Introduction to Neutrino Physics

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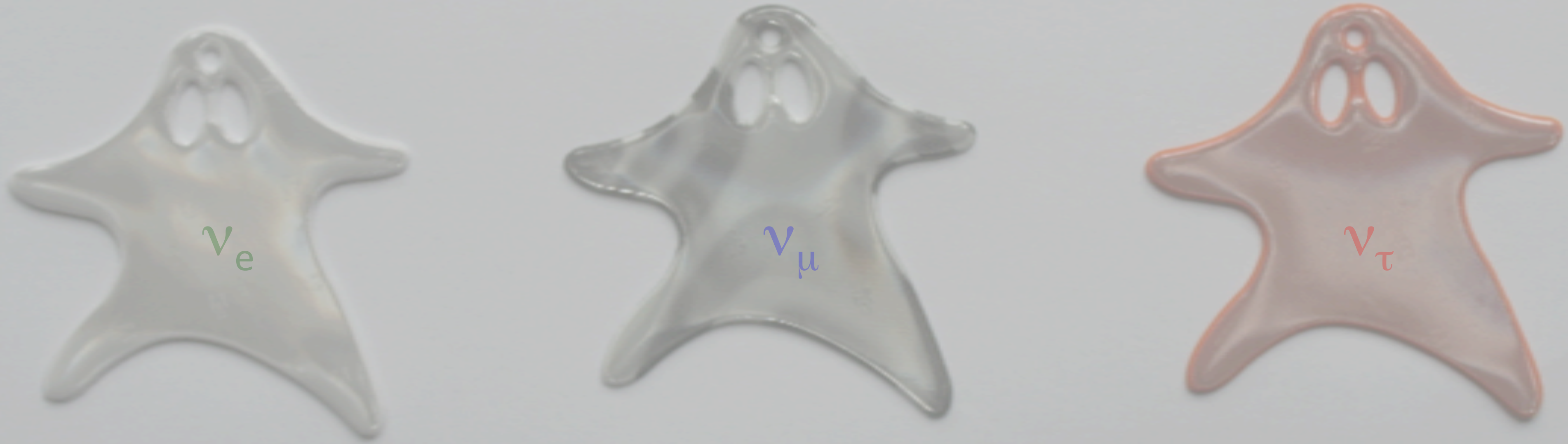


Lecture 3

Neutrino oscillations Part 3

Neutrinoless double beta decay Part 1

Recap lecture 2

- Neutrino mixing parameters (θ, Δm^2) for "solar" and "atmospheric" neutrino sectors have been well measured
  - Results dominated by SNO, KamLAND ("solar"); Super-Kamiokande, MINOS ("atmospheric")
- We are seeing the first results from experiments that will tell us about the subdominant θ_{13}
  - T2K, MINOS
  - More on that today
- θ_{13} must be > 0 for δ to exist
  - But there is another possibility for leptonic CP violation if neutrinos are Majorana particles
- $\sin^2 2\theta_{13}$ must be >~ 0.01 to be experimentally accessible
  - This would open up an avenue for leptonic CPv

Outline lecture 3

- θ_{13} with reactor experiments
- Wrap-up of neutrino-oscillations
- Neutrino mass
- Majorana neutrinos and the see-saw mechanism

θ_{13}: Long-baseline accelerator vs. reactor experiments

LBL accelerator experiments:

- Look for appearance ($\nu_\mu \to \nu_e$) in pure ν_μ beam vs. *L* and *E*
- Near detector to measure background ν_es (beam + mis-id)
- $P(\nu_\mu \rightarrow \nu_e) = f(\delta, \text{sign}(\Delta m_{31}^2))$

Reactor experiments:

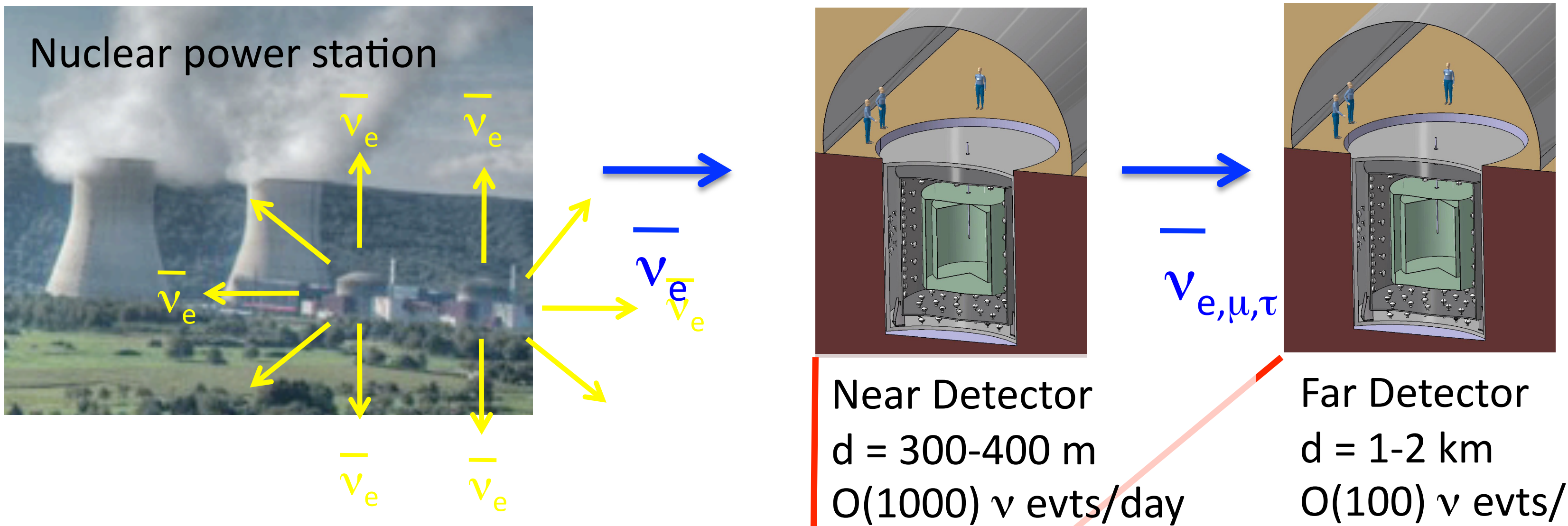
- Look for disappearance ($\bar{\nu}_e \to \bar{\nu}_e$) as a fnc of *L* and *E*
- Near detector to measure unoscillated flux
- $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ independent of δ; matter effects small

Combination of appearance and disappearance very powerful if comparable sensitivity

MINOS, T2K, NOνA

Double Chooz, Daya Bay, RENO

θ_{13} measurements at reactors

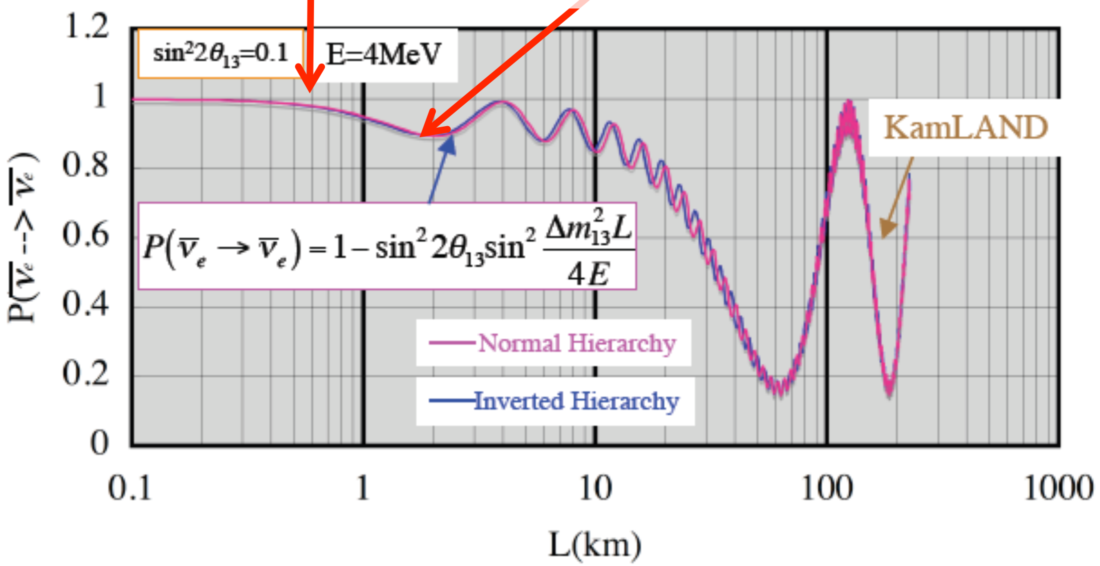


Near Detector
d = 300-400 m
O(1000) ν evts/day

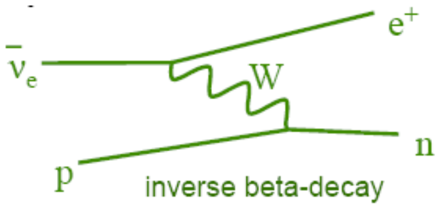
Far Detector
d = 1-2 km
O(100) ν evts/day

Present limit from CHOOZ (single-detector expt in ’90s): $\sin^2(2\theta_{13}) < 0.15$ (90% C.L.) at $\Delta m^2_{31} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

Dominant source of systematic error in CHOOZ: Reactor neutrino spectrum



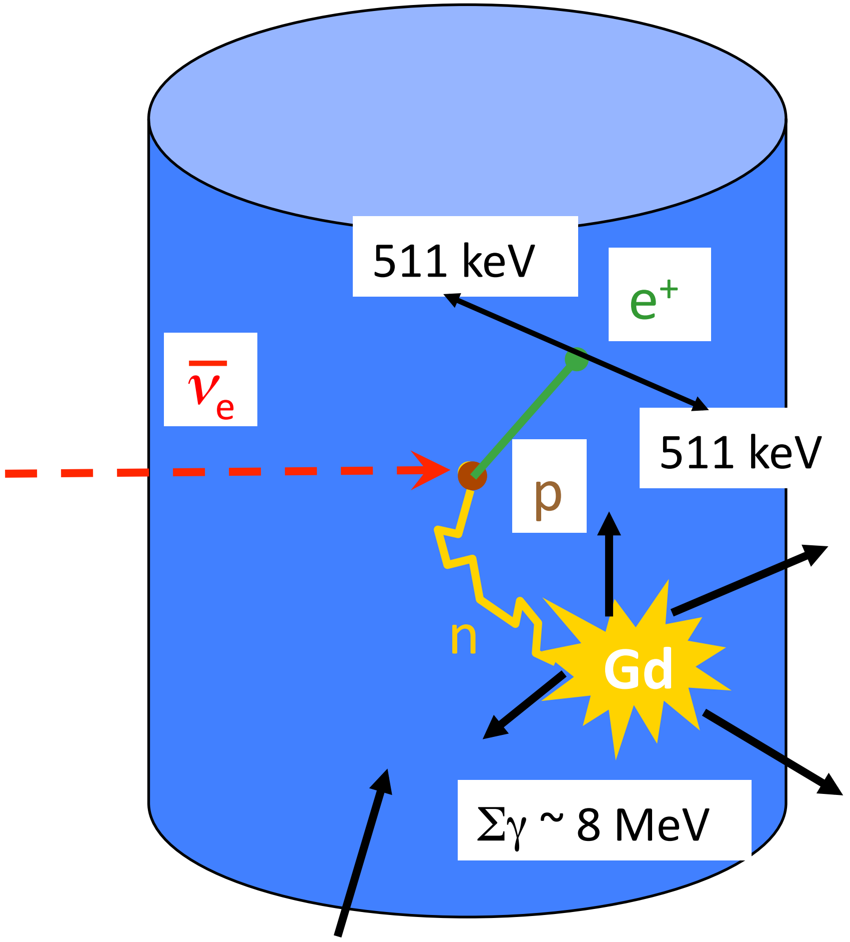
Neutrino detection



Inverse beta decay:
$\bar{\nu}_e + p \rightarrow n + e^+$

→ Prompt annihilation

→ $n + Gd \rightarrow Gd^* + \gamma s$ (8 MeV)
Delayed: $\Delta t \sim 30\ \mu s$



Neutrino event: coincidence in time, space and energy

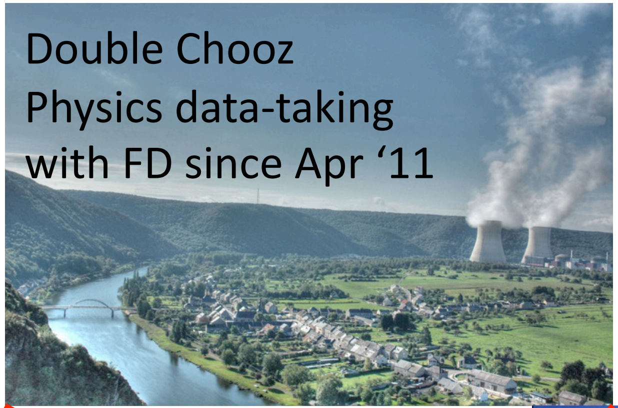
Neutrino energy:

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{m_n - m_p + m_{e^+}}_{\text{Threshold: 1.8 MeV}}$$

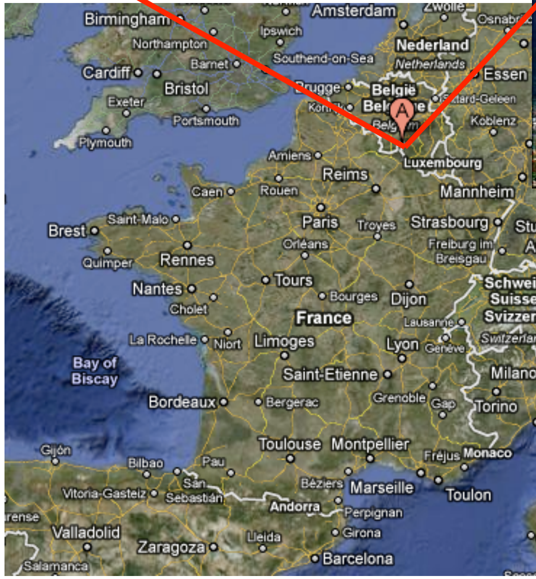
Target: Gd-loaded liquid scintillator

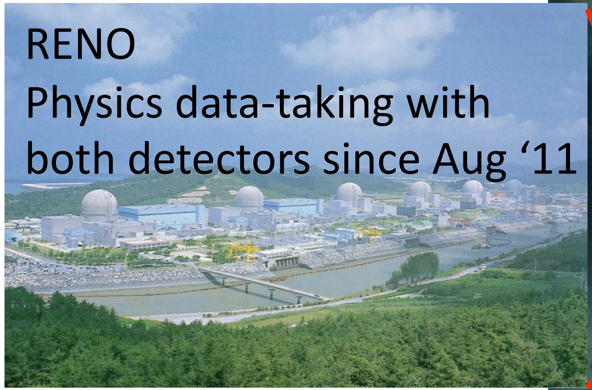
Gadolinium (Gd) improves n capture

Three reactor experiments

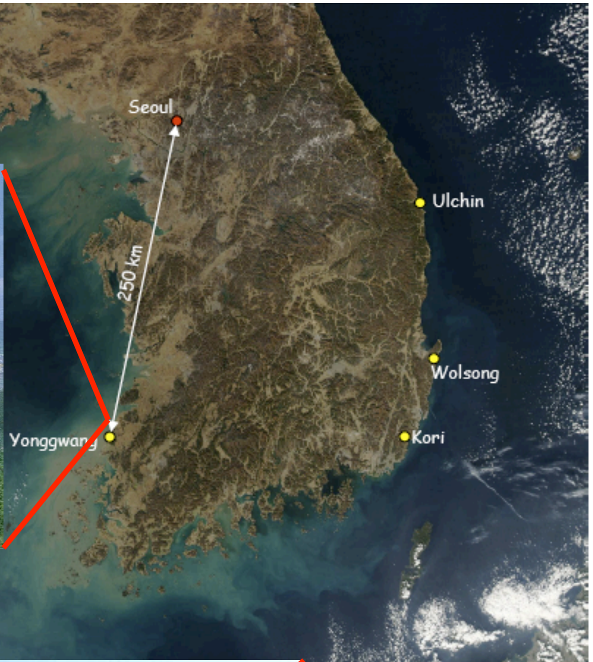


Double Chooz
Physics data-taking
with FD since Apr ‘11





RENO
Physics data-taking with
both detectors since Aug ‘11



Daya Bay
Data-taking with 2 of 8 detectors since Aug ‘11

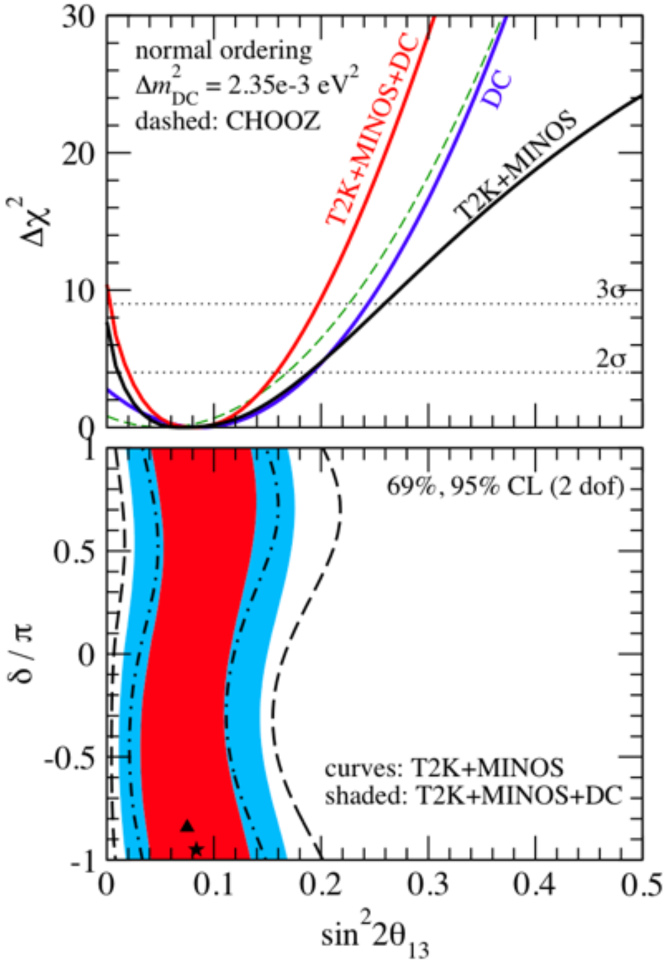
First result from Double Chooz

- Result from first six months of data-taking released on 9 Nov
- Best fit:

$$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst}) \text{ at } 68\% \text{ C.L.}$$

- My comments:
  - Less than 2σ significance on its own
  - Remember: Far Detector only
  - Regard these early results as health checks of the experiments

Combined analysis of Double Chooz, T2K and MINOS (normal mass ordering)



▲ T2K + MINOS best fit

★ T2K + MINOS + DC best fit

Future results on θ_{13}

- RENO expected to release their first results soon
- T2K was set back by the earth quake on 11 March 2011. Expect to start up their beam early next year
- Ramp-up over next few years:
  - Gradual increase of T2K beam intensity
  - Double Chooz Near Detector in 2013
  - Daya Bay 8 detectors eventually
- Expect to see the bulk of the results within the next five years

Stock-taking on neutrino oscillations

- The 10+ last years have moved forward our knowledge about neutrinos in leaps and bounds
- From evidence of ν flavour change by Super-K in 1998 and solar neutrino oscillations by SNO in 2002 to solid measurements of the parameters of the two dominant oscillation sectors
- In ~5 years from now, we should know whether $\sin^2 2\theta_{13}$ is > or < 0.01. If early indications are anything to go by, then we will have measured its value
- If so, and especially with NOvA coming online (2013-2014), we will be hunting for the mass hierarchy
- The value of $\sin^2 2\theta_{13}$ will inform plans for upgrades and future experiments to hunt for δ
- Either way, there is food for thought for the theorists: Why is θ_{13} so small – or maybe even zero? And why is neutrino mixing so much larger than quark mixing?

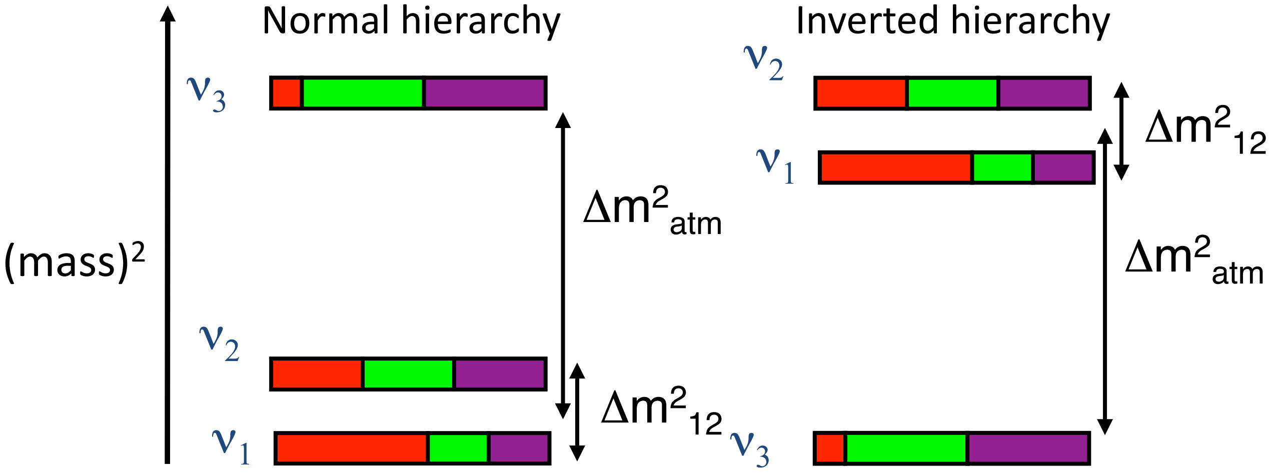
Neutrino mass
and
neutrinoless double beta decay

What do we know about the neutrino mass?

1. Neutrino oscillations don’t tell us anything about absolute neutrino masses

What do we know about the neutrino mass?

From neutrino oscillations:



- The heaviest neutrino must be at least at heavy as Δm_{atm}

$$\Delta m^2_{atm} \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2 \quad \Rightarrow \quad m_\nu \geq 50\ \mathrm{meV}$$

What else do we know about the neutrino mass?

- From cosmological observations:

$$m_\nu < \ \sim 1\ \text{eV}$$

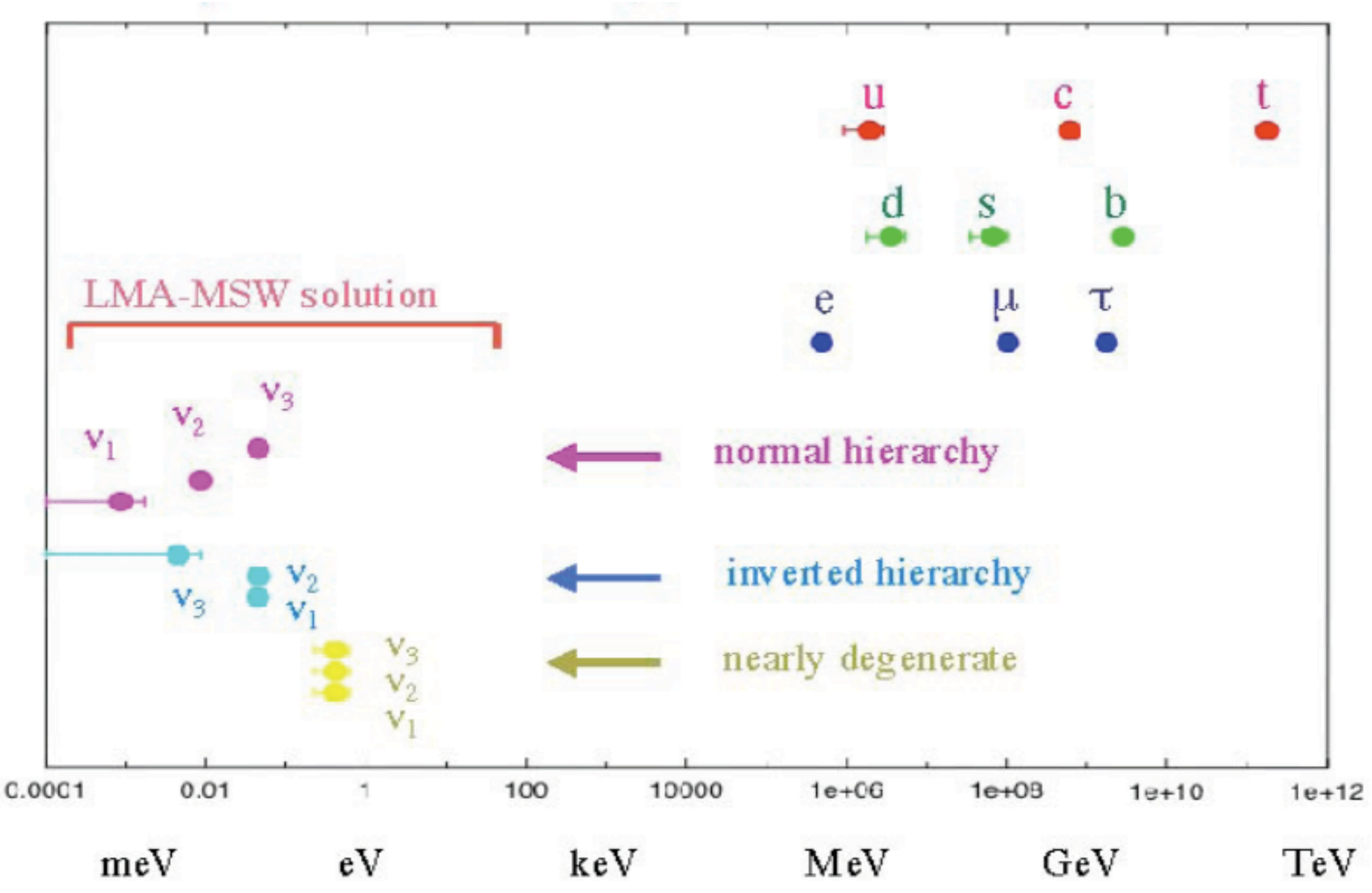
- So:

$$\boxed{50\ \text{meV} < m_\nu < \ \sim 1\ \text{eV}}$$

There are, of course, constraints on the neutrino mass from other observations as well

- Constrained to within two (~accessible) orders of magnitude → a lot of experimental interest in this question

Why are neutrinos so light?



Neutrino mass and the Standard Model

- Standard Model: neutrinos massless
  - – Contains only left-handed neutrino field ν_L that couples to W and Z
- Straightforward to extend SM: accommodate ν masses in the same way as quark and lepton masses
  - – Left-right coupling to the Higgs field
  - – Add right-handed field ν_R, and construct a “Dirac mass term”:

$$\mathcal{L}_D = -m_D\left(\overline{\upsilon_L}\nu_R + \overline{\upsilon_R}\nu_L\right)$$

Dirac and Majorana mass terms

$$\mathcal{L}_D = -m_D\left(\overline{\upsilon_L}\nu_R + \overline{\upsilon_R}\nu_L\right)$$

- Conserves lepton number *L*
  - Distinguishes between particle and anti-particle
    - Now $\overline{\upsilon}_i \neq \nu_i$, as for charged leptons and quarks
    - Dirac neutrino

- Neutrino neutral: can also construct a “Majorana mass term”

$$\mathcal{L}_M = -\frac{m_M}{2}\left(\overline{\upsilon_R^c}\nu_R + \overline{\upsilon_L^c}\nu_L\right)$$

out of the right-handed field ν_R and its charge conjugate $\nu^c{}_R$

  - Right-handed field has no SM couplings, so no gauge quantum numbers
  - Note: m_M is a different constant to m_D

Majorana neutrinos

$$\mathcal{L}_M = -\frac{m_M}{2}\left(\overline{\upsilon_R^c}\nu_R + \overline{\upsilon_L^c}\nu_L\right)$$

- $\mathcal{L}_M$ mixes neutrino and antineutrino
  - No conservation of lepton number *L*
  - Majorana neutrino

- If we insist that SM conserve *L* → no Majorana mass terms

- Instead: require only general principles of gauge invariance and renormalisability → expect Majorana mass terms, and hence *L* violation and Majorana neutrinos

- Note that quarks and charged leptons cannot have Majorana mass terms
  - Mix fermion and antifermion → non-conservation of electric charge

Combining Dirac and Majorana

$$\mathcal{L}_{D+M} = -\frac{1}{2}\begin{pmatrix}\overline{\upsilon_L} & \overline{\upsilon_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & m_M\end{pmatrix}\begin{pmatrix}\upsilon_L^c \\ \upsilon_R\end{pmatrix} + h.c.$$

See-saw mechanism

$$\mathcal{L}_{D+M} = -\frac{1}{2}\begin{pmatrix}\overline{\upsilon_L} & \overline{\upsilon_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & m_M\end{pmatrix}\begin{pmatrix}\upsilon_L^c \\ \upsilon_R\end{pmatrix} + h.c.$$

- If $m_M >> m_D$, then diagonalising this matrix gives the following eigenvalues:
  - (Nearly) right-handed Majorana neutrino with mass ~m_M
  - (Nearly) left-handed Majorana neutrino with mass ~m_D^2/m_M
- You should find that
  - The solution to the larger eigenvalue is trivial
  - The smaller eigenvalue is, in fact, negative(!) – it can be absorbed by a redefinition of the neutrino field

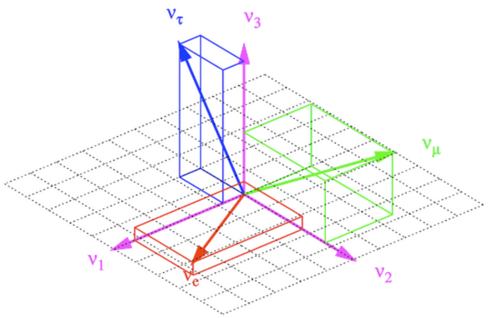
See-saw mechanism

$$\mathcal{L}_{D+M} = -\frac{1}{2}\begin{pmatrix} \overline{\upsilon_L} & \overline{\upsilon_R^c} \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}\begin{pmatrix} \upsilon_L^c \\ \upsilon_R \end{pmatrix} + h.c.$$

- Can choose m_M and m_D such that mass of left-handed neutrino becomes tiny, consistent with observation, and right-handed neutrino extremely heavy
- Requires neutrinos to be Majorana, i.e. its own anti-particle…

- The see-saw mechanism is the most popular explanation of why neutrinos are so light

Mixing matrix revisited



$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{\text{CP}}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{\text{CP}}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U_{\text{Maj}}^{\text{diag}}$$

where

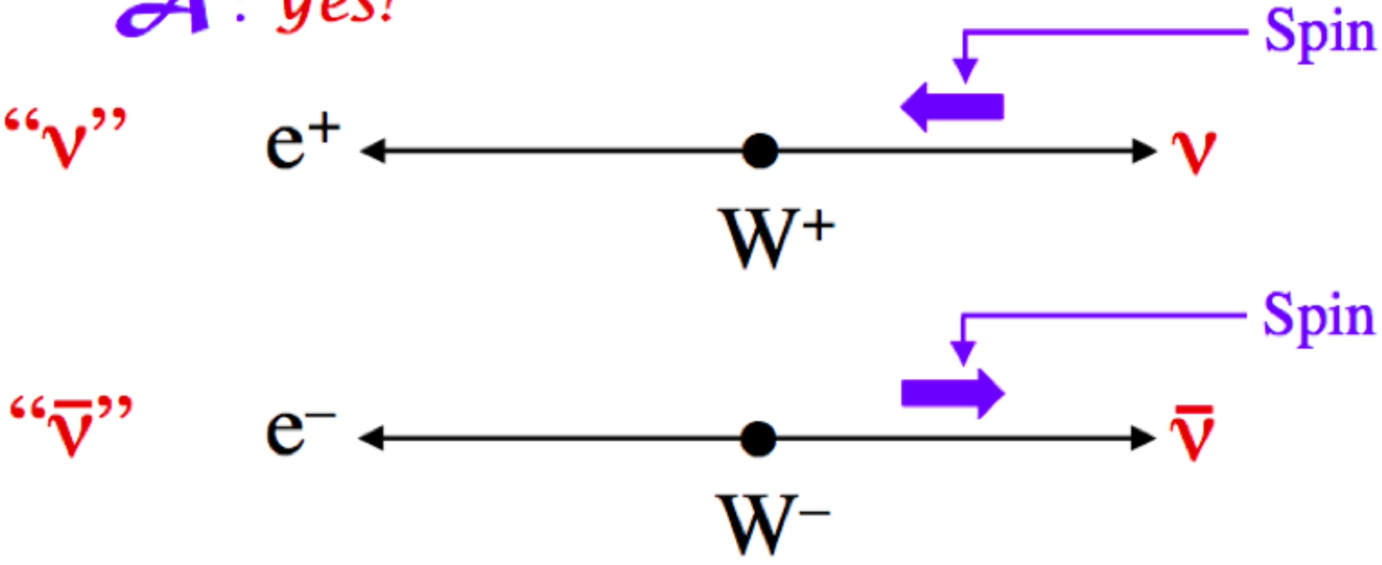
$$U_{\text{Maj}}^{\text{diag}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

α and β are Majorana CP-violating phases

Choice of two diagonal elements is arbitrary

Q : *Does matter still affect ν and $\bar{\nu}$ differently when $\bar{\nu} = \nu$?*

A : *Yes!*



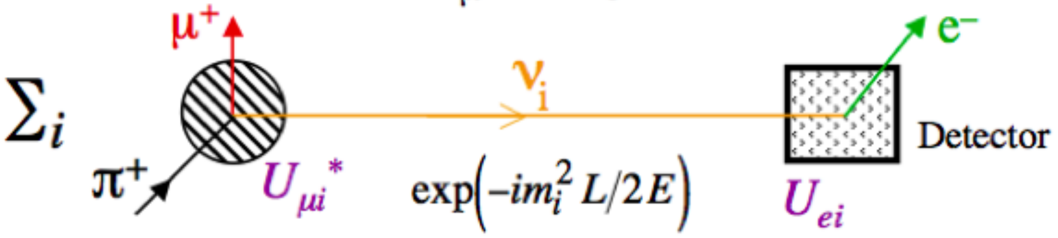
The weak interactions violate ***parity***. Neutrino – matter interactions depend on the neutrino ***polarization***.

Slide from B Kayser

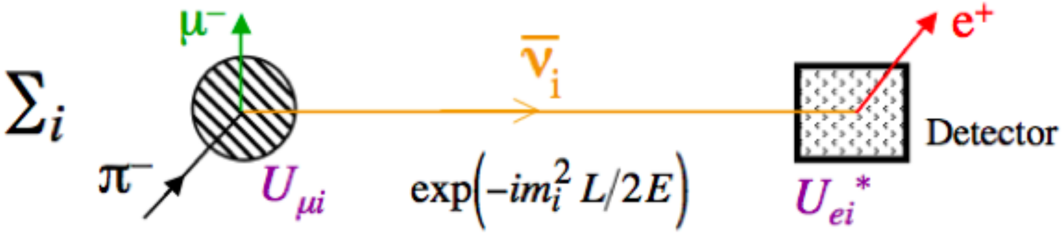
Q : Can CP violation still lead to
$P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq P(\nu_\mu \to \nu_e)$ when $\bar{\nu} = \nu$?

A : Certainly!

Compare $\nu_\mu \to \nu_e$



with "$\bar{\nu}_\mu \to \bar{\nu}_e$"



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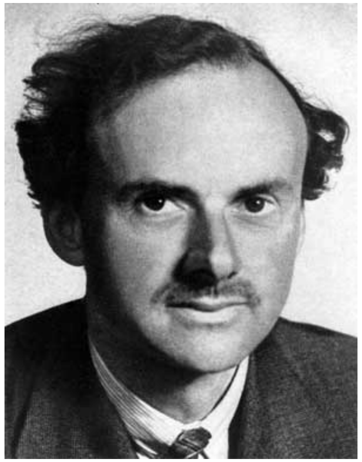

Paul Dirac

So, how can one find out whether the neutrino is a Dirac or a Majorana particle?
And what is the mass of the neutrino?

Subject of Lecture 4!

Ettore Majorana

Back-ups