Lab-Based Neutrino Experiments

Kate Scholberg, Duke University
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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

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Majorana vs Dirac?

Overview of NLDBD

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The three-flavor neutrino paradigm

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

Parameterize mixing matrix U as

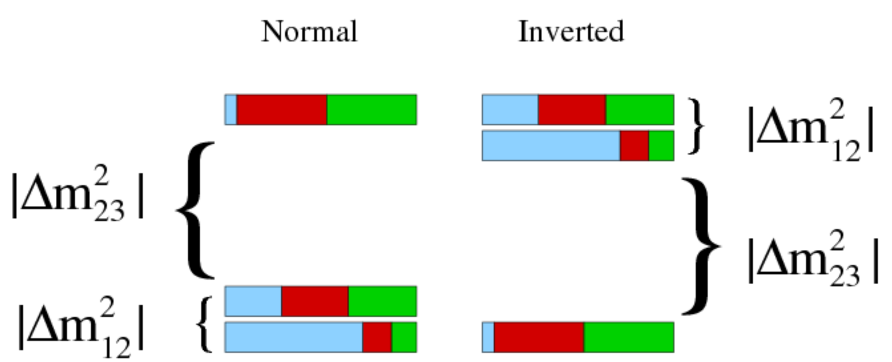
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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

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



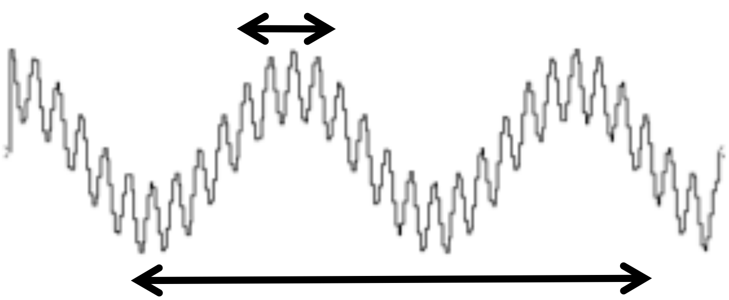
Oscillation probabilities in a 3-flavor context

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

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j \quad \text{(L in km, E in GeV, m in eV)}$$

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

oscillatory behavior in L and E



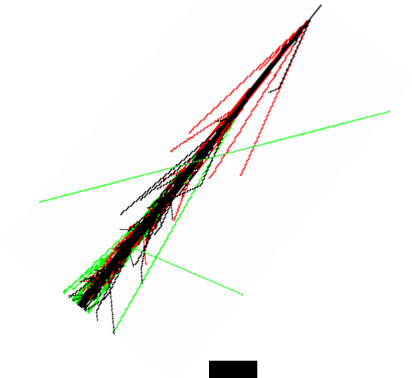
$$|\Delta m^2_{23}| >> |\Delta m^2_{12}|$$ ➔ two frequency scales

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

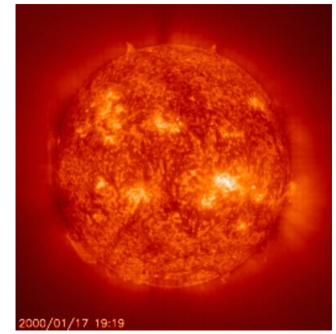
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

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

atmospheric



solar



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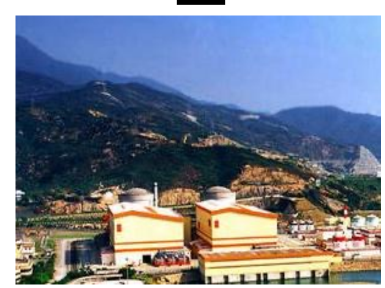
beams



reactor

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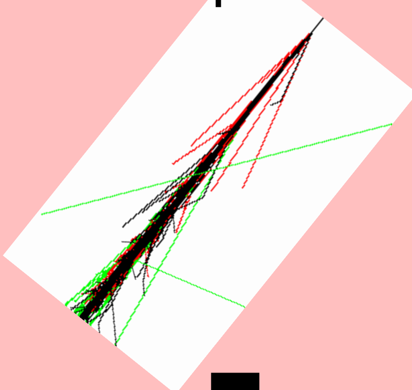
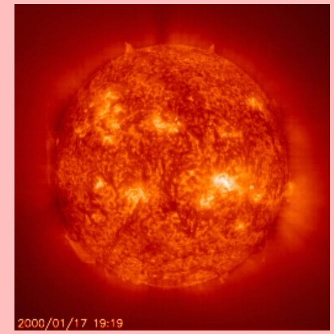


signal with
“wild” neutrinos...

solar



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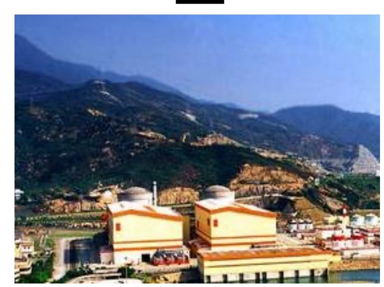

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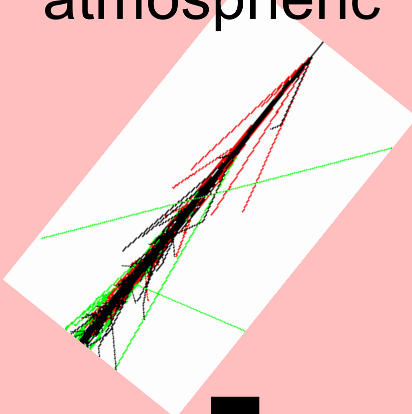

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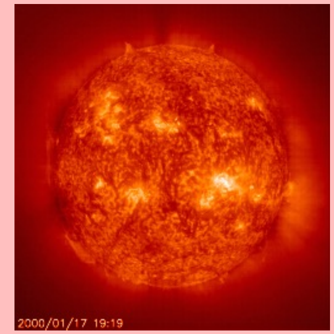

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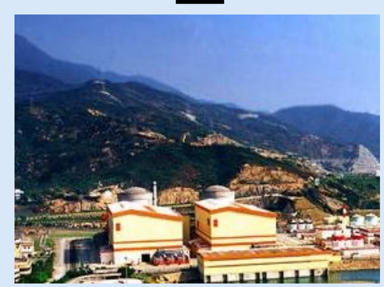
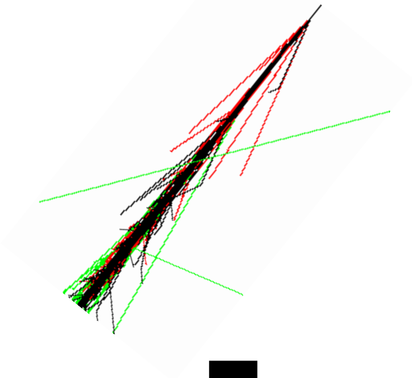
confirmed with
“tame” ones...

beams

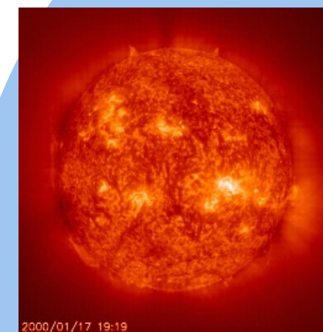


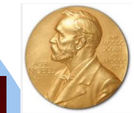
reactor

atmospheric



solar





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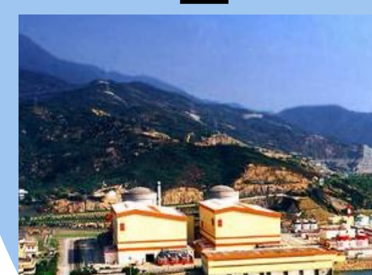
beams

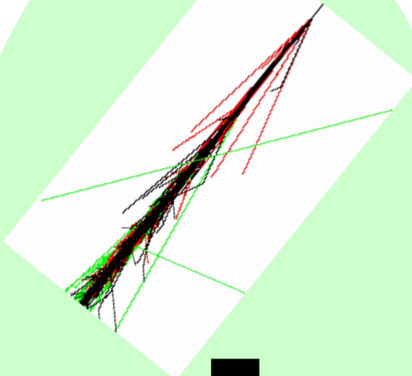
$\Delta m^2_{12}, \theta_{12}$

"Solar" sector: solar ν oscillations confirmed with reactors

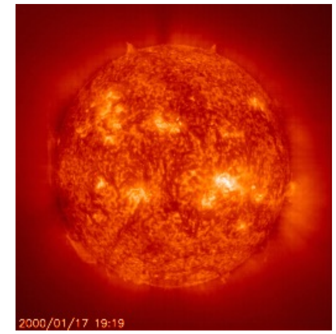


reactor

atmospheric



solar



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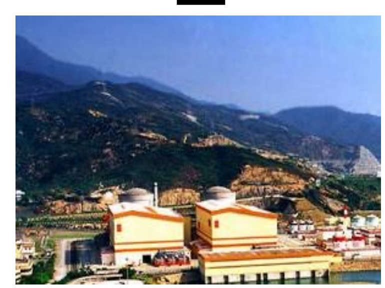
$$

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

"Atmospheric" sector

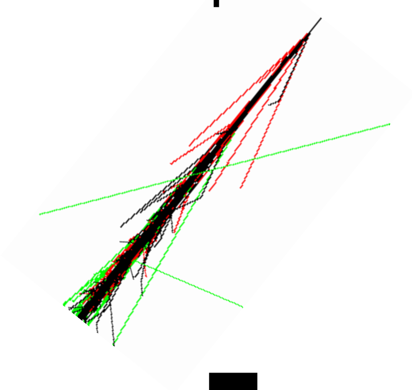
beams



reactor

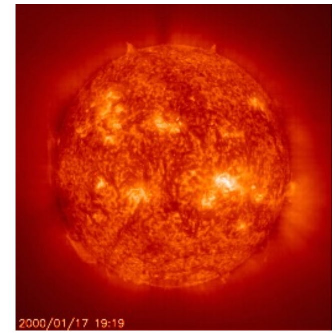
The mixing angle θ_{13}: information from beams and burns!

atmospheric



$\theta_{13,}$ the "twist in the middle"

solar



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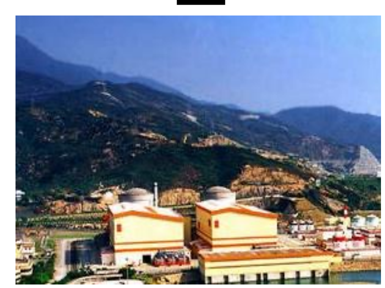
beams

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

$\nu_\mu \rightarrow \nu_e$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_x$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\nu_\mu \rightarrow \nu_x$

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The three-flavor picture fits the data well

Global three-flavor fits to all data

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
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	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
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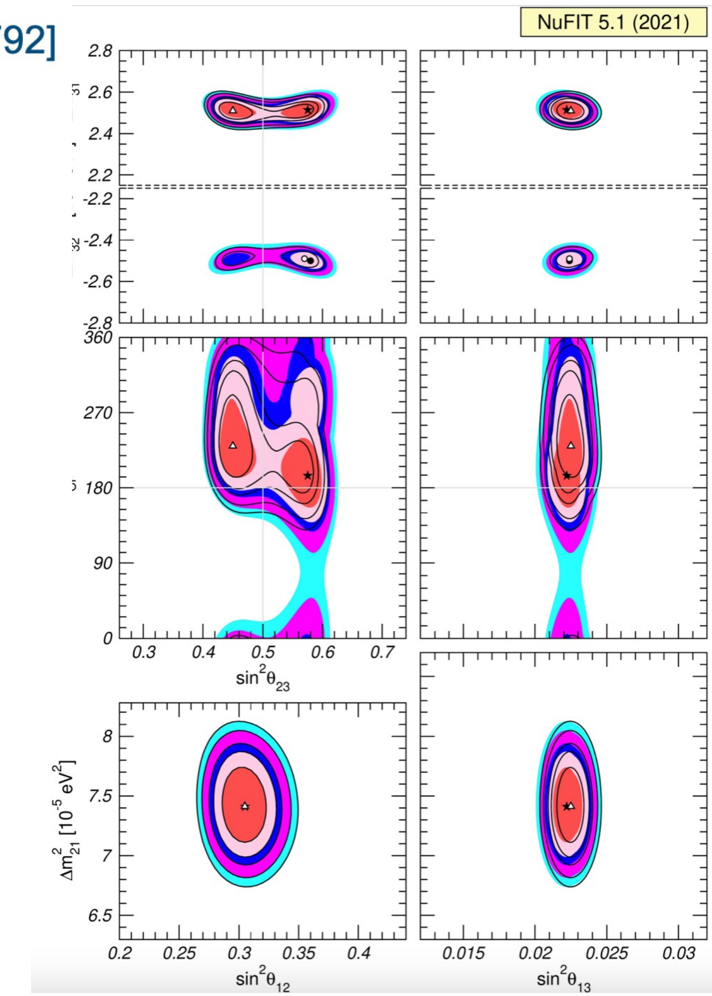

$$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0 \text{ for NO and } \Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0 \text{ for IO.}$$

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

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

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

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sign of Δm^2 unknown (ordering of masses)

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

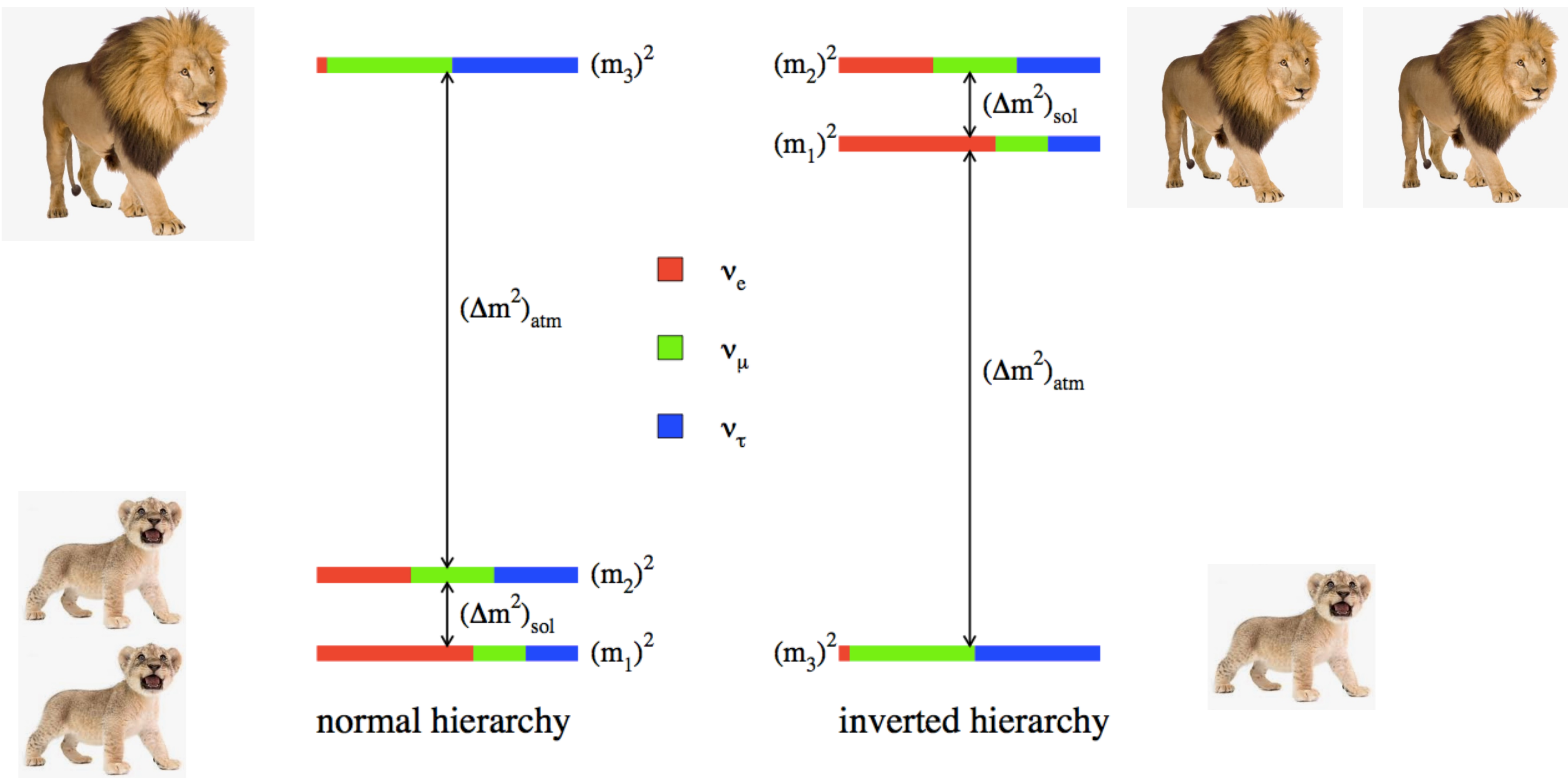
poor knowledge

sign of Δm^2 unknown (ordering of masses)

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]



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

There are many ways to determine the mass ordering

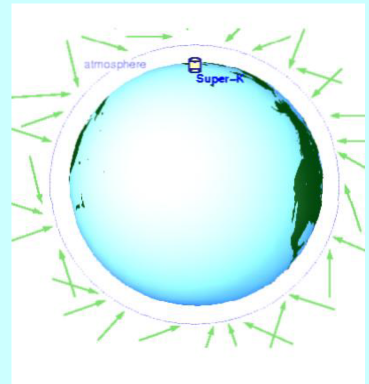
They are all challenging...

Four of the possible ways to get MO

Long-baseline beams

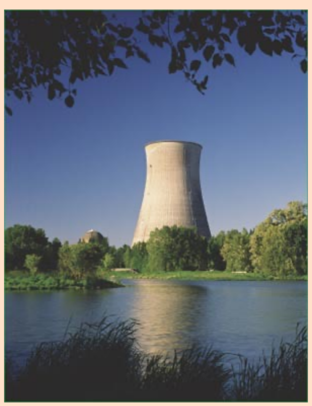
Hyper-K, LBNF/DUNE

Atmospheric neutrinos



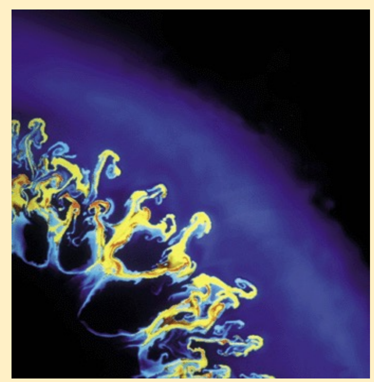
Super-K, Hyper-K, IceCube, KM3Net, DUNE, INO

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

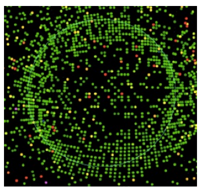
T2K
J-PARC to Kamioka
295 km, 380-750 kW

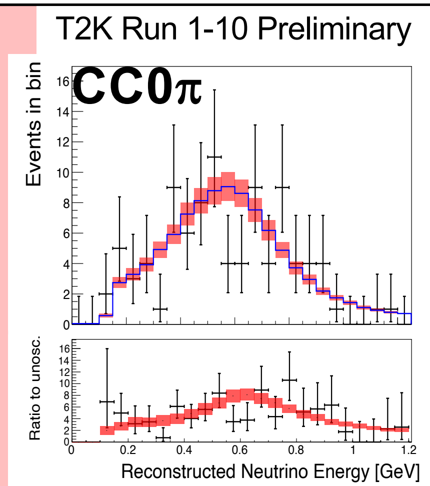
T2K appearance and disappearance samples*

Neutrino mode

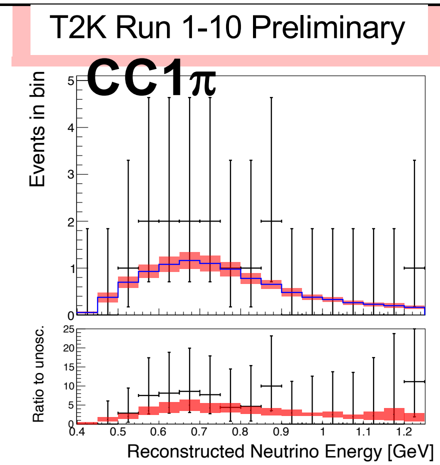
Antineutrino mode

Electron neutrino appearance

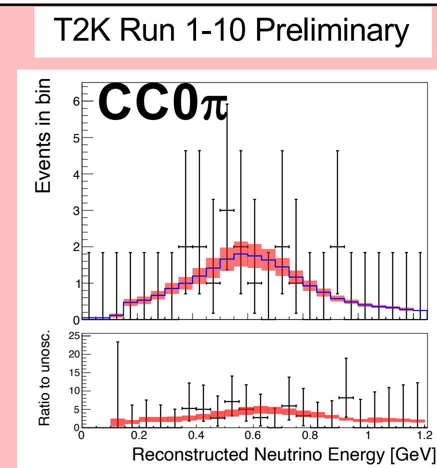




94 events

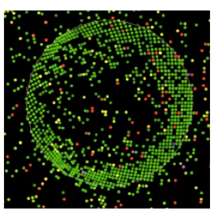


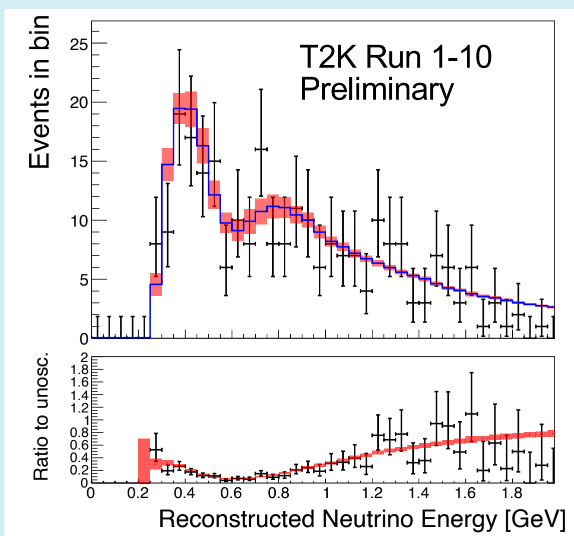
14 events



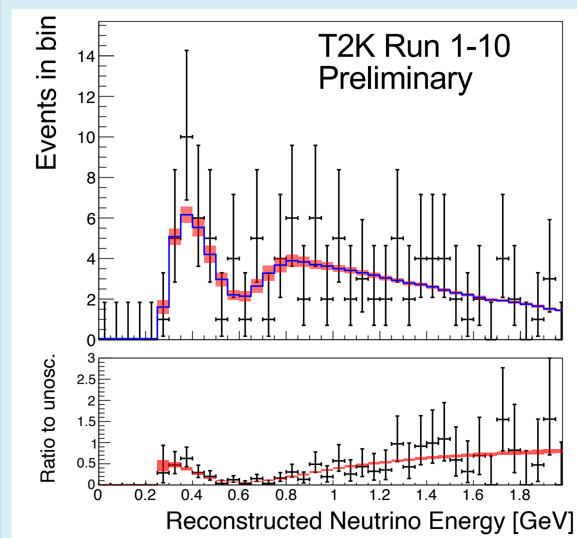
16 events

Muon neutrino disappearance





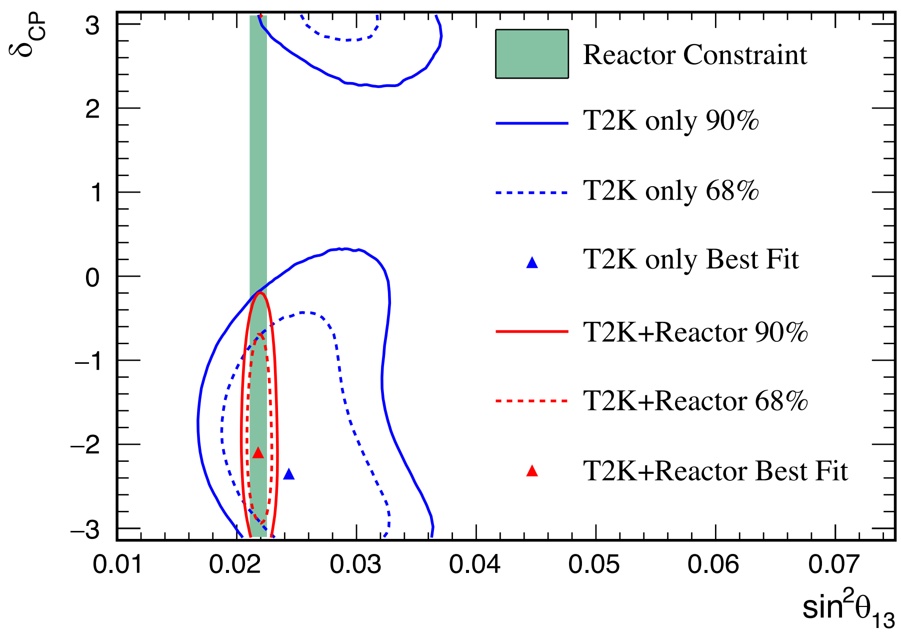
318 events

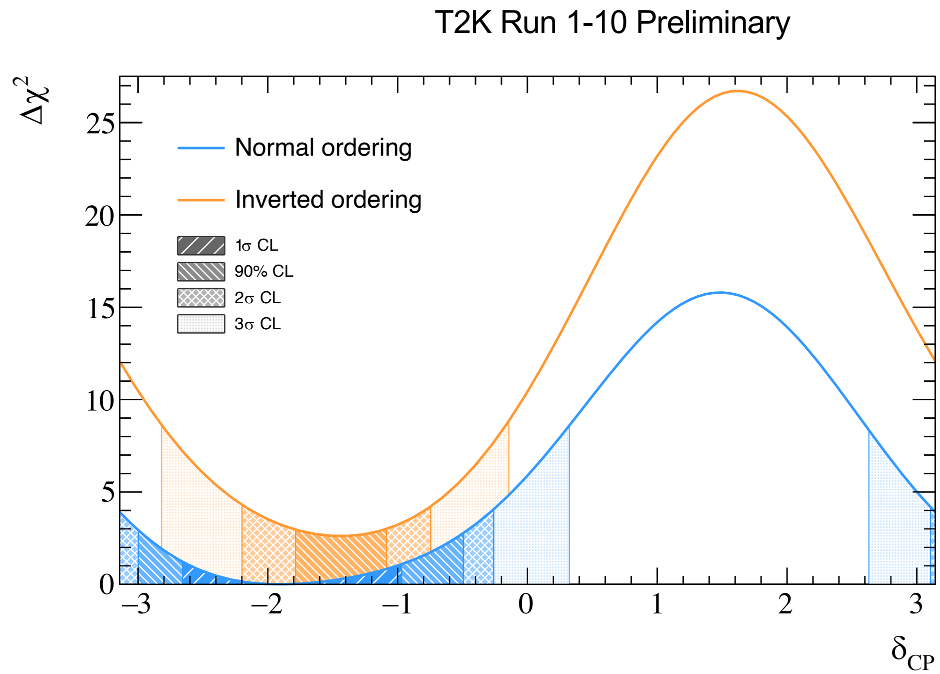


137 events

*New result shown at Nu2022 includes multi-ring sample + tweaks

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

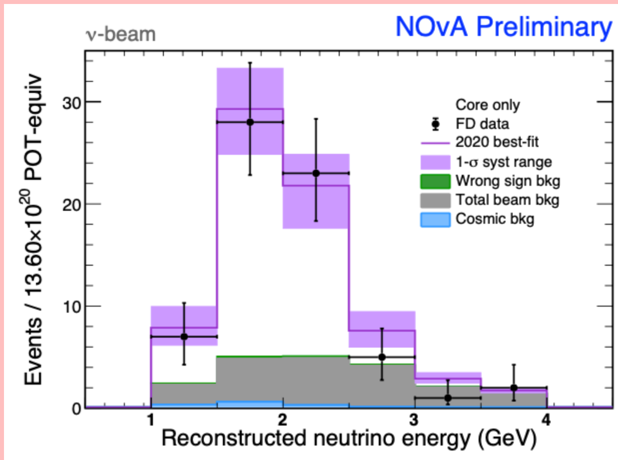
P. Dunne, Nu2020

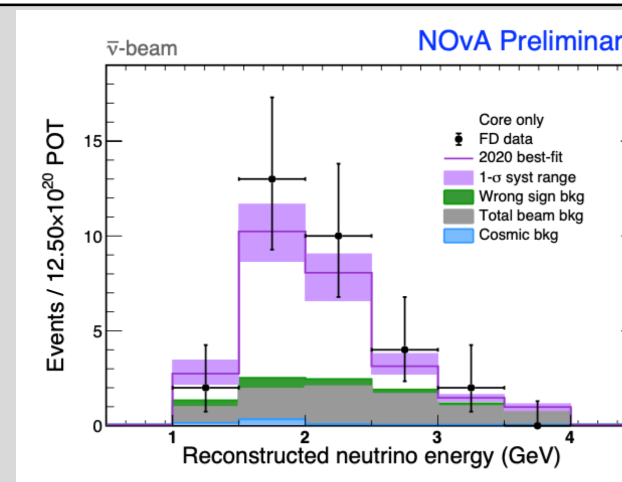
*2020 result

NOvA appearance and disappearance

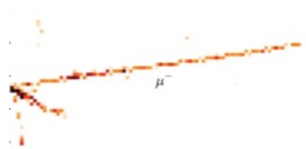
	Neutrinos 13.6 x 10^{20} pot	Antineutrinos 12.5 x 10^{20} pot
Electron neutrino appearance	see plot 3 below	see plot 4 below
Muon neutrino disappearance	see plot 5 below	see plot 6 below

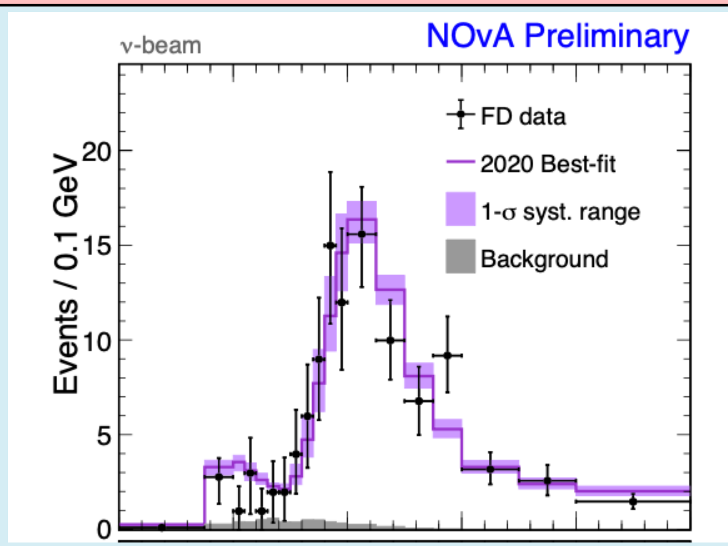
Electron neutrino appearance

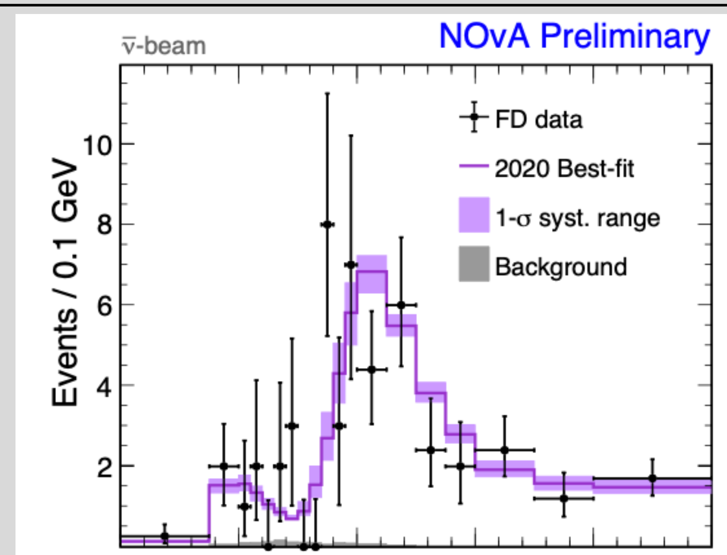




Muon neutrino disappearance



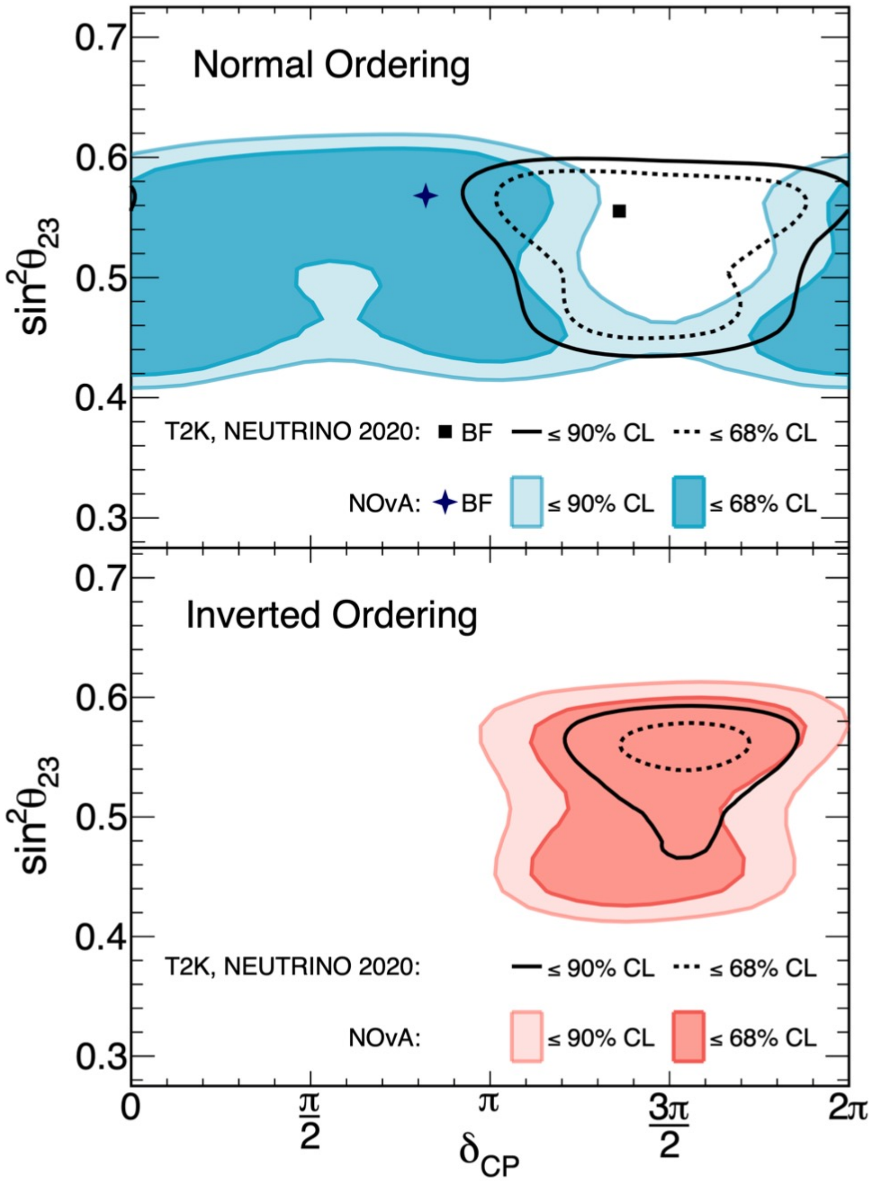




M. Strait, Neutel 2021

NOvA Parameter Fit Results

2020 data set: https://arxiv.org/abs/2108.08219

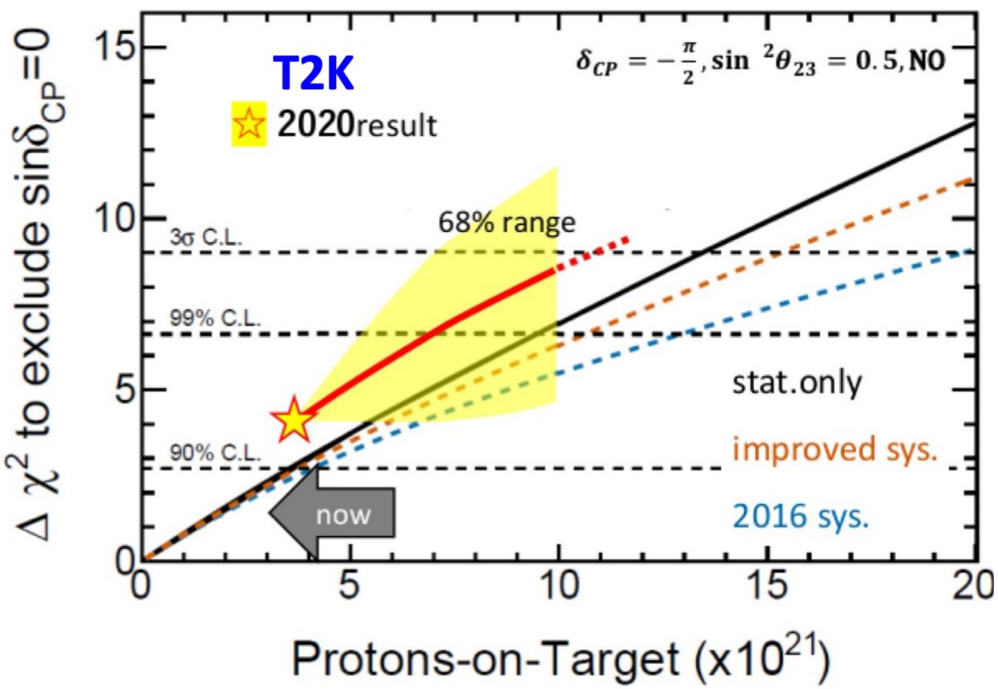


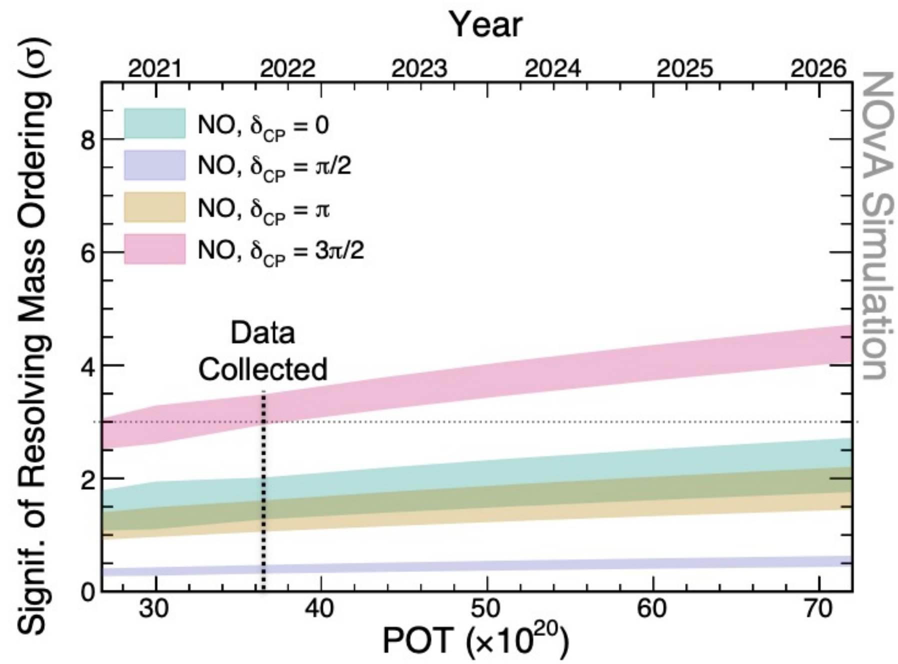
- all values of δ allowed
- weak preference for upper octant
- exclude $\delta=\pi/2$ for IH at $>3\sigma$
- very weak tension w/T2K

...overall, kind of smelling like normal ordering and $\delta=-\pi/2$... but not "evidence" yet...

J. Hartnell, Nu2022

Future Prospects for T2K and NOvA





J. Hartnell, Nu2022

- Beam upgrade to >1 MW by ~2026
- Expect 10e21 POT by ~2027

- Will more than double dataset
- 3σ for 30-40% of CP δ range

Joint T2K-NOvA analysis in the works

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

...current generation is statistics-limited, but reasonable chance of 2-3σ on δ/MO in next ~ 5 years

Current experiments with ~5 yr projections (so, *c.* 2027)

Precision on θ_{12}, θ_{13}, Δm^2_{21}

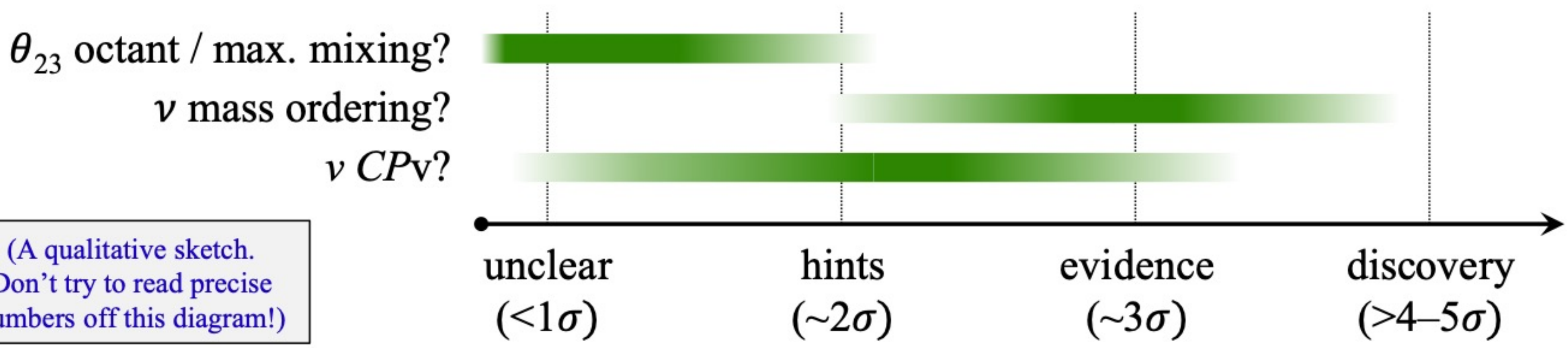
→ Minimal changes until next-gen experiments *(e.g., JUNO)*

Precision on θ_{23}, $|\Delta m^2_{32}|$

→ Some gains to come in current generation. Large gains in next-gen.

3-flavor "structural" questions

→ Reach heavily depends on (*still unknown!*) actual answers



(A qualitative sketch. Don't try to read precise numbers off this diagram!)

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

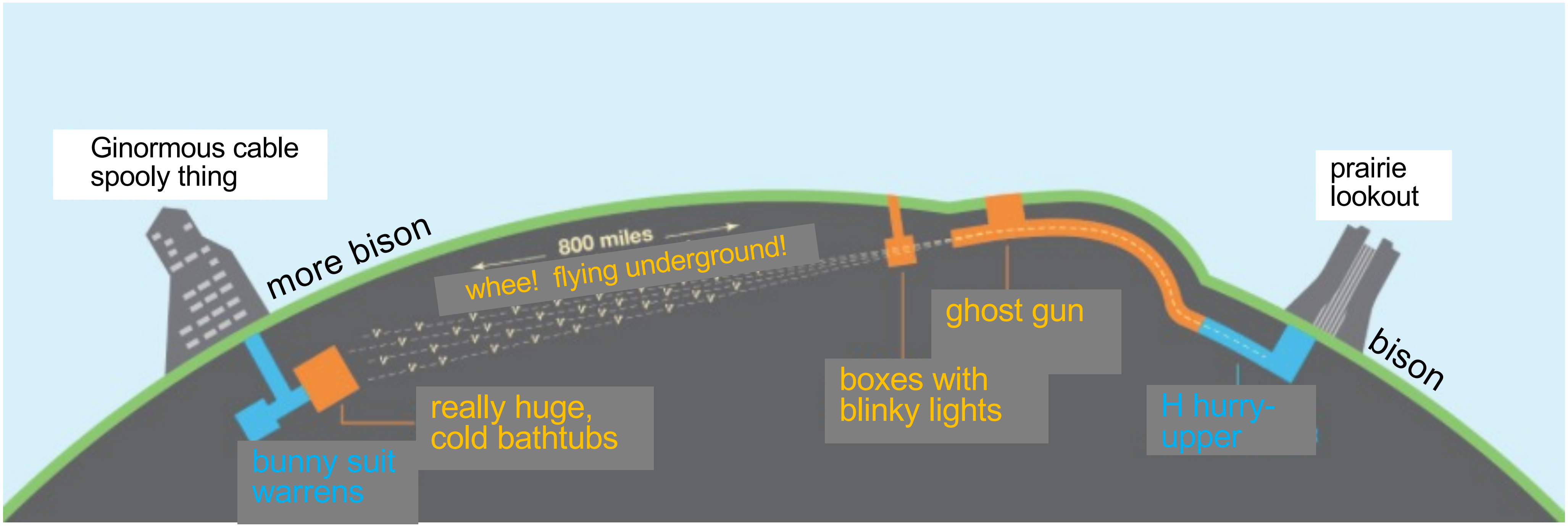
NOνA
FNAL to Ash River
810 km, 400-700 kW

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

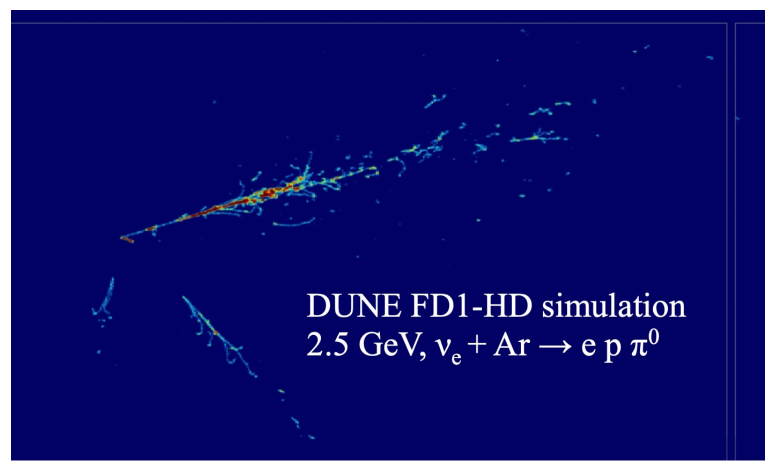
LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW

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

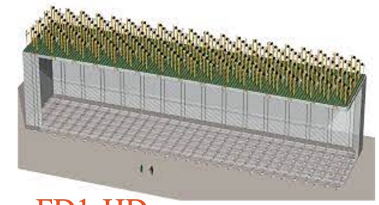
Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility



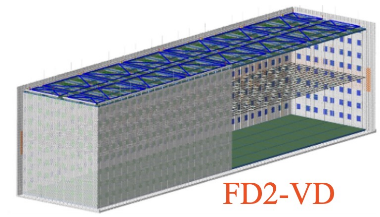
- new 1.2 MW beam (upgradable to 2.4 MW) Fermilab to South Dakota
- 1300 km baseline
- 40-kton fiducial **liquid argon TPC** far detector
- Also proton decay, solar, supernova, atmospheric neutrinos...



The DUNE far detector:
4 x 17 kton of LAr,
horizontal &vertical drift designs



FD1-HD



FD2-VD

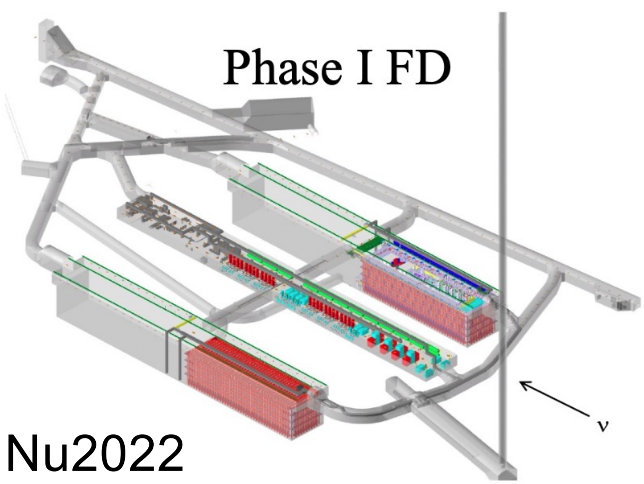
by end of this decade

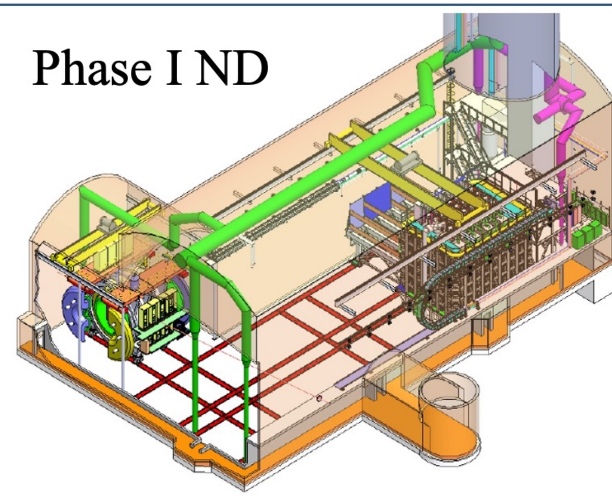
Phase I

- Ramp to 1.2 MW beam intensity
- Two 17kt (10kt fid.) LAr TPC FD modules. One HD on VD.
- Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND
- Moveable to enable PRISM

Phase II Upgrades

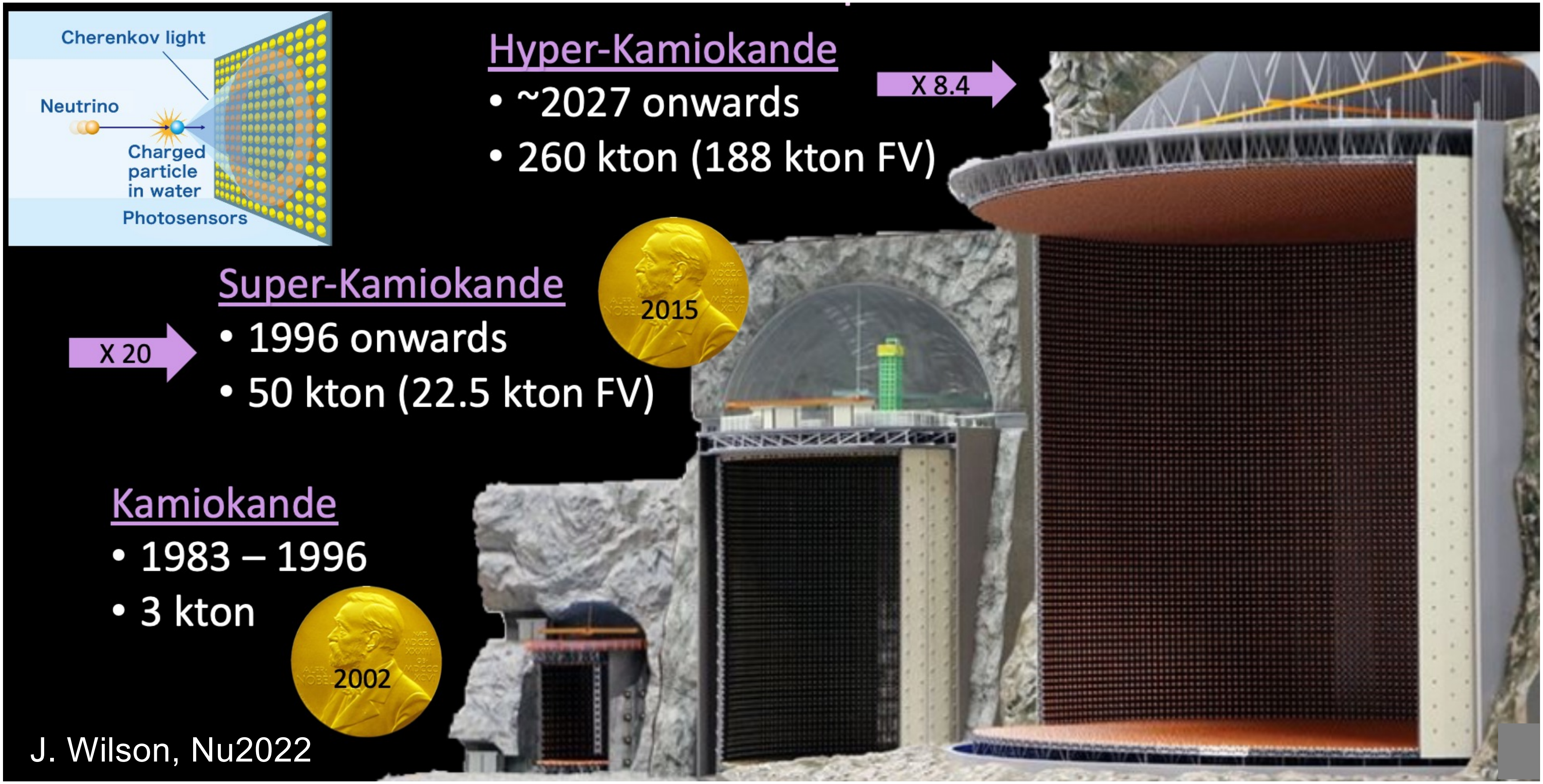
- Proton beam increase to 2.4 MW
- Four 17kt LAr TPC FD modules
- TMS Upgraded to ND-Gar to provide enhanced ND interaction physics capabilities.





M. Muether, Nu2022

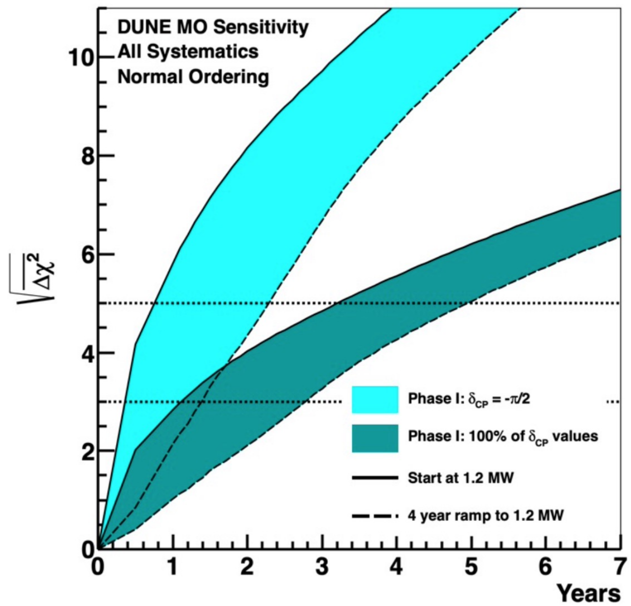
Hyper-Kamiokande

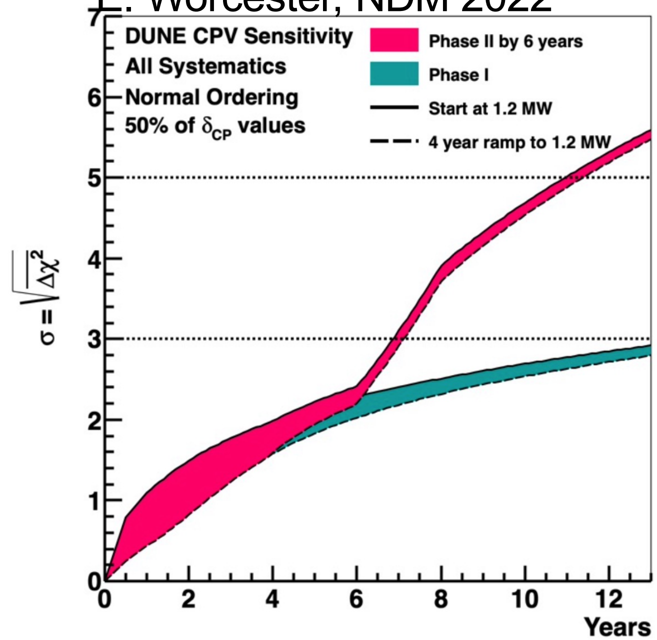


- Beam from J-PARC 295 km away, upgrade to 1.3 MW
- Many non-accelerator physics topics

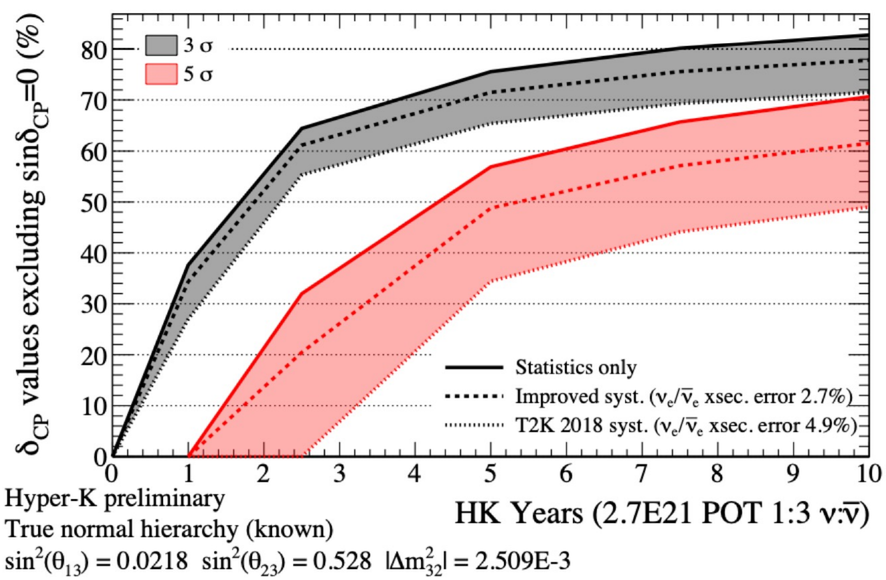
MO & CPV Sensitivity of DUNE and Hyper-K

E. Worcester, NDM 2022





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



...and HK/DUNE combo helps resolve some degeneracies

... eventually limited by systematics (neutrino interactions)

F. Di Lodovico, NeuTel 2021

Long-baseline beam experiments

Past — Current — Future

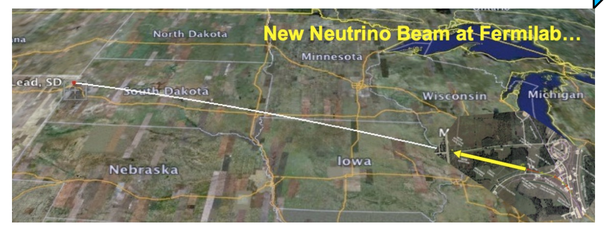
K2K
KEK to Kamioka
250 km, 5 kW

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

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
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 (➔2.4 MW)

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

And beyond...
ESSnuB, T2HKK
neutrino factories...





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

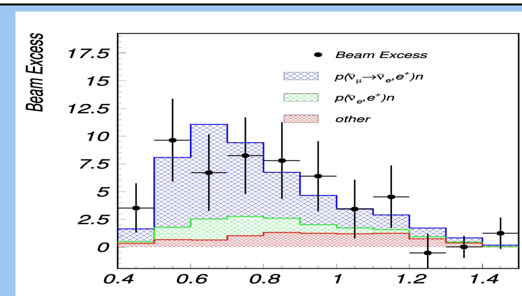
There are already some slightly uncomfortable data that **don't fit that paradigm**...

\begin{nu-paradigm}

Outstanding ‘anomalies’

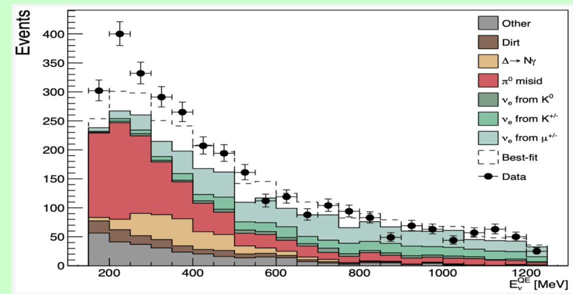
LSND @ LANL (~30 MeV, 30 m)

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



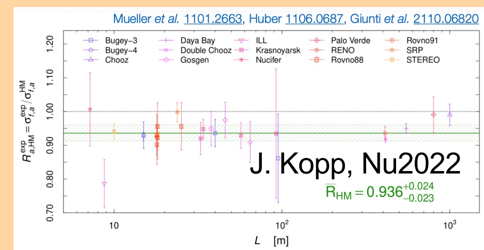
MiniBooNE @ FNAL ($\nu,\overline{\nu}$ ~1 GeV, 0.5 km)

- unexplained >3 σ excess for E < 475 MeV in neutrinos
  "low-energy excess" inconsistent w/ LSND oscillation
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antinus



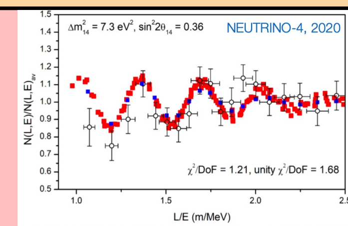
"Reactor flux anomaly"

deficit of reactor antinue absolute flux
wrt calculation



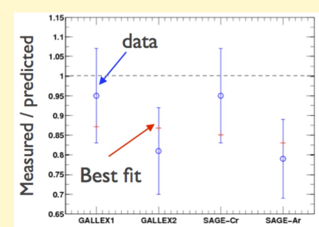
"Reactor spectral anomaly"

a wiggle, but in only one expt...

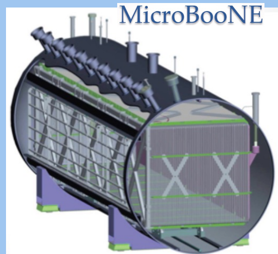


"Gallium anomaly"

~3σ deficit of nue flux from 51-Cr source in Ga

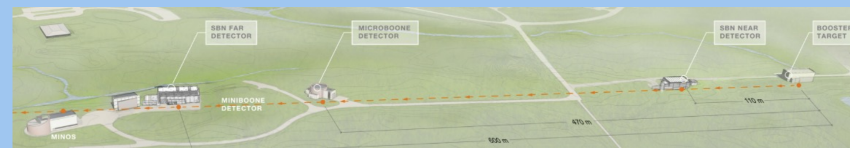


Many experiments going after (light) sterile neutrinos...

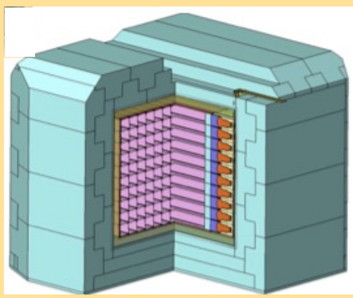


Experiments with beams

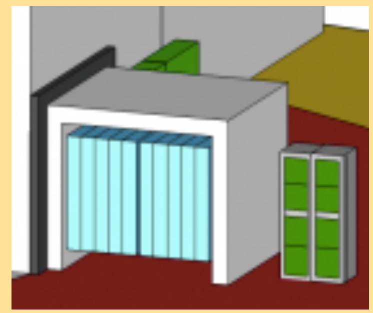
(meson decay in flight and at rest)



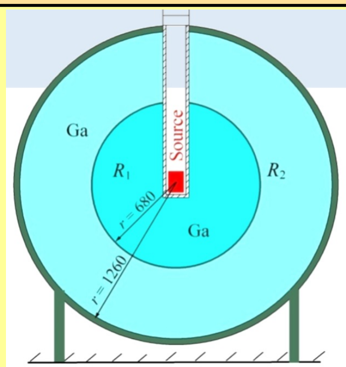
FNAL SBN, JSNS^2, ...



Experiments at reactors

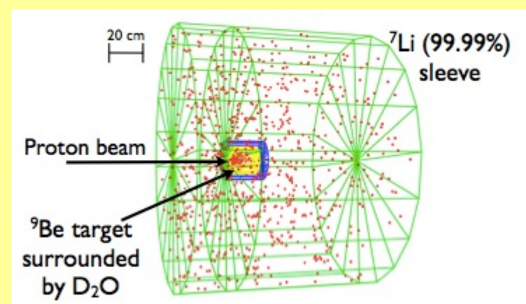


PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....



Experiments with radioactive sources

IsoDAR, BEST...

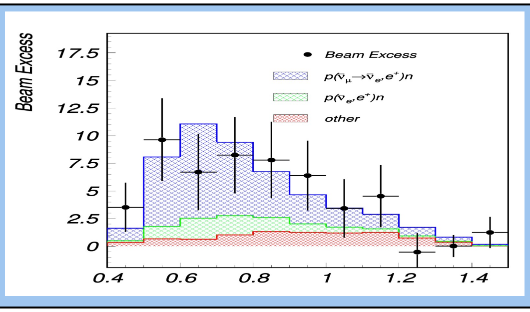


and many more, including experiments with other "day jobs"

Status of attempts to resolve anomalies...

LSND @ LANL (~30 MeV, 30 m)

Unresolved... JSNS^2 will test



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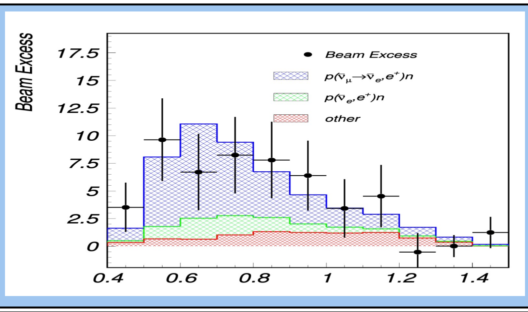
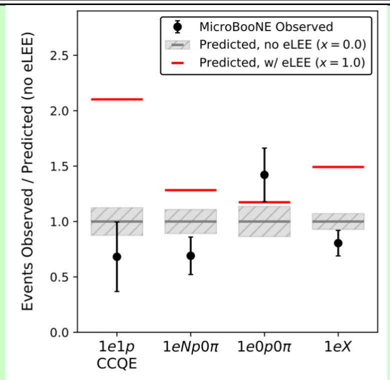


MiniBooNE @ FNAL ($\nu, \bar{\nu}$ ~1 GeV, 0.5 km)

Unresolved.... Results from MicrobooNE rule out specific electron/gamma final state explanations so far

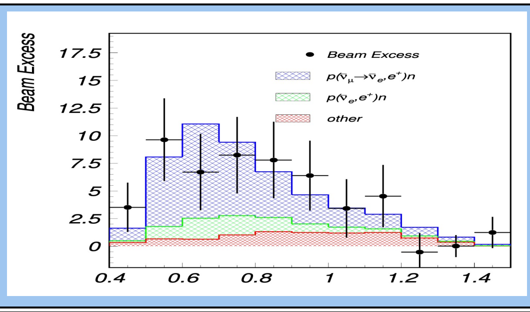
....more data from FNAL SBN program soon



Status of attempts to resolve anomalies...

LSND @ LANL (~30 MeV, 30 m)

Unresolved... JSNS[2] will test



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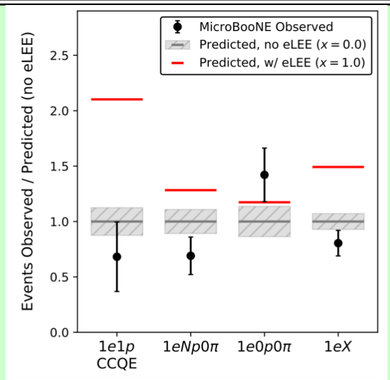
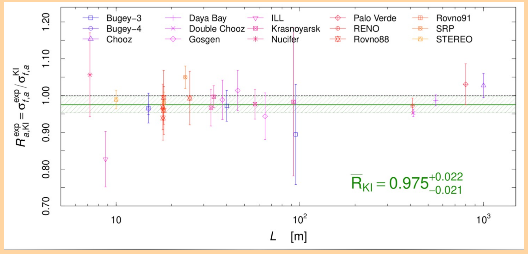


"Reactor flux anomaly"

Resolved (probably?) with new input β-decay spectra from 235-U fission

J. Kopp, Nu2022



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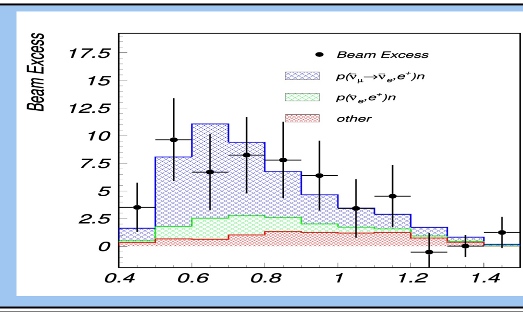

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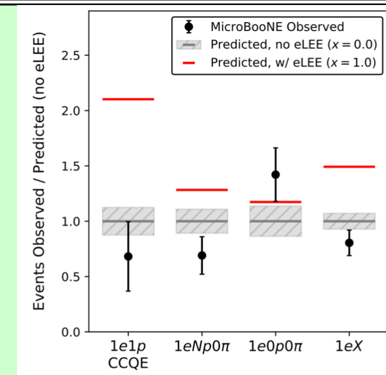

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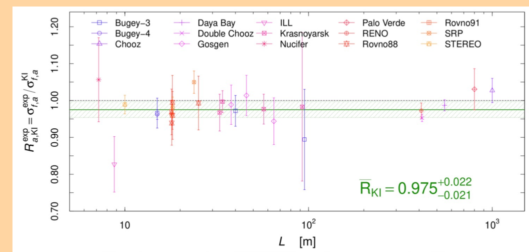
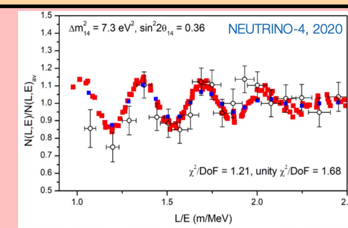


"Reactor spectral anomaly"

Unresolved... statistical issues..? but more data coming

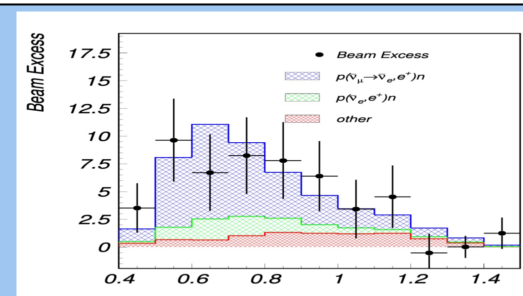
PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....



Status of attempts to resolve anomalies...

LSND @ LANL (~30 MeV, 30 m)

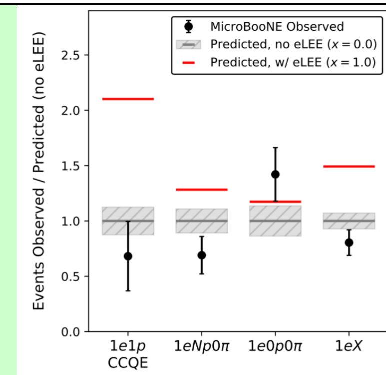
Unresolved... JSNS^2 will test



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

Unresolved.... Results from MicrobooNE rule out specific electron/gamma final state explanations so far

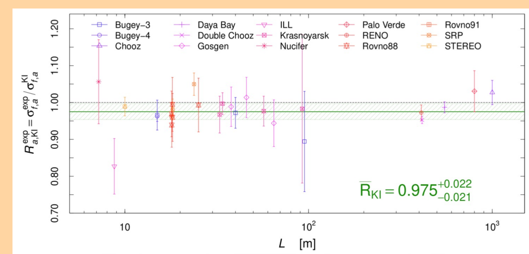
....more data from FNAL SBN program soon



"Reactor flux anomaly"

Resolved (probably?) with new input β-decay spectra from 235-U fission

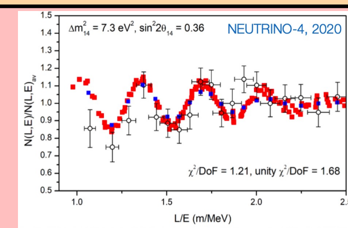
J. Kopp, Nu2022



"Reactor spectral anomaly"

Unresolved... statistical issues..? but more data coming

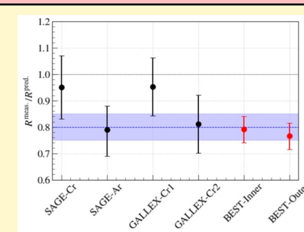
PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....



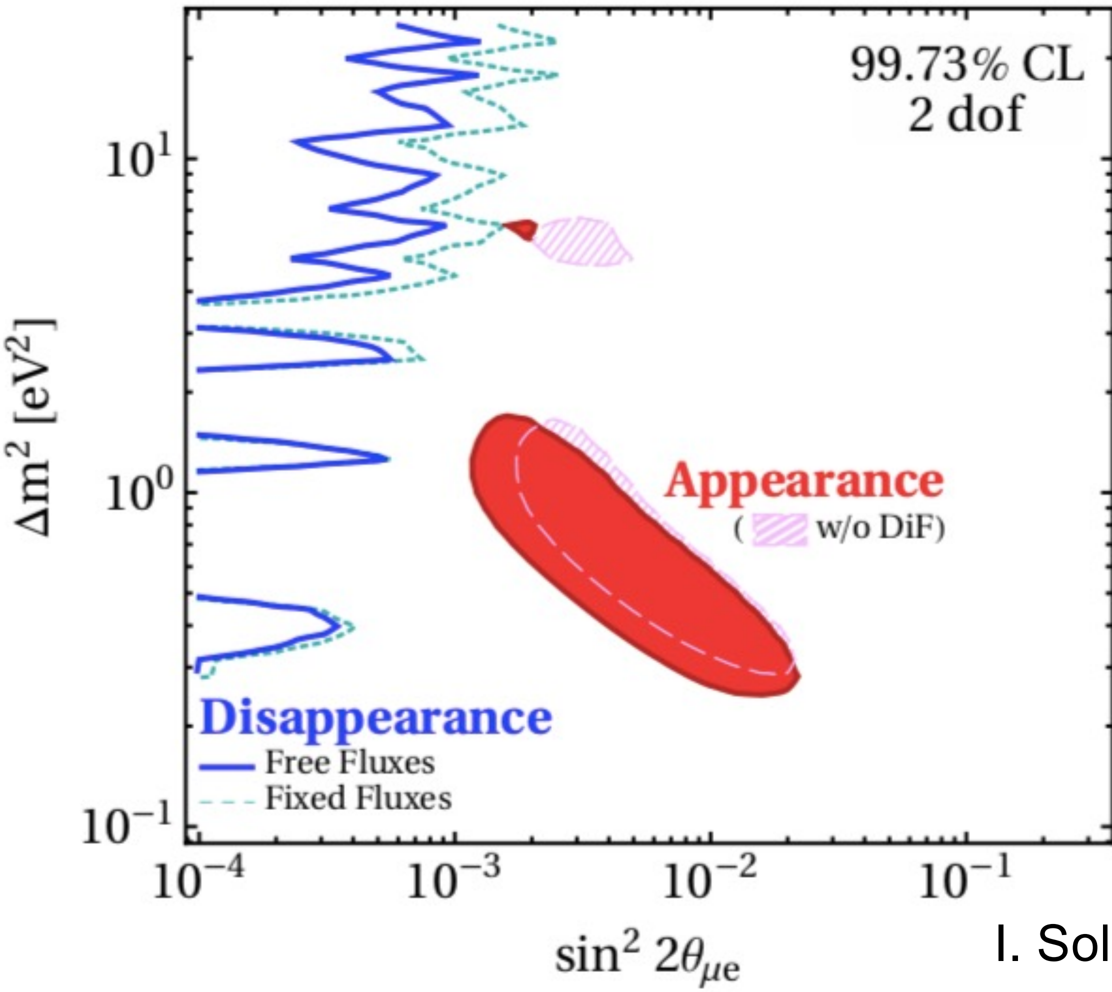
"Gallium anomaly"

Unresolved...Confirmed w/new BEST results

No baseline dependence



Fits to "all" the data are uncomfortable...



I. Soler

Appearance and disappearance data
are in fairly serious tension

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

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

...oops no \end{nu-paradigm}...

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?

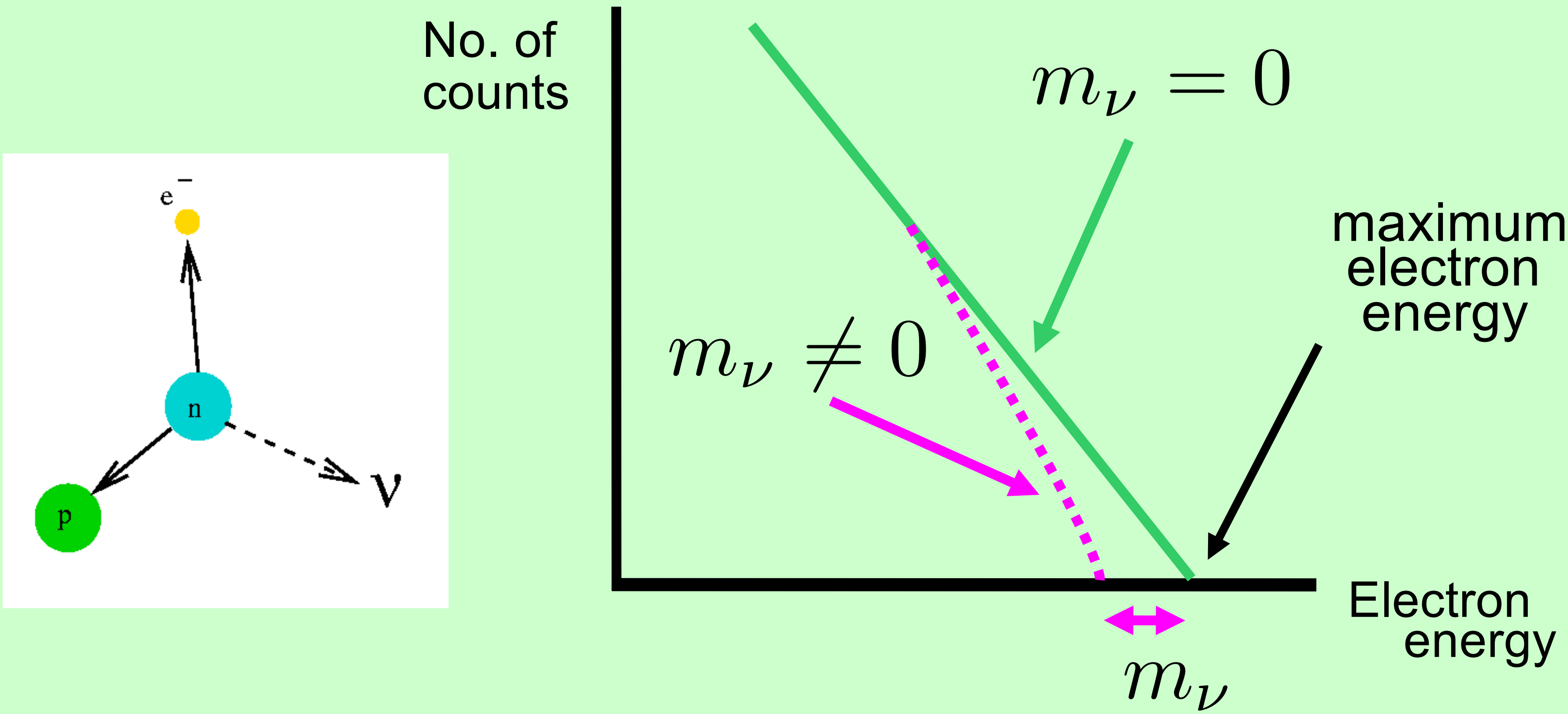
Overview of NLDBD

The mass pattern

The mass scale

The mass nature

Kinematic experiments for absolute neutrino mass



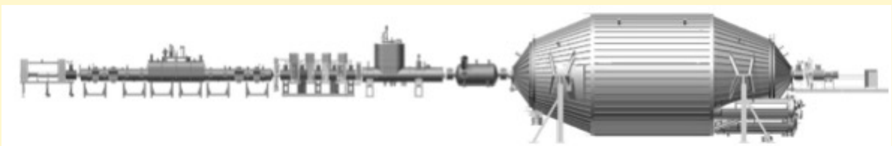
Look for distortion of β-decay spectrum near endpoint

Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

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

18.6 keV endpoint

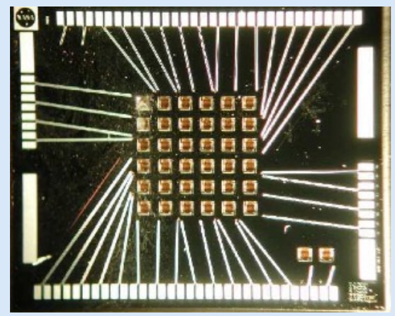


Sensitivity to ~0.2 eV

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

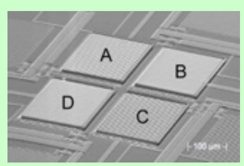
Holmium

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

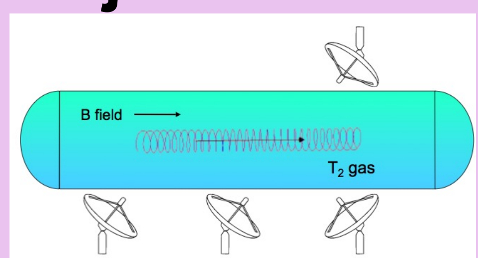


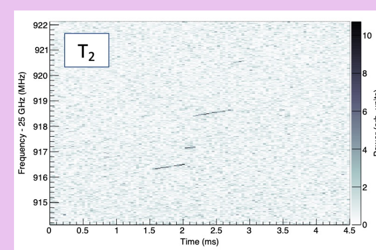
Electron capture decay,
ν mass affects deexcitation spectrum
R&D in progress

R&D

Cyclotron radiation tritium spectrometer: Project 8

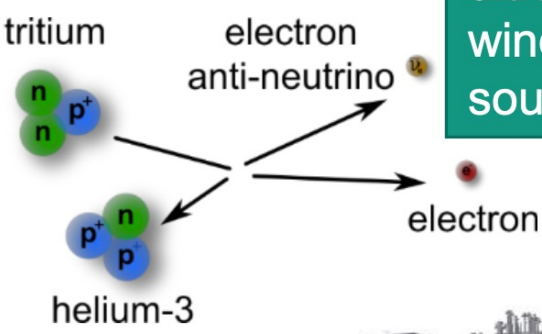
R&D, first m_β limit



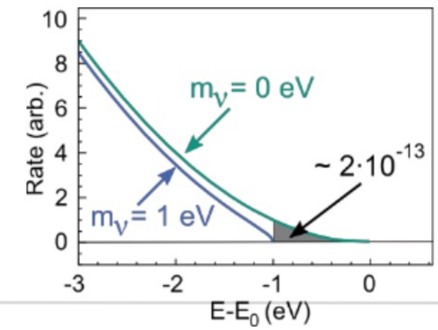


Long-term potential for
atomic tritium w/low uncertainties
aiming for 40 meV in long term

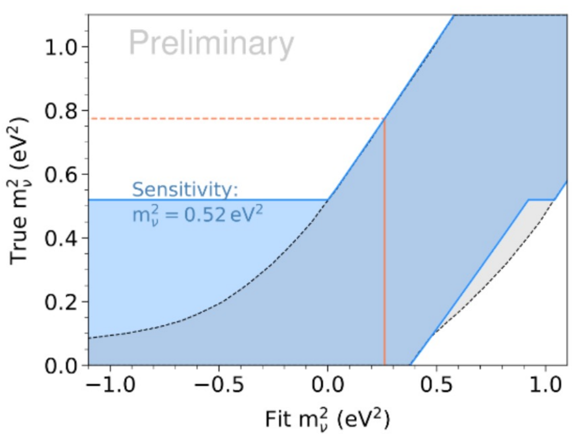
KATRIN results



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 2[nd] campaign
$m_\nu < 0.9$ eV (90% CL)

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

Combined:
< 0.8 eV (90% CL)

Expect sensitivity to **0.2 eV** by 2025

Magnus Schlösser – MORIOND2021

KATRIN Collab. Nat. Phys. **18,** 160–166 (2022)

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

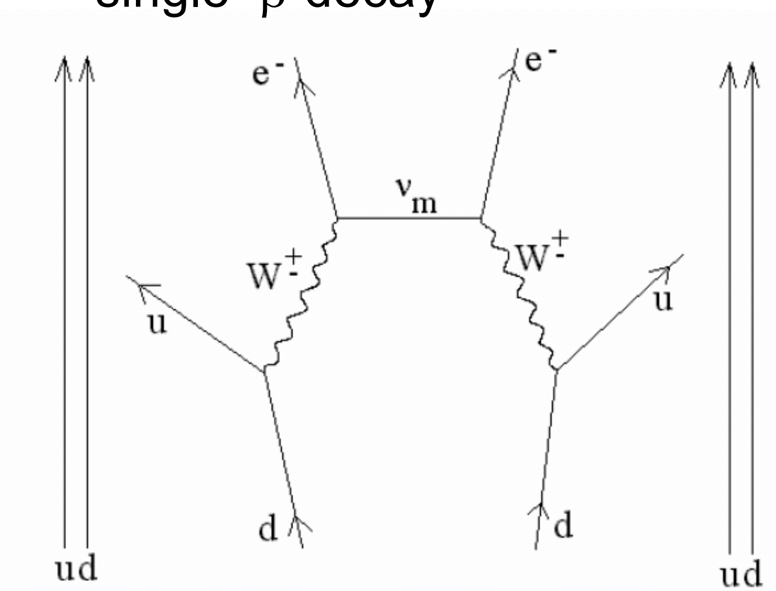
The mass pattern

The mass scale

The mass nature

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

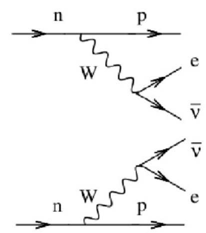
Best (only) experimental strategy: look for
neutrinoless double beta decay
in isotopes for which it is energetically possible and which don't single β-decay



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

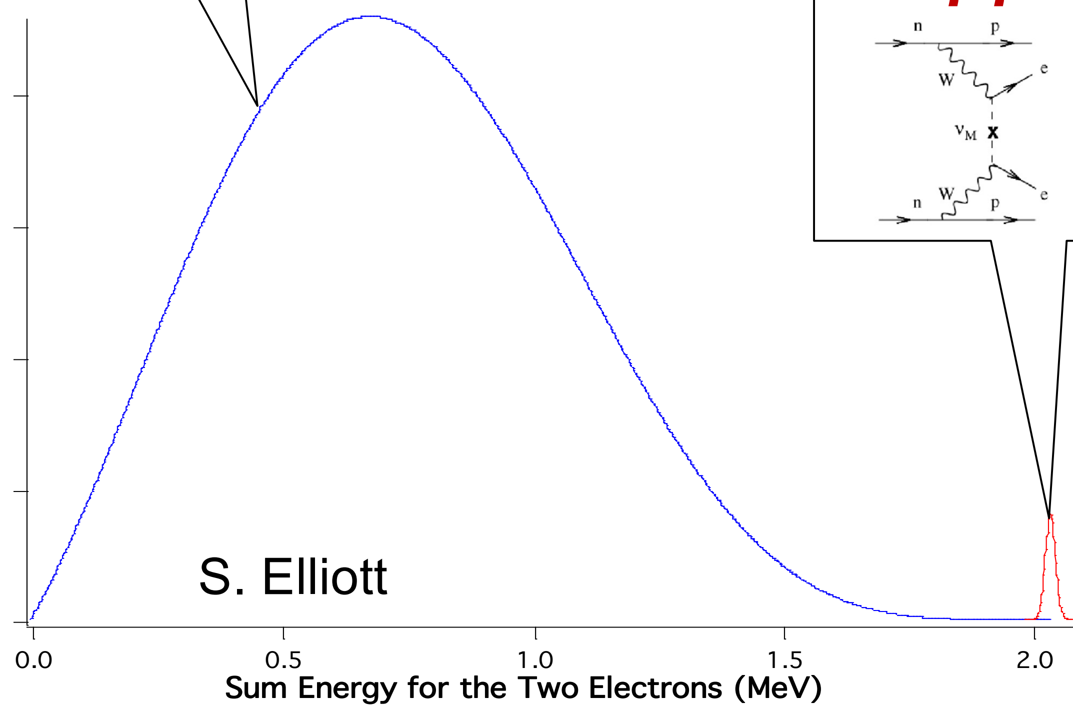
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

2νββ
(SM 2nd order weak process

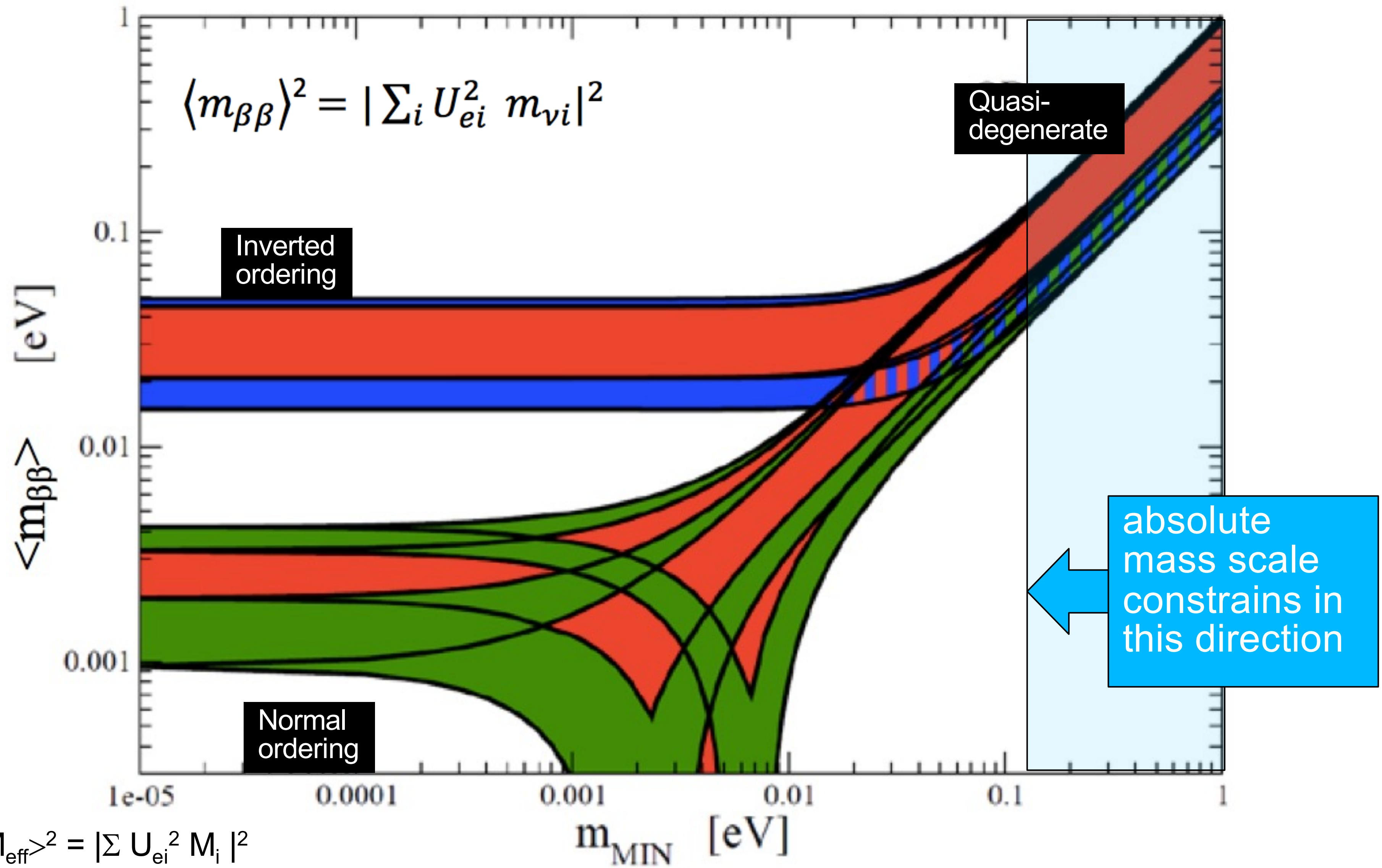


Observable: peak in the two-electron spectrum corresponding to ν-less final state

0νββ



The NLDBD T-Shirt Plot



$\langle M_{eff}\rangle^2 = |\Sigma\ U_{ei}^2\ M_i\ |^2$

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

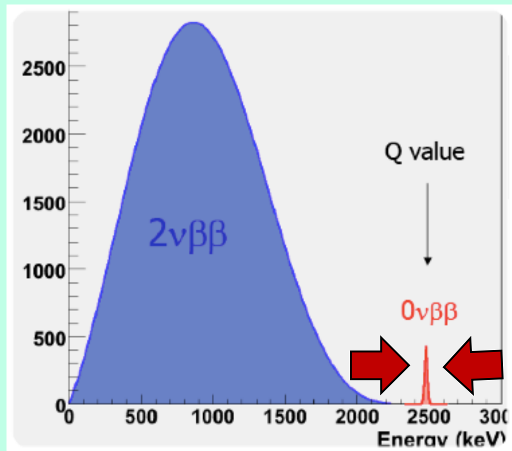
Extent of the regions determined by uncertainties on Majorana phases and mixing matrix elements

General NLDBD experiment strategies

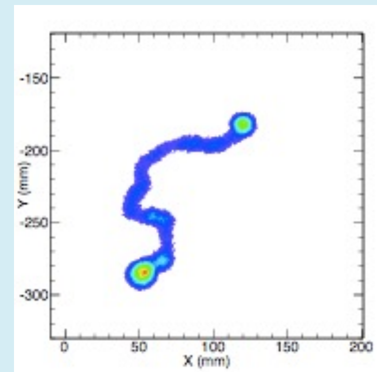
$$T_{1/2} > \frac{\ln 2\ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

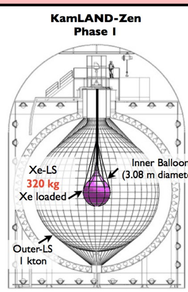
The "Brute Force" Approach

The "Peak-Squeezer" Approach

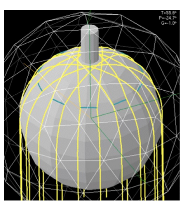


The "Final-State Judgement" Approach

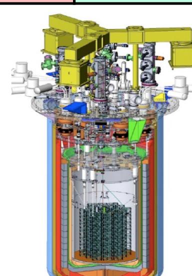




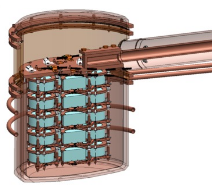
KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)



CUORICINO/ CUORE (^{130}Te)

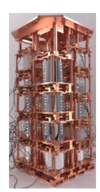


MAJORANA (^{76}Ge)

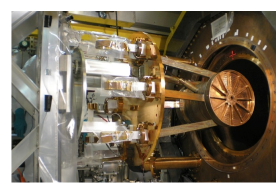
CUPID (^{82}Se)

CUPID -Mo (^{100}Mo)

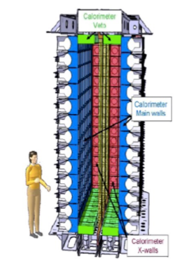
GERDA (^{76}Ge)



AMORE (^{100}Mo)



EXO (^{136}Xe)



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

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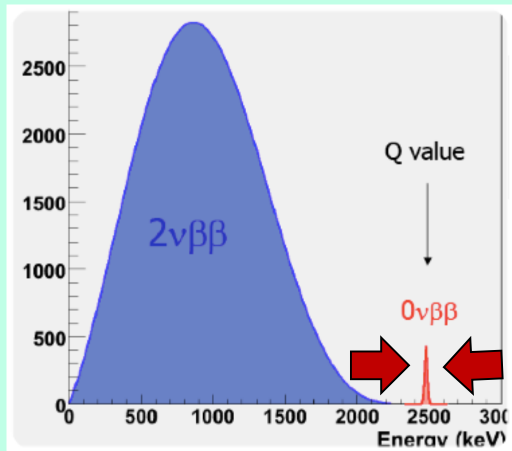

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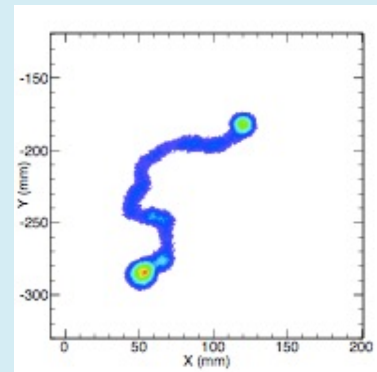

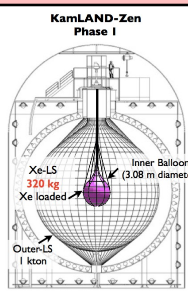

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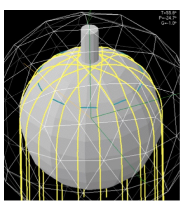

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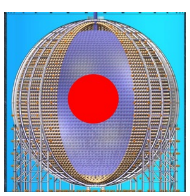
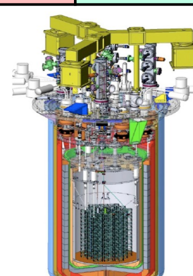
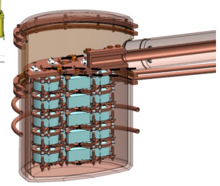


JUNO-ββ (^{136}Xe, ^{130}Te)



CUORICINO/ CUORE (^{130}Te)



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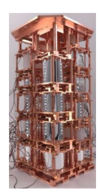
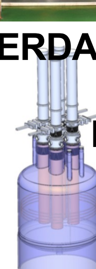
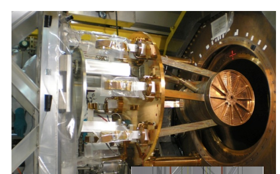


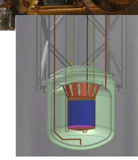
AMORE (^{100}Mo)

GERDA (^{76}Ge)

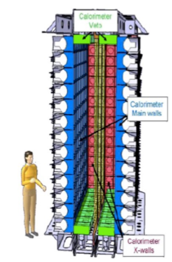


LEGEND (^{76}Ge)





EXO /nEXO (^{136}Xe)



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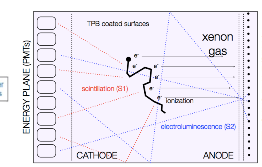


NEXT (^{136}Xe)

+more future ideas...

Current limits

Now at ~100 meV scale

Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

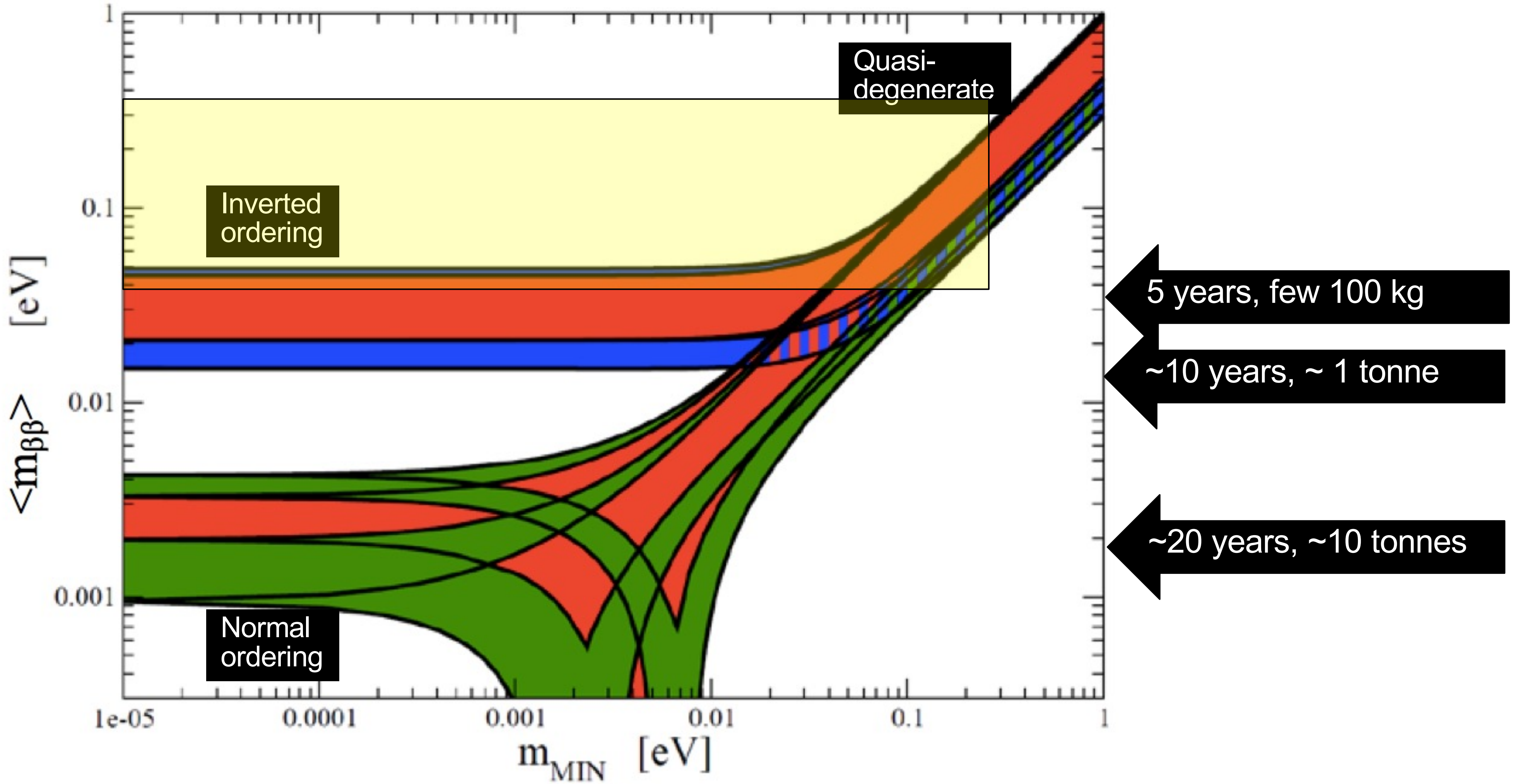
Future prospects

Push down an order of magnitude on ~decade time scale w/tonne-scale

	Isotope	Mass(t)	$<m_{\beta\beta}>$,meV
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
LEGEND-1000	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO-ββ	^{136}Xe	50	4-10
	^{130}Te	100	3-14

Simkovic, Schoenert, Wang, Zolotarova, Nu2022

Overall Long-Term Prospects for NLDBD



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

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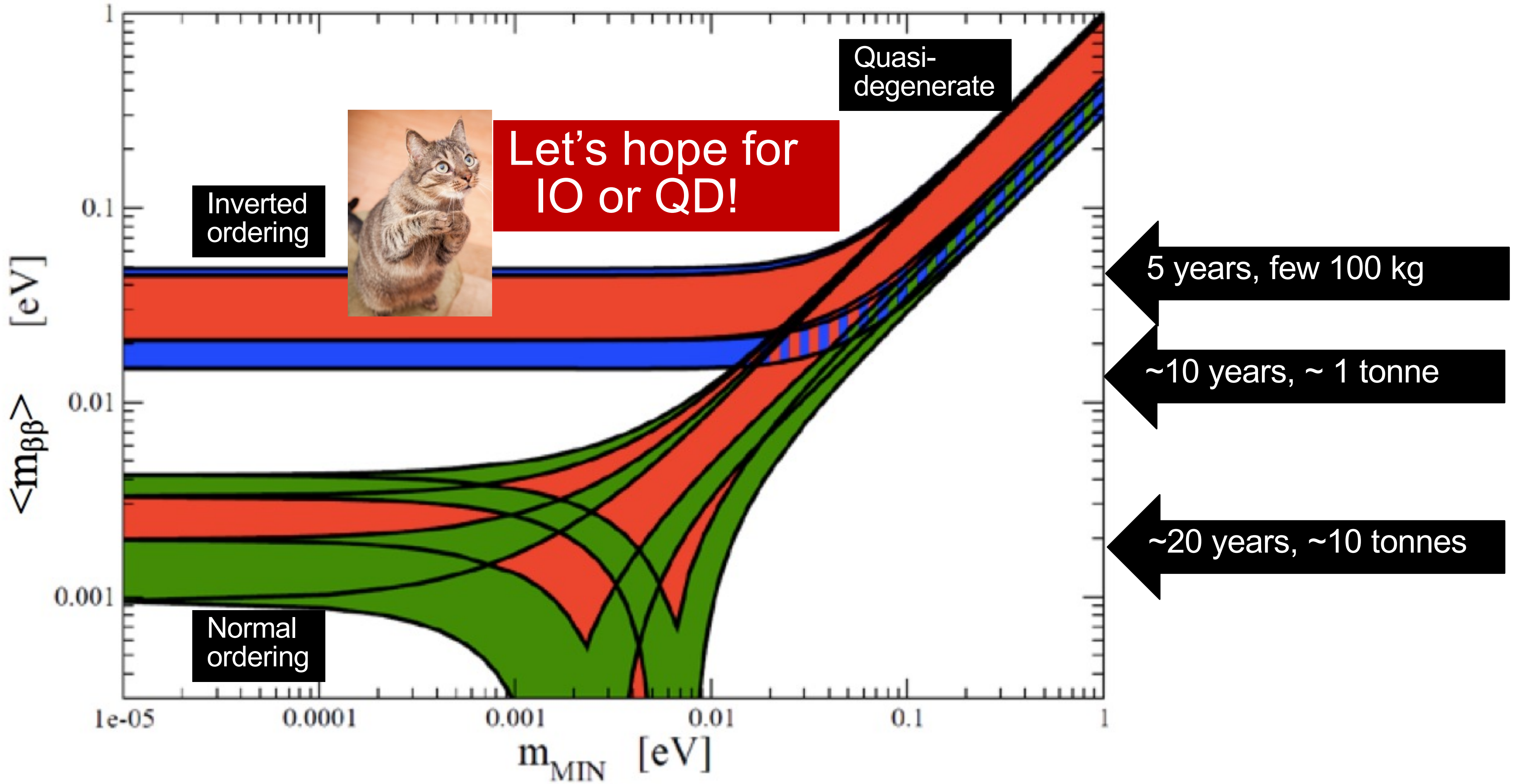

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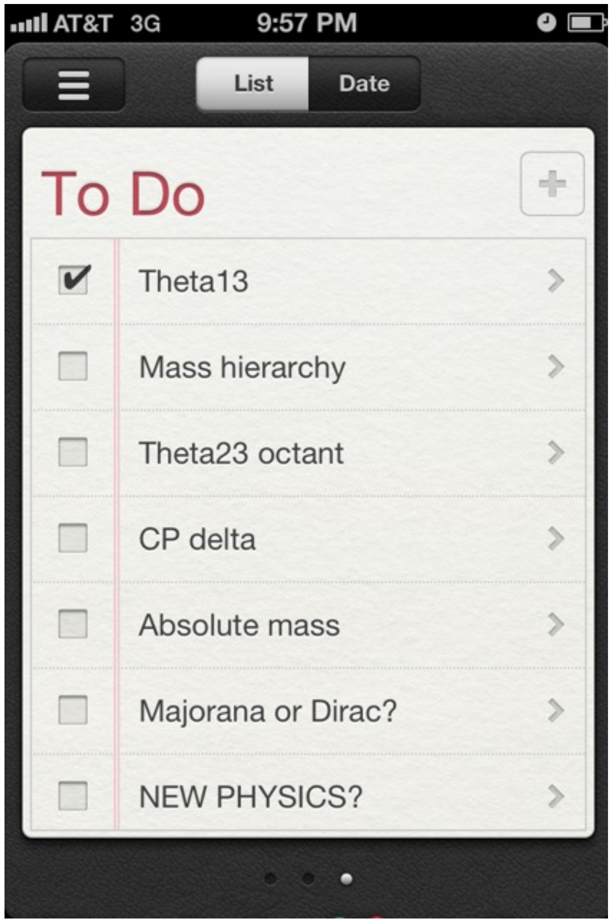
Overall Summary

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



My IPhone from 11 years ago!*

*I have never found a good to-do list app...

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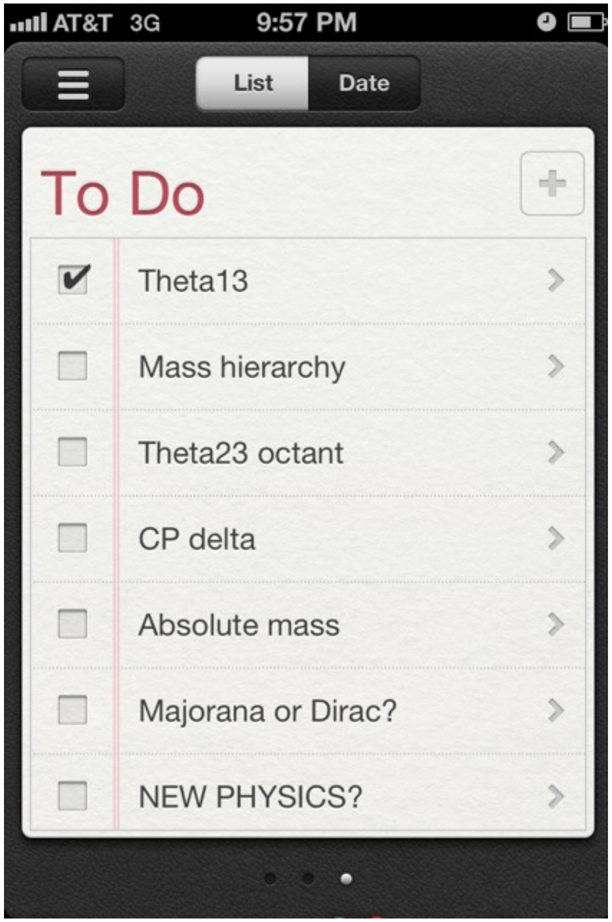

getting 2σ-ish results ... good prospects for 3σ (+?) in next ~5 years but will need DUNE/HK for 5σ

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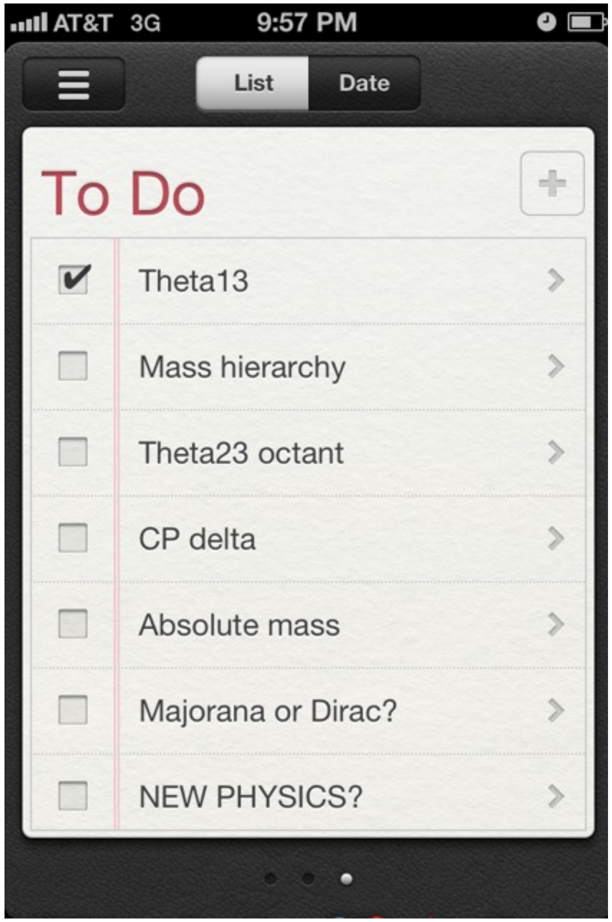

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More from KATRIN to come!

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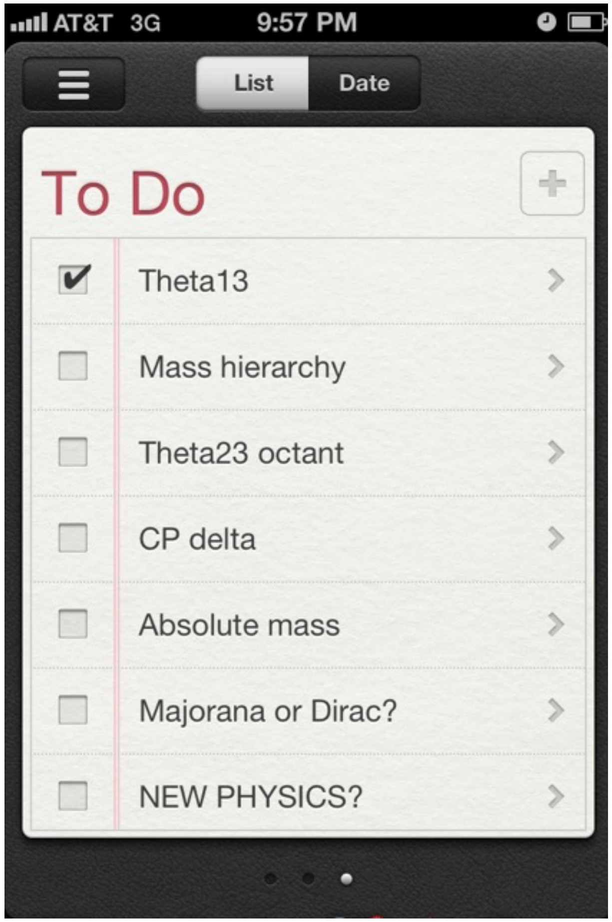

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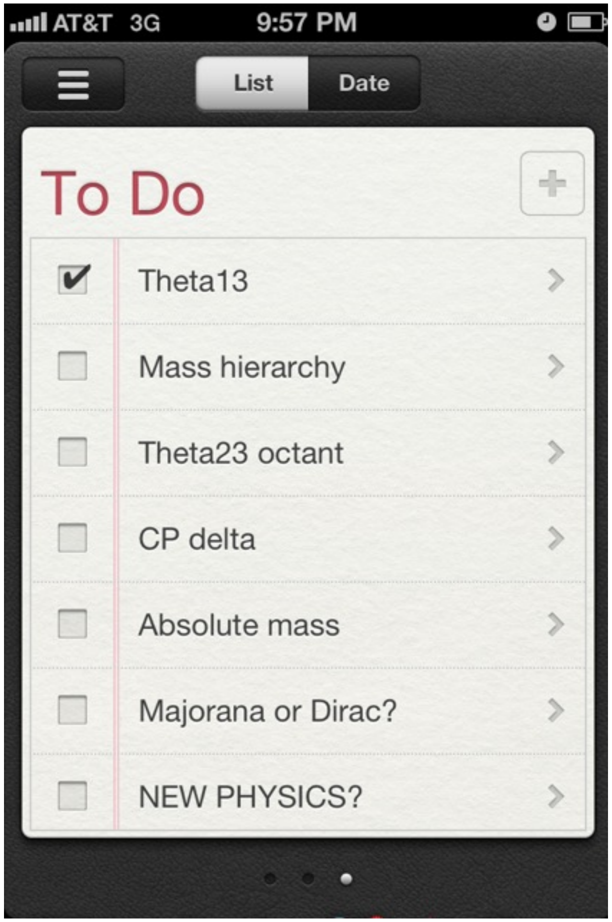

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There could be surprises....

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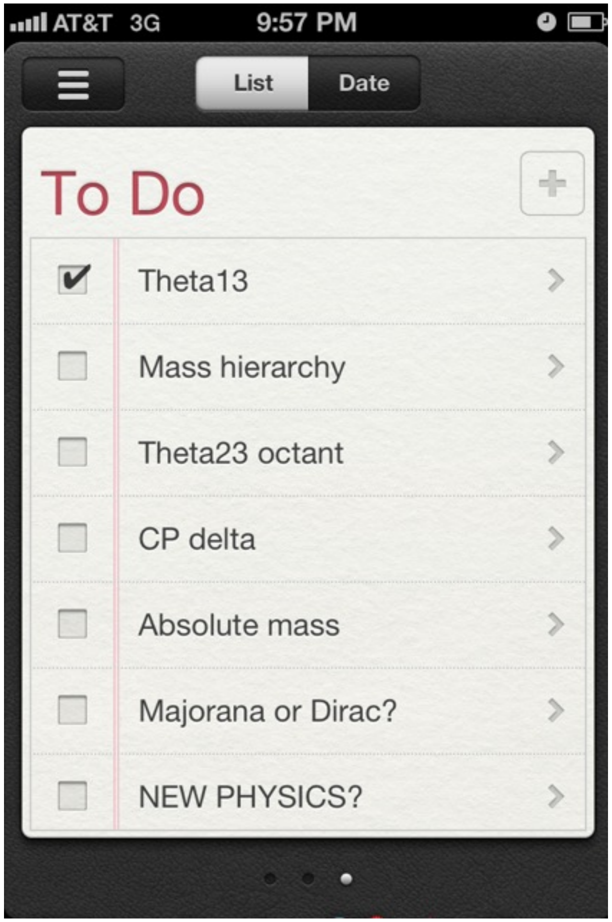

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More from KATRIN to come!

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!