Neutrino Results:
Non- Accelerator Experiments

Kate Scholberg, Duke University

IMFP, Salamanca, April 2018

What I will cover

Knowns and unknowns in neutrino physics

Neutrino Oscillations

"Solar" sector

"Atmospheric" sector

The twist in the middle

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

Beyond 3-flavor?

(+xscns)

The mass pattern and mixing matrix

Absolute Mass

βdk endpoint, cosmology

The mass scale

Majorana vs Dirac?

Neutrinoless $\beta\beta$dk

The mass nature

Yesterday

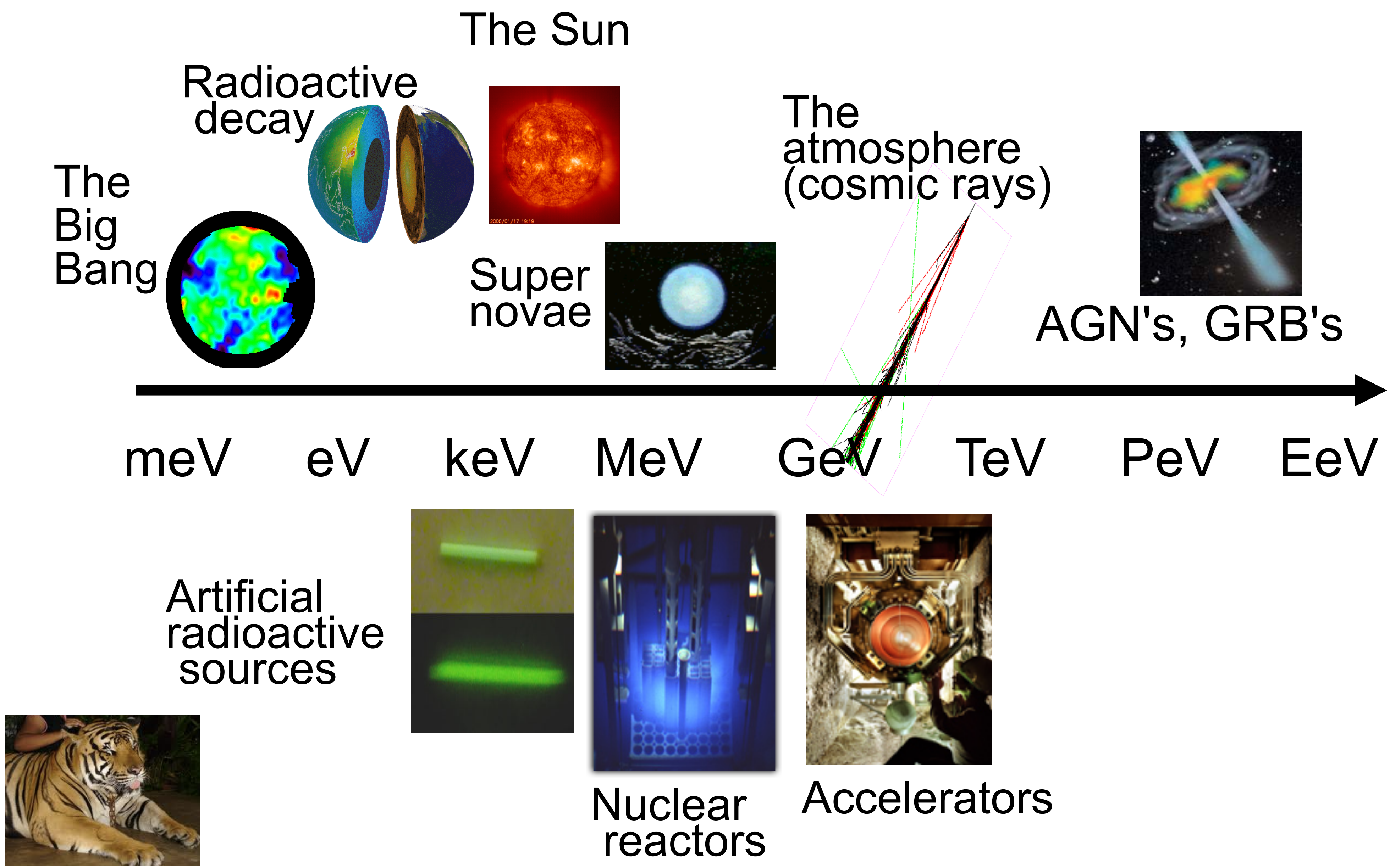
The 3-flavor picture

Accelerator experiments

Today

Non-accelerator experiments

Wild and tame neutrinos



Unknowns in neutrino physics: can address with non-accelerator ν's too!

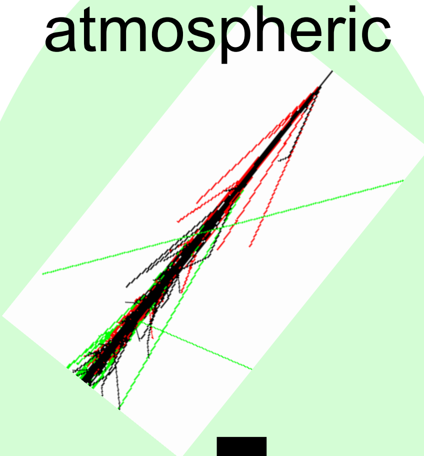
parameter	best fit $\pm$ 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.56$\pm$0.19	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.55$\pm$0.04	2.43–2.67
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	2.49$\pm$0.04	2.37-2.61
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$	2.73–3.79
$\theta_{12}/^\circ$	$34.5^{+1.1}_{-1.0}$	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$ [a]	3.84–6.35
$\theta_{23}/^\circ$	41.0$\pm$1.1	38.3–52.8
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$ [b]	3.88–6.38
$\theta_{23}/^\circ$	50.5$\pm$1.0	38.5–53.0
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.155^{+0.090}_{-0.075}$	1.89–2.39
$\theta_{13}/^\circ$	$8.44^{+0.18}_{-0.15}$	7.9–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.140^{+0.082}_{-0.085}$	1.89–2.39
$\theta_{13}/^\circ$	$8.41^{+0.16}_{-0.17}$	7.9–8.9
δ/π (NO)	$1.40^{+0.31}_{-0.20}$	0.00–2.00
$\delta/^\circ$	252^{+56}_{-36}	0–360
δ/π (IO)	$1.44^{+0.26}_{-0.23}$	0.00–0.17 & 0.79–2.00
$\delta/^\circ$	259^{+47}_{-41}	0–31 & 142–360

sign of Δm^2 unknown (ordering of masses)

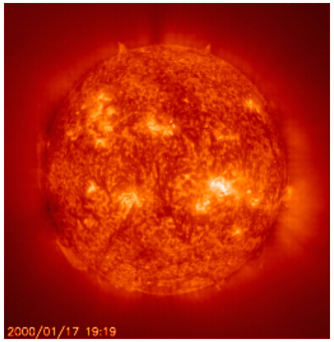
Is θ_{23} non-negligibly greater or smaller than 45 deg?

mostly unknown

P. F. de Salas[1], D. V. Forero[2,3,*] C. A. Ternes[1], M. Tórtola[1,†] and J. W. F. Valle[1‡] atmospheric



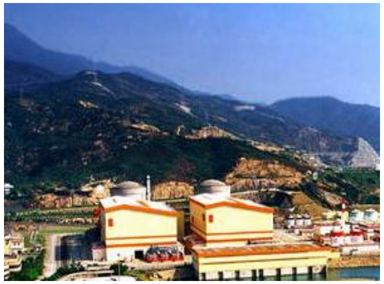
solar



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

beams

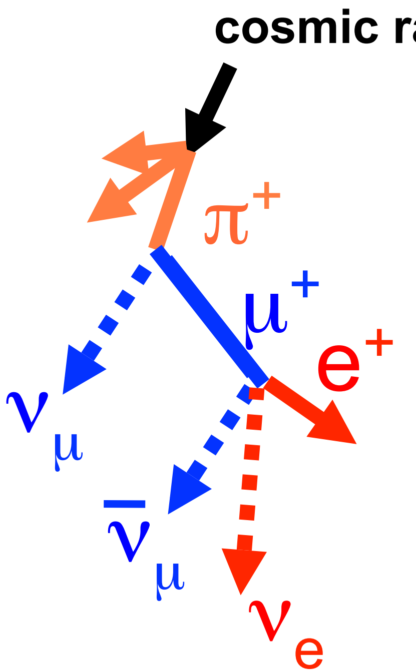
"Atmospheric" sector

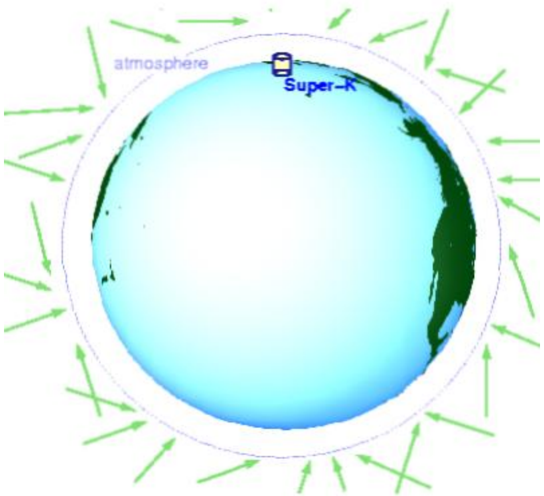


reactor

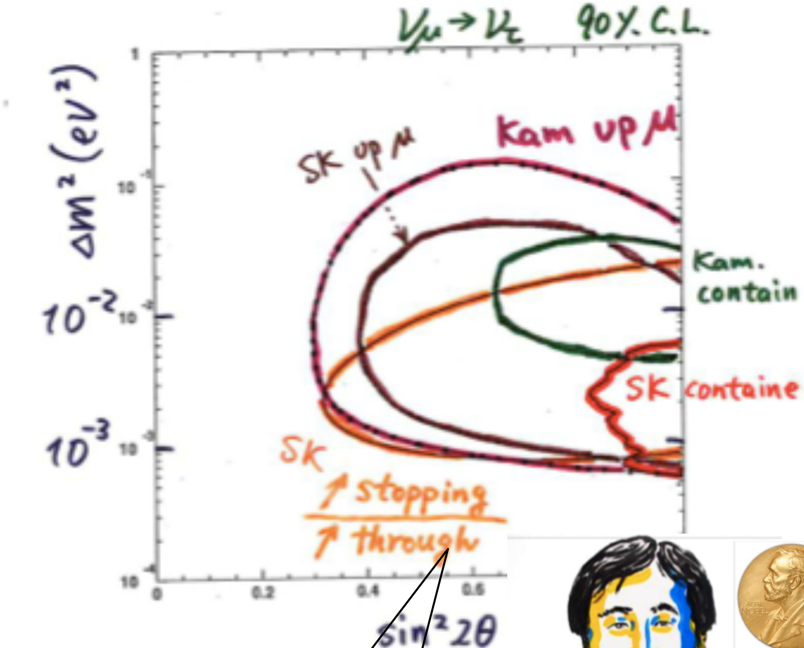
Atmospheric neutrinos

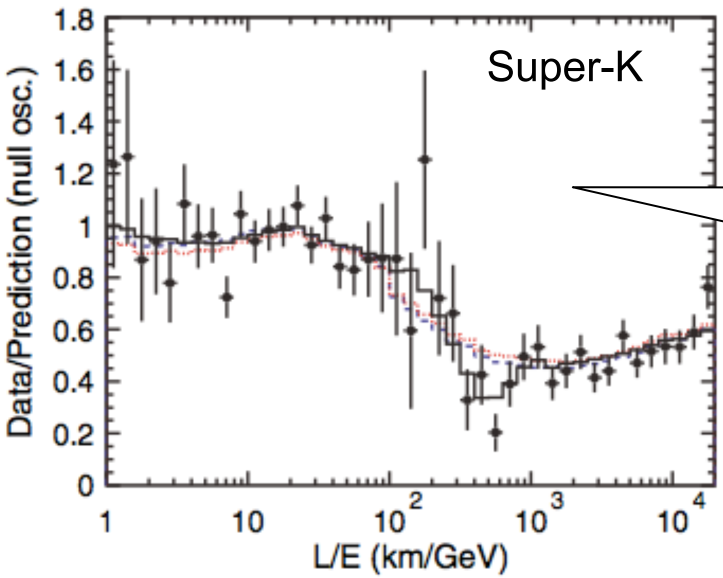
The neutrinos are free, and have a range of baselines & energies





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

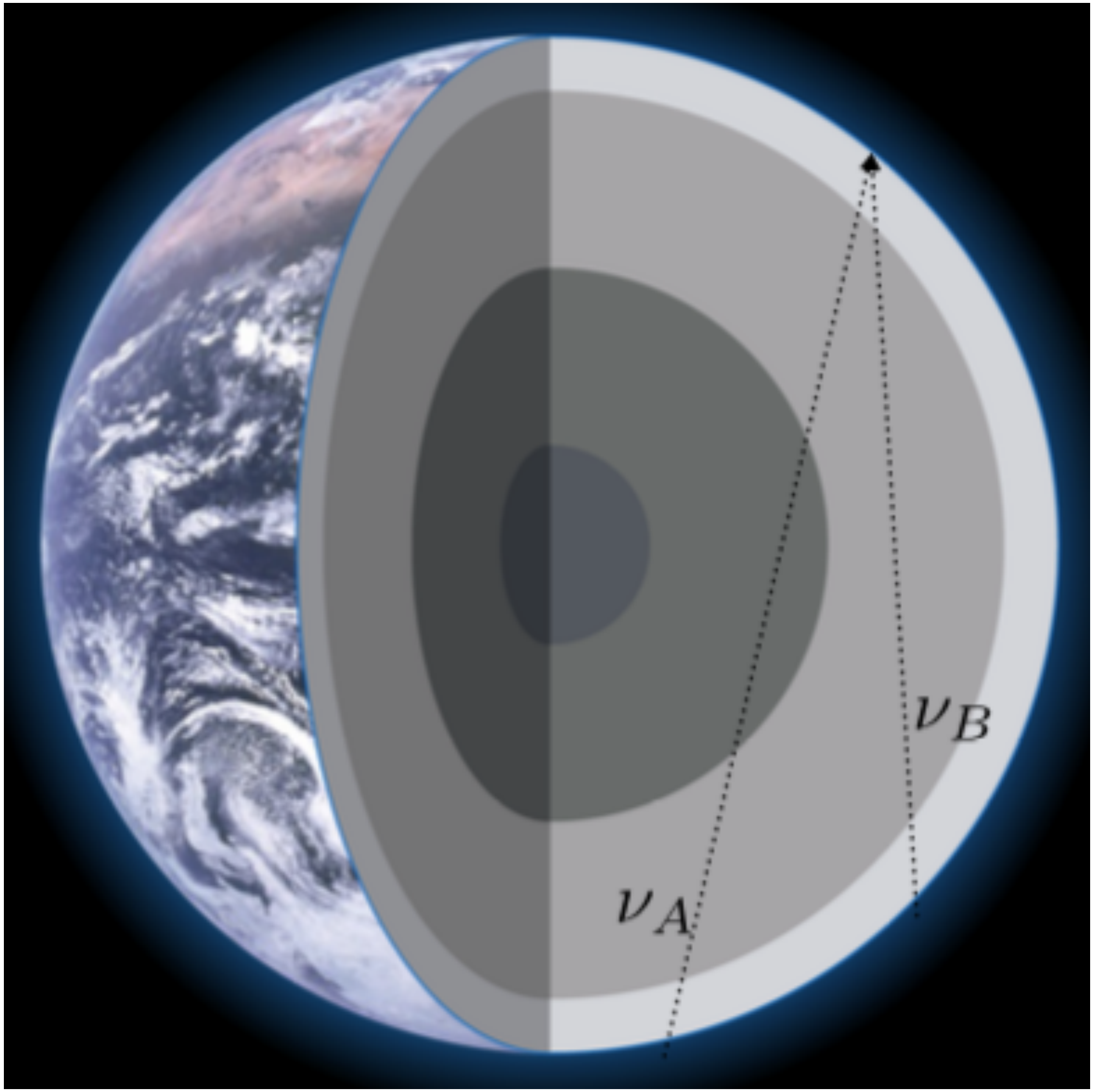




Clear ν_μ disappearance

Well described by
23 oscillation parameters:
$|\Delta m^2_{32}| \sim 2 \times 10^{-3}$ eV^2,
~ maximal mixing

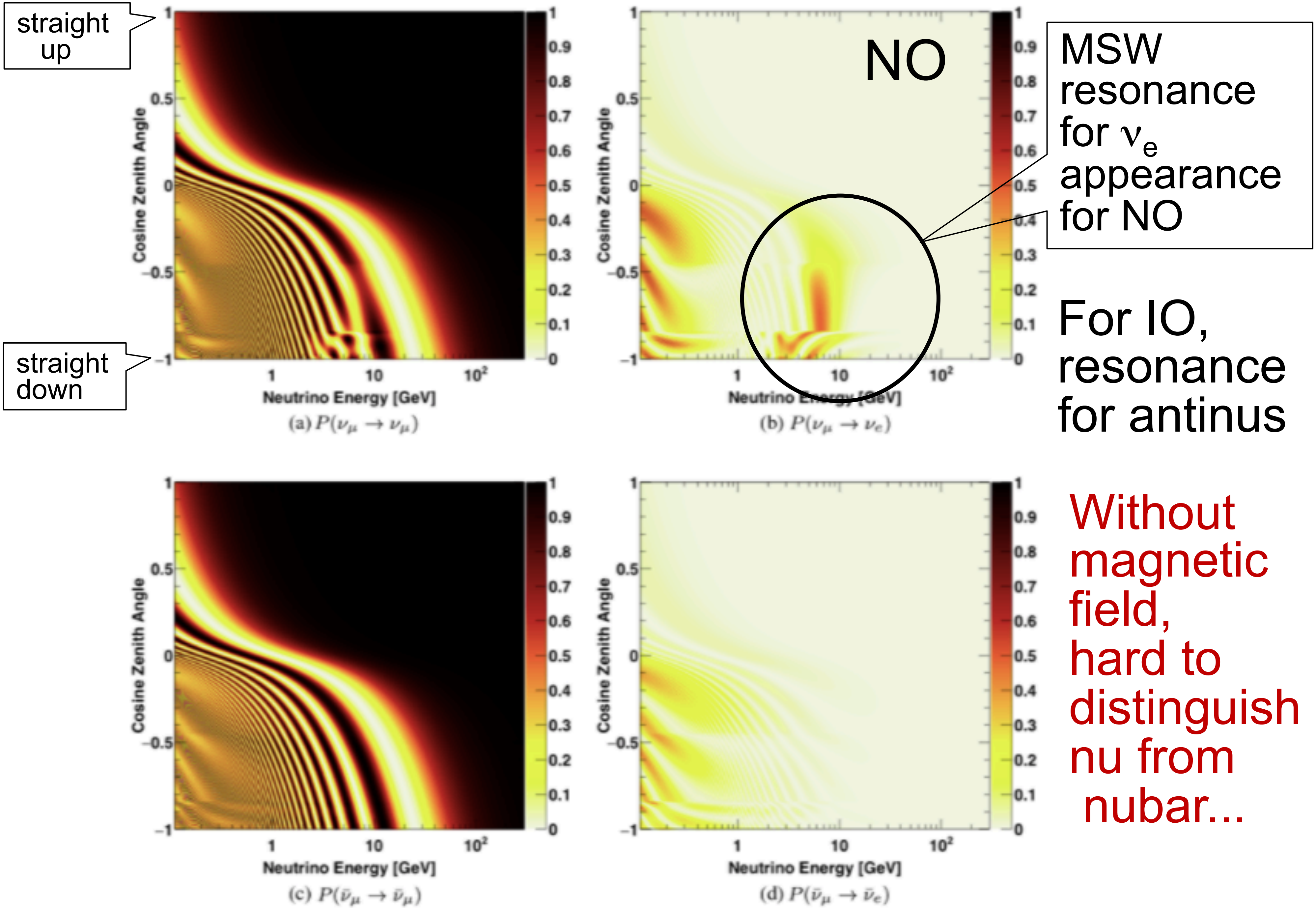
There is more to be had from atmospheric ν's...



Matter resonance in the Earth gives information on MO and CP δ

Abe et al., PRD 97, 072001 (2018)

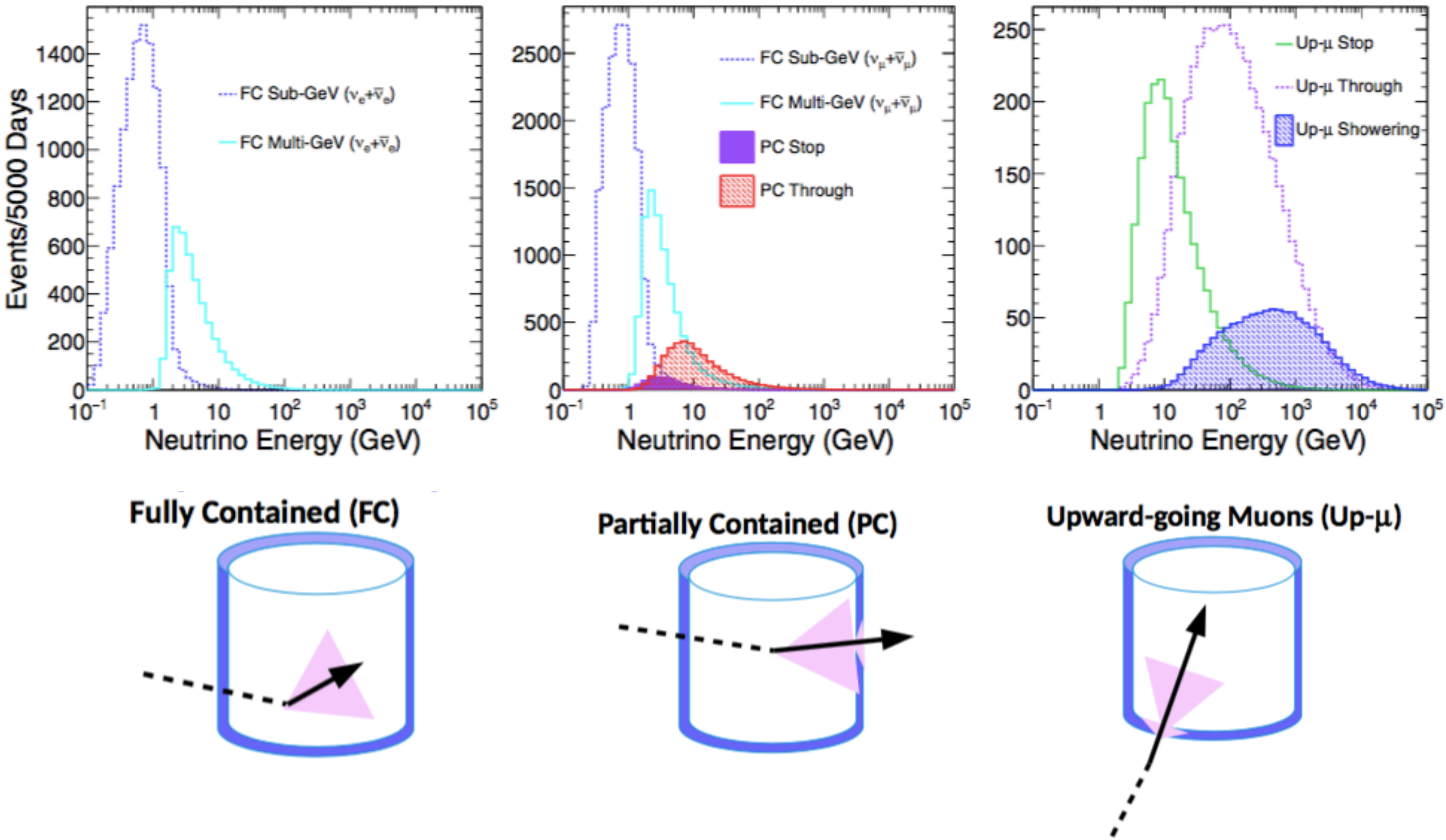
Earth "oscillograms"



Without magnetic field, hard to distinguish nu from nubar...

Super-K atmospheric neutrino samples

Different topologies represent different ν parent energies



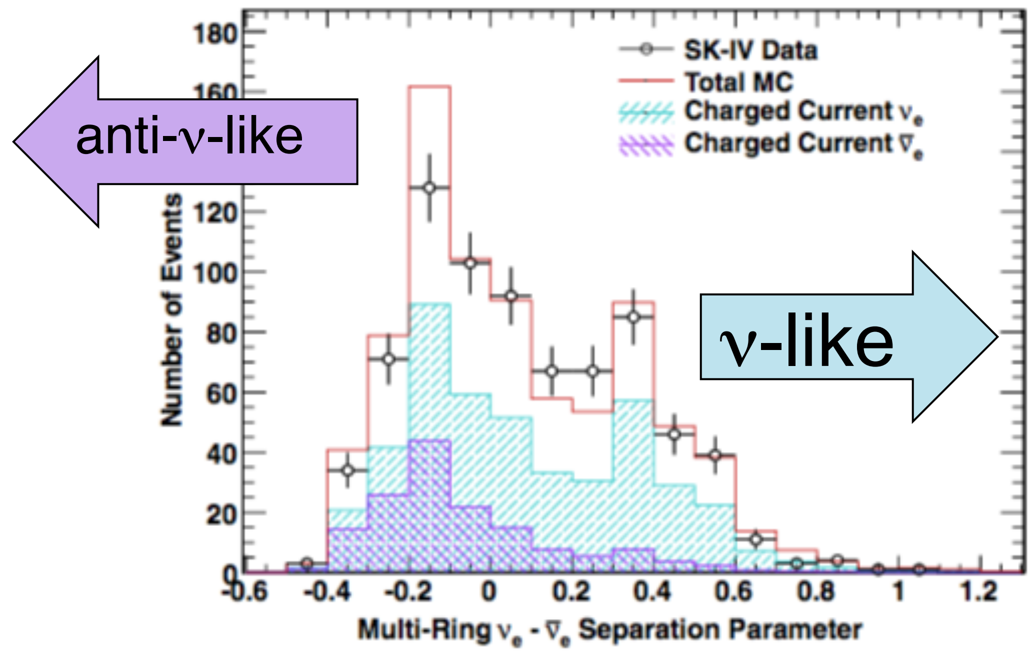
Neutrinos and antineutrinos can be *statistically* separated in SK

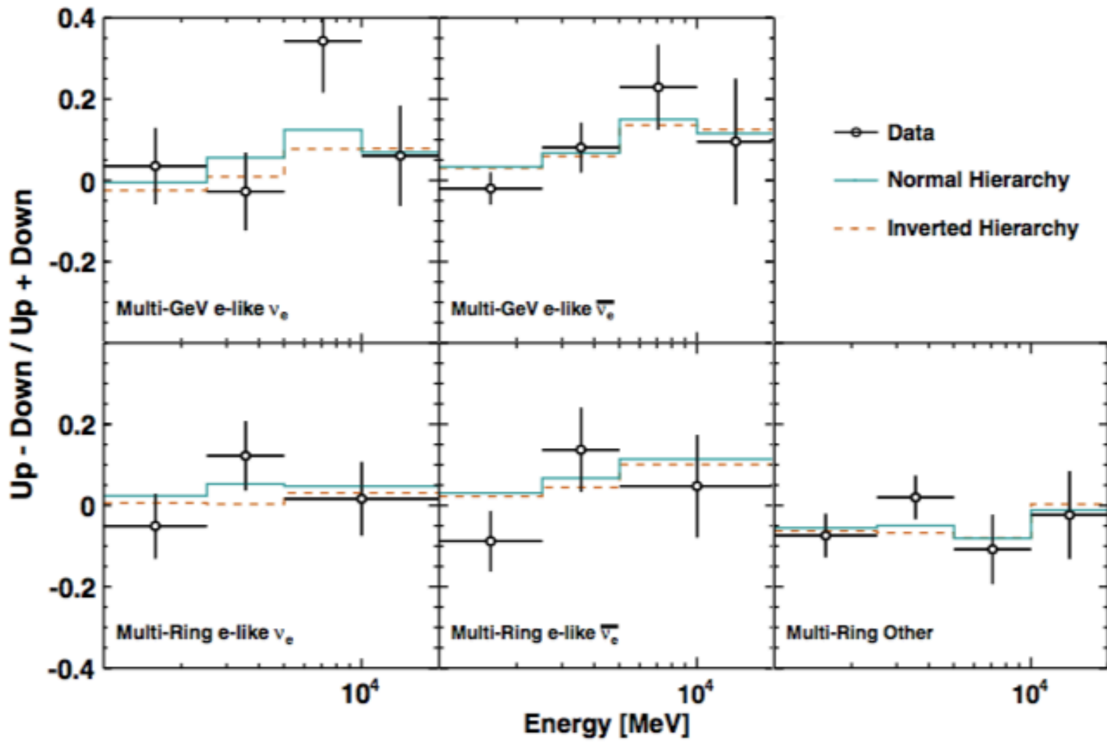
Likelihoods based on

- particle ID of most energetic ring
- fraction of its total momentum
- no. of decay electrons
- largest distance to decay e vertex

+

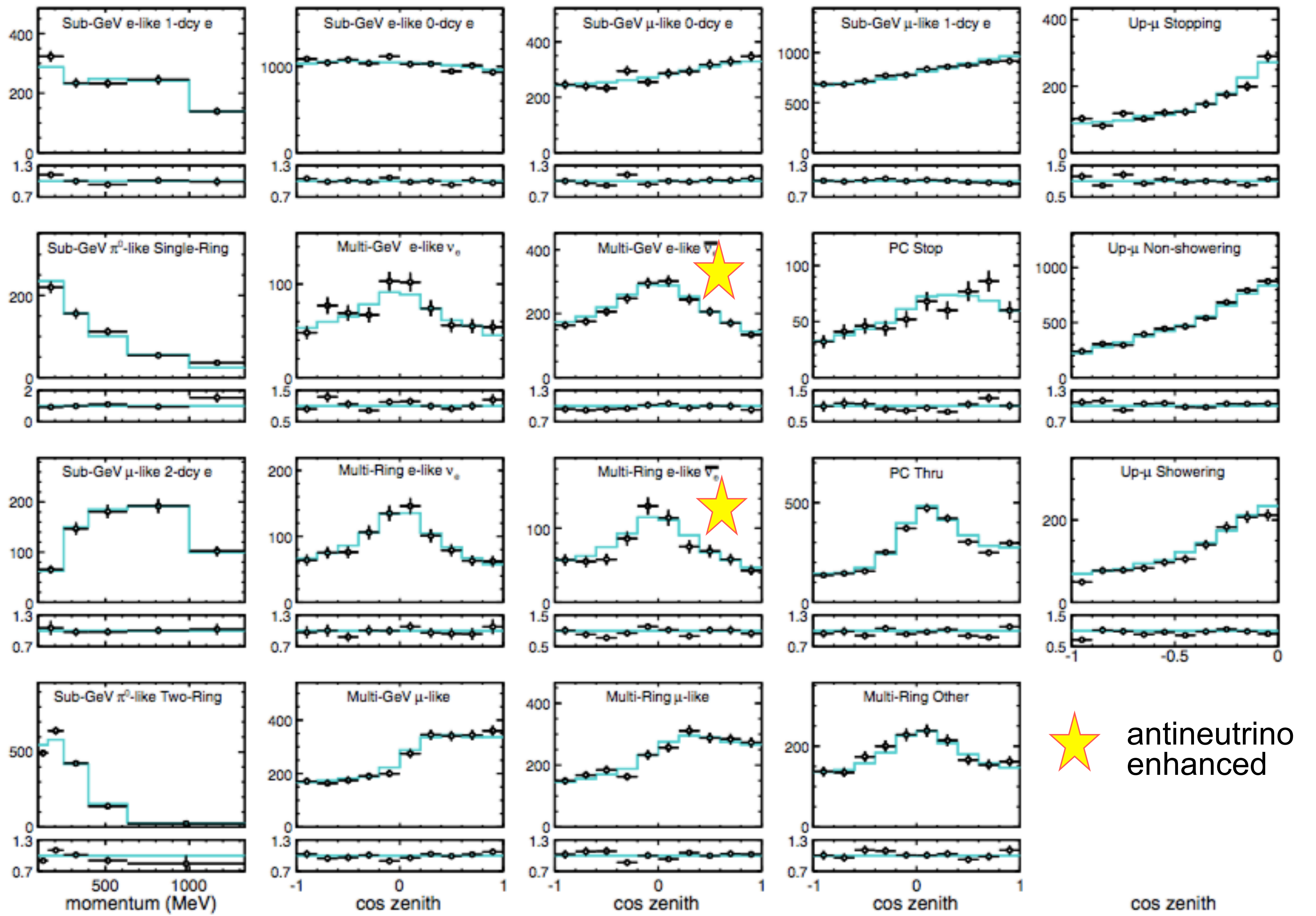
- no. of decay electrons
- no. of rings
- transverse momentum





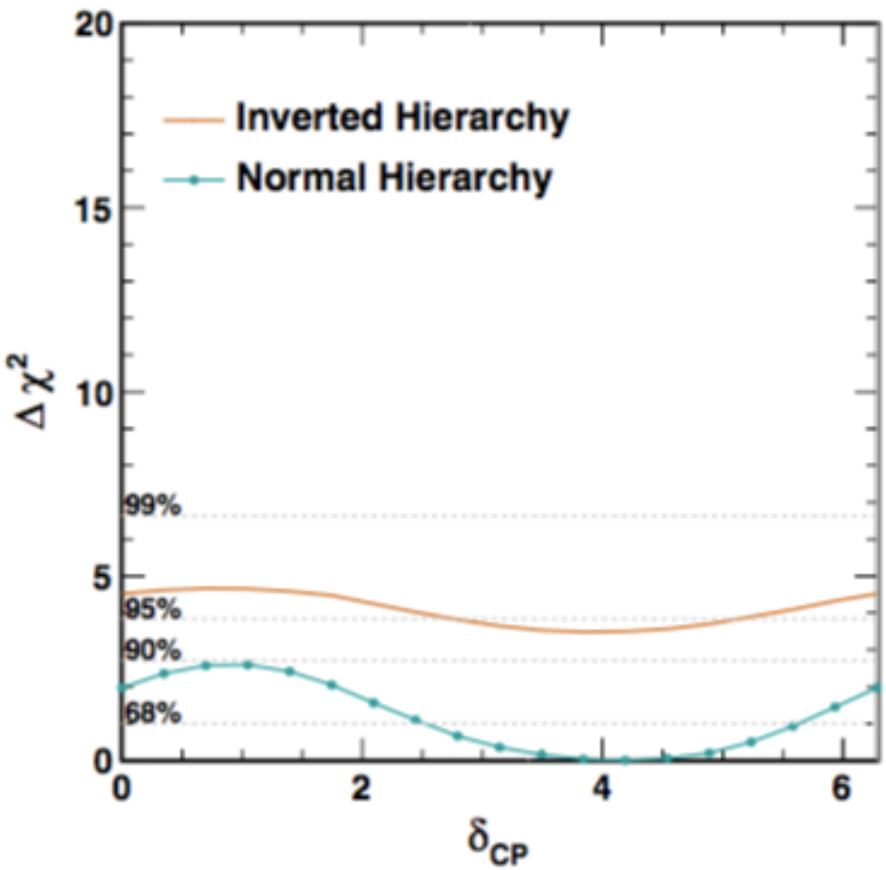
5326 days of SK data: still statistically limited

SK atmospheric data samples

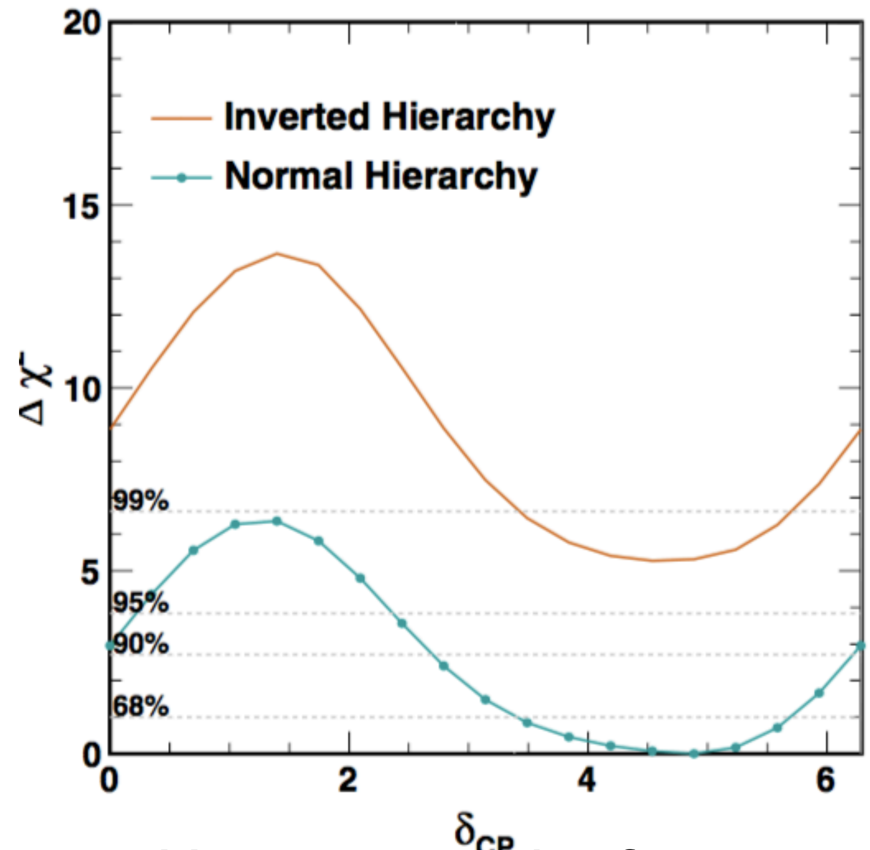


SK atmospheric neutrino fit

Abe et al., PRD 97, 072001 (2018)



SK only

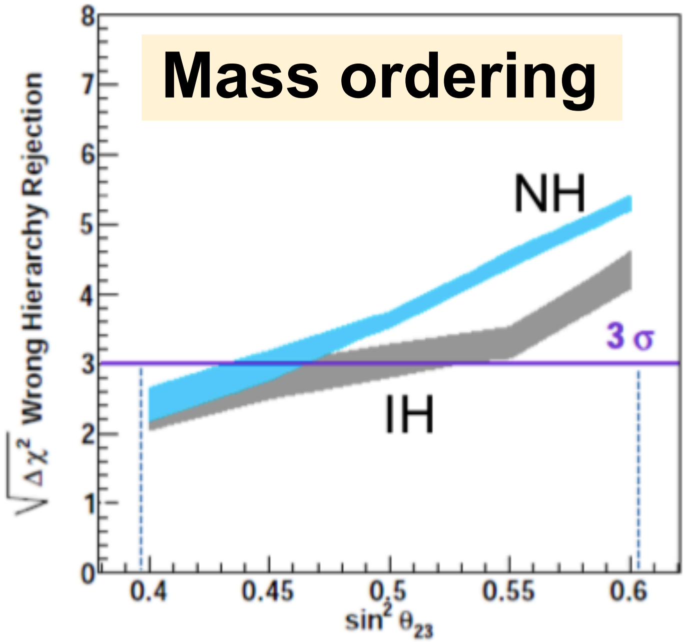


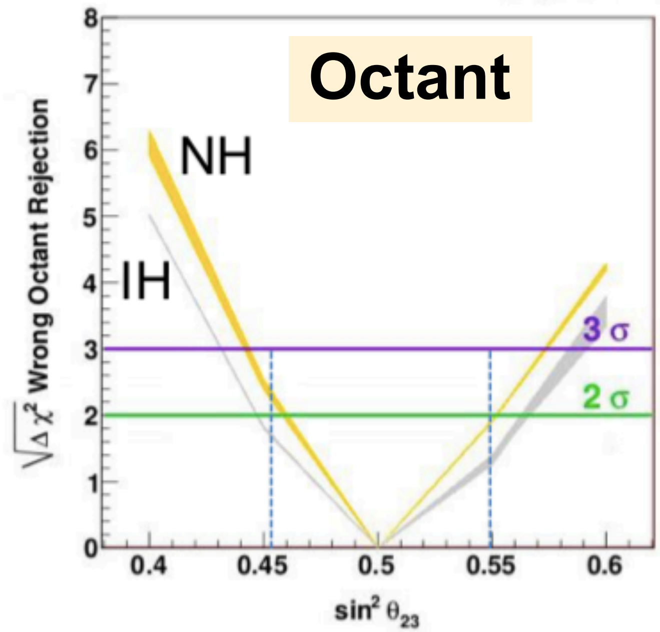
Uses constraint from published T2K data and $\sin^2\theta_{13} = 0.0219 \pm 0.0012$

Normal ordering and $\delta=3\pi/2$ favored

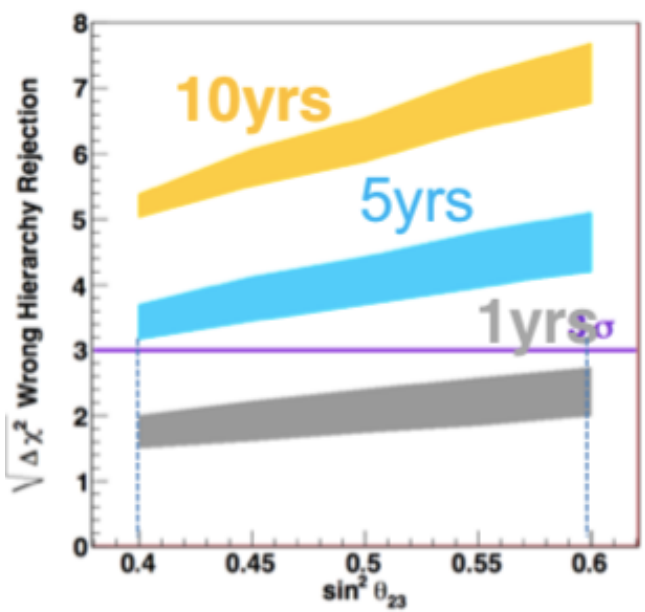
Hyper-K atmospheric neutrino sensitivity

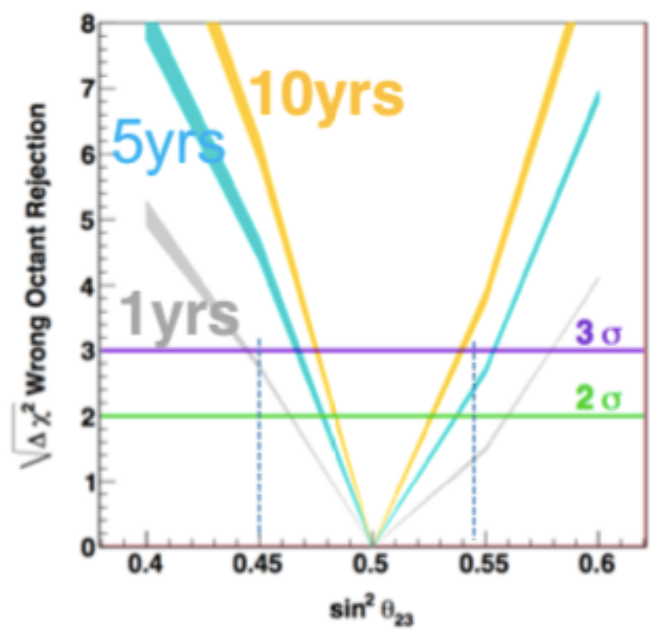
F. Di Lodovico





Atmospheric neutrinos, 10 years

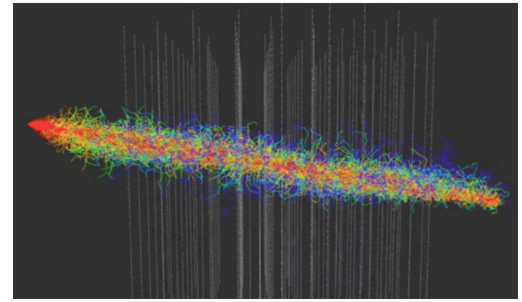


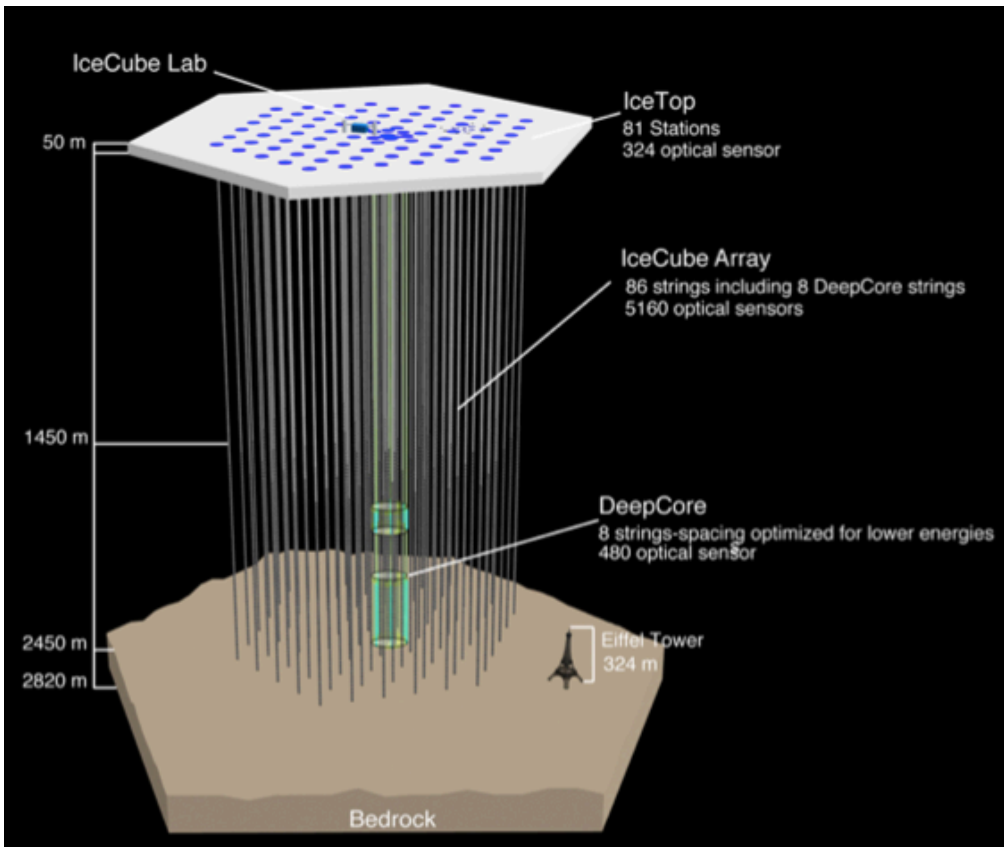


Atmospheric neutrinos + beam

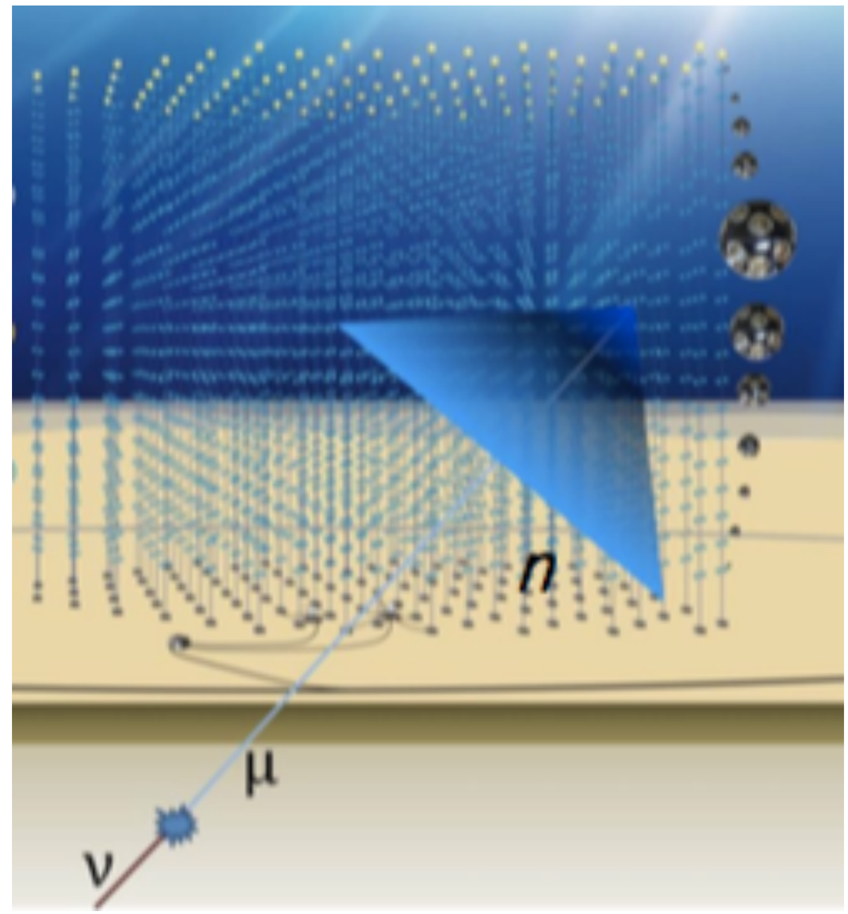
Long-string detectors in water and ice

Bash it with statistics
in huge volume!
.. but reconstruction
harder in sparse PMT arrays



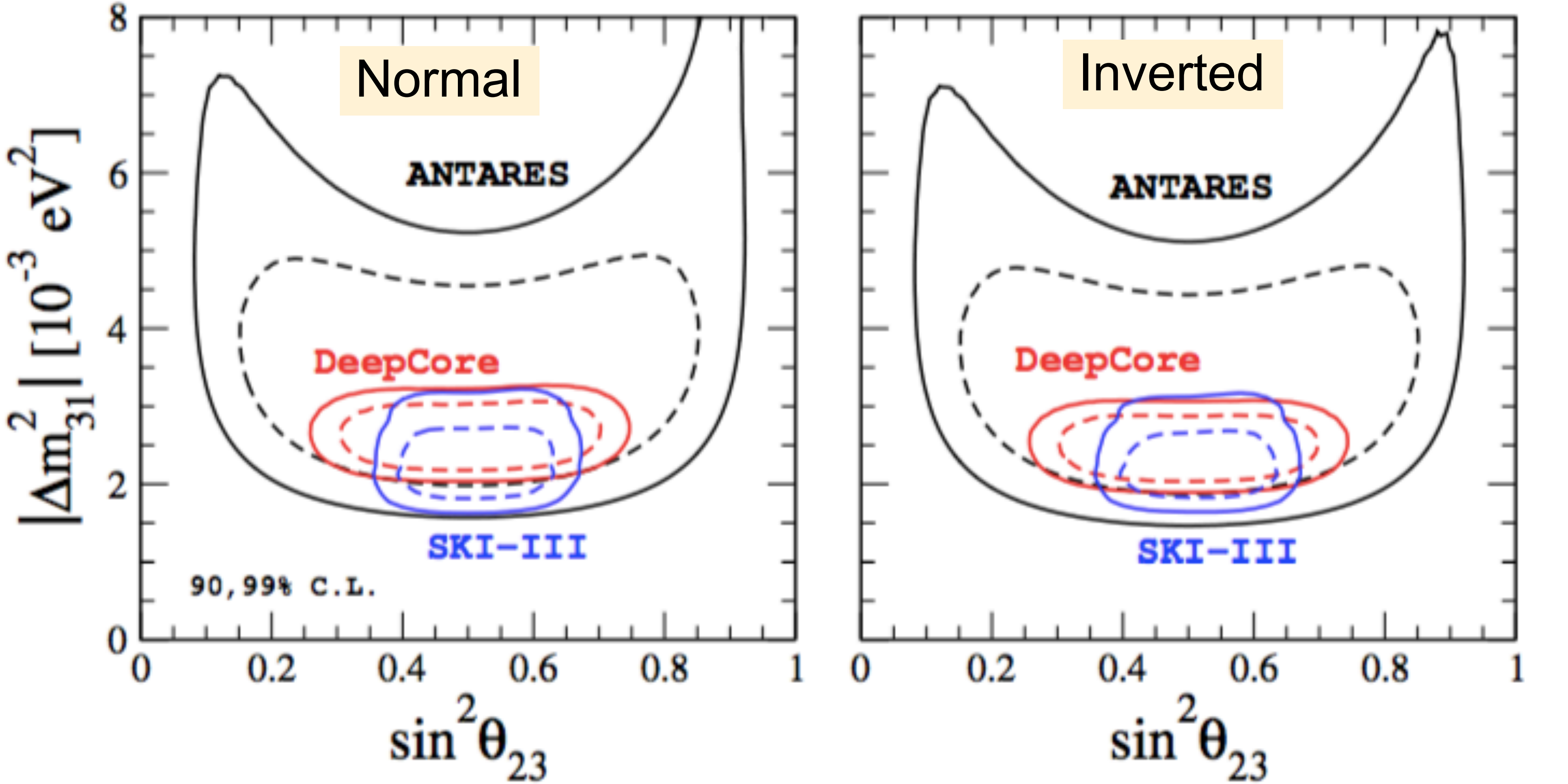


IceCube/DeepCore/
IceCube-Gen2/PINGU



ANTARES/KM3Net/ORCA

Muon neutrino disappearance from long-string experiments

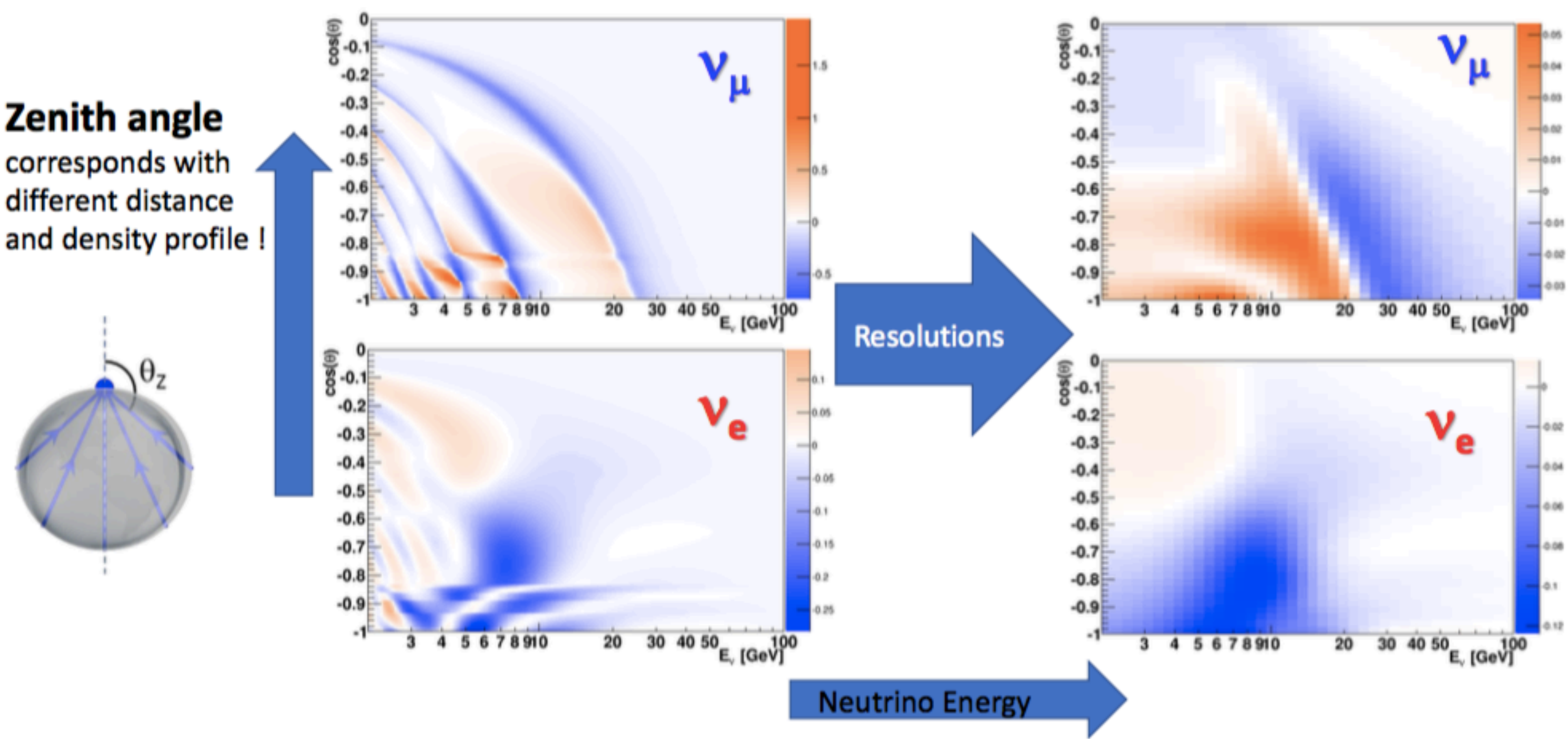


P. F. de Salas[1], D. V. Forero [2,3],* C. A. Ternes[1], M. Tórtola [1],† and J. W. F. Valle [1‡]

Going after mass ordering

Akhmedov, Razzaque, and Smirnov 1205.7071

Relative difference in event numbers between normal and inverted hierarchy $(N_{IH}-N_{NH})/N_{NH}$

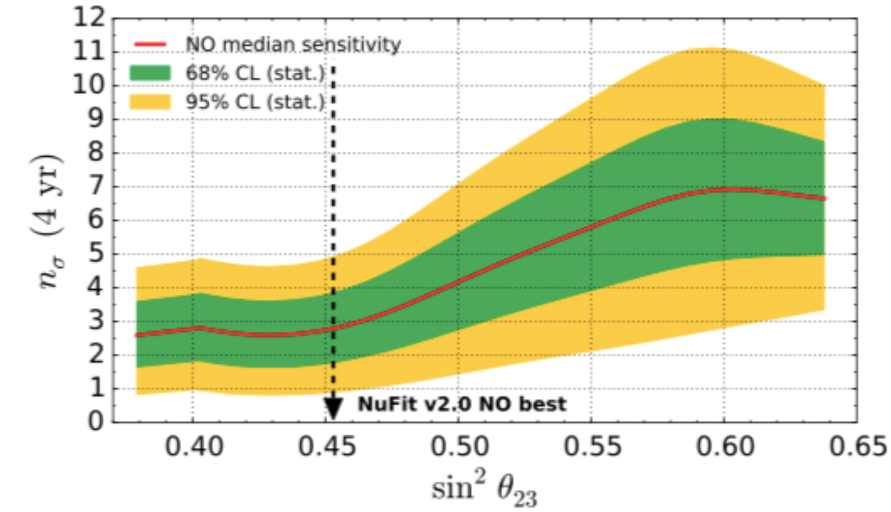


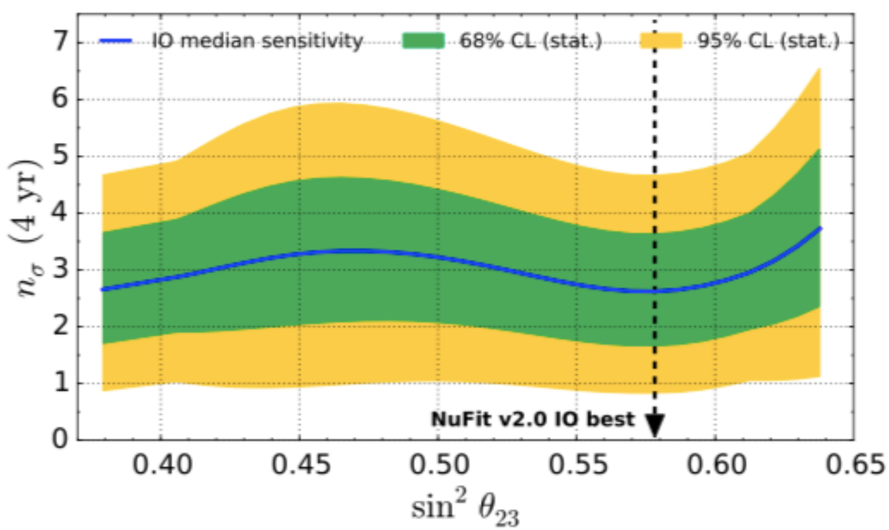
R.Bruijn

Sensitive to systematics

Projected sensitivities to mass ordering

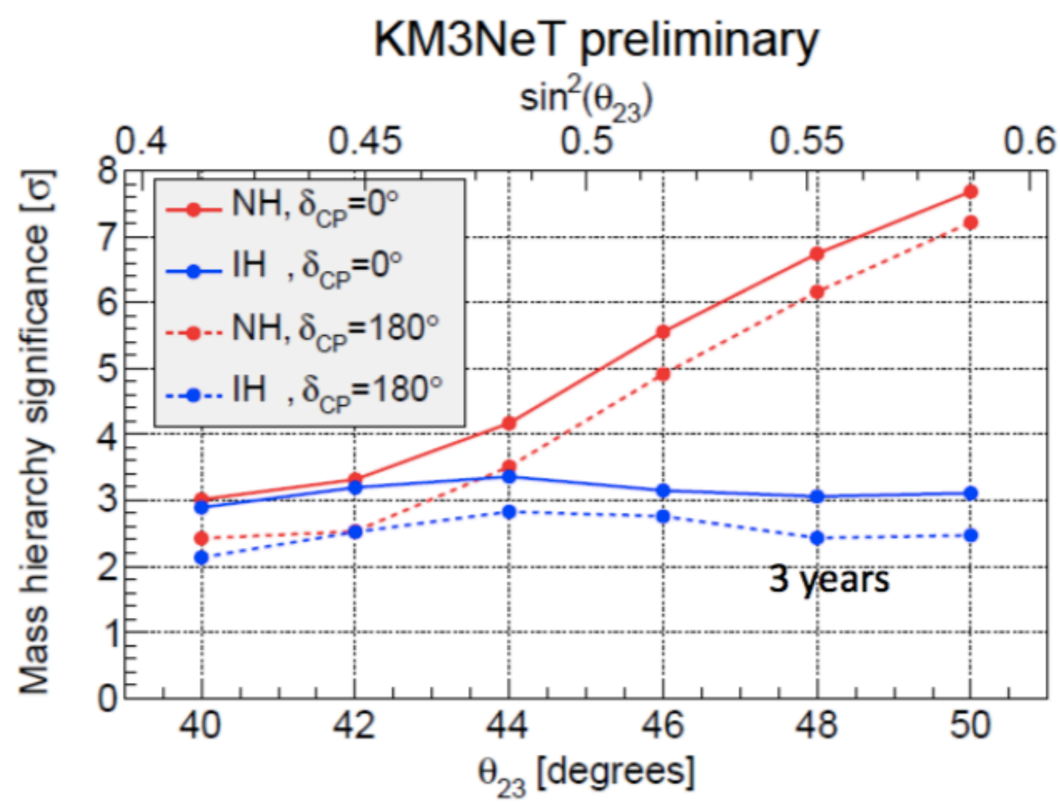
IceCube-Gen2/PINGU





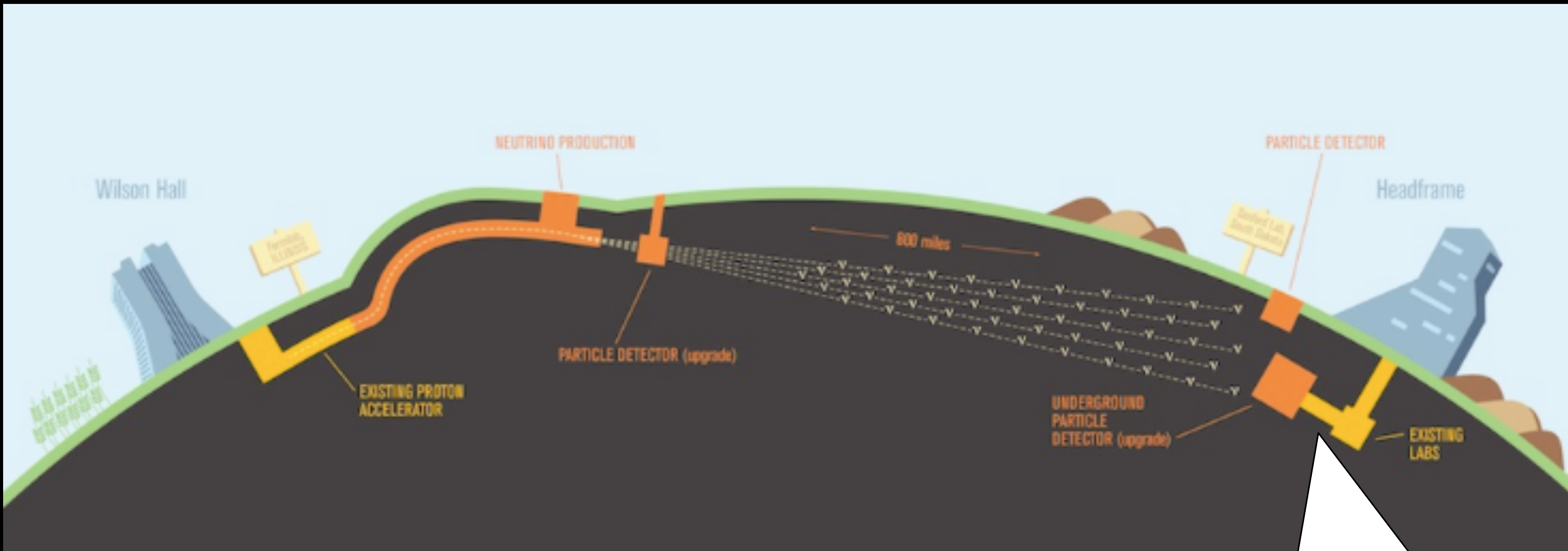
arXiv:1607.02671

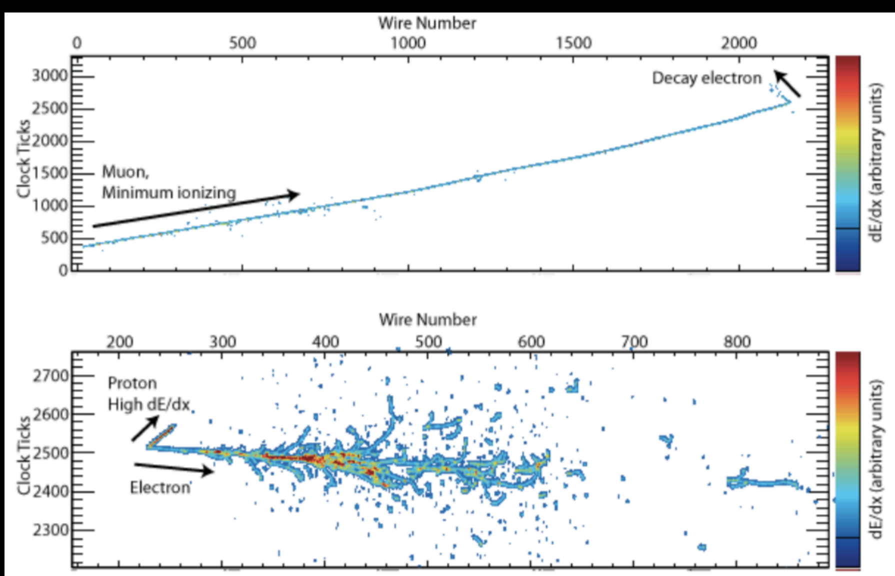
KM3Net ORCA

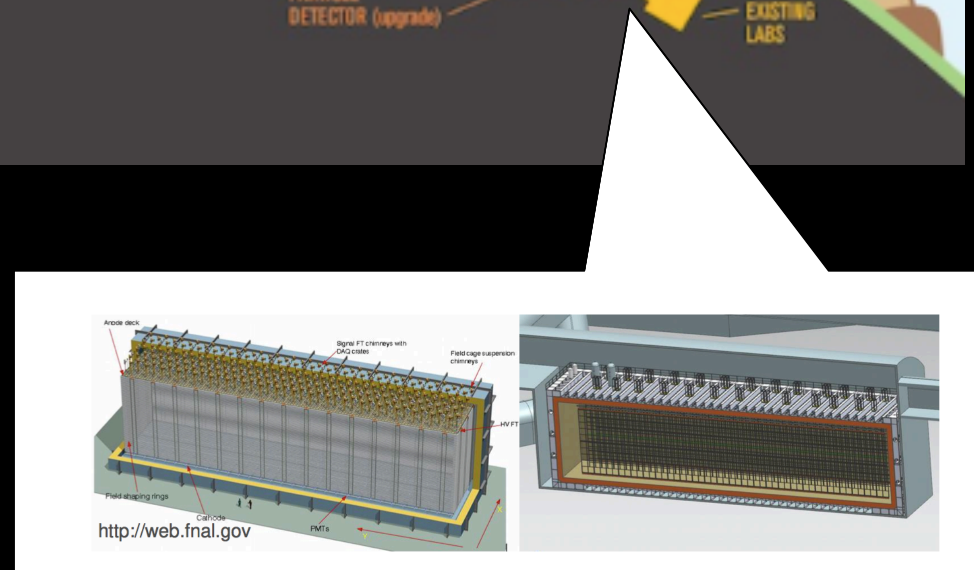


R. Bruijn, Moriond 2018

Atmospheric neutrinos in DUNE

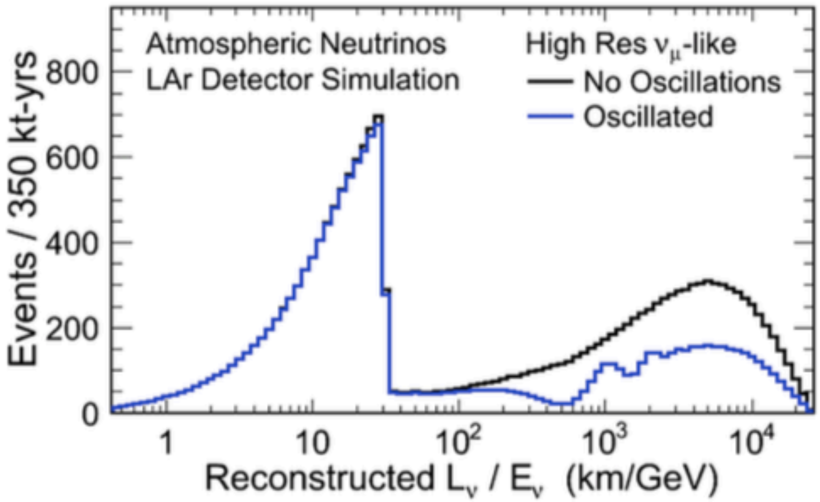


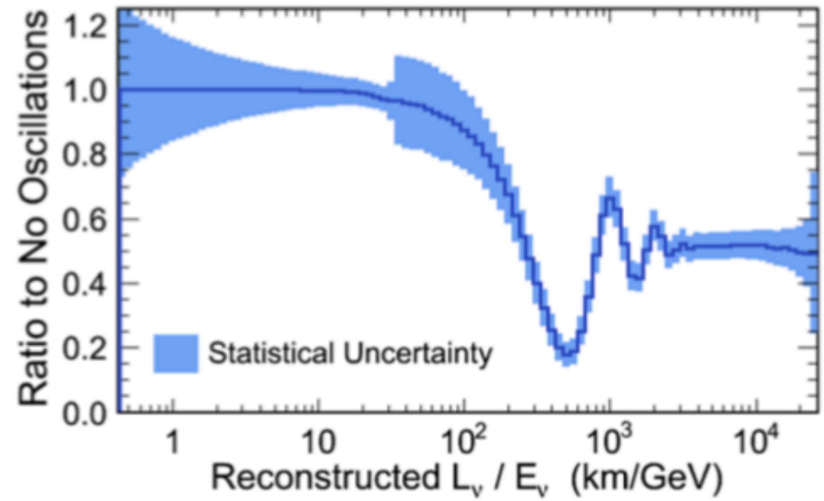


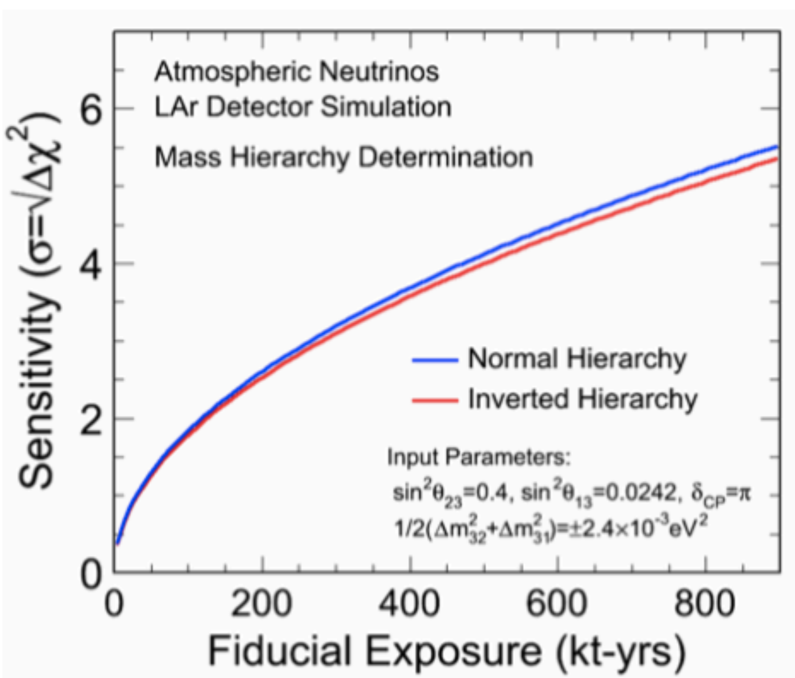


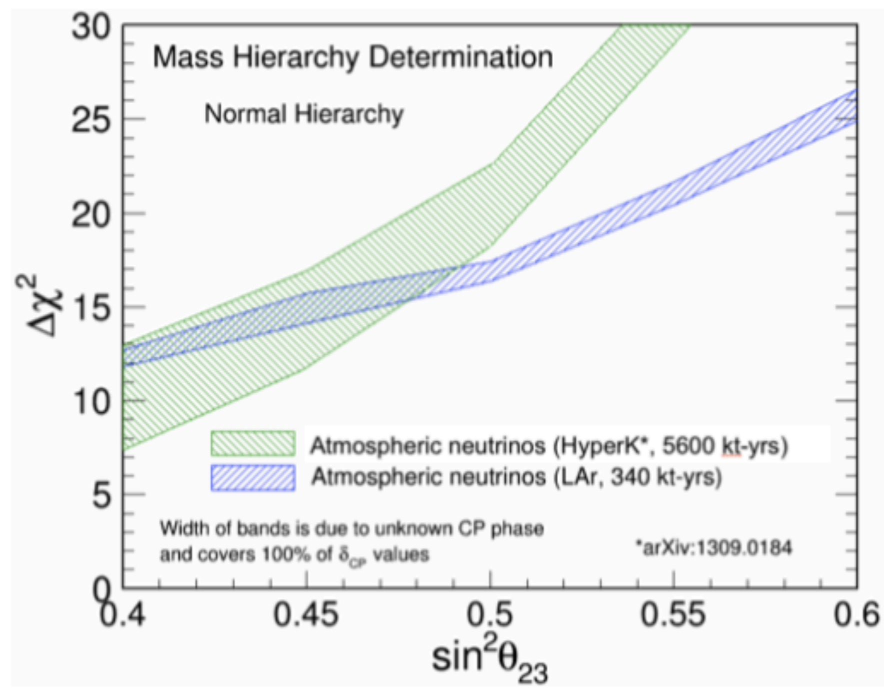
Advantage is precision reconstruction (E, L)

Atmospheric neutrinos with DUNE

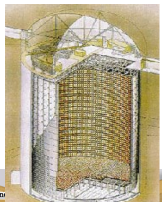


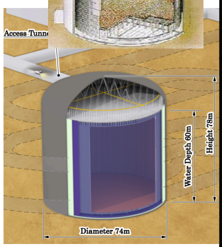


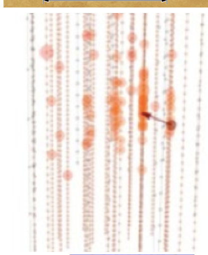


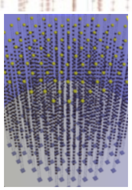


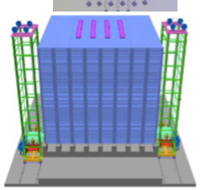
Experiments going after MO with atmnus

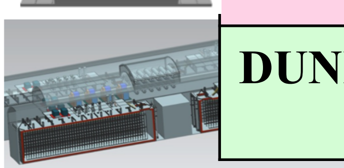






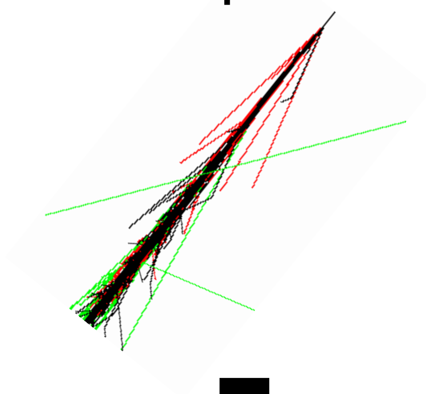




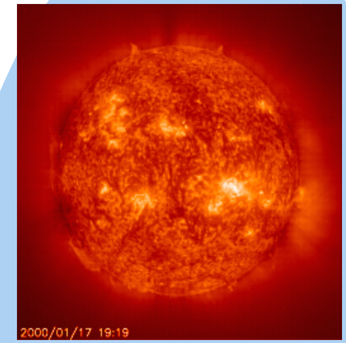


Experiment	**Type**	**Location**	**Reconstruction**	**Mass (kt)**	**Notes**
Super-K	Water Cherenkov	Japan	Good	22.5	Good reconstruction, low stats
Hyper-K	Water Cherenkov	Japan	Good	317	Good reconstruction and stats
IceCube DeepCore	Long String Water Ch.	South Pole	Difficult	Mton	Systematics under study, **huge stats**
PINGU	Long String Water Ch.	South Pole	Improved	Mton	Systematics under study, **huge stats**
KM3NET/ ORCA	Long String Water Ch.	Europe	Improved	Mton	Systematics under study**, huge stats**
ICAL@INO	Iron Calorimeter	India	Good	50	Magnetized➔ lepton sign selection
DUNE	LArTPC	USA	Excellent	40	**Excellent reconstruction**

atmospheric



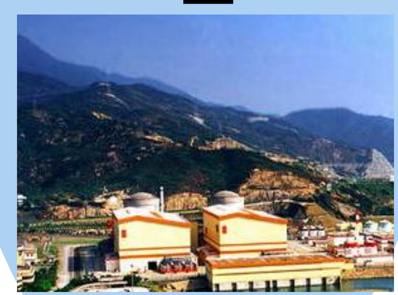
solar



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

beams

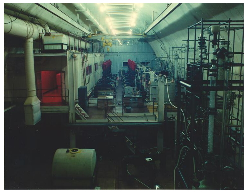
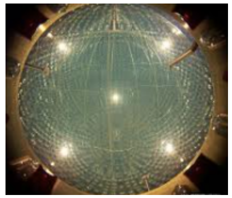
“Solar” sector: solar ν oscillations confirmed with reactors

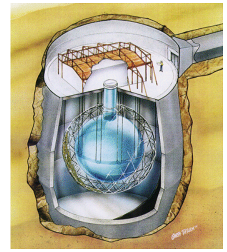
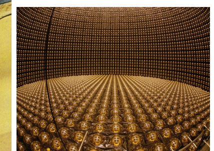


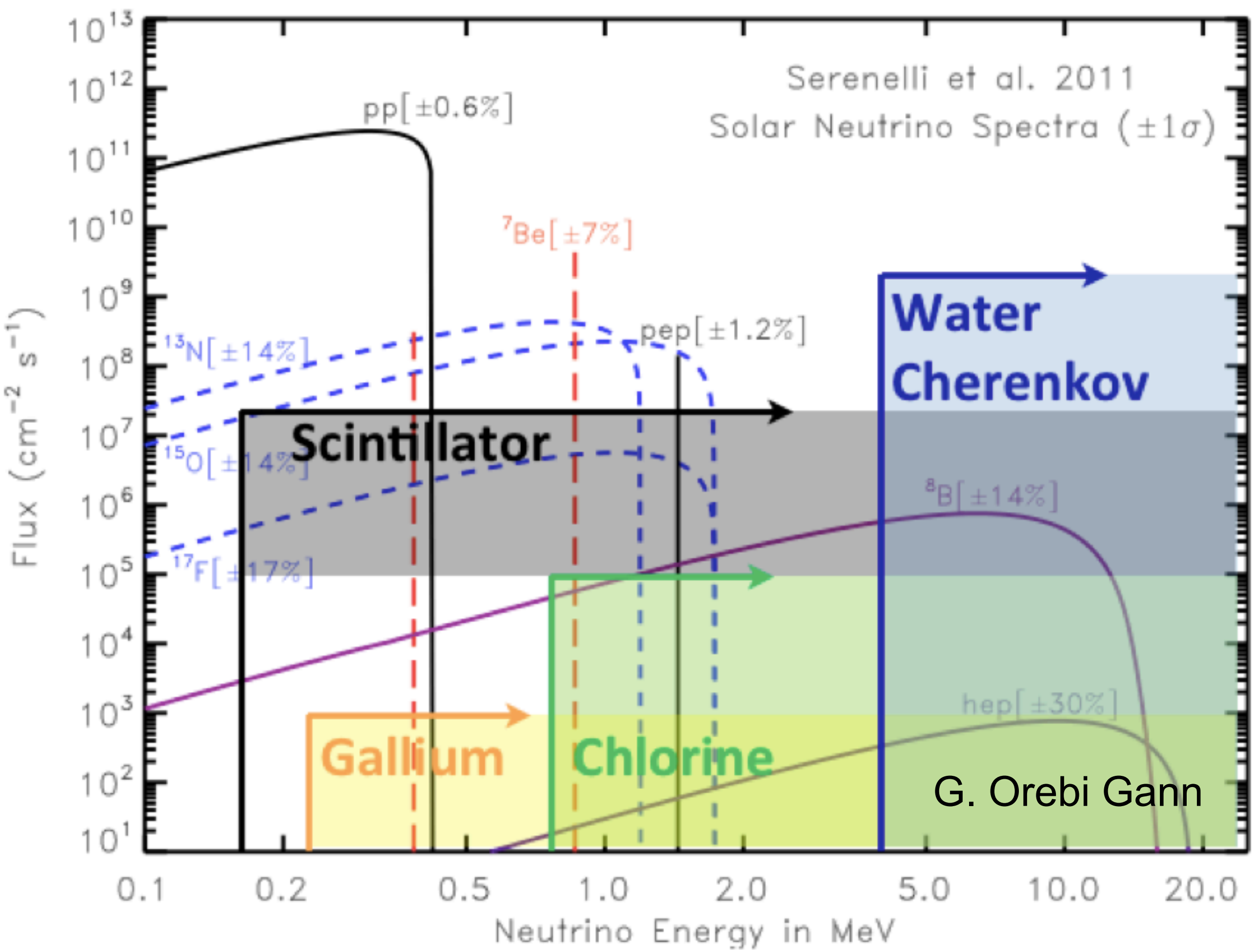
reactor

Solar and reactor neutrinos

Multiple measurements over ~5 decades

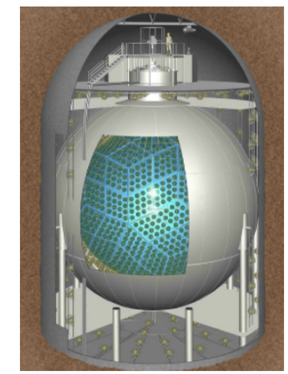


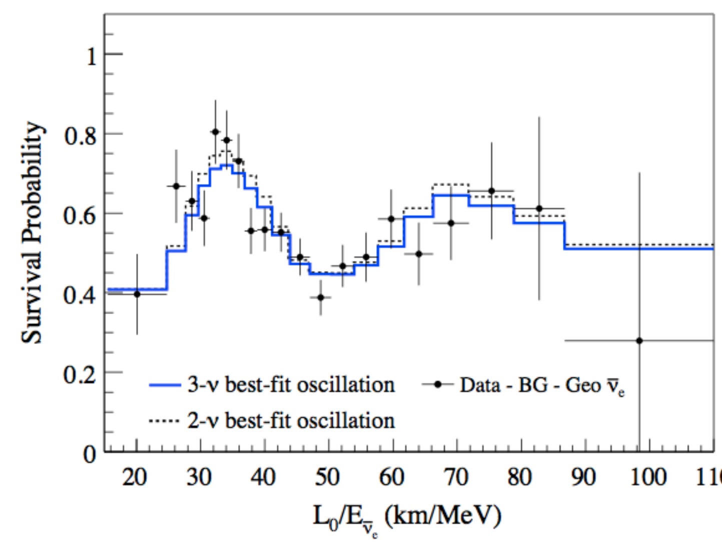
ν_e disappearance, confirmed directly as

$$\nu_e \longrightarrow \nu_{\mu,\tau}$$

by SNO....

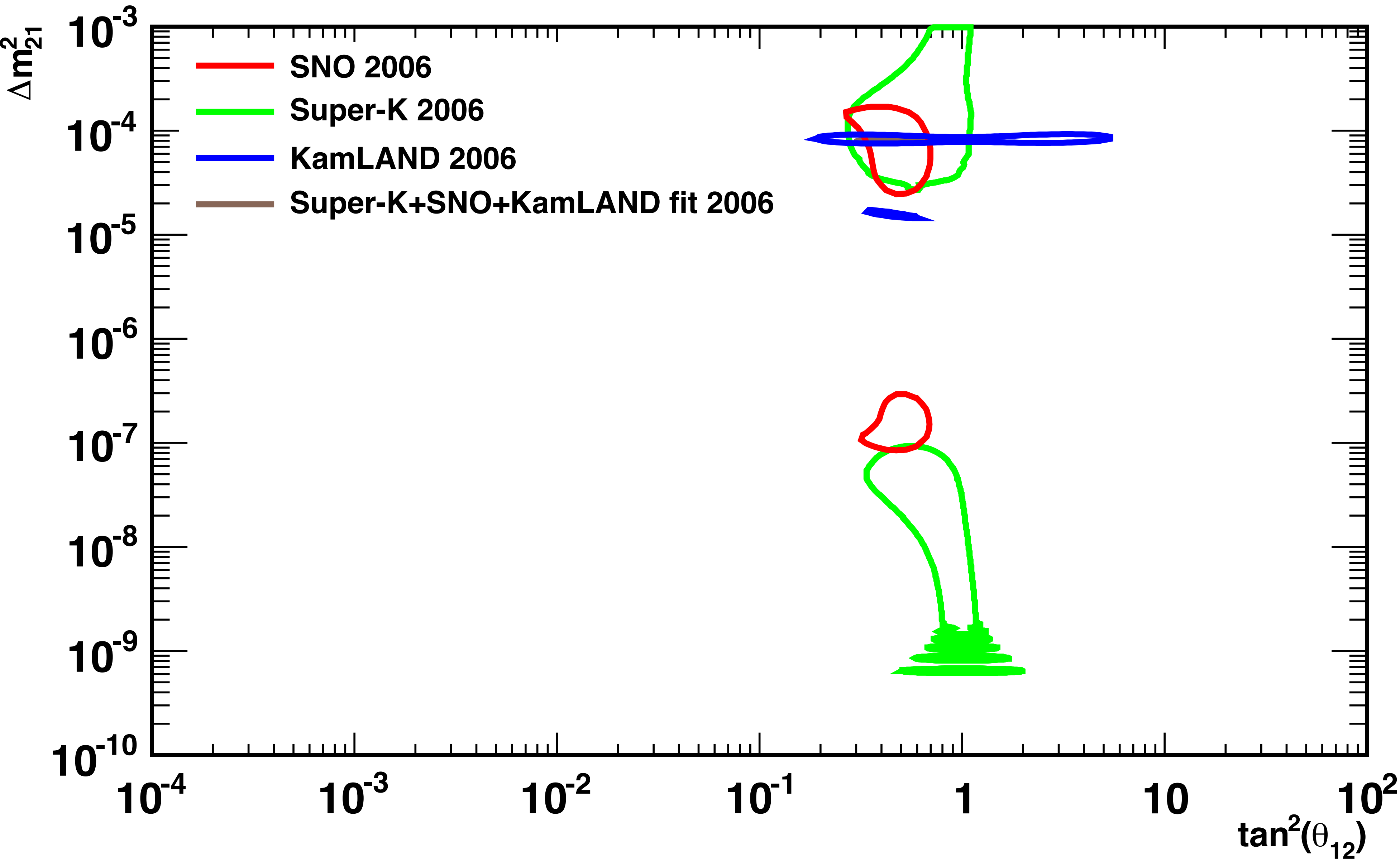
...and wavelength measured precisely w/ reactor $\bar{\nu}_e$ by KamLAND





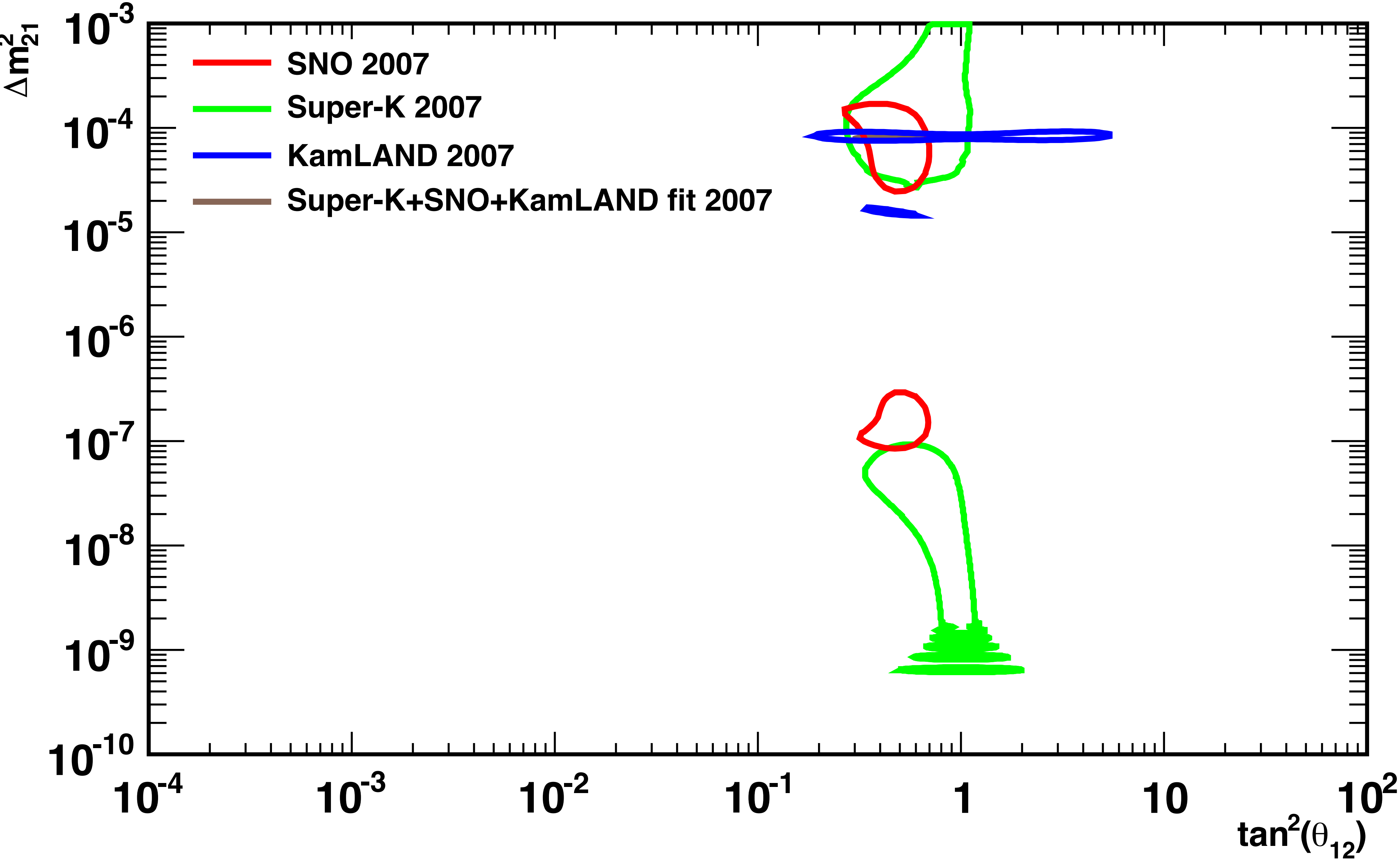
A “movie” over 8 years of solar (12) parameter space

plots made by H. Lim from
H. Murayama’s PDG web page



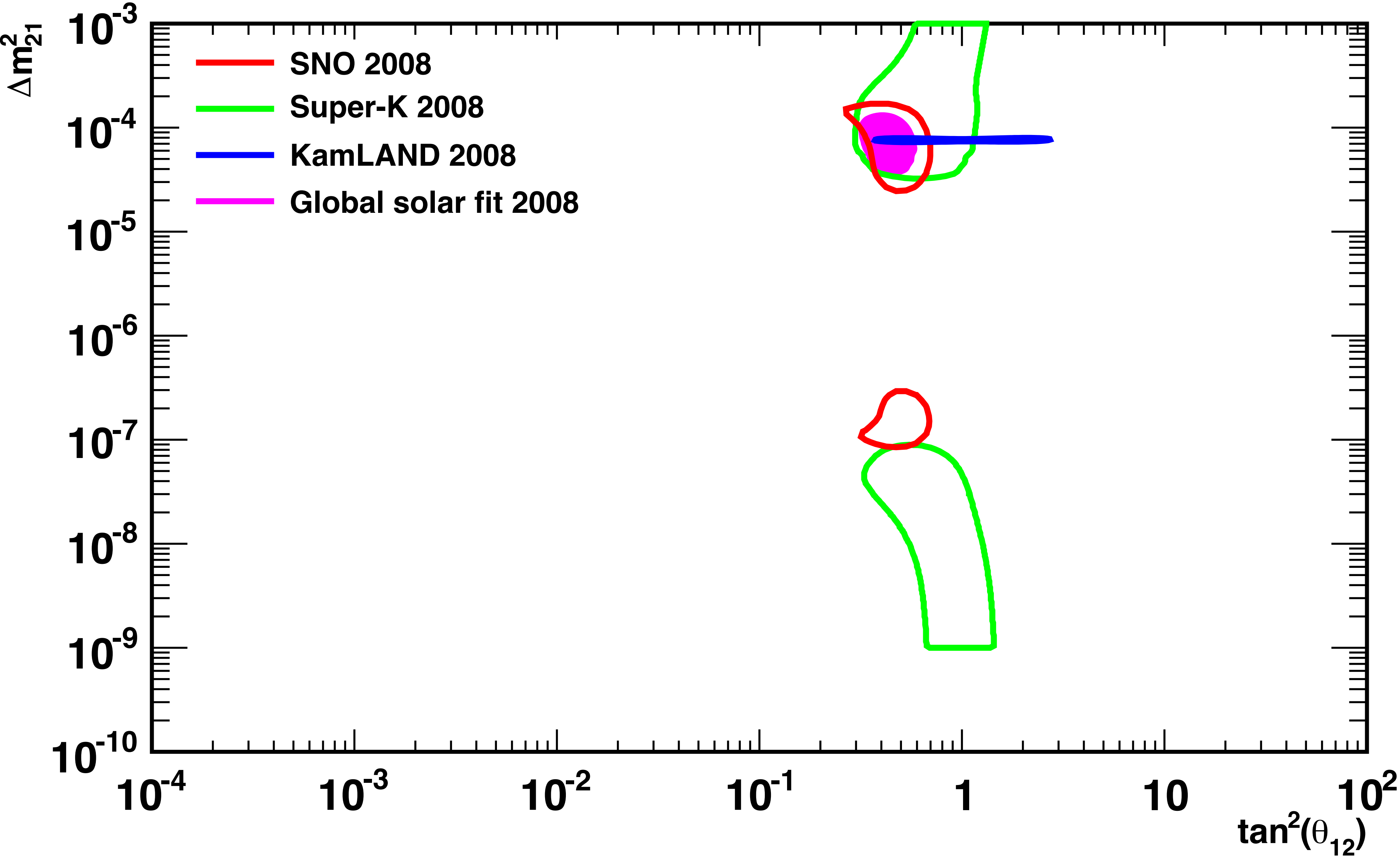
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO 2006
Super-K 2006
KamLAND 2006
Super-K+SNO+KamLAND fit 2006
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2006



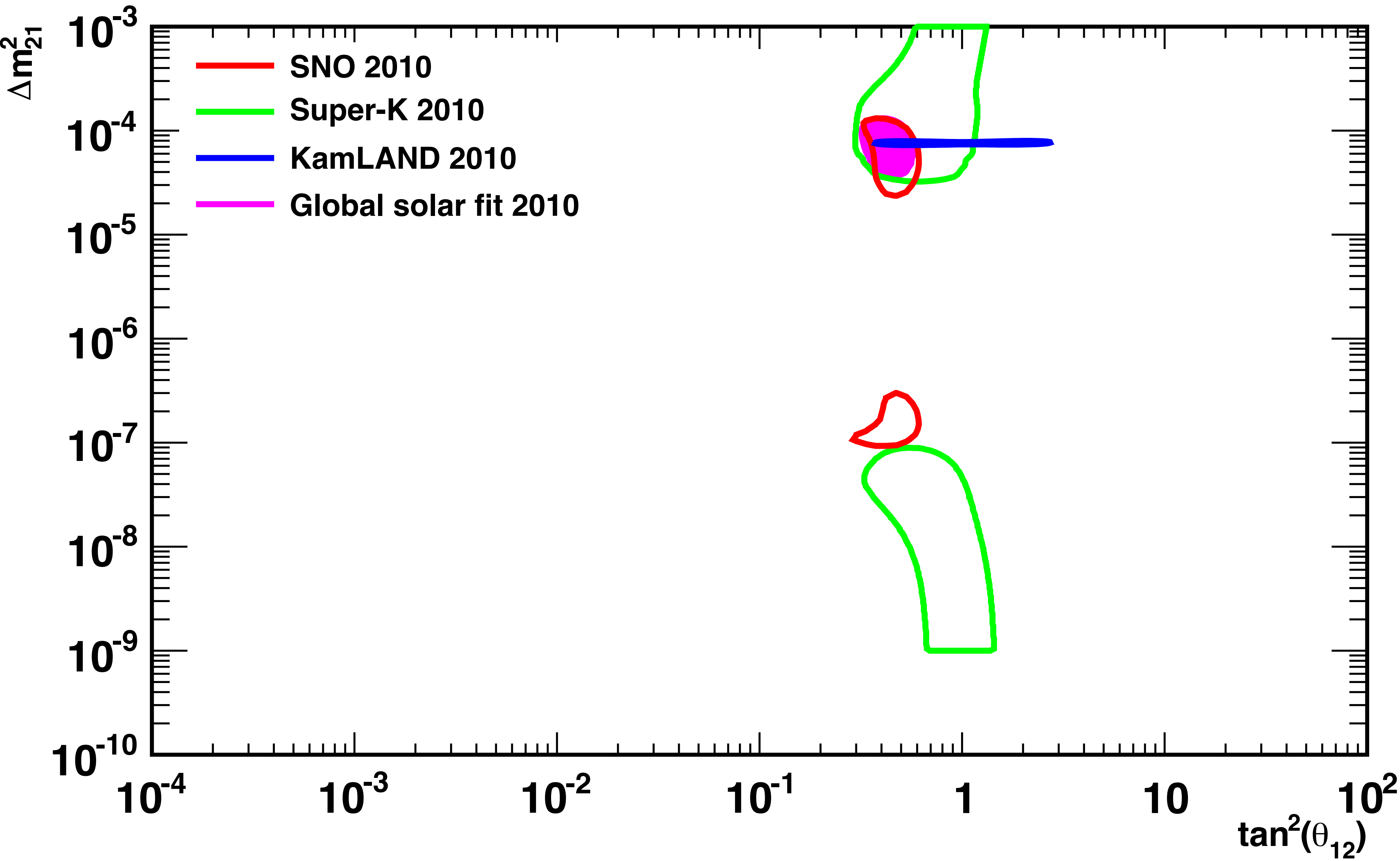
SNO 2007
Super-K 2007
KamLAND 2007
Super-K+SNO+KamLAND fit 2007
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2007



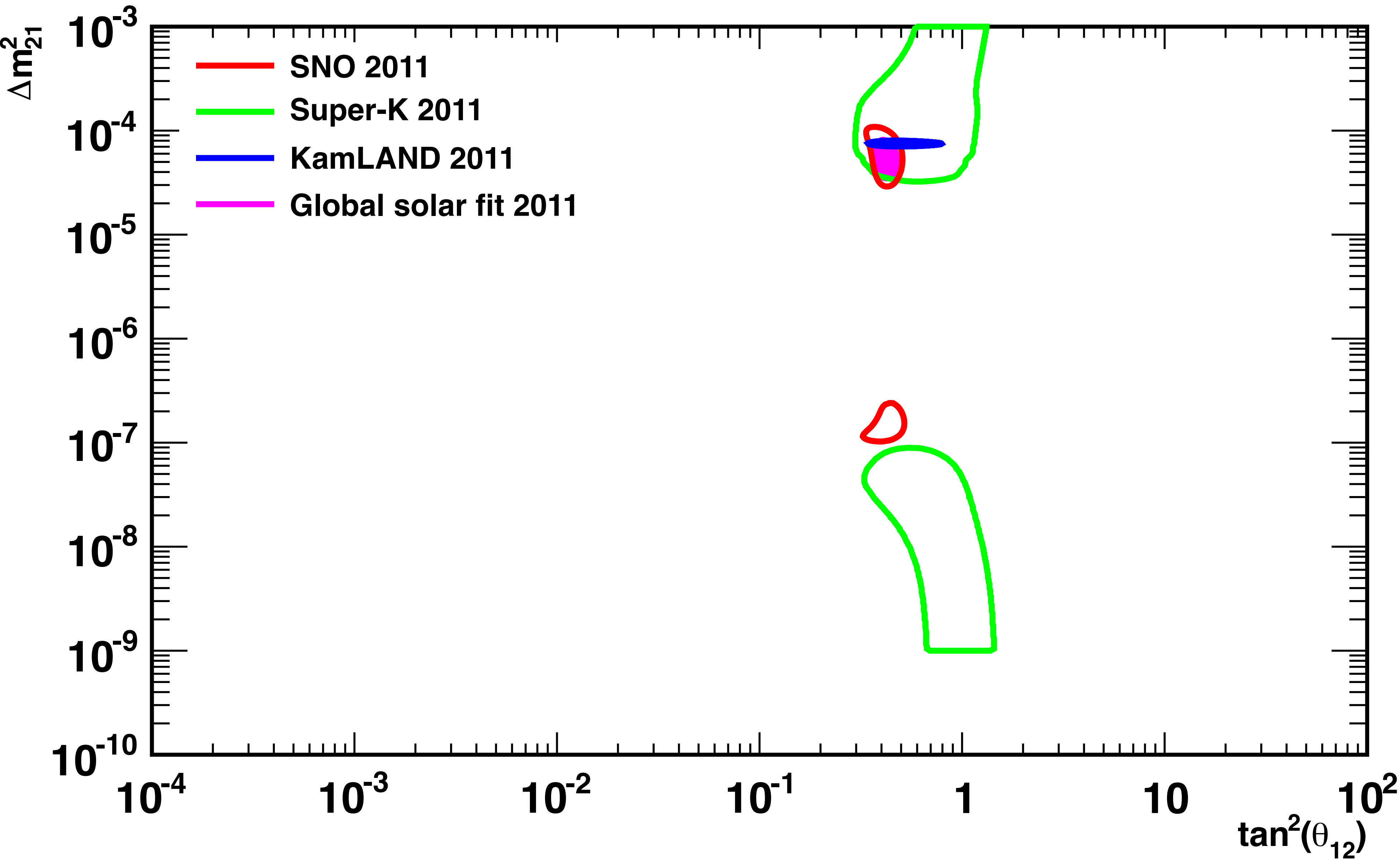
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
SNO 2008
Super-K 2008
KamLAND 2008
Global solar fit 2008
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2008

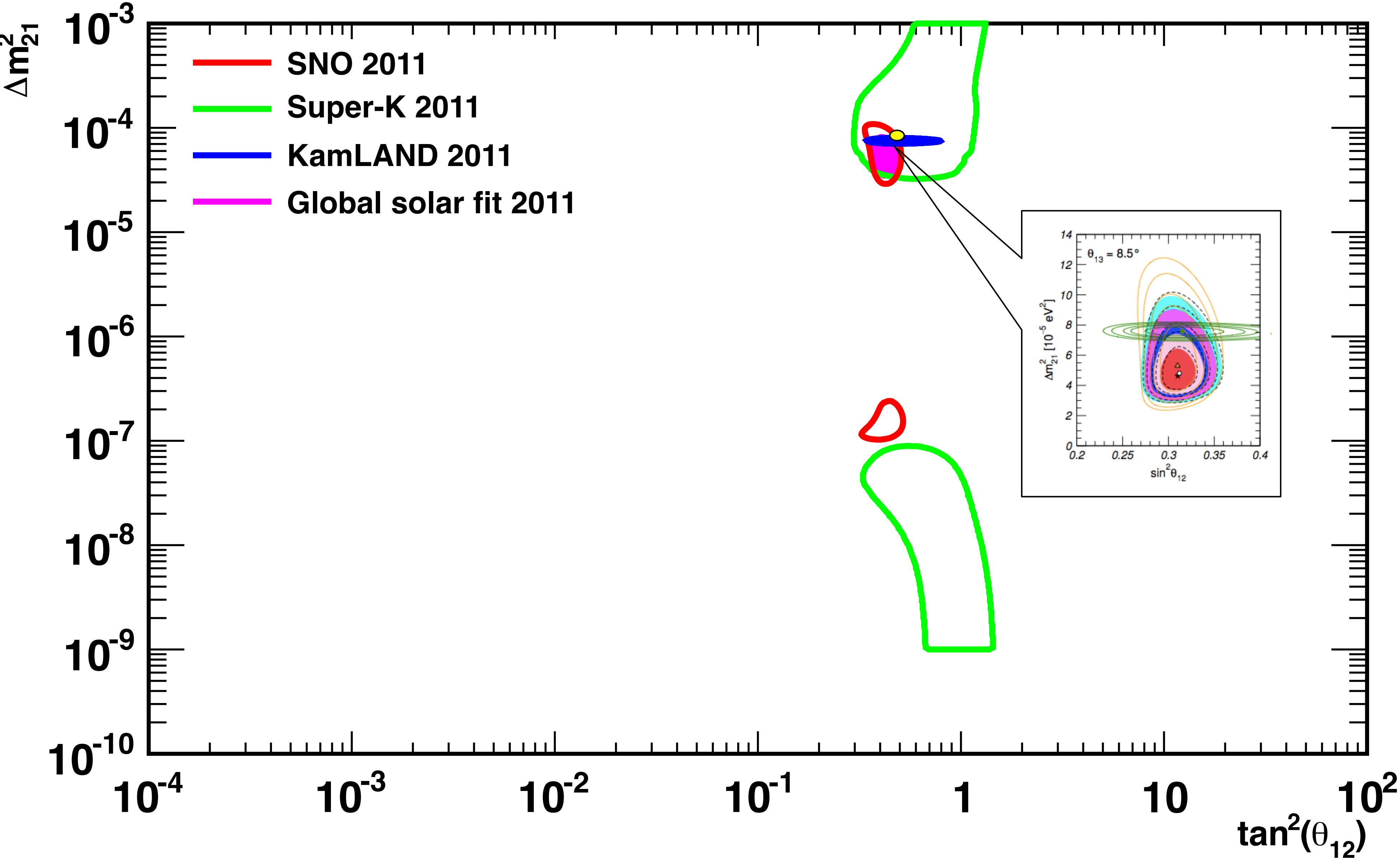


SNO 2010
Super-K 2010
KamLAND 2010
Global solar fit 2010
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2010

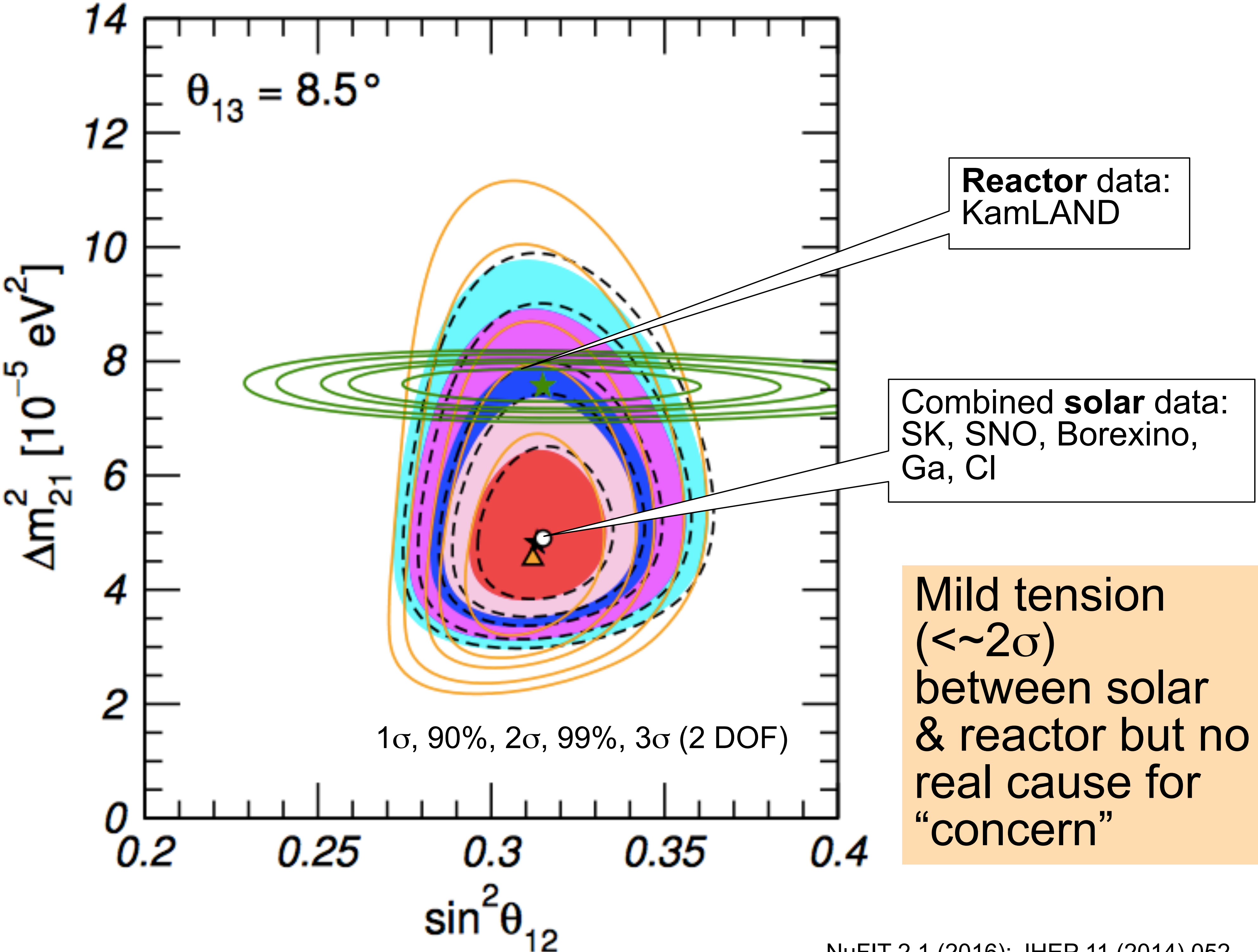

SNO 2011
Super-K 2011
KamLAND 2011
Global solar fit 2011
Δm^2_{21}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
$\tan^2(\theta_{12})$

2011



2011

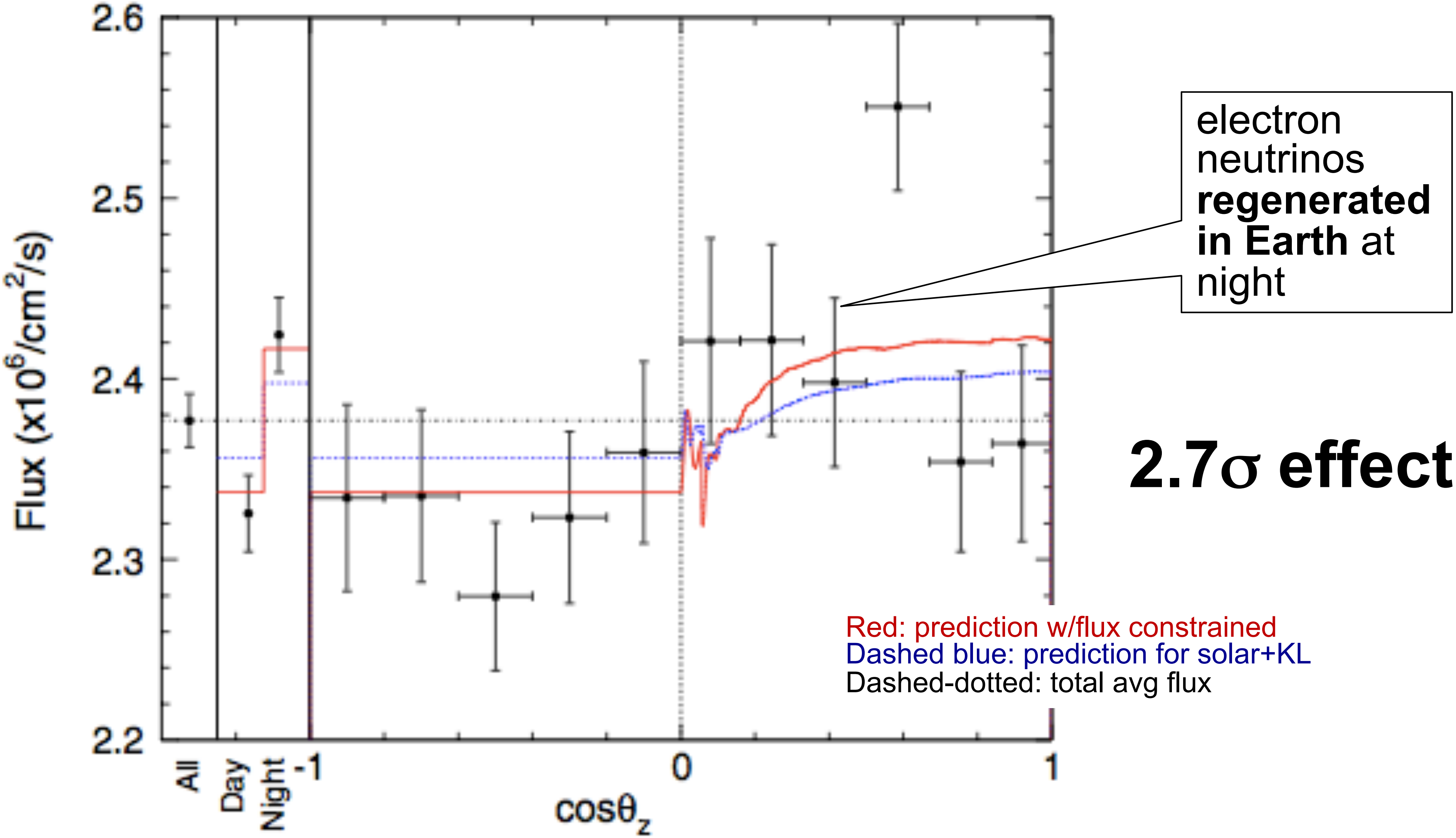
Recent global fit (solar & KL) from Gonzalez-Garcia et al., JHEP 11(2014) 052



Mild tension (<~2σ) between solar & reactor but no real cause for "concern"

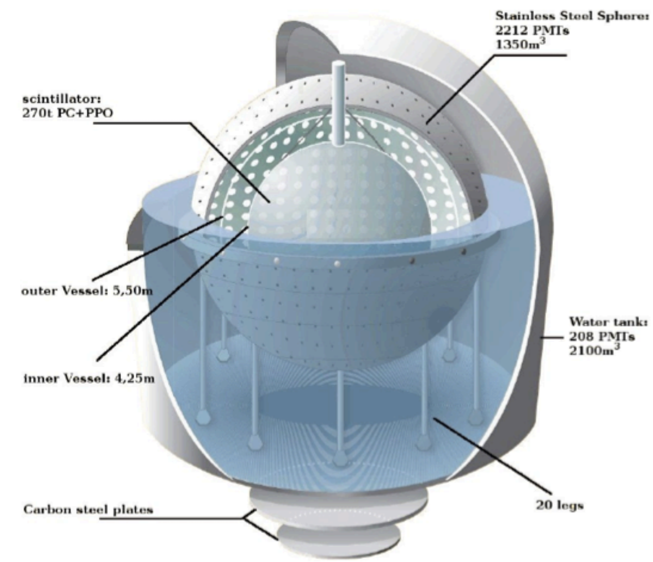
NuFIT 2.1 (2016); JHEP 11 (2014) 052

From Super-K: **day/night asymmetry observed; first direct observation of matter effects**

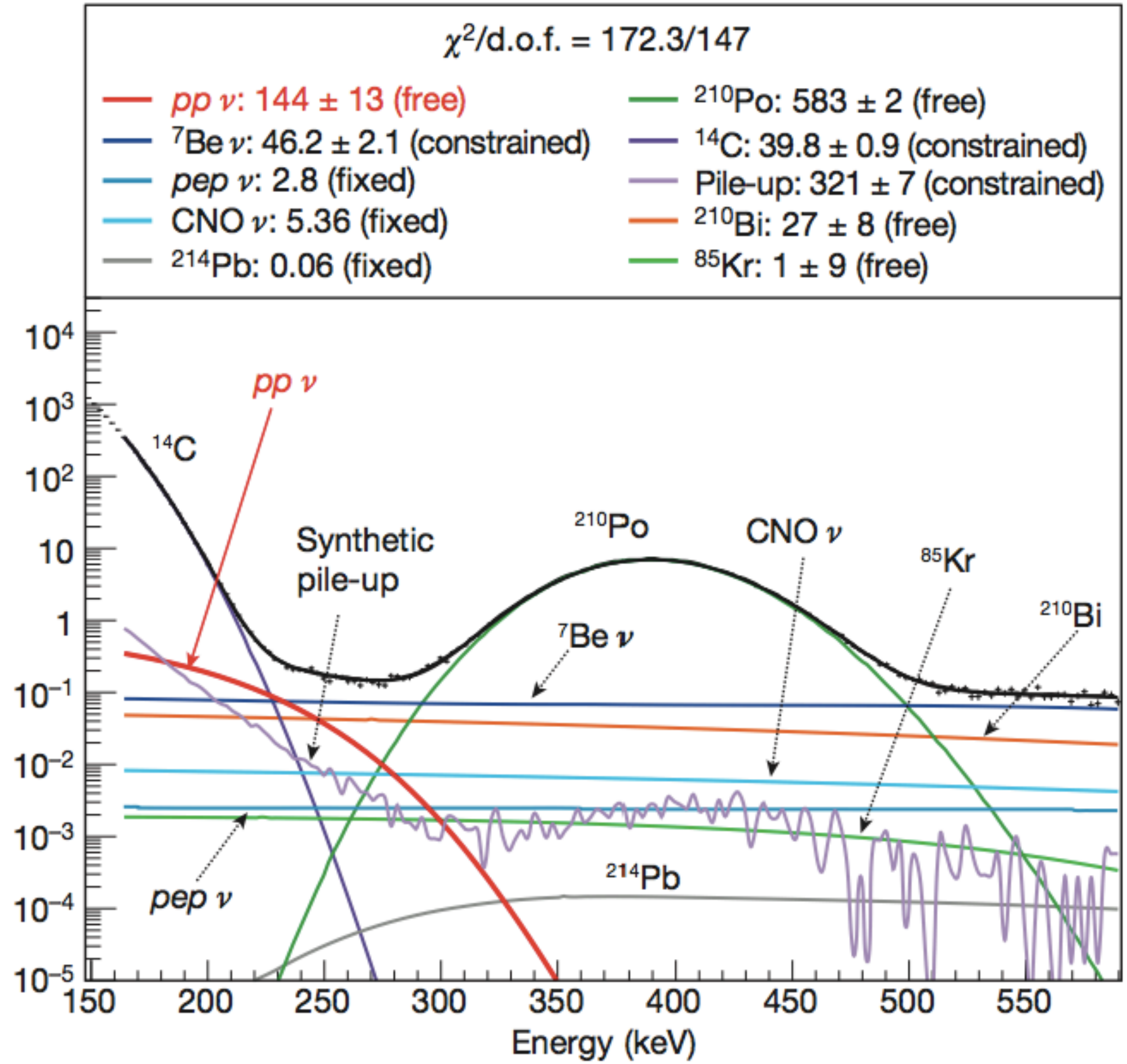


2.7σ effect

First real-time measurement of the **solar pp flux** by Borexino... a heroic victory over background



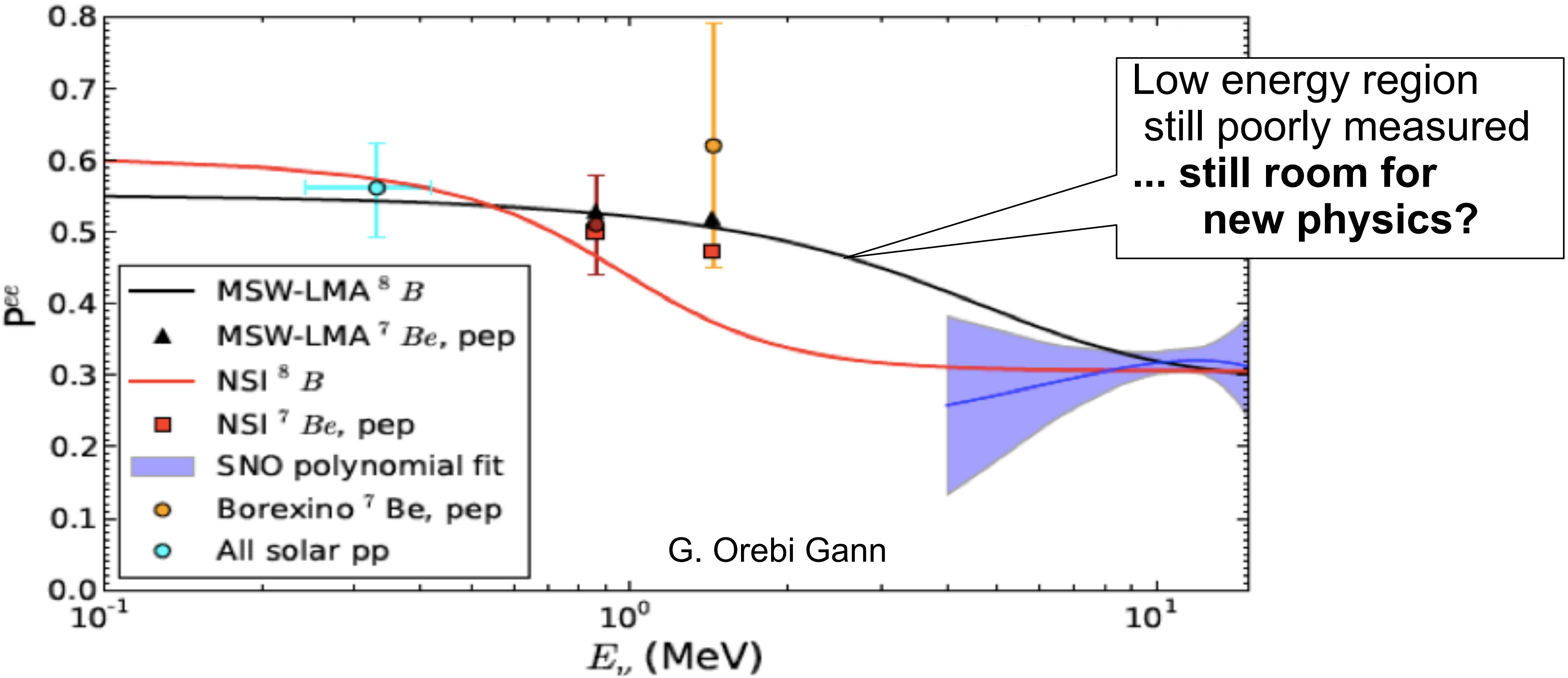
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$



Nature 512 (2014) 385

What's next for solar neutrinos?

We now have the basic picture, but there are are still gaps & discrepancies...



...and still some solar physics puzzles ➔ neutrino info can help

Future detectors: SNO+, Hyper-K, JUNO, DUNE (Theia...)

What I will cover

Knowns and unknowns in neutrino physics

Neutrino Oscillations

"Solar" sector
"Atmospheric" sector
The twist in the middle
Remaining unknowns in the 3-flavor picture: MO and CP δ
Beyond 3-flavor?
(+xscns)

The mass pattern and mixing matrix

Yesterday

The 3-flavor picture

Accelerator experiments

Absolute Mass

βdk endpoint, cosmology

The mass scale

Today

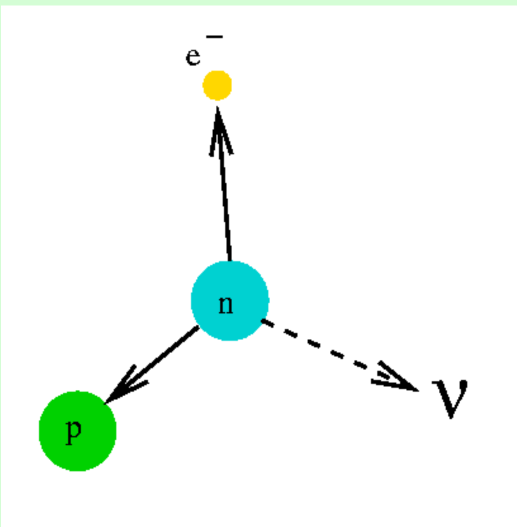
Non-accelerator experiments

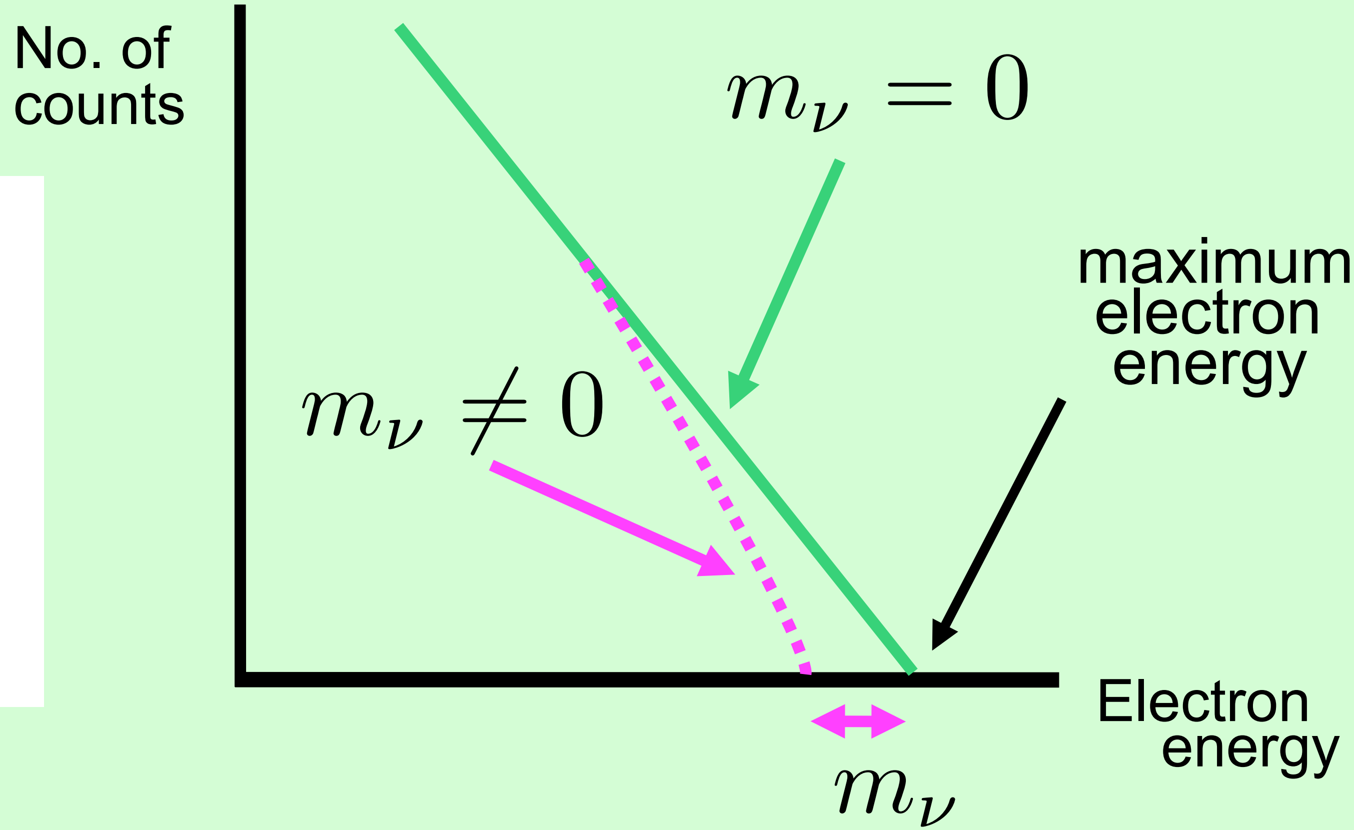
Majorana vs Dirac?

Neutrinoless $\beta\beta$dk

The mass nature

Kinematic experiments for absolute neutrino mass





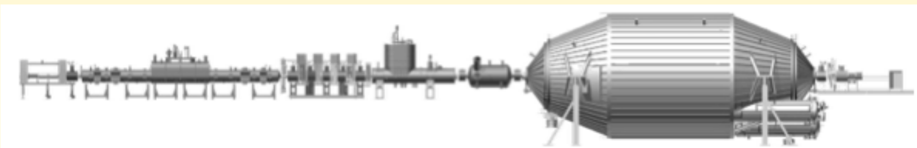
Look for distortion of β-decay spectrum near endpoint

Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

$^{3}\text{H} \rightarrow ^{3}\text{He} + e^{-} + \bar{\nu}_{e}$

18.6 keV endpoint

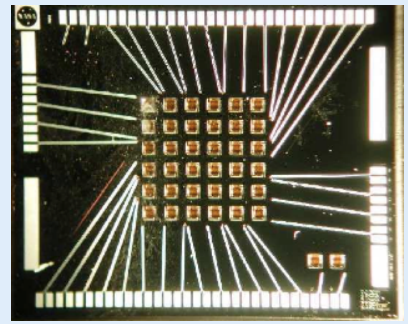


Sensitivity to ~0.2 eV
Data in 2018

turning on soon

Thermal calorimetry

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



$^{187}\text{Re} \rightarrow ^{187}\text{Os} + e^{-} + \bar{\nu}_{e}$

2.5 keV endpoint

Hard to scale up...

R&D...

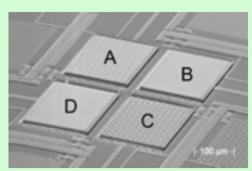
Holmium

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

$$^{163}_{67}\text{Ho} \rightarrow ^{163}_{66}\text{Dy}^{*} + \nu_{e}$$

$$^{163}_{66}\text{Dy}^{*} \rightarrow ^{163}_{66}\text{Dy} + E_{C}$$

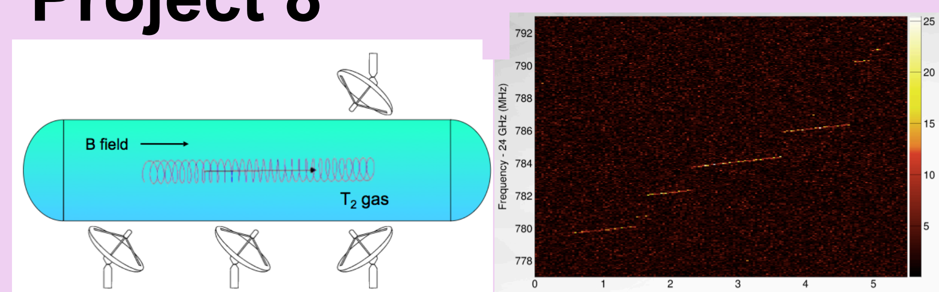
metallic magnetic calorimeters



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

R&D

Cyclotron radiation tritium spectrometer: Project 8



First single electrons seen

R&D

What I will cover

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"Solar" sector

"Atmospheric" sector

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Absolute Mass

βdk endpoint, cosmology

The mass scale

Majorana vs Dirac?

Neutrinoless $\beta\beta$dk

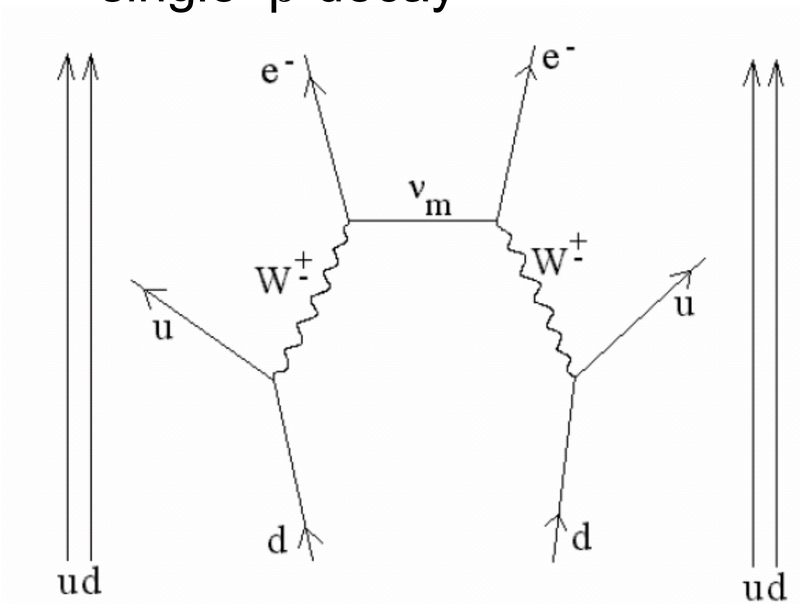
The mass nature

Today

Non-accelerator experiments

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

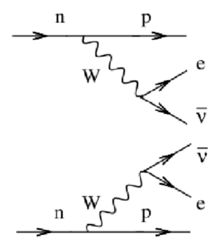


Only possible for Majorana ν
(...or exotic physics)

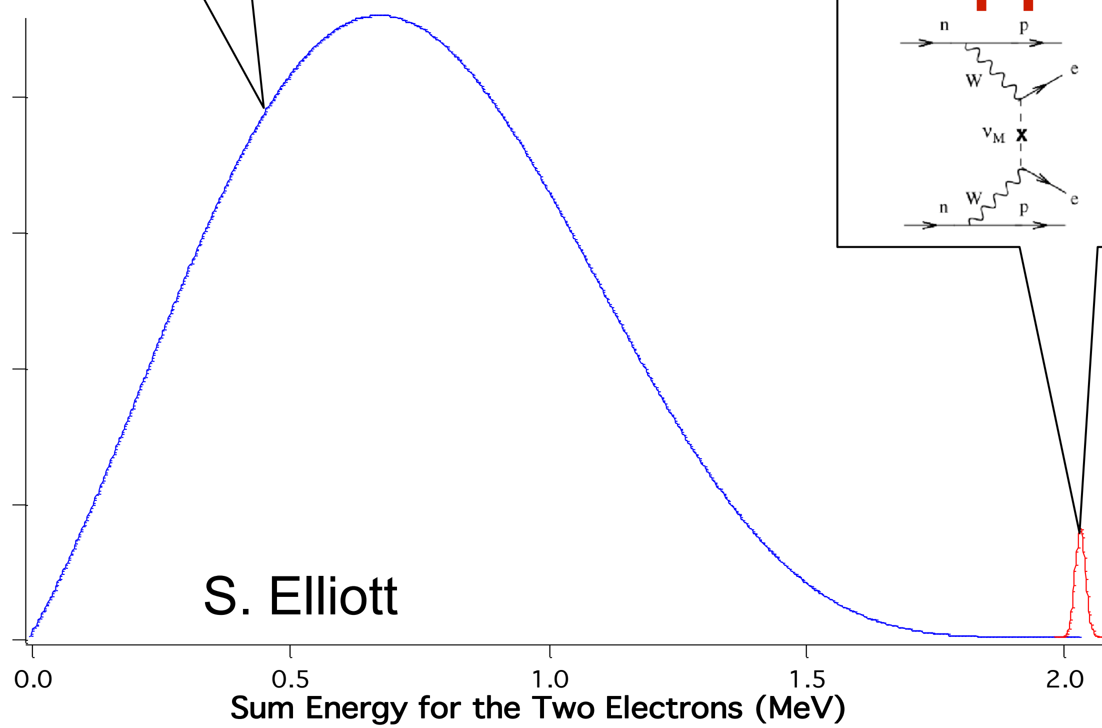
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

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

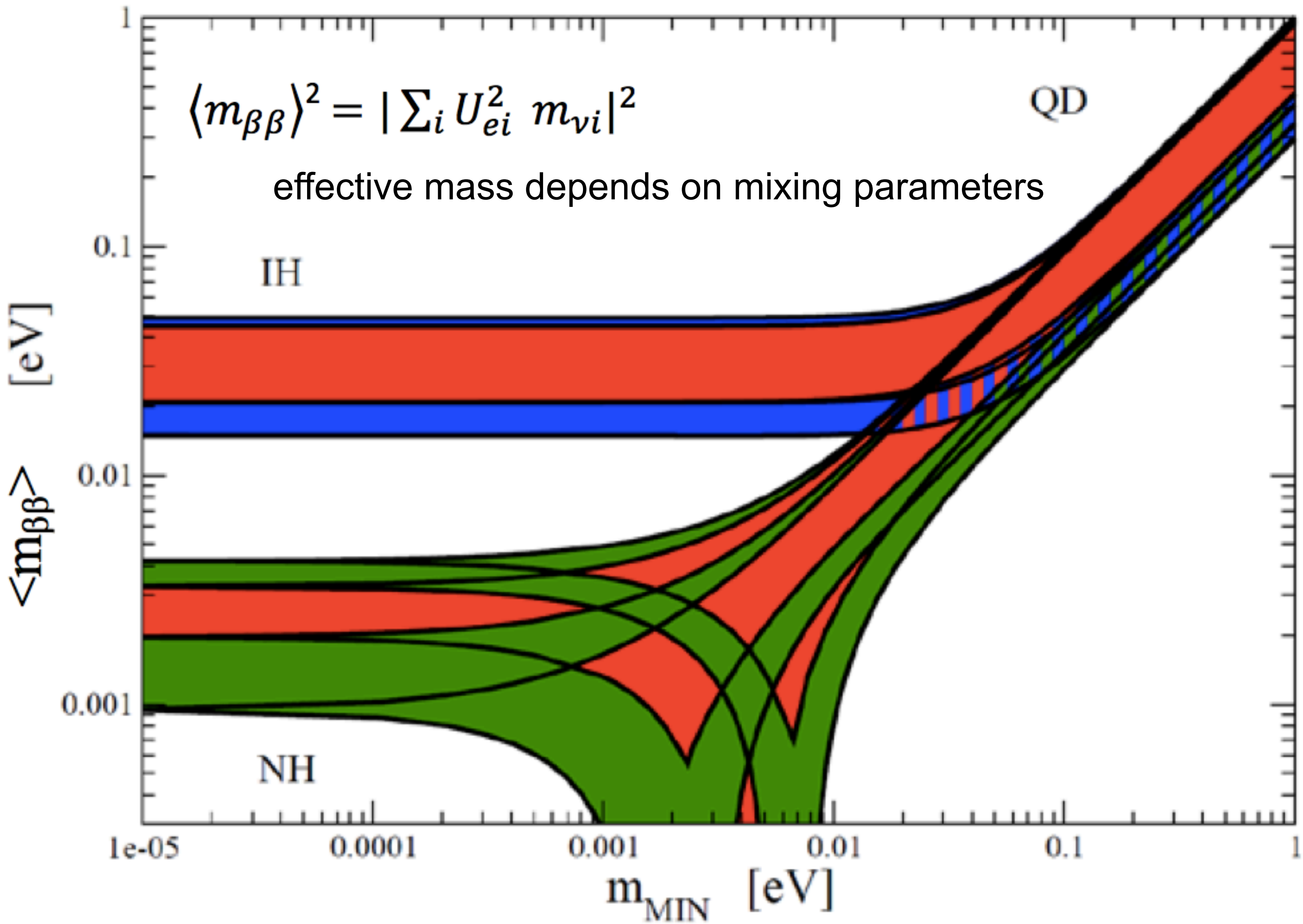
2νββ
(SM 2nd order weak process)



0νββ



The NLDBD T-Shirt Plot

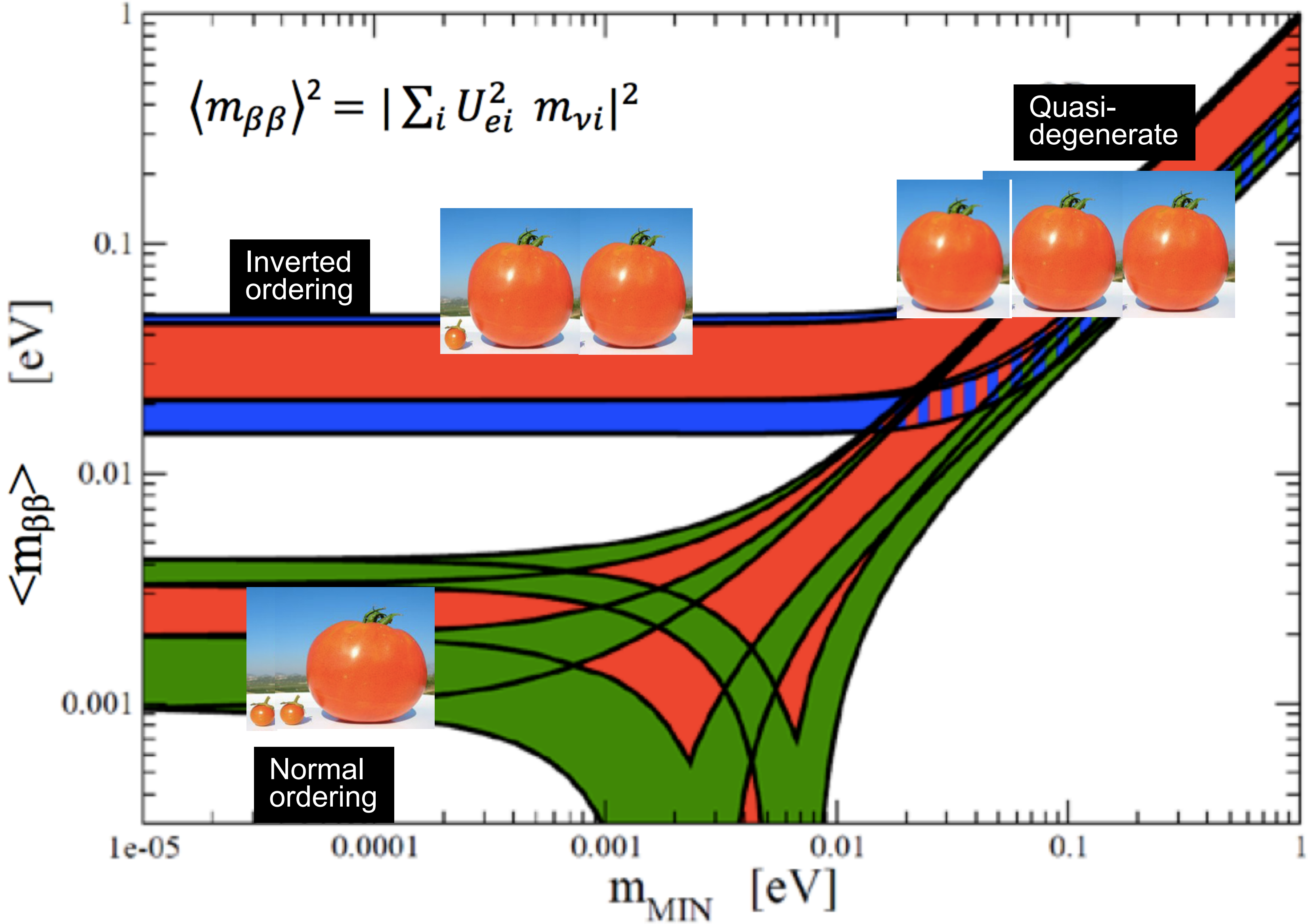


If **neutrinos are Majorana*, experimental results must fall in the shaded regions**

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

*and standard 3-flavor picture

The NLDBD T-Shirt Plot



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

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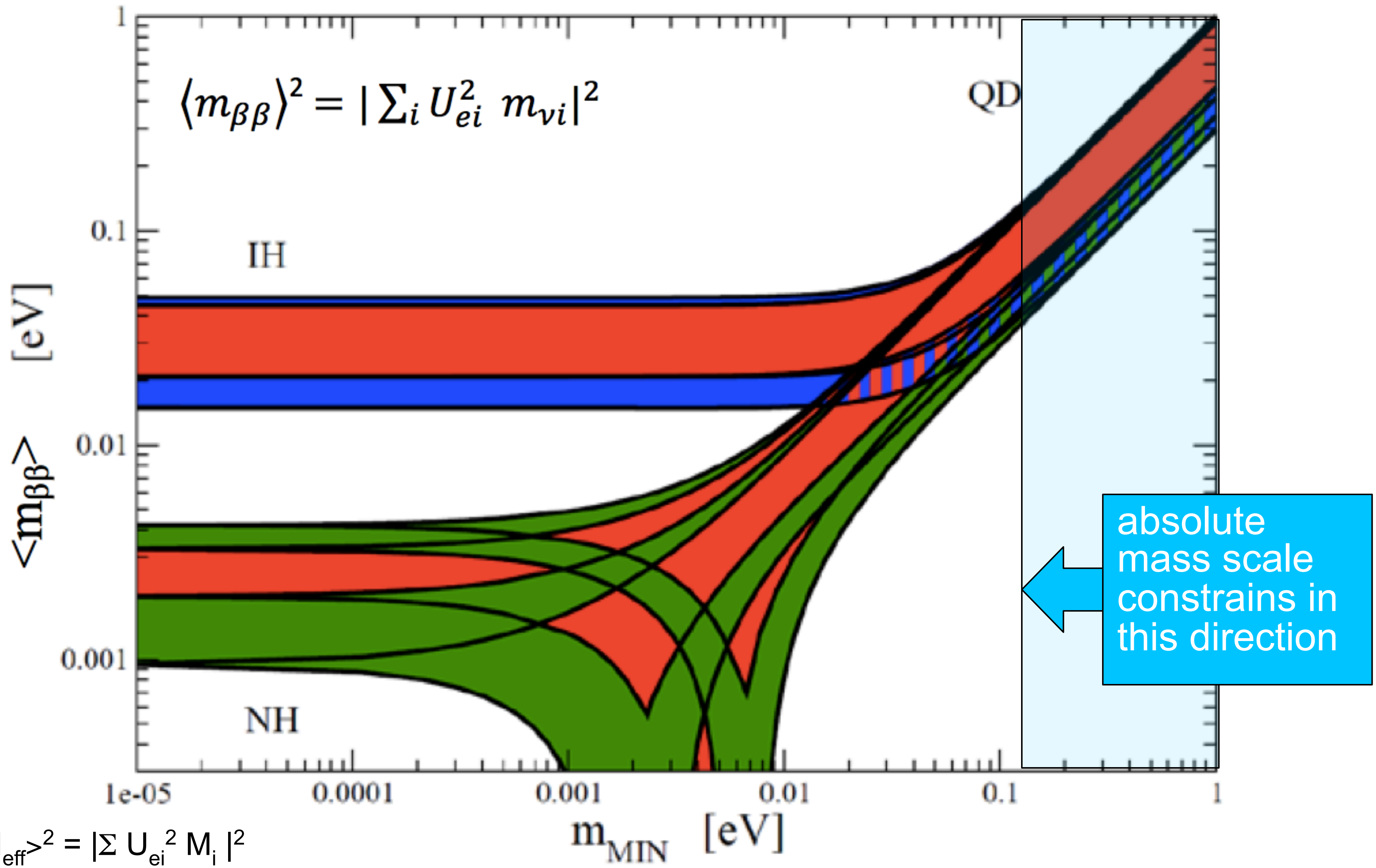
The NLDBD T-Shirt Plot



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

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

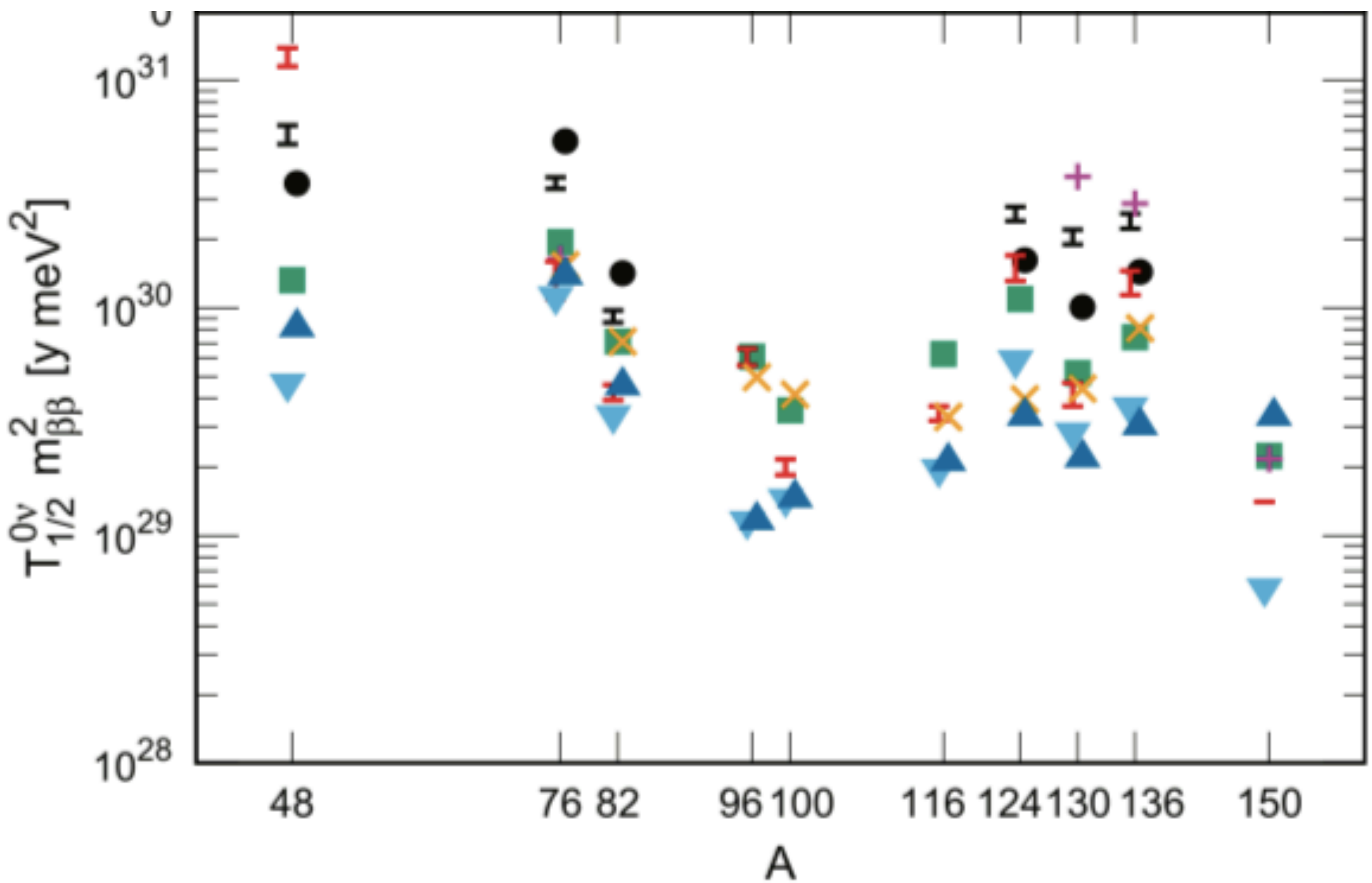
Extent of the regions determined by uncertainties on Majorana phases and mixing matrix elements

Nuclear matrix elements

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

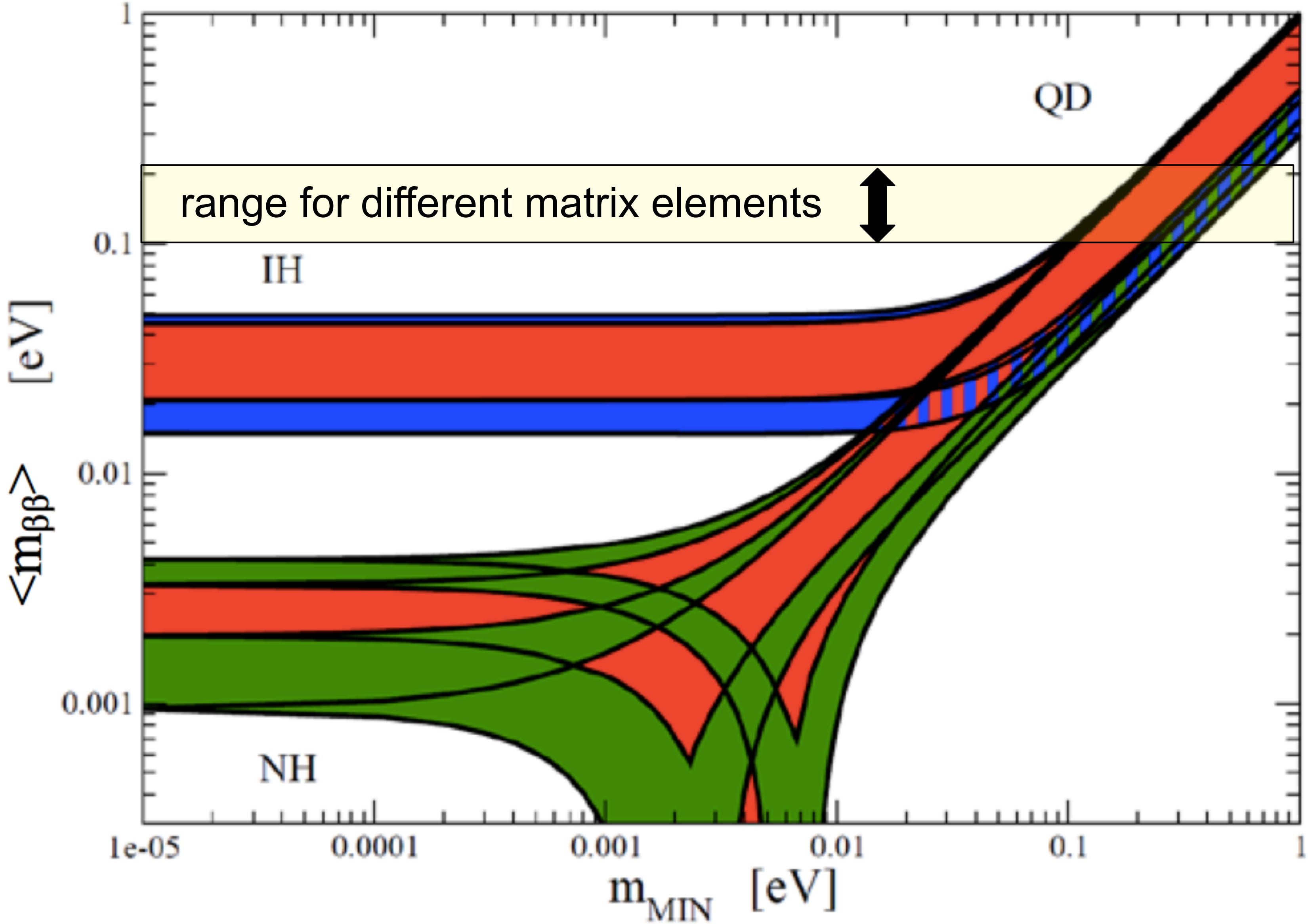
Neutrinoless double beta decay half-lives, assuming <M_{eff}> at bottom of IH region, for different matrix element calculations

Jonathan Engel and Javier Menéndez 2017 *Rep. Prog. Phys.* **80** 046301



Calculations vary by ~order of magnitude ➔ more theory underway!

(and a measurement may need confirmation w/more than one isotope)



An experimental measurement of half-life limit corresponds to a band, incorporating uncertainties on matrix element

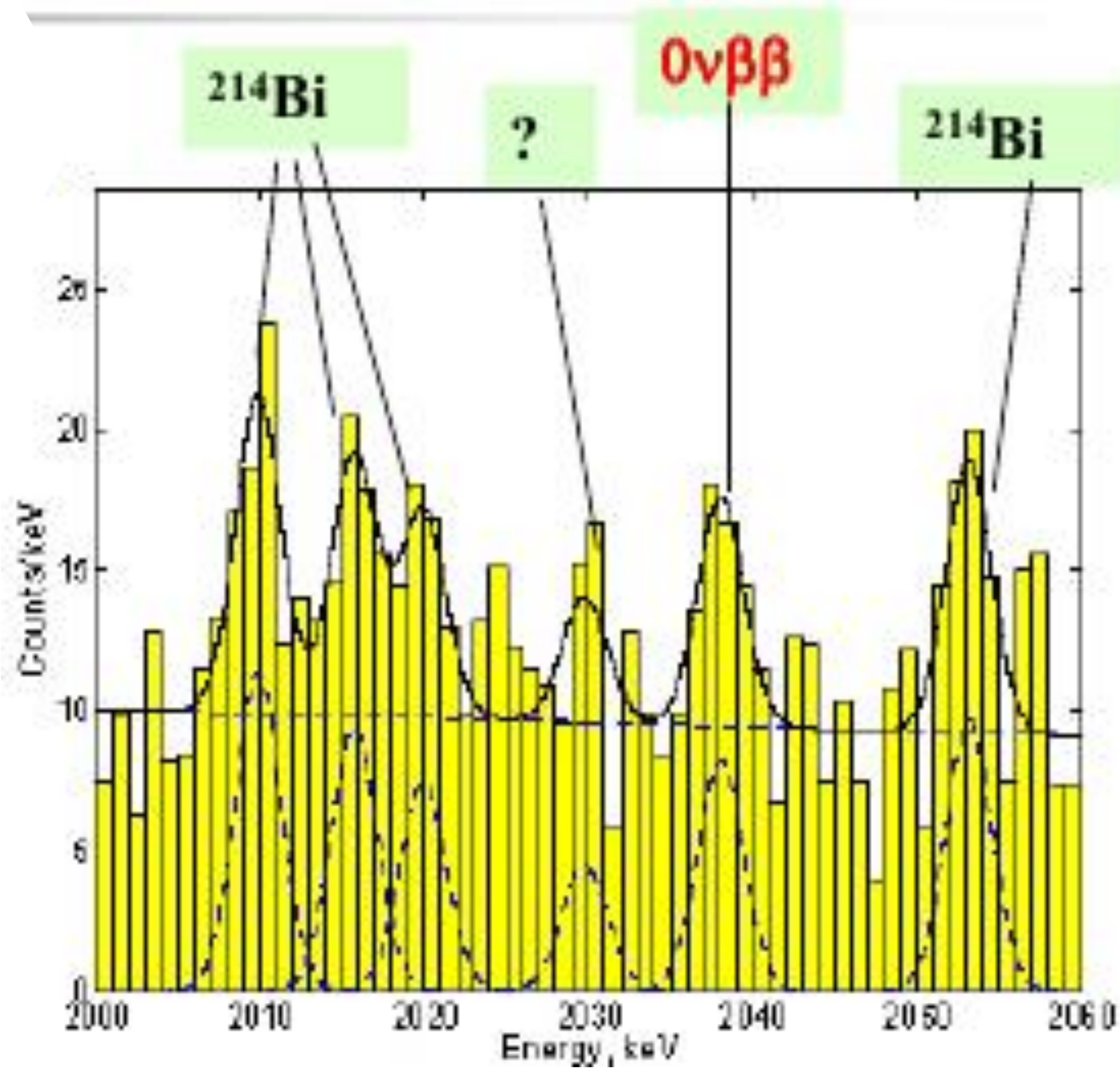
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

A controversial claim:

Heidelberg-Moscow experiment

Klapdor-Kleingrothaus et al.

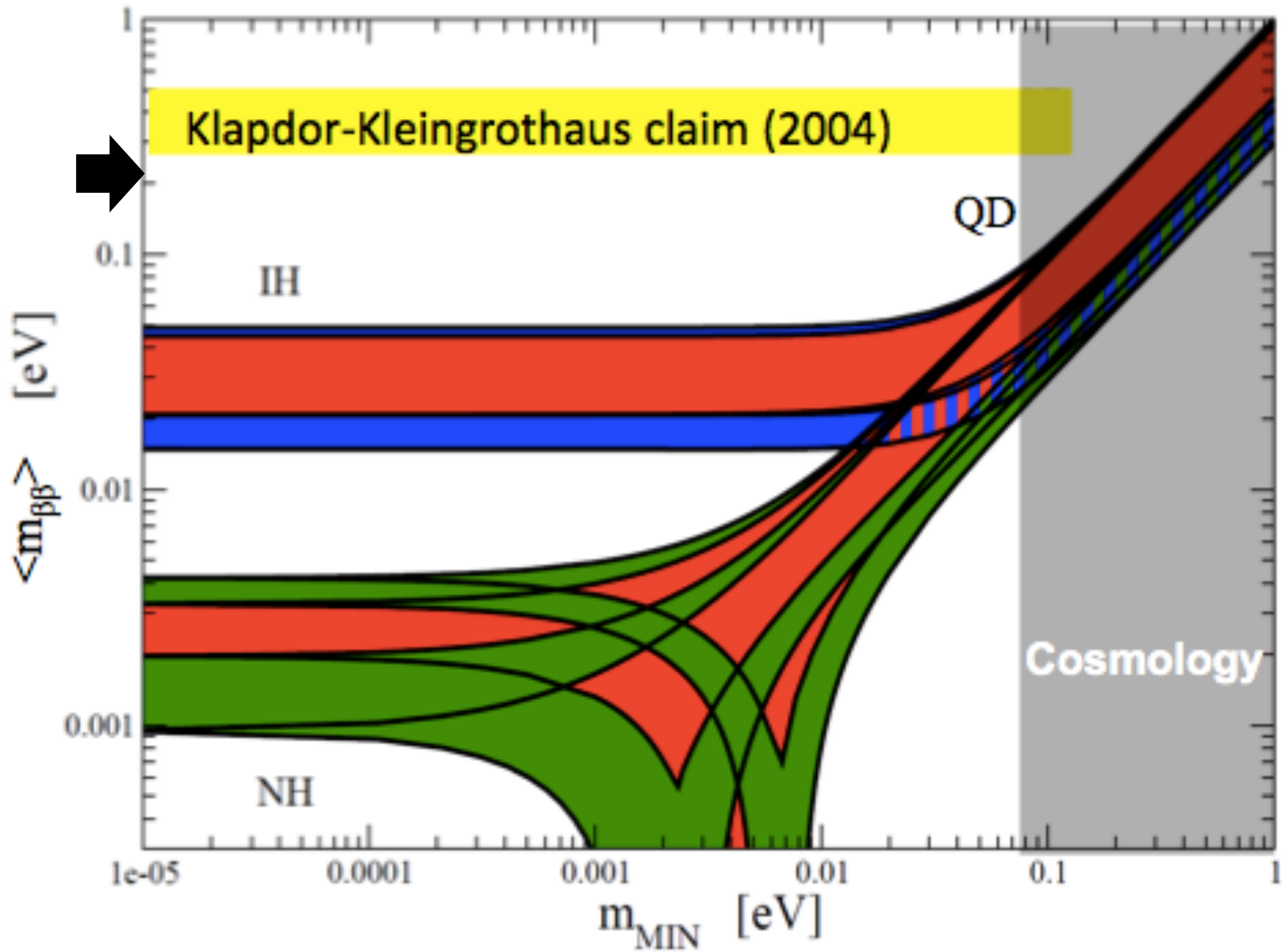
NIM A522, 371 (2004)



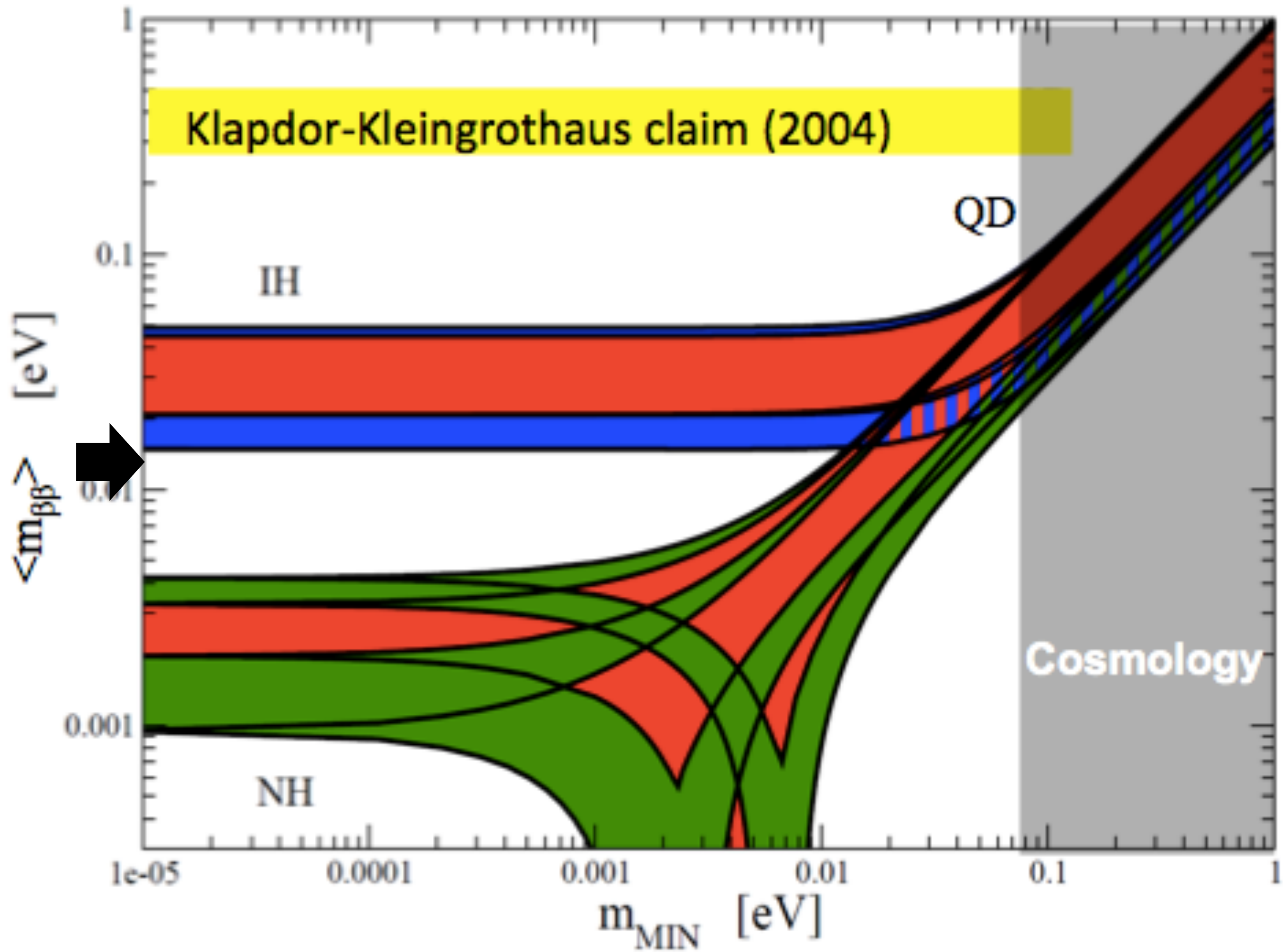
Ge crystal, 70 kg-years

Claim <m_{eff}> = 440 meV

Over the last ~decade the NLDBD experimental goal has been to attain sensitivity better than this claim...

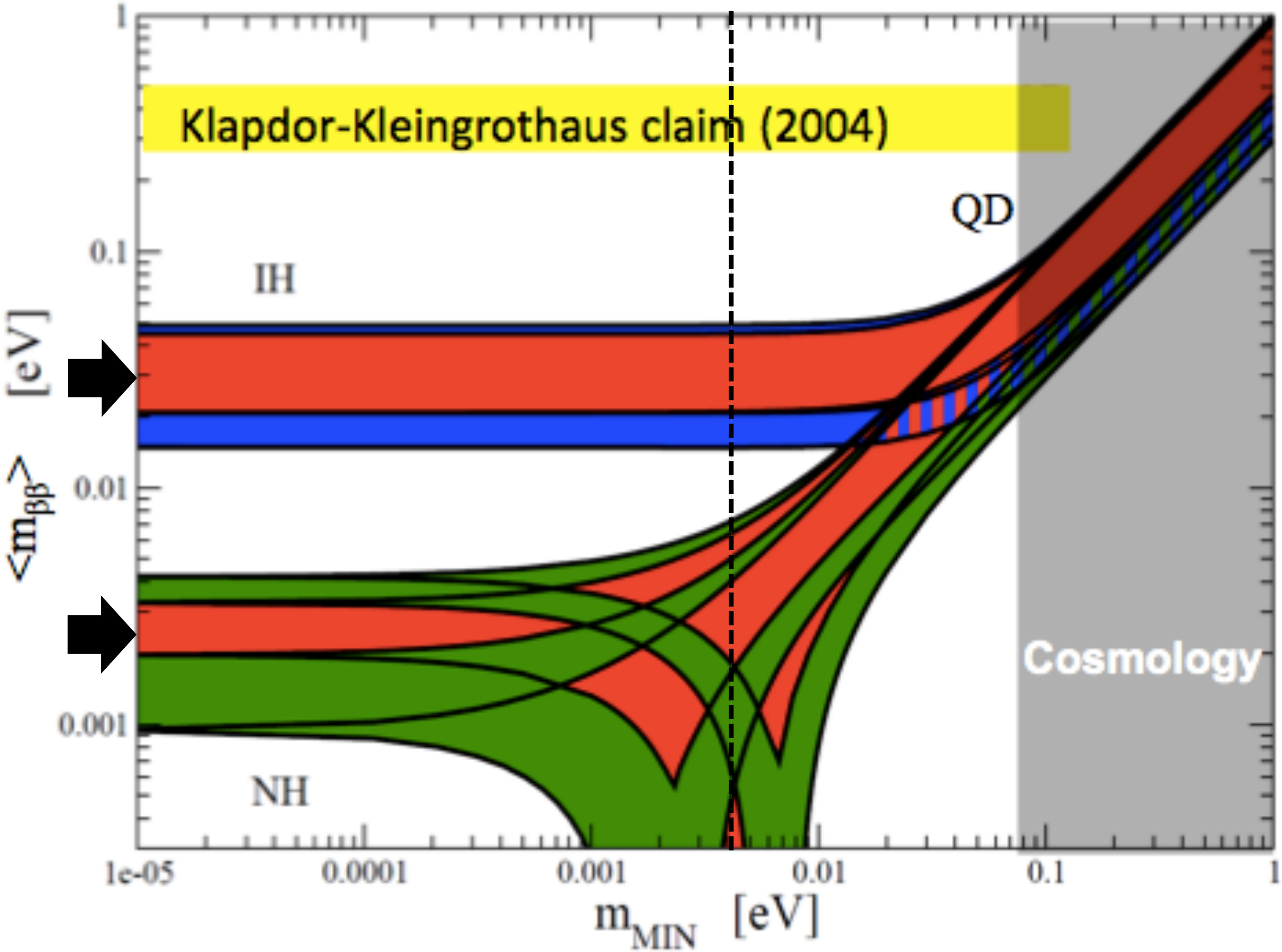


New goal, however, is to get below the inverted hierarchy region

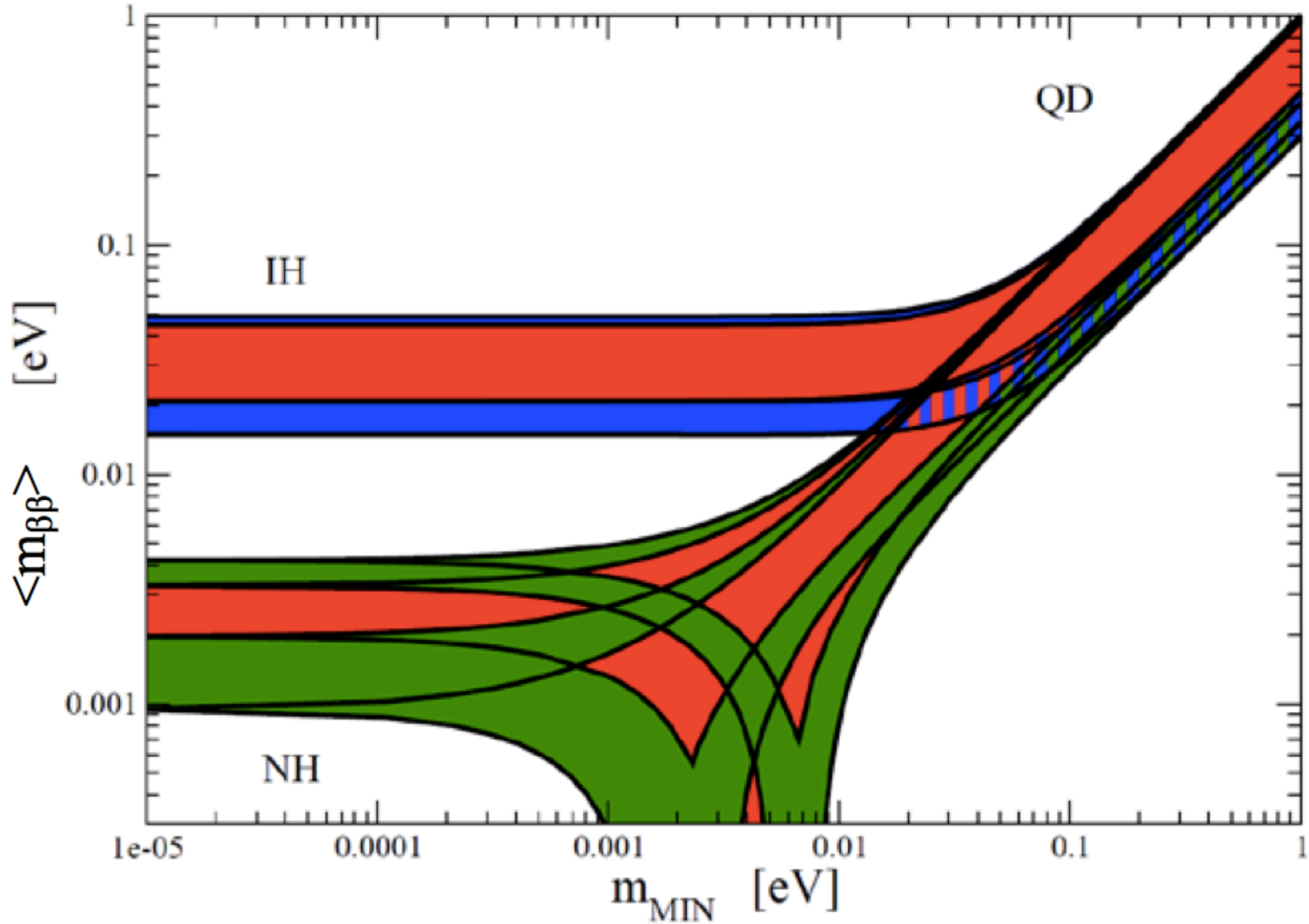


Comments:

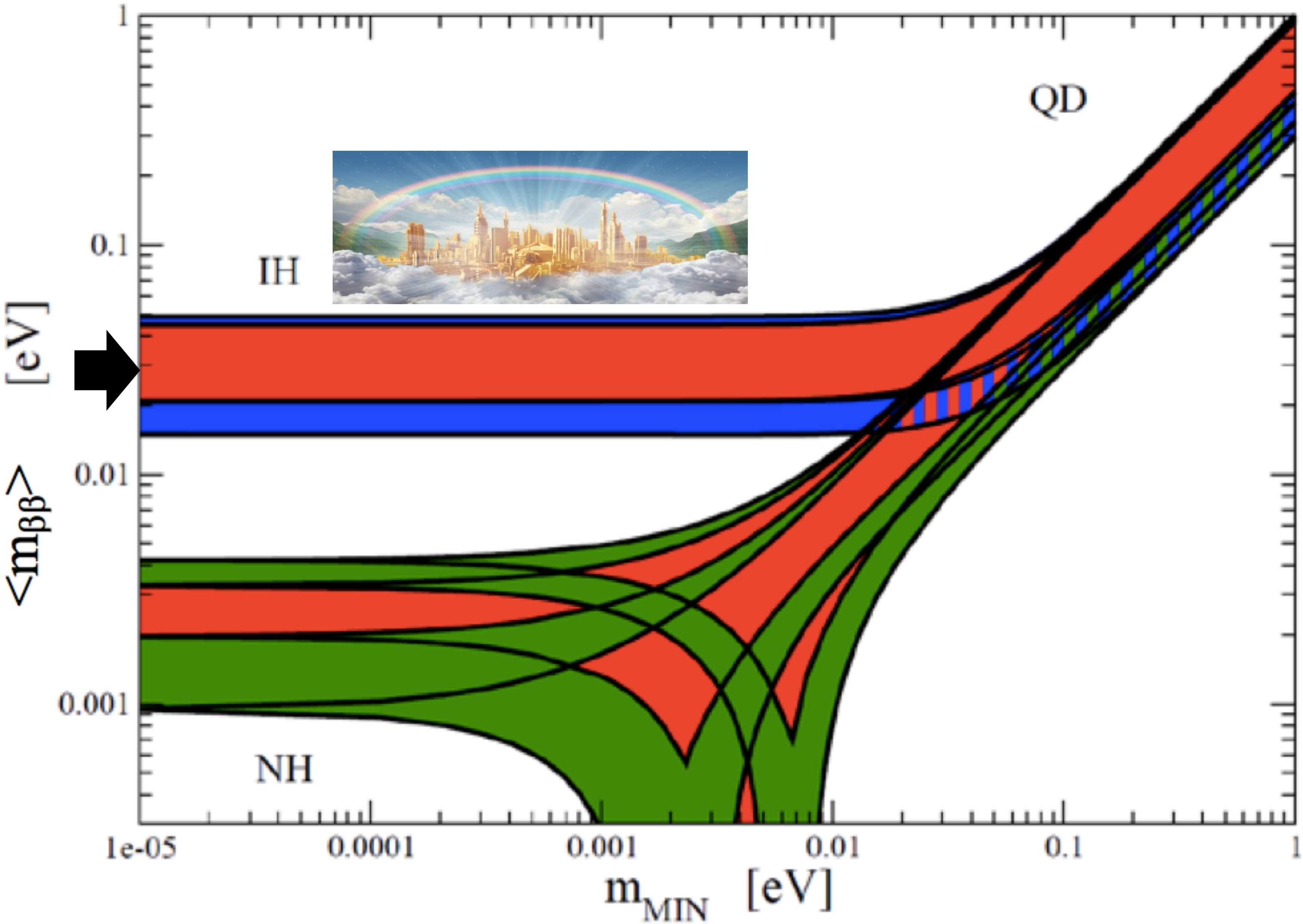
if you measure a NLDBD signal, in either IH or NH region, and direct mass limit is sufficiently low (not likely in near future!) then *in principle* you determine the hierarchy....



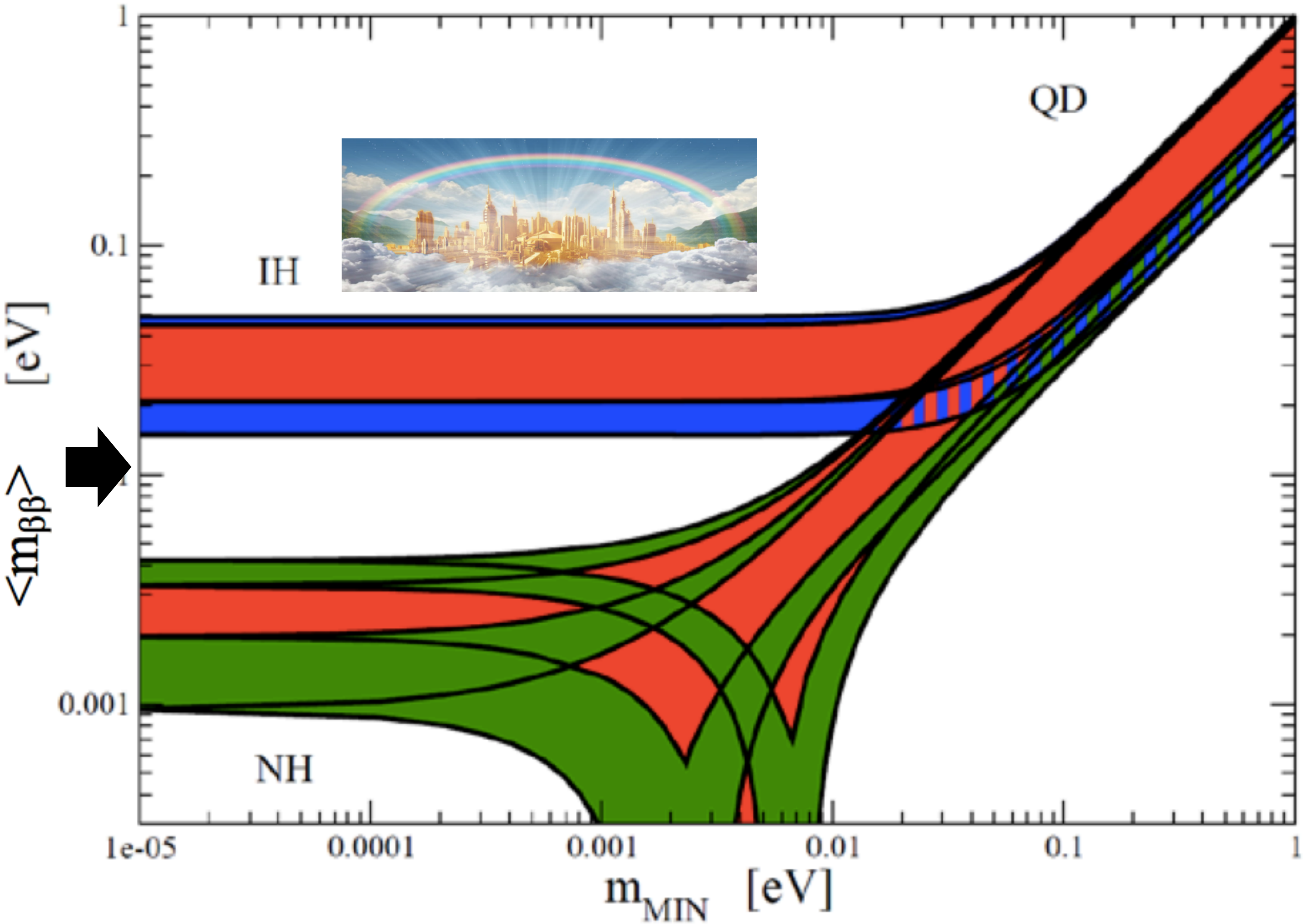
... but much more likely is that the the hierarchy is determined *first* by long-baseline (or other) experiments ...



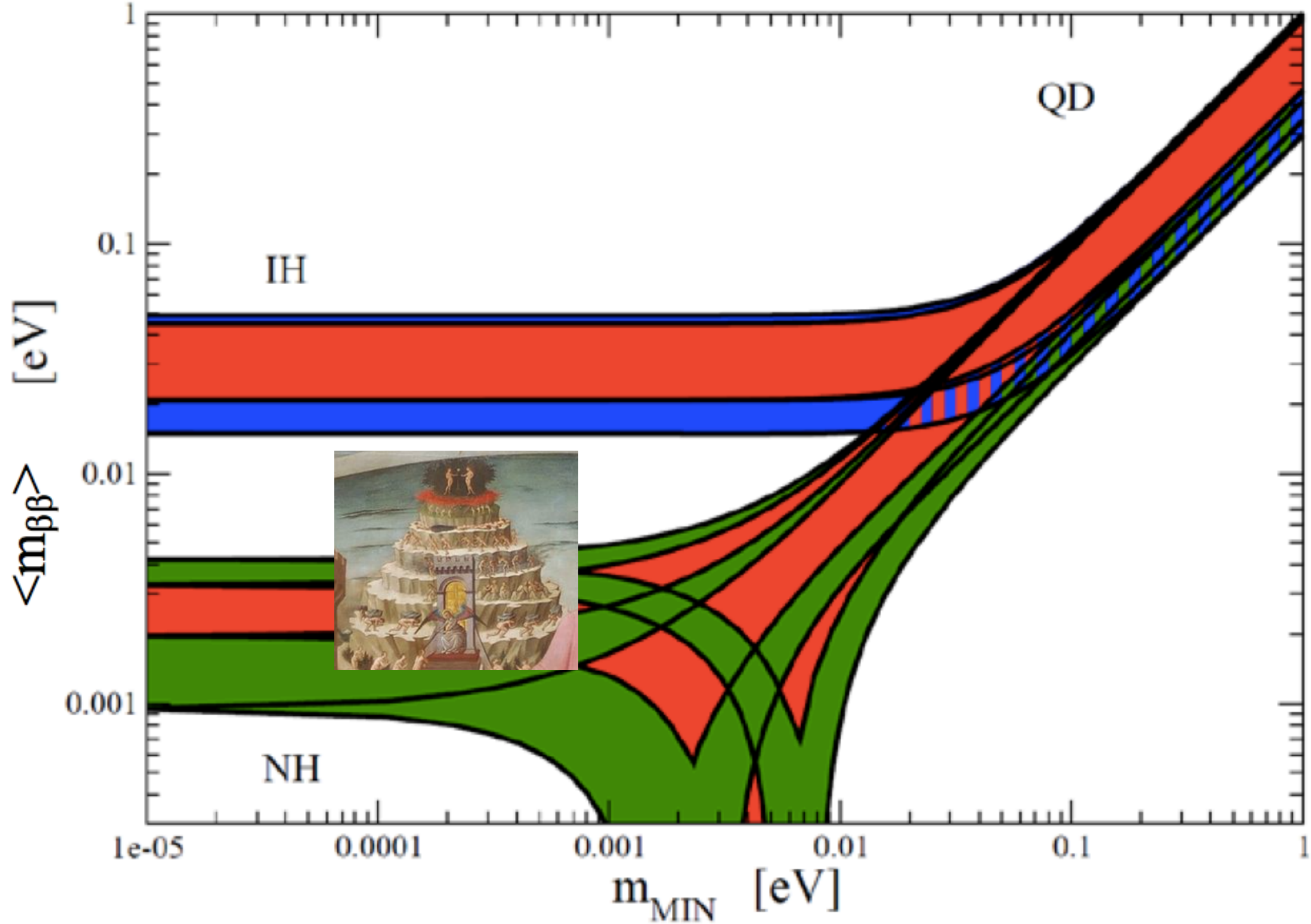
...if it’s inverted, *and* neutrinos are Majorana, then we’ll see NLDBD!



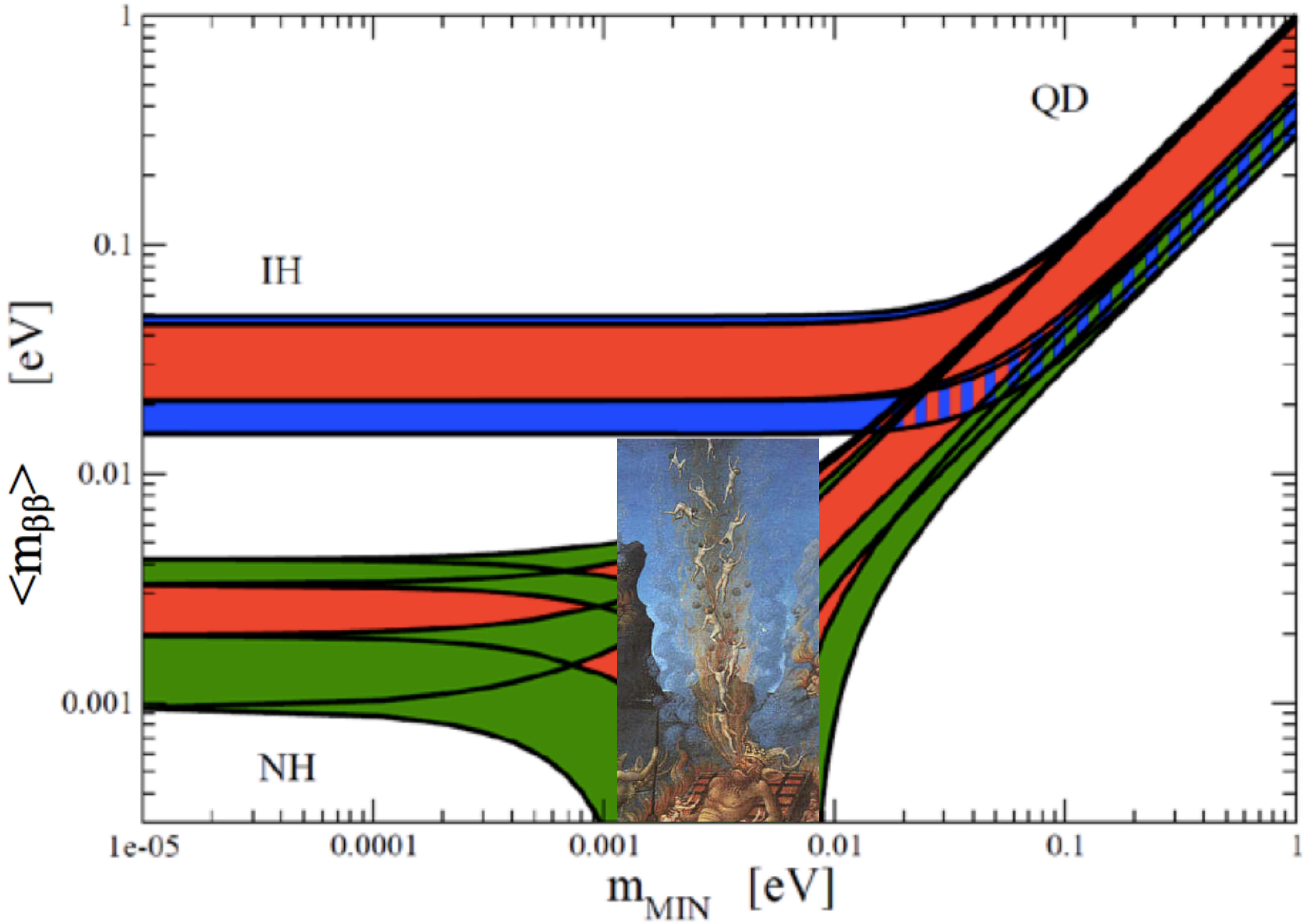
... or, if you know independently the hierarchy to be inverted, *and* you measure a limit below IH region, then you know (assuming Nature is not diabolical) that neutrinos are *not* Majorana!



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...



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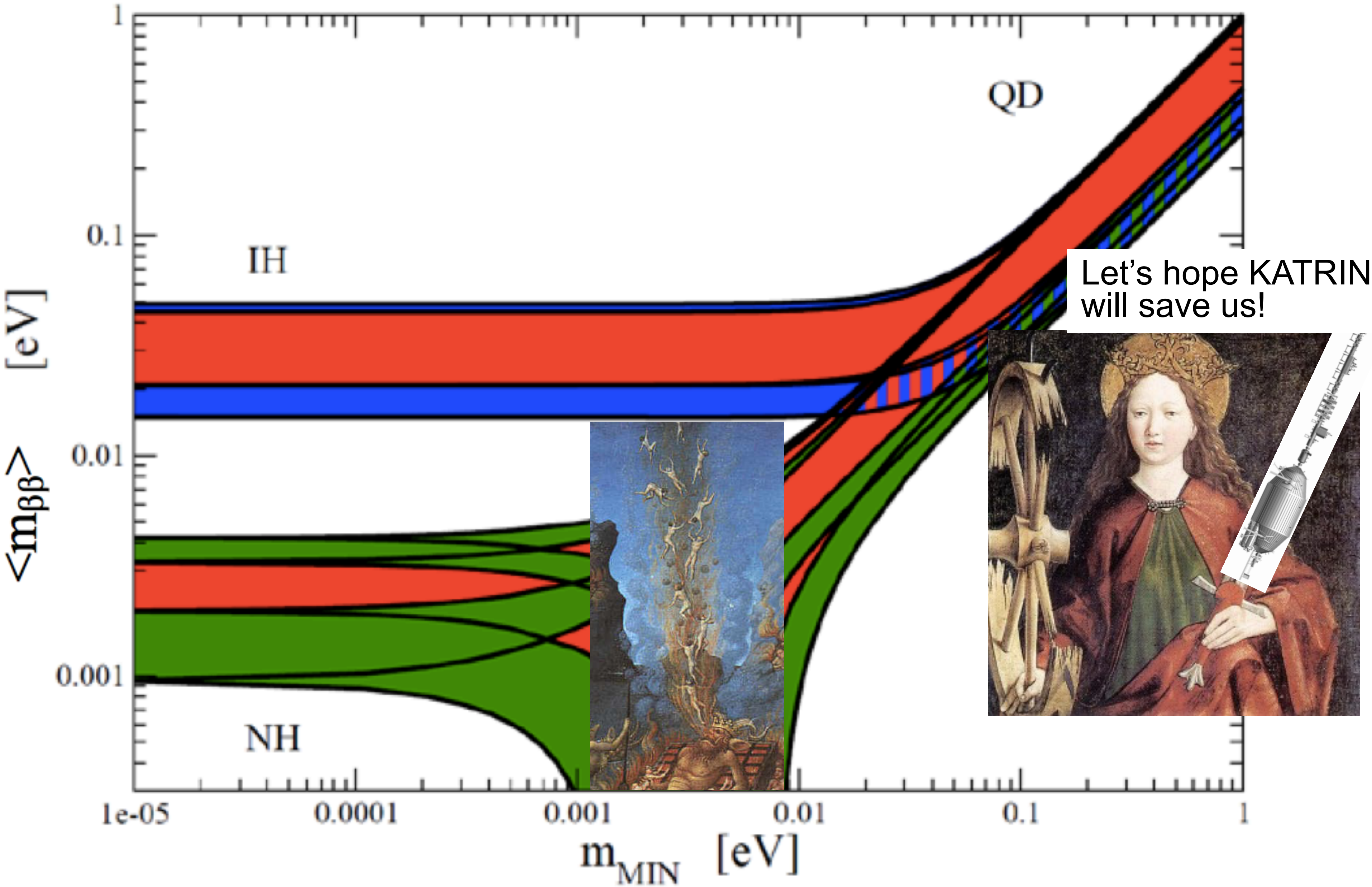
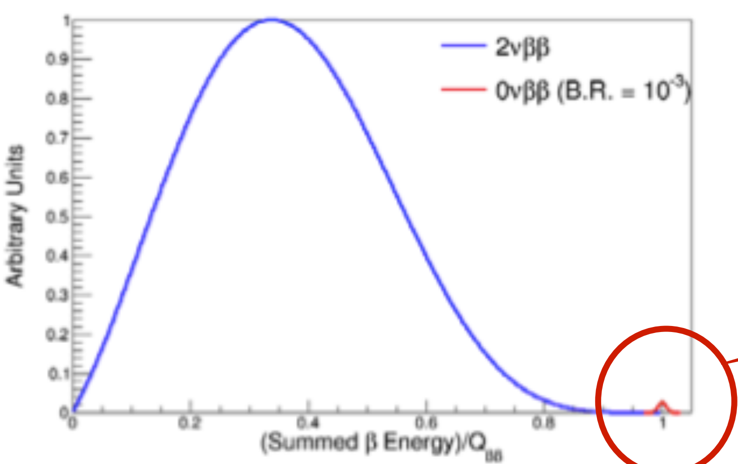


Experimental sensitivity

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

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE



want lots of signal
and no background
in Region of Interest

Go after the numerator:

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

ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation
of B background events in ROI of width ΔE

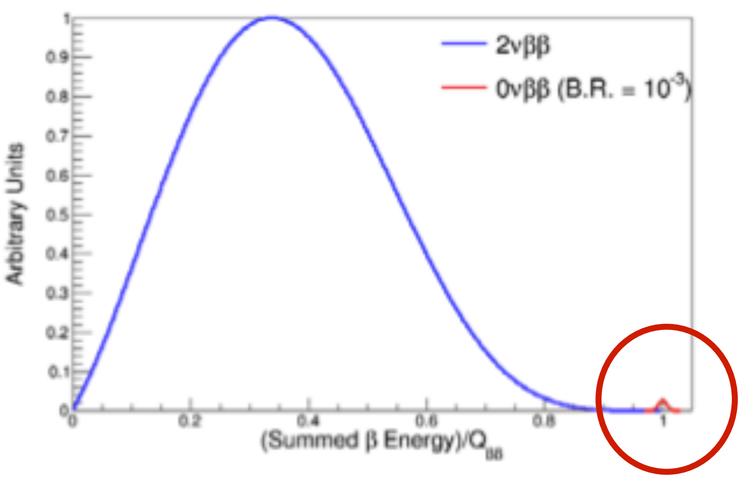
Want lots of candidate isotope!
At lifetime of $10^{26\text{-}27}$ yr (<$m_{\beta\beta}$>~ 50 meV in IH region)
need ~ 10^4 moles (~ 1 tonne) for 1 count/yr

➔ want high natural abundance

Go after the denominator:

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

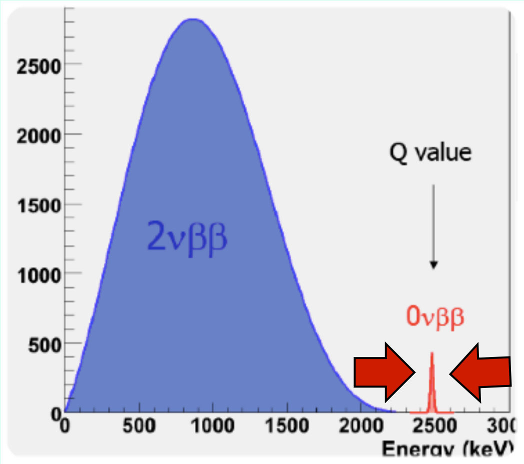
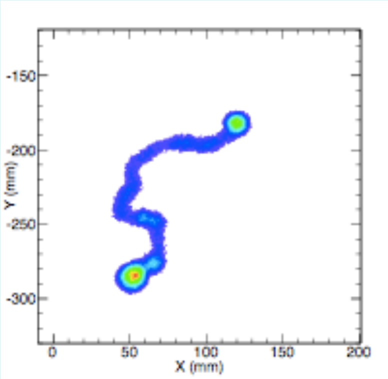
ε: detection efficiency
N_{source}: number of isotope nuclei
T: observation time
UL(B(T) ΔE): upper limit for expectation of B background events in ROI of width ΔE



- Want **small ΔE** to avoid the 2νββ "friendly fire" and exclude other background
- Generally want **high Q** value to keep away from background
- Beat down all other background ... **ultra-cleanliness, underground** location needed

General NLDBD experiment strategies

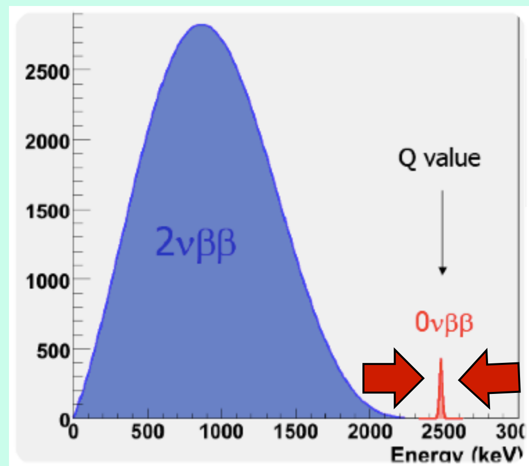
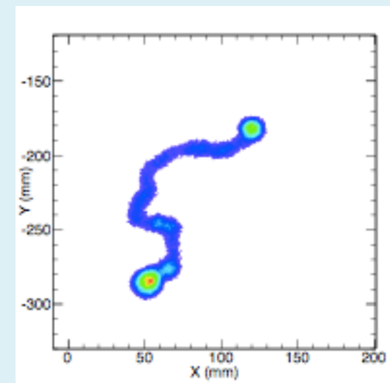
$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

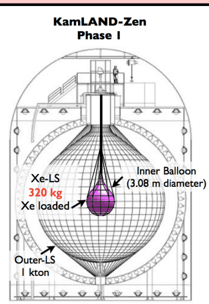
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
	 	
focus on the numerator with **a huge amount of material** (often sacrificing resolution)	focus on the denominator by **squeezing down ΔE** (various technologies)	try to make the background zero by **tracking or tagging**

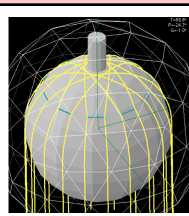
...some experiments take hybrid approaches...

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
		





SNO+
(^{130}Te)

KamLAND-Zen
(^{136}Xe)

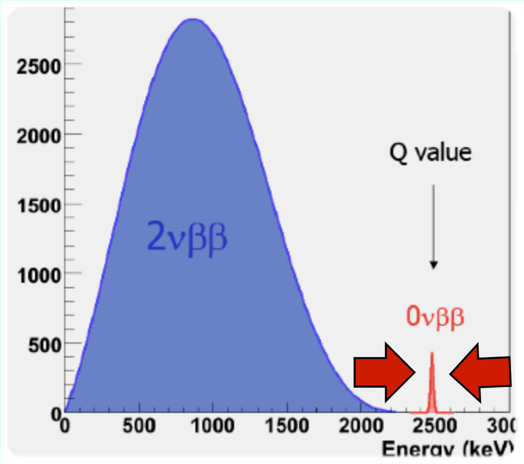
+more future ideas...

General NLDBD experiment strategies

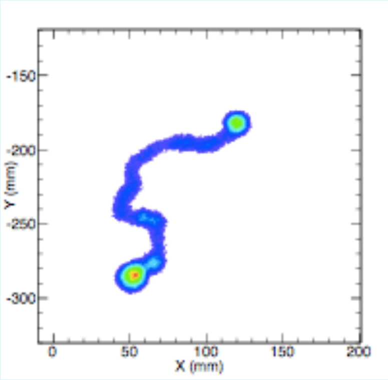
$$T_{1/2} > \frac{\ln 2 \ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

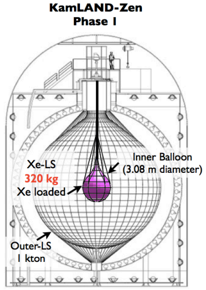
The "Brute Force" Approach

The "Peak-Squeezer" Approach

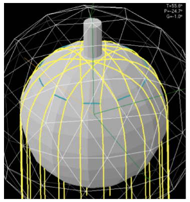


The "Final-State Judgement" Approach

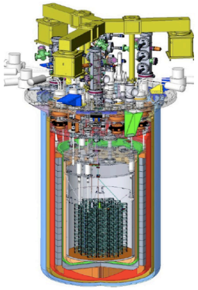




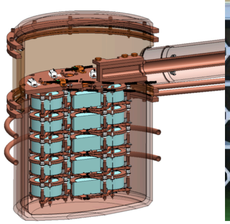
KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)



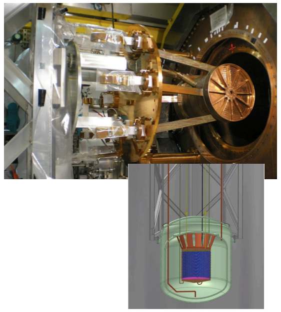
CUORICINO/ CUORE (^{130}Te)



MAJORANA (^{76}Ge)

CUPID (^{82}Se)

GERDA (^{76}Ge)



EXO/nEXO (^{136}Xe)

+more future ideas...

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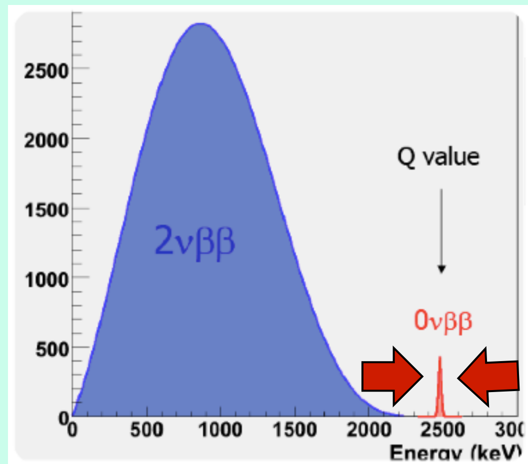
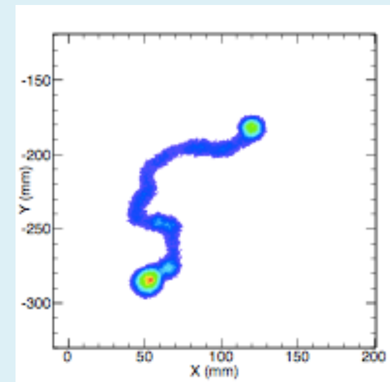
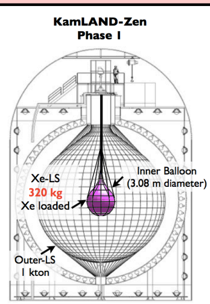
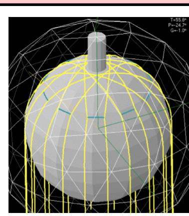


The "Final-State Judgement" Approach

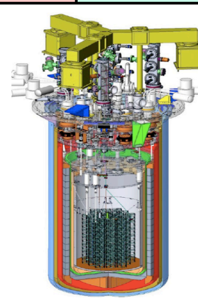




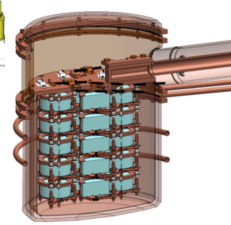
KamLAND-Zen (^{136}Xe)



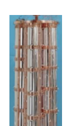
SNO+ (^{130}Te)



CUORICINO/ CUORE (^{130}Te)

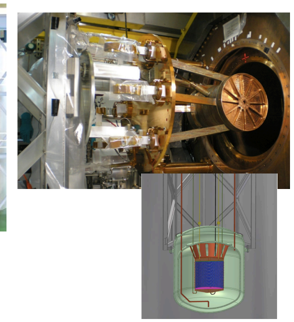


MAJORANA (^{76}Ge)

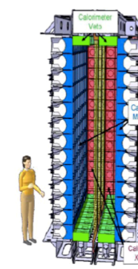


CUPID (^{82}Se)

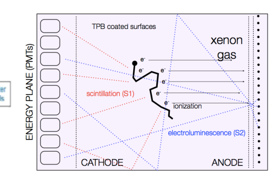
GERDA (^{76}Ge)



EXO/nEXO (^{136}Xe)



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



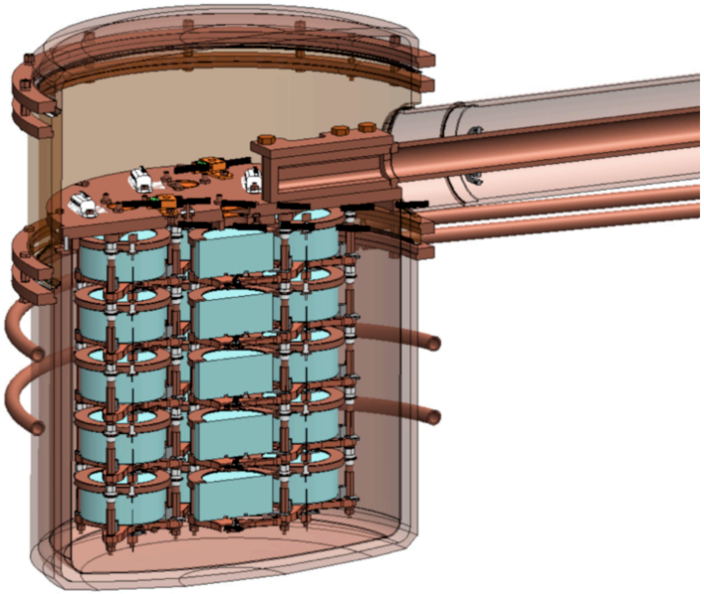
NEXT (^{136}Xe)

+more future ideas...

Peak-Squeezers: Germanium

Germanium diode detectors
enriched in ^{76}Ge; very good energy resolution

MAJORANA DEMONSTRATOR



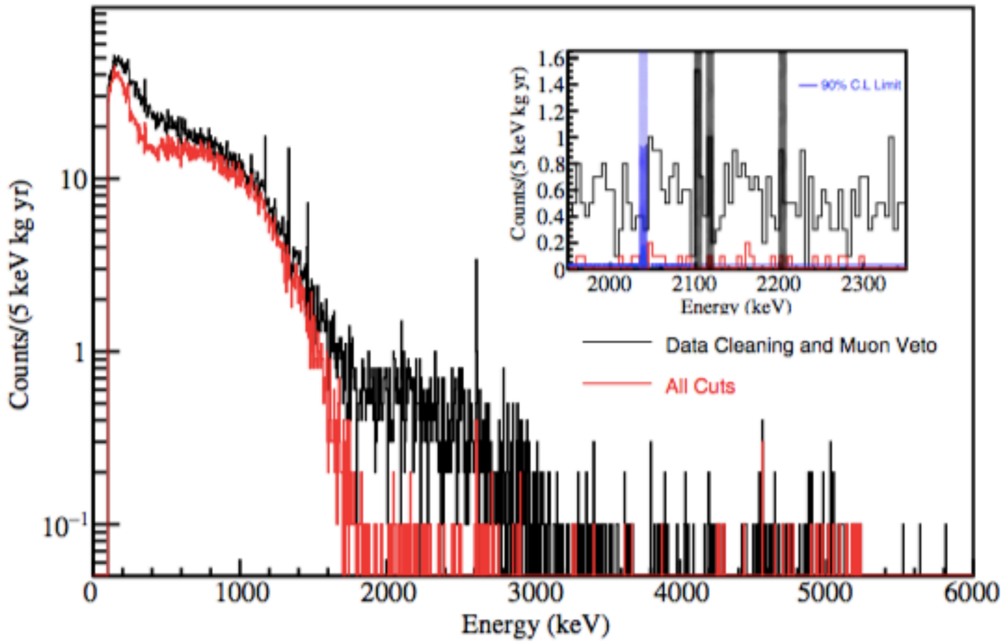
- Sanford Lab in South Dakota
- 26 kg ^{76}Ge
- segmented detector strategy

GERDA

- Gran Sasso, Italy
- 31 kg ^{76}Ge
- detectors submerged in LAr

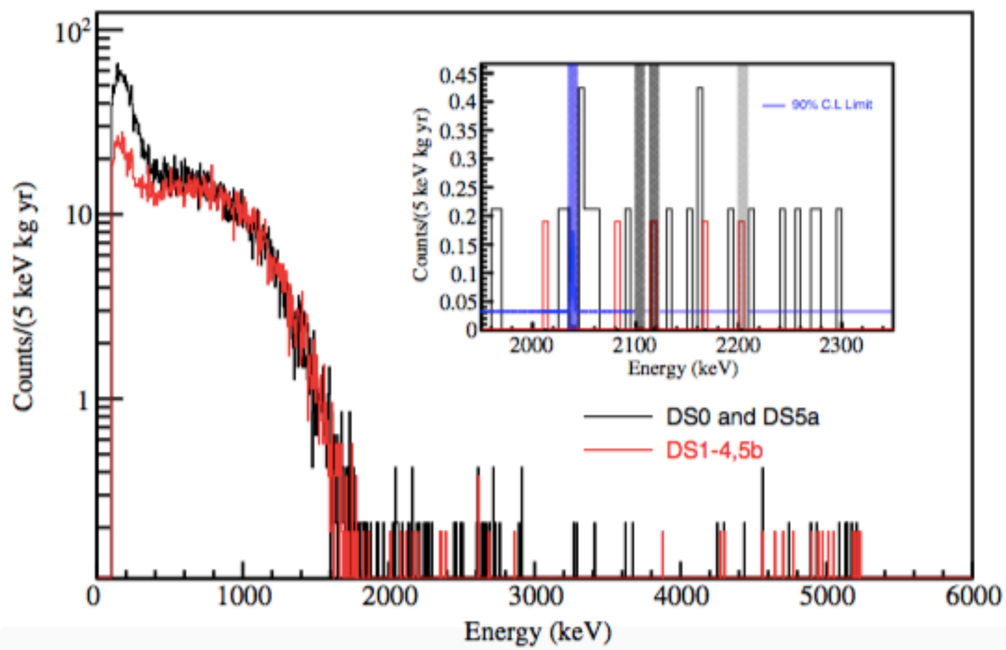
Collaborations merging for LEGEND

New results from Majorana Demonstrator



2.5 keV FWHM resolution
9.95 kg-yr exposure
In lowest bg dataset:

$4.0^{+3.1}_{-2.5}$ counts/(FWHM t yr)

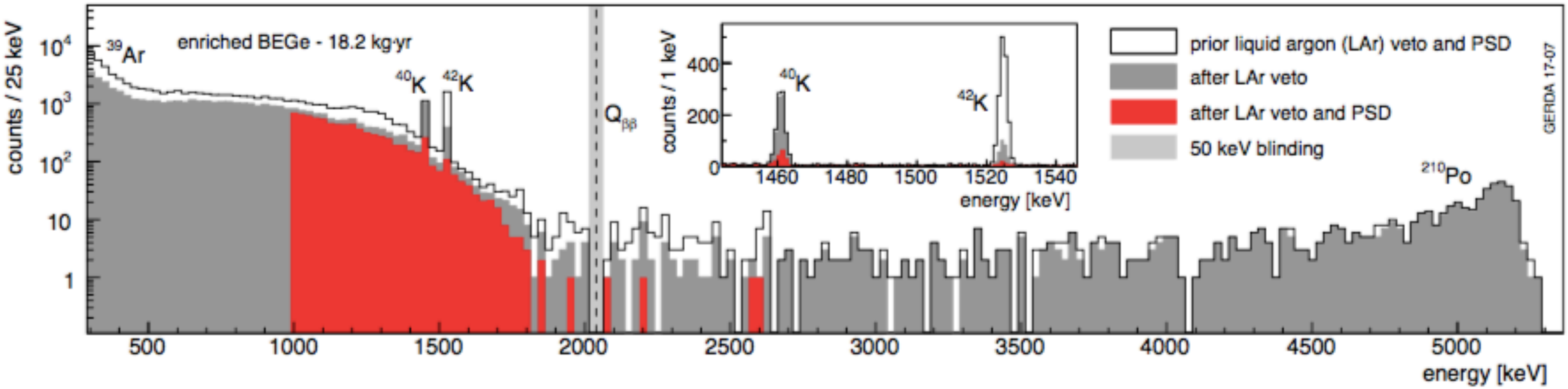


Combining datasets:

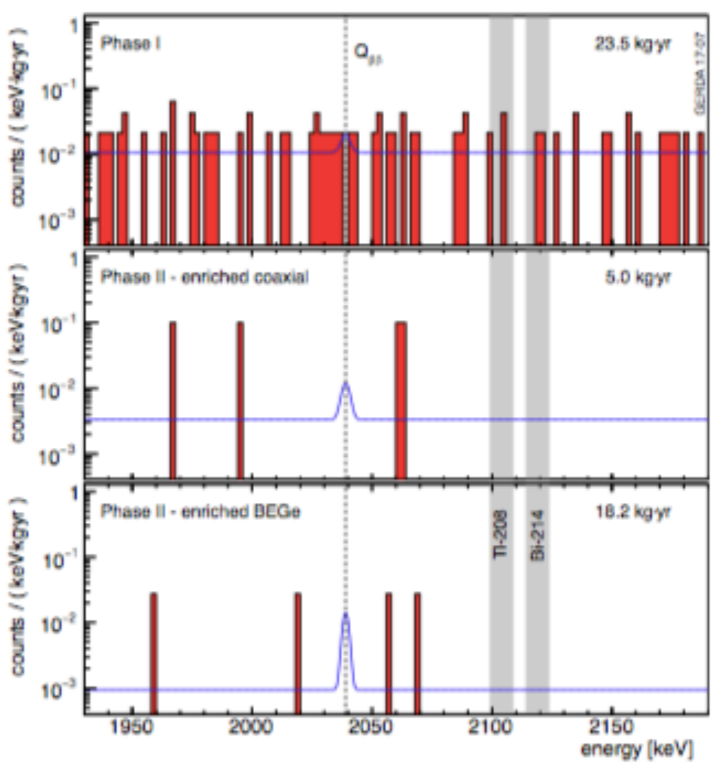
$T_{1/2} > 1.9 \times 10^{25}$ yr @90% C.L

$m_{\beta\beta} < 240\text{-}520$ meV

New results from GERDA



arXiv:1803.11100



Combining datasets:

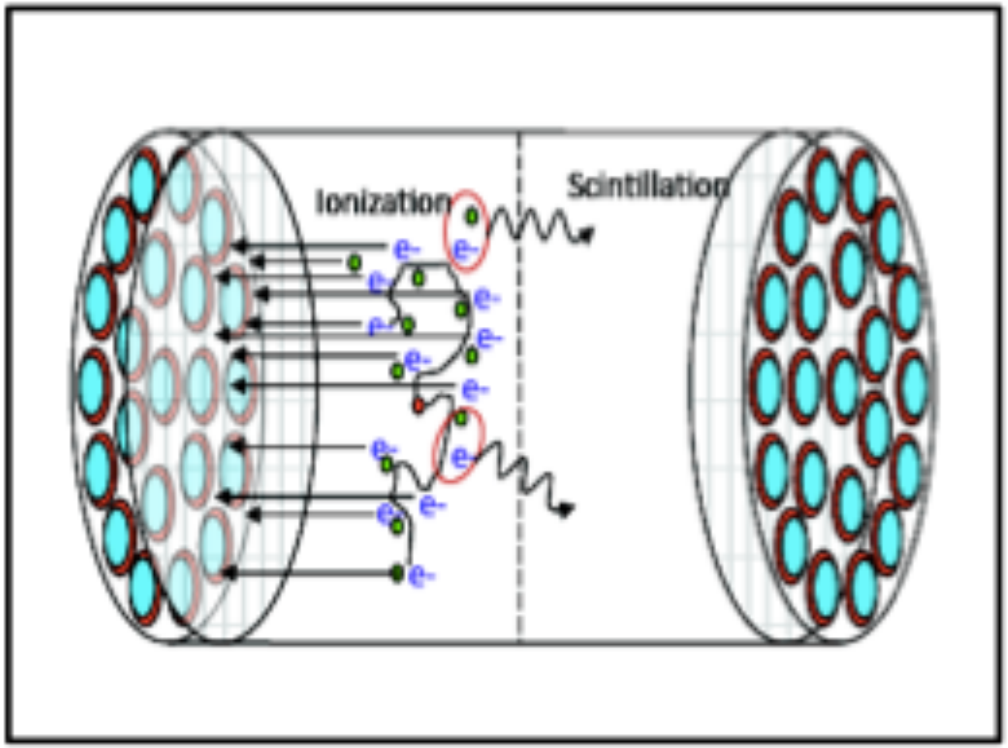
$T_{1/2} > 8 \times 10^{25}$ yr

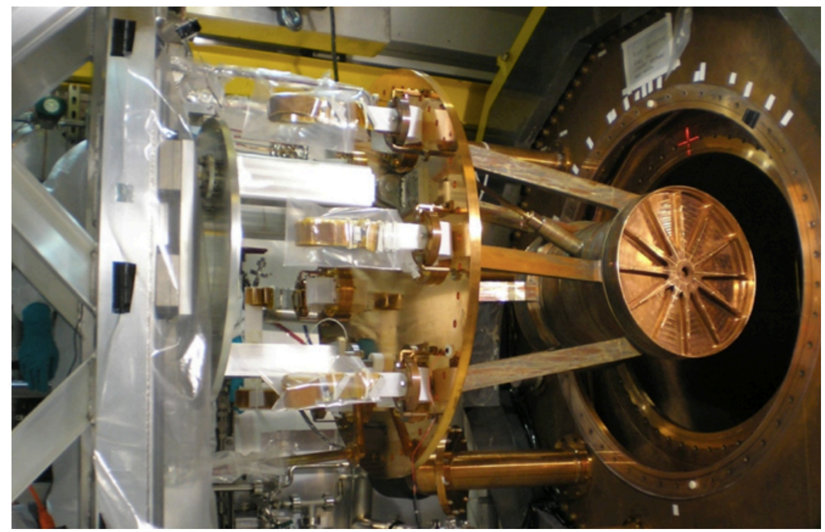
@90% C.L

$m_{\beta\beta} < 120\text{-}260$ meV

EXO

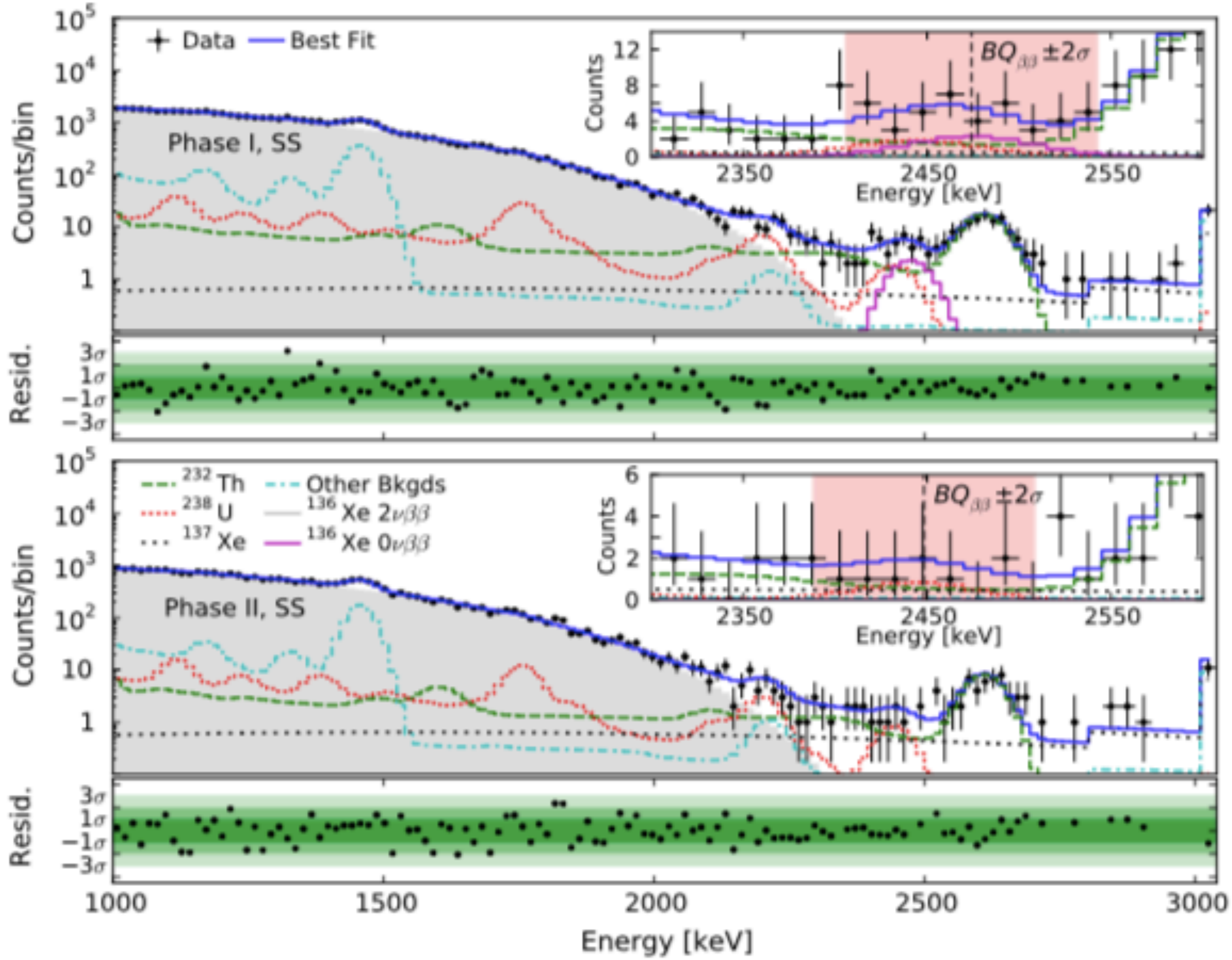
Liquid xenon
TPC





- no tracking, but single (0ν) -vs-multisite (bg) selection
- use scintillation & ionization
- WIPP in New Mexico
- EXO-200: 80.6% enriched ^{136}Xe, Q=2.479 MeV

New results from EXO-200



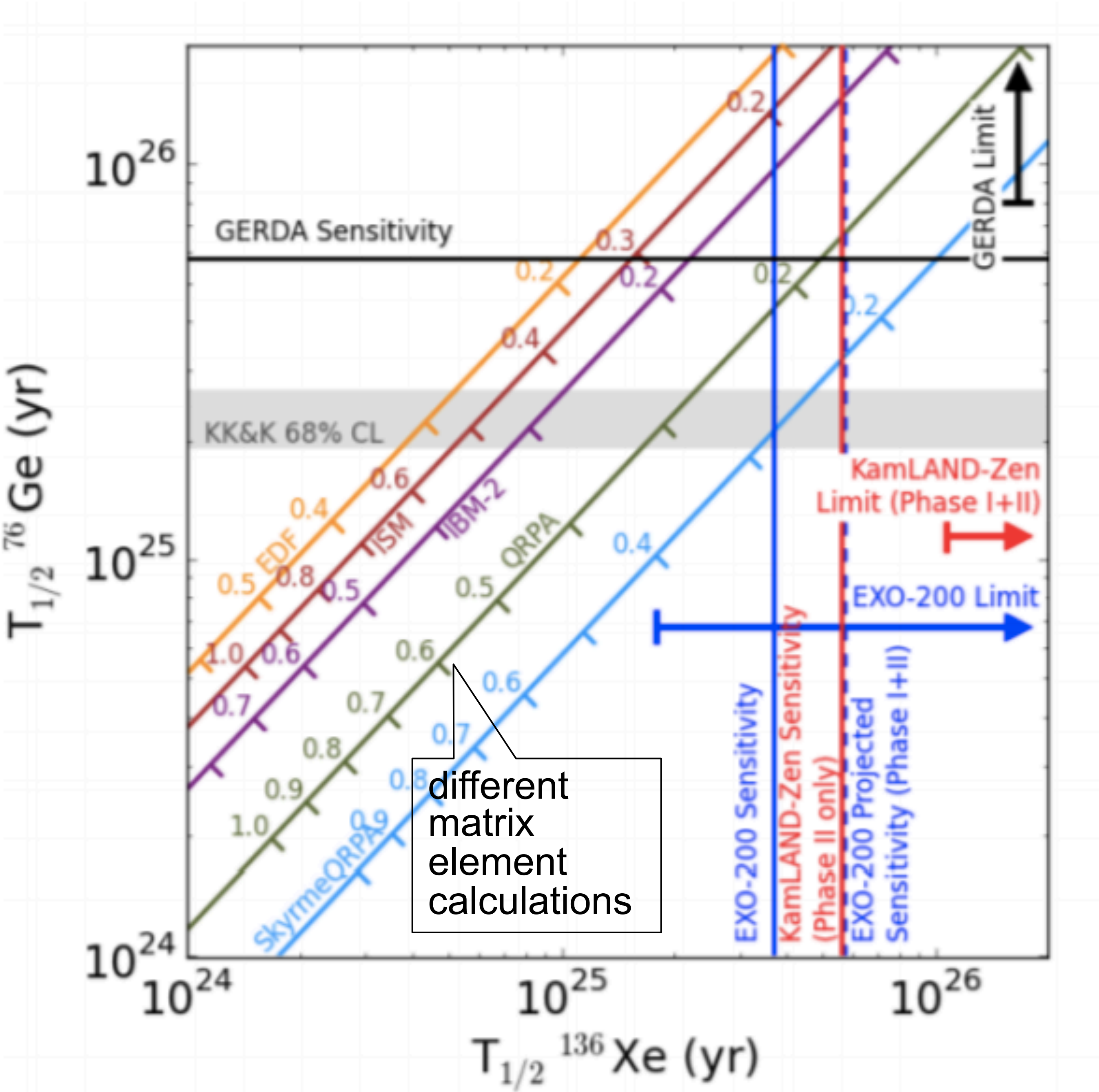
No statistically significant excess in the ROI

Sensitivity of 3.7×10^{25} yr
$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}$ yr
$\langle m_{\beta\beta} \rangle < 147 - 398$ meV

(90% CL)

arXiv: 1707.08707

Current limits, ^{76}Ge vs. ^{136}Xe:



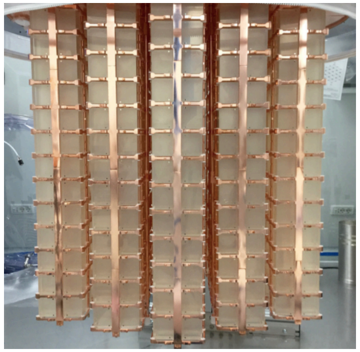
A. Der Mesrobian-Kabakian, Moriond

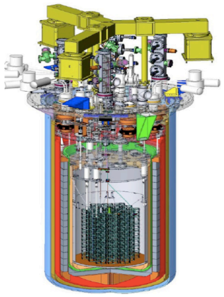
KK is basically ruled out now

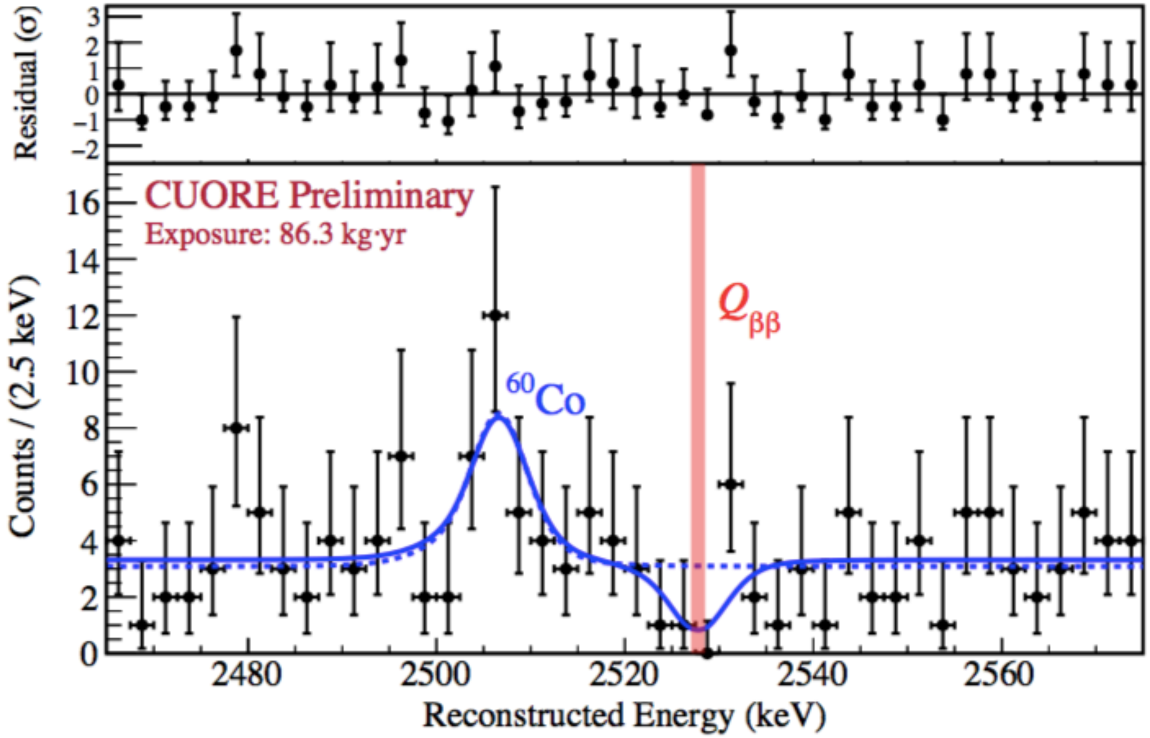
KK $T_{1/2}$ for ^{136}Xe is smaller than Xe limits for basically all matrix element assumptions

New Results from CUORE

Cryogenic bolometer w/ TeO_2







Fit components:

- Flat background
- ^{60}Co sum peak
- Peak at $Q_{\beta\beta}$

Half-life limit 90% CL:

- $T^{0\nu} > 1.3 \times 10^{25}$ yr

	Background (counts / keV / kg / y)	Efficiency (%)
Dataset 1	$1.49_{-0.17}^{+0.18} \cdot 10^{-2}$	75.7 ± 3.0
Dataset 2	$1.35_{-0.18}^{+0.20} \cdot 10^{-2}$	83.0 ± 2.6

Efficiency:

- Analysis cuts
- ββ single crystal containment (88%)

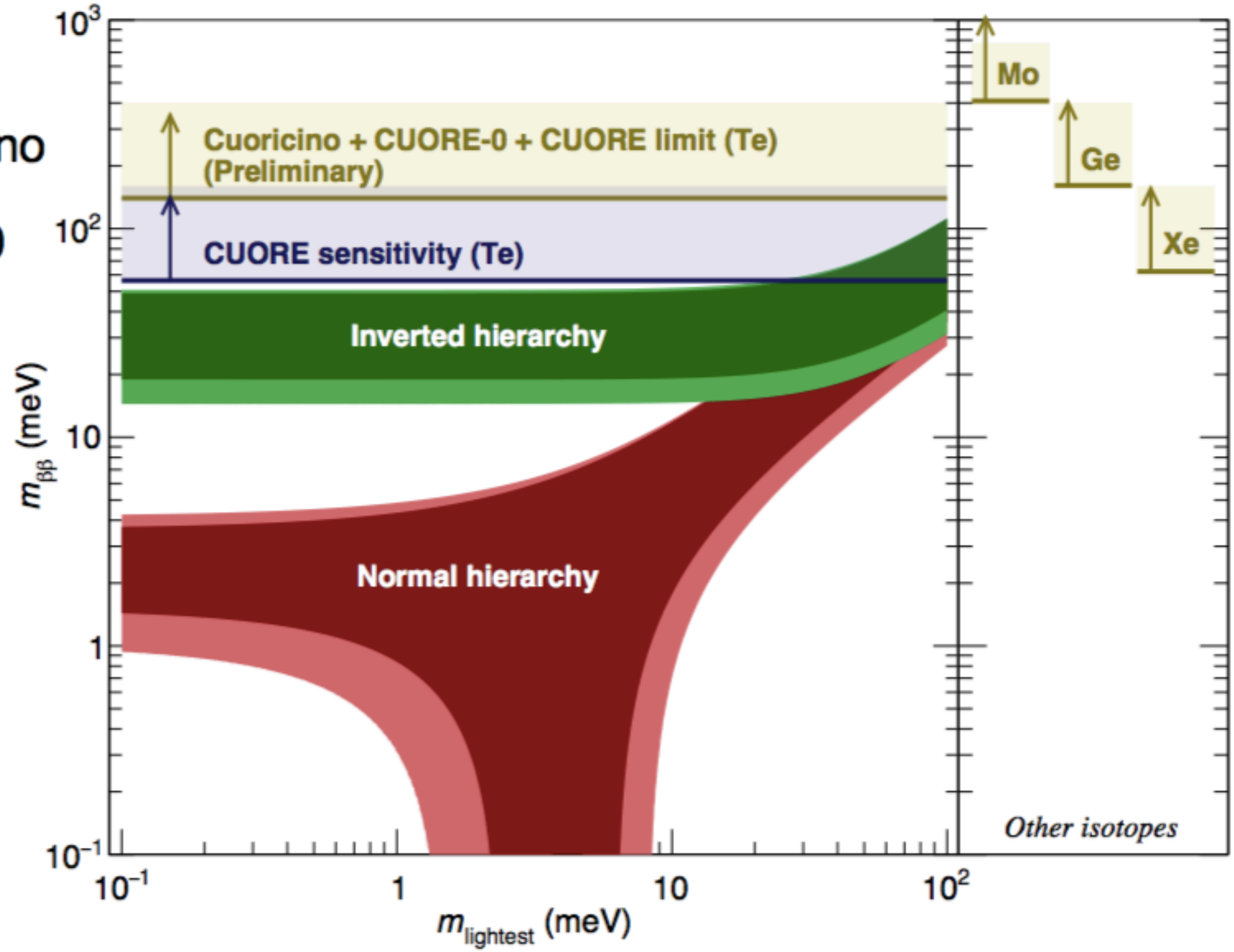
New Results from CUORE

Exposure ^{130}Te:

- 19.75 kg yr Cuoricino
- 9.8 kg yr CUORE-0
- 24.0 kg yr CUORE

Combined 90% limit:

- $T^{0\nu} > 1.5 \times 10^{25}$ yr
- $m_{\beta\beta} < 140\text{-}400$ meV

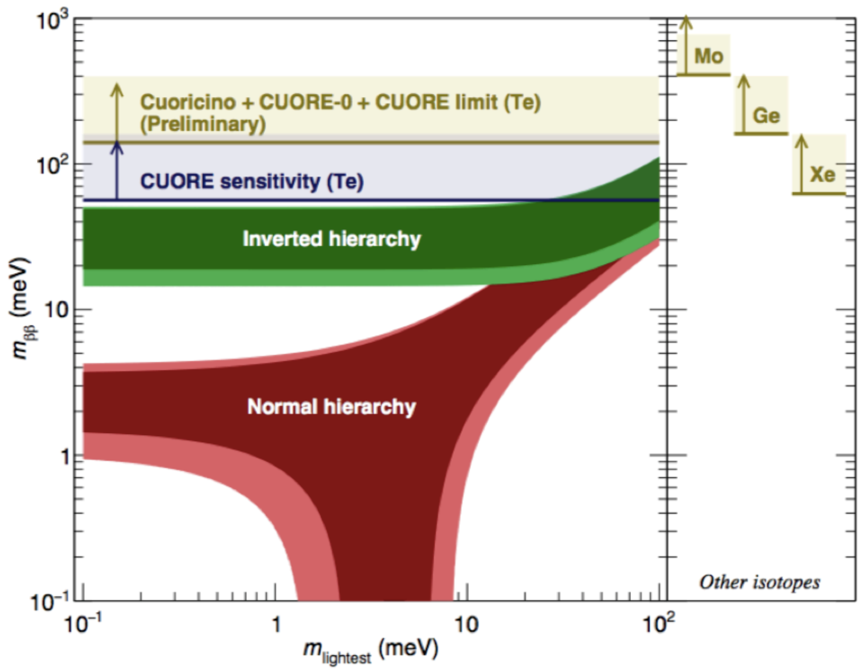


Experimental half lives:
^{130}Te: 1.5×10^{25} yr from this analysis
^{76}Ge: 5.3×10^{25} yr from Nature 544, 47–52 (2017)
^{136}Xe: 1.1×10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1×10^{24} yr from Phys. Rev. D 89, 111101 (2014)
CUORE sensitivity: 9.0×10^{25} yr

Summary of recent best results

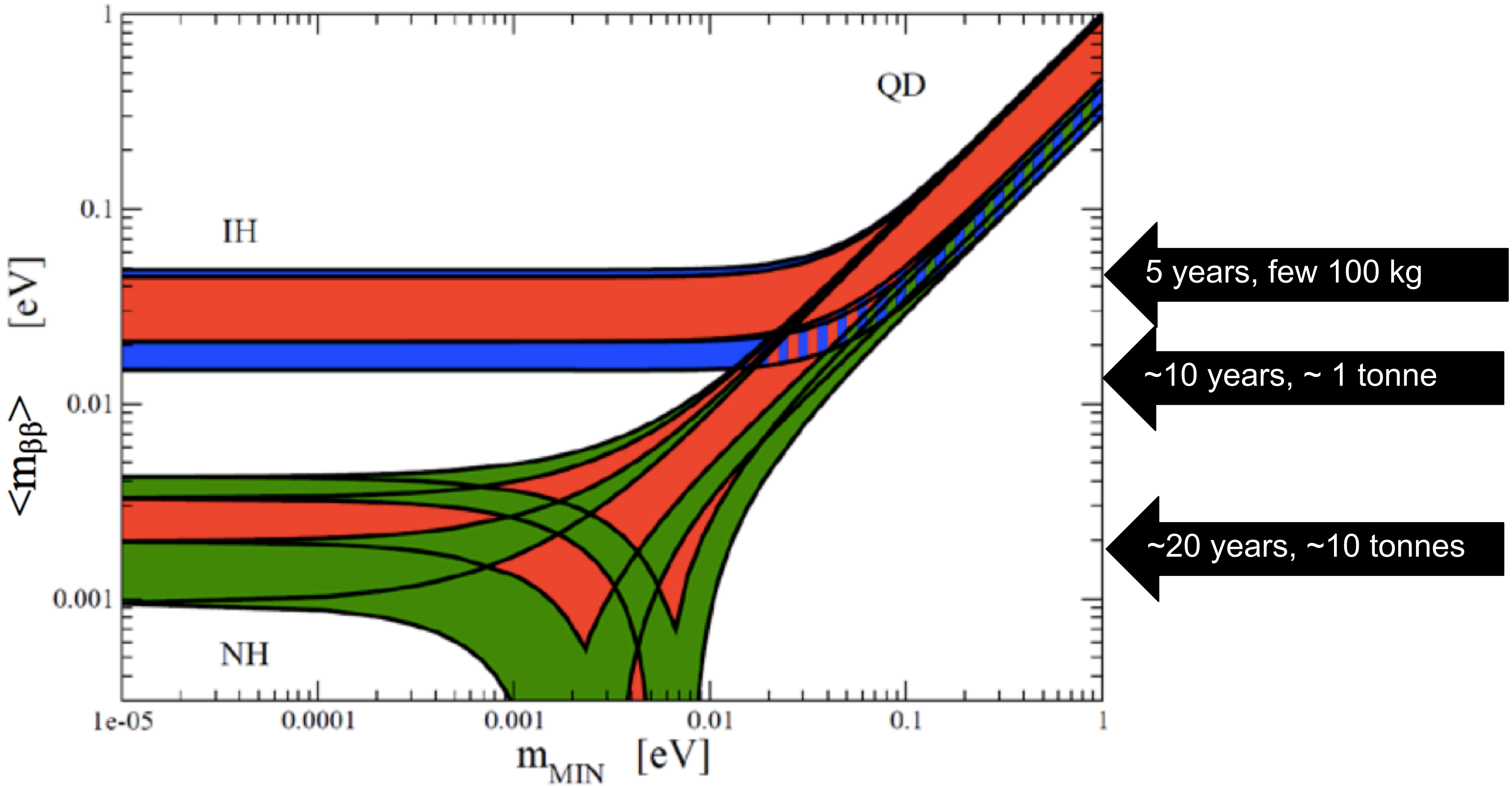
experiment		isotope	M_i [kg]	NME	sensitivity $T^{0\nu}_{1/2}$ [10^{25} yr]	sensitivity $m_{\beta\beta}$ [eV]	limit $T^{0\nu}_{1/2}$ [10^{25} yr]	limit $m_{\beta\beta}$ [eV]
GERDA		^{76}Ge	31	2.8-6.1	5.8	0.14–0.30	8.0	0.12–0.26
MAJORANA	[13]	^{76}Ge	26	2.8-6.1	2.1	0.23–0.51	1.9	0.24–0.53
KamLAND-Zen	[24]	^{136}Xe	343	1.6-4.8	5.6	0.07–0.22	10.7	0.05–0.16
EXO	[25, 26]	^{136}Xe	161	1.6-4.8	1.9	0.13–0.37	1.1	0.17–0.49
CUORE	[27, 28]	^{130}Te	206	1.4-6.4	0.7	0.16–0.73	1.5	0.11–0.50

arXiv:1803.11100



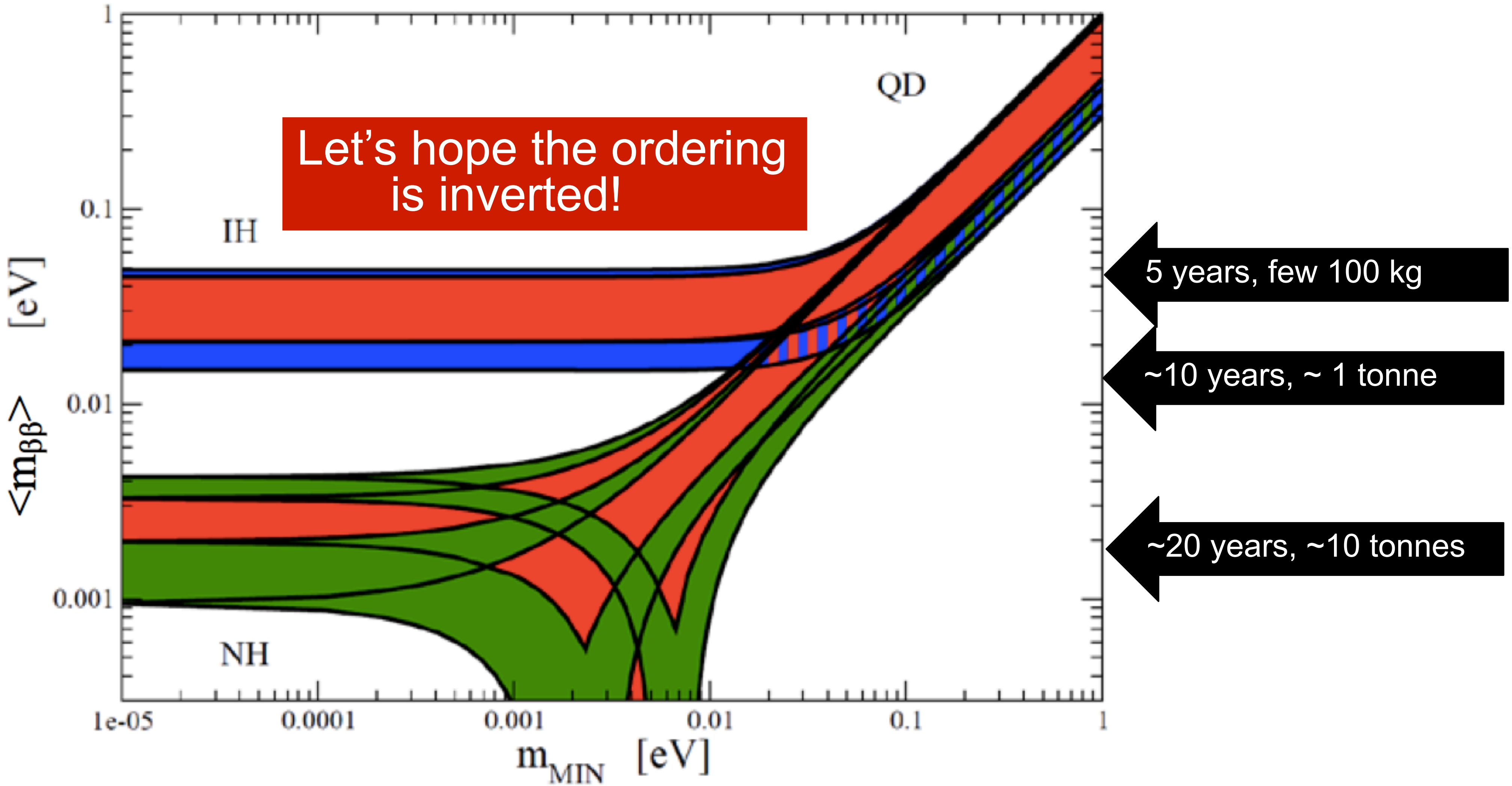
Just starting to graze the IH region

Overall Long-Term Prospects for NLDBD



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

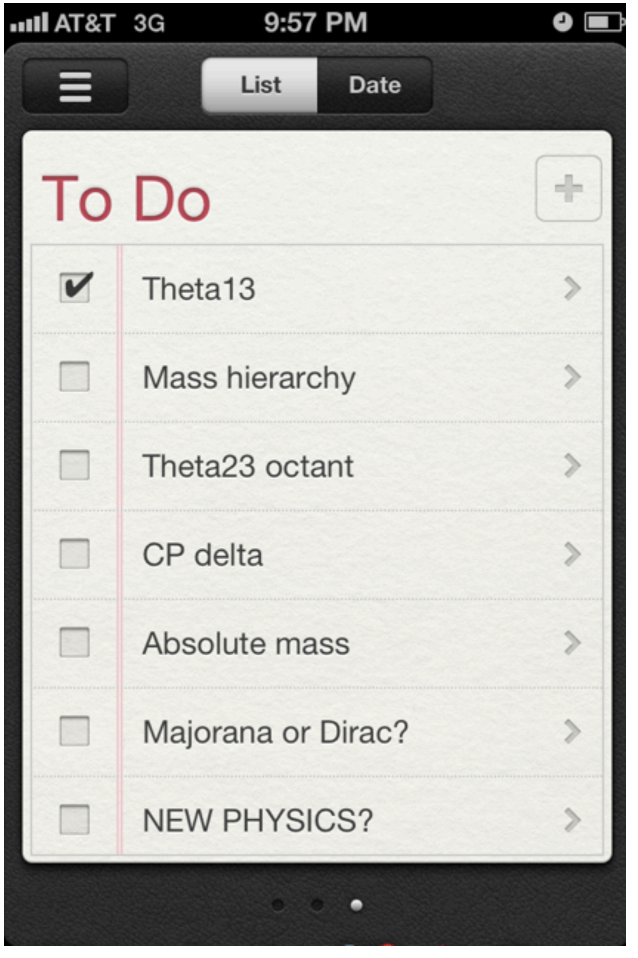
Overall Long-Term Prospects for NLDBD



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

Overall Summary

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



What is the pattern of masses and mixings? Does the 3-flavor paradigm hold? Are there sterile neutrinos or other exotic new physics? How did the matter-antimatter asymmetry come to be? Why are neutrinos so light? ...

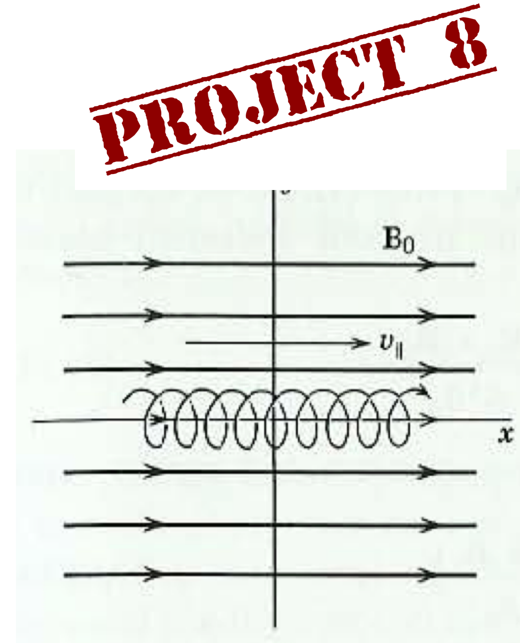
Still exciting years ahead!

Extras/backups

New idea:

use cyclotron radiation to measure spectrum

(B. Monreal and J. Formaggio, PRD 80:051301, 2009)



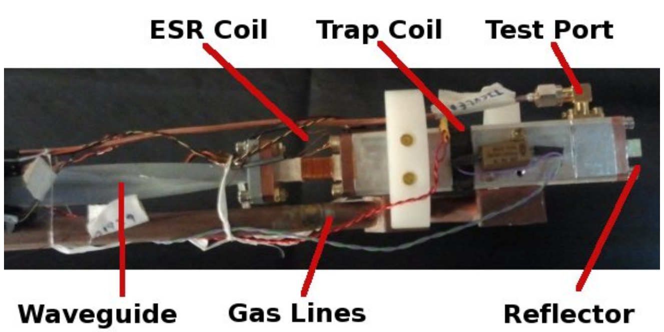
$$\omega = \frac{qB}{\gamma m} \equiv \frac{\omega_c}{\gamma}$$

measured frequency maps to electron energy

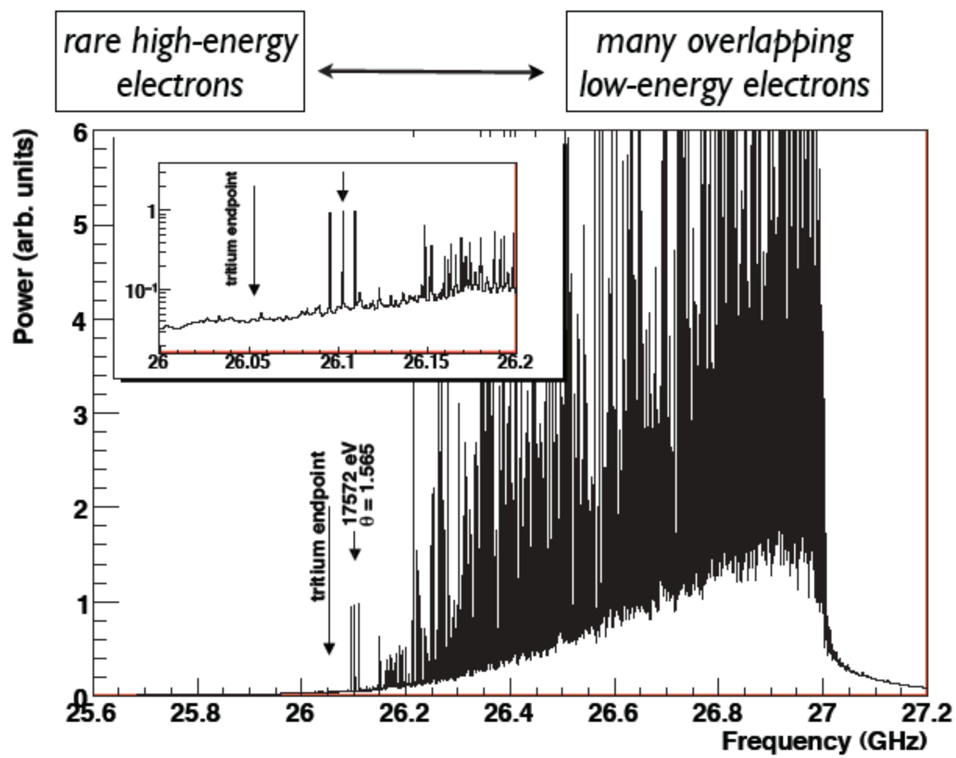
$$\omega_c = 1.758820150(44) \times 10^{11}\ \mathrm{rad/s/T}$$

Avoid the limiting systematics of the MAC-E filter technique for tritium decays

... R&D underway



25.5-GHz waveguide cell



100,000 tritium decays in 30μs

H. Robertson

Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

G. Gratta

want large Q value!

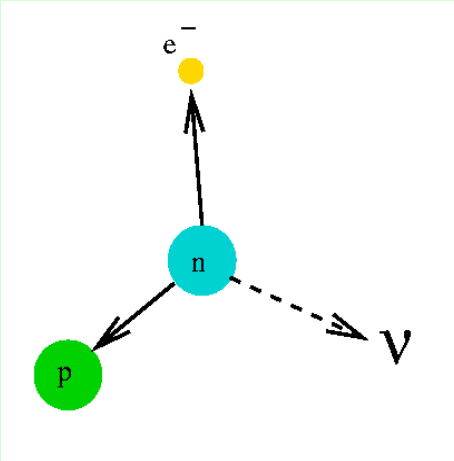
want high natural abundance!

Neutrinoless Double Beta Decay Experiments:
many isotopes and technologies

Experiment	Isotope	Mass	Technique	Status	Location
AMoRE [164, 165]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES [166]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL [167]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA [168]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0 [151]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
CUORE [151]	^{130}Te	206 kg	TeO_2 bolometers	Constr. (2014)	Gran Sasso
DCBA [169]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200 [152, 153, 154]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO [155]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA [150, 170]	^{76}Ge	$\sim$35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO [171]	^{160}Gd	2 t	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen [156, 158]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LZ [161]	^{136}Xe	600 kg	Two-phase ^{nat}Xe TPC/scint	Proposal	SURF
LUCIFER [172, 173]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [147, 148, 149]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [174]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem [162]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO [162]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [159, 160]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
SNO+ [39, 175, 176]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

From arXiv: 1310.4340

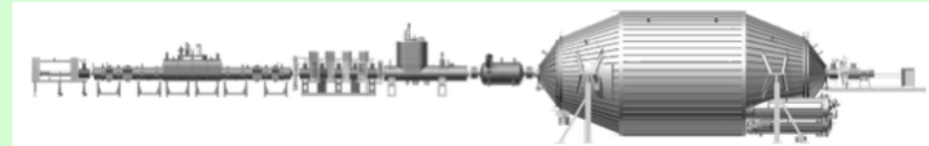
Absolute neutrino mass (not accessible via oscillations!)

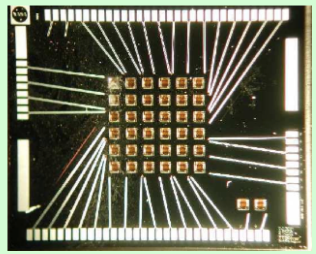


Look for distortion of β-decay spectrum near endpoint

KATRIN

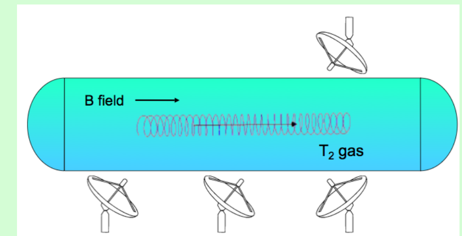
Sensitivity to ~0.2 eV
Data in 2017





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

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



Other ideas in R&D: thermal calorimetry, holmium, cyclotron radiation

Fits to cosmological data:
CMB, large scale structure,
high Z supernovae,
weak lensing,...
(model-dependent)

$$\sum m_i <\sim 0.6 \text{ eV}$$