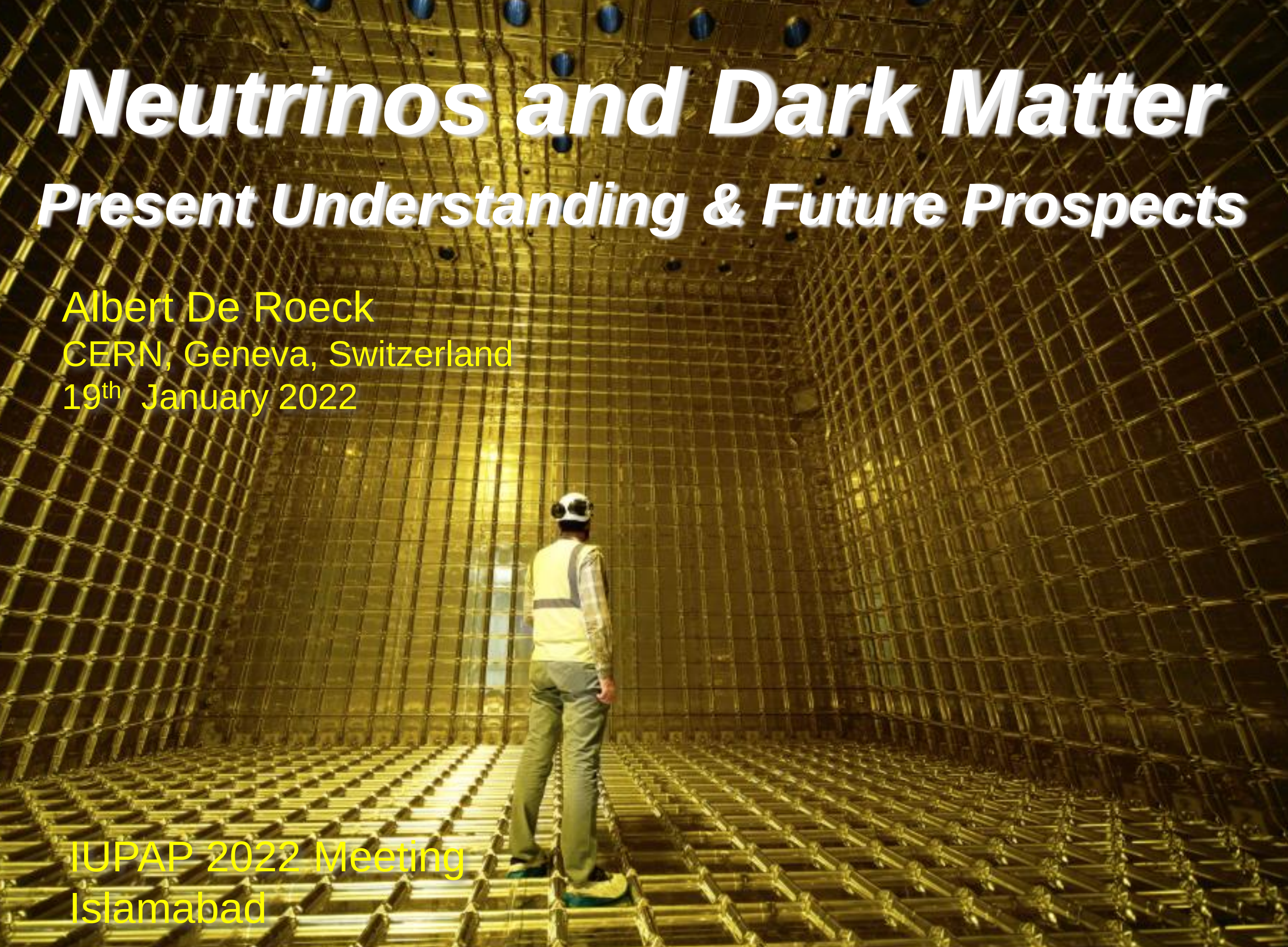


Neutrinos and Dark Matter

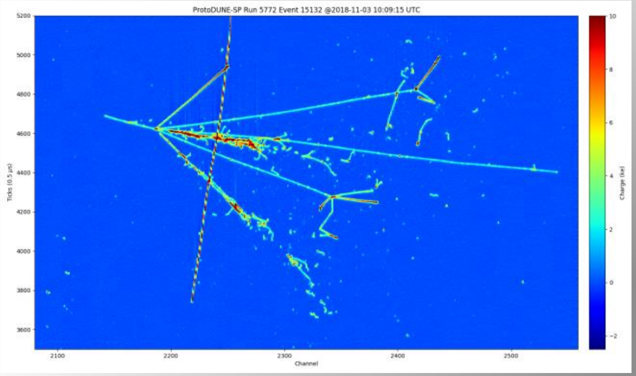
Present Understanding & Future Prospects

Albert De Roeck
CERN, Geneva, Switzerland

19th January 2022

IUPAP 2022 Meeting
Islamabad

Outline



Pion event in the ProtoDUNE at CERN

Speaker of today

- Introduction

Neutrinos

- Neutrinos oscillate and have mass
- Oscillation experiments results
- Neutrino properties: mass and Majorana/Dirac nature
- Future Neutrino experiments

Dark Matter

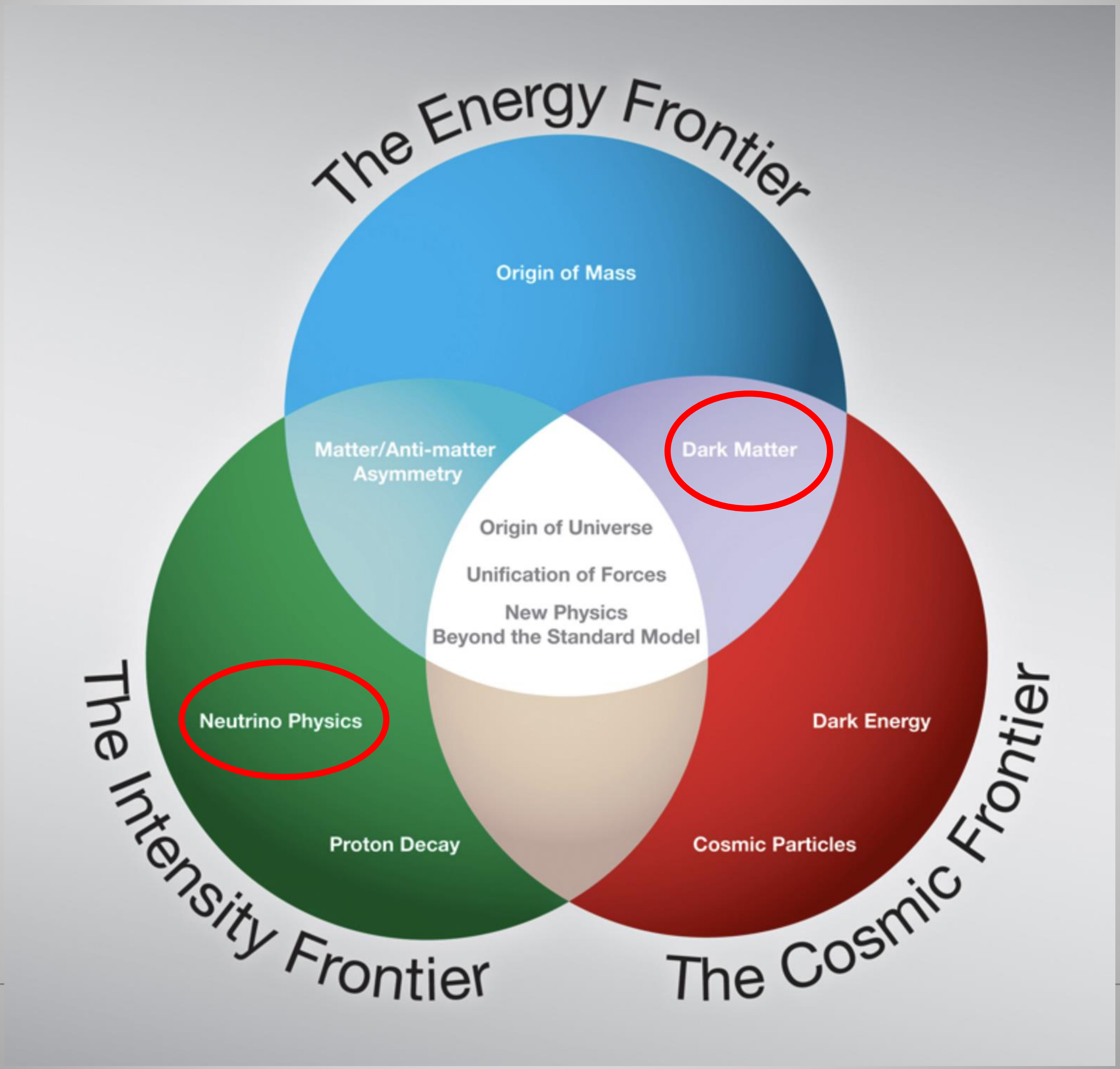
- Experiments and search results
- Future Dark Matter experiments
- Summary

Neutrinos and Dark Matter

- Neutrinos are by now well established particles (but it took 26 years to observe them..)
  - They do not behave as a priori expected in the SM and have a very small but definite non-zero mass. Properties of the neutrinos are yet not well known to date.
- The Nature of dark matter is not known at all. We even don't know if it is a particle. Ideas have been evolving with time.
  - We have only search limits so far. If a particle, then DM is likely neutral and weakly interacting.
- Both programs have a strong experimental community and program, typically using deep underground facilities, low background environments, and they have synergies
  - Eg. also the LHC is a place to search DM, and 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)

Fundamental questions on the laws of the Universe

2015



Neutrinos

Neutrinos are still mysterious particles

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

Neutrinos are Everywhere !

from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

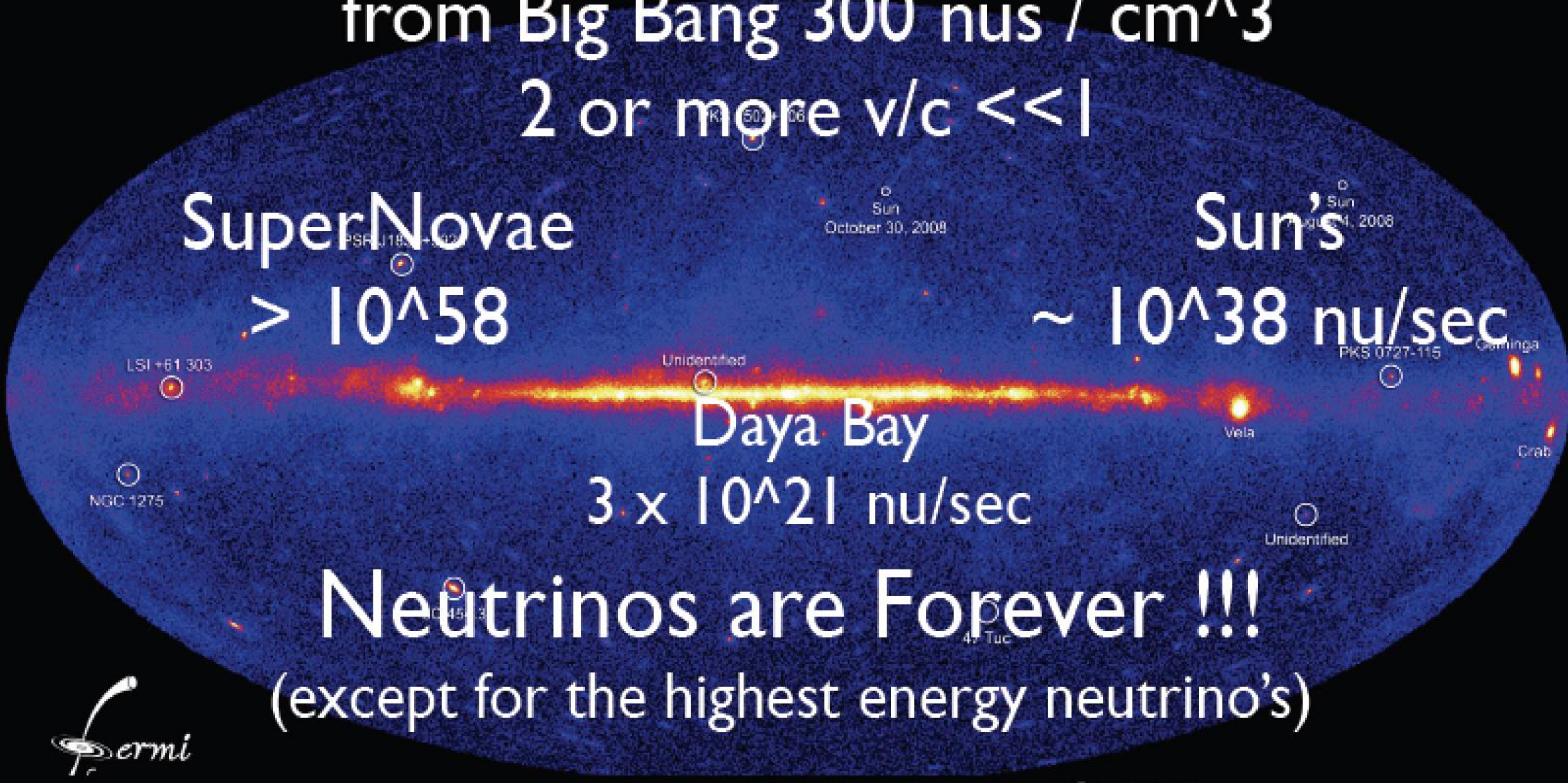
~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

Neutrinos are Forever !!!

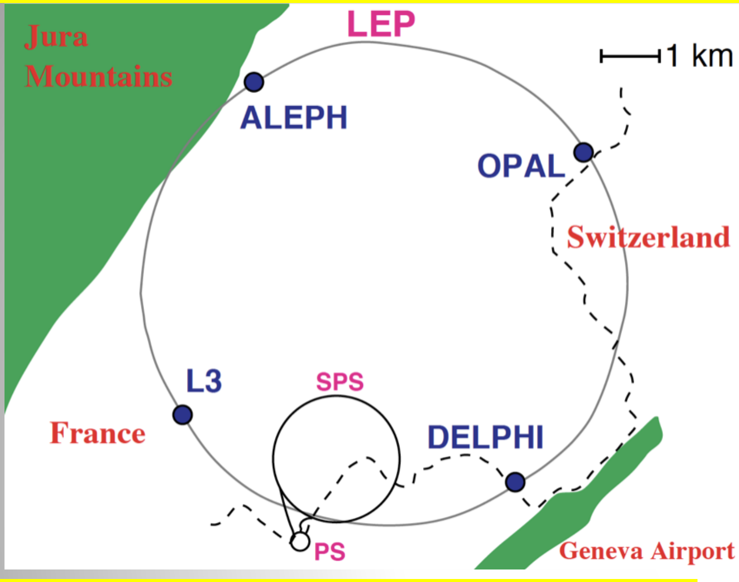
(except for the highest energy neutrino's)

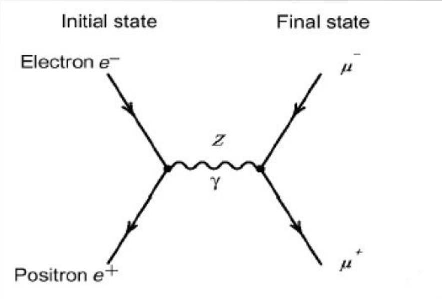


therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrinos come in 3 Flavours

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



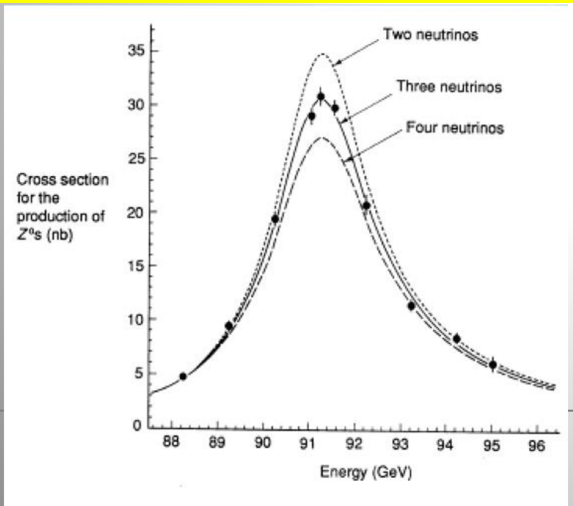


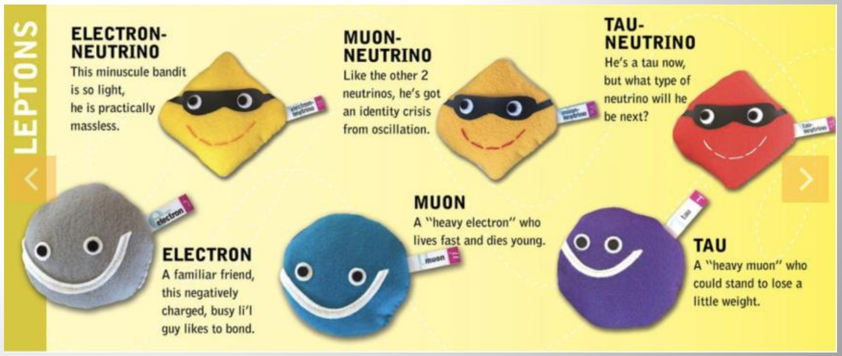
The width of the Z-boson gives the number of neutrinos

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

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

Detailed study of the Z-boson

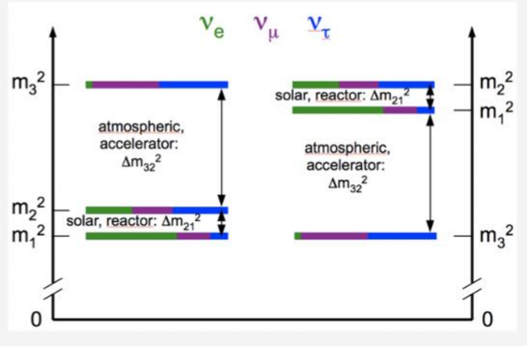




LEP: three active neutrinos with mass<45 GeV

Neutrinos

Neutrino experiments today -> Open Questions!

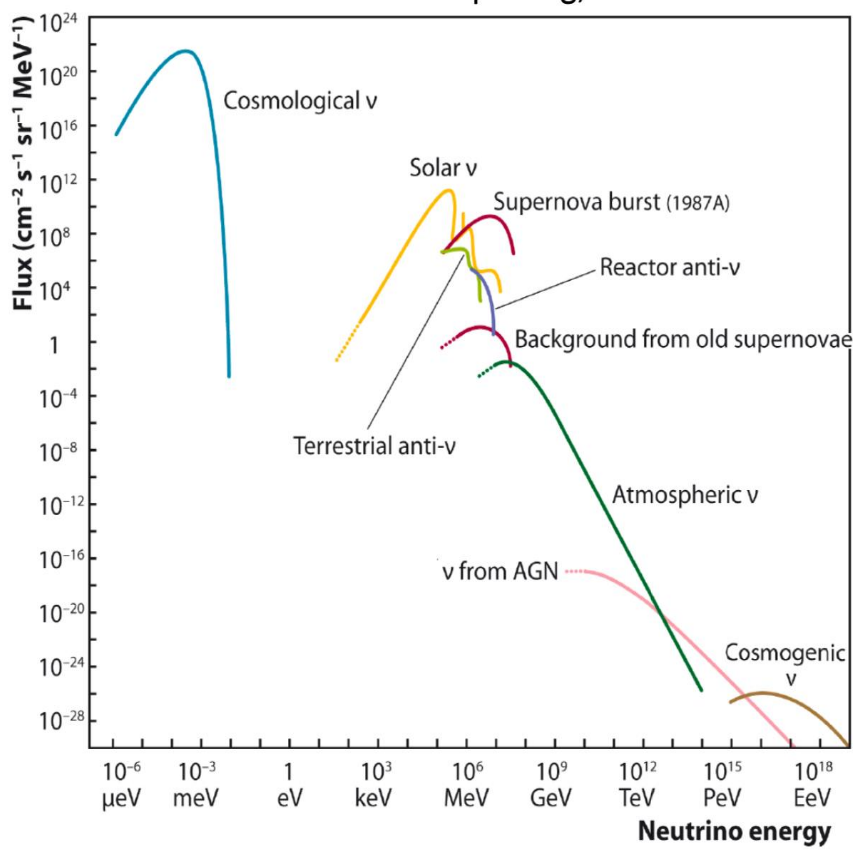


- Neutrino mass values?
- Neutrino mass hierarchy? Normal or Inverted?
- CP violation in the lepton sector? Are neutrinos key the baryon asymmetry in the Universe?
- Are neutrinos their own antiparticles? -> LNV processes
- Do right-handed/sterile/heavy neutrinos exist?
- Are there non-standard neutrino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

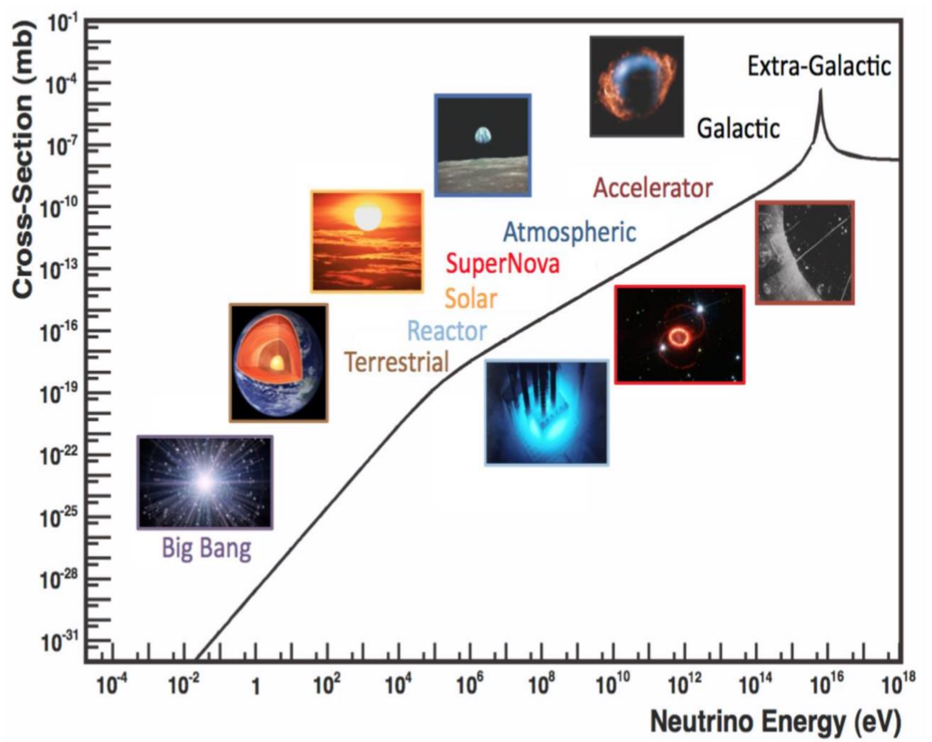
Neutrinos are an essential part of our Universe and our very existence, and can provide answers to some of the key fundamental questions today

Neutrino Sources, Flux and Cross Sections

C. Spiering, arXiv:1207.4952



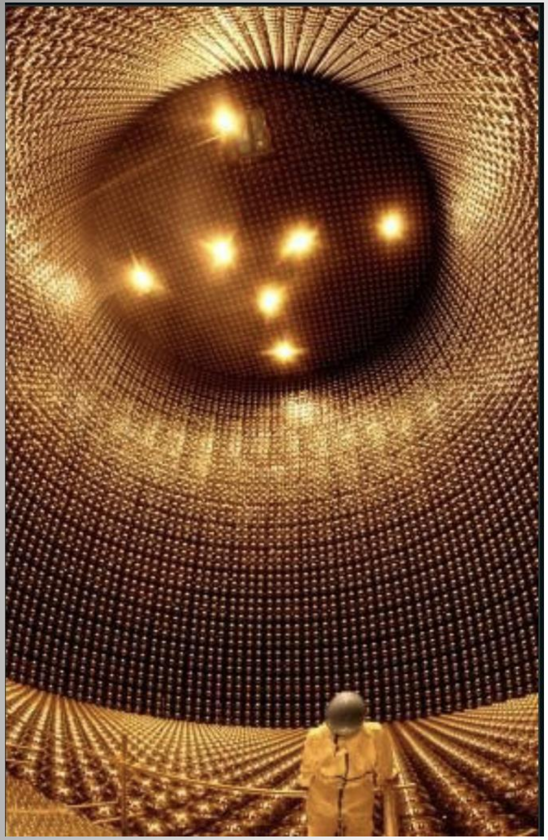
J. Formaggio, G.P. Zeller, arXiv:1305.7513

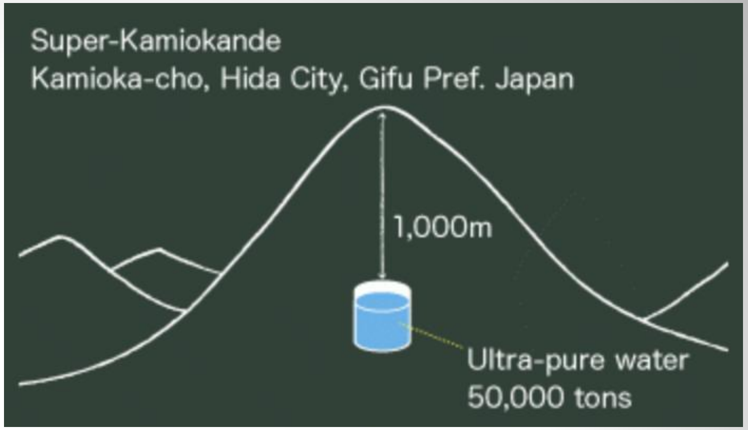


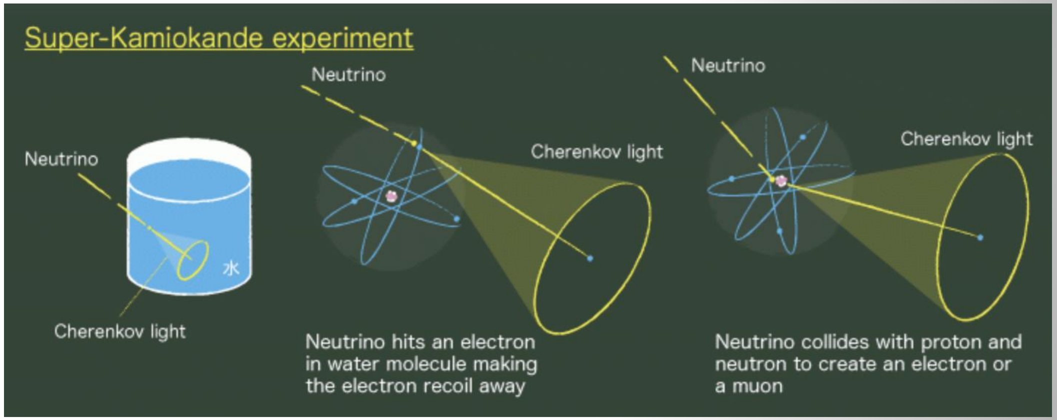
Cosmological and background from old supernovae neutrinos not yet observed!

Detecting neutrinos is challenging
Very large detectors are needed

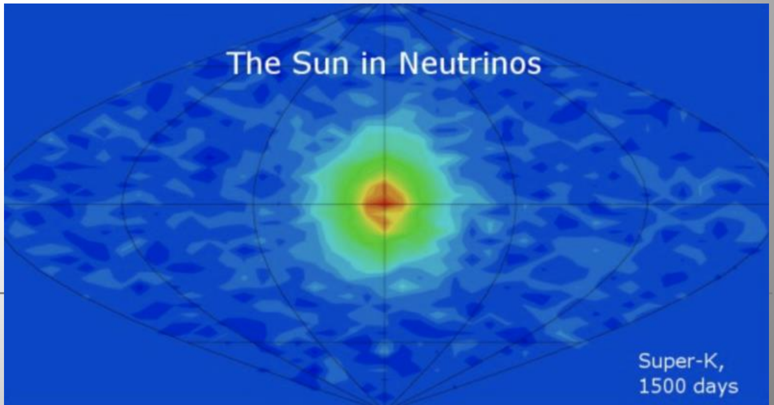
SuperKamiokande



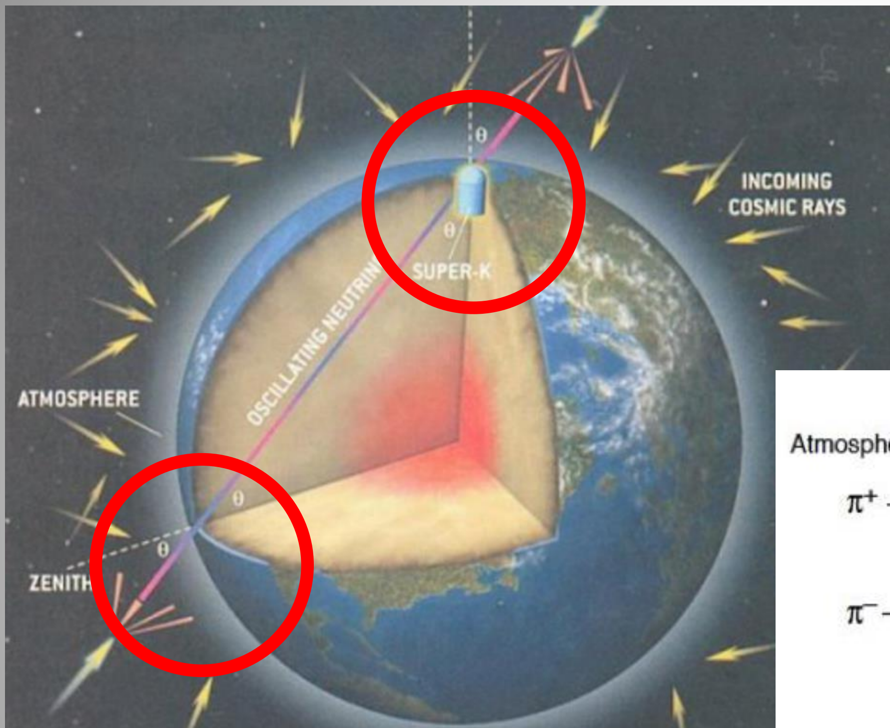




50,000 tons of ultra-pure water, watched by 13,000 photomultipliers

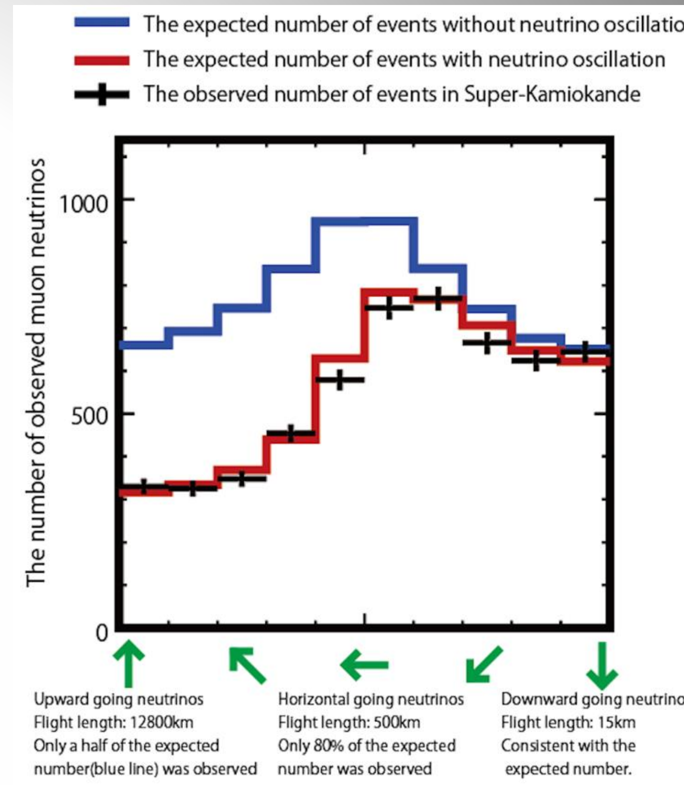


Neutrinos Oscillate! (1998)



Atmospheric neutrino source

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

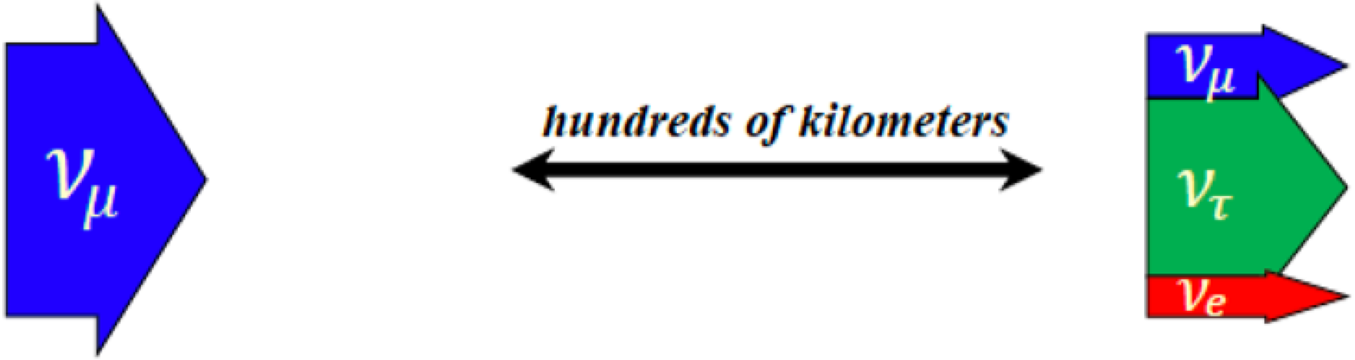


1998: The Super-Kamiokande experiment in Japan used a massive underground detector filled with ultrapure water.

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

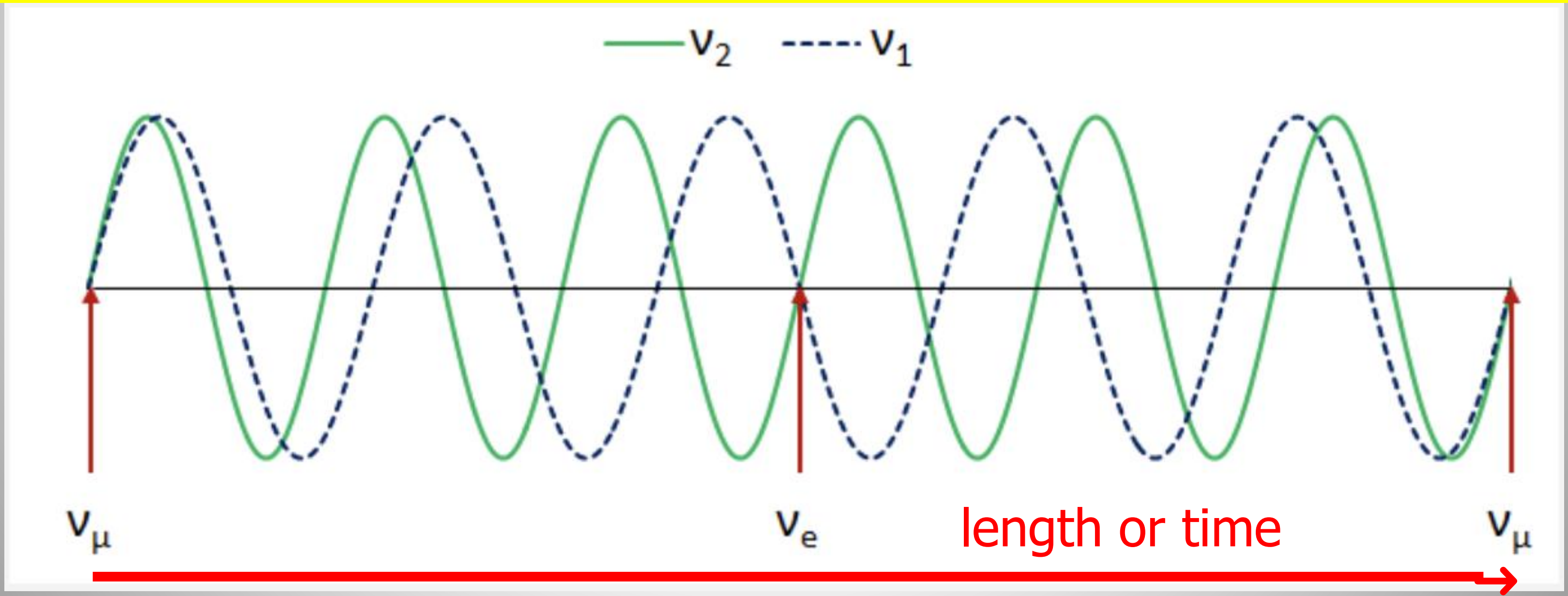
Flavor states

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

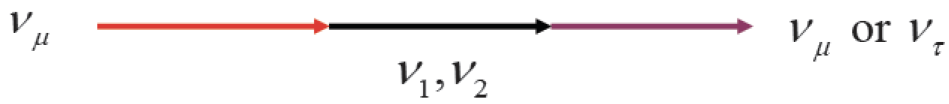
Hence the picture looks as follows: (propagation as a superposition of two masses)



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

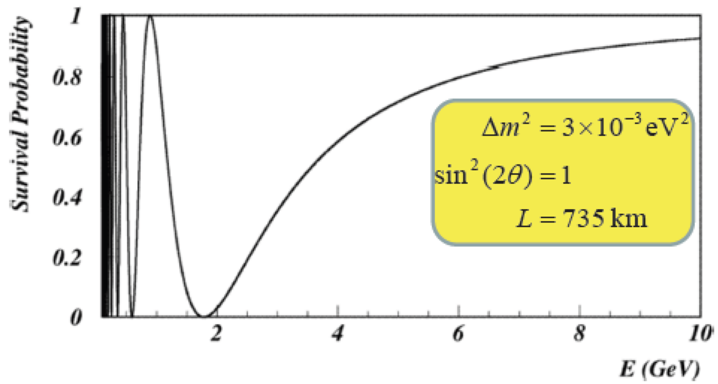
Neutrino Oscillations

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



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

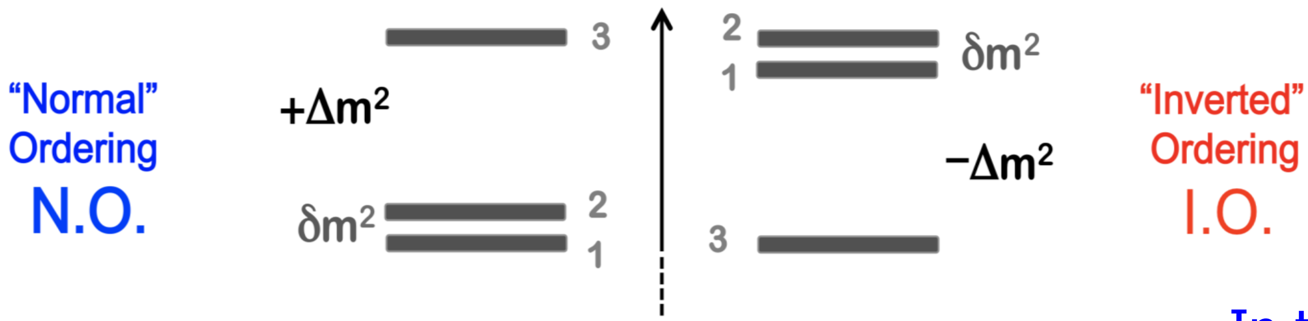
$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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")



+ 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

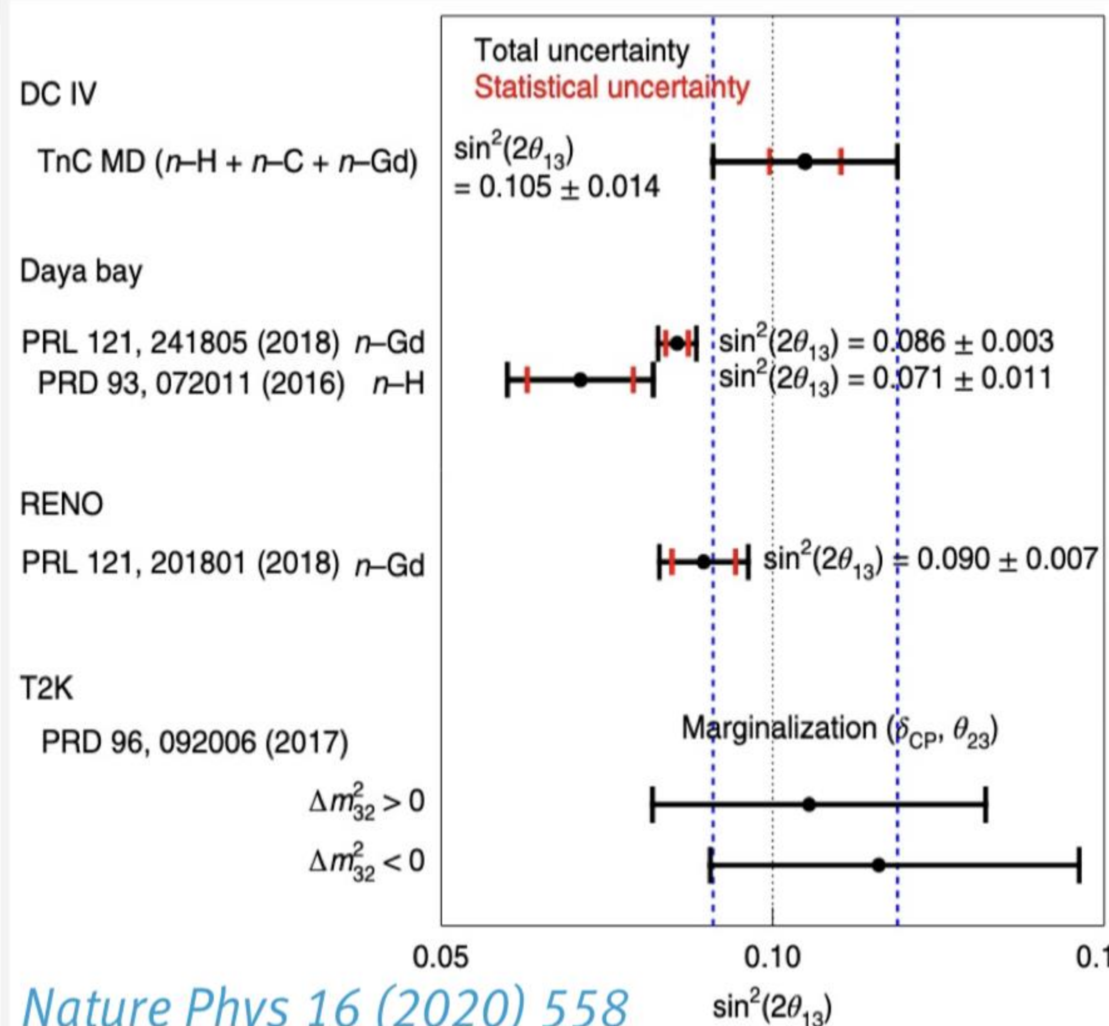
Short Baseline Experiments

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



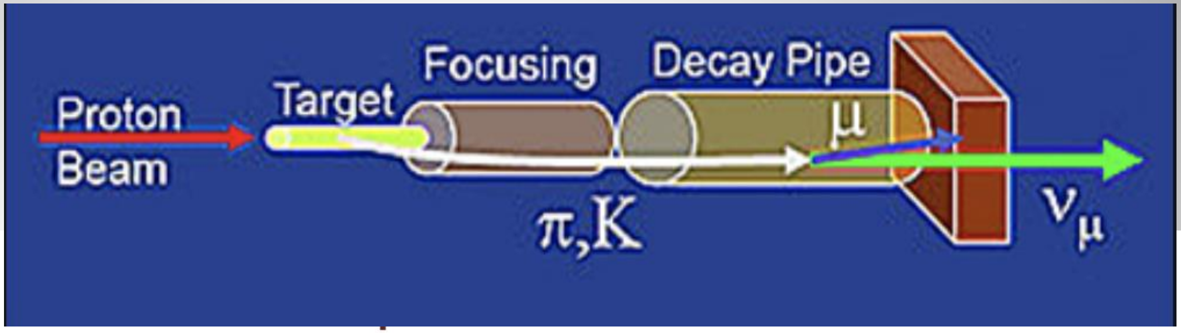
Nature Phys 16 (2020) 558

Daya Bay

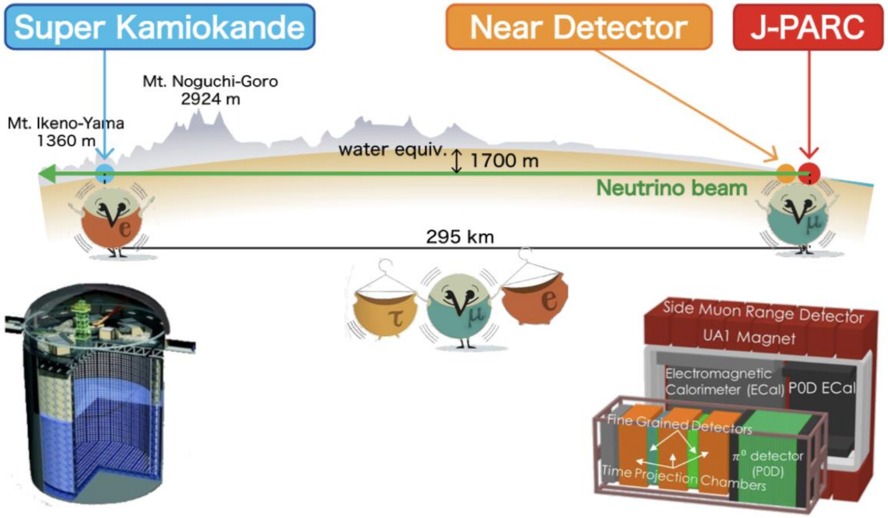
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

Accelerator Based Neutrino Experiments

Neutrinos from accelerators

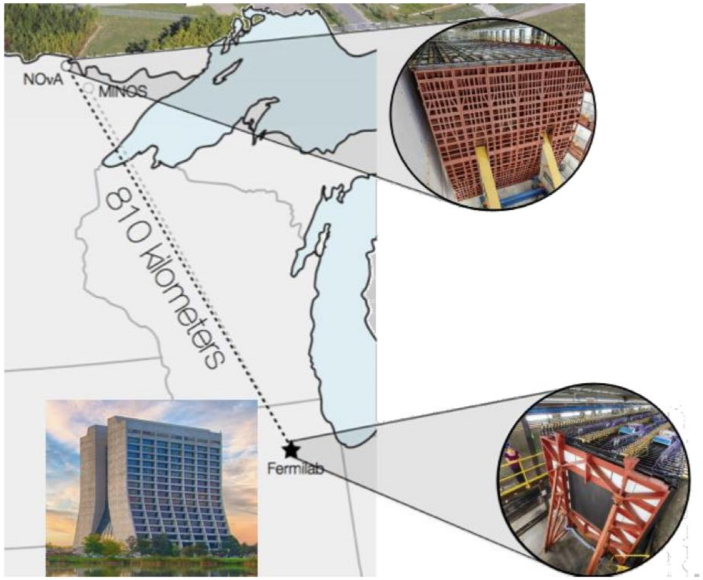


T2K



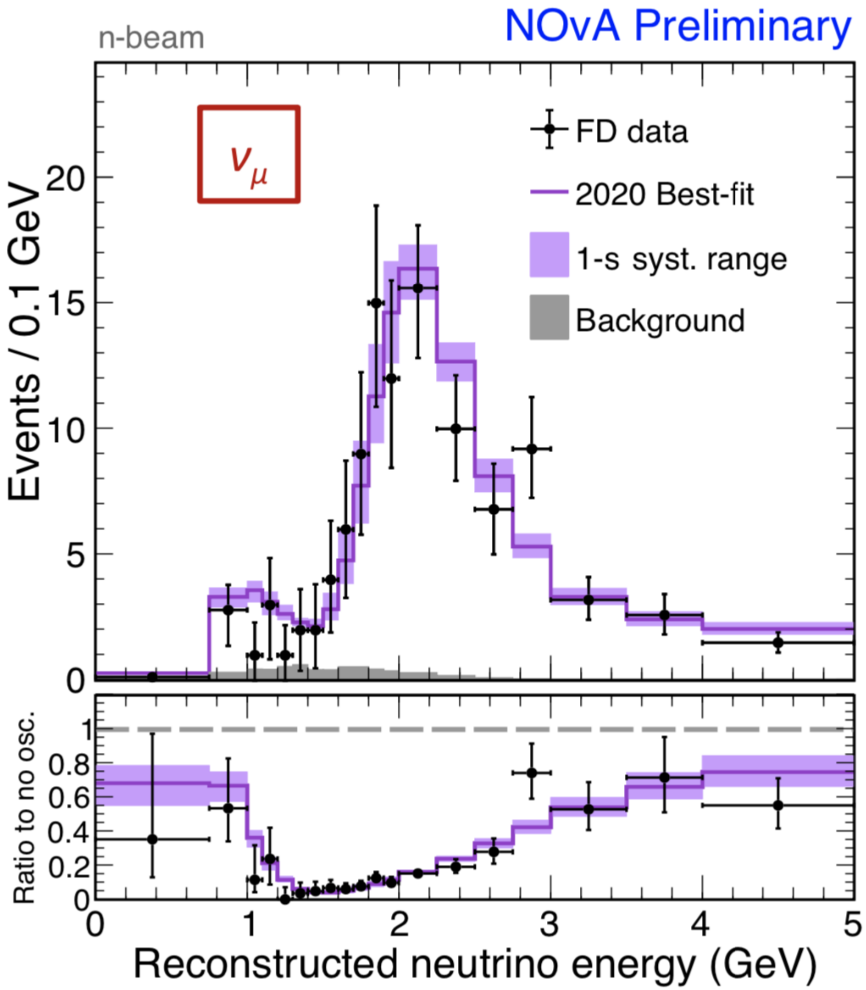
Baseline: 295 km
Peak E_ν: ~0.6 GeV (off-axis)
Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

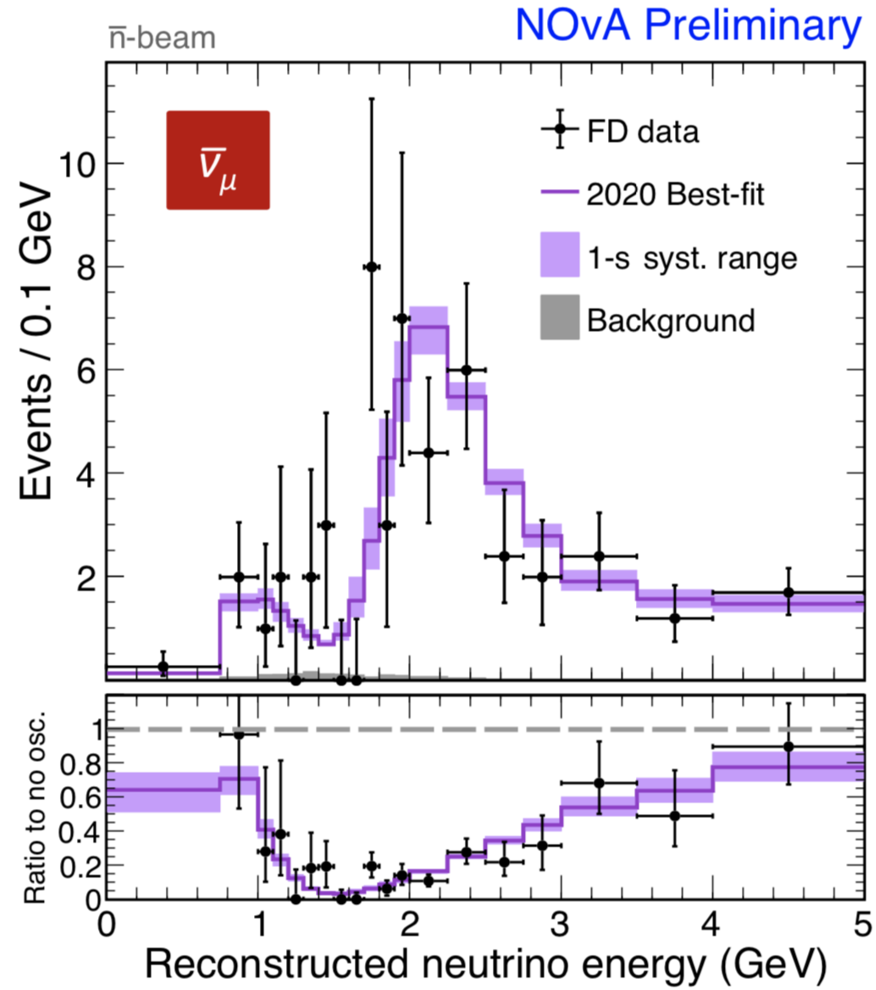


- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

Muon Neutrino Disappearance



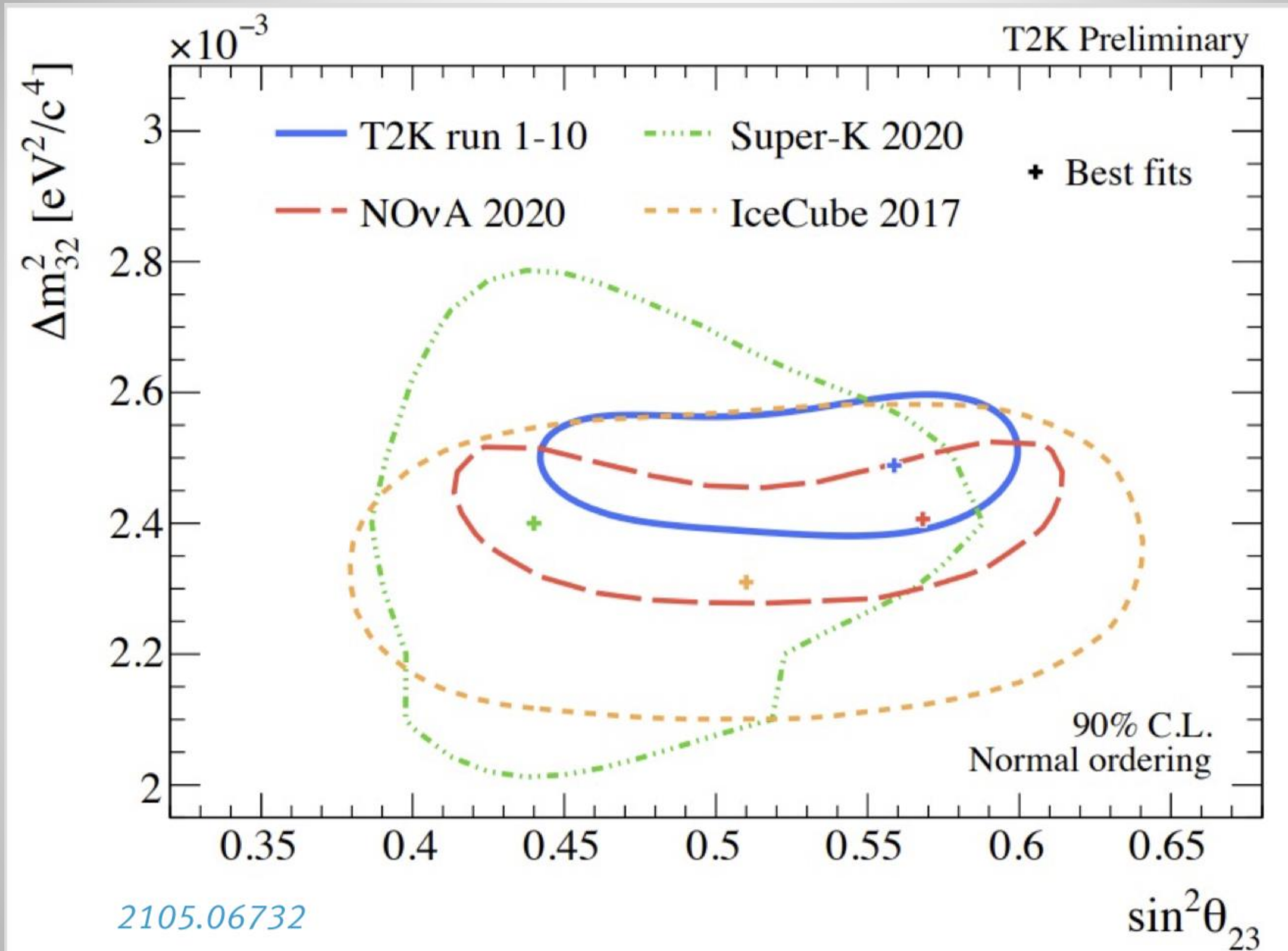
211 events, 8.2 background



105 events, 2.1 background

Neutrino Experiments

2105.06732



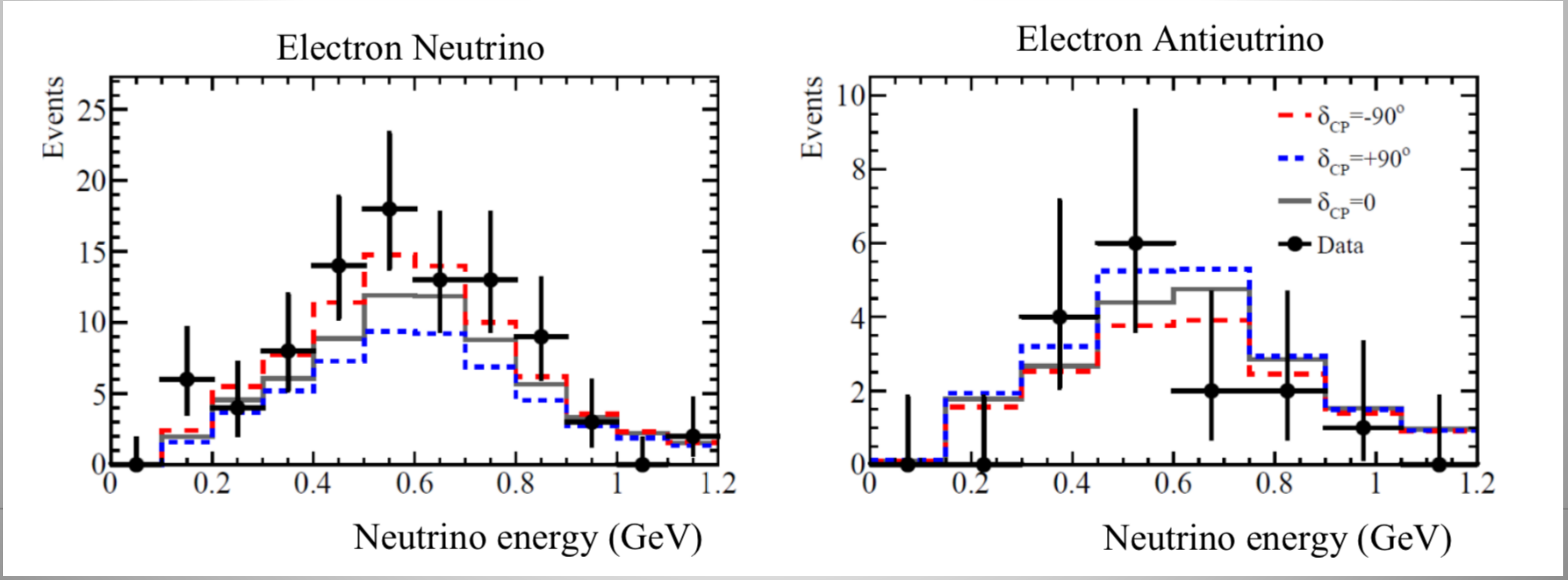
Atmospheric parameter determinations by several experiments
Results are consistent

CP Violation: T2K Measurement

Do neutrinos and anti-neutrinos oscillate differently ?

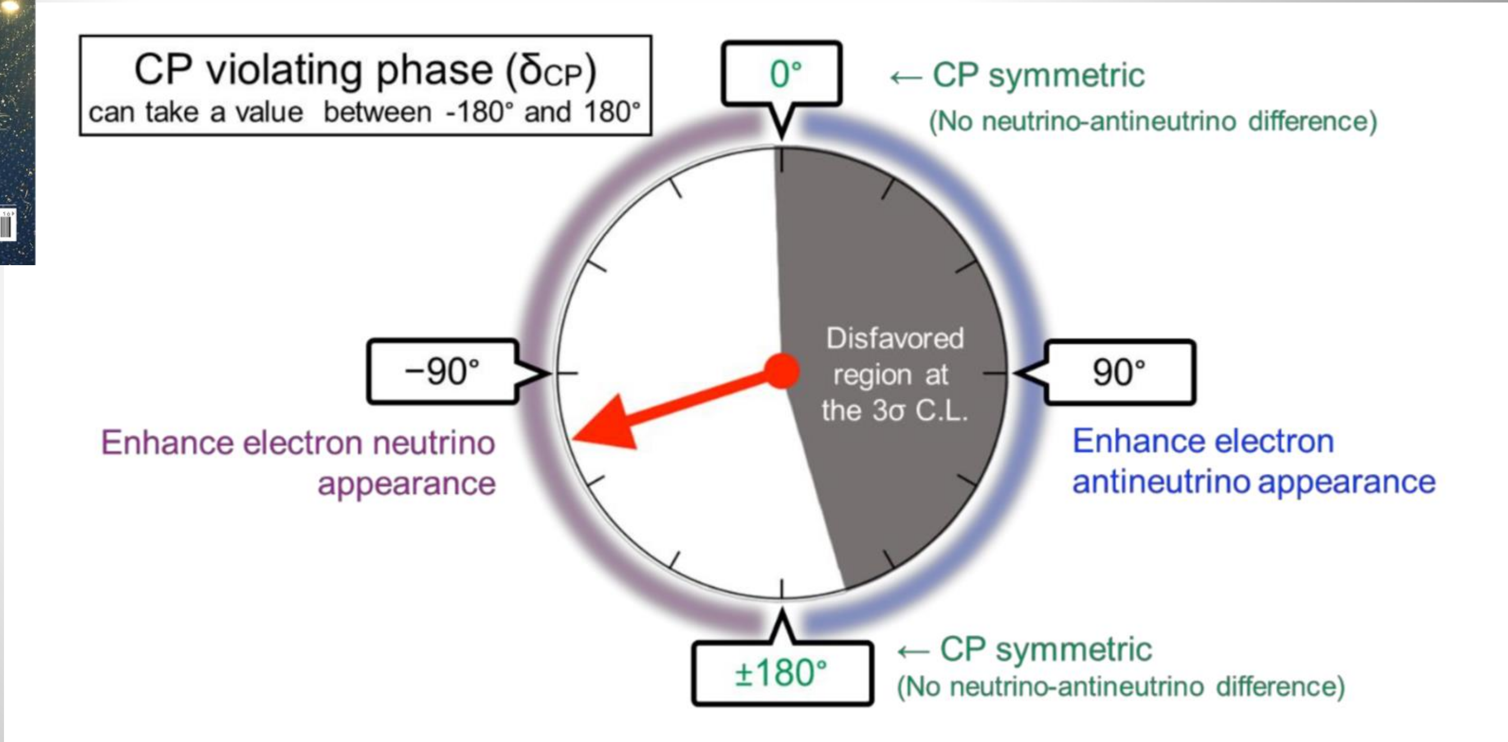
Measured versus expected electron-(anti)neutrino events in SK as function of the assumed CP- angle

	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

Taking all available data together…

arXiv:2007.14792

NuFIT group

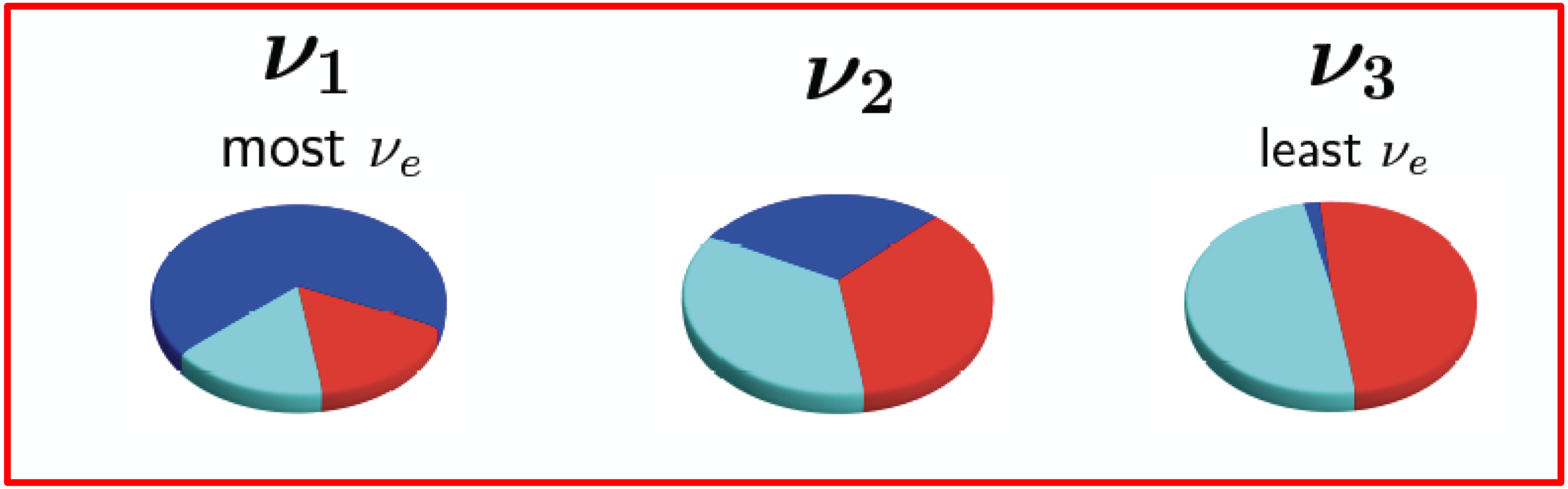
with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	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

Neutrino Oscillations

Neutrino Mass EigenStates or Propagation States:

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



$\nu_e =$ 

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ 

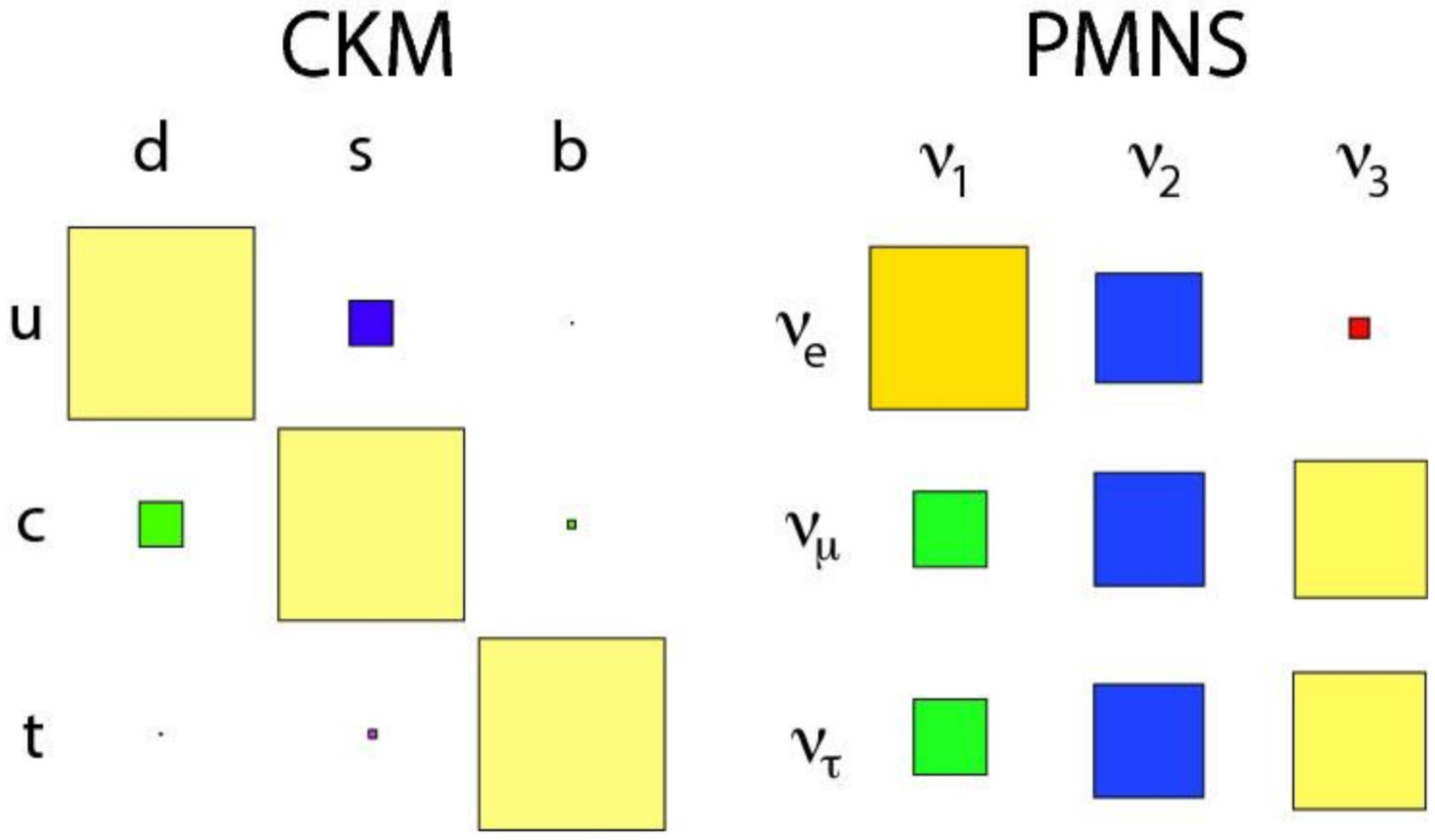
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

$\nu_\tau =$ 

Unitarity
SK, Opera
ICECUBE ?

CMK vs PMNS

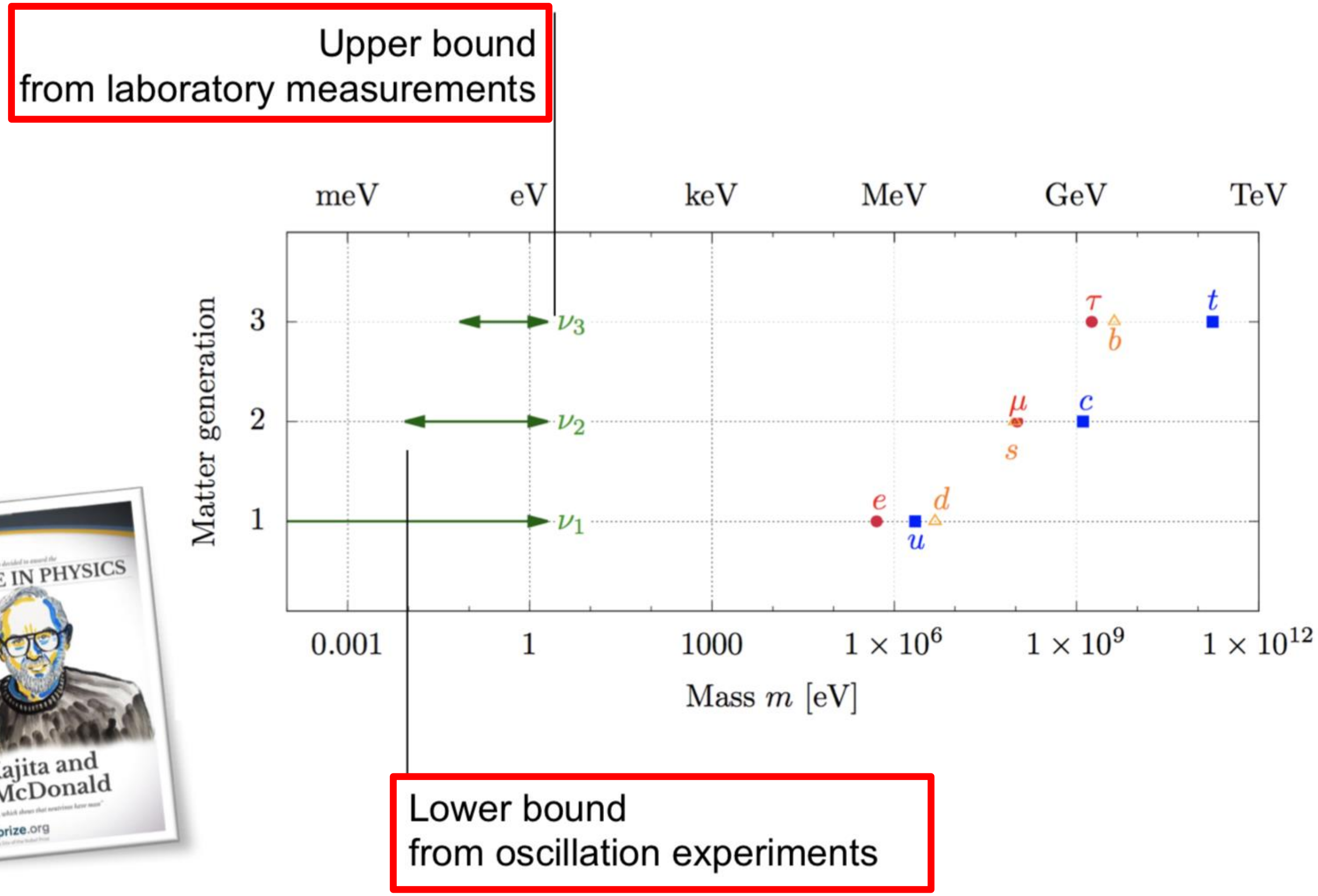
Why is Neutrino mixing so different from quark mixing?
What does that tell us?

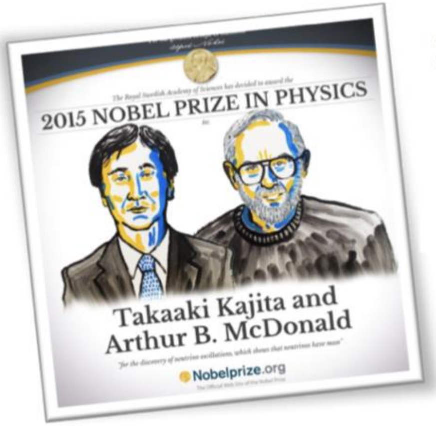


The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.

Neutrino Mass

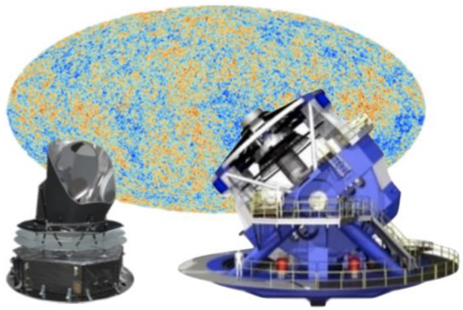
Neutrinos versus other known fermions

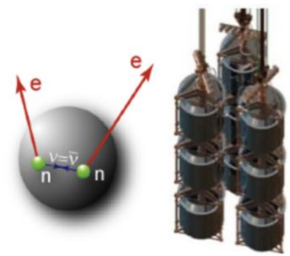


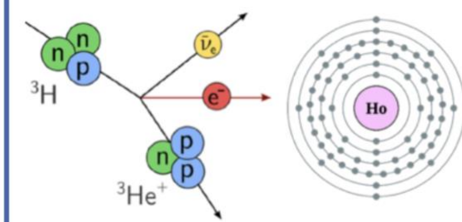


Neutrino Mass Measurents

Complementary paths to the ν mass scale



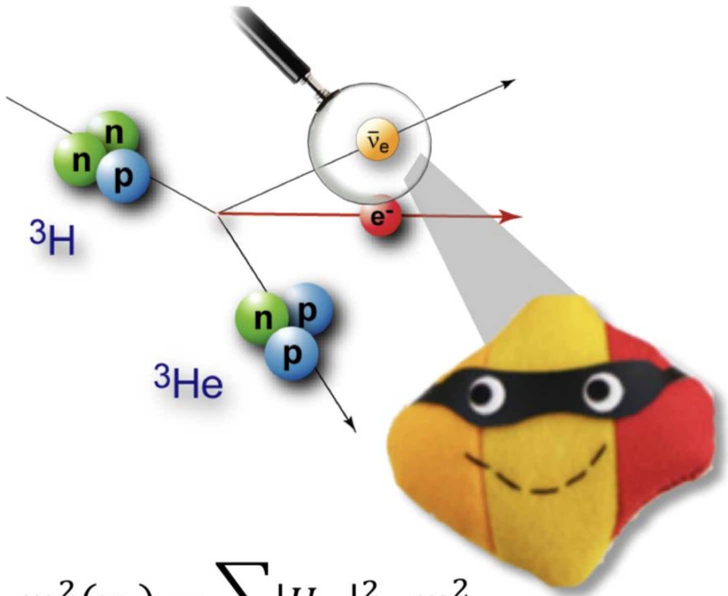




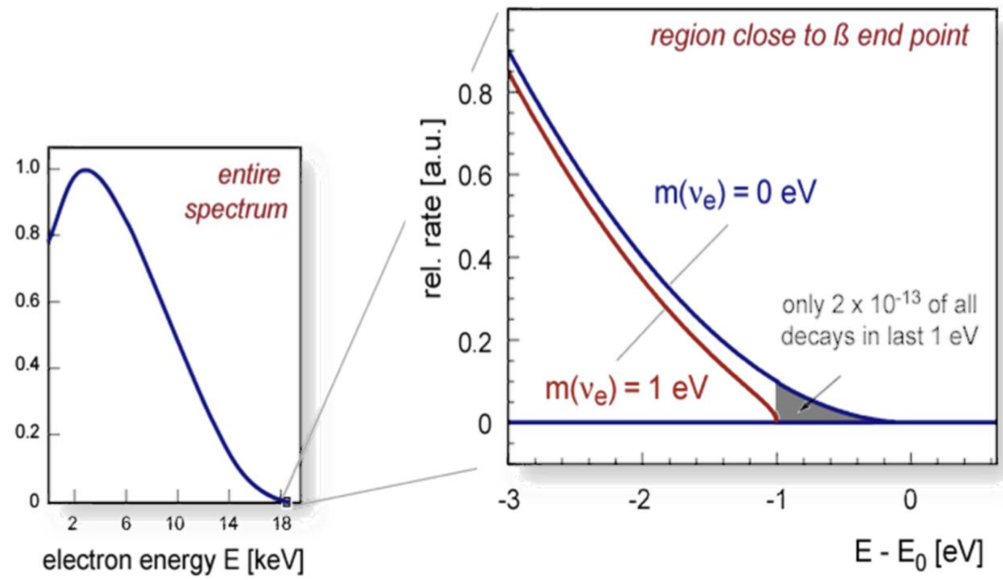
	Cosmology	Search for 0νββ	Kinematics of weak decays
Method	Structure of Universe at early and evolved stages	ββ-decay of ^{76}Ge, ^{130}Te, ^{136}Xe, …	β-decay of ^{3}H, EC of ^{163}Ho
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\lvert \sum_i U^2_{ei}\, m_i \right\rvert^2$	$m^2_\beta = \sum_i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

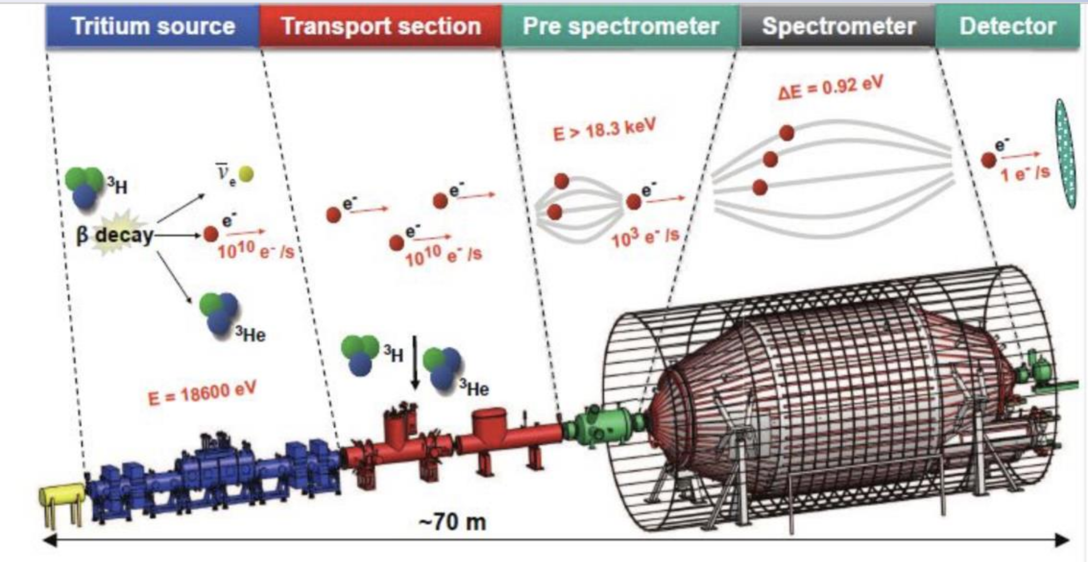


$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



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

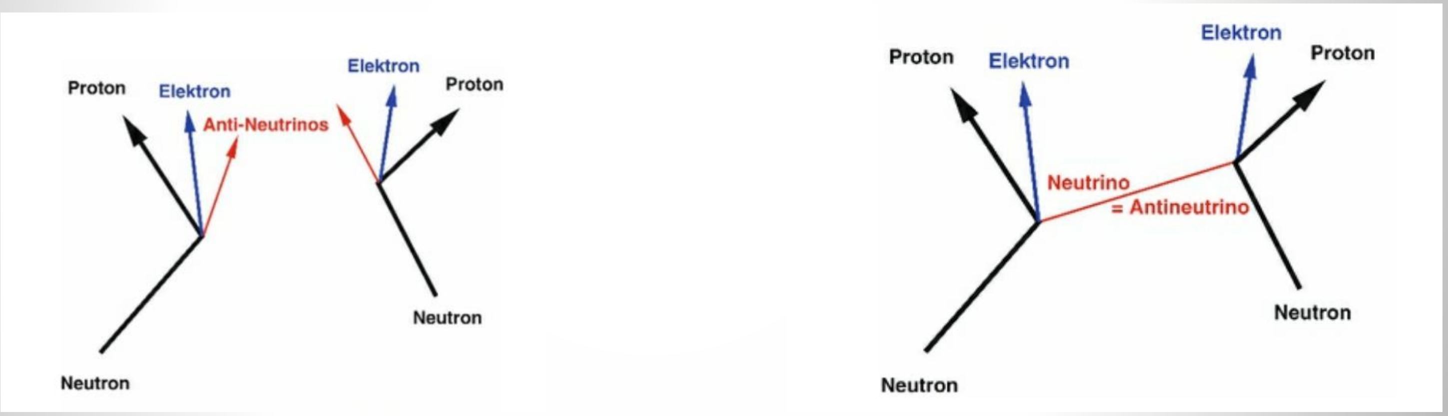
To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

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

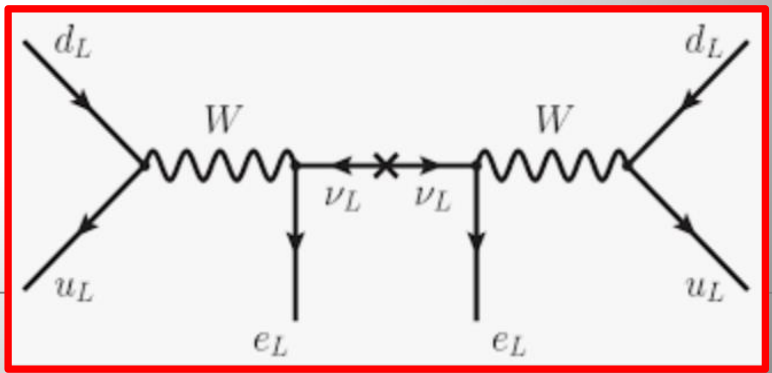
arXiv:2105.08533

Neutrinoless Double Beta Decay

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



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



Neutrinoless Double Beta Decay

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

Final results: arXiv:2009.06079

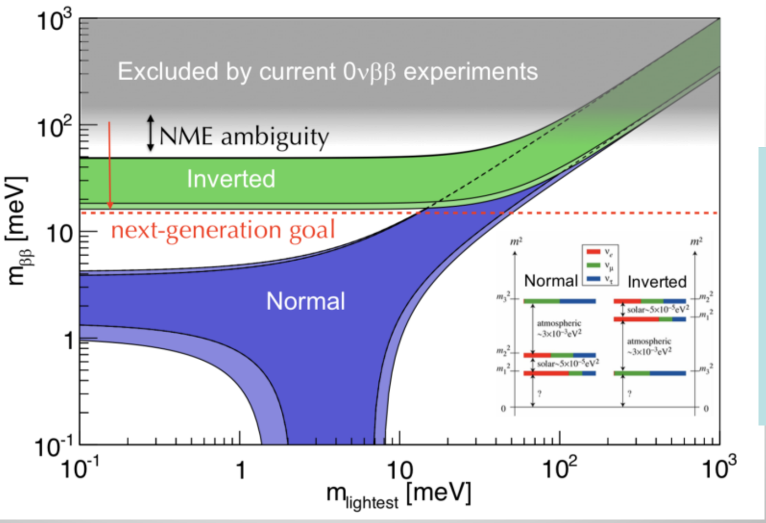
127.2 kg.year exposure between 2011-2019

Experiment now completed
No $0\nu\beta\beta$ signal observed ☹

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

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

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

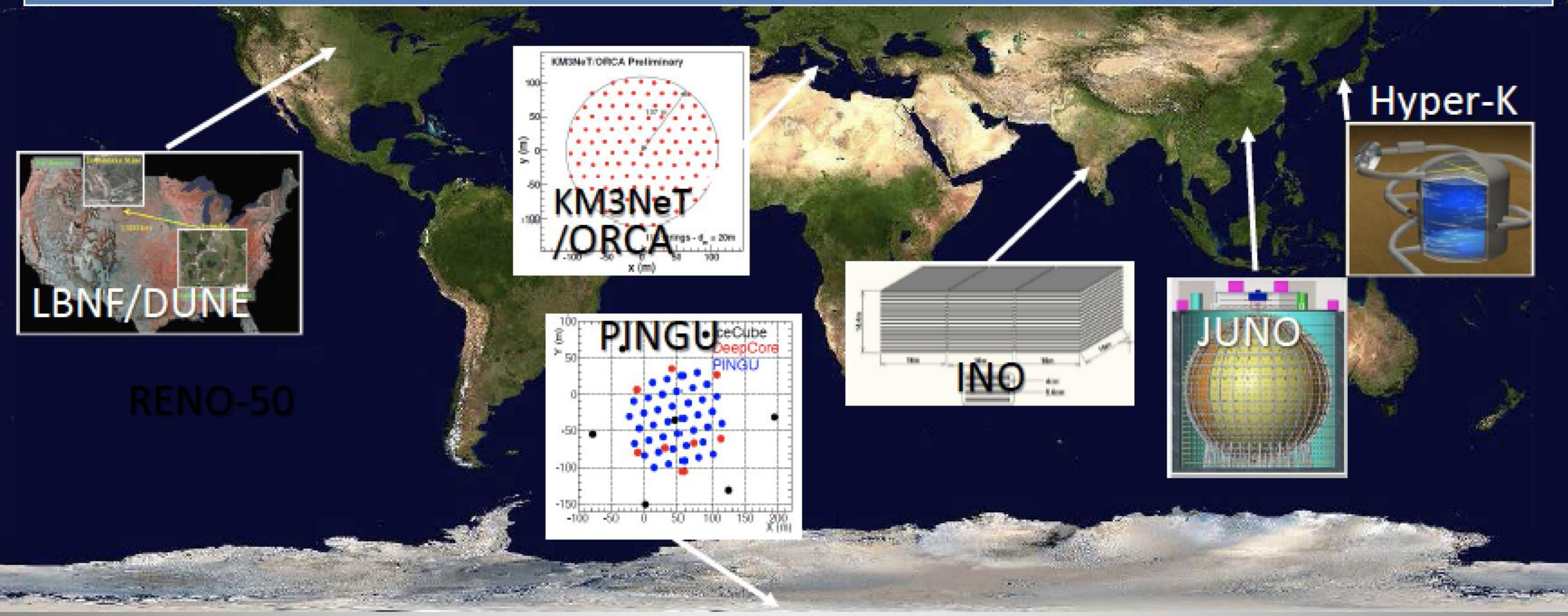


Many experiments operating, planned or in R&D: LEGEND SNO+, NEXT…

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.



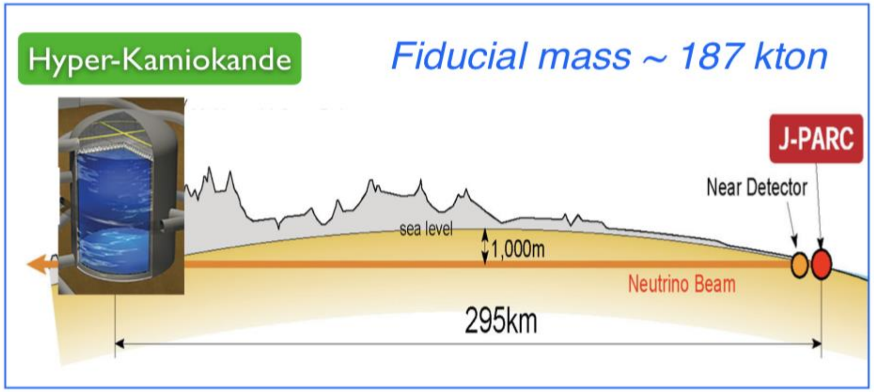
Future Neutrino Experiments

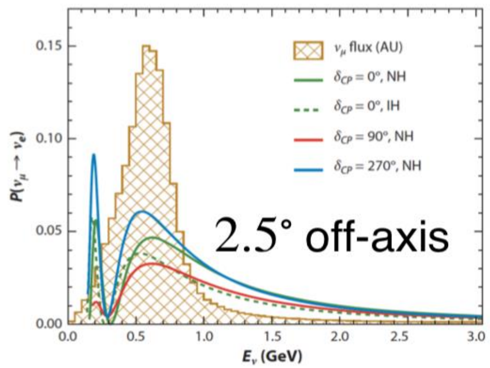
CERN

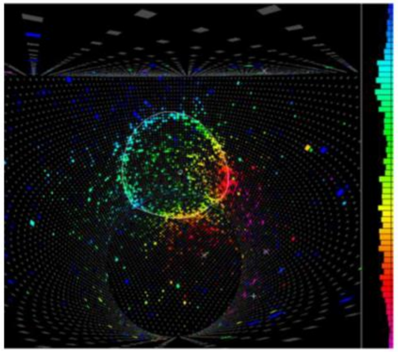
Long-baseline experiments: T2HK and DUNE

First data in 2027 (?)

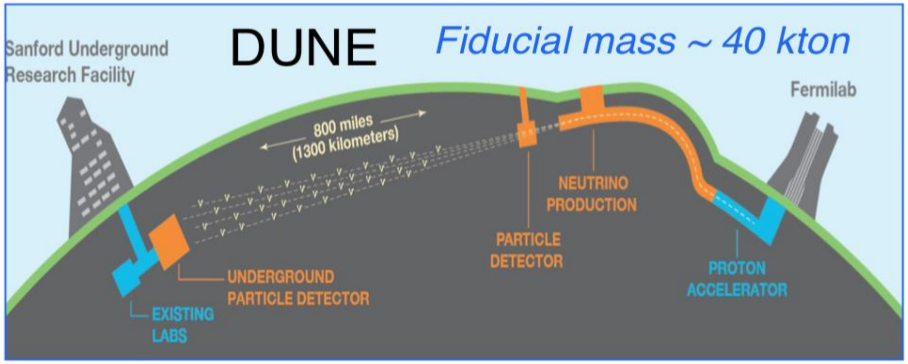
- Towards the measurement of the CP violating phase and Mass Hierarchy
  - ✦ Search for different $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities

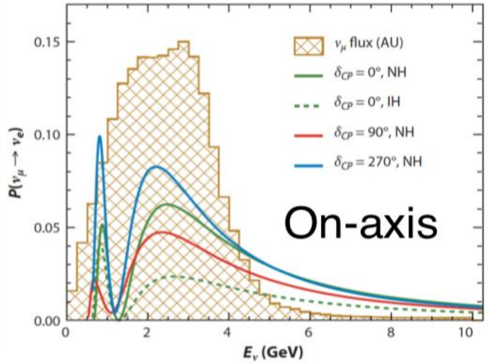


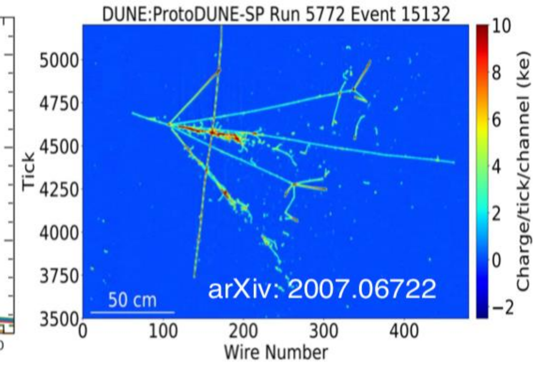




Annu. Rev. Nucl. Part. Sci. 2016. 66:47–71



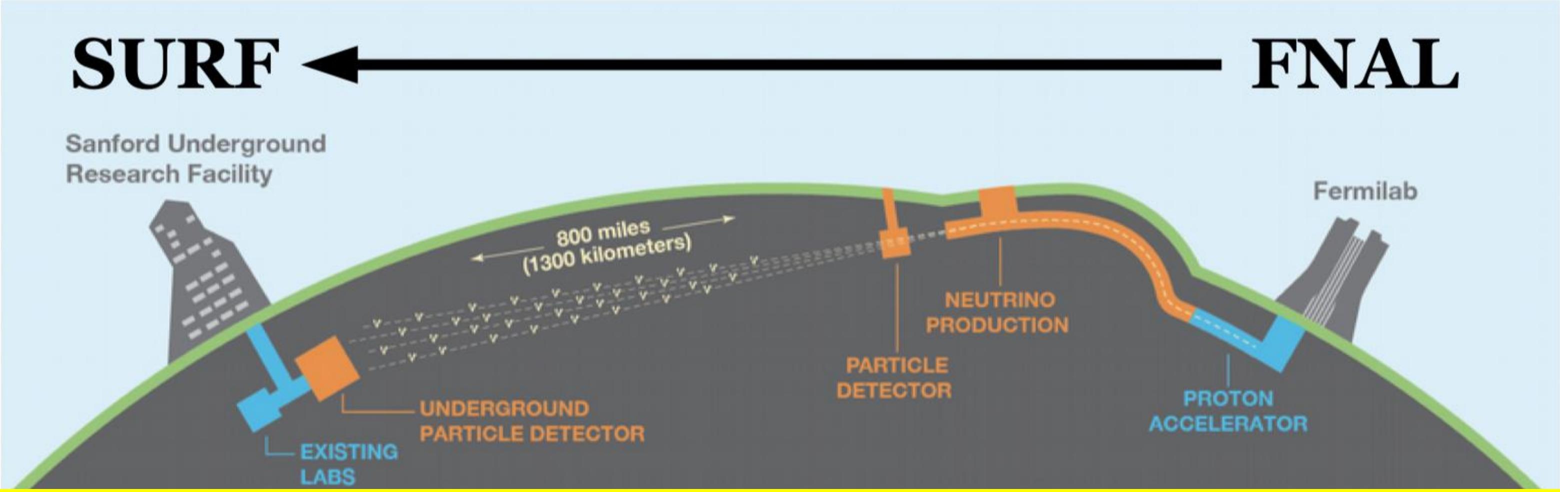




DUNE "Observatory"

- "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:

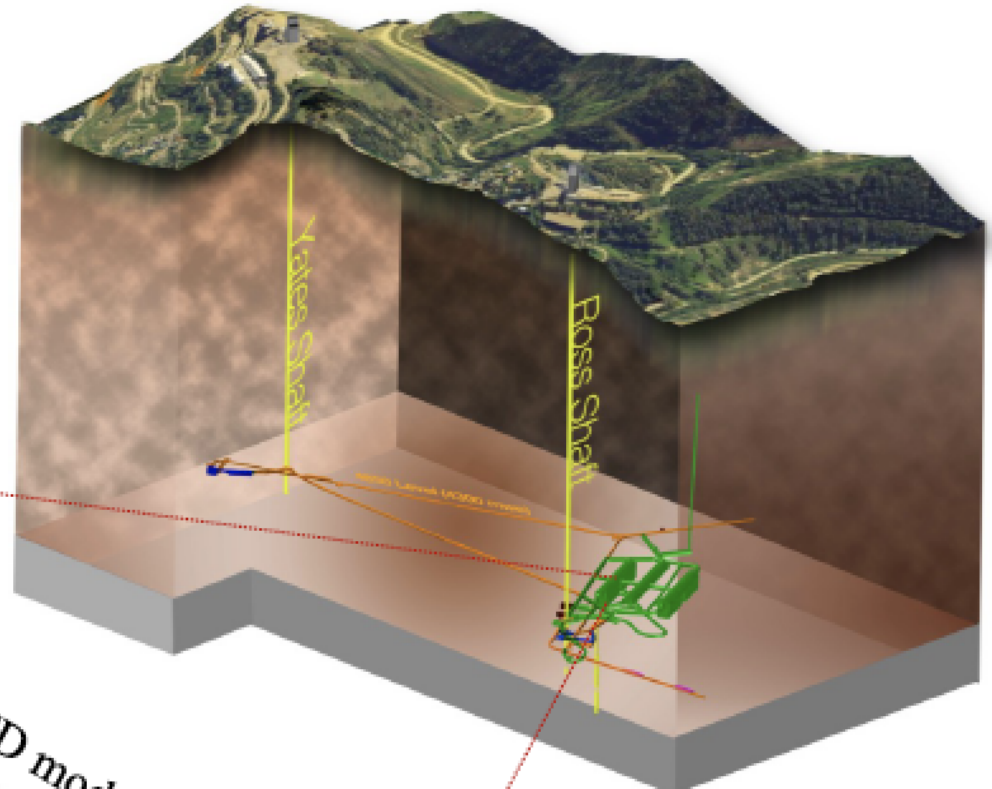
- 1229 collaborators from
- 184 institutions in
- 31 countries + CERN

Still more groups joining

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

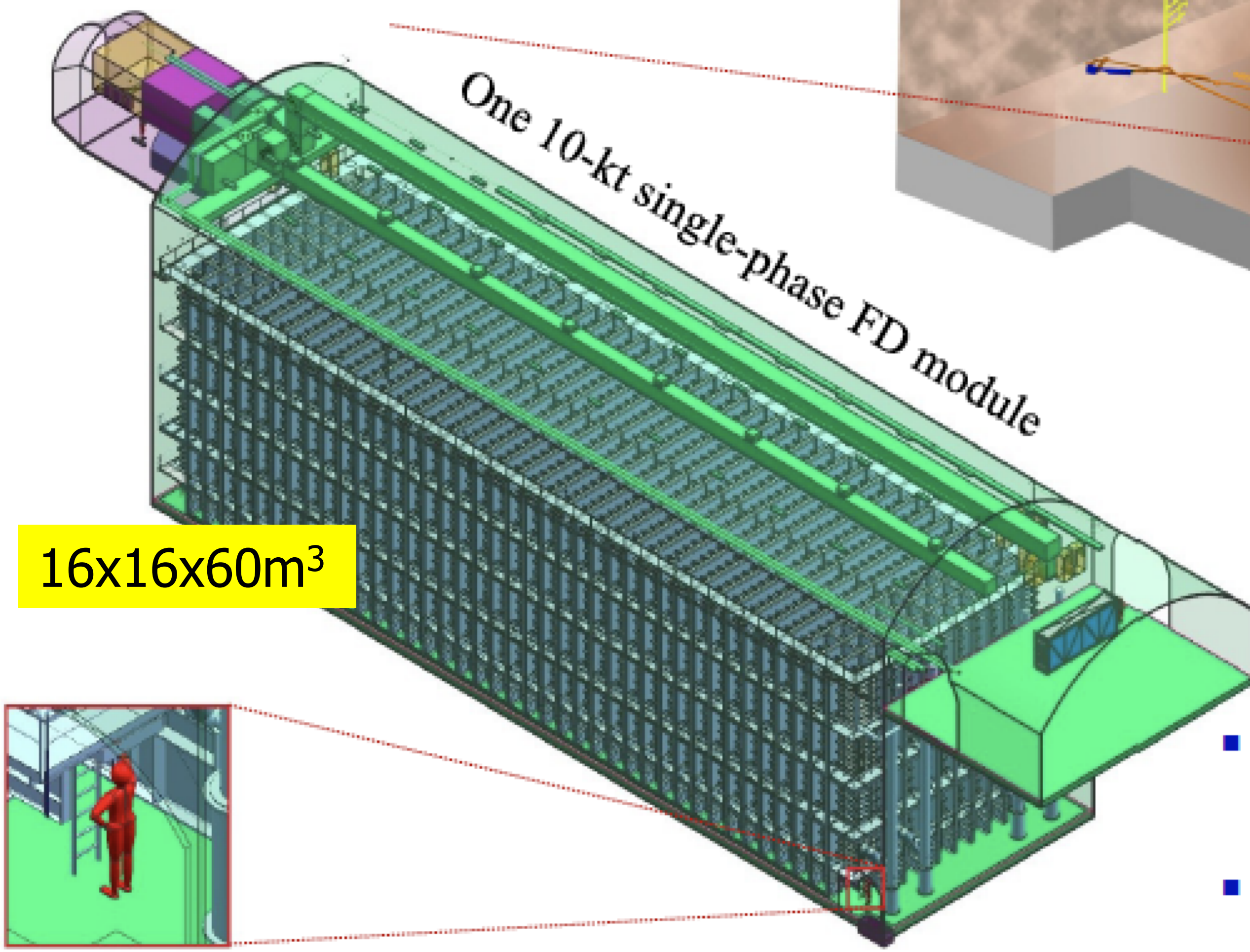
DUNE Far Detector

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



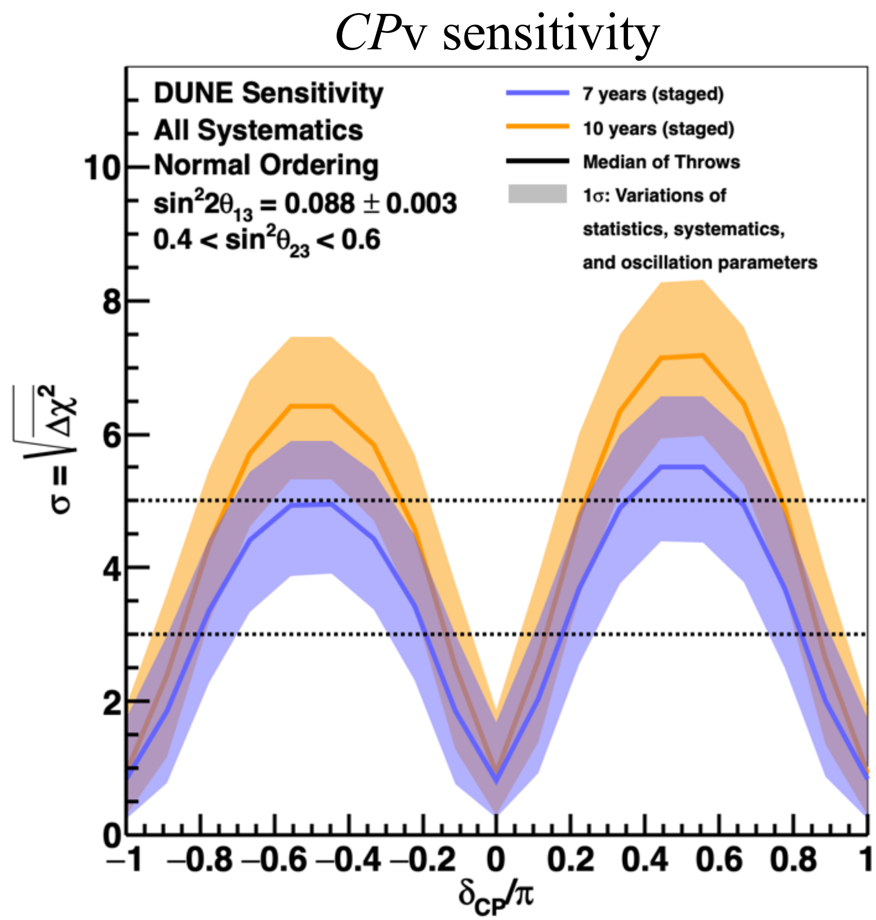
Sanford Underground Research Facility (SURF)

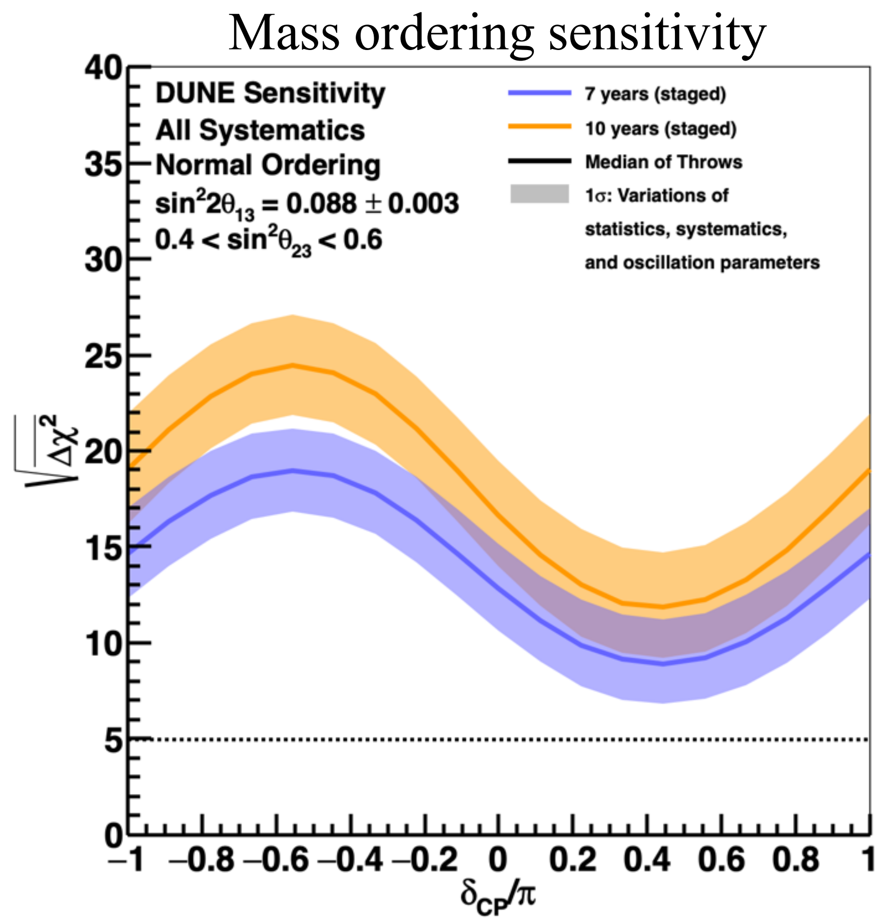
1.5 km underground



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

DUNE: CP Violation and Mass Ordering





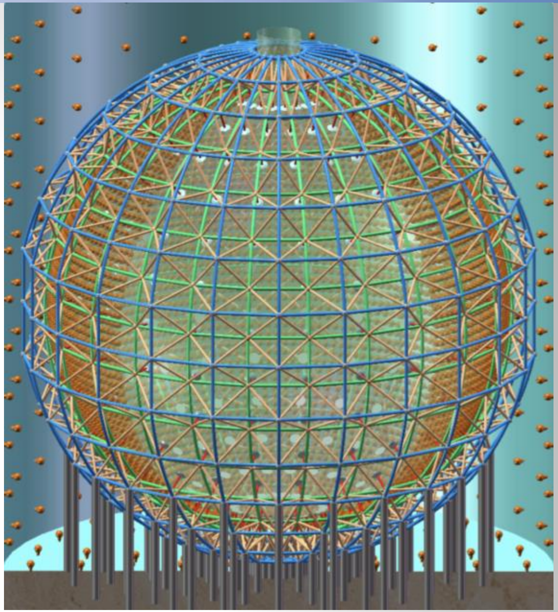
- Updated Sensitivity with realistic systematics and reconstruction
  - Move quickly to potential ***CP*** **violation discovery**
  - Rapid, definitive **mass ordering determination** (>5σ)

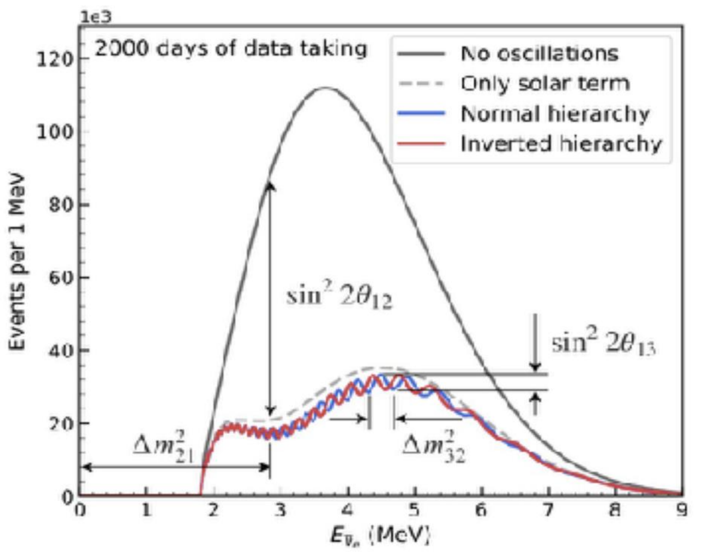
arXiv:2002.03005

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)

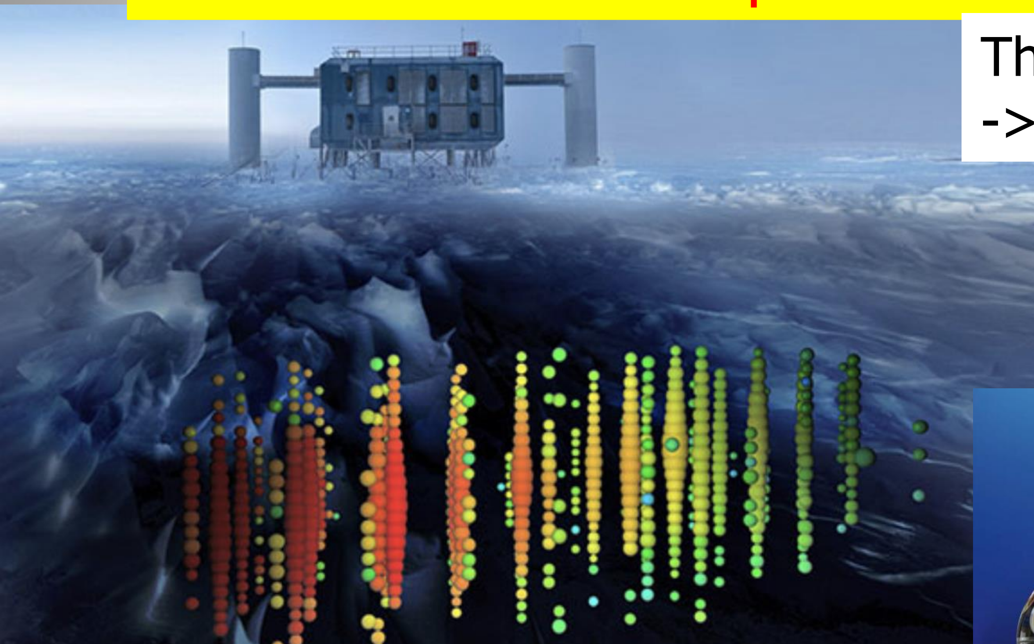




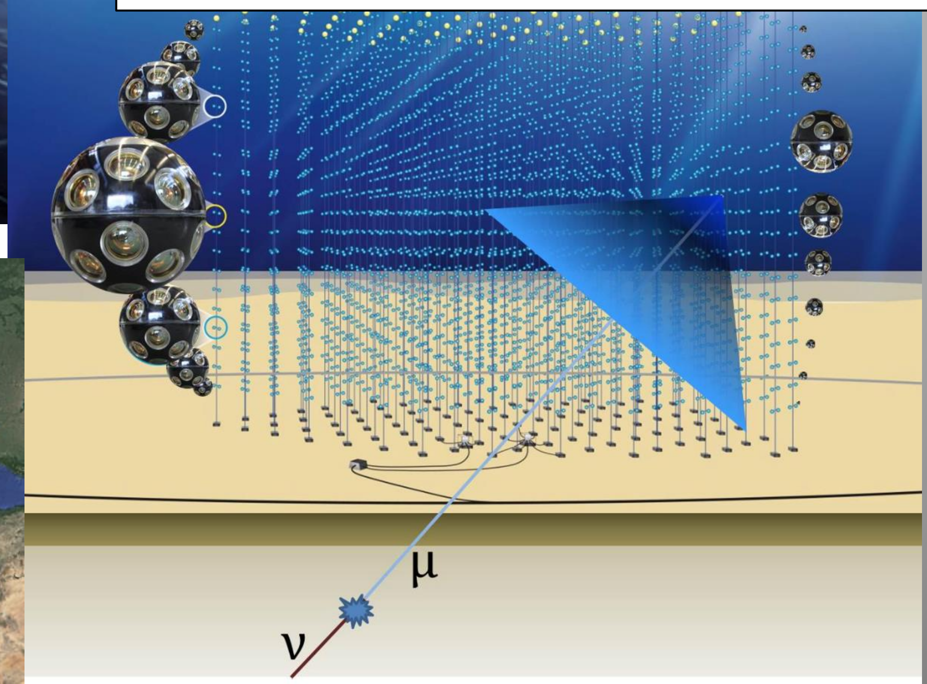
Neutrino Astronomy

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



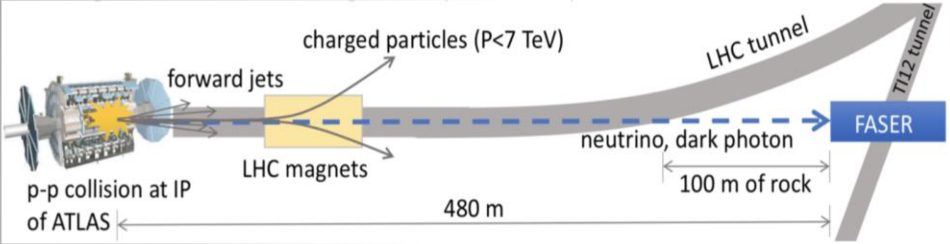
The KM3NET Experiment: 6 strings now/ full detector by 2025
-> In the Mediterranian sea



+ANTARES
+Lake Baikal

Neutrinos @ the LHC: SND@LHC

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



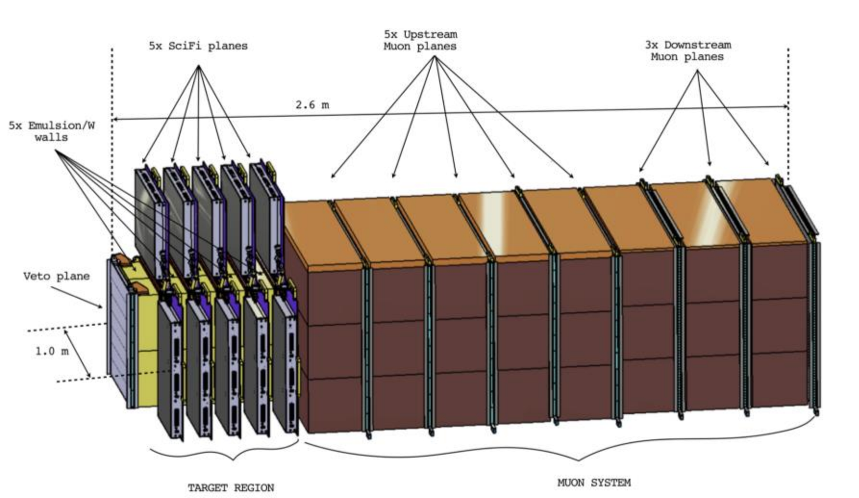
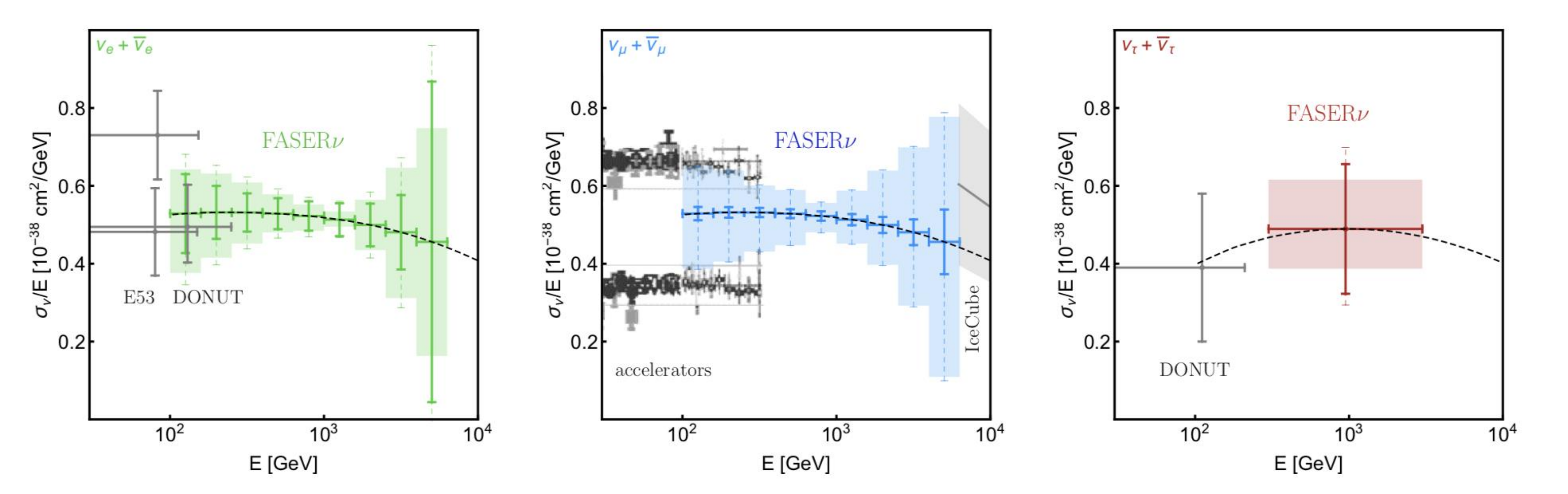


Figure 5: Layout of the proposed SND@LHC detector.

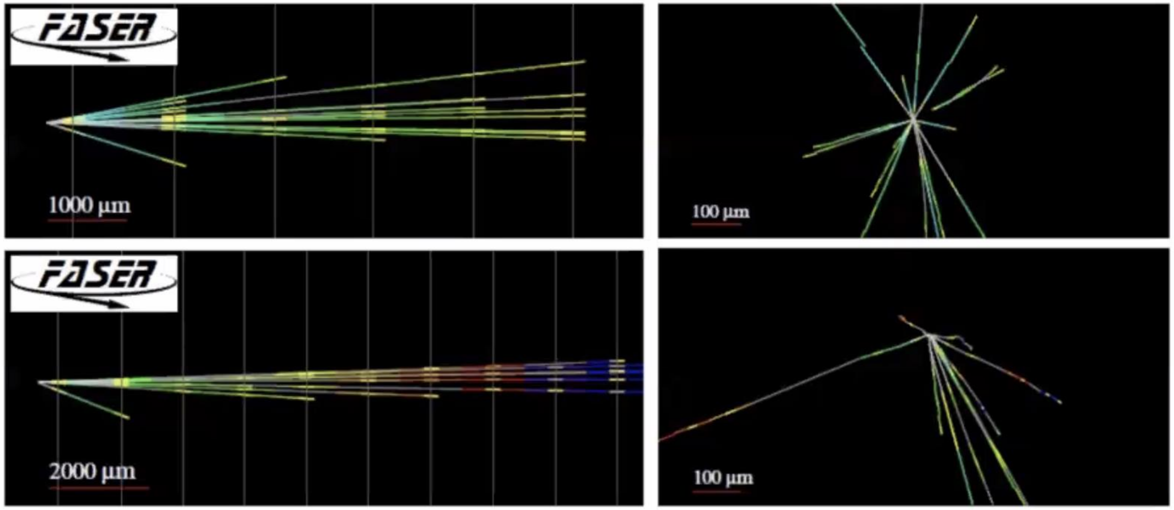
SND= Scattering and neutrino detector



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

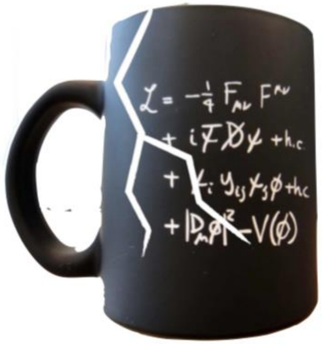
First neutrino interaction candidates at the LHC

(FASER Collaboration)

I. INTRODUCTION

SUMMARY: Neutrinos

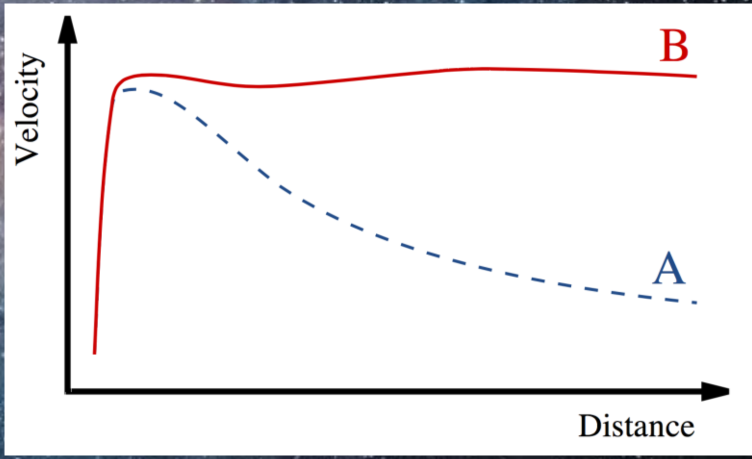
- Neutrinos studies is a vibrant field of research, and has still many open questions! Right-handed partners? Large CP violation? More than 3 neutrinos? NS Interactions? Are neutrinos their own anti-particle?
- Now comes the age of neutrino precision physics with DUNE & T2HK and neutrino astronomy: look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

Dark Matter in the Universe

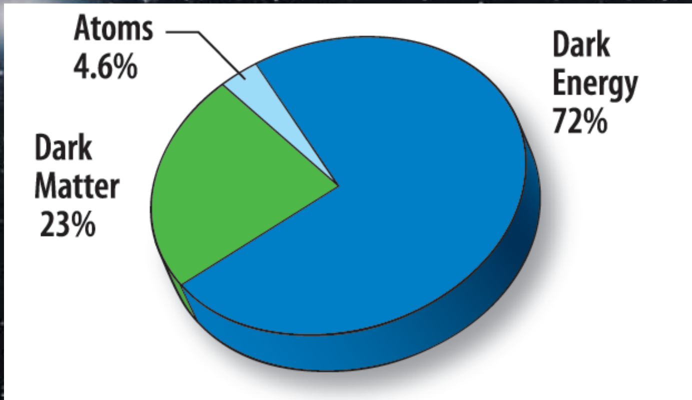
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



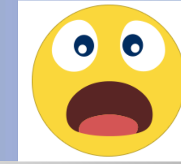
Physics Beyond the Standard Model…

F. Zwicky 1898-1974

Vera Rubin ~ 1970



The Dark World??



Does it mean that there are also….

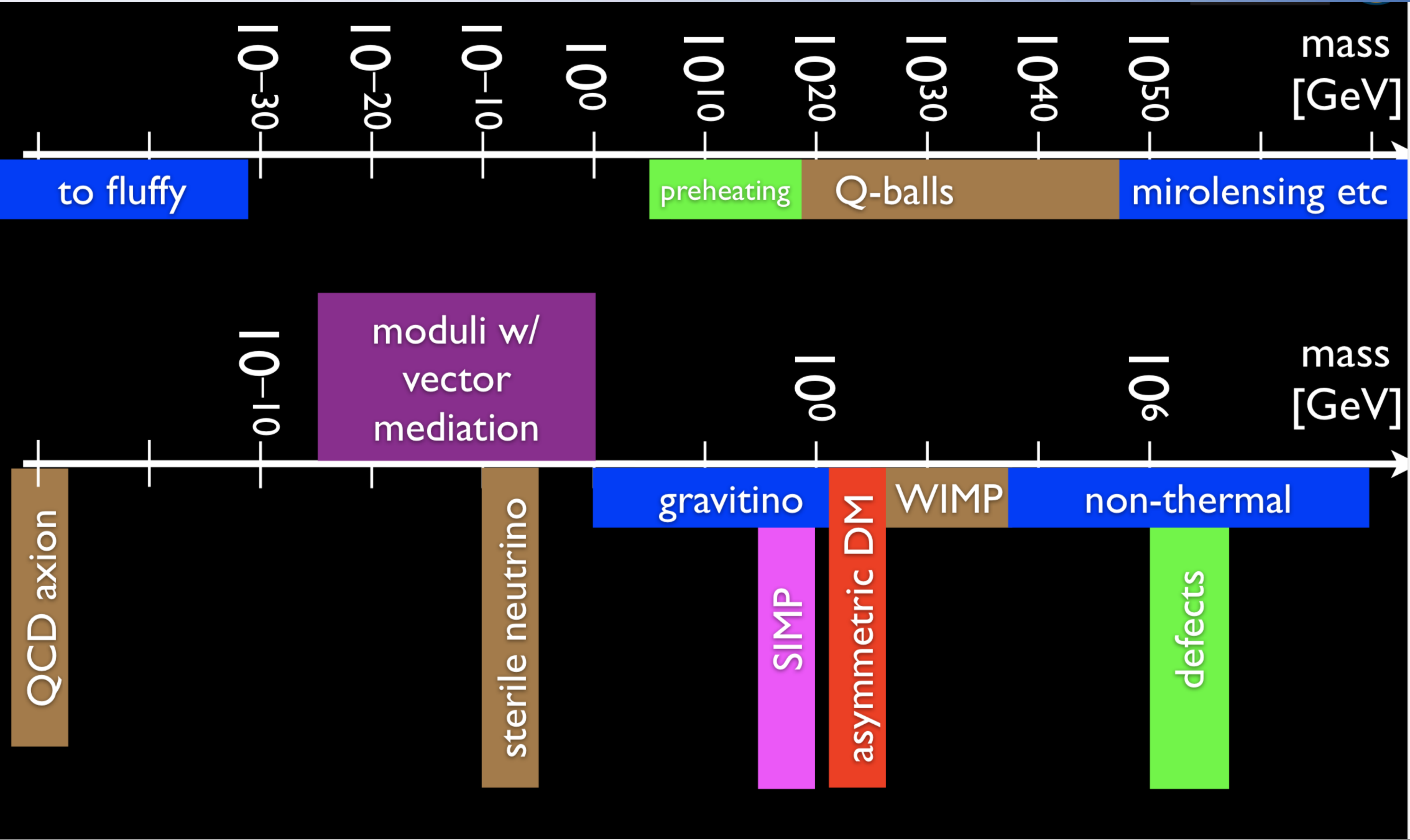
Dark Forces?

Or even Dark People?

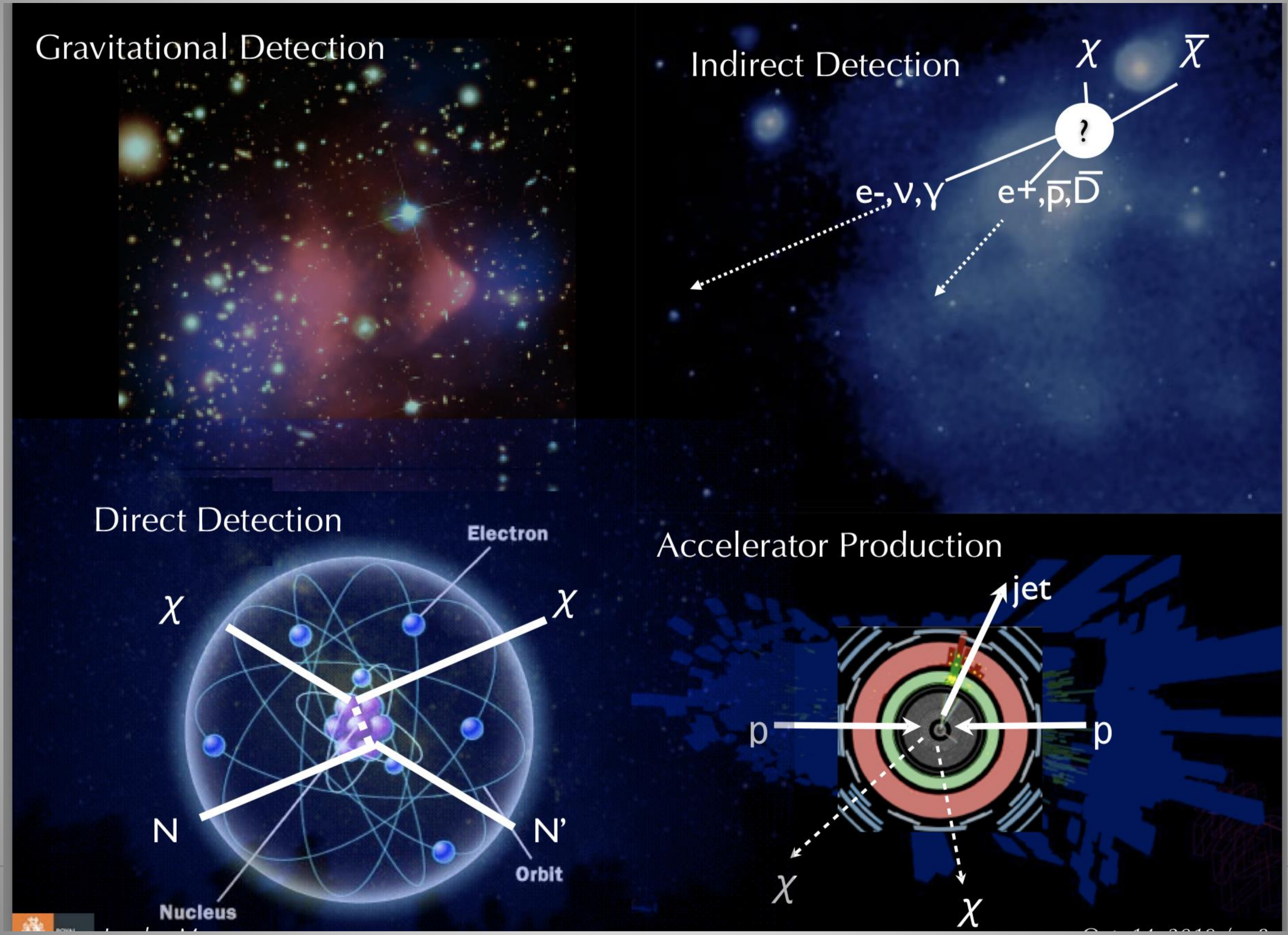
No! We assume some simple interactions between dark matter particles in their environment, and a way to detect them

But what is dark matter?

Dark Matter "Candidates"

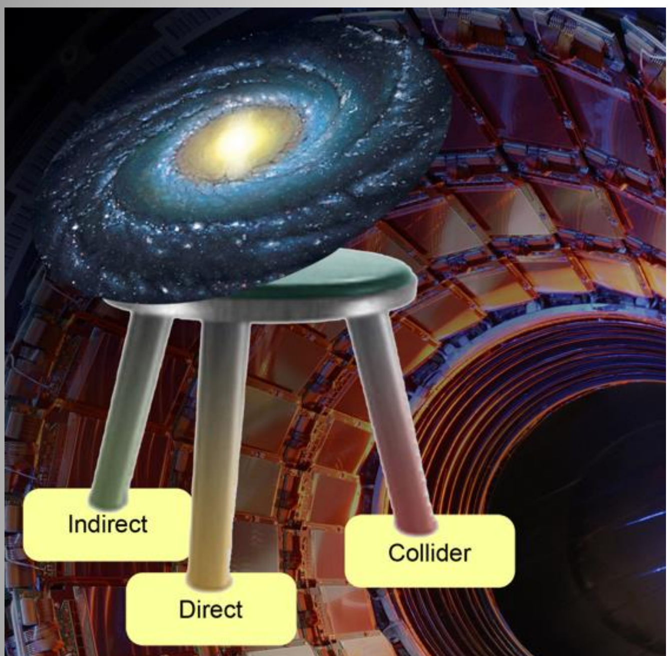


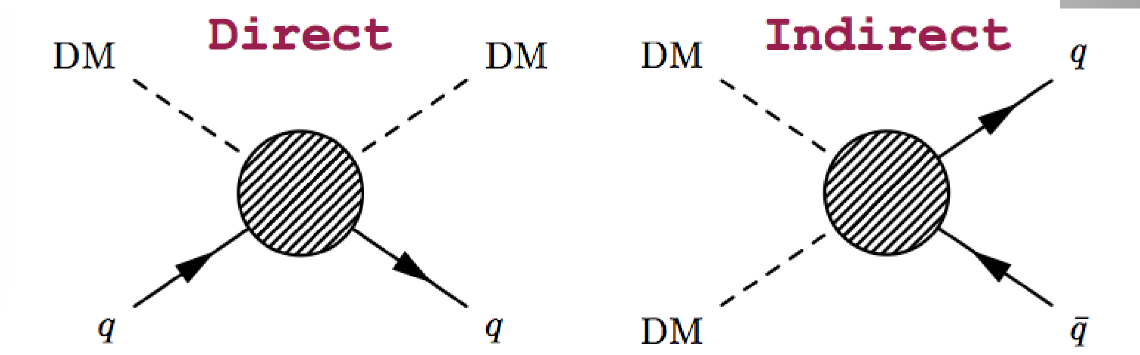
Dark Matter Searches

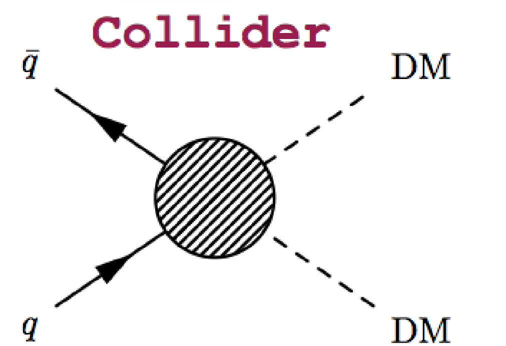


The Generic Dark Matter Connection

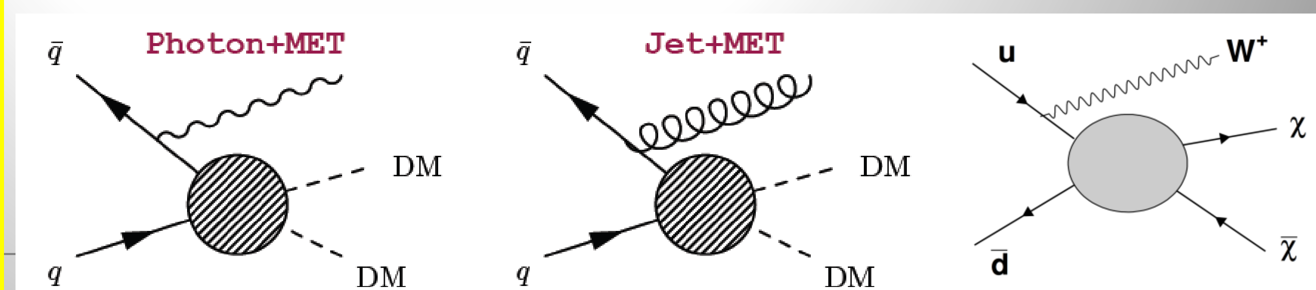
Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)







Use effective theory or better simplified models to relate measurements to Dark Matter studies



Direct Searches Overview

Searches for WIMP hypothesis in the GeV to TeV range

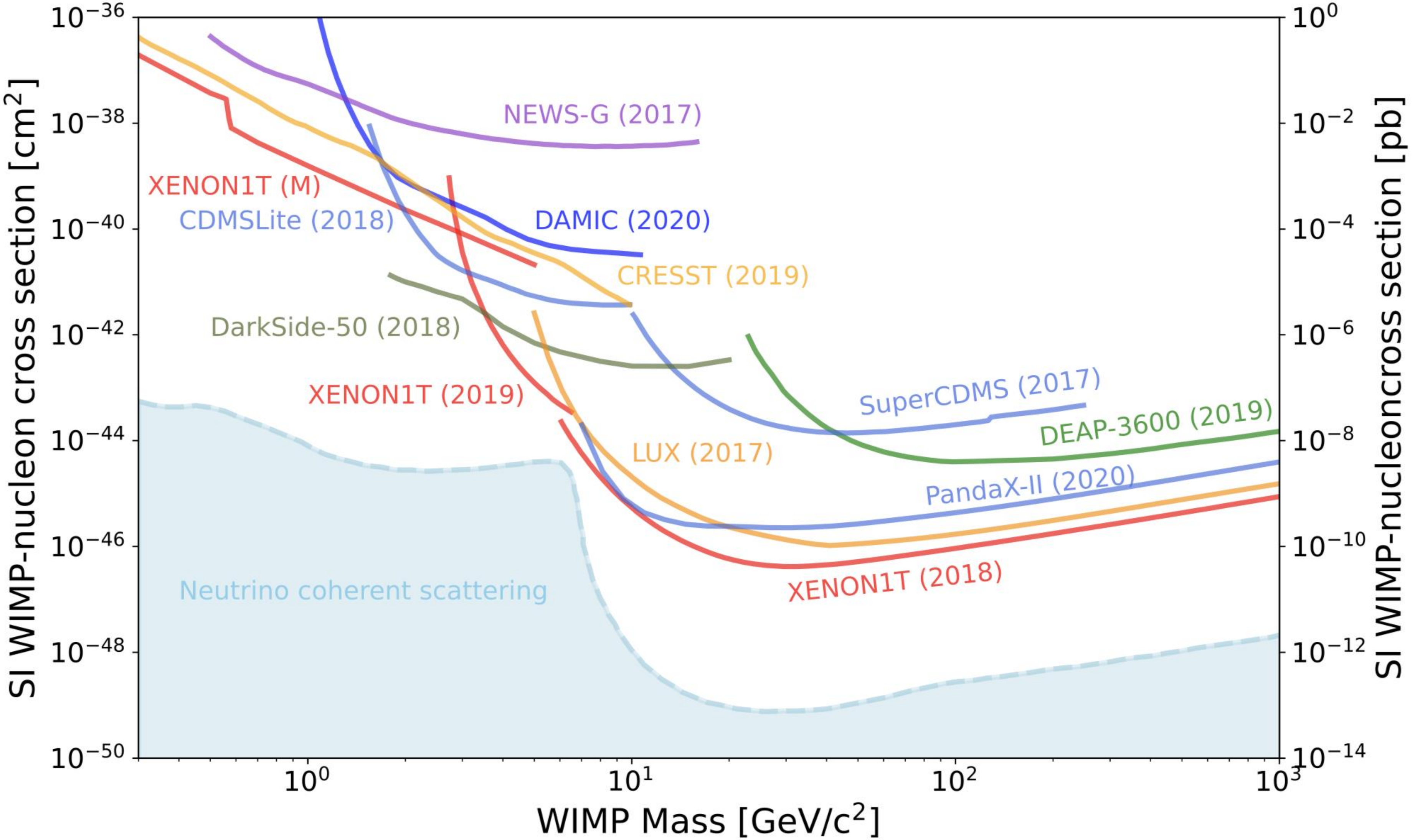
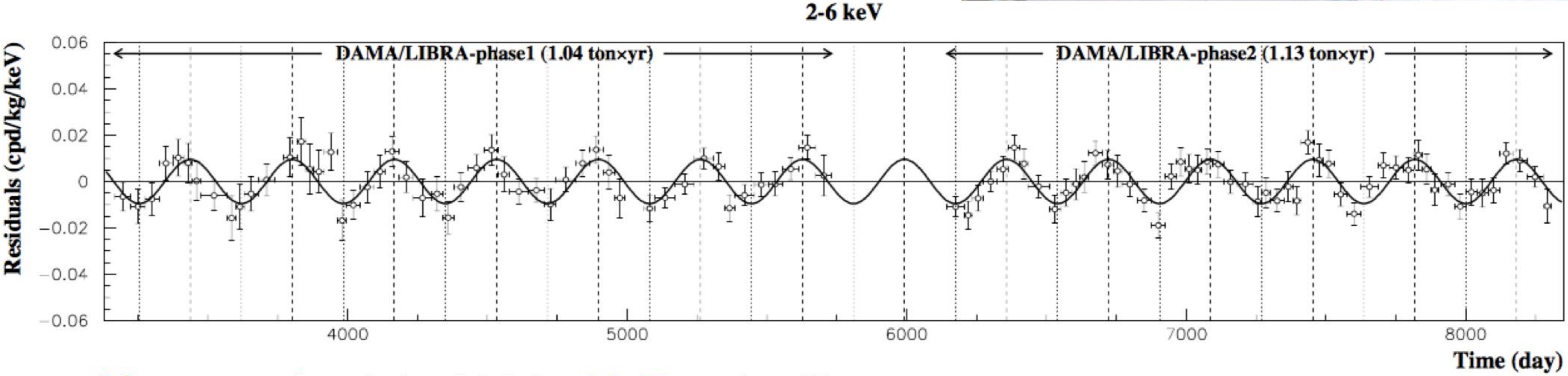


Figure updated from PDG, Prog. Theor. Exp. Phys. 2020 (2020) 083C01

DAMA results still await confirmation

- Ultra radio-pure NaI crystals @LNGS
- Annual modulation of the background rate in the energy region (2 – 6) keV
- Last results (2018): signal at 12.9 σ

Nucl. Phys. At. Energy 19 (2018) 307



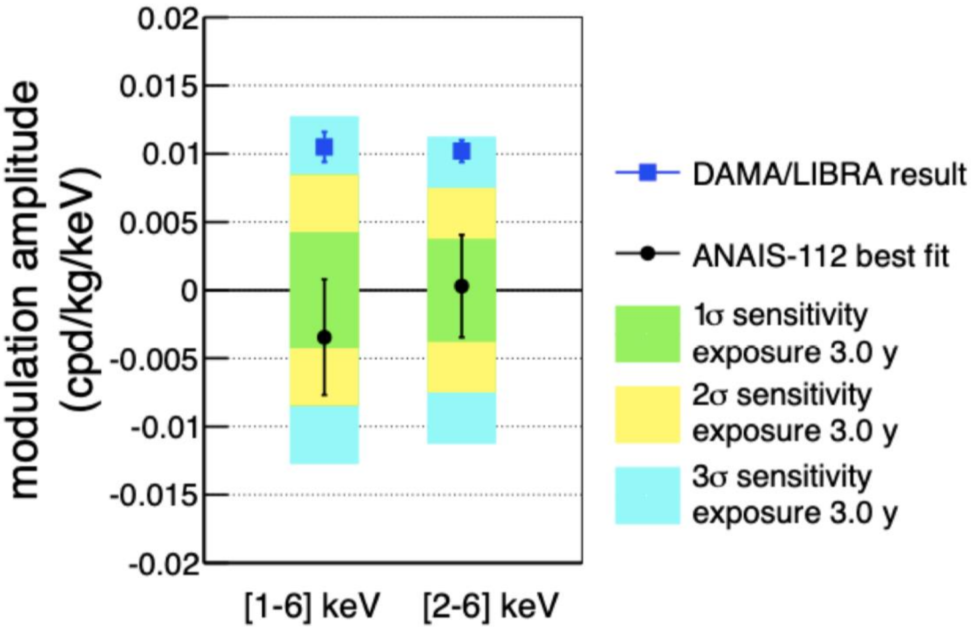
→ New results July 2021: 13.7 σ significance @EPS-HEP conference by P. Belli

WIMP interpretation in contradiction with many other results

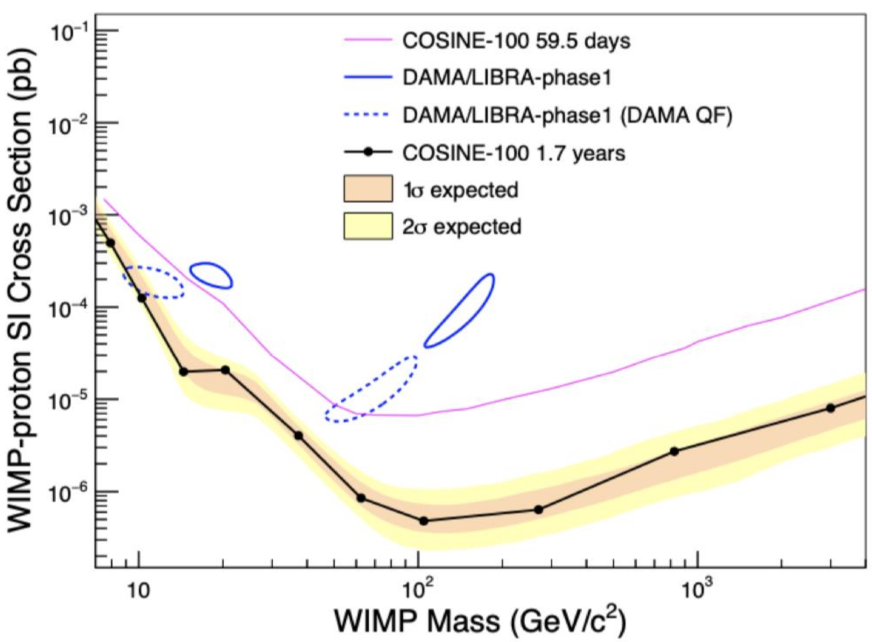
Worldwide effort to verify/refute this result

No confirmation yet but jury still out

ANAIS, PRD 103 (2021) 102005 & arXiv:2103.01175



COSINE-100, Sci.Adv. 7 (2021) 46 & arXiv:2104.03537



ANAIS @Canfranc:

- DAMA modulation disfavoured at 3.3 σ for [1-6] keV at 2.6 σ for [2-6] keV
- Sensitivity above 3 σ within 2022

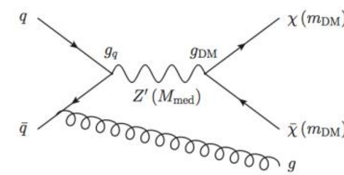
COSINE-100 @Yangyang:

- DAMA SI signal excluded
- Modulation analysis compatible with both DAMA and no modulation

Mono-object Searches @ LHC

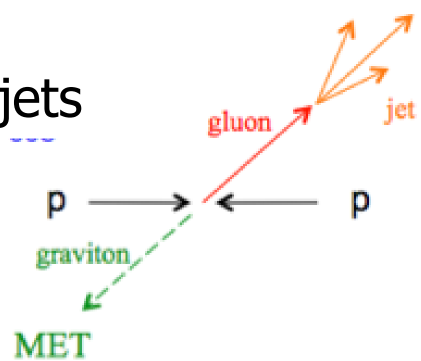
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Effective Field Theories for DM interpretation are under scrutiny!
Alternatives such as SMS proposed

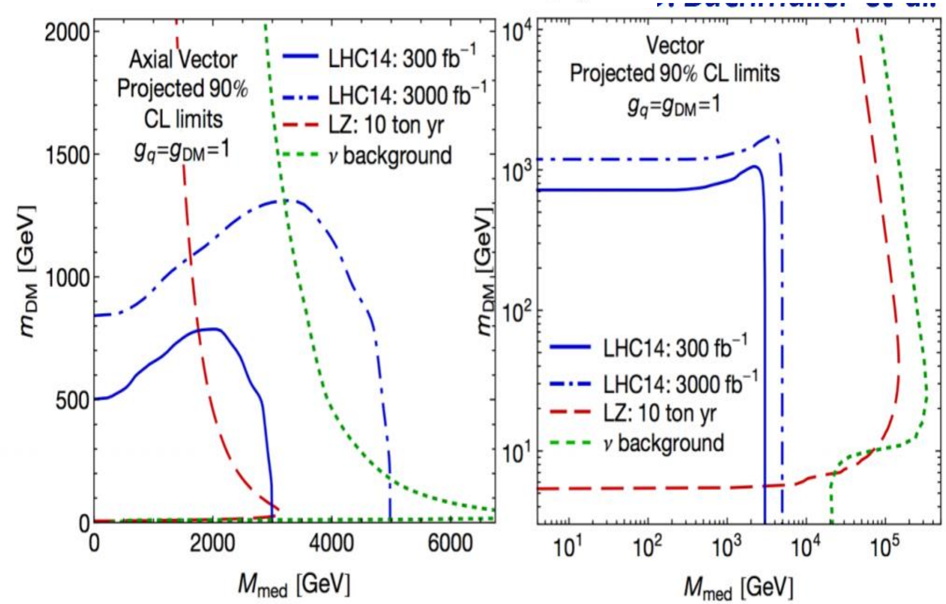


arXiv:1407.8257
arXiv:1411.0535

Example Monojets



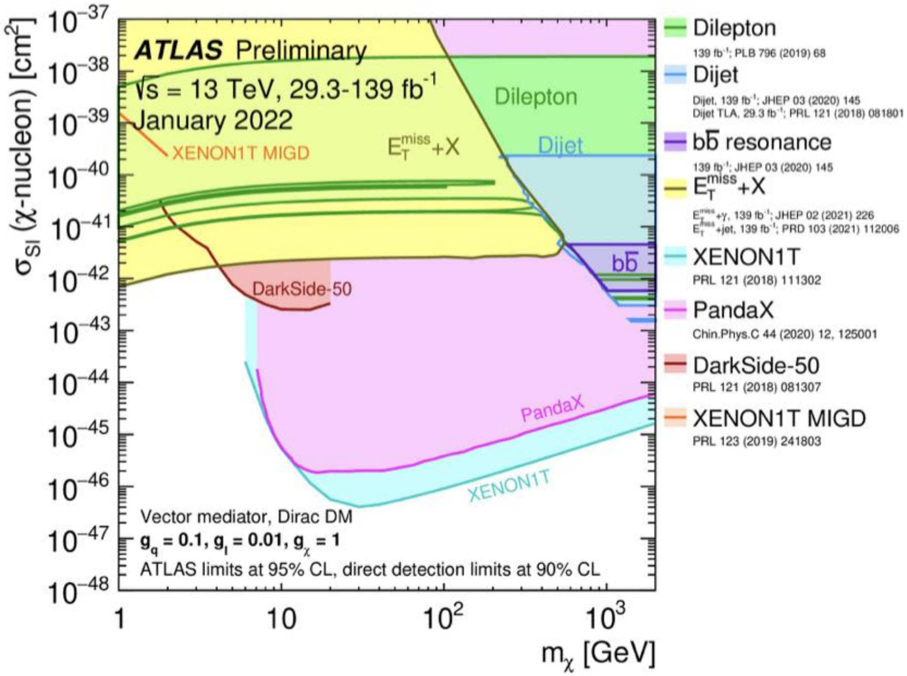
Dark Matter?



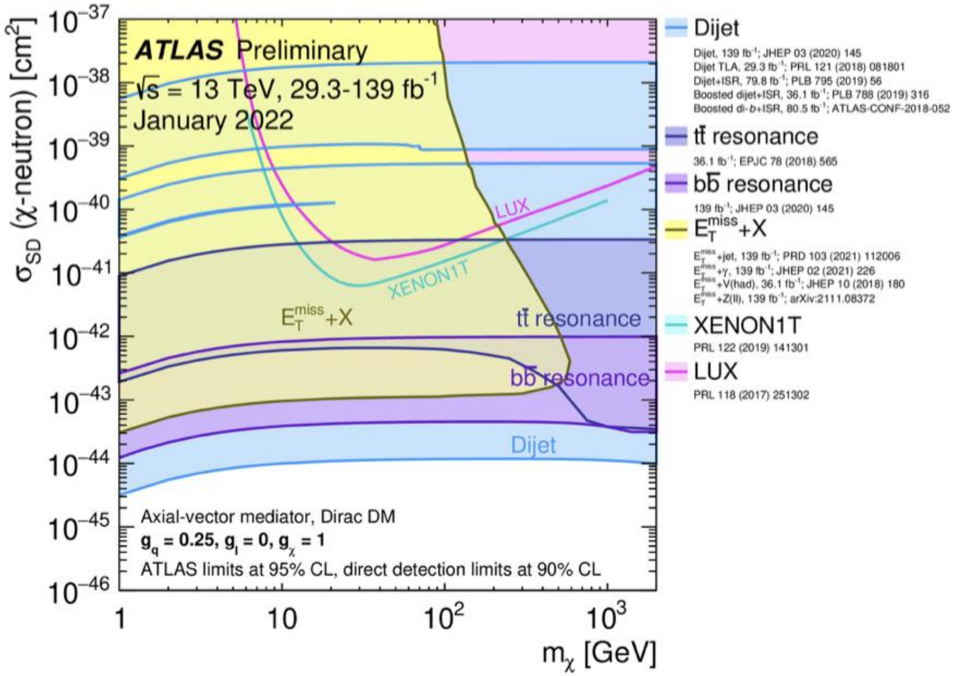
LHC Comparison with Direct Detection

Upper limits on scattering cross-section can be set to compare with direct detection results using Simplified Models (note: collider sensitivity is model dependent!)

Vector mediator and Spin independent direct limits



Axial-vector mediator and Spin dependent direct limits

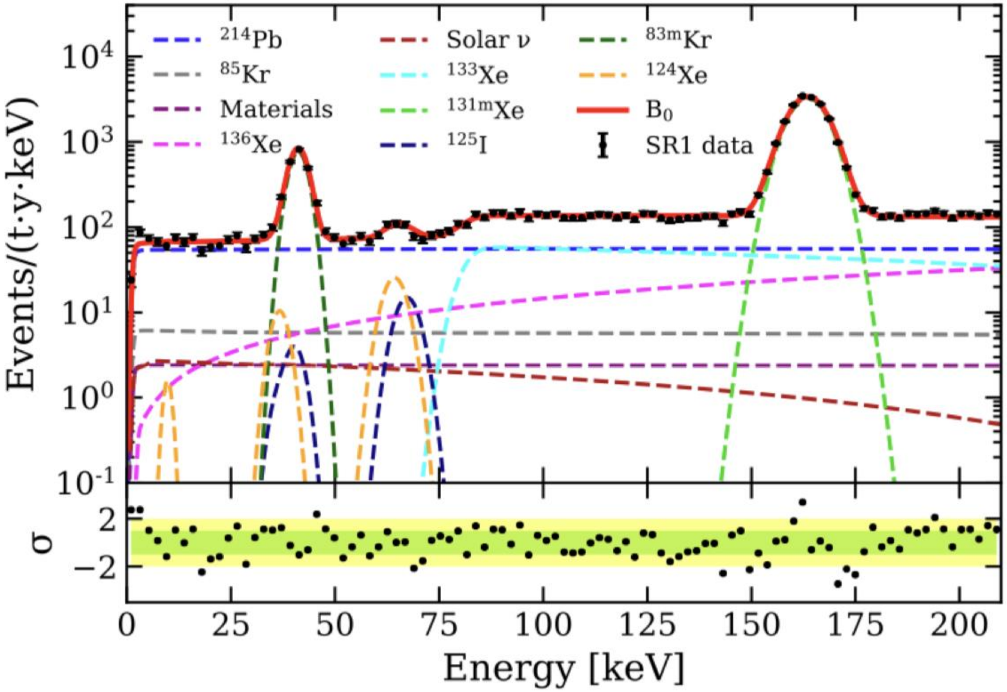


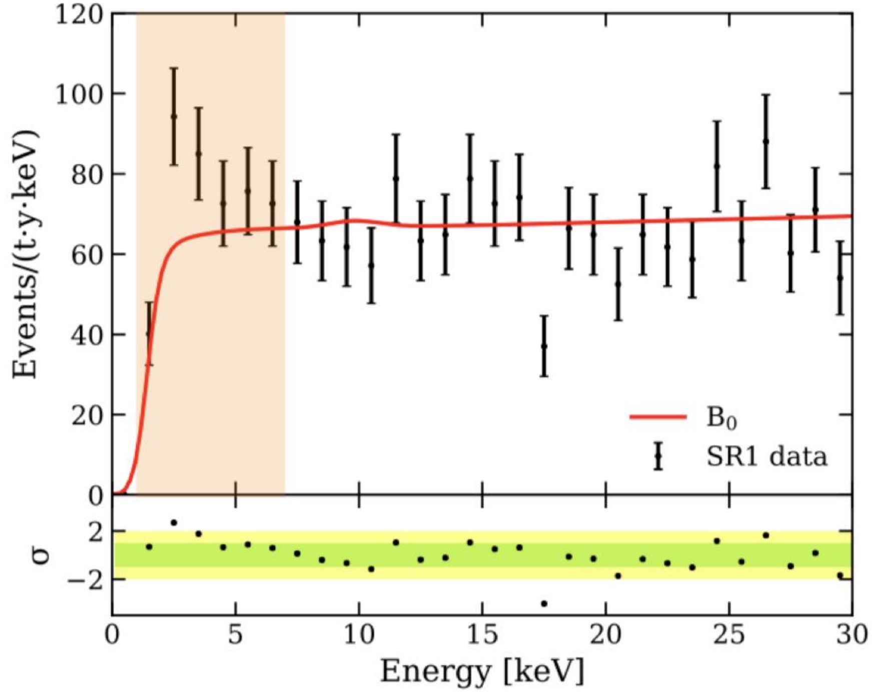
More reliable comparisons with direct detection results now possible via the Simplified Models method

90% CL limits

A Signal in Xenon1T??

Xenon1T is a 3.5T Xenon-based direct DM detection experiment in Gran Sasso





XENON1T, Phys. Rev. D 102 (2020) 072004 & arXiv: 2006.09721

Low energy scattered electrons

Excess of events in (1-7) keV in the background region

- ~ 3.3 σ statistical significance
- A lot of excitement (> 350 citations since June 2020)
- Unclear origin: Tritium? or Axion signal? or something else?

Xenon Detectors

XENON 10 (LNGS)
ZEPLIN (Boulby)

10 kg

2010

100 kg

XENON 100 (LNGS)

LUX (250 kg, SURF),

PANDA-X (500 kg, CJPL)

XMASS (0.8t, Kamioka)

2015

1,000 kg

XENON 1T (1t, LNGS)

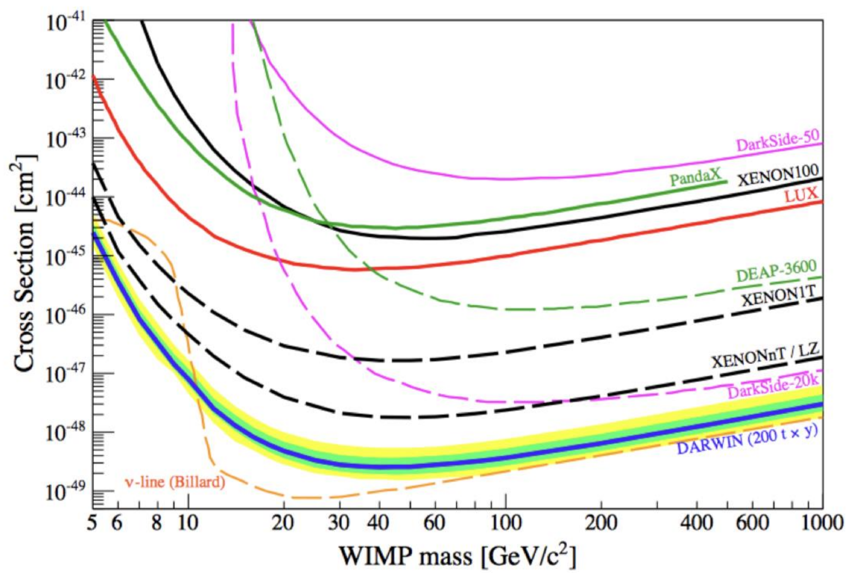
PandaX-4:(4t, CJPL)

XENONnT: (6t, LNGS)
LZ: (7t, SURF)

2020

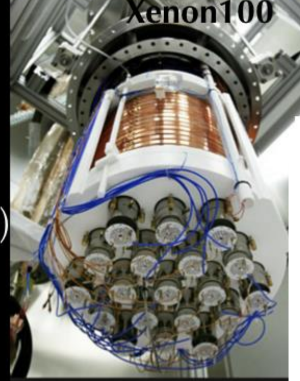
10,000 kg

***Future: DARWIN**: 50 t*

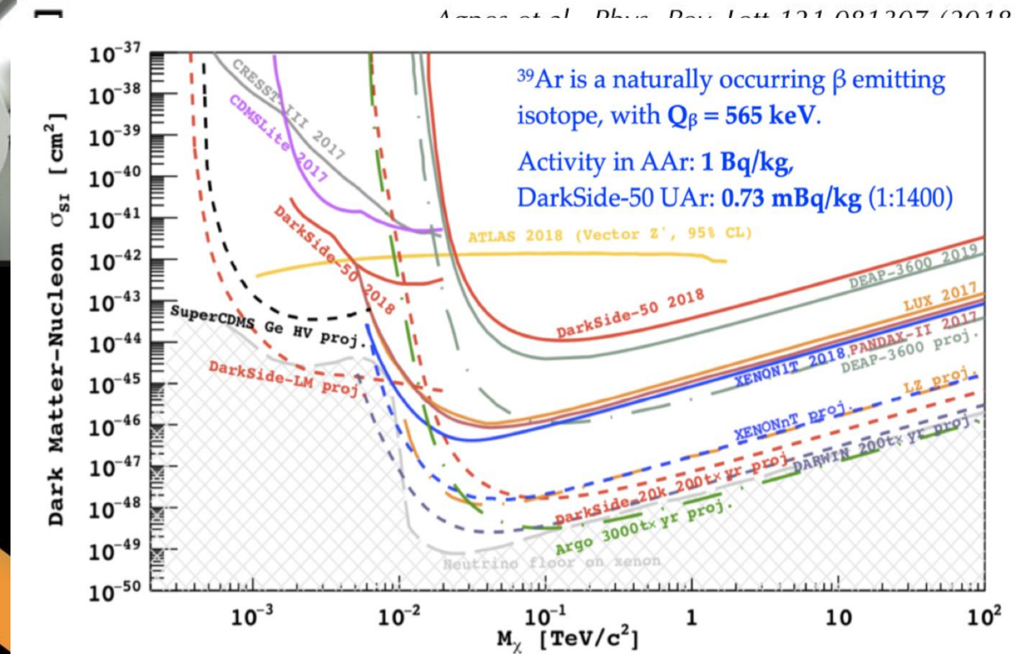


DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001

Argon Detectors



DarkSide-50: leading SI limit at 1-5 GeV/c² for WIMP-nucleus and WIMP-e scattering



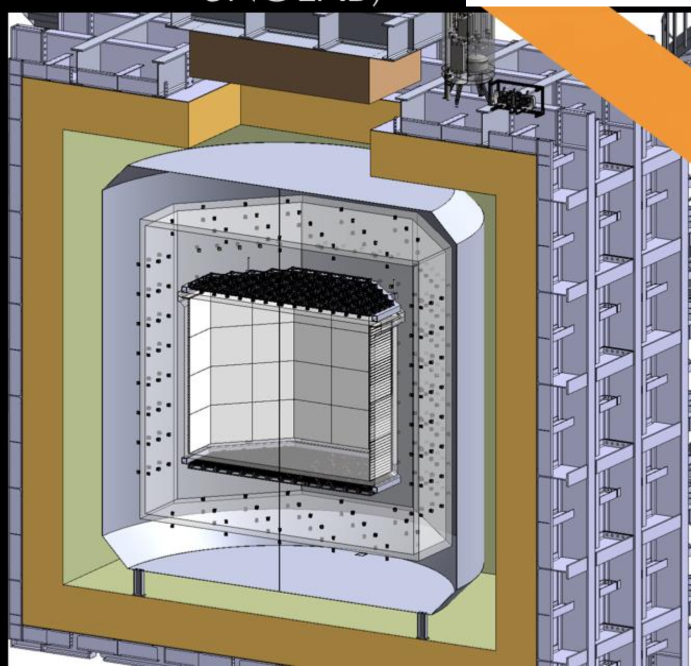
10 kg — 2010 — **DarkSide-50** (50 kg, LNGS)

100 kg — **ArDM** (1t, LSC)

1,000 kg — 2015 — **DEAP-3600** (3.6t, SNOLAB)

DEAP-3600:
parts-per-billion level "S1" particle ID, ultrapure acrylic cryostat

Ajaj et al, Phys. Rev. D (2019)



Global Argon Dark Matter Collaboration formed

APPEC

10,000 kg — 2020

DarkSide-20k (50t, LNGS)

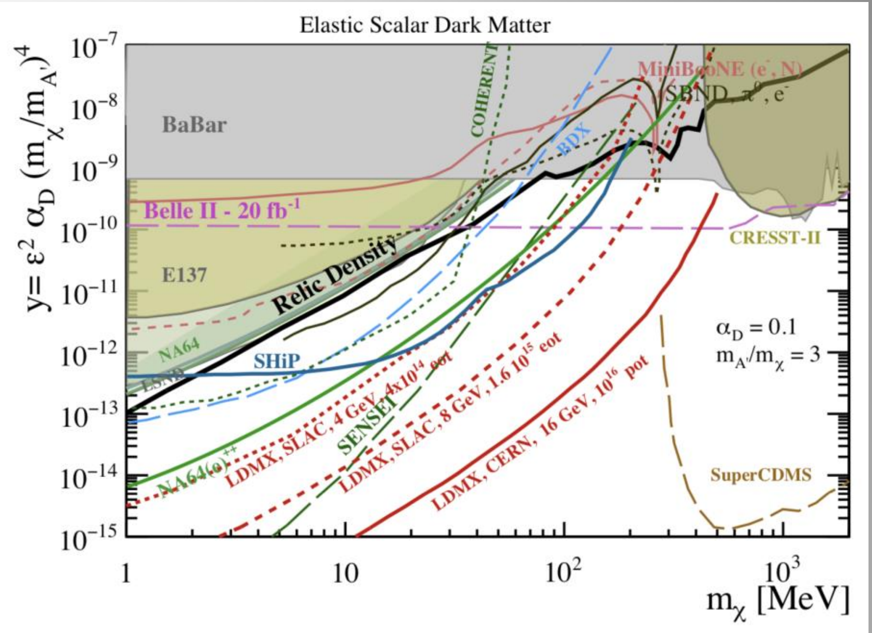
100,000 kg

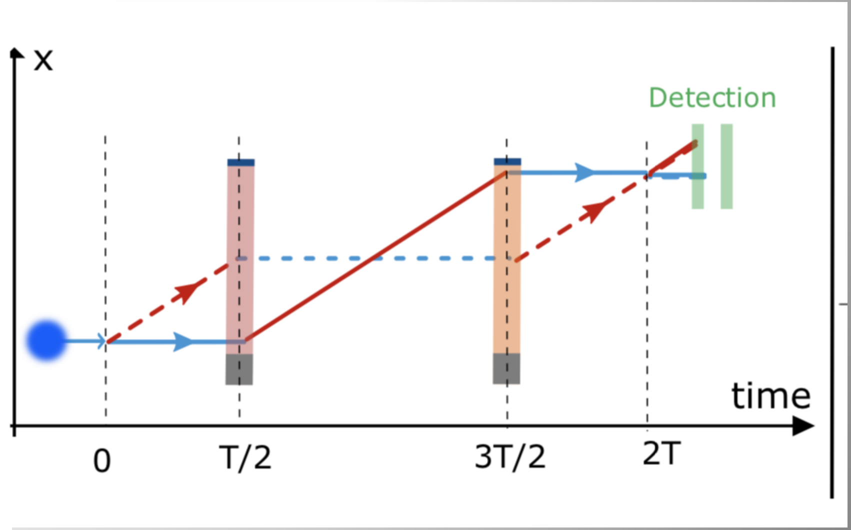
***Future: ARGO**: 400 t*

More examples of Ongoing Activities

- New techniques for direct experiments eg directional detectors, bolometers, superheated liquids, crystals…
- Light Dark Matter searches at high intensity fixed target experiments
- Axion and ALP searches
- Quantum interference devices, eg cold atom interferometers
- … And many more

The multi-prong attack on Dark Matter is on!





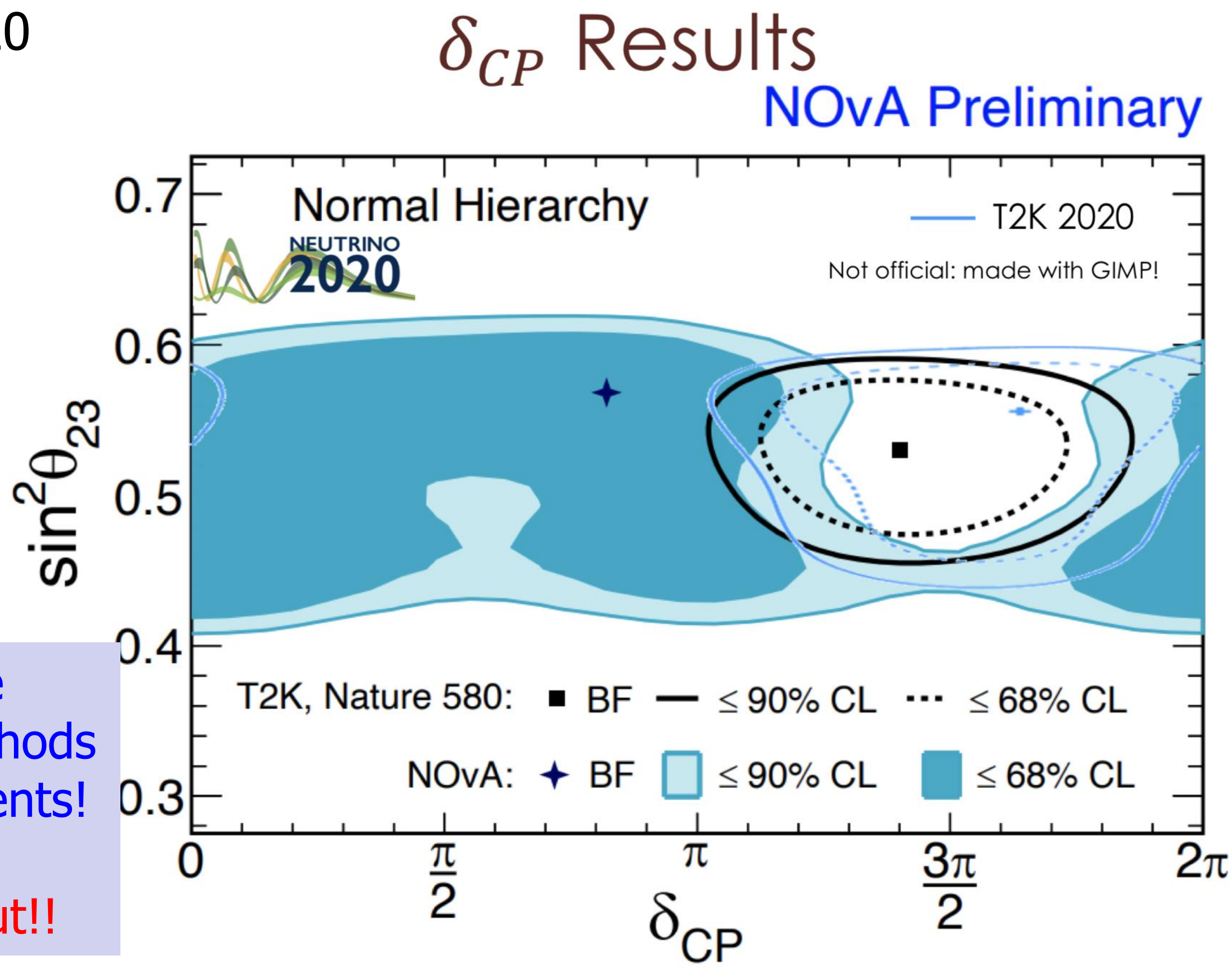
Summary

- Both the Neutrino studies and Dark Matter searches have a strong program for the future, with new experiments and new experimental technologies being developped
- The coming decade will be key for precision neutrino physics and will increase dramatically the search region in sensitivity for DM and for explore more DM canditates
- Lot's of oppertunities for young scientists to get engaged in these fields!
- And perhaps one day soon

Back-up

CP Violation T2K/NOvA Results

Summer 2020 update

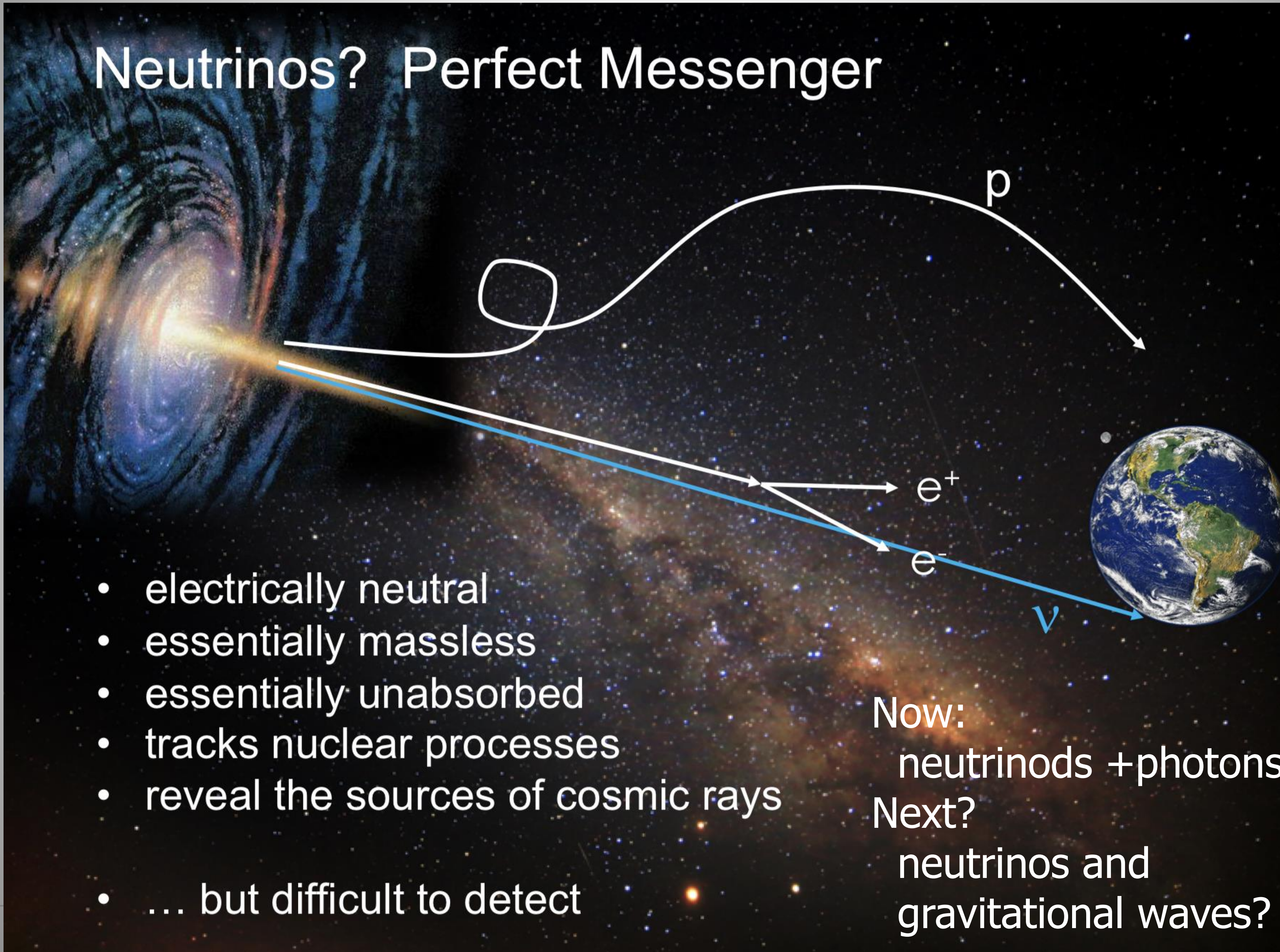


Good to have different methods and experiments!

Jury is still out!!

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

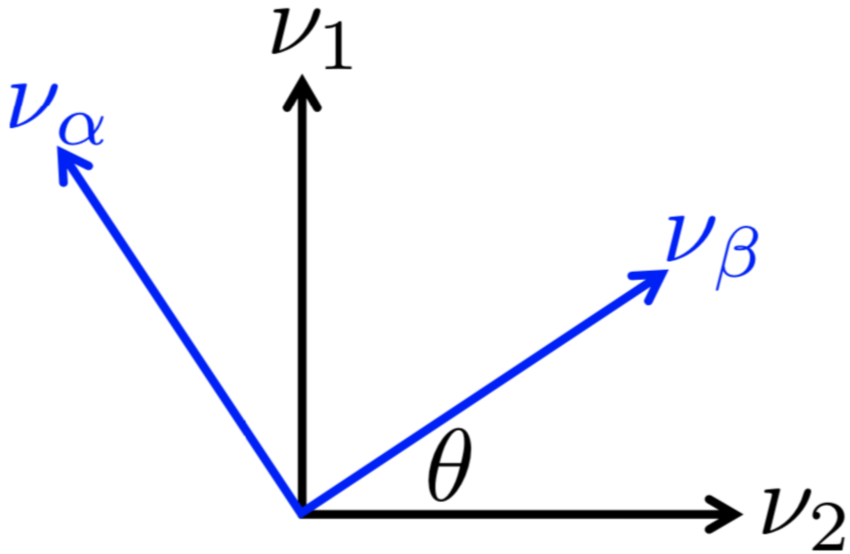
Multi Messenger Astronomy



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

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

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

Direct Searches Overview

Searches for WIMP hypothesis in the GeV to TeV range