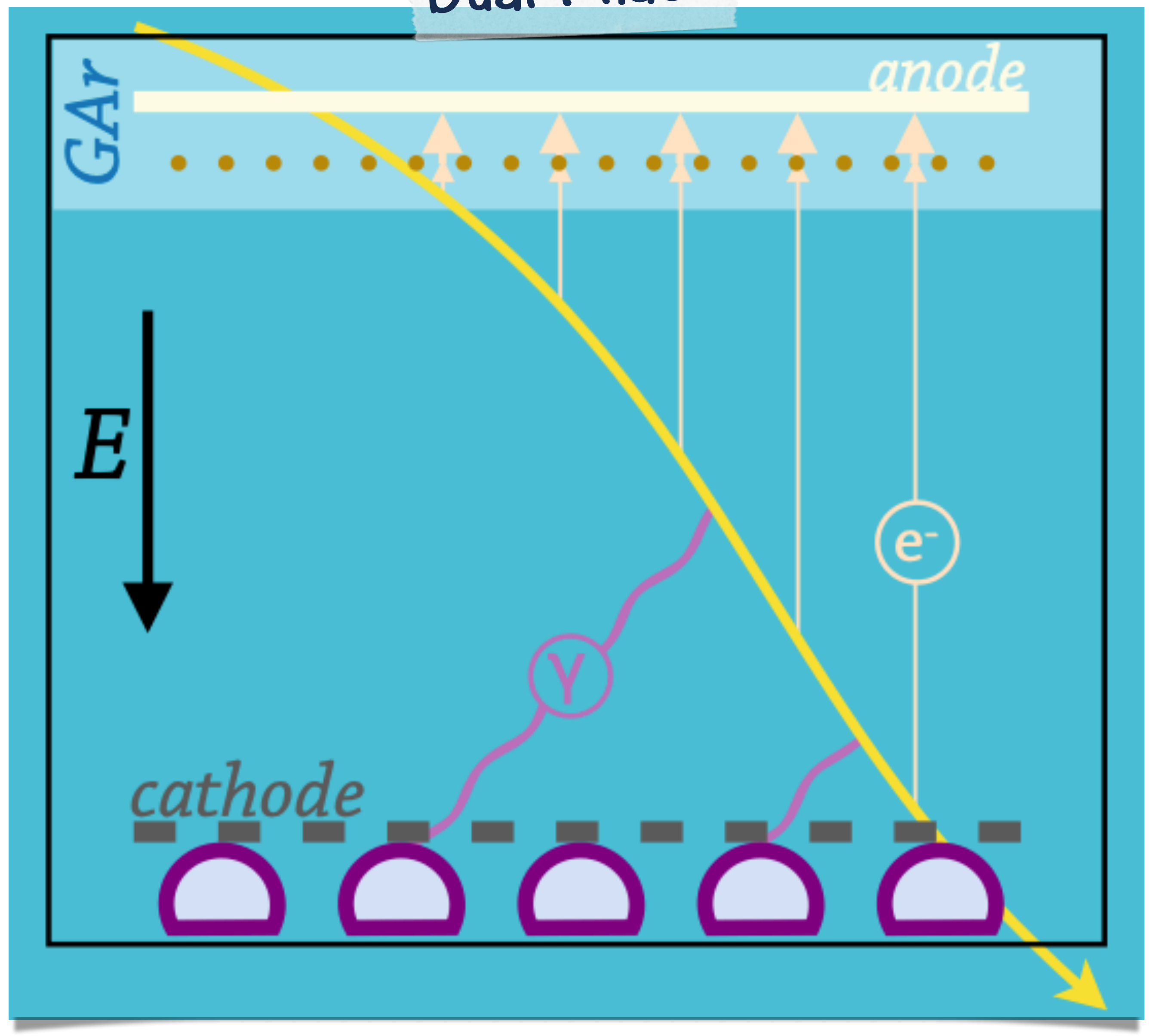
- remove the gas amplification
- move the cathode in the middle
- add two anodes
- be sure that you can collect all the light

images' credit: Laura Zambelli

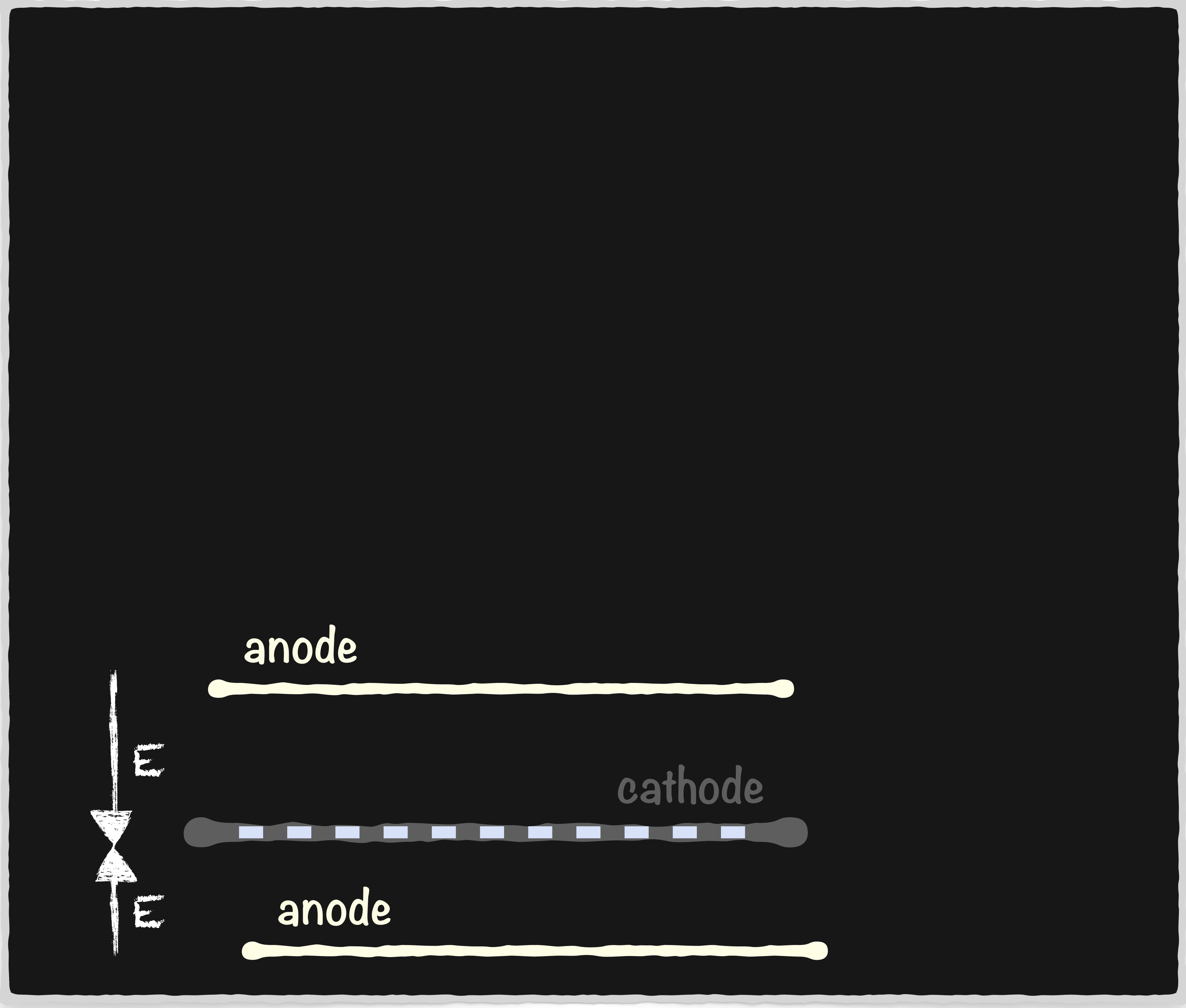
Horizontal-Drift



Dual-Phase



- difficult to extrapolate at the kton scale for DUNE-FD



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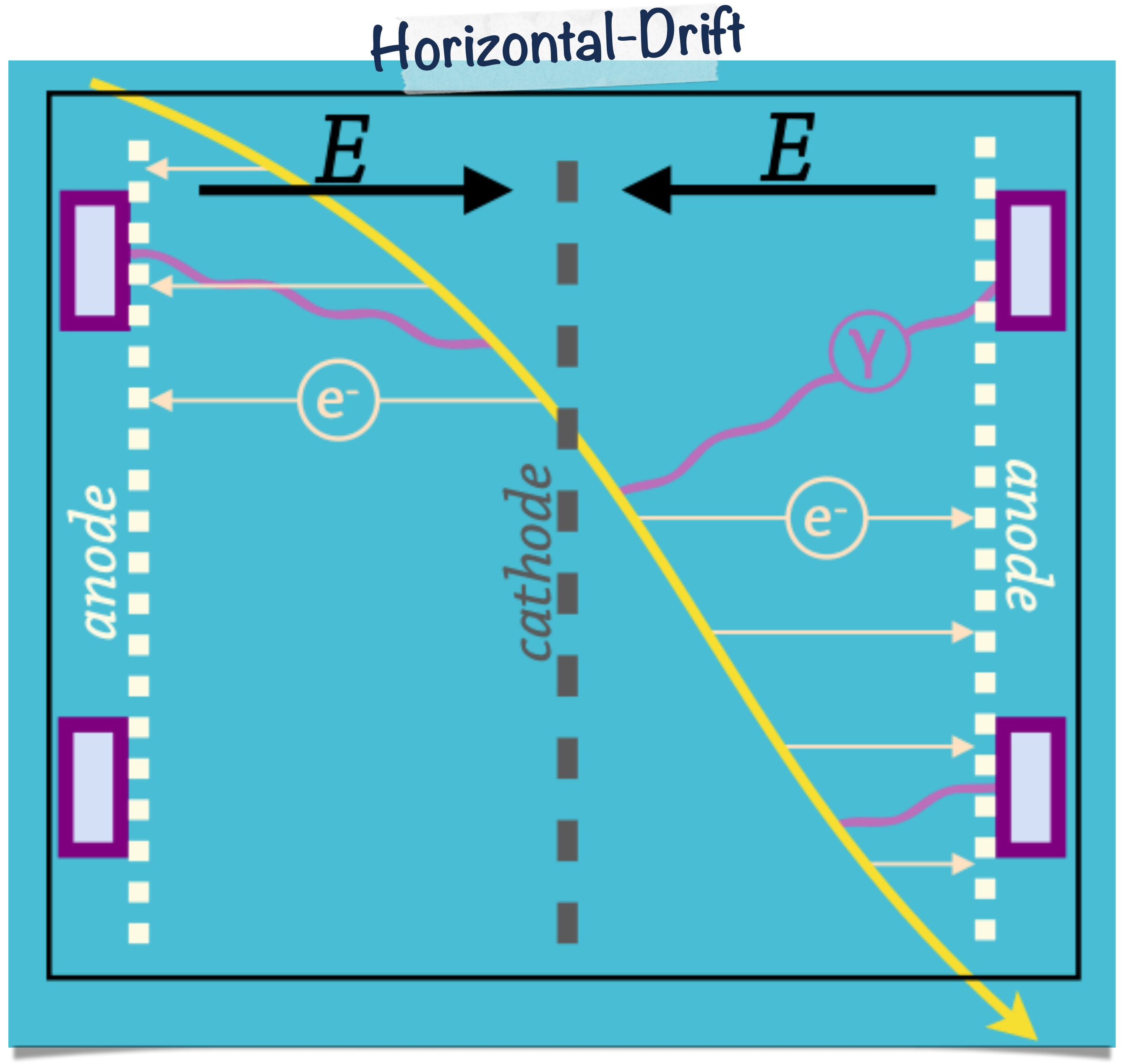
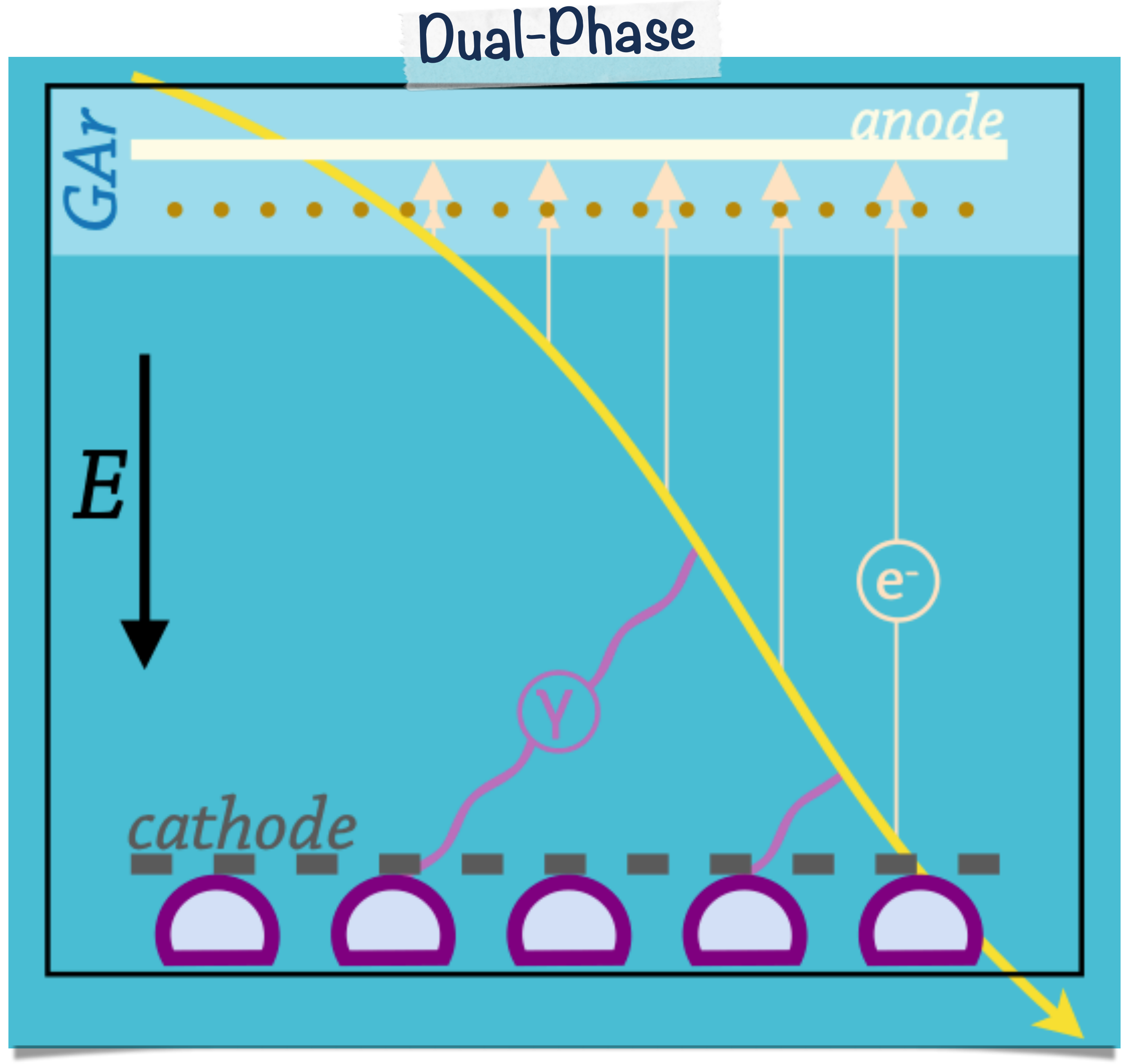
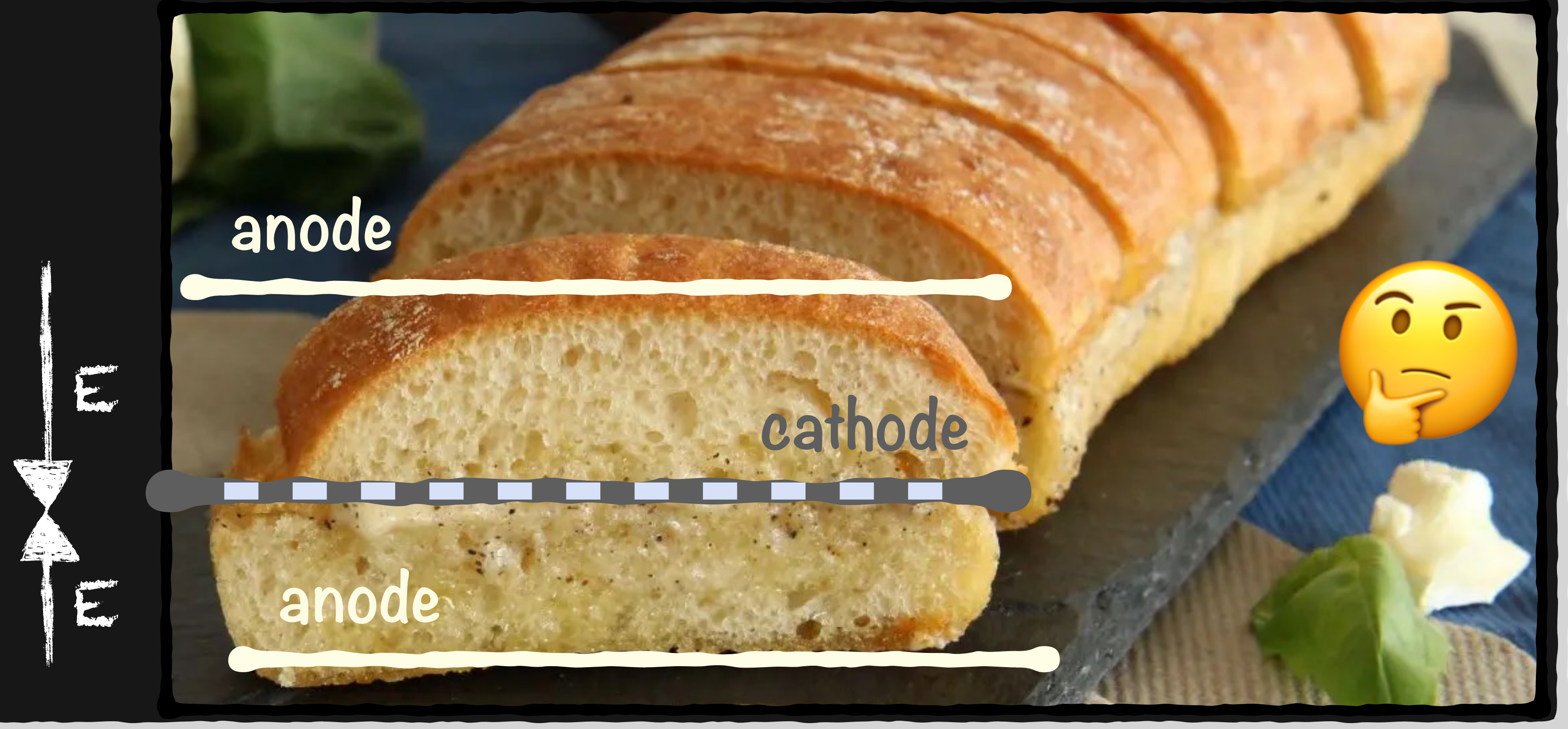




- difficult to extrapolate at the kton scale for DUNE-FD

The "Préfou" prototype:
- 250g de farine
- 1 sachet de levure de boulanger
- 20 g de bourre demi-sale
- 15 cl d'eau tiède
- 2 cuilleres à soupe de sucre en poudre



Deep Underground Neutrino Experiment (DUNE)

- since 2016, long R&D program at CERN
- *additional requirements for non-beam physics*
  - larger active volume
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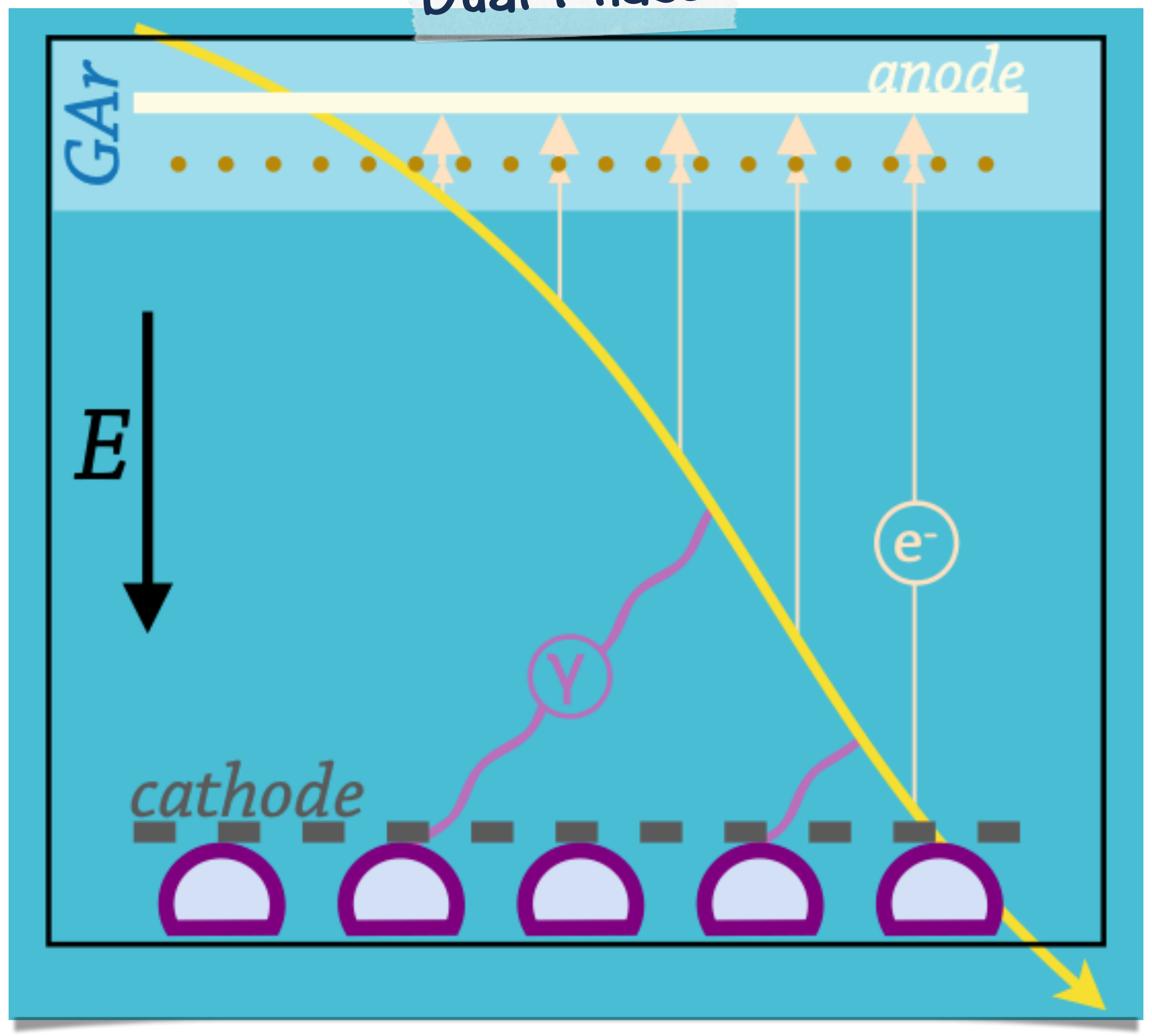
Dual-Phase



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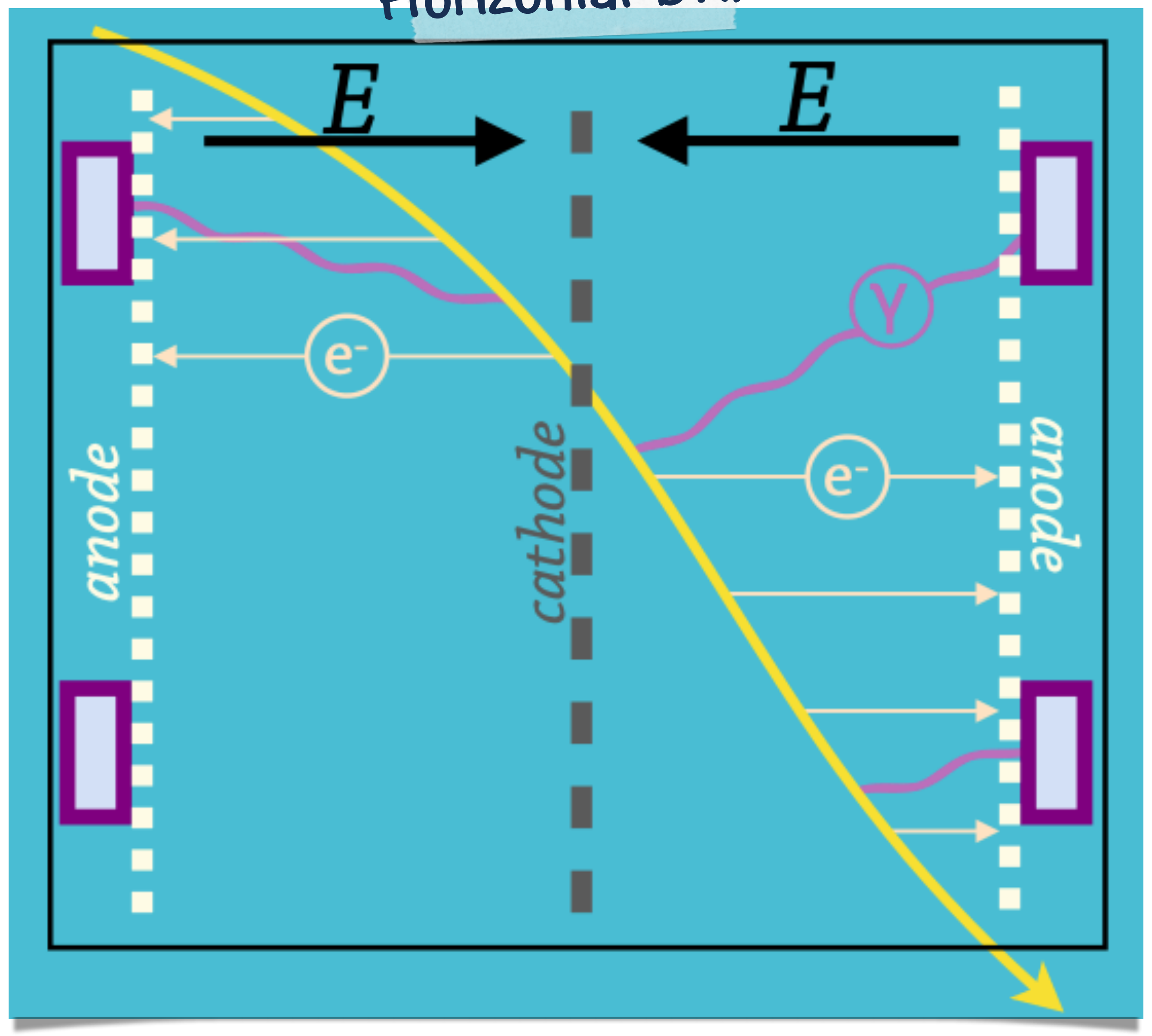
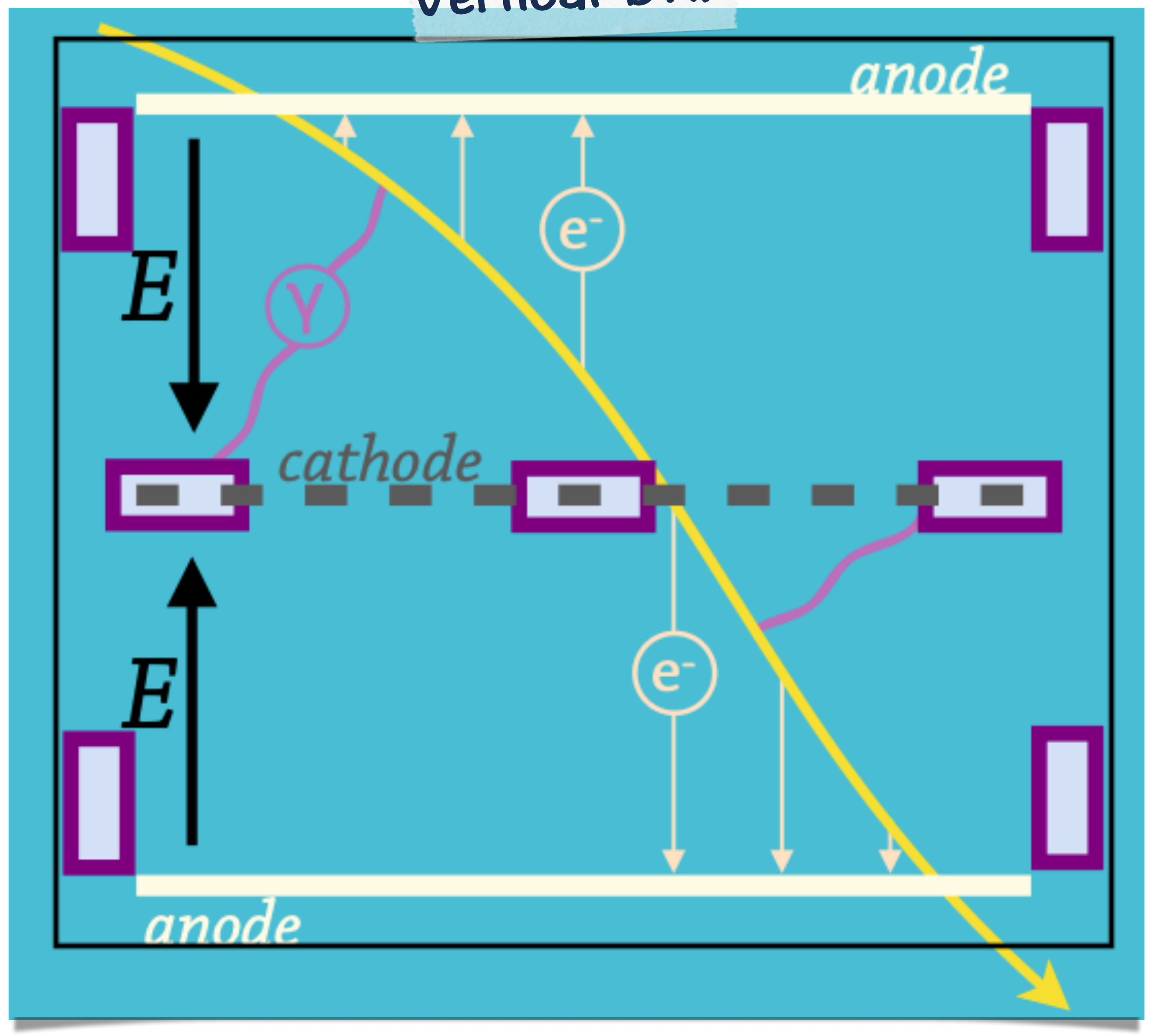
Horizontal-Drift



Vertical-Drift



✔

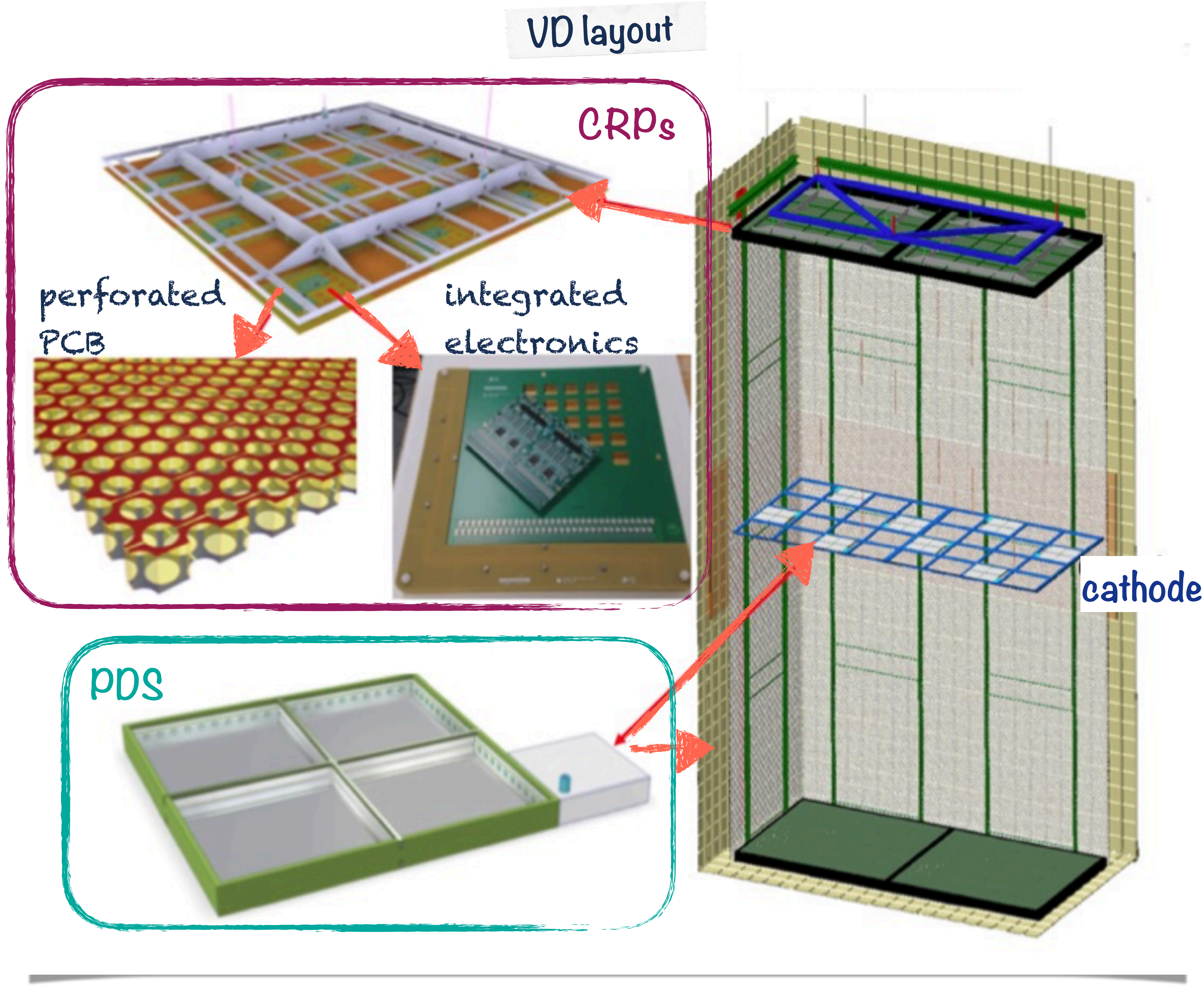
images' credit: Laura Zambelli

Deep Underground Neutrino Experiment (DUNE)

- Vertical Drift configuration under construction to be testes at CERN (Module-0 prototype)
- 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

more details in Joshua's talk!

more details in Ariel's talk!



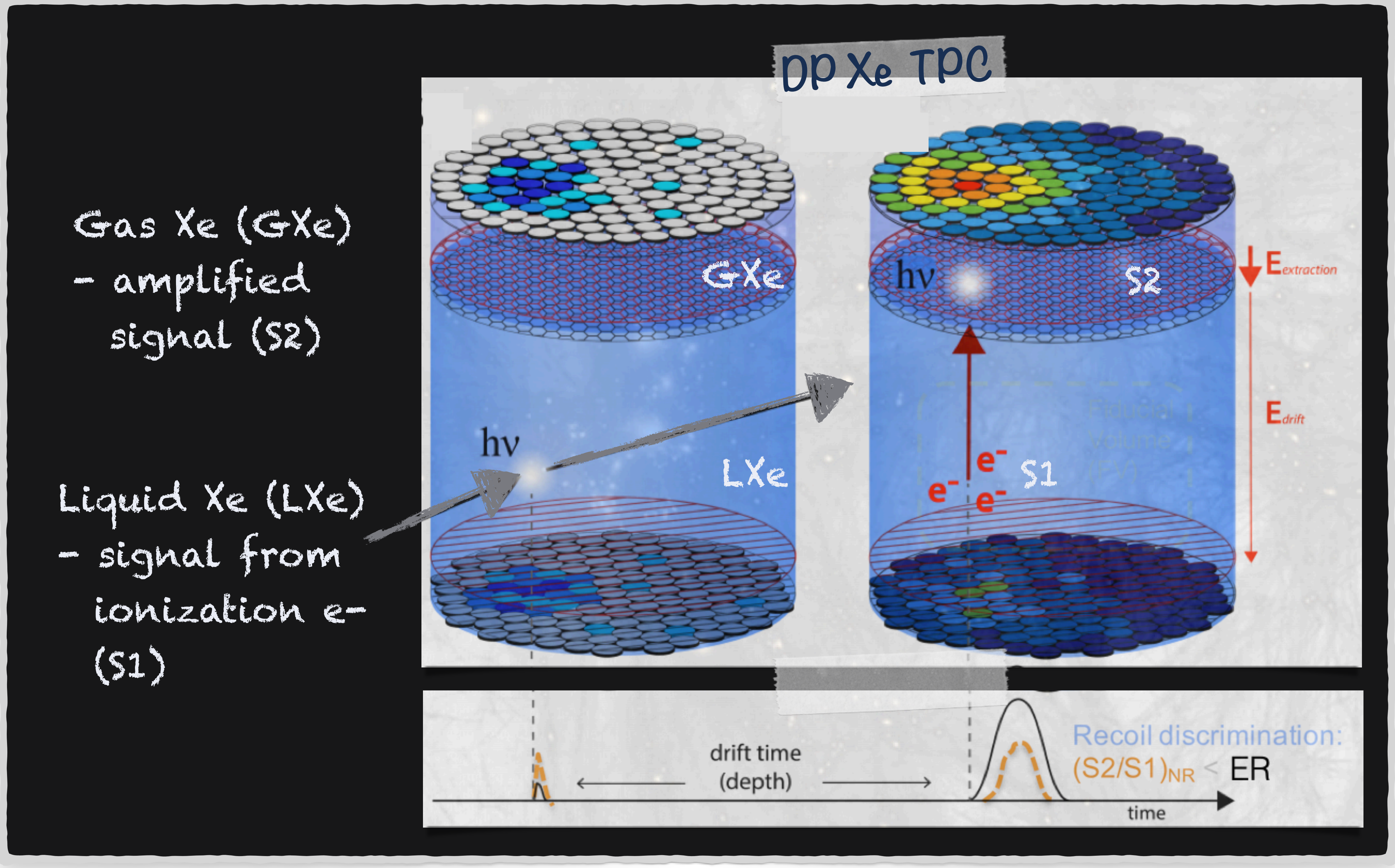
* *Arapuca in Brazilian means "trap", they act as light traps*

Next generation neutrino experiments

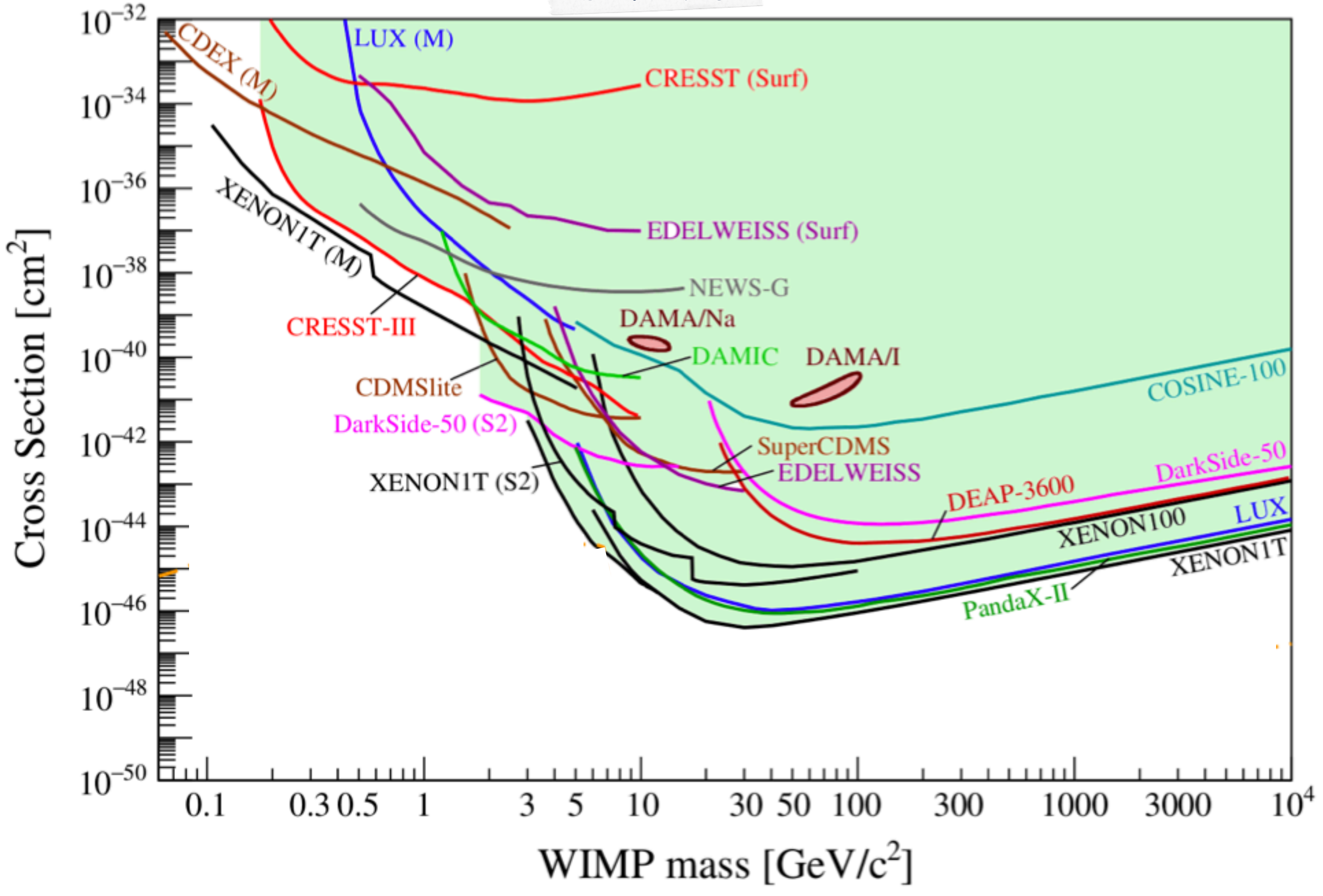
Nobel gas detector: Xenon, DarkSide

- high purity, very good light yield, strong background rejection
- optimal configuration for dark matter (DM) searches
- **double-phase (DP) nobel gas TPC**, allowing for amplification of faint signals

DP Xe TPC



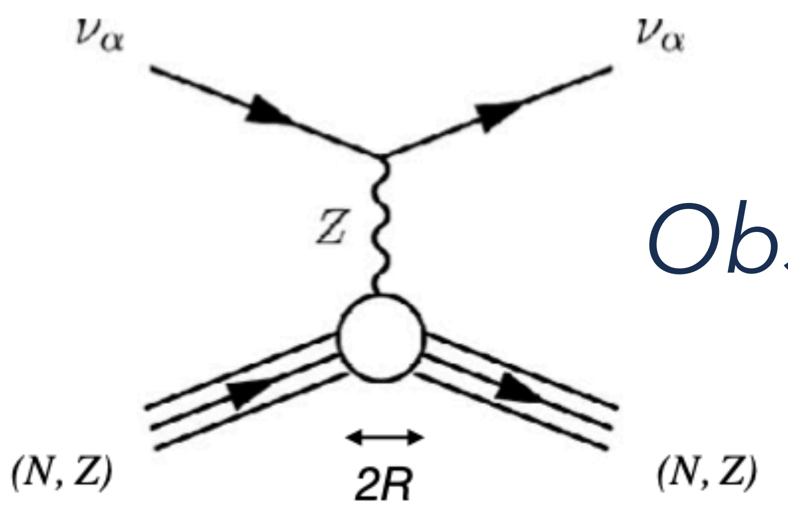
DM limits



Next generation neutrino experiments

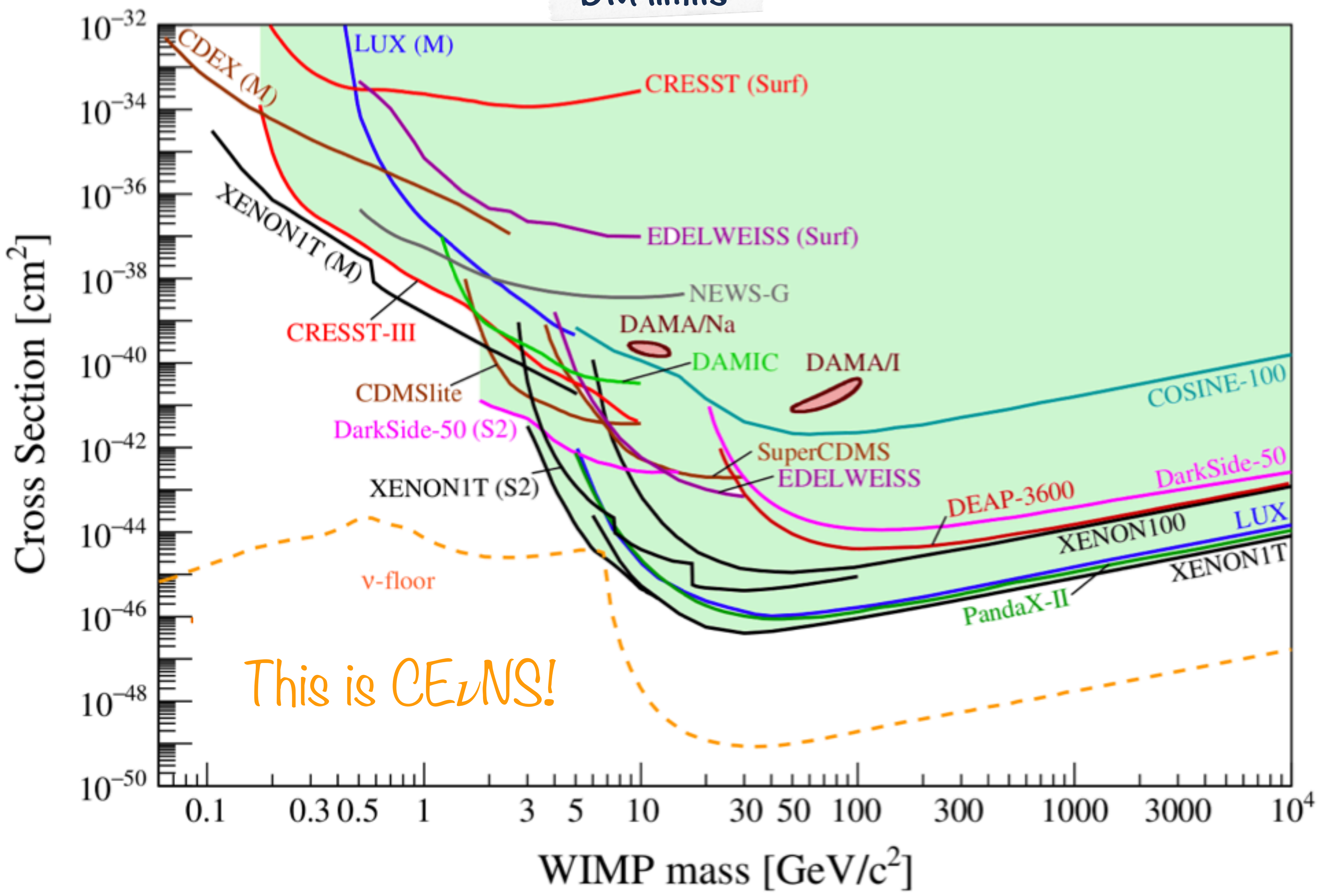
- *neutrino floor*: coherent elastic neutrinos-Nucleus scattering (CEνNS) is the main background for DM searches…but interesting signal for neutrino physics!

CEνNS



Observed for the first time in 2017!

DM limits

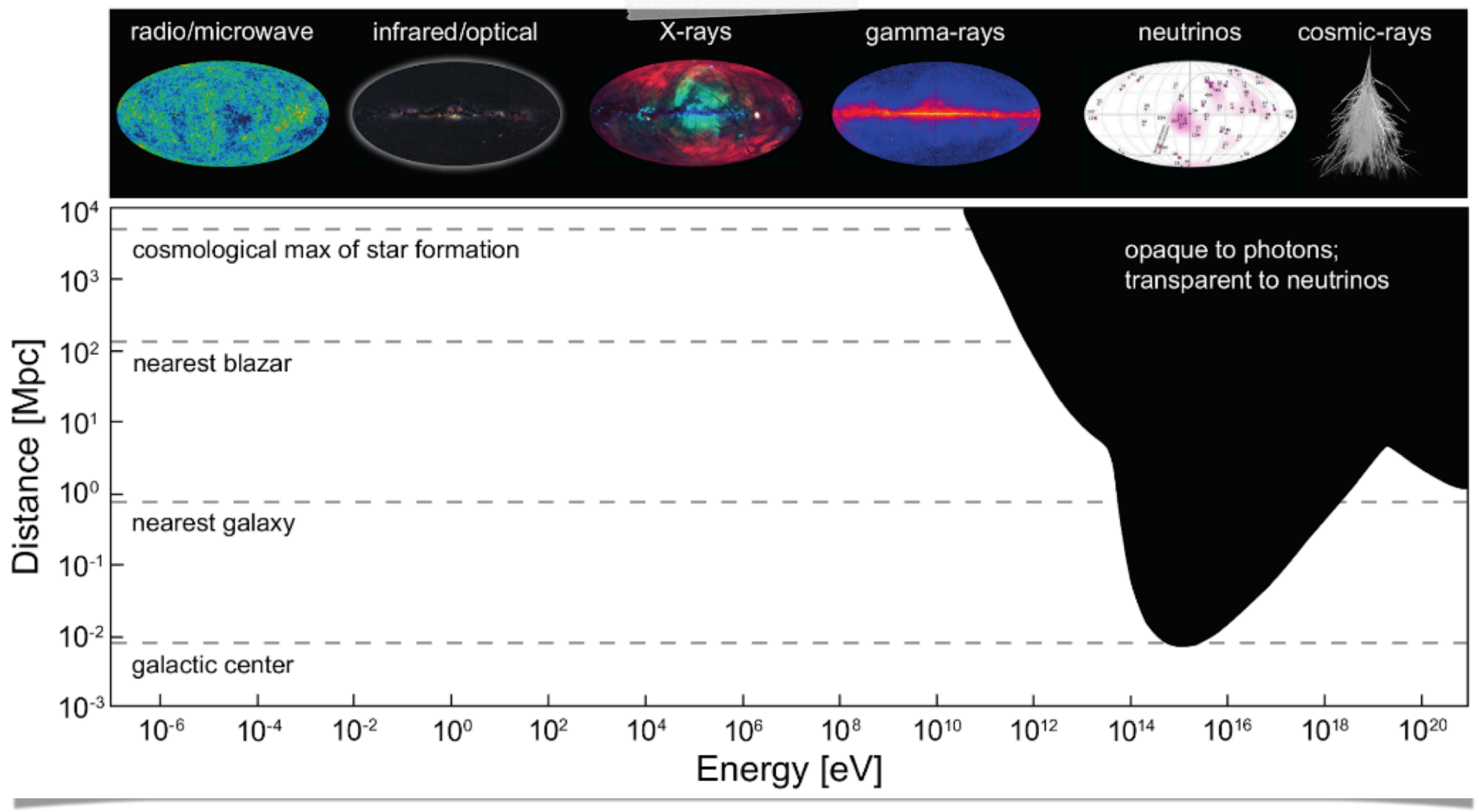


more details in Quentin's talk!

Neutrino telescopes

Neutrino telescopes: KM3NeT and IceCube/DeepCore
- huge active volume (~ km^3)
- able to detect neutrinos with energy up to PeV
- neutrinos travel weakly interacting, optimal for pointing!

	KM3NeT	IceCube/DeepCore
Location	North hemisphere	South Pole
Energy	~(3,100) GeV; (TeV, PeV)	~(10, 60) GeV; (0.1 TeV, 1 EeV)
Medium	water	ice
Completed by	2028	already taking

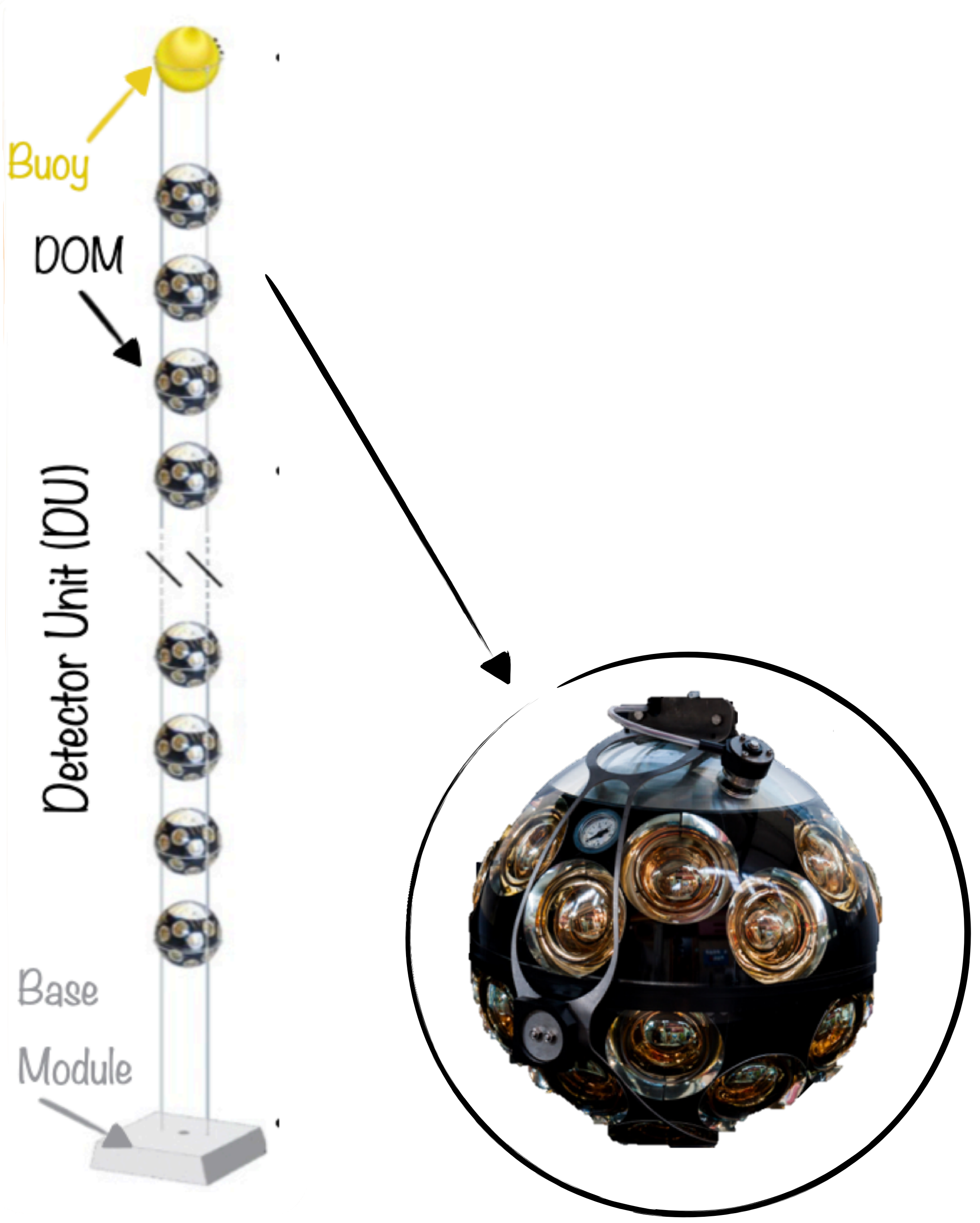


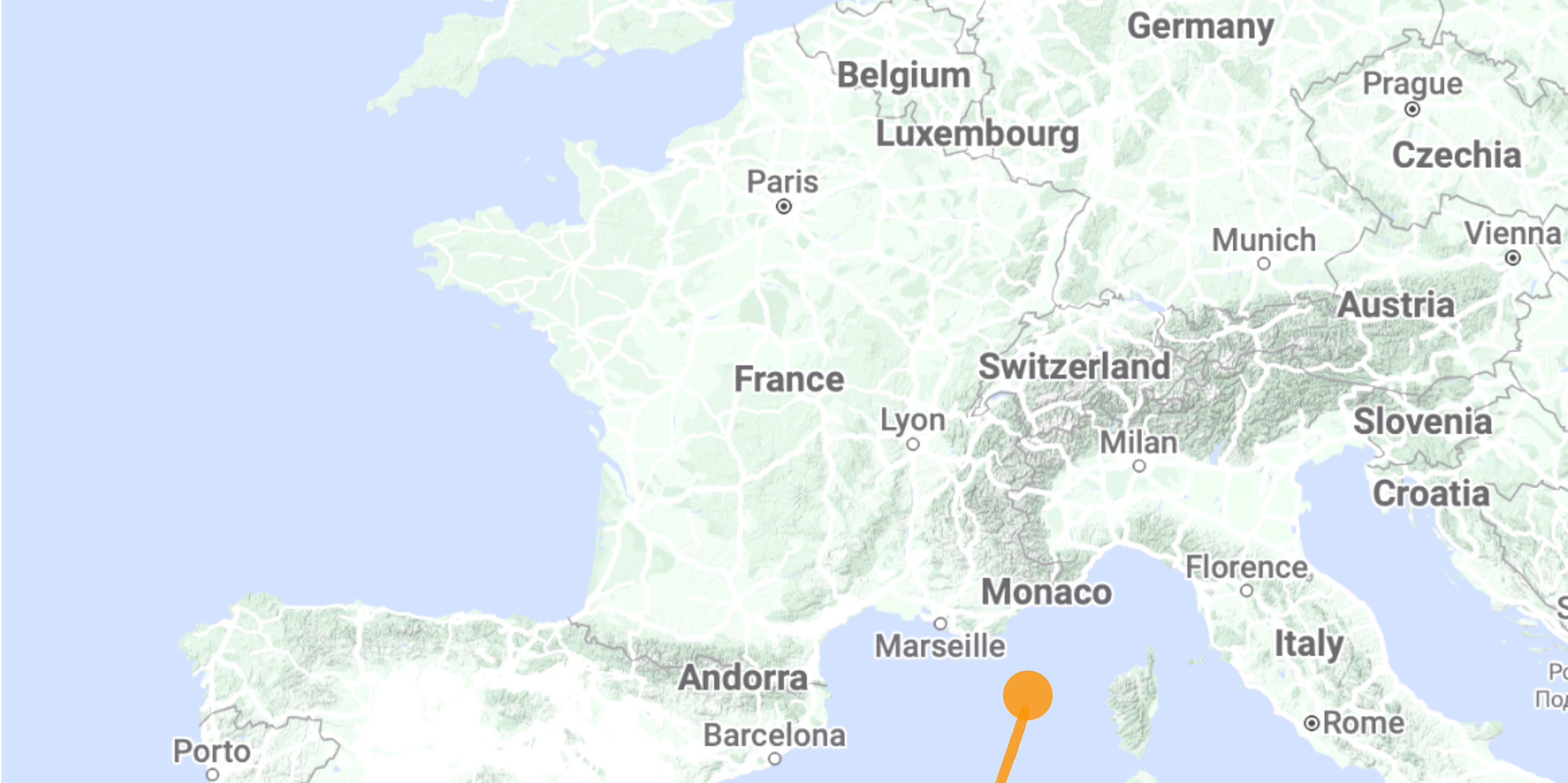
They will exploit potentials of multi-messenger astronomy!

KM3NeT: ARCA and ORCA

Under construction in the deep Mediterranean Sea:

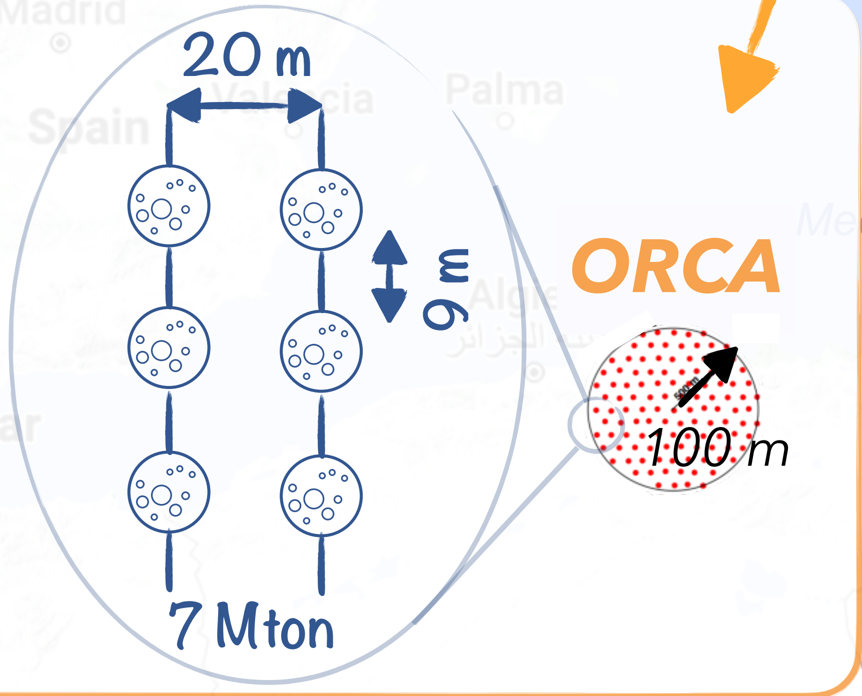
- two detection sites, broad physics program:
  - ARCA, **neutrino astronomy** in E ~ (TeV, PeV)
  - ORCA, **neutrino oscillations** in E~ (3, 100) GeV





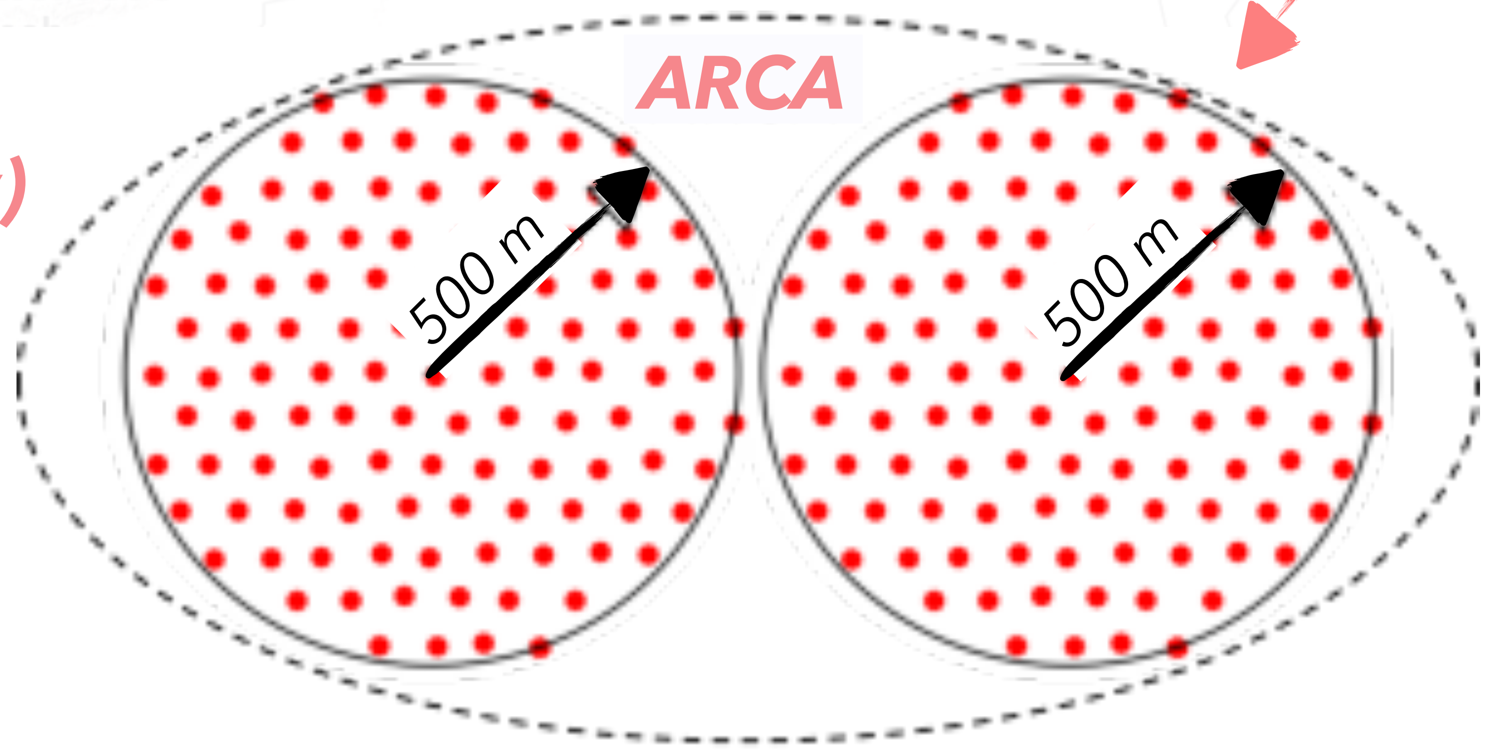
offshore Toulon (France)

- depth: 2450 m
- Detection Units (DUs): 115
- instrumented vol. ~ 18%



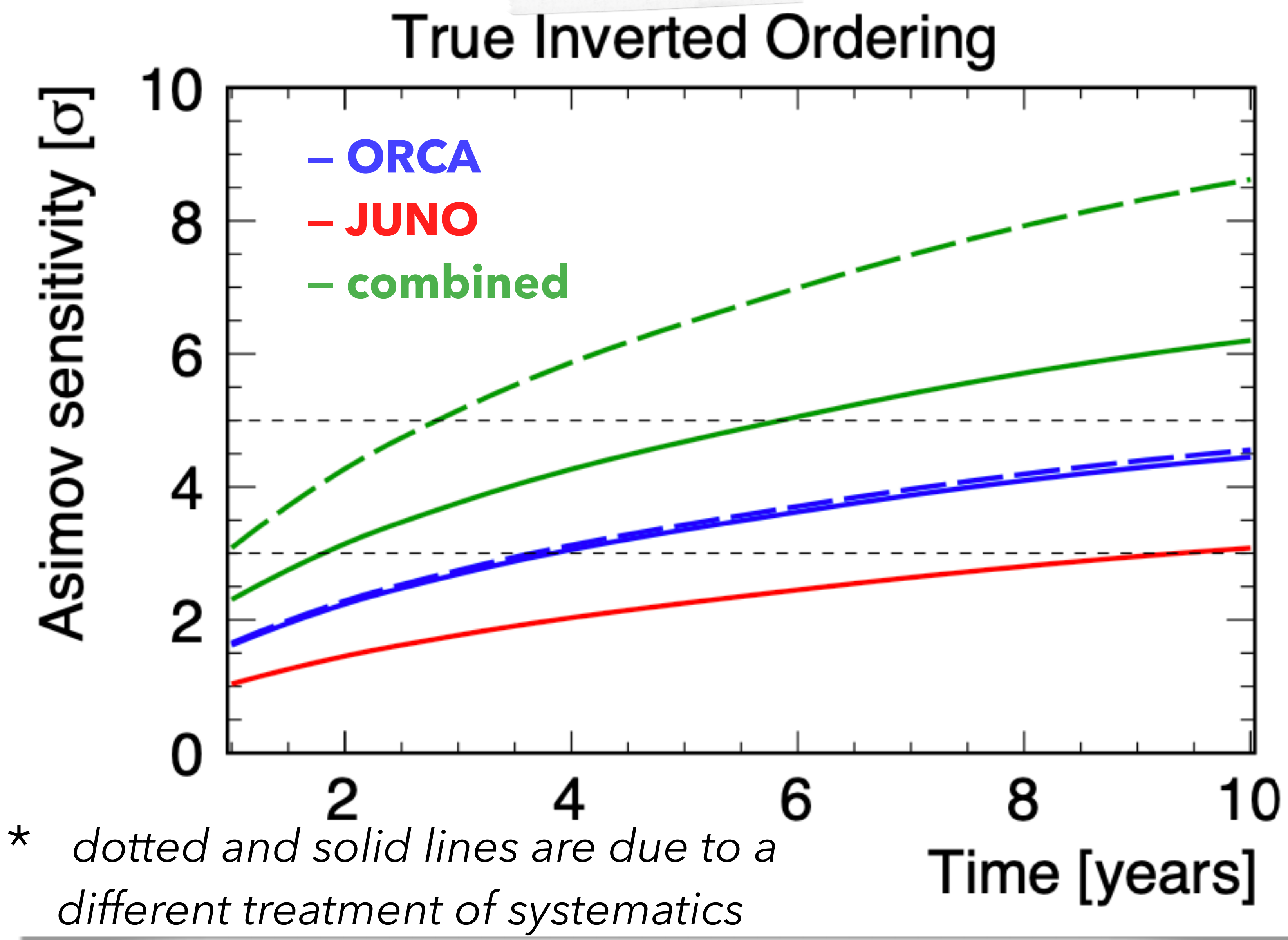
offshore CapoPassero (Italy)

- depth: 3560 m
- DUs: 230
- instrumented vol. ~ 9%



KM3NeT/ORCA

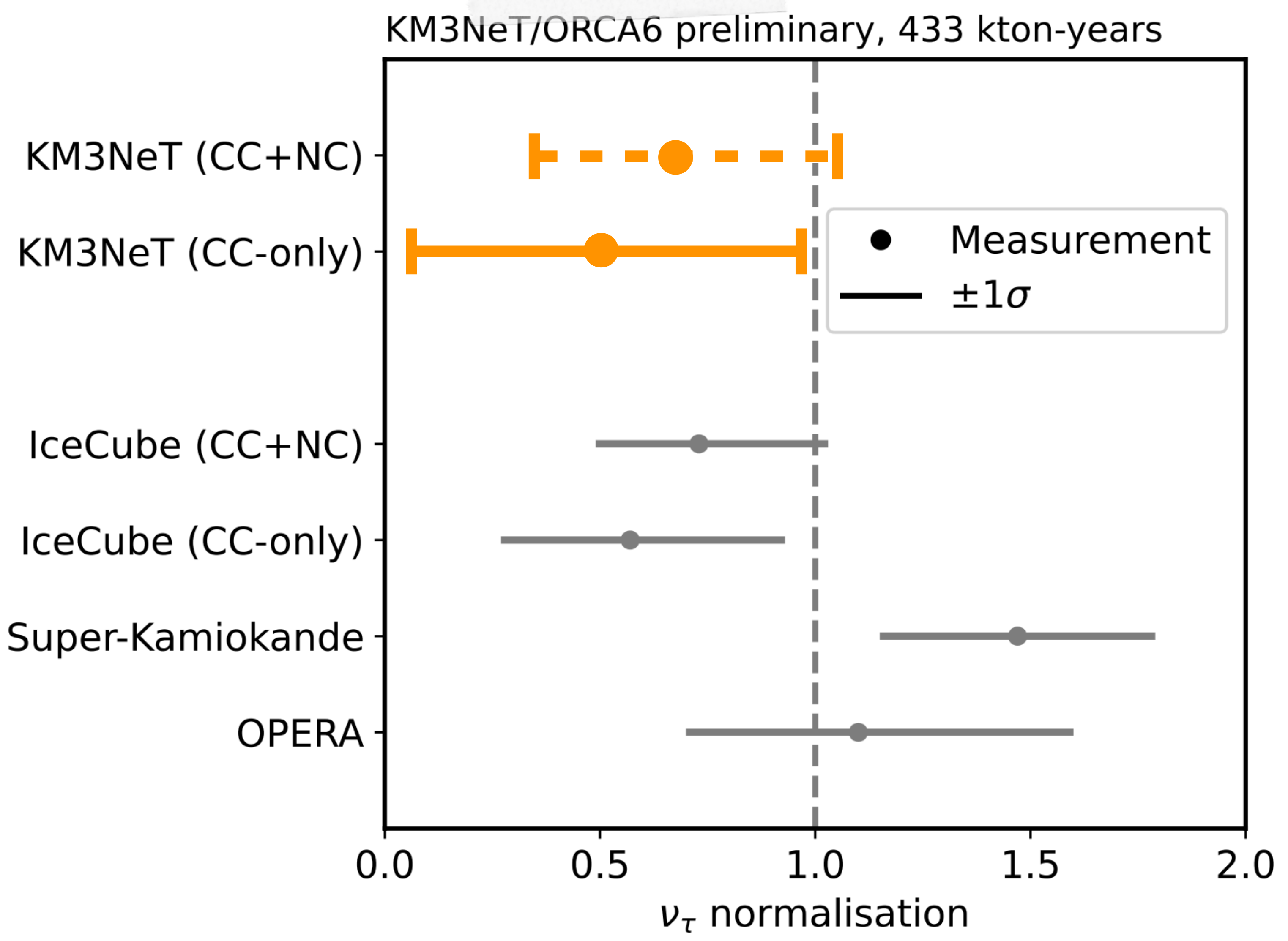
- atmospheric neutrinos: wide **energy range** and **baseline** (~cosine zenith angle of the interacting neutrino)
  - early measurement of NMO, precision measurement of Δm^2_{32}, θ_{23}, test of PMNS matrix unitarity

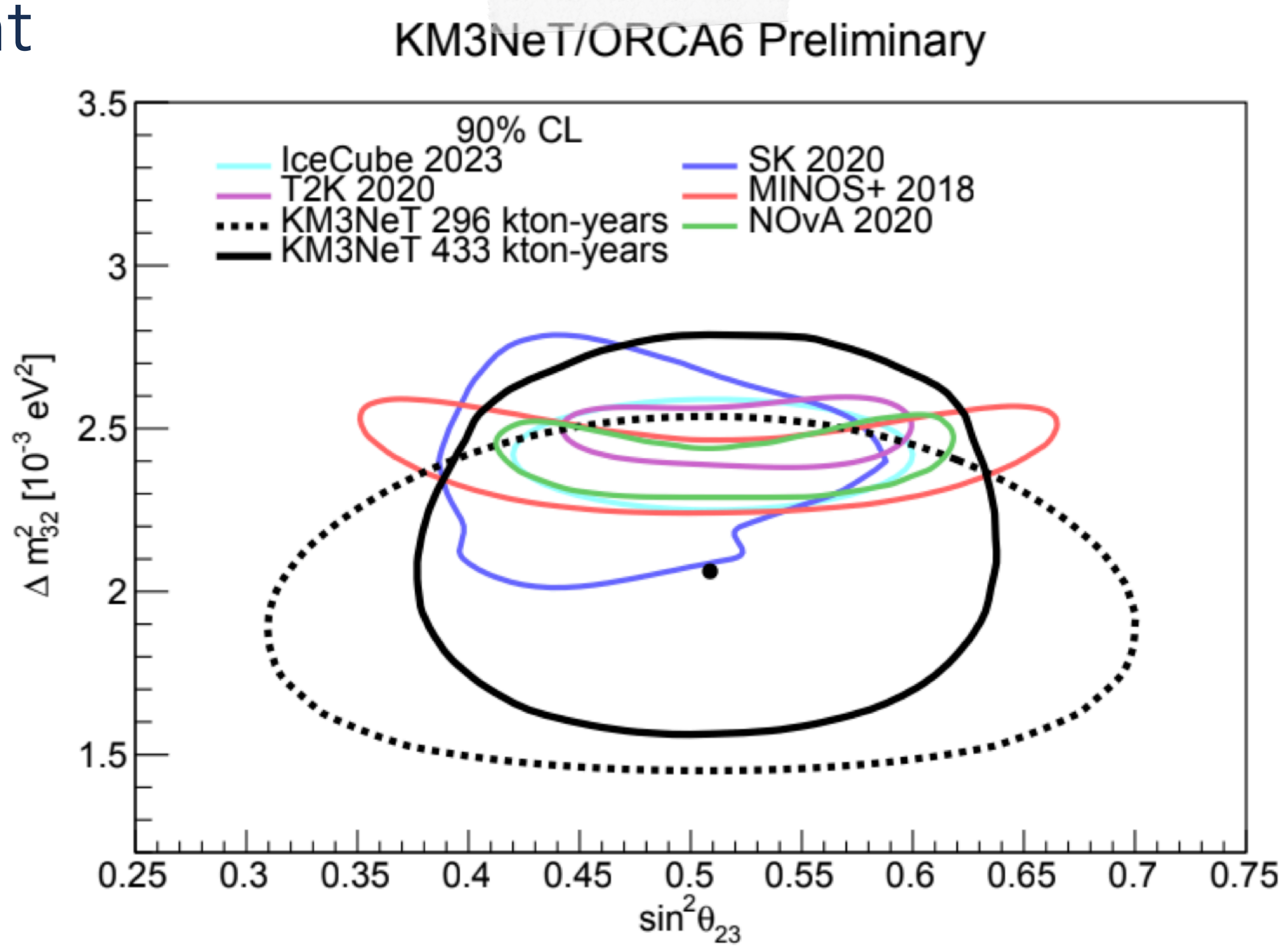


* dotted and solid lines are due to a different treatment of systematics

- NMO, 5σ sensitivity to IO after 5 years (if alone) or in 2 years if combined with JUNO

- first analyses based on data collected with 6 DUs:
  - atmospheric oscillation parameters
  - first ν_τ appearance measurement

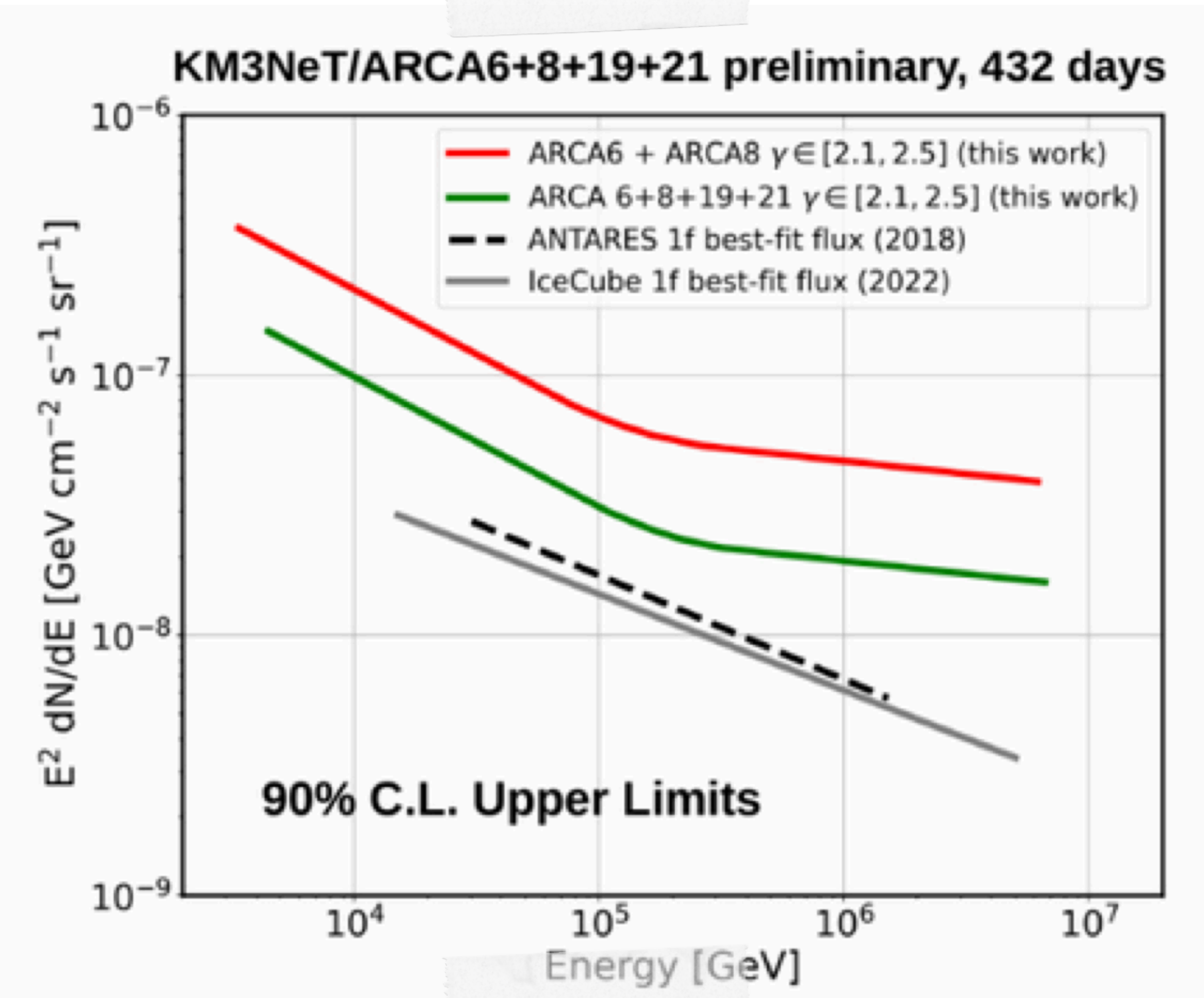


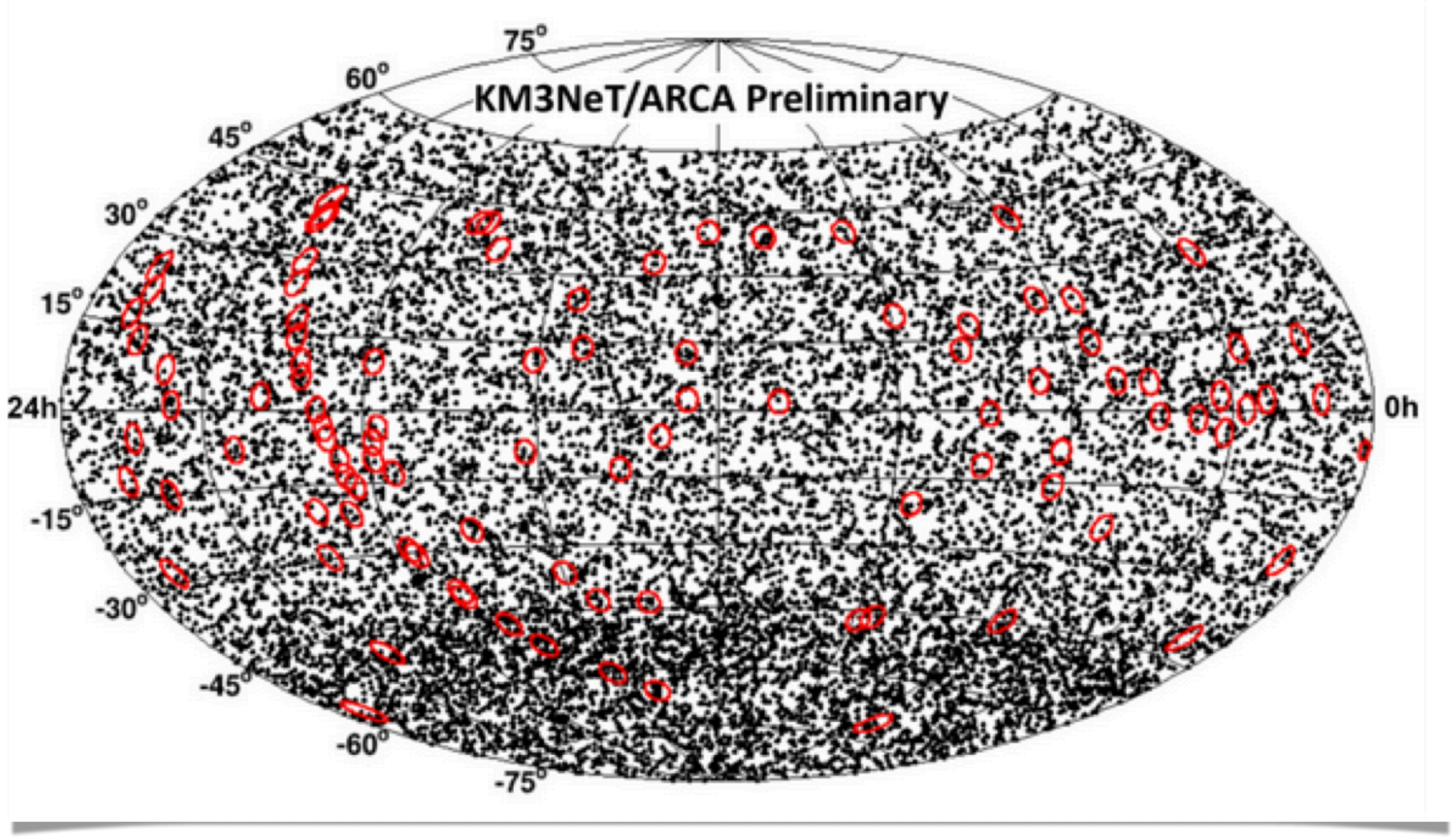


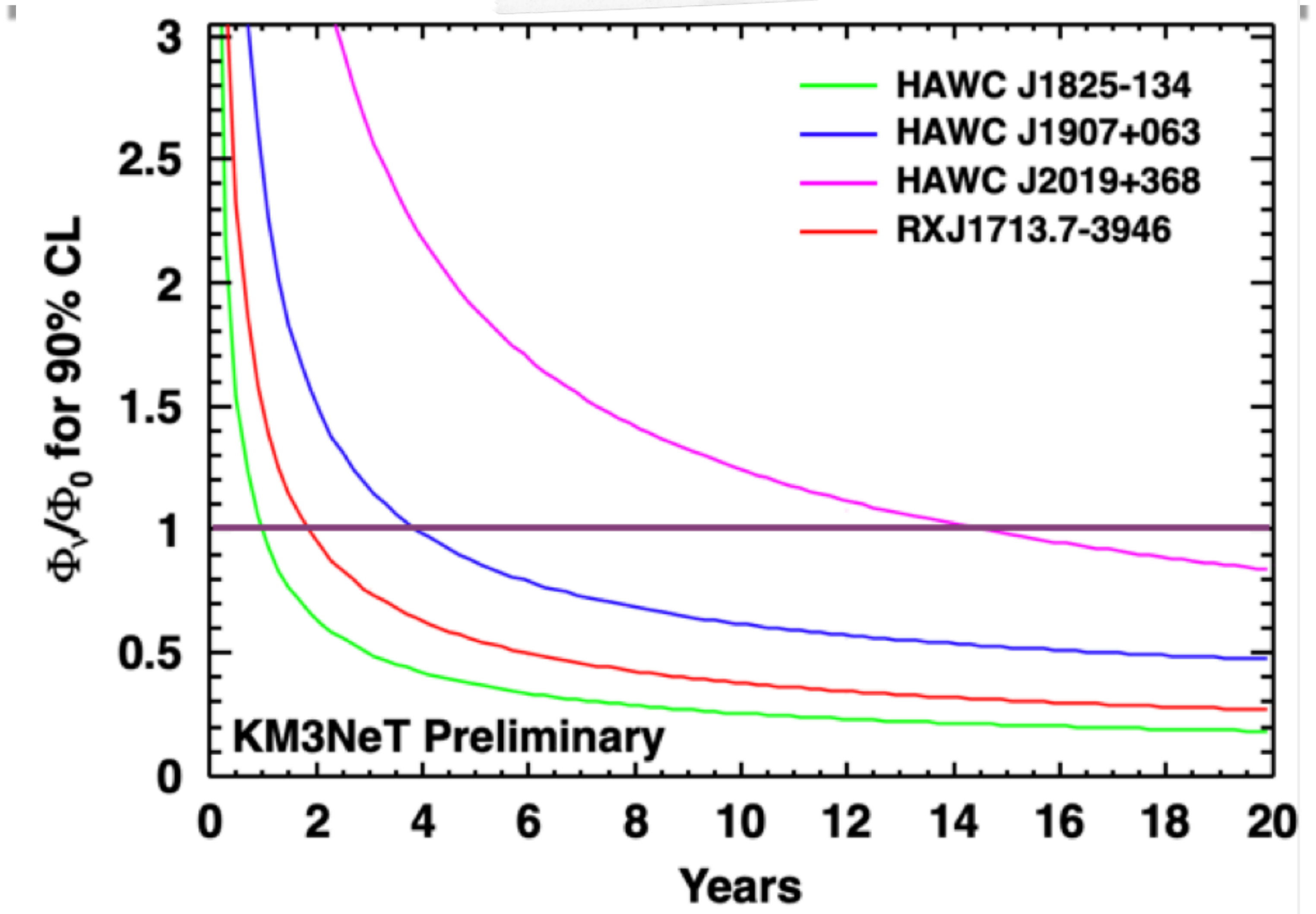
more details in Santiago's talk!

KM3NeT/ARCA

- neutrino astronomy: extremely good pointing performance (at PeV, ~0.1^0 for tracks and 1^0 for showers)
    - upper limit to **diffuse flux of astrophysical neutrinos**
    - complementary to IceCube for **point-like sources**
    - sensitivity to **extended galactic sources**
- **alert for multi messenger follow-up**!







more details in Felix's talk!

Conclusions

It’s impossible to summarize neutrino history in 30 min but it is definitely full of funny anecdotes (search for them!)

We still understand only a small portion of the “new physics” hidden behind neutrino oscillation (but we are optimistic and we believe we will soon understood more of it!)

We don’t know whether neutrinos are actually three or more (and if the others are even more introvert than the three we observed!)

We don’t know whether they are their own antiparticles (Majorana did, though..but he disappeared!)

..just stay tuned
(at least for the remaining 2h!!)

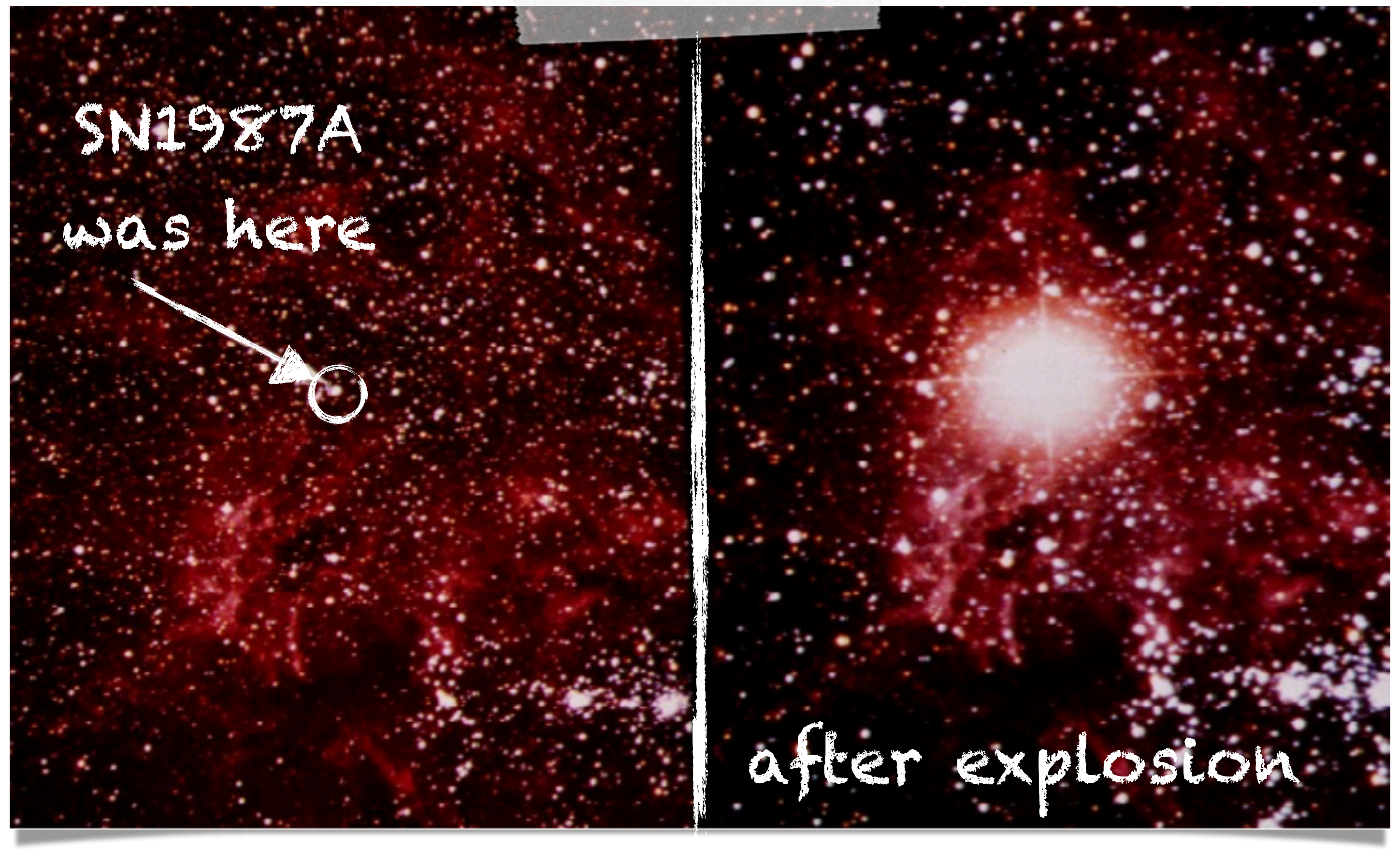
Deeply Learning from Neutrino Interactions with the KM3NeT neutrino telescope	*Santiago Peña Martinez*	14:30 - 15:00
Multi-messenger observations with the KM3NeT telescope: search for high energy neutrinos coinciding with fast radio bursts	*Felix Bretaudeau*	
Search for Coherent Elastic Scattering of Solar Neutrinos in XENONnT	*Mr Quentin Pellegrini*	15:30 - 16:00
Pause café		16:00 - 16:30
Study of the Photon Detection System in DUNE using simulation techniques	*Ariel Cohen*	16:30 - 17:00
Induction signal characterization in the vertical drift TPC for the DUNE project	*Joshua Pinchault*	17:00 - 17:30

Extra slides

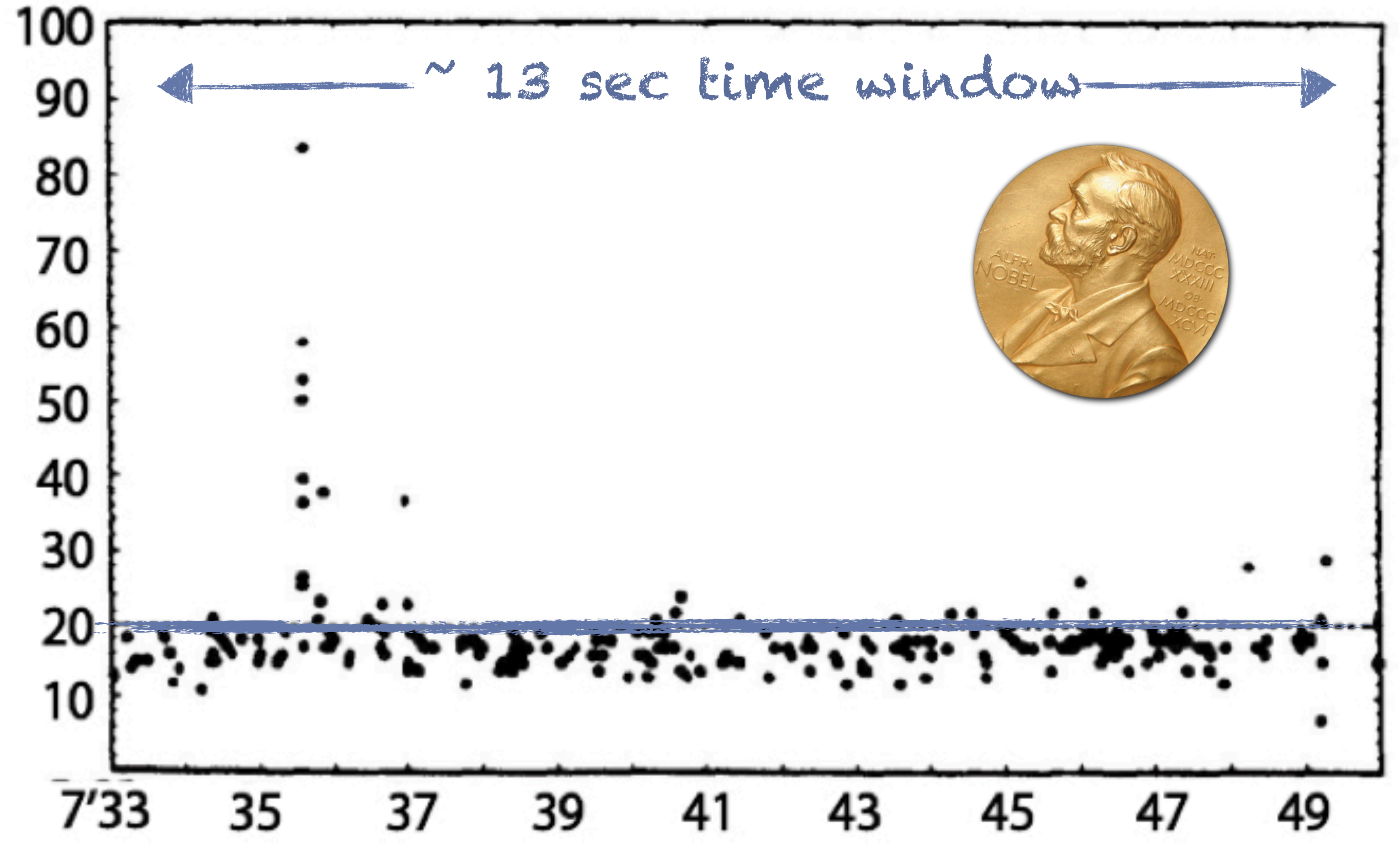
Neutrino astronomy

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

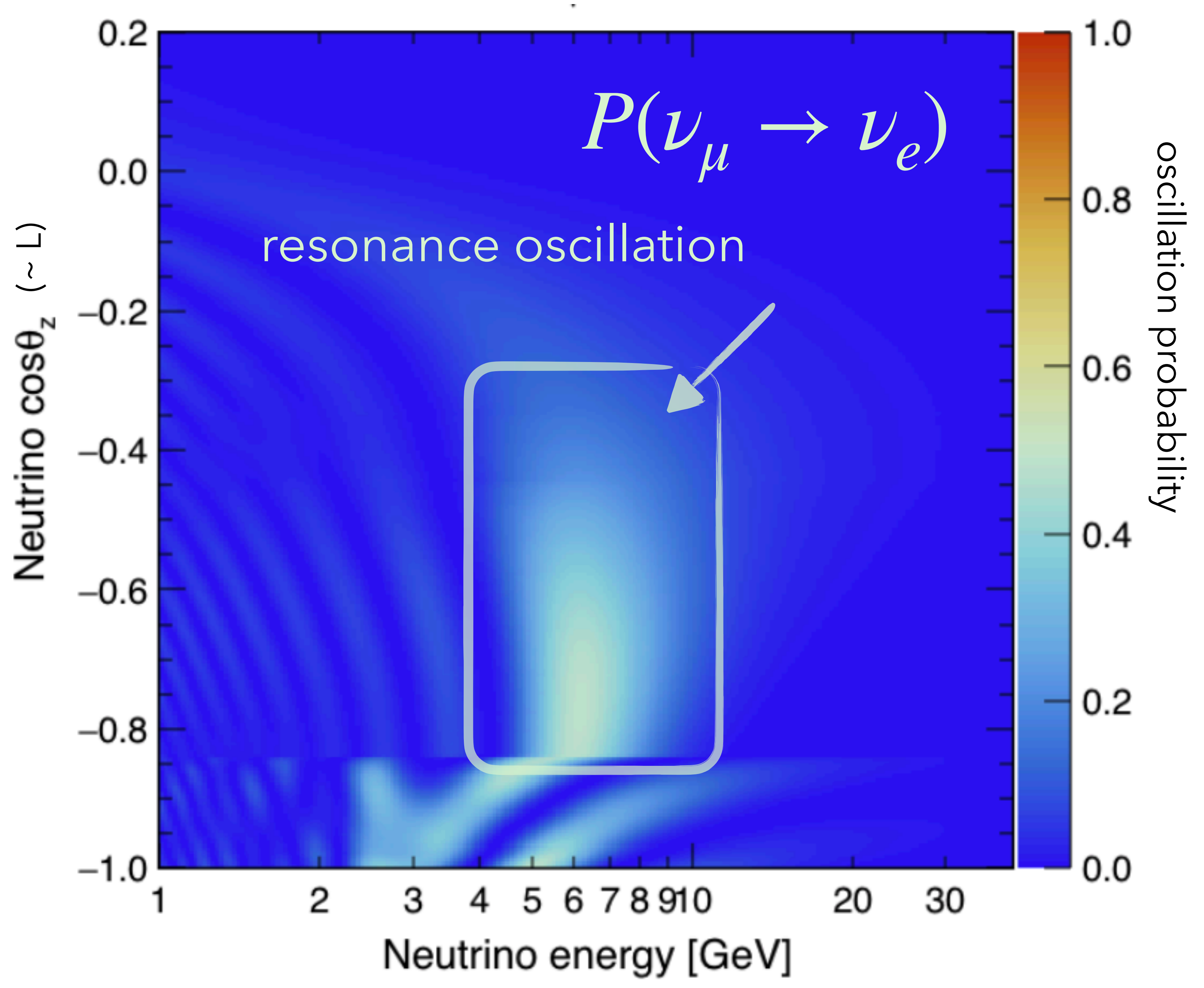
- a SN in the Large Magellan Cloud exploded on Feb. 23rd 1987, 7:33 UTC
    - neutrino signal arrived ~3h before the light signal
    - signal detected by three experiments: 11 events by Kamiokande-II, 8 events by IMB, 5 events by Baksan
      (*Nobel prize in 2002!*)



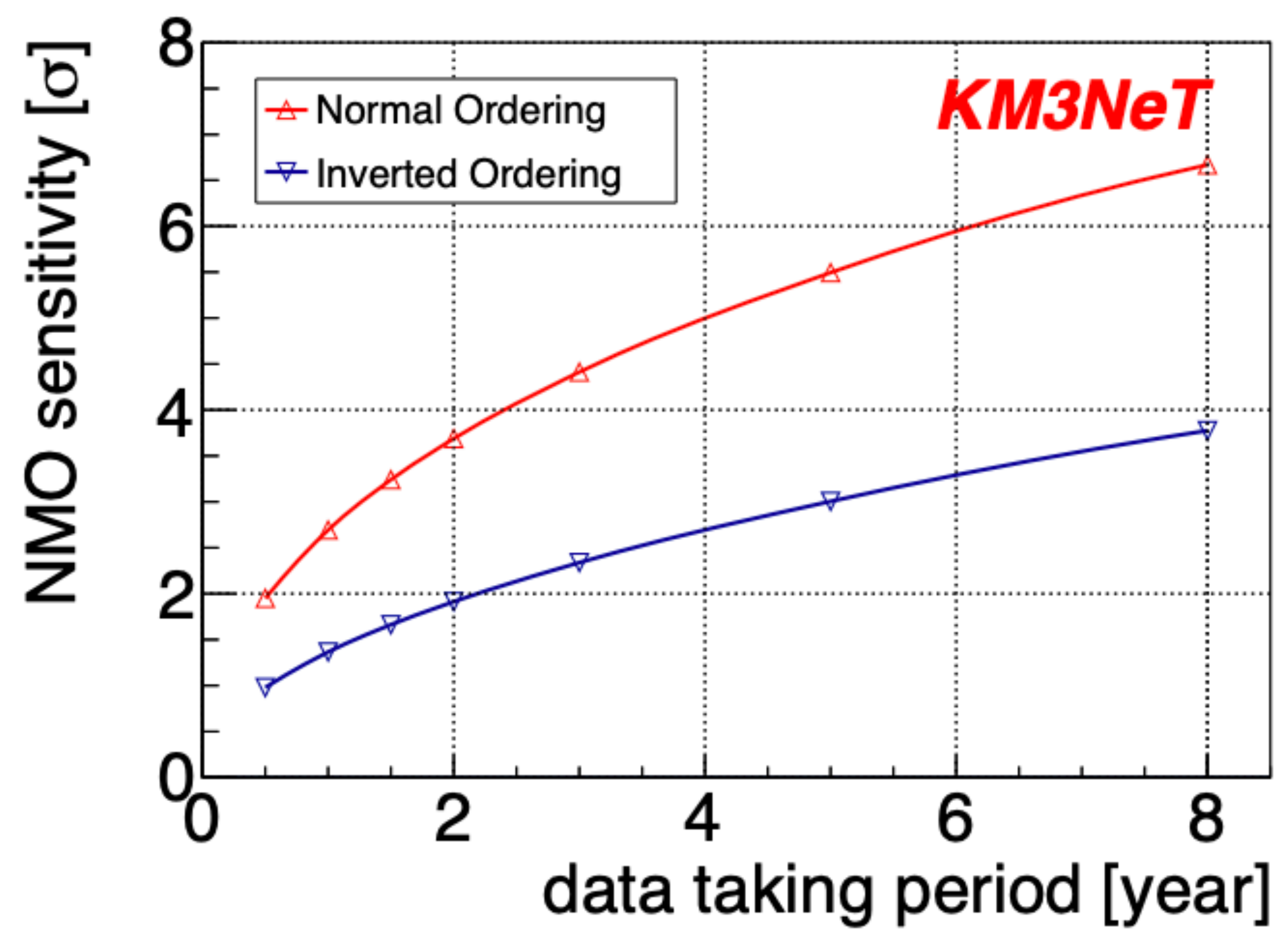
SN are expected to explode ~1/century…
so, now, all the experiments are waiting for the next one!



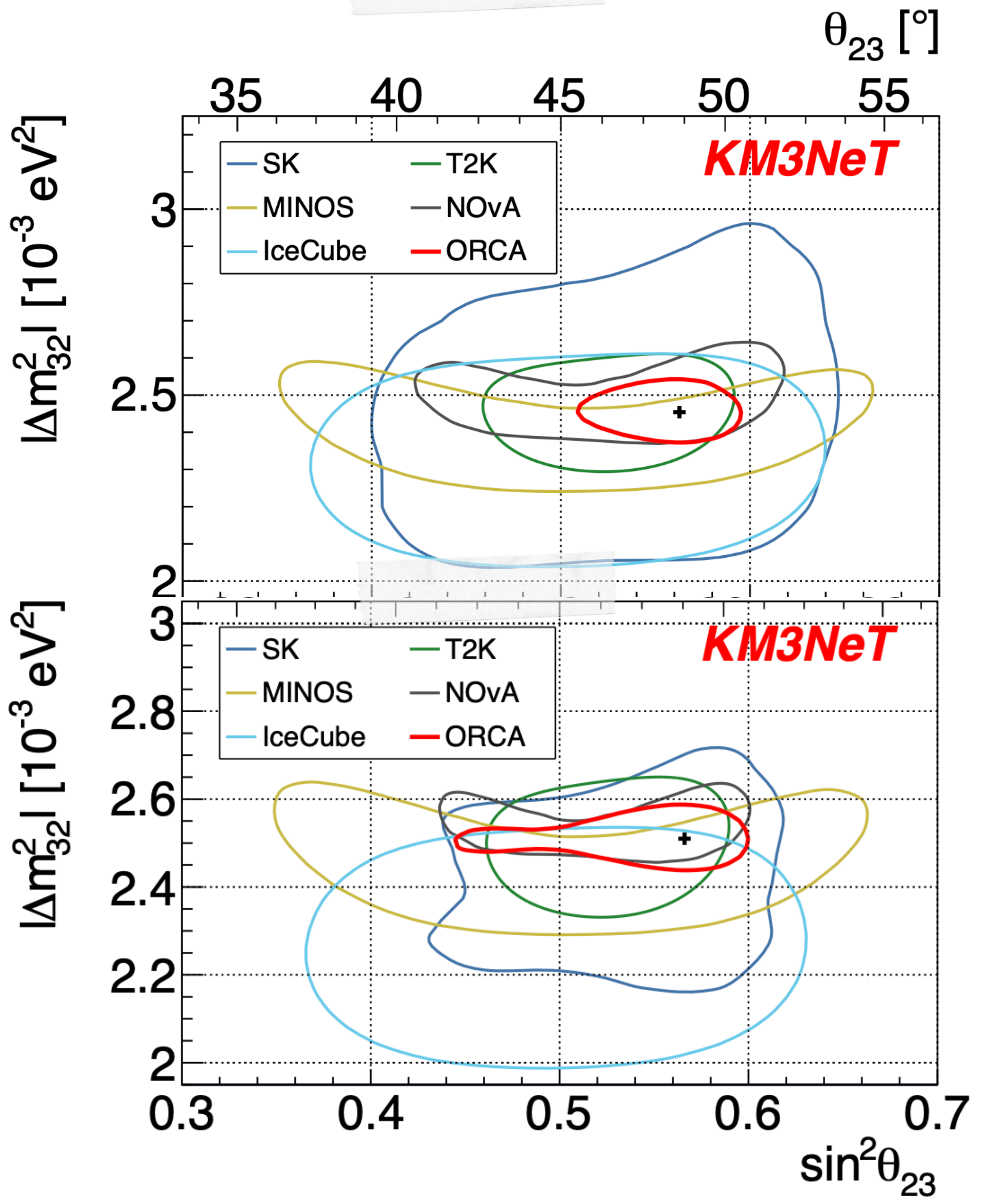
KM3NeT/ORCA



$P(\nu_\mu \rightarrow \nu_e)$
resonance oscillation
Neutrino $\cos\theta_z$ (~ L)
Neutrino energy [GeV]
oscillation probability



KM3NeT
Normal Ordering
Inverted Ordering
NMO sensitivity [σ]
data taking period [year]



θ_{23} [°]
KM3NeT
SK
T2K
MINOS
NOvA
IceCube
ORCA
$|\Delta m^2_{32}|$ [10^{-3} eV^2]
$\sin^2\theta_{23}$