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

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

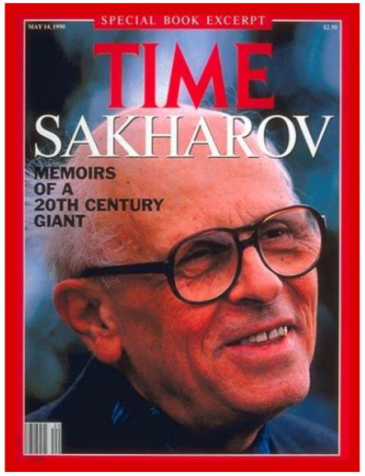
Flavor states

(*) Pontecorvo-Maki-Nakagawa-Sakata Matrix

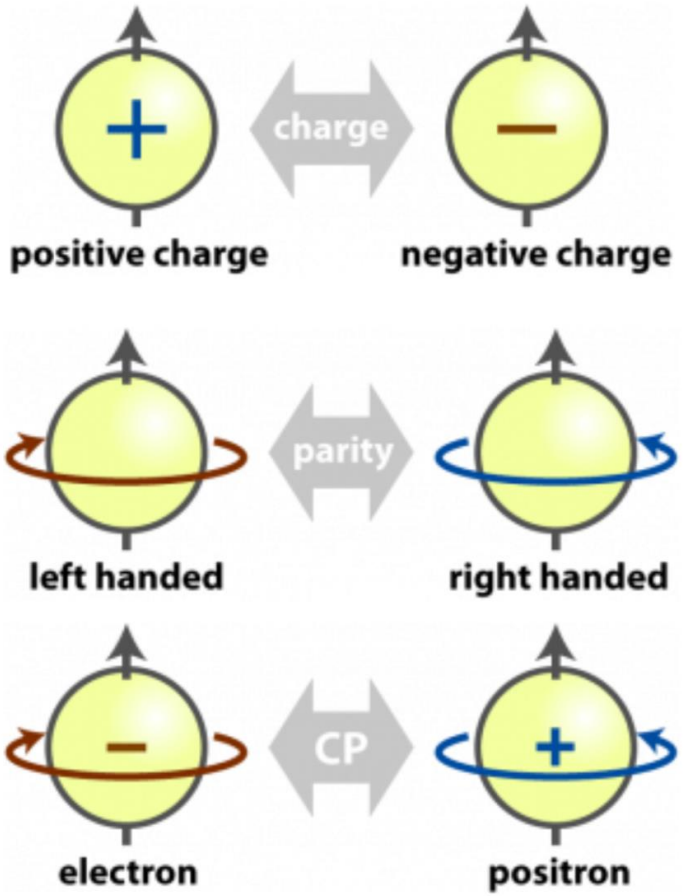
NB: charged leptons are mass eigenstates and don't oscillate!

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

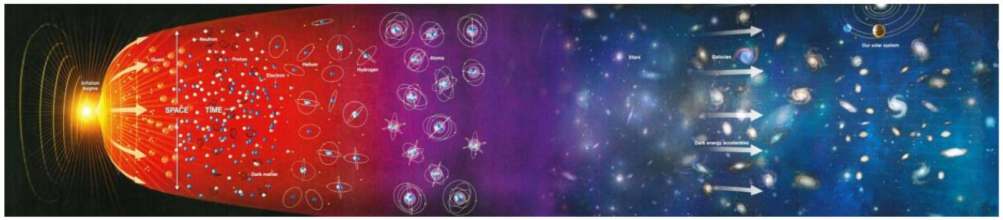


CP Violation

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

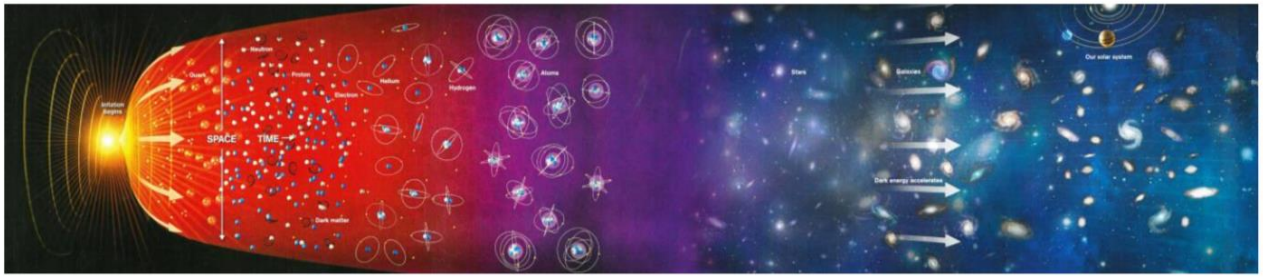
$$c_{ij} = \cos\theta_{ij}; s_{ij} = \sin\theta_{ij}$$

- 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

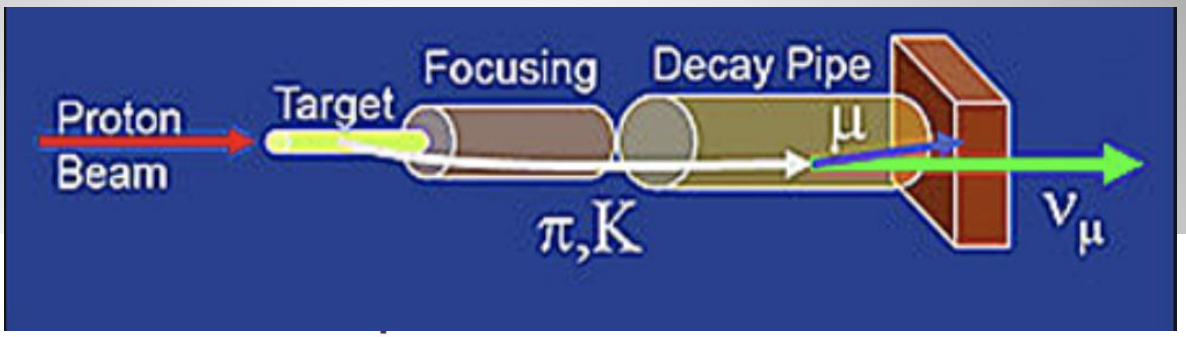
- The same is true for the CKM matrix, where CP violation has been observed for quark processes.
- CP violation in the quark sector is too small to describe the matter dominance in the Universe.
- Discovery of CP violation with neutrinos would lend support to the Leptogenesis model – Leptogenesis would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



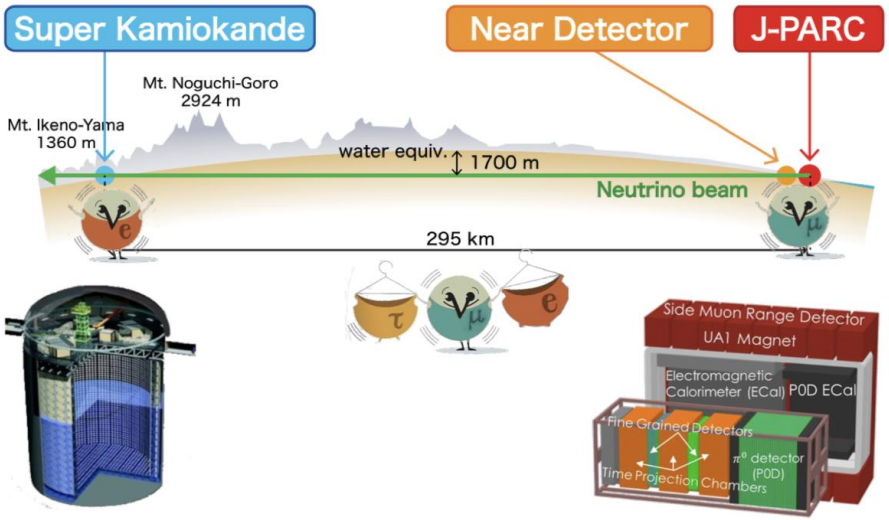
Best option to measure the CPV phase δ -> use accelerator neutrinos

Accelerator Based Neutrino Experiments

Neutrinos from accelerators

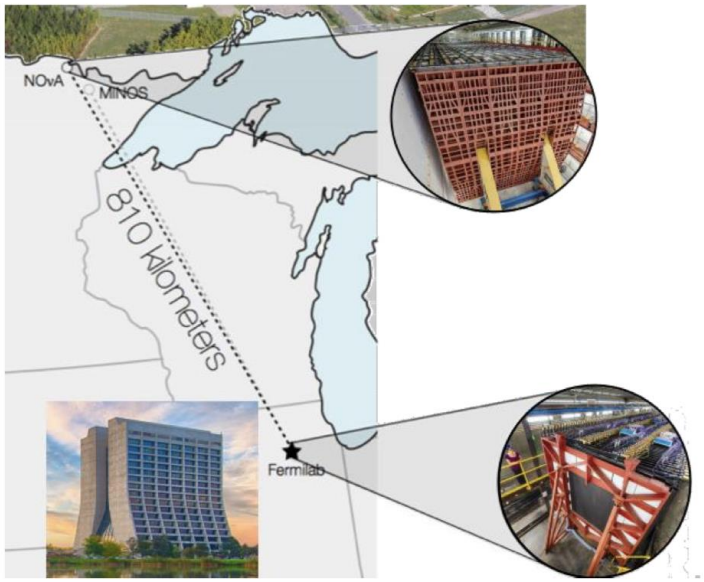


T2K



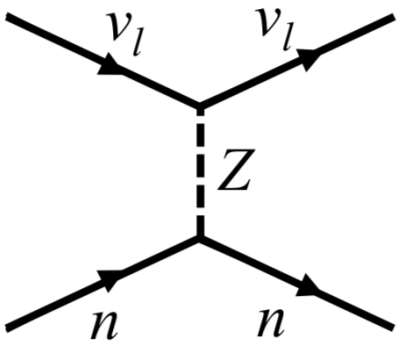
Baseline: 295 km
Peak E_ν: ~0.6 GeV (off-axis)
Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

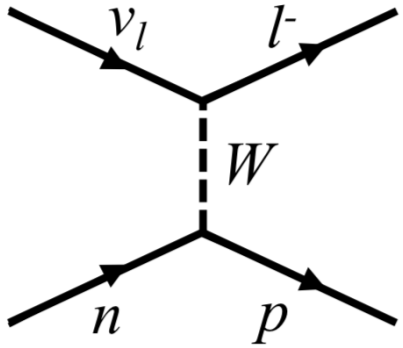


- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

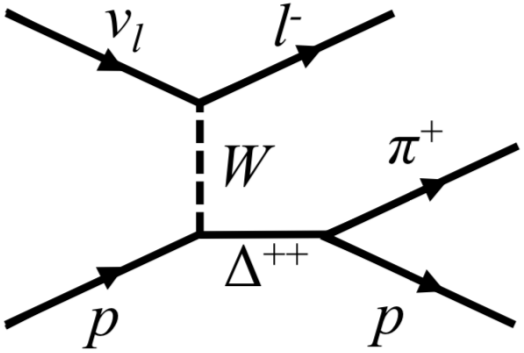
Neutrino Interactions



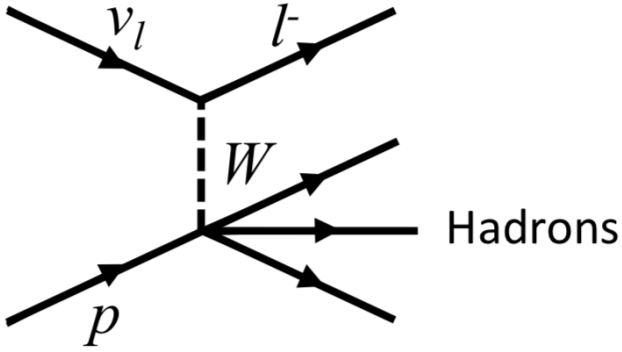
Elastic scattering



Quasi-elastic scattering
(lowest energies)



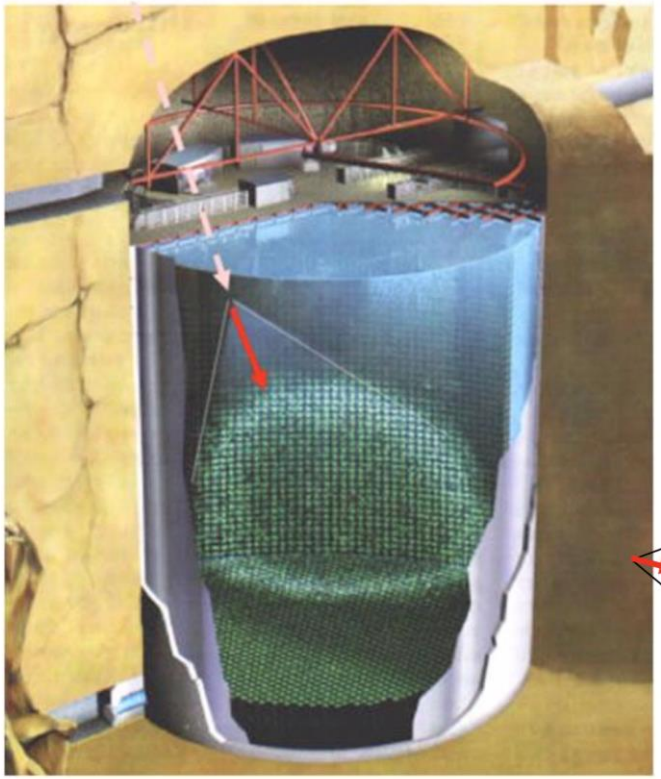
Resonance
(Energies ~1 GeV)

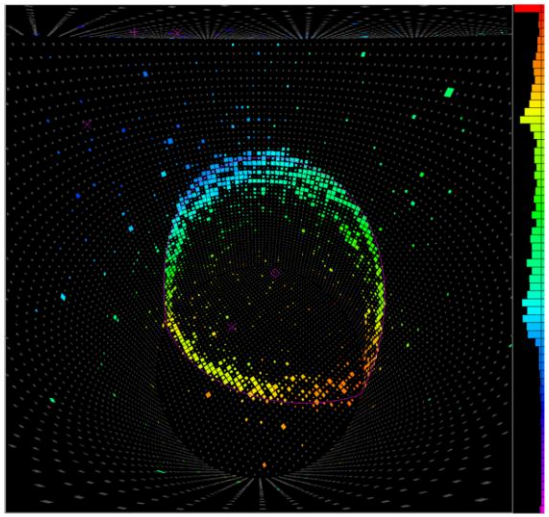


Deep inelastic scattering
Highest energies (>1 GeV)

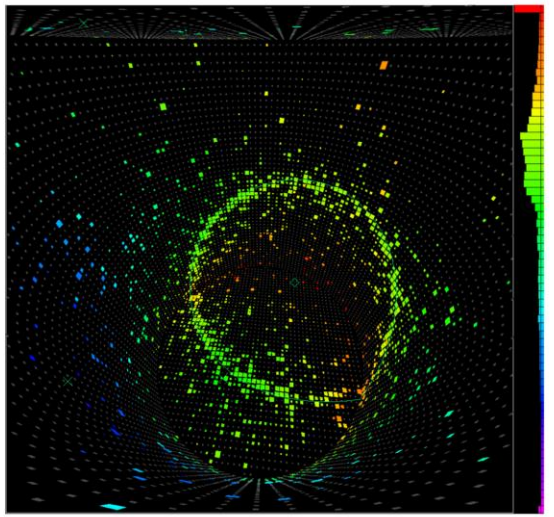
Example: Interactions in SuperKamiokande

SK is the large detector of the T2K experiment

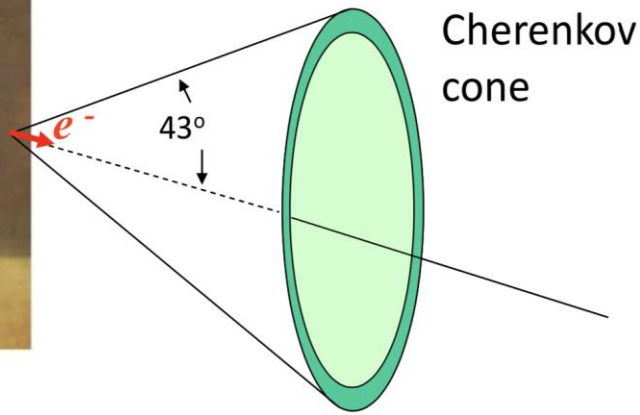




$$\nu_\mu + X \rightarrow \mu^- + X'$$



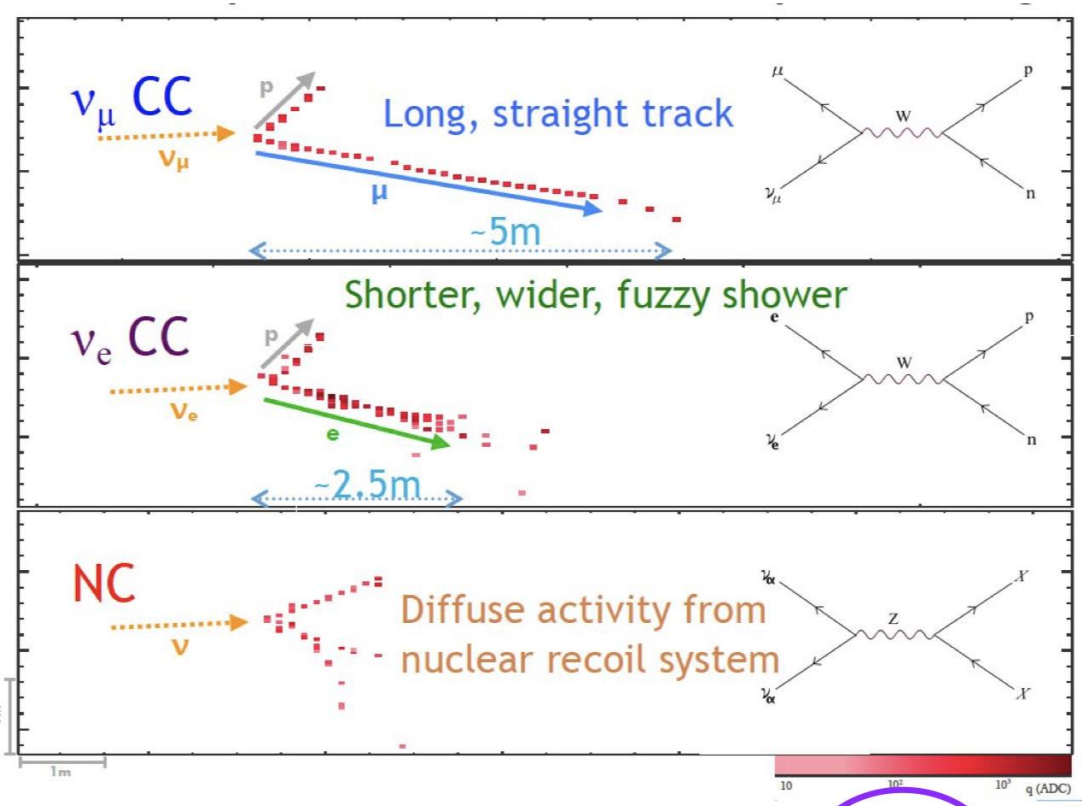
$$\nu_e + X \rightarrow e^- + X'$$

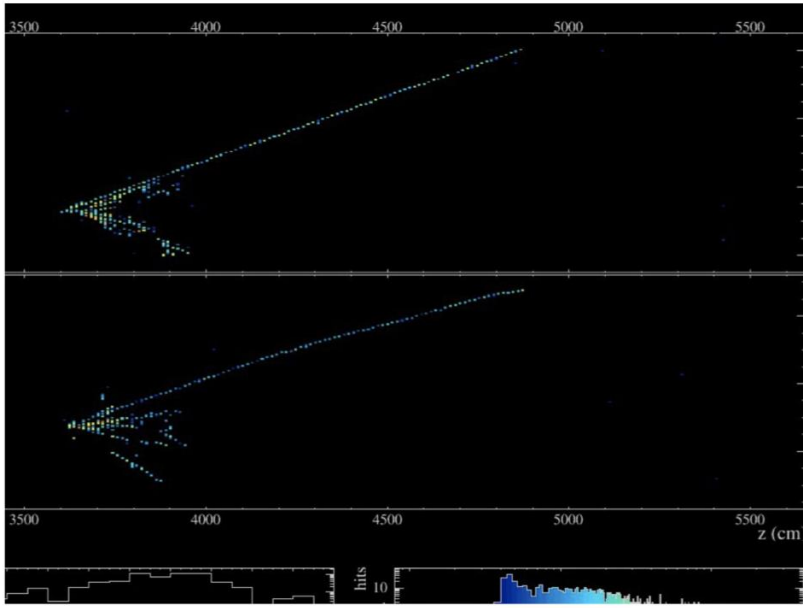


Electrons have more multiple scattering on the water -> Rings are more fuzzy

Example: Interactions in NOvA

NOvA: Liquid Scintillator Detector (cell readout)

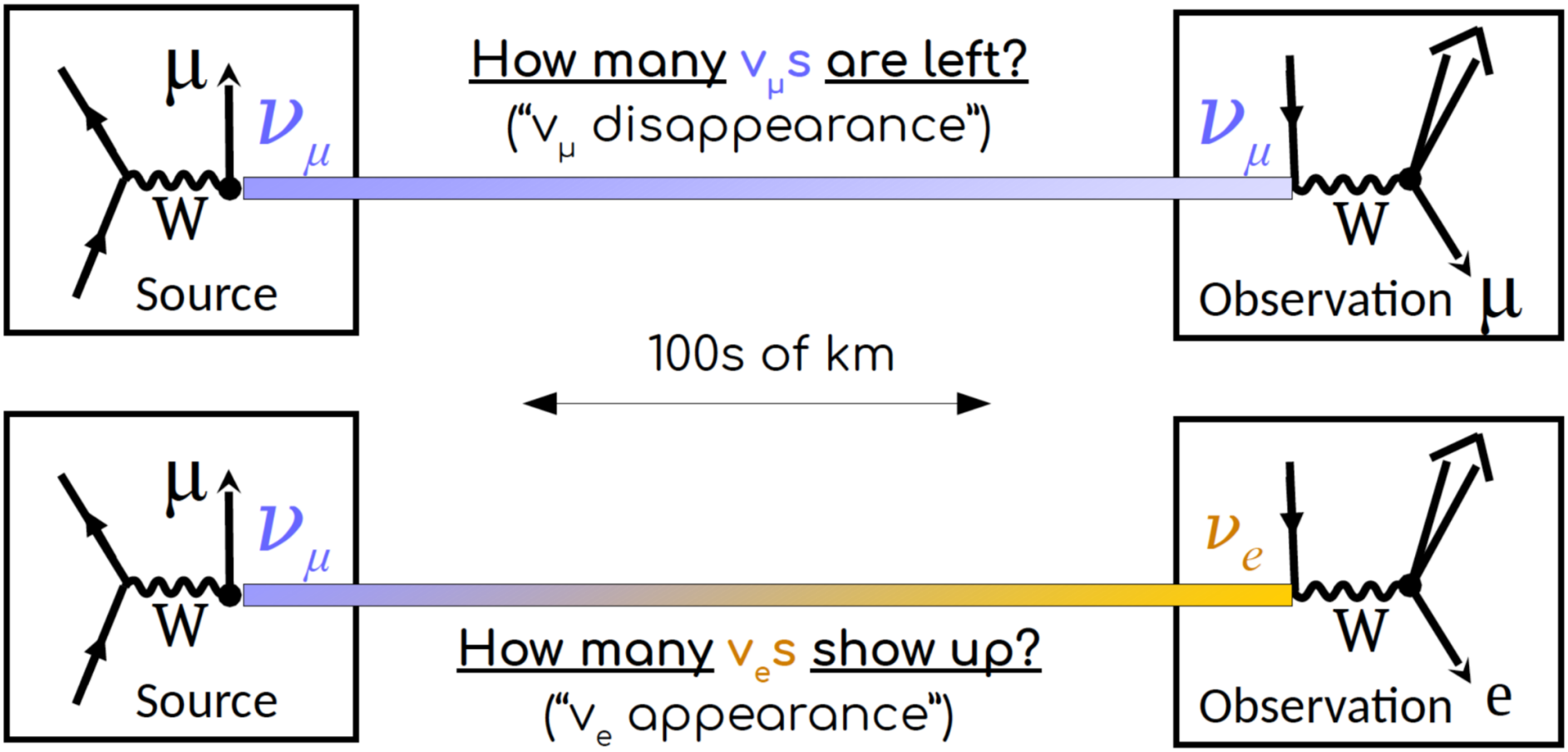




Credit: NOvA collaboration

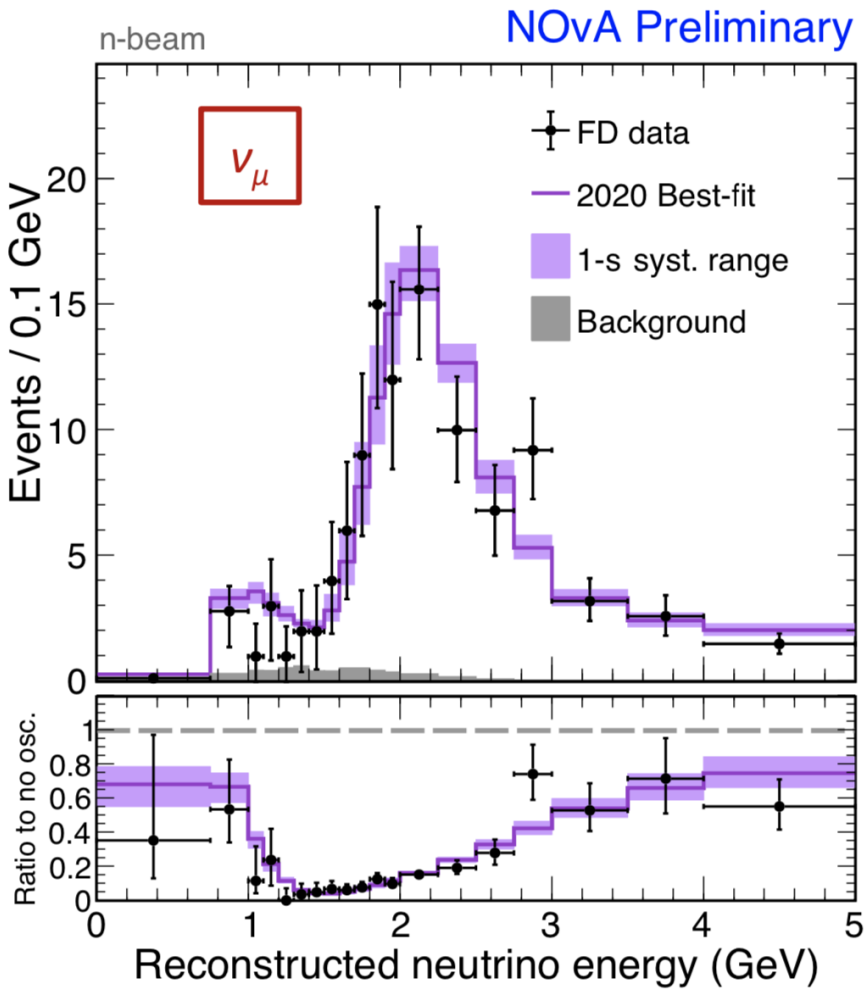
$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$$

Extracting the Information

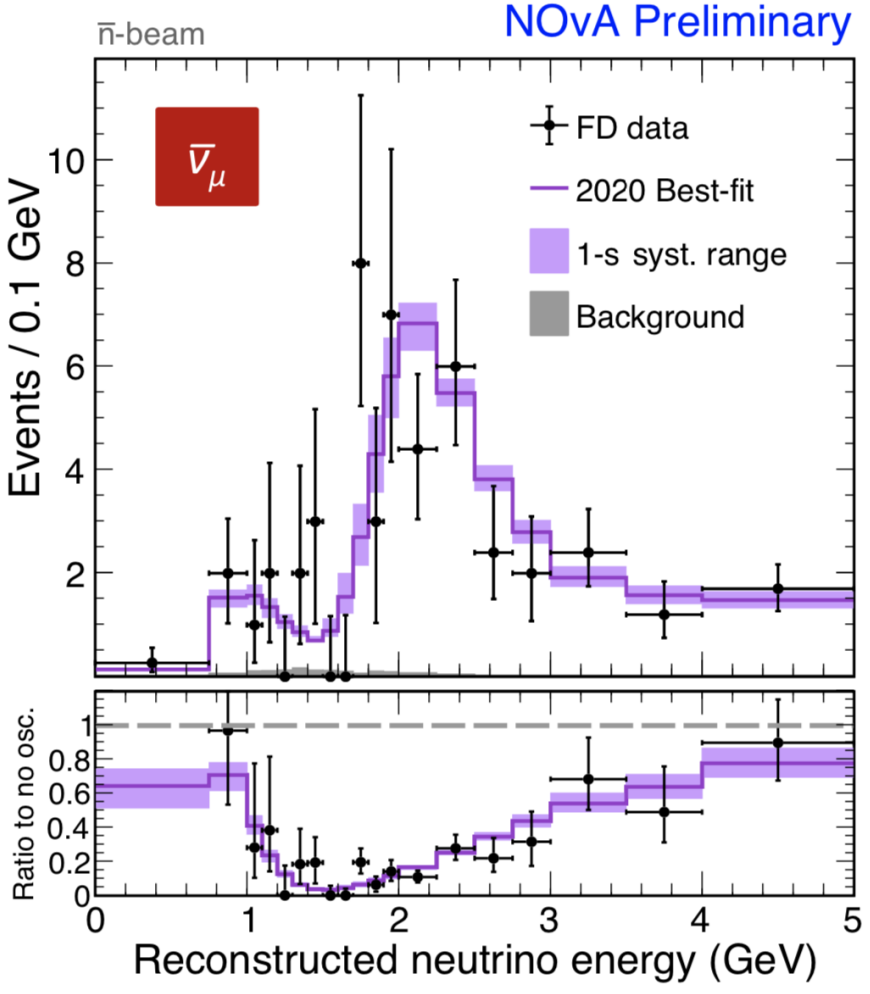


CPV: Do neutrinos and anti-neutrinos oscillate differently ?

Muon Neutrino Disappearance



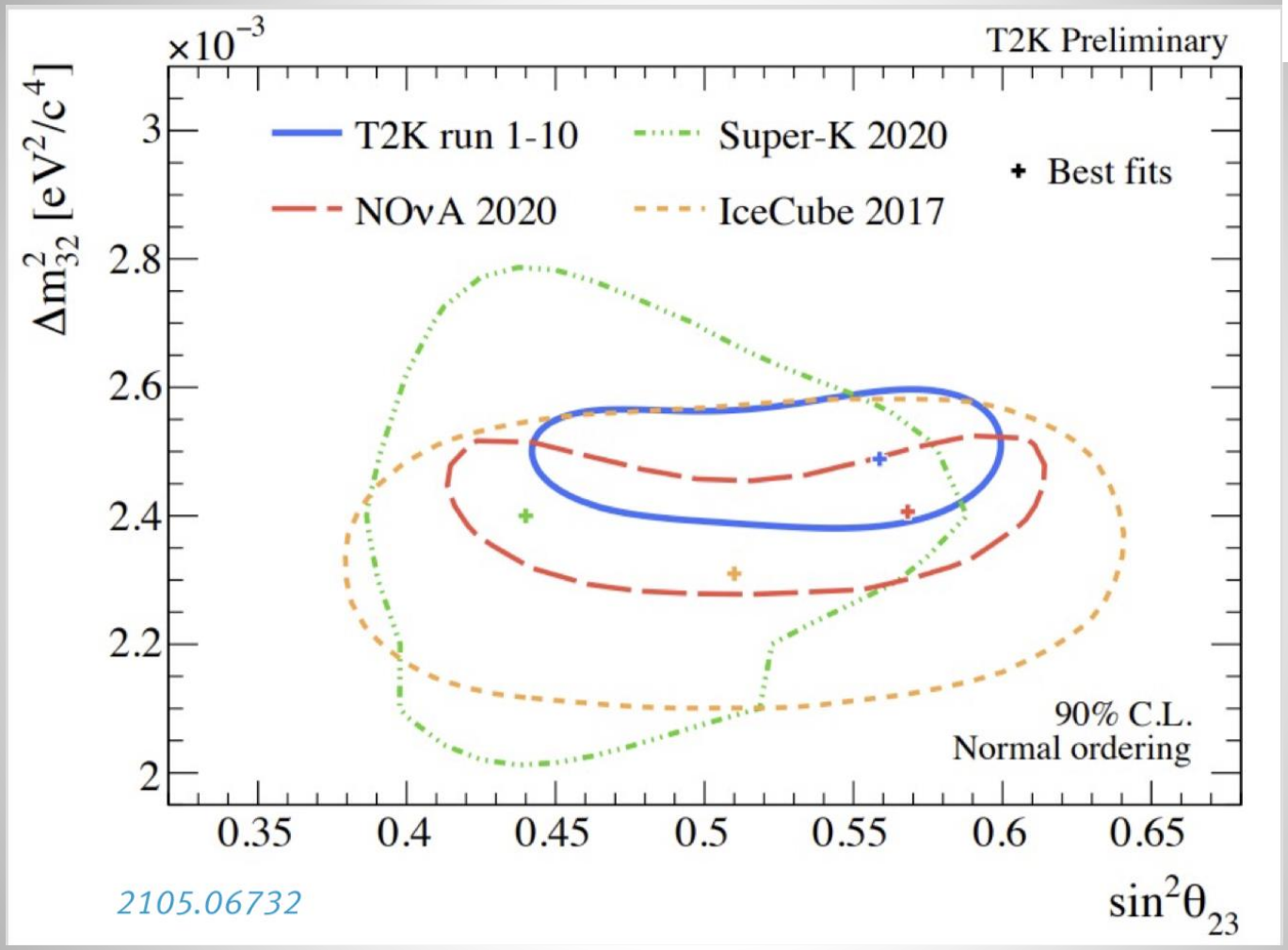
211 events, 8.2 background



105 events, 2.1 background

Neutrino Experiments

2105.06732



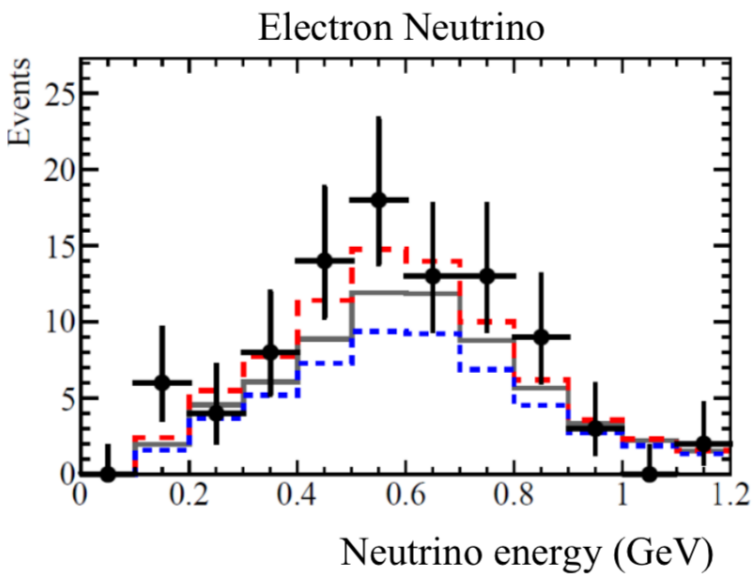
Atmospheric parameter determinations by several experiments
Results are consistent

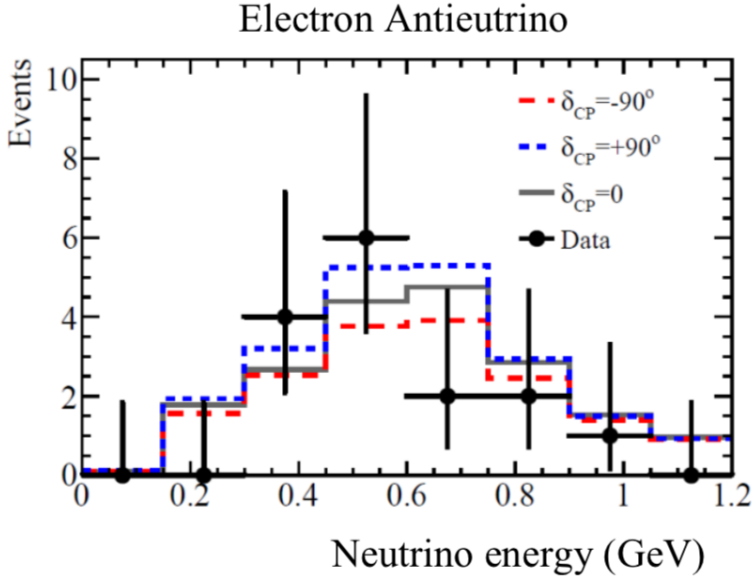
CP Violation: T2K Measurement

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

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

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





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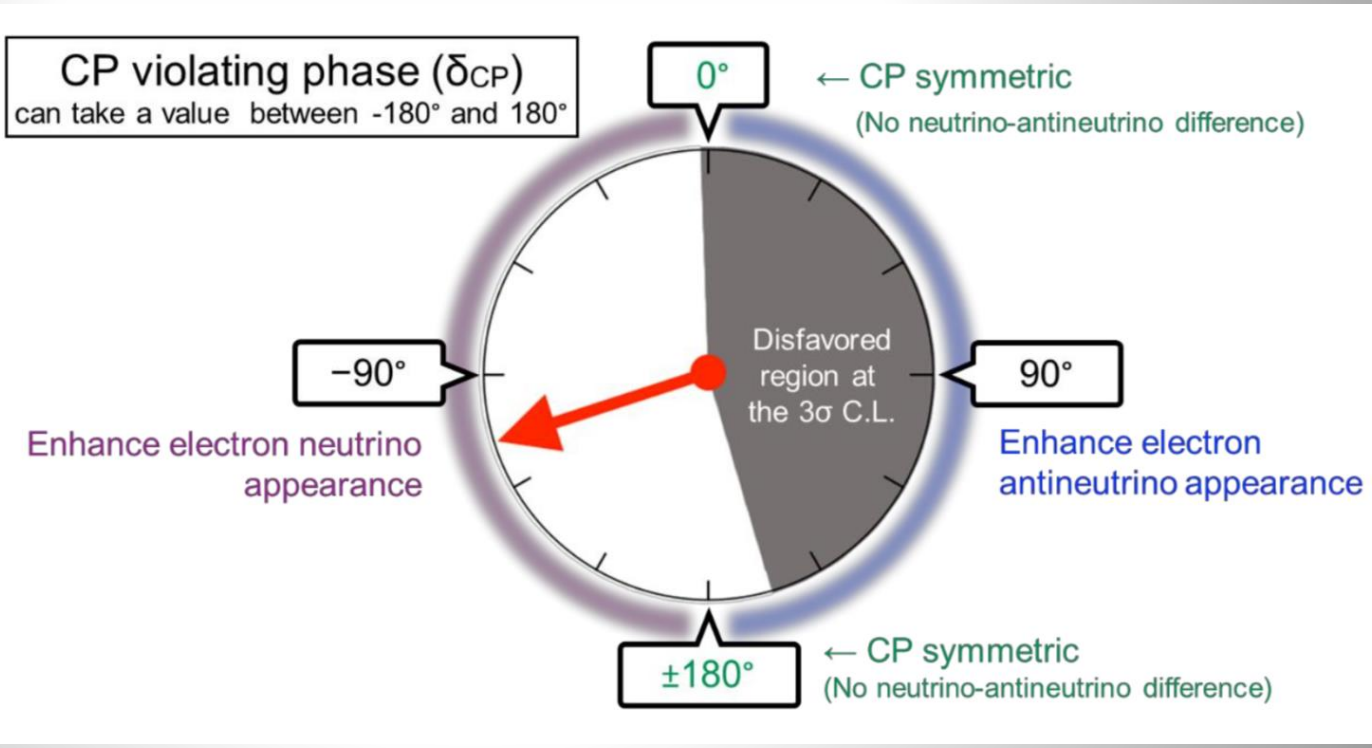
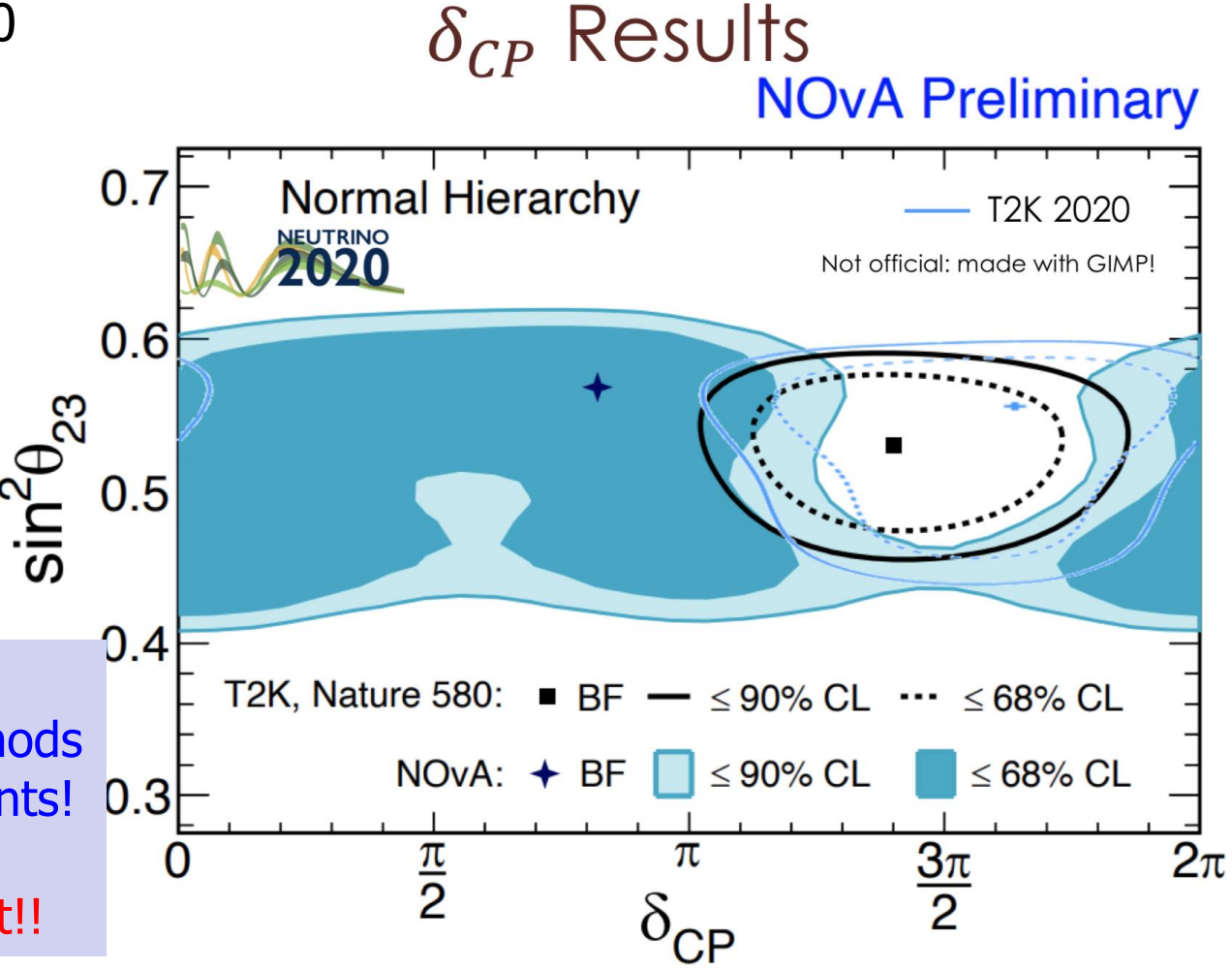


The gray region is disfavored by 99.7% (3σ) CL
The values 0 and 180 degrees are disfavoured at 95% CL

CP Violation T2K/NOvA Results

Summer 2020 update

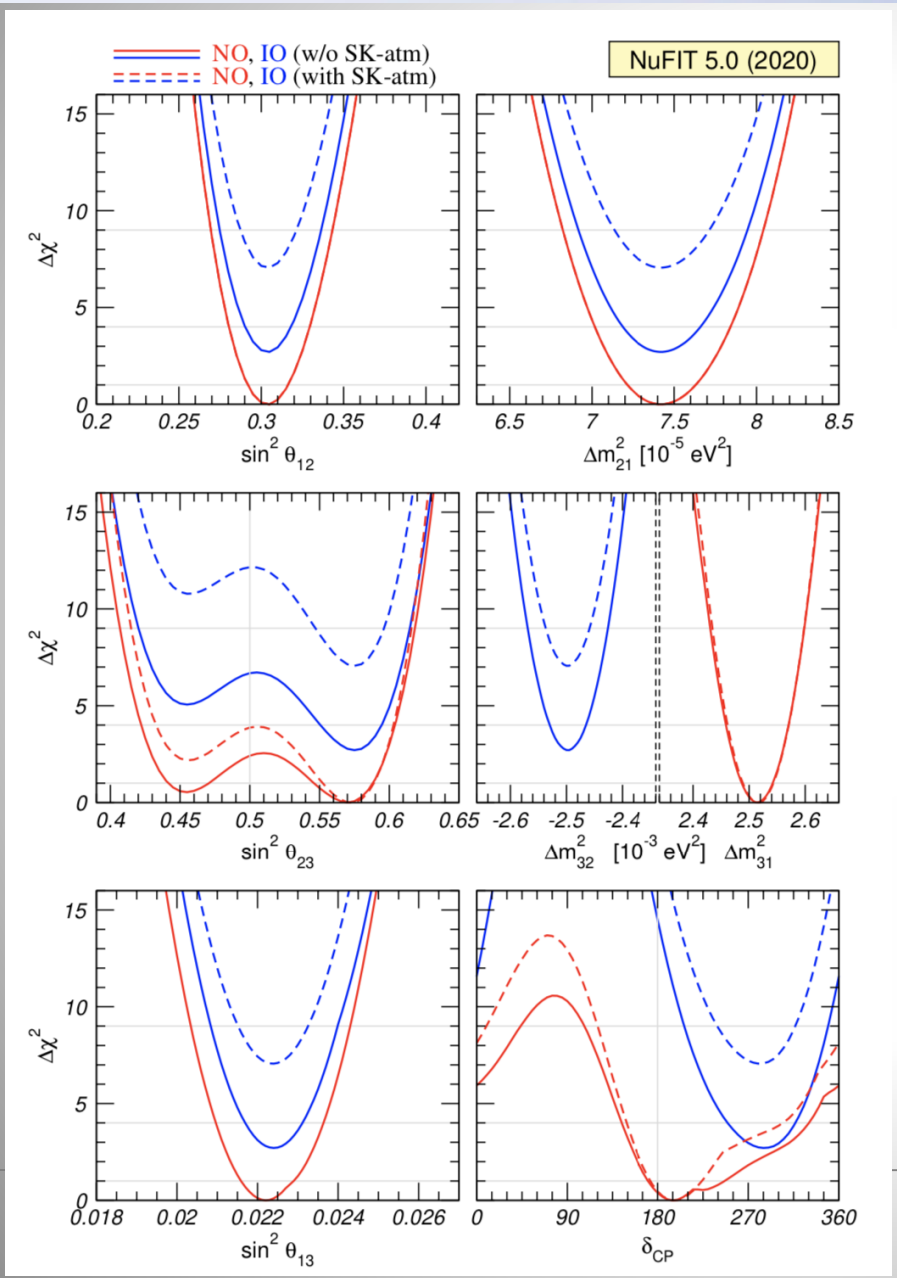


Good to have different methods and experiments!

Jury is still out!!

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

Taking all available data together…



arXiv:2007.14792

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

Inverse mass odering 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..

Taking all available data together…

arXiv:2007.14792

Overall oscillation data fit from the NuFIT group

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

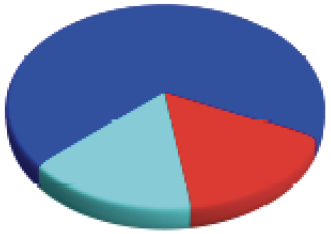
To explore Beyond the Standard Model ~ 10 times better precision is needed

Neutrino Oscillations

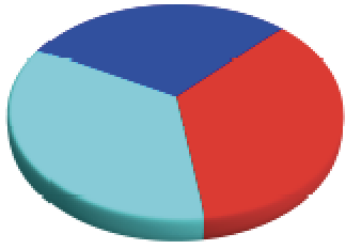
Neutrino Mass EigenStates or Propagation States:

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

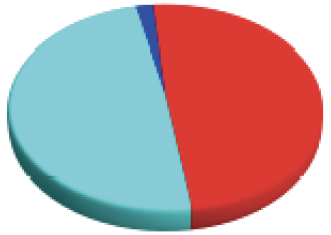
ν_1 most ν_e



ν_2



ν_3 least ν_e



$\nu_e =$

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$

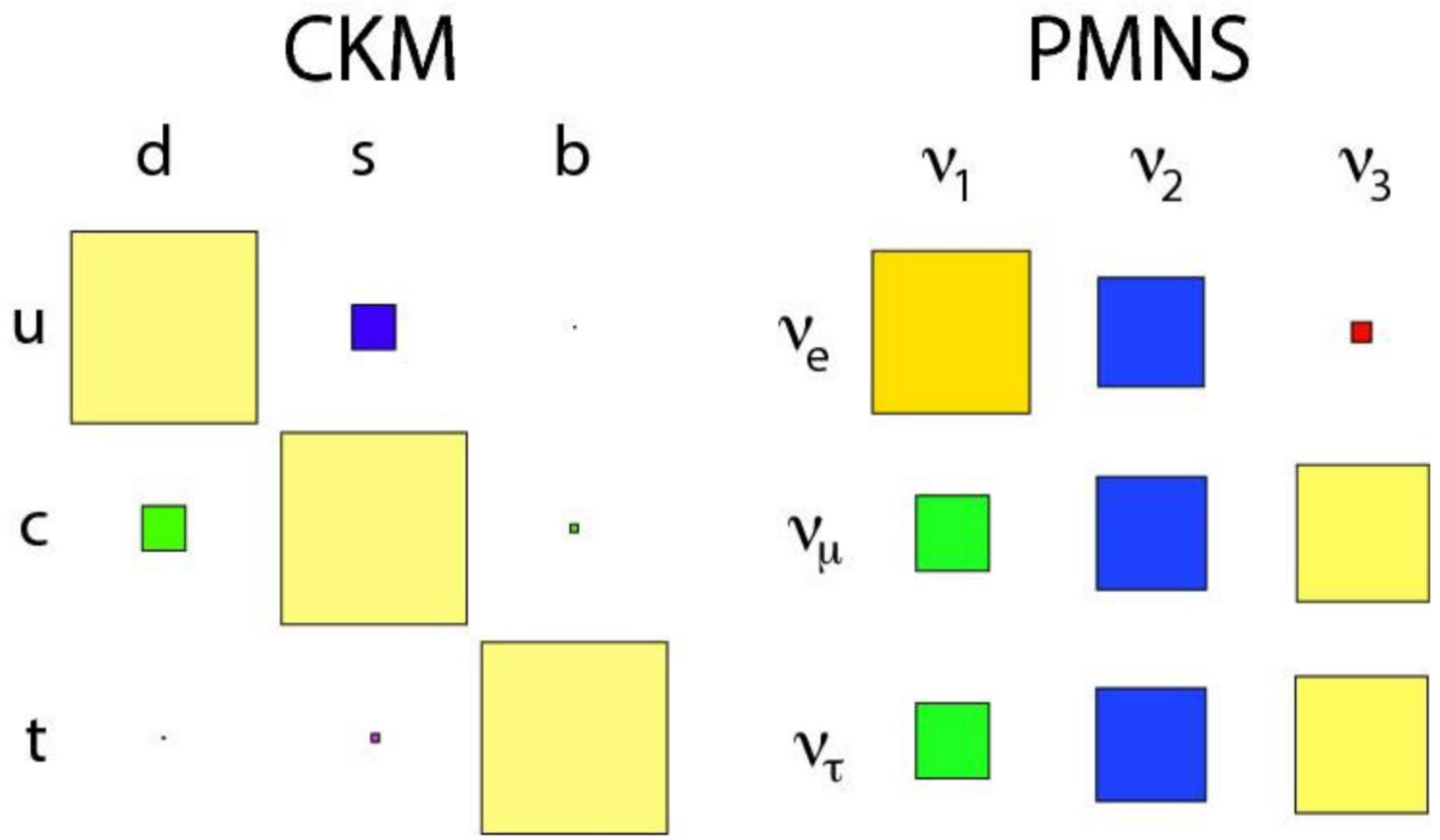
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$

Unitarity
SK, Opera
ICECUBE ?

CKM vs PMNS

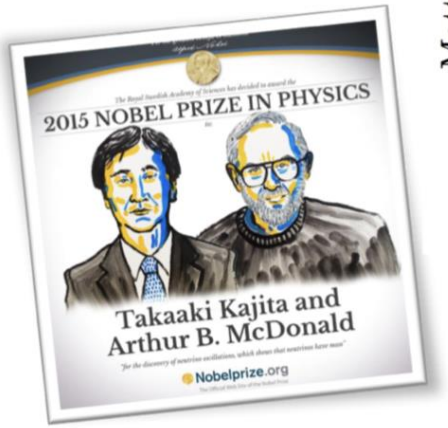
Why is Neutrino mixing so different from quark mixing?
What does that tell us?



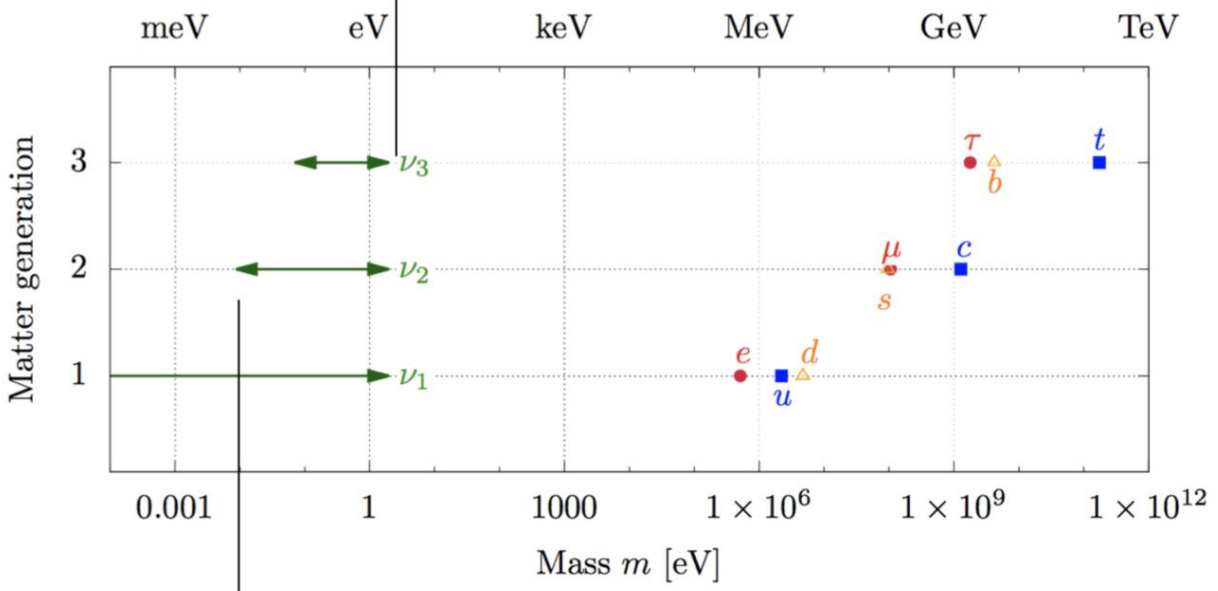
The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.

Neutrino Mass

Neutrinos versus other known fermions



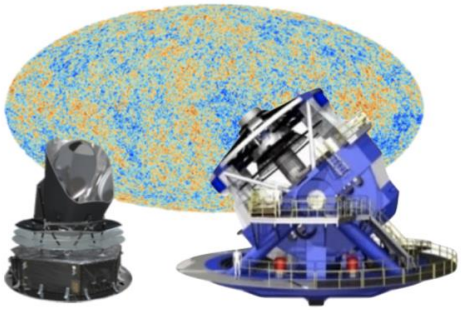
Upper bound
from laboratory measurements

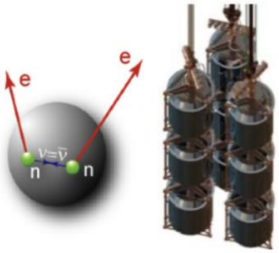


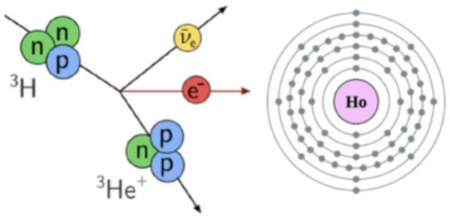
Lower bound
from oscillation experiments

Neutrino mass measurents

Complementary paths to the ν mass scale



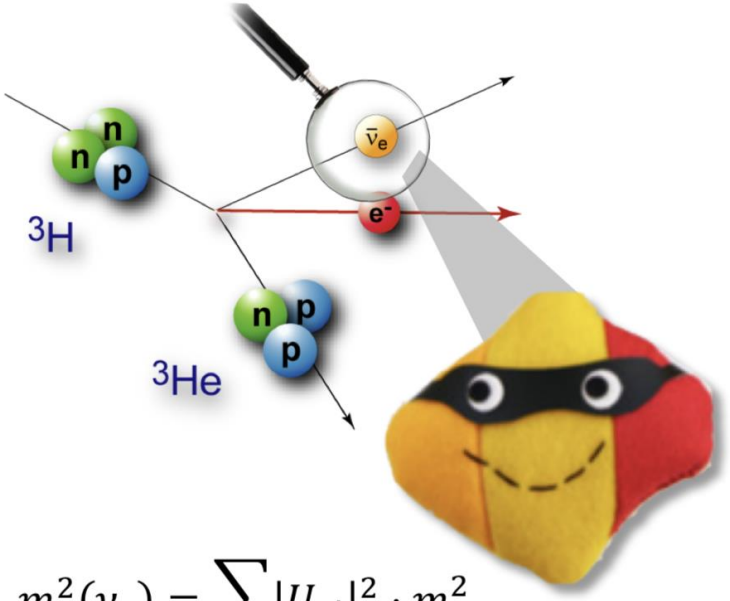




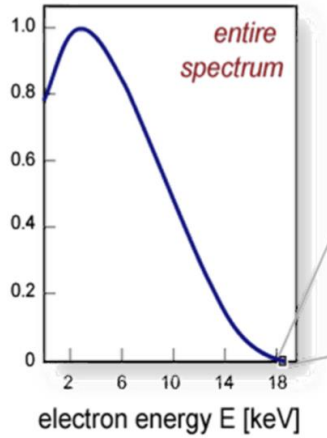
	Cosmology	Search for 0νββ	Kinematics of weak decays
Method	Structure of Universe at early and evolved stages	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\lvert \sum_i U^2_{ei}\, m_i \right\rvert^2$	$m^2_\beta = \sum_i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

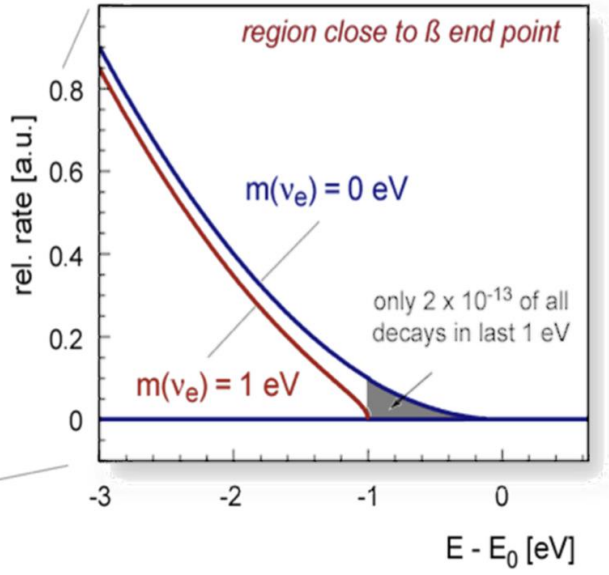
Neutrino mass measurents

The KATRIN experiment: endpoint measurement of tritium decay



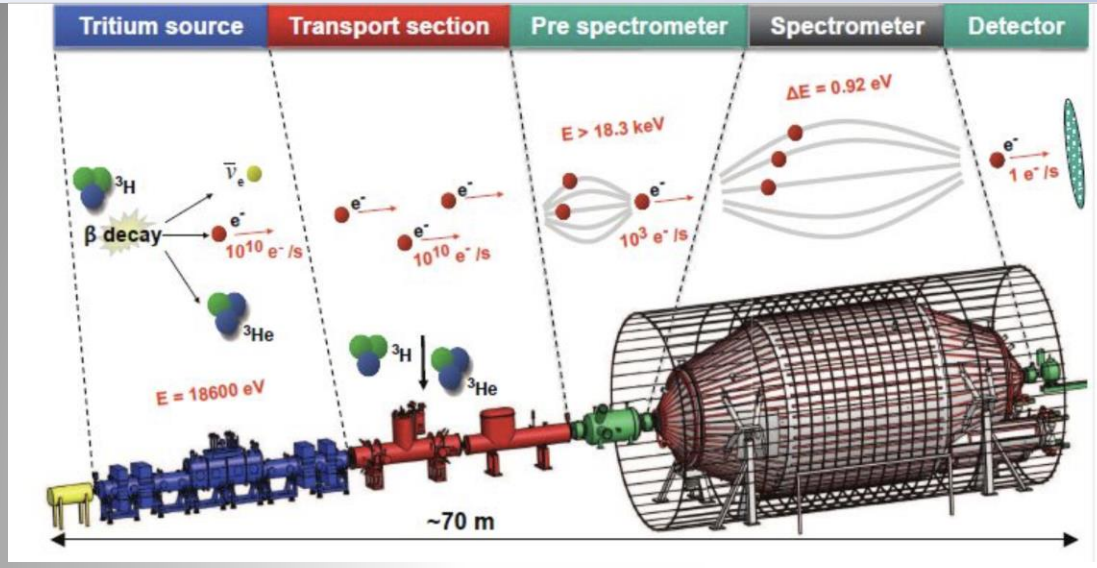
$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$





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

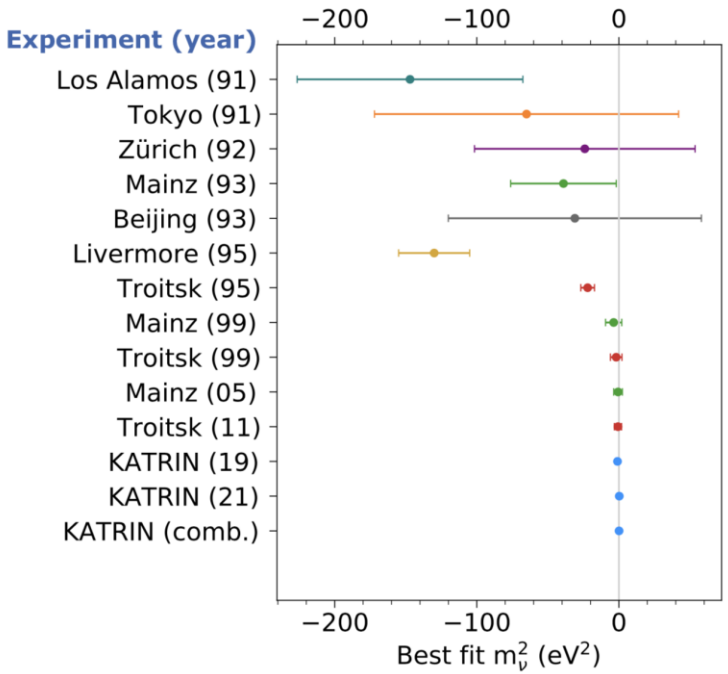
KATRIN Experiment: the Mass of ν_e



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

First result $M\nu_e < 1.1$ eV (September 2019)

KATRIN Experiment: the Mass of ν_e



World evolution over last 30 years

Instrument development
+ dedicated systematics experiments
+ theoretical model

Scale-up & further development
of MAC-E technique
with gaseous source

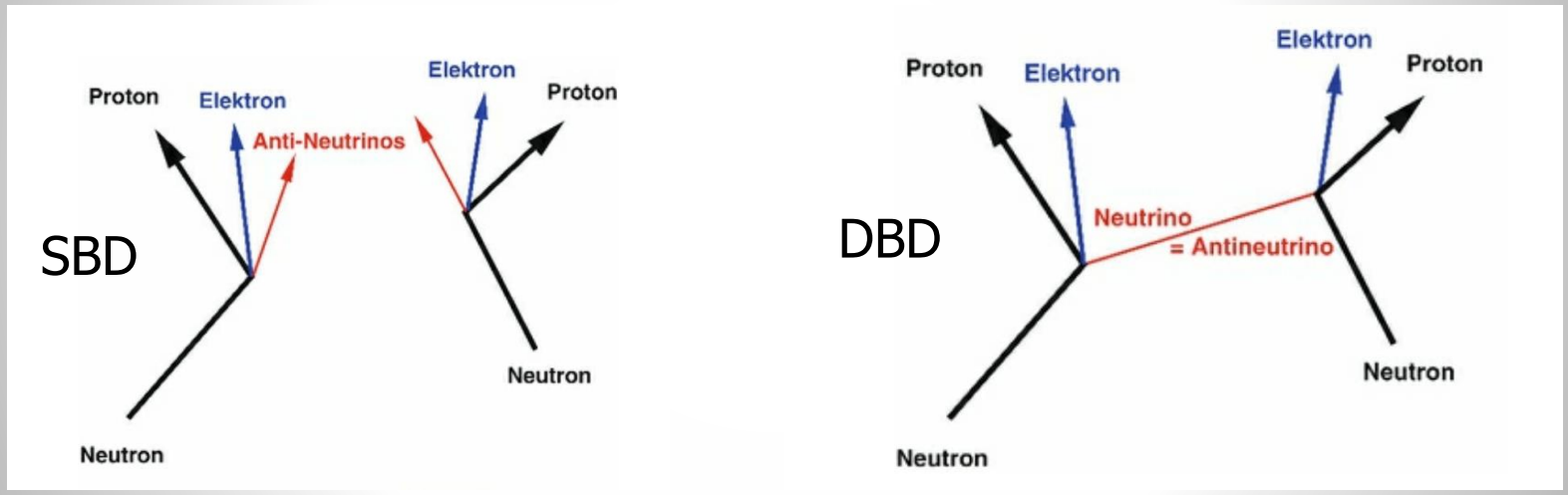
Latest Result (May 2021):

- **First sub-eV result** from KATRIN: arXiv:2105.08533
  m(ν) < 0.8 eV (90% CL) from just few months of data

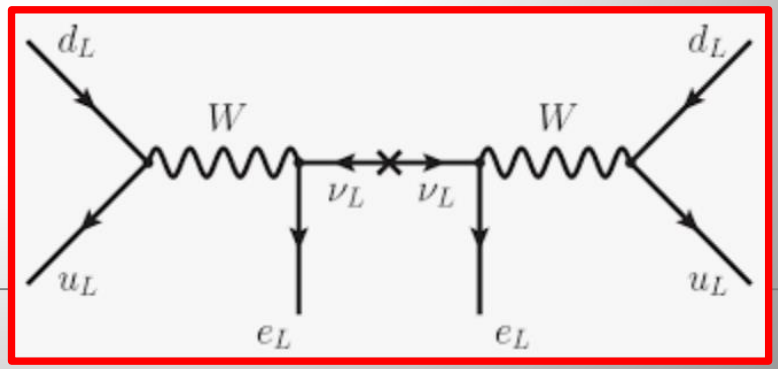
- Five-year target sensitivity: 0.2 eV (90% CL)

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



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

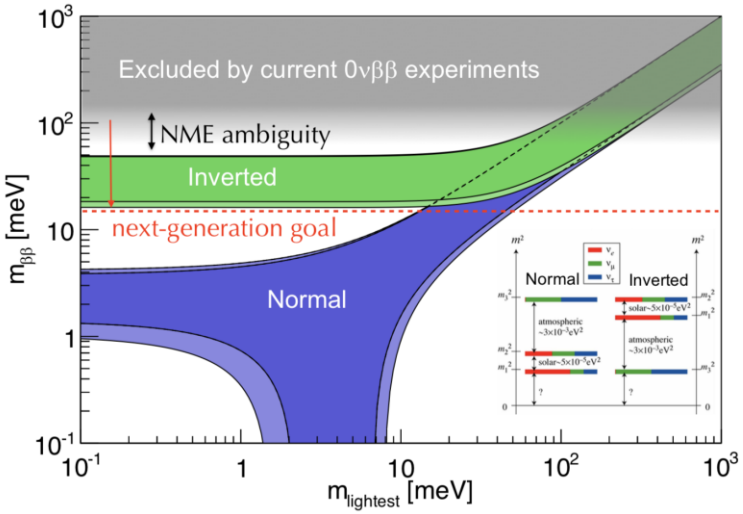
127.2 kg.year exposure
between 2011-2019

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

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



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

Neutrinoless Double Beta Decay

Experiments

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

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? $m(\nu_e) < 0.8$ eV
- What generates the neutrino mass? Seesaw? Other?
- Is the neutrino a Majorana particle? Still open..
- Reactor and accelerator experiments are zooming in on oscillation properties

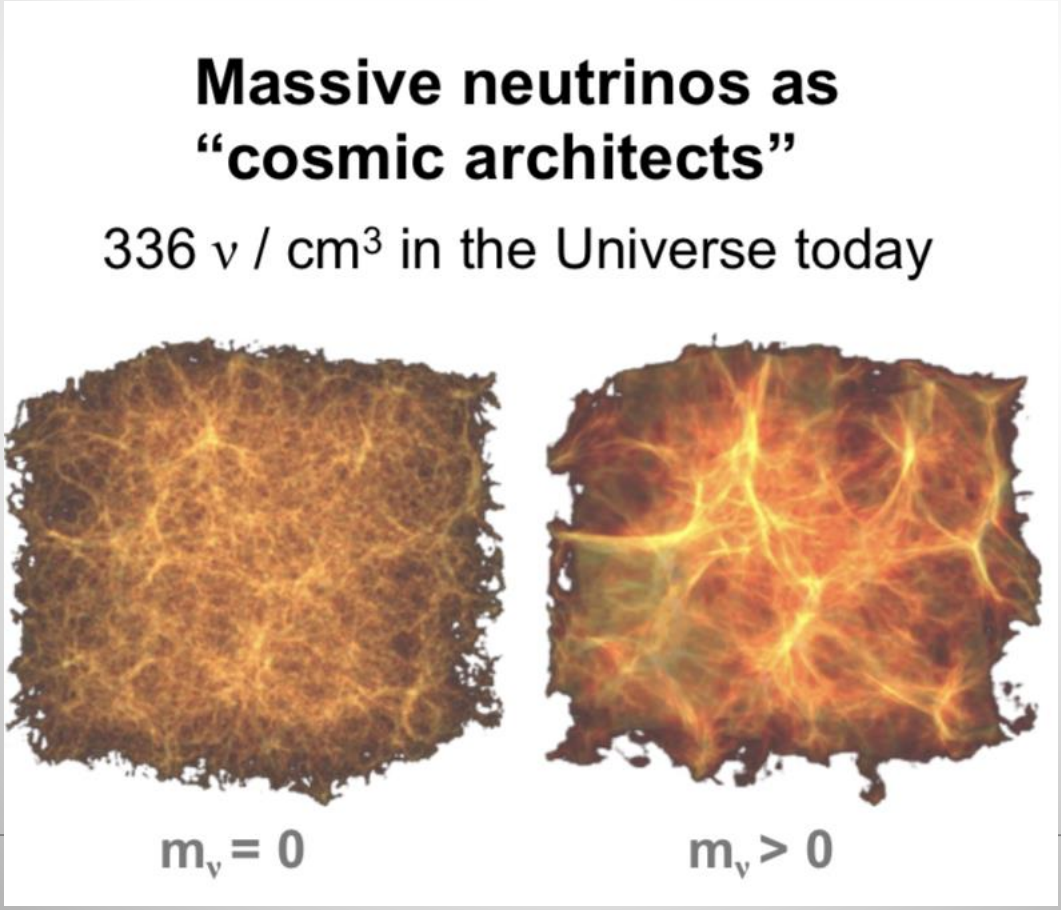
=> Last part: on cosmological neutrinos, on future experiments, and searches for BSM physics (neutrino and others, using neutrino detectors)

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

Neutrinos and Structure

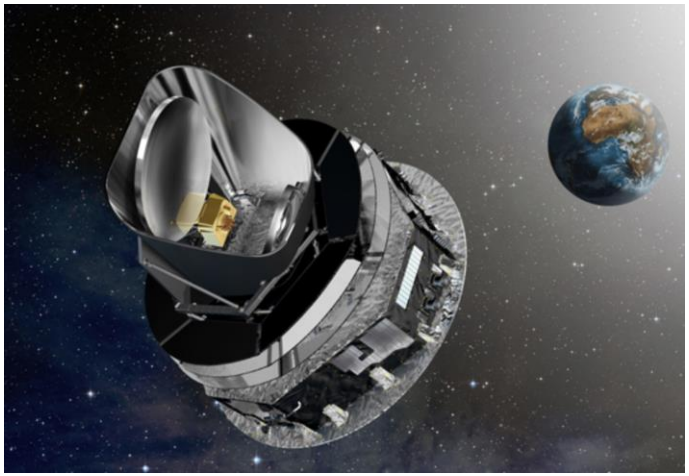
- If the mass of the neutrinos would be 40 eV or more, the universe would have already collapsed under its own gravity before human beings could walk the earth…



Neutrino Mass

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

$$\sum m_\nu < 0.12\,\mathrm{eV}$$

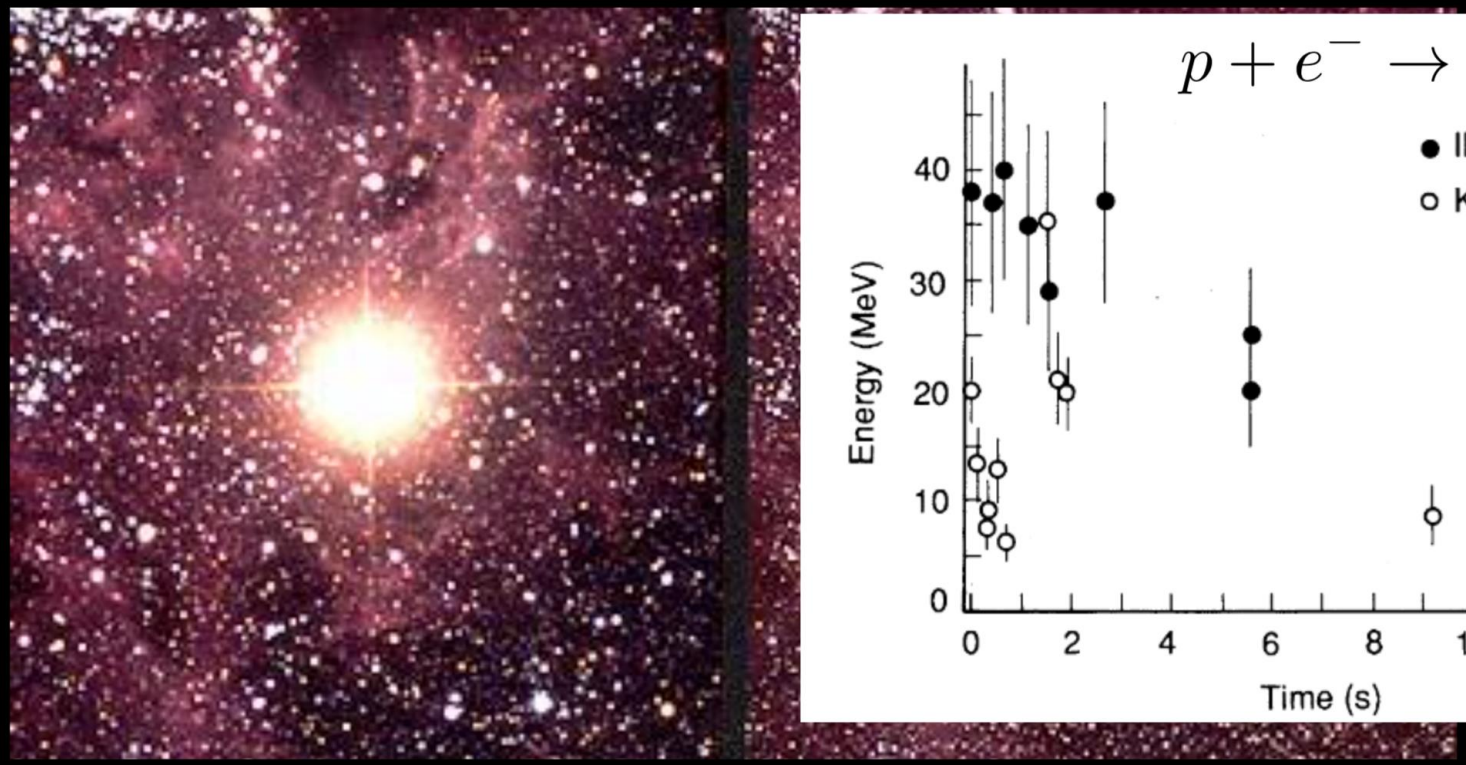


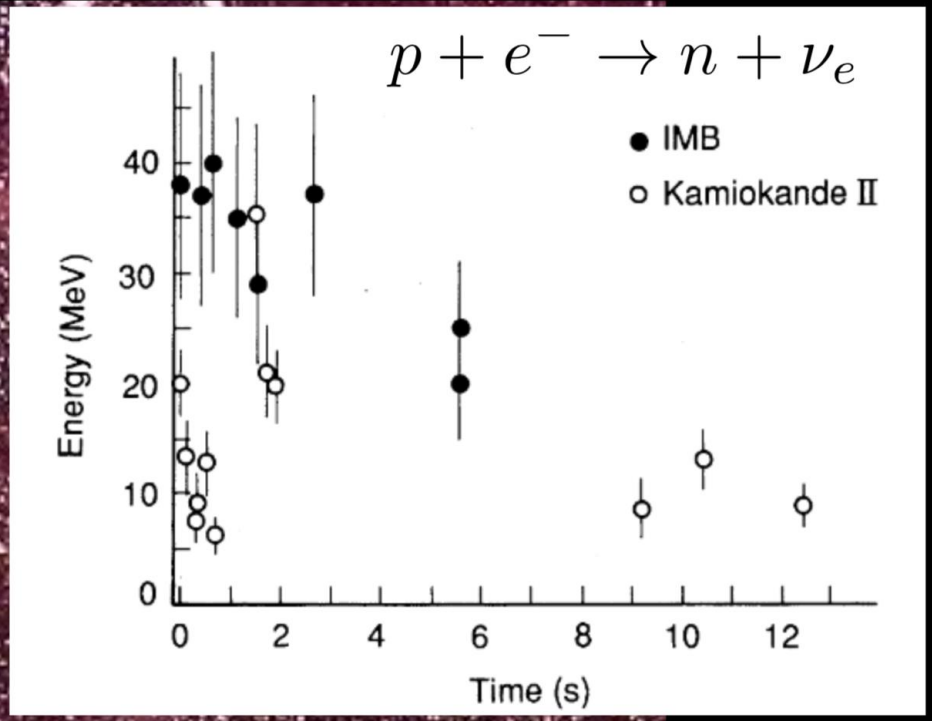
- This assumes however that neutrinos are stable with a lifetime larger than the age of the Universe
- If decays are allowed the limit can as much as 1eV
- These measurements are sensitive to the neutrino masses through the gravitational effects of the relic neutrinos left over from the Big Bang on the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

Study of Supernova Explosions

Supernova 1987A
in the Large Magellanic Cloud (55 kpc away)

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



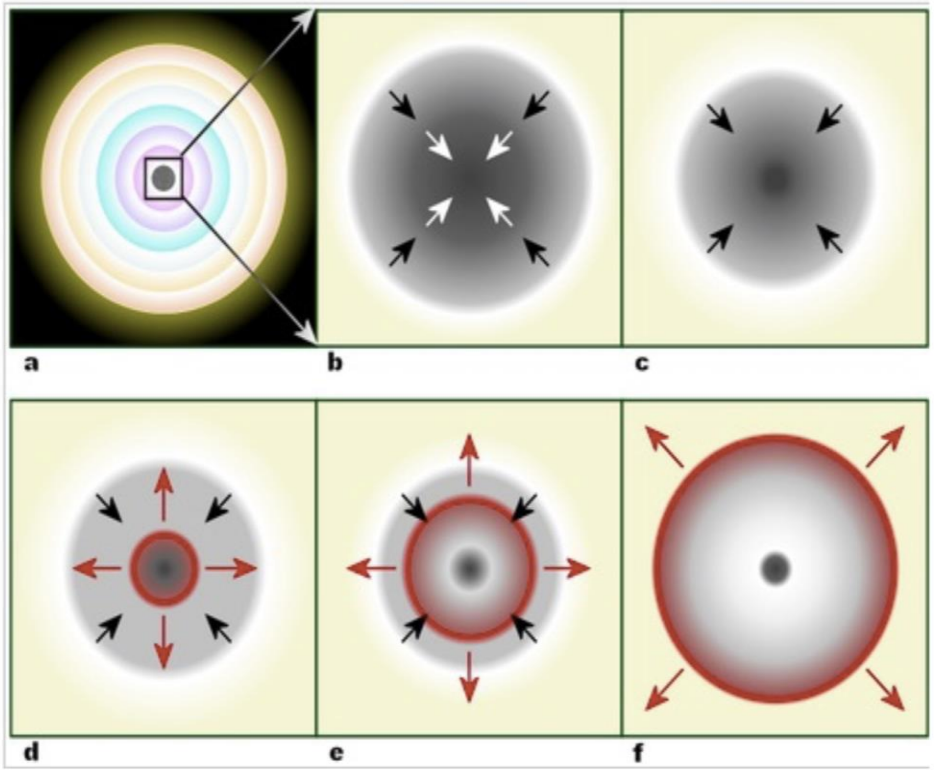


For comparison: the Milky Way is about 34 kpc across

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:

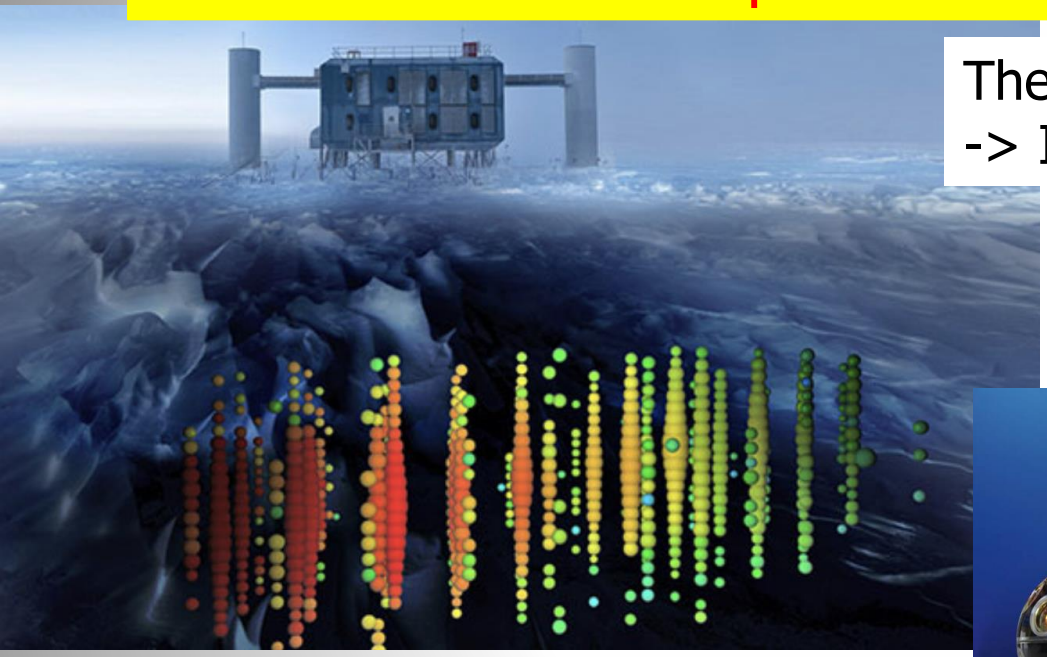
$$p + e^- \rightarrow n + \nu_e$$

- 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....)

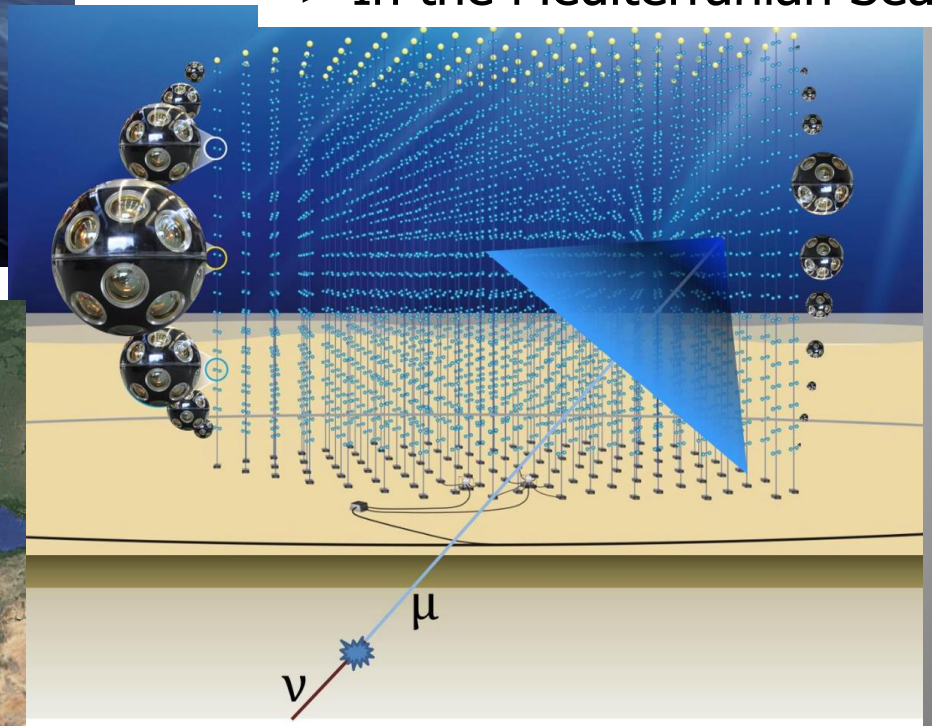
Neutrino Astronomy

Build gigantic detectors 1 km^3 of size and beyond...
Use the resources of planet Earth

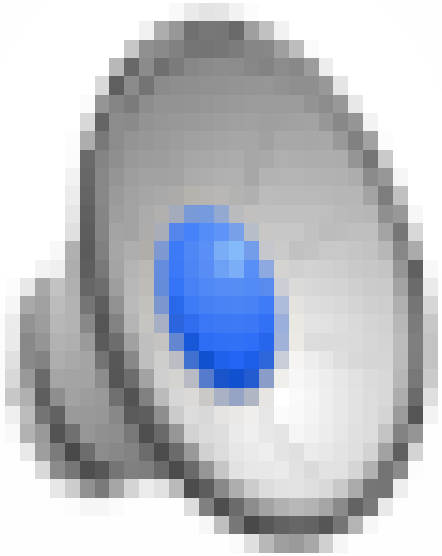


The IceCube Experiment
-> In the ice of Antartica

The KM3NET Experiment
-> In the Mediterranian Sea

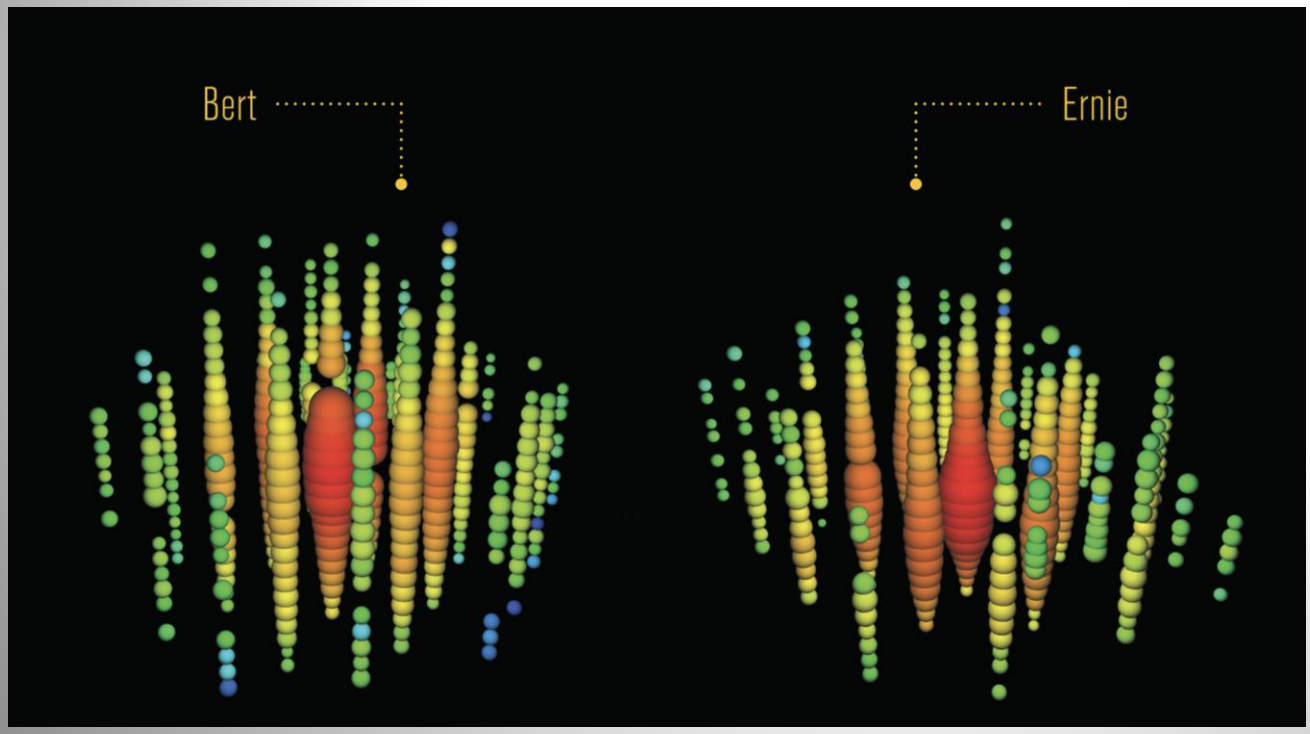


Neutrinos in the Ice

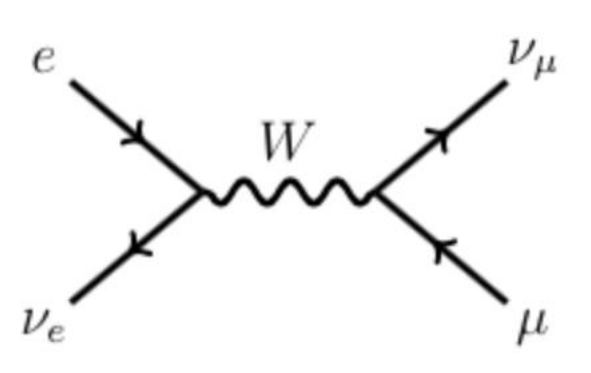


Most Energetic Neutrino Interactions

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



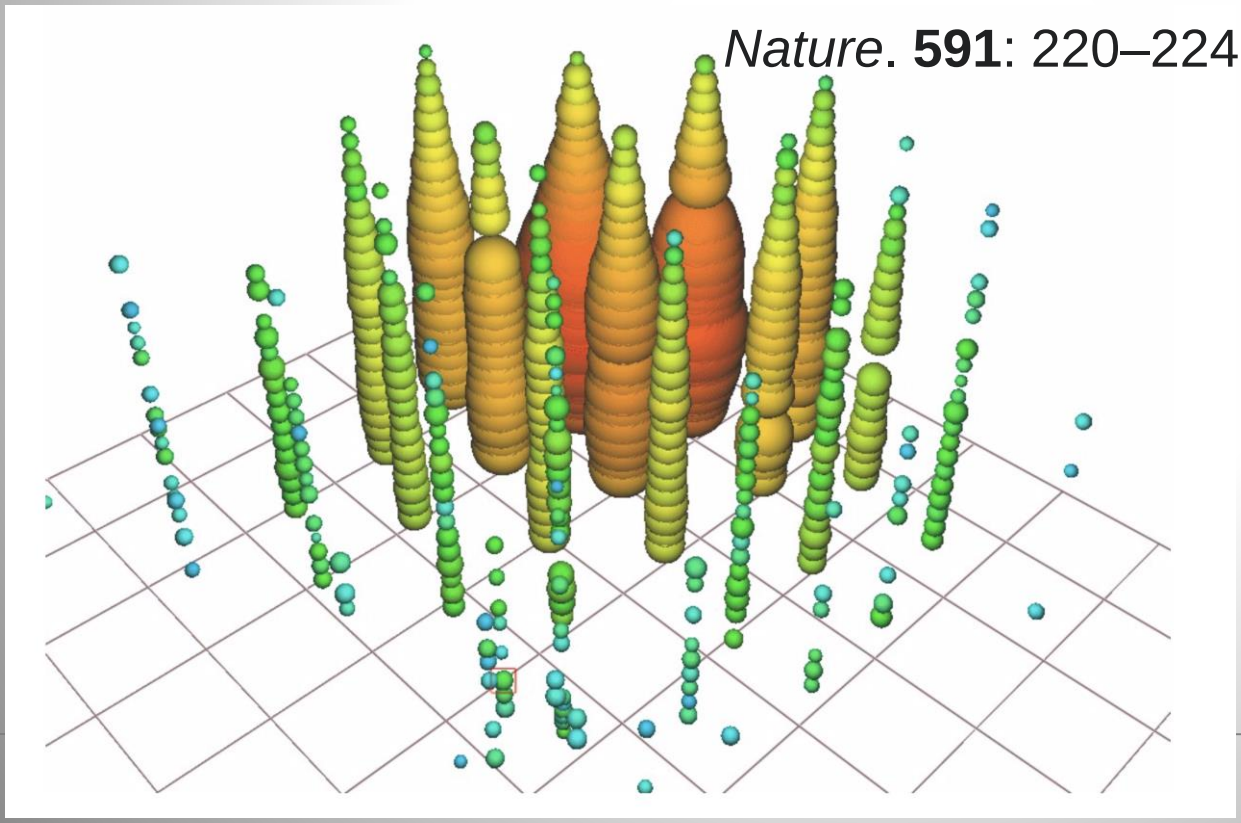
Observation of a Glashow Resonance



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

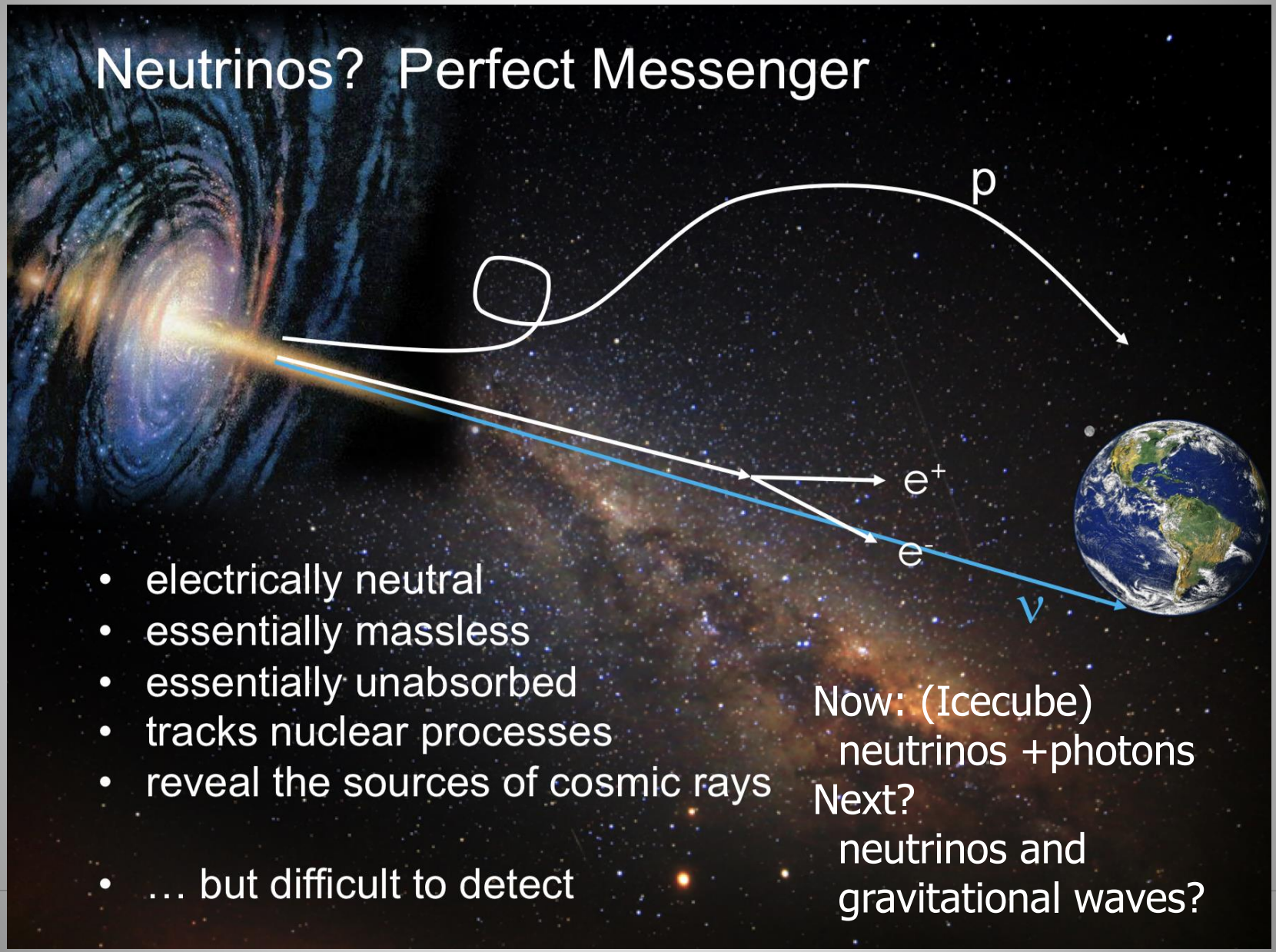
Event seen with an estmated energy of 6.05 PeV (8/12/2016)

Nature. **591**: 220–224



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

Multi-Messenger Astronomy

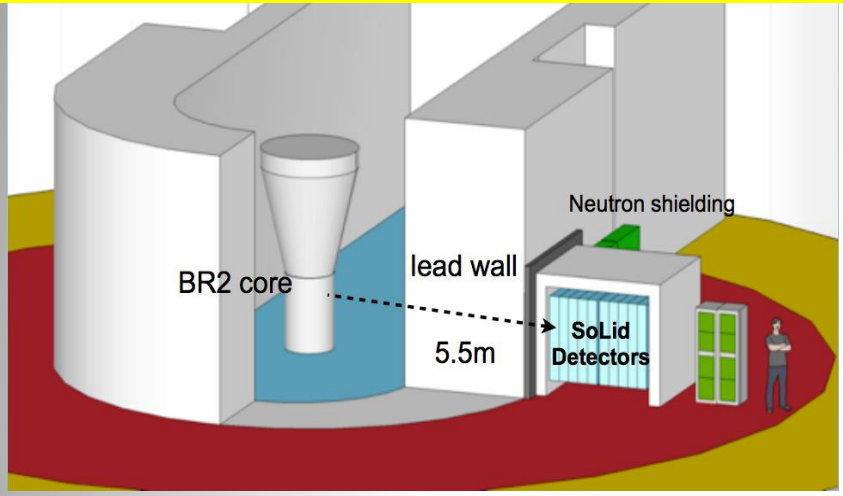


Are there more than 3 Neutrinos?

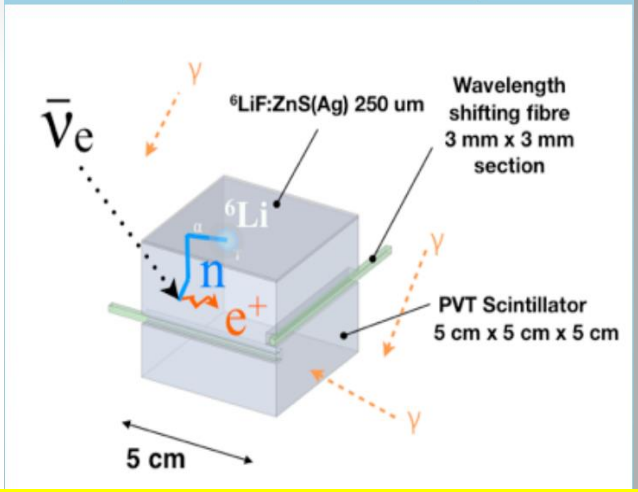
- Is there is a 4th (5th…) neutrino then it has to be quasi-sterile, ie should not couple significantly to other fermions and bosons, as we know from measurements at LEP
- Could mix with the known neutrinos
- Some indication since more than 10 years (LSND, reactor anomalies, Gallium anomalies)
- The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

New Short Baseline Experiments will check!

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

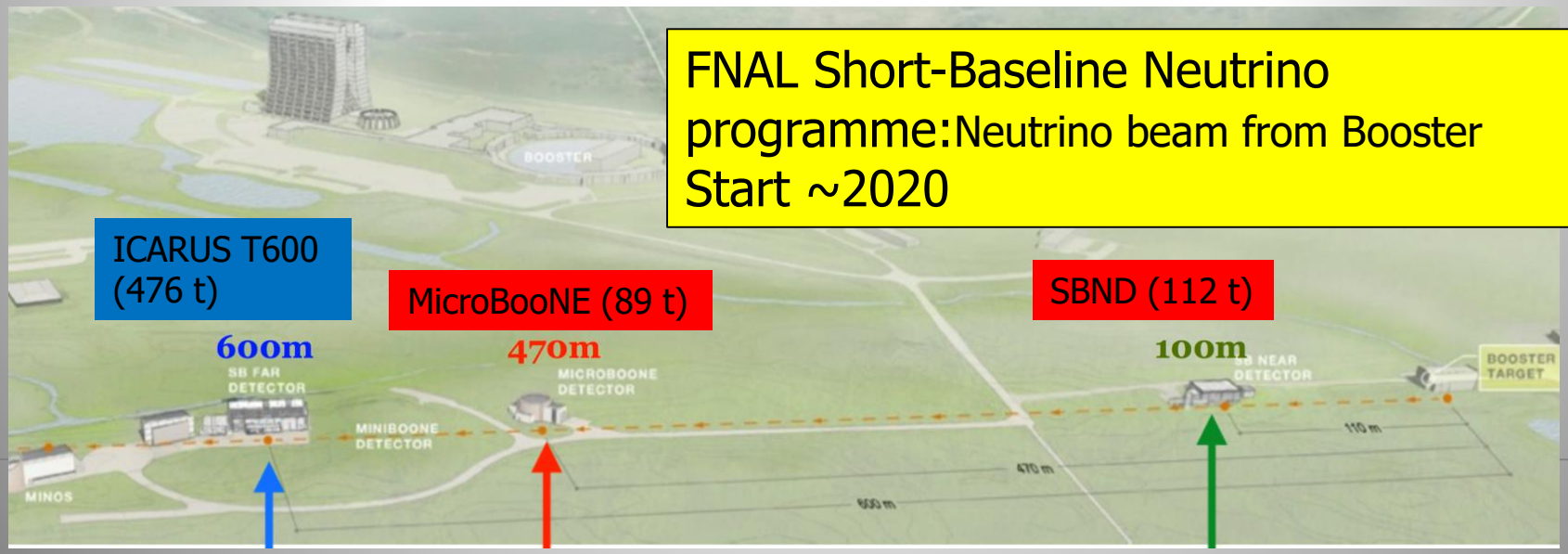


$\bar{\nu}_e + p \rightarrow e^+ + n$

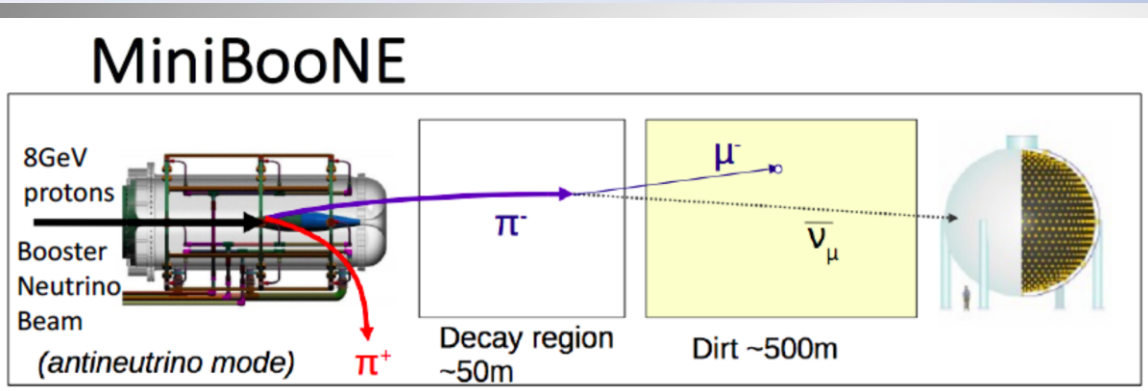


Also: Prospect, STEREO, DANSS, NEOS

FNAL Short-Baseline Neutrino programme: Neutrino beam from Booster
Start ~2020

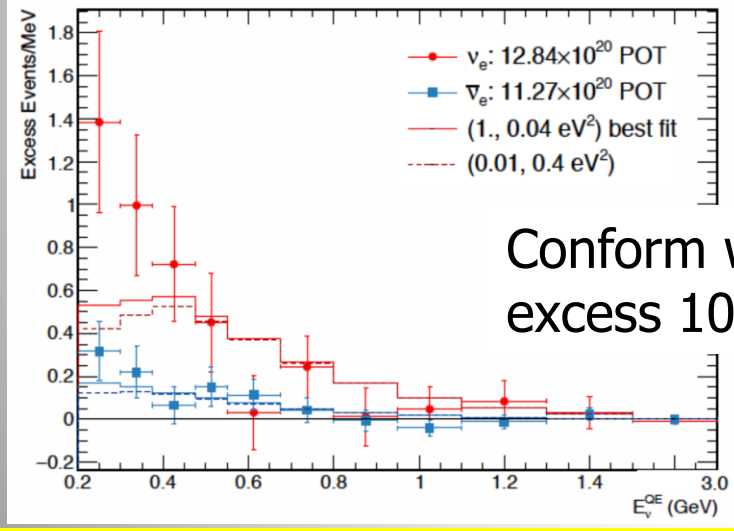


MiniBooNE 2018



Search for electron neutrino appearance in short baseline accelerator experiment.
6.3 sigma excess reported combining the data with LSND

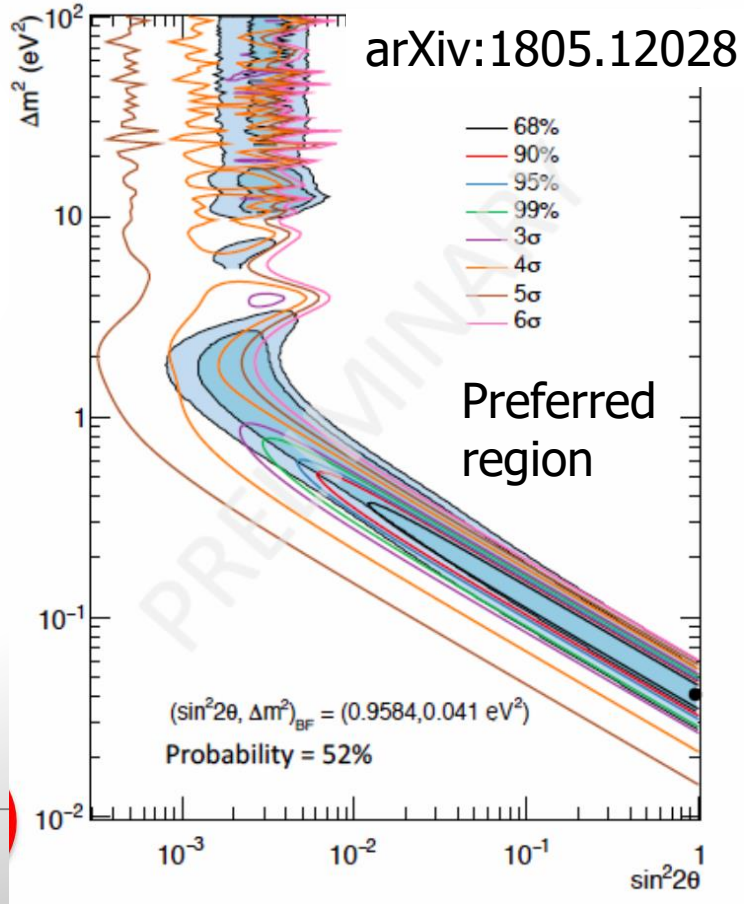
Excess of events over expectation



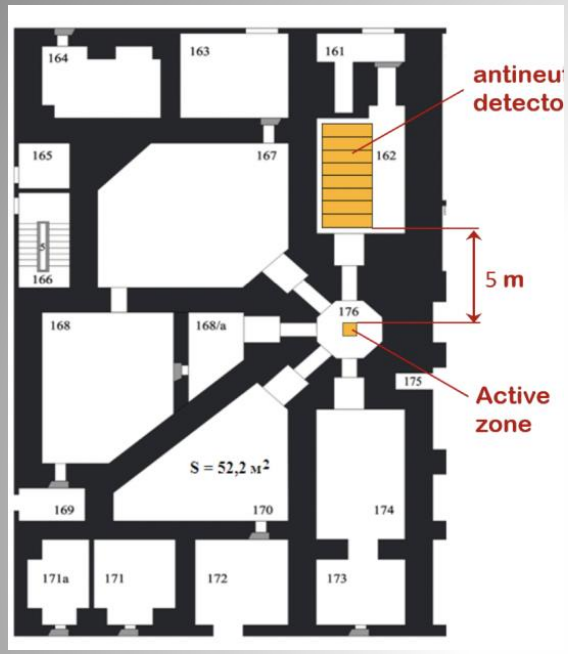
Conform with LSND excess 10 years ago

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

arXiv:1805.12028



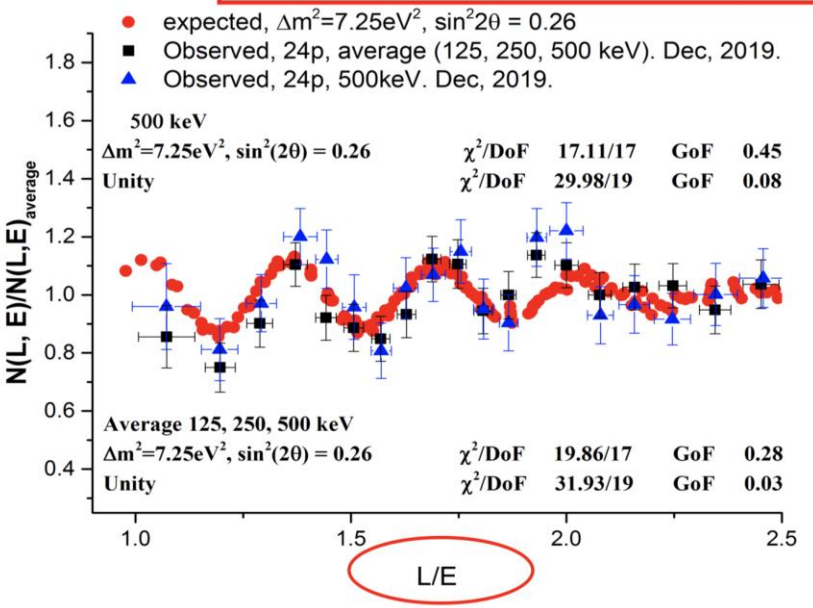
Neutrino-4 Experiment: 2020



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

3 years long measurement
2.8σ signific.

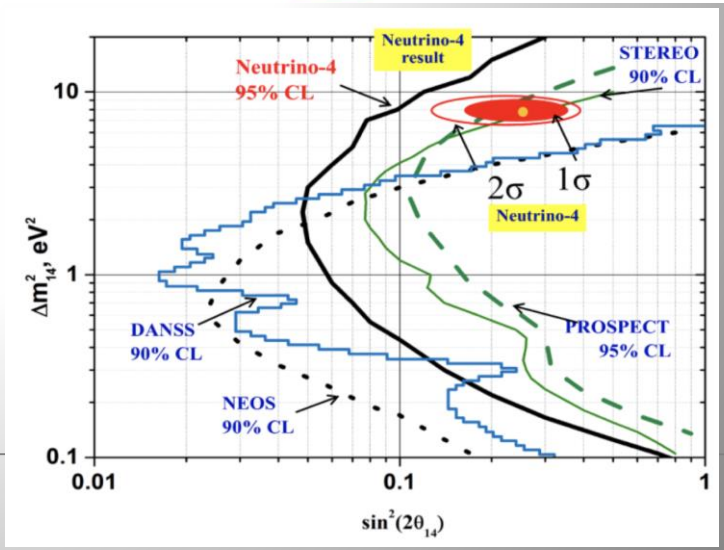
$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \sin^2\left(1.27 \frac{\Delta m^2_{14}[eV^2]L[m]}{E_{\tilde{\nu}}[MeV]}\right)$$



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

arXiv:2101.06785

- Issues with the energy resolution
- Less biased approach -> ~2.2σ effect only
- "No-oscillation scenario" not excludedat 3σ

The jury is still out!

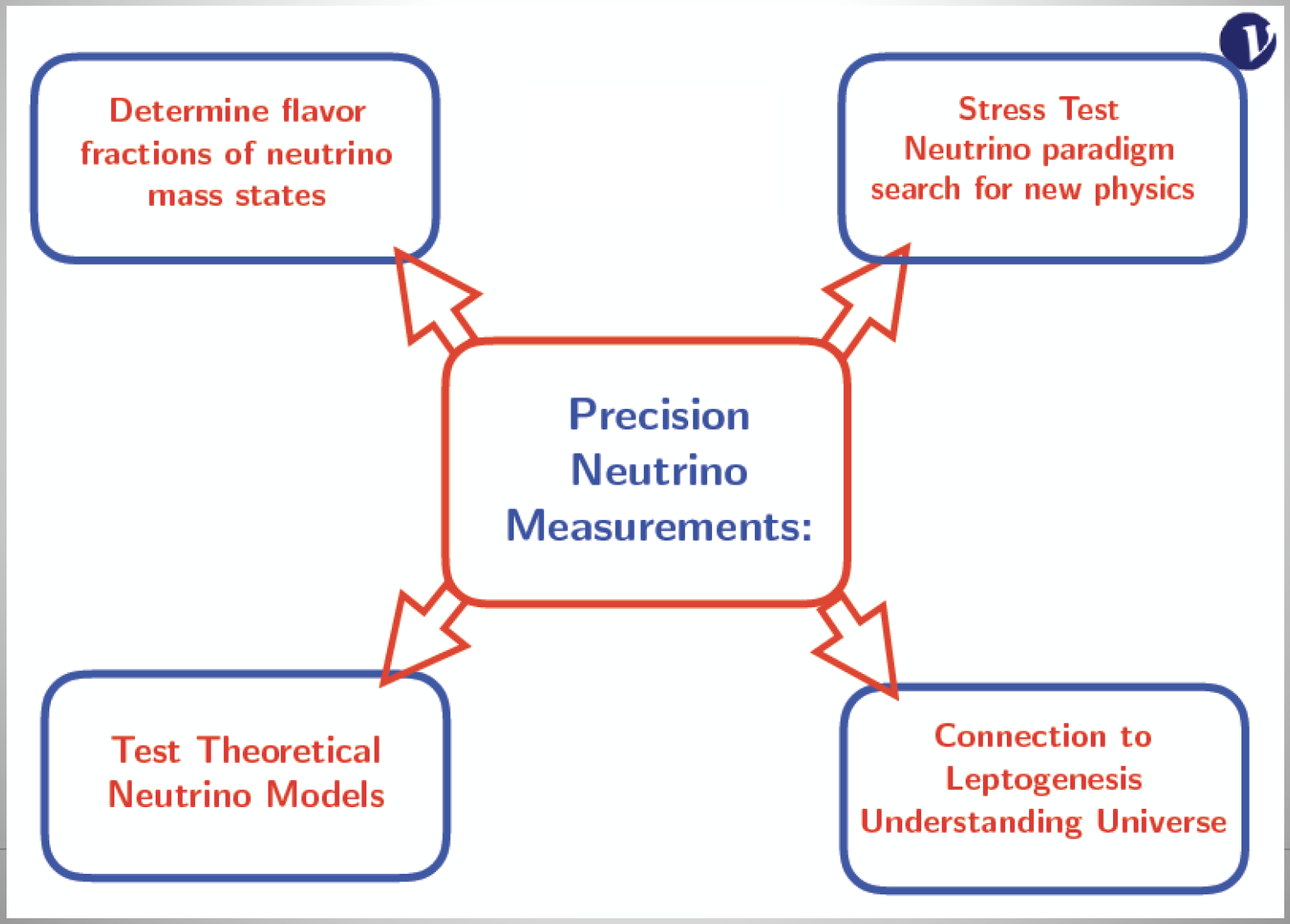
The Future

"The age of precision physics with neutrinos"

Detectors for oscillation physics studies

Precision Neutrino Physics

We are entering the era of precision neutrino physics !!

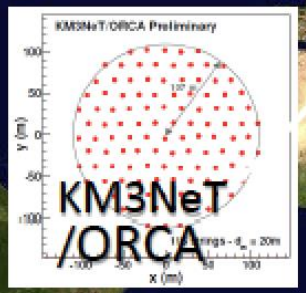


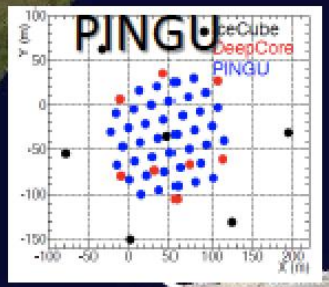
Future Neutrino Experiments

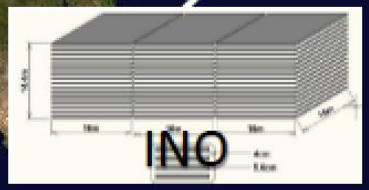
Eg. experiments that will contribute to the mass ordering question

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.

RENO-50





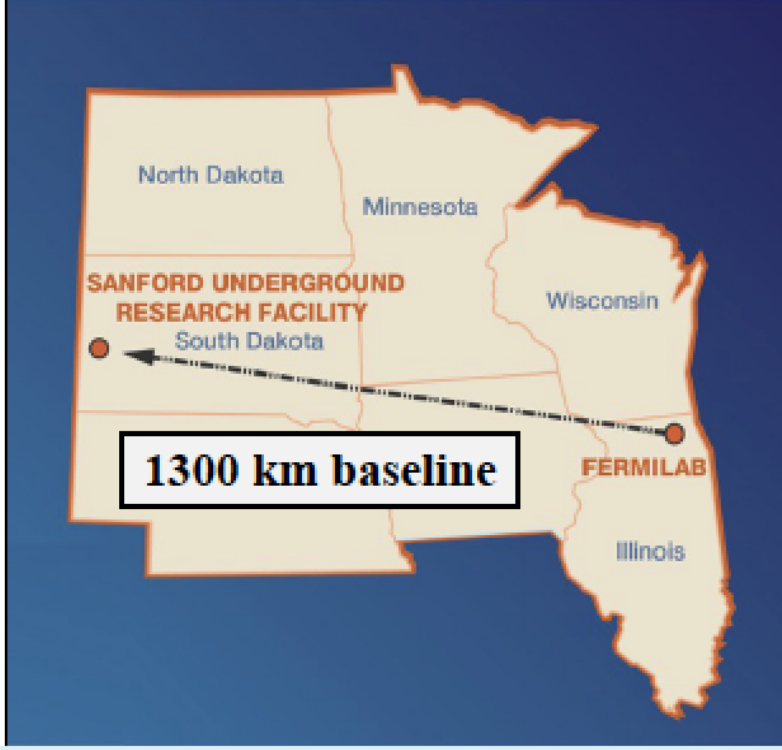


Hyper-K

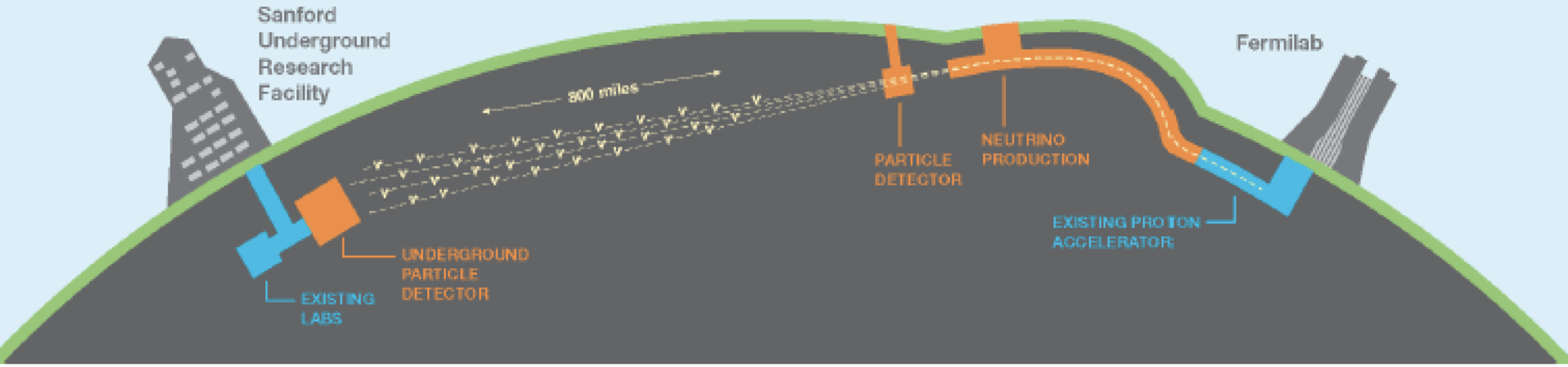
DUNE

Deep Underground Neutrino Experiment

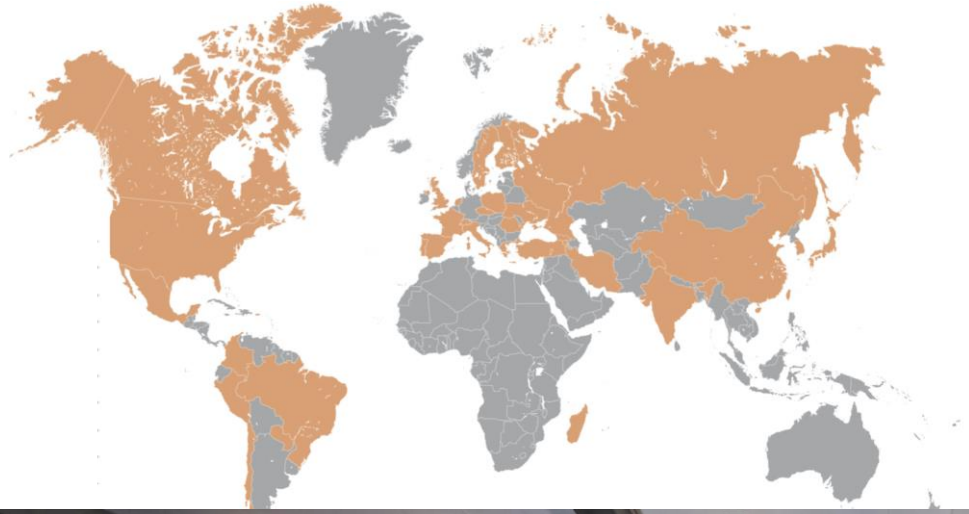
A next generation experiment for **neutrino science**, **nucleon decay**, and **supernova physics**



Operation starts in 2027



DUNE – a global collaboration



Status October 2020:

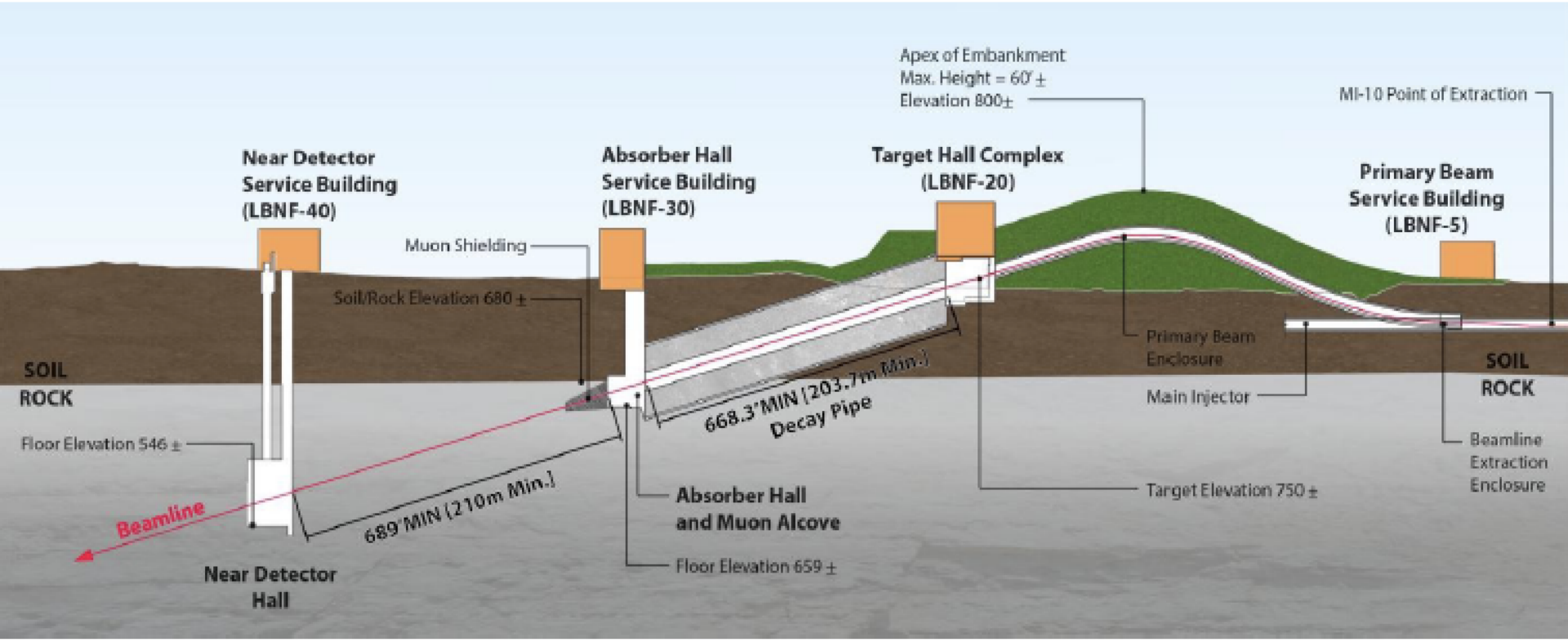
- 1229 collaborators from
- 184 institutions in
- 31 countries + CERN

Still more groups joining

Collaboration meeting at CERN end of January 2020 -> 350 participants!

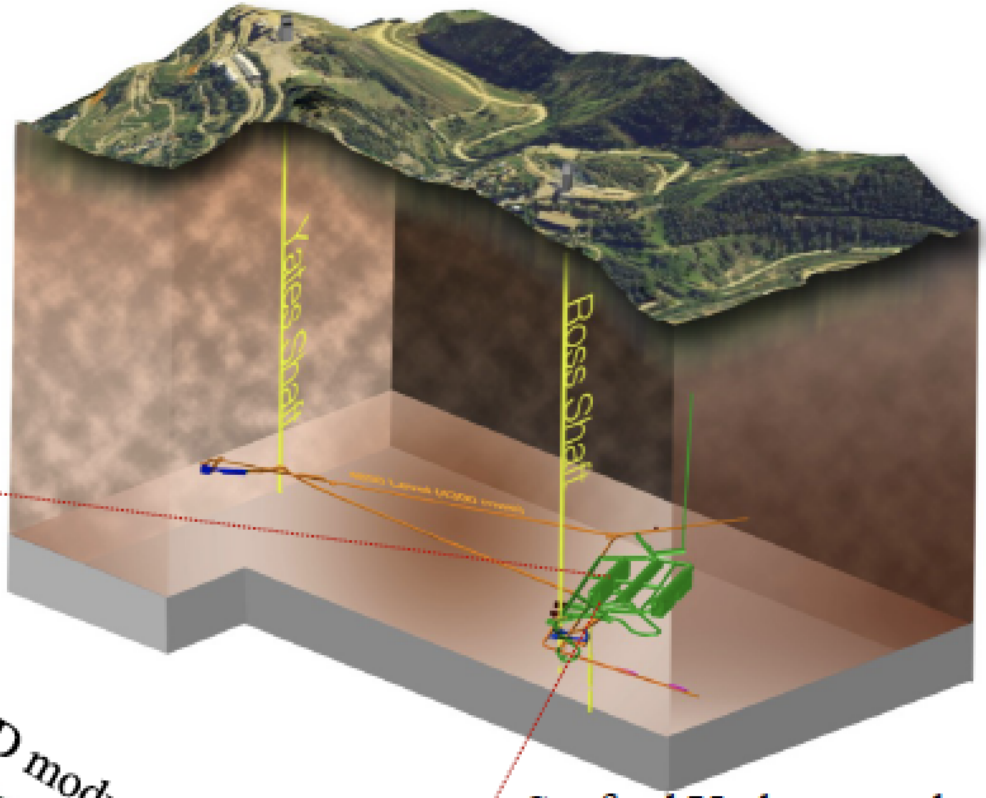
Long Baseline Neutrino Facility (LBNF)

- **DUNE:** The international scientific collaboration
- **LBNF:** DOE/Fermilab-hosted facilities project, with international participation
- **Horn-focused beamline** similar to NuMI beamline
  - 60 – 120 GeV protons from Fermilab's Main Injector
  - 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
  - Initial power 1.1 MW, upgradable to 2.4 MW



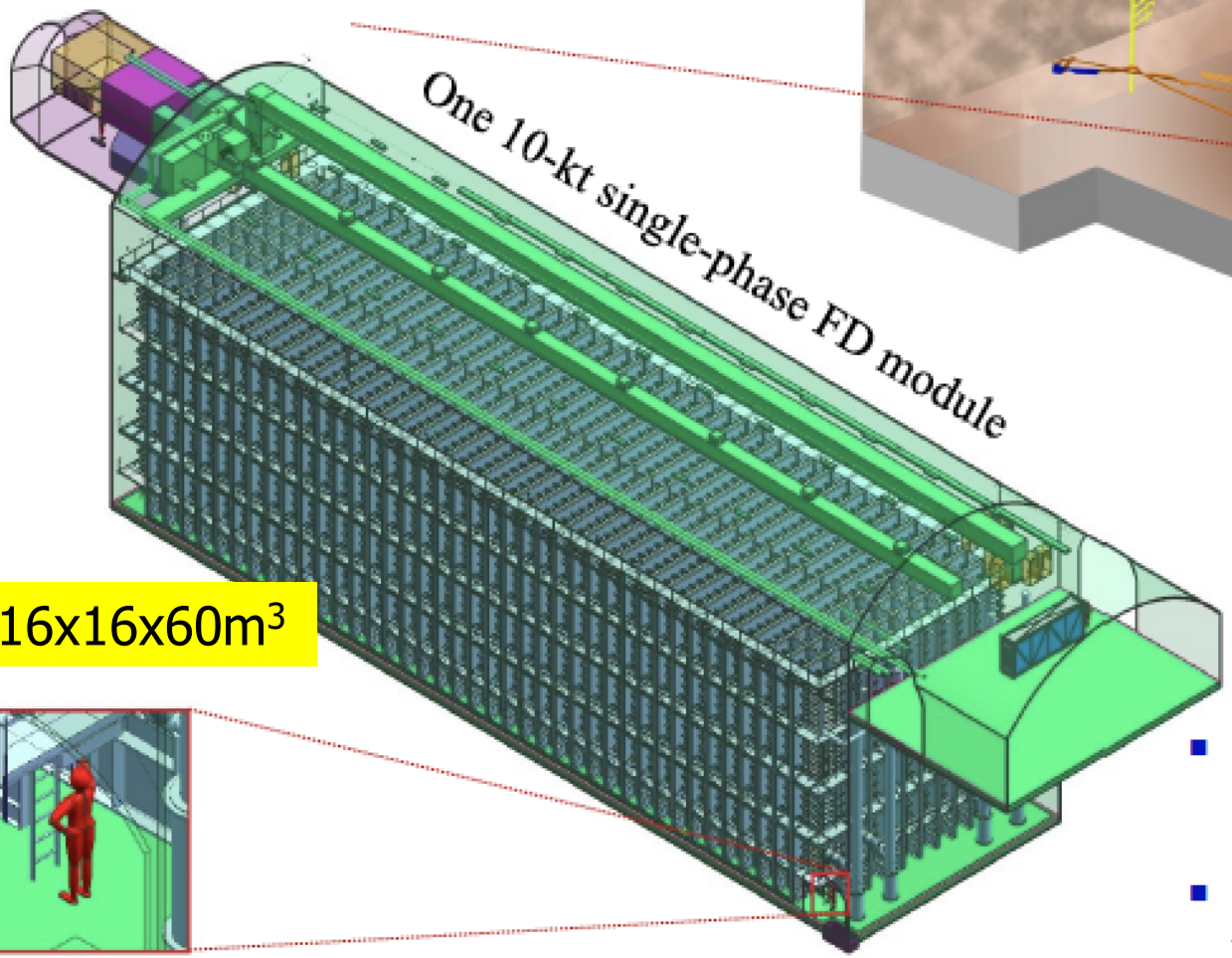
DUNE Far Detector

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



Sanford Underground Research Facility (SURF)

1.5 km underground

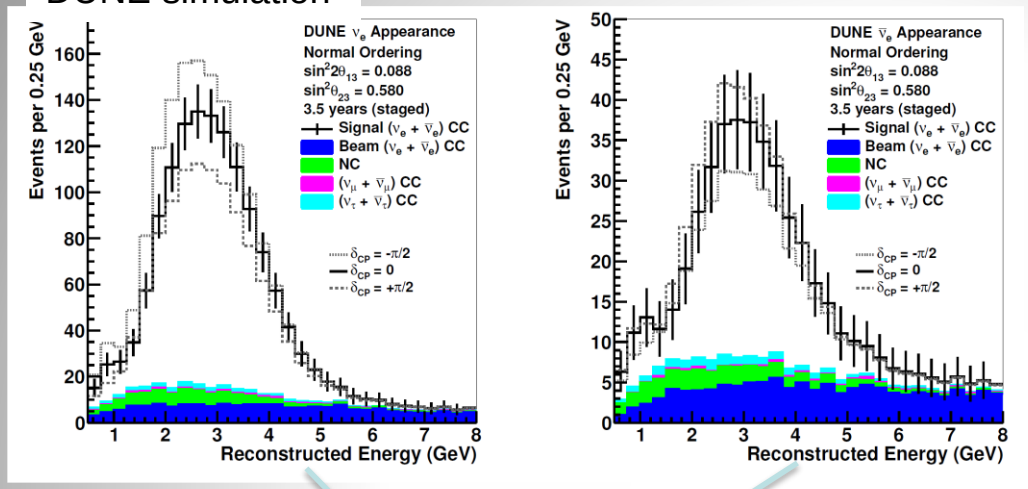


16x16x60m^3

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

Expected number of neutrinos

DUNE simulation

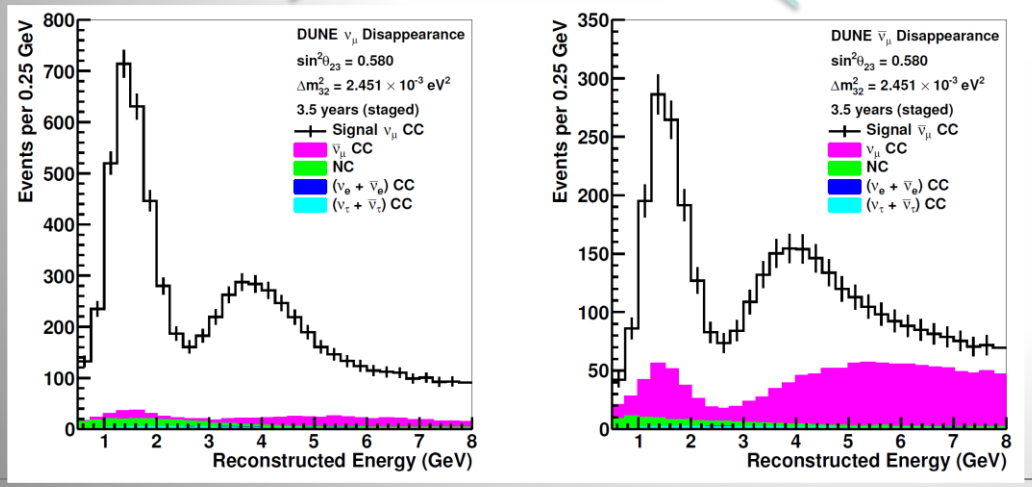


Global Fit

Oscillation Parameter

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

(normal ordering)



~10,000 ν_μ / $\bar{\nu}_?$ events

Matter Effects

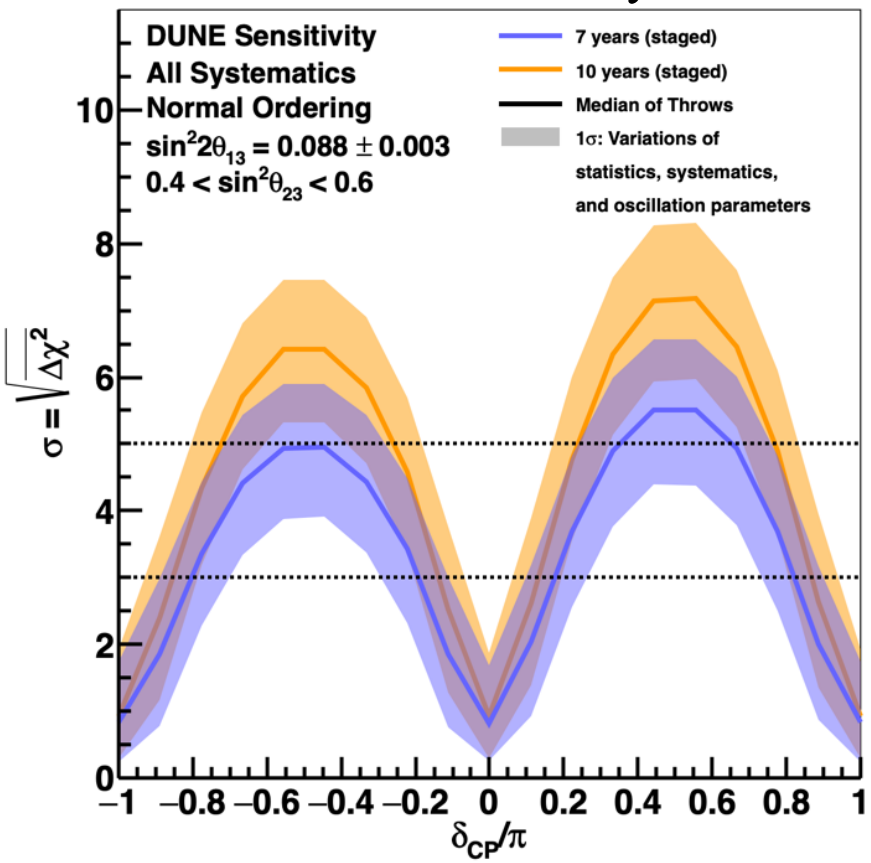
- The probability for ν_e appearance:

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\rm CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$
$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu,\ a = G_F N_e/\sqrt{2},$$

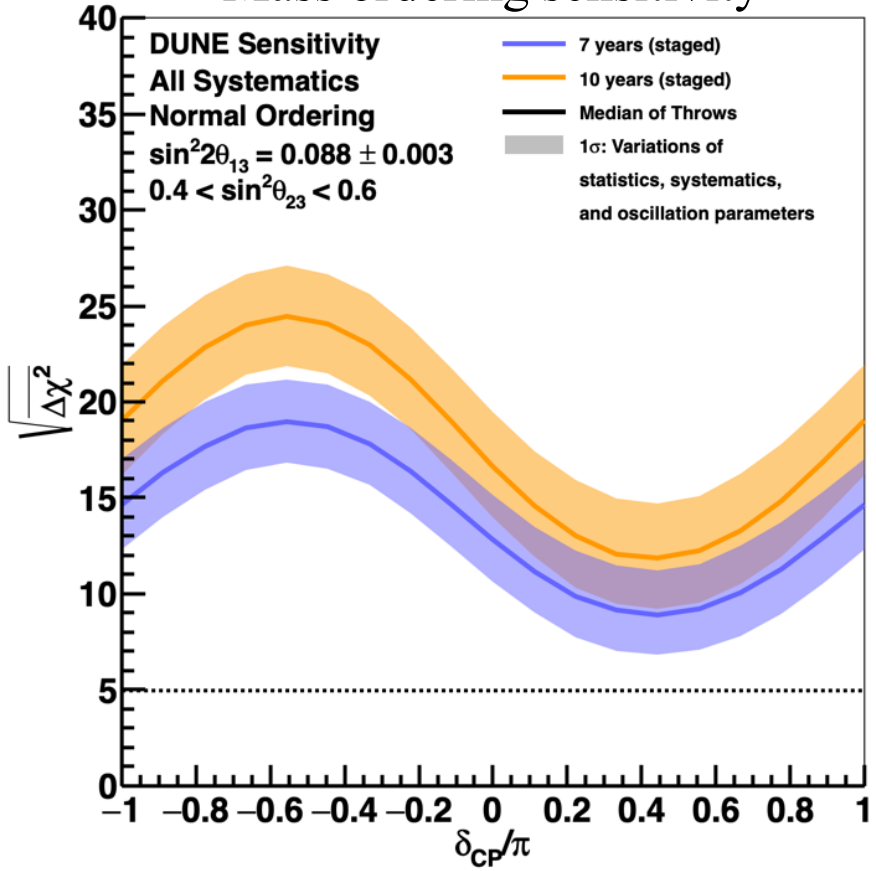
- both δ_{CP} and *a* (matter effect) switch signs in going from the $\nu_\mu \to \nu_e$ to the anti-neutrino process
- The origin of the matter effect asymmetry is simply the presence of electrons and absence of positrons in the Earth.

DUNE: CP Violation and Mass Ordering

*CP*v sensitivity



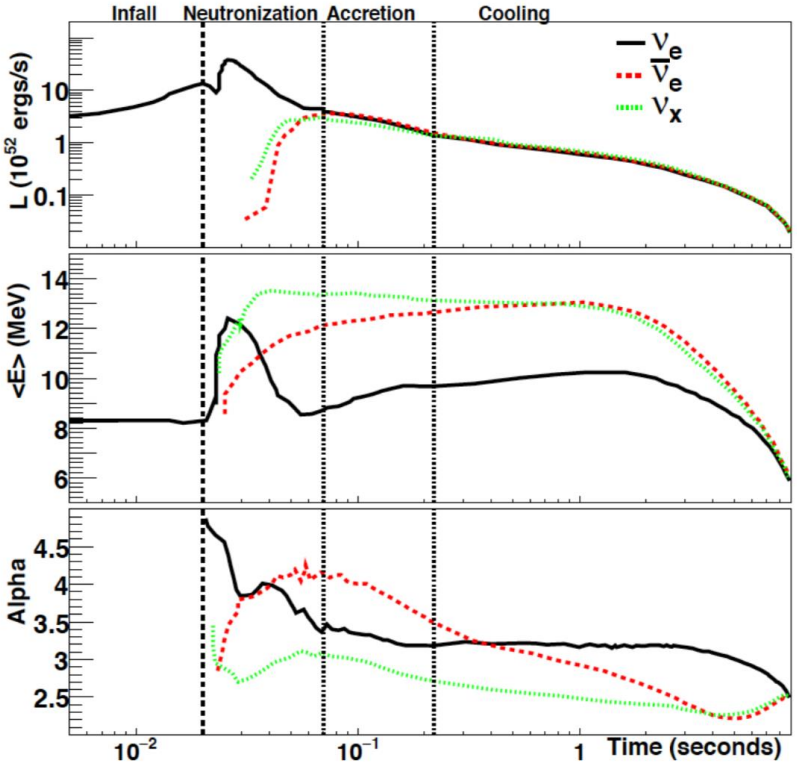
Mass ordering sensitivity

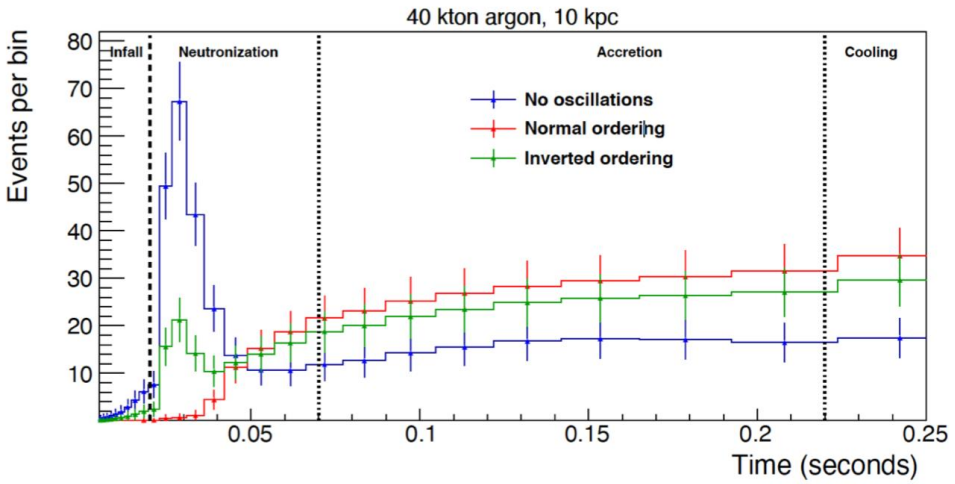


- Updated Sensitivity with realistic systematics and reconstruction
  - Move quickly to potential ***CP* violation discovery**
  - Rapid, definitive **mass ordering determination** (>5σ)

arXiv:2002.03005

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

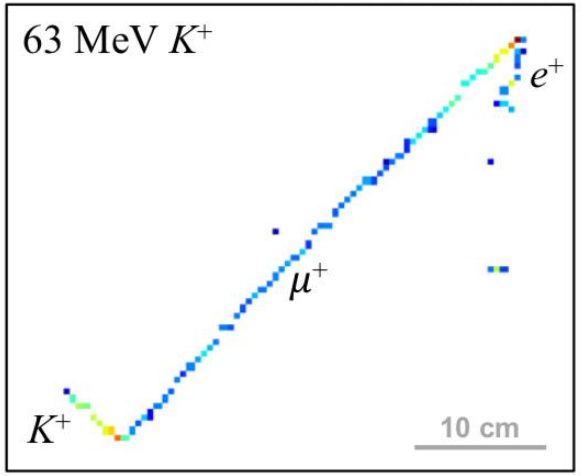
$p \to K\bar{\nu}$ Tracking and dE/dx for rejection of ν_μ CC background ($p + \mu$ final state)

~0.5 bkgnd at 400 kt-yr, 30% signal efficiency
If no signal: **$\tau/B > 1.3\times10^{34}$ yr (90% C.L.)**

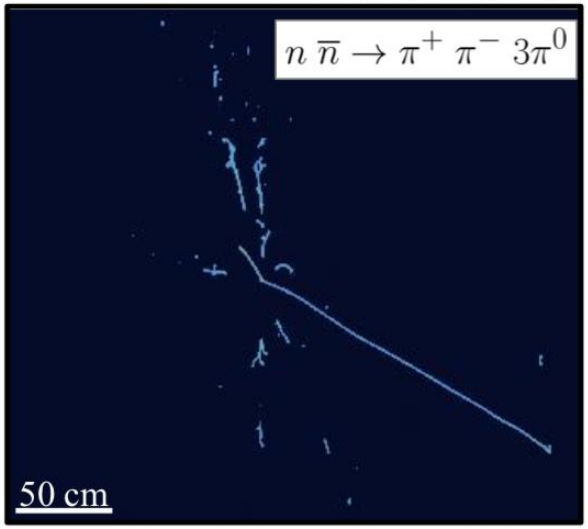
n-$\bar{n}$ osc. Spherical spray of hadrons with $E \approx 2M_n$ and net momentum $\lesssim p_F \sim 300$ MeV

Free-neutron-equivalent sensitivity:
$\tau_{free,osc} > 5.5\times10^{8}$ s (90% C.L.)

DUNE simulation



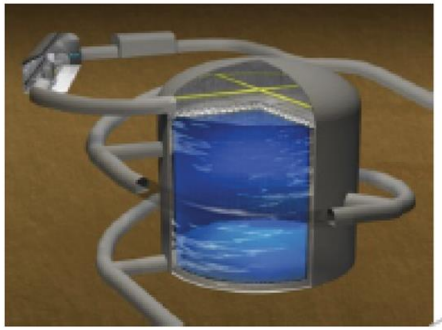
DUNE simulation



Hyper-Kamiokande

Upgrade of the Super-kamiokande experiment in Japan

First data in 2027



Hyper-K

J-PARC
Accelerator Complex

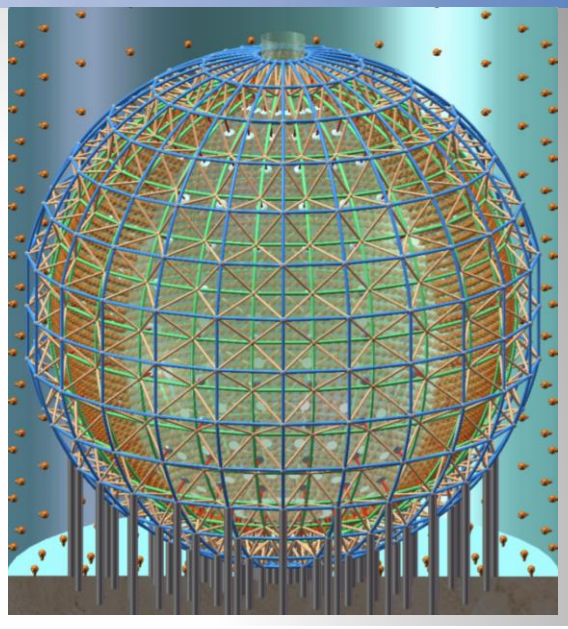
- ✓Gigantic neutrino and nucleon decay detector
  - ✓186 kton fiducial mass : ~10 × Super-K
  - ✓× 2 higher photon sensitivity than Super-K
  - ✓Superb detector capability, technology still evolving
  - ✓2nd oscillation maximum by 2nd tank in Korea under study
- ✓MW-class world-leading ν-beam by upgraded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

Sub-GeV ν beam

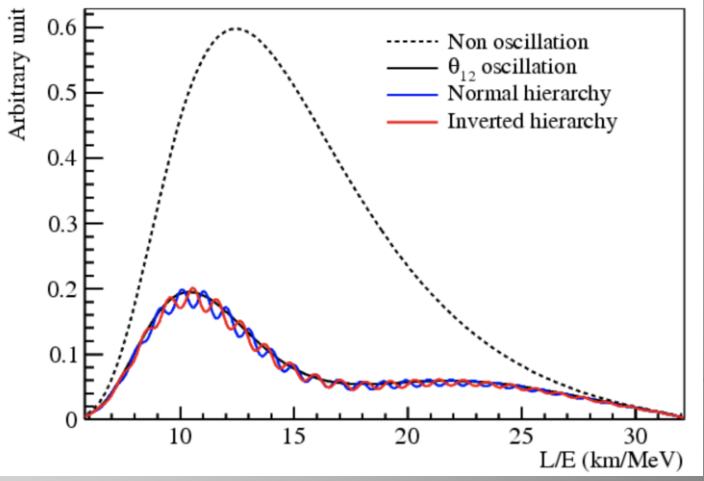
The JUNO Experiment

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 in 2022/2023.

Its main physics goal is the 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 3-4 sigma within six years of running.

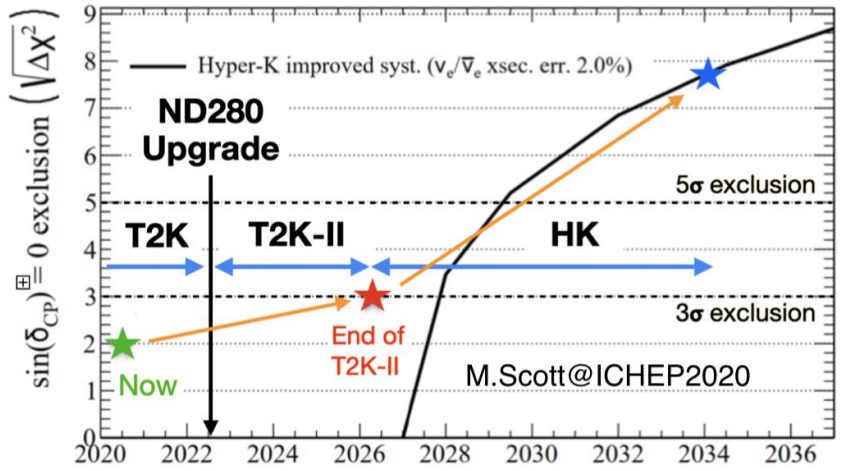


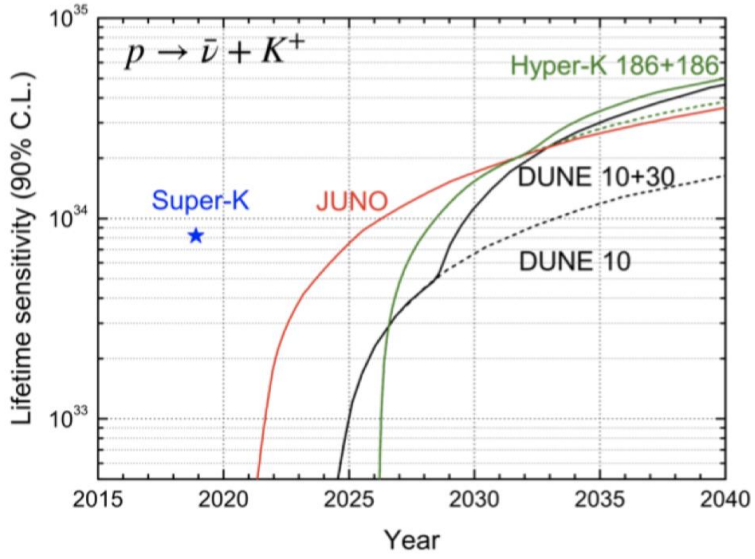
The JUNO Collaboration has ~several hundred physicists

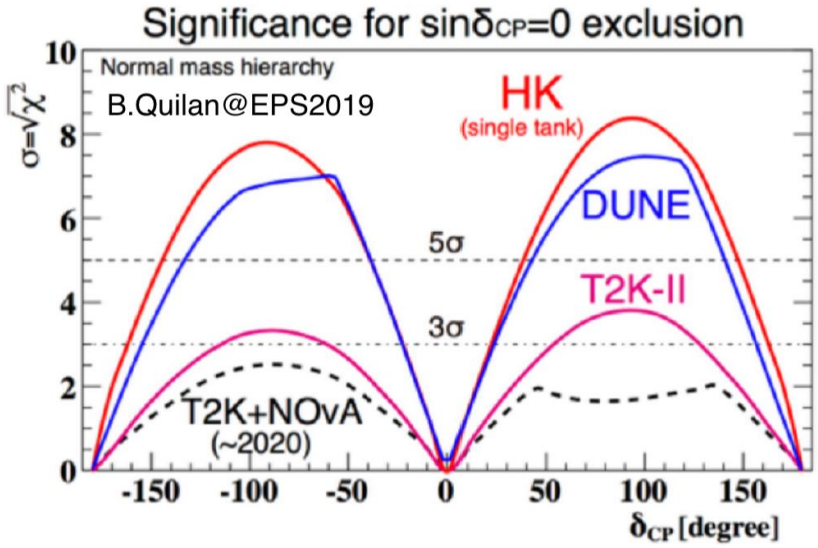


Future Neutrino Experiments

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

Next Generation Experiments

European Spalation Source, Lund

ESSνSB

ESS NEUTRINO SUPER BEAM

Goal: CPV via targeted measurements at 2nd Oscillation Max

Neutrino Superbeam at European Spallation Source

Lund, Sweden

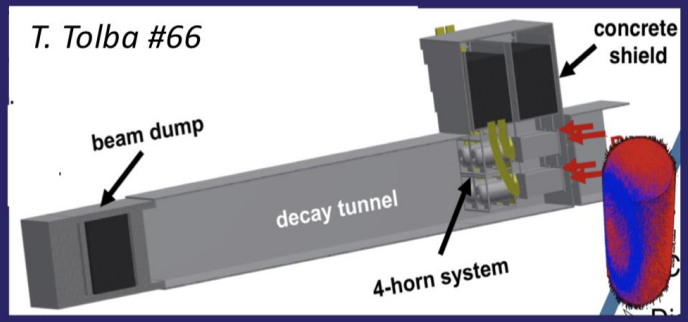
360 km

540 km

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

@ Far Site:

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



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

Experiments ready by ~2035?

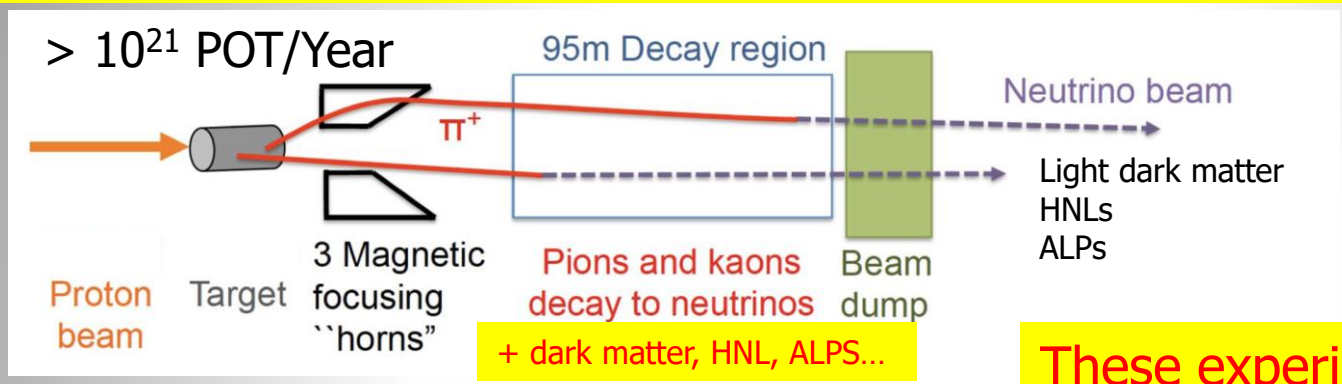
Also: new/tagged beams
NuStorm muon storage ring
…

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!

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



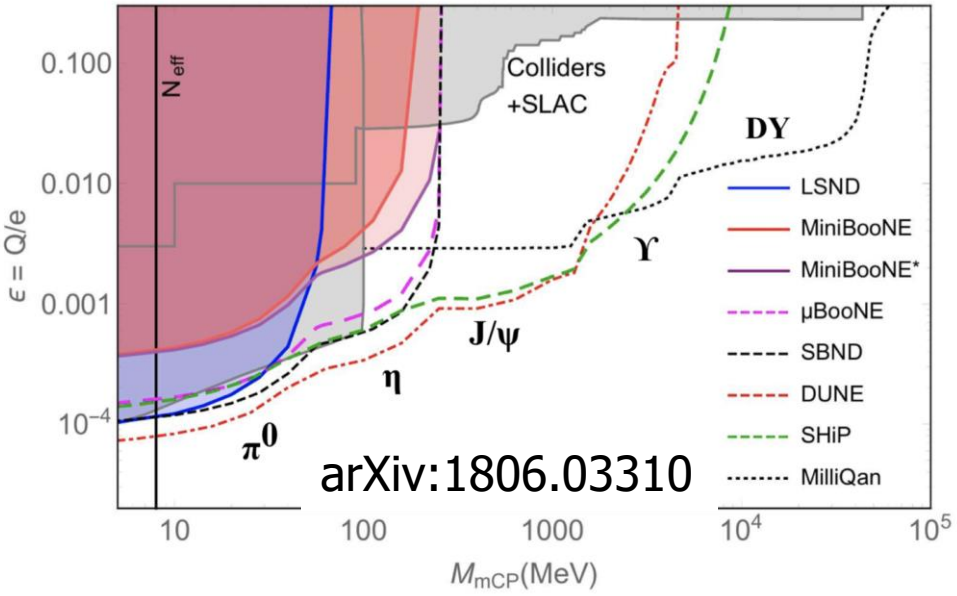
+ dark matter, HNL, ALPS…

Near Detector: few 100m away from the dump

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

Example millicharges:



arXiv:1806.03310

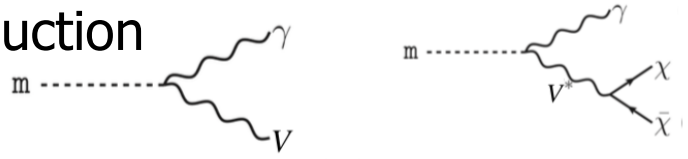
NEXT-GENERATION NEUTRINO EXPERIMENTS
(PART 1: BSM NEUTRINO PHYSICS AND DARK MATTER)

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]

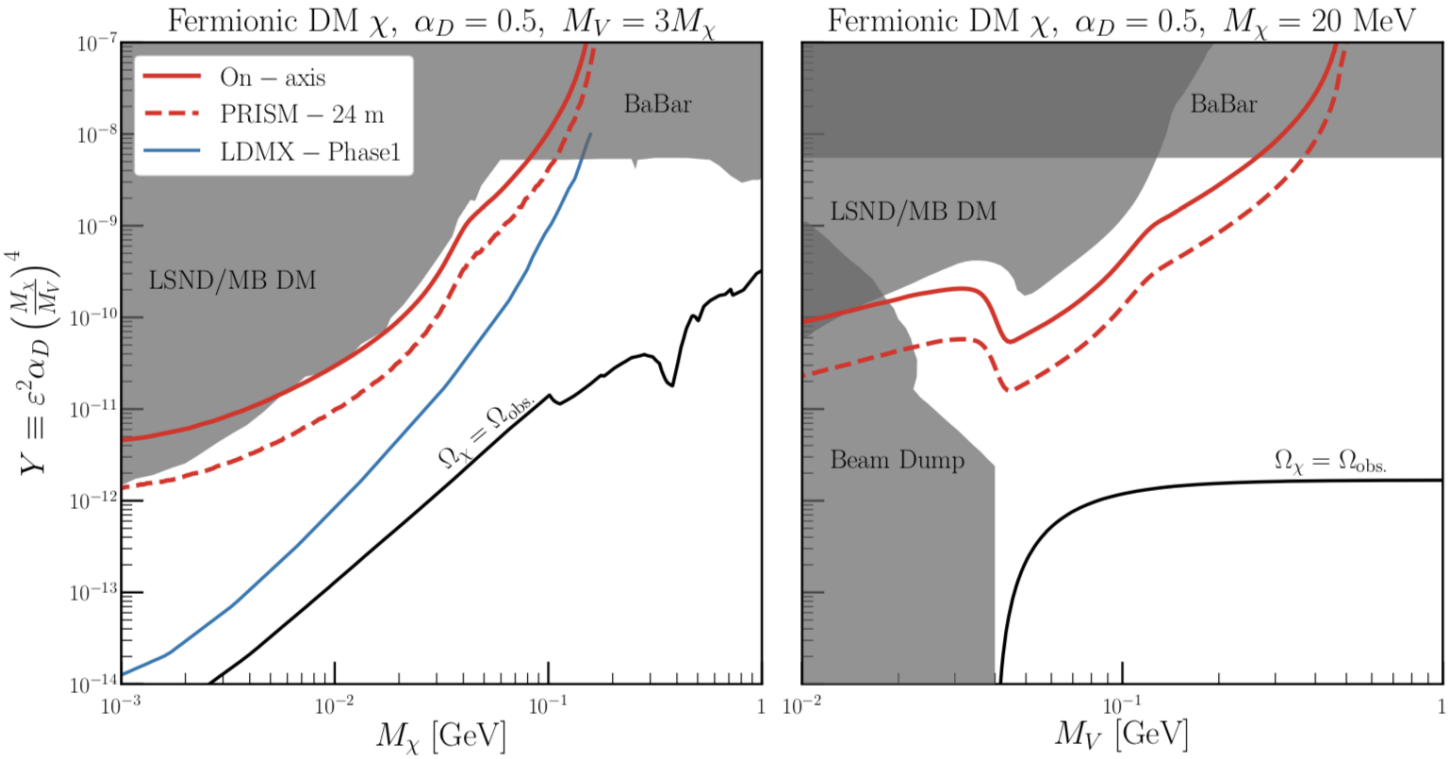
Searches for Low Mass Dark Matter

Light dark matter produced at the accelerator (meson decays)

Production

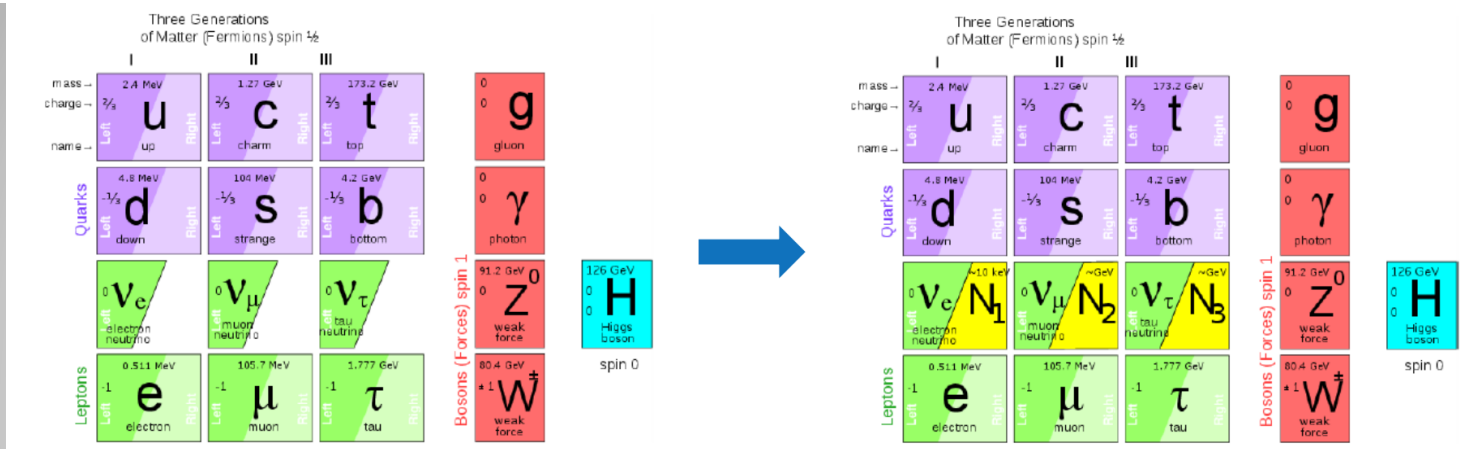


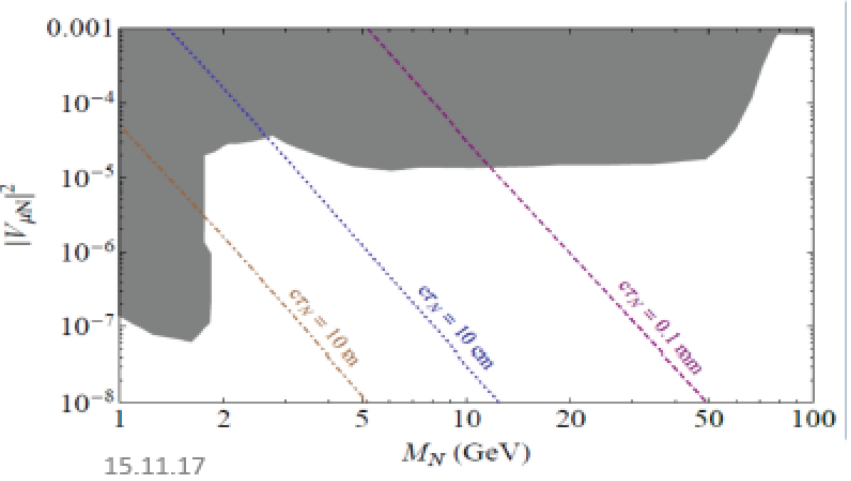
Elastic scattering



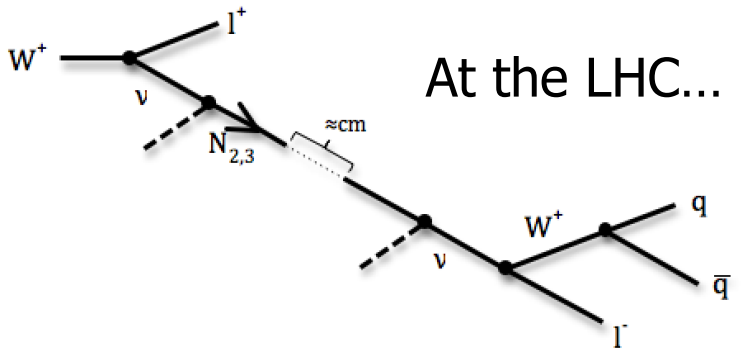
Heavy Neutral Leptons

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



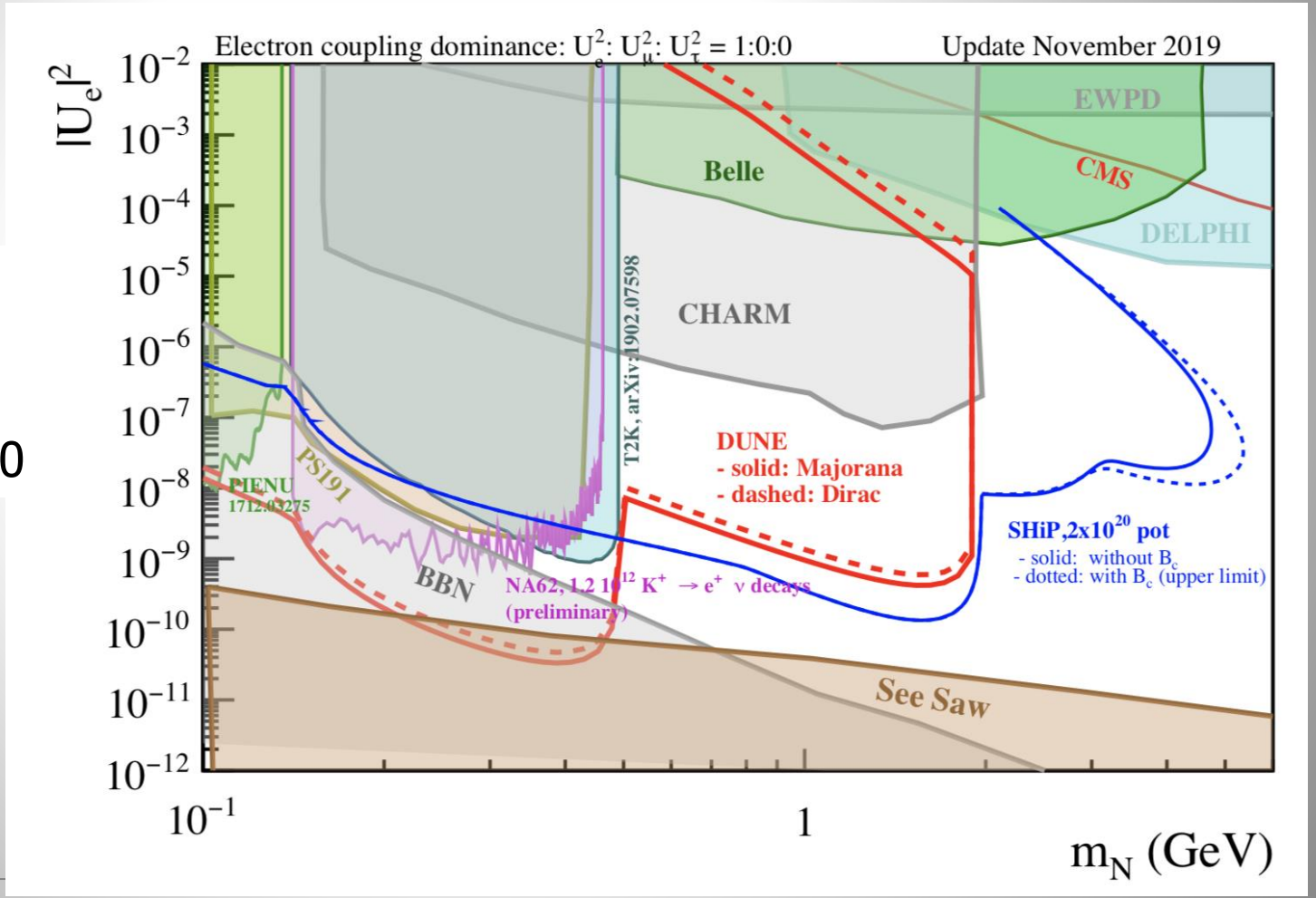
At the LHC…

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

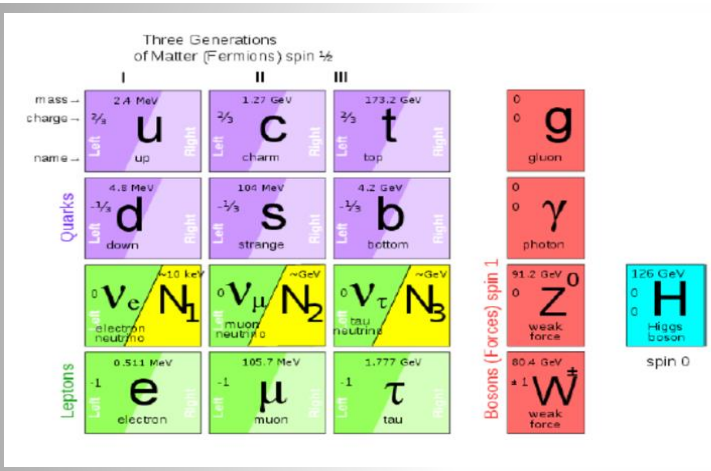


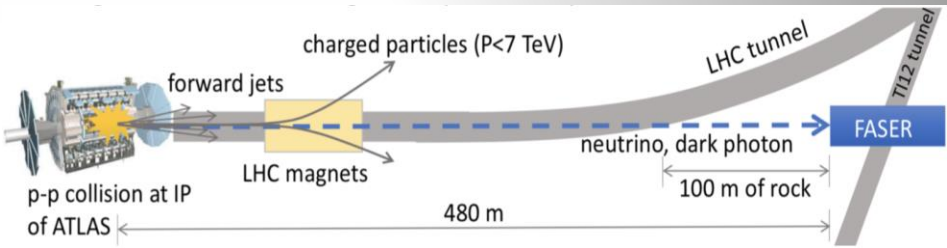
Neutrinos @ the LHC: Examples

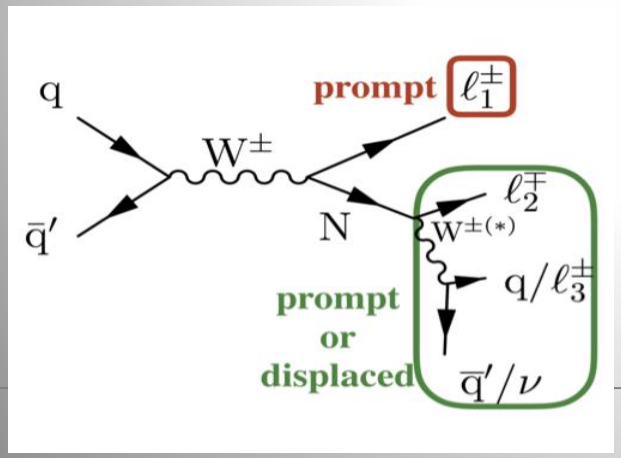
Searches for right-handed neutrinos at the LHC

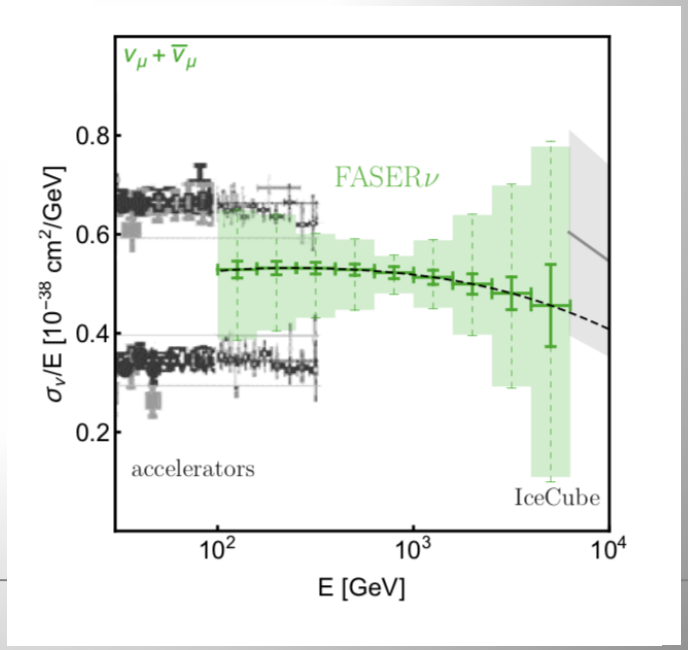
SND@LHC and FASER-Nu are 400m forward of the IPs and can study TeV-neutrinos with emulsion detectors

νMSM (Neutrino Minimal Standard Model)



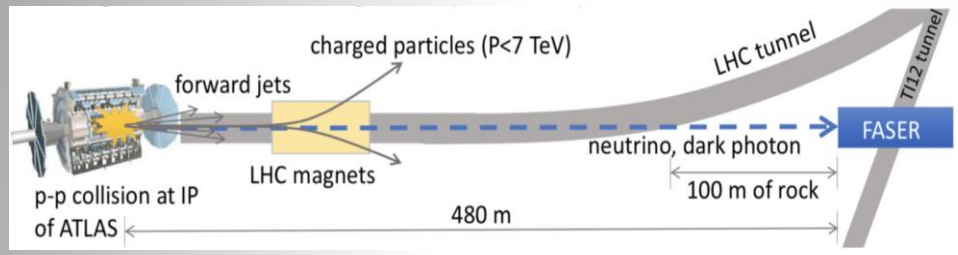






Neutrinos @ the LHC: SND@LHC

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



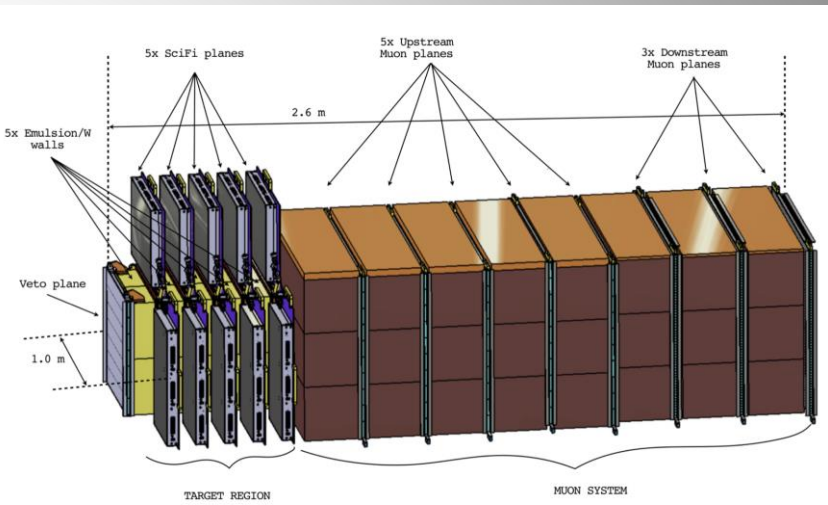
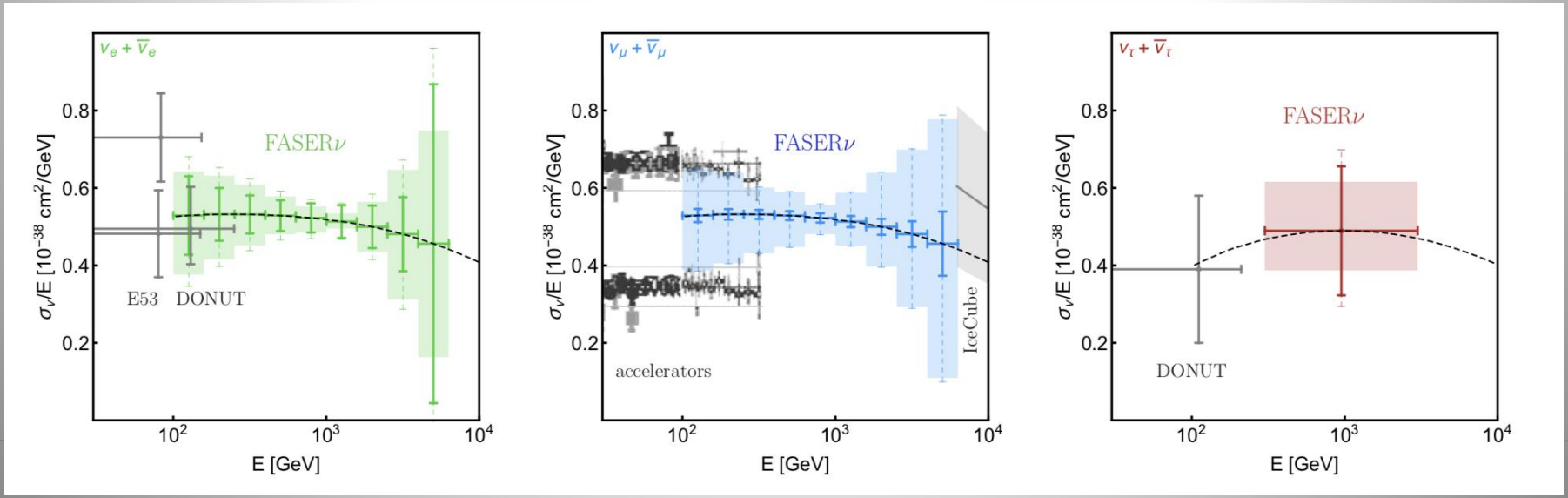


Figure 5: Layout of the proposed SND@LHC detector.

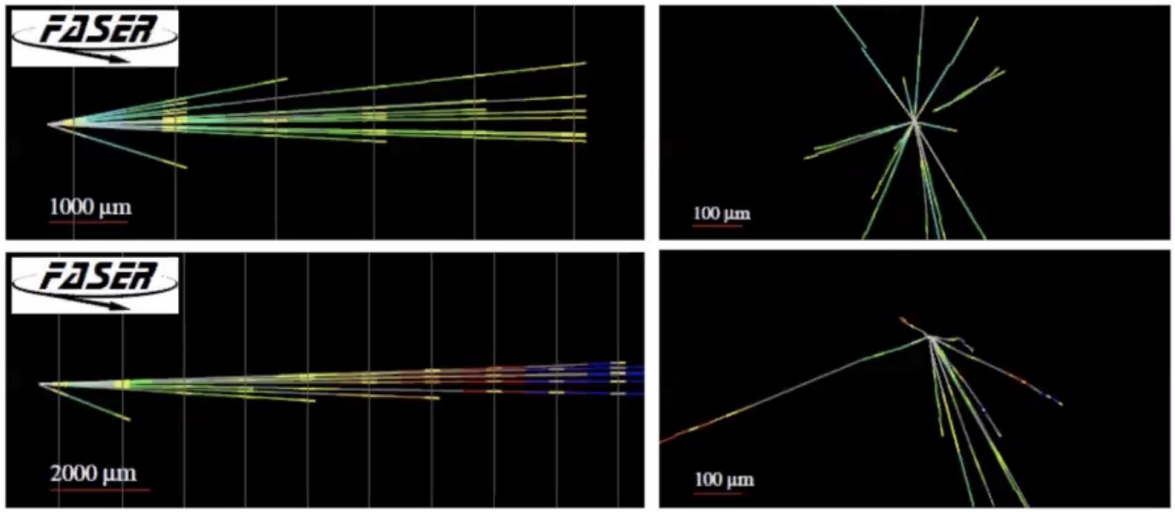
SND= Scattering and neutrino detector



First Observed neutrinos in FASER-ν

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

Neutrino interaction candidates



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

First neutrino interaction candidates at the LHC, arXiv:2105.06197

First neutrino interaction candidates at the LHC

(FASER Collaboration)

FASERν at the CERN Large Hadron Collider (LHC) is designed to directly detect collider neutrinos for the first time and study their cross sections at TeV energies, where no such measurements currently exist. In 2018, a pilot detector employing emulsion films was installed in the far-forward region of ATLAS, 480 m from the interaction point, and collected 12.2 fb^{-1} of proton-proton collision data at a center-of-mass energy of 13 TeV. We describe the analysis of this pilot run data and the observation of the first neutrino interaction candidates at the LHC. This milestone paves the way for high-energy neutrino measurements at current and future colliders.

I. INTRODUCTION

There has been a longstanding interest in detecting neutrinos produced as collidera [1–4], but to date no collider neutrino has ever been directly detected. Proton-proton (pp) collisions at a center-of-mass energy of 14 TeV during LHC Run-3, with an expected integrated luminosity of 150 fb^{-1}, will produce a high-intensity beam of $\mathcal{O}(10^{17})$ neutrinos in the far-forward direction with mean interaction energy of about 1 TeV. FASERν [7] is designed to detect these neutrinos and study their prop-

A Multi-Frontier Problem

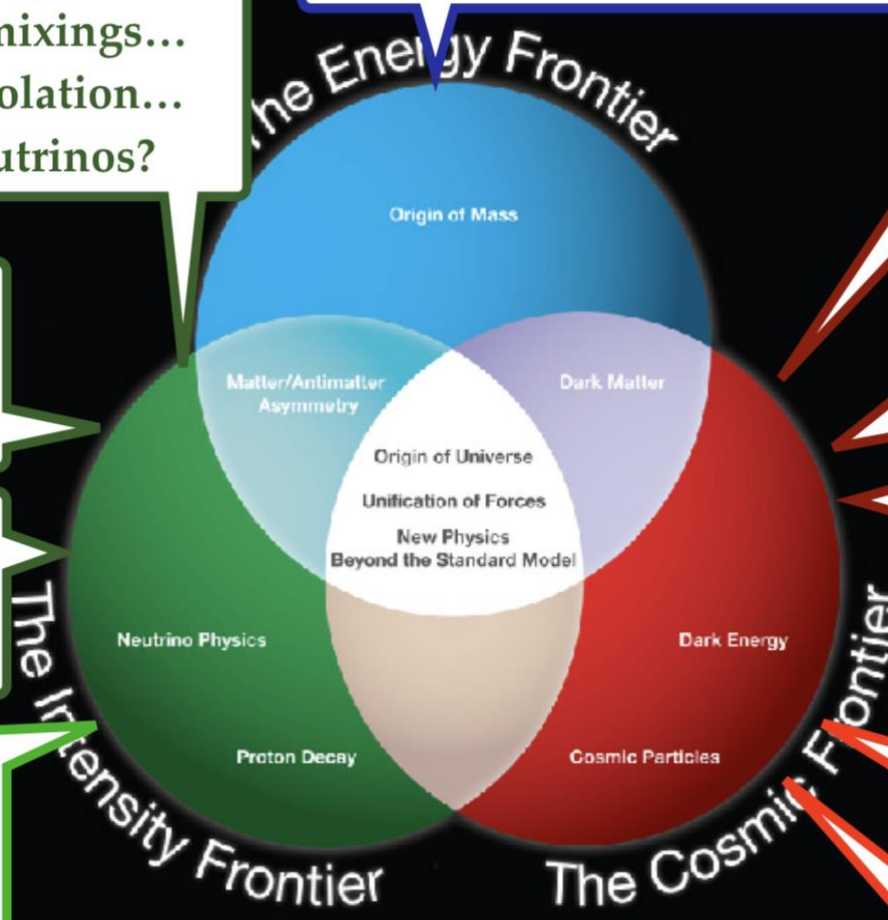
Collider Probes of the origin of neutrino mass

neutrino oscillation experiments
mass differences, mixings…
… hierarchy, CP violation…
…light sterile neutrinos?

absolute neutrino
mass searches
(KATRIN ect.)

neutrinoless
double β decay:
Dirac or Majorana?

fixed target
experiments
(SHiP, NA62, …)



CMB and LSS :
absolute neutrino mass

CMB and BBN :
light sterile neutrinos?

IceCube
"neutrino astronomy"

Cosmic Neutrino
Background

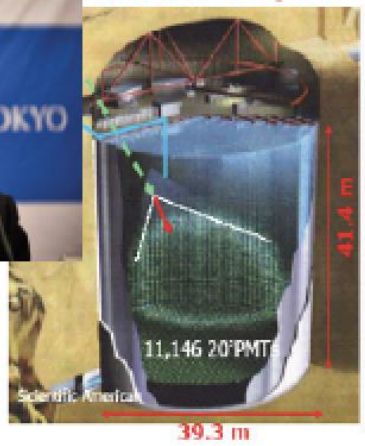
Leptogenesis?

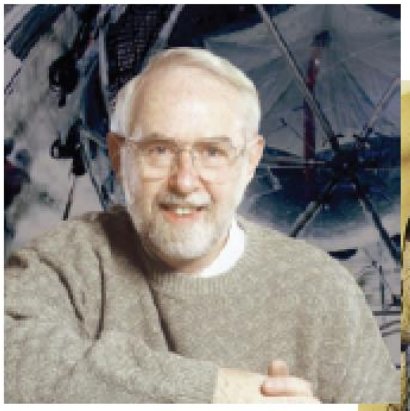
Sterile Neutrino
Dark Matter?

NOBEL 2015

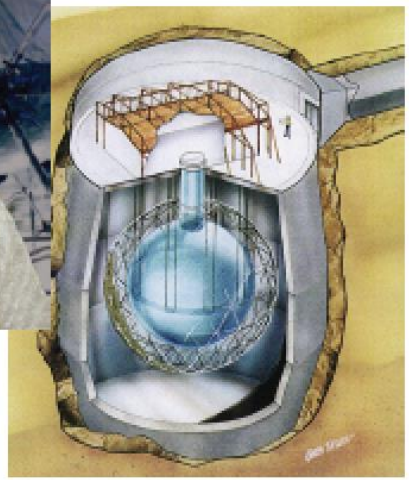
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Takaaki Kajita
SuperKamiokaNDE





Art McDonald
SNO

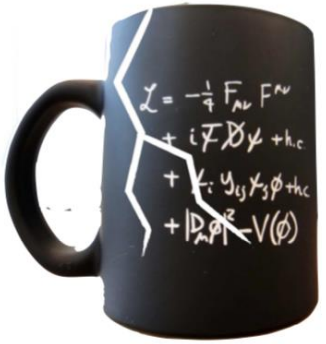


"for the discovery of neutrino flavor transformations, which shows that neutrinos have mass"

3 Other Nobel prizes for Neutrino Physics
-2002: R. Davis and M. Koshiba
-1995: F. Reines
-1988: L. Lederman, M. Schwartz and J. Steinberger

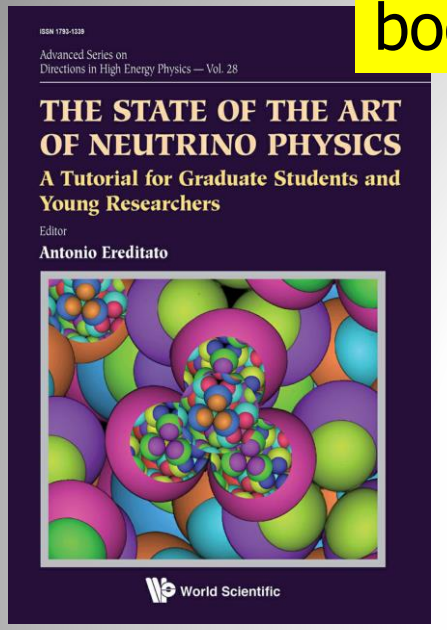
SUMMARY: Neutrinos

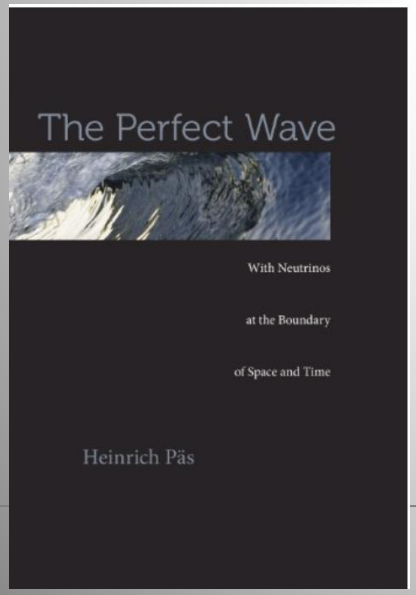
- Neutrinos studies is a vibrant field of research, and has still many open questions! Right-handed partners? Large CP violation? More than 3 neutrinos? Non-Standard Interactions? Are neutrinos their own anti-particle?
- Now comes the age of neutrino precision physics with DUNE & T2HK and neutrino astronomy: 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??



More on Neutrinos..

books





school

Recent visit on 12/8/2021

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

https://indico.cern.ch/event/1011452/

Backup

Neutrinos and New Physics

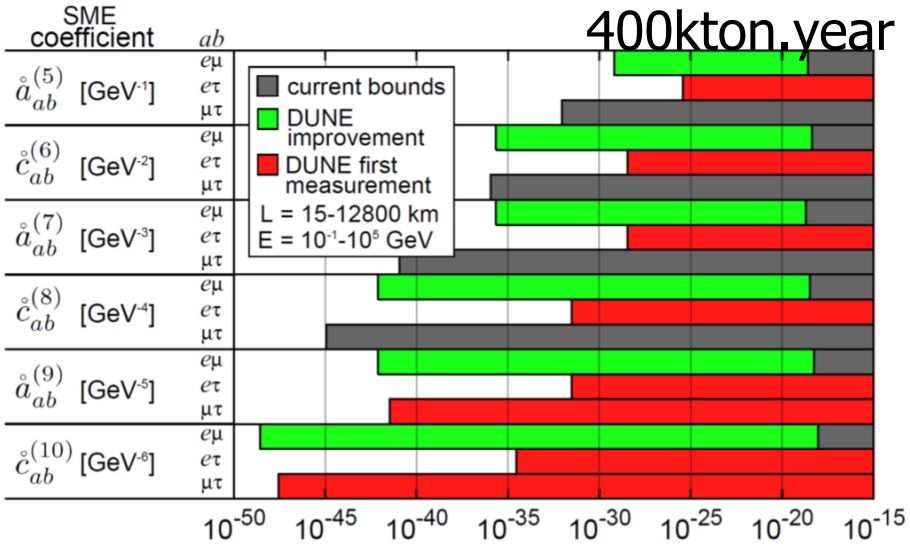
Neutrinos have connections to many other BSM or New Physics ares, also studied eg at the LHC

- 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)??
- ….

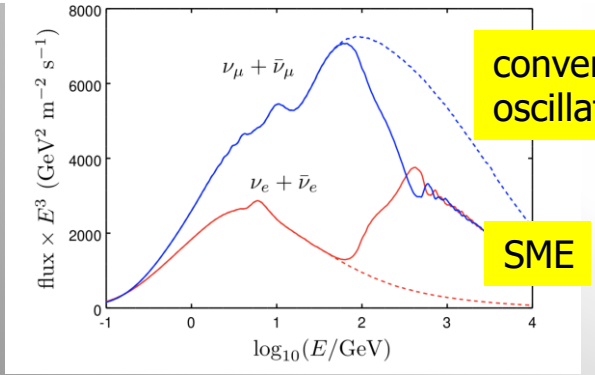
Atmospherics and Supernovae

Sensitivities to Lorentz and CPT violation

DUNE atmospheric sensitivities to Lorentz and CPT Violation

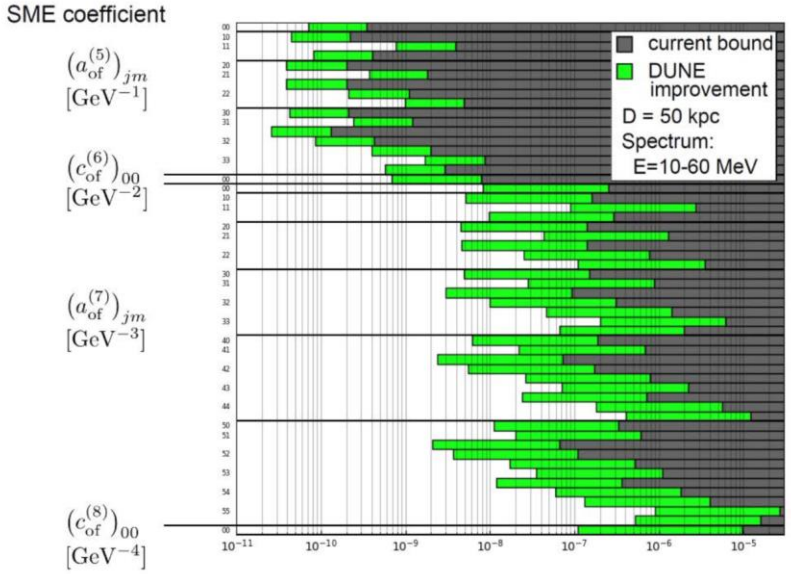


Analyzed in the SME (Standard Model Extension) framework



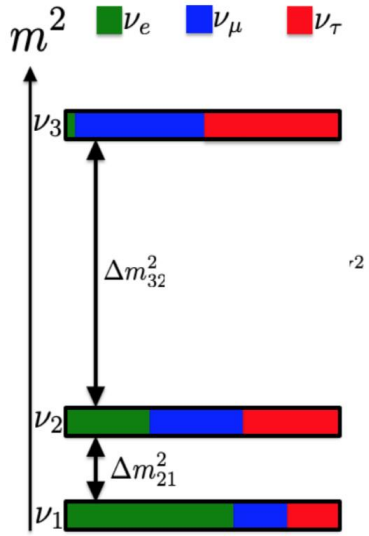
Atmospheric neutrino flux

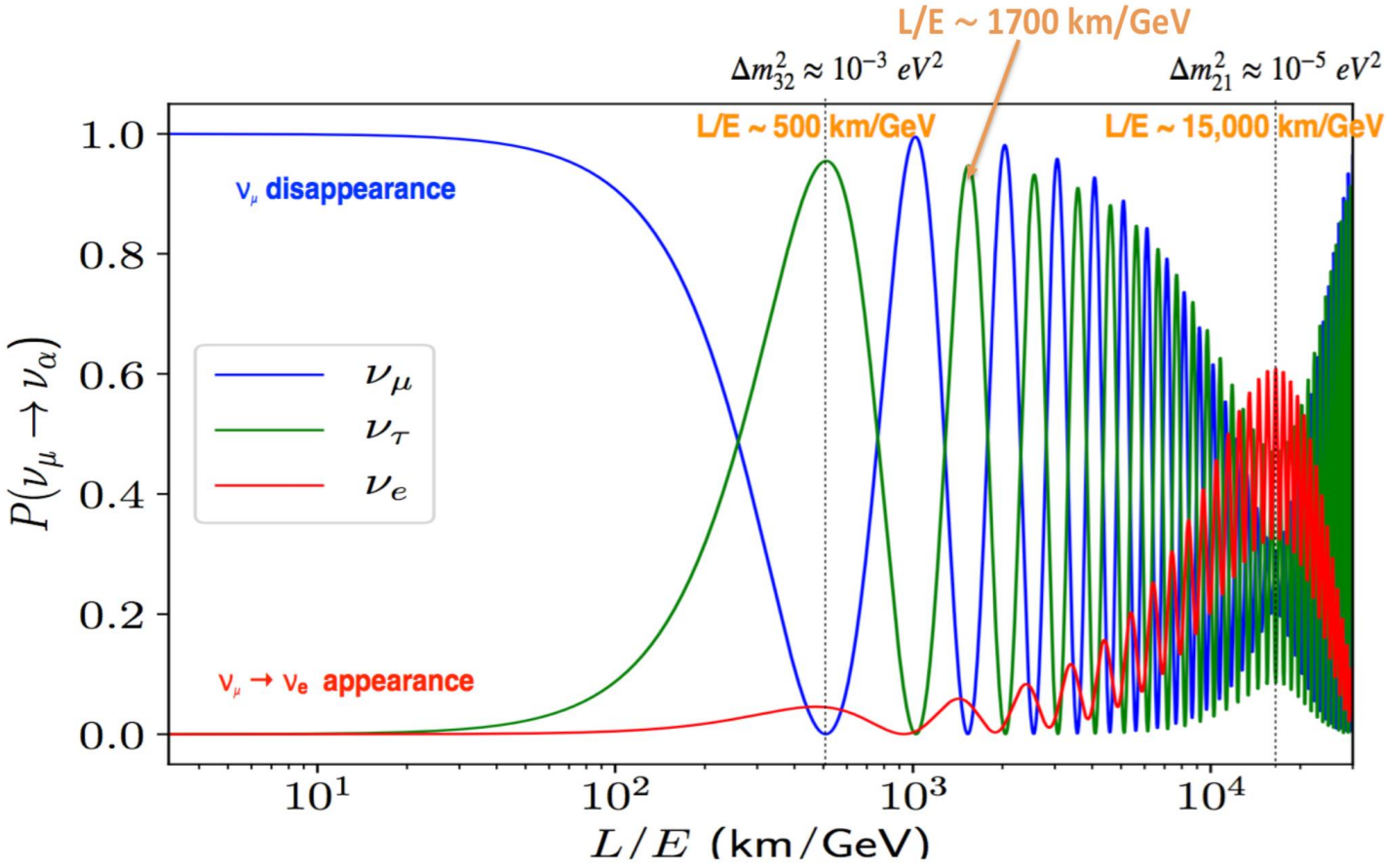
DUNE supernova sensitivities to Lorentz and CPT violation



Oscillation free coefficients

Finding the Oscillation Maximum





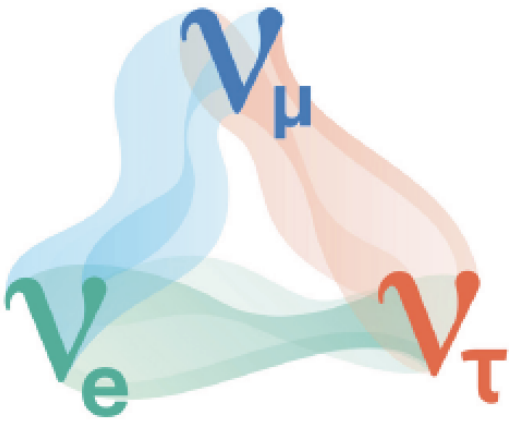
Typical neutrino beam energy is around 2.5 GeV

Neutrino Oscillations

Interactions:

simple

complicated



$= U$

unitary matrix ?

complicated

simple

Propagation:

masses ?