Puzzles in Neutrinos

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MIT

PANIC11 Pedagogical Lectures
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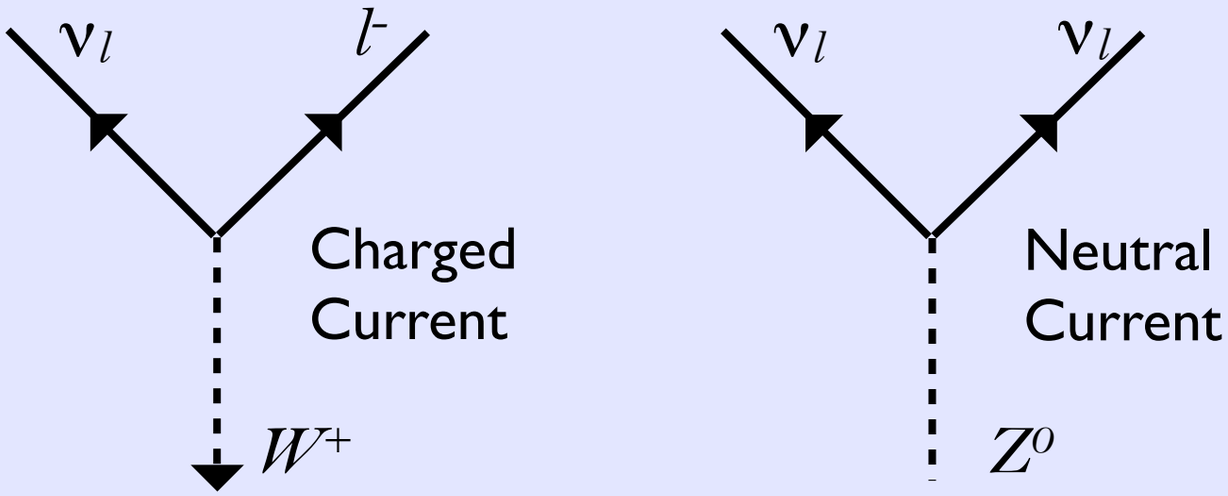
Laboratory for Nuclear Science

PANIC11

The basic facts

- Three flavors, each associated with a charged lepton
- Weak interactions only
- Very small masses

Quarks	u	c	t	γ	Bosons
	d	s	b	g	
Leptons	ν_e	ν_μ	ν_τ	Z	
	e	μ	τ	W	



Why is this interesting?

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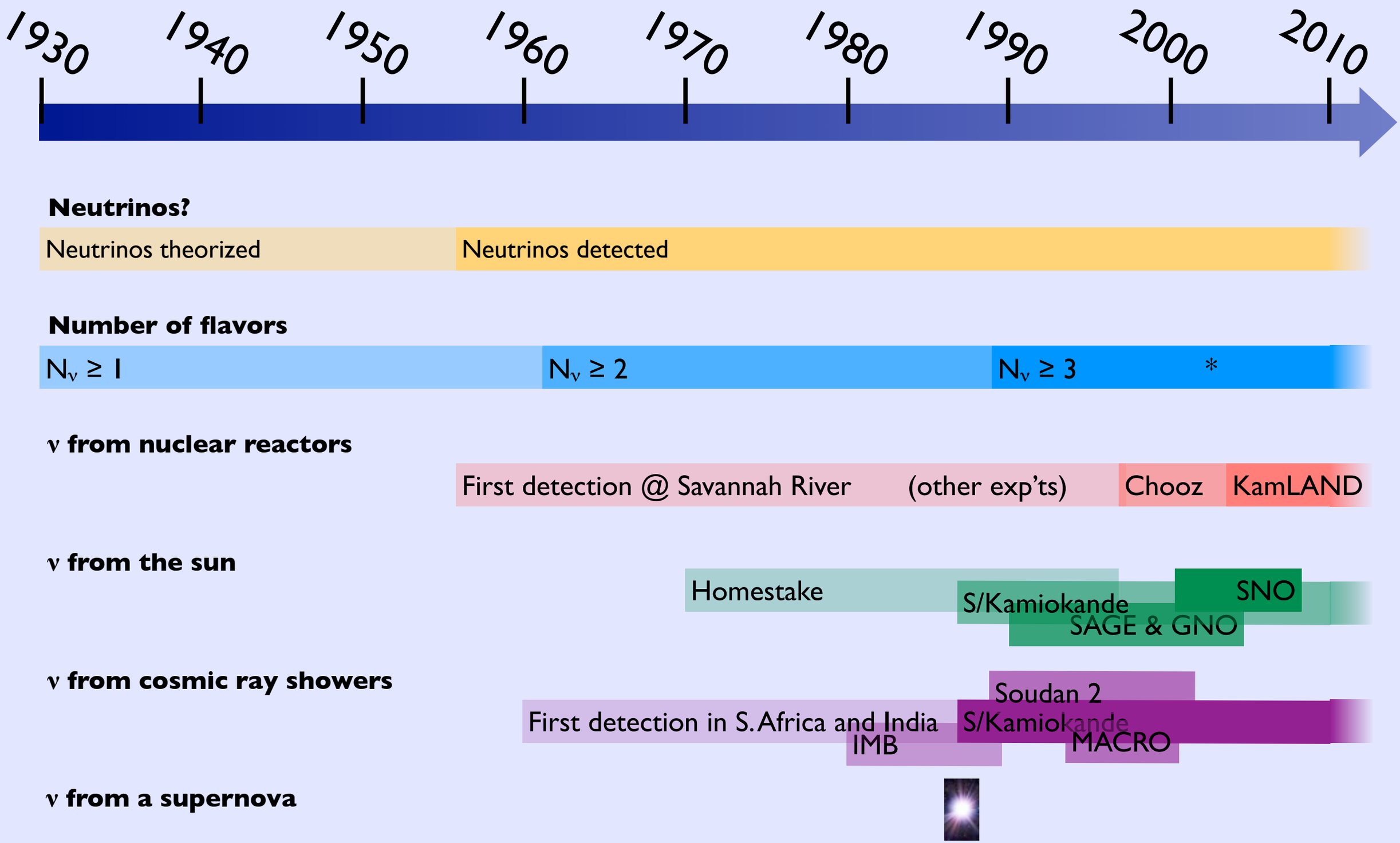
- Most common particle out there: $\approx 330\ cm^{-3}$
- Providing previously-unknown insights into the Standard Model
- Affect structure formation in the universe
- Just starting to look at human-scale applications

Some history



Neutrino Sources

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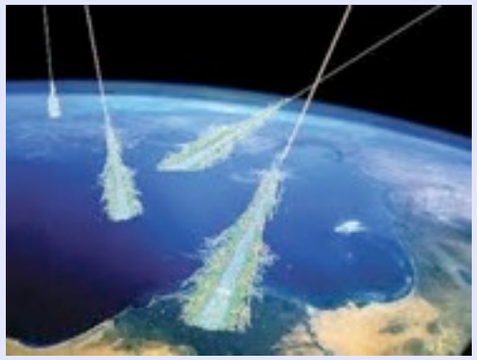
Terrestrial

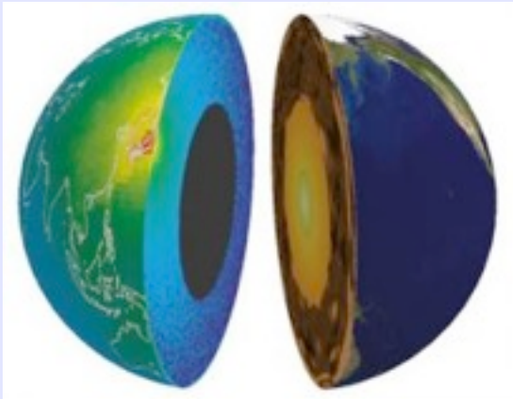
Nuclear Reactors

Accelerators



Cosmic ray showers

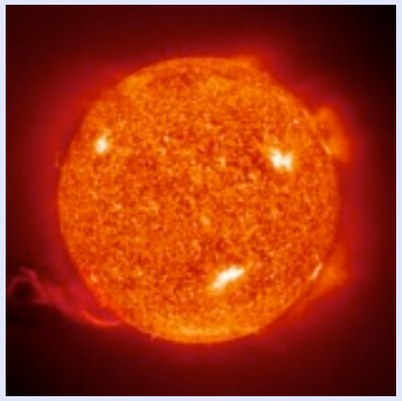
The Earth



Astrophysical

The Big Bang

Supernovae



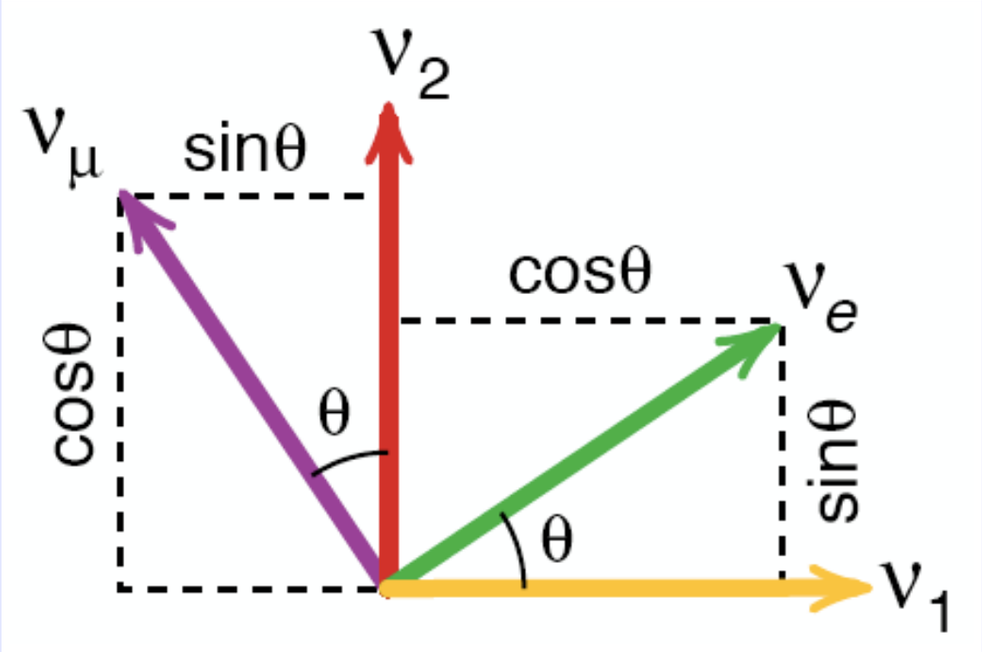
The Sun

Other astrophysical sources

Mass vs. Flavor

Neutrino flavor states ≠
Neutrino mass states

- Flavor states are eigenstates of the weak interaction
- Mass states are eigenstates of the Hamiltonian



2-ν oscillations

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In the 2-neutrino approximation

Neutrino flavor and mass states

$$\begin{pmatrix} \nu_e \\ \nu_{\mu\tau} \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Flavor-change probability

$$P(\nu_e \to \nu_{\mu\tau}) = |\langle \nu_{\mu\tau} | \nu(t) \rangle|^2 = \sin^2(2\theta_{12}) \sin^2\left(1.27 \Delta m^2_{21} \frac{L}{E}\right)$$

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1$$

"Survival probability" = $P(\nu_e \to \nu_e)$ = $1 - P(\nu_e \to \nu_{\mu\tau})$

2-ν oscillations

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In the 2-neutrino approximation

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3-ν oscillations

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MNSP Matrix - Maki, Nakagawa, Sakata, and Pontecorvo

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_1} & 0 \\ 0 & 0 & e^{i(\phi_2+\delta)} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

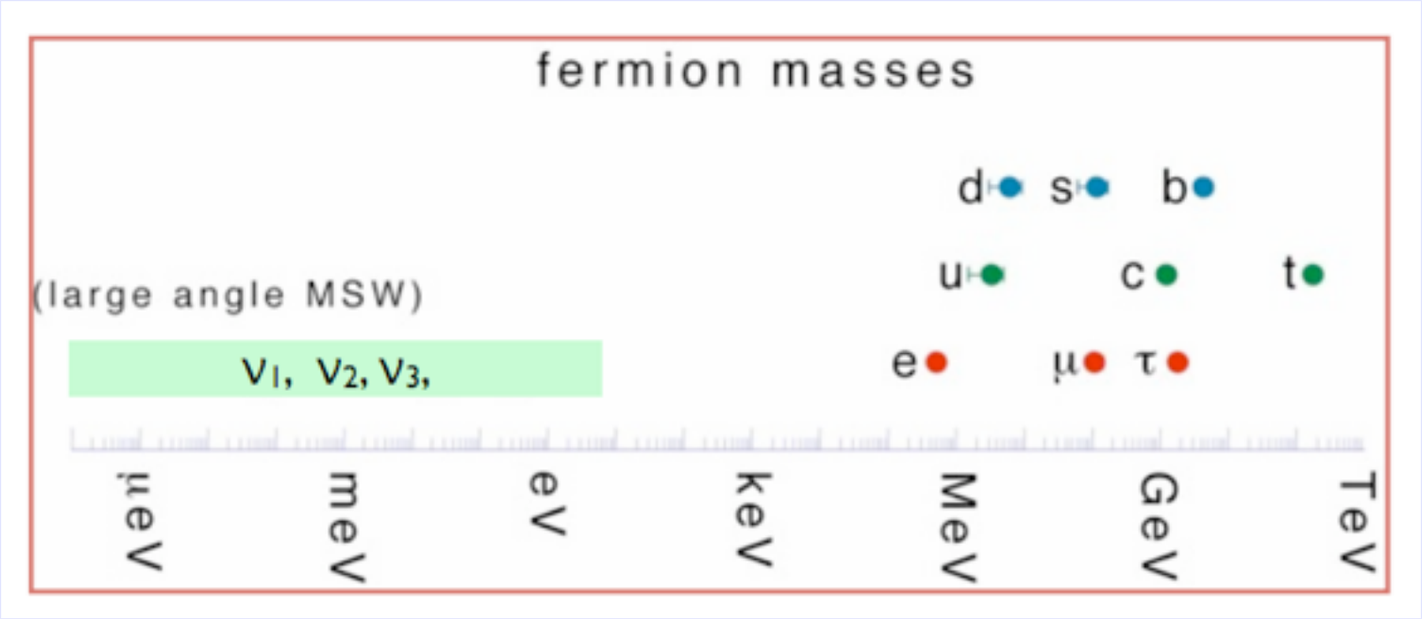
θ_{23}: cosmic ray and accelerator experiments $\theta_{23} \approx 45^\circ$	θ_{13}: reactor and accelerator experiments δ is a CP-violating phase $\theta_{13} < 15^\circ$	θ_{12}: solar experiments and KamLAND $\theta_{12} \approx 34^\circ$	Majorana Phases $\beta\beta$ decay

$c_{23} \equiv \cos\theta_{23}$

$s_{23} \equiv \sin\theta_{23}$

Neutrino masses

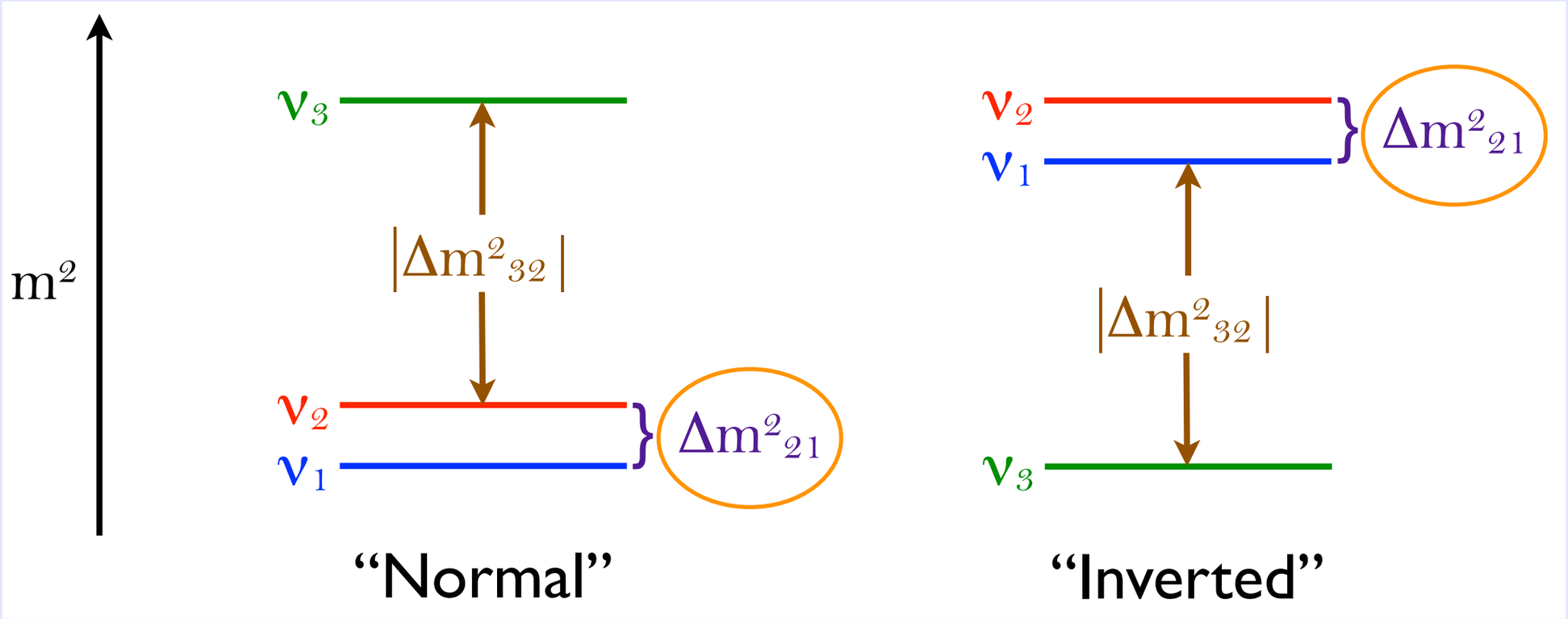
- At least two masses are non-zero
- They are very small



- We have measured two mass separations
  - ❖ $\Delta m^2_{21} \approx 8 \times 10^{-5}\ \mathrm{eV}^2$
  - ❖ $\Delta m^2_{32} \approx 3 \times 10^{-3}\ \mathrm{eV}^2$

Mass Hierarchy

- We know the value and sign of $\Delta m^2{}_{12}$
- We know the absolute value of $\Delta m^2{}_{23}$



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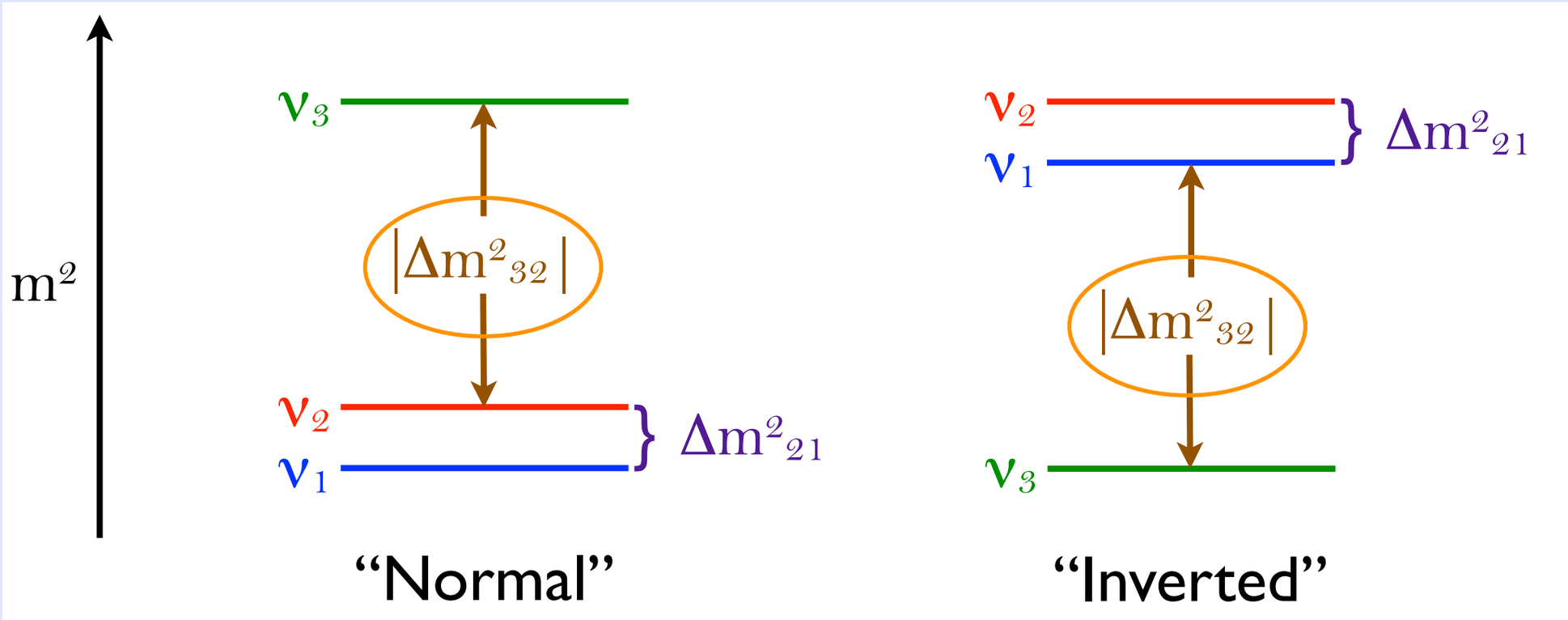

Open Questions

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Does $\overline{\nu} = \nu$?
Where does neutrino mass come from?
What is the absolute mass scale?
What is the mass hierarchy?
What is θ_{13}?
Is there leptonic CP violation?
Are there sterile neutrinos?

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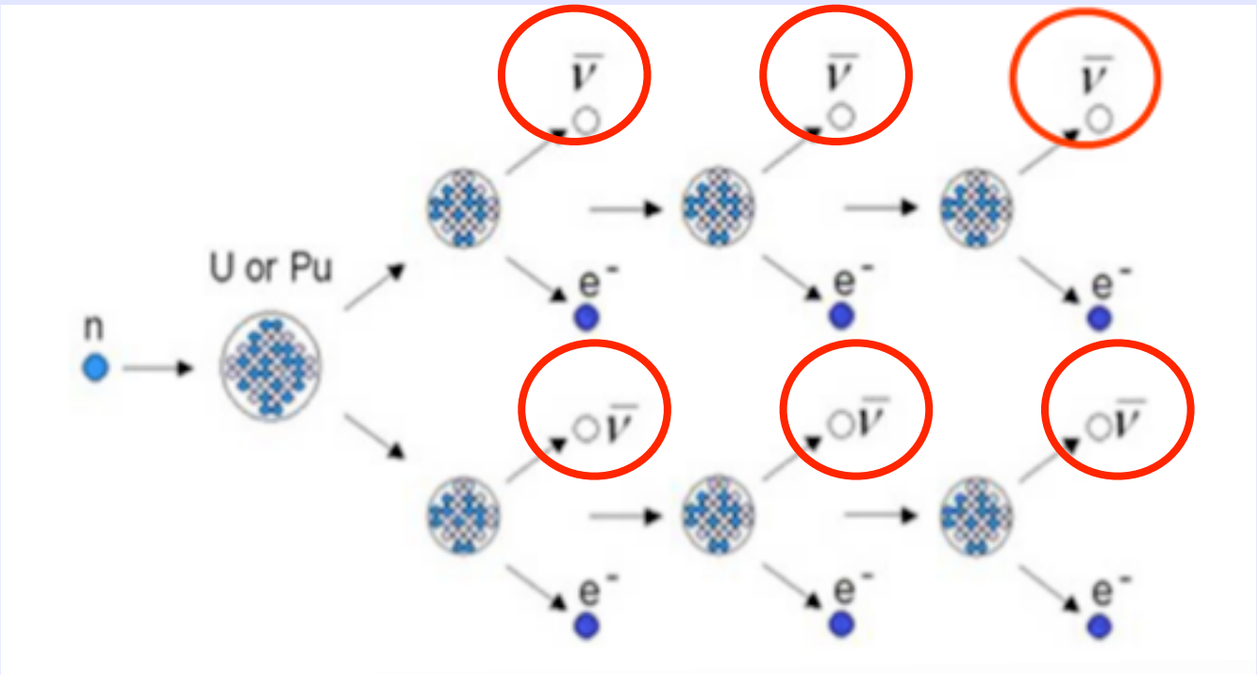
What is θ_{13}?

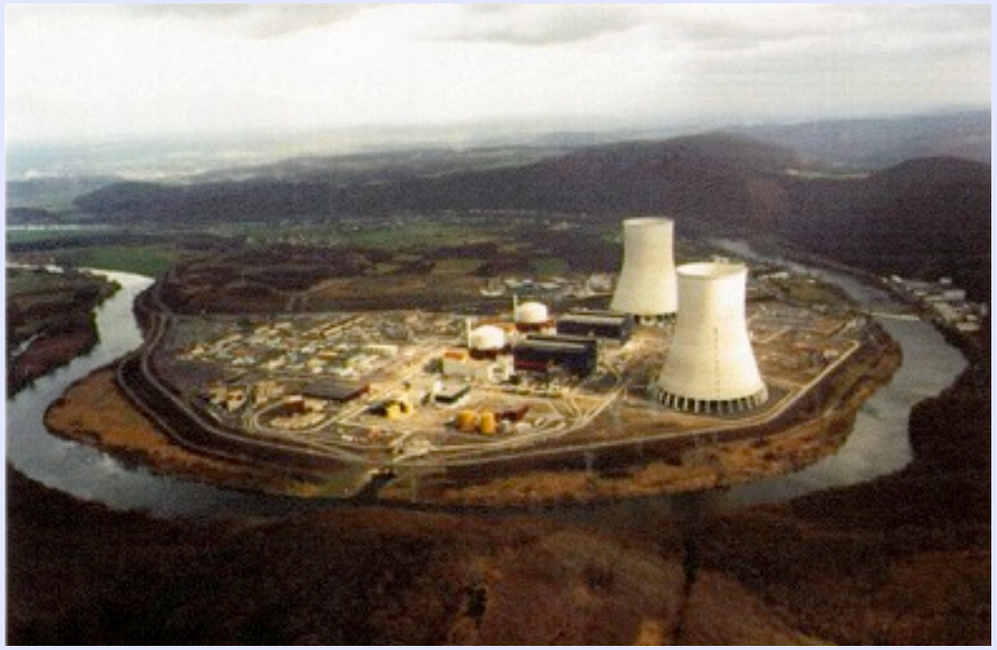
Why measure θ_{13}?

- Because it's there
- θ_{13} must be measurable for us to measure
  - the CP-violating phase δ
  - the mass hierarchy

Reactor Experiments

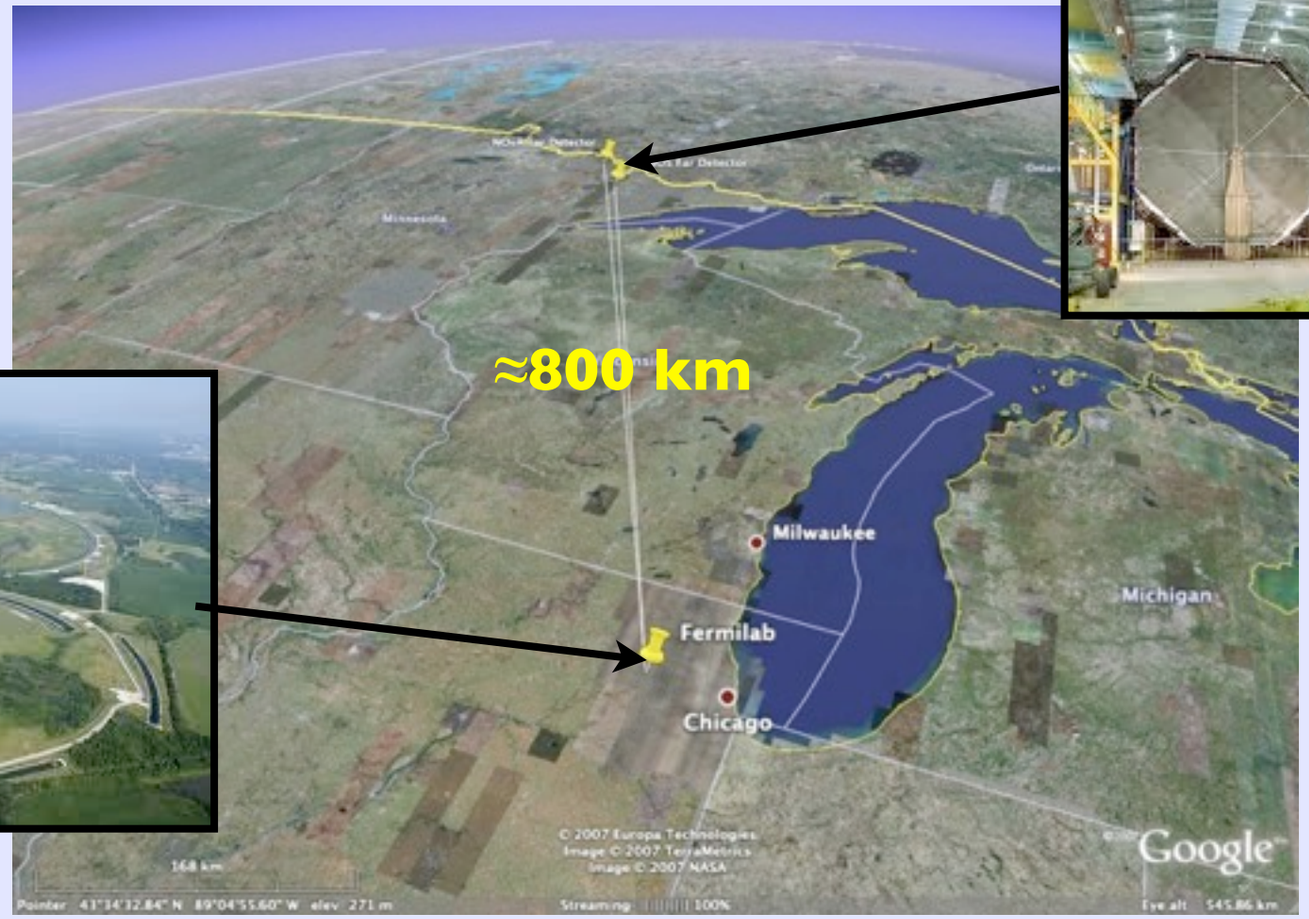


- Beta decays of fission fragments release $\overline{\nu}_e$
- Look for $\overline{\nu}_e$ disappearance
- Probe θ_{13} directly
- $P(\overline{\nu}_e \to \overline{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \ldots$



Accelerator Experiments

- Long-baseline = hundreds of km
- Neutrinos produced in pion decays
- Sensitive to θ_{13}, CP-violating phase, and the mass hierarchy
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$



State of the art

Upcoming reactor experiments

- Double Chooz
- Daya Bay
- RENO

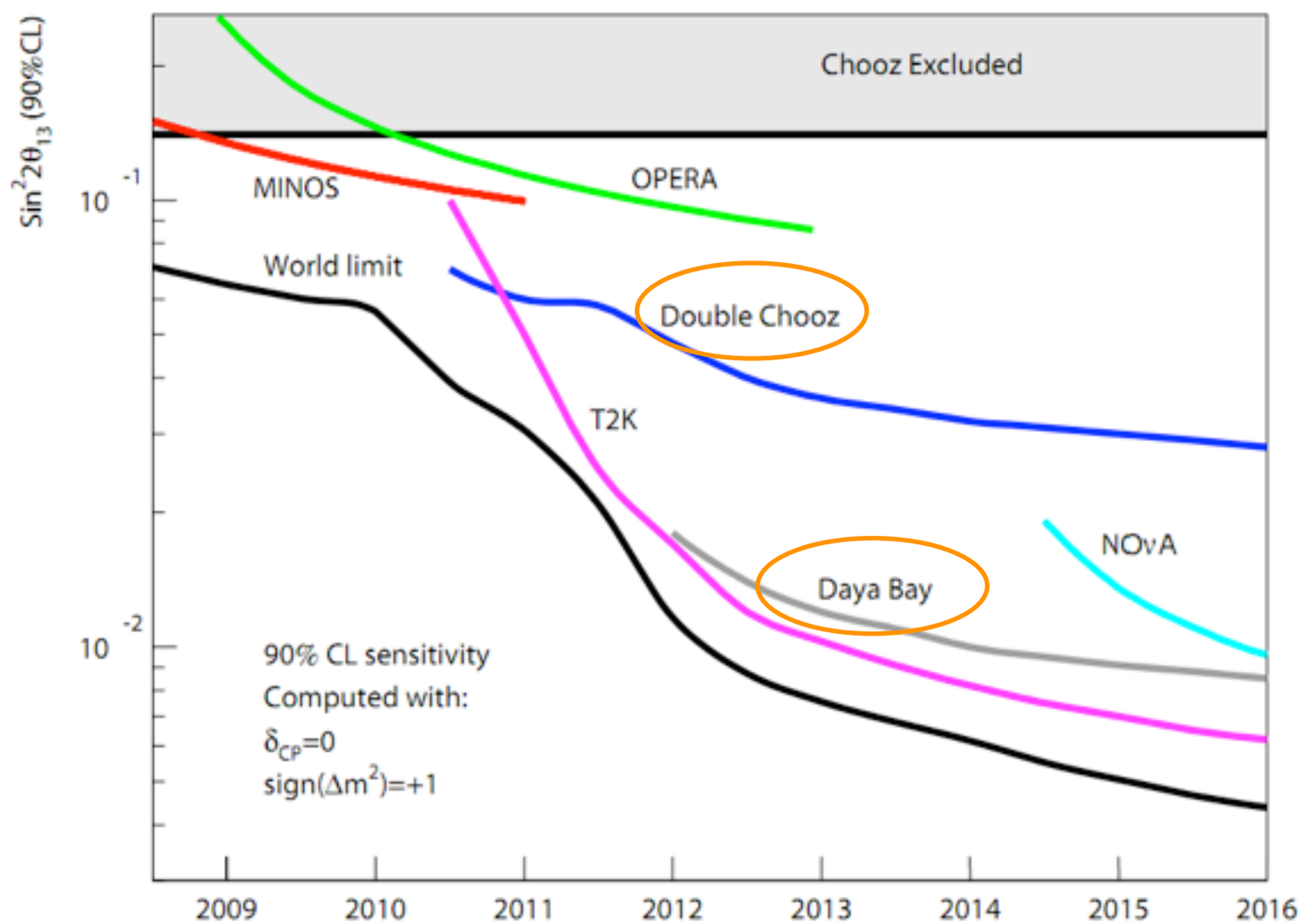


Figure from M. Mezzetto, 2009

Hot off the presses

T2K and MINOS have both released recent results!

Both experiments exclude $\theta_{13} = 0$

- T2K (June 14): @ 2.5σ
- MINOS (June 24): @ 1.7σ
- (assuming $\delta_{CP}=0$)

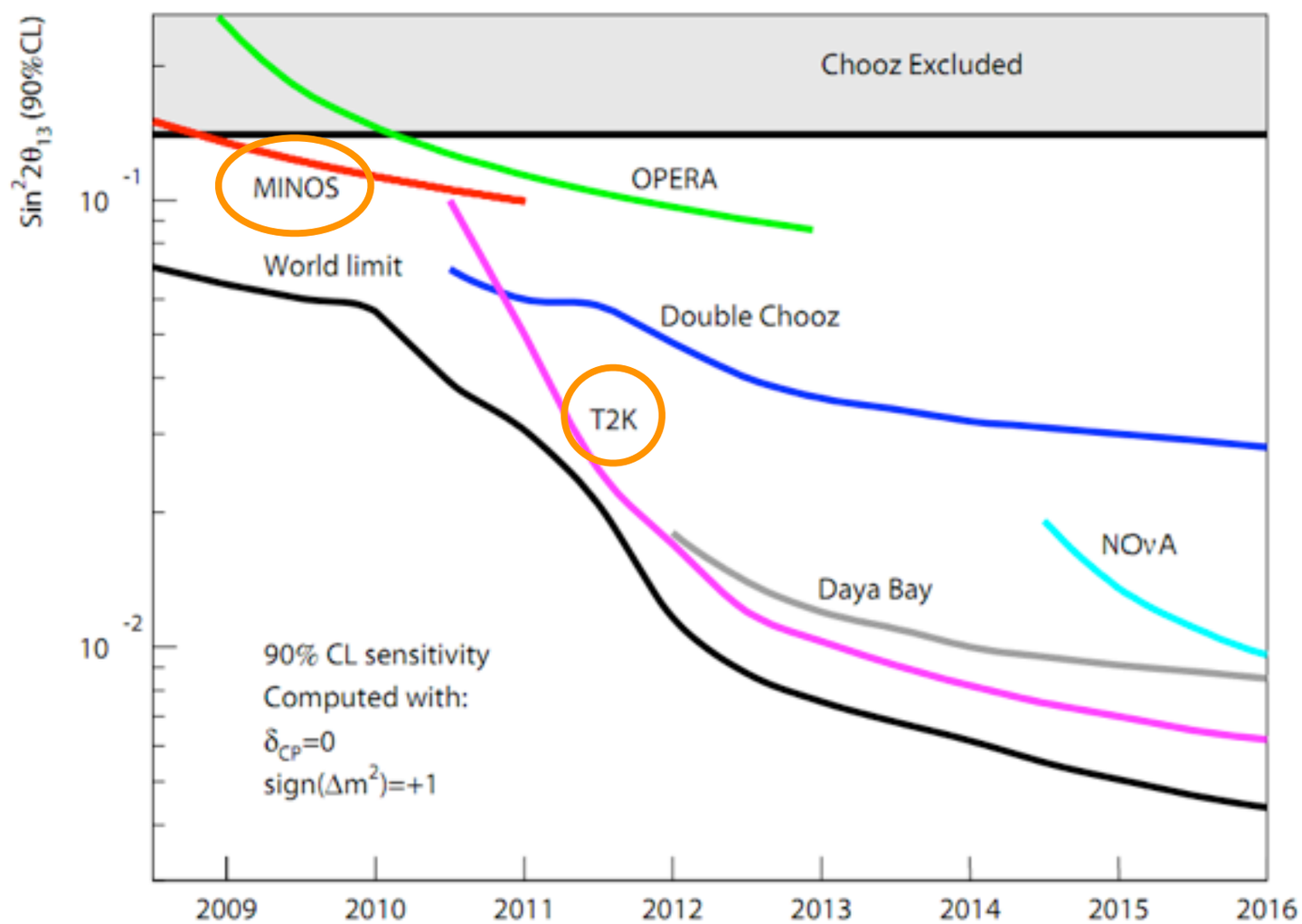
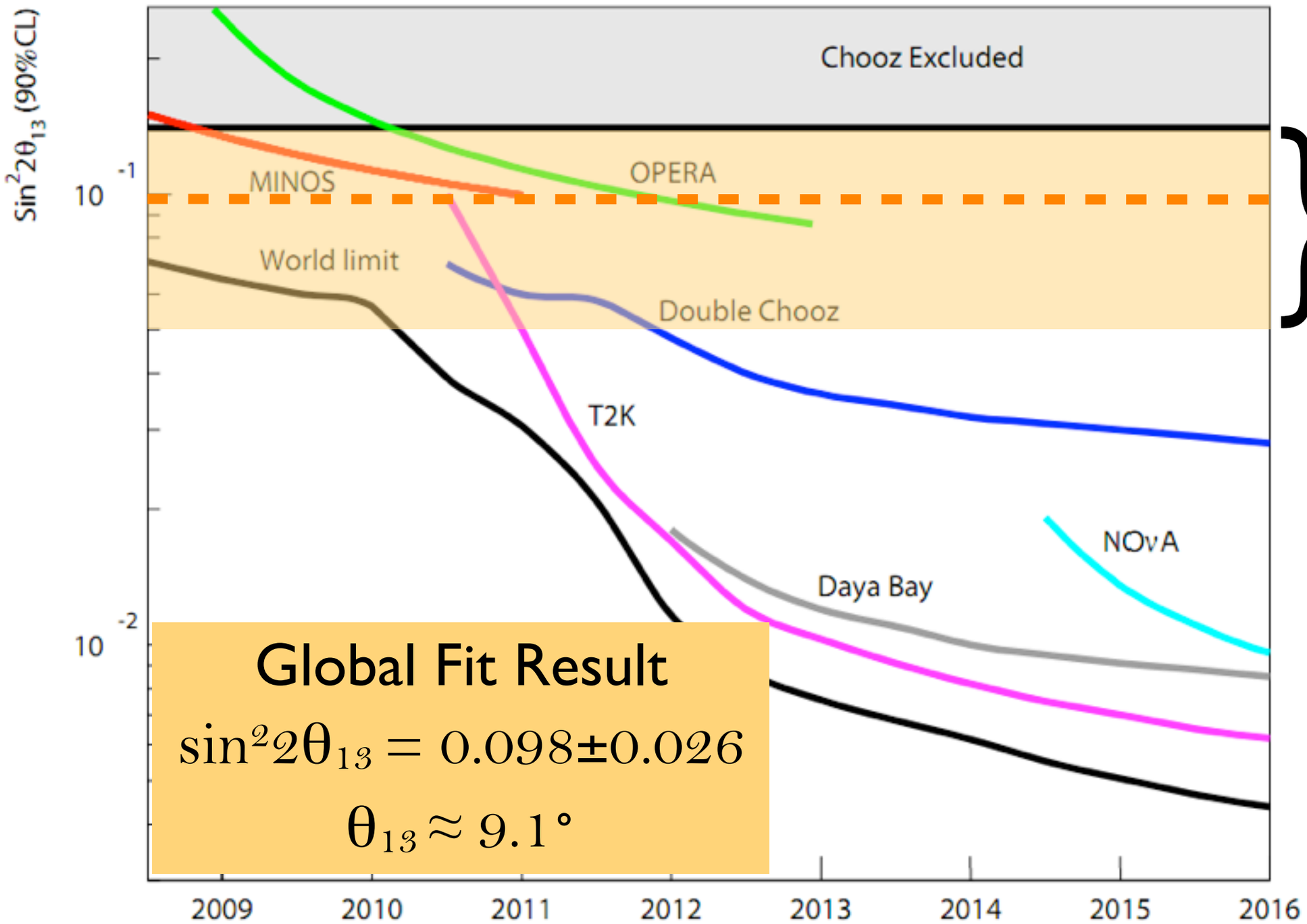


Figure from M. Mezzetto, 2009

Bleeding edge



Global Fit Result

$$\sin^2 2\theta_{13} = 0.098 \pm 0.026$$

$$\theta_{13} \approx 9.1^\circ$$

Original figure from M. Mezzetto, 2009

Central value and 90% CL uncertainty from G.L. Fogli, *et al*, 2011

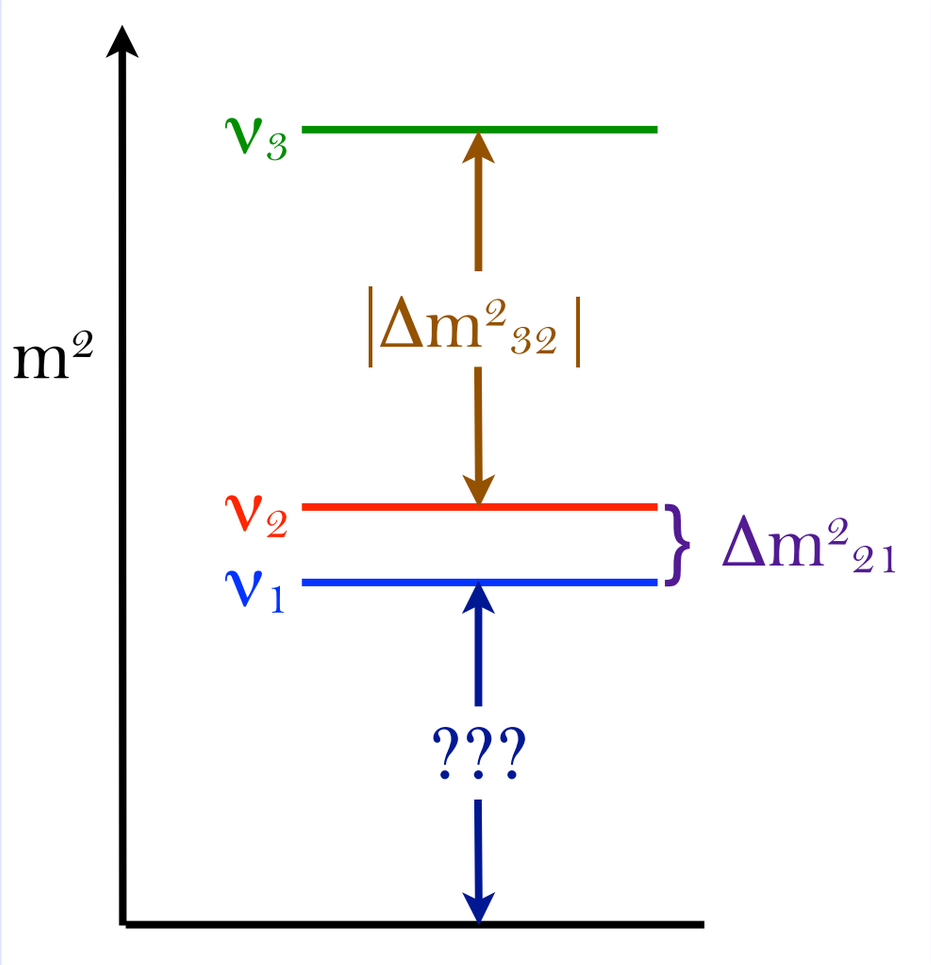
θ_{13} experiment talks

- Reactor
  - Double Chooz: 1E
  - Daya Bay: 3E
- Long Baseline
  - T2K: 1E, 2E
  - NOνA: 3E
  - MINOS: 5F

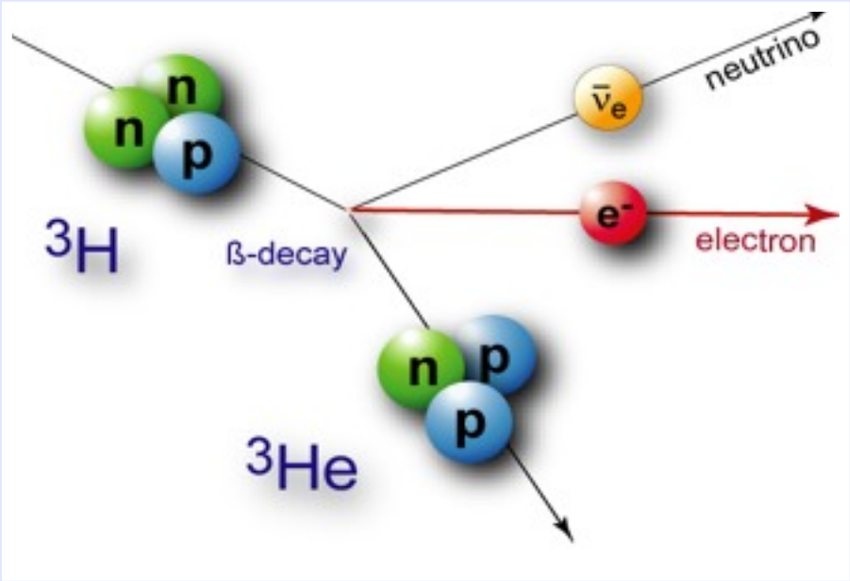
What is the absolute mass scale?

Absolute Mass Scale

- We know the mass differences …
- … but not the absolute mass scale
- Can measure with single beta decay isotopes
  - ^{3}H or ^{187}Re
- Can also measure with cosmology

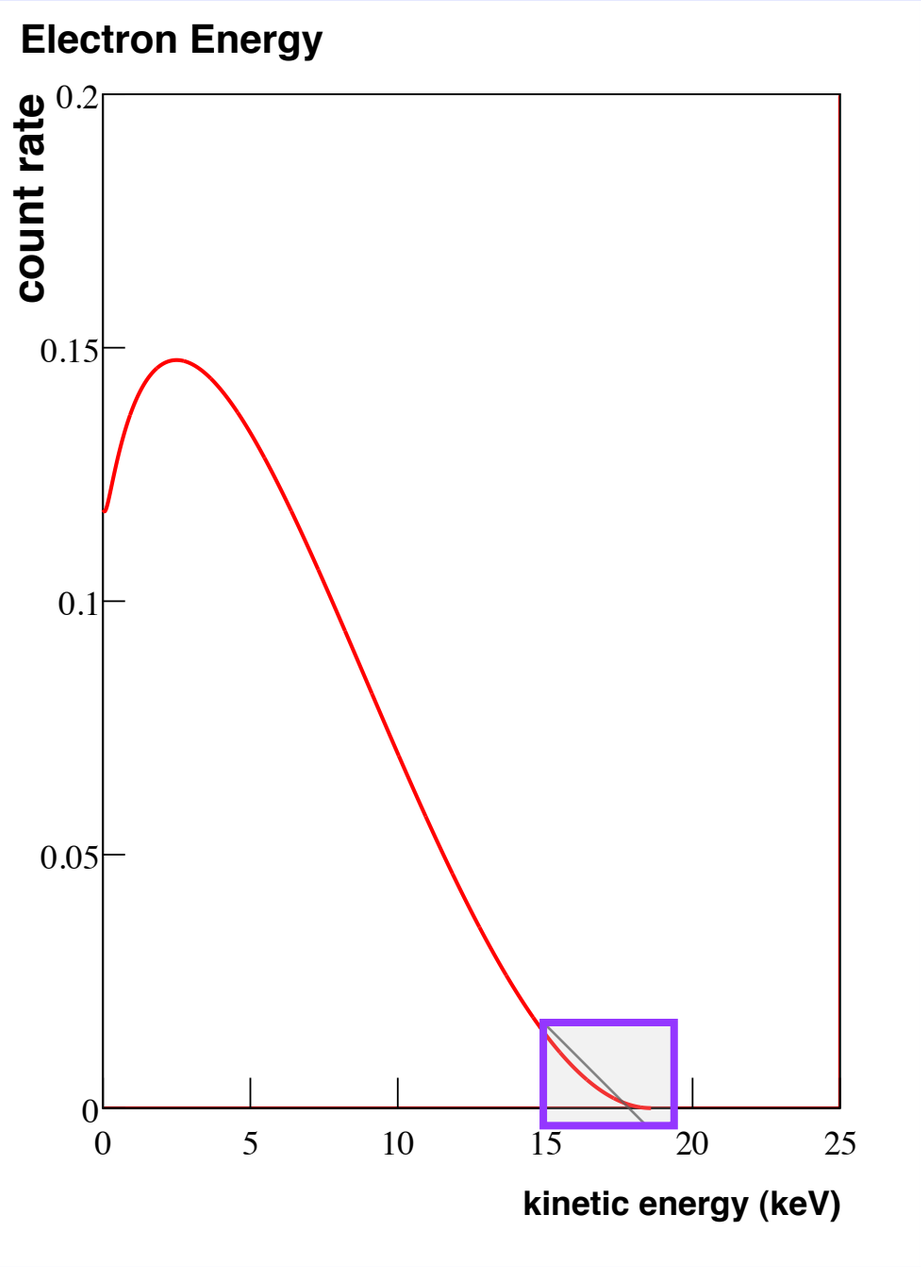


^{3}H Beta Decay



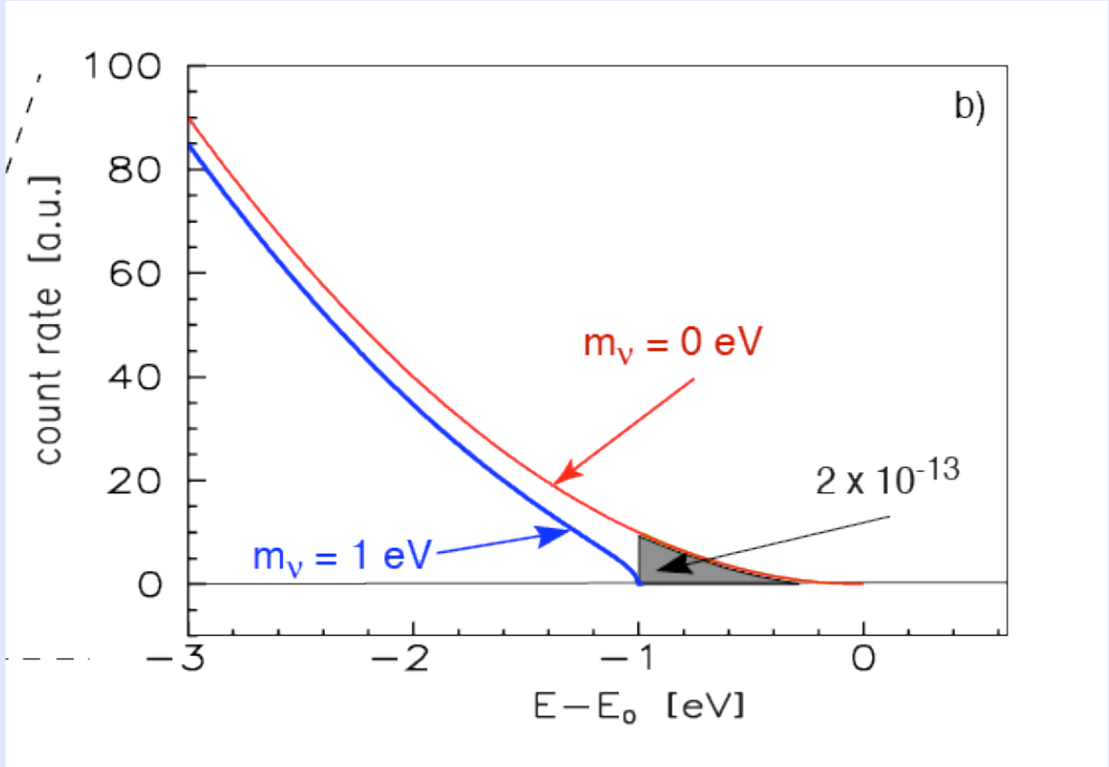
. . . from which one detects the electron

Energy Spectrum



The shape is modified by neutrino mass, squared

Zoom in on the endpoint . . .



Use a large spectrometer to filter out the high-energy electrons

The KATRIN Spectrometer

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Mass Limits from ^{3}H

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- Predecessors: Mainz and Troitsk
  - ❖ Current limit: $m_\nu < 2.2\ \mathrm{eV}$

- Under construction: KATRIN
  - ❖ Sensitivity down to $m_\nu < 0.2\ \mathrm{eV}$
  - ❖ Talk in session 3E

- Future experiment: Project 8
  - ❖ Talk in session 5E

To sum up . . .

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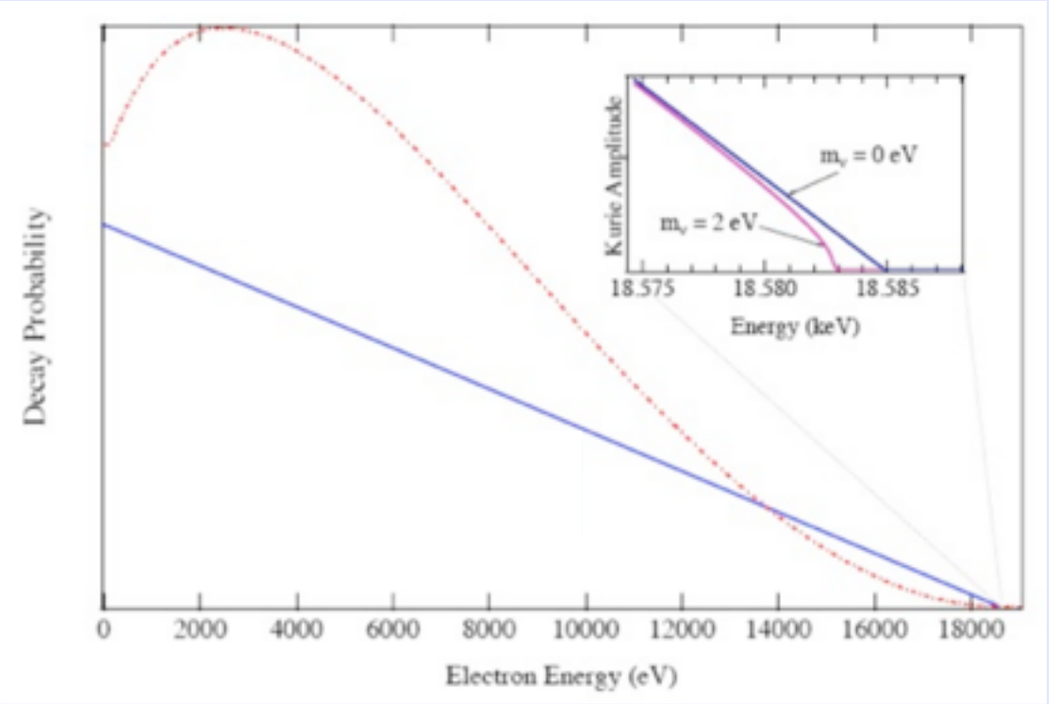
- We have known about neutrinos for ~80 years
- In the past 15 years neutrino physics has been revolutionized
- The current generation of experiments continues to make amazing progress
- There are plenty of intriguing questions left to answer
- Check out sessions 1E, 2D, 2E, 3E, 4E, 5E and 5F, and Plenary 2 for the latest neutrino news!

ν mass limit: b decay

- ^{3}H beta decay
  - ❖ Current limit: mn < 2.2 eV
  - ❖ Goal for KATRIN: mn < 0.2 eV
  - ❖ Beyond KATRIN: Project 8
- ^{187}Re beta decay
  - ❖ Goal for MARE: mn < 2 eV
- Single beta decay talks:
  - ❖ KATRIN (3E), Project 8 (5E)



Neutrino Mass Models

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- See-saw mechanism
- mention other models

Does $\bar{\nu} = \nu$

- If yes, then the $\overline{\nu_i}$ are "Majorana" neutrinos
  - The SM Lagrangian has Majorana mass terms, e.g. $\mathrm{m_L}\overline{\nu_\mathrm{L}}\nu_\mathrm{L}{}^\mathrm{c}$
  - Lepton number is not conserved

- Dirac masses are the analogues of the SM quark and charged lepton masses
  - Dirac mass terms: $\mathrm{m_D}\overline{\nu_\mathrm{L}}\nu_\mathrm{R}$

Zero-ν Double Beta Decay

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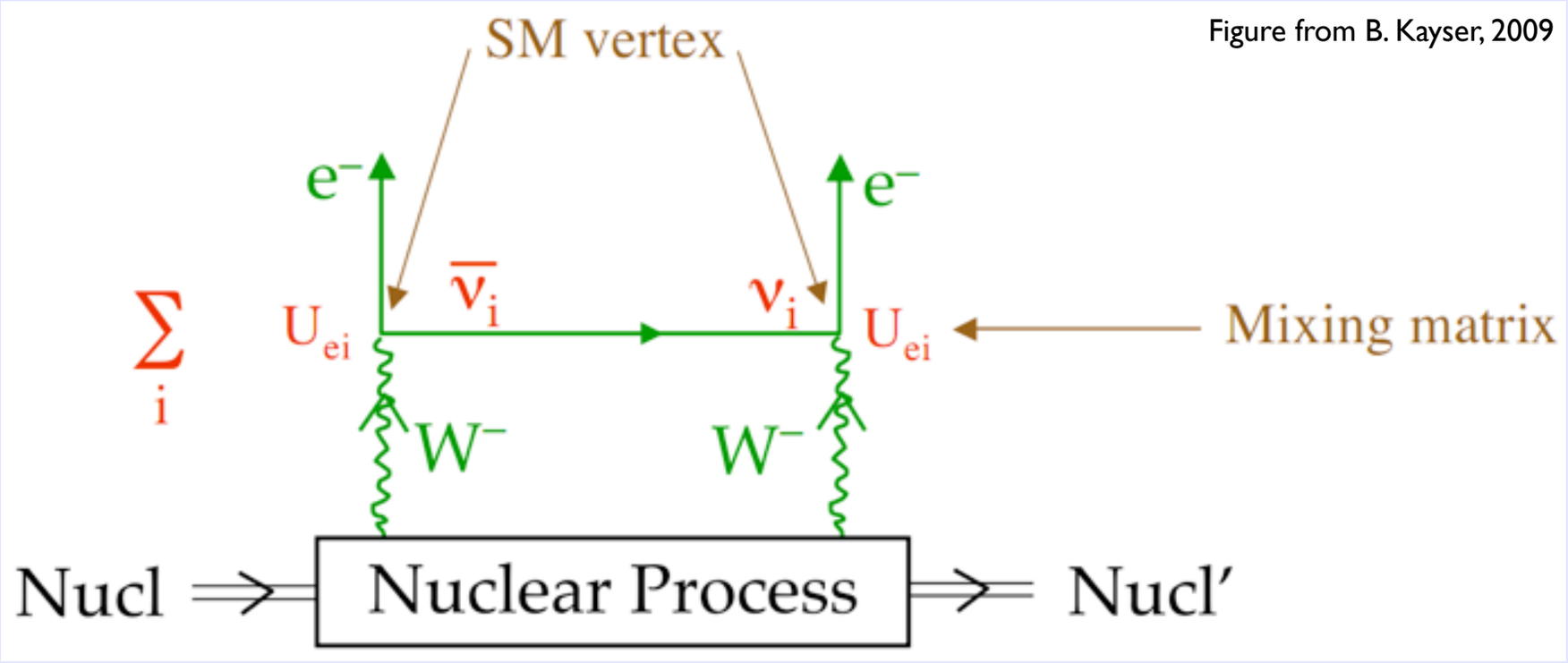
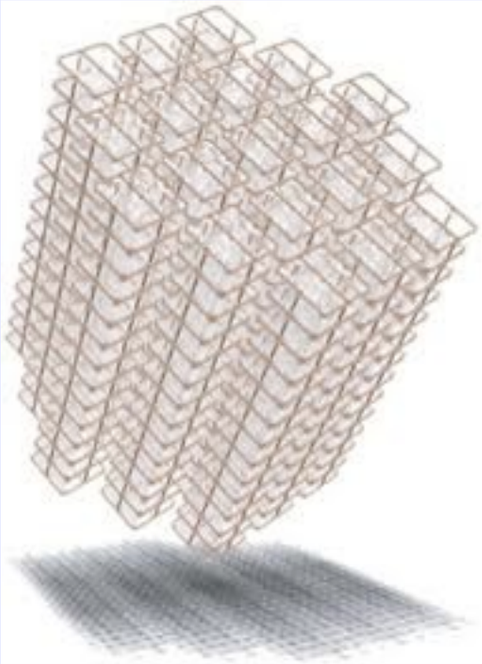
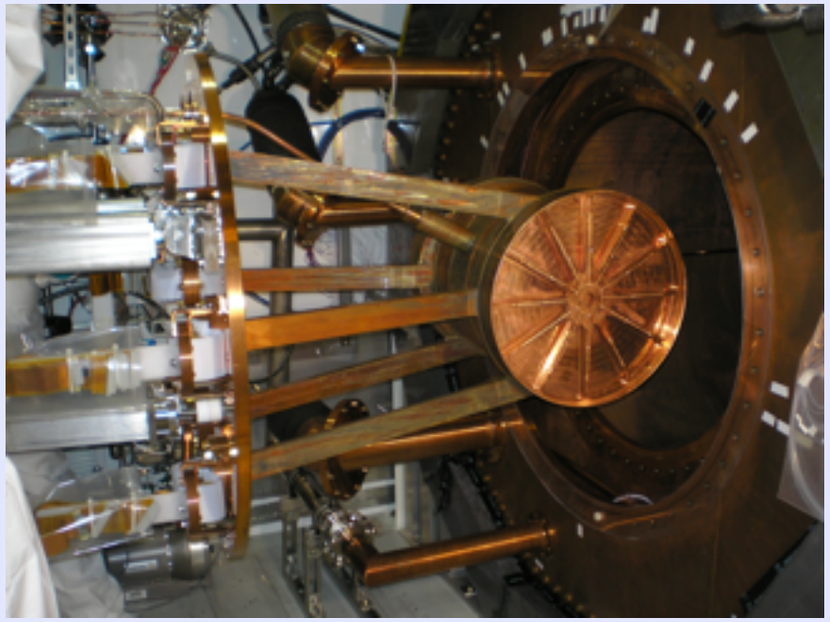
- Observation of zero-neutrino double-beta ($0\nu\beta\beta$) decay implies Majorana neutrinos



State of the art: 0νββ





- [limits from Neutrino2010]
- Check out session 4E for the latest news

CP Violation

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- Through leptogenesis would result in the baryon asymmetry observed in the universe
- Outgrowth of the see saw mechanism
- Heavy neutrinos created at the big bang would decay into +/- charged leptons
- If nu interactions violate CP, then heavy nu interactions would too
- Would have had different rates of decays N->l-+higgs+ and N->l++higgs-
- sphaeleron process takes lepton asymmetry and turns it into a baryon asymmetry

CP Violation

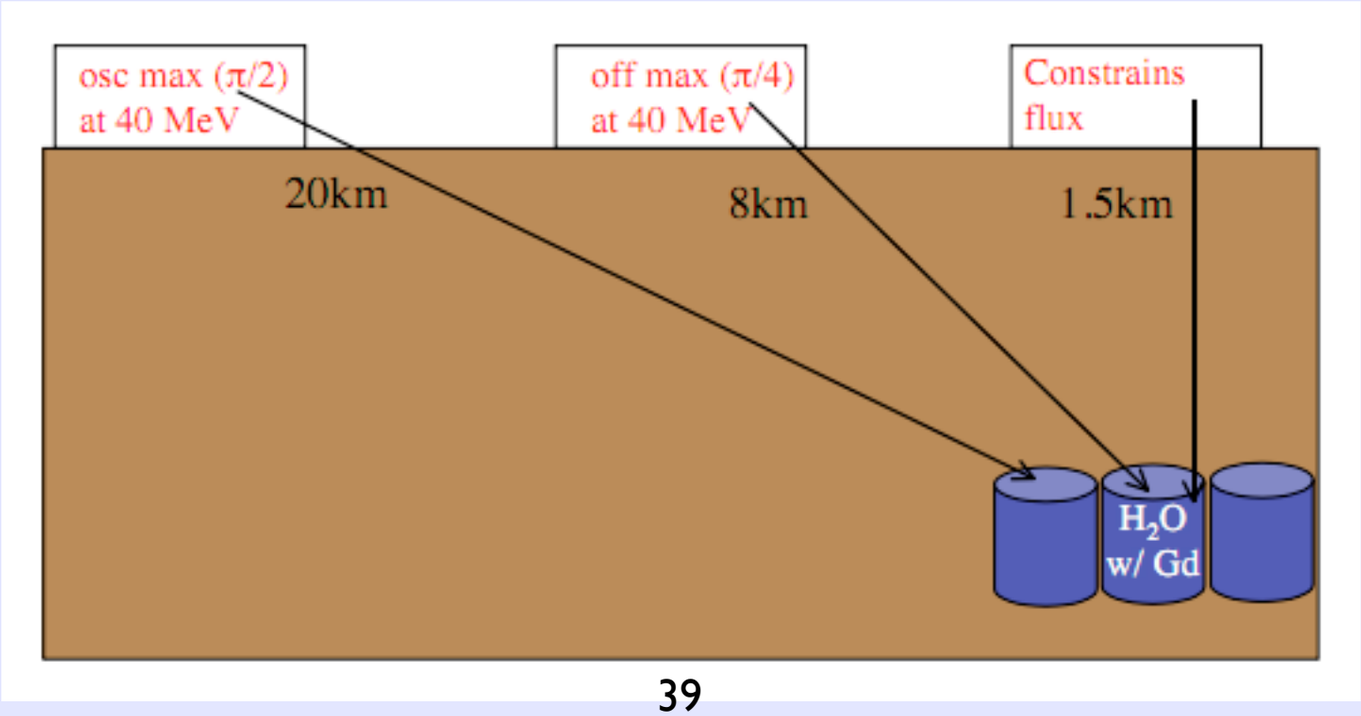
- There is a CP-violating phase in the MNSP matrix

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

- If any mixing angle is too small, CP violation won't be seen in the neutrinos
- Lepton CP violation could explain the matter/antimatter asymmetry in the universe

Observing CP Violation

- Use accelerators at different baselines
- look for $P(\bar{\nu}_a \rightarrow \bar{\nu}_b) \neq P(\nu_a \rightarrow \nu_b)$
- See the talk on the DAEdALUS experiment ()



Sterile Neutrinos?

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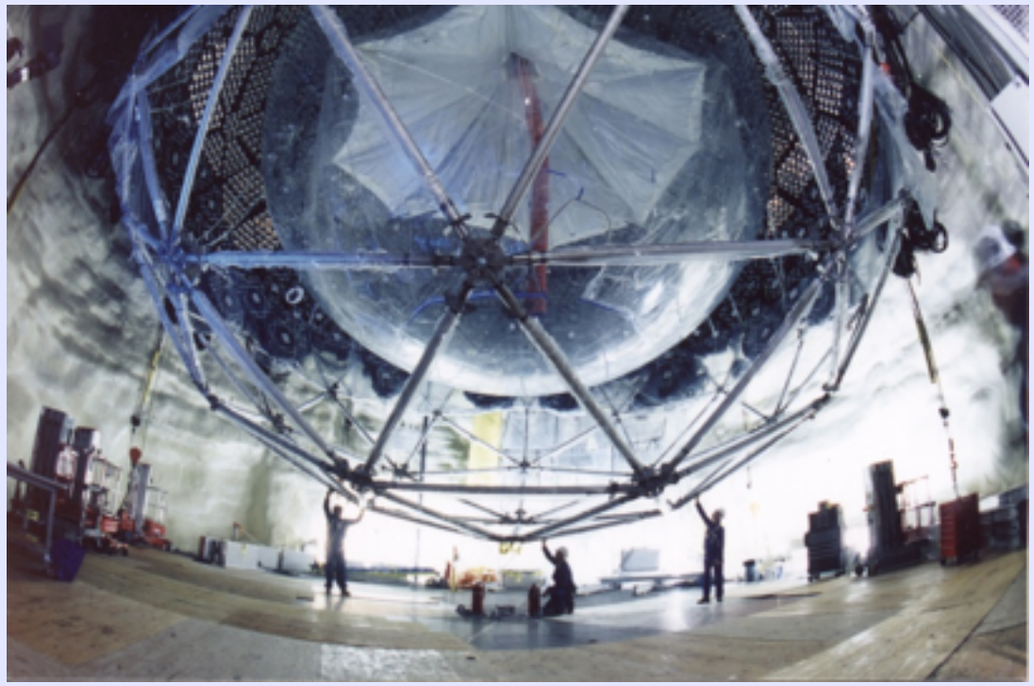
- Evidence from LSND
- Z width gives 3 active flavors ($Z \to \nu\bar{\nu}$)
- if >3 flavors, the extra must not couple to the Z

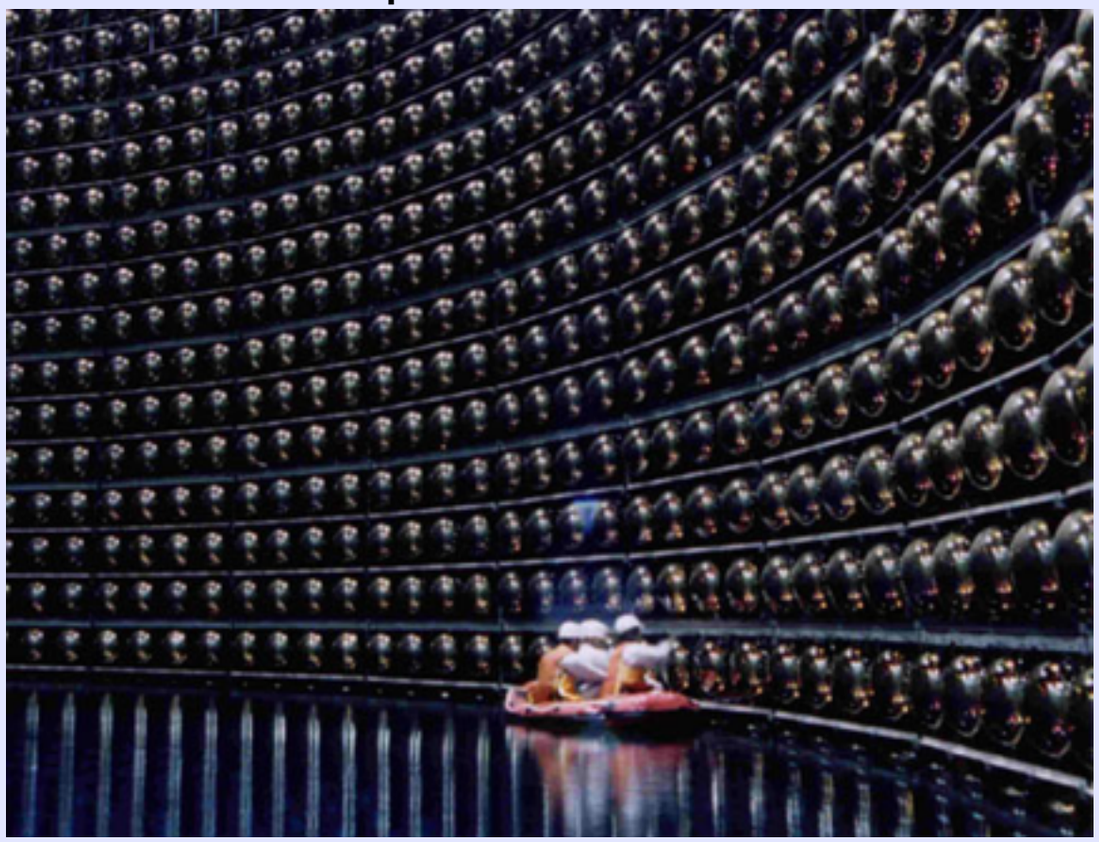
From oscillations . . .

- We know that there are at least two mass separations
  - $Dm^2_{21} \sim= 7.58 \text{ x } 10^{-5} \text{ eV}^2$
    (solar & KamLAND)
  - $Dm^2_{32} \sim= 2.35 \text{ x } 10^{-3} \text{ eV}^2$
    (atmospheric & accelerator)



SNO

SuperKamiokande



- And we know two of the three mixing angles
  - $q_{12} = 0.306 \text{ +/- } 0.017$
  - $q_{23} = 0.42 \ ^{+0.08}_{-0.03}$

Data from G.L. Fogli, *et al*, 2011

Sterile Neutrinos?

- Discuss recent results from MiniBooNE and new reactor flux information