Searching for neutrinos in France

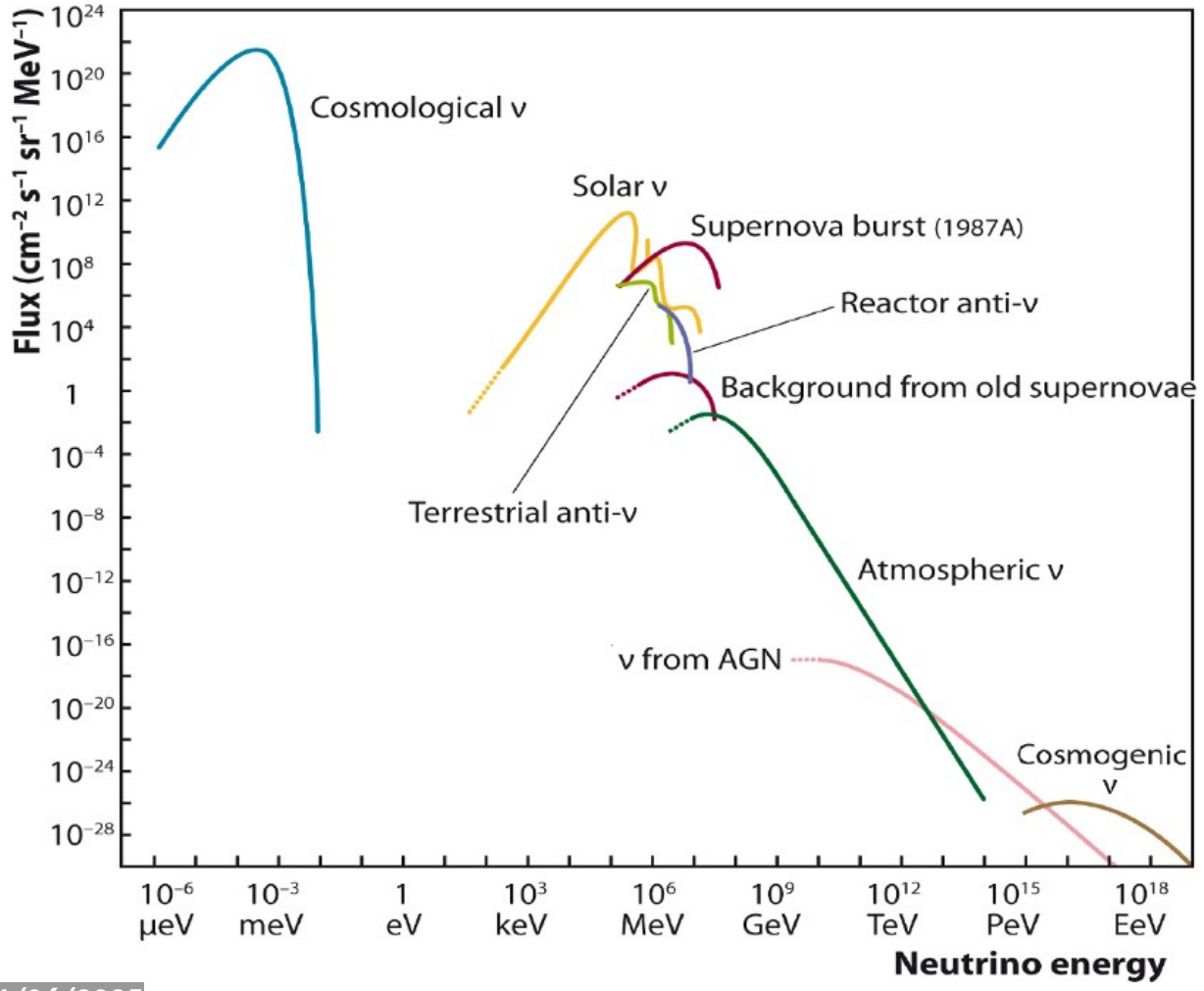
France-Ukraine workshop

IJCLab

Thibaut Houdy

12th of June, 2025

Neutrinos flux on Earth



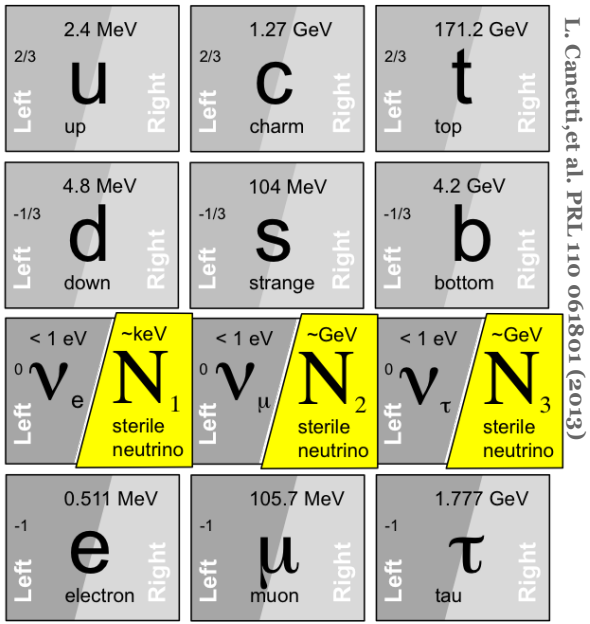
- **Most abundant massive particle in the Universe**
- **A lot of astrophysical sources that can be used as neutrino test bench (and vice versa)**
- **One of the most obvious door toward physics beyond standard model**

Neutrino properties

Why do they change flavours in propagation?

What is the mass of the neutrinos?

How do we describe neutrino in SM : Majorana? Dirac?



L. Canetti,et al. PRL 110 061801 (2013)

How is this mass generated? Existence of a right-handed neutrino?

Is neutrino BSM-proof? Neutrino charge radius?

Neutrinos oscillation

- Neutrinos oscillation → non superposition between mass and flavour eigenstates
  → at least 2 non-zero masses

- How do we model the neutrino oscillation?

$$P_{\alpha\to\alpha}(t) = 1 - \sin^2(2\theta_{ij}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

distance

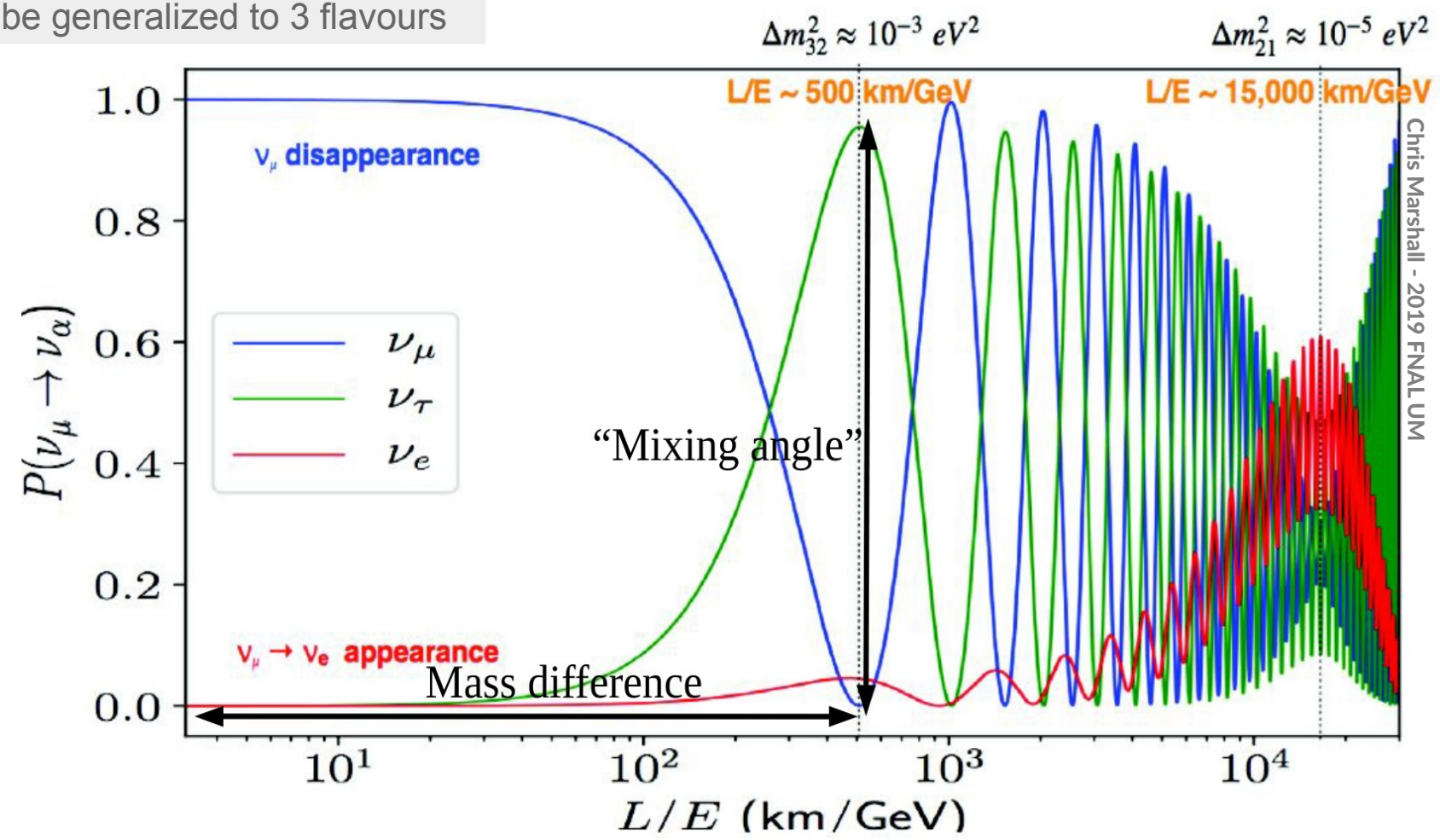
energy

- How to measure these parameters?

L,E fixed and counting neutrino → **Access to Δm^2 et θ!**

Neutrinos oscillation

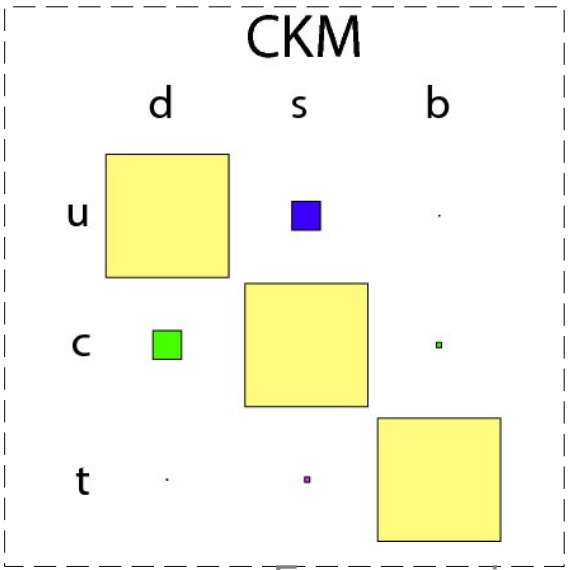
- It can be generalized to 3 flavours

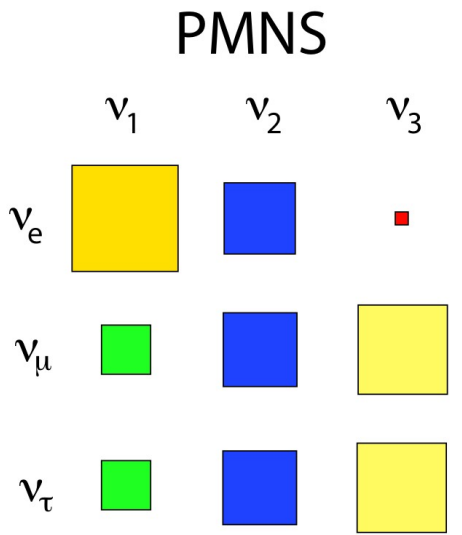


Neutrinos oscillation

- How do we model the neutrino oscillation?

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \mathrm{U_{PMNS}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \quad \text{with} \quad \mathrm{U_{PMNS}} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}e^{i\alpha} & 0 & 0\\ 0 & e^{i\beta} & 0\\ 0 & 0 & 1\end{pmatrix} ?$$





For comparison

Neutrinos oscillation

$\Theta_{23} \sim 40 - 52$

$\Theta_{13} \sim 8.2 - 8.9$

$\Theta_{12} \sim 31.6 - 35.9$

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

?

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

NuFit 5.3, march 2024

Neutrinos oscillation

$\Theta_{23} \sim 40 - 52$

$\Theta_{13} \sim 8.2 - 8.9$

$\Theta_{12} \sim 31.6 - 35.9$

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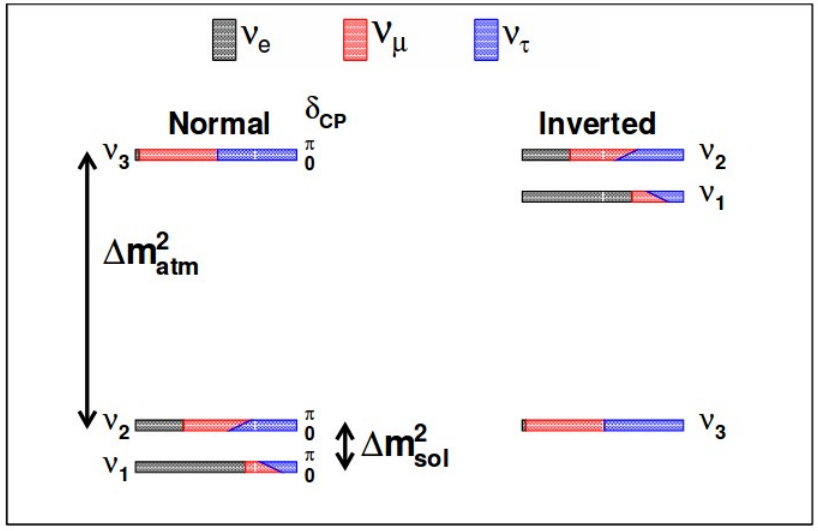
?

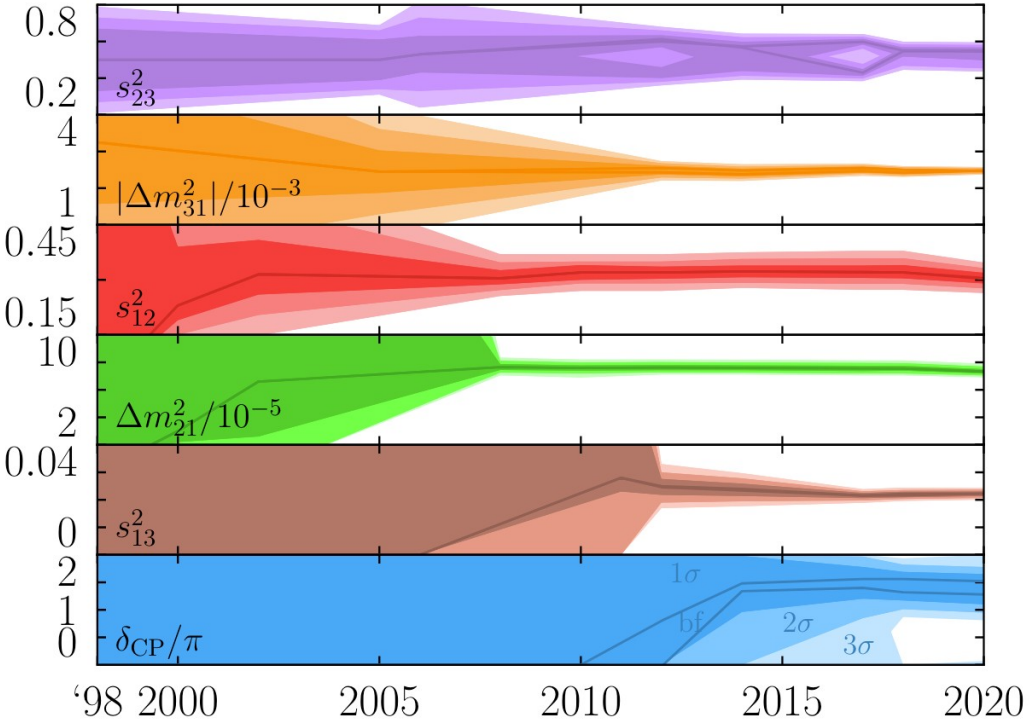


$\delta_{CP} \sim [-169,-25]$ [NH]
$\delta_{CP} \sim [-84,-72]$ [IH]

$\Delta m_{21}^2 \sim 7.4 \times 10^{-5} eV^2$

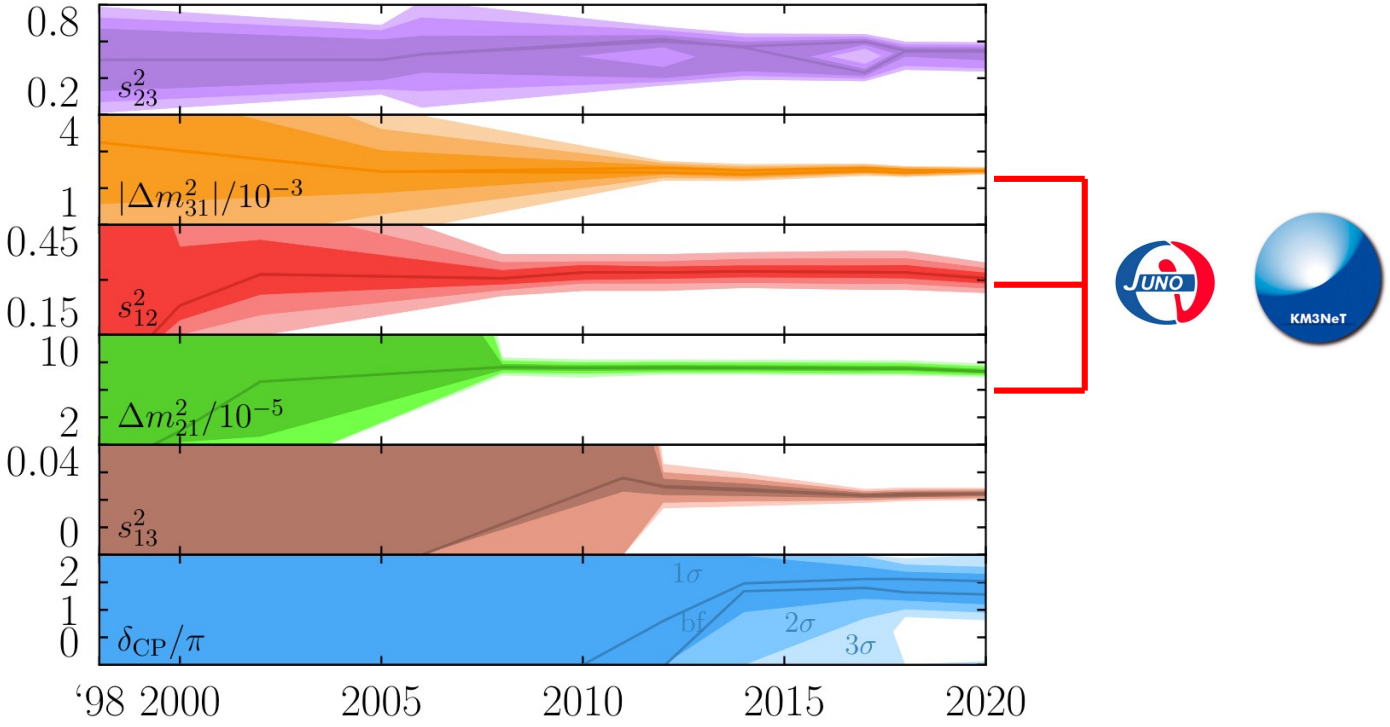
Δm_{31}^2 { $+2.51 \times 10^{-3} eV^2$ [NH]
$-2.50 \times 10^{-3} eV^2$ [IH]

Neutrinos oscillation



After the discovering time, we are entering the neutrino oscillation parameters precision era → large detectors for increasing statistics and low systematics

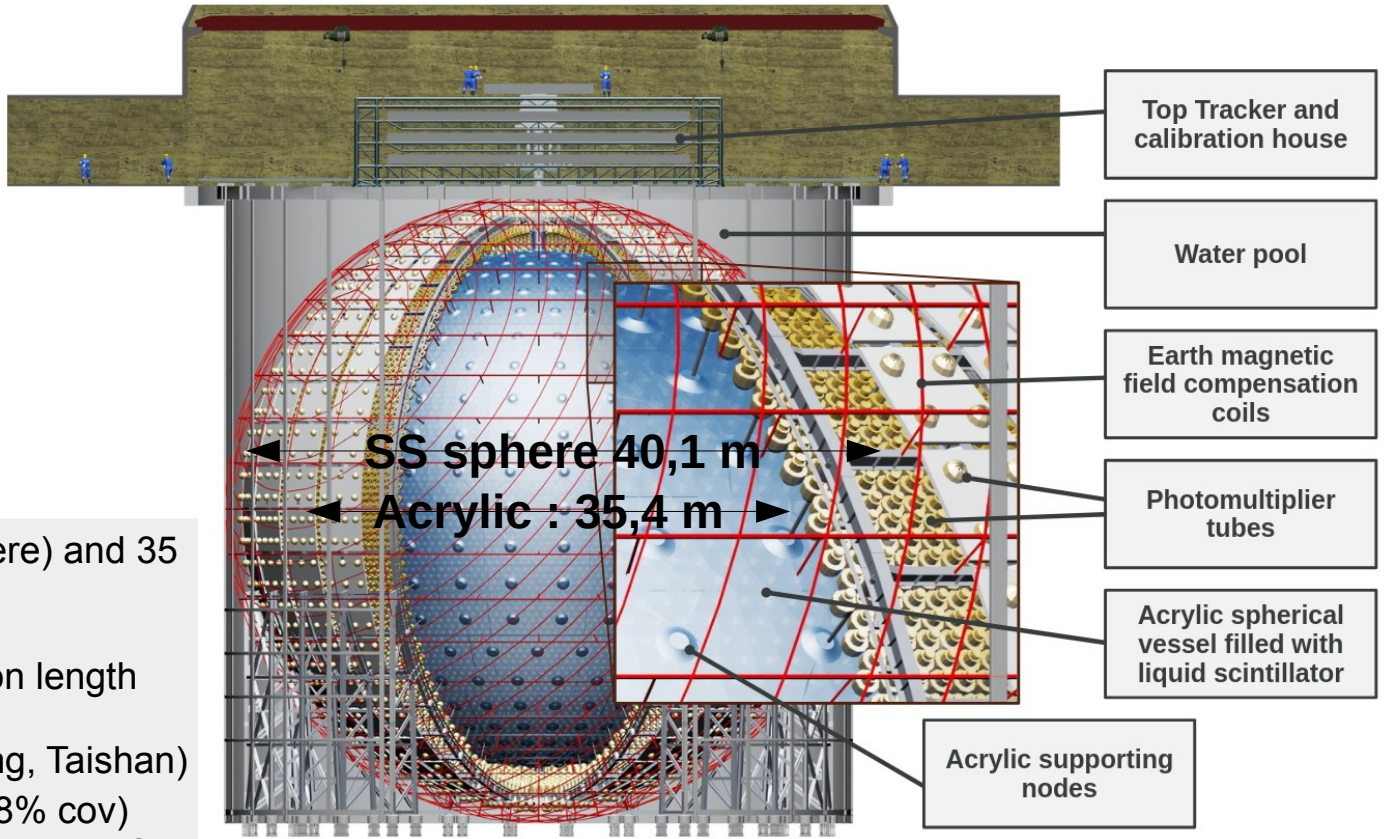
Neutrinos oscillation



After the discovering time, we are entering the neutrino oscillation parameters precision era → large detectors for increasing statistics and low systematics

JUNO

- 20 kt of liquid scintillator (acrylic sphere) and 35 kt water active muon veto (cylinder)
- 700 m of overburden rock
- 3% of resolution at 1 MeV (attenuation length >20m (430 nm))
- 26,6 GW_{th} of nuclear plants (Yangjiang, Taishan)
- PMTs : 17 612 (20'') + 25 600 (3'') (78% cov)
- TAO satellite detector 44-m away of Taishan for unoscillated spectrum

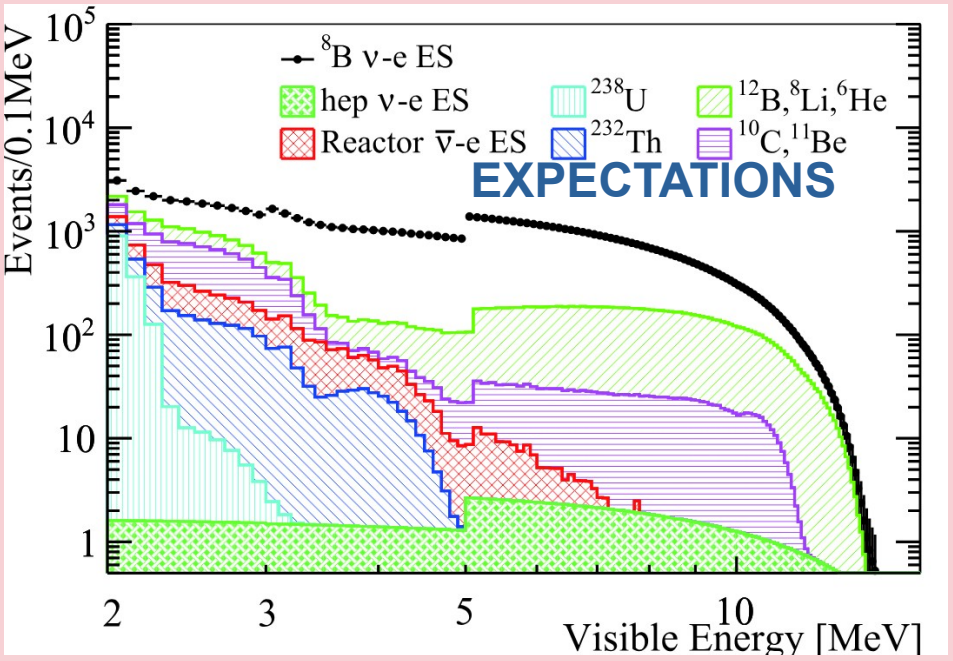


Contributions in France : IJCLab-Orsay, CENBG-Bordeaux, IPHC-Strasbourg, CPPM-Marseille, Subatech-Nantes
(Veto top trackers, 3'' PMT electronics and box)

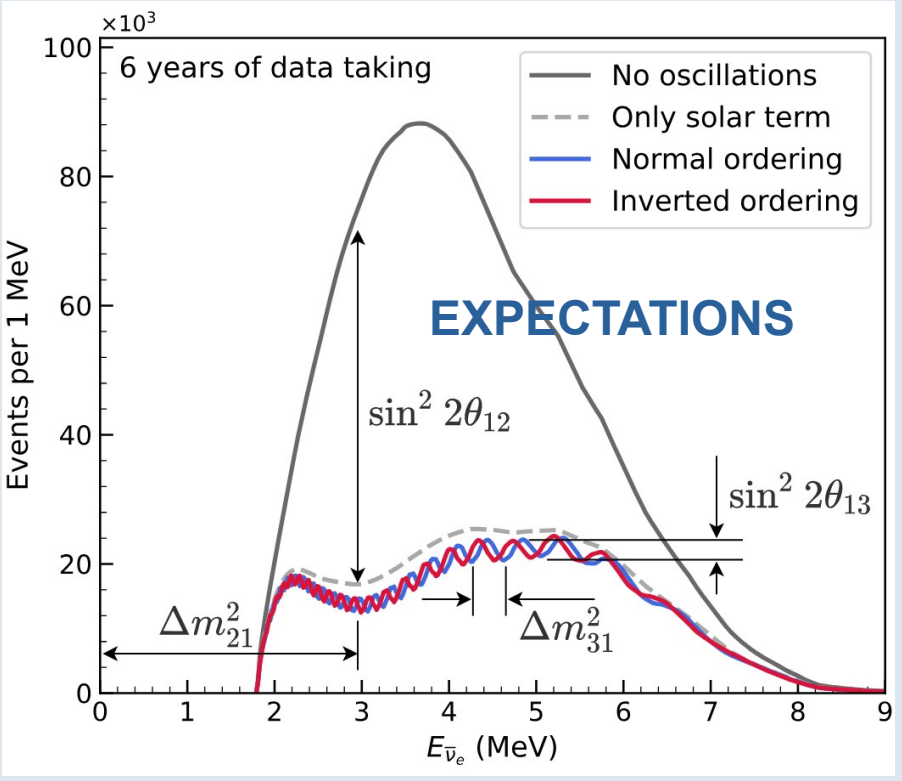
JUNO

Target :

- measuring **reactor neutrinos** via IBD (~45 ev/day)
  - → Mass hierarchy (3σ in 6 y)
  - → Δm^2_{12}, $\sin^2(2\theta_{12})$, Δm^2_{31}



Angel Abusleme et al 2021 Chinese Phys. C 45 023004

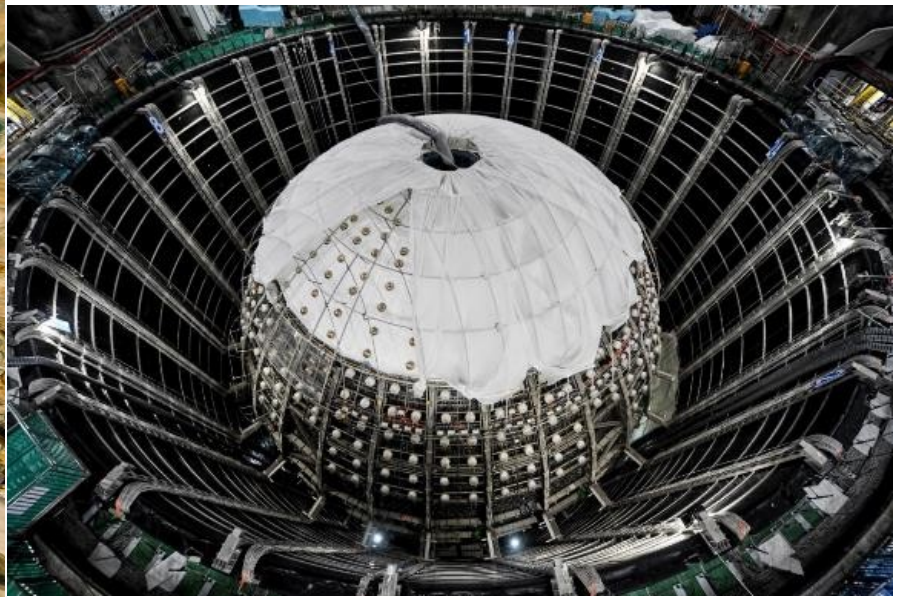


- measuring solar neutrinos via elastic scattering (~ 17 ev/day, depends on R cut)

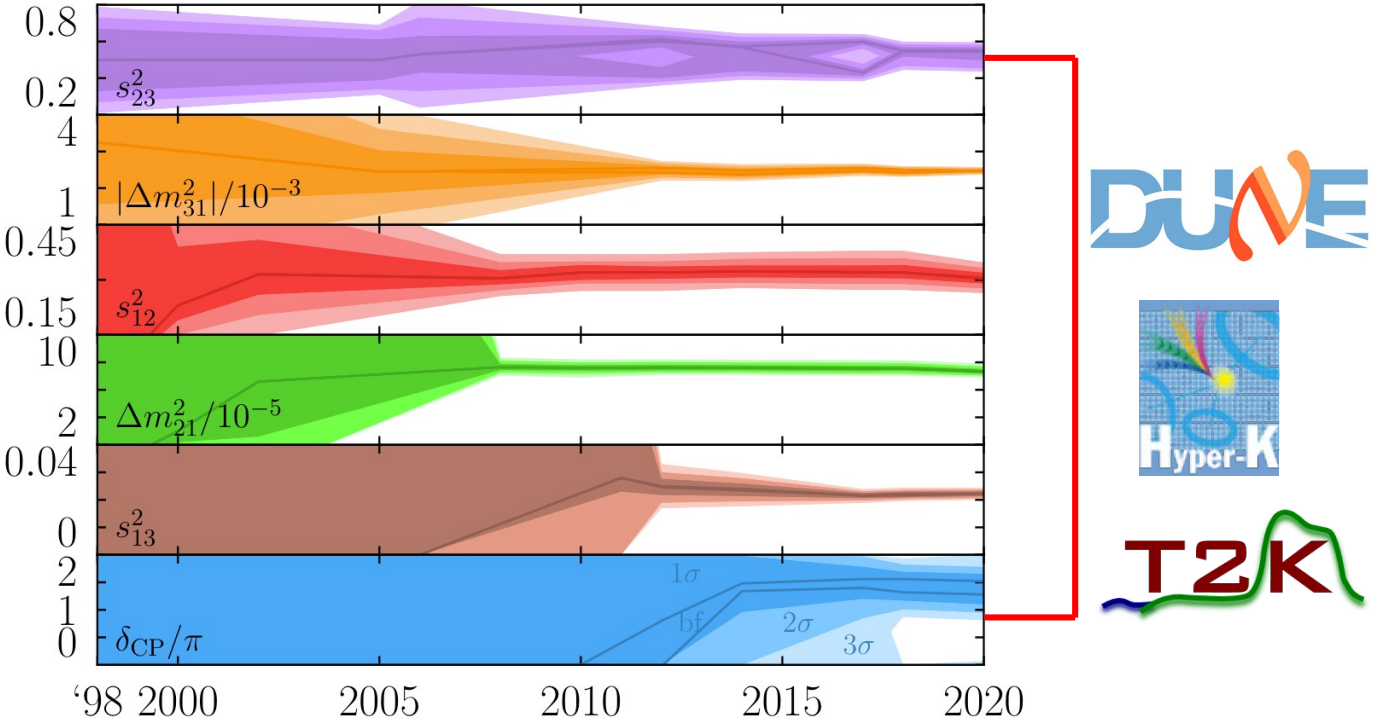
JUNO

Status :

- Excavation completed
- SS sphere built, acrylic sphere tested and installed
- Liquid purification plant commissioned
- PMTs calibrated and installed
- Filling of the sphere. Data soon



Neutrinos oscillation

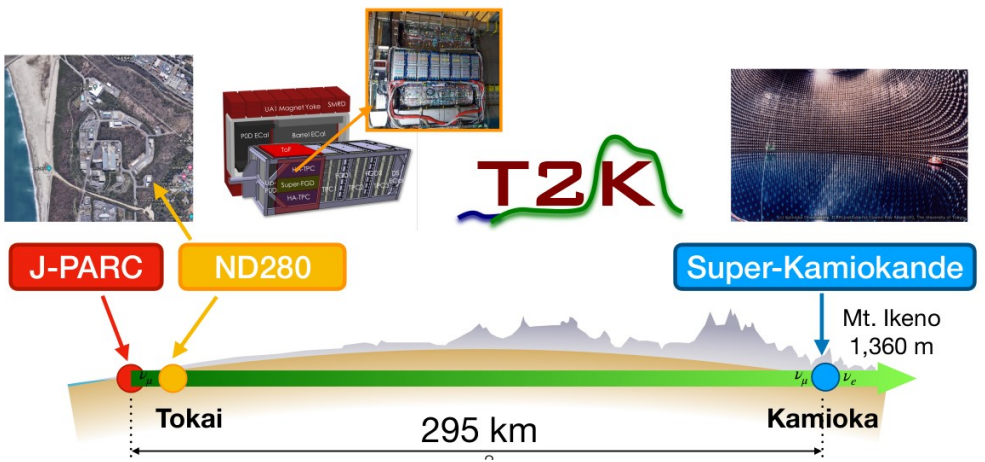


After the discovering time, we are entering the neutrino oscillation parameters precision era → large detectors for increasing statistics and low systematics

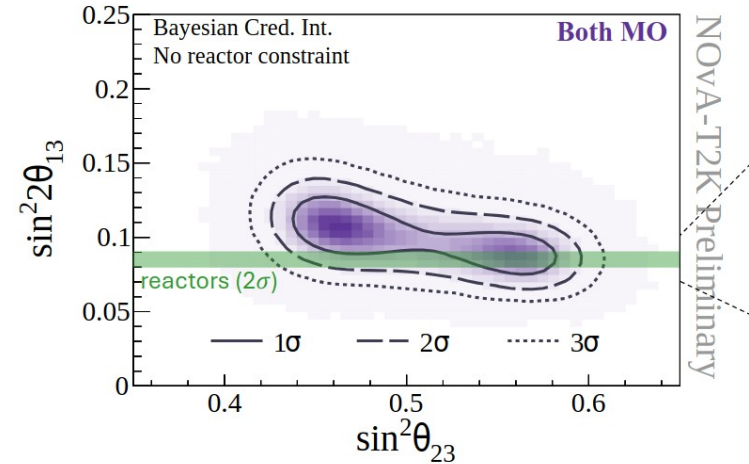
T2K

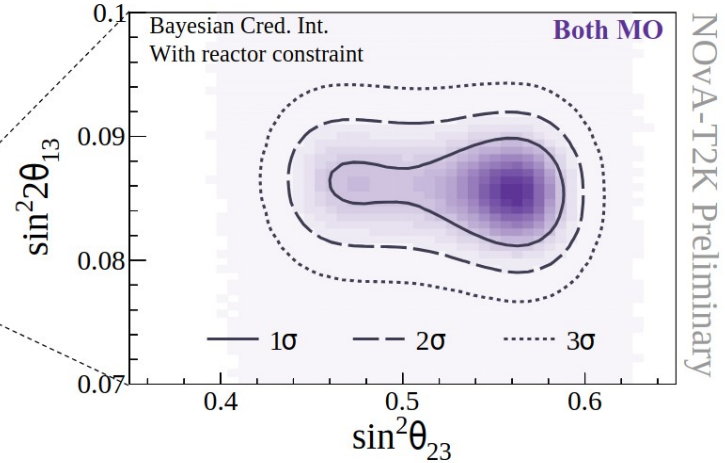
- Beam off-axis to select ~600 MeV ν_μ and $\bar{\nu}_\mu$ from J-PARC in Tokai toward SK (295 km)
- Measurement of oscillation by comparing near detector (ND280) and far detector (SK)
- Appearance of ν_e and $\bar{\nu}_e$ gives θ_{13} and δ_{CP}
- Disappearance of ν_μ and $\bar{\nu}_\mu$ gives θ_{23} and Δm^2_{32}
- Programs are over and analysis is on-going, in particular joint-fit

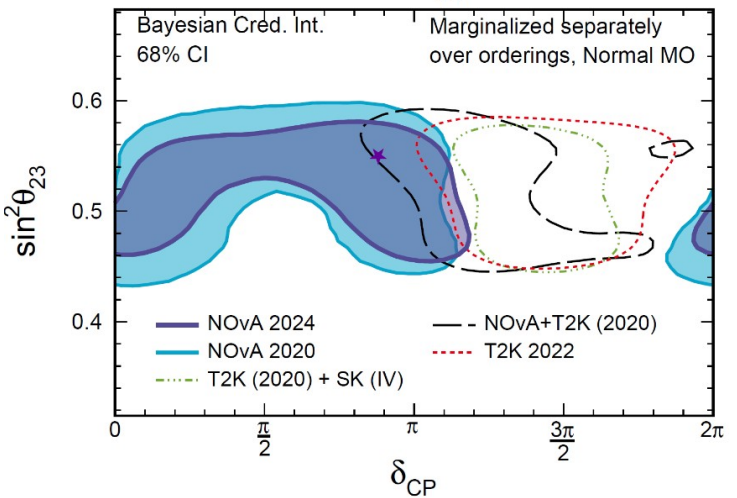
Contributions in France : LPNHE-Paris, CEA-Saclay, LLR-Palaiseau, IP2I-Lyon
(upagrade of the near detector : micromegas and electronics of HA-TPC and Super-FGD)

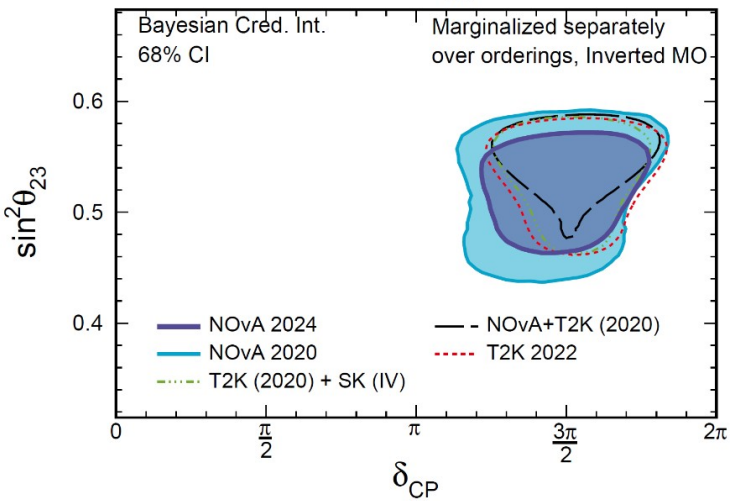


T2K


Bayesian Cred. Int.
No reactor constraint
Both MO
reactors (2σ)
1σ
2σ
3σ
$\sin^2 2\theta_{13}$
$\sin^2\theta_{23}$
NOvA-T2K Preliminary


Bayesian Cred. Int.
With reactor constraint
Both MO
1σ
2σ
3σ
$\sin^2 2\theta_{13}$
$\sin^2\theta_{23}$
NOvA-T2K Preliminary


Bayesian Cred. Int.
68% CI
Marginalized separately
over orderings, Normal MO
NOvA 2024
NOvA 2020
T2K (2020) + SK (IV)
NOvA+T2K (2020)
T2K 2022
$\sin^2\theta_{23}$
δ_{CP}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NOvA 2024
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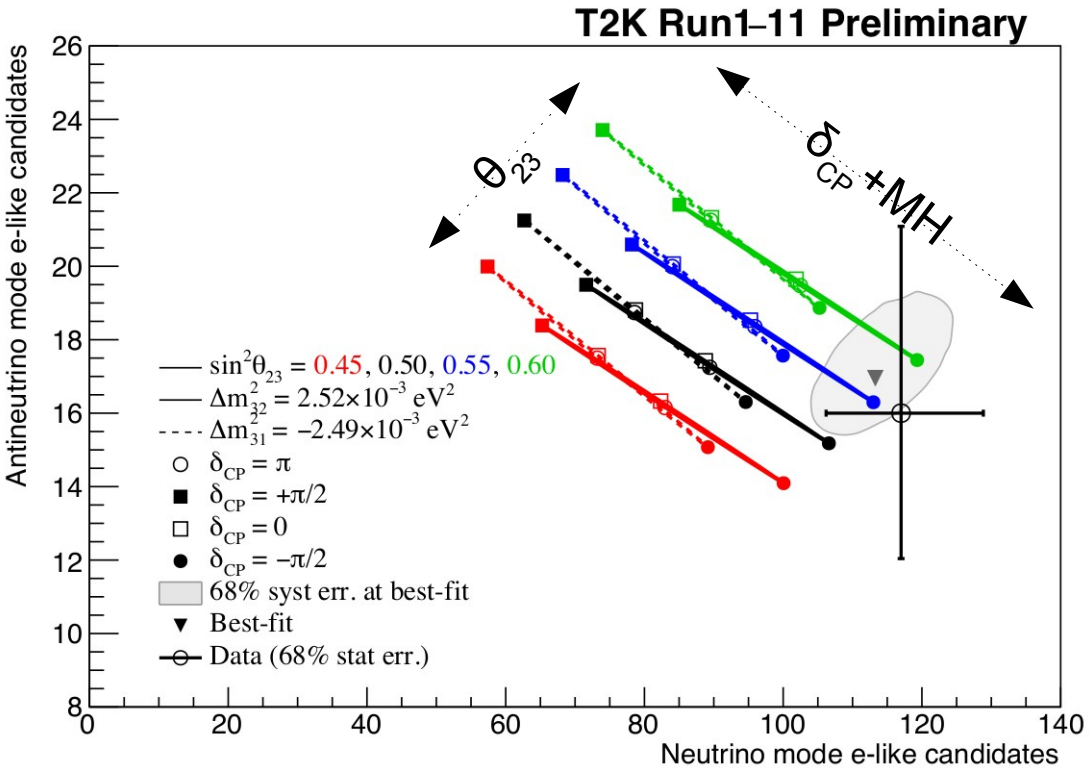
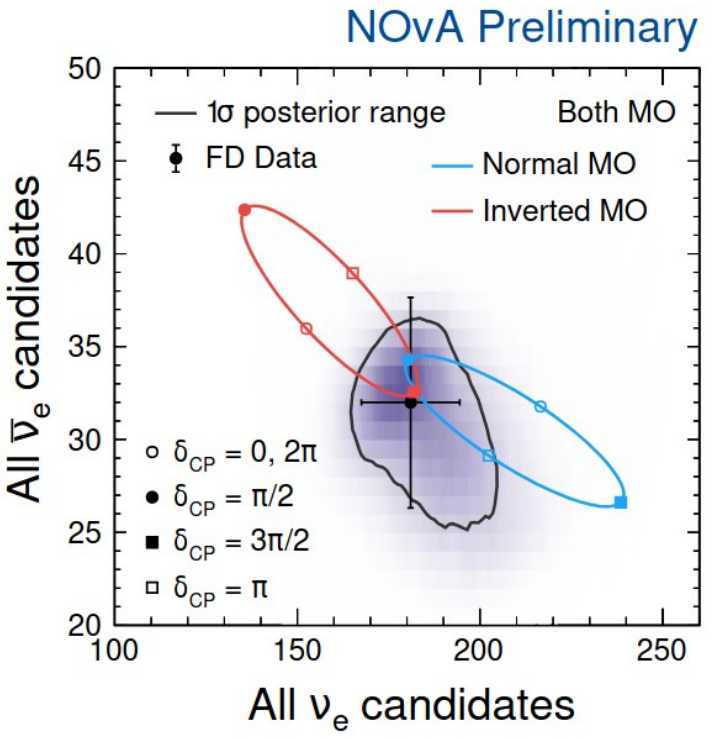
T2K 2022
$\sin^2\theta_{23}$
δ_{CP}

Neutrinos oscillation

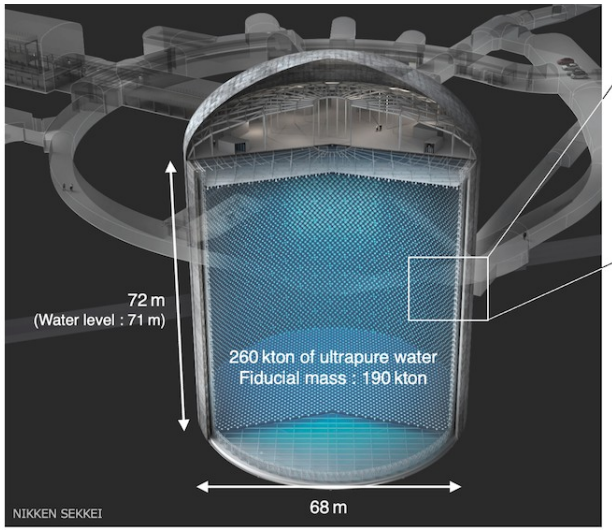
A complex problem : θ_{23}, δ_{CP} and mass hierarchy are correlated

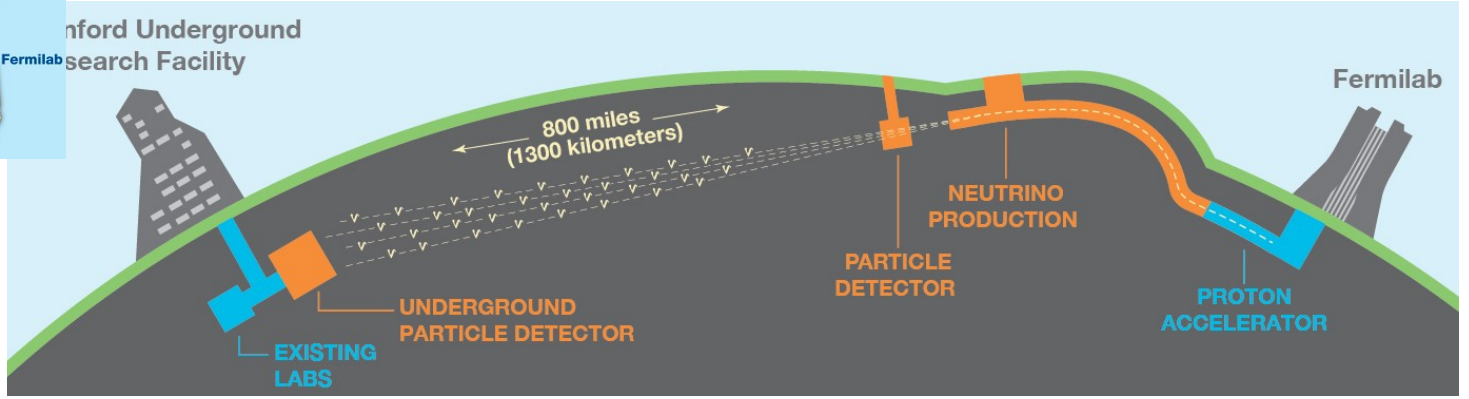




Next-gen experiments

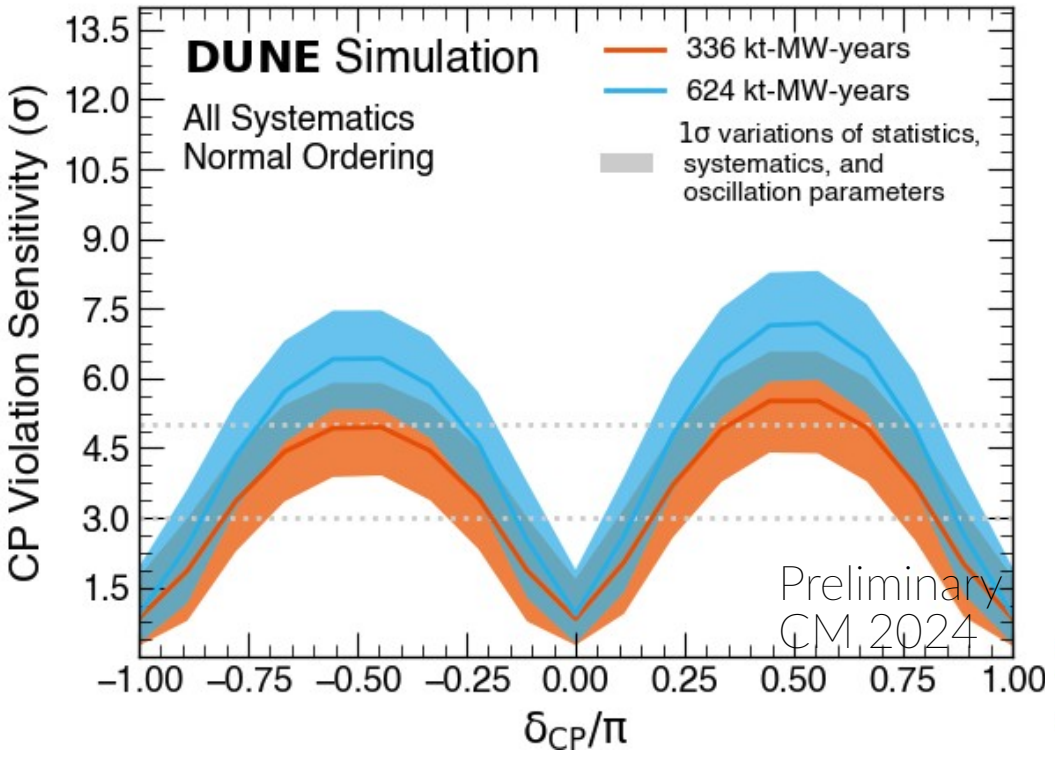
- 0.6 → 1.3 MW beam in JPARC
- HK : 190 kt (8.4xSK)
- 2.5° off-axis →780 MeV
- Starting in 2027
- Upgrade of ND280
- Cerenkov in ultrapure water
- 40 000 PMTs
- Inner/Outer detector for active veto and passive shielding
- (Gd for CCQE tagging of low energy antineutrinos? maybe)

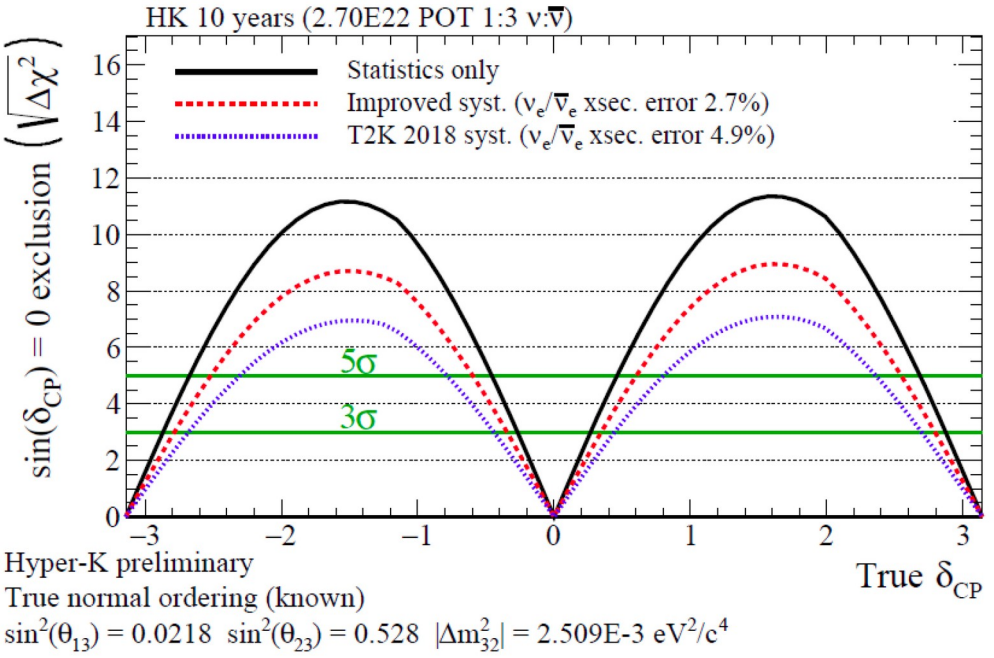




See Y. Kermaidic presentation

Measuring δ_{CP}





Next-gen experiments

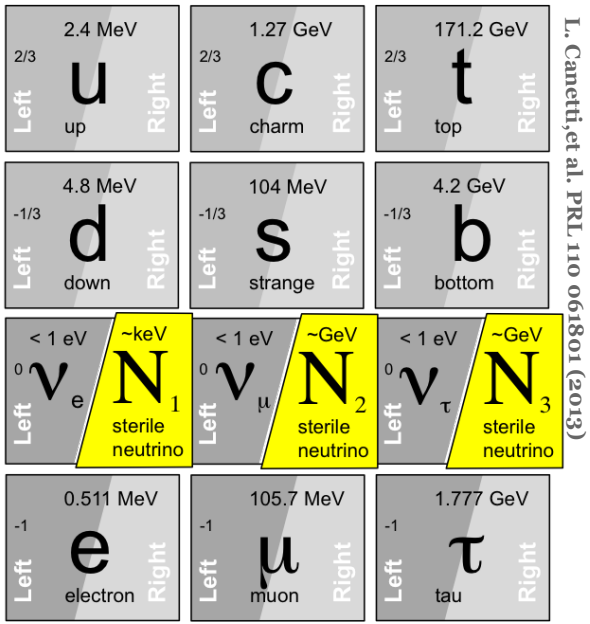
Excavation completed in Kamioka and in South Dakota
Data expected for 2027 (HK) and 2030 (DUNE)

Neutrino properties

Why do they change flavours in propagation?

What is the mass of the neutrinos?

How do we describe neutrino in SM : Majorana? Dirac?



L. Canetti,et al. PRL 110 061801 (2013)

Standard Model

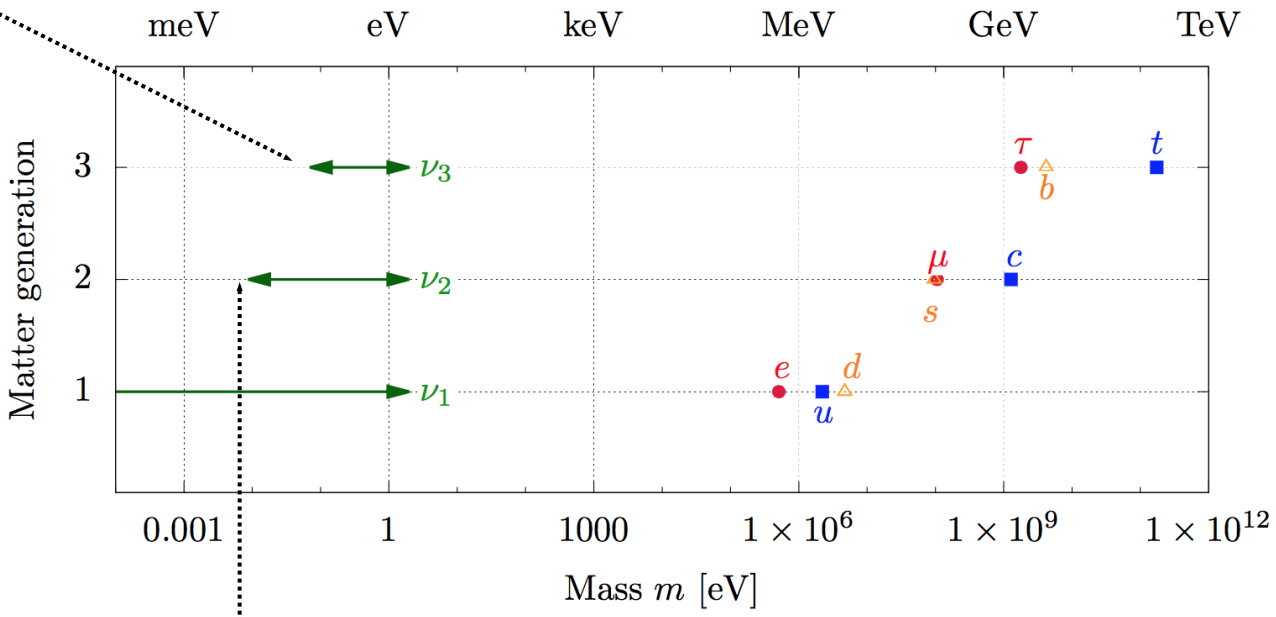
How is this mass generated? Existence of a right-handed neutrino?

Is neutrino BSM-proof? Neutrino charge radius?

Neutrino mass

51 meV

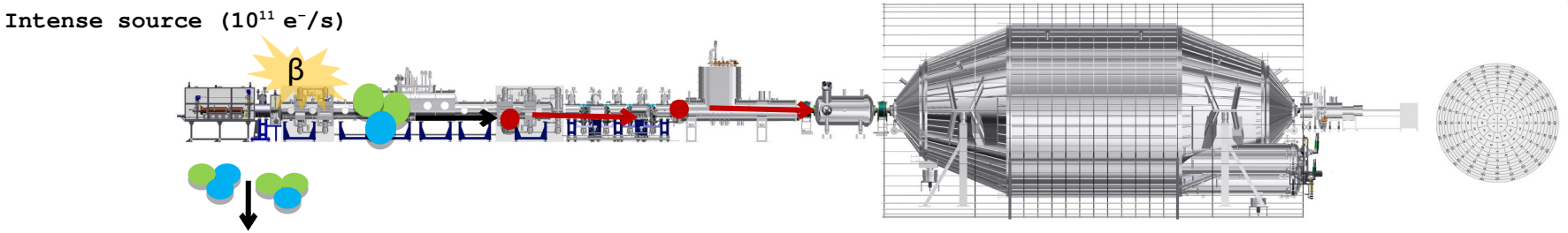
$$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2} \quad +2.515^{+0.028}_{-0.028}$$

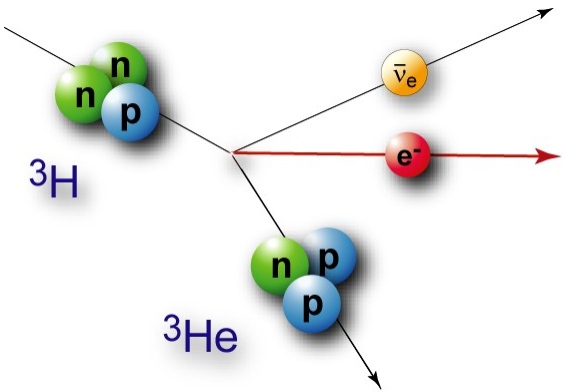


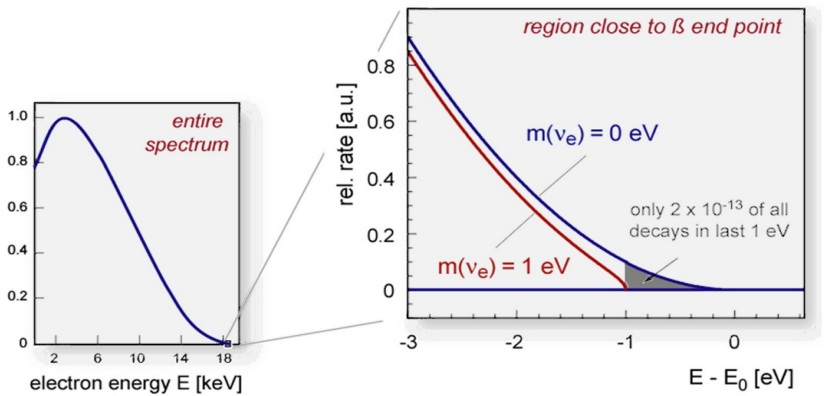
$$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2} \quad 7.42^{+0.21}_{-0.20}$$

8.6 meV

Neutrino mass



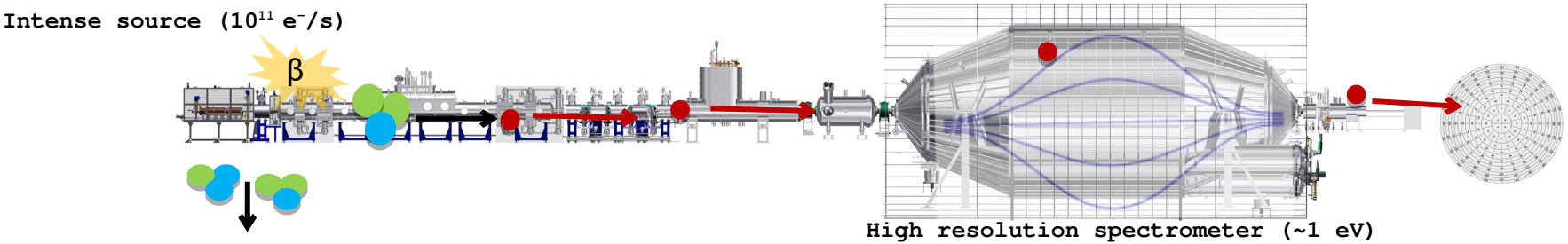


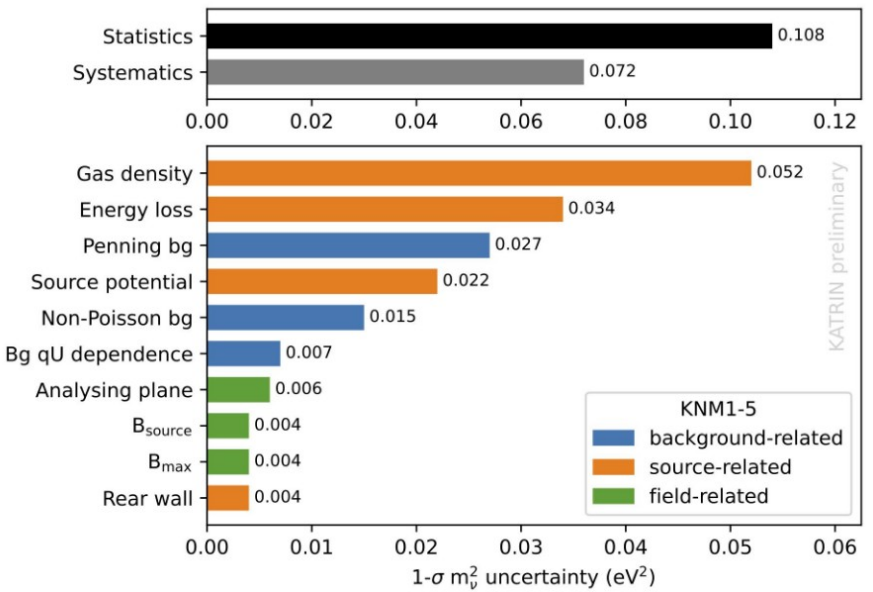


- Ultra-strong β-source 10^{11} decays/s
- Low background level < 0.1 cps
- Excellent energy resolution ~ 1 eV
- Precise understanding of spectrum

Contribution in France : CEA-Saclay (data analysis)

Neutrino mass



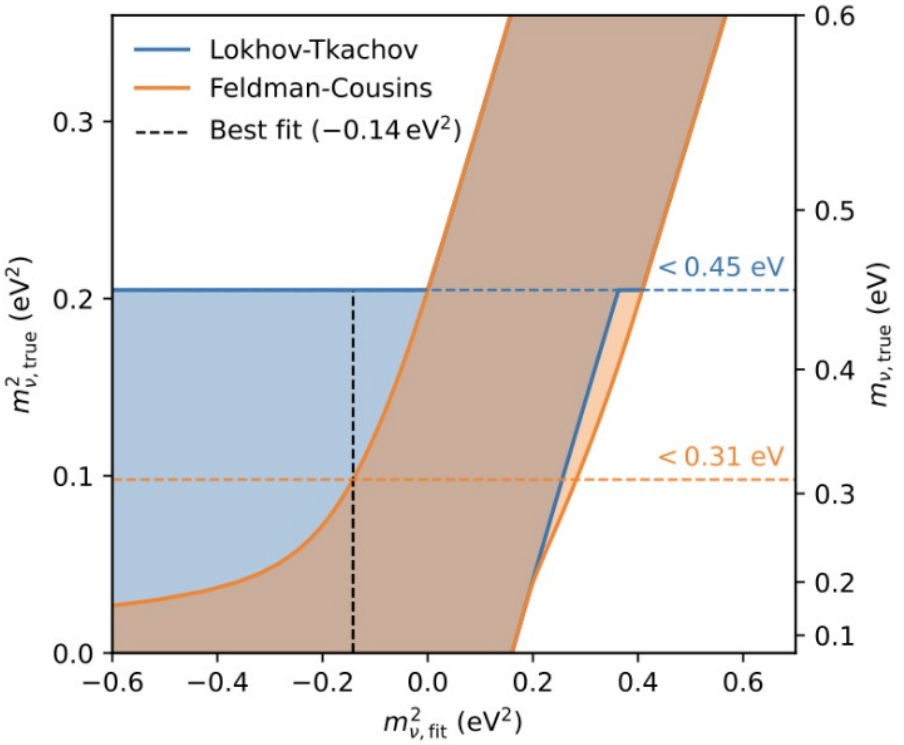


Neutrino mass

- Sensitivity of result dominated by statistics.
- Simultaneous maximum likelihood fit with common m_ν^2 parameter.
- Excellent goodness-of-fit: p-value=0.84
- Best-fit value: $m_\nu^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$

  → Negative m_ν^2 estimates allowed by the spectrum model to accommodate statistical fluctuations.
- KATRIN's new upper limit:

$$m_\nu < 0.45\,\mathrm{eV}\ (90\,\%\ \mathrm{CL})$$



From Thierry Lasserre (CEA/MPIK), IRN Neutrino 2024

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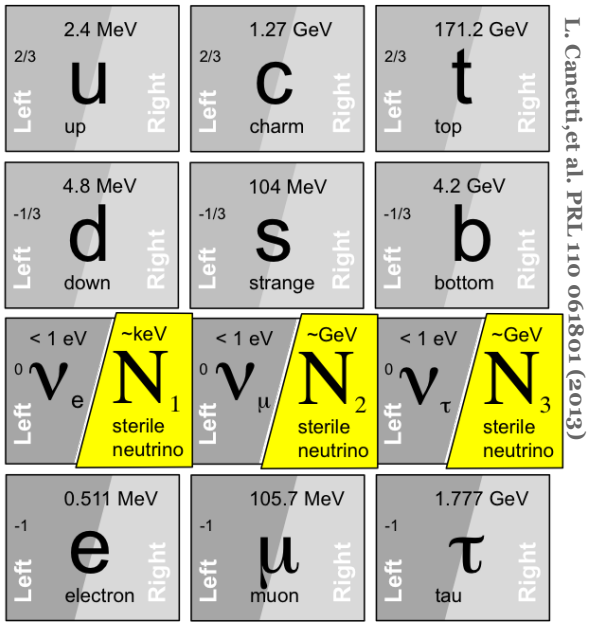

L. Canetti,et al. PRL 110 061801 (2013)

Standard Model

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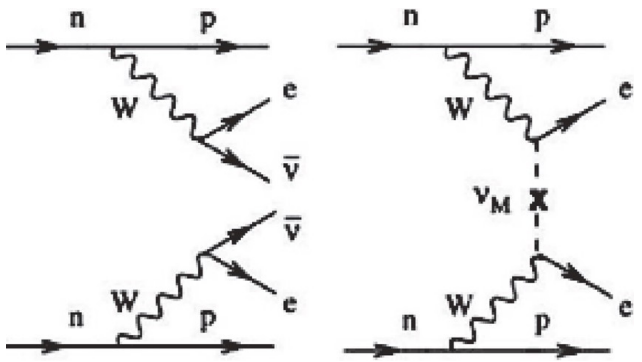
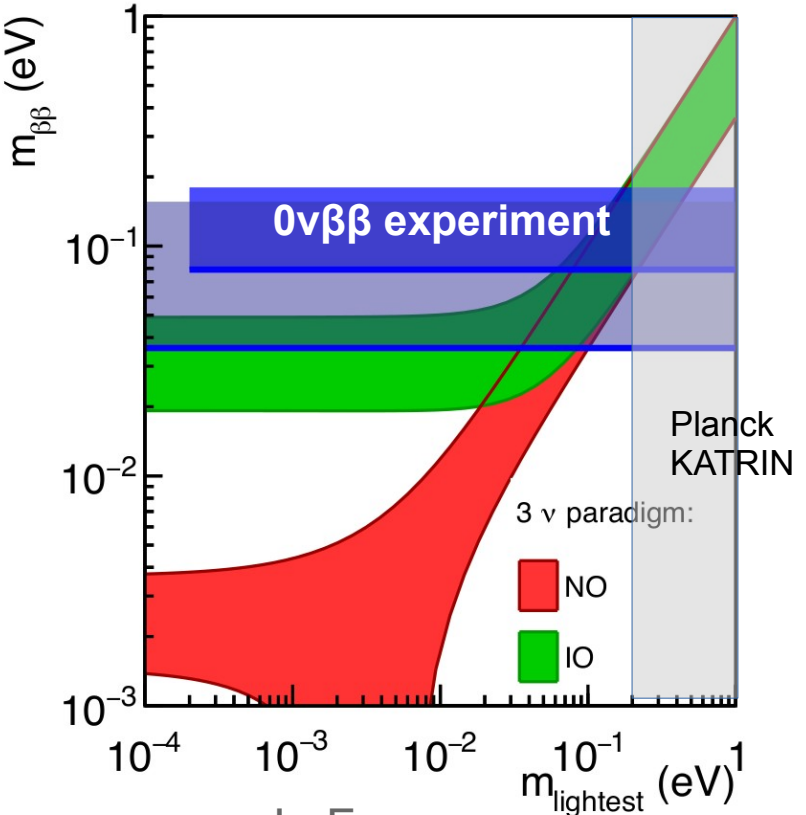
Neutrino nature - 0νββ

Nature of the neutrino : Dirac, Majorana, composit
link with how to write a mass term in the SM Lagrangian



$$\left({}^{0\nu}T_{1/2}\right)^{-1} \propto |M^{0\nu}|^2 m_{\beta\beta}^2$$

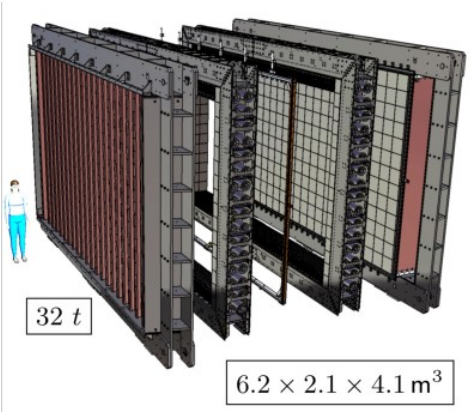
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

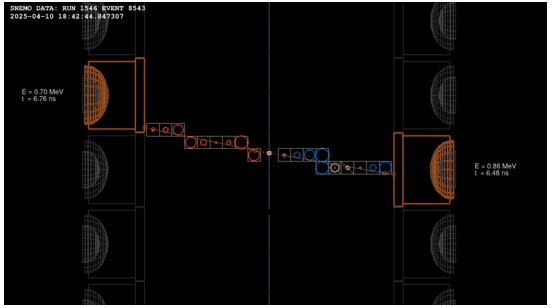


In France :
→ CUORE/CUPID
→ SuperNEMO

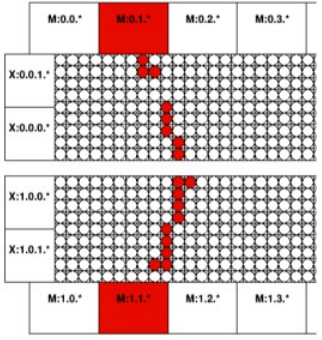
SuperNEMO

- **Multi-isotope approach with thin foils**
- Important know-how in case of discovery by other experiments
  fine decay topology available (single electron spectrum/ang. dist.)
- Background mitigation by factor 30 w.r.t. NEMO-3
- Energy resolution : 8% @ 1 MeV
- Mass : 7 kg of ^{82}Se
- Demonstrator installation/commissioning at LSM
  - Traco-calo detector is operational
  - Background reduction setup (Ra, γ, n) to come in 22'

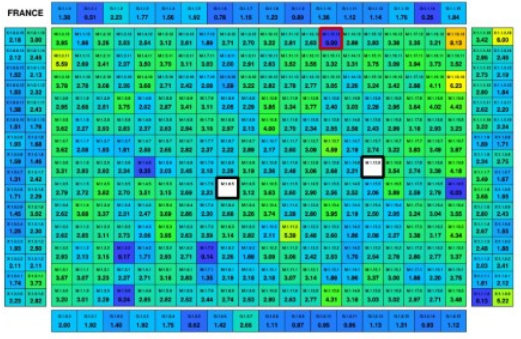




tracker



calorimeter

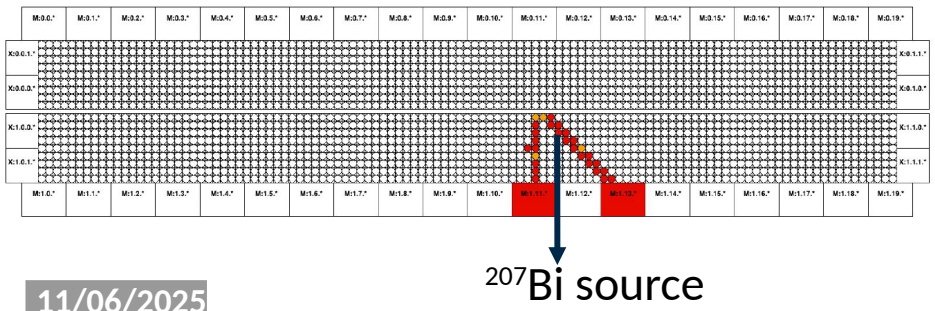


SuperNEMO

Status :

- Shielding is ready
  - iron shield for gammas,
  - polyethiylen (4 faces) shield for neutron
  - water shield (2 faces) for neutron
- Helium recycle system ready
- Waiting for radon gaz extraction facility
- Data expected this year

Time resolution measurement with the optical sensors

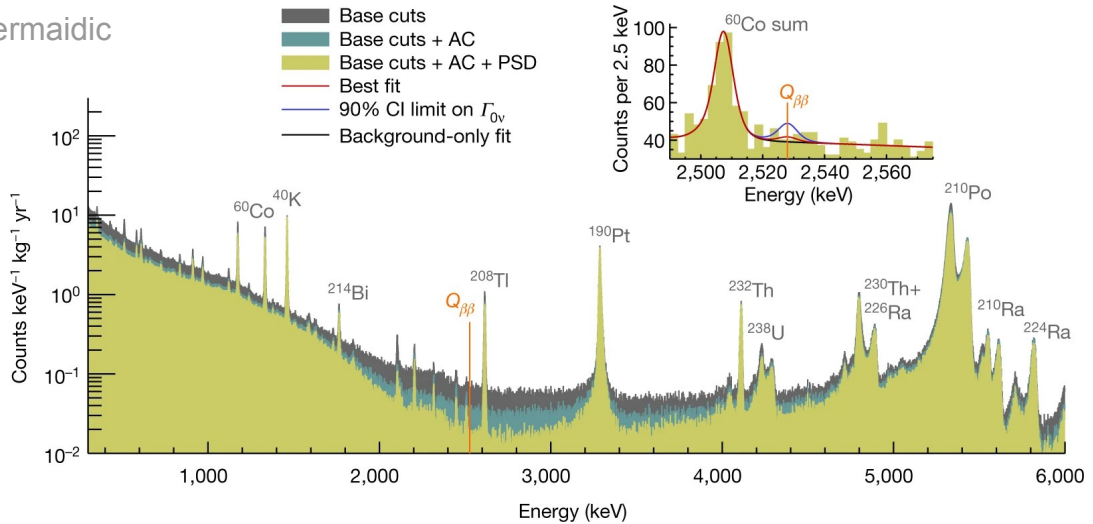


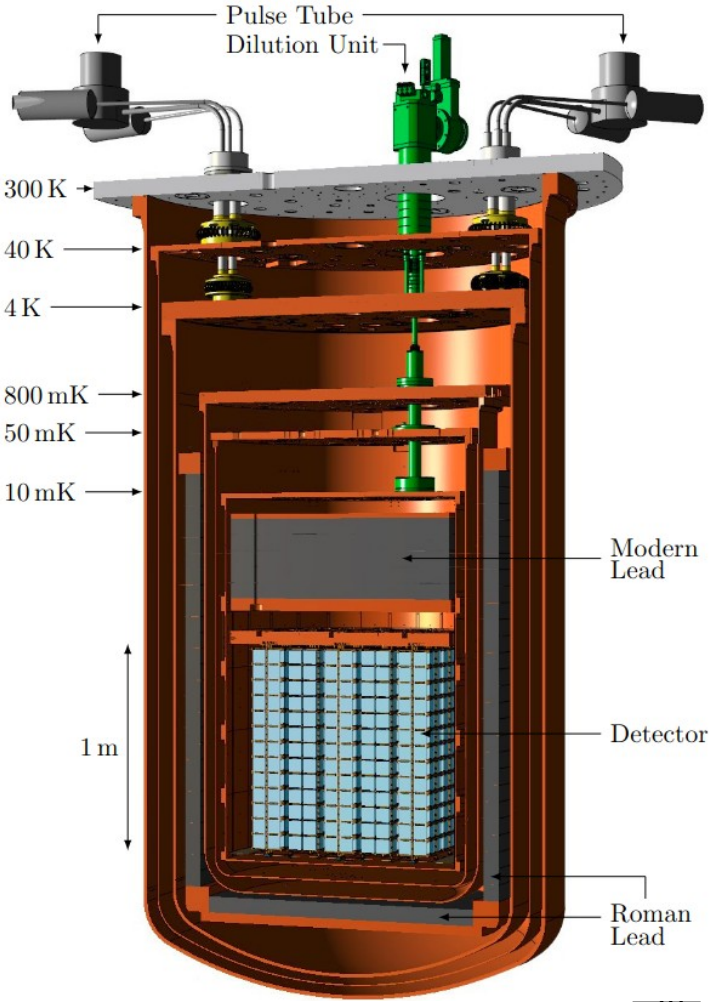
Contributions in France:
IJCLab-Orsay, LP2I-Bordeaux, LPC-Caen, CPPM-Marseille
LAPP-Annecy
(Calorimeter design and construction,
integration of the demonstrator at LSM Modane,
commissionning and data analysis)

CUORE/CUPID

- ^{130}Te $Q_{\beta\beta} = 2528$ keV - $T^{2\nu}_{1/2} \sim 8 \times 10^{20}$ yr
- 988 TeO_2 crystals with an active mass of 206 kg
- Natural abondance: 35% - no enrichment
- **Largest mK cryostat in the world**
- Very good energy resolution : 7.8 keV FWHM @ $Q_{\beta\beta}$
- $T^{0\nu}_{1/2} > 0.2 \times 10^{26}$ yr $-$ $m_{\beta\beta} < [90 - 305]$ meV (90% C.L.) with 1038.4 kg.yr
- **Stable operation of the cryostat demonstrated in 2021**
  continue the data taking while waiting for CUPID
- Problematic α/γ background → active veto needed (CUPID)

Credit : Y.Kermaidic



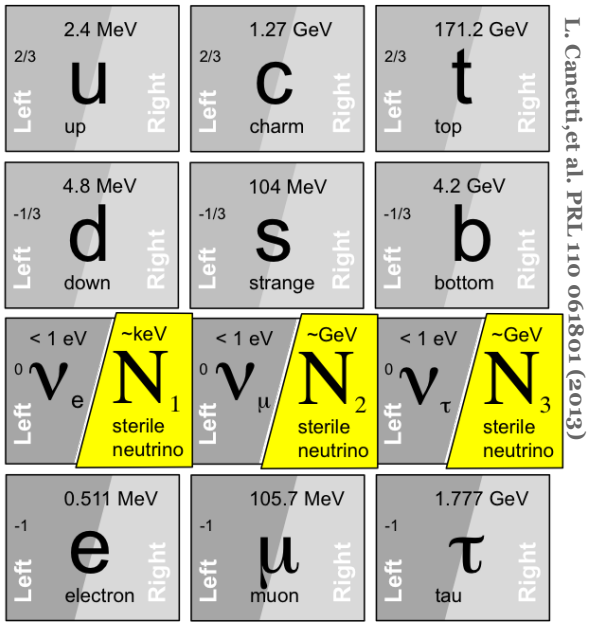


Neutrino properties

Why do they change flavours in propagation?

What is the mass of the neutrinos?

How do we describe neutrino in SM : Majorana? Dirac?



L. Canetti,et al. PRL 110 061801 (2013)

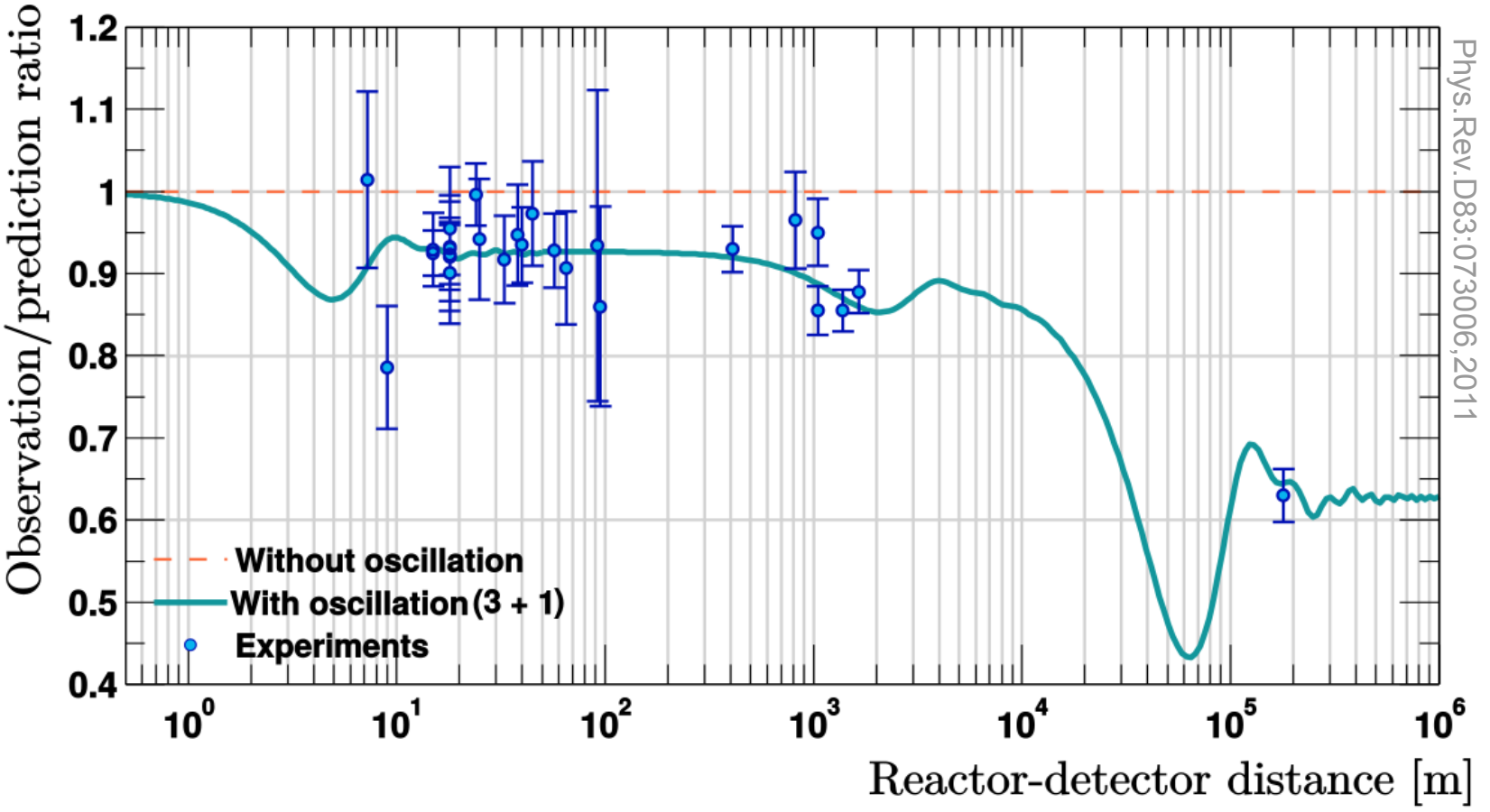
Standard Model

How is this mass generated? Existence of a right-handed neutrino?

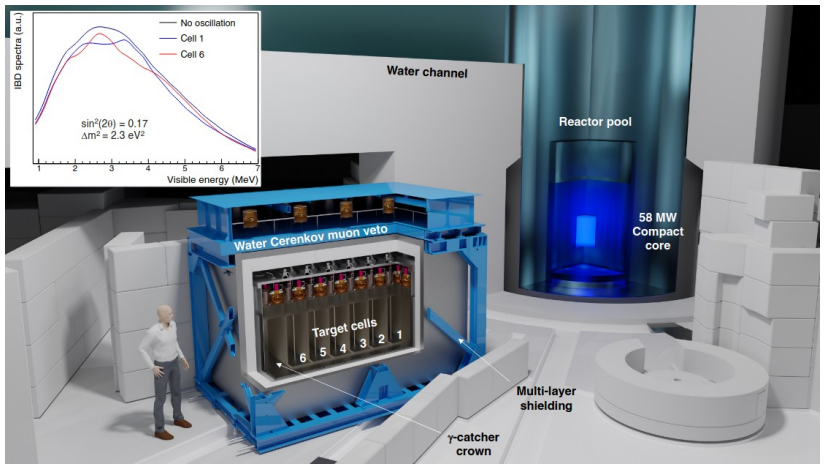
Is neutrino BSM-proof? Neutrino charge radius?

eV-sterile neutrino

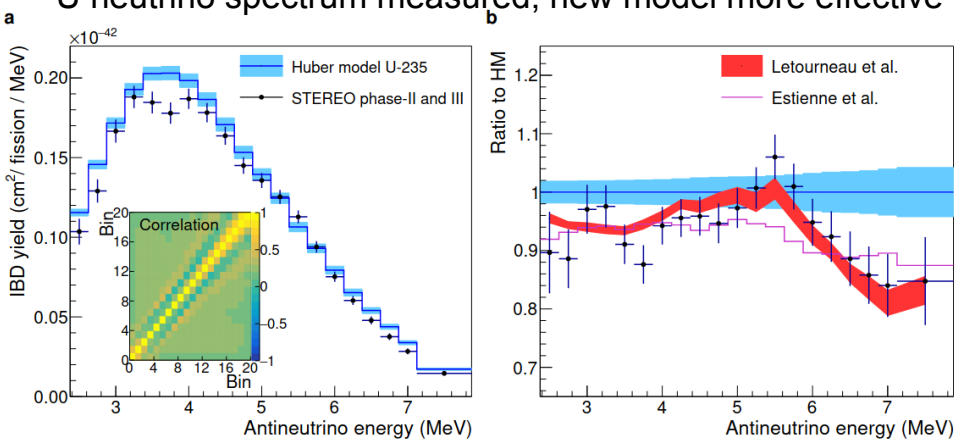
The Reactor Antineutrino Anomaly

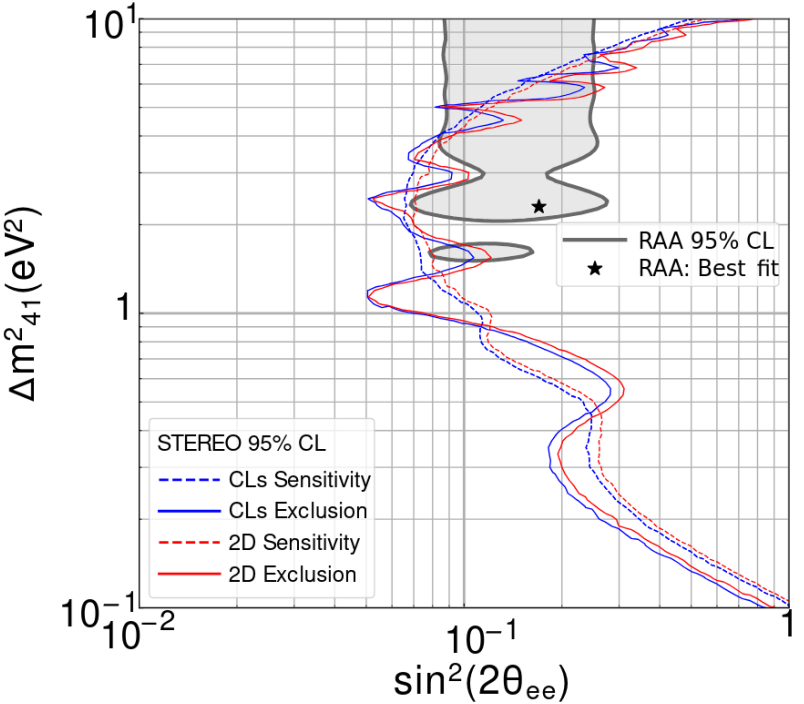


STEREO



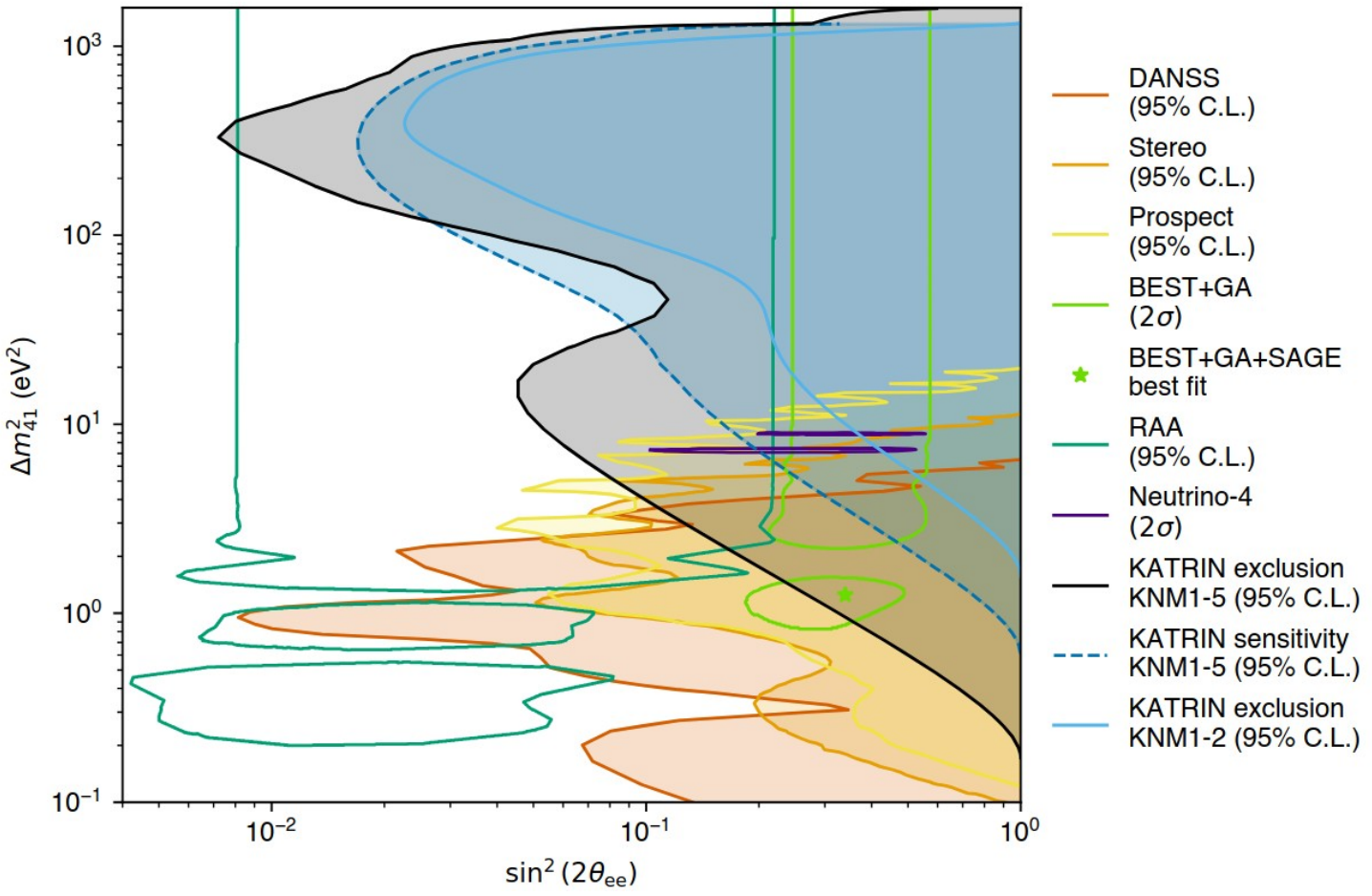
^{235}U neutrino spectrum measured, new model more effective



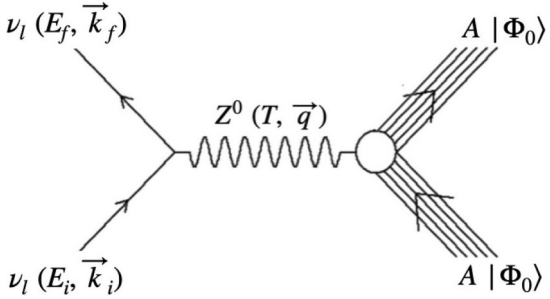


Contributions in France :
LPSC-Grenoble, LAPP-Annecy,
CEA-Saclay, LPNHE-Paris, LP2I-Bordeaux
(Design, construction, analysis)

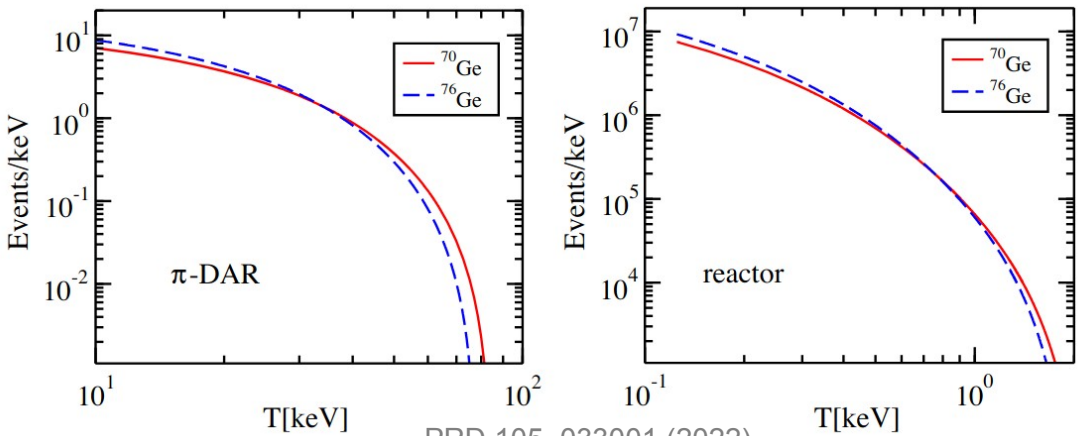
STEREO+KATRIN



CEvNS

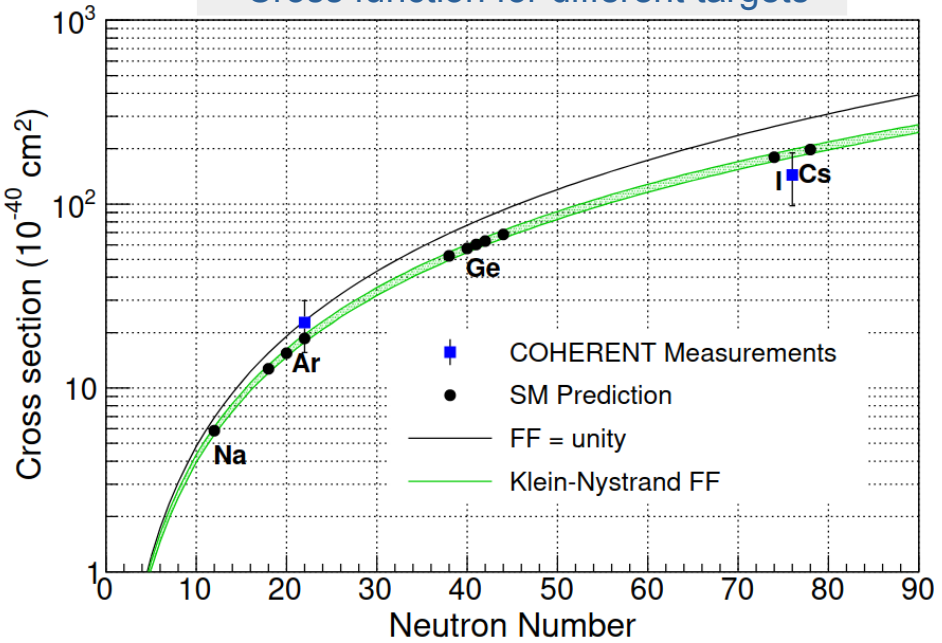


Rate as a function of recoil energy threshold



PRD 105, 033001 (2022)

Cross function for different targets



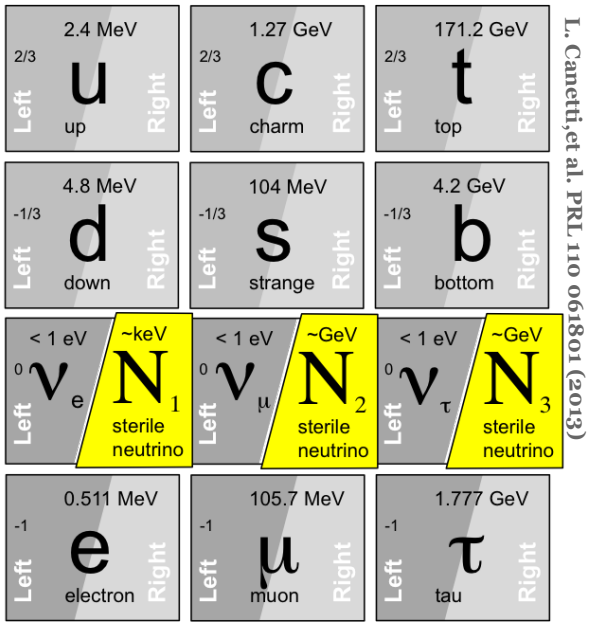
In France :
→ Ricochet
→ Nucleus

Neutrino properties

Why do they change flavours in propagation?

What is the mass of the neutrinos?

How do we describe neutrino in SM : Majorana? Dirac?



L. Canetti,et al. PRL 110 061801 (2013)

How is this mass generated? Existence of a right-handed neutrino?

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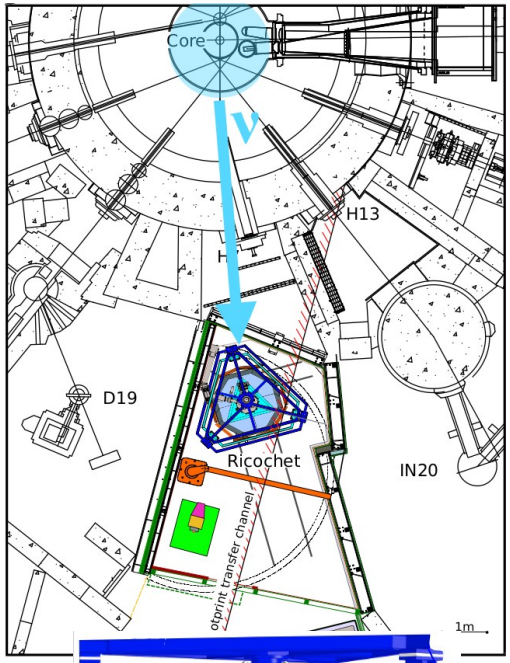
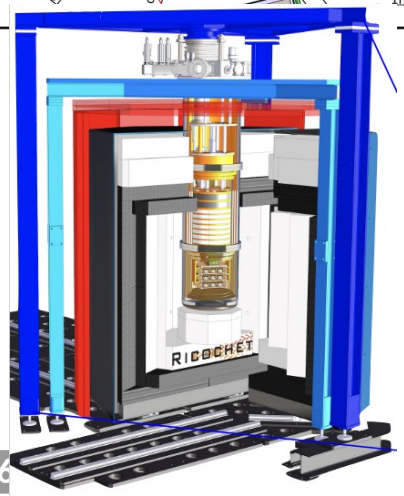
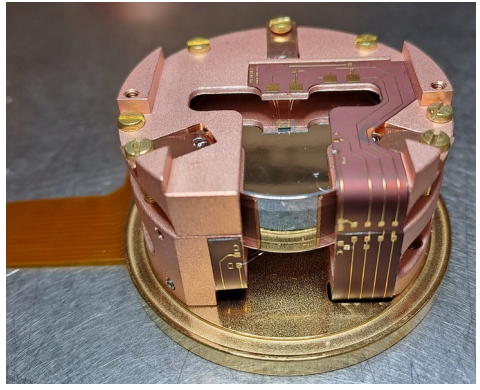
Ricochet

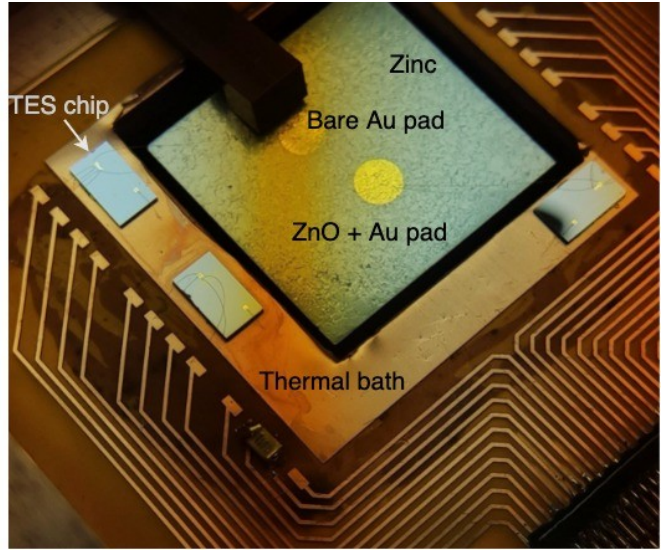




Located at ILL, Grenoble.
Expected CevNS rate : ~ 11 evts/day/kg (above 50 eV)
Passive+active shielding+vacuum cryostat (10 mK)
2 different technologies explored :

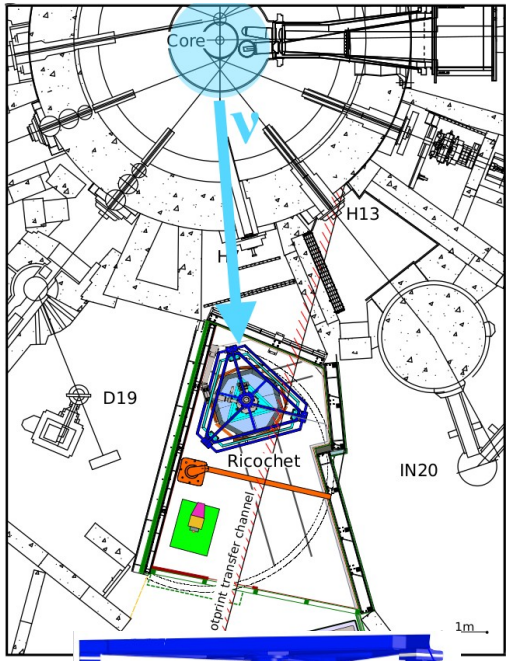
- Cryocubes (Germanium, I&Q)
- Q-array (supraconducting Zinc, PSA)

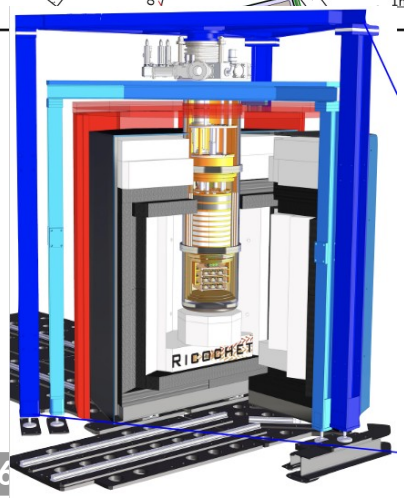




Contributions in France : IP2I-Lyon, LPSC-Grenoble

Ricochet





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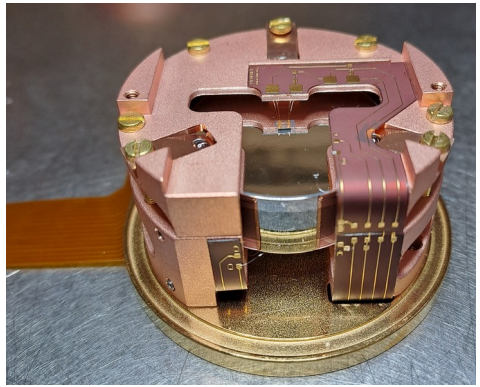
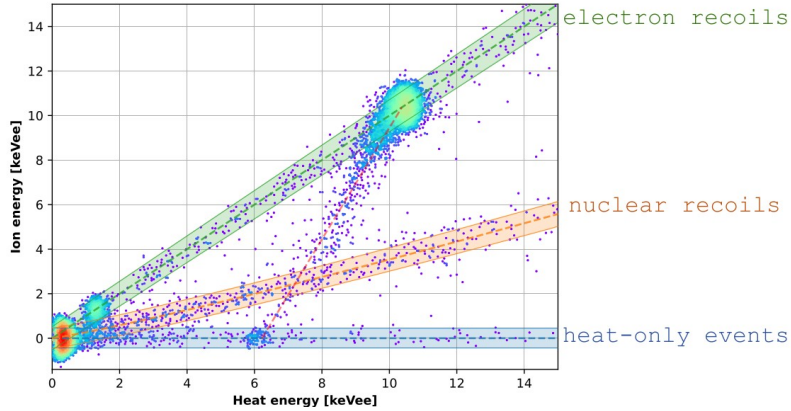
What are the cryocubes :

- 1 layer of 42-g of Germanium
- Ionisation and heat signal
- 9 existing in 3 cryocube, a full array of 17 ready for Summer





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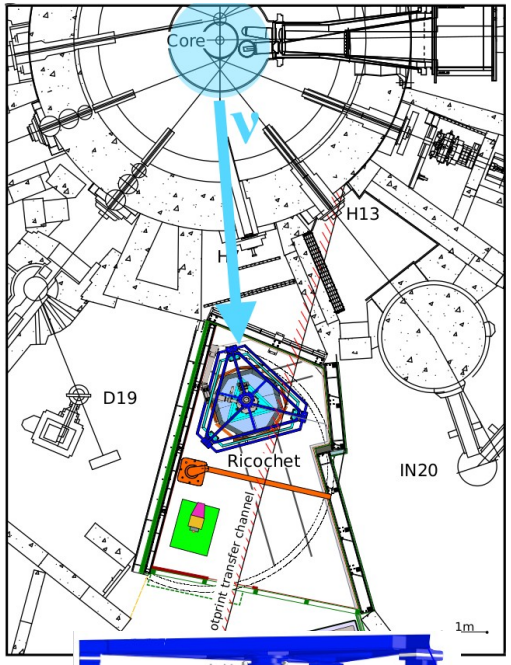

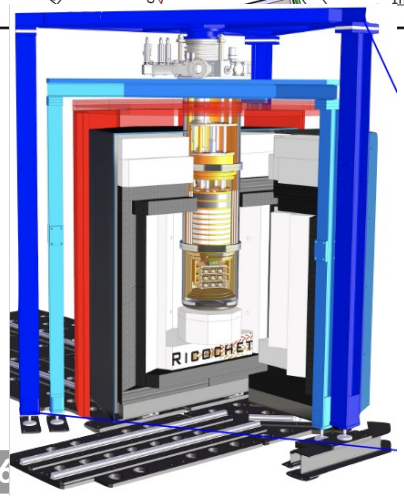

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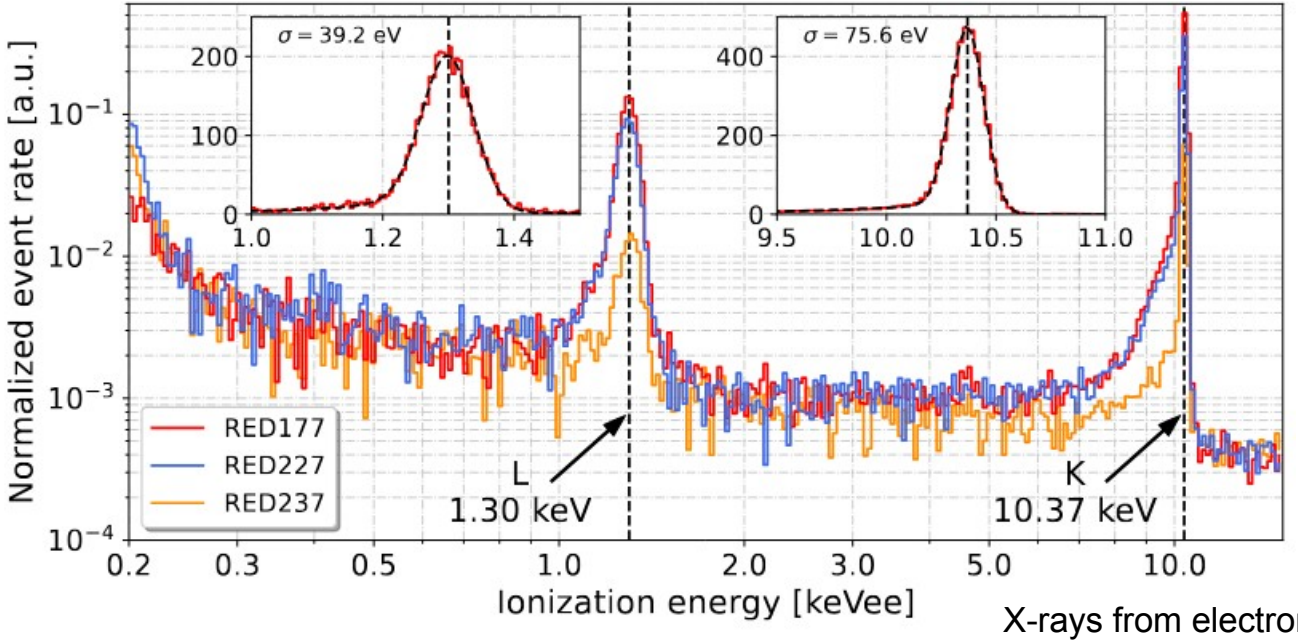
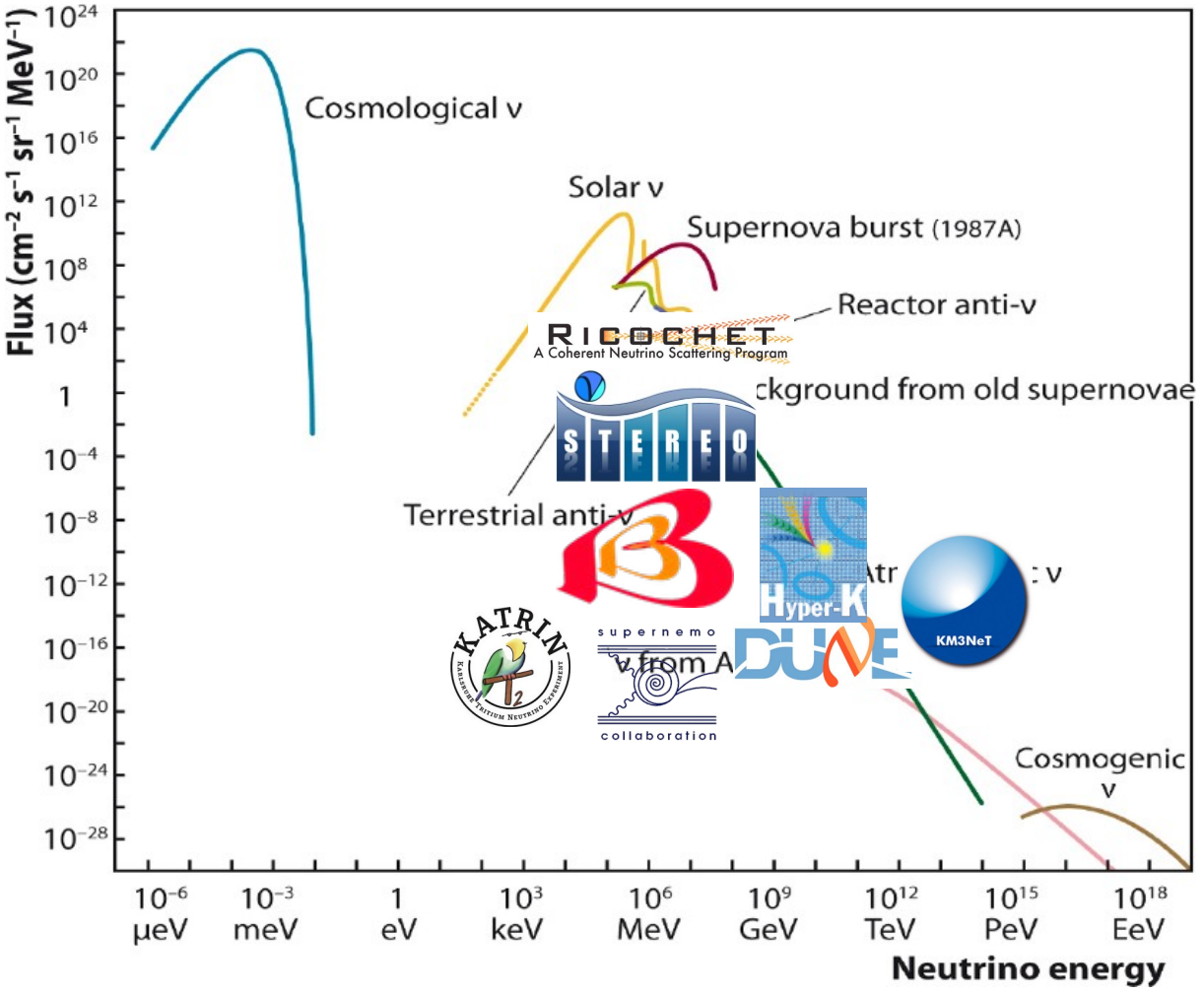


X-rays from electron capture decay of ^{71}Ge

Conclusion


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
RICOCHET
A Coherent Neutrino Scattering Program
ckground from old supernovae
STEREO
Terrestrial anti-ν
Hyper-K
KM3NeT
DUNE
KATRIN
supernemo
collaboration
Cosmogenic
ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy


Thank you