Physics with neutrino experiments

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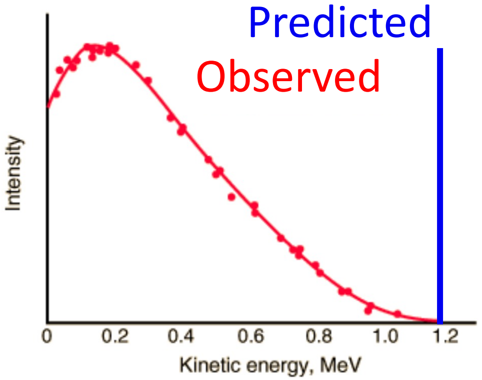
Pheno 2022 @ Pittsburg
05/10/22

A little bit of $\boldsymbol{\nu}$ history (experimental)

$\beta\ decay$: $n \rightarrow p + e$



Desperate Remedy!

$n \rightarrow p + e + \overline{\boldsymbol{\nu}_e}$

1930 **1960** **1990** **2020**

Neutrino Postulated

Pauli: “Will never be detected…”

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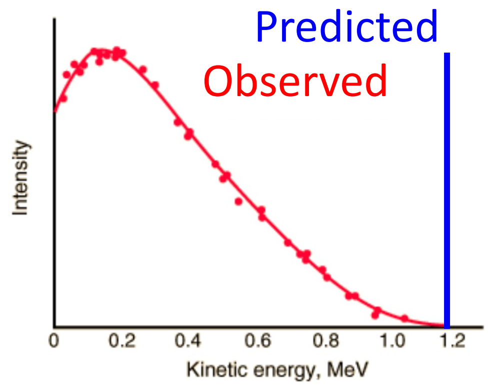

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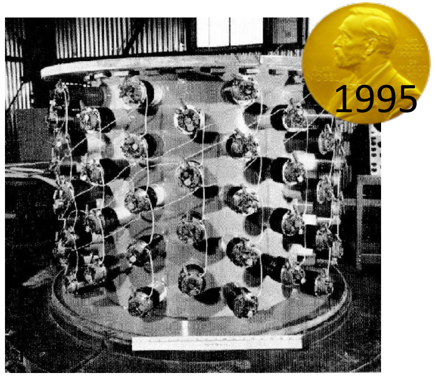
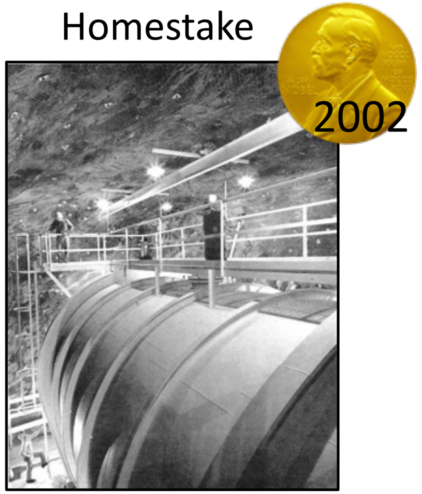


Solar neutrino problem

?

Homestake



1930

1960

Only 1/3 ν_e observed than predicted

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First observation of neutrinos (anti ν_e, ν_μ)

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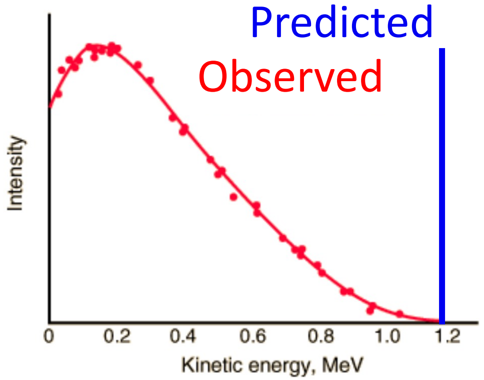

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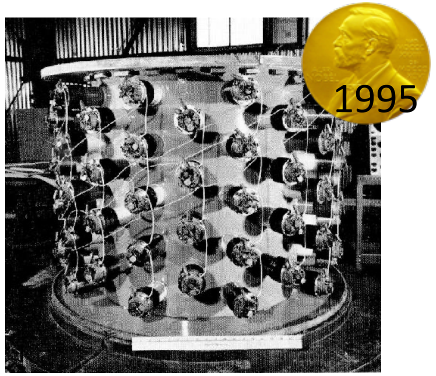

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☀ √

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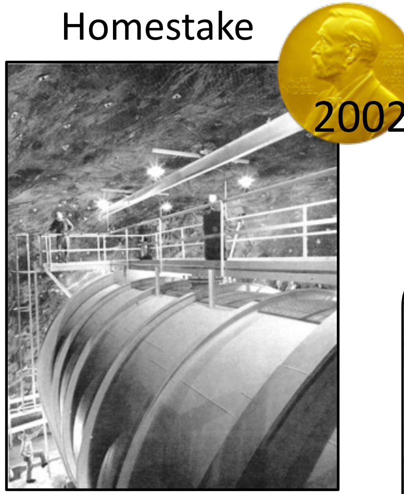
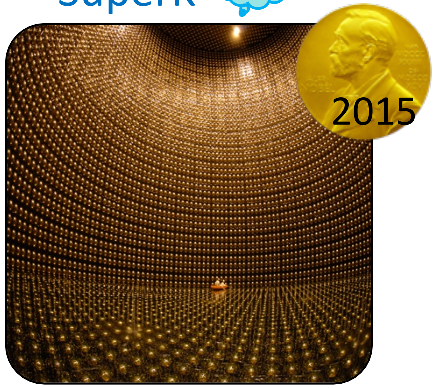


Only 1/3 ν_e observed than predicted

SuperK



SNO ☀

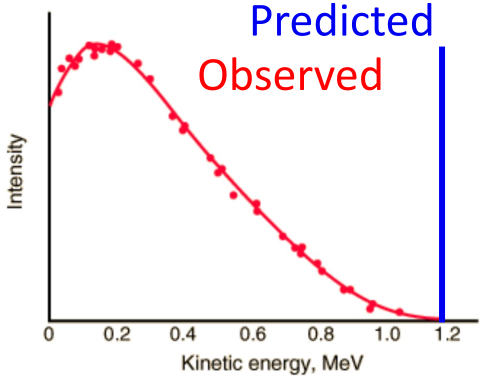
1990

2020

Discovery of Neutrino Oscillations!

A little bit of ν history (experimental)

β *decay*: $n \rightarrow p + e$



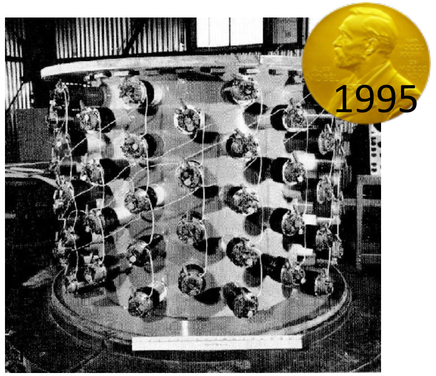
Desperate Remedy!

$n \rightarrow p + e + \overline{\nu_e}$

1930

Neutrino Postulated

Pauli: “~~Will never be detected…~~”



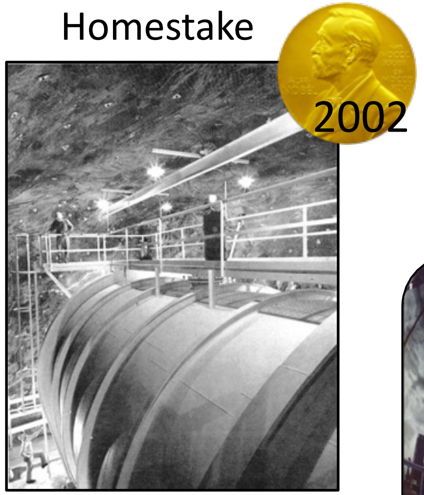
1960

First observation of neutrinos (anti ν_e, ν_μ)

Solar neutrino problem

√

Homestake



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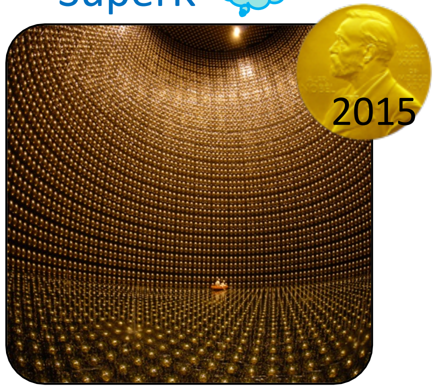


SNO

1990

Discovery of tau neutrino

Discovery of Neutrino Oscillation!

AINITA
IceCube
PINGU
MINOS
KM3NET
T2K
MiniBooNE
Hyper-K
MINERvA
ICARUS
MicroBooNE
SBND
NOvA
DUNE
Daya Bay
KamLAND
Double Chooz
RENO
PROSPECT
JUNO
Borexino
SNO+
SuperK
PTOLEMY

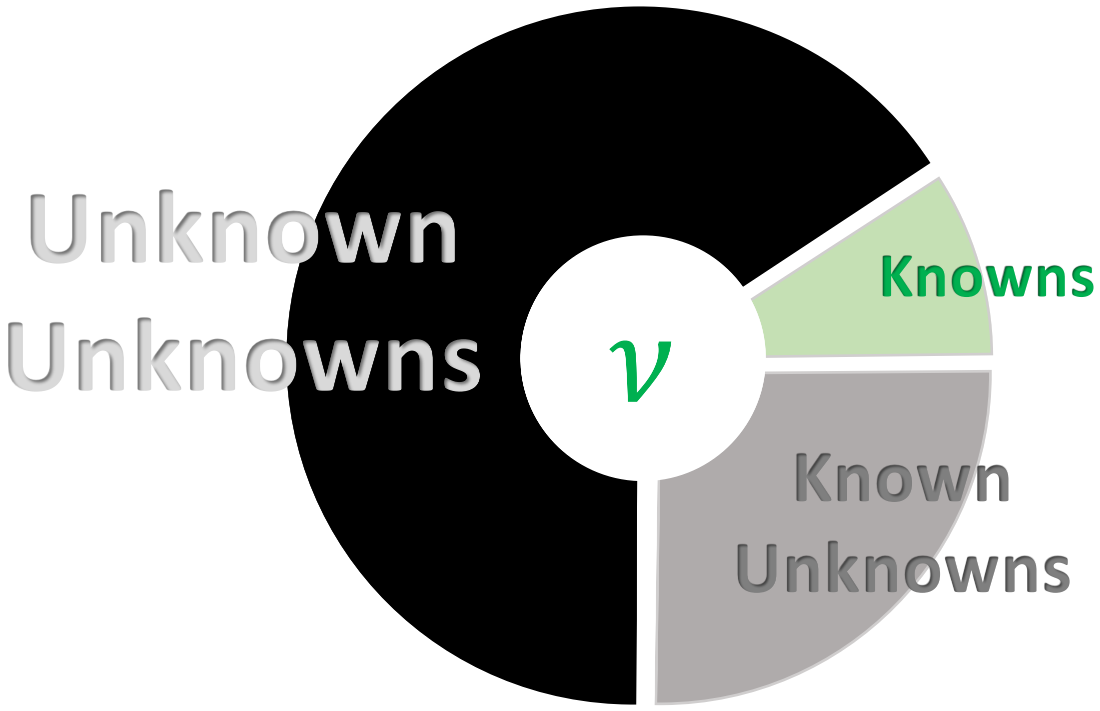
2020

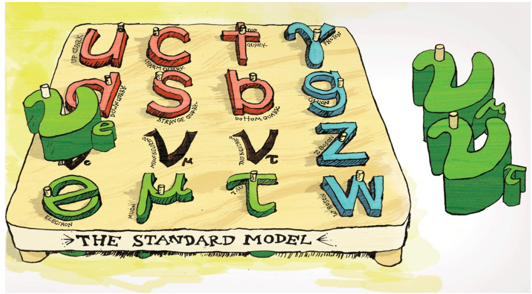
Measuring Oscillation parameters

Neutrinos are the least known particles in the Standard Model

New particles?
New Symmetries?
Hierarchy problem?

GUT?
Extra dimension?
Dark matter?
Portal to Dark sector?



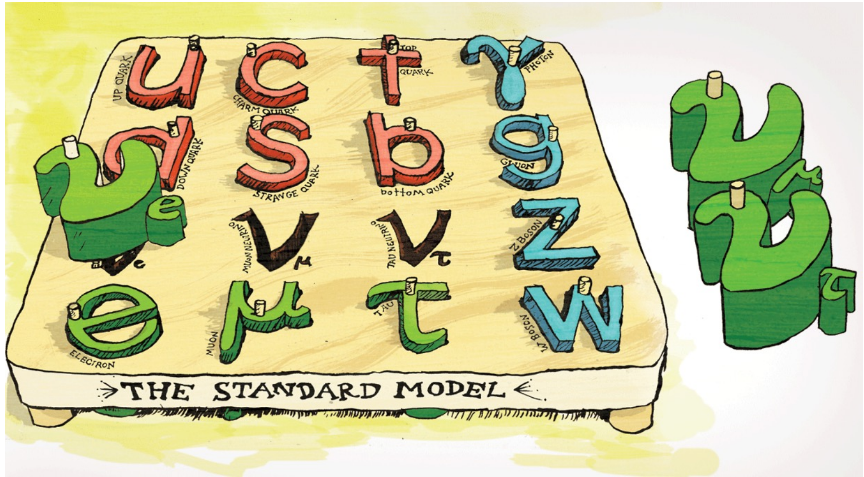


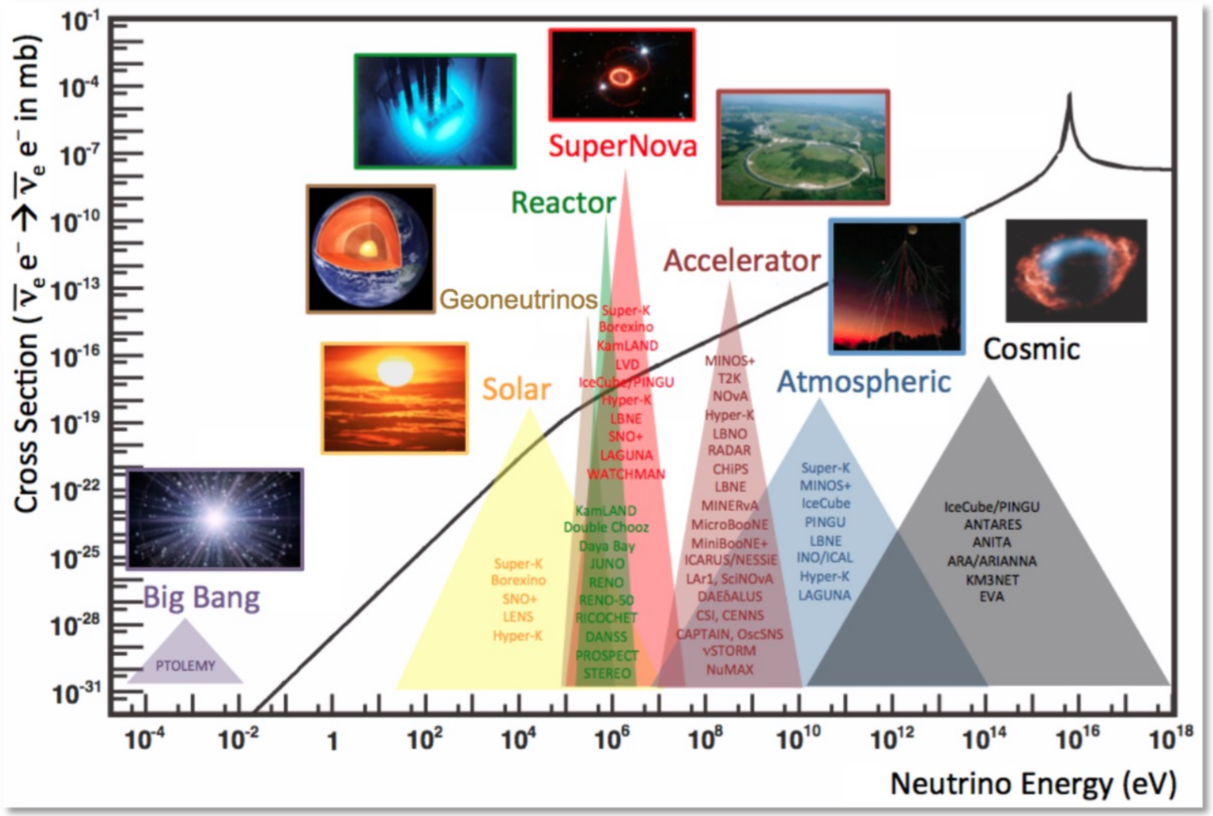
CP violation?
Mass ordering?
Dirac or Majorana?
Absolute mass?
Matter-antimatter asymmetry?

Mysterious neutrinos provide the ideal experimental playground for new physics discovery

The Knowns - “ν-101”

- Electric charge neutral lepton
- 3 flavors: ν_e, ν_μ, ν_τ
- Interact only through weak interaction
- Only left handed ν’s are observed

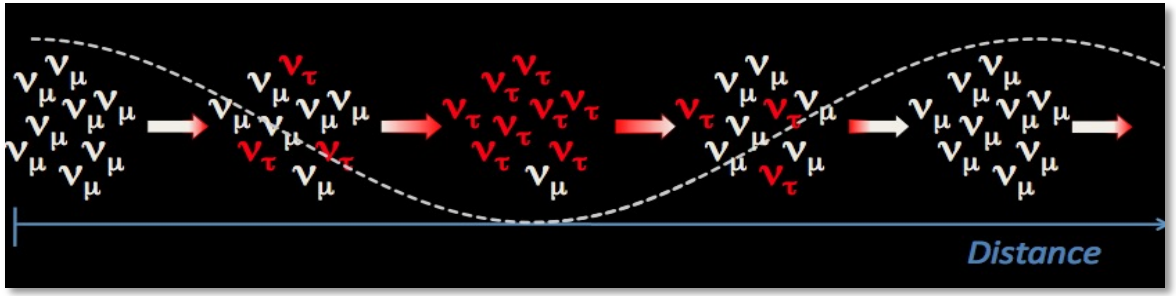




- Most abundant matter particle
  - “Wild”: cosmic, sun, earth, bananas!
  - “Artificial”: accelerator, reactor
- Energy span over 20 orders of magnitude
- Weakly interact: cross-section ~10^{-38} cm^2/GeV
- **Oscillate -> have mass**

Neutrino Oscillation

Neutrino oscillation



Born & detected as Flavor States

Travel as Mass states

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

Mixing matrix

Mixing angle θ determines the amplitude of oscillation

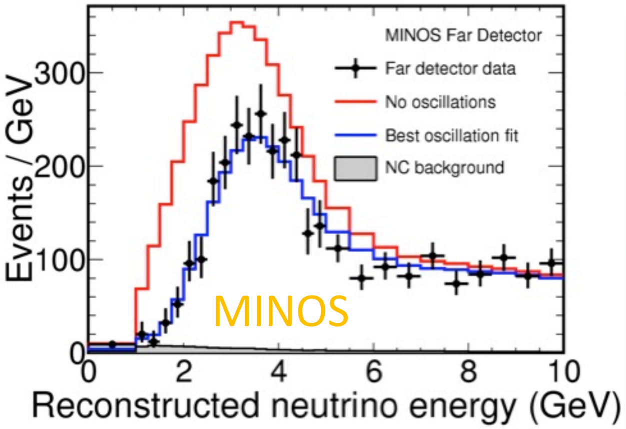
$$\boxed{P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}$$

Δm^2 determines the frequency of the oscillation as function of L/E

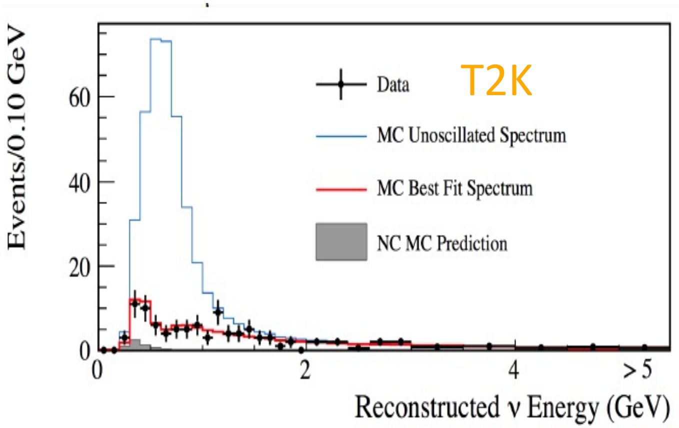
Experiments choose L and neutrino flavors, measure the oscillation probability as a function of neutrino energy (E_ν) to determine oscillation parameters θ, Δm^2.

Measure oscillation parameters

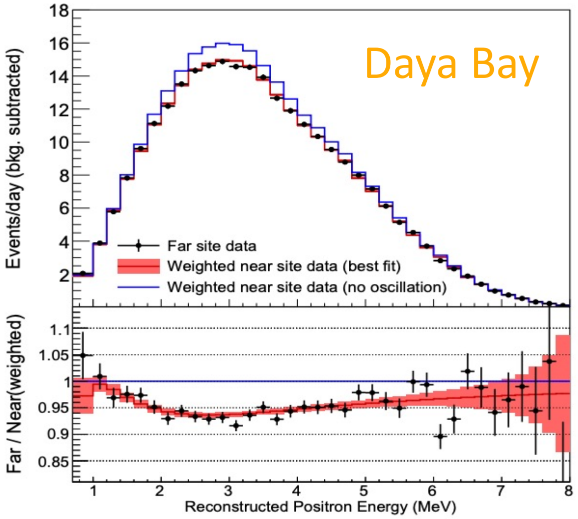
ν_μ disappearance



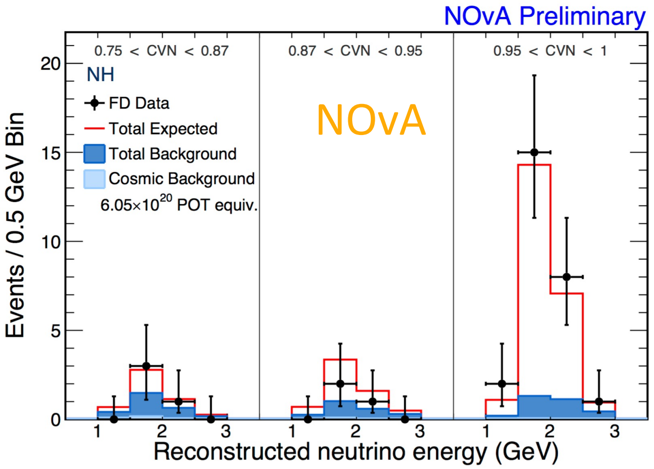
ν_μ disappearance



$\bar{\nu}_e$ disappearance



ν_e appearance

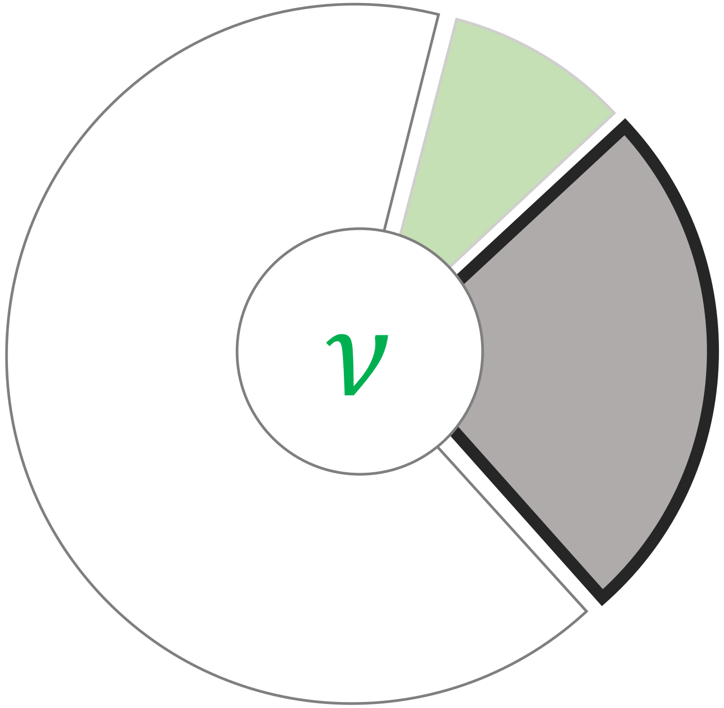


Over two decades of **Oscillation experiments** have established…

3−ν paradigm

$$|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

- **3 mixing angles**: $\theta_{12} \sim 33°, \theta_{13} \sim 8°, \theta_{23} \sim 45°$
- **2 mass splittings**: $\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$, $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$
- **1 CP violation phase δ_{CP}**



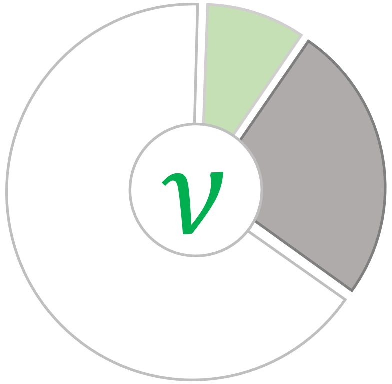
Known Unknowns

Other oscillation parameters?

What's the absolute neutrino masses?

What's the origin of neutrino mass?

Are there more than 3 types of neutrinos?



The Known Unknowns – More oscillation parameters

Find answers in long baseline ν oscillation experiments

NOvA: 14 kton liquid scintillator cells
E ~ 2 GeV;

T2K: 50 kton water Cherenkov detector
E ~ 0.6 GeV;

Both measure ν_μ disappearance ν_e appearance rates at far detector and constrain the systematics using near detector data.

CP phase
δ_{CP}

Still relatively low sensitivity $\boldsymbol{\delta_{CP}}$

best fits from the two exps. do not agree completely (depend on mass ordering)

Mass ordering
$m_1 >$ or $< m_3$

NOvA: Best fit land in Normal Ordering $m_3 > m_1$

T2K: Not very sensitive

θ_{23} Octant
> or <$45°$?

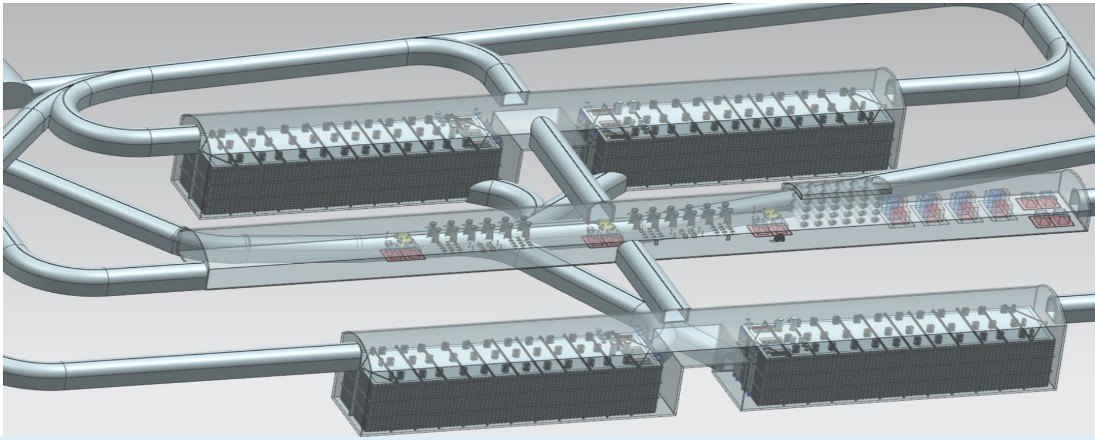
No evidence of deviation from maximum mixing
Both measure $0.4 < \sin^2\theta_{23} < 0.6$

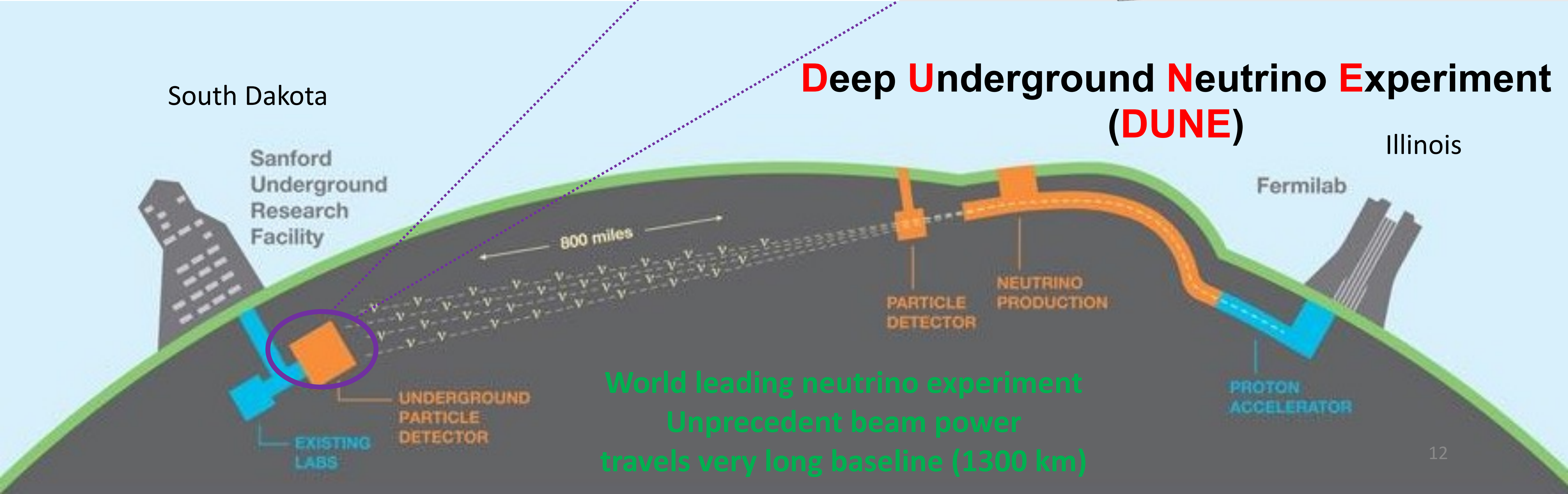
Current experiments still cannot provide a clear picture (>3σ) of these oscillation parameters. How do we move forward?

Next gen. long baseline ν exp.

More advanced detectors
More optimal baseline and neutrino energy
More powerful beam
Higher statistics

40 kton Liquid Argon detector
located ~1 mile underground





Deep Underground Neutrino Experiment
(DUNE)

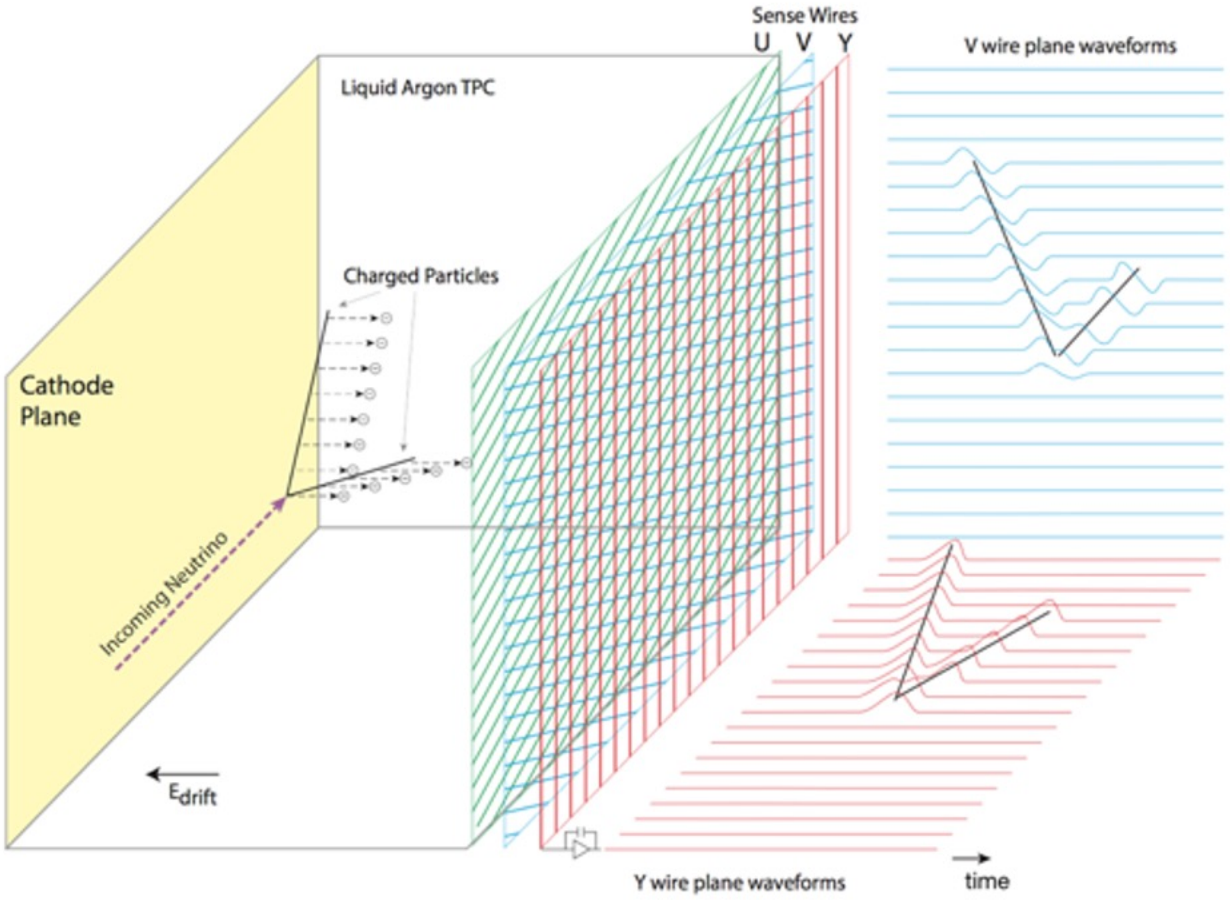
South Dakota

Illinois

World leading neutrino experiment
Unprecedent beam power
travels very long baseline (1300 km)

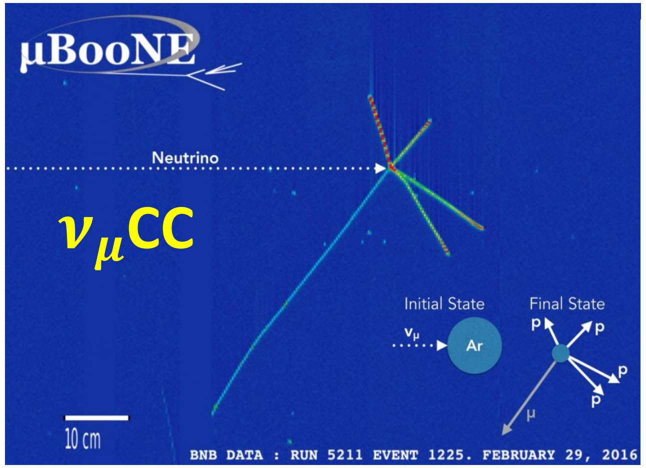
“It” detector – Liquid Argon Time Projection Chamber

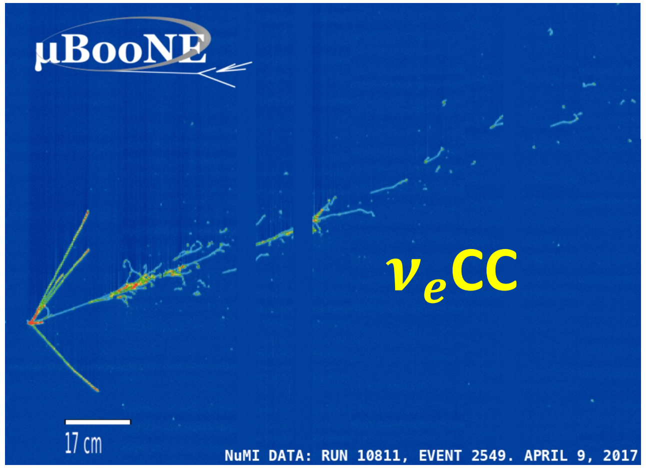
- Charged particles lose energy through Ar collision (**scintillation light**) and ionization (**drift electrons**)
- Fast scintillation light signal triggers the recording of events.
- Ionization electrons drift towards anode wire planes under E field.
- Capability of full 3D reconstruction in 4π.
- Amount of charge collected indicates the amount of energy loss from ionization.



Future long-baseline program

EJPC 80 (2020) 978

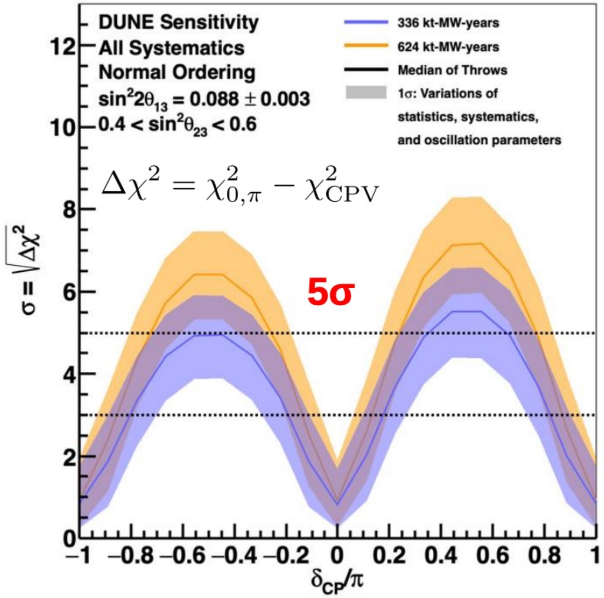




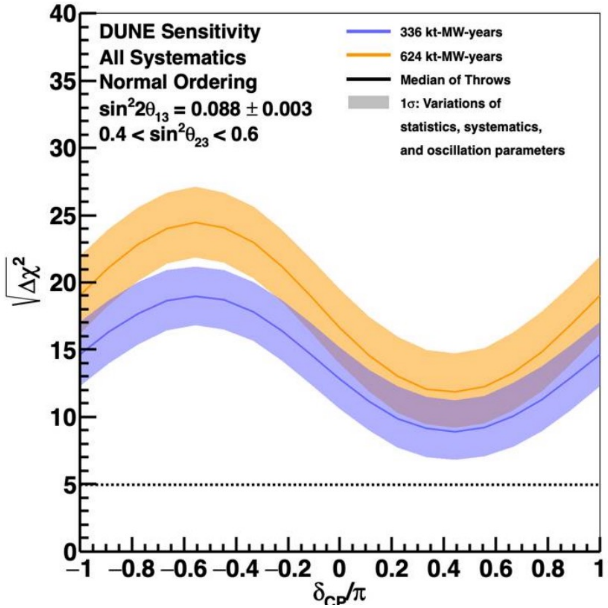
+

anti-neutrino mode

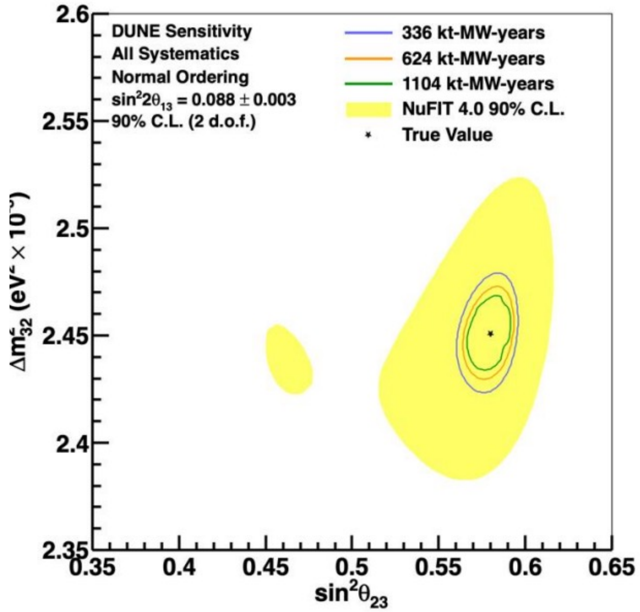
DUNE prospects



>5σ discovery potential for half of δ_{CP} values



Unrivaled ability to resolve mass ordering

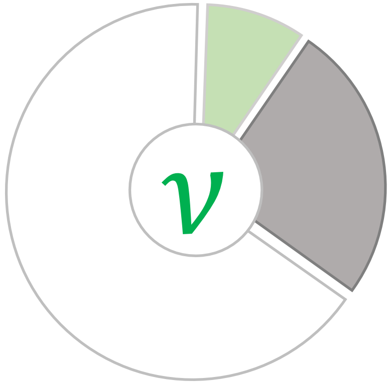


World leading result for theta 23

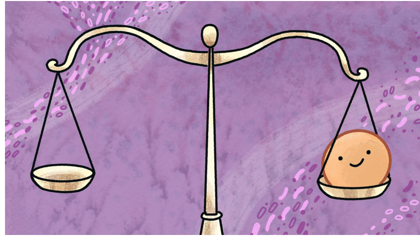
One experiment to measure all oscillation parameters at once.

In parallel, another large scale long-baseline exp. HyperK @ Japan. Different detector technology and beamline offer complementarity.

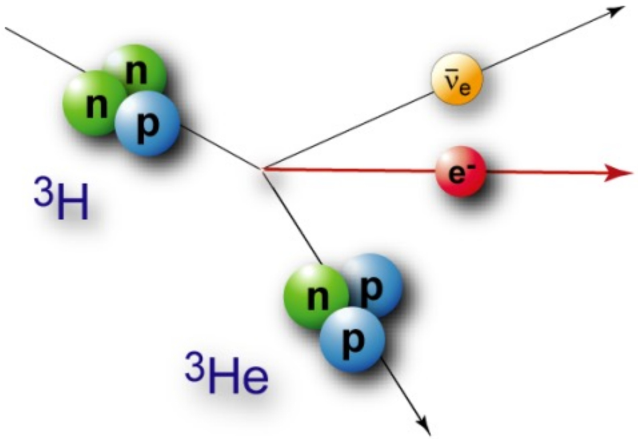
Combined result from both experiments offer stronger constraint oscillation parameters.



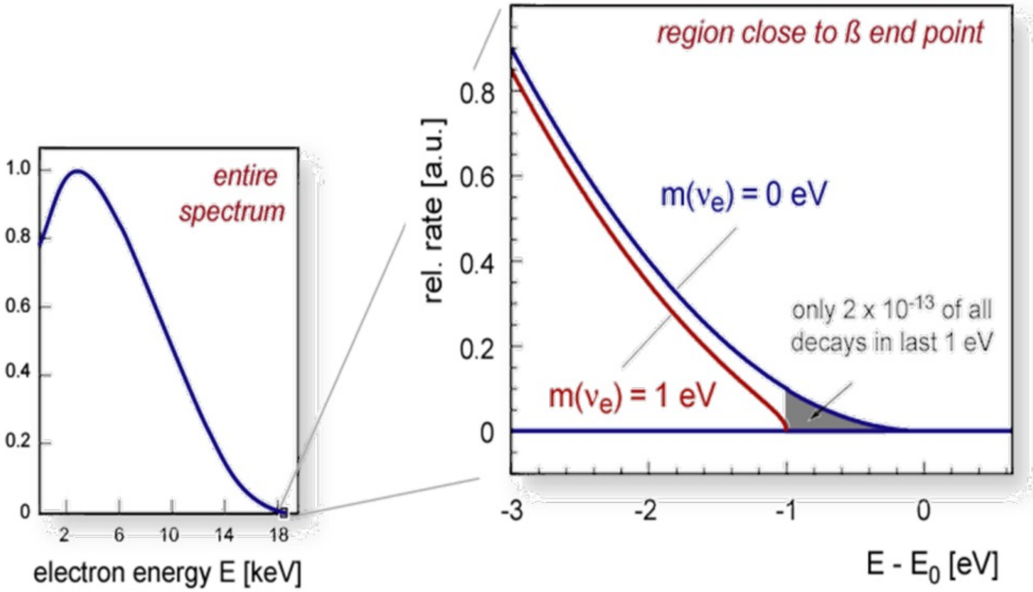
The Known Unknowns – Absolute Neutrino mass



Direct neutrino mass measurement through high energy resolution of the tritium beta decay spectrum



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

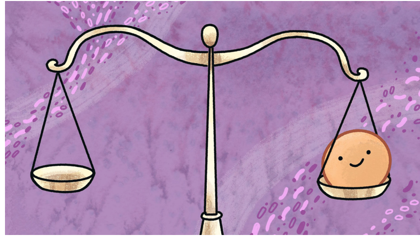


A sensitive neutrino mass experiment needs:

- Strong tritium source for signal statistics
- Low background
- Excellent energy resolution (sub-eV)
- Precise understanding of the beta decay spectrum (modeling)

From Susanne Mertens Neutrino 2020 talk

Direct neutrino mass experiments



Karlsruhe
Tritium
Neutrino
Experiment

KATRIN Experiment

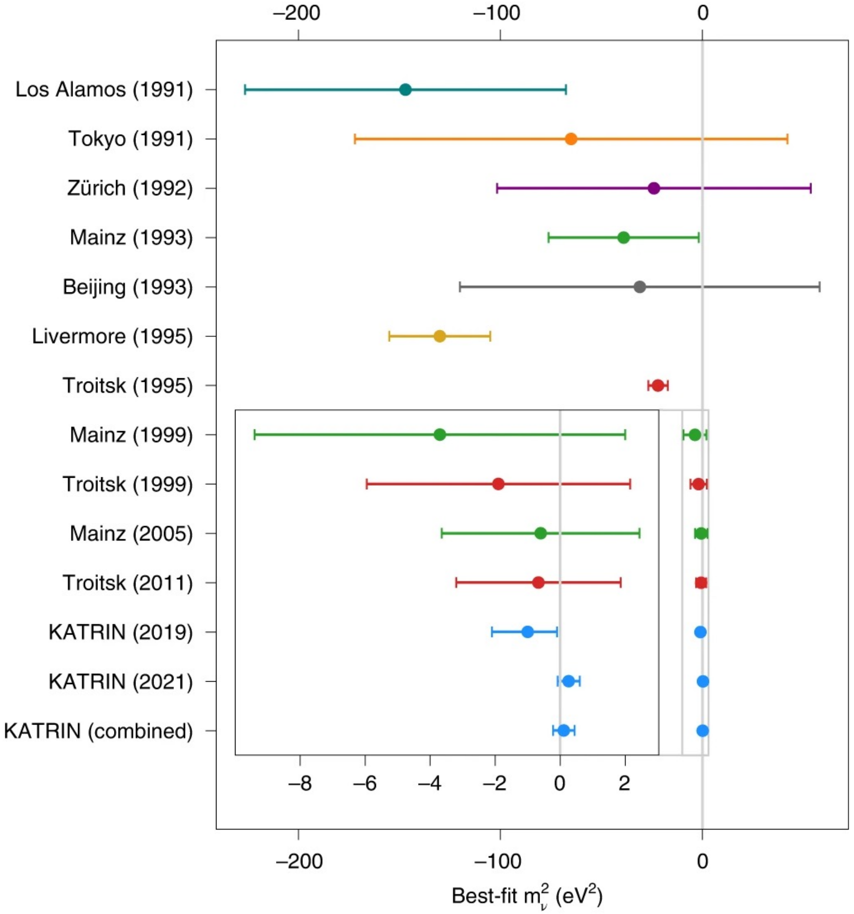
Beta-decay electrons are:

- produced from gaseous tritium source (10^{11} decays/s)
- transported with strong magnetic field (4T)
- energy measured by spectrometer with ~1eV resolution
- rate counted by the Focal Plane detector

m_{ν} Sensitivity designed goal: 0.2 eV.

Latest Result (from Nature):

m_{ν} sensitivity = 0.7 eV at 90% CL
Upper limit: m_{ν} < 0.9 eV c^{-2}



Other neutrino mass experiments:
Project 4, ECHo, HOLEMS, NuMECS

Cosmology constraints:

$\sum m_i$ < 0.17 eV

The Known Unknowns – Origin of Neutrino Mass

$$m_\nu \sim m_D + m_M$$

Dirac Mass

Same mechanism as other SM fermions

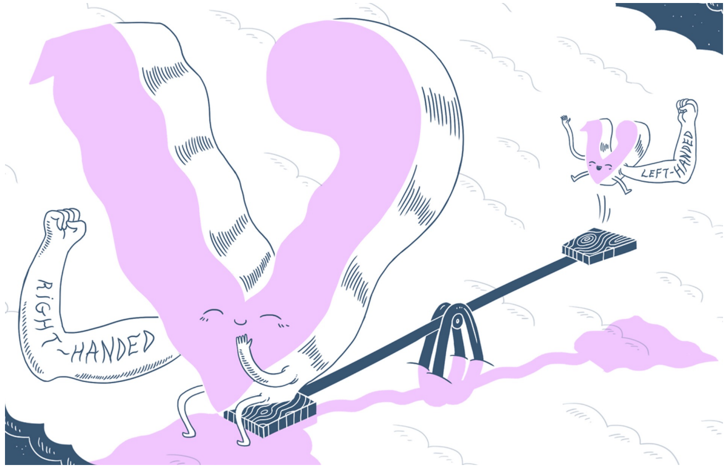
Requires very small coupling constants to make the neutrino light. Feel unnatural?

Majorana Mass

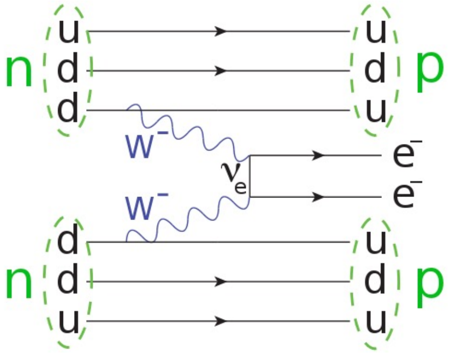
Mixing between light ν_L & heavy ν_R.

Neutrino is its own anti-particle.

Break the SM global symmetry. Lepton number violation



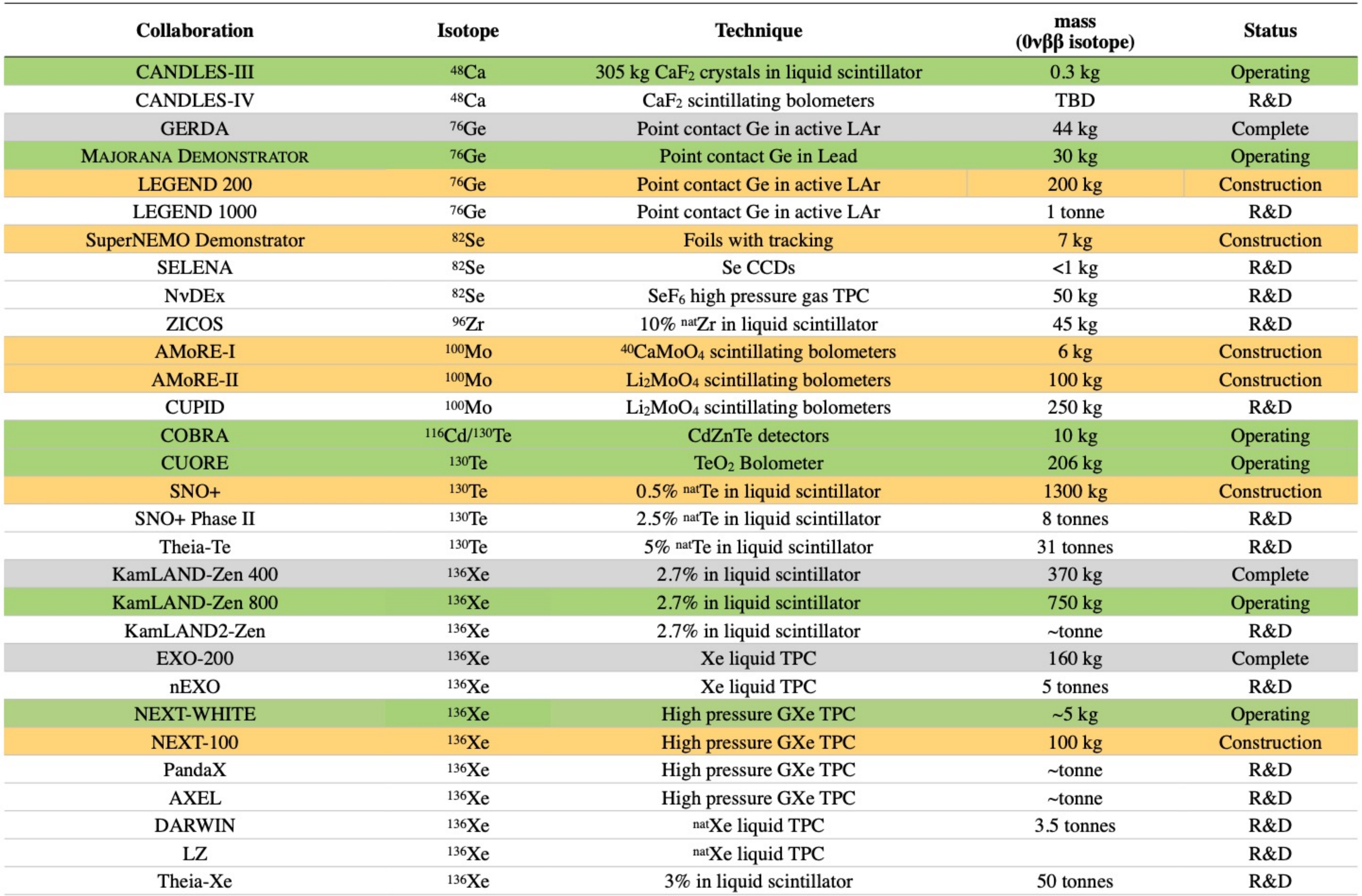
Seesaw Mechanism



Neutrinoless double beta decay ($0\nu\beta\beta$), if occur, directly proves lepton number violation and indicate neutrino's Majorana nature.

Decay width: $\Gamma^{0\nu}_{\beta\beta} \sim \langle m_{\beta\beta} \rangle^2$

$0\nu\beta\beta$ 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

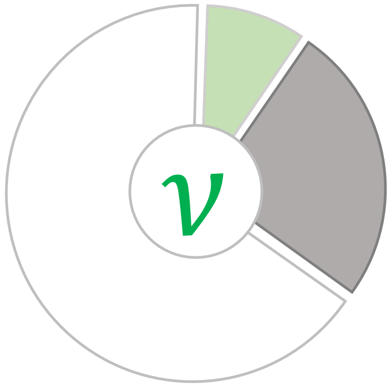
R&D Construction Operating Complete

Diverse, rich and mature field.

- Different isotopes
- Different detection technologies
- Different sizes
- Different stages.

Current limits:
Lifetime 10^{25} to 10^{26} year

Updated from J. Wilkerson



The Known Unknowns – Sterile neutrinos

FAQs:

Q: Are there more than 3 type of neutrinos?
A: It’s certainty possible, but with conditions. The new hidden neutrinos do not participate in the weak interactions, hence “sterile”.

Q: how can we look for sterile neutrinos if they don’t interact?
A: we expect sterile neutrino to mix with the active neutrinos just like mixing in the 3-ν paradigm. These additional mixings will manifest in neutrino oscillation.

Q: What’s their mass?
A: Without knowing the symmetry that dictate the scale, sterile ν’s weight can be anything.

$$U^{\text{Extended}}_{\text{PMNS}} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}}^{U^{3\text{x}3}_{\text{PMNS}}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \end{matrix} & \begin{matrix} \ddots & \vdots \end{matrix} \\ \begin{matrix} U_{s_n1} & U_{s_n2} & U_{s_n3} \end{matrix} & \begin{matrix} \cdots & U_{s_nn} \end{matrix} \end{pmatrix}$$

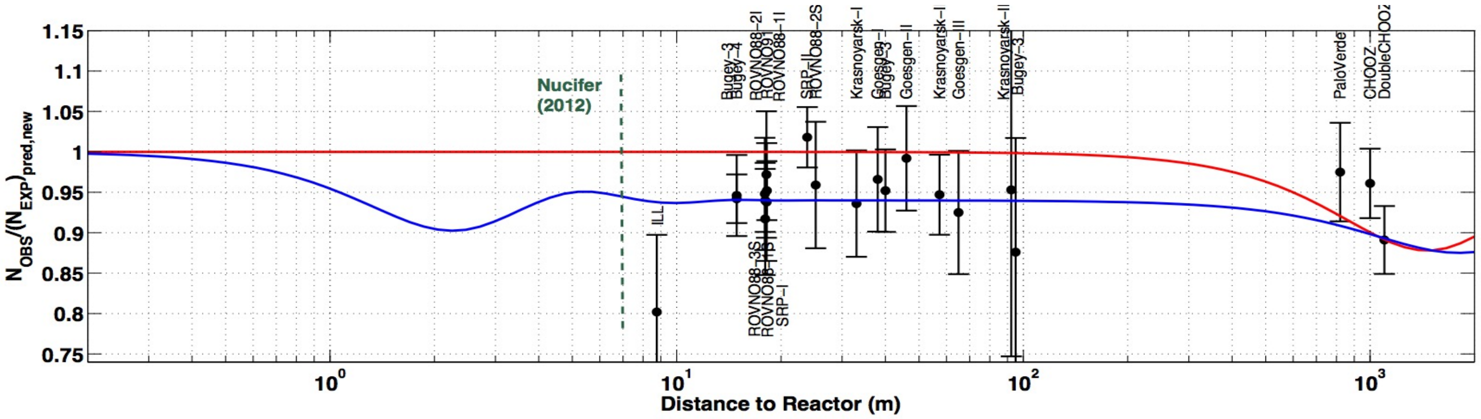
But we are not completely in the dark!

Experiments could guide the hunt, at least help pick the starting point.

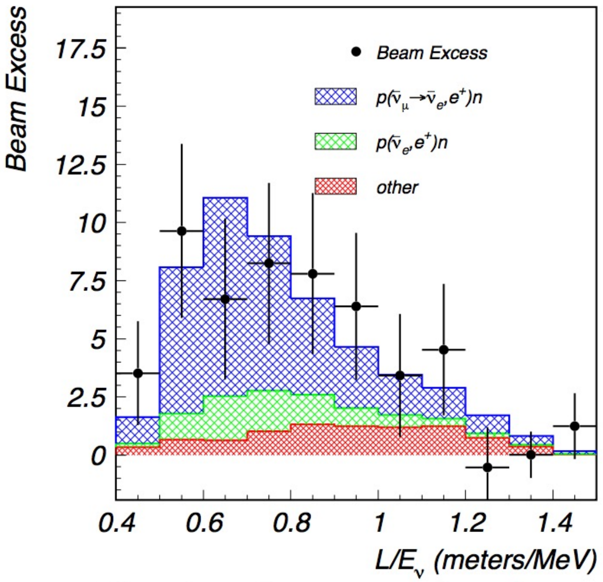
“Short baseline neutrino anomalies”

Short baseline neutrino anomalies

“Reactor Anomaly” $\overline{\nu_e}$ **deficit**



LSND $\overline{\nu_e}$ **Excess**



Phys.Rev. D64:112007 (2001)

Hint oscillation from additional

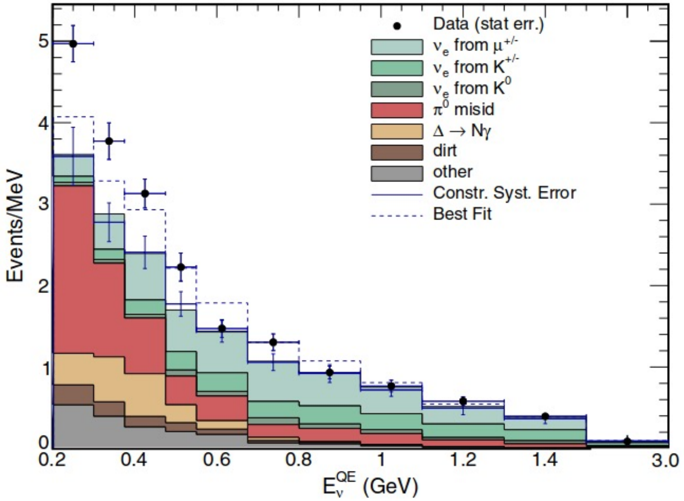
“Sterile” neutrino(s)

$m_4 \sim 1eV$

MiniBooNE

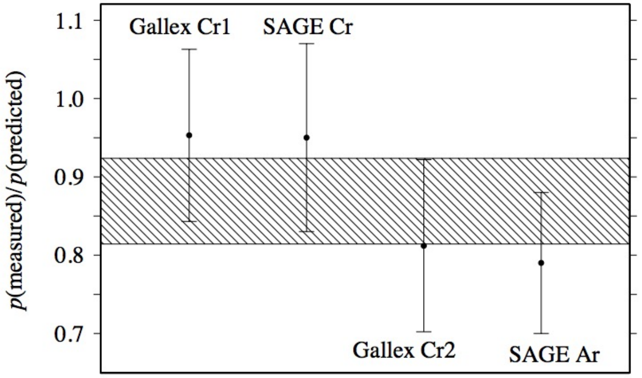
$\nu_e/\overline{\nu_e}$ **Excess**

at low energy



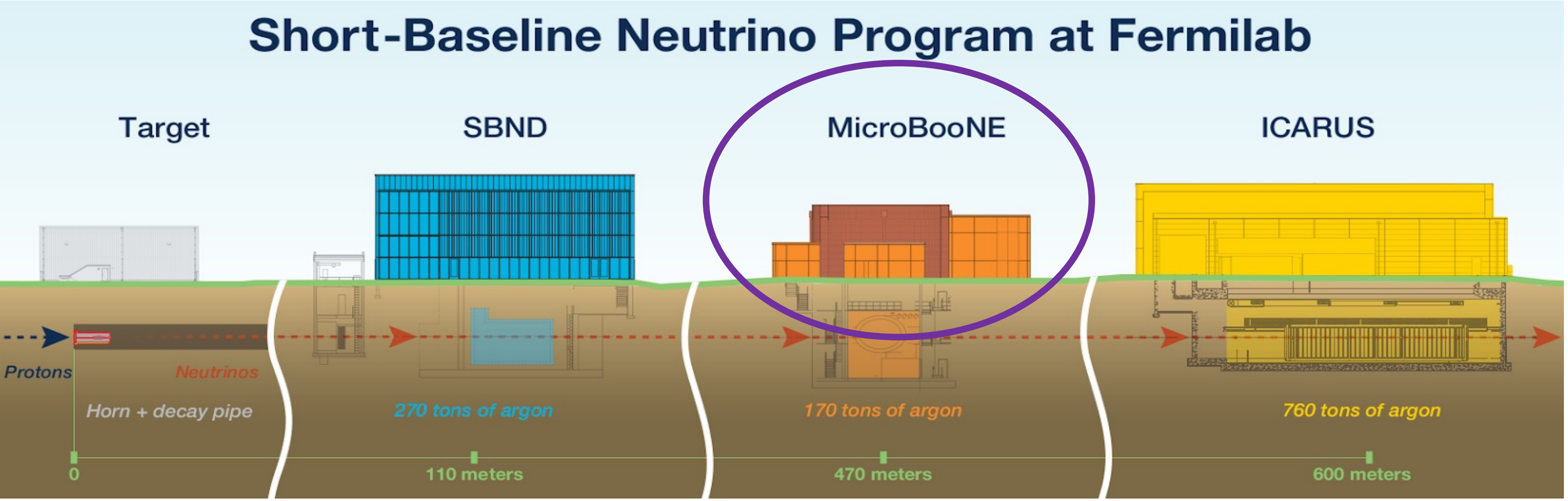
@ Fermilab
On-axis of Booster neutrino beamline

“Gallium Anomaly”
solar ν_e **deficit**



Phys.Rev. D64:112007 (2001)

Resolving short baseline neutrino anomalies



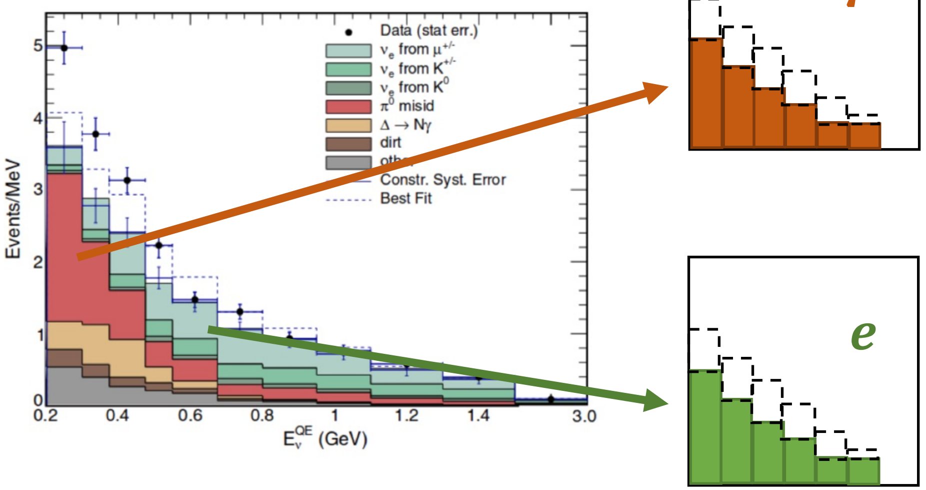
SBN: Three LArTPCs on Fermilab's Booster Neutrino beamline.

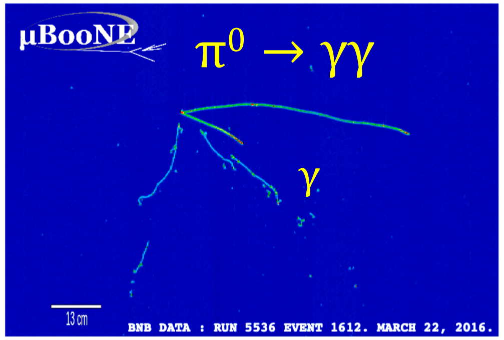
Goal: direct test of ~1eV sterile neutrino hinted from the previous short baseline neutrino anomalies.

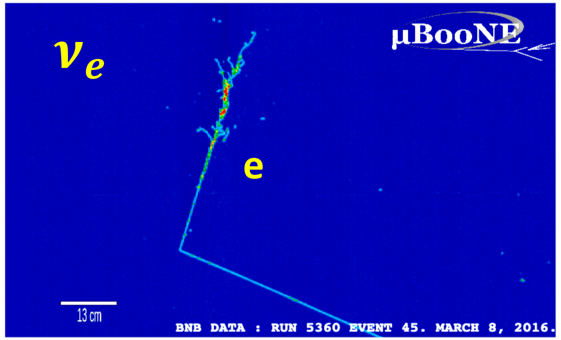
MicroBooNE is the first and the longest operating LArTPC experiment in the US, and has collected 1.5e21 POT neutrino data.

Primary goal is to address the MiniBooNE "Low-Energy-Excess" anomaly with LArTPC's capability of distinguishing electrons from photons.

MiniBooNE, PRL **121**, 221801 (2018)

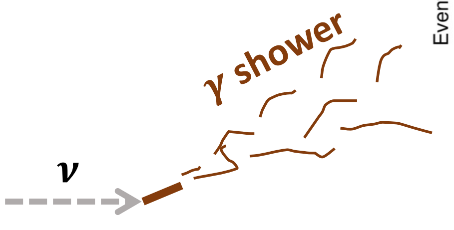


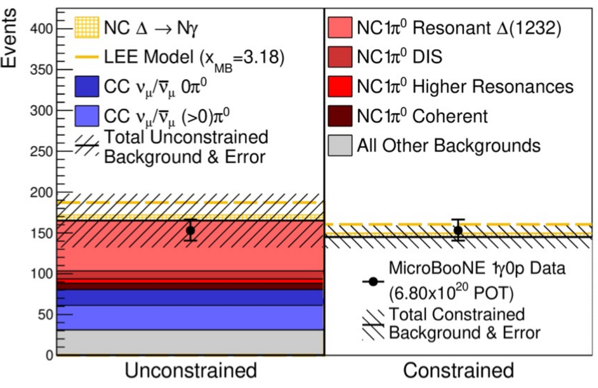


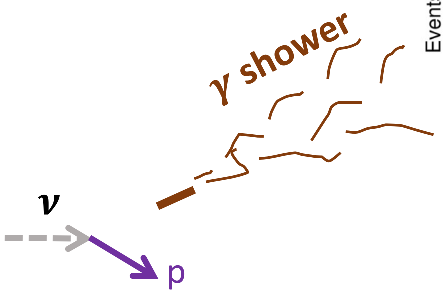


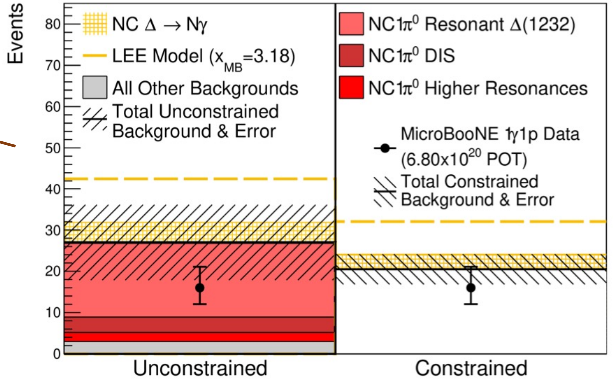
MicroBooNE “Low-Energy-Excess” first results

Photon search in Δ→Nγ channel



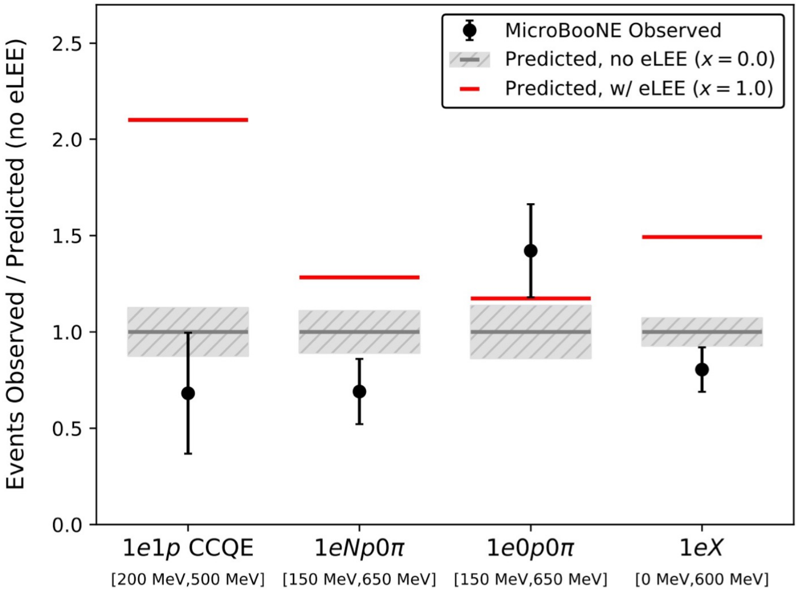


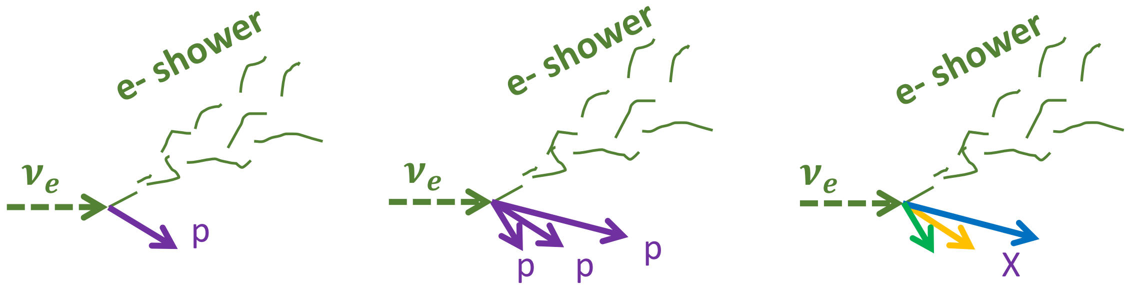




No data excess observed in the specific single photon channel NC Δ→Nγ (PRL 128, 111801)
The photon hypothesis for MiniBooNE excess is not ruled out in MicroBooNE

Electron searches

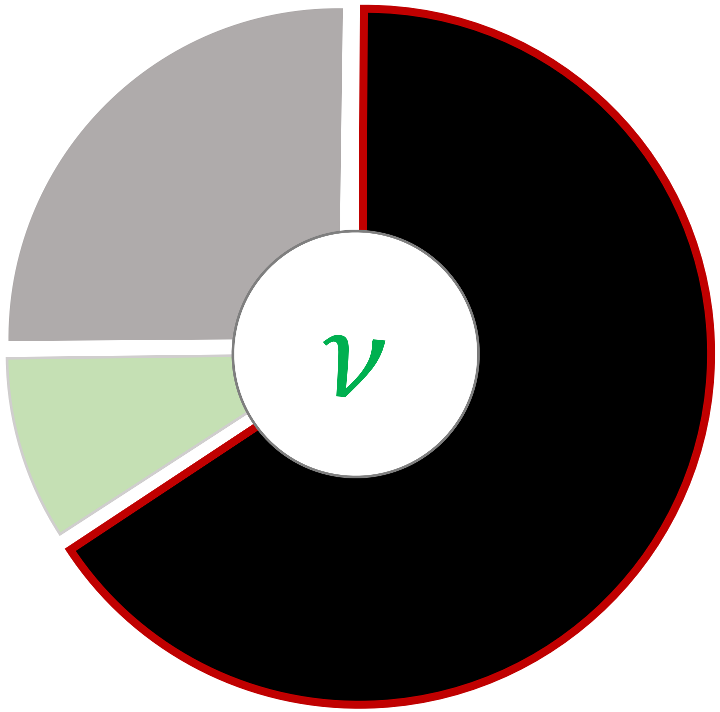




Observe ν_e rate in agreement or below prediction
Reject the ν_e are fully responsible for the MiniBooNE excess at >97% C.L. in all analyses (2110.14054)

First results raise the stakes for BSM searches in MicroBooNE

5σ result to confirm or exclude eV sterile neutrino needs oscillation analysis from SBN



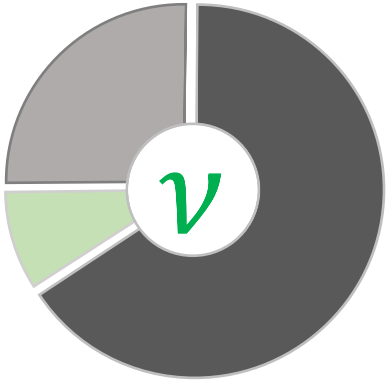
Unknown Unknowns

Broad range of questions:

New particles?

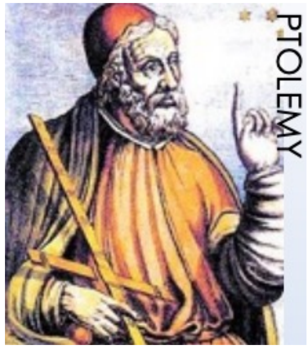
New symmetries?

Connection to dark sector?



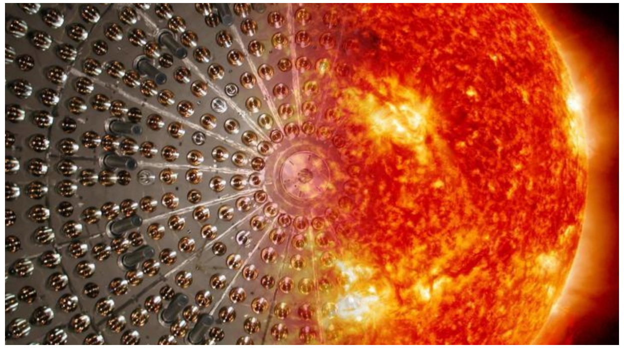
The Unknown Unknowns

PROLEMY



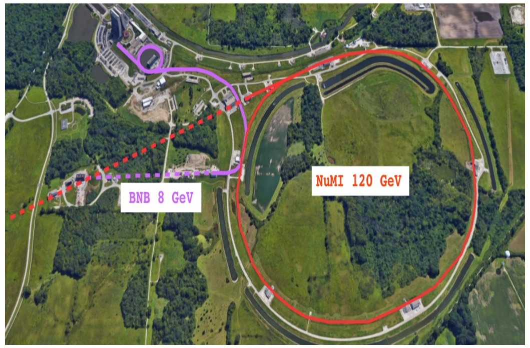
Relic neutrino
Neutrino mass
Majorana or Dirac?
Dark matter

Solar ν



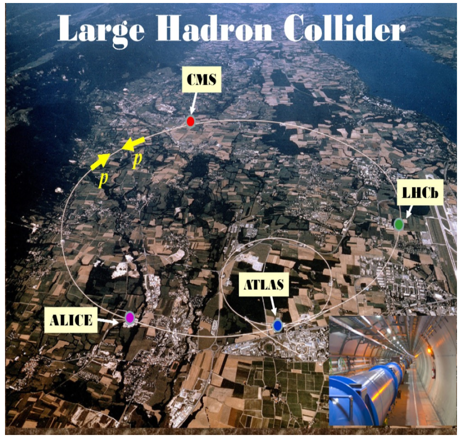
Solar model
Sterile neutrinos
Neutrino oscillation

Accelerator ν



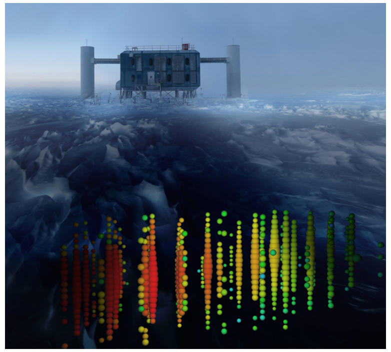
Heavy Neutral Leptons
Long lived Particle
ν portal to dark sector
Axion Like Particle
Millicharged particles
Lorentz invariance
CPT symmetry
eV sterile neutrino

Collider



Heavy Neutral Leptons
Long lived Particle
Dark Matter
Millicharged particles
SUSY

ICEBUBE

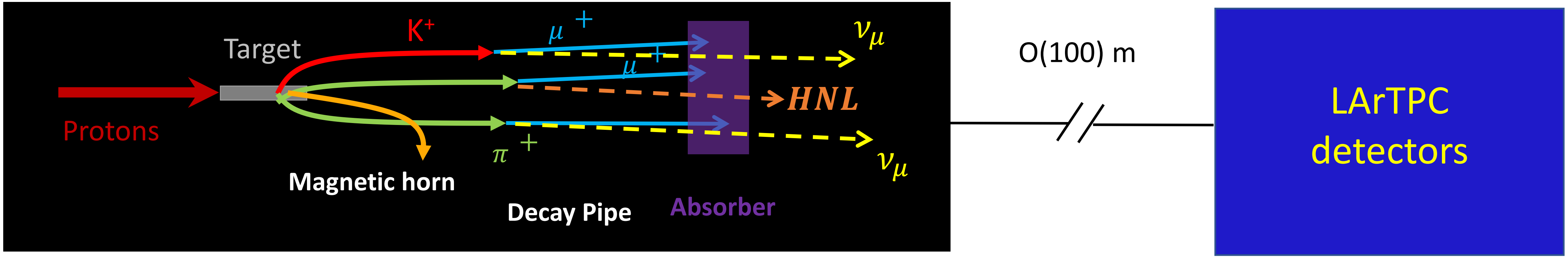


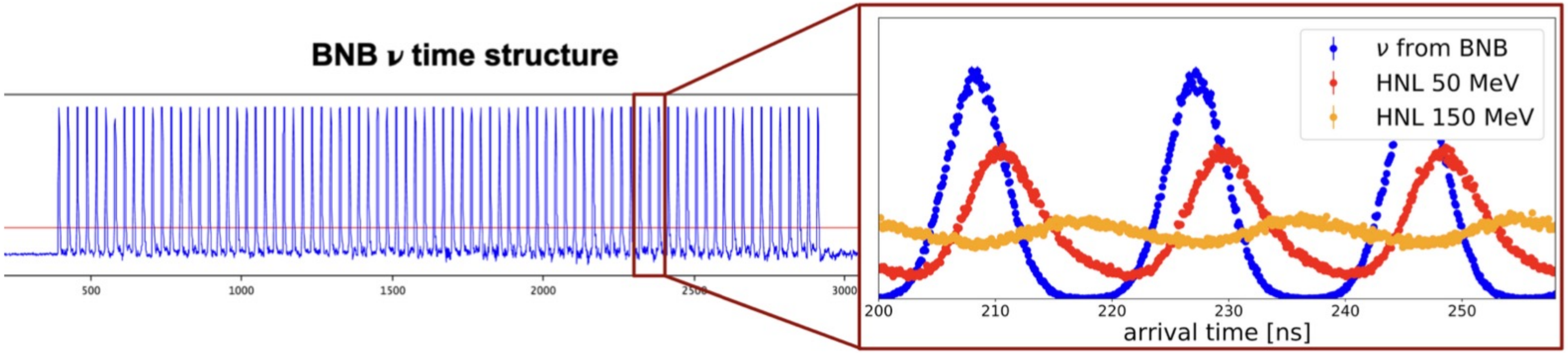
Sterile neutrinos
Mass ordering
Dark Matter
Astrophysics, e.g. Supernovae
Neutrino NSI
CPT symmetry

...meV eV keV MeV GeV TeV PeV ...

Energy Scale of experiments are probing

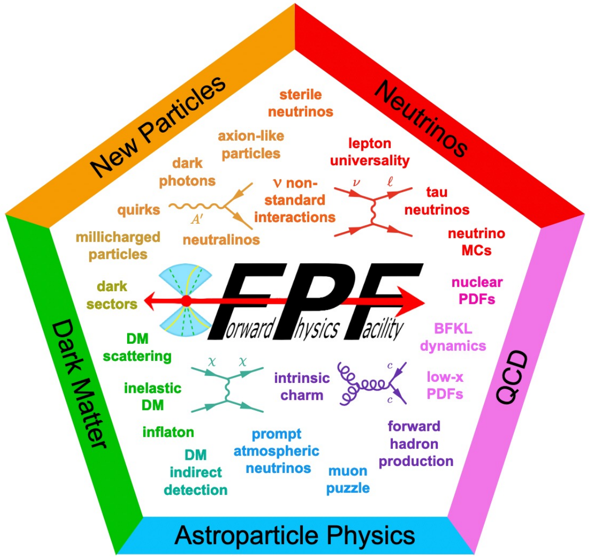
New physics searches with accelerator $\nu's$ @ MeV-GeV





The massive long-lived particles produced at the same time as neutrinos will arrive at the detector later. If we can measure the time-of-flight with ~1 ns resolution, we can use timing to distinguish new particles from neutrino background. We can already demonstrate <2 ns timing resolution in MicroBooNE!

New physics searches with collider $\nu's$ @ GeV-TeV



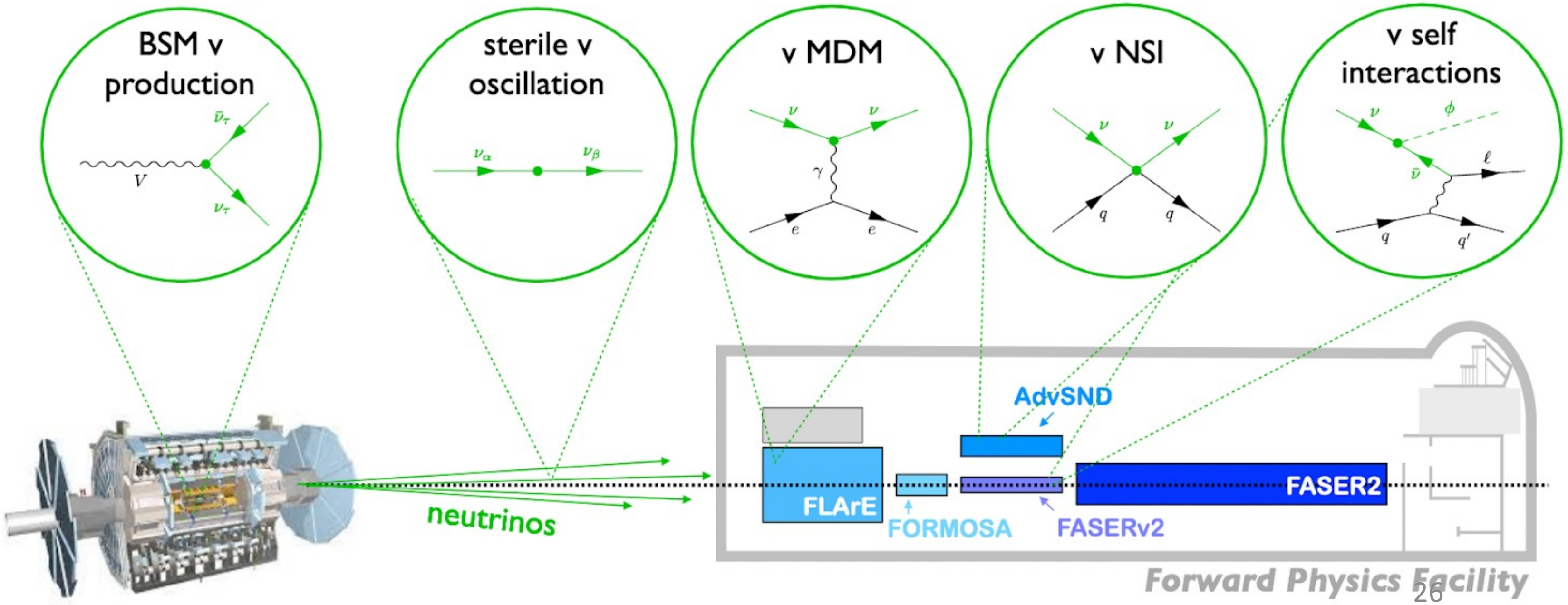
Forward Physics Facility @ LHC

Snowmass White Paper: [arXiv:2203.05090](https://arxiv.org/abs/2203.05090).

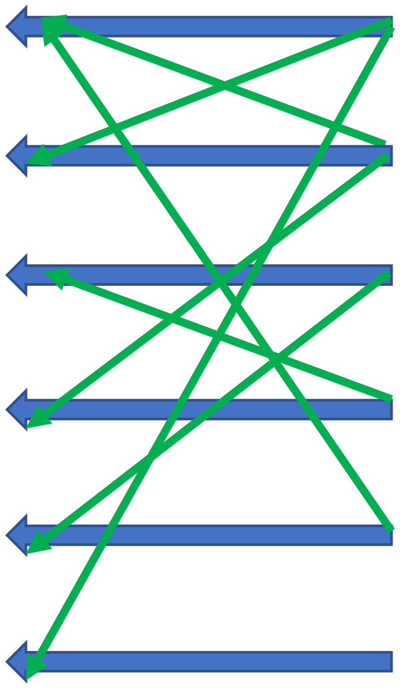
High energy neutrinos [100s GeV - TeV] from p-p collisions in ATLAS detector.

Rich physics complementary to Fermilab accelerator program:
- Neutrino interactions, tau neutrinos
- BSM searches with neutrinos

Neutrino detectors:
- FASERν [emulsion detector]
- FLArE [LArTPC]



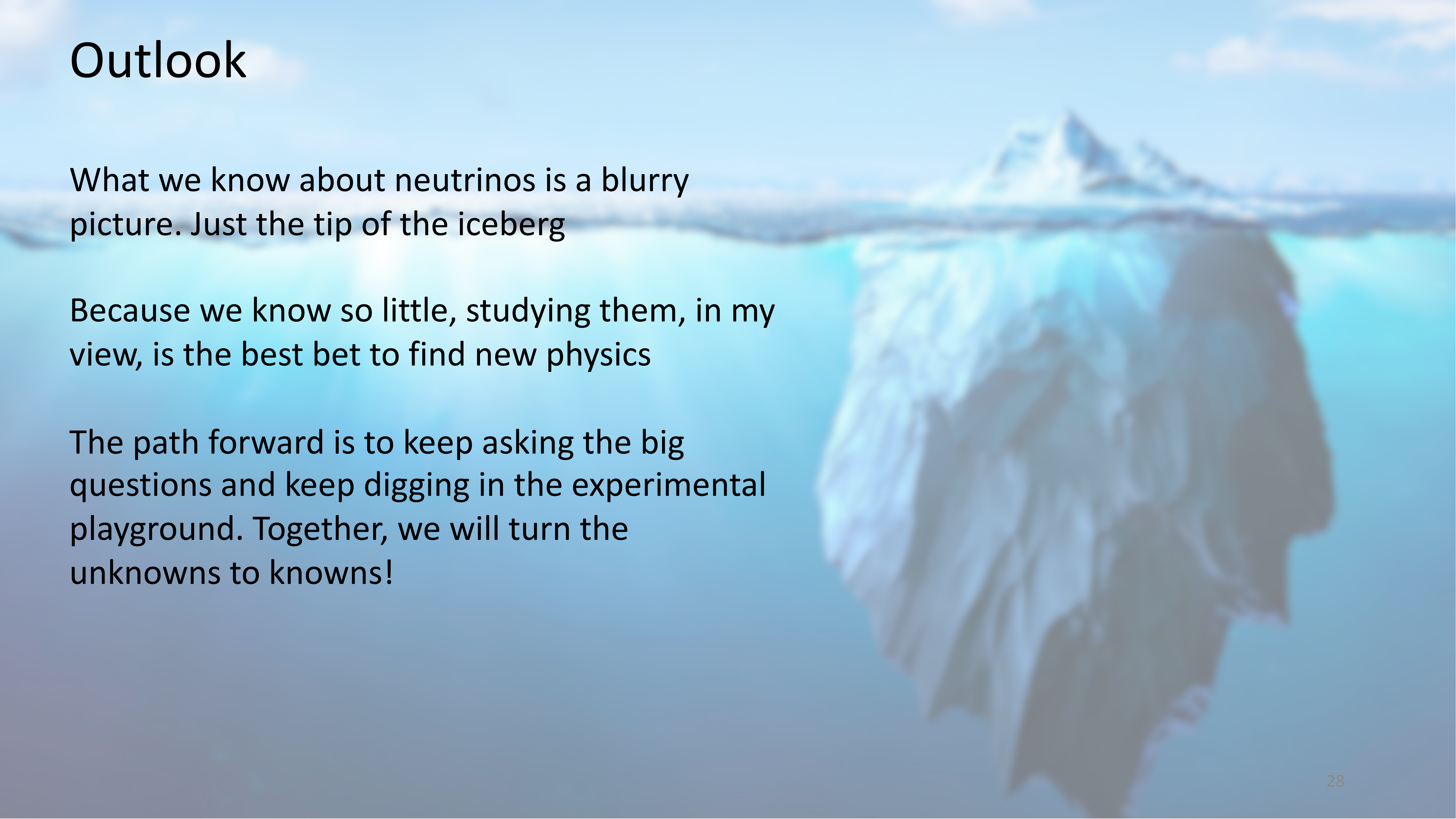
ν Experiments



CP violation?	Long baseline neutrino oscillation (e.g. DUNE)
Normal or inverted Mass Ordering?	Long baseline neutrino oscillation (e.g. DUNE)
Absolute Neutrino Mass?	Tritium beta decay experiments (e.g. KATRIN)
Neutrino mass origin? Dirac or Majorana	$0\nu\beta\beta$ experiments
More than 3 flavor? Sterile neutrinos	Short baseline neutrino oscillation (e.g. SBN)
New particles, new symmetries, dark sector?	Parameter space sweep from all experiments

Neutrino experiments are connected to each other through big questions!
Diverse experimental program is the key to open the door to the unknown world

Outlook



What we know about neutrinos is a blurry picture. Just the tip of the iceberg

Because we know so little, studying them, in my view, is the best bet to find new physics

The path forward is to keep asking the big questions and keep digging in the experimental playground. Together, we will turn the unknowns to knowns!