QSFP 2021 – Experimental Neutrino Physics

Lecture 3

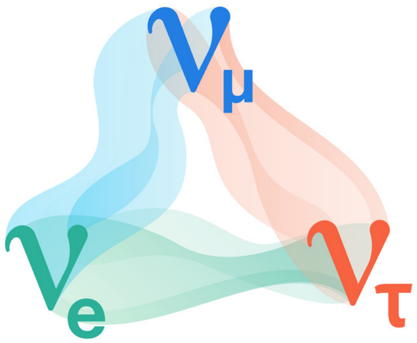
September 17, 2021

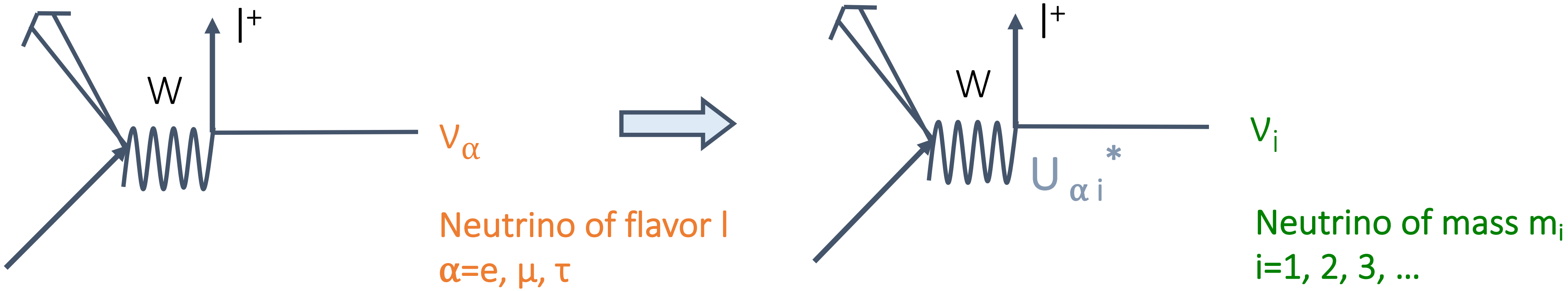
Thierry Lasserre – CEA - Saclay

Email: thierry.lasserre@cea.fr

Established Neutrino Physics

- 3 flavor ν_e, ν_μ, ν_τ, spin ½, neutral, left handed, σ(1 MeV)≈10^{-44} cm^2
- Tiny masses: 0.04 eV < m_ν < ≈ 1 eV
- Flavor mixing: two views on W-decay:





- Flavor mixing: PMNS matrix U: $|\nu_i\rangle = \Sigma\, U_{\alpha i}\, |\nu_\alpha\rangle$

3ν Oscillation Formalism

Atmospheric | Cross-Mixing | Solar | Majorana CP phases (L violating processes)

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

PMNS mixing matrix

$\theta_{23}\ \sim 45°$: "atm." angle | $\theta_{13}\ \sim 9°$ | $\theta_{12}\ \sim 34°$: "solar" angle

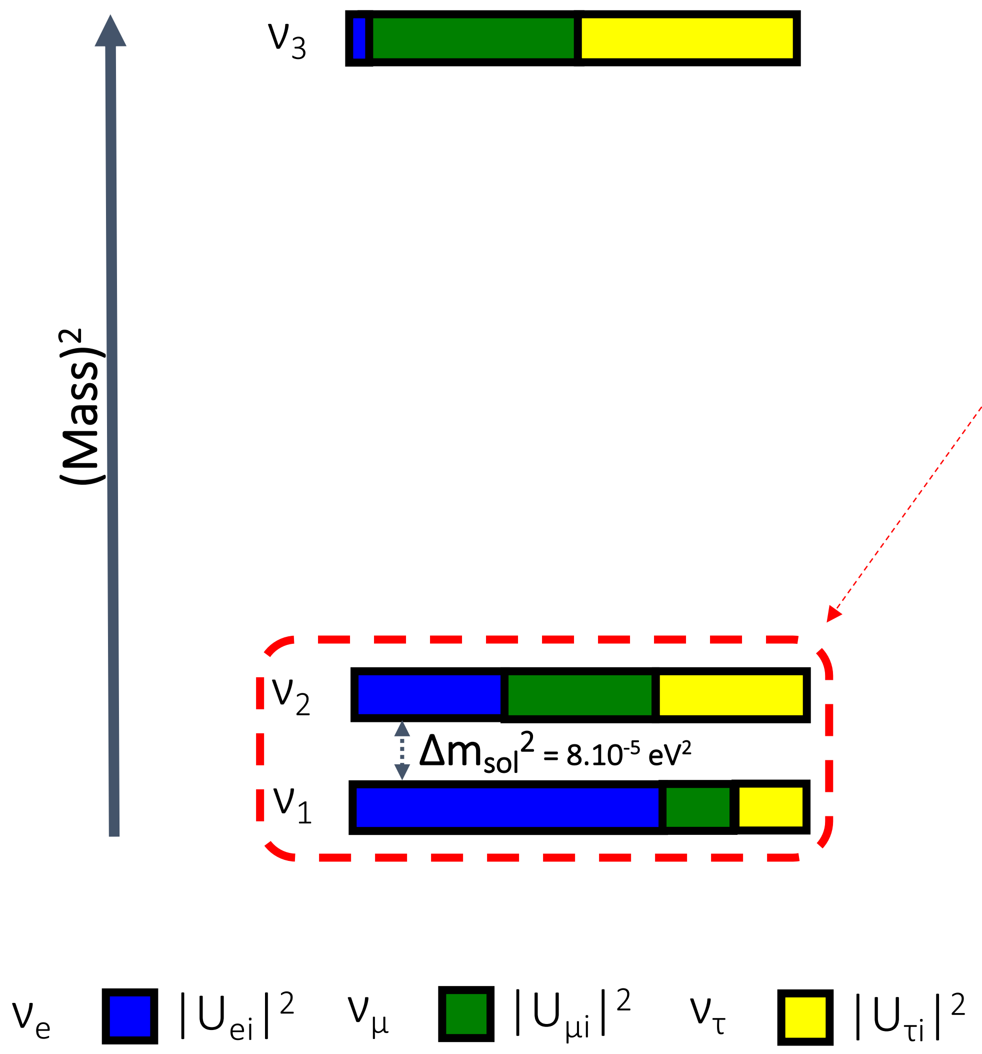
δ dirac CP phase

- 3 masses $m_{1,2,3}$: $\Delta m^2_{sol} = m_2^2 - m_1^2 \sim 8\ 10^{-5}\ eV^2$ & $\Delta m^2_{atm} = |m_3^2 - m_1^2| \sim 2\ 10^{-3}\ eV^2$
- Oscillation in vacuum : $P(\nu_x \to \nu_x) \approx 1 - \mathbf{sin^2(2\theta_i)} \times \sin^2\left(1.3 \cdot \boldsymbol{\Delta m_i^2} \cdot \frac{\mathbf{L}}{\mathbf{E}}\right)$

tunable

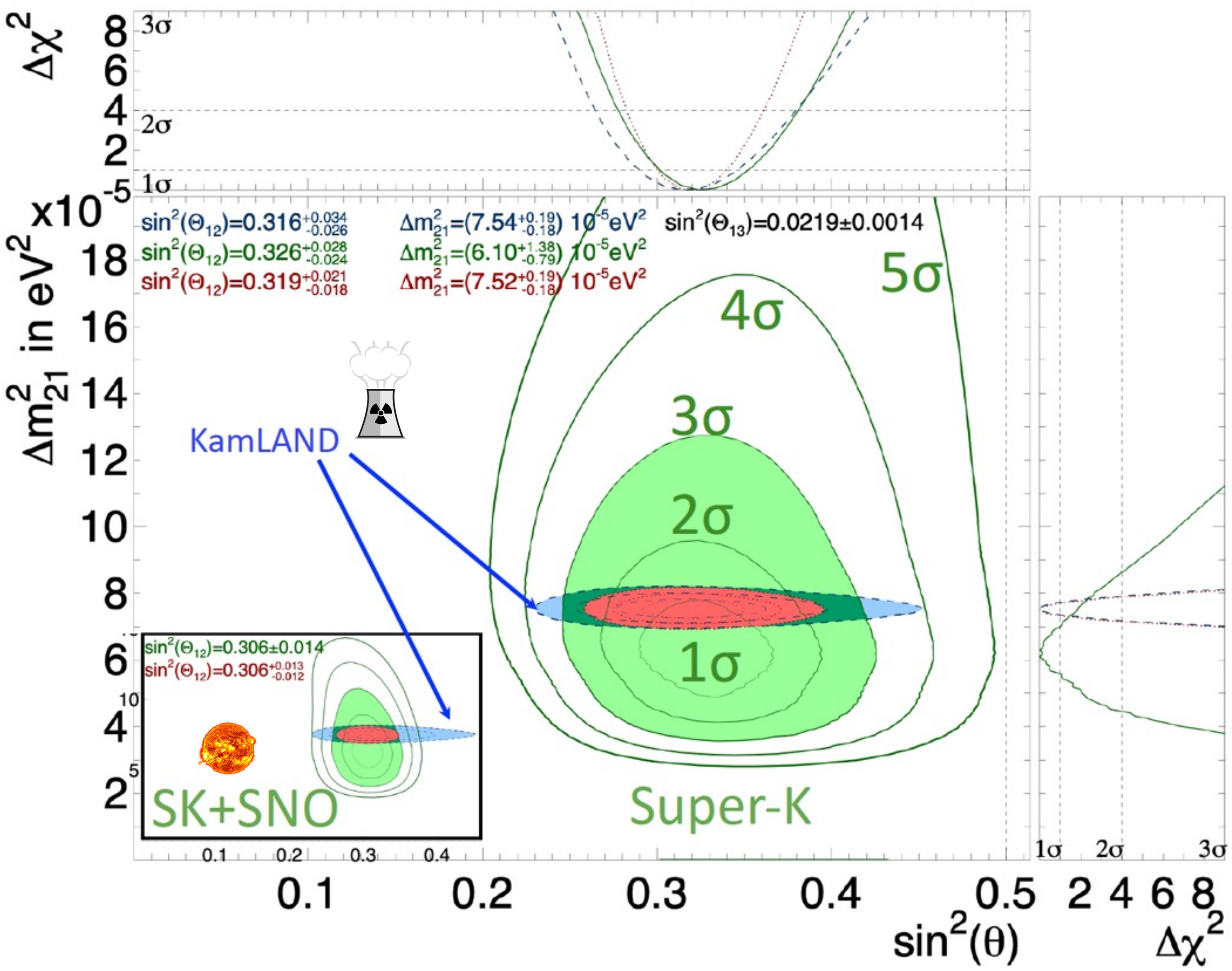
What are the leptonic mixing parameters?

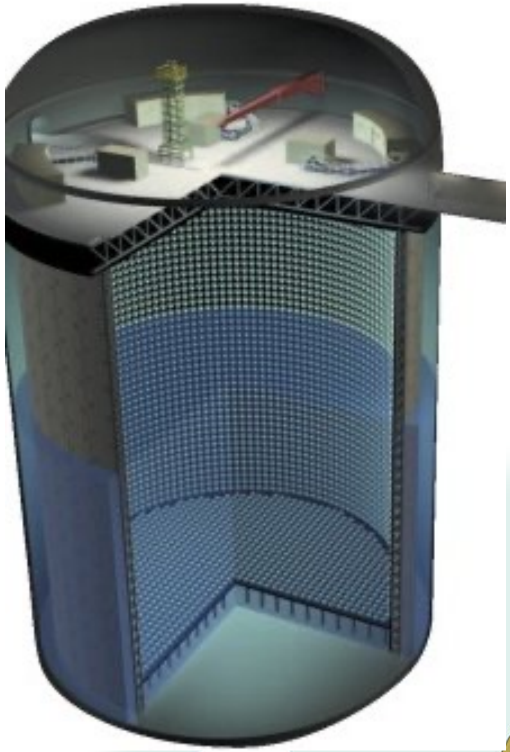
Δm^2_{21} & θ_{12}

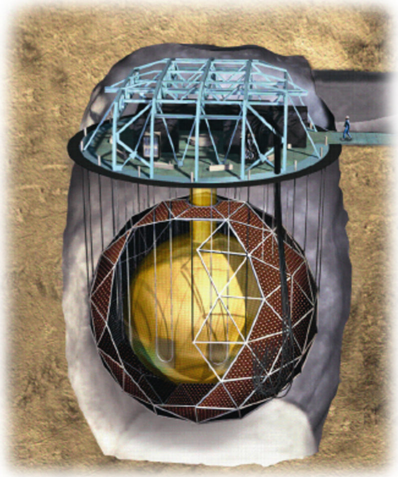


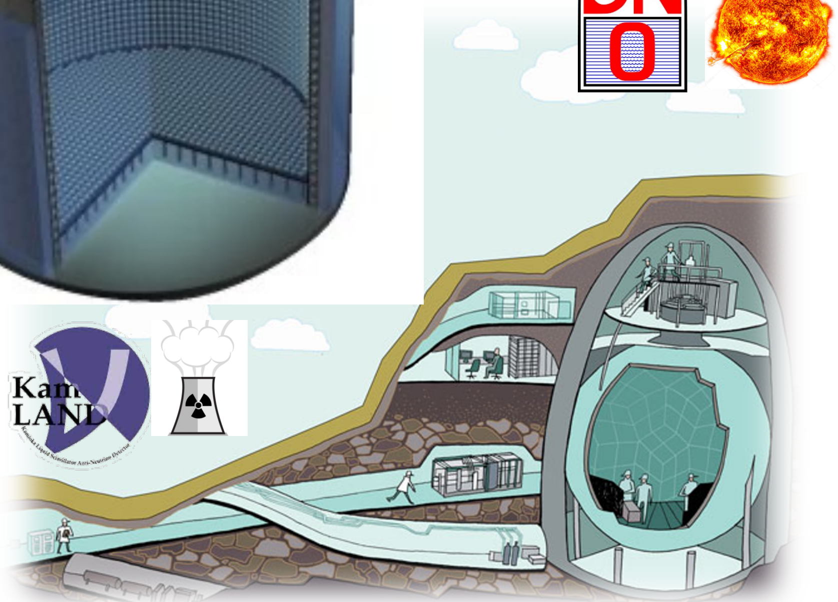
- Δm^2 (eV^2) ~ L(km) / E(MeV)
- Reactor
  L ~ 100 km & E ~ MeV
- Solar
  MSW flavor transition

Solar + Reactor Experiments



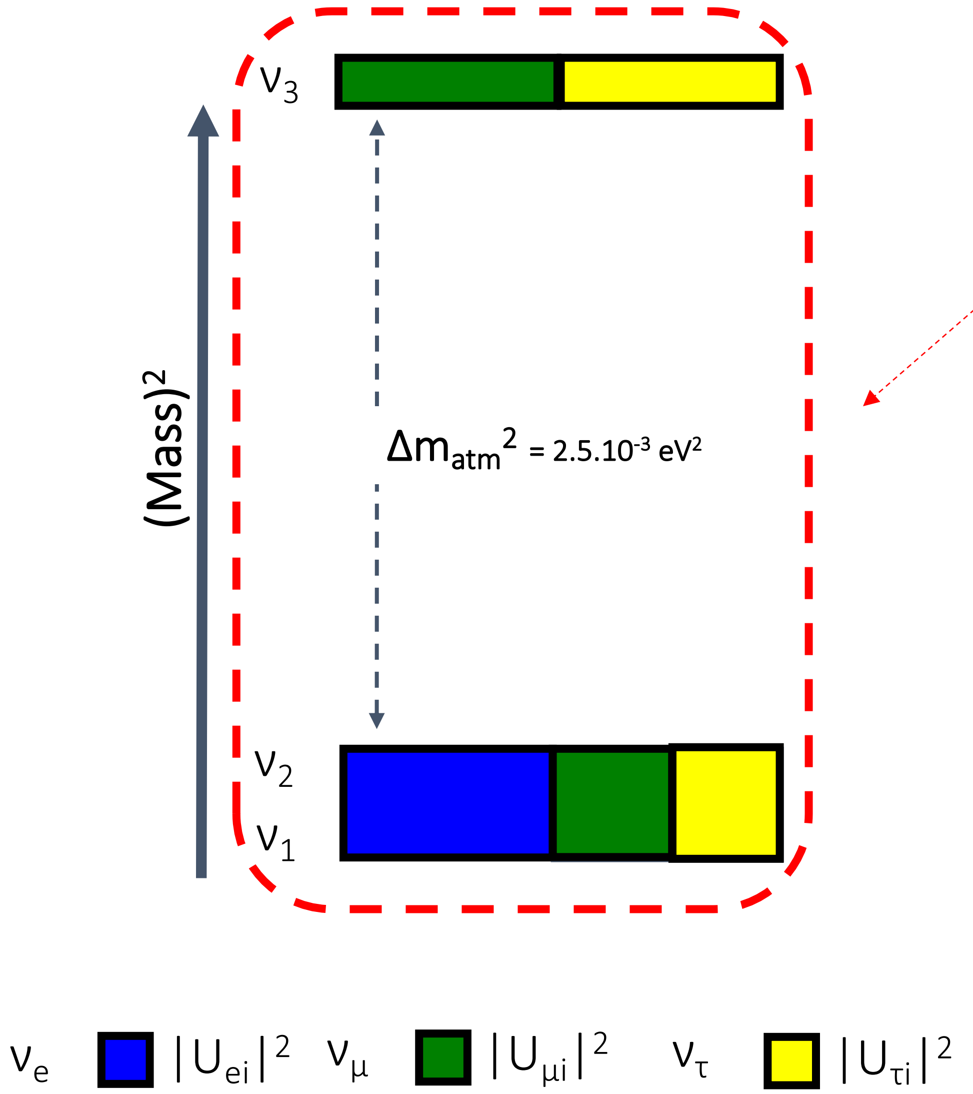






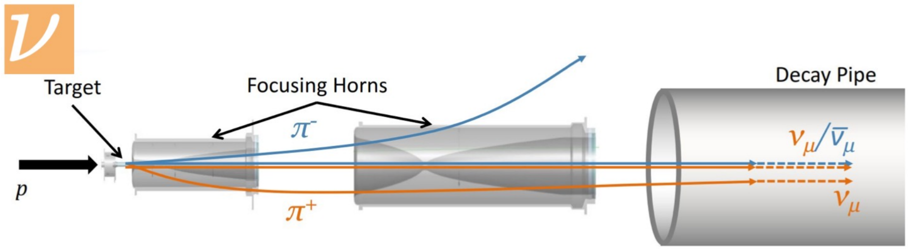
- Consistent Solar/Reactor Δm^2_{21} & θ_{12}

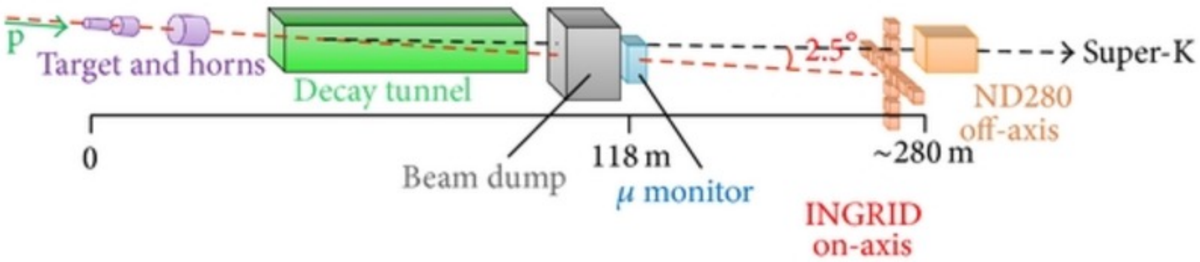
Δm^2_{31} & θ_{23}

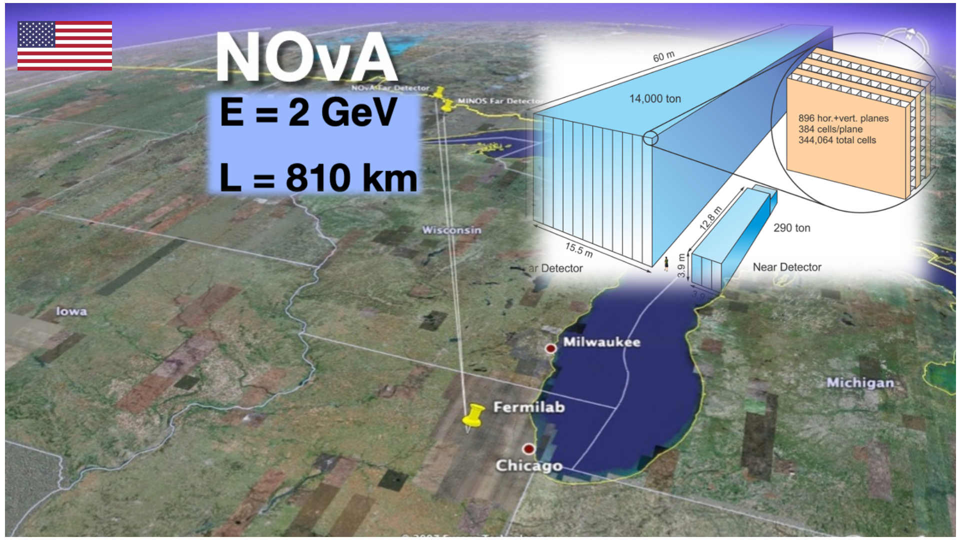


- Δm^2 (eV^2) ~ L(km) / E(MeV)
- Atmospheric neutrinos:
  L ~ 10^4 km & E ~ 1-30 GeV
- Reactors neutrinos:
  L ~ 1 km & E ~ 3 MeV
- Accelerator neutrinos:
  L ~ 1000 km & E ~ 3 GeV

Long-baseline Accelerator Experiments (LBL)

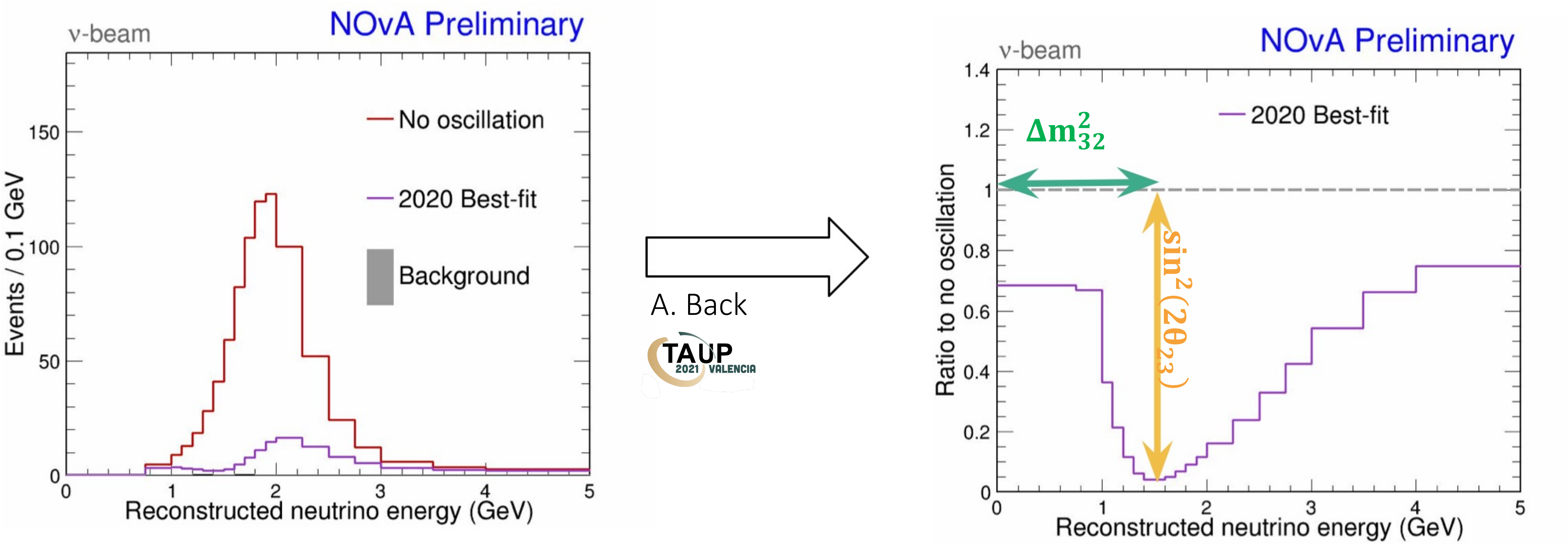






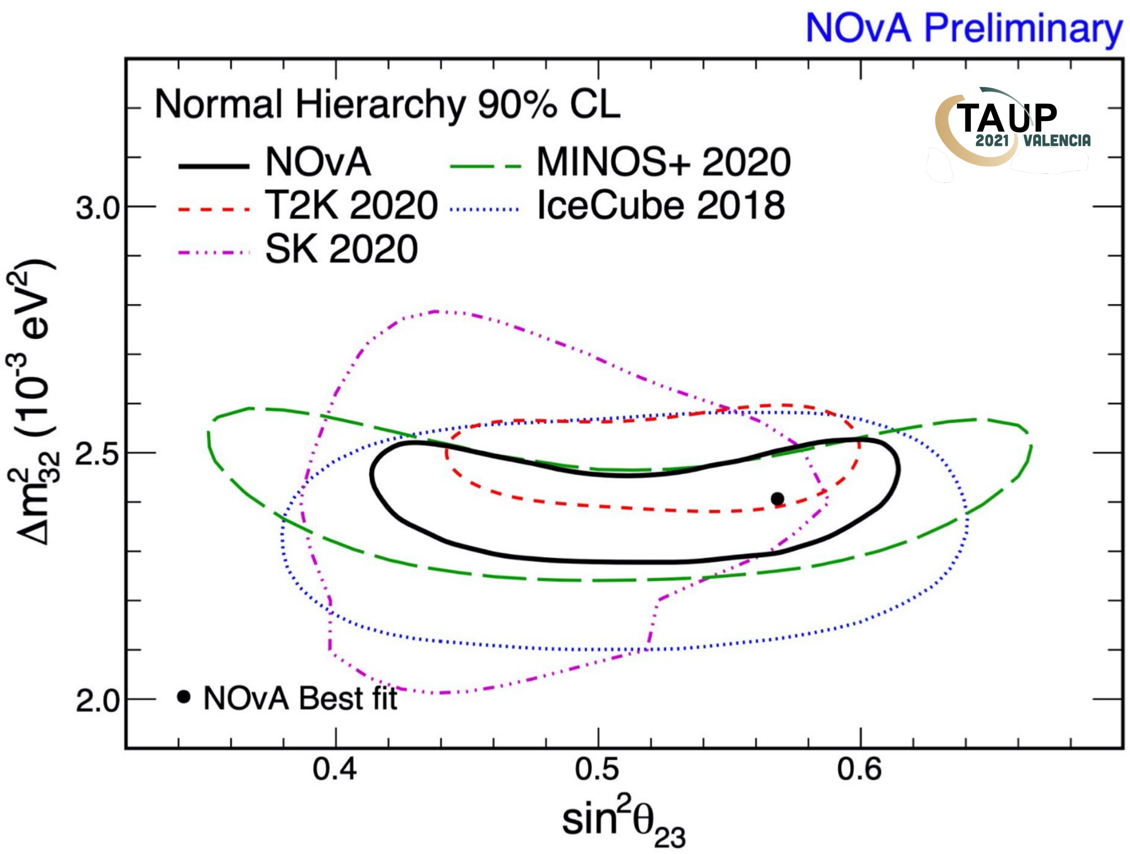
- Explore multiple oscillation modes (ν_μ dissapearance – ν_e and $\bar{\nu}_e$ appearance)
- Different baselines and energies. Complementary to address parameter degeneracies

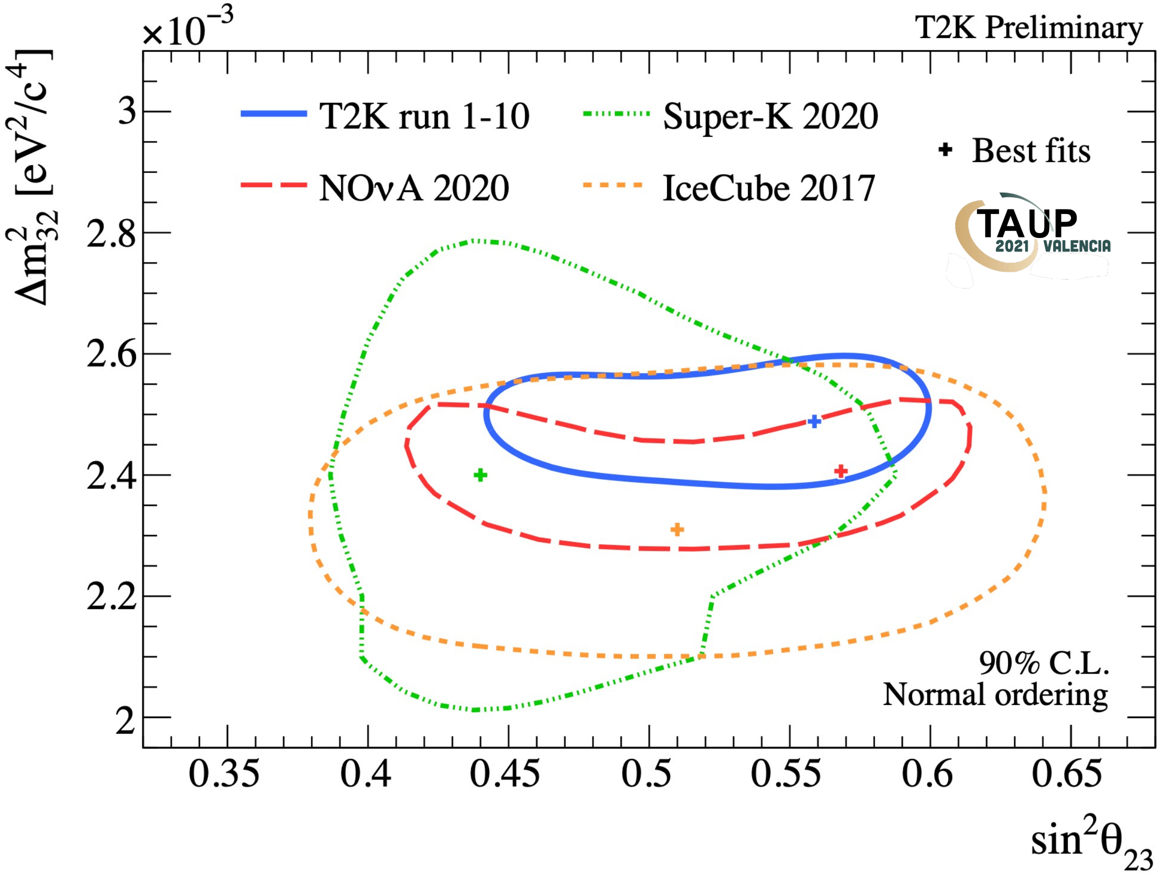
ν_μ Dissapearance



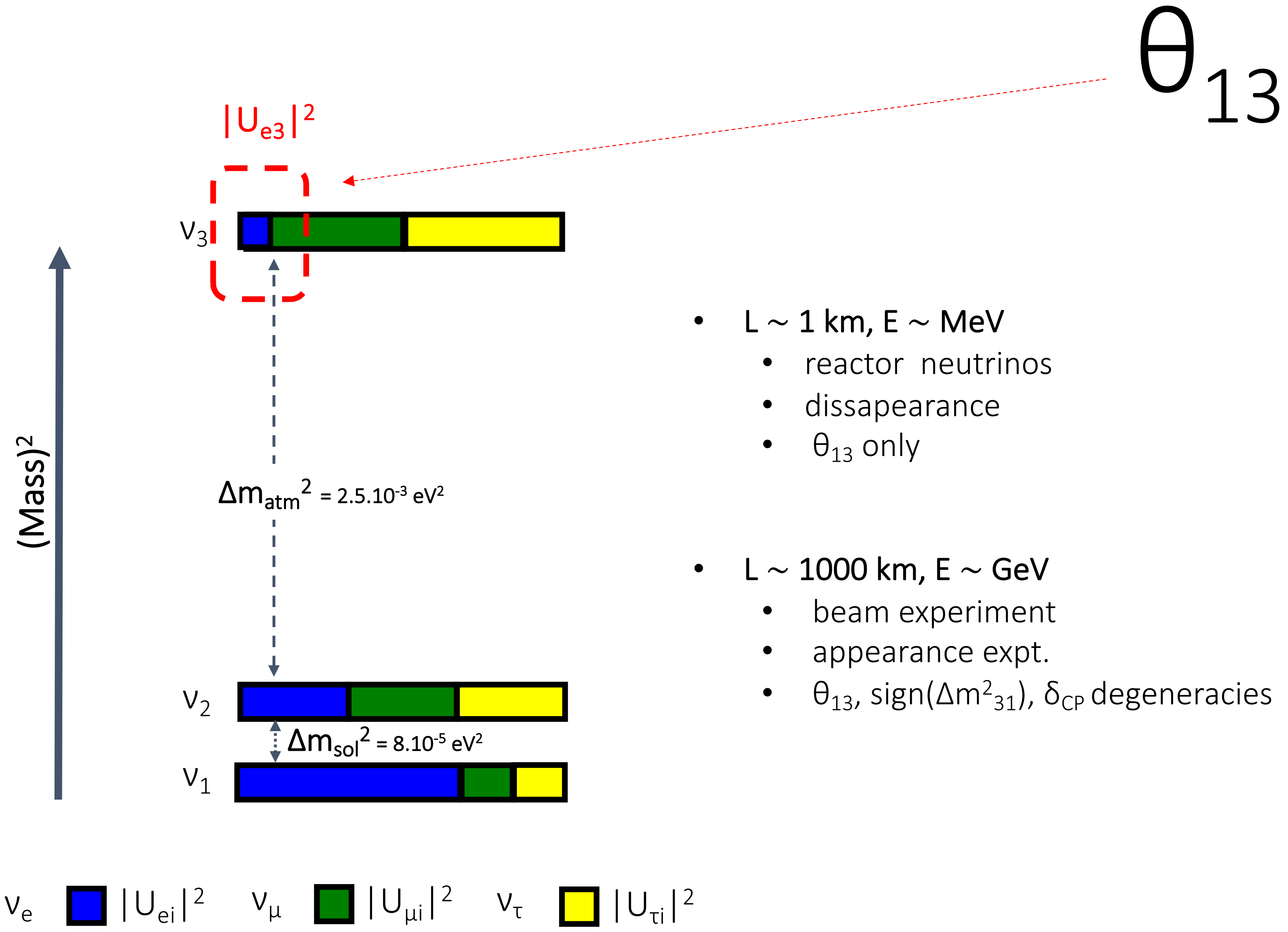
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \times \sin^2\left(\frac{1.3 \cdot \Delta m^2_{32} \cdot L}{E}\right)$$

ν_μ Dissapearance Results (LBL, Atmospheric ν's)





- Accurate & consistent measurements of Δm^2_{31} & θ_{23}
- Slight preference to normal mass ordering and upper octant, θ_{23} >45°

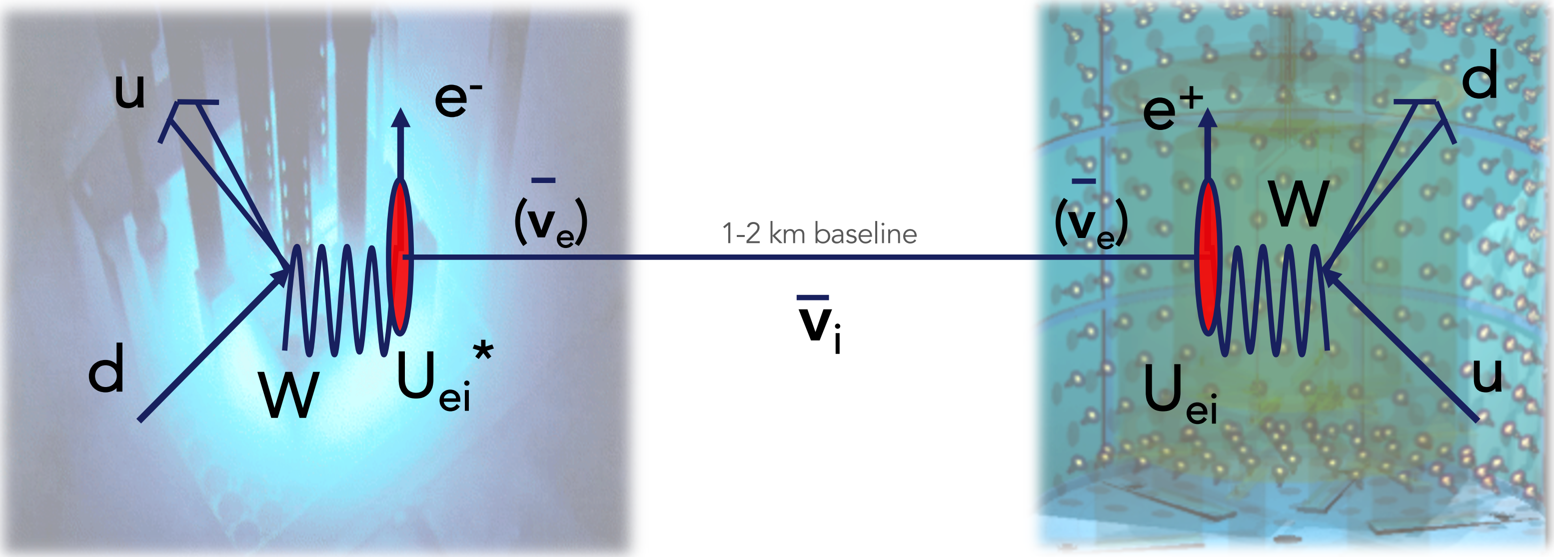


- $L \sim 1$ km, $E \sim$ MeV
  - reactor neutrinos
  - dissapearance
  - θ_{13} only
- $L \sim 1000$ km, $E \sim$ GeV
  - beam experiment
  - appearance expt.
  - θ_{13}, sign(Δm^2_{31}), δ_{CP} degeneracies

θ_{13} at Nuclear Reactors

$$^{235}U + n_{th} \rightarrow X + Y \rightarrow \beta - decays$$

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

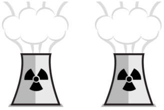


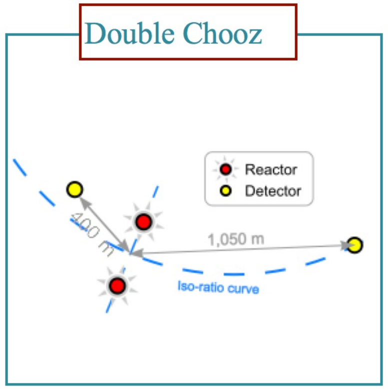
Reactor core

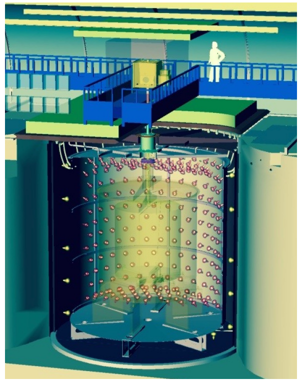
Target free protons

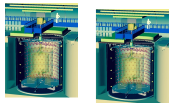
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \mathbf{sin^2(2\theta_{13})} \times \sin^2\left(\frac{1.3 \cdot \Delta m^2_{32} \cdot L}{E}\right)$$

Clean measurement of θ_{13}



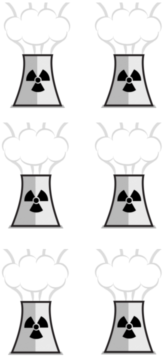


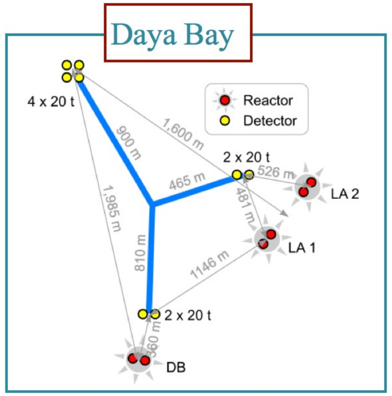


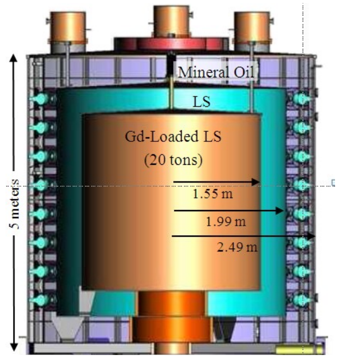


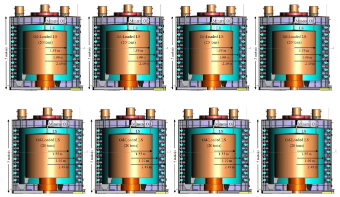
20-40 m^3

Stopped data taking in 2018



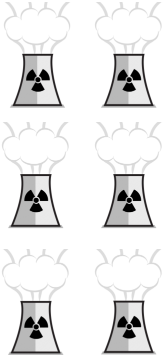


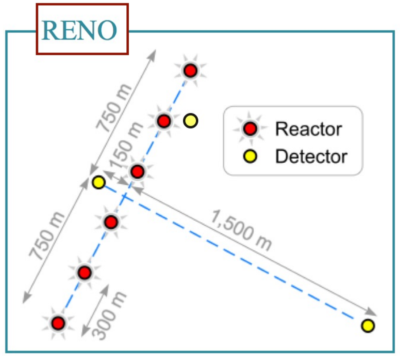


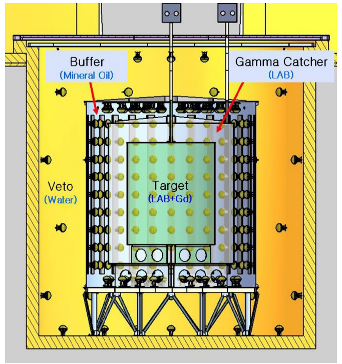


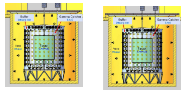
200 m^3

Running till 2022





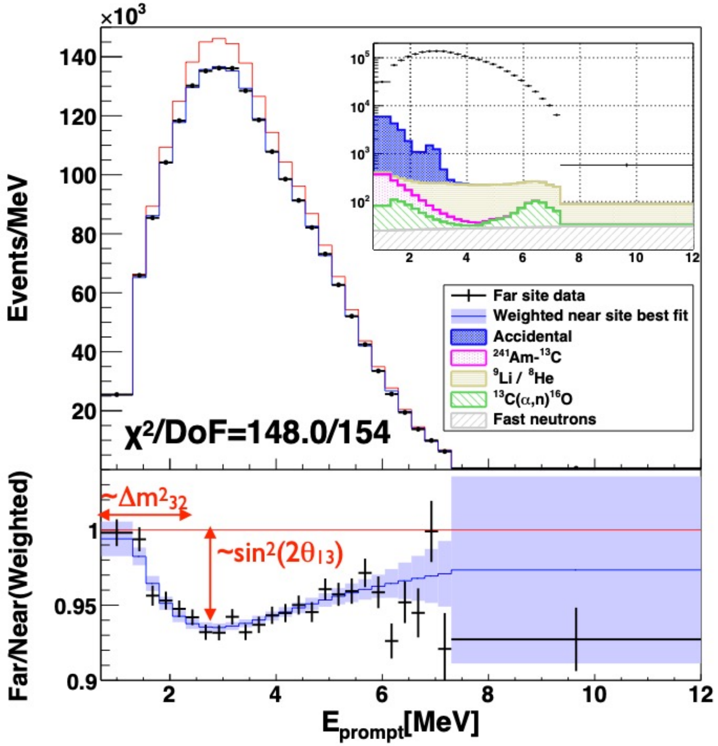




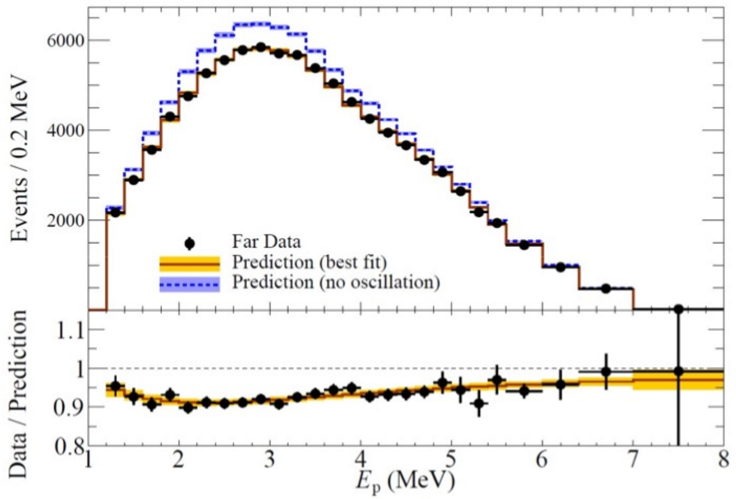
40 m^3

Running for a few years

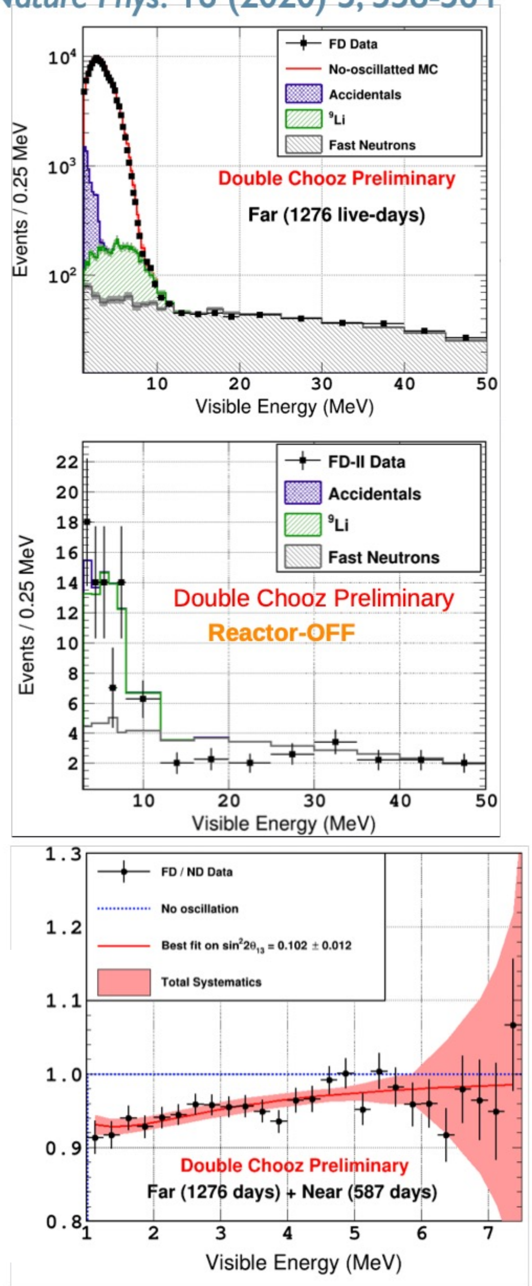
Daya Bay
Phys.Rev.Lett. 121 (2018) 24, 241805



RENO,
Phys.Rev.Lett. 121 (2018) 20, 201801

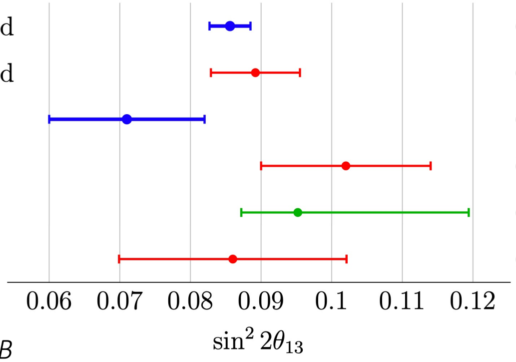


Double Chooz
Nature Phys. 16 (2020) 5, 558-564



C. Jollet

Experiment		Value
Daya Bay	nGd	0.0856 ± 0.0029
RENO	nGd	0.0892 ± 0.0063
Daya Bay	nH	0.071 ± 0.011
Double CHOOZ		0.102 ± 0.012
T2K		$0.0952^{+0.0242}_{-0.0080}$
RENO	nH	0.0860 ± 0.0161



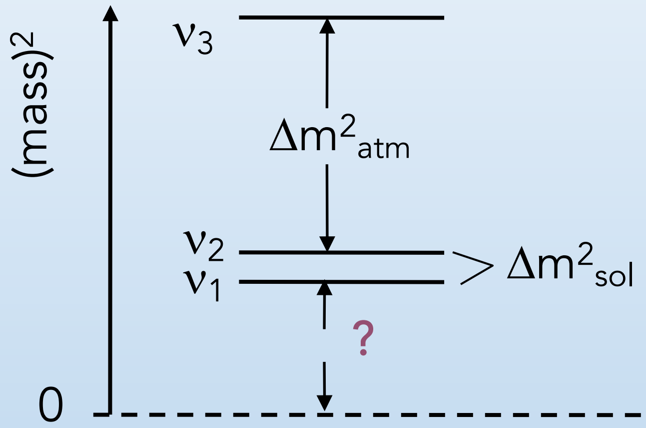
Snowmass2021-LOI DB

Capturing neutrino properties

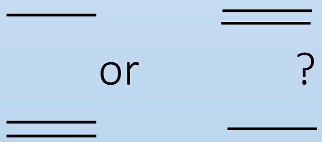
Neutrino Property	Neutrino Source(s)	Method	Status
Δm^2_{21}	reactor, sun	$\nu -$ oscillations	✓ (2.2%)
θ_{12}	reactor, sun	$\nu -$ oscillations	✓ (4.4%)
Δm^2_{31}	accelerator, reactor, atmospheric	$\nu -$ oscillations	✓ (1.3%)
sign of Δm^2_{31}	accelerator, reactor, atmospheric	$\nu -$ oscillations	✗ 2σ hints
θ_{23}	accelerator, atmospheric	$\nu -$ oscillations	✓ (5.0%)
θ_{13}	reactor, accelerator	$\nu -$ oscillations	✓ (3.8%)
δ	accelerator	$\nu -$ oscillations	✗
Dirac / Majorana	specific isotopes	$0\nu\beta\beta$	✗
m_1, m_2, m_3	specific isotopes, $C\nu B$	$\beta, EC, 0\nu\beta\beta$- cosmology	[range]

Facts & open questions: overview

- Masses of the mass eigenstates ν_i?



- Spectral pattern or ?

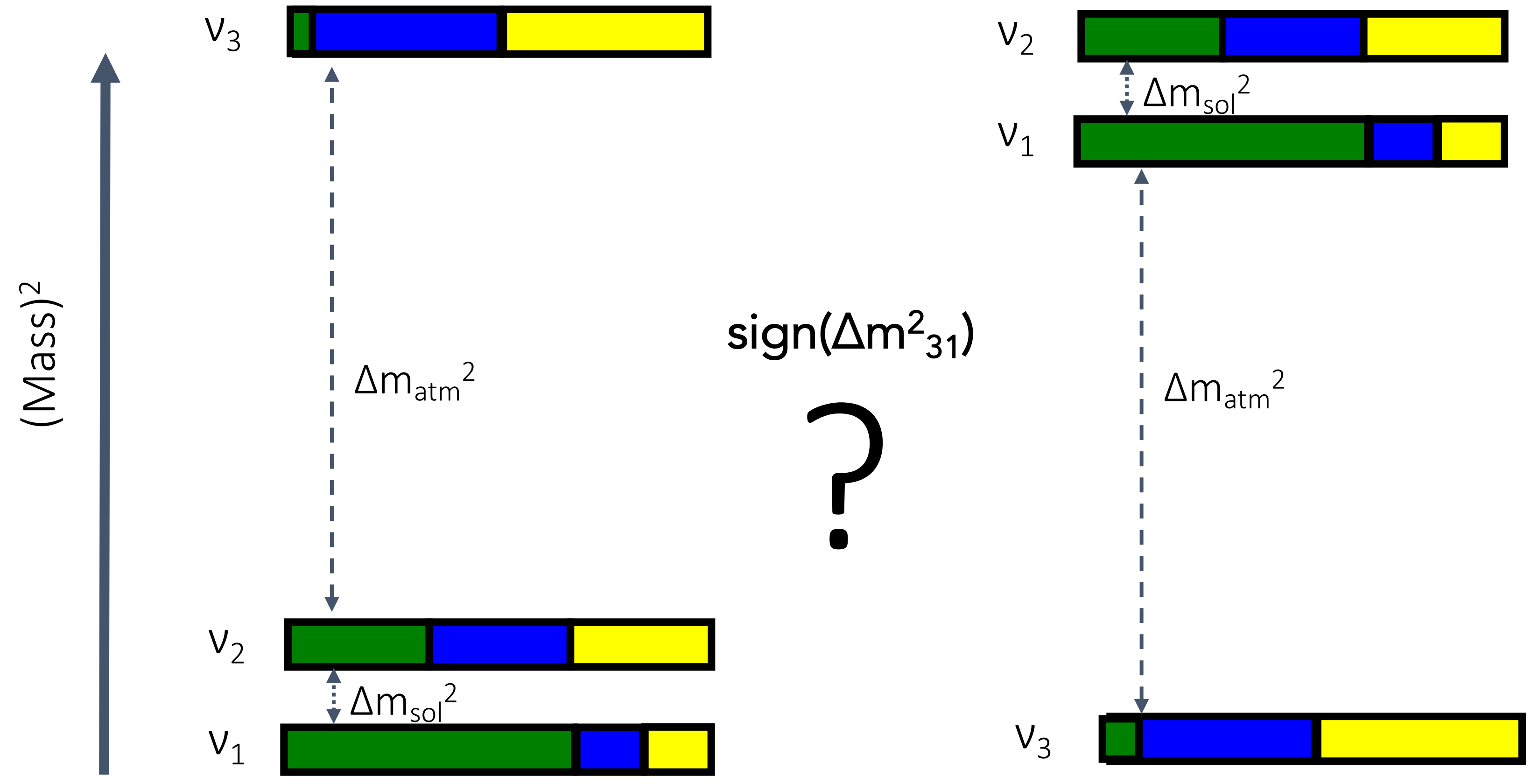


- Lepton Number conservation (Dirac or Majorana) ?

- Is CP violated in the neutrino sector?

- Are there additional (sterile) neutrino states

What is the spectral mass pattern ?
(mass ordering or hierarchy)

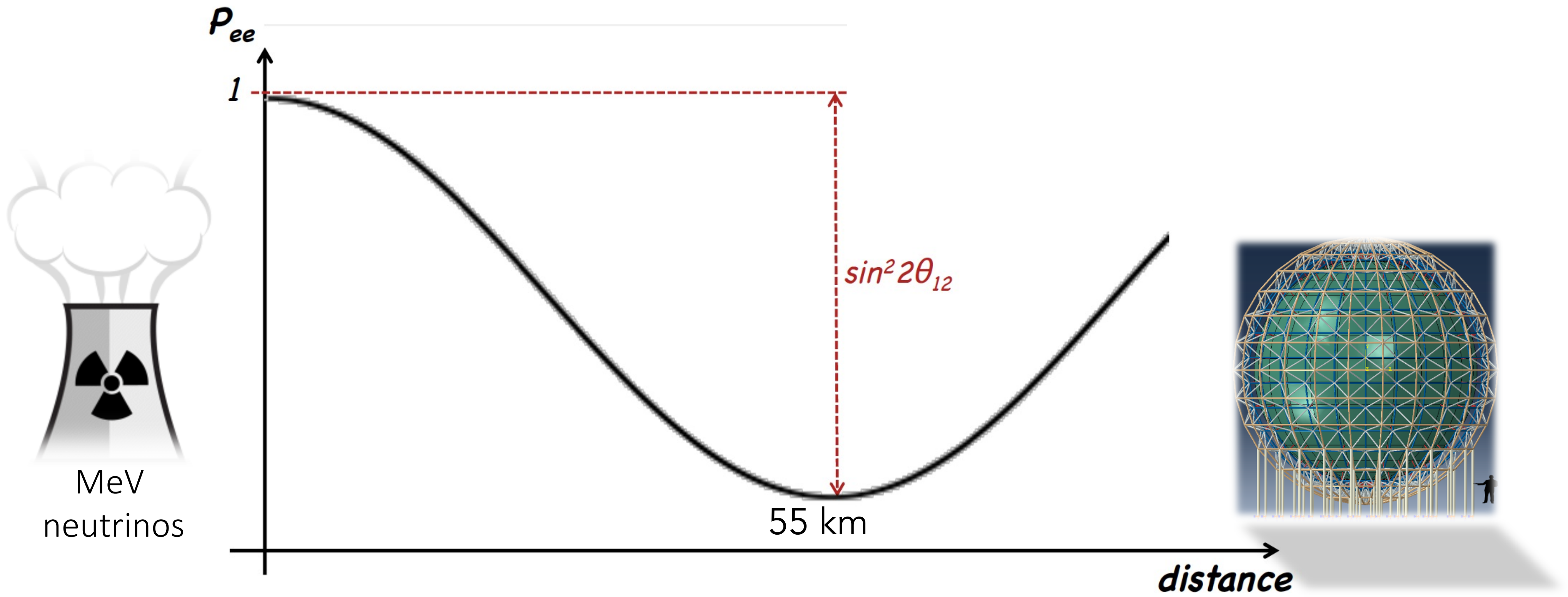


ν_e $|U_{ei}|^2$ ν_μ $|U_{\mu i}|^2$ ν_τ $|U_{\tau i}|^2$

sign(Δm^2_{31}) with reactor neutrinos

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \frac{1}{2}(1-|U_{e3}|^2)^2 \sin^2 2\Theta_{12} \left(1 - \cos \frac{\Delta m^2_{21} L}{2E}\right)$$

Solar



sign(Δm^2_{31}) with reactor neutrinos

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - 2|U_{e3}|^2(1-|U_{e3}|^2)\left(1-\cos\frac{\Delta m^2_{31} L}{2E}\right)$$

Atmospheric

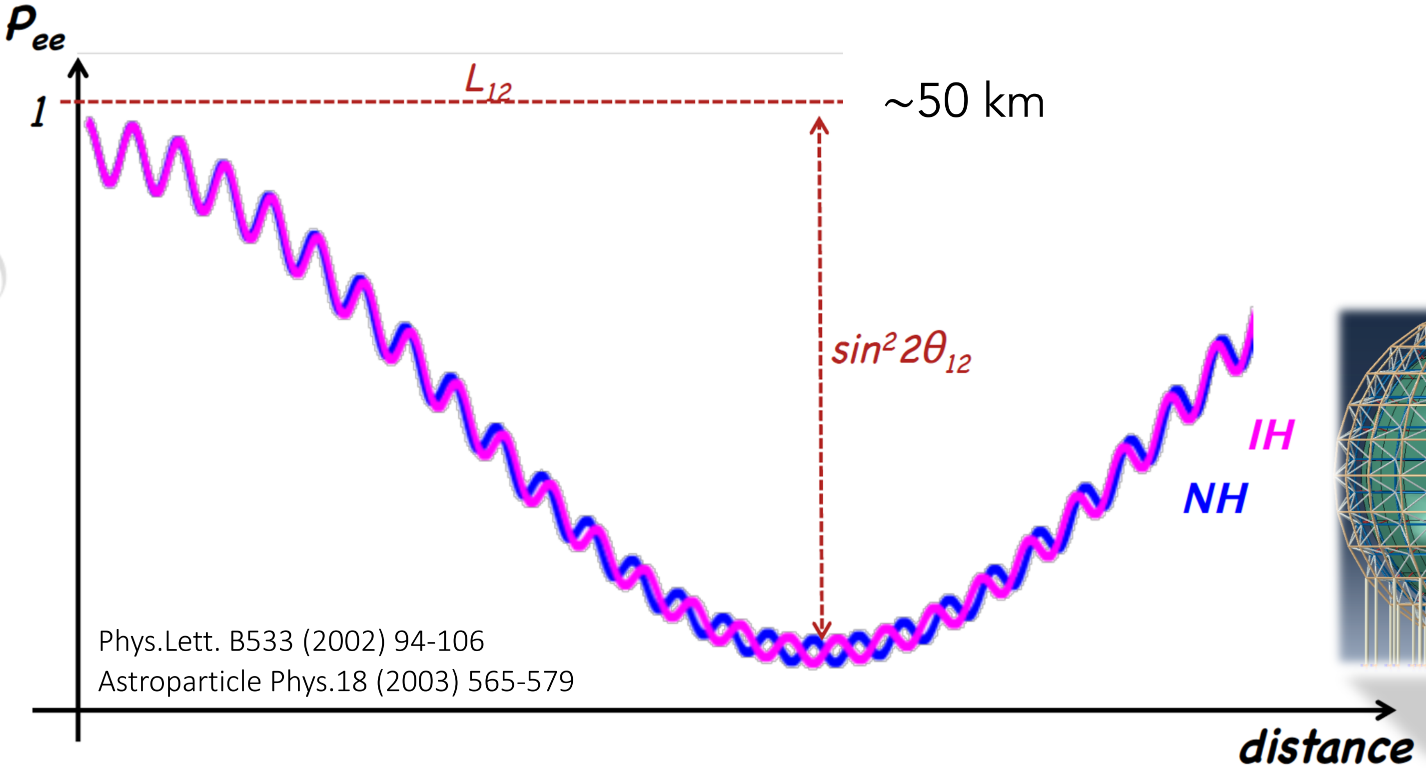
$$-\frac{1}{2}(1-|U_{e3}|^2)^2 \sin^2 2\Theta_{12}\left(1-\cos\frac{\Delta m^2_{21} L}{2E}\right)$$

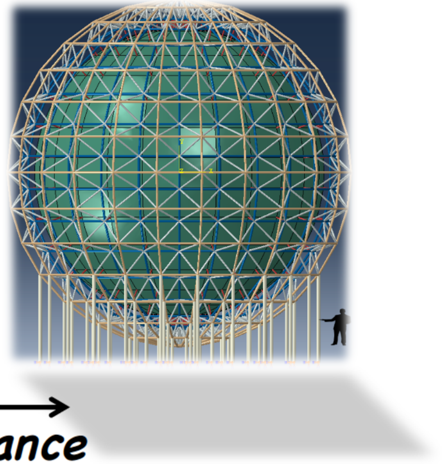
Solar

Interference

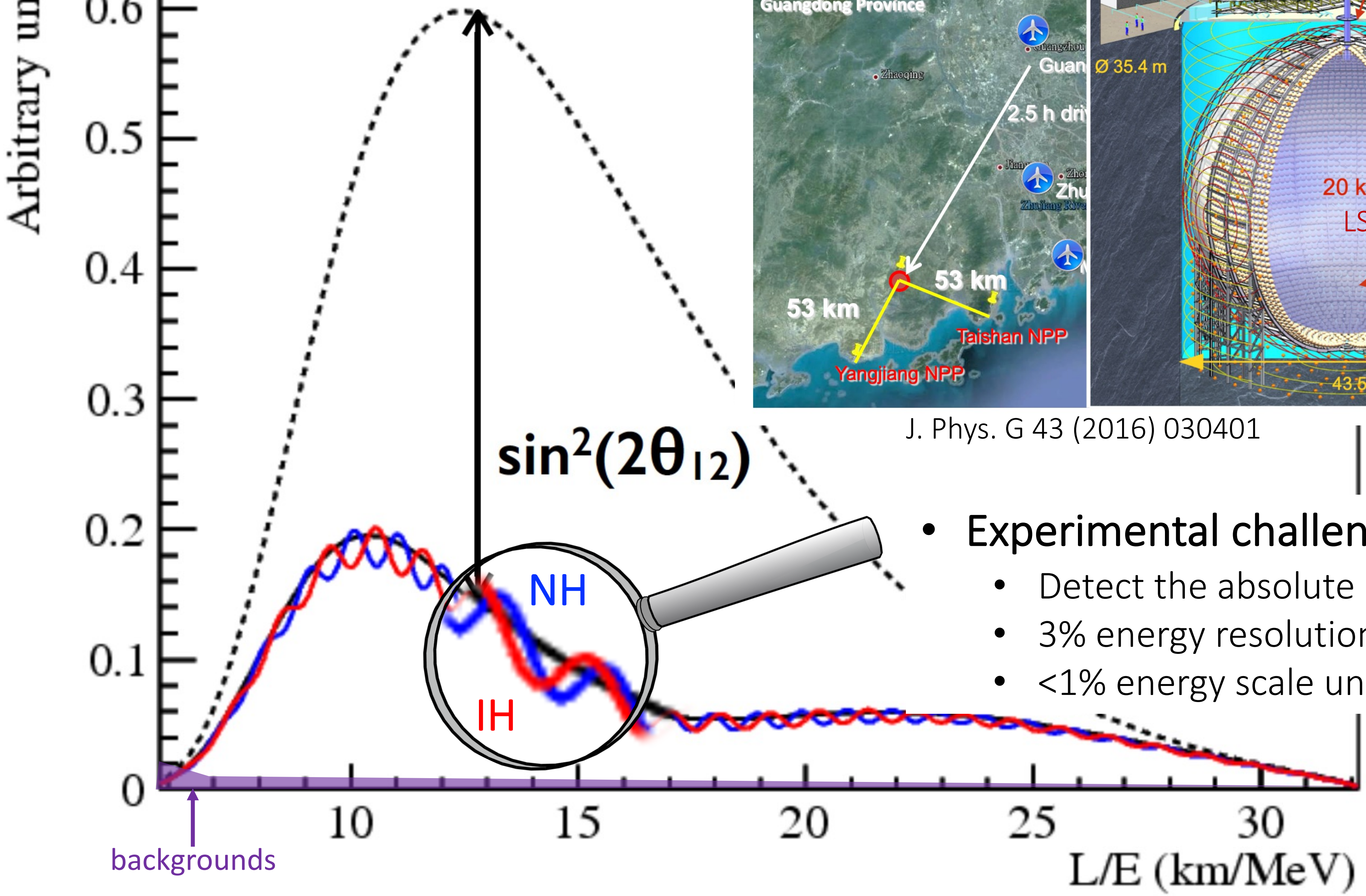
$$+2|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\Theta_{12}\left(\cos\left(\frac{\Delta m^2_{31} L}{2E}-\frac{\Delta m^2_{21} L}{2E}\right)-\cos\frac{\Delta m^2_{31} L}{2E}\right)$$

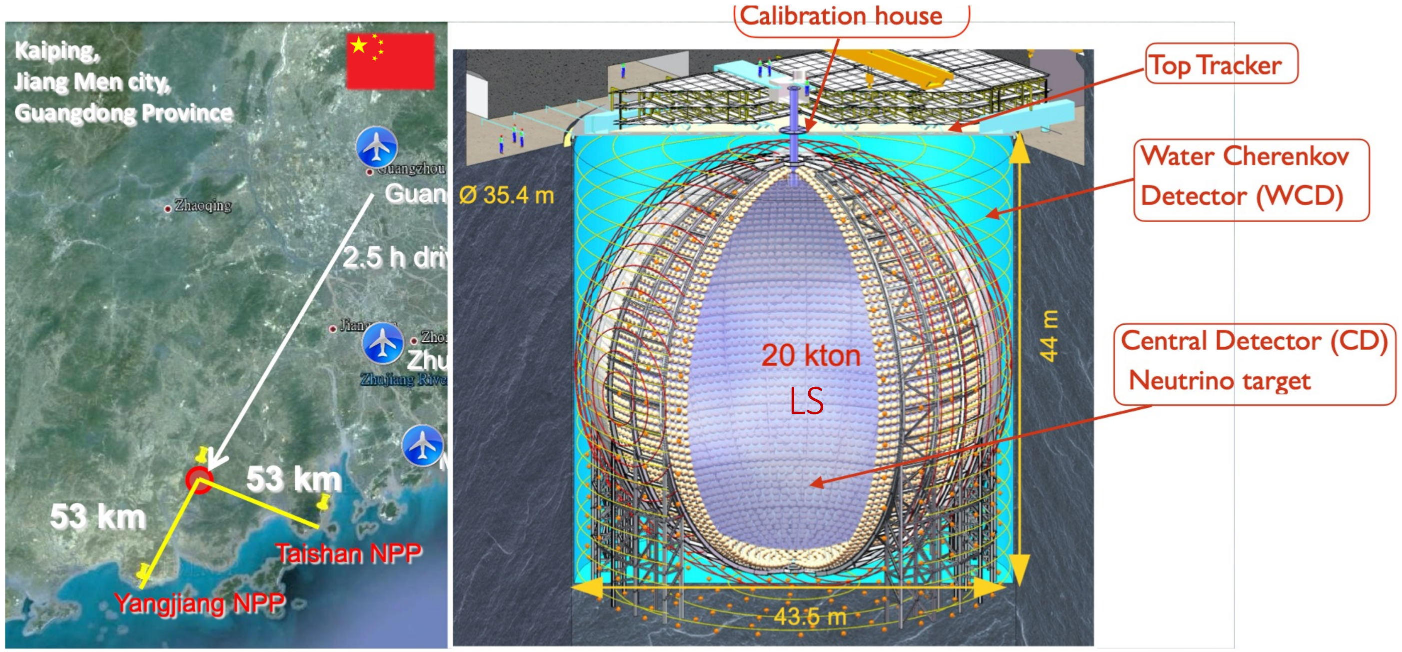
MeV neutrinos





20 kt JUNO Experiment (start in 2023)

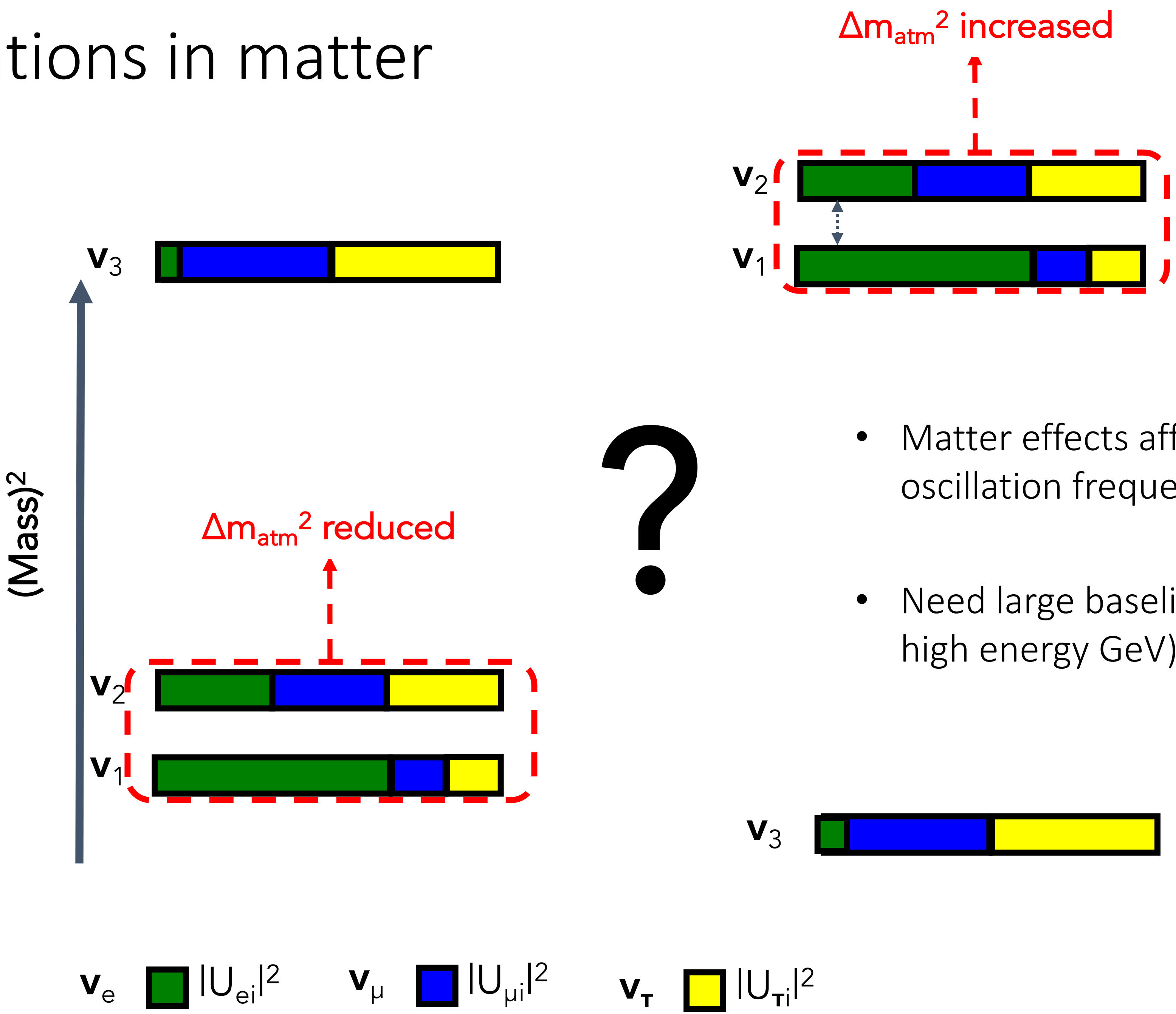




J. Phys. G 43 (2016) 030401

- Experimental challenges (for 3σ in 6 years)
  - Detect the absolute location of the wiggles
  - 3% energy resolution
  - <1% energy scale uncertainty

Oscillations in matter



- Matter effects affect the oscillation frequency
- Need large baselines (>>100km), high energy GeV)

Do the behavior of ν violate CP?

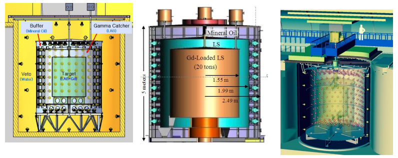
Neutrino & Antineutrino Oscillations

$$P(\nu_\mu \rightarrow \nu_e) \approx \alpha + \beta \ \sin \delta_{CP}$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \alpha - \beta \ \sin \delta_{CP}$$

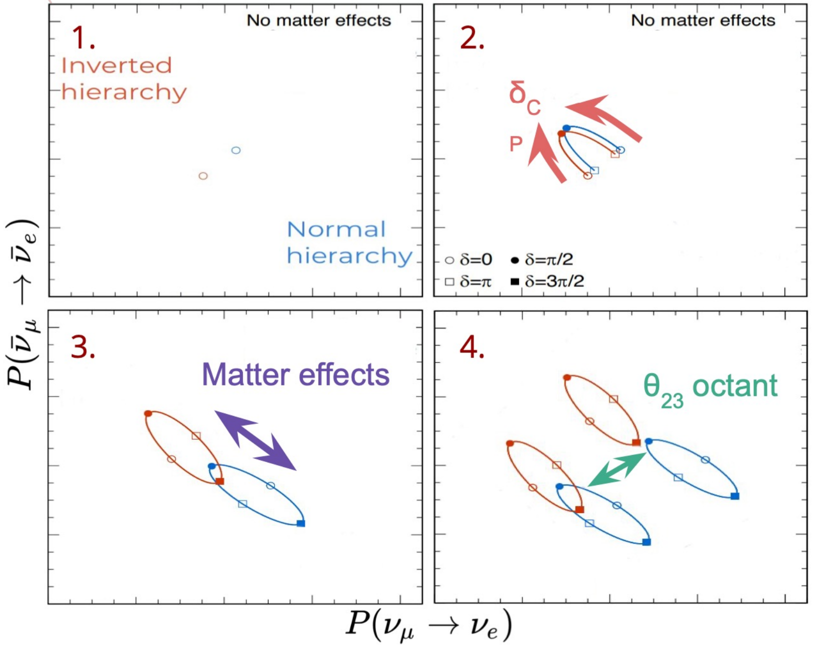
Asymmetry parameter

$$A_{CP} \sim \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} = \frac{\sin(\Delta m^2 L/4E) \sin\theta_{12} \sin\theta_{13} \sin \delta_{CP}}{\sin^2\theta_{13} + \ldots}$$



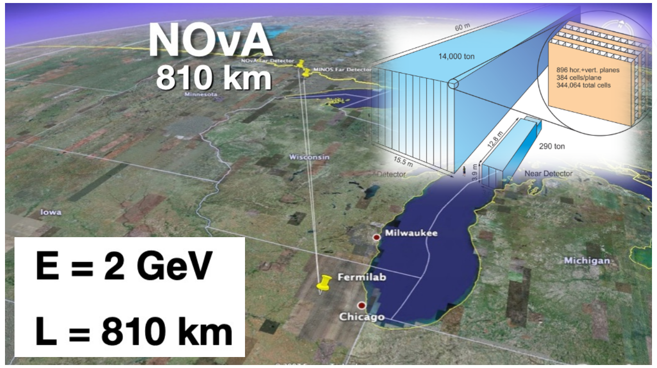
Fixed by reactor experiments

Correlations & Degeneracies

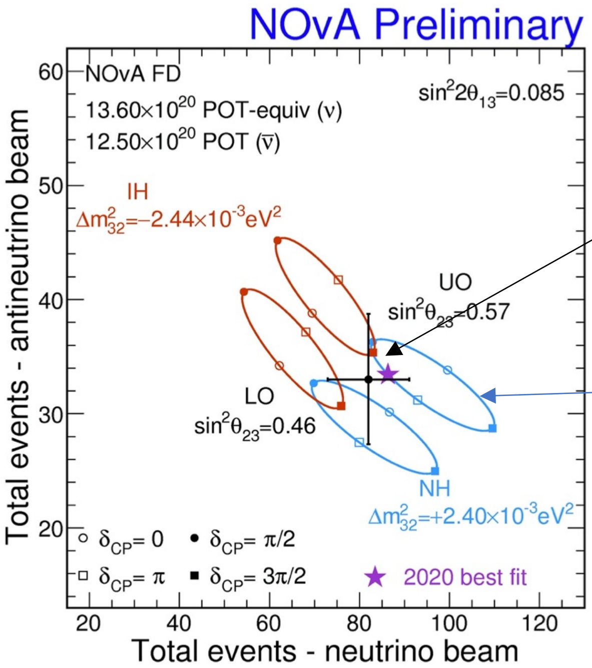


1. Mass ordering
2. CP violation effect
3. Matter effects
4. octant of θ_{23}

NOvA & T2K $\nu_e / \bar{\nu}_e$ Appearance



T2K



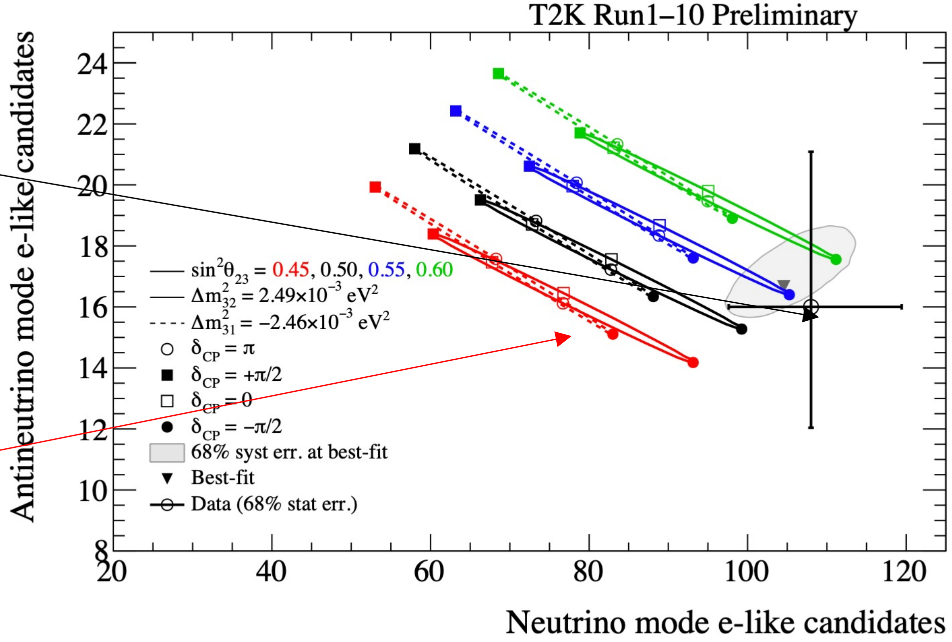
Data

Model

Model

Model

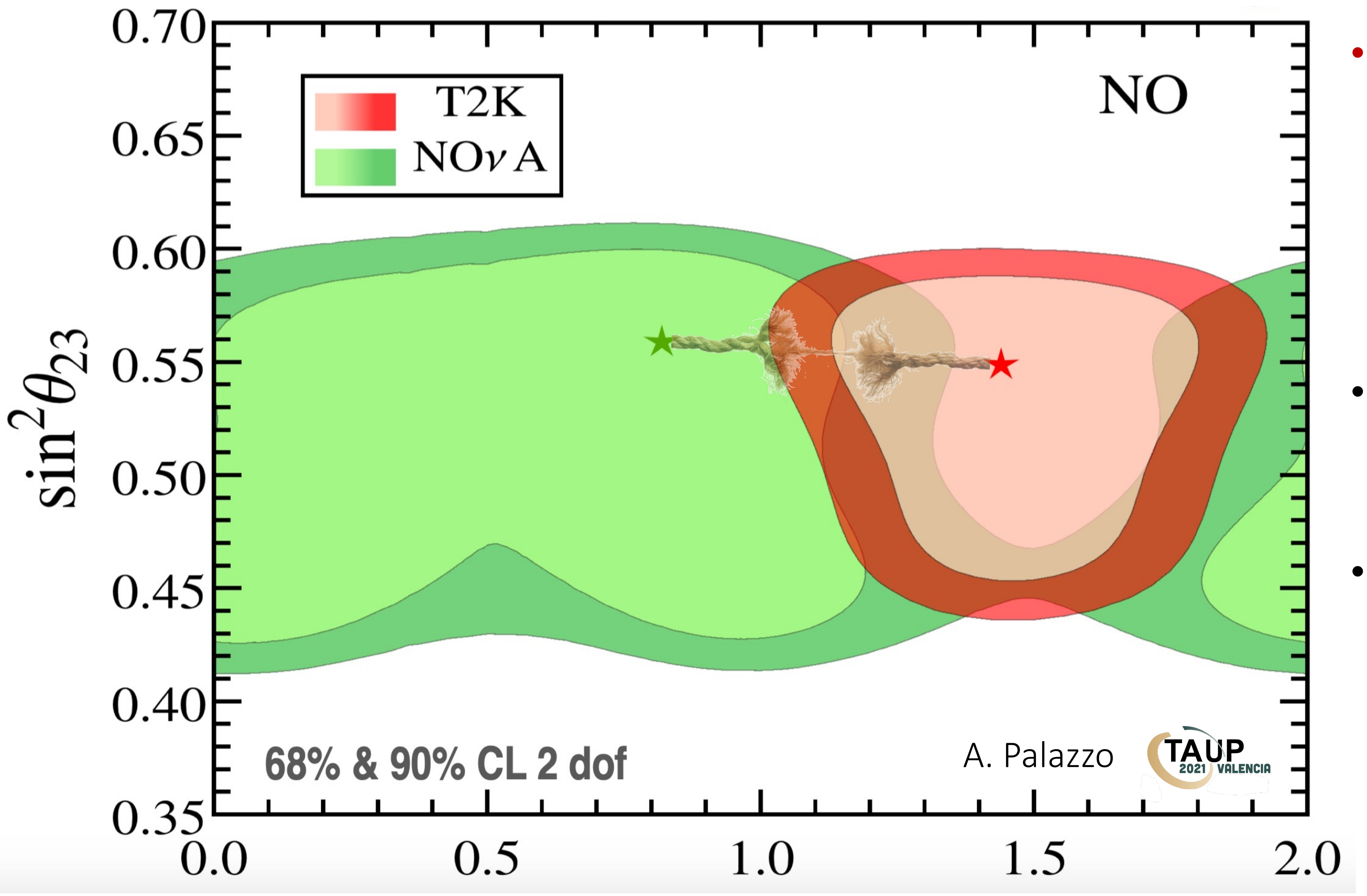
Model



NOvA favors $\delta_{CP} \sim 0.8\pi$ (NO)

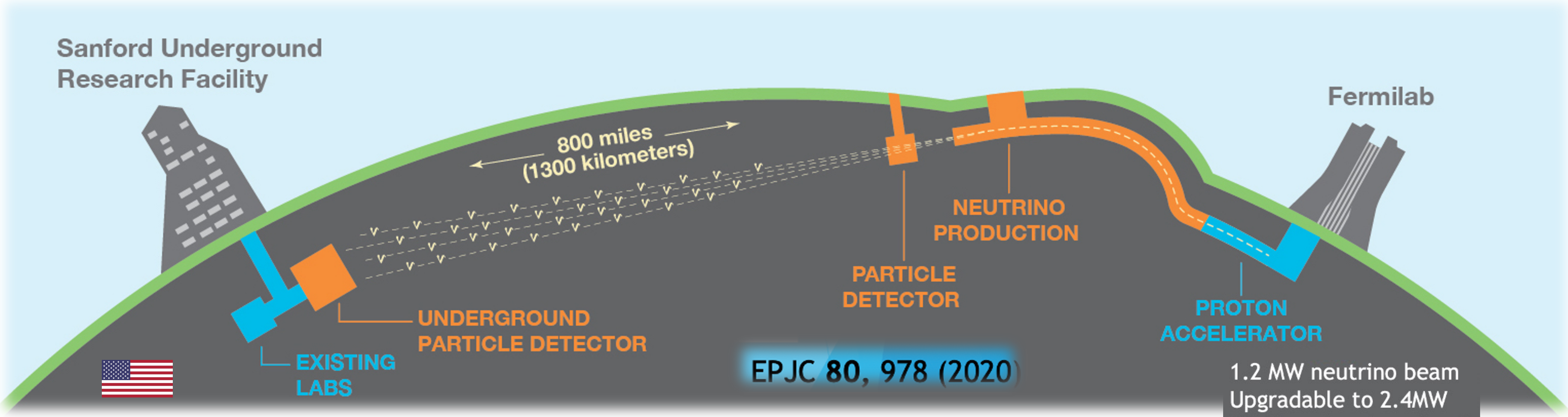
T2K favors $\delta_{CP} \sim 1.5\pi$ (NO)

NOvA & T2K $\nu_e / \bar{\nu}_e$ Appearance



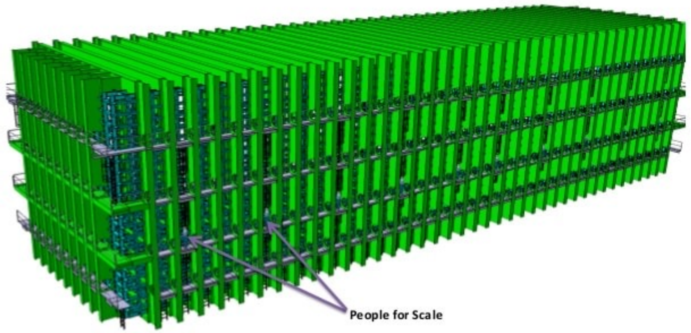
- In Normal Ordering, tension in the evaluation of $\boldsymbol{\delta_{CP}}$
  - statistical fluctuation?
  - systematic error?
  - Joint analysis ongoing
- Inverted ordering is disfavored by all other data
- (too) large NSI could solve the tension

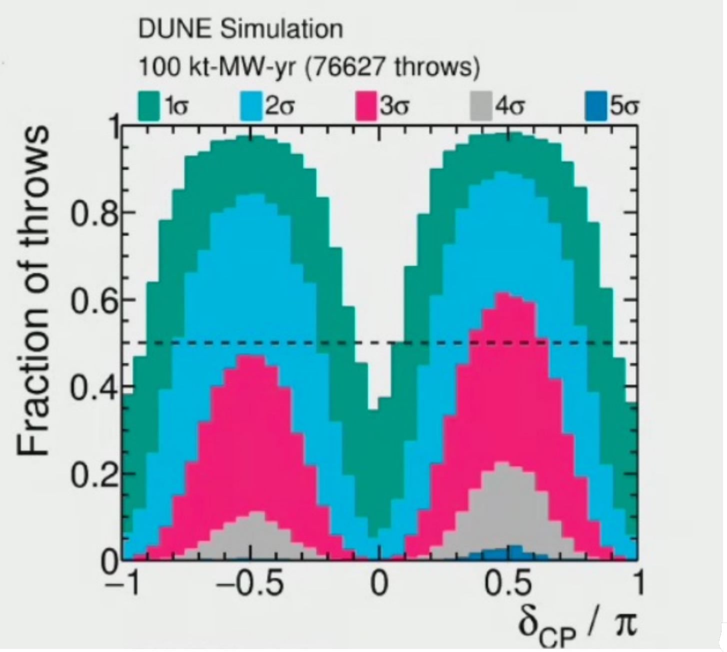
The DUNE Experiment – Start in late 20’s



1.2 MW neutrino beam
Upgradable to 2.4MW
PIP-II project baselined

- 1300 km baseline
- Liquid Argon TPC
- 4 x 10 kt fiducial



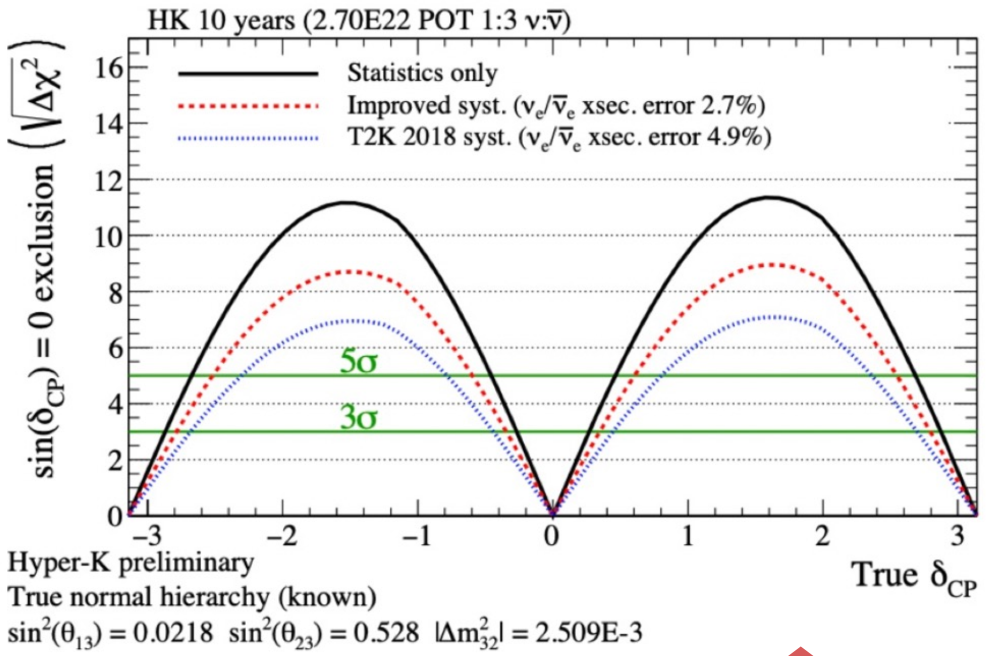


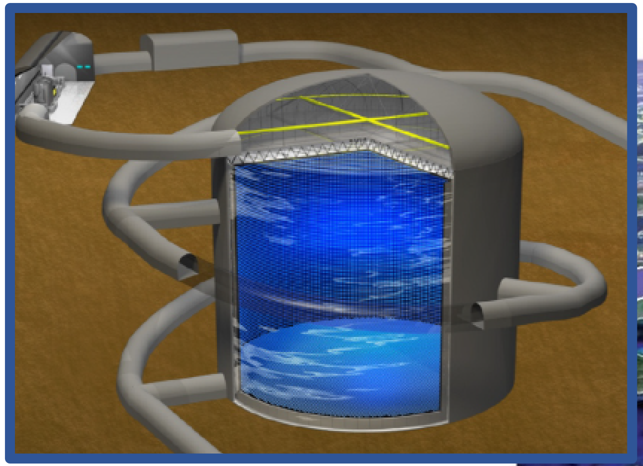
- 3σ for $\delta_{CP} = \pm\frac{\pi}{2}$: 100 kt.MW.y
- For 50% of δ_{CP} values:
  - 3σ: 200 kt.MW.y
  - 5σ: 650 kt.MW.y (10 years)

TAUP 2021 VALENCIA C. Wilkinson

The Hyper-Kamiokande Experiment – Start in 2027

Construction started
in May 2021

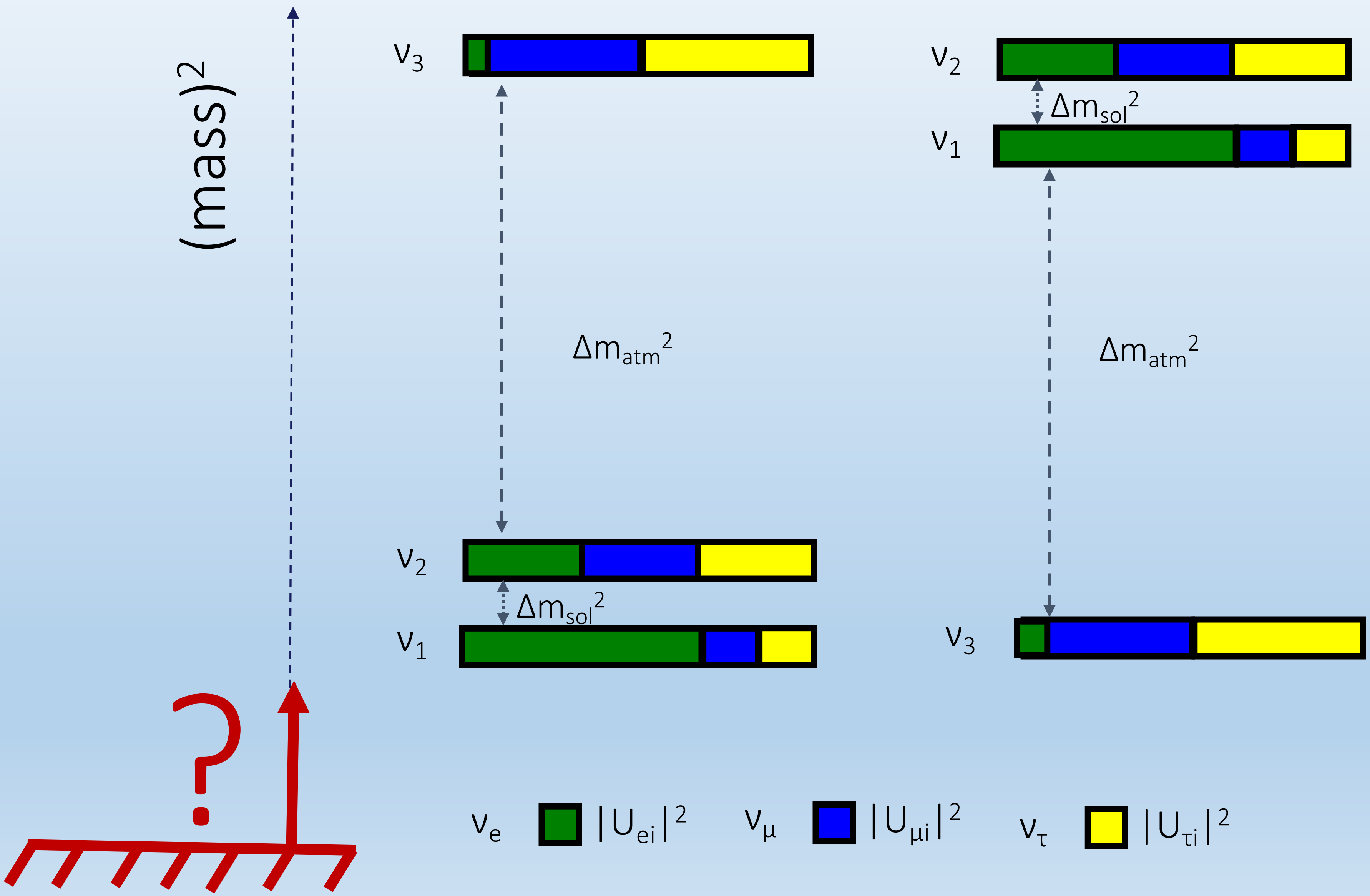




- HK is x8 SK
- Water Cherenkov
- 200 kt fiducial

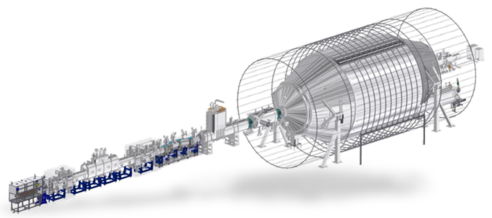
Significance to exclude $\delta_{CP} = 0$ (i.e. exclude CP Conservation) after 10 years

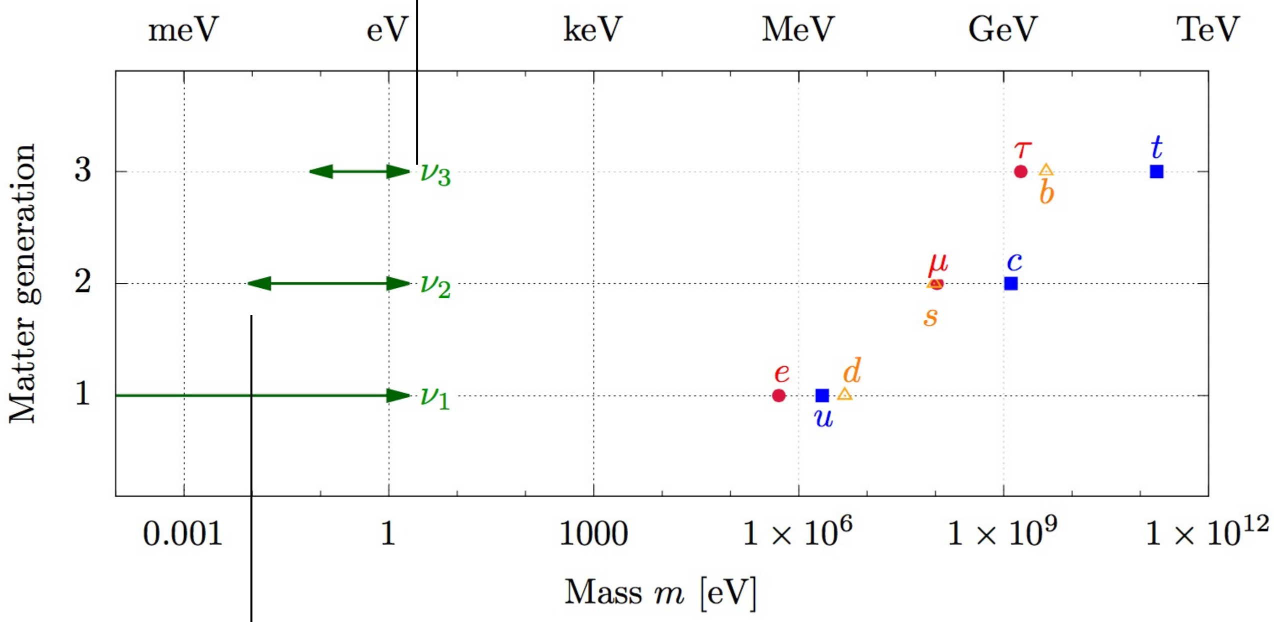
The absolute neutrino mass scale

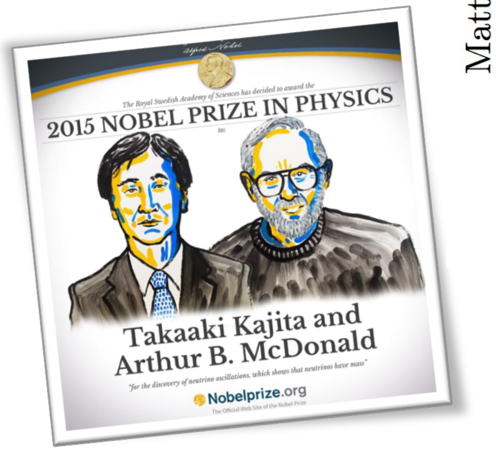


Tiny neutrino masses

Upper bound
from laboratory measurements







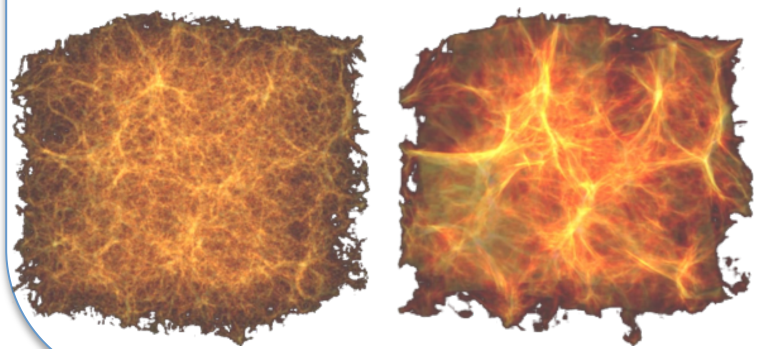
Lower bound
from oscillation experiments

Neutrino masses

Cosmology

Rely on cosmological model
potential: m_ν = 10 meV
e.g. Planck + LSS + BAO ...

$$m_{cosmo} = \sum_i m_i$$



Search for 0νββ

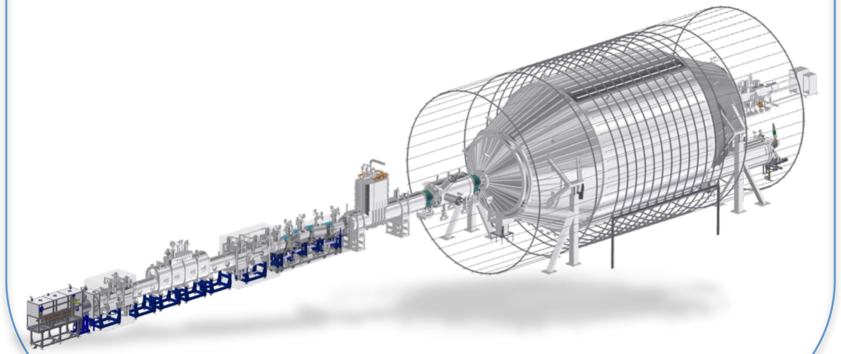
Laboratory-based
potential: $m_{\beta\beta}$ = 15-50 meV
e.g. LEGEND, Cupid

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

Kinematics of β-decay

Laboratory-based
potential: m_β = 50 - 200 meV
e.g. KATRIN

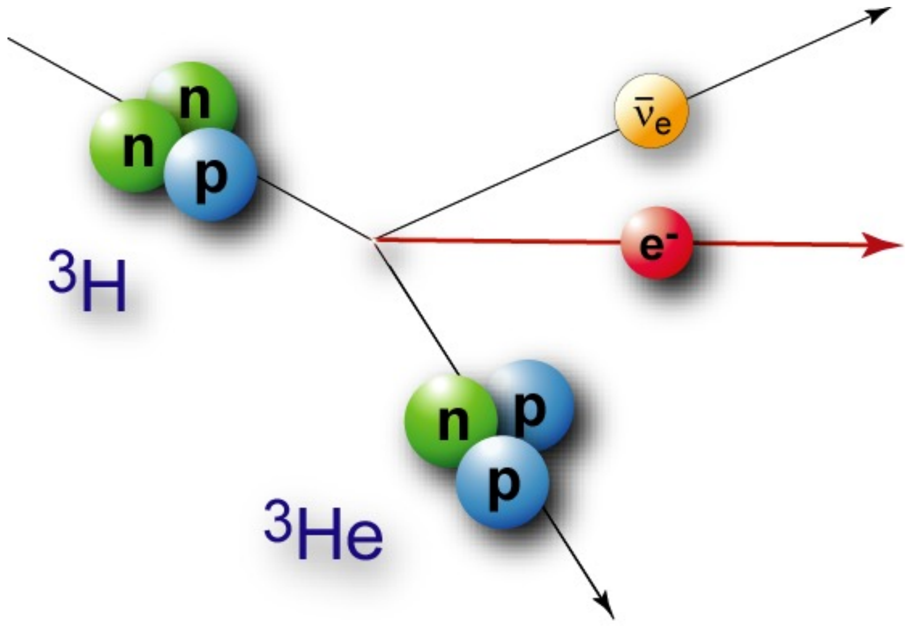
$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$



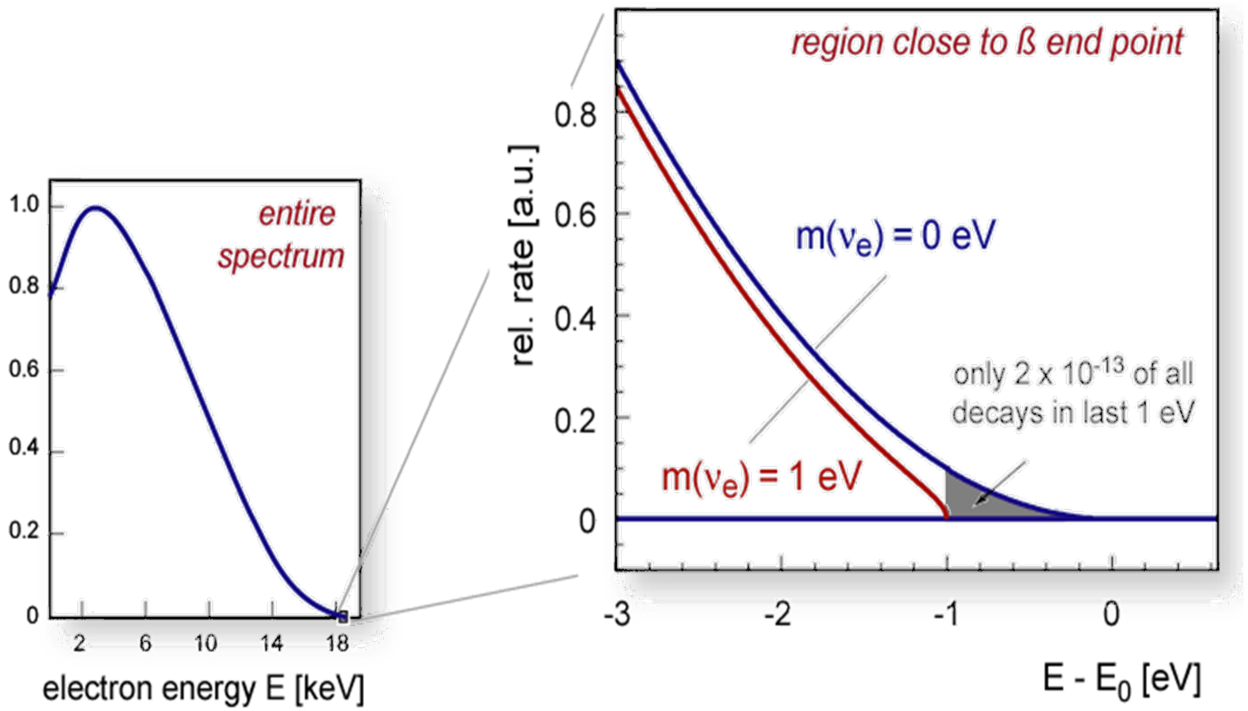
Lower bounds: from oscillation experiments

Upper bounds: from laboratory measurements & Cosmology

General idea of kinematics measurements



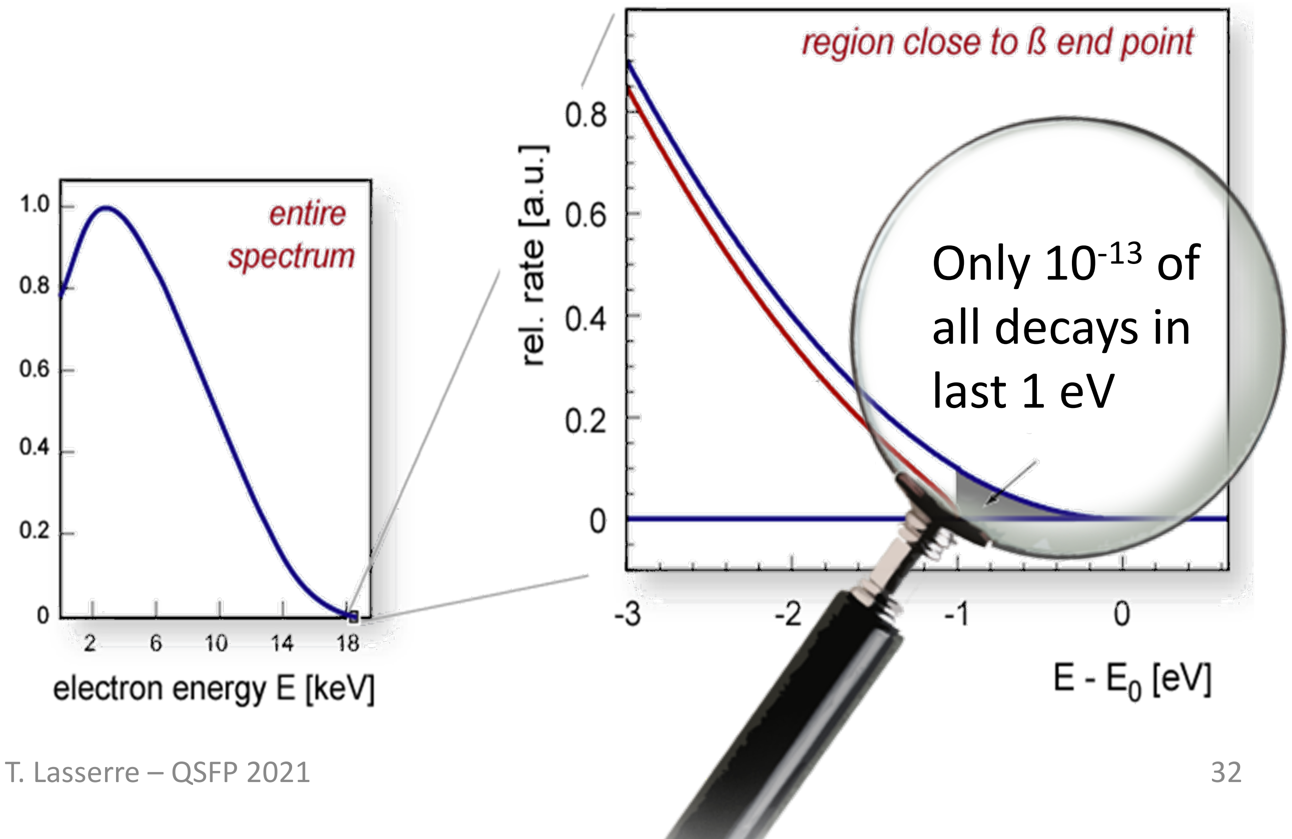
Signal: shape distortion close to the endpoint
- ✓ Independent of cosmology
- ✓ Independent of neutrino nature



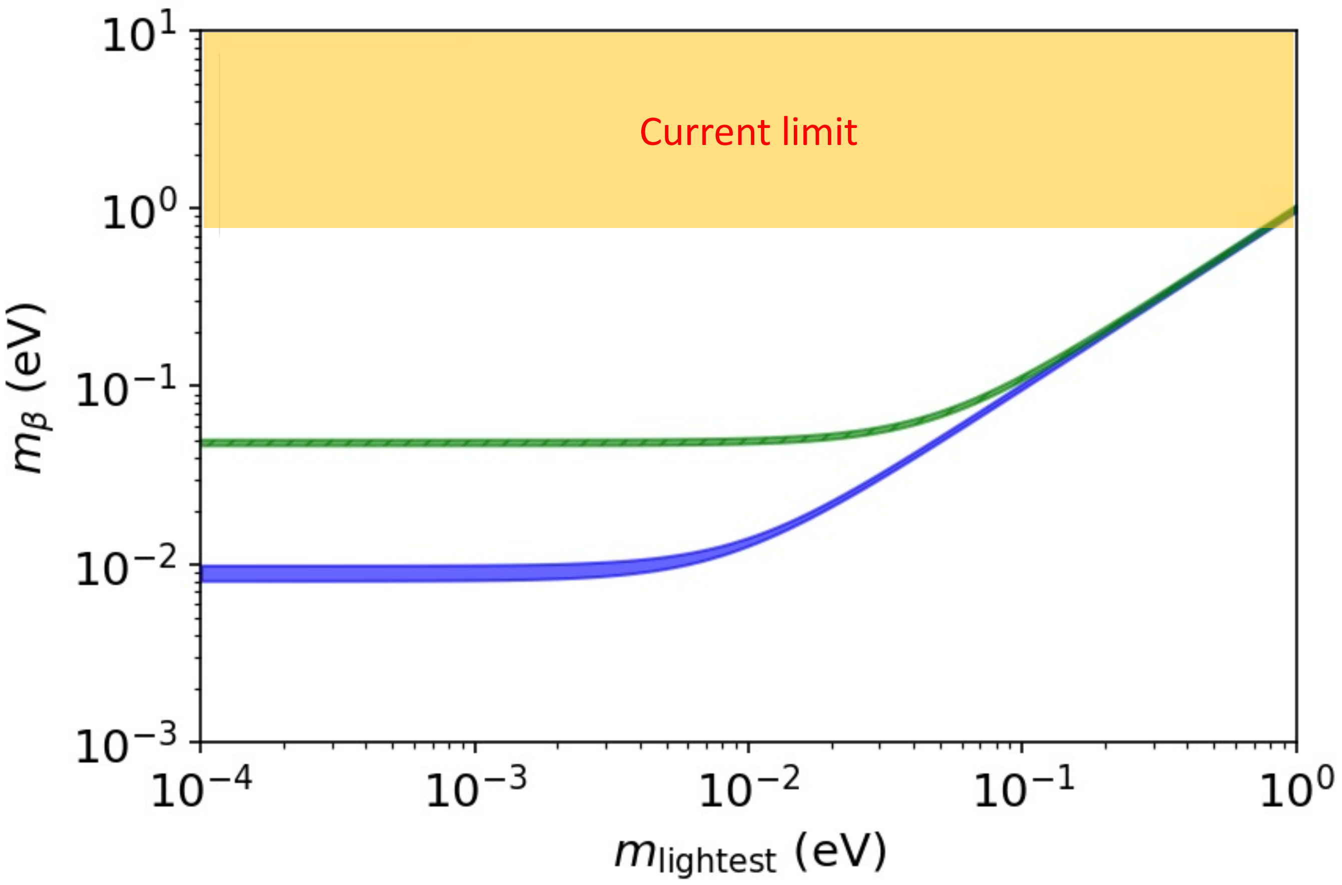
The experimental challenge

Key requirements:

- Ultra-strong radioactive source
  - Tritium (12.3 years, E_0 = 18.6 keV)
  - Holmium (4500 years, E_0 = 2.8 keV)
- Excellent energy resolution (~ 1 eV)
- Low background (< 100 mcps)

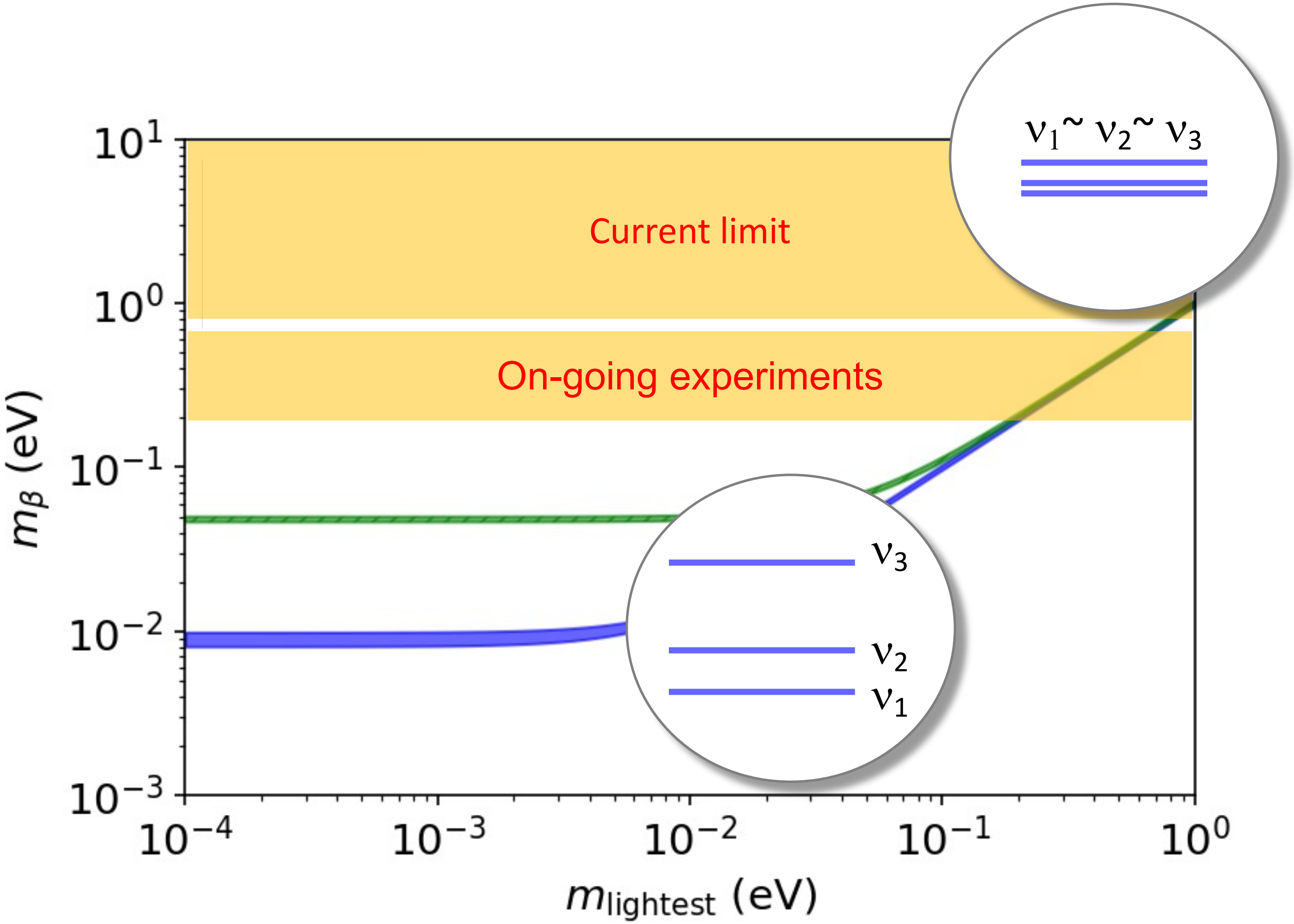


Where do we stand?



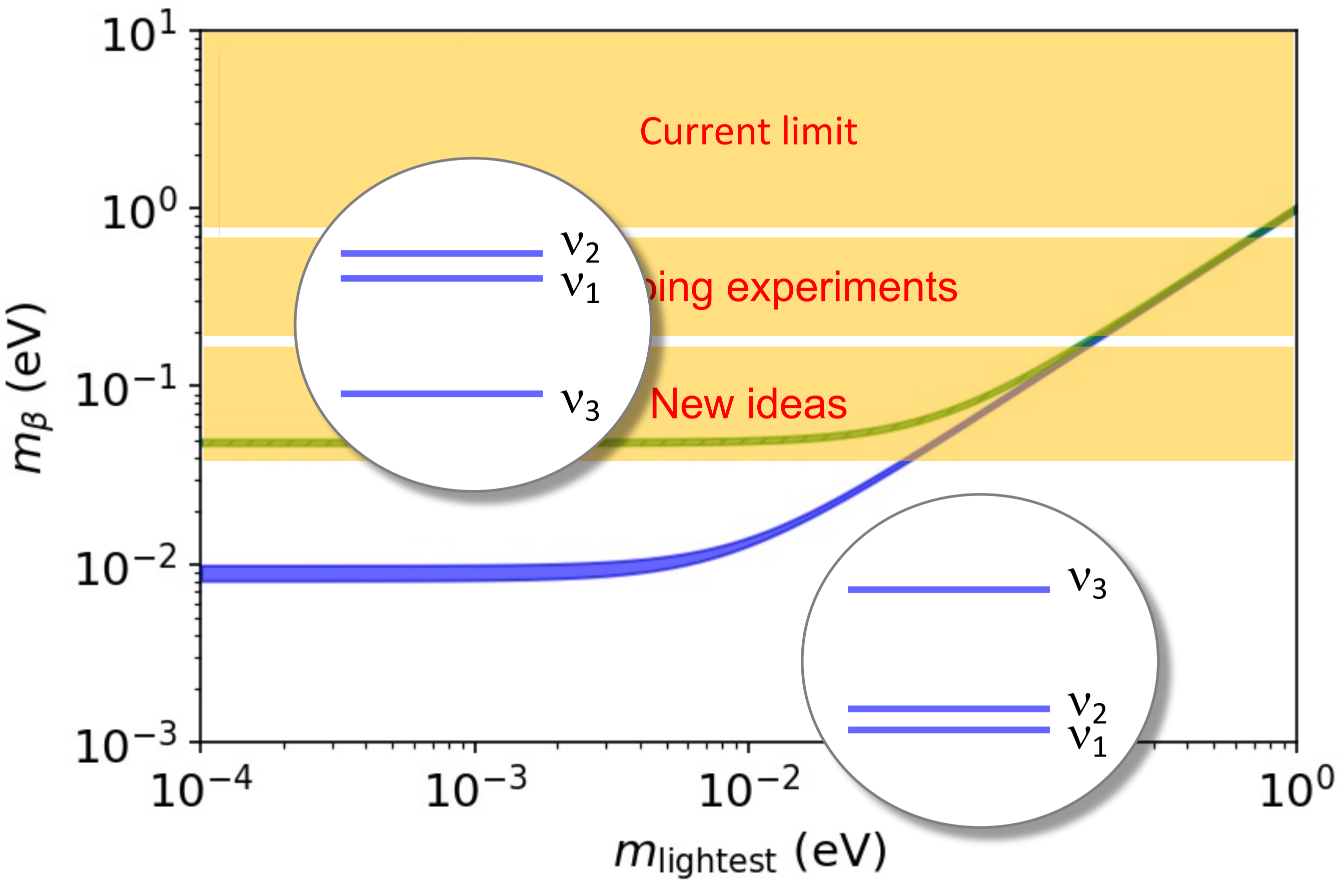
- Current best limit:
  $m_\nu < 0.8$ eV (90% CL)
  KATRIN data release
  KATRIN(2021)

Where do we stand?



- Current best limit:
  $m_\nu < 1.1$ eV (90% CL)
  KATRIN data release
  KATRIN (2021)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario

Where do we stand?



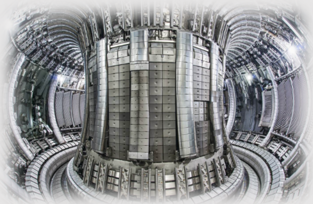
- Current best limit:
  $m_\nu < 1.1$ eV (90% CL)
  KATRIN data release
  KATRIN (2021)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario
- Future:
  Resolve **normal** vs **inverted** neutrino mass ordering

Experimental technologies

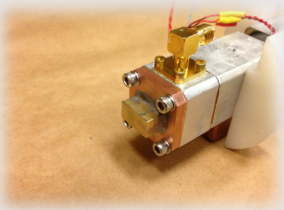
KATRIN
(Tritium)

Electrostatic filter (MAC-E)

QTNM
(Tritium)



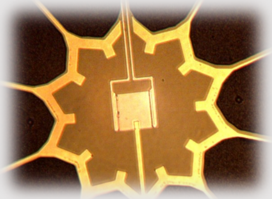
Project-8
(Tritium)



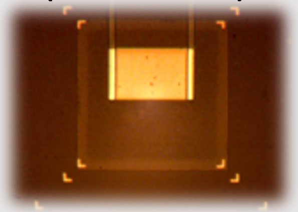
Cyclotron Radiation

Ptolemy
(Tritium)

Holmes
(Holmium)

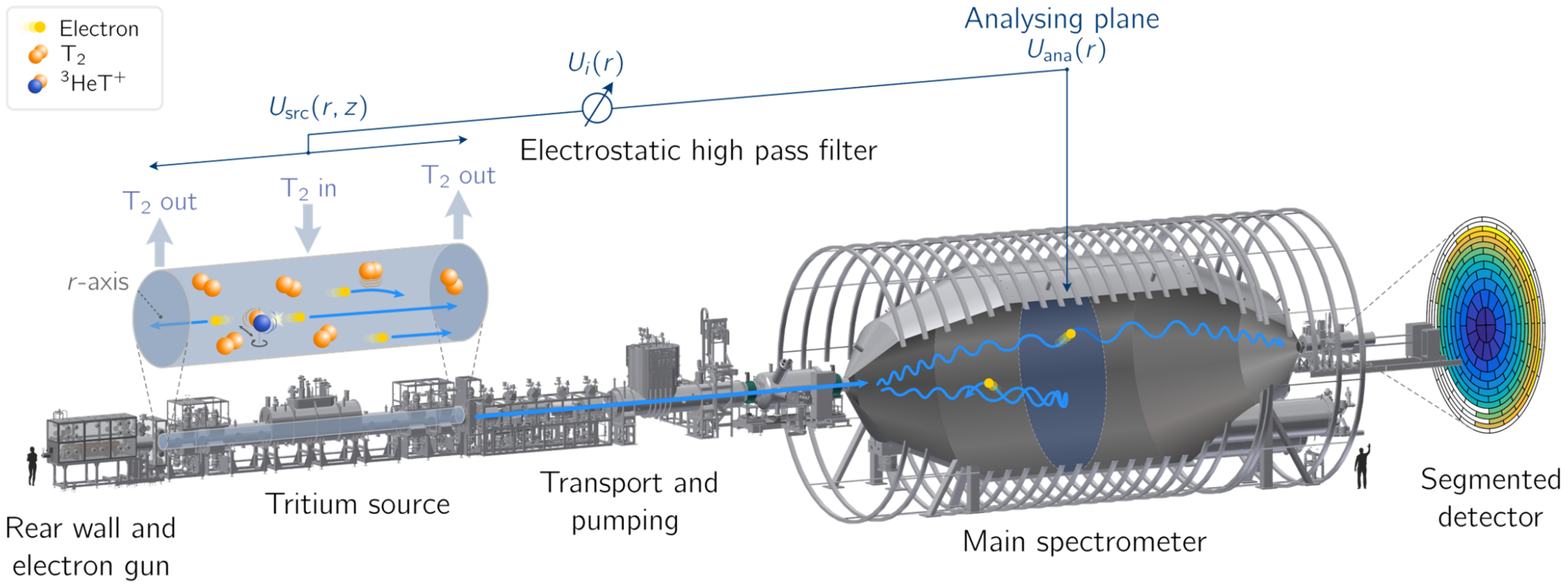


ECHo
(Holmium)



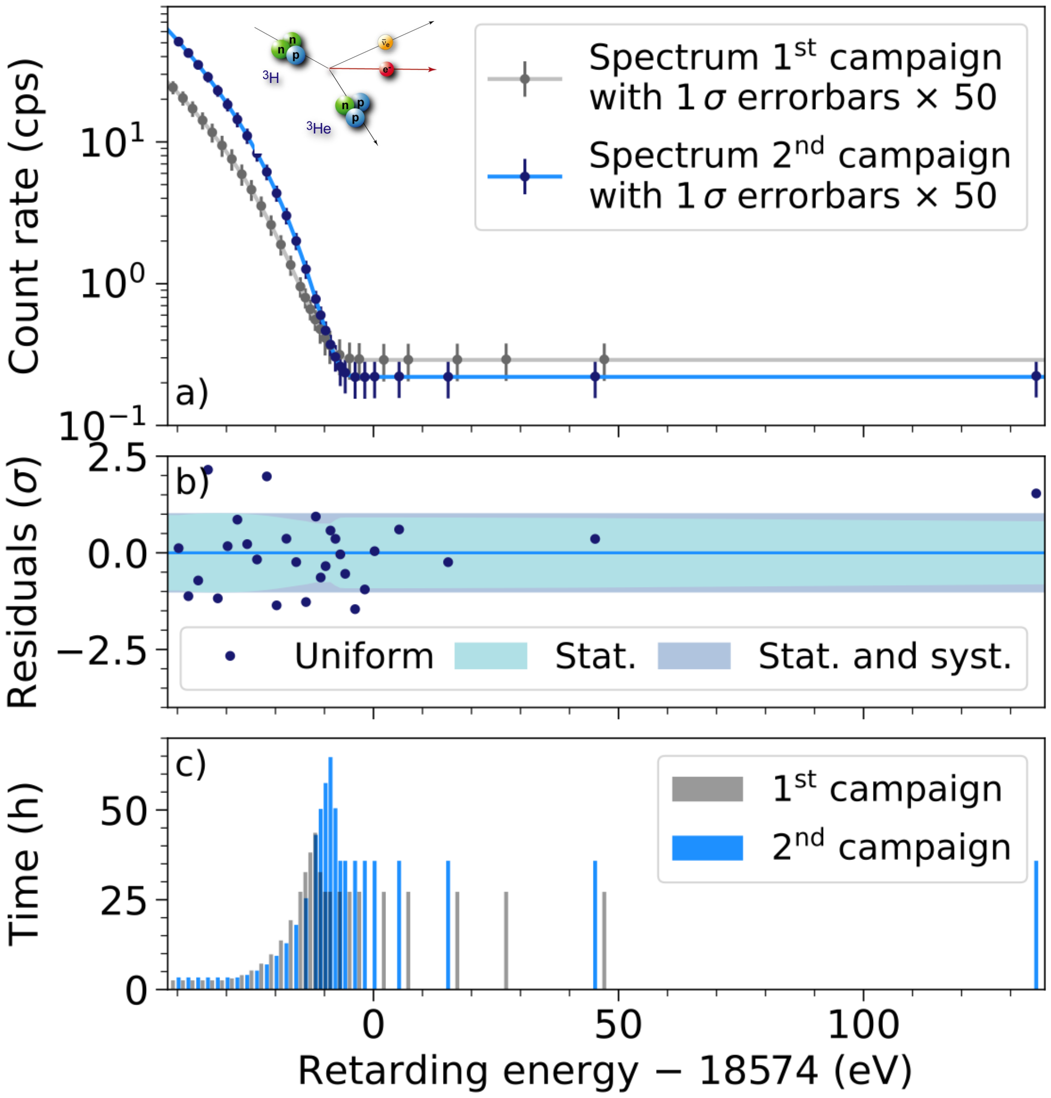
Phonons (Heat)

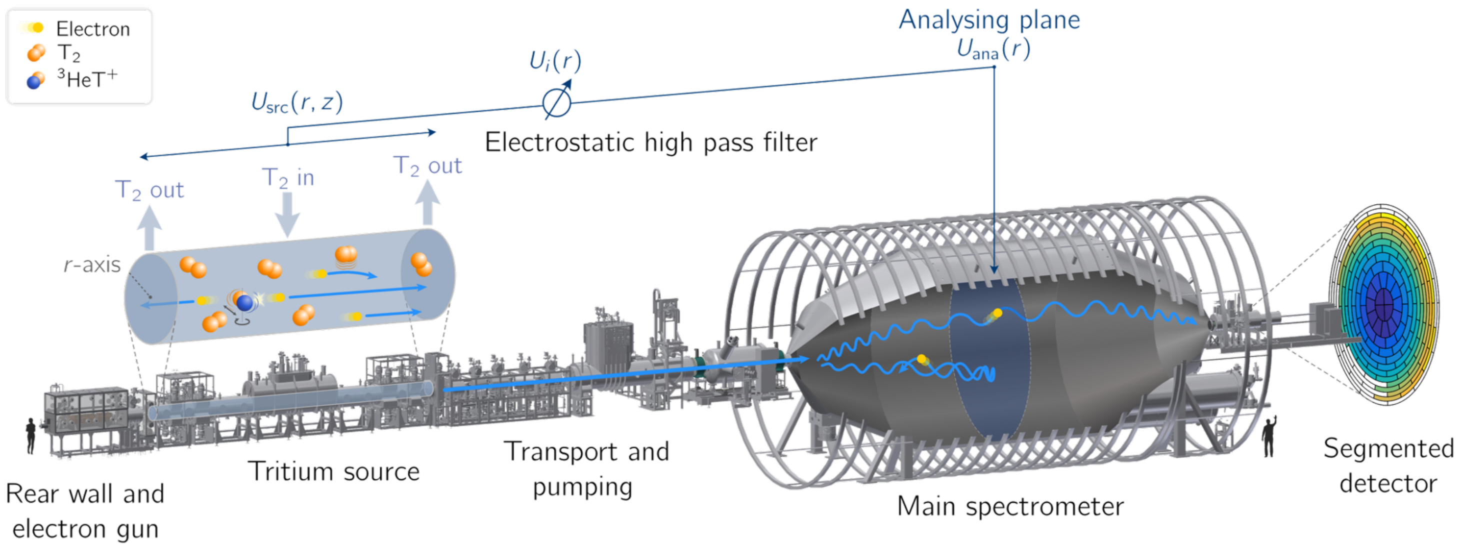
The KATRIN experiment



KATRIN 2019 Science Runs – 1st sub-eV upper limit

https://arxiv.org/abs/2105.08533



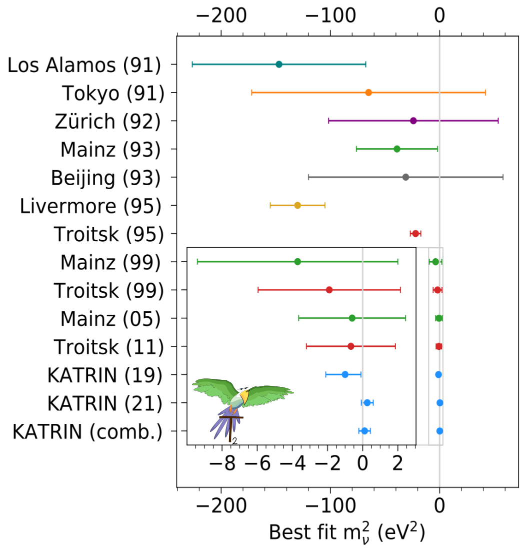


2021 results:

6.5 million events

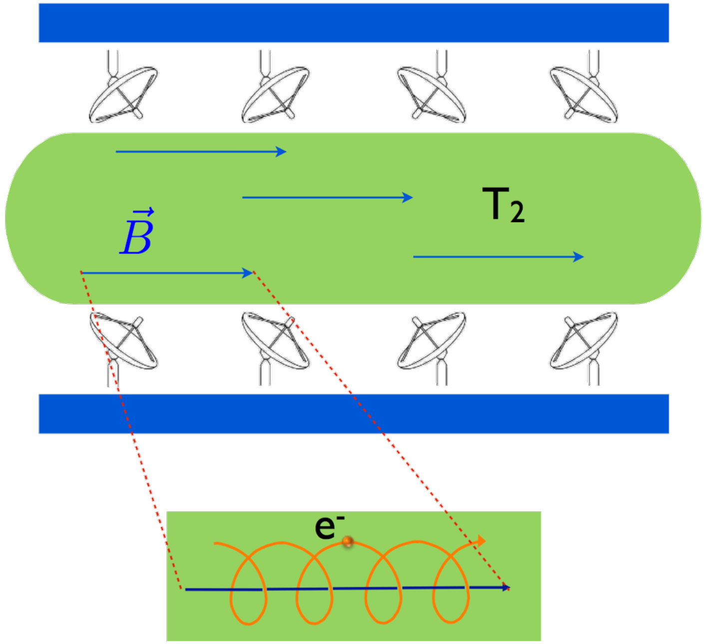
$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2 = (0.1^{+0.3}_{-0.3})\mathrm{eV}^2$

$\mathbf{m_\nu < 0.8}$ **eV (90% CL)**



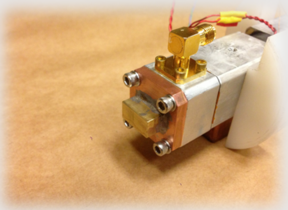
Improving over KATRIN: CRE Technologies

Cyclotron Radiation Emission Spectroscopy (CRES)

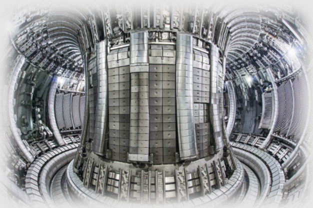


$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$

Project-8
(Tritium)



QTNM
(Tritium)



Electrostatic filter (MAC-E)

Cyclotron Radiation

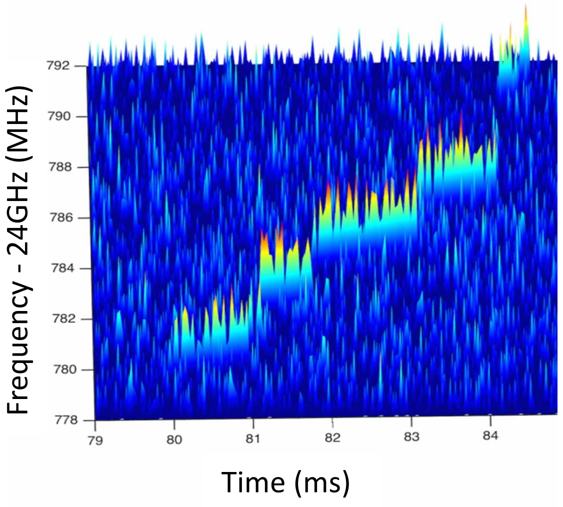
Phonons

Project 8

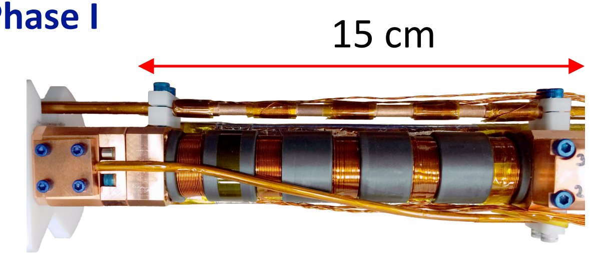
✓ **Phase I (2014-16)**
demonstration of CRES technique

✓ **Phase II (completed 2020)**
mol. tritium spectrum with small waveguide cell

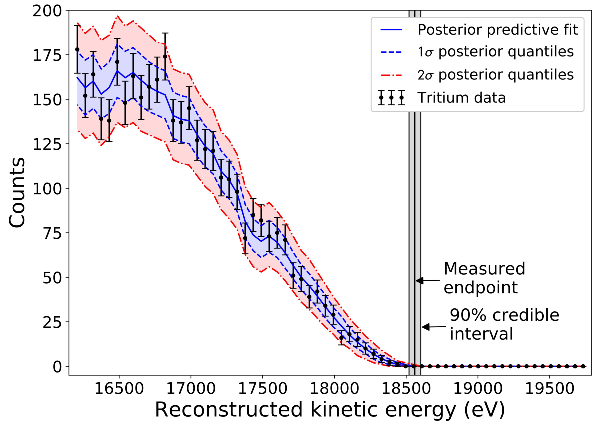
- **Phase III (next)**
large-volume cell with open antenna array
- **Phase IV (in prep.)**
develop atomic tritium source
- **Ultimate goal:**
40 meV sensitivity



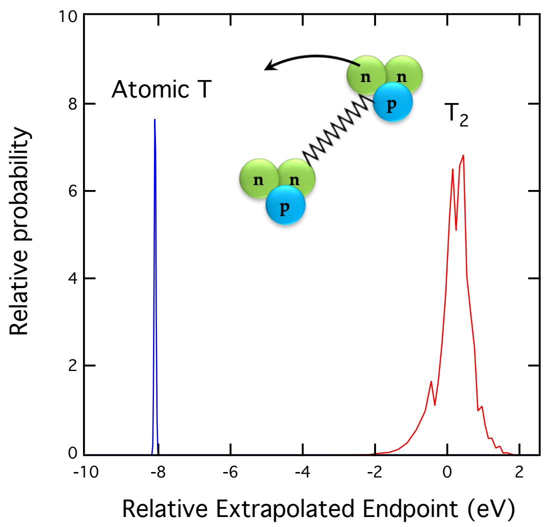
Phase I

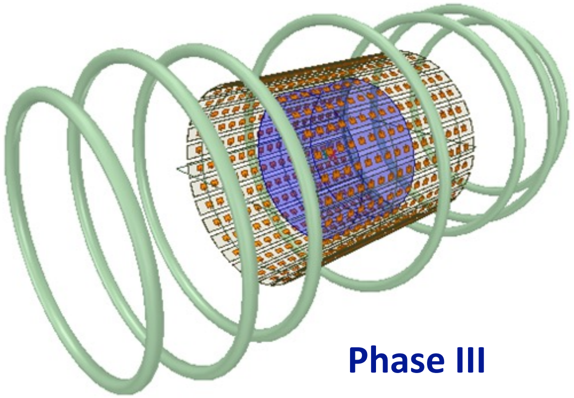


Phase II



Phase IV

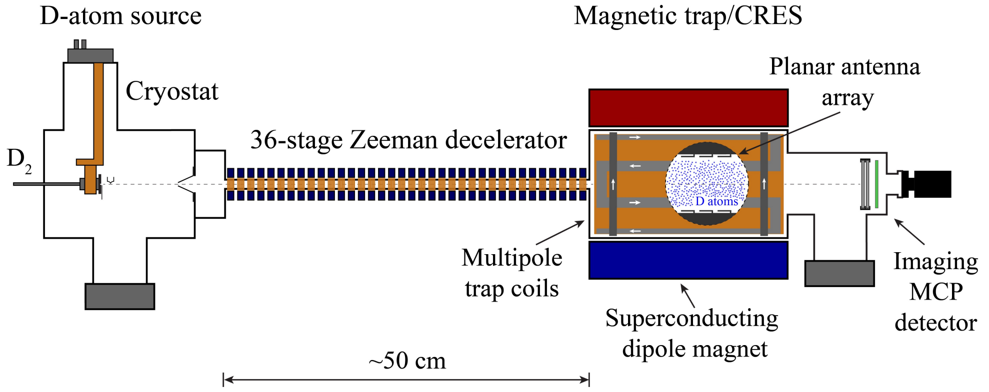


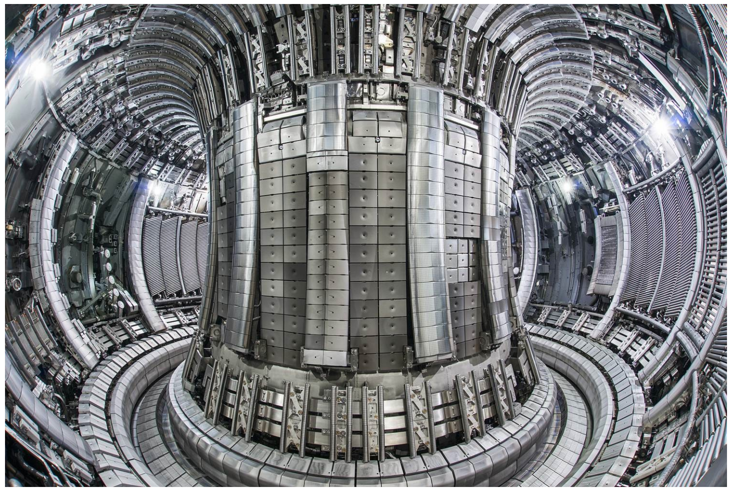


Phase III

QTNM: Quantum Technology for Neutrino Mass*

- *Goal*: To build on recent **investment** in **quantum sensors** to assess feasibility of an **experiment** capable of a positive **neutrino mass measurement** from **^{3}H β-decay** using **CRES** technology.
- 2021-2024: CRESDA:
  CRES based on Deuterium but "Tritium-ready"
- 2025-2029:
  - CRESDA at tritium facility)
  - Tritium phase demonstration
  - O(eV) sensitivity
- "Ultimate" international project > 2029
  - O(meV) sensitivity





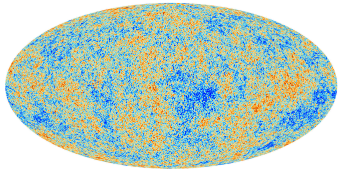
*one of 7 projects funded for 3 years under the UKRI **QTFP** Programme

Neutrino Mass & Cosmology

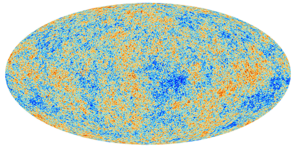
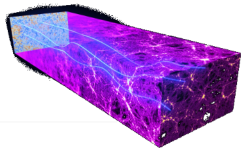
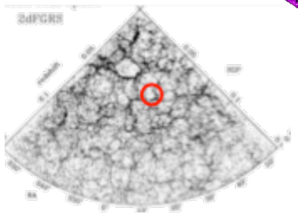
$\sum_i m_i$

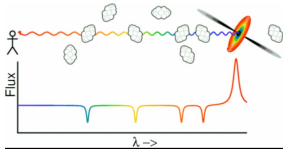
$> \sim 1$ **eV**: $\nu' s$ become non relativistic before recombination

- Imprint in the CMB spectrum
- Rock-solid upper bound

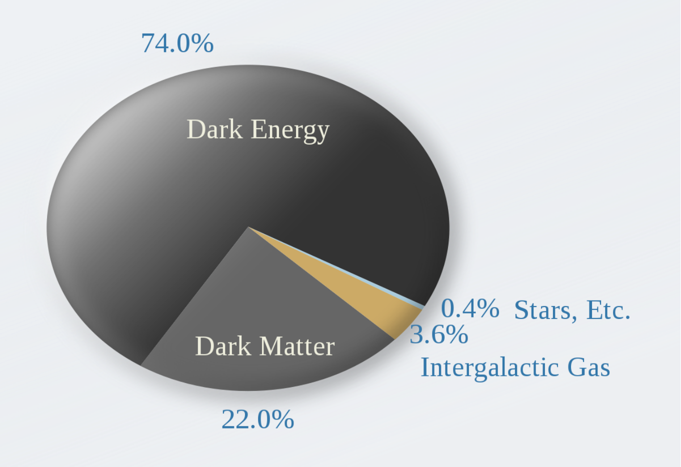


$< \ \sim 1$ **eV**: $\nu' s$ become non relativistic after recombination

- ν masses suppress the matter power spectrum on small scales
- Constraints from:
  - CMB 
  - + CMB-lensing 
  - + BAO 

  - + RSD
  - + Lyman-α 

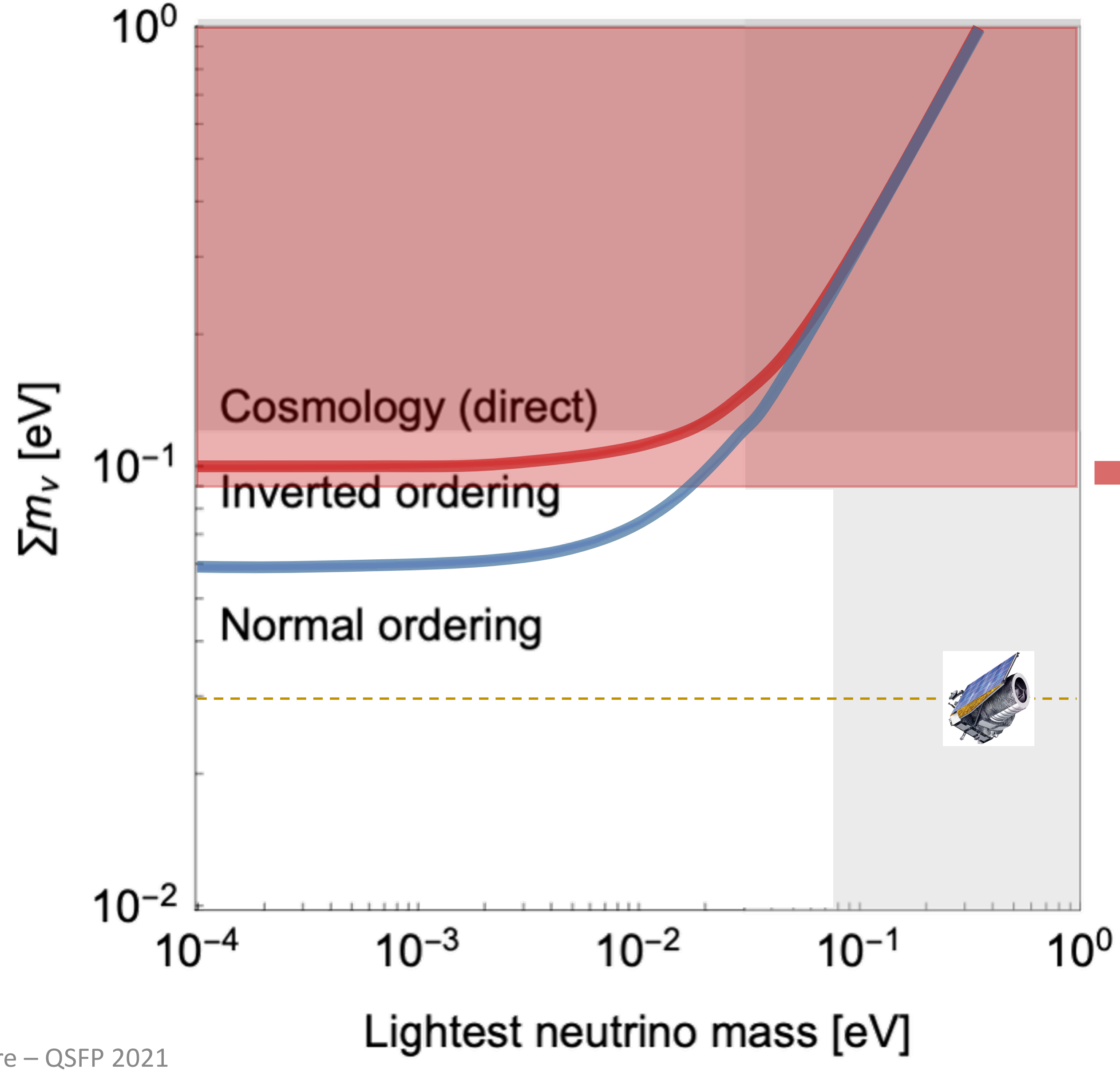
Constraints based on Λ**CDM**



JCAP 04 (2020) 038

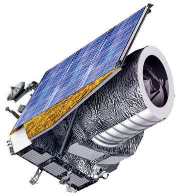
$$\sum m_i < 0.09 \text{ eV}$$

Neutrino Mass & Cosmology



$$\sum \mathbf{m_i} < \mathbf{0.09\ eV}$$

- Disfavor the Inverted Ordering
- Prospects – signal expected!
  - DESI LSS
  - Euclid $\sum m_i < 0.03$ eV

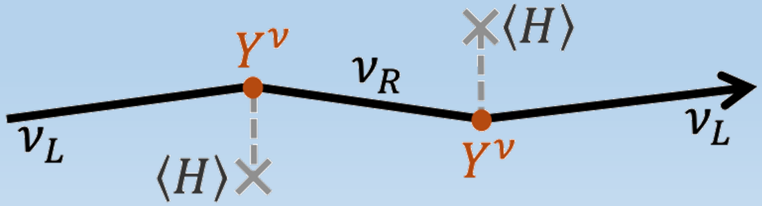


Is Lepton Number conserved?

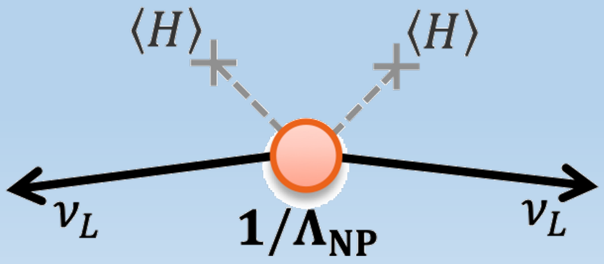
Creation of matter without antimatter partners ?

Dirac or Majorana ν?

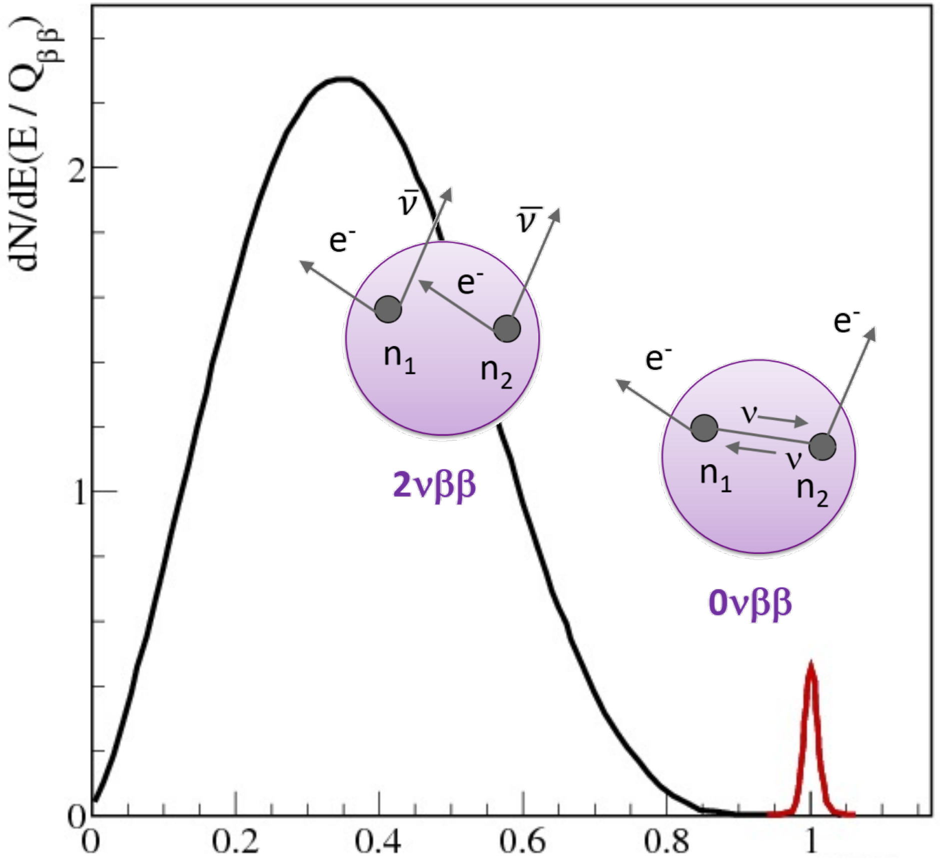
$$\nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix}$$



$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$



$0\nu\beta\beta$ Decay: General Idea



Energy of the two beta electrons

If $0\nu\beta\beta$ is discovered:

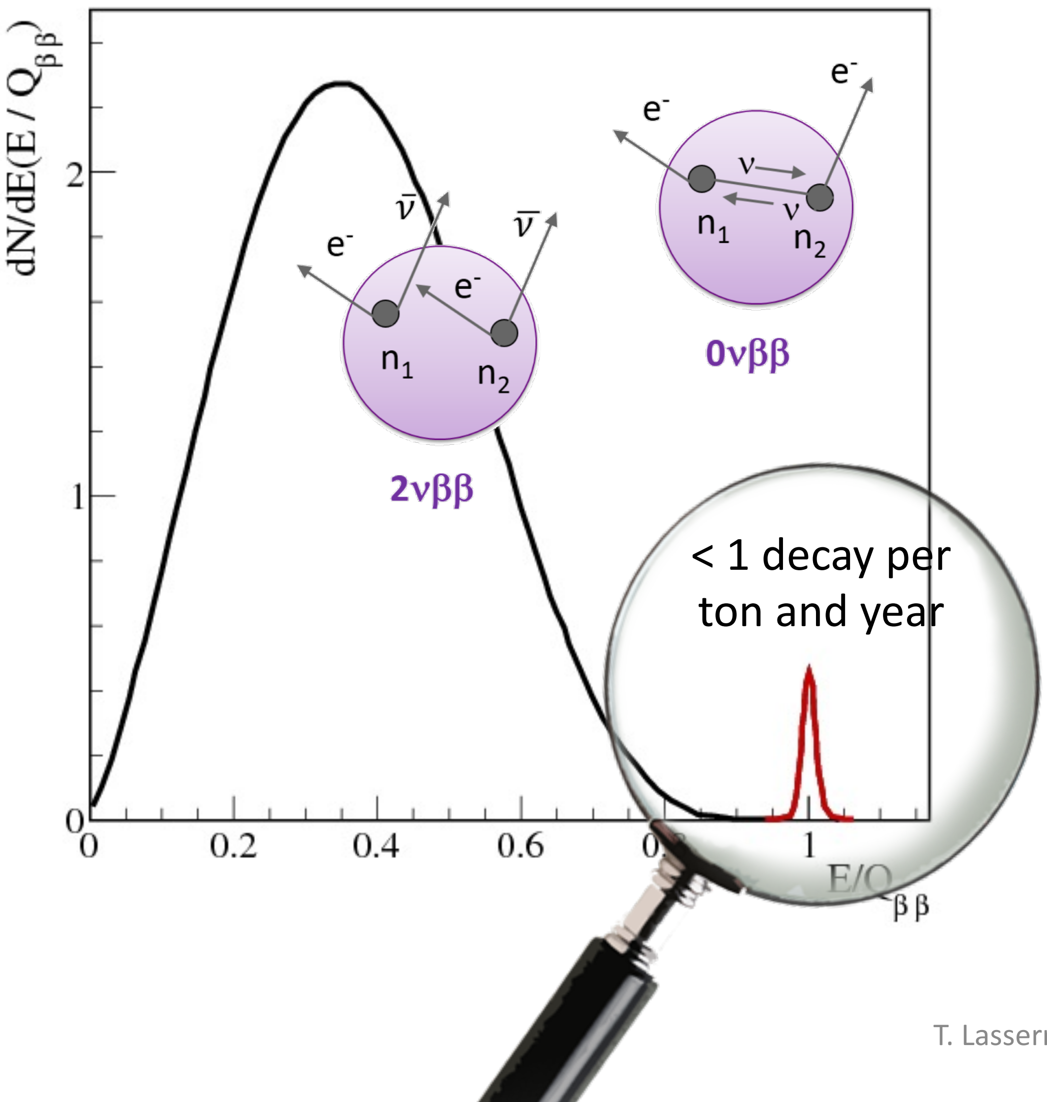
- Proof that neutrinos are Majorana particles and that Lepton number is violated
- Half life reveals neutrino mass

$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 \cdot G_{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \boldsymbol{m_{\beta\beta}^2}$$

^{48}Ca, ^{76}Ge*, ^{82}Se, ^{96}Zr, ^{100}Mo*, ^{110}Pd, ^{116}Cd, ^{124}Sn, ^{130}Te*, ^{136}Xe*, and ^{150}Nd

* Most promising for next-generation searches

$0\nu\beta\beta$ Decay: Experimental Challenges



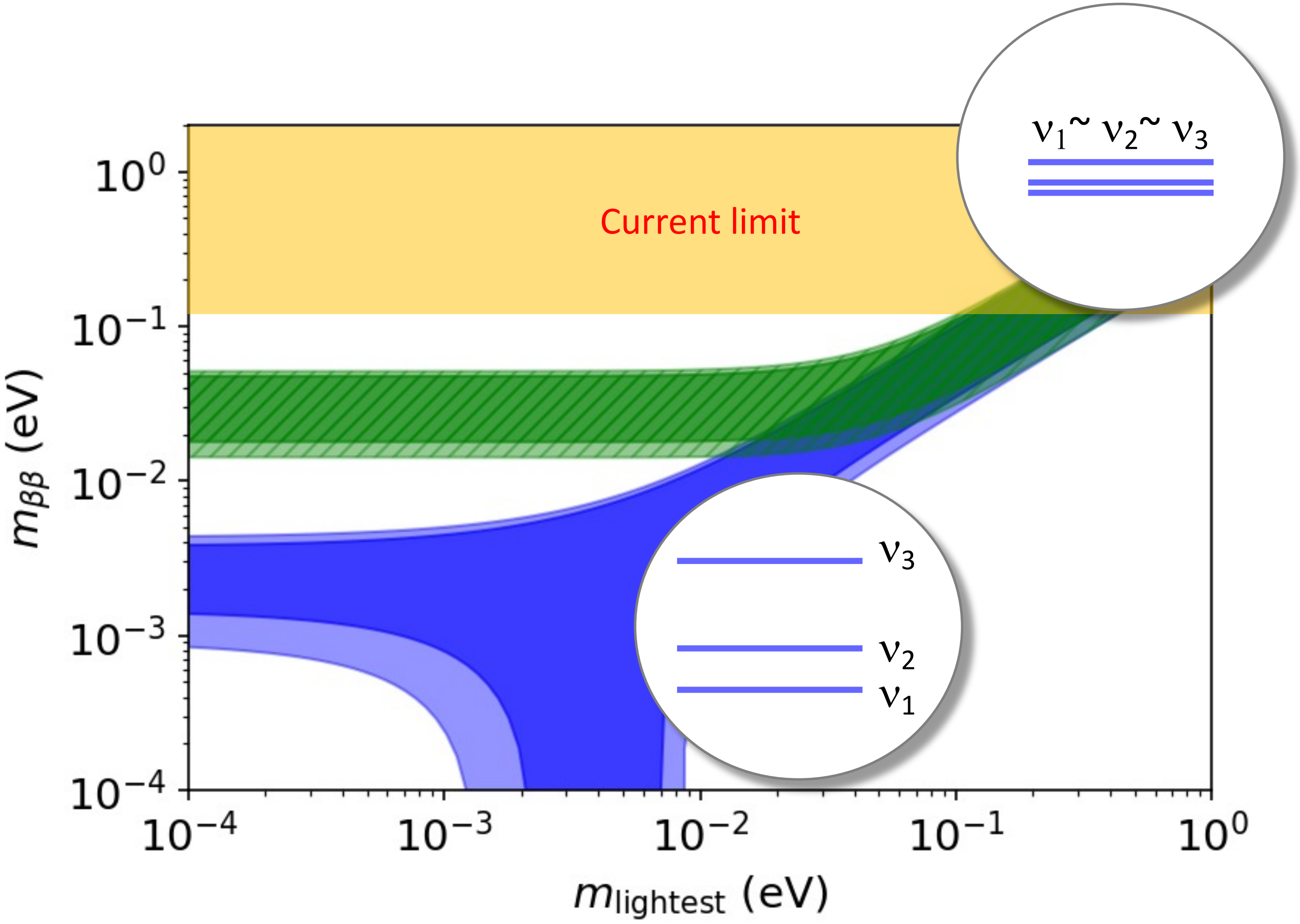
<u>Never observed – Best limits $T^{0\nu}_{1/2} > 10^{24}$ - 10^{26} y</u>

$$\frac{10^{25}\ \mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2$$

<u>Key requirements:</u>

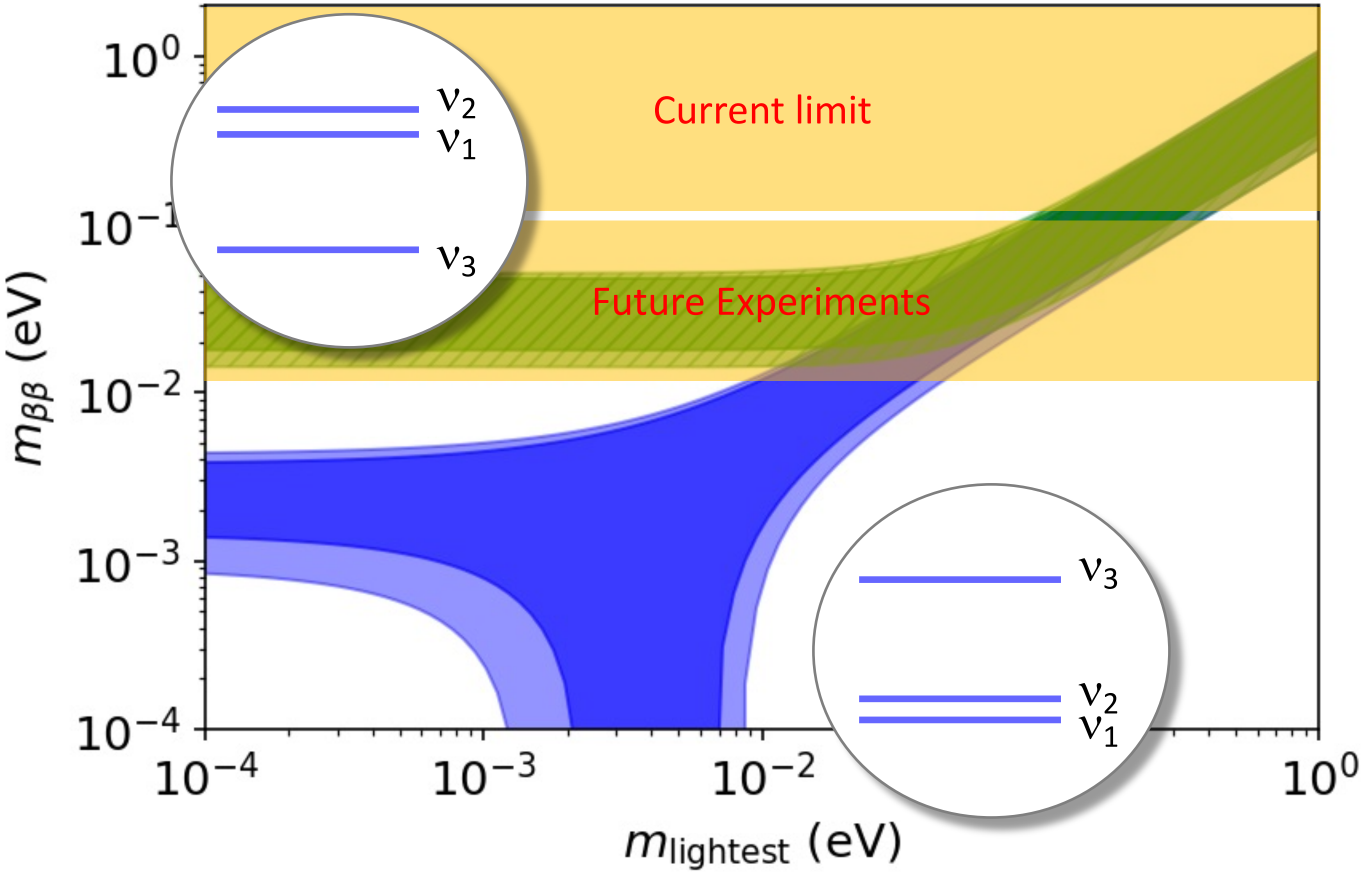
- Large exposure (tonne-scale)
- Excellent energy resolution (~ 1% @ $Q_{\beta\beta}$)
- Ultra-low background (< 1 cts/year/t/ROI)

Where do we stand?



- Current limits (GERDA):
  $T_{1/2} > \mathcal{O}(10^{26}$ y) (90% CL)
  $m_{\beta\beta} < \mathcal{O}(100)$ meV
  Phys. Rev. Lett. 117 (2016), 082503
  Phys. Rev. Lett. 120 (2018) 132503

Where do we stand?



- Current limits (GERDA):
  $T_{1/2} > \mathcal{O}(10^{26}$ y) (90% CL)
  $m_{\beta\beta} < \mathcal{O}(100)$ meV
  Phys. Rev. Lett. 117 (2016), 082503
  Phys. Rev. Lett. 120 (2018) 132503

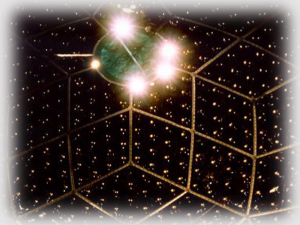
- Goal of future experiments:
  Probe inverted mass ordering

Experimental efforts

KamLand Zen 800 (136-Xe)
SNO+ (130-Te)

DARWIN (136-Xe)

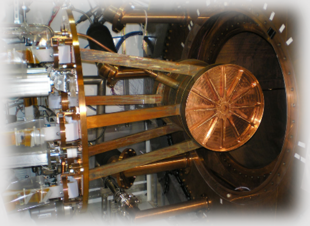
KamLand Zen
(^{136}Xe)



CUPID (100-Mo)

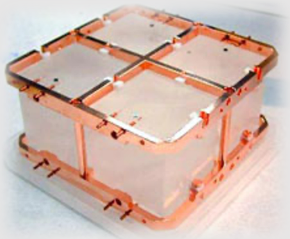
Scintillation

EXO-200
(^{136}Xe)



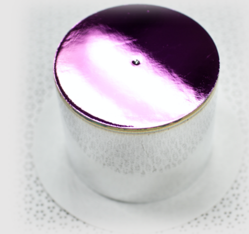
nEXO (136-Xe)
NEXT (136-Xe)
PANDA-X (136-Xe)

CUORE
(^{130}Te)



LEGEND (^{76}Ge)

MAJORANA
GERDA (^{76}Ge)

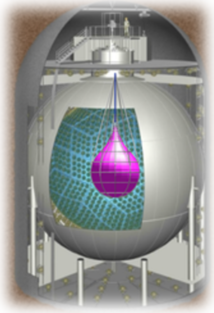


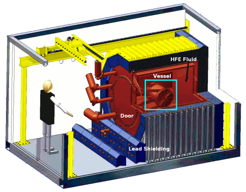
Phonons

Ionization

AMORE, Super-NEMO-Demonstrator, COBRA, CANDLES, and many more

Latest $0\nu\beta\beta$ Results





Large source mass
Easily scalable

Fluid embedded source

KamLAND-Zen 400	Dilution in liquid scintillator	^{136}Xe
EXO-200	Liquid TPC	^{136}Xe

Completed
Data taking

TAUP 2021 VALENCIA A. Giuliani

High energy resolution / efficiency

Crystal embedded source

MAJORANA DEM.	Semiconductor detectors	^{76}Ge
GERDA	Semiconductor detectors	^{76}Ge
CUPID-0	Scintillating bolometers	^{82}Se
CUPID-Mo	Scintillating bolometers	^{100}Mo
CUORE	Bolometers	^{130}Te

Latest $0\nu\beta\beta$ Results

$T_{1/2} > 10^{24}$ y 90% C.I. restricted club

GERDA $T_{1/2} > 1.8\times10^{26}$ y
Phys. Rev. Lett. 125, 252502 (2020)

KamLAND-Zen 400 $T_{1/2} > 1.07\times10^{26}$ y
Phys. Rev. Lett. 117, 082503 (2016)

EXO-200 $T_{1/2} > 3.5\times10^{25}$ y
Phys. Rev. Lett. 123, 161802 (2019)

MAJORANA dem. $T_{1/2} > 2.7\times10^{25}$ y
Phys. Rev. C 100, 025501

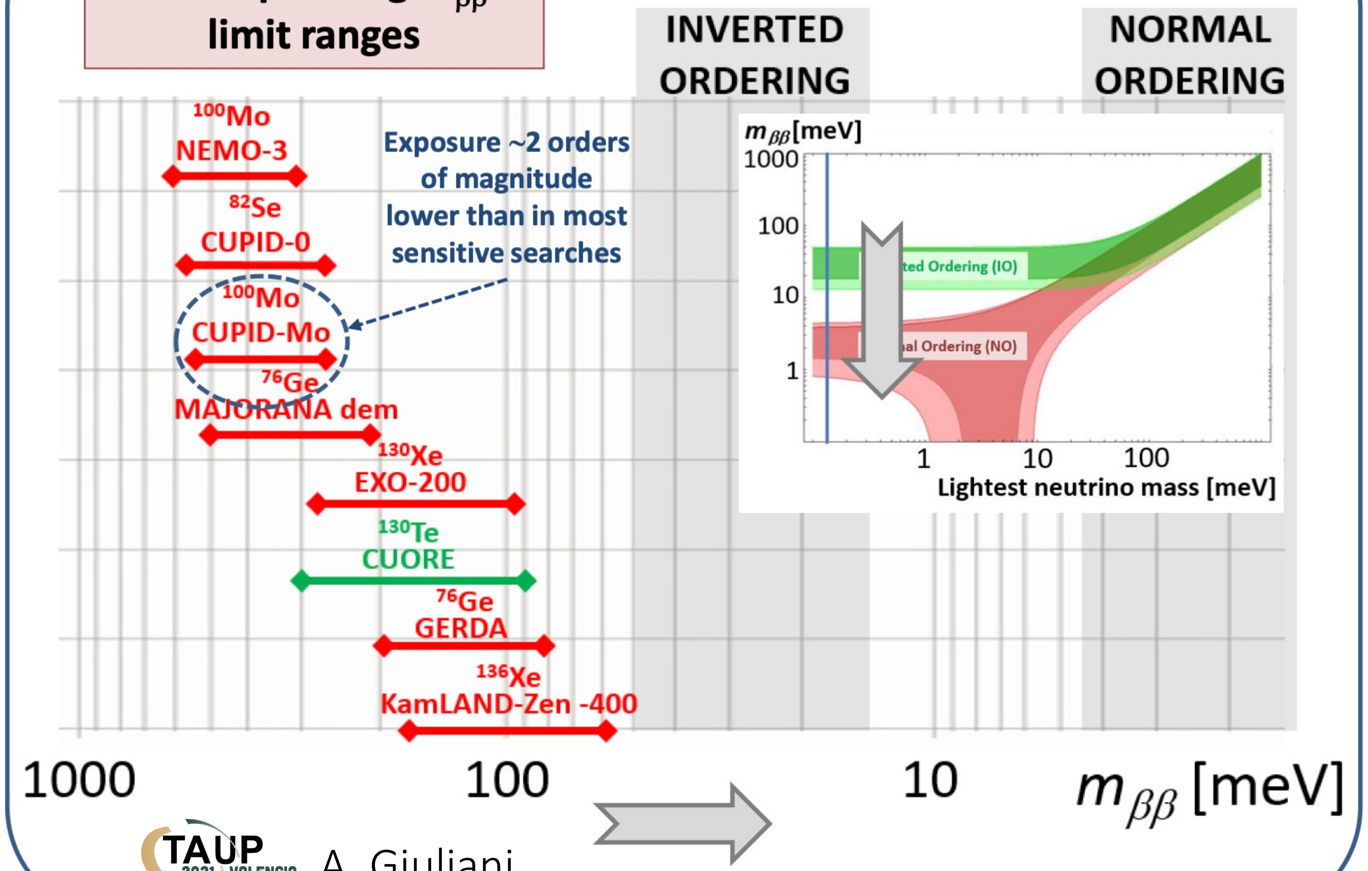
CUORE $T_{1/2} > 2.2\times10^{25}$ y
arXiv:1907.09376

CUPID-0 NEW $T_{1/2} > 4.7\times10^{24}$ y
L. Pagnanini, this conference

CUPID-Mo NEW $T_{1/2} > 1.8\times10^{24}$ y
B. Welliver, this conference

NEMO-3 $T_{1/2} > 1.1\times10^{24}$ y
Phys. Rev. D 92, 072011 (2015)

Corresponding $m_{\beta\beta}$ limit ranges



TAUP 2021 VALENCIA A. Giuliani

Prospects within 5 years

and beyond…

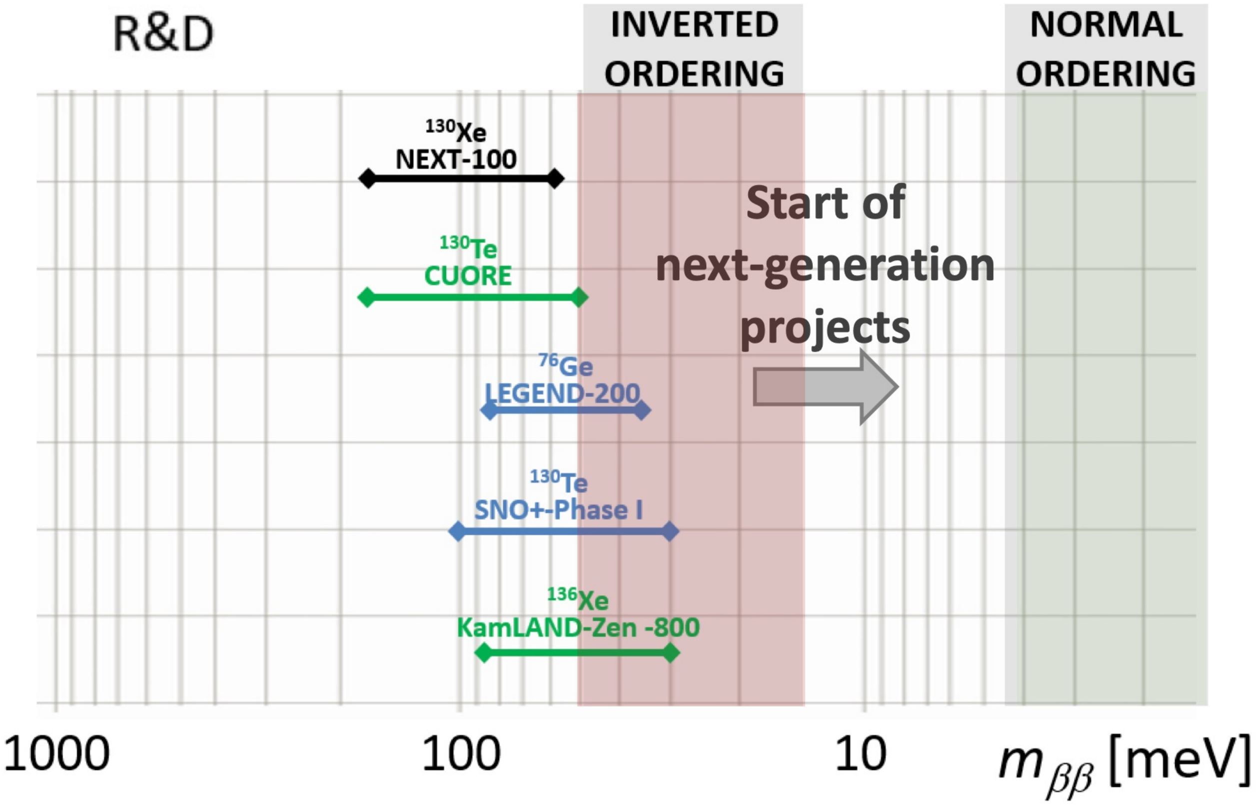
Data taking

Construction / Commissioning

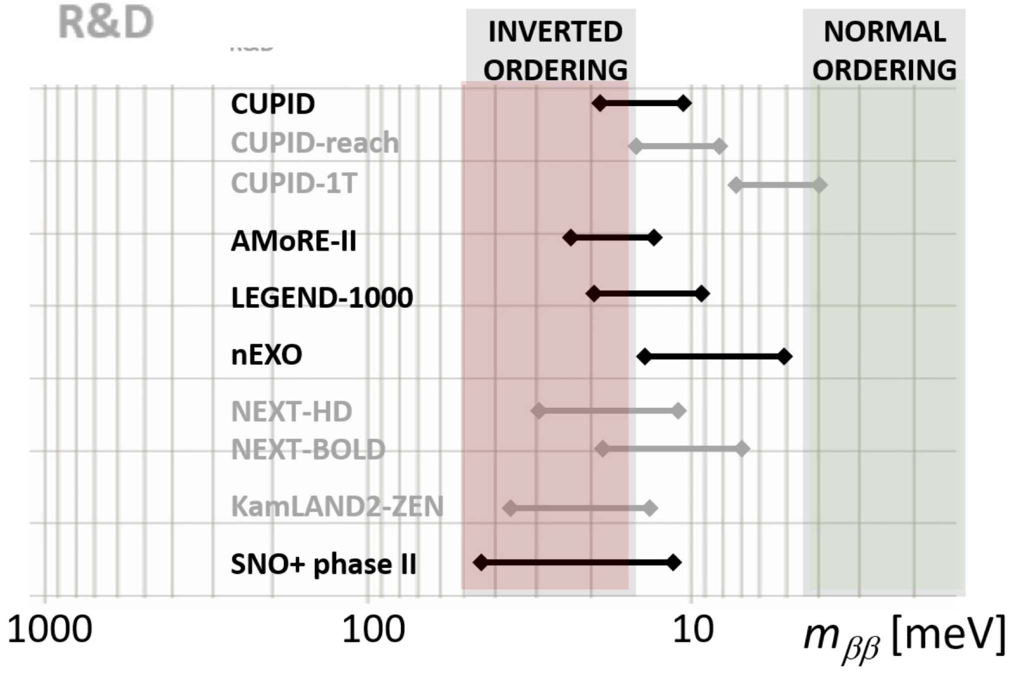
Advanced R&D

R&D

TAUP 2021 VALENCIA A. Giuliani

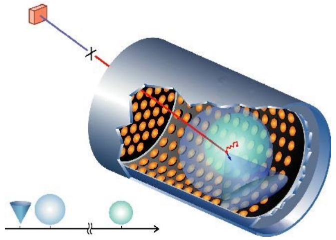


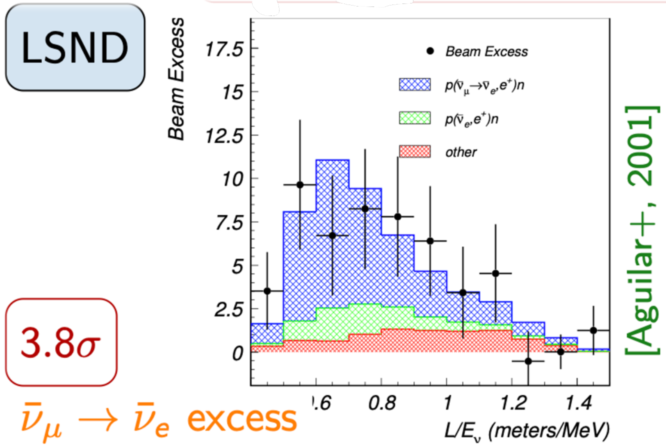
Planned experiments are expected reach their final sensitivity by 2030-2040



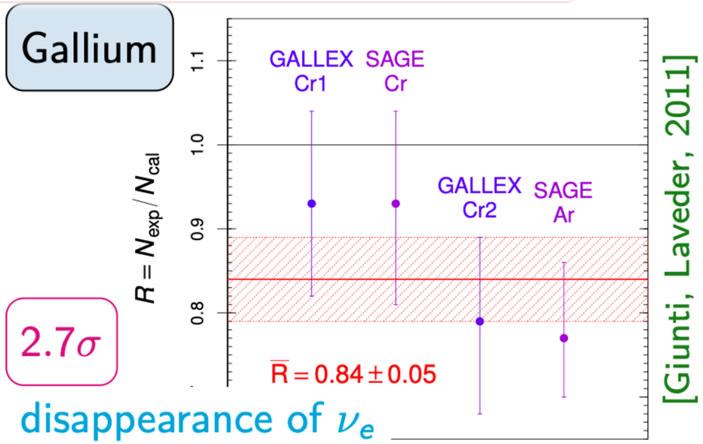
Are there additional light (sterile) ν states?

A bunch of unexplained anomalies at $\mathbf{L_{[m]}/E_{[MeV]}} \sim 1$

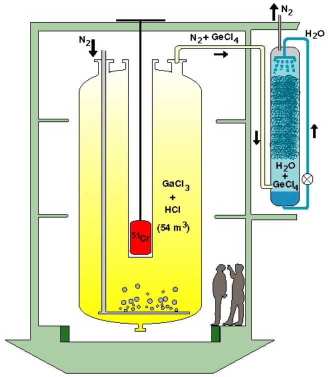


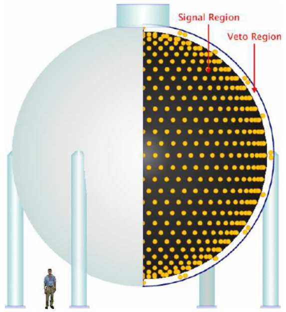


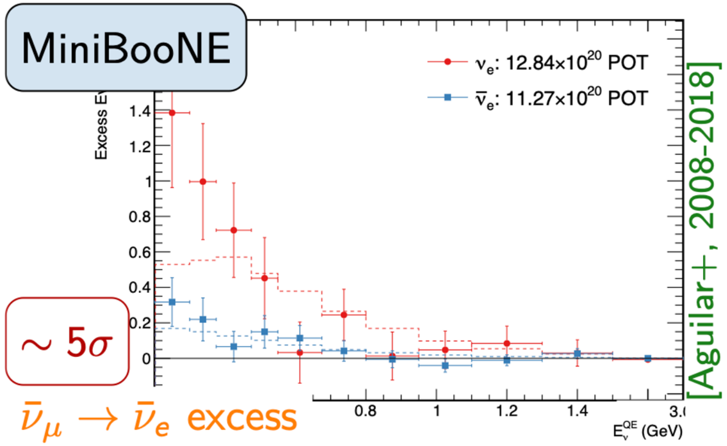
$\bar{\nu}_\mu \to \bar{\nu}_e$ excess



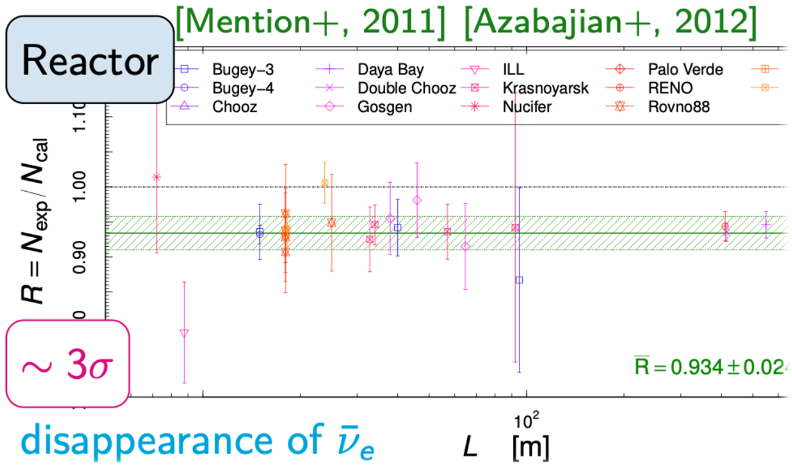
disappearance of ν_e



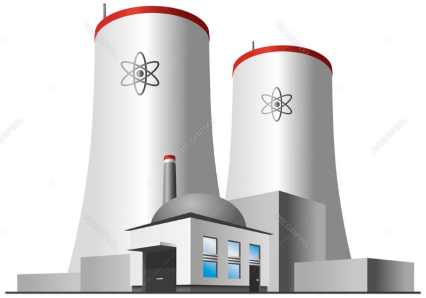




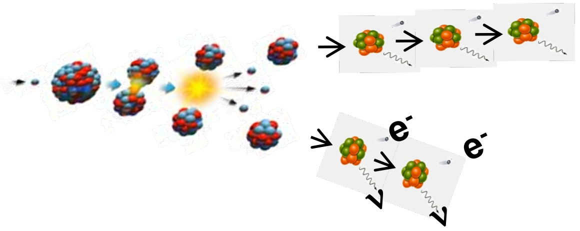
$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

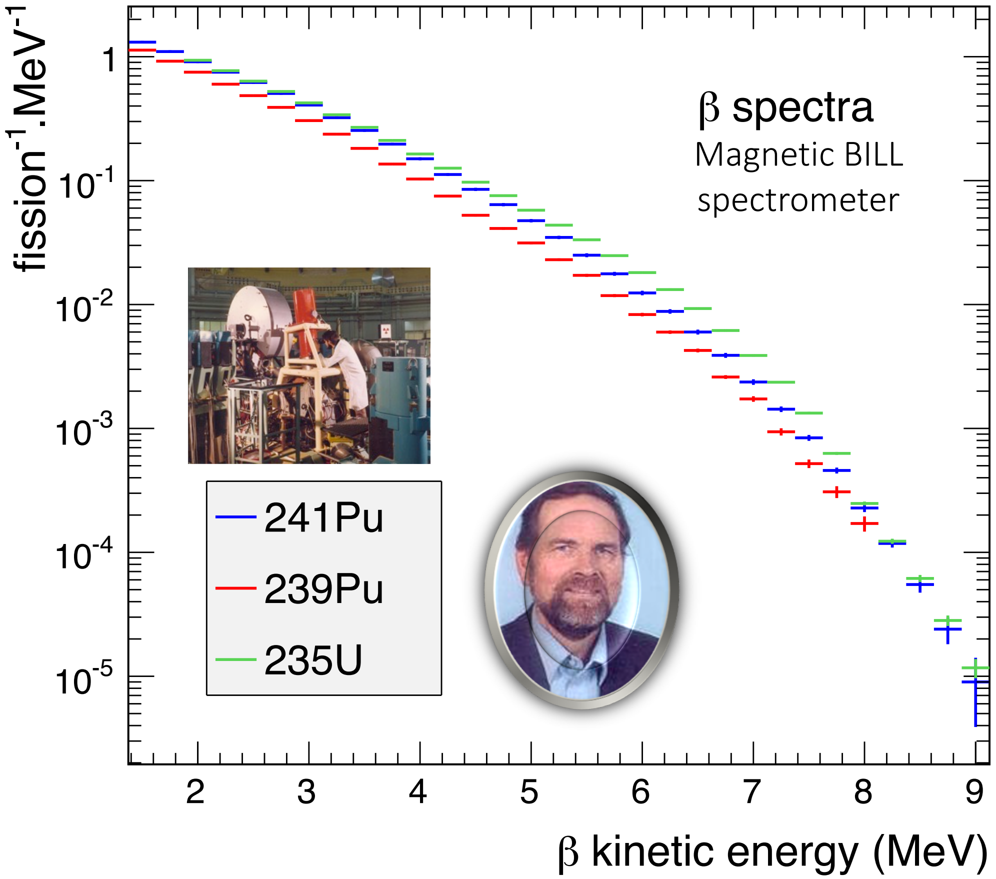


disappearance of $\bar{\nu}_e$



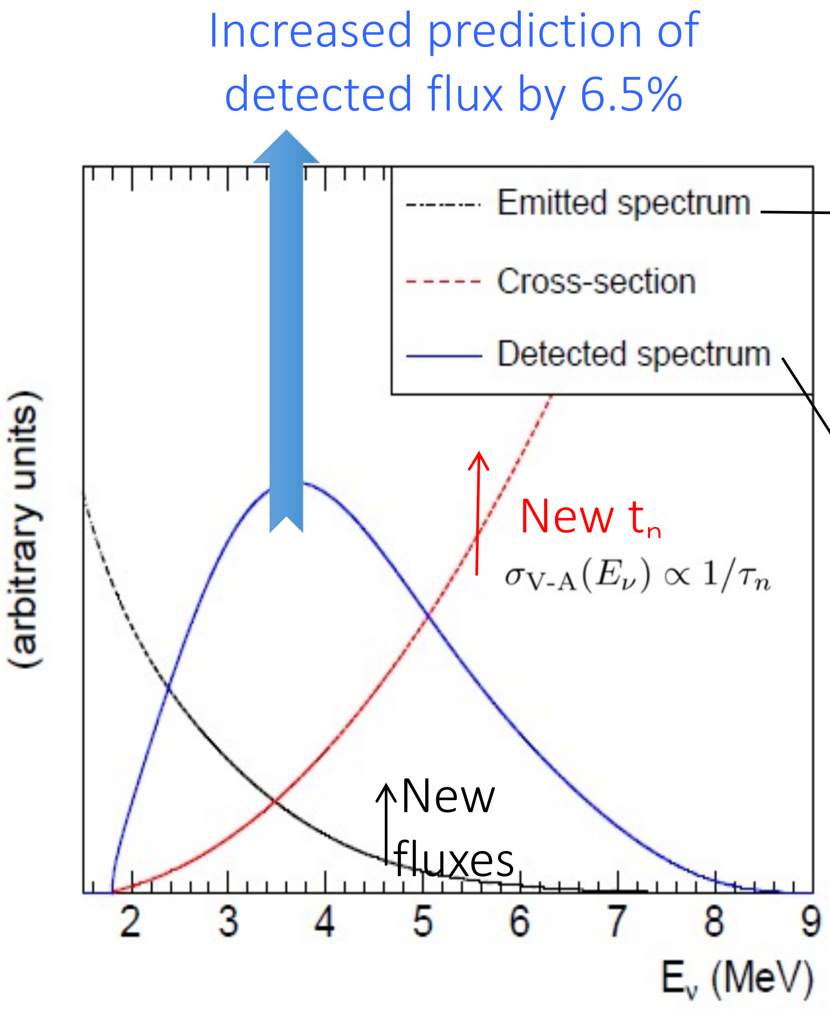
Reactor Neutrino Flux and Spectra





2011: Reevaluation of the $e-\nu$ conversion procedure – Flux reevaluated at + 3.5%!

Reevaluation of the reactor neutrino fluxes in 2011



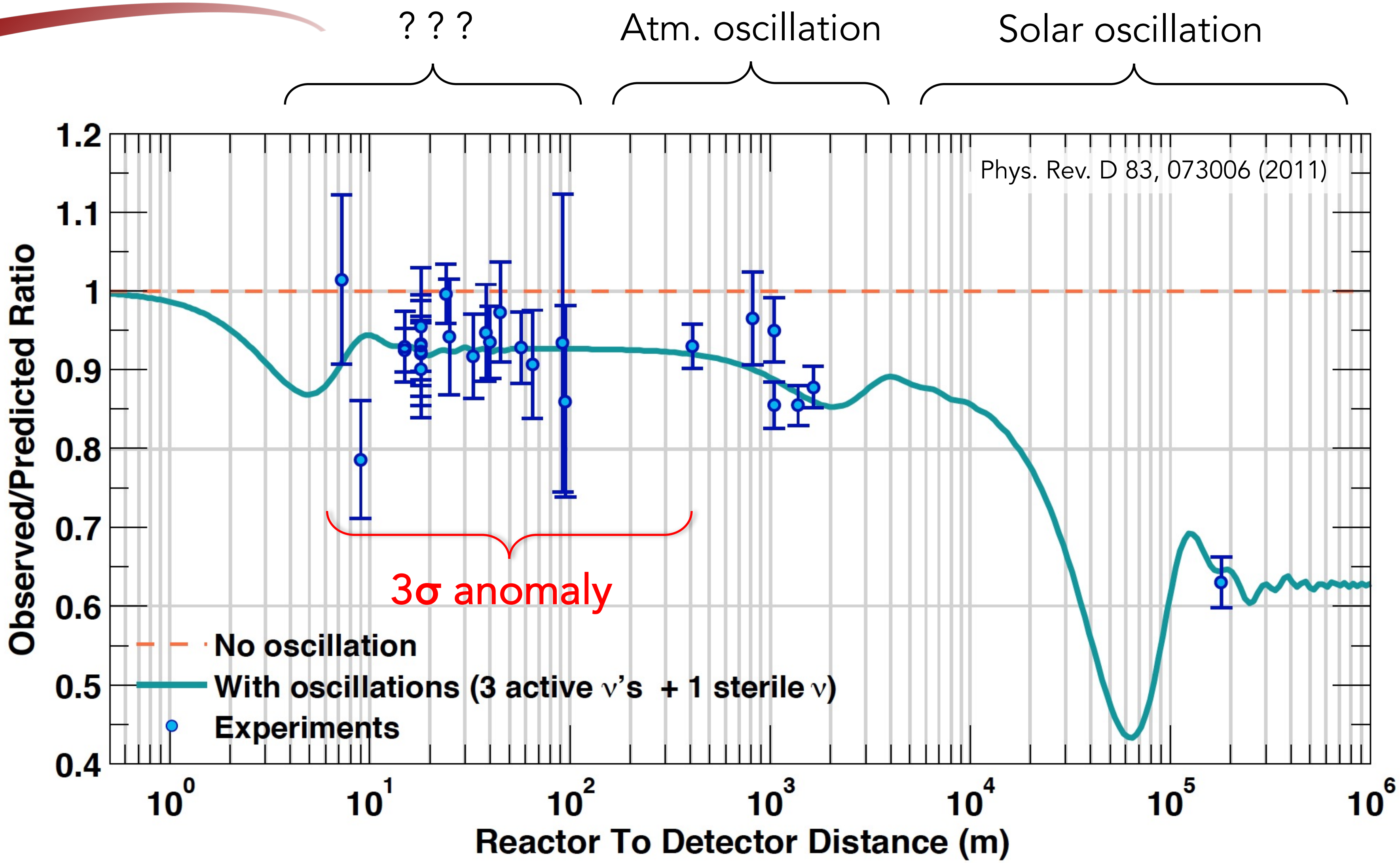
i) Neutrino Emission:

- Improved reactor neutrino spectra → +3.5%
- Accounting for long-lived isotopes in reactors → +1%

i) Neutrino Detection:

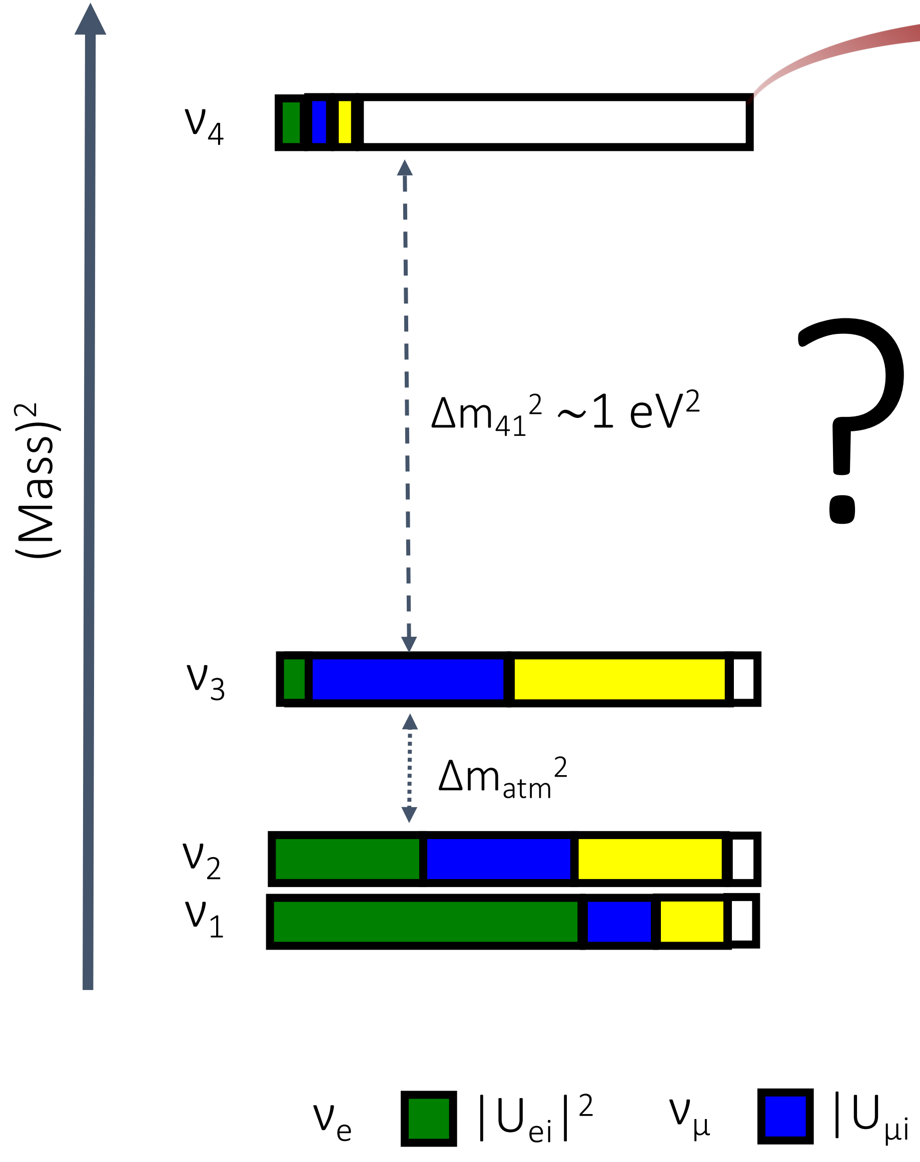
- Reevaluation of σ_{IBD} → +1.5% (evolution of the neutron life time)
- Reanalysis of all SBL experiments

A motivation: the reactor antineutrino anomaly - 2011



- Neutrino fluxes are not understood at short distance <100m
- Could be a hint for the existence of light sterile neutrino?
- Could be a systematic effect?
- Not yet understood
- Relevant for reactor monitoring

Are there additional neutrinos (mainly steriles) ?



- New eV-scale massive neutrino?
  - No – or extra-weak SM interaction
  - Mixing with active ν's

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

$\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e$

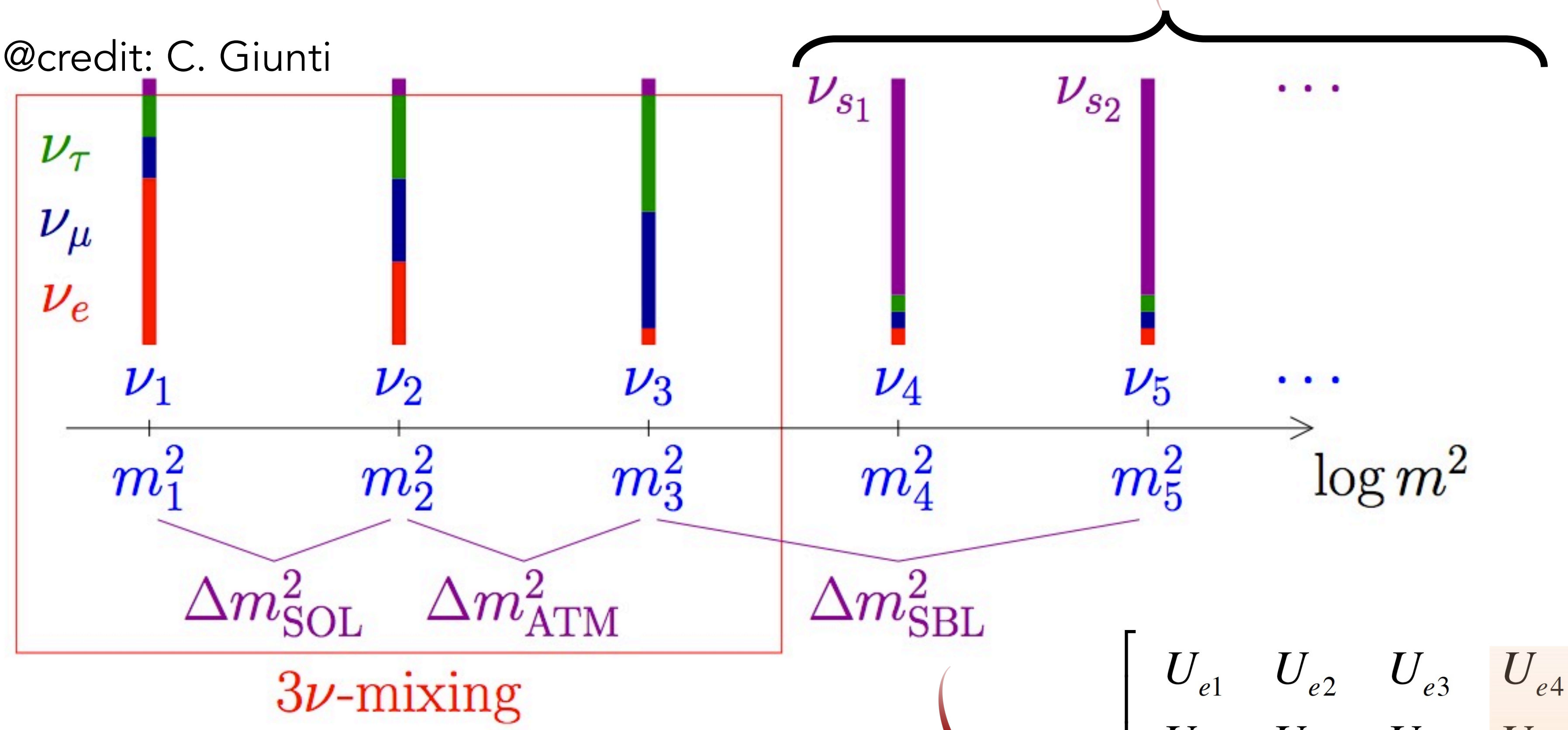
$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

Or more sterile neutrinos?

- No – or extra-weak SM interaction
- Mixing with active ν's

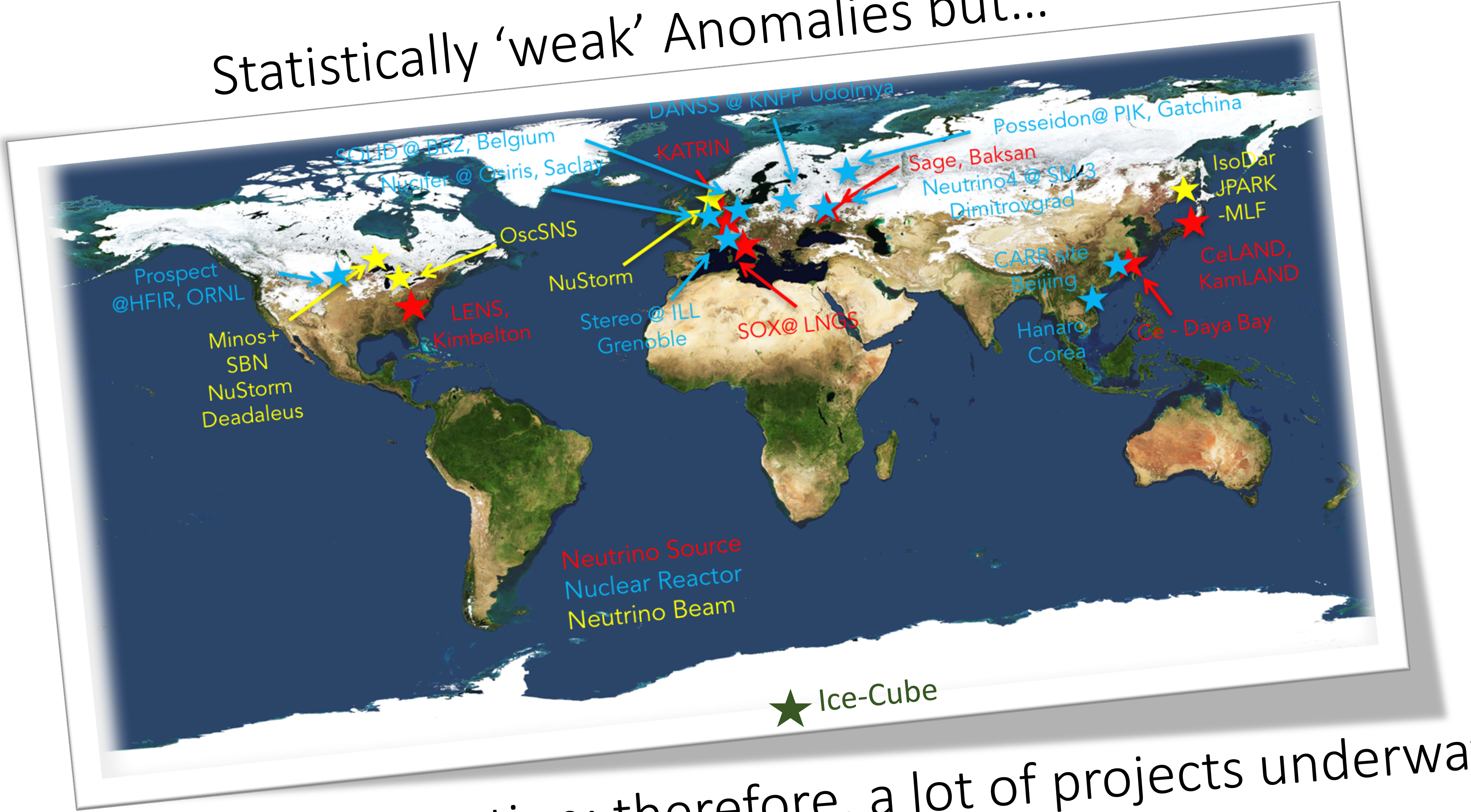
@credit: C. Giunti



$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

- Expansion of the PMNS mixing matrix in the case of 1 additional neutrino

Statistically ‘weak’ Anomalies but…



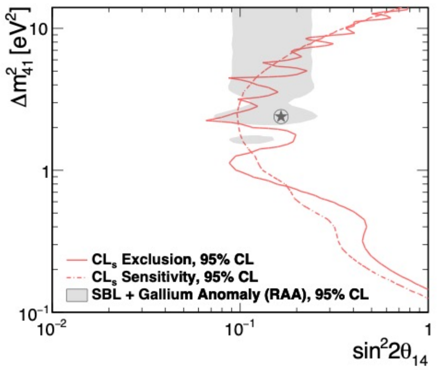
An important question: therefore, a lot of projects underway

Experimental results do not favor sterile neutrinos

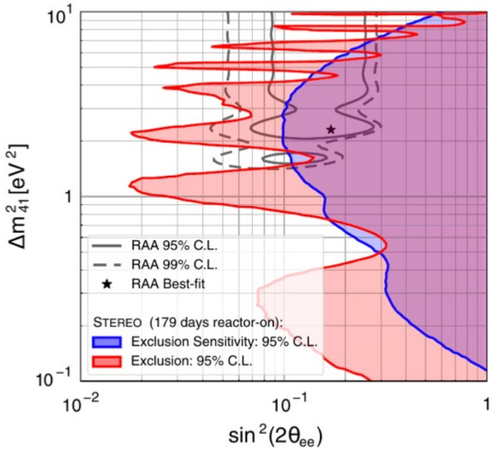
S. Gariazzo

Exclusion of GA+RAA by SBL reactor experiments

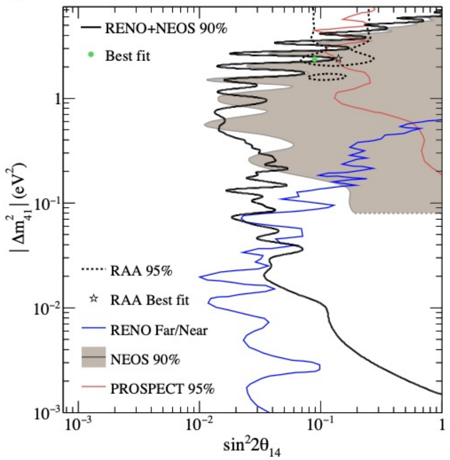
[PROSPECT, PRD 2020]



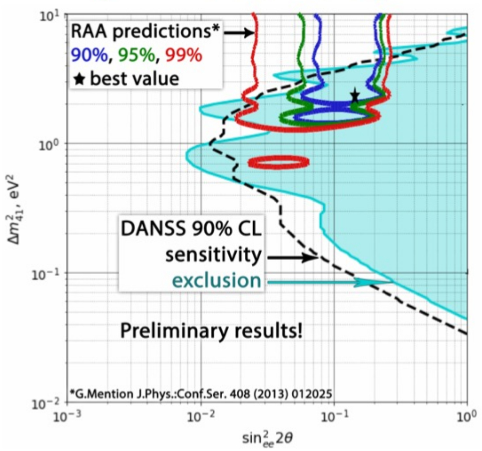
[STEREO, PRD 2020]



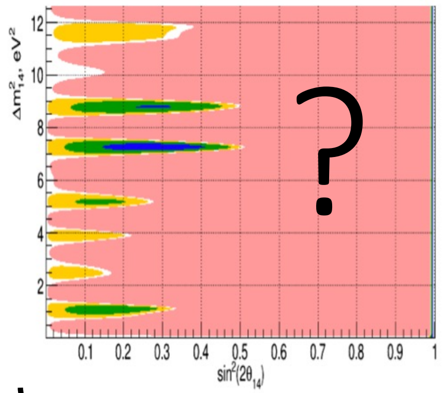
[RENO+NEOS, 2020]



[DANSS, 2020]



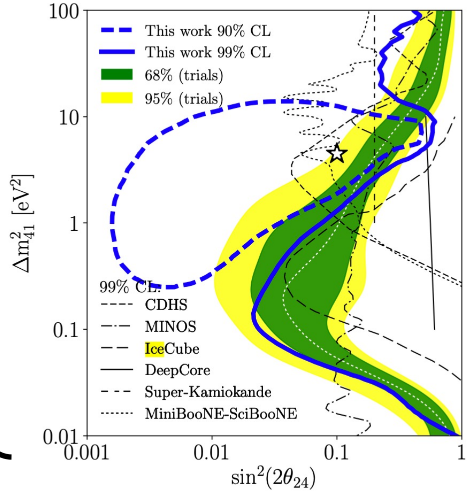
[Neutrino-4, PZETF 2020]



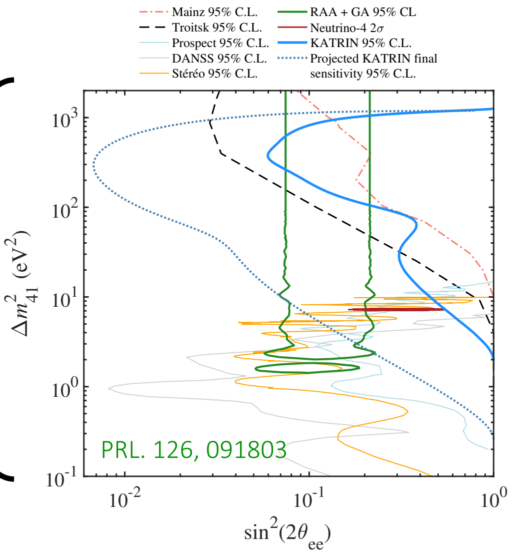
Claimed > 3σ evidence for ν_s
(tension with other SLB results)

99% ν_μ DIS exclusion

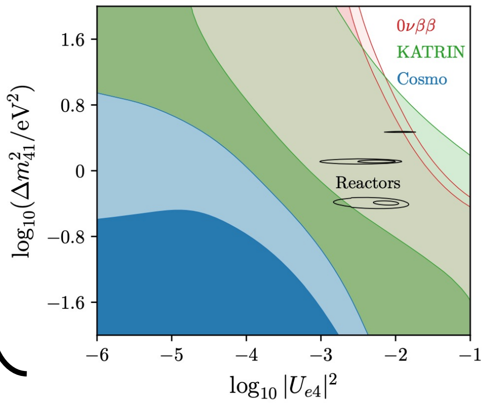
[IceCube, PRL 2020]



KATRIN

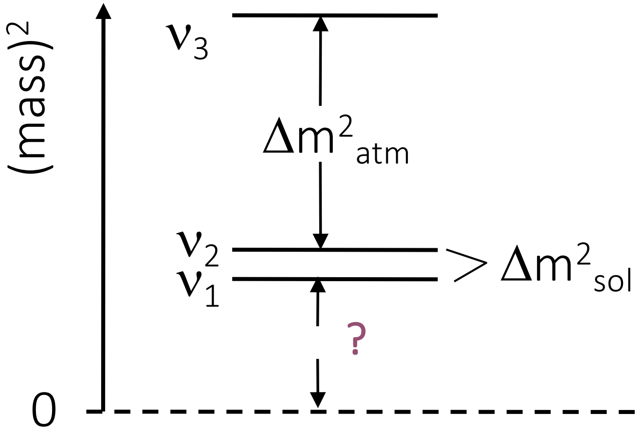


Strong constraints
From cosmology
arXiv:2003.02289

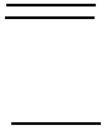


Prospects

- Masses of the mass eigenstates ν_i? } %-ish precision



} within 5 years?

- Spectral pattern  or  } within 5 years?

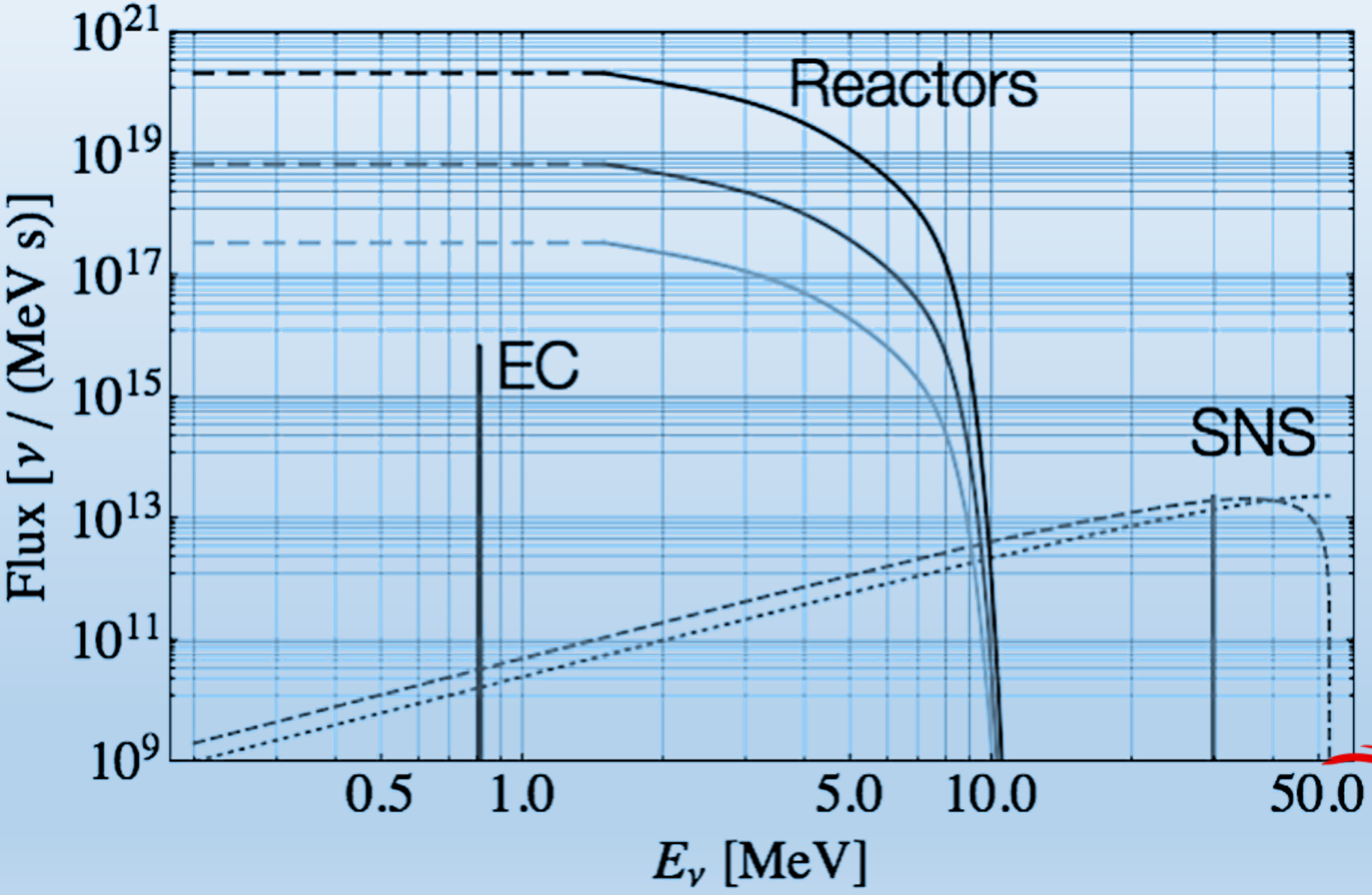
- Lepton Number conservation (Dirac or Majorana) ? } ?

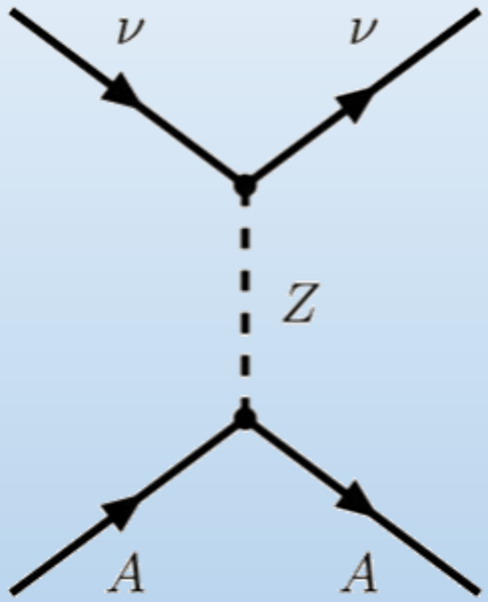
- Is CP violated in the neutrino sector? } within 10 years?

- Are there additional (sterile) neutrino states } RAA+GAA probed within 5y?

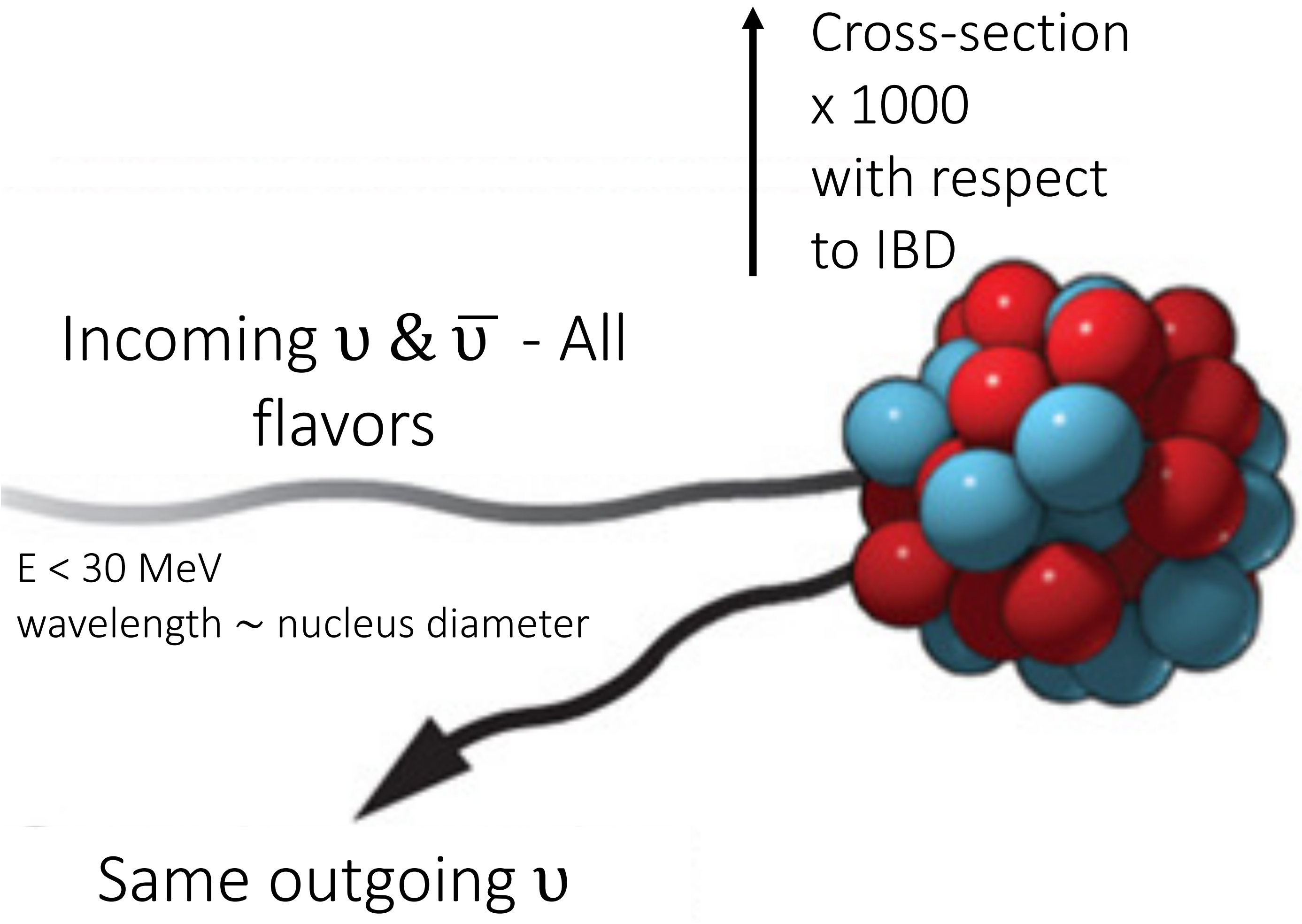
- Are there Non Standard ν Interactions (NSνI) } ?

Coherent elastic neutrino nucleus scattering (CEvNS)

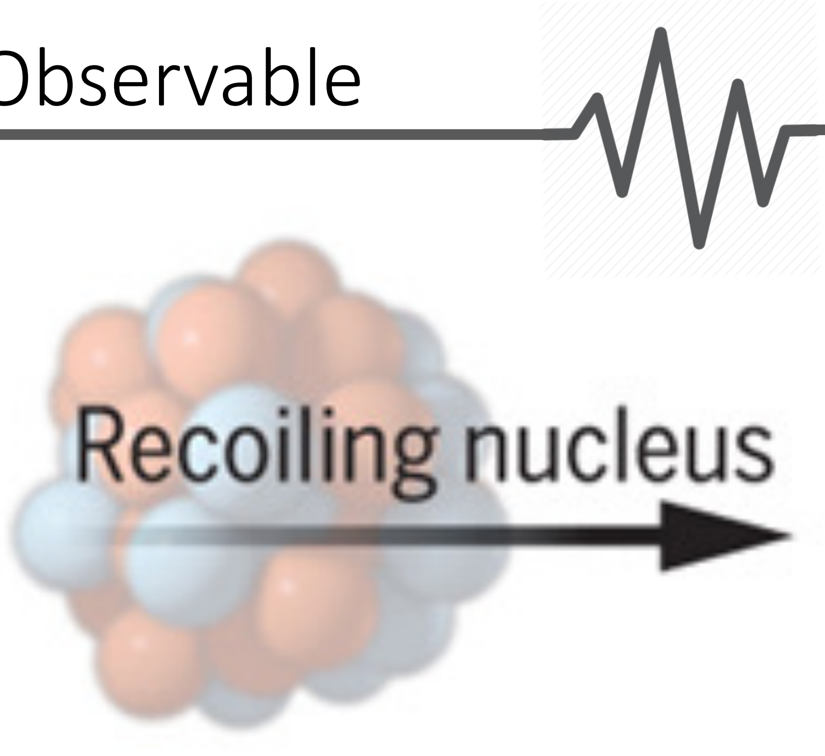




Coherent elastic neutrino nucleus scattering (CEVNS)



Observable



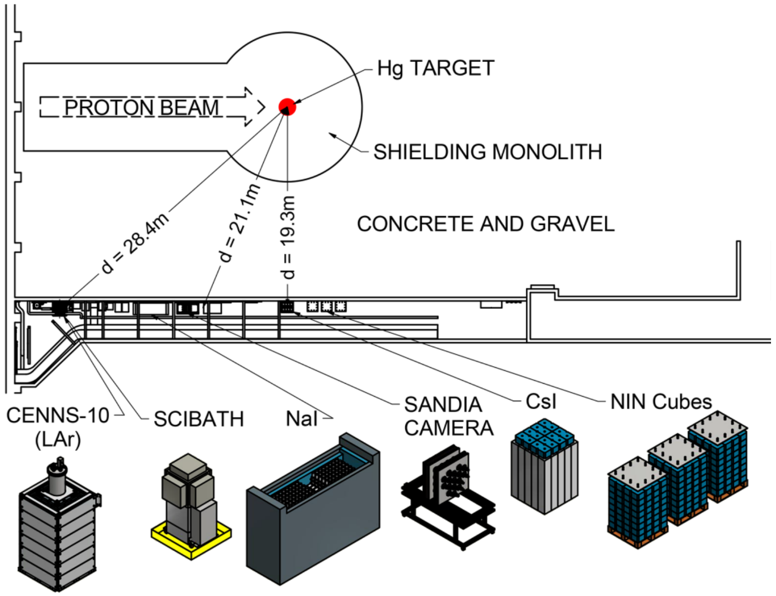
Nucleus recoils as a solid body

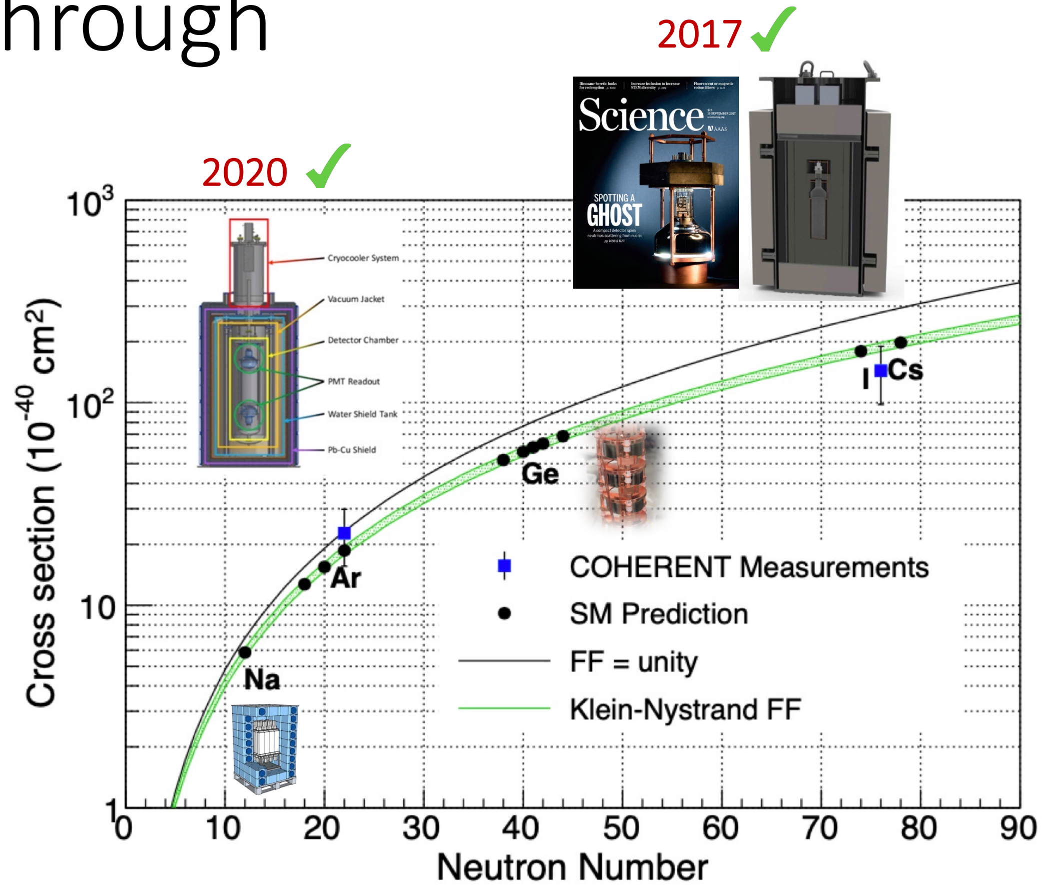
→ O(10 – 1000 eV) energy deposition

→ Hard to discriminate against backgrounds

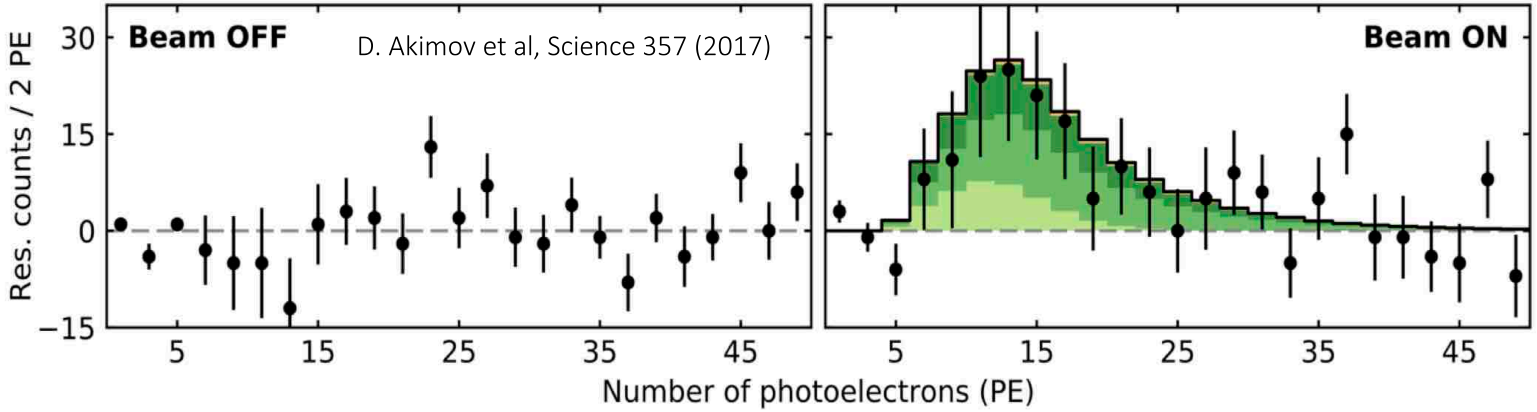
The COHERENT experiment breakthrough

Spallation Neutron Source facility, Oakridge





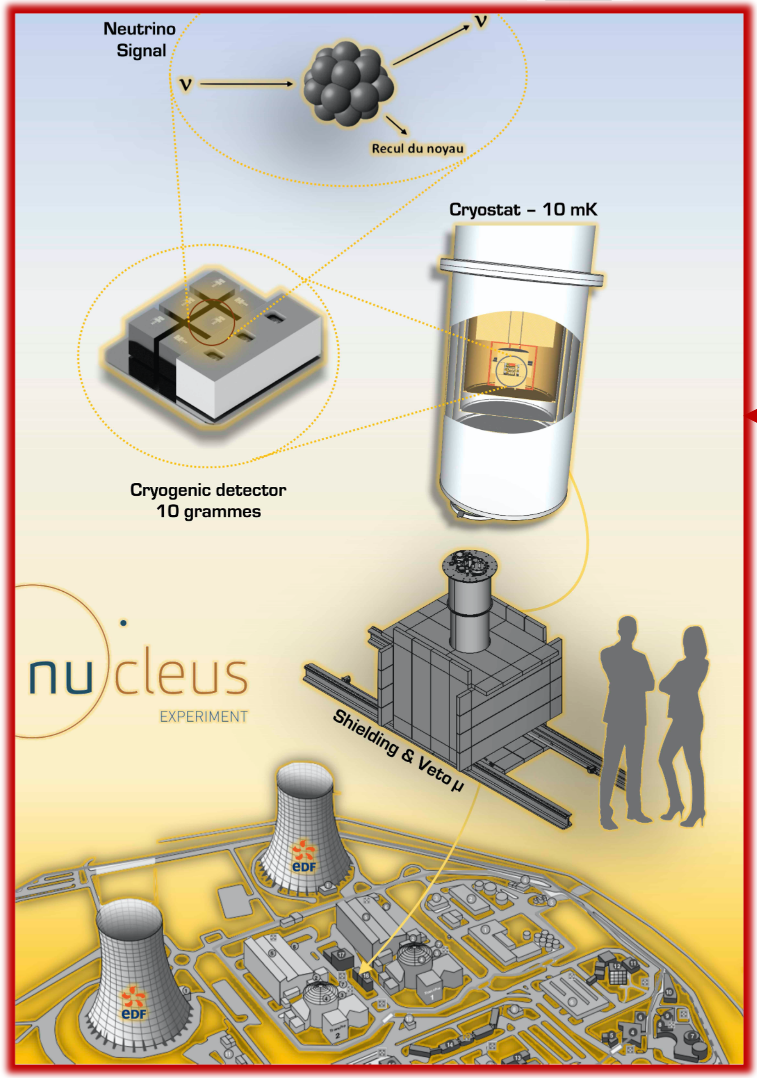
First observation with CsI[Na]

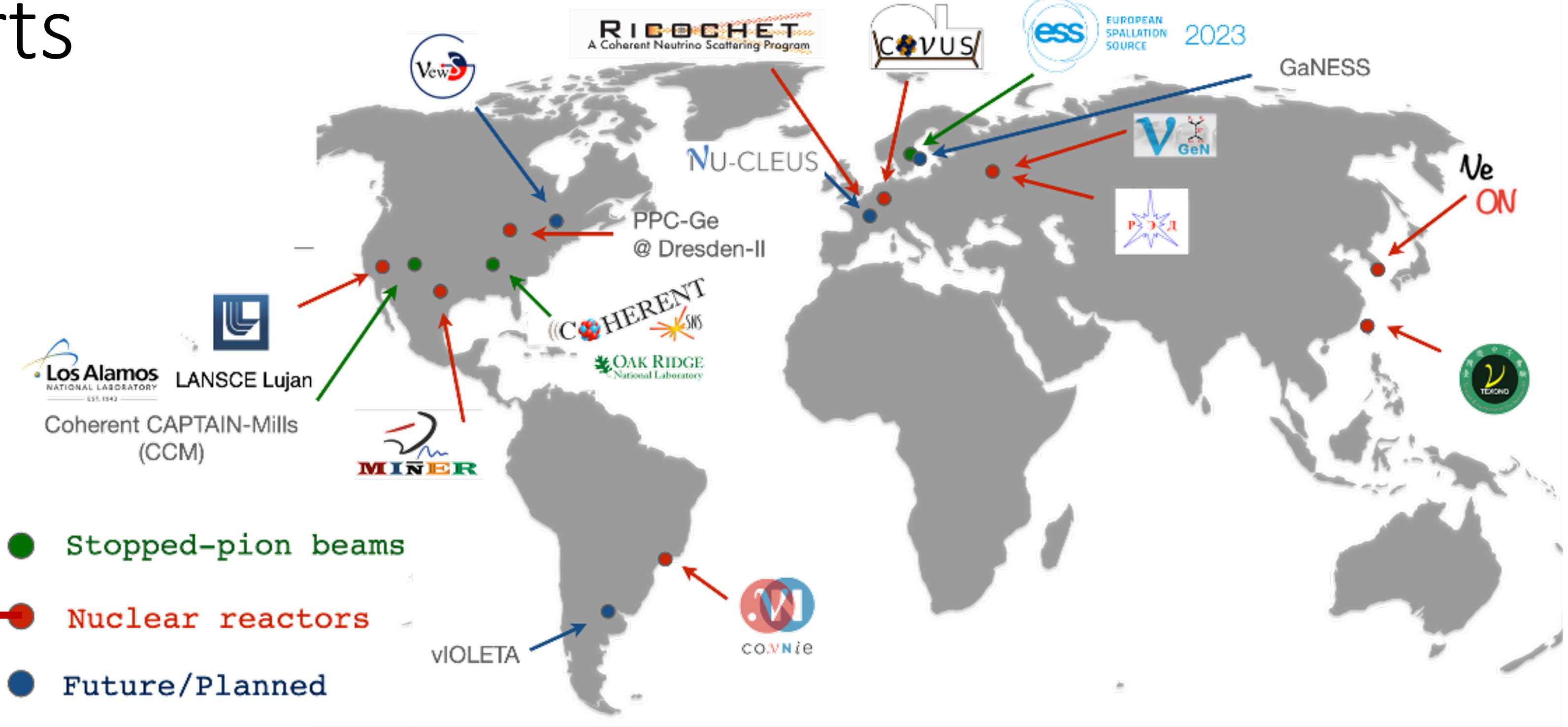


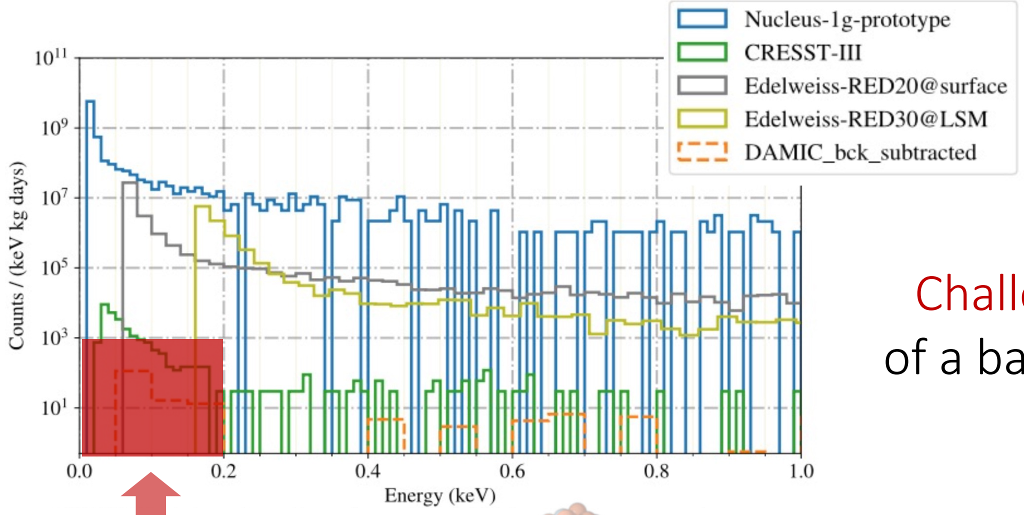
- Measure cross-section N^2 dependence
- Appealing BSM physics probe

Ongoing CEvNS efforts

Not yet observed @





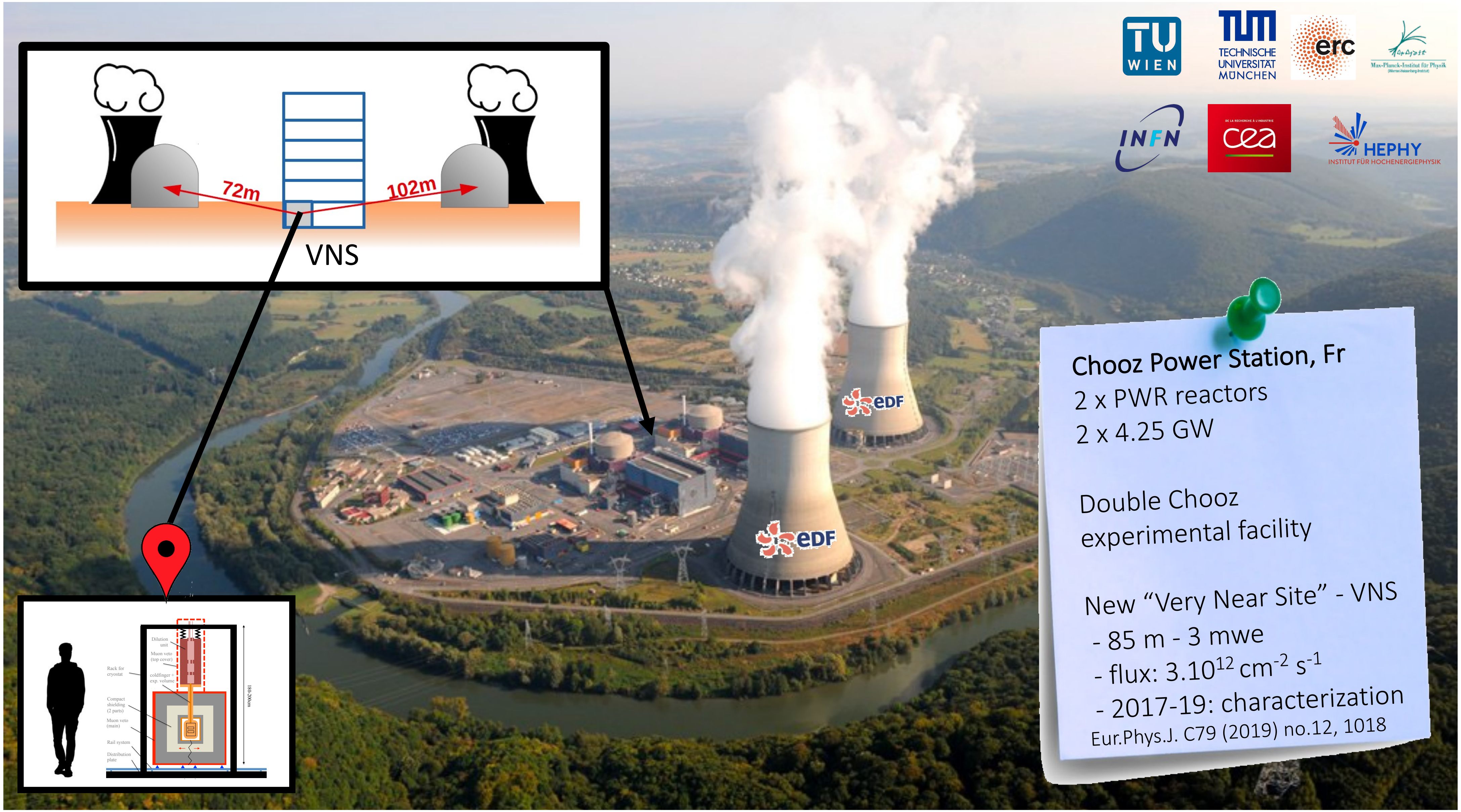


CEvNS signal

Workshop,
15.-16.06.21
https://indico.cern.ch/event/1013203/

Challenge: many observations of a background rise at E<100 eV
Unknown origin…

The NUCLEUS Experiment at Chooz



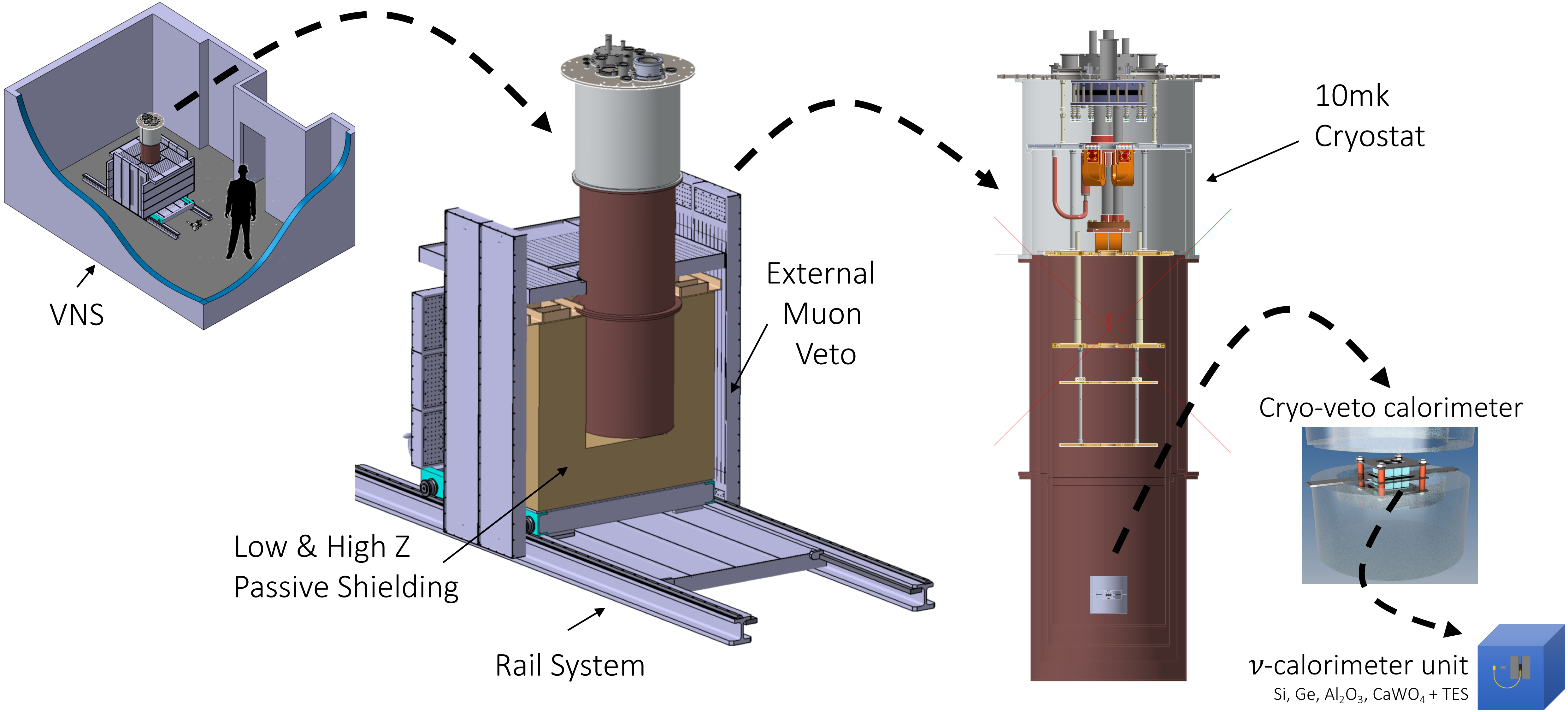
Chooz Power Station, Fr
2 x PWR reactors
2 x 4.25 GW

Double Chooz
experimental facility

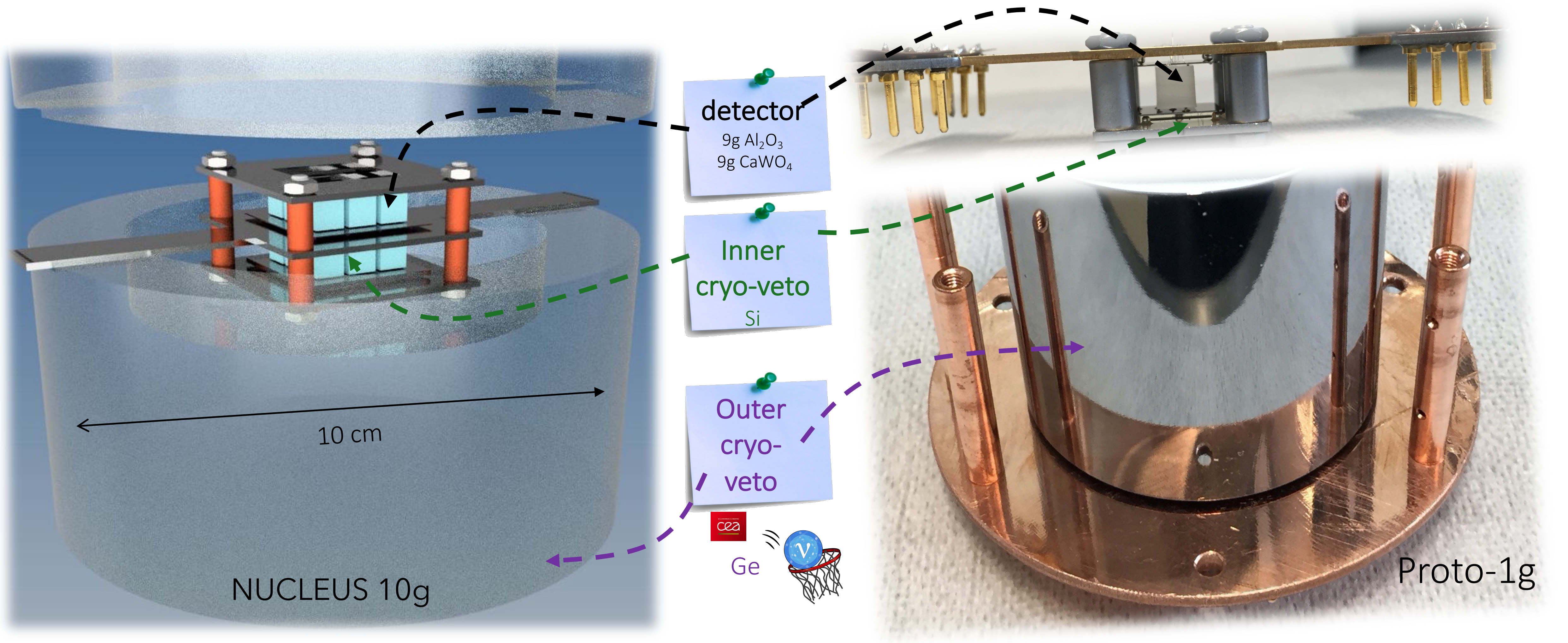
New "Very Near Site" - VNS
- 85 m - 3 mwe
- flux: 3.10^{12} cm^{-2} s^{-1}
- 2017-19: characterization

Eur.Phys.J. C79 (2019) no.12, 1018

NUCLEUS Detector in a Nutshell

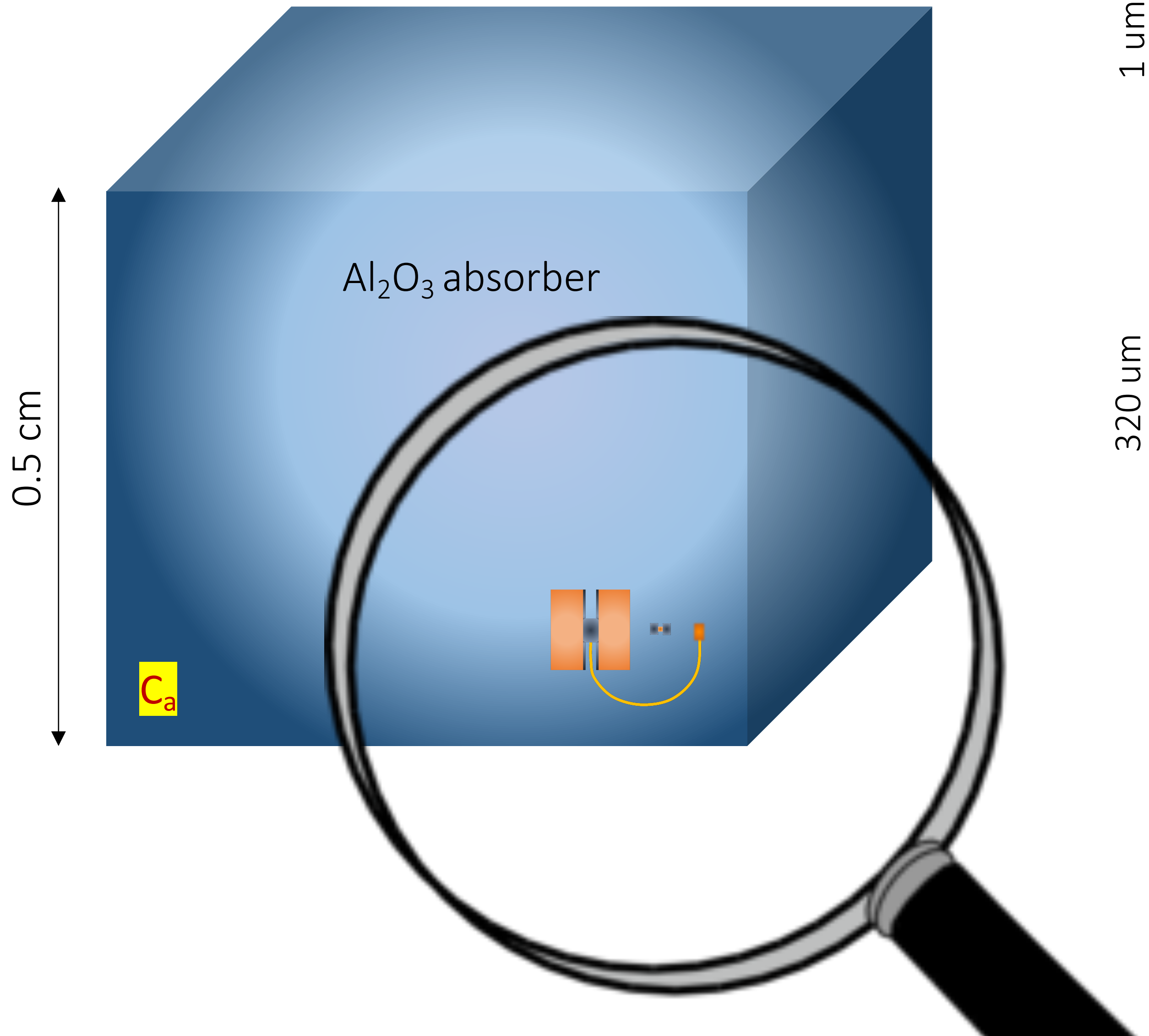


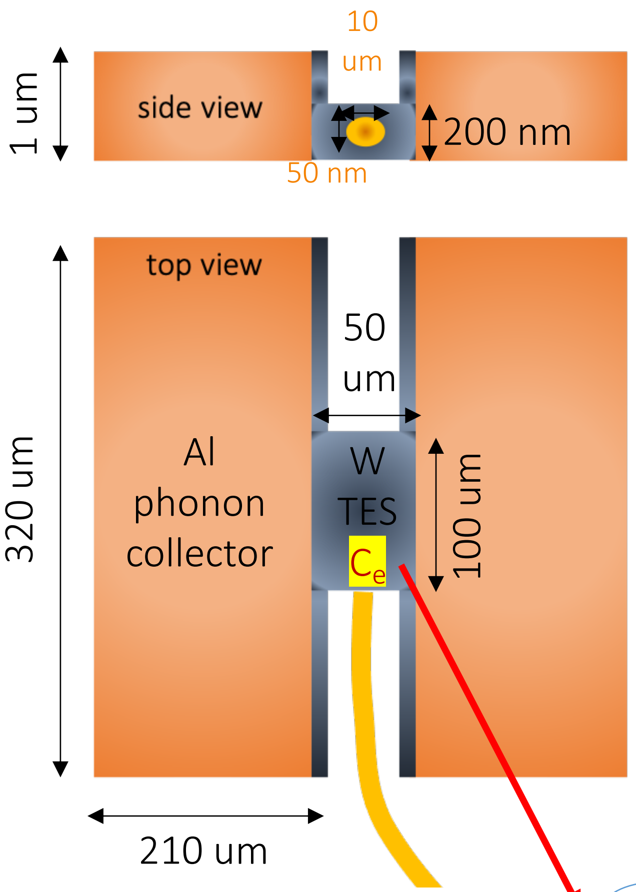
Inner Neutrino Calorimeter & Vetos



Functionality demonstrated in 2019 → Construction of NUCLEUS 10g in 2020

NUCLEUS Crystal Module + Thermometer

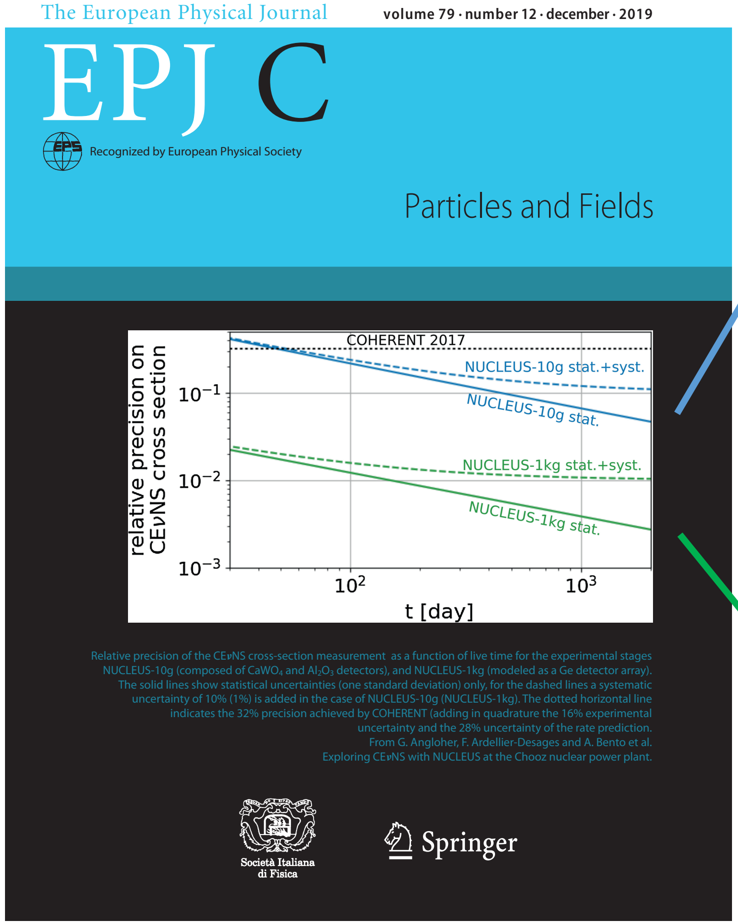




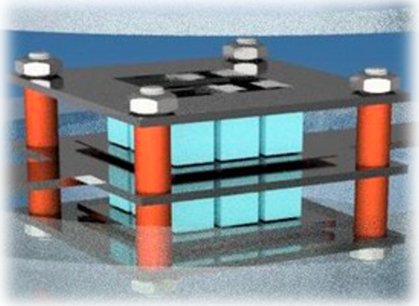
E_{phonon}

- Measure O(10-6) K temperature eelvation
- SQUID (superconducting quantum interference device) readout

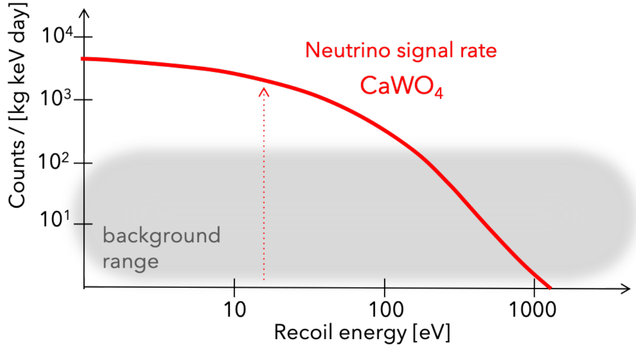
NUCLEUS Physics Reach



Phase I: NUCLEUS-10g – 2022



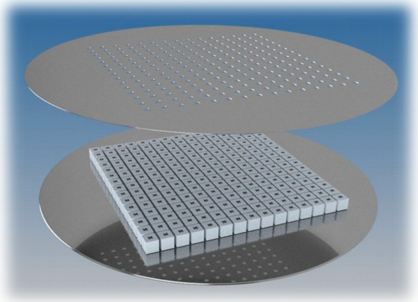
9 x $CaWO_4$ + 9 x Al_2O_3



S = 150 counts / year

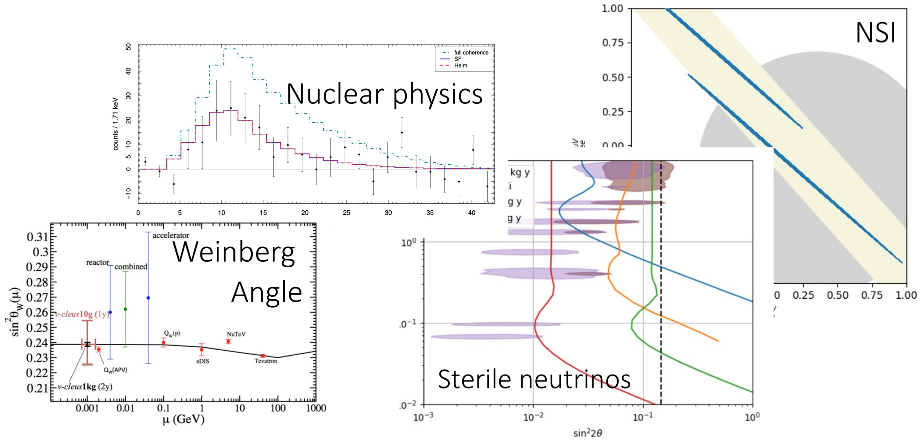
B < 300 counts / year

Phase II : NUCLEUS-1kg – 2024 – SM & BSM



Ge, Multi-target ?

$S > 10^{3\text{-}4}$ counts / year



. . .