Neutrinos!

Present Understanding & Future Prospects

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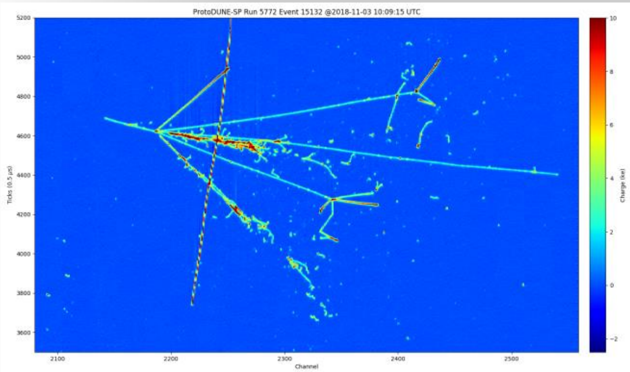
CERN, Geneva, Switzerland
30th August 2021

CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

Outline

- 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)
- Neutrino experiments at the LHC
- Summary



Pion event in the ProtoDUNE at CERN

Speaker of today

Neutrinos

- Neutrinos at the CERN-Fermilab Hadron Collider Physics Summer School?
  - No neutrino collider any time soon ☺ (***νν*** collisions do happen plentifully in supernova explosions…). Neutrino factory..?
- Fermilab has a strong ongoing program on neutrino physics
  - Eg DONUT, MINOS, MINERvA, MicroBooNE, MiniBooNE, NOvA…
  - And future: ICARUS, SBND, DUNE…
- CERN is coming back "on-line" in neutrino physics. Significant investment with the Neutrino Platform
  - ProtoDUNEs, participating in DUNE, SBN, T2K,..
- The LHC is also becoming a place to study neutrinos, via searches for new or heavy neutrinos, or more recently via news experiments that will measure high energy neutrino interactions (FASER(-Nu), SND@LHC)

Neutrino Collider

Theory Colloquia

The Large Neutrino Collider

by Pedro Machado (Fermilab)

Wednesday 18 Nov 2020, 14:00 → 15:00 Europe/Zurich

Zoom only (CERN)

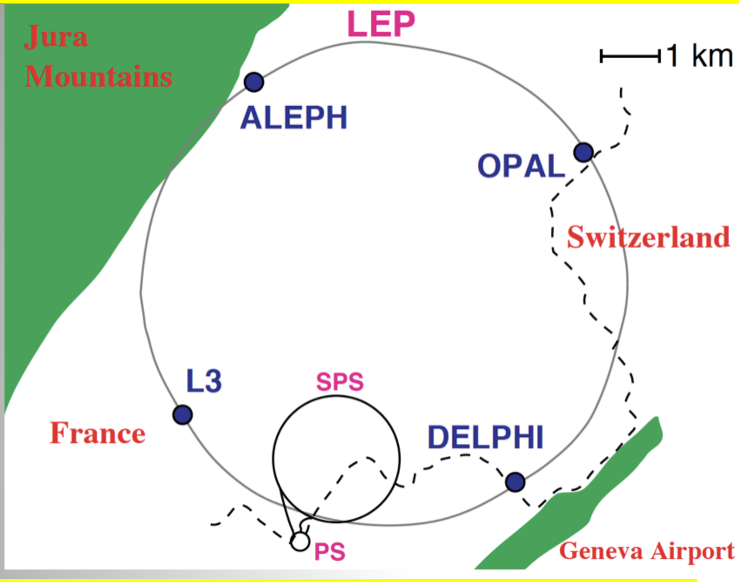
Neutrinos

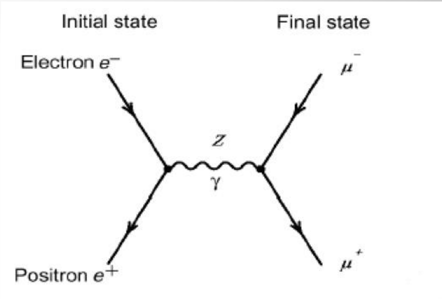
Neutrinos are still mysterious particles

- 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 come in 3 Flavours

LEP e+e- collider at CERN (1988-2000)



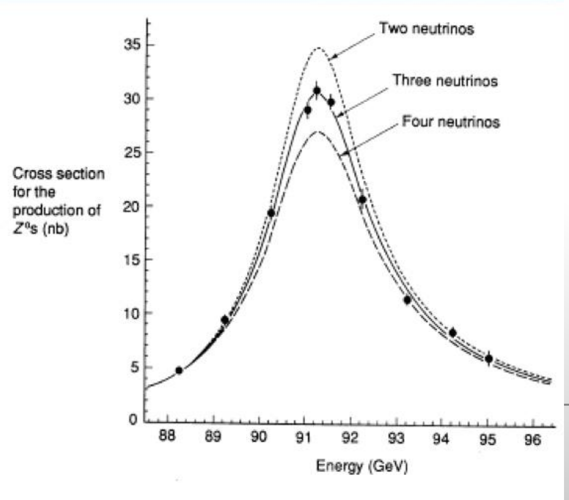


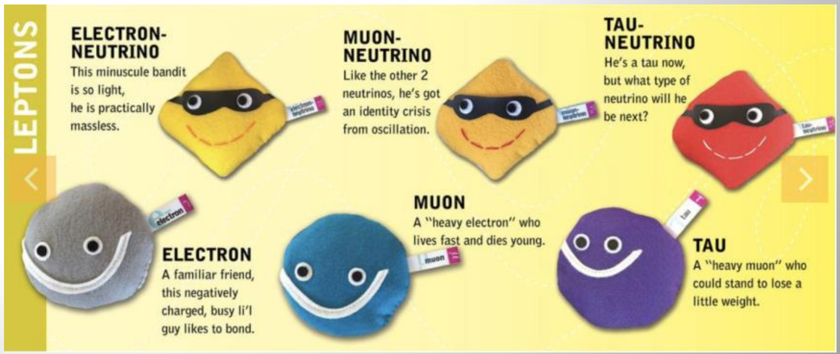
The width of the Z-boson gives the number of neutrinos

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_l + N_\nu \Gamma_\nu$$

$$N_\nu = 2.99 \pm 0.02$$

Detailed study of the Z-boson



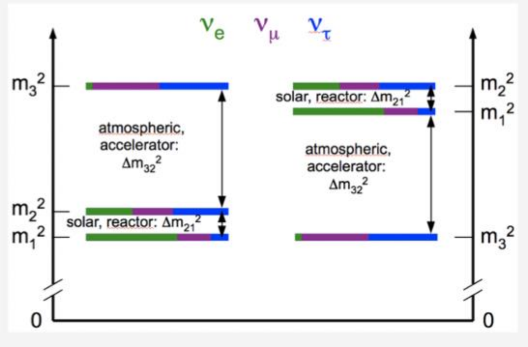


LEP: three active neutrinos with mass<45 GeV

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?

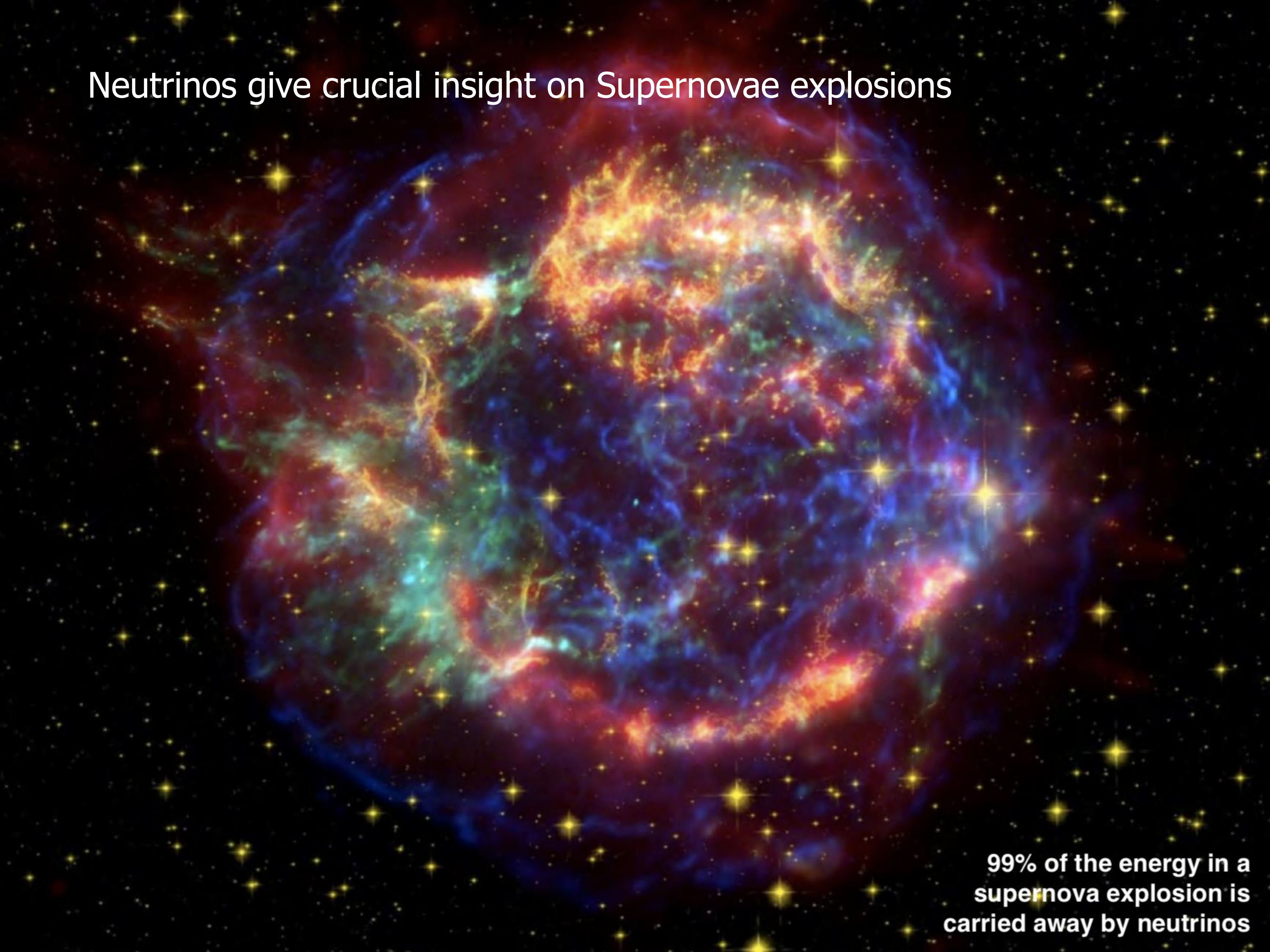


- Are neutrinos their own antiparticles? -> LNV processes
- Do right-handed/sterile/heavy neutrinos exist?
- Are there non-standard neutrino interactions?
- Neutrinos and Dark Matter?
- Testing of CPT..
- Neutrinos are Chameleons: They can change flavour!!

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

Plenty of neutrinos in the Universe

Neutrinos give crucial insight on Supernovae explosions



99% of the energy in a supernova explosion is carried away by neutrinos

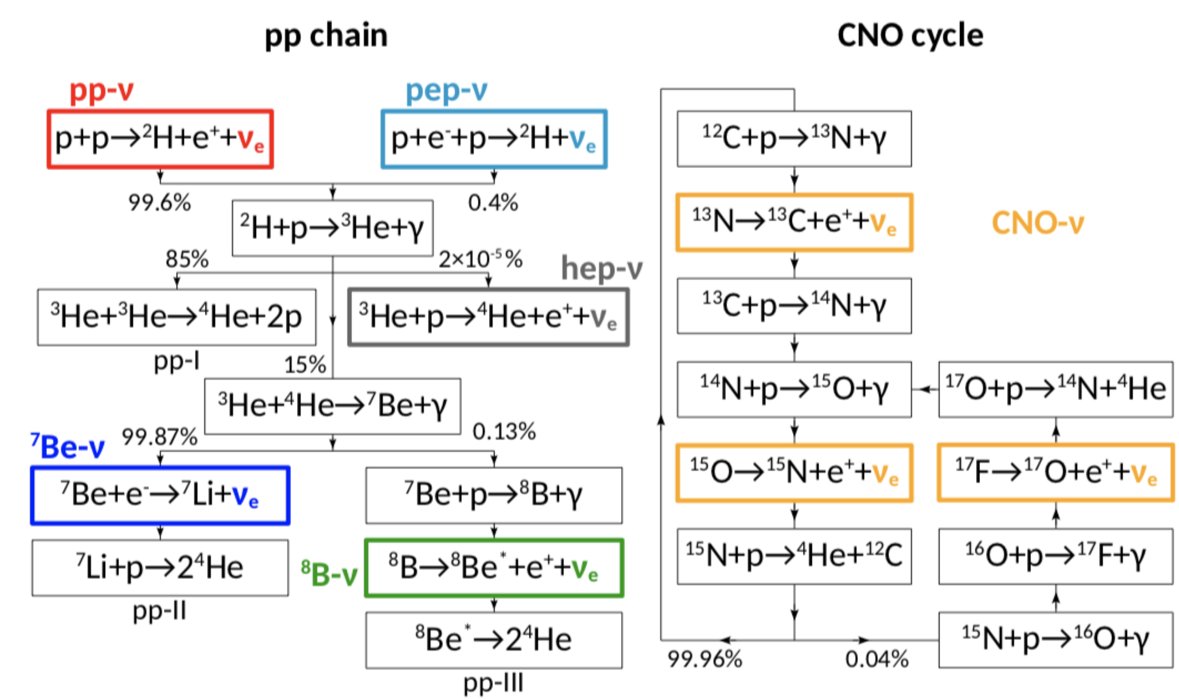
Neutrinos allow us to to look into the heart of the sun

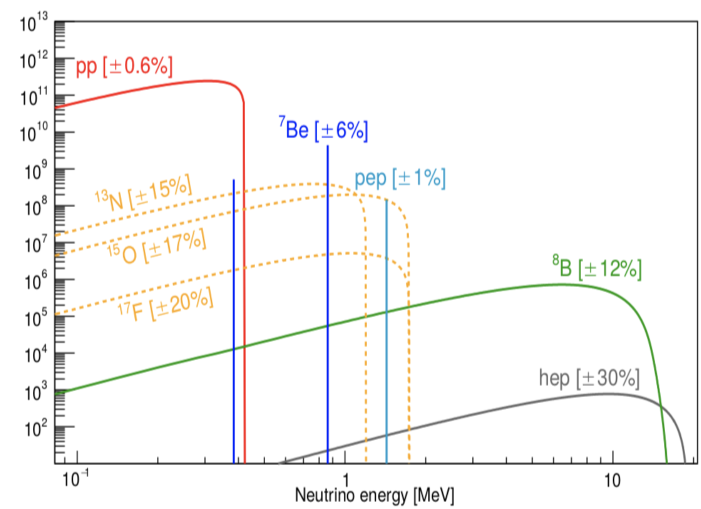
10^{38} neutrinos per second
are produced by the Sun

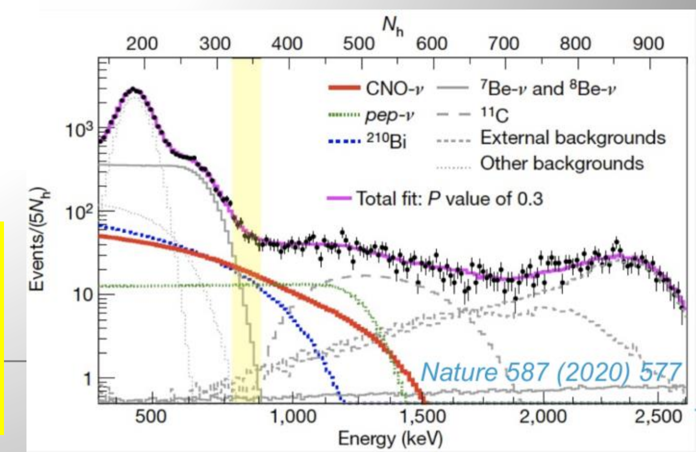
(with a flux of ~10^{11}/cm^2/sec at the Earth)

Solar Neutrinos

Neutrino measurements allow to understand how the sun works

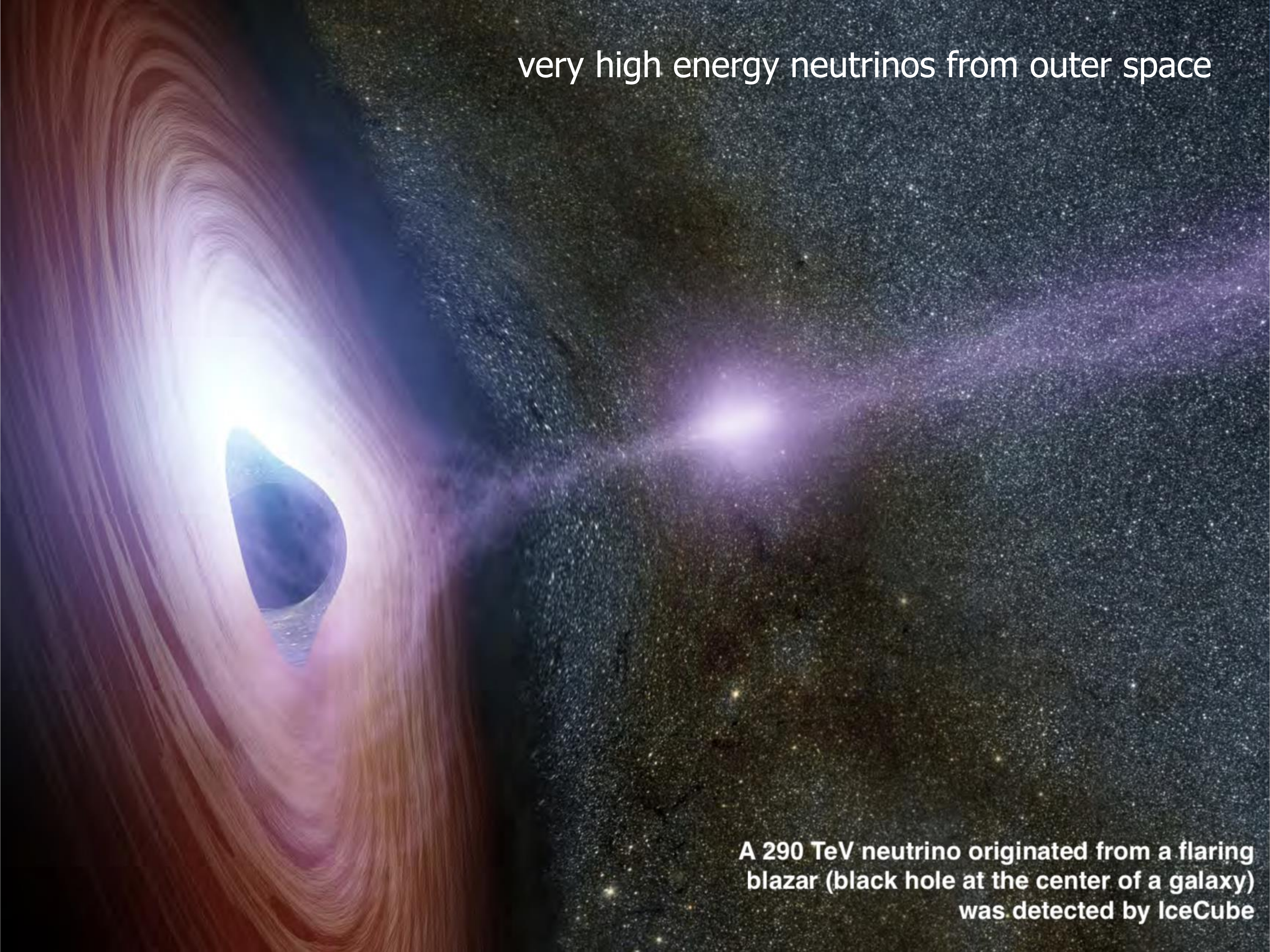






2020: Borexino measured the CNO cycle ->
Nature 687 (220) 577

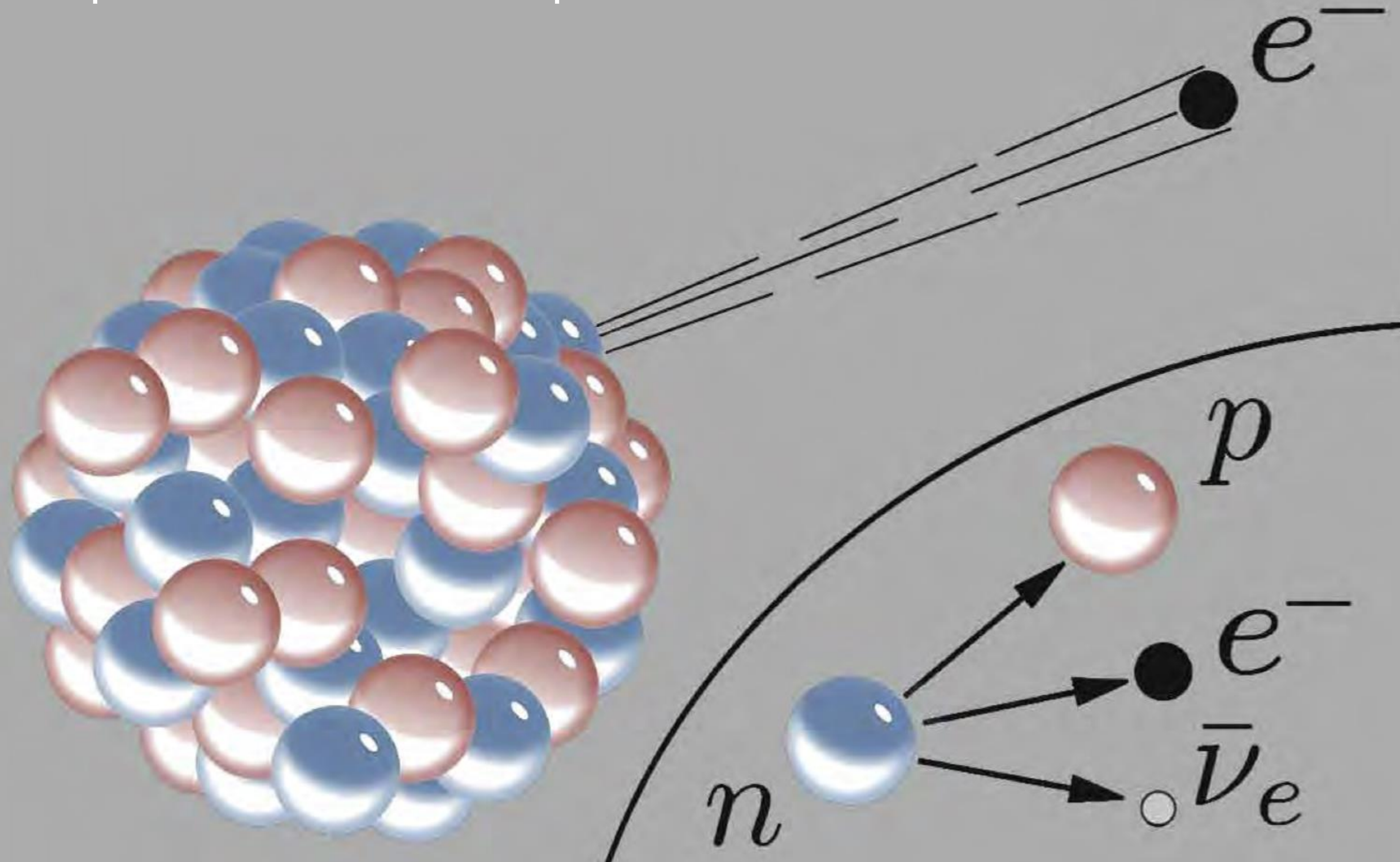
very high energy neutrinos from outer space



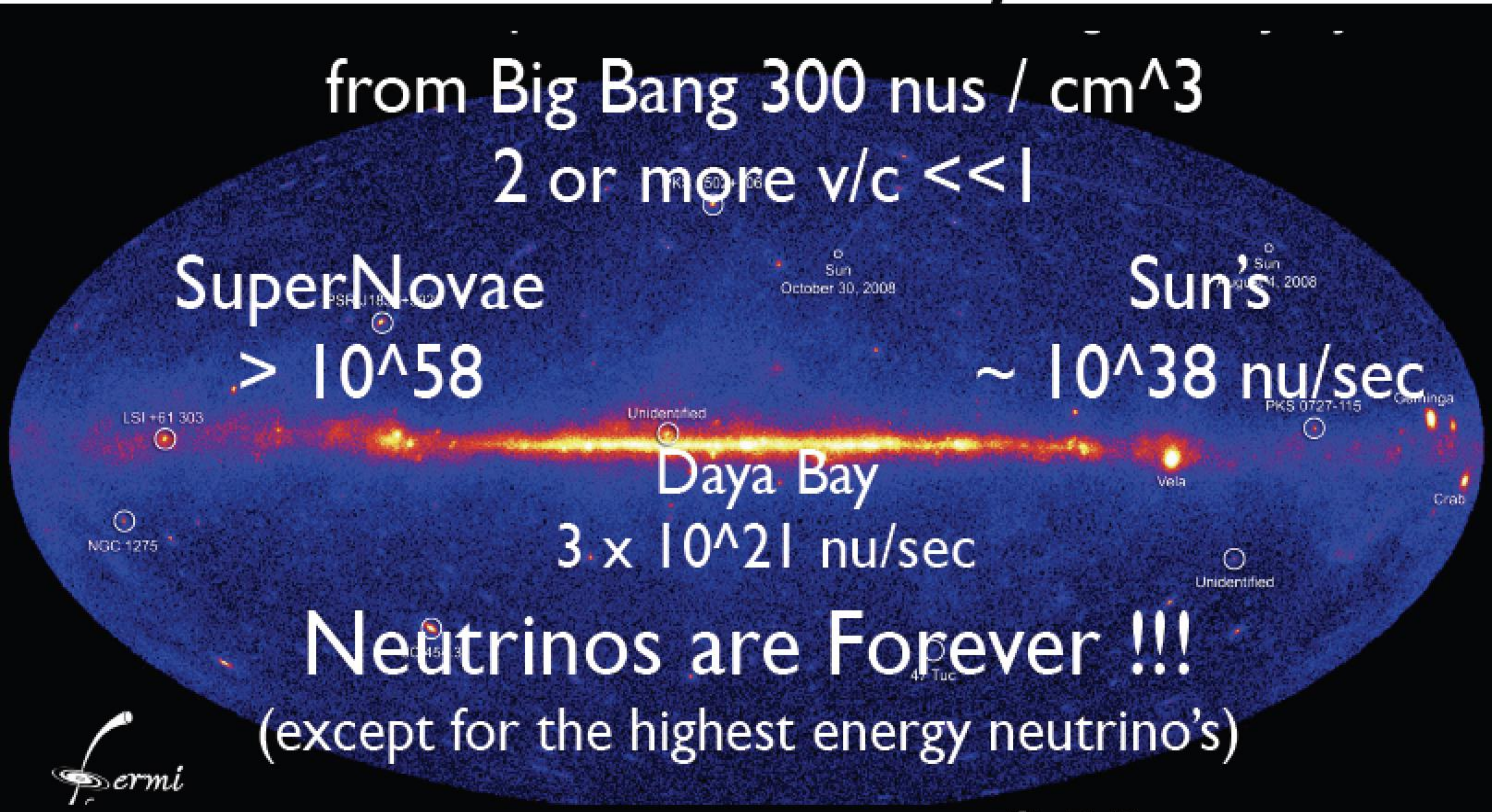
A 290 TeV neutrino originated from a flaring blazar (black hole at the center of a galaxy) was detected by IceCube


Reactors produce > 10^{21} neutrinos per second

Radioactive beta-decay
The process that led to the postulation of the neutrino



Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

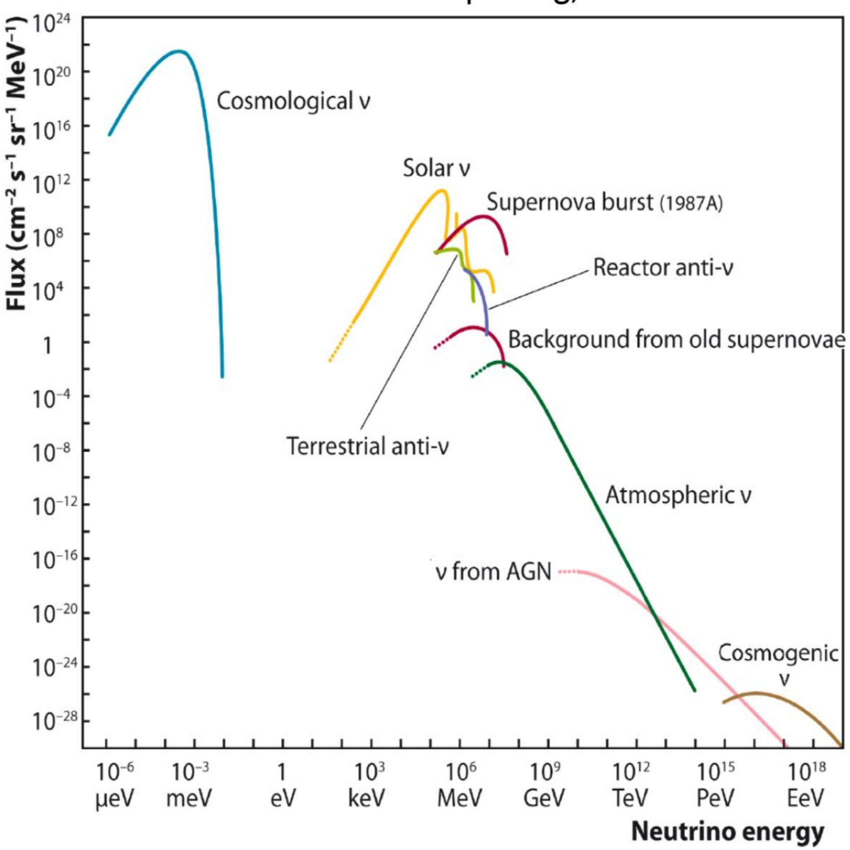
Neutrinos are Forever !!!

(except for the highest energy neutrino's)

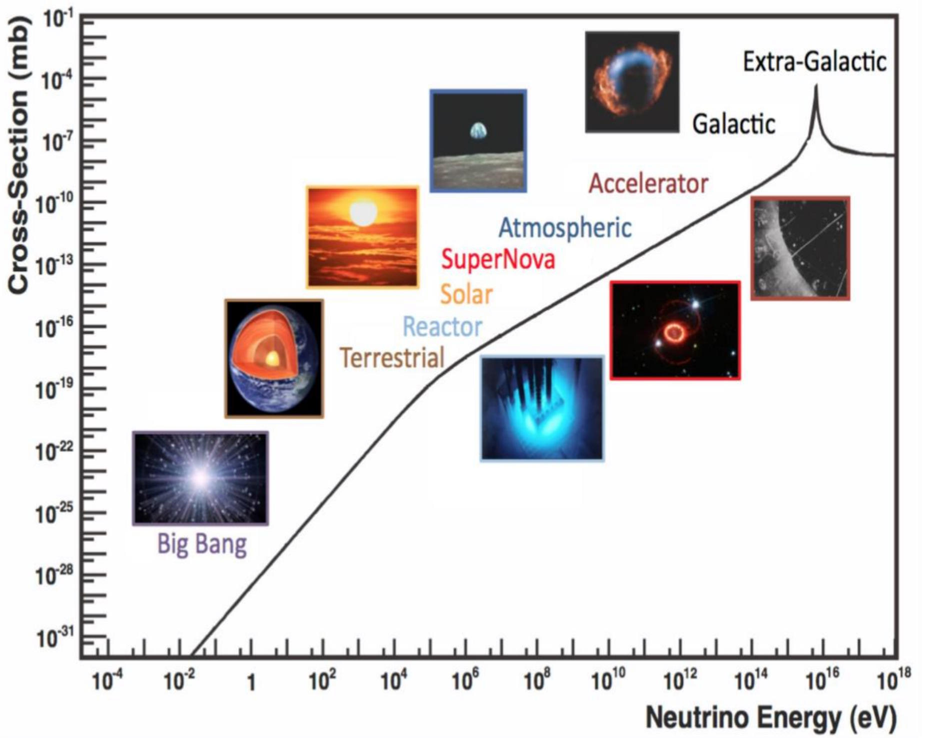
therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrino Sources, Flux and Cross Sections

C. Spiering, arXiv:1207.4952



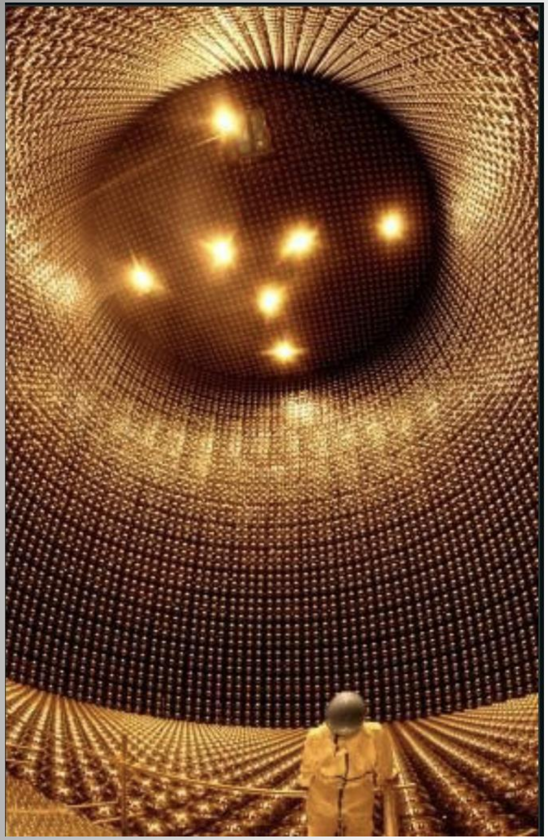
J. Formaggio, G.P. Zeller, arXiv:1305.7513

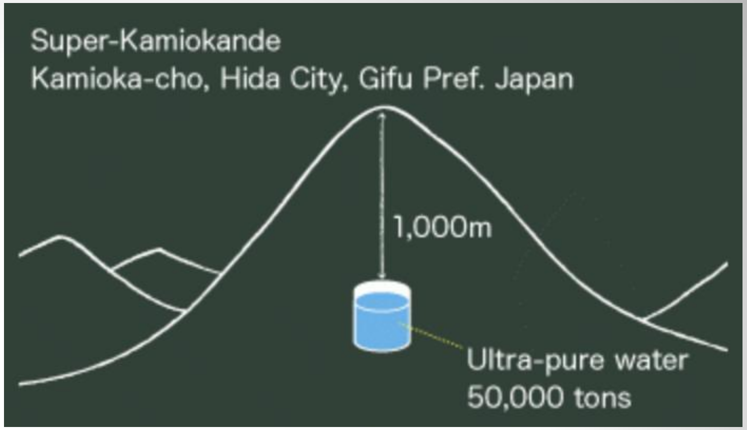


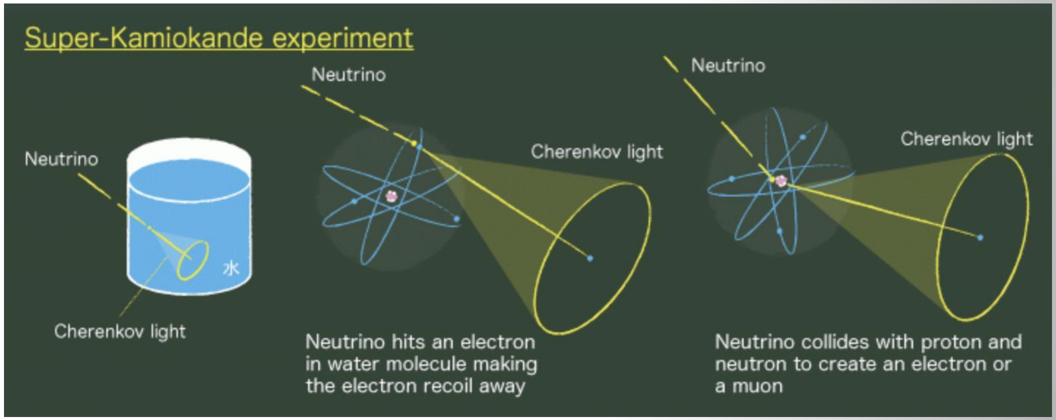
Cosmological and background from old supernovae neutrinos not yet observed!

Detecting neutrinos is challenging
Very large detectors are needed

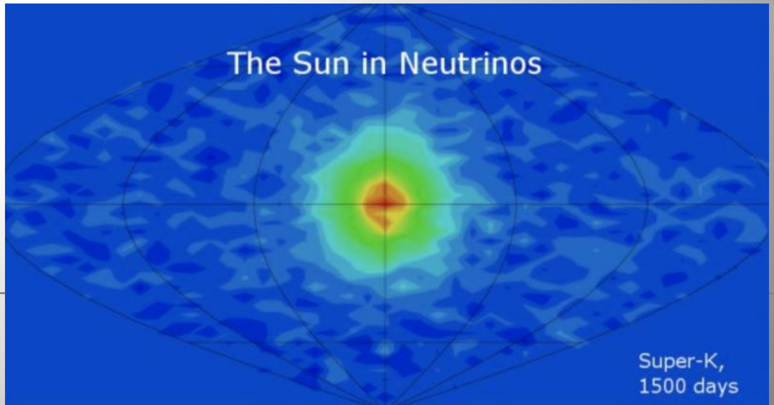
SuperKamiokande



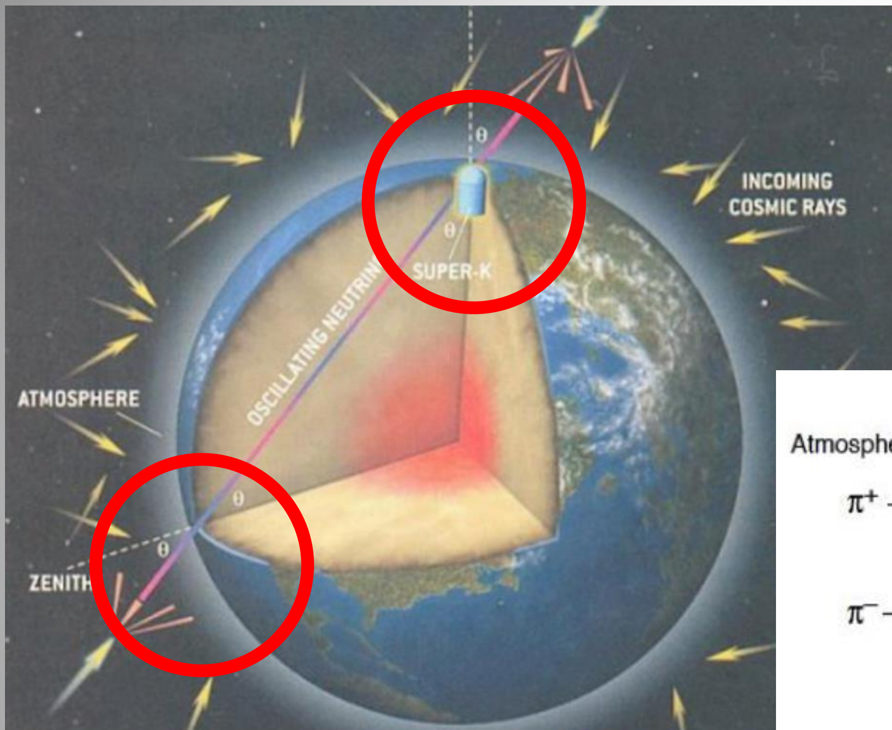




50,000 tons of ultra-pure water, watched by 13,000 photomultipliers

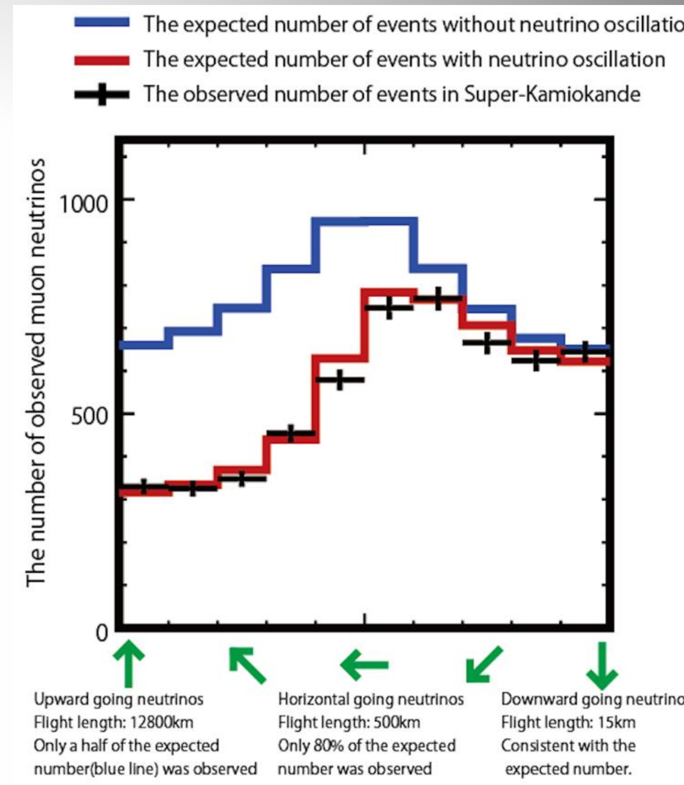


Neutrinos Oscillate! (1998)



Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

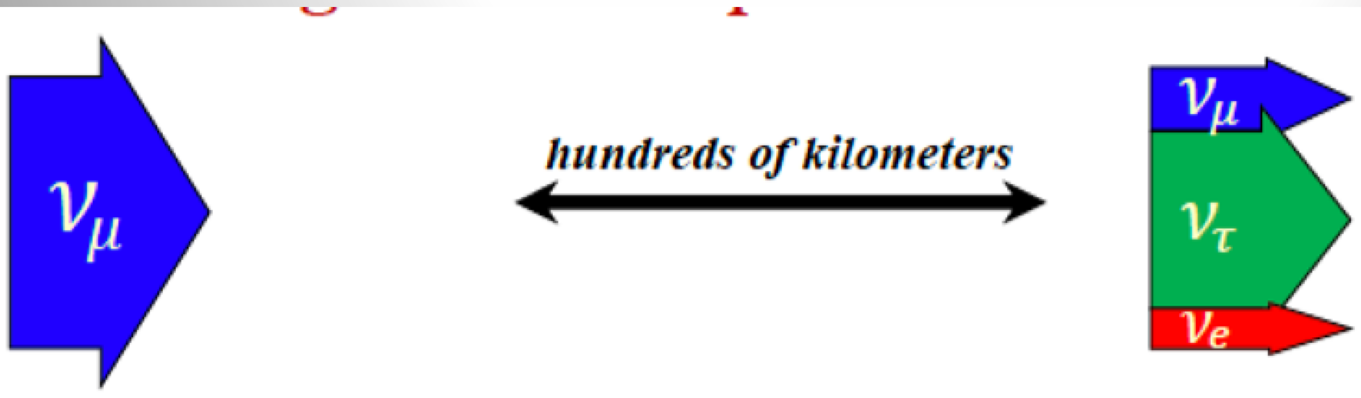


1998: The Super-Kamiokande experiment in Japan used a massive underground detector filled with ultrapure water.

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

Neutrino Oscillations

- Important discovery in 1998: neutrino oscillations
- Neutrino oscillation is a quantum mechanical phenomenon whereby a neutrino created with a specific lepton flavor (electron, muon, or tau) can later be measured to have a different flavor. The probability of measuring a particular flavor for a neutrino varies between 3 known states as it propagates through space
- Neutrino oscillations only possible if neutrinos have a non-zero mass! Neutrino oscillations -> Neutrinos have mass!!



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

(*) Pontecorvo-Maki-Nakagawa-Sakata Matrix

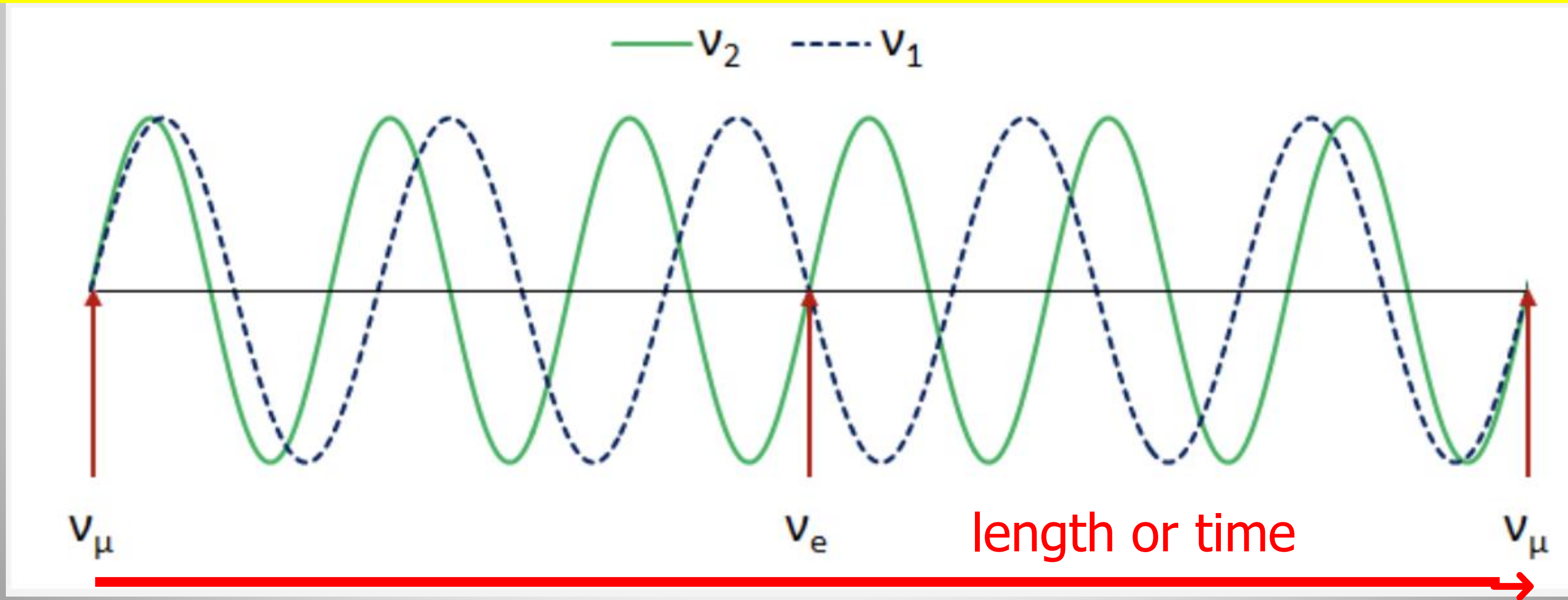
Flavor states

Neutrino Oscillations

The bizarre world of Quantum Mechanics: particles and waves

Take that the neutrino particle is a hybrid of two mass states v1 and v2 as it travels through space the associated waves of these mass states advance at a different rate

Hence the picture looks as follows: (propagation as a superposition of two masses)

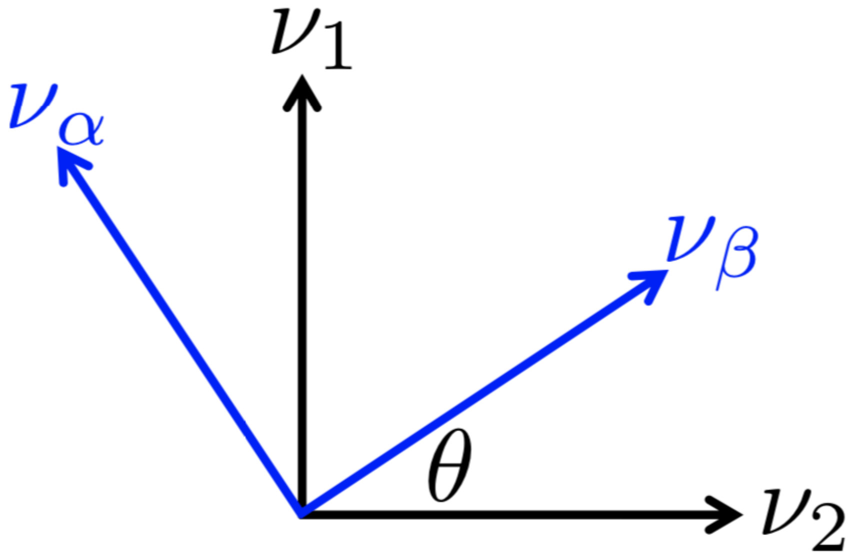


The neutrinos change identity (flavor) along the way…!!

Two Flavour Oscillations

Flavour states | "Rotation Matrix" | Mass states

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

Two Flavour Oscillations

$$|\nu(t)\rangle = e^{i(E_1 t - pL)}\cos(\theta)|\nu_1\rangle + e^{i(E_2 t - pL)}\sin(\theta)|\nu_2\rangle$$

plane wave

$$\langle\nu_\beta|\nu(t)\rangle = \sin(\theta)\cos(\theta)(e^{i(E_2 t - pL)} - e^{i(E_1 t - pL)})$$

$$E \approx p + \frac{m_i^2}{2E} \quad \text{and} \quad t = \frac{L}{c}$$

ultra-relativistic

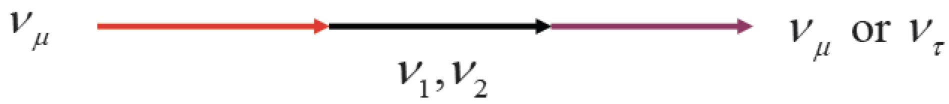
$$\langle\nu_\beta|\nu(t)\rangle = \sin(\theta)\cos(\theta)(e^{i\frac{m_2^2 L}{2E}} - e^{i\frac{m_1^2 L}{2E}}) = \sin(\theta)\cos(\theta)e^{i\frac{\Delta m_i^2 L}{2E}}$$

$$P(\nu_\alpha \to \nu_\beta) = \langle\nu_\beta|\nu(t)\rangle^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m_i^2 L}{2E}\right)$$

Neutrino Oscillations

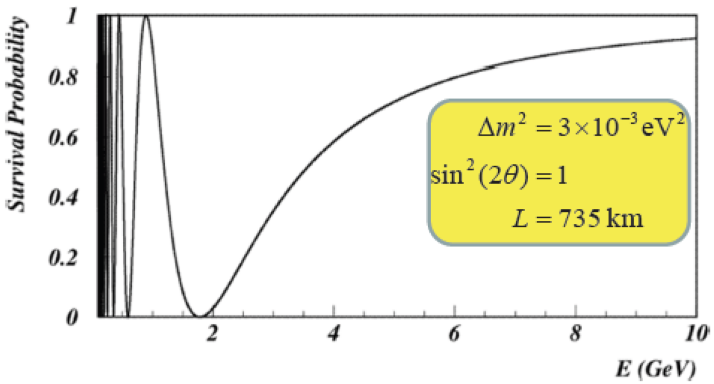
Neutrino oscillations is a pure Quantum Mechanical effect

The effect depends on the mass difference between flavor states



$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



- $\Delta m^2_{21} = m^2_2 - m^2_1 \approx 8 * 10^{-5}$ eV² => wavelength of ~100km
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 2 * 10^{-3}$ eV² => wavelength of ~1km

Absolute mass values? Mass hierarchy?

Neutrino Oscillations

- Since >20 years an active field of study and data from many experiments collected:
  - Long baseline accelerator experiments (LBL)
  - Short baseline reactor experiments
  - Atmospheric neutrinos
  - Solar Neutrinos
  - Neutrinoless double beta decay experiments

LBL experiments in the US and Japan
SuperKamiokande, Icecube

Neutrino Oscillations

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

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

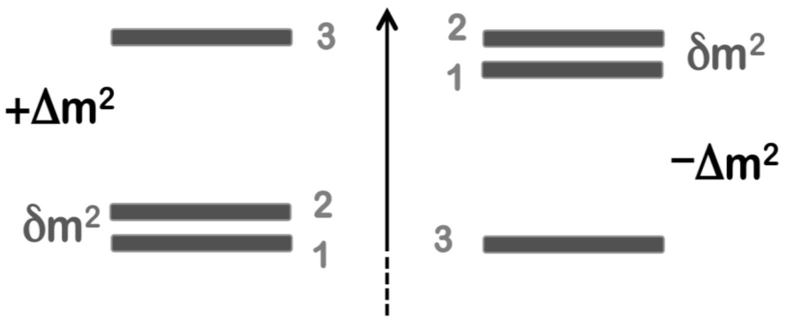
θ_{23} rotation — θ_{13} rotation — θ_{12} rotation

+ CPV "Dirac" phase δ

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

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

"Normal" Ordering
N.O.



"Inverted" Ordering
I.O.

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

In total 6 parameters to determine
- -3 angles
- -2 mass differences
- -1 CP violation phase

Neutrino Oscillations

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

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

"Atmospheric"

"Solar"

ν_μ disappearance

Solar neutrino oscillation

ν_e appearance in ν_μ beam
Or
reactor neutrino experiments

ν–less double beta decay

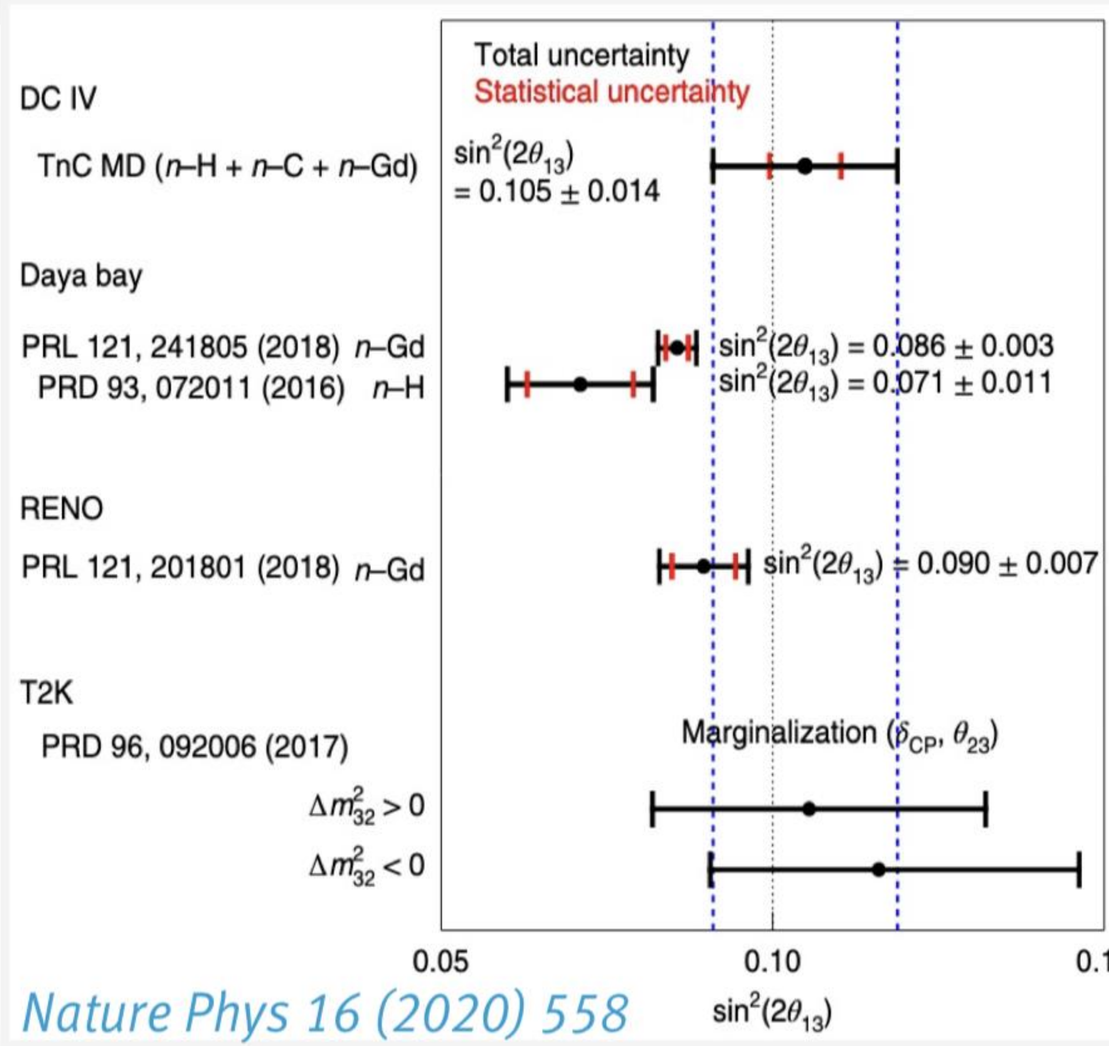
Short Baseline Experiments

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



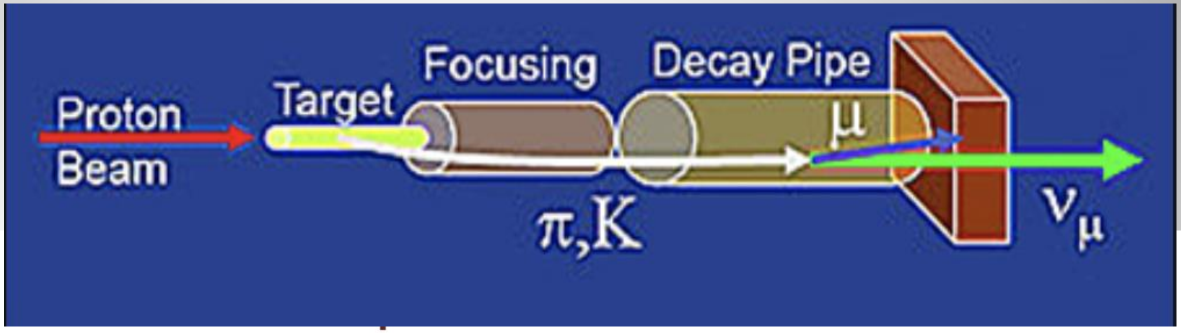
Nature Phys 16 (2020) 558

$$\sin^2\theta_{13} = 0.0220 \pm 0.0007$$

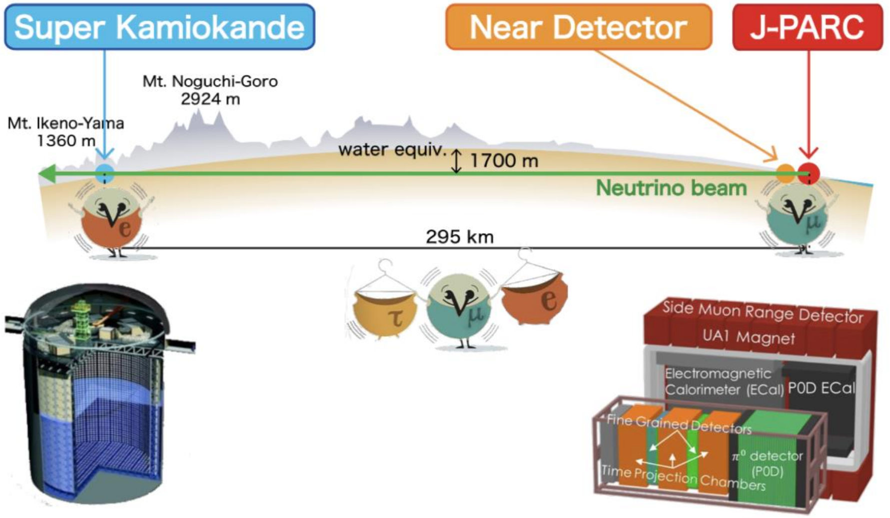
(PDG2021 using Double Chooz, Reno, Daya Bay)

Accelerator Based Neutrino Experiments

Neutrinos from accelerators

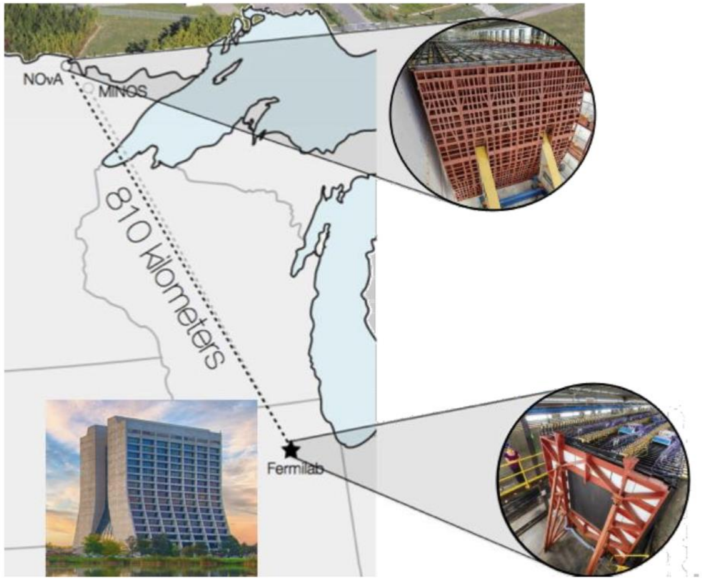


T2K



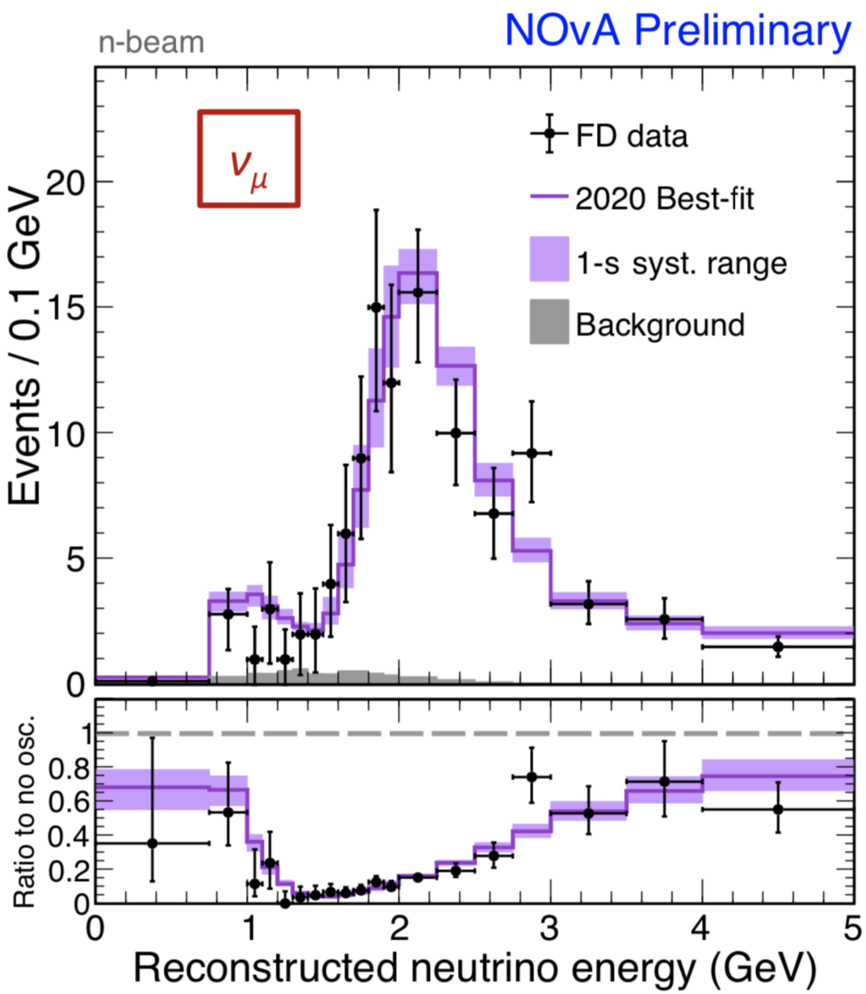
Baseline: 295 km
Peak E_ν: ~0.6 GeV (off-axis)
Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

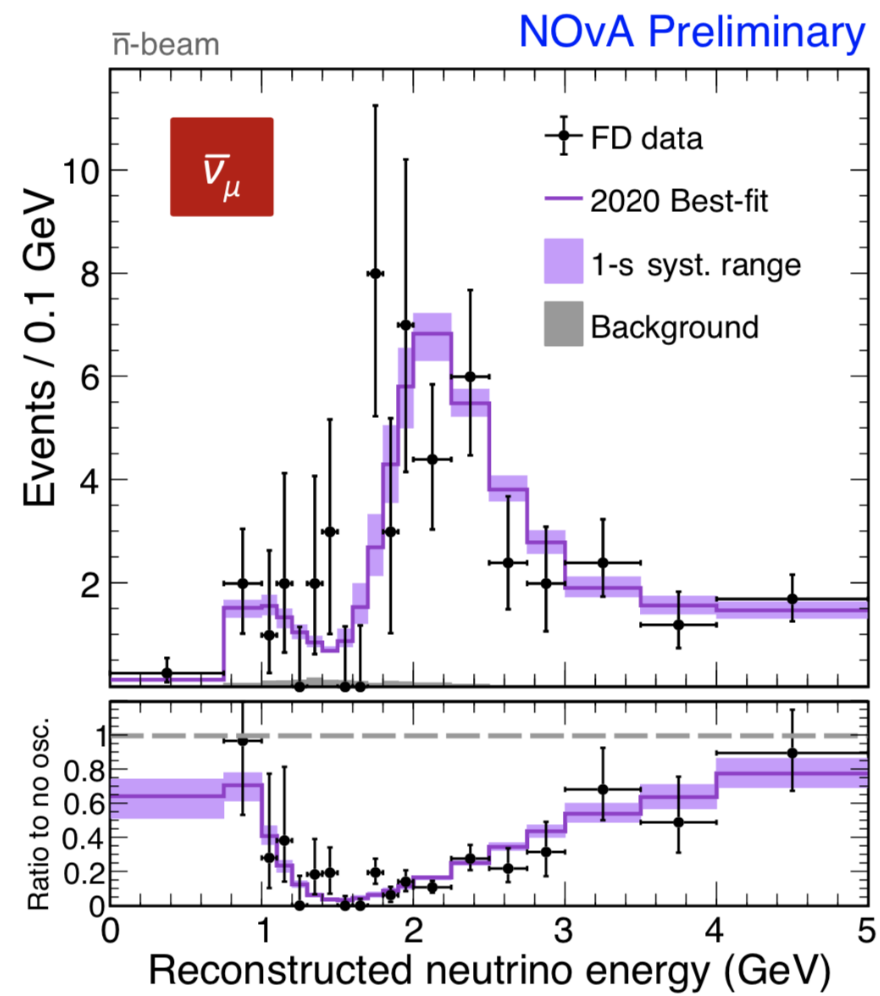


- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

Muon Neutrino Disappearance



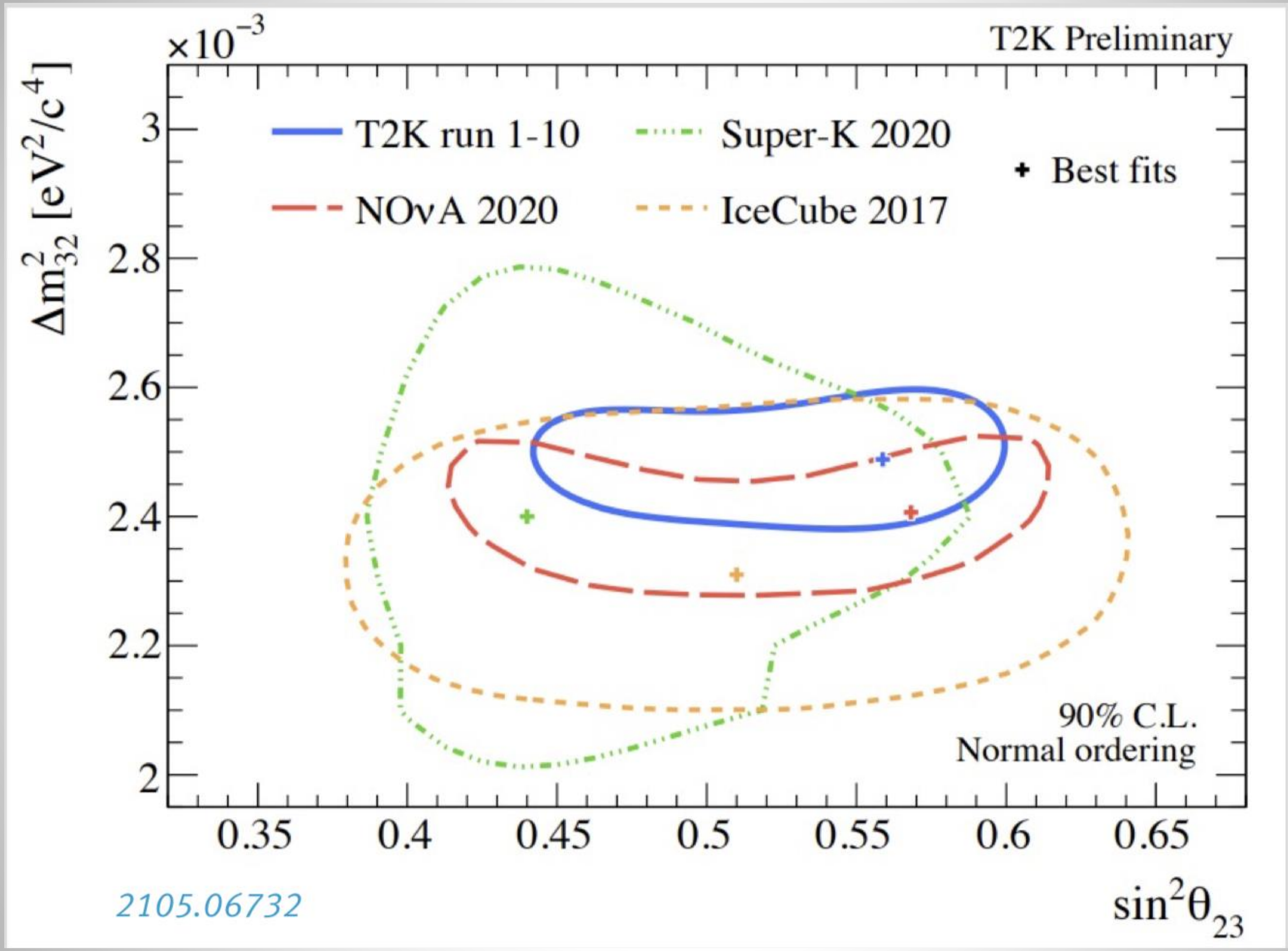
211 events, 8.2 background



105 events, 2.1 background

Neutrino Experiments

2105.06732



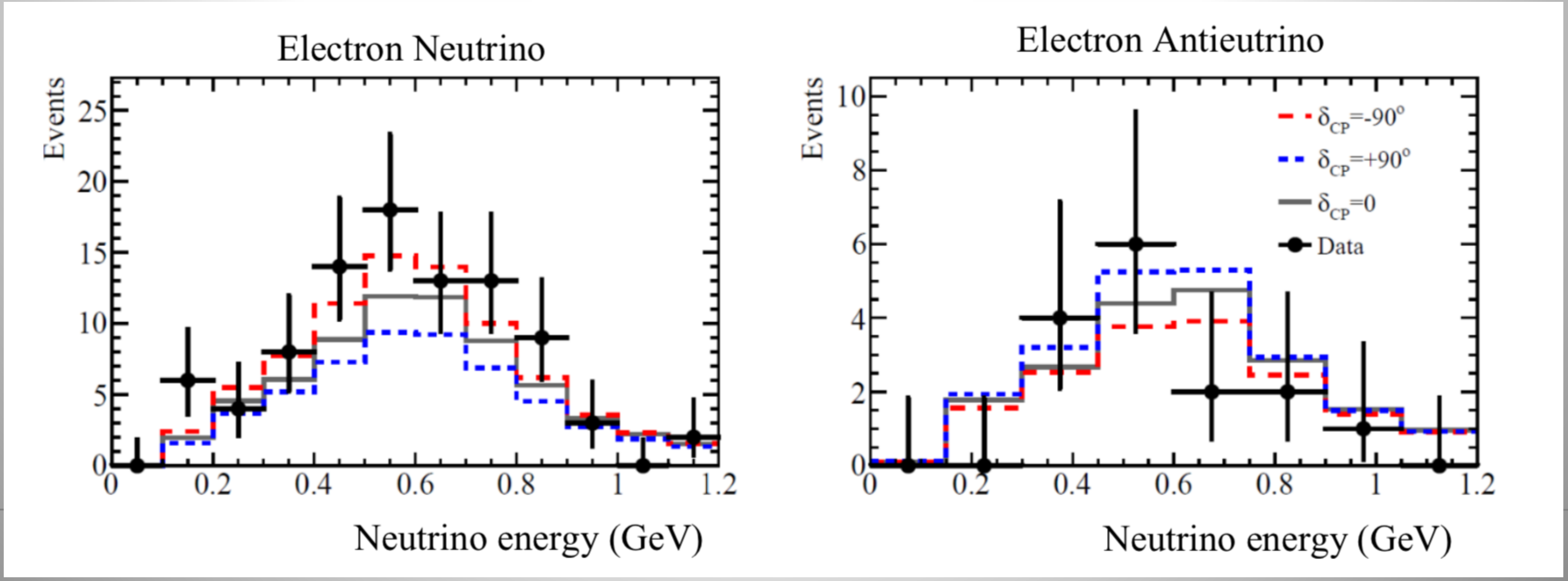
Atmospheric parameter determinations by several experiments
Results are consistent

CP Violation: T2K Measurement

Do neutrinos and anti-neutrinos oscillate differently ?

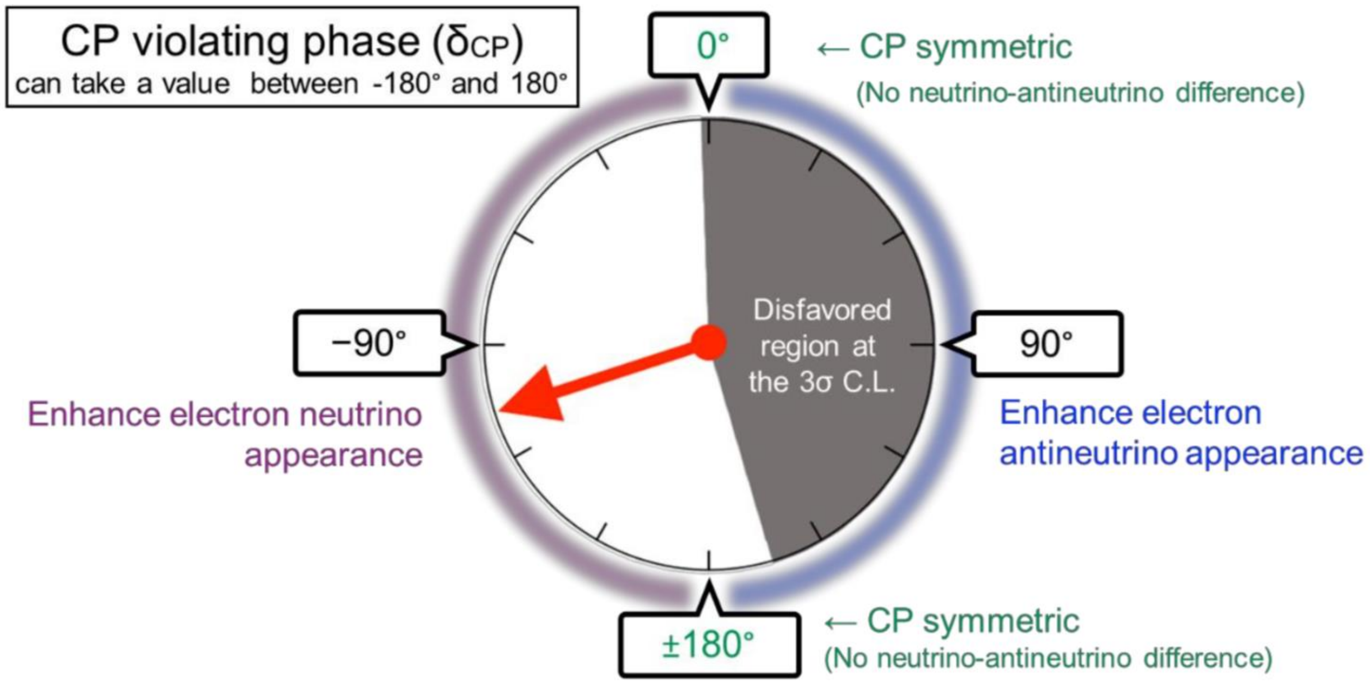
Measured versus expected electron-(anti)neutrino events in SK as function of the assumed CP- angle

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



CP Violation: Latest T2K Result

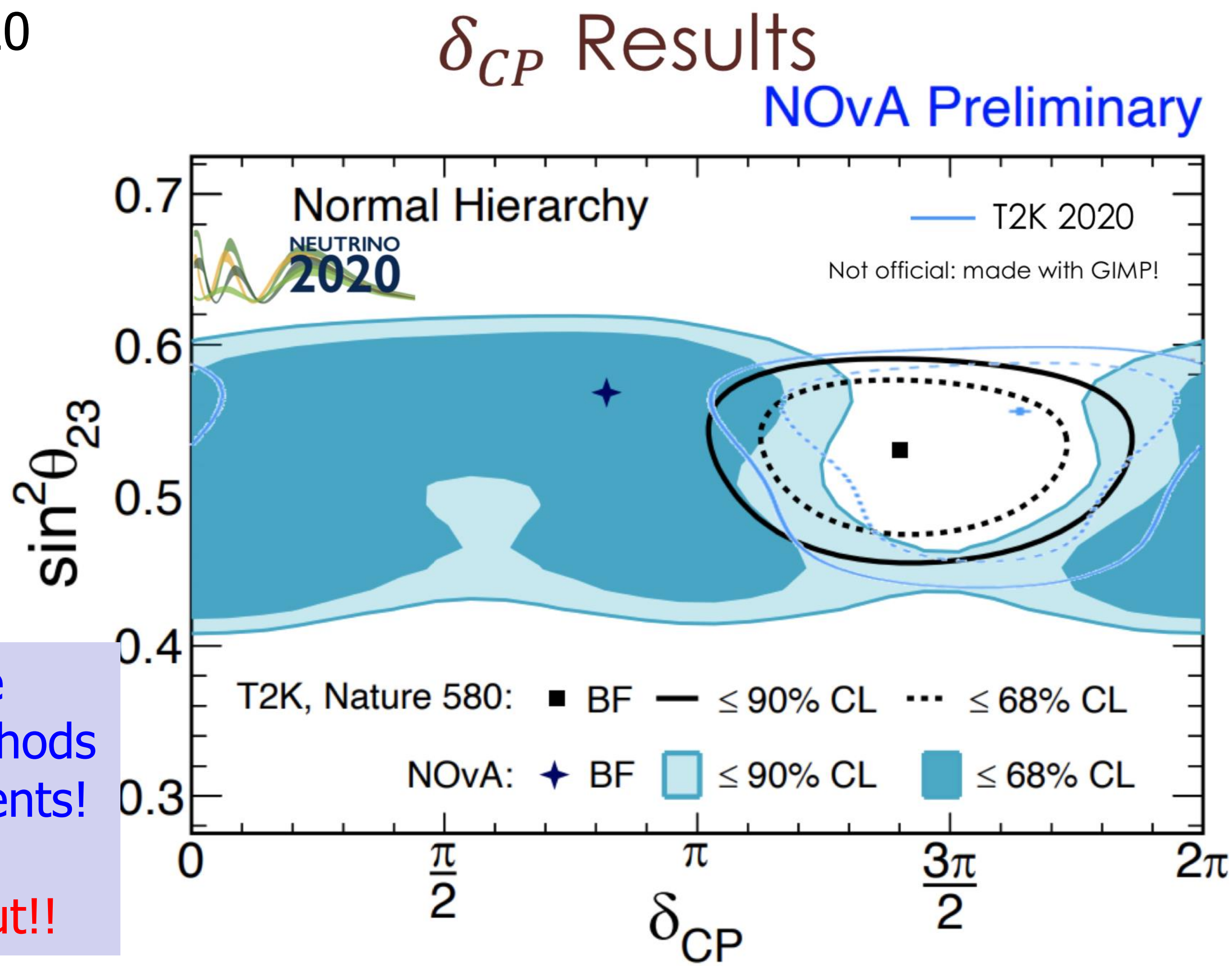
Nature Magazine April 16/4/2020
and arXiv:: 1910.03887



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

CP Violation T2K/NOvA Results

Summer 2020 update



Good to have different methods and experiments!

Jury is still out!!

Some tension between NOvA and T2K results! Joint analysis required? -> more experimental data needed … (and coming..)

Taking all available data together…

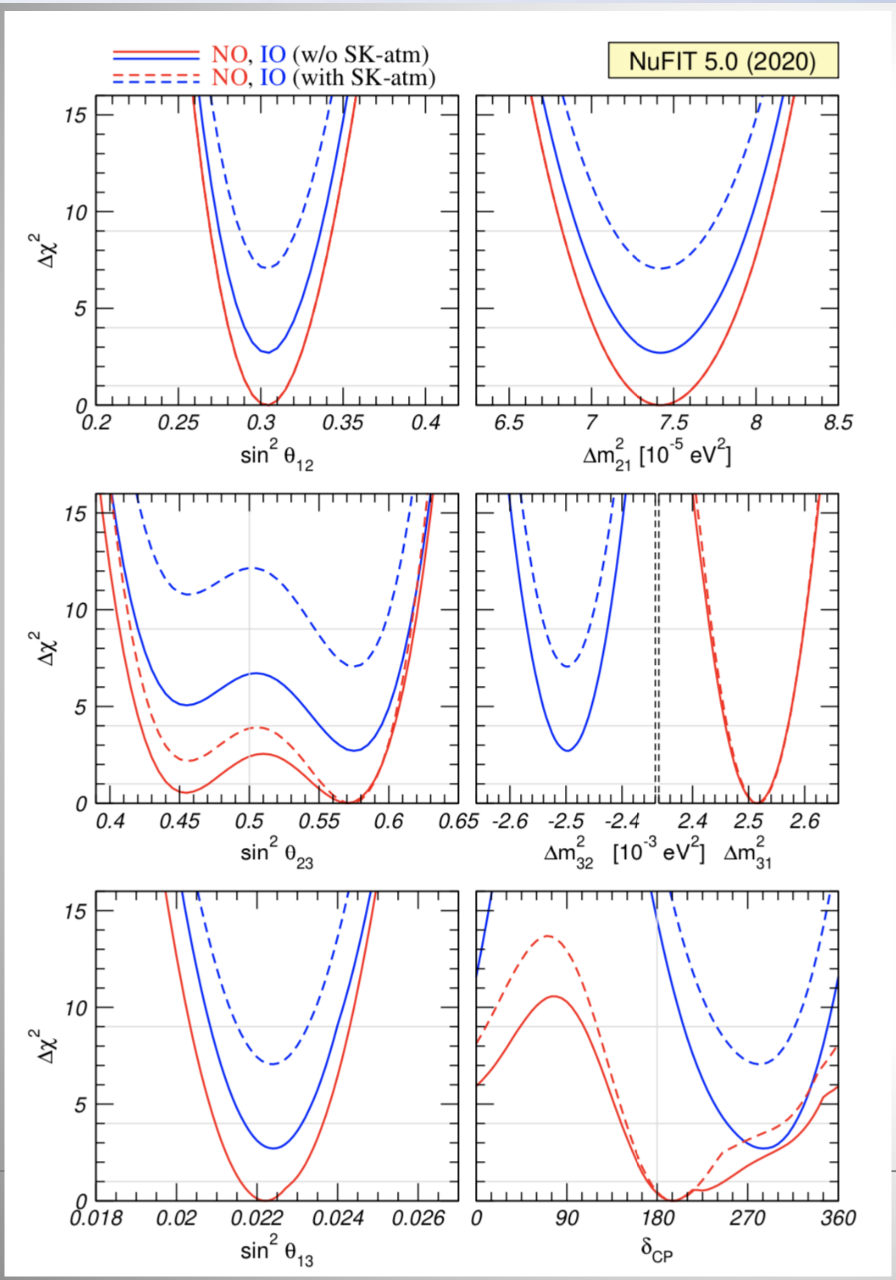
arXiv:2007.14792

NuFIT group

with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	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 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)

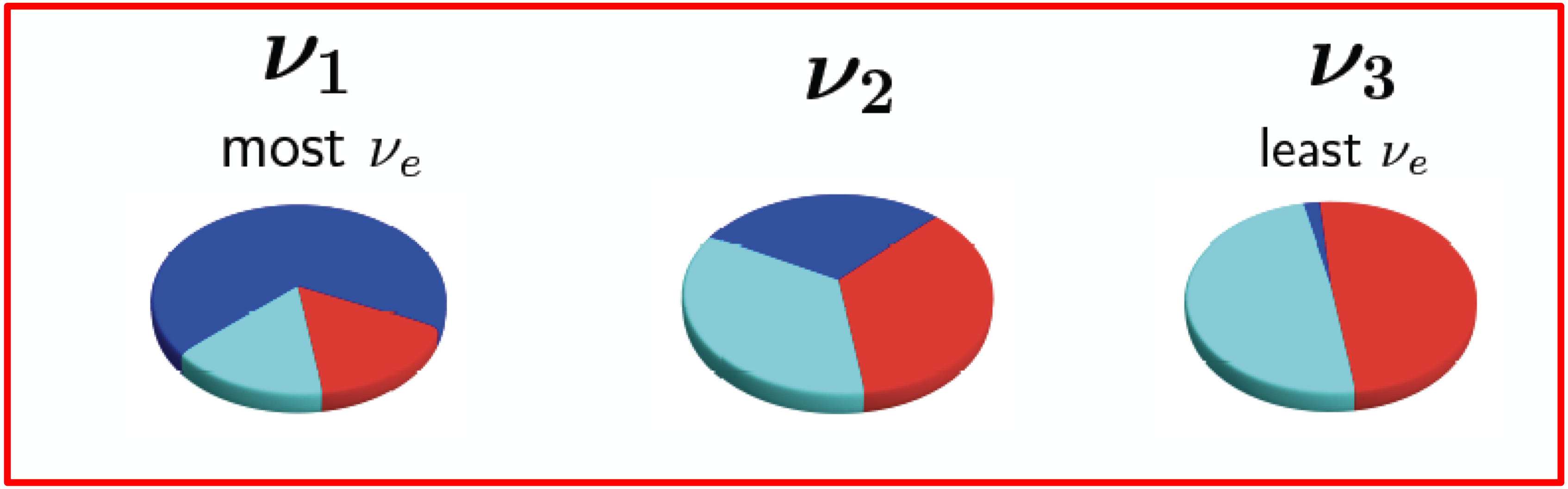
Data mainly from reactors, long baseline experiments, atmospheric, solar neutrinos…

But the Jury is still out..

Neutrino Oscillations

Neutrino Mass EigenStates or Propagation States:

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



$\nu_e =$ (dark blue)

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ (light blue)

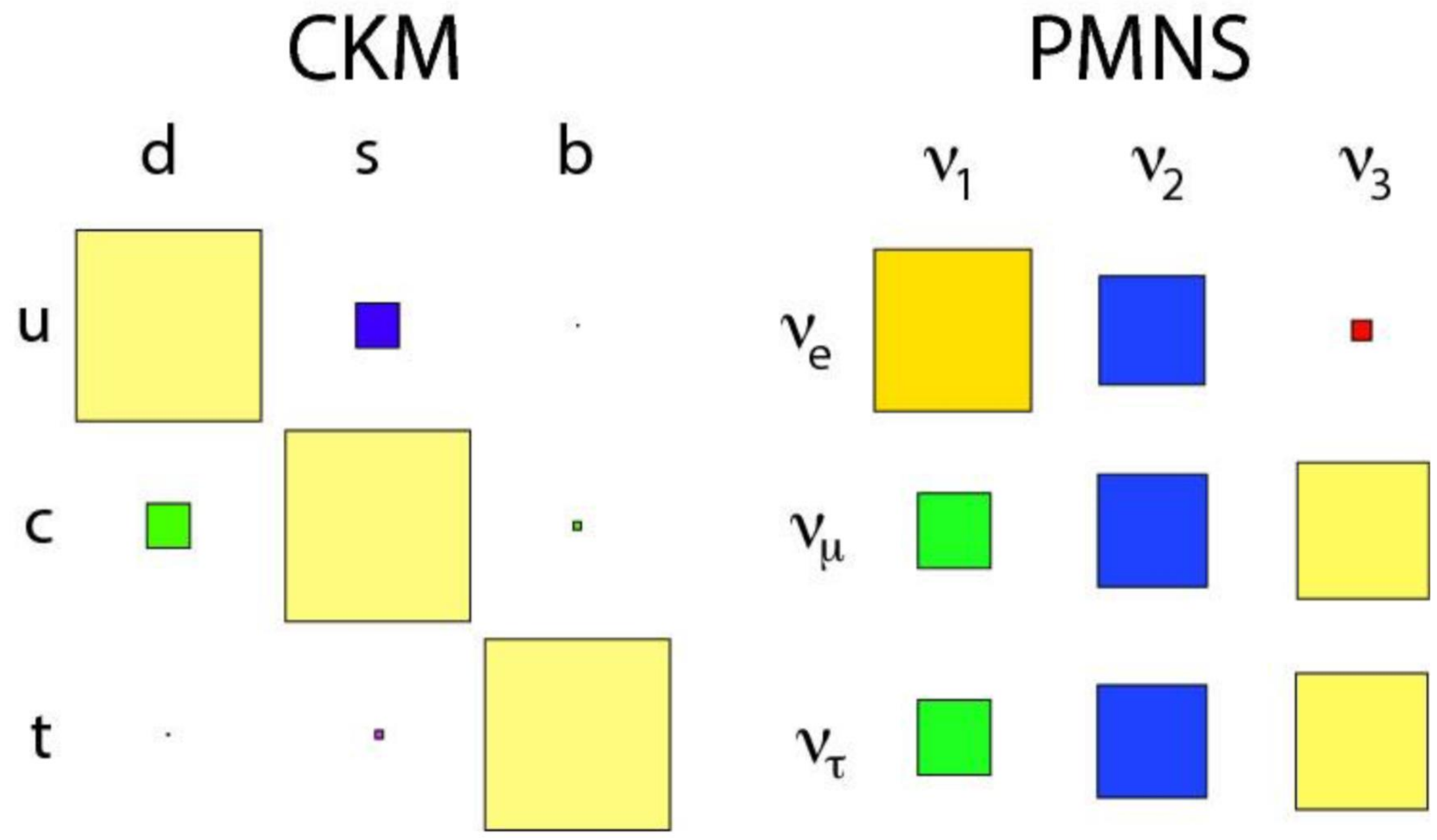
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$ (red)

Unitarity
SK, Opera
ICECUBE ?

CMK vs PMNS

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

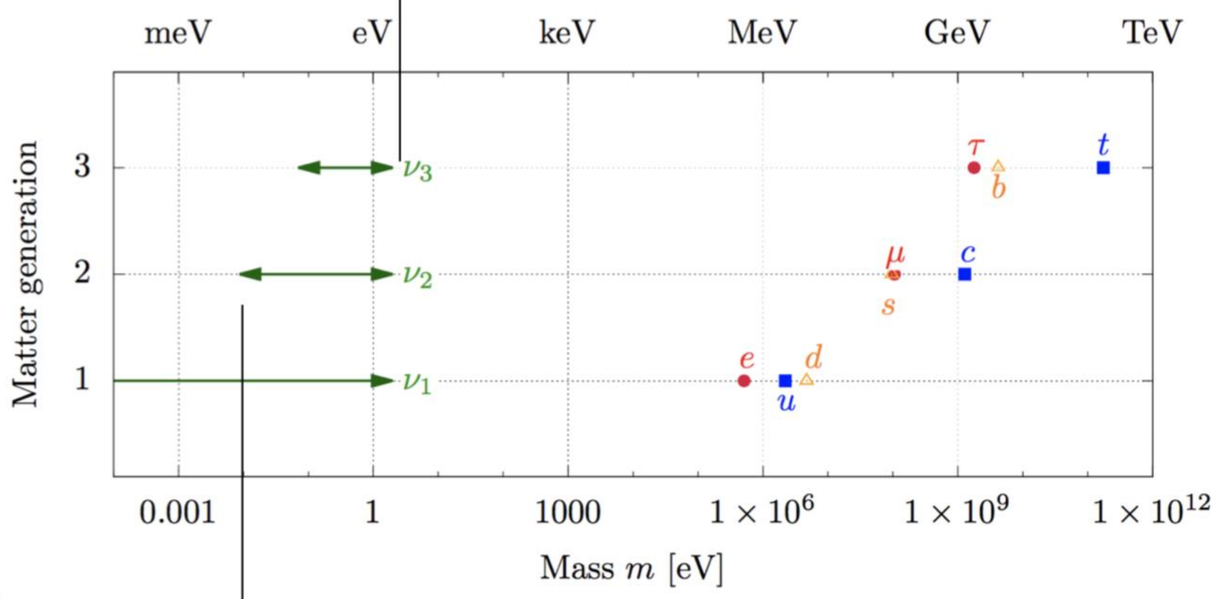


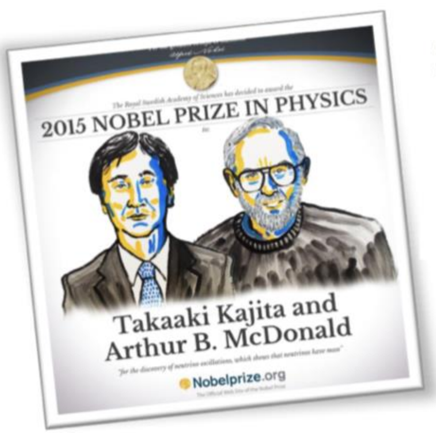
The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.

Neutrino Mass

Neutrinos versus other known fermions

Upper bound
from laboratory measurements

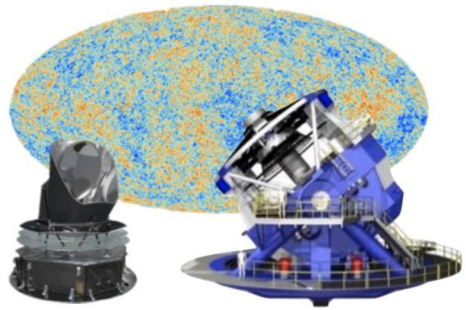


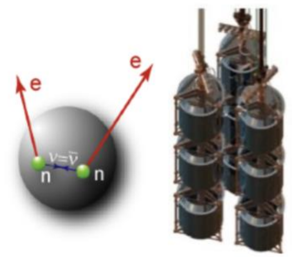


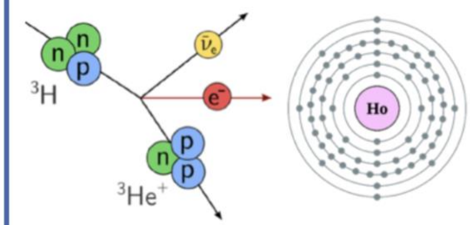
Lower bound
from oscillation experiments

Neutrino Mass Measurents

Complementary paths to the ν mass scale



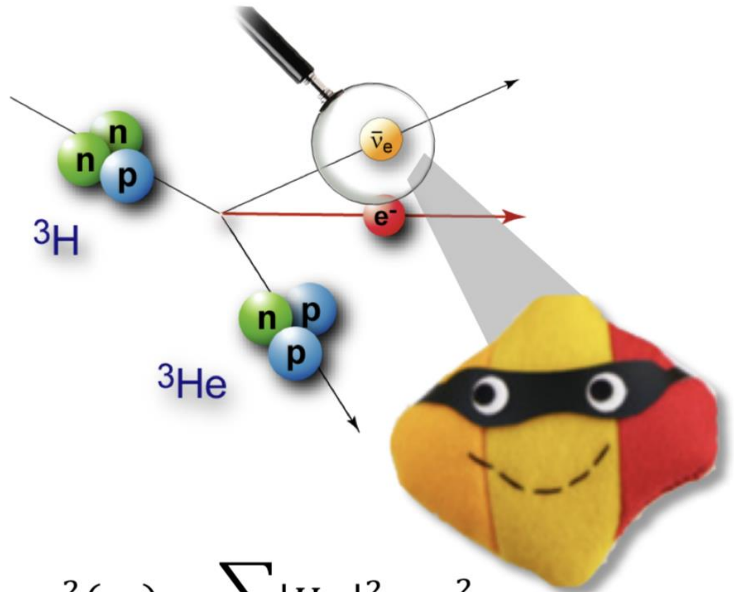




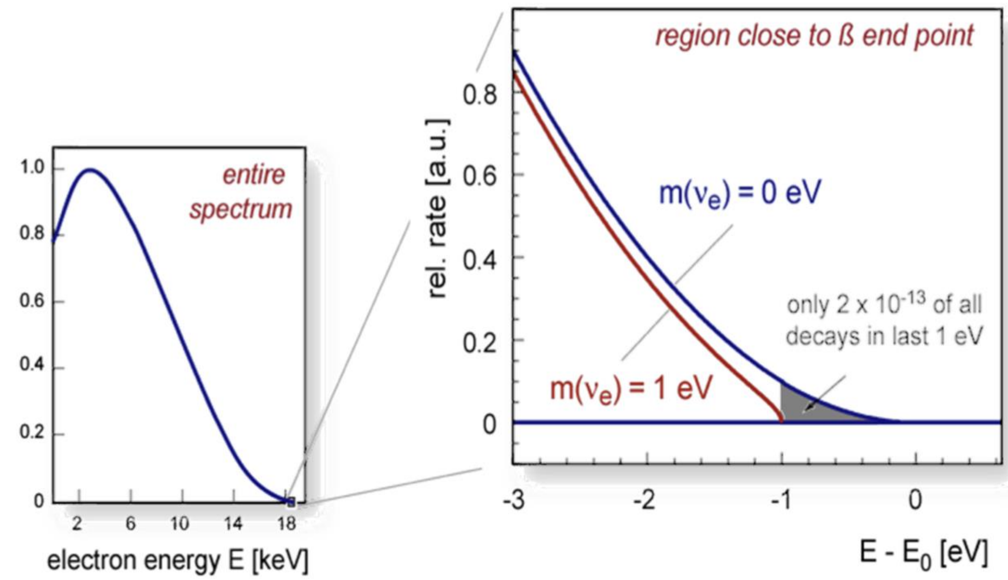
	Cosmology	Search for 0νββ	Kinematics of weak decays
Method	Structure of Universe at early and evolved stages	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\|\sum_i U^2_{ei}\, m_i\right\|^2$	$m^2_\beta = \sum_i \|U_{ei}\|^2\, m^2_i$
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

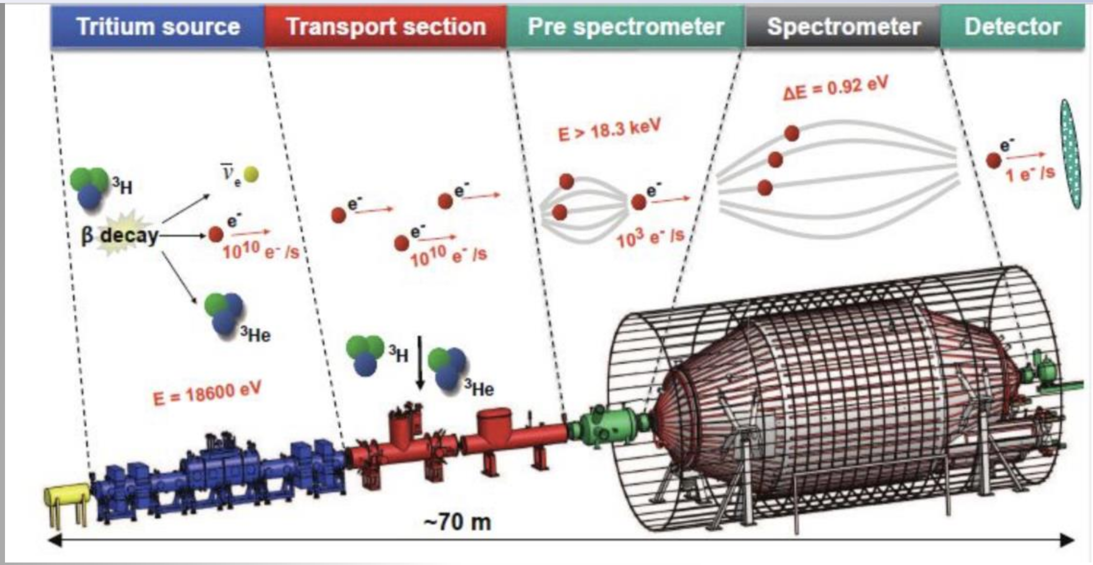


$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



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

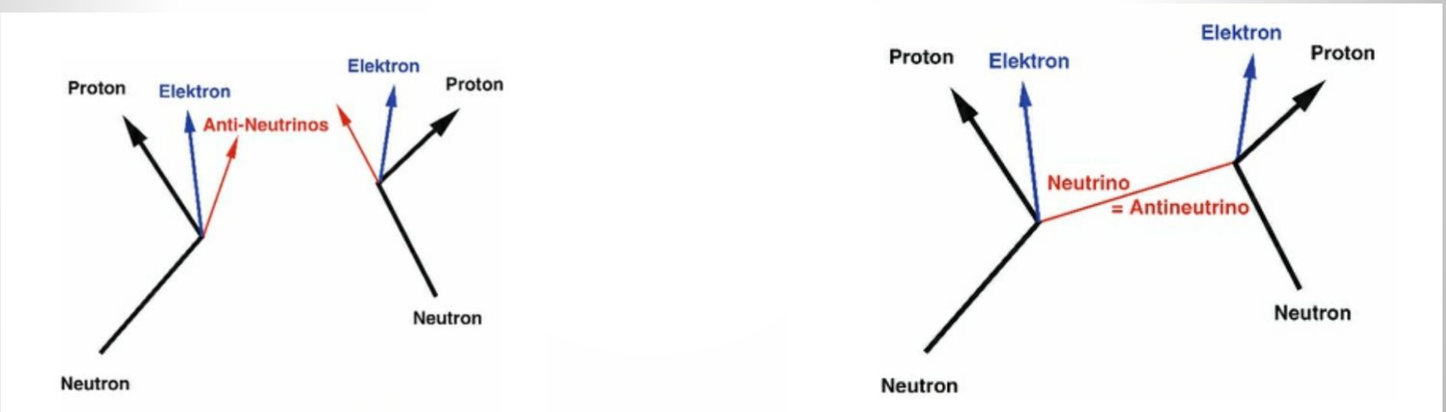


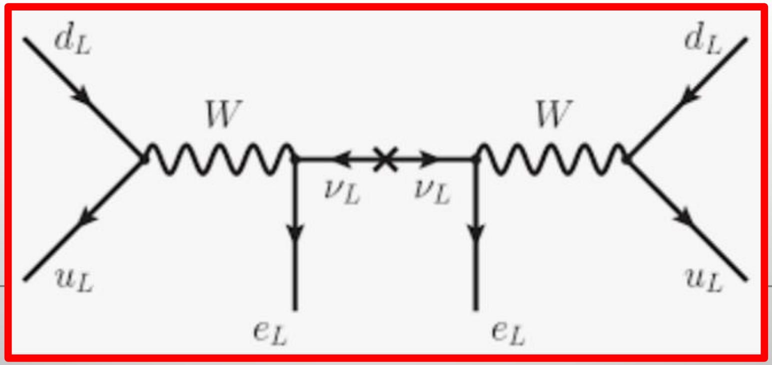
The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to measure the mass up to projected sensitivity of 0.2eV
To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

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

Neutrinoless Double Beta Decay

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





Neutrinoless Double Beta Decay

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

Final results: arXiv:2009.06079

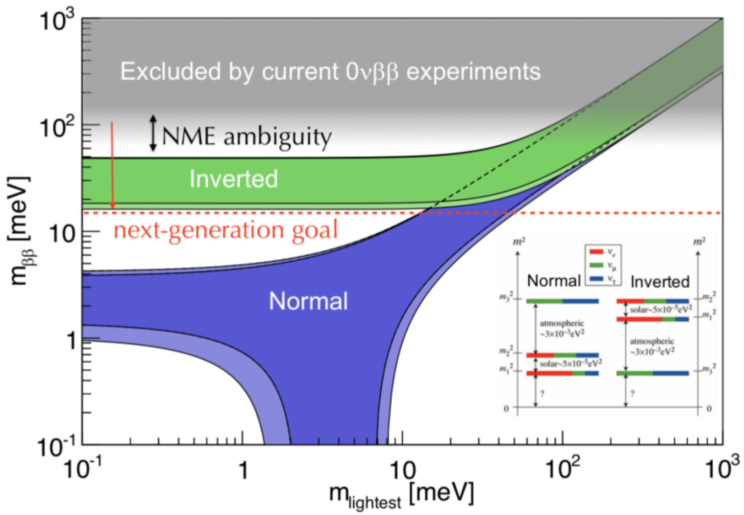
127.2 kg.year exposure
between 2011-2019

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

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

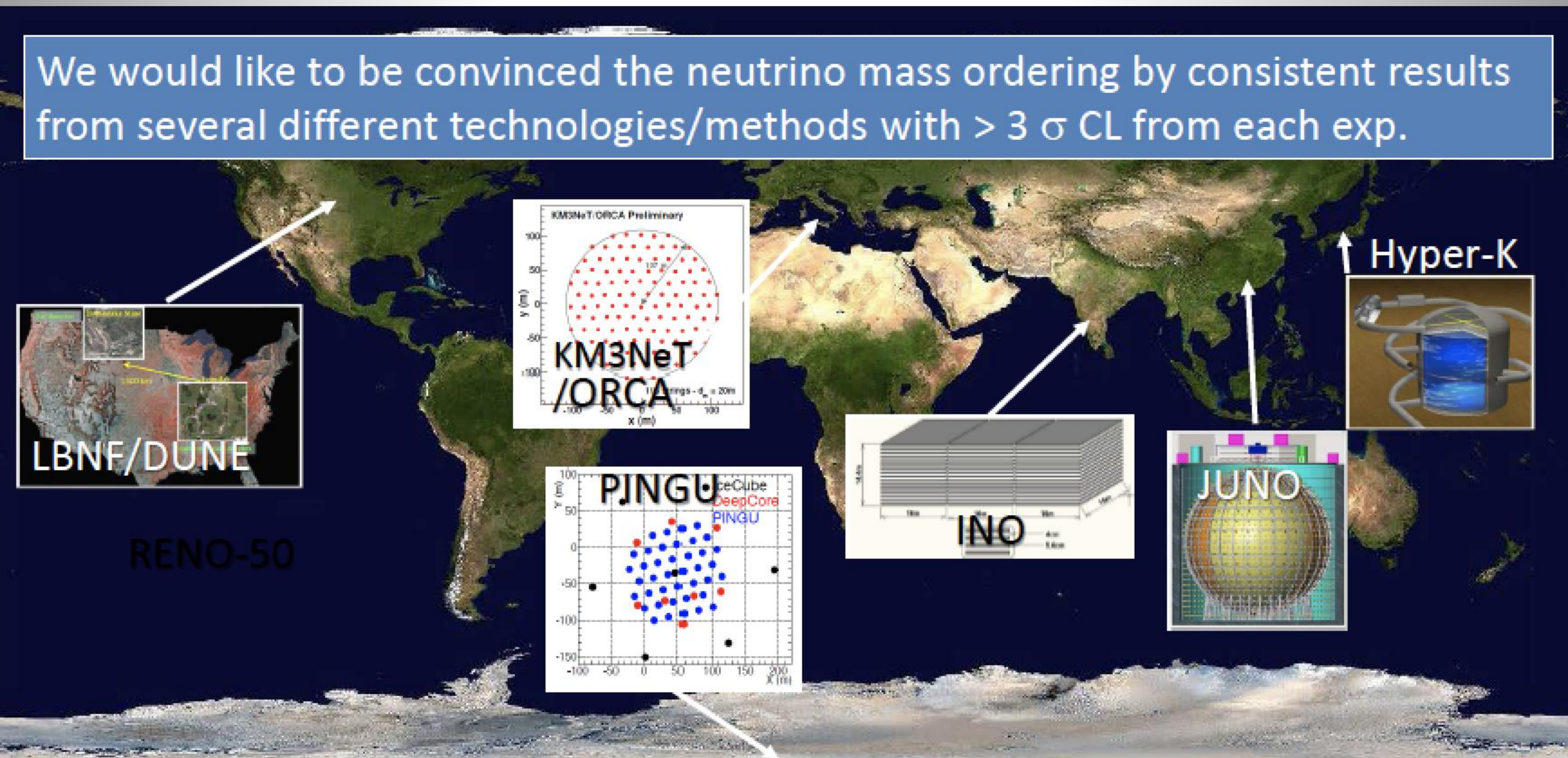


Many experiments operating, planned or in R&D: LEGEND SNO+, NEXT…

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 σ CL from each exp.



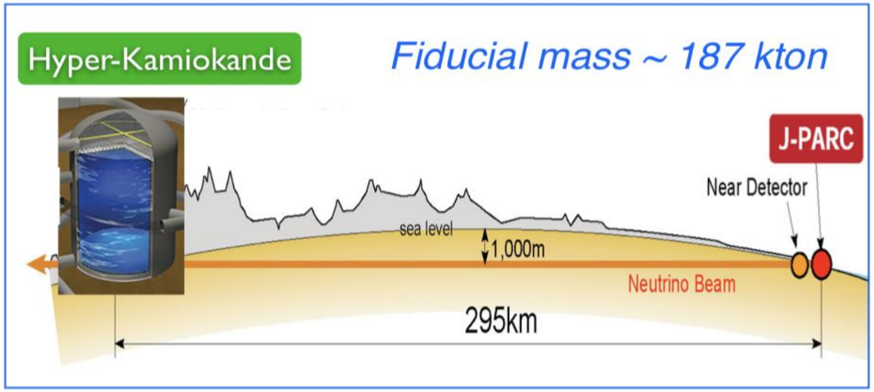
Future Neutrino Experiments

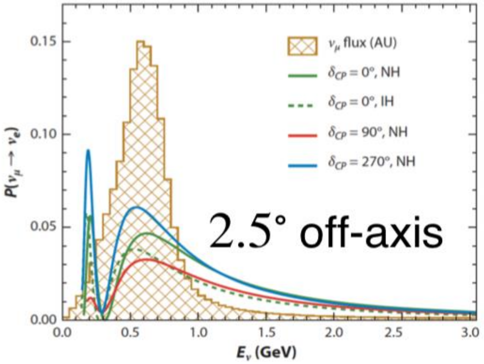
CERN

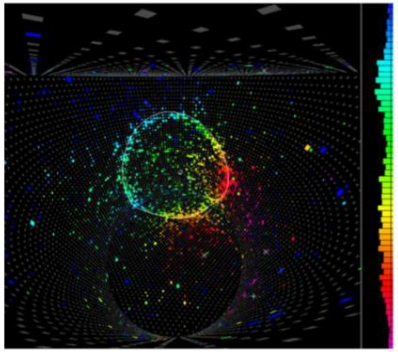
Long-baseline experiments: T2HK and DUNE

First data in 2027 (?)

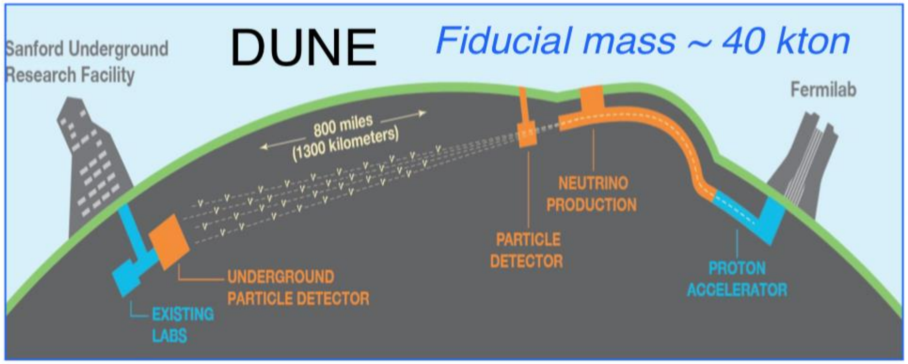
- Towards the measurement of the CP violating phase and Mass Hierarchy
  - Search for different $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities

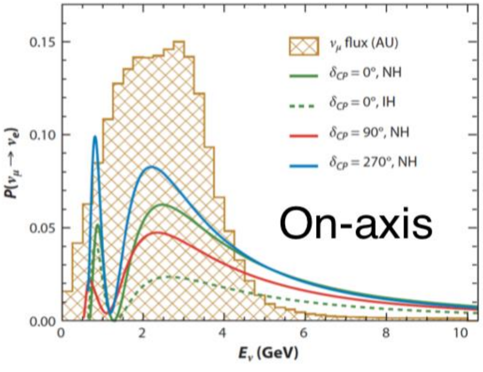


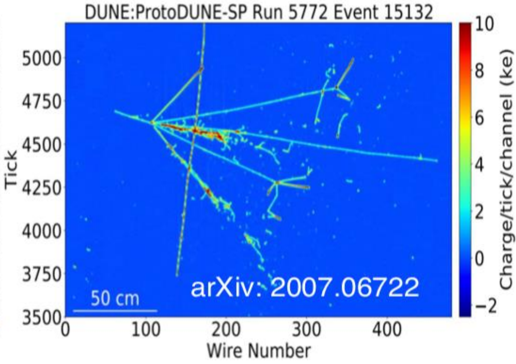




Annu. Rev. Nucl. Part. Sci. 2016. 66:47–71



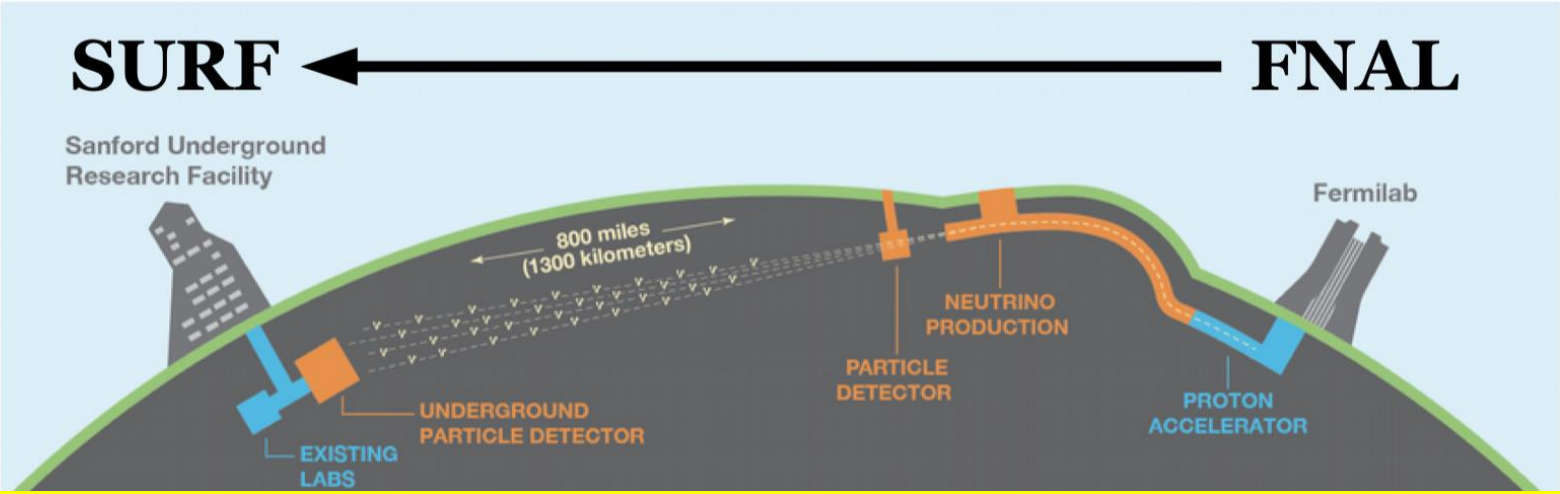




DUNE "Observatory"

- "Deep Underground Neutrino Experiment"
  - 1300 km baseline
  - Large (70 kt) LArTPC **far detector** 1.5 km underground
  - **Near detector** w/ LAr component

- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - $\boldsymbol{\delta_{CP}}$, θ_{23}, θ_{13}
    - **Ordering of ν masses**
  - Supernova burst neutrinos
  - BSM processes (baryon number violation, NSI, etc.)



DUNE: samples 1000's to 10000's of events->Neutrino Precision Physics!

DUNE – a global collaboration

Status October 2020:

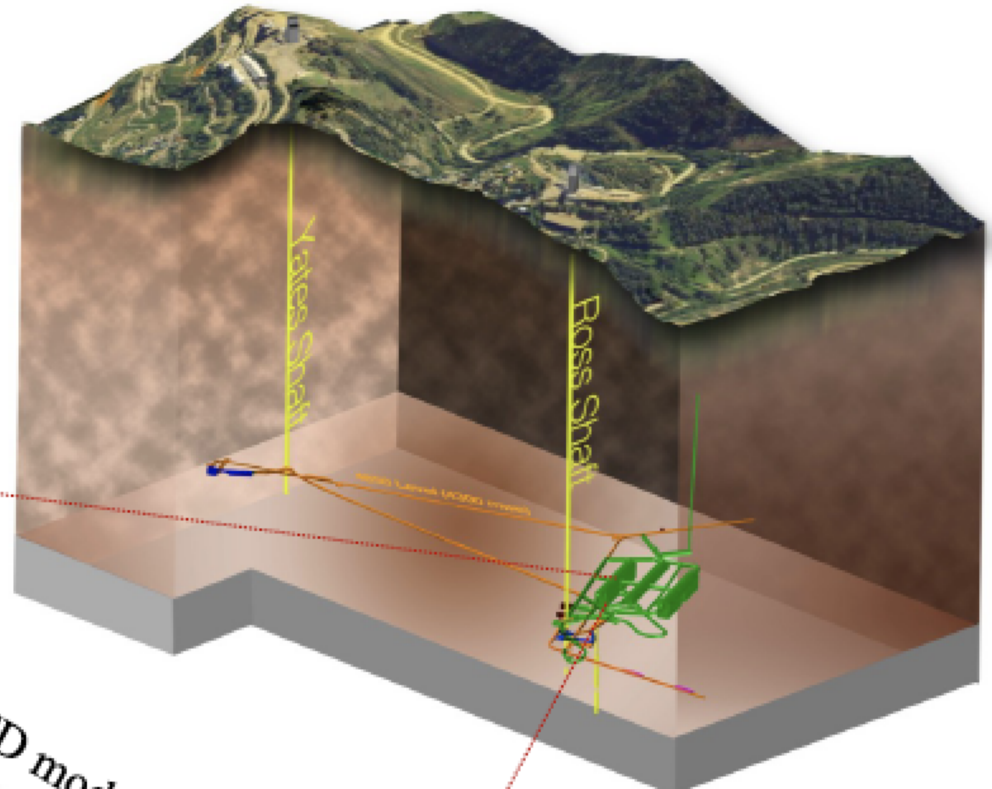
- 1229 collaborators from
- 184 institutions in
- 31 countries + CERN

Still more groups joining

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

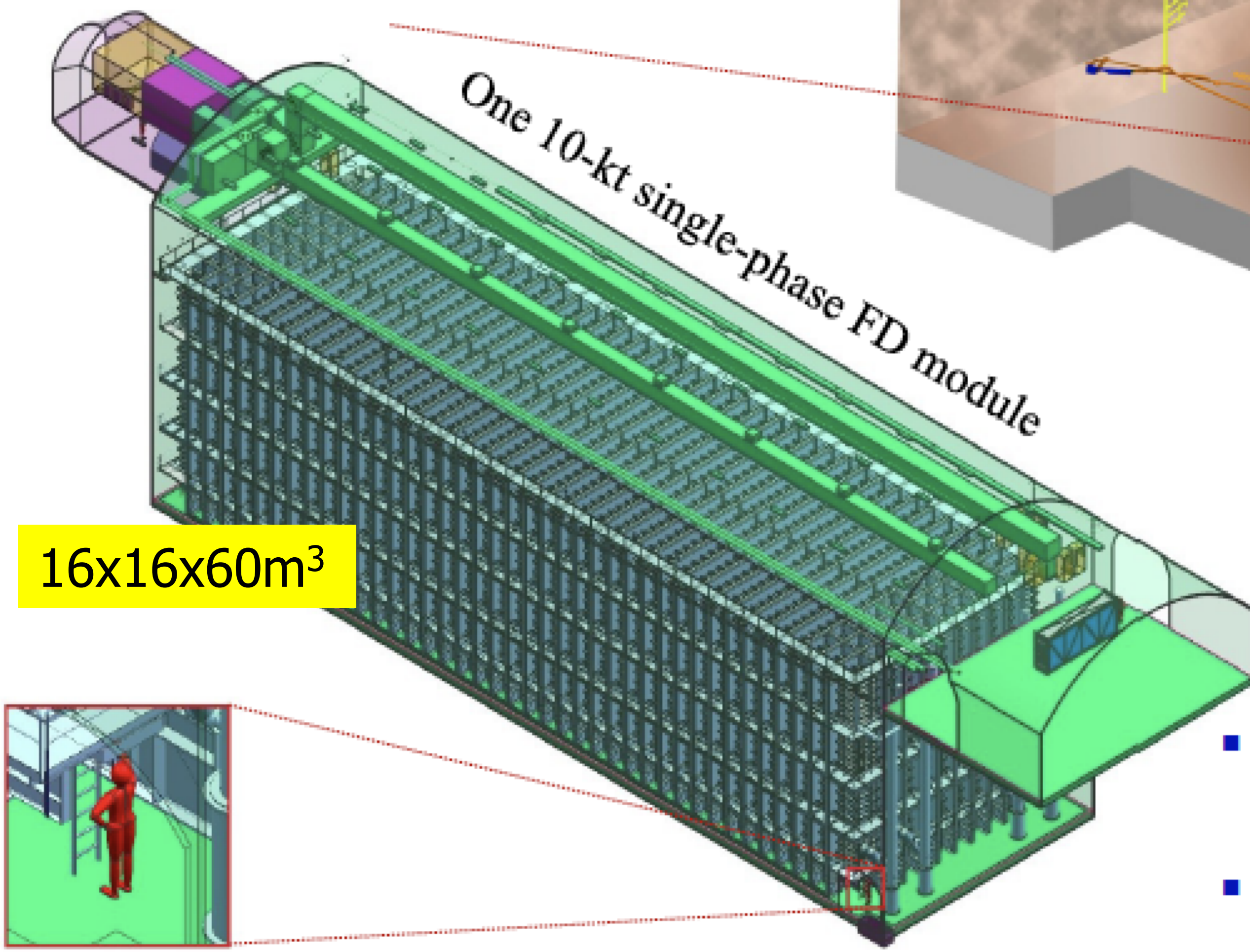
DUNE Far Detector

- **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



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

Neutrino Experiments and CERN

ProtoDUNE: Prototype at scale 1/20 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

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

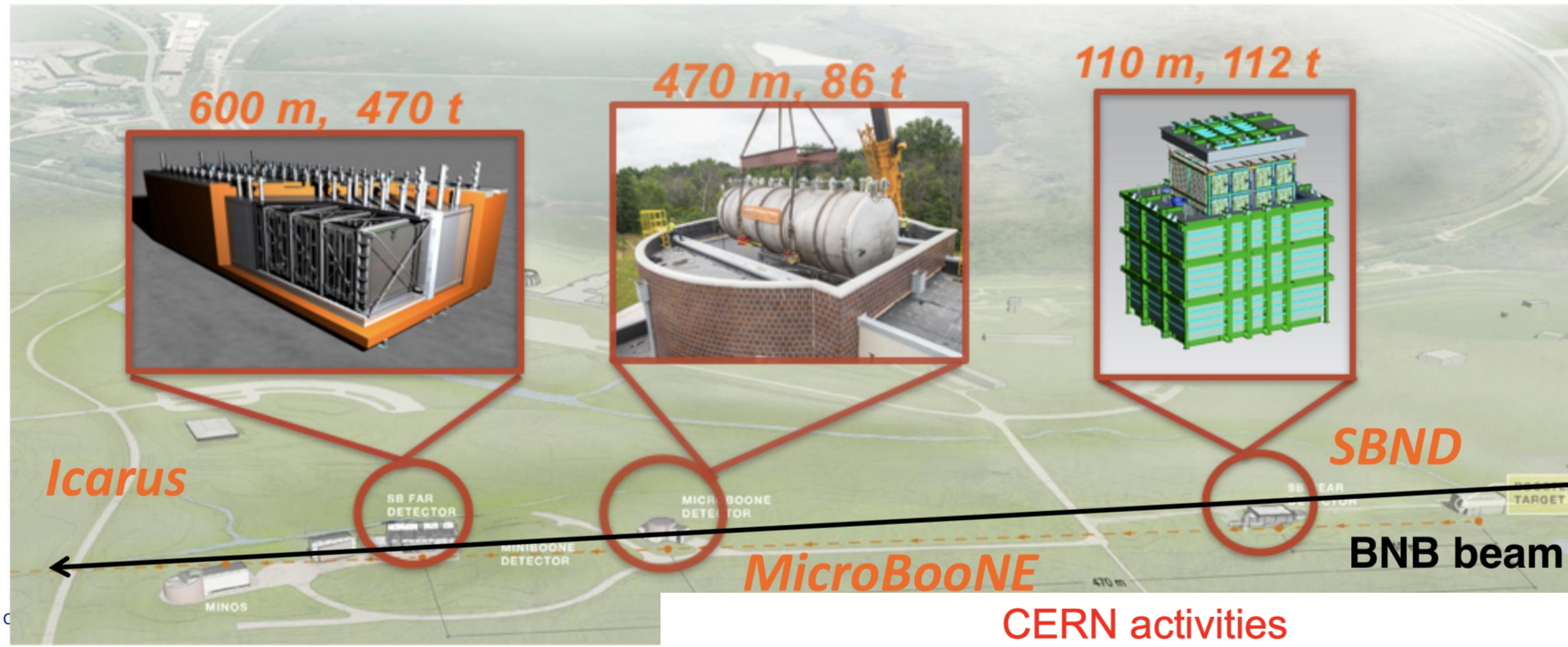
Other activities

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

NP01: ICARUS

SBN will verify the sterile neutrino hypothesis both in appearance and disappearance channels

ICARUS was a detector operational at the LNGS, Gran Sasso, and was refurbished to operate on surface at CERN and transported to FNAL in 2017



CERN activities

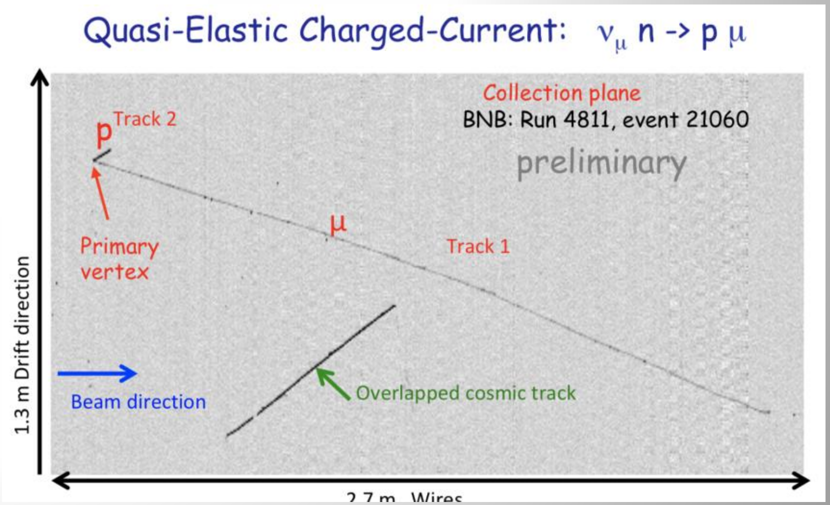
- Bring the 2 ICARUS active detectors from LNGS to CERN
- Construct new cryostats (cold and warm)
- Bring the two cold cryostats to FNAL
- Provide a large muon tagger for tagging cosmics
- Participate in the commissioning and physics exploitation

ICARUS at FNAL

Leaving CERN 12 June 2017

Positioning of the two ICARUS modules (cold cryostats) in final position in a new building at FNAL

ICARUS filled with liquid argon in 2020



First neutrino BNB candidates in ICARUS June 2021
First production run will start in October

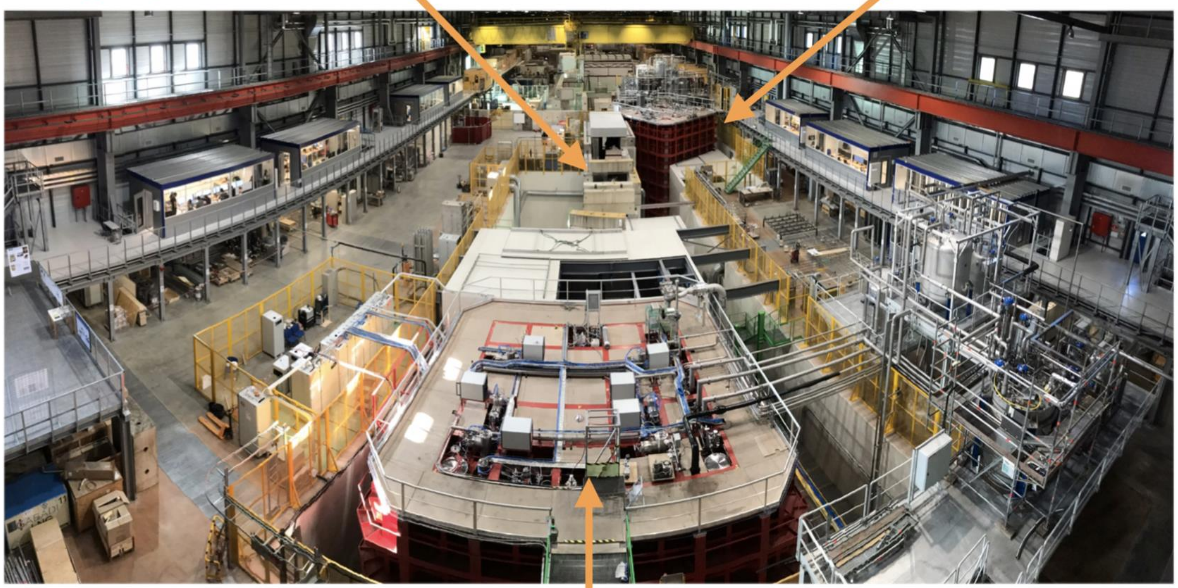
NP02/NP04 ProtoDUNES

ProtoDUNE as the necessary step to demonstrate the feasibility of the LAr technology for large detectors

- Largest liquid argon time projection chambers (LArTPCs) ever built

Charged particle beam

ProtoDUNE-DP



ProtoDUNE-SP

- **Prototypes at the scale 1:20, with modules at the DUNE scale**
- **Two technologies investigated (LAr single phase, LAr double phase)**

The EHN1 Hall at CERN

The Neutrino Platform hall

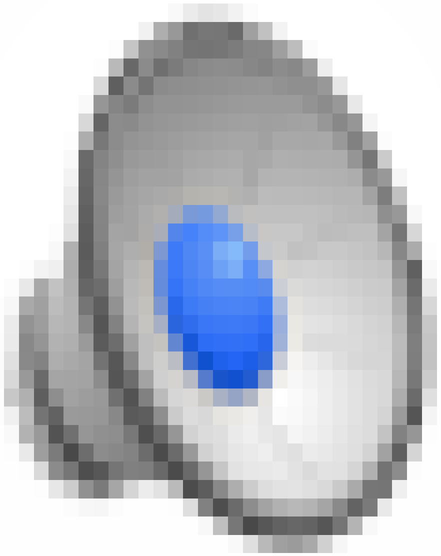
Virtual Visit to the Neutrino Platform

Recent visit on 12/8/2021

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

Liquid Argon Time Projection Chamber

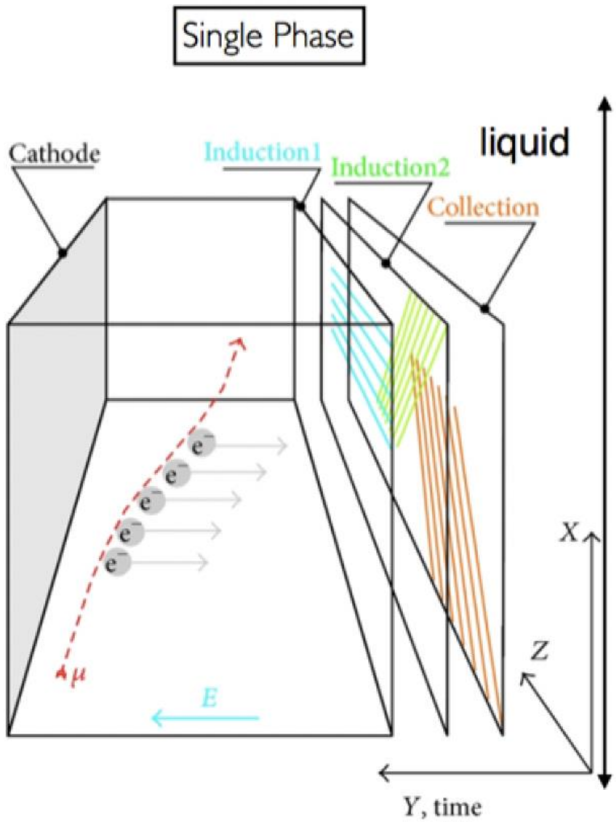
The ‘electronic’ bubble chamber for neutrino experiments



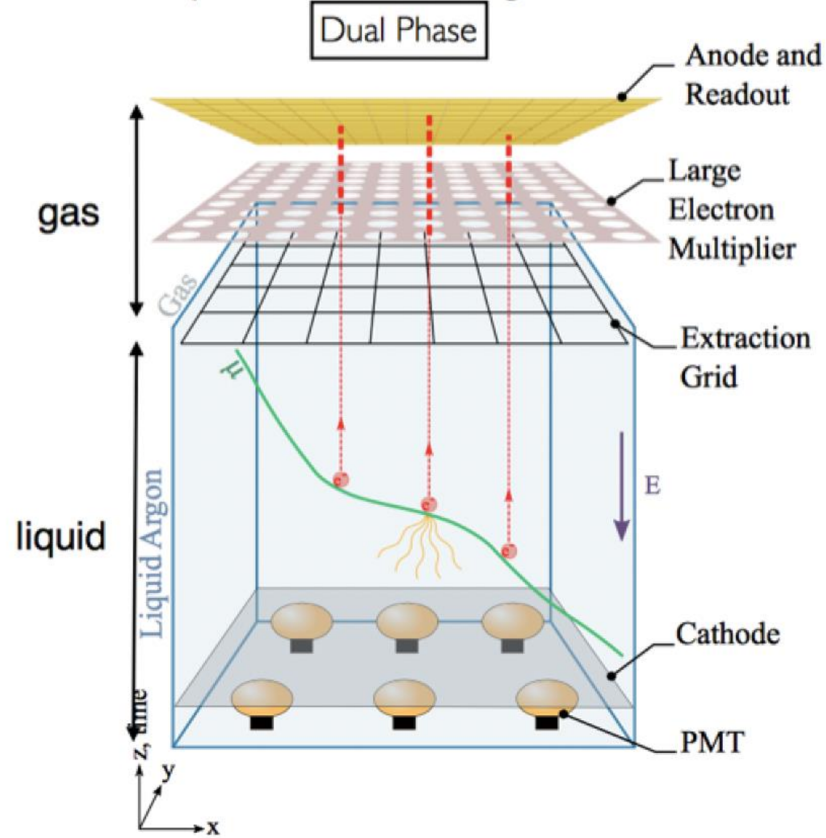
The ProtoDUNES

The Dual Phase turned out to be very complex and this idea for the technology has now been replaced by a so called "vertical drift" LArTPC technque

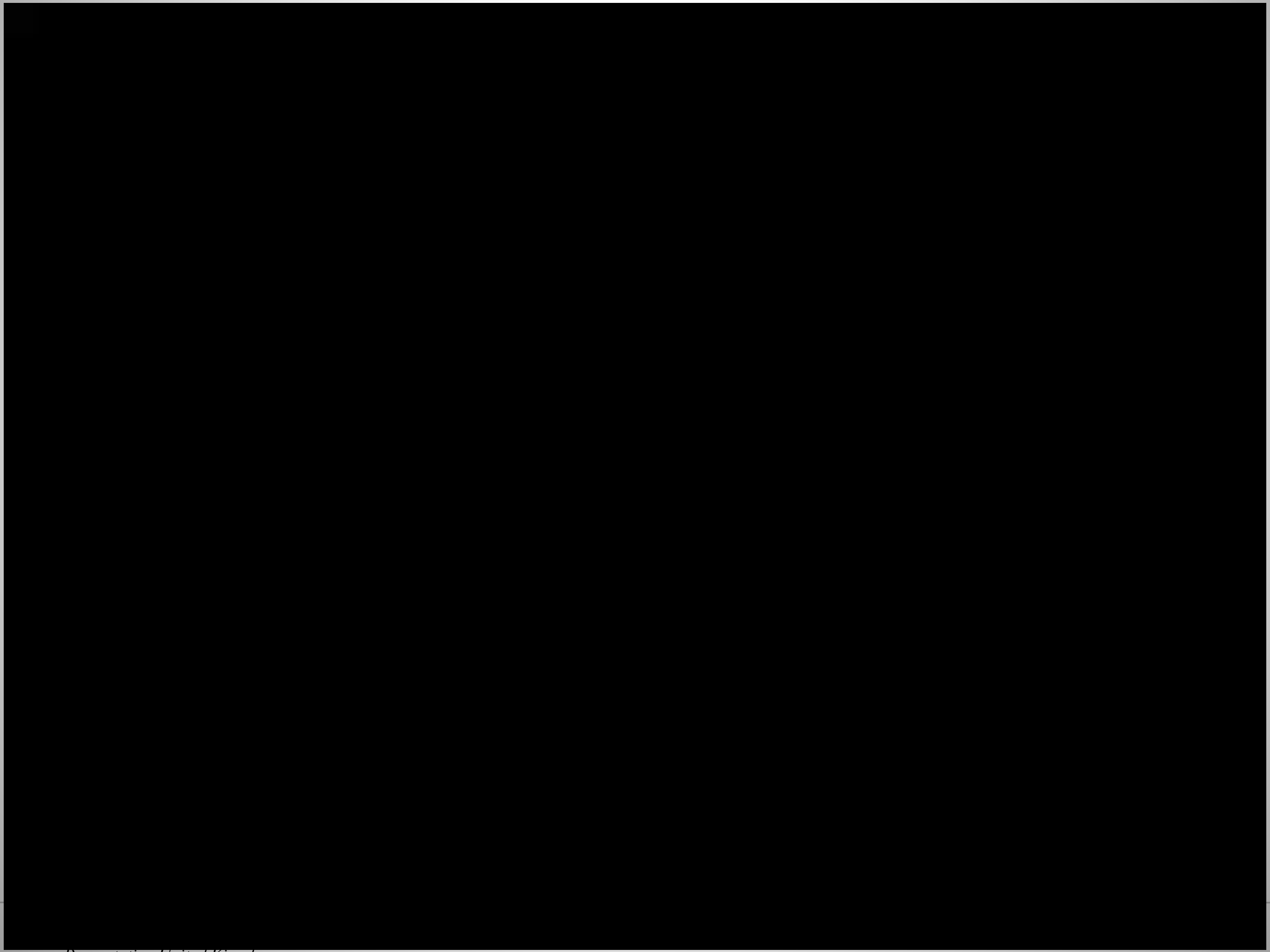
- ionisation charges are drifted horizontally and readout by wires.
- No amplification of the signal.



- ionisation charges are drifted vertical and readout by PCB anodes.
- amplification of the signal in LEMs

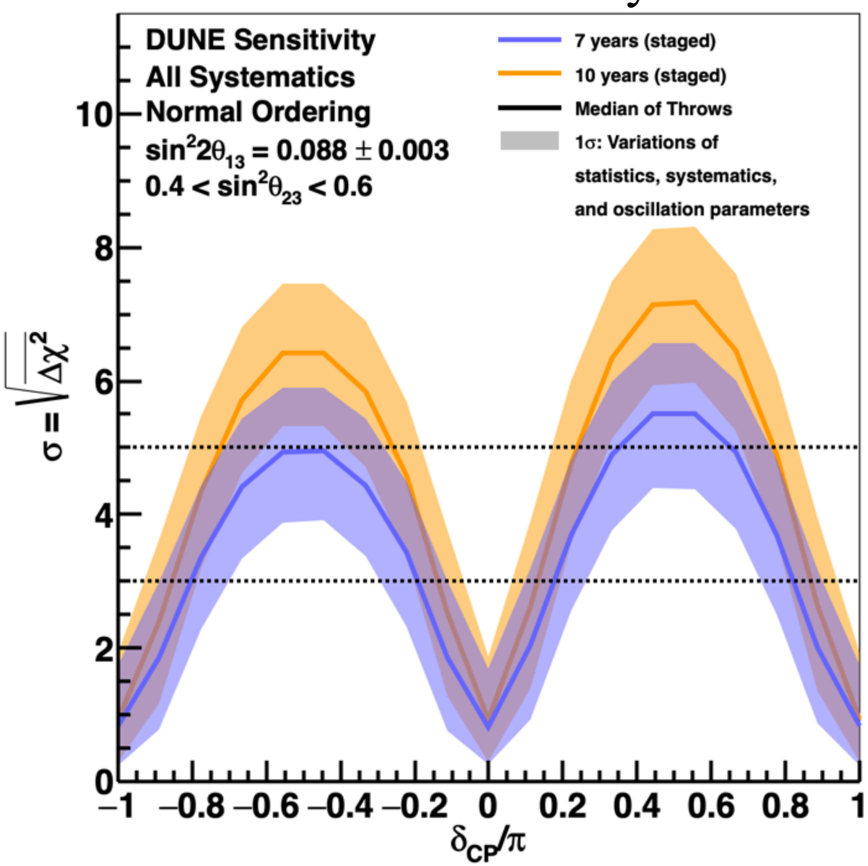


This new idea wil be fully tested within 1-2 years using the NP02

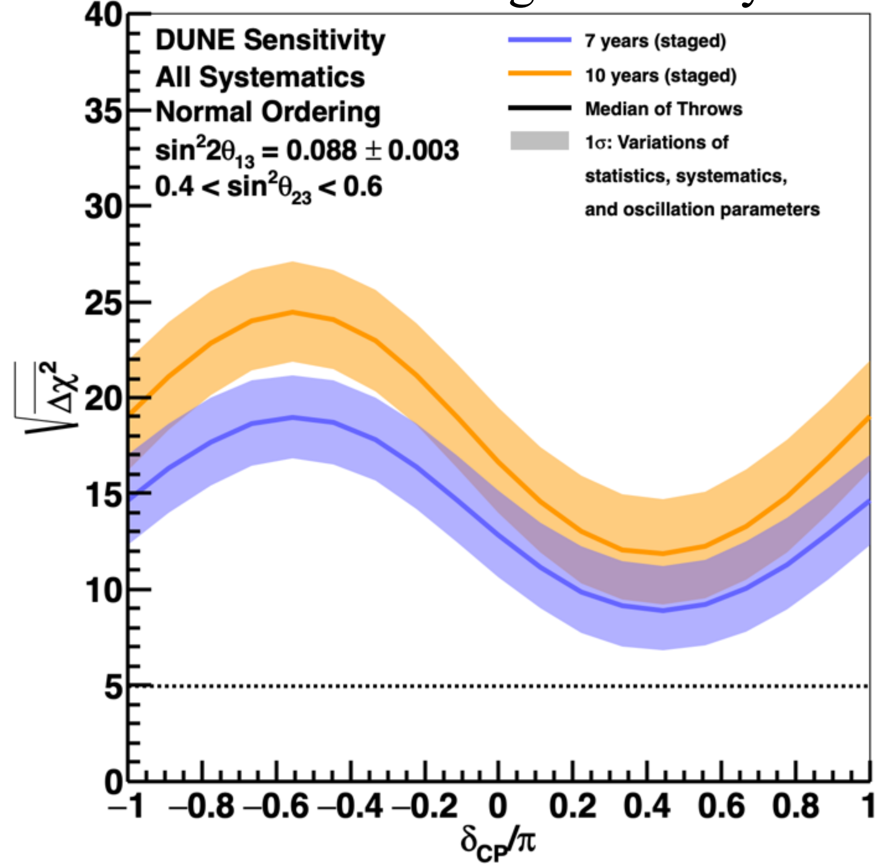


DUNE: CP Violation and Mass Ordering

*CP*v sensitivity



Mass ordering sensitivity

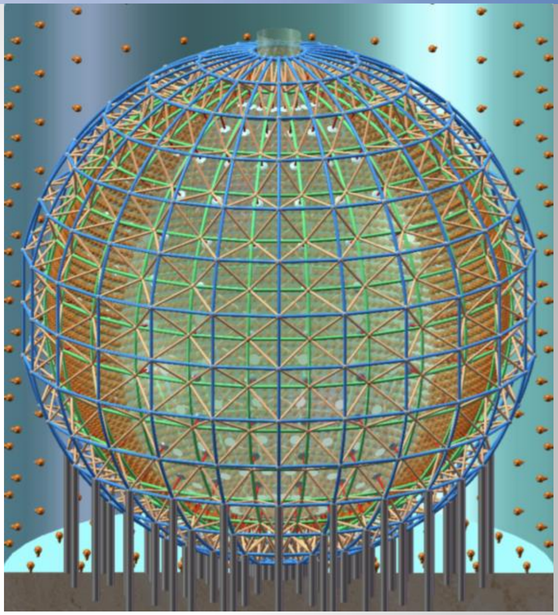


- Updated Sensitivity with realistic systematics and reconstruction
  - Move quickly to potential ***CP* violation discovery**
  - Rapid, definitive **mass ordering determination** (>5σ)

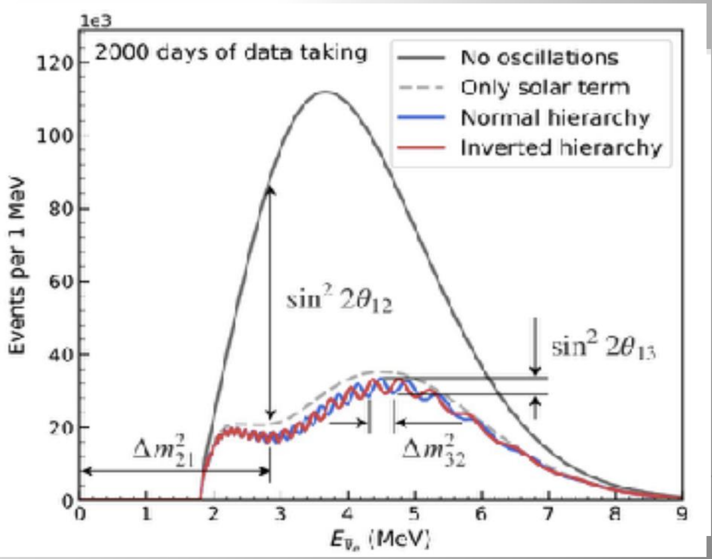
arXiv:2002.03005

Near Future: 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/start2023



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)



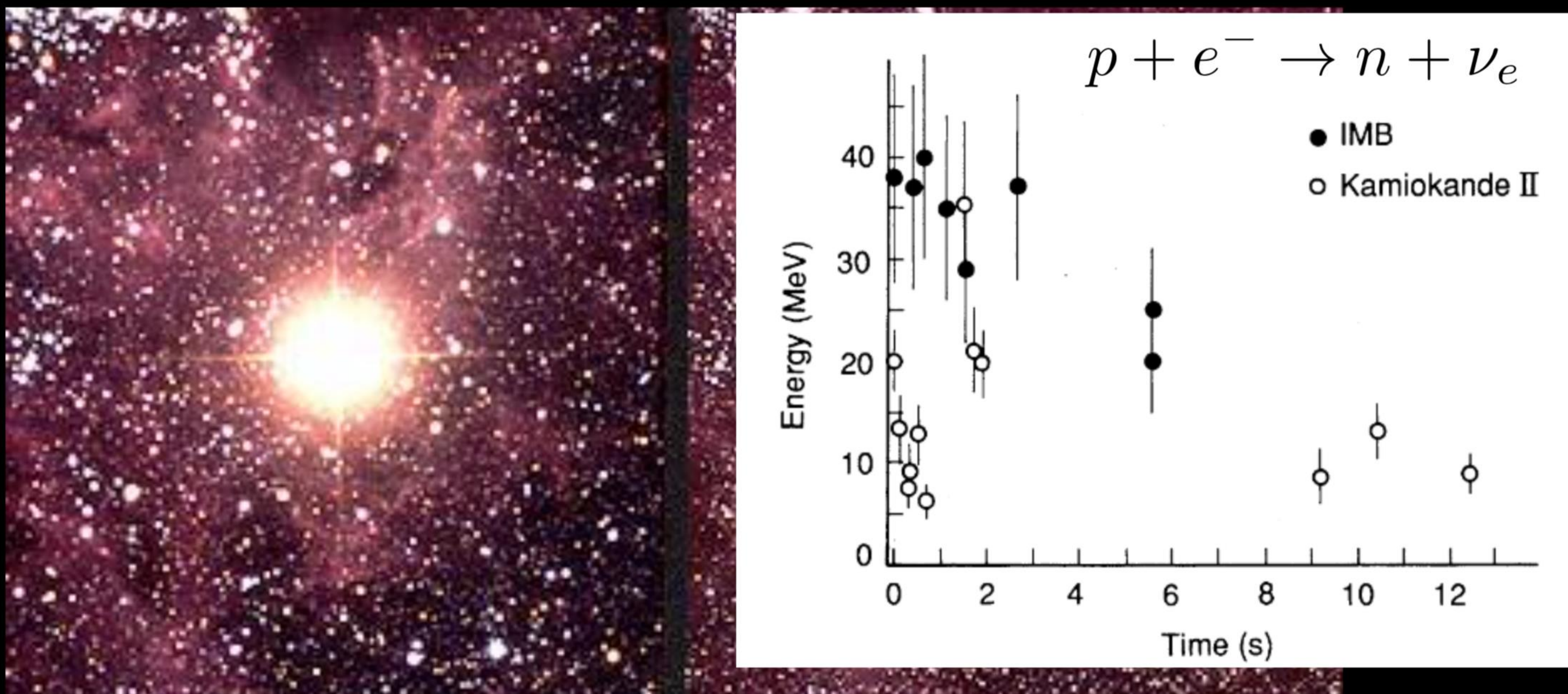
Neutrinos & Cosmos

- 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

Study of Supernova Explosions

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

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

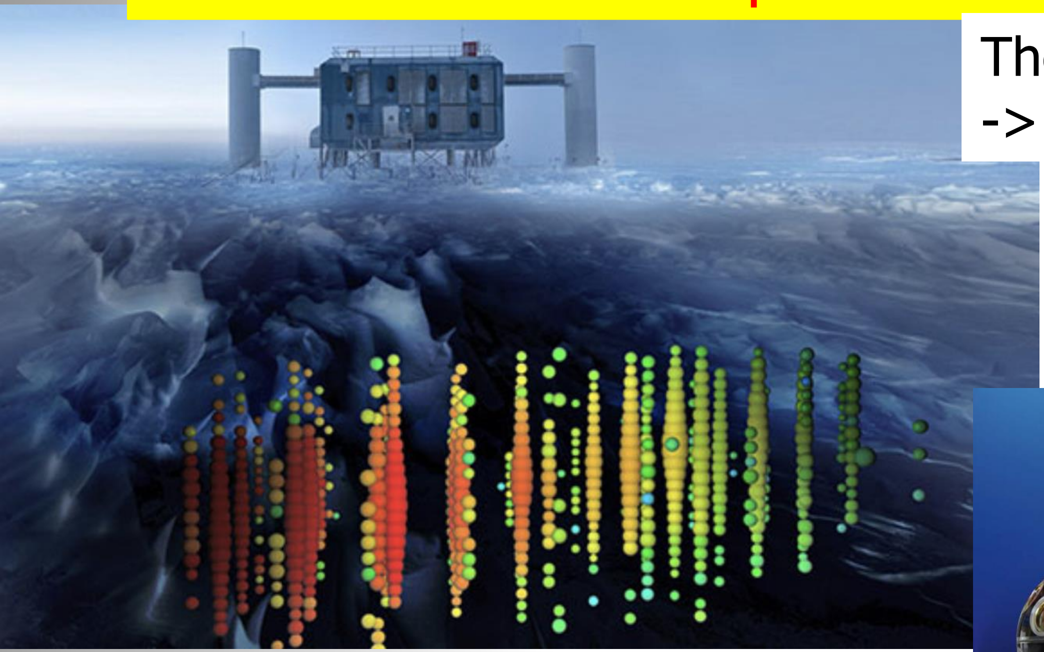


For comparison: the Milky Way is about 34 kpc across

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

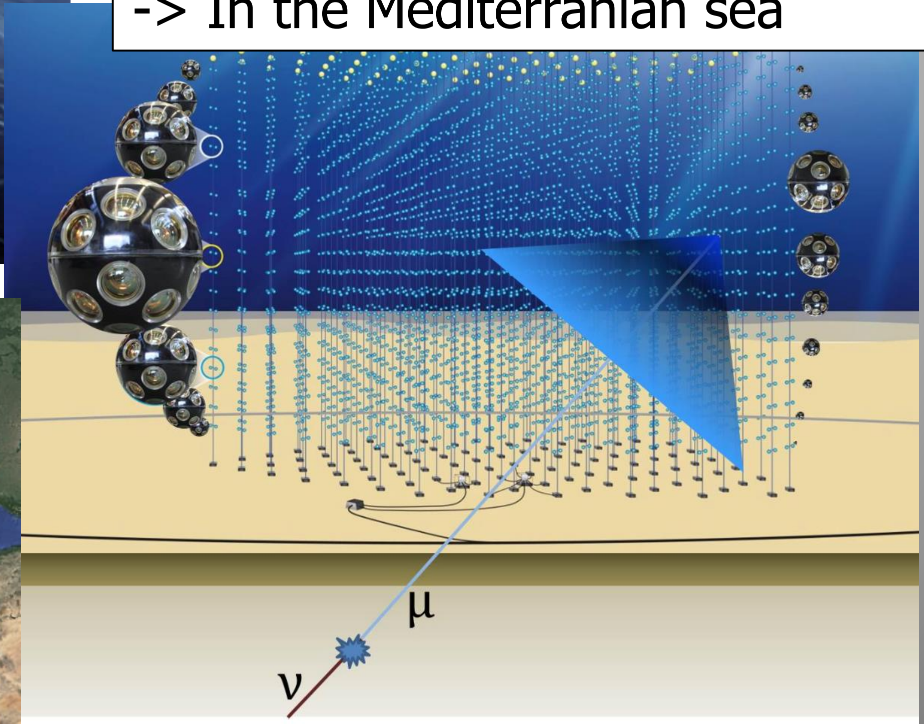
Neutrino Astronomy

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



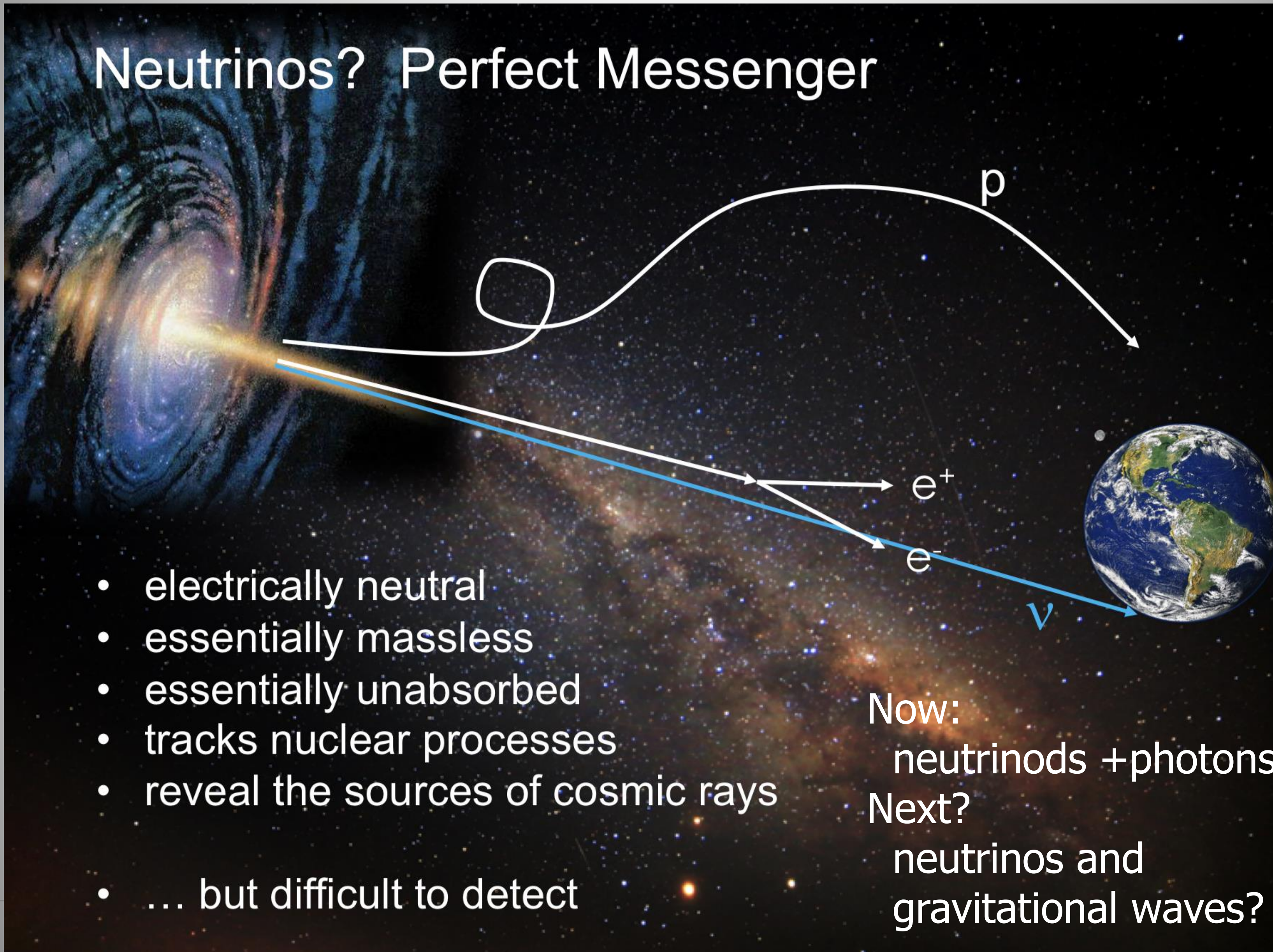
The IceCube Experiment: operational
-> In the ice of Antarctica

The KM3NET Experiment: 6 strings now/ full detector by 2025
-> In the Mediterranian sea

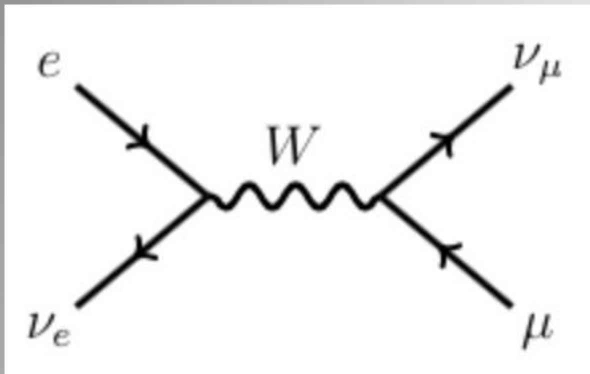


+ANTARES
+Lake Baikal

Multi Messenger Astronomy

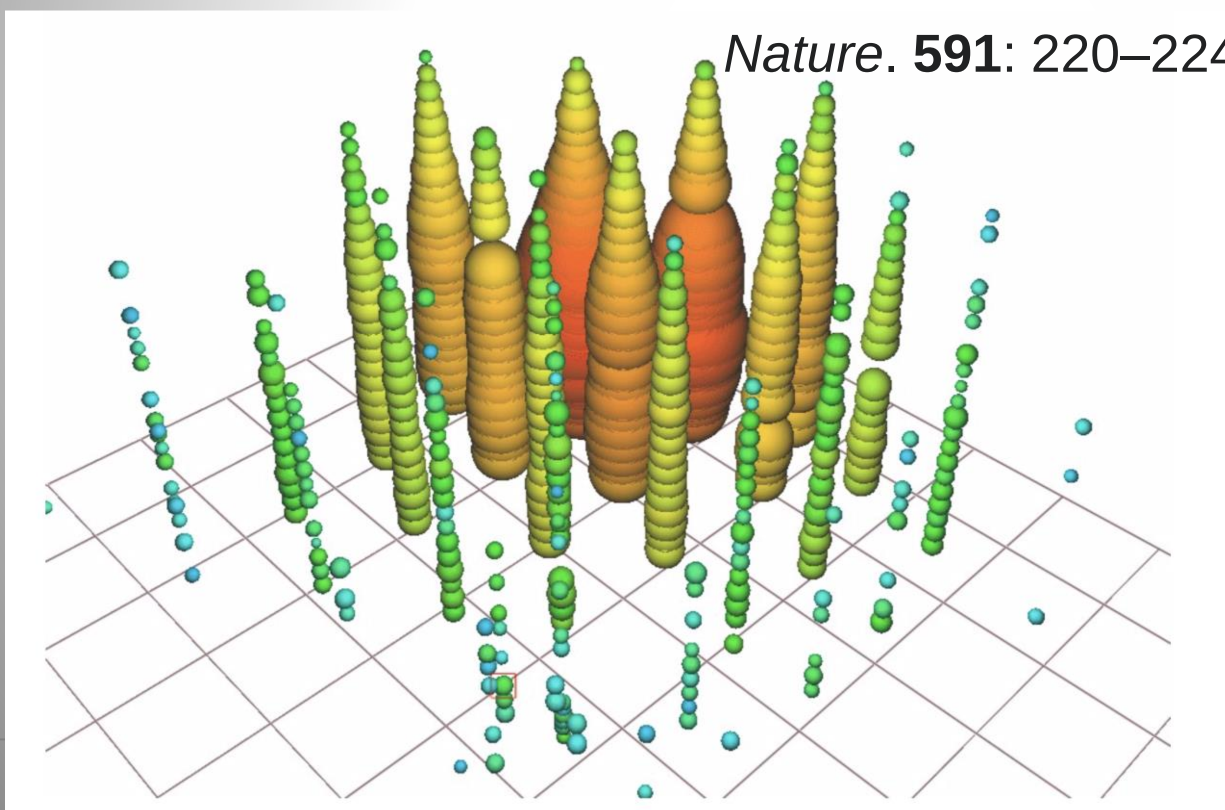


Observation of a Glashow Resonance



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

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



Nature. **591**: 220–224

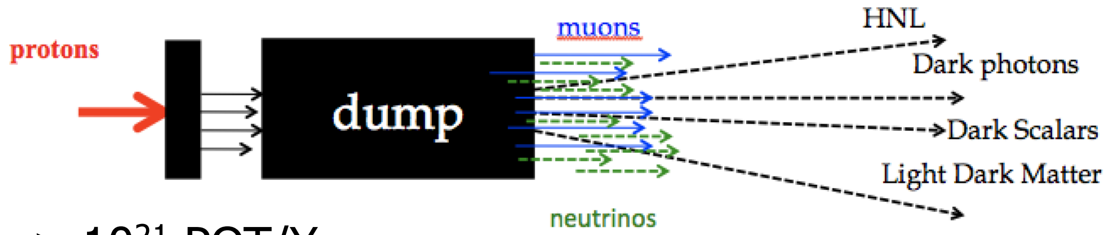
$$E_\nu = \frac{M_W^2 - (m_e^2 + m_\nu^2)}{2m_e} \approx \frac{M_W^2}{2m_e}$$

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



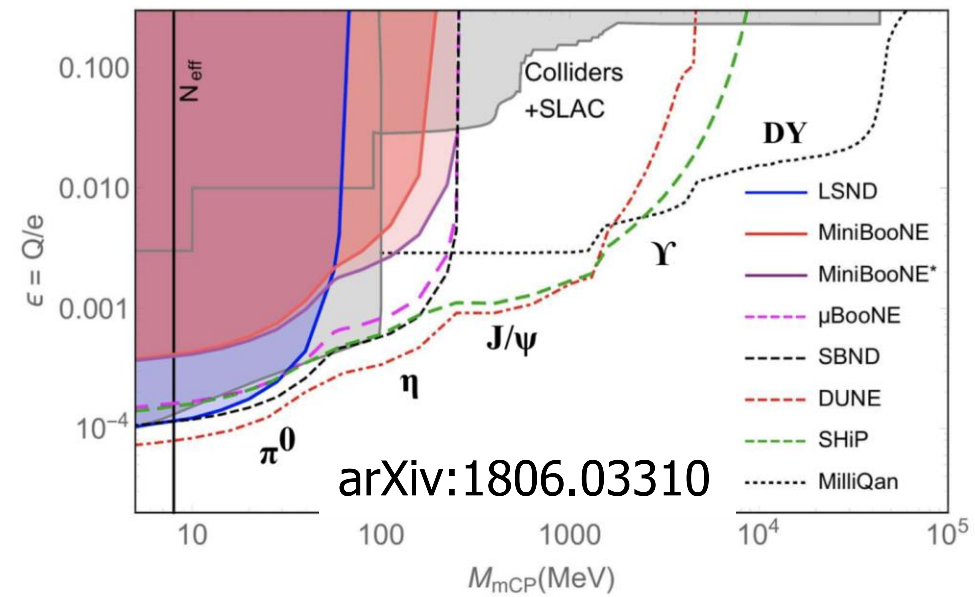
> 10^{21} POT/Year

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
- -ALPs
- -mini/millicharges

arXiv:1907.08311

Example millicharges:



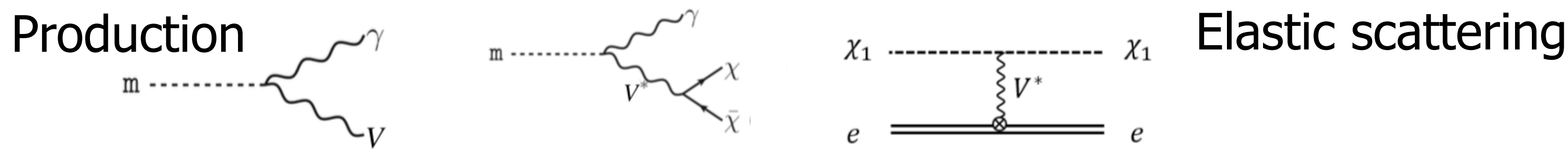
arXiv:1806.03310

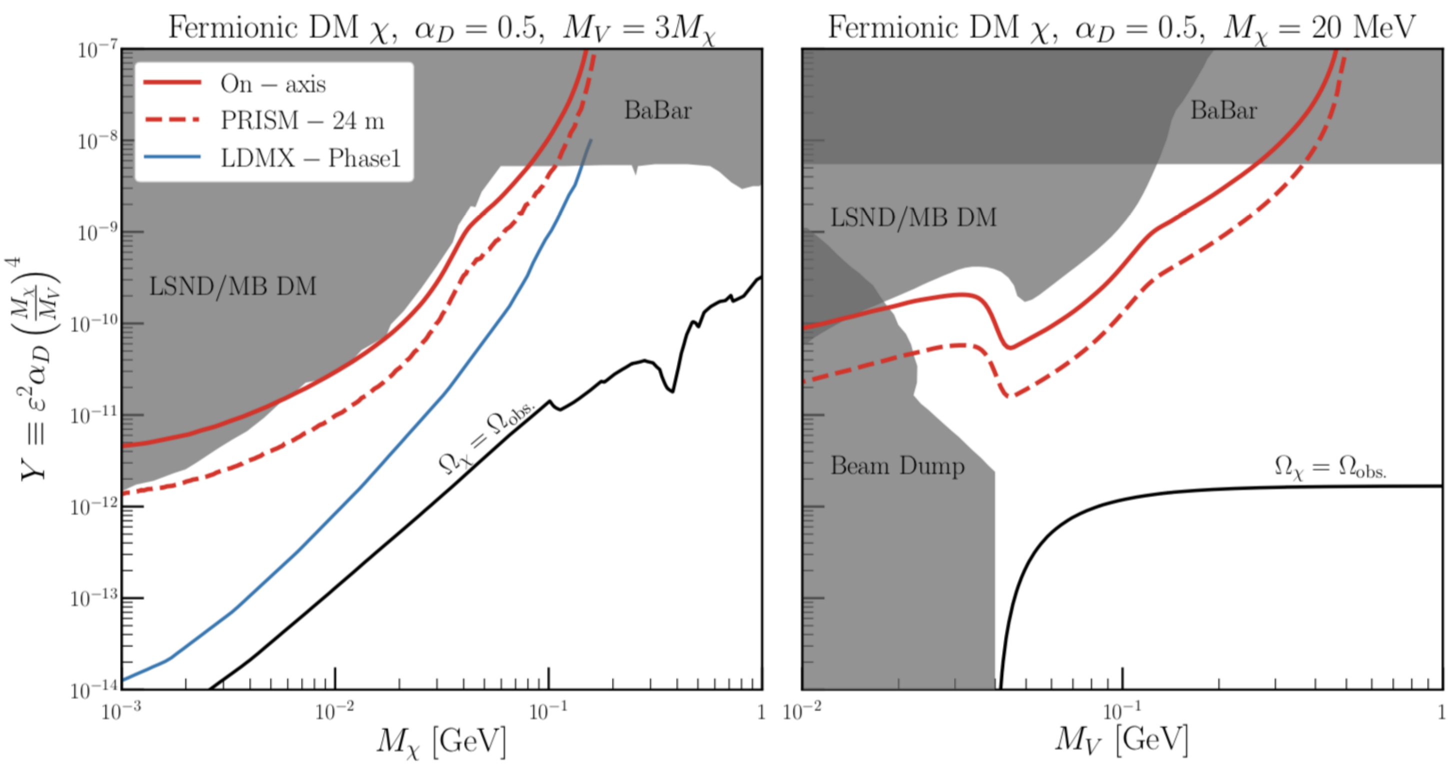
WHITE PAPER ON NEW OPPORTUNITIES AT THE NEXT-GENERATION NEUTRINO EXPERIMENTS
(PART 1: BSM NEUTRINO PHYSICS AND DARK MATTER)

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)

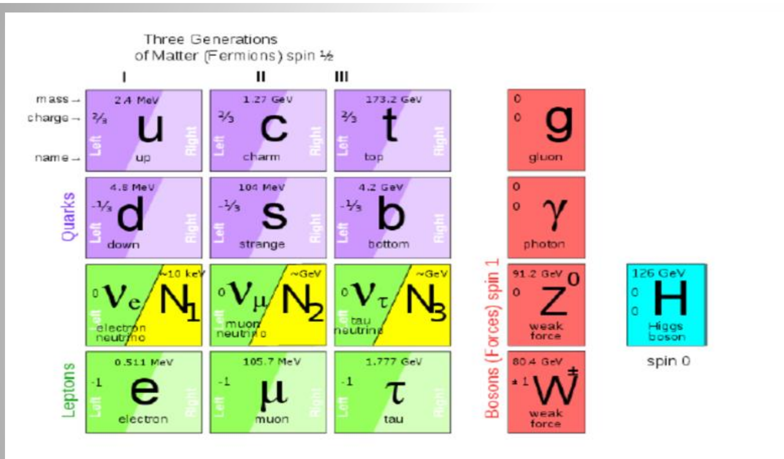


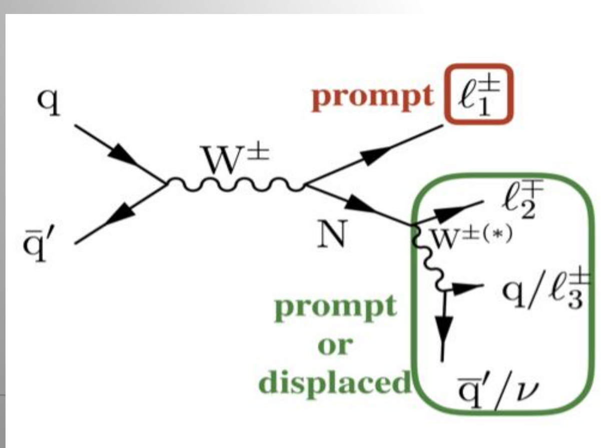


Neutrinos @ the LHC: Examples

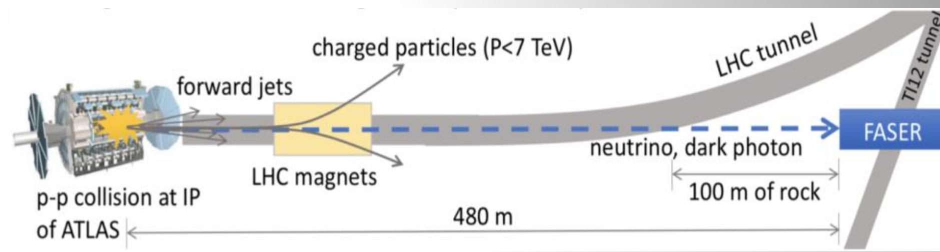
Searches for right-handed neutrinos at the LHC

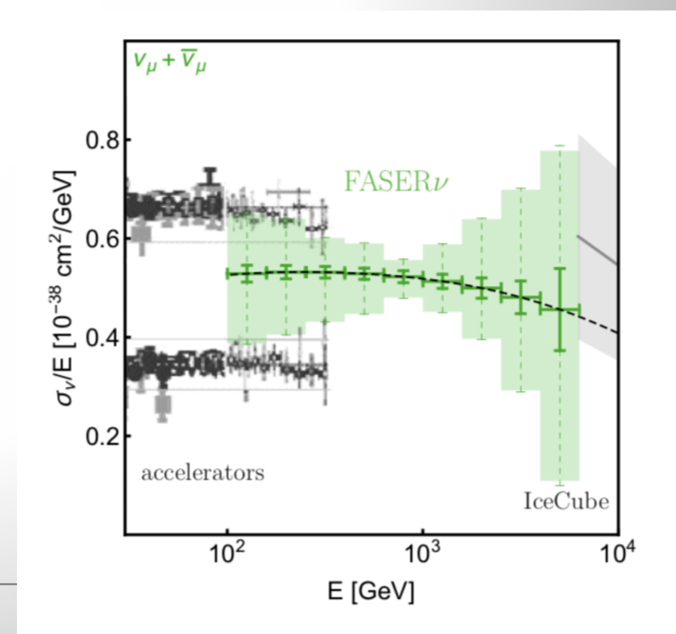
νMSM (Neutrino Minimal Standard Model)





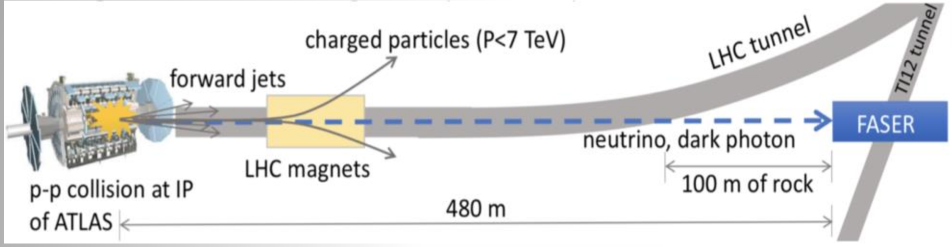
SND@LHC and FASER-Nu are 400m forward of the IPs and can study TeV-neutrinos with emulsion detectors





Neutrinos @ the LHC: SND@LHC

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



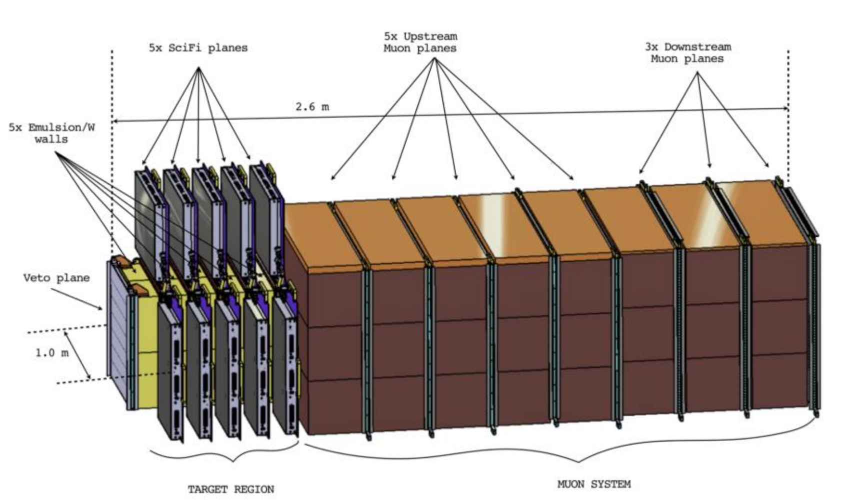
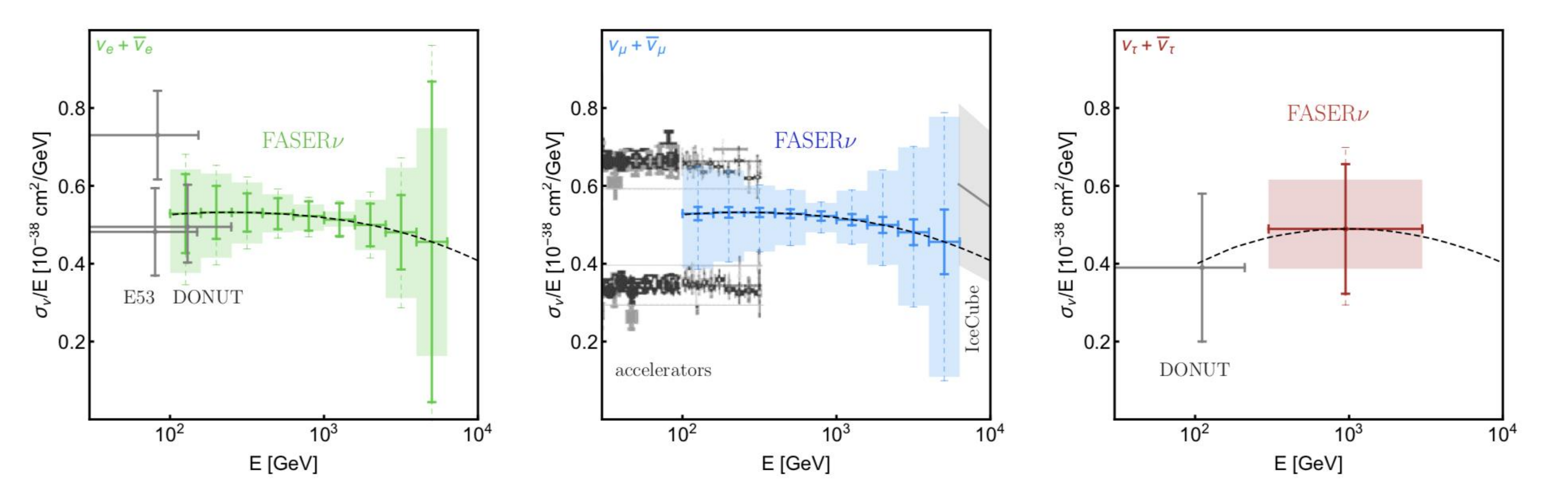


Figure 5: Layout of the proposed SND@LHC detector.

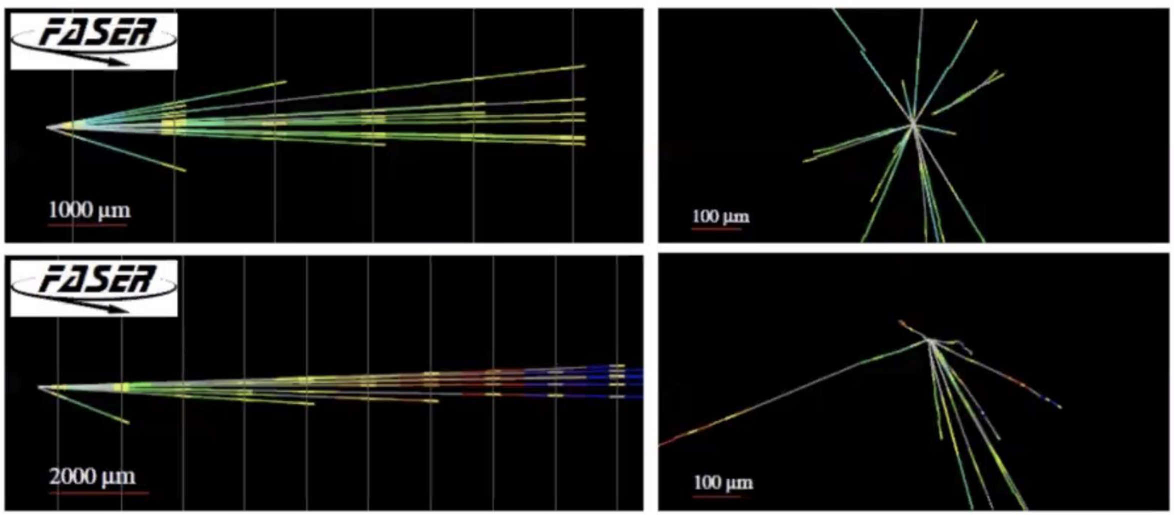
SND= Scattering and neutrino detector



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

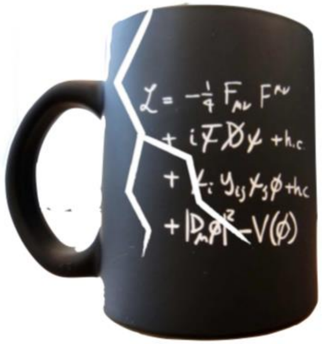
(FASER Collaboration)

I. INTRODUCTION

arXiv:2105.06197v1 [hep-ex] 13 May 2021

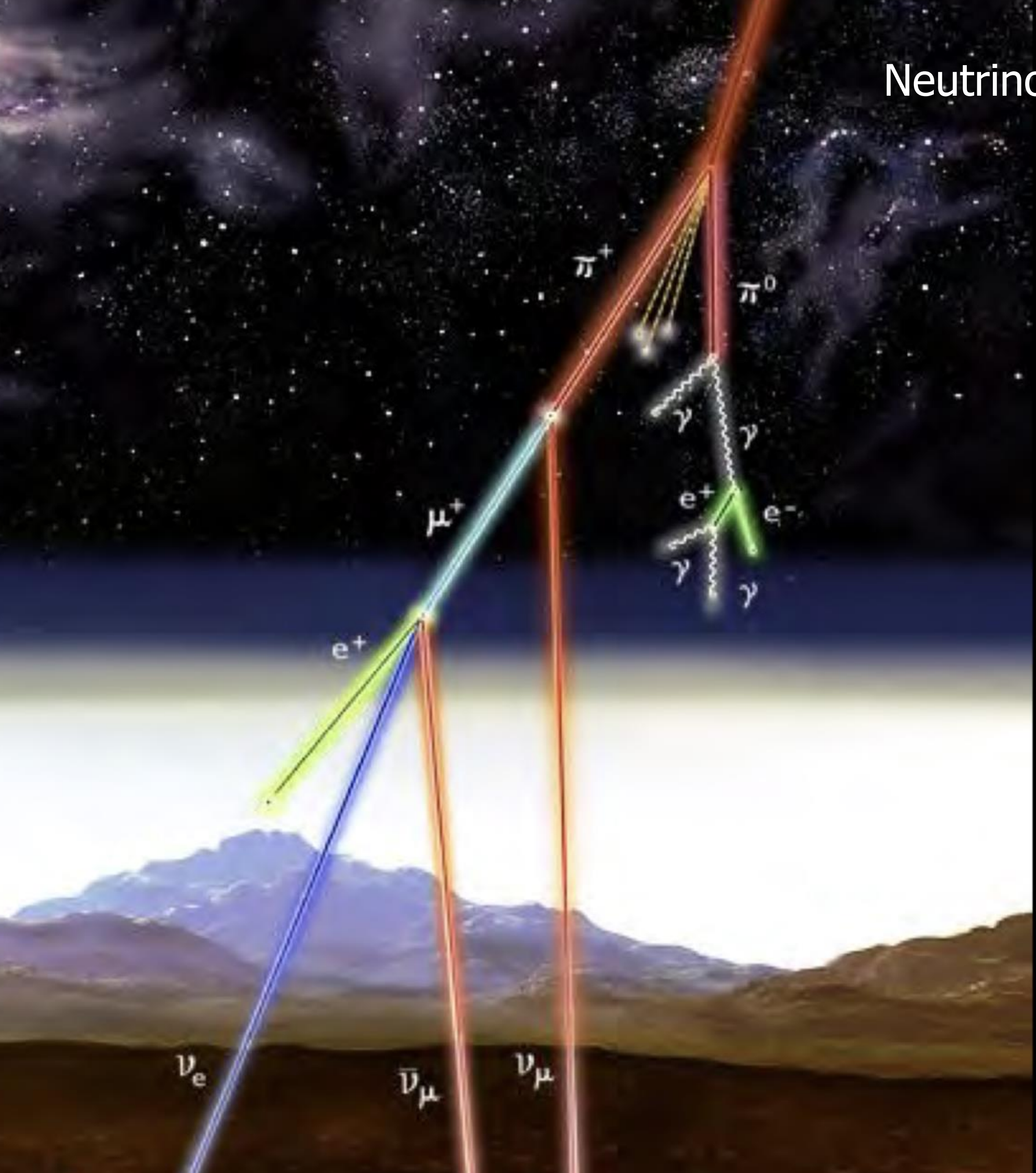
SUMMARY: Neutrinos

- 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??



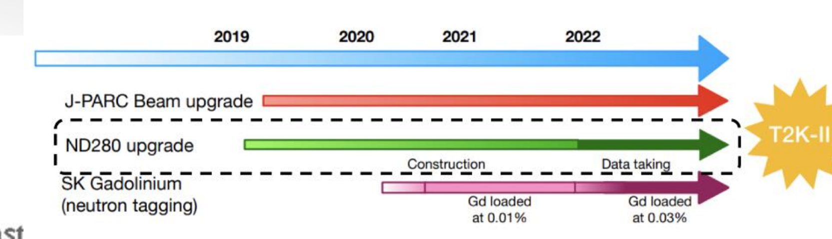
Backup

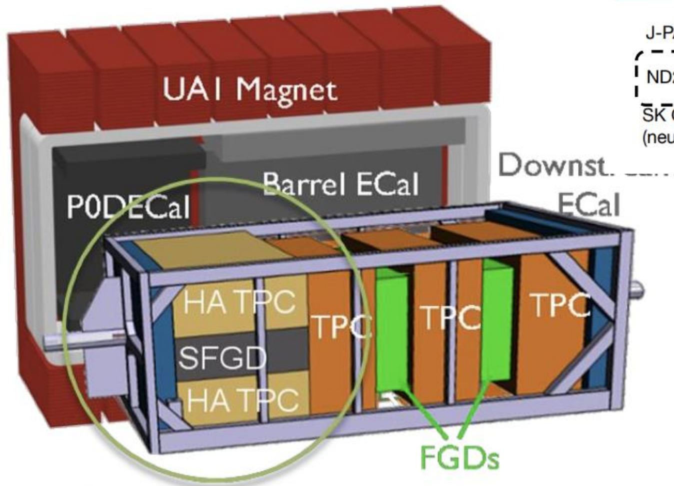
Neutrinos from cosmic rays

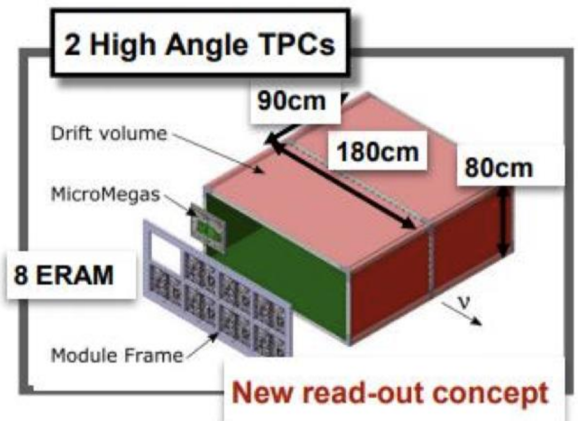


Neutrinos are also produced in the atmosphere

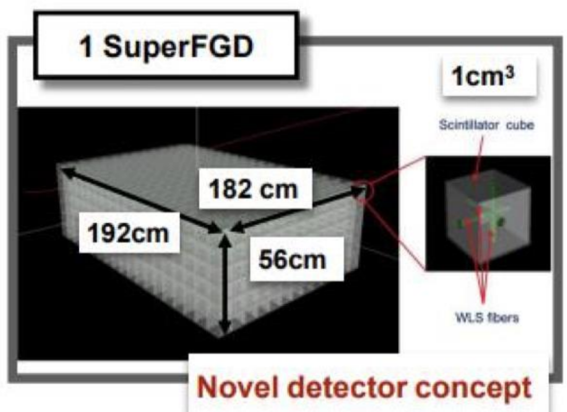
NP07: The T2K ND280 Upgrade



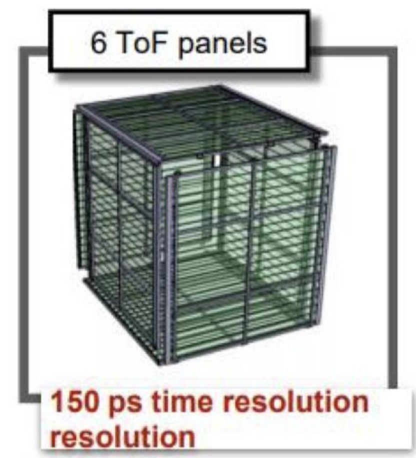




NIM A 957 163286 (2020)



JINST 13, P02006 (2018)
JINST 15 P12003 (2020)



JPS Conf. Proc. 27, 011005 (2019)

CERN involved in the HA TPCs and SuperFGD
Much of the assembly done at CERN as we speak.. Transport CERN ->Tokai early next year

A Multi-Frontier Problem

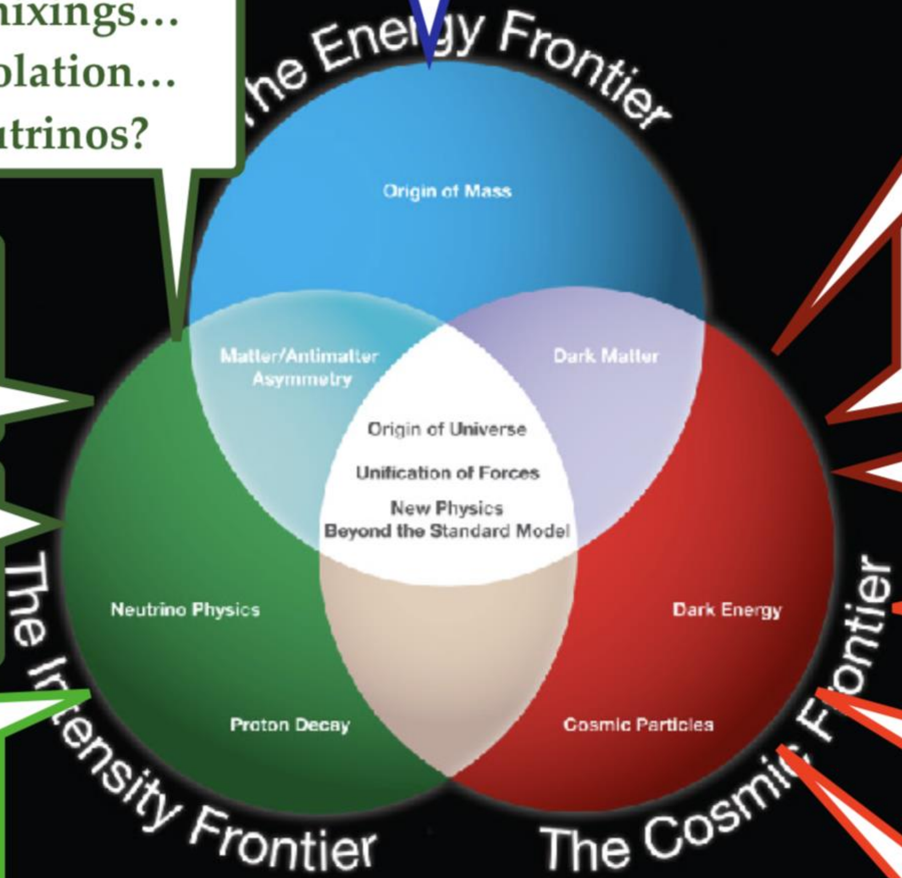
Collider Probes of the origin of neutrino mass

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"

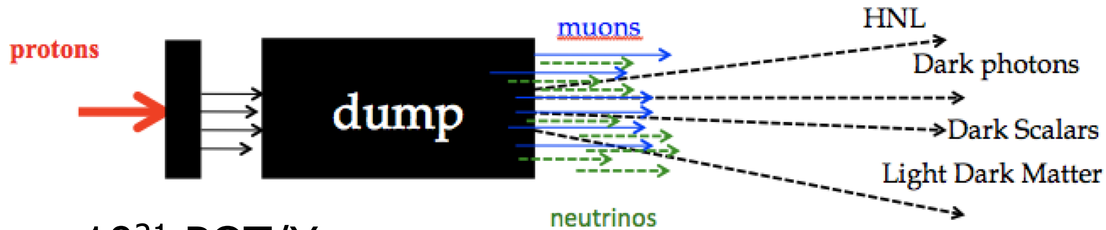
Cosmic Neutrino
Background

Leptogenesis?

Sterile Neutrino
Dark Matter?

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



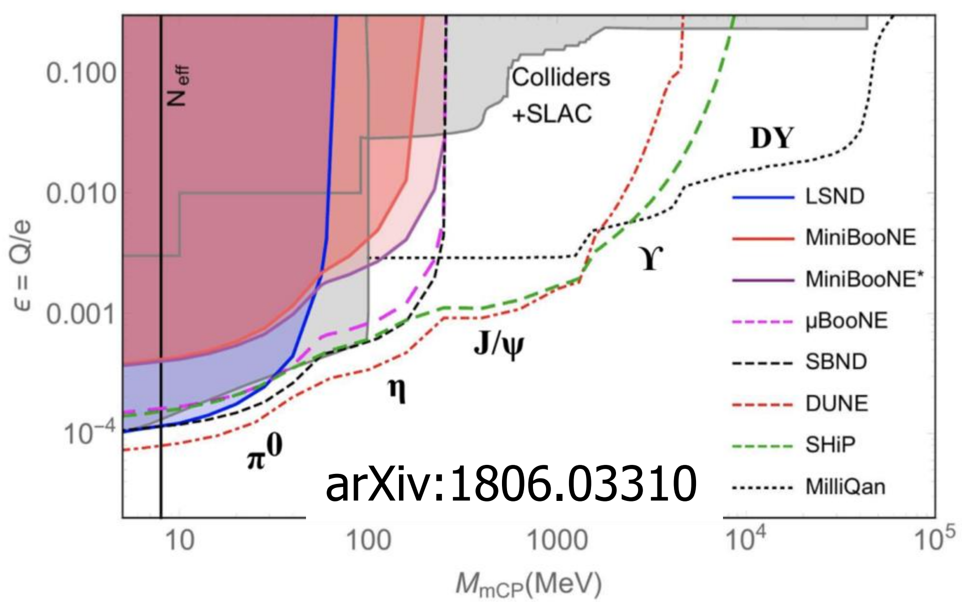
> 10^{21} POT/Year

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
- -ALPs
- -mini/millicharges

arXiv:1907.08311

Example millicharges:



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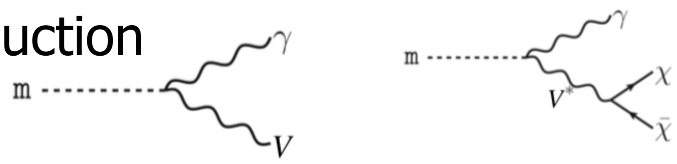
Searches for Low Mass Dark Matter

Light dark matter produced at the accelerator (meson decays)

Production



Elastic scattering