Neutrinos!

Experimental Highlights

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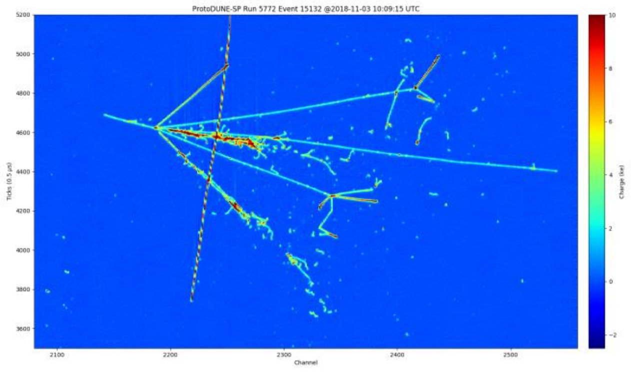
2 September 2022

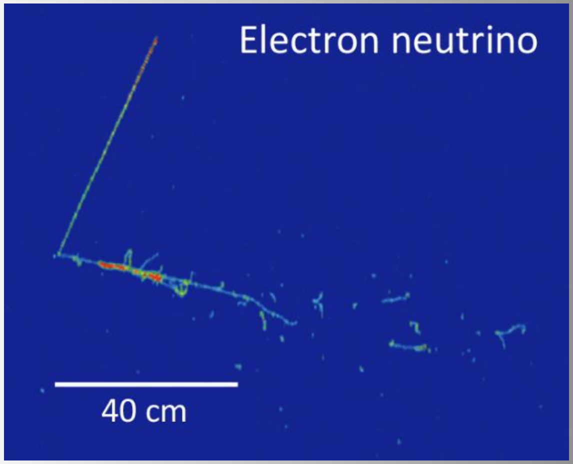
Corfu Summer Institute
Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece

Outline

- Introduction to neutrinos
- Results from oscillation experiments
- Next generation of experiments
- Neutrino properties: mass and Majorana/Dirac nature
- Anomalies/Sterile Neutrino Search
- Large neutrino telescopes
- Neutrino experiments at the LHC
- (other topics)
- Summary



Pion event in the ProtoDUNE at CERN



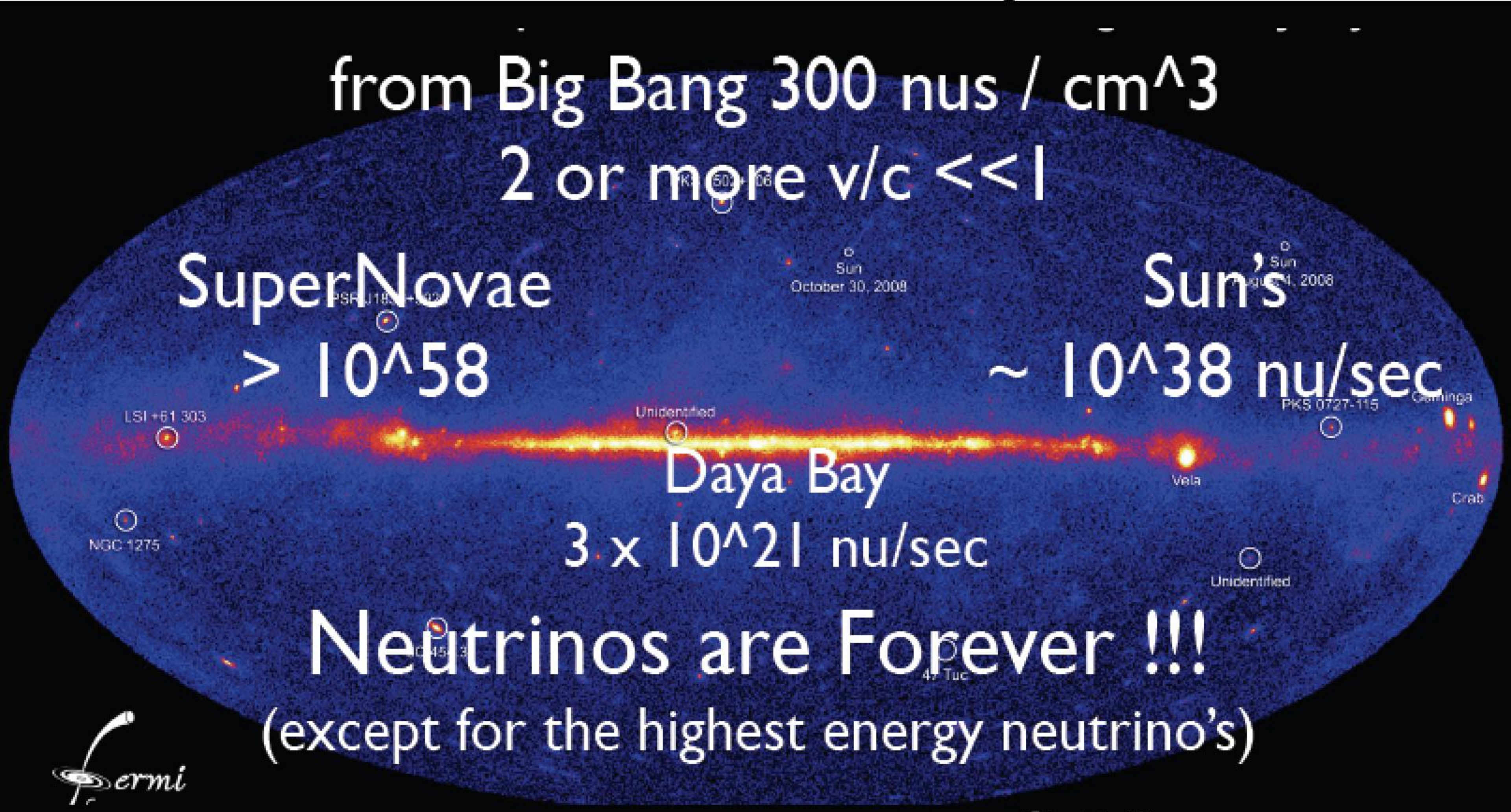
Electron neutrino event in the ICARUS detector at FNAL

Neutrinos

Neutrinos are still mysterious particles

- Have only (left handed) weak interactions
- Are mass-less in the (minimal) SM … until 1998
- Are the only neutral fermions in the SM
- Could be Majorana or Dirac fermions
- Neutrinos are produced everywhere
  - Solar neutrinos
  - Atmospheric neutrinos
  - Neutrinos from supernova explosions
  - Primordial neutrinos from the Big Bang
  - Nuclear reactor created neutrinos
  - Accelerator created neutrinos
  - Geoneutrinos, Radioactive decay, even from your body…

Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

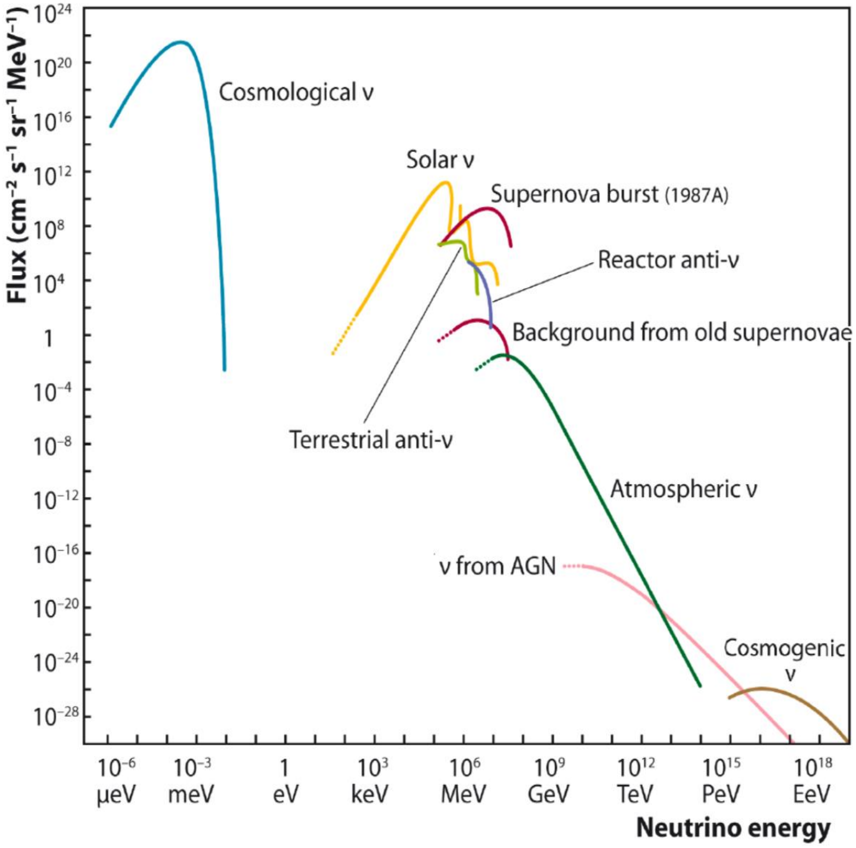
Neutrinos are Forever !!!

(except for the highest energy neutrino's)

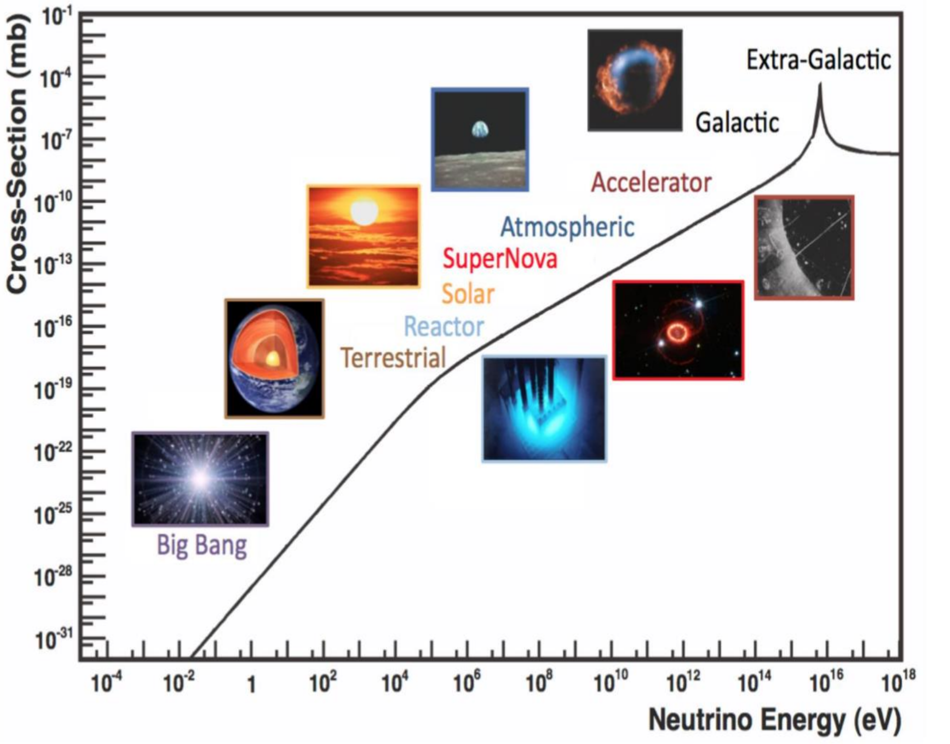
therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrino Sources, Flux and Cross Sections

C. Spiering, arXiv:1207.4952

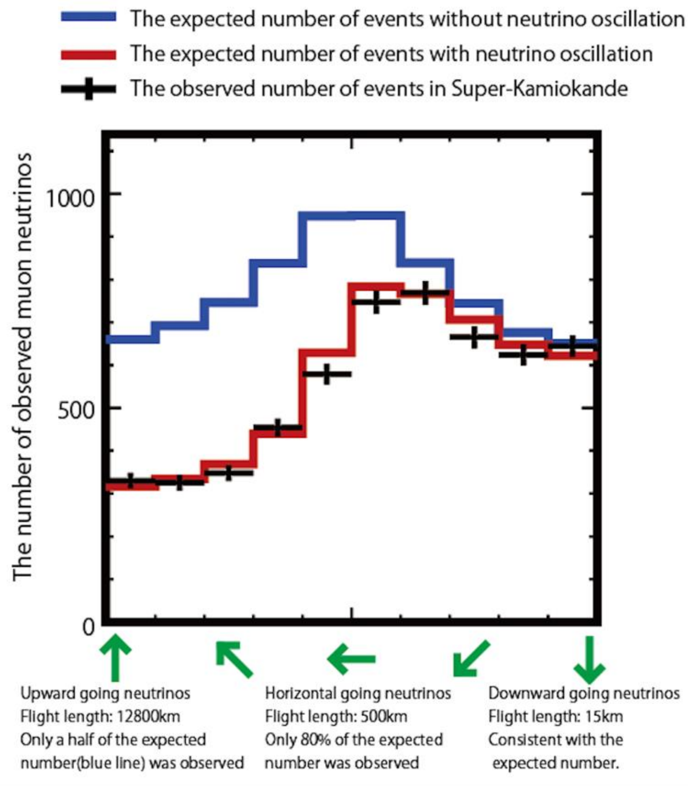


J. Formaggio, G.P. Zeller, arXiv:1305.7513



Cosmological and background from old supernovae neutrinos not yet observed!

Neutrinos Oscillate! (1998)

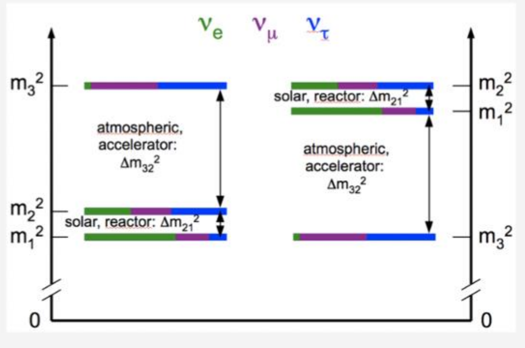


1998: The Super-Kamiokande experiment in Japan used a massive underground detector filled with ultrapure water.

They announced first evidence of neutrino oscillations. The experiment showed that muon neutrinos disappear as they travel through the earth to the detector It also offered an explanation for the observed solar neutrino discrepancy.

Neutrinos

Neutrino experiments today -> Open Questions!

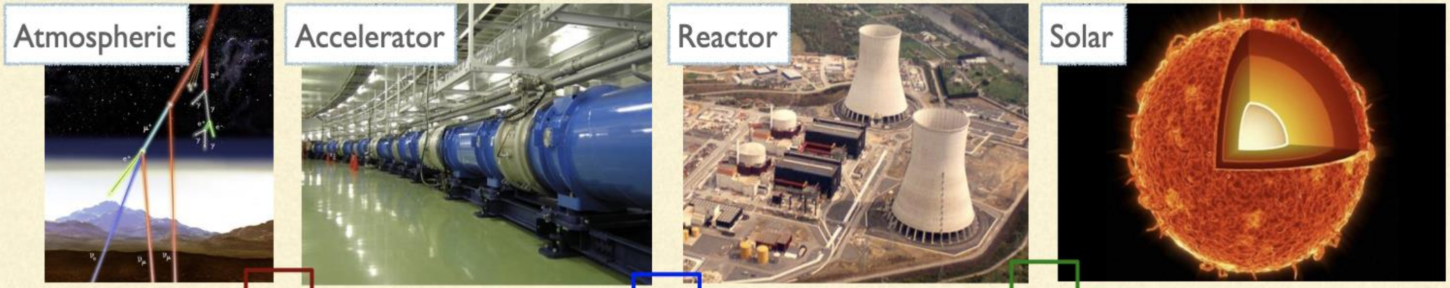


- Neutrino mass values? Origin of the Masses?
- Neutrino mass hierarchy? Normal or Inverted?
- CP violation in the lepton sector? Are neutrinos key the baryon asymmetry in the Universe?
- Are neutrinos their own antiparticles? -> LNV processes
- Do right-handed/sterile/heavy neutrinos exist?
- Are there non-standard neutrino interactions?
- Neutrinos and Dark Matter?
- Testing of CPT..
- Neutrinos are Chameleons:
  They can change flavour!!

Neutrinos are an essential part of our Universe and our very existence, and can provide answers to some of the key fundamental questions today

Neutrino Oscillations

Neutrino mixing: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix



$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillations governed by

* PDG 2022

- three mixing angles:
  - $\theta_{12} \approx 34^\circ$, $\theta_{13} \approx 9^\circ$, $\theta_{23} \approx 48^\circ$ (41-51 within 3σ)
- two mass squared differences:
  - $\Delta m^2_{21} \approx 7.4\times10^{-5}\,\text{eV}^2$ and $|\Delta m^2_{32}| \approx 2.5\times10^{-3}\,\text{eV}^2$
- source-detector baseline and neutrino energy

In total 6 parameters to determine:

-3 angles
-2 mass differences
-1 CP violation phase

Neutrino Oscillations

Mixings and phases: **CKM→ PMNS** (Pontecorvo-Maki-Nakagawa-Sakata)

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} rotation

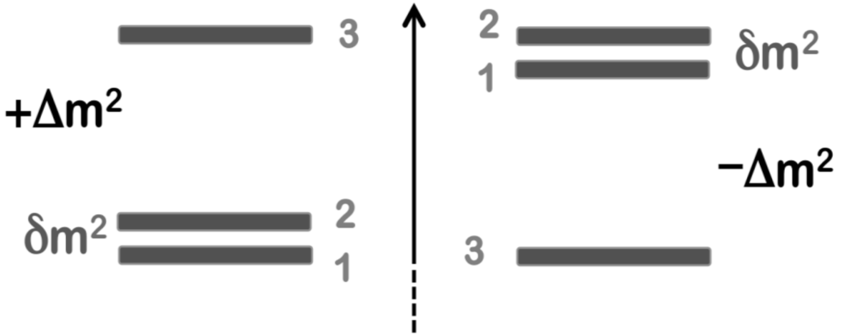
θ_{13} rotatio $c_{ij} = \cos\theta_{ij};\, s_{ij} = \sin\theta_{ij}$

+ CPV "Dirac" phase δ

Mass [squared] spectrum (E ~ p + $m^2/2E$ + "interaction energy")

"Normal" Ordering

N.O.



"Inverted" Ordering

I.O.

+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density

Short Baseline Experiments

Measuring the mixing angle θ_{13}:

Daya Bay (China)
Eight anti-neutrino detectors
(liquid scintillator based)
within 2 km of 6 reactors

RENO (South Korea)
Two anti-neutrino detectors
(liquid scintillator based)
~up to 1.5 km of 6 reactors

Double Chooz (France)
Two anti-neutrino detectors
(liquid scintillator based)
within 0.4-1 km of the reactors

- New results from Daya Bay nGd capture:

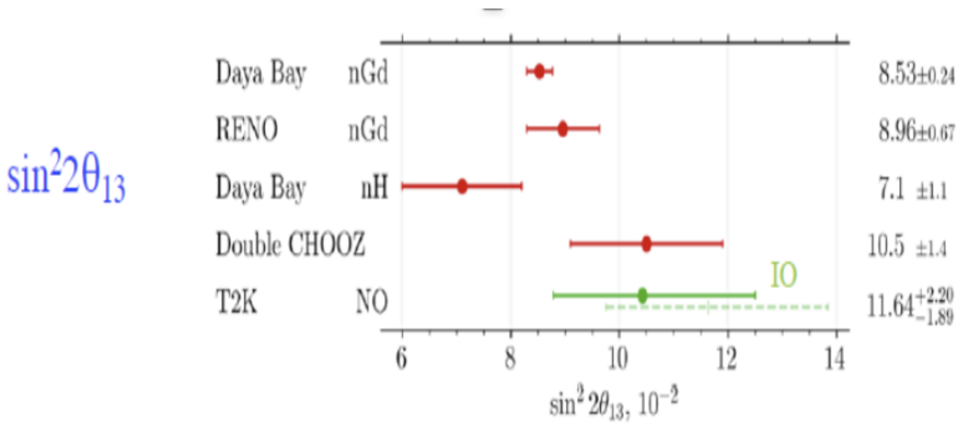
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024} \qquad (2.8\% \text{ precision})$$

- Expect final results from Daya Bay on combined nGd+nH analysis: 2.6% for $\sin^2 2\theta_{13}$?
- RENO reported new results(up to 2019)

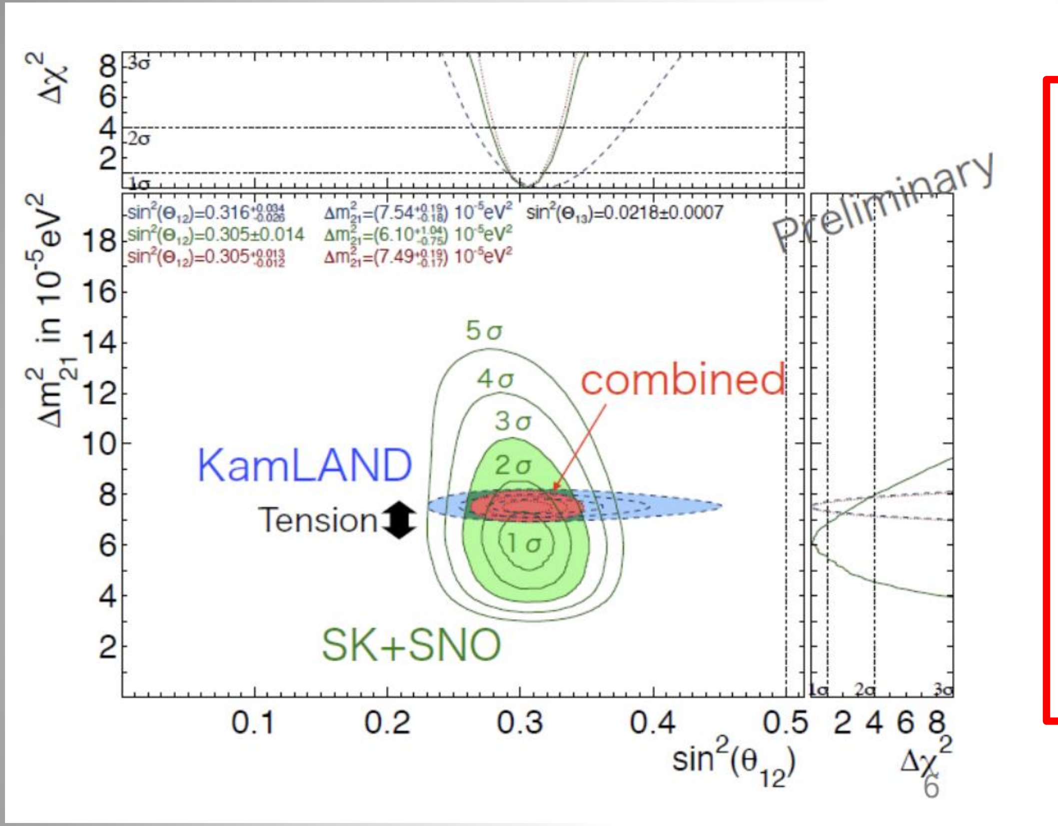
$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(\text{stat.}) \pm 0.0045(\text{sys.}) \qquad (\pm\ 7.0\ \%)$$

- RENO will continue for another ~3 years

$\sin^2 2\theta_{13}$: 6.4%; Δm^2_{ee}: 4.1%



Solar Neutrino Parameters



$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$

$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$

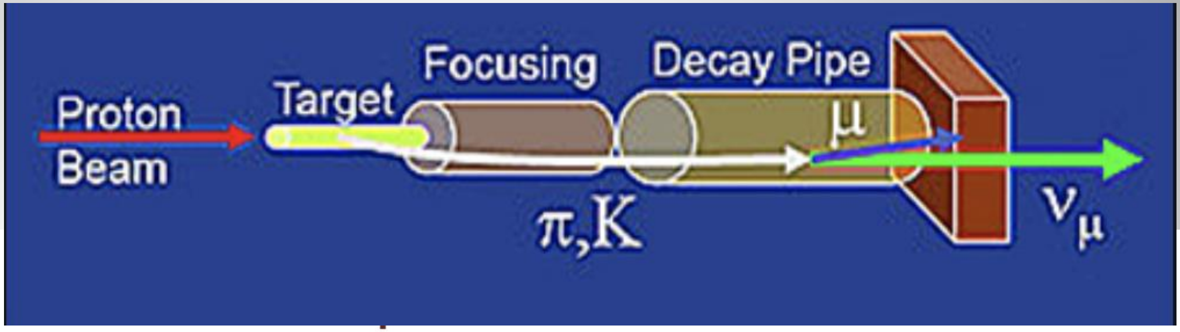
$$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$$

$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$$

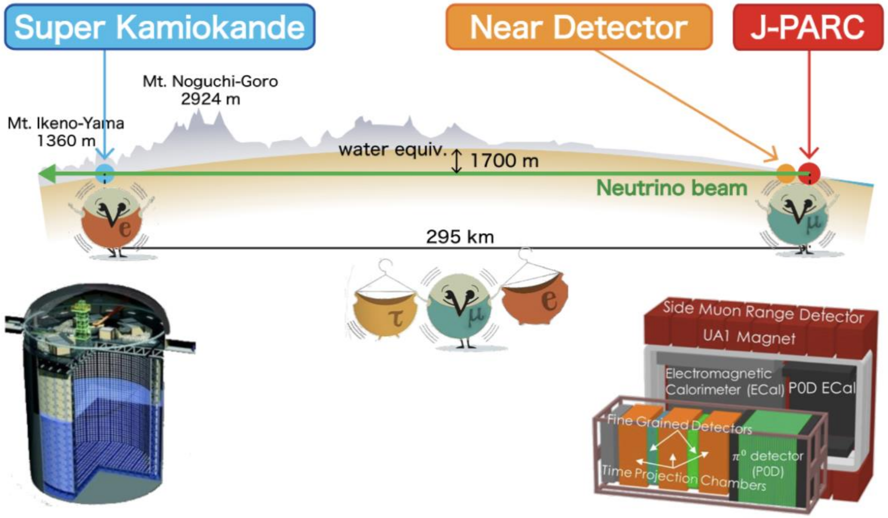
- Tension between solar & reactor result still there, 1.5σ.
- JUNO can simultaneously measure Δm^2_{21} and θ_{12} using reactor antineutrinos and solar neutrinos with a great precision.
- HyperK will improve the solar neutrino result

Accelerator Based Neutrino Experiments

Neutrinos from accelerators

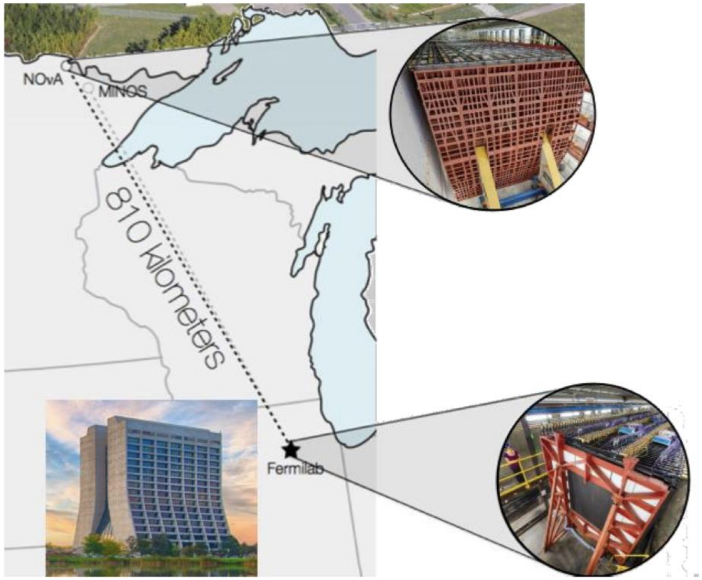


T2K



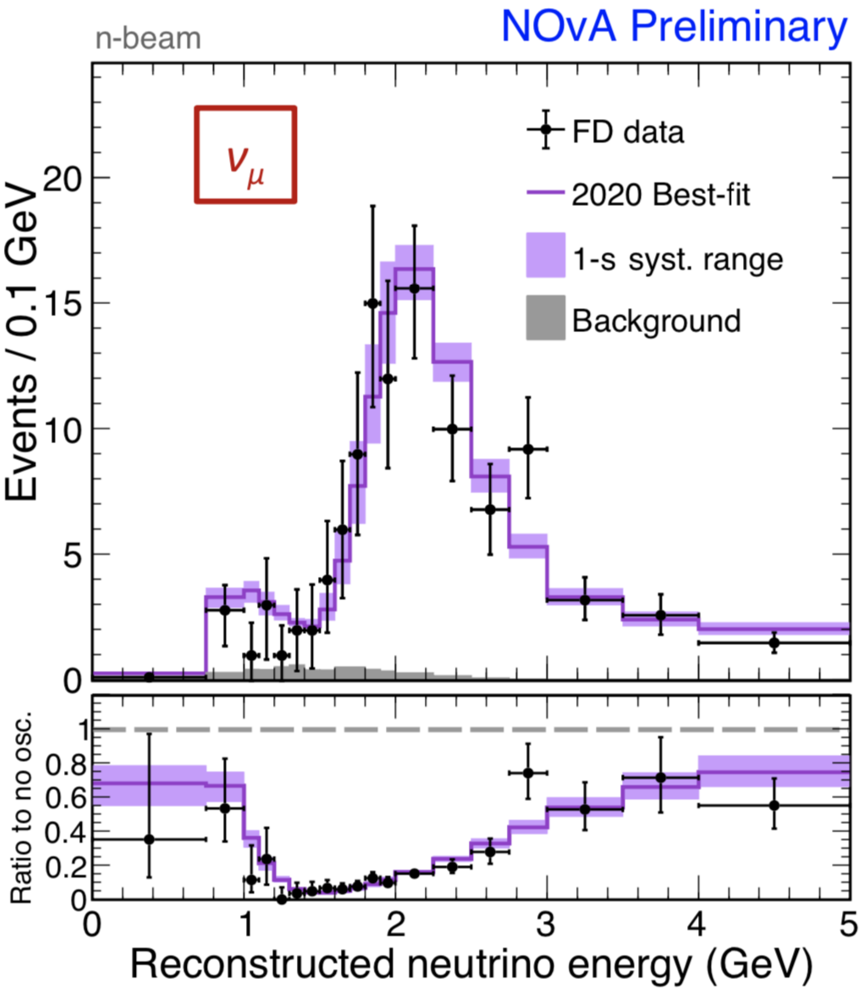
Baseline: 295 km
Peak E_ν: ~0.6 GeV (off-axis)
Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

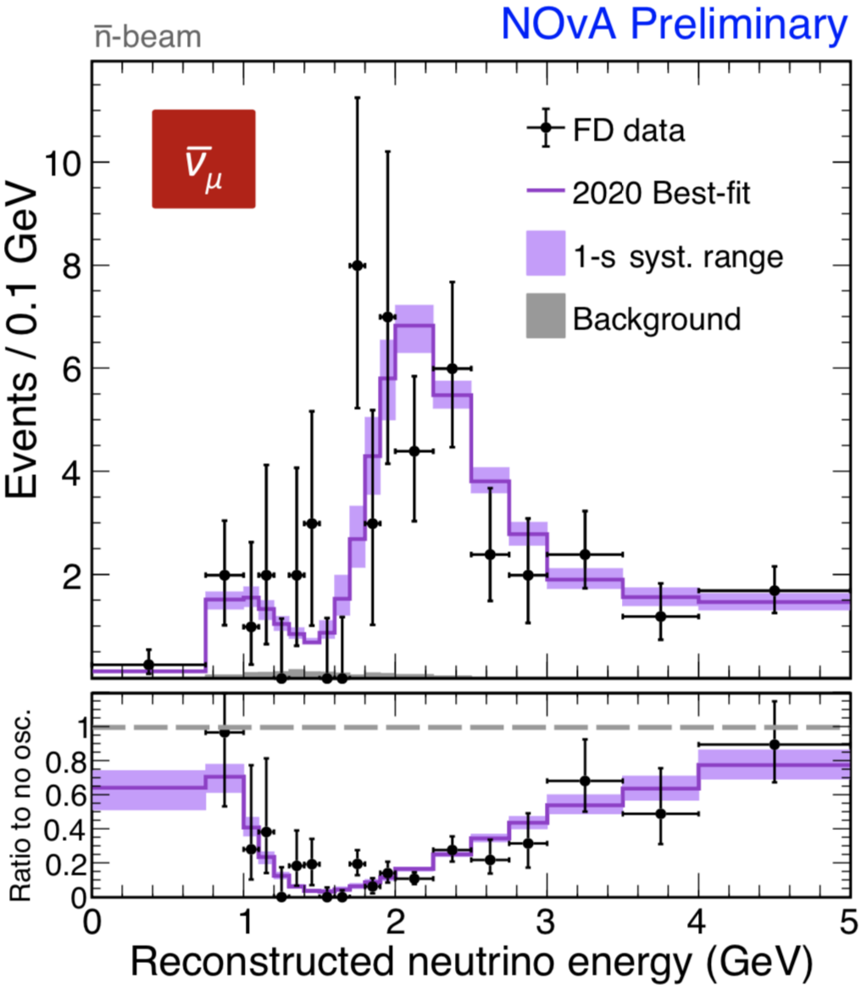


- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

Muon Neutrino Disappearance



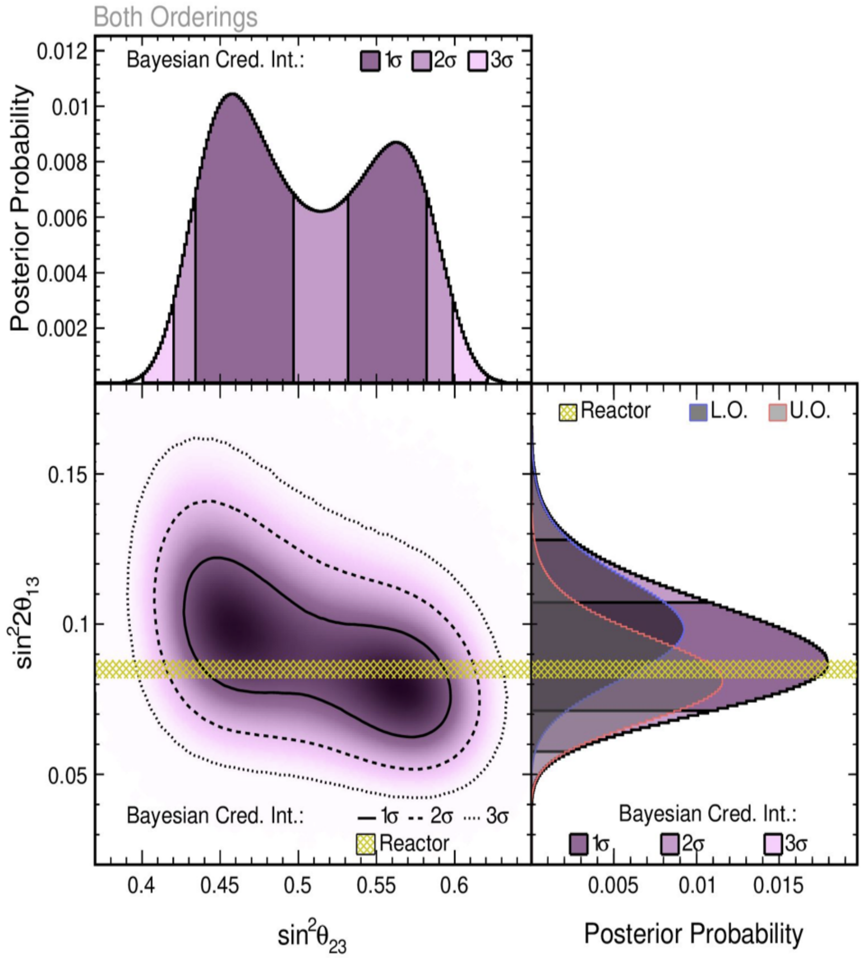
211 events, 8.2 background



105 events, 2.1 background

NOvA Results

Measurement of θ_{13}



- The results so far all use a constraint on θ_{13} from reactor experiments.
- The Bayesian interpretation of our data allows us to drop this constraint and make a NOvA measurement of θ_{13}.

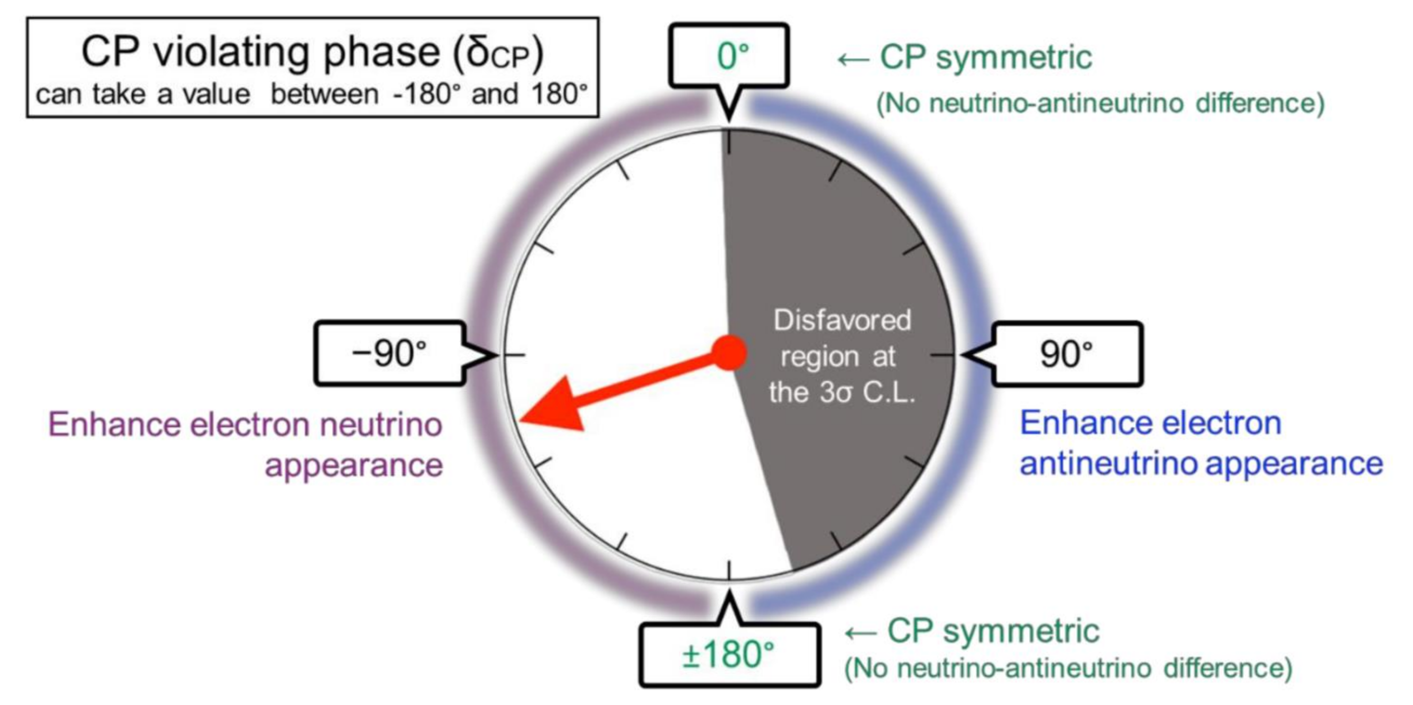
$$\boxed{\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}}$$

- Consistent with the measurements from reactor experiments.
- Good test of PMNS consistency → NOvA measurement uses a very different strategy to reactor experiments.

CP Violation: T2K Result

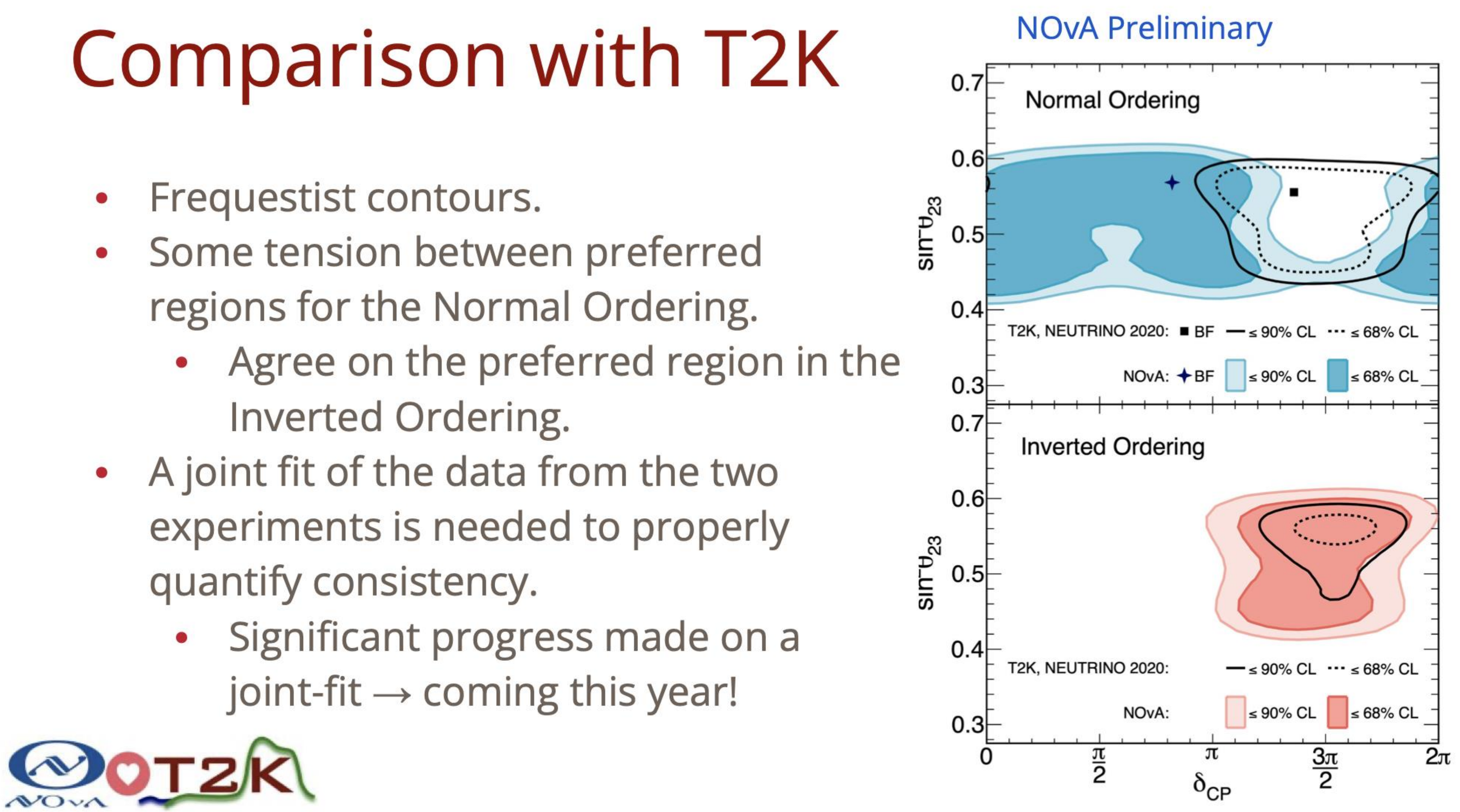
Nature Magazine April 16/4/2020
and arXiv:: 1910.03887

Determination of $\boldsymbol{\delta}_{CP}$
Appearance of $\boldsymbol{\nu}_e$ events



The gray region is disfavored by 99.7% (3σ) CL
The values 0 and 180 degrees are disfavoured at 95% CL

NOvA Results



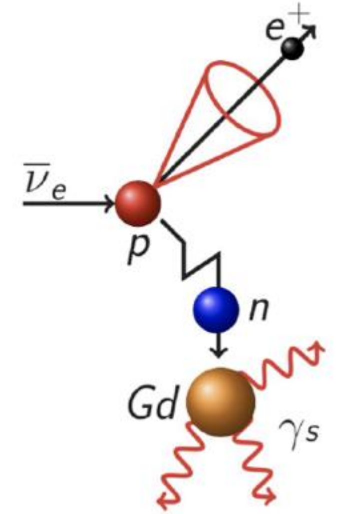
Comparison with T2K

- Frequestist contours.
- Some tension between preferred regions for the Normal Ordering.
  - Agree on the preferred region in the Inverted Ordering.
- A joint fit of the data from the two experiments is needed to properly quantify consistency.
  - Significant progress made on a joint-fit → coming this year!

NOvA/T2K will continue to take data till 2026/2027
-> double the statistics of present analyses, reduce systematics

T2K Future

- Gadolinium now added to SK water: not yet used in analysis but neutron signal seen
- Significant enhancement in neutron capture: anti-neutrino events tagging
- Also the T2K neutrino beamline upgrade on-going

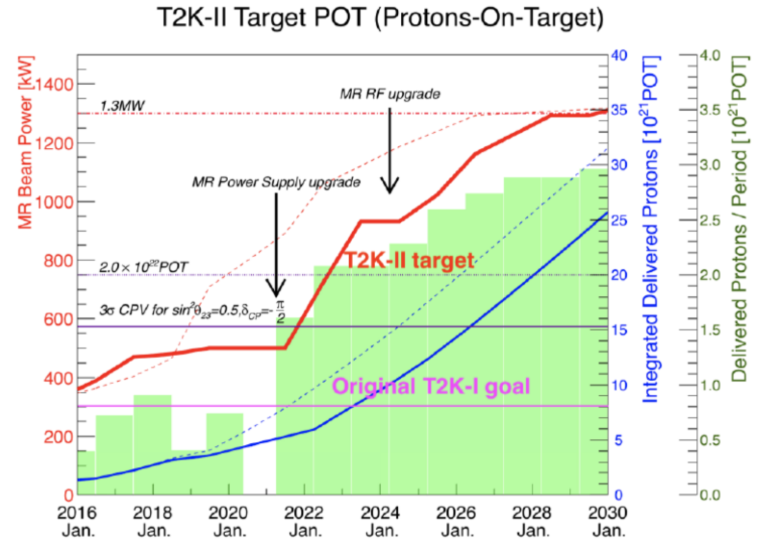


8 MeV γ cascade

Accumulate more data in the next years

- Reduce systematics uncertainties
- Replica of the beam target has been put proton beam of NA61 this summer
- Reach 3σ for non-CPV rejection prior to Hyper-Kamiokande era

+ upgrade of the ND280 near detector

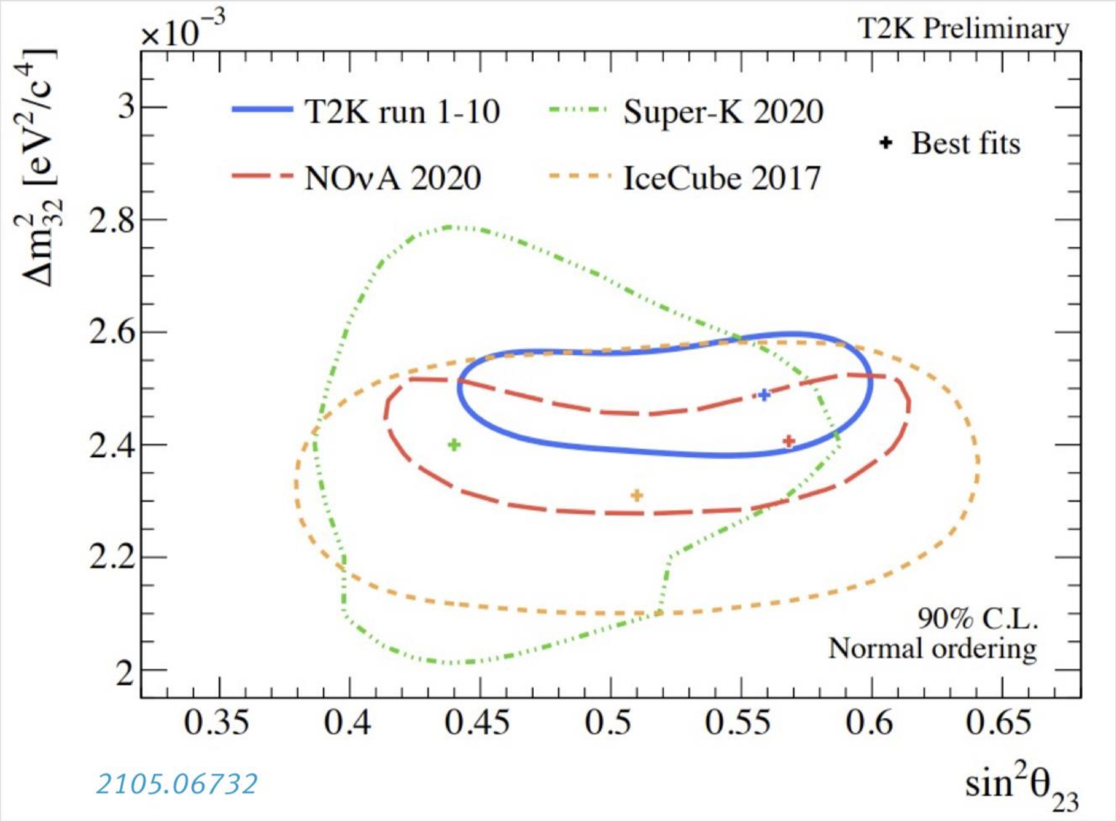


T2K/NOvA

- No large new data included sets since e.g. last year. Updates focussed more on analysis sophistication rather than additional statistics.
- Data taking continues, but significant improvements will take time
- Upgraded neutrino cross sections and flux modeling to reduce systematics
- Expected for later this year
  - T2K/NOvA common analysis ongoing to improve precision (and check on differences)
  - T2K+HK atmospheric joint fit

Neutrino Experiments

- Atmospheric parameter determinations by several experiments
- Results are consistent

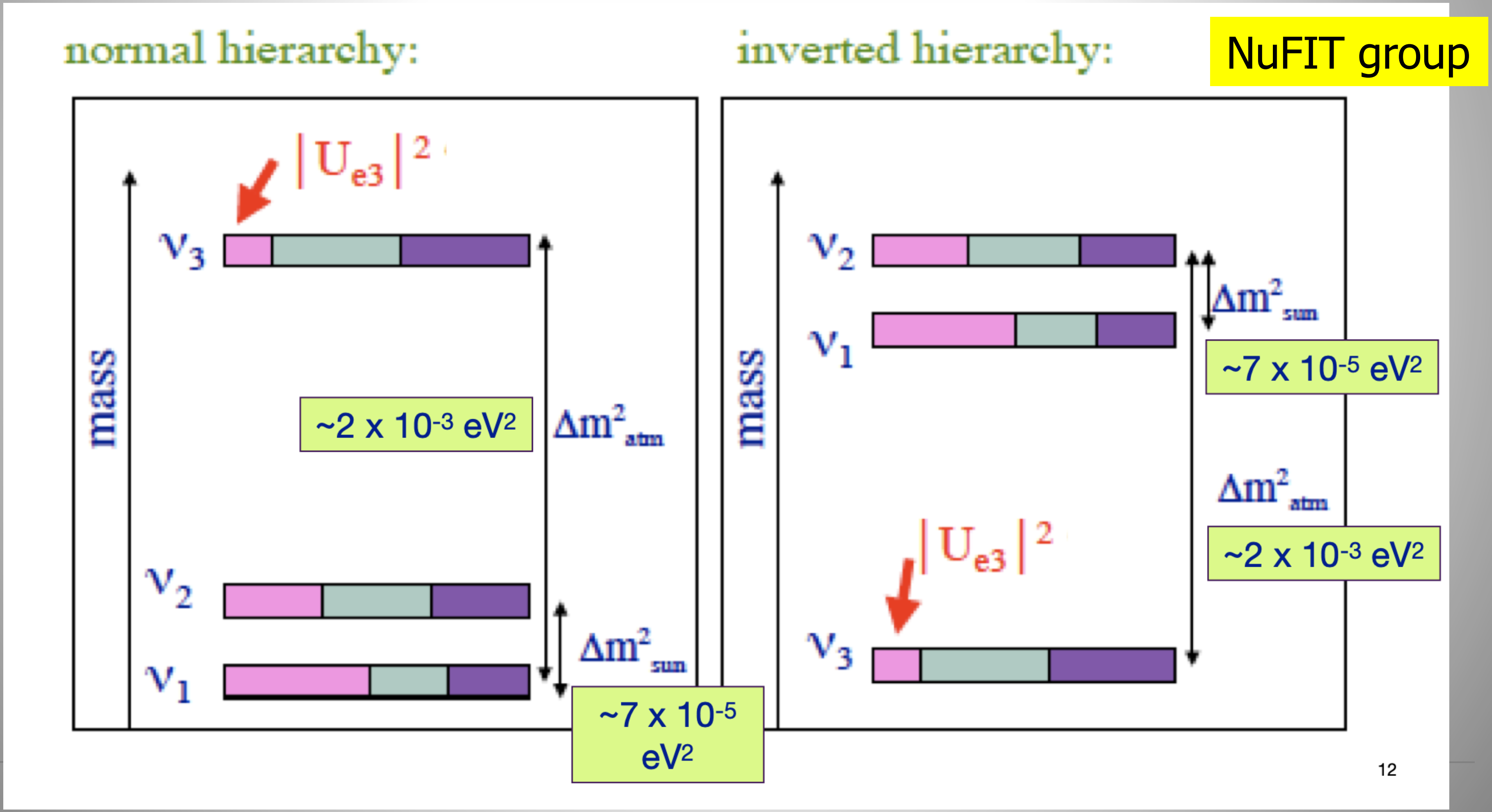


2105.06732

- Δm^2_{32} -vs-$\sin^2\theta_{23}$: at 90% CL, θ_{23} contours overlap. T2K and NOνA favour upper octant while Super-K prefers lower

General Picture

Approximate flavor compostion of the mass eigenstates and mass differences (squared)



NuFIT group

~2 x 10^{-3} eV^2

~7 x 10^{-5} eV^2

~7 x 10^{-5} eV^2

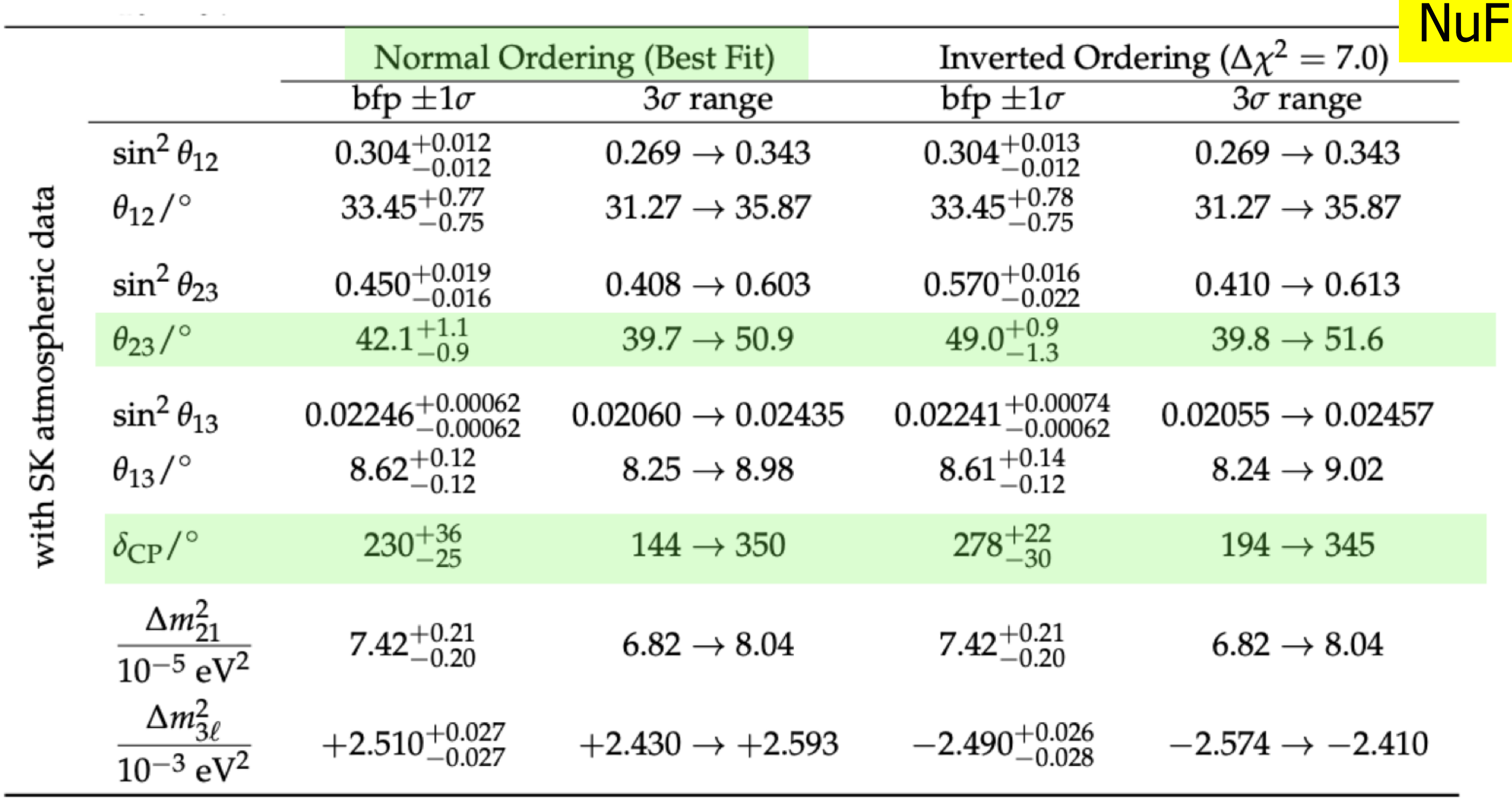
~2 x 10^{-3} eV^2

Recent Global Neutrino Data Fits

Recent 3-neutrino global analysis

Gonzalez-Garcia, Maltoni, Schwetz (NuFIT),
2111.03086

NuFIT group



with SK atmospheric data

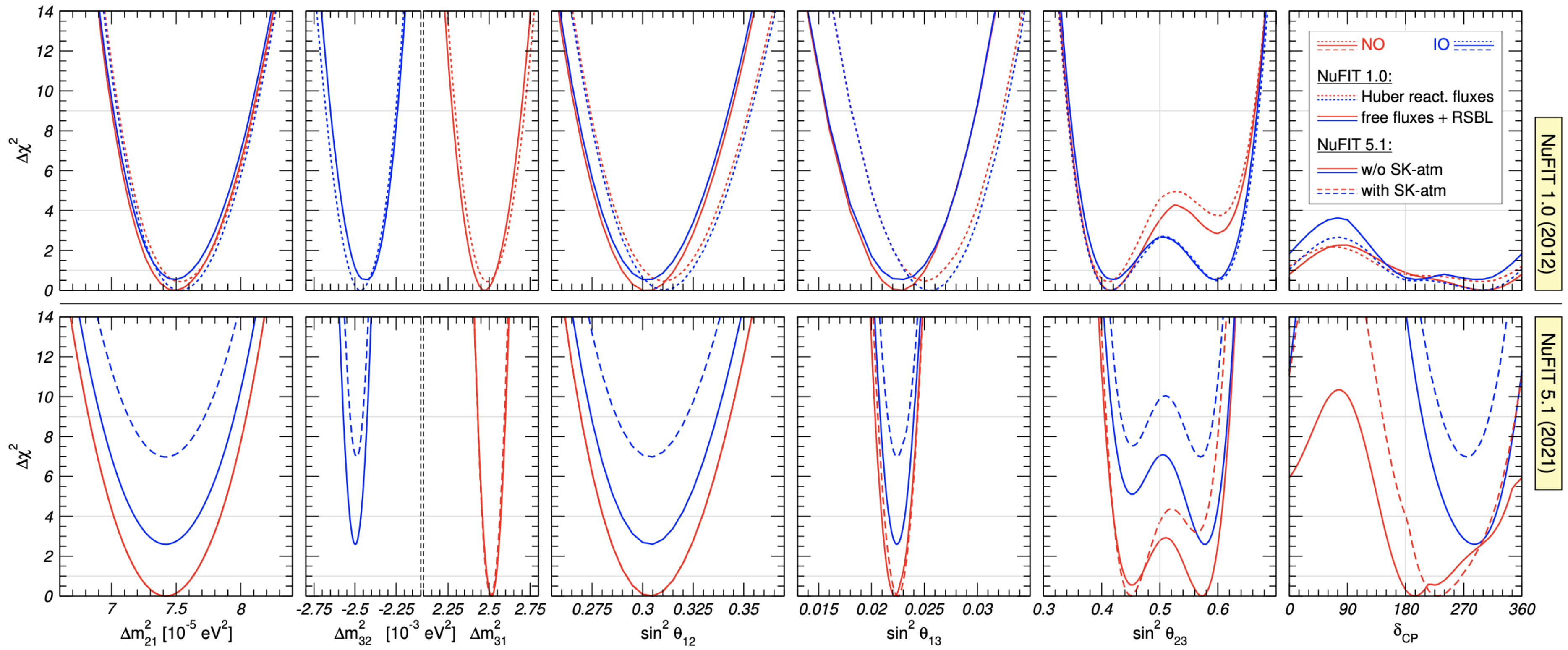
	Normal Ordering (Best Fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{\rm CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

- Hints for $\theta_{23} \neq \pi/4$
- Mild hints for a Dirac CP phase **δ**
- Mild hint in favor of Normal Ordering

Recent Global Neutrino Data Fits

Recent 3-neutrino global analysis

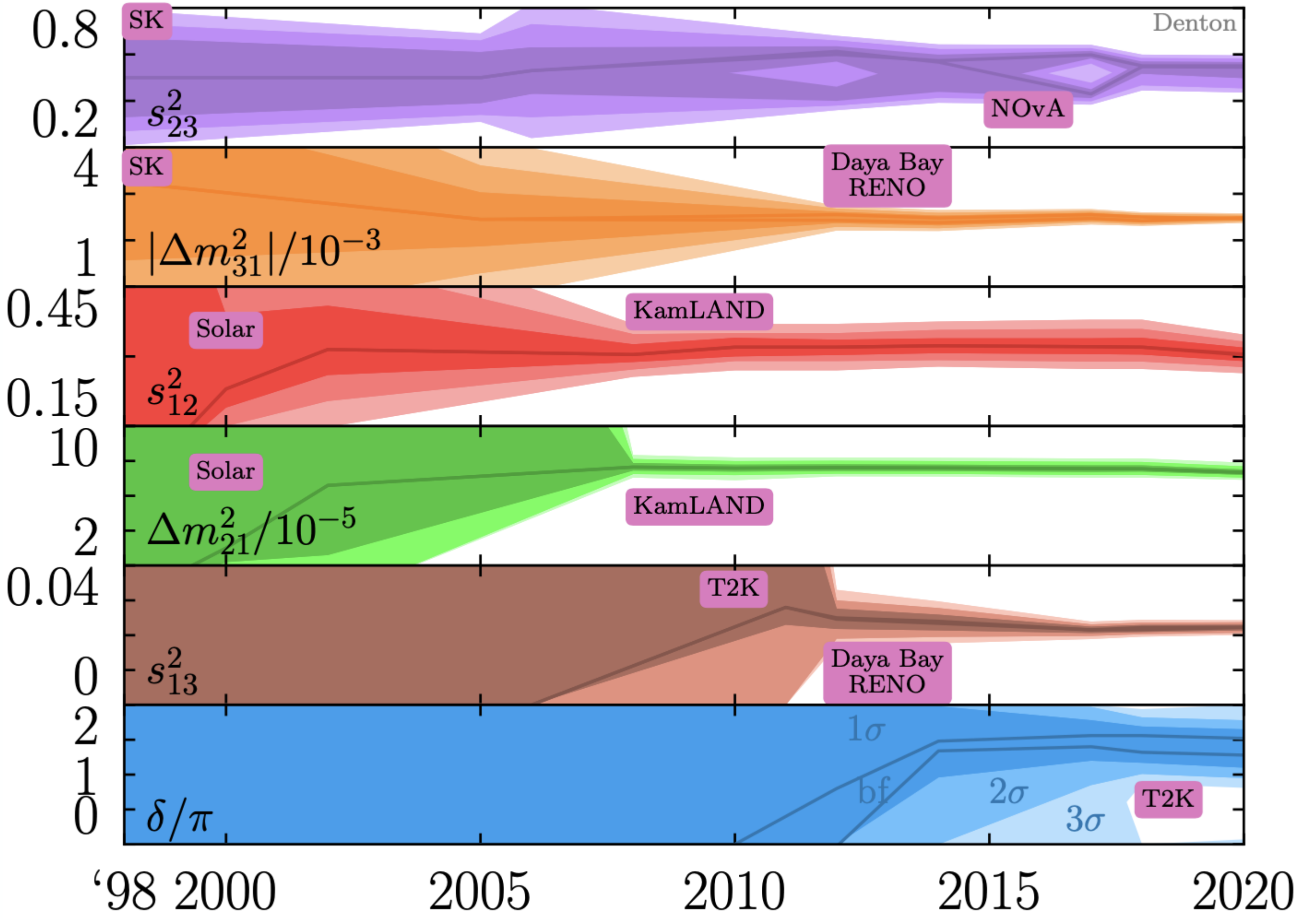
NuFIT group



Details on the **$\Delta\chi^2$**

Neutrino Parameter Evolution

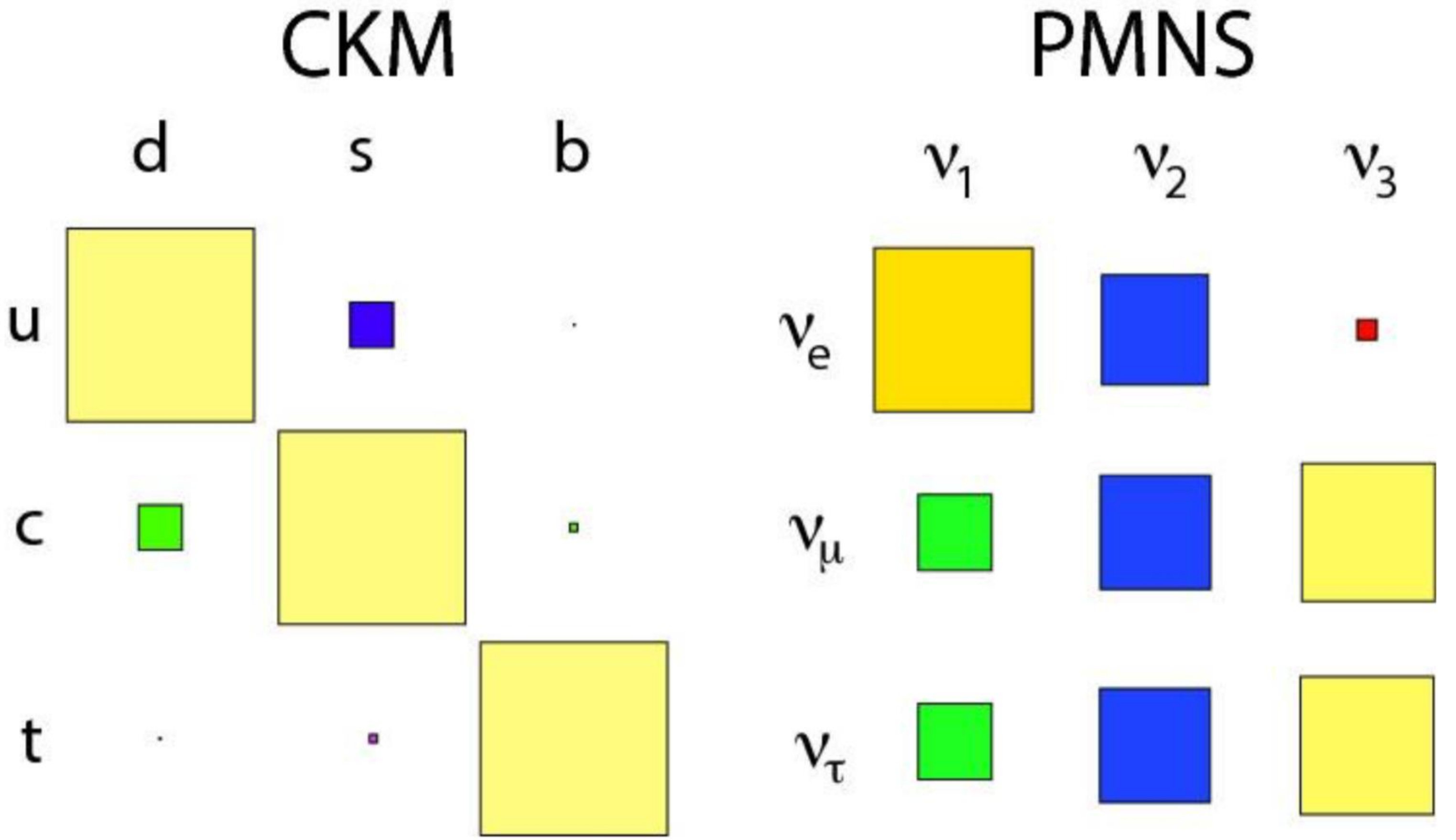
Towards precision physics



The past 20 years have seen a remarkable progress in determining neutrino properties!

CMK vs PMNS

Why is neutrino mixing so different from quark mixing?
What does that tell us?

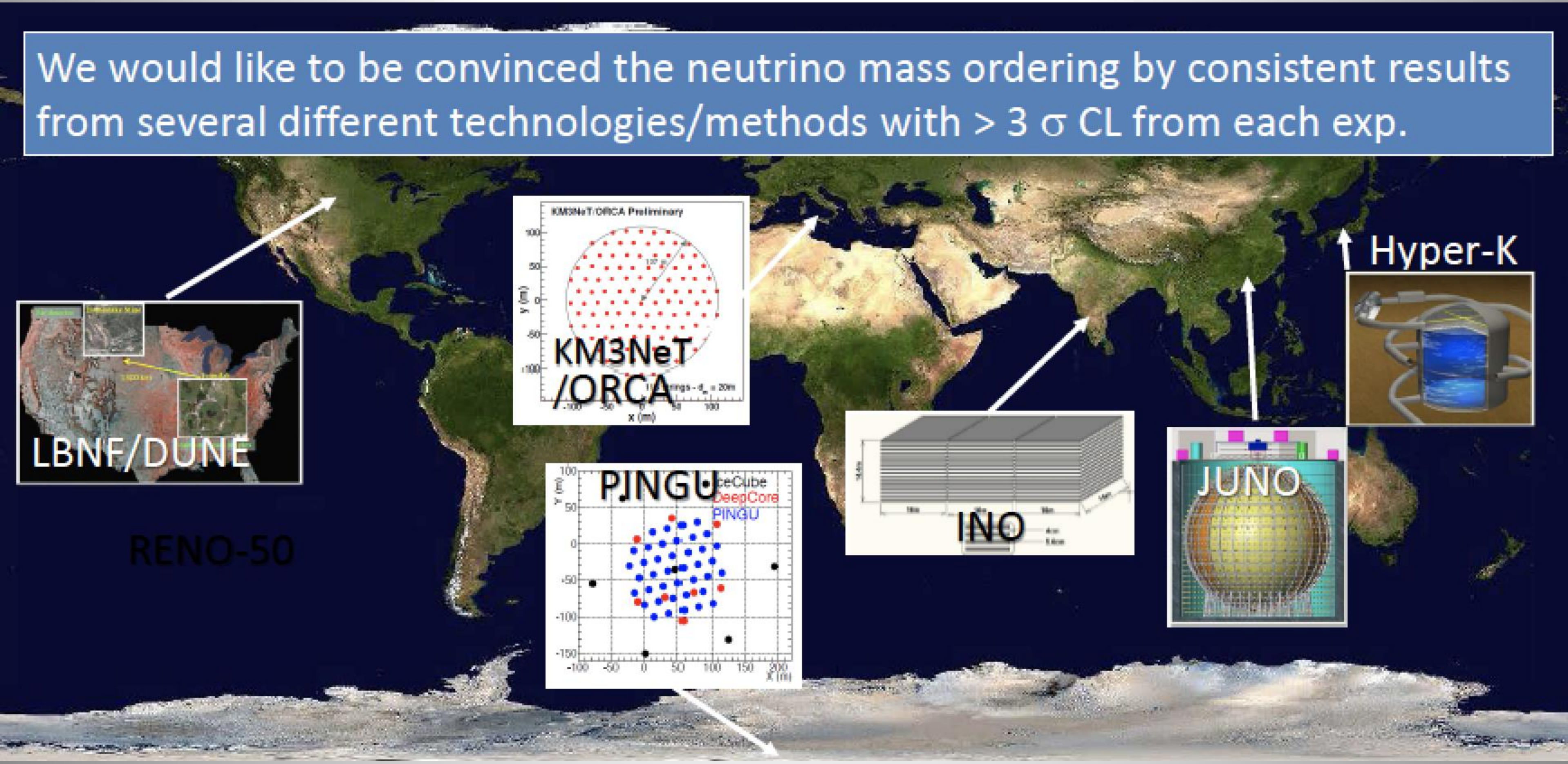


The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.

Future Neutrino Experiments

Eg. experiments that will contribute to the mass ordering question

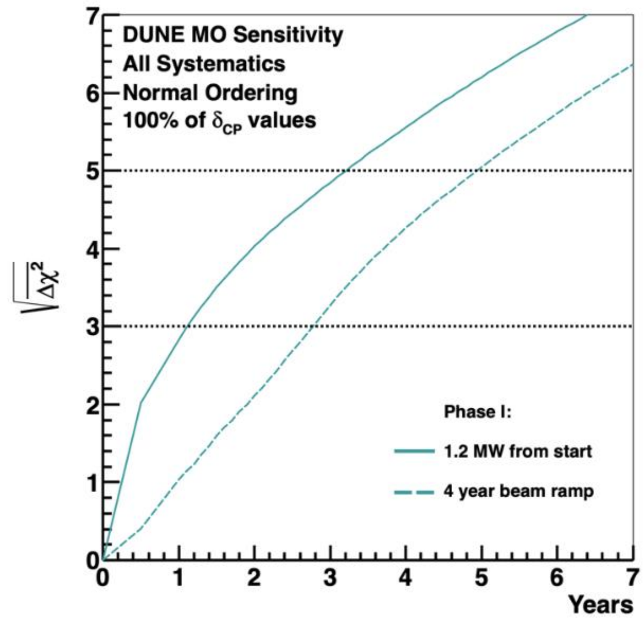
We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.

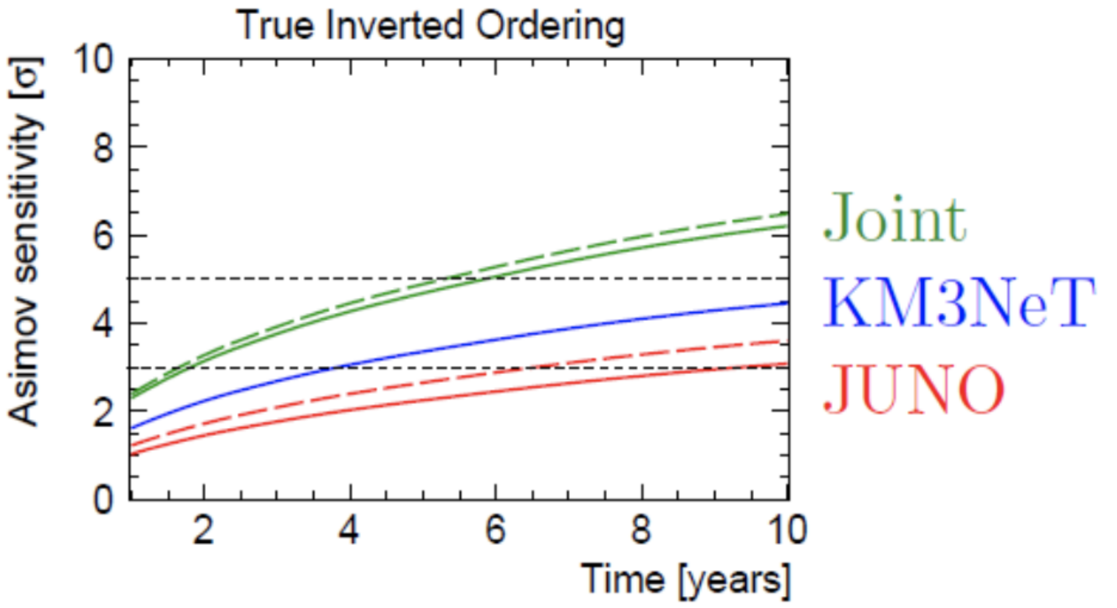


Mass Hierarchy

- No concrete evidence of MO from individual experiment (T2K, Nova and SuperK)
- Global fit seems slightly prefer NO(<3σ)
- Definite answer will come from DUNE, JUNO, HyperK, ORCA and Icecube.

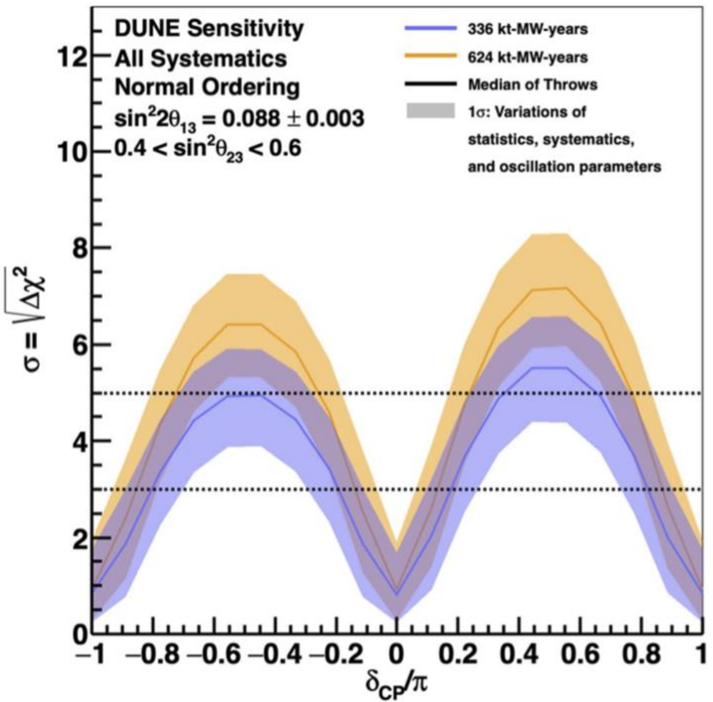
DUNE

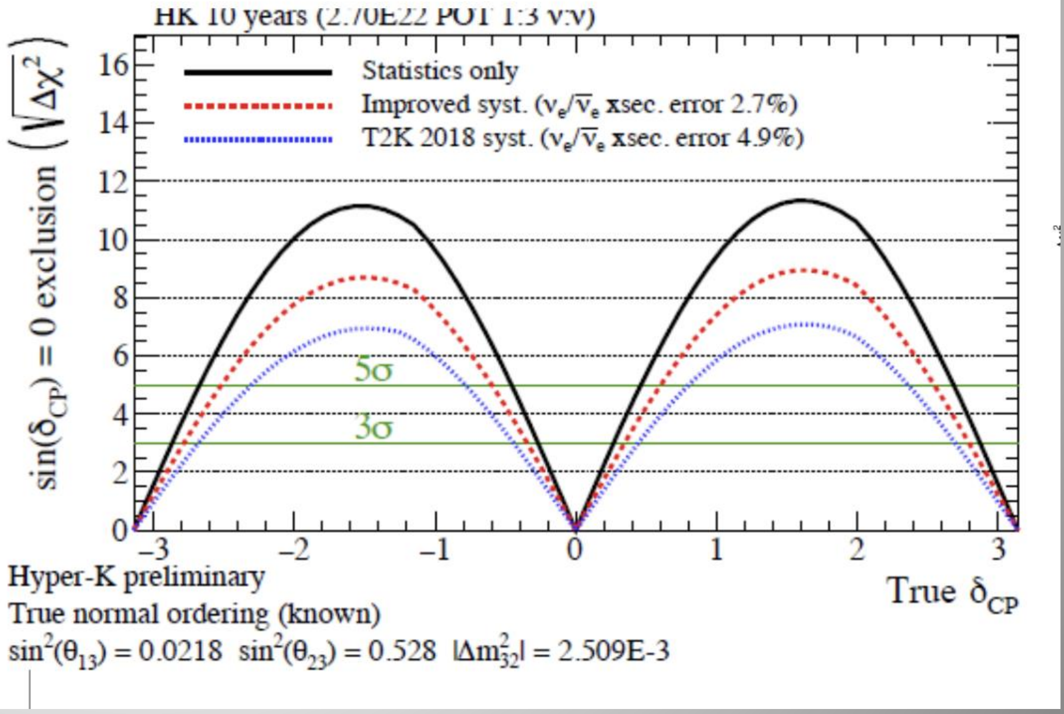




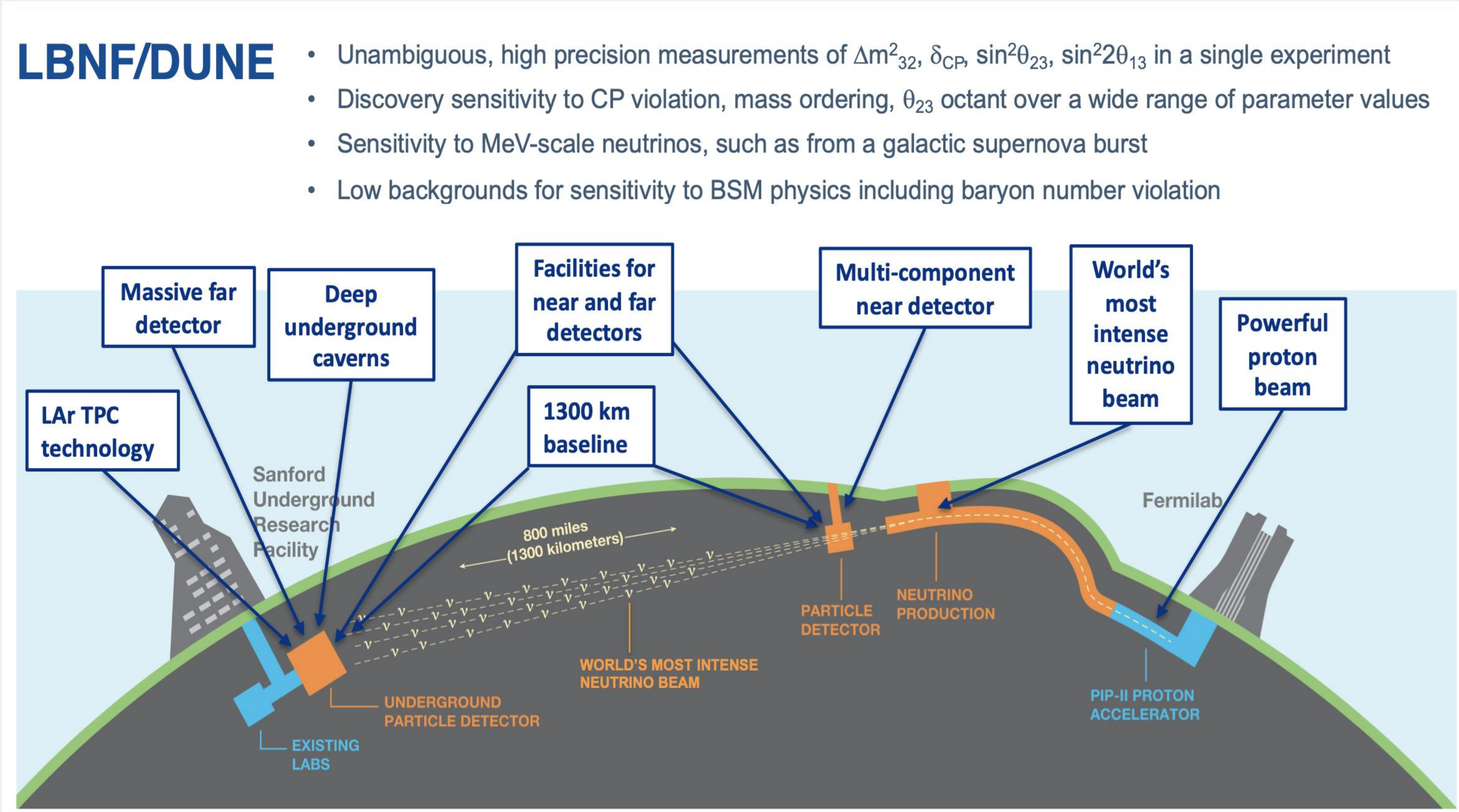
CP Phase

- ~270º (-90º) seems slightly favored
- Combined analysis may give more preference, but not stable yet
- DUNE & HyperK can give a more definite answer
- Further improvement may come from KNO, ESSnuSB, and THEIA





LNBF/DUNE



LBNF/DUNE

- Unambiguous, high precision measurements of Δm^2_{32}, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ in a single experiment
- Discovery sensitivity to CP violation, mass ordering, θ_{23} octant over a wide range of parameter values
- Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst
- Low backgrounds for sensitivity to BSM physics including baryon number violation

Massive far detector

Deep underground caverns

Facilities for near and far detectors

Multi-component near detector

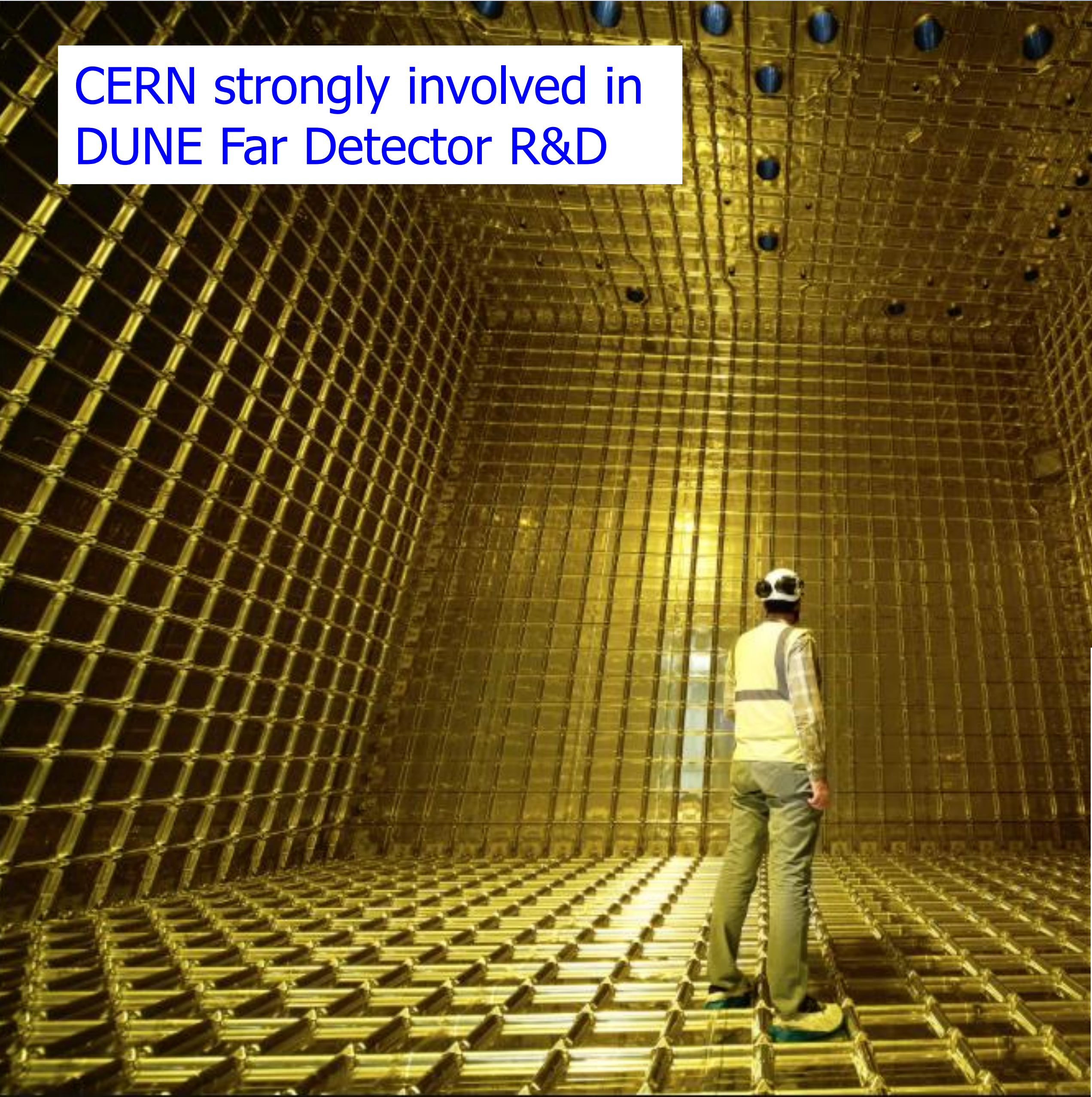
World's most intense neutrino beam

Powerful proton beam

LAr TPC technology

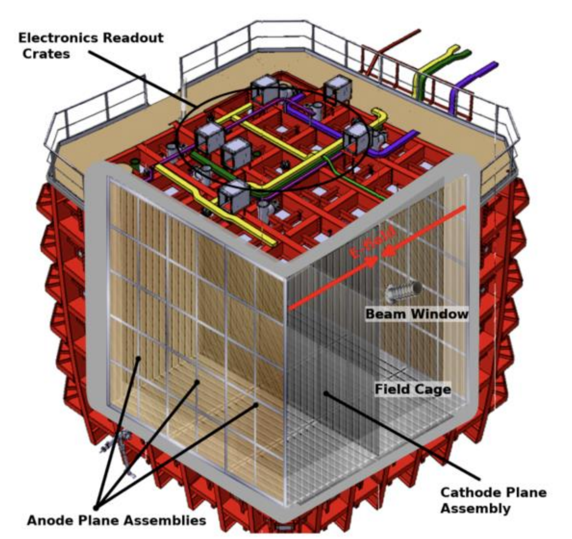
1300 km baseline

The CERN Neutrino Platform

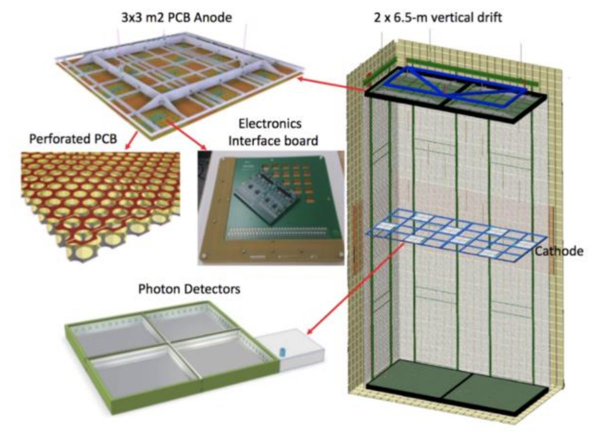


CERN strongly involved in DUNE Far Detector R&D

FD1 Horizontal Drift

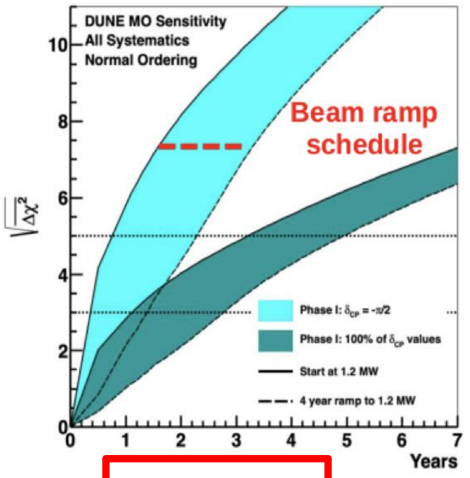


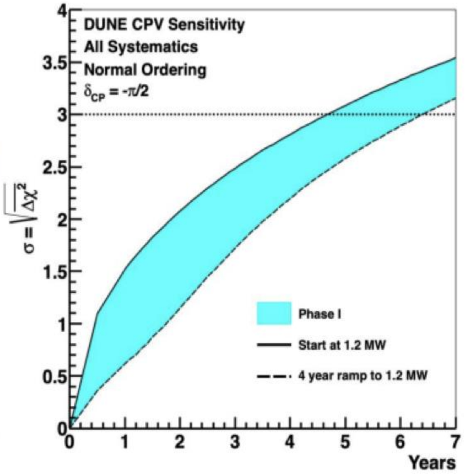
FD2 vertical Drift (NEW)



CRPs

DUNE staging





Phase I:

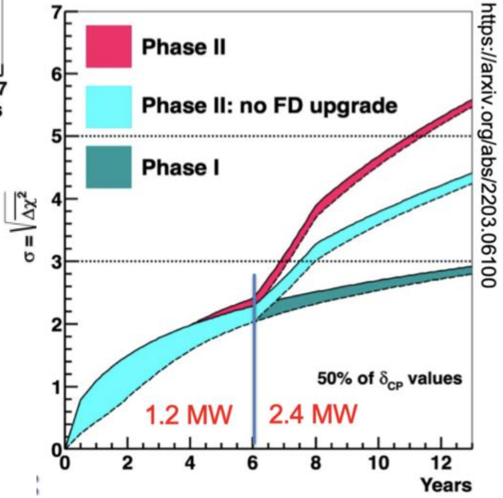
Construction ends around ~2030

- ✔ Unambiguous MO
- ✔ 3σ CPV at maximal δ_{CP}

Phase II:

- ✔ P5 goal of 5σ CPV for 50% of δ_{CP}
- ✔ Precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}

Requires 2.4 MW, 40 kt and full ND

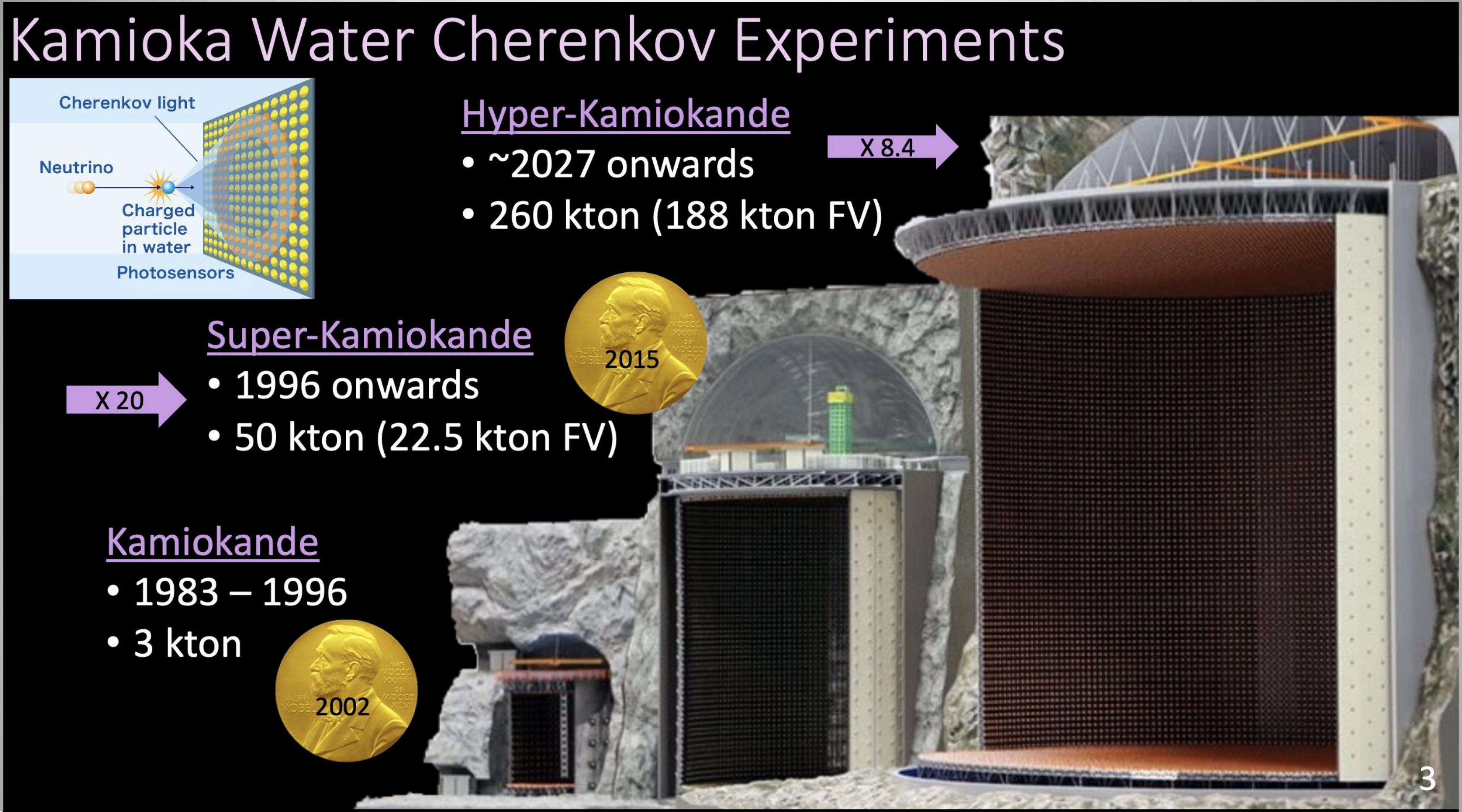


Construction should start around ~2030:

FD mass
ND upgrade
Beam upgrade

Figures from SNOWMASS neutrino colloquium by C. Wilkinson

The Hyper-K/T2HK Experiment



Kamioka Water Cherenkov Experiments

Hyper-Kamiokande
- ~2027 onwards
- 260 kton (188 kton FV)

Super-Kamiokande
- 1996 onwards
- 50 kton (22.5 kton FV)

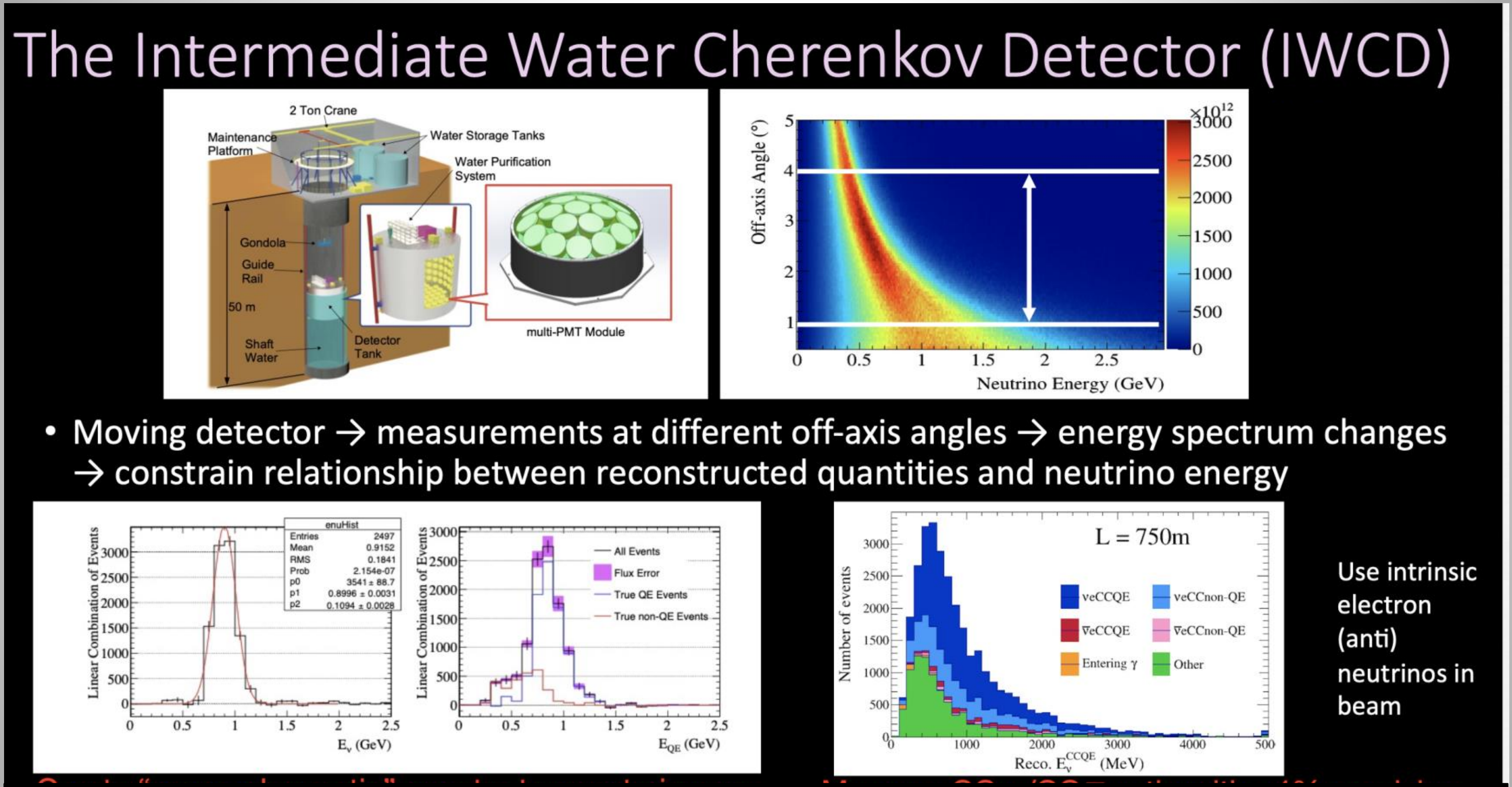
Kamiokande
- 1983 – 1996
- 3 kton

- Hyper-Kamiokande is the next generation neutrino experiment in Japan
  - 260 kton Underground water Cherenkov far detector
  - 1.3 MW upgraded neutrino beam from JPARC
  - Upgraded and additional near detectors

+a detector in Korea?

The Hyper-K/T2HK Experiment

Use the upgraded neutrino beam from JPARC



The Intermediate Water Cherenkov Detector (IWCD)

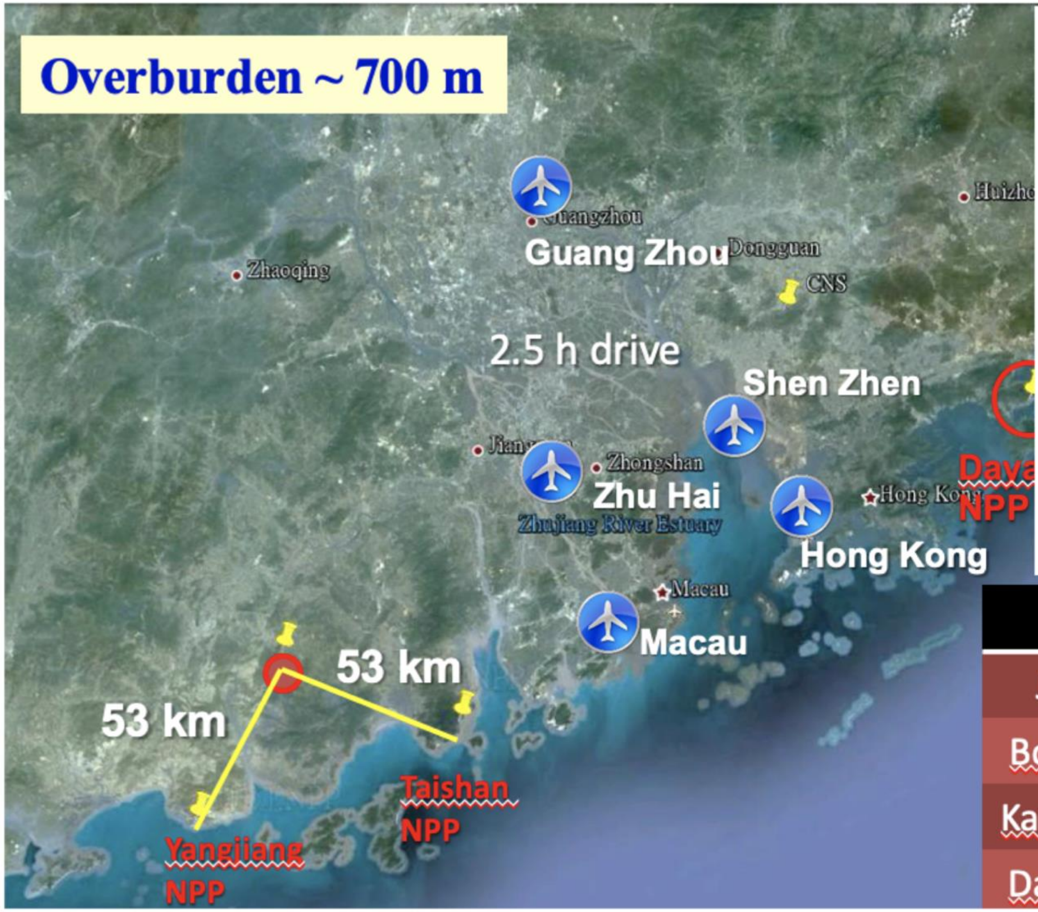
- Moving detector → measurements at different off-axis angles → energy spectrum changes → constrain relationship between reconstructed quantities and neutrino energy

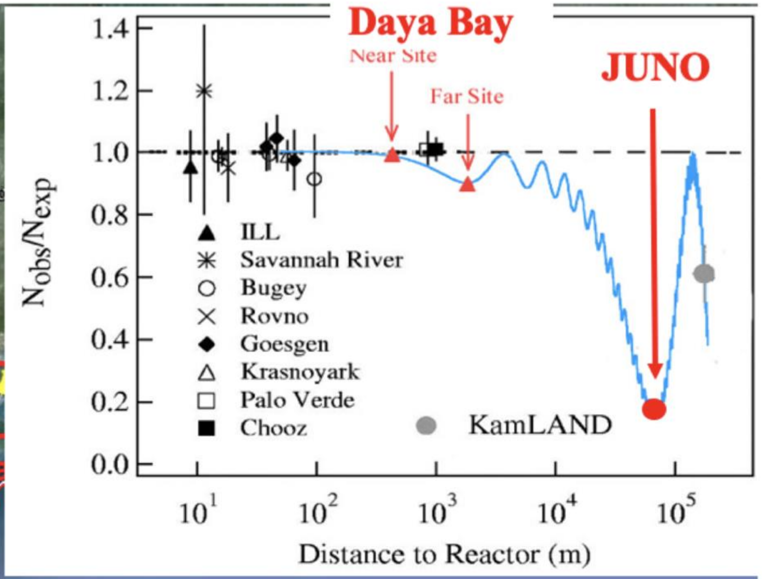
Use intrinsic electron (anti) neutrinos in beam

- Hyper-K aims to reveal the full picture of neutrino oscillations
  - CP violation, mass ordering, θ_{23} octant…
- Astrophysical observations
  - Supernova bursts, solar neutrinos, supernova relic neutrinos
- Search for proton decay improves on current limits by order of magnitude

The Juno Experiment

- A 20 kt liquid scintillator detector at ~53 km baseline from reactors for neutrino mass hierarchy, precision determination of oscillation parameters and astrophysics



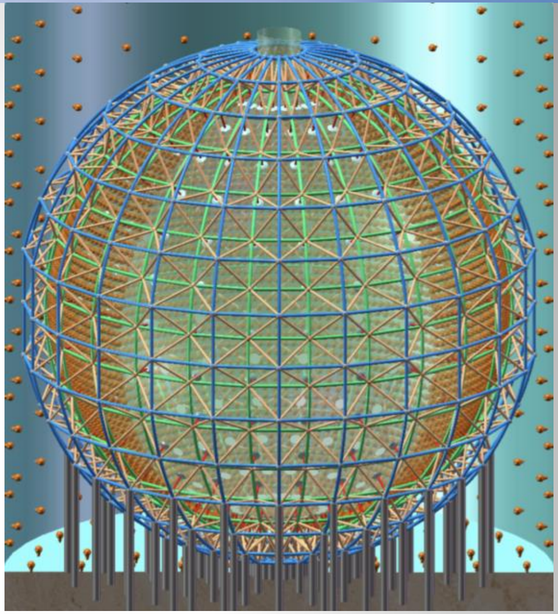


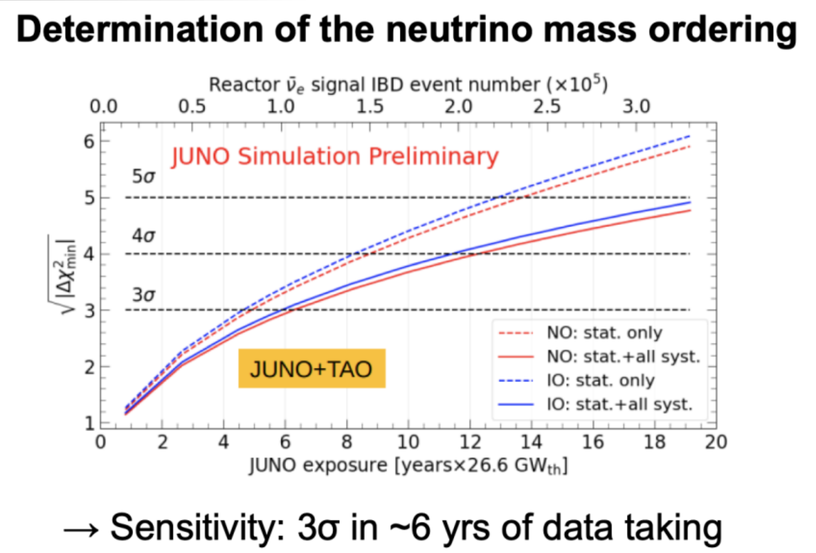
	Target mass [t]	energy resolution
JUNO	20,000	3% @ 1 MeV
Borexino	300	5% @ 1 MeV
KamLAND	1,000	6% @ 1 MeV
Daya Bay	20	8% @ 1 MeV

The JUNO Experiment

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton multi-purpose liquid scintillator detector (~20 times the size of present detectors, including 18000 20″ PMTs) expected to start data taking in 2023

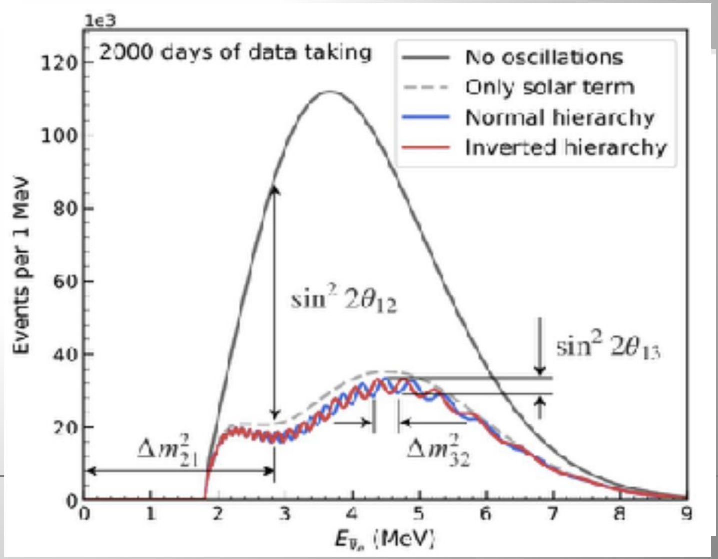
With an energy resolution of 3% at 1 MeV, JUNO determine the mass ordering with a significance of 3 sigma within six years



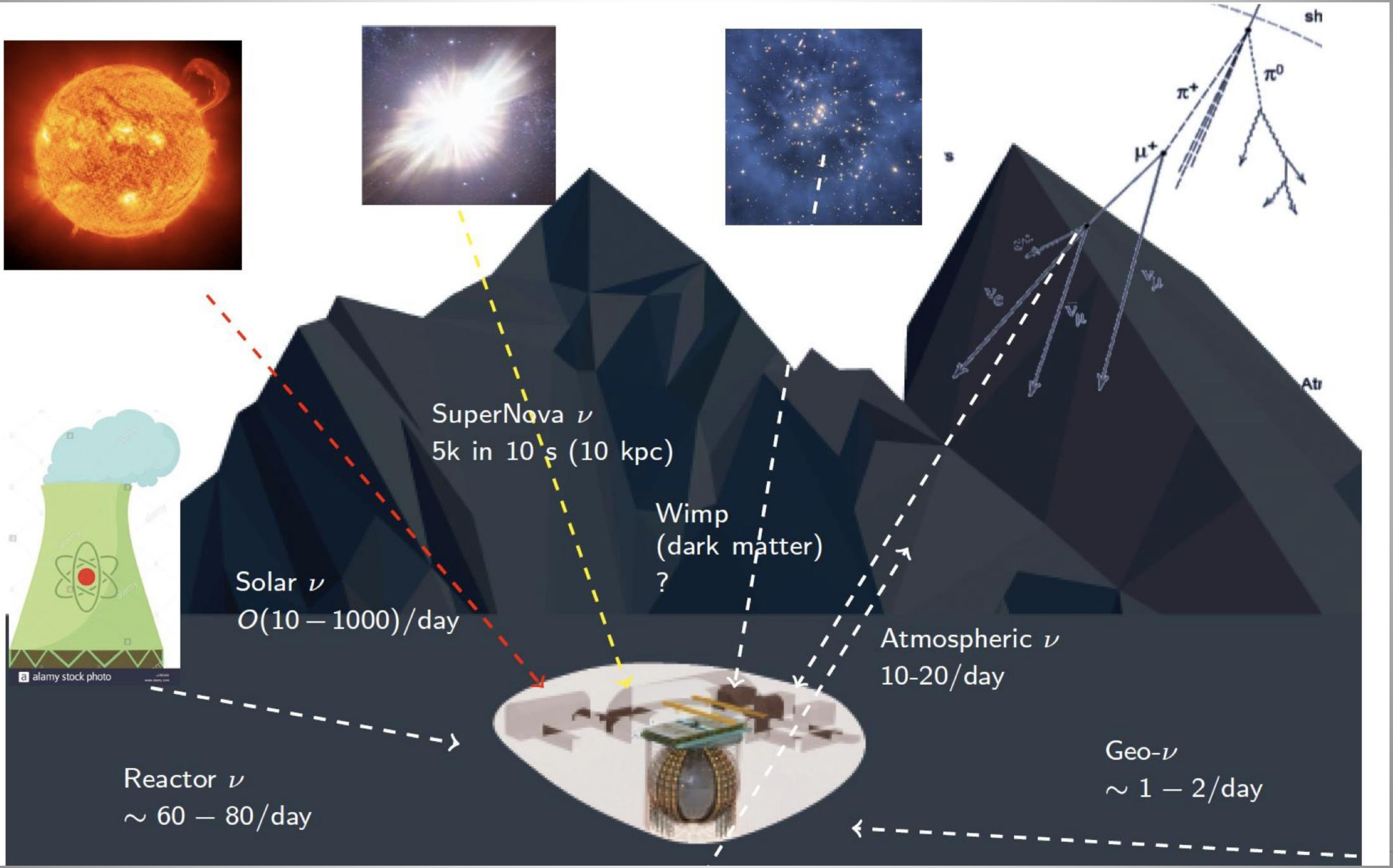


Determination of the neutrino mass ordering

→ Sensitivity: 3σ in ~6 yrs of data taking



The Juno Experiment



SuperNova ν
5k in 10 s (10 kpc)

Wimp
(dark matter)
?

Solar ν
$O(10-1000)$/day

Atmospheric ν
10-20/day

Reactor ν
$\sim 60-80$/day

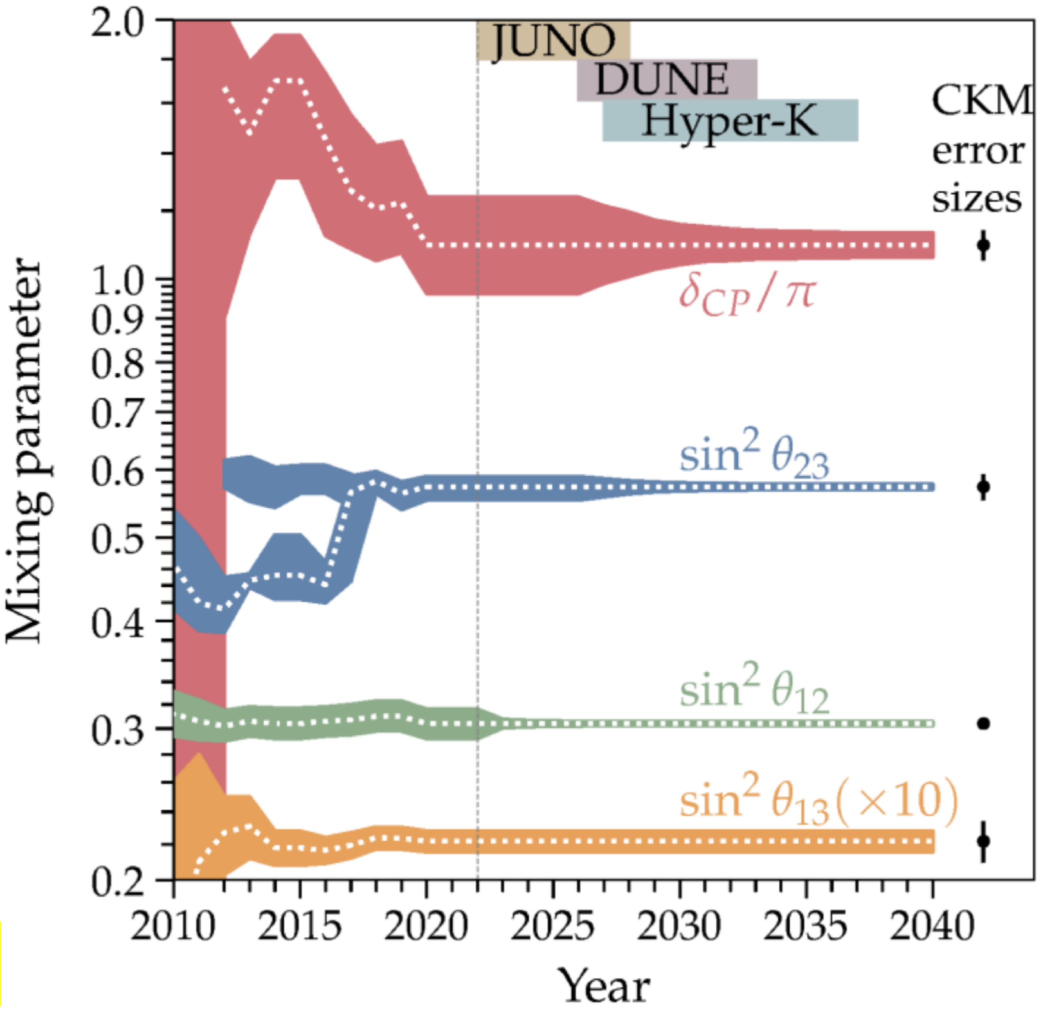
Geo-ν
$\sim 1-2$/day

Expectation for the Next Two Decades

Future: Significant Improvement Expected

- JUNO will determine most oscillation parameters to a sub-percent level
- T2K and Nova will improve $\sin^2\theta_{23}$ slightly
- ORCA, Icecube, DUNE and HyperK can improve $\sin^2\theta_{23}$ significantly:

  ~4%(PDG2020) ➔ ~1.8%(1 exp.)
- Combined analysis may reach ~ 1% for $\sin^2\theta_{23}$
- θ_{23} octant can be probed with a good sensitivity



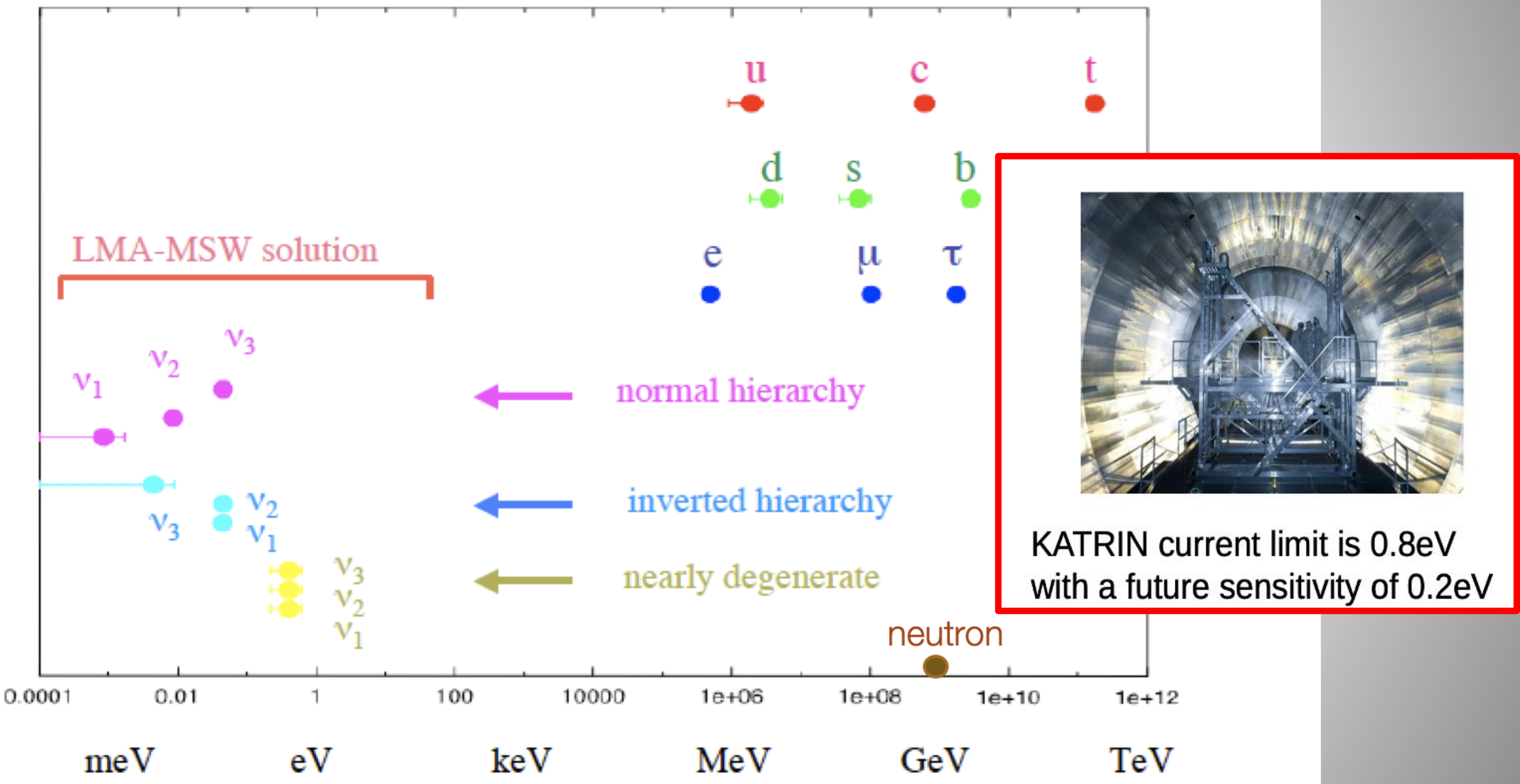
-> Precision at the percent level

Neutrino mass

Neutrino Mass

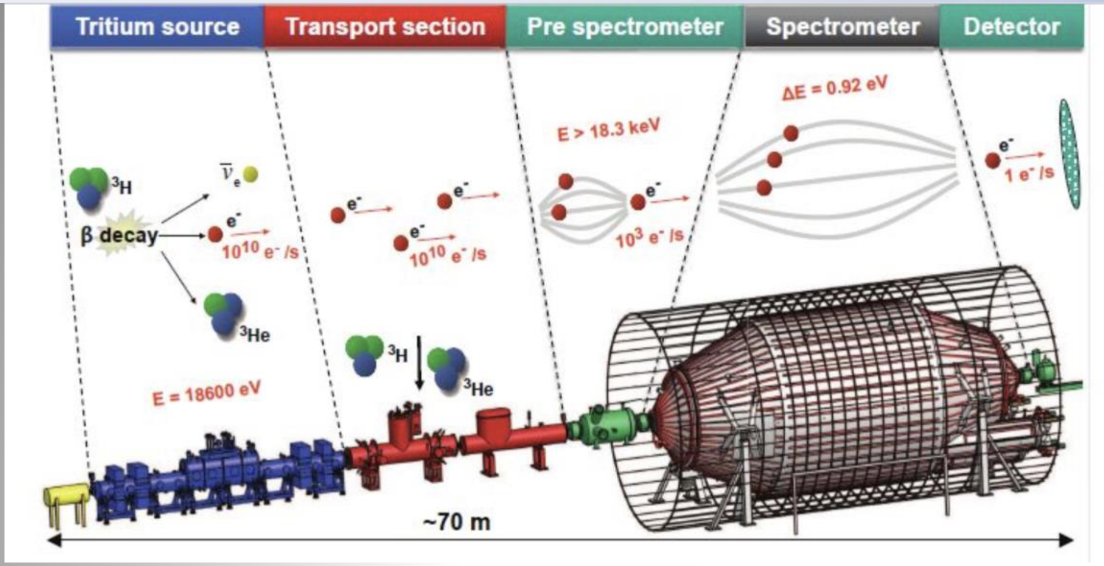
The smalness of the neutrino mass

$m_\nu \ll m_{e,\,u,\,d}$



KATRIN current limit is 0.8eV
with a future sensitivity of 0.2eV

KATRIN Experiment: the Mass of ν_e



The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to measure the mass up to projected sensitivity of 0.2eV
To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

Recent result $M\nu_e < 0.8$ eV (May 2021)

New Future Projects

β decays: New Projects

- ECHO & HOLMS: calorimetric sensors coupled to ^{163}Ho implanted sources
  - Obtained neutrino mass limit: ~ 150 eV
  - Promise: ~ 1eV

Usable to ~0.1 eV?

- Project 8: Cyclotron Radiation Emission Spectroscopy(CRES)
  - Phase I: prove of principle
  - Phase II successful
    - Uncertainties understood
    - m_β < 178 eV @90% C.L.
  - Phase III:
    - Atomic T system & Larger cavity
    - Goal in 5 years: m_β < 0.4 eV
  - Phase IV: 5 years ?
    - Goal: m_β < 0.04 eV

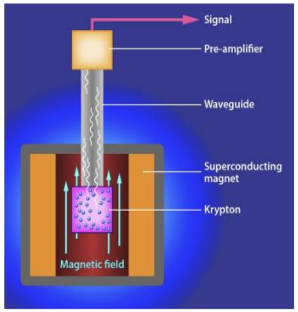
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

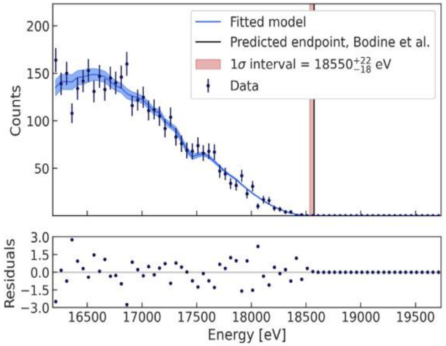
$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

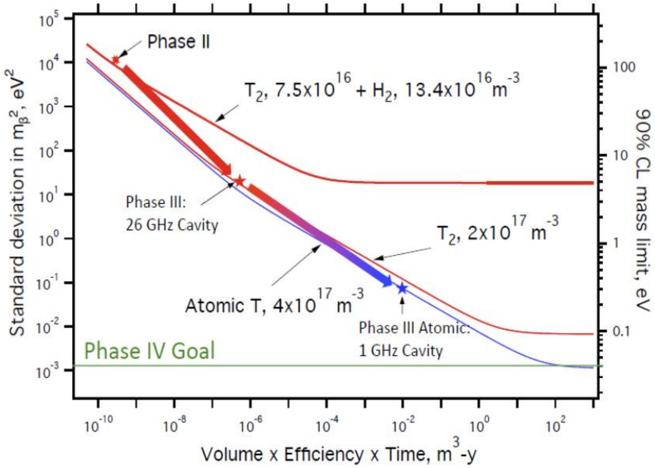
- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = (2.833 ± 0.030^{stat} ± 0.015^{syst}) keV

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

1 mm³







Neutrinoless Double Beta Decay

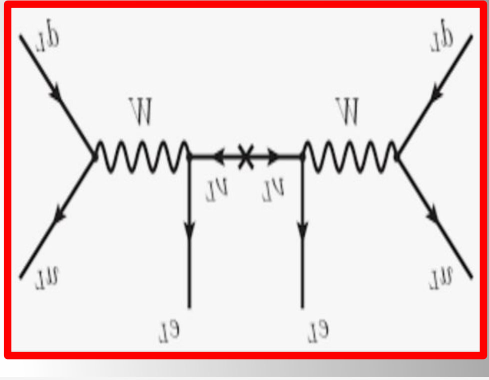
GERDA (GERmanium Detector Array) experimemt at LNGS (Gran Sasso/IT)

Final results: arXiv:2009.06079

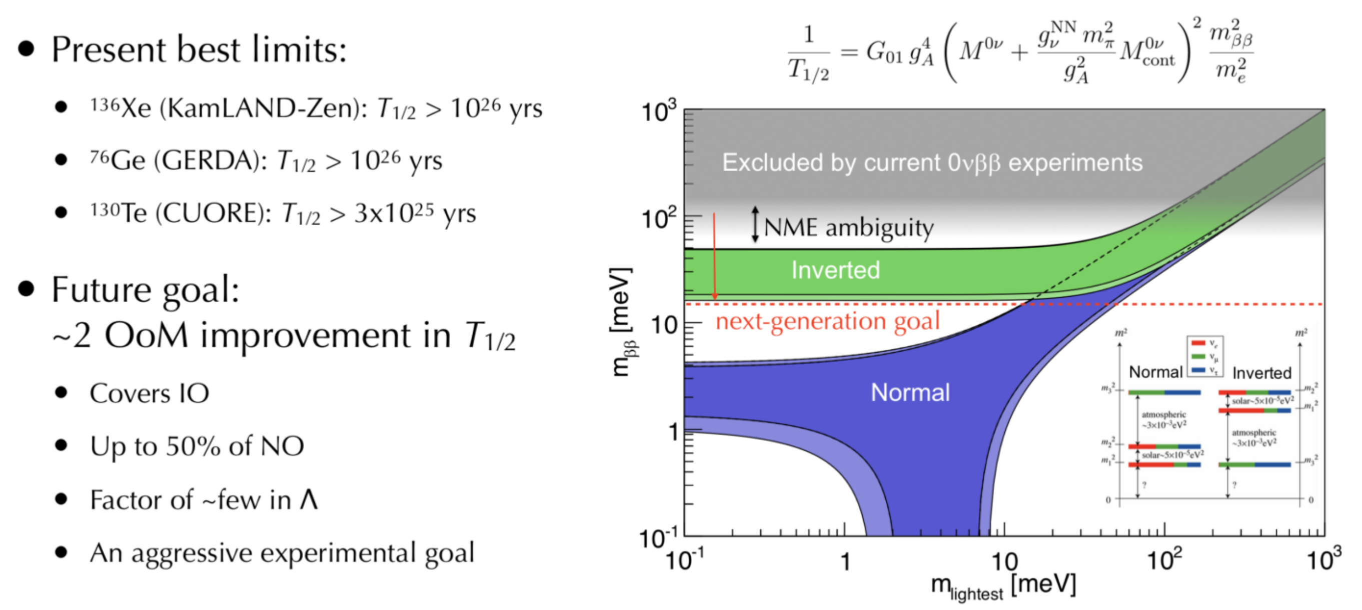
127.2 kg.year exposure between 2011-2019

Experiment now completed

No $0\nu\beta\beta$ signal observed ☹



upper mass limit: $m_{\beta\beta} < 79 - 180$ **meV**



- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3\text{x}10^{25}$ yrs
- Future goal:
  ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal

$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{\mathrm{NN}}\, m_\pi^2}{g_A^2} M^{0\nu}_{\mathrm{cont}} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

Neutrinoless Double Beta Decay

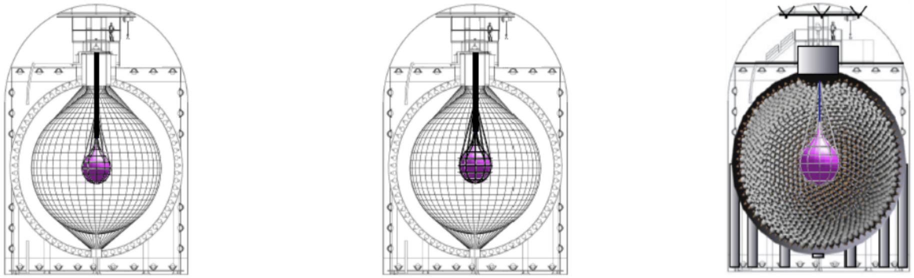
ββ decays: KamLAND-Zen

- Load 3% ^{136}Xe(91% enriched) into LS
- Fill LS into a balloon at the center of KamLAND
- Improvement of KamLAND-Zen 800 over KamLAND-Zen 400:
  - ^{136}Xe amount doubled
  - Balloon produced in class-1 cleanroom: 10 times less ^{232}Th background
  - New rejection method for C & Xe spallation products
- Reached the IO region for the first time

$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \text{yr at } 90\%\ \text{C.L.}$$

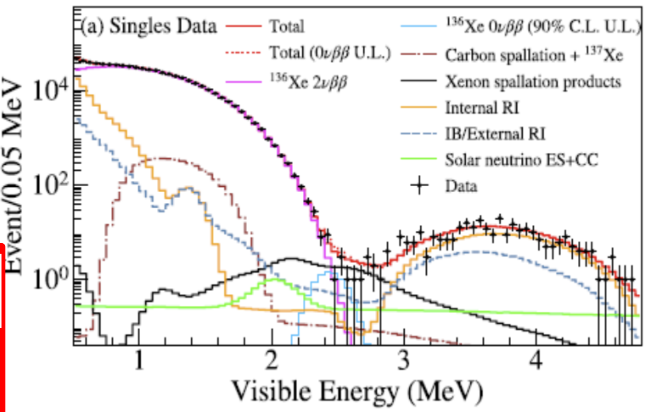
$$m_{\beta\beta} < 36 - 156\ \text{meV}$$

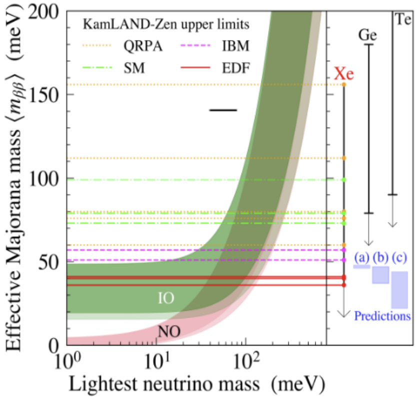
Past	Present	Future
KamLAND-Zen 400	**KamLAND-Zen 800**	**KamLAND2-Zen**
320-380 kg of Xenon	~750 kg of Xenon	~1 ton of ^{136}Xe
Data taking in 2011 - 2015	DAQ started in 2019	Better energy resolution



Reanalysis $\xrightarrow{\text{combined}}$ **1st result** arXiv:2203.02139v1 [hep-ex]

& Long paper in preparation

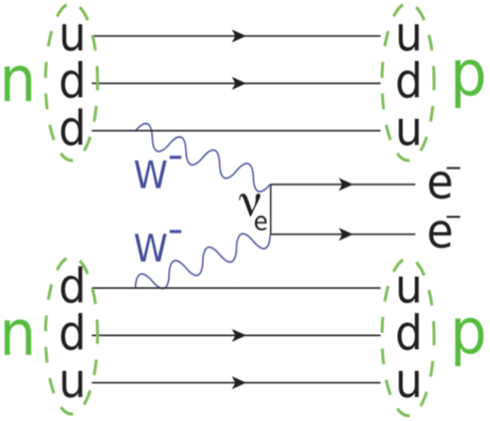


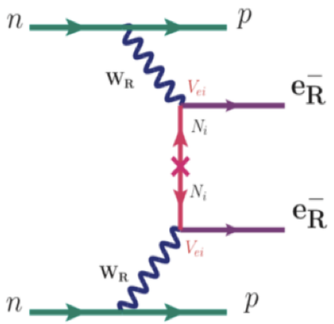


Neutrinoless Double Beta Decay

The question is still unanswered:

Are neutrinos their own antiparticles?

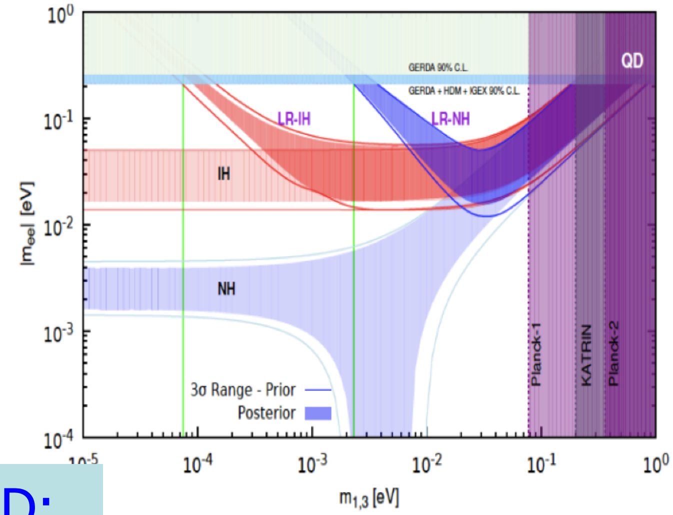




Left-Right Symmetric Model, $M_{W_R} \sim 2$ TeV, $M_N = 1$ TeV, $g_R \sim 2/3\, g_L$

JHEP 10 (2015) 077

Ton scale 0nuBB experiments will cover the inverted hierarchy by 2035



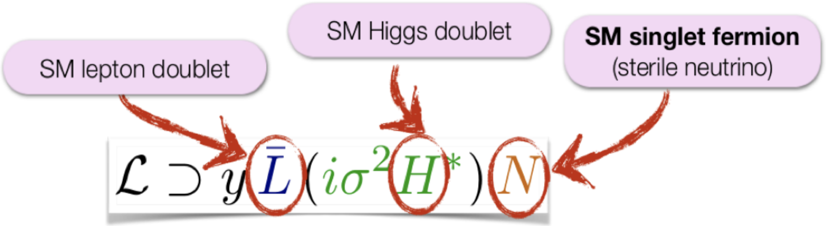
Many experiments operating, planned or in R&D: LEGEND, SNO+, NEXT, CUPID, THEIA…

New Physics Searches

Neutrinos and BSM

Discovering new things

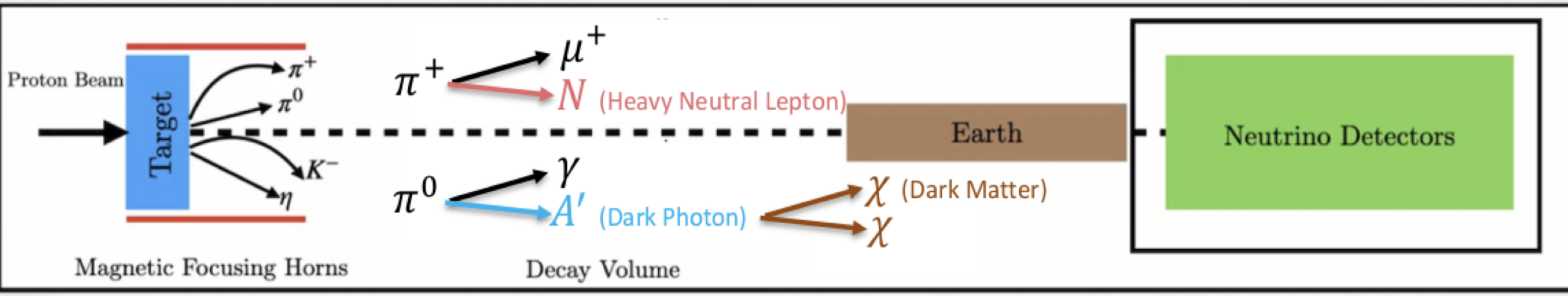
- New neutrinos or new neutrino interactions



$$\mathcal{L} \supset y \bar{L} (i\sigma^2 H^*) N$$

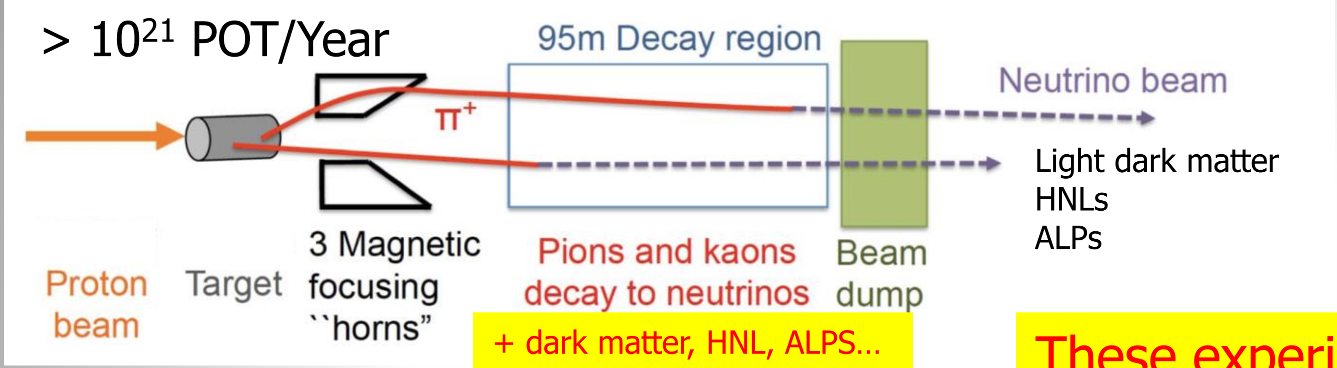
- New light states not related to neutrinos

Figures from SNOWMASS neutrino colloquia by J. Kopp and Z. Tabrizi



Neutrino Detectors as Beam Dump Experiments

High intensity frontier for low mass particles with very weak couplings
->upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams

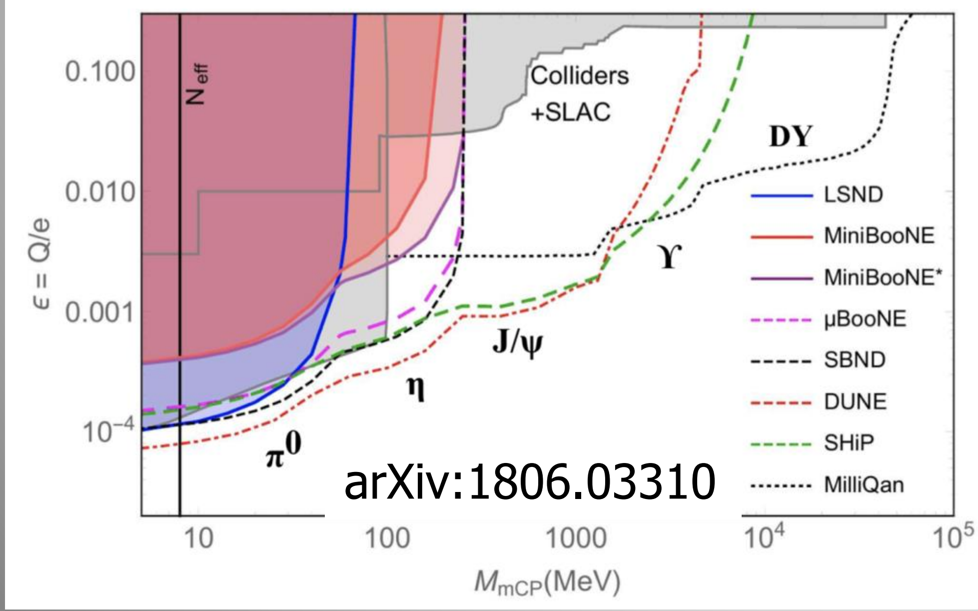


> 10^{21} POT/Year

+ dark matter, HNL, ALPS…

SBL or LBL Near Detectors are a few 100m away from the dump

Example millicharges:



arXiv:1806.03310

These experiments can perform searches for low mass New Physics particles eg

-HNL/sterile neutrinos

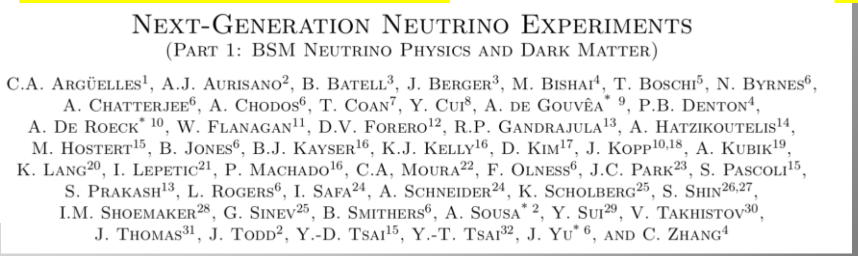
-dark photons/light dark matter

-Axion-Like particles

-mini/millicharges

…

arXiv:1907.08311

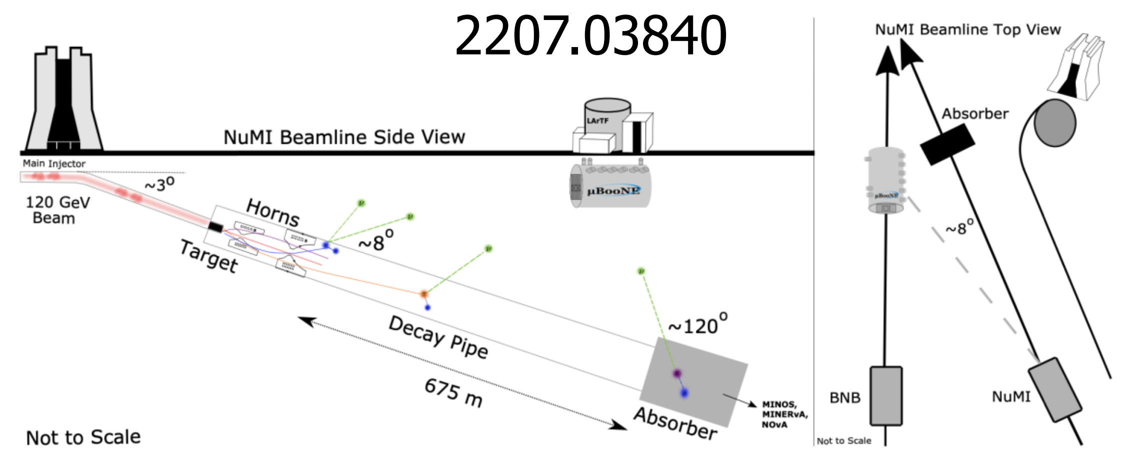


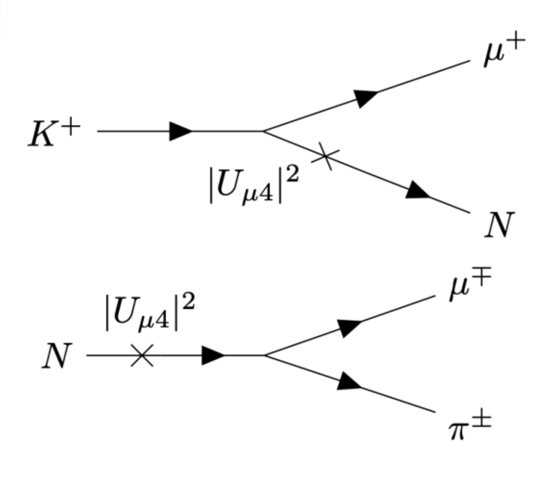
NEXT-GENERATION NEUTRINO EXPERIMENTS
(PART 1: BSM NEUTRINO PHYSICS AND DARK MATTER)

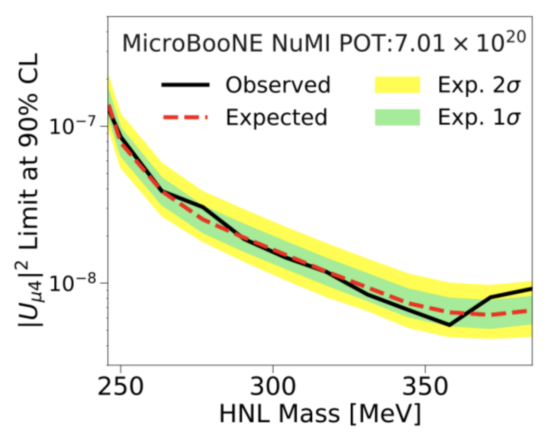
C.A. ARGÜELLES[1], A.J. AURISANO[2], B. BATELL[3], J. BERGER[3], M. BISHAI[4], T. BOSCHI[5], N. BYRNES[6], A. CHATTERJEE[6], A. CHODOS[6], T. COAN[7], Y. CUI[8], A. DE GOUVÊA[* 9], P.B. DENTON[4], A. DE ROECK[* 10], W. FLANAGAN[11], D.V. FORERO[12], R.P. GANDRAJULA[13], A. HATZIKOUTELIS[14], M. HOSTERT[15], B. JONES[6], B.J. KAYSER[16], K.J. KELLY[16], D. KIM[17], J. KOPP[10,18], A. KUBIK[19], K. LANG[20], I. LEPETIC[21], P. MACHADO[16], C.A, MOURA[22], F. OLNESS[6], J.C. PARK[23], S. PASCOLI[15], S. PRAKASH[13], L. ROGERS[6], I. SAFA[24], A. SCHNEIDER[24], K. SCHOLBERG[25], S. SHIN[26,27], I.M. SHOEMAKER[28], G. SINEV[25], B. SMITHERS[6], A. SOUSA[* 2], Y. SUI[29], V. TAKHISTOV[30], J. THOMAS[31], J. TODD[2], Y.-D. TSAI[15], Y.-T. TSAI[32], J. YU[* 6], AND C. ZHANG[4]

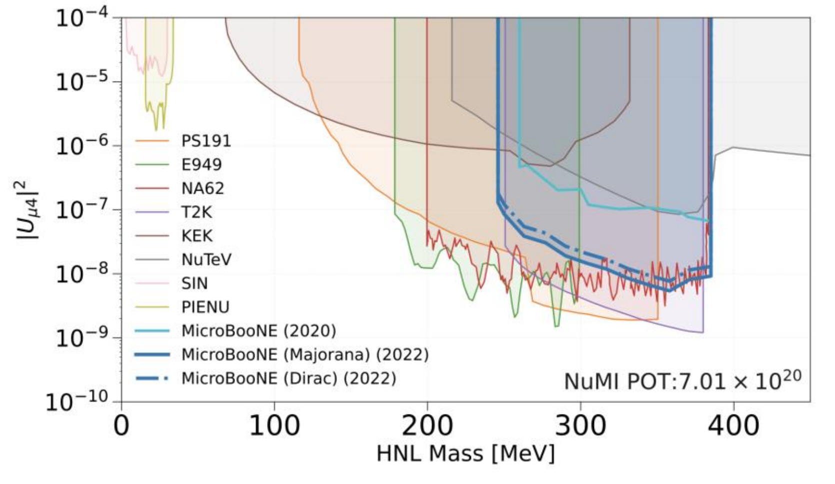
MicroBooNE HNL Search

Using KDARs: Kaons Decays At Rest from the NUMI beam asorber









These limits on $|U_{\mu4}|^2$ represent an order of magnitude improvement in sensitivity compared to the previous MicroBooNE result.

Anomalies

search for sterile neutrino

with $\Delta m^2 \sim 1\ \mathrm{eV}^2$

Sterile Neutrinos

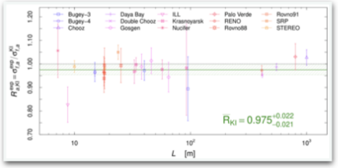
Several anomalies around in the community since some years…
Additional sterile neutrinos as a possible candidate explanation

- ☑ Very generic extension of SM
  - ○ can be leftover of extended gauge multiplet
- ☑ Useful phenomenological tool
  - ○ can explain ν masses (seesaw mechanism, m ~ TeV…M_{Pl})
  - ○ can explain cosmic baryon asymmetry (leptogenesis, m»100 GeV)
  - ○ can explain dark matter (m ~ keV)
  - ○ can explain oscillation anomalies (m ~ eV)
    Promote mixing matrix to 4 x 4, oscillation formula unchanged:

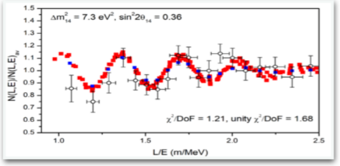
$$P_{\alpha\to\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i(E_j - E_k)T\right]$$

J. Kopp, Neutrino 2022

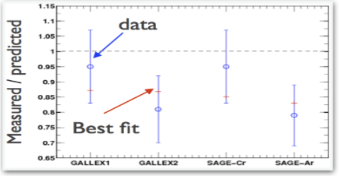
Anomalies



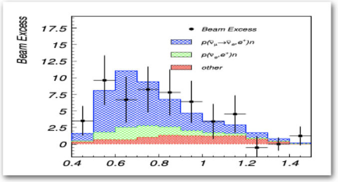
reactor flux anomaly
resolved with new input data
to flux calculation



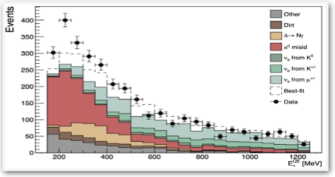
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



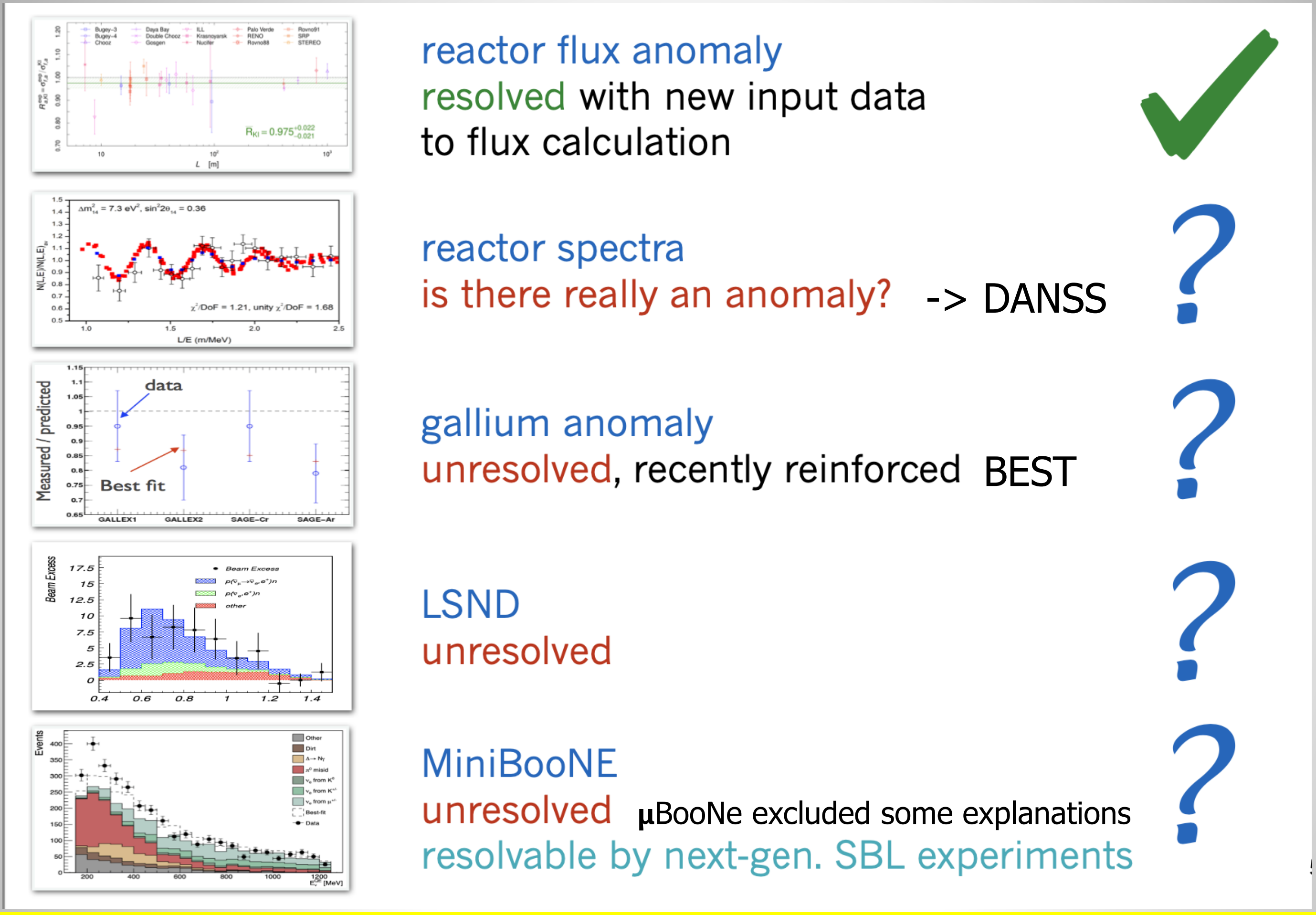
LSND
unresolved



MiniBooNE
unresolved
resolvable by next-gen. SBL experiments

- Most anomalies at ~3-4 σ level
- Simplest 3+1 model seems in tension to cover all anomalies
  - Some anomalies seems real, but maybe not related to sterile neutrinos

Neutrino Anomalies



reactor flux anomaly
resolved with new input data
to flux calculation ✓

reactor spectra
is there really an anomaly? -> DANSS ?

gallium anomaly
unresolved, recently reinforced BEST ?

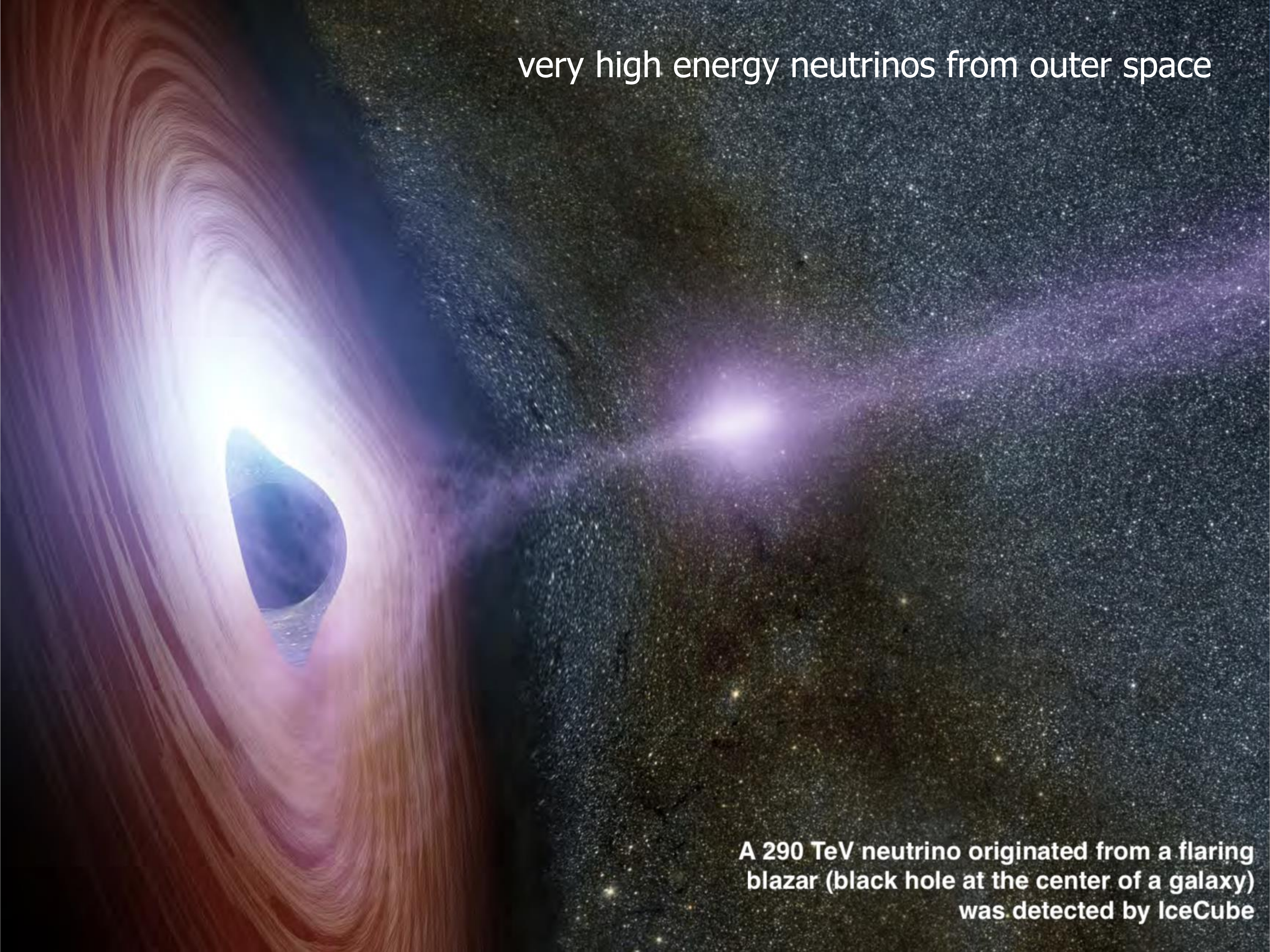
LSND
unresolved ?

MiniBooNE
unresolved µBooNe excluded some explanations ?
resolvable by next-gen. SBL experiments

More details in the backup

- Jury still out on many of these anaomalies. No clear picture emerging yet.
- Simple sterile neutrino would not fit all the data. Tensions on all sides…
- Future: Reactor experiments continuing or new ones (eg JSNS^2) or
  new experiments at the FNAL short neutrino baseline… (ICARUS, SBND)

very high energy neutrinos from outer space

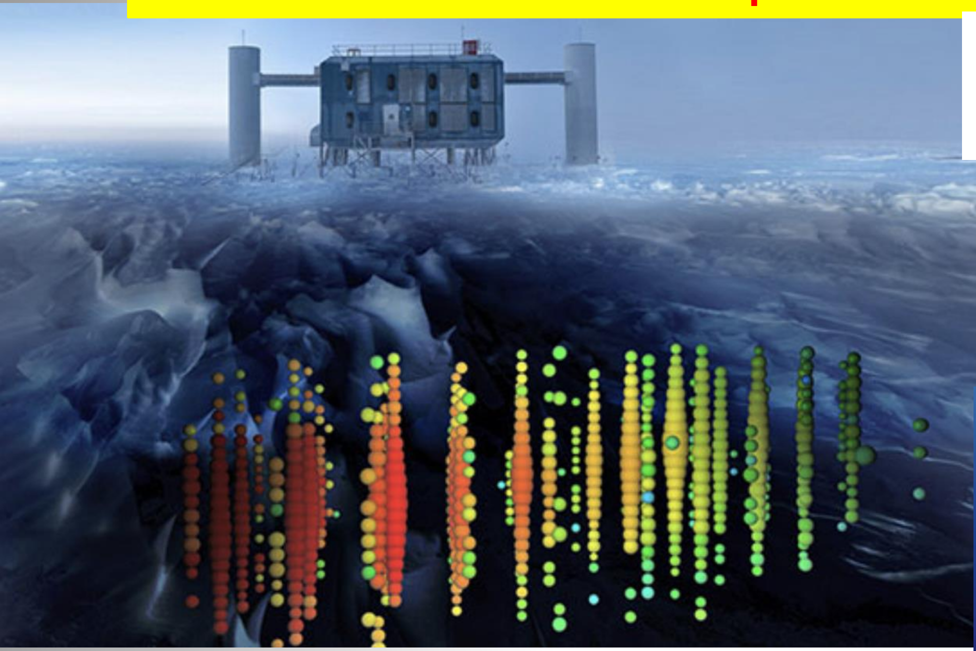


A 290 TeV neutrino originated from a flaring blazar (black hole at the center of a galaxy) was detected by IceCube

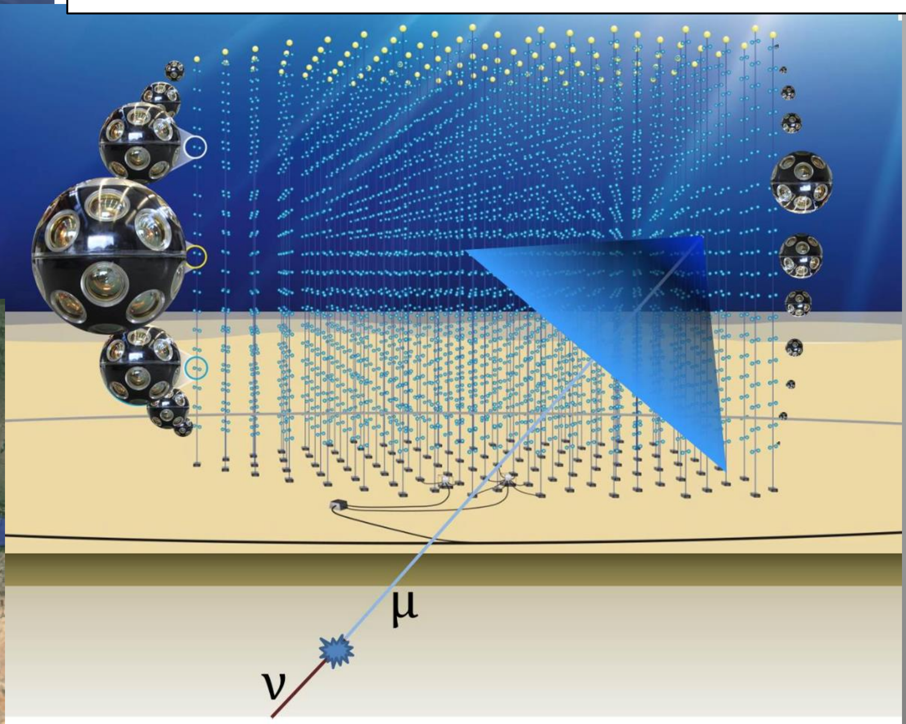
Neutrino Astronomy

Gigantic detectors 1 km^3 of size and beyond…
Use the resources of planet Earth

The IceCube Experiment: operational
-> In the ice of Antarctica



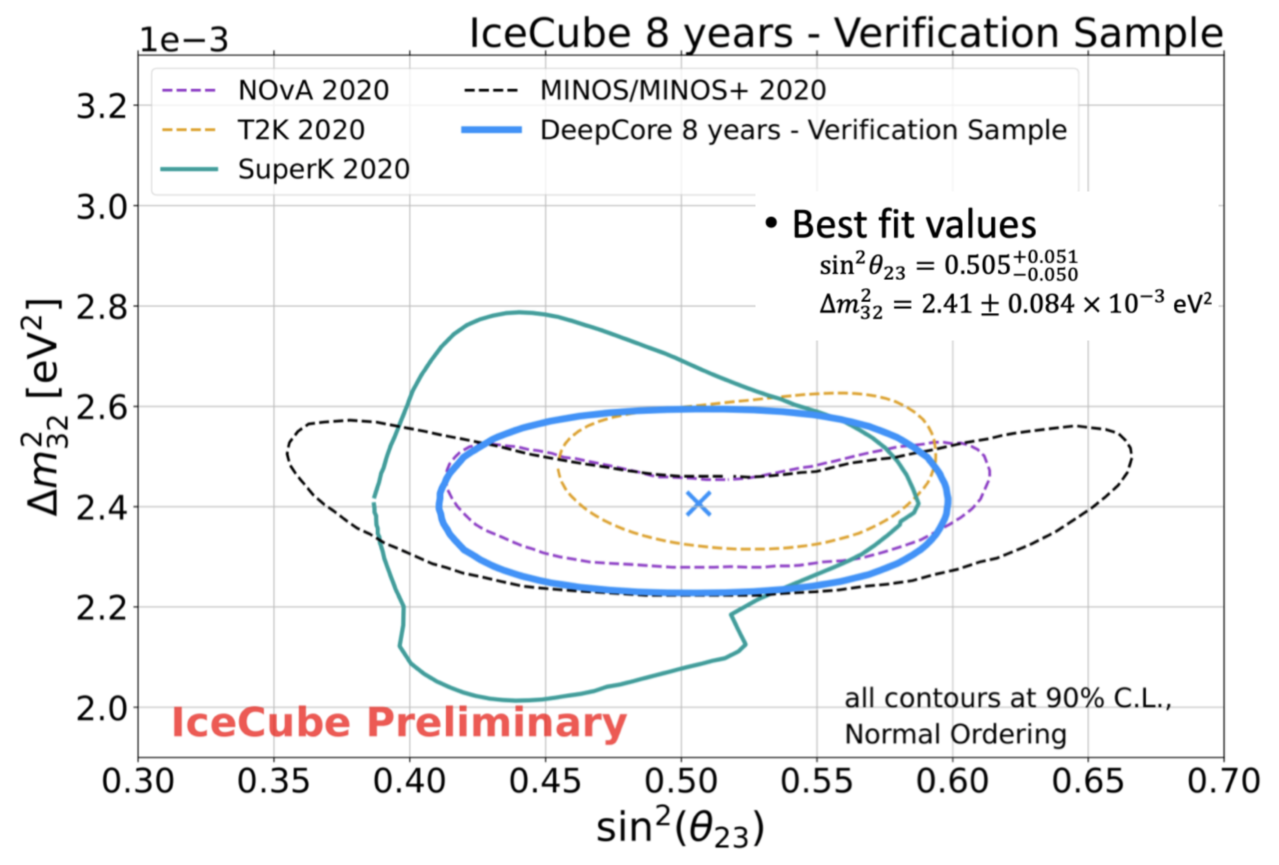
The KM3NET Experiment: 20 DU strings now/ full detector by 2026
-> In the Mediterranean sea…



ANTARES retired ths summer after 14 years

The IceCube Experiment

Result from 8 year data collection with DeepCore

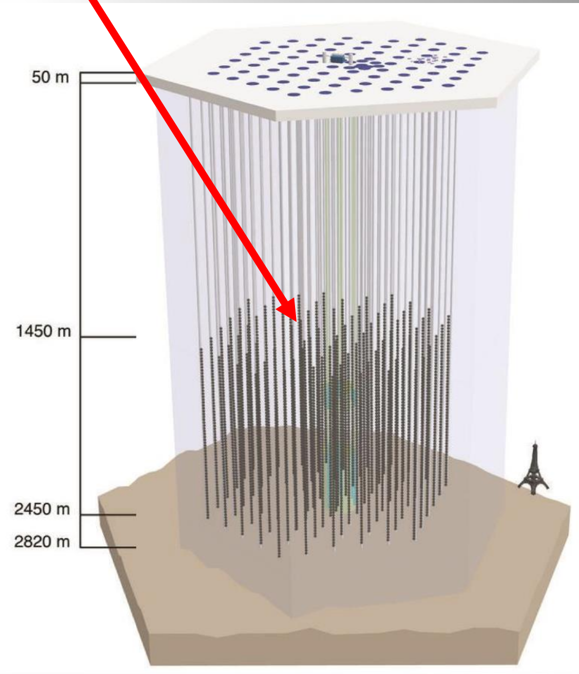


- Best fit values

$\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$

$\Delta m^2_{32} = 2.41 \pm 0.084 \times 10^{-3}$ eV²

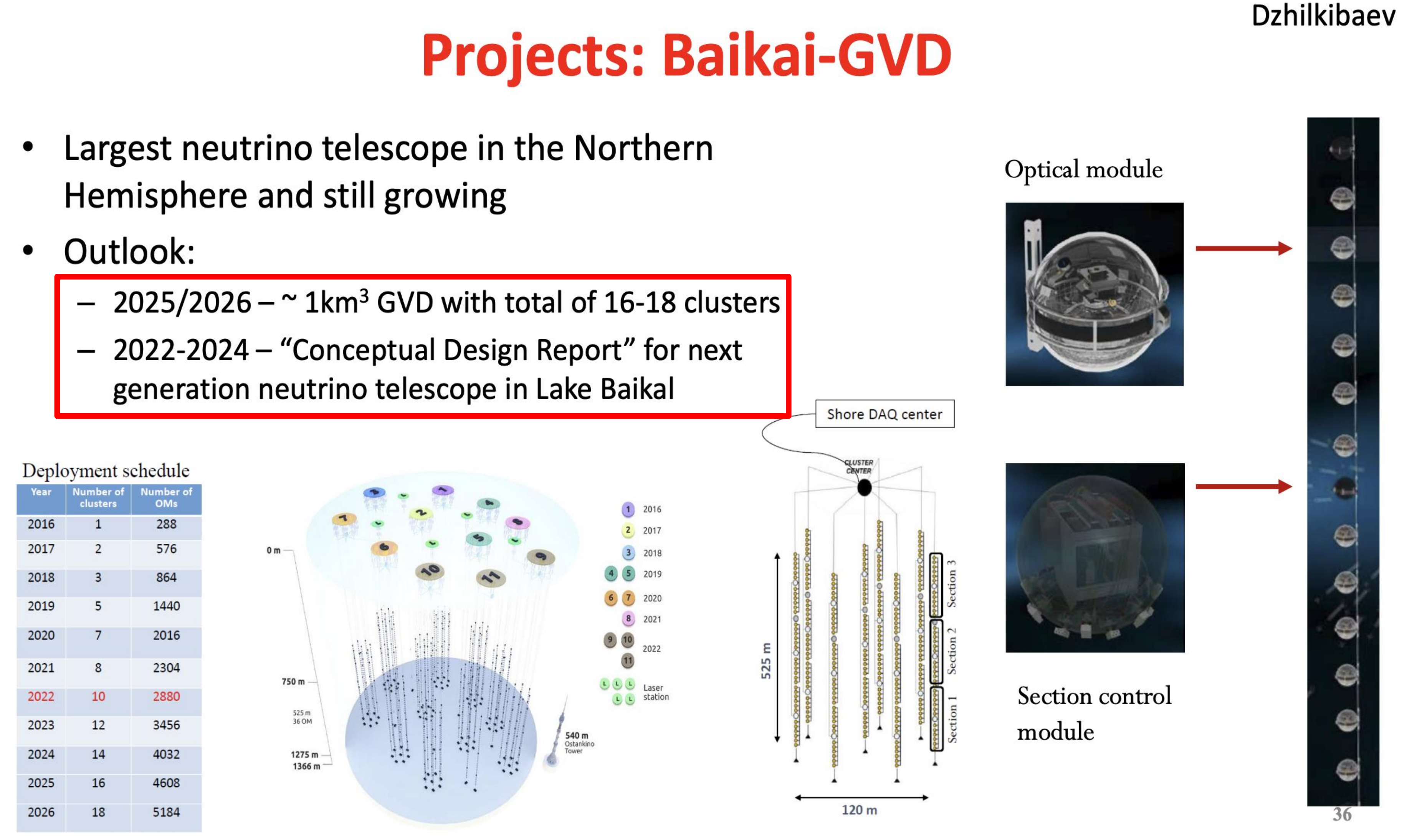
all contours at 90% C.L.,
Normal Ordering



Very competitive measurement….

The Baikal-GVD Experiment

Baikal-GVD Gigaton Volume Detector



Dzhilkibaev

Projects: Baikai-GVD

- Largest neutrino telescope in the Northern Hemisphere and still growing
- Outlook:
  - 2025/2026 – ~ 1km^3 GVD with total of 16-18 clusters
  - 2022-2024 – "Conceptual Design Report" for next generation neutrino telescope in Lake Baikal

Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032
2025	16	4608
2026	18	5184

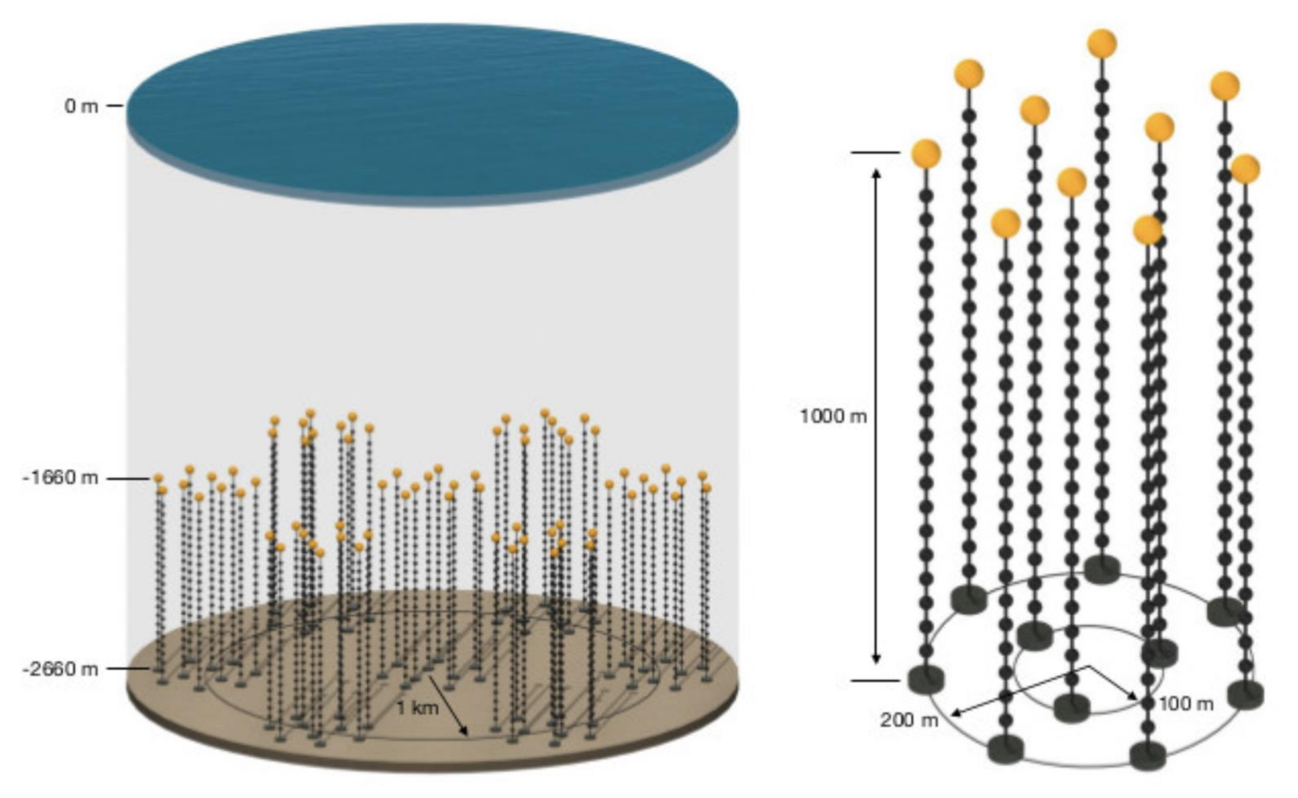
The P-ONE Proposal

The Pacific Ocean Neutrino Experiment

P-ONE

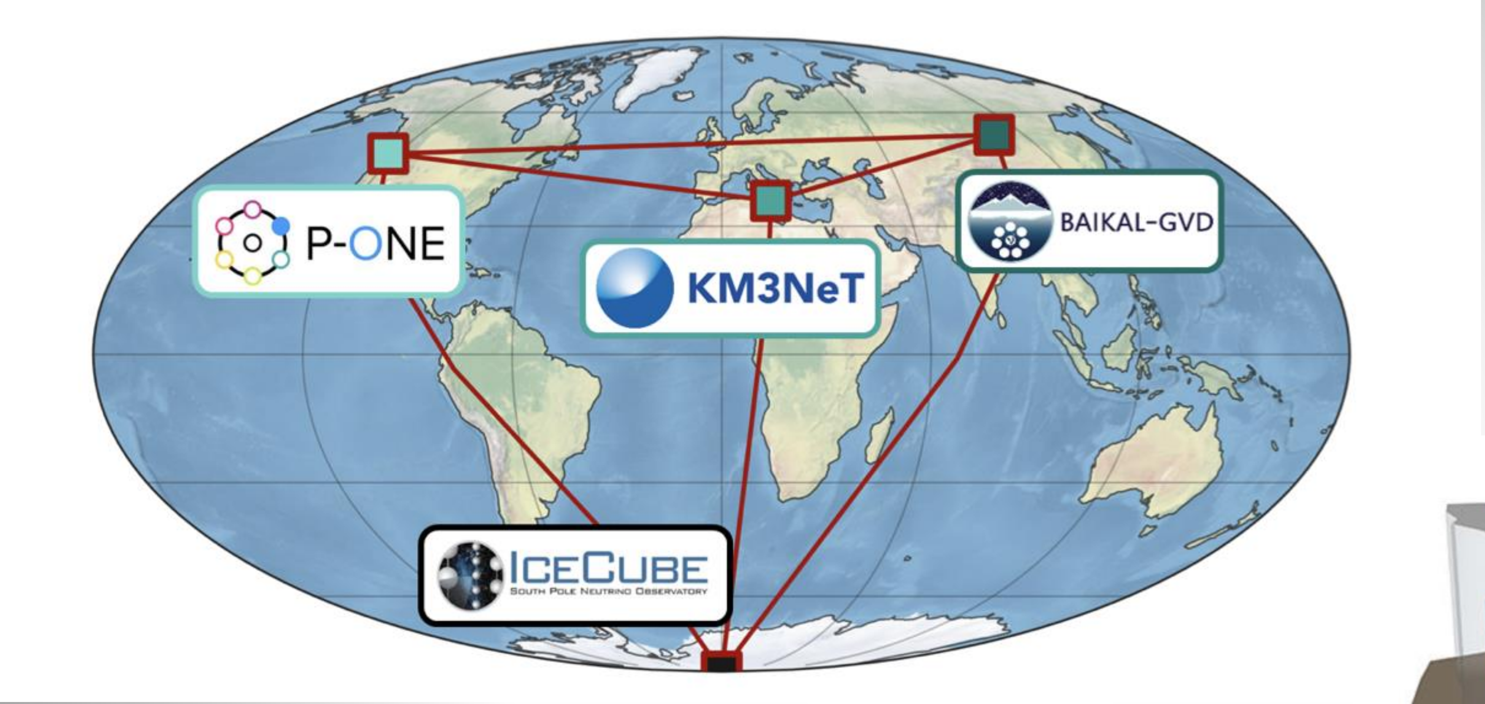
A multi-km^3 neutrino telescope; the first to be hosted by an existing oceanographic infrastructure.

2111.13133

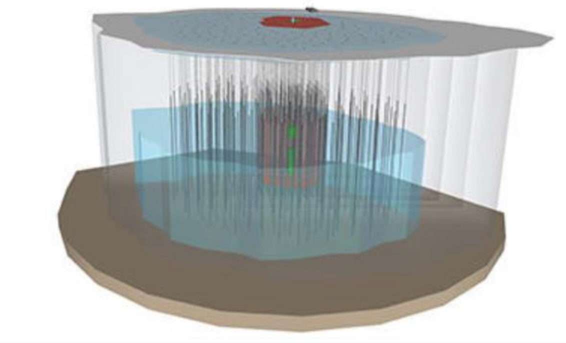


Experiment for energies above 50 TeV. A first segment is planned to be installed in a four weeks sea operation in 2023/24

Large Neutrino Observatories



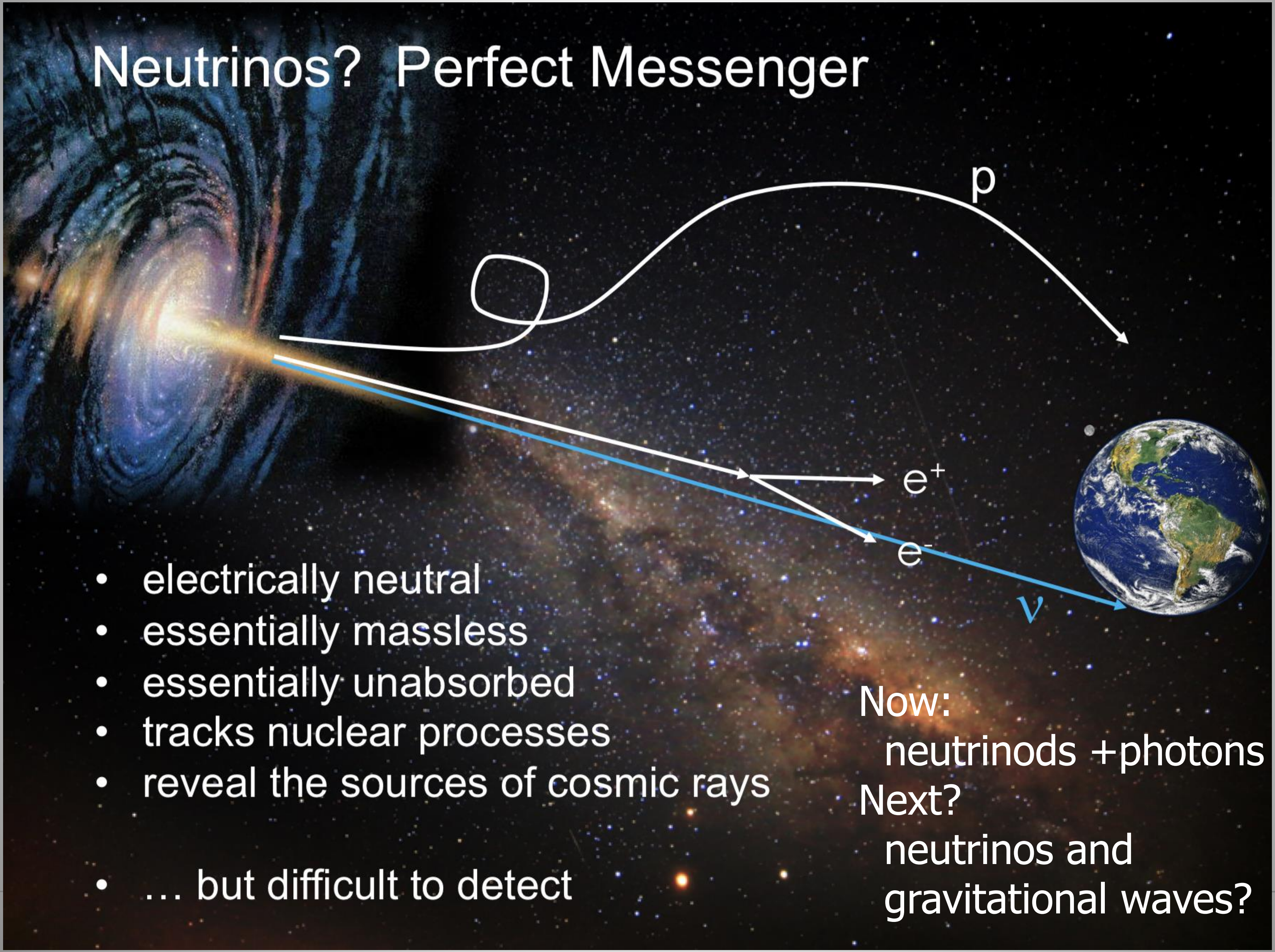
IceCube GEN-2
10 km^3



When combined and used as a single distributed planetary instrument (Planetary Neutrino Monitoring System (PLEnUM)), it would cover almost the entire sky

Huge increase of the detection probability for > 50 TeV neutrinos

Multi Messenger Astronomy…



Neutrinos? Perfect Messenger

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect

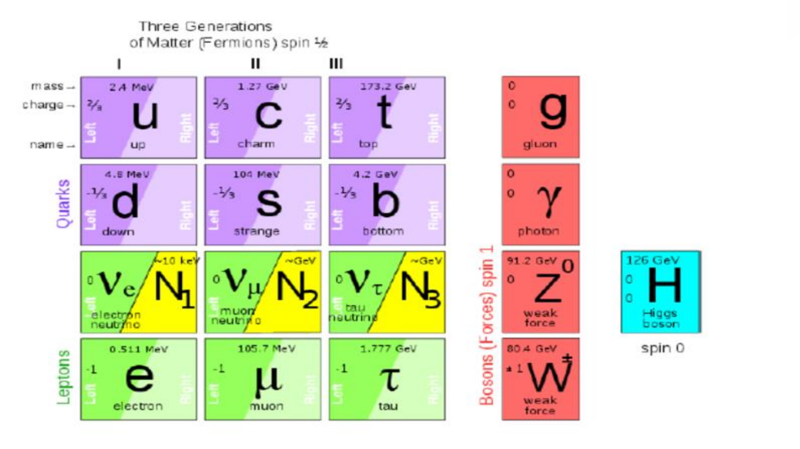
Now:
neutrinods +photons
Next?
neutrinos and
gravitational waves?

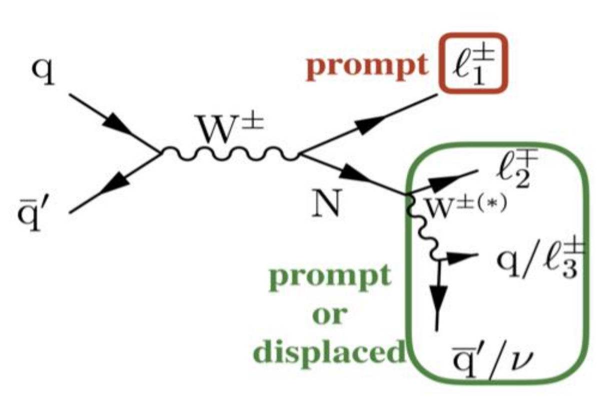
Neutrinos at the LHC!

Neutrinos @ the LHC: Examples

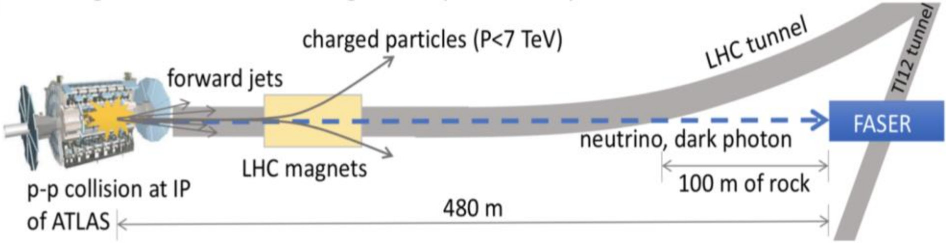
Searches for right-handed neutrinos at the LHC

νMSM (Neutrino Minimal Standard Model)

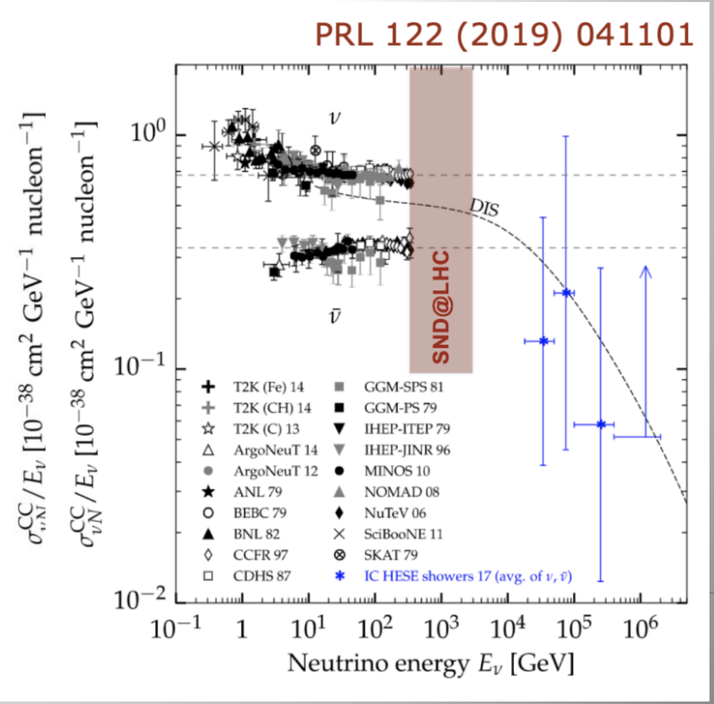




SND@LHC and FASERν are ~480m forward of the IPs and can study TeV-neutrinos with emulsion detectors

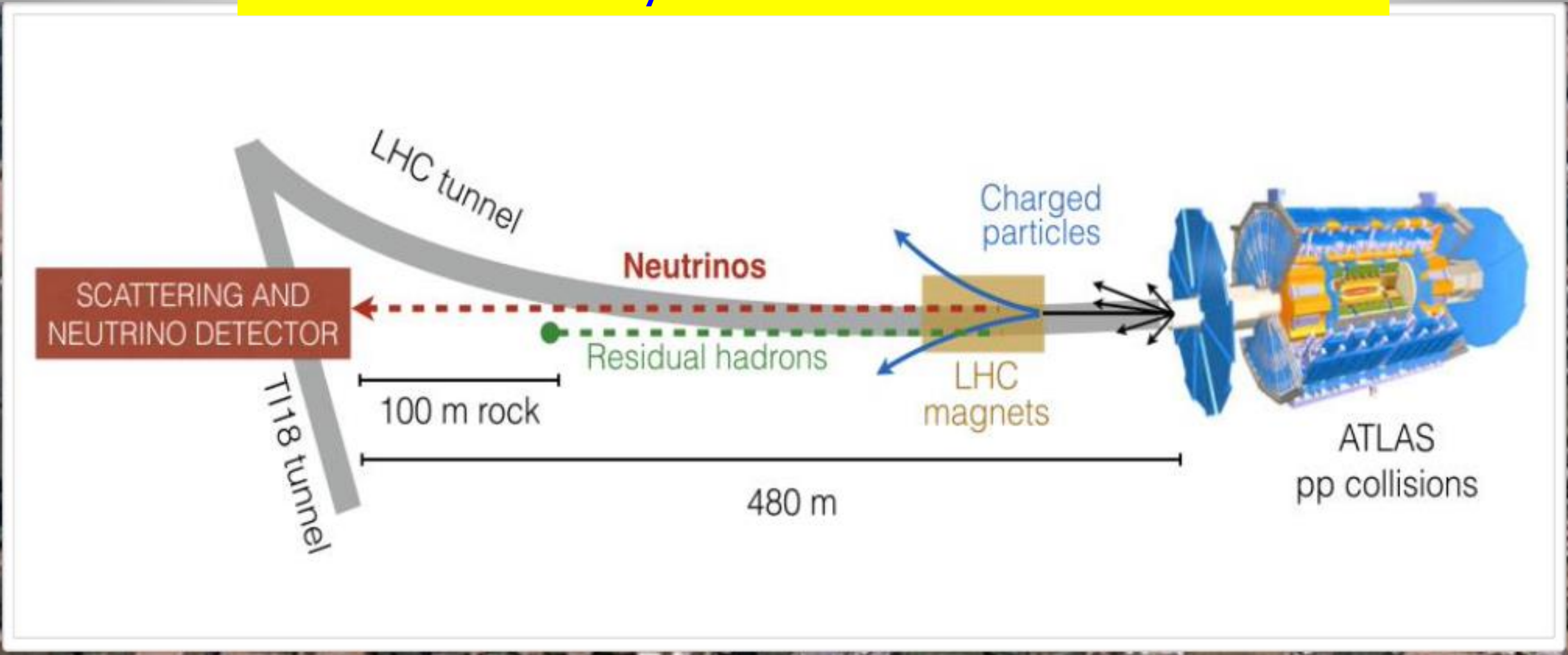


PRL 122 (2019) 041101



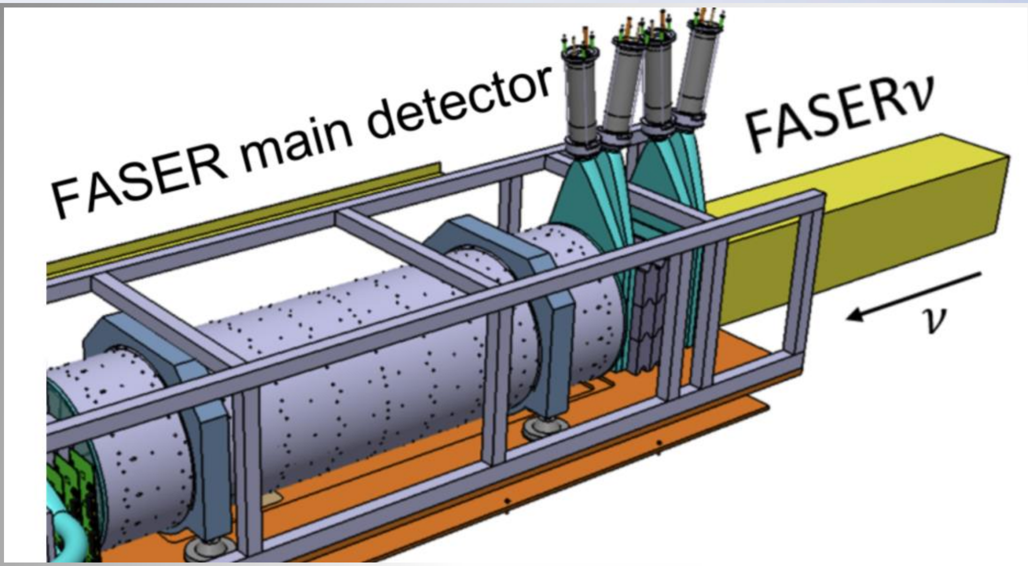
Measuring Neutrino Interactions @ LHC

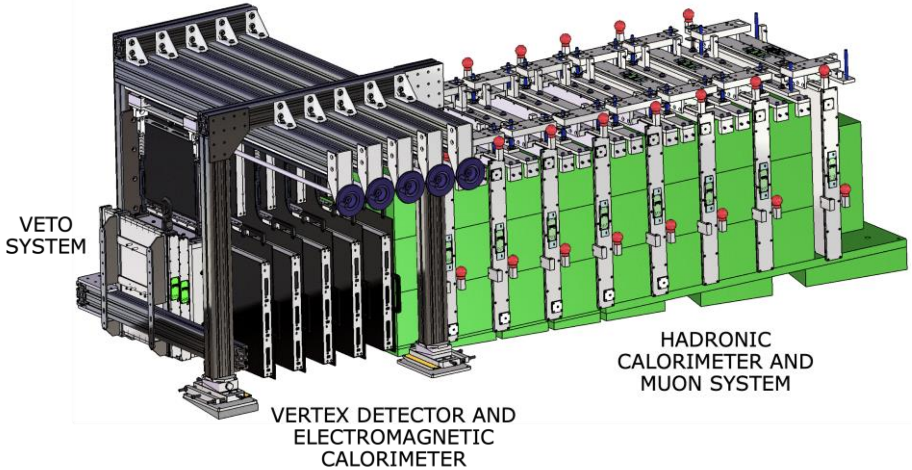
SND@LHC and FASERν are 480m forward of the IPs and can study TeV-neutrinos



FASER was approved in 2019. FASERν (extension with emulsion) in 2020.
SND@LHC was proposed in 2020 and approved in 2021.
Both experiments take now data with the start of the Run-3 at the LHC

FASERν and SND@LHC

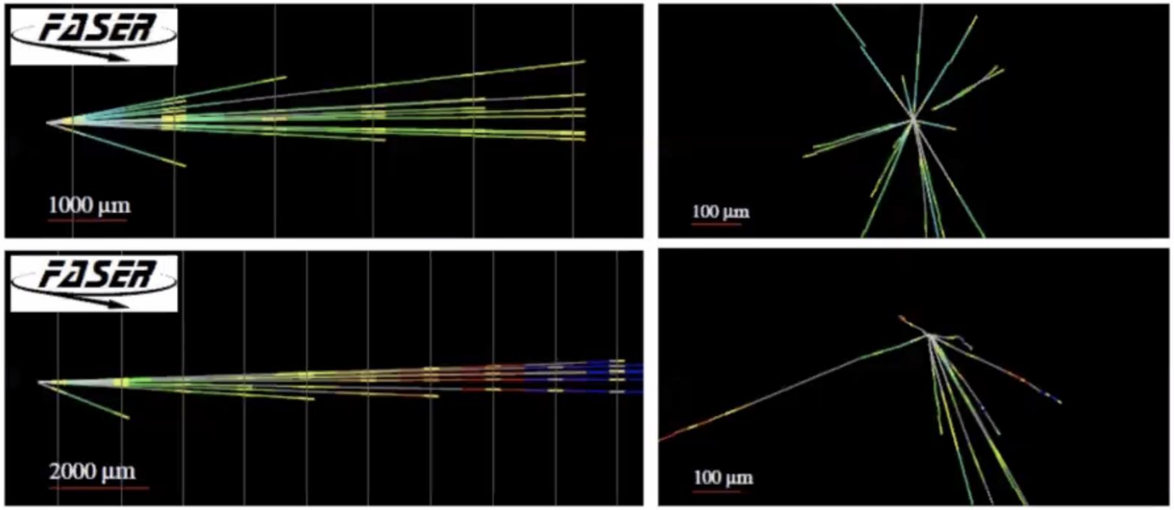




First Observed neutrinos in FASER-ν

These are the first ever directly observed neutrinos at the LHC!!

Neutrino interaction candidates



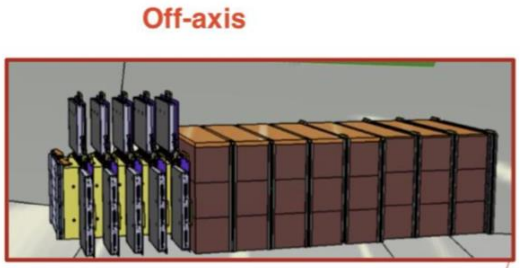
Highlights the potential of the forward LHC location fro neutrino physics!

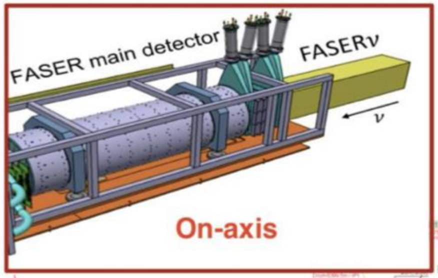
First neutrino interaction candidates at the LHC, arXiv:2105.06197

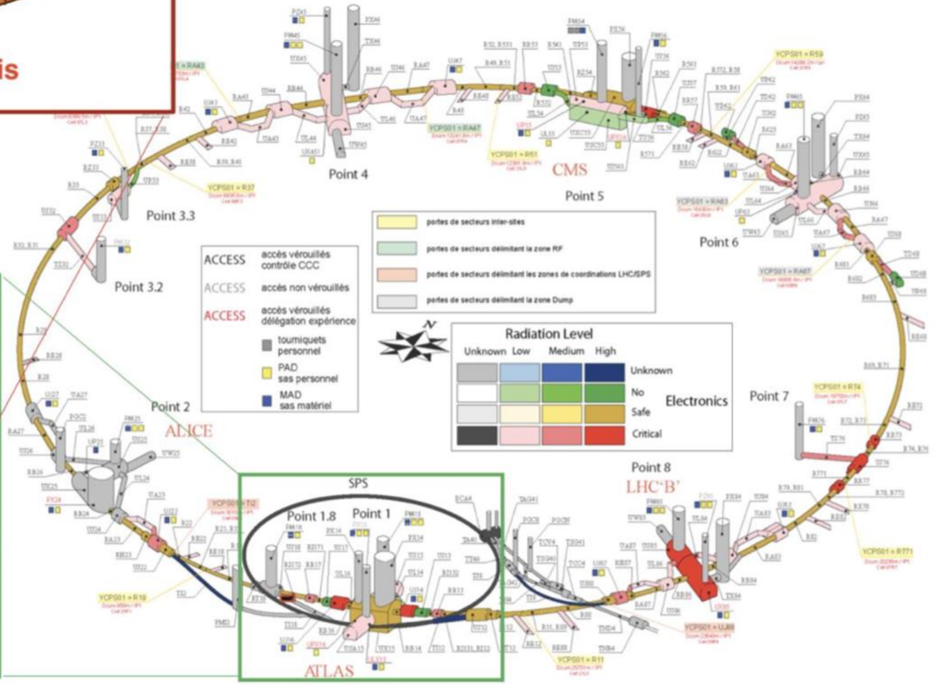
First neutrino interaction candidates at the LHC

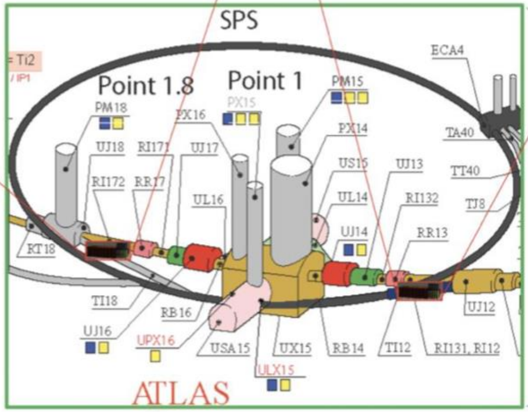
SND@LHC and FASER

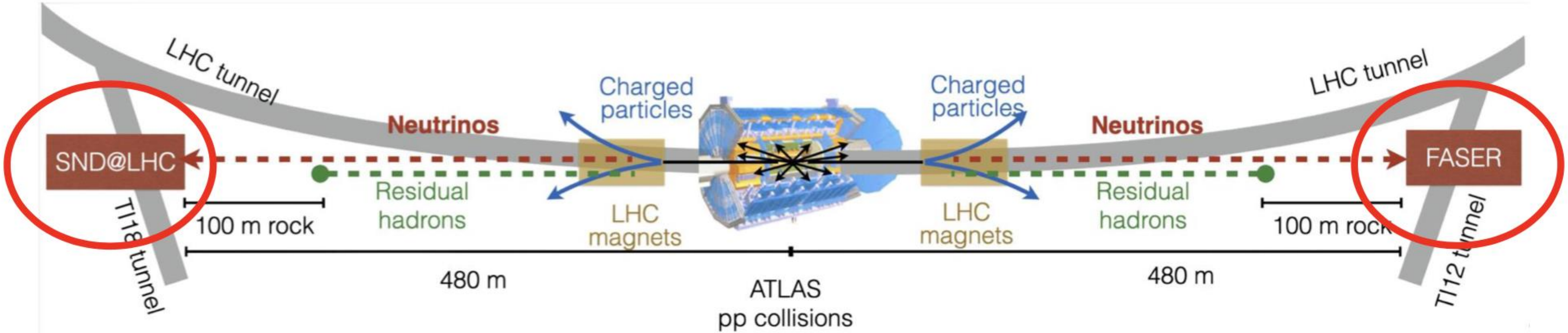
- 480 m away from the IP
- Charged particles deflected by LHC magnets
- Shielding from the IP provided by 100 m rock



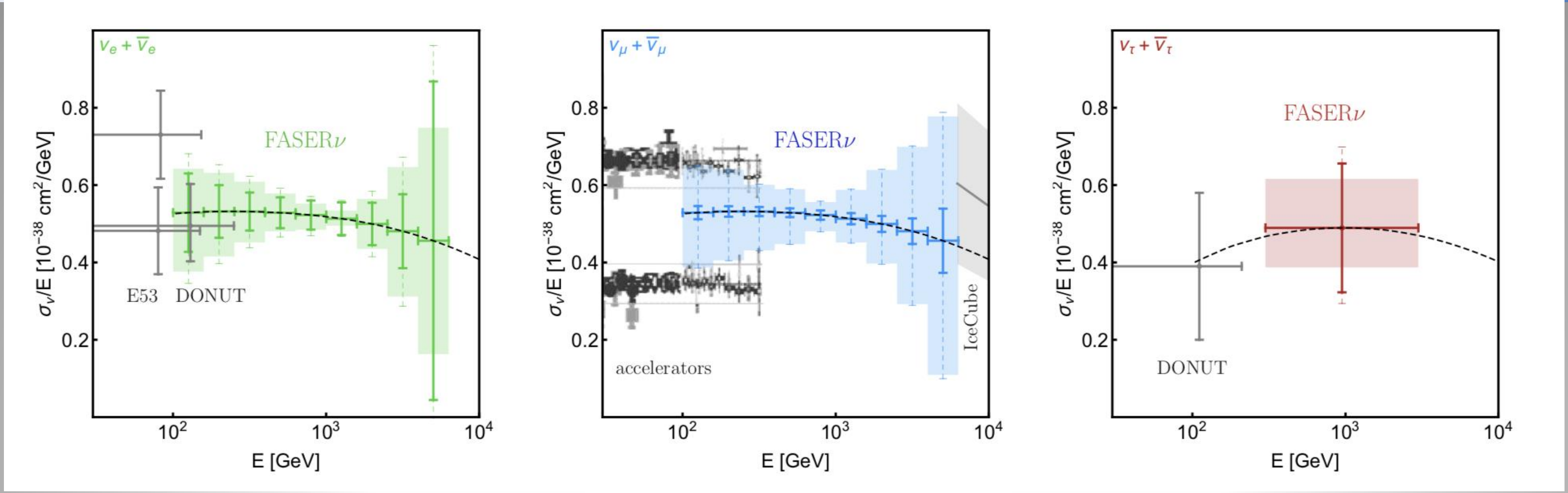




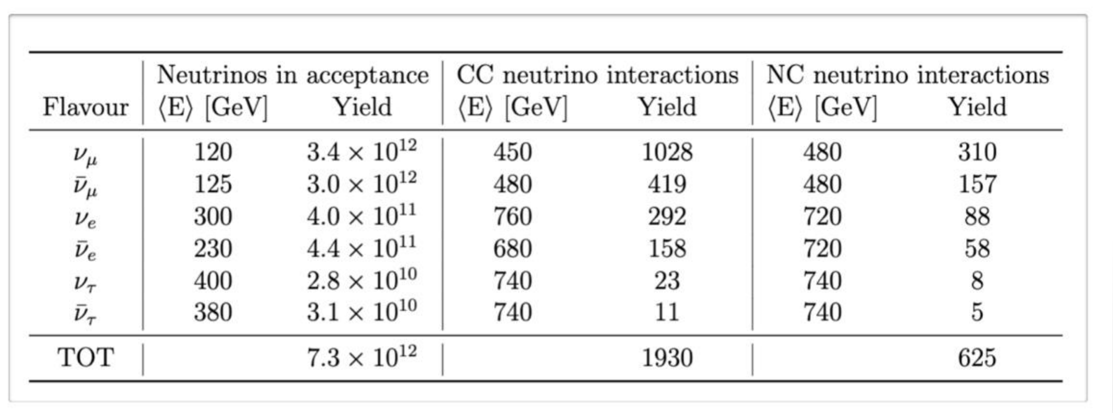




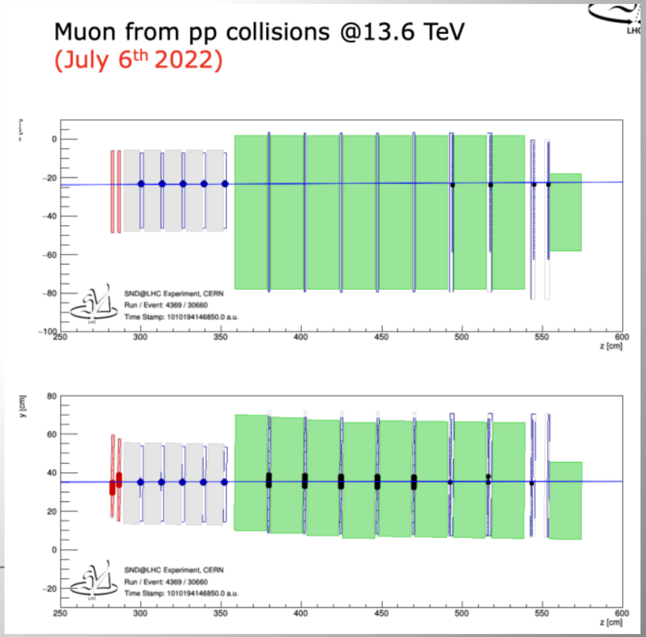
Neutrinos @ the LHC: SND@LHC



Expected # of neutrino interactions in Run-3



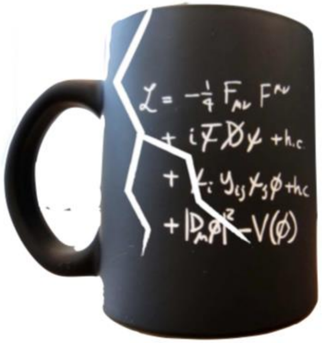
Flavour	Neutrinos in acceptance ⟨E⟩ [GeV]	Neutrinos in acceptance Yield	CC neutrino interactions ⟨E⟩ [GeV]	CC neutrino interactions Yield	NC neutrino interactions ⟨E⟩ [GeV]	NC neutrino interactions Yield
ν_μ	120	3.4×10^{12}	450	1028	480	310
$\bar{\nu}_\mu$	125	3.0×10^{12}	480	419	480	157
ν_e	300	4.0×10^{11}	760	292	720	88
$\bar{\nu}_e$	230	4.4×10^{11}	680	158	720	58
ν_τ	400	2.8×10^{10}	740	23	740	8
$\bar{\nu}_\tau$	380	3.1×10^{10}	740	11	740	5
TOT		7.3×10^{12}		1930		625



Muon from pp collisions @13.6 TeV
(July 6th 2022)

SUMMARY: Neutrinos

- Neutrinos studies is a vibrant field of research, and has still many open questions! Right-handed partners? Strong CP violation? More than 3 neutrinos? NS Interactions? Are neutrinos their own anti-particle?
- Now comes the age of neutrino precision physics with DUNE & T2HK and neutrino astronomy: look inside the sun, understand supernovae explosions, multi-messenger astronomy…
- Detailed study of PMNS oscillation parameters by experiments is key to the understanding
- Large experiments are really “observatories”
- The history of neutrino research showed many surprises. What surprise is waiting for us next??

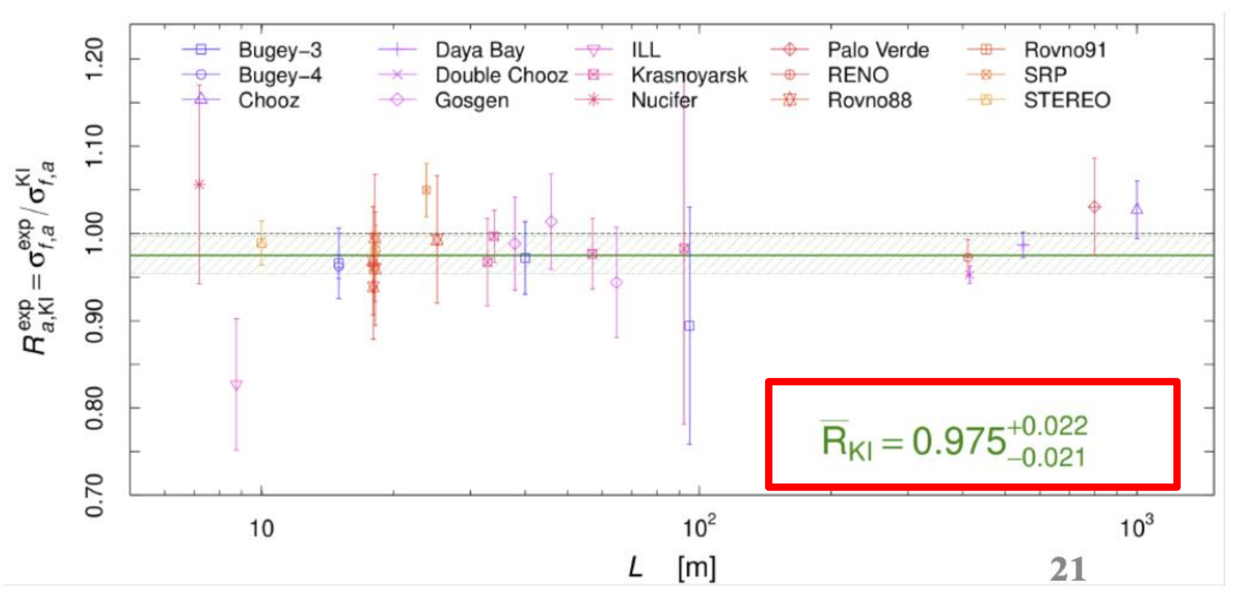


Backup

Reactor Anomaly

Deficit in reactor anti-electron neutrinos has been reported since years.

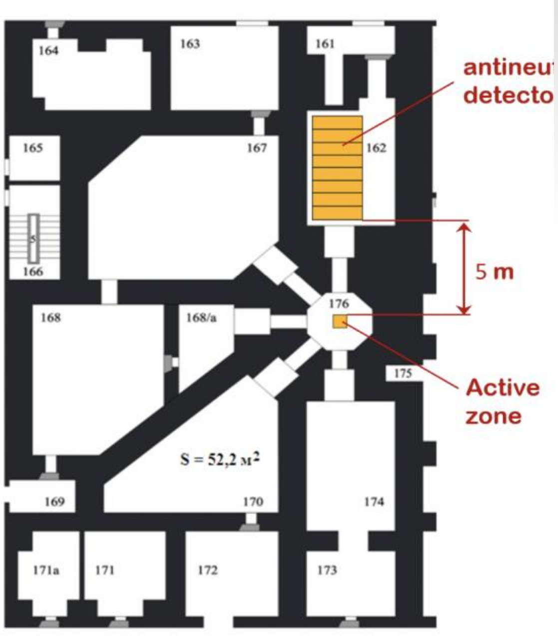
- Flux deficit can be explained as sterile neutrino
- Many experiments reported new results, no oscillation signals beyond 2σ, except
  - Neutrino-4 sees a 2.7σ oscillation signal, but rejected by STEREO at 3.1σ
- Daya Bay reported that the flux deficit is mostly from ^{235}U
- Other reactor and dedicated ^{235}U spectrum measurement confirmed the Daya Bay result



Updated estimate of R

Compatible with R=1

Short baseline Reactor:Neutrino-4 Exp.

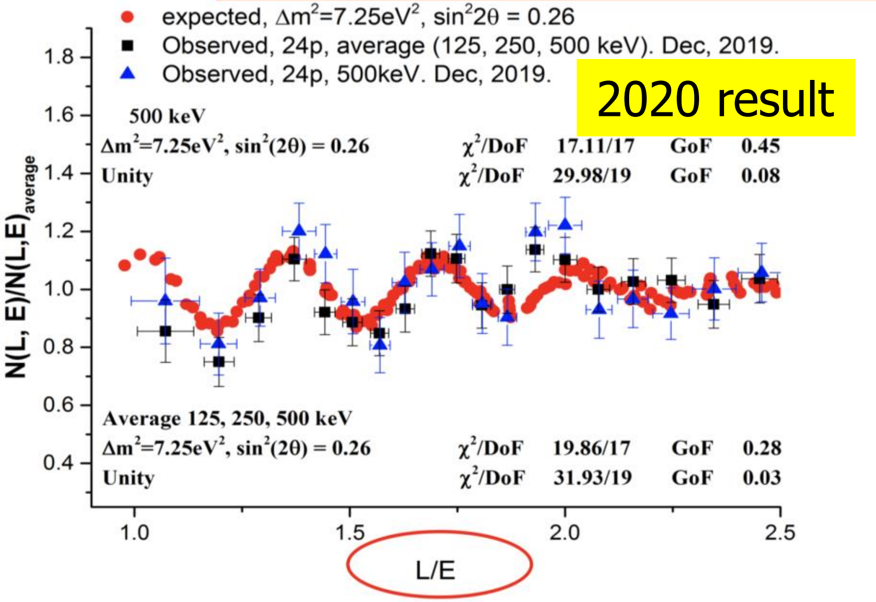


2m^3 liquid scintillator detector at a 90 MW reactor in Russia

3 years long measurement 2.8σ signific.

arXiv:1809.10561 (Jan 2020)

$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14}\ \sin^2\left(1.27\frac{\Delta m^2_{14}[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\tilde{\nu}}[\mathrm{MeV}]}\right)$$



2020 result

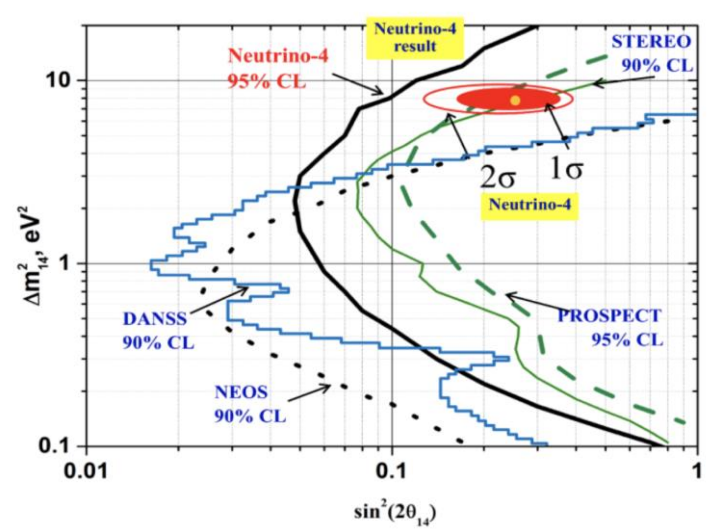
$$\Delta m^2_{14} = 7.25 \pm 0.13_{st} \pm 1.08_{syst} = 7.25 \pm 1.09$$

$$\sin^2 2\theta = 0.26 \pm 0.08_{stat} \pm 0.05_{syst} = 0.26 \pm 0.09 (2.8\sigma)$$

Data analysis strongly critized
- Issues with the energy resolution
- Less biased approach -> ~2.2σ effect only
- “No-oscillation scenario” not excluded at 3σ

arXiv:2101.06785

The Jury is still out…

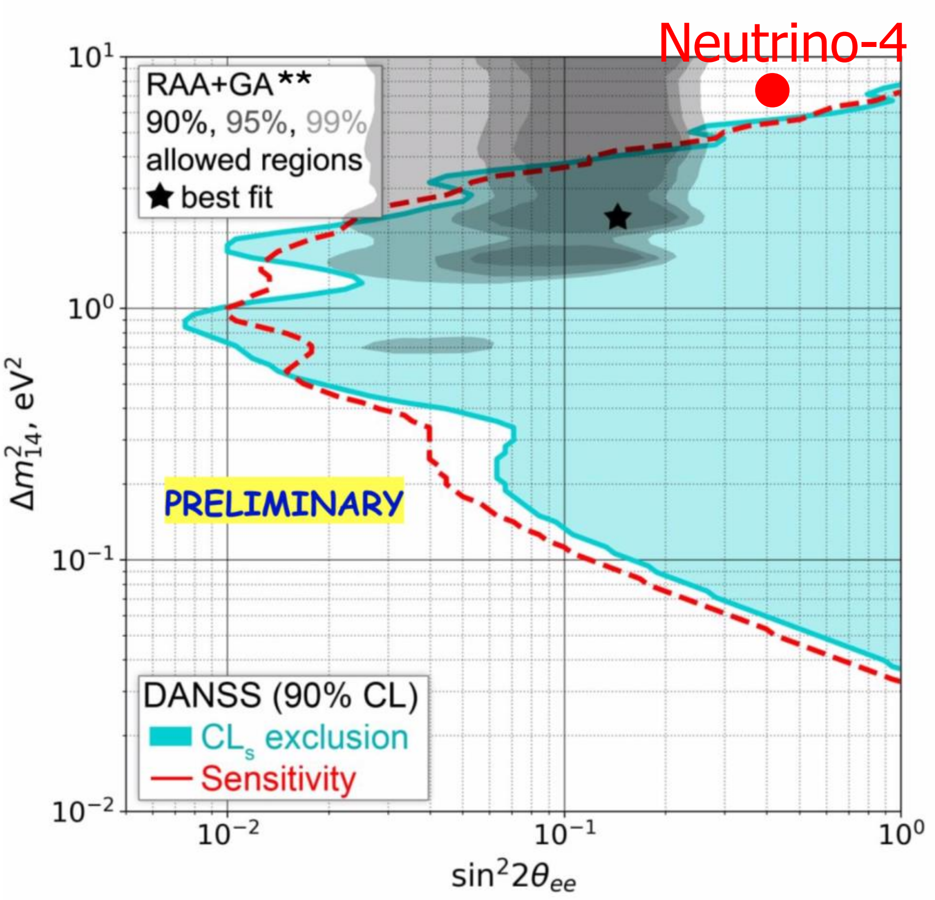


Result from DANSS

EPS-HEP 2021

- **DANSS records about 5 thousand antineutrino events per day with cosmic background ~1.7%, S/B>50**

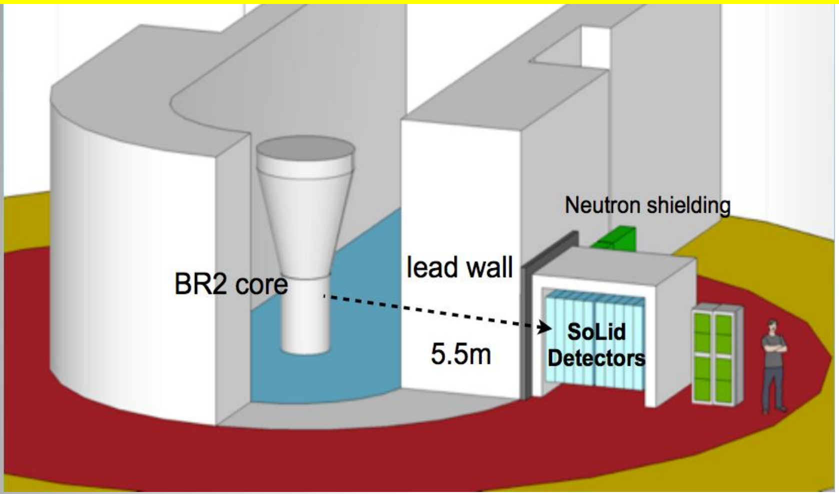
5.5 million IBD events were collected in 5 years

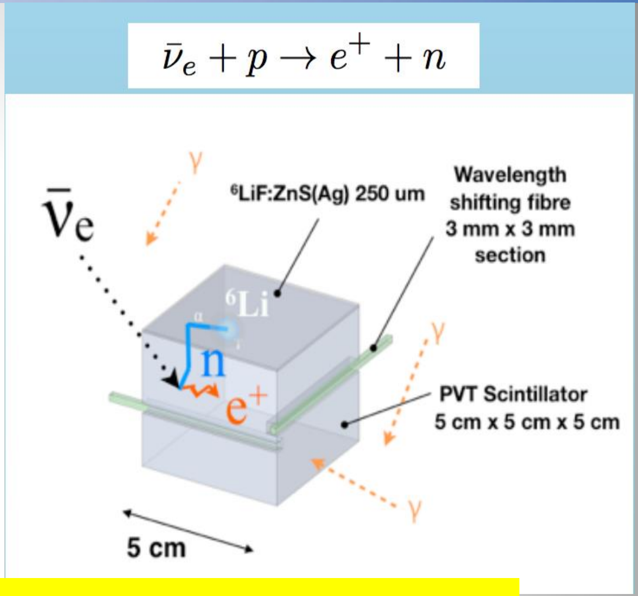


DANSS does yet cover up to Neutrino-4, but with the upgraded detector and 1-2 years additional data taking they will…
DANSS itself sees very weak hints of a signal around 1 eV^2

New Short Baseline Experiments will check!

Experiments at reactors, eg the SoLid experiment @BR2 reactor in Belgium



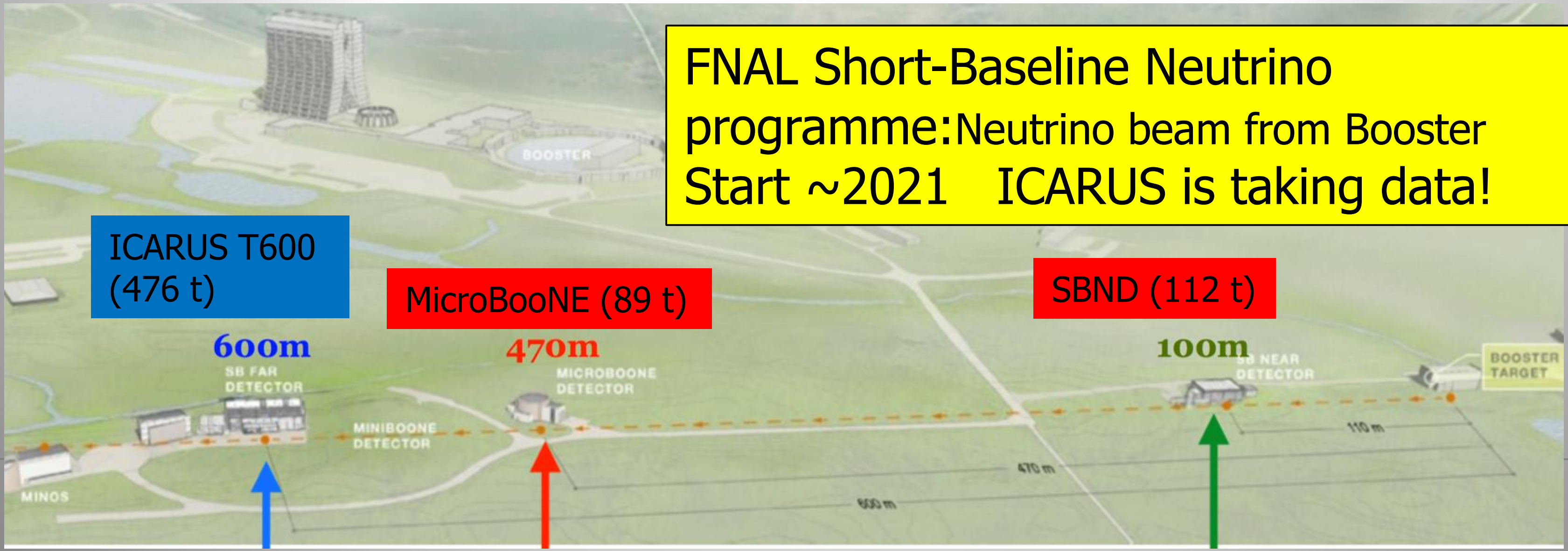


$\bar{\nu}_e + p \rightarrow e^+ + n$

Also: Prospect, STEREO, NEOS…

FNAL Short-Baseline Neutrino programme: Neutrino beam from Booster

Start ~2021 ICARUS is taking data!



ICARUS T600 (476 t)

MicroBooNE (89 t)

SBND (112 t)

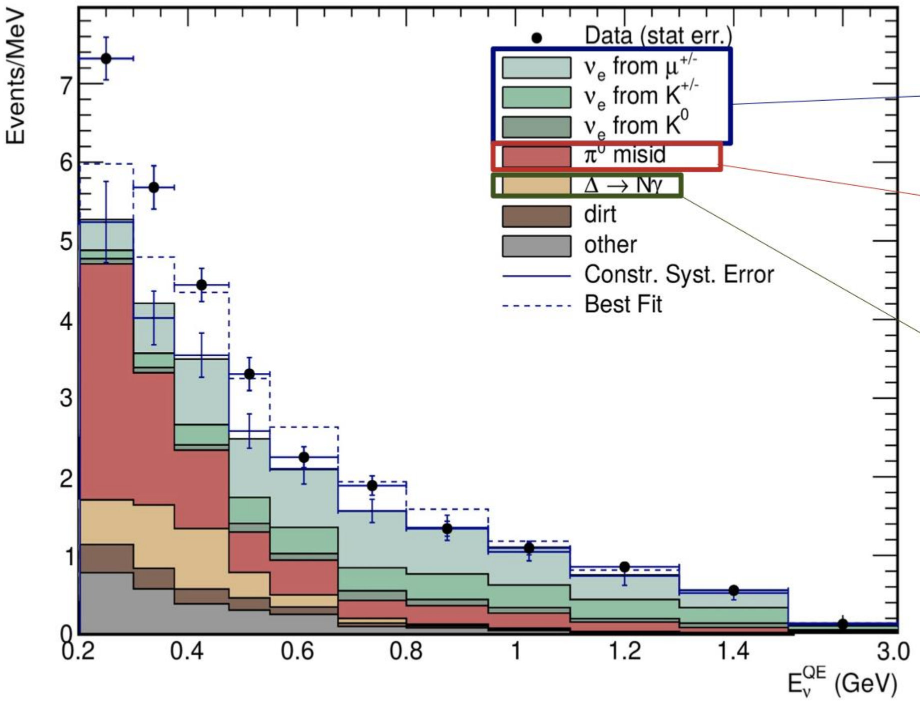
The MiniBoone Low Energy Excess

MiniBooNe followed up on LNSD anomaly

MiniBooNe Cherenkov Detector (min. oil)

- ☑ $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam (~3σ)
- ☑ Source—detector distance ("baseline") ~ 30 m
- ☑ $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations?

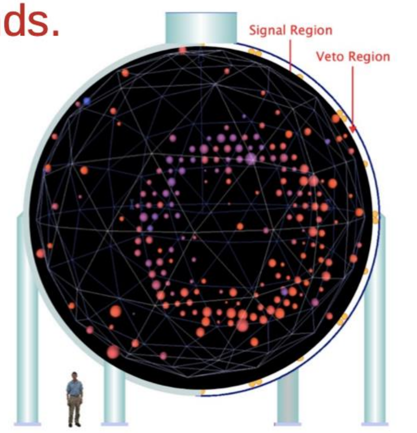
MiniBooNE Electron-like selection has a lot of photon backgrounds.



Flux?

Mis-ID'd pi-zero background (measured in-situ).

Mis-ID'd photon background?



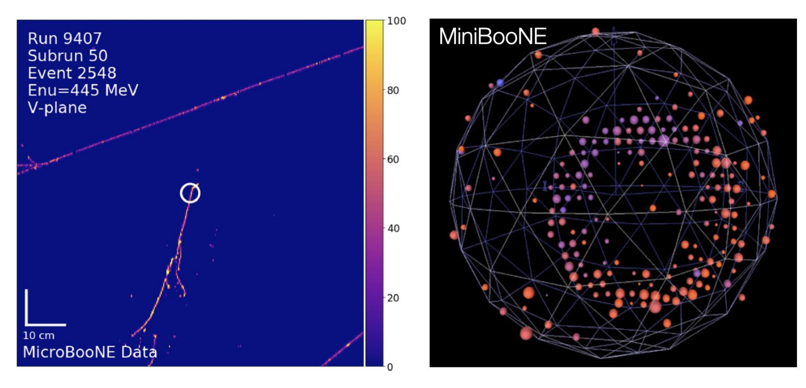
Event display: MiniBooNE collaboration

Or real electron neutrino appearance?

Sees 4.5σ excess in neutrino mode, 4.7σ in antineutrino mode.

MicroBooNE

MicroBoone to resolve the issue?



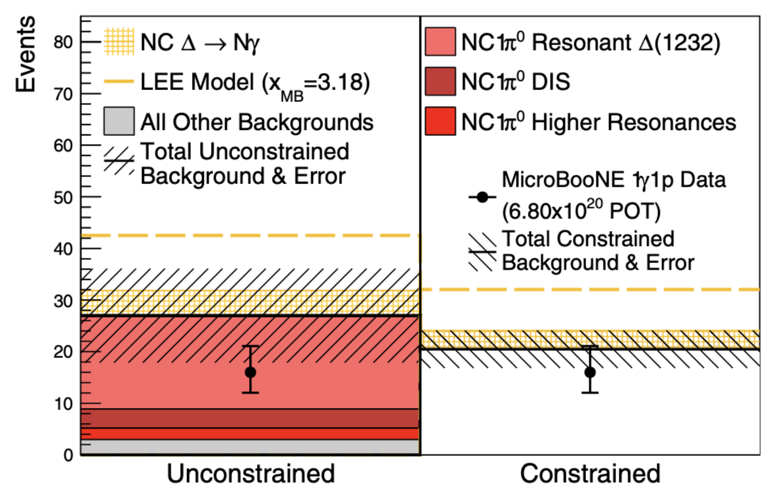
☑ 80 ton LAr TPC

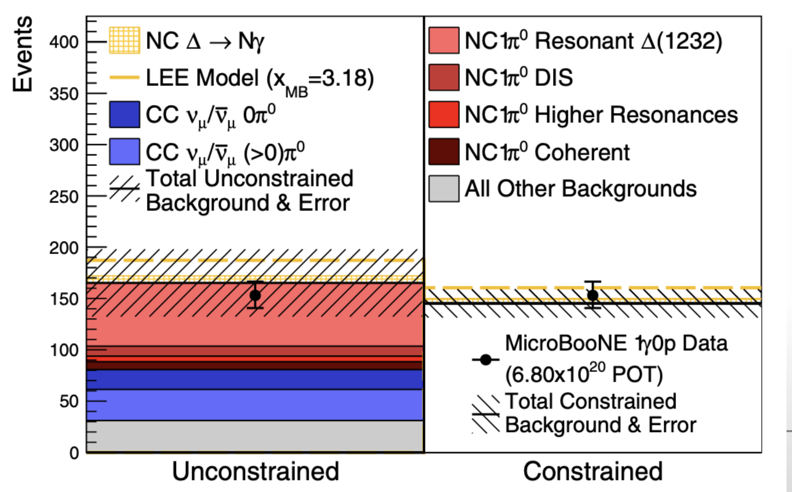
☑ Very good event reconstruction capabilities

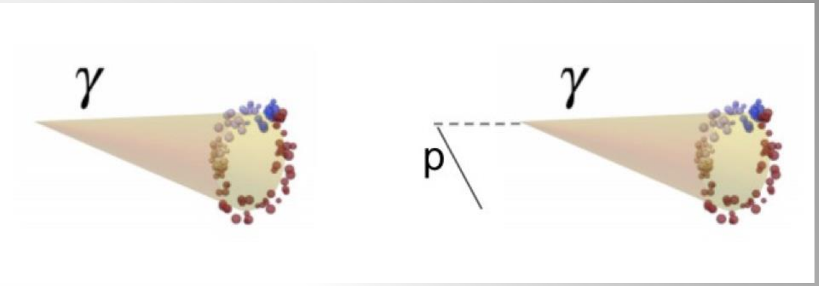
- can distinguish $e^{\pm}$ from γ

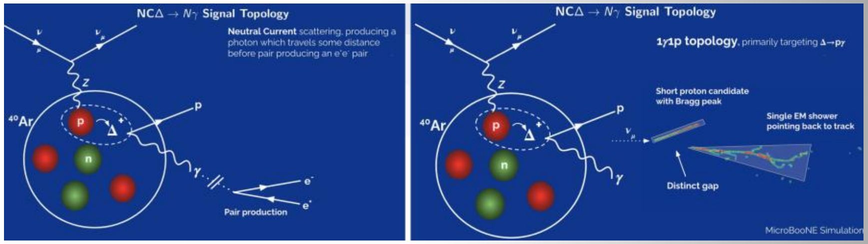
MicroBooNE

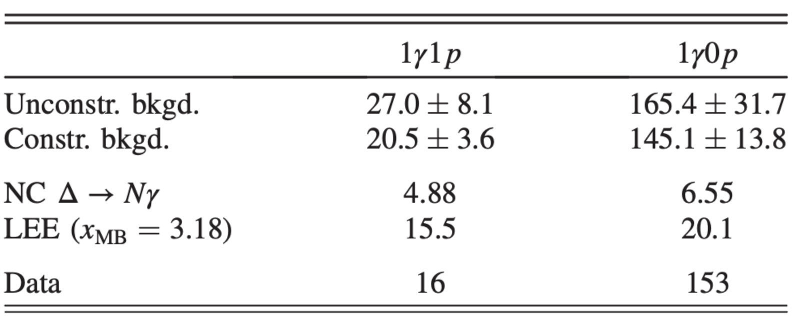
Check additional sources of photons









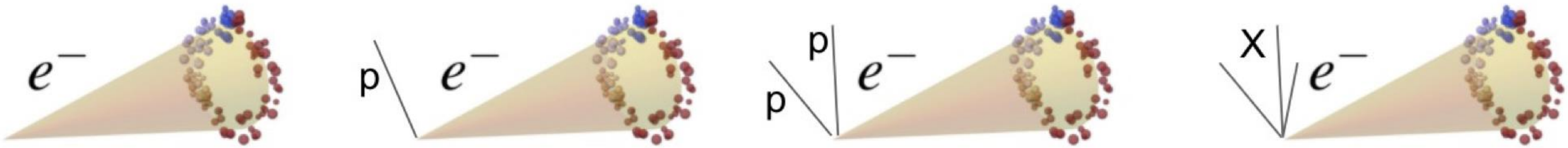


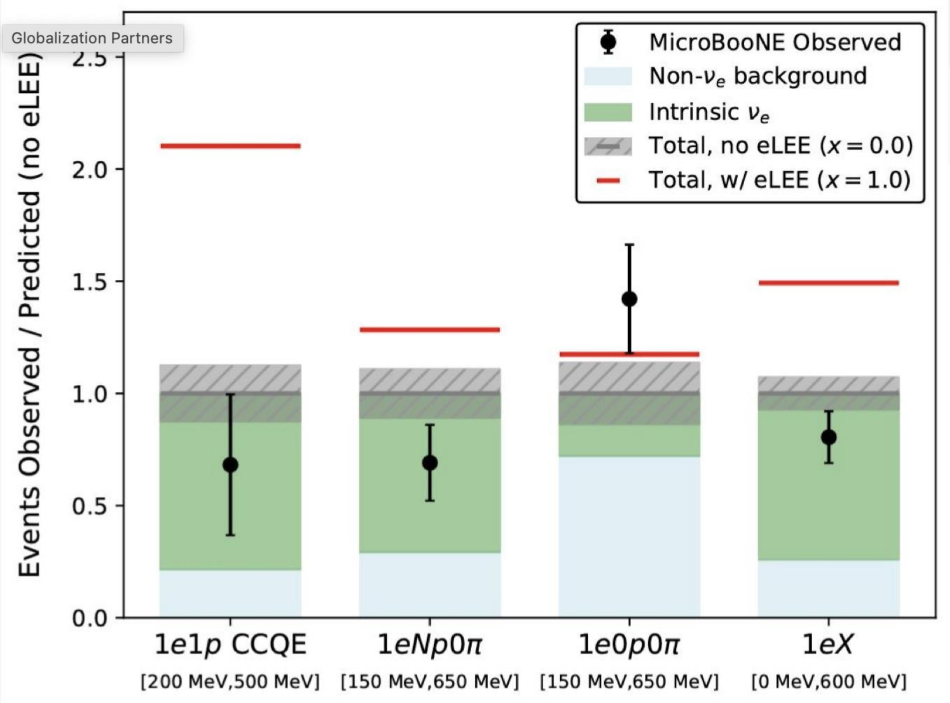
	$1\gamma1p$	$1\gamma0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \to N\gamma$	4.88	6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	15.5	20.1
Data	16	153

Disfavours the NCΔ → Nγ explanation of **LEE** at **94.8%** confidence level.

MicroBooNe

Check additional sources of electrons from k now processes





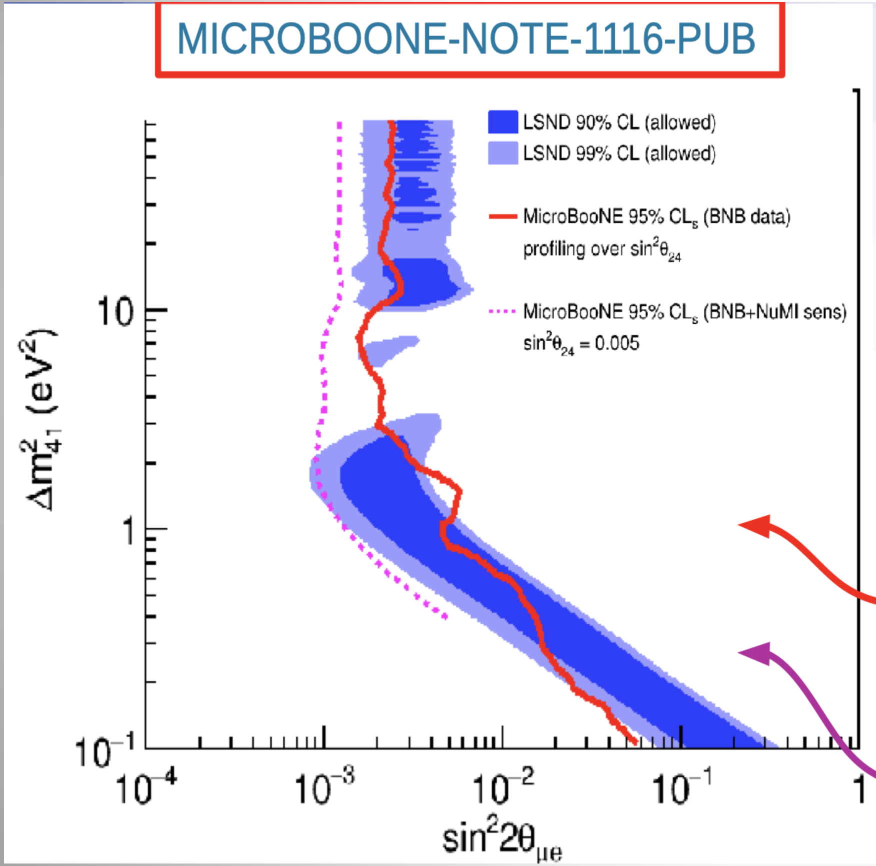
Reject the hypothesis that simple charged current ν_e fully explains the MiniBooNE excess at >97% CL in all analyses.

So far the MiniBooNe excess remains unexplained…

MicroBoone

NEW:MicrobooNe direct constraints on eV^2 scale sterile neutrinos

M. Uchida Rencont. de Vietnam, 2 weeks ago



The **inclusive CC ν_e** results have subsequently been turned into a direct bound on eV scale sterile neutrinos.

As the inclusive CC ν_e selection utilises high statistics CC ν_μ events to help constrain systematics, **a full 3+1 sterile neutrino fit must be performed** in order to fully take into account all possible flavour transitions.

- With this **full 3+1 analysis**, part of the LSND allowed region is excluded by the MicroBooNE 95% CL limit,
- Combining both data sets significantly improves sensitivity → **Upcoming BNB + NuMI analysis** will be sensitive to full LSND allowed regions.

…Not sure what the MiniBoone excess is yet, but sterile neutrino not favored

The Gallium Anomaly

POPULAR MECHANICS

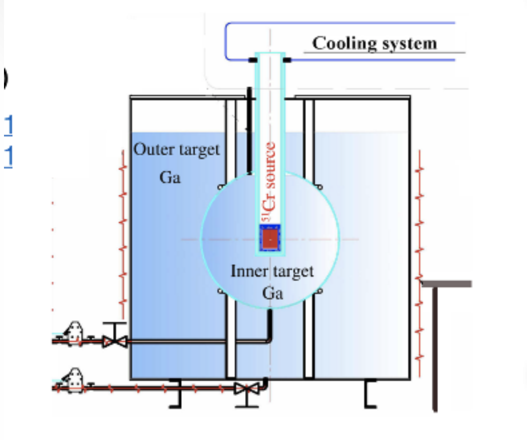
Physicists May Have Stumbled Upon an Entirely New Elementary Particle

July 2022

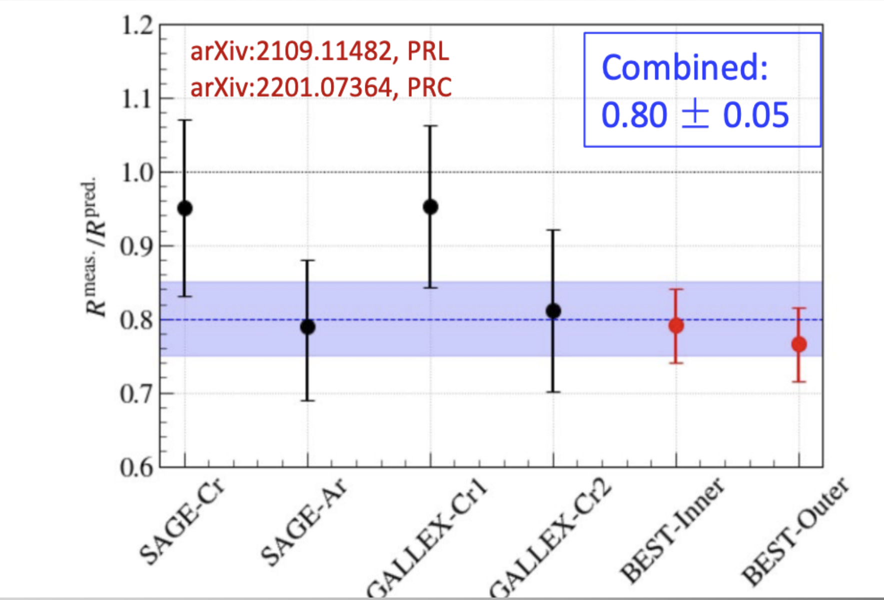
BEST arXiv:2109.11482
Barinov Gorbunov arXiv:2109.14654

The gallium anomaly, is the missing electron-neutrino flux from ^{37}Ar and ^{51}Cr electron-capture decays as measured by GALLEX and SAGE solar-neutrino exp.

The Baksan Experiment on Sterile Transitions (BEST) probes the gallium anomaly and its possible connections to oscillations between active and sterile neutrinos.



- BEST confirmed GALLEX & SAGE deficit, but no dependence on the oscillation baseline
- Katrin+Reactor experiments excluded most regions of the Ga anomaly
- Seems not due to sterile neutrinos but other explanations should be looked for.



arXiv:2109.11482, PRL
arXiv:2201.07364, PRC

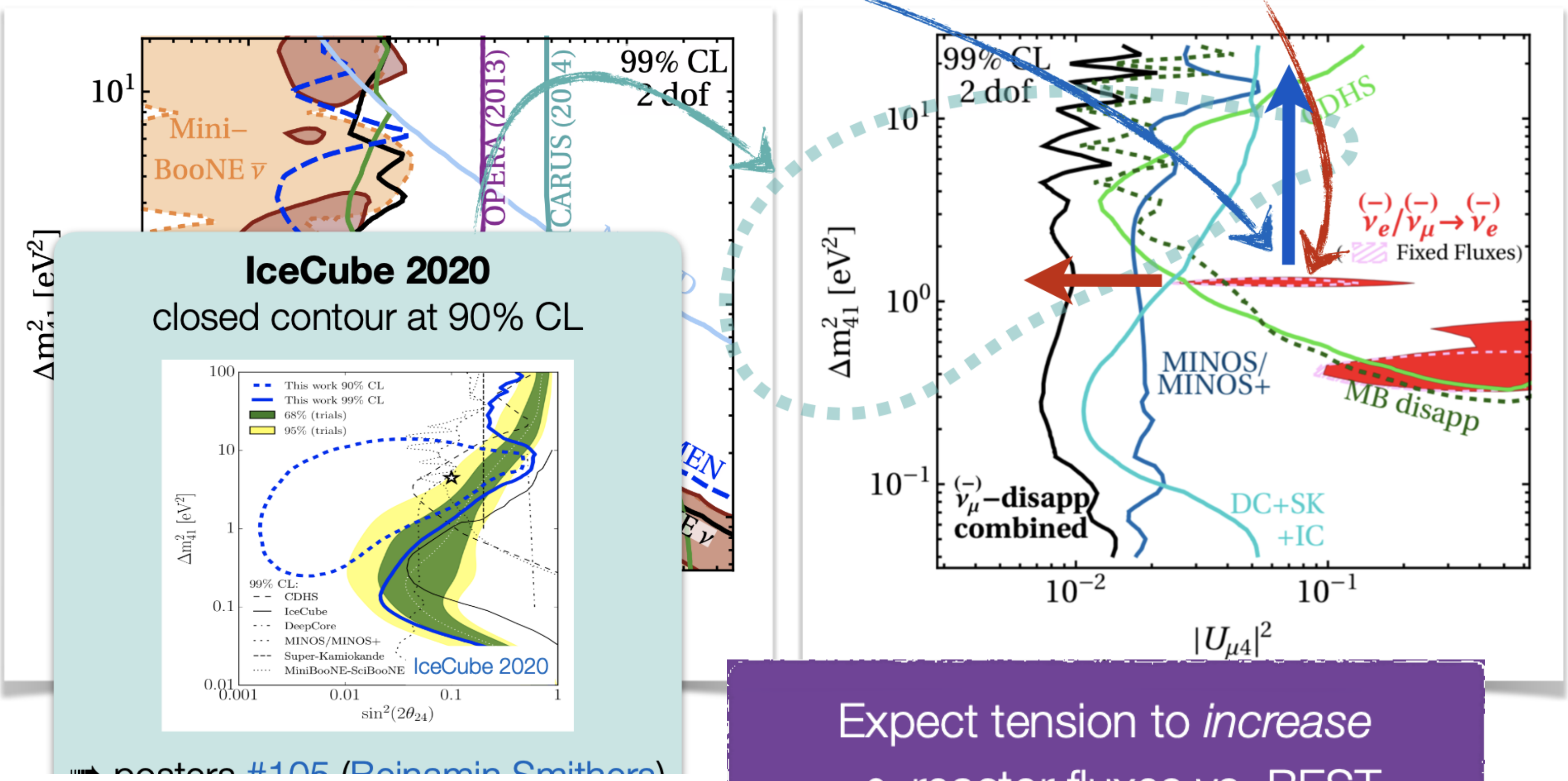
Combined:
0.80 ± 0.05

Summary Plots

Recent Up

BEST and **Neutrino-4**
push towards larger $|\Delta m_{41}|^2$

BEST and **μBooNE**
push towards lower $|U_{\mu 4}|^2$



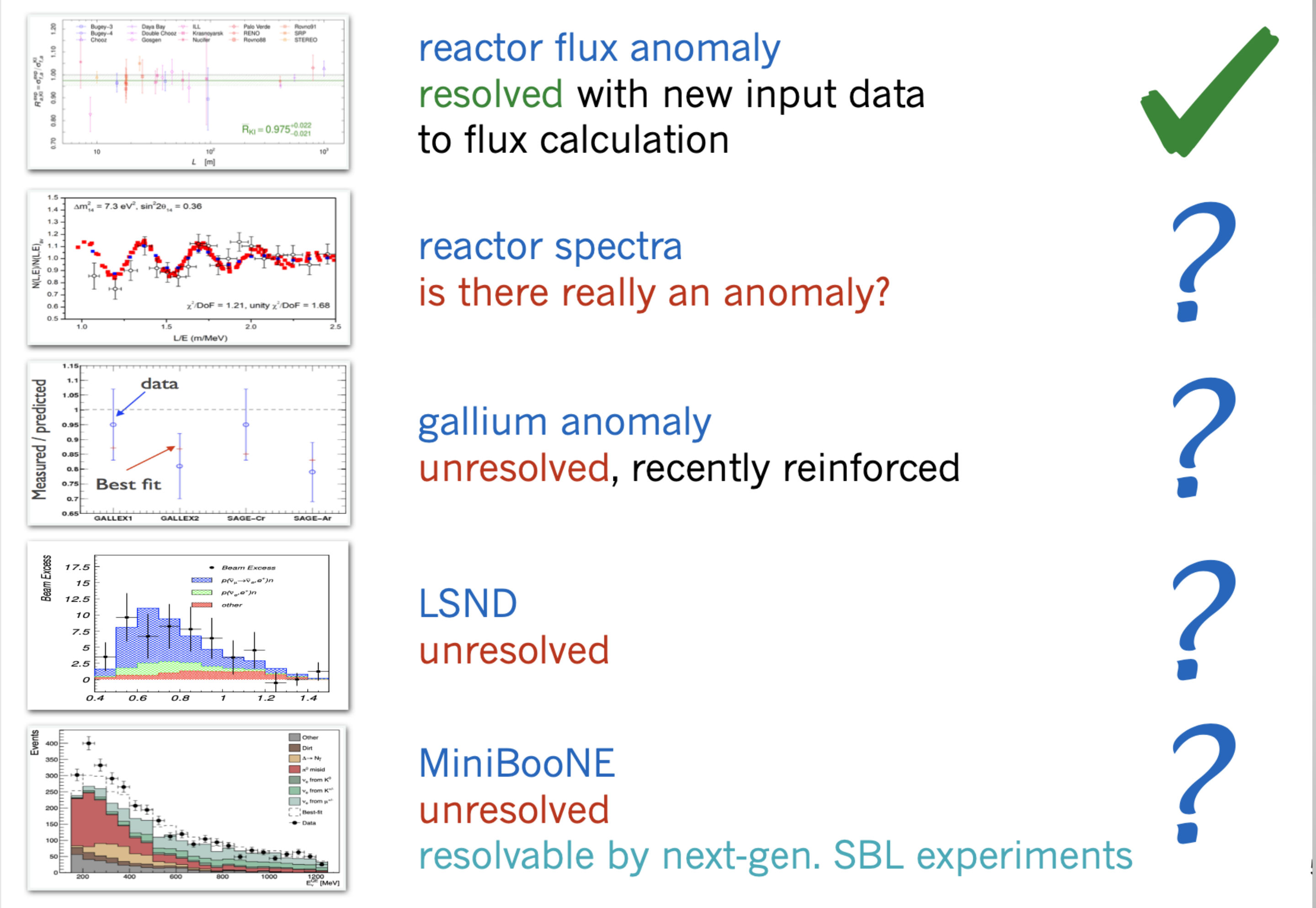
IceCube 2020
closed contour at 90% CL

➡ posters #105 (Benjamin Smithers)

Expect tension to *increase*

- reactor fluxes vs. BEST
- MiniBooNE vs. μBooNE

Neutrino Anomalies



reactor flux anomaly
resolved with new input data
to flux calculation ✓

reactor spectra
is there really an anomaly? ?

gallium anomaly
unresolved, recently reinforced ?

LSND
unresolved ?

MiniBooNE
unresolved
resolvable by next-gen. SBL experiments ?

- Jury still out on many of these anaomalies. No clear picture emerging yet.
- Future: Reactor experiments continuing or new ones (eg JSNS2) or new experiments at the FNAL short neutrino baseline… (ICARUS, SBND)

The Near Future

☑ Look for more exotic signatures (no know SM candidates)

- single-γ production unrelated to the $\Delta(1232)$?
- single electrons unrelated to ν_e?
- boosted e^+e^- pairs?

☑ More data incoming:

- μBooNE / SBND / ICARUS at Fermilab
- SBL reactor + gallium experiments
- JSNS-2
- Long-baseline Experiments, Neutrino Telescopes, ...
- Future Proposals (IsoDAR, ...)

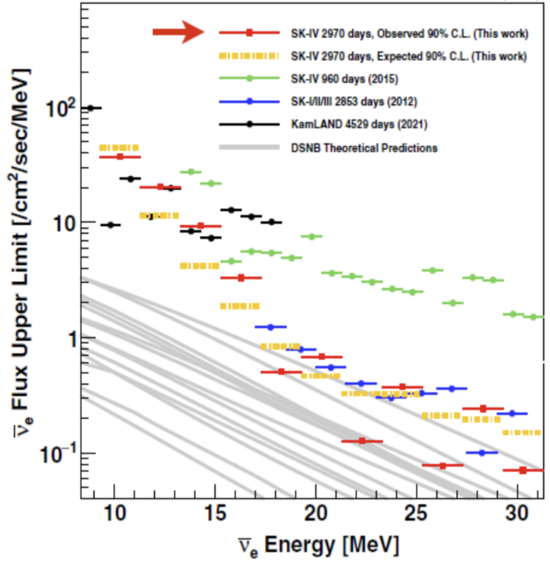
Diffuse Neutrinos

Diffused Supernova Neutrinos

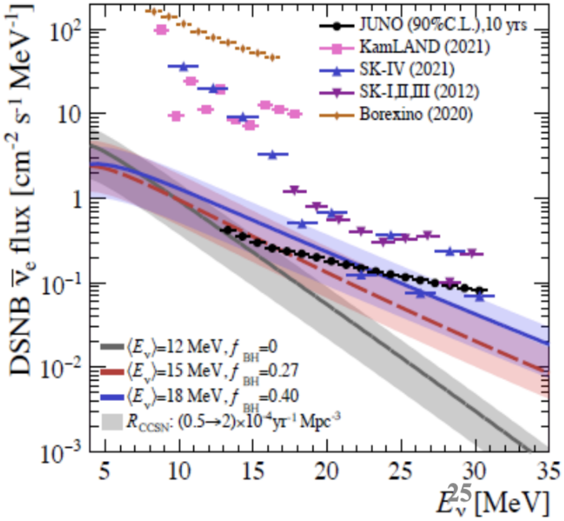
- Latest results from SuperK
    - Sensitive to 1.5 $\overline{\nu}_e$/cm²/s, Horiuchi+09 model is 1.9
    - Combined upper limit of 2.6 $\overline{\nu}_e$/cm²/s
        - Most optimistic signals are excluded
    - Best fit is $1.3^{+0.90}_{-0.85}$ $\overline{\nu}_e$/cm²/s
        - 1.5σ excess over background expectation
  - Signal right at the corner ?
- SuperK-Gd successfully operated for 2 years with 0.01% loading. Phase 2 with 0.03% loading just started
- JUNO can significantly improve the sensitivity
- Future experiments: HyperK, DUNE, THEIA, …
- Shall be discovered in ~15 years from now !

Mastbaum,Vagins,Zhao

PRD **104**, 122002 (2021)



JUNO, arXiv:2205.08830v1



CEvNS

Pershey, Bonifazi, Giunti

Coherent Elastic Neutrino-Nucleus Scattering

New results from COHERENT

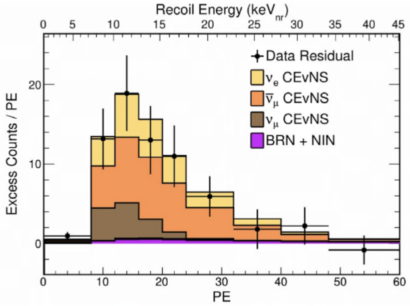
- full-exposure CsI[Na] data: 11.6 σ, shape and rate agrees well with SM
- Ar data: 3 σ
- NSI and dark matter searches

Dresden-II found a strong preference for CEvNS signals at reactors using Ge detector(<3σ)

Tens other experiments at beams and reactors: no signals yet

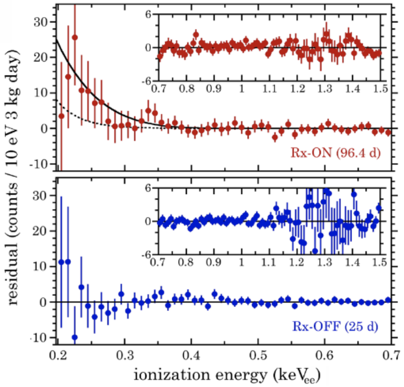
Upgrades and new experiments on the way

Powerful for searches: DM, NSI, Magnetic Moments…



COHERENT CEvNS detectors

Target	Technology	Fid. Mass	Threshold	Deployment
CsI[Na]	Scintillation	14.6	6.5 keV$_{nr}$	2015
Liquid Ar	Scintillation	24.4/610 kg	20 keV$_{nr}$	2017/≈2023
Ge	Ionization	18 kg	0.4 keV$_{ee}$	2022
NaI[Tl]	Scintillation	3500 kg	13 keV$_{nr}$	2022

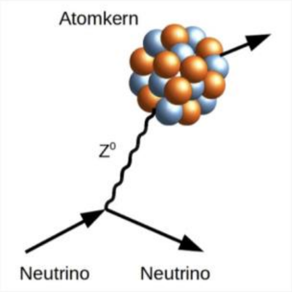


2202.09672

● Future/Planned

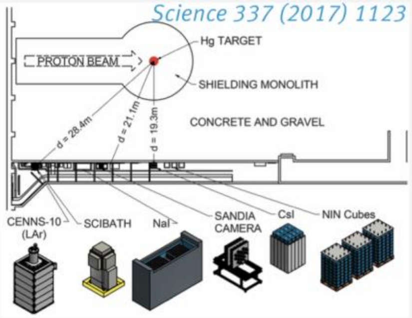
CEνNS: coherent elastic ν nucleon scattering

CEνNS observed on argon by COHERENT

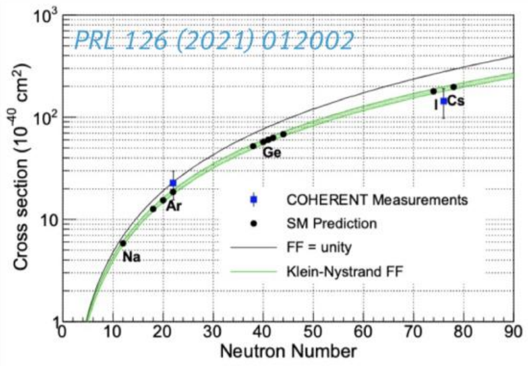


www.mpi-hd.mpg.de

Science 337 (2017) 1123

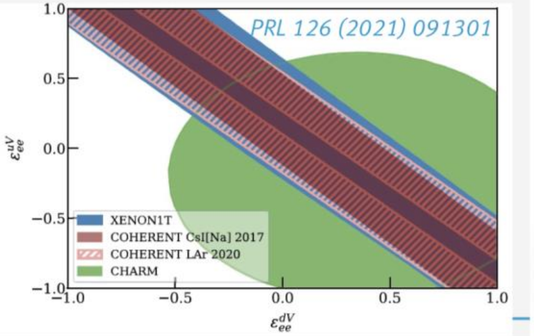


PRL 126 (2021) 012002

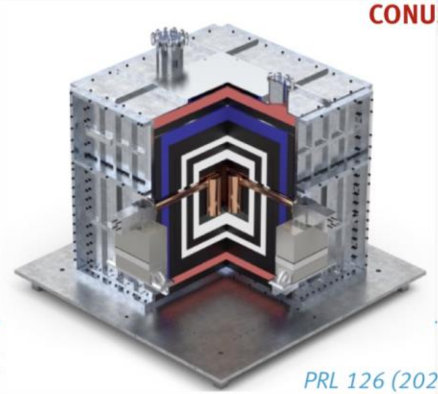


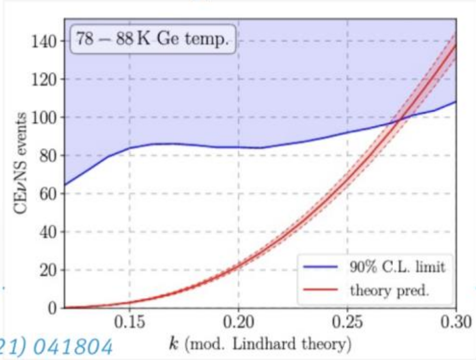
CEνNS open a new window for searching for BSM physics: NSI, Dirac vs Majorana

PRL 126 (2021) 091301



CONUS limit *CEνNS upper limit on Ge*

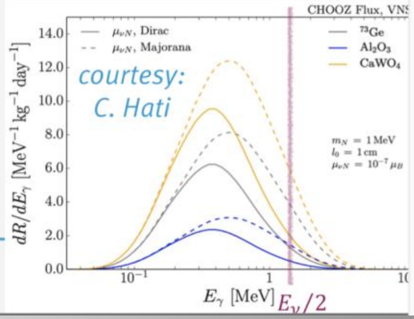




PRL 126 (2021) 041804

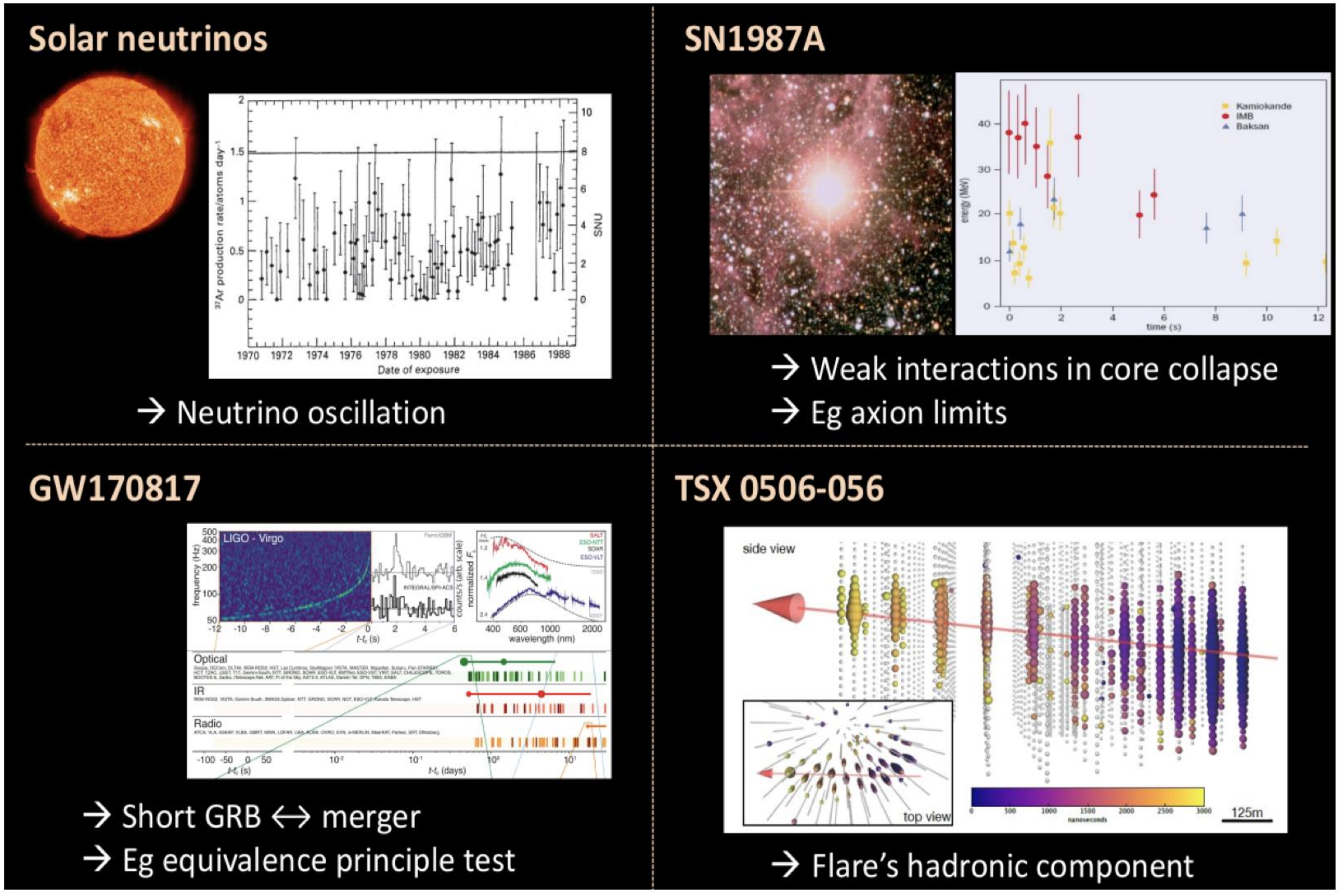
NUCLEUS@CHOOZ

e.g. differentiate Dirac/Majorona ν in radiative CEνNS



More Neutrinos

Neutrinos as messengers



Solar neutrinos

→ Neutrino oscillation

SN1987A

→ Weak interactions in core collapse
→ Eg axion limits

GW170817

→ Short GRB ↔ merger
→ Eg equivalence principle test

TSX 0506-056

→ Flare's hadronic component

Neutrinos are one leg of multi-messenger astronomy

Combination with photons from radio to gamma rays
and gravitational waves

Figures from SNOWMASS neutrino colloquium by S. Horiuchi

Next Generation Experiments

European Spallation Source, Lund

ESSνSB

ESS NEUTRINO SUPER BEAM

Goal: CPV via targeted measurements at 2nd Oscillation Max

Neutrino Superbeam at
European Spallation Source

Lund, Sweden

360 km

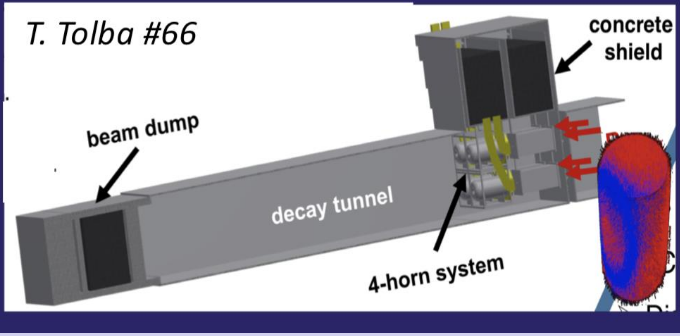
540 km

Also about 10^{20} μ/year produced---provides R&D opportunity for Neutrino Factory or muon collider

@ Far Site:

- Megaton-scale underground Water Cherenkov detector
  Allows broad program including
  PDK, astrophysical νs

- 5 MW/2.5 GeV protons
- accumulation ring of ~400 m
  - Shortens pulse from 2.86 ms to few μs
  - Required by 350 kA horn
  - Also allows for decay-at-rest experiments using neutron target
- 4 target/horn system, 25 m decay tunnel
  - ~300 MeV neutrinos
- near detector

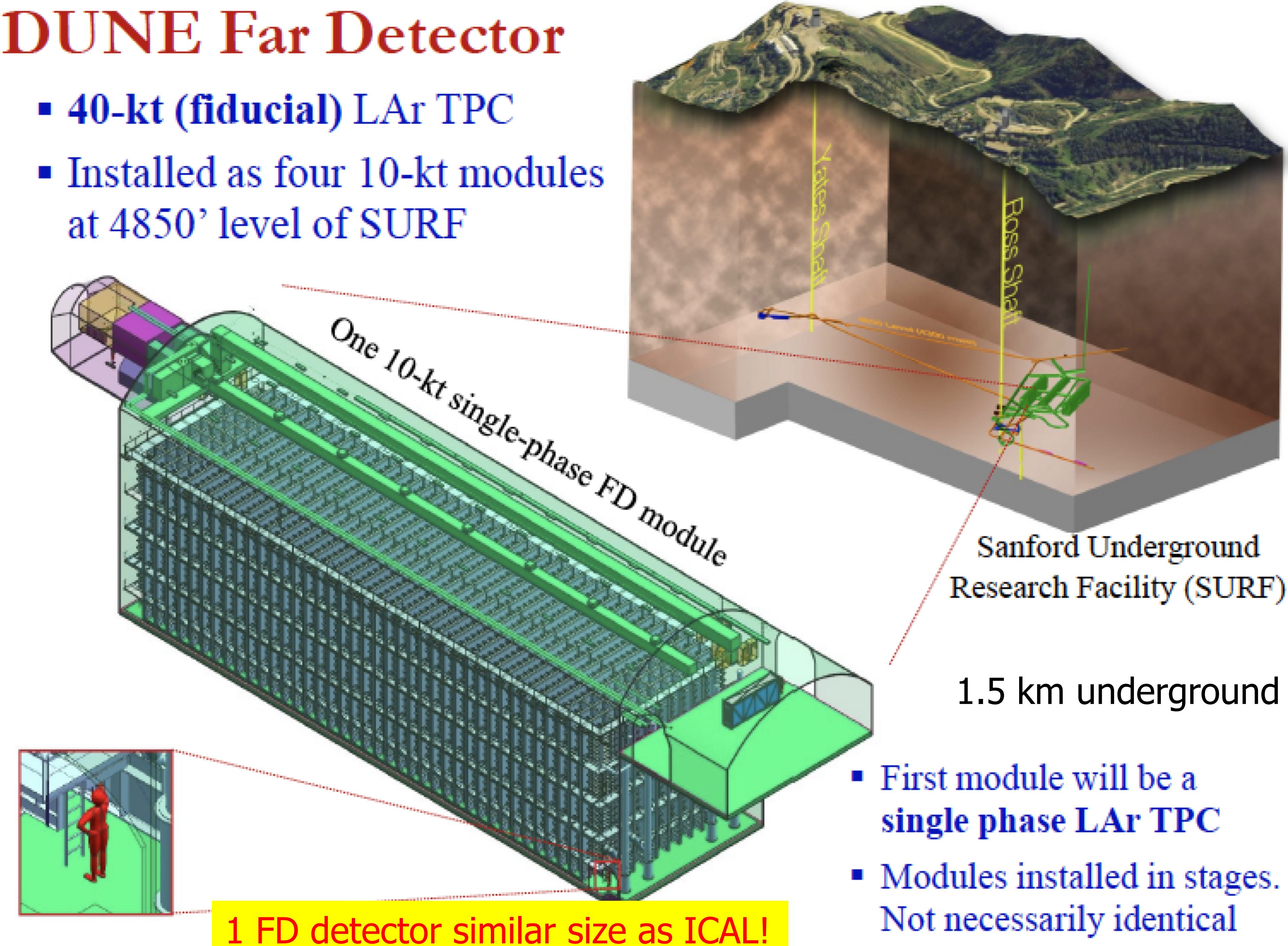


Also: new/tagged beams
NuStorm muon storage ring
...

Experiments ready by ~2035?

DUNE Far Detector

- **40-kt (fiducial)** LAr TPC
- Installed as four 10-kt modules at 4850’ level of SURF



One 10-kt single-phase FD module

Sanford Underground Research Facility (SURF)

1.5 km underground

- First module will be a **single phase LAr TPC**
- Modules installed in stages. Not necessarily identical

1 FD detector similar size as ICAL!

Summary

- In ~10 years from now, oscillation will mostly be understood: mass hierarchy and CP phase will be known
- Neutrino absolute masses may be measured in ~20 years, through cosmology, beta decays and double beta decays
- Majorana neutrino nature maybe determined in ~30 years
- Sterile neutrinos are unlikely the cause of reactor and Ga anomalies, but still possible for the LSND anomaly
- A new era of astrophysics with multi-messengers, including neutrinos
- Many new projects will start within 10 years
- A bright future