

Neutrinos!

Experimental Highlights

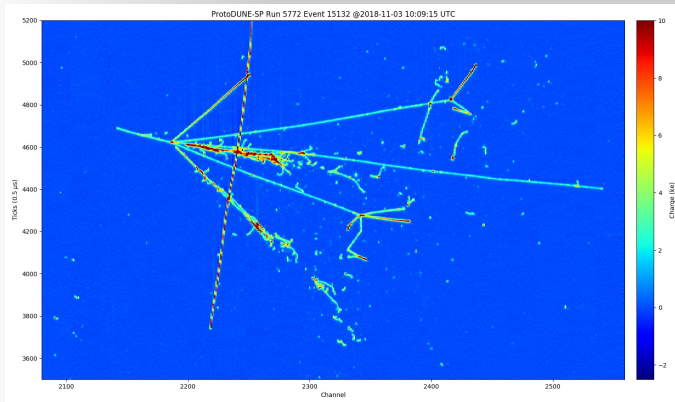
Albert De Roeck
CERN, Geneva, Switzerland
31 August 2021



Corfu Summer Institute

21st Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece 2021

Outline



Pion event in the ProtoDUNE at CERN



Speaker of today

- Introduction to neutrinos
- Neutrinos oscillate and have mass
- Physics oscillation experiments
- Neutrino properties: mass and Majorana/Dirac nature
- Future experiments & **CERN Neutrino Platform**
- (Cosmic Neutrinos)
- (Sterile Neutrino Search)
- Neutrino experiments at the LHC
- Summary

Neutrinos

Neutrinos are still mysterious particles

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

Neutrinos are Everywhere !



from Big Bang $300 \text{ nus} / \text{cm}^3$

2 or more $v/c \ll 1$

SuperNovae
 $> 10^{58}$

Sun's
 $\sim 10^{38} \text{ nu/sec}$

Daya Bay

$3 \times 10^{21} \text{ nu/sec}$

Neutrinos are Forever !!!

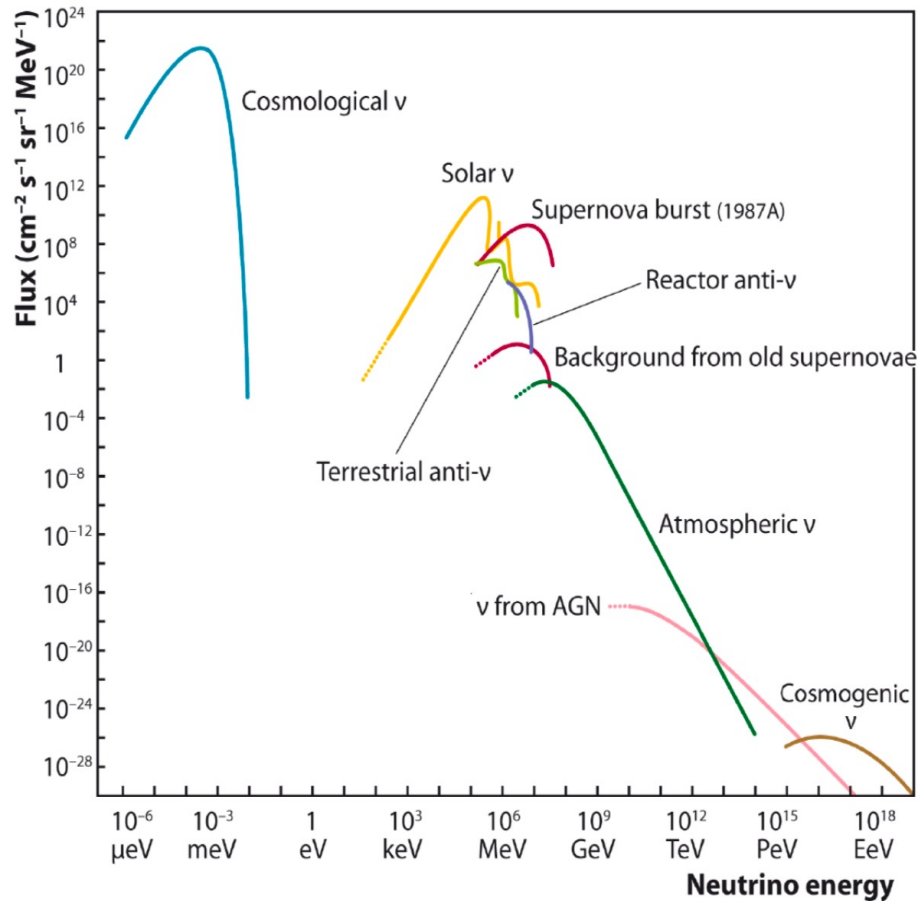
(except for the highest energy neutrino's)



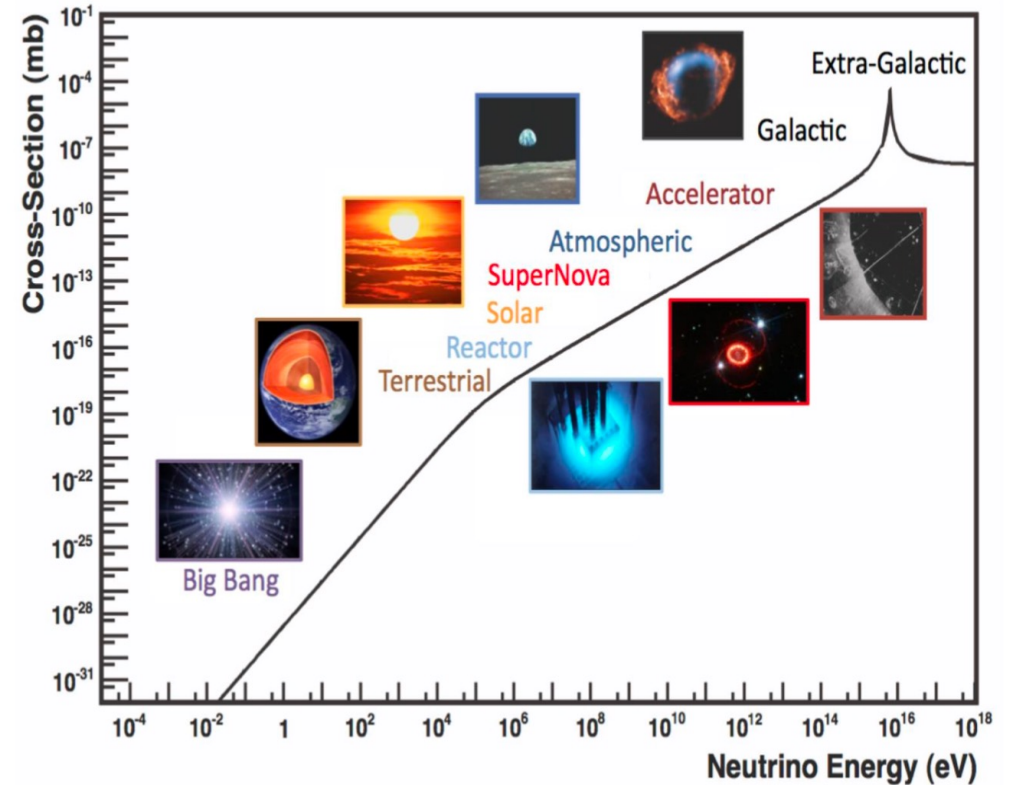
therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrino Sources, Flux and Cross Sections

C. Spiering, arXiv:1207.4952



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

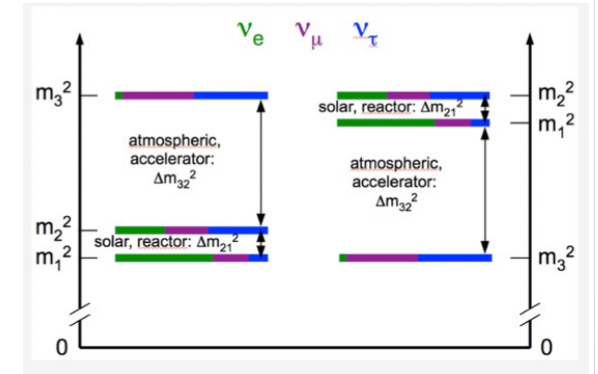


Cosmological and background from old supernovae neutrinos not yet observed!

Neutrinos

Neutrino experiments today -> Open Questions!

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



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

Neutrinos allow us to look into the heart of the sun

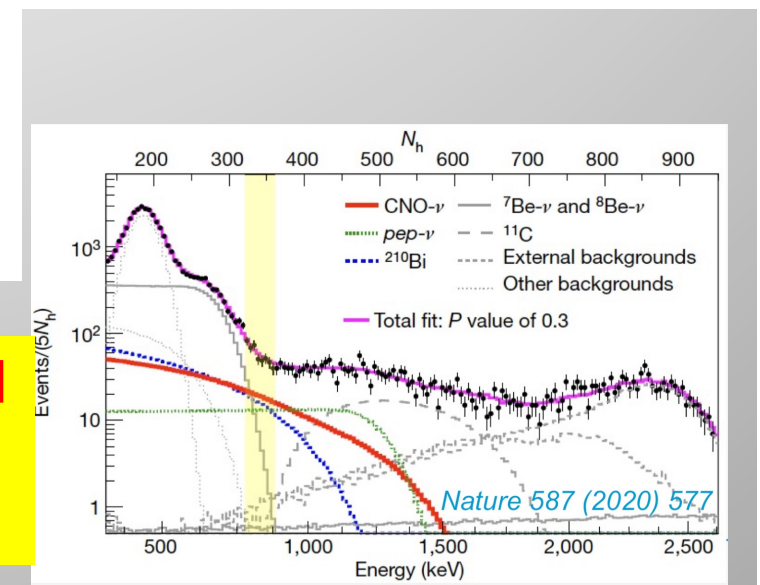
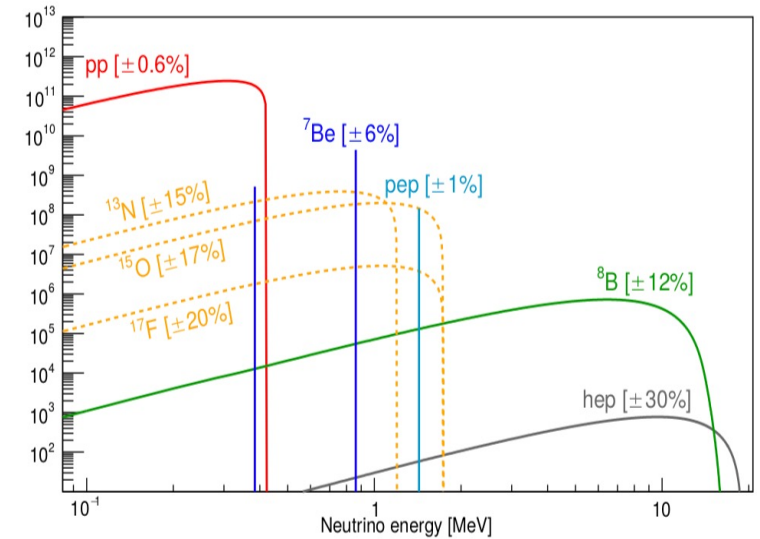
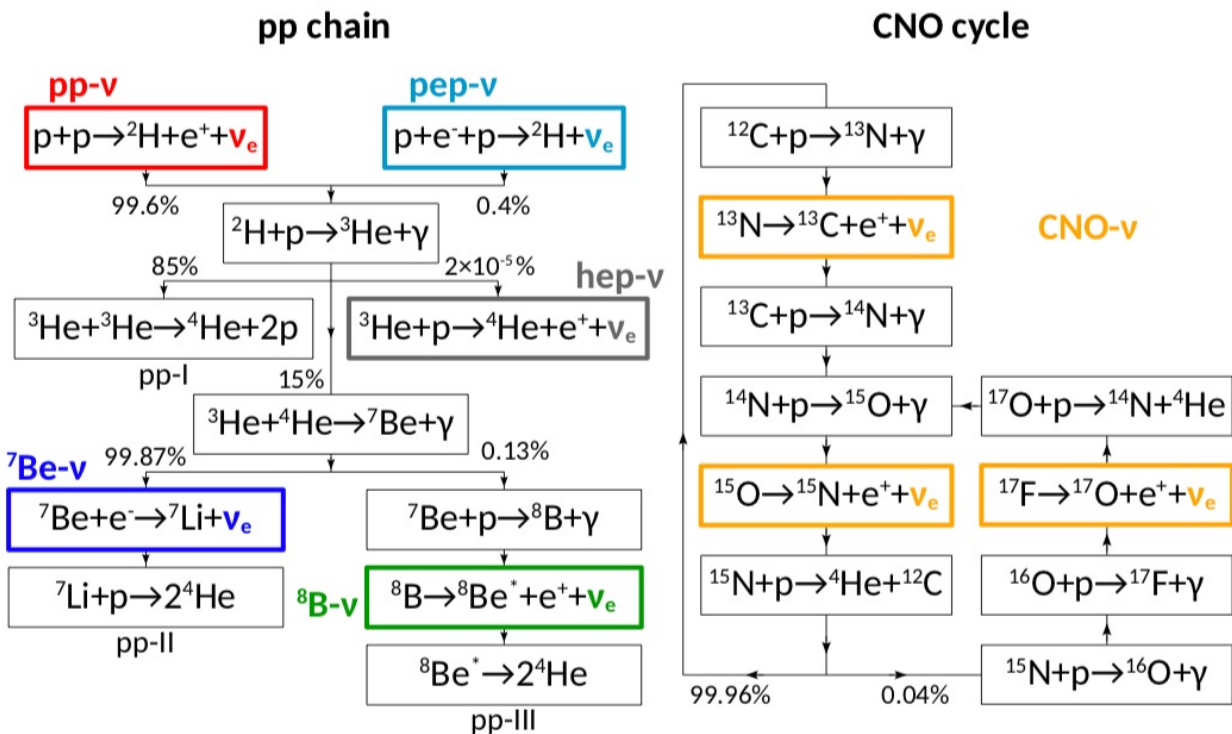


10^{38} neutrinos per second
are produced by the Sun

(with a flux of $\sim 10^{11}/\text{cm}^2/\text{sec}$ at the Earth)

Solar Neutrinos

Neutrino measurements allow to understand how the sun works



2020: Borexino measured the CNO cycle -> Nature 687 (220) 577

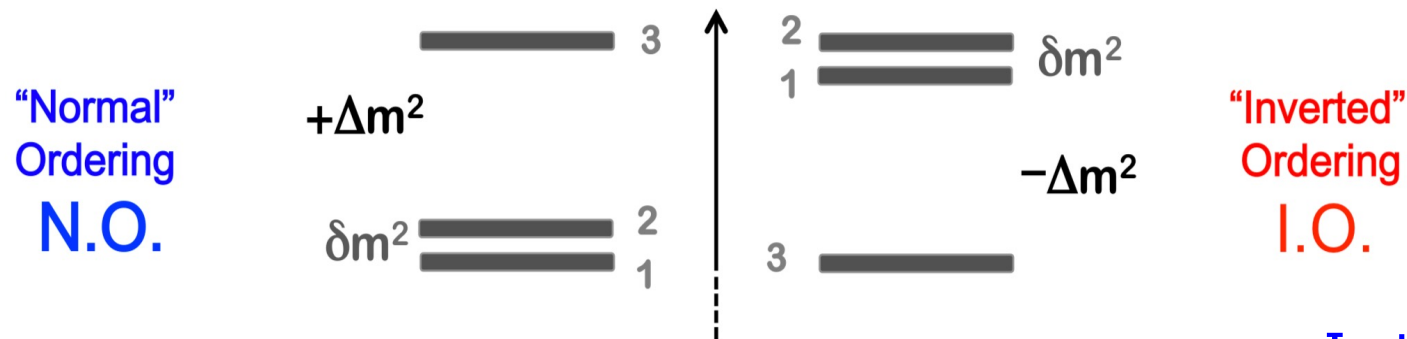
Neutrino Oscillations

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

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

θ_{23} rotation θ_{13} rotation θ_{12} rotation
 + CPV "Dirac" phase δ $c_{ij} = \cos \theta_{ij}; s_{ij} = \sin \theta_{ij}$

Mass [squared] spectrum ($E \sim p + m^2/2E + \text{"interaction energy"}$)



+ interactions in matter → effective terms $\sim G_F \cdot E \cdot \text{density}$

In total 6 parameters to determine

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

Short Baseline Experiments

Measuring the mixing angle θ_{13}

Daya Bay (China)

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

RENO (South Korea)

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

Double Chooz (France)

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

DC IV **Double Chooz**

TnC MD (n -H + n -C + n -Gd)

Daya bay

PRL 121, 241805 (2018) n -Gd

PRD 93, 072011 (2016) n -H

RENO

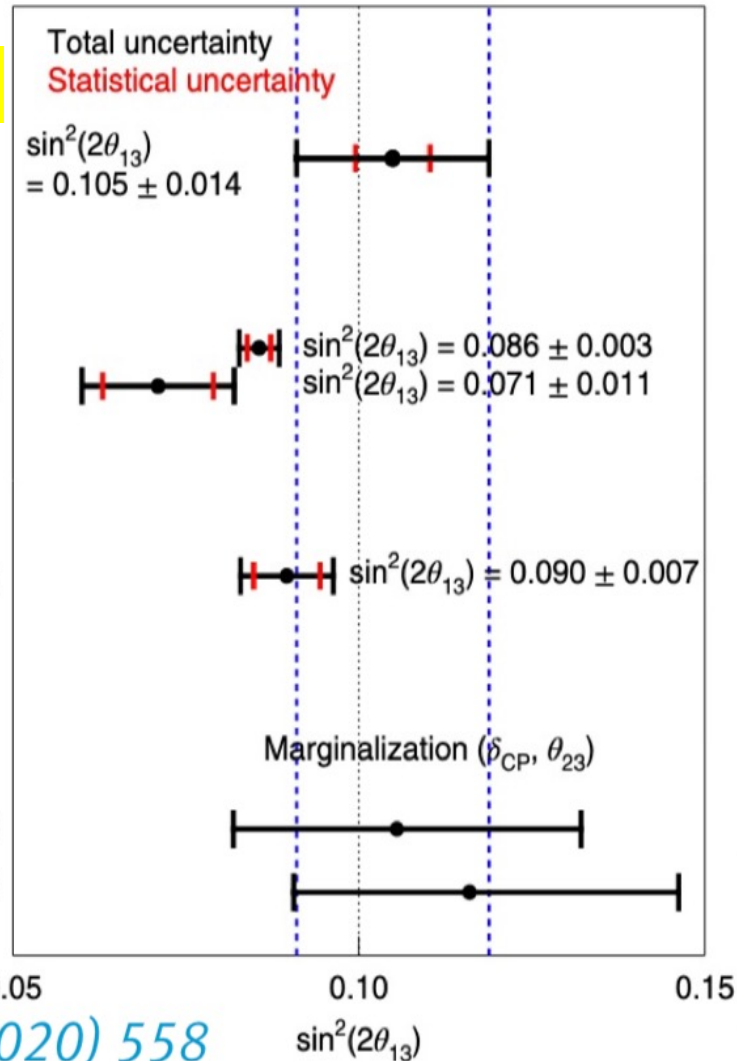
PRL 121, 201801 (2018) n -Gd

T2K

PRD 96, 092006 (2017)

$\Delta m_{32}^2 > 0$

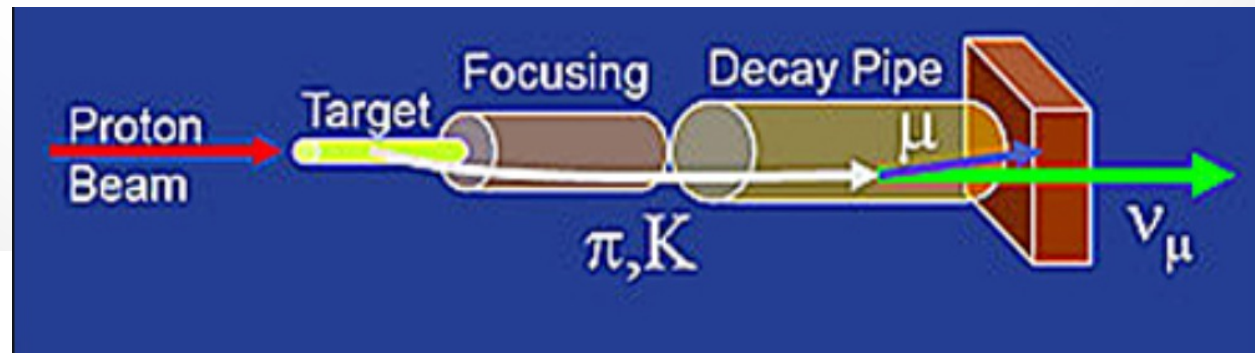
$\Delta m_{32}^2 < 0$



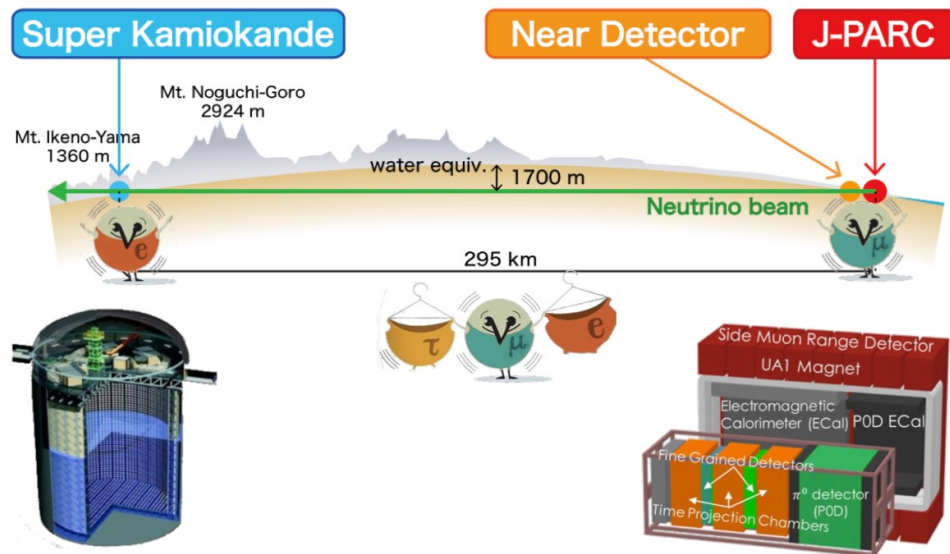
$\sin^2 \theta_{13} = 0.0220 \pm 0.0007$
(PDG2021 using Double Chooz, Reno, Daya Bay)

Accelerator Based Neutrino Experiments

Neutrinos from accelerators

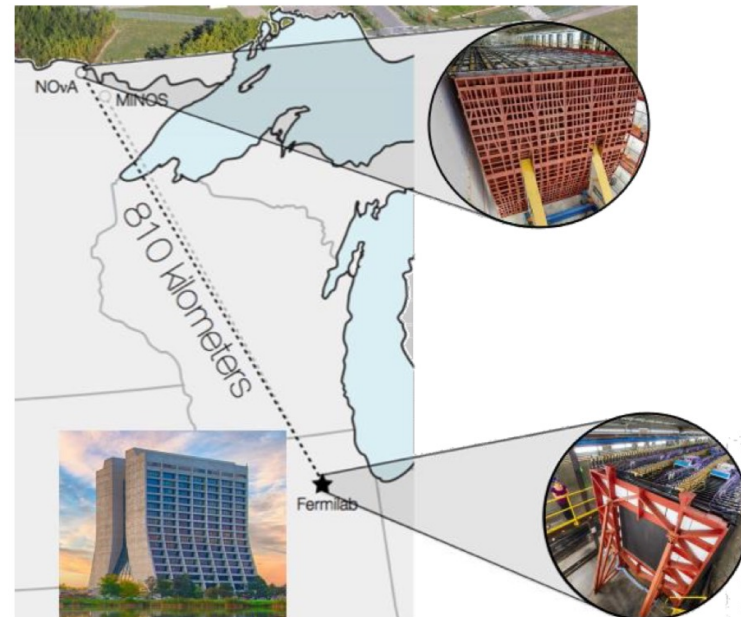


T2K



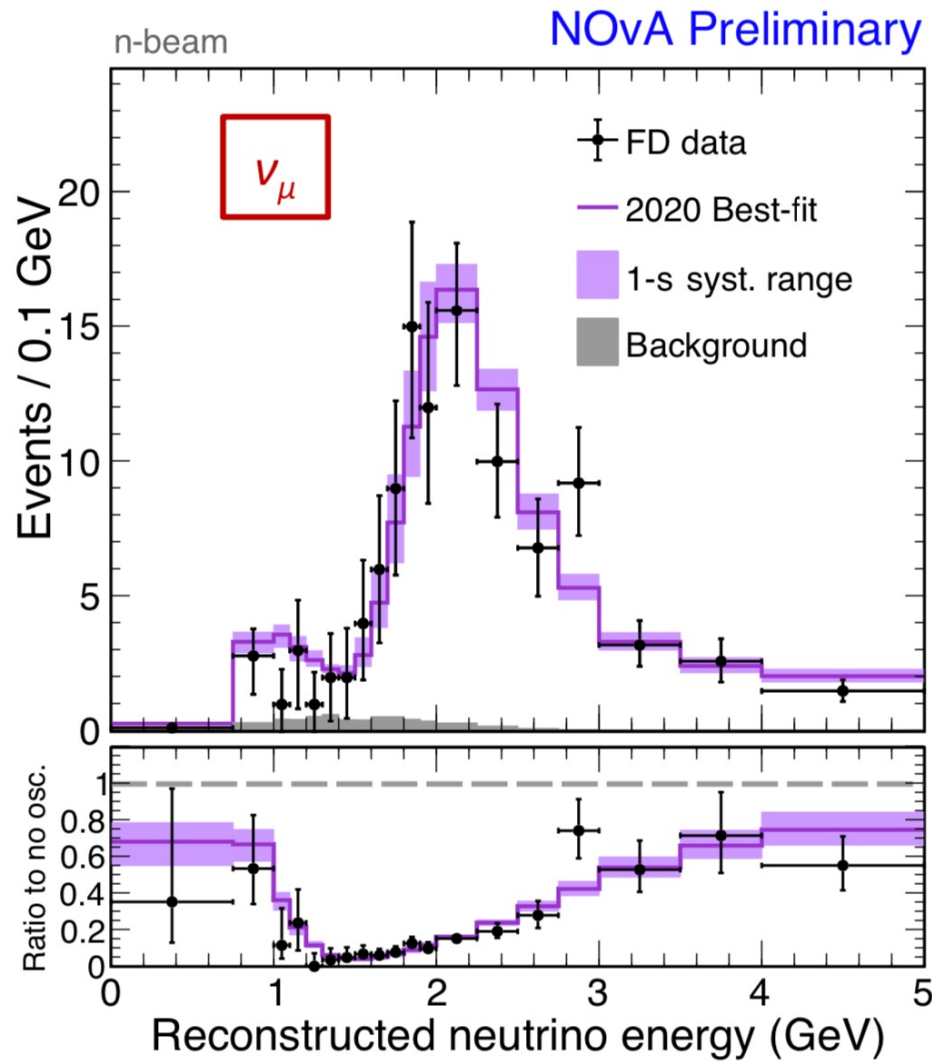
Baseline: 295 km
 Peak E_ν : ~ 0.6 GeV (off-axis)
 Near detector: ND280 (~ 2 T C/O targets, TPC tracking, magnetised)
 Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

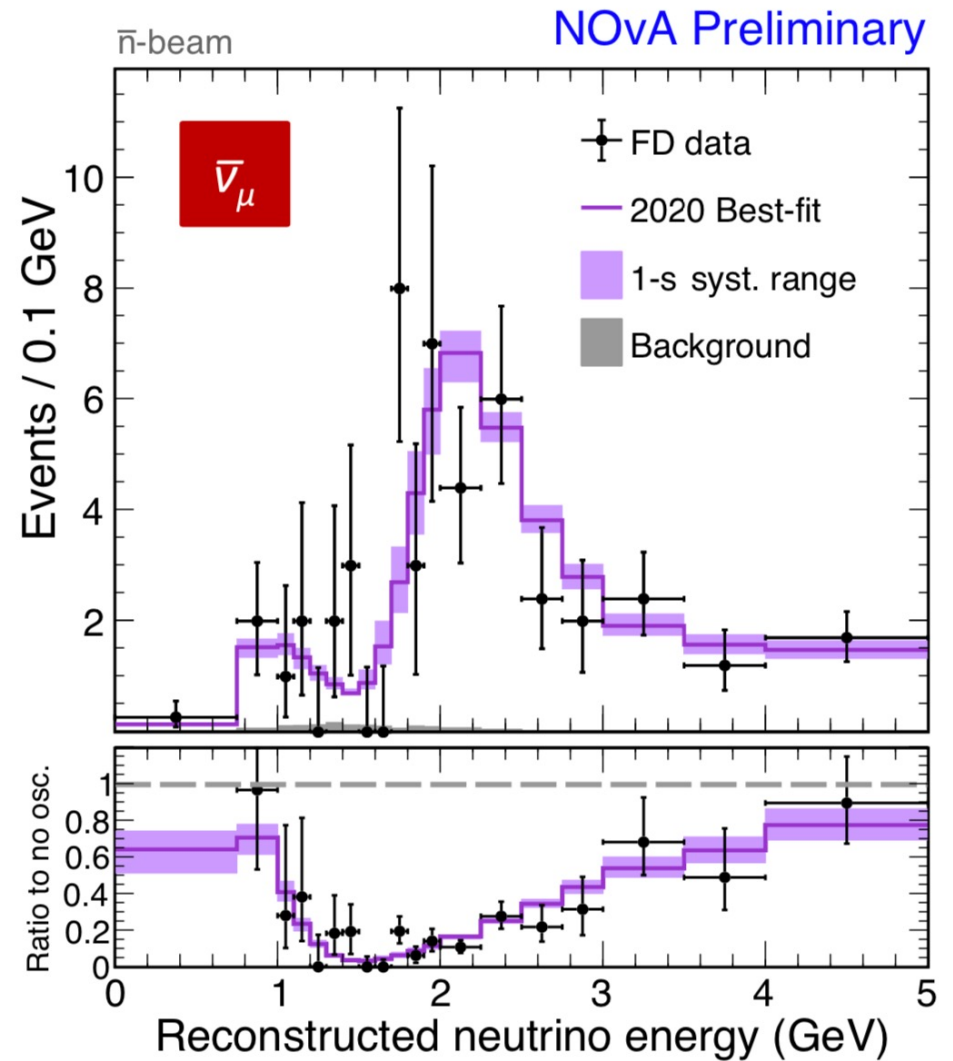


- Baseline: 810 km
- Peak E_ν : ~ 2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

Muon Neutrino Disappearance



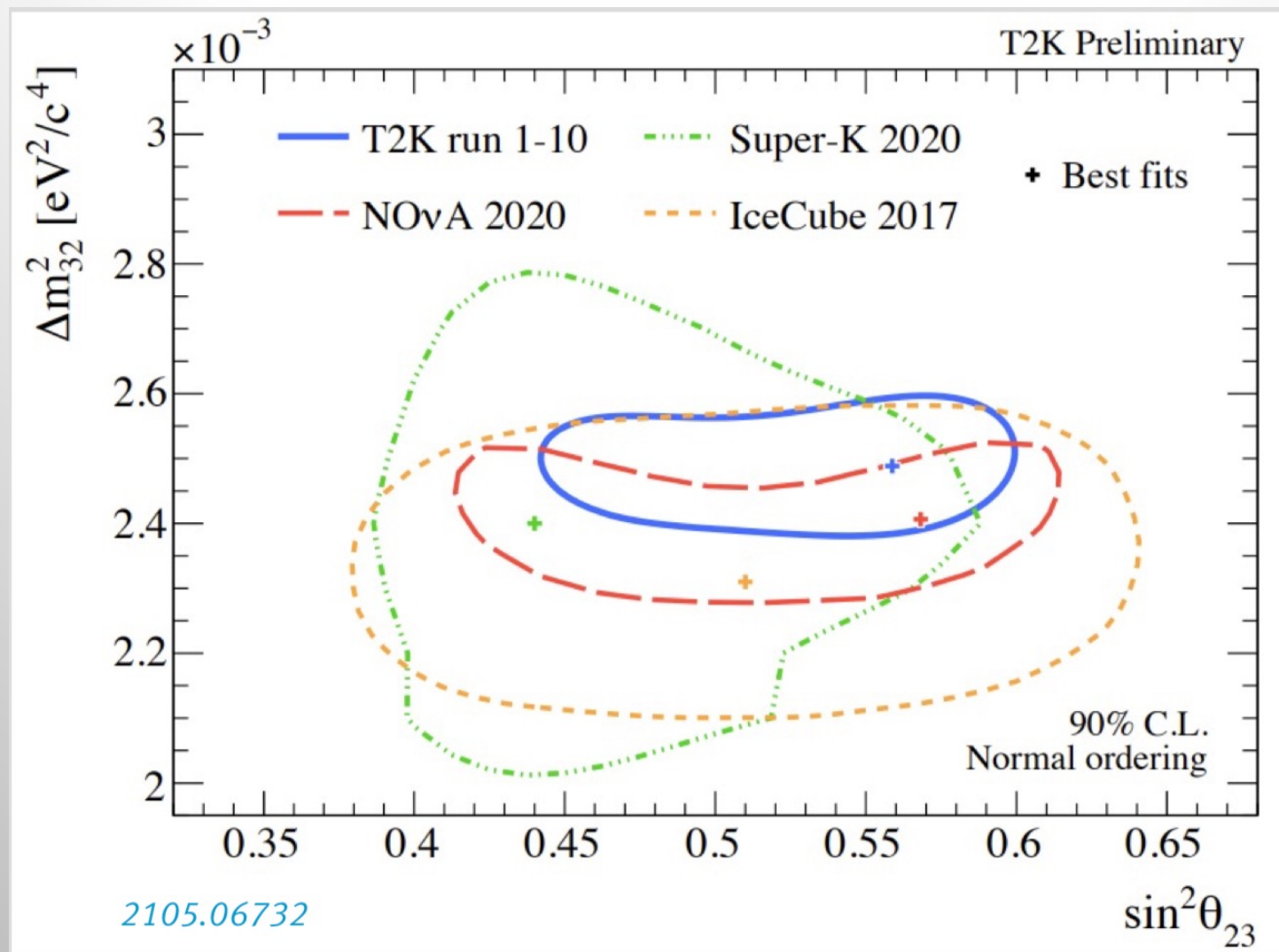
211 events, 8.2 background



105 events, 2.1 background

Neutrino Experiments

2105.06732



- Atmospheric parameter determinations by several experiments
- Results are consistent

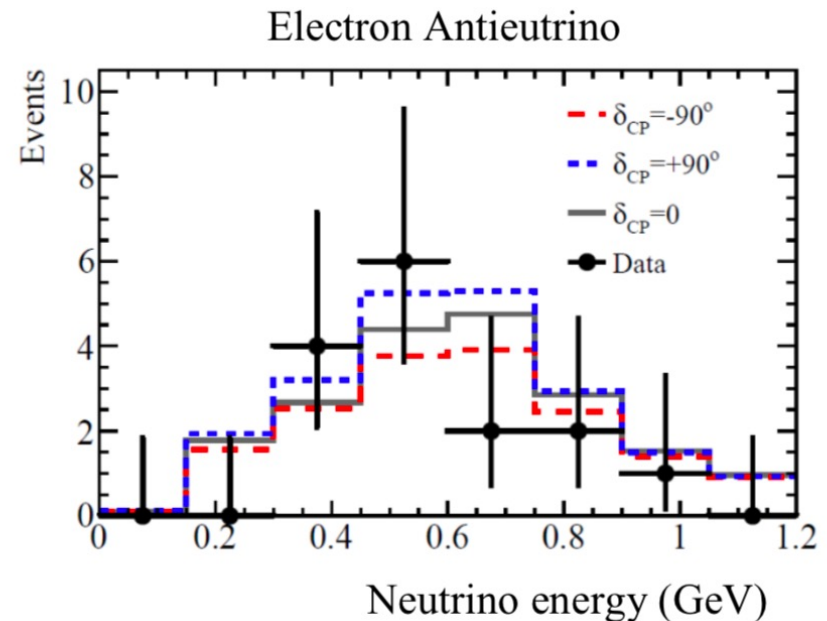
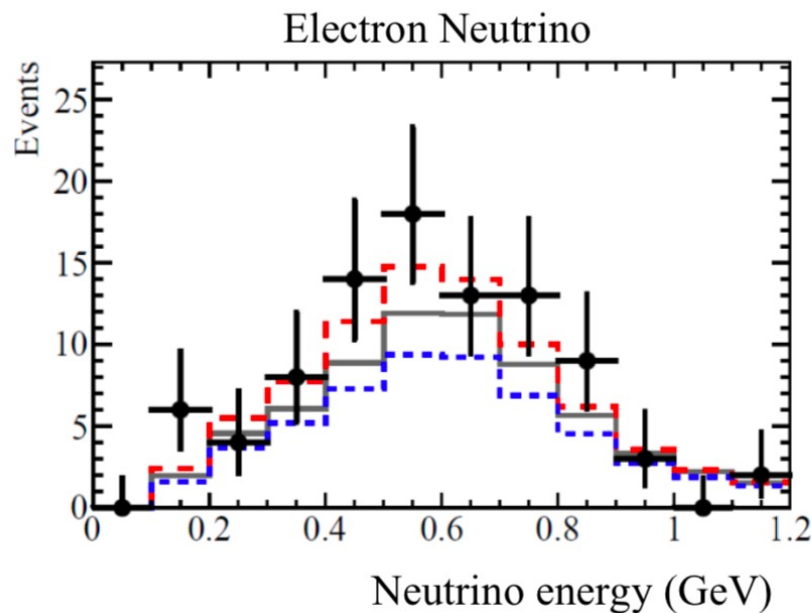
CP Violation: T2K Measurement

Do neutrinos and anti-neutrinos oscillate differently ?

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

	Observed	Expectation	
		$\delta_{CP} = -90^\circ$	$\delta_{CP} = +90^\circ$
Electron neutrino	90	82	56
Electron antineutrino	15	17	22

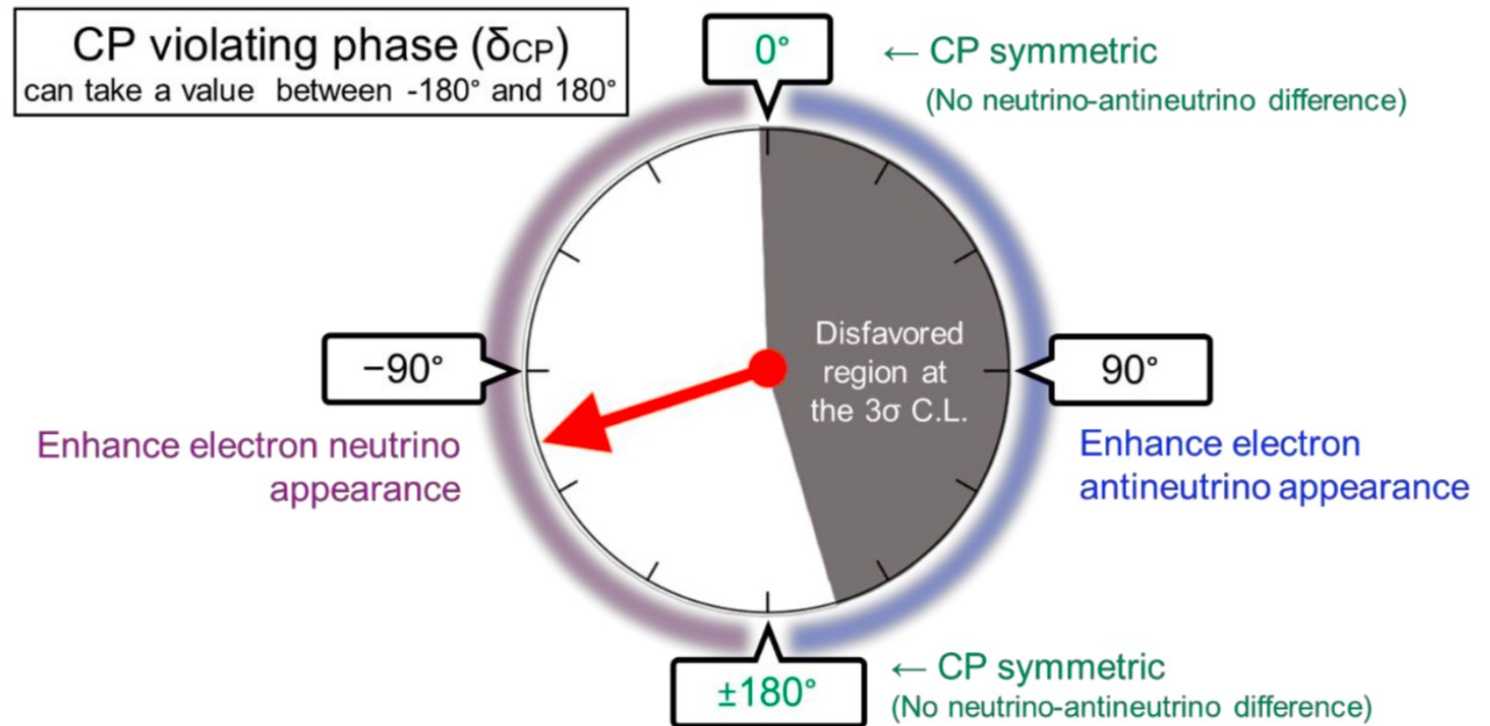
$\delta_{CP}=0$
 ~ 70
 ~ 20



CP Violation: T2K Result



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



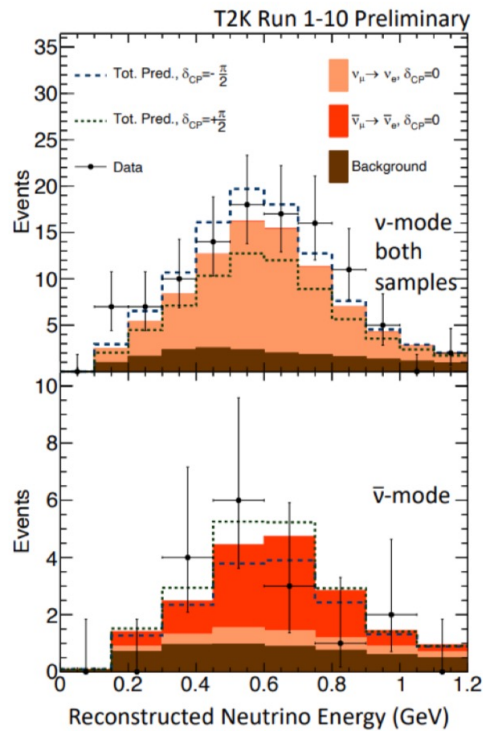
The gray region is disfavored by 99.7% (3σ) CL
The values 0 and 180 degrees are disfavoured at 95% CL

CP Violation Results

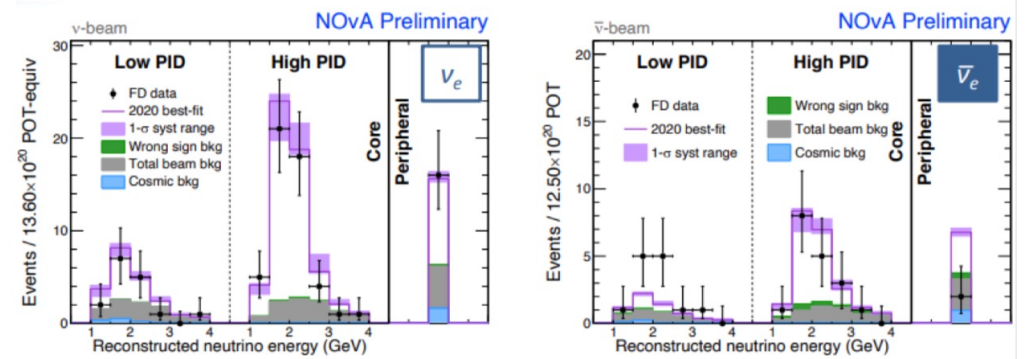
Updates from NOvA and T2K summer 2020..

ν_e appearance data

T2K



NOvA



Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4 σ evidence of $\bar{\nu}_e$ appearance

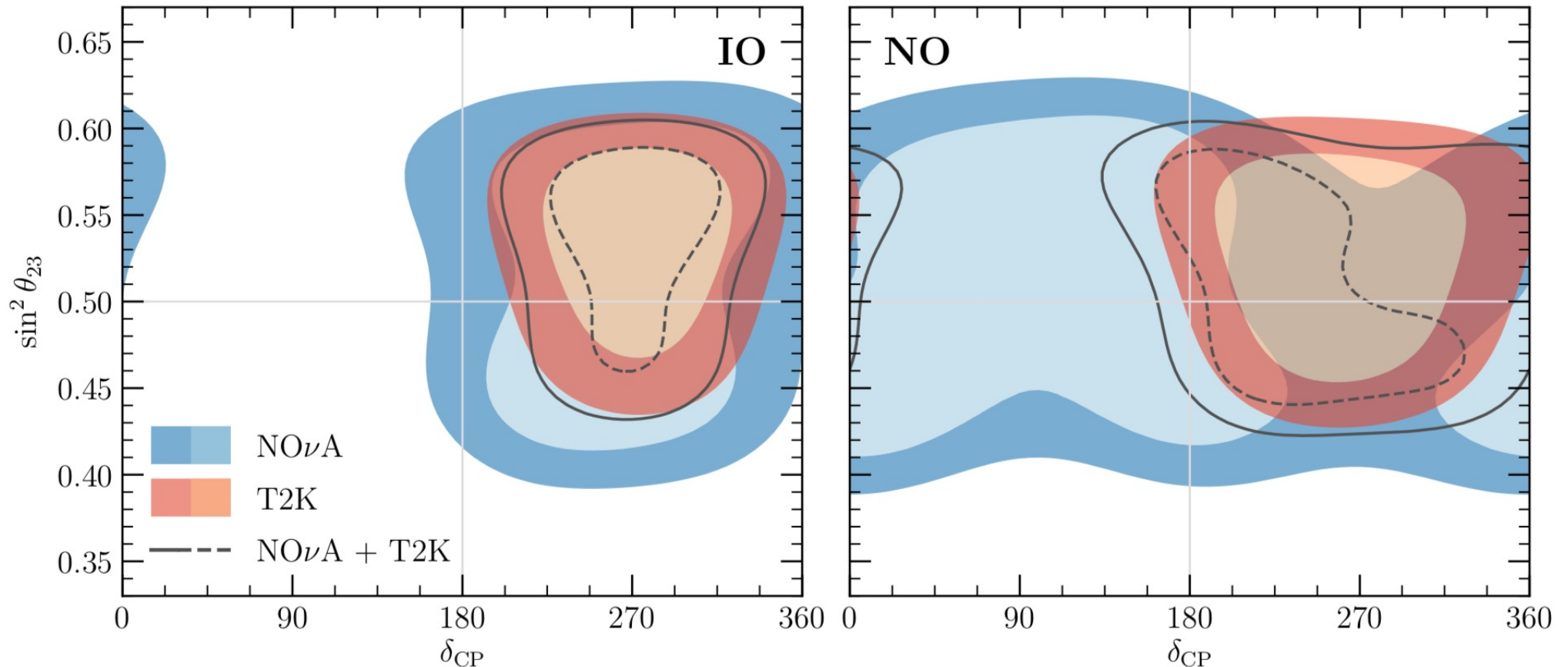
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Re	97.62	82.44	67.56	82.74	94
RHC 1Re	16.69	18.96	20.90	18.63	16
FHC 1R ν_e CC1 π^+	9.20	8.01	6.51	7.71	14

CP Violation T2K/NOvA Results

Summer 2020
update

arXiv:2007.14792

NuFIT group



Some tension between NOvA and T2K results for NO mass ordering
-> more experimental data needed ... (and coming..)

Taking all available data together...

arXiv:2007.14792

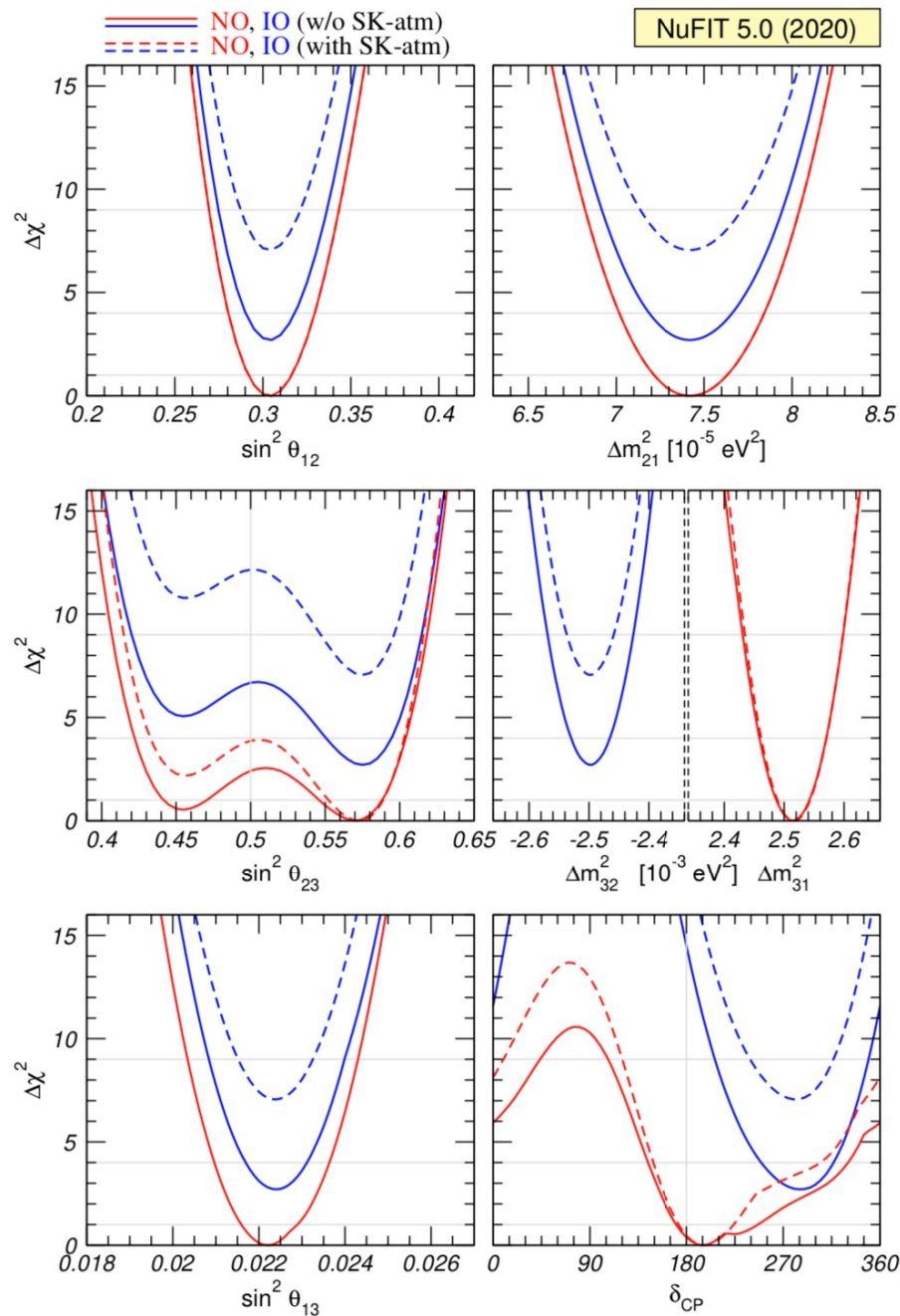
NuFIT group

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)		
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	
with SK atmospheric data	$\sin^2 \theta_{12}$	$0.304^{+0.012}_{-0.012}$	0.269 \rightarrow 0.343	$0.304^{+0.013}_{-0.012}$	0.269 \rightarrow 0.343
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	31.27 \rightarrow 35.86	$33.45^{+0.78}_{-0.75}$	31.27 \rightarrow 35.87
	$\sin^2 \theta_{23}$	$0.573^{+0.016}_{-0.020}$	0.415 \rightarrow 0.616	$0.575^{+0.016}_{-0.019}$	0.419 \rightarrow 0.617
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	40.1 \rightarrow 51.7	$49.3^{+0.9}_{-1.1}$	40.3 \rightarrow 51.8
	$\sin^2 \theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	0.02032 \rightarrow 0.02410	$0.02238^{+0.00063}_{-0.00062}$	0.02052 \rightarrow 0.02428
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	8.20 \rightarrow 8.93	$8.60^{+0.12}_{-0.12}$	8.24 \rightarrow 8.96
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	120 \rightarrow 369	282^{+26}_{-30}	193 \rightarrow 352
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.42^{+0.21}_{-0.20}$	6.82 \rightarrow 8.04	$7.42^{+0.21}_{-0.20}$	6.82 \rightarrow 8.04
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \rightarrow +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \rightarrow -2.414$

To explore Beyond the Standard Model ~ 10 times better precision needed

Taking all available data together...

arXiv:2007.14792



Minimized $\Delta\chi$ distributions
for the 3 neutrino hypothesis
fit off all data

Inverse mass ordering is
disfavoured slightly compared
to the normal mass ordering in
the global fit by about 1.6 sigma
(2.7 sigma when including SK)

Data mainly from reactors,
long baseline experiments,
atmospheric, solar neutrinos...

But the Jury is still out..

Neutrino Oscillations

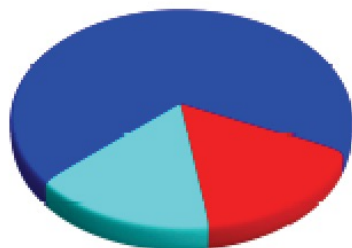
Neutrino Mass EigenStates or Propagation States:



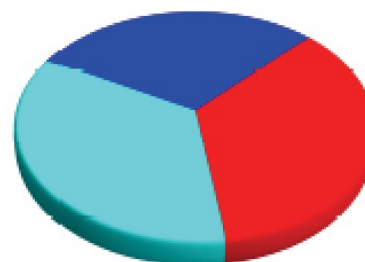
$$\text{Propagator } \nu_j \rightarrow \nu_k = \delta_{jk} e^{-i \left(\frac{m_j^2 L}{2E\nu} \right)}$$

ν_1

most ν_e

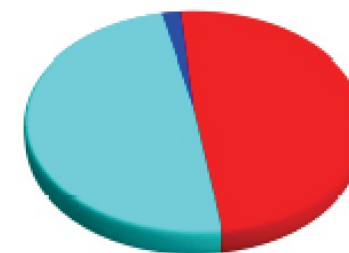


ν_2



ν_3

least ν_e



$\nu_e =$ 

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, ...

$\nu_\mu =$ 

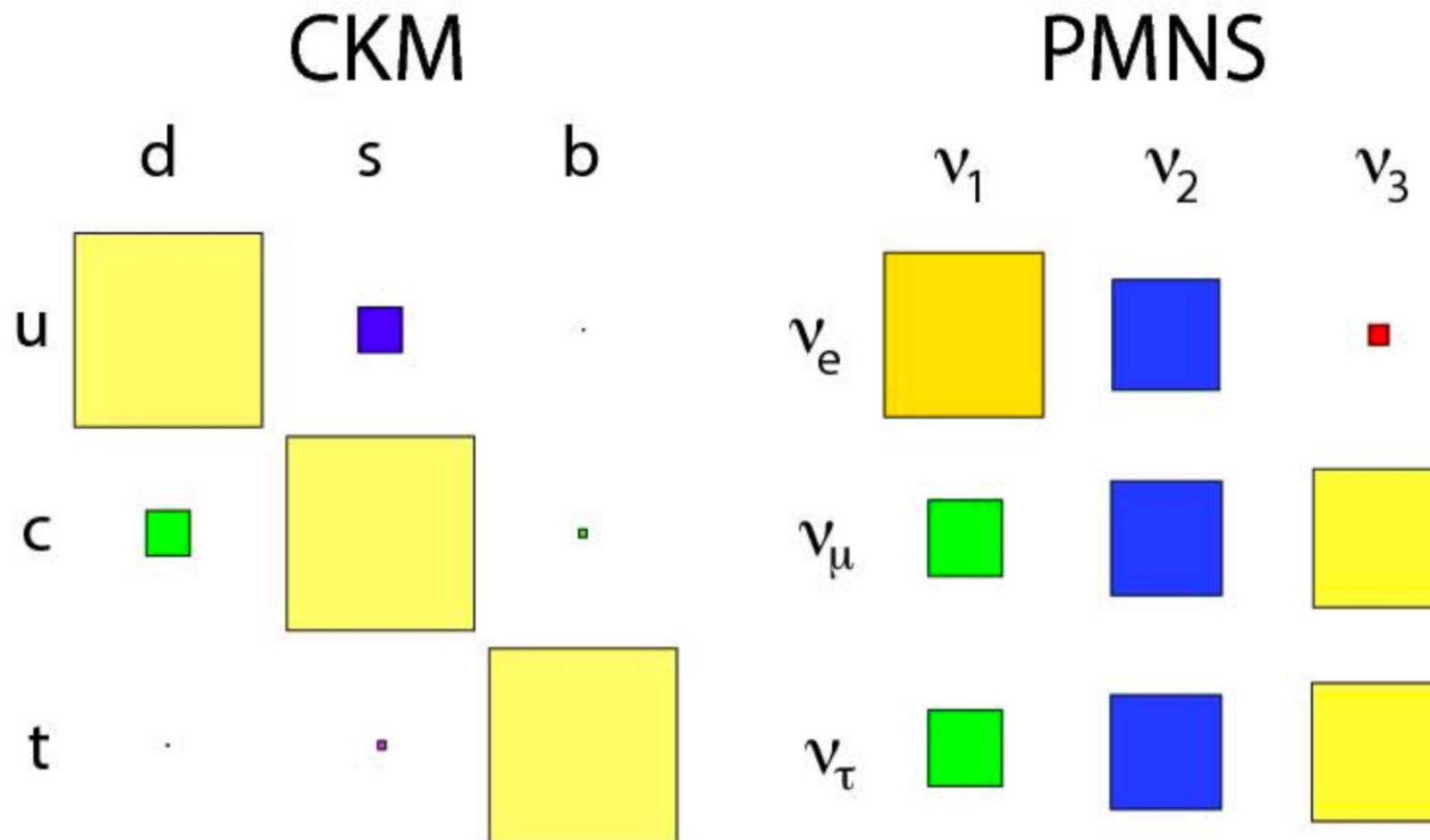
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$ 

Unitarity
SK, Opera
ICECUBE ?

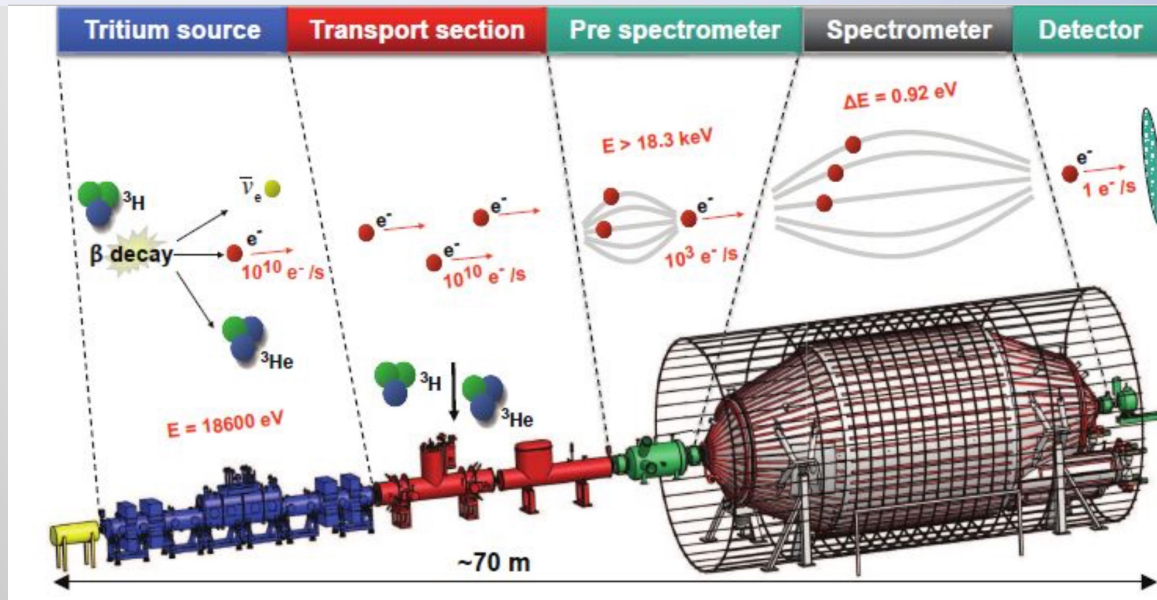
CKM vs PMNS

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.

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 $M_{\nu_e} < 0.8 \text{ eV}$ (May 2021)



Neutrinoless Double Beta Decay

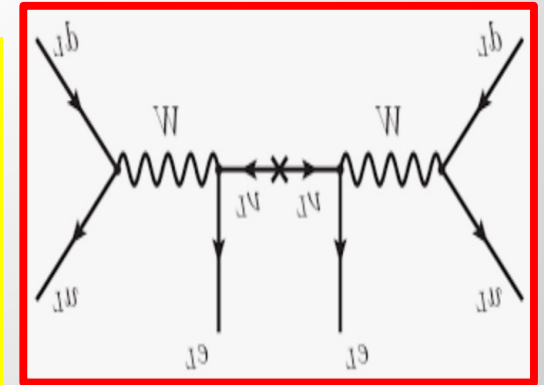
GERDA (GERmanium Detector Array) experiment at LNGS (Gran Sasso/IT)

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

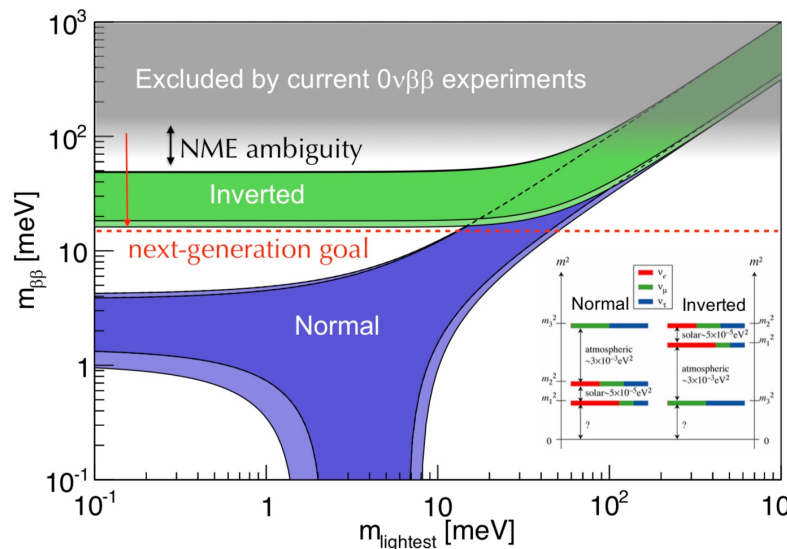
● Present best limits:

- ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
- ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
- ^{130}Te (CUORE): $T_{1/2} > 3 \times 10^{25}$ 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

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

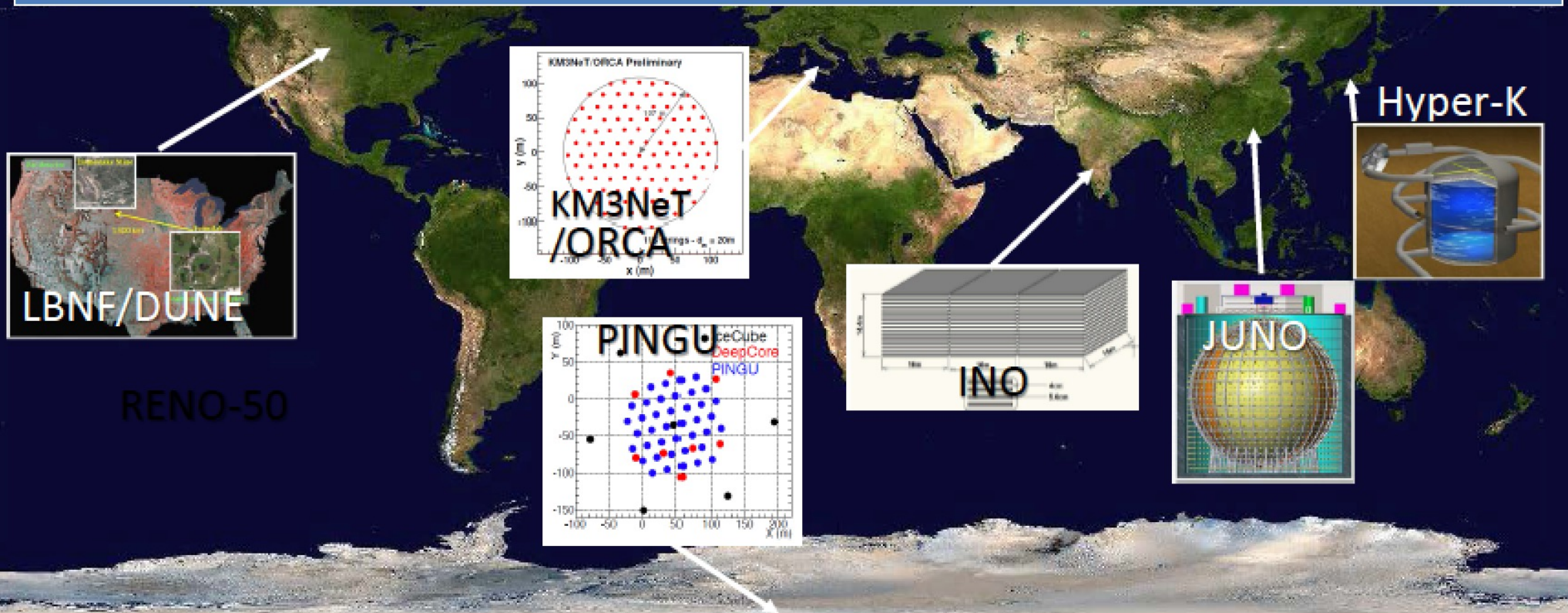


Many experiments
operating, planned
or in R&D: LEGEND
SNO+, NEXT...

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 $> 3 \sigma$ CL from each exp.



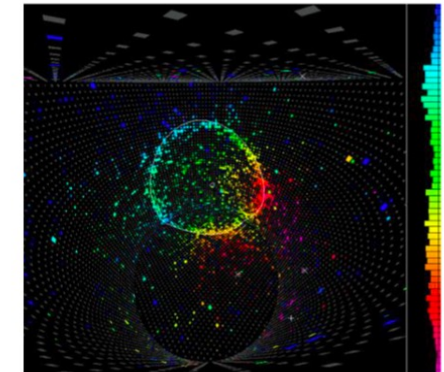
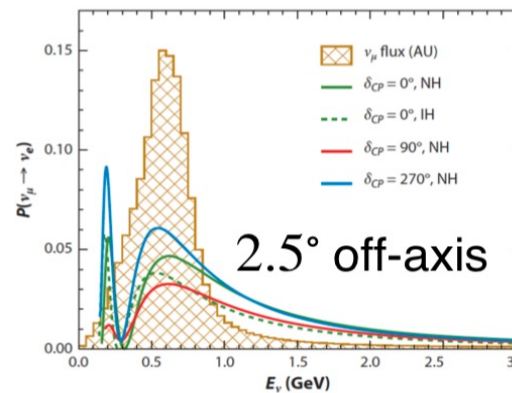
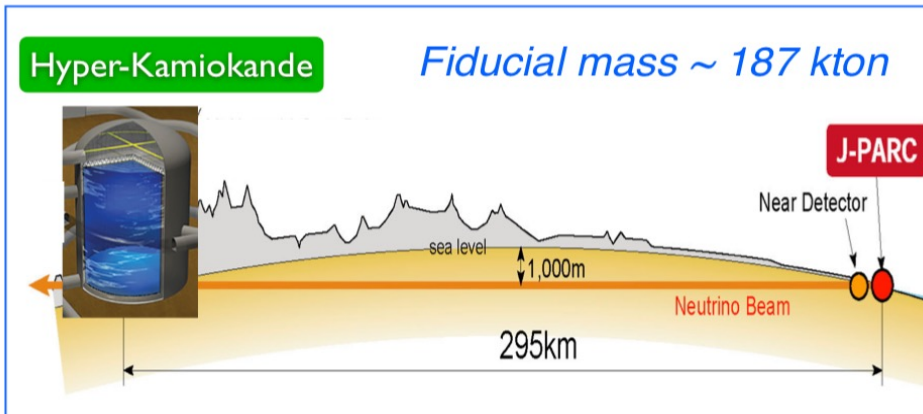
Future Neutrino Experiments

CERN

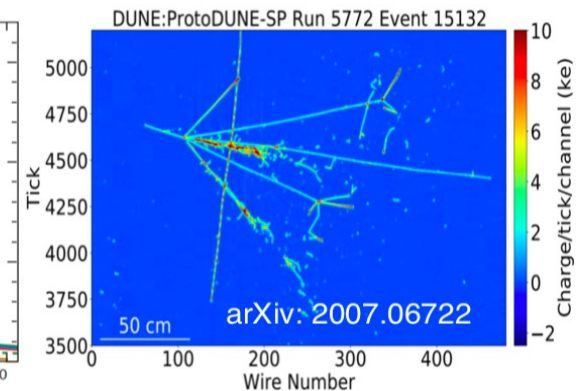
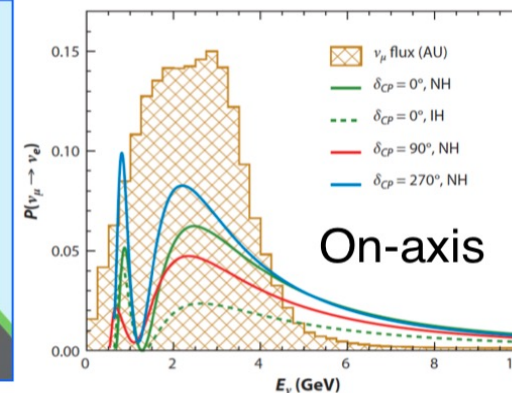
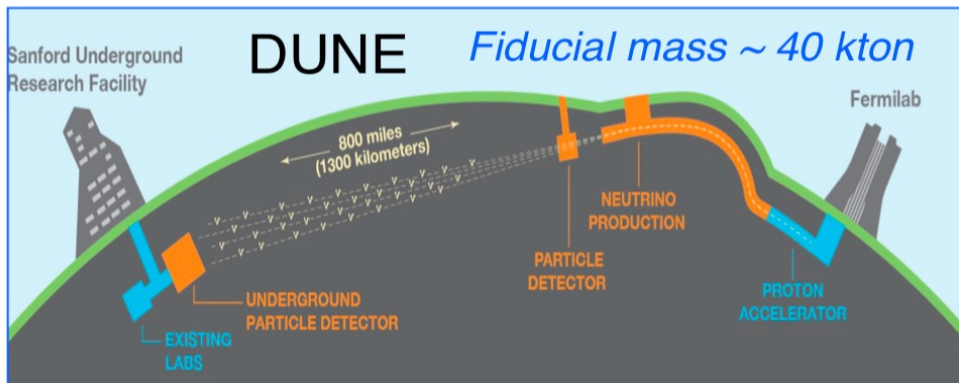
Long-baseline experiments: T2HK and DUNE

First data in 2027 (?)

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

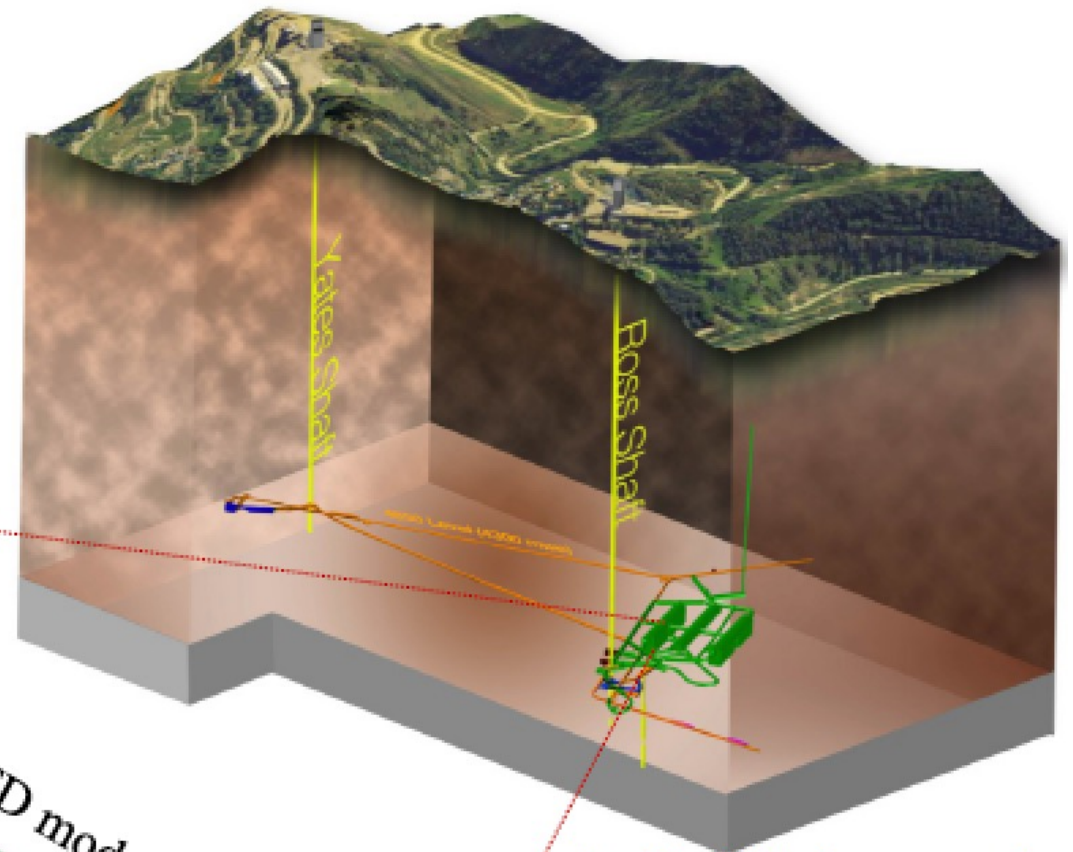
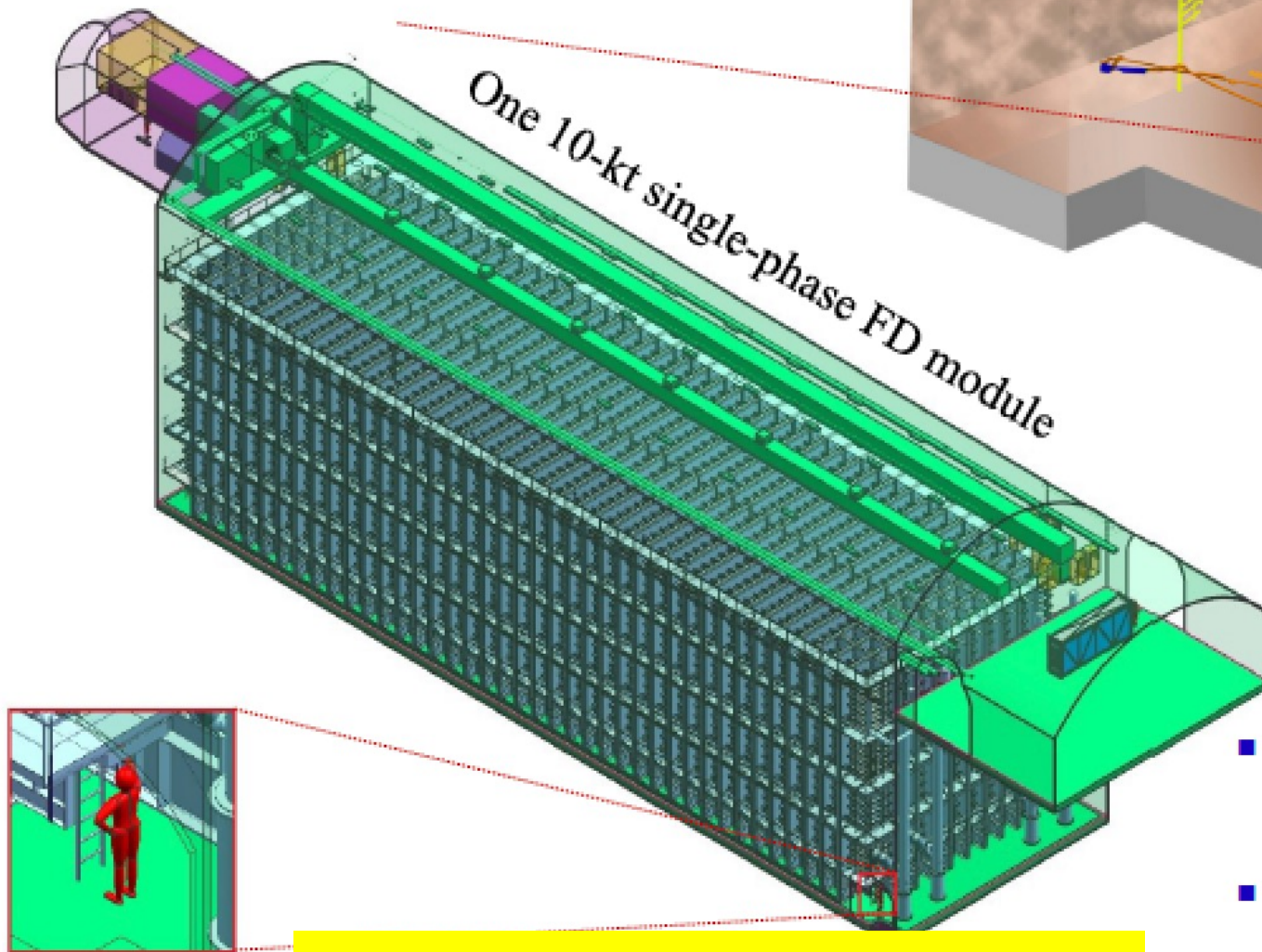


Annu. Rev. Nucl. Part. Sci. 2016. 66:47–71



DUNE Far Detector

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



Sanford Underground
Research Facility (SURF)

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

Neutrino Experiments and CERN



ProtoDUNE: Prototype at scale 1/25 of a DUNE far detector module

No neutrino beam since switching-off the LNS beam to Gran Sasso in 2015

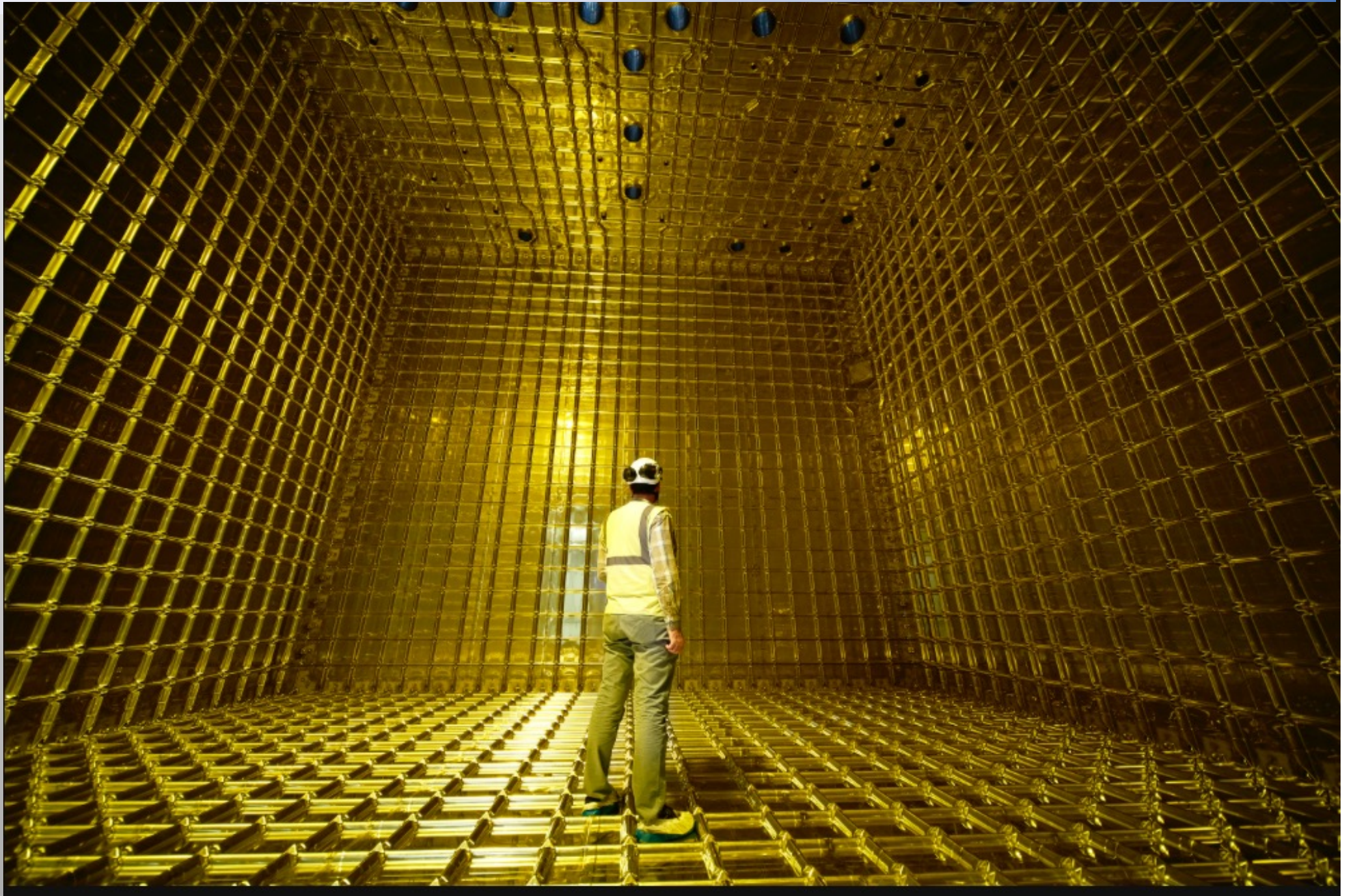
As of 2000: No neutrino experiments at CERN since CHORUS and NOMAD

In 2014, as a result of the European Strategy for Particle Physics at the time it was decided CERN would engage again in accelerator based neutrino experiments

- Creation of the Neutrino platform
- Creation of a Neutrino experimental Group in 2016 (and Theory forum)

2022: Neutrino experiments will be back at CERN ... see later

The CERN Neutrino Platform



Present Status of NP Projects

7 MOUs signed:

- ✓ NP01: ICARUS overhauling + FNAL activities
- ✓ NP02: R&D on a double phase LAr TPC technology (protoDUNE DP)
- ✓ NP03: generic R&D on neutrino detectors and facilities
- ✓ NP04: R&D on a single phase LAr TPC technology (protoDUNE SP)
- ✓ NP05: Baby Mind muon spectrometer for a T2K near detector
- ✓ NP06: ENUBET, R&D on a neutrino beta beam
- ✓ NP07: ND280, a new T2K Near Detector

Cooperation agreements

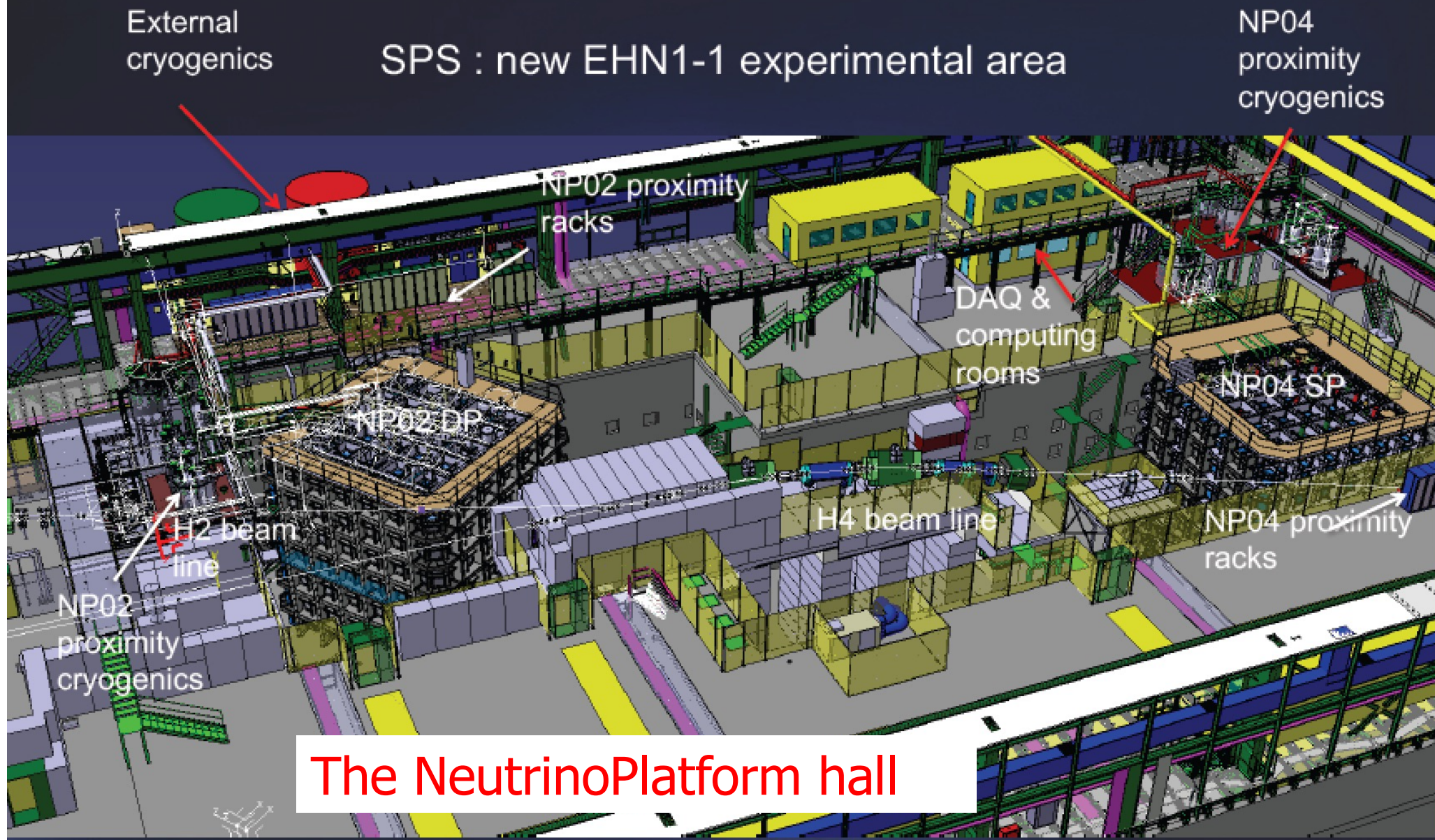
- CERN participation in the USA LBNF/DUNE project
- CERN delivery in kind to USA of the first large LBNF cryostat
- CERN participation in the FNAL short baseline Neutrino program
- CERN technical participation in the Darkside project at LNGS

Other activities

- NP participation in the CERN FASER and SND@LHC project

The EHN1 Hall at CERN

Next step : ~800 ton LAr prototypes



Virtual Visit to the Neutrino Platform

Recent visit on 12/8/2021



INTERNATIONAL NEUTRINO SUMMER SCHOOL 2021

2-13 AUGUST 2021

SPEAKERS:

Neutrino Astronomy: Carlos Argüelles
Neutrinos in Cosmology: Gabriela Barenboim
Making a Neutrino Beam: Mary Bishai
Liquid Argon Detectors: Flavio Cavanna
Neutrinos and Dark Matter: Sandhya Choudhry
Neutrino Interactions/Cross Sections: Stephen Dolan
Direct Neutrino Mass Measurements: Joe Formaggio
Future Vision for Neutrino Physics: Sheldon Glashow

Neutrino Mass Models: Andro de Gouvea
Neutrinoless Double Beta Decay: Julia Herz
Reactor Neutrinos: Patrick Huber
Water Cherenkov Detectors: Tadayoshi Nakaya
Neutrino Mixing & Oscillations: Silvia Pascoli
Geoneutrinos: Ingrid Semeneç
CEVNS: Kate Scholberg
Supernova Neutrinos: Irene Tamborra

ORGANIZERS:

Albert De Roeck
Joachim Kopp
Claire Lee
Bibhusan Shakya

VIRTUAL:

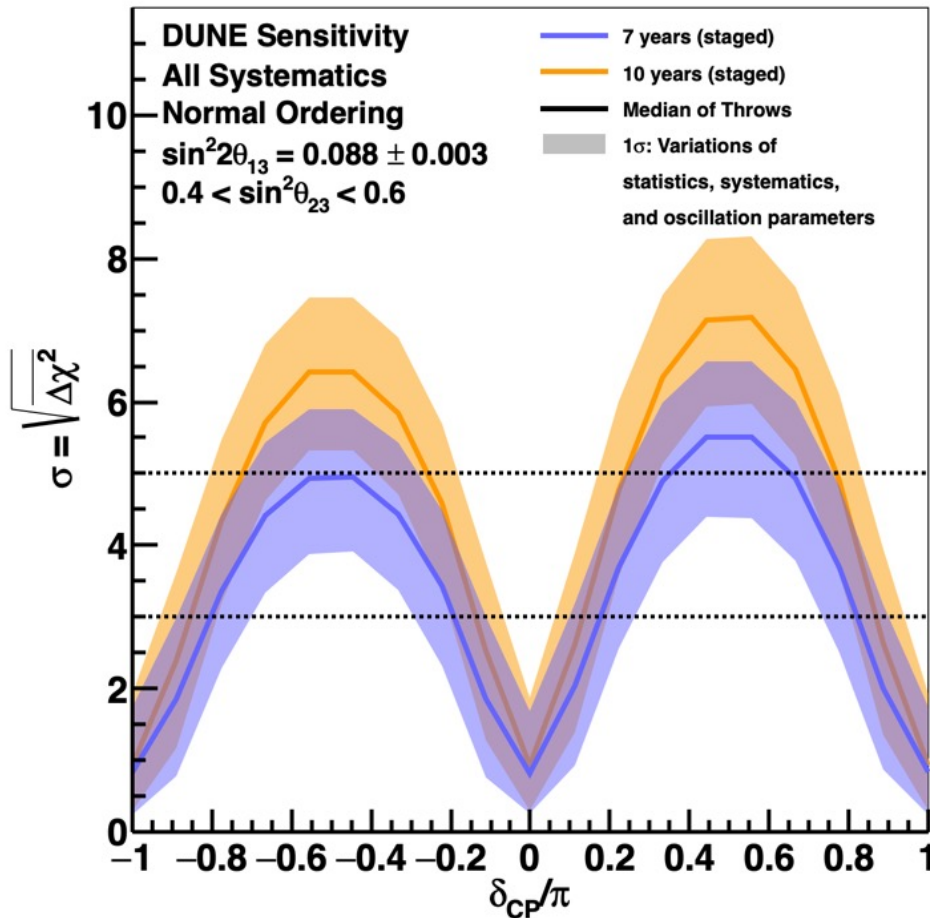
<https://indico.cern.ch/event/1011452/>
CERN-Neutrino-Summer-School-organisers@cern.ch



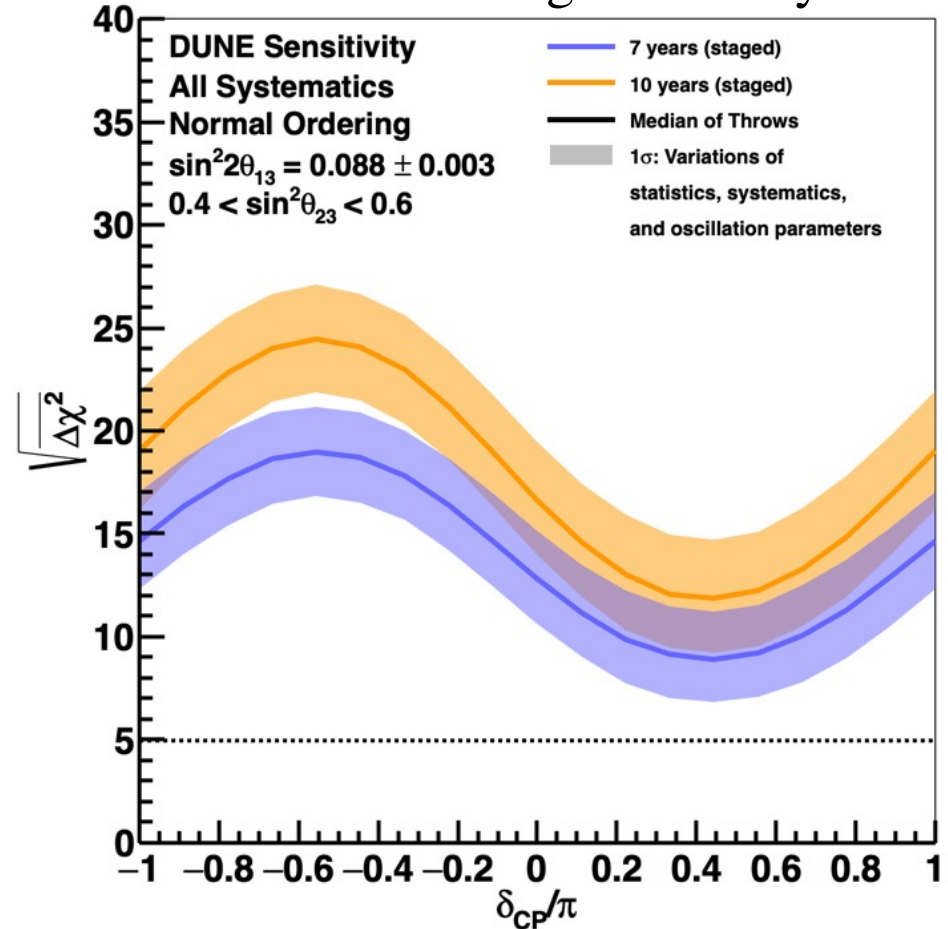
Video on the agenda of the school
<https://indico.cern.ch/event/1011452/>

CP Violation and Mass Ordering

CPv sensitivity

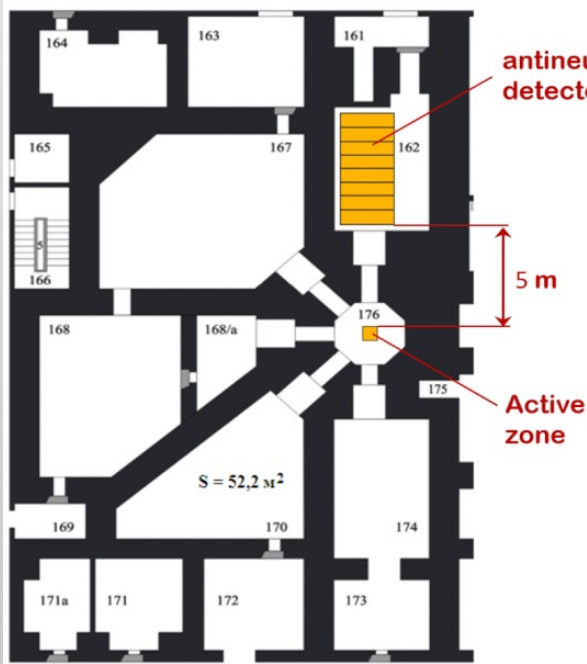


Mass ordering sensitivity



- Updated Sensitivity with realistic systematics and reconstruction
 - Move quickly to potential **CP violation discovery** [arXiv:2002.03005](https://arxiv.org/abs/2002.03005)
 - Rapid, definitive **mass ordering determination** ($>5\sigma$)

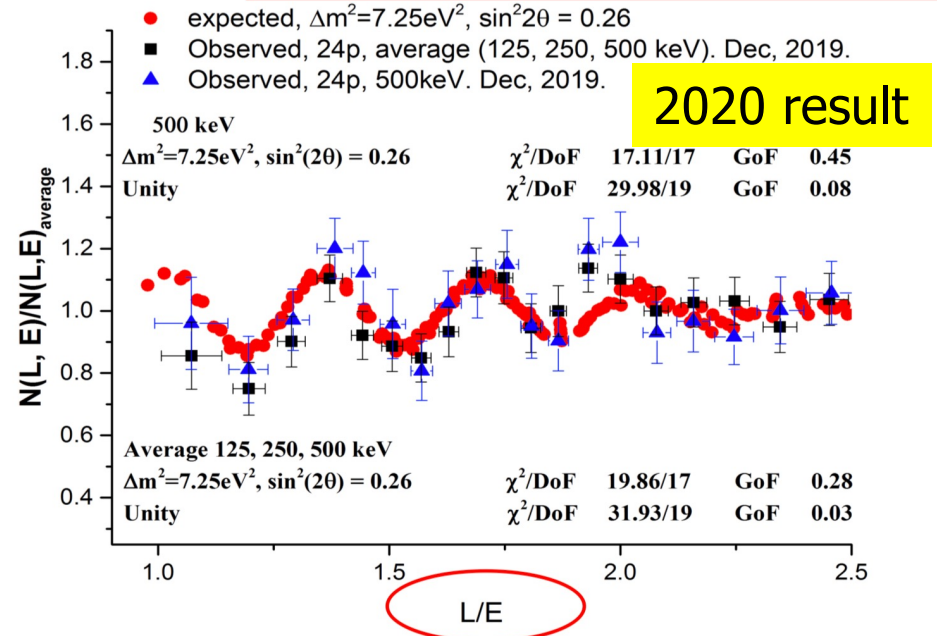
Short baseline Reactor: Neutrino-4 Exp.



2m³ liquid scintillator detector at a 90 MW reactor in Russia

3 years long measurement
2.8σ signific.

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



arXiv:1809.10561 (Jan 2020)

$$\Delta m_{14}^2 = 7.25 \pm 0.13_{\text{stat}} \pm 1.08_{\text{syst}} = 7.25 \pm 1.09$$

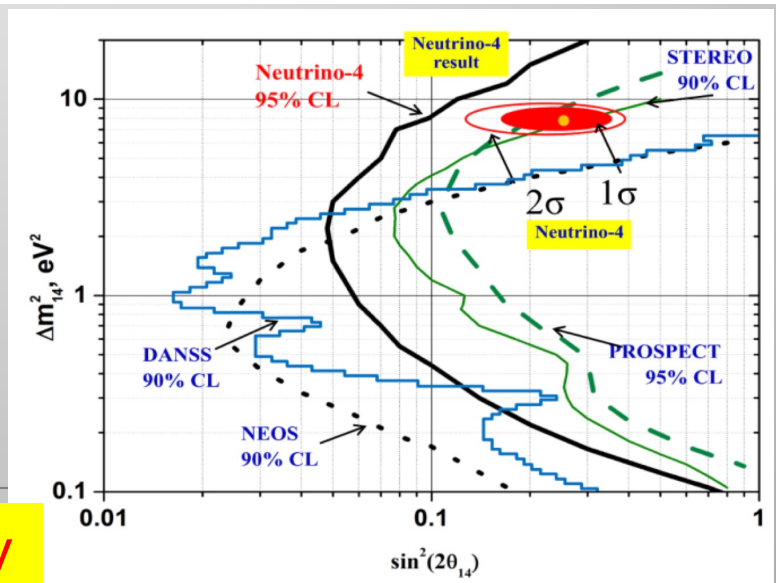
$$\sin^2 2\theta = 0.26 \pm 0.08_{\text{stat}} \pm 0.05_{\text{syst}} = 0.26 \pm 0.09 (2.8\sigma)$$

Data analysis strongly criticized

- Issues with the energy resolution
- Less biased approach -> $\sim 2.2\sigma$ effect only
- "No-oscillation scenario" not excluded at 3σ

arXiv:2101.06785

More discussion by Alexei on Friday

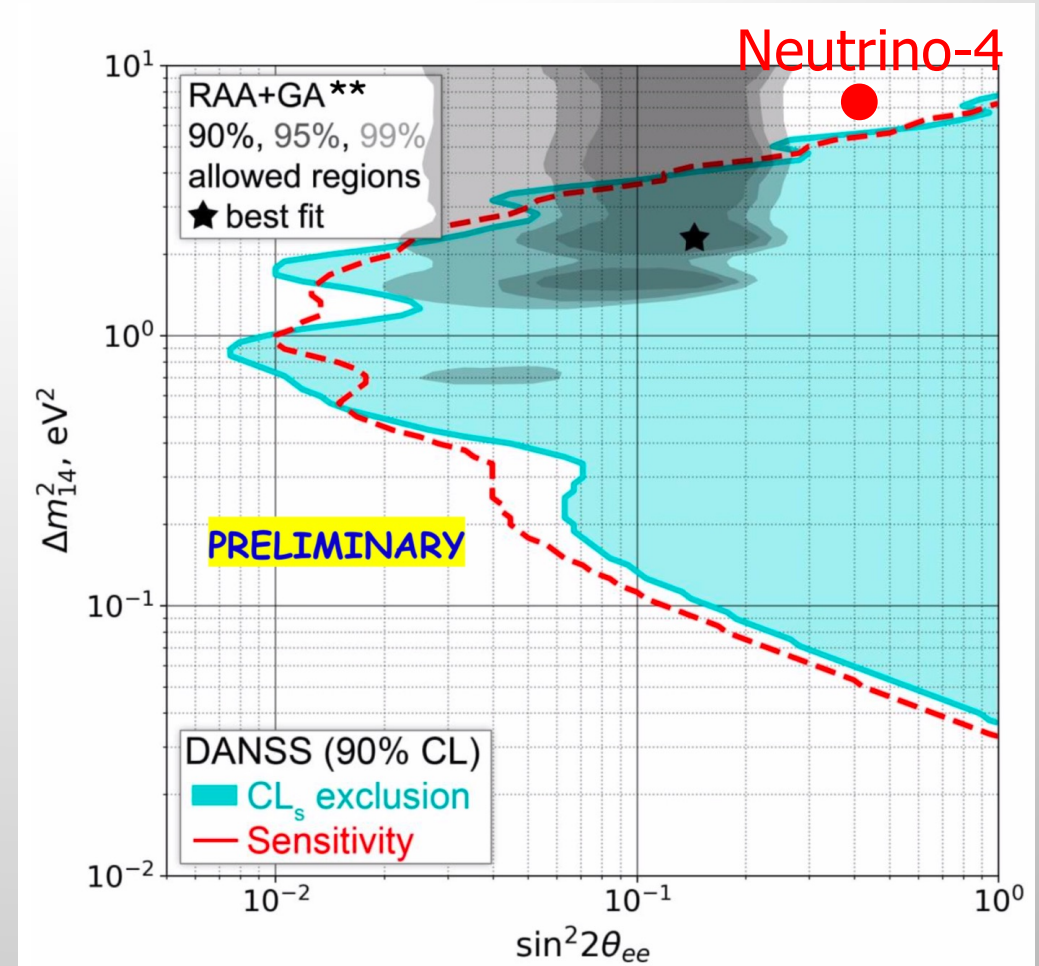
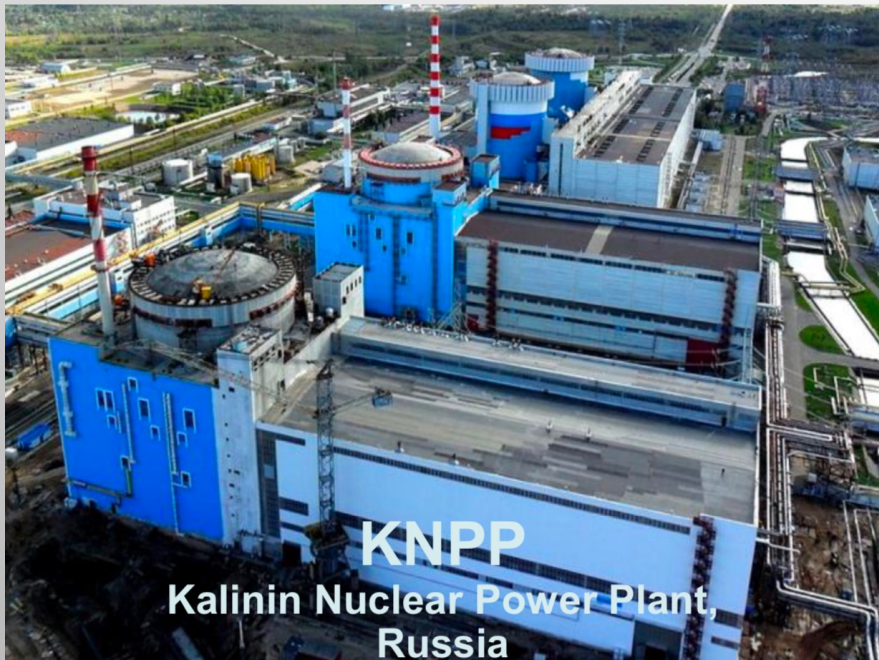


New Result from DANSS

EPS-HEP 2021

□ DANSS records about 5 thousand antineutrino events per day with cosmic background $\sim 1.7\%$, $S/B > 50$

5.5 million IBD events were collected in 5 years



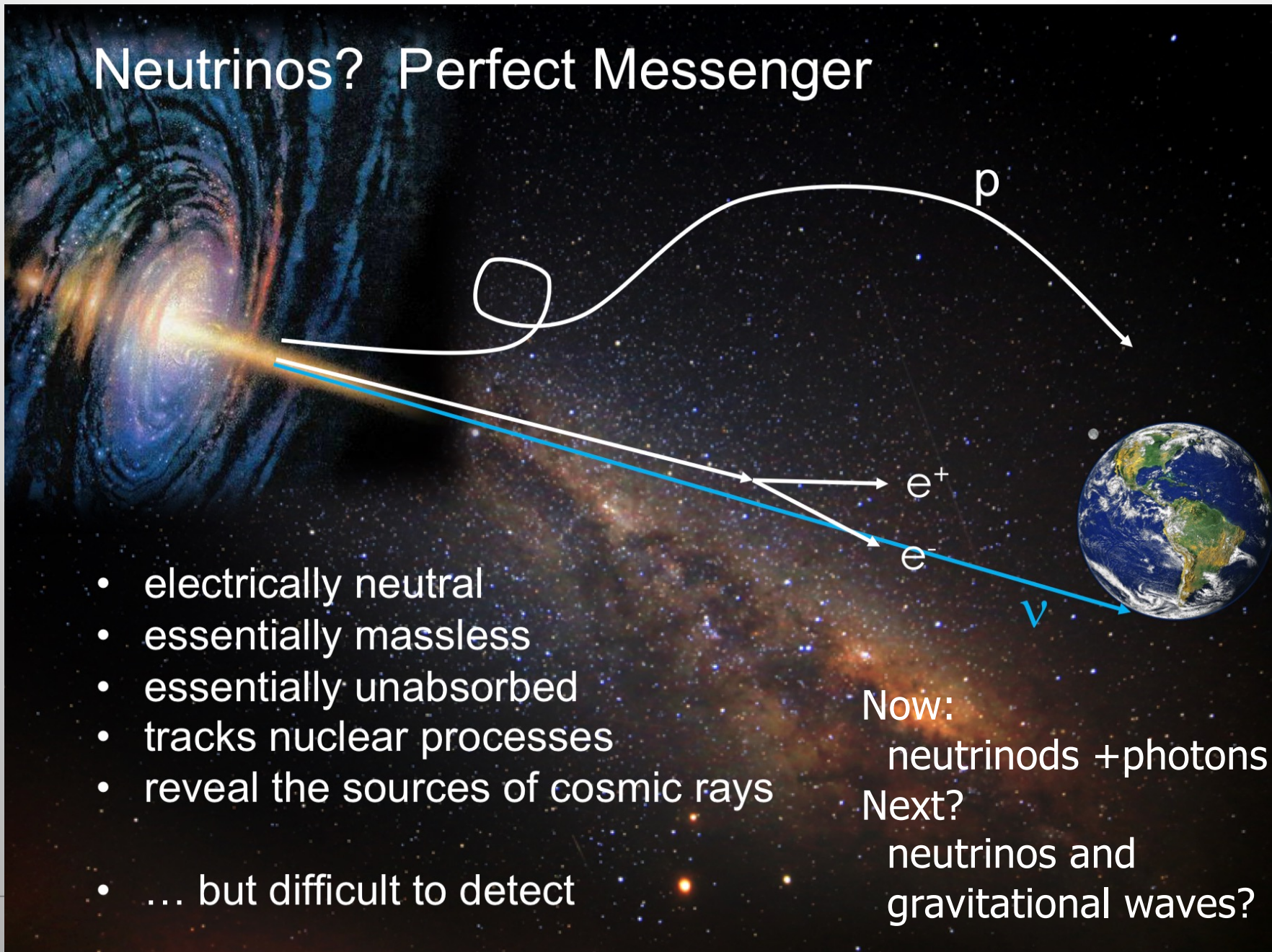
DANSS does yet cover up to Neutrino-4, but with the upgraded detector and 1-2 years additional data taking they will...

Multi Messenger Astronomy

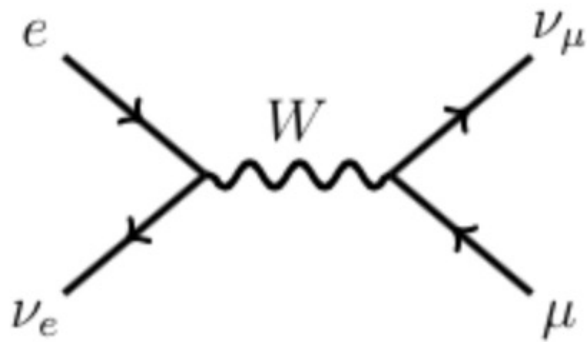
Neutrinos? Perfect Messenger

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays
- ... but difficult to detect

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



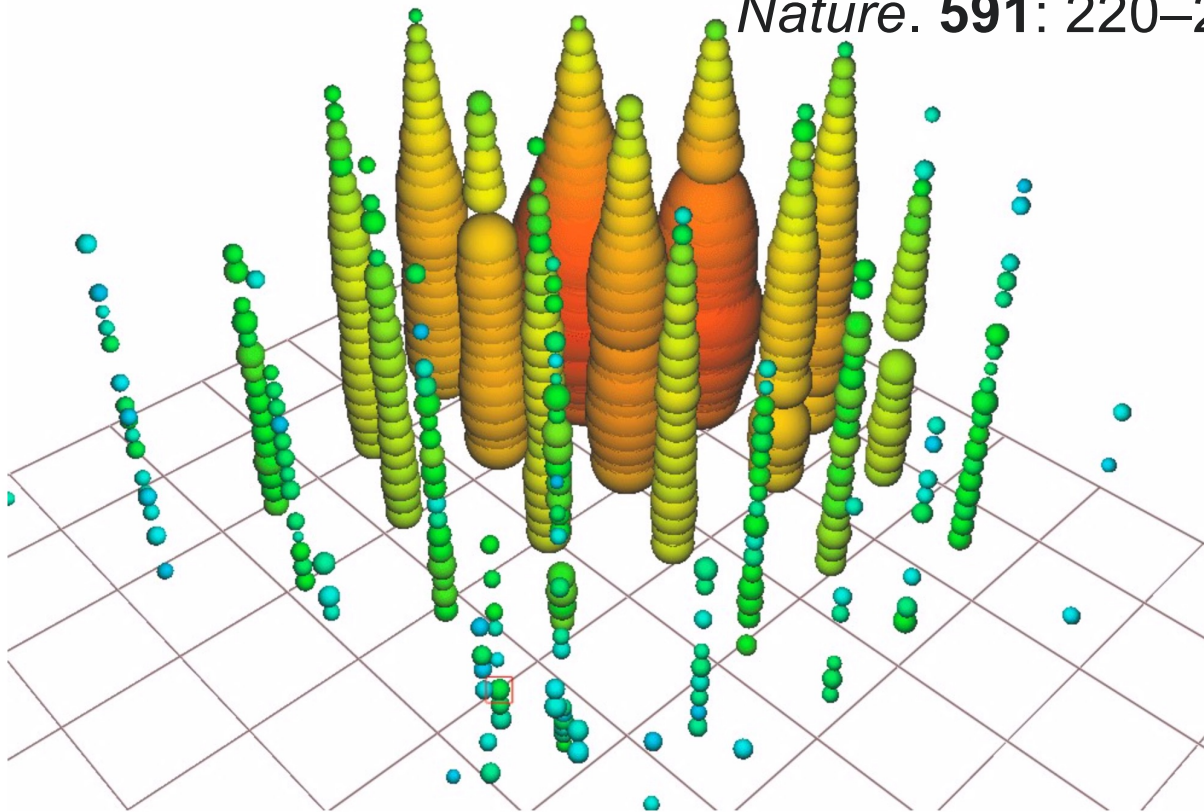
Observation of a Glashow Resonance



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

Event seen with an estimated energy of 6.05 TeV
in IceCube (8/12/2016)

Nature. 591: 220–224



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

Neutrinos @ the LHC: Examples

Searches for right-handed neutrinos at the LHC

SND@LHC and FASER-Nu are 400m forward of the IPs and can study TeV-neutrinos with emulsion detectors

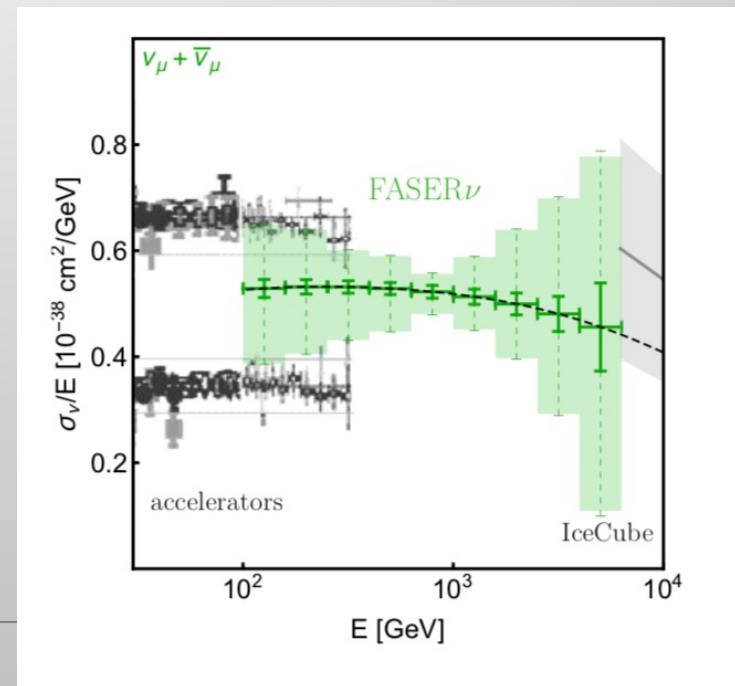
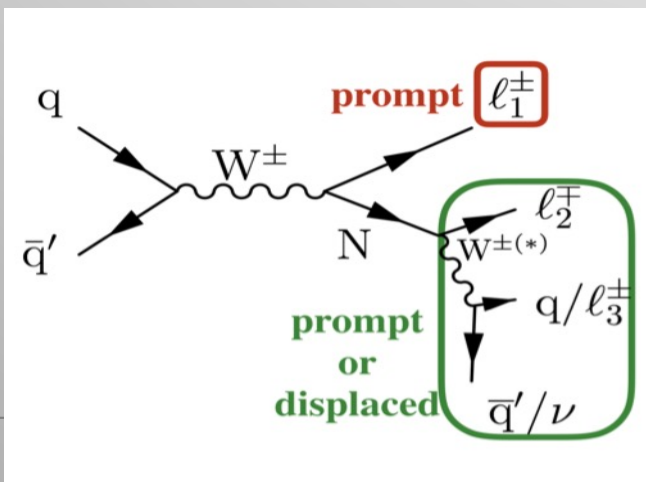
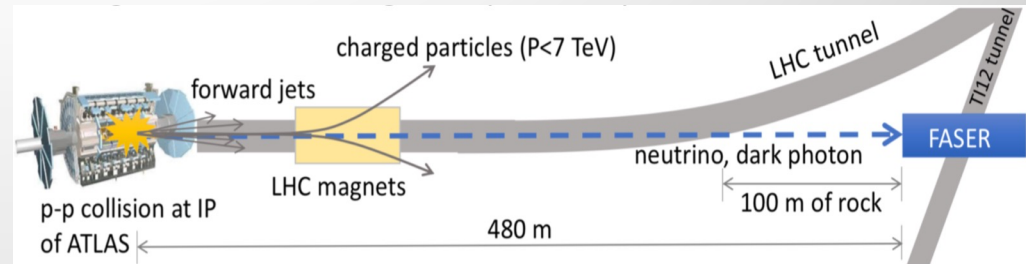
ν MSM (Neutrino Minimal Standard Model)

Three Generations of Matter (Fermions) spin $\frac{1}{2}$

	I	II	III		
mass	2.4 MeV	1.27 GeV	173.2 GeV	0	126 GeV
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
name	u up	c charm	t top	g gluon	H Higgs boson
Quarks	d down	s strange	b bottom	γ photon	Z weak force
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W [±] weak force	
Leptons	e electron	μ muon	τ tau		

Bosons (Forces) spin 1

spin 0



Neutrinos @ the LHC: SND@LHC

SND is 400m forward of the IPs and can Study TeV-neutrinos with emulsion and tracking+muon/calorimeters

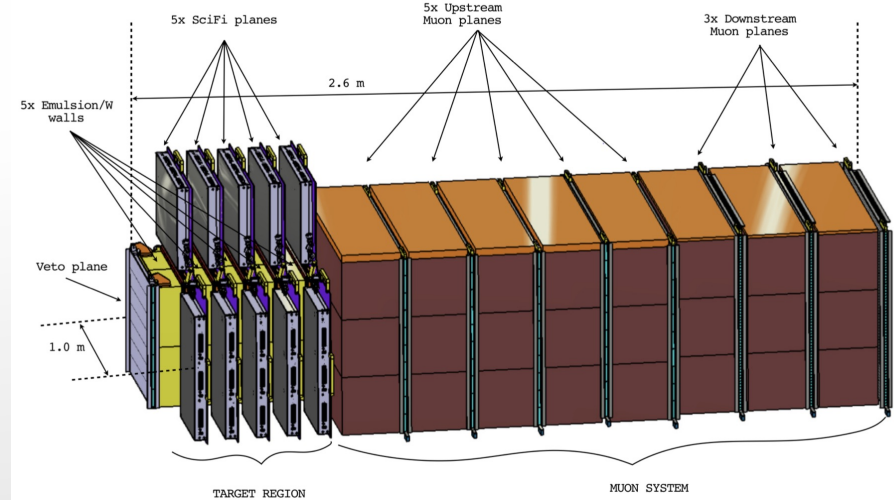
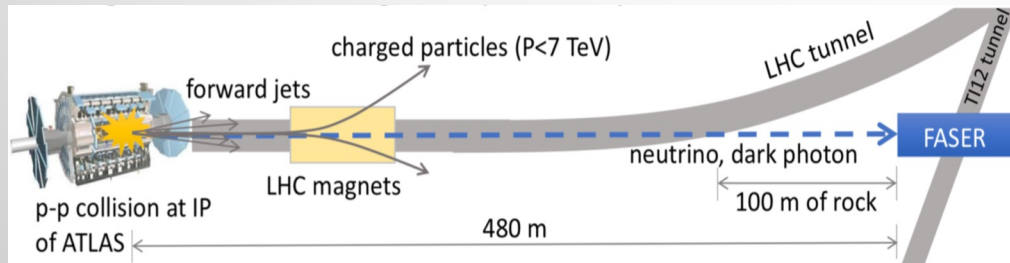
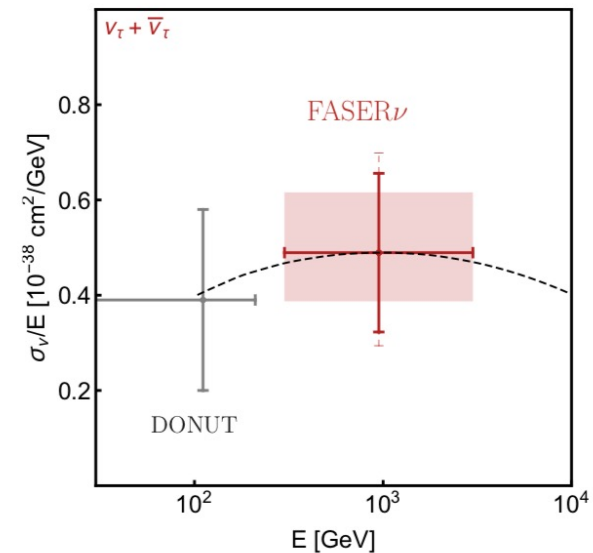
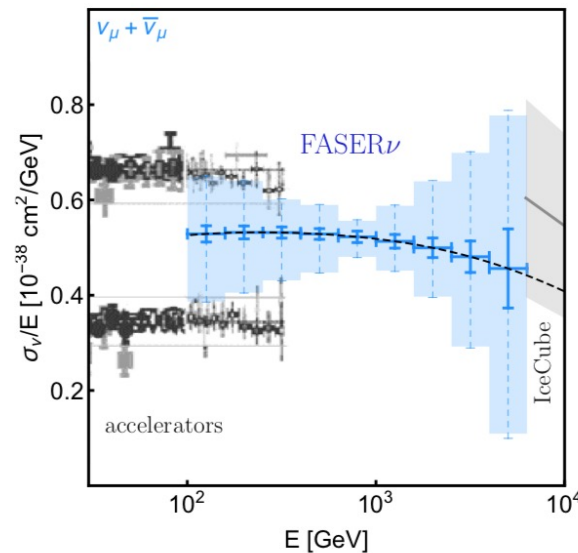
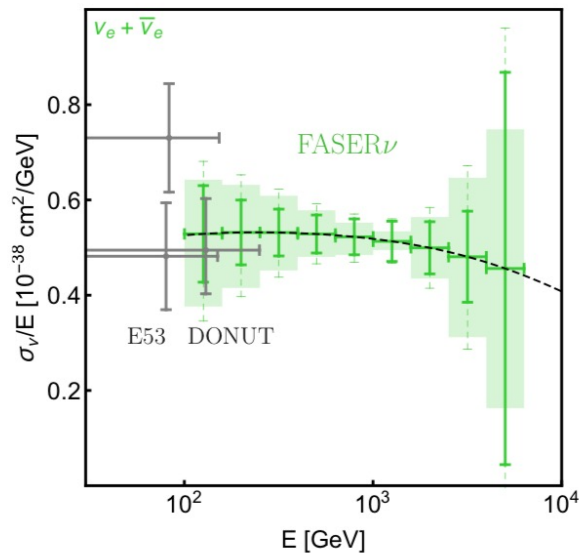


Figure 5: Layout of the proposed SND@LHC detector.

SND= Scattering and neutrino detector

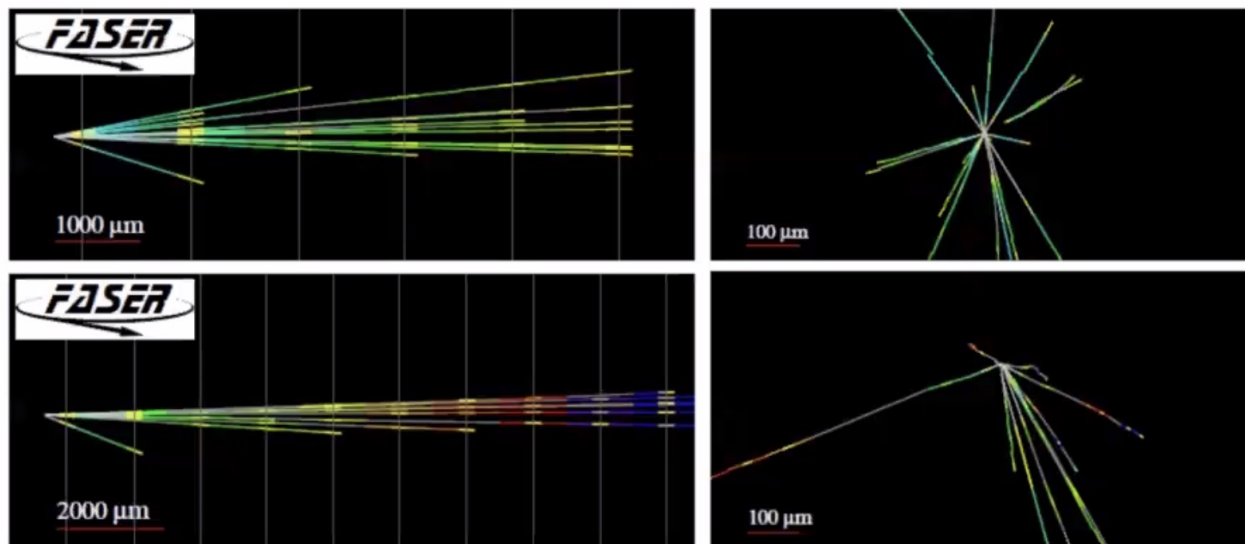


First Observed neutrinos in FASER- ν

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

Neutrino interaction candidates

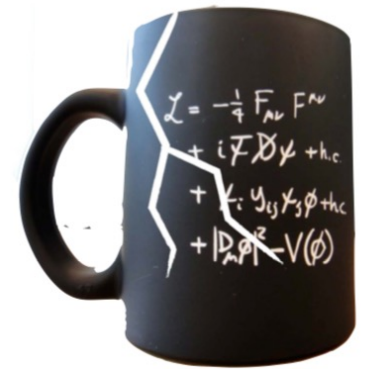
First neutrino interaction candidates at the LHC, [arXiv:2105.06197](https://arxiv.org/abs/2105.06197)



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

SUMMARY: Neutrinos

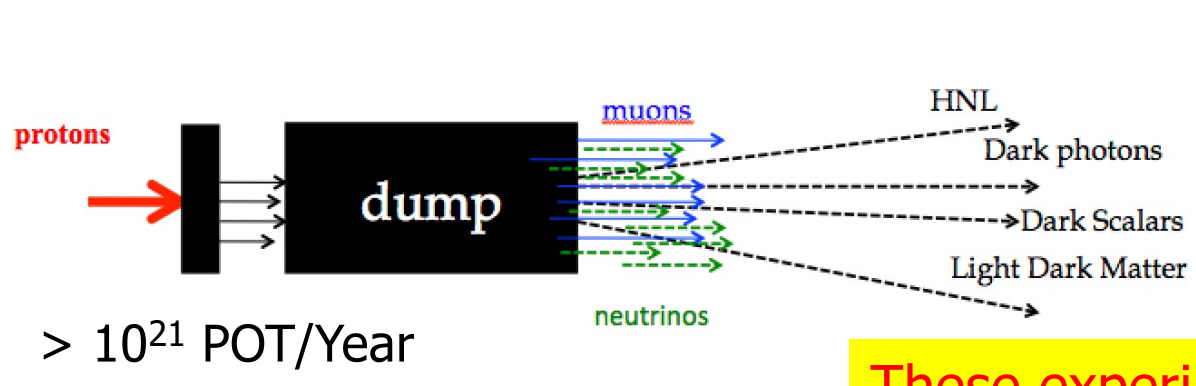
- Neutrinos studies is a vibrant field of research, and has still many open questions! Right-handed partners? Strong CP violation? More than 3 neutrinos? NS Interactions? Are neutrinos their own anti-particle?
- Now comes the age of neutrino precision physics with DUNE & T2HK and neutrino astronomy: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



Backup

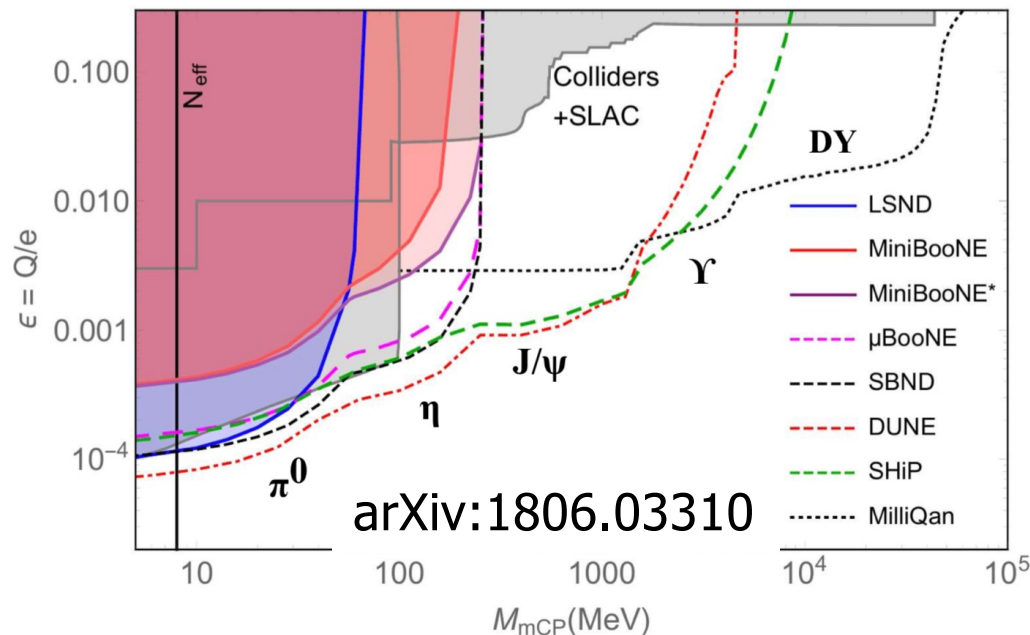
NDs as Beam Dump Experiments

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



Near Detector:
 few 100m away
 from the dump

Example millicharges:



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

- HNL/sterile neutrinos
- dark photons
- ALPs
- mini/millicharges

arXiv:1907.08311

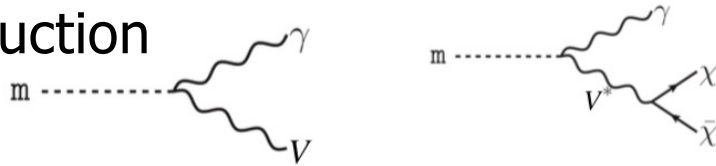
WHITE PAPER ON NEW OPPORTUNITIES AT THE
 NEXT-GENERATION NEUTRINO EXPERIMENTS
 (PART 1: BSM NEUTRINO PHYSICS AND DARK MATTER)

C.A. ARGÜELLES¹, A.J. AURISANO², B. BATELL³, J. BERGER³, M. BISHAI⁴, T. BOSCH⁵, N. BYRNES⁶,
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 S. PRAKASH¹³, L. ROGERS⁶, I. SAFA²⁴, A. SCHNEIDER²⁴, K. SCHOLBERG²⁵, S. SHIN^{26,27},
 I.M. SHOEMAKER²⁸, G. SINEV²⁵, B. SMITHERS⁶, A. SOUSA^{* 2}, Y. SUI²⁹, V. TAKHISTOV³⁰,
 J. THOMAS³¹, J. TODD², Y.-D. TSAI¹⁵, Y.-T. TSAI³², J. YU^{* 6}, AND C. ZHANG⁴

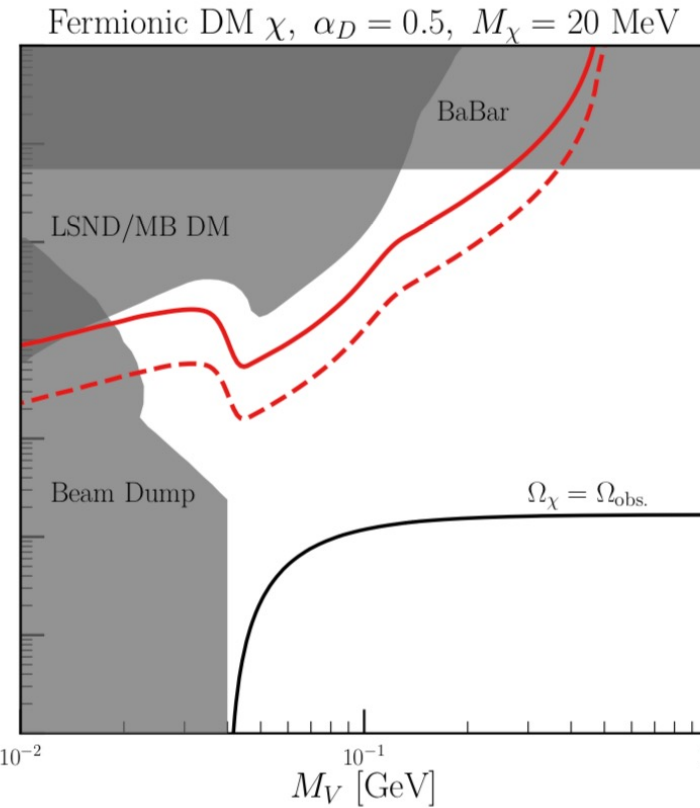
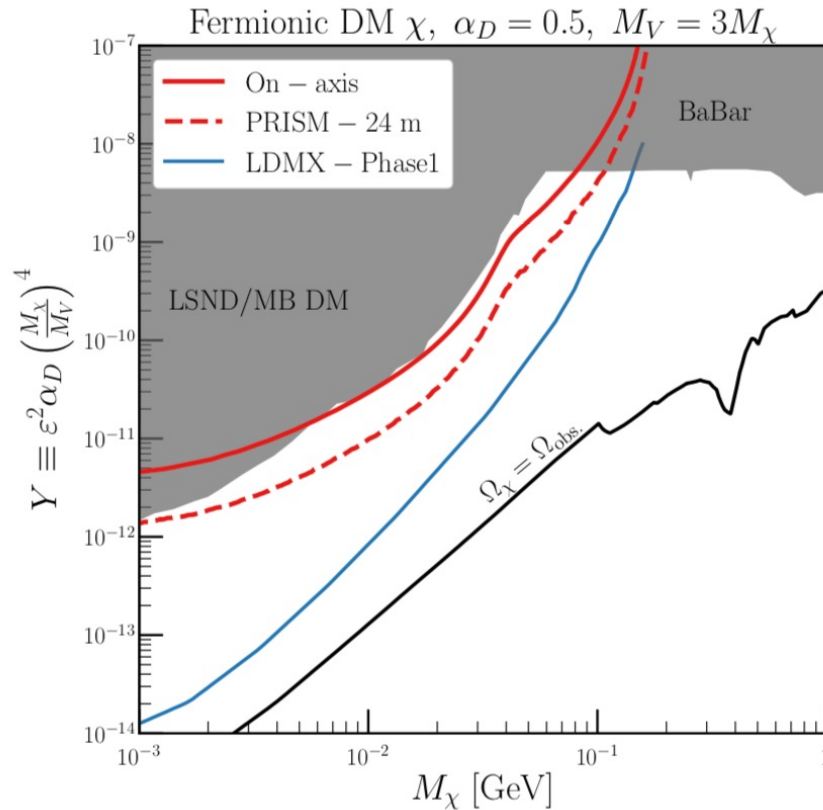
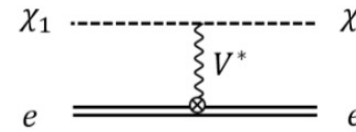
Searches for Low Mass Dark Matter

Light dark matter produced at the accelerator (meson decays)

Production



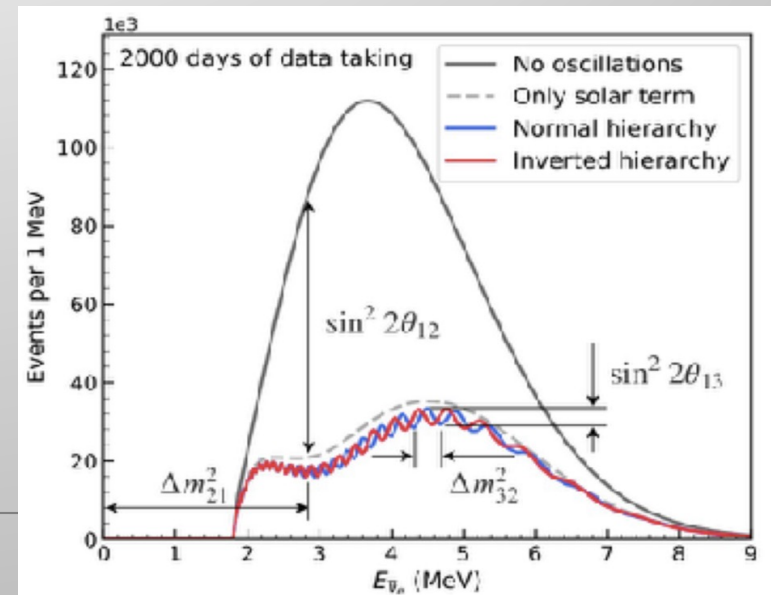
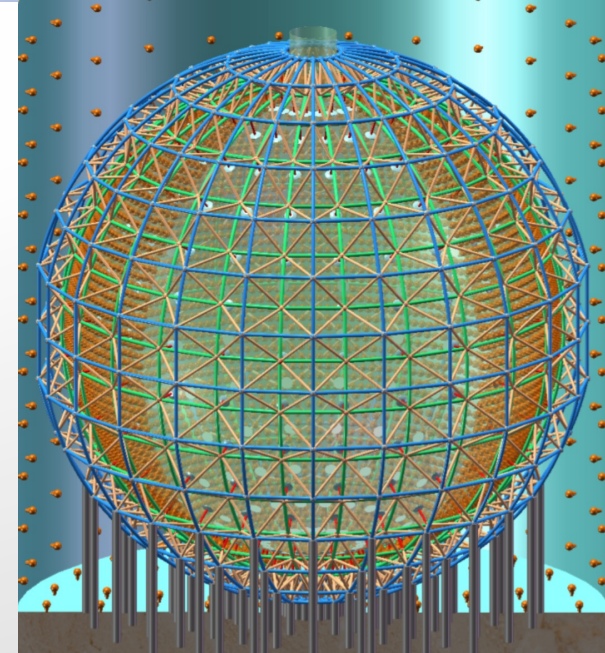
Elastic scattering



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) being built in a dedicated underground laboratory (700 m underground) in China and expected to start data taking end 2022/start 2023

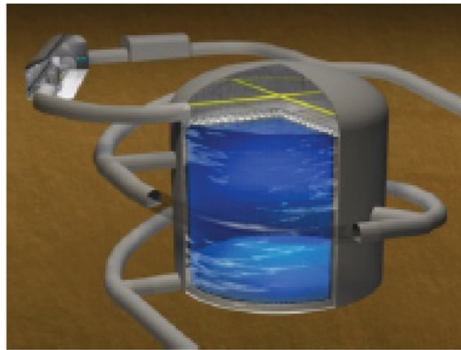
Determination of the neutrino mass ordering using electron anti-neutrinos from two nuclear power plants at a baseline of about 53 km. With an unprecedented energy resolution of 3% at 1 MeV, JUNO will be able to determine the mass ordering with a significance of 3 sigma within six years of running. (4-5 sigma with acc. exp. and IceCube)



Hyper-Kamiokande

Upgrade of the Super-kamiokande experiment in Japan

First data in 2027



Hyper-K



J-PARC
Accelerator Complex



- ✓ Gigantic neutrino and nucleon decay detector
 - ✓ 186 kton fiducial mass : $\sim 10 \times$ Super-K
 - ✓ $\times 2$ higher photon sensitivity than Super-K
 - ✓ Superb detector capability, technology still evolving
 - ✓ 2nd oscillation maximum by 2nd tank in Korea under study
- ✓ MW-class world-leading ν -beam by upgraded J-PARC
- ✓ Project now is a priority project by MEXT's Roadmap

Sub-GeV ν beam