Latest experimental results in the field of neutrino physics

Thierry Lasserre
(thierry.lasserre@cea.fr)

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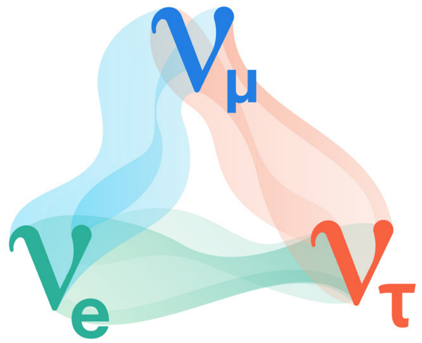
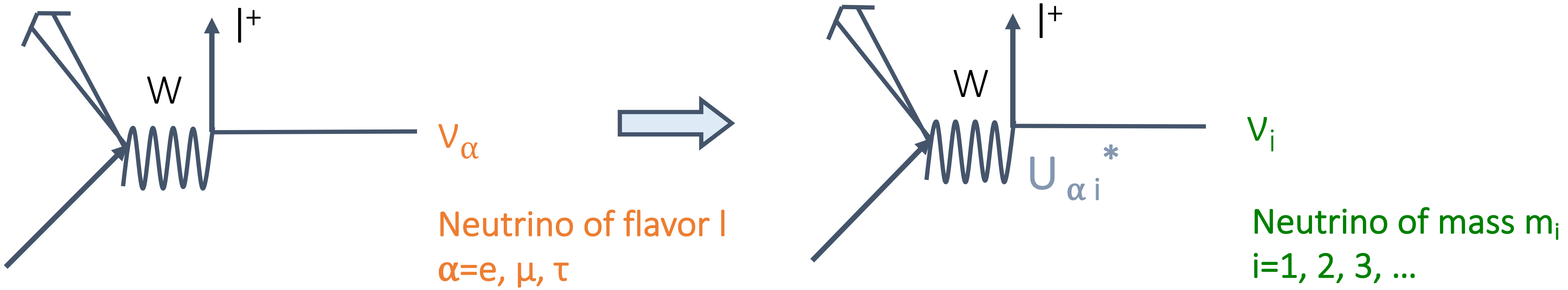
Established Neutrino Physics

- 3 flavor ν_e, ν_μ, ν_τ, spin ½, neutral, left handed, $\sigma(1\ \mathrm{MeV}) \approx 10^{-44}\ \mathrm{cm}^2$
- Tiny masses: $0.04\ \mathrm{eV} < m_\nu < \approx 1\ \mathrm{eV}$
- 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

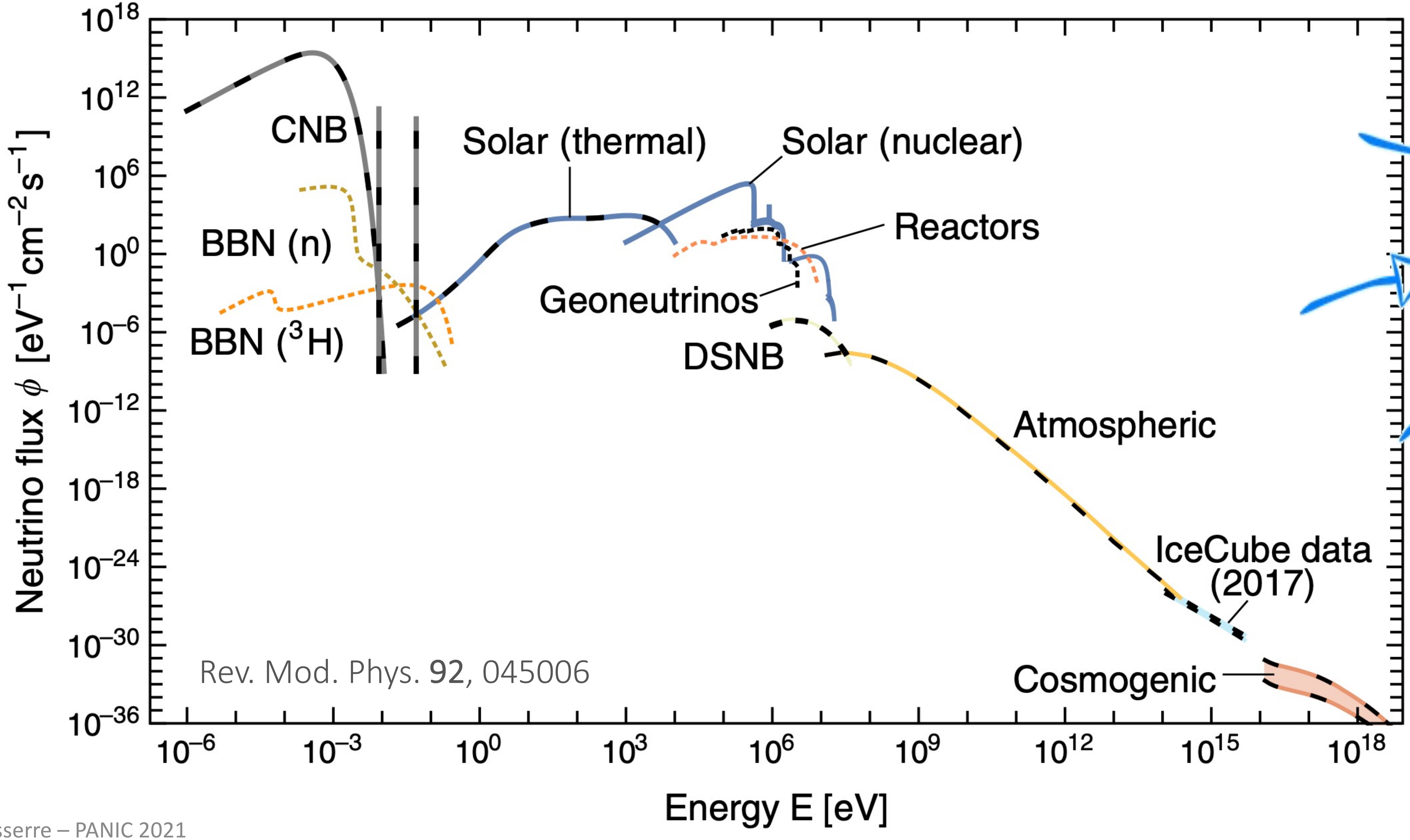
$\theta_{23} \sim 45°$: "atm." angle | $\theta_{13} \sim 9°$ | $\theta_{12} \sim 34°$: "solar" angle

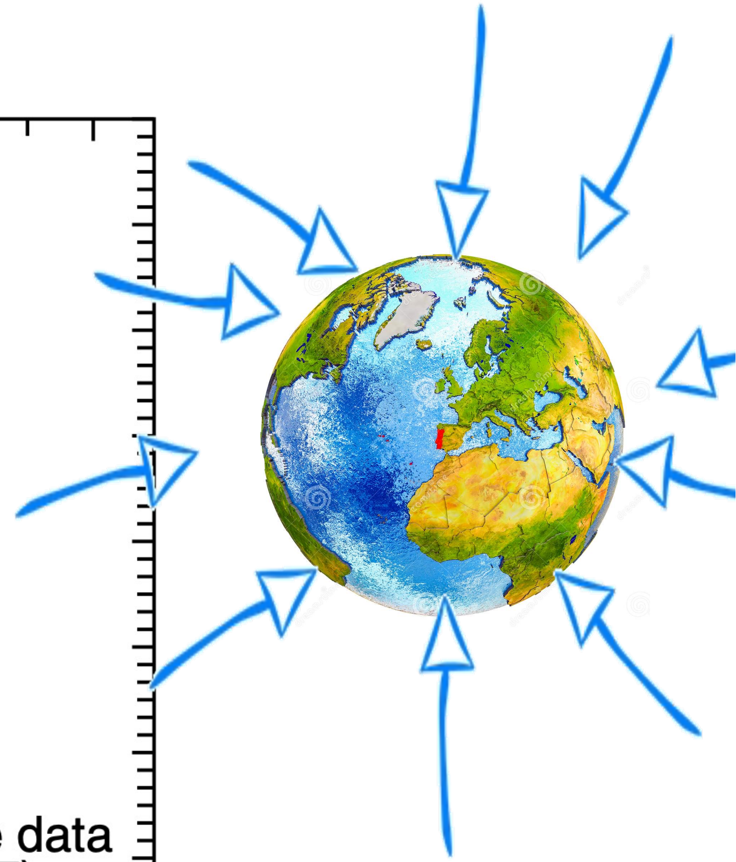
δ dirac CP phase

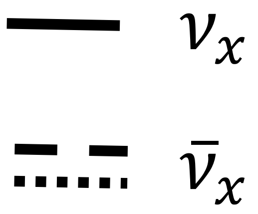
- 3 masses $m_{1,2,3}$: $\Delta m^2_{sol} = m_2^2 - m_1^2 \sim 8\ 10^{-5}\ eV^2$ & $\Delta m^2_{atm} = |m_3^2 - m_1^2| \sim 2\ 10^{-3}\ eV^2$
- Oscillation in vacuum : $\mathrm{P}(\nu_x \rightarrow \nu_x) \approx 1 - \mathbf{sin^2(2\theta_i)} \times \sin^2\left(1.3 \cdot \boldsymbol{\Delta m_i^2} \cdot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

tunable

Grand unified neutrino spectrum

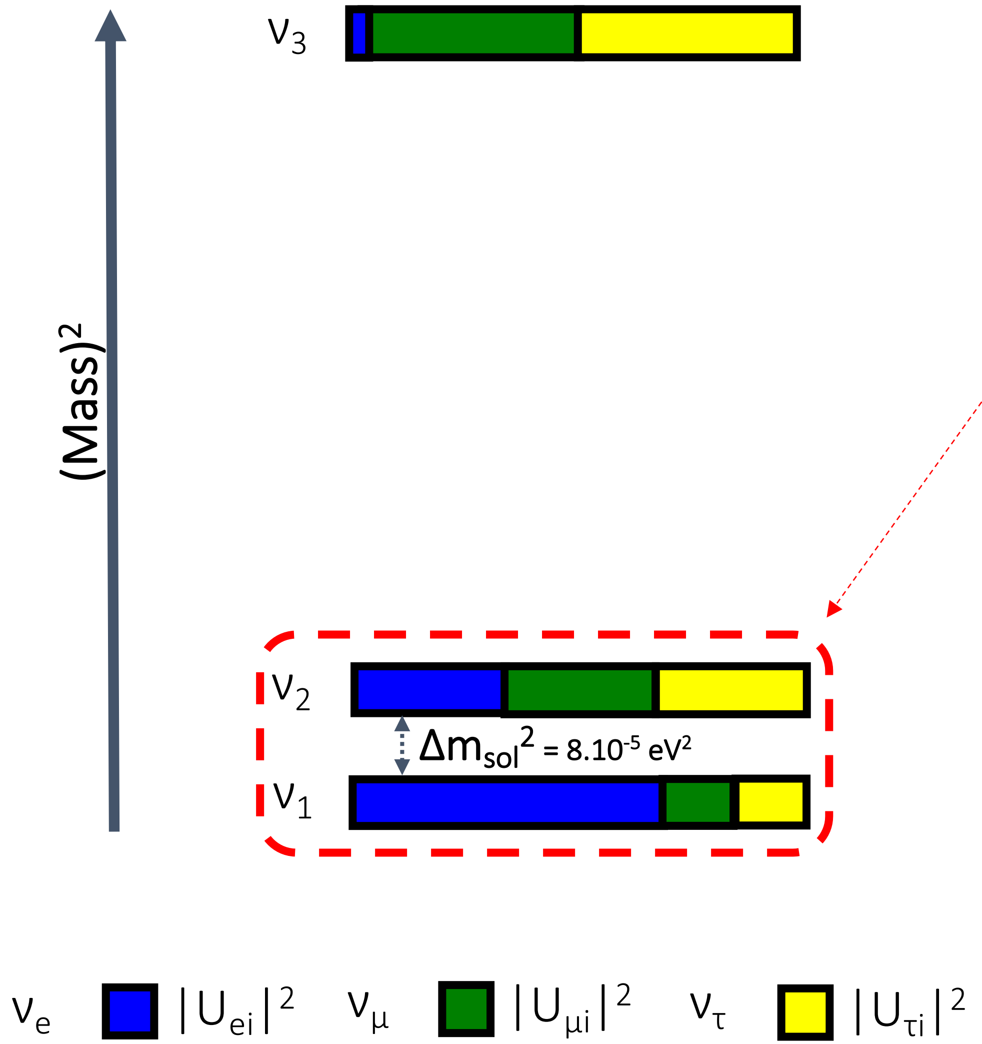






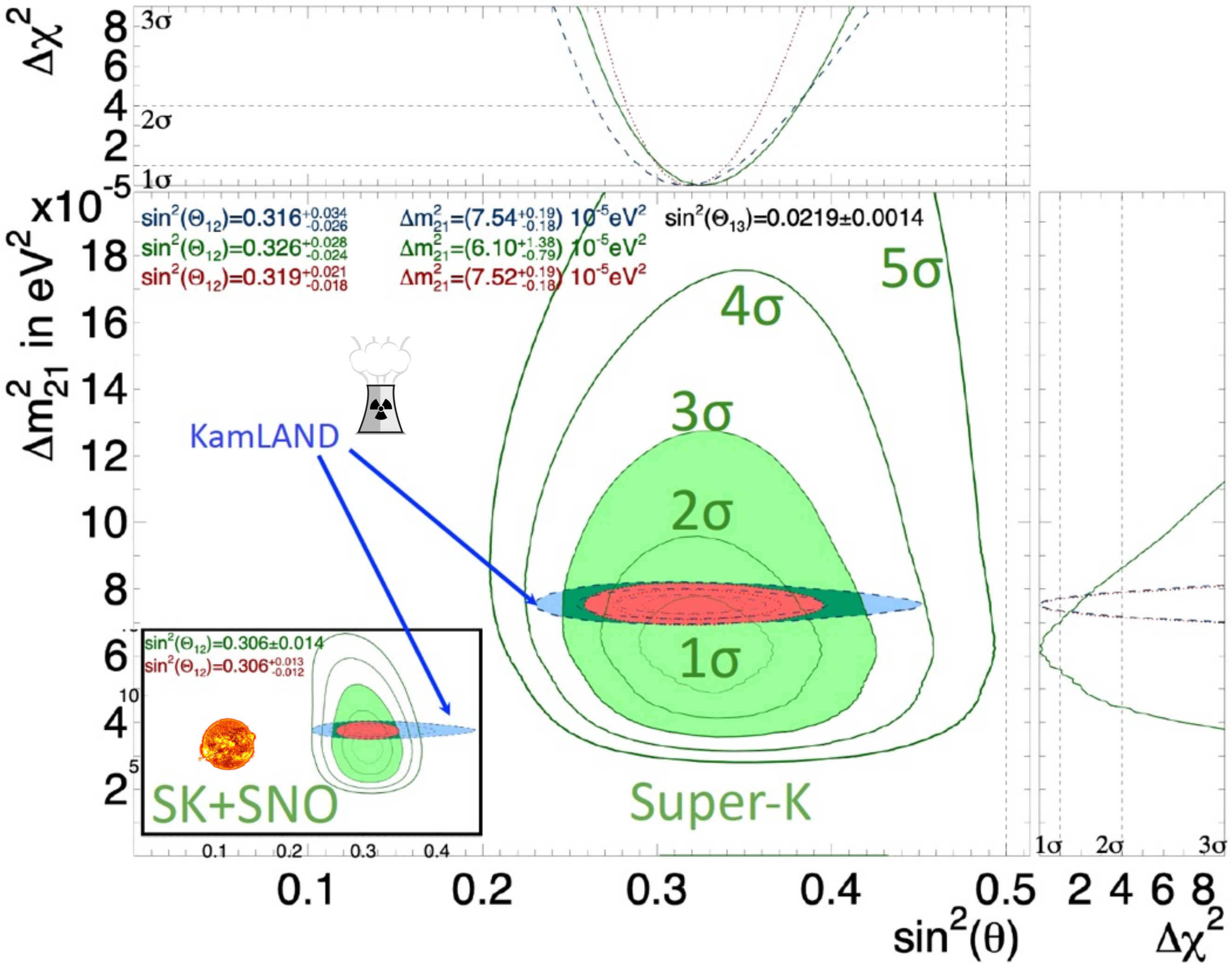
Measurements of the neutrino mixing parameters

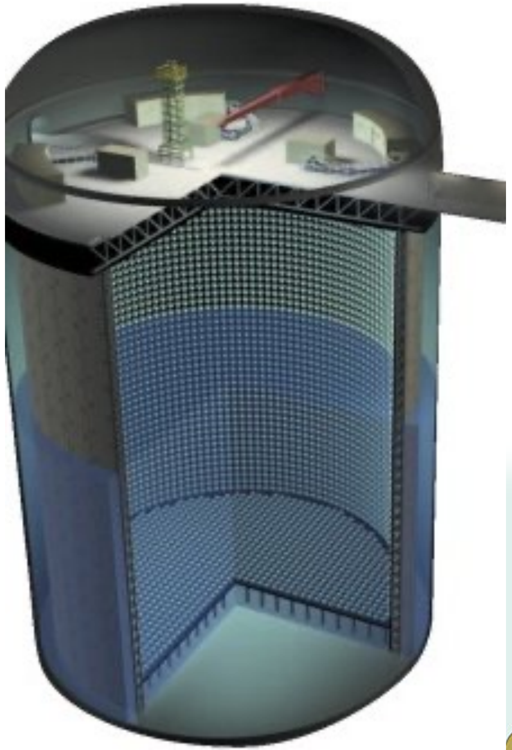
Δm^2_{21} & θ_{12}

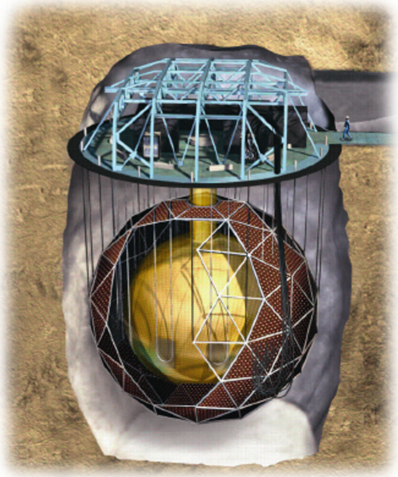


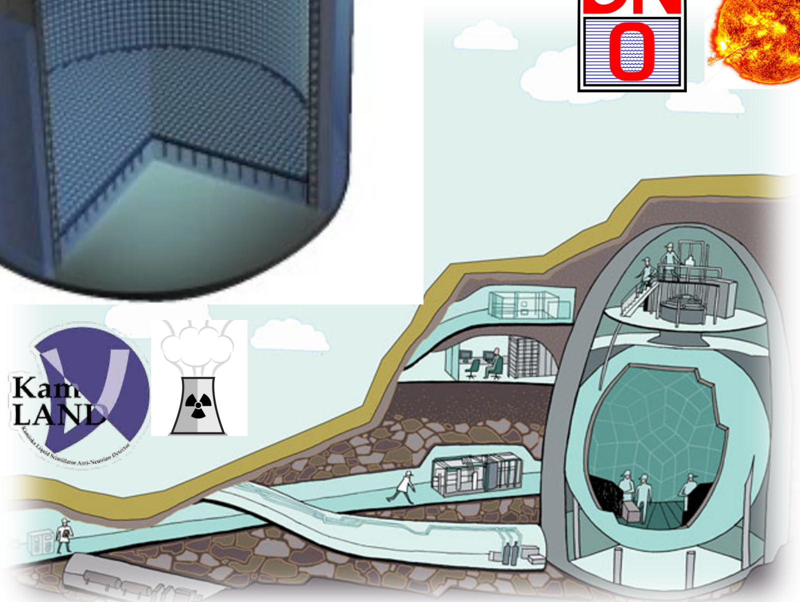
- Δm^2 (eV^2) ~ L(km) / E(MeV)
- Reactor
  L ~ 100 km & E ~ MeV
- Solar
  MSW flavor transition

Solar + Reactor Experiments



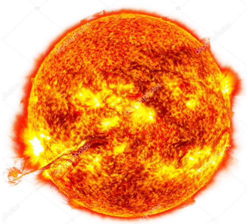




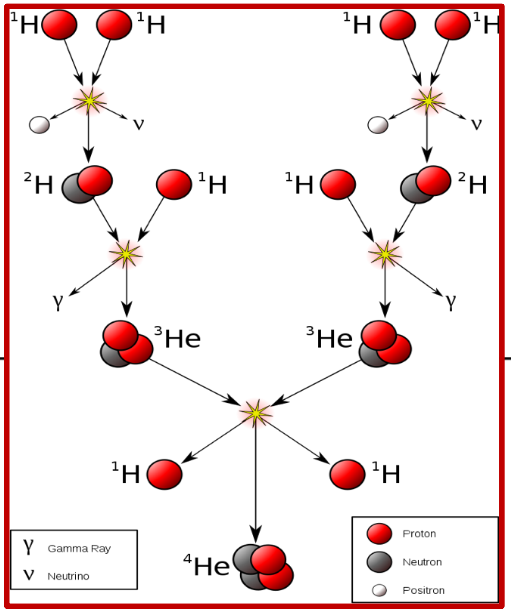


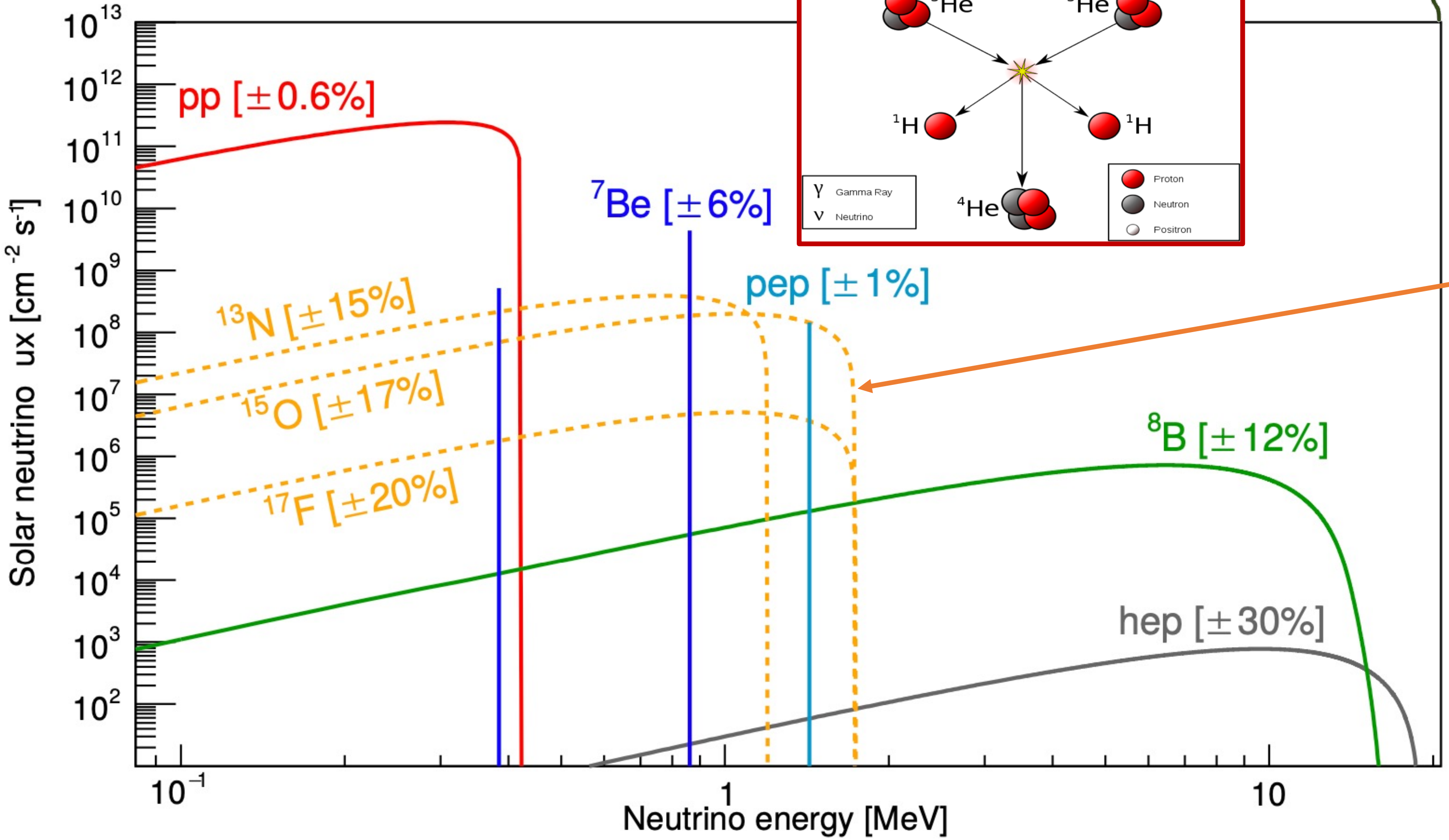
- Consistent Solar/Reactor Δm^2_{21} & θ_{12}

Solar Neutrinos

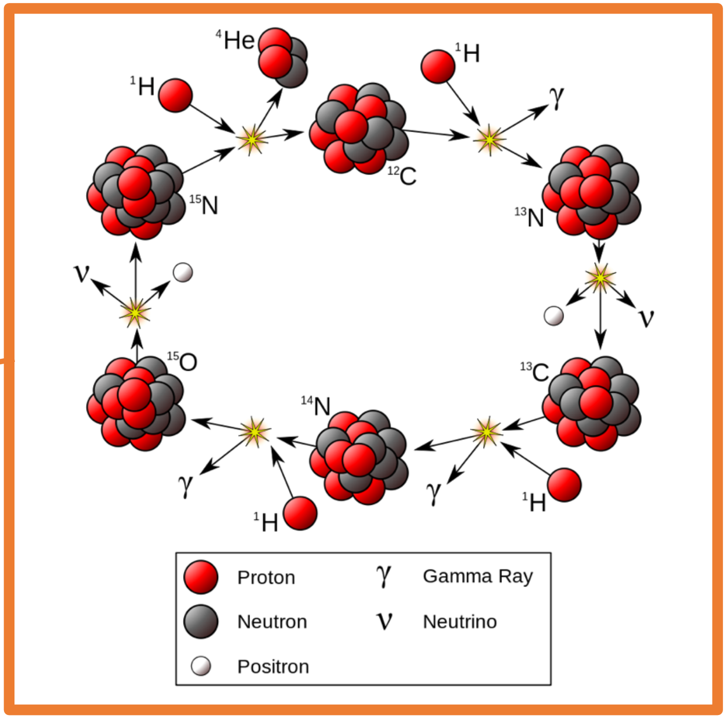


pp-chain: ~99% solar energy





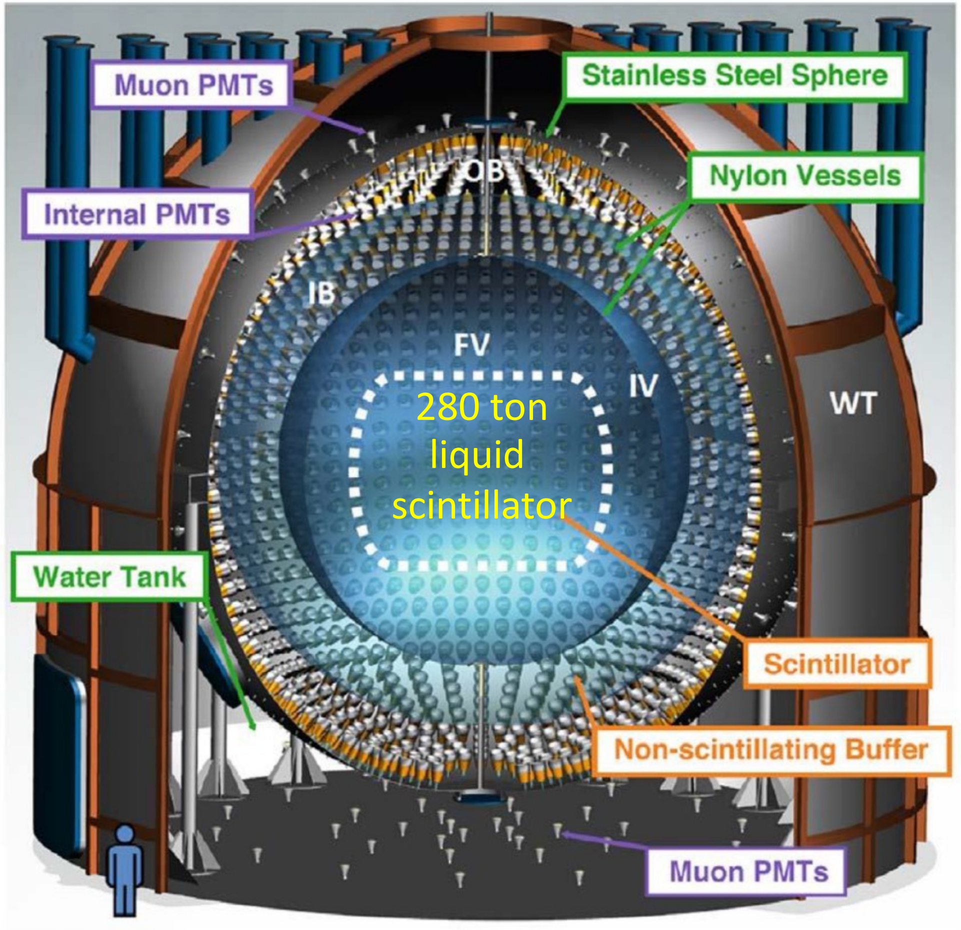
CNO-cycle: < 1% solar energy

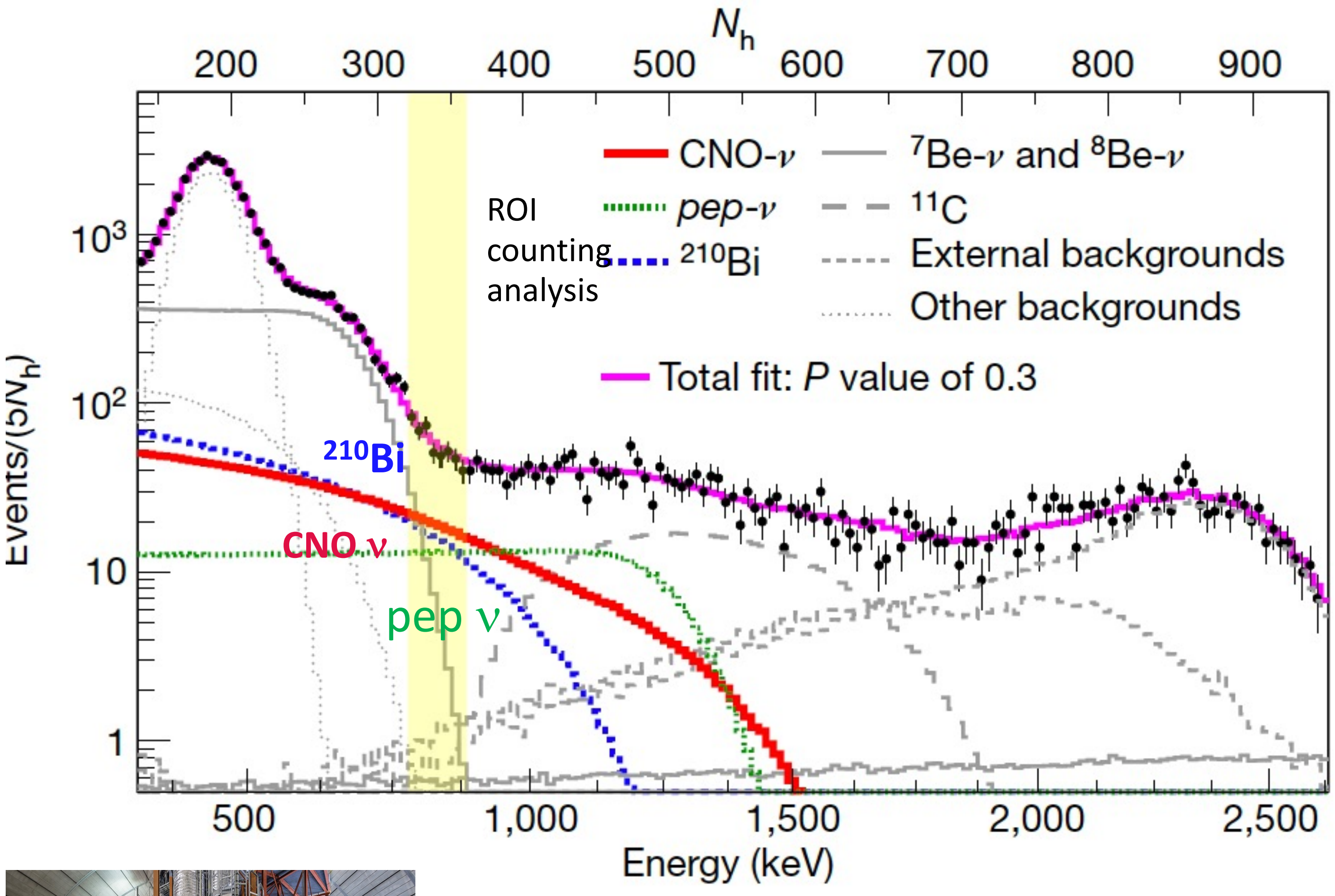


Dominant energy source for stars $M > 1.3 \times M_{Sun}$

Experimental evidence of the CNO process by Borexino

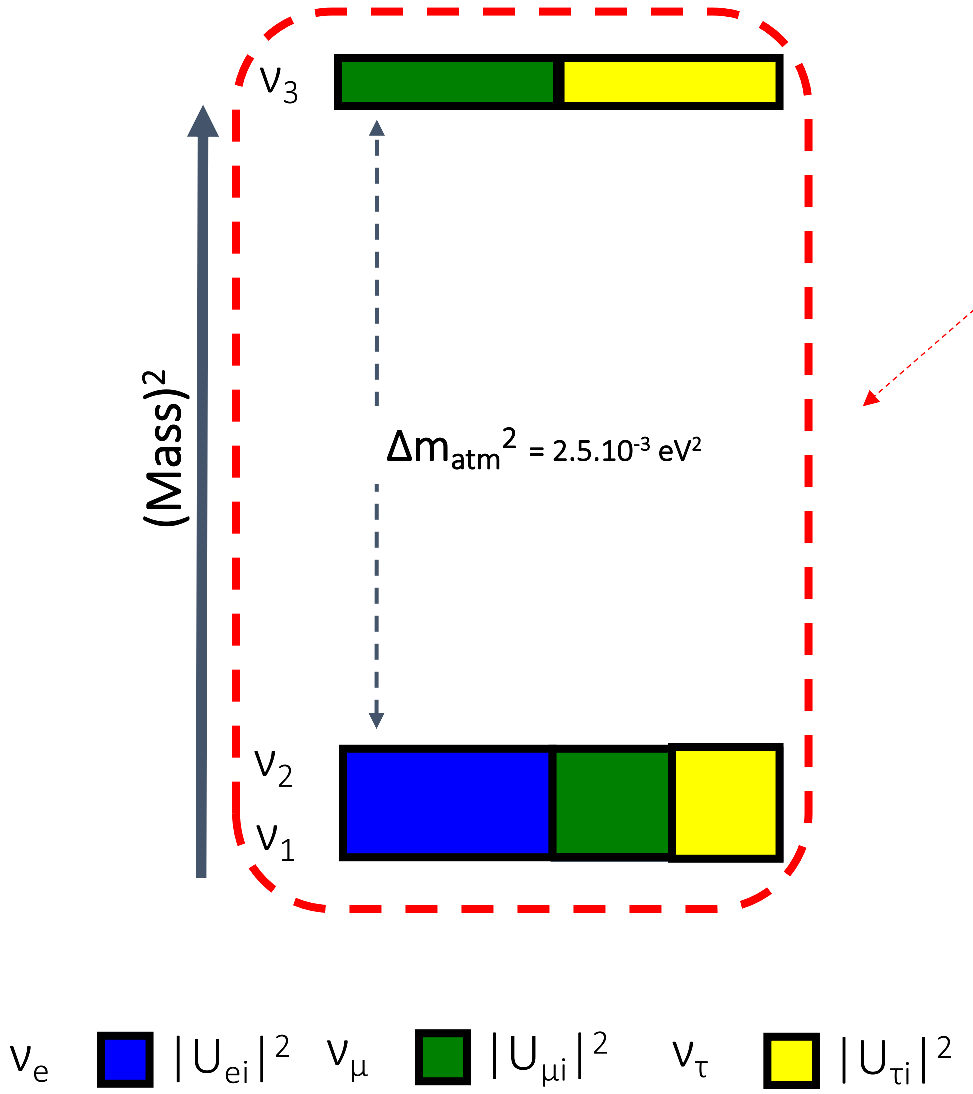
Nature 587 (2020) 577





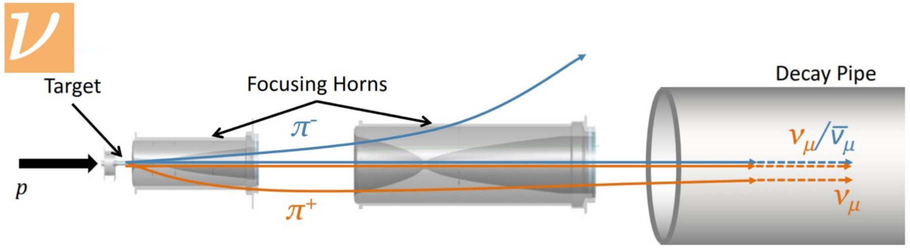
5σ significance CNO-neutrinos observation by Borexino

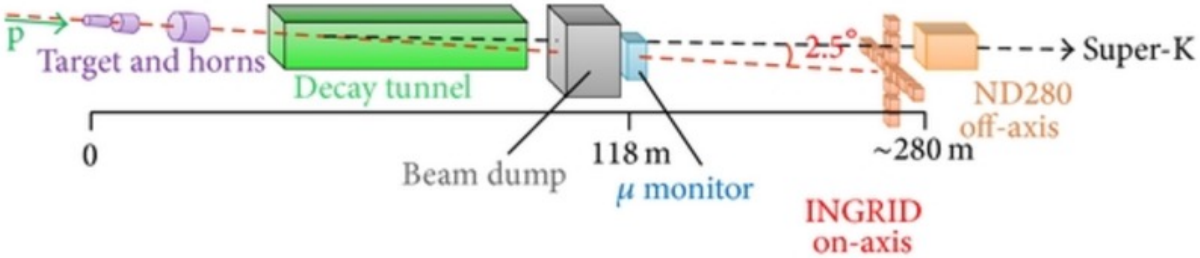
Δm^2_{31} & θ_{23}

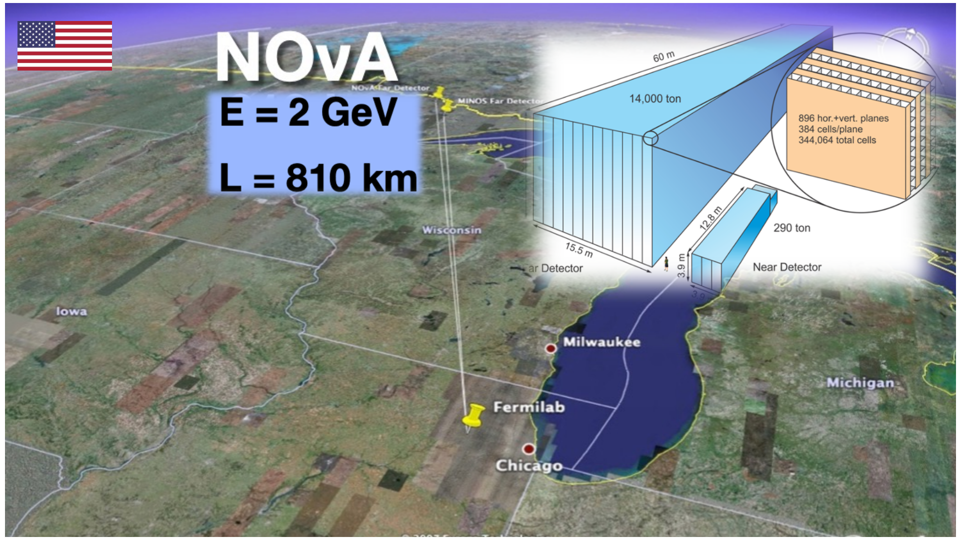


- Δm^2 (eV^2) ~ L(km) / E(MeV)
- Atmospheric neutrinos:
  L ~ 10^4 km & E ~ 1-30 GeV
- Reactors neutrinos:
  L ~ 1 km & E ~ 3 MeV
- Accelerator neutrinos:
  L ~ 1000 km & E ~ 3 GeV

Long-baseline Accelerator Experiments (LBL)



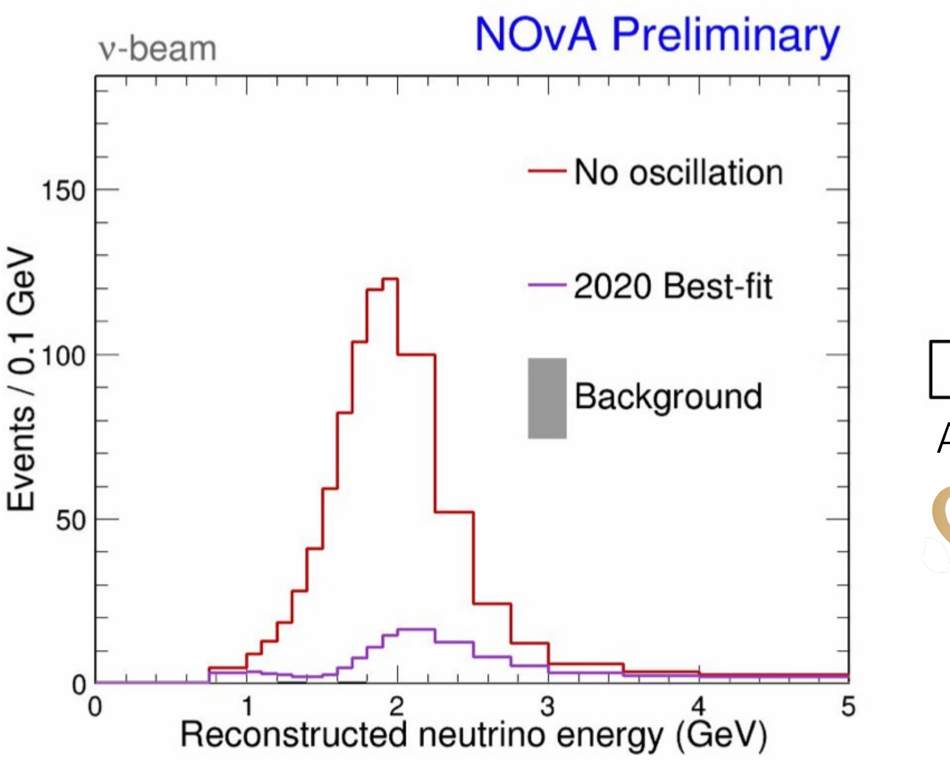




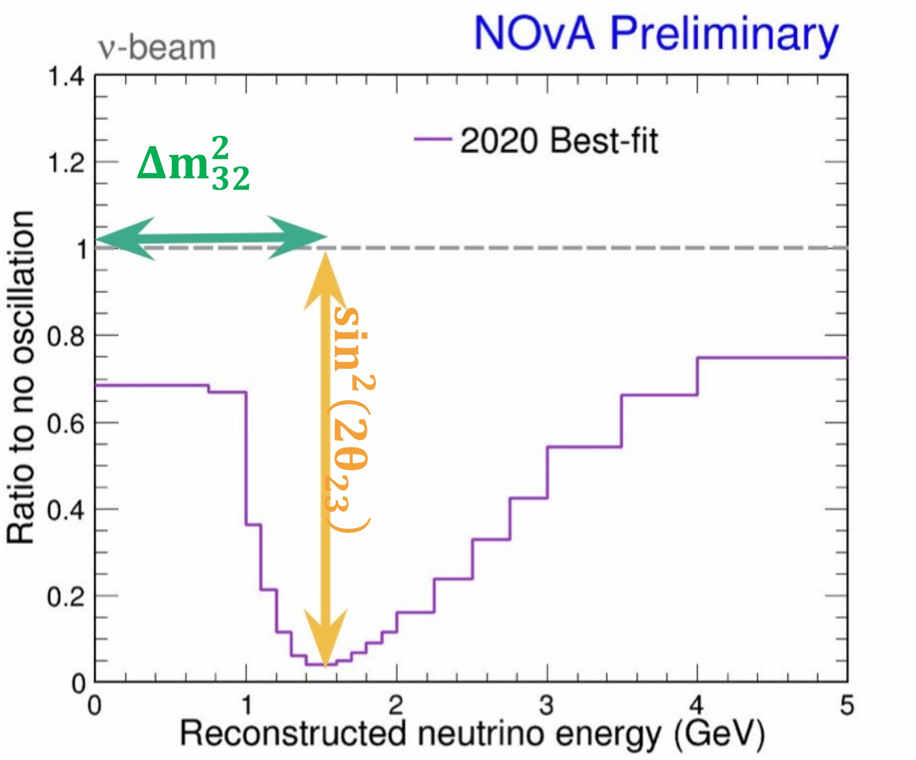
Gd-upgrade 2020

- 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

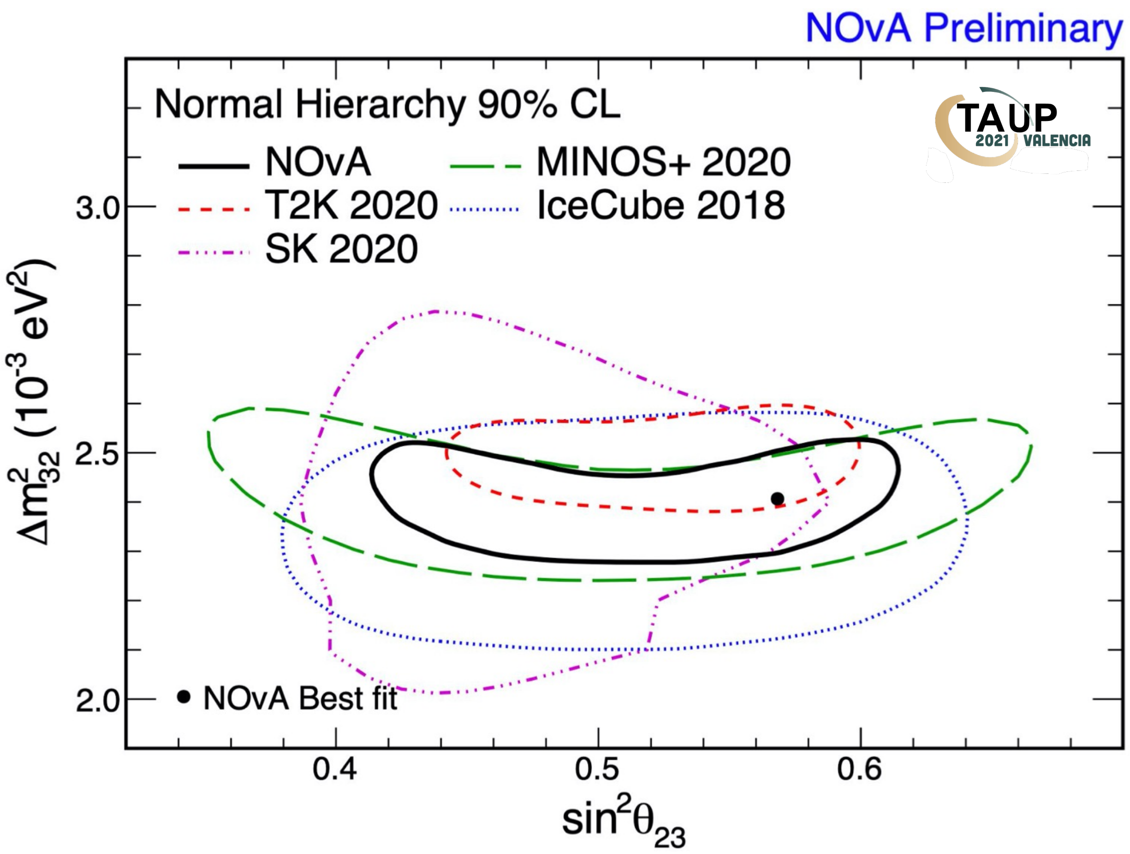


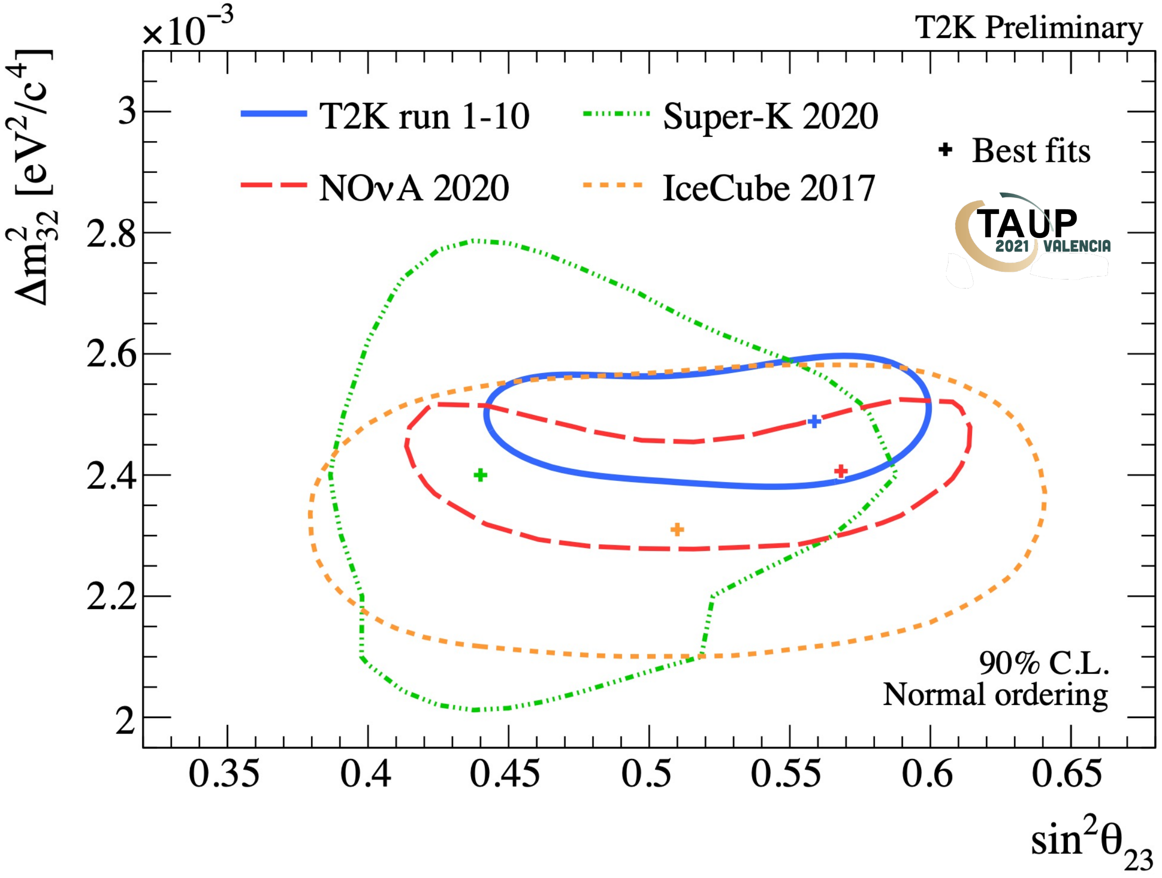
A. Back



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

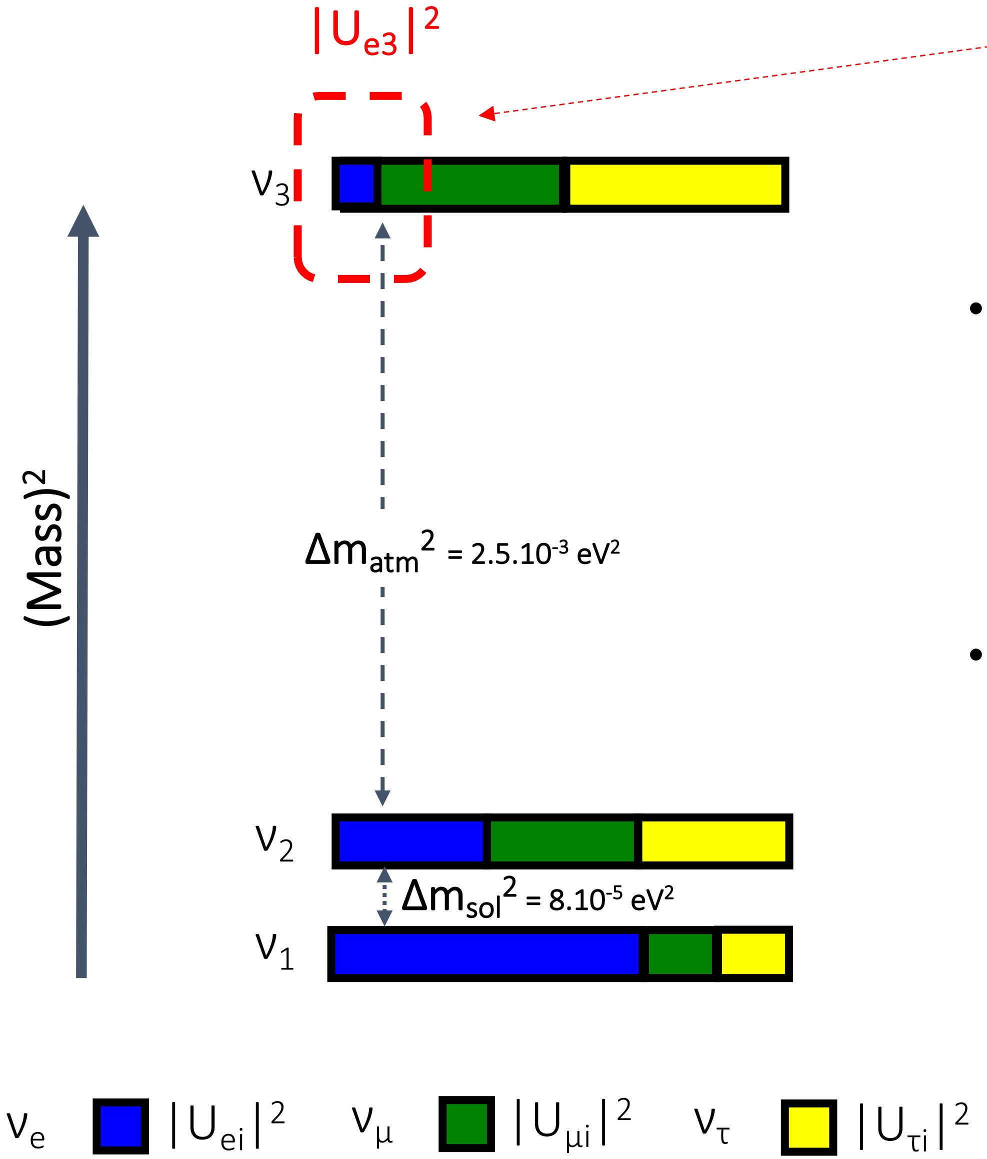
ν_μ Dissapearance Results (LBL, Atmospheric ν's)





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

θ_{13}

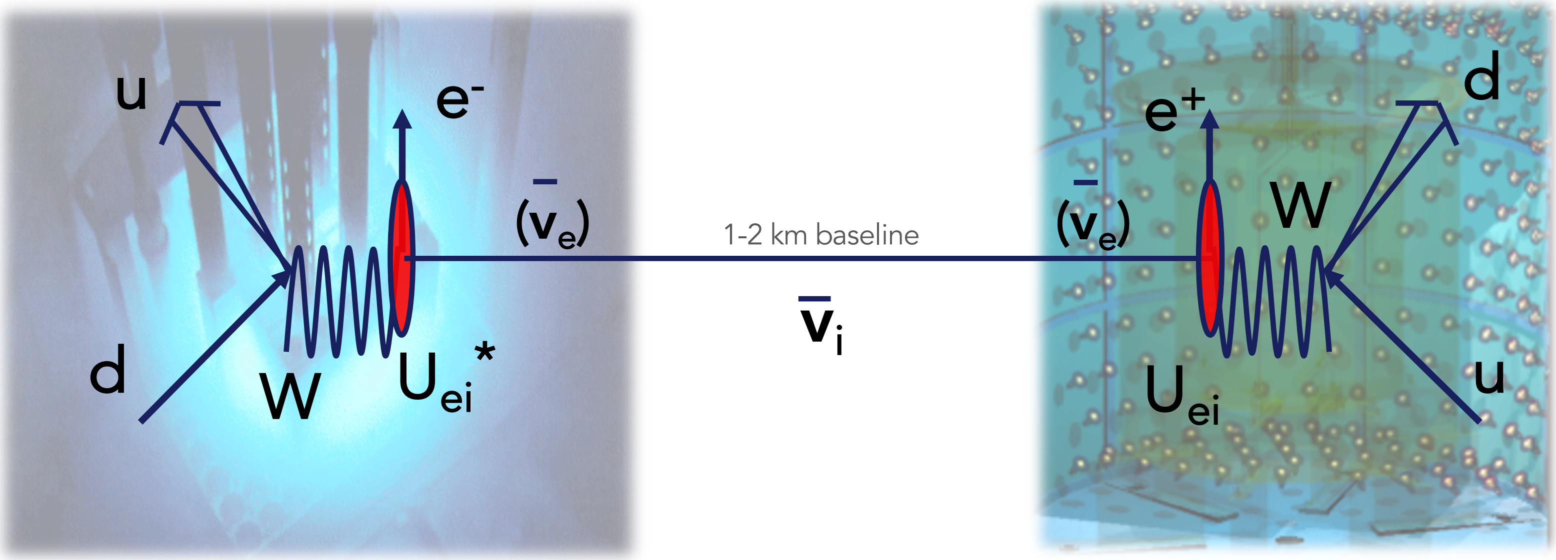


- L ~ 1 km, E ~ MeV
  - reactor neutrinos
  - dissapearance
  - θ_{13} only
- L ~ 1000 km, E ~ GeV
  - beam experiment
  - appearance expt.
  - θ_{13}, sign(Δm^2_{31}), δ_{CP} degeneracies

θ_{13} at Nuclear Reactors

$^{235}\mathrm{U} + \mathrm{n}_{\mathrm{th}} \rightarrow \mathrm{X} + \mathrm{Y} \rightarrow \beta - \mathrm{decays}$

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



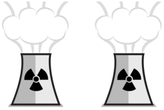
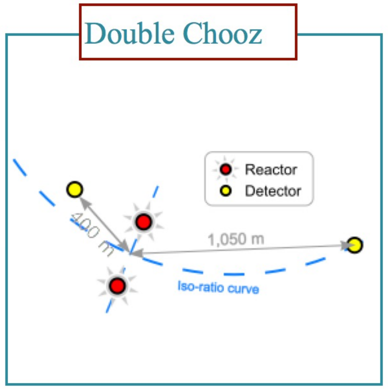
Reactor core

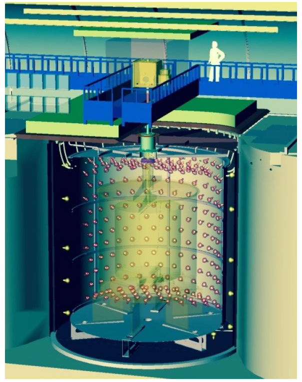
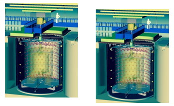
Target free protons

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

Clean measurement of θ_{13}

Double Chooz

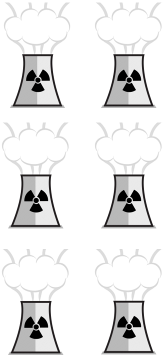
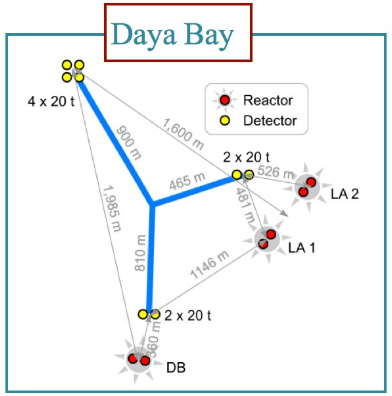



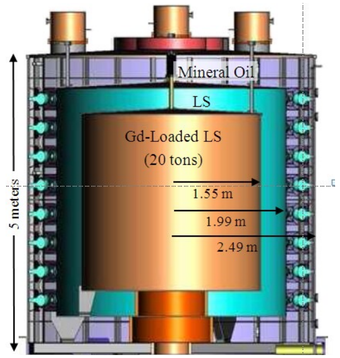




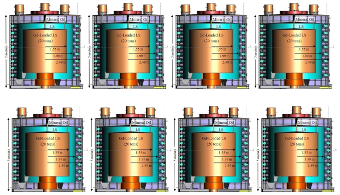
$20\text{-}40\ m^3$

Stopped data taking in 2018

Daya Bay

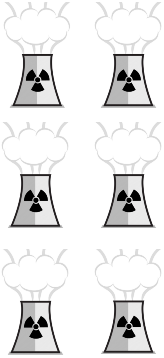
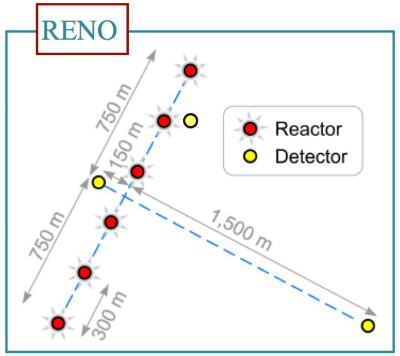



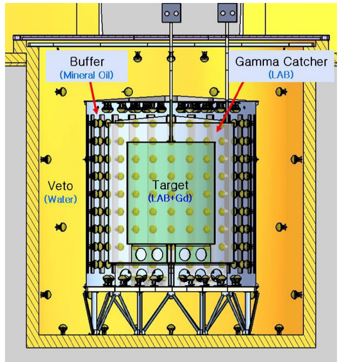


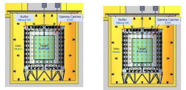
$200\ m^3$

Running till 2022

RENO

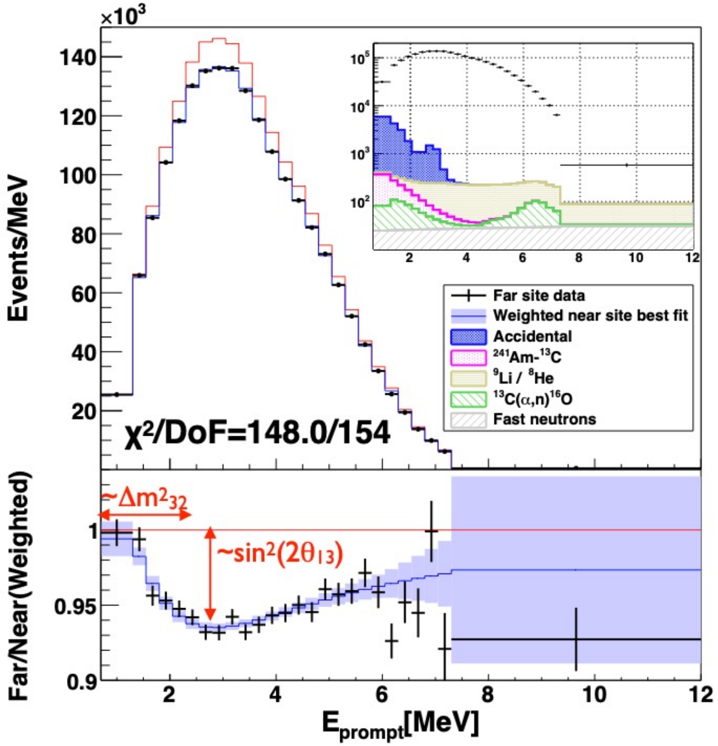





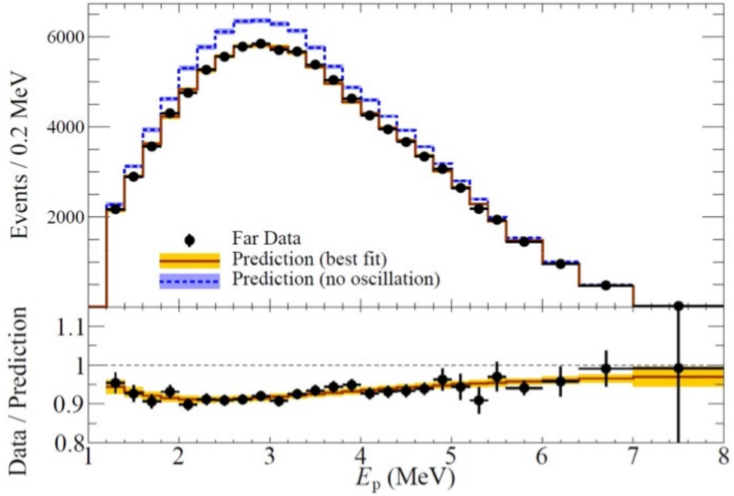
$40\ m^3$

Running for a few years

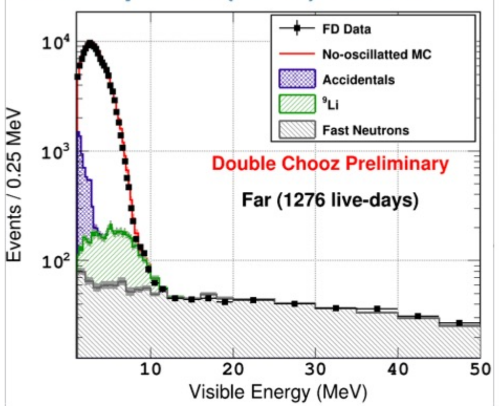
Daya Bay
Phys.Rev.Lett. 121 (2018) 24, 241805

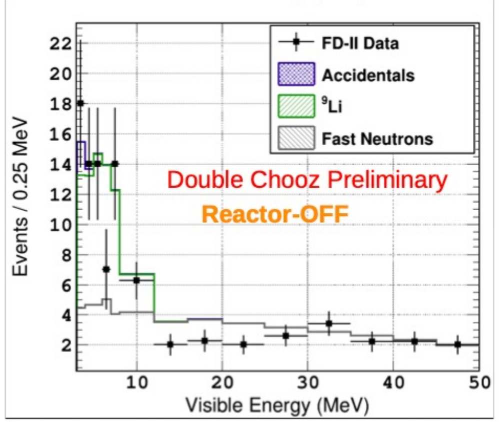


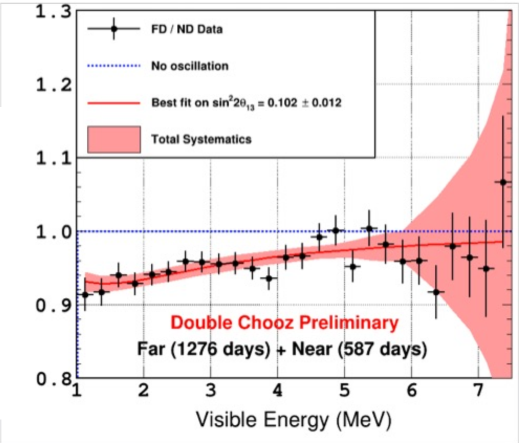
RENO,
Phys.Rev.Lett. 121 (2018) 20, 201801



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

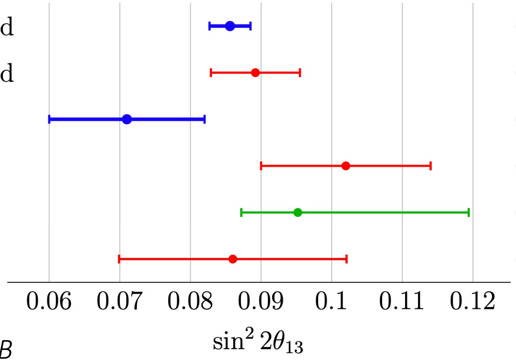






C. Jollet

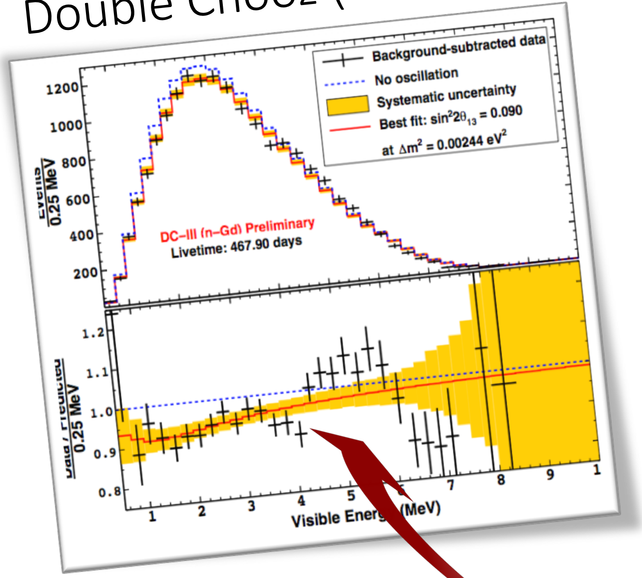
Experiment		Value
Daya Bay	nGd	0.0856 ± 0.0029
RENO	nGd	0.0892 ± 0.0063
Daya Bay	nH	0.071 ± 0.011
Double CHOOZ		0.102 ± 0.012
T2K		$0.0952^{+0.0242}_{-0.0080}$
RENO	nH	0.0860 ± 0.0161



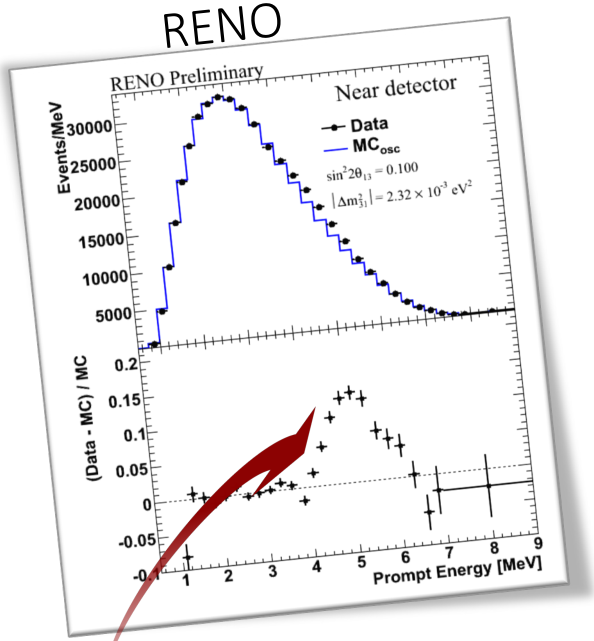
Snowmass2021-LOI DB

A new anomaly revealed in reactor neutrino spectra

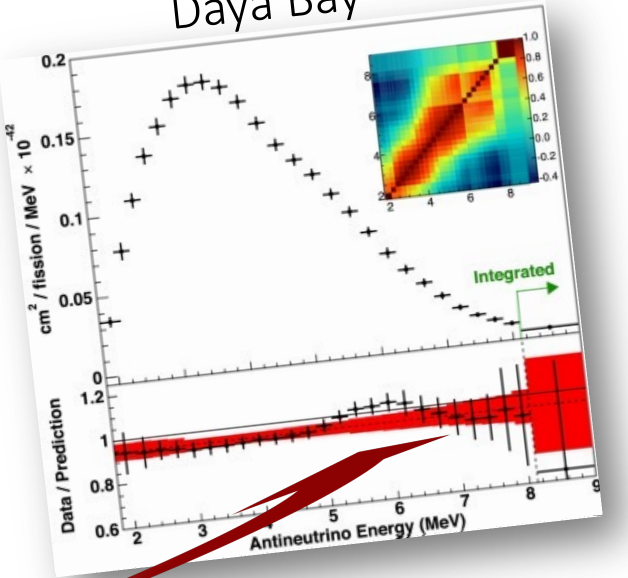
Double Chooz (2014)



RENO



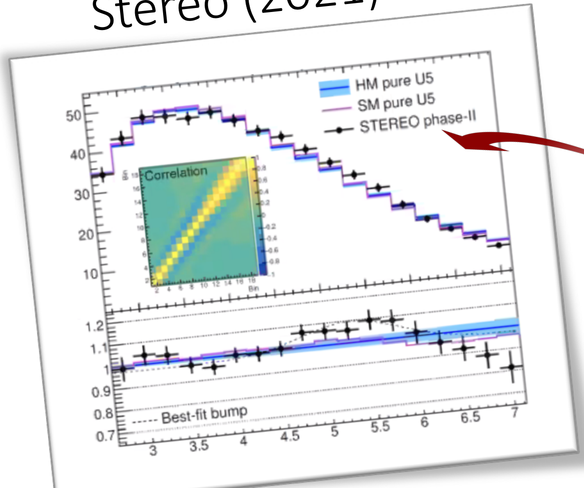
Daya Bay



So-called 5 MeV bump

(LEU ^{235}U + ^{239}Pu)

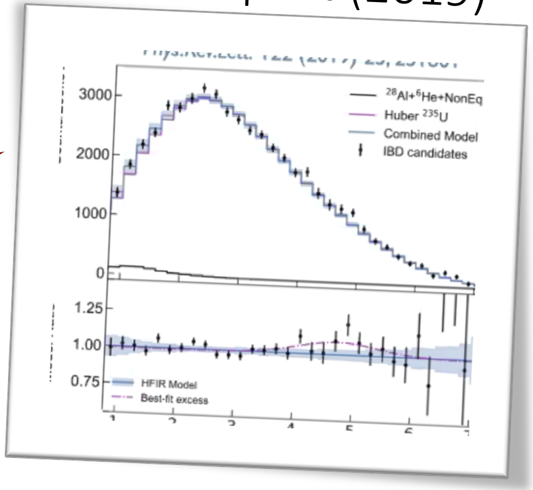
Stéréo (2021)



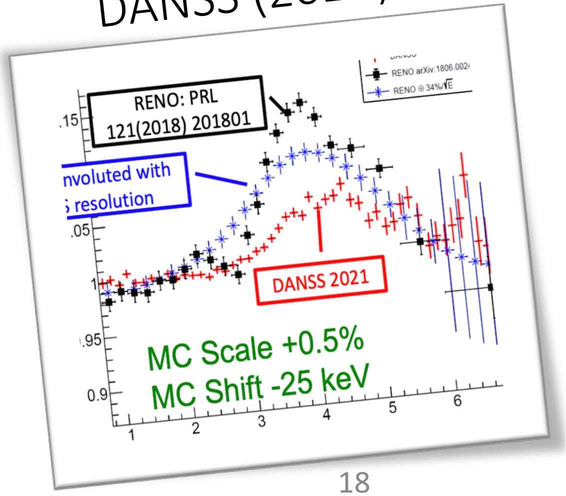
Confirmations

(HEU ^{235}U)

Prospect (2019)



DANSS (2021)



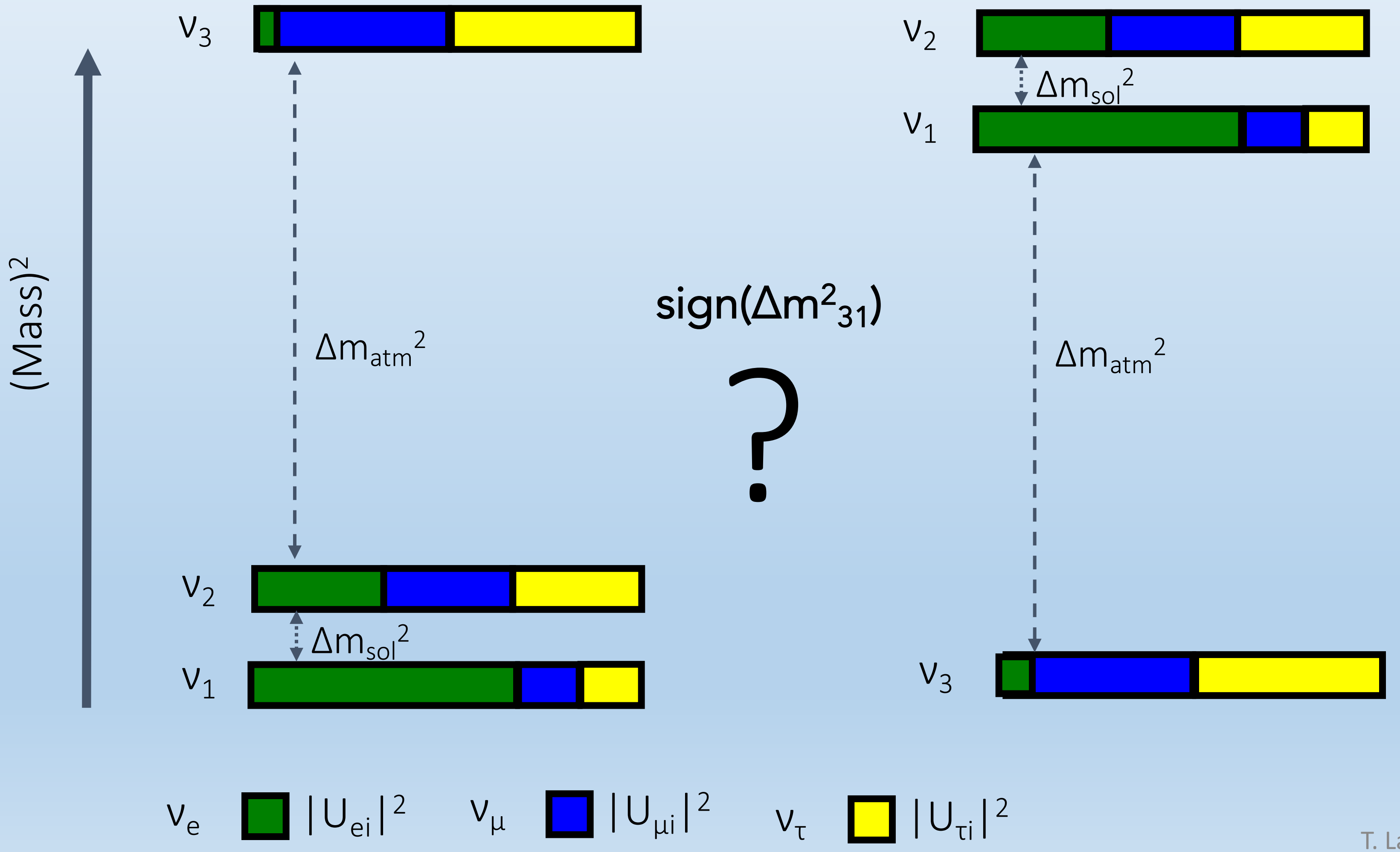
Reactor ν-spectra?

T. Lasserre
PANIC 2021

Capturing neutrino properties

Neutrino Property	Neutrino Source(s)	Method	Status
Δm^2_{21}	reactor, sun	ν – oscillations	✓ (2.2%)
θ_{12}	reactor, sun	ν – oscillations	✓ (4.4%)
Δm^2_{31}	accelerator, reactor, atmospheric	ν – oscillations	✓ (1.3%)
sign of Δm^2_{31}	accelerator, reactor, atmospheric	ν – oscillations	✗ 2σ hints
θ_{23}	accelerator, atmospheric	ν – oscillations	✓ (5.0%)
θ_{13}	reactor, accelerator	ν – oscillations	✓ (3.8%)
δ	accelerator	ν – 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]

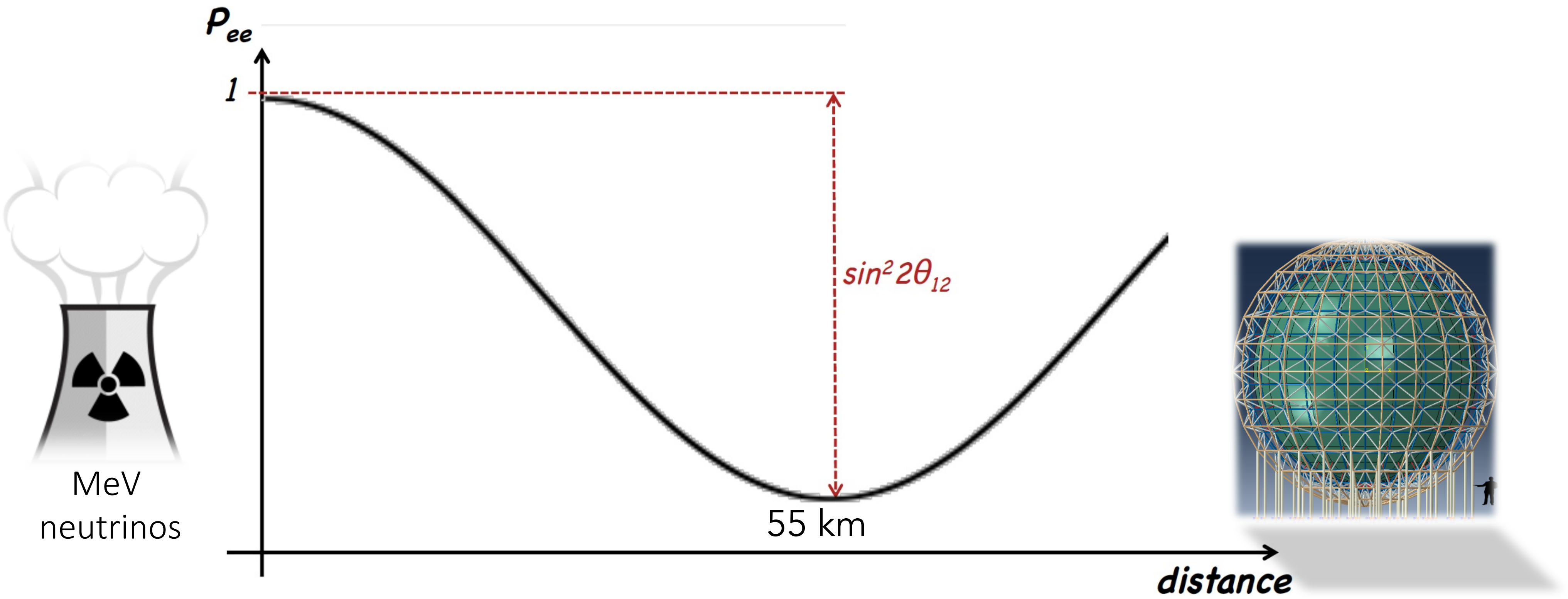
What is the spectral mass pattern ? (mass ordering or hierarchy)



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

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

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

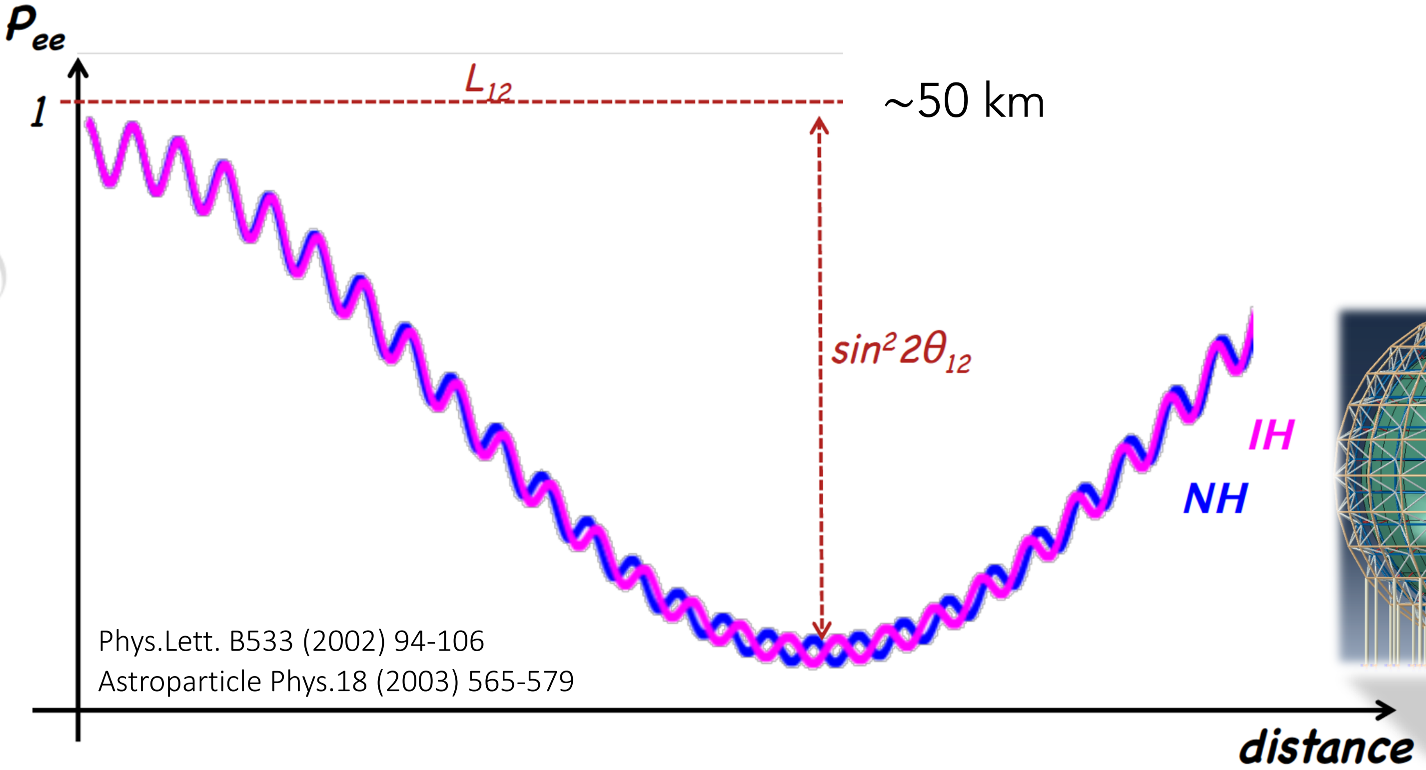
$$-\frac{1}{2}(1-|U_{e3}|^2)^2 \sin^2 2\Theta_{12}\left(1-\cos\frac{\Delta m^2_{21}L}{2E}\right)$$

Solar

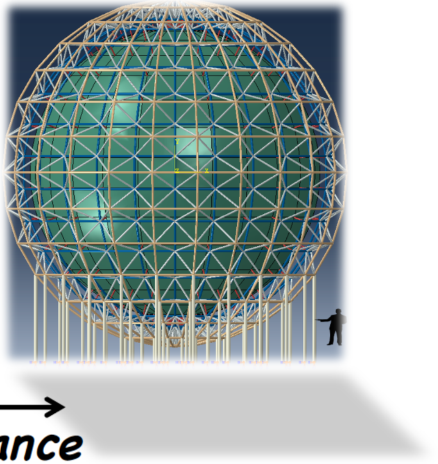
$$+2|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\Theta_{12}\left(\cos\left(\frac{\Delta m^2_{31}L}{2E}-\frac{\Delta m^2_{21}L}{2E}\right)-\cos\frac{\Delta m^2_{31}L}{2E}\right)$$

Interference

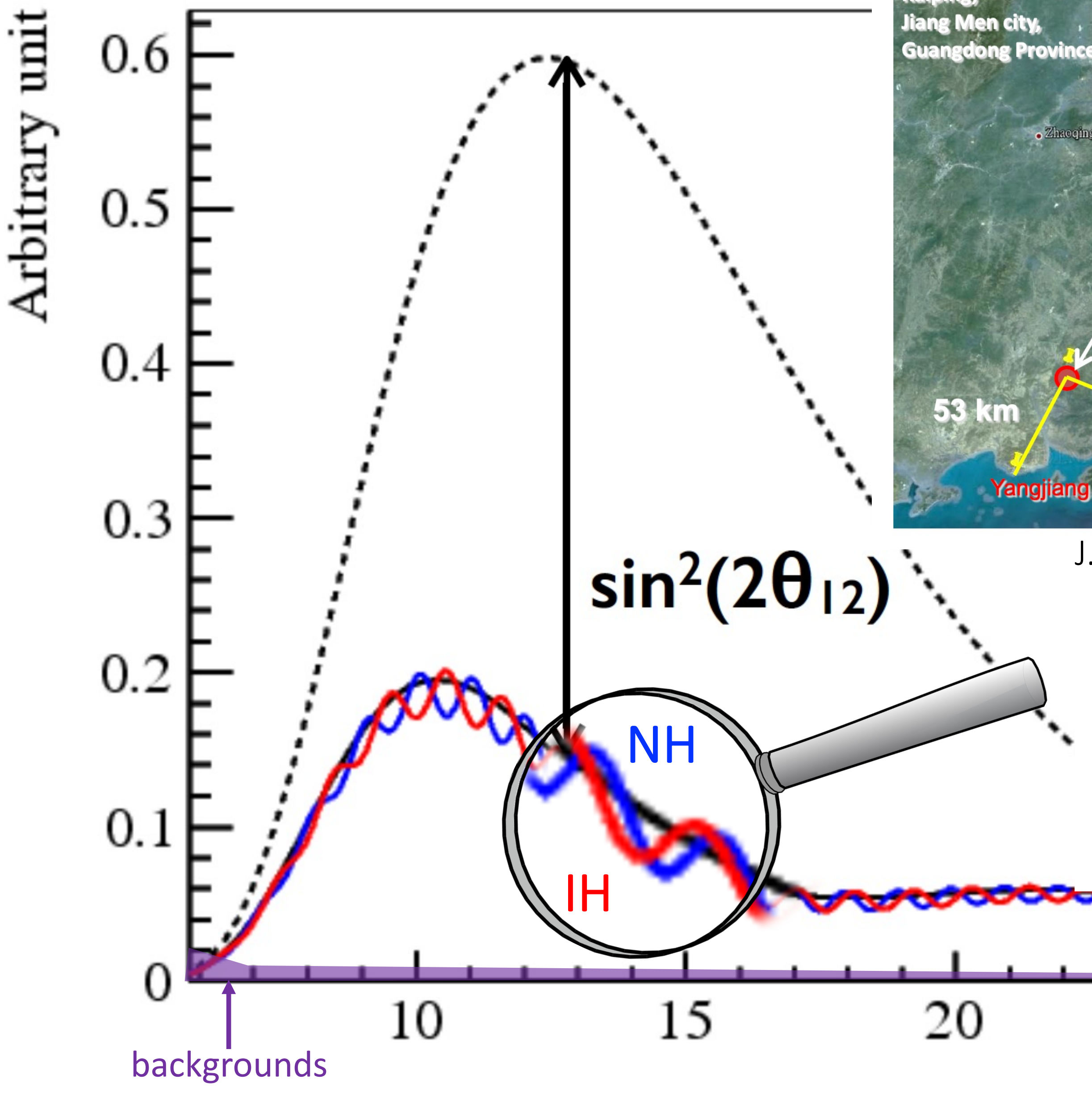
MeV neutrinos

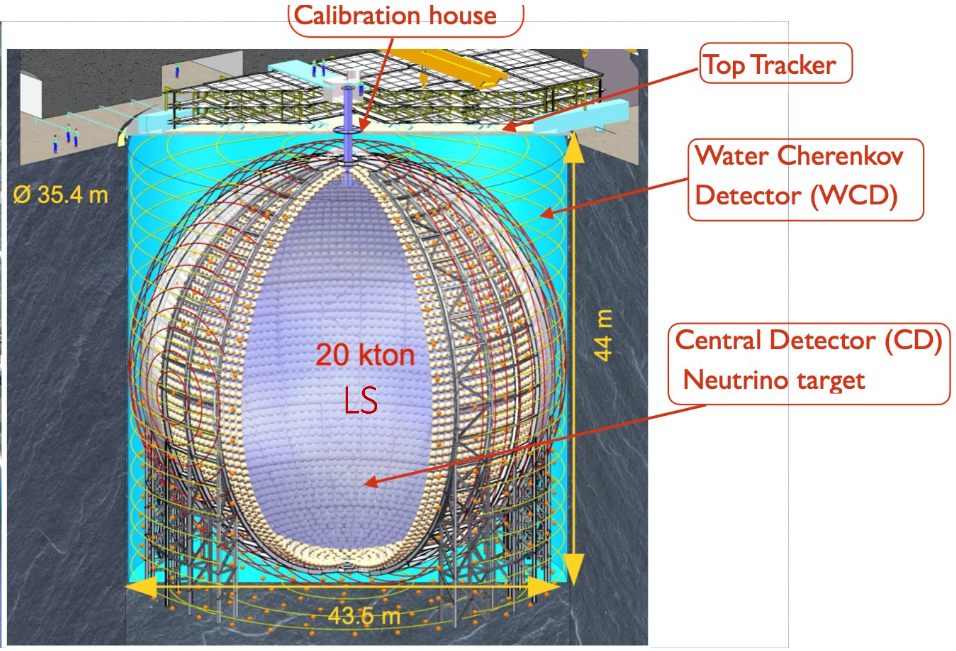


Phys.Lett. B533 (2002) 94-106
Astroparticle Phys.18 (2003) 565-579



20 kt JUNO Experiment (start in 2023)

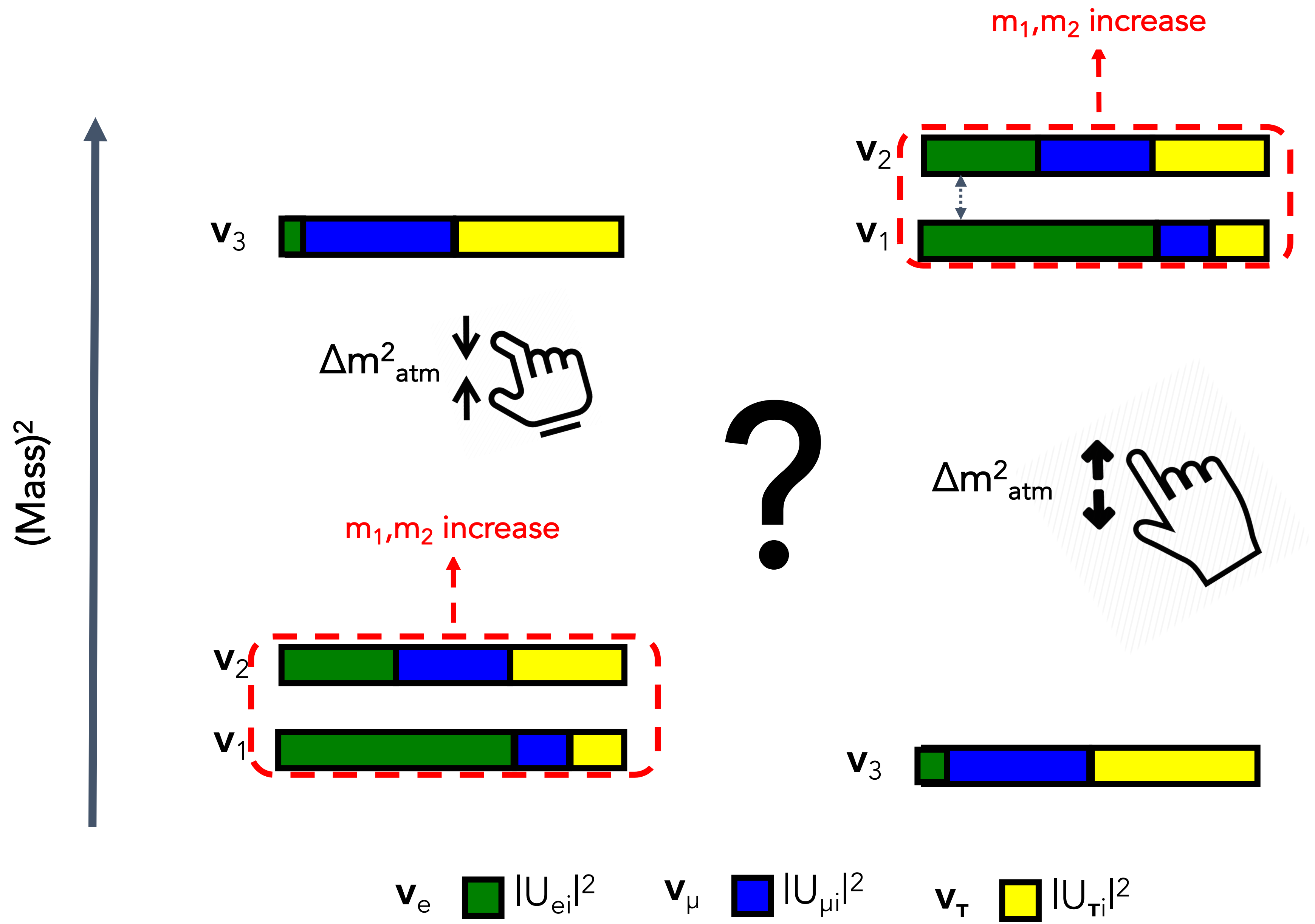




J. Phys. G 43 (2016) 030401

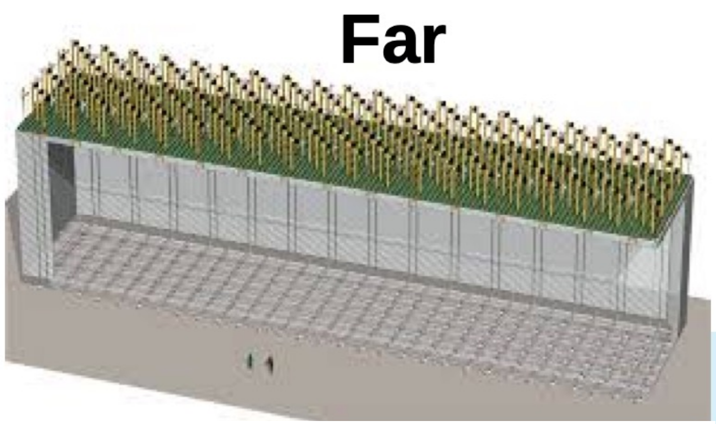
- Experimental challenges (for 3σ in 6 years)
  - Detect the absolute location of the wiggles
  - 3% energy resolution
  - <1% energy scale uncertainty

Oscillations in matter



- Matter effects affect Δm^2_{atm} oscillation frequency
- Need:
  - Long baselines >>100km
  - High energies O(GeV)

The DUNE experiment – Start in 2027



4 x 17 kt

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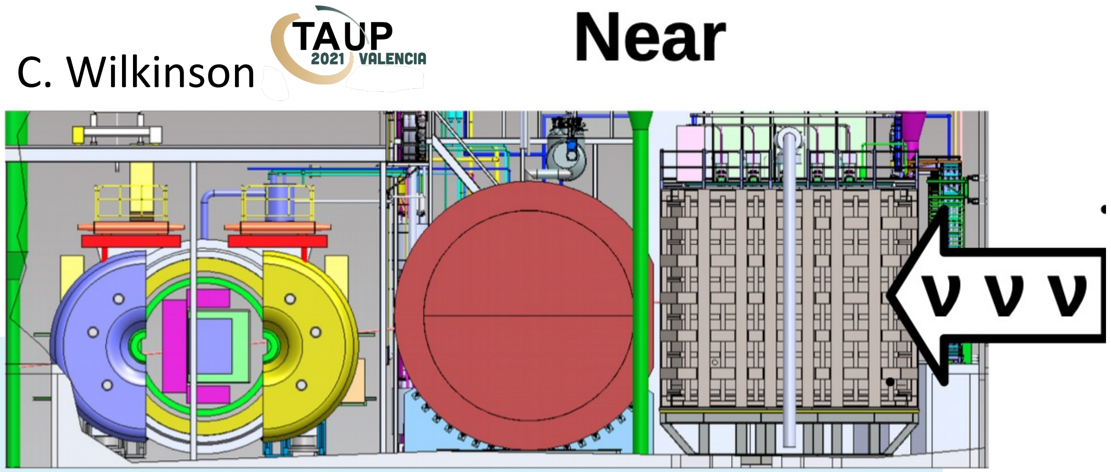
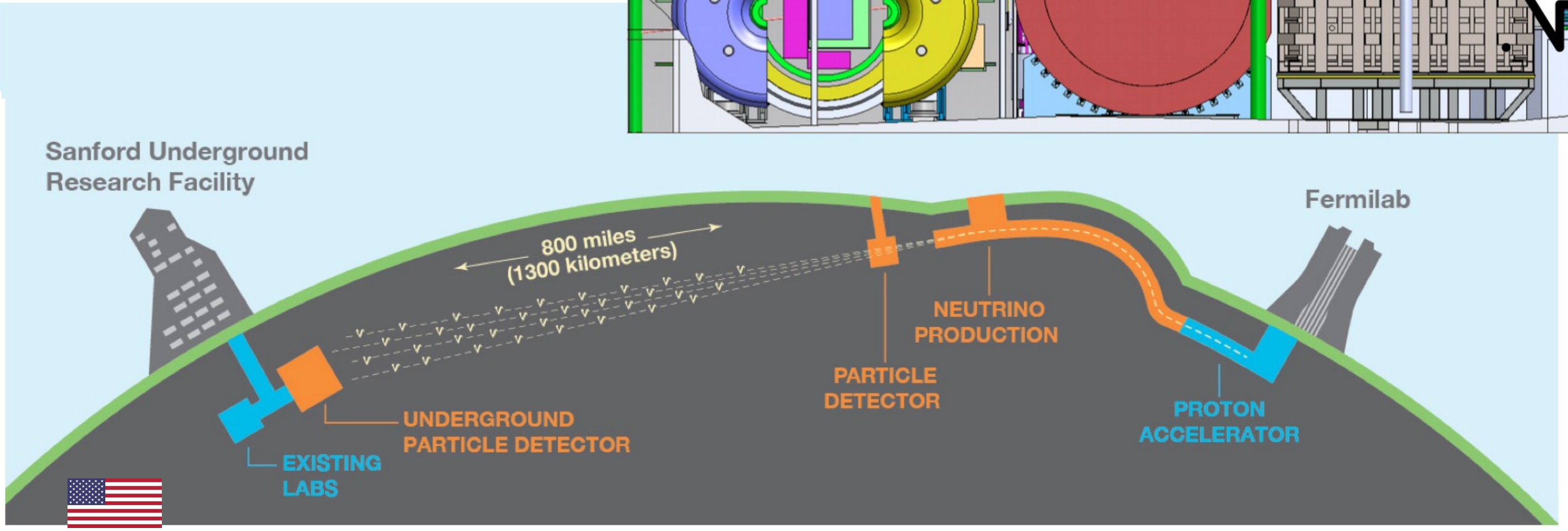




Fermilab:
- 1.2→2.4 MW neutrino beam
- Near detector system at Fermilab

SURF
- 4 x 17 kt LAr far detector modules
- 1285 km baseline

- First MO statements after 12 kt-MW-yr exposures (1 year)
- 99% C.L. statement after 66 kt-MW-yr for both orderings (6 years)

Do the behavior of ν violate CP?

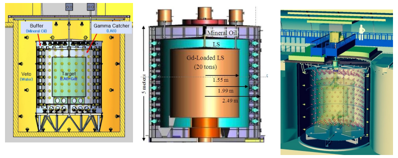
Neutrino & Antineutrino Oscillations

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

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

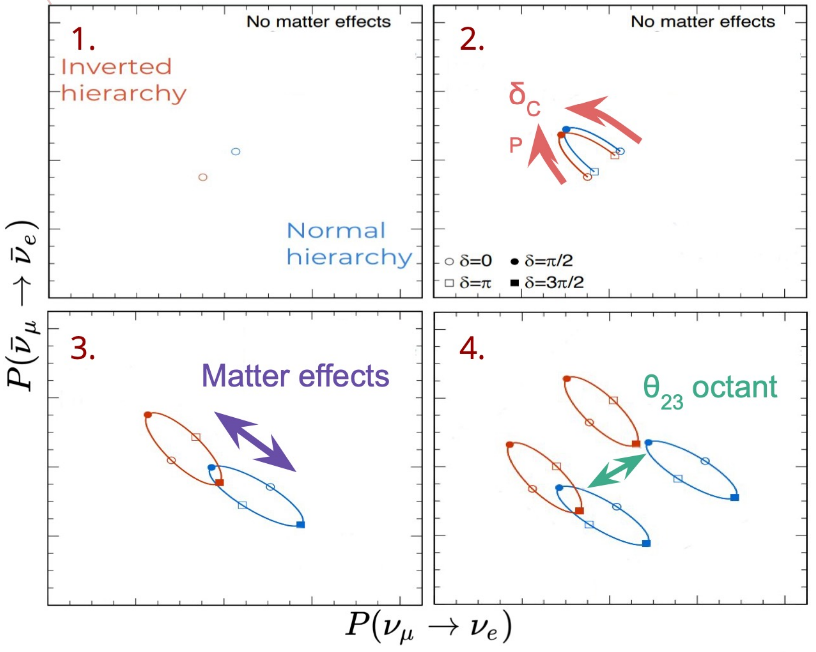
Asymmetry parameter

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



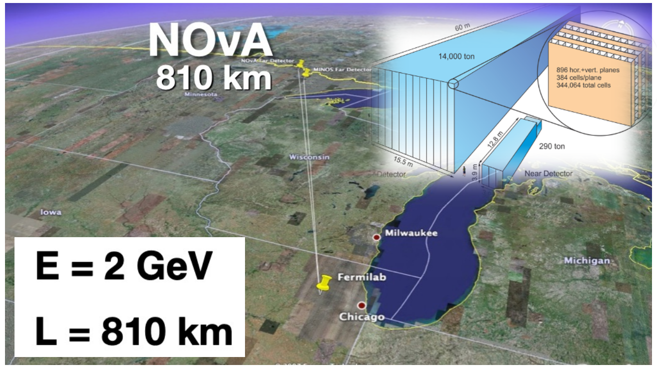
Fixed by reactor experiments

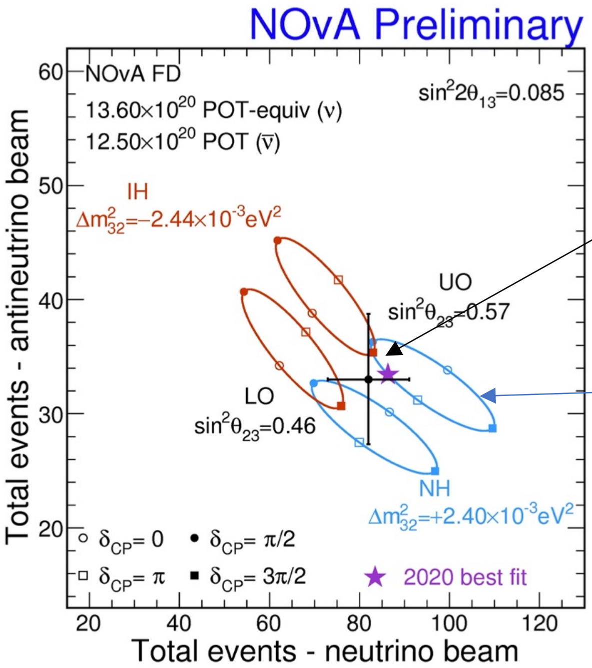
Correlations & Degeneracies



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

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





Data

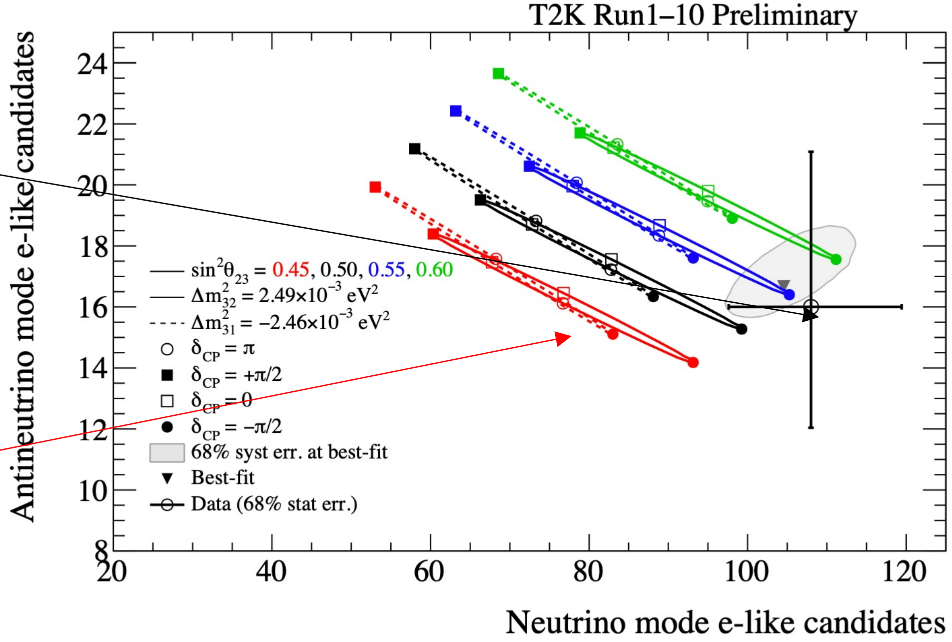
Model

Model

Model

Model

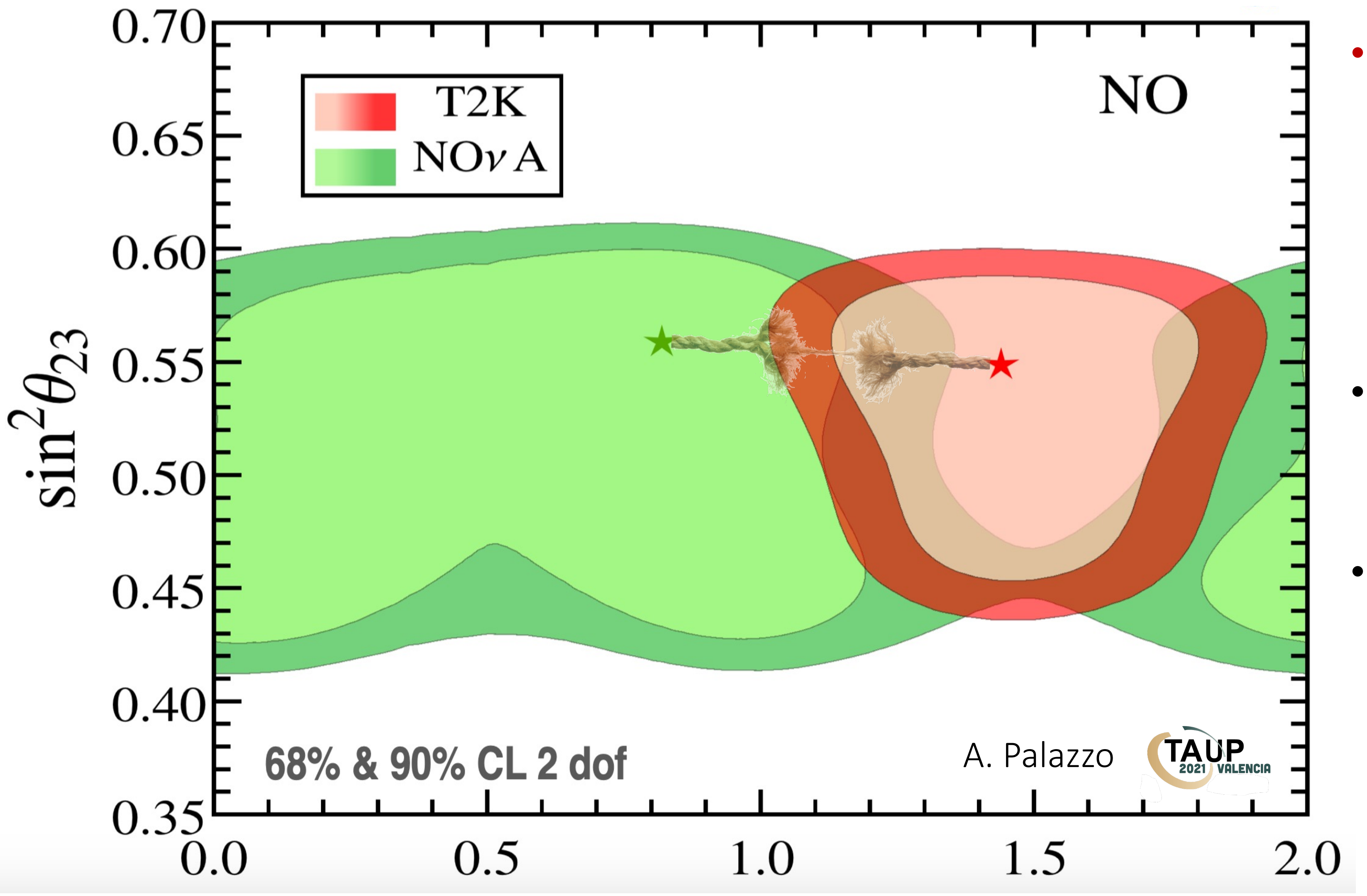
T2K



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

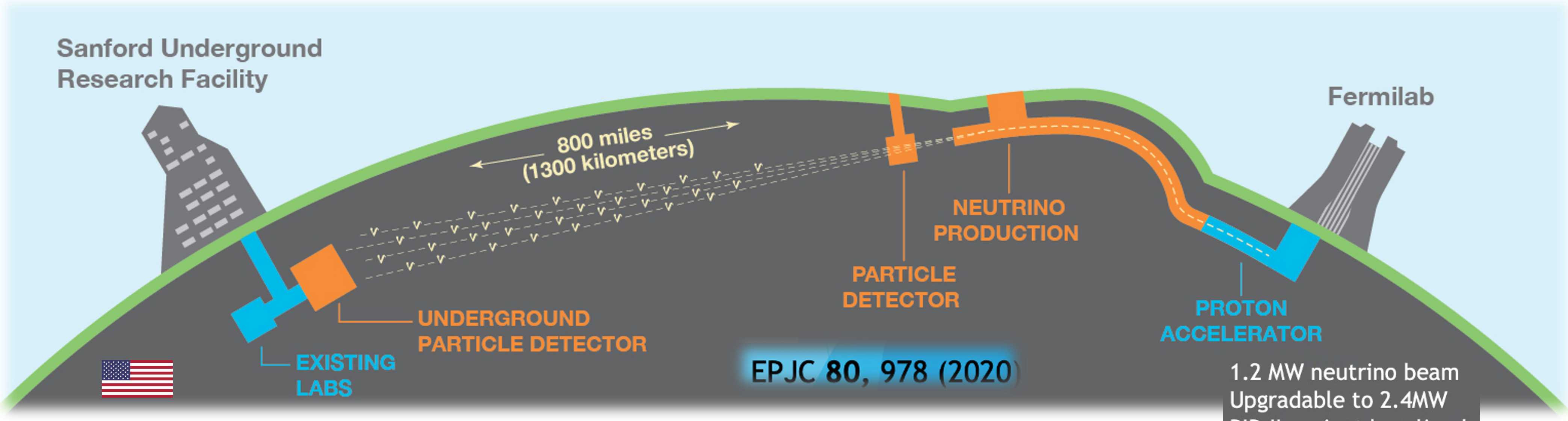
T2K favors $\delta_{CP} \sim 1.5\pi$ (NO)

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



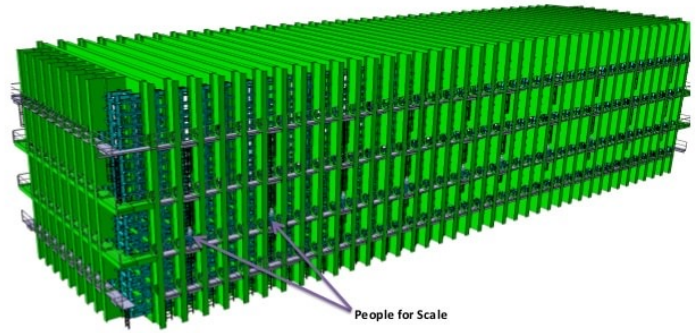
- In Normal Ordering, tension in the evaluation of δ_{CP}
  - statistical fluctuation?
  - systematic error?
  - Joint analysis ongoing
- Inverted ordering is disfavored by all other data
- (too) large NSI could solve the tension

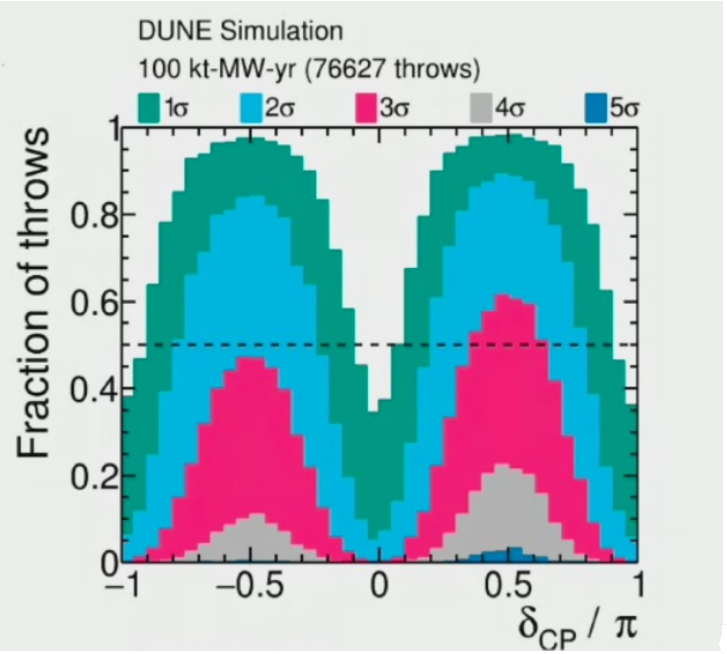
The DUNE Experiment – Start in late 20's



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)

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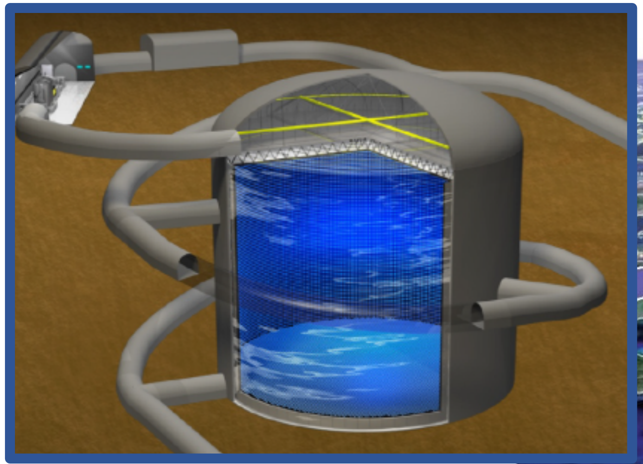
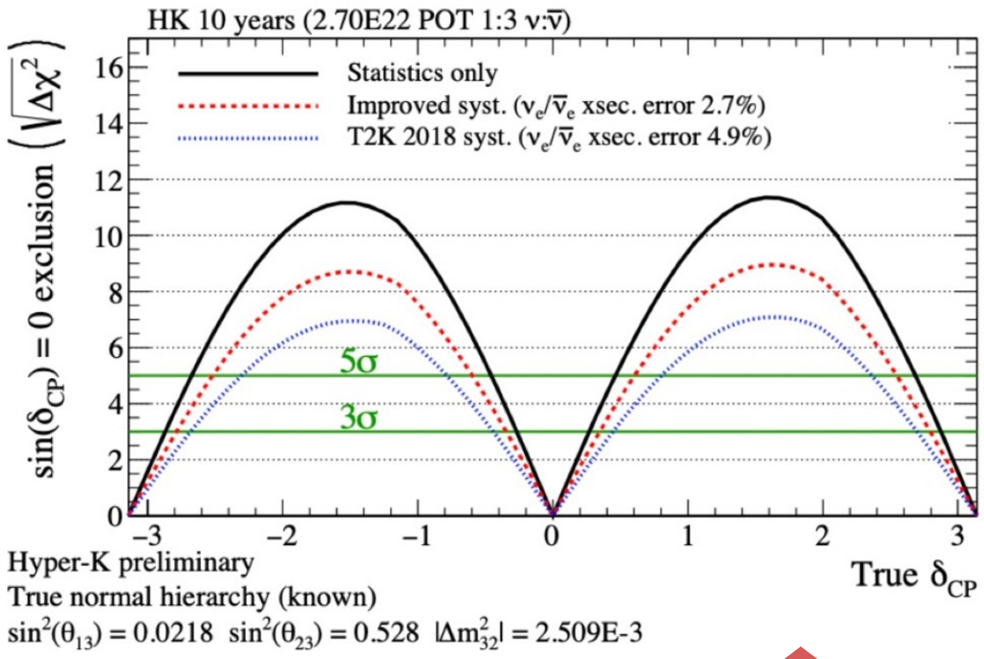
The Hyper-Kamiokande Experiment – Start in 2027

Construction started
in May 2021

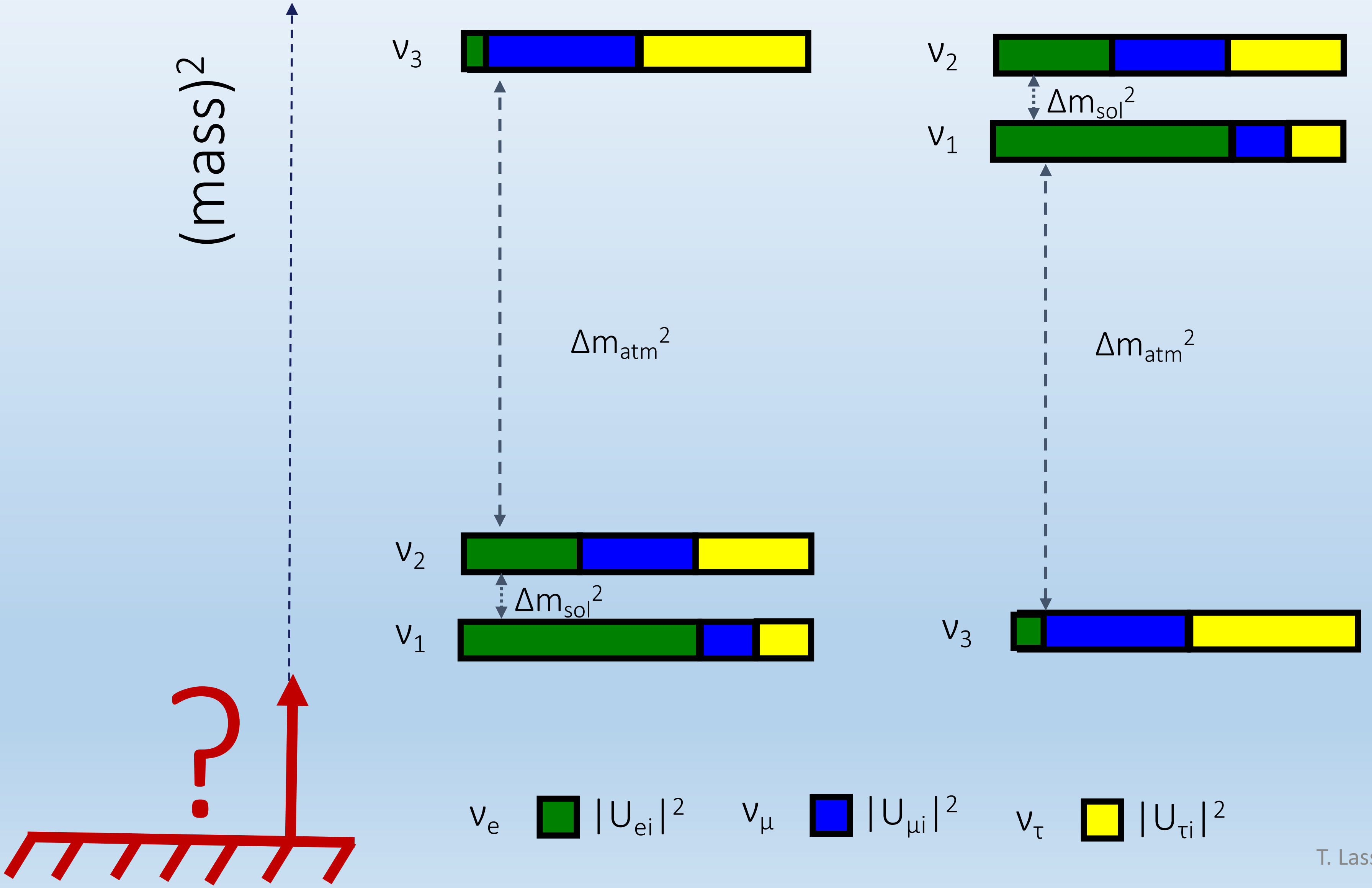




- HK is x8 SK
- Water Cherenkov
- 200 kt fiducial

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

The absolute neutrino mass scale

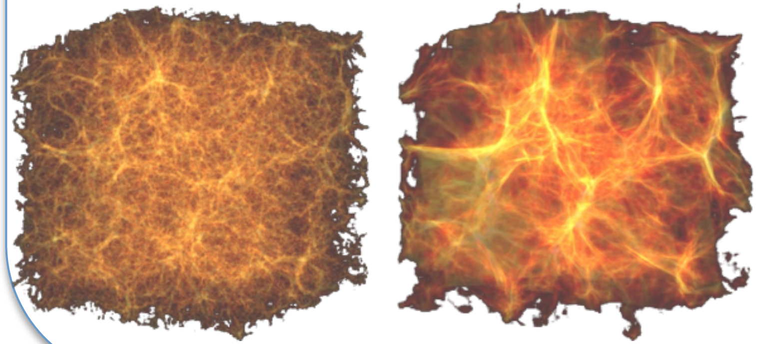


Neutrino masses

Cosmology

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

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



Search for 0νββ

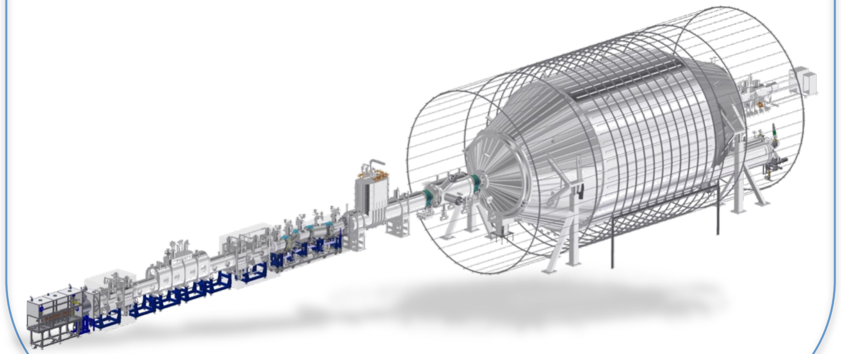
Laboratory-based
potential: $m_{\beta\beta}$ = 15-50 meV
e.g. LEGEND, Cupid

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

Kinematics of β-decay

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

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

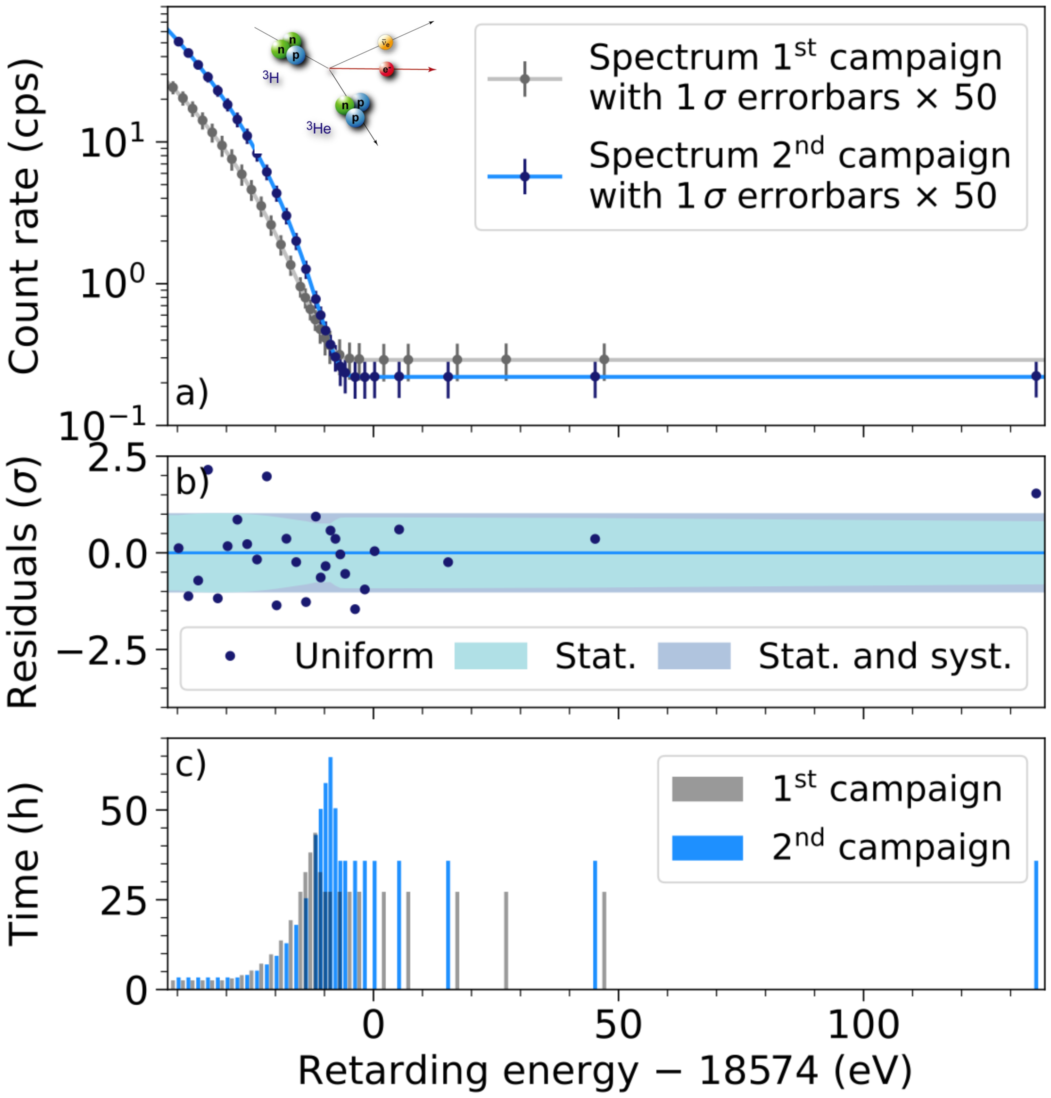


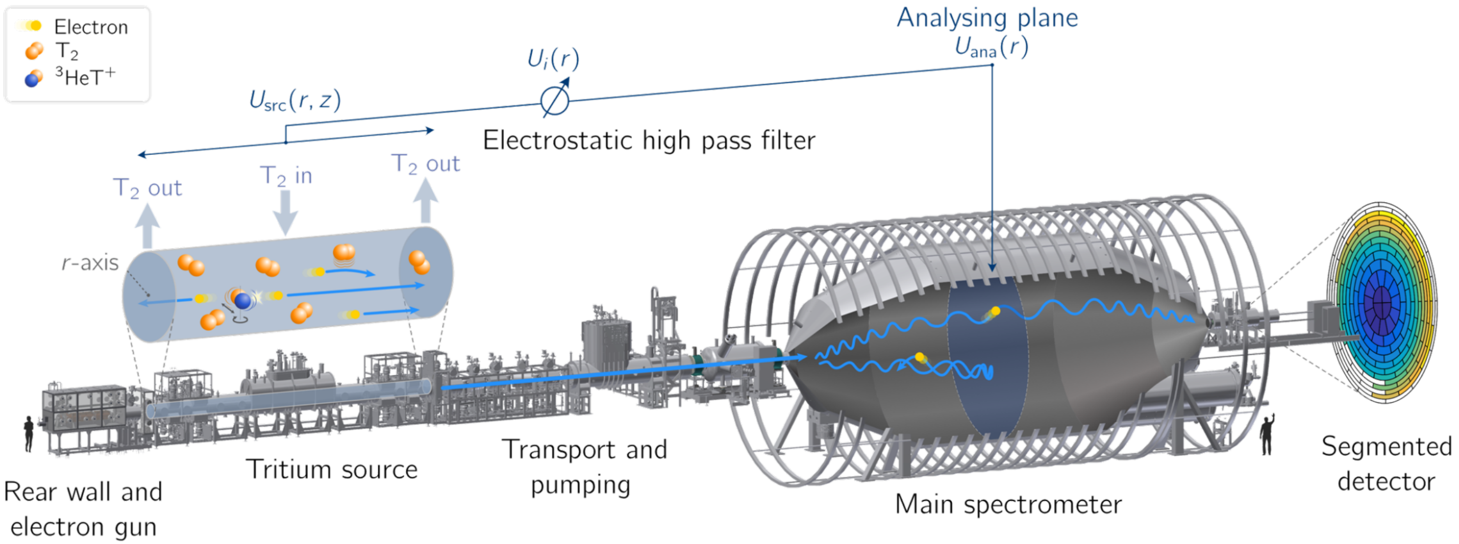
Lower bounds: from oscillation experiments

Upper bounds: from laboratory measurements & Cosmology

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

https://arxiv.org/abs/2105.08533



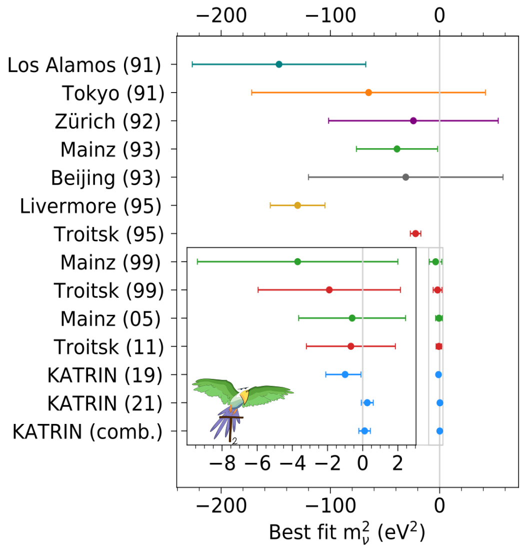


2021 results:

6.5 million events

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

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

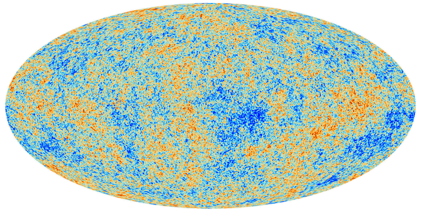


Cosmology

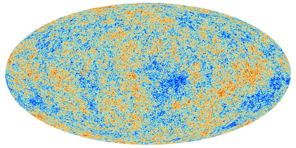
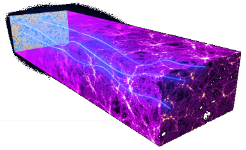
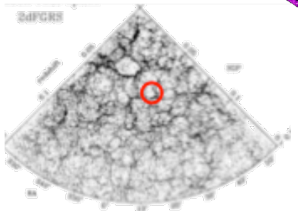
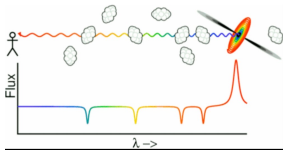
$$\sum_i m_i$$

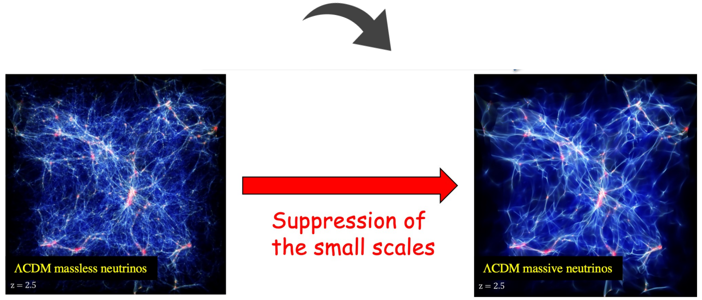
$> \sim 1\ \mathrm{eV}$: $\nu's$ become non relativistic before recombination

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

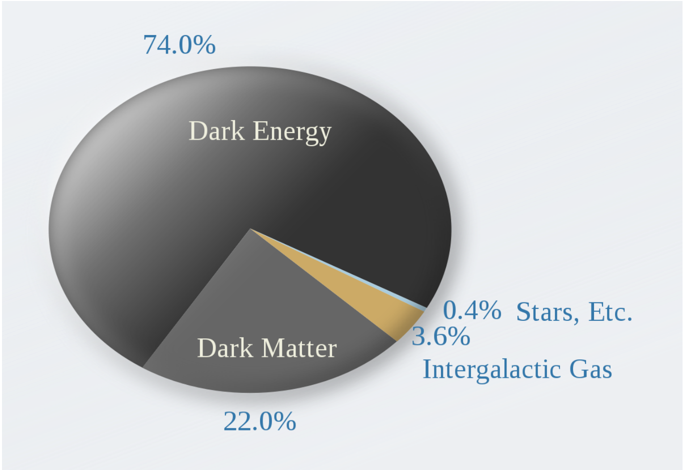


$< \sim 1\ \mathrm{eV}$: $\nu's$ become non relativistic after recombination

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



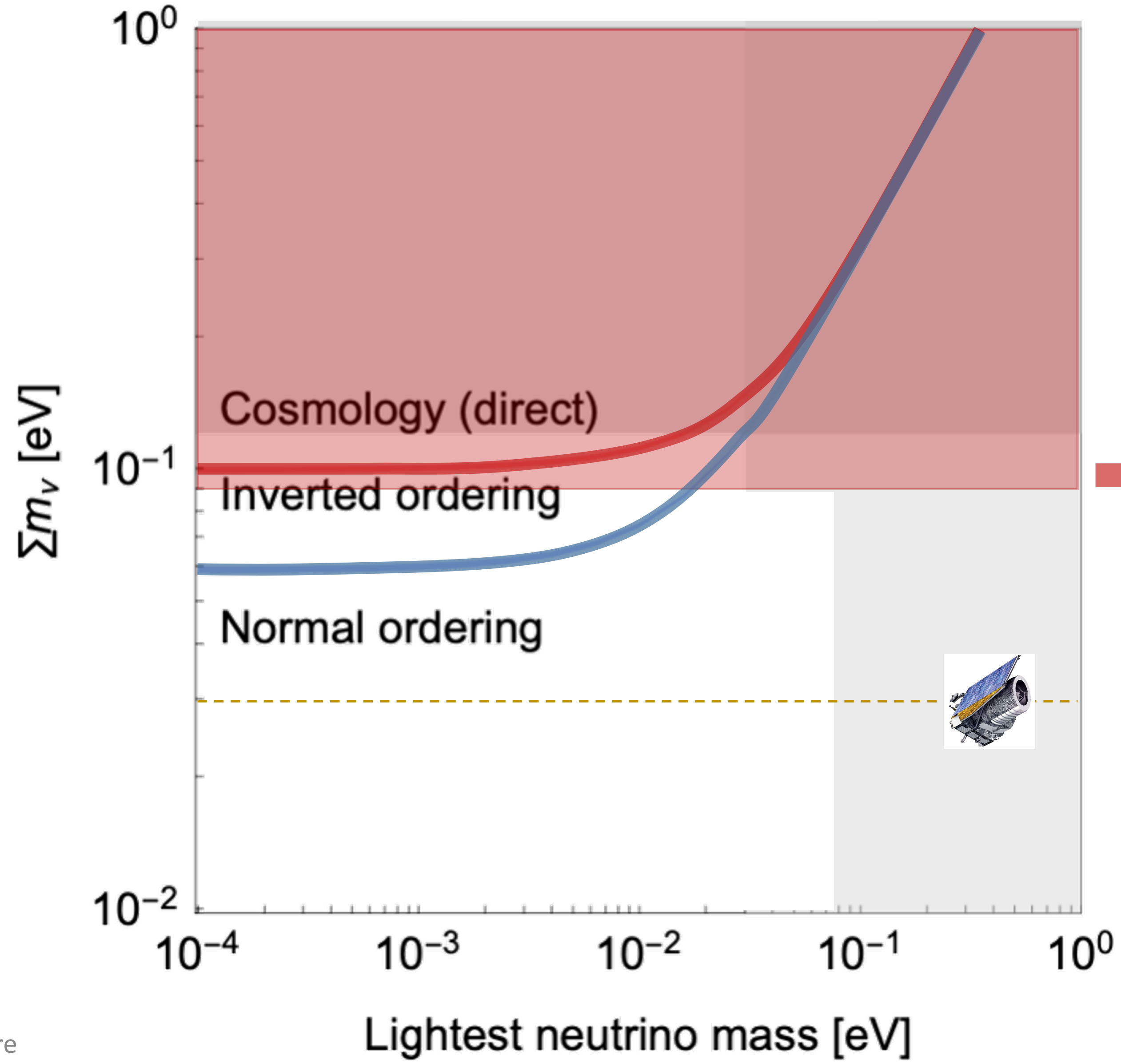
Constraints based on ΛCDM



JCAP 04 (2020) 038

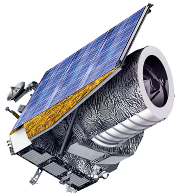
$$\sum m_i < 0.09\ \mathrm{eV}$$

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

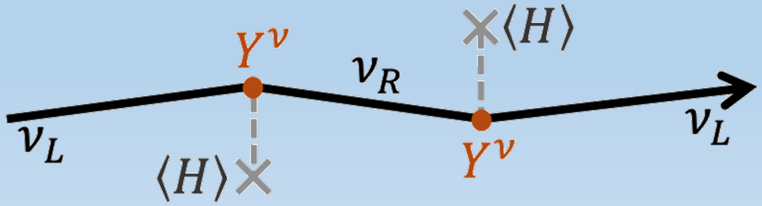


Is Lepton Number conserved?

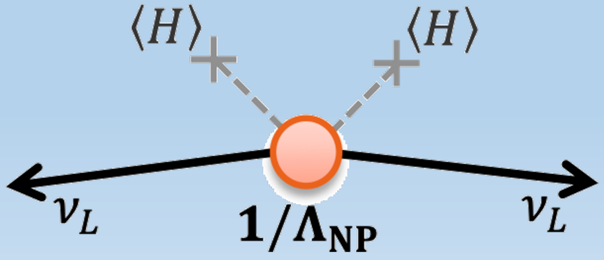
Creation of matter without antimatter partners ?

Dirac or Majorana ν?

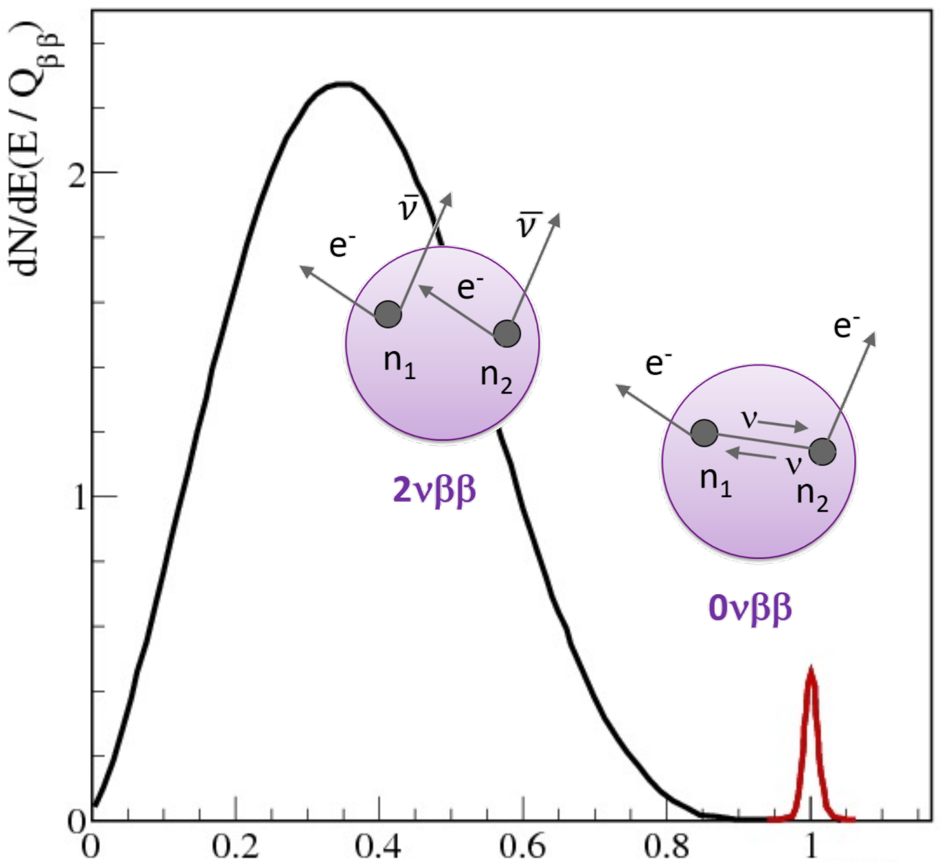
$$\nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix}$$



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



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



Energy of the two beta electrons

<u>If $0\nu\beta\beta$ is discovered:</u>

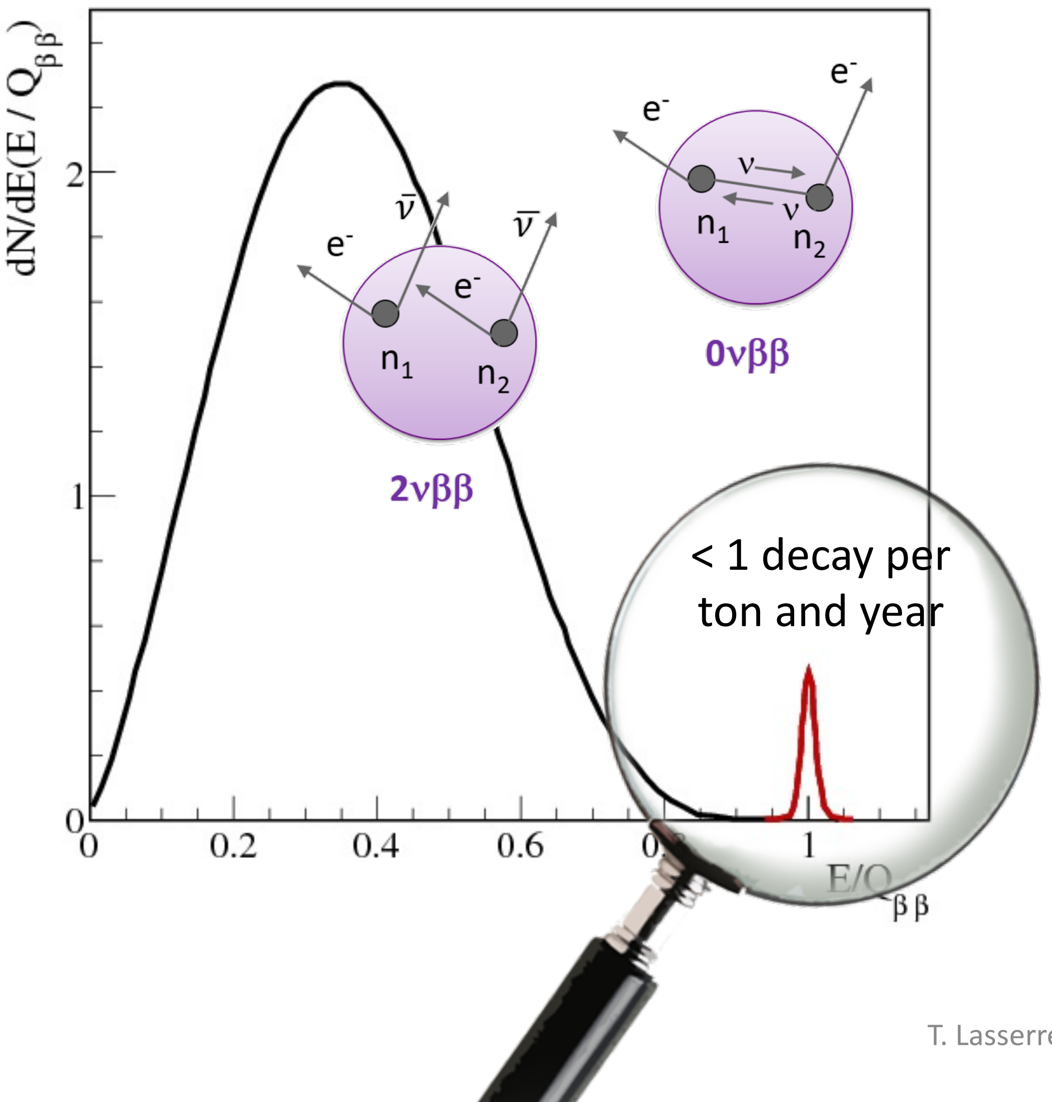
- Proof that neutrinos are Majorana particles and that Lepton number is violated
- Half life reveals neutrino mass

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

^{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 $T_{1/2}^{0\nu}$ > 10^{24} - 10^{26} y</u>

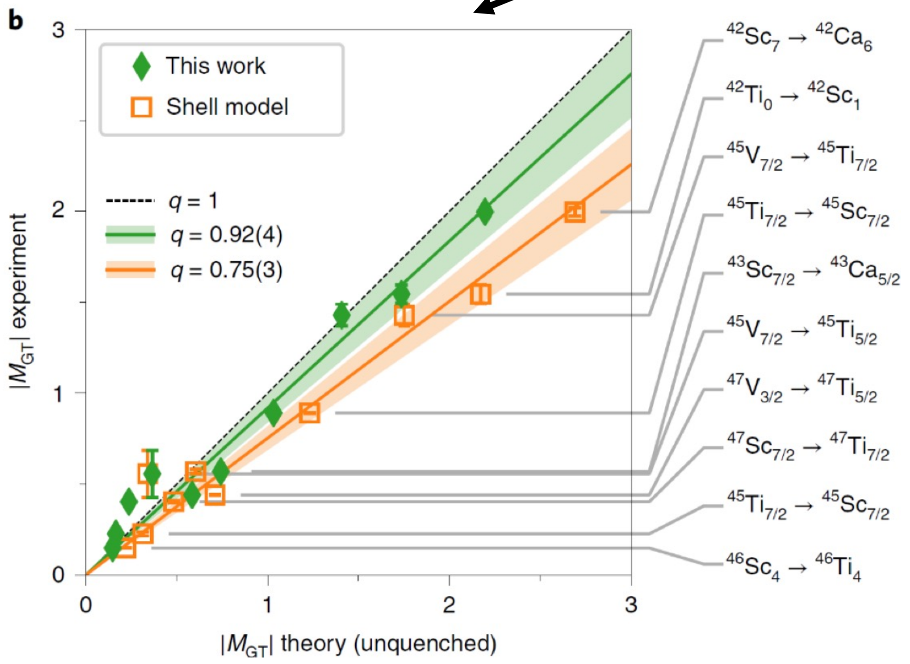
$$\frac{10^{25}\,\mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2$$

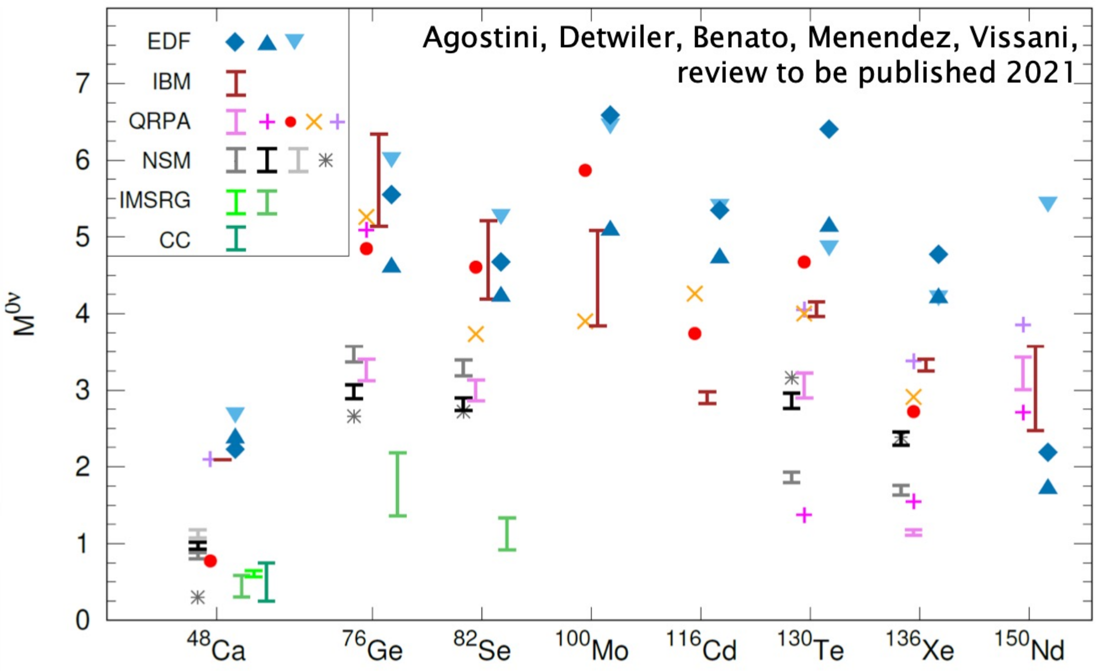
<u>Key requirements:</u>

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

Link to Nuclear Physics

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

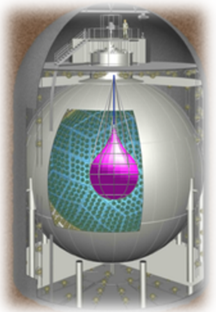


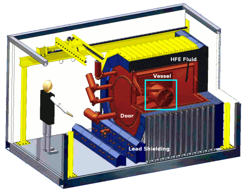


Quenching of axial nucleon coupling g_A?

Factor 2 – 3 uncertainty between nuclear models

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

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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)

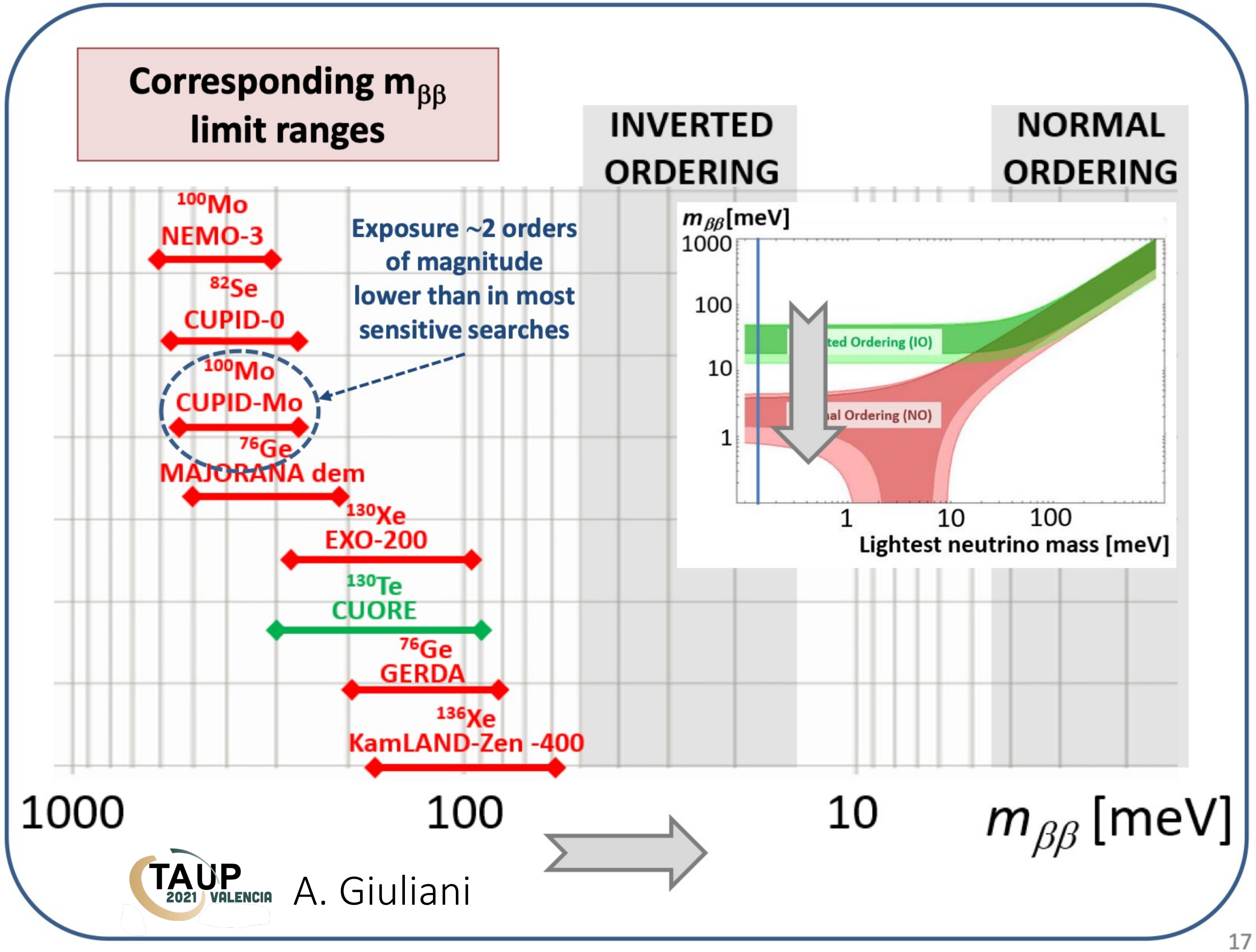
MAJORANA dem. $T_{1/2} > 2.7\times10^{25}$ y
Phys. Rev. C 100, 025501

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)



Prospects within 5 years

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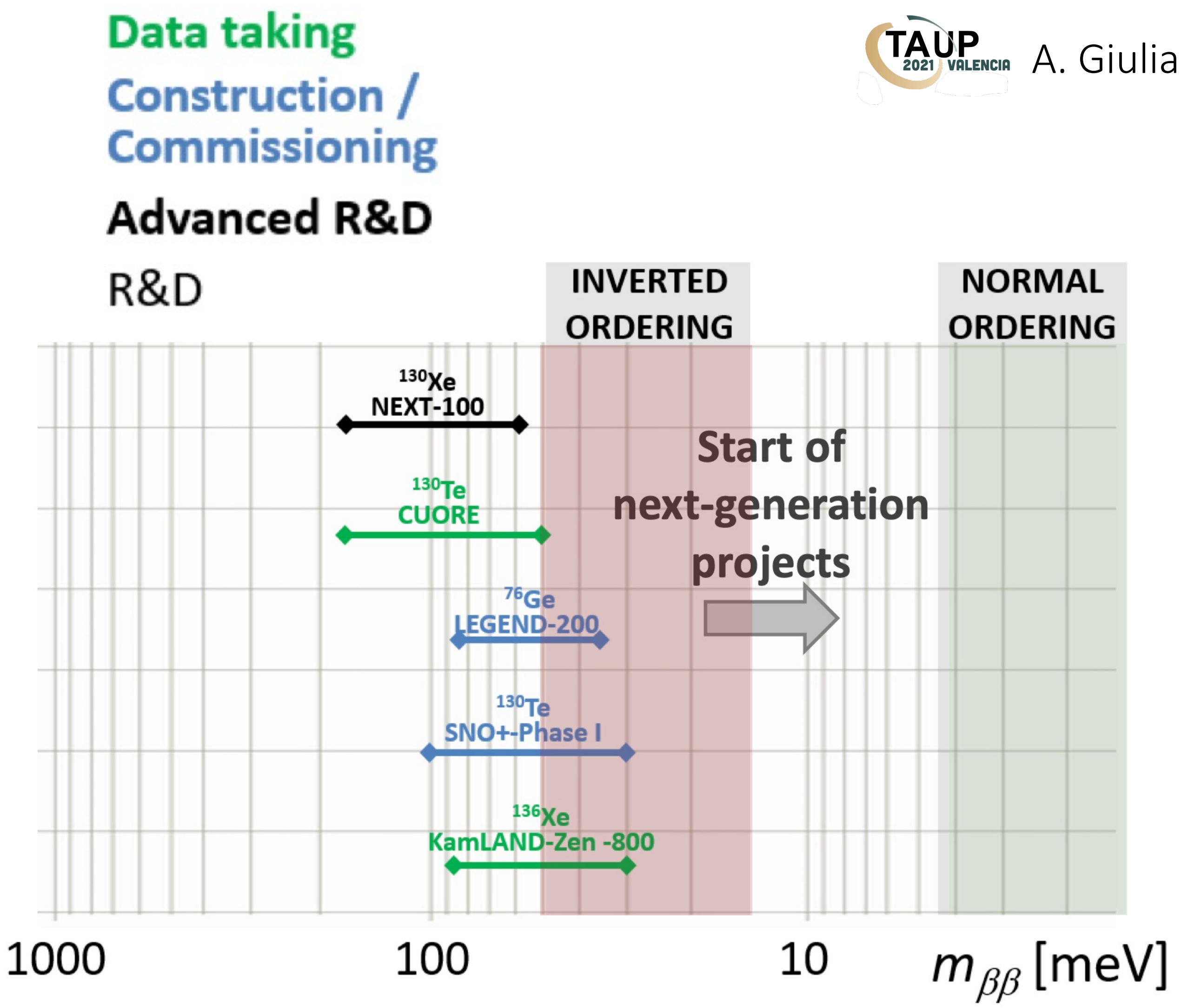
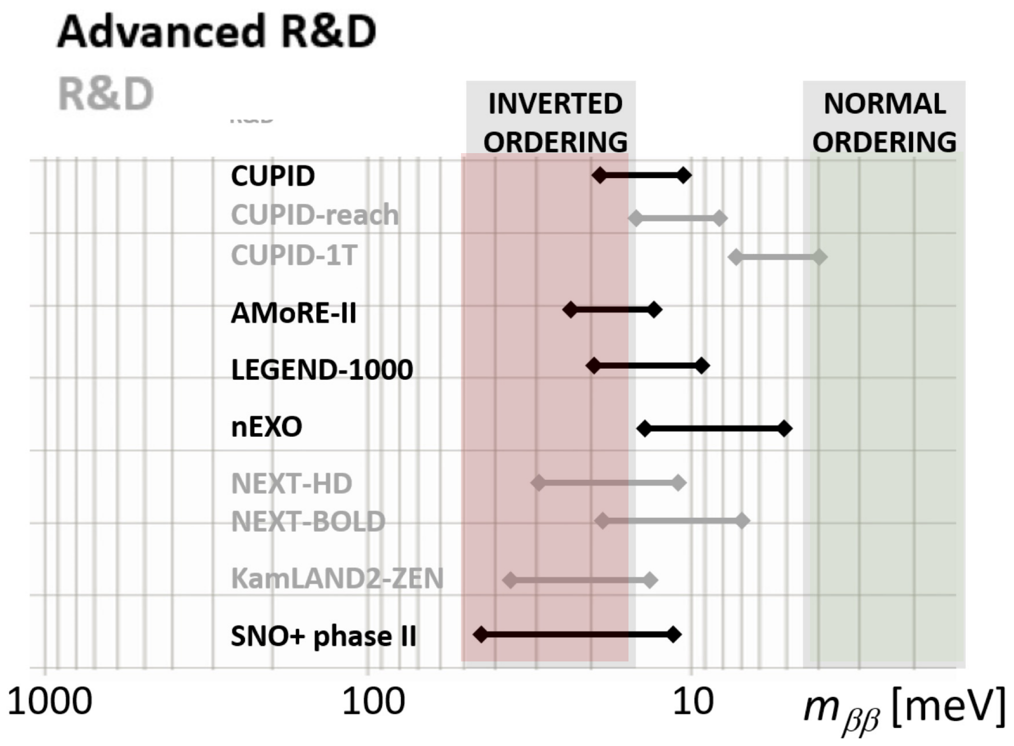


and beyond…

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



Are there additional light (sterile) ν states?

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

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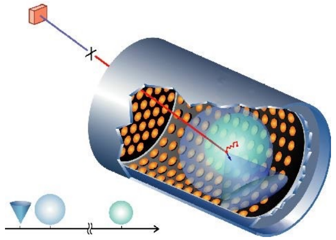
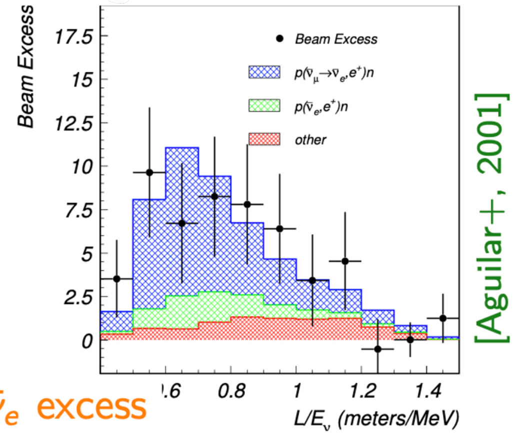


LSND

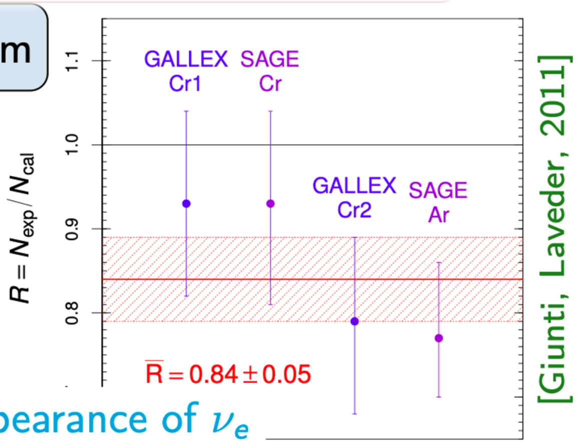
3.8σ



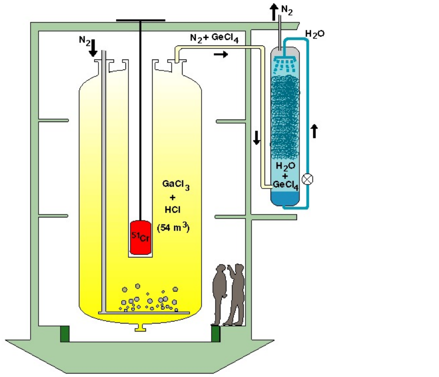
$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

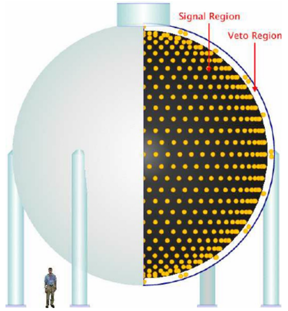
Gallium

2.7σ



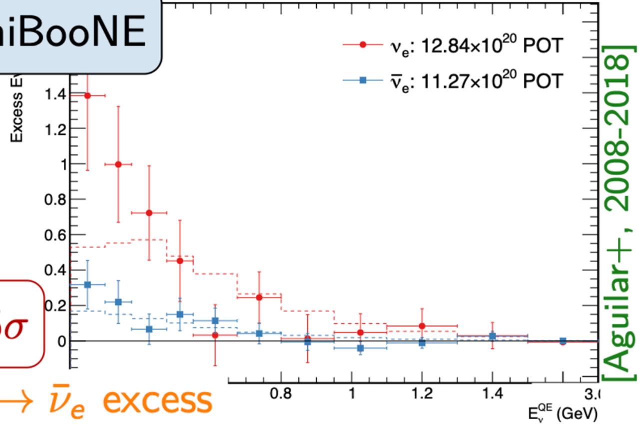
disappearance of ν_e





MiniBooNE

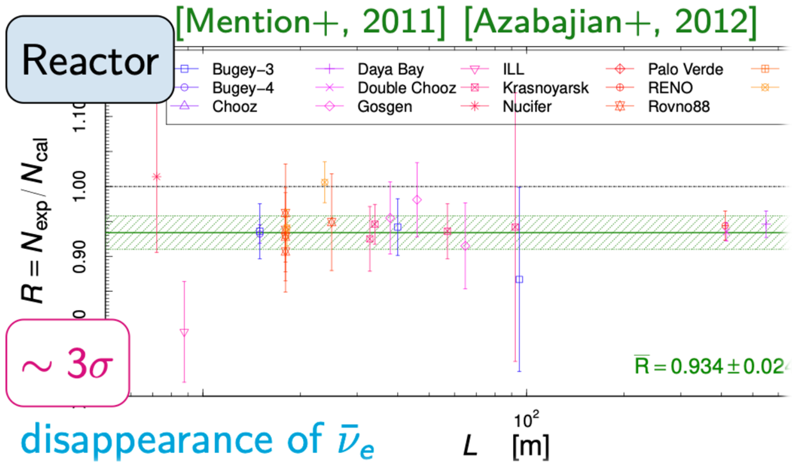
$\sim 5\sigma$



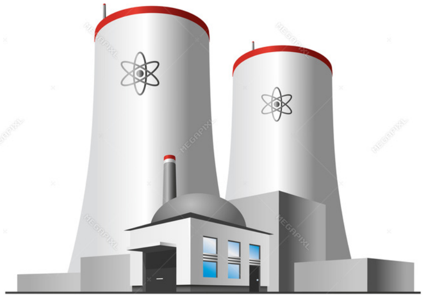
$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Reactor

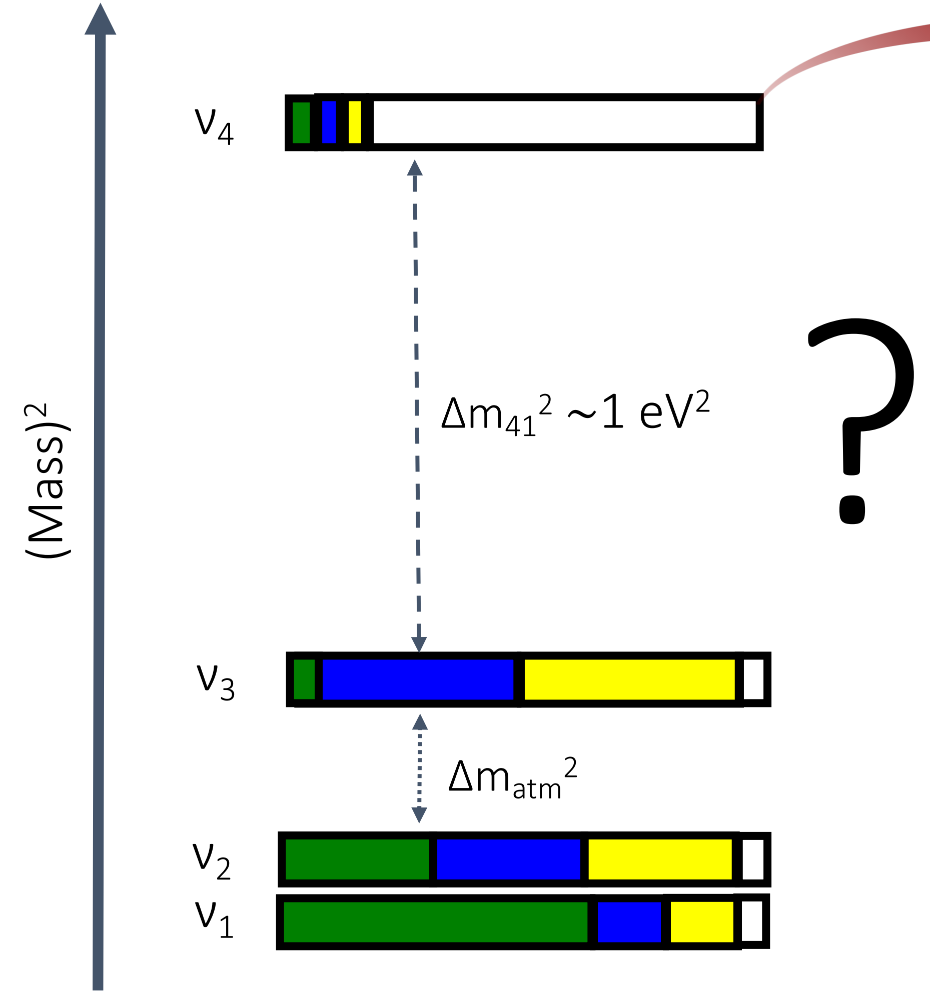
$\sim 3\sigma$



disappearance of $\bar{\nu}_e$



Are there additional neutrinos (mainly steriles) ?



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

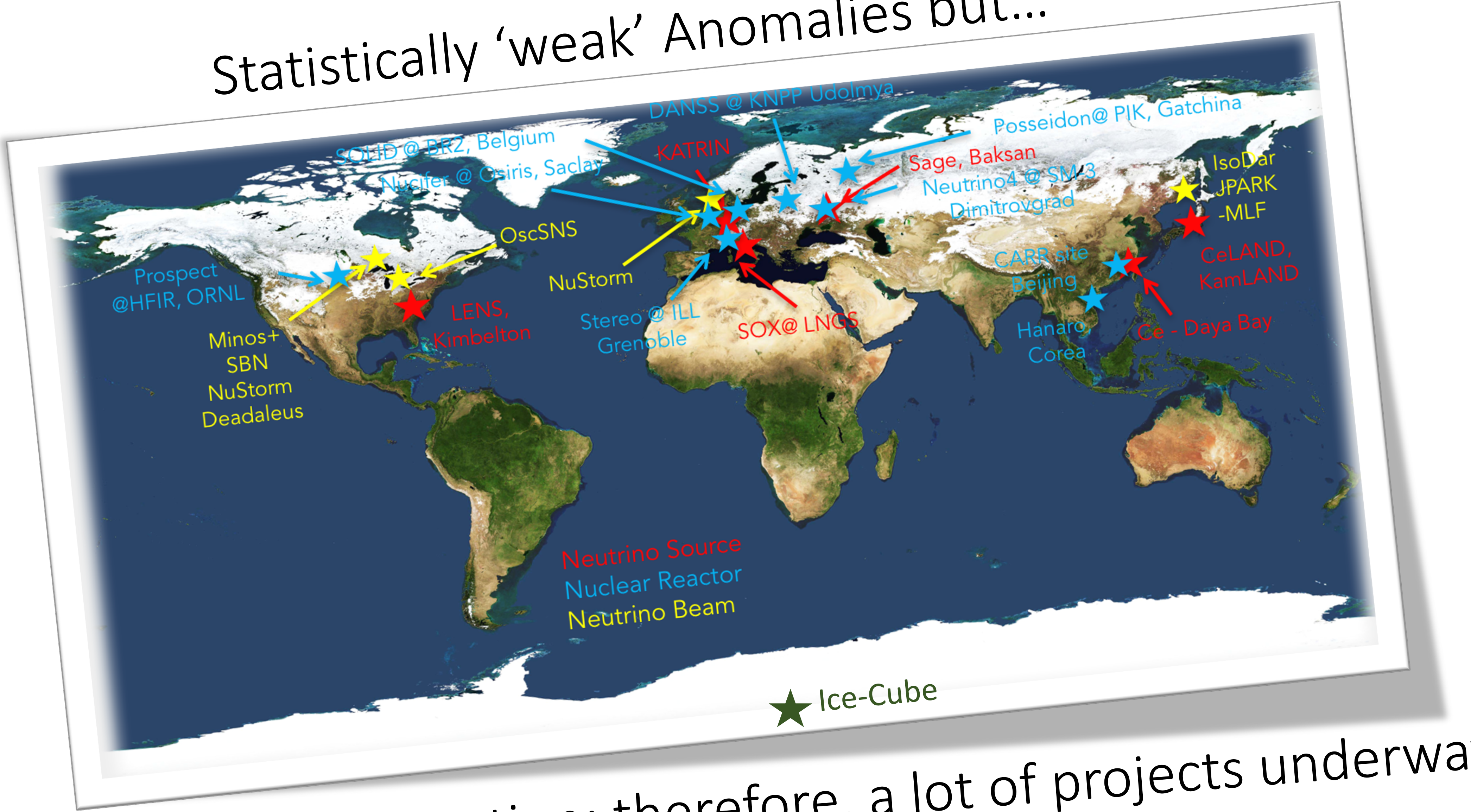
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

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

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

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

Statistically ‘weak’ Anomalies but…



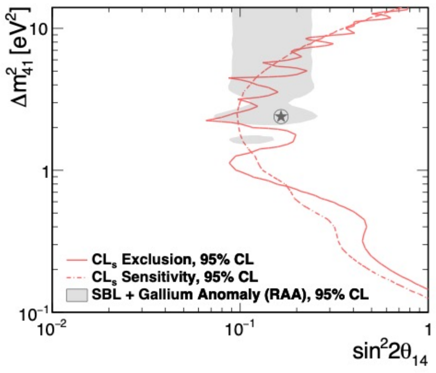
An important question: therefore, a lot of projects underway

Experimental results do not favor sterile neutrinos

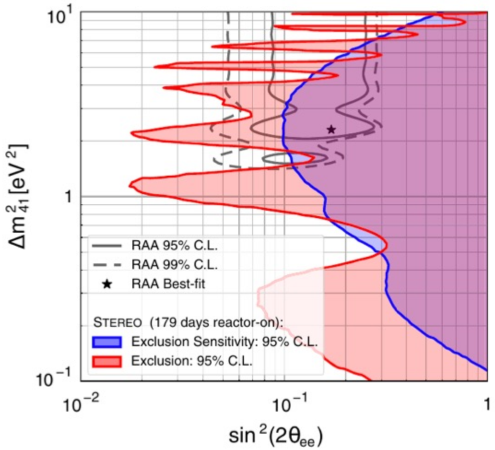
S. Gariazzo

Exclusion of GA+RAA by SBL reactor experiments

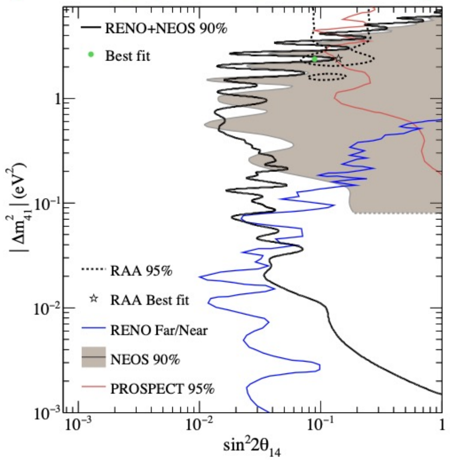
[PROSPECT, PRD 2020]



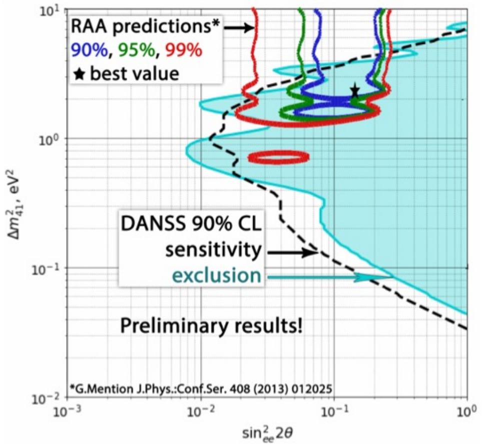
[STEREO, PRD 2020]



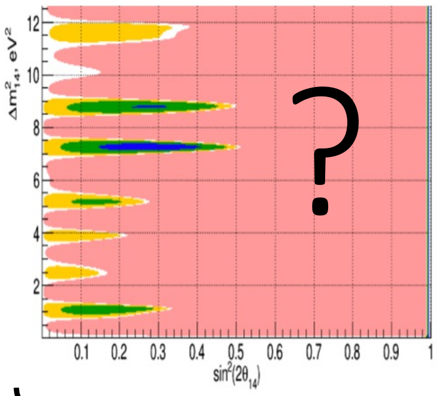
[RENO+NEOS, 2020]



[DANSS, 2020]



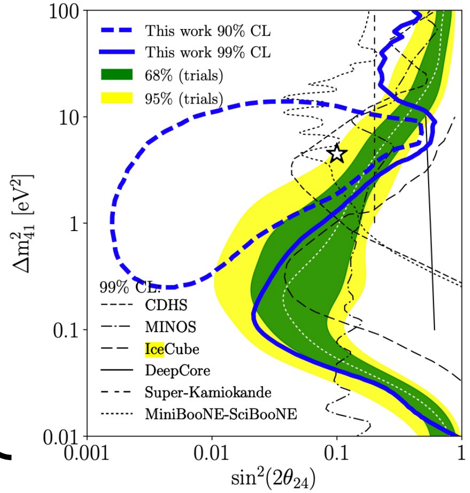
[Neutrino-4, PZETF 2020]



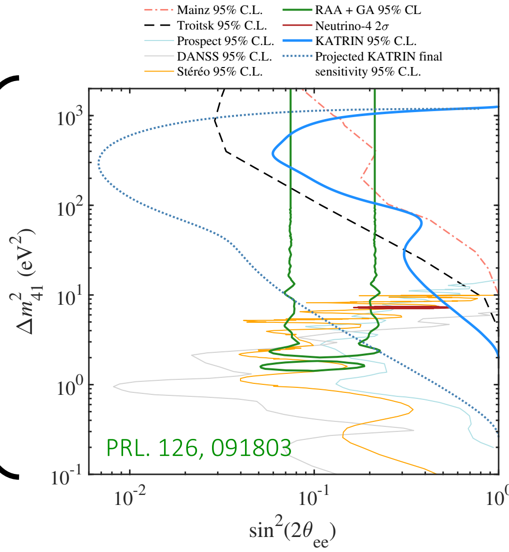
Claimed > 3σ evidence for ν_s (tension with other SLB results)

99% ν_μ DIS exclusion

[IceCube, PRL 2020]

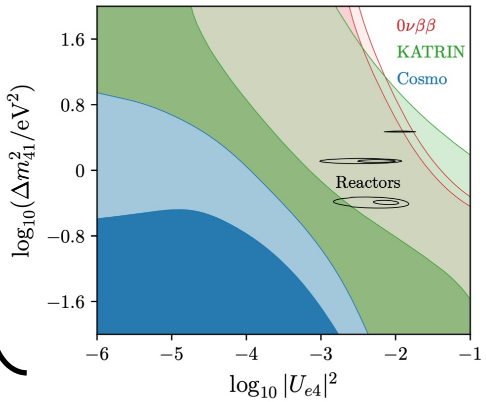


KATRIN

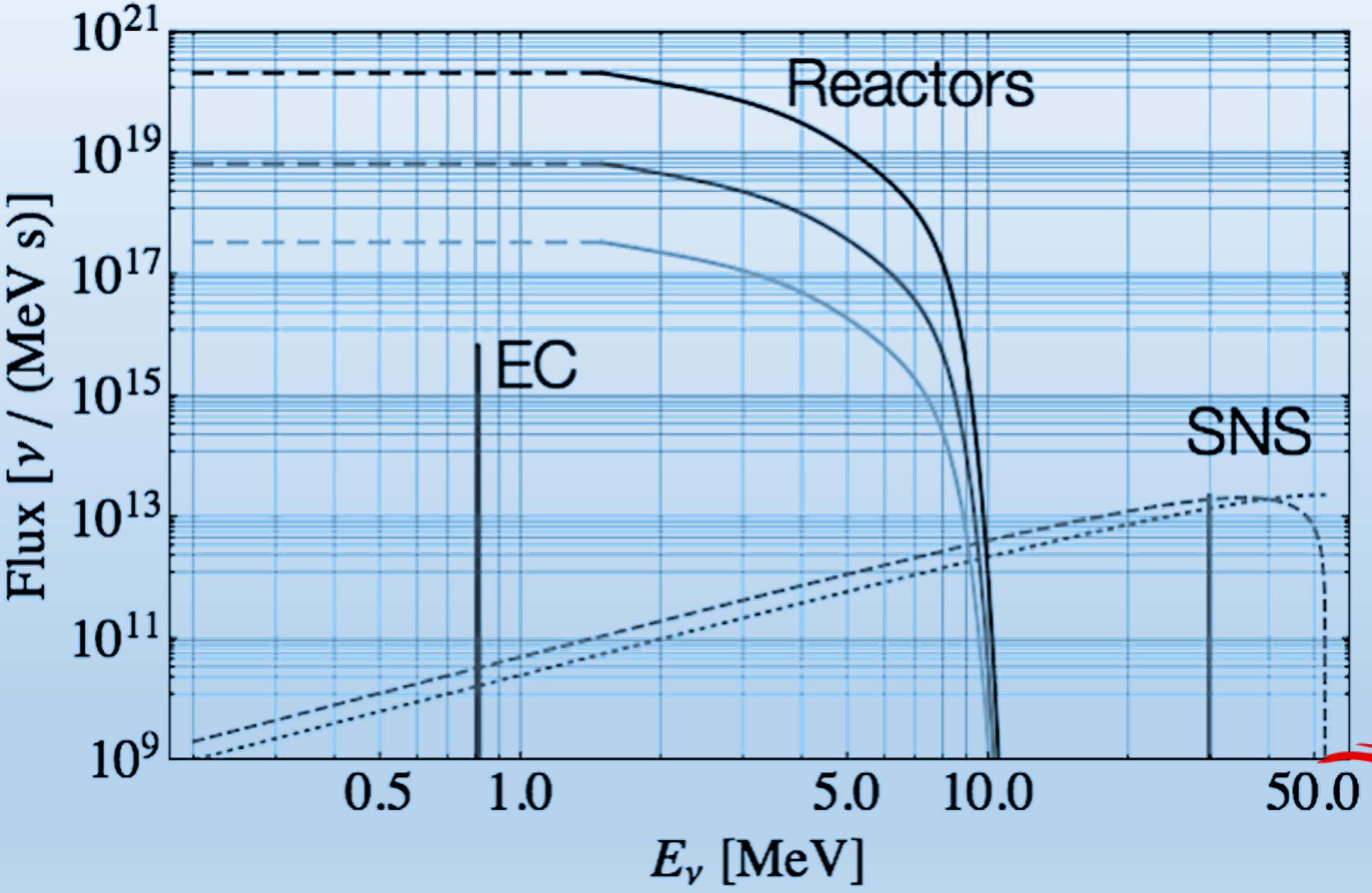


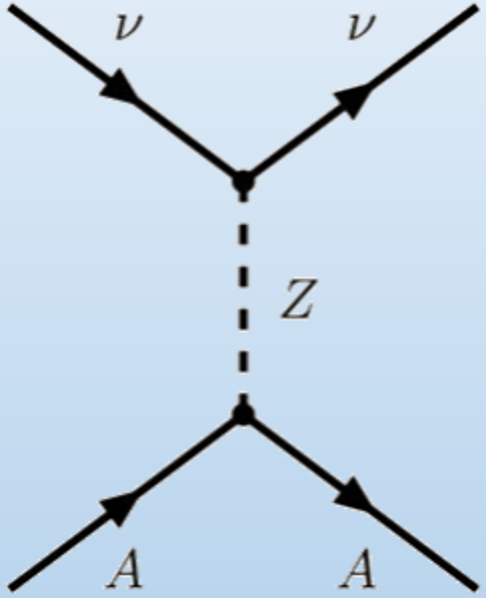
Strong constraints From cosmology

arXiv:2003.02289



Coherent elastic neutrino nucleus scattering (CEvNS)



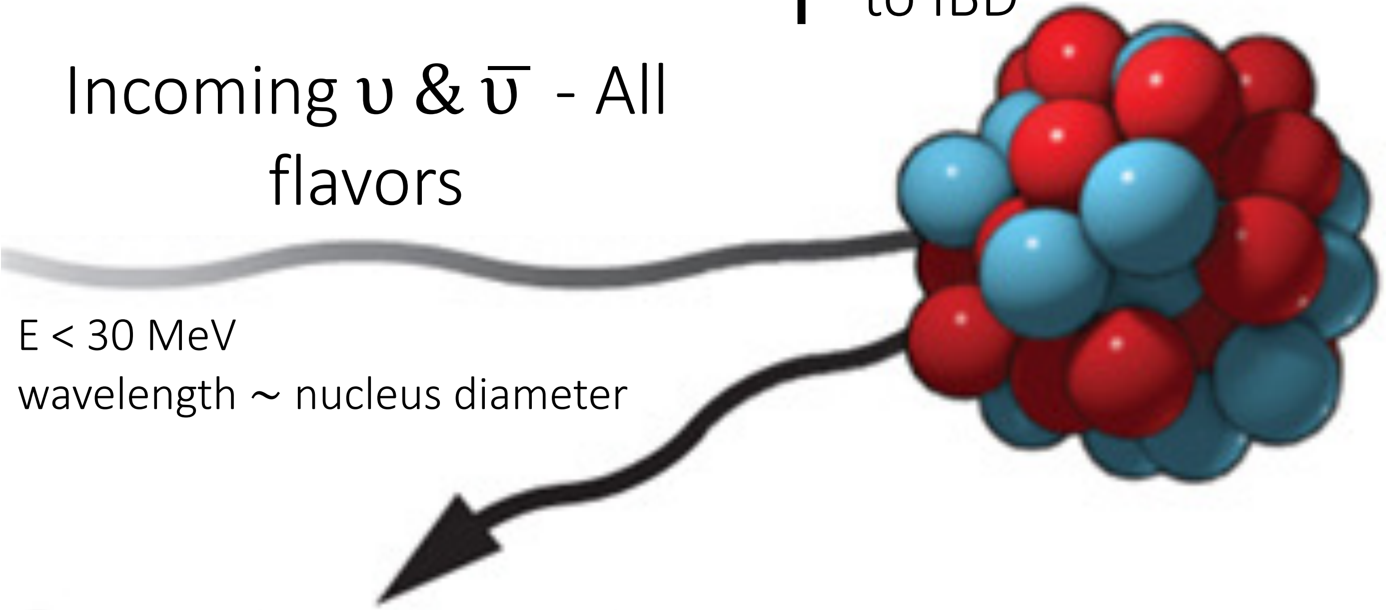


Loss of coherence

Coherent elastic neutrino nucleus scattering (CEVNS)

Cross-section
x 1000
with respect
to IBD

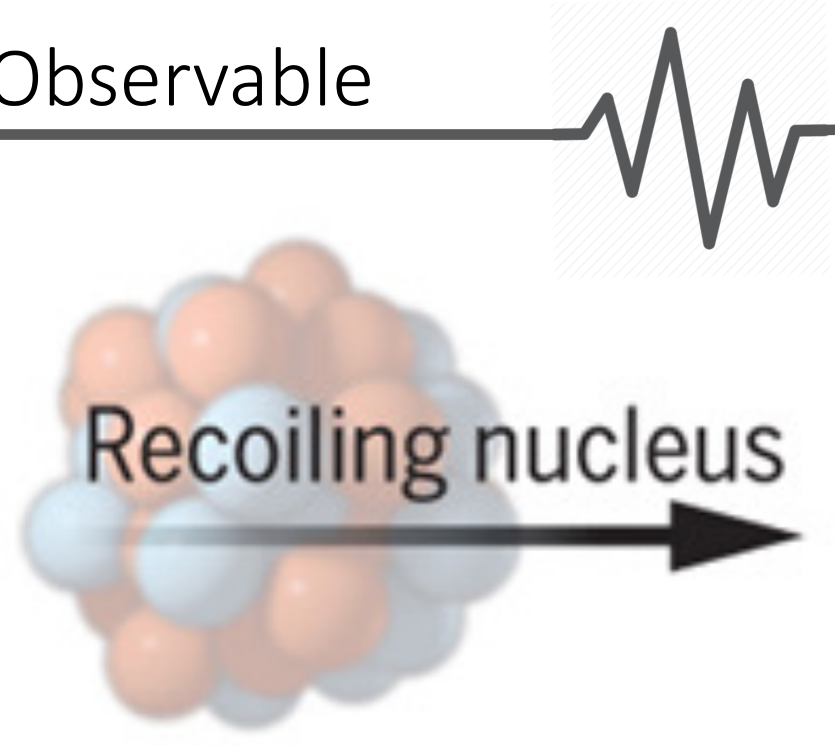
Incoming υ & $\bar{\upsilon}$ - All flavors



E < 30 MeV
wavelength ~ nucleus diameter

Same outgoing υ

Observable

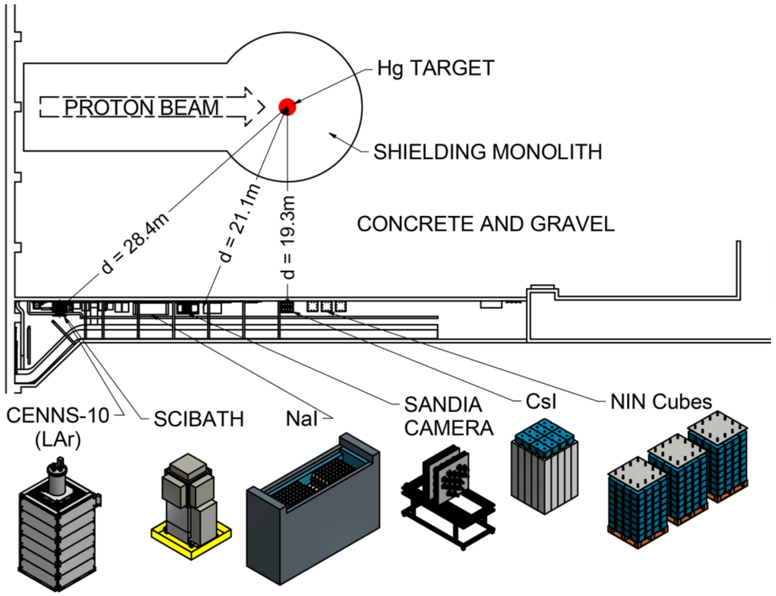


Nucleus recoils as a solid body

→ O(10 – 1000 eV) energy deposition
→ Hard to discriminate against backgrounds

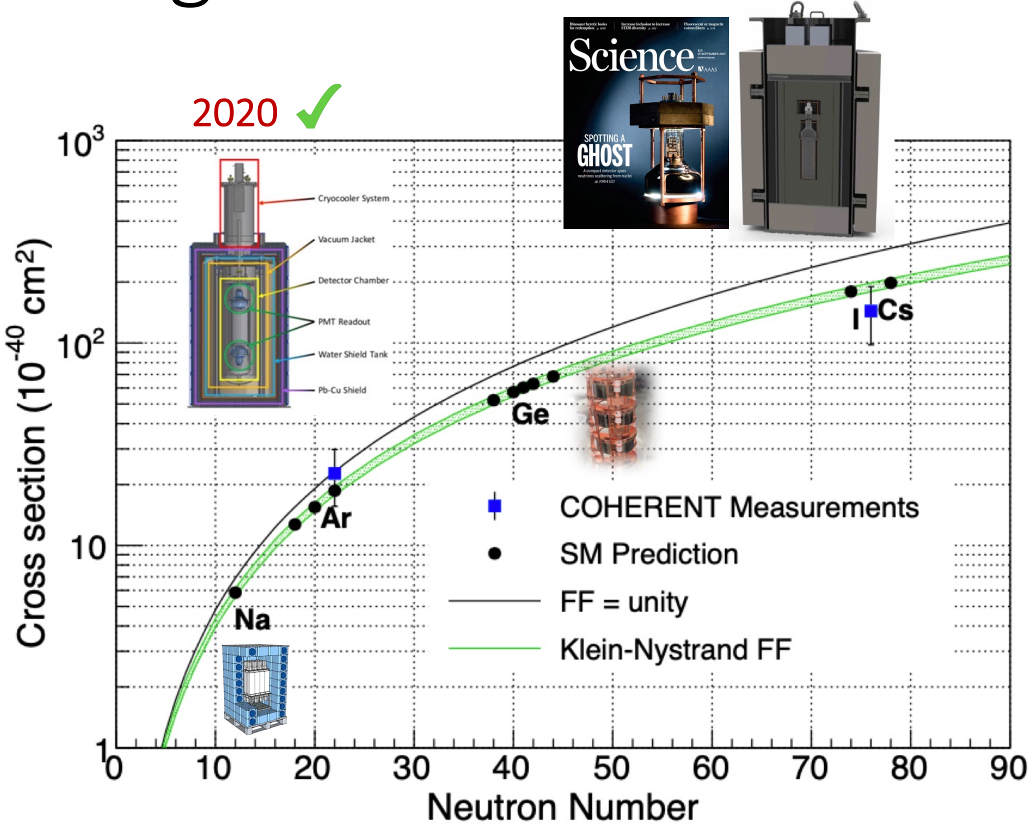
The COHERENT experiment breakthrough

Spallation Neutron Source facility, Oakridge

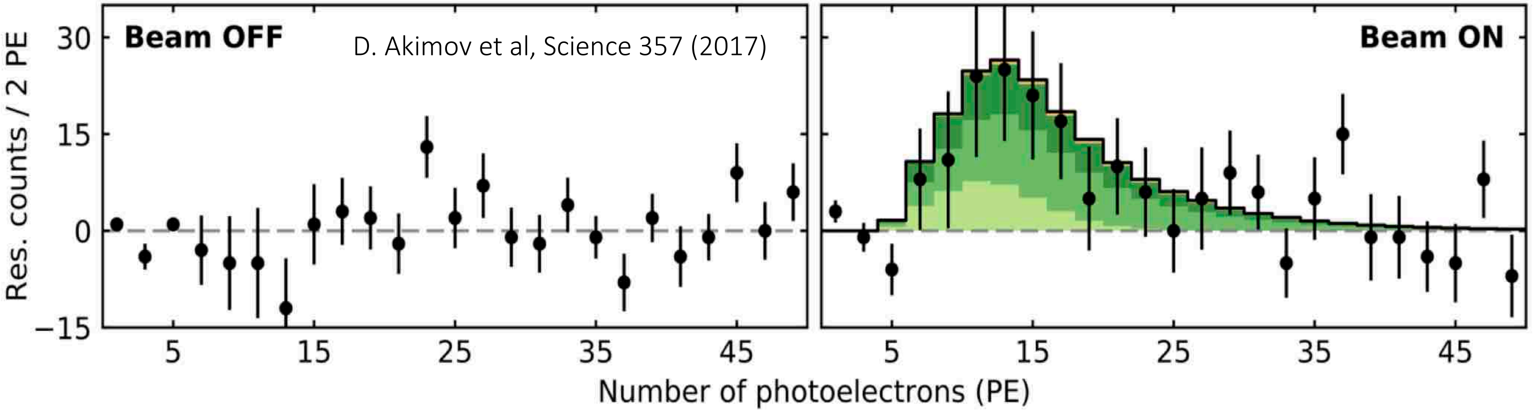


2017 ✓

2020 ✓



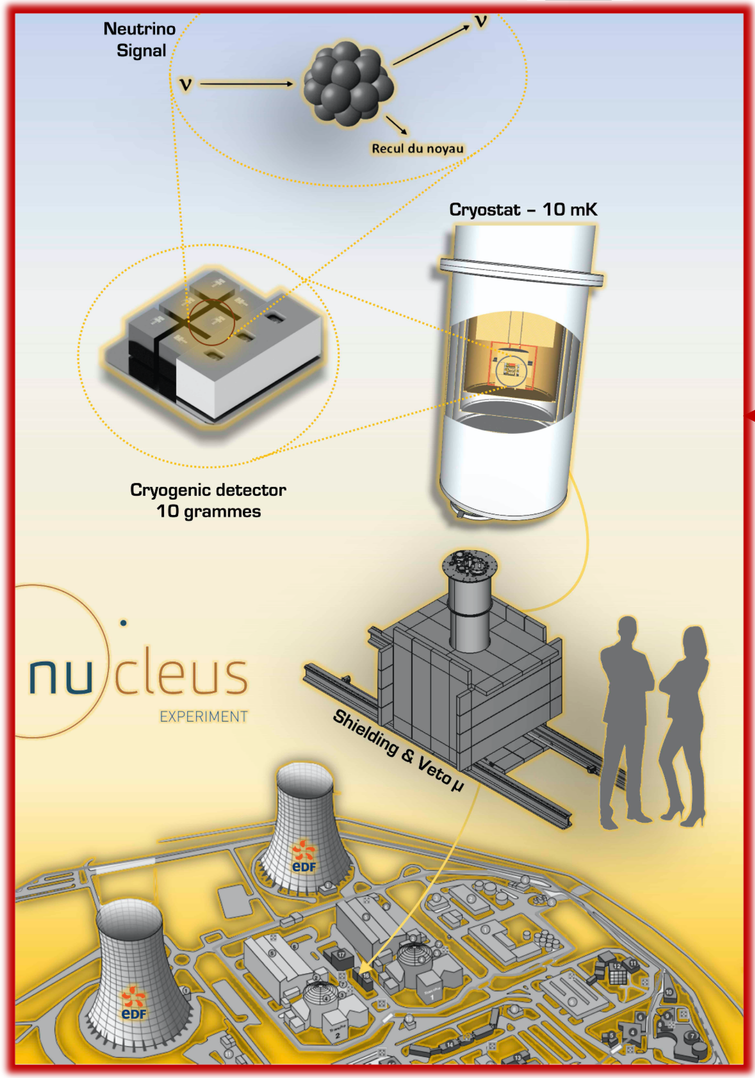
First observation with CsI[Na]

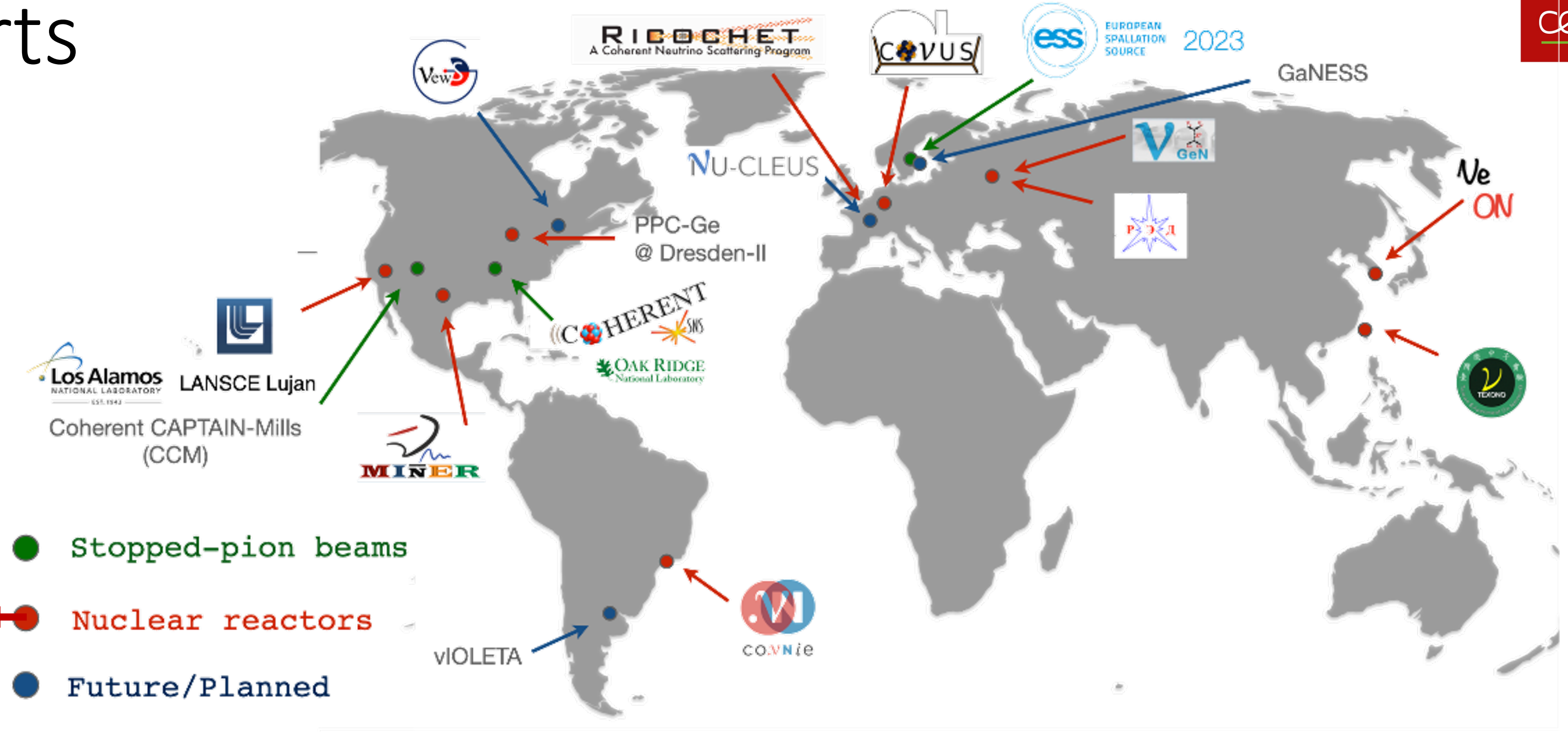


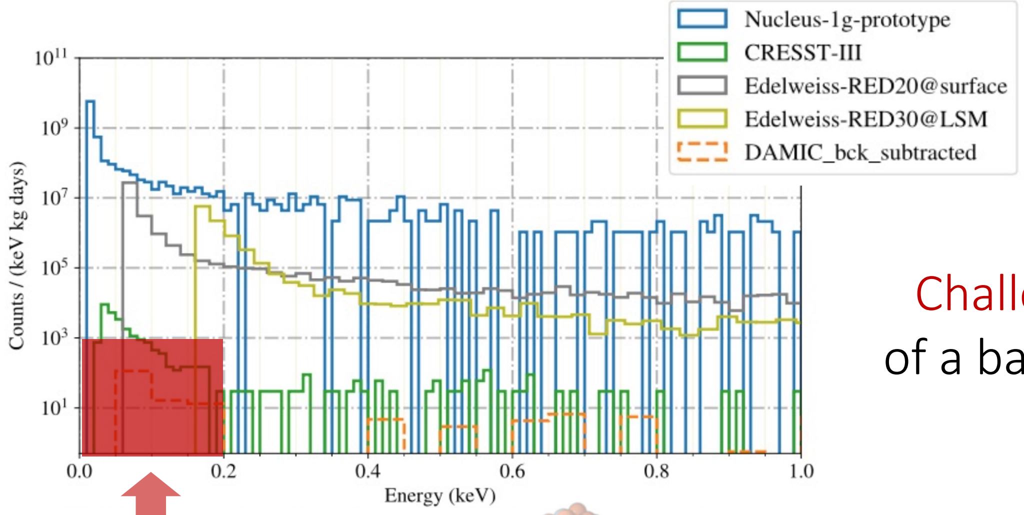
- Measure cross-section N^2 dependence
- Appealing BSM physics probe

Ongoing CEvNS efforts

Not yet observed @







CEvNS signal

Recoiling nucleus

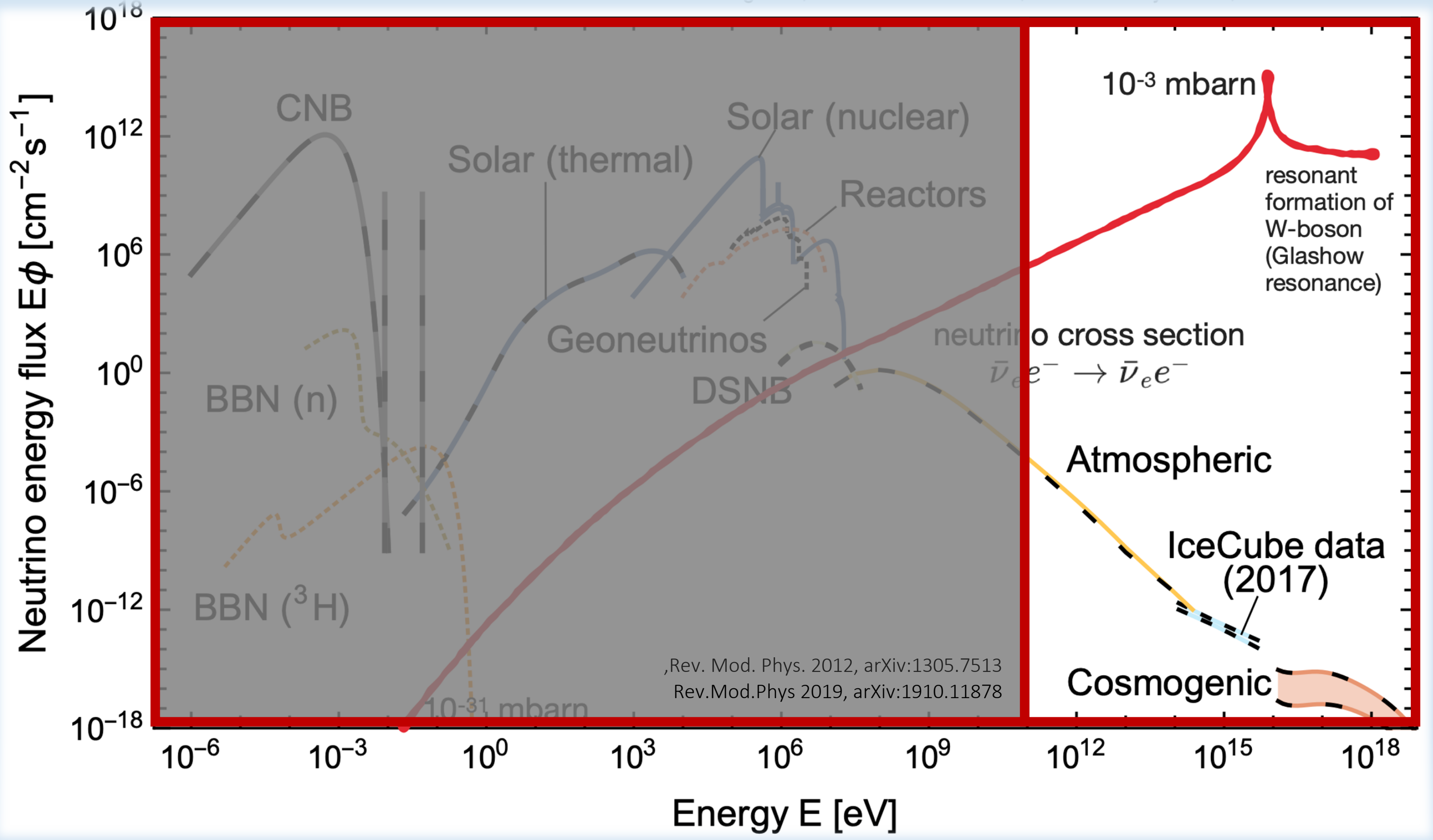
EXCESS Workshop, 15.-16.06.21

https://indico.cern.ch/event/1013203/

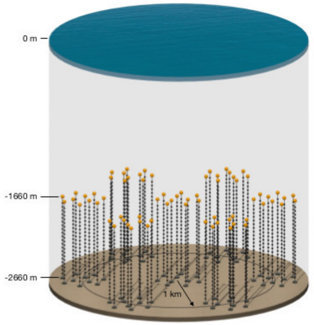
Challenge: many observations of a background rise at E<100 eV

Unknown origin…

Astrophysical neutrinos

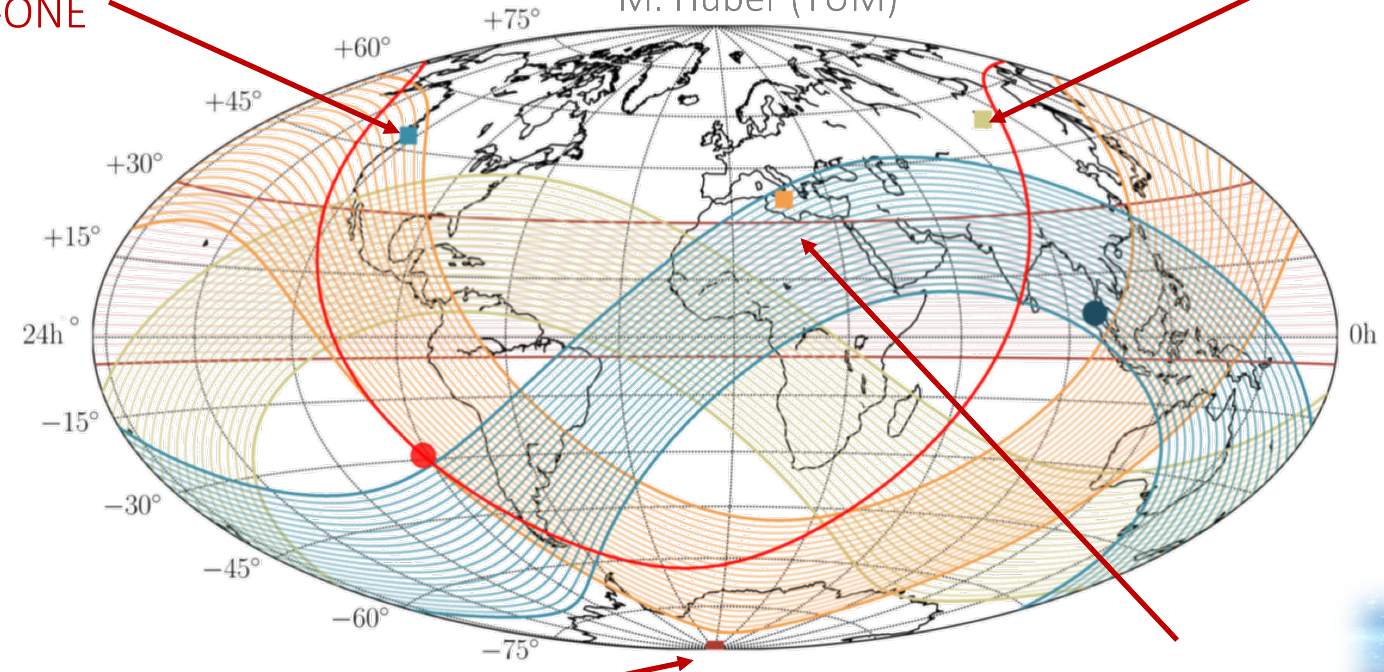


Water Cherenkov Neutrino Telescopes

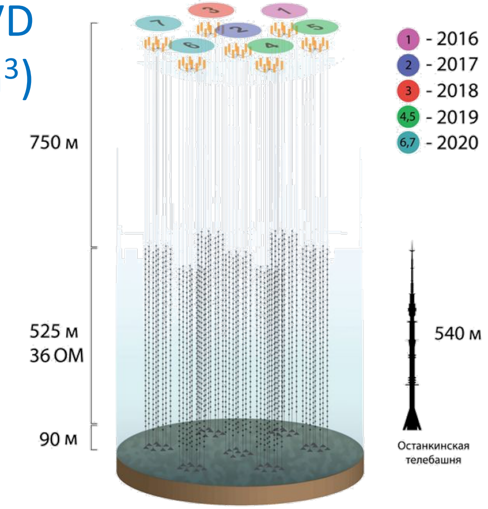


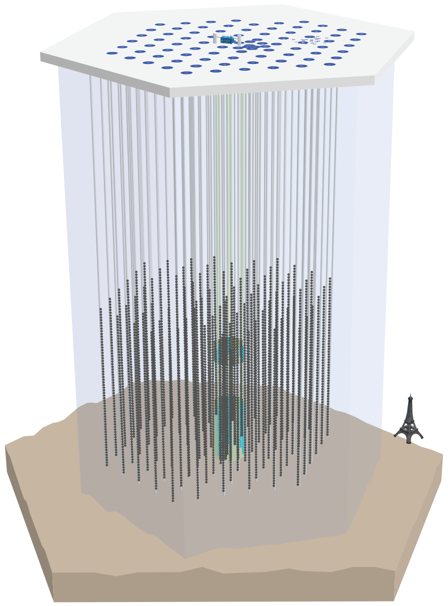
STRAW
P-ONE

M. Huber (TUM)



Baikal GVD
(1 km^3)



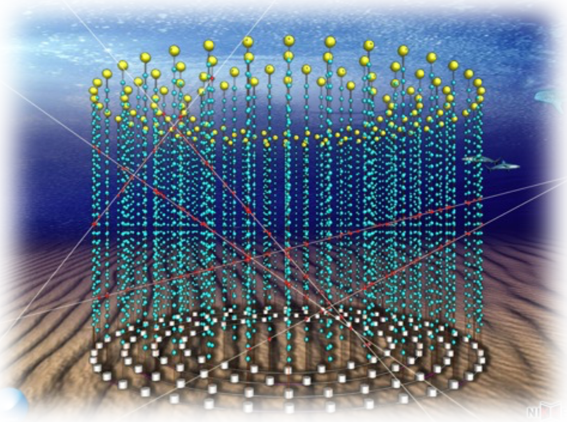


IceCube
(1 km^3)
Upgrade
Gen 2
(7.9 km^3)

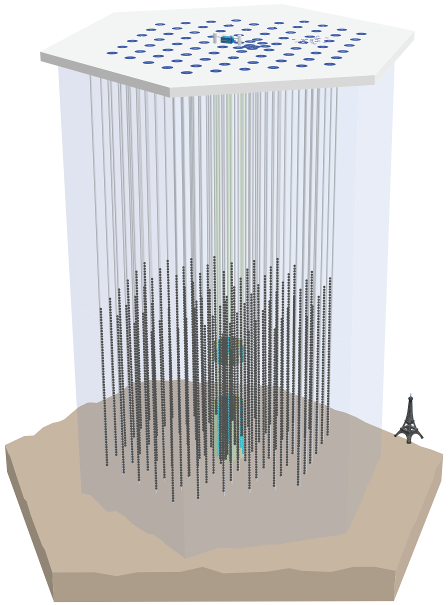
running
under construction
proposed/planned

ANTARES
(0.01 km^3)

KM3Net
(1.1 km^3)

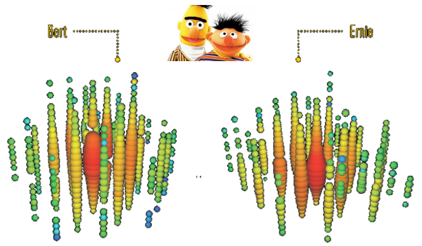


A Glance at ν Astronomy with Ice-Cube

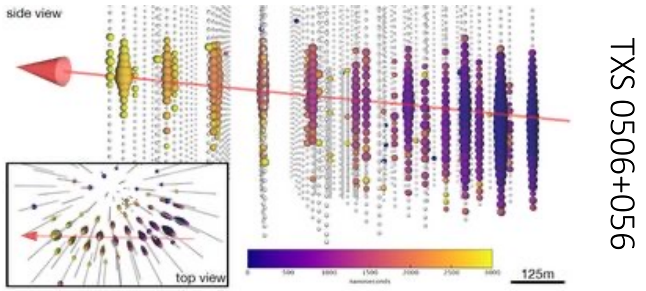


IceCube
(1 km^3)

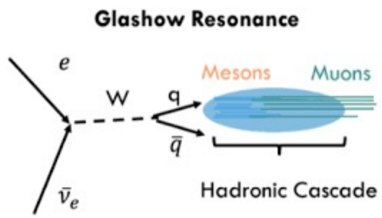
- Since 2013 — Astrophysical neutrinos discovered (extra-galactic origin)



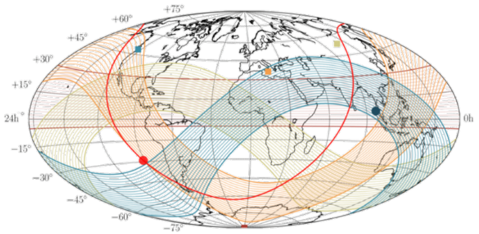
- 2018 — Evidence for first source ν events in a direction of a flaring blazar



- 2019 —First Glashow resonance observed

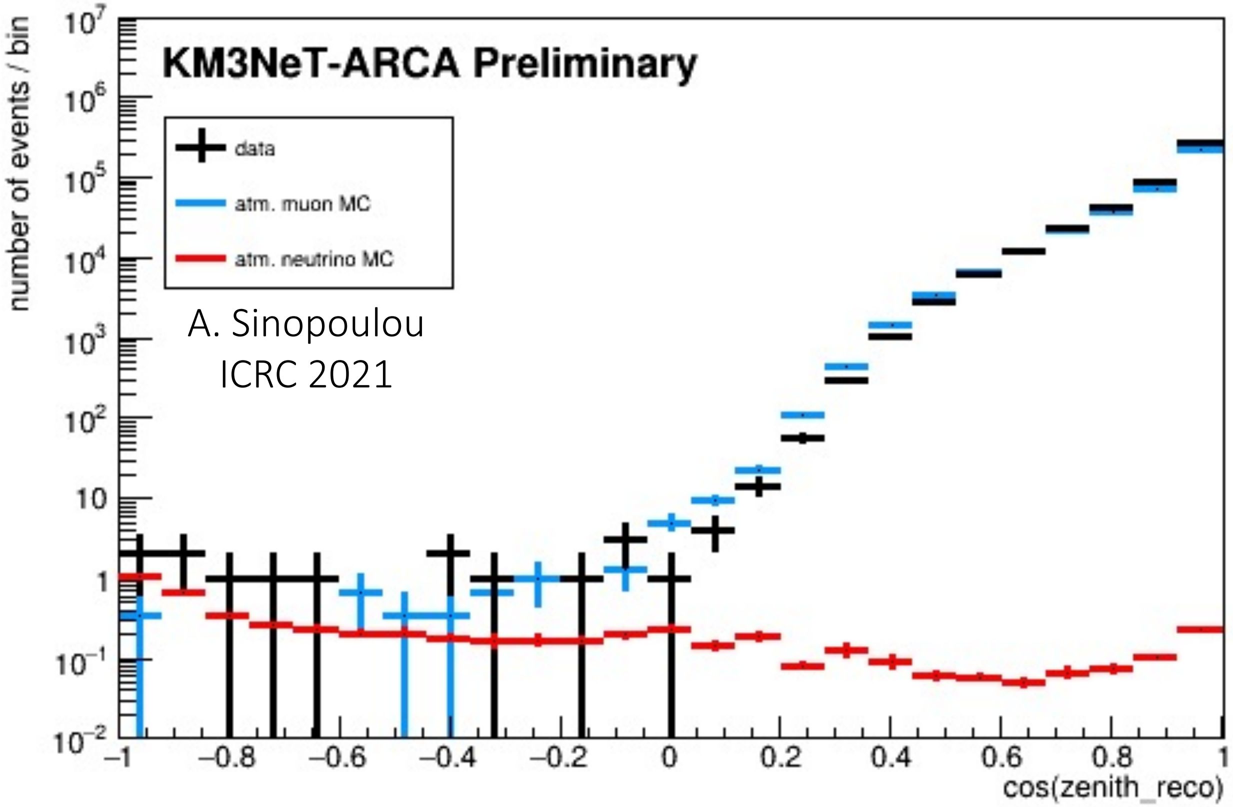


- Neutrino astronomy is now a reality
  Need for (even) larger telescopes!



KM3Net First Lights

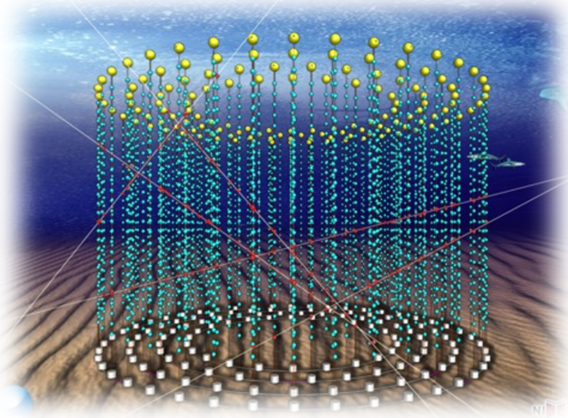
Detection of atmospheric neutrinos
with 19 days of partial ARCA



A. Sinopoulou
ICRC 2021

up-going

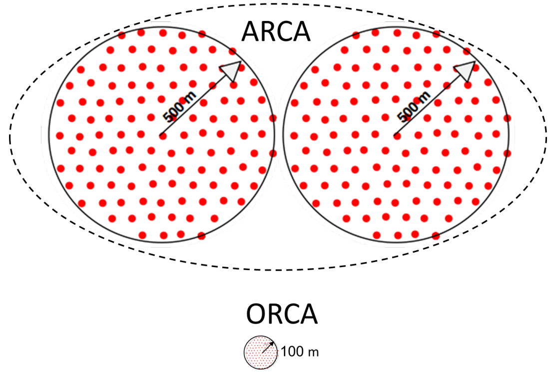
down-going



ANTARES
(0.01 km^3)

KM3Net
(1.1 km^3)

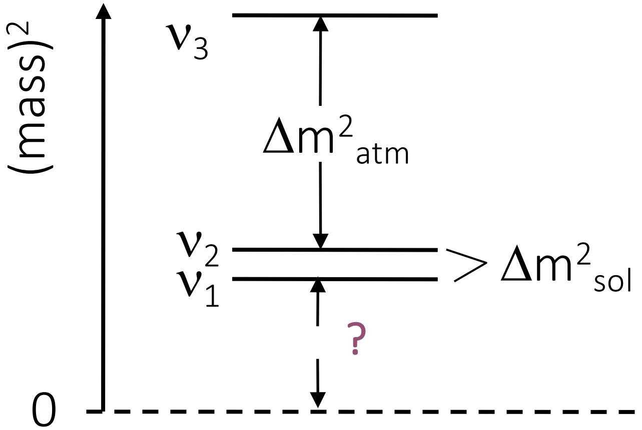
ARCA: large array for high-energy neutrinos



ORCA: dense array for low-energy neutrinos
(Neutrino oscillations – Mass Ordering)

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) } ?

Thank you for your attention

Report of the efforts of large collaborations and many people

All my apologies if your favorite topics could not be covered