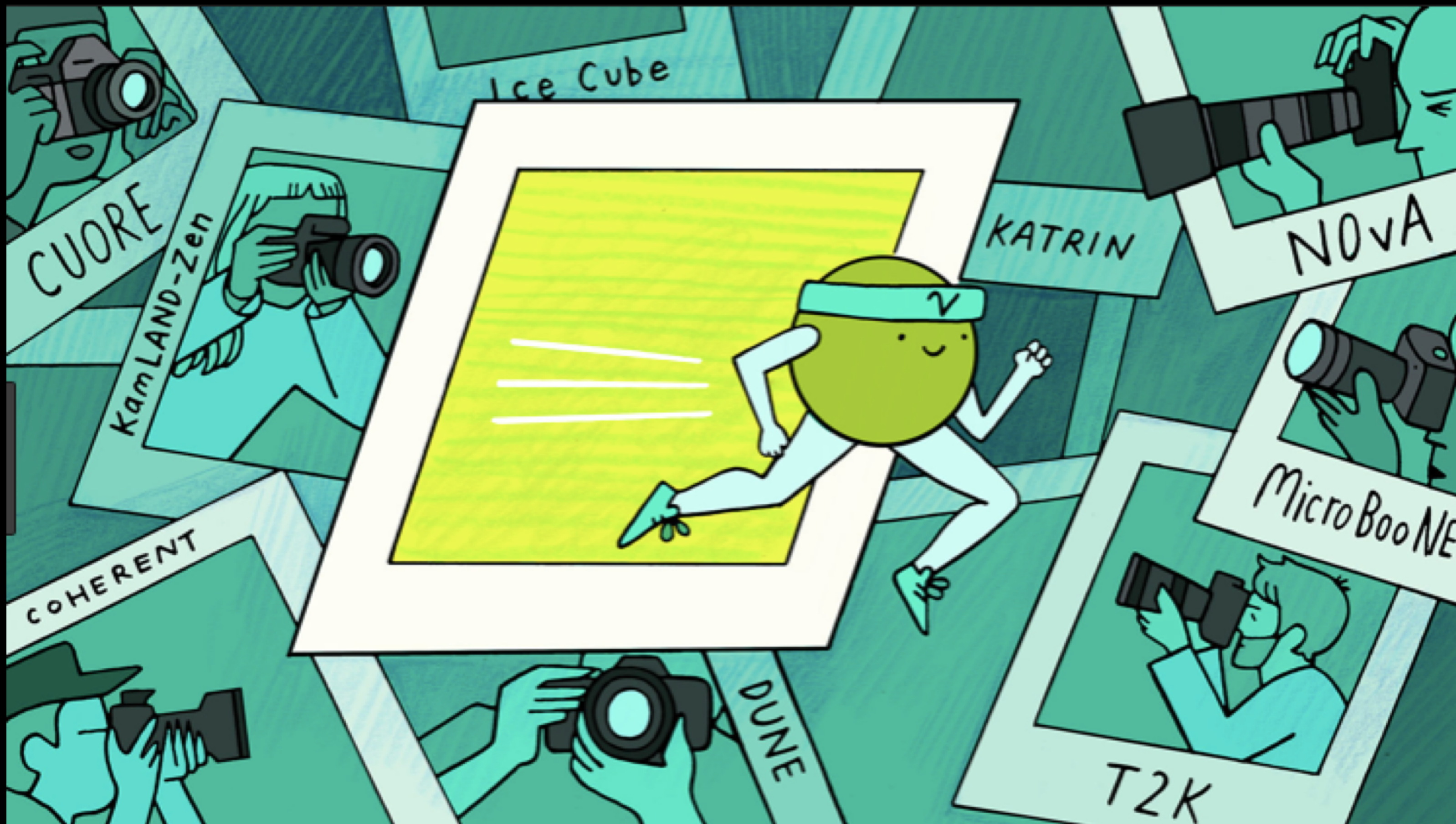
Neutrino Experimental Programs



Symmetry magazine

Kate Scholberg, Duke University
SUSY 2019, Corpus Christi
May 20, 2019

What I will cover

Experimental knowledge and programs to move forward

Neutrino Oscillations

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

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

Beyond 3-flavor?

The mass pattern

Absolute Mass

Status and prospects

The mass scale

Majorana vs Dirac?

Overview of NLDBD

The mass nature

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

What I will cover

Experimental knowledge and programs to move forward

Neutrino Oscillations

Latest 3-flavor results

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

Beyond 3-flavor?

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

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

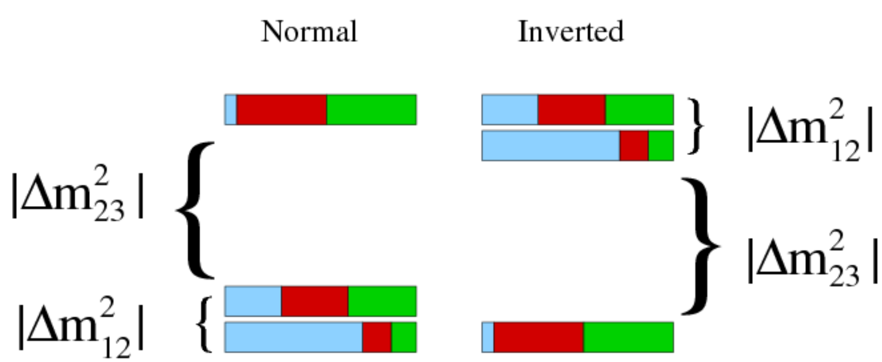
Parameterize mixing matrix U as

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

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

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

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

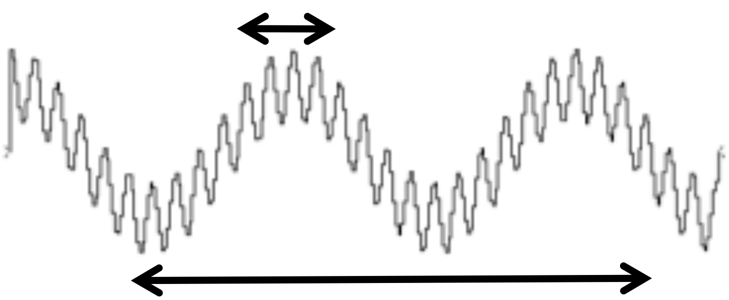
$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^* |\nu_i\rangle$$

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

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

$$\pm\, 2 \sum_{i>j} \Im(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin(2.54 \Delta m_{ij}^2 L/E)$$

oscillatory behavior in L and E



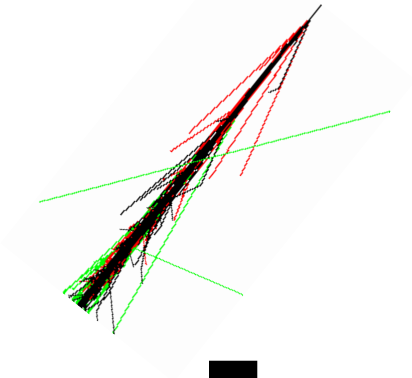
$$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$$ ➔ two frequency scales

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

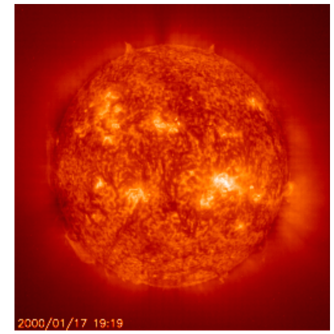
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27 \Delta m^2 L}{E}\right)$$

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

atmospheric

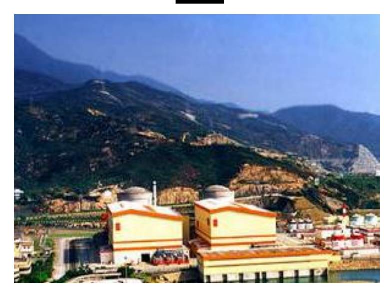


solar



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

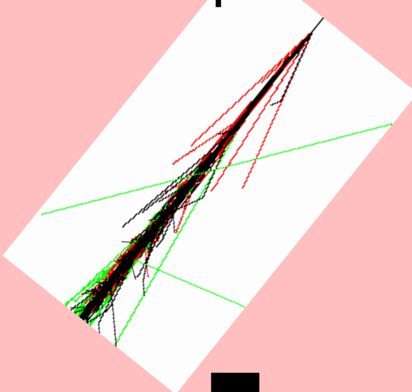
beams



reactor

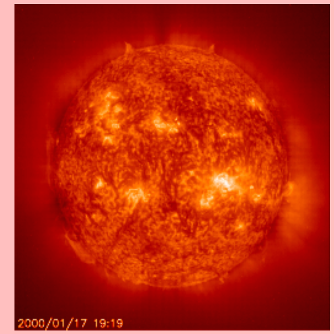
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
“wild” neutrinos...

solar



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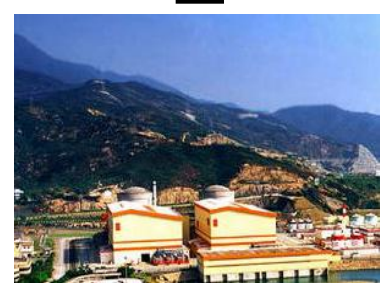
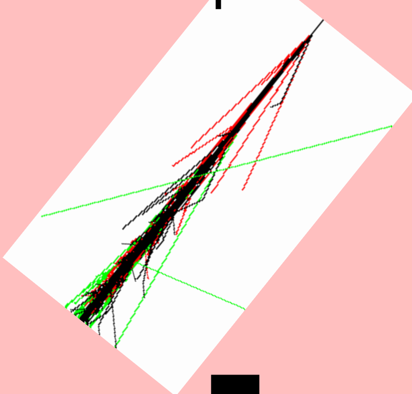
beams



reactor

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

atmospheric



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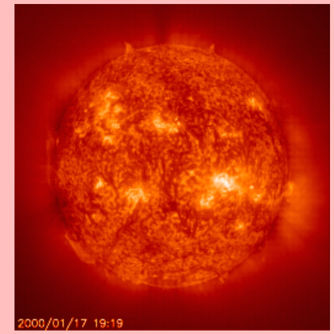
solar



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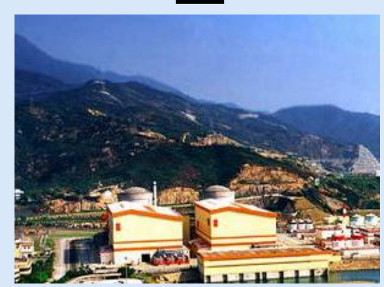
$$

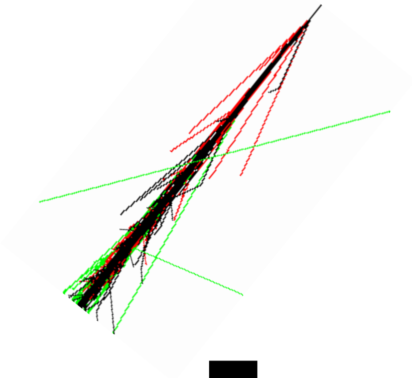
beams

confirmed with
“tame” ones...

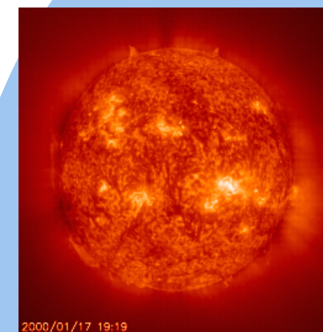


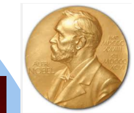
reactor

atmospheric



solar





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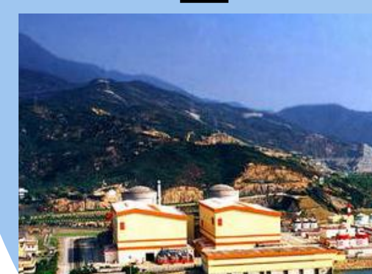
beams

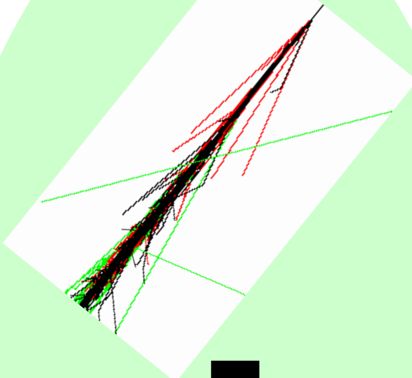
$\Delta m^2_{12}, \theta_{12}$

"Solar" sector: solar ν oscillations confirmed with reactors

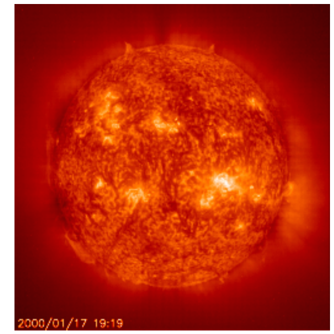


reactor

atmospheric



solar



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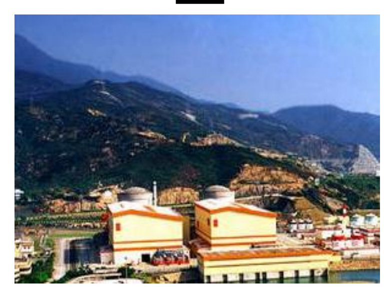
beams

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

"Atmospheric" sector



reactor

Long-baseline beam experiments: taming the source

Past — Current — Future

K2K

KEK to Kamioka
250 km, 5 kW

Long-baseline beam experiments: taming the source

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

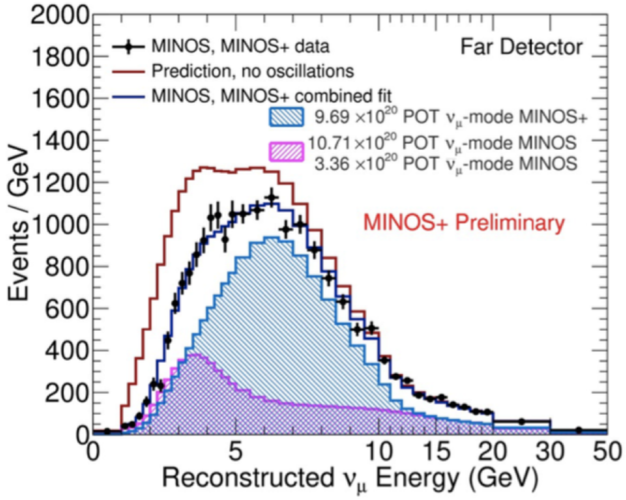
T2K
J-PARC to Kamioka
295 km, 380-750 kW

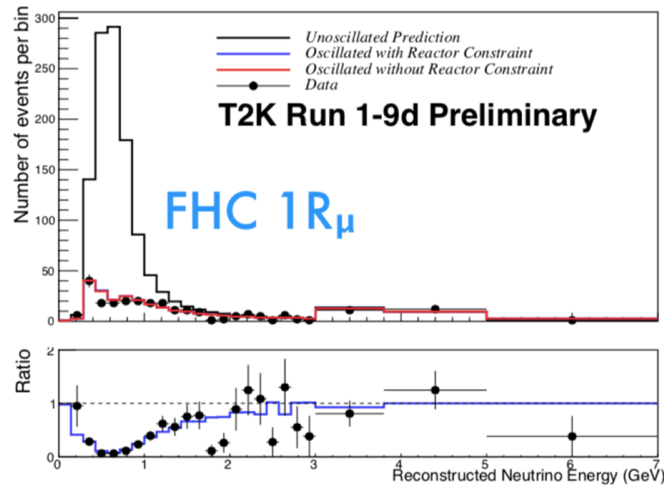
Muon neutrino disappearance

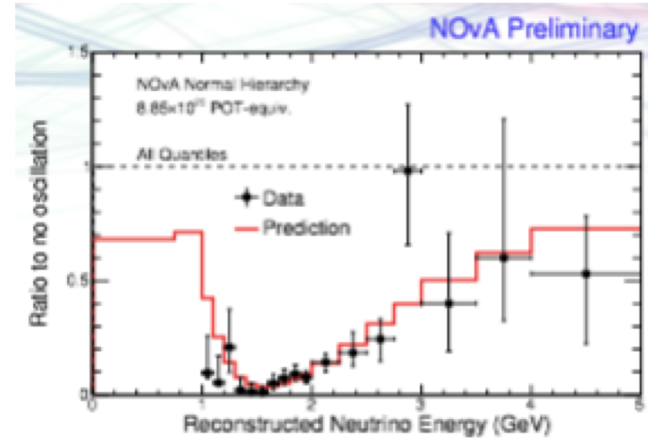
MINOS, MINOS+

T2K

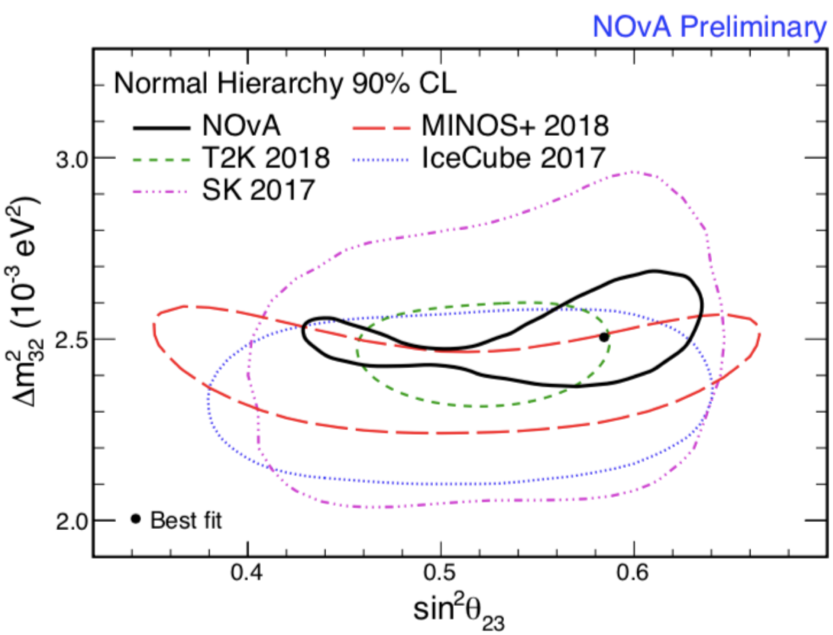
NOvA







A. Aurisiano, Nu2018



P. Vahle, APS 2019

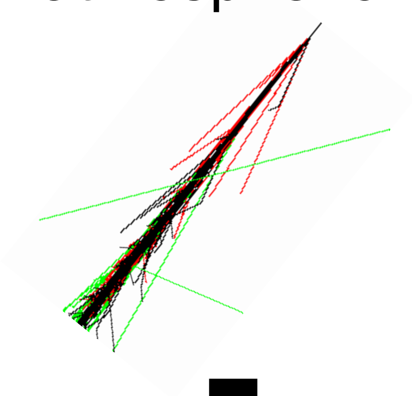
+ antinumu in MINOS, T2K

+ tau appearance in SK, OPERA

All beam & atmnus point to consistent parameters

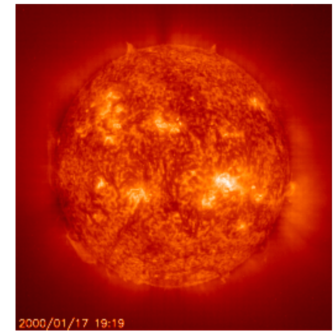
The mixing angle θ_{13}: information from beams and burns!

atmospheric



θ_{13}, the "twist in the middle"

solar



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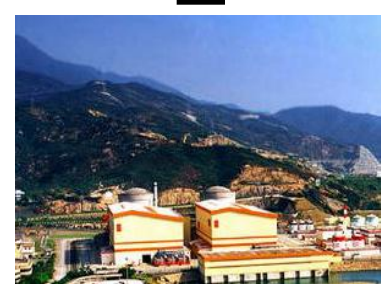
beams

Before 2011, known to be small

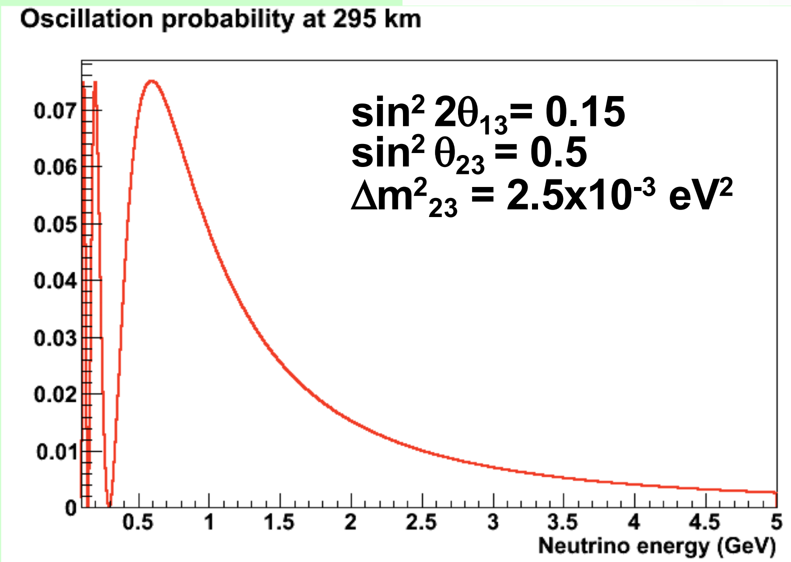


reactor

How to measure θ_{13}

Beams

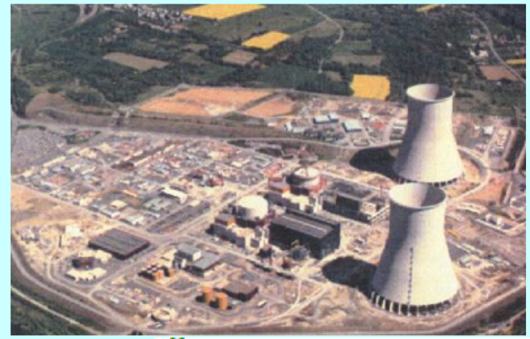
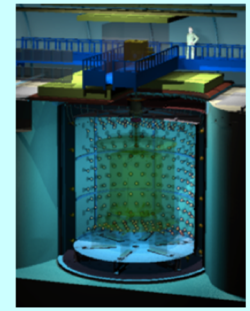
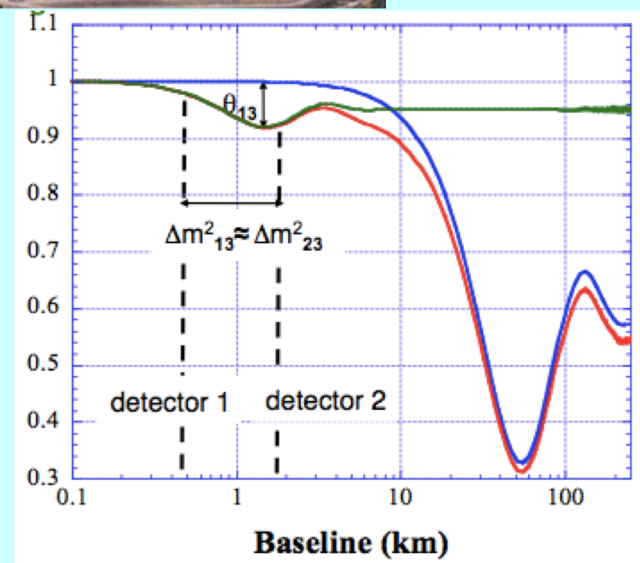




Look for *appearance*
of ~GeV ν_e in ν_μ beam
on ~300 km distance scale

K2K, MINOS(+), T2K, NOνA

Reactors

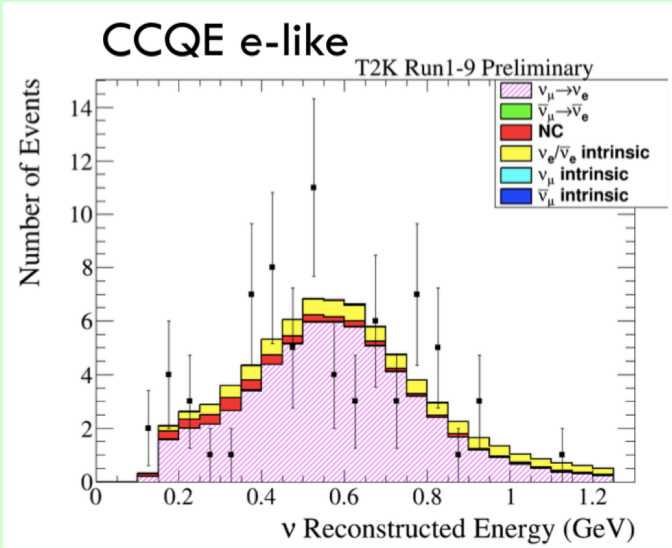




Look for *disappearance*
of ~few-MeV $\bar{\nu}_e$
on ~km distance scale

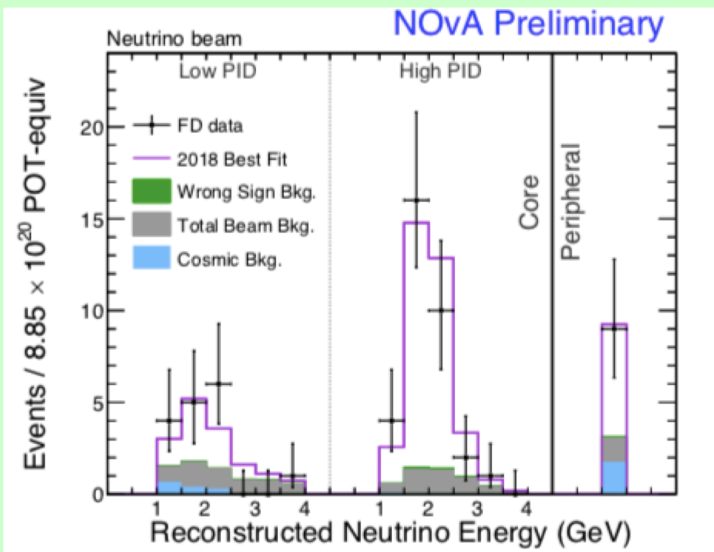
CHOOZ, Double Chooz, Daya Bay, RENO

θ_{13} from beams and burns

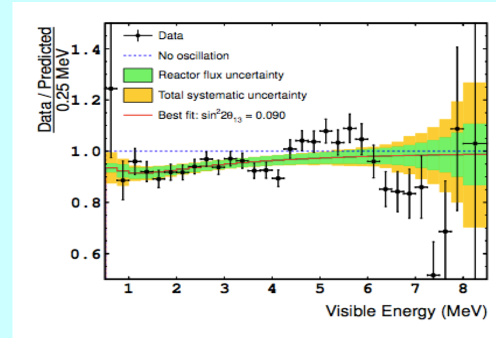
T2K



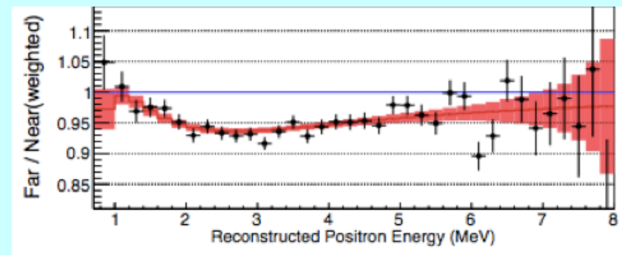
NOvA



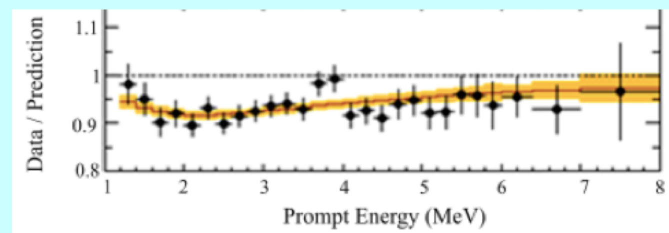
Double Chooz



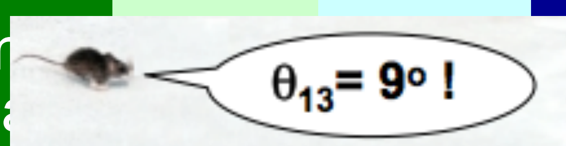
Daya Bay



RENO



Appearance of electron neutrinos i a muon neutrino bea



Disappearance of reactor antineutrinos with characteristic near-far spectral distortion

But single-parameter/two-flavor fits are so 2012...

information 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

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

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

Esteban, I., Gonzalez-Garcia, M.C., Hernandez-Cabezudo, A. et al. J. High Energ. Phys. (2019) 2019: 106. https://doi.org/10.1007/JHEP01(2019)106

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

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
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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

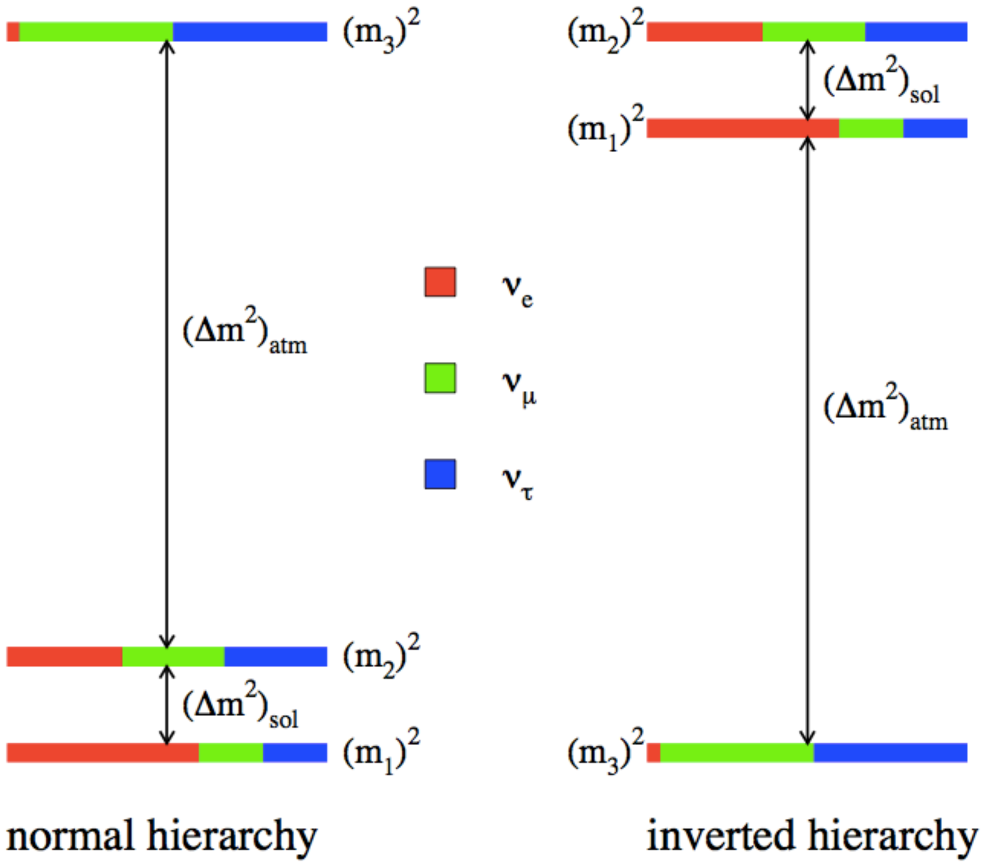
sign of Δm^2 unknown (ordering of masses)

Esteban, I., Gonzalez-Garcia, M.C., Hernandez-Cabezudo, A. et al. J. High Energ. Phys. (2019) 2019: 106. https://doi.org/10.1007/JHEP01(2019)106

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

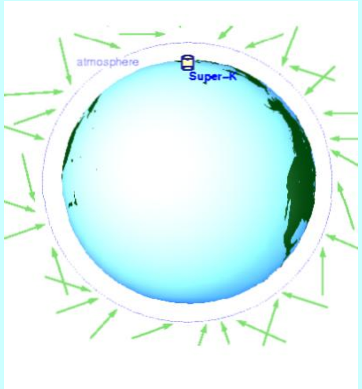
They are all challenging...

Four of the possible ways to get MO

Long-baseline beams

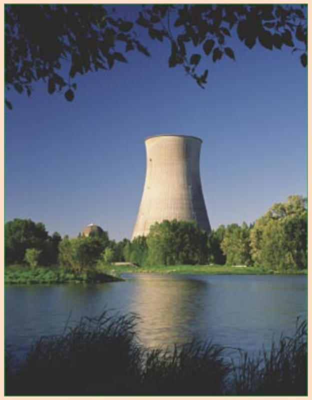
Hyper-K, LBNF/DUNE

Atmospheric neutrinos



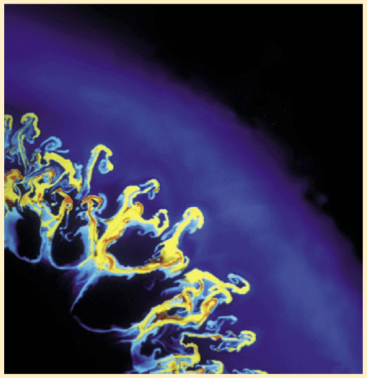
Super-K, Hyper-K, IceCube, KM3Net, DUNE, INO

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)

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

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

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

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

Past

K2K
KEK to Kamioka
250 km, 5 kW

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

CNGS
CERN to LNGS
730 km, 400 kW

Current

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

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

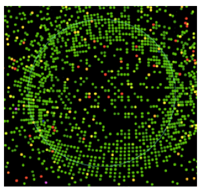
Future

T2K appearance and disappearance

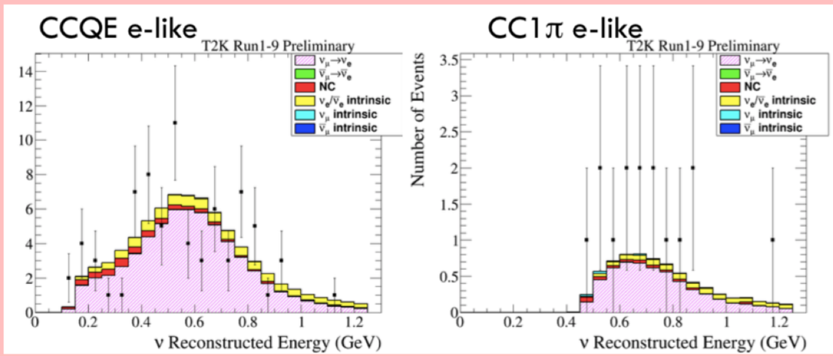
Neutrinos 1.51 x 10^{21} pot

Antineutrinos 1.65 x 10^{21} pot

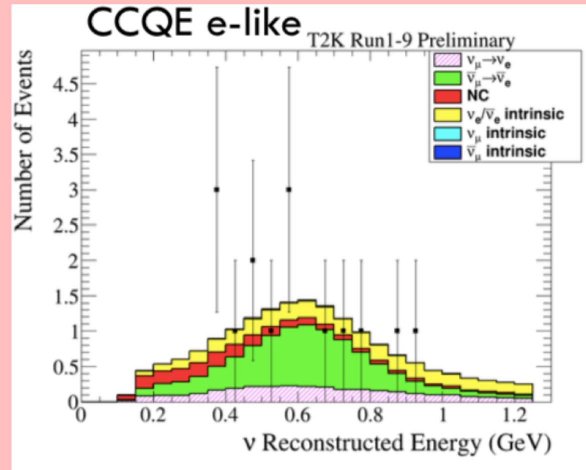
Electron neutrino appearance



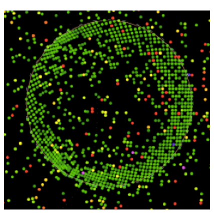
Neutrinos:



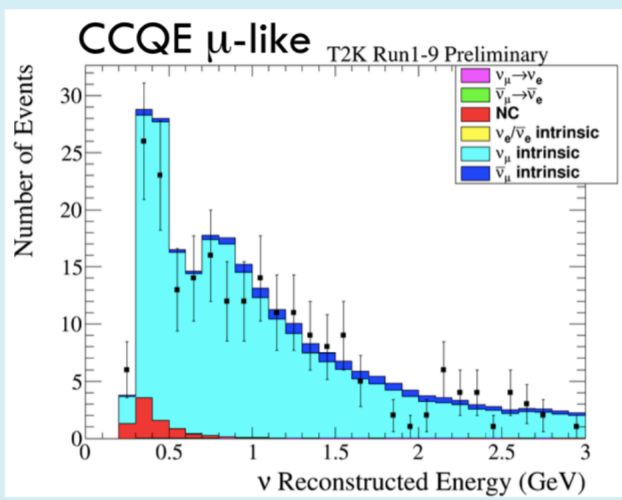
Antineutrinos:



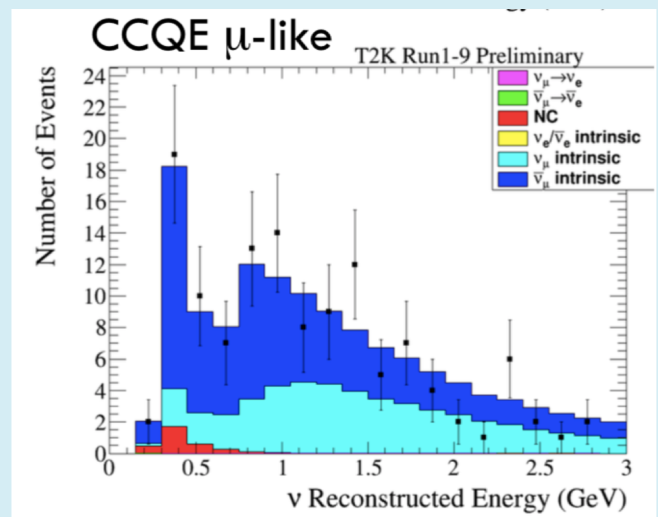
Muon neutrino disappearance



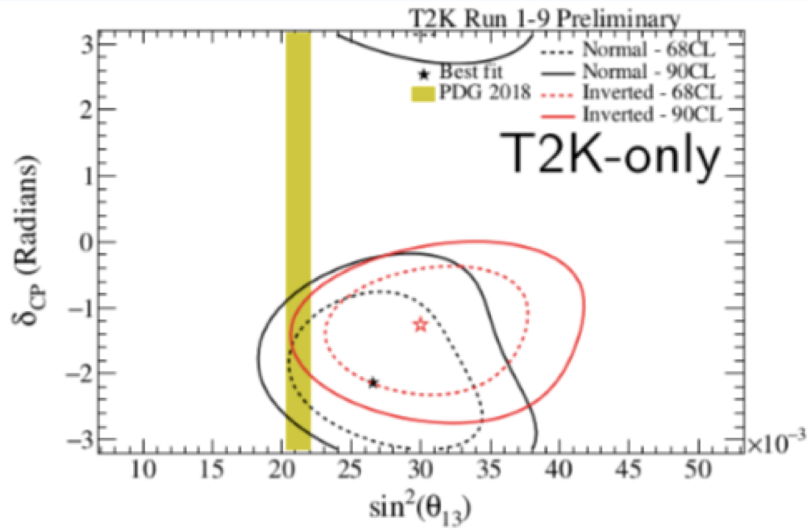
Neutrinos:

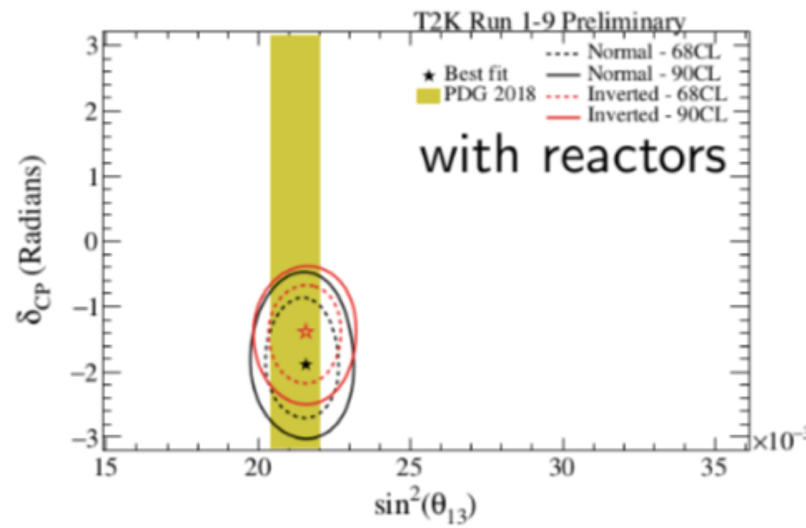


Antineutrinos:

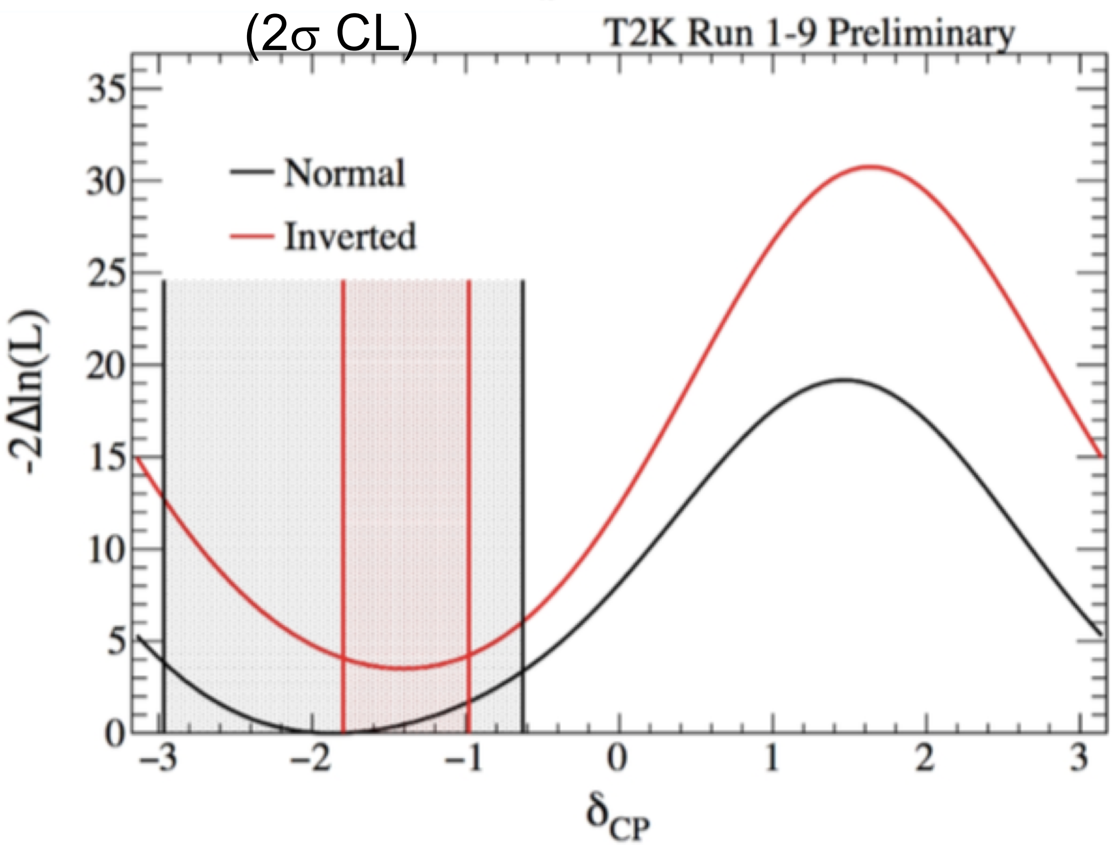


Joint fit to all T2K data





Gzarnecki, LaThuile 2019

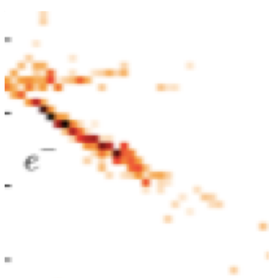
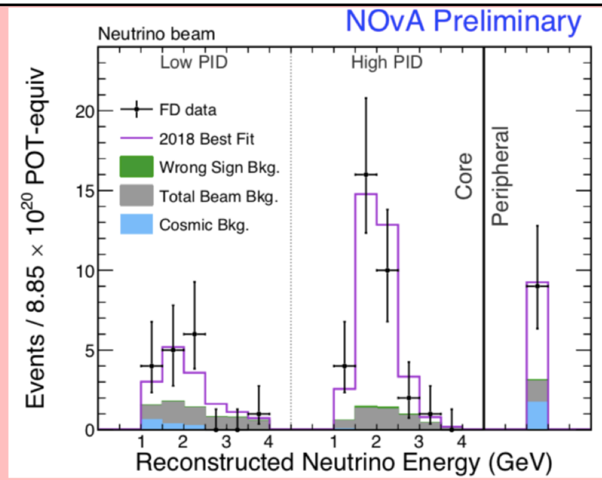
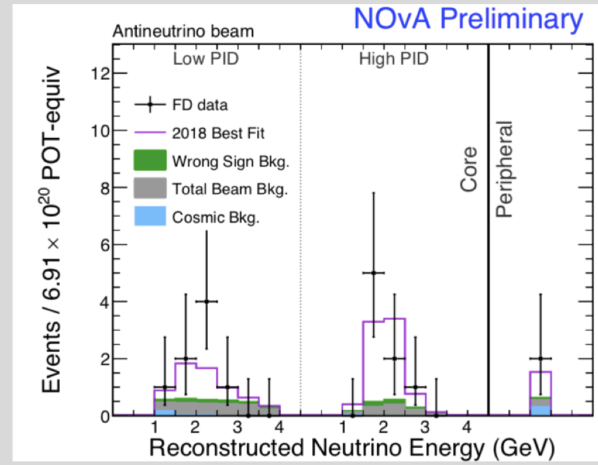
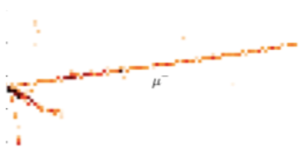
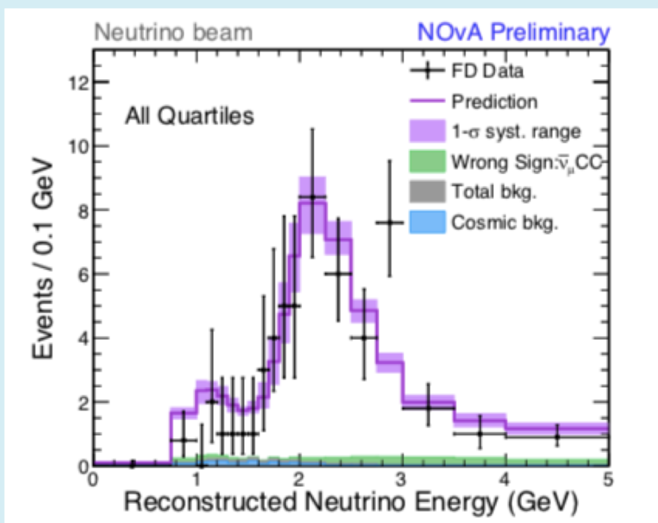
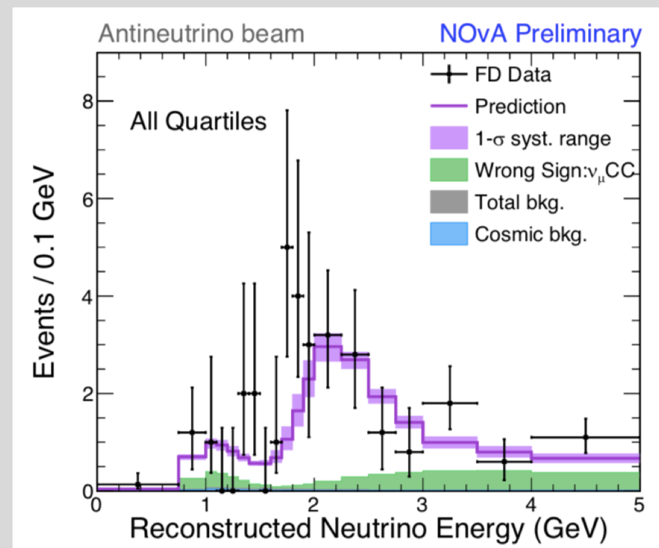


NO preferred,
posterior prob 89%

Best fits:
NO: δ=-1.885
IP: δ=-1.387

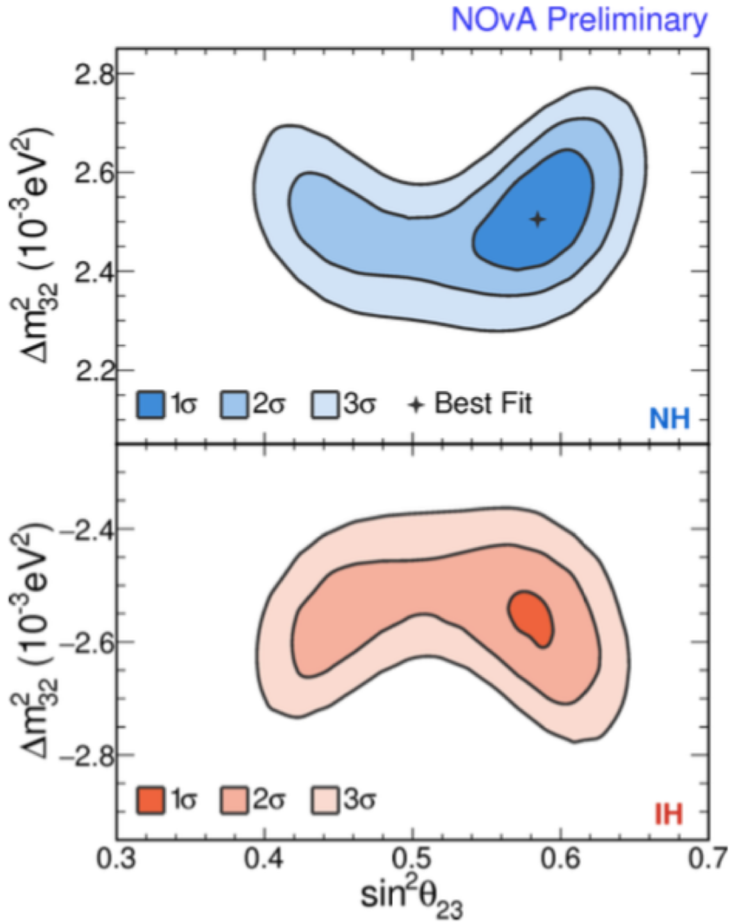
CP-conserving
values disfavored at 2σ

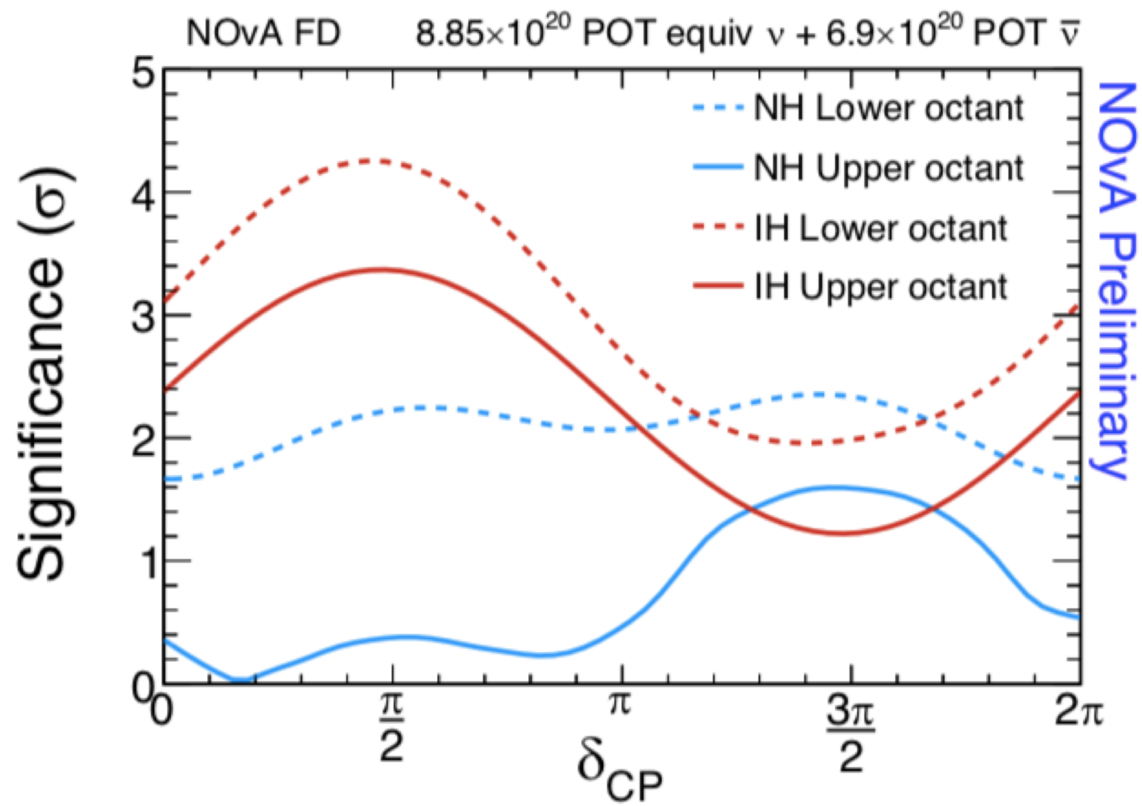
NOvA appearance and disappearance

	Neutrinos 8.85 x 10^{20} pot	Antineutrinos 6.9 x 10^{20} pot
Electron neutrino appearance  	 	
Muon neutrino disappearance  	 	

P. Vahle, APS 2018

NOvA Parameter Fit Results



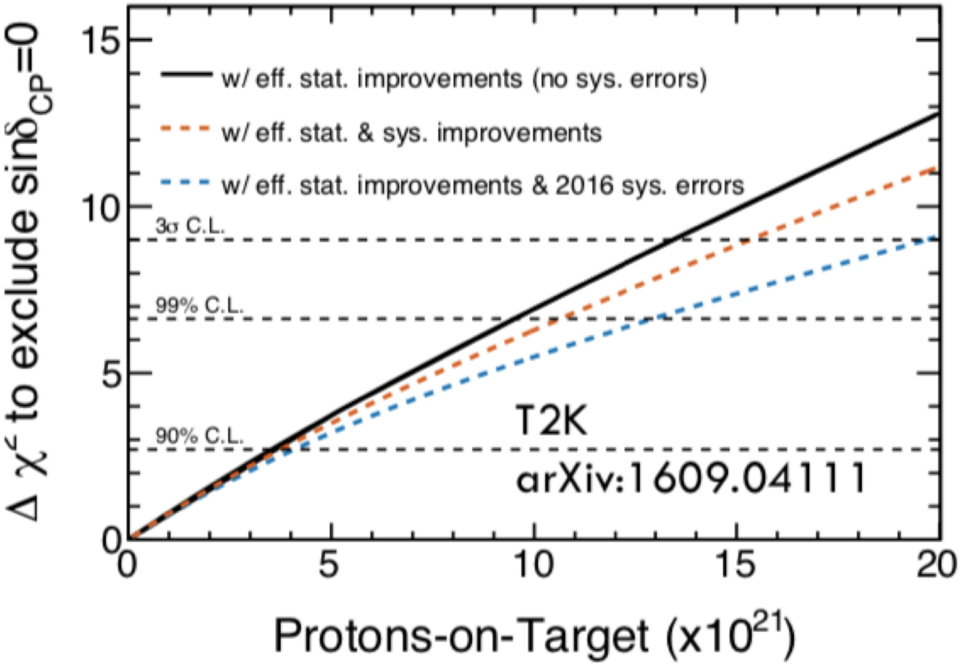


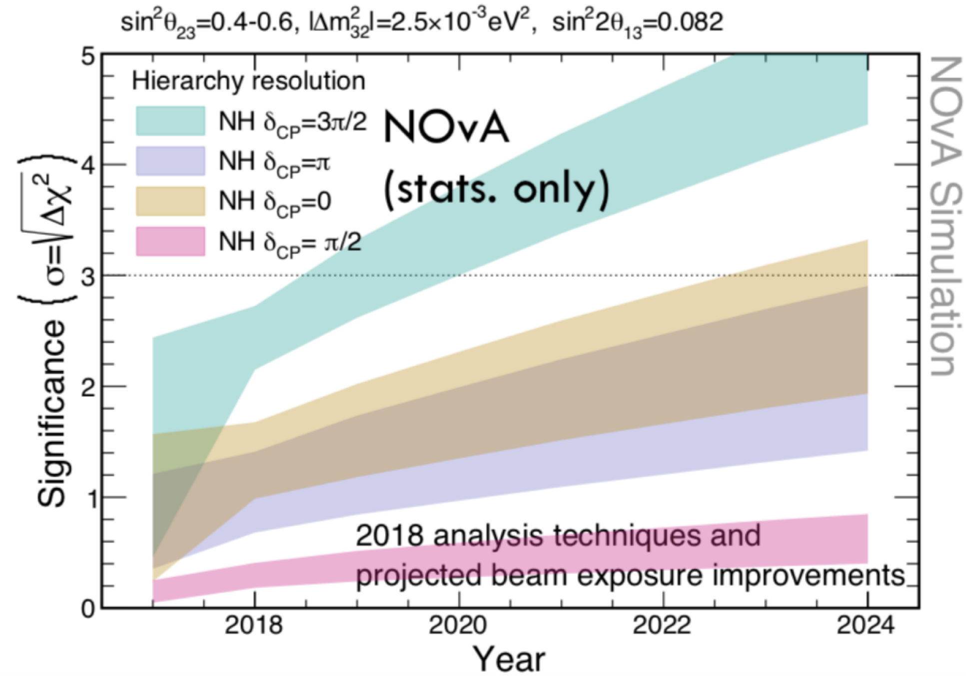
NH preferred at 1.8σ

IH at $\delta_{CP} = \pi/2$ disfavored at >3σ

P. Vahle, APS 2018

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 being upgraded... now refurbished as "SK-IV" and soon to be **SK-Gd** with Gd doping for n capture

And the future...

Past → **Current** → **Future**

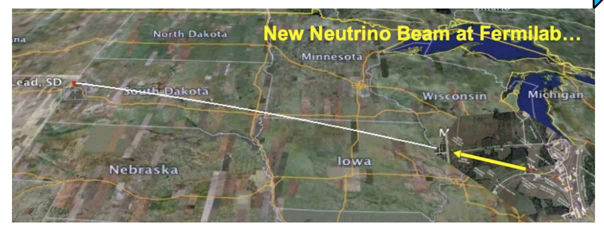
K2K
KEK to Kamioka
250 km, 5 kW

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



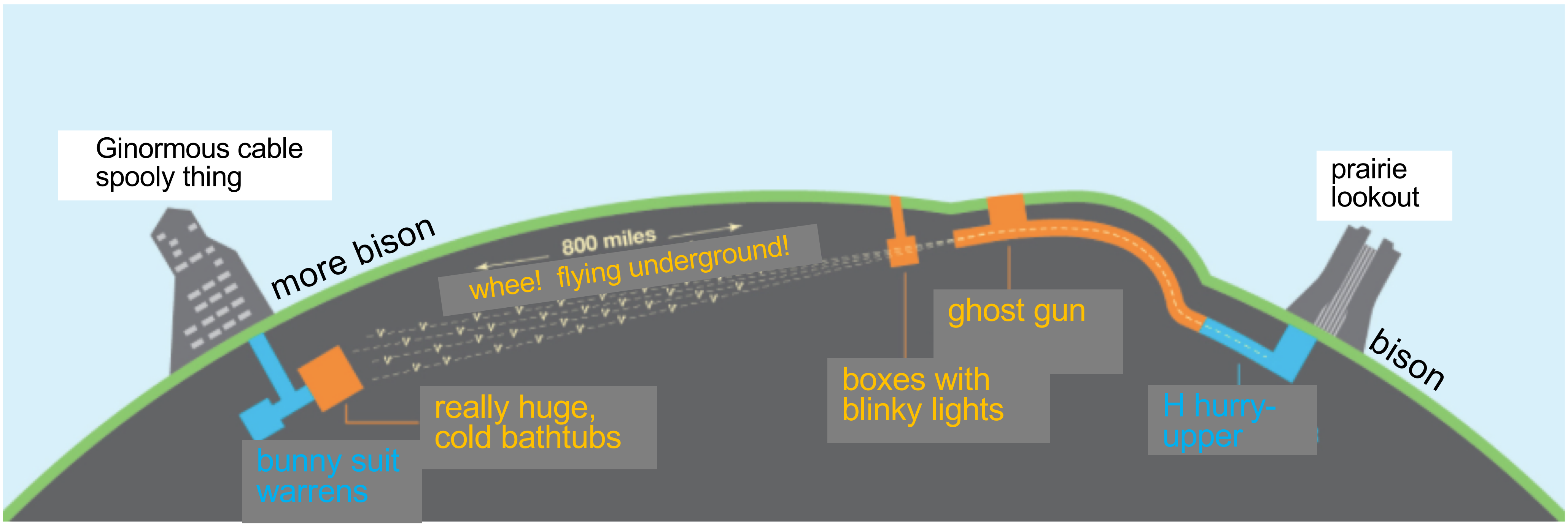
LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW

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



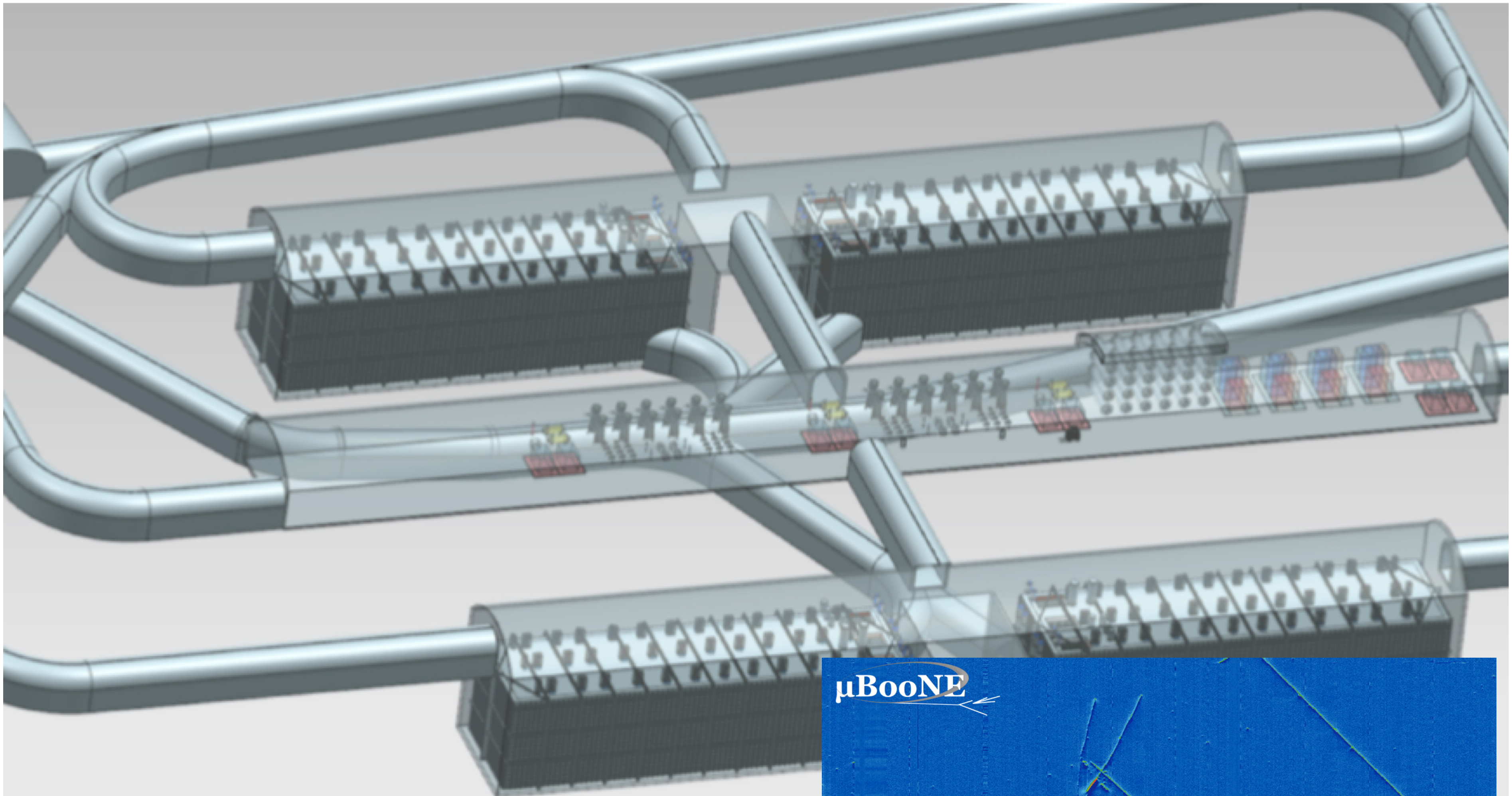

Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility

next big US-based international particle physics project

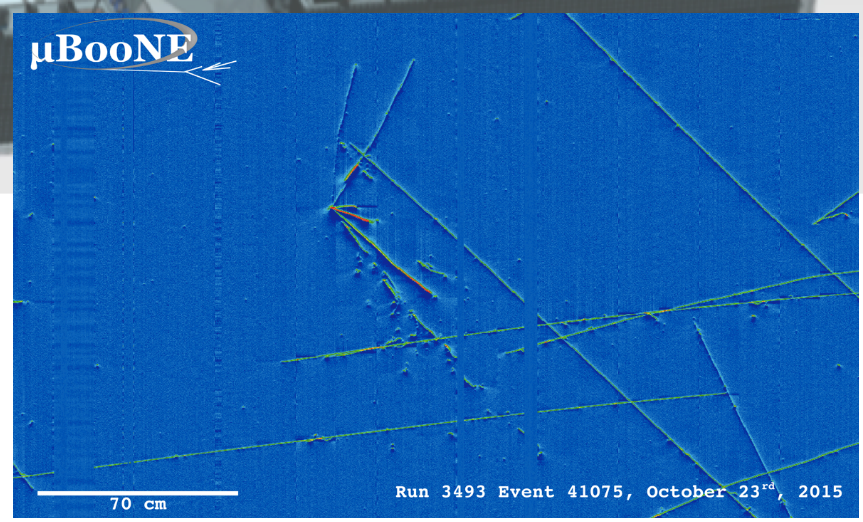


- new 1.2 MW beam, Fermilab to SD
- 1300 km baseline
- 40-kton fiducial liquid argon TPC far detector
- Also proton decay, supernova, atmospheric...

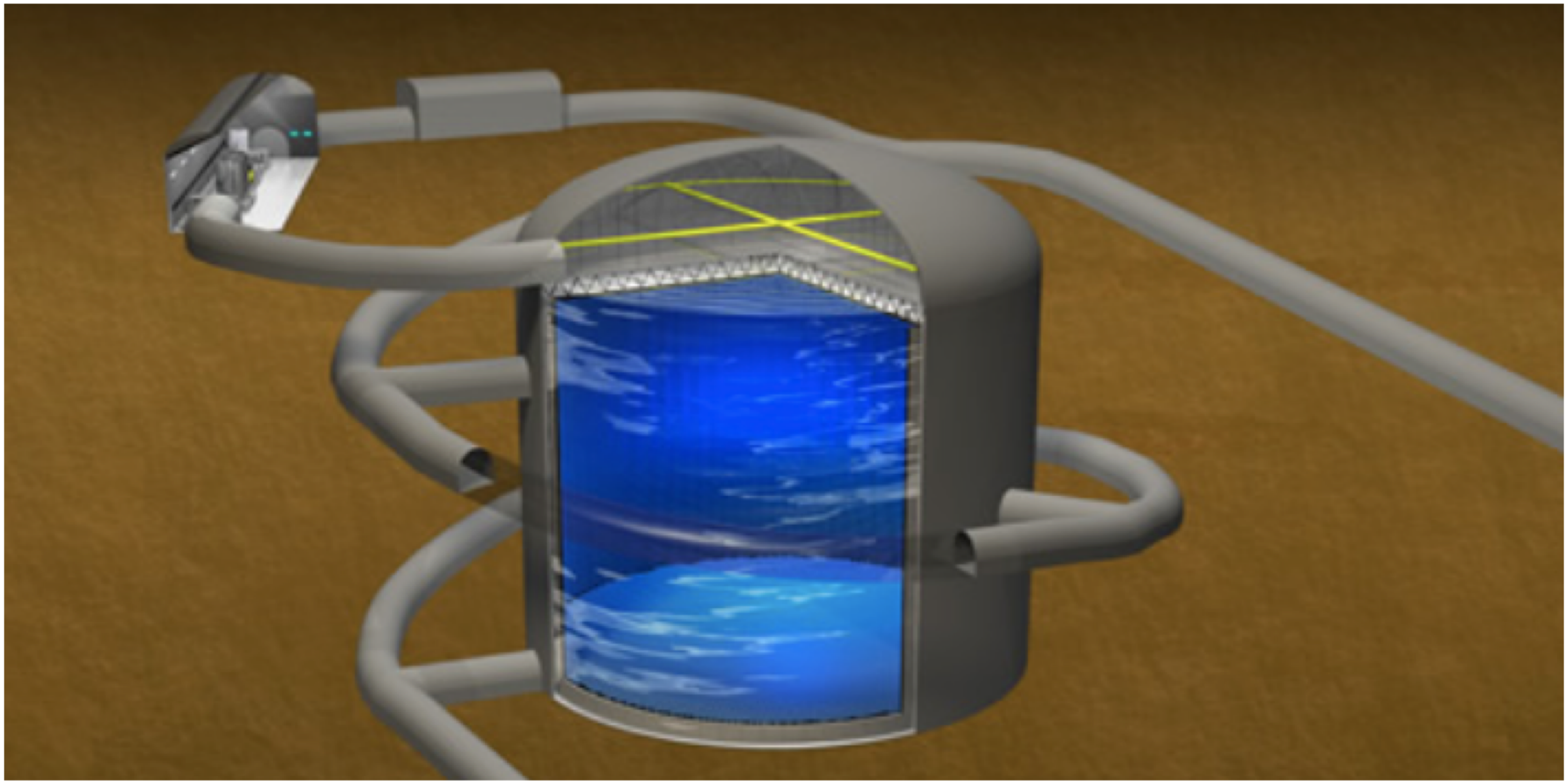
The DUNE far detector: 70,000 tons of liquid argon



- exquisitely precise tracking
- single-phase and dual-phase technology under consideration (prototypes @ CERN)
- Technical Design Report soon!



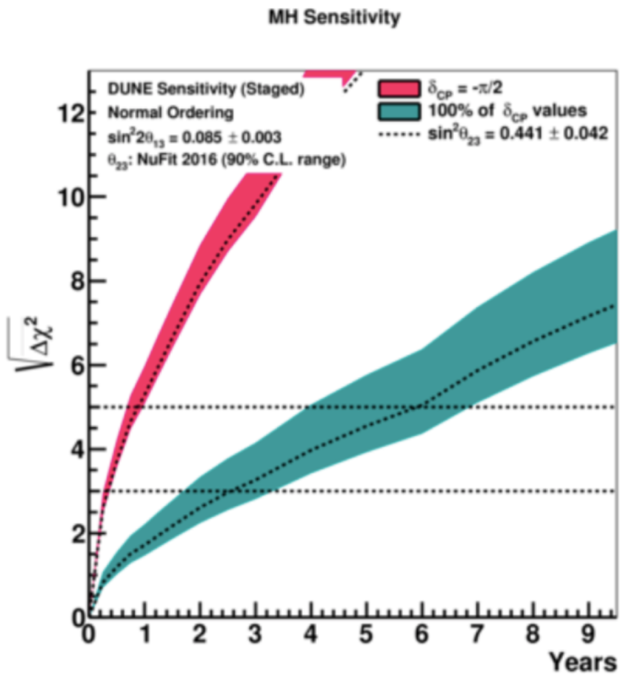
Hyper-Kamiokande

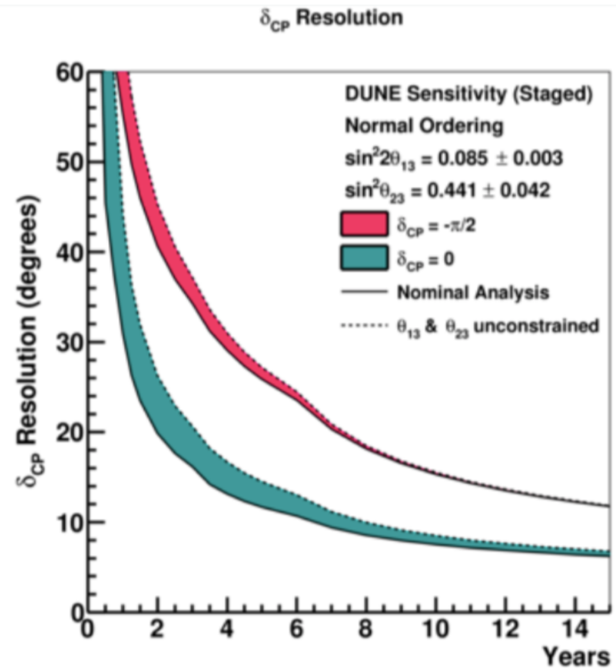


M.Shiozawa

- 317 kton fiducial volume in 2 staged tanks
- Beam from J-PARC 295 km away
- Discussion of 2nd detector in Korea
- Many non-accelerator physics topics

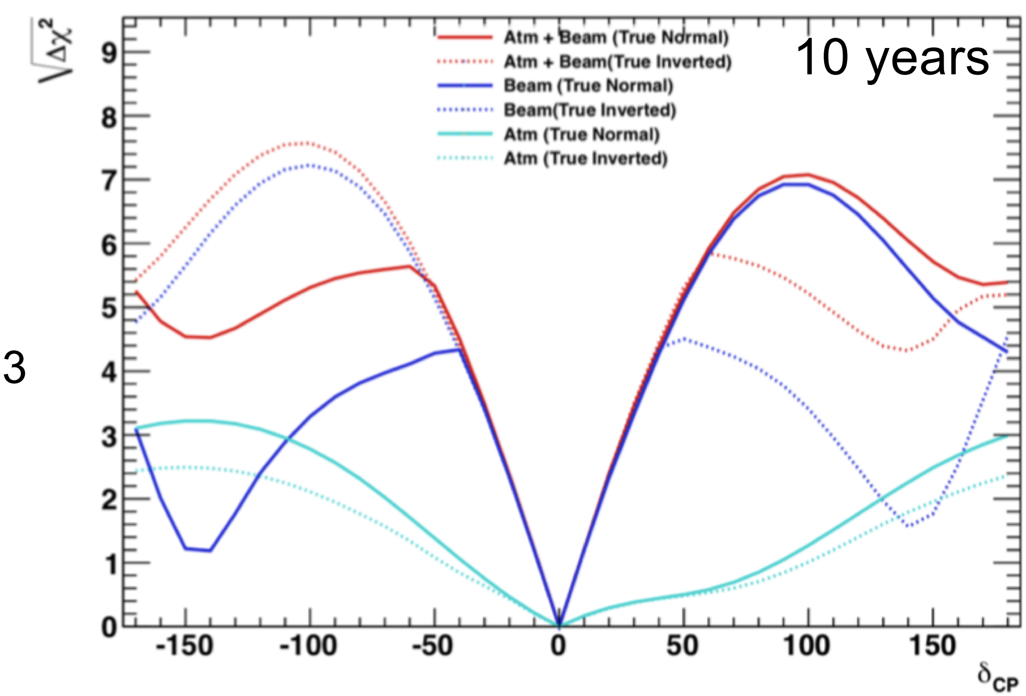
MO & CPV Sensitivity of DUNE and Hyper-K





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

HK design report, arXiv: 1805.04163



Improved CP δ sensitivity with atmospheric neutrinos as well

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 (➔2.3 MW)

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

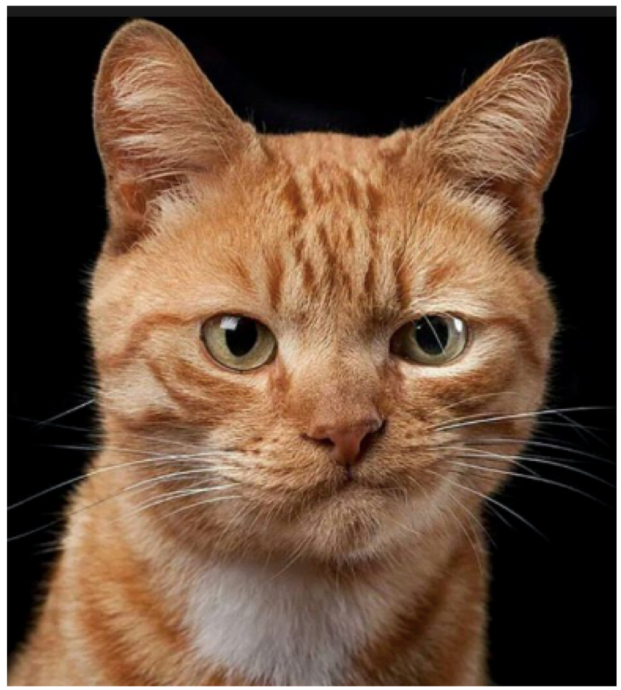
And beyond...
ESSnuB,
neutrino factories...





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

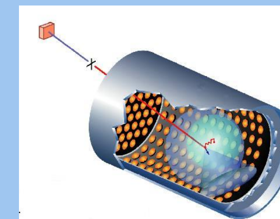
There are already some slightly uncomfortable data that **don't fit that paradigm**...



Open a parenthesis: (

Outstanding ‘anomalies’

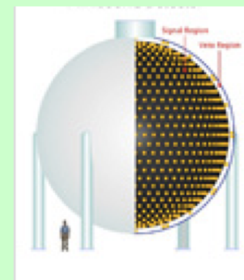
LSND @ LANL (~30 MeV, 30 m)



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)



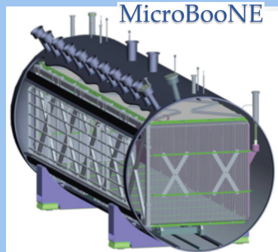
- unexplained >3 σ excess for E < 475 MeV in neutrinos (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos (consistent 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’)

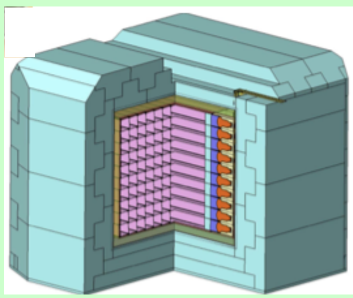
Sterile neutrinos? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle & astrophysics
[cosmology w/Planck now consistent w/3 flavors... but allows 4...]
Or some other new physics??

Many experiments going after steriles...

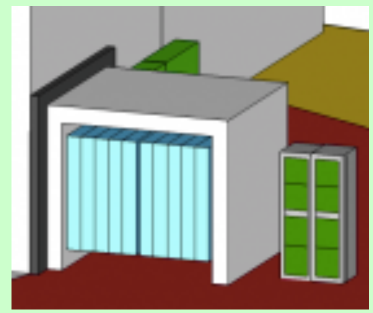


Experiments with beams
(meson decay in flight and at rest)

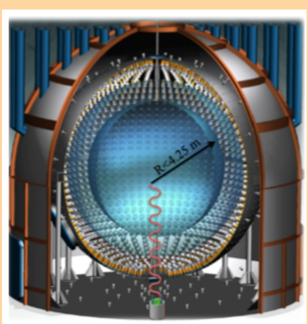
FNAL SBN, JSNS^2, ...



Experiments at reactors

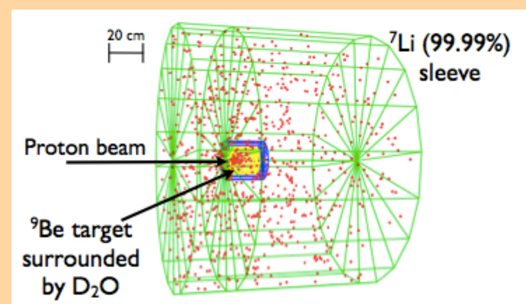


PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER....



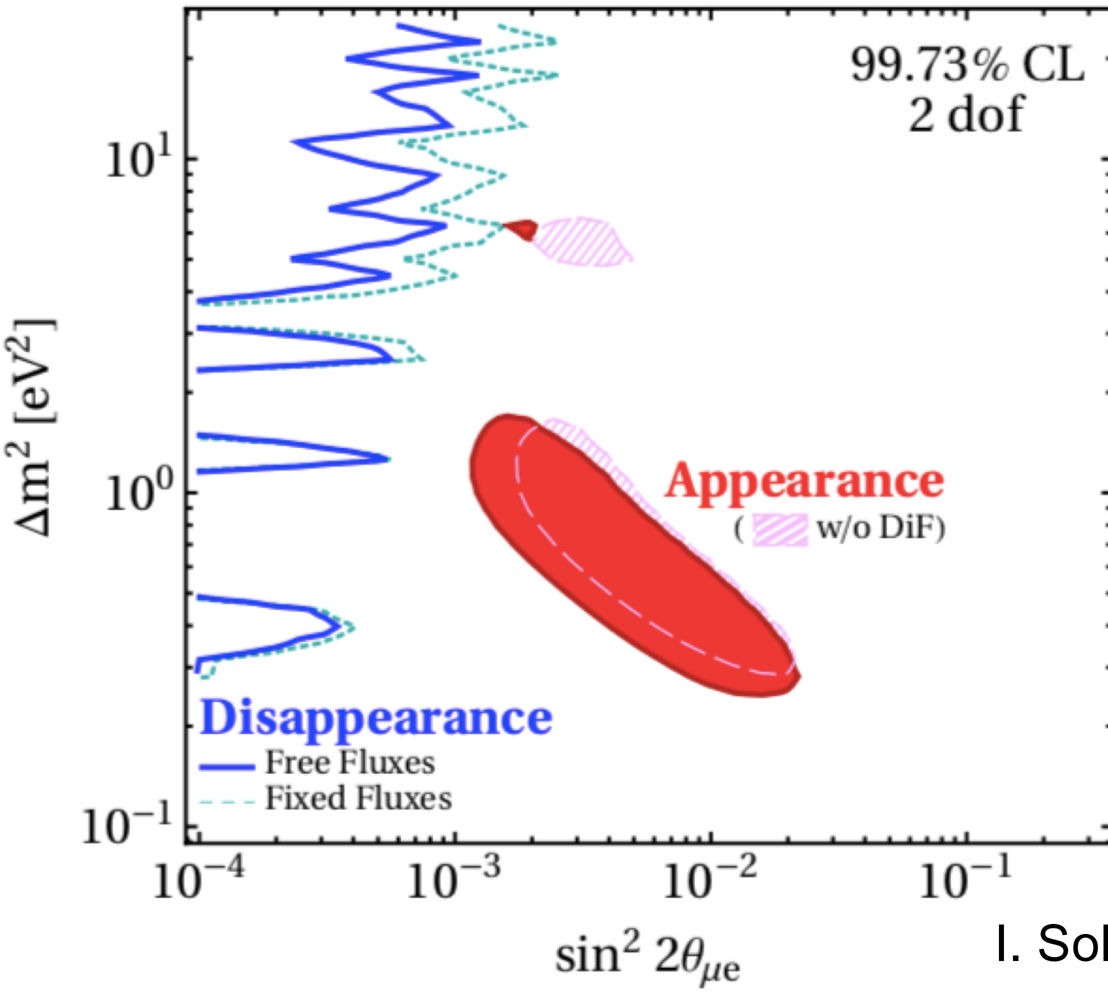
Experiments with radioactive sources

(CeSOX), IsoDAR, ...



and many more...

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



I. Soler

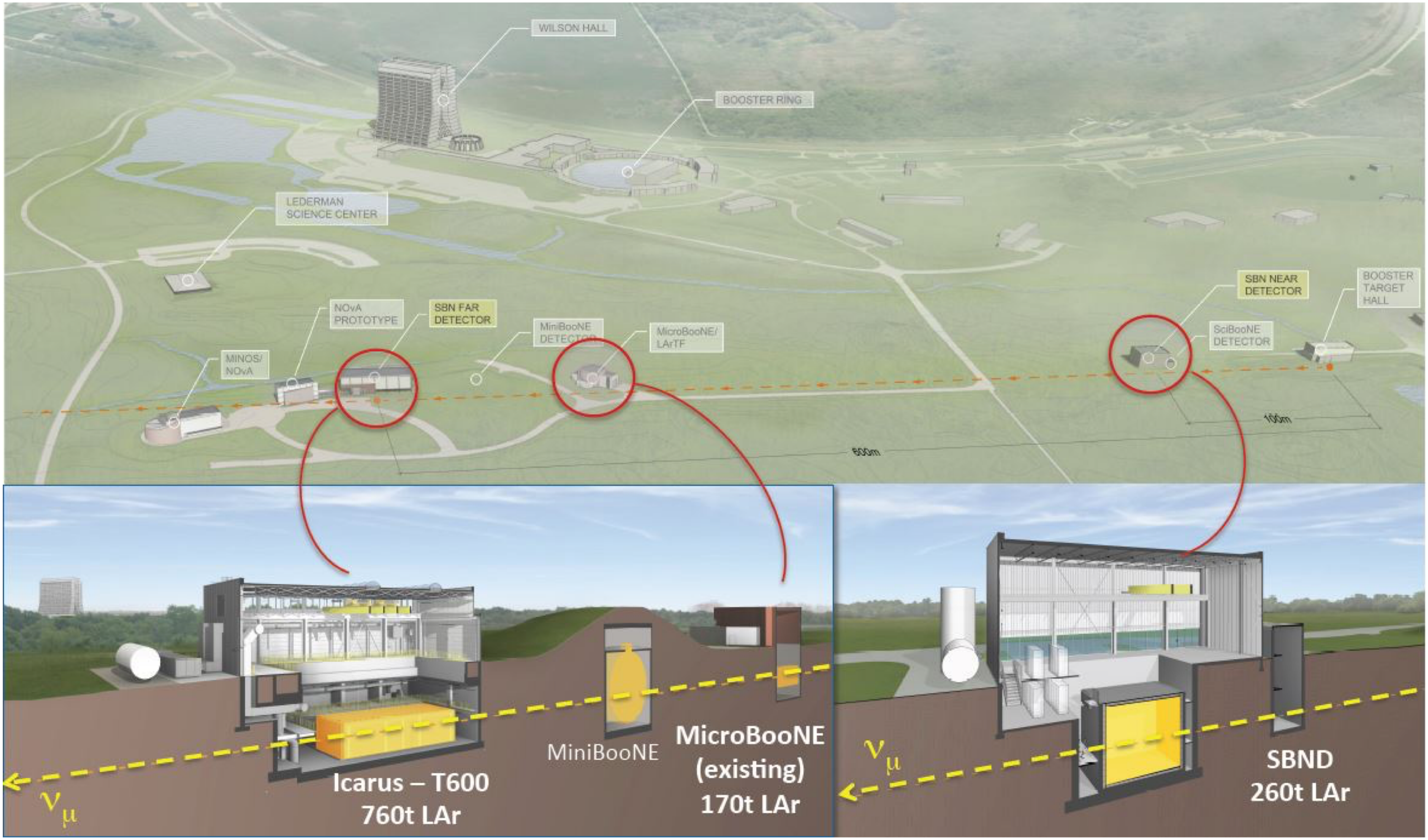
Appearance and disappearance data are in fairly serious tension

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

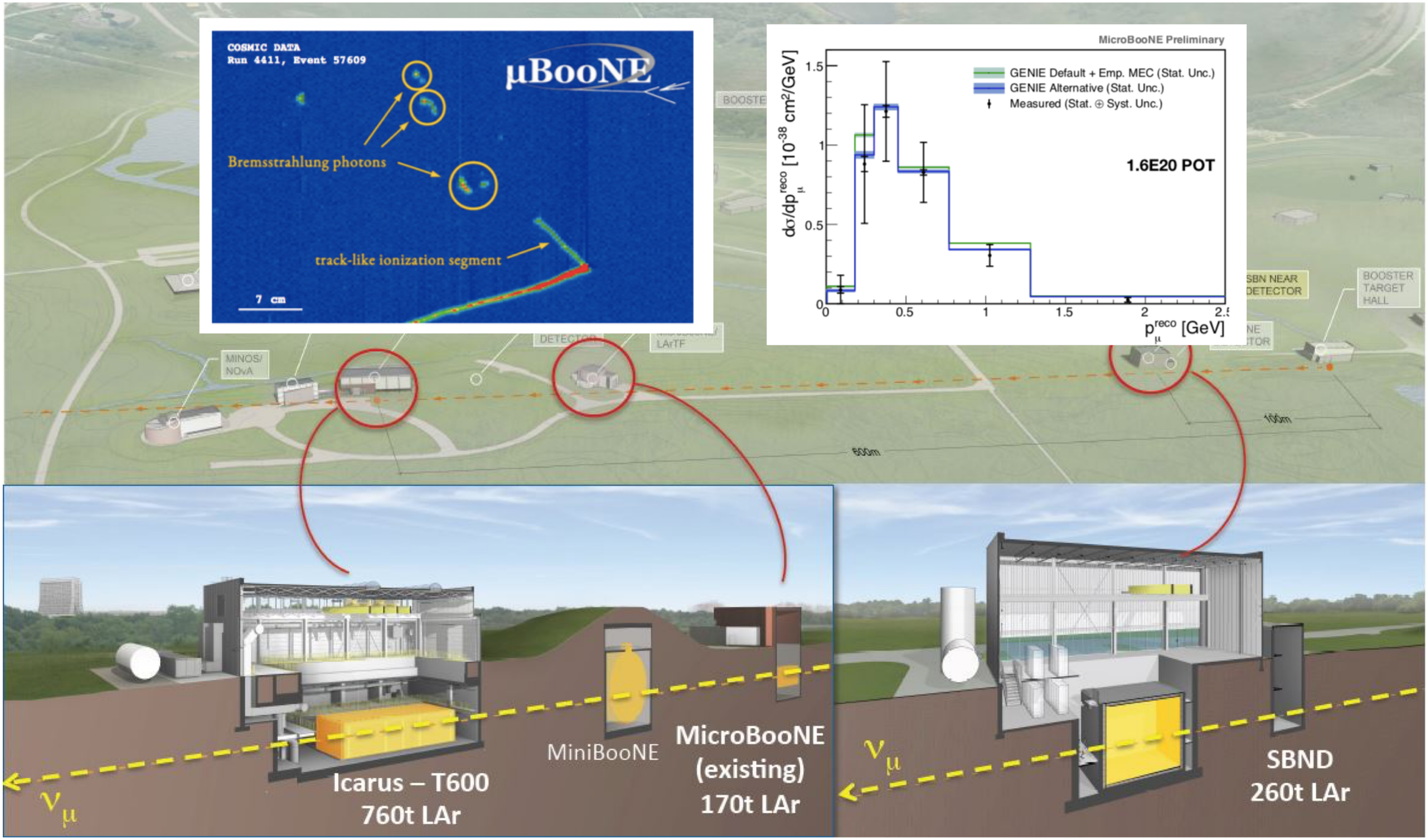
[does not include PROSPECT, STEREO new data]

... parenthesis not closed...

Short-baseline program at FNAL



Results from MicroBooNE are starting to arrive



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

What I will cover

Experimental knowledge and programs to move forward

Neutrino Oscillations

Latest 3-flavor results

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

Beyond 3-flavor?

The mass pattern

Absolute Mass

Status and prospects

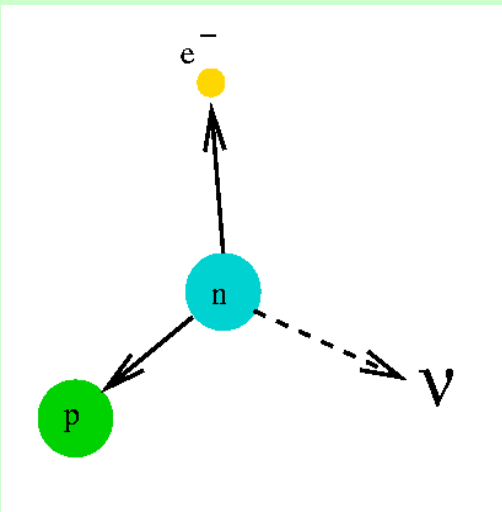
The mass scale

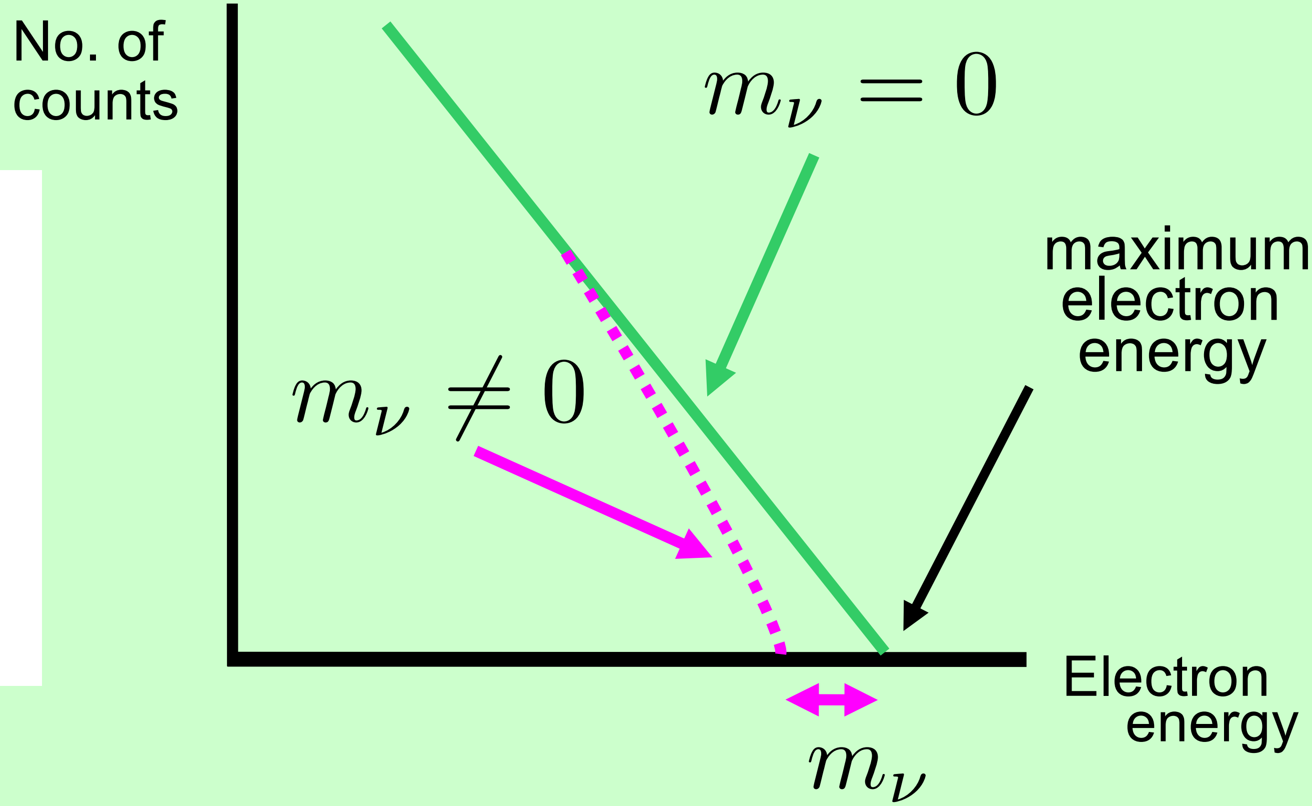
Majorana vs Dirac?

Overview of NLDBD

The mass nature

Kinematic experiments for absolute neutrino mass





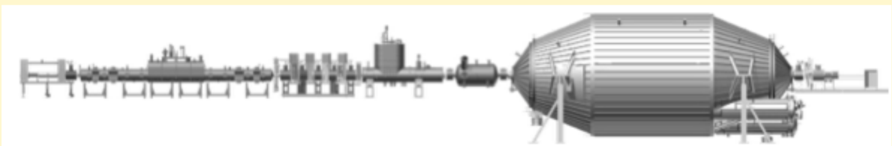
Look for distortion of β-decay spectrum near endpoint

Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

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

18.6 keV endpoint

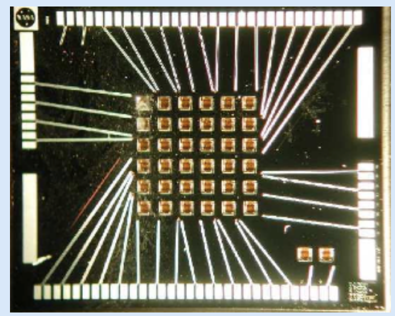


Sensitivity to ~0.2 eV

Results soon!

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

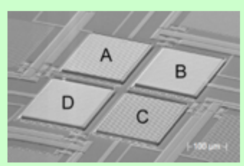
Holmium

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

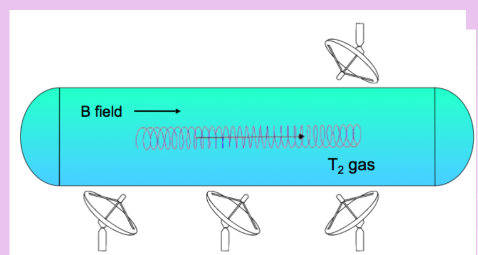


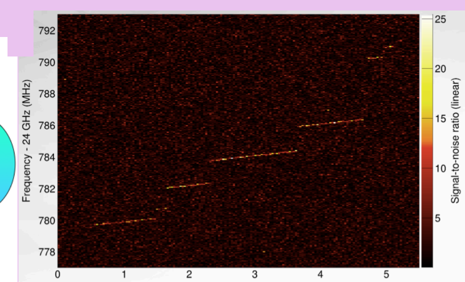
Electron capture decay,
ν mass affects deexcitation spectrum
R&D in progress

R&D

Cyclotron radiation tritium spectrometer: Project 8

R&D





Long-term potential for
atomic tritium w/low uncertainties

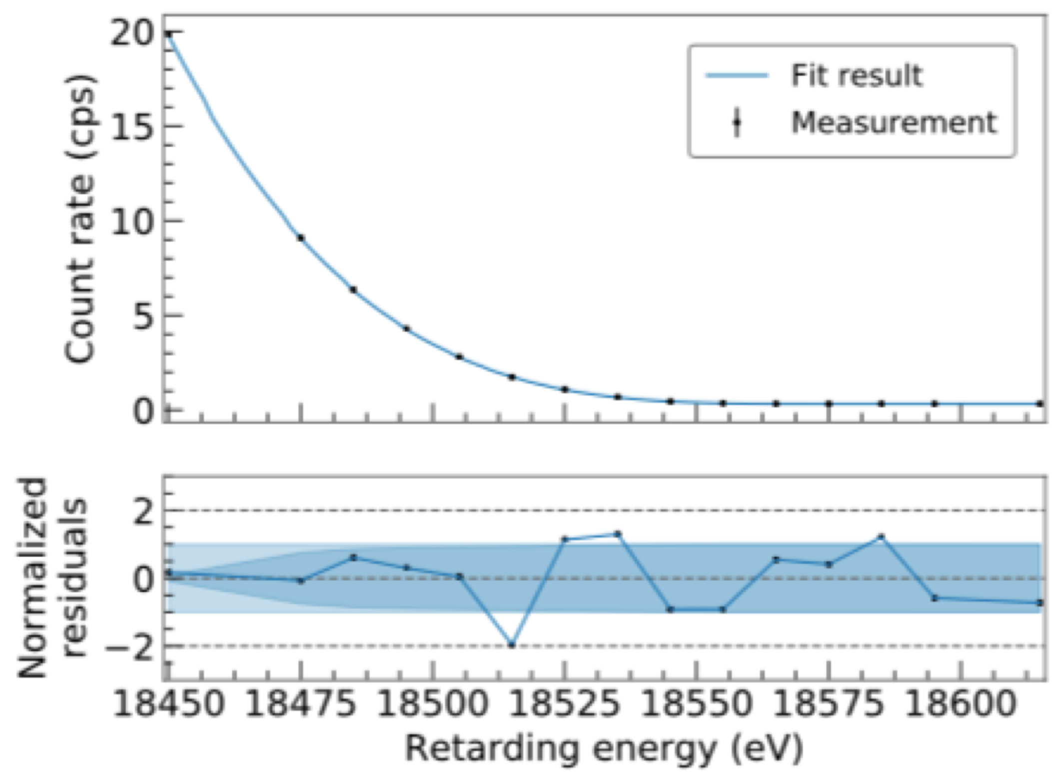
KATRIN: Status

S. Mertens, APS 2018

- **2018: First Tritium**
  (0.5% nominal activity = 500 MBq)

✓0.1% source stability demonstrated

✓Excellent agreement of data with model expectation



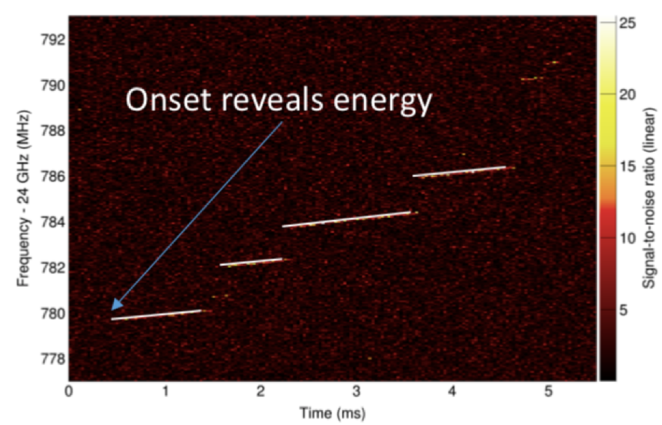
- **Now**: KATRIN is taking data, first improved neutrino mass results in 2019
- **Future**: keV-scale sterile neutrino search
  arXiv:1810.06711 (2018)

Project 8

✓**2015**: Proof of principle
Phys. Rev. Lett. 114, 1162501 (2015)

✓**2017**: Demonstration of excellent energy resolution ~3 eV
J.Phys. G44 (2017) no.5, 054004

✓**2018**: First tritium electrons detected



What I will cover

Experimental knowledge and programs to move forward

Neutrino Oscillations

Latest 3-flavor results

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

Beyond 3-flavor?

The mass pattern

Absolute Mass

Status and prospects

The mass scale

Majorana vs Dirac?

Overview of NLDBD

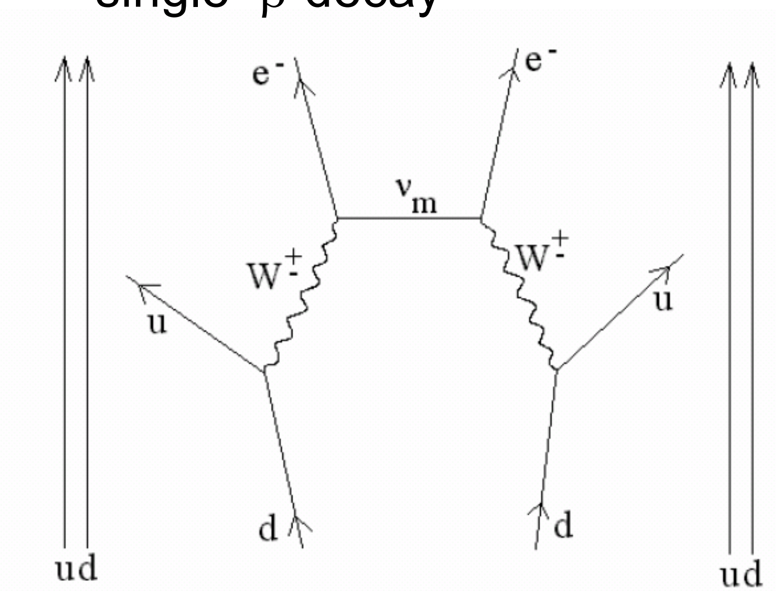
The mass nature

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

Best (only) experimental strategy: look for

neutrinoless double beta decay

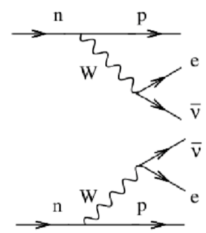
in isotopes for which it is energetically possible and which don't single β-decay



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

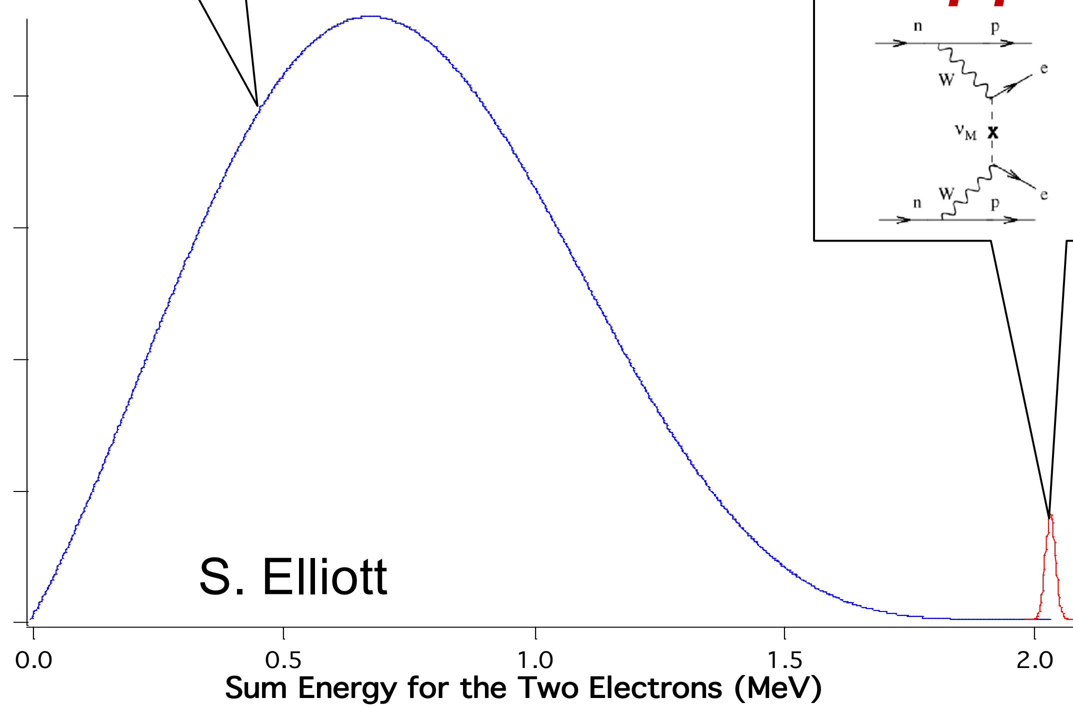
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

2νββ (SM 2nd order weak process)

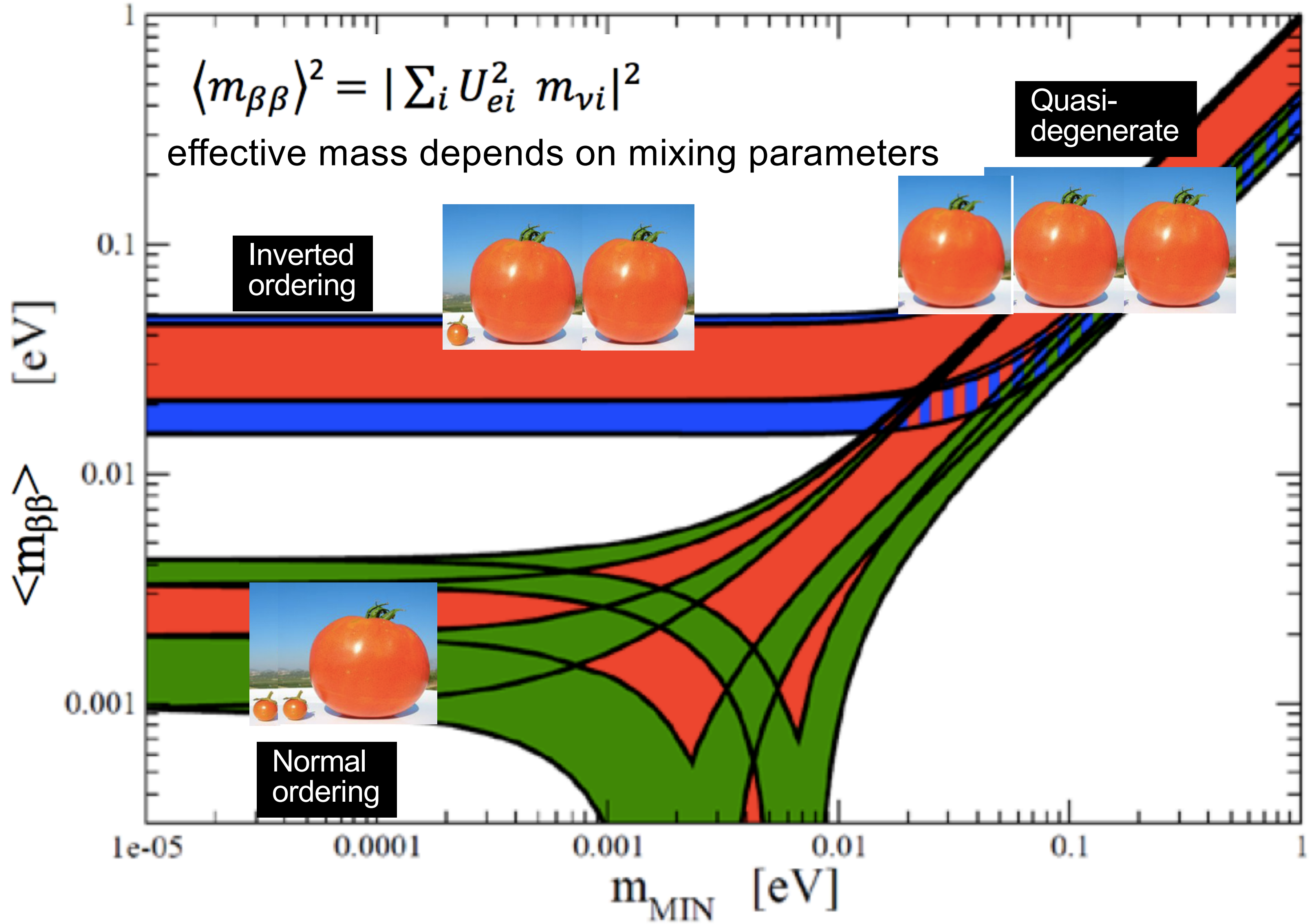


Observable: peak in the two-electron spectrum corresponding to ν-less final state

0νββ



The NLDBD T-Shirt Plot

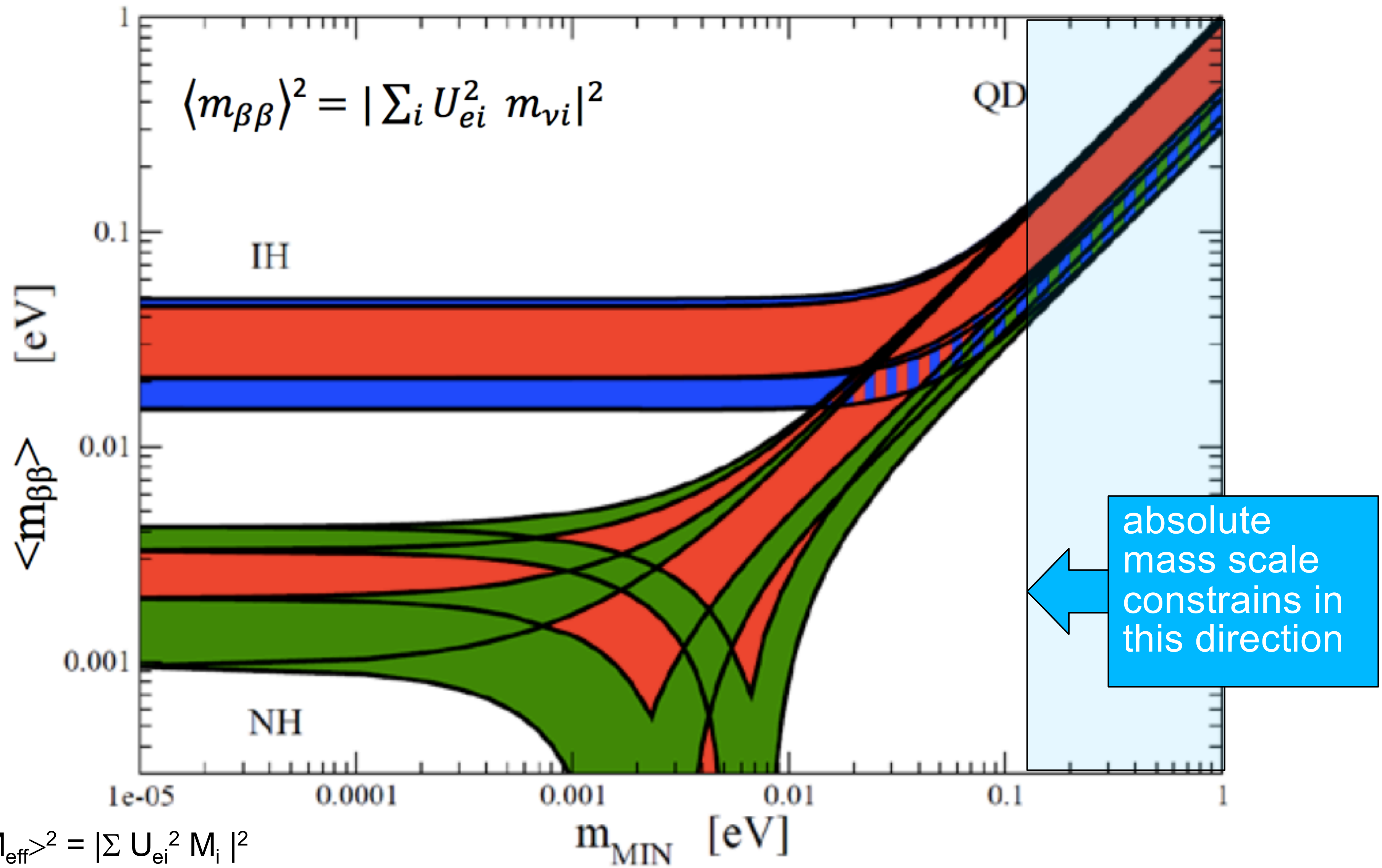


***If* neutrinos are Majorana*, experimental results must fall in the shaded regions**

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

*and standard 3-flavor picture

The NLDBD T-Shirt Plot

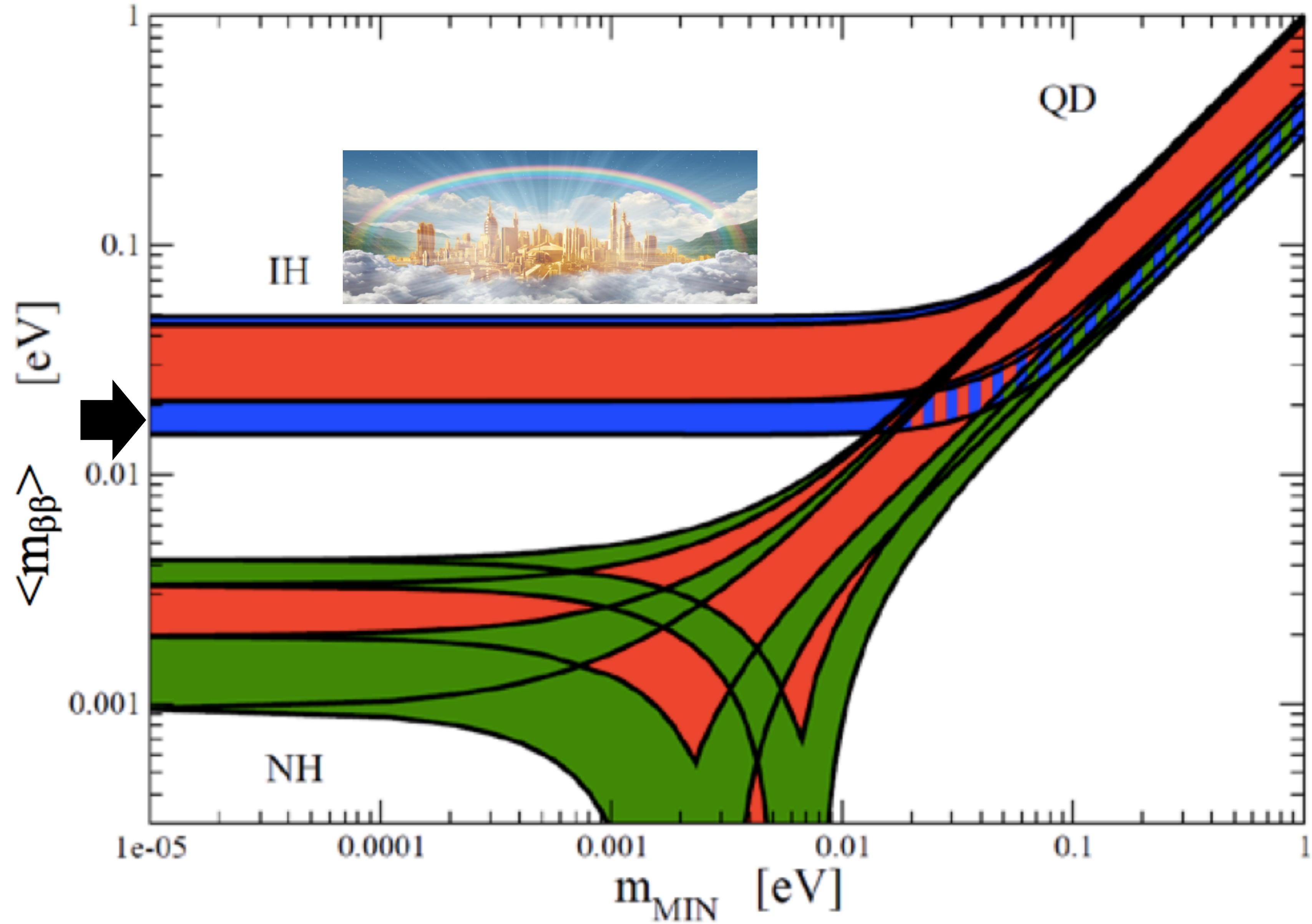


$<M_{eff}>^2 = |\Sigma \; U_{ei}^2 \; M_i \;|^2$

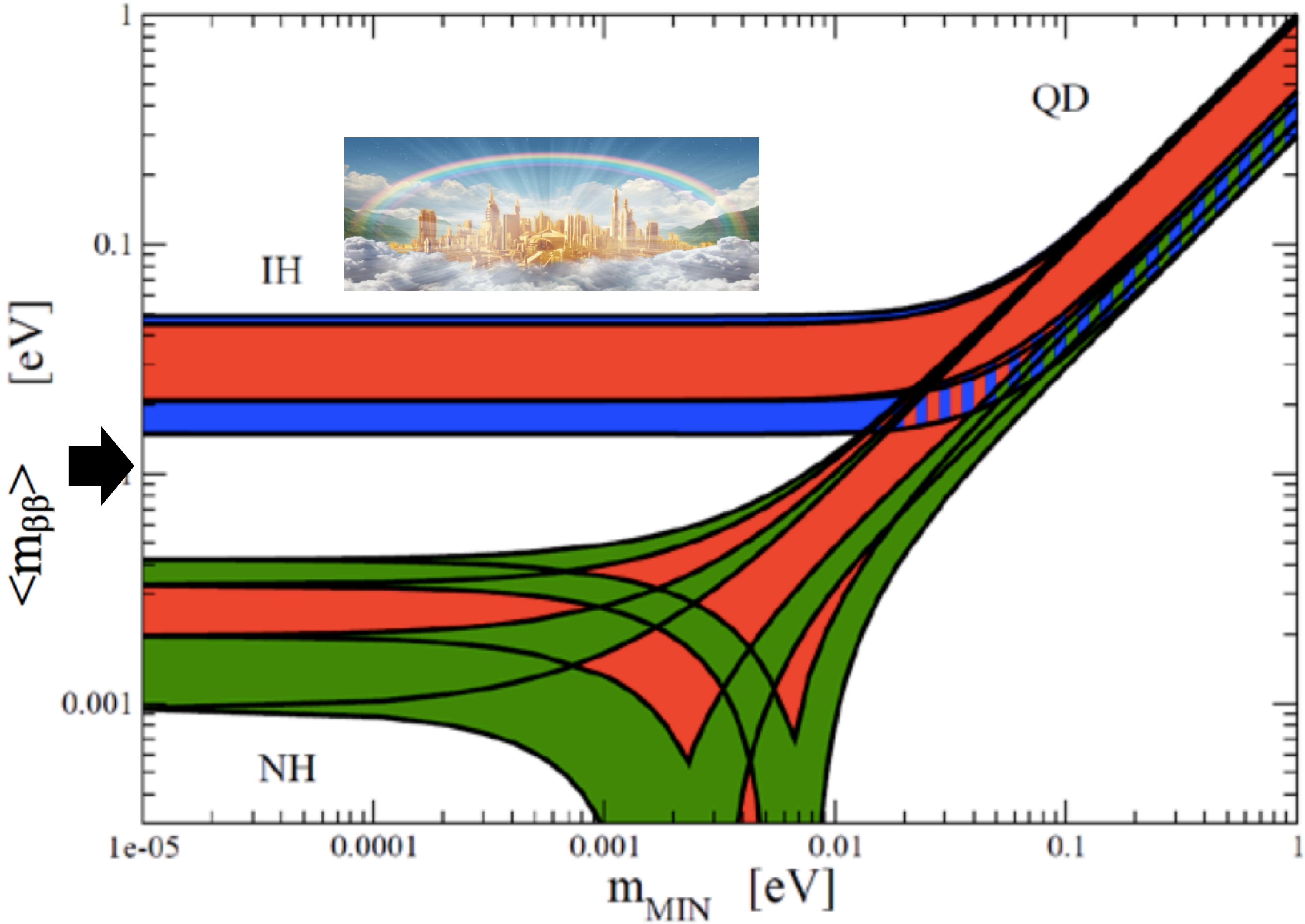
If **neutrinos are Majorana, experimental results must fall in the shaded regions**

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

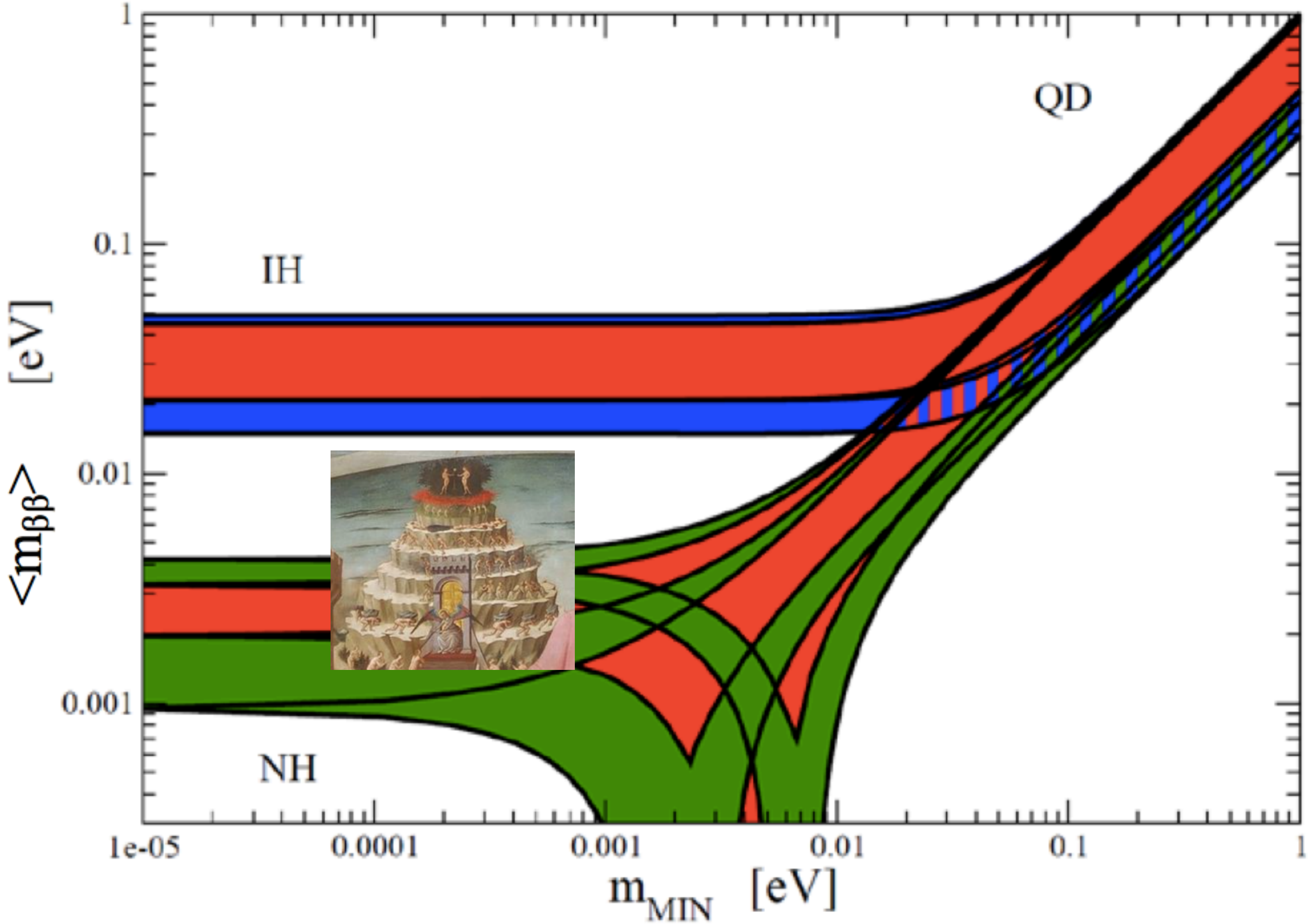
If the hierarchy is inverted, *and* neutrinos are Majorana,
then we'll see NLDBD if we can get to ~few 10 meV sensitivity



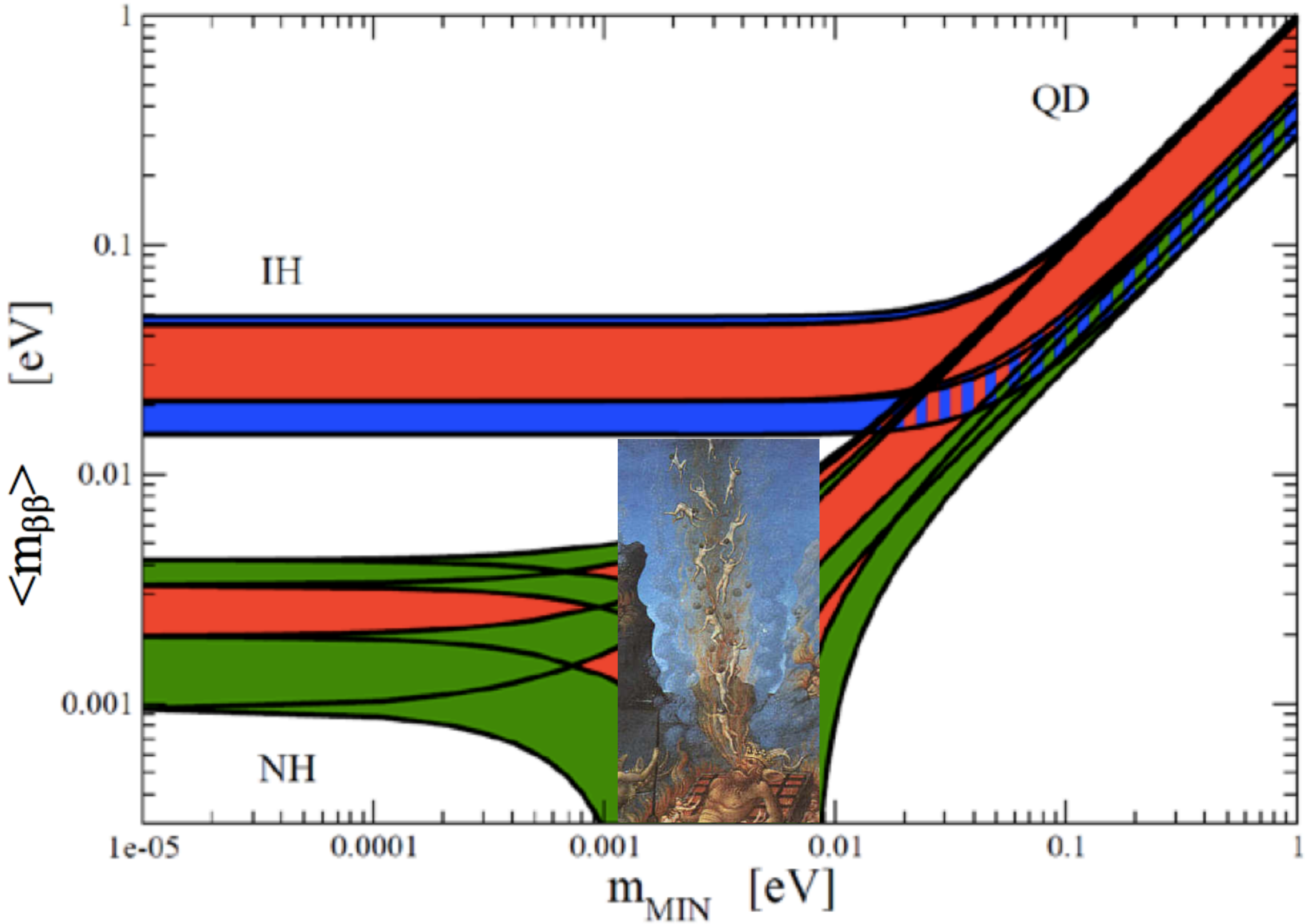
... or, if we know independently the hierarchy to
be inverted, *and* we measure a limit below IH region,
then we know (assuming Nature is not diabolical)
that neutrinos are *not* Majorana!



If the hierarchy is known independently to be normal, then life could be hard, unless absolute mass scale large

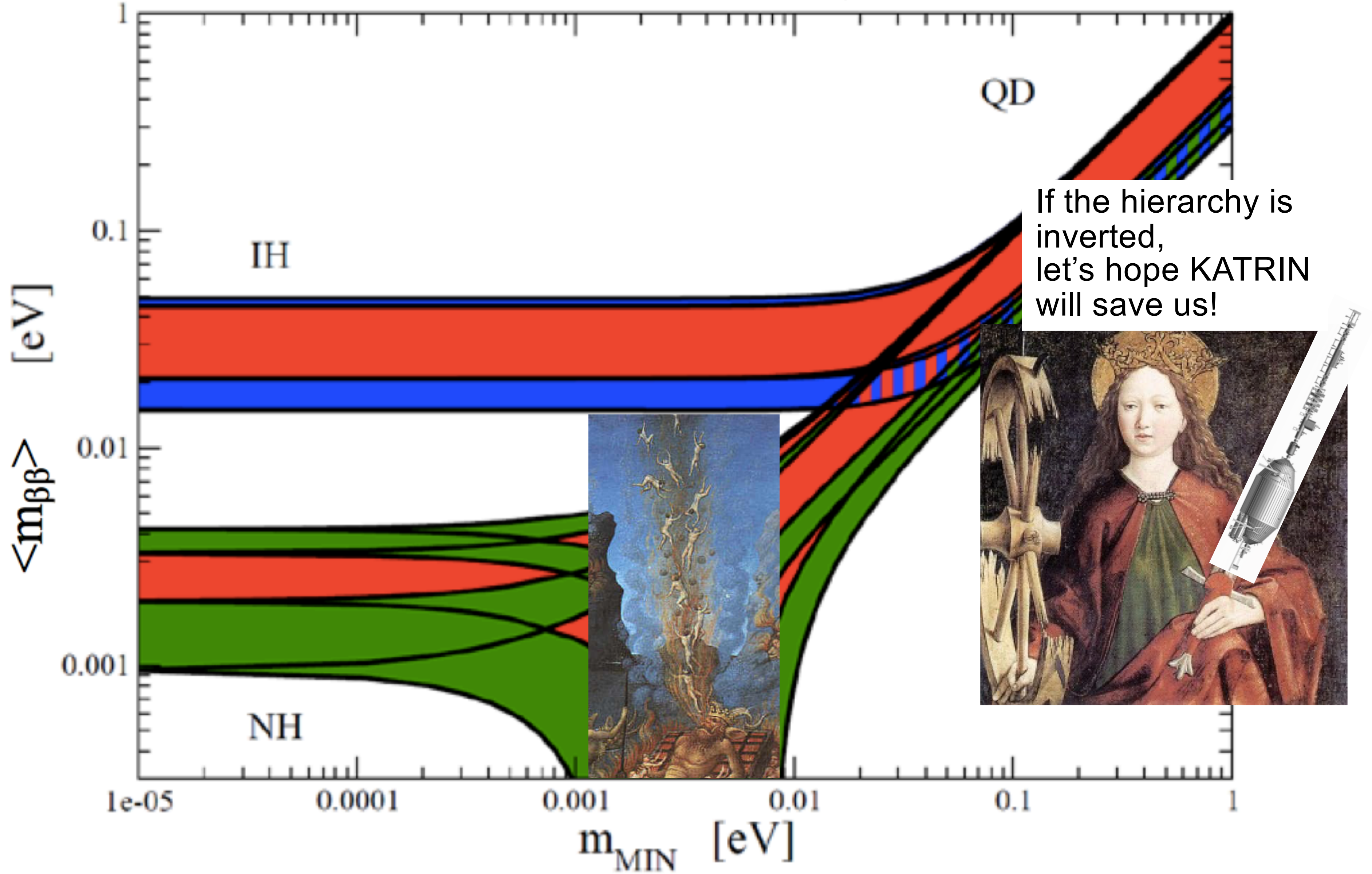


And Nature *could* be diabolical, with parameters conspiring to make $<m_{\beta\beta}>$ ~ zero...



And Nature *could* be diabolical, with parameters conspiring to make $<m_{\beta\beta}>$ ~ zero.

...but the mass scale could still be large!



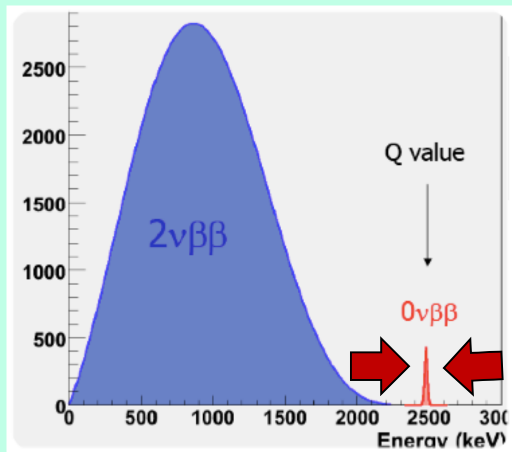
General NLDBD experiment strategies

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

The "Brute Force" Approach

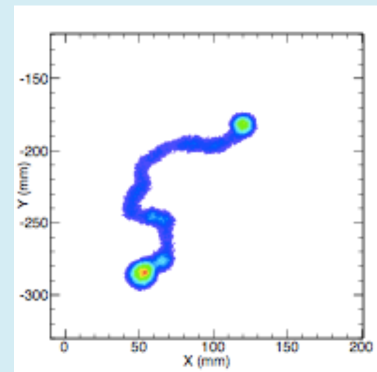
focus on the numerator with **a huge amount of material**
(often sacrificing resolution)

The "Peak-Squeezer" Approach



focus on the denominator by **squeezing down ΔE**
(various technologies)

The "Final-State Judgement" Approach

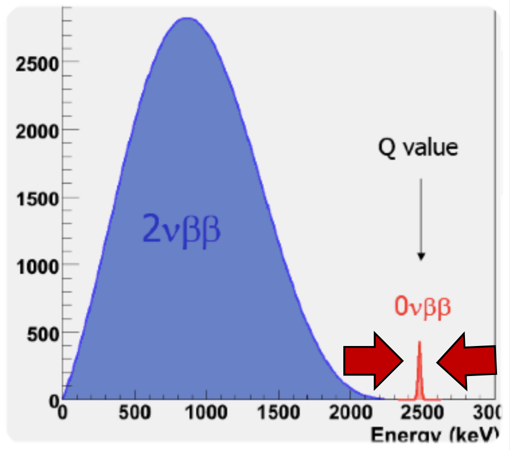
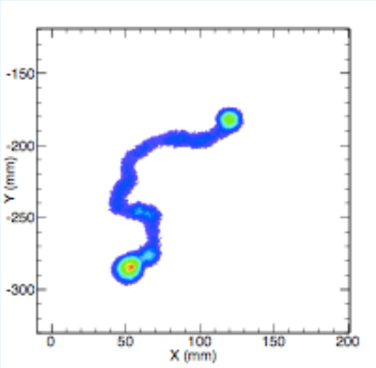


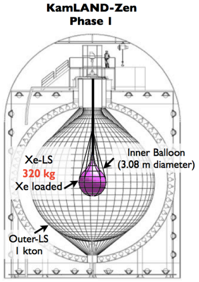
try to make the background zero by **tracking or tagging**

...some experiments take hybrid approaches...

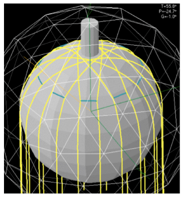
General NLDBD experiment strategies

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

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



KamLAND-Zen
(^{136}Xe)



SNO+
(^{130}Te)

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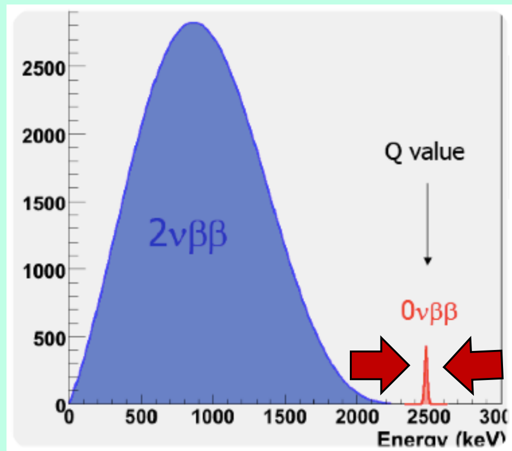

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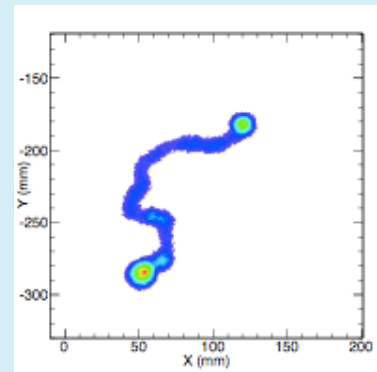

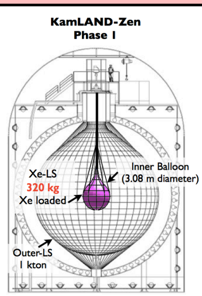

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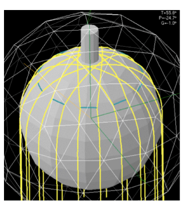

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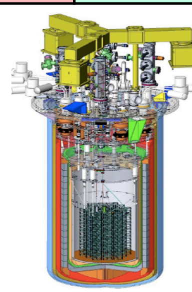
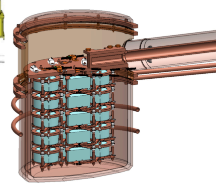


CUORICINO/ CUORE (^{130}Te)

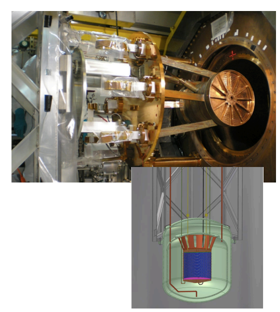


MAJORANA (^{76}Ge)

GERDA (^{76}Ge)

CUPID (^{82}Se)

LEGEND (^{76}Ge)



EXO/nEXO (^{136}Xe)

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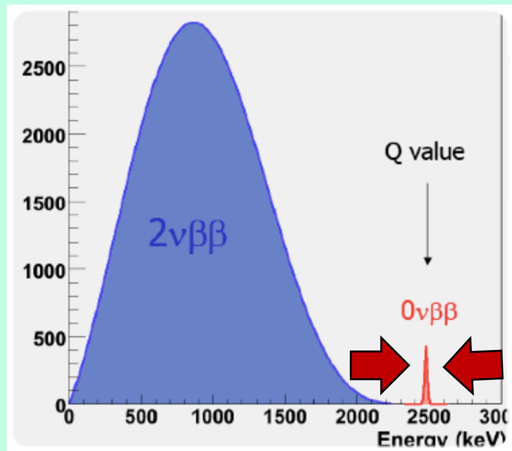

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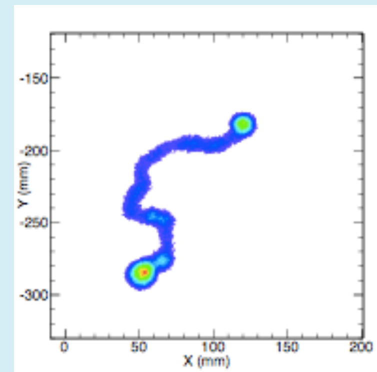

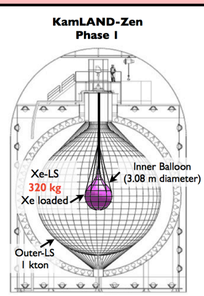

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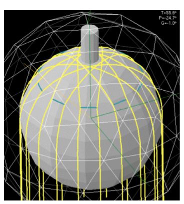

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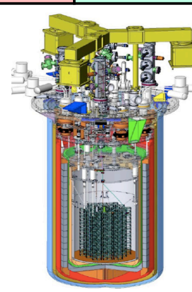

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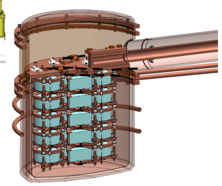

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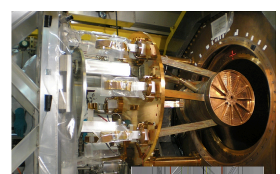
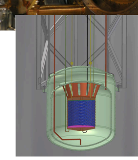

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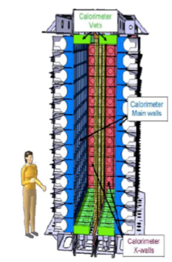
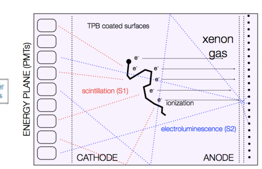


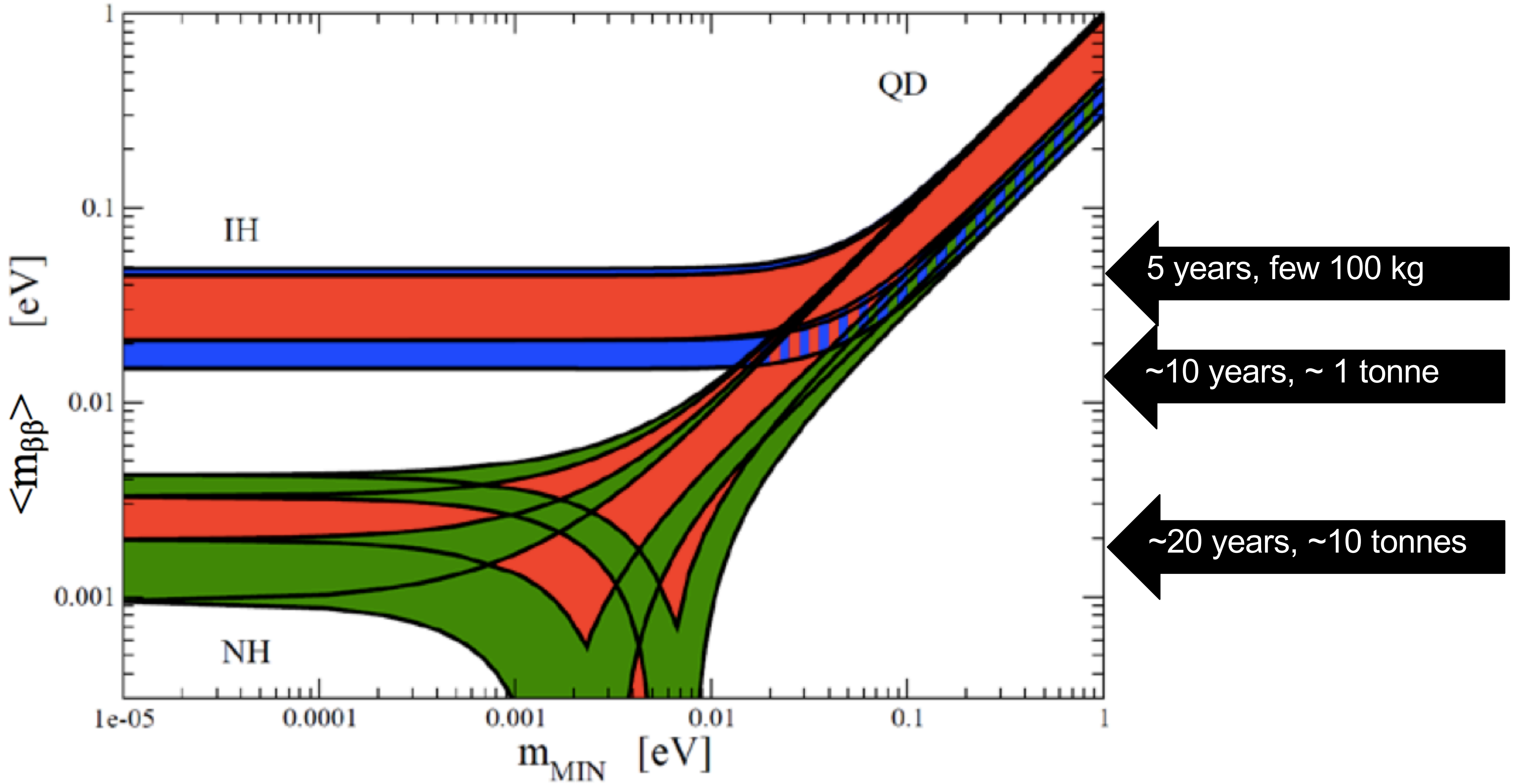
NEMO/ SuperNEMO (various/^{82}Se)



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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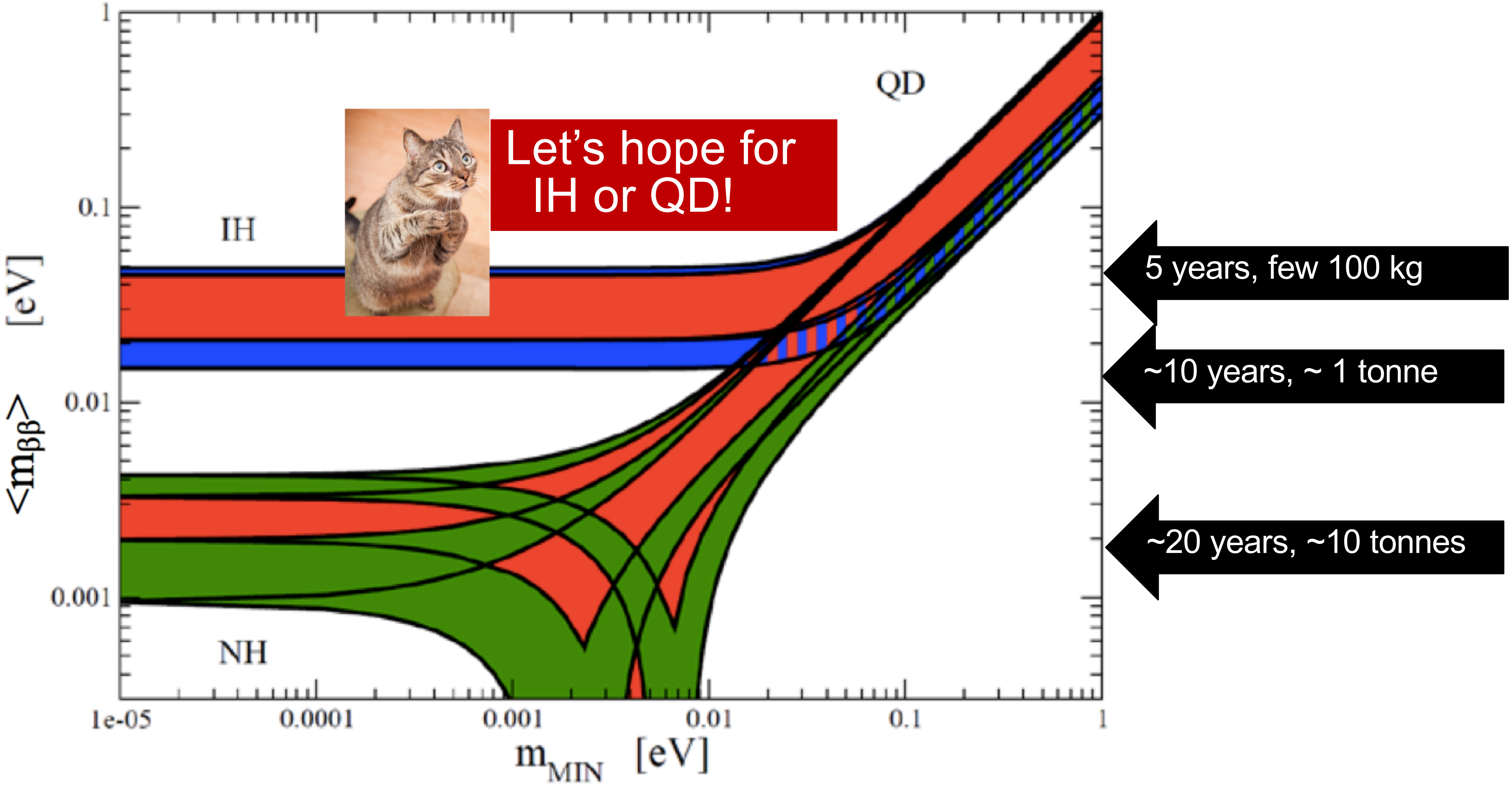

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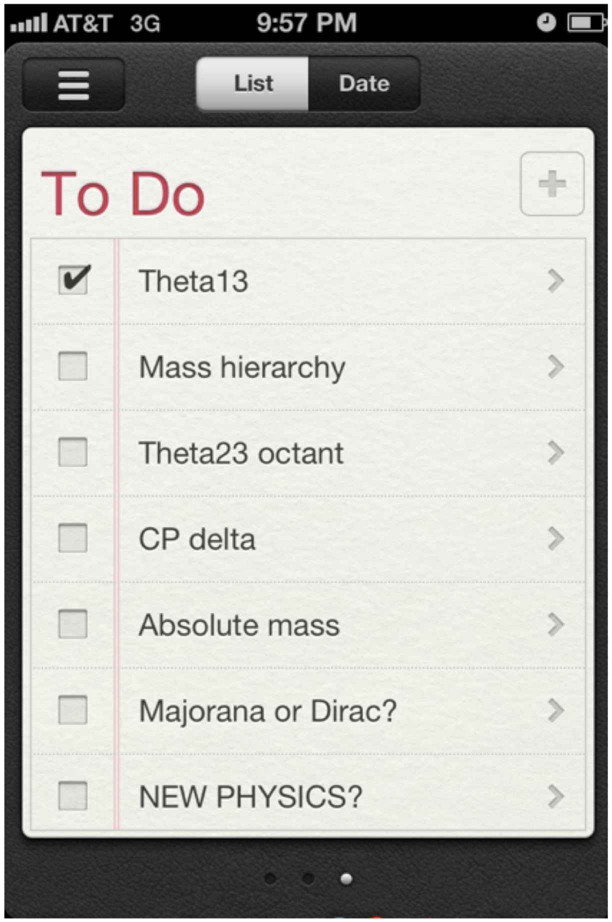
Overall Summary

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



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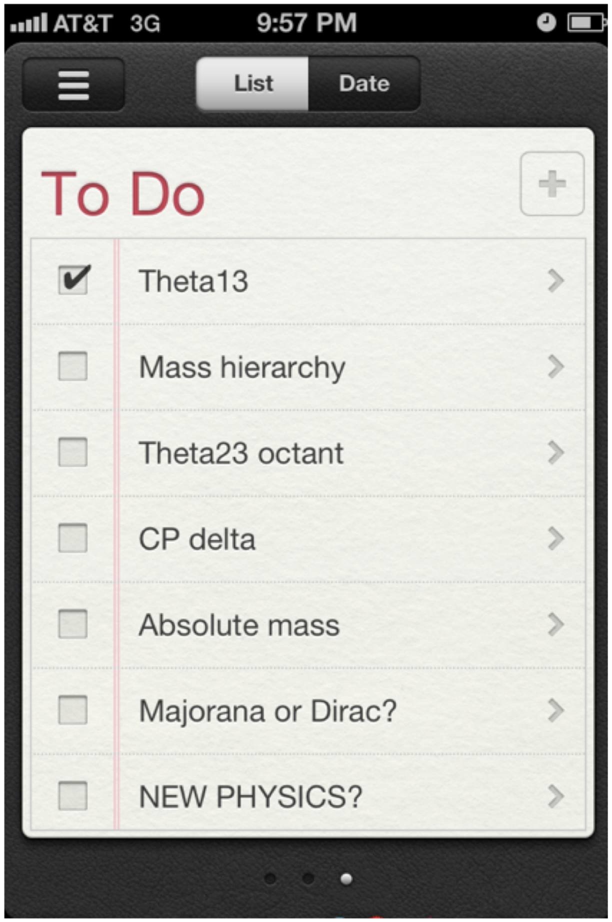

getting 2σ-ish results
... good prospects for
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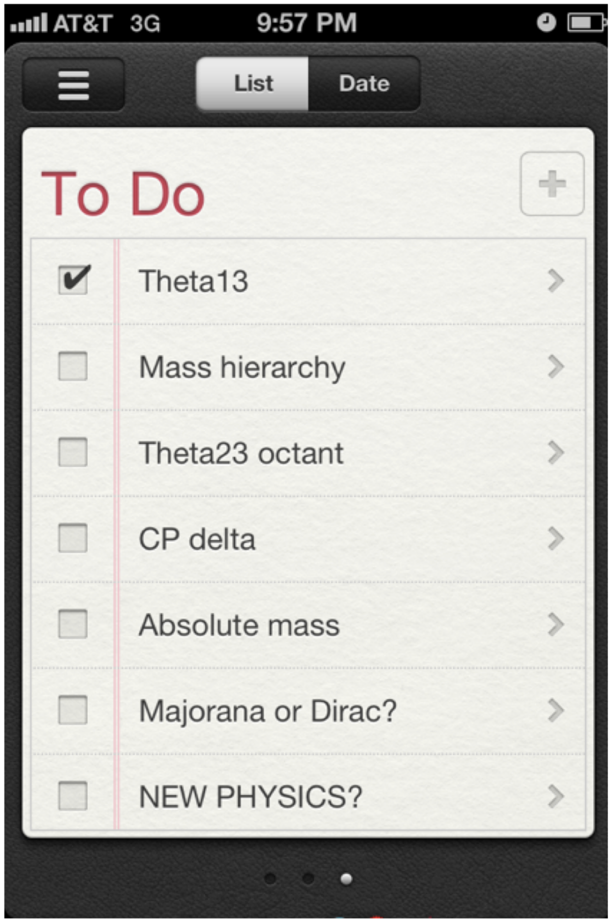

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Looking forward to KATRIN!

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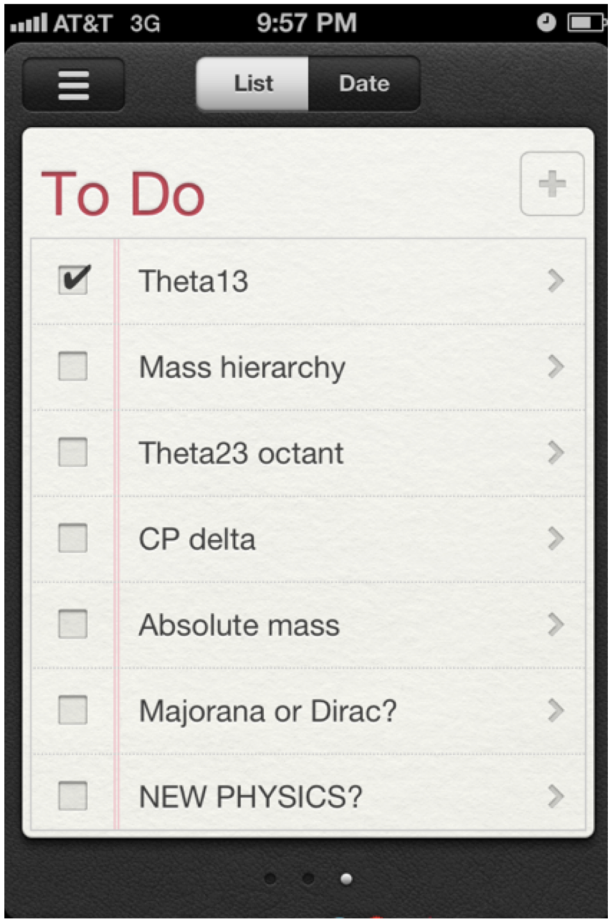

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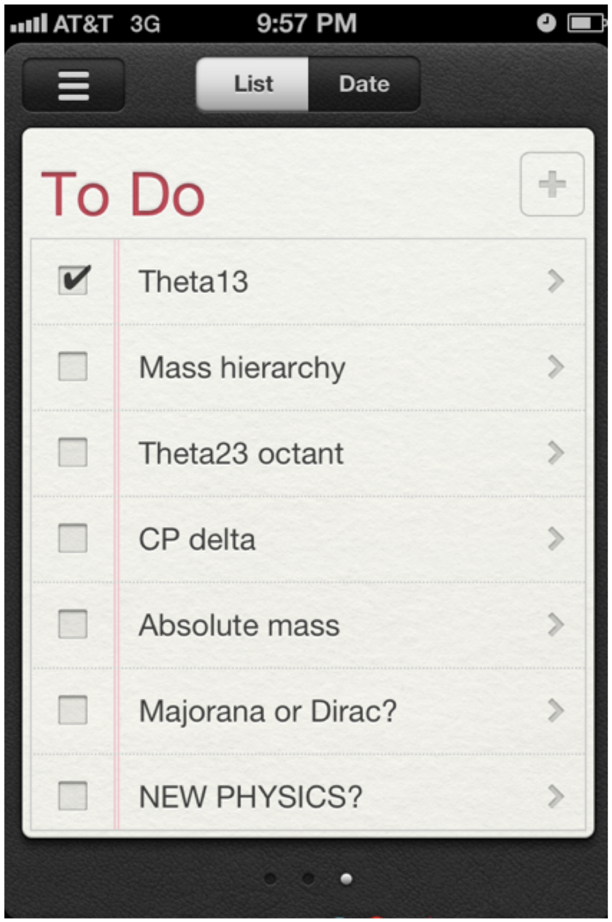

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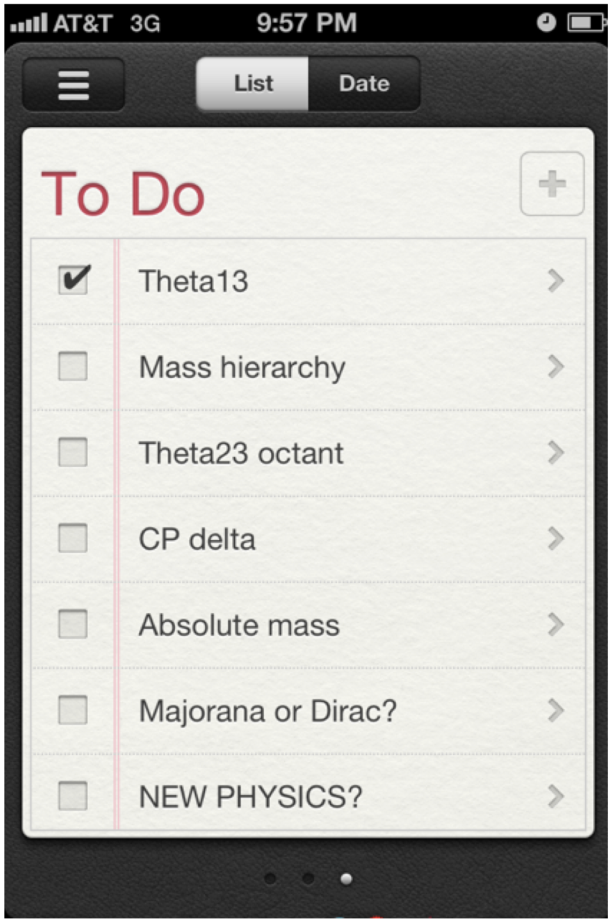

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Looking forward to KATRIN!

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!