http://moriond.in2p3.fr

Résumé des Rencontres de Moriond 2024

Electroweak Interactions & Unified Theories

Very High Energy Phenomena in the Universe

Cosmology

QCD and High Energy Interactions

S. Loucatos

DPhP-Irfu et APC

22/4/24

58th **Rencontres de Moriond** session devoted to **ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES March 24-31, 2024**.

.....

La Thuile is a pleasant winter sport resort located in the Italian Alps, at 1450 m alt., about 120 km from Geneva. Conference founded in 1966 by Jean Tran Thanh Van.

Meribel 1974

Subventionnée par l'Irfu et la DRF

Organisateurs CEA:

F. Déliot coord EW

D. Denegri

S. Loucatos

E. Moulin

L. Schoeffel

F. Vernizzi

Ch. Yèche

Neutrino mixing sum rules
Katrin
Probing the heavy neutrino hypothesis
T2K
NOvA
Legend
Pheno & cosmo implications of scotogenic 3-loop neutrino mass models
SuperK
Sterile neutrino overview
17:00
CUORE
FASER
Destabilizing Matter through a Long-Range Force
Icecube
Alpha-g

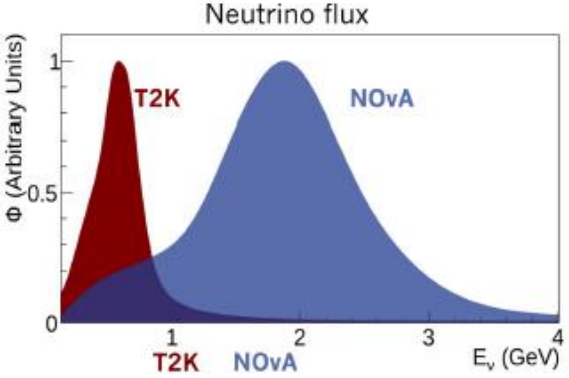
Majorana mass generation, GWs and cosmological tensions
Borexino
Probing Reheating with Graviton Bremsstrahlung
PANDA X DM and neutrino-less double beta decay
Status of dark photons
LZ DM
17:00
Axions review
ALPS
Signals of boosted dark matter and neutrinos
First results of axion search with LIDA
21cm signal sensitivity to dark matter decay
Keplerian decline

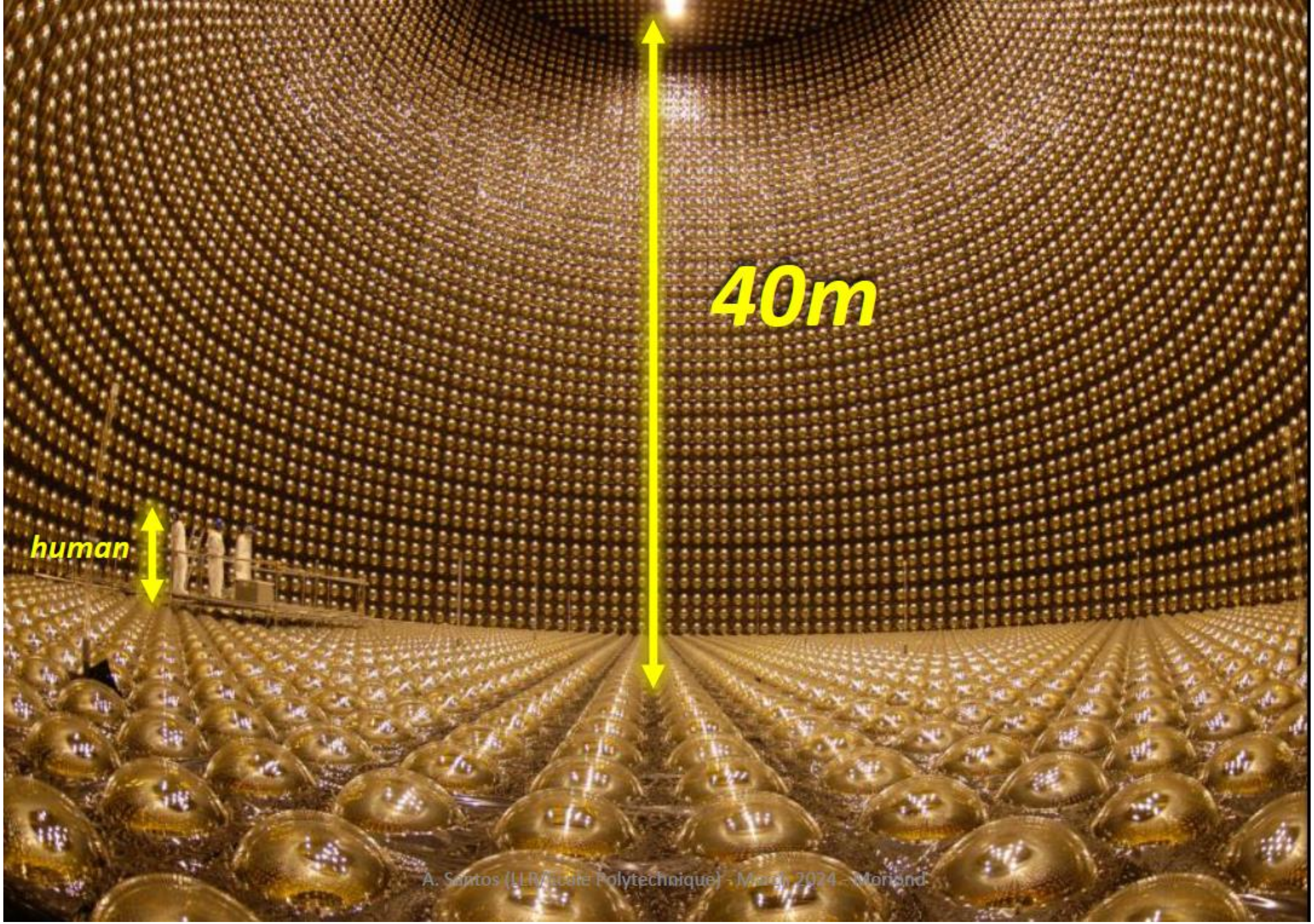
Weather for study, less for ski

Neutrinos

	T2K	NOvA
L (baseline)	295 km	810 km
Energy (beam peak)	0.6 GeV	2 GeV
Matter effect*	~ ±9%	~ ±19%
CP effect*	~ ±30%	~ ±25%

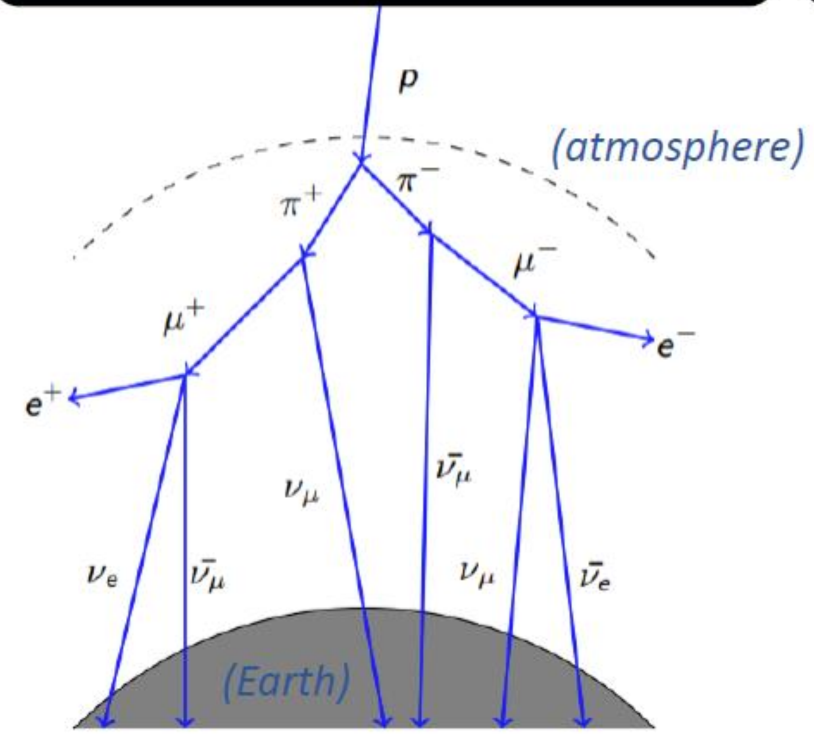
*calculated at beam peak energy



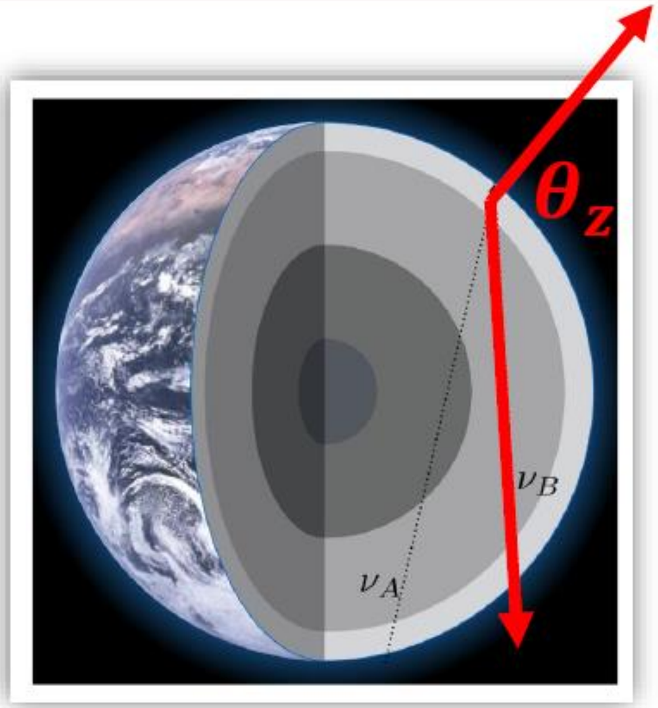

40m
human

Extracting physics from atmospheric neutrino oscillations

Neutrinos produced by cosmic rays!

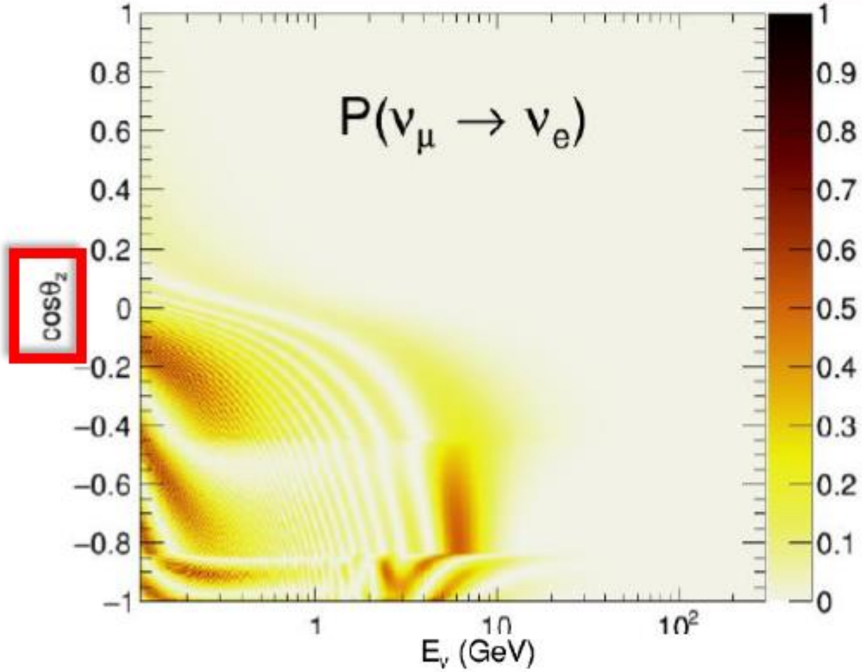


Large range in energy and distances!



Rich landscape of flavor oscillations!

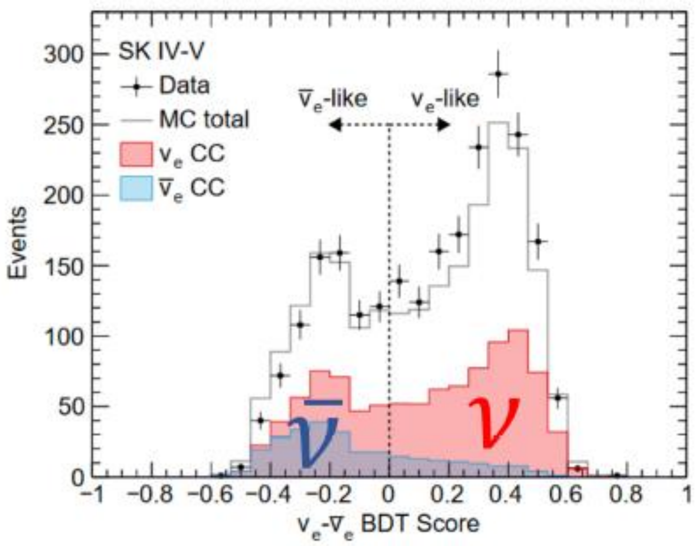
arXiv:2311.05105v1 (2023)

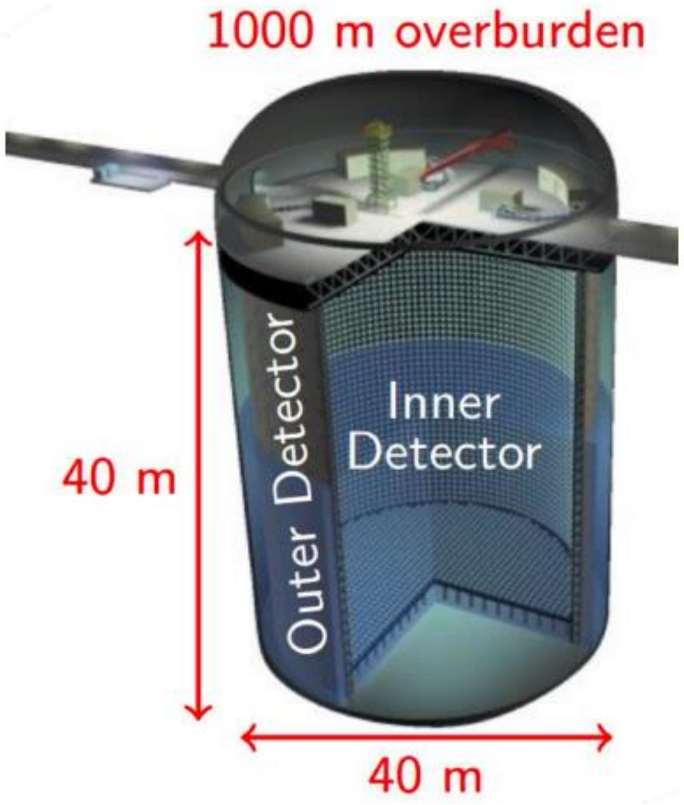


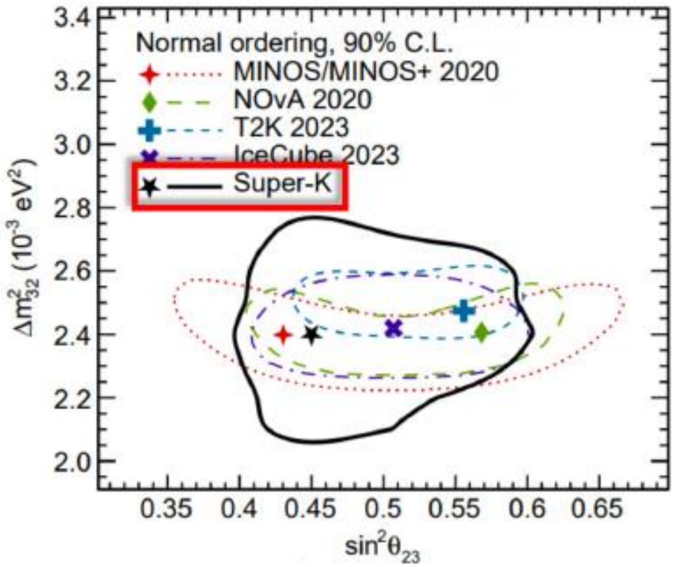
Latest results from Super Kamiokande (Andrew Santos)

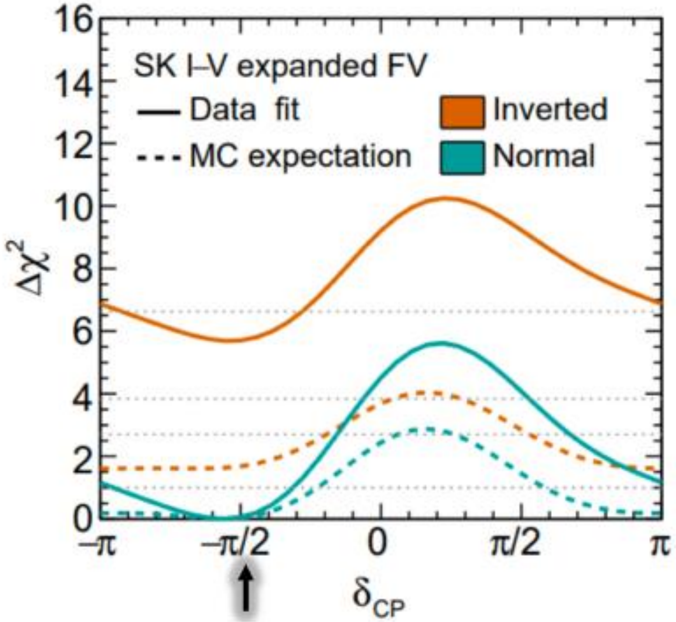
Around 11 000 PMTs in inner detector with an outer detector muon veto
Gadolinium-doped water since 2020 for easier neutron capture identification
Running since 1996 (phases I-VII)

Study of atm ν :
Fully-contained (expanded fiducial volume)
e-like vs μ-like (event topology)
New neutron tagging (ν vs anti-ν interactions)
New BDT for enhanced ν sample from anti-ν









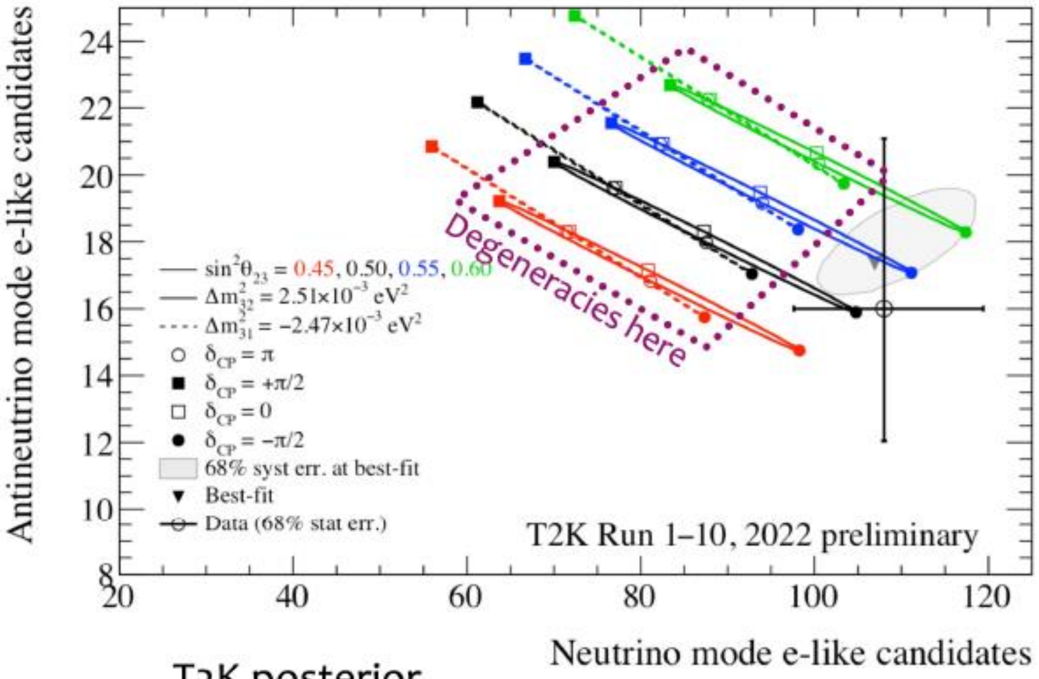
Competitive measurements (especially θ_{23}) with other experiments

Best-fit $\boldsymbol{\delta_{CP}}$: preferring $\delta_{CP} = -\pi/2$ is maximal CP violation
Favour normal hierarchy at around 2σ
+ Combination with T2K

Latest results from T2K experiment
(Phill Lichfield)

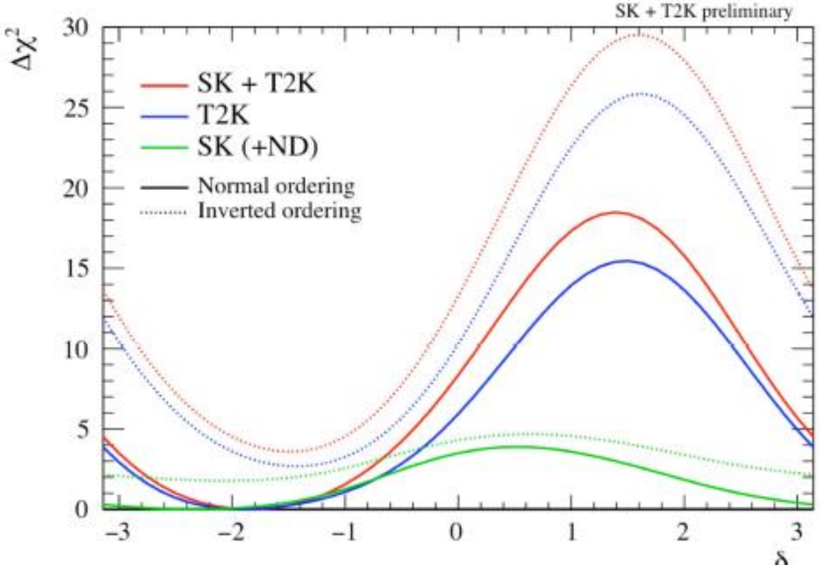
In 2020 : end of run10
From 2021-2023 : upgrades (beam power, ND80)
Feb 2024 : data taking

T2K (ν beam) and SK (ν atm) combination :
(December 2023)
MSW resonance changes mixing for high energy neutrinos:
~13 GeV (crust); ~2.5 GeV (core)
SK helps in breaking T2K's MO – δ_{CP} degeneracies
Construct full correlation for joint analysis



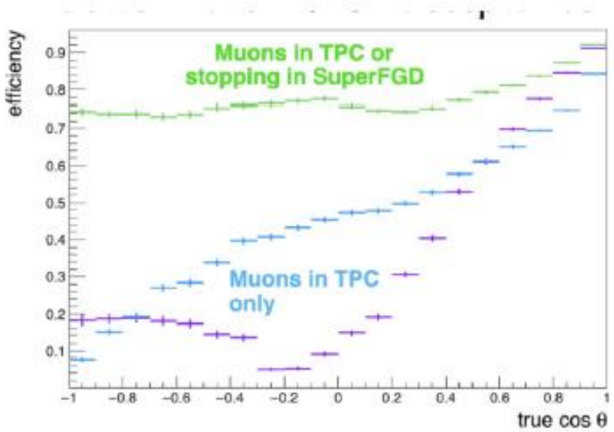
T2K posterior probability	
$\Delta m^2_{32} > 0$	0.80
$\Delta m^2 < 0$	0.20

Find $\delta_{CP} = -0.63^{+0.31}_{-0.22}\,\pi$



CP conservation disfavoured by 'about' 2σ

Upgrade ND80 :
replacement of the high-angle tracker



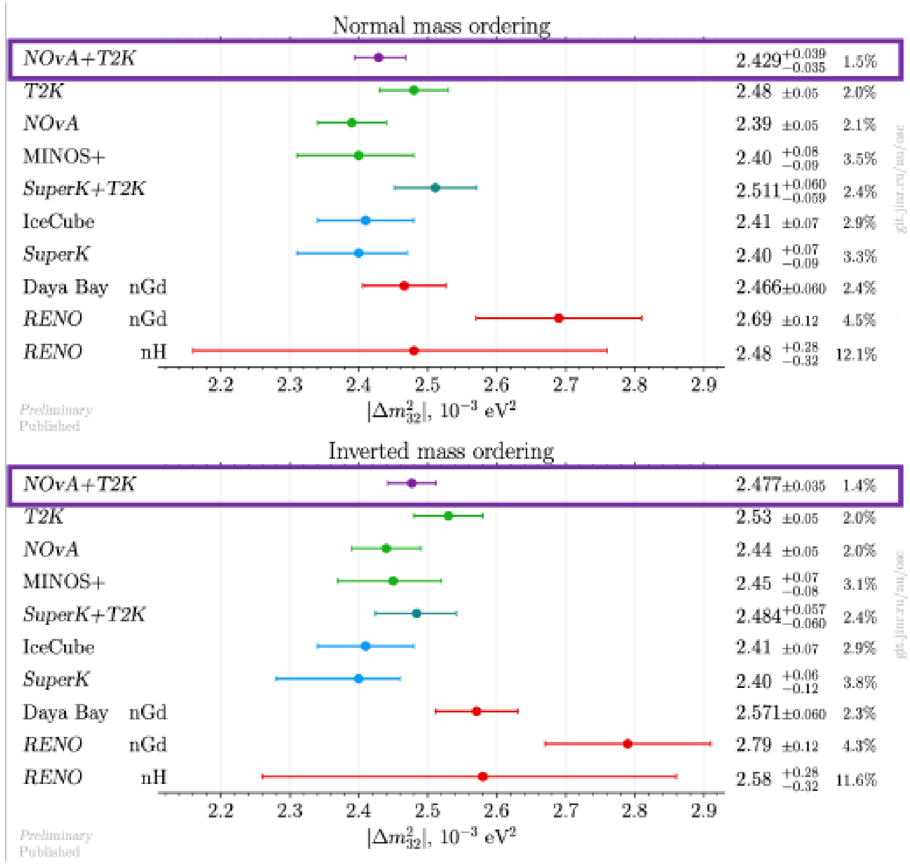
Run up to 2028 (when HK starts)

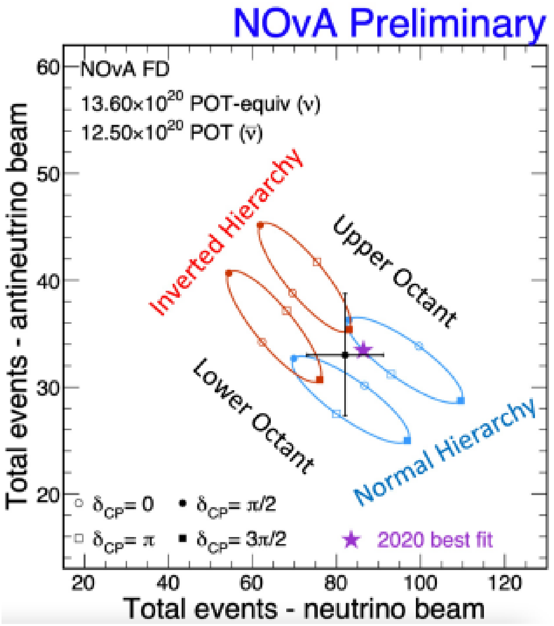
N0vA and T2K joint results
(Mayly Sanchez)

- Lot of work (cross-checks) to combine NOvA and T2K results

The experiments have different ν energy, ν interactions, matter effect ...
Different analyses approaches
In particular : matter effects modify the energy spectrum depending on the NMO and ν versus anti-ν
Effect is larger for longer baseline

Channel	NOvA	T2K
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)
$\bar{\nu}_e$	33	16
ν_μ	211	318
$\bar{\nu}_\mu$	105	137

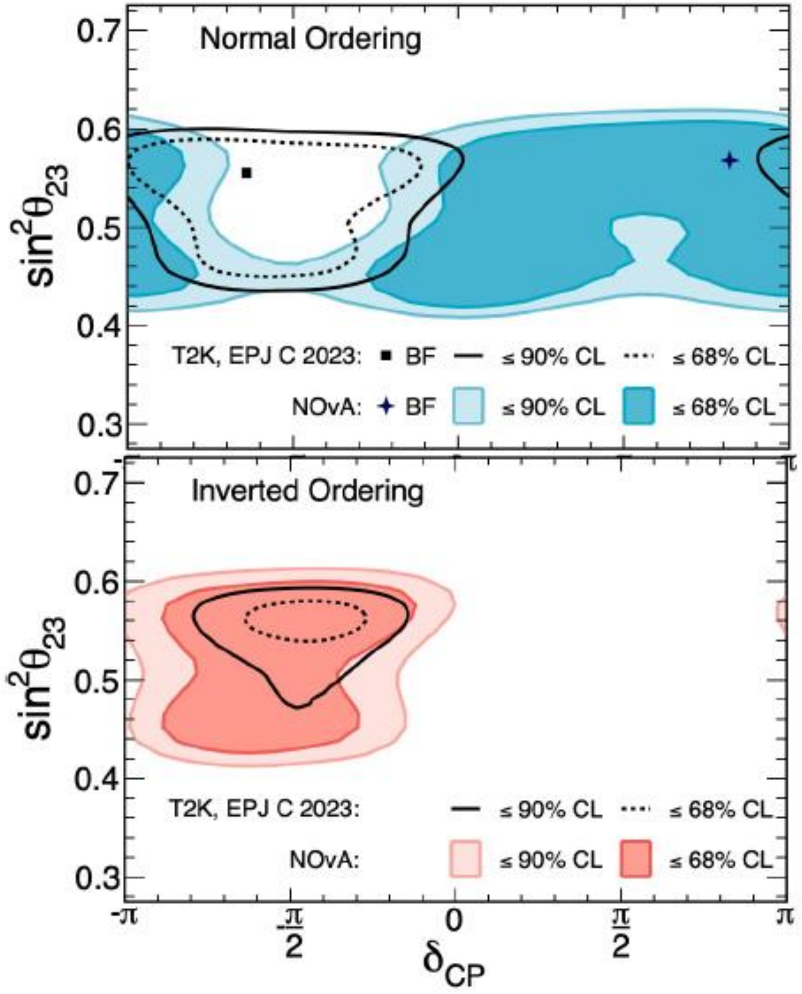


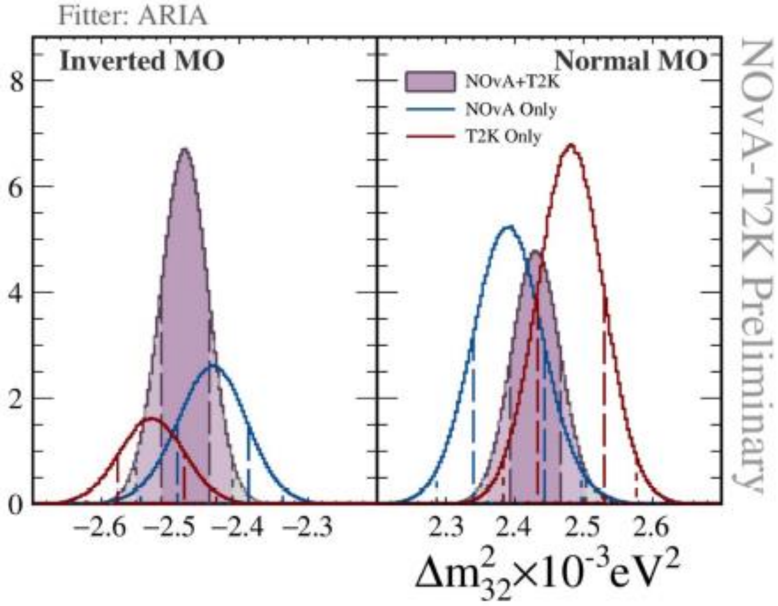


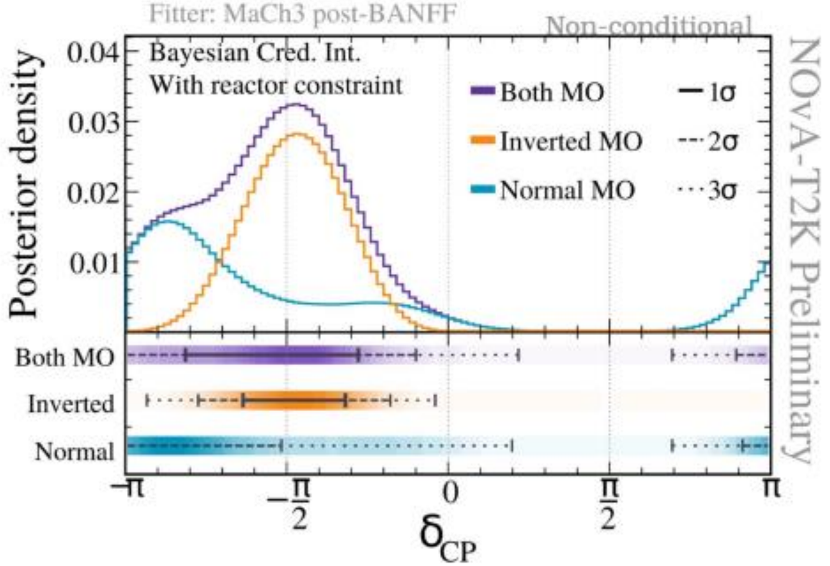
The joint analysis shows a strong constraint on $|\Delta m^2_{32}|$

N0vA and T2K joint results
(Mayly Sanchez)

T2K measurements isolate the impact of CP violation whereas NOvA has more mass ordering sensitivity







Including the Δm^2_{32} constraint from the Daya Bay experiment reverses the preference back to NO

The ν mass ordering remains inconclusive

$\delta_{CP} = \pi/2$ lies outside 3σ interval for both mass orderings

CP conserving values for the IO fall outside the 3σ range

→ Need more data

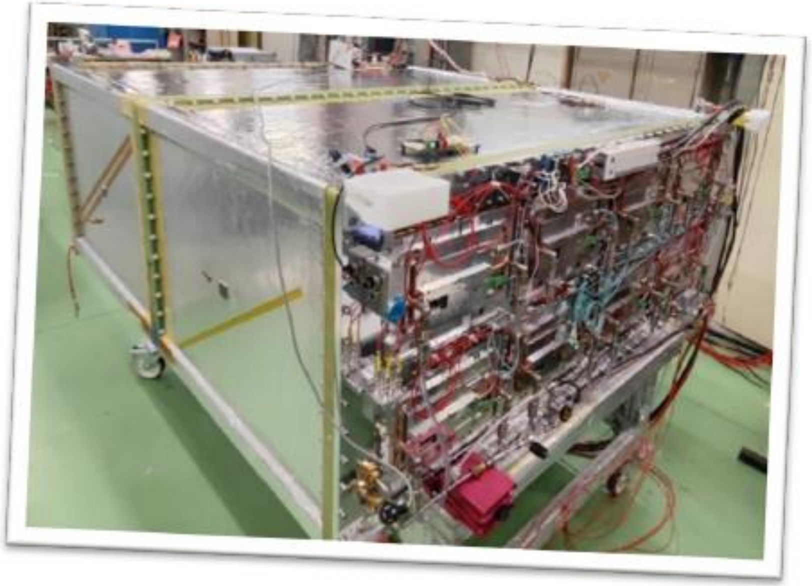
Maybe some installation pics?

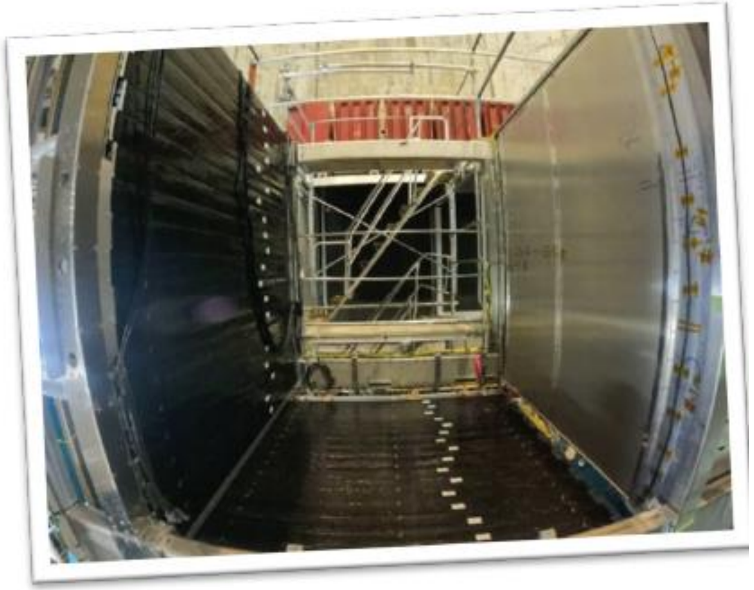
- Most of upgrade now installed.
- Top HA-TPC taking cosmics at CERN

◀ S-FGD during assembly, with guide fibre

▼ Installing ToF into ND280

▼ Checkout of Bottom HA-TPC

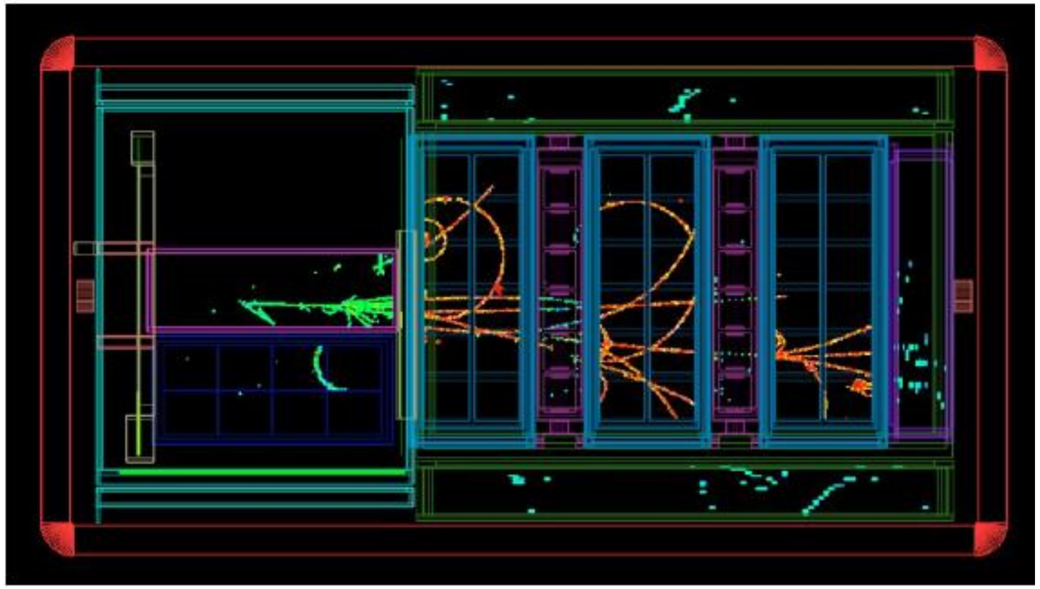


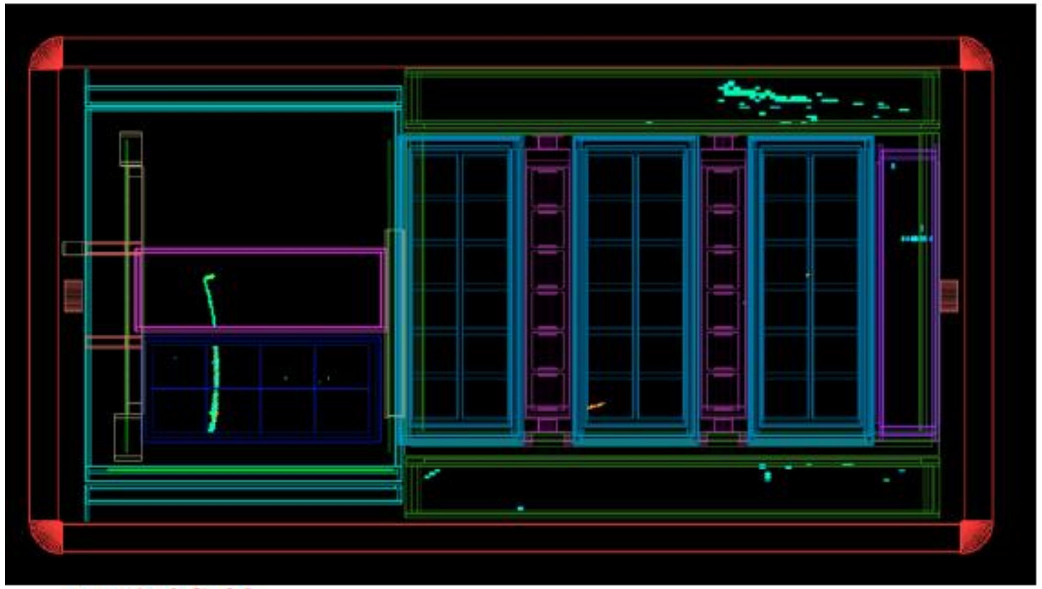


Event displays (December 2023)

[Looks like a…] **very high angle** muon, with forward-going **recoil proton**

- Would struggle to reconstruct this in the 'classic' tracker



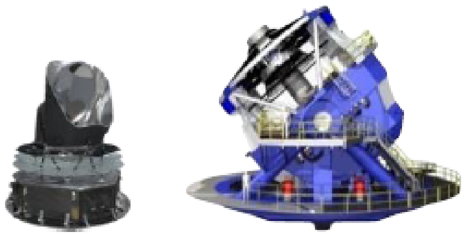


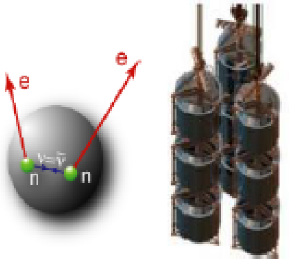
Very busy event showing ND280 'classic' and upgrade detectors together

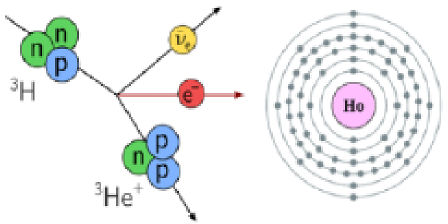
- Notice **higher resolution** of SuperFGD compared to original FGDs

KATRIN (A. Marsteller)

Access to the absolute neutrino mass scale







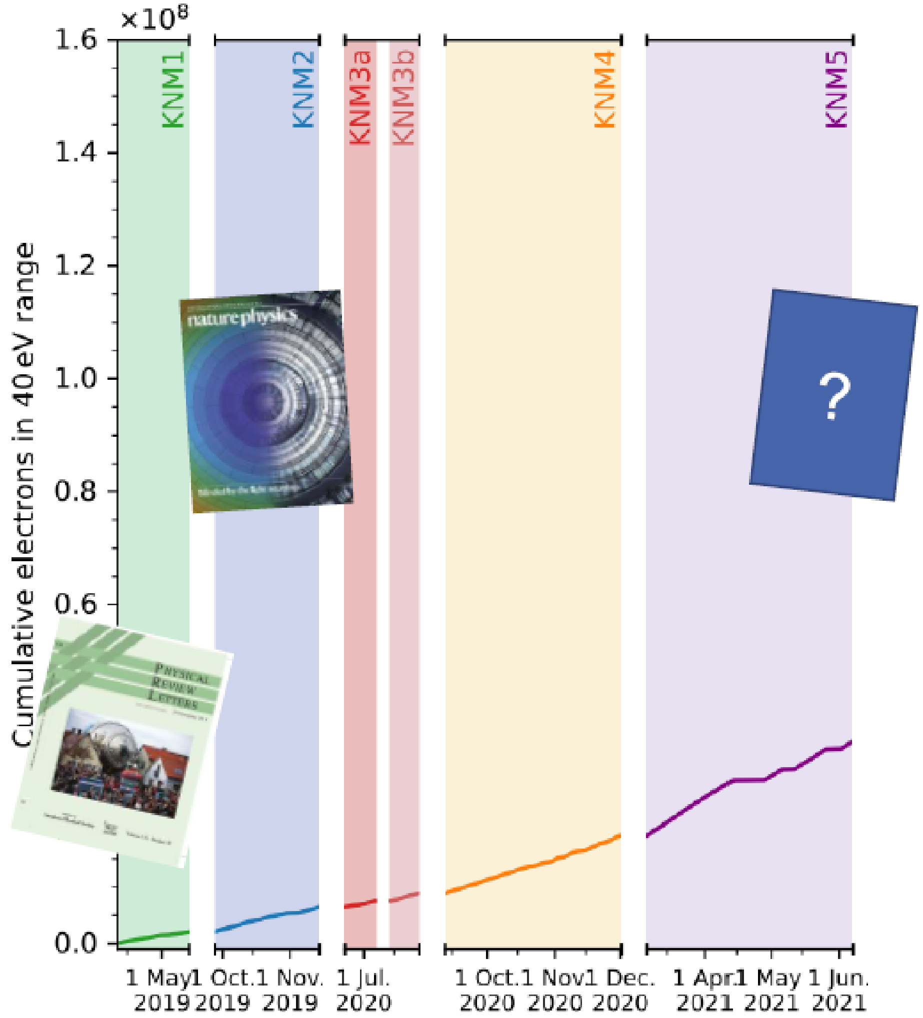
	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$	$m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$
Present upper limit	0.12 eV*	0.18 eV*	0.8 eV
Model dependence	Multi-parameter cosmological model	- Majorana ν - nuclear matrix elements, g_A	**Direct**, only kinematics; no cancellations in incoherent sum

Stöcker et al., Phys.Rev.D 103 (2021) 12, 123508
Tanseri et al., JHEAp 36 (2022), 1-26

M. Agostini et al., Phys. Rev. Lett. 125, 252502
S. Abe et al., Phys. Rev. Lett. 130, 051801

M. Aker et al., Nat. Phys. 18, 160–166 (2022)

Next analysis release



- Combined analysis of first five campaigns (KNM1-5)
  - Currently in final preparation
  - Data release in summer
- Sensitivity projection:

$$m_\nu < 0.5\ eV\ (90\%\ C.L.)$$

Searching for 0νββ in the Cuore experiment

(Irene Nutini) - New results

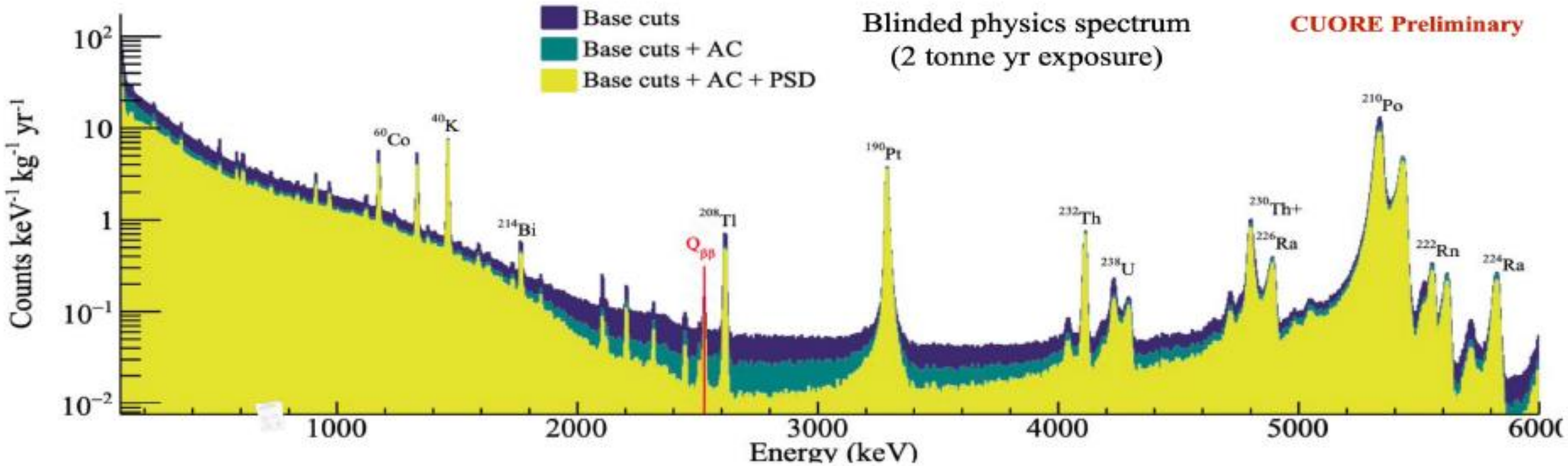
CUORE : Cryogenic Underground Observatory for Rare Events

Cryogenic experiment at tonne-scale,
utilising oxide of tellurium TeO_2 thermal detectors operated at ~10 mK
Located at Laboratori Nazionali del Gran Sasso

Challenges :
- low temperature and low vibrations over time for about 1000 detectors
- low background

Results today based on data taken from 2017-2023, for 2039 kg.yr TeO_2

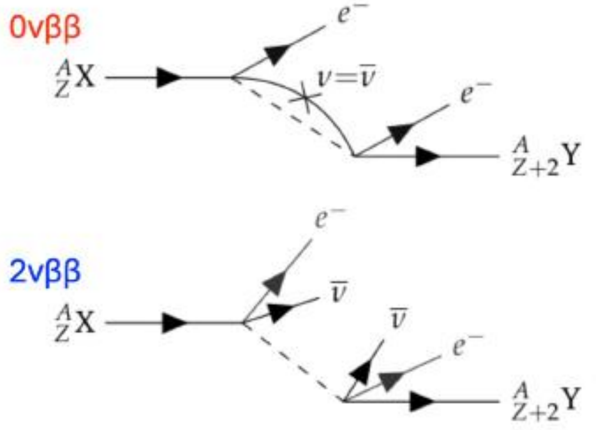
Reference 208Tl gamma peak at 2615 keV from calibration data

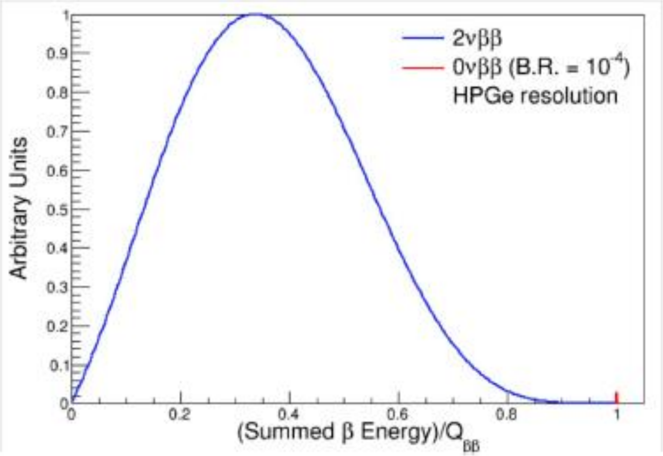


Beyond Standard Model process (ΔL = 2)

$$(A, Z) \longrightarrow (A, Z+2) + 2e^-$$

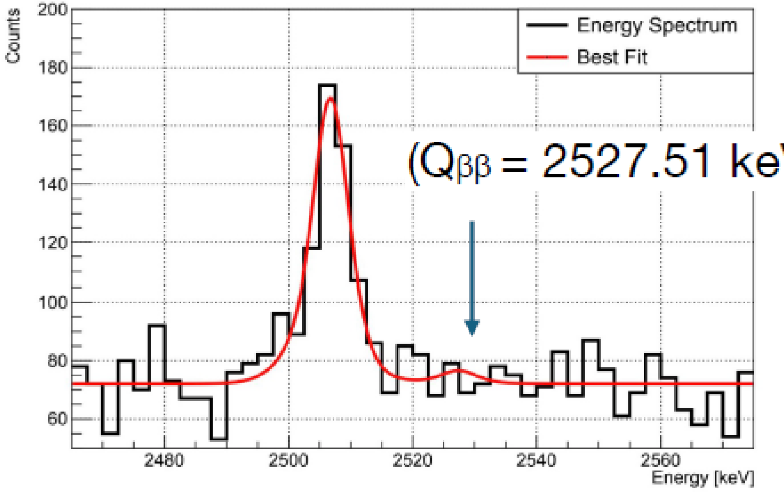
Not yet observed: $T^{1/2}_{0\nu\beta\beta} > 10^{22\text{-}26}$ yr





($Q_{\beta\beta}$ = 2527.51 keV)

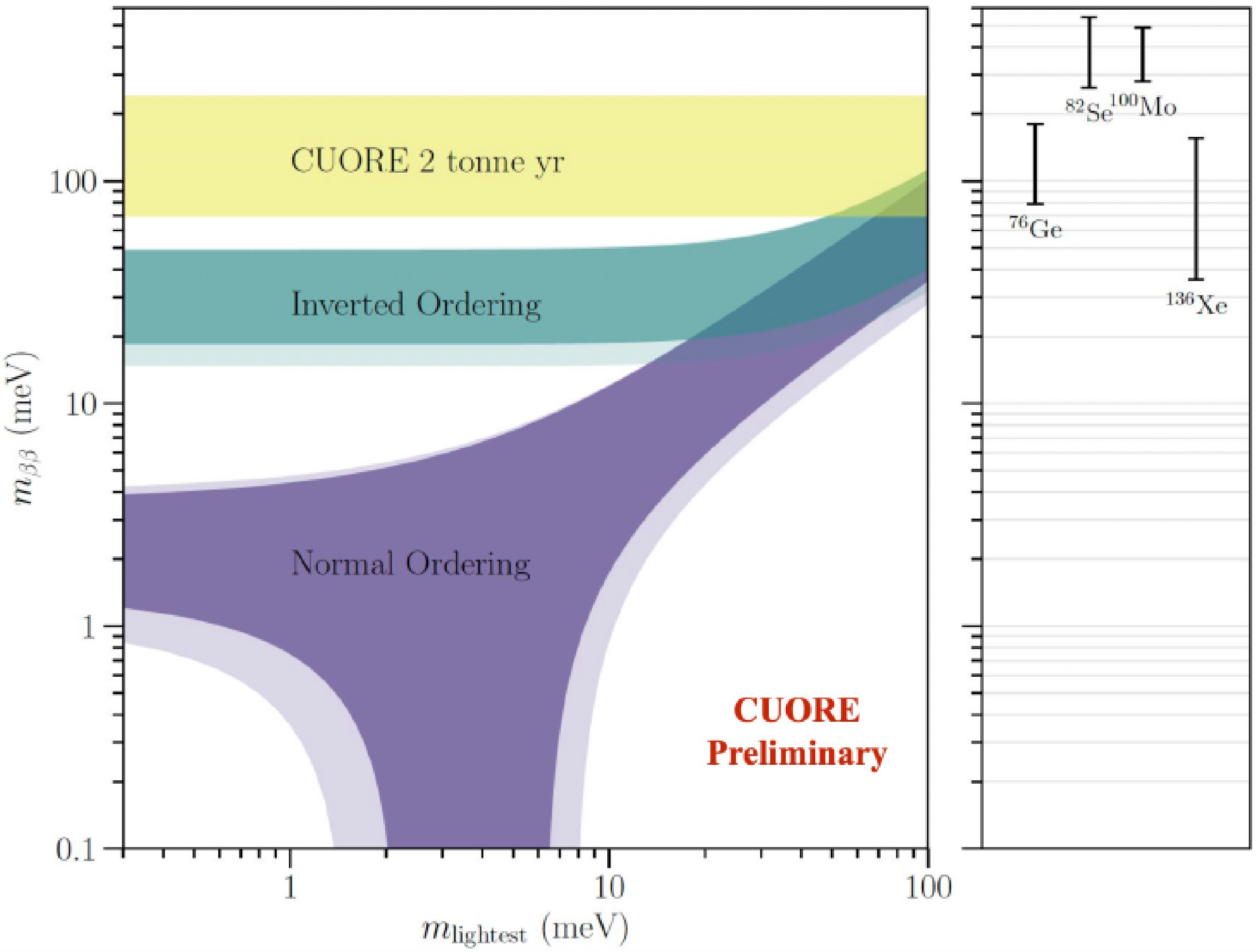
Searching for 0νββ in the Cuore experiment
(Irene Nutini)



$T_{0\nu}^{1/2}$ (^{130}Te) > 3.8 x 10^{25} yr

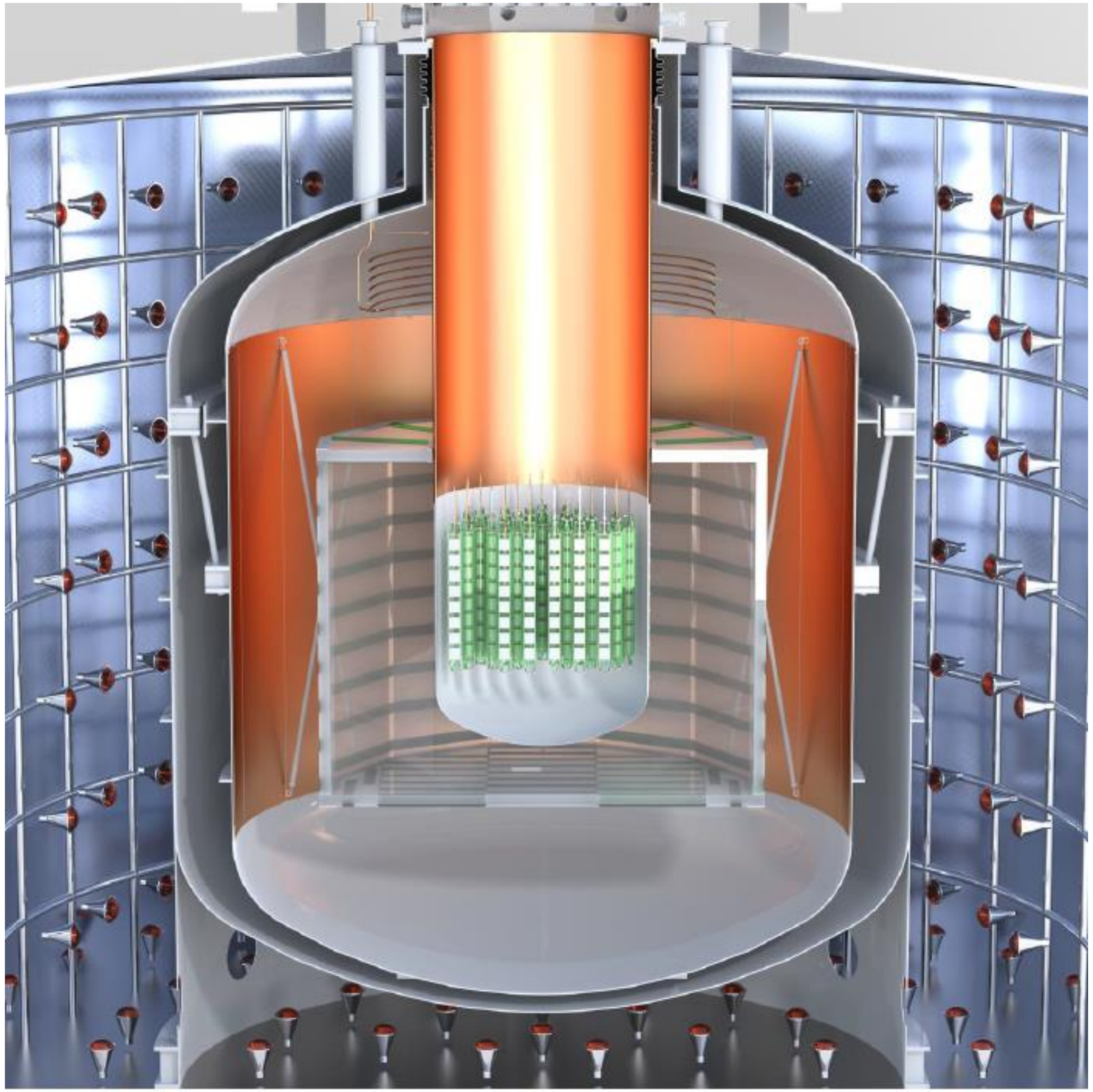
(90%C.I. including syst.)

(new most stringent limit for ^{130}Te)



Limit on the effective Majorana mass, assuming light Majorana neutrino-exchange:
$m_{\beta\beta}$ < 70-240 meV

LEGEND 200 (then 1000) **(CJ. Burton)**



- Initial phase of the project
- Currently operational at LNGS in Italy with ~140 kg of Ge detectors enriched in ^{76}Ge
  - Will have 200 kg operational - upgrade planned for later this year
- Multiple detector systems allow event classification/background rejection

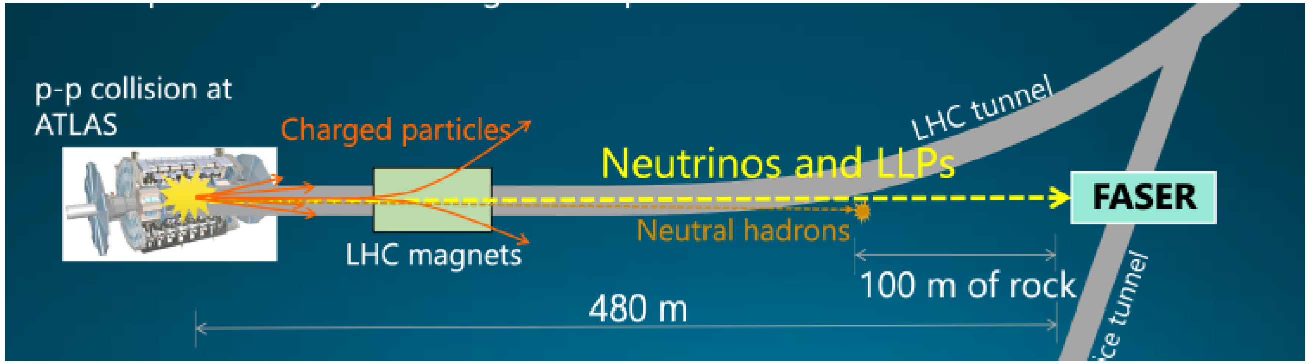
- Next-generation 0νββ detection system
- Location TBD
- Expected to have 1000 kg of detectors operational in the final configuration
- Widespread improvements and lessons learned from LEGEND-200 aim to reduce background x20 compared to LEGEND-200

For ^{76}Ge, $T_{1/2} > 10^{28}$ for 0νββ corresponds to a neutrino effective mass measurement of $m_{eff} \approx 18$ meV

For LEGEND-200's target background of 2×10^{-4}, dataset is compatible (0.48 expected events, 1 observed)

Faser experiment

(Akitaka Ariga) – New results



Forward search experiment at the LHC

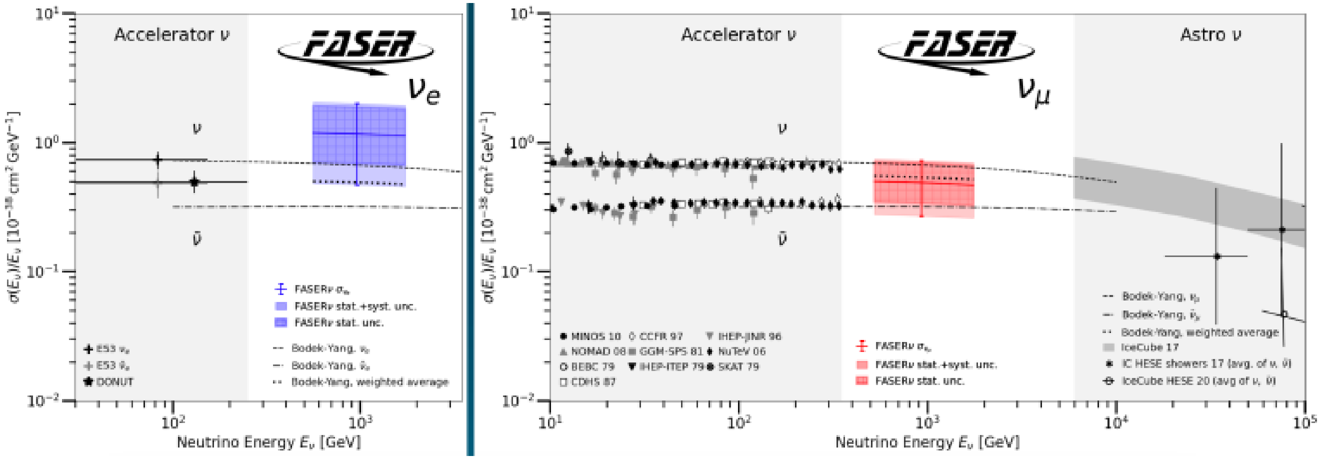
Targets long-lived BSM particles (e.g. A', ALPs) and SM ν

Located 480 m downstream of ATLAS interaction point

LHC-FASER is taking data in LHC Run 3, ~70 fb^{-1} collected, Run4 is approved

- Neutrino studies : Emulsion/tungsten neutrino detector

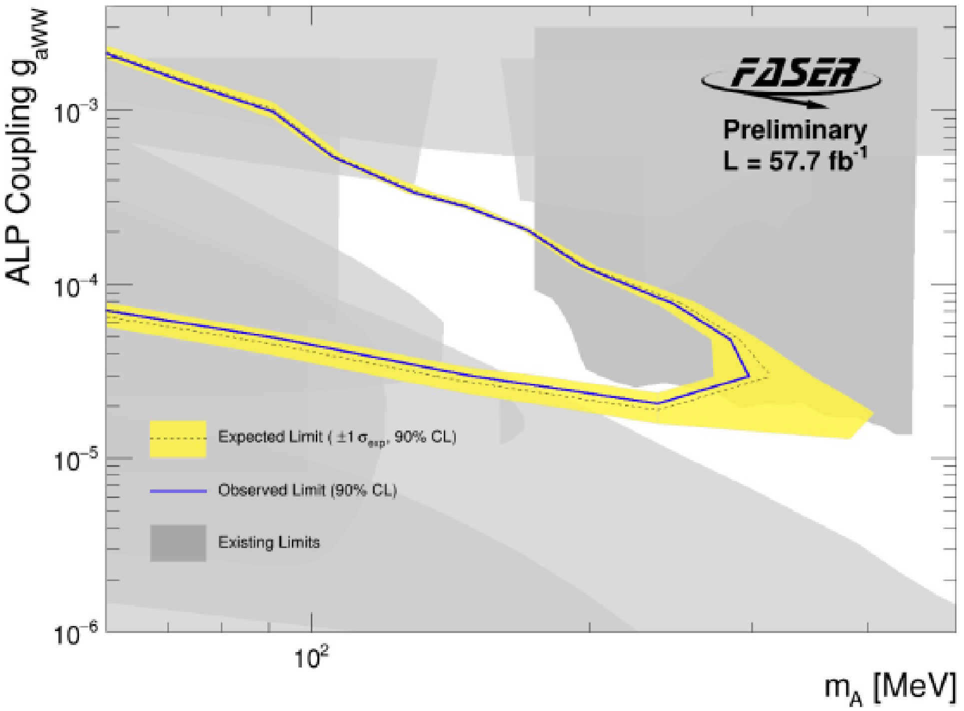
  Measure neutrino cross sections at unexplored TeV energies, constrain hadron production at pp collisions



- Axion-like Particles (ALPs) search results

  Signal: $a \rightarrow \gamma\gamma$ appearing from 'nothing' with ~TeV of energy

- Have also performed a dark photon search



Sterile neutrinos

(Mikhail Danilov)

There are several experimental indications of a new neutrino with $\Delta m^2 \sim 1\ eV^2$, $Sin^2 2\theta_{ee} \sim 0.1$, Must be Sterile since $\Gamma_z \rightarrow N_\nu = 3$

1. LSND, MiniBoone: ν_e ($\bar{\nu}_e$) appearance in ν_μ ($\bar{\nu}_\mu$) beams: Signif. > 6σ

   Not confirmed by MicroBoone arXiv:2110.14054v2 but not excluded

2. SAGE and GALEX ν_e deficit (GA) confirmed by BEST: Signif. > 5σ

   arXiv: 2109.11482, arXiv: 2201.07364 , PRL 128,232501

3 Reactor $\bar{\nu}_e$ deficit (RAA): Signif. ~ 3σ

   Explained by KI (arXiv:2103.01684), DayaBay, RENO experiments and new reactor neutrino flux models?

   Estienne et al arXiv:1904.09358, Letourneau et al, arxXiv:2205.14954, Perisse etal(BESTIOLE) arXiv:2304.14992V2

4. Neutrino-4 claim of sterile neutrino observation

   $\Delta m^2 = 7.3 \pm 1.17 eV^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$ Signif.=2.7σ

   Phys.Rev.D 104, 032003 (2021)

These are statistically strongest laboratory indications of physics BSM!

3+1 ν model is usually used in analysis with extended 4x4 PMNS matrix U_{ij}

$P_{ee} \approx 1 - \sin^2 2\Theta_{ee} \sin^2(\Delta m^2_{14} L/4E)$ with $\sin^2 2\Theta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2)$

$P_{\mu\mu} \approx 1 - \sin^2 2\Theta_{\mu\mu} \sin^2(\Delta m^2_{14} L/4E)$ with $\sin^2 2\Theta_{\mu\mu} = 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$

$P_{\mu e} \approx \sin^2 2\Theta_{\mu e} \sin^2(\Delta m^2_{14} L/4E) \sim 4|U_{e4}|^2 |U_{\mu 4}|^2 \approx \sin^2 2\Theta_{ee} \sin^2 2\Theta_{\mu\mu}/4$

Conclusions

(Mikhail Danilov)

- LSND and MiniBooNE anomalies are disfavored by MicroBooNE
- ν_s explanation of LEE is still possible but contradicts disapp. experiments
- MicroBooNE(NuMI), SBNP and JSNS^2 will soon clarify the situation

- GA is in serious tension with many experiments but agrees with Neutrino-4
- Many ideas of possible conventional or BSM explanation but not convincing
- ν_s explanation of GA is still marginally possible
- BEST with ^{65}Zn source – smoking gun test for many explanations

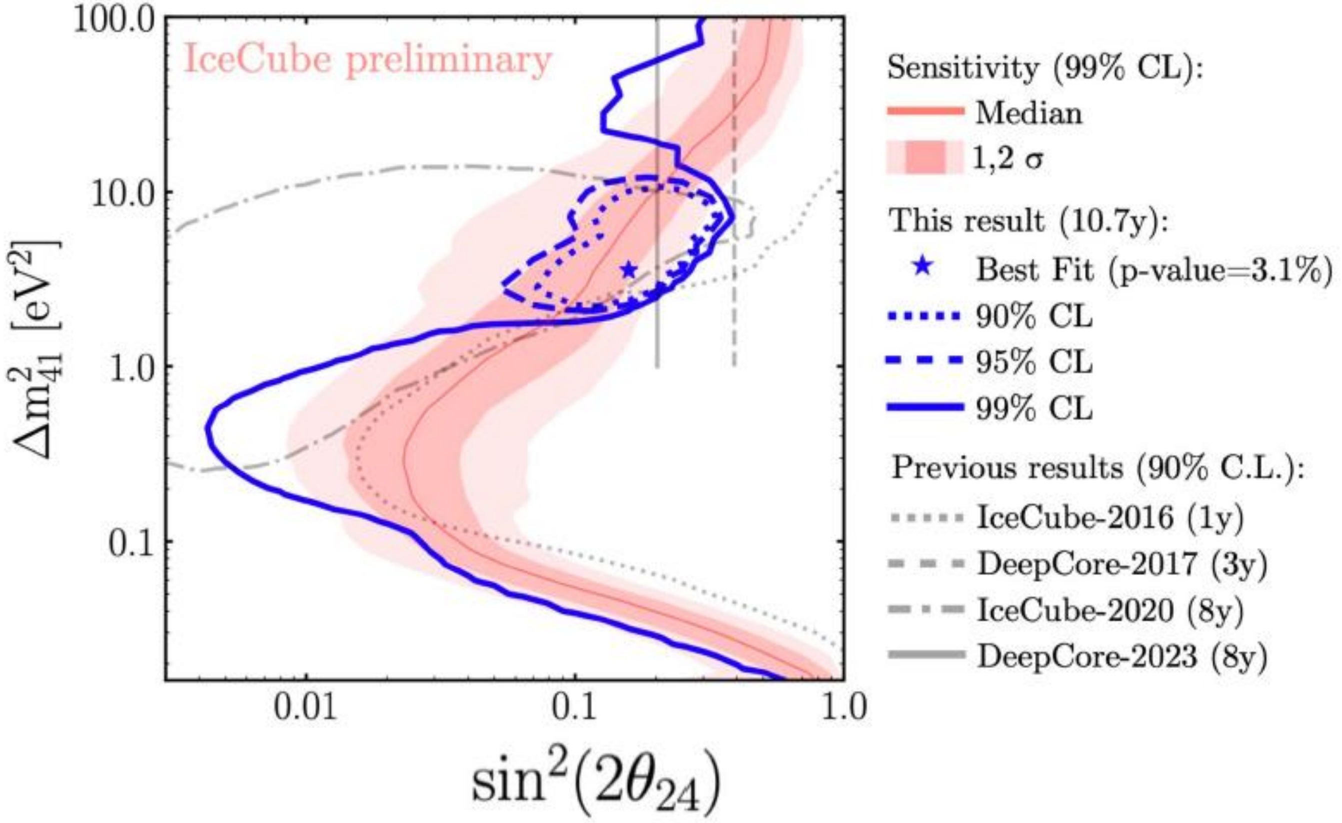
- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments (with exception of DANSS) and new Reactor flux models
- Spectral analysis still indicates ν_s with a small $\sin^2 2\theta_{ee}$ at ~3σ
- Neutrino-4 claim of ν_s observation is in tension with many results but not excluded
- Upgraded VSBL reactor experiments will clarify the situation
  Upgraded Neutrino-4+ is already taking data, Neutrino-4M will start in 2024

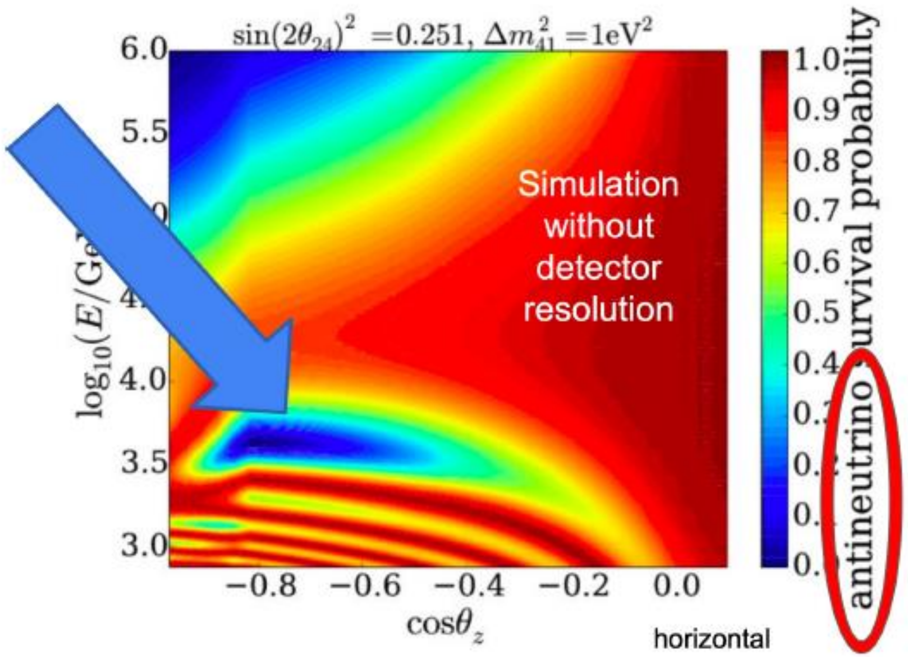
Cosmological constraints were not discussed but models exist which remove them
See e.g. Davoudiasl,Denton arXiv:2301.09651 Explains Ga, LSND, MiniBooNE, DM

Experimental evidence for ν_s is fading away but not excluded

Search for New Physics in IceCube
(John Hardin)

Search for sterile neutrino :
The sterile portion does not interact in the earth.
Different matter potential for sterile and non-sterile neutrinos
Produces a resonant term.
➔ Matter effect : large disappearance of upgoing anti-ν





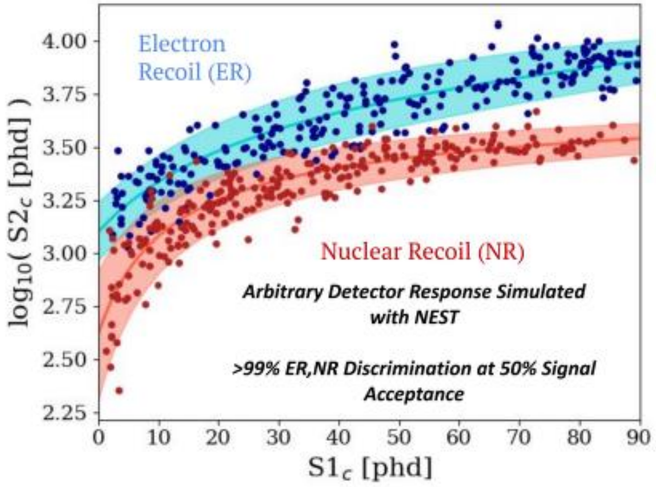
- $\Delta m^2 = 3.5$eV^2
- $\sin^2(2\theta_{24}) = 0.16$

The p-value for the null hypothesis of sterile neutrinos in the muon disappearance channel is 3.1%
Does not rise to evidence

Dark matter searches

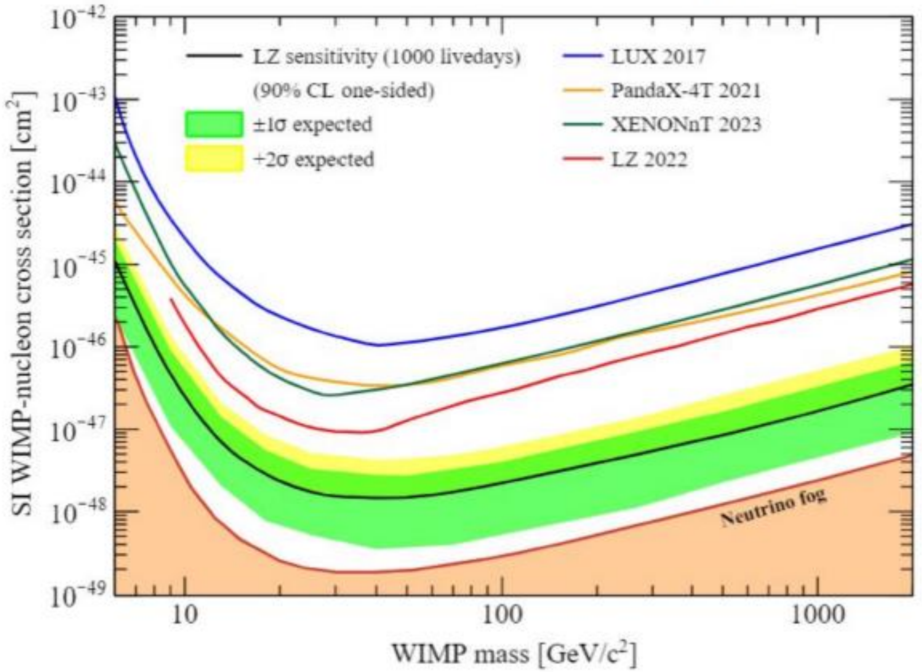
Results from LUX-ZEPLIN (Greg Rischbieter) **and** **Results from PANDAX (Ning Zhou)**

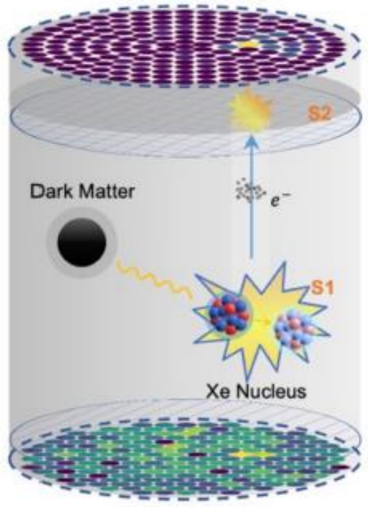
WIMP direct detection with a Dual Phase TPC - Measures the Scintillation (S1) and Ionization (S2) response
Precise E measurement – 3D position reconstruction – Discrimination btw nuclear recoil and electron recoil signals
Xenon target



-Data collected between Dec. 2021-May 2022
-5.5 ± 0.2 tonnes fiducial volume
Reach : 9.2×10^{-48} cm^2

Recap :
limits on DM-nucleon scattering (SI) :





-Commissioning started from Nov/2020 (95 days) –
-Sensitive volume: 3.7 tonnes Xenon
Reach : 3.8×10^{-47}cm^2

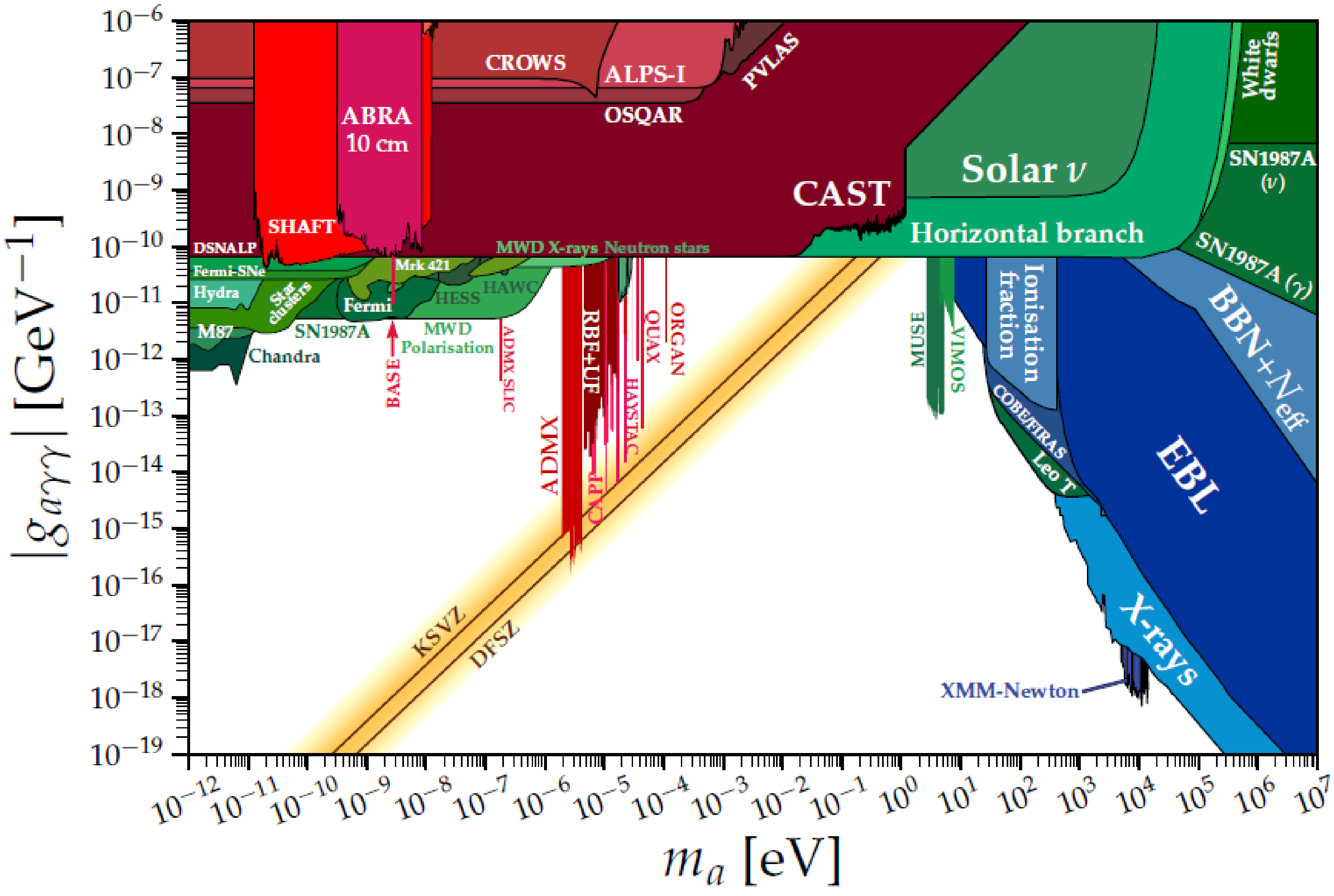
New results: searches beyong Spin-independent WIMPS:

Residual weak EM properties: coupling with photons (millicharged, charge radius, ... UV complete models

Non-Relativistic Effective Field Theory

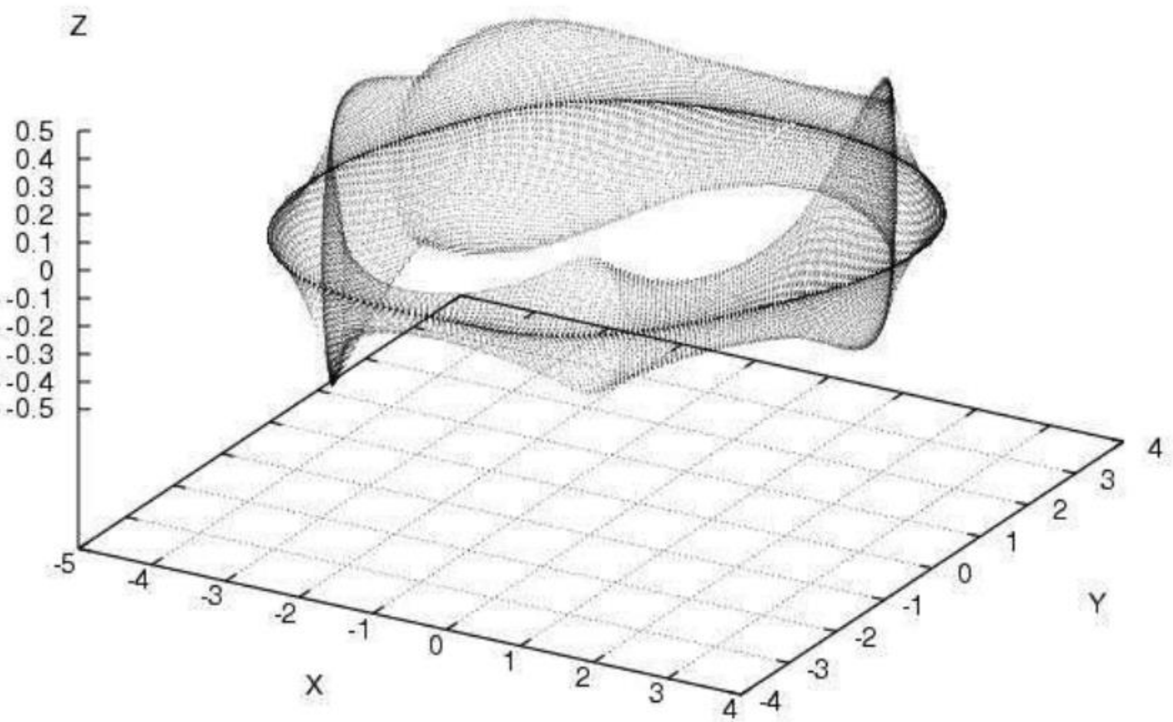
Axion photon constraints

(Pierre Sikivie)



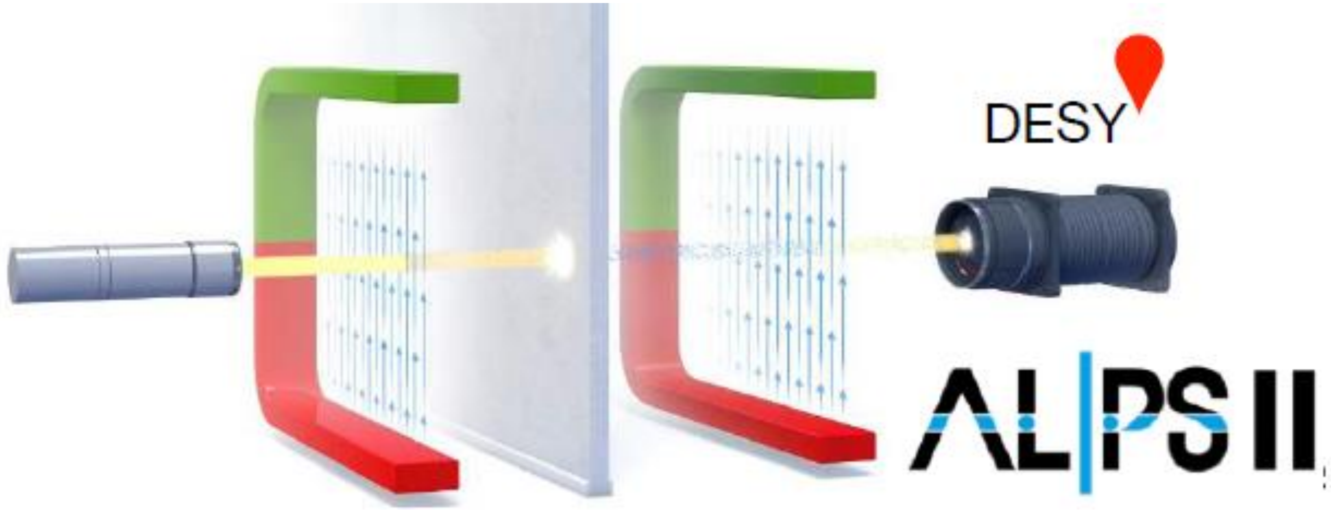
from https://cajohare.github.io/AxionLimits/ by Ciaran O'Hare

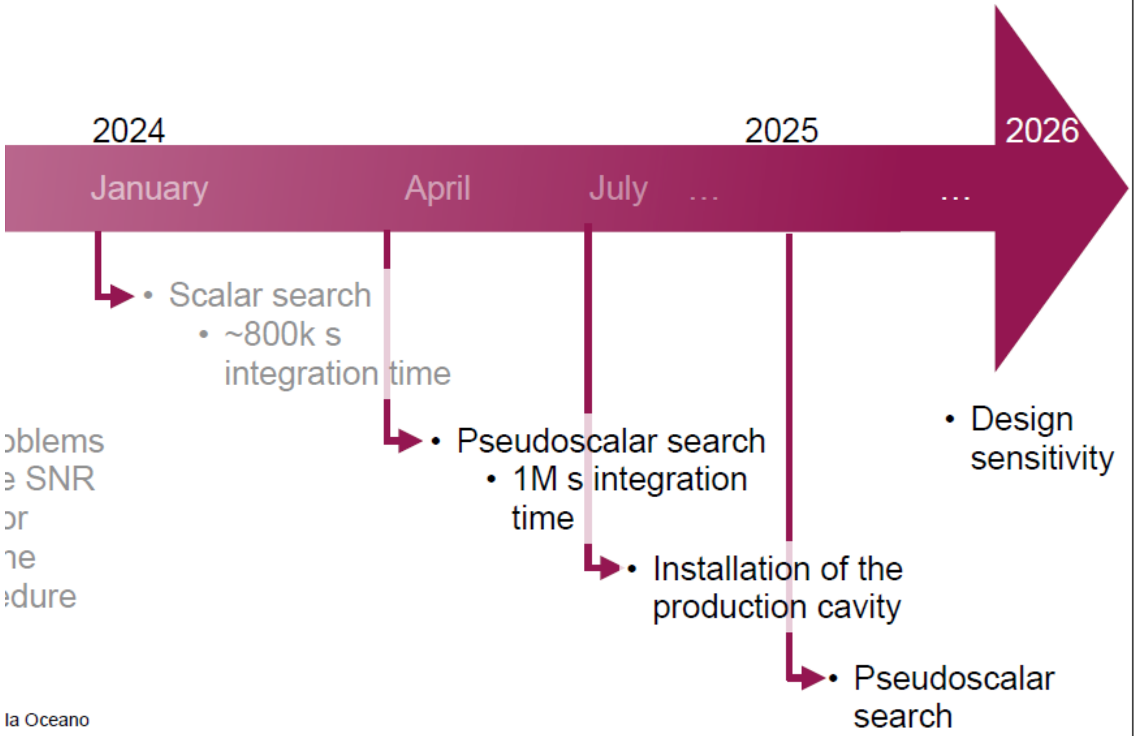
- Axions solve the strong CP problem
- A population of cold axions is naturally produced in the early universe which may be the dark matter today
- Axion dark matter is detectable
- Axion dark matter has distinctive properties in large scale structure formation



Light-shining-through-walls

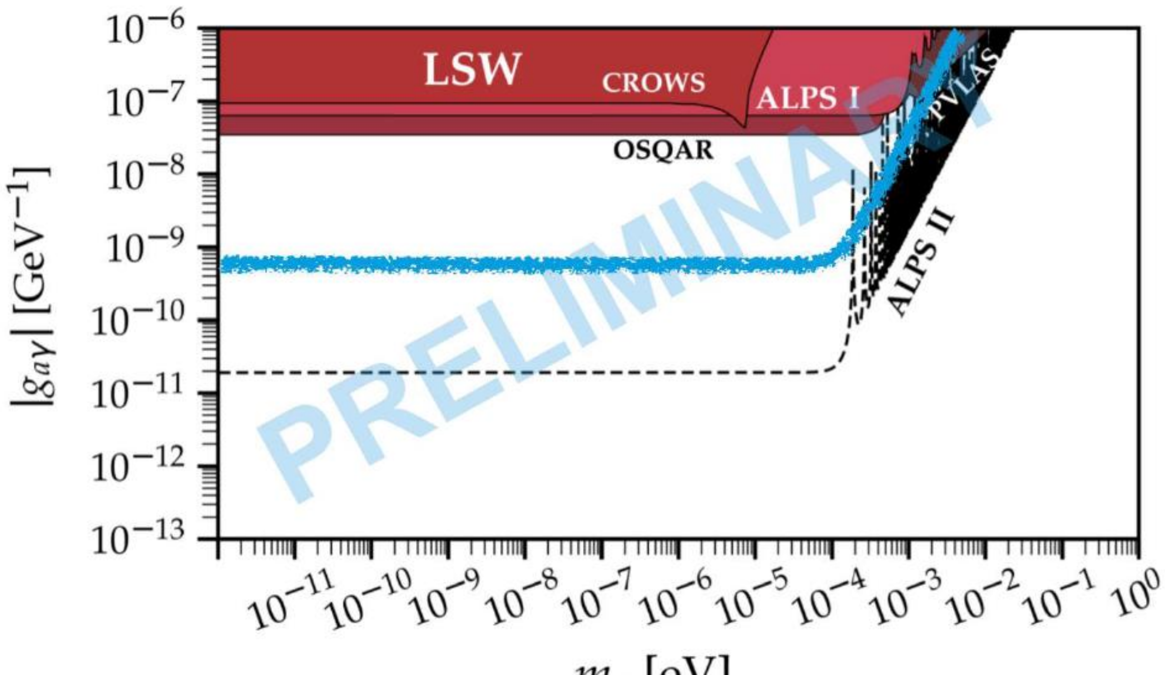
(Isabella Oceano)





Preliminary sensitivity estimate

Scalar search

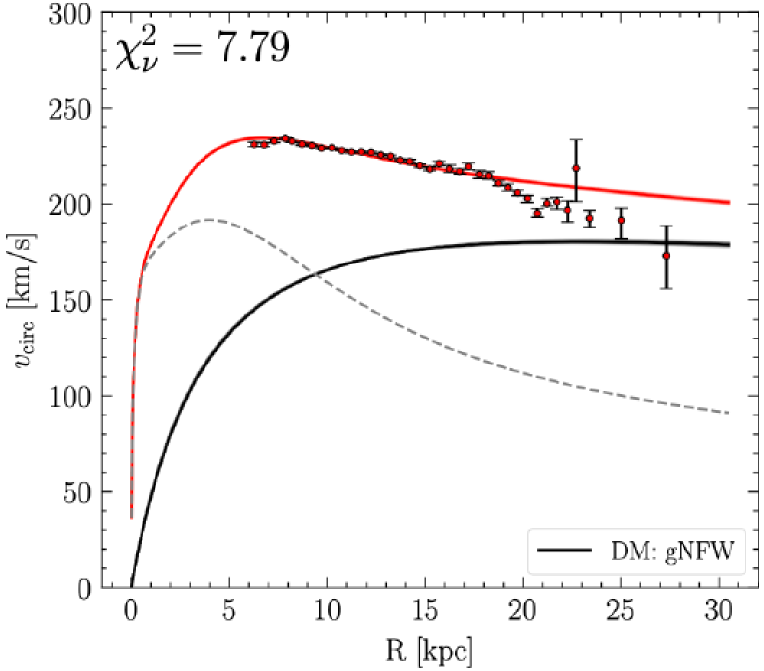


Detection of the Keplerian decline in the Milky Way rotation curve

ΛCDM

In the MW, $M_{\rm Baryon} \sim 0.6 \times 10^{11} M_{\odot}$ and $M_{\rm Dyn} \sim 2.1 \times 10^{11} M_{\odot}$, the mass ratio of DM to the baryon is $\sim 2 - 2.5$, which is smaller than the universal estimate of ~6 (Planck Collaboration et al. 2020).

- generalised NFW profile is also unlikely (Ou et al. 2023, Fig. 7)



Selected theory talks:

Neutrino mixing sum rules — **Steven King**
Katrin
Probing the heavy neutrino hypothesis
T2K
NOvA
Legend
Pheno & cosmo implications of scotogenic 3-loop neutrino mass models — **Téssio de Melo**
SuperK
Sterile neutrino overview
17:00
CUORE
FASER
Destabilizing Matter through a Long-Range Force
Icecube
Alpha-g

Majorana mass generation, GWs and cosmological tensions — **Pasquale di Bari**
Borexino
Probing Reheating with Graviton Bremsstrahlung
PANDA X DM and neutrino-less double beta decay
Status of dark photons — **Jim Cline**
LZ DM
17:00
Axions review — **Pierre Sikivie**
ALPS
Signals of boosted dark matter and neutrinos
First results of axion search with LIDA
21cm signal sensitivity to dark matter decay
Keplerian decline

Merci de votre attention

Bonus slides

Axions and ALPs

Pseudoscalar

In addition to the derivative couplings to standard model matter and most importantly in the context of light shining through a wall matters, axions and ALPs can also have anomalous couplings to electromagnetic fields (photons), in analogy to Equation (3),

$$\mathcal{L} \supset \frac{g}{4}\,\phi\, F_{\mu\nu}\tilde{F}^{\mu\nu} = -g\,\phi\, E \cdot B, \qquad (6)$$

LIPSS used 1 m long, 1.77 T dipole

magnets. They focused their search on scalar ALPs (the laser polarisation was perpendicular to the direction of the magnetic field)

Scalar

The phenomenology arising from the coupling in Equation (6) stays very much unchanged also for a second type of two photon coupling,

$$\mathcal{L} \supset \frac{g}{4}\,\phi\, F_{\mu\nu}F^{\mu\nu} = g\,\phi\left(B^2 - E^2\right), \qquad (9)$$

which in a magnetic field produces mixing between the axion-like particle ϕ and the photon component which is *perpendicular* to the external field. Particles featuring

Light shining through walls
Javier Redondo & Andreas Ringwald
Contemporary Physics, 52:3, 211-236,
DOI: 10.1080/00107514.2011.563516

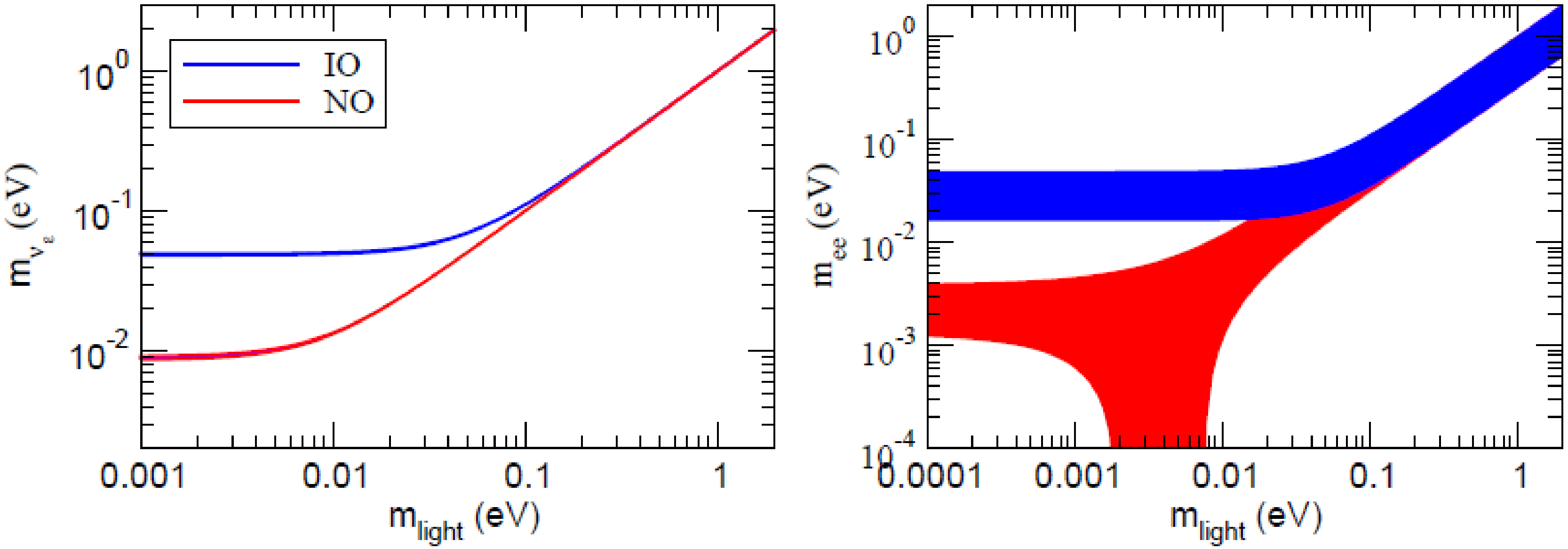


Figure 14.11: Allowed 95% CL ranges (1 dof) for the neutrino mass observable determined in ^3H beta decay (left panel) and in $0\nu\beta\beta$ (right panel) in the framework of 3ν mixing as a function of the lightest neutrino mass. The ranges are obtained by projecting the results of the global analysis of oscillation data (w/o SK-atm) in Ref. [184]. The region for each ordering is defined with respect to its local minimum.

for the two orderings. As a consequence of the dependence on the unknown Majorana phases, the allowed range of m_{ee} for a given value of m_{light} and ordering is substantially broader than that of m_{ν_e}. Nevertheless, the results of oscillation experiments imply a lower bound on the effective Majorana mass for the IO, which at 95%CL reads $m_{ee} > 0.016$ eV.

PDG

Mixing in matter (PDG 2020)

The instantaneous mass eigenstates in matter, ν_i^m, are the eigenstates of the Hamiltonian H in (14.56) for a fixed value of x, and they are related to the interaction basis by

$$\vec{\nu} = \tilde{U}(x)\vec{\nu^m} \, . \tag{14.59}$$

The corresponding instantaneous eigenvalues of H are $\mu_i(x)^2/(2E)$ with $\mu_i(x)$ being the instantaneous effective neutrino masses.

Let us take for simplicity a neutrino state which is an admixture of only two neutrino species $|\nu_\alpha\rangle$ and $|\nu_\beta\rangle$, so the two instantaneous mass eigenstates in matter ν_1^m and ν_2^m have instantaneous effective neutrino masses

$$\begin{aligned} \mu_{1,2}^2(x) &= \frac{m_1^2 + m_2^2}{2} + E[V_\alpha + V_\beta] \\ &\mp \frac{1}{2}\sqrt{\left[\Delta m^2 \cos 2\theta - A\right]^2 + \left[\Delta m^2 \sin 2\theta\right]^2} \, , \end{aligned} \tag{14.60}$$

and $\tilde{U}(x)$ is a 2x2 rotation matrix with the instantaneous mixing angle in matter given by

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A} . \qquad (14.61)$$

In the Eqs.(14.60) and (14.61) A is

$$A \equiv 2E(V_\alpha - V_\beta) , \qquad (14.62)$$

and its sign depends on depends on the composition of the medium and on the flavour composition of the neutrino state considered. From the expressions above we see that for a given sign of A the mixing angle in matter is larger(smaller) than in vacuum if this last one is in the first (second) octant. We see that the symmetry about 45 degrees which existing in vacuum oscillations between two neutrino states is broken by the matter potential in propagation in a medium. The expressions