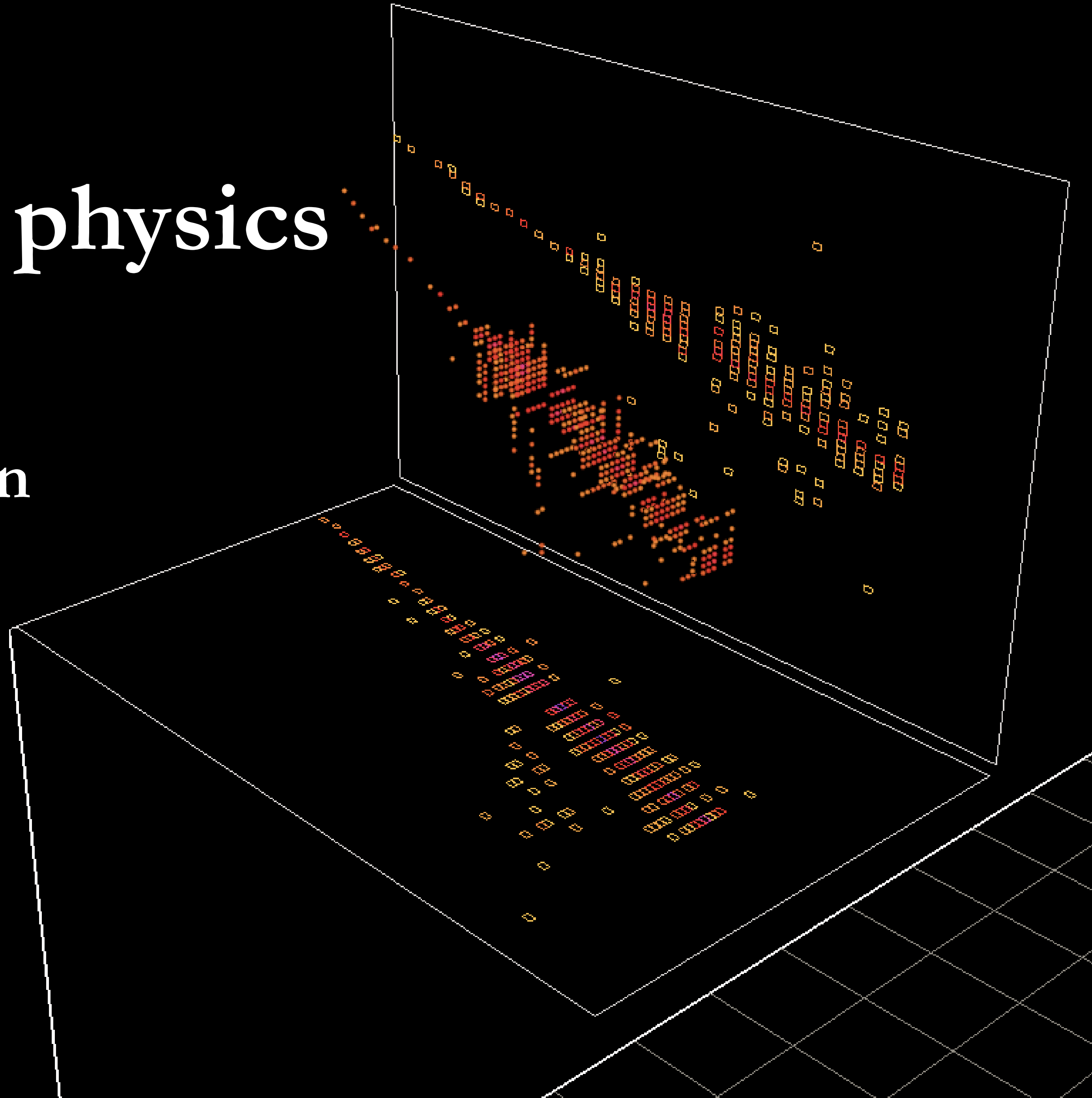
Neutrino physics

Ryan Patterson
Caltech

HCPSS
August 21, 2020



(Figure from "Report of the 2013 Community Summer Study")

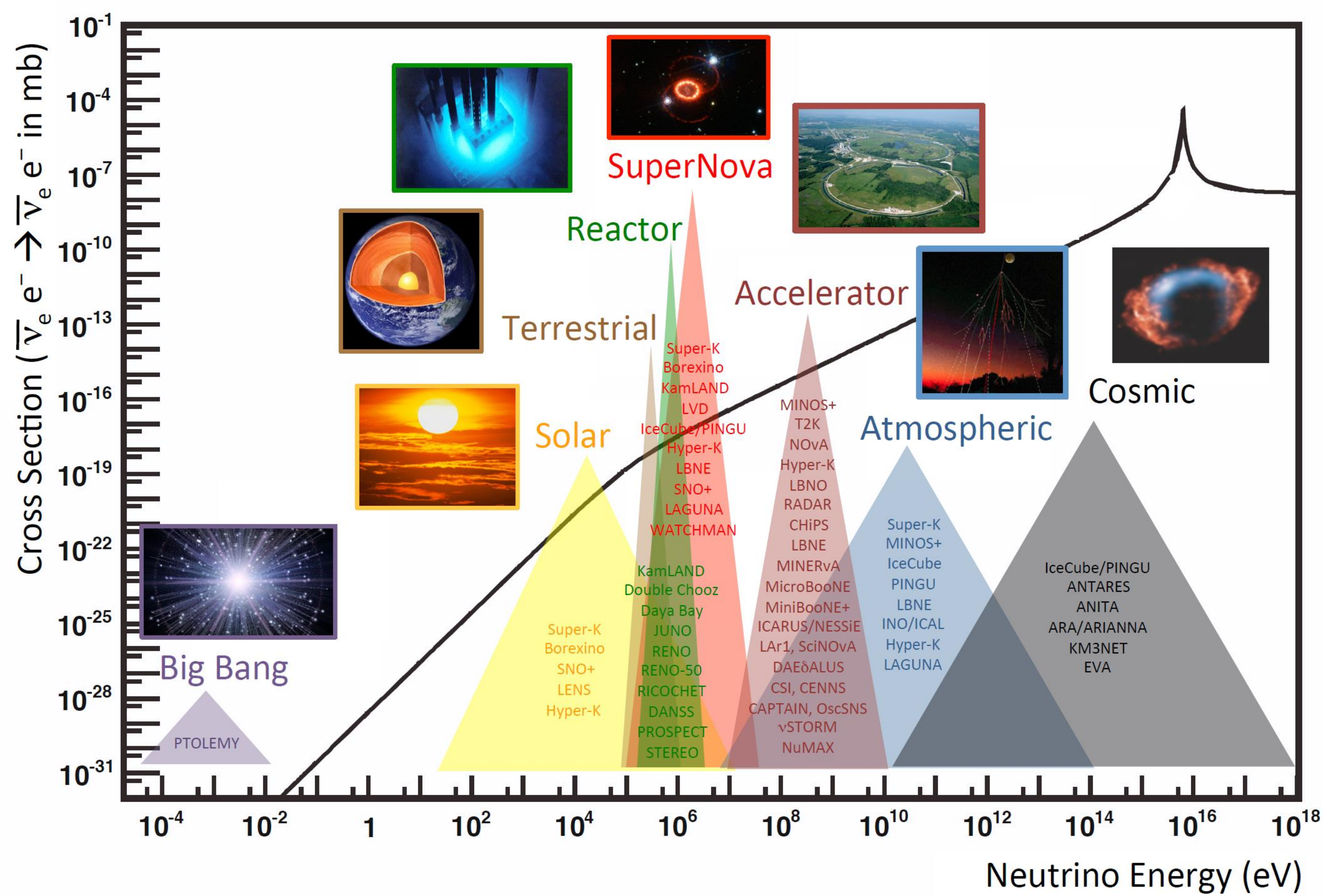


Figure 2-2. *Neutrino interaction cross section as a function of energy, showing typical energy regimes accessible by different neutrino sources and experiments. The curve shows the scattering cross section for $\bar{\nu}_e\, e^- \to e^-\, \bar{\nu}_e$ on free electrons, for illustration. Figure is modified from [9]*

Neutrino oscillations

Three neutrino flavors

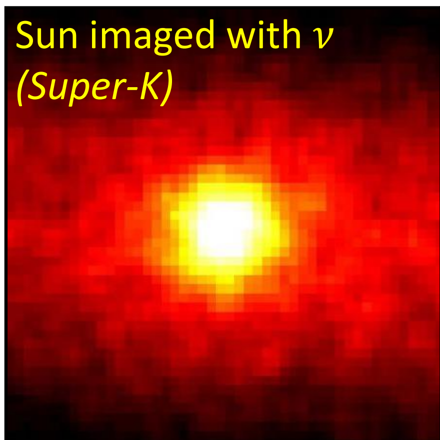
ν_e ν_μ ν_τ

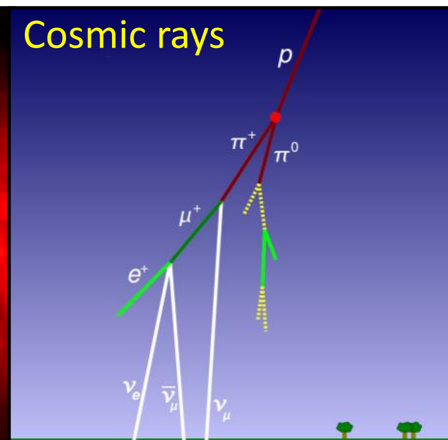
$P(\nu_\alpha \to \nu_\beta)$ depends on…

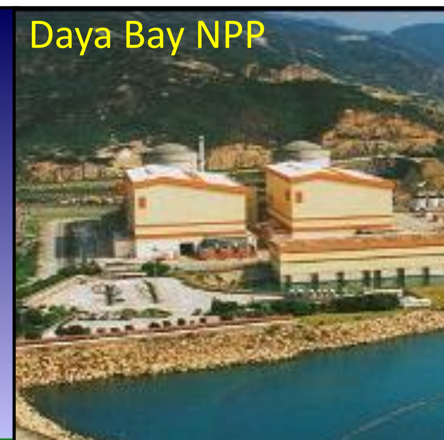
mixing matrix U_{PMNS}
mass-squared splittings Δm^2_{ij}

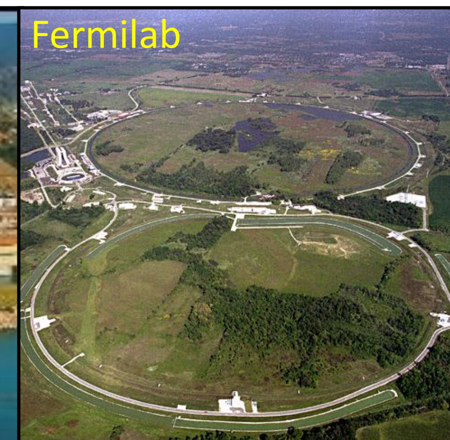
Observed using…

solar, atmospheric, reactor, and accelerator ν sources









Neutrino oscillations

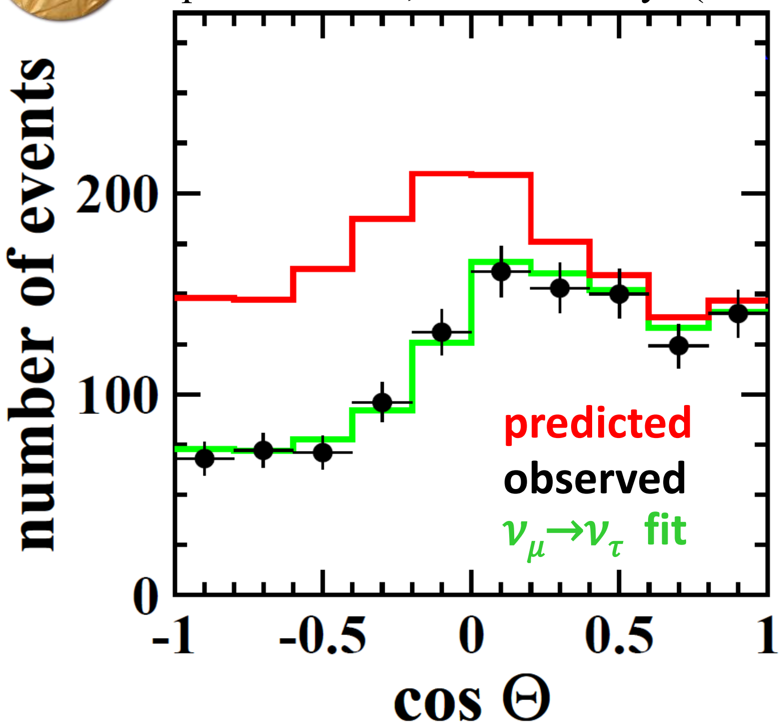
Three neutrino flavors

ν_e ν_μ ν_τ

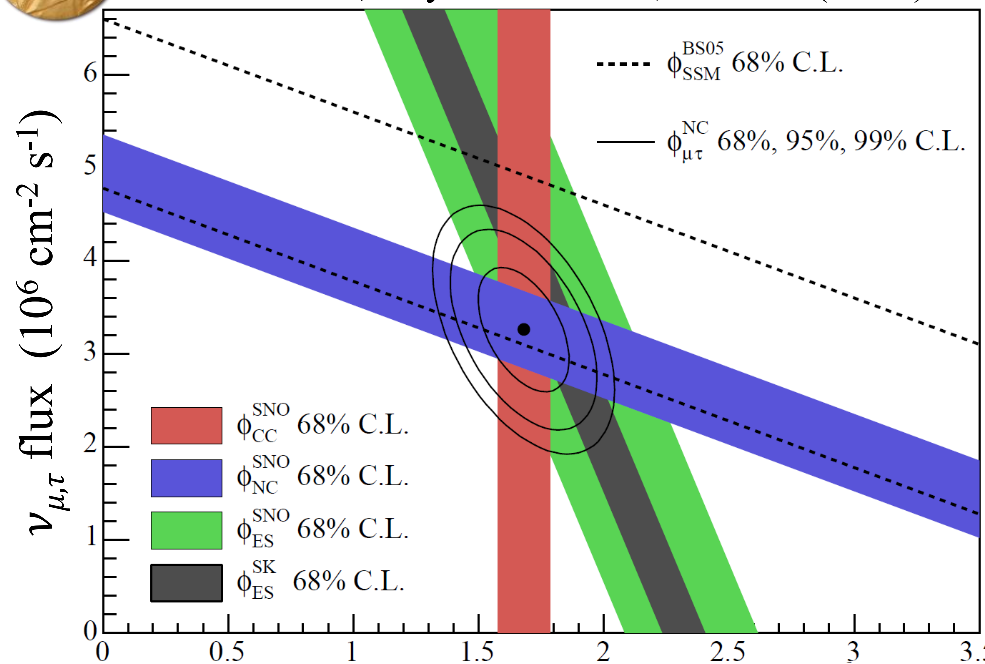
$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on…

mixing matrix U_{PMNS}
mass-squared splittings Δm^2_{ij}

Atmospheric ν_μ flux vs. zenith angle
Super-K collab., 1144 live-days (2000)



Solar neutrino fluxes (^{8}B decay)
SNO collab., Phys. Rev. C **72**, 055502 (2005)



- The presence of neutrino oscillation implies neutrino mass

→ *see functional dependence later*

- Oscillations do not provide a measure of the neutrino masses

→ *depends only on differences in squared masses*

So what are the actual masses?

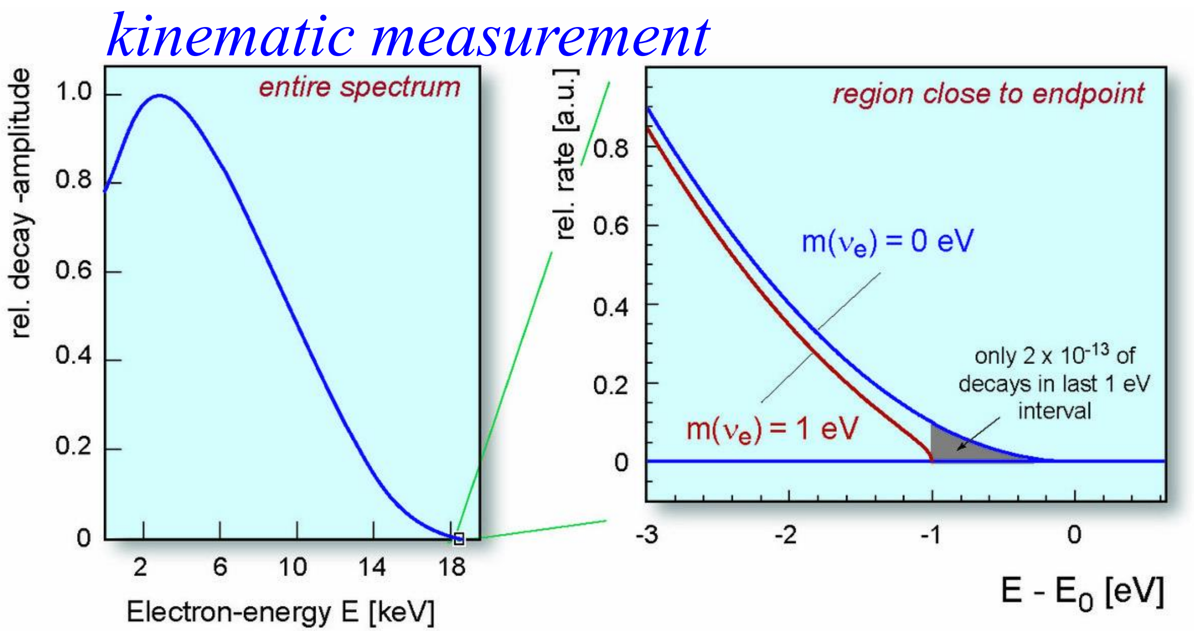
- **Cosmological observations** → sum of neutrino masses.
  Best limits: $\boldsymbol{\Sigma m_i}$ **< 0.12 eV** (95% C.L.) *CMB TT/TE/EE + LSS + BAO*

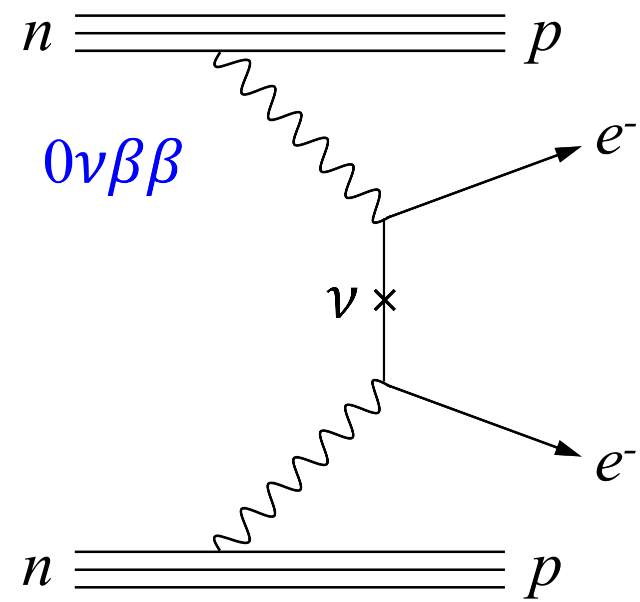
- ***β*-decay kinematic measurement** → effective ν_e mass, a.k.a. m_β:

$$m_\beta^2 = \sum |U_{ei}|^2 m_i^2$$

- **0*νββ* decay process (if Majorana-*ν*-mediated)** → effective mass $m_{\beta\beta}$:

$$m_{\beta\beta}^2 = \left|\sum U_{ei}^2 m_i\right|^2$$

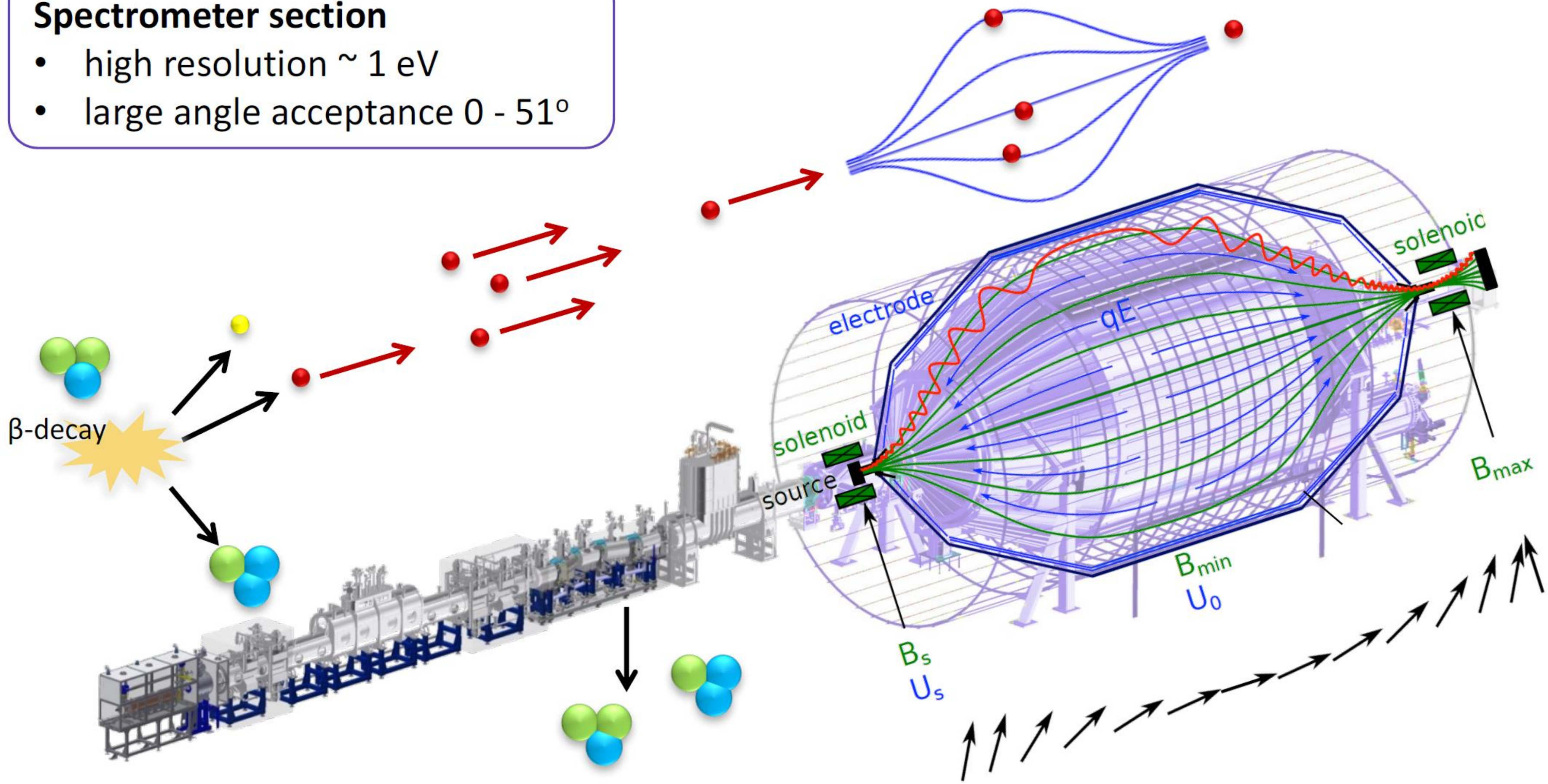




Kinematic mass measurement: KATRIN

Precision spectroscopy near the endpoint of tritium beta decay

Spectrometer section
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°

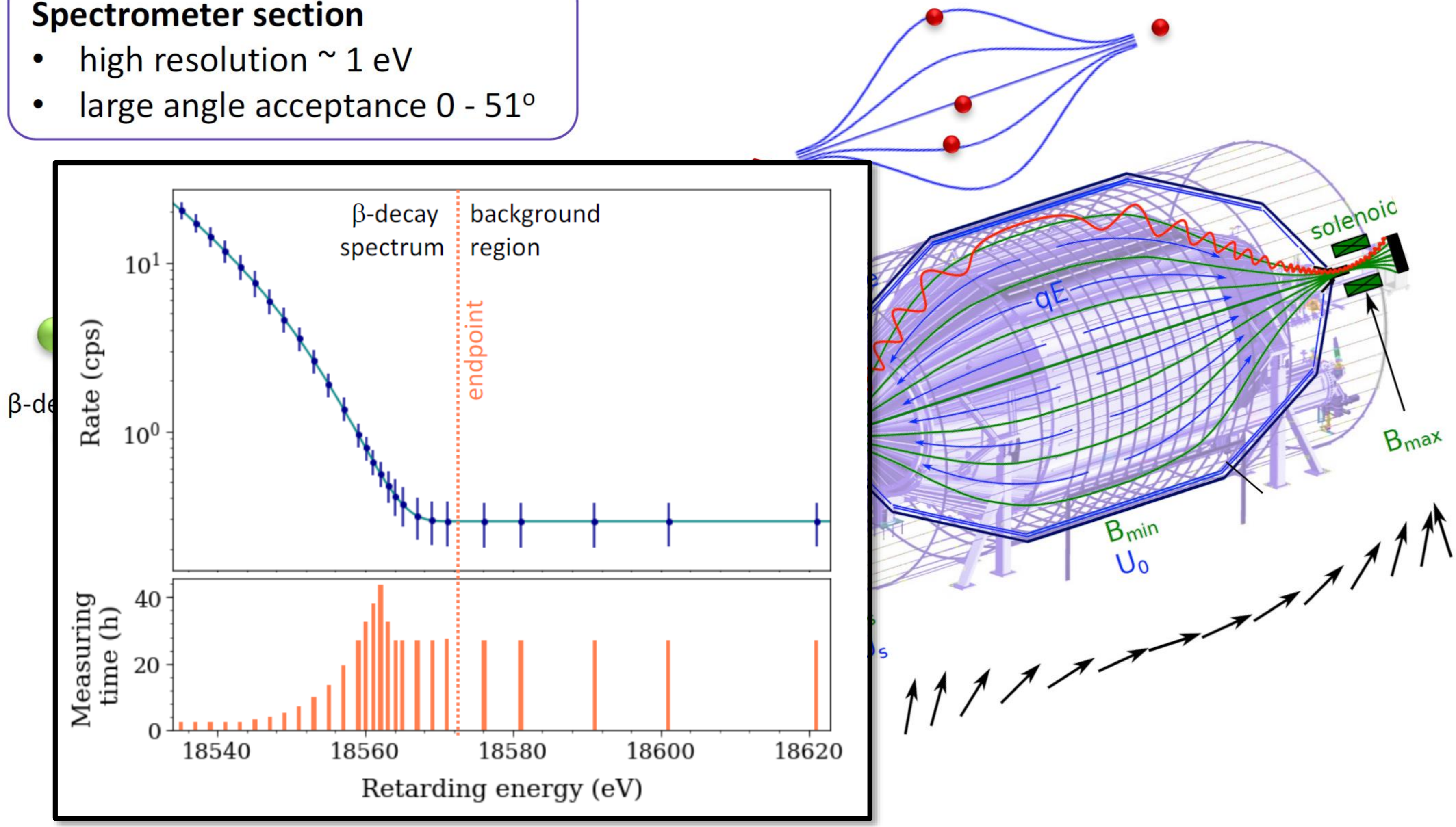


Mertens/KATRIN (Nu2020)

Kinematic mass measurement: KATRIN

Precision spectroscopy near the endpoint of tritium beta decay

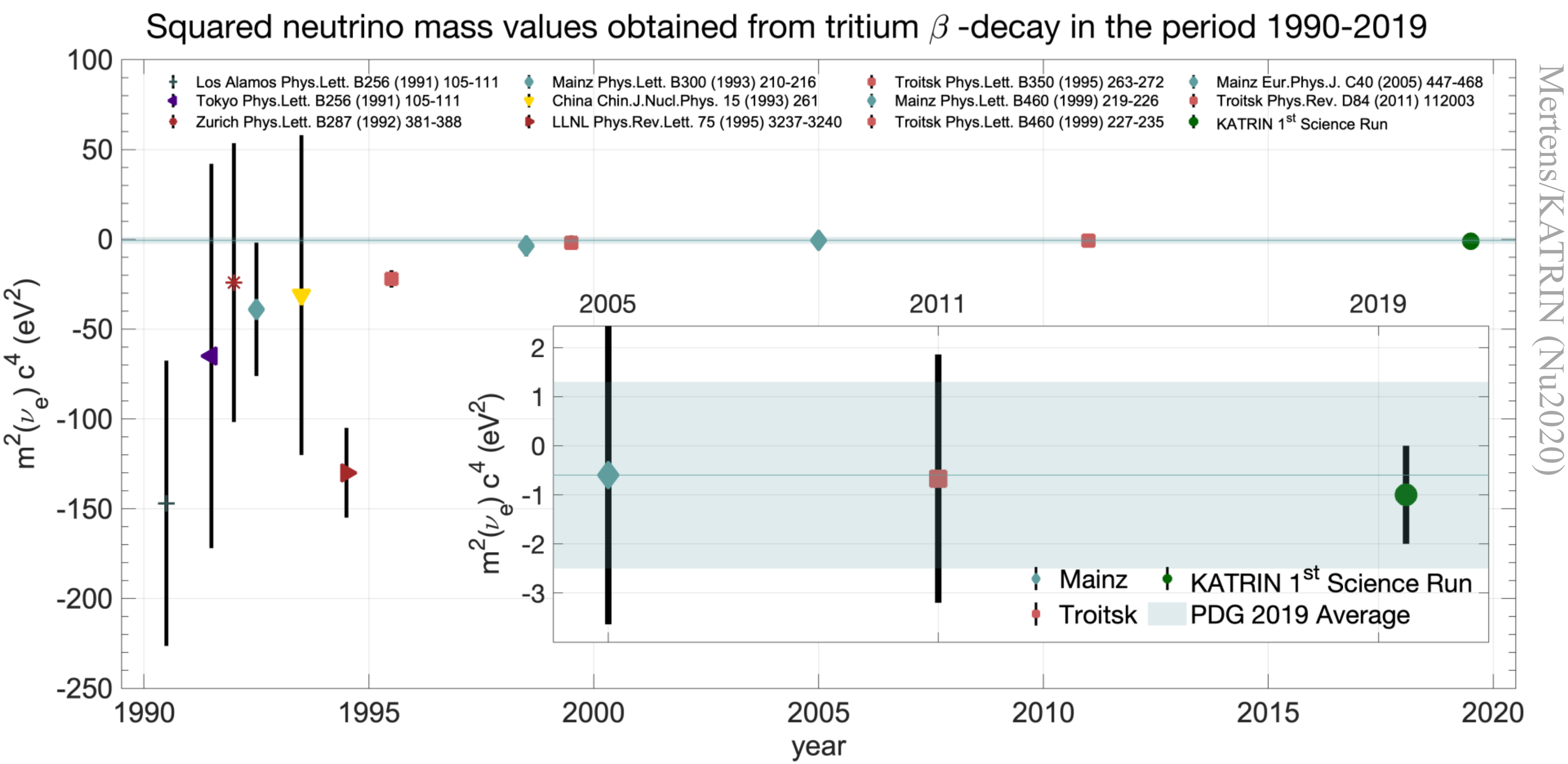
Spectrometer section
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°



Mertens/KATRIN (Nu2020)

Kinematic mass measurement: KATRIN

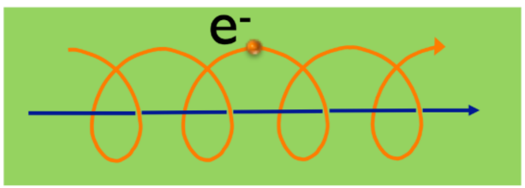
Precision spectroscopy near the endpoint of tritium beta decay



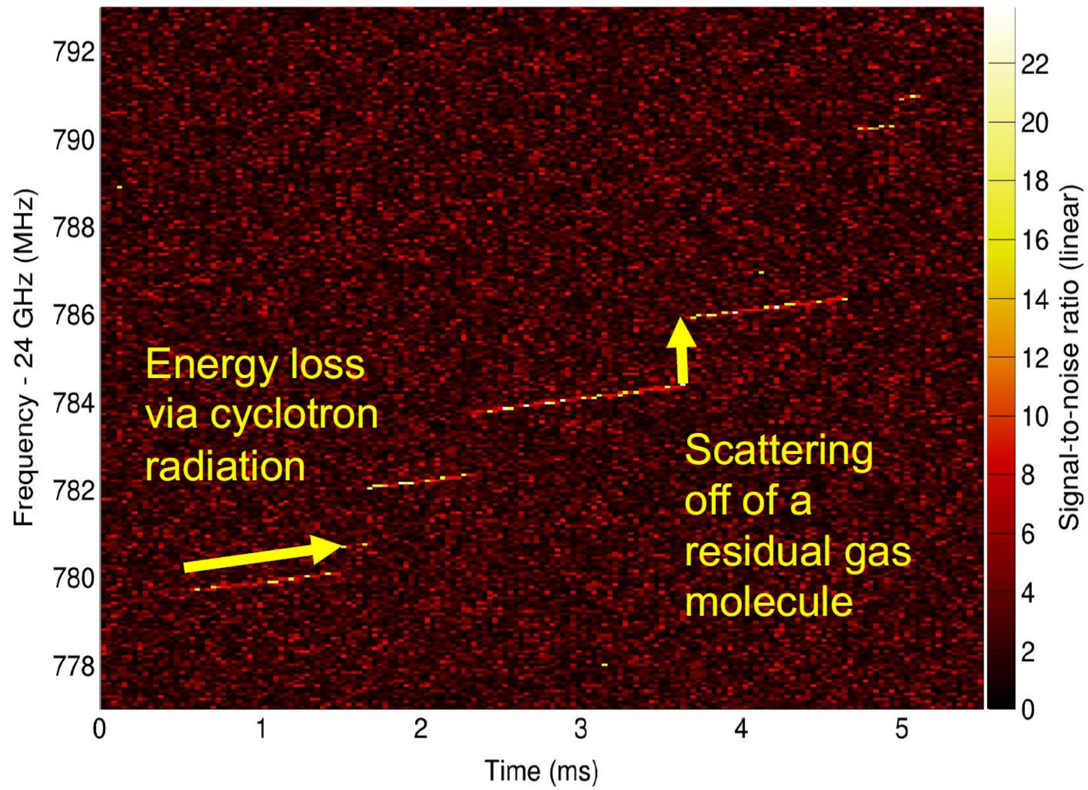
KATRIN latest: $m_\beta < 1.1$ **eV** (90% C.L.)

Kinematic mass measurement: alternatives

- **Spectroscopy through <u>cyclotron radiation</u>: "Project 8"**



$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$



Oblath/Project 8 (Nu2020)

- **^{163}Ho <u>electron capture</u>: study resulting excitation spectra instead using microcalorimetric techniques.**

Neutrinoless double beta decay

- $0\nu\beta\beta$ searches practical in isotopes where single beta decay is kinematically disallowed. $2\nu\beta\beta$ still present as a background.
  - *multiple good candidate isotopes available and in use*

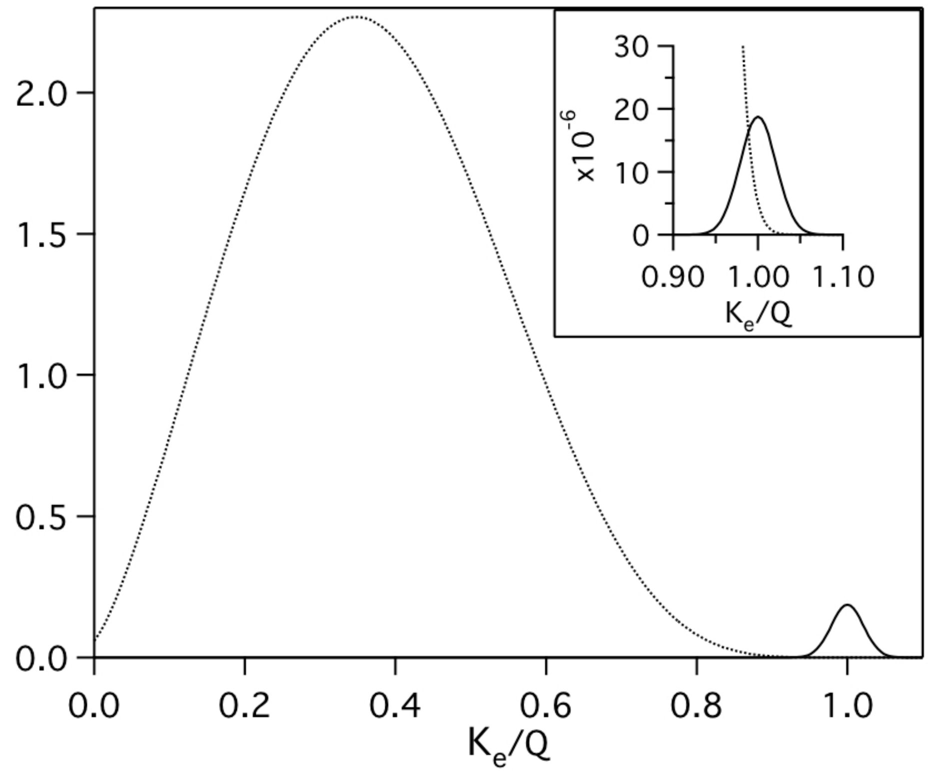
- *General approach*:

  - Clean materials, active and passive shielding

  - **Excellent energy resolution** at endpoint, or some compensating feature if not

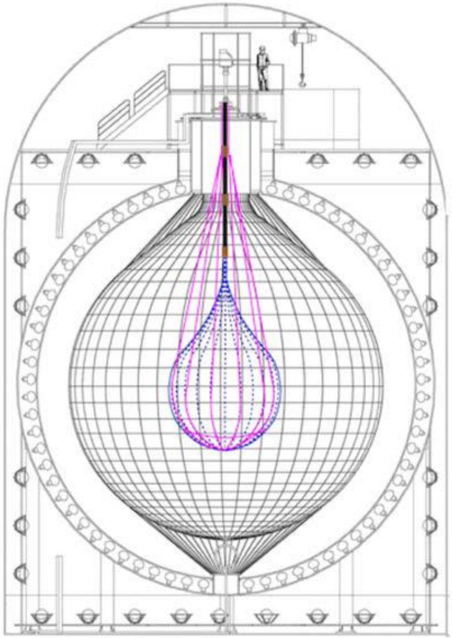
  - Lots of the target isotope (total mass × enrichment fraction)

Example $0\nu\beta\beta$ signature



S. R. Elliott and P. Vogel, Ann. Rev. Nucl. Part. Sci. **52**, 115 (2002)

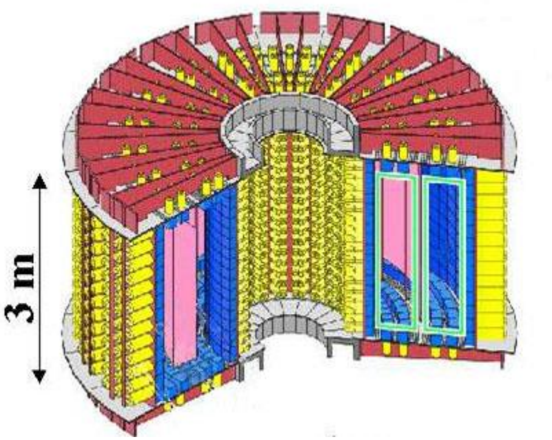
$0\nu\beta\beta$: many techniques



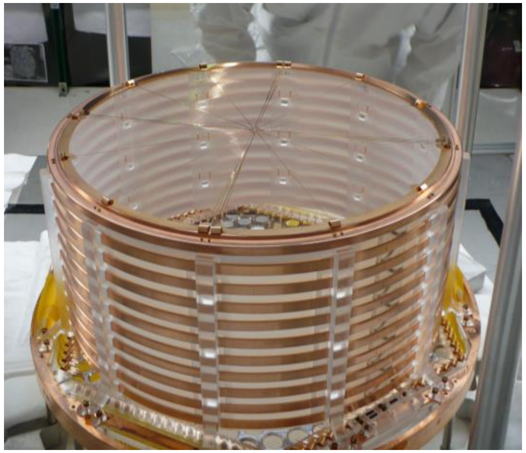
Large volume scintillator detectors
(KamLAND-Zen [Xe], SNO+ [Te])

Scintillating bolometers
(CANDLES [Ca], CUORE [Te],
CUPID [Mo])

Cryogenic semiconductor detectors
(GERDA [Ge], MAJORANA [Ge],
LEGEND [Ge])



Tracking detectors
(NEMO, SuperNEMO [Se, others])



Liquid and HP gas TPCs
(EXO [Xe], NEXT [Xe], LZ [Xe])

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	$^{116}Cd/^{130}Te$	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

R&D Construction Operating Complete

$0\nu\beta\beta$: status

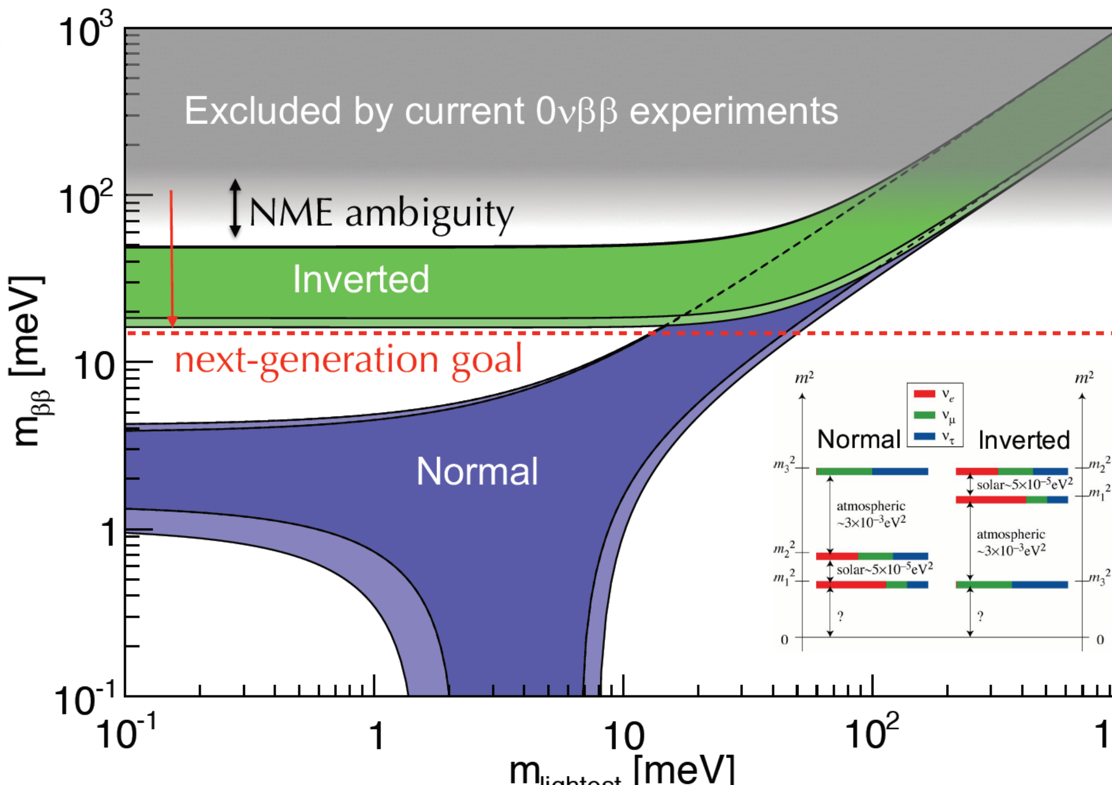
- Best $T_{1/2}$ limits at present:

^{136}Xe	(KamLAND-Zen)	$>1.07\times10^{26}$ yr (90% C.L.)
^{76}Ge	(GERDA)	$>1.8\times10^{26}$ yr (90% C.L.)
^{130}Te	(CUORE)	$>3.2\times10^{25}$ yr (90% C.L.)

- **Complication:** turning lifetime limits into $m_{\beta\beta}$ limits requires nuclear matrix elements that are poorly known
  - *factor of 2-3 uncertainty*

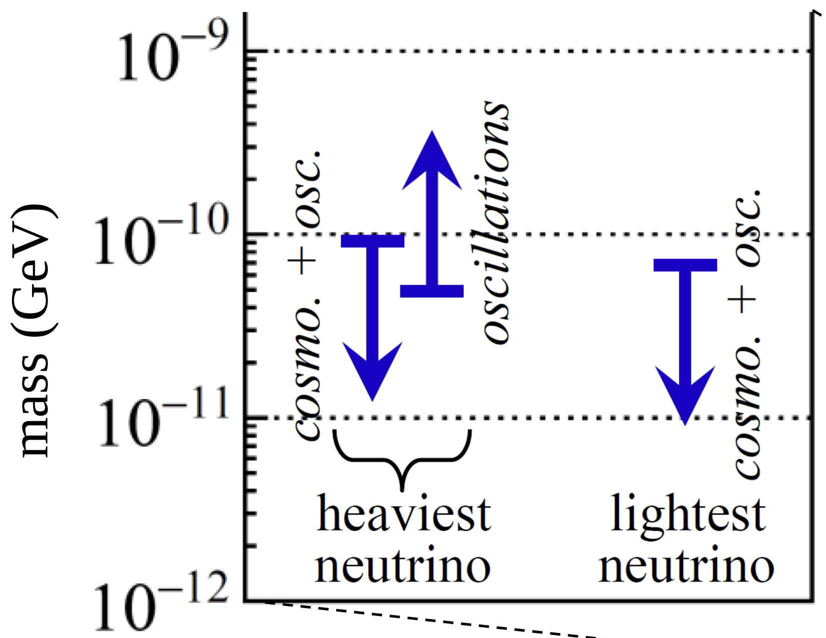
- Over next decade, increase mass while keeping backgrounds at bay to cover inverted mass ordering regime.

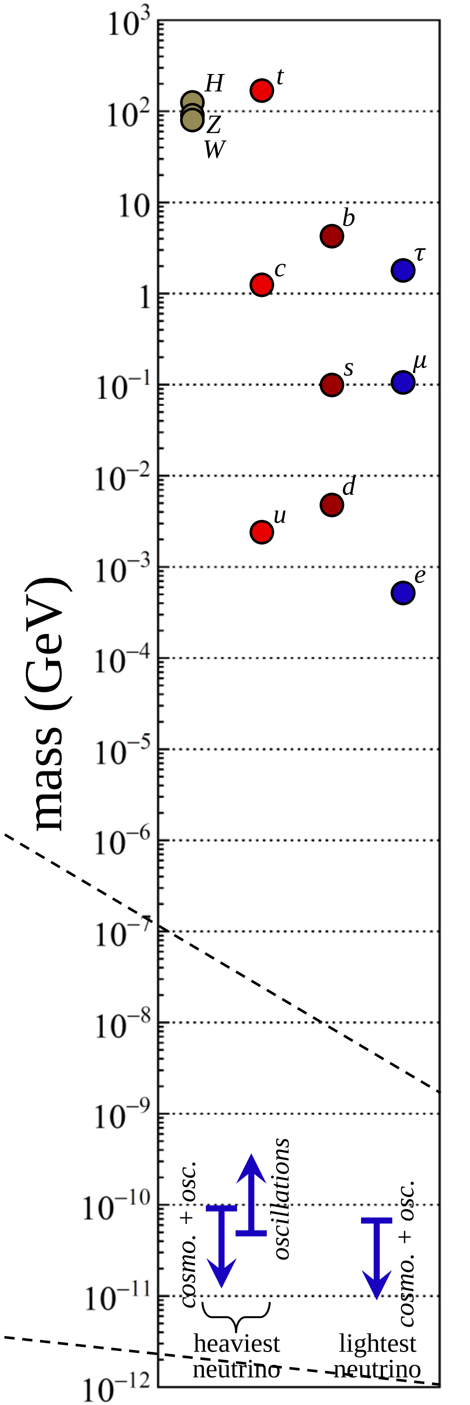
$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{NN}\, m_\pi^2}{g_A^2} M^{0\nu}_{cont} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



J. Detweiler (Nu2020)

Neutrino mass: why so small?



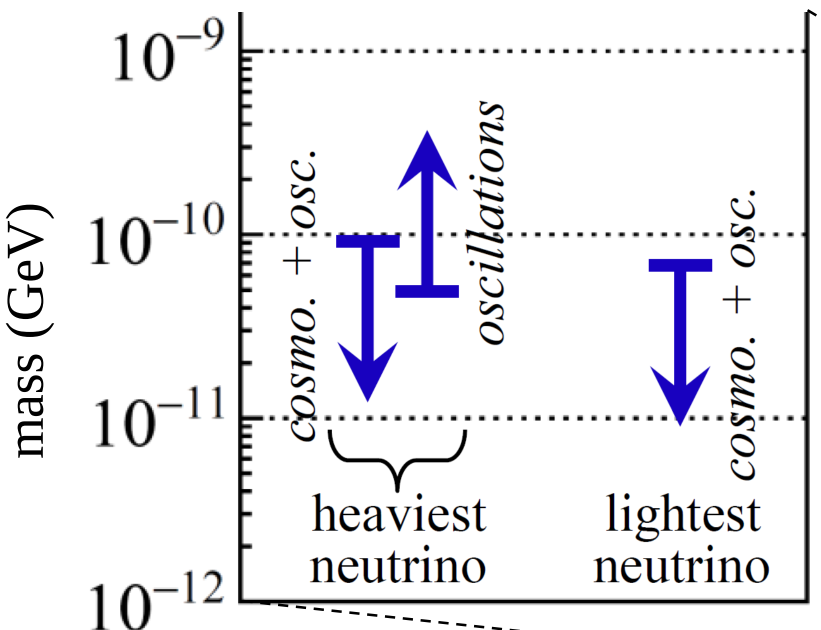


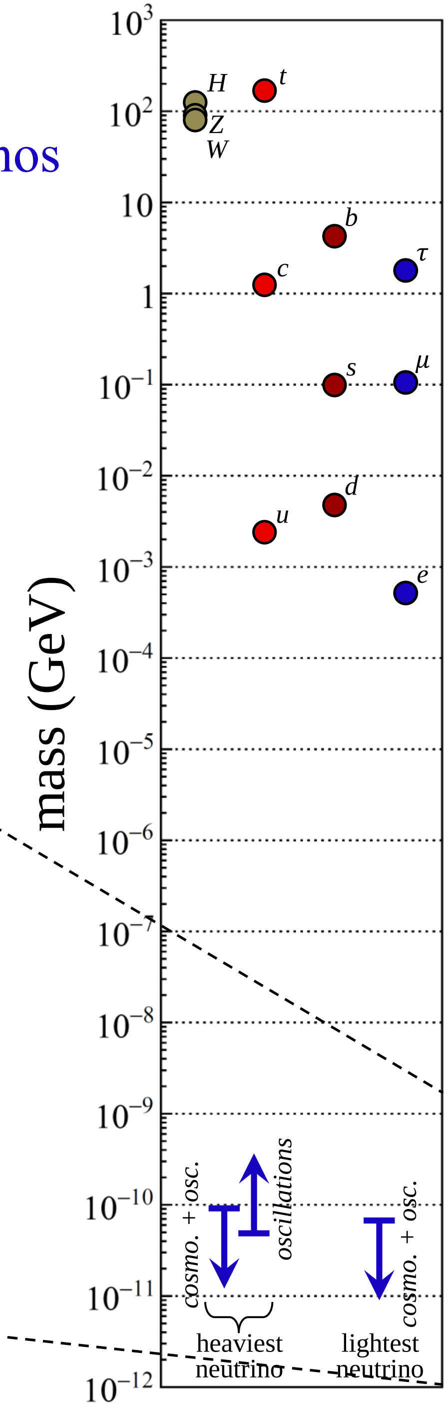
Neutrino mass: why so small?

See-saw mechanism? – Heavy (possibly GUT-scale) RH neutrinos alongside light LH neutrinos:

$$m_\nu \sim \frac{m_{\mathrm{EW}}^2}{m_{\mathrm{GUT}}} \sim \frac{(10^2\ \mathrm{GeV})^2}{10^{15}\ \mathrm{GeV}}$$

$$\sim 10^{-11}\ \mathrm{GeV}$$





Neutrino mass: why so small?

See-saw mechanism? – Heavy (possibly GUT-scale) RH neutrinos alongside light LH neutrinos:

$$m_\nu \sim \frac{m_{\mathrm{EW}}^2}{m_{\mathrm{GUT}}} \sim \frac{(10^2\ \mathrm{GeV})^2}{10^{15}\ \mathrm{GeV}}$$

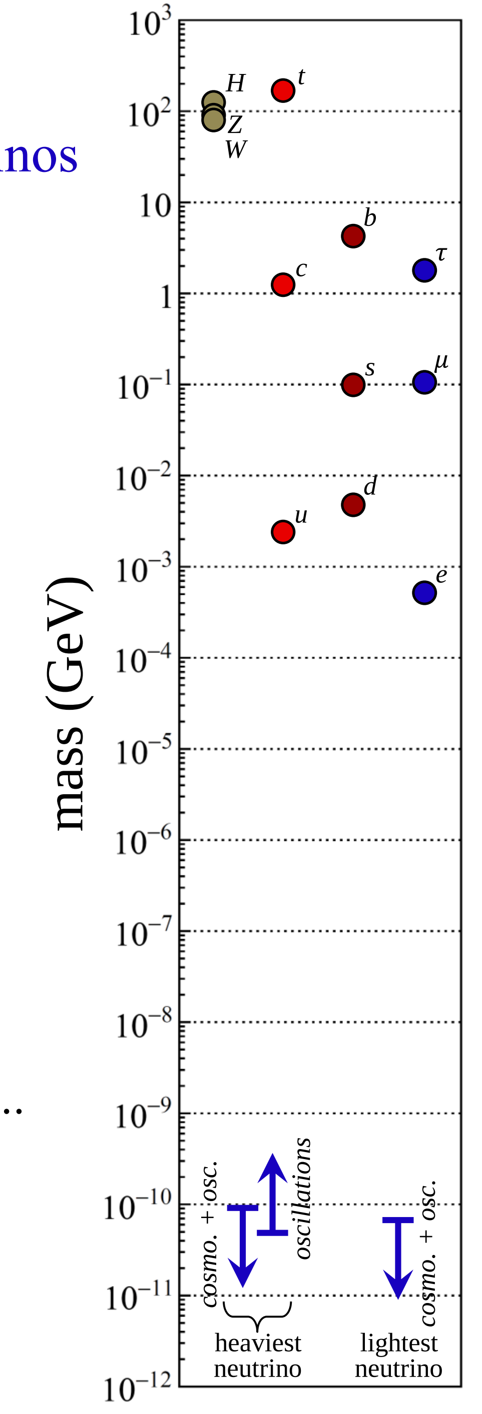
$$\sim 10^{-11}\ \mathrm{GeV}$$

Would imply that the **physics of neutrino mass** is connected to **extremely high energy scales**.

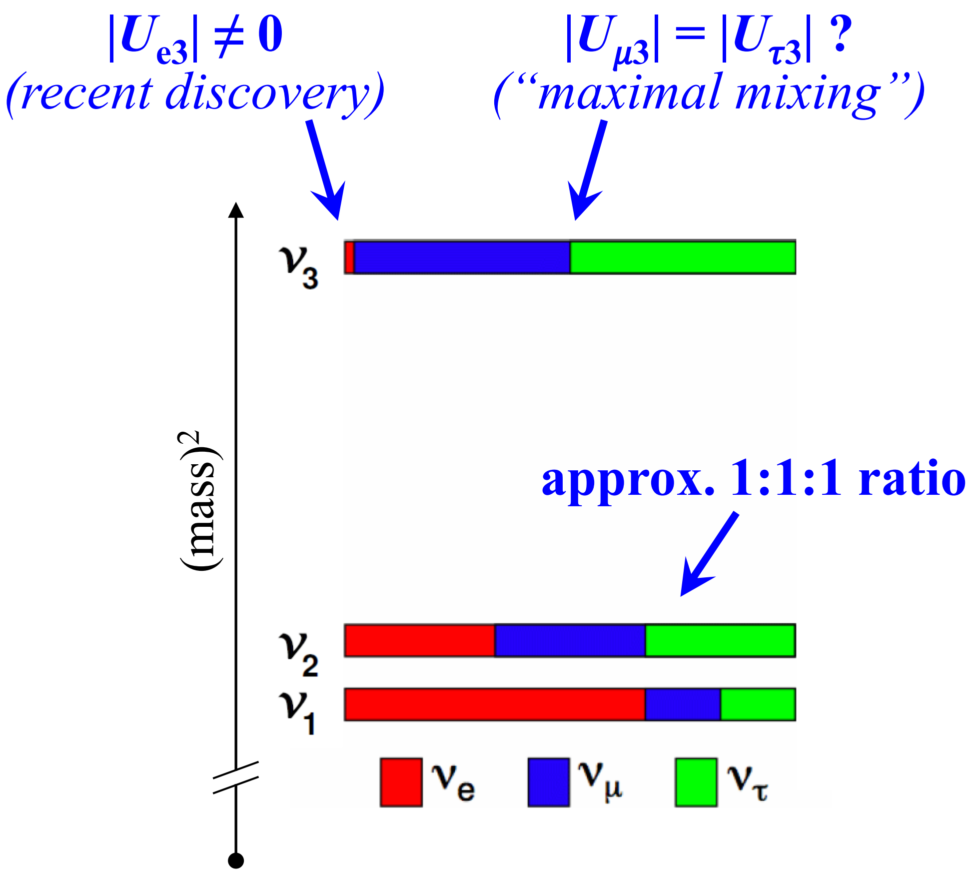
Potential new physics signatures in oscillation expts:

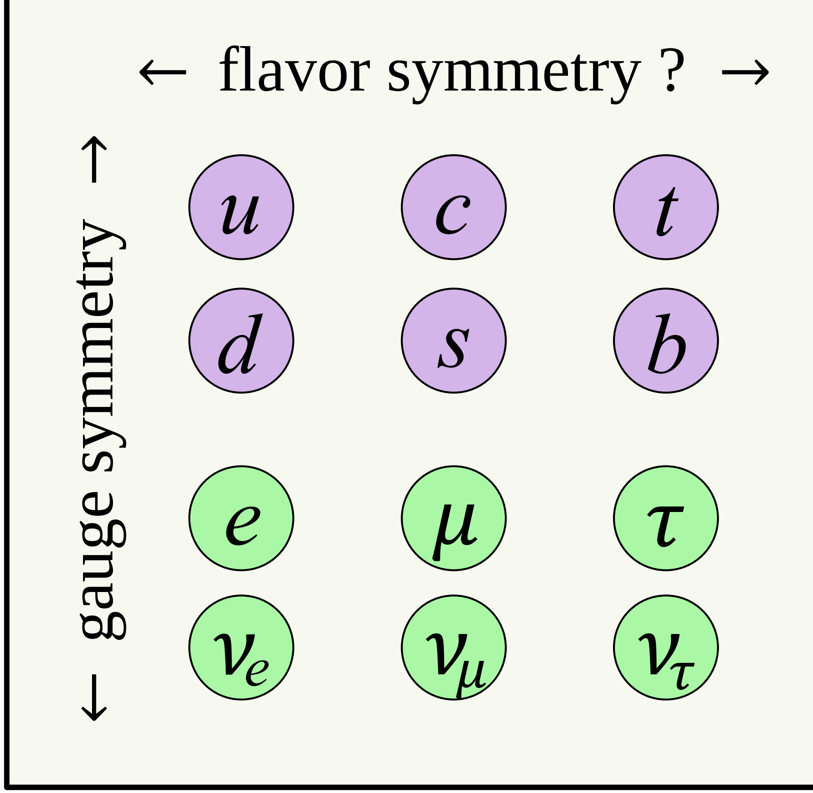
non-unitarity, non-standard interactions, >3 neutrinos, large extra dimensions, effective CPTv, decoherence, neutrino decay, …

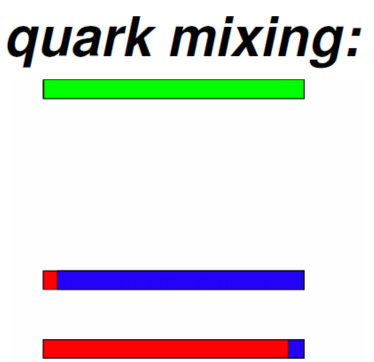
Now textbook material, the see-saw mechanism goes back to P. Minkowski (1977); M. Gell-Mann, P. Ramond and R. Slansky (1979); and T. Yanagida (1979)



Flavor structure



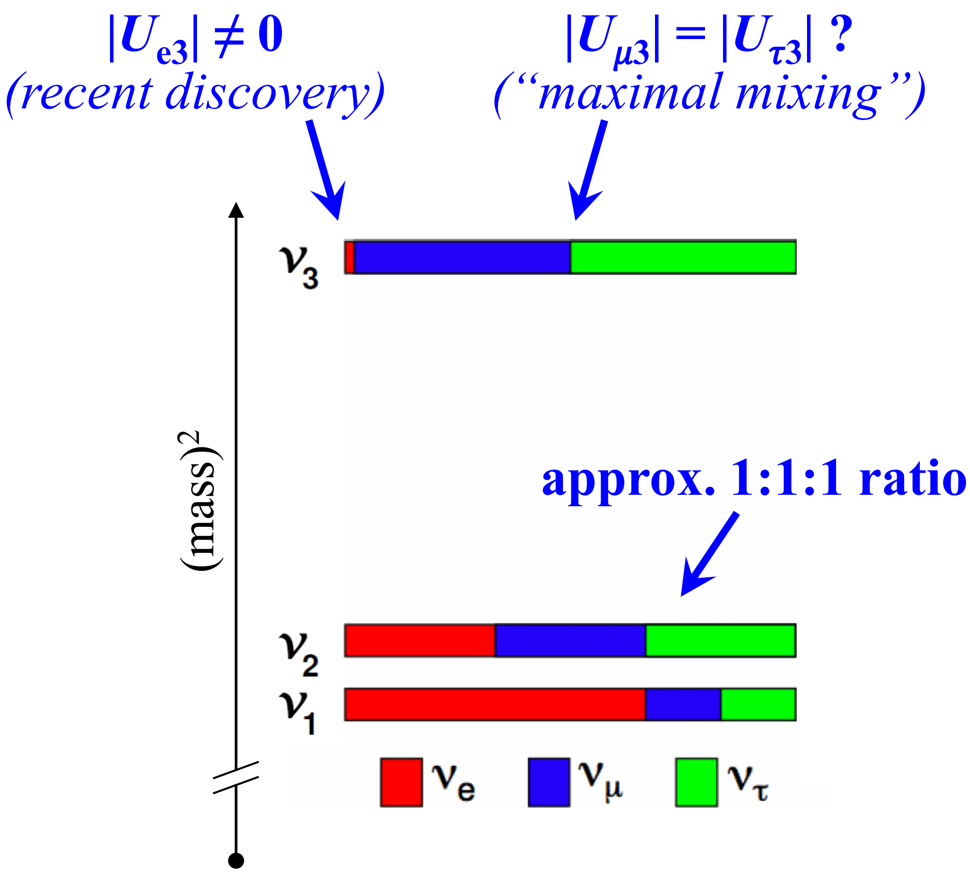




What **flavor symmetry** can produce this pattern of mixings and masses, and how is that symmetry broken?

More broadly: what are the **dynamical origins** of fermion masses, mixings, and *CP* violation?

Flavor structure



Experimental question:

☆ $\sin^2\theta_{23} \neq 0.5$?

Non-maximal mixing?
If so, which way does it break?

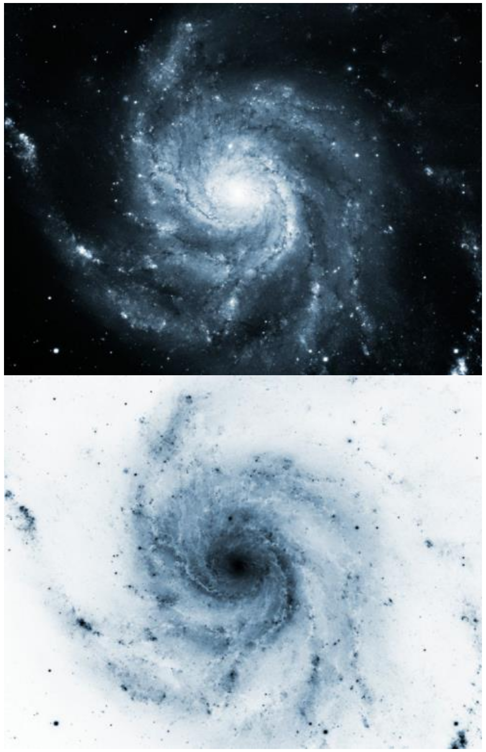
Standard parametrization of PMNS matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP violation

New source of *CP* violation required to explain baryon asymmetry of universe

part-per-billion level of matter/antimatter asymmetry in early universe



Neutrino *CP*v **allowed in νSM**, but not yet observed

…due so far to the experimental challenge, not physics!

Leptogenesis[1] **is a workable solution** for the baryon asymmetry, but need to first **find *any* leptonic (neutrino) *CP*v**

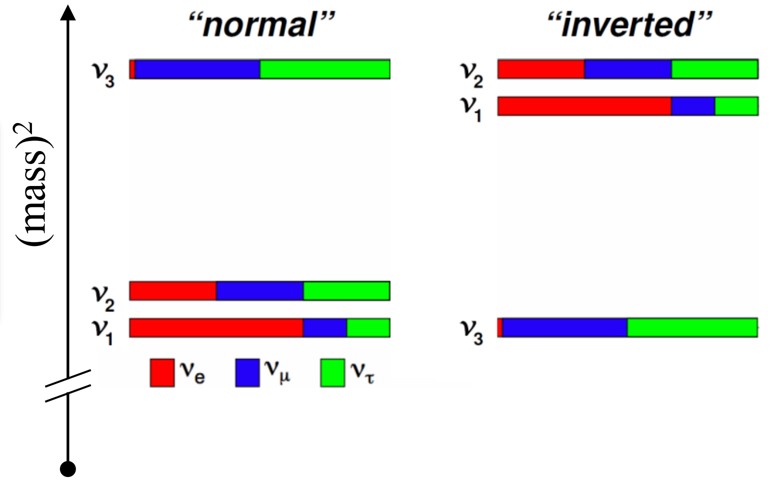
★ $\sin\delta \neq 0$?

Leptonic CP violation?

[1] M. Fukugita and T. Yanagida (1986); rich history since then.

ν mass hierarchy

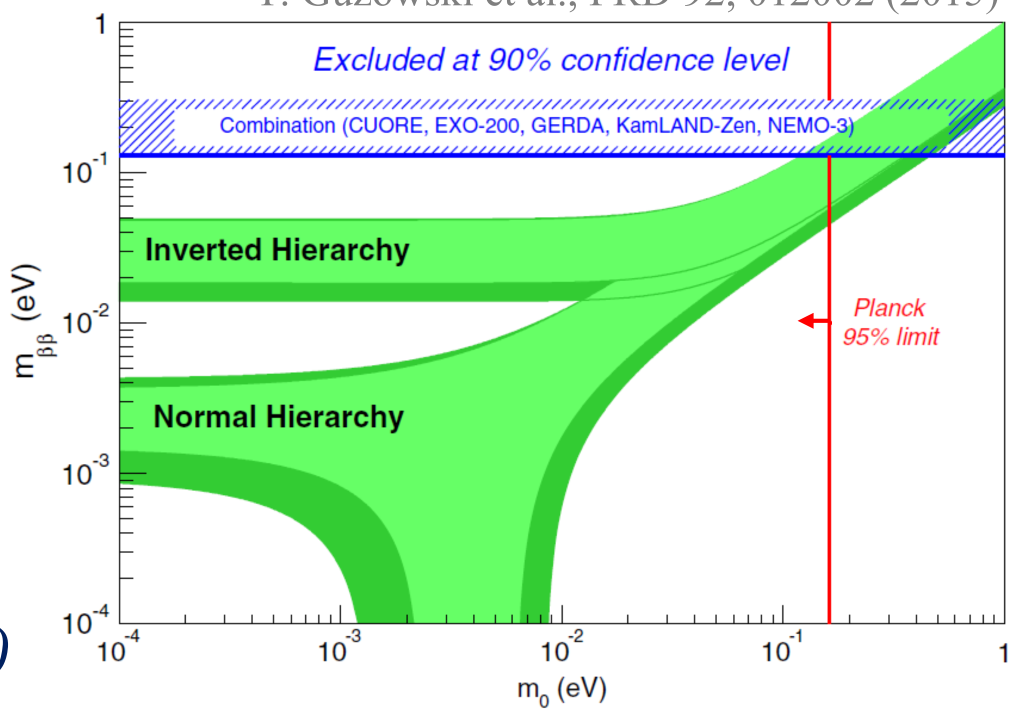
★ Are the electron-rich states ν_1 & ν_2 **heavier or lighter** than ν_3?



Far-reaching implications for such a simple question:

- **$0\nu\beta\beta$** and **Majorana nature of ν**
- Experimental approach to and interpretation of m_β
- **Cosmology** and **astrophysics**
- **Theoretical frameworks** for flavor and mass generation

P. Guzowski et al., PRD 92, 012002 (2015)



Notice:

An inverted hierarchy implies **<1.5% mass degeneracy**.

→ *Would hint at…??* *(cf.: π^+/π^0)*

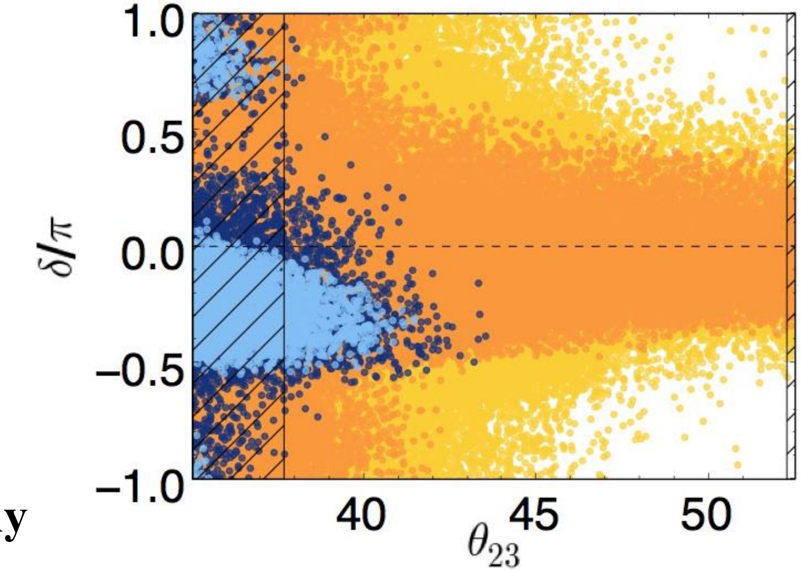
Flavor: A core problem for 21st century particle physics

Flurry of theoretical work.

Discrete flavor groups (A_4, S_4, $\Delta(3n^2)$, …) often combined with GUTs. Non-trivial flavor texture in heavy sector.

Emphasis on genuine predictive power. Explicit connections between low energy observables and leptogenesis.

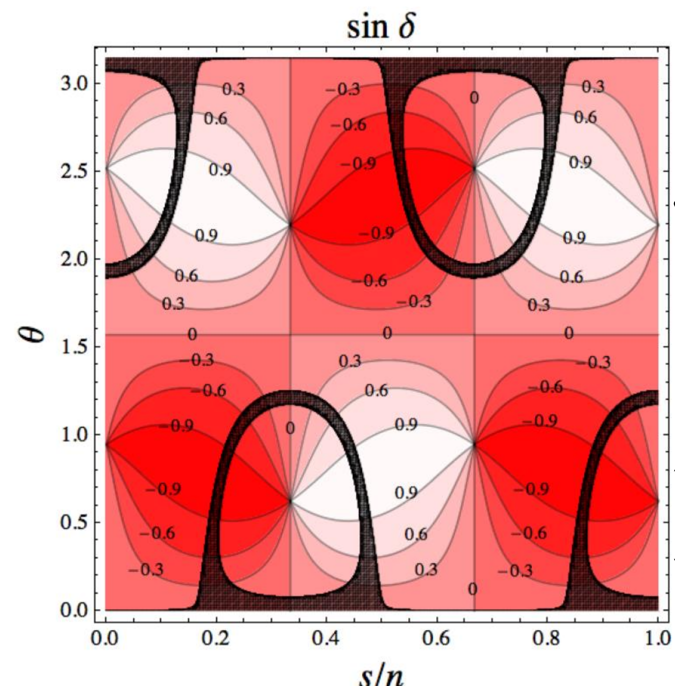
Often **immutable preferences** for **mass hierarchy** and **μ/τ asymmetry**



Di Bari, Marzola, Re Fiorentin
Nucl. Phys. B **893**, 122 (2015)

tan β	Output			
5	θ^q_{12}	13.027°	θ^l_{12}	34.3°
	θ^q_{13}	0.1802°	θ^l_{13}	8.67°
	θ^q_{23}	2.054°	θ^l_{23}	45.8°
	δ^q	69.18°	δ^l	-86.7°
	y_u	2.92×10^{-6}	Δm^2_{21}	7.38×10^{-5} eV^2
	y_c	1.43×10^{-3}	Δm^2_{31}	2.48×10^{-3} eV^2
	y_t	5.34×10^{-1}		
	y_d	4.30×10^{-6}	y_e	1.97×10^{-6}
	y_s	9.51×10^{-5}	y_μ	4.16×10^{-4}
	y_b	7.05×10^{-3}	y_τ	7.05×10^{-3}

Björkeroth, de Anda,
de Medeiros Varzielas, King
JHEP **06**, 141 (2015)



Hagedorn, Meroni, Molinaro
Nucl. Phys. B **891**, 499 (2015)

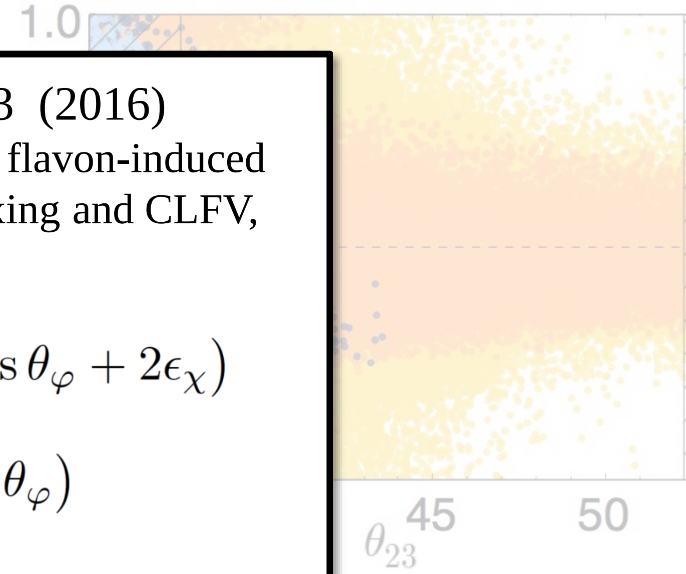
Flurry of theoretical work

Discrete flavor groups combined with GUTs. in heavy sector.

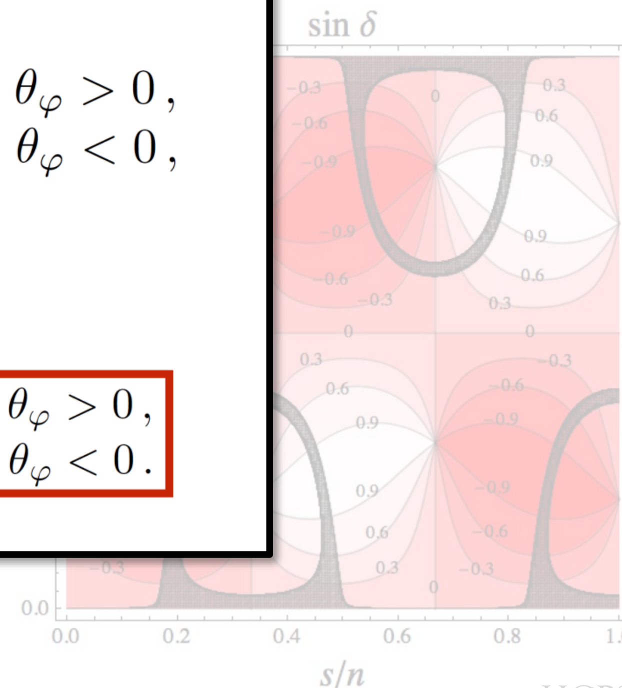
Emphasis on genuine p connections between l and leptogenesis.

Often **immutable pref** and **μ/τ asymmetry**

$\tan\beta$				
5	θ^q_{12}	13.027°		
	θ^q_{13}	0.1802°		
	θ^q_{23}	2.054°		
	δ^q	69.18°		
	y_u	2.92×10^{-6}		
	y_c	1.43×10^{-3}		
	y_t	5.34×10^{-1}		
	y_d	4.30×10^{-6}		
	y_s	9.51×10^{-5}		
	y_b	7.05×10^{-3}	y_τ	7.05×10^{-3}



Di Bari, Marzola, Re Fiorentin
Nucl. Phys. B **893**, 122 (2015)



Hagedorn, Meroni, Molinaro
Nucl. Phys. B **891**, 499 (2015)

Pascoli and Zhou, JHEP **06**, 73 (2016)

Flavor symmetry $A_4 \times Z_2 \times Z_4$; flavon-induced connections between flavor mixing and CLFV, ***and…***

$$\sin\theta_{12} = \frac{1}{\sqrt{3}}\left(1 - 2|\epsilon_\varphi|\cos\theta_\varphi + 2\epsilon_\chi\right)$$

$$\sin\theta_{23} = \frac{1}{\sqrt{2}}\left(1 + |\epsilon_\varphi|\cos\theta_\varphi\right)$$

$$\sin\theta_{13} = \sqrt{2}|\epsilon_\varphi \sin\theta_\varphi|$$

$$\delta = \begin{cases} 270^\circ - 2|\epsilon_\varphi|\sin\theta_\varphi\,, & \theta_\varphi > 0\,, \\ 90^\circ - 2|\epsilon_\varphi|\sin\theta_\varphi\,, & \theta_\varphi < 0\,, \end{cases}$$

$$\boxed{\epsilon_\varphi = |\epsilon_\varphi| e^{i\theta_\varphi}}$$

$$\boxed{\delta \approx \begin{cases} 270^\circ - \sqrt{2}\theta_{13}\,, & \theta_\varphi > 0\,, \\ 90^\circ + \sqrt{2}\theta_{13}\,, & \theta_\varphi < 0\,. \end{cases}}$$

- A lot of the neutrino sector is practically probed through the **study of neutrino oscillations**

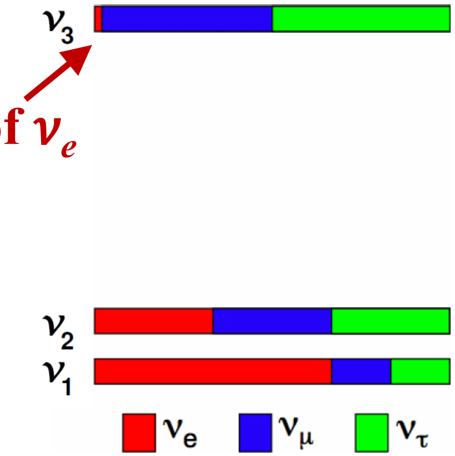
- Oscillation experiments come in many shapes to access particular pieces of the intertwined puzzle

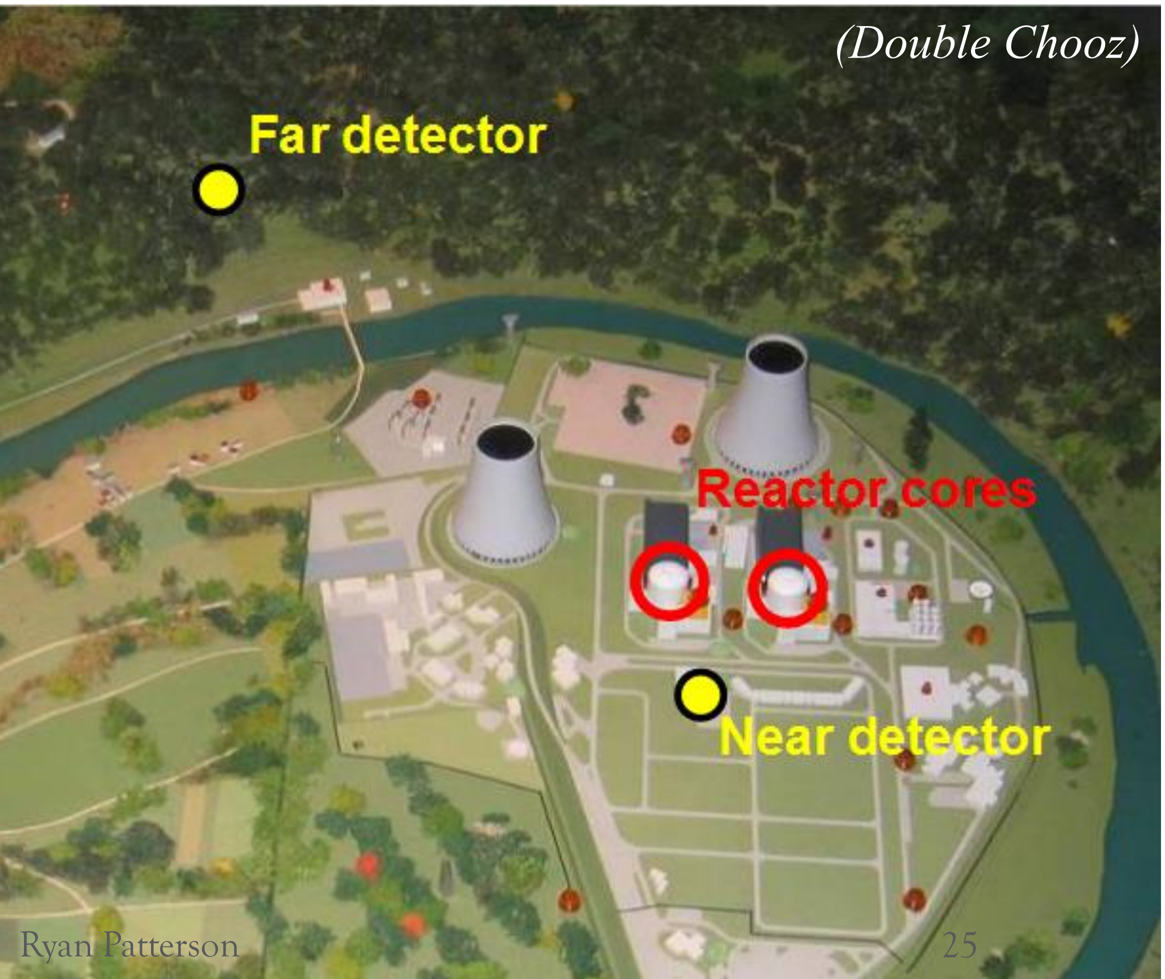
Reactors at short baselines

- θ_{13} **was last mixing angle** to be bracketed. Previously just known to be rather **small relative to θ_{12}, θ_{23}**
- **Reactor expts.** use inverse beta decay: $\overline{\nu}_e + p \rightarrow e^+ + n$

  prompt e^+ signal, delayed n-capture signal

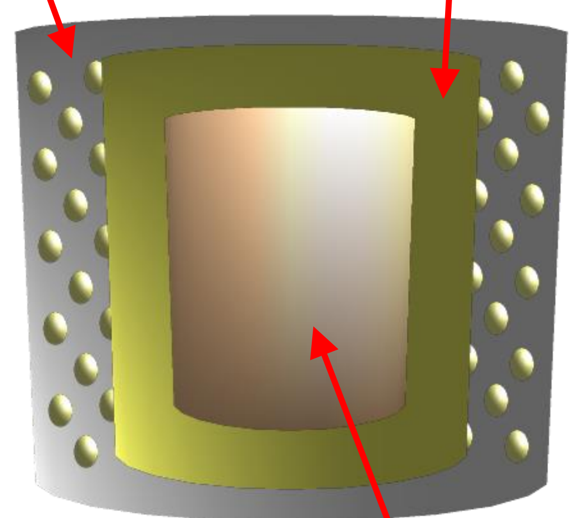
a bit of ν_e



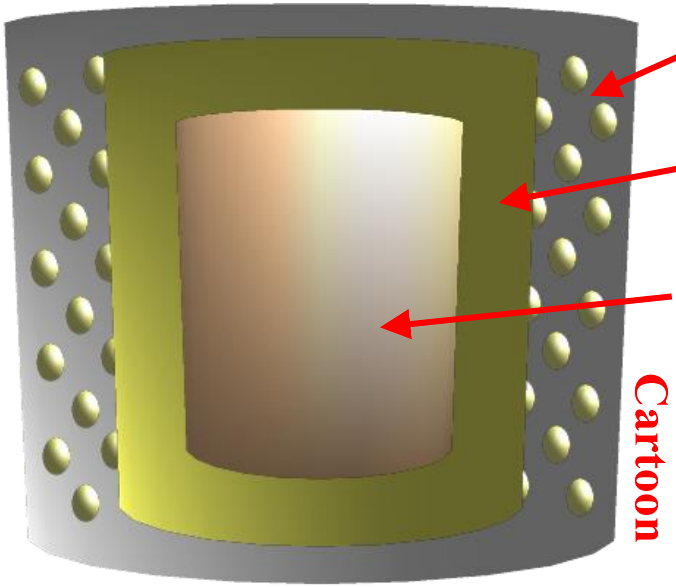


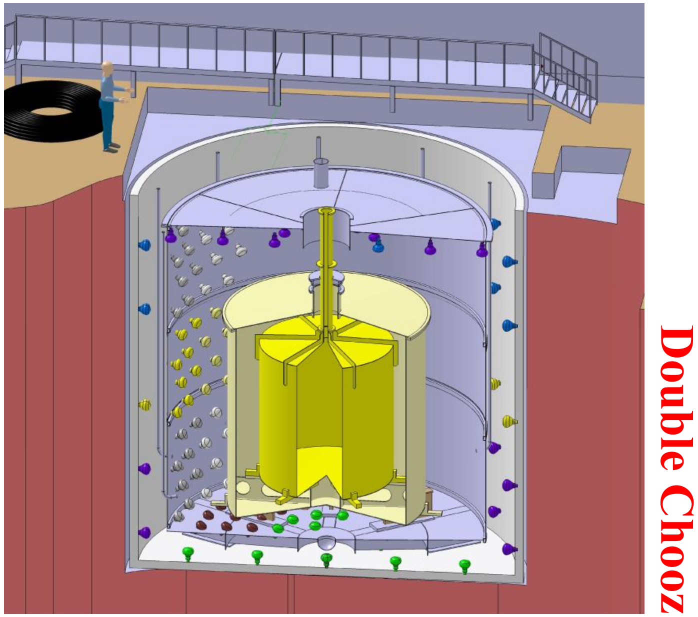
Outer buffer region surrounded by PMTs

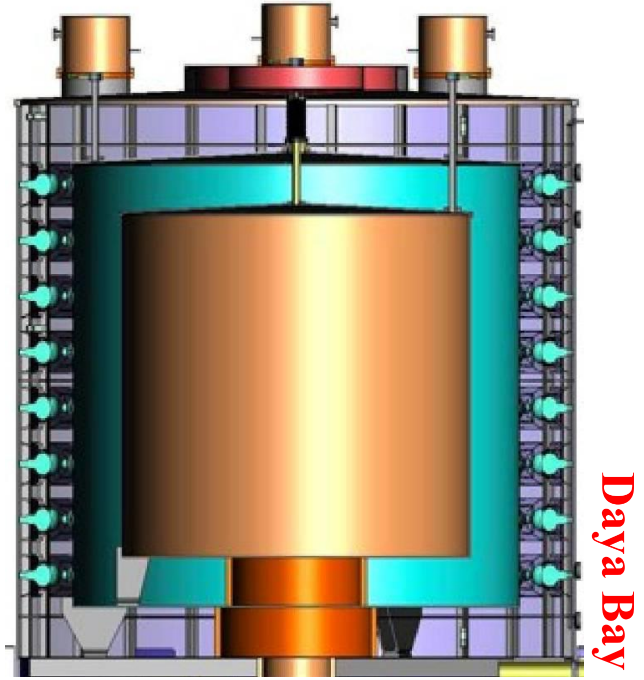
Gamma catcher (undoped scintillator)

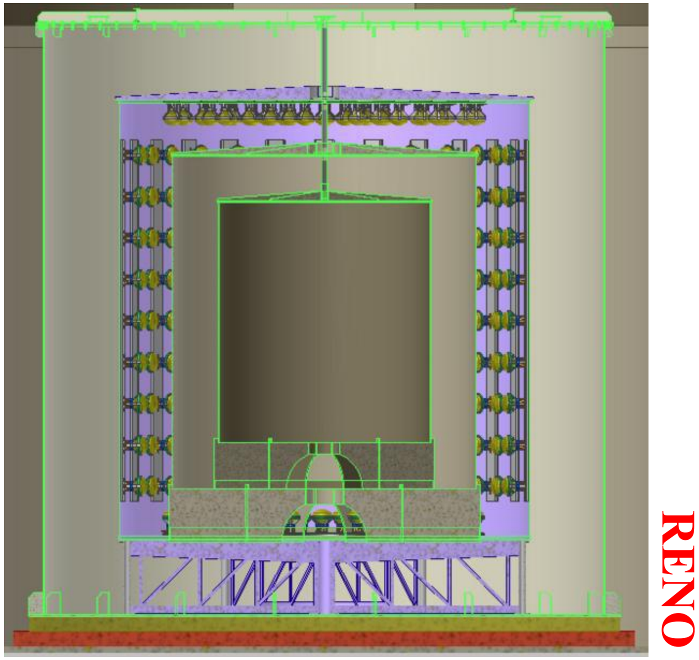


Target region (Gd-doped scintillator)


Buffer
Gamma catcher
Target
Cartoon


Double Chooz


Daya Bay


RENO

Reactors at short baselines

- **Clean measurement** of a single parameter, θ_{13}:
  - Baseline too short for neutrino mass hierarchy to matter (via matter effects)
  - $\bar{\nu}_e \rightarrow \bar{\nu}_e$ process is *CP* symmetric
  - L/E too small for $\Delta m^2{}_{21}$ to matter much

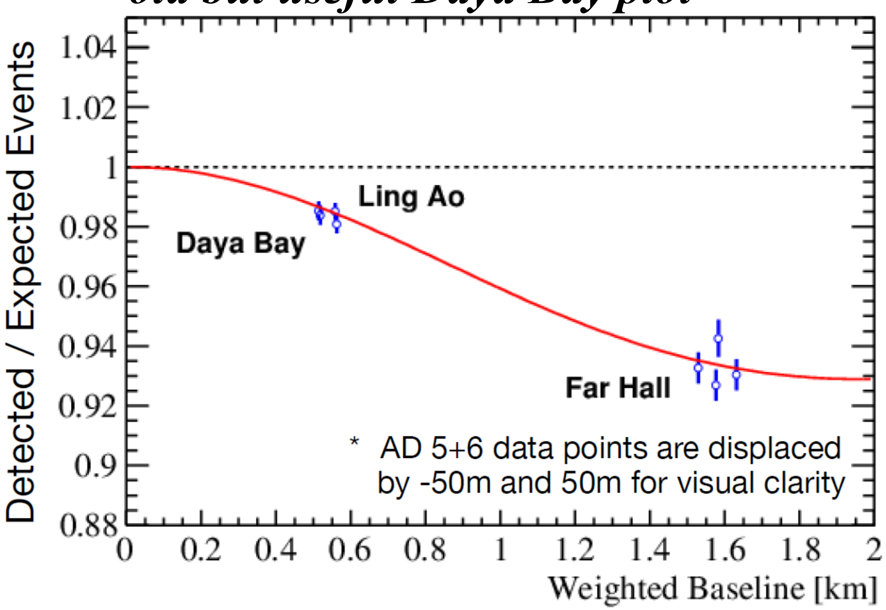
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

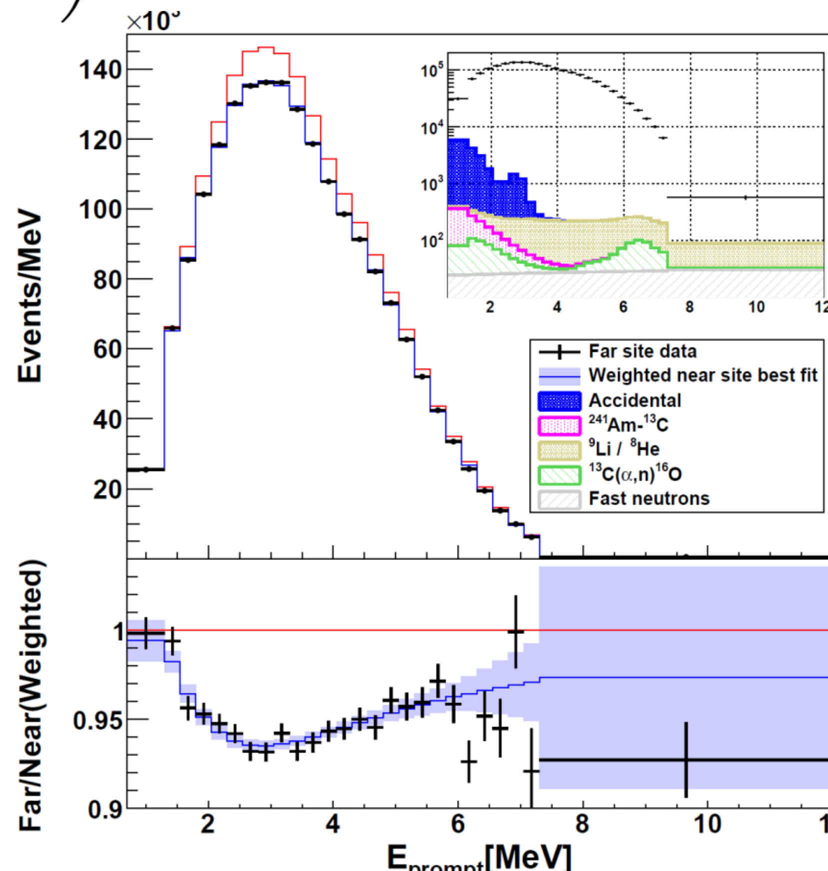
Daya Bay result:

$$\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$$

Daya Bay experiment holds best measurement

old but useful Daya Bay plot



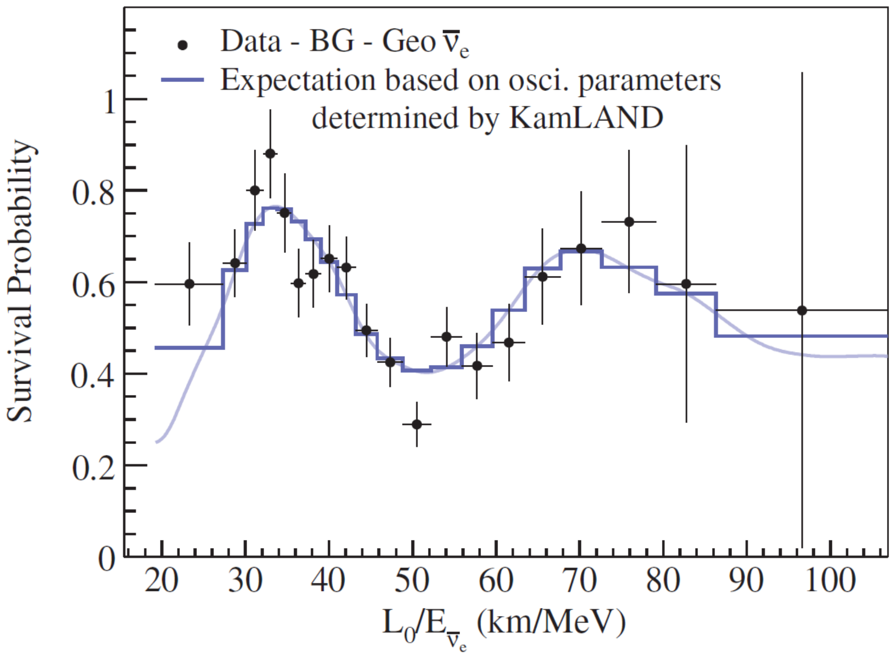


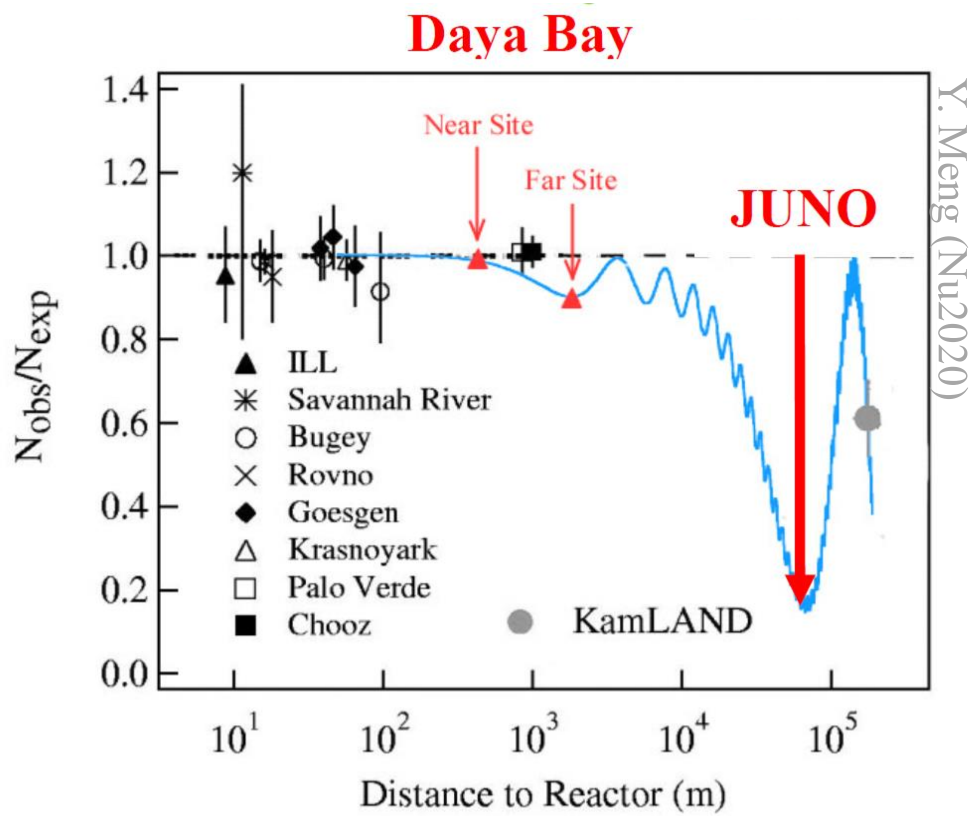
Daya Bay Collab., Phys. Rev. Lett. **121**, 241805

Reactors at medium baselines

- **Same *E* (reactor source), increase *L* by ~30×**
  - Now tuned to Δm^2_{21}-driven oscillations ("solar" oscillations)
  - θ_{13} small / subdominant now (θ_{12} the leading mixing angle)
  - The faster oscillations are blurred out by energy resolution as well

KamLAND measured terrestrially what the other experiments saw with solar neutrinos (where MSW effect is central!)





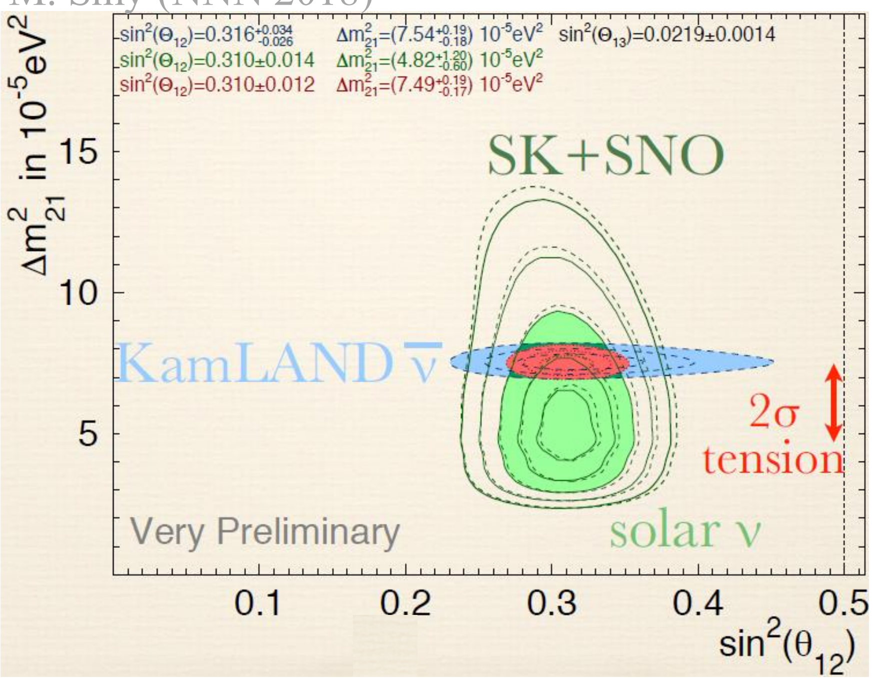
JUNO: Future experiment high precision and perhaps to observe dominant and subdominant oscillations together (→ mass hierarchy)

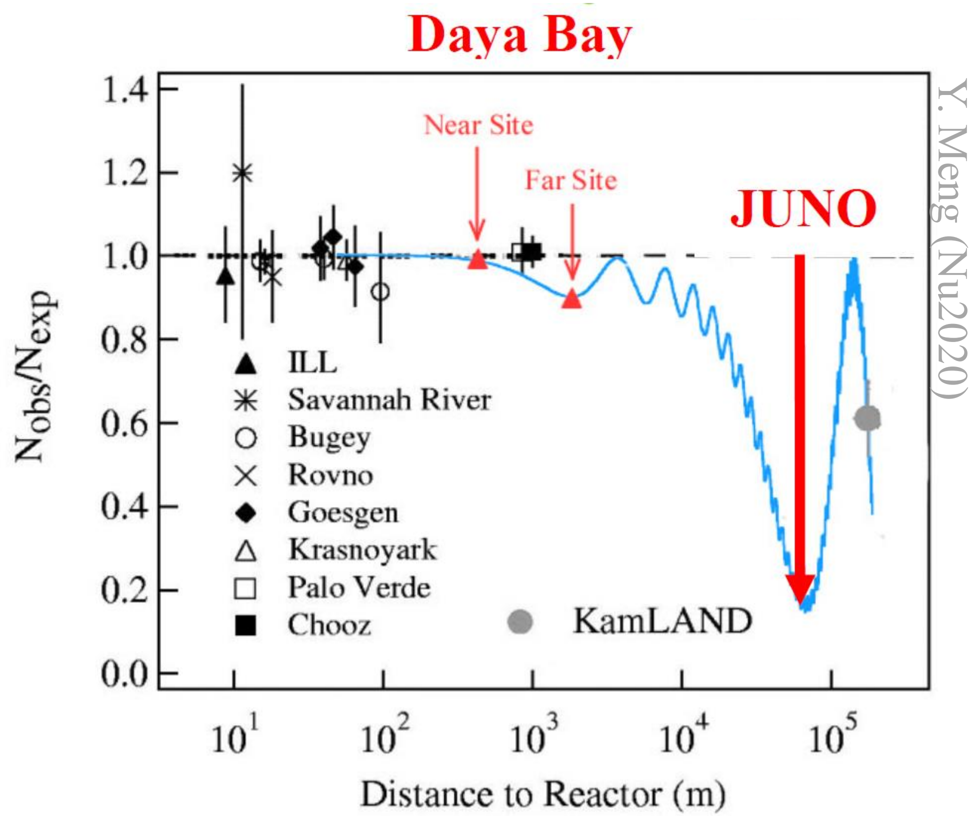
Reactors at medium baselines

- **Same E (reactor source), increase L by ~30×**
  - Now tuned to Δm^2_{21}-driven oscillations ("solar" oscillations)
  - θ_{13} small / subdominant now (θ_{12} the leading mixing angle)
  - The faster oscillations are blurred out by energy resolution as well

KamLAND measured terrestrially what the other experiments saw with solar neutrinos (where MSW effect is central!)

M. Smy (NNN 2018)



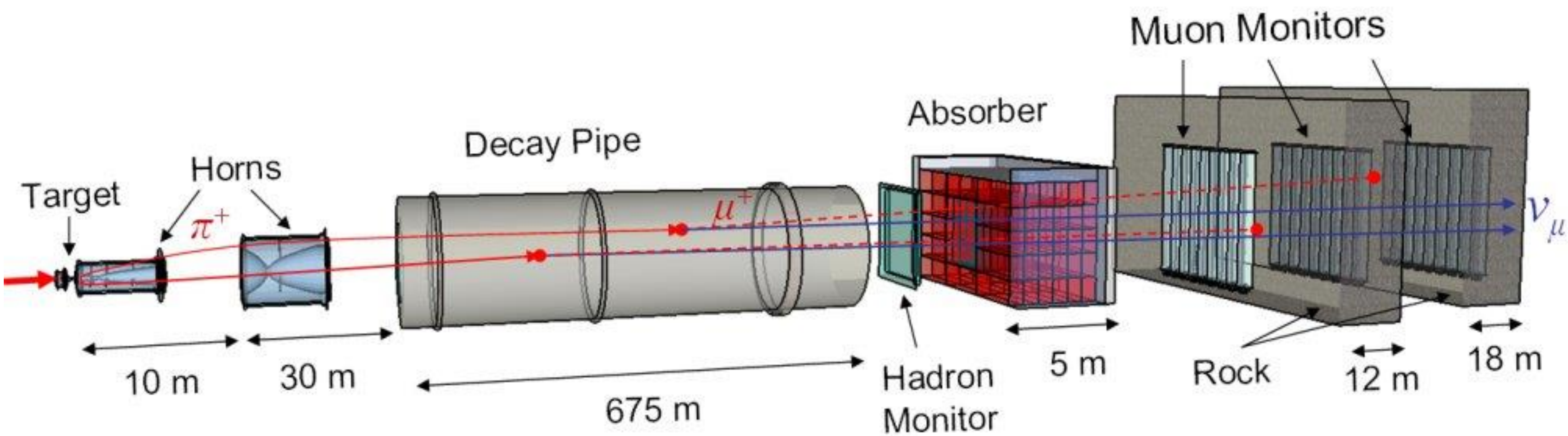


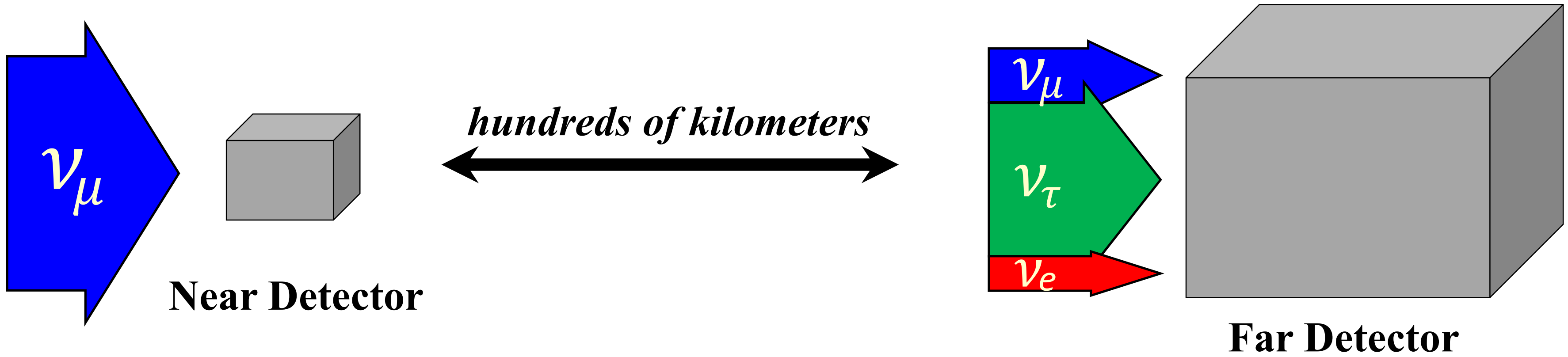
JUNO: Future experiment high precision and perhaps to observe dominant and subdominant oscillations together (→ mass hierarchy)

Long-baseline oscillation experiments

- **Higher *E* (~GeV), longer *L*, more accessible channels**
  - $\nu_\mu \rightarrow \nu_e / \nu_\mu / \nu_\tau$: enough *E* to make charged lepton partners in CC interactions (though ν_τ somewhat specialized (*e.g.*, OPERA expt.))
  - Multiple relevant PMNS parameters
  - Larger mass splitting relevant
  - Large (massive) far detector needed

Example accelerator source (**NuMI beamline diagram**):



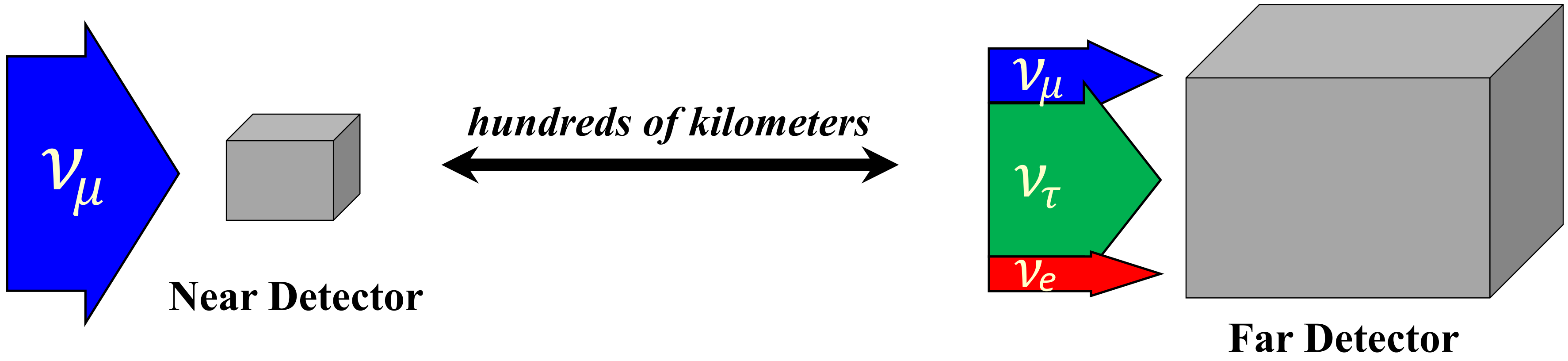


ν_μ survival (or "disappearance"):

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \underbrace{\sin^2 2\theta_{23}} \sin^2(\Delta m^2_{32} L/4E)$$

experimental data are **consistent with unity**
(*i.e.*, maximal mixing)

...to leading order



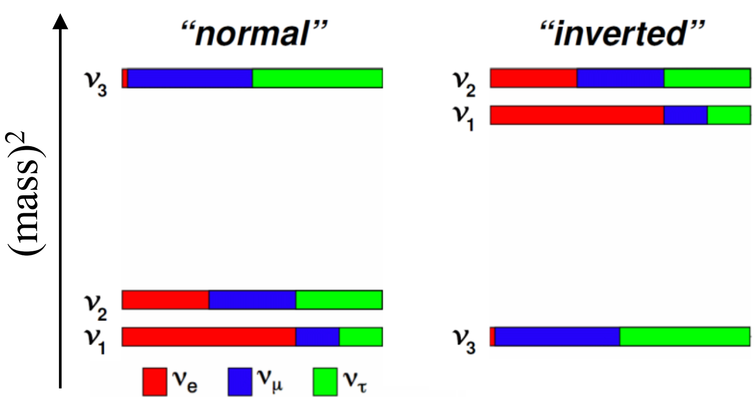
ν_e appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2(\Delta m^2_{32}L/4E)$$

*...plus potentially large **CPv** and **matter effect*** modifications!*

* ν_e see different potential than $\nu_{\mu,\tau}$ when propagating through matter (here, the earth)

⇒ a hierarchy-dependent effect !



$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4 \quad . \tag{13.39}$$

Here, $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ is the small ($\sim 1/30$) ratio between the solar and atmospheric squared-mass splittings, and

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \quad , \tag{13.40}$$

$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \quad , \tag{13.41}$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \quad , \tag{13.42}$$

and

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \quad . \tag{13.43}$$

In these expressions, $\Delta \equiv \Delta m^2_{31} L/4E$ is the kinematical phase of the oscillation. The quantity $x \equiv 2\sqrt{2} G_F N_e E/\Delta m^2_{31}$, with G_F the Fermi coupling constant and N_e the electron number density, is a measure of the importance of the matter effect resulting from coherent forward-scattering of electron neutrinos from ambient electrons as the neutrinos travel through the earth from the source to the detector [cf. Sec. I].

(From PDG)

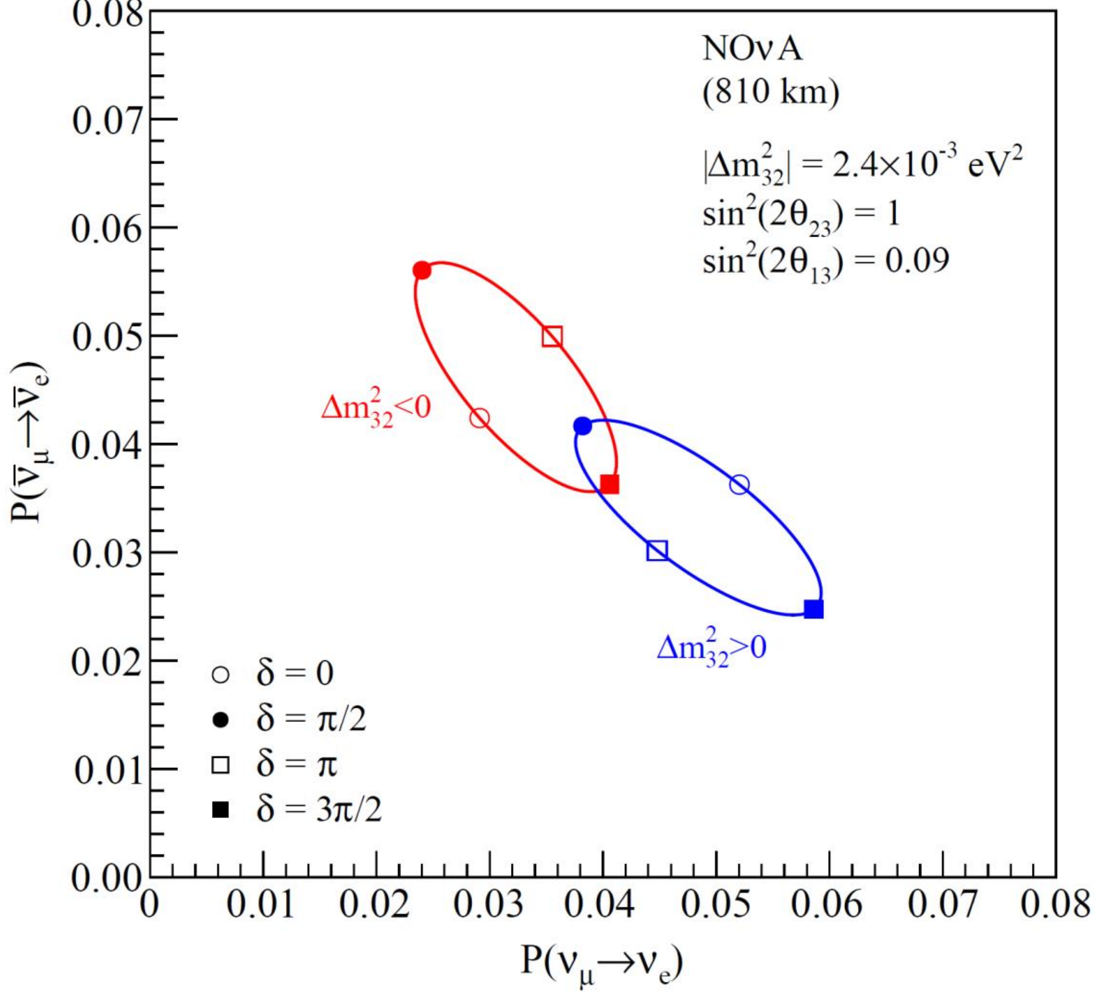
(for antineutrinos, $x \to -x$ and $\delta \to -\delta$)

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs. $P(\nu_\mu \to \nu_e)$

for a 2 GeV neutrino in NOvA

→ Dependence on $\boldsymbol{\delta}$
and **$\boldsymbol{\nu}$ mass hierarchy**

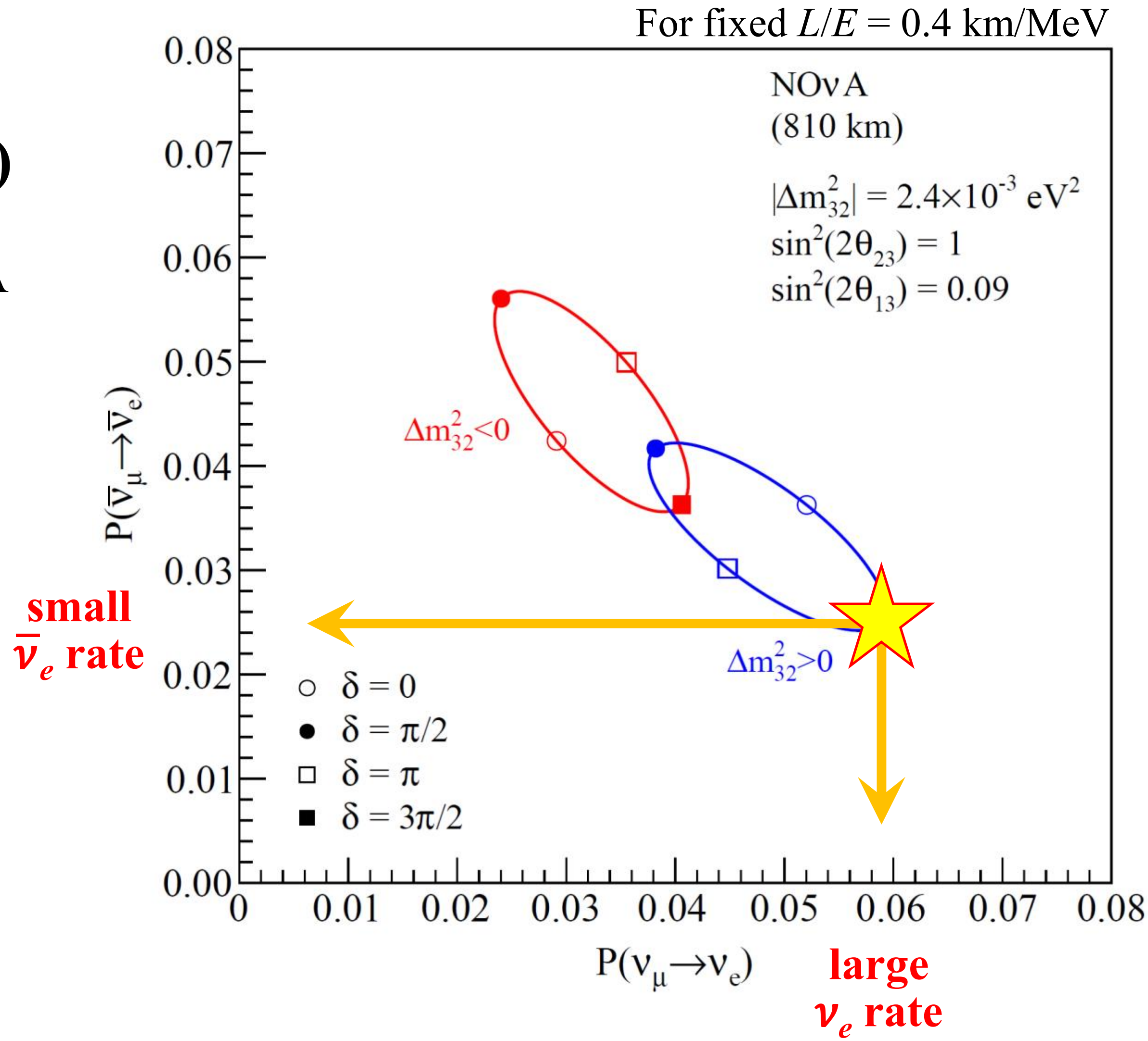
For fixed L/E = 0.4 km/MeV



$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

for a 2 GeV neutrino in NOvA

→ Dependence on δ and **ν mass hierarchy**

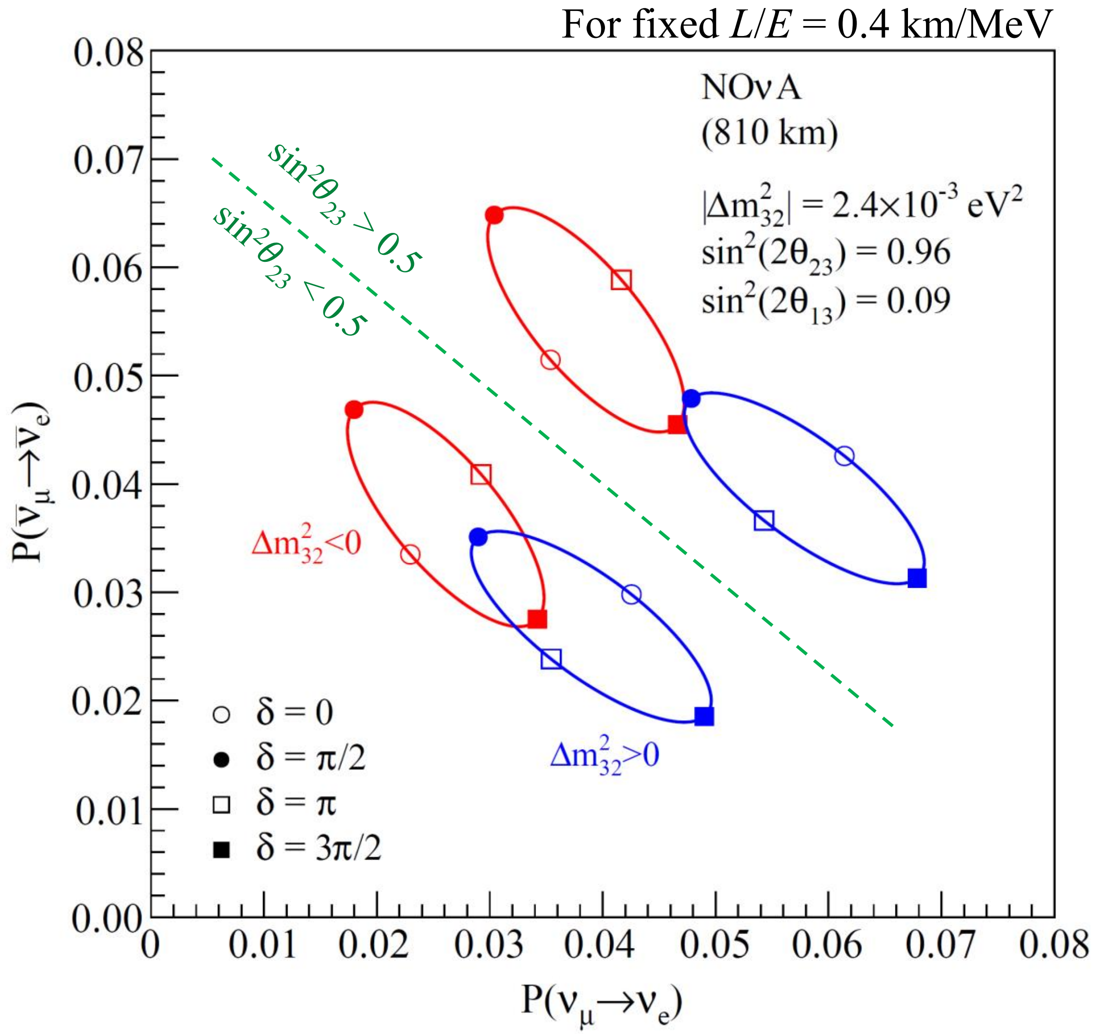


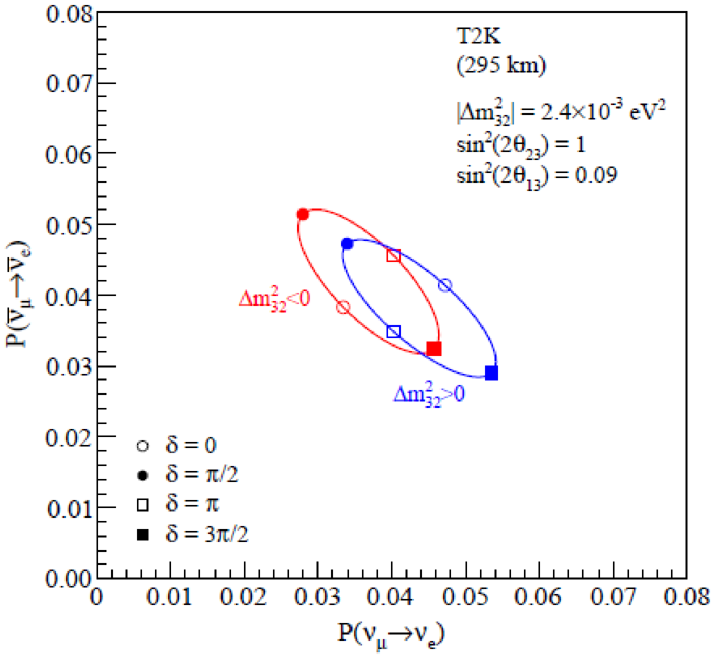
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

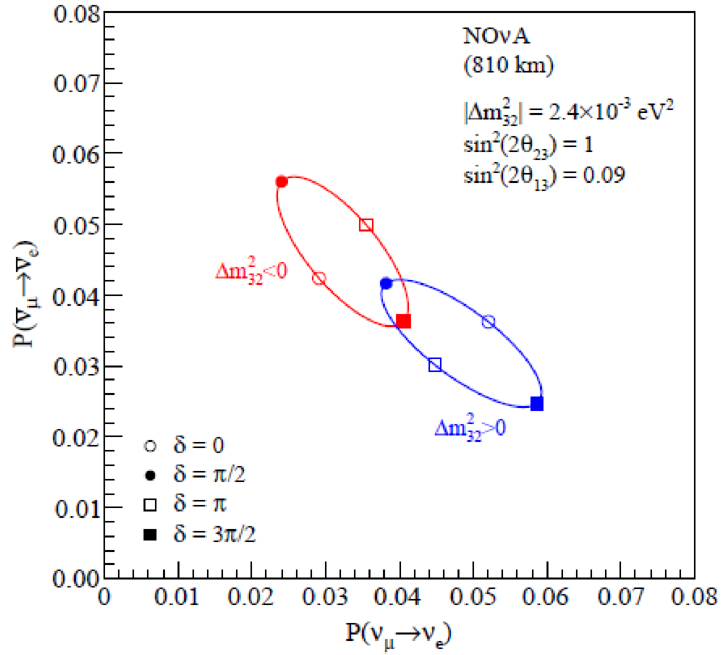
for a 2 GeV neutrino in NOvA

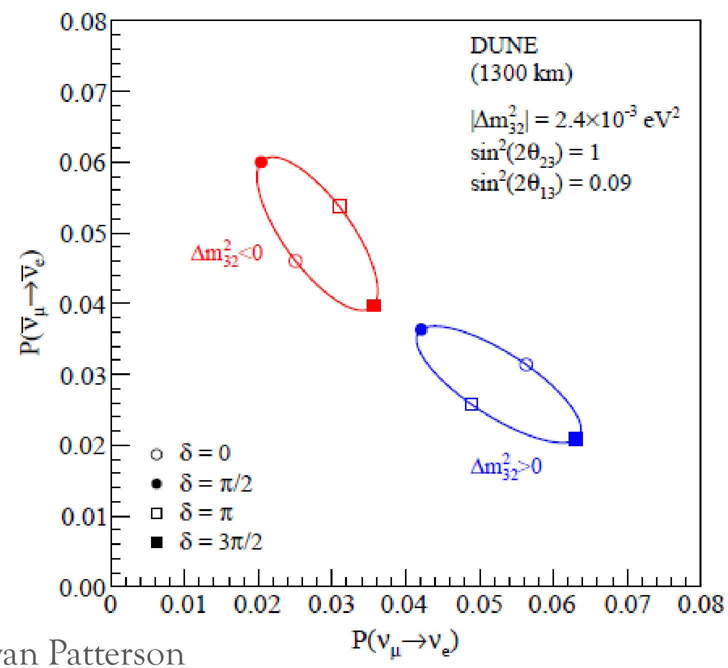
→ Dependence on δ and **ν mass hierarchy**

→ $P \propto \sin^2\theta_{23}$ *[approx.]*







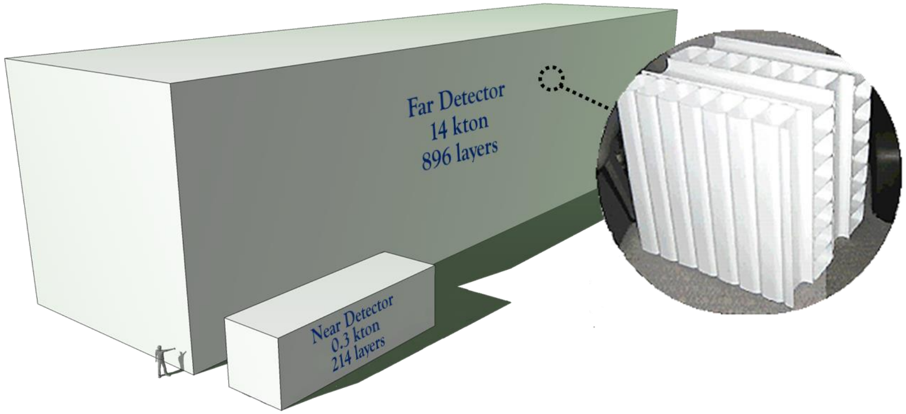


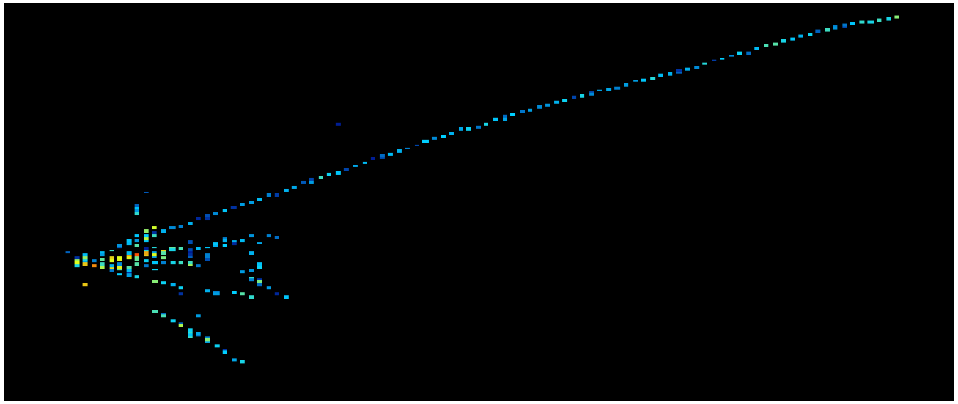
T2K, NOvA, and DUNE baselines for a single *L/E* value.

These differ solely in the influence of matter effects

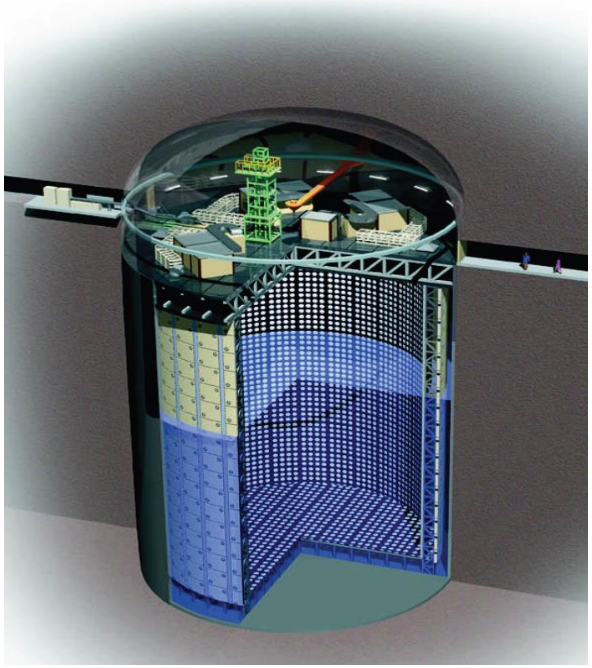
Illustrative only! Other parameters are held fixed, and experiments (esp. DUNE) probe a range of neutrino energies.

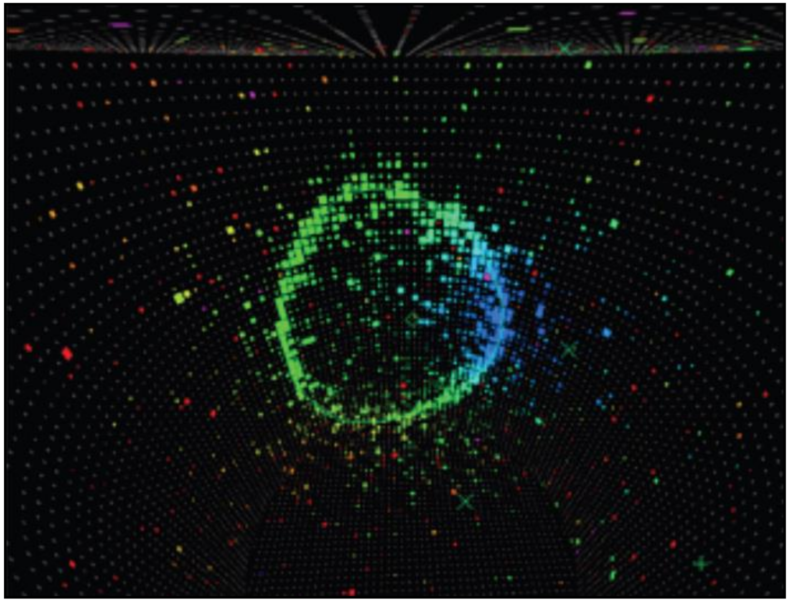
NOvA Far Detector and event display



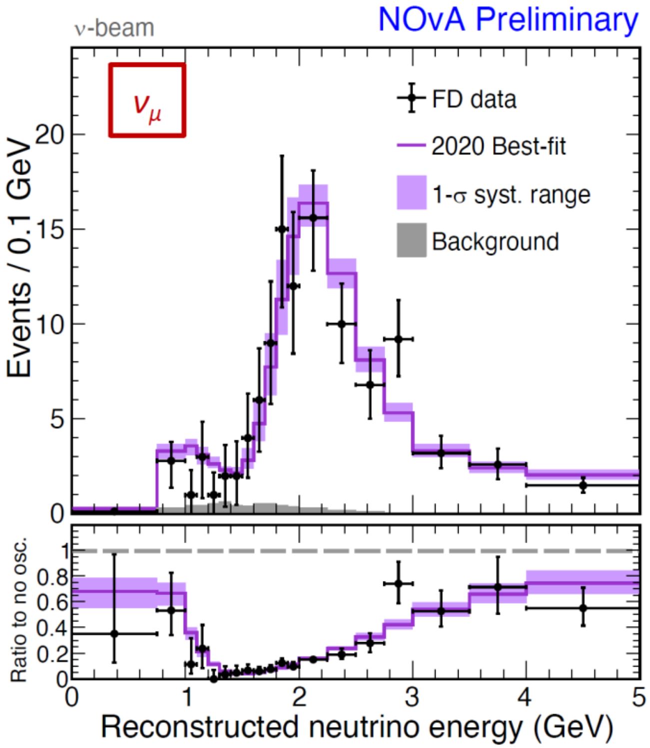


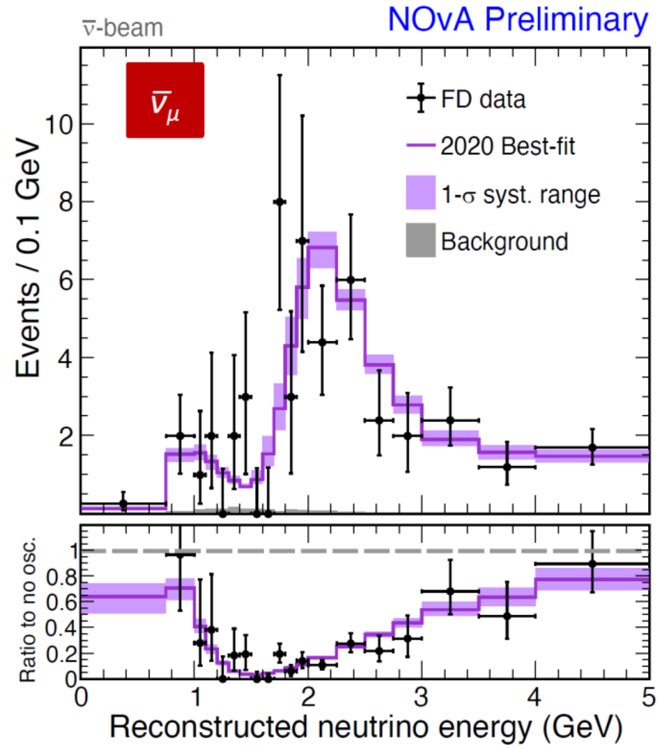
T2K Far Detector (Super-K) and event display

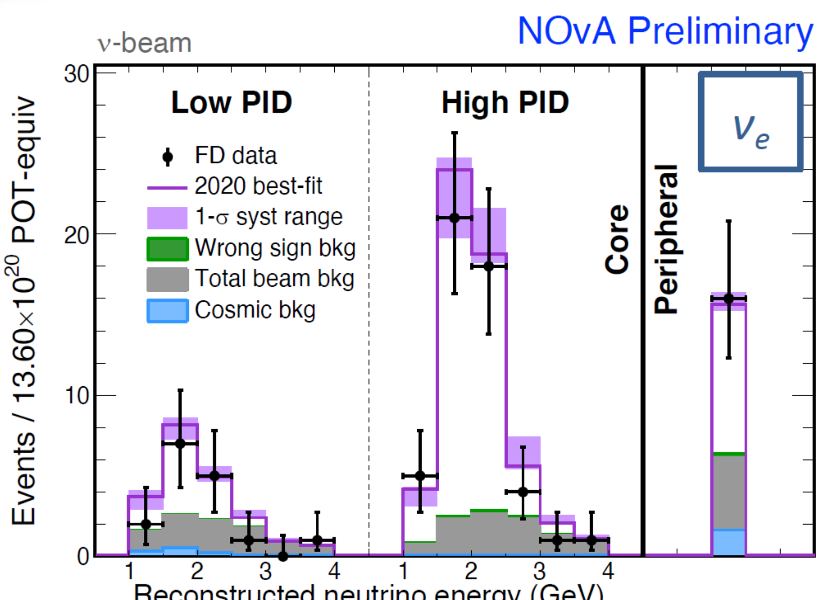


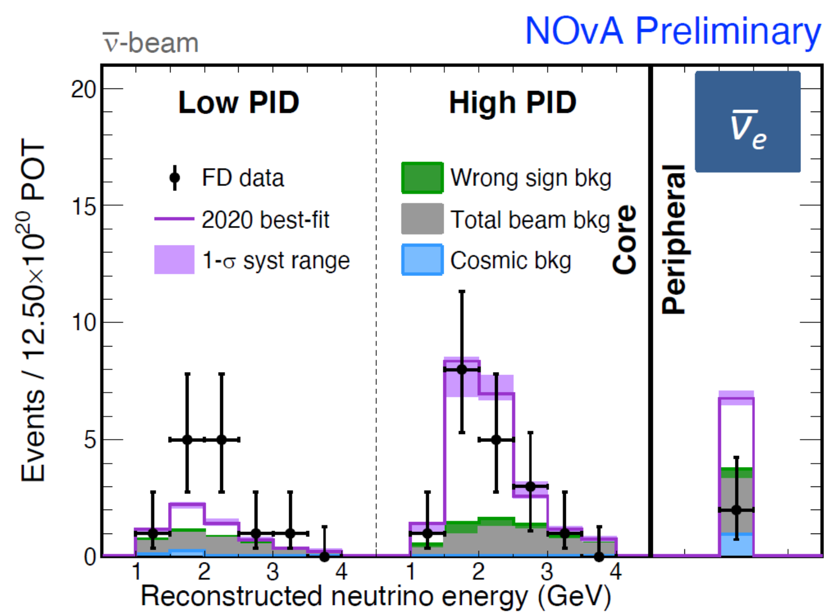


Example
LBL data set
(Latest NOvA)



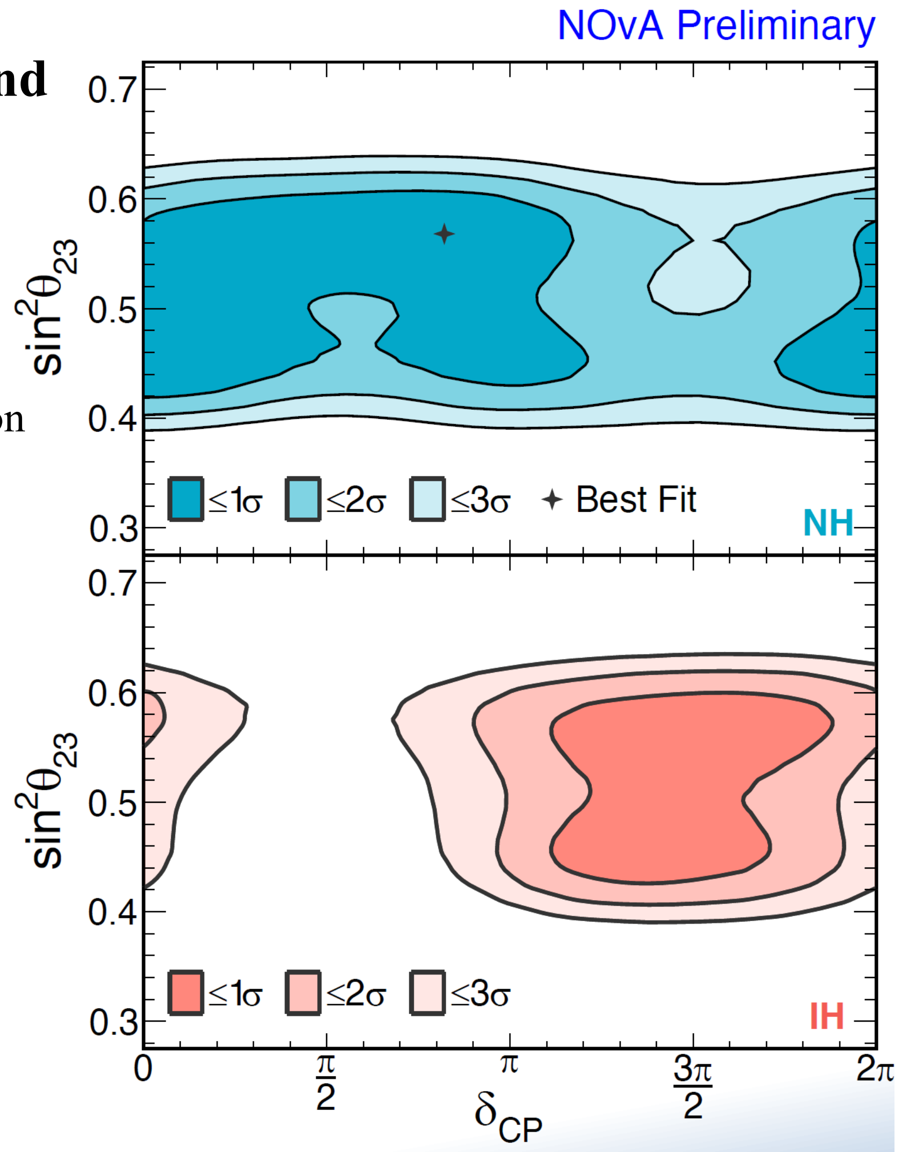






Latest T2K and NOvA results

Intertwined, multidimensional parameter space. Looking at just a slice here.

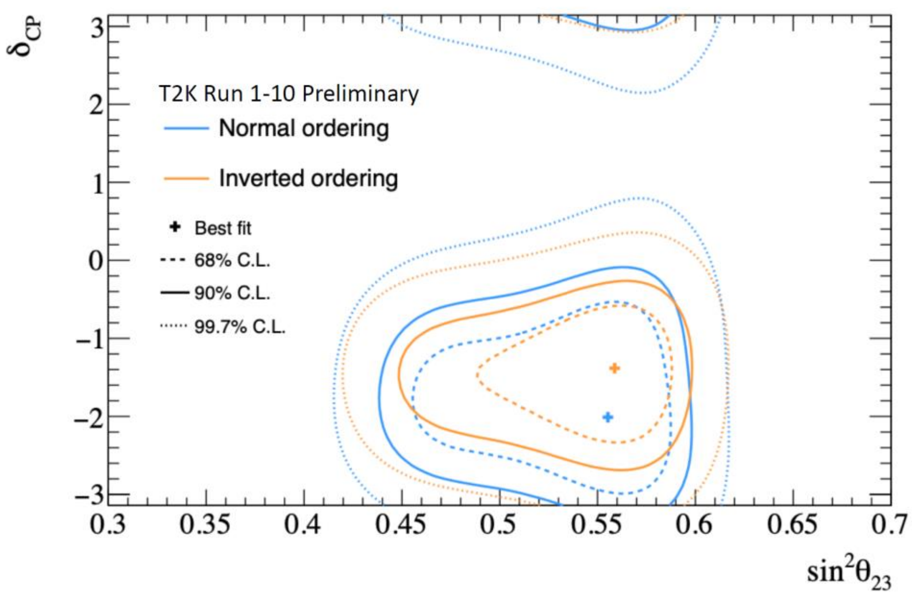


Let's walk through some observations and conclusions

- *If you're looking at this without the audio, sorry!*

High-level observations:

- Some CP violation is preferred over no CP violation
- Hierarchy preference is still slight, but the favored choice (NH) leads to tension elsewhere
- Non-maximal mixing / upper octant preferred

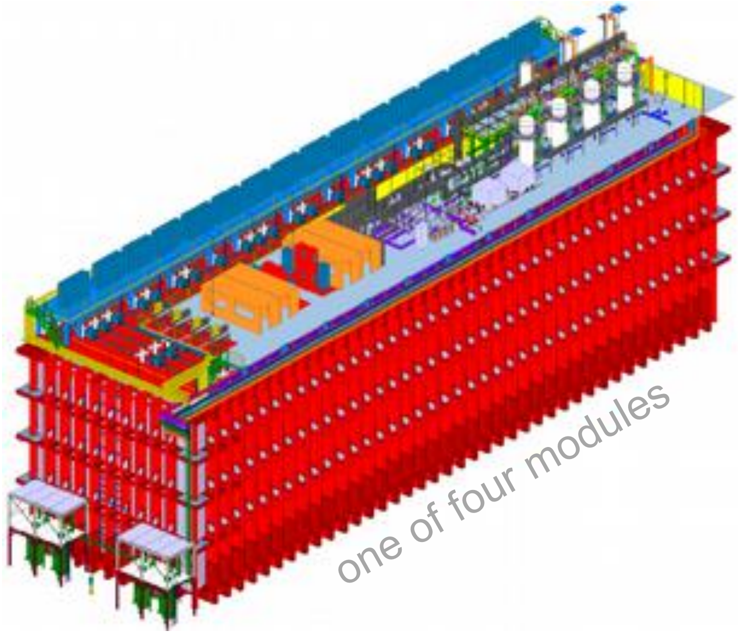


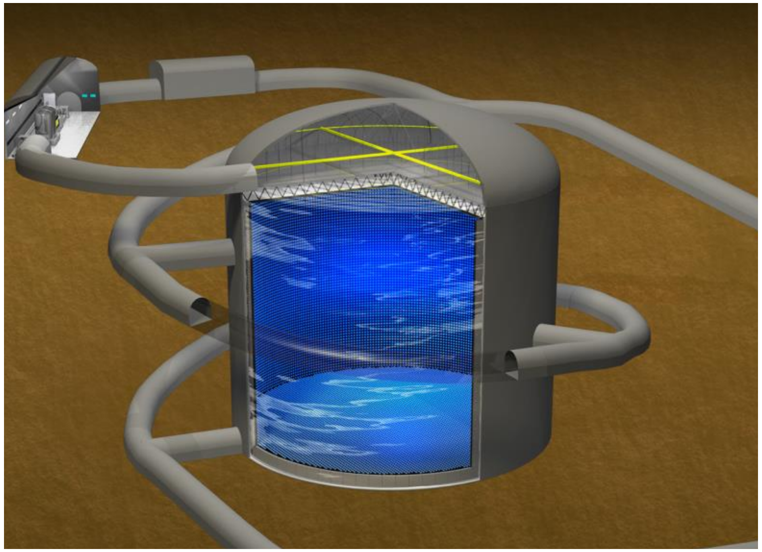
Future LBL Experiments

- **Major leap in sensitivity for neutrino sector questions**
  - Also: supernova neutrinos (see later)
  - Also: many beyond-the-SM physics searches, incl. baryon number violation

DUNE
- very long baseline (1300 km)
- LAr TPC detector (70 kton)
- Superb PID, low thresholds
- New beam from Fermilab

HyperK (T2HK)
- Same baseline as T2K (295 km)
- Water Cherenkov detector
- Massive (260 kton)
- Upgraded beam from J-PARC





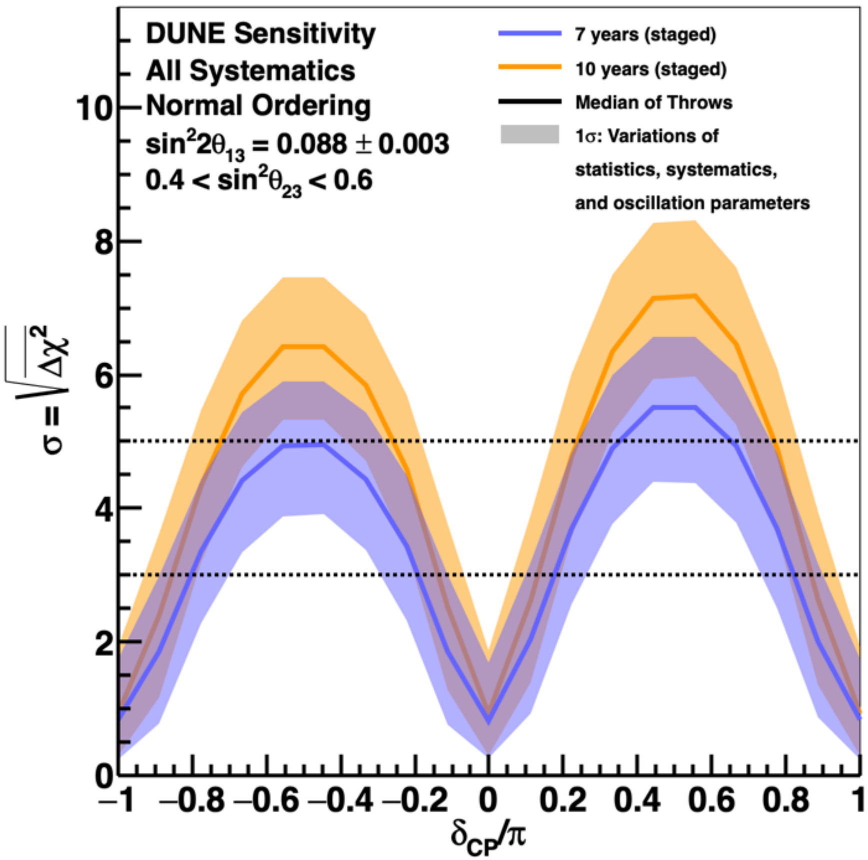
Future LBL Experiments

Key neutrino sensitivity points

(10 yrs, "staged" exposure)

- *CP*v @ **5σ for >50%** of δ values [Both]
- *CP*v @ **3σ for ~75%** of δ values [Both]
- δ resolution **7° – 17°/23°** [DUNE/HK]
- Mass hierarchy in 1 – 2 yrs:
  >5σ [DUNE]
- Mass hierarchy at 10 yrs;:
  5 – 7σ (atm. ν) [HK]
  8 – "20σ+" (beam ν) [DUNE]
- Octant determination **>5σ** if θ_{23} is outside of roughly [43°, 49°] [Both]

DUNE *CP*v sensitivity

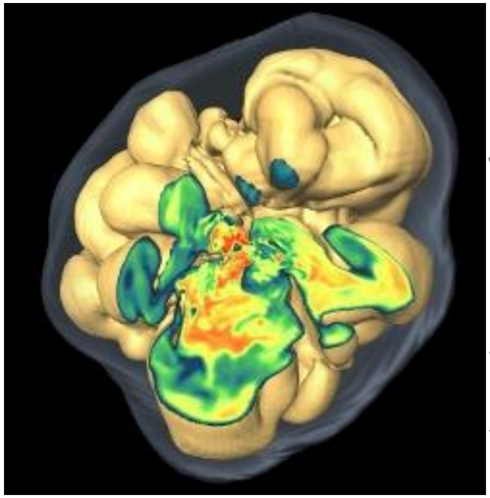


Remarkably similar in mainline ν sector performance, save for hierarchy

Complementary in accessible supernova and solar channels, BSM channels, detection techniques, systematics

Supernova neutrinos

- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass ordering, nuclear equation of state, exotica



S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

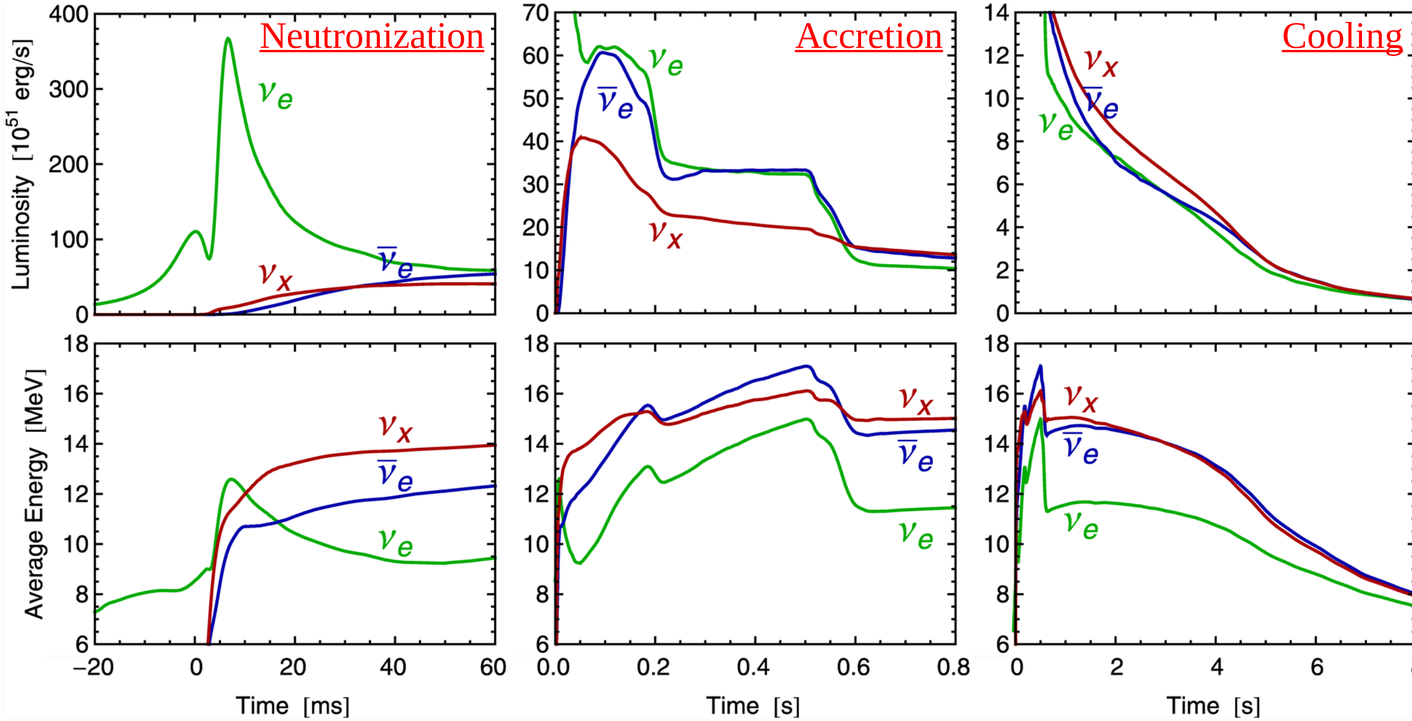
Key interaction channels (few to 40 MeV)

$\nu + e$ elastic
good directionality

$\bar{\nu}_e$ CC
inv. β decay; Gd doping in water detectors will help see the neutrons

ν_e CC
accessible in argon! unique flux features

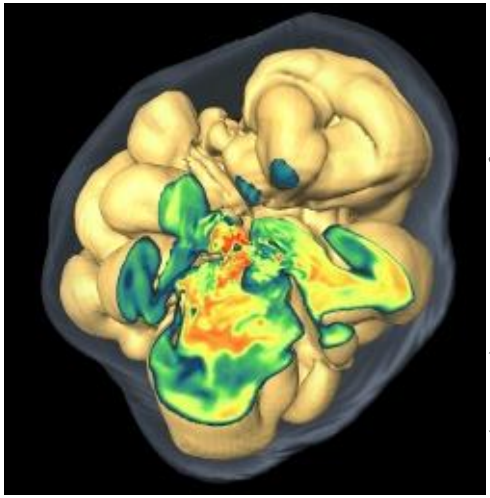
ν NC
flavor agnostic, but hard to work with



Garching model (27 $M_\odot$)

Supernova neutrinos

- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass ordering, nuclear equation of state, exotica



S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

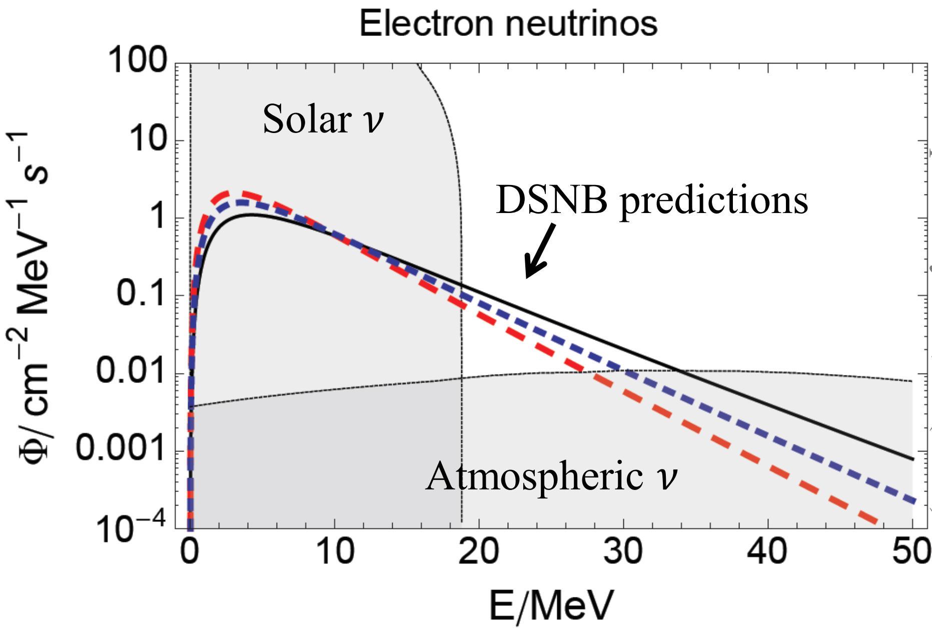
Single galactic supernova event

→ would yield thousands of interactions in the large detectors

Diffuse supernova neutrino backg'd

Should be there.

Not yet observed. Best limits from Super-K within factor of two of model prediction(s).



C. Lunardini,
Astropart. Phys. **79**, 49 (2016)

Brief look at light sterile neutrinos

(different from sterile neutrinos as DM, massive RH sterile partners as in mass generator or leptogenesis, etc.)

Sterile neutrinos

- Here: Light sterile neutrinos that mix with familiar active ones
  - distinct from, *e.g.*, sterile neutrinos as DM, massive RH sterile partners invoved in mass generation or leptogenesis, generic heavy neutral leptons, etc.

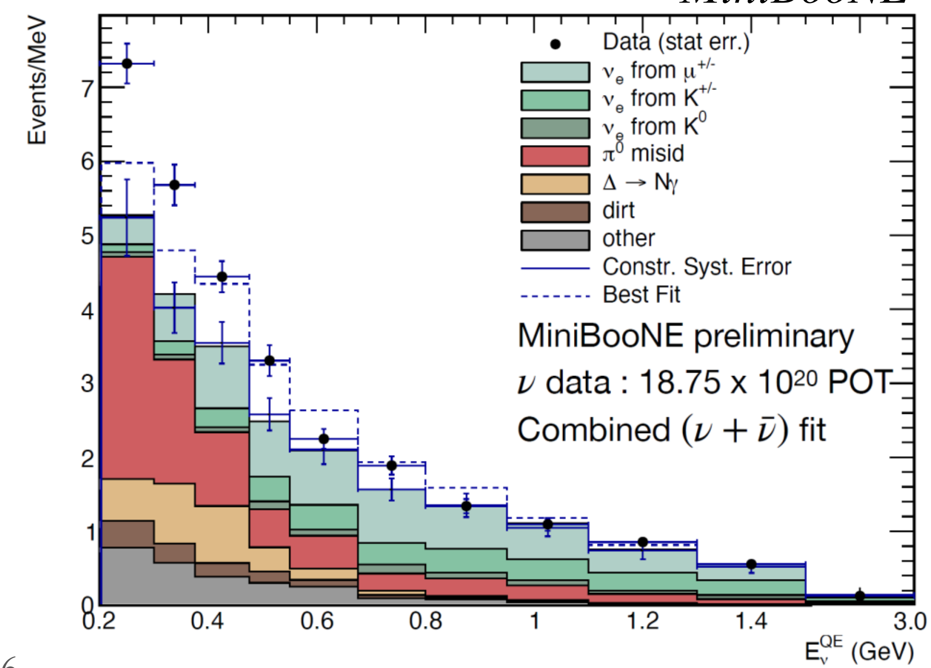
- Only three light active neutrinos (from Z width)

- In the 1990s, **LSND expt reported anomalous ν_e and $\bar{\nu}_e$ appearance**
  - could not be accommodated with only three neutrinos
  - one interpretation is oscillations involving a 4th (sterile) neutrino

- MiniBooNE followed up at higher E (same L/E)
  - **reported 5σ excess**

- Many null results using various techniques over past two decades
  - *KARMEN, Bugey, Super-K, MINOS(+), ICARUS, IceCube, Planck, NOvA, T2K, Daya Bay, DANSS, PROSPECT, …*

MiniBooNE



Sterile neutrinos

- But neither a nail in the coffin nor an unambiguous signal has been forthcoming

  - Model dependence in comparing across different techniques (*e.g.*, disappeance vs. appearance searches; 3+1 vs. 3+*n* models)
  - No clear L/E oscillation signature
  - Background worries (well-founded or not) (*e.g.*, MiniBooNE can't distinguish γ from e)

- Upcoming and most directly analogous measurement will be from MicroBooNE and the broader Fermilab "short baseline" program

  - same appearance channel(s) as LSND and MiniBooNE: $\nu_\mu \rightarrow \nu_e$ (and anti-ν)
  - and, LAr TPC detectors can rule out γ backgrounds
  - but, exposure isn't enormous, and control of systematics not yet demonstrated

- A number of LBL, SBL, reactor, spallation neutron source, and cosmological measurements are underway or in development

(Editorial comment: none will soon solve the issue in the first bullet)

So much didn't fit in the limited time!

- **Atmospheric neutrinos**
  - Wide range of energies, copious source, range of physics topics
  - LBL beam experiments generally outperform for standard PMNS measurements
- **Ultra high energy neutrinos (extraterrestrial sources)**
  - Very large detectors or detector arrays (*e.g.*, IceCube, ARA)
  - Addressing astrophysical questions mostly, but also some particle physics (*e.g.*, cross sections at very high energies)
- **Geoneutrinos**
  - Neutrinos generated from within the earth radiologically
  - Addressing questions of planetary structure and formation
- **Solar neutrinos**
  - The pioneering neutrino oscillation laboratory
  - Now, addressing solar physics (*e.g.*, solar metallicity) more than particle physics
- **ν interactions**
  - interactions on nuclear targets poorly constrained
  - recent: 1st measurement of ν coherenet scattering (eventual DM background?)
- **Precision PMNS**
  - toward neutrino "unitarity triangle"
  - flavor structure → model constraints
- **Neutrino-related BSM physics**
  - Non-standard interactions, large extra dimensions, CPTν, neutrino tridents, ...