Status of Neutrino Experiments

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Experimental Directions in Neutrino Physics

Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

I will focus mostly here, with some (over)emphasis on long-baseline oscillations....

Many, many interesting things I will *not* cover: astrophysical neutrinos, cosmological neutrinos, cross sections, CEvNS, non-standard neutrino interactions and other BSM physics, geoneutrinos, practical applications...

The three flavor paradigm

what's known,
what's left to measure?

Neutrino Oscillations

"Solar" sector
"Atmospheric" sector
The twist in the middle

Remaining unknowns in the 3-flavor picture:
MO and CP δ

The mass pattern

Absolute Mass

Status and prospects

The mass scale

Majorana vs Dirac?

Overview of NLDBD

The mass nature

The three flavor paradigm

what's known,
what's left to measure?

Neutrino Oscillations

Latest 3-flavor results

Remaining unknowns in the 3-flavor picture:
MO and CP δ

The mass pattern

Absolute Mass

Status and prospects

The mass scale

Majorana vs Dirac?

Overview of NLDBD

The mass nature

The three-flavor neutrino paradigm

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi}|\nu_i\rangle$$

Parameterize mixing matrix U as

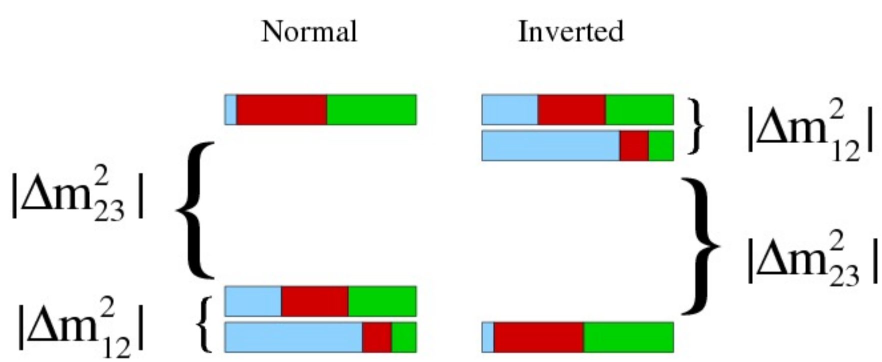
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

signs of the mass differences matter



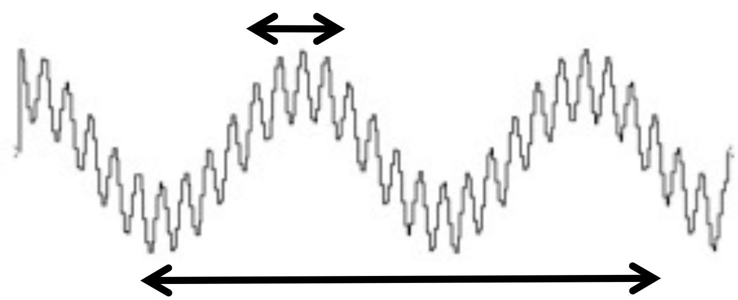
Oscillation probabilities in a 3-flavor context

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^* |\nu_i\rangle$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \qquad \text{(L in km, E in GeV, m in eV)}$$

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4 \sum_{i>j} \Re(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin^2(1.27 \Delta m_{ij}^2 L/E)$$
$$\pm 2 \sum_{i>j} \Im(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin(2.54 \Delta m_{ij}^2 L/E)$$

oscillatory behavior in L and E



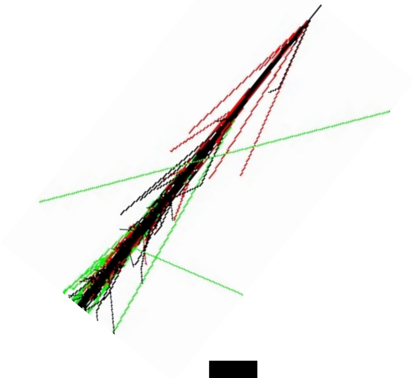
$$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$$ ➔ two frequency scales

For appropriate L/E (and U_{ij}), oscillations “decouple”, and probability can be described by the 2-flavor expression

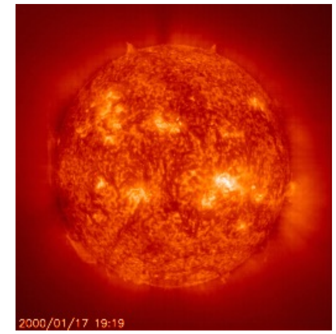
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



solar



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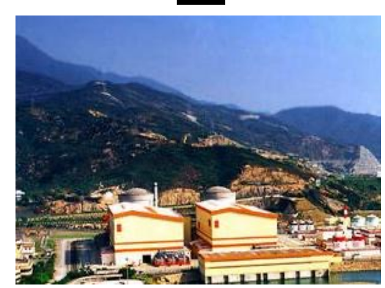
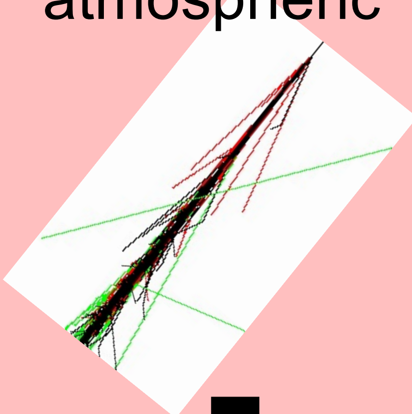
beams



reactor

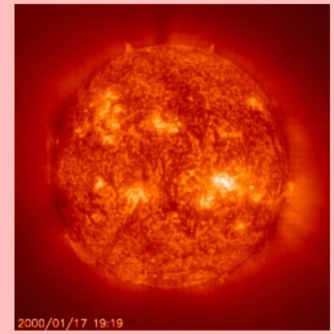
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
"wild" neutrinos...

solar



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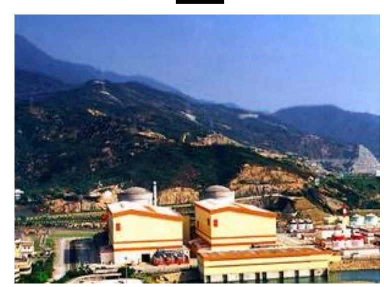

reactor

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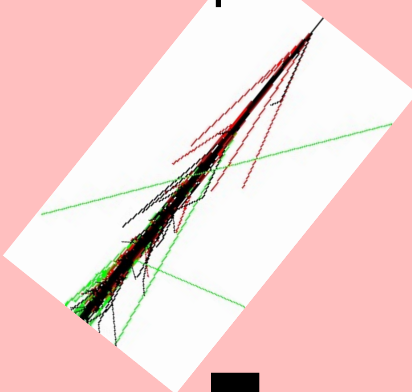
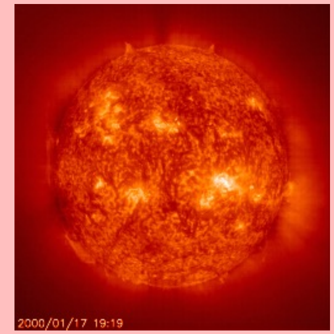


solar

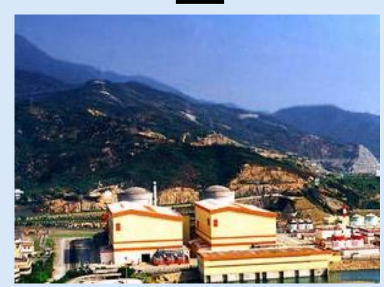


signal with
“wild” neutrinos...

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

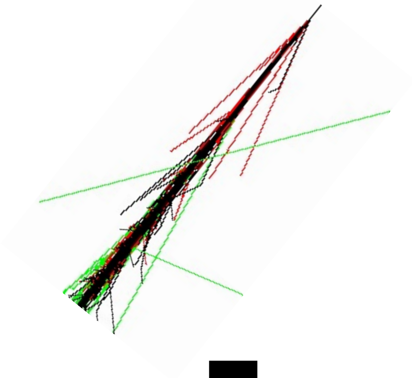
confirmed with
“tame” ones...

beams

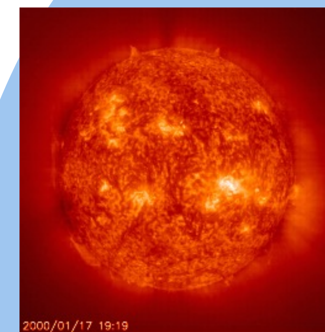


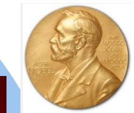
reactor

atmospheric



solar





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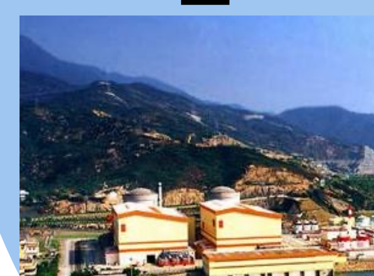
beams

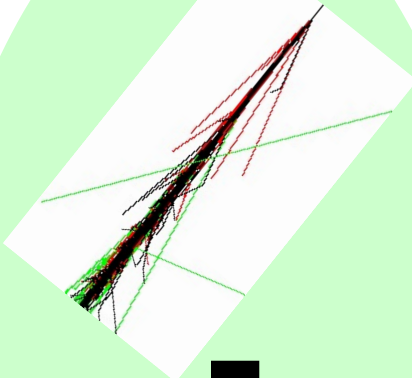
$$\Delta m^2_{12}, \theta_{12}$$

"Solar" sector: solar ν oscillations confirmed with reactors

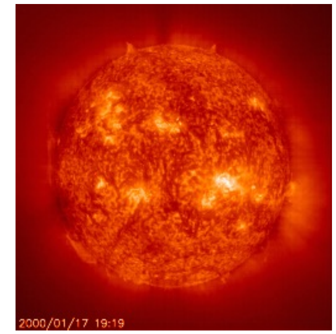


reactor

atmospheric



solar



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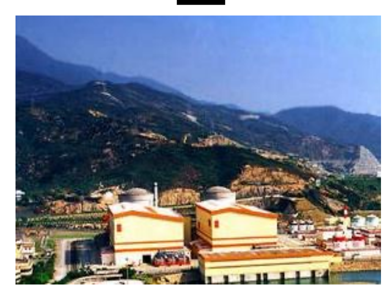
$|\Delta m^2_{23}|, \theta_{23}$

"Atmospheric" sector

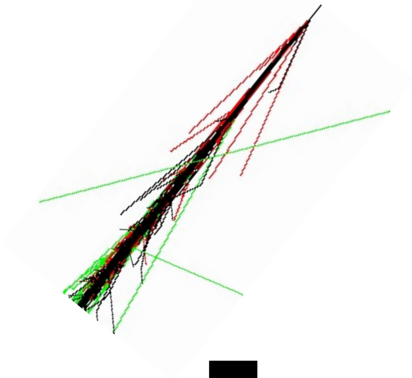
beams



reactor

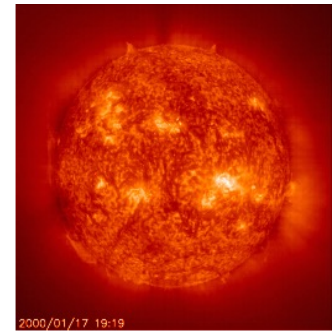
The mixing angle θ_{13}: information from beams and burns!

atmospheric



θ_{13}, the "twist in the middle"

solar



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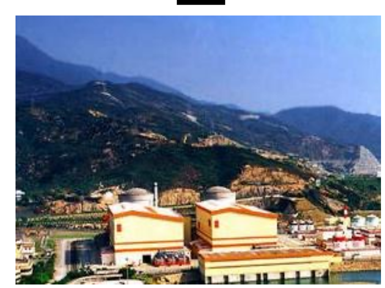
beams

reactors



K2K, MINOS(+), **T2K, NOνA**

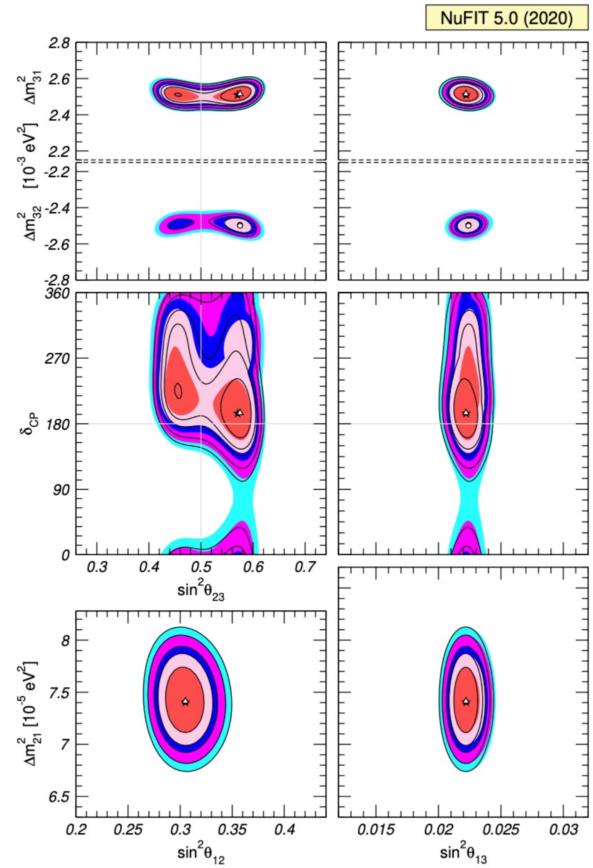
CHOOZ, **Double Chooz, Daya Bay, RENO**

Oscillation fit information is now extracted with **joint fits to multiple oscillation channels**, neutrinos and antineutrinos, all data

The three-flavor picture fits the data well

Global three-flavor fits to all data

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}	$193 \to 352$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$



$$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0 \text{ for NO and } \Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0 \text{ for IO.}$$

Esteban et al., arXiv:2007.14792, 10.1007/JHEP09(2020)178

What do we *not* know about the three-flavor paradigm?

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
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$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO.

Is θ_{23} non-negligibly greater or smaller than 45 deg?

poor knowledge

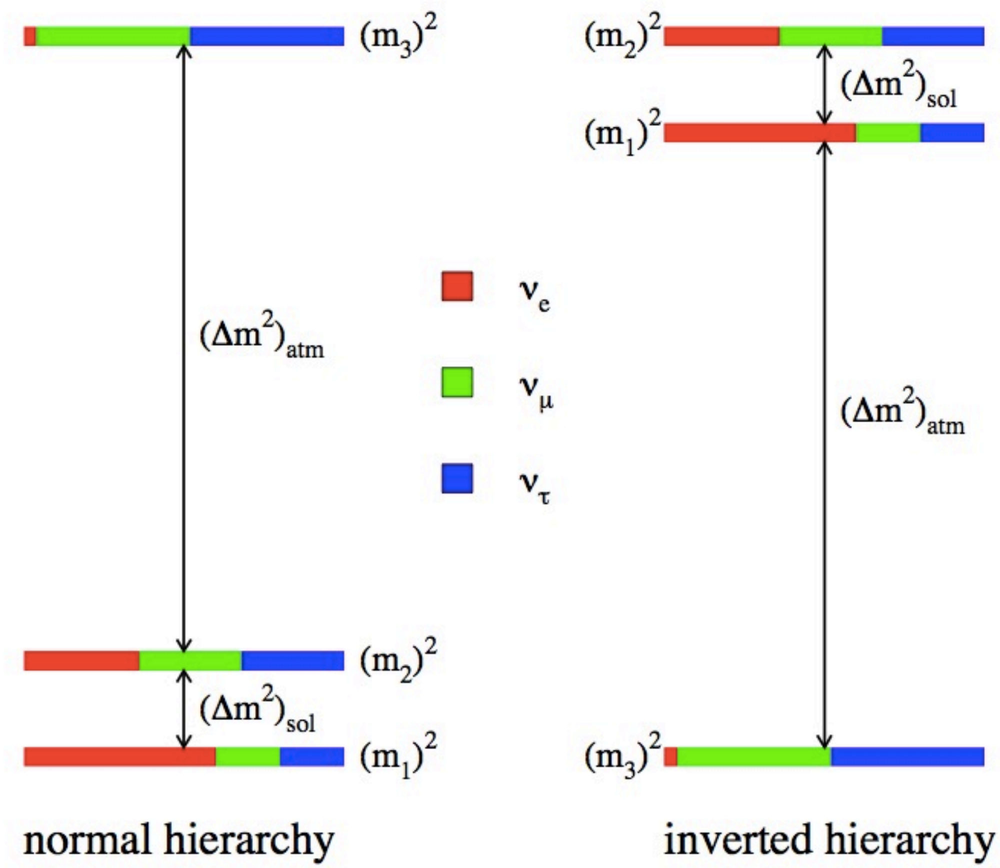
sign of Δm^2 unknown (ordering of masses)

Esteban et al., arXiv:2007.14792, 10.1007/JHEP09(2020)178

Next on the list to go after experimentally:

mass ordering (sign of Δm^2_{32})

[Note: "mass hierarchy" is now uncool to say, as masses may be quasi-degenerate]



$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

There are many ways to determine the mass ordering

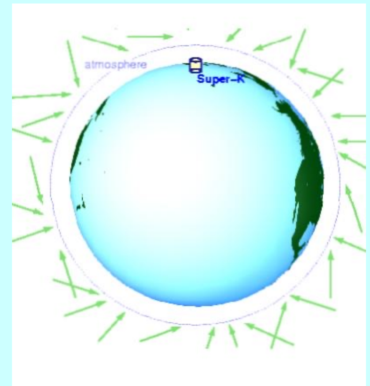
They are all challenging...

Four of the possible ways to get MO

Long-baseline beams

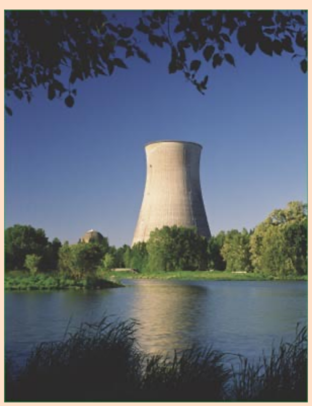
Hyper-K, LBNF/DUNE

Atmospheric neutrinos



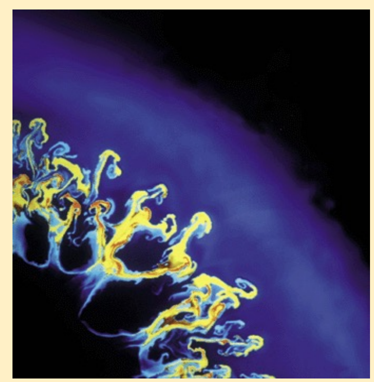
Super-K, Hyper-K, IceCube, KM3Net, DUNE, INO

Reactors



JUNO

Supernovae



Many existing & future detectors

Long-baseline beams

Other methods are very promising,
but the long-baseline method
is the only one that's ***guaranteed*** with
sufficient exposure at long baseline
(...but it's tangled with CP violation)

Long-baseline approach for going after MO and CP

Measure transition probabilities for

$\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

through matter

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$
$$+\tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

Change of sign for antineutrinos

A. Cervera et al., Nucl. Phys. B 579 (2000)

$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$

$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \; \tilde{B}_\mp \equiv |A \mp \Delta_{13}|, \; A = \sqrt{2}G_F N_e$

Different probabilities as a function of L& E for neutrinos and antineutrinos, depending on:

- CP δ
- matter density (Earth has electrons, not positrons)

Where we are now with long-baseline experiments

Past | Current | Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

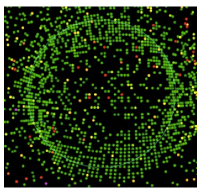
CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

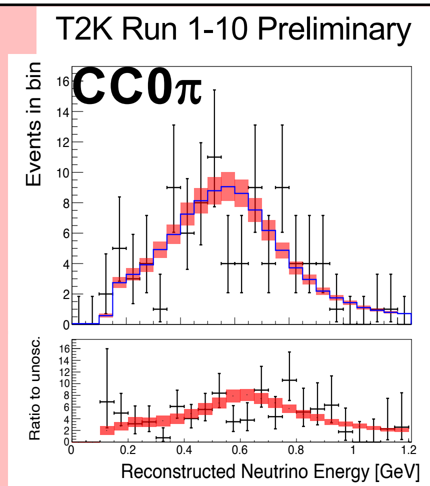
T2K
J-PARC to Kamioka
295 km, 380-750 kW

T2K appearance and disappearance samples

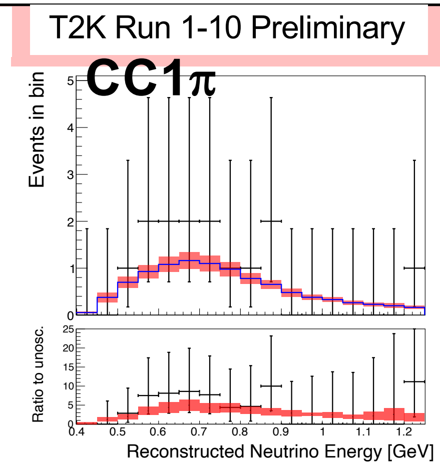
Electron neutrino appearance



Neutrino mode

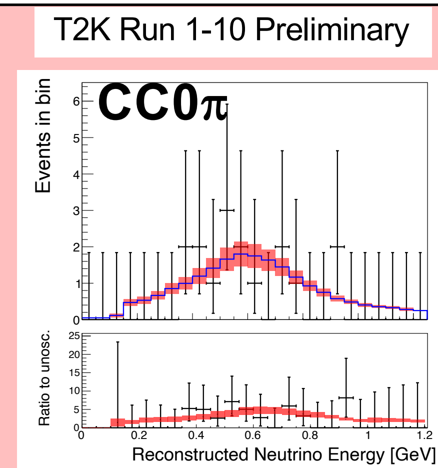


94 events



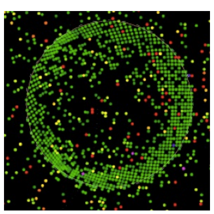
14 events

Antineutrino mode

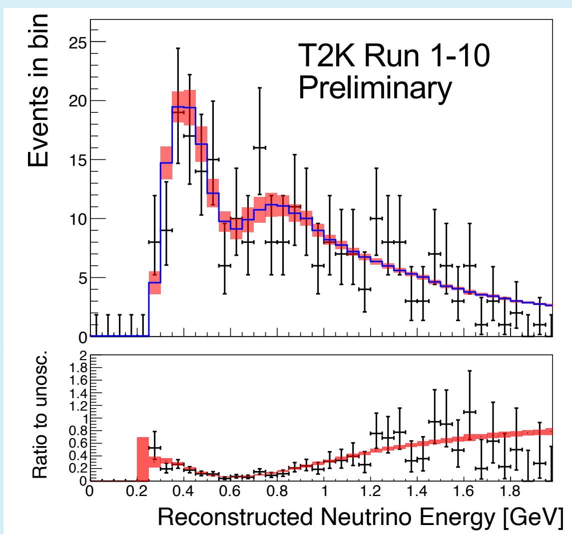


16 events

Muon neutrino disappearance

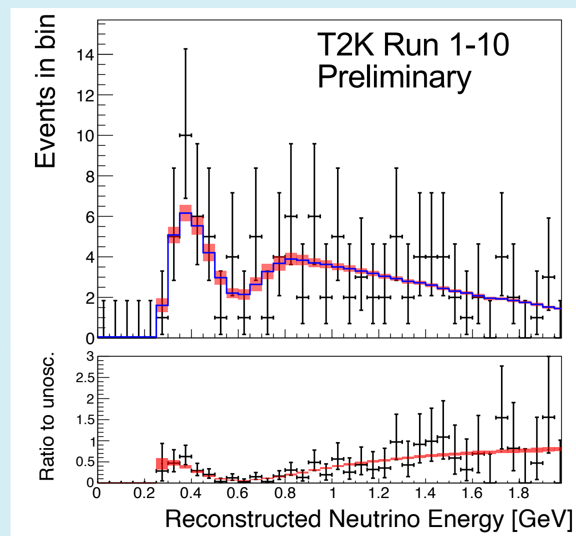


Neutrino mode



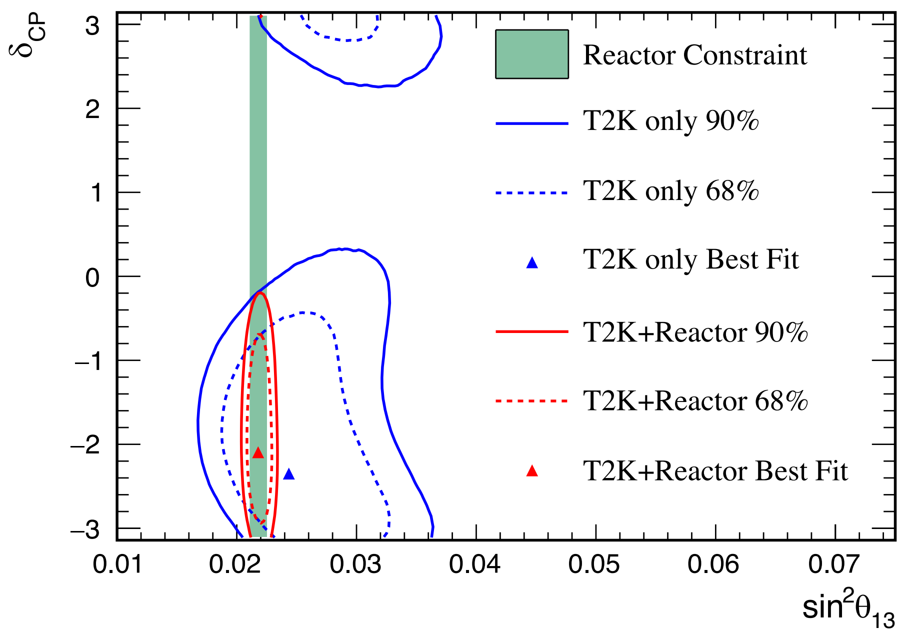
318 events

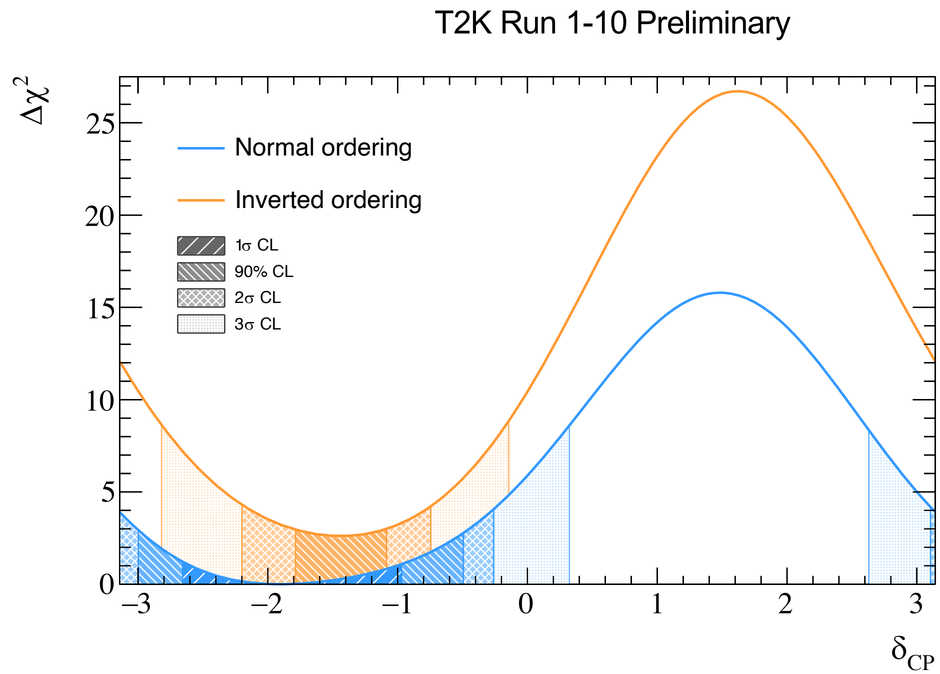
Antineutrino mode



137 events

Joint fit to all T2K data



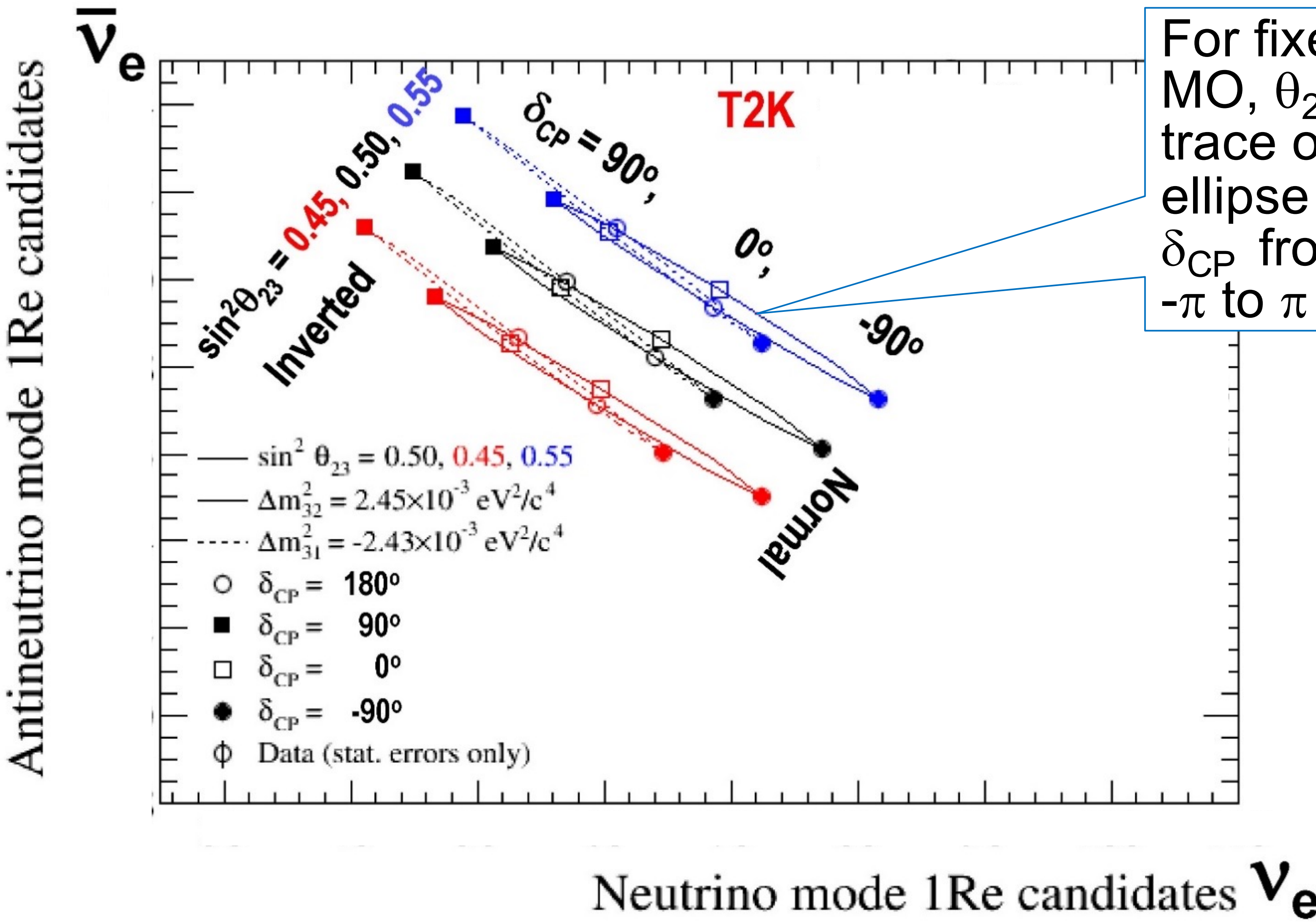


- 35% of CP δ values excluded at 3σ marginalized across mass orderings
- CP-conserving values (0, π) excluded at 90% but not quite at 2σ
- Weak preference for normal ordering

P. Dunne, Nu2020

"Bi-event rate plot":

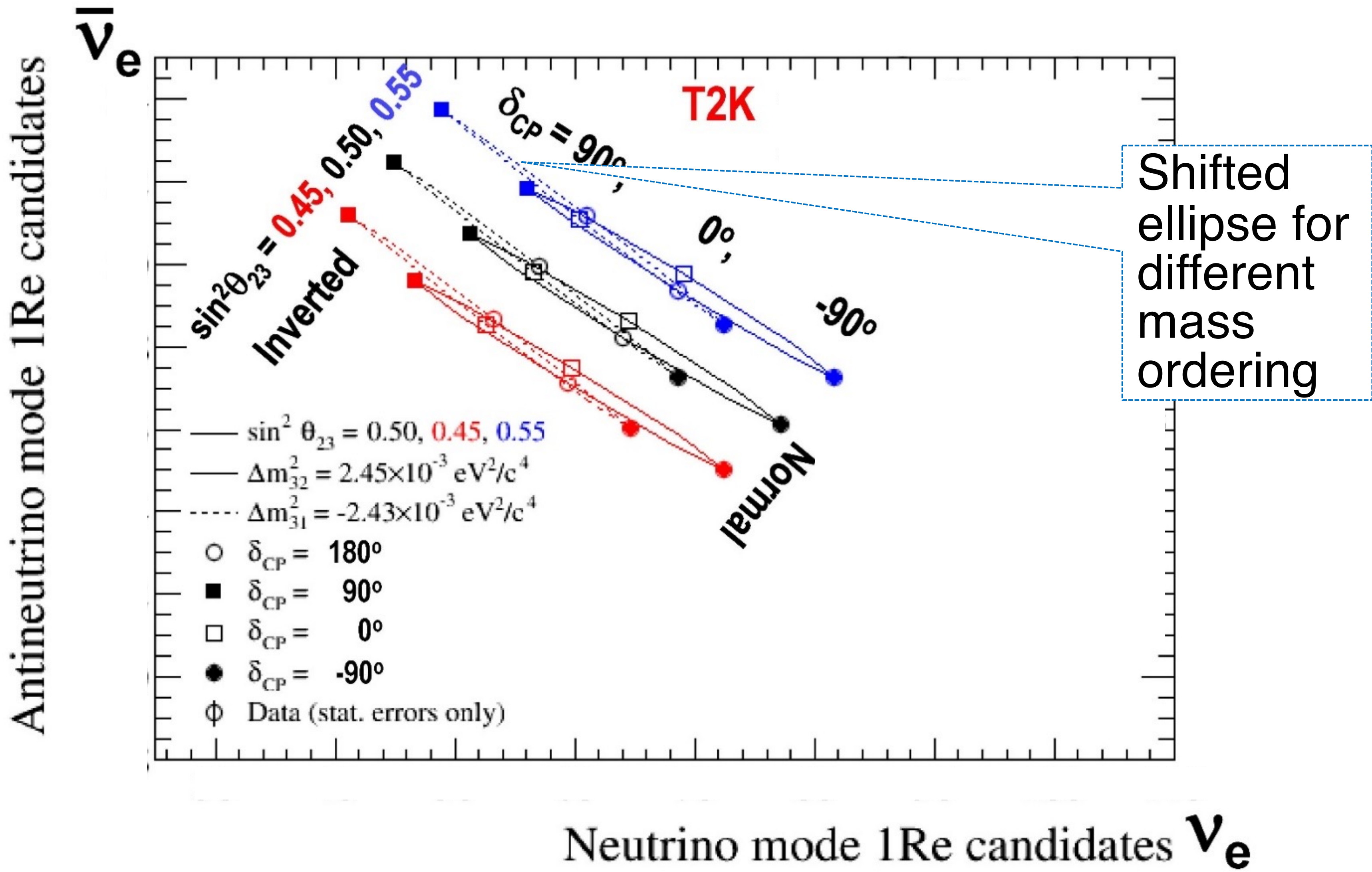
compare electron neutrinos and antineutrino counts to visualize parameter sensitivity (& degeneracies)



For fixed MO, θ_{23}: trace out ellipse for δ_{CP} from $-\pi$ to π

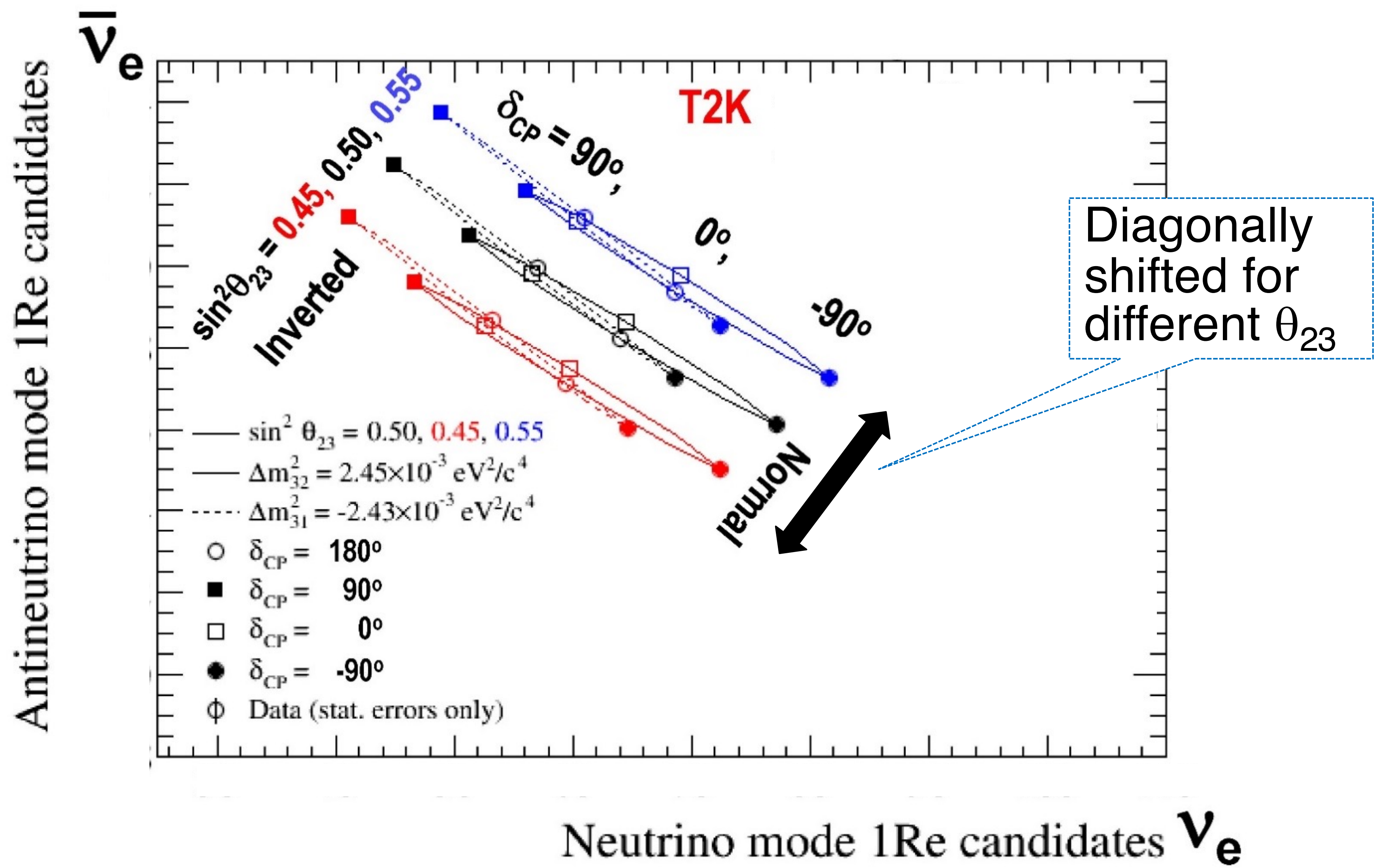
"Bi-event rate plot":

compare electron neutrinos and antineutrino counts to visualize parameter sensitivity (& degeneracies)

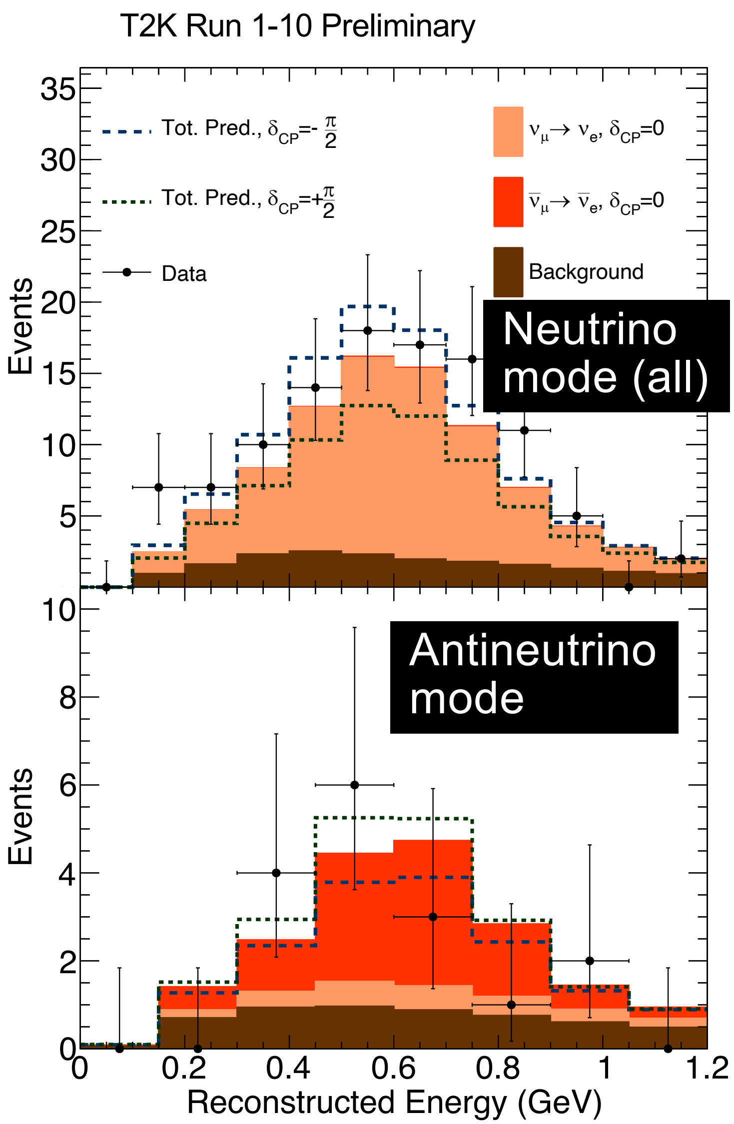


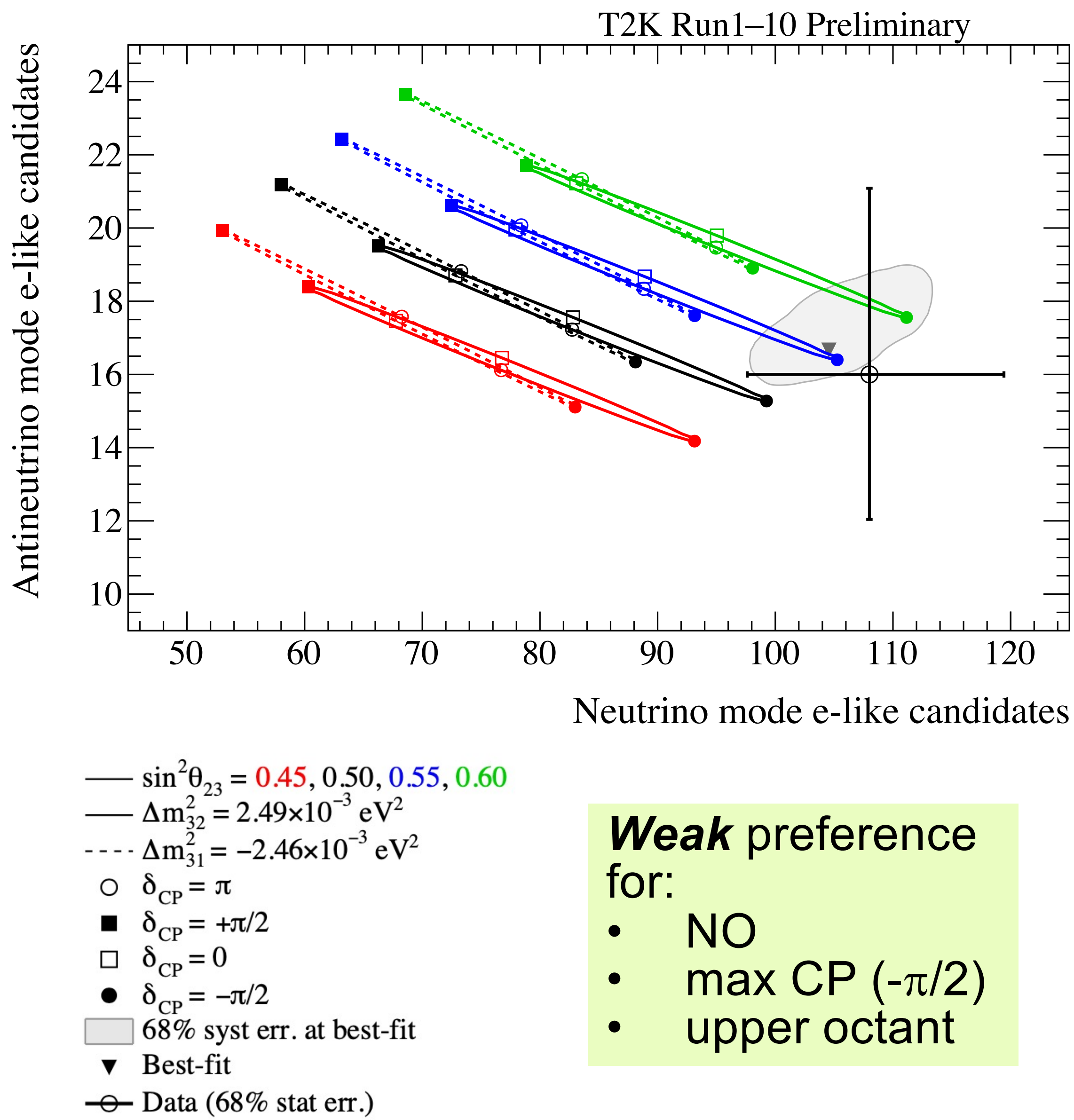
“Bi-event rate plot”:

compare electron neutrinos and antineutrino counts to visualize parameter sensitivity (& degeneracies)



“Bi-event rate” plot for T2K Run 1-10 electron-like SK samples

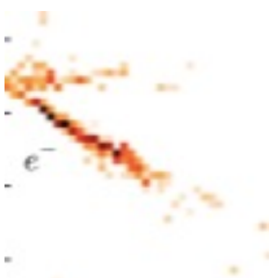
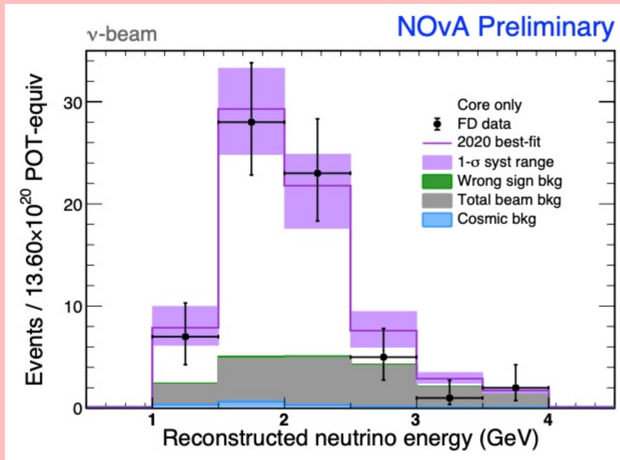
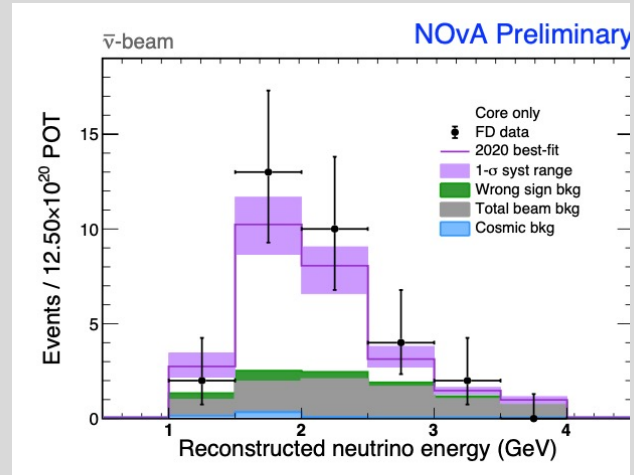
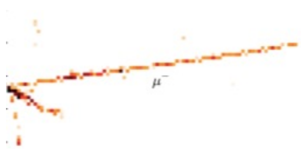
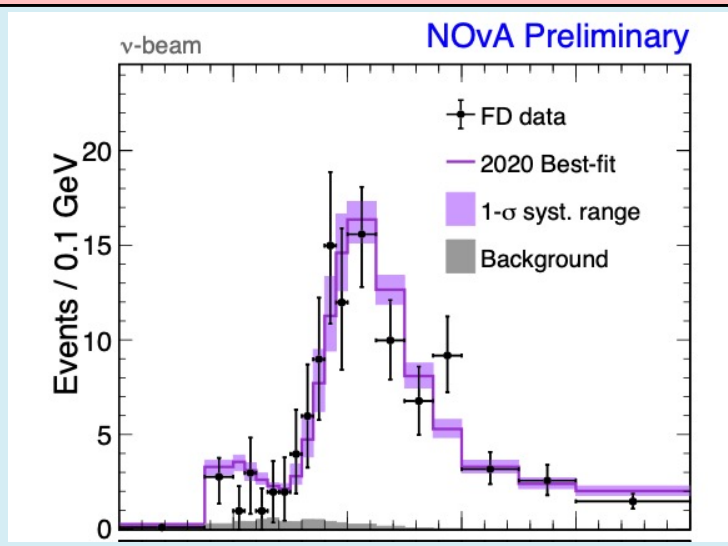
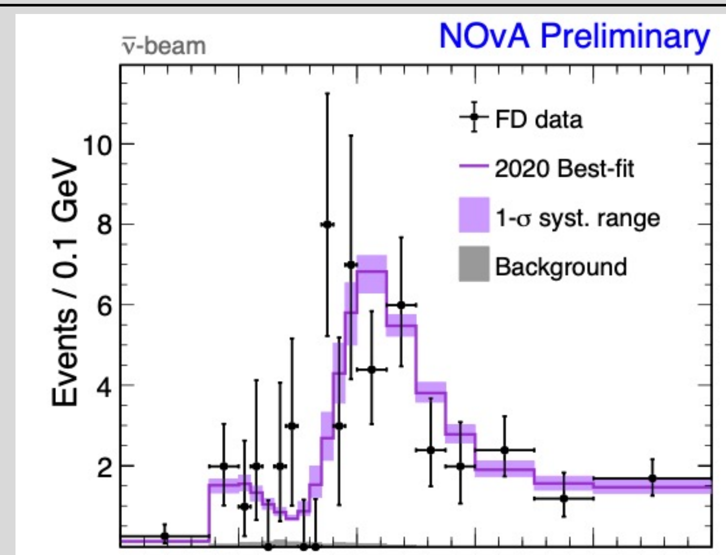




Weak **preference for:**

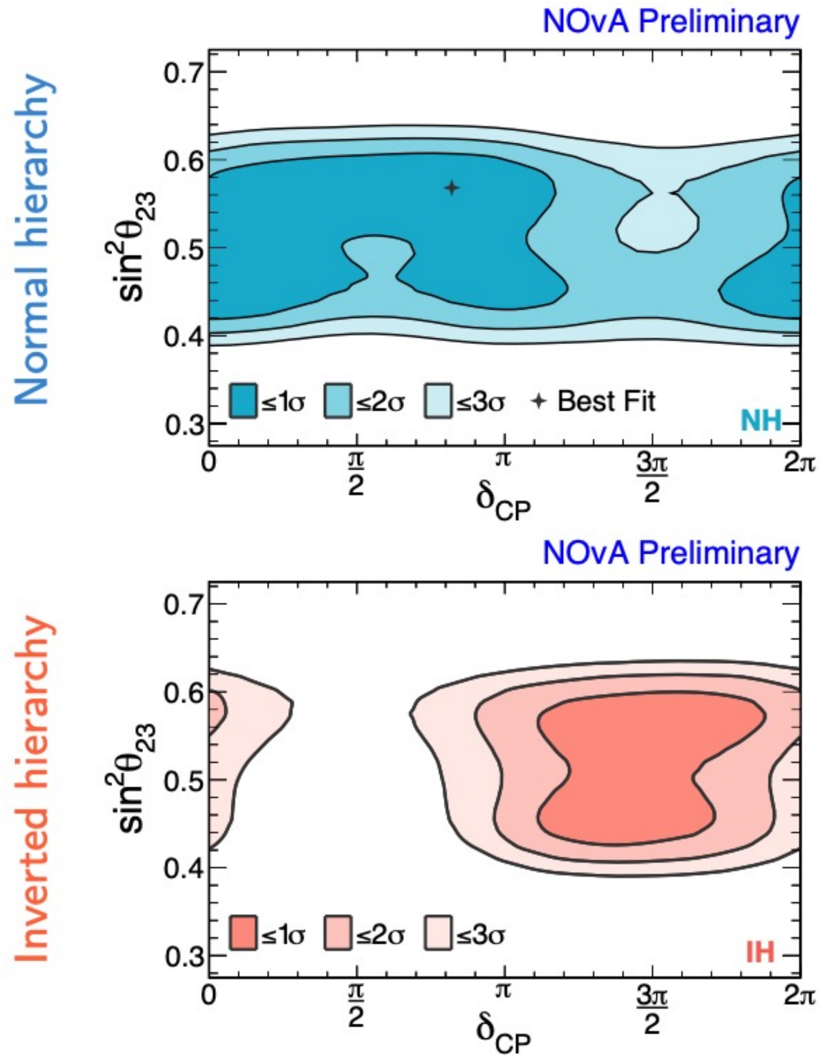
- NO
- max CP ($-\pi/2$)
- upper octant

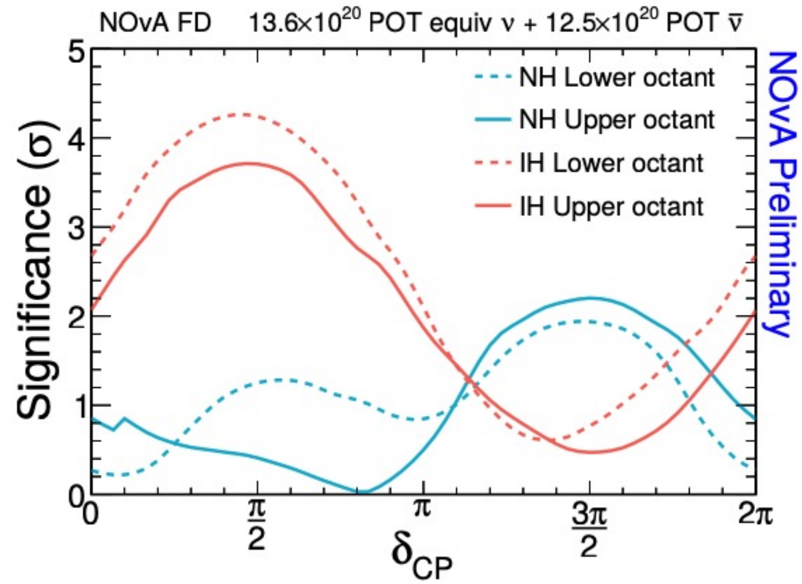
NOvA appearance and disappearance

	Neutrinos 13.6×10^{20} pot	**Antineutrinos** 12.5×10^{20} pot
Electron neutrino appearance 		
Muon neutrino disappearance 		

M. Strait, Neutel 2021

NOvA Parameter Fit Results



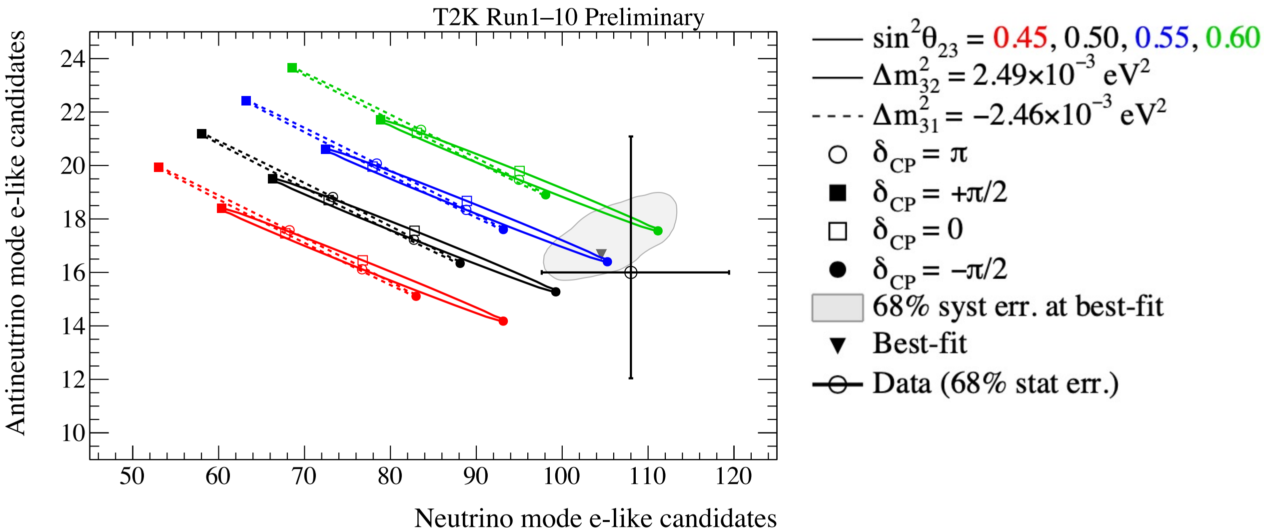


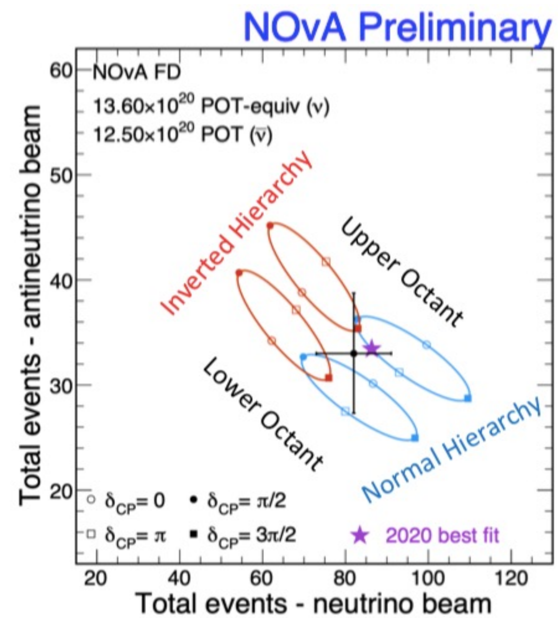
- All values of δ allowed
- Prefer normal hierarchy by 1.0σ
- Prefer **upper octant** by 1.2σ
- Exclude $\delta = \pi/2$ in IH at $> 3\sigma$

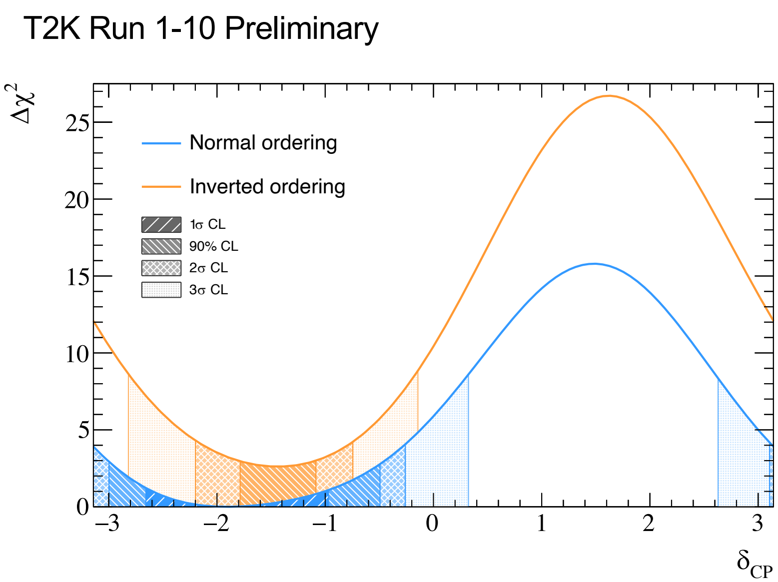
M. Strait, Neutel 2021

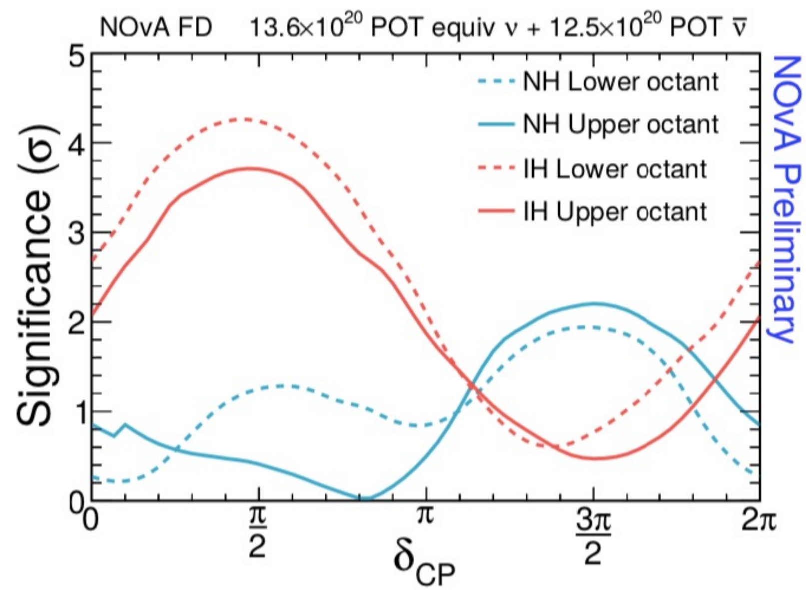
T2K vs NOvA results

A. Himmel, Nu2020



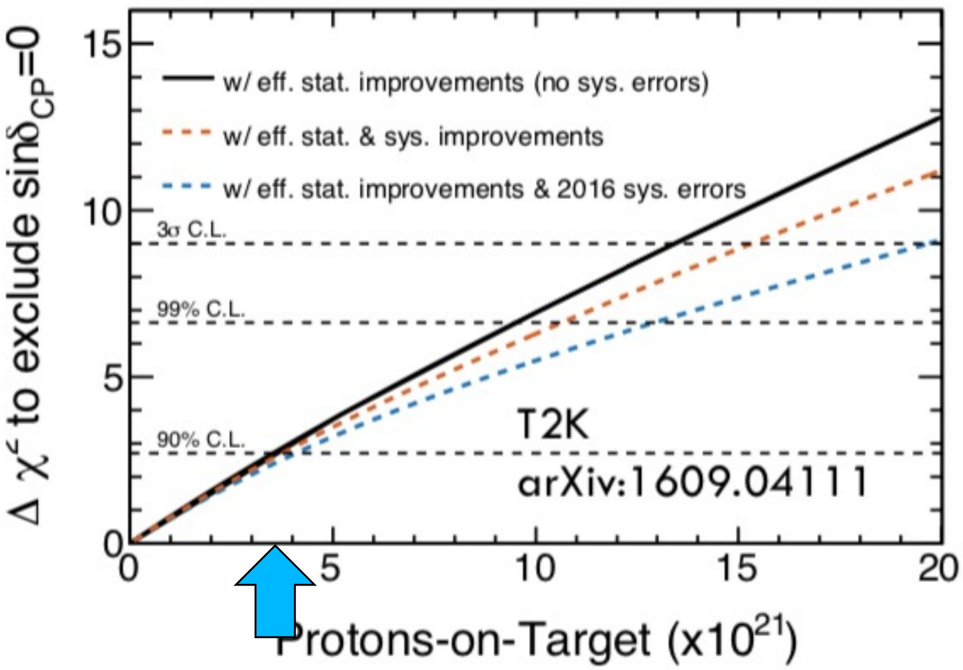


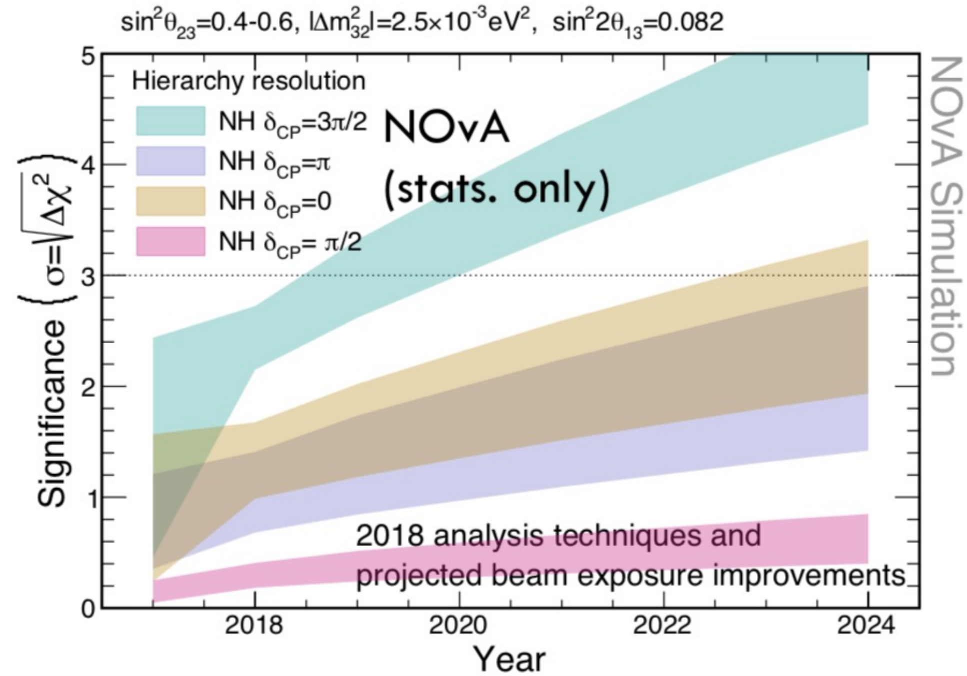




- NOvA sees no strong asymmetry in ν_e/ν_e-bar appearance

Future Prospects for T2K and NOvA





P. Vahle, APS 2018

- Approved 7.8e21 POT by 2021
- Beam upgrade to >1 MW in 2022
- T2K-II: 20e21 POT by ~2026

- For favorable parameters, NOvA will reach 3σ MO sensitivity by 2020
- 3σ for 30-50% of CP δ range by 2024

Joint T2K-NOvA analysis in the works

NEW ...and Super-K now running as **SK-Gd** with Gd doping for n capture

And the future...

Past → Current → Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

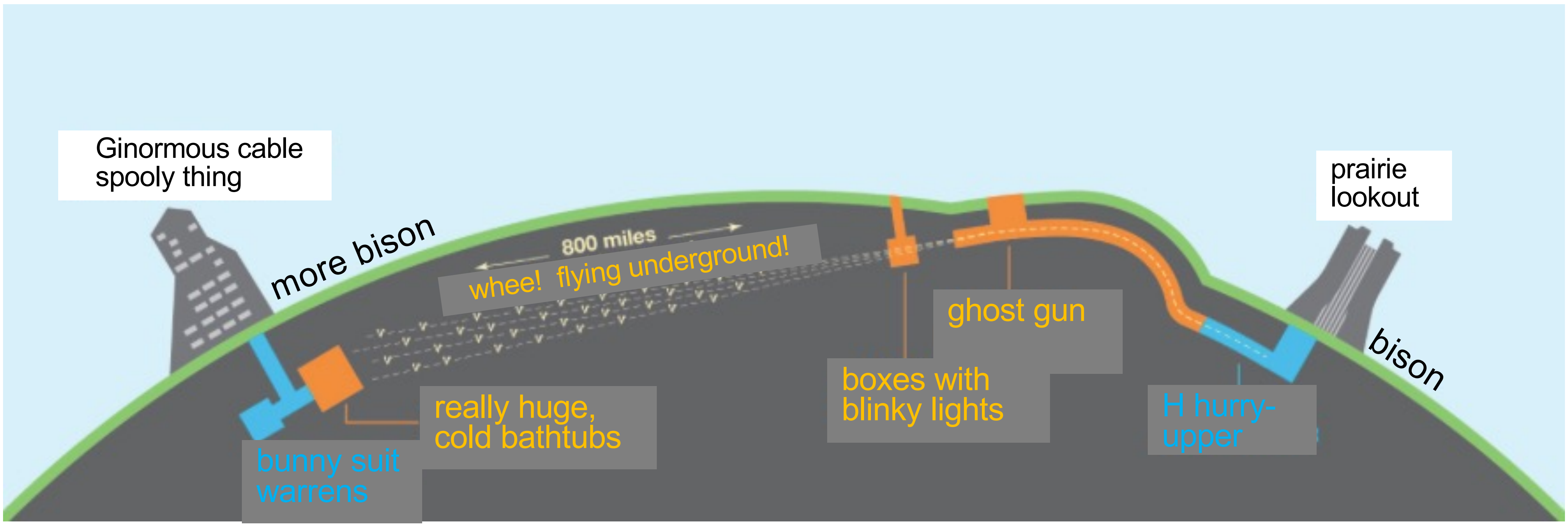
T2K (II)
J-PARC to Kamioka
295 km, 380-750 kW ➔>1 MW

LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW

Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)

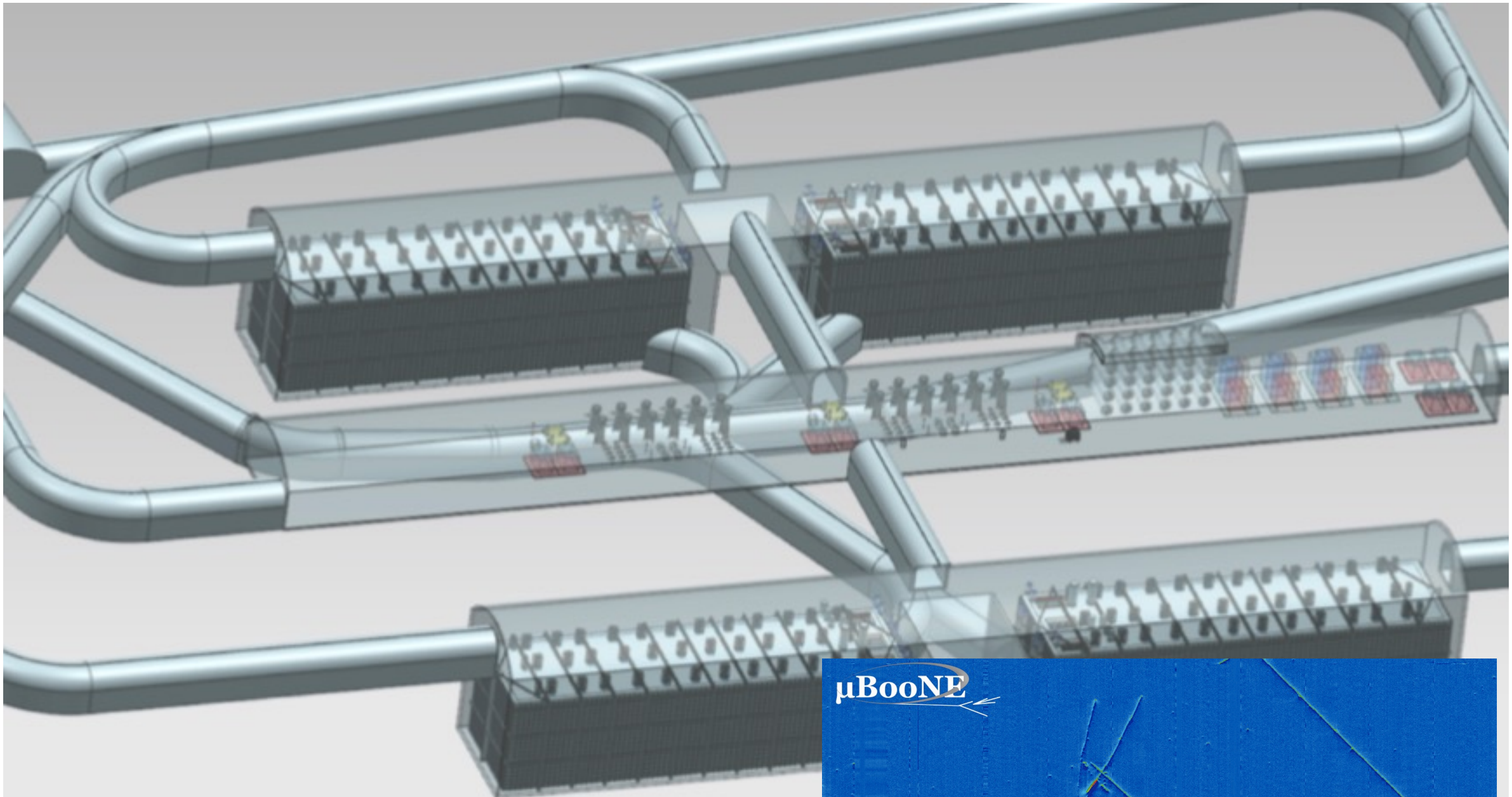


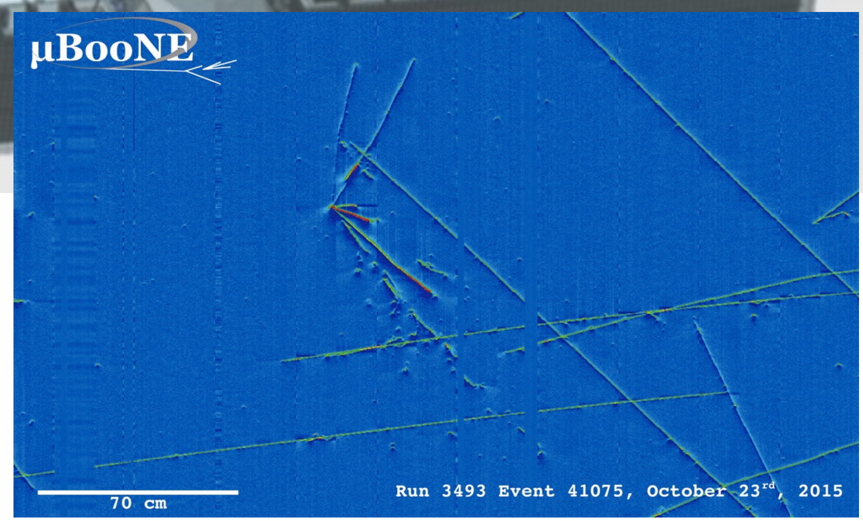

Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility



- new 1.2 MW beam (upgradable to 2.4 MW), Fermilab to SD
- 1300 km baseline
- 40-kton fiducial liquid argon TPC far detector
- Also proton decay, supernova, atmospheric neutrinos...

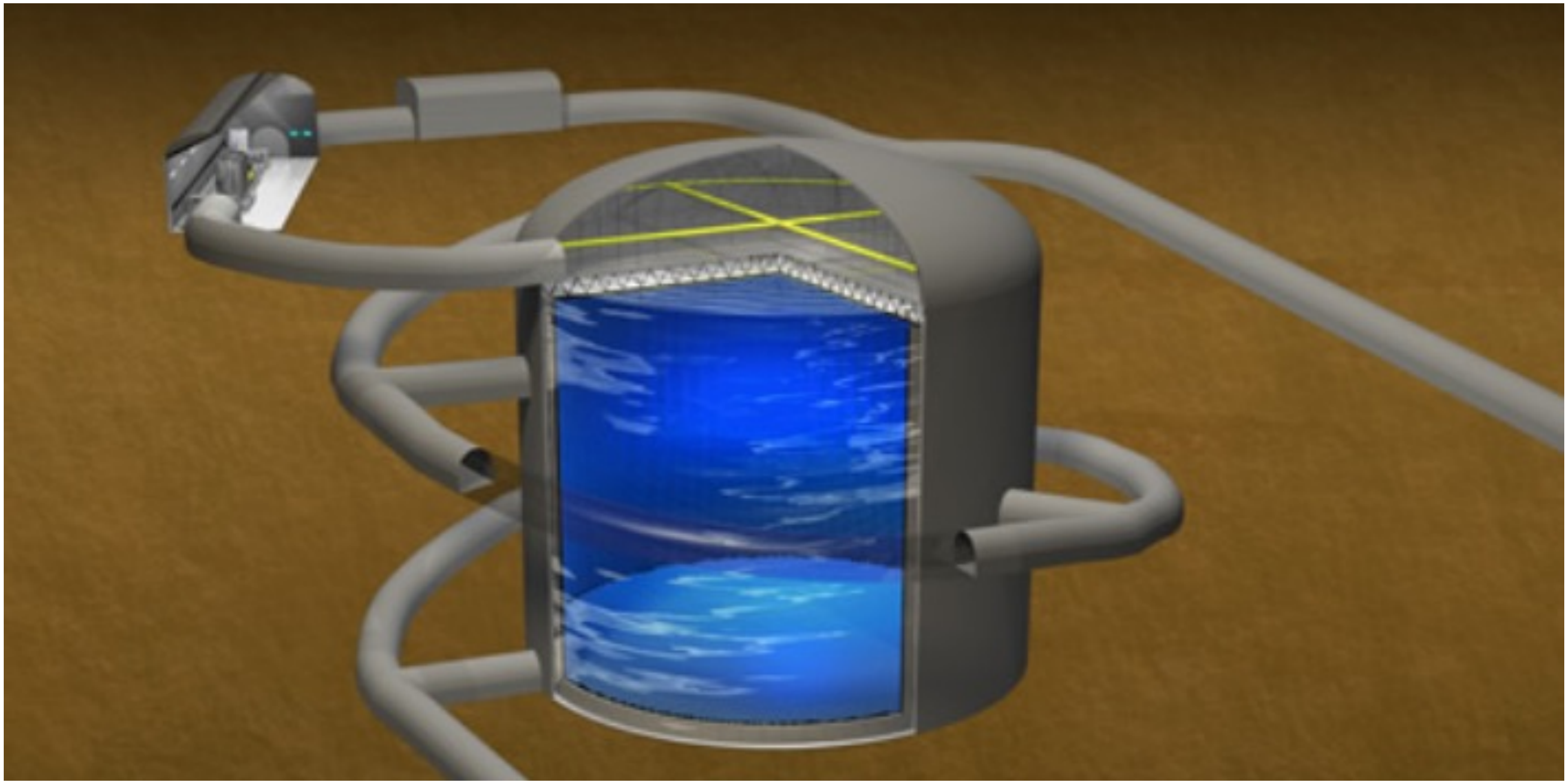
The DUNE far detector: 70,000 tons of liquid argon





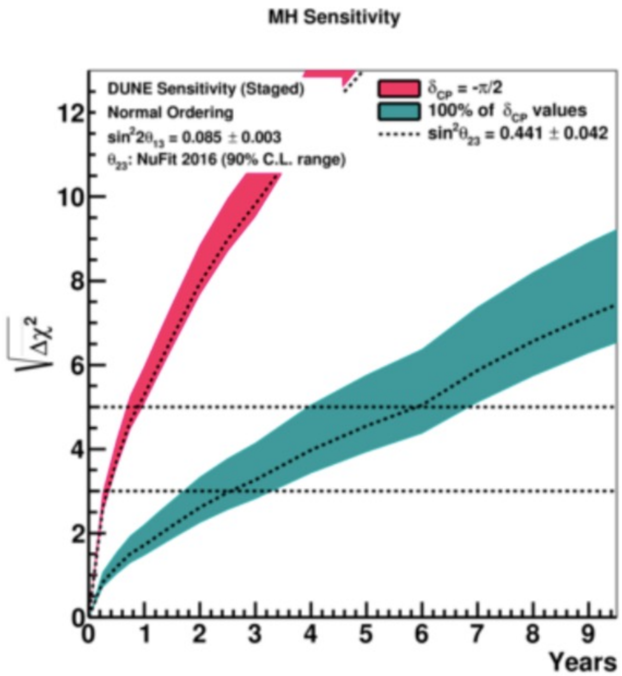
- exquisitely precise tracking
- single-phase and dual-phase technology under consideration (prototypes @ CERN)
- Technical Design Report complete
- multiple complementary near detectors

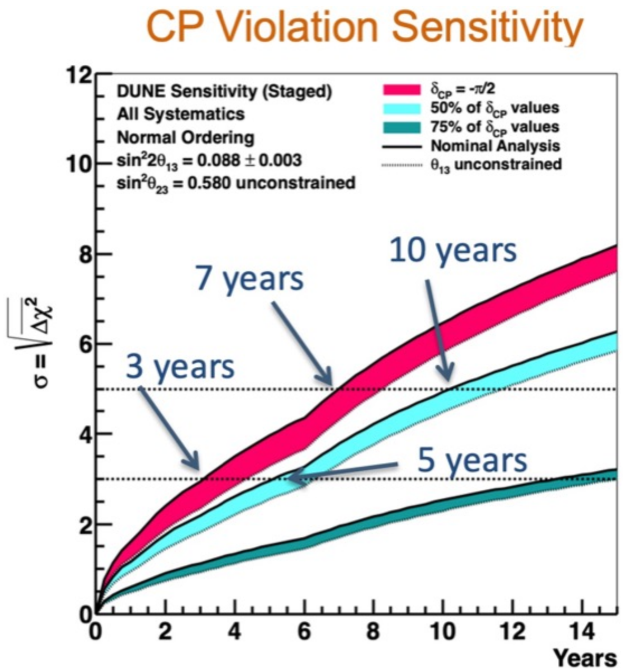
Hyper-Kamiokande



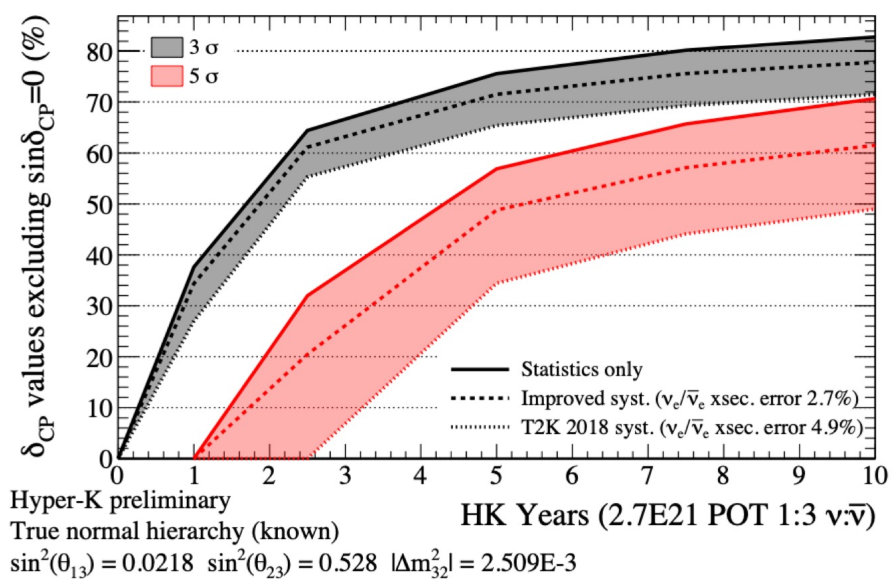
- 260k (188k) ton mass
- Beam from J-PARC 295 km away, upgrade to 1.3 MW
- Construction has started; expect data in 2027
- Many non-accelerator physics topics

MO & CPV Sensitivity of DUNE and Hyper-K





DUNE
will nail
down MO
very fast thanks
to long baseline;
also good CP δ
sensitivity



Improved
CP δ sensitivity
with atmospheric
neutrinos as well

F. Di Lodovico, NeuTel 2021

Long-baseline beam experiments

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
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295 km, 380-750 kW ➔>1 MW

LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2.4 MW)

Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)

And beyond...
ESSnuB,
neutrino factories...





All of this discussion is in the context of the standard 3-flavor picture and testing that paradigm....

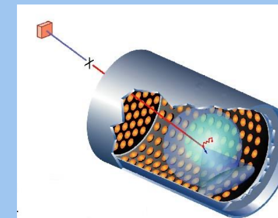
There are already some slightly uncomfortable data that **don't fit that paradigm**...

Open a parenthesis: (

Outstanding 'anomalies'

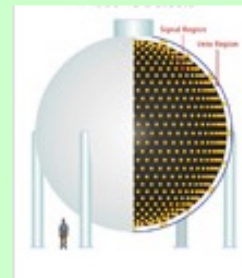
LSND @ LANL (~30 MeV, 30 m)

Excess of $\overline{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



➔ $\Delta m^2 \sim 1\ eV^2$: inconsistent with 3 ν masses

MiniBooNE @ FNAL ($\nu,\overline{\nu}$ ~1 GeV, 0.5 km)



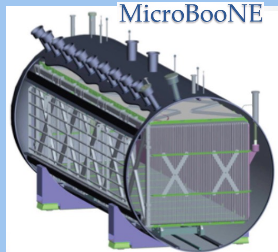
- unexplained >3 σ excess for E < 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos
  (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos
  (consistent w/ LSND)
- for E>200 MeV, both nu and nubar consistent with LSND
- **new 2018 analysis w/ x2 ν data has higher-significance excess**

????

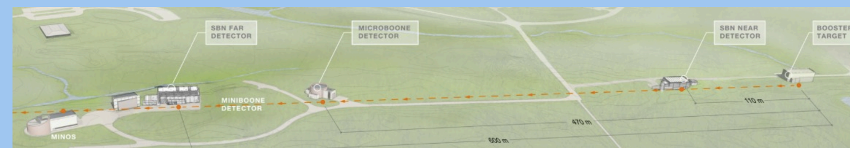
Also: possible deficits of reactor $\overline{\nu}_e$ ('reactor anomaly') and source ν_e ('gallium anomaly')

Sterile neutrinos? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle & astrophysics
[cosmology w/Planck now consistent w/3 flavors... but allows 4...]
Or some other new physics??

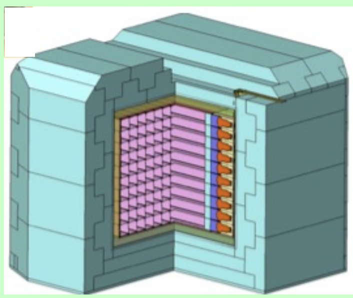
Many experiments going after steriles...



Experiments with beams
(meson decay in flight and at rest)

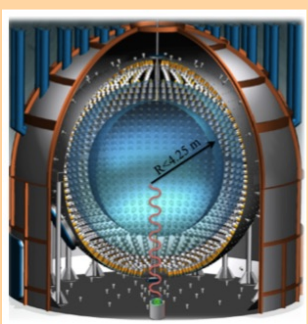


FNAL SBN, JSNS^2, ...



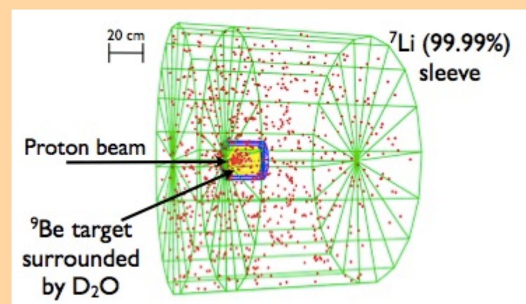
Experiments at reactors

PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....



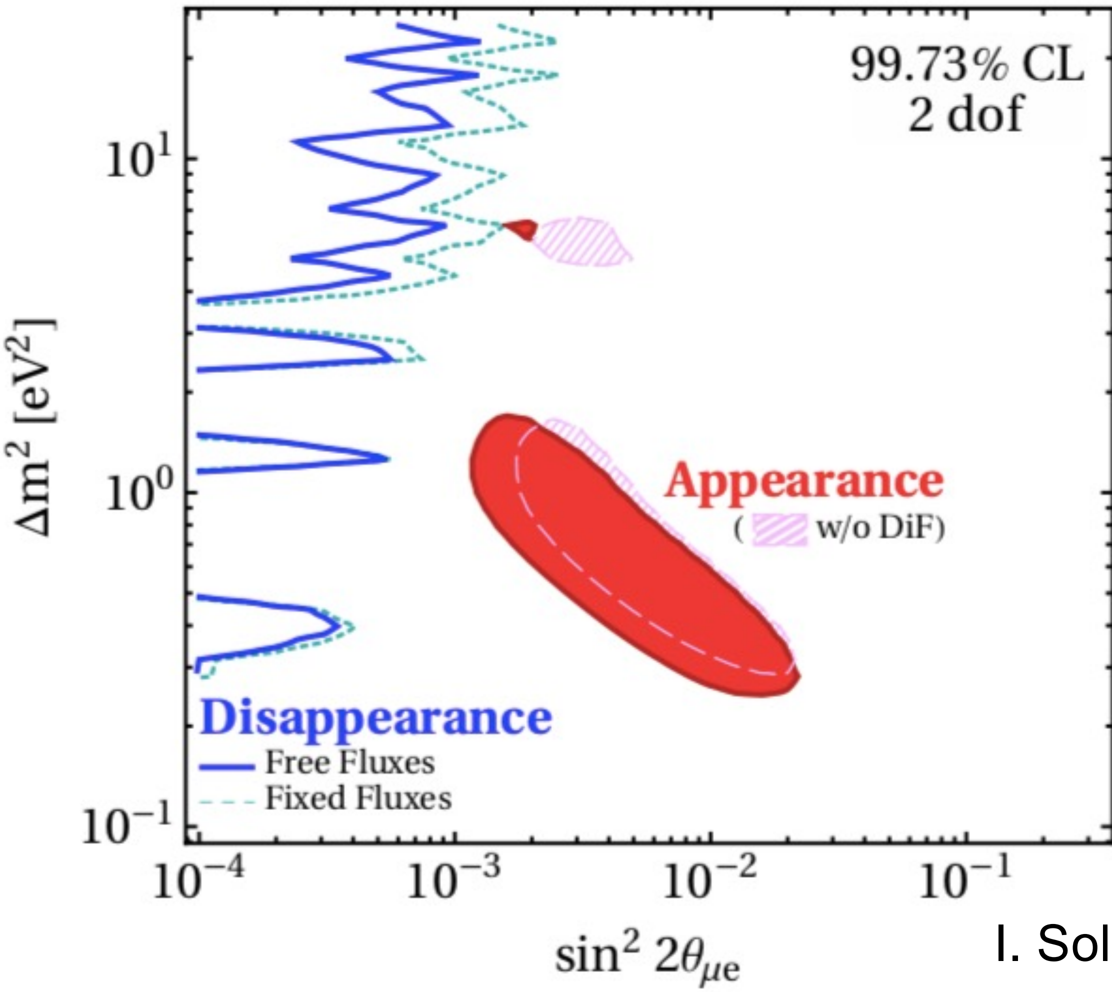
Experiments with radioactive sources

(CeSOX), IsoDAR, BEST...



and many more... no clear picture yet...

Fits to “all” the data are uncomfortable...



I. Soler

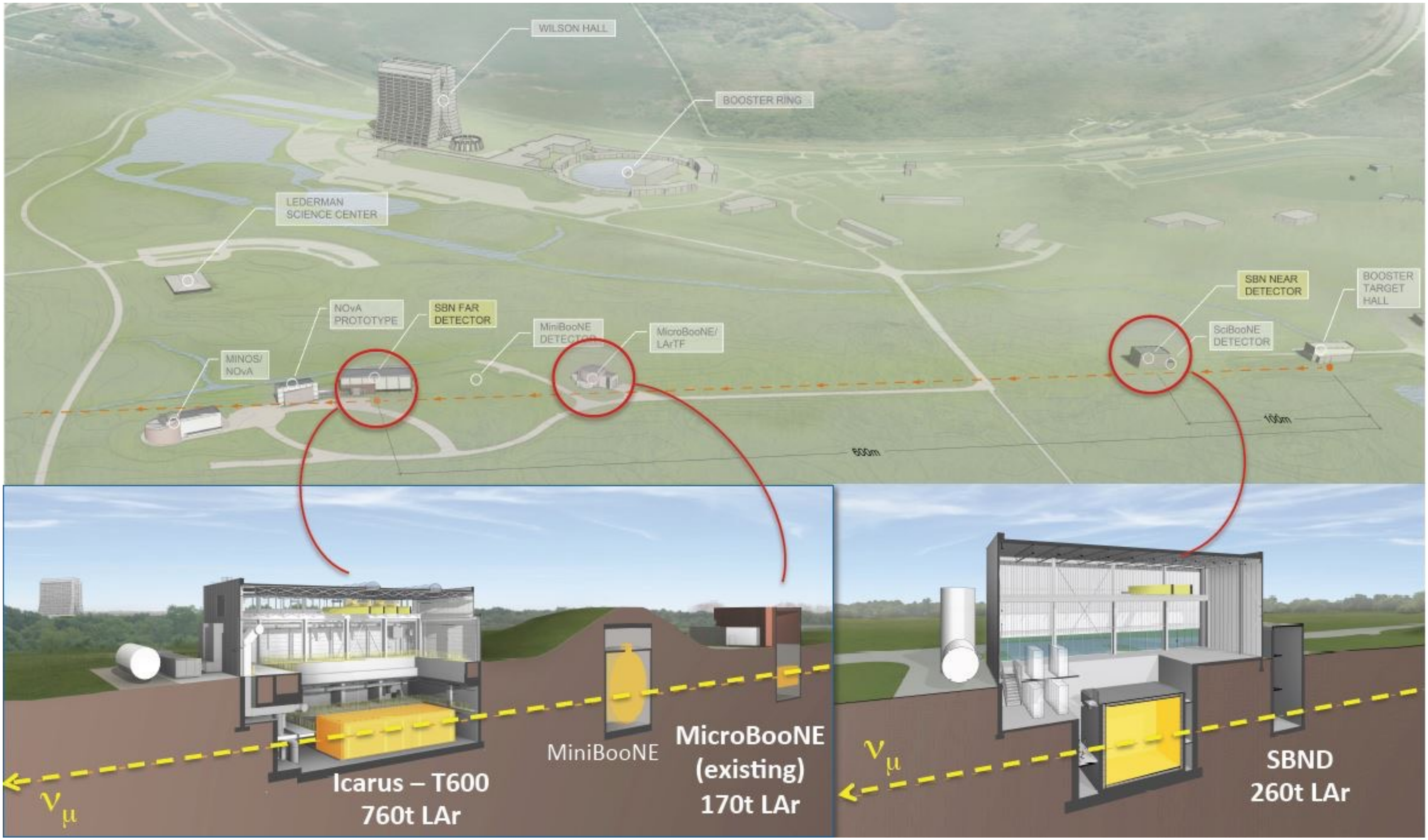
Appearance and disappearance data are in fairly serious tension

M. Dentler et al. https://doi.org/10.1007/JHEP08(2018)010

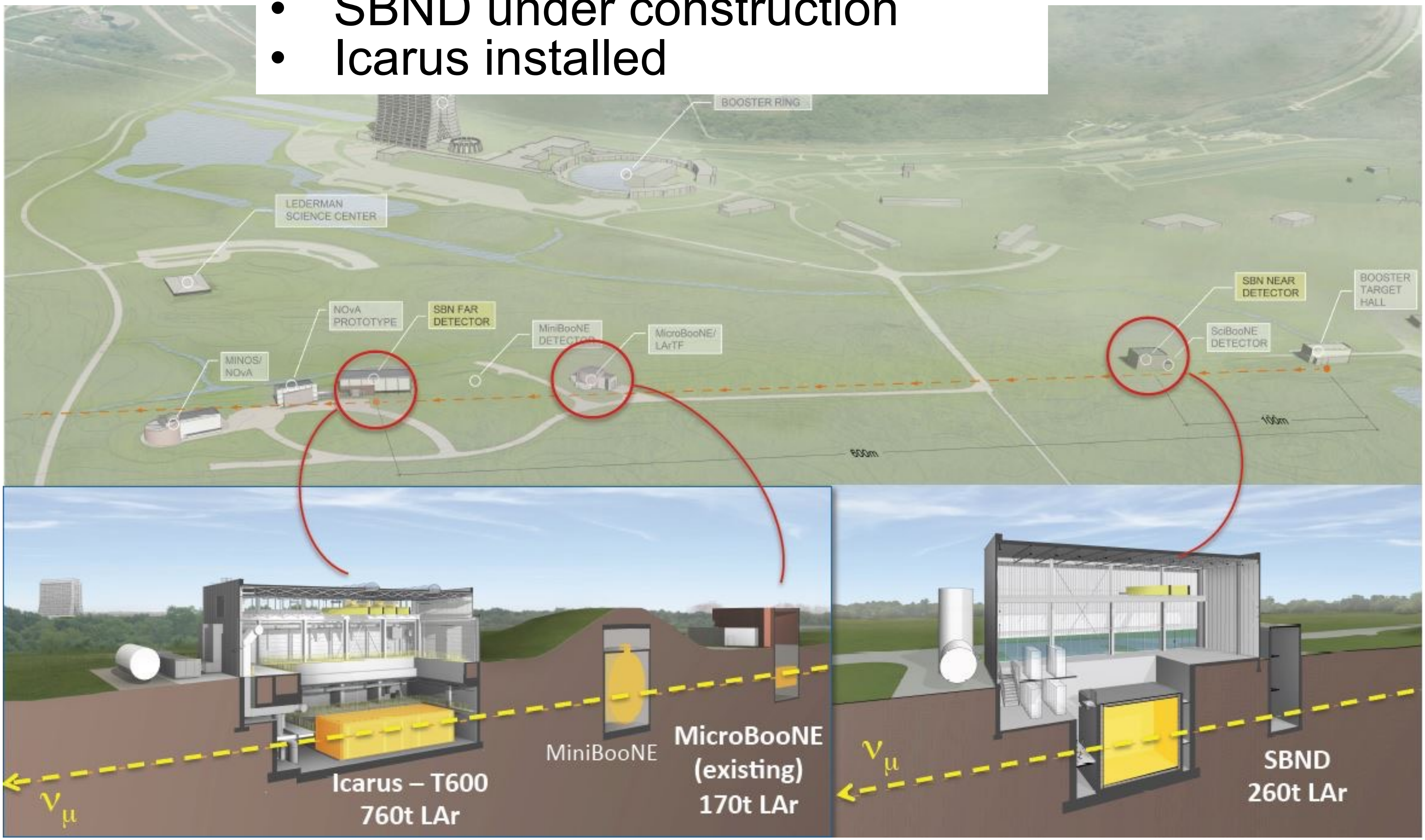
[does not include PROSPECT, STEREO + other new data]

... parenthesis not closed...

Short-baseline program at FNAL



- Many results from MicroBooNE
- SBND under construction
- Icarus installed



→valuable program of LArTPC development, neutrino cross sections
Expect low-energy excess results soon...

Neutrino Oscillations

Latest 3-flavor results

Remaining unknowns in the 3-flavor picture: **MH and CP δ**

Beyond 3-flavor?

Absolute Mass

Status and prospects

Majorana vs Dirac?

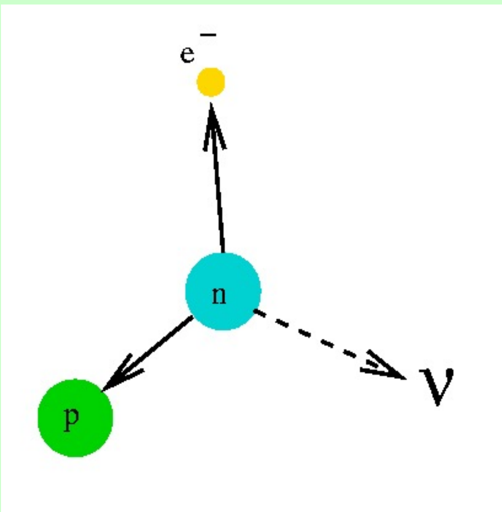
Overview of NLDBD

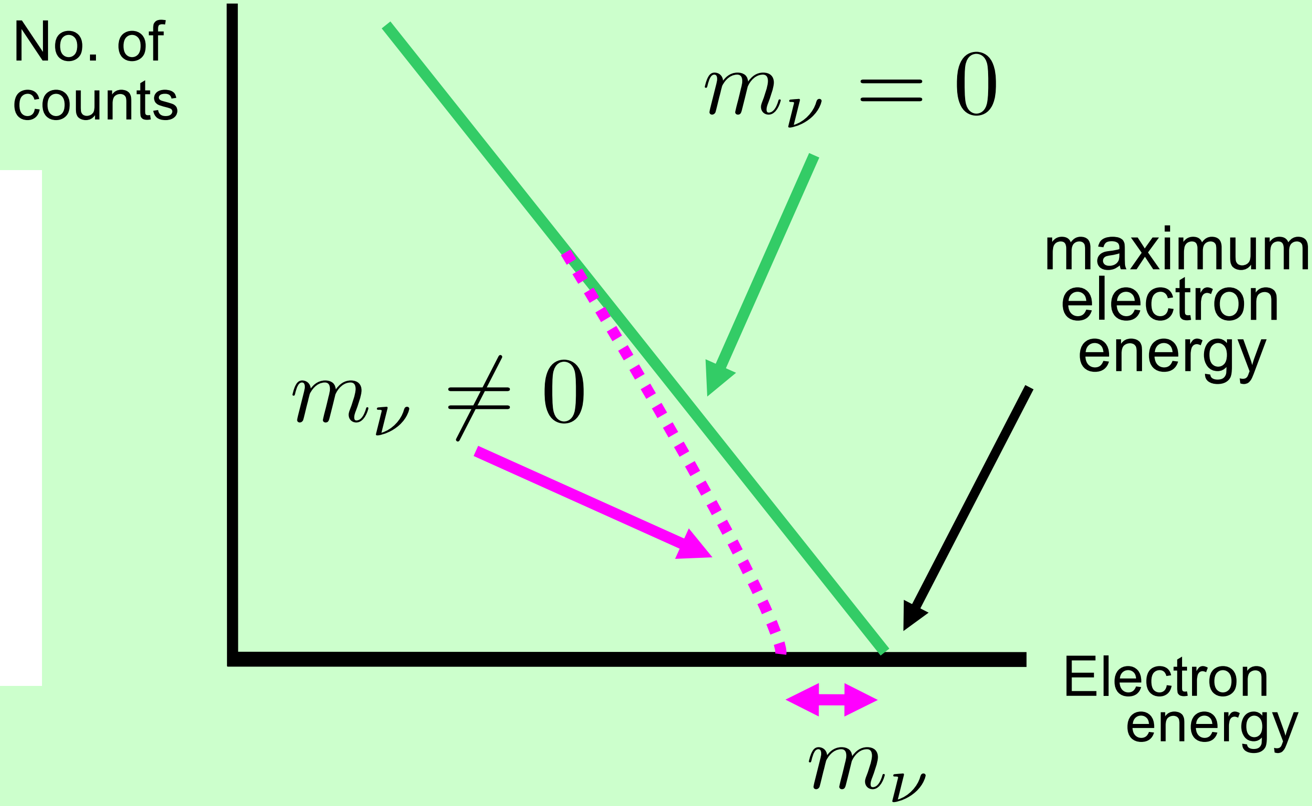
The mass pattern

The mass scale

The mass nature

Kinematic experiments for absolute neutrino mass





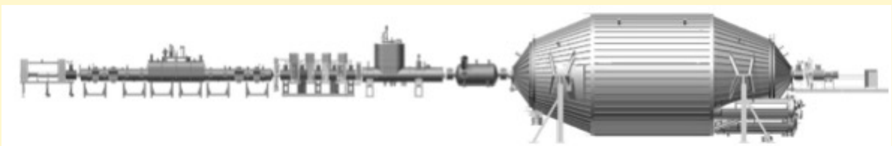
Look for distortion of β-decay spectrum near endpoint

Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$

18.6 keV endpoint

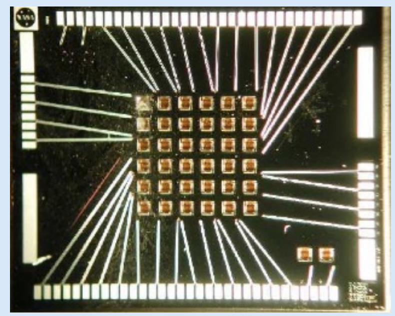


Sensitivity to ~0.2 eV

First results, taking more data

Thermal calorimetry

e.g., **MANU, MIBETA, MARE**



$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^{-} + \bar{\nu}_e$

2.5 keV endpoint

Hard to scale up...

No longer pursued

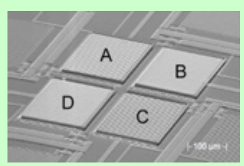
Holmium

e.g., **ECHo, HOLMES**

$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

metallic magnetic calorimeters

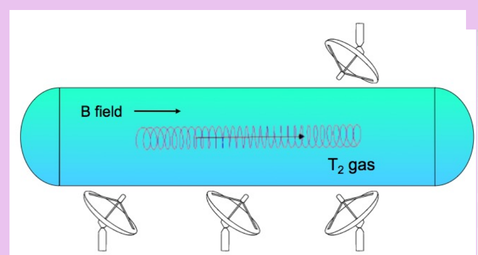


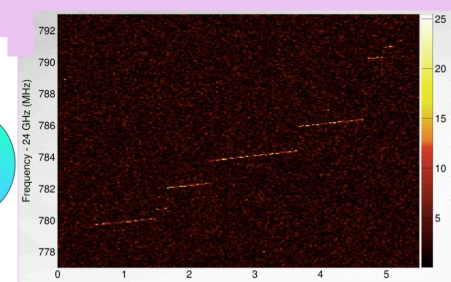
Electron capture decay,
ν mass affects deexcitation spectrum
R&D in progress

R&D

Cyclotron radiation tritium spectrometer: Project 8

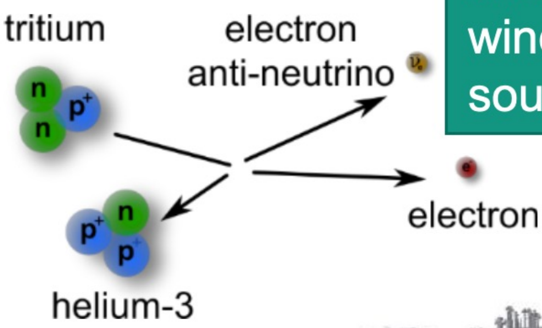
R&D



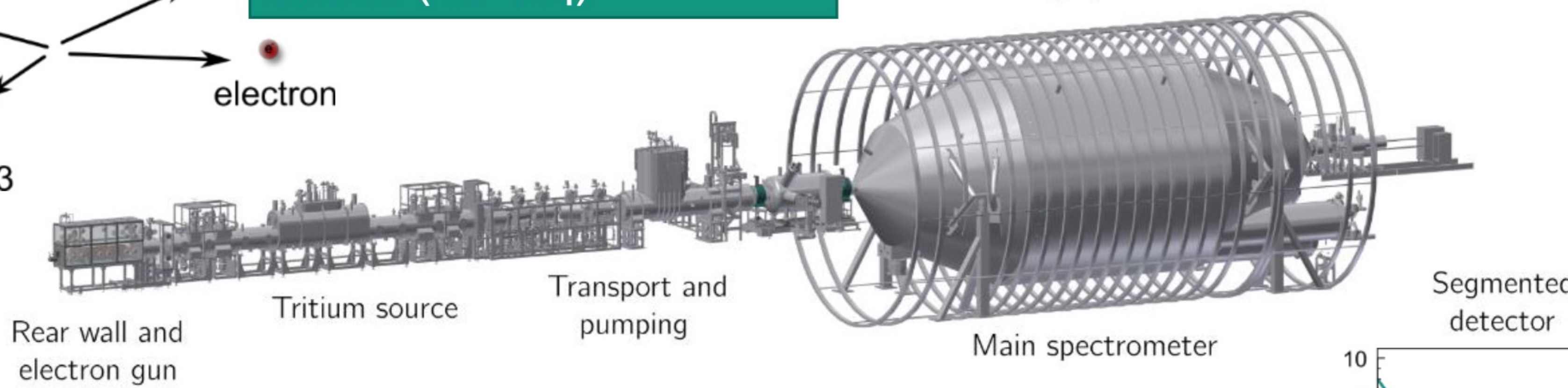


Long-term potential for
atomic tritium w/low uncertainties

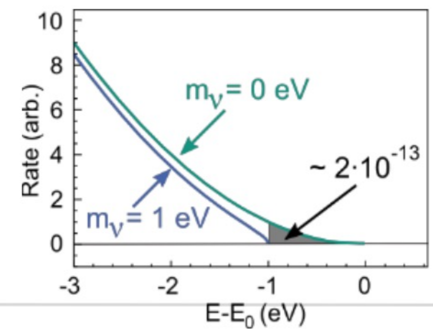
KATRIN results

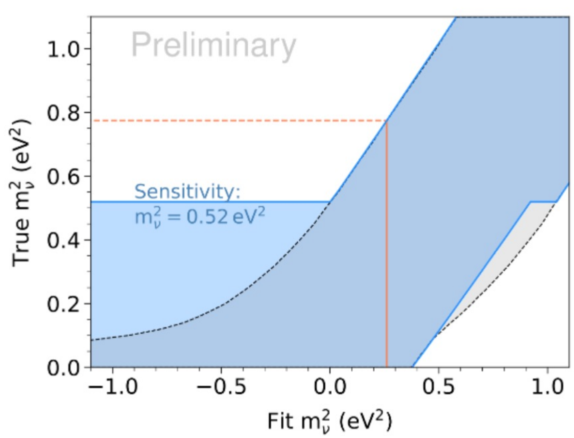


ultra-stable high-luminosity windowless gaseous tritium source (10^{11} Bq)



high-resolution MAC-E filter with < 1 eV energy resolution





Experimental sensitivity $m_\nu < 0.7$ eV (90% CL)

- Lokhov-Tkachov (90 % CL)
- Feldman-Cousins (90 % CL)
- Fit result: $m_\nu^2 = 0.26$ eV^2
- m_ν^2 limit = 0.8 eV^2 (90 % CL)
  m_ν limit = 0.9 eV (90 % CL)

New limit from 2nd campaign
$m_\nu < 0.9$ eV (90% CL)

First campaign $m_\nu < 1.1$ eV (90% CL)

5% of total stats; ultimate sensitivity **0.2 eV**

Magnus Schlösser – MORIOND2021

Neutrino Oscillations

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The mass pattern

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Majorana vs Dirac?

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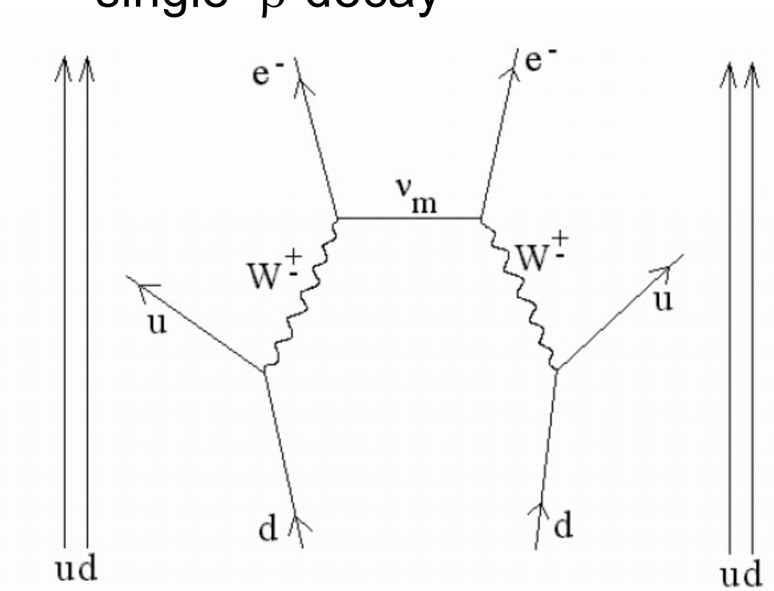
The mass nature

Are neutrinos **Majorana** or **Dirac**?

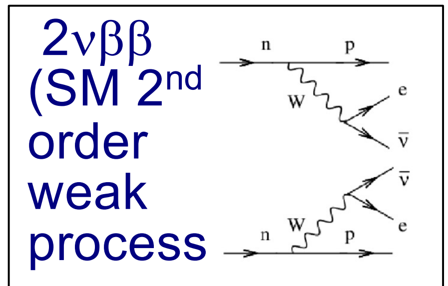
Best (only) experimental strategy: look for
neutrinoless double beta decay
in isotopes for which it is energetically possible and which don't single β-decay

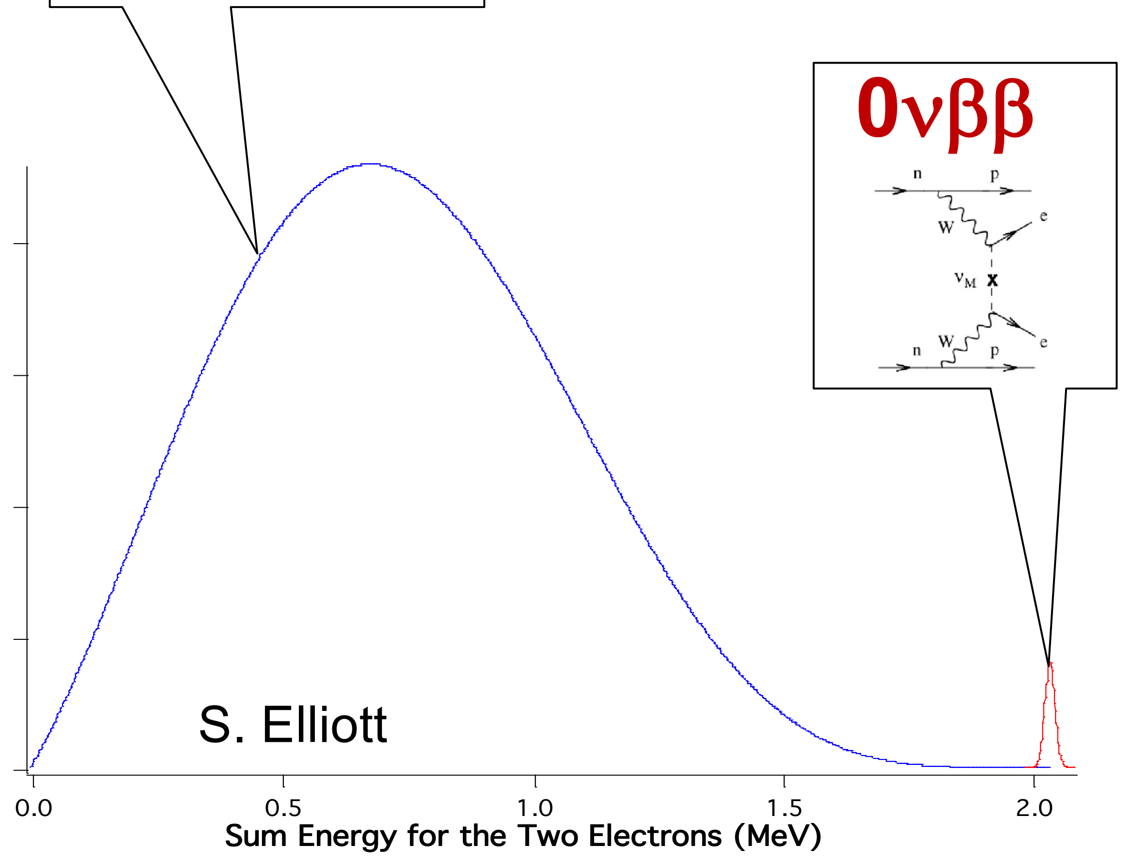
Observable: peak in the two-electron spectrum corresponding to ν-less final state



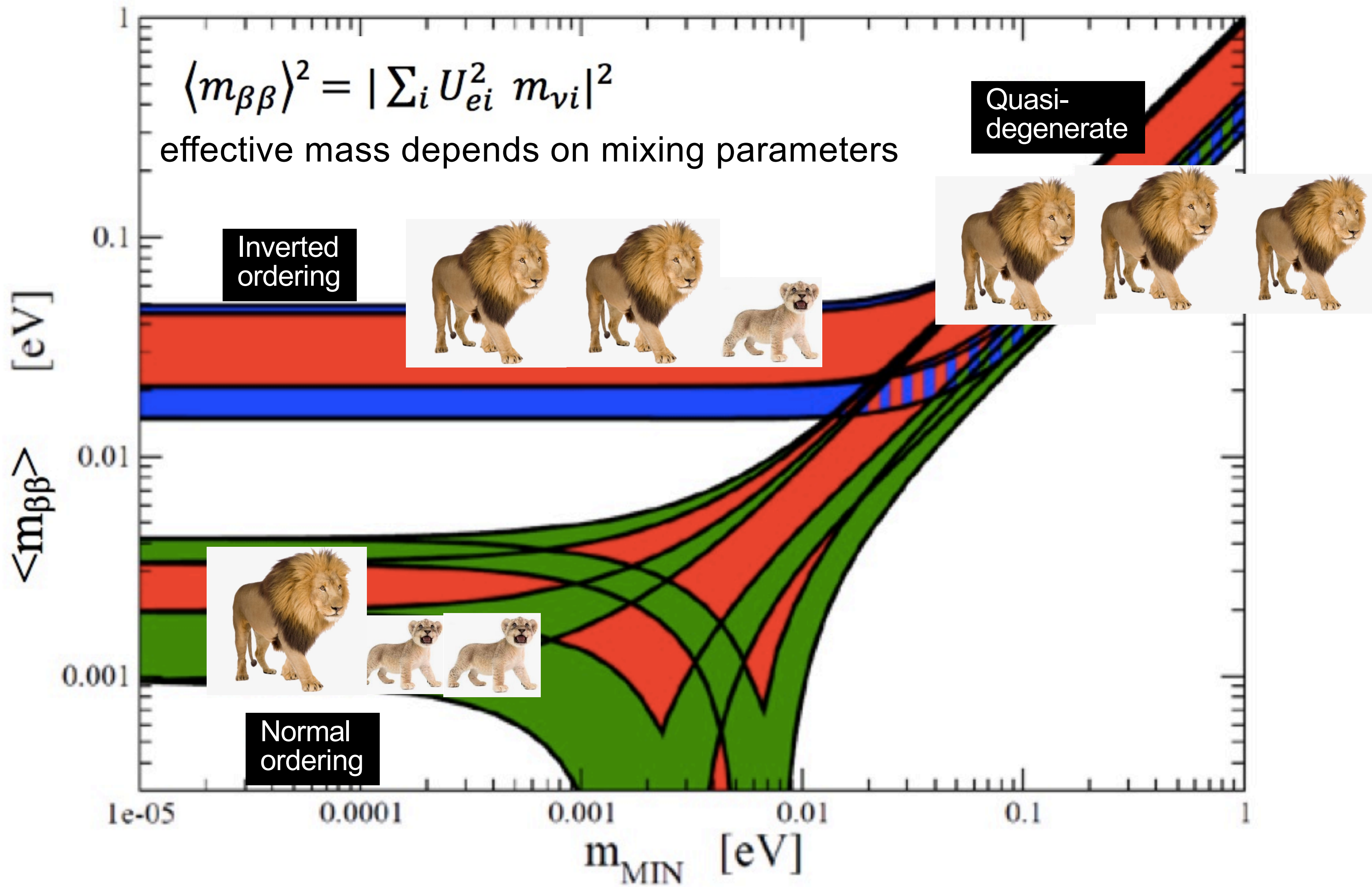
Only possible for Majorana ν
(...or exotic physics)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$





The NLDBD T-Shirt Plot

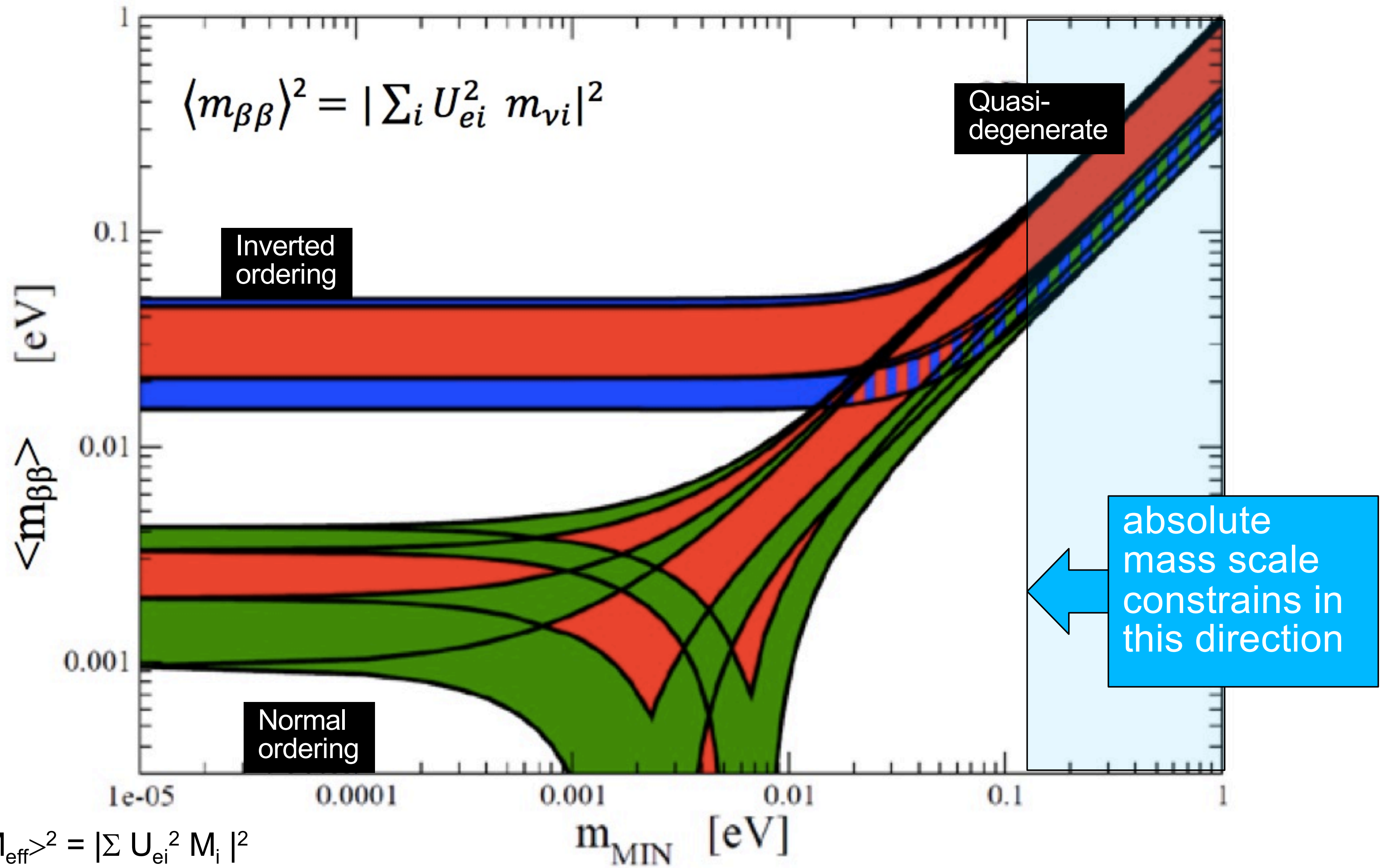


***If* neutrinos are Majorana*, experimental results must fall in the shaded regions**

Extent of the regions determined by uncertainties on Majorana phases and mixing matrix elements

*and standard 3-flavor picture

The NLDBD T-Shirt Plot



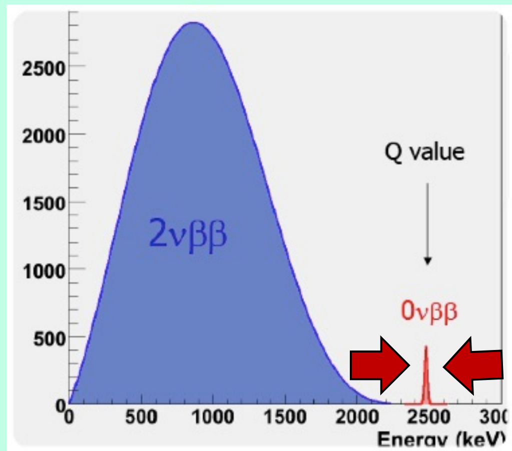
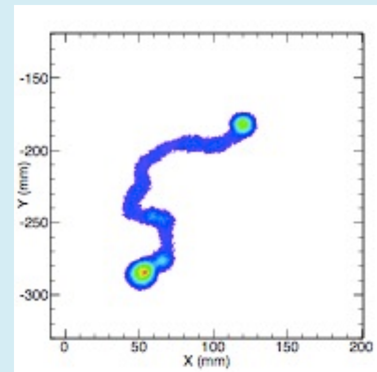
$<M_{eff}>^2 = |\Sigma\, U_{ei}^2\, M_i\, |^2$

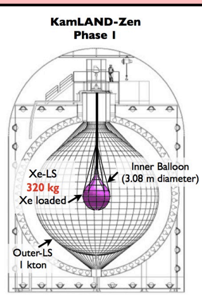
If **neutrinos are Majorana, experimental results must fall in the shaded regions**

Extent of the regions determined by uncertainties on Majorana phases and mixing matrix elements

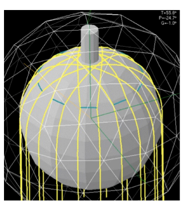
General NLDBD experiment strategies

$$T_{1/2} > \frac{\ln 2 \; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

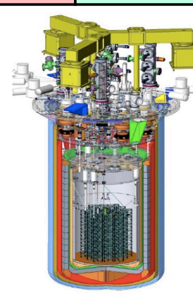
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		



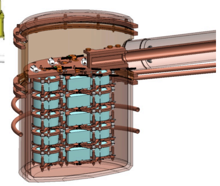
KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)



CUORICINO/ CUORE (^{130}Te)

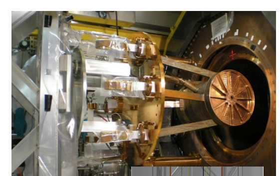


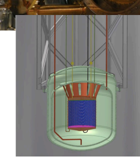
MAJORANA (^{76}Ge)

GERDA (^{76}Ge)

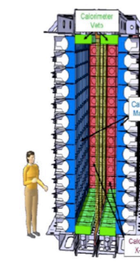
CUPID (^{82}Se)

LEGEND (^{76}Ge)

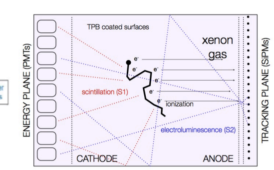




EXO/nEXO (^{136}Xe)



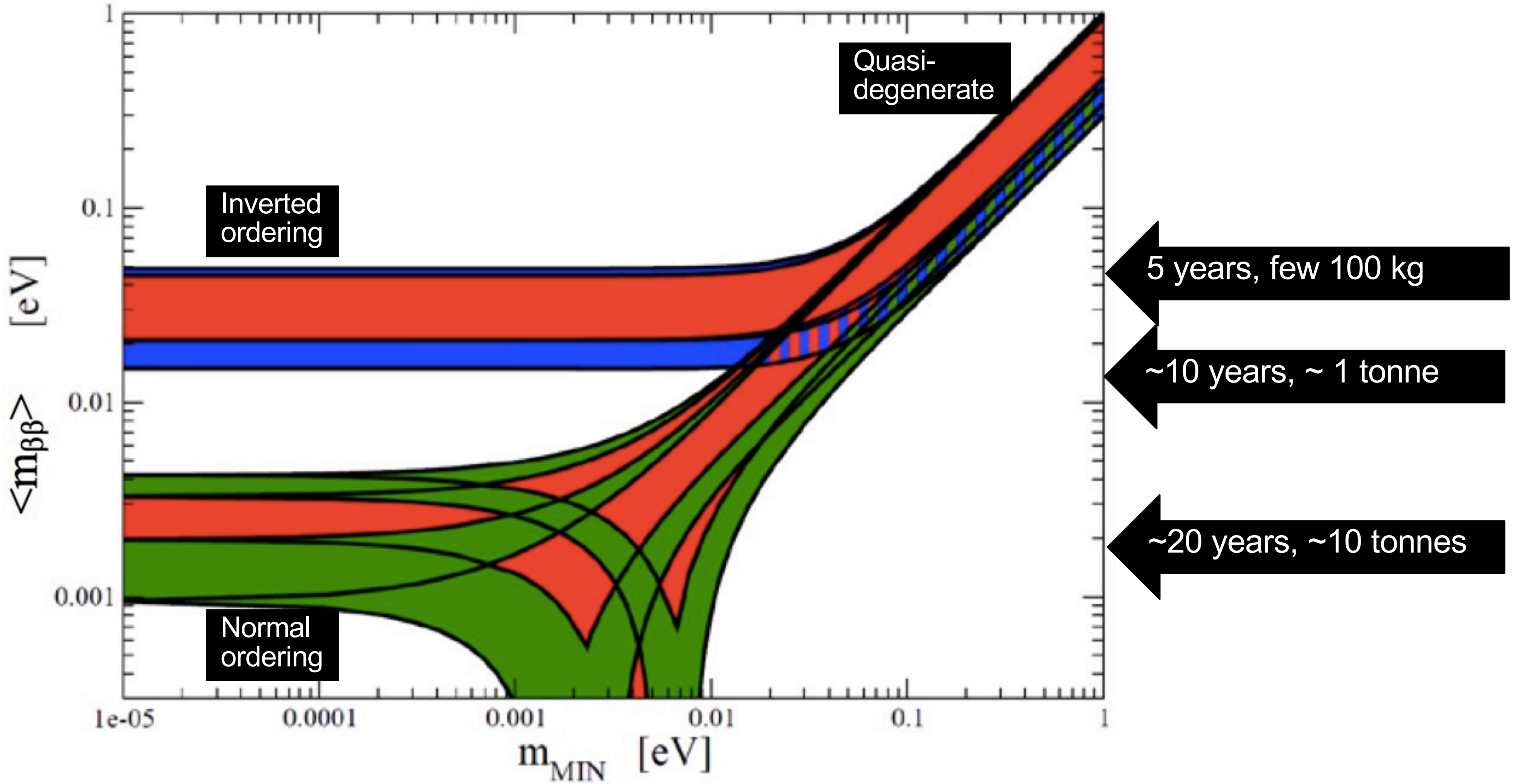
NEMO/ SuperNEMO (various/^{82}Se)



NEXT (^{136}Xe)

+more future ideas...

Overall Long-Term Prospects for NLDBD



In the long term will need more than one isotope...
theory needed too!

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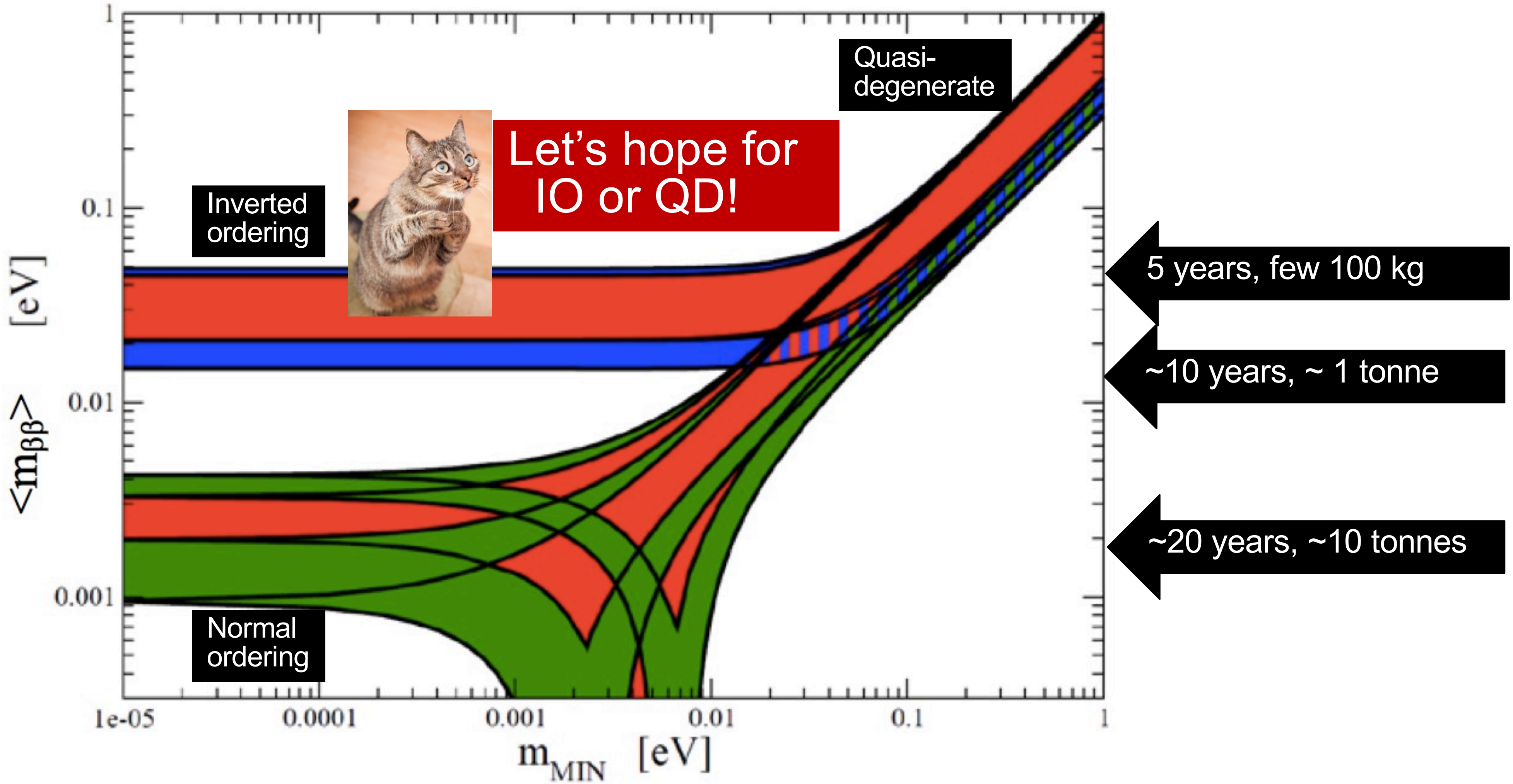

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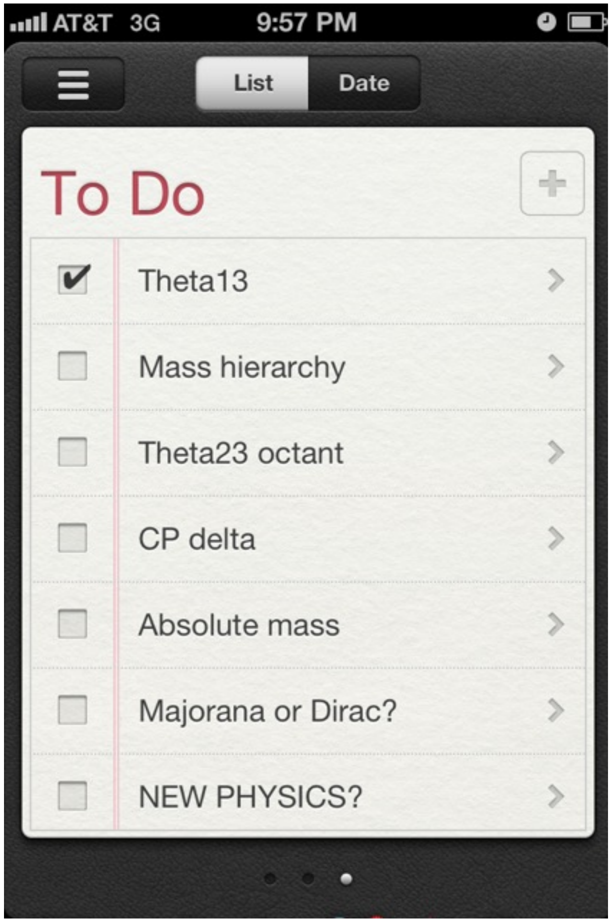
Huge progress in understanding of neutrinos over the last 20 years, **but still many outstanding questions**



My IPhone from 10 years ago!

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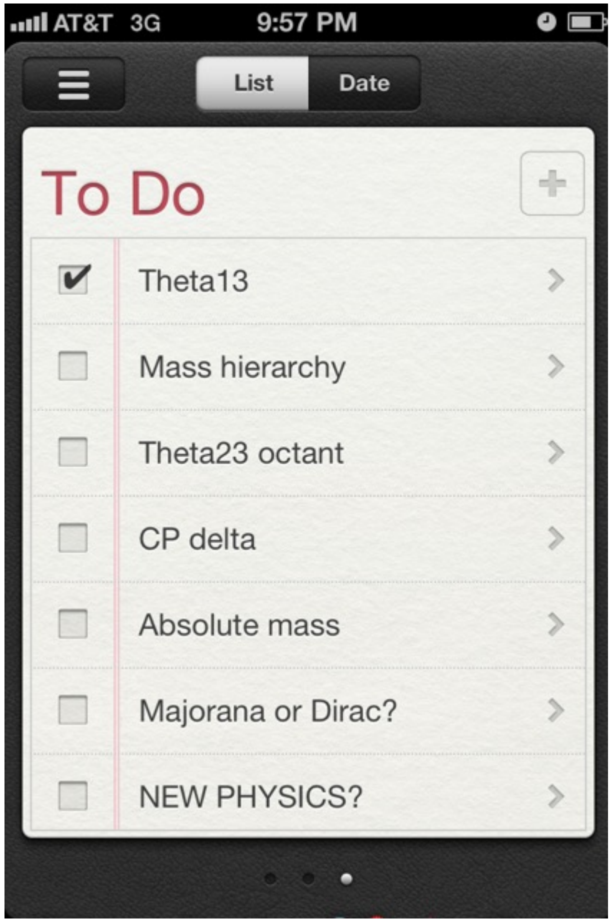

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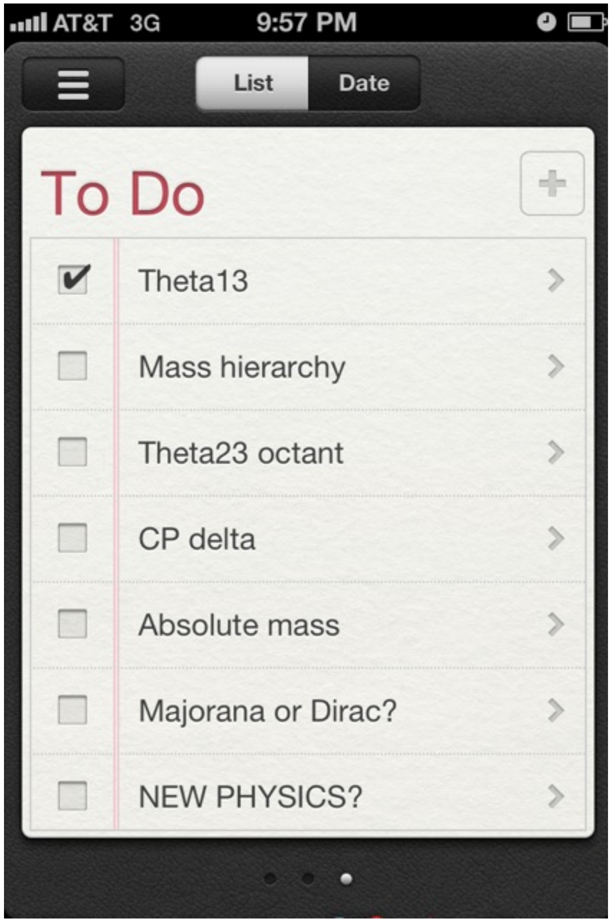

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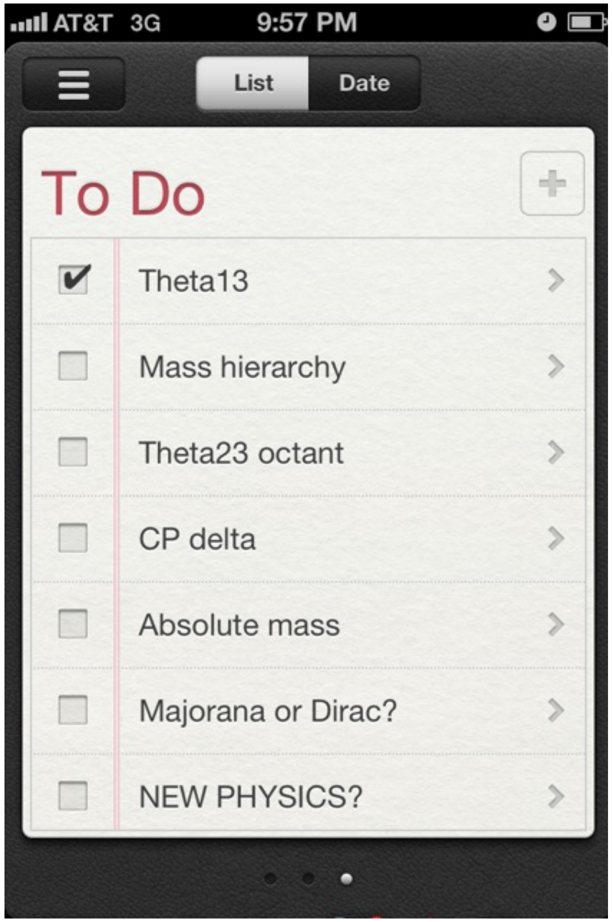

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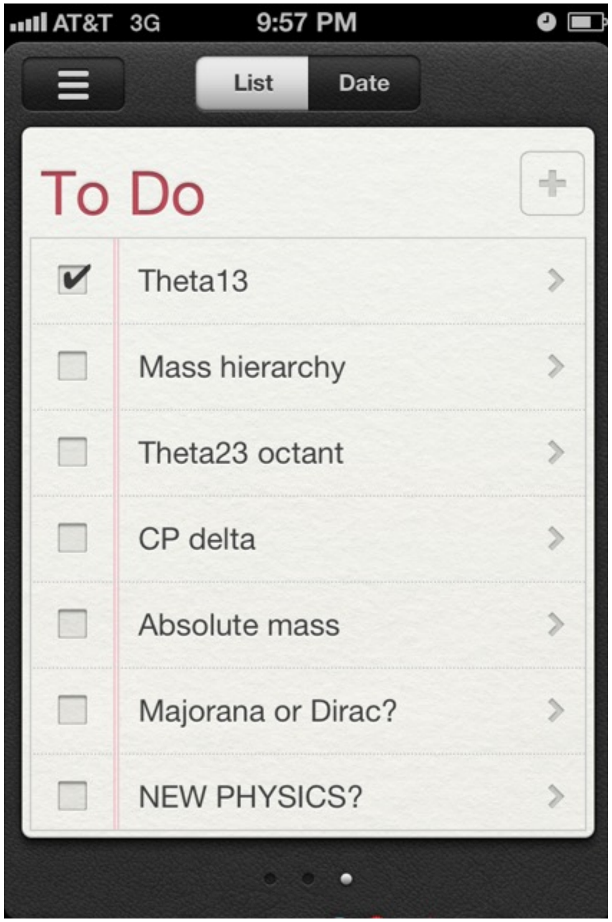

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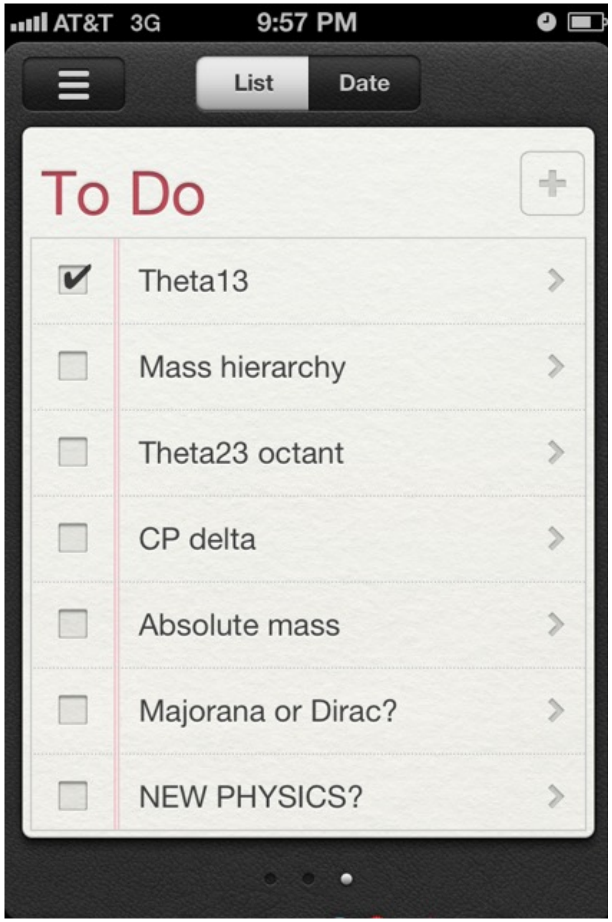

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More from KATRIN to come!

Hoping Nature is kind...

There could be surprises....

What's the reason for the pattern of masses and mixings?
How might sterile neutrinos or other exotic new physics fit in?
How did the matter-antimatter asymmetry come to be?
...

Still exciting years ahead!

Extras/Backups

From L. Berns, Moriond 2021

NOvA + T2K

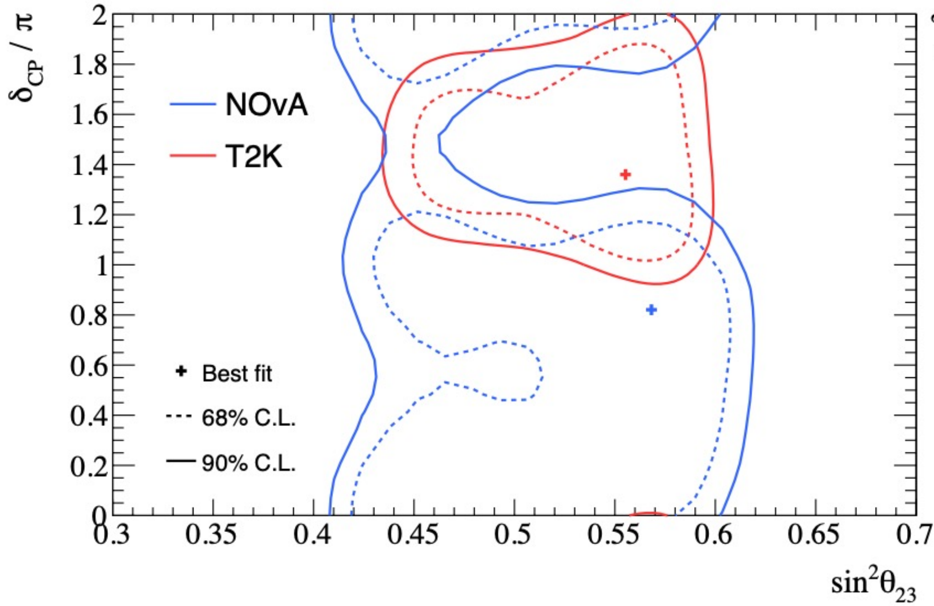
Ongoing joint fits

SK + T2K

atmospheric + accelerator

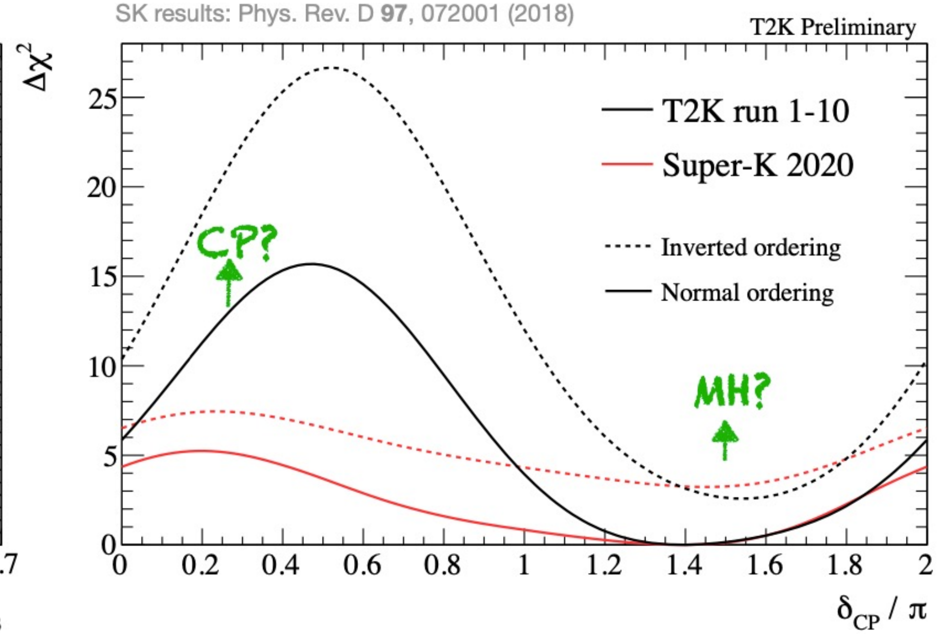
Comparison of released contours (not joint fit)

NOvA results: A. Himmel (2020) Zenodo, T2K Preliminary



Comparison of released contours (not joint fit)

SK results: Phys. Rev. D **97**, 072001 (2018)



- Joint fits between experiments with different oscillation baselines/energies and detector technologies

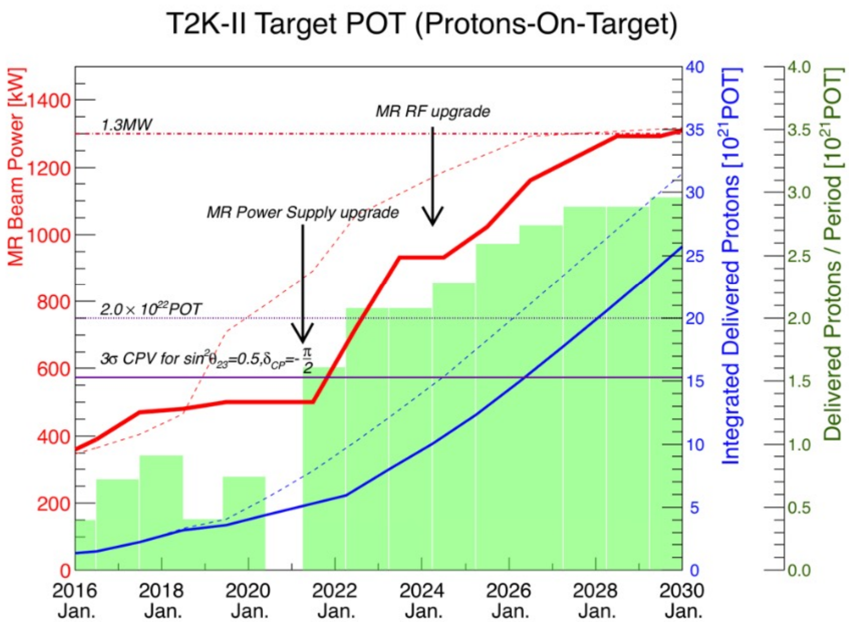
→ expect increased sensitivity in δ_{CP}, mass ordering, θ_{23} octant **beyond** stats increase from resolved degeneracies and syst constraints

- important to understand potentially non-trivial syst. **correlations** between experiments

Agreements are signed between experiments and joint work ongoing. Stay tuned!

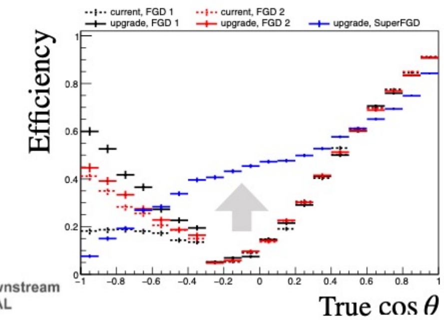
From L. Berns, Moriond 2021

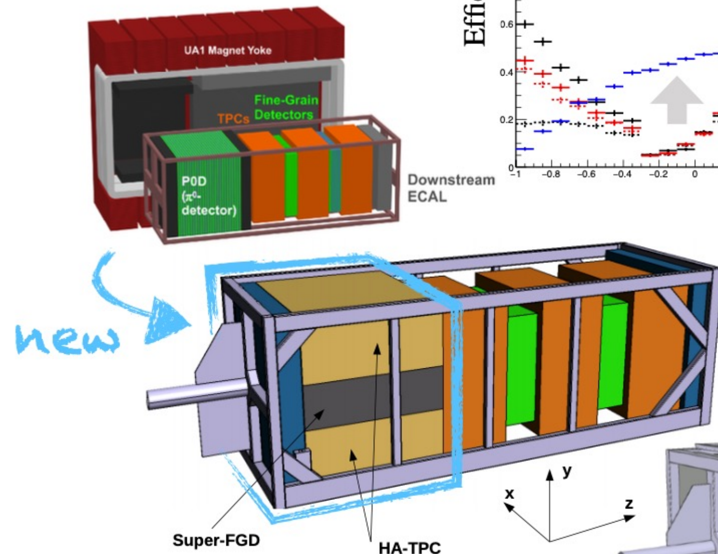
Beam line upgrade

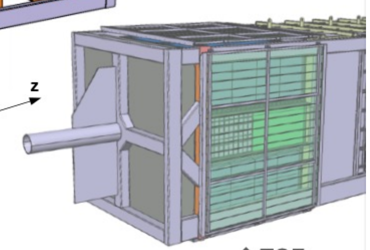


- Increase **beam power** from ~500 kW to 1.3 MW via upgrades to main ring power supply and RF (mostly increased rep rate)
- Many upgrades to neutrino beamline (target, beam monitors, …) to accept 1.3 MW beam
- Increase **horn current** 250 kA → 320 kA for ~10% more neutrinos/beam-power and reduced wrong-sign background

ND280 upgrade







Replace **P0D** with
3D scintillation detector +
high-angle TPCs +
TOF enclosure

→ 4π acceptance like SK

→ lower (proton) mom. threshold

Reduce xsec systematics via better understanding of nuclear effects.

DUNE: Near Detector (ND)

- **DUNE ND complex**

  Multiple complementary systems:

  - **ND-LAr**: modular, pixelated LArTPC

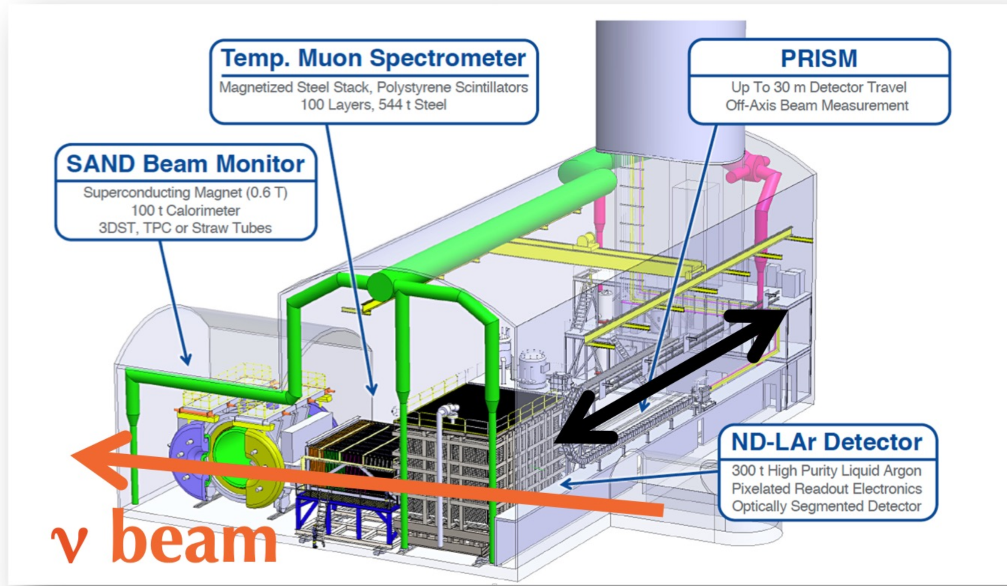
    Primary target, similar to FD

  - **TMS → ND-GAr**: measures muons not captured by LArTPC → high-pressure GArTPC, surrounded by ECAL and magnet

    Muon spectrometer; nuclear interaction model constraints

  - **SAND**: tracker surrounded by ECAL and magnet

    On-axis beam spectrum/time-stability monitor



ND-LAr/TMS are **movable on/off-axis (PRISM)**

Probes different neutrino energies

G. Karagiorgi, Neutel 2021