Experimental Results on Neutrinos

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UK HEP Forum

"Cosmology, Gravitation and Particle Physics"

28 November 2017

MANCHESTER 1824

Neutrinos as messengers of physics at large scales

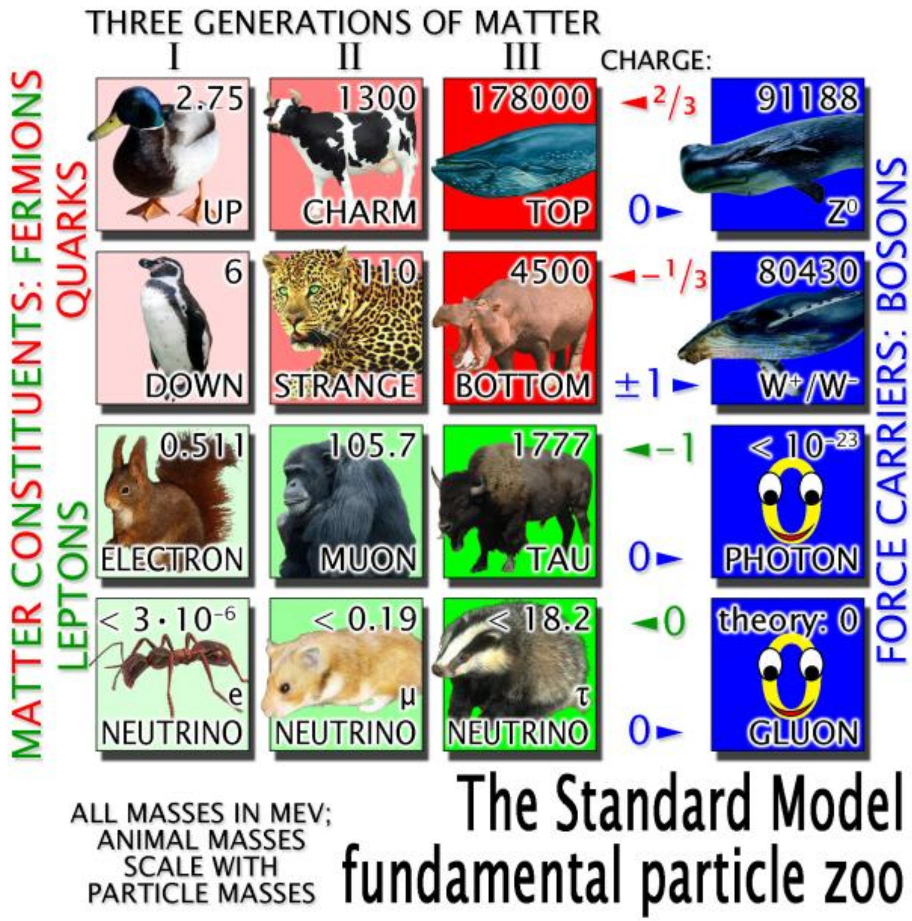
Neutrino masses anomalously small:

- not due to Higgs mechanism?
- first sign of physics beyond the SM?
- might be linked to physics at high scales through *see-saw* mechanism:

$$\mathcal{L} \sim -\frac{1}{2}\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

Minimal extension to Standard Model:
- right-handed neutrinos (ν_R)
- Majorana mass term M

$$m_\nu \approx \frac{m_D^2}{M} \qquad m_D \sim 1\ \mathrm{GeV} \qquad M \sim 10^{12} - 10^{16}\ \mathrm{GeV}$$



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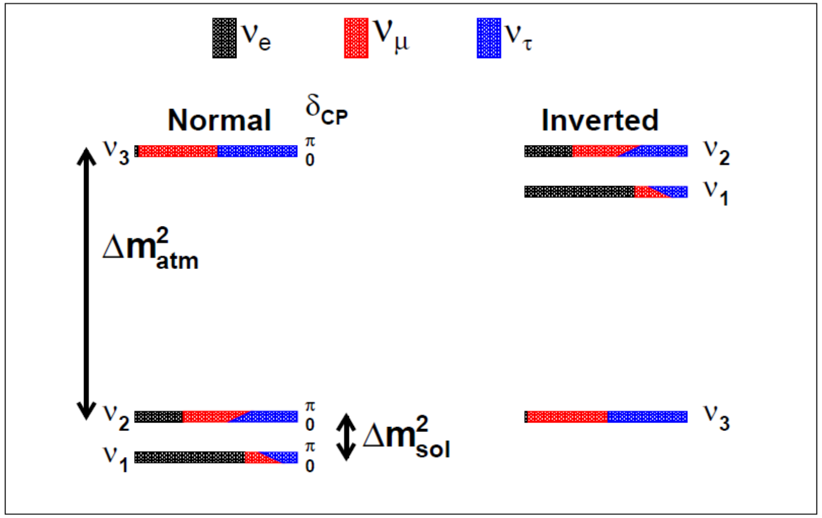
$$M \sim 10^{12} - 10^{16} \text{ GeV}$$

We don't know

- the absolute neutrino mass scale
- the ordering of the neutrino mass eigenstates (hierarchy).

Neutrino Mass Hierarchy



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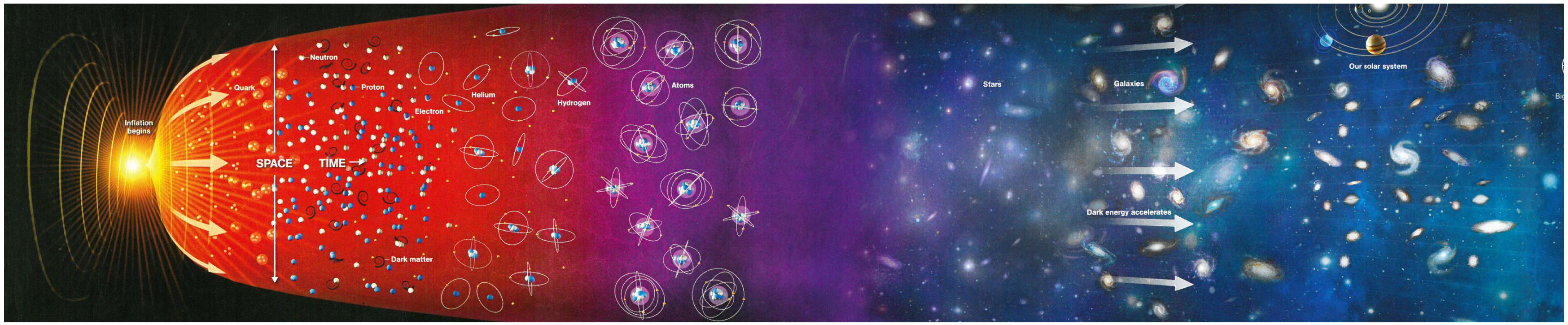
Testing the "three-flavour" paradigm

complex phase leads to CPV

$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP Violation in the lepton sector might provide support for *Leptogenesis* as mechanism to generate the Universe's matter-antimatter asymmetry.

CP Violation: $\delta \neq \{0, \pi\}$ $s_{ij} = \sin\theta_{ij}\ ;\ c_{ij} = \cos\theta_{ij}$



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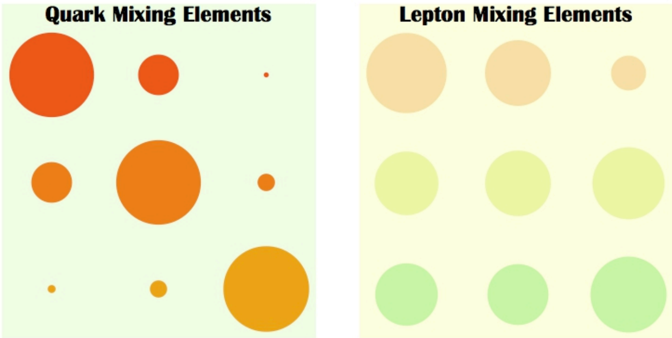
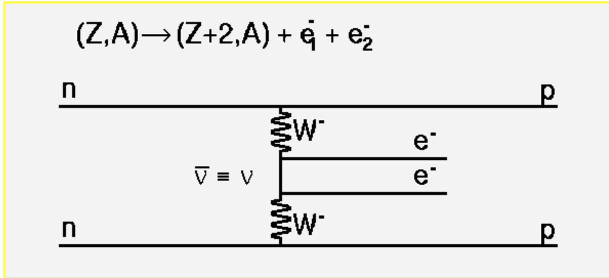
Caveat:
No direct evidence for *Leptogenesis*, since a model is needed to connect the low-scale CPV observed here to high-scale CPV for heavy neutrinos that lead to *Leptogenesis*.

Other questions

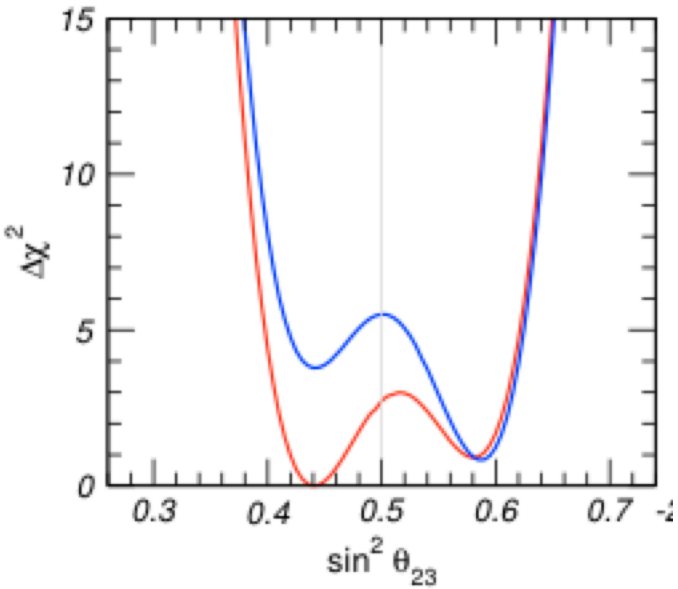
Why are CKM and PMNS matrices different?



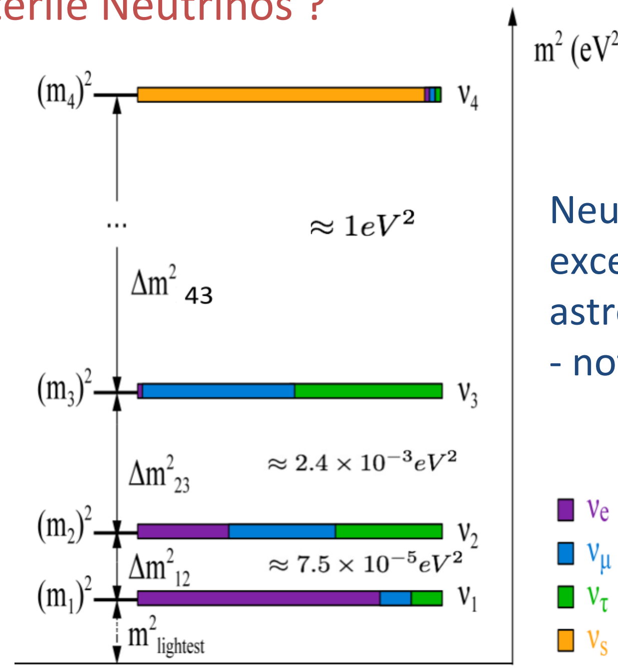
Are neutrinos Majorana?



Which θ_{23} octant? Maximal mixing?



Sterile Neutrinos ?



Neutrinos are also excellent astrophysical probes - not discussed here.

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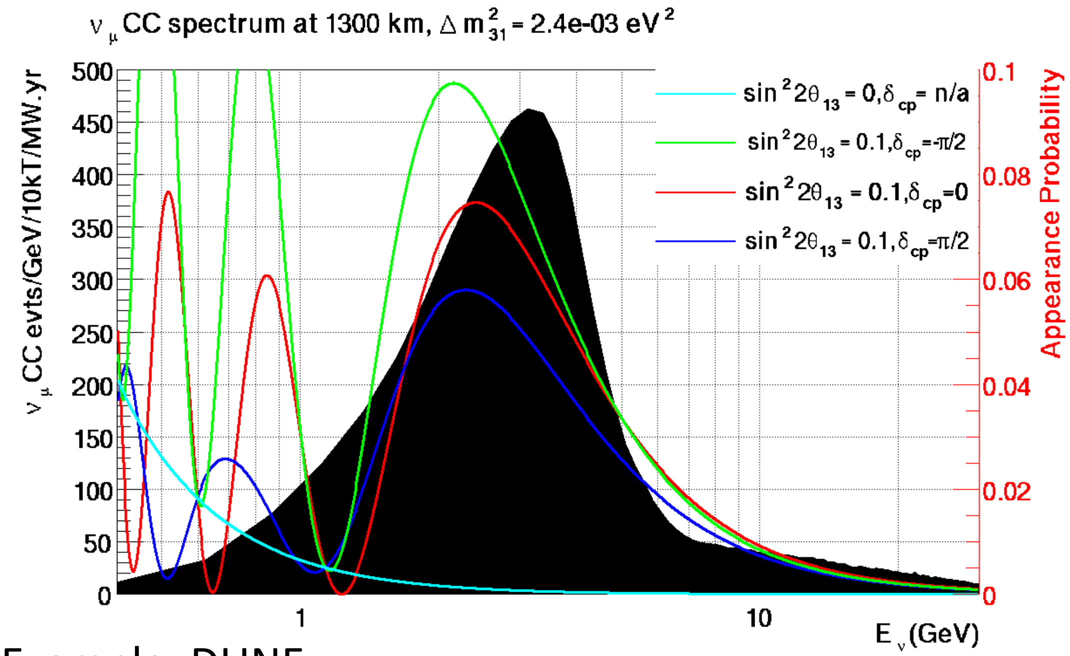
ν_e appearance gives access to δ

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \boxed{\sin^2\theta_{23}}\,\boxed{\sin^2 2\theta_{13}}\,\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - \boxed{aL})^2}\Delta_{31}^2 \\
& + \boxed{\sin 2\theta_{23}}\,\boxed{\sin 2\theta_{13}}\,\sin 2\theta_{12}\,\frac{\sin(\Delta_{31} - \boxed{aL})}{(\Delta_{31} - aL)}\Delta_{31}\,\frac{\sin(\boxed{aL})}{(\boxed{aL})}\Delta_{21}\cos(\Delta_{31} + \delta_{CP}) \\
& + \boxed{\cos^2\theta_{23}}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\boxed{aL})}{(\boxed{aL})^2}\Delta_{21}^2,
\end{aligned}
$$

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



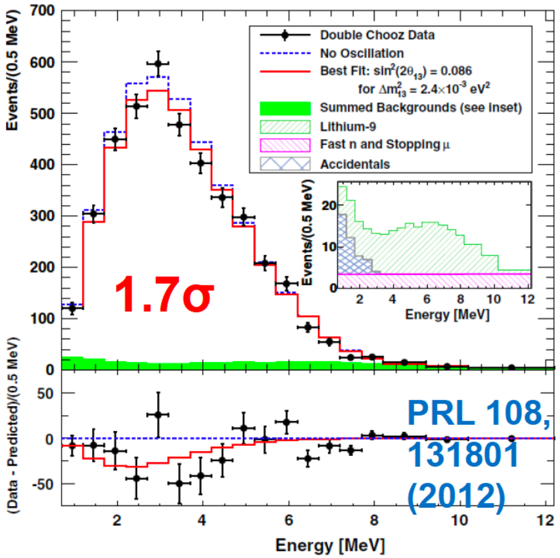
Example: DUNE

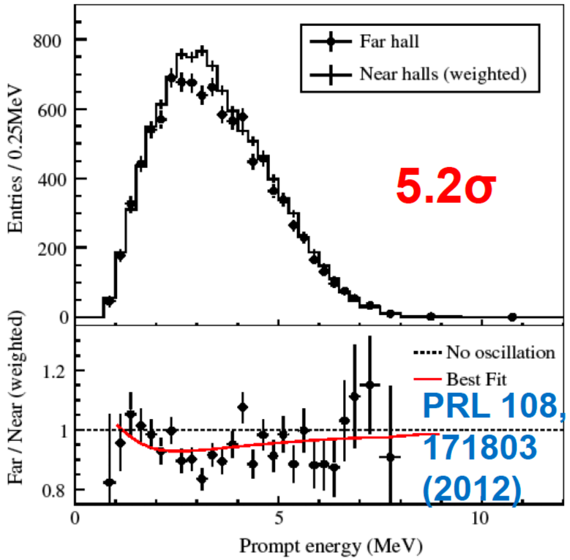
- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects (MSW).
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample.

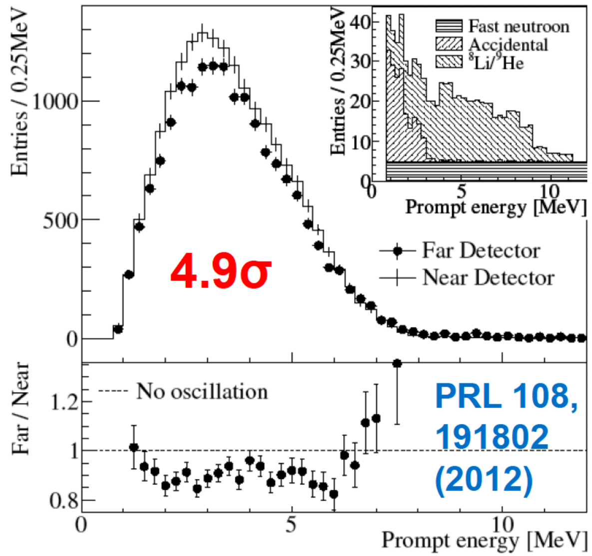
The θ_{13} miracle

M. He, NNN17

Double Chooz with only a far detector (Nov. 2011)	Daya Bay (March 2012)	RENO (April 2012)







Rate+shape

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\mathrm{stat}) \pm 0.030(\mathrm{syst})$$

Rate only

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat.}) \pm 0.005(\mathrm{syst.})$$

Rate only

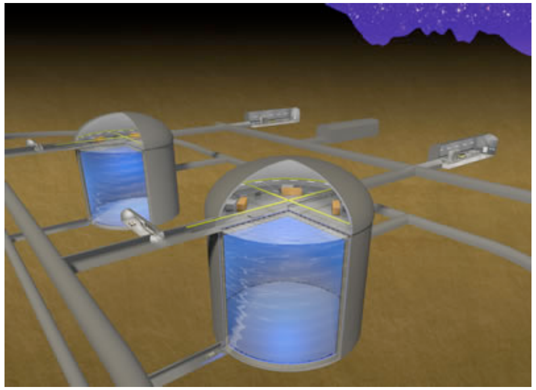
$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\mathrm{stat.}) \pm 0.011(\mathrm{syst.})$$

Optimising L/E

L ≈ 200 km

$$\frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\mathrm{GeV}$$

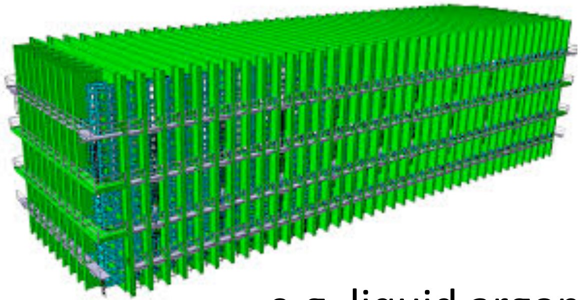
- no matter effects; first oscillation maximum.
- use narrow width beam (off axis).



Water Cherenkov

L > 1000 km

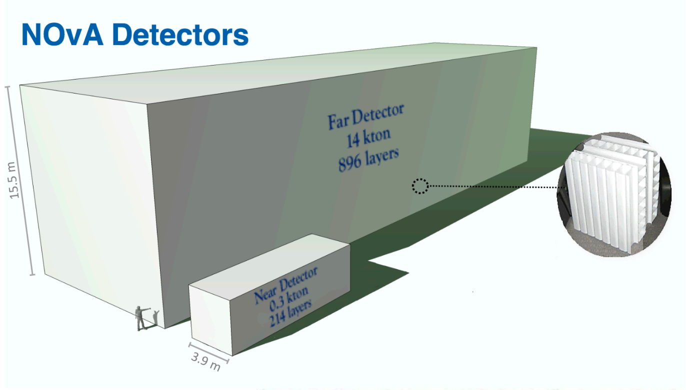
$$\frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \qquad E_\nu > 2\,\mathrm{GeV}$$

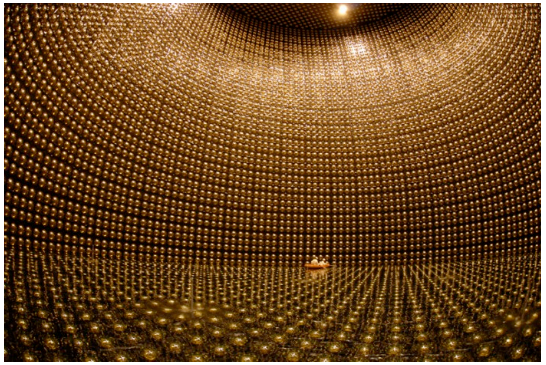


e.g. liquid argon

- matter effects; first and second oscillation maximum.
- use broad-band beam (on axis).
- unfold CP and MH effects through energy dependence.

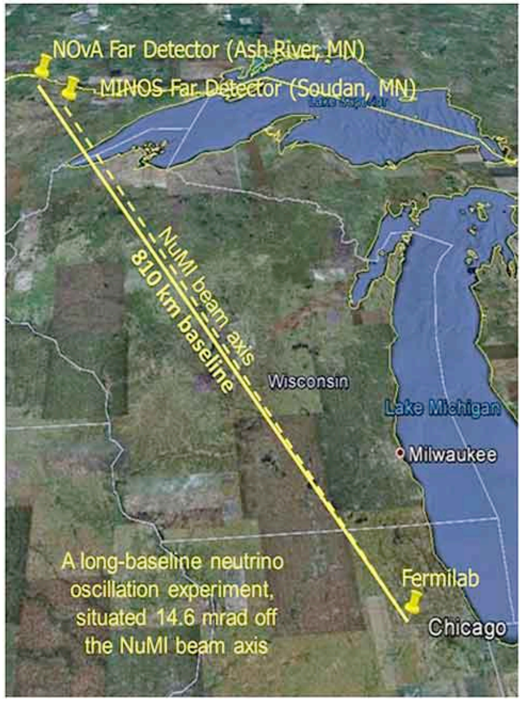
Operating Long-baseline Experiments

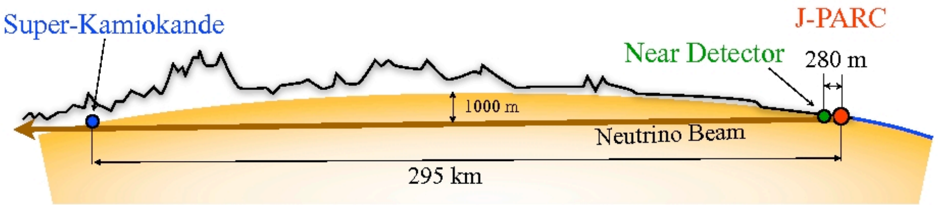


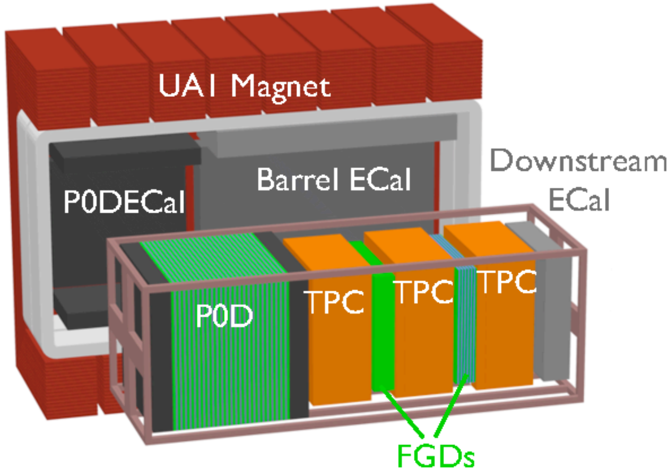


T2K
295 km

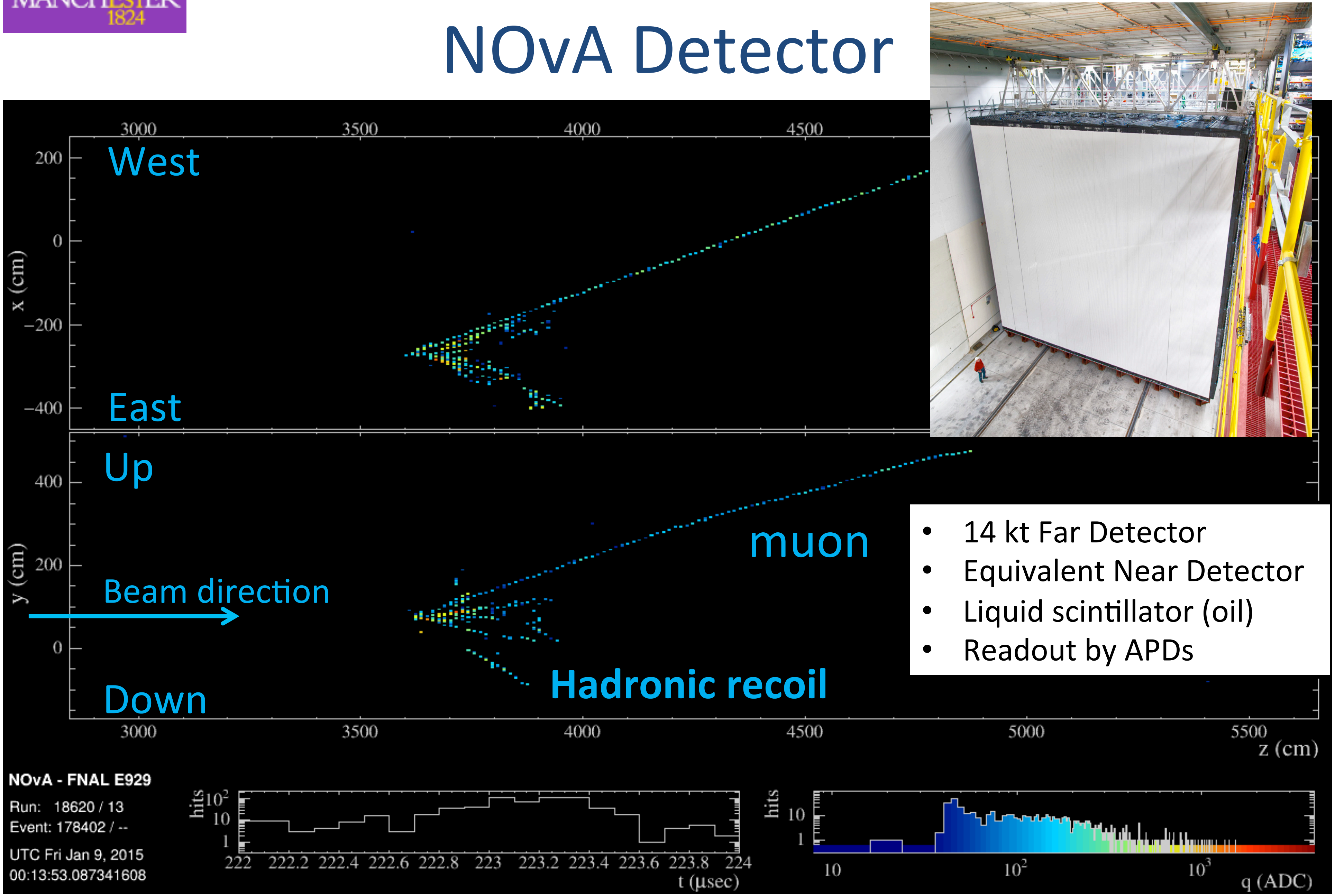
NOvA
810 km







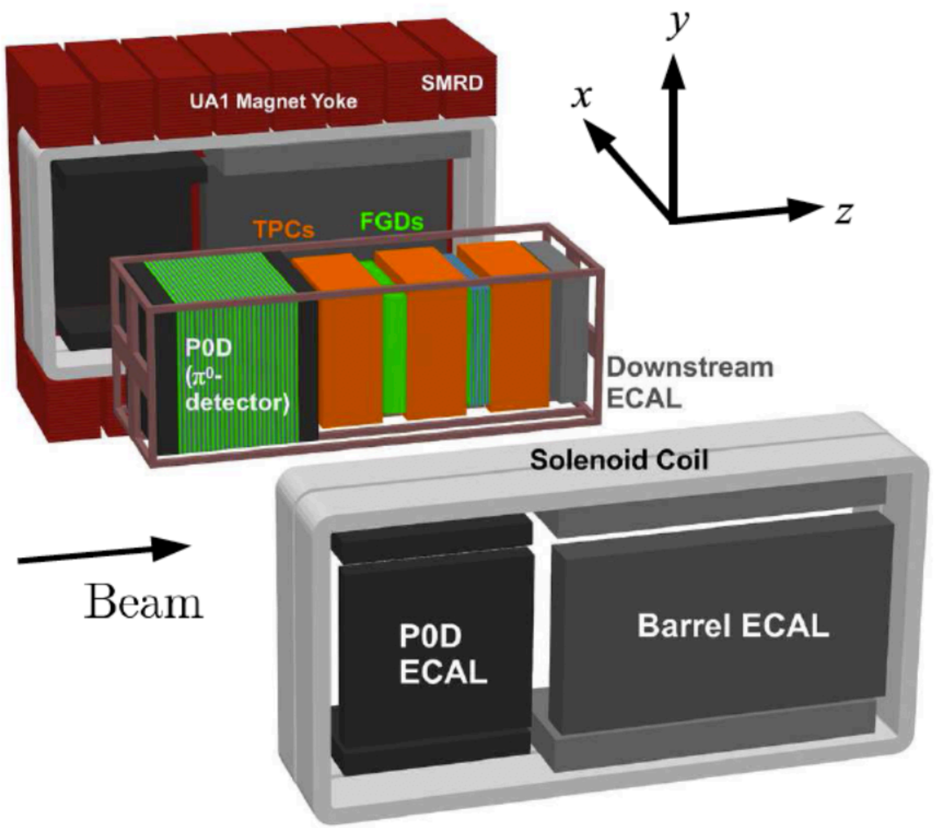
NOvA Detector

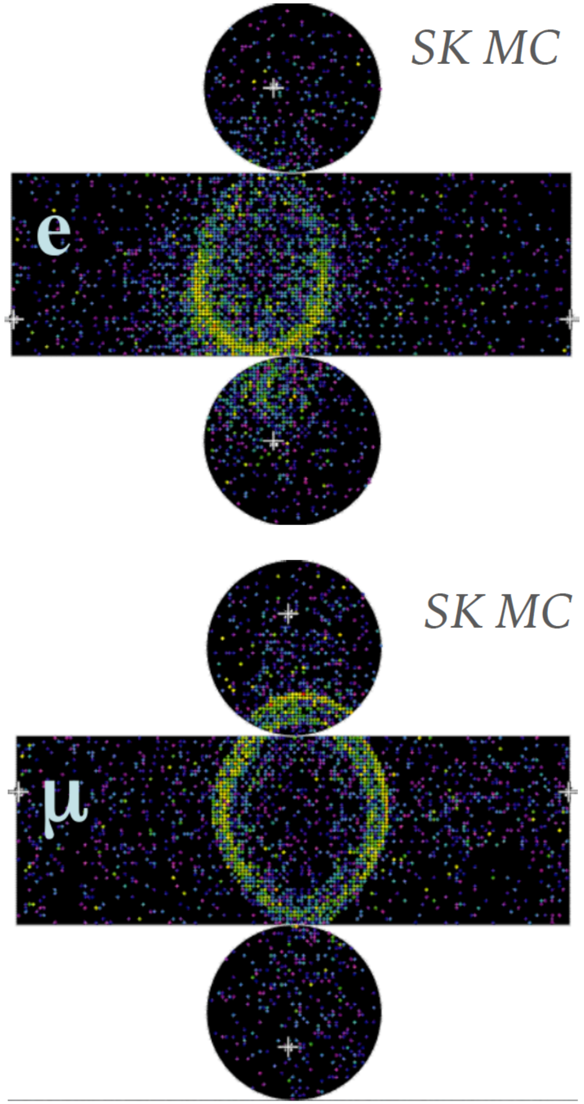


- 14 kt Far Detector
- Equivalent Near Detector
- Liquid scintillator (oil)
- Readout by APDs

T2K Detector

Water Cherenkov





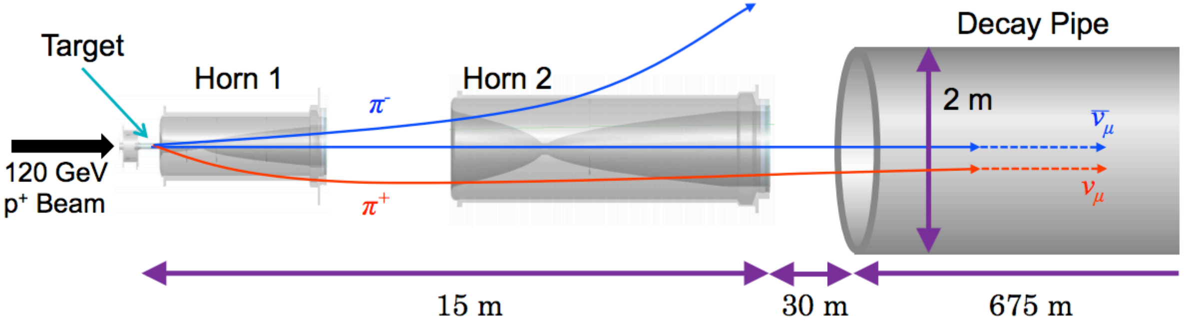
"fuzzy"

"sharp"

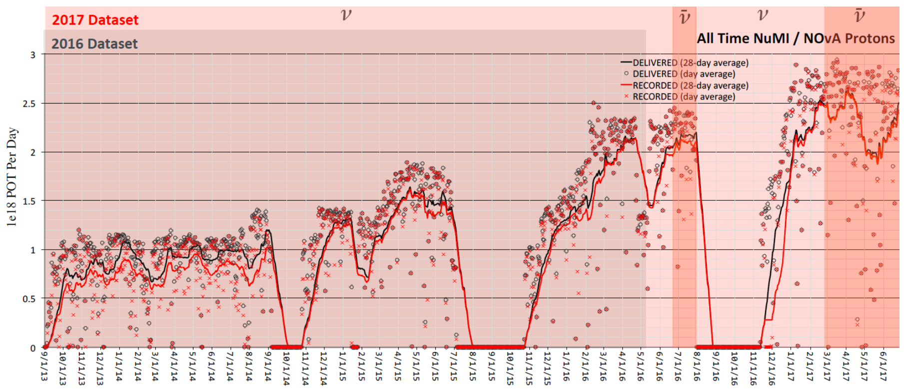
Different technologies for Near and Far Detector

Neutrino beams

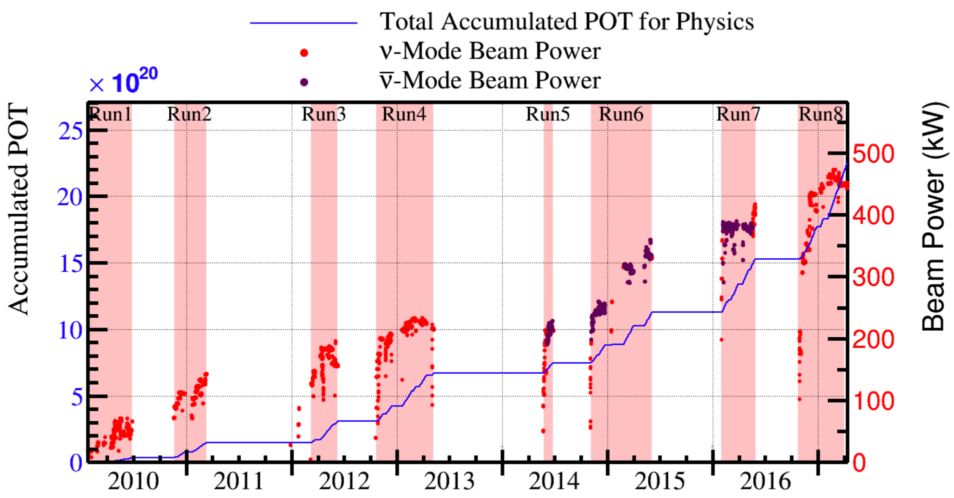
off-axis



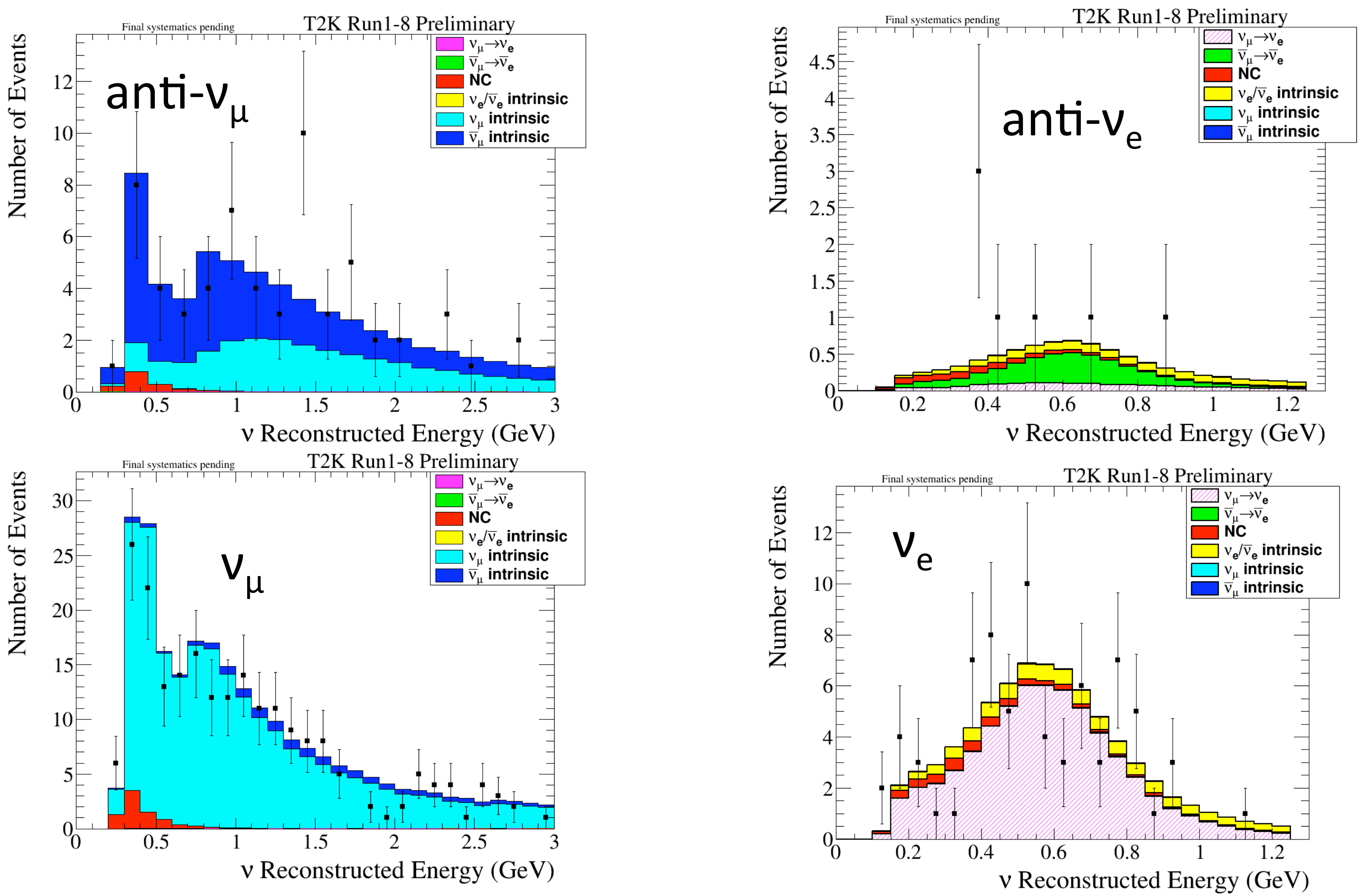
NOvA: 17% of approved POTs



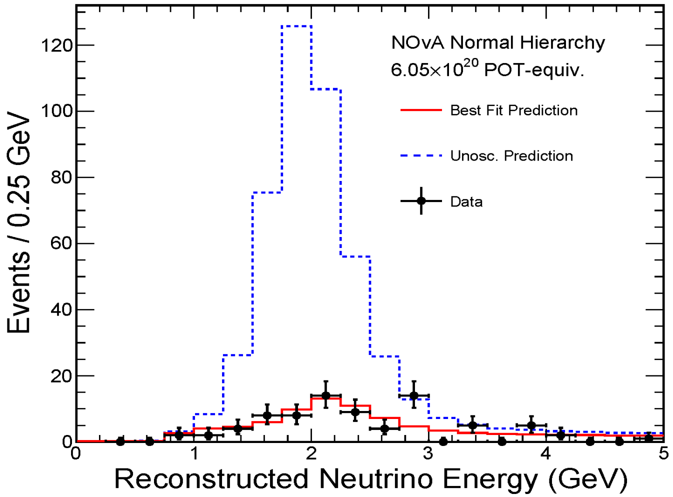
T2K: 30% or approved POTs

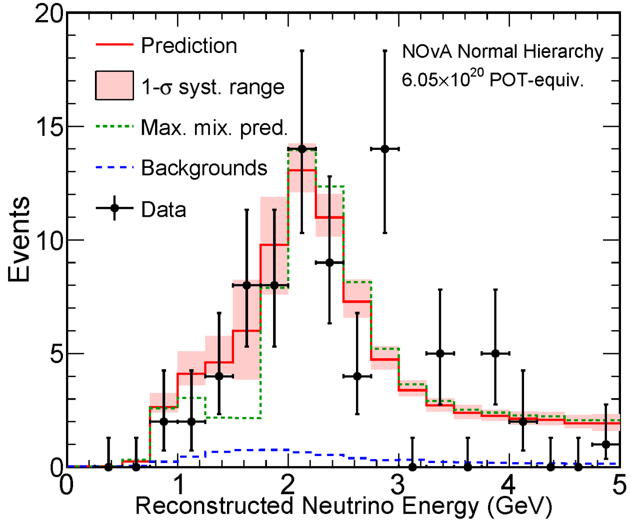


T2K Far Detector Rates

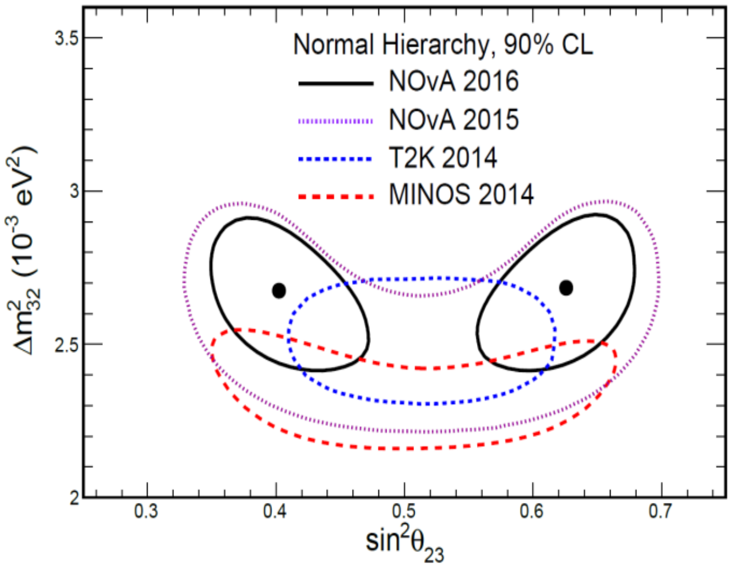


NOvA – ν_μ Disappearance





78 events observed



Exclude maximal mixing at 2.6 σ

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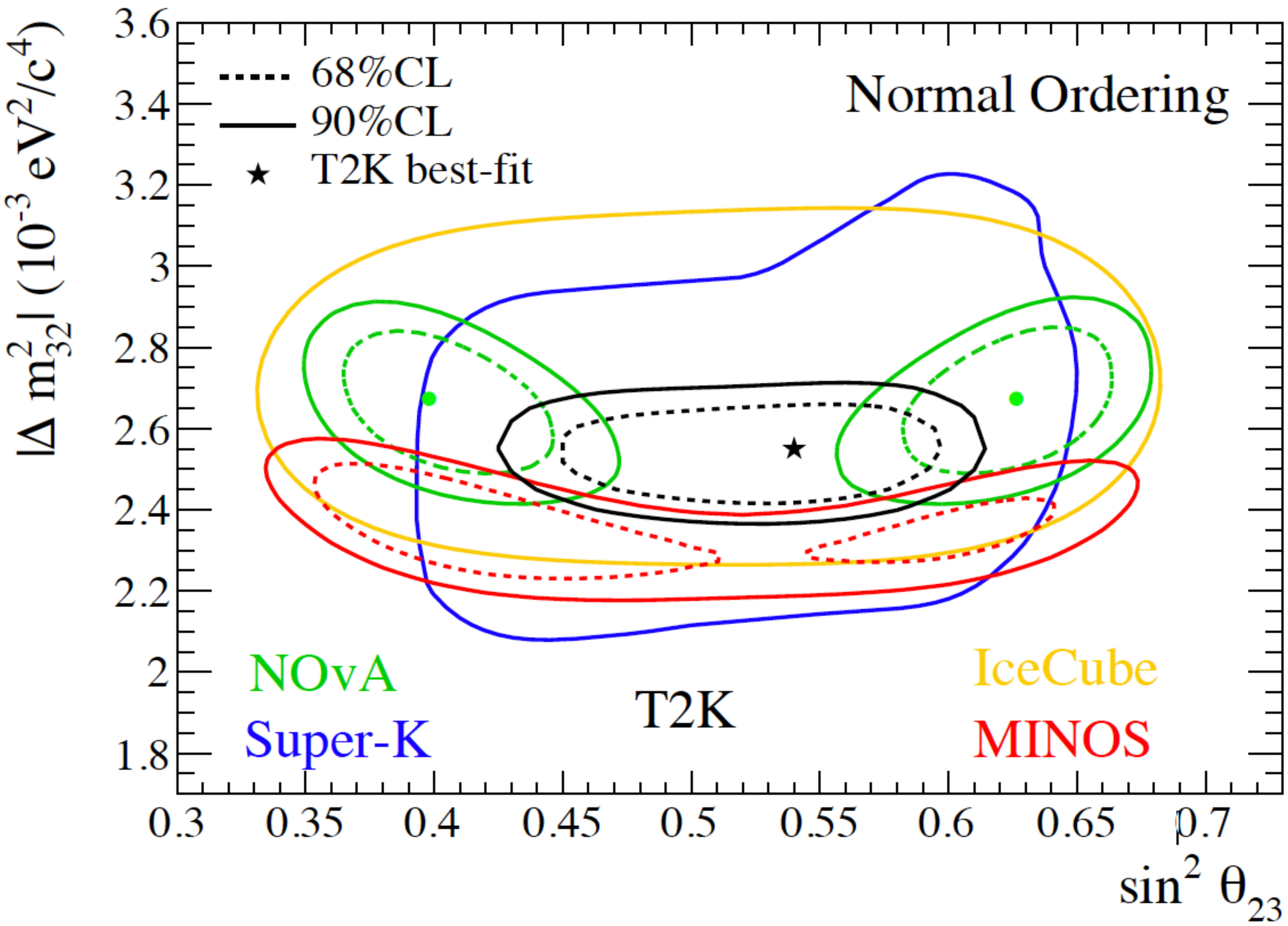
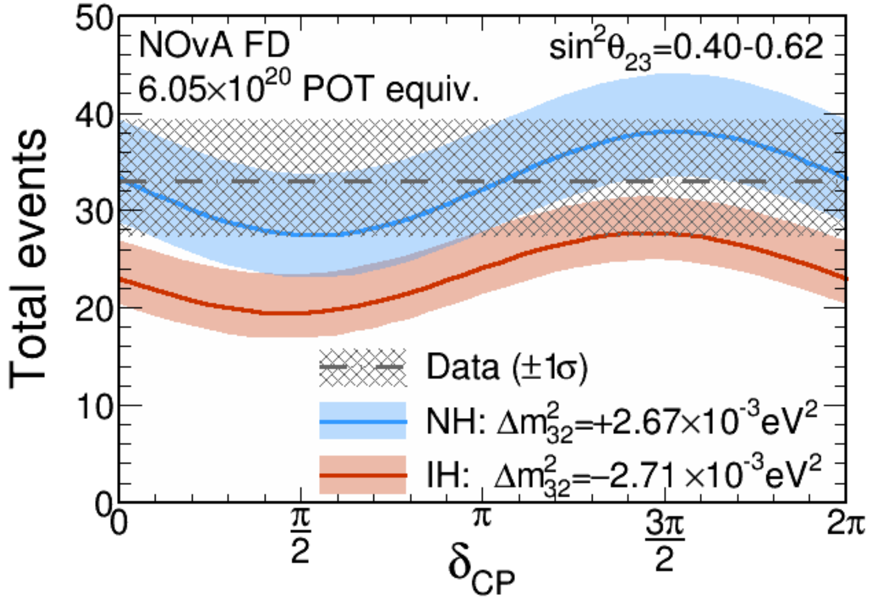
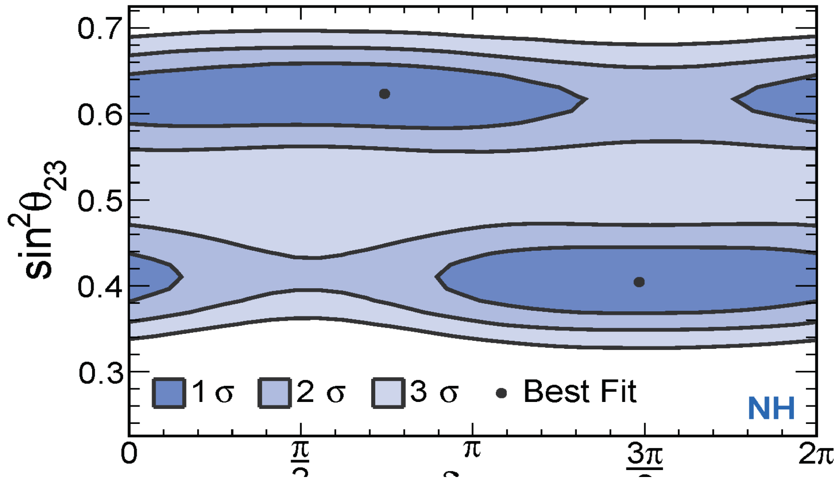
NOvA vs T2K

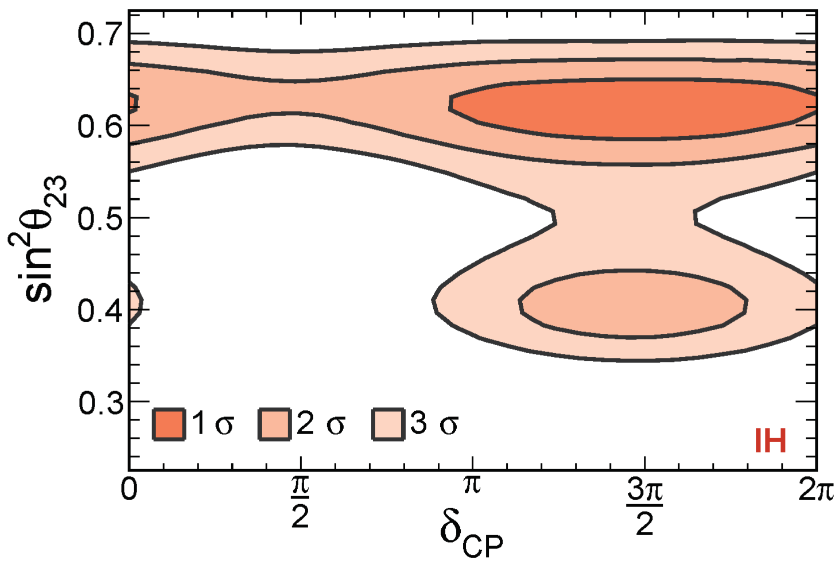
NOvA excludes maximal mixing at 2.6 σ



NOvA – ν_e Appearance

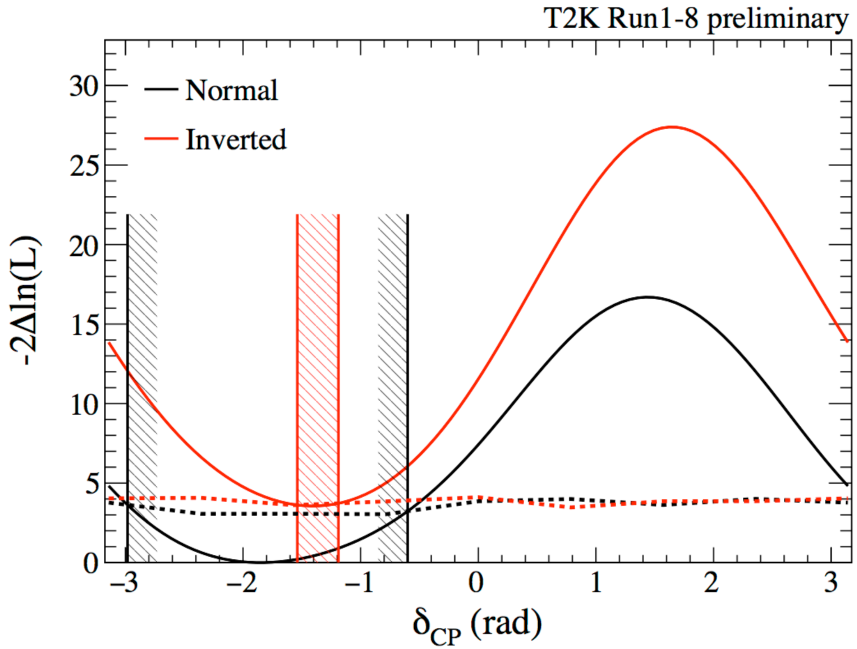






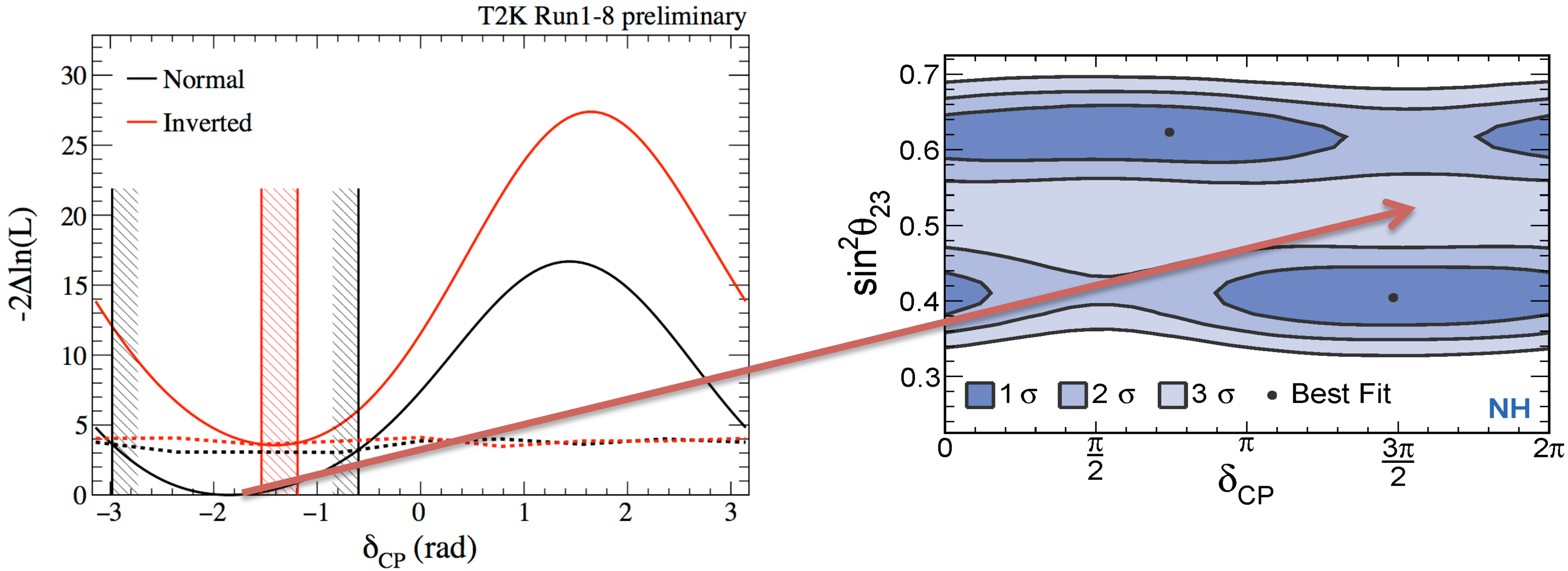
- Normal Hierarchy favoured
- Need anti-neutrino data to resolve degeneracies.
- Lower left octant in inverted hierarchy excluded at 3σ for all δ

CP Phase



- T2K: CP conservation hypothesis outside 2σ interval.

Status Quo



- Both experiments slightly prefer normal hierarchy and δ=-π/2.
- (Different preference for maximal vs. non-maximal mixing)

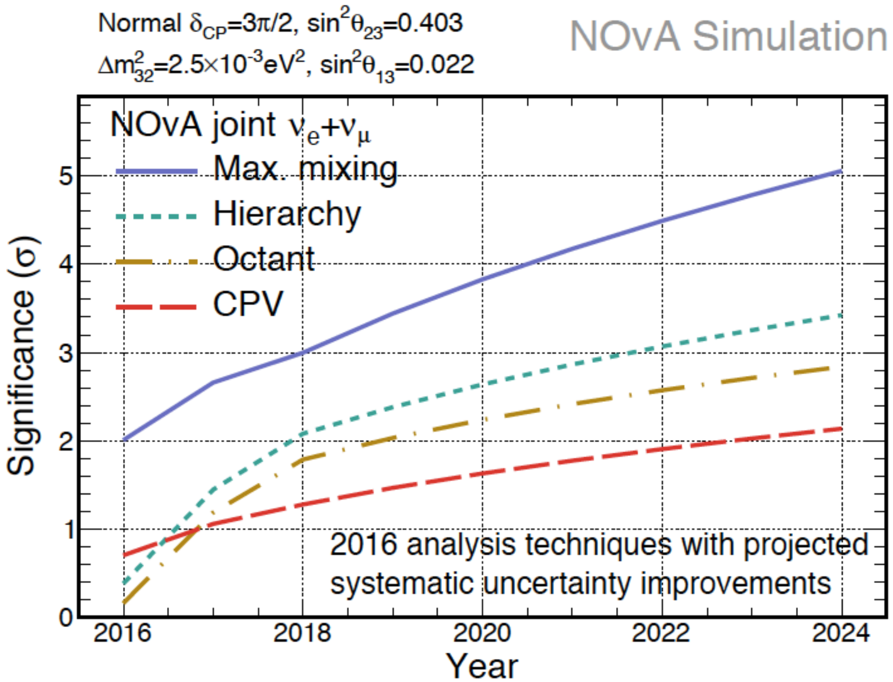
T2K – Far Detector Rates

	Predicted Rates				Observed
Sample	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	$\boxed{6.92}$	6.01	4.87	5.78	$\boxed{15}$
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

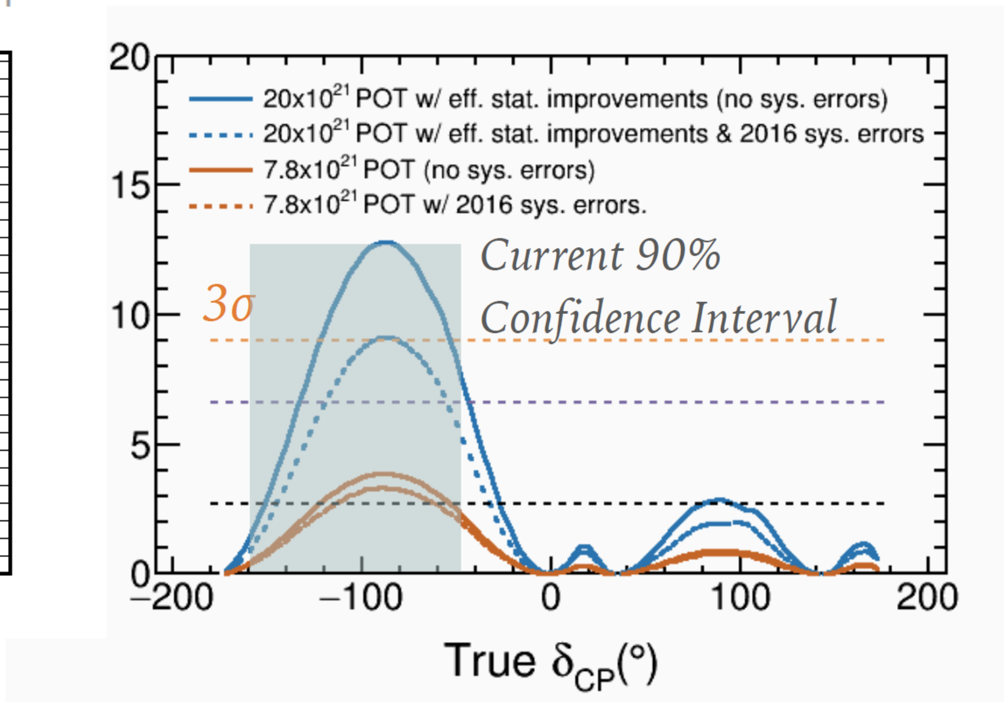
Sensitivity driven by electron-like excess of events

T2K and NOvA Projections

NOvA

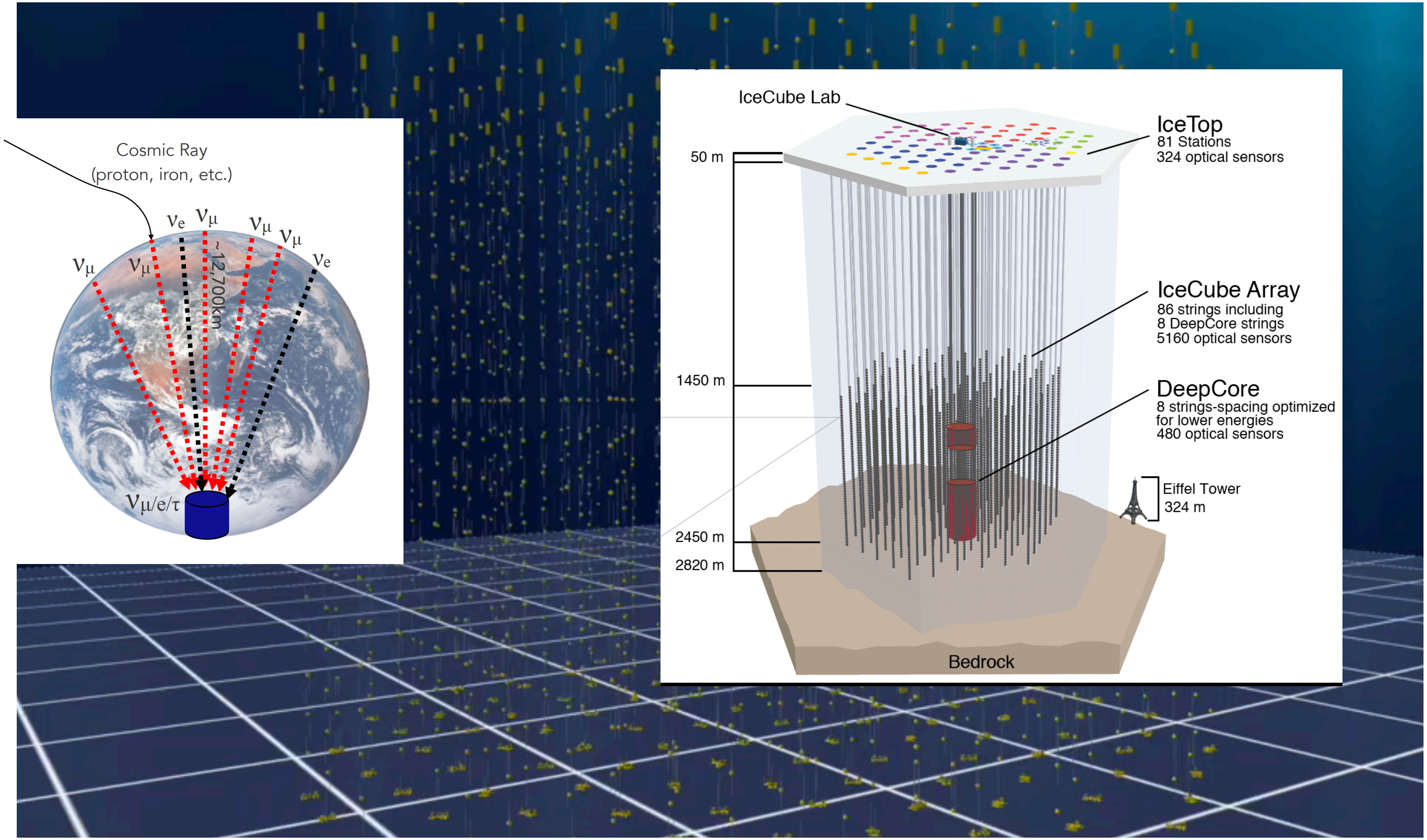


T2K

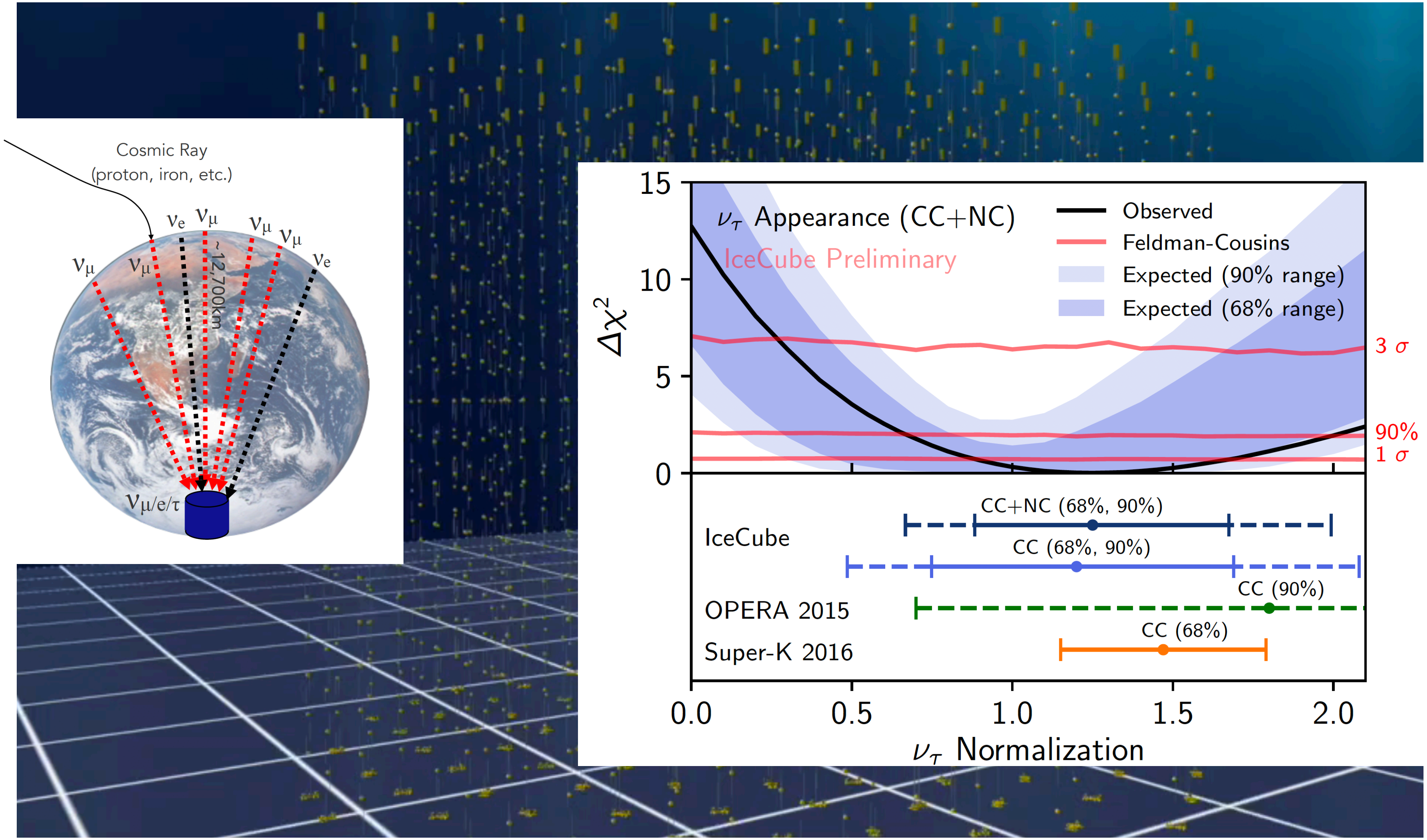


- Currently have 17% (NOvA) and 30% (T2K) of approved POTs
- Expect ≈ 2-3σ on CPV by the time DUNE and HK turn on

IceCube and KM3NET



IceCube and KM3NET



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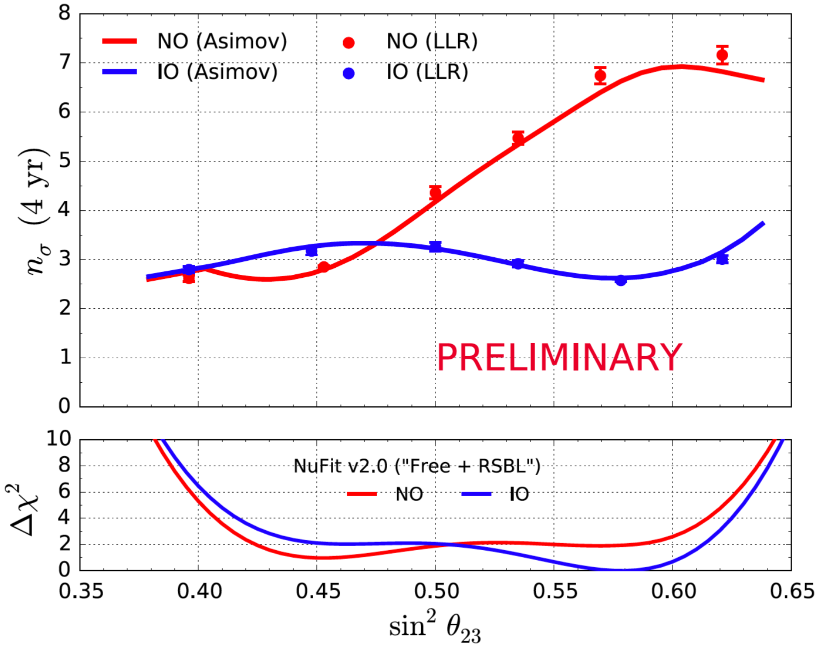
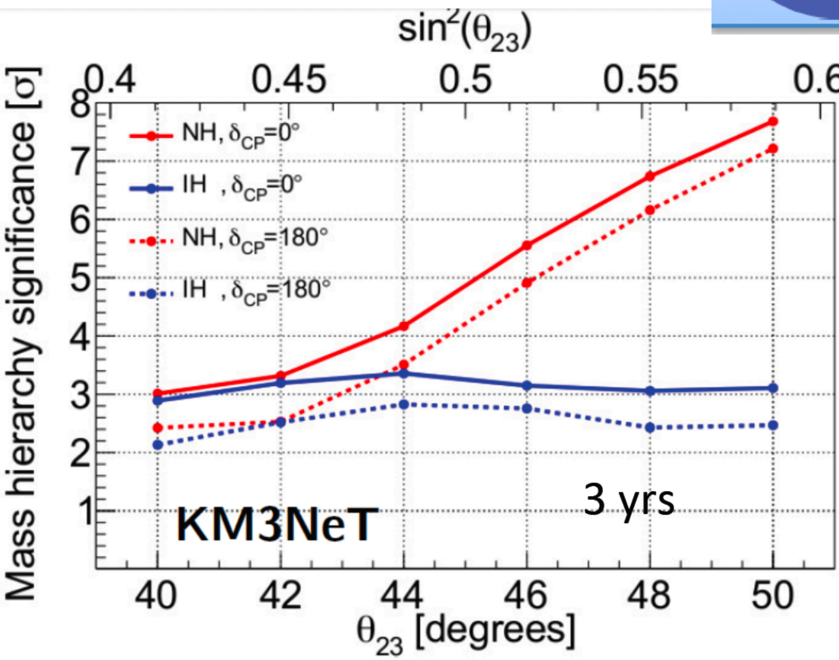
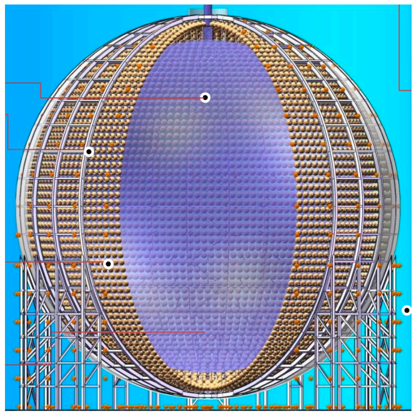
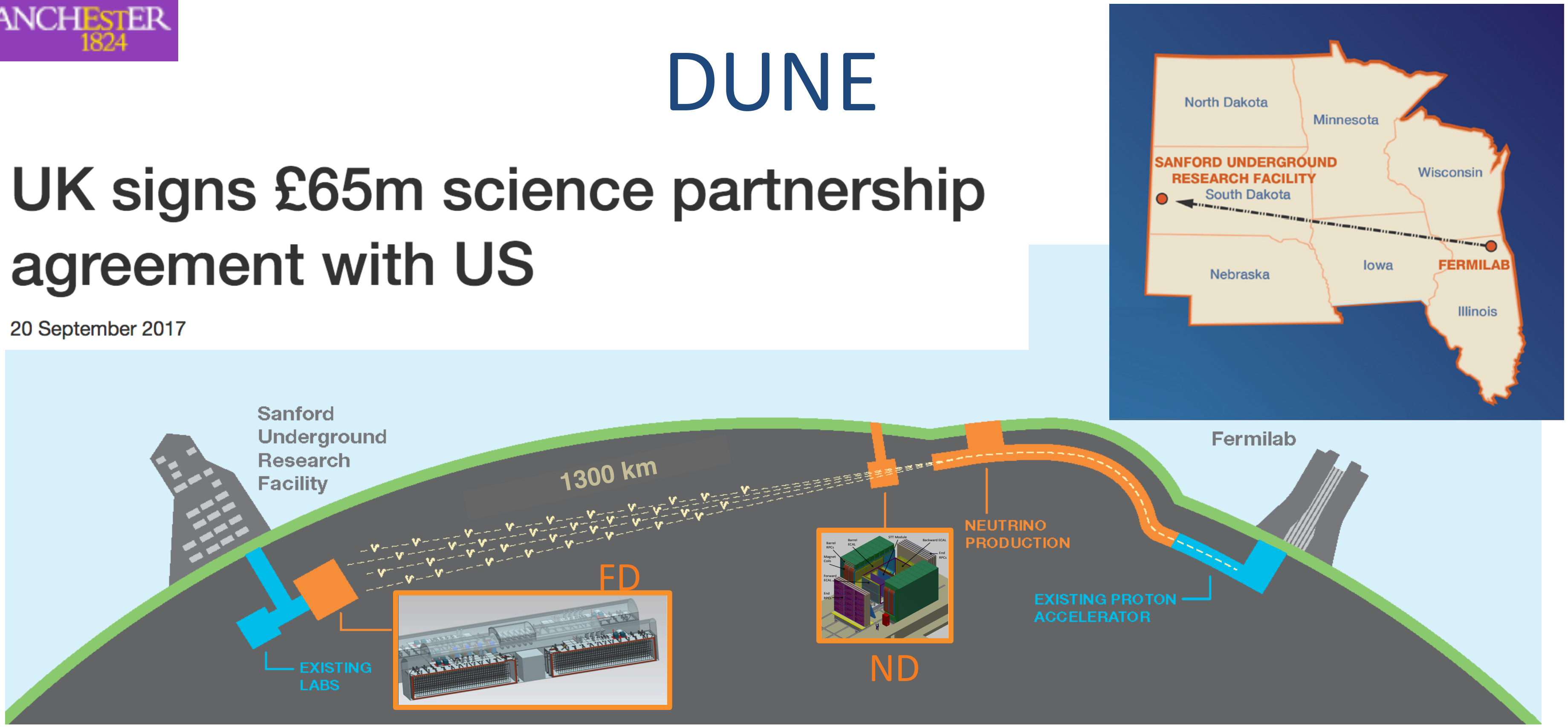






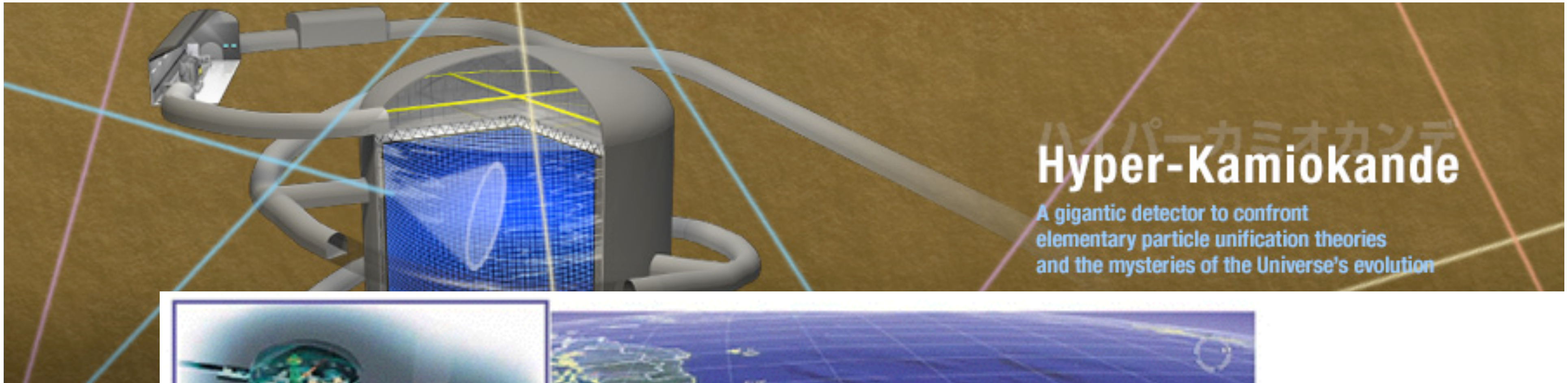
Good chance to resolve mass hierarchy before next-generation LBL experiments turn on.

DUNE



- Approximately 40 kt fiducial mass liquid argon Far Detector.
- Located 1300 km baseline at SURF's 1478 m level (2,300 mwe).
- Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

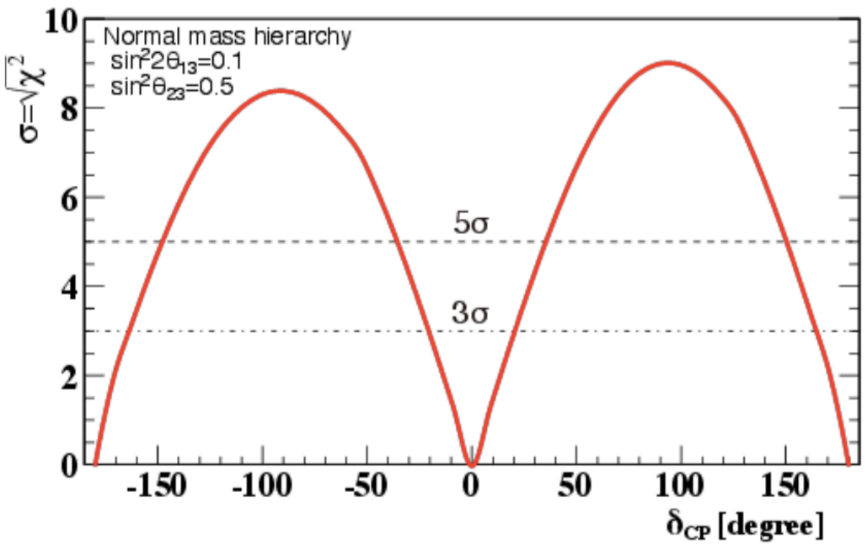
Hyper-Kamiokande



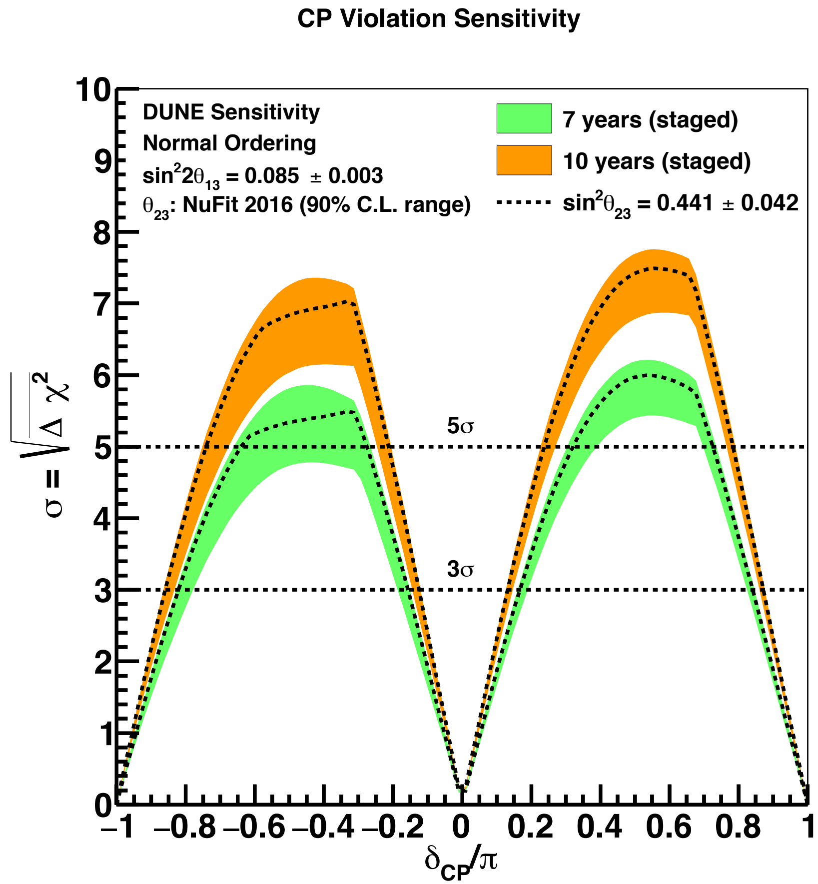
- Bigger detectors (260 kton = 5 x SK)
- More beam power

Sensitivity CP Phase

Hyper-K

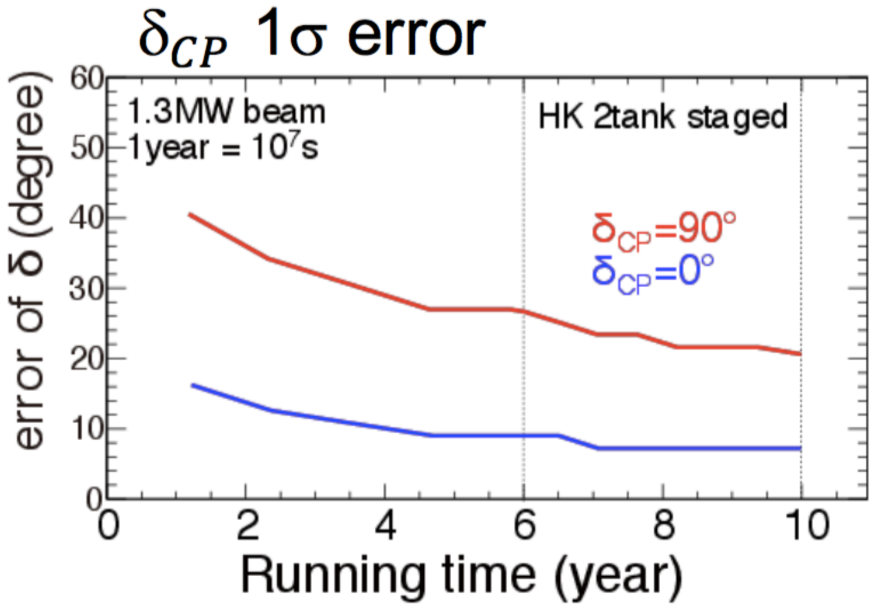


DUNE

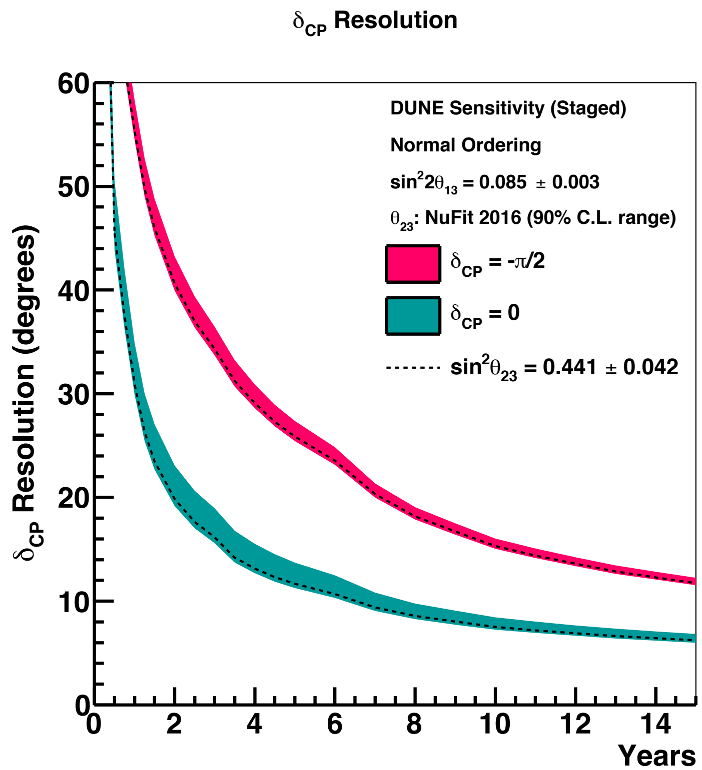


Sensitivity CP Phase

Hyper-K



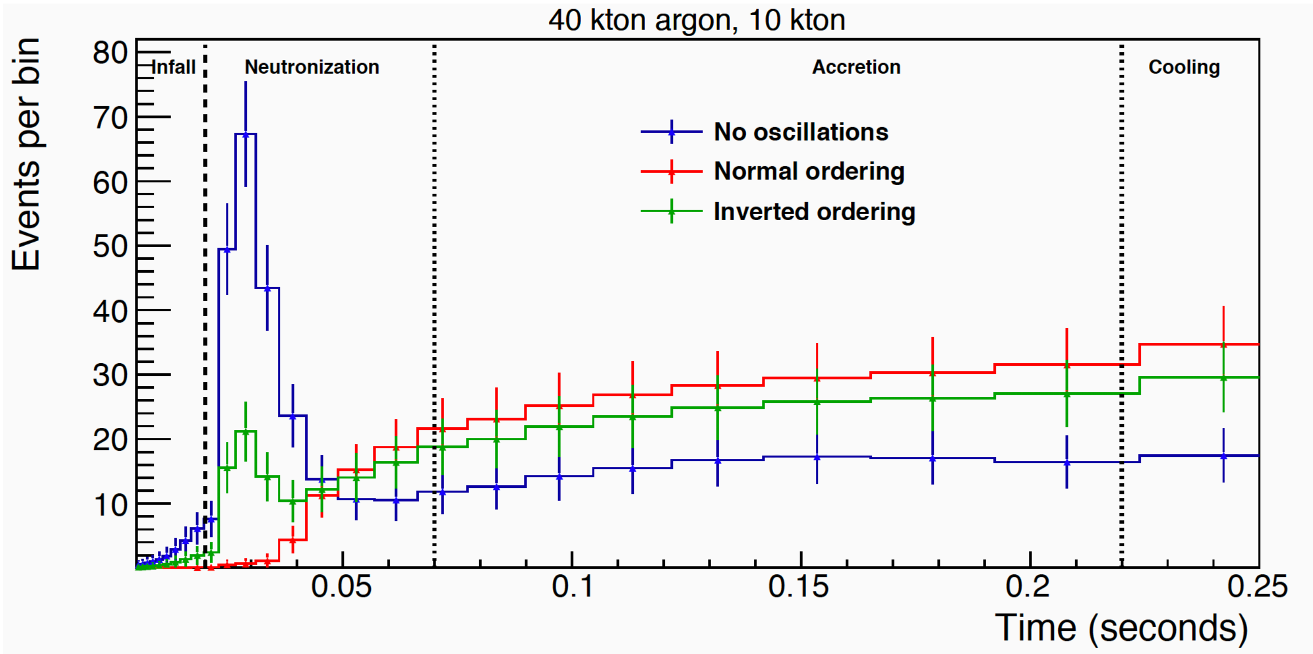
DUNE



Supernova and Mass Hierarchy

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

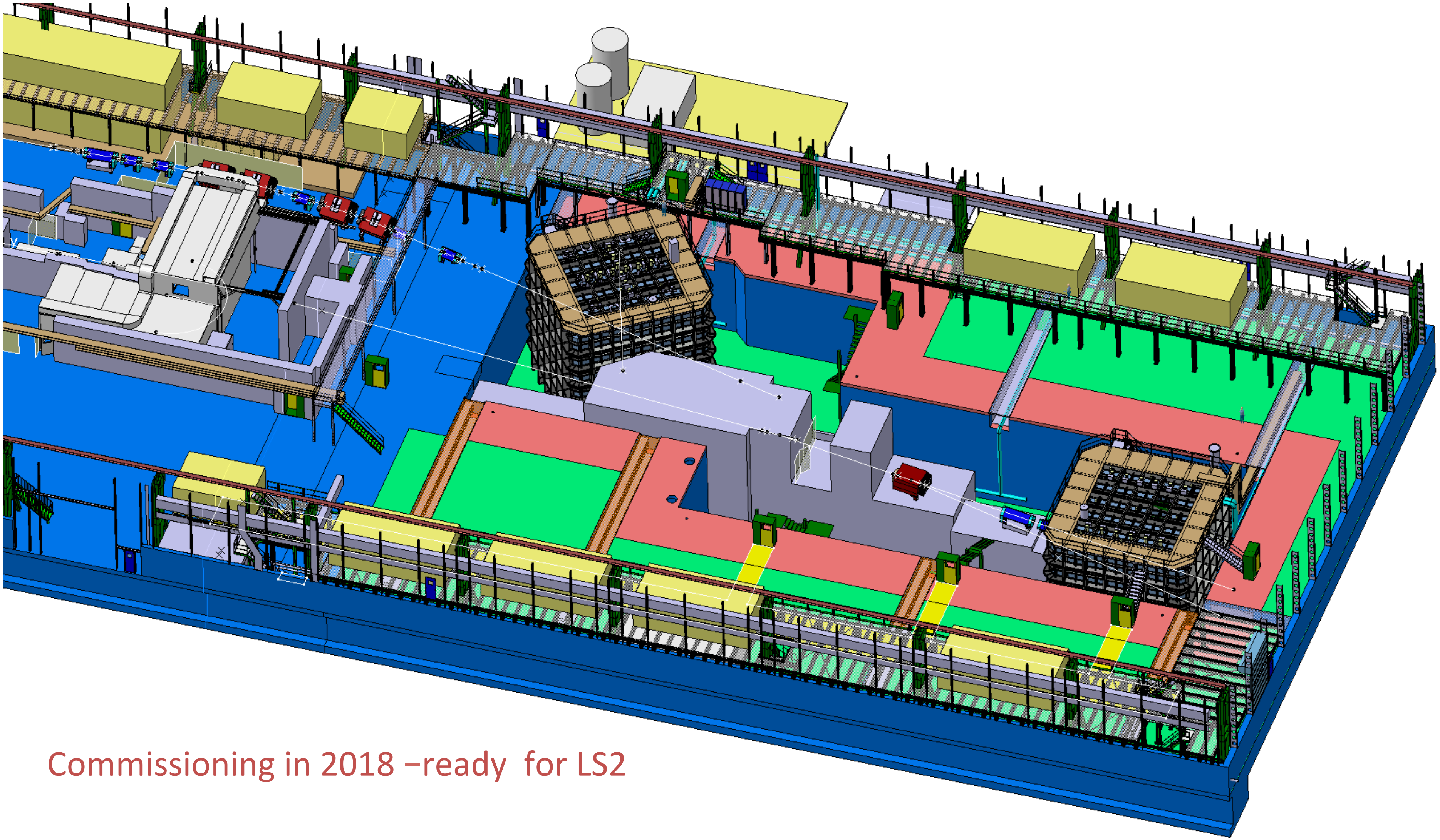
Supernova at 10 kpc in DUNE (40 kt), time dependent signal



"Instant" determination of mass hierarchy ..

Garching model, ICARUS energy resolution, 5 MeV threshold

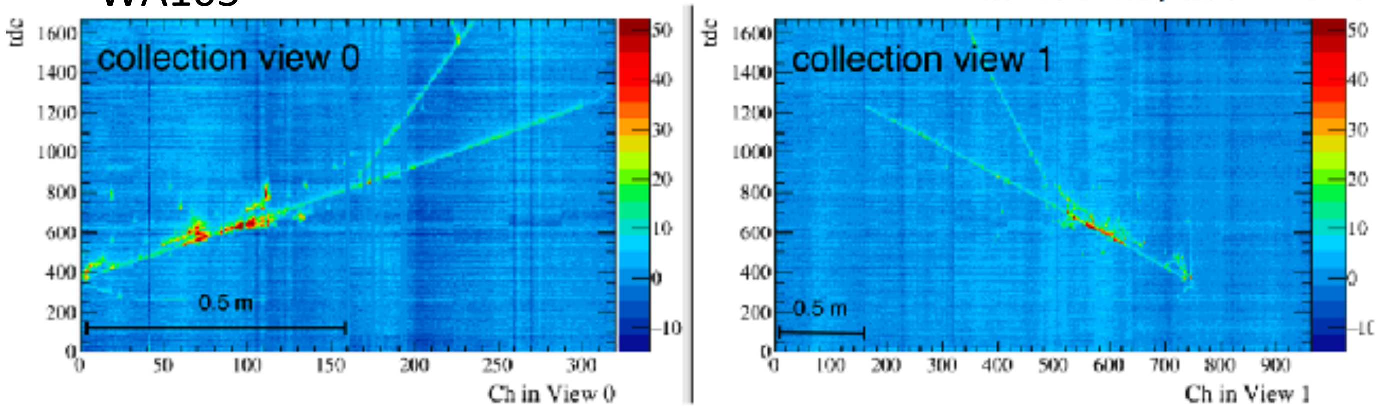
ProtoDUNE@CERN

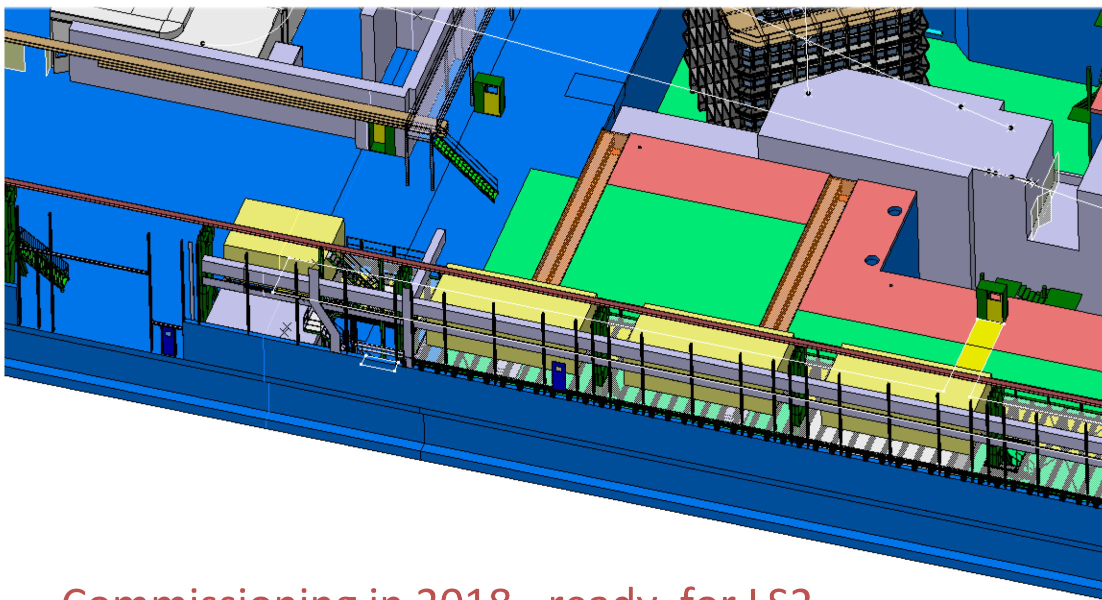


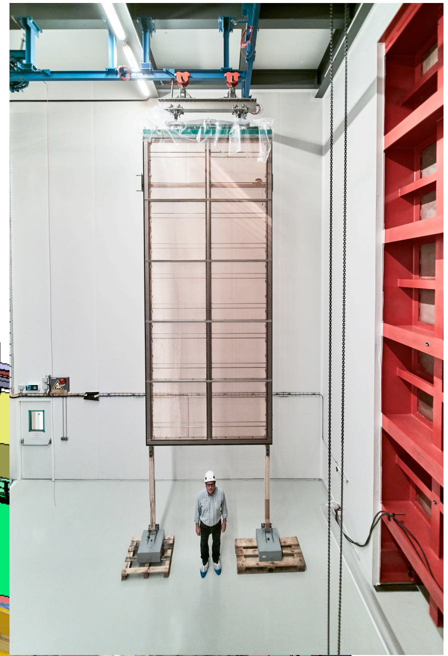
Commissioning in 2018 −ready for LS2

ProtoDUNEs@CERN

WA105



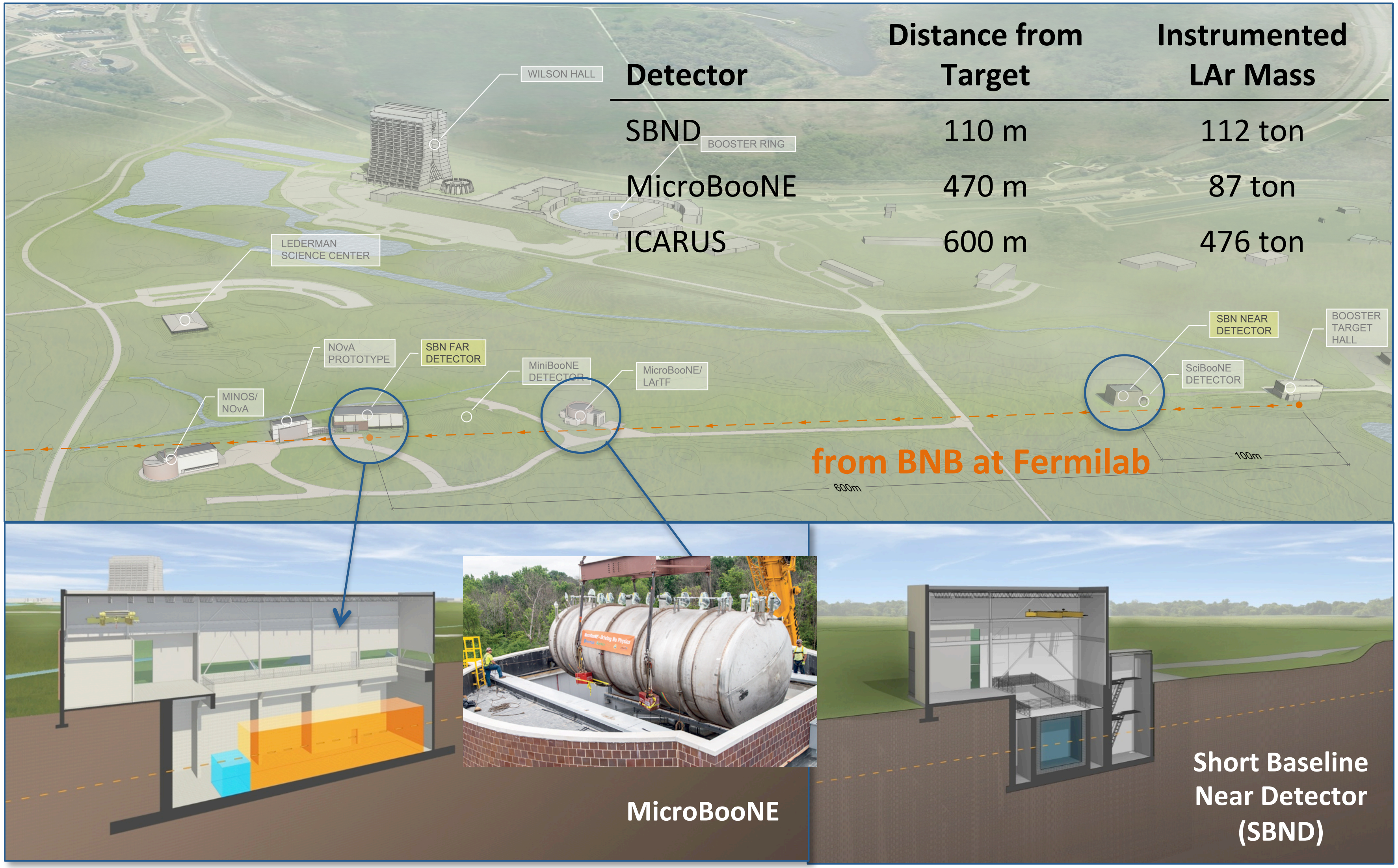




Commissioning in 2018 –ready for LS2

Short-baseline experiments

Detector	Distance from Target	Instrumented LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton



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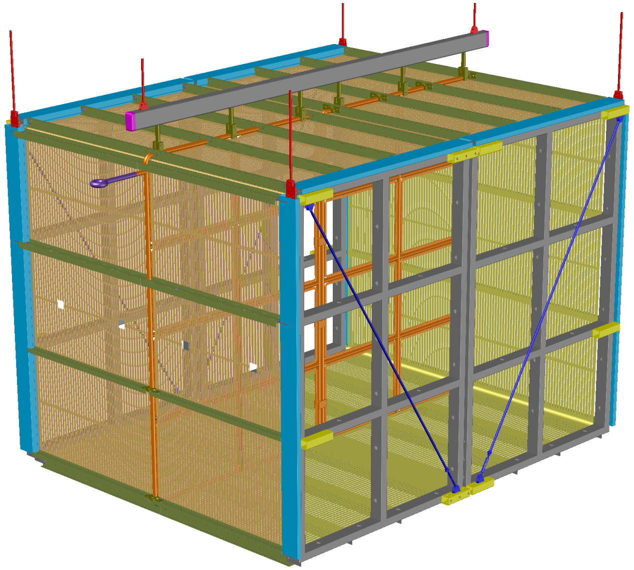
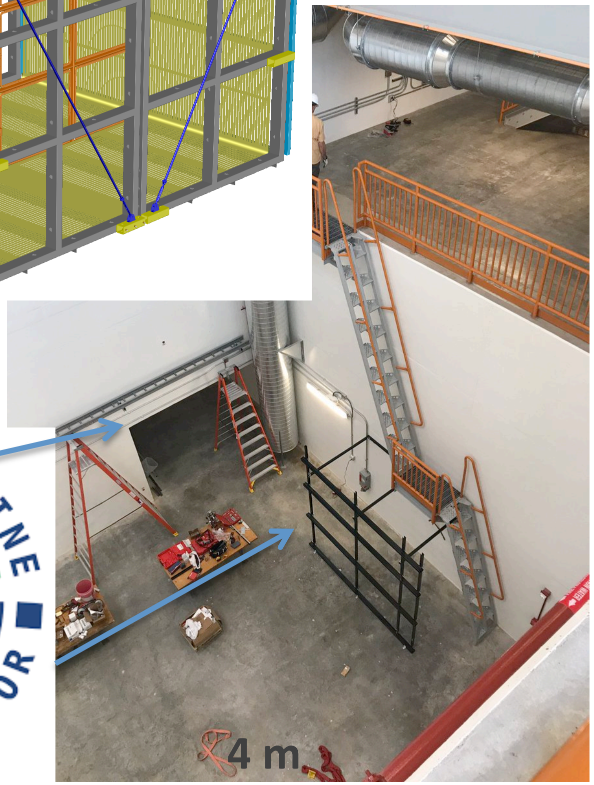
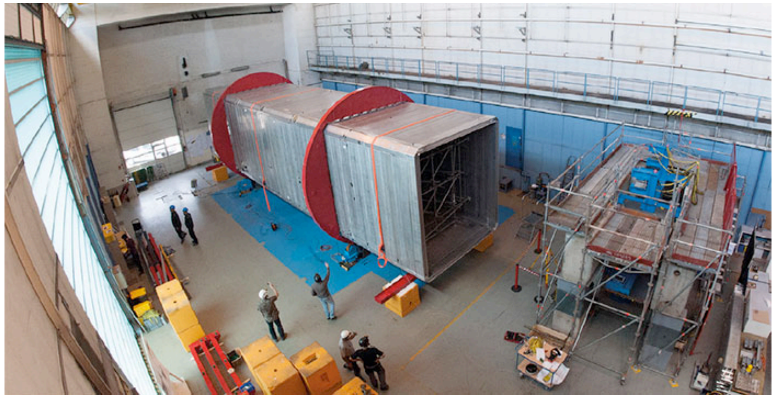
SBND and ICARUS

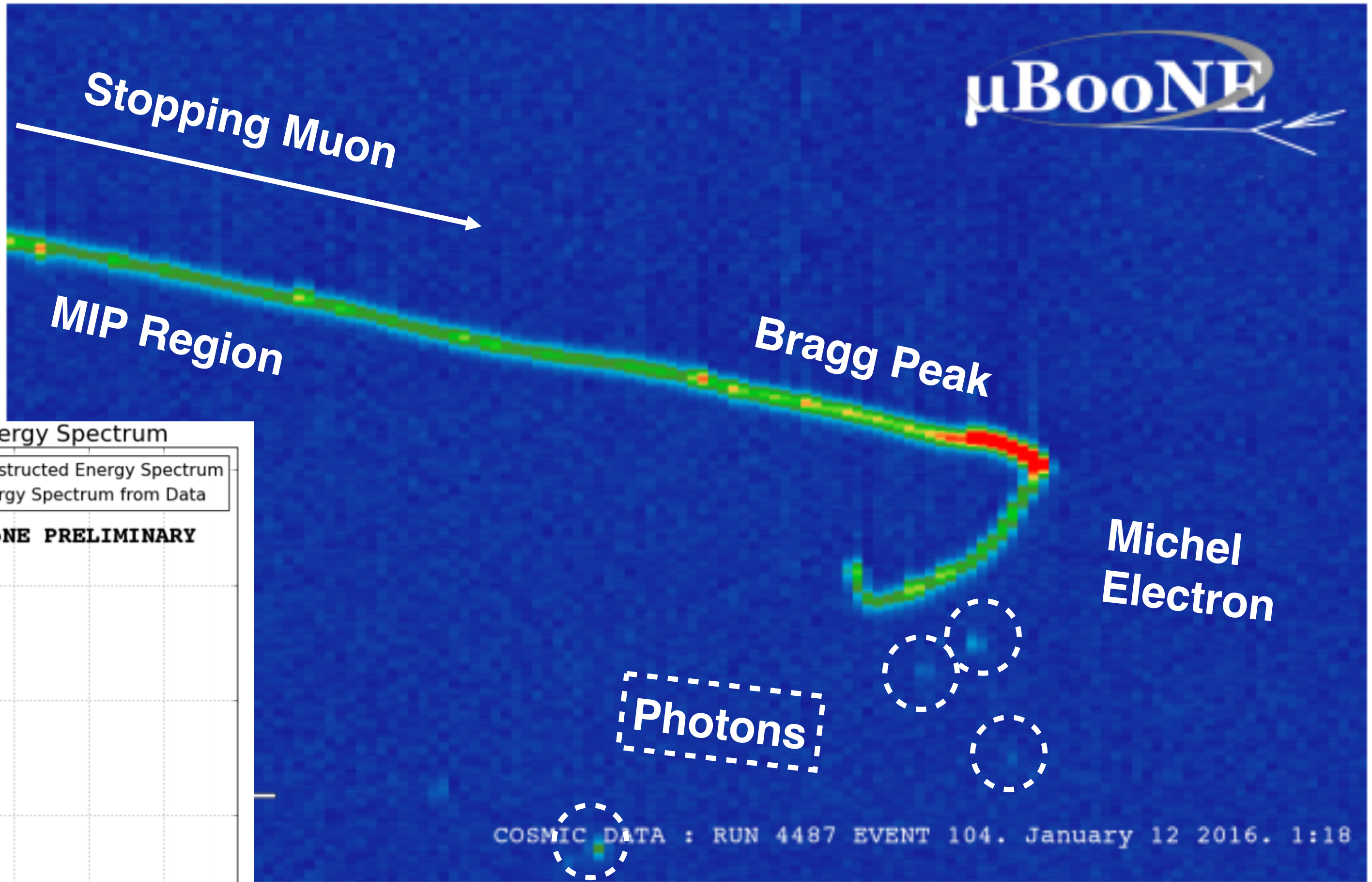


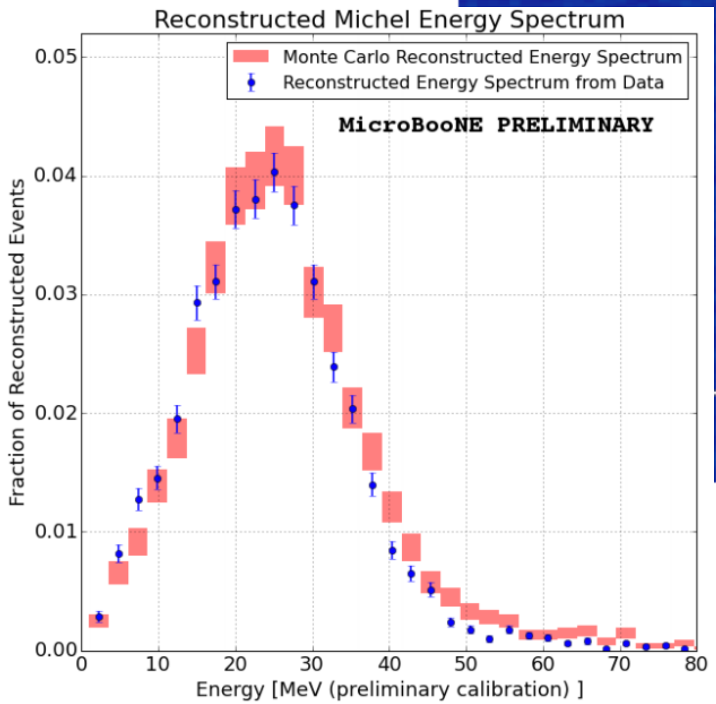




Michel Electrons at MicroBooNE

Demonstration of 'text book' measurements using liquid-argon

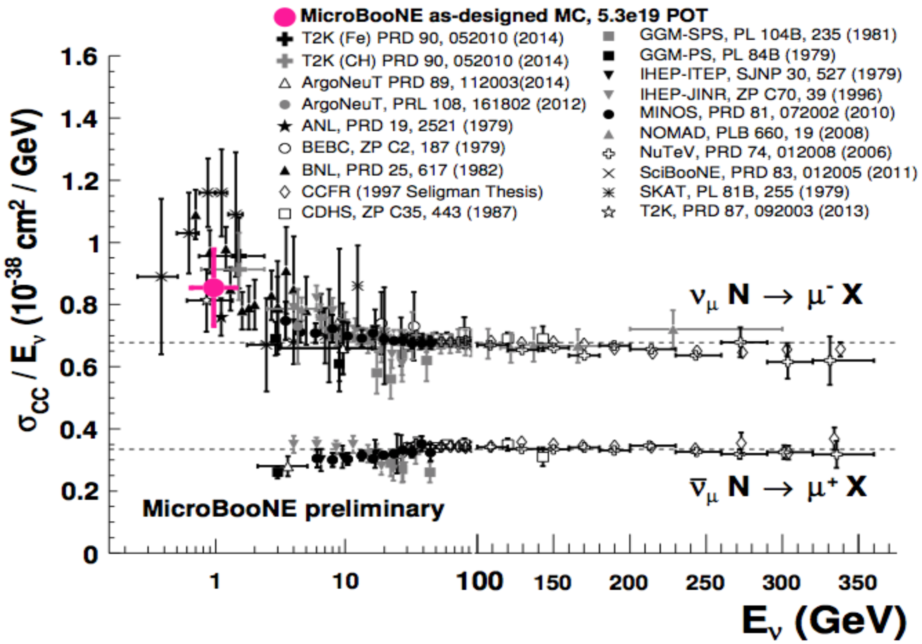


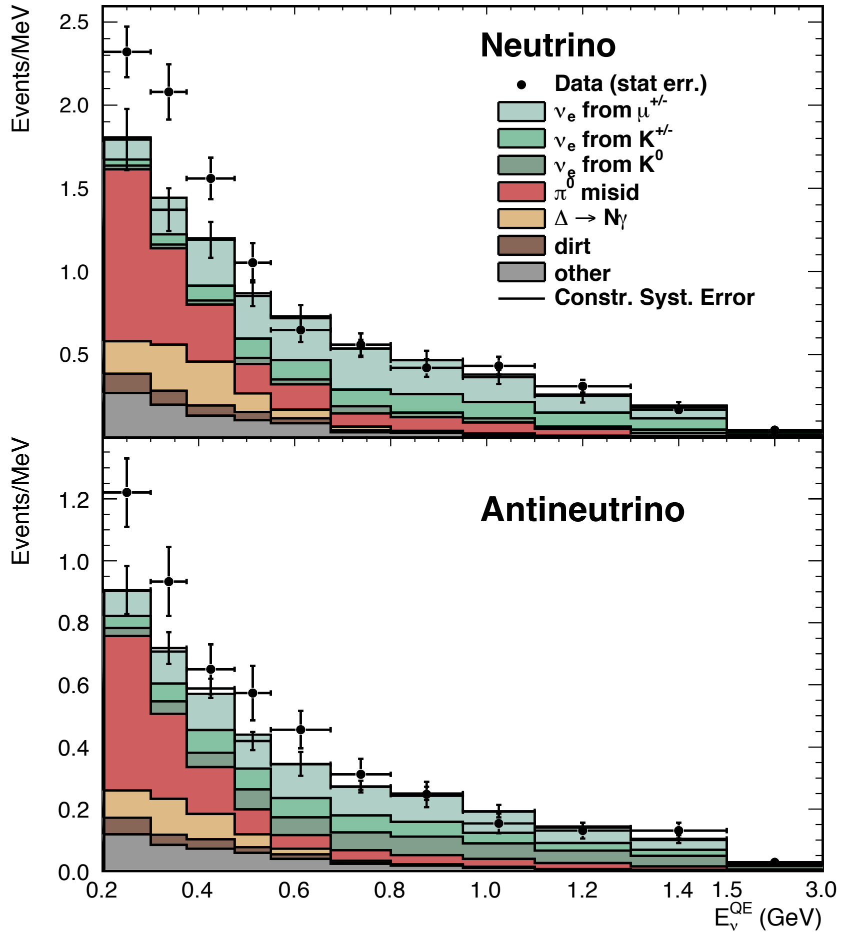


LAr detectors can discriminate electrons from photons

SBN Physics Goals

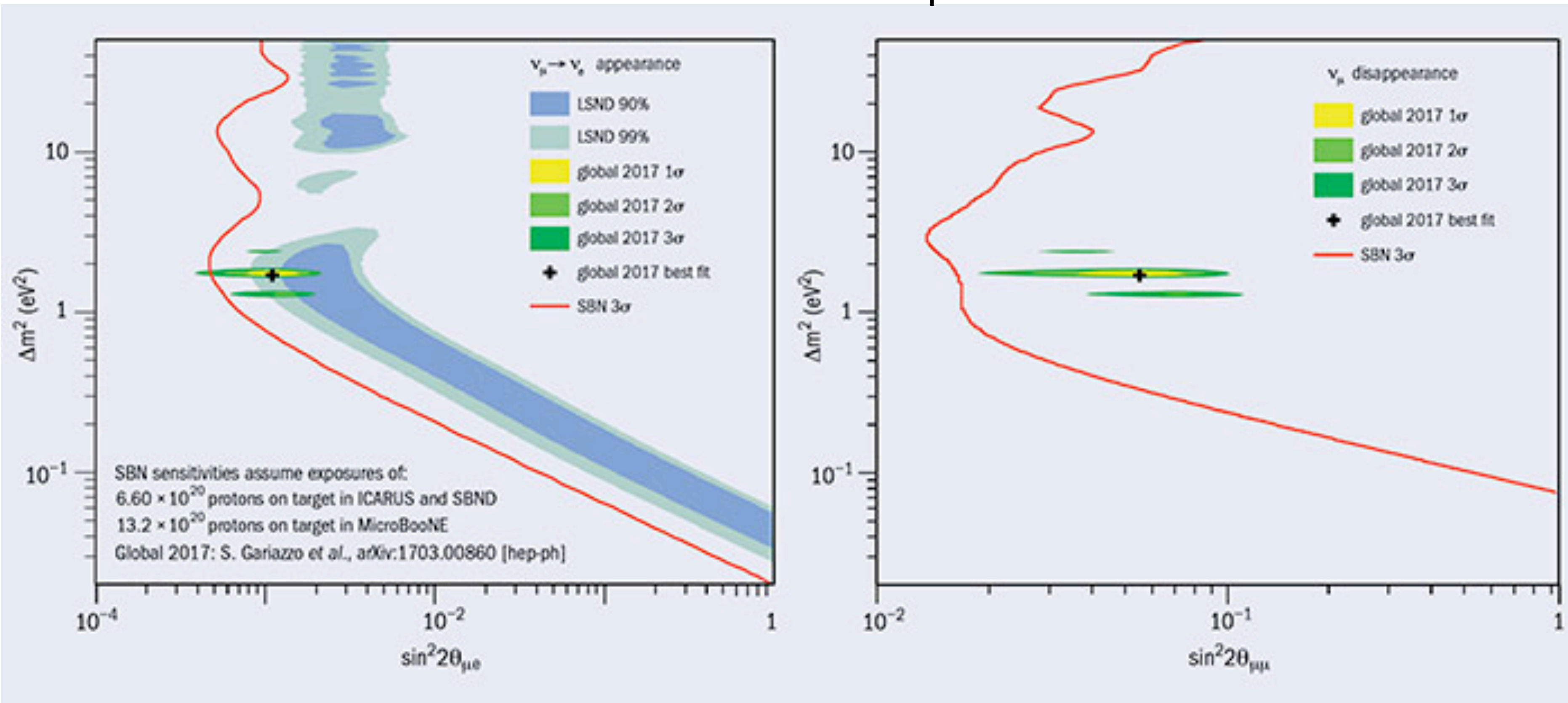
- Explore MiniBooNE (and other) anomalies.
- Search for low-mass sterile neutrinos (~ 1 eV).
- Measure neutrino cross sections on argon – important for DUNE programme.





Sterile Neutrinos

ν_e appearance ν_μ disappearance



Sterile neutrino searches effectively test "three-flavour paradigm".

$$P_{\nu_\mu \to \nu_e}(L/E) \approx 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

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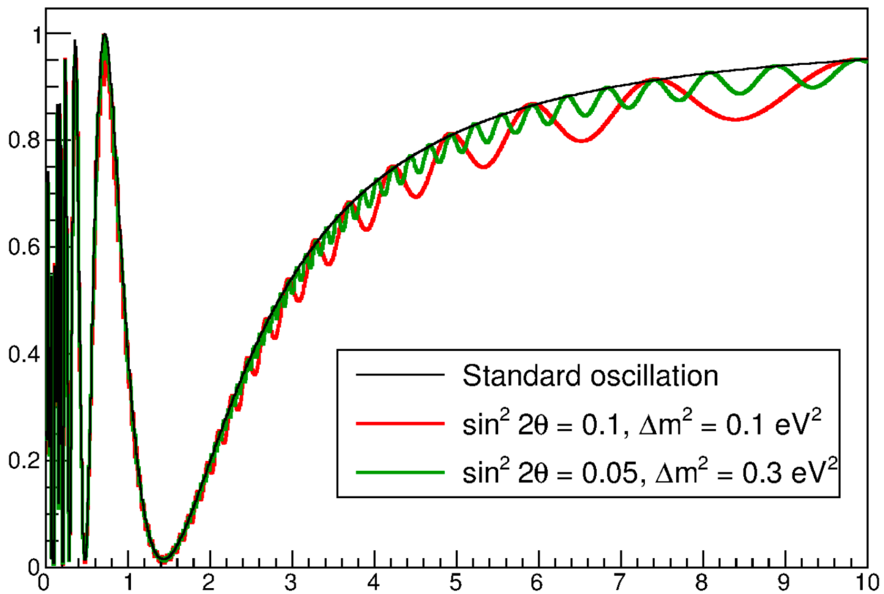
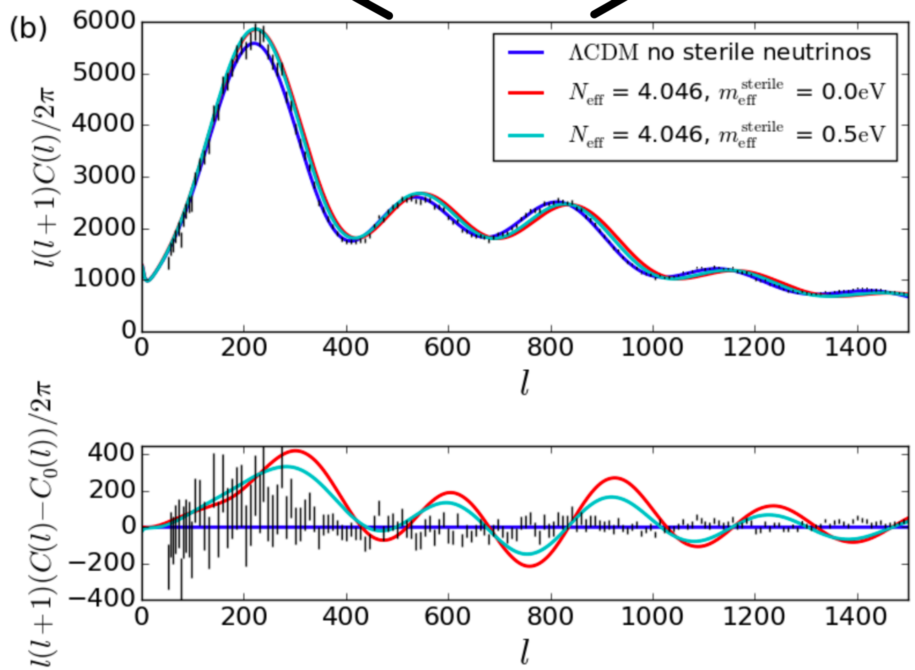
Particle Physics and Cosmology



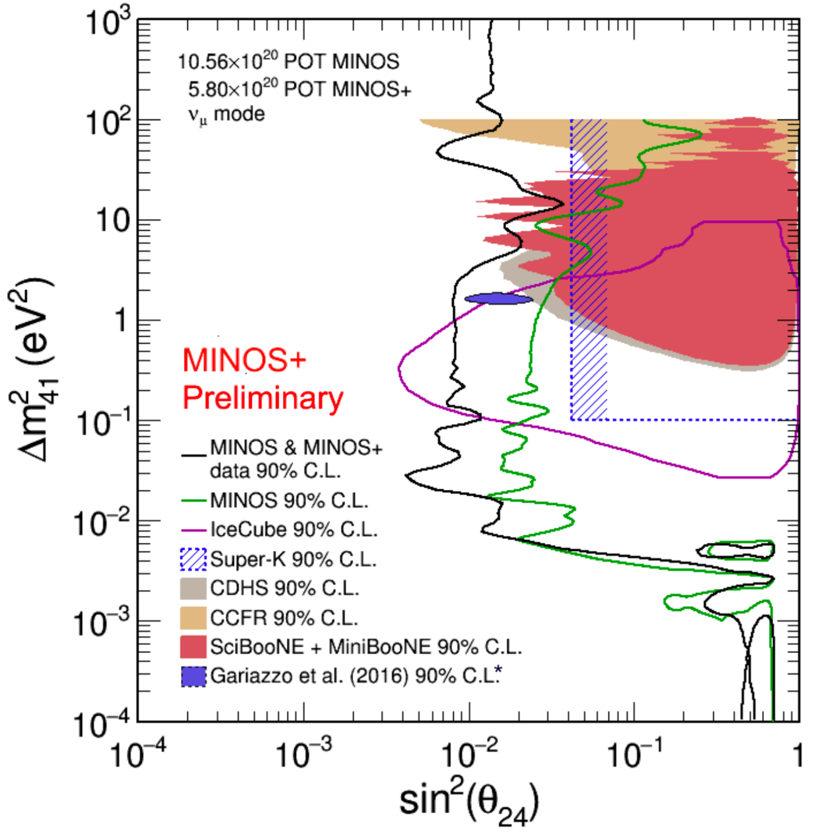
More radiation reduces angular scale

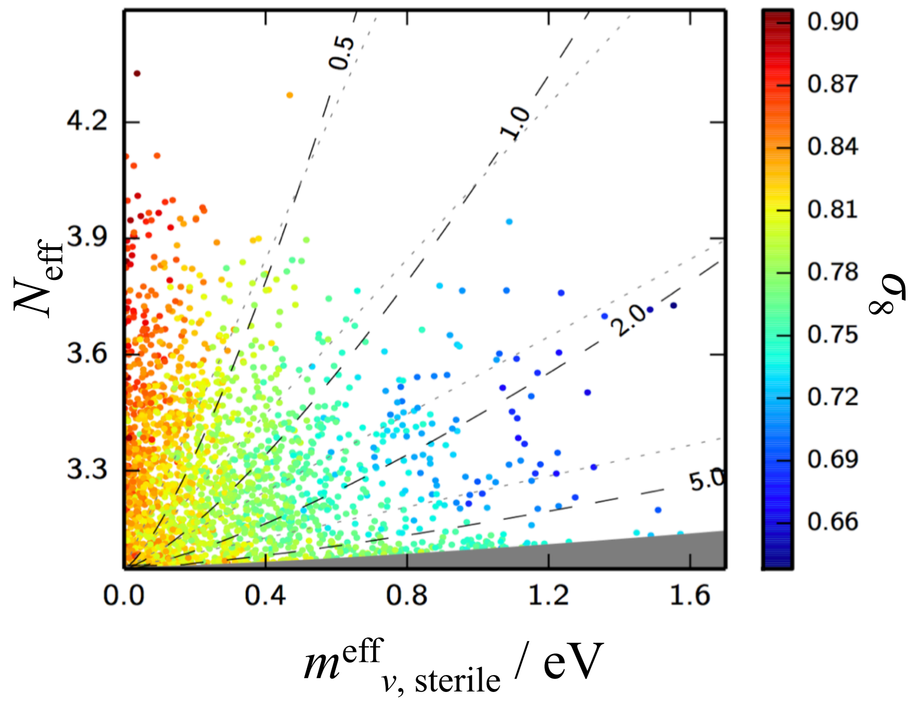


$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

- The amount of radiation (*p*,) related to the effective number of relativistic degrees of freedom, N_{eff}
- N_{eff} can be interpreted as 'number of neutrino flavours'

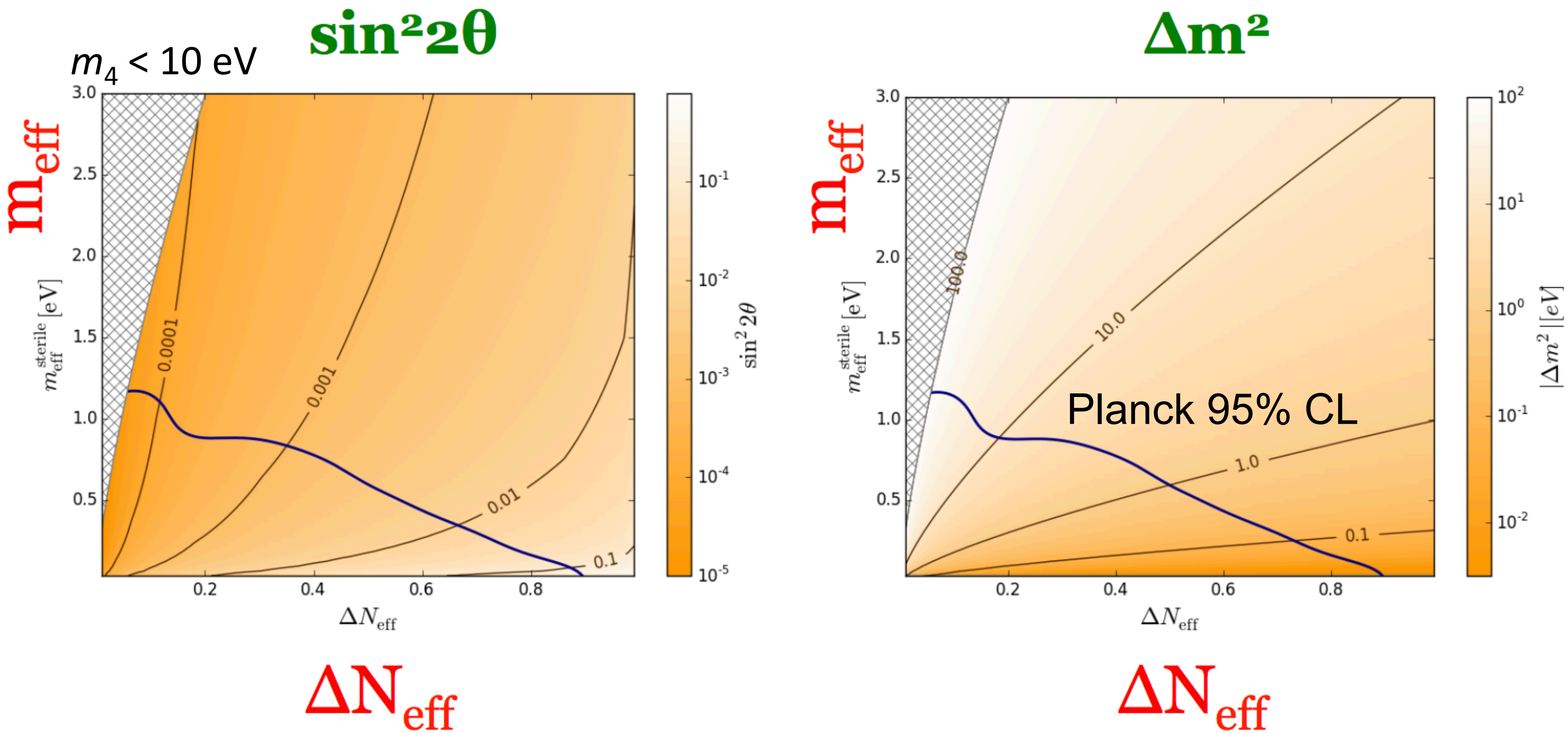
Particle Physics and Cosmology





Relate $(\sin^2\theta, \Delta m^2)$ to $(N_{\mathrm{eff}}, m^{\mathrm{eff}})$

Particle Physics and Cosmology



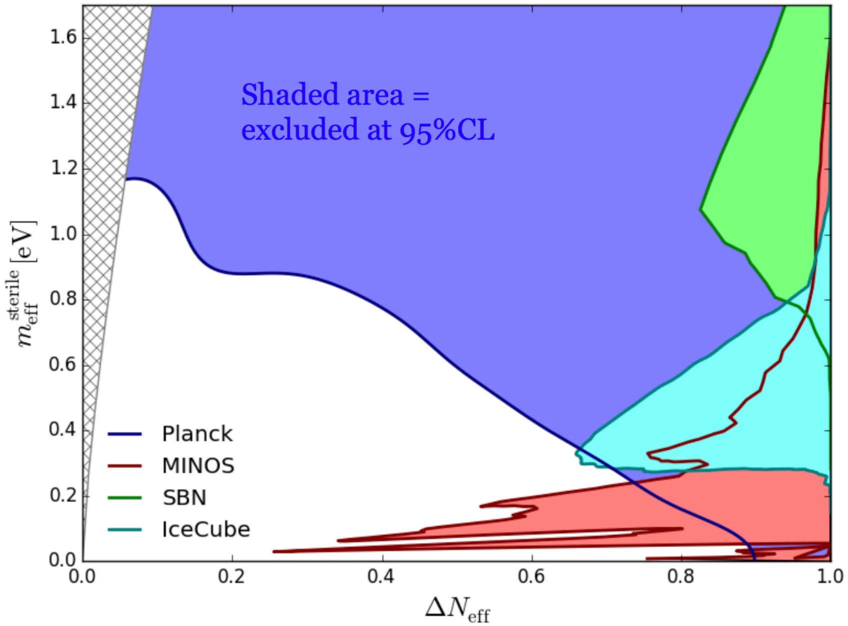
Solve quantum kinetic equations that govern thermalisation using LASAGNA

ν_μ Disappearance (1+1 model)

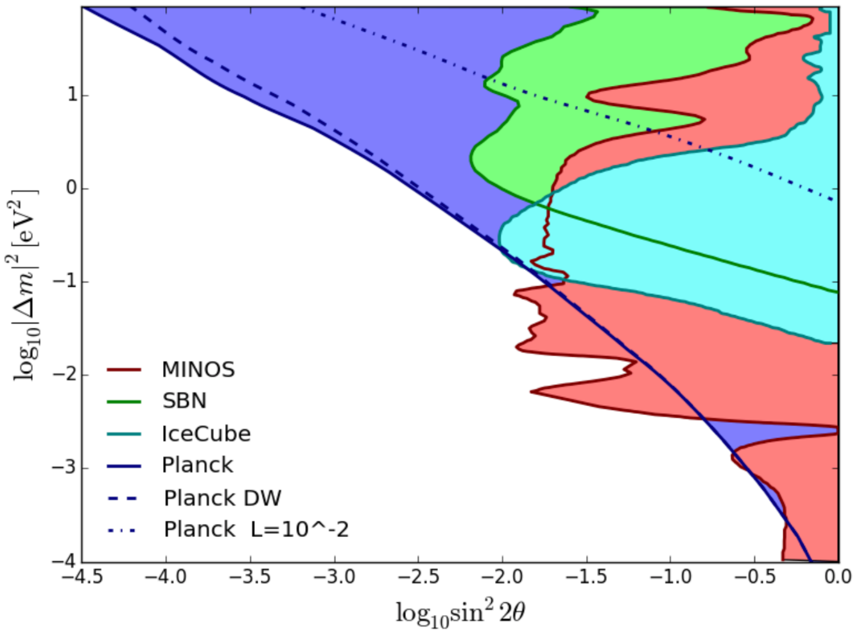
1 active and 1 sterile flavour

S. Bridle *et al.*, Phys. Lett. **B764**, 322 (2017)

m_{eff}



$\log|\Delta m|^2$

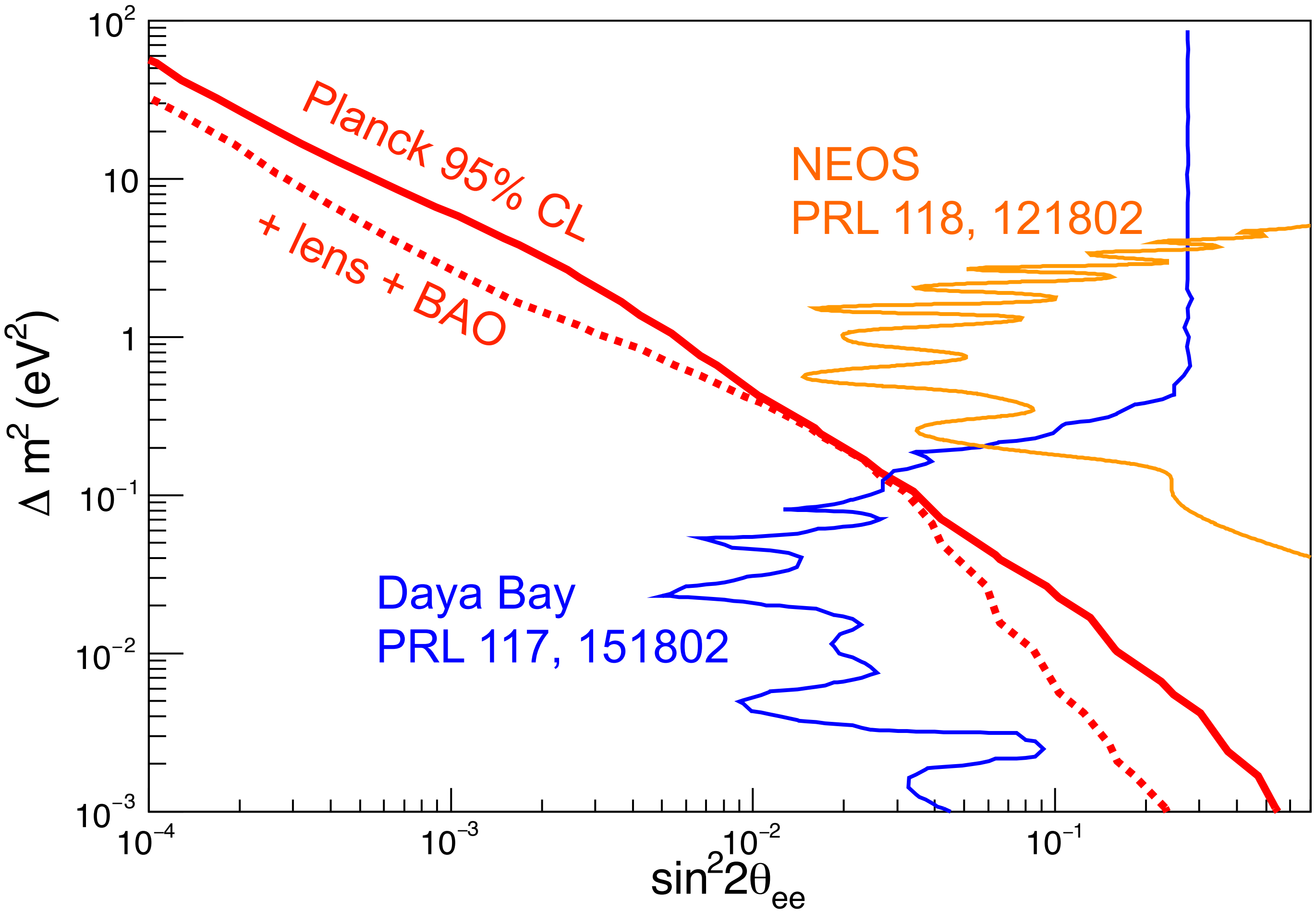


ΔN_{eff}

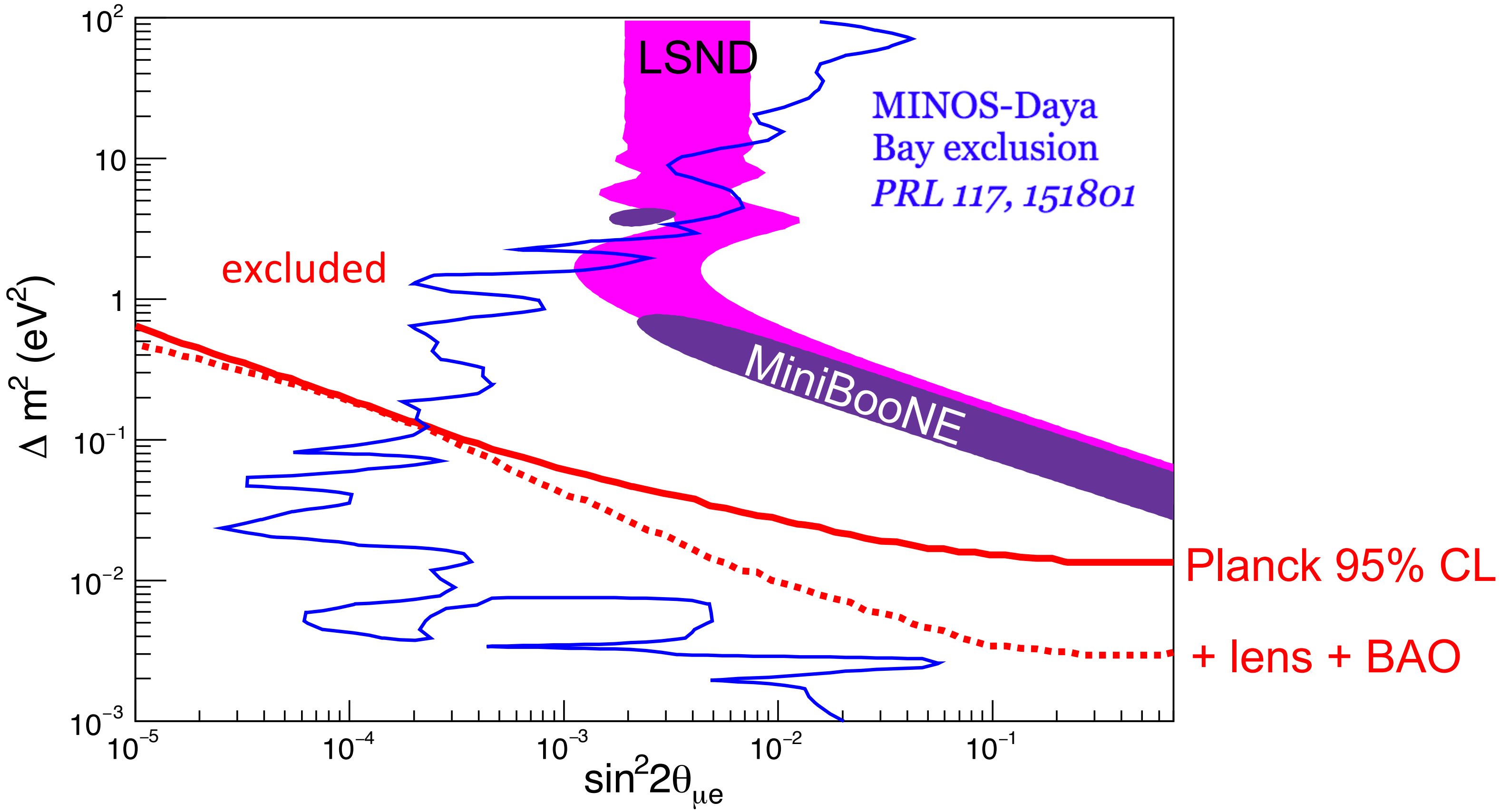
$\log \sin^2(2\vartheta)$

ν_e Disappearance (1+1)

1+1 model only allows to study one active-sterile mixing angle at a time



Moving to a 3+1 model



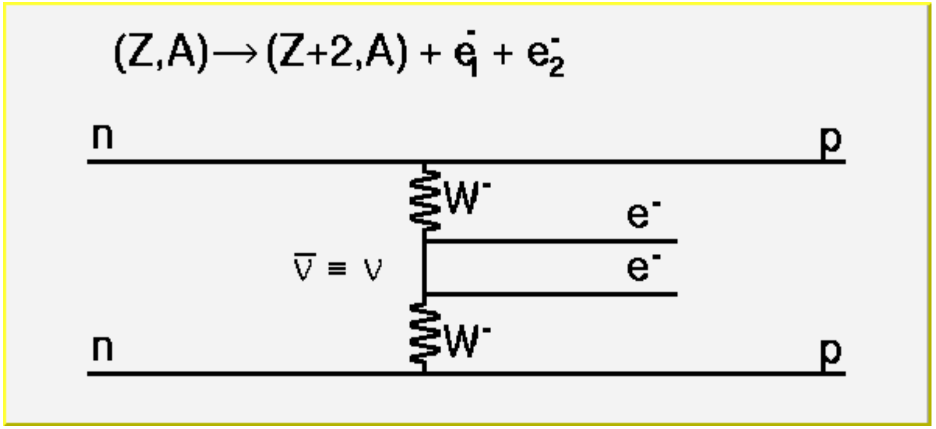
- Daya Bay/MINOS combination of ν_e/ν_μ disappearance data.
- Planck exclusion obtained using mean-momentum approximation
- Comparison is necessarily model-dependent.

Neutrinoless Double-β Decay

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

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana Phases

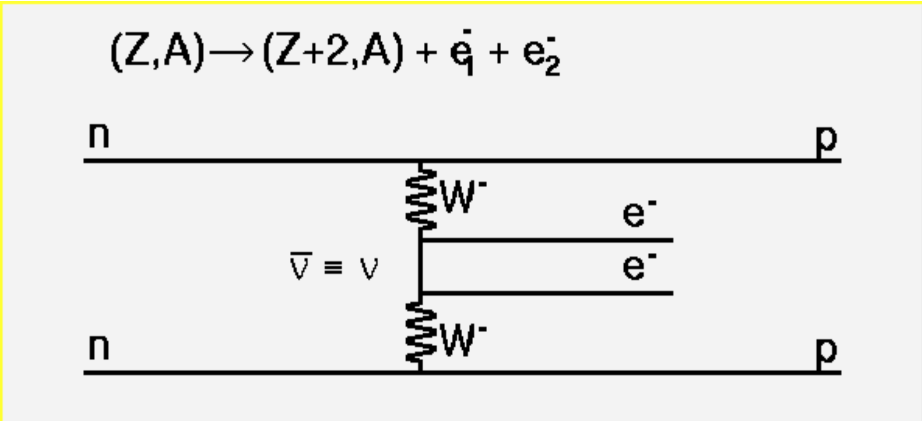


$$\frac{1}{T^{2\nu}_{1/2}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

ΔL = 2 - only possible for Majorana neutrinos with m > 0

Creation of Electrons

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



$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana Phases

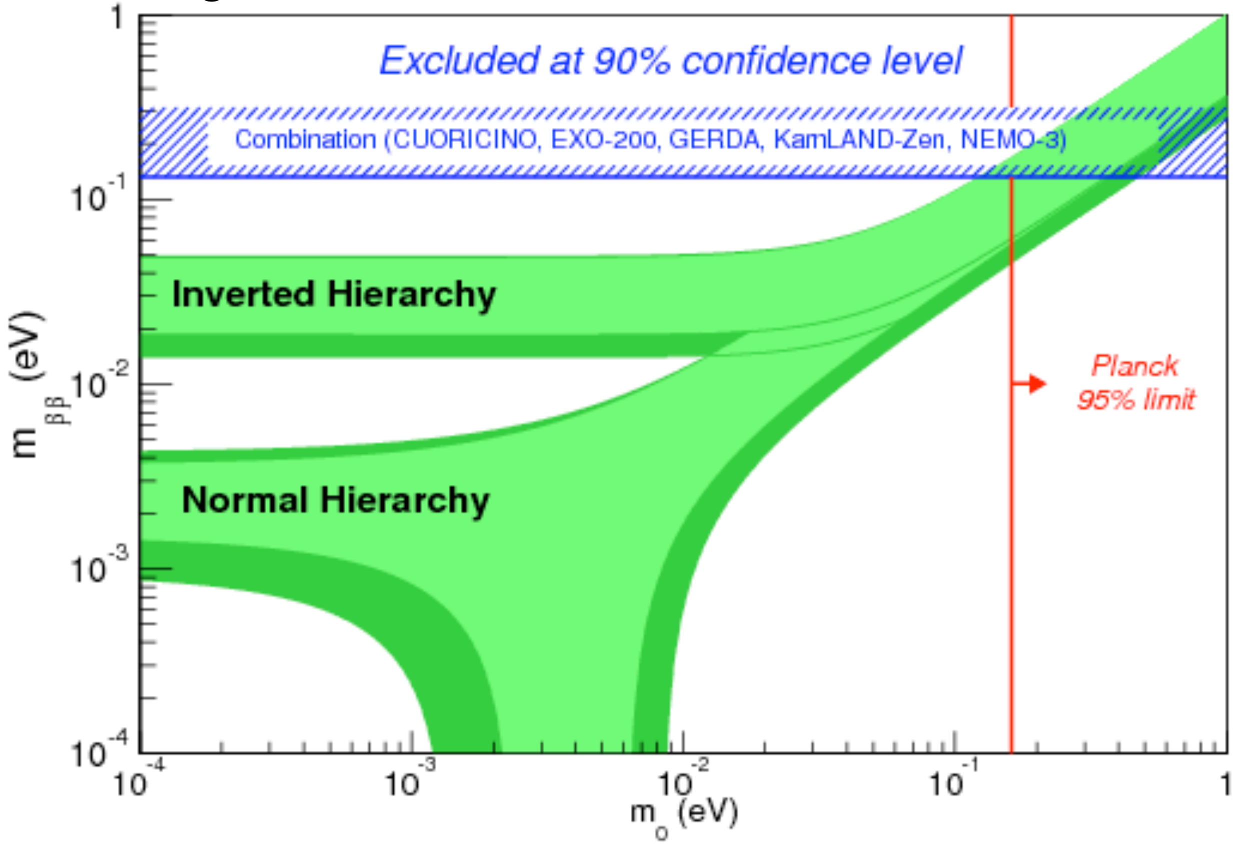
$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

ΔL = 2 - only possible for Majorana neutrinos with m > 0

Status 2015

Full combination using correlations

Phys.Rev. D92 (2015) no.1, 012002



- Goal of current and near-future experiments: cover inverted hierarchy.
- Width of bands depend on mixing parameters (within 3 flavour model).
- Oscillation experiments provide input regarding hierarchy.
- Only cover running experiments that gave updates this year.

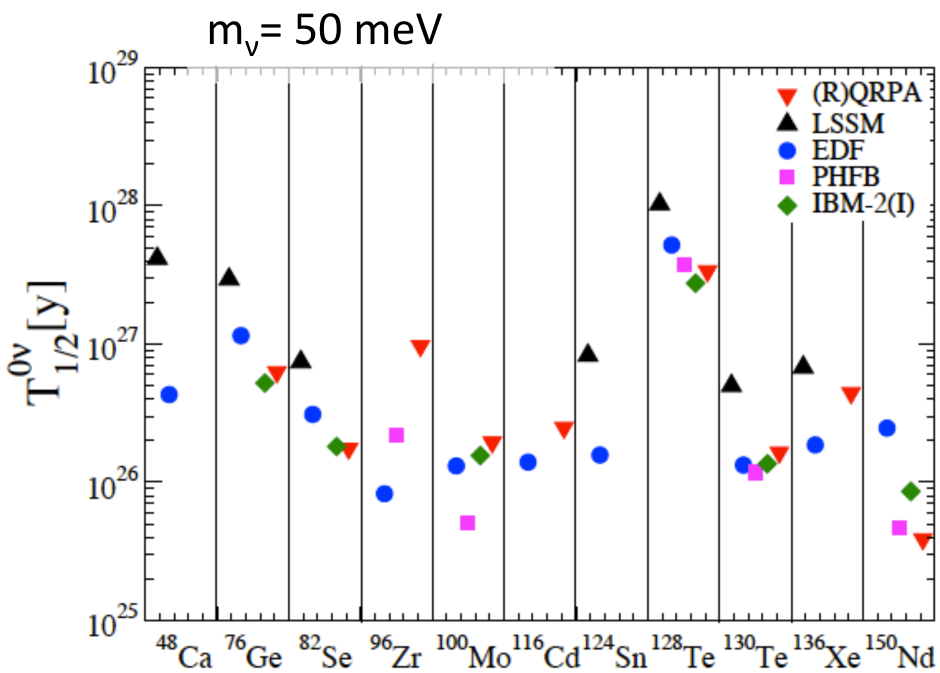
How to build a 0νββ experiment

$$T_{1/2}^{\beta\beta 0\nu} > N_A \cdot \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot t}{(N_{bg} \cdot \Delta E)}}$$

- Increase efficiency and mass
- Decrease background
- Improve energy resolution

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \langle m_\nu \rangle^2$$

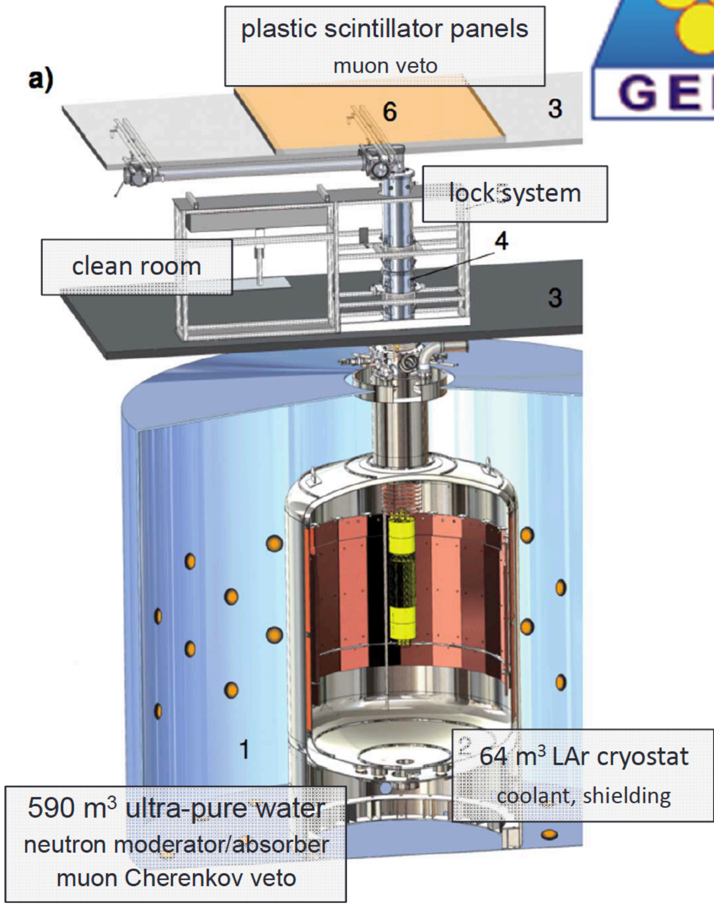
- Optimize phase space factor and NME.
- Choose isotopes that can be easily enriched.



J. Vergados et al., arXiv:1205.0649

CUORE (Cupid) and Gerda (Legend)

Germanium

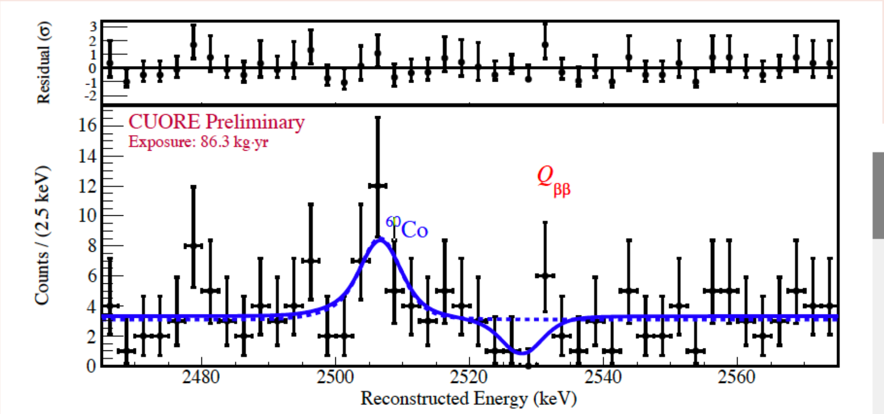


TeO_2 Bolometer

CUORE and Gerda

CUORE first results (Oct 2017)

arXiv:1710.07988 [nucl-ex]



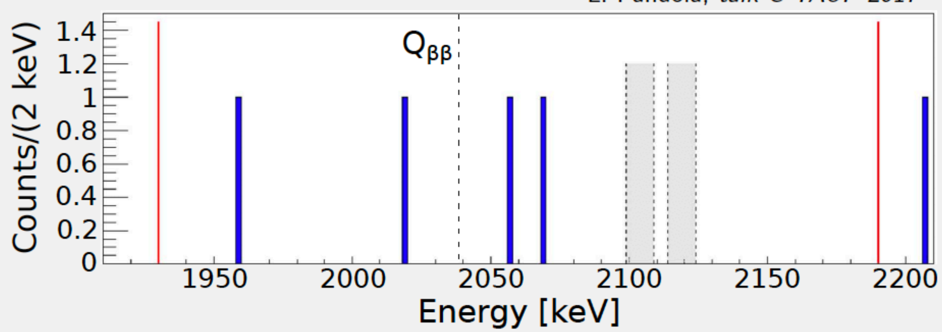
$t^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 1.5 \cdot 10^{25}$ yr @ 90% C. L.

$T_{1/2} > 1.5 \times 10^{25}$ years

Stefano Dell'Oro, NNN17

GERDA-II new results (Jul 2017)

L. Pandola, *talk @ TAUP 2017*

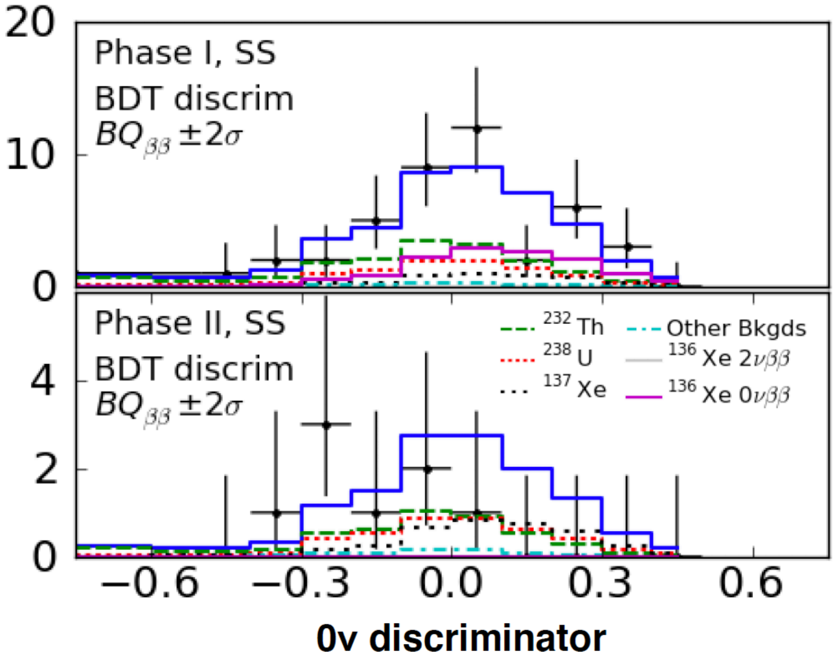


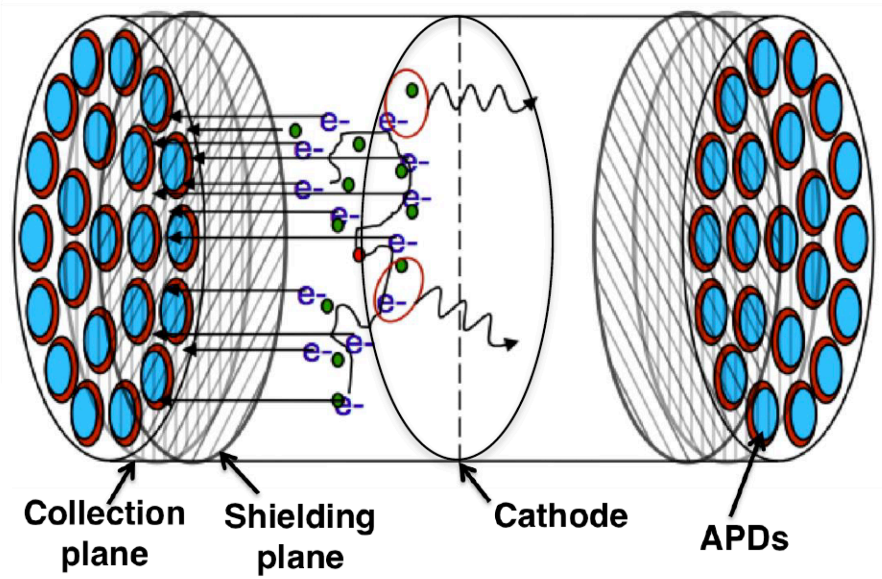
$t^{0\nu}_{1/2} > 8.0 \cdot 10^{25}$ yr @ 90% C. L.

Low background experiments
with excellent energy resolution.

$T_{1/2} > 8.0 \times 10^{25}$ years

EXO-200



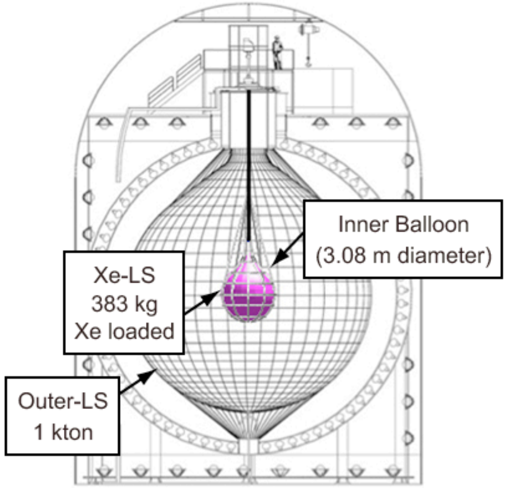


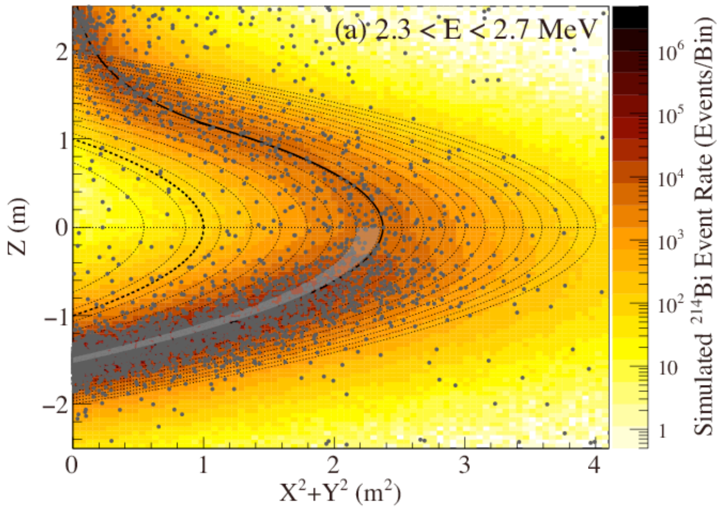
$T_{1/2} > 1.8 \times 10^{25}$ years

$m_{\beta\beta} < 147 - 398$ meV

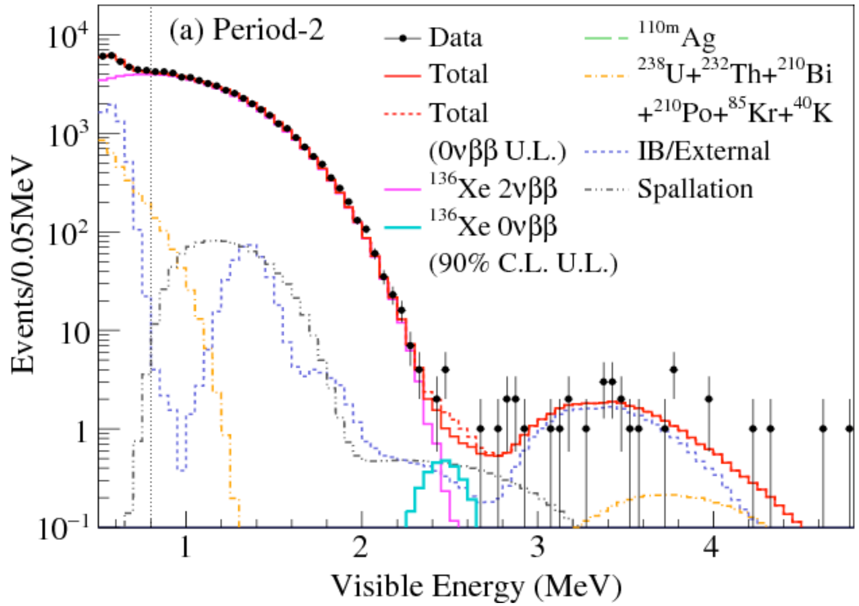
KamLAND-Zen

13 tons of Xe-loaded scintillator
 - lower energy resolution



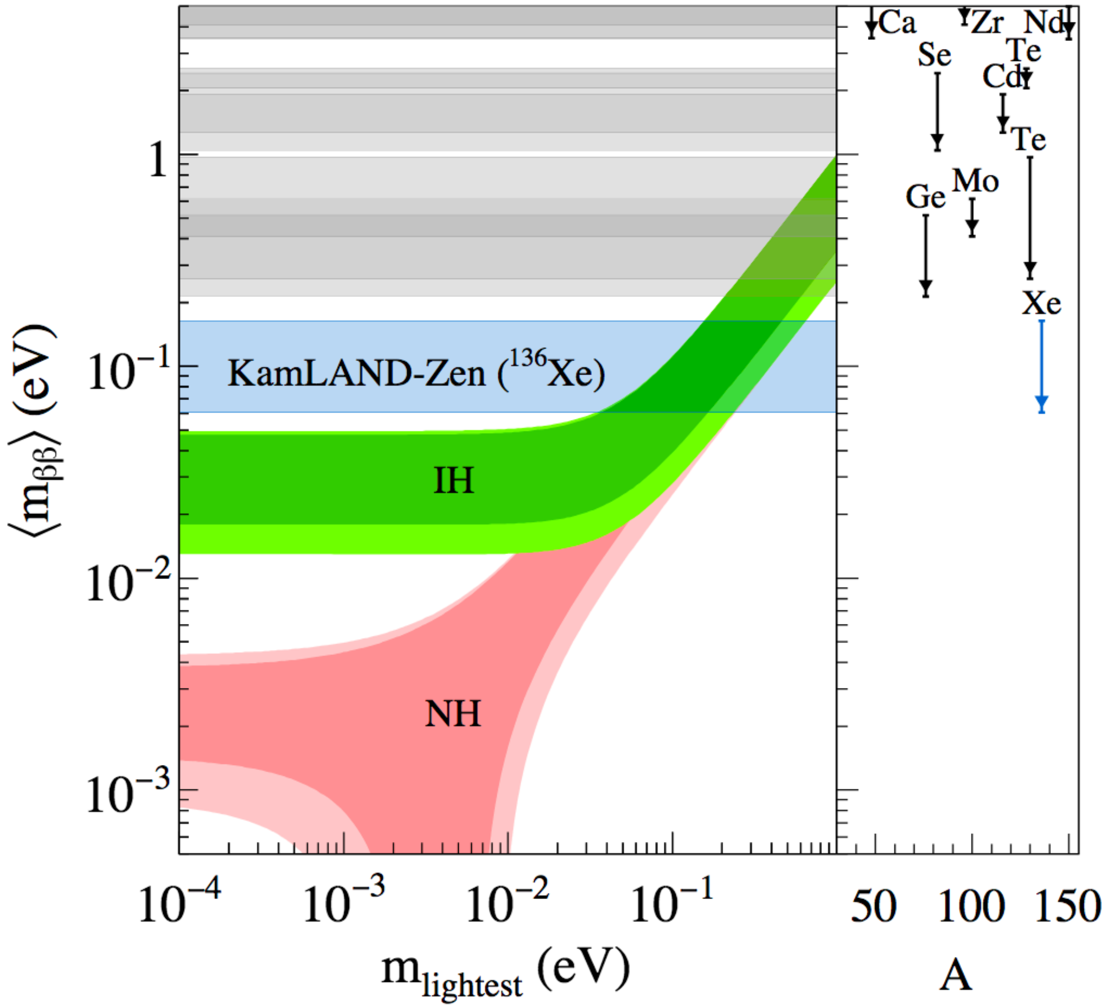


Full data set not shown



$T_{1/2} > 1.07 \times 10^{26}$ years
$m_{\beta\beta} < 61 - 165$ meV

KamLAND-Zen



Future discovery:

- Need more than one isotope.
- Need more than one experiment.
- If underlying process is not just mass mechanism, need topological reconstruction (e.g. SuperNEMO).

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Summary

- Current long-baseline experiments have preference for NH and CP violation, but statistical significance is low.
- Future programme progressing well; will ultimately resolve these questions and test three-flavour paradigm.
- Experiments severely constrain light sterile neutrinos.
- Neutrinoless double-β decay experiments are coming close to probing inverted hierarchy.