Neutrinos!

Present Understanding & Future Prospects

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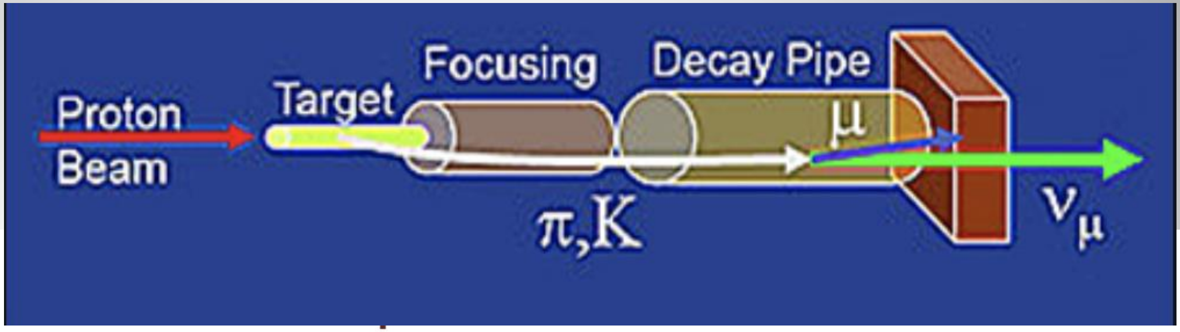
2 Lectures

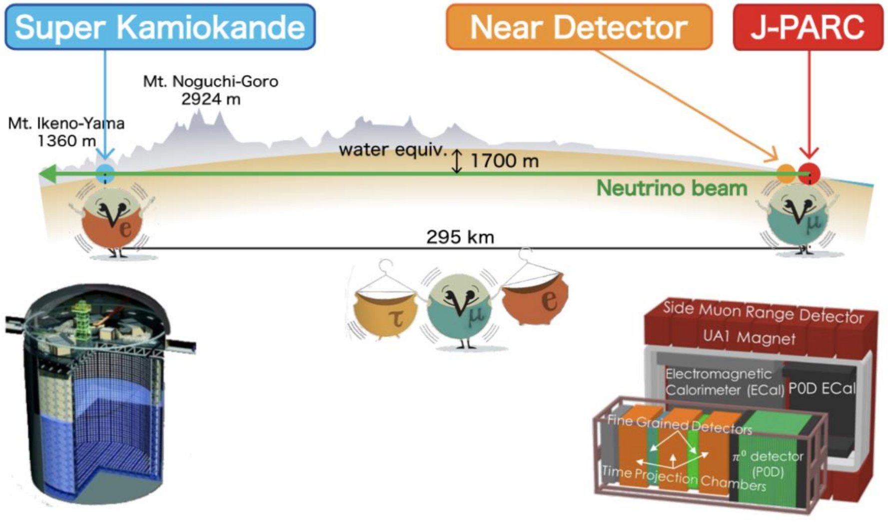
- Lecture 1:
  - Introduction to neutrinos
  - History of neutrino physics and open questions.
  - Neutrino oscillation physics (part I)
- Lecture 2:
  - Neutrino oscillation physics (part II)
  - Neutrino properties
  - Cosmological neutrinos
  - Searches for the 4th generation
  - Next generation of neutrino experiments & LHC

Accelerator Based Neutrino Experiments

Neutrinos from accelerators

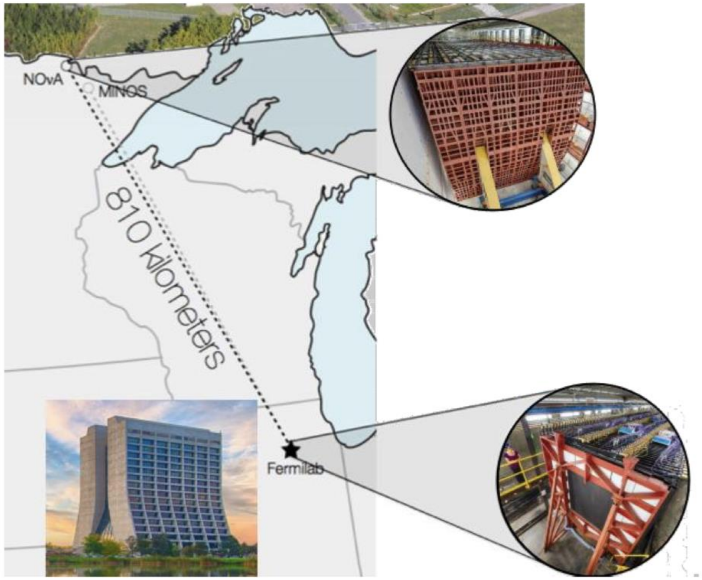


T2K



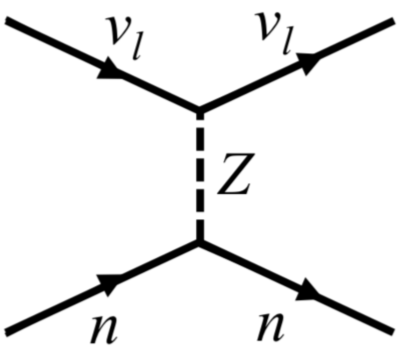
Baseline: 295 km
Peak E_ν: ~0.6 GeV (off-axis)
Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

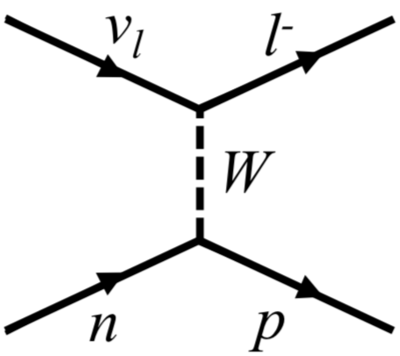


- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

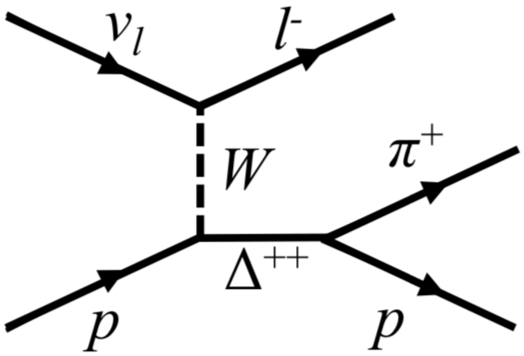
Neutrino Interactions



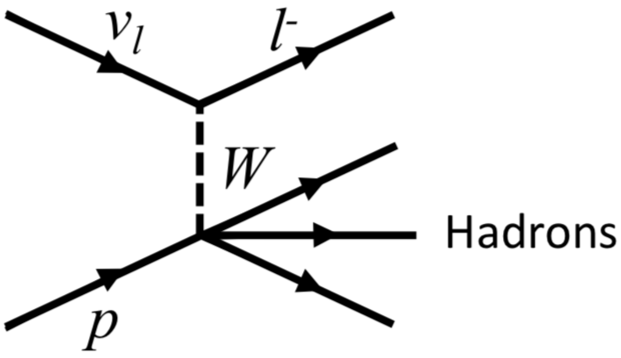
Elastic scattering



Quasi-elastic scattering
(lowest energies)

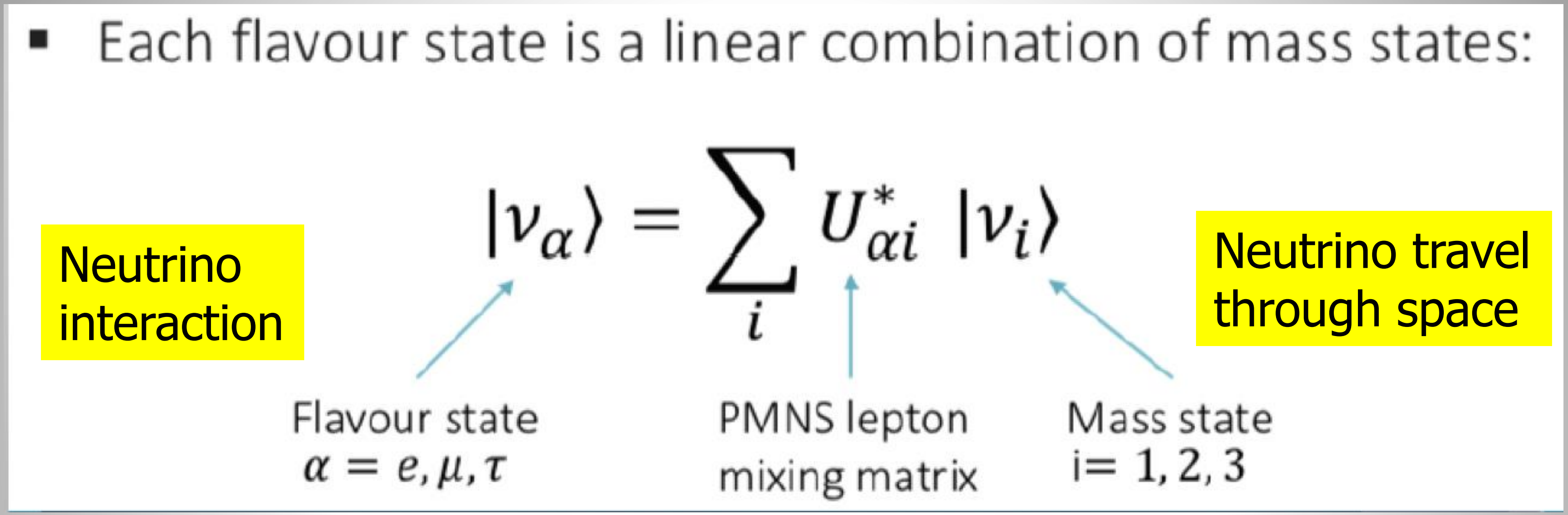


Resonance
(Energies ~1 GeV)



Deep inelastic scattering
Highest energies (>1 GeV)

Neutrino oscillations



- Each flavour state is a linear combination of mass states:

Neutrino interaction

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \; |\nu_i\rangle$$

Neutrino travel through space

Flavour state
$\alpha = e, \mu, \tau$

PMNS lepton mixing matrix

Mass state
i= 1, 2, 3

Flavor states

(*) Pontecorvo-Maki-Nakagawa-Sakata Matrix

ELECTRON-NEUTRINO
This minuscule bandit is so light, he is practically massless.

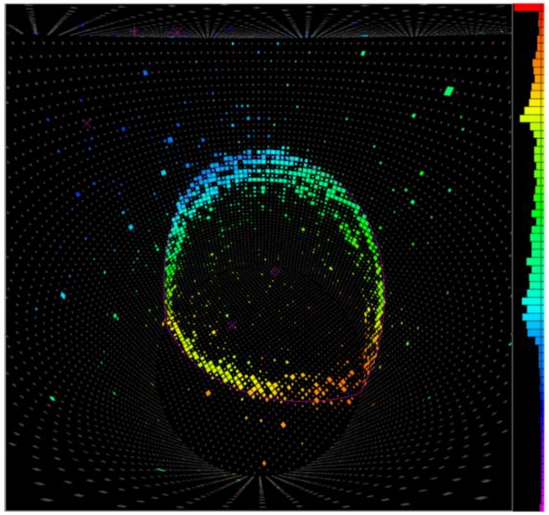
MUON-NEUTRINO
Like the other 2 neutrinos, he's got an identity crisis from oscillation.

TAU-NEUTRINO
He's a tau now, but what type of neutrino will he be next?

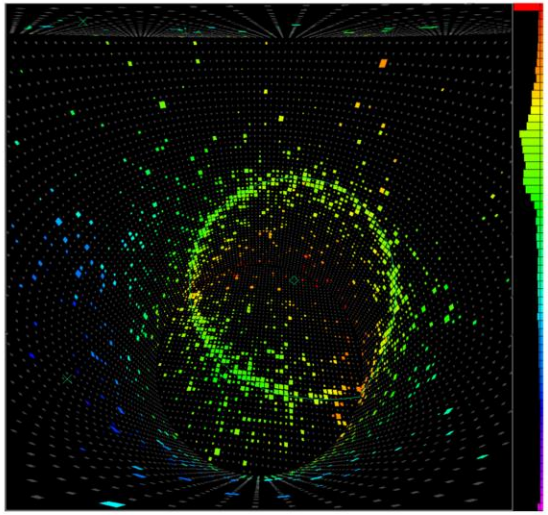
NB: charged leptons are mass eigenstates and don't oscillate!

Example: Interactions in SuperKamiokande

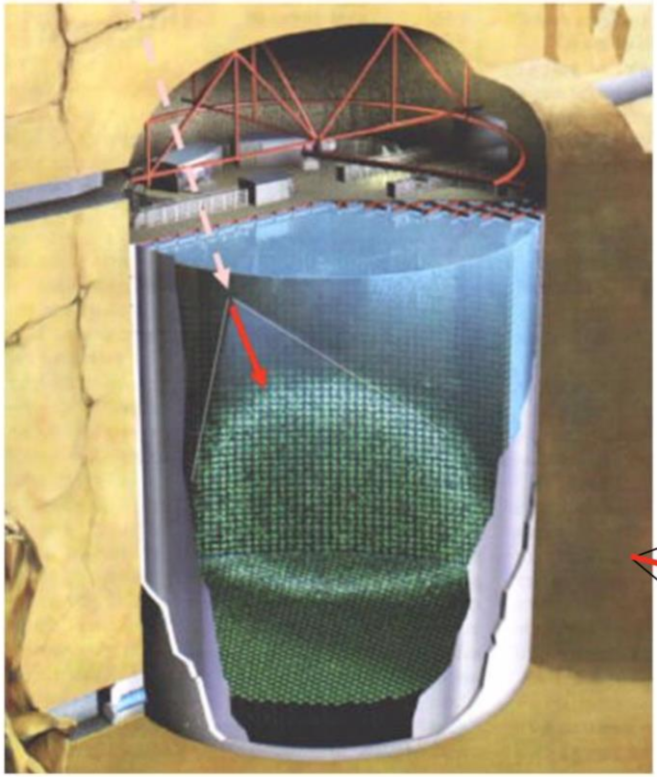
SK is the large detector of the T2K experiment

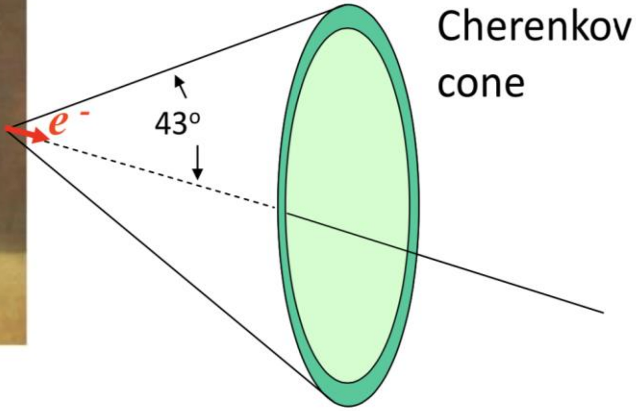


$$\nu_\mu + X \rightarrow \mu^- + X'$$



$$\nu_e + X \rightarrow e^- + X'$$

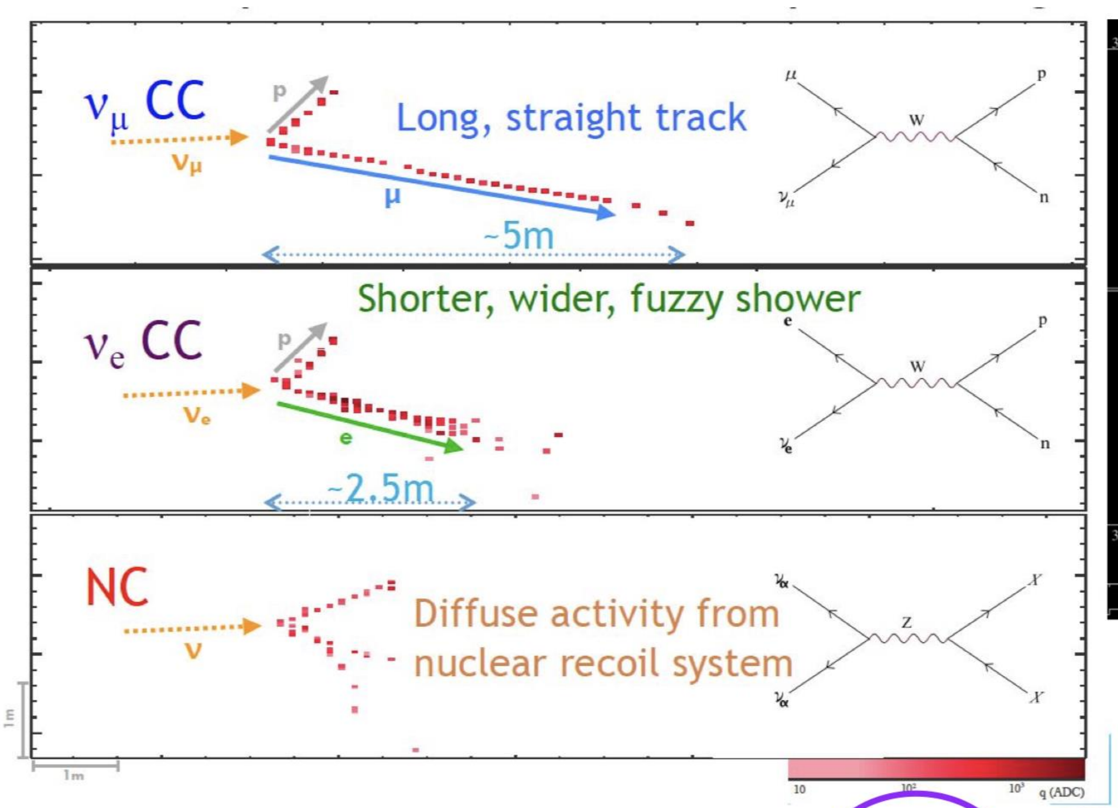


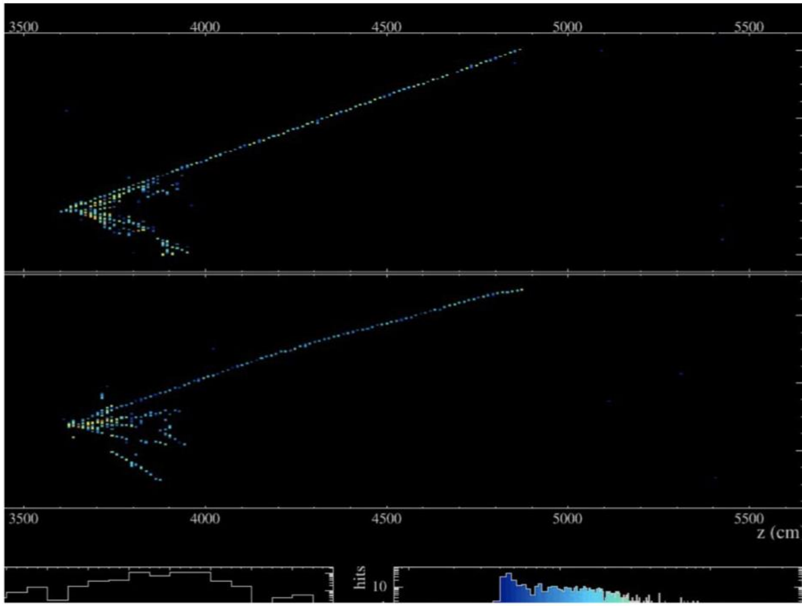


Electrons have more multiple scattering on the water ->
Rings are more fuzzy

Example: Interactions in NOvA

NOvA: Liquid Scintillator Detector (cell readout)

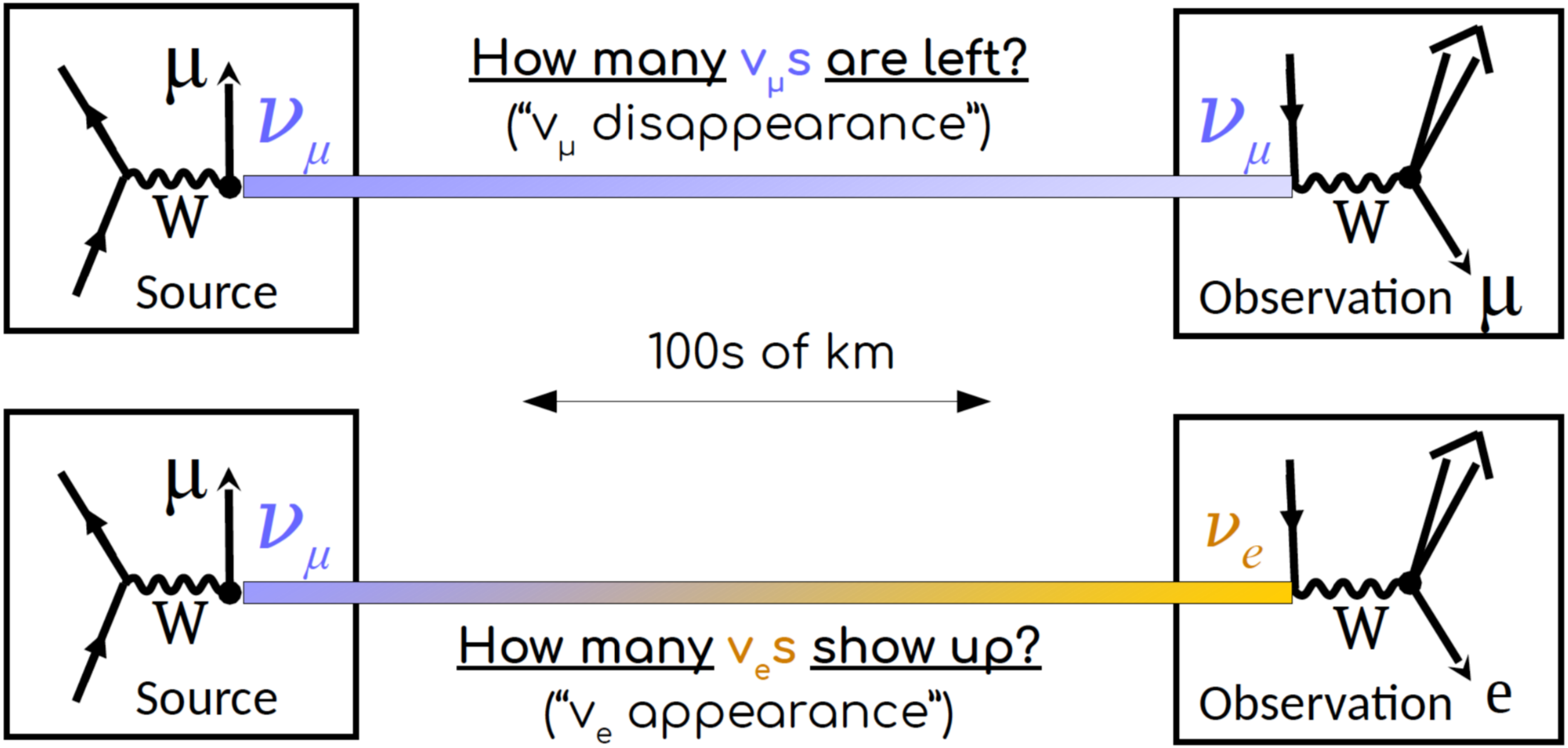




Credit: NOvA collaboration

$$N_{FD} \sim \Phi(E_\nu)\boxed{\sigma(E_\nu)}\boxed{\epsilon_{FD}}P(\nu_\mu \rightarrow \nu_e)$$

Extracting the Information



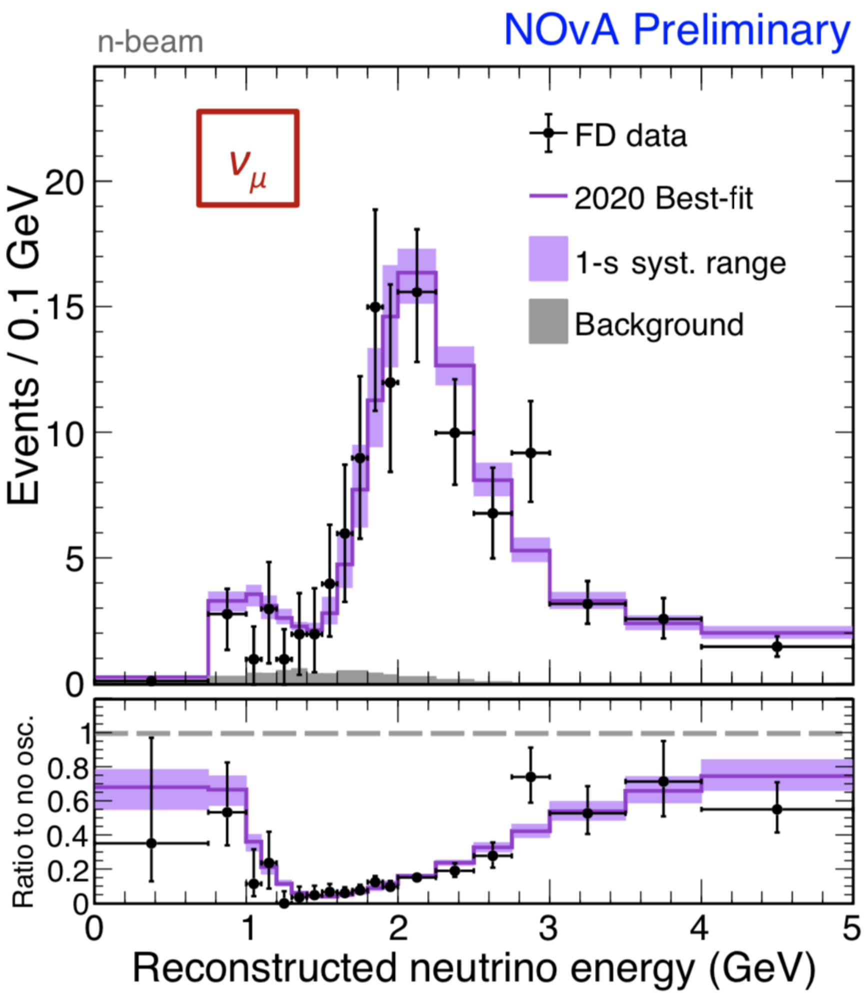
How many ν_μs are left?
("ν_μ disappearance")

100s of km

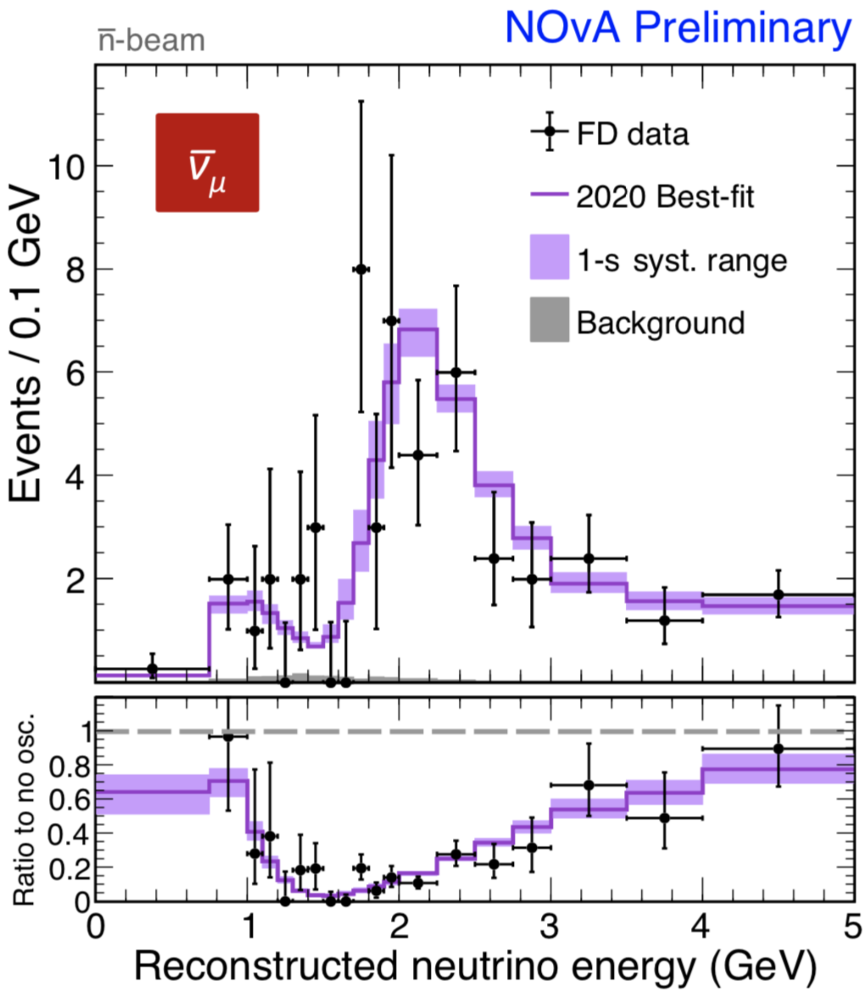
How many ν_es show up?
("ν_e appearance")

CPV: Do neutrinos and anti-neutrinos oscillate differently ?

Muon Neutrino Disappearance



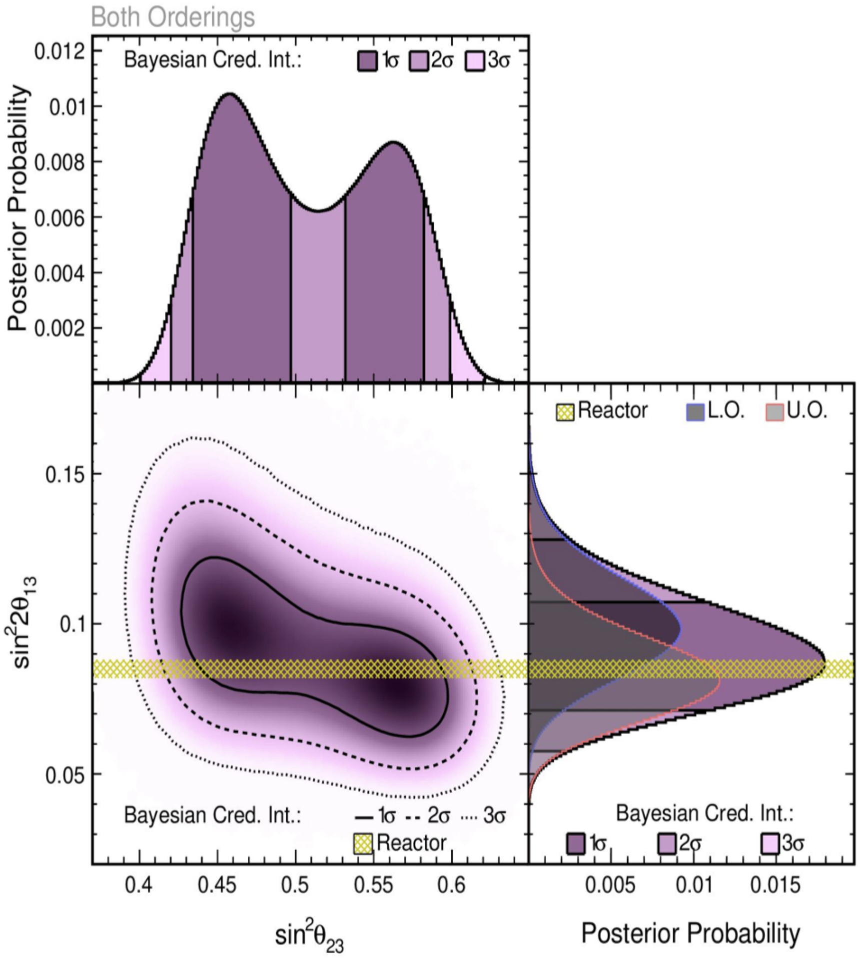
211 events, 8.2 background



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 with Neutrinos?

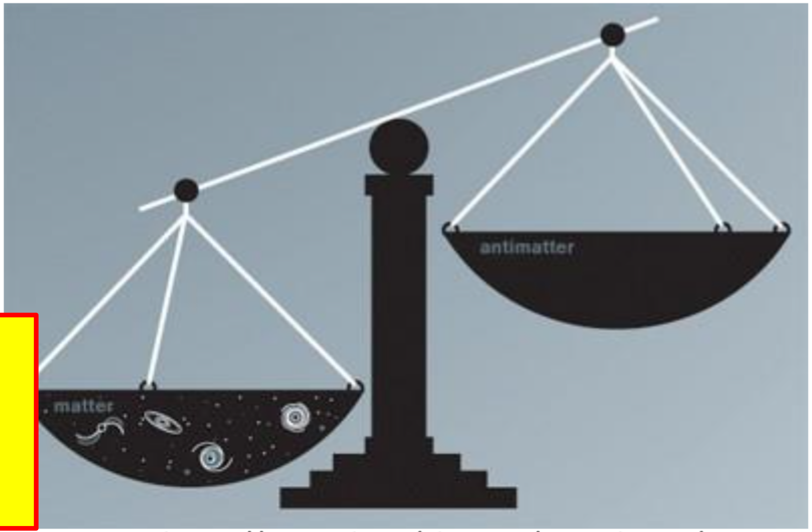
Do neutrinos and anti-neutrinos oscillate differently ?

CP violation

- One of major questions in physics
  - Why is our Universe mostly matter? Where is antimatter?
- Possible answer is CP violation
  - Observed CP violation in strong sector is too small to explain this
  - CP violation in lepton sector may be solution
    - Measuring δ_{CP} will help

☆ $\sin\delta \neq 0$?

Leptonic CP violation?



https://essnusb.eu/glossary/cp-violation/

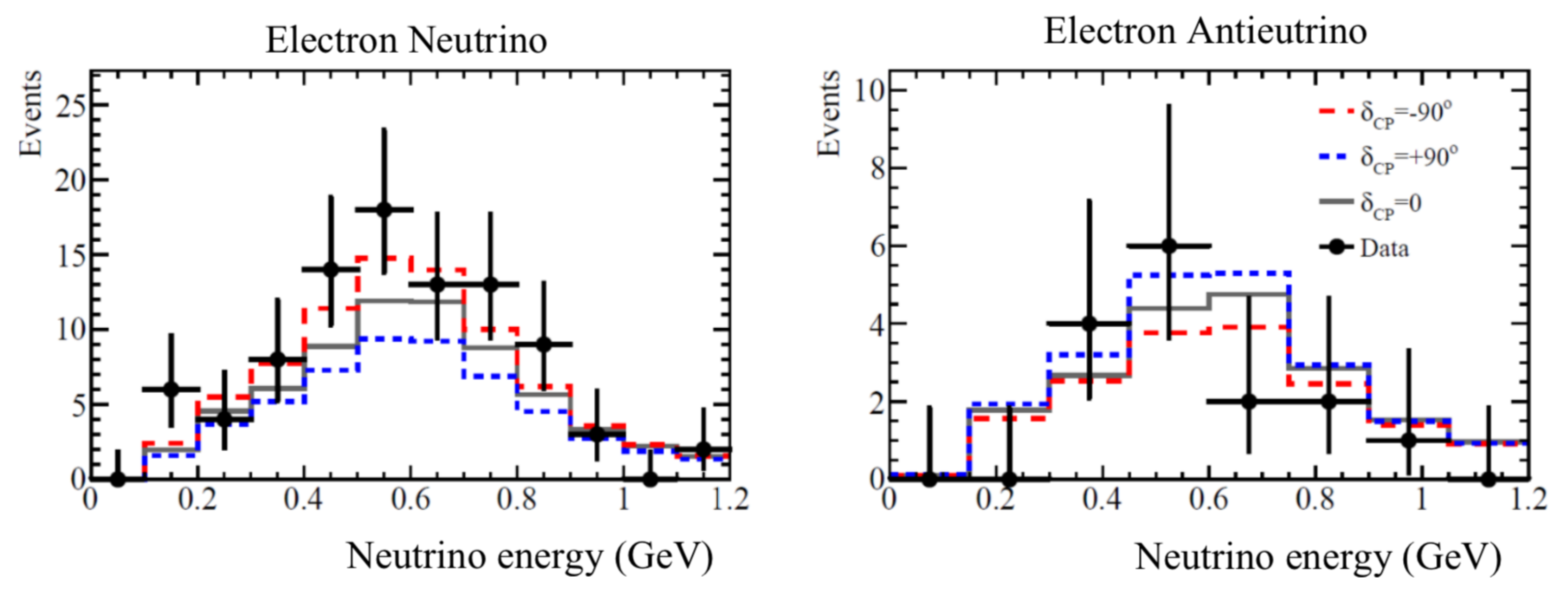
Neutrinos could be the key to one of the most important questions today:
Where is the anti-matter in our Universe?

CP Violation: T2K Measurement

Do neutrinos and anti-neutrinos oscillate differently ?

Measured versus expected electron-(anti)neutrino events in SK as function of the assumed CP- angle

	Expected If δ=0	Expectation	
		$\delta_{CP} = -90°$	$\delta_{CP} = +90°$
Electron neutrino	70	82	56
Electron antineutrino	20	17	22



CP Violation: T2K Measurement

The international journal of science / 16 April 2020

nature

THE MIRROR CRACK'D

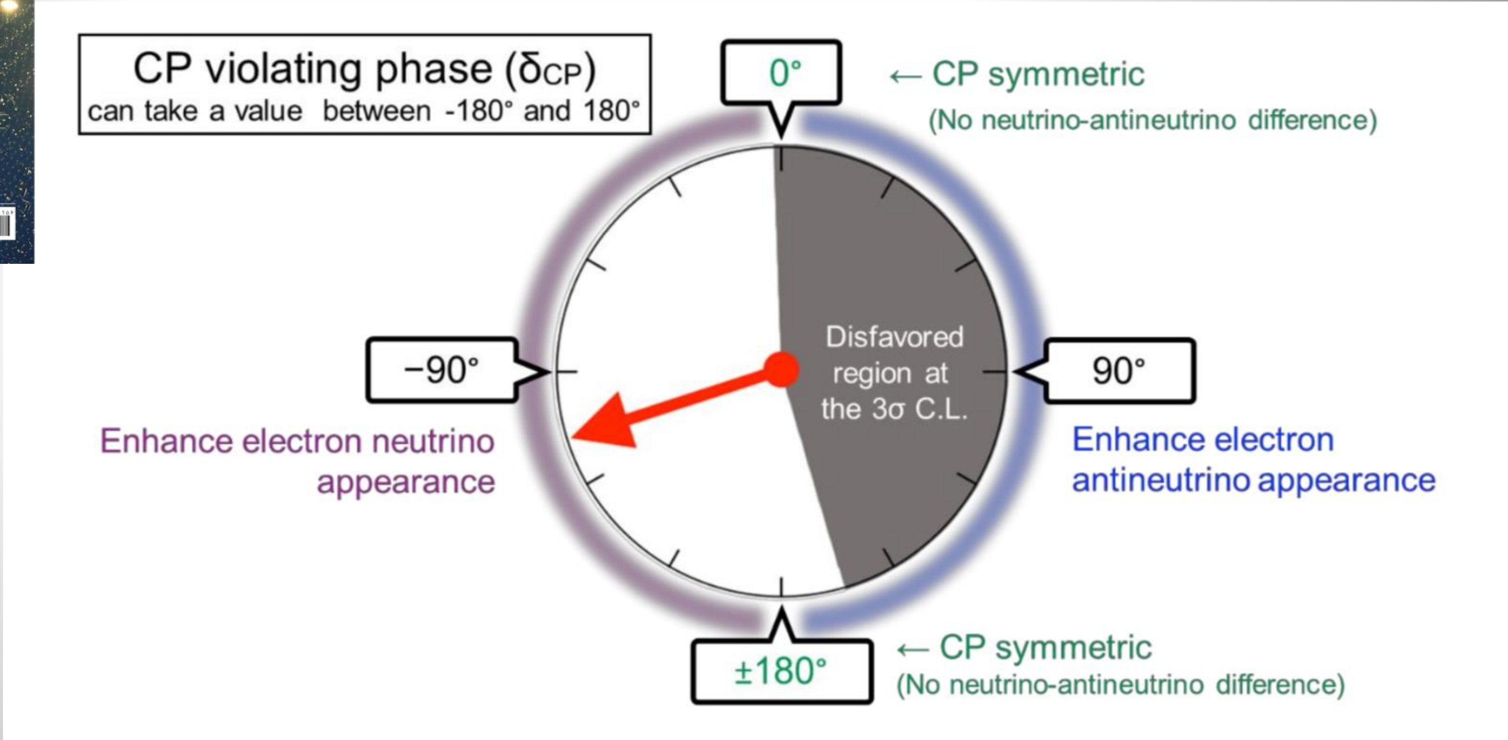
An indication of matter–antimatter symmetry violation in neutrinos

Coronavirus The models driving the global response to the pandemic

Hot source Remnants of primordial nitrogen in Earth's mantle

Origin of a species Revised age for Broken Hill skull adds twist to human evolution

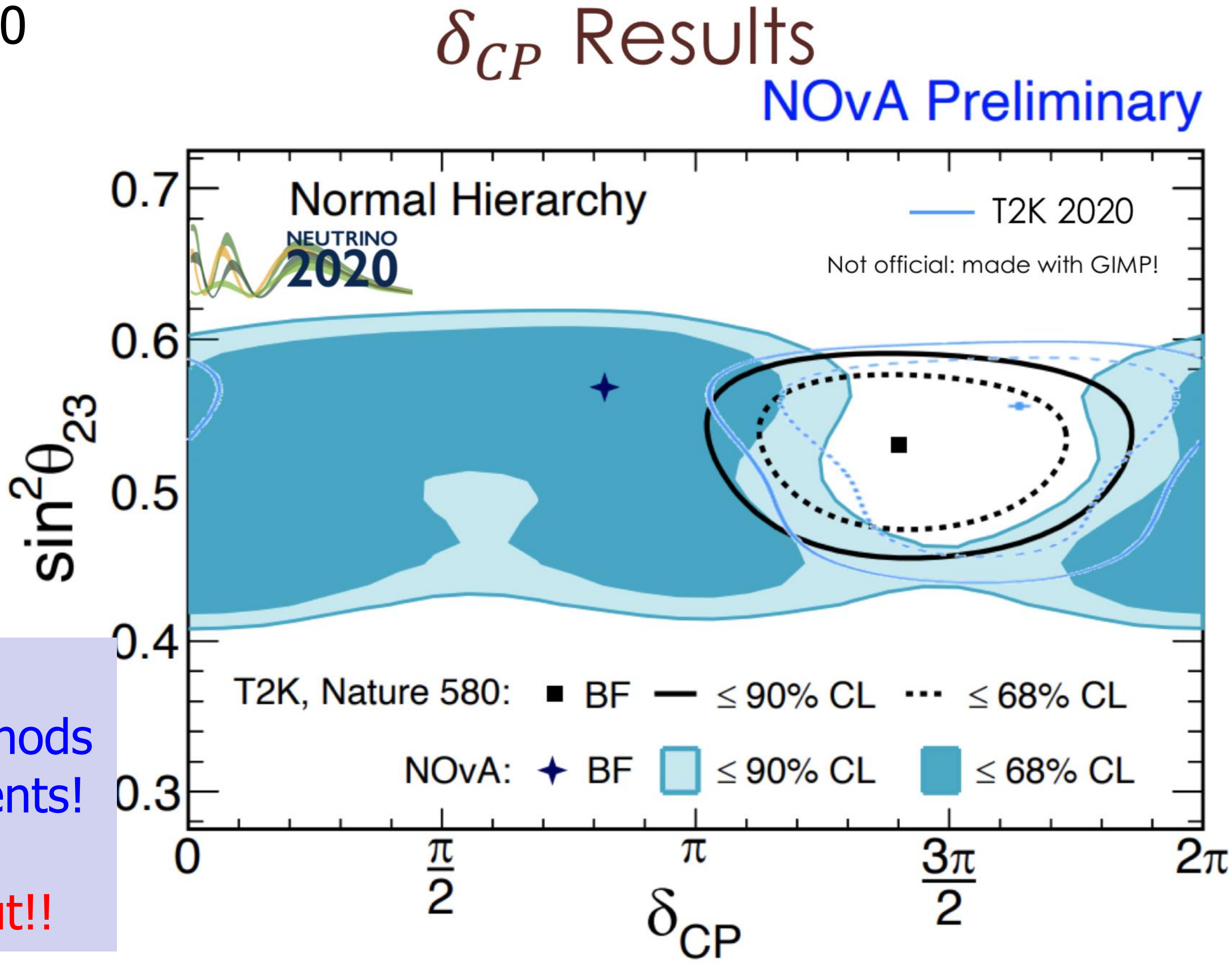
Nature Magazine April 16/4/2020
and arXiv:: 1910.03887



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

CP Violation T2K/NOvA Results

Summer 2020 update



Good to have different methods and experiments!

Jury is still out!!

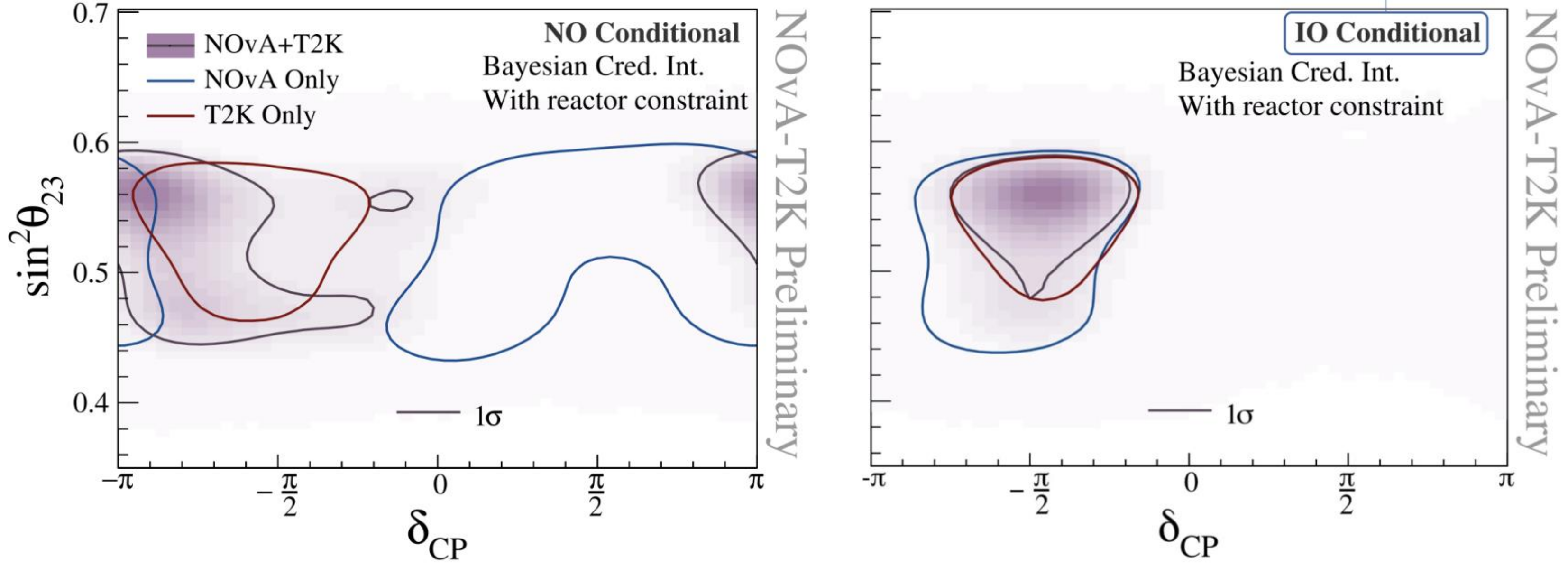
Tension between NOvA and T2K results! Joint analysis required?
-> more experimental data needed

NOvA/T2K Joint Analysis

NOvA-T2K joint fit: PMNS parameters

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

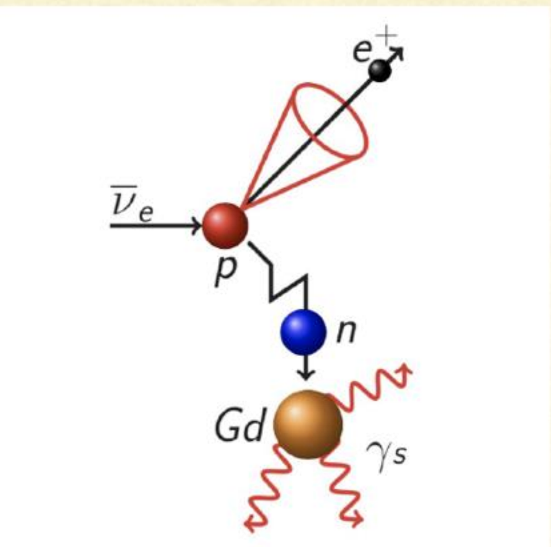
"assuming IO is true"
(does not include relative probability of IO vs. NO)



- Yield **strong constraint on Δm^2_{32}**
- Weakly prefer IO or NO depending on which reactor constraint is applied
- **Strongly favor CP violation in Inverted Ordering**

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

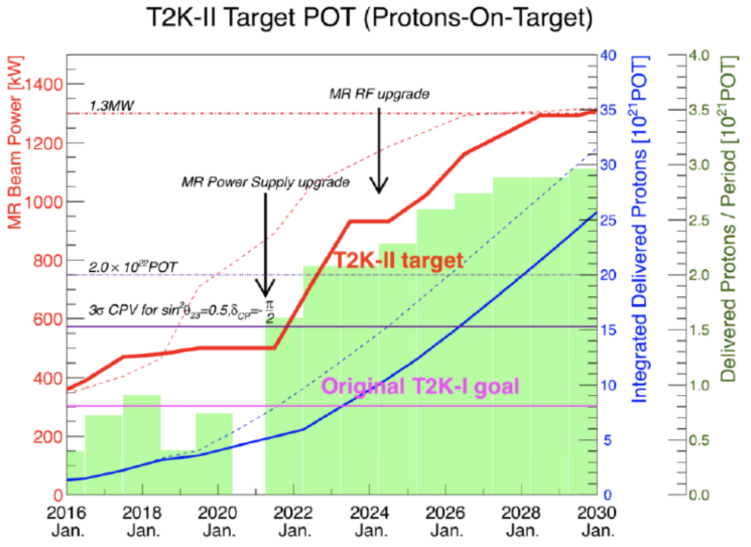


8 MeV γ cascade

Accumulate more data in the next years

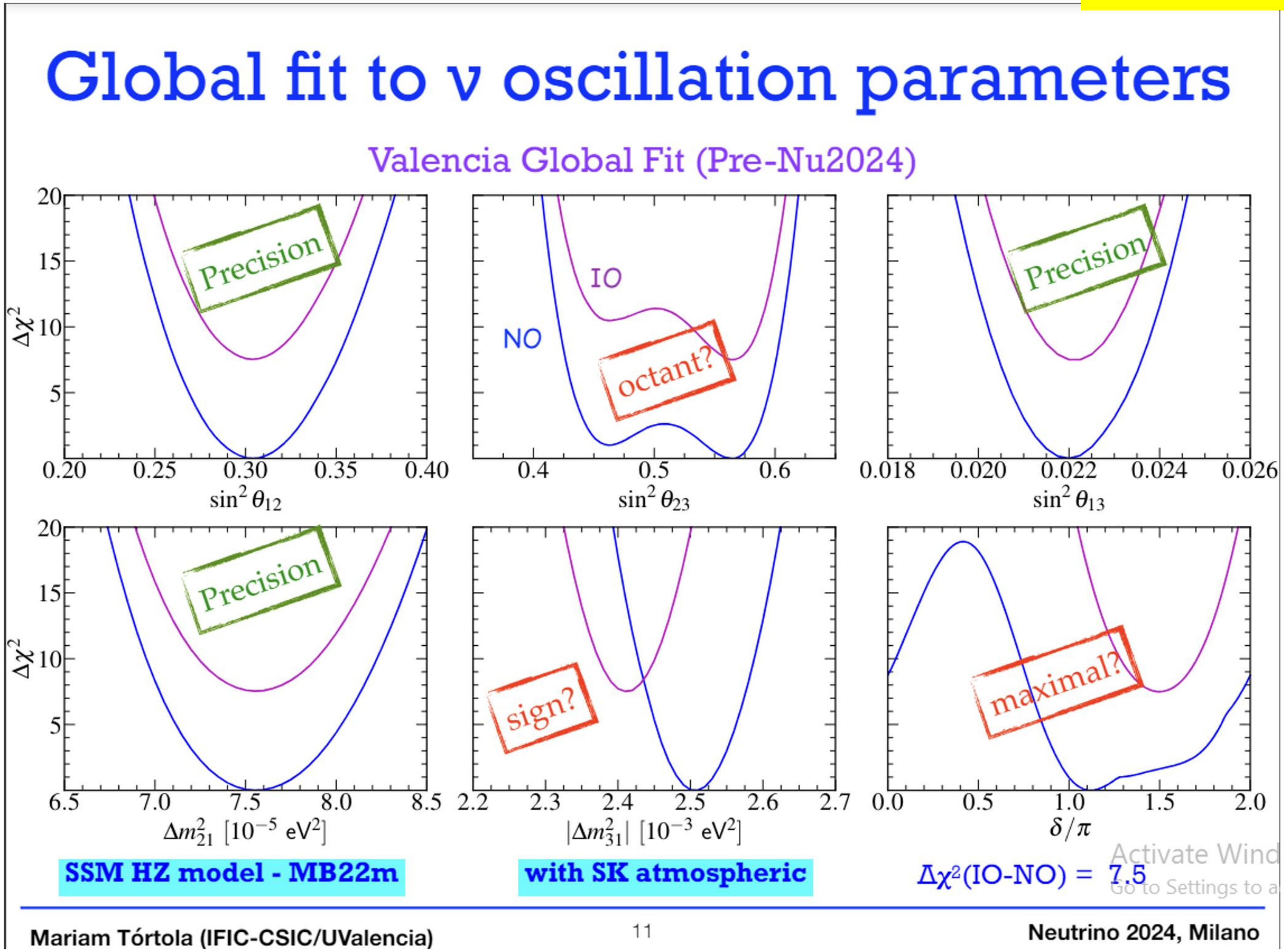
- Reduce systematics uncertainties
- Replica of the beam target has been put proton beam of NA61 this summer
- Reach 3σ for non-CPV rejection prior to Hyper-Kamiokande
- T2K+HK atmospheric joint fit

+ upgrade of the ND280 near detector



Recent Global Neutrino Data Fits

Neutrino2024



Global fit to ν oscillation parameters

Valencia Global Fit (Pre-Nu2024)

SSM HZ model - MB22m

with SK atmospheric

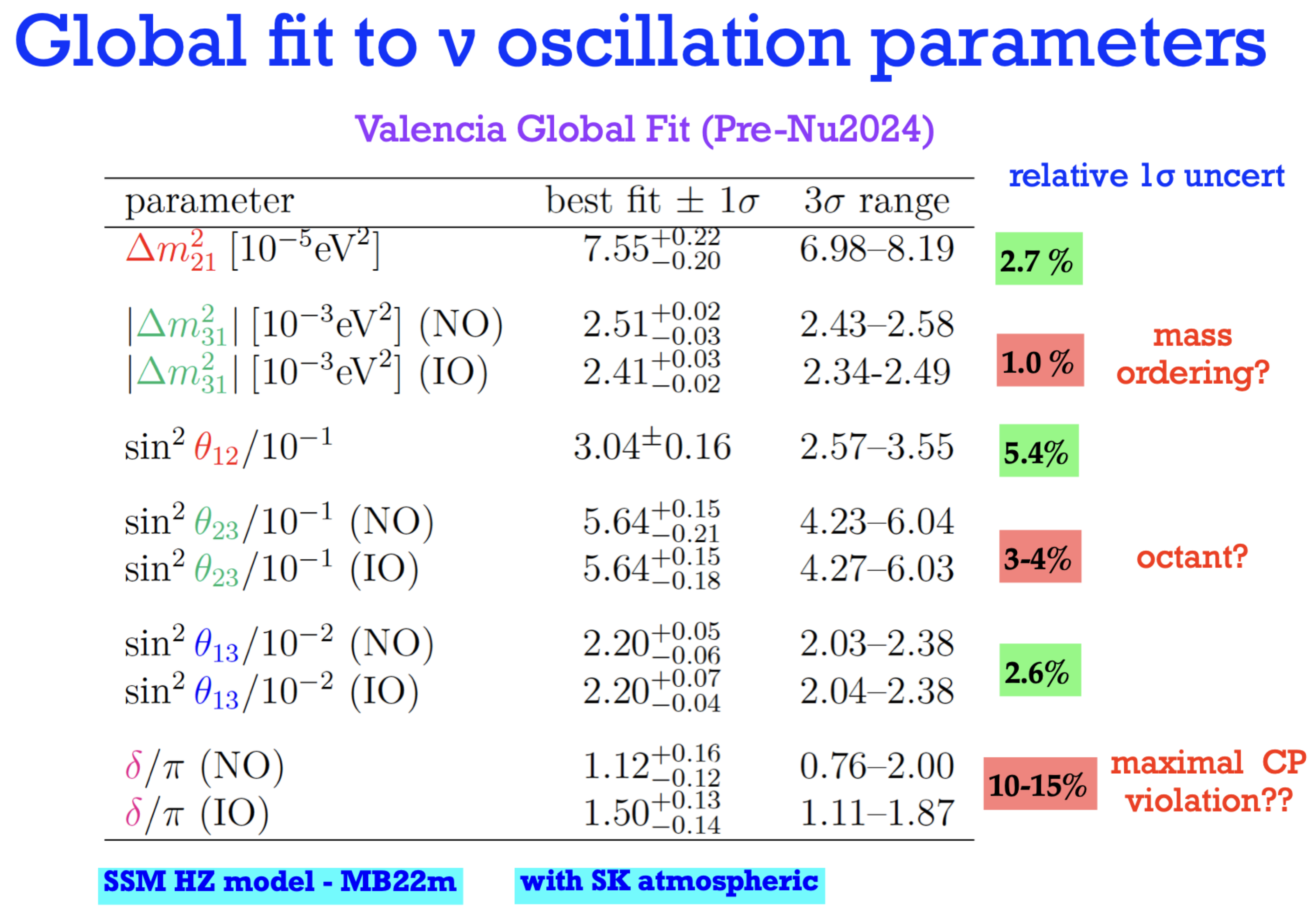
$\Delta\chi^2$(IO-NO) = 7.5

No conclusion yet concerning the mass ordering or the T (CP) violation! <u>5σ wanted</u>

Recent Global Neutrino Data Fits

Recent 3-neutrino global analysis

Neutrino2024



Global fit to ν oscillation parameters

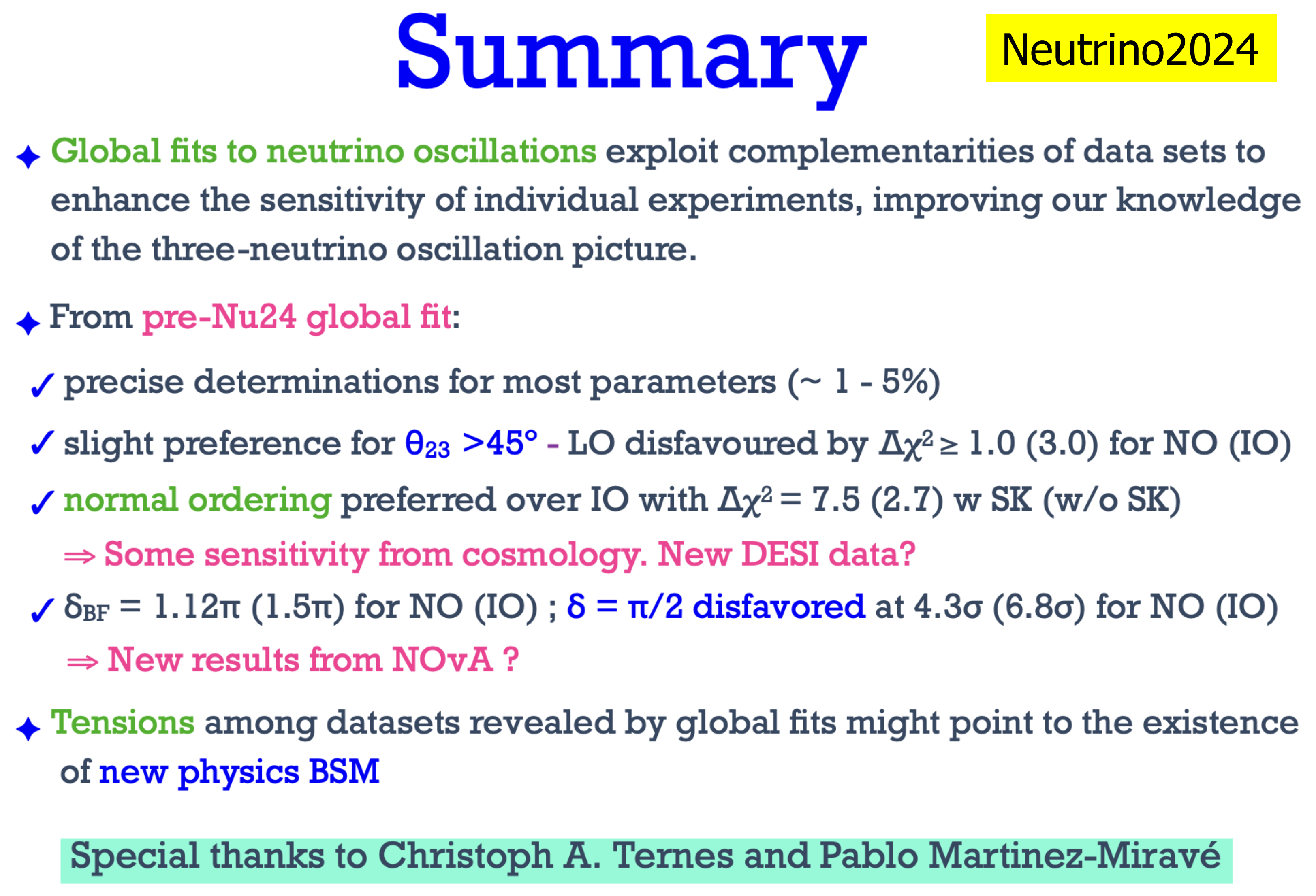
Valencia Global Fit (Pre-Nu2024)

parameter	best fit ± 1σ	3σ range	relative 1σ uncert	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	**2.7 %**	
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	**1.0 %**	mass ordering?
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.41^{+0.03}_{-0.02}$	2.34-2.49		
$\sin^2\theta_{12}/10^{-1}$	3.04 ± 0.16	2.57–3.55	**5.4%**	
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	**3-4%**	octant?
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03		
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38	**2.6%**	
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38		
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	**10-15%**	maximal CP violation??
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87		

SSM HZ model - MB22m

with SK atmospheric

Results of Global Fits



Summary

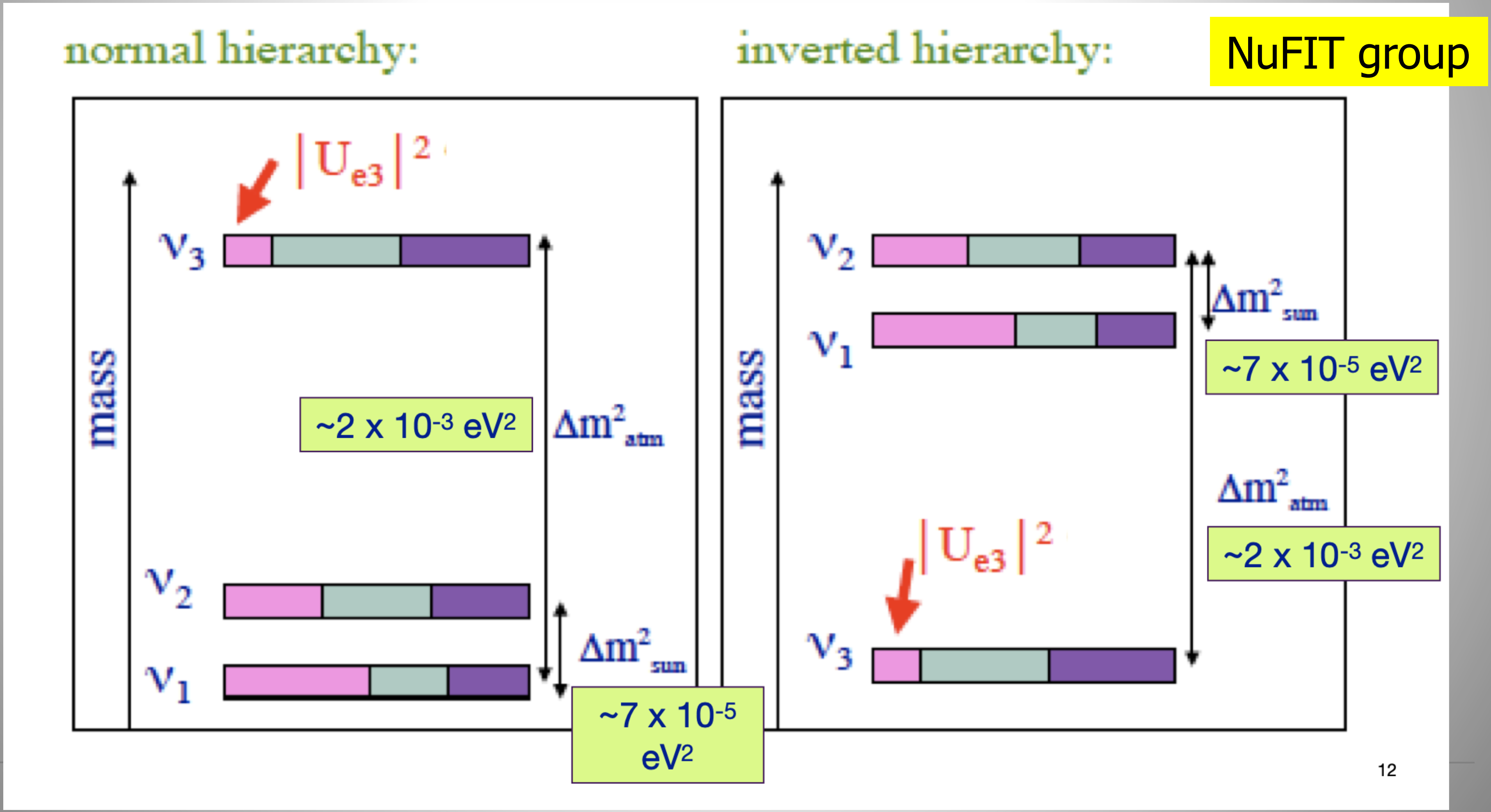
Neutrino2024

- Global fits to neutrino oscillations exploit complementarities of data sets to enhance the sensitivity of individual experiments, improving our knowledge of the three-neutrino oscillation picture.
- From pre-Nu24 global fit:
  - ✓ precise determinations for most parameters (~ 1 - 5%)
  - ✓ slight preference for $\theta_{23} > 45°$ - LO disfavoured by $\Delta\chi^2 \geq 1.0$ (3.0) for NO (IO)
  - ✓ normal ordering preferred over IO with $\Delta\chi^2 = 7.5$ (2.7) w SK (w/o SK)
    - ⇒ Some sensitivity from cosmology. New DESI data?
  - ✓ $\delta_{BF} = 1.12\pi$ (1.5π) for NO (IO) ; $\delta = \pi/2$ disfavored at 4.3σ (6.8σ) for NO (IO)
    - ⇒ New results from NOvA ?
- Tensions among datasets revealed by global fits might point to the existence of new physics BSM

Special thanks to Christoph A. Ternes and Pablo Martinez-Miravé

General Picture

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



NuFIT group

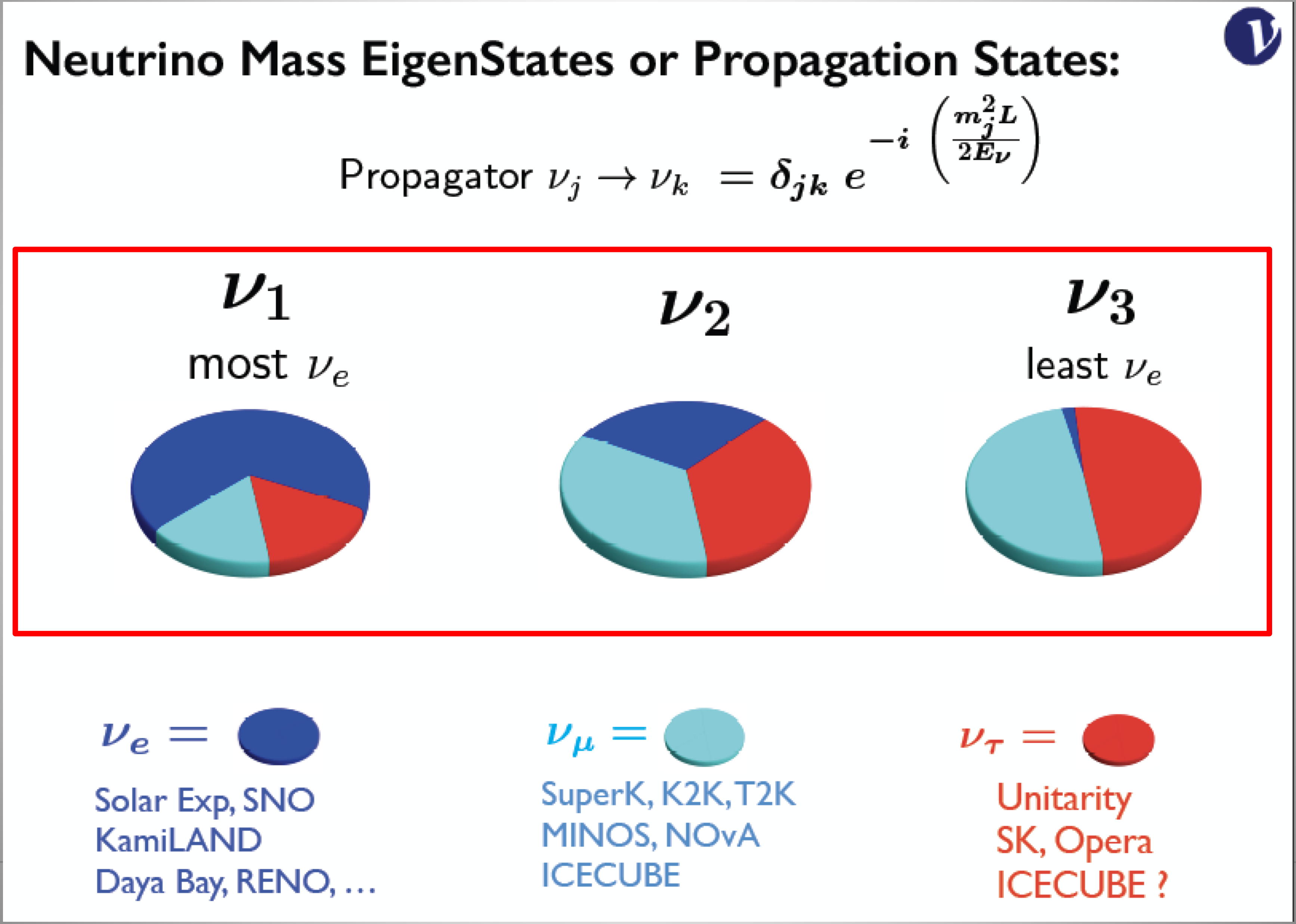
~2 x 10^{-3} eV^2

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

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

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

Neutrino Oscillations



Neutrino Mass EigenStates or Propagation States:

Propagator $\nu_j \to \nu_k \;= \delta_{jk}\; e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$

ν_1 most ν_e

ν_2

ν_3 least ν_e

$\nu_e =$ ●

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ ●

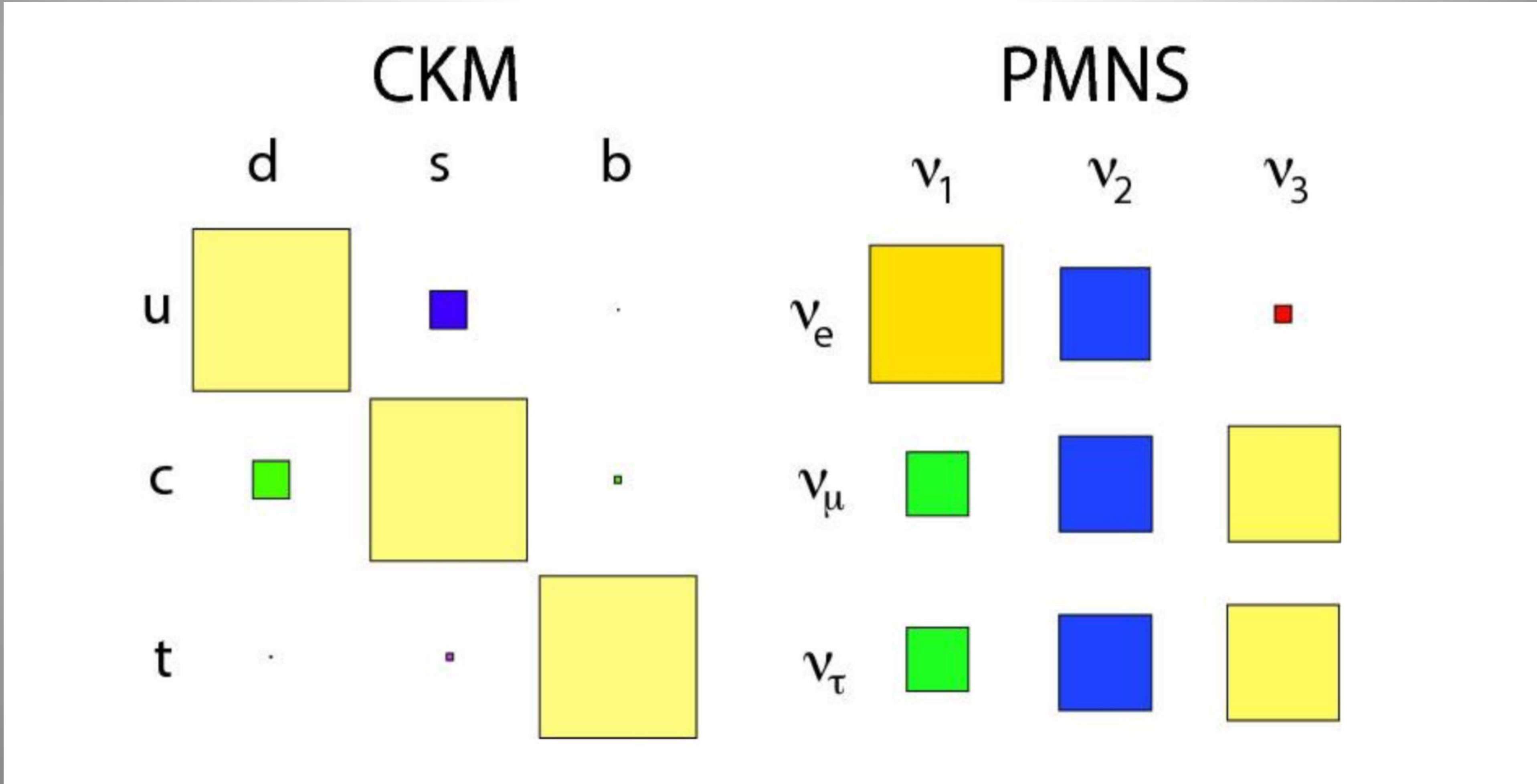
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$ ●

Unitarity
SK, Opera
ICECUBE ?

CKM vs PMNS

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



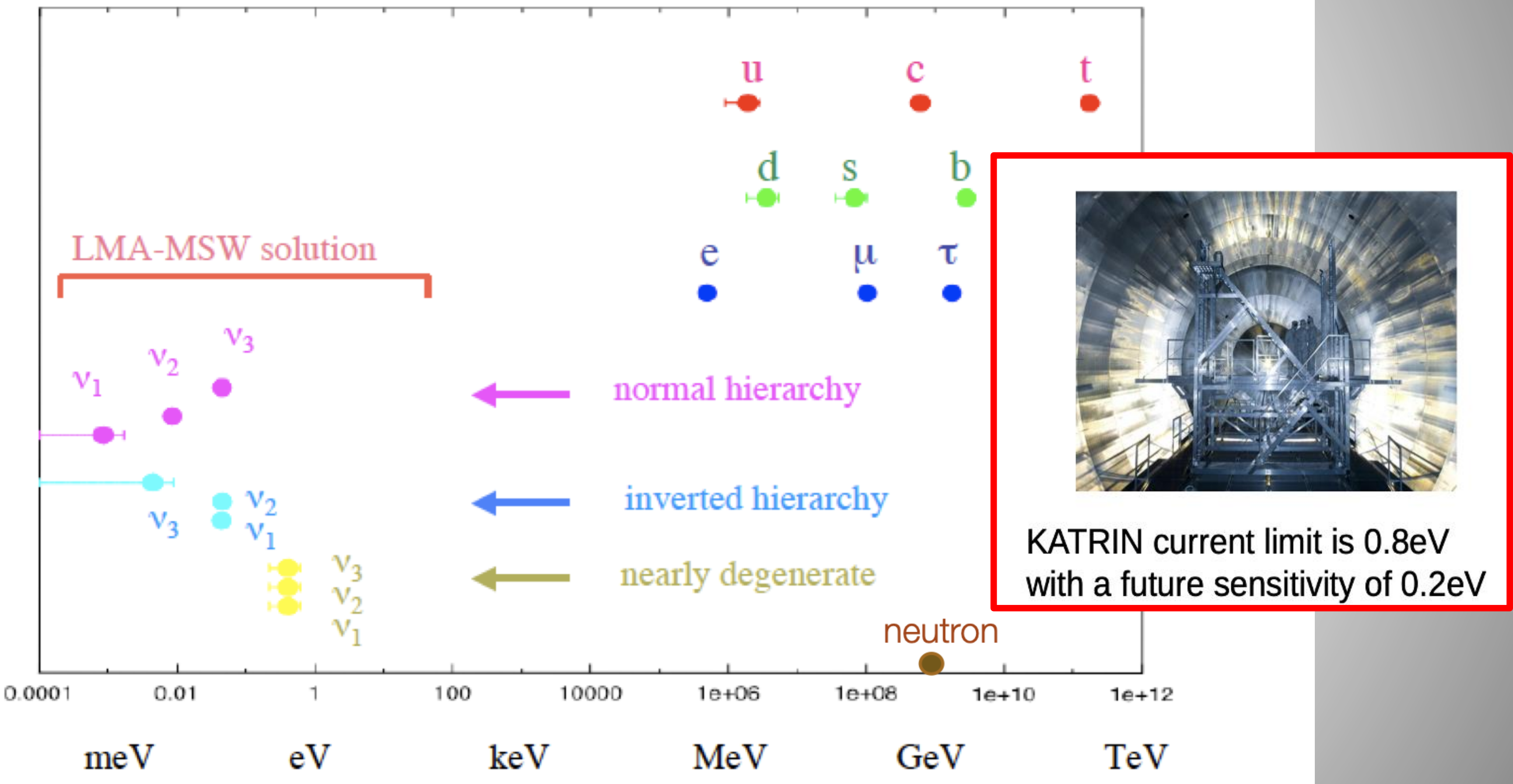
The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.

Neutrino Properties

Neutrino Mass

The smallness of the neutrino mass

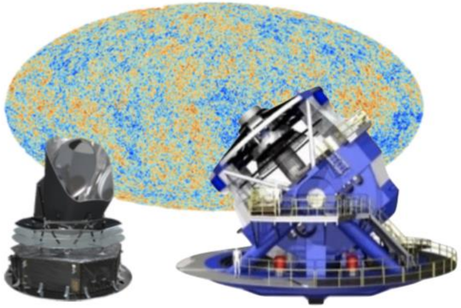
$m_\nu \ll m_{e,\,u,\,d}$

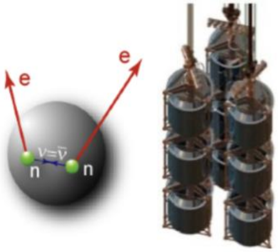


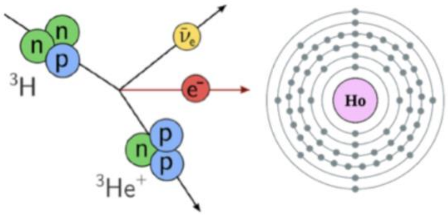
KATRIN current limit is 0.8eV
with a future sensitivity of 0.2eV

Neutrino mass measurents

Complementary paths to the ν mass scale





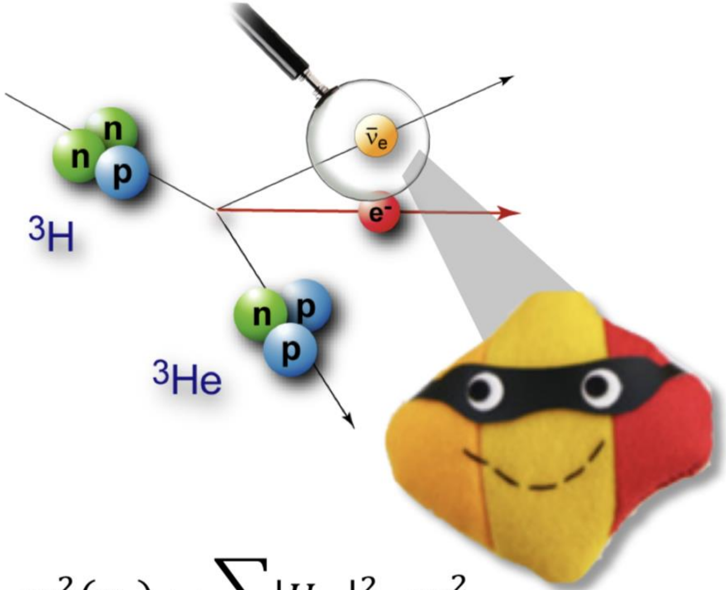


	Cosmology	**Search for 0νββ**	**Kinematics of weak decays**
Method	Structure of Universe at early and evolved stages	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$	$m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$
Model assumptions	Multi-parameter cosmological model (ΛCDM)	- Majorana nature of neutrinos? - No BSM contributions other than m(ν)?	Only kinematics; “**direct**” measurement

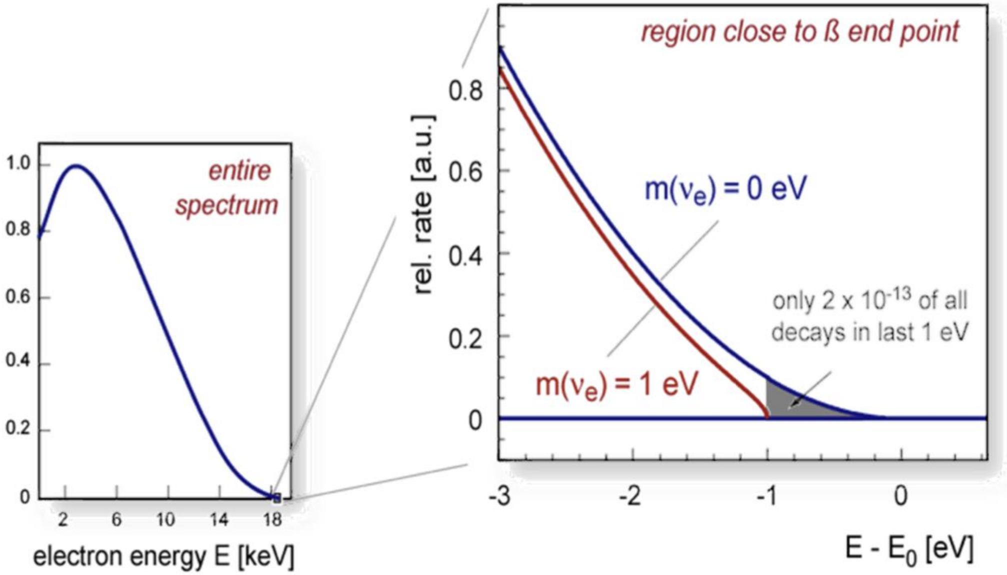
Neutrino mass measurents

The KATRIN experiment: endpoint measurement of tritium decay

KATRIN: KArlsruhe TRItium Neutrino

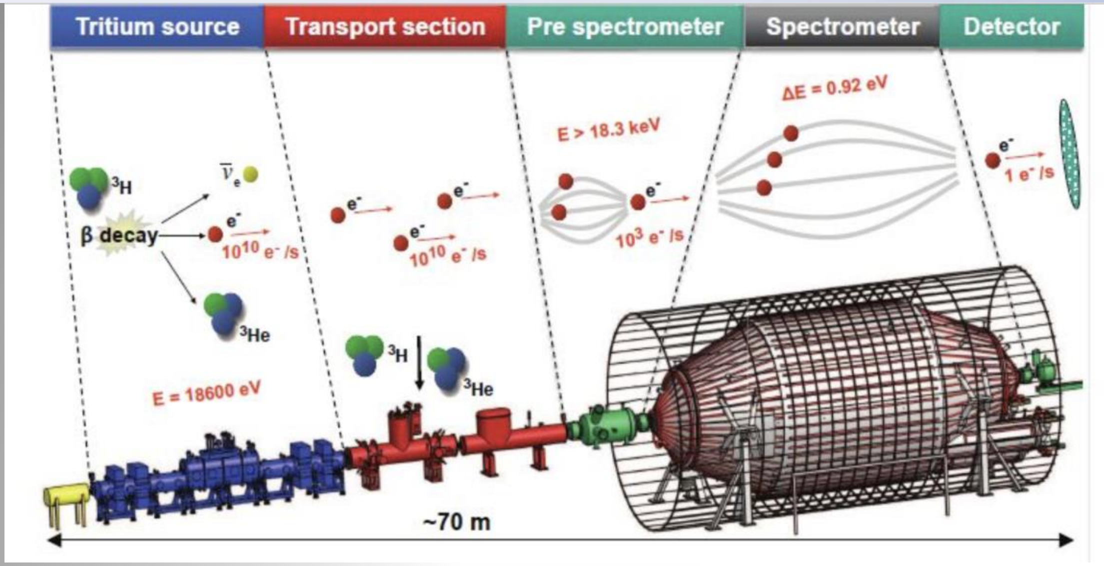


$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



What is measured really in this experiment is the effective electron anti-neutrino mass defined by $m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$ with U_{ei} the PMNS mixing elements

KATRIN Experiment: the Mass of ν_e



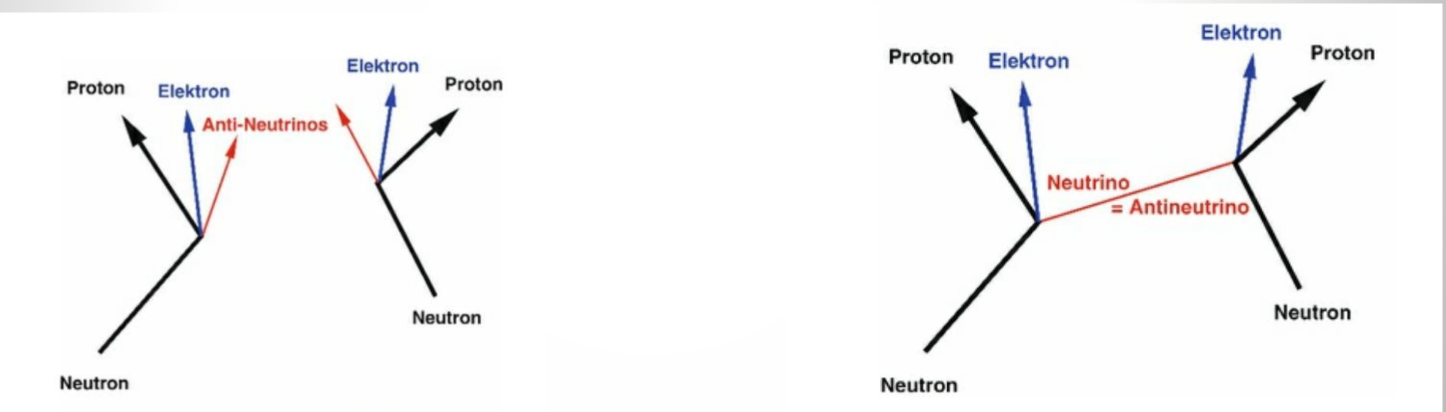
The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to measure the mass up to projected sensitivity of 0.2 eV

To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

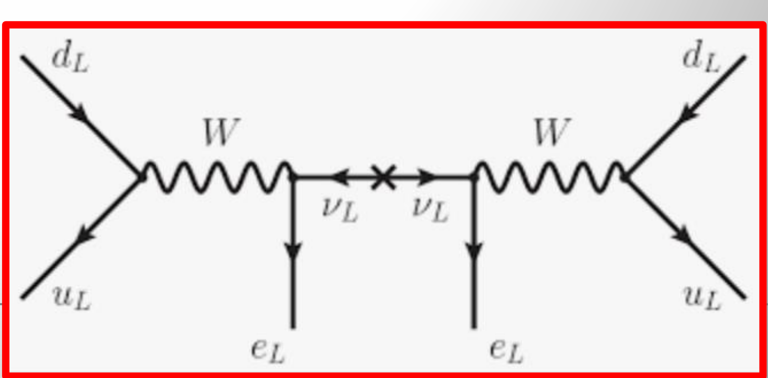
Recent result $M\nu_e < 0.45$ eV (June 2024)

Neutrinoless Double Beta Decay

- Are neutrinos their own antiparticle? We do not know this yet!
- The highly anticipated experimental test is the observation of neutrino-less double beta decay, ie two simultaneous beta-decays within one nucleons, without neutrino emission
- This would be the first evidence of lepton number violation!



Some nuclei have DBD if for an SBD the binding energy of the Z+1 nucleus is lower than the original, but for DBD (Z+2) it is higher



Neutrinoless Double Beta Decay

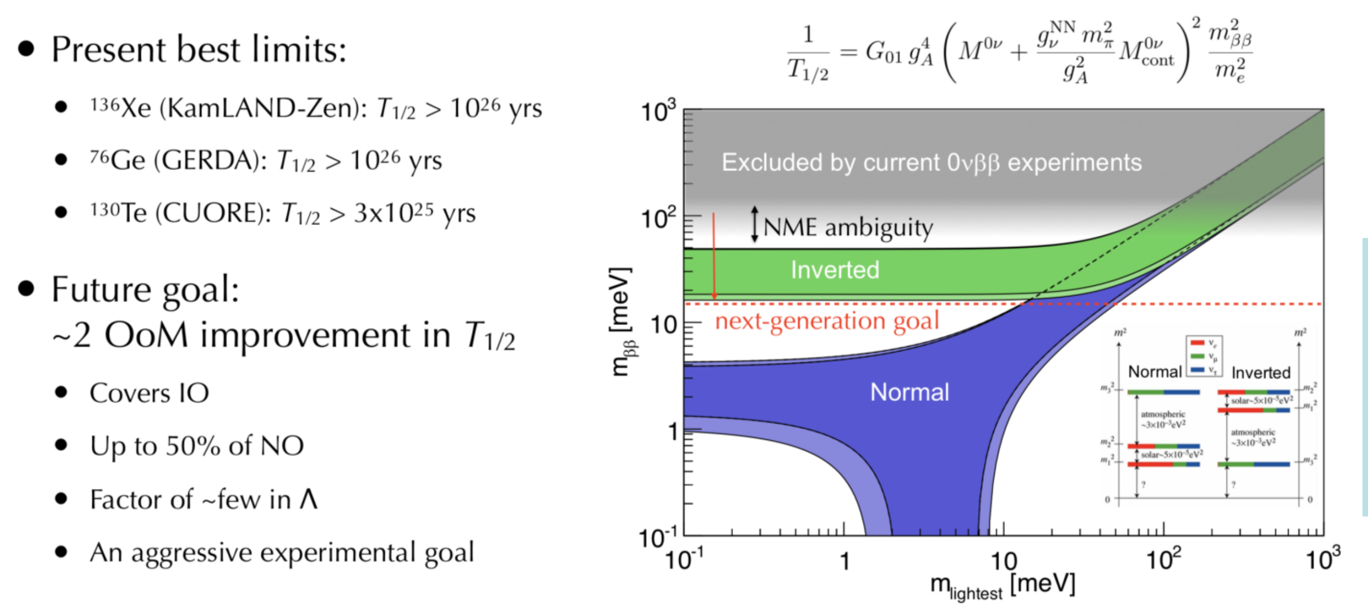
GERDA (GERmanium Detector Array) experimemt at LNGS (Gran Sasso/IT)

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**



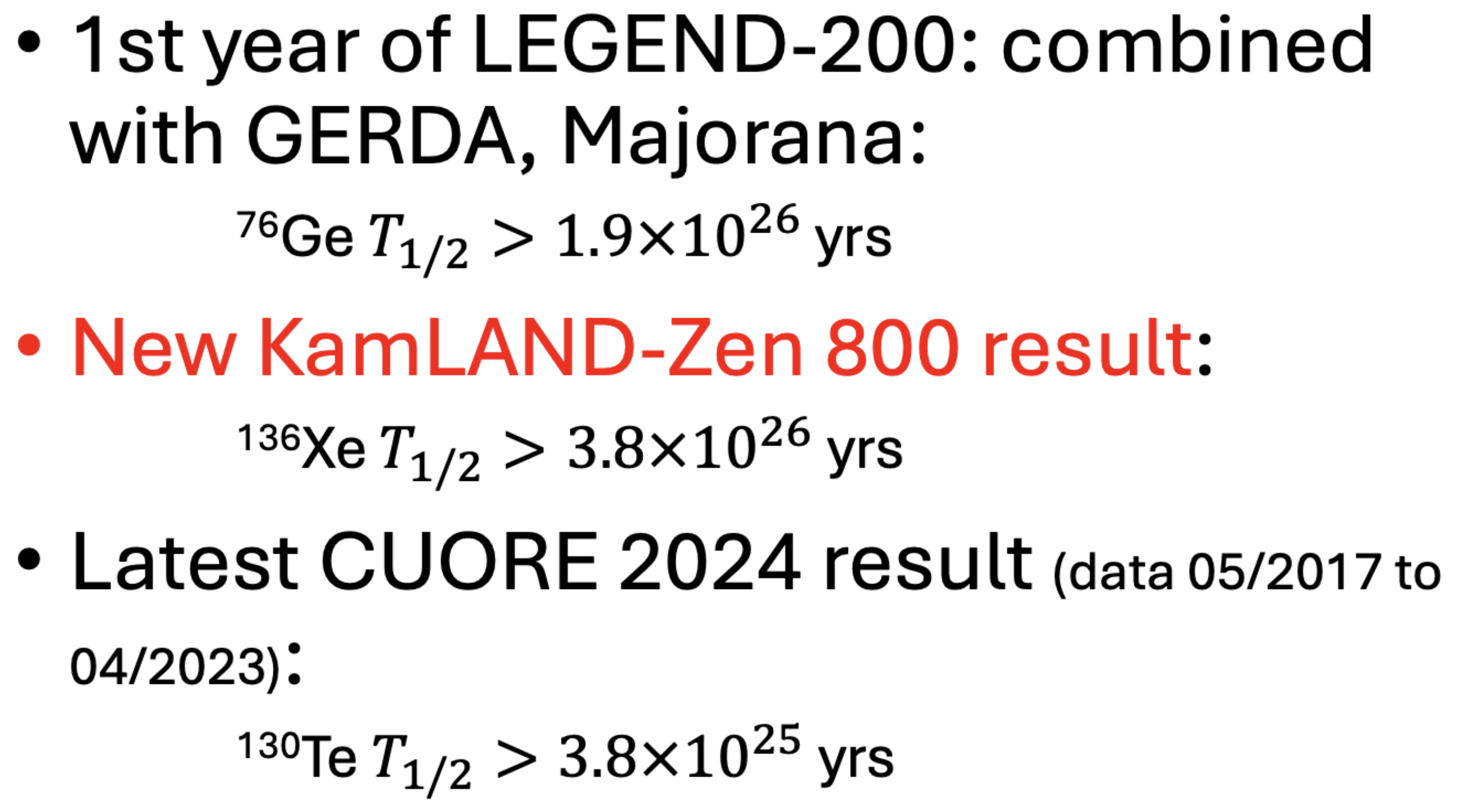
- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3\text{x}10^{25}$ yrs
- Future goal:
  ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental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

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

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

Neutrinoless Double Beta Decay

Most Recent numbers (Neutrino2024)



- 1st year of LEGEND-200: combined with GERDA, Majorana:

  ^{76}Ge $T_{1/2} > 1.9{\times}10^{26}$ yrs

- New KamLAND-Zen 800 result:

  ^{136}Xe $T_{1/2} > 3.8{\times}10^{26}$ yrs

- Latest CUORE 2024 result (data 05/2017 to 04/2023):

  ^{130}Te $T_{1/2} > 3.8{\times}10^{25}$ yrs

Summary: Neutrino Properties

- Neutrinos oscillate and hence have a (tiny) mass, as found in atmospheric neutrinos and neutrinos from the sun
- How small is the mass? $m(\boldsymbol{\nu}_e) < 0.45$ eV
- What generates the neutrino mass? See-saw? Other?
- Is the neutrino a Majorana particle? Still open..
- Reactor and accelerator experiments are zooming in on oscillation properties

=> Last part: on anomalies, cosmological neutrinos, future experiments, and searches for BSM physics (neutrino and others, using neutrino detectors)

Anomalies

search for sterile neutrino

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

Sterile Neutrinos

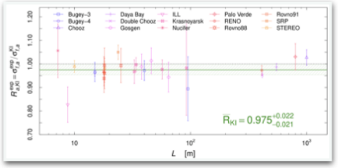
Several anomalies around in the community since some years…
Additional sterile neutrinos as a possible candidate explanation

- ☑ 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:

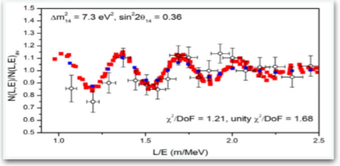
$$P_{\alpha\to\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i(E_j - E_k)T\right]$$

J. Kopp, Neutrino 2022

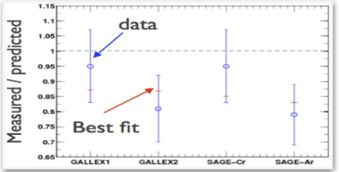
Anomalies



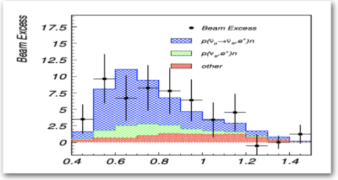
reactor flux anomaly
resolved with new input data
to flux calculation



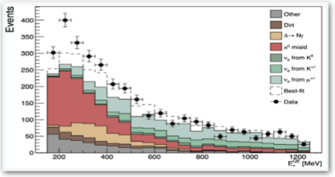
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



LSND
unresolved



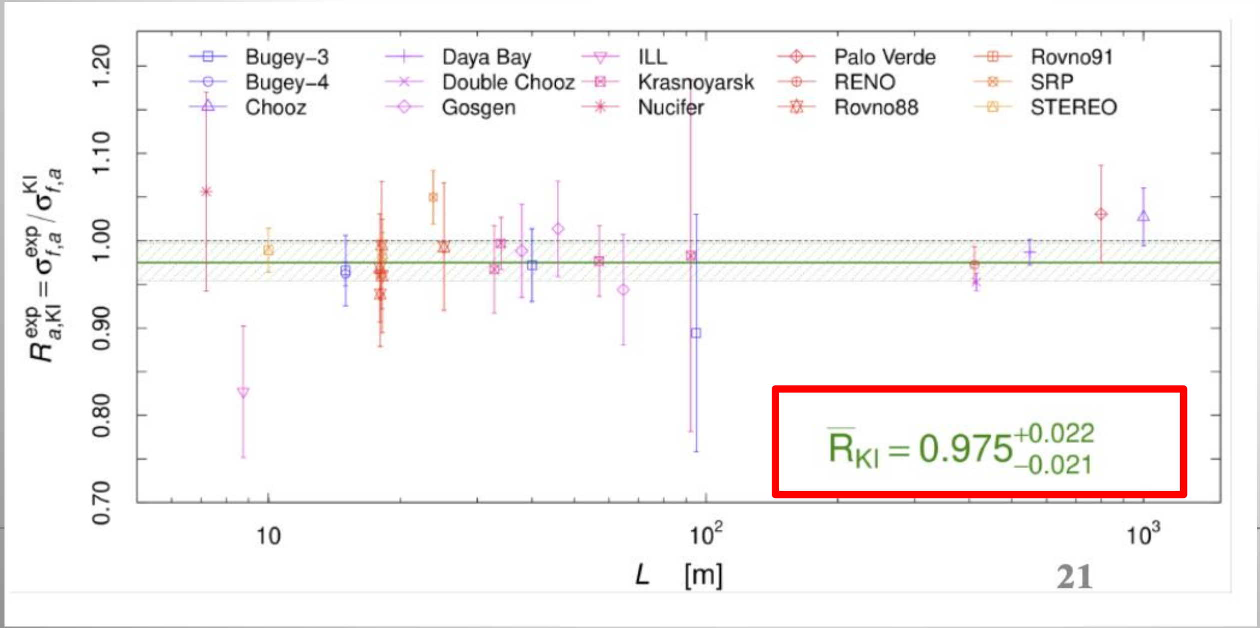
MiniBooNE
unresolved
resolvable by next-gen. SBL experiments

- 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

Reactor Anomaly

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

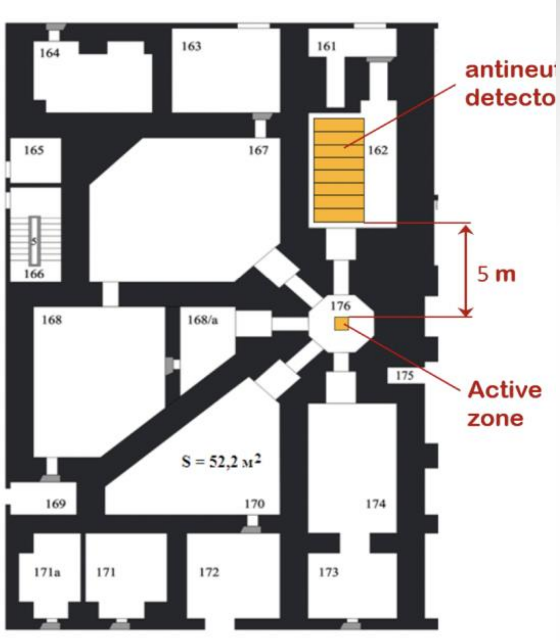
- Flux deficit can be explained as sterile neutrino
- Many experiments reported new results, no oscillation signals beyond 2σ, except
  - Neutrino-4 sees a 2.7σ oscillation signal, but rejected by STEREO at 3.1σ
- Daya Bay reported that the flux deficit is mostly from ^{235}U
- Other reactor and dedicated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



Updated estimate of R

Compatible with R=1

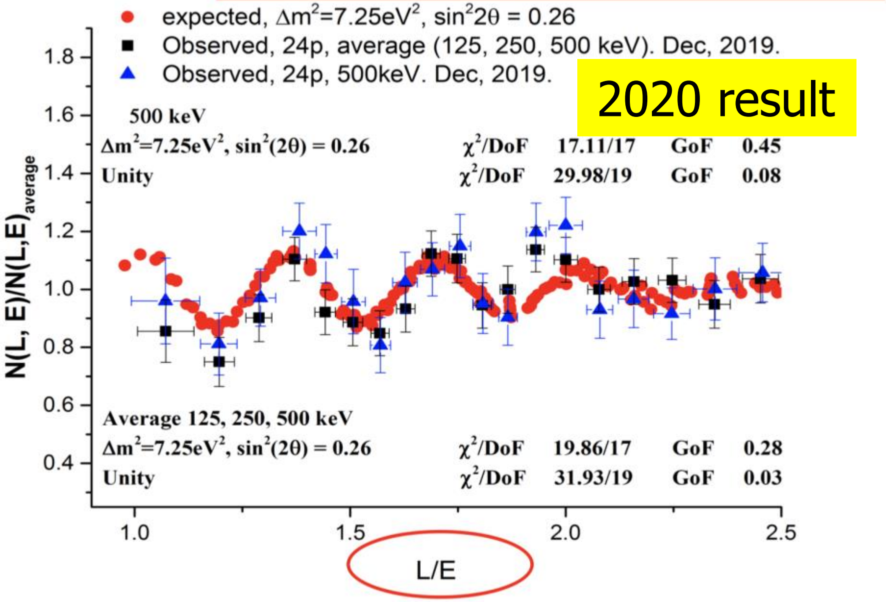
Short baseline Reactor:Neutrino-4 Exp.



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

3 years long measurement
2.8σ signific.

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



2020 result

arXiv:1809.10561 (Jan 2020)

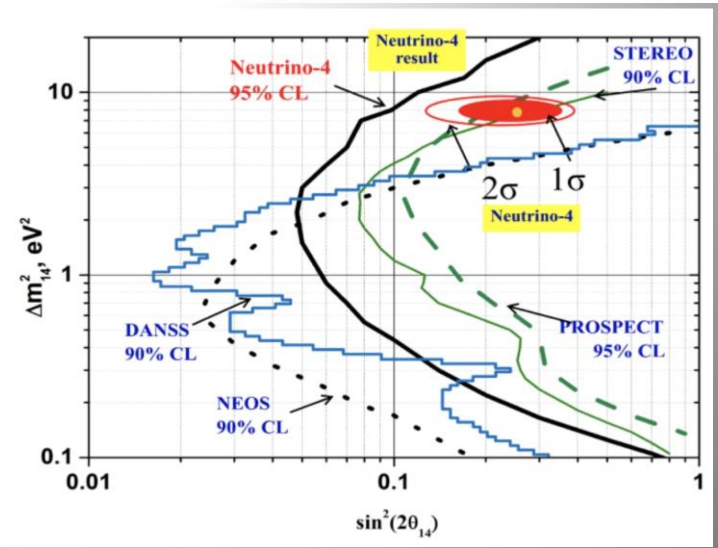
$$\Delta m^2_{14} = 7.25 \pm 0.13_{st} \pm 1.08_{syst} = 7.25 \pm 1.09$$

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

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…

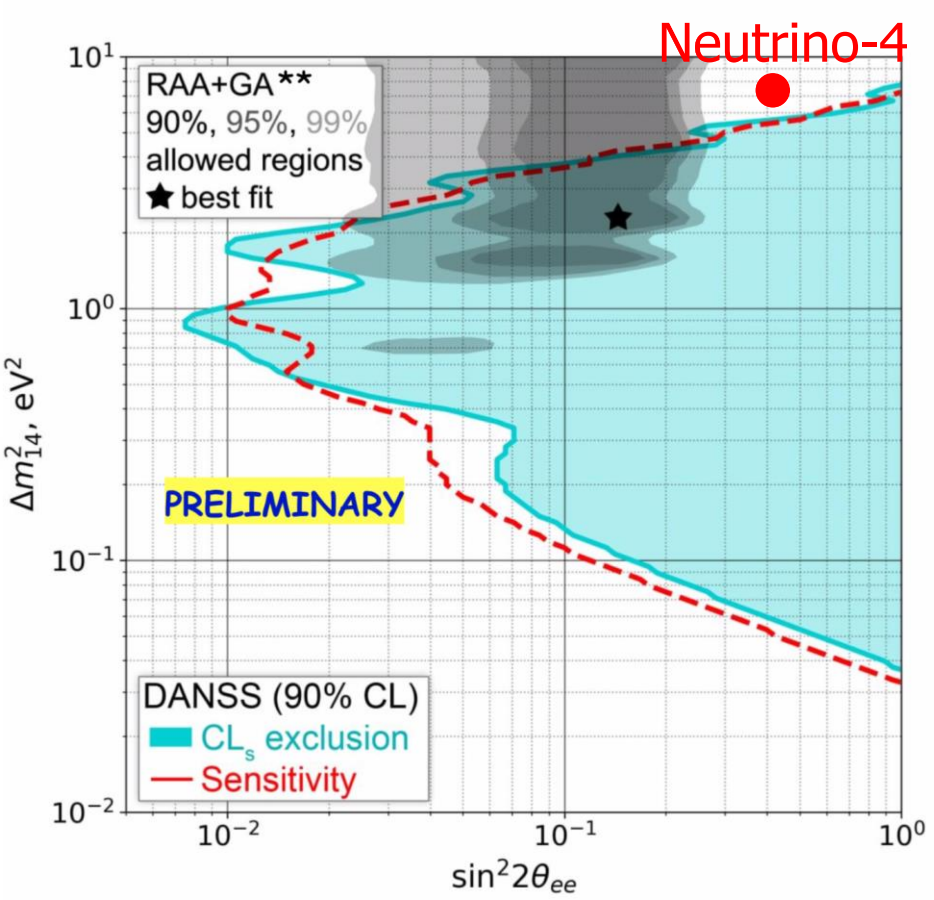


Result from DANSS

EPS-HEP 2021

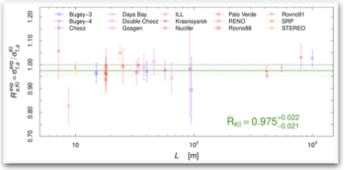
- DANSS records about 5 thousand antineutrino events per day with cosmic background ~1.7%, S/B>50

5.5 million IBD events were collected in 5 years



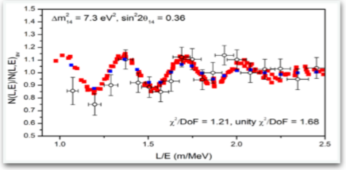
DANSS does not yet cover up to Neutrino-4, but with the upgraded detector and 1-2 years additional data taking they will…
DANSS itself sees very weak hints of a signal around 1 eV^2

Neutrino Anomalies



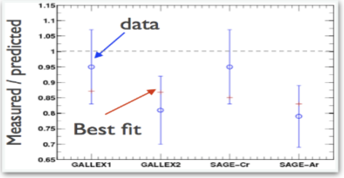
reactor flux anomaly
resolved with new input data
to flux calculation

✓



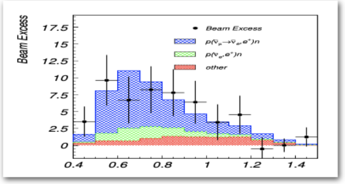
reactor spectra
is there really an anomaly? -> DANSS

?



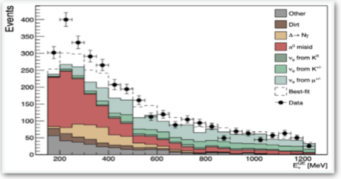
gallium anomaly
unresolved, recently reinforced BEST

?



LSND
unresolved

?



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

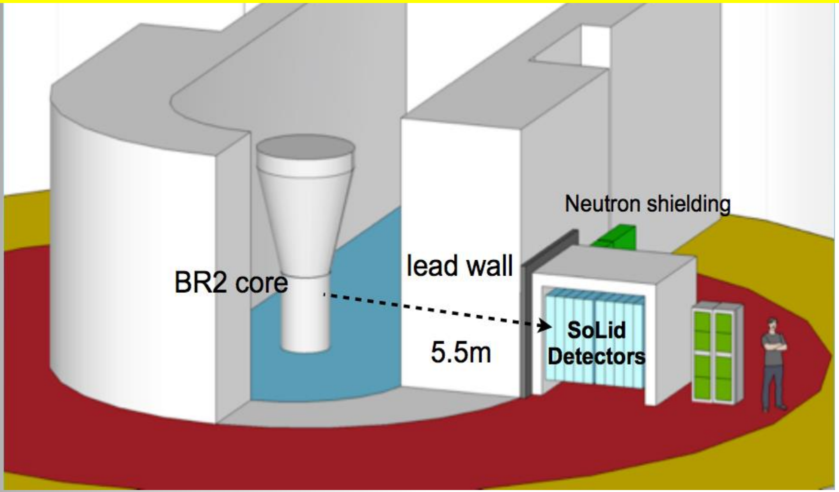
?

More details in the backup

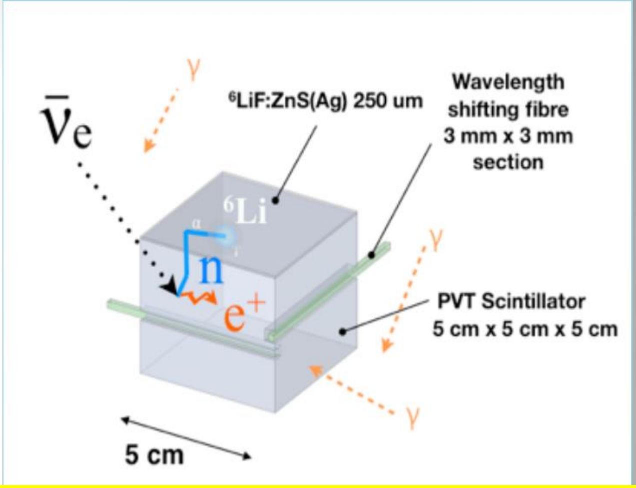
- Jury still out on many of these anomalies. No clear picture emerging yet.
- Simple sterile neutrino would not fit all the data. Tensions on all sides…
- Future: Reactor experiments continuing or new ones (eg JSNS^2) or new experiments at the FNAL short neutrino baseline… (ICARUS, SBND)

New Short Baseline Experiments will check!

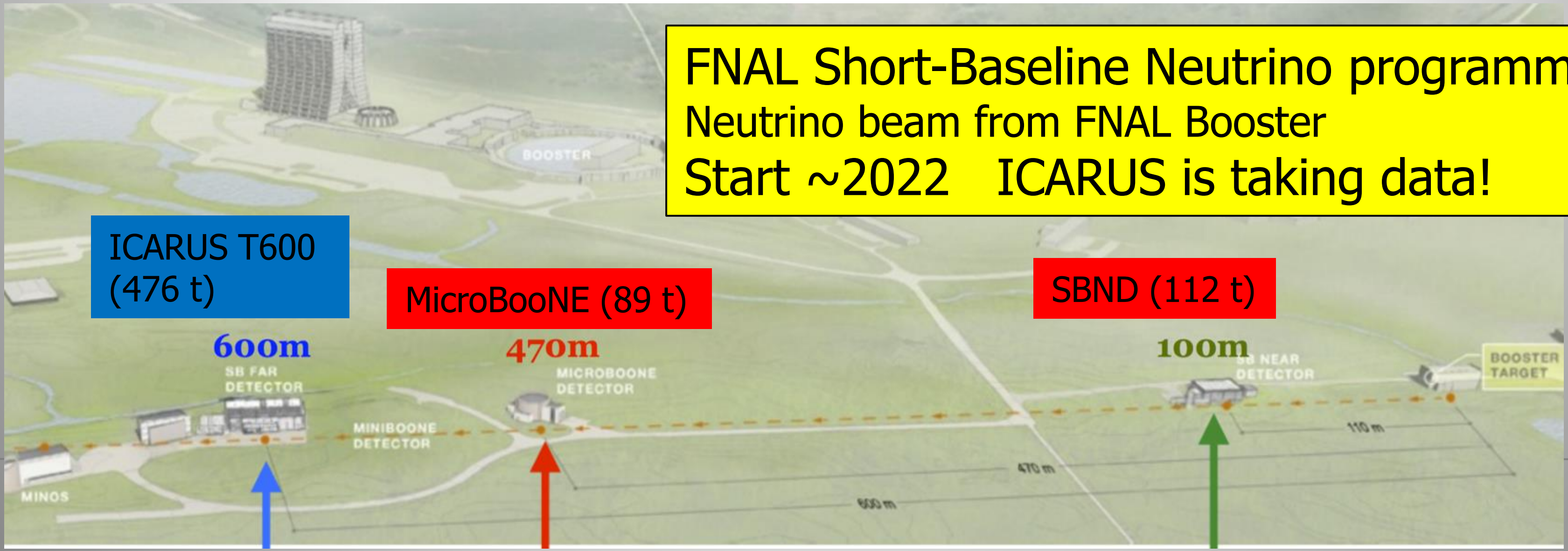
Experiments at reactors, eg the SoLid experiment @BR2 reactor in Belgium



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



Also: Prospect, STEREO, DANSS, NEOS



FNAL Short-Baseline Neutrino programme:
Neutrino beam from FNAL Booster
Start ~2022 ICARUS is taking data!

ICARUS T600 (476 t)

MicroBooNE (89 t)

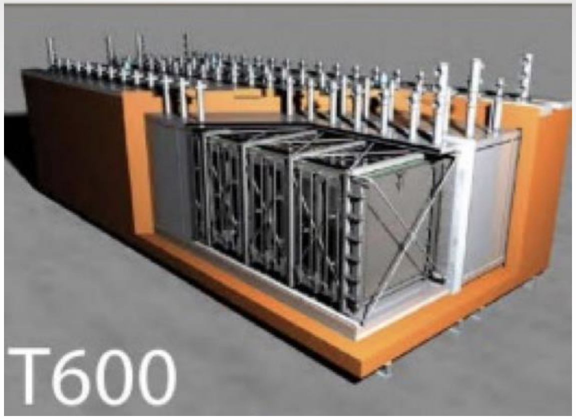
SBND (112 t)

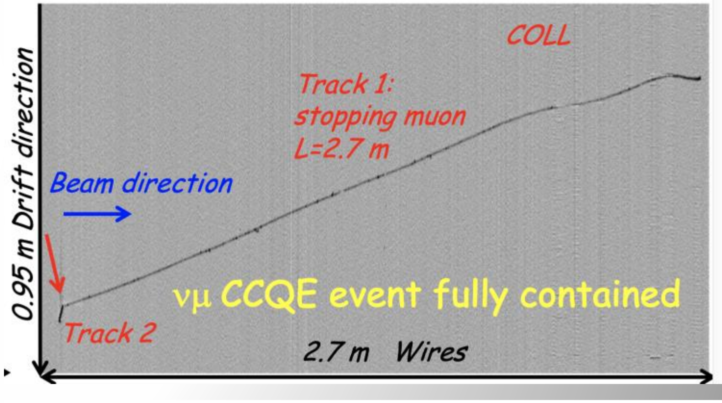
ICARUS @ FNAL

ICARUS-T600

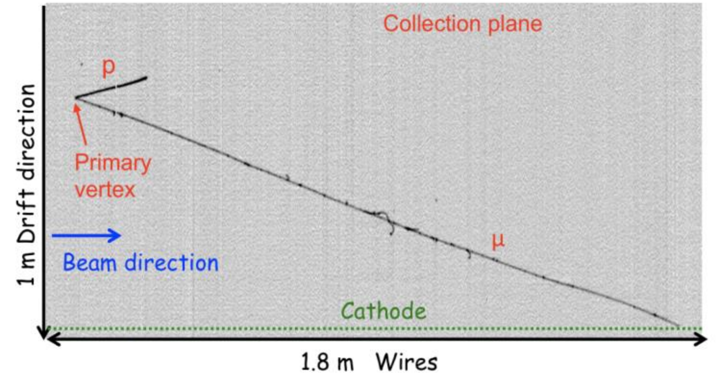
IMAGING
COSMIC
AND
RARE
UNDERGROUND
SIGNALS

BNB baseline: 600 m
Total LAr: 760 ton
Active LAr: **476 ton**
NuMI off-axis angle*: 5.9°

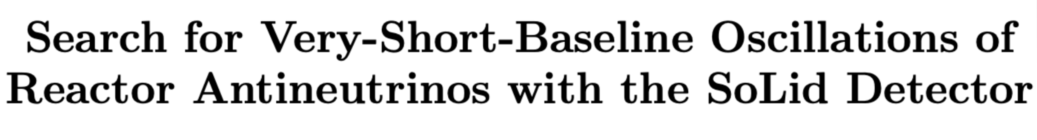




ICARUS is taking data since start of 2022
ICARUS will challenge the Neutrino4 claim
in ~ 2025…



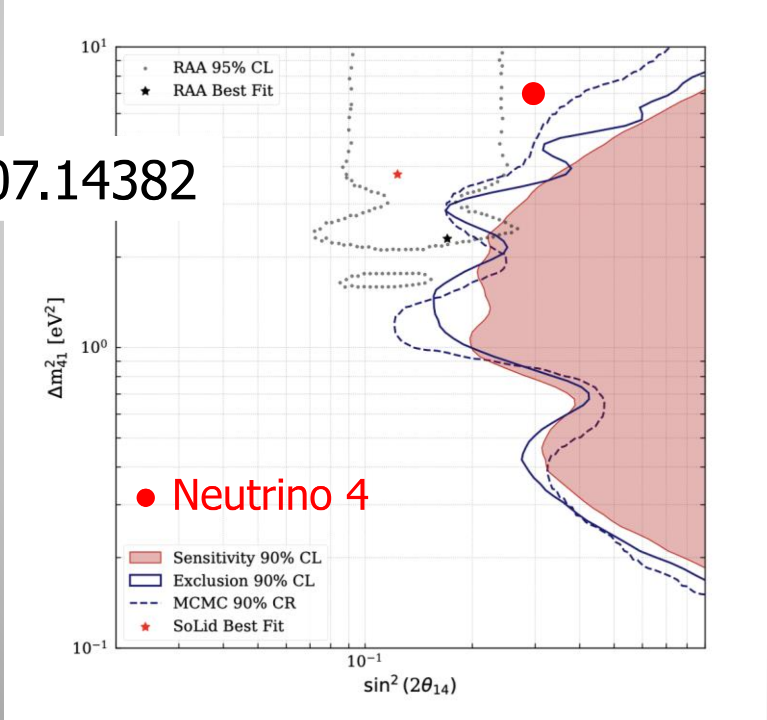
The Solid Experiment



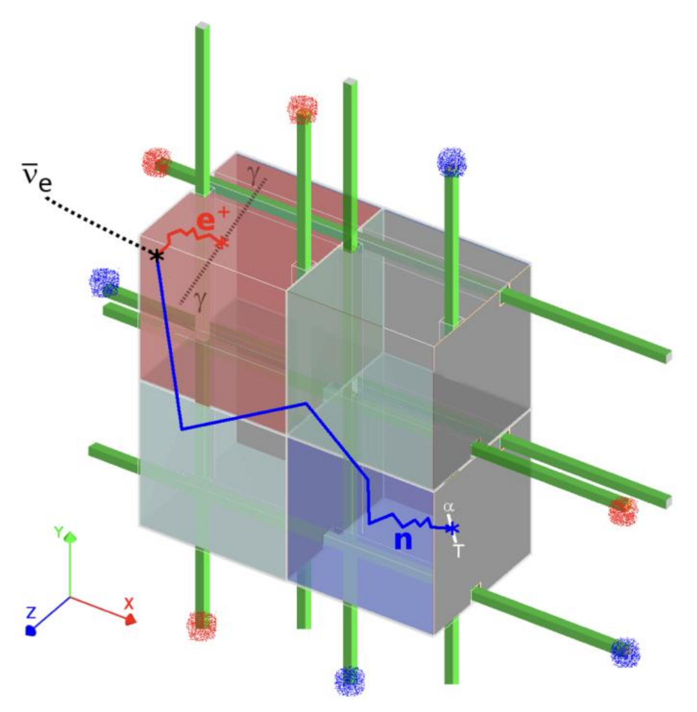
Search for Very-Short-Baseline Oscillations of Reactor Antineutrinos with the SoLid Detector

- First physics result from this experiment
- Belgian groups from UA, UG and VUB

2407.14382



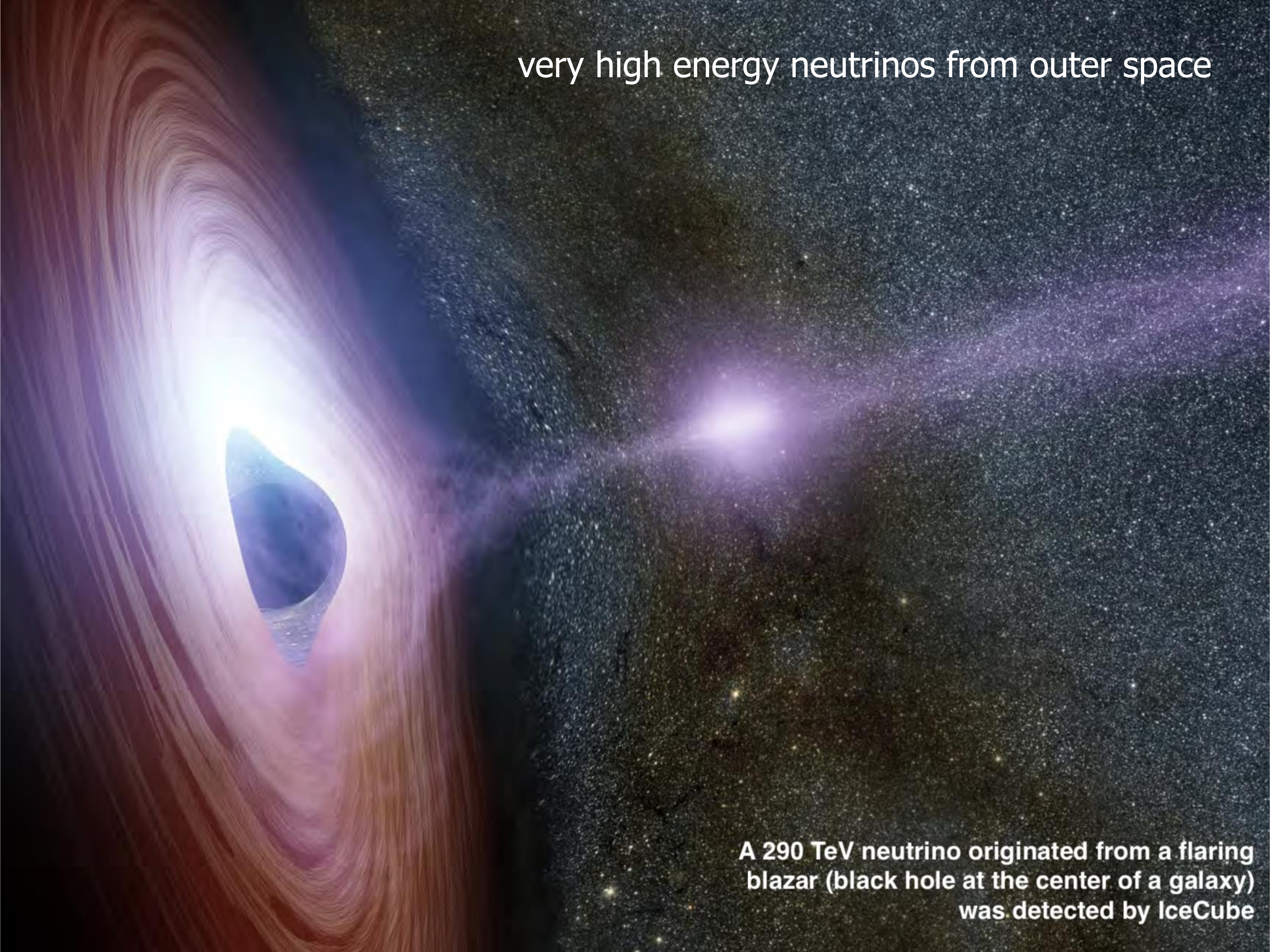
● Neutrino 4



No oscillations observed. Neutrino-4 close to be excluded.. (as expected)

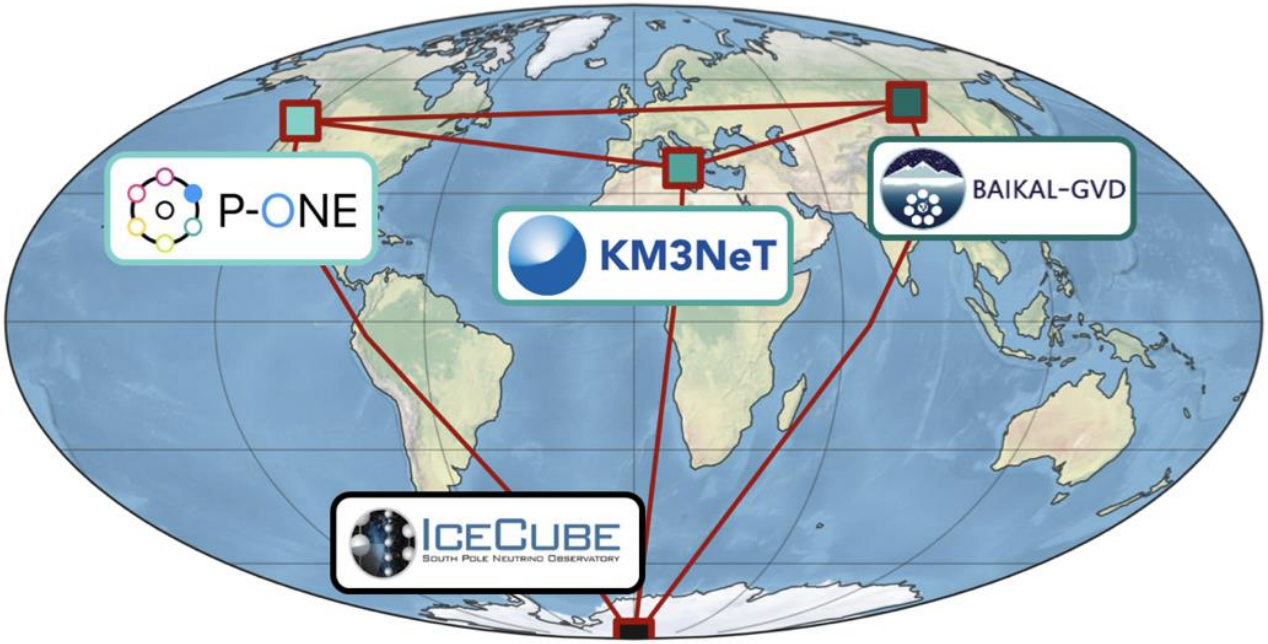
Astrophysical Sources of Neutrinos

very high energy neutrinos from outer space

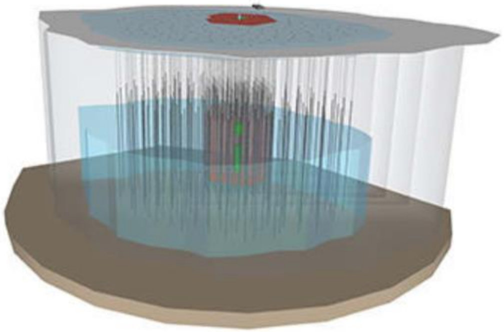


A 290 TeV neutrino originated from a flaring blazar (black hole at the center of a galaxy) was detected by IceCube

Large Neutrino Observatories



IceCube GEN-2
10 km^3



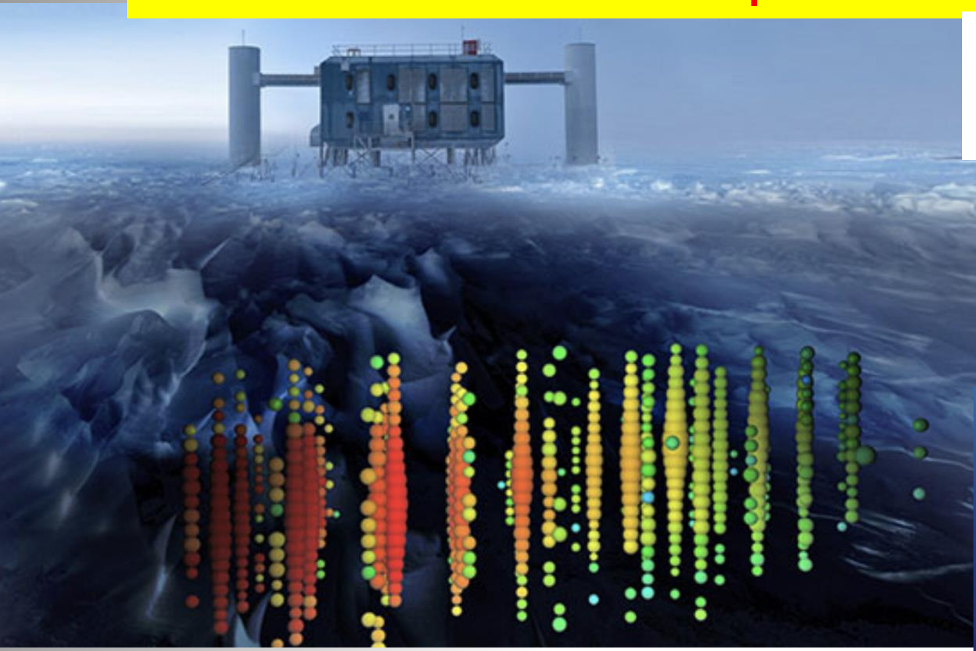
When combined and used as a single distributed planetary instrument (Planetary Neutrino Monitoring System (PLEnUM)), it would cover almost the entire sky

Huge increase of the detection probability for > 50 TeV neutrinos

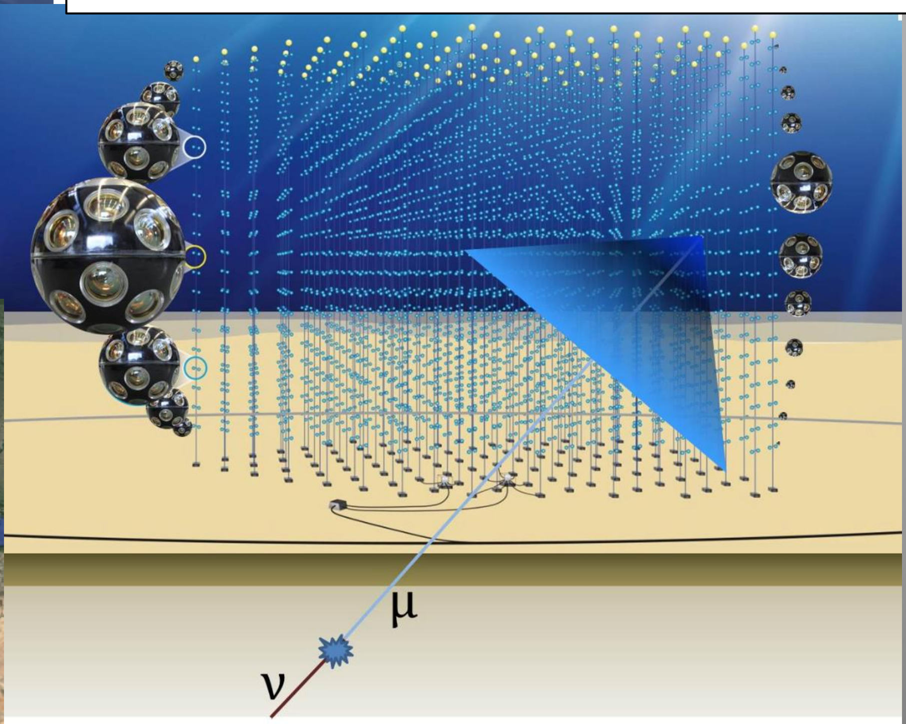
Neutrino Astronomy

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: ~40 DU strings now/ full detector by 2026
-> In the Mediterranean sea…

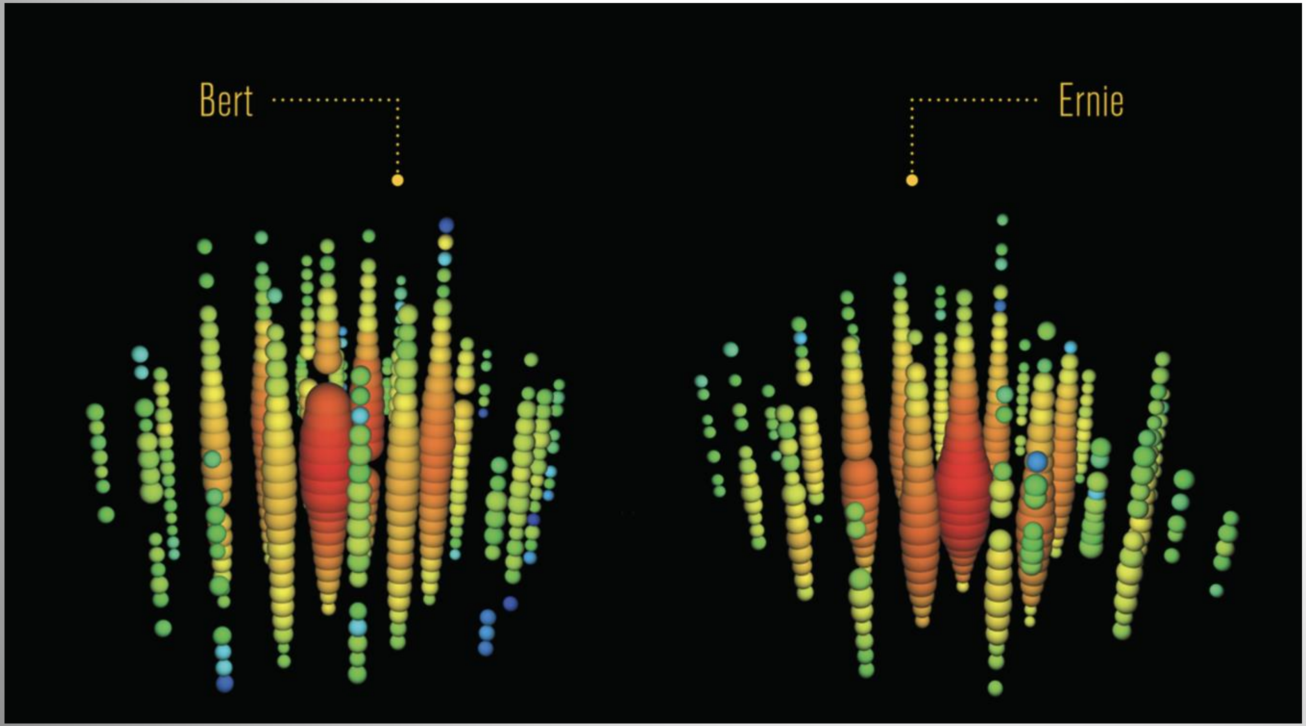


ANTARES retired this summer after 14 years

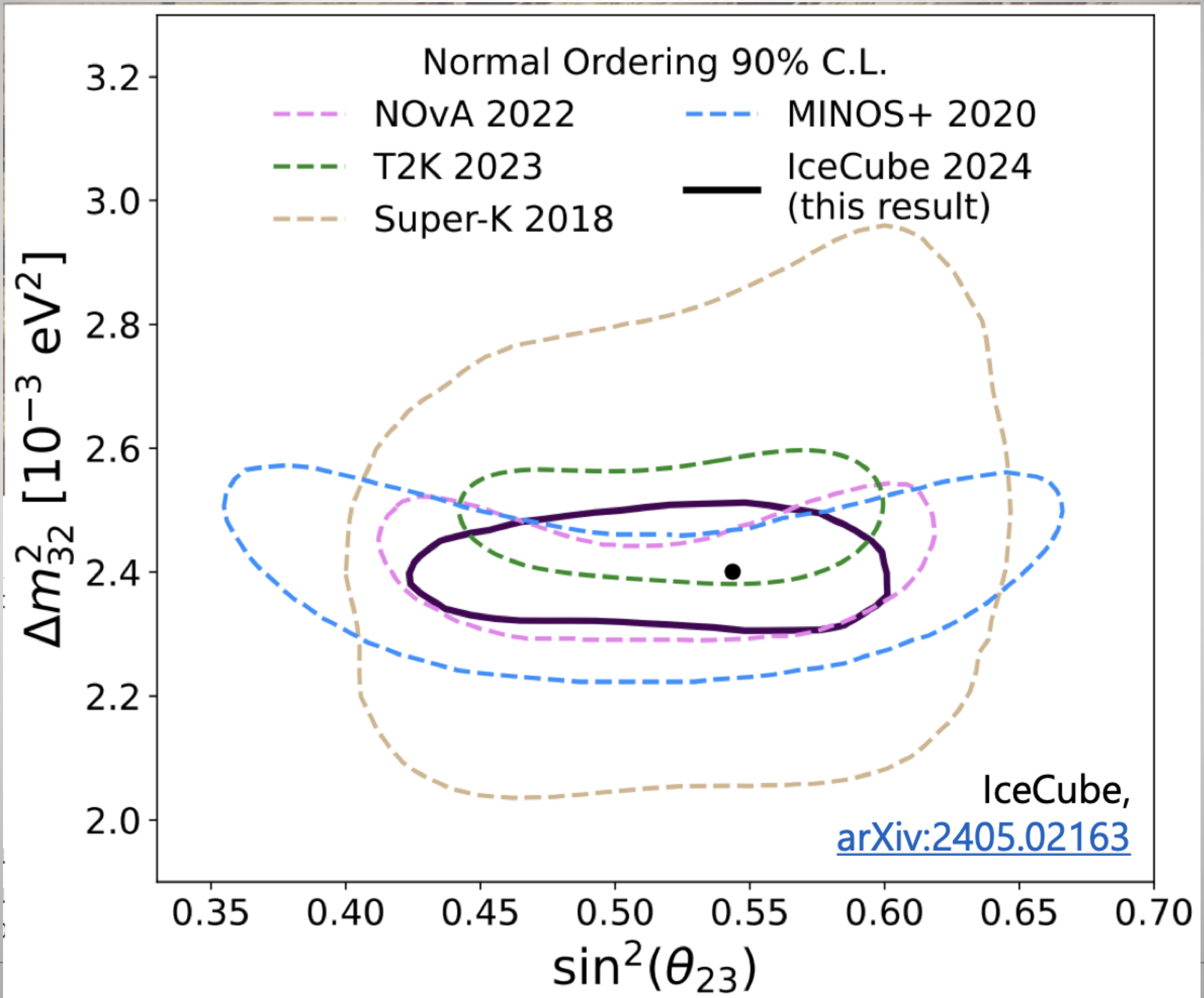
Neutrinos in the Ice

Most Energetic Neutrino Interactions

2012: Extra-galactic neutrinos with Energies around 1-2 PeV observed in the IceCube detector (1 PeV = 10^6 GeV)
They were named “Bert” and “Ernie



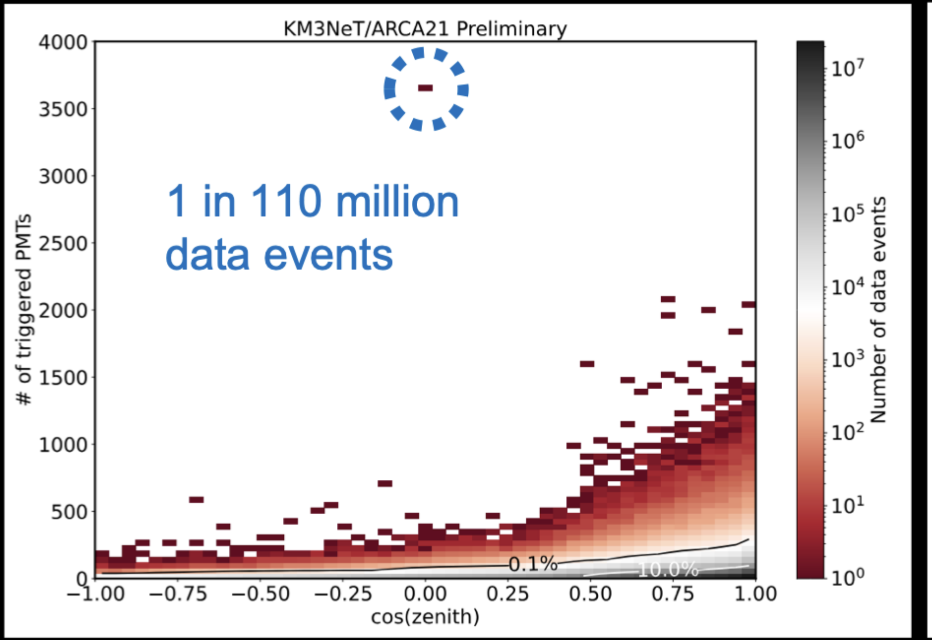
The IceCube Experiment



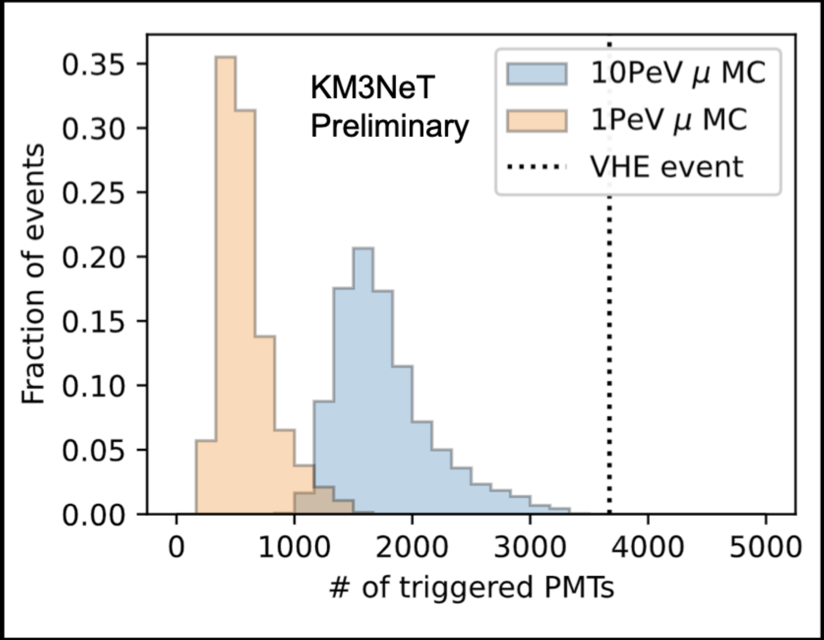
KM3NeT

Uncharted Territory

- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV



1 in 110 million data events



The Baikal-GVD Experiment

Baikal-GVD Gigaton Volume Detector

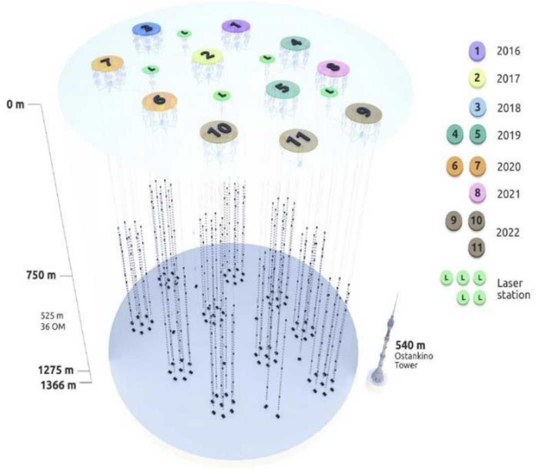
Dzhilkibaev

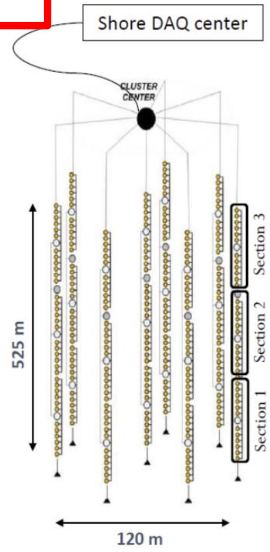
Projects: Baikai-GVD

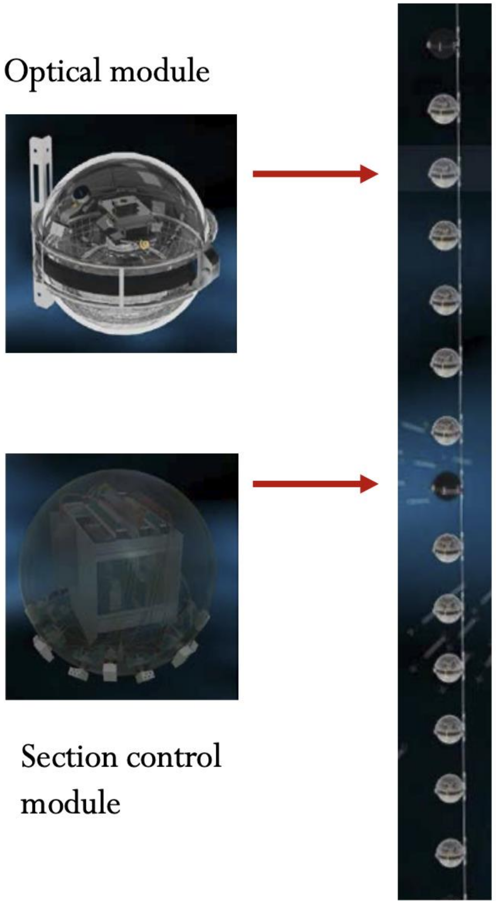
- Largest neutrino telescope in the Northern Hemisphere and still growing
- Outlook:
  - 2025/2026 – ~ 1km^3 GVD with total of 16-18 clusters
  - 2022-2024 – “Conceptual Design Report” for next generation neutrino telescope in Lake Baikal

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







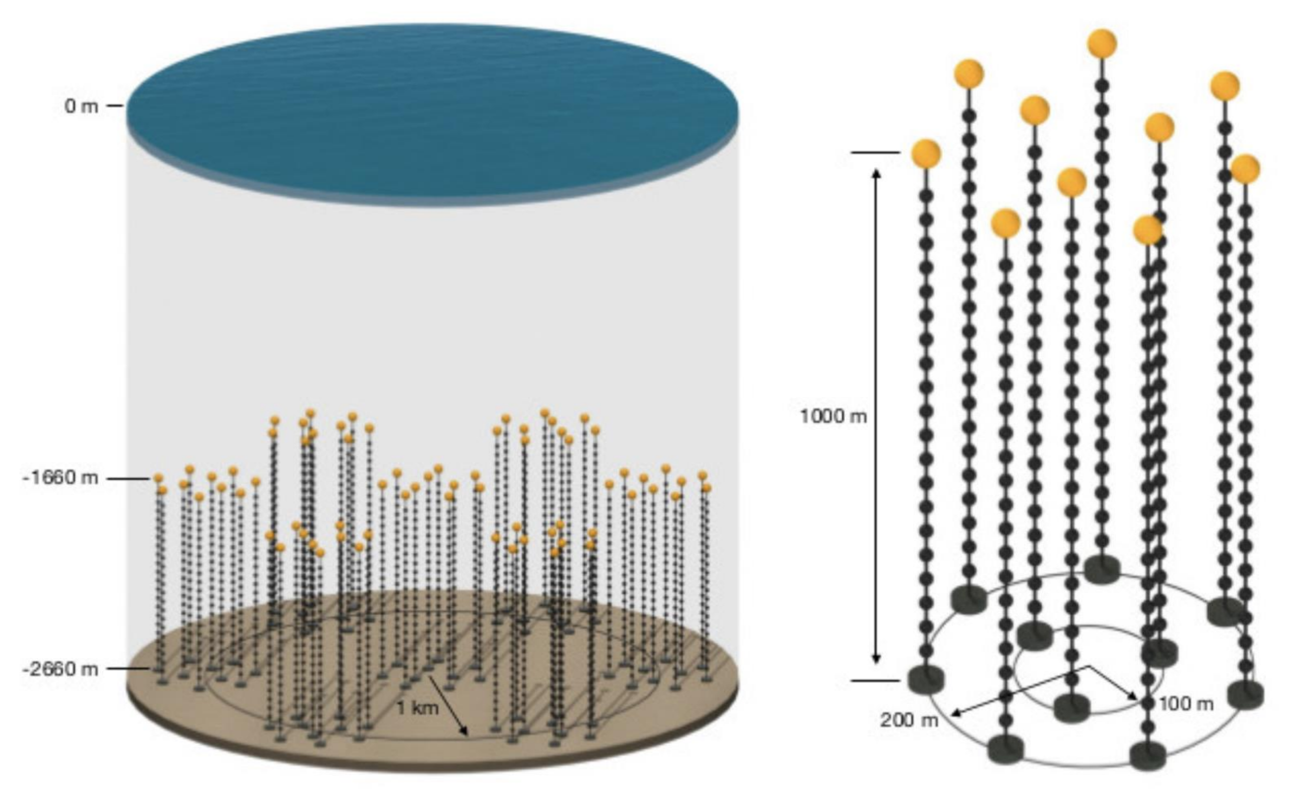
The P-ONE Proposal

The Pacific Ocean Neutrino Experiment

P-ONE

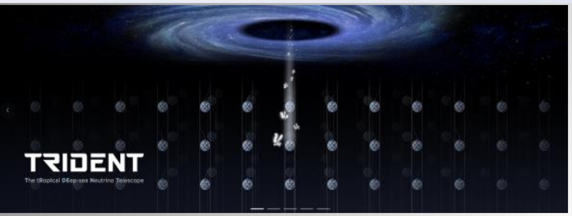
A multi-km^3 neutrino telescope; the first to be hosted by an existing oceanographic infrastructure.

2111.13133

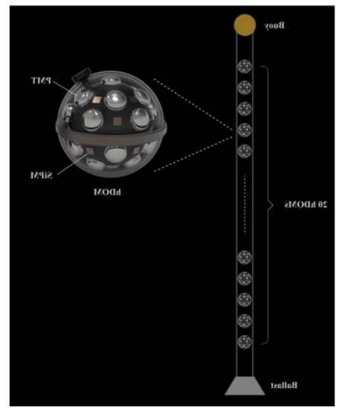


Experiment for energies above 50 TeV. A first segment is planned to be installed in a four weeks sea operation in 2023/24

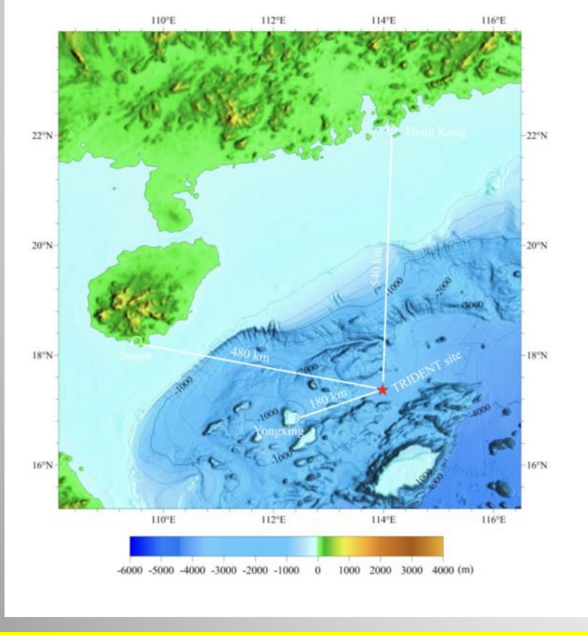
Large Neutrino Observatories

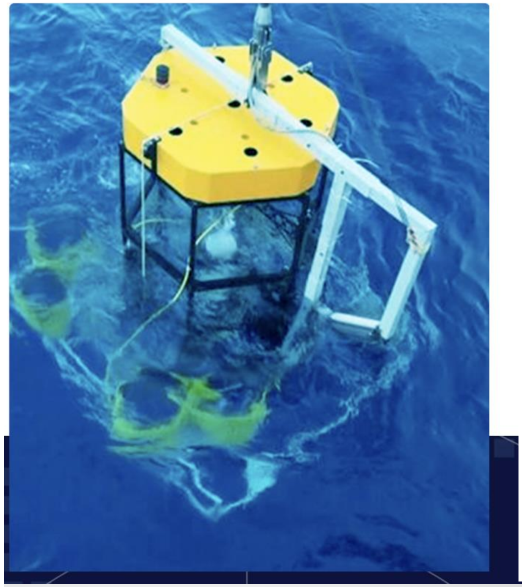


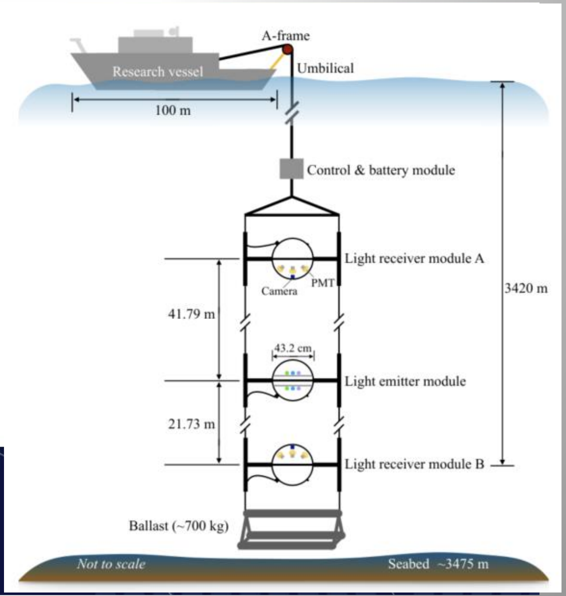
TRIDENT TRopical DEep-sea Neutrino Telescope



TRIDENT will have 20,000 digital optical modules to cover an 8 km^3 area
Located in the South China sea

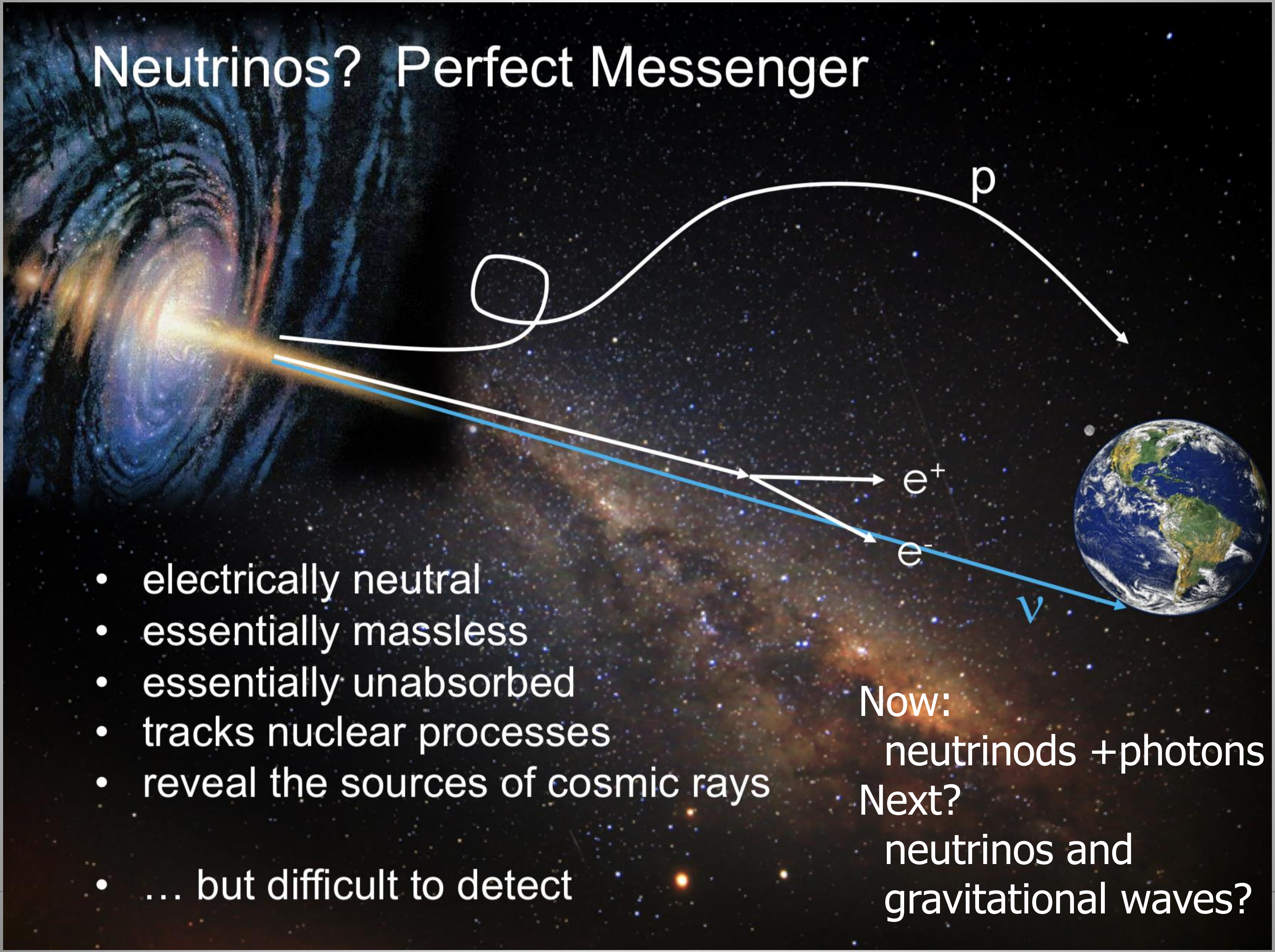






More future projects: HUNT, TAMBO, GRAND, BEACON, RNO-G, PUEO…

Multi Messenger Astronomy…



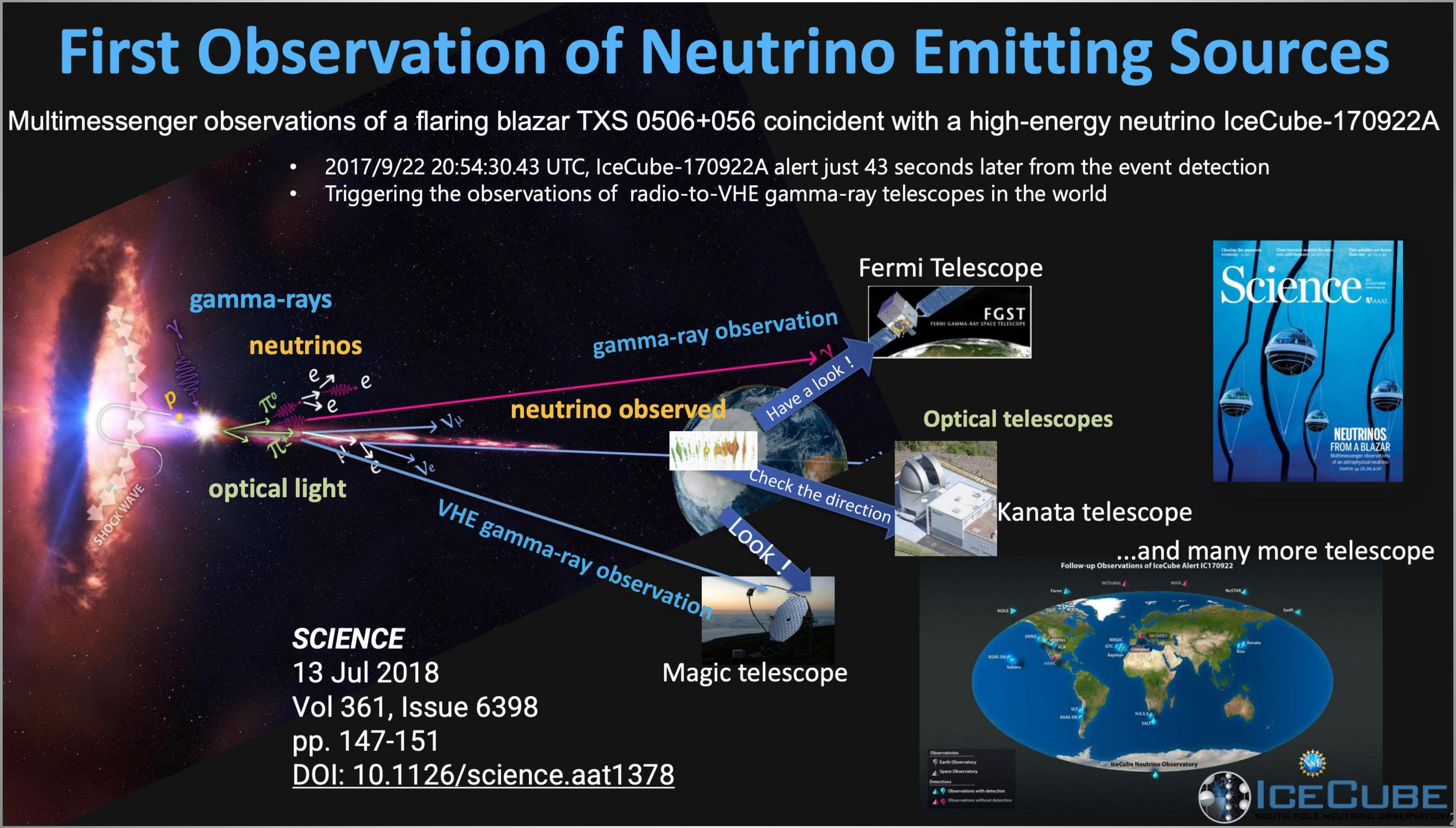
Neutrinos? Perfect Messenger

- 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?

Multi Messenger Astronomy…



First Observation of Neutrino Emitting Sources

Multimessenger observations of a flaring blazar TXS 0506+056 coincident with a high-energy neutrino IceCube-170922A

- 2017/9/22 20:54:30.43 UTC, IceCube-170922A alert just 43 seconds later from the event detection
- Triggering the observations of radio-to-VHE gamma-ray telescopes in the world

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DOI: 10.1126/science.aat1378

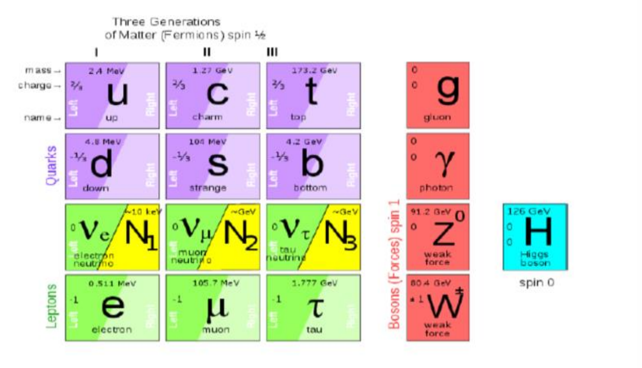
Neutrinos at the LHC!

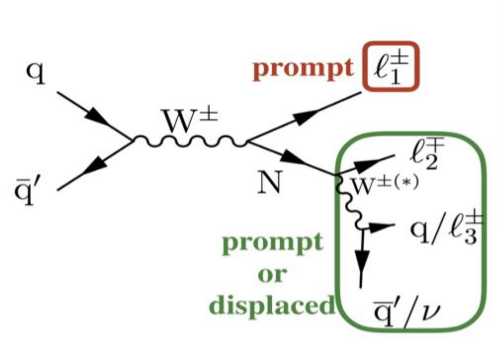
Neutrinos @ the LHC: Examples

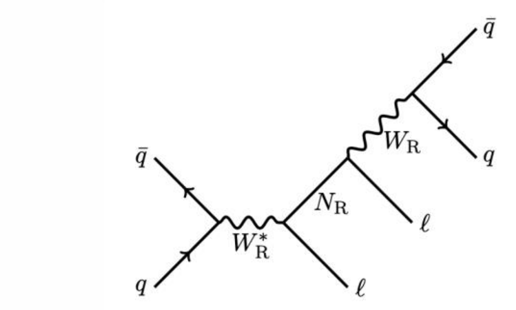
Searches for right-handed neutrinos at the LHC

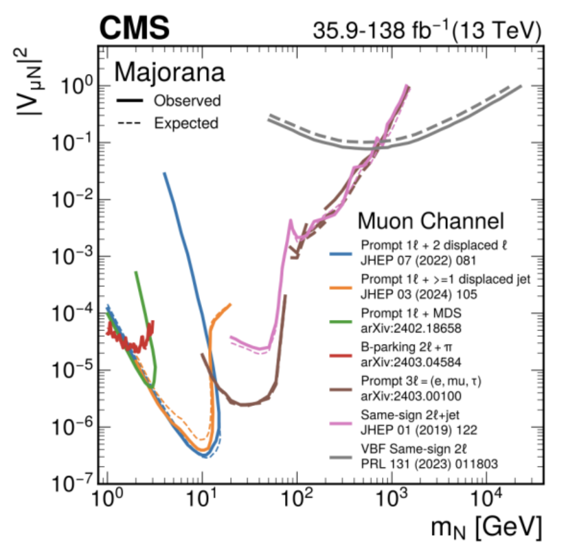
νMSM (Neutrino Minimal Standard Model)

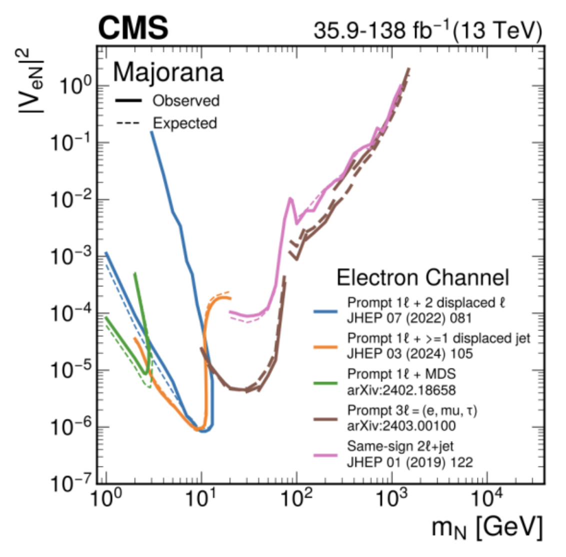
TeV scale right handed Neutrinos

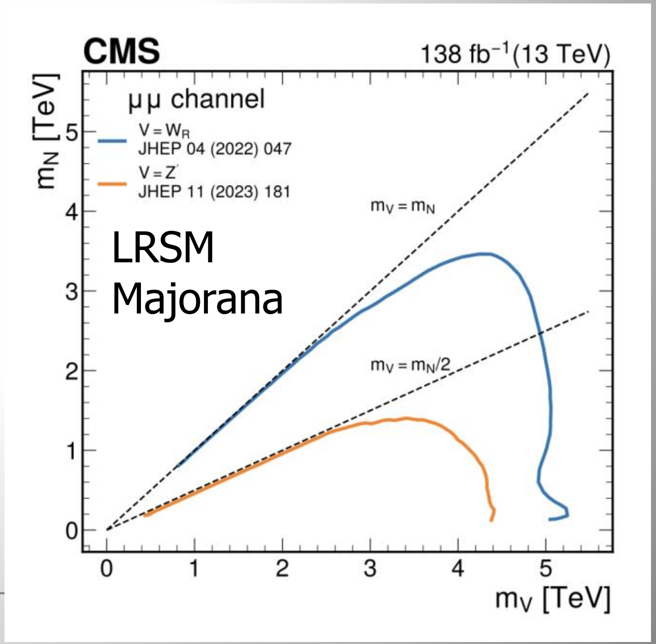






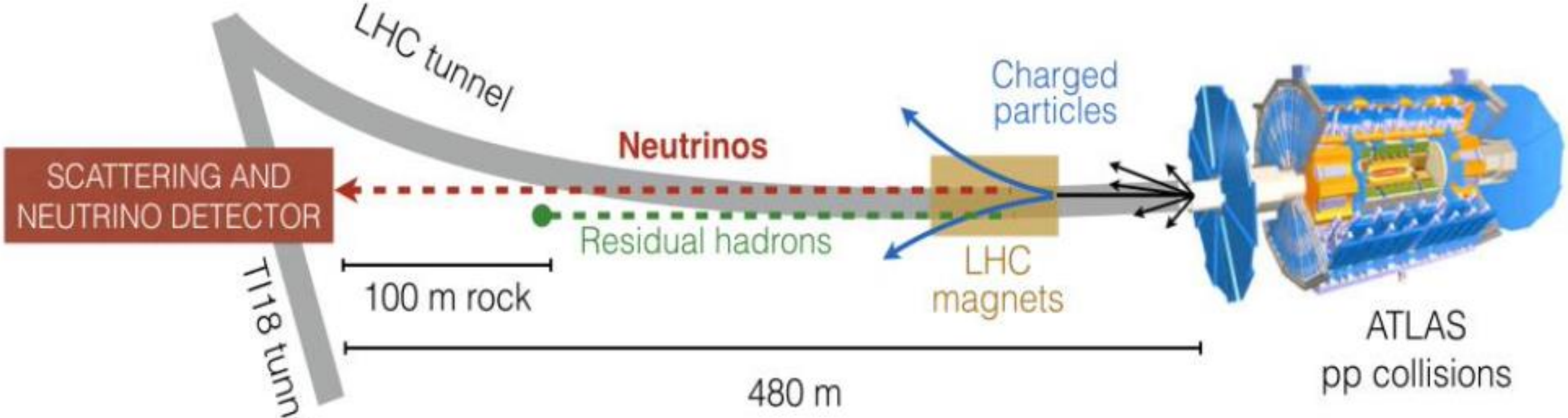


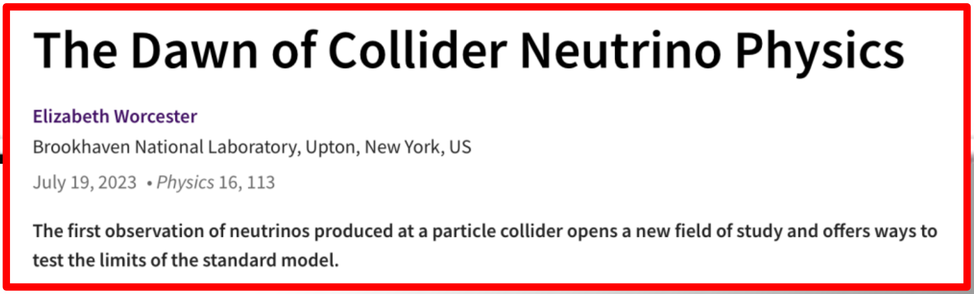




Measuring Neutrino Interactions @ LHC

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





The Dawn of Collider Neutrino Physics

Elizabeth Worcester

Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113

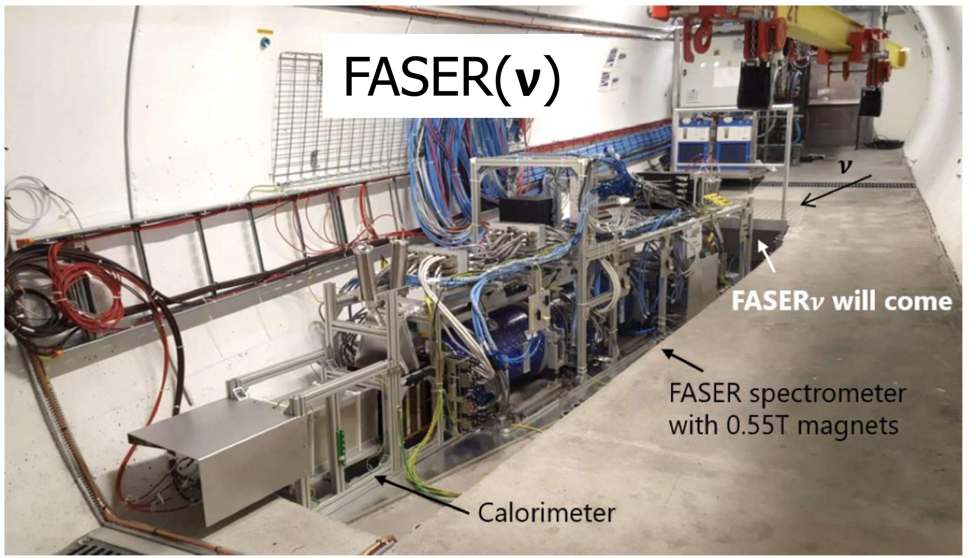
The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.

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

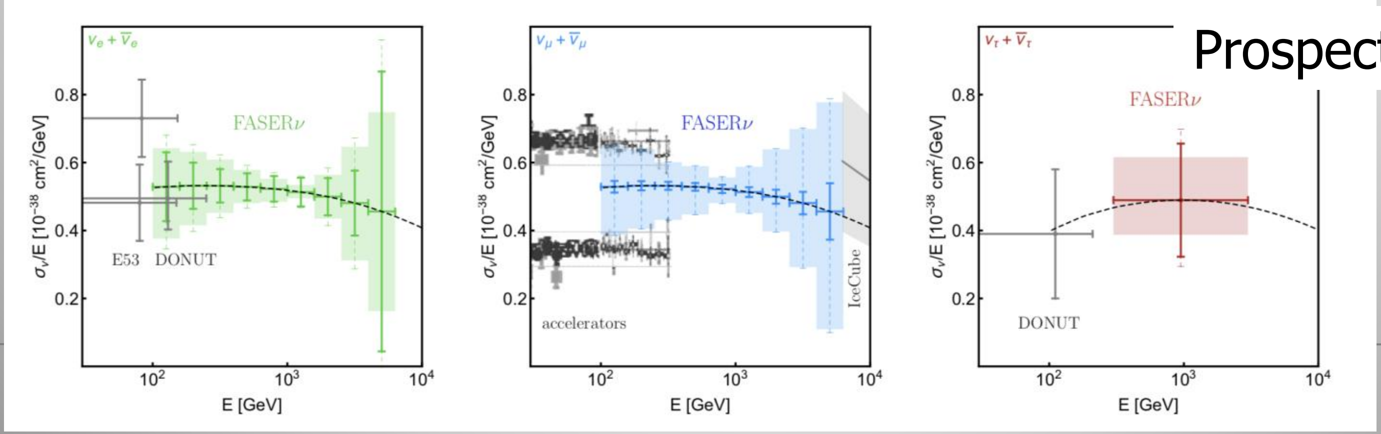
Neutrinos @ the LHC: SND@LHC & FASERν

SND@LHC/FASERν are 480m forward and can study TeV-neutrinos with emulsion and tracking+muon/calo detectors

SND= Scattering and Neutrino Detector

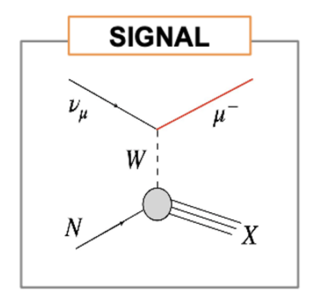


Prospects for Run 3



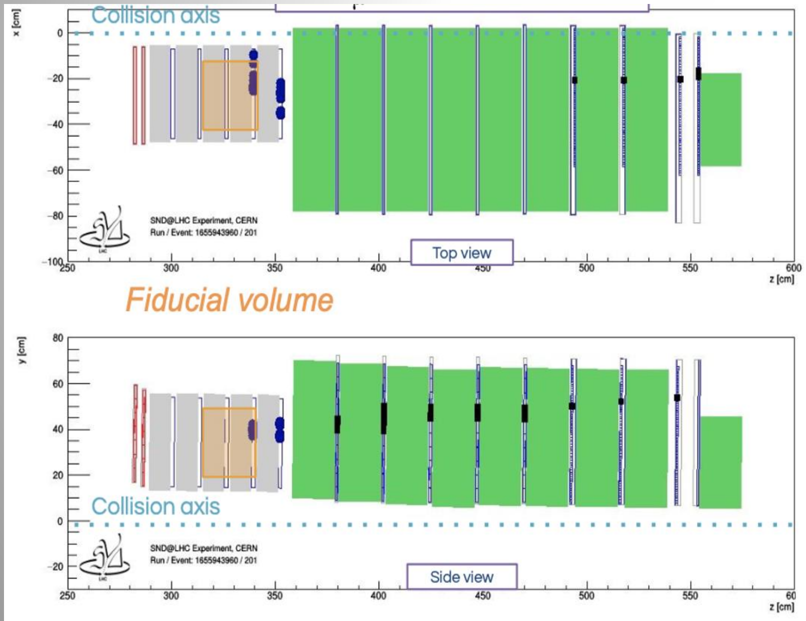
First Results from FASER and SND@LHC

First direct observation of neutrinos produced at the LHC in the charged current muon channel



SND@LHC (off-axis)

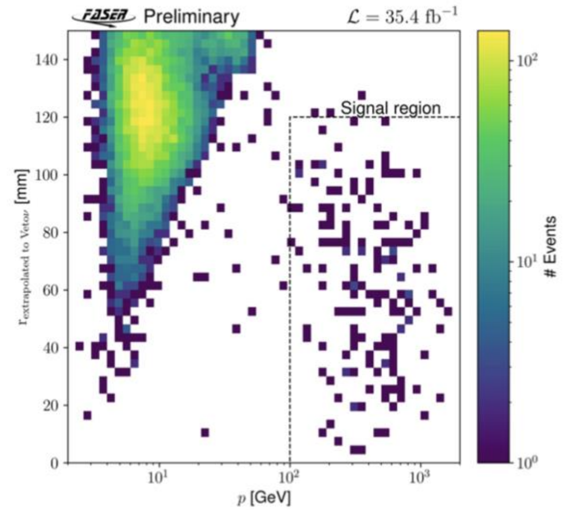
2305.09383



- Observed ν_μ **candidates**: 8 (expected 5)
- Preliminary estimate of background yield: 0.2

FASER (on-axis)

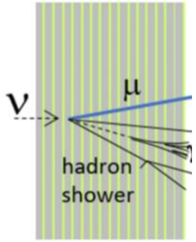
2303.14185



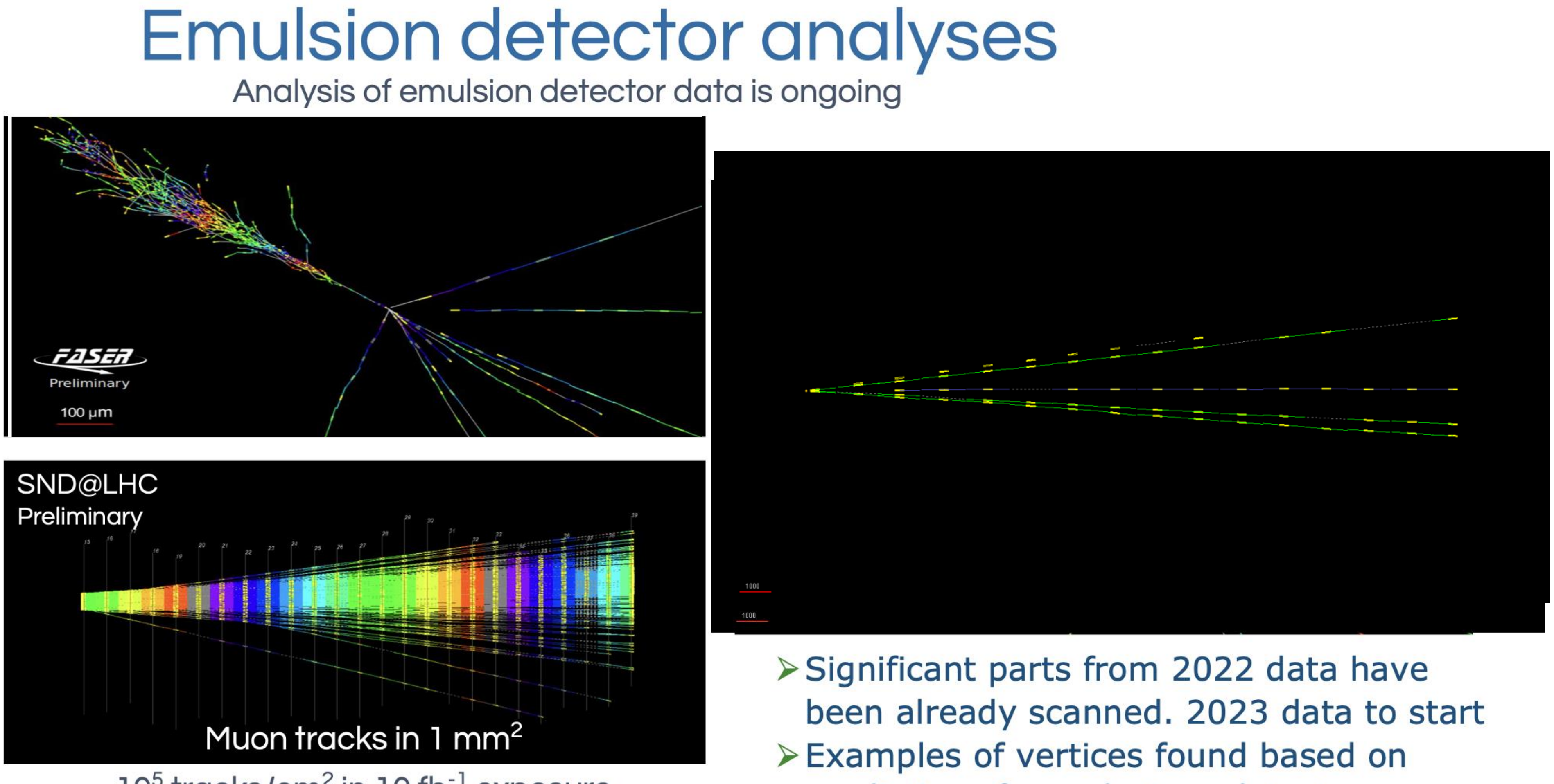
153 observed events in signal region

SND@LHC & FASER

Neutrino target:
emulsion sandwich with 1 mm
tungsten plates (58 layers)



Excellent spatial resolution of the emulsuon: ~ 1 μm



Emulsion detector analyses

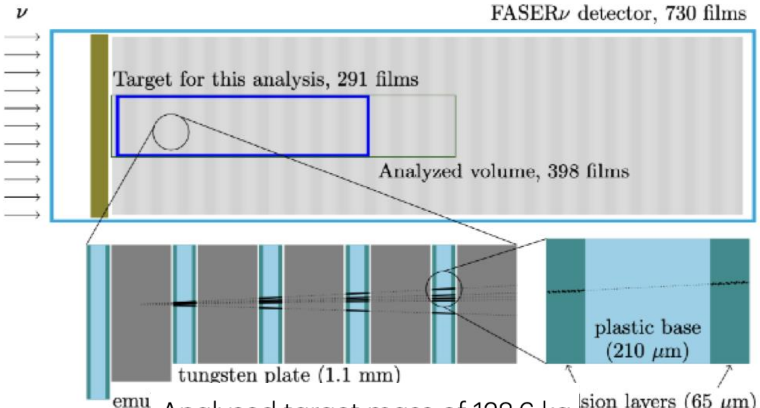
Analysis of emulsion detector data is ongoing

10^5 tracks/cm^2 in 10 fb^{-1} exposure

- Significant parts from 2022 data have been already scanned. 2023 data to start
- Examples of vertices found based on

ν_e and ν_μ Interaction Cross Sections

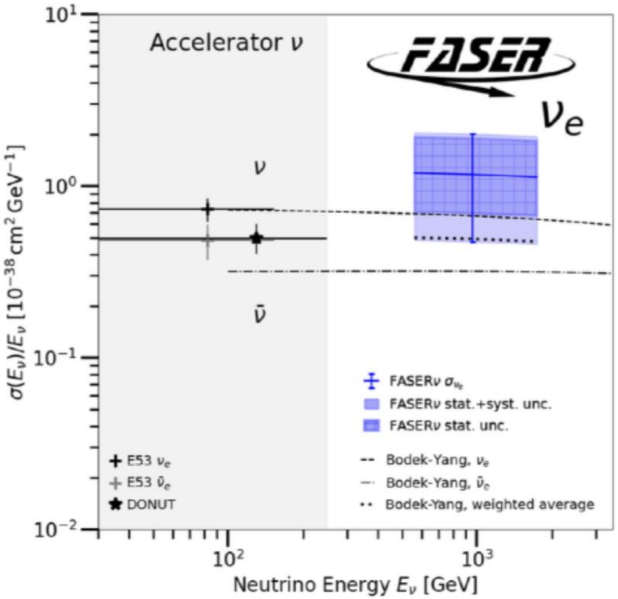
First measurements!

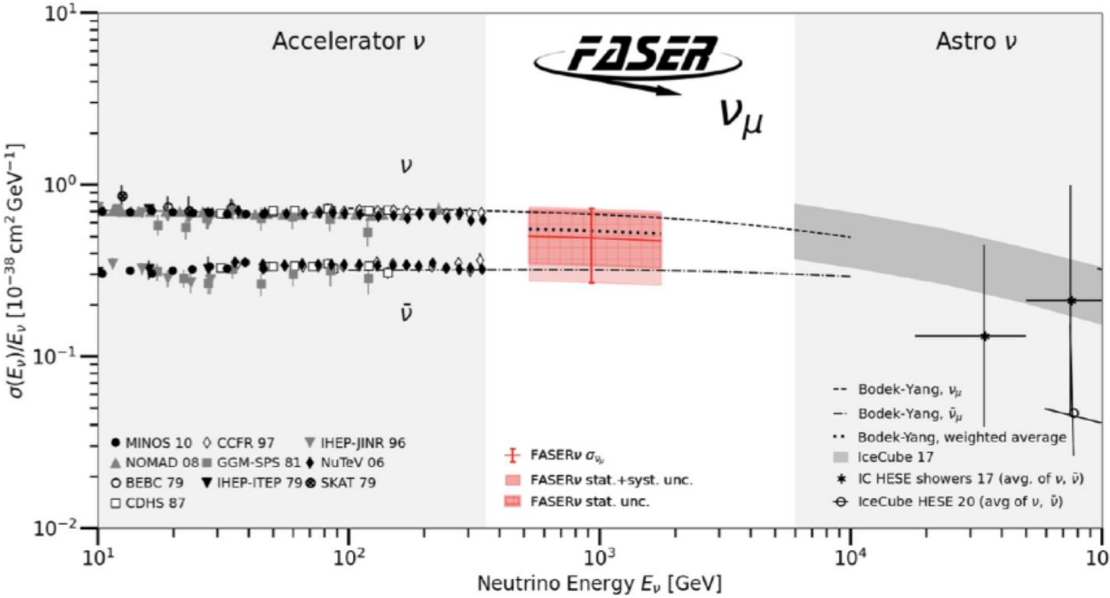


Analysed target mass of 128.6 kg

- Only small fraction of 2022 analyzed so far
- Candidate vertices reconstructed in emulsion films
  - Energy measurement (e) from shower multiplicity
  - Momentum measurement (μ) from track RMS (via Multiplescattering)
- Electron neutrino events observed: 4 (5.2σ)
- Muon neutrino events observed: 8 (5.7σ)

2403.12520

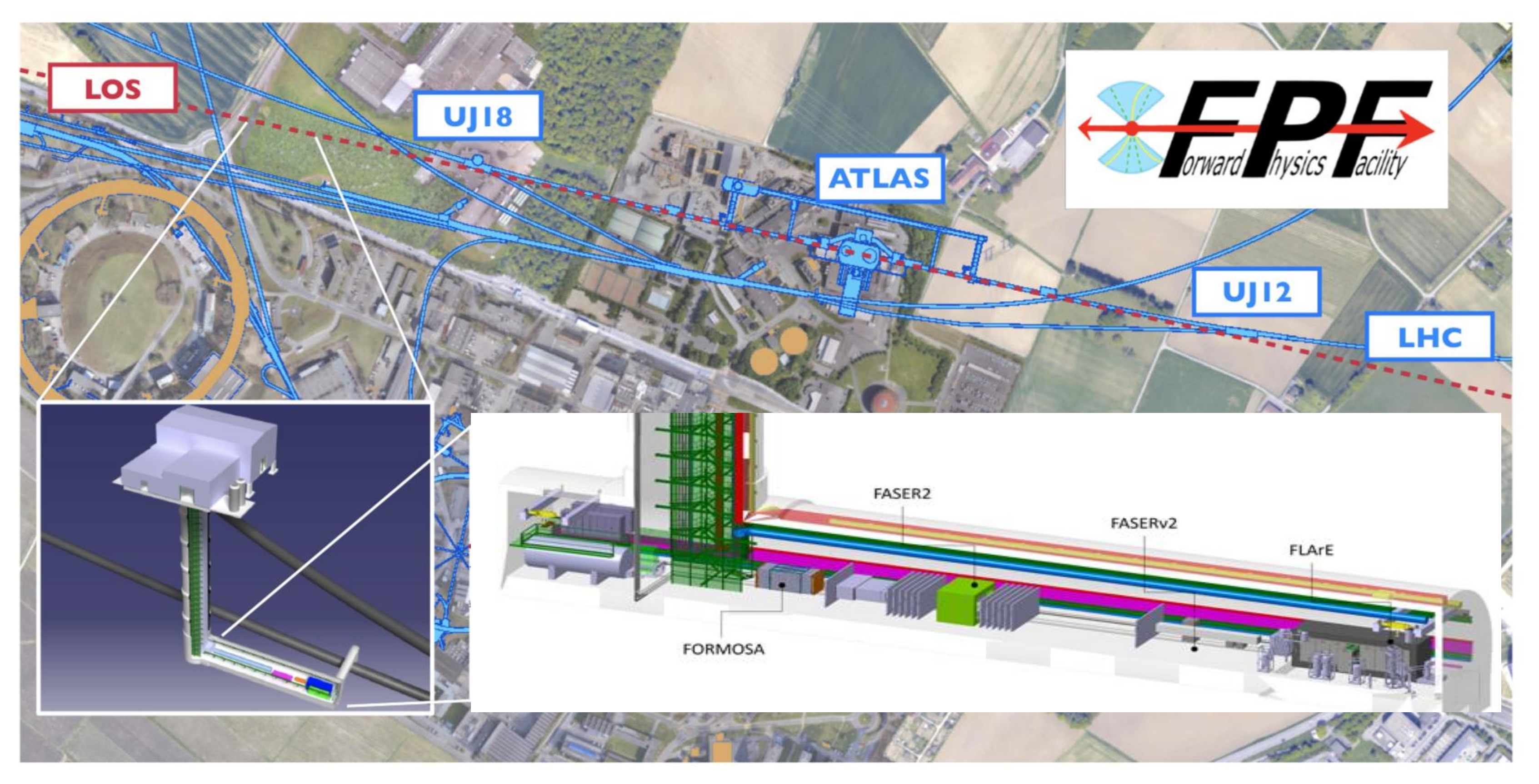




NEW: The Forward Physics Facility

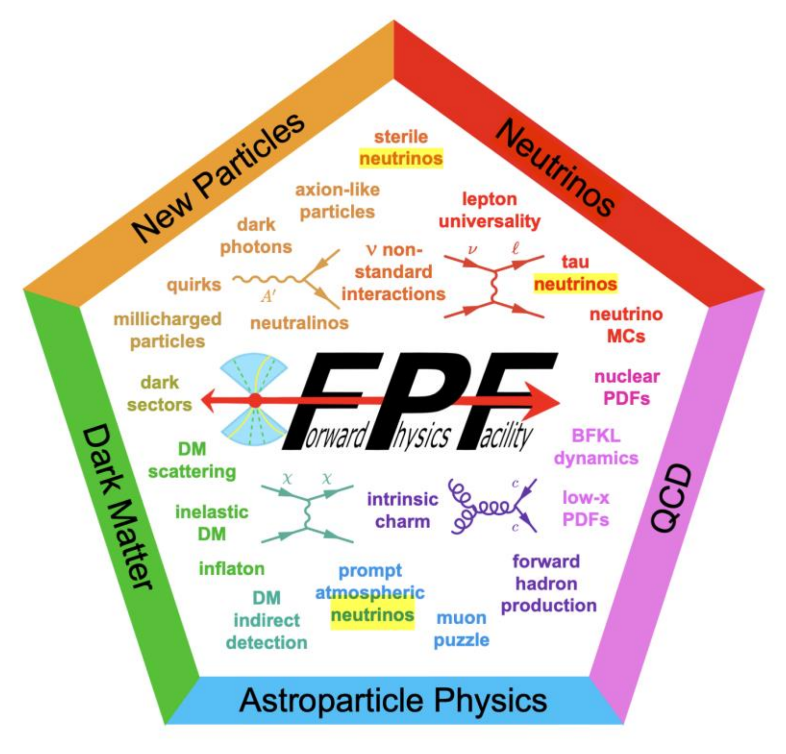
Origin: Letter of intent contributed to the Snowmass21 process.
Based on the FASER experience and studies: propose to have a Forward Physics Facility (FPF) experimental hall with room to include forward detectors for new physics searches (and QCD): FASER2, others

2203.05090



Neutrino Experiments for the HL-LHC?

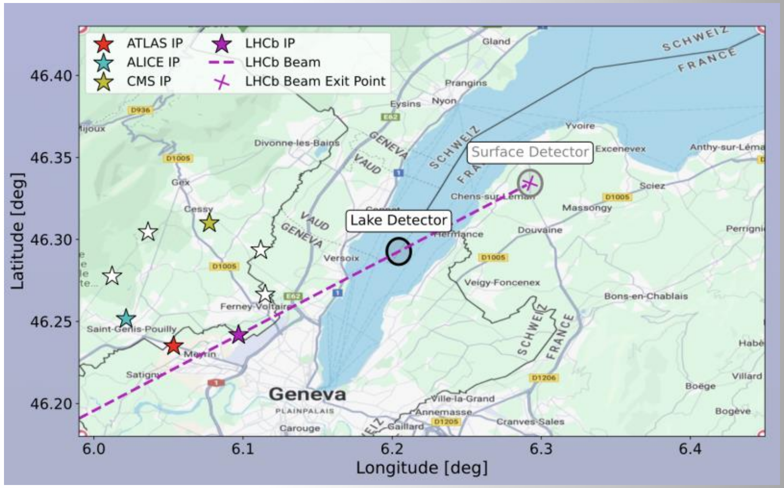
- The Forward Physics Facility: A new underground area for forward experiments



- Covers neutrino physics and much more…
- Detailed study reported in 2022.05090

- Neutrinos in Lake Geneva??

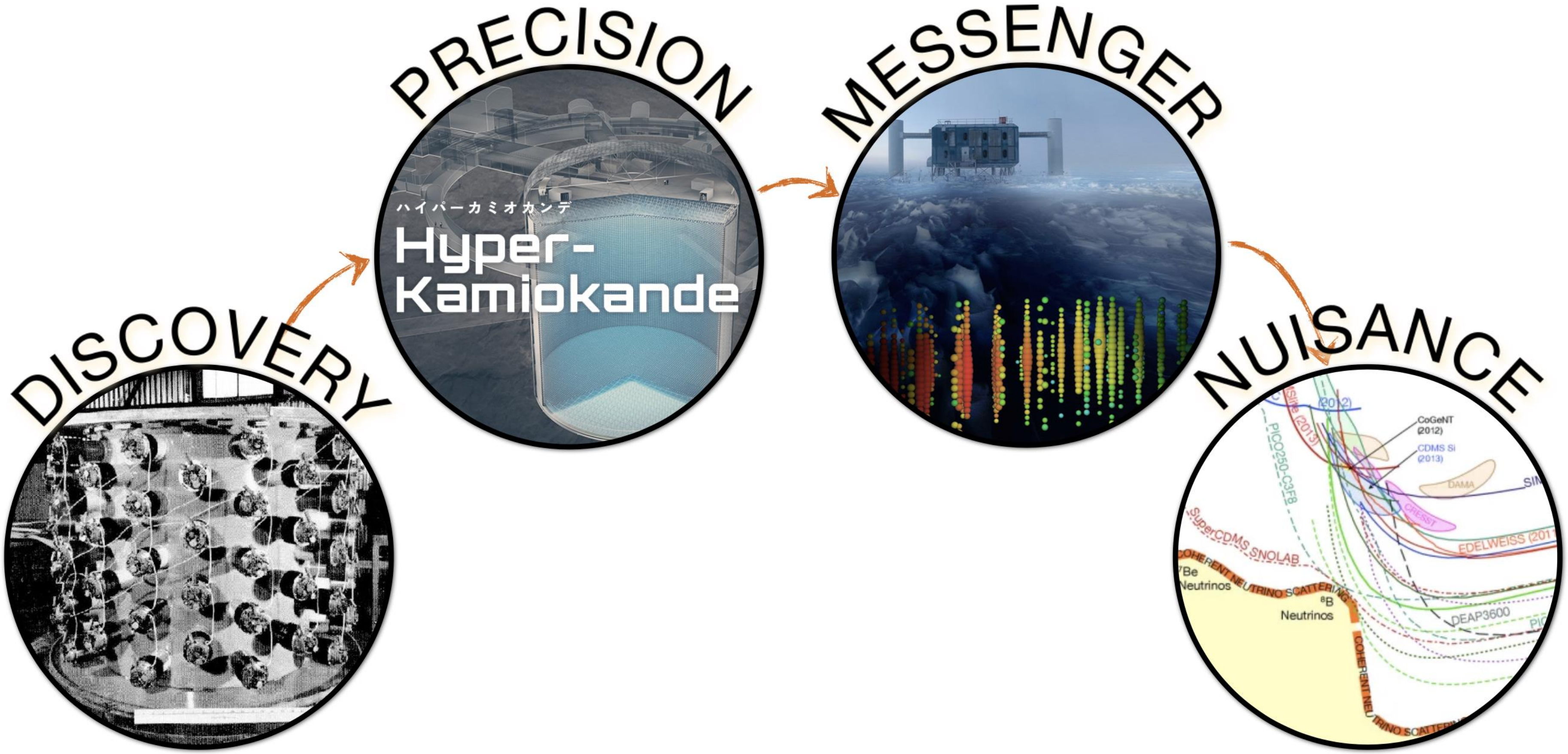
Neutrino2024



- A large detector in or just outside Lake Geneva? A fresh idea.. (N. Kamp et al., Neutrino24 Poster)

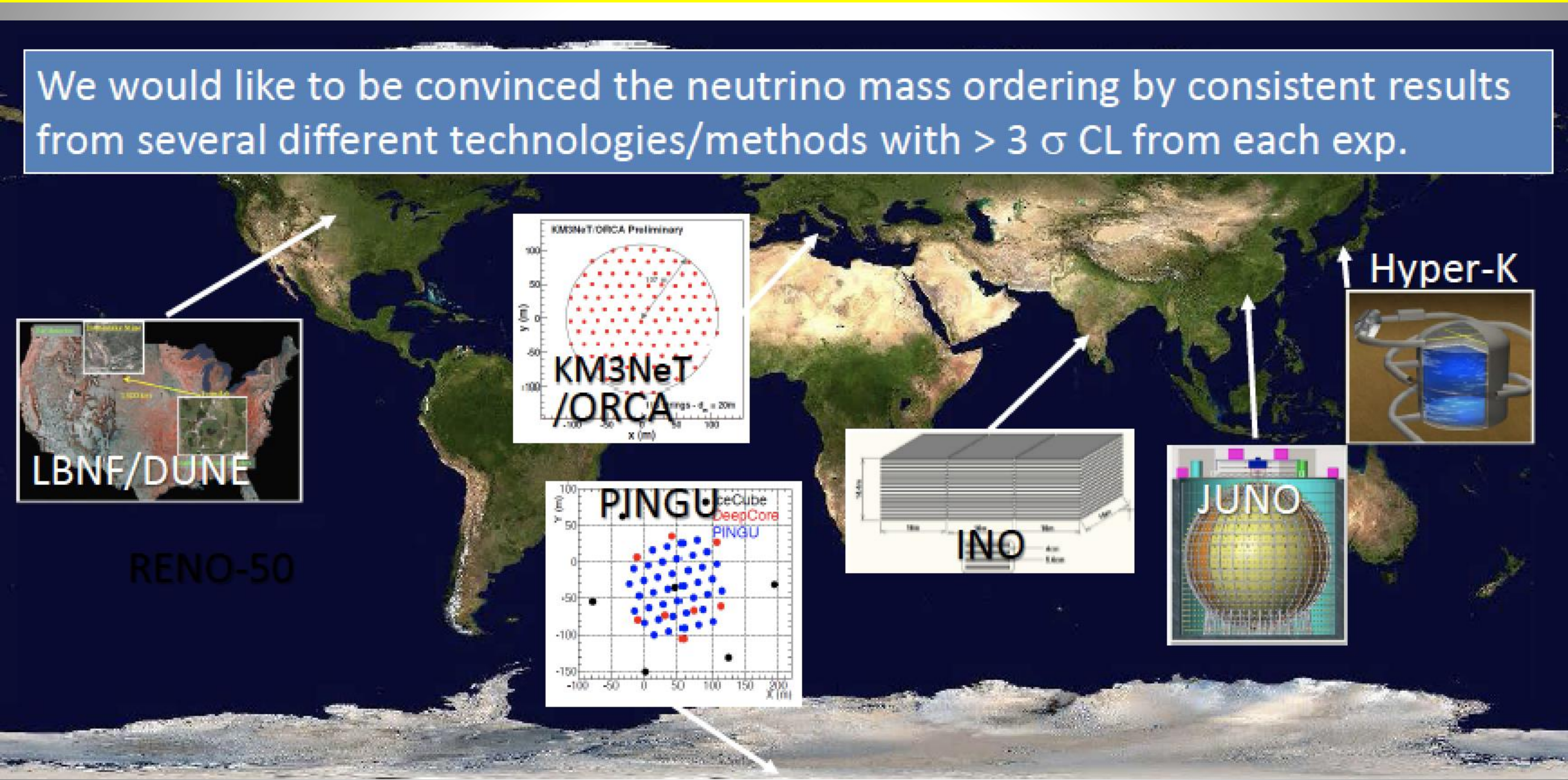
Near Future Neutrino Experiments

Ongoing Neutrino History



Future Neutrino Experiments

Eg. experiments that will contribute to the mass ordering question



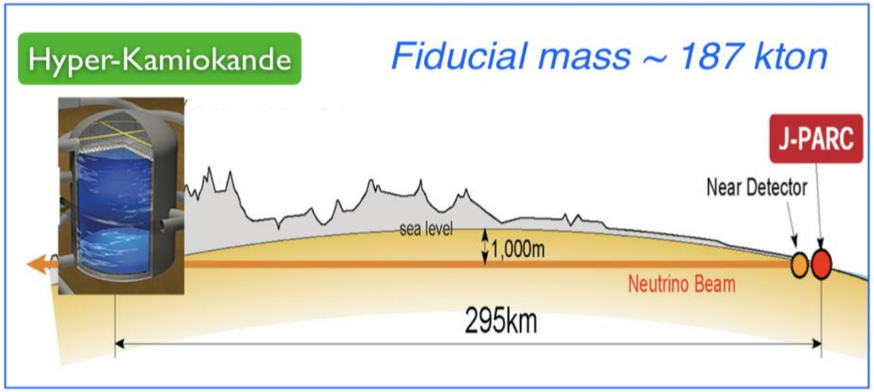
We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.

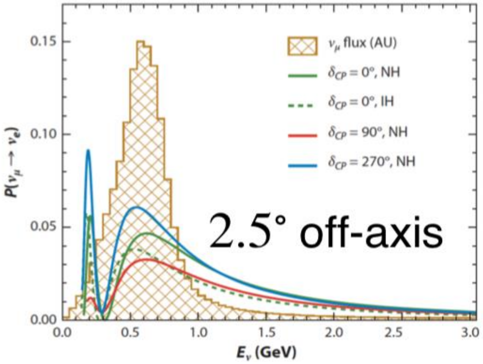
JUNO start in 2025 T2HK/DUNE start in ~2027-2030

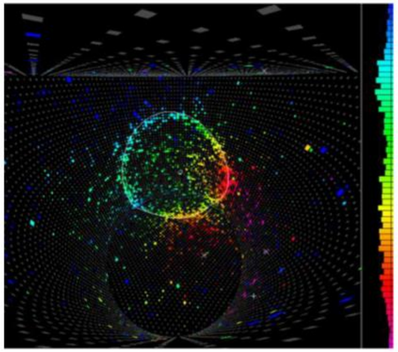
Future Neutrino Experiments

Long-baseline experiments: T2HK and DUNE

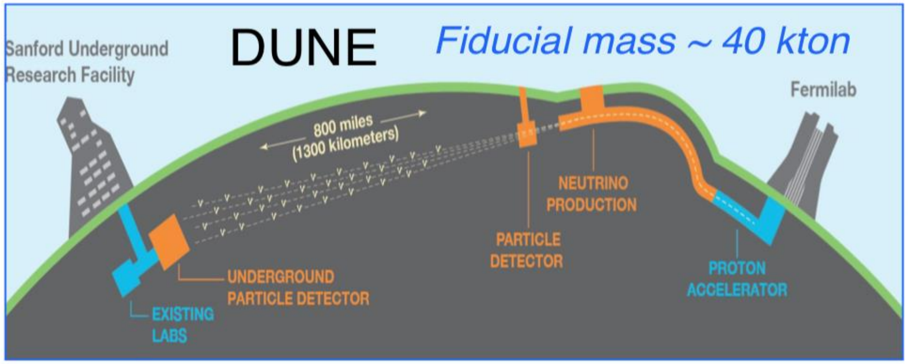
- Towards the measurement of the CP violating phase and Mass Hierarchy
  - ✦ Search for different $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities

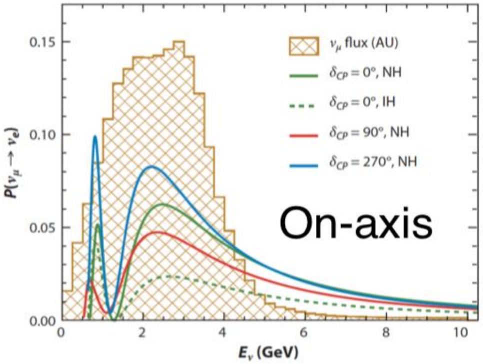


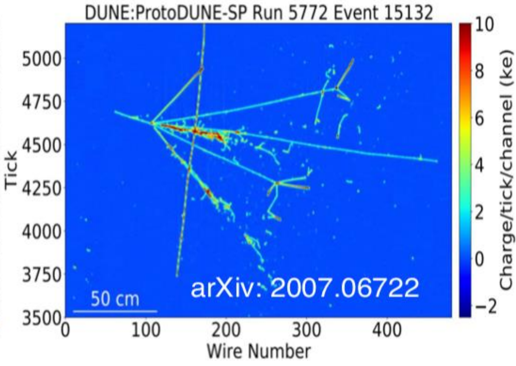




Annu. Rev. Nucl. Part. Sci. 2016. 66:47–71



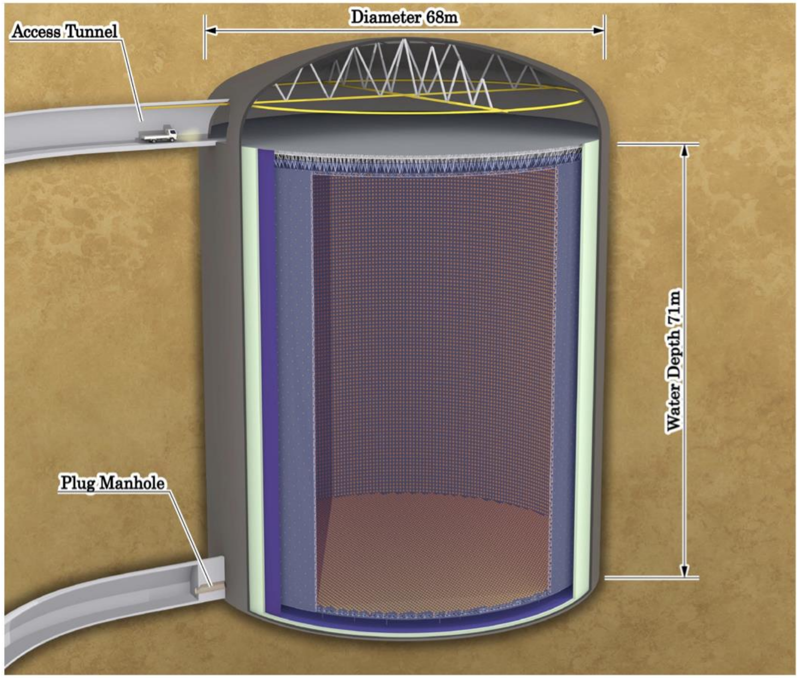


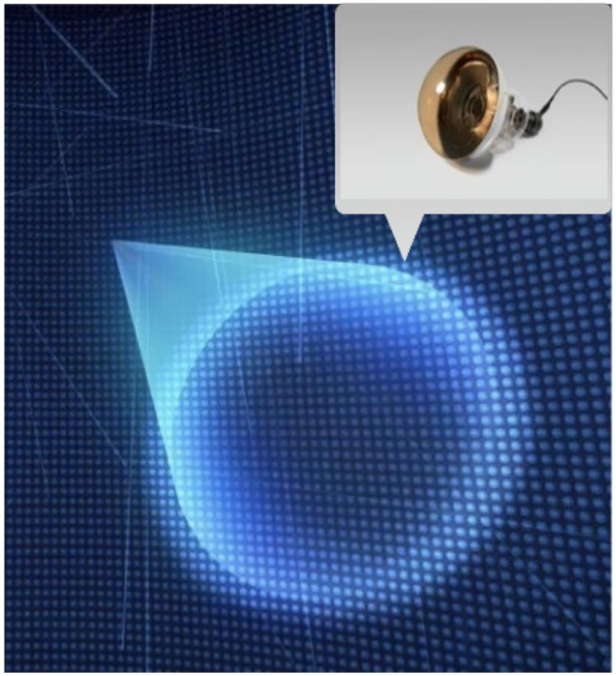


The T2HK Experiment

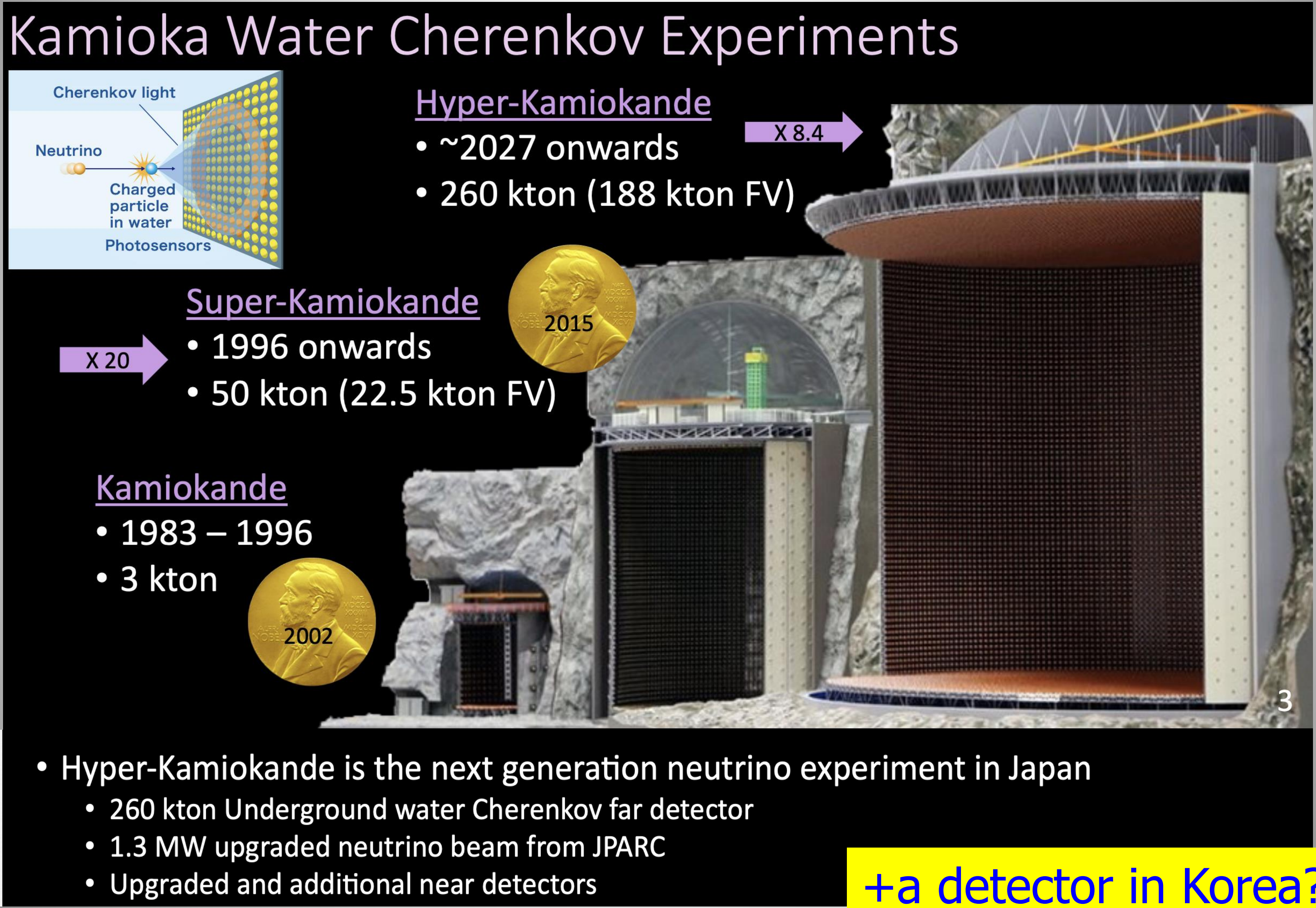
Hyper-Kamiokande Detector

- The Hyper-Kamiokande detector is the next generation water Cherenkov detector in Kamioka, Japan, with an accelerator and near detector complex at J-PARC in Tokai
- Size: 258 kton, with fiducial mass ~8 times larger than Super-K,
- Baseline: 20,000 50-cm photomultiplier tubes (PMT), ~2,000 multi-PMT modules and 7,200 outer detector 8-cm PMTs with wavelength shifting (WLS) panels





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)

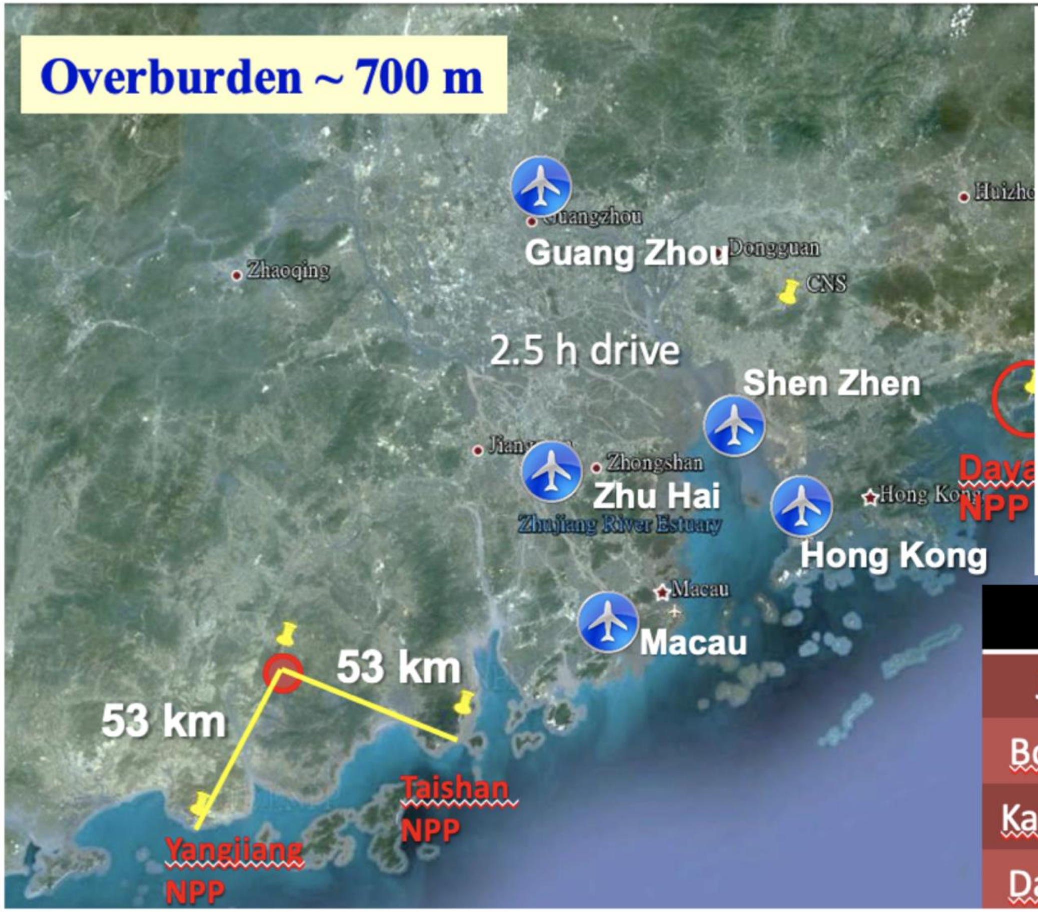
Kamiokande
- 1983 – 1996
- 3 kton

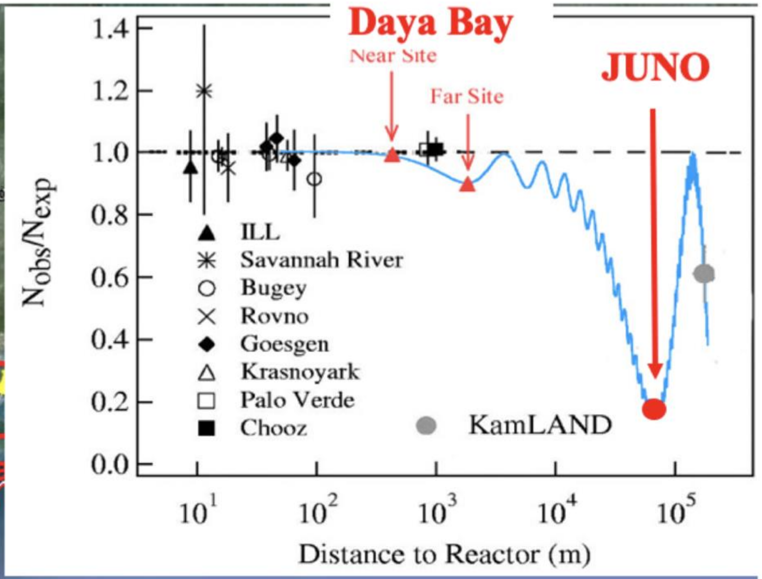
- Hyper-Kamiokande is the next generation neutrino experiment in Japan
  - 260 kton Underground water Cherenkov far detector
  - 1.3 MW upgraded neutrino beam from JPARC
  - Upgraded and additional near detectors

+a detector in Korea?

The 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



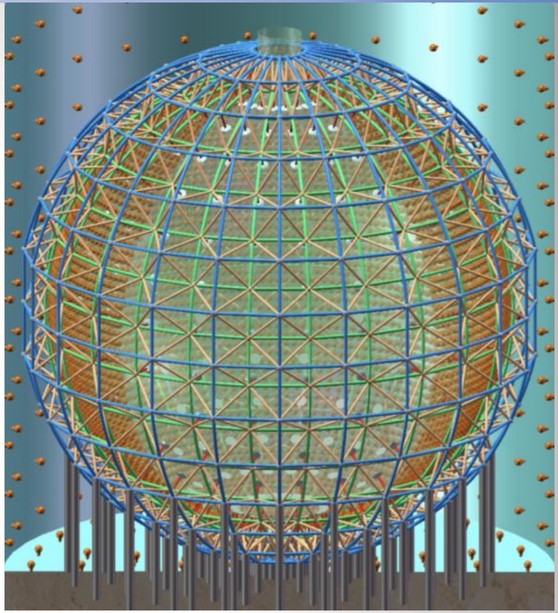


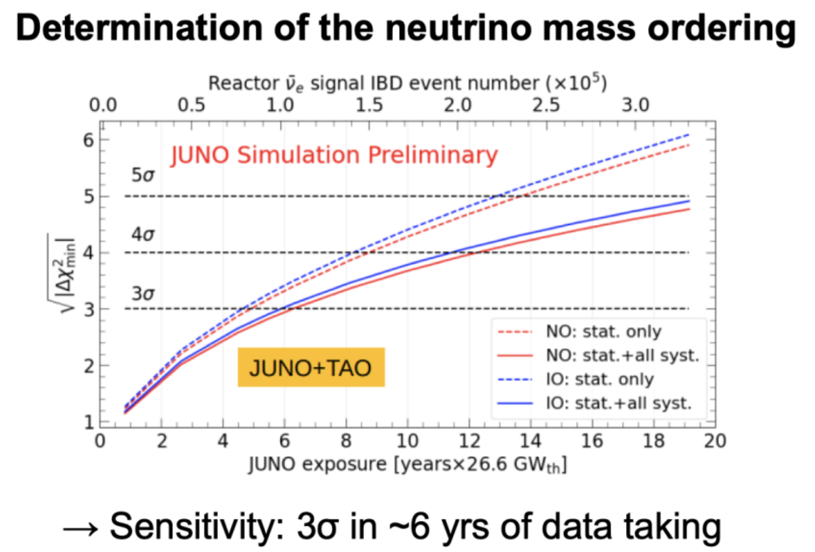
	Target mass [t]	energy resolution
JUNO	20,000	3% @ 1 MeV
Borexino	300	5% @ 1 MeV
KamLAND	1,000	6% @ 1 MeV
Daya Bay	20	8% @ 1 MeV

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 2024/2025

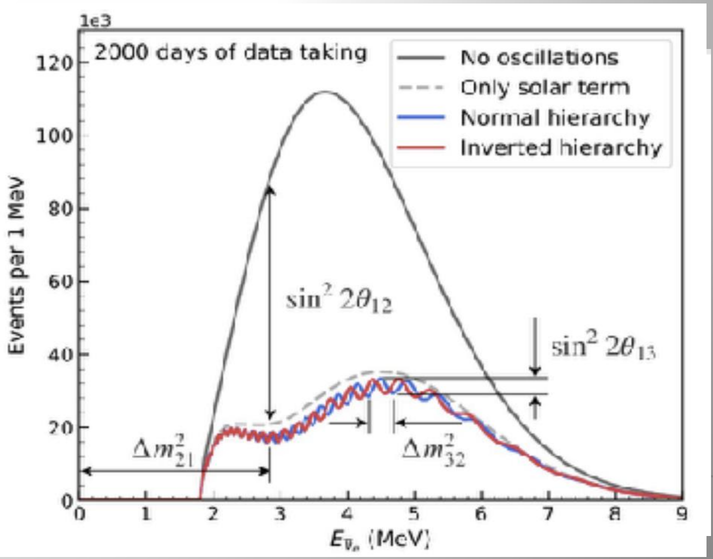
With an energy resolution of 3% at 1 MeV, JUNO determine the mass ordering with a significance of 3 sigma within six years



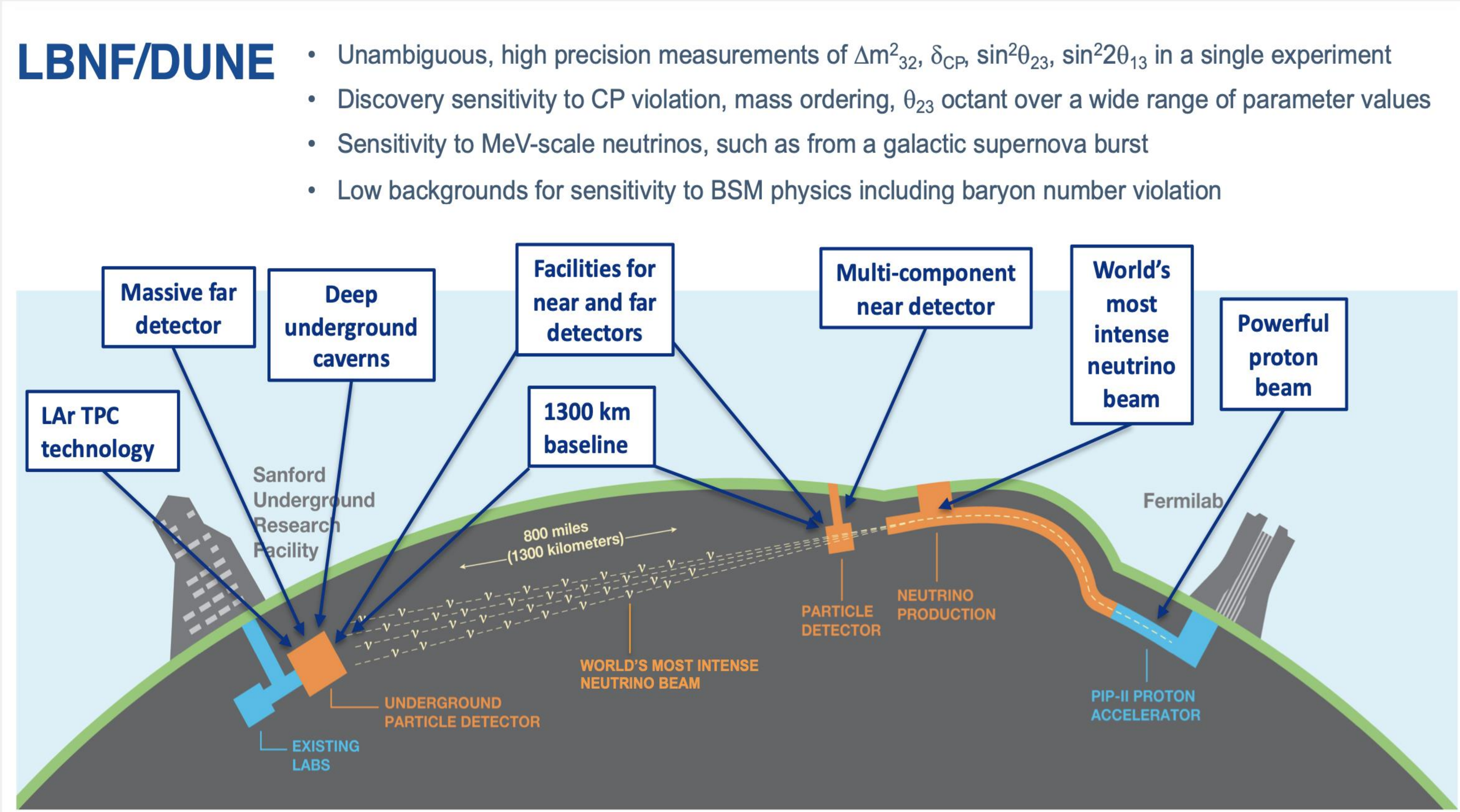


Determination of the neutrino mass ordering

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



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

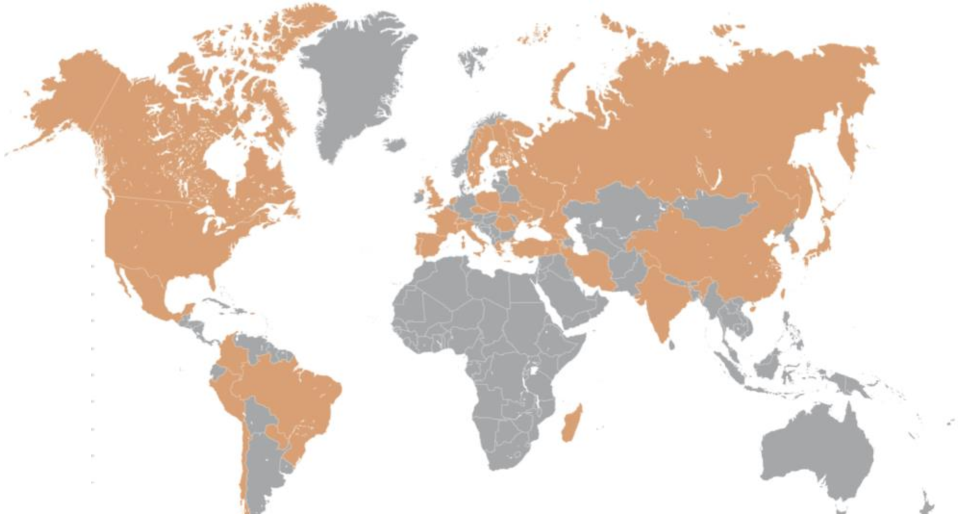
World's most intense neutrino beam

Powerful proton beam

LAr TPC technology

1300 km baseline

DUNE – a global collaboration



- 1400+ collaborators from
- 200+ institutions in
- 33 countries + CERN

Still more groups joining

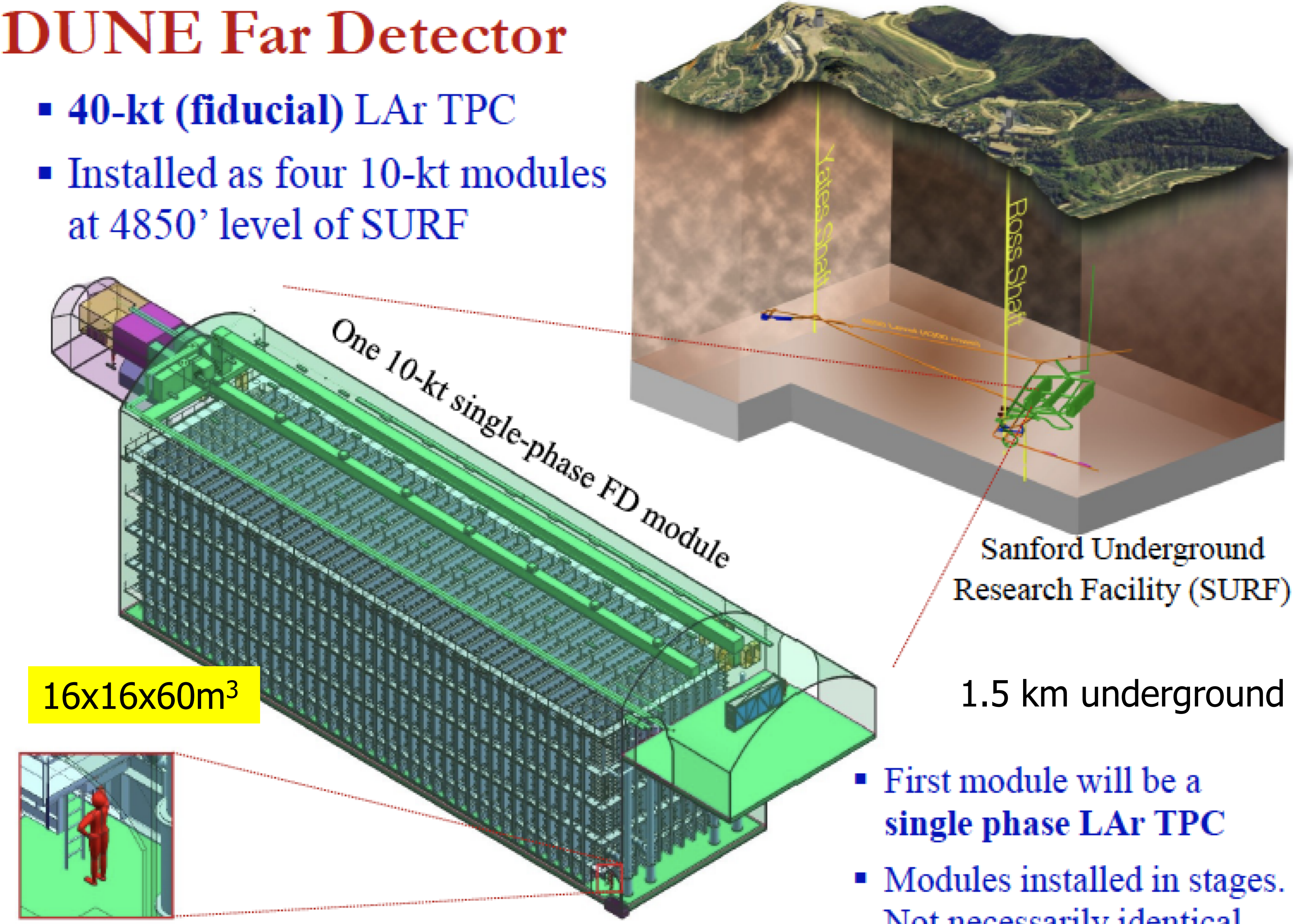
DUNE Jan 2023

Collaboration meeting at CERN

Total participants : 581 In person: 354 (largest on record) Zoom:227

DUNE Far Detector

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



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

Large Neutrino Observatories

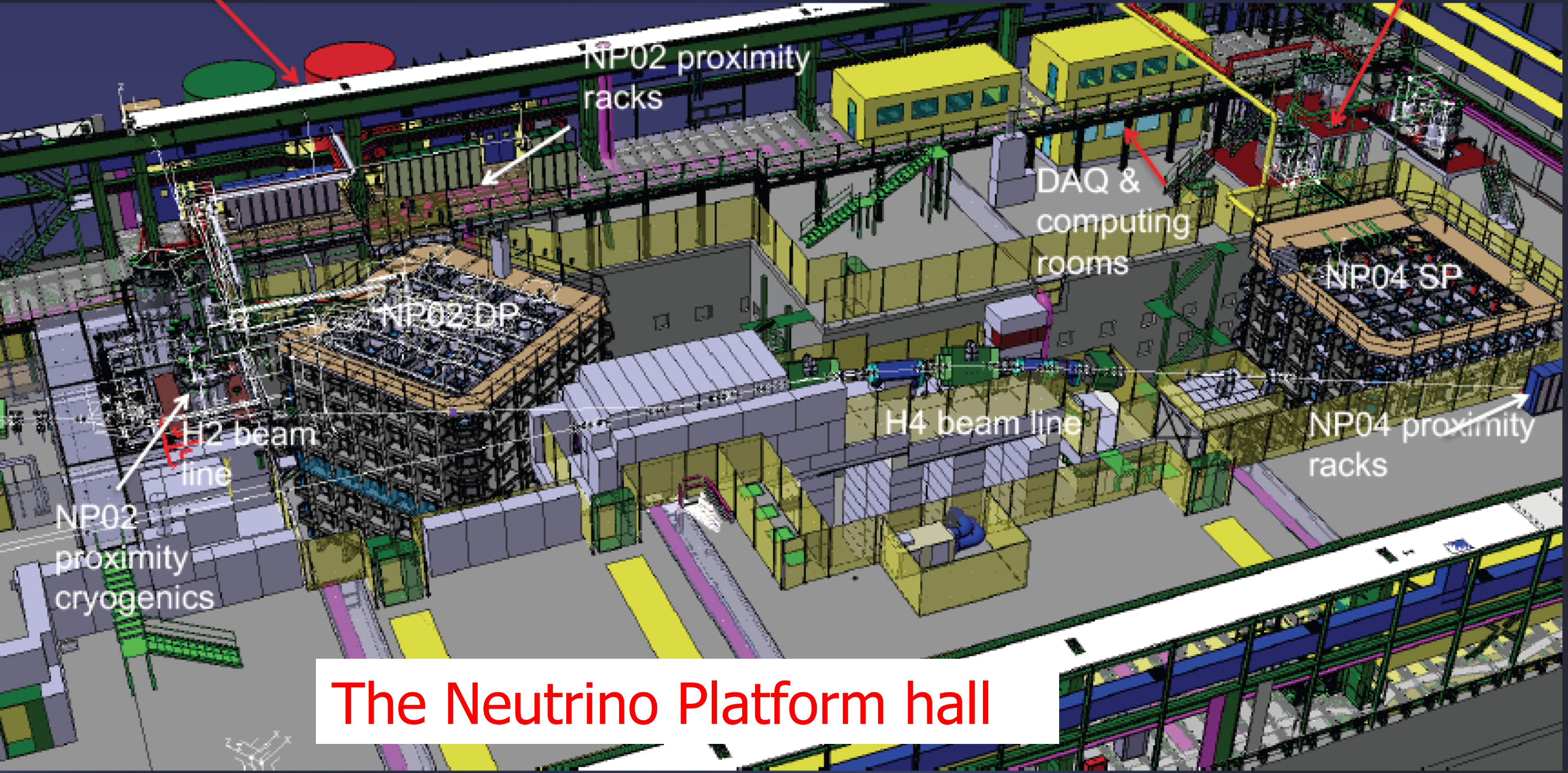
Last Month !

A ribbon-cutting event was held at the Sanford Underground Research Facility in Lead, S.D. to mark the completion of excavation work for LBNF/DUNE. Credit: Ryan Postel

The EHN1 Hall at CERN

Next step : ~800 ton LAr prototypes

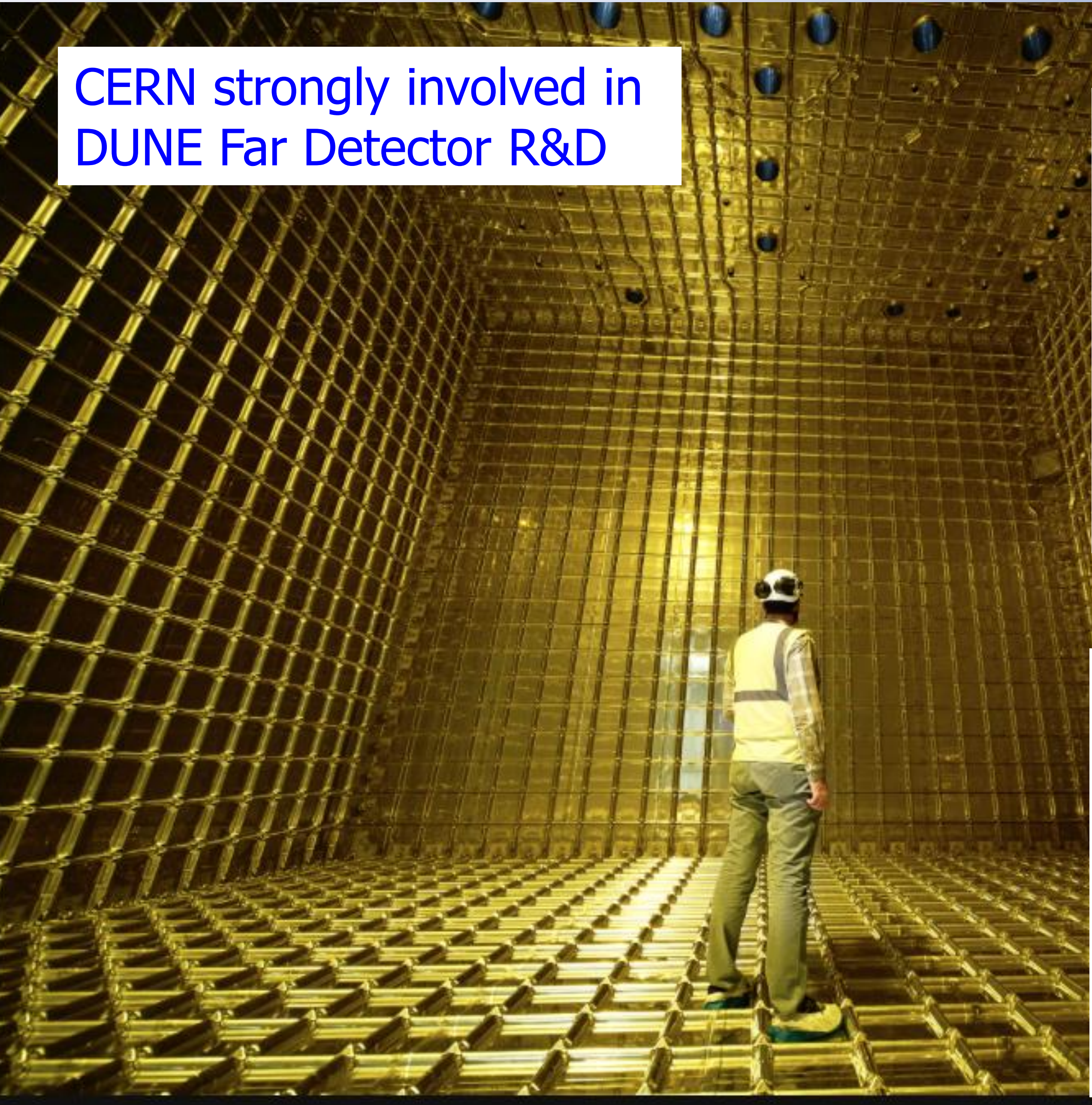
SPS : new EHN1-1 experimental area



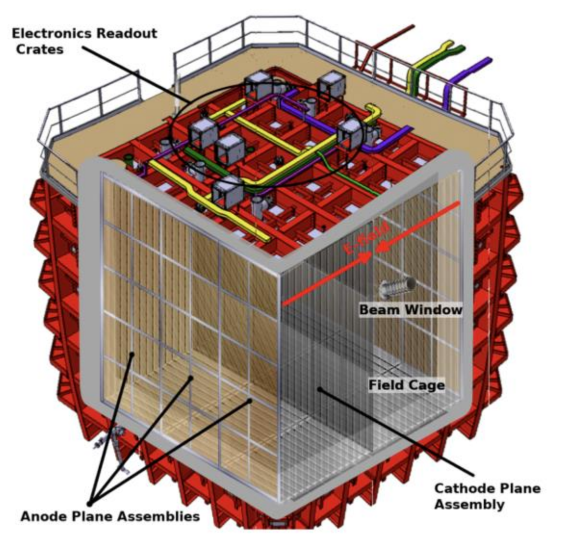
The Neutrino Platform hall

The CERN Neutrino Platform

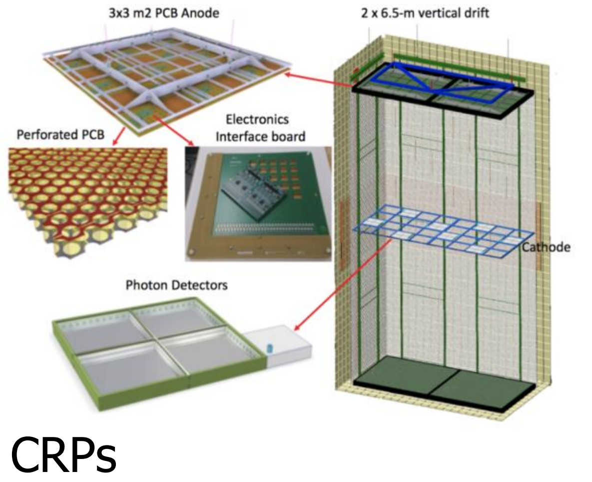
CERN strongly involved in DUNE Far Detector R&D



FD1 Horizontal Drift



FD2 vertical Drift (NEW)



Liquid Argon Time Projection Chamber

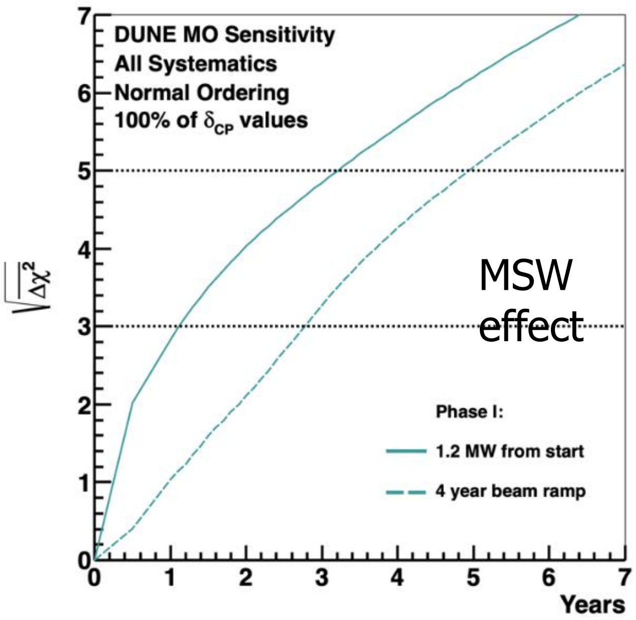
The ‘electronic’ bubble chamber for neutrino experiments

High mass for neutrino detectors

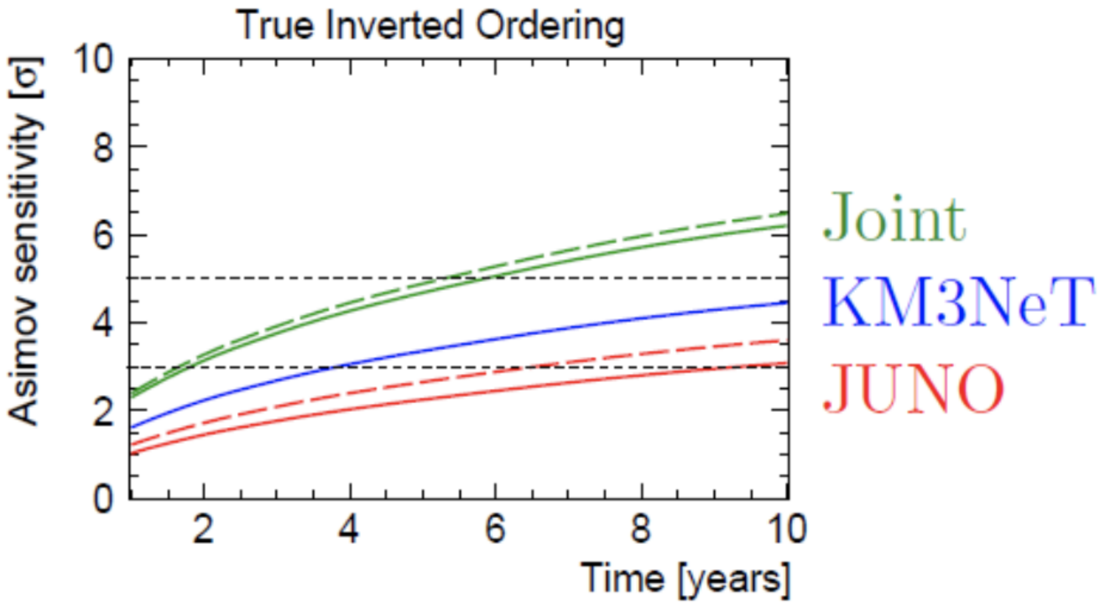
Mass Hierarchy/Ordering

- 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

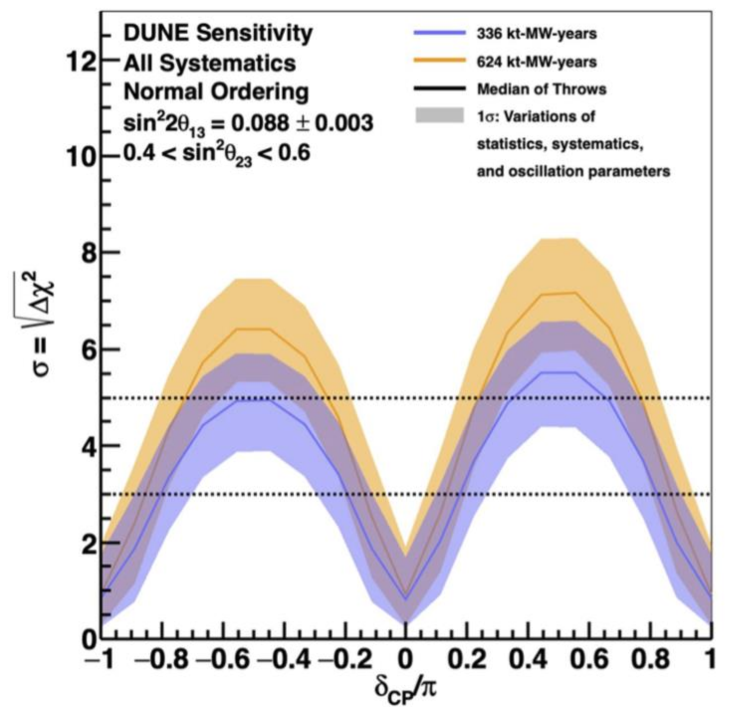


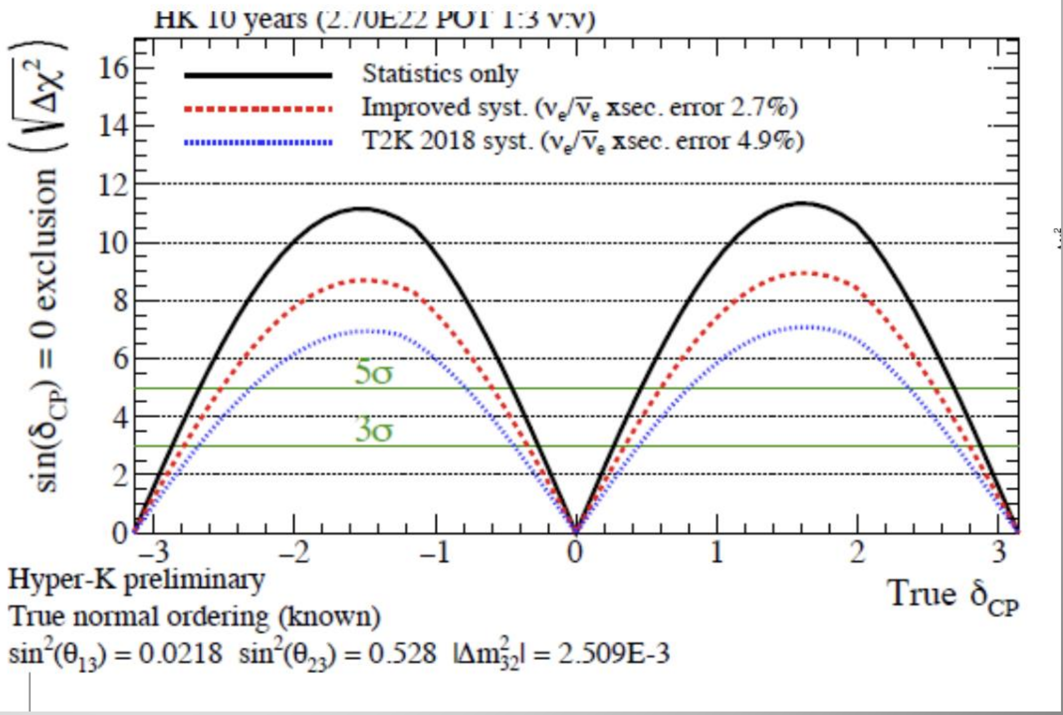
MSW effect



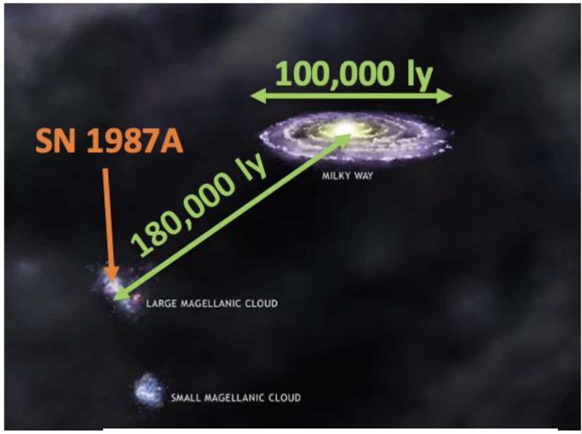
CP Phase

- ~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

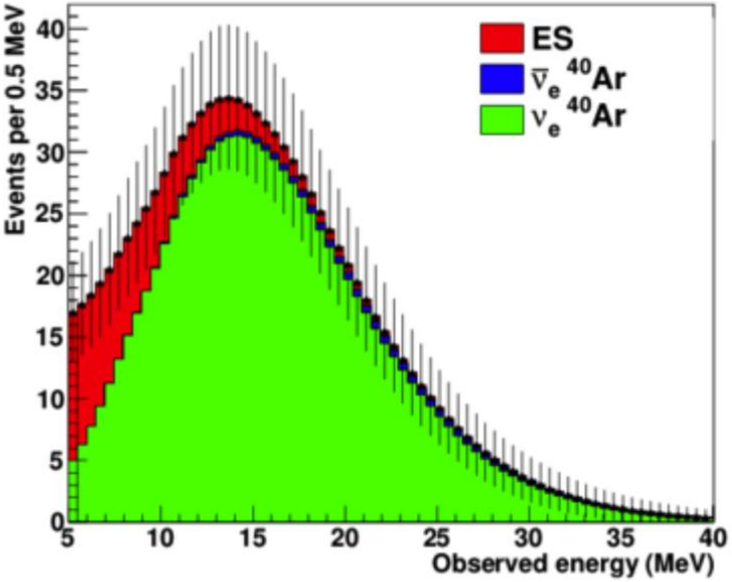


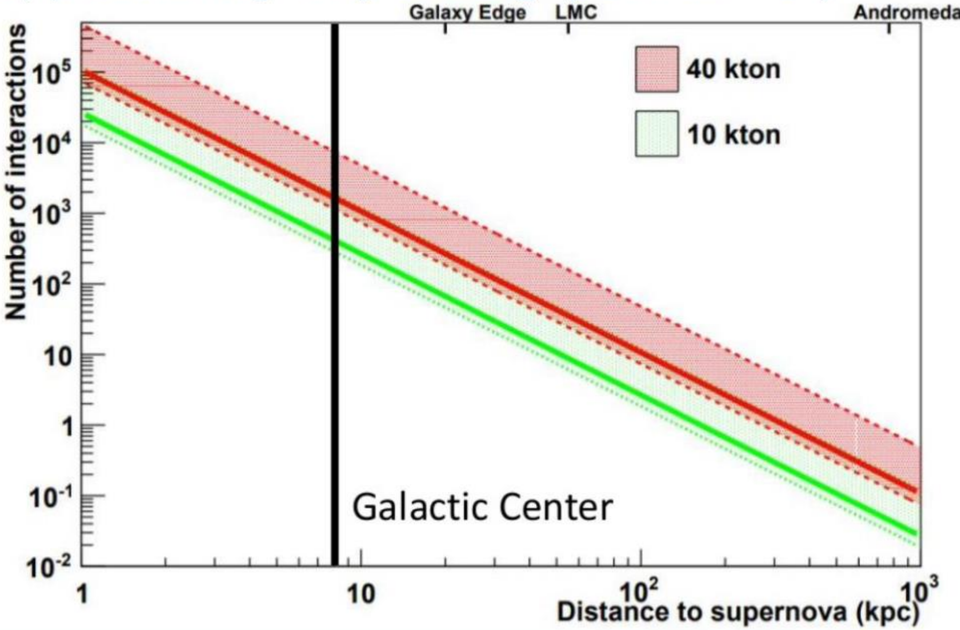


Supernova neutrinos



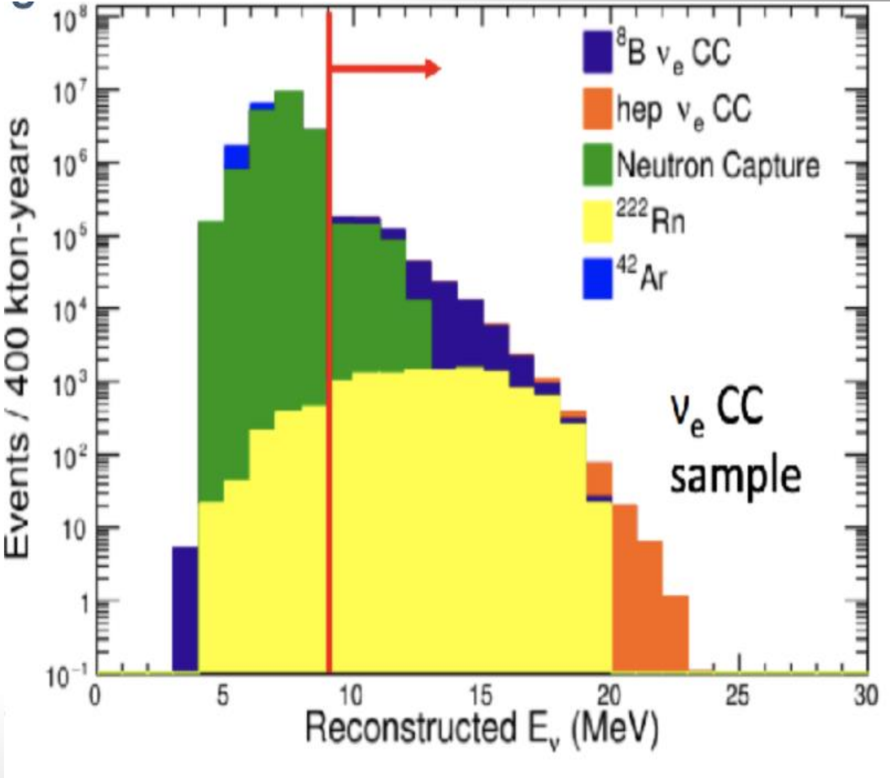
- Expect to detect 1,000s of neutrinos from supernova close to Milky Way center
  - On order of 1 event from Andromeda
  - The $\boldsymbol{\nu}_e$ flavor dominates. Detectable in DUNE via $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$
  - Great information for SN models, possibility of pointing (res. of ~5°)





Solar Neutrinos in DUNE

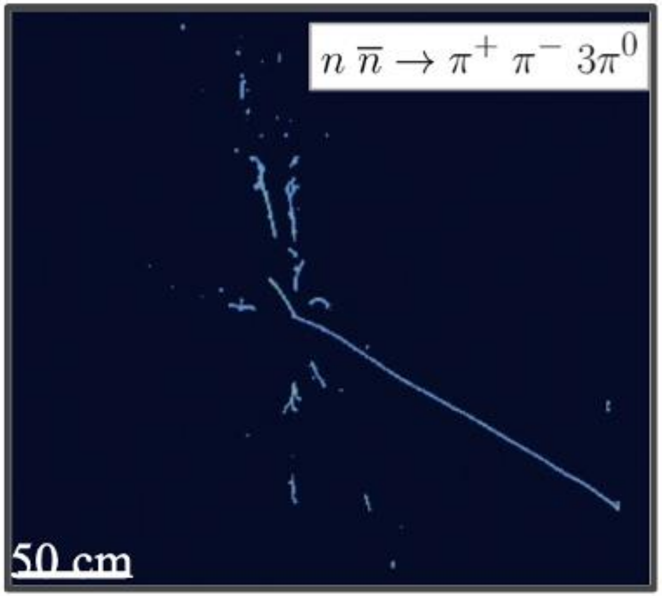
- DUNE will record an enormous amount of solar neutrinos ⟶ several events/day/kt.
- Backgrounds are very important. Neutron capture dominates (9 MeV analysis threshold).
- Discovery potential for hep neutrinos in DUNE!
- Precision of neutrino mixing and fluxes.
- DUNE has favorable sensitivity for measuring Δm^2_{21}.
- **On-going full DUNE study.**



Baryon Number Violation

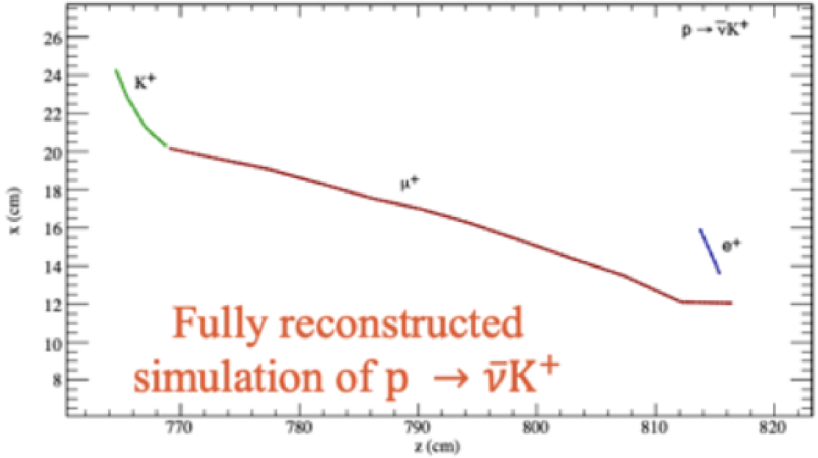
- Neutron anti-neutron oscillations and proton decay with 400kt-yr of data taking

FD: $n - \overline{n}$ oscillation



Free-neutron-equivalent sensitivity:
$\tau_{\mathrm{free,osc}} > 5.5 \times 10^8$ s (90% C.L.)

FD: Proton Decays

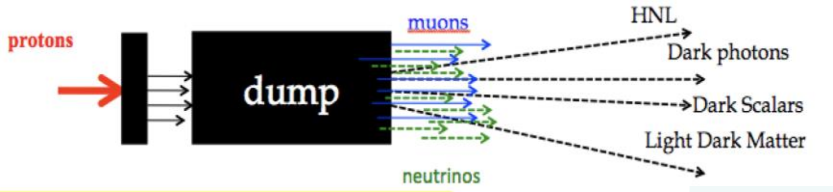


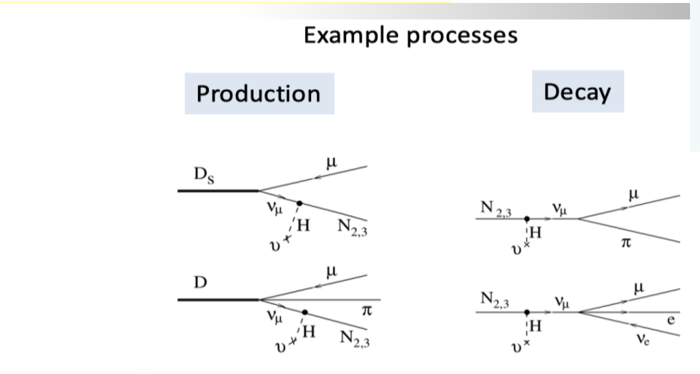
Fully reconstructed simulation of p $\to \bar{\nu}K^+$

0.5 bkg events for 400 kt-yr, 30% signal efficiency
Sensitivity (no signal): $\tau/B >$ 1.3×10^{34} yr (90% C.L.)

Searches for BSM Physics

- High intensity proton beam on target/dump can be a source for low mass BSM particle production
- ND detectors at ~600m can detect BSM particle scattering or decays.
- Examples are: light dark matter, dark scalars, dark photons, axions, heavy neutral leptons (HNLs).
- Example shown here for HNLs





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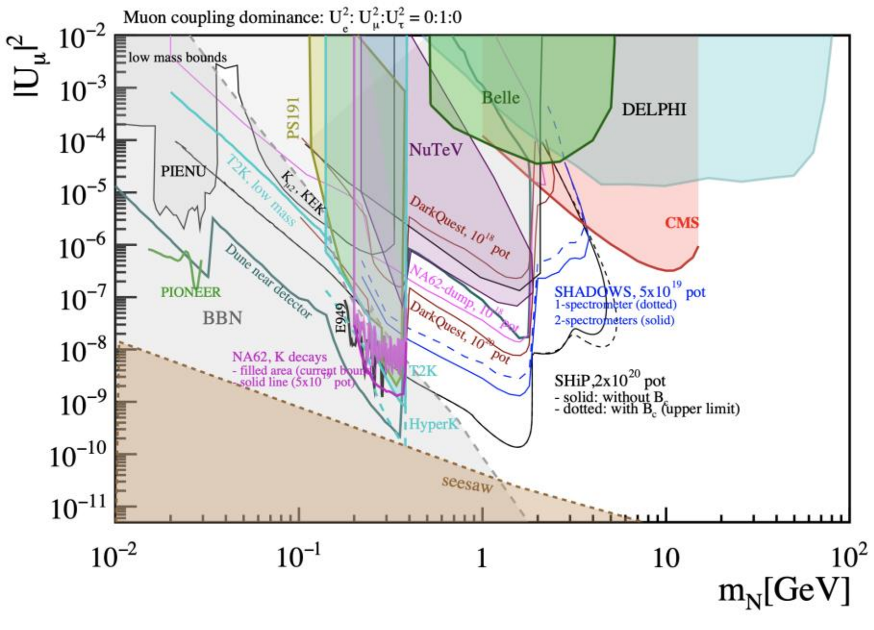
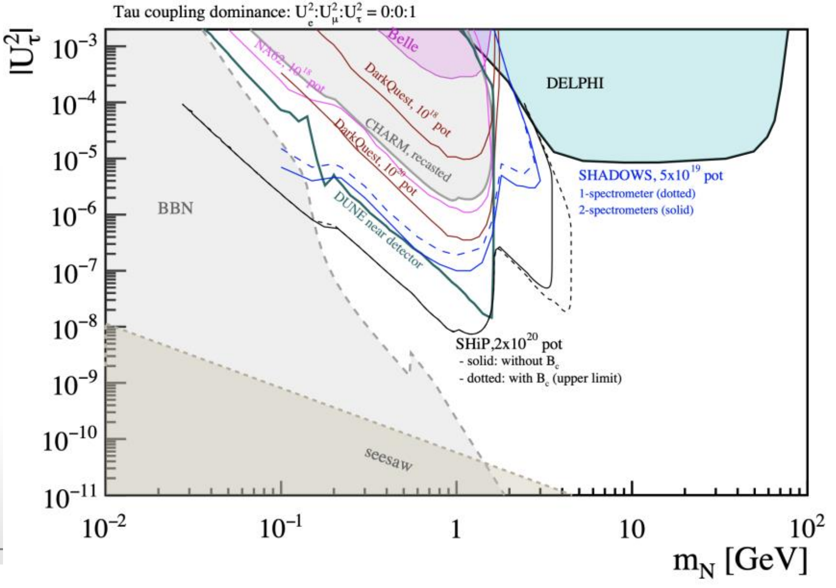
Near
Detecter

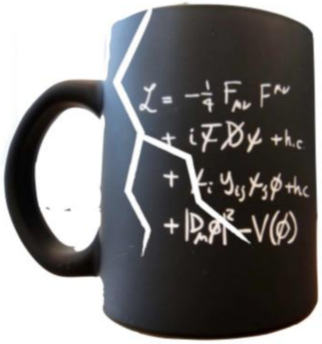




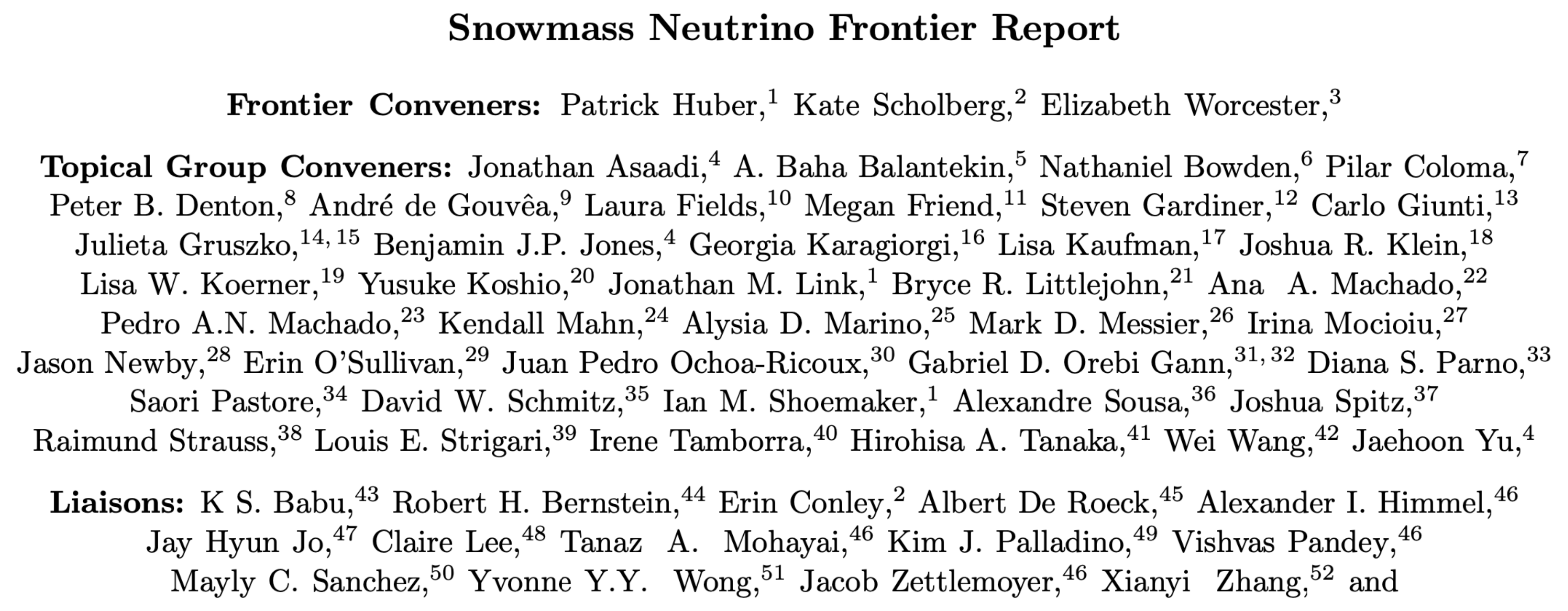
arXiv:2203.08039

SUMMARY: Neutrinos

- Neutrino studies is a vibrant field of research, and has still many open questions! Right-handed partners? Large CP violation? More than 3 neutrinos? Non Standard 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??



Further reading



Snowmass Neutrino Frontier Report

Frontier Conveners: Patrick Huber,[1] Kate Scholberg,[2] Elizabeth Worcester,[3]

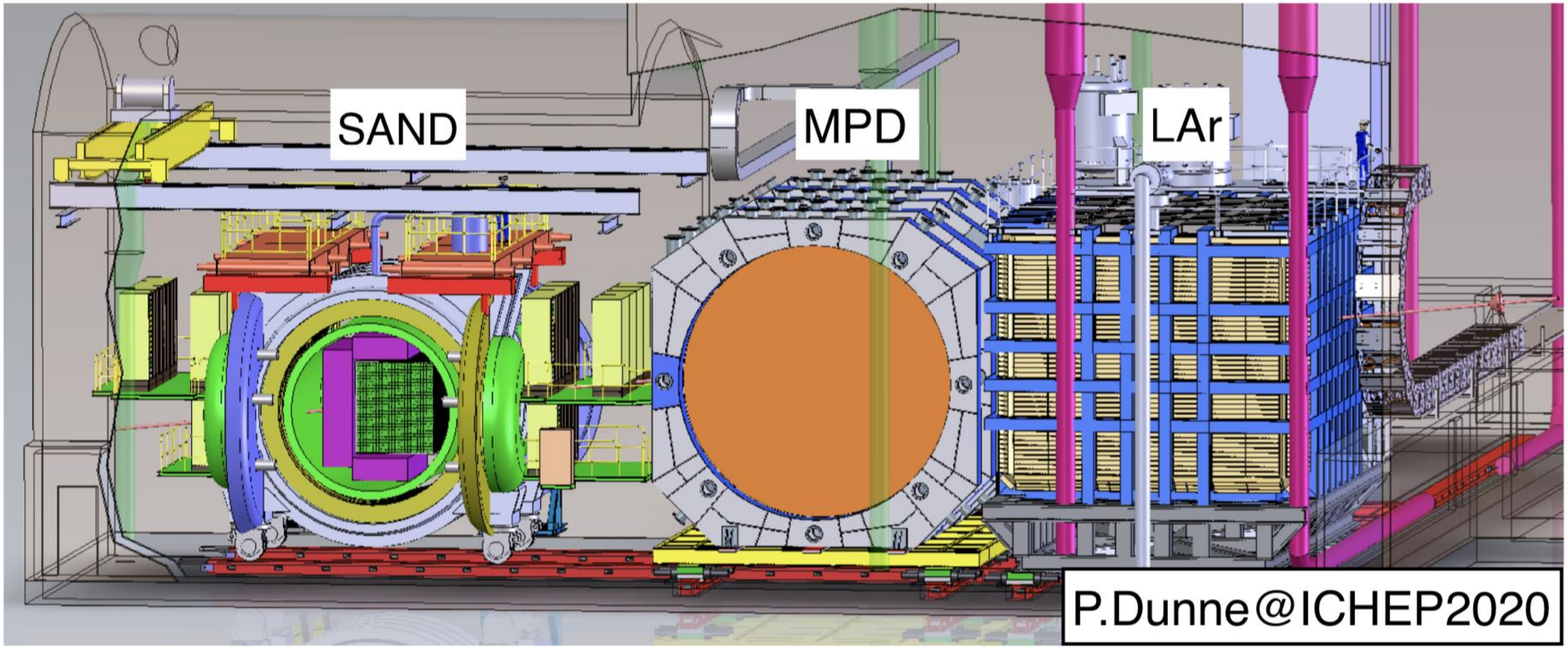
Topical Group Conveners: Jonathan Asaadi,[4] A. Baha Balantekin,[5] Nathaniel Bowden,[6] Pilar Coloma,[7] Peter B. Denton,[8] André de Gouvêa,[9] Laura Fields,[10] Megan Friend,[11] Steven Gardiner,[12] Carlo Giunti,[13] Julieta Gruszko,[14, 15] Benjamin J.P. Jones,[4] Georgia Karagiorgi,[16] Lisa Kaufman,[17] Joshua R. Klein,[18] Lisa W. Koerner,[19] Yusuke Koshio,[20] Jonathan M. Link,[1] Bryce R. Littlejohn,[21] Ana A. Machado,[22] Pedro A.N. Machado,[23] Kendall Mahn,[24] Alysia D. Marino,[25] Mark D. Messier,[26] Irina Mocioiu,[27] Jason Newby,[28] Erin O'Sullivan,[29] Juan Pedro Ochoa-Ricoux,[30] Gabriel D. Orebi Gann,[31, 32] Diana S. Parno,[33] Saori Pastore,[34] David W. Schmitz,[35] Ian M. Shoemaker,[1] Alexandre Sousa,[36] Joshua Spitz,[37] Raimund Strauss,[38] Louis E. Strigari,[39] Irene Tamborra,[40] Hirohisa A. Tanaka,[41] Wei Wang,[42] Jaehoon Yu,[4]

Liaisons: K S. Babu,[43] Robert H. Bernstein,[44] Erin Conley,[2] Albert De Roeck,[45] Alexander I. Himmel,[46] Jay Hyun Jo,[47] Claire Lee,[48] Tanaz A. Mohayai,[46] Kim J. Palladino,[49] Vishvas Pandey,[46] Mayly C. Sanchez,[50] Yvonne Y.Y. Wong,[51] Jacob Zettlemoyer,[46] Xianyi Zhang,[52] and

arXiv:2211.08641

Backup

The DUNE Near Detector



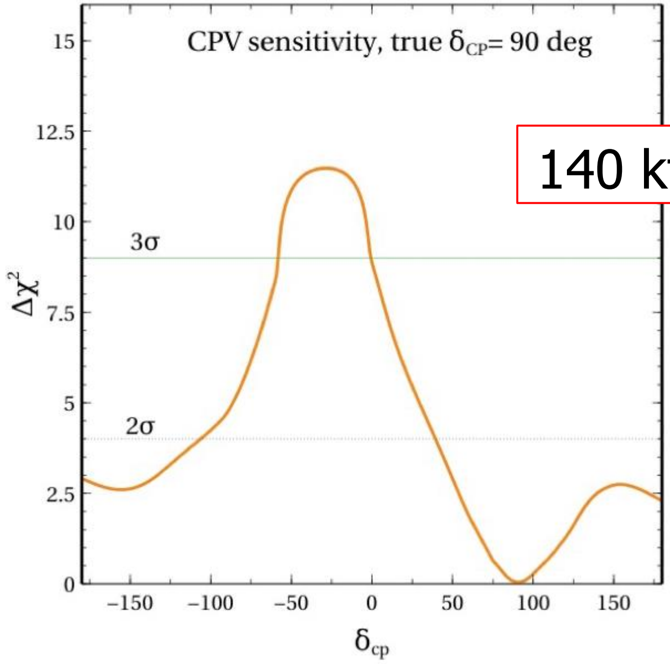
P.Dunne@ICHEP2020

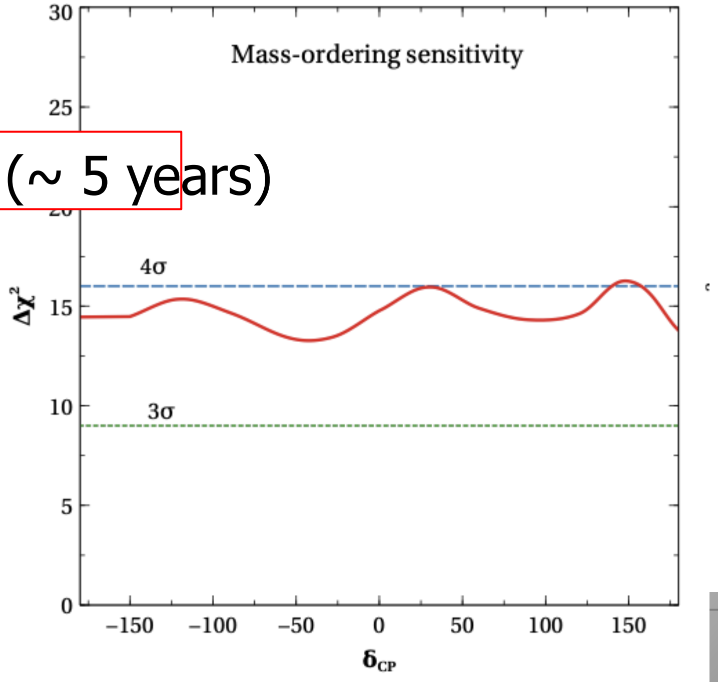
- Three main near detector complexes:
  - System for on-Axis Neutrino Detection (SAND)
  - HpTPC+ECAL (ND-GAR)
  - Liquid Argon (ND-LAr)
- Complementarity necessary to achieve:
  - Detection of ν interactions in argon nucleus, Low-momentum threshold for protons, Neutron detection, Beam monitor, ν flux estimation

The near detector is necessary to normalize te neutrino flux
It will also be used for searching for BSM physics

Atmospheric Neutrinos

- Likely the first two large forward detectors wil be completed before the intensive beam is ready to deliver the accelerator neutrinos
- But atmospheric neutrinos are always there!!
- Example: recent study by A. Chaterjee and ADR in 2402.16441
- Use final state even topologies for (anti)neutrino ID

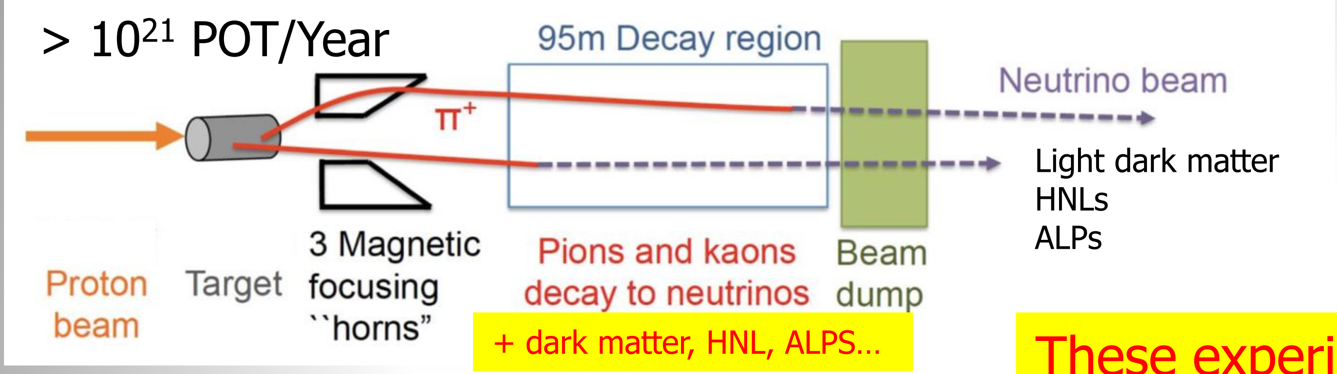




140 kt.years (~ 5 years)

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



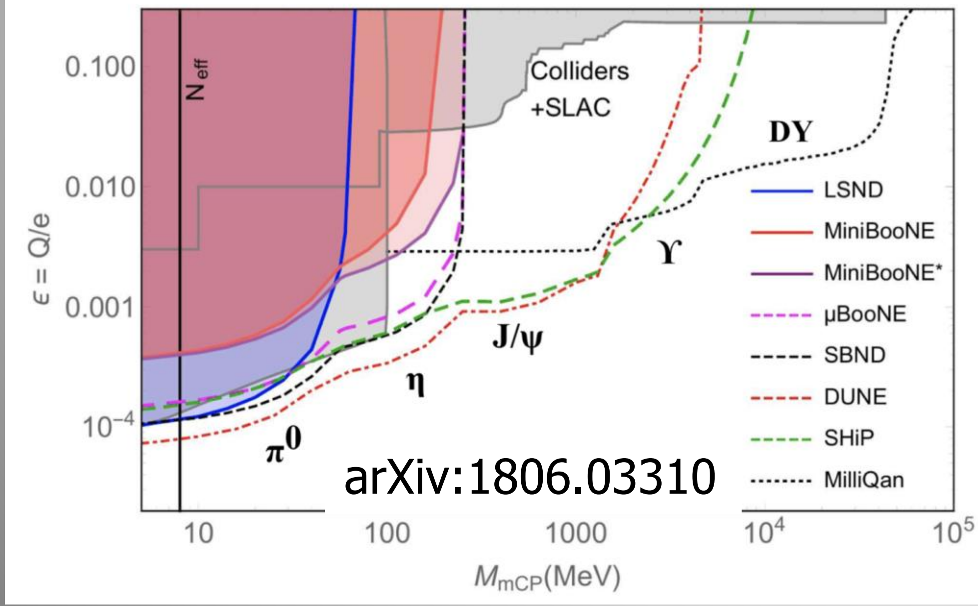
> 10^{21} POT/Year

Light dark matter
HNLs
ALPs

+ dark matter, HNL, ALPS…

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

Example millicharges:

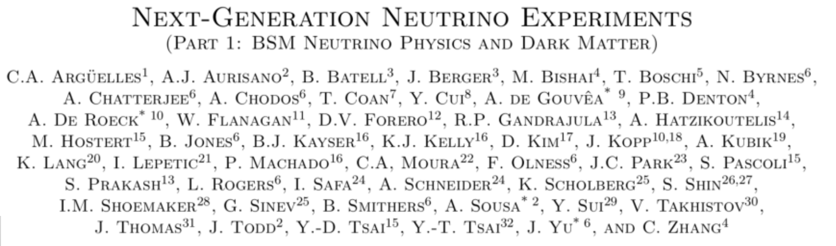


arXiv:1806.03310

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

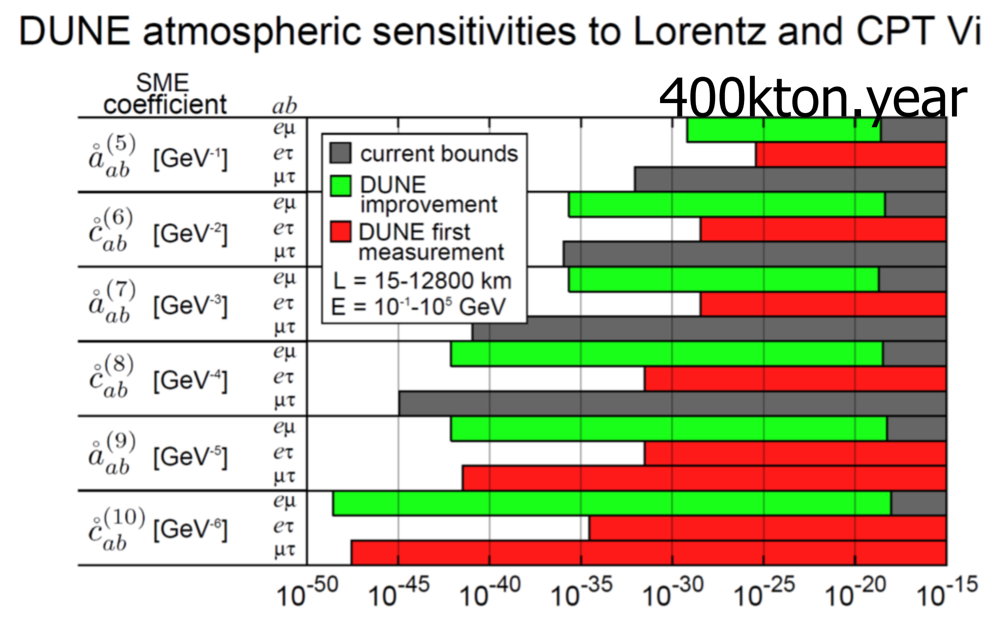


NEXT-GENERATION NEUTRINO EXPERIMENTS
(PART 1: BSM NEUTRINO PHYSICS AND DARK MATTER)

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]

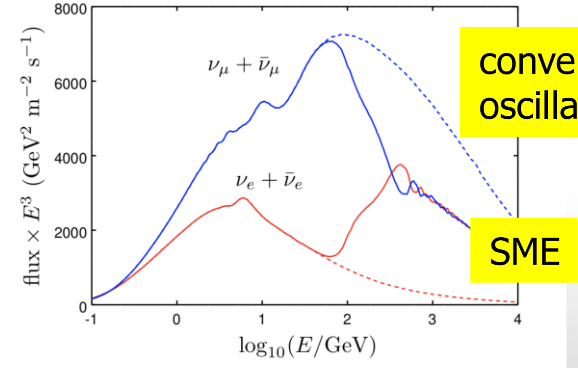
Atmospherics and Supernovae

Sensitivities to Lorentz and CPT violation


DUNE atmospheric sensitivities to Lorentz and CPT Violation

400kton.year

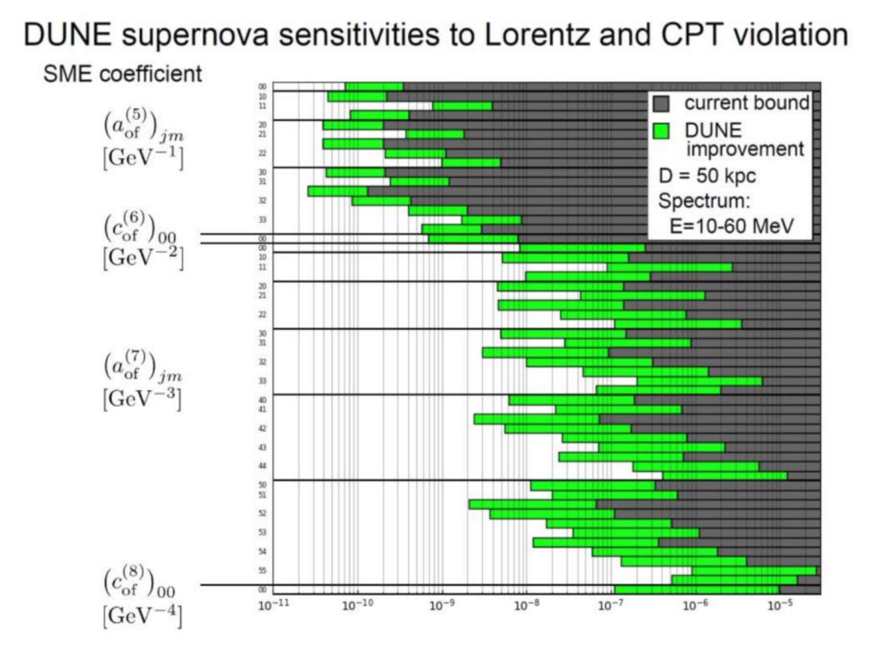
Analyzed in the SME (Standard Model Extension) framework



conventional oscillation

SME

Atmospheric neutrino flux

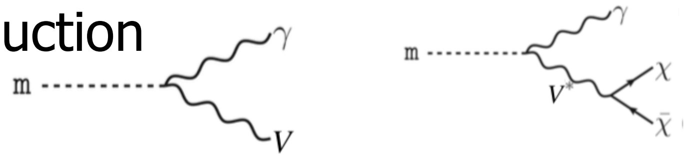

DUNE supernova sensitivities to Lorentz and CPT violation

Oscillation free coefficients

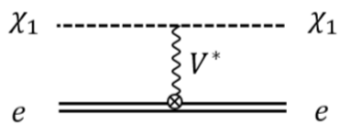
Searches for Low Mass Dark Matter

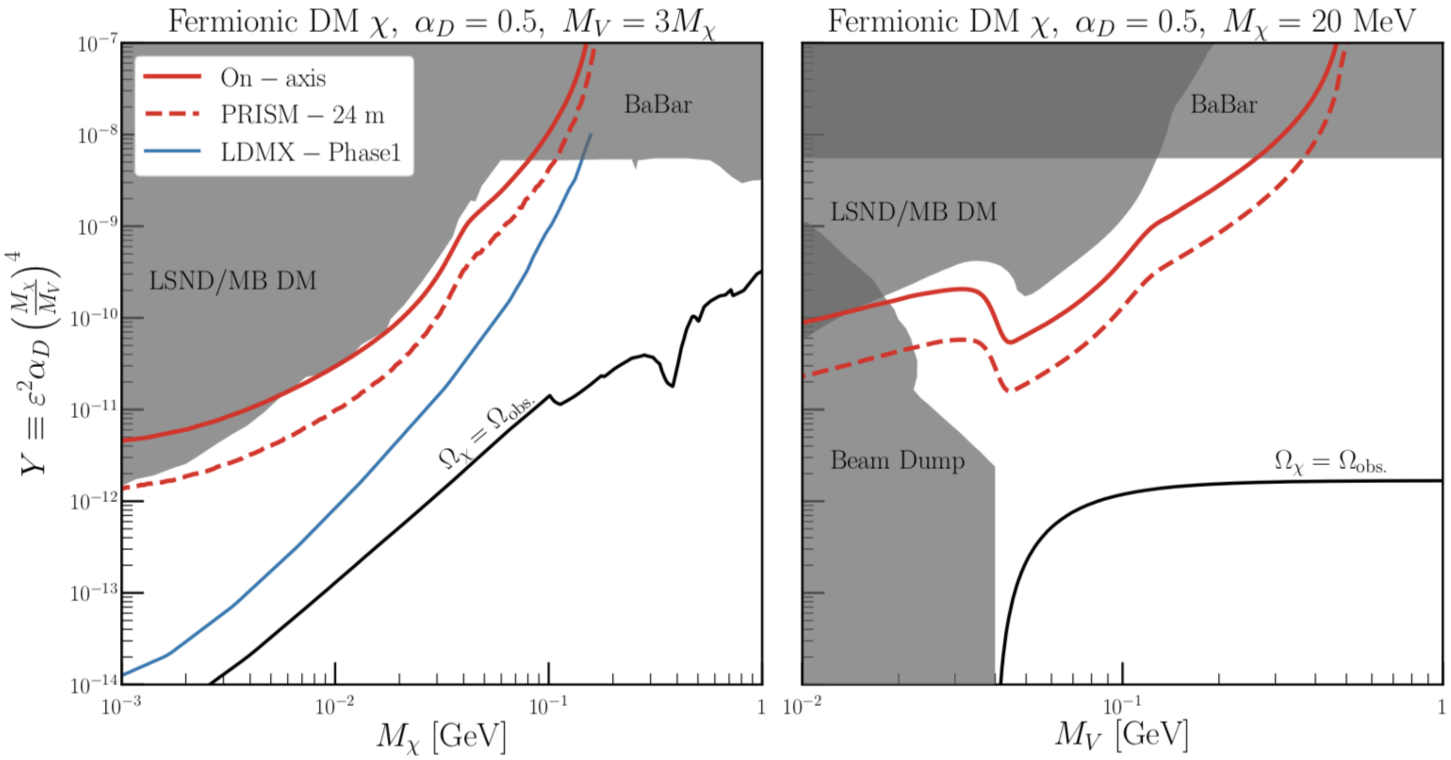
Light dark matter produced at the accelerator (meson decays)

Production



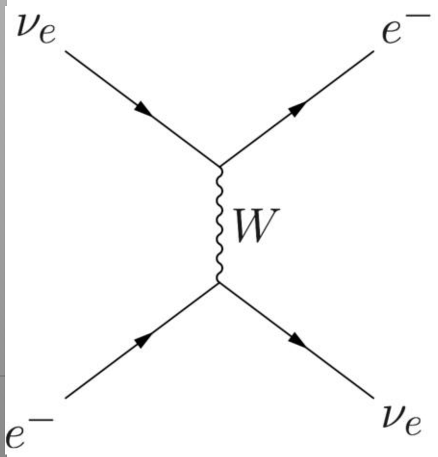
Elastic scattering

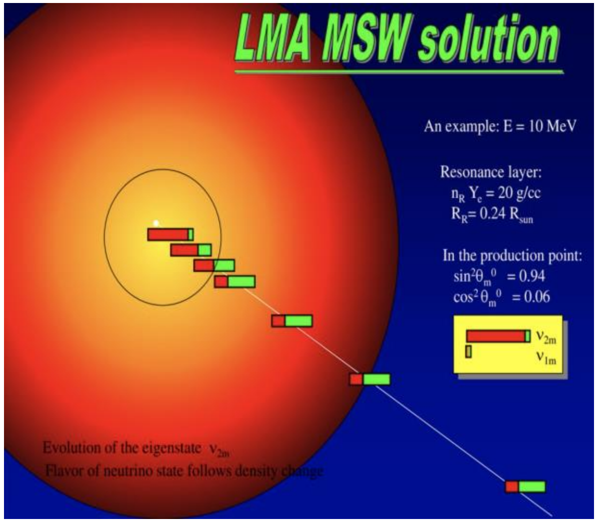


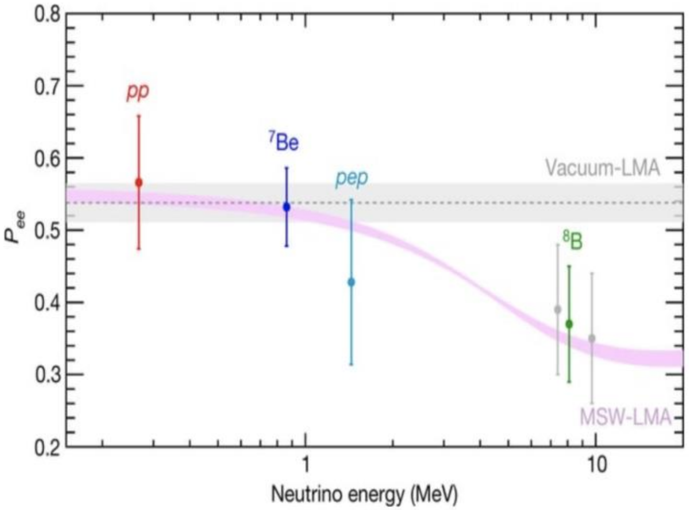


Note: MSW or Matter Effect

- When neutrinos travel over long distances through dense matter (Sun, Earth), their propagation is modified through coherent forward scattering off electrons (…like light in matter)
- This effect modifies the flavour oscillation probability (Mikhaev, Smirnov, Wolfenstein). Once the neutrino leaves the sun it is in a pure mass eigenstate consisting predominantly of the muon and tau flavors; no more further oscillation until it reaches earth.
- The MSW effect predicts a flavor conversion of solar neutrinos, that is independent of the distance between the sun and earth, of a factor 3 for the electron neutrinos (without any fine tuning)







Matter Effects

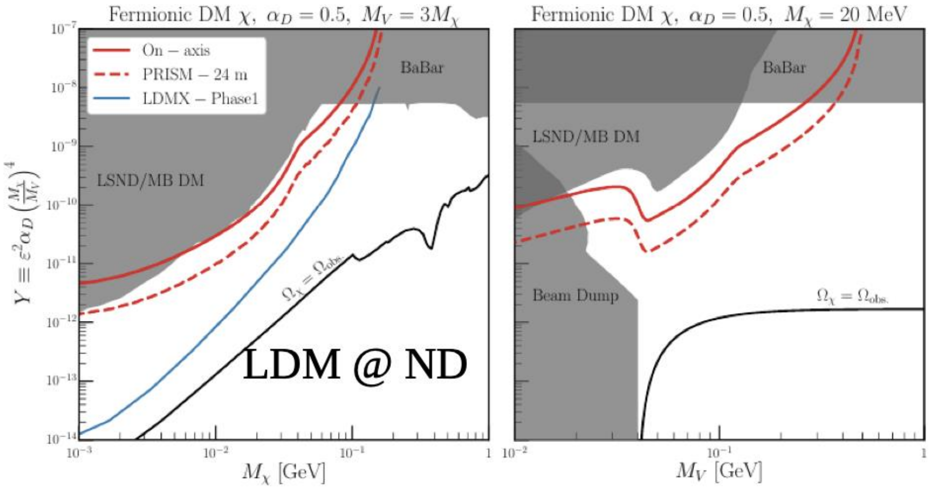
- The probability for ν_e appearance:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;\; \simeq \;\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu, \; a = G_F N_e/\sqrt{2},$$

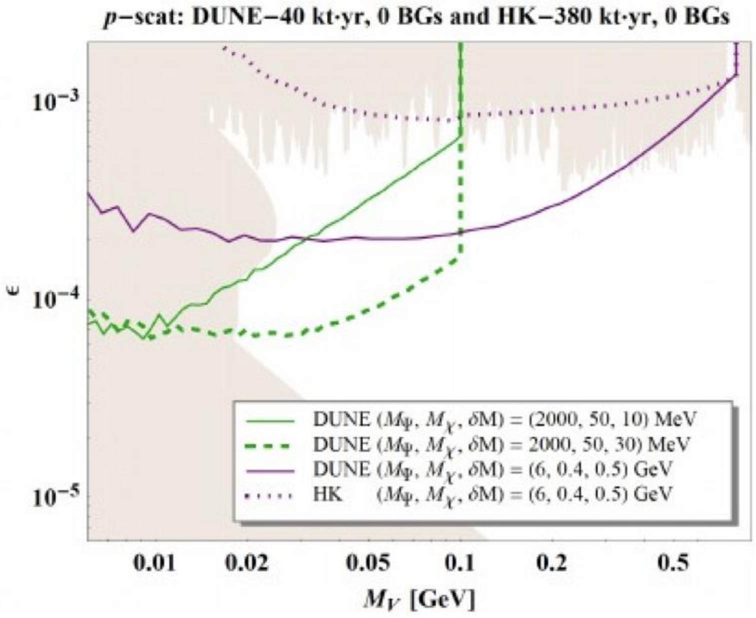
- both δ_{CP} and *a* (matter effect) switch signs in going from the $\nu_\mu \to \nu_e$ to the anti-neutrino process
- The origin of the matter effect asymmetry is simply the presence of electrons and absence of positrons in the Earth.

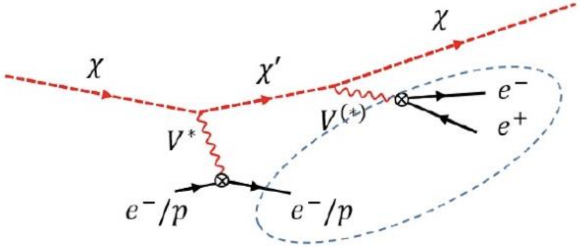
Not just Neutrino Frontier: Dark matter at DUNE ND & FD



- ND-LAr is sensitive to DM produced in beamline, off-axis data helps to control SM backgrounds

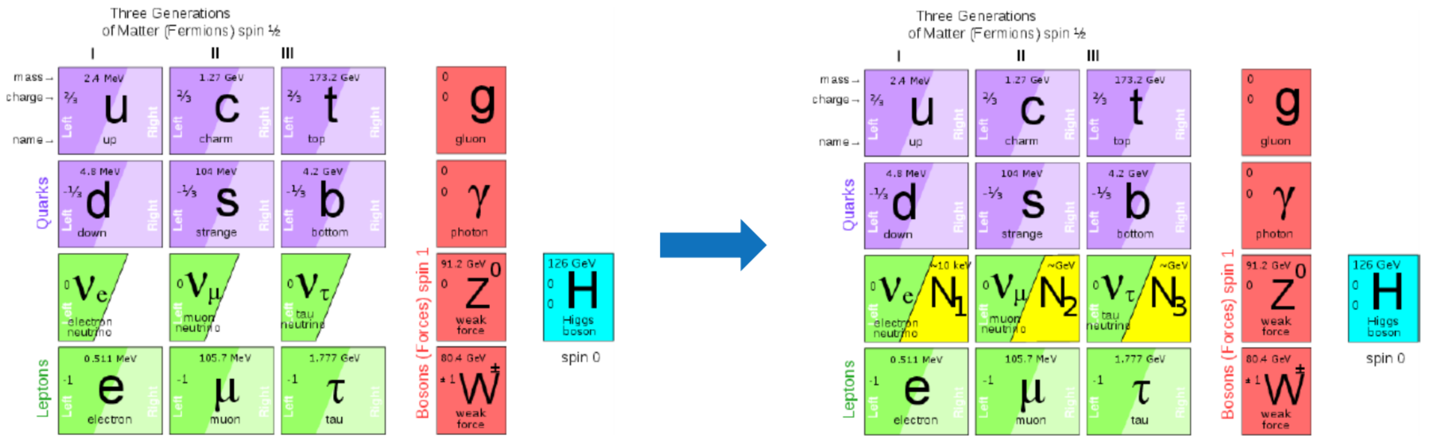
- FD is sensitive to inelastic dark matter of cosmic origin

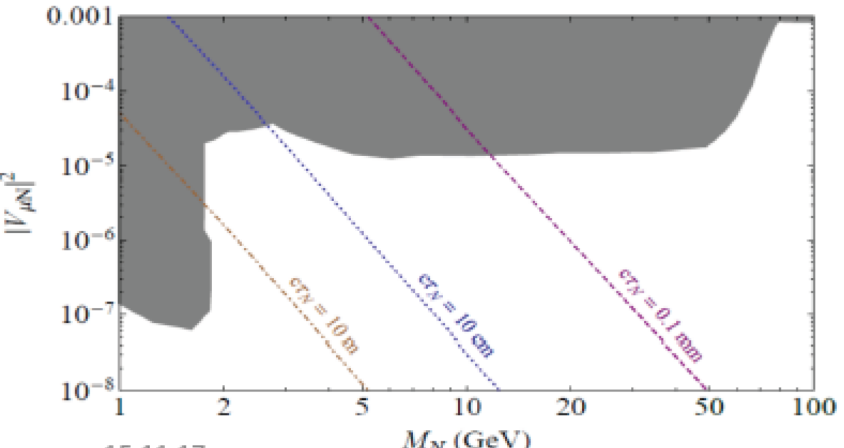




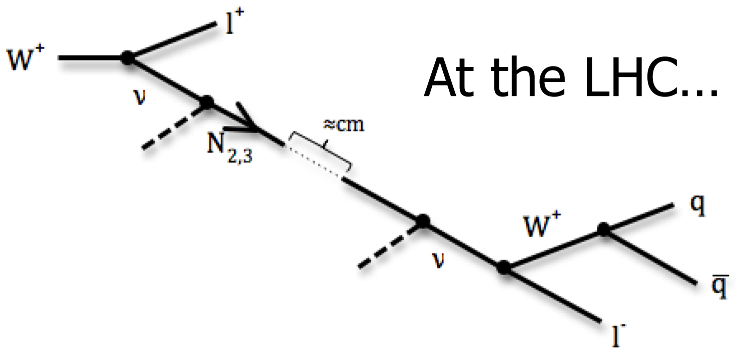
Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.





D.Gorbunov, M.Shaposhnikov JHEP 0710 (2007) 015

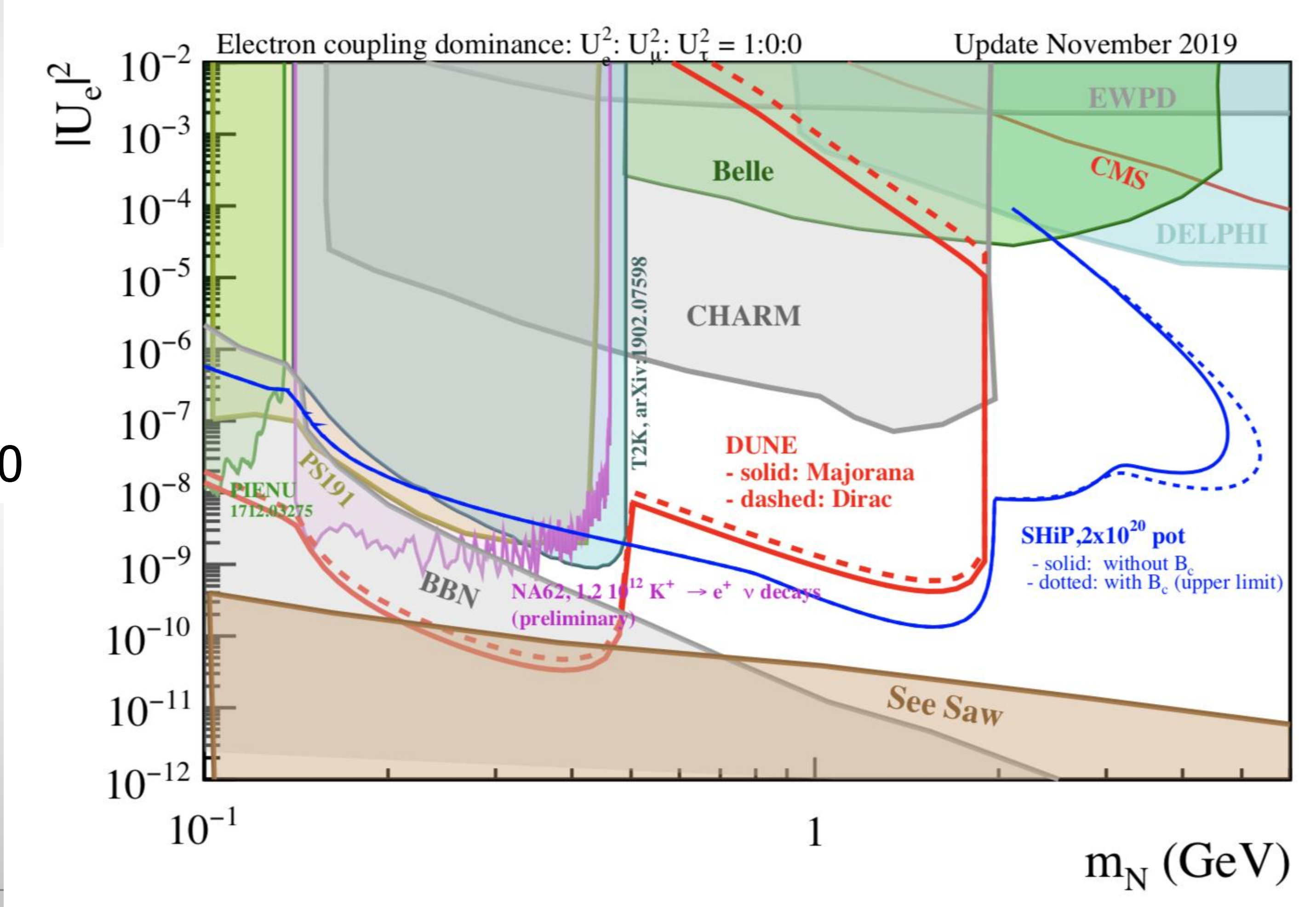


At the LHC…

First LHC results on prompt studies
Majorana/Dirac? Now studies with displaced jets/lepton analyses. L~ 1m?

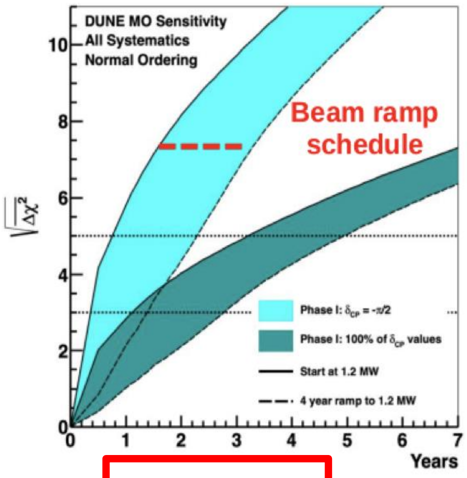
Heavy Neutral Lepton Searches

Projection for the DUNE Near Detector (7+7 years)
HNLs produced in meson decays (pions, kaons, Ds…)

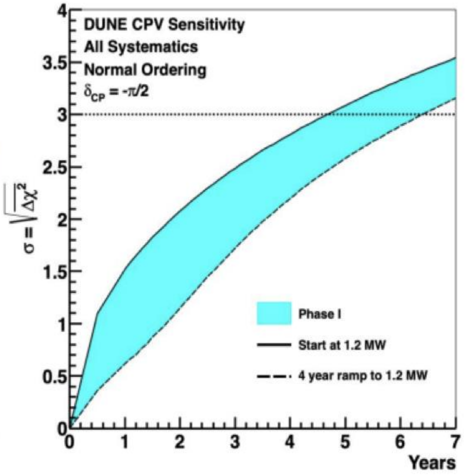


H.Sfar,
G. Christodoulou
ADR
in arXiv:2103.13910

DUNE staging



Beam ramp schedule



Phase I:

Construction ends around ~2030

✔ Unambiguous MO

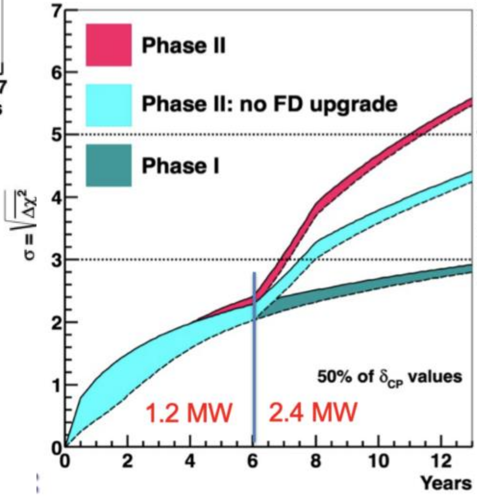
✔ 3σ CPV at maximal δ_{CP}

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



https://arxiv.org/abs/2203.06100

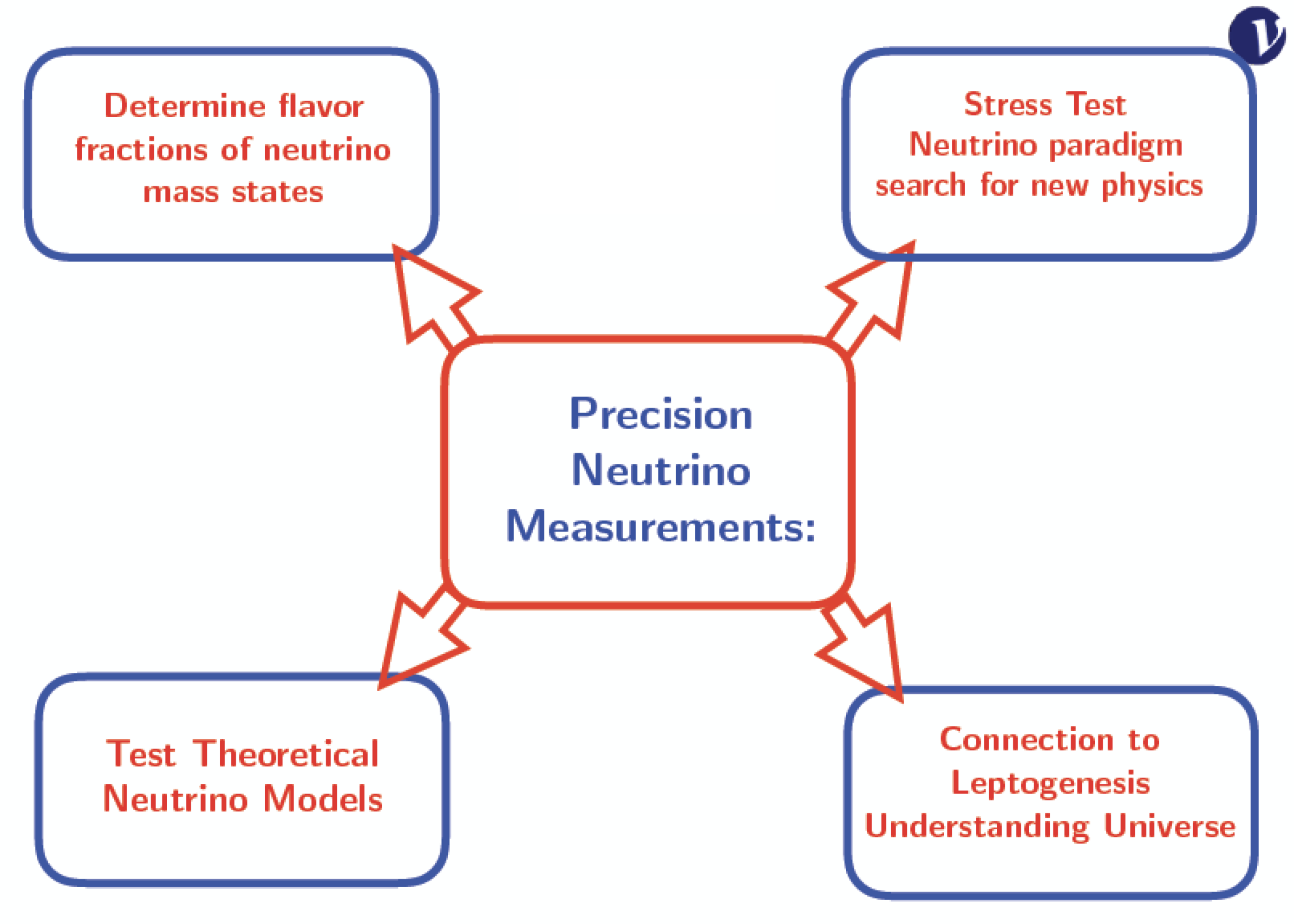
Construction should start around ~2030:

FD mass
ND upgrade
Beam upgrade

Figures from SNOWMASS neutrino colloquium by C. Wilkinson

Precision Neutrino Physics

We are entering the era of precision neutrino physics !!



Precision Neutrino Measurements:

Determine flavor fractions of neutrino mass states

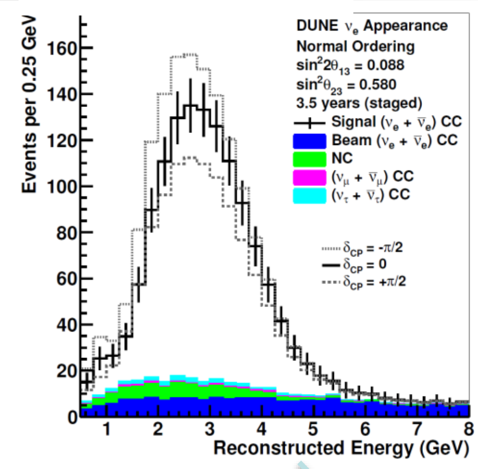
Stress Test Neutrino paradigm search for new physics

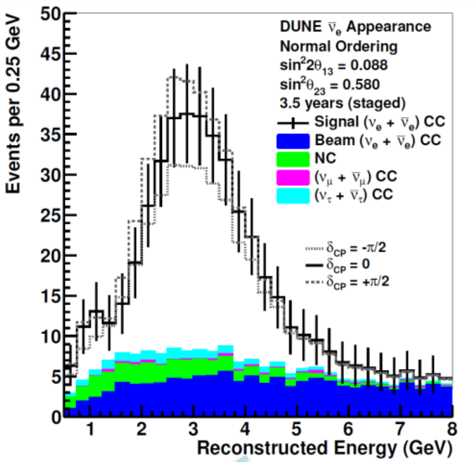
Test Theoretical Neutrino Models

Connection to Leptogenesis Understanding Universe

Expected number of neutrinos

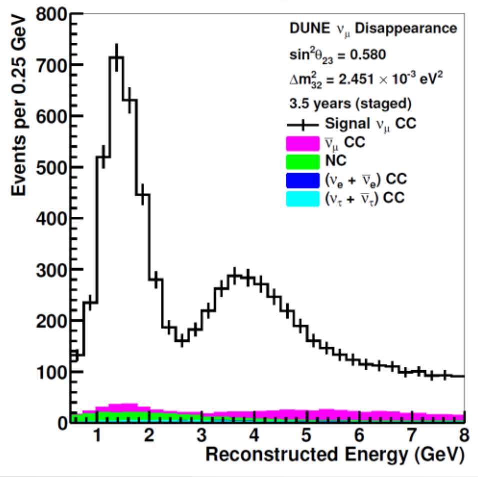
DUNE simulation

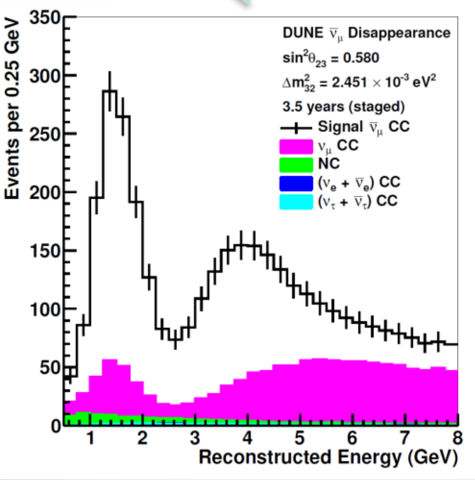




Global Fit

Oscillation Parameter



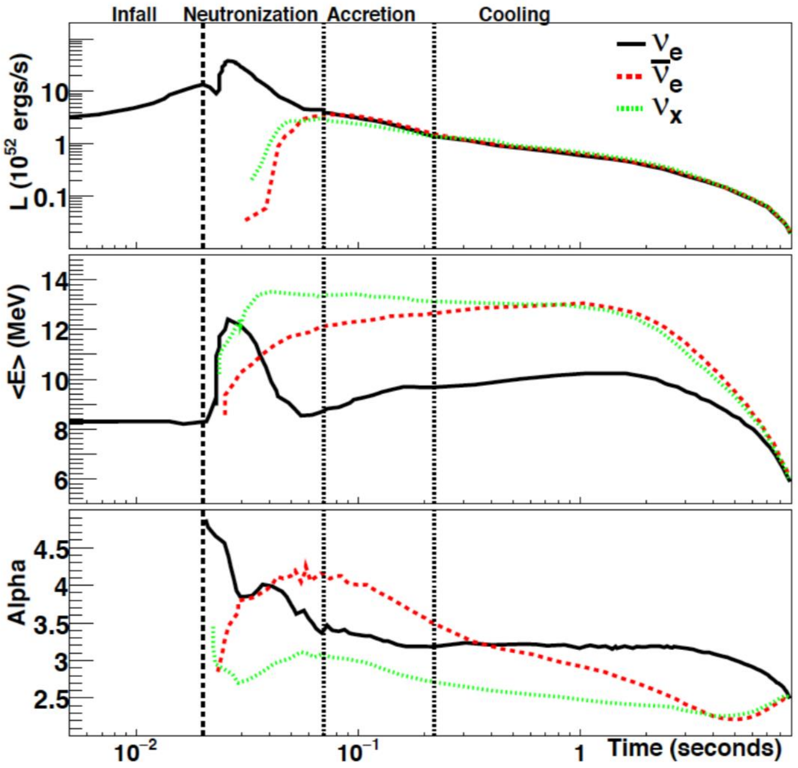


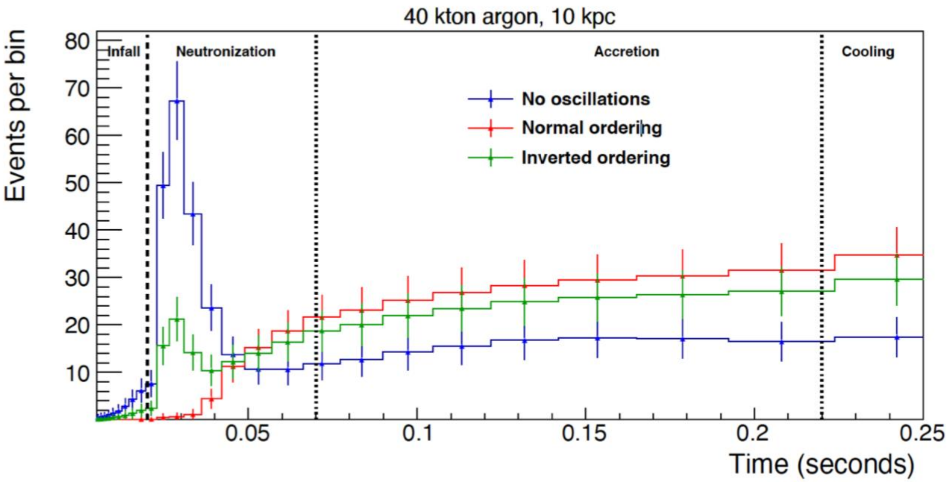
~1,000 ν_e / $\bar{\nu}_e$
appearance events
in 7 years!

(normal ordering)

~10,000 ν_μ / $\bar{\nu}_\mu$ events

Supernova Signal in DUNE





- Neutrinos arrive before the light and can trigger observation by optical telescopes.
- Potentially a signal of 1000s of neutrinos in DUNE.
- Signal will teach us both about neutrinos and about the supernova mechanism.

Physics Beyond The Standard Model

Many avenues for searches

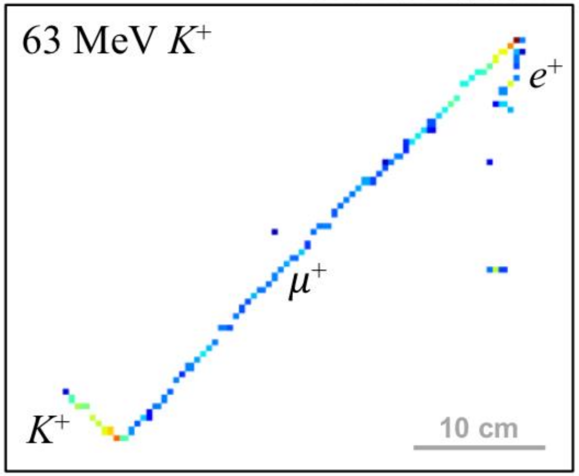
- **Baryon number violation**
  General feature of GUTs. Rich model space.
  Many search modes being explored in DUNE.

Updated simulation/reconstruction/analysis:
More details and more channels in TDR

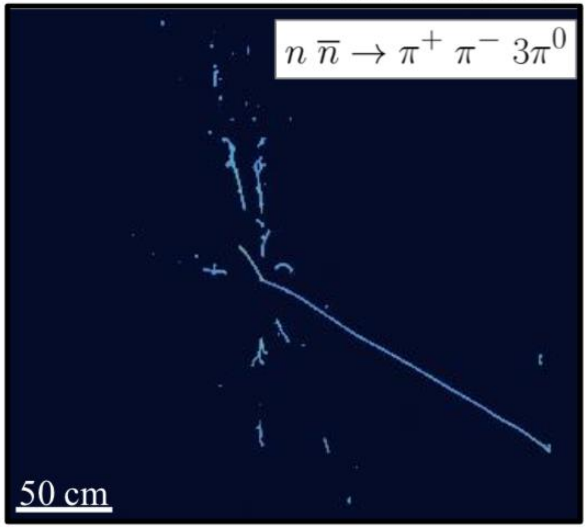
***p* → *K*$\bar{\nu}$**	Tracking and *dE*/*dx* for rejection of ν_μ CC background ($p + \mu$ final state) ~0.5 bkgnd at 400 kt-yr, 30% signal efficiency *If no signal:* **$\tau/B > 1.3\times10^{34}$ yr (90% C.L.)**

***n*-$\bar{n}$ osc.**	Spherical spray of hadrons with $E \approx 2M_n$ and net momentum $\lesssim p_F \sim 300$ MeV Free-neutron-equivalent sensitivity: **$\tau_{\text{free,osc}} > 5.5\times10^{8}$ s (90% C.L.)**

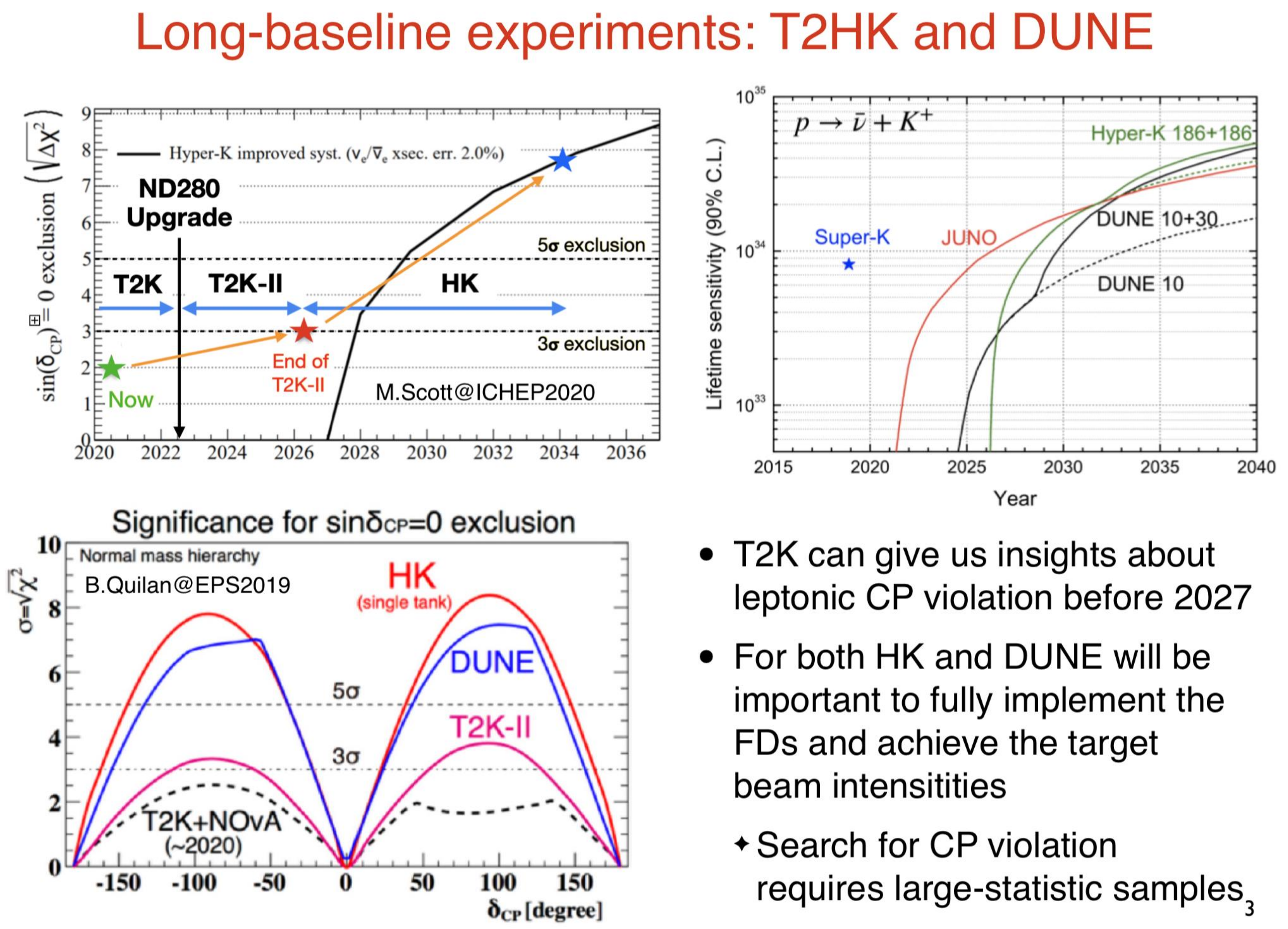
DUNE simulation



DUNE simulation



Future Neutrino Experiments



Long-baseline experiments: T2HK and DUNE

- T2K can give us insights about leptonic CP violation before 2027
- For both HK and DUNE will be important to fully implement the FDs and achieve the target beam intensitities
  - ✦ Search for CP violation requires large-statistic samples

New Opportunities with New Facilities

- The new faciltities are generally large, often based on cutting edge detector technologies
- These detectors allow for programs for searches for new physics not directly related to neutrinos
- This is drawing increasing attention in the community, in particular related to the “high intensity frontier”
- Reversely, the Large Hadron Collider can also contribute to the neutrino physics program
    - Searches for right-handed neutrinos (heavy and light)
    - BSM physics (extra dimensions, SUSY…)
    - New: Neutrino experiments at the LHC!

Next Generation Experiments

European Spallation Source, Lund

ESSνSB

Goal: CPV via targeted measurements at 2nd Oscillation Max

Neutrino Superbeam at
European Spallation Source

Lund, Sweden

360 km

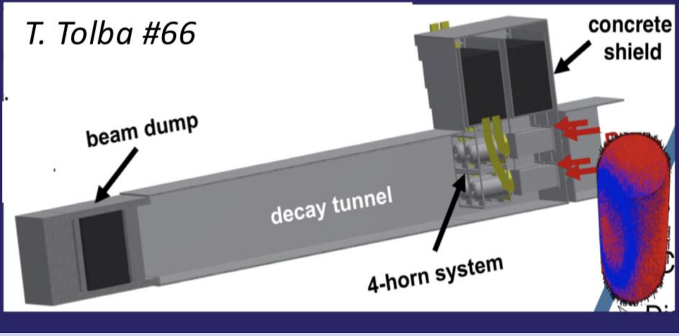
540 km

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



Experiments ready by ~2035?

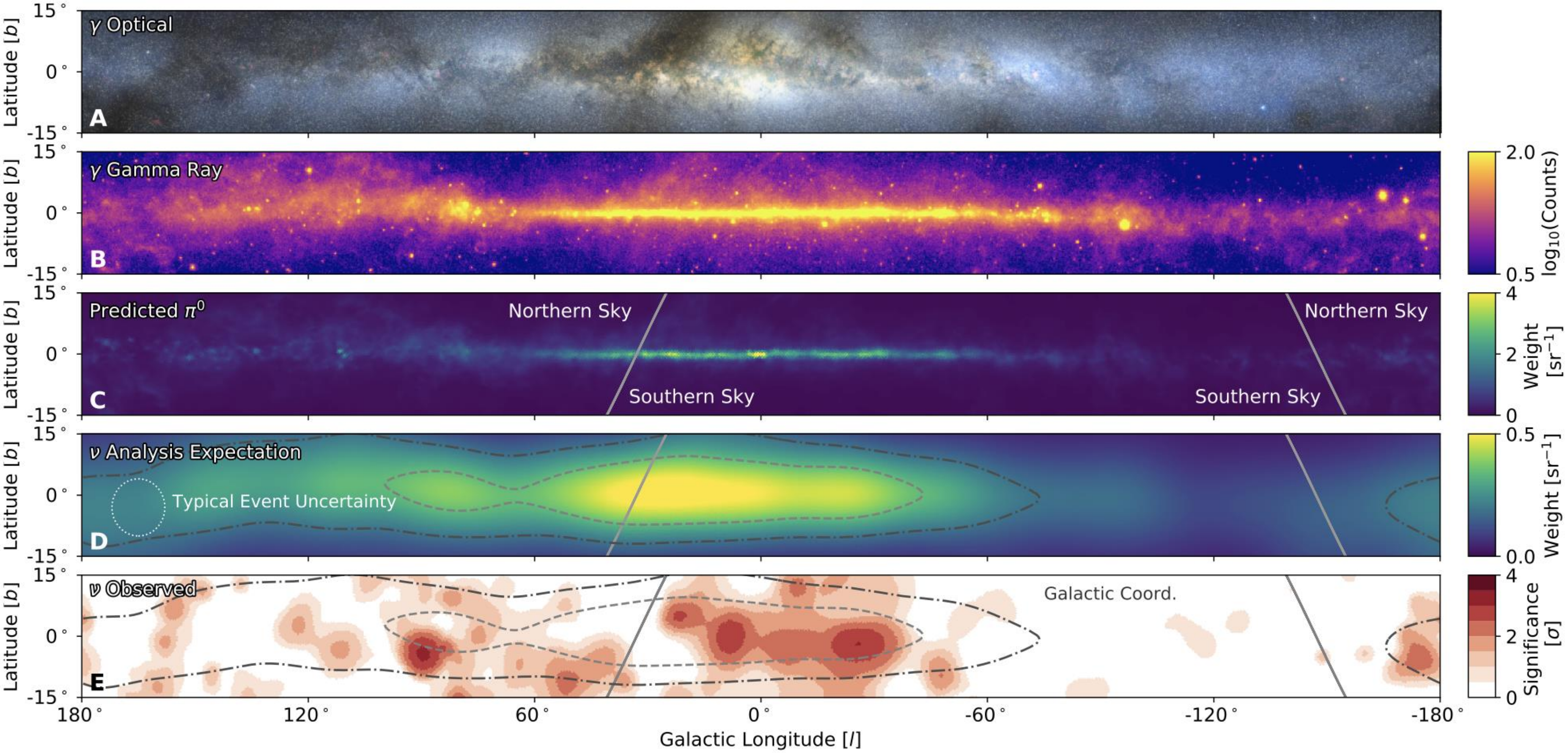
Also: new/tagged beams
NuStorm muon storage ring
…

Neutrinos & Cosmos

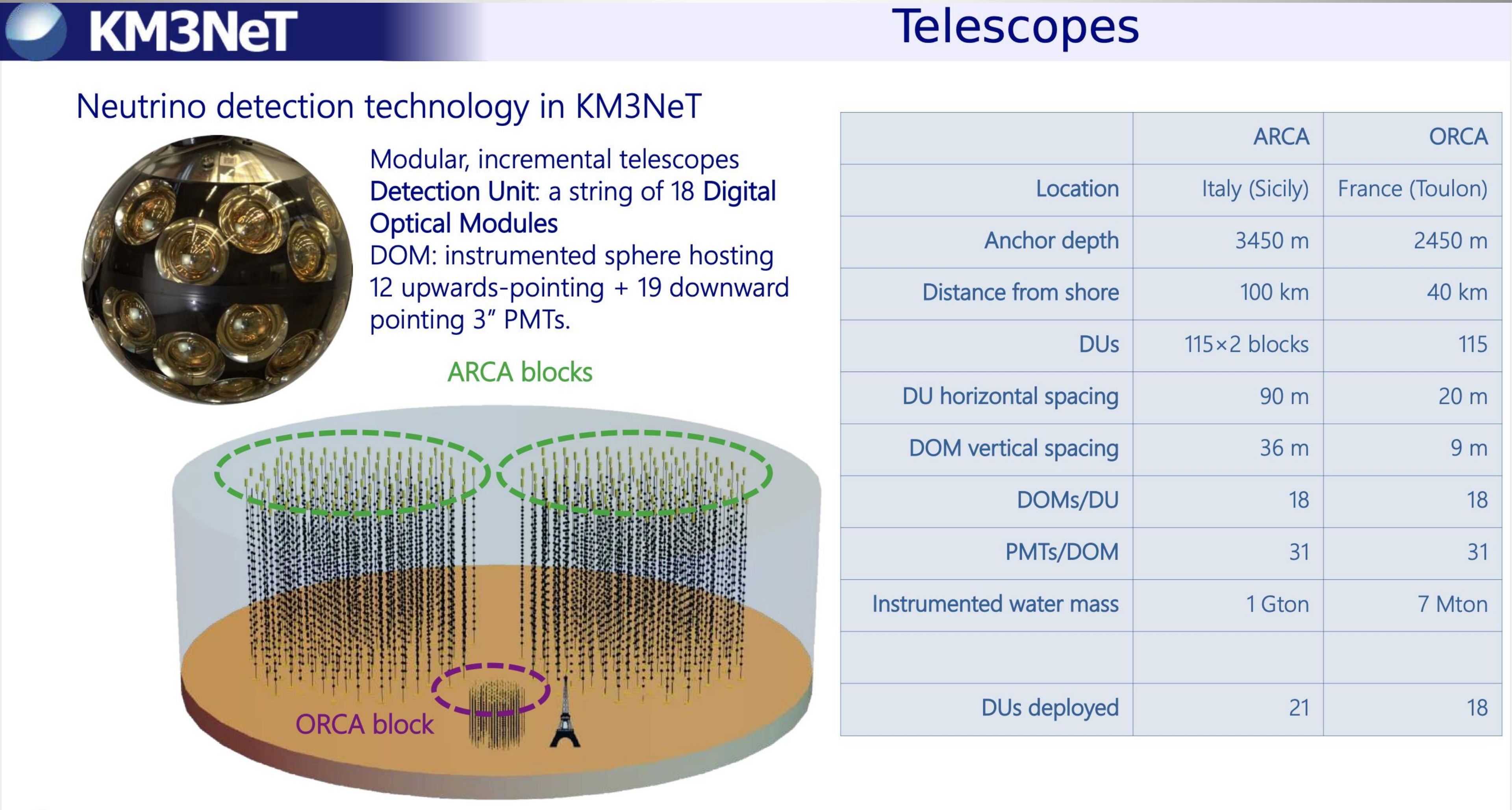
- Neutrinos very relevant for cosmological studies. Examples:
  - Neutrinos affecting the Big Bang nucleo-synthesis.
  - Relic neutrinos from the Big Bang: cosmic neutrino background, probe beyond the CMB horizon
  - Neutrinos from supernova explosions: study supernova dynamics
  - Mass limits on neutrinos and number of different neutrinos from cosmology (eg from Planck)
- Sum of the mass of all the neutrinos in the Universe is larger than the mass of all the stars

New from IceCube

The plane of the Milky Way galaxy with neutrinos



KM3NET



KM3NeT

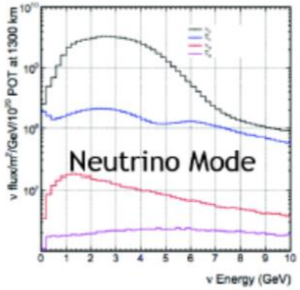
Telescopes

Neutrino detection technology in KM3NeT

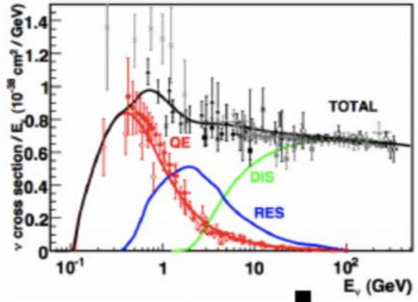
Modular, incremental telescopes
Detection Unit: a string of 18 **Digital Optical Modules**
DOM: instrumented sphere hosting 12 upwards-pointing + 19 downward pointing 3″ PMTs.

	ARCA	ORCA
Location	Italy (Sicily)	France (Toulon)
Anchor depth	3450 m	2450 m
Distance from shore	100 km	40 km
DUs	115×2 blocks	115
DU horizontal spacing	90 m	20 m
DOM vertical spacing	36 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31
Instrumented water mass	1 Gton	7 Mton
DUs deployed	21	18

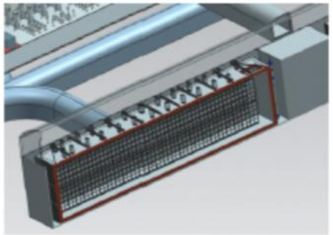
ν Flux



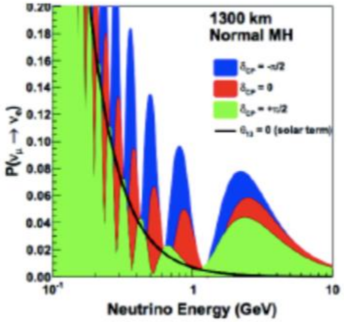
ν-Ar interactions



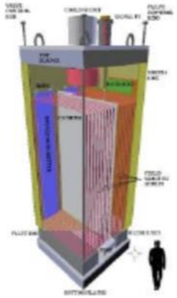
Far Detector



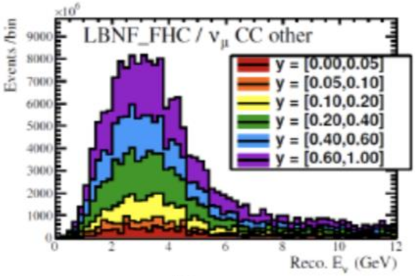
Oscillations

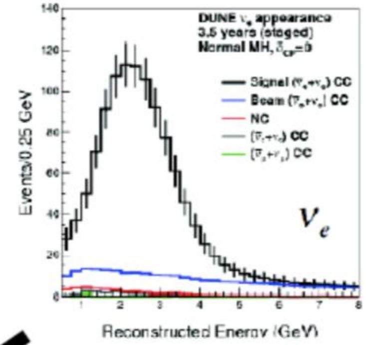


Near Detector

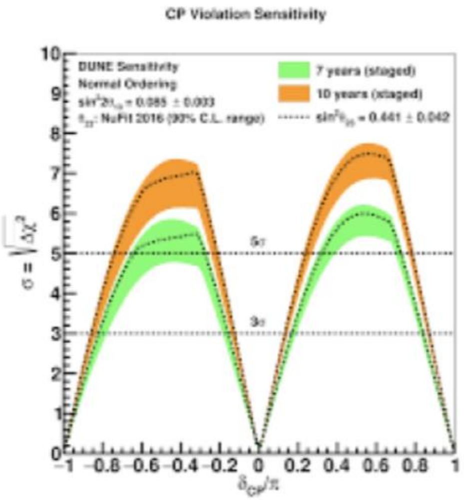


ND and FD Spectra





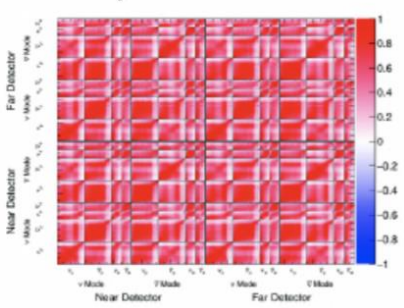
Final Sensitivity



Statistical Test

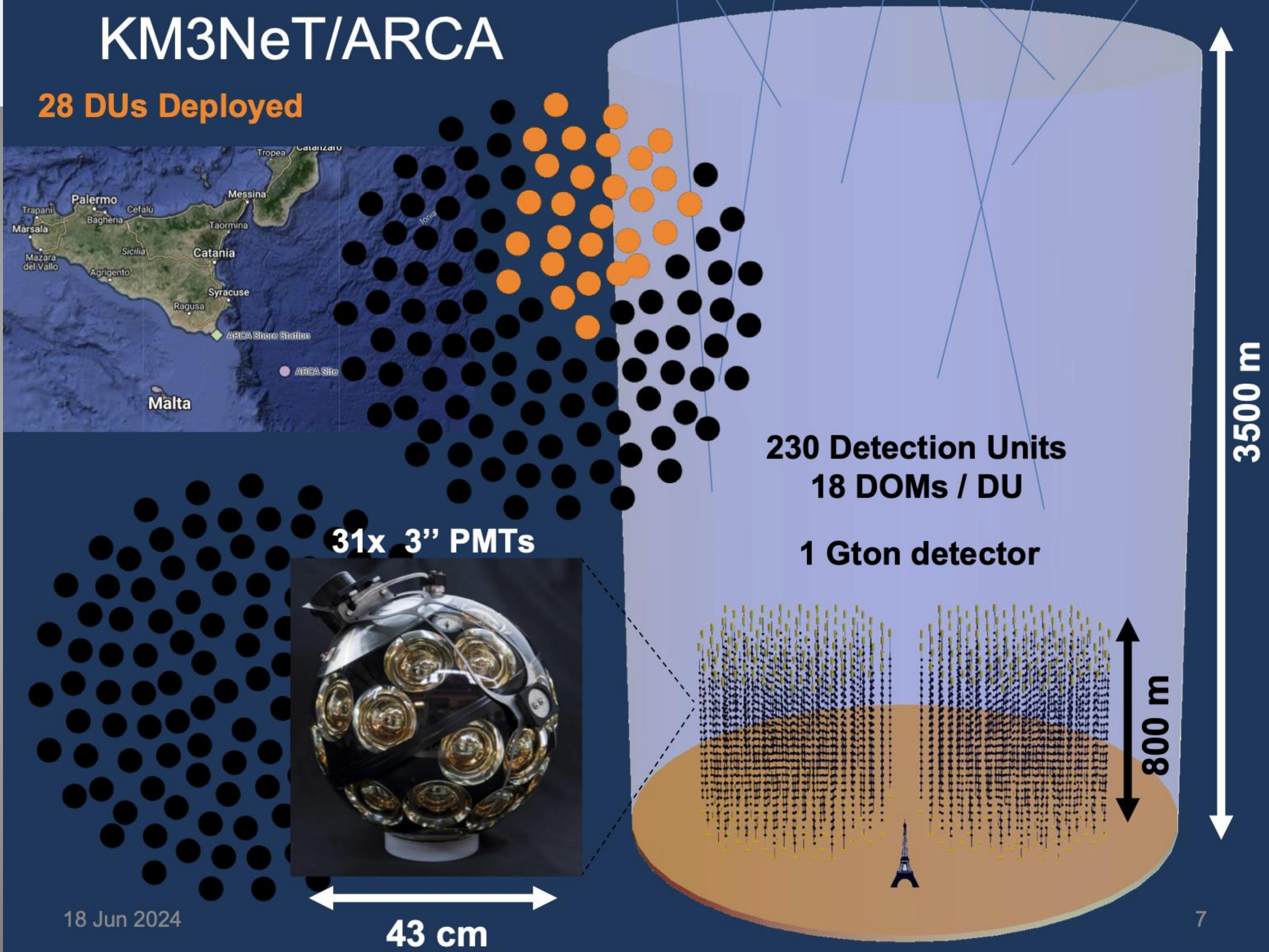
$$\boxed{\sqrt{\Delta\chi^2}}$$

Systematics



KM3NeT/ARCA

28 DUs Deployed



31x 3'' PMTs

43 cm

230 Detection Units
18 DOMs / DU

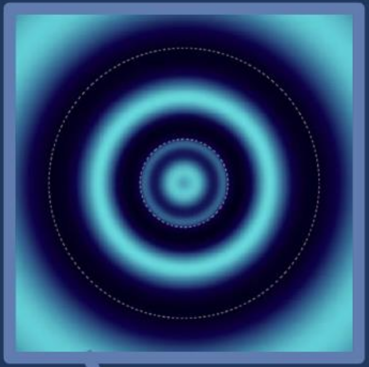
1 Gton detector

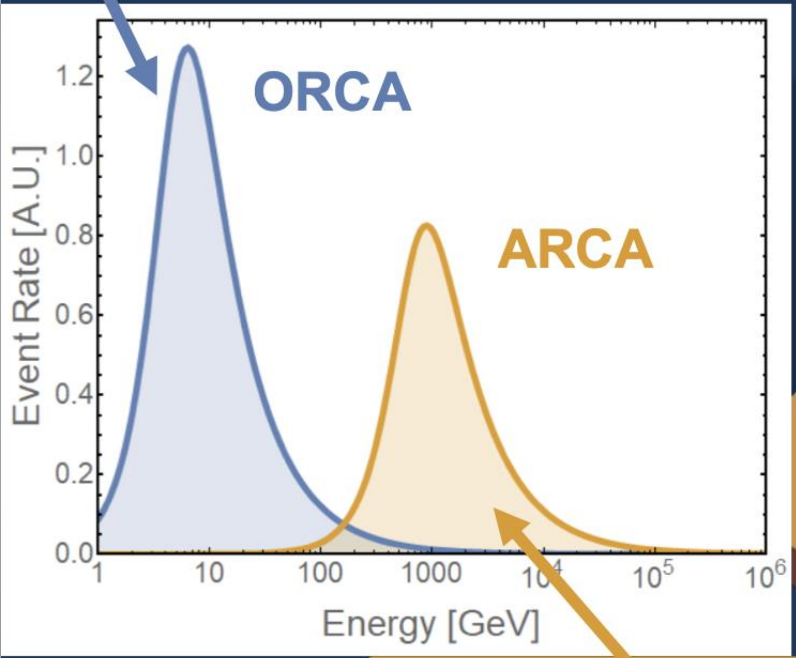
HyperK

Excavation of the HK cavern will be completed by the end of this year!

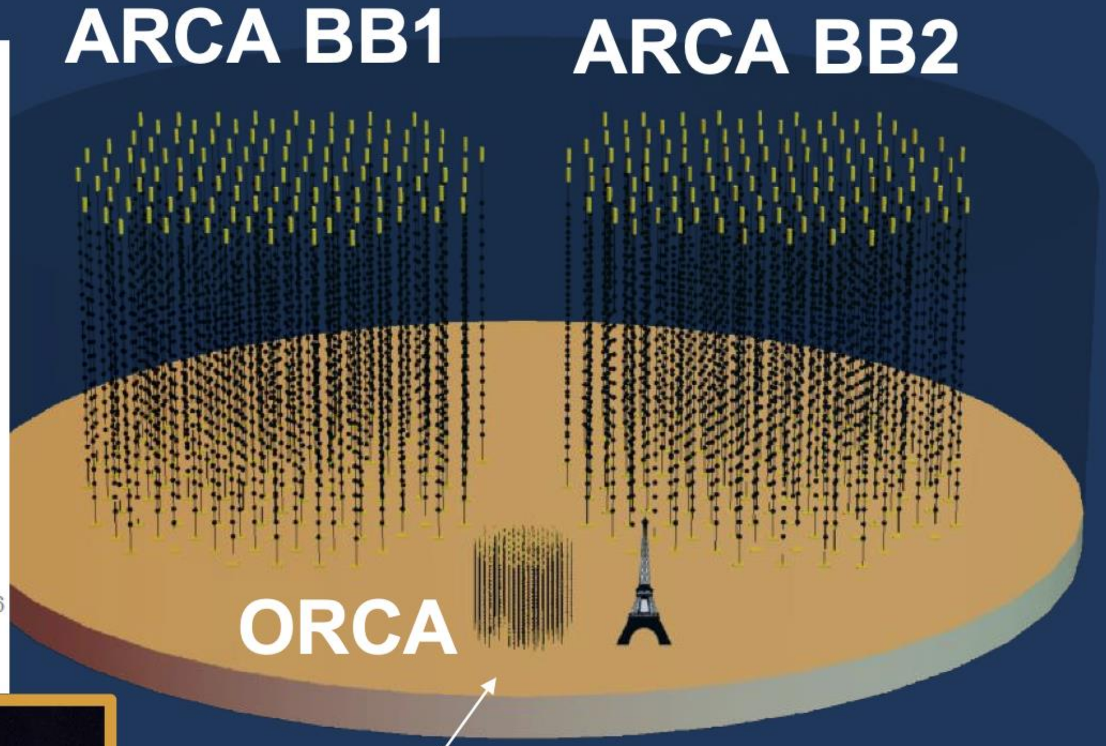
PMT production ongoing, >10,000 delivered.
Screening both at Hamamatsu and Kamioka

Two Detector Scales

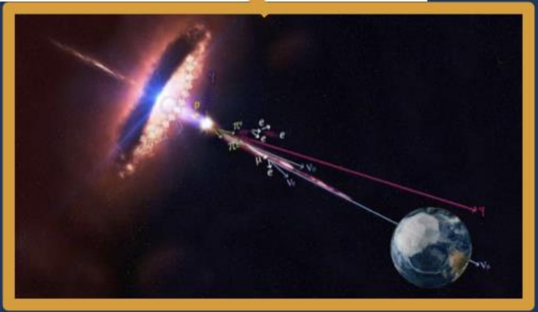




36m vert. x 90m horiz. spacing TeV - PeV



9m vert. x 20m horiz. spacing
GeV - TeV

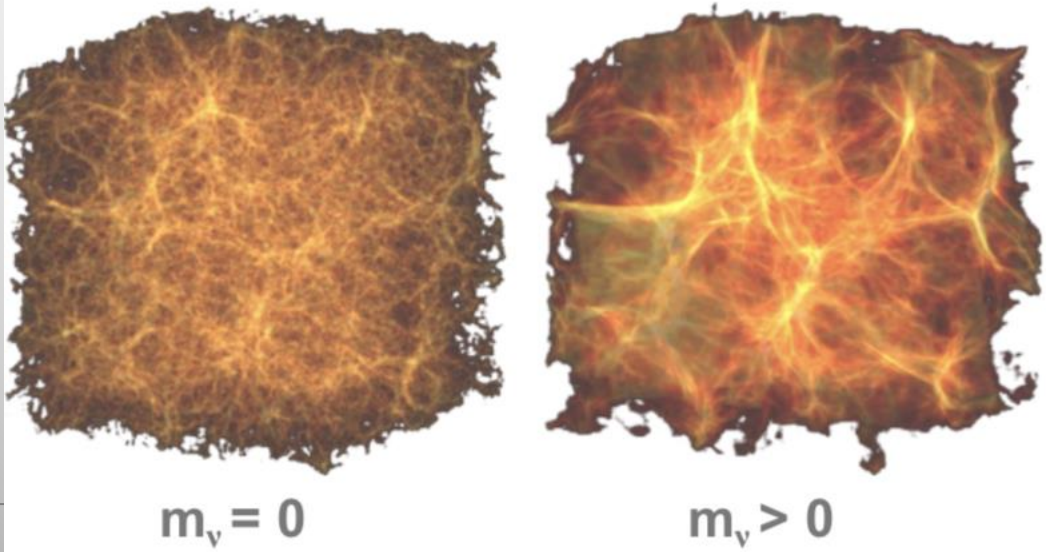


Neutrinos and Structure

- If the mass of the neutrinos would be 40 eV or more, the universe would have already collapsed under its own gravity before human beings could walk the earth…

Massive neutrinos as “cosmic architects”

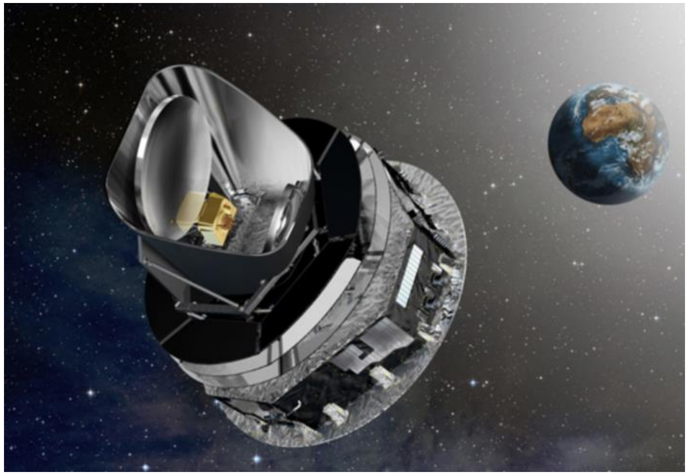
336 ν / cm³ in the Universe today



Neutrino Mass

- Cosmological limit on the sum of the masses of neutrino flavors e.g. from the Planck satelite experiment:

$$\sum m_\nu < 0.05 \text{ eV}$$



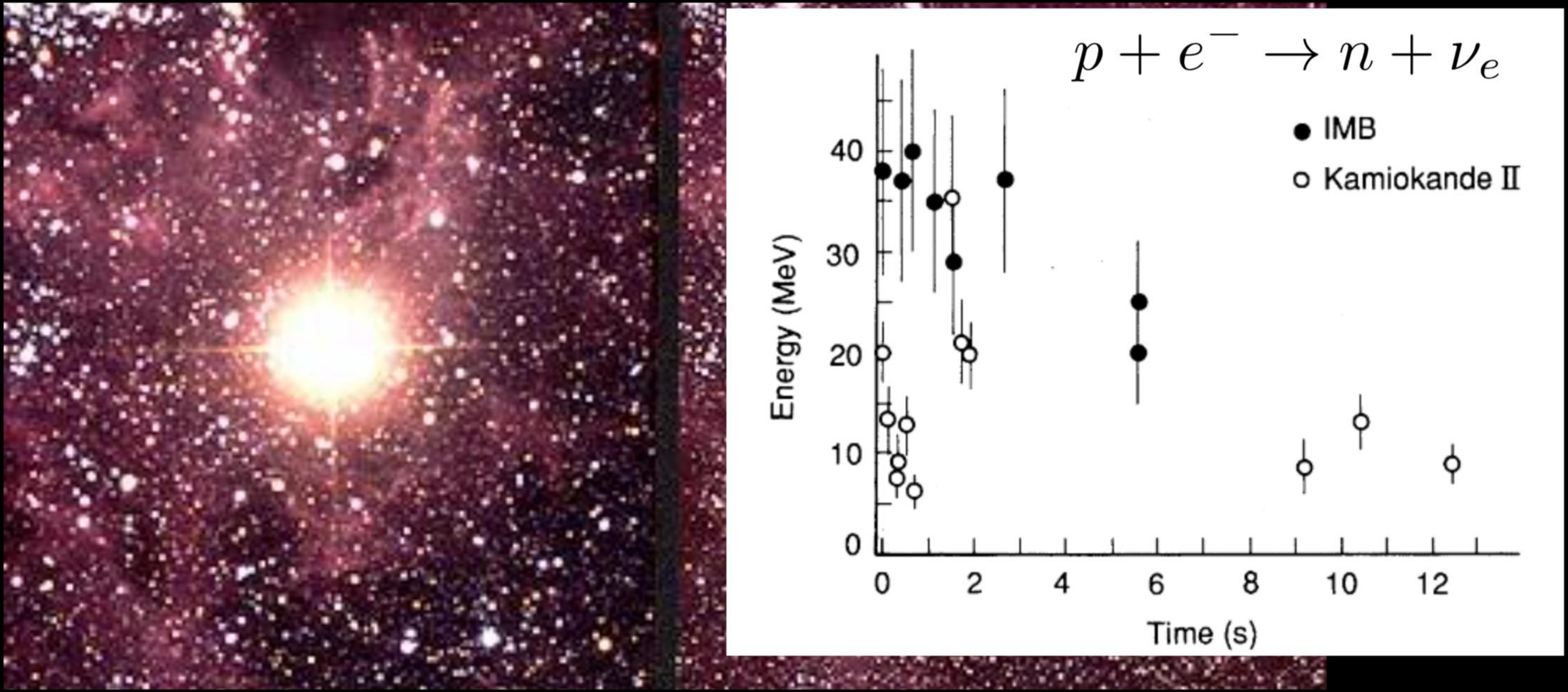
- This assumes however that neutrinos are stable with a lifetime larger than the age of the Universe
- If decays are allowed the limit can as much as 1eV
- These measurements are sensitive to the neutrino masses through the gravitational effects of the relic neutrinos left over from the Big Bang on the CMB

Study of Supernova Explosions

Supernova 1987A

in the Large Magellanic Cloud (55 kpc away)

SN1987A, about 24 neutrinos observed, 3 hours before photons.



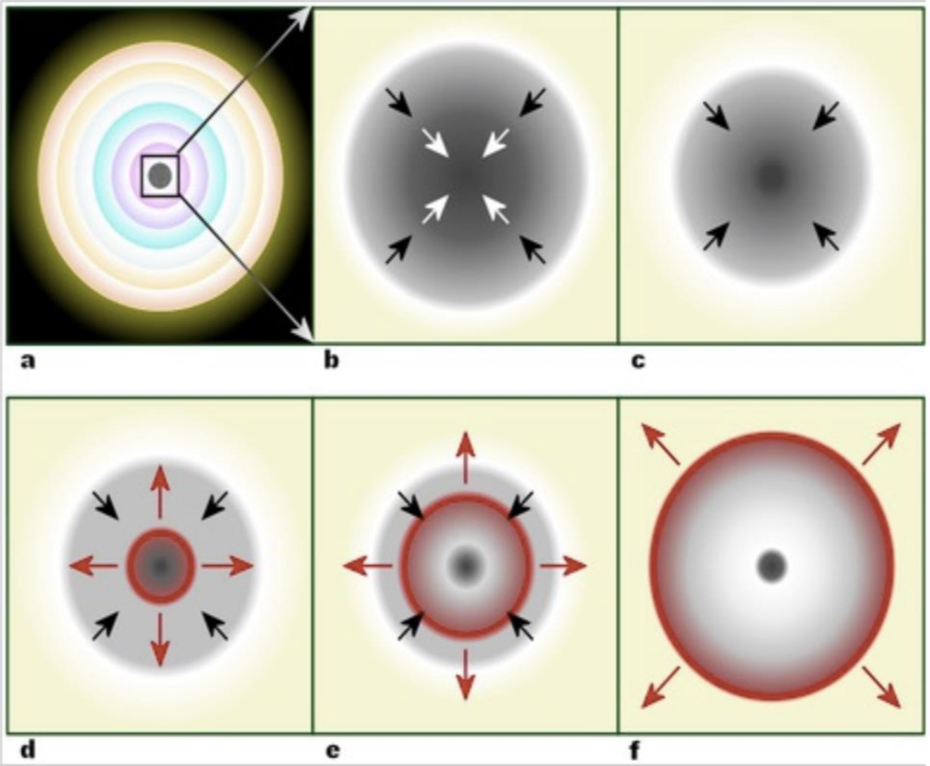
$$p + e^- \rightarrow n + \nu_e$$

For comparison: the Milky Way is about 34 kpc across

In 1987 in total ~24 events were detected in 3 experiments

Type II Supernovae

Gravitational collapse of a massive start at the end of its life



Compact remnant: neutron start or black hole

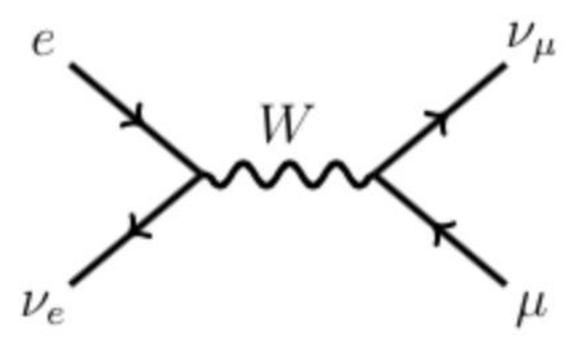
- Dropping an object turns gravitational 'potential energy' into 'kinetic energy' when an object falls.
- As the star falls inward the gravitational energy has to go somewhere:

$$p + e^- \rightarrow n + \nu_e$$

- Neutrinos only interact weakly, so easiest for them to escape.
- About 99% of the huge binding energy of the neutron star is shed within about 10 seconds in the form of neutrinos.

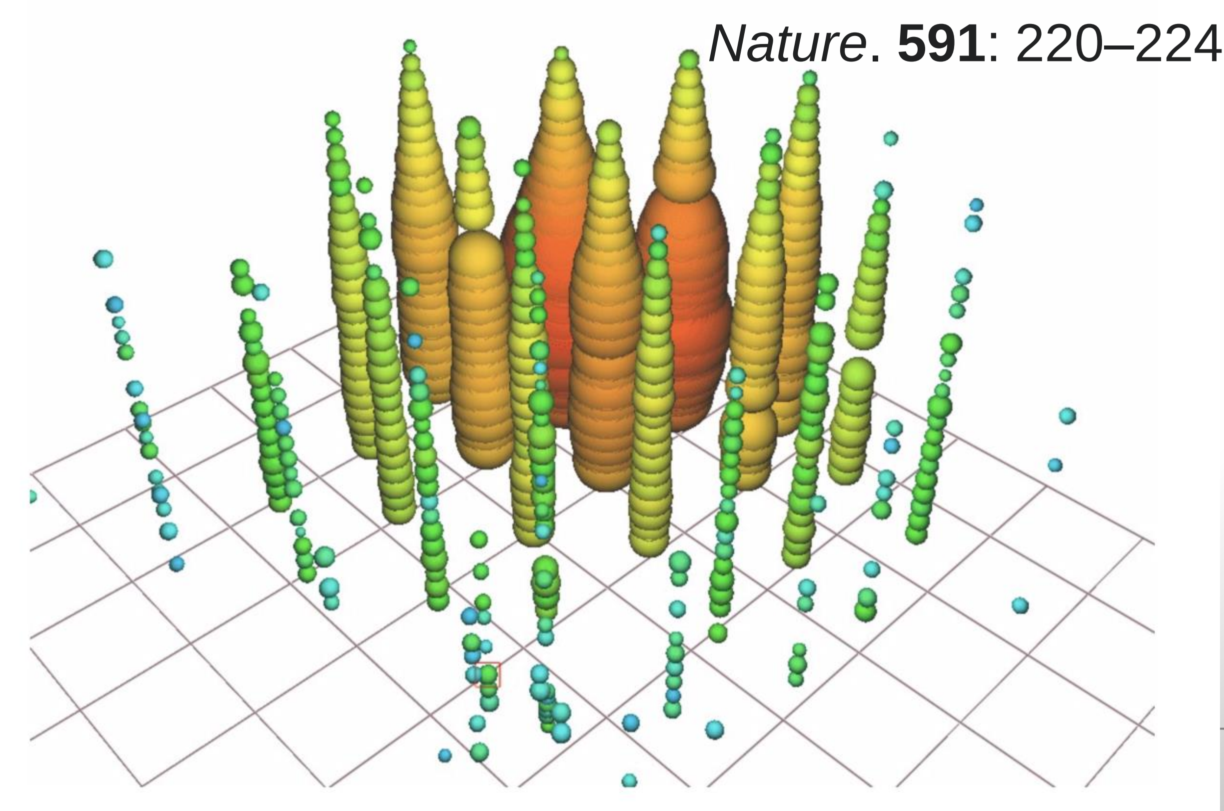
We are waiting for the next nearby supernova to go off (it is kinda late….)

Observation of a Glashow Resonance



Scattering on electrons to form a W boson
Electron antineutrino with energy of ~6.3 PeV required

Event seen with an estmated energy of 6.05 PeV (8/12/2016)



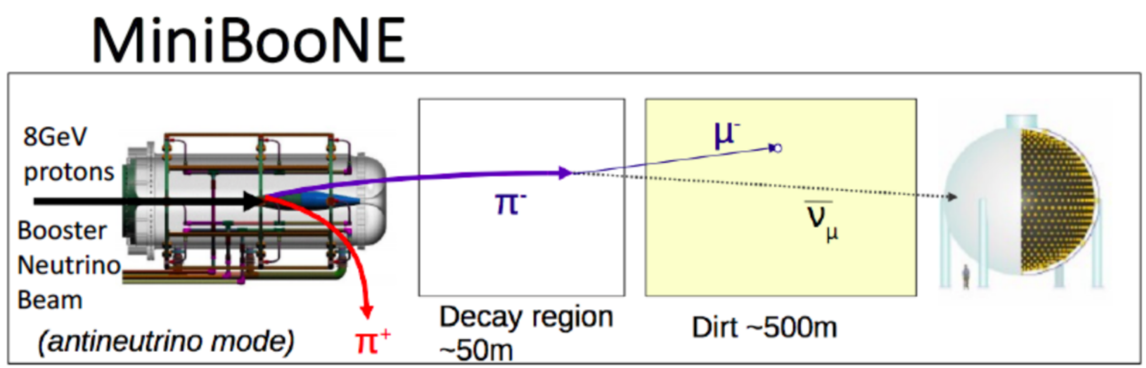
Nature. **591**: 220–224

$$E_\nu = \frac{M_W^2 - (m_e^2 + m_\nu^2)}{2m_e} \approx \frac{M_W^2}{2m_e}$$

Are there more than 3 Neutrinos?

- Is there is a 4th (5th…) neutrino then it has to be quasi-sterile, ie should not couple significantly to other fermions and bosons, as we know from measurements at LEP
- Could mix with the known neutrinos
- Some indication since more than 10 years (LSND, reactor anomalies, Gallium anomalies)
- The interpretation is still controversial/unclear..

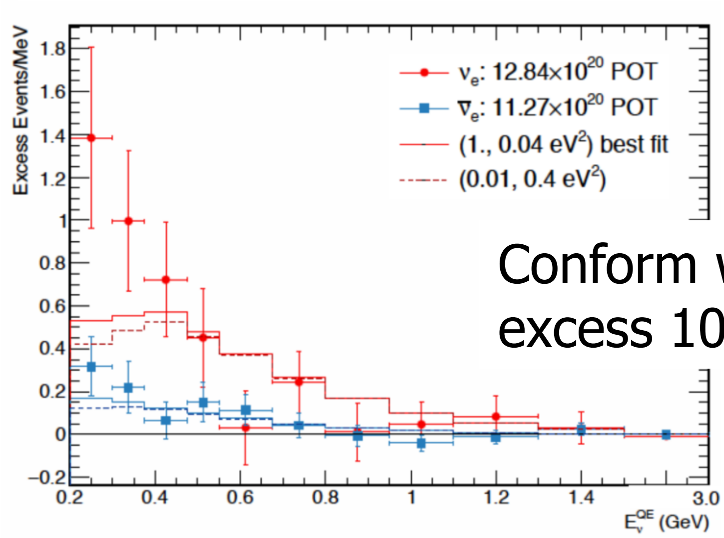
MiniBooNE 2018



Search for electron neutrino appearance in short baseline accelerator experiment.

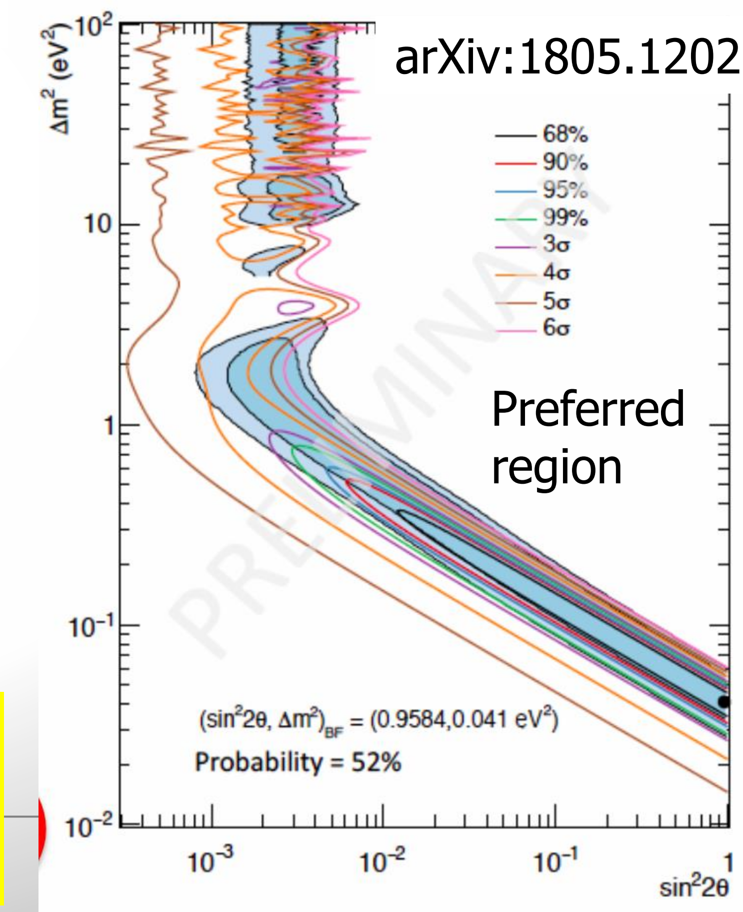
6.3 sigma excess reported combining the data with LSND

Excess of events over expectation



Conform with LSND excess 10 years ago

arXiv:1805.12028



Preferred region

Caused by a new sterile neutrino?
The jury is still out..
Breaking News: No signal in MicroBoone..!!

Neutrinos and New Physics

Neutrinos have connections to many other BSM or New Physics ares, also studied eg at the LHC

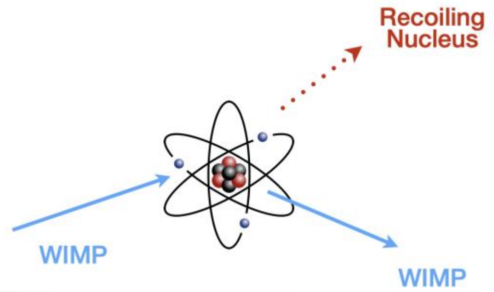
- Connection with GUTs (heavy righthanded neutrinos)
- Supersymmetry (sneutrinos and other)
- Extra dimensions/wormholes
- Dark matter
- Leptogenesis
- Dark energy
- Cosmology/inflation/abundance of H/He changes when more than 3 neutrinos
- Time travel? (right handed neutrinods in extra dimensions)??
- ….

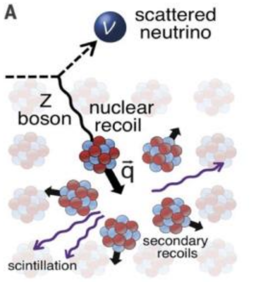
Neutrino Floor/Fog

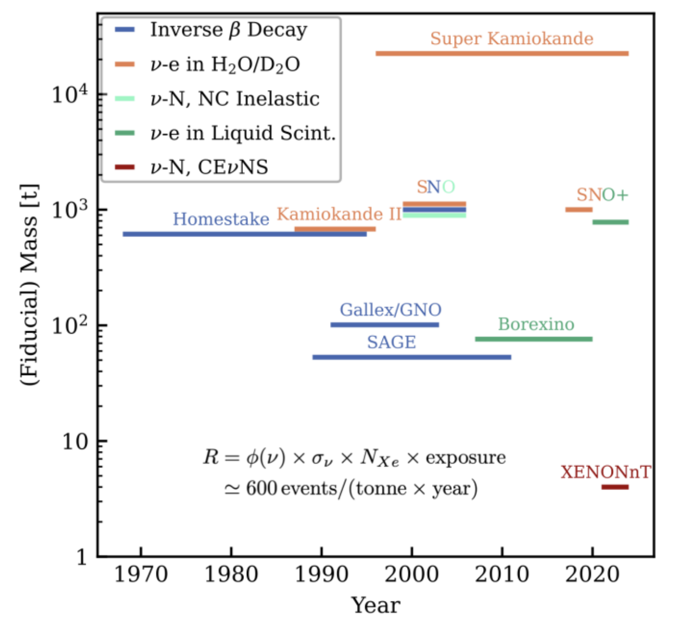
AUGUST 8, 2024 | 5 MIN READ

A ‘Neutrino Fog’ Is Starting to Cloud the Search for Dark Matter

With the detection of a long-predicted “neutrino fog,” the search for particles of dark matter has entered a new age of both possibility and peril







$$R = \phi(\nu) \times \sigma_\nu \times N_{Xe} \times \text{exposure}$$
$$\simeq 600\,\text{events}/(\text{tonne} \times \text{year})$$

First Measurement of CEvNS with a Xe Target

$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\implies \boxed{\sigma \propto N^2}$$

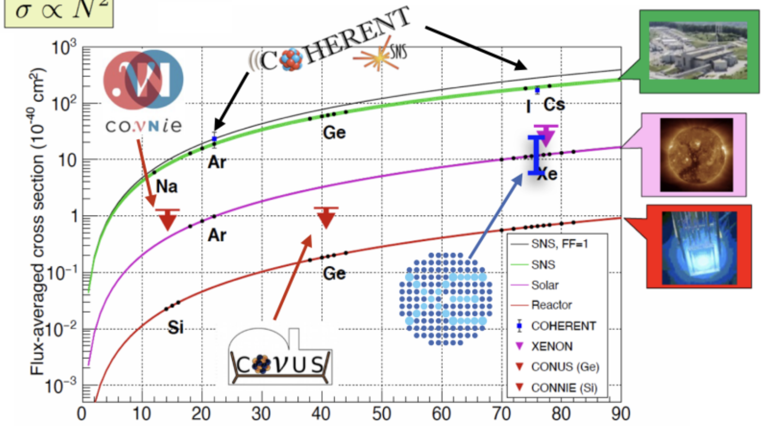


Figure credit: Kate Scholberg

Conclusions

Sterile Neutrinos

- **Short Baseline**

- 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

- **Gallium**

-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

- **Reactor Neutrinos**

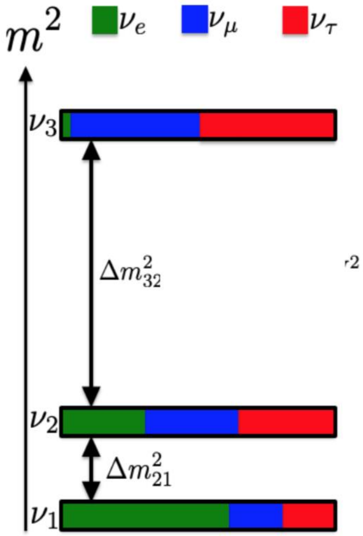
- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments (with exception of DANSS) and new Reactor flux models
- Spectral analysis still indicates ν_s with a small $\sin^2 2\Theta_{ee}$ at ~3σ
- Neutrino-4 claim of ν_s observation is in tension with many results but not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

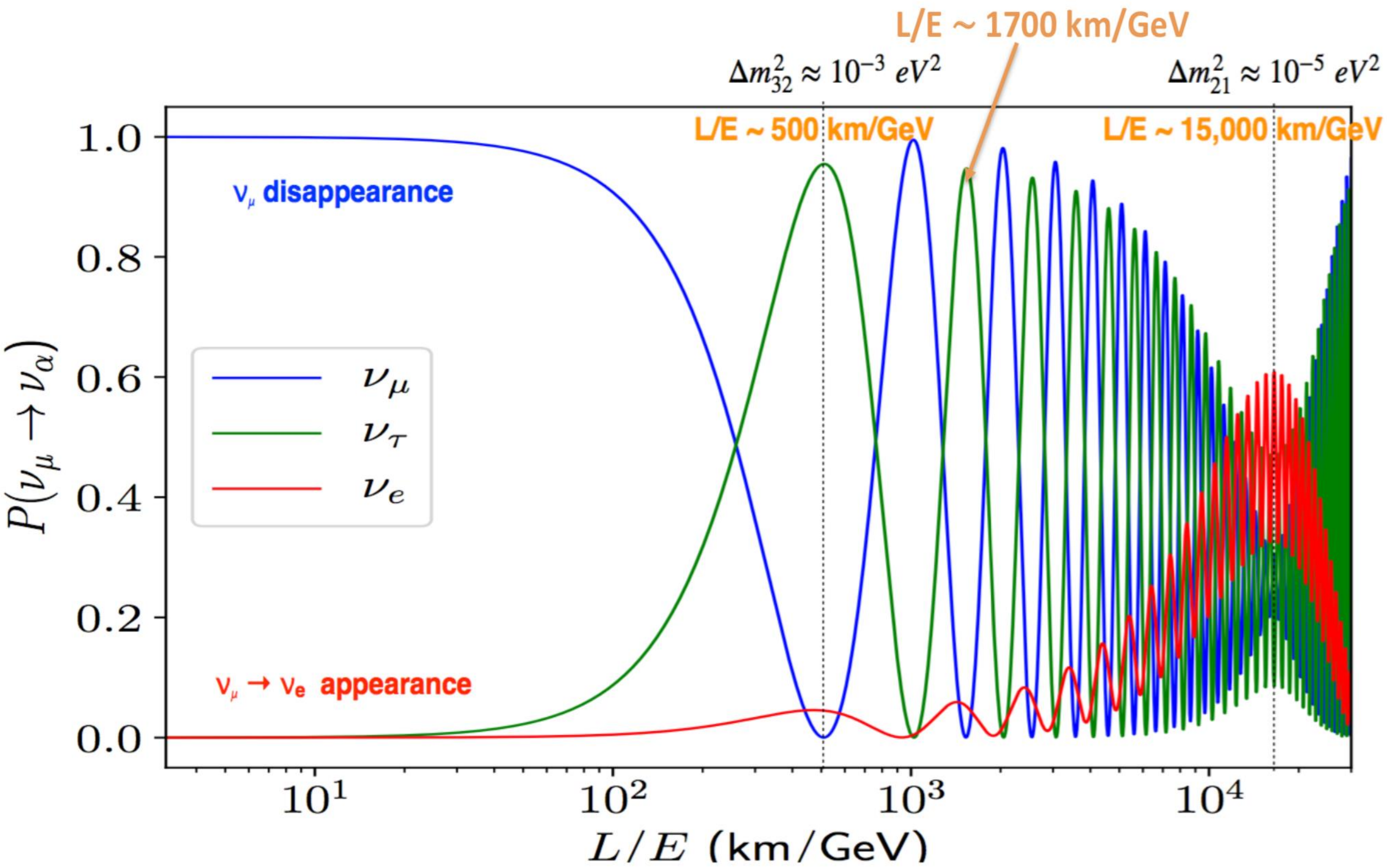
Cosmological constraints were not discussed but models exist which remove them

See e.g. Davoudiasl,Denton arXiv:2301.09651 Explains Ga, LSND, MiniBooNE, DM

Experimental evidence for ν_s is fading away but not excluded

Finding the Oscillation Maximum




L/E ~ 1700 km/GeV

L/E ~ 500 km/GeV

L/E ~ 15,000 km/GeV

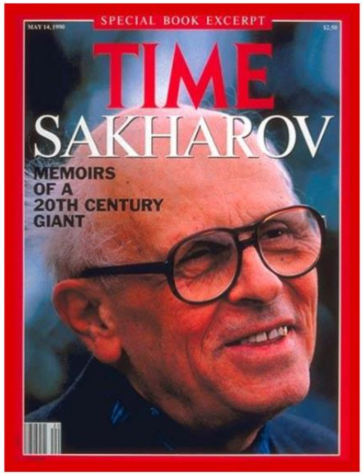
ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$ appearance

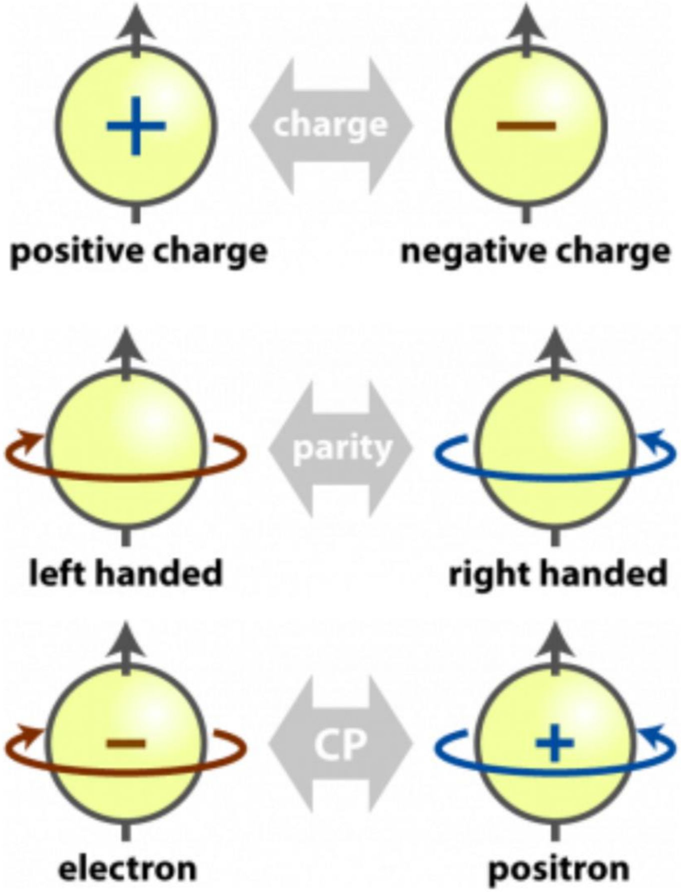
Typical neutrino beam energy is around 2.5 GeV

Matter-Antimatter Asymmetry

- A tiny ($\approx 10^{-10}$) asymmetry between particle and anti-particles led to our matter dominated universe
- One of the conditions for this asymmetry is violation of *CP symmetry*
- The observation of *CP violation* involving neutrinos could provide support for a theory called *Leptogenesis*



1. Baryon number violation
2. CP violation
3. Departure from thermal equilibrium

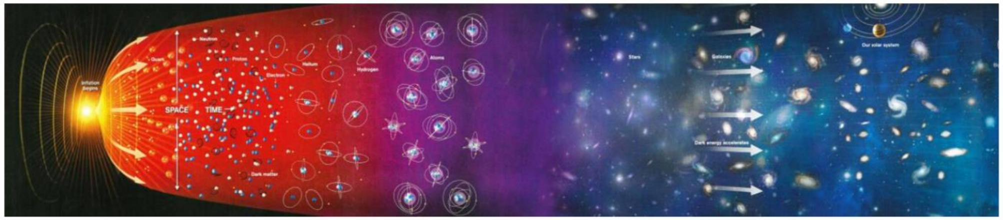


CP Violation

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

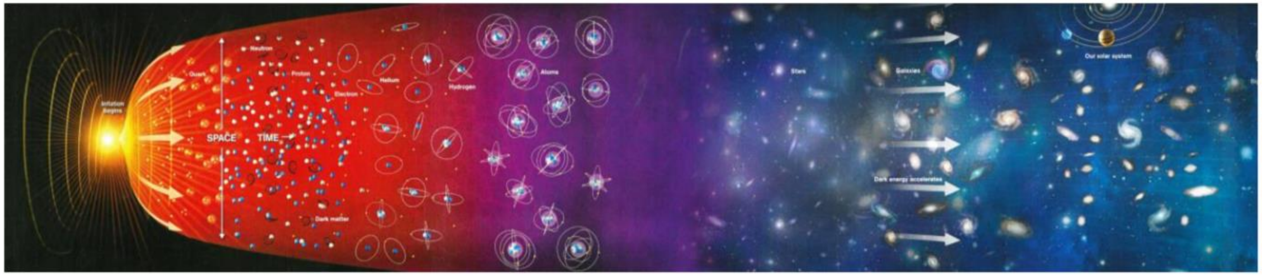
$$c_{ij} = \cos\theta_{ij}; s_{ij} = \sin\theta_{ij}$$

- A 2x2 ”rotation” matrix is real, whereas a 3x3 rotation matrix is imaginary (phase δ).
- CP violation (the difference between a process and its CP conjugate) is only possible when the matrix is imaginary (3 generations!).



CP Violation

- The same is true for the CKM matrix, where CP violation has been observed for quark processes.
- CP violation in the quark sector is too small to describe the matter dominance in the Universe.
- Discovery of CP violation with neutrinos would lend support to the Leptogenesis model – Leptogenesis would happen at large scales, e.g. through a heavy right-handed neutrino N_R (see-saw mechanism).



Best option to measure the CPV phase δ -> use accelerator neutrinos