Introduction to Neutrino Physics

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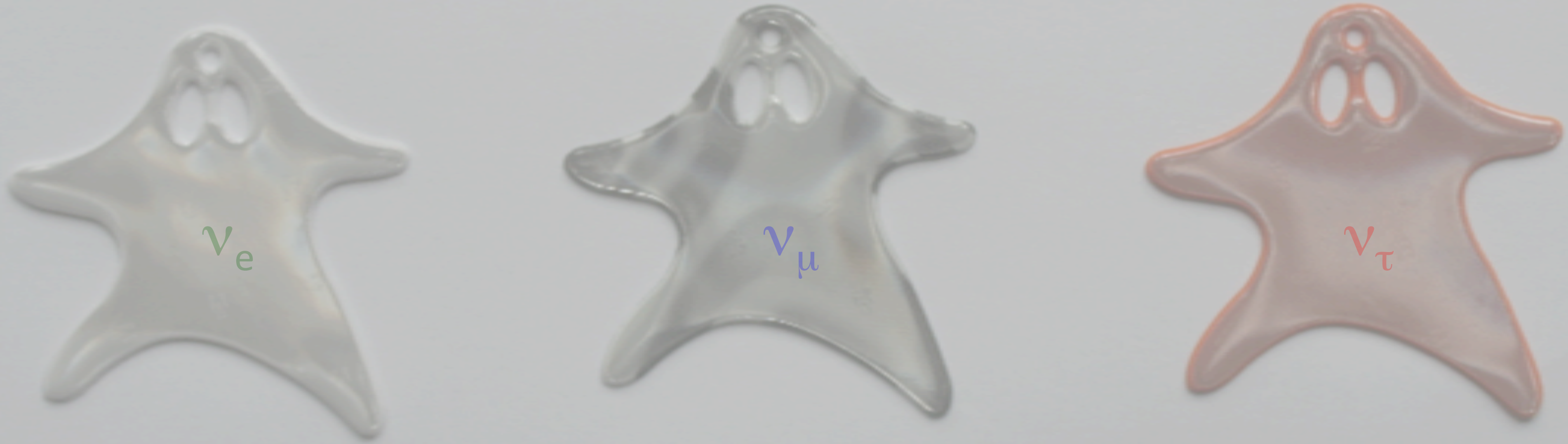


Lecture 1

Neutrino oscillations Part I

Neutrino

- “The little neutral one” in Italian
- A subatomic particle with almost no mass, no charge, no magnetic moment, and which interacts only rarely
- Neutrinos make up the same fraction of mass in the universe as stars and planets do
- They exhibit bizarre behavior when travelling through space: They change form from one type of neutrino to another. No other particle does this

Overview of lecture course

- Introduction to the course and to neutrinos
- Neutrino oscillation formalism
- “Solar” neutrinos
- Atmospheric and long-baseline neutrinos
- θ_{13} and CP violation

~
L1
&
L2+

- Neutrino mass, Majorana neutrinos, the see-saw mechanism
- Neutrinoless double beta decay: theory and experiment

~
L3-
&
L4

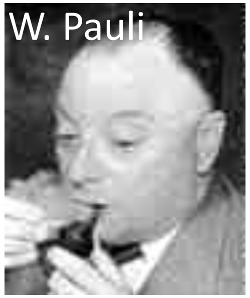
- “The neutrino speed of light thing” – OPERA
- SN1987a (hopefully!)
- Wrap-up and outlook

~
L5

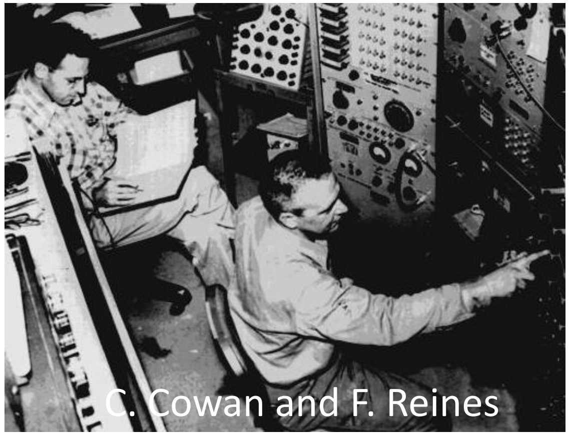
Outline lecture 1

- Neutrinos: introduction and a little history
- Neutrino oscillation formalism:
  two- and three-neutrino oscillations
- Solar neutrinos (continued tomorrow)
- Suggested reading

The discovery of the neutrino



- 1920s: Puzzle: Radioactive β decay appears to break energy conservation: electron has continuous spectrum!
- 1930: "Desperate remedy": Wolfgang Pauli suggests new particle carrying off missing energy without being detected
- 1933: Enrico Fermi formulates comprehensive theory of radioactive decays
  - Pauli's particle crucial
  - "Neutrino" – the little neutral one
- 1956: Fred Reines and Clyde Cowan detect neutrinos created by nuclear reactor
  - Savannah River, South Carolina, USA
  - Case of champagne from Pauli
  - 1995 Nobel Prize (Reines)



The discovery of the neutrino

- 1962: Leon Lederman, Mel Schwartz and Jack Steinberger detect muon neutrinos
  - Created neutrino beam at accelerator lab (Brookhaven, NY)
  - 1988 Nobel Prize
- 2000: DONUT collaboration sees first direct evidence of tau neutrino
  - Fermilab, Chicago


L. Lederman, M. Schwartz and J. Steinberger


DONUT Collaboration

Minnesota
D. Ciampa, C. Erickson, M. Graham,
K. Heller, E. Maher, R. Rusack, R. Schwienhorst,
J. Sielaff, J. Trammell, J. Wilcox

Fermilab
B.Baller, D.Boehnlein,W.Freeman,
B.Lundberg, J.Morfin, R. Rameika

Kansas State
P. Berghaus, M. Kubanstev, N.W. Reay,
R. Sidwell, N. Stanton, S. Yoshida

Pittsburgh
T. Akdogan, V. Paolone

Tufts University
T. Kafka,W. Oliver, T. Patzak , J. Schneps,

South Carolina
A. Kulik, C. Rosenfeld

U. California/Davis
P. Yager

Nagoya University
N. Hashizume, K. Hoshino, H. Iinuma,
H. Jikou, K. Ito, M. Kobayashi, M.
Miyanishi, M. Komatsu, M. Nakamura, K.
Nakajima, T. Nakano, K. Niwa, N. Nonaka,
K. Okada, T. Yamamori

Aichi Univ. of Education
K. Kodama, N. Ushida

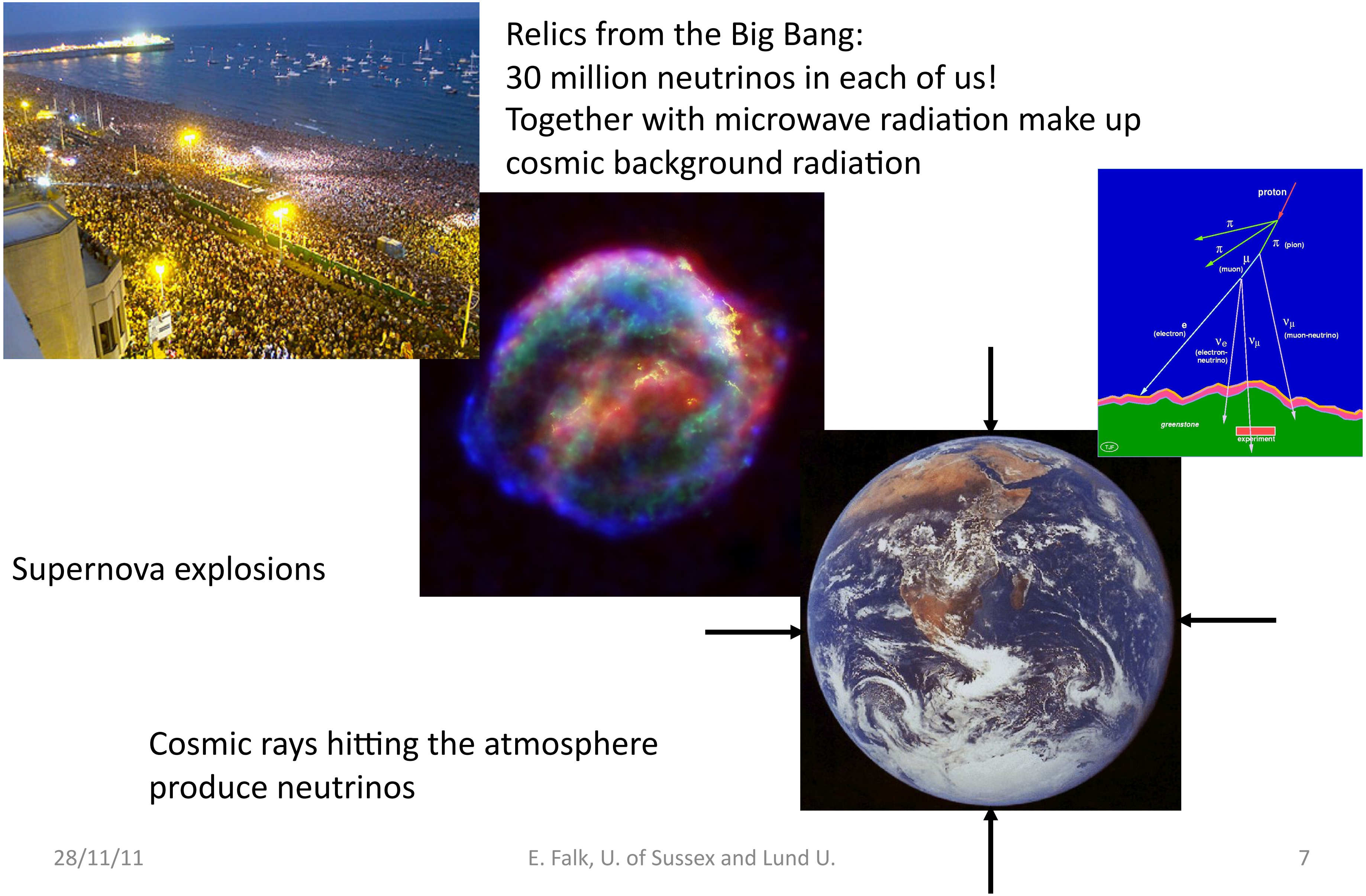
Kobe University
S. Aoki, T. Hara

Gyeongsang University
J.S. Song, I.G. Park, S.H. Chung

Kon-kuk University
J.T. Rhee

Univ. of Athens
C. Andreopoulos, G. Tzanakos, N. Saoulidou

Lots of neutrinos!



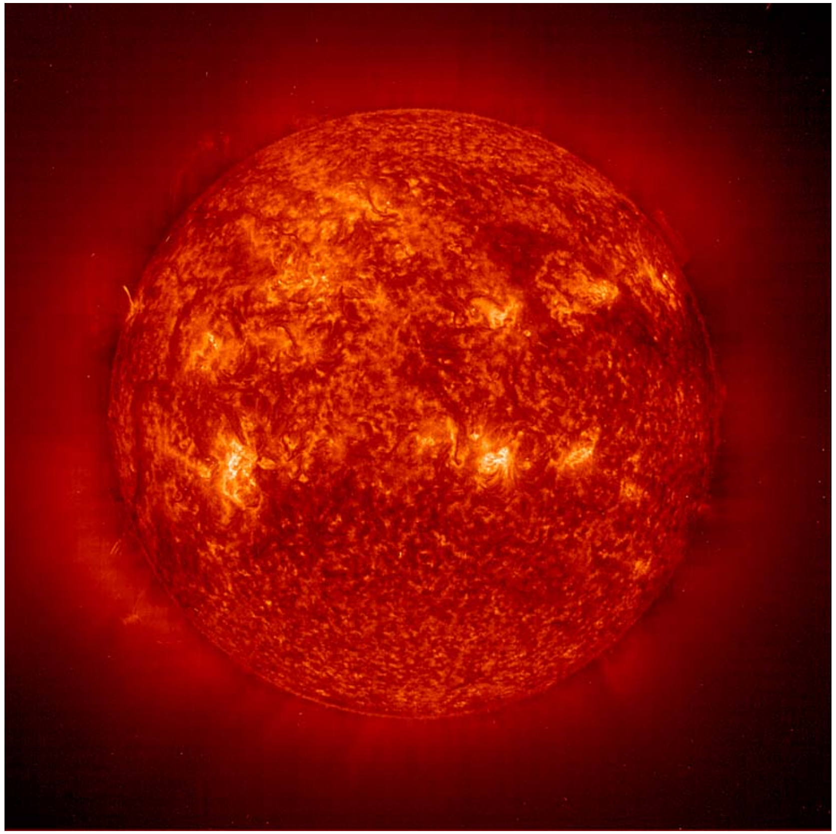
Relics from the Big Bang:
30 million neutrinos in each of us!
Together with microwave radiation make up cosmic background radiation

Supernova explosions

Cosmic rays hitting the atmosphere produce neutrinos

Lots of neutrinos!

But most of the neutrinos
passing through us
come from the sun



- Nuclear fusion:
  - Mainly from pp cycle: 4 p combine with 2 e^- to form a He^{2+} and $2\nu_e$
- 100 billion neutrinos from the sun pass through each of your fingernails—every second!

Elusive neutrinos

> "The chances of a neutrino actually hitting something as it travels through all this howling emptiness [that is the Earth] are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."
>
> -- Douglas Adams, (1952-2001)

This happens to be correct: see
http://faculty.otterbein.edu/NTagg/Otterbein/Publications_files/eggsandwich.pdf
for the calculation

Why do we care?

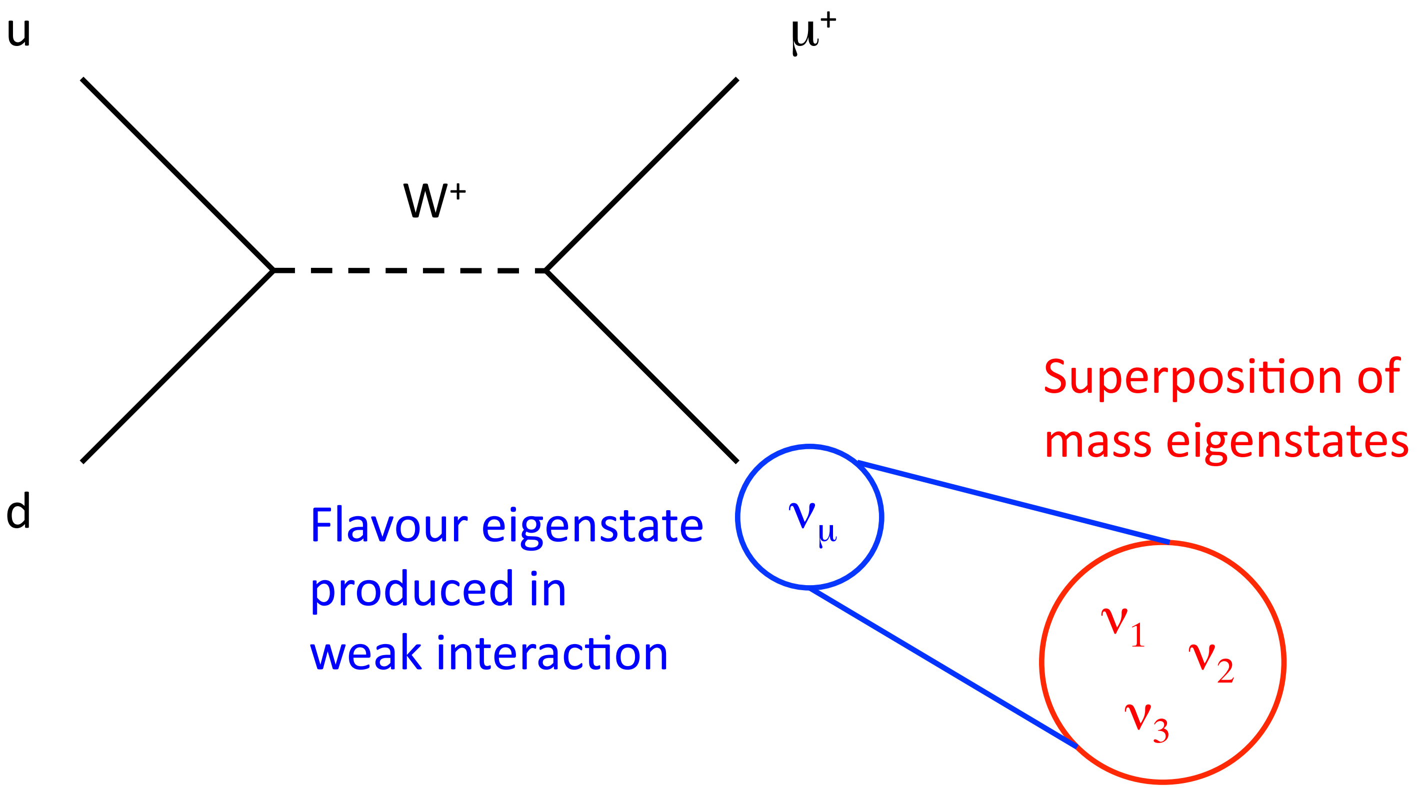
- Fundamental part of nature
- Poorly understood, compared to other nature's other building blocks

For example:

- What are the neutrino masses?
- What is the pattern for neutrino flavour mixing?
- Is the neutrino its own antiparticle?
  - The ultimate neutral particle
- Do neutrinos violate CP?
- Do neutrinos constitute dark matter?
- What can neutrinos and the universe tell us about each other?
- Can neutrinos help explain the matter-antimatter asymmetry in the universe?

Massive neutrinos

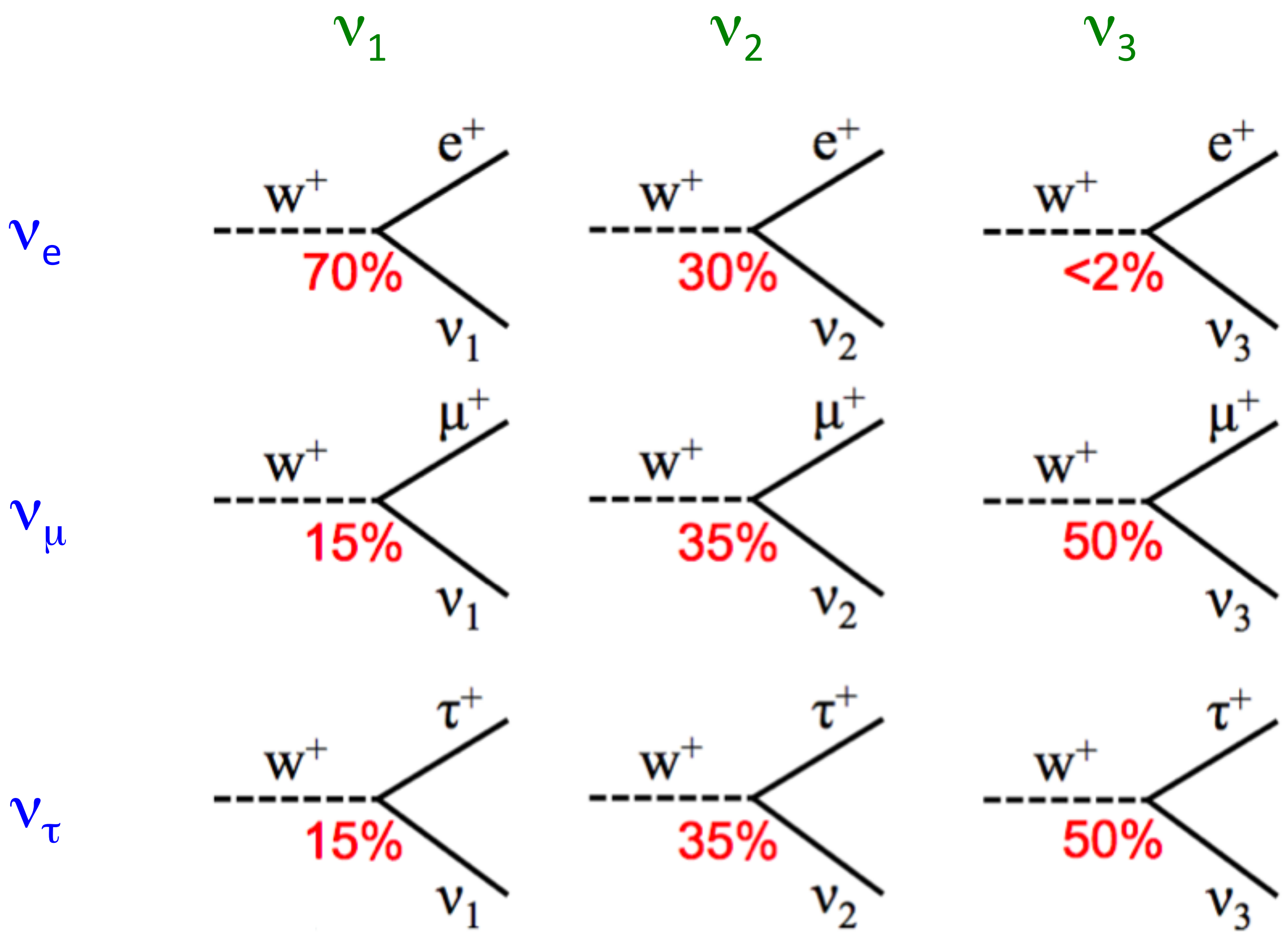
Neutrino mass eigenstates are not the same as the flavour eigenstates



Superposition of
mass eigenstates

Flavour eigenstate
produced in
weak interaction

Current situation



Neutrino oscillations: concept

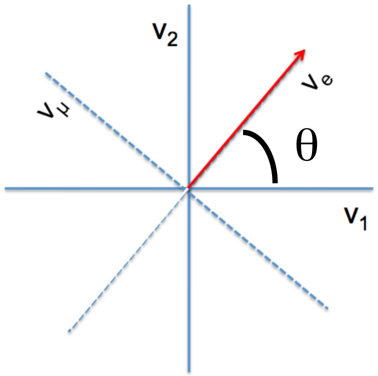
- Write down the relation between mass eigenstates and flavour eigenstates as a rotation with angle θ:

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

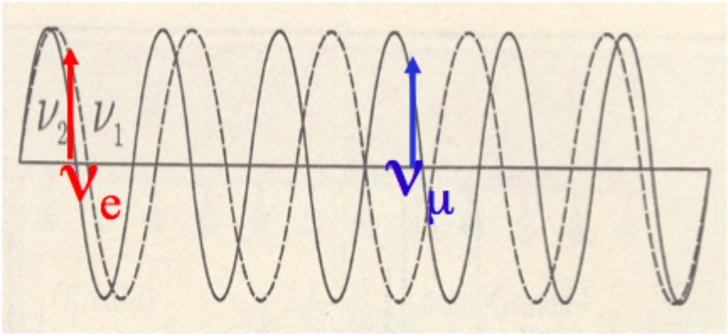
- The mass eigenstates have different momenta and thus travel at slightly different speeds: get out of phase
  - IF masses are different!
  - Assumption: energy is the same
- Detection probability for a given flavour changes with distance travelled

Neutrino oscillations: concept

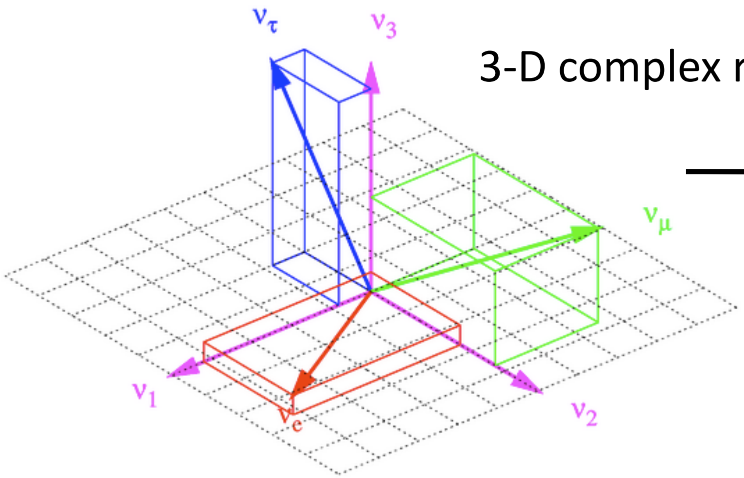
Two flavours:



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



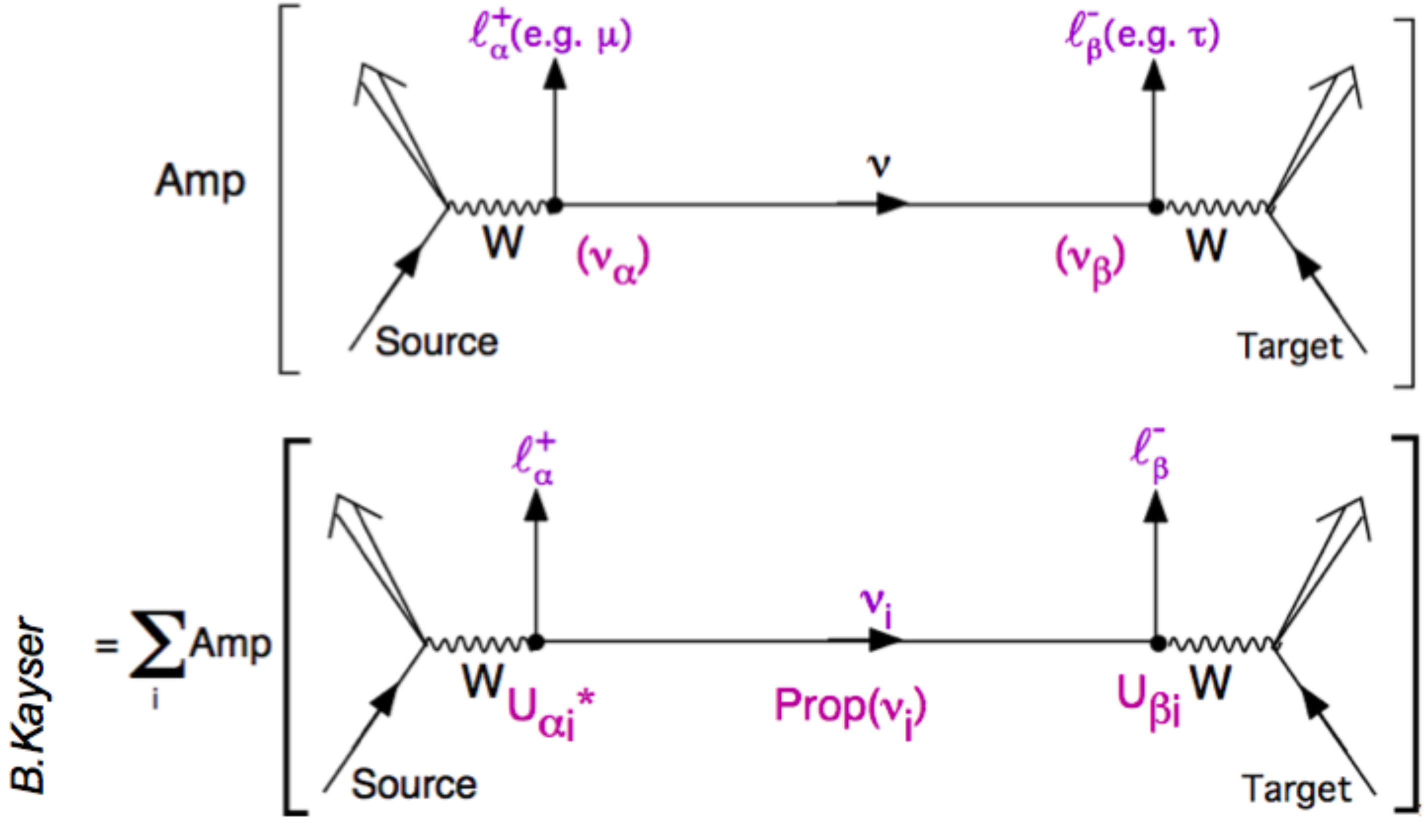
Three flavours:



3-D complex rotation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation amplitude



Outline of derivation

1. Weak eigenstates ν_α in terms of mass eigenstates ν_k:

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\,|\nu_k\rangle \qquad (\alpha = e, \mu, \tau)$$

Assuming plane wave

$$|\nu_k(t)\rangle \overset{\downarrow}{=} e^{-iE_k t}\,|\nu_k\rangle$$

where energy eigenvalues: $E_k = \sqrt{\vec{p}^{\,2} + m_k^2}$

2. Transition probability $\nu_\alpha \rightarrow \nu_\beta$ from amplitude squared:

$$P_{\nu_\alpha\to\nu_\beta}(t) = \left|A_{\nu_\alpha\to\nu_\beta}(t)\right|^2 = \sum_{k,j} U^*_{\alpha k}\,U_{\beta k}\,U_{\alpha j}\,U^*_{\beta j}\,e^{-i(E_k-E_j)t}$$

3. For ultrarelativistic neutrinos (E >> m):

Neglecting mass contribution

$$E_k - E_j \simeq \frac{\Delta m^2_{kj}}{2E} \quad \text{where} \quad \Delta m^2_{kj} \equiv m_k^2 - m_j^2 \quad \text{and} \quad E \overset{\downarrow}{=} |\vec{p}|$$

4. Using distance travelled *L* instead of time *t* (*t* = *L*, as neutrino speed ≈ *c*):

$$\boxed{P_{\nu_\alpha\to\nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha k}\,U_{\beta k}\,U_{\alpha j}\,U^*_{\beta j}\,\exp\left(-i\,\frac{\Delta m^2_{kj}L}{2E}\right)}$$

Two-neutrino oscillations

Using

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

with result from previous slide,

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U_{\alpha k}^{*} \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^{*} \, \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$$

transition probability becomes:

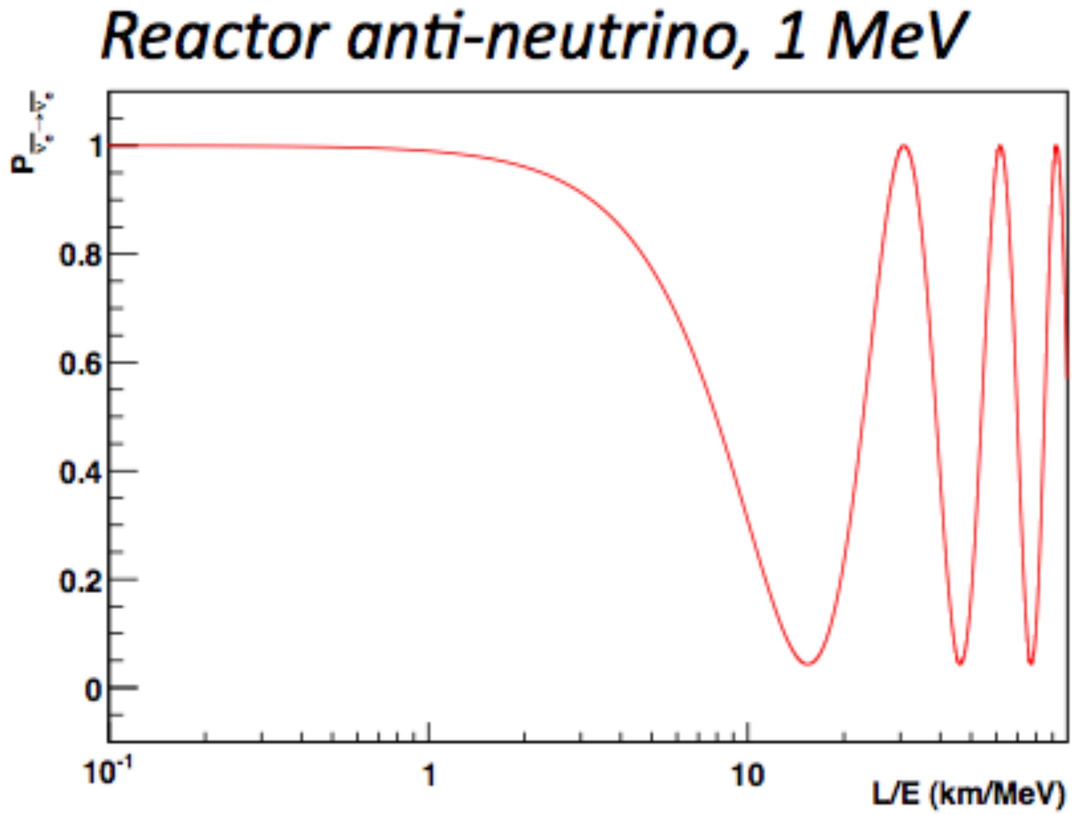
$$P_{\nu_\alpha \to \nu_\beta}(L) = \frac{\sin^2 2\theta}{2}\left[1 - \cos\left(2\pi \frac{L}{L^{osc}}\right)\right] \quad L^{osc} = \frac{4\pi E}{\Delta m^2}$$

Physical constants

$$\boxed{\Leftrightarrow P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$$

Experimental parameters

Two-neutrino oscillations

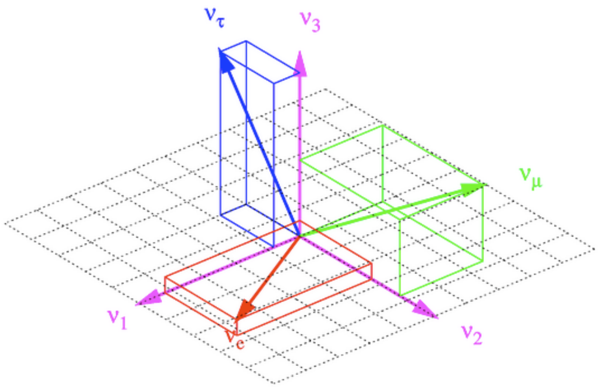

Reactor anti-neutrino, 1 MeV

$$\Delta m^2_{12} = 8 \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_{12} = 39^o$$

$$\boxed{\Leftrightarrow P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$$

Three-neutrino oscillations



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}}_{U_{\text{PMNS}}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata

Mixing matrix U_{PMNS} can be factored into three 2-D rotational matrices × U_{maj} (diagonal, so not relevant for oscillations)

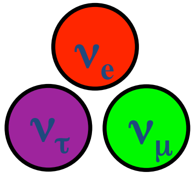
Three independent mixing angles

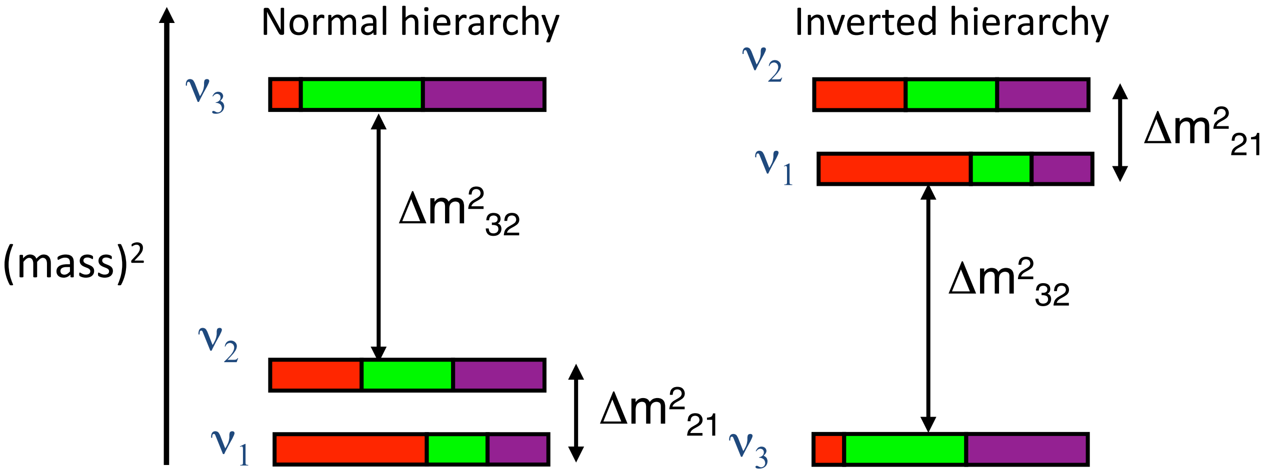
CP-violation phase

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

Mass hierarchy

We don’t know the ordering the mass splittings Δm_2 – but we do know that $\nu_2 >> \nu_1$





Current knowledge

“Atmospheric” from atmosphere and accelerators

“Subdominant” or “third”

CP-violation phase = ?

“Solar” from sun + reactors

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

Well measured:

$\theta_{23} = (45 \pm 7)^{\circ}$
-> ~equal mixing of ν_{μ} and ν_{τ}

$\Delta m^2_{32} \approx \Delta m^2_{\mathrm{atm}} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$

Until this summer ~unknown:

$\theta_{13} <\sim 10^{\circ}$

Now ~3σ indications that $\theta_{13} < 10^{\circ}$

$|\Delta m^2_{31}| \approx \Delta m^2_{32}$
but $\Delta m^2_{31} > 0$ or < 0
(normal or inverted hierarchy)?

Well measured:

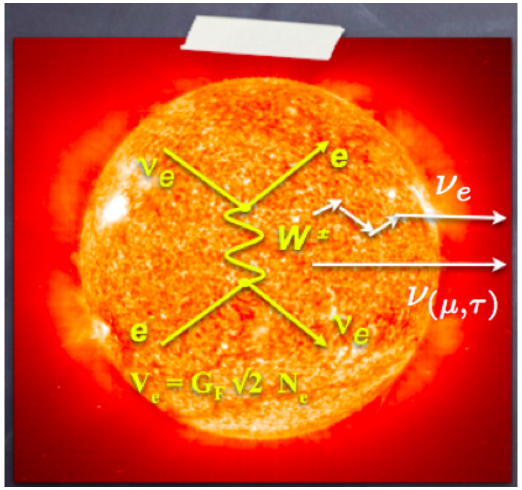
$\theta_{12} = (34 \pm 3)^{\circ}$
-> ν_1 is predominantly ν_e

$\Delta m^2_{21} = 7.6 \times 10^{-5}$ eV

$\nu_2 > \nu_1$ (sign of Δm^2_{21})
from matter effects in sun

Matter oscillations

Linc Wolfenstein
(1978)



MSW effect:
Electron neutrinos feel a “drag”
due to extra contribution
from W exchange

1. Low electron density (the Earth):

$$P_{\nu_\alpha\to\nu_\beta} = \sin^2 2\theta_M \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)$$

Effective θ_M and Δm^2

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + \boxed{(\cos 2\theta - x)^2}}$$

$$\Delta m_M^2 = \Delta m^2\sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

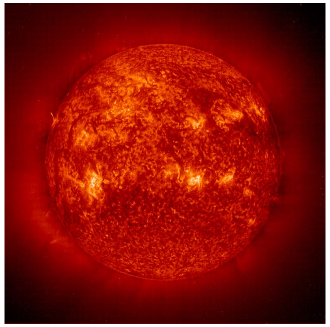
$$x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

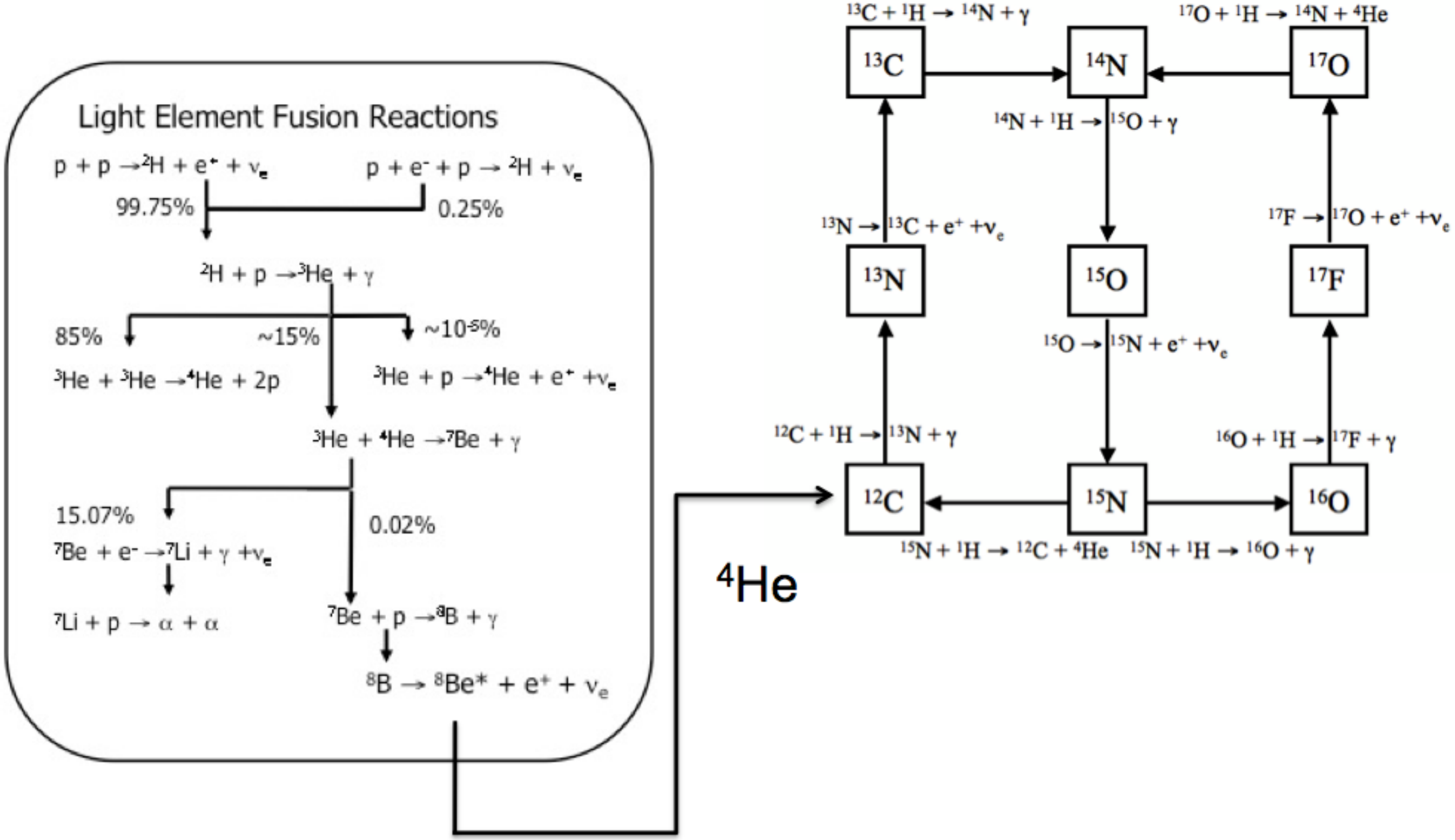
N_e = electron density

2. Resonant MSW:
   $\theta_M = \pi/4$
   Total transition between two flavours

3. Varying N_e (the Sun):
   $d\theta_M/dx \neq 0$
   Adiabatic transition between effective mass eigenstates

Energy production in the sun





Light Element Fusion Reactions

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ 99.75%

$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$ 0.25%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

85% ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

~15% ${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

$\sim 10^{-5}\%$ ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

15.07% ${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$

${}^{7}Li + p \rightarrow \alpha + \alpha$

0.02% ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

${}^{4}He$

${}^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$

${}^{17}O + {}^{1}H \rightarrow {}^{14}N + {}^{4}He$

${}^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$

${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$

${}^{17}F \rightarrow {}^{17}O + e^{+} + \nu_e$

${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$

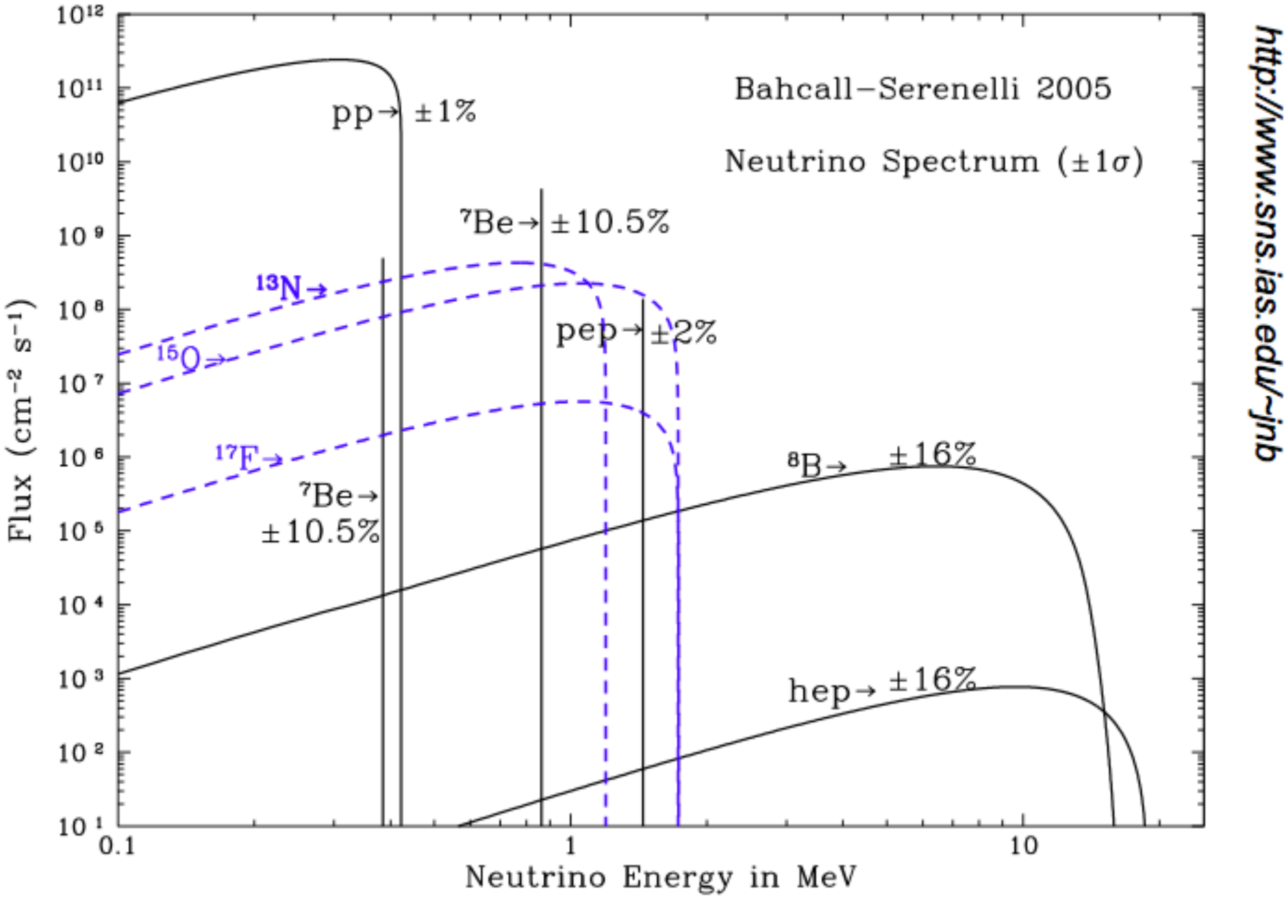
${}^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$

${}^{16}O + {}^{1}H \rightarrow {}^{17}F + \gamma$

${}^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$

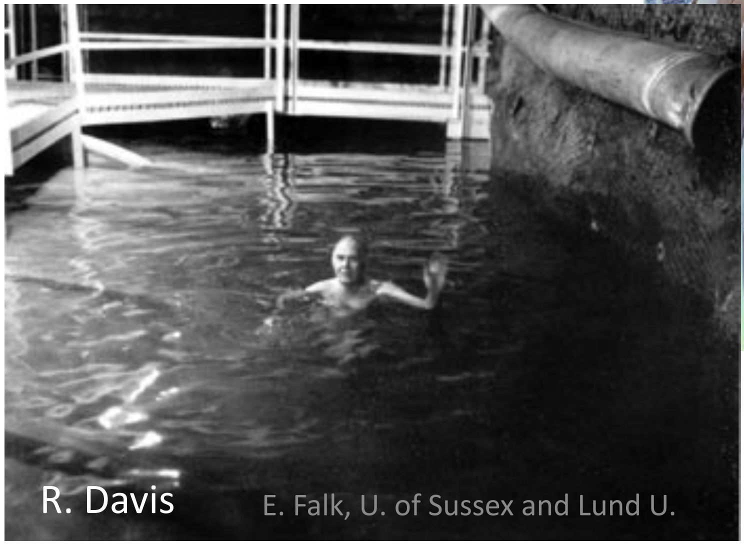
${}^{15}N + {}^{1}H \rightarrow {}^{16}O + \gamma$

Neutrino production in the sun



40 years ago:
Homestake chlorine experiment

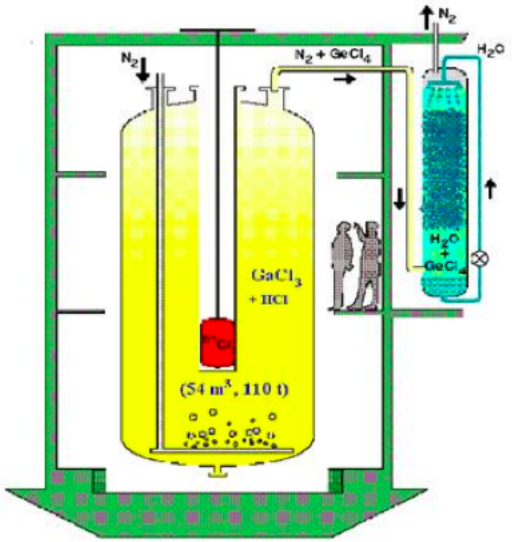
- First experiment to study neutrinos from the sun
- Homestake Gold Mine, South Dakota, USA
- Big tank of chlorine-based cleaning fluid
  - $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$
- Counted electron neutrinos (ν_e)
- Saw 1/3 of neutrinos expected from luminosity
  - The “solar neutrino problem”
- Ray Davis: Nobel Prize 2002



R. Davis

Experimental techniques

Gallium experiments

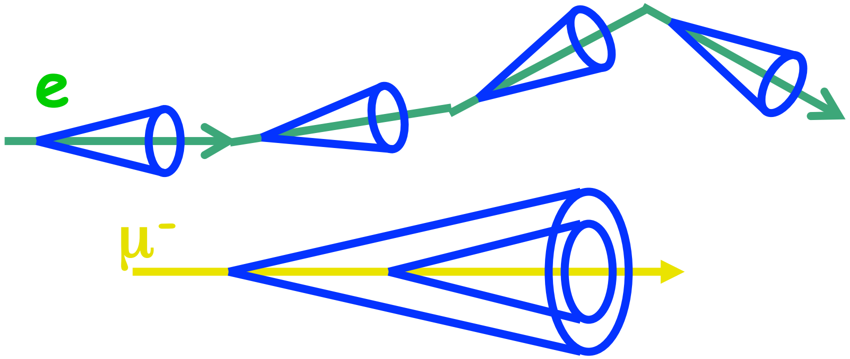


$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-.$$

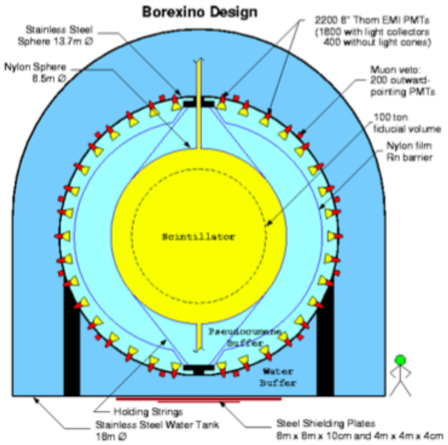
Liquid-scintillator detectors

Neutrinos: Elastic scattering on electrons
Anti-neutrinos (reactor):
Inverse beta decay: $\overline{\nu}_e + p \rightarrow n + e^+$

Water Cherenkov experiments

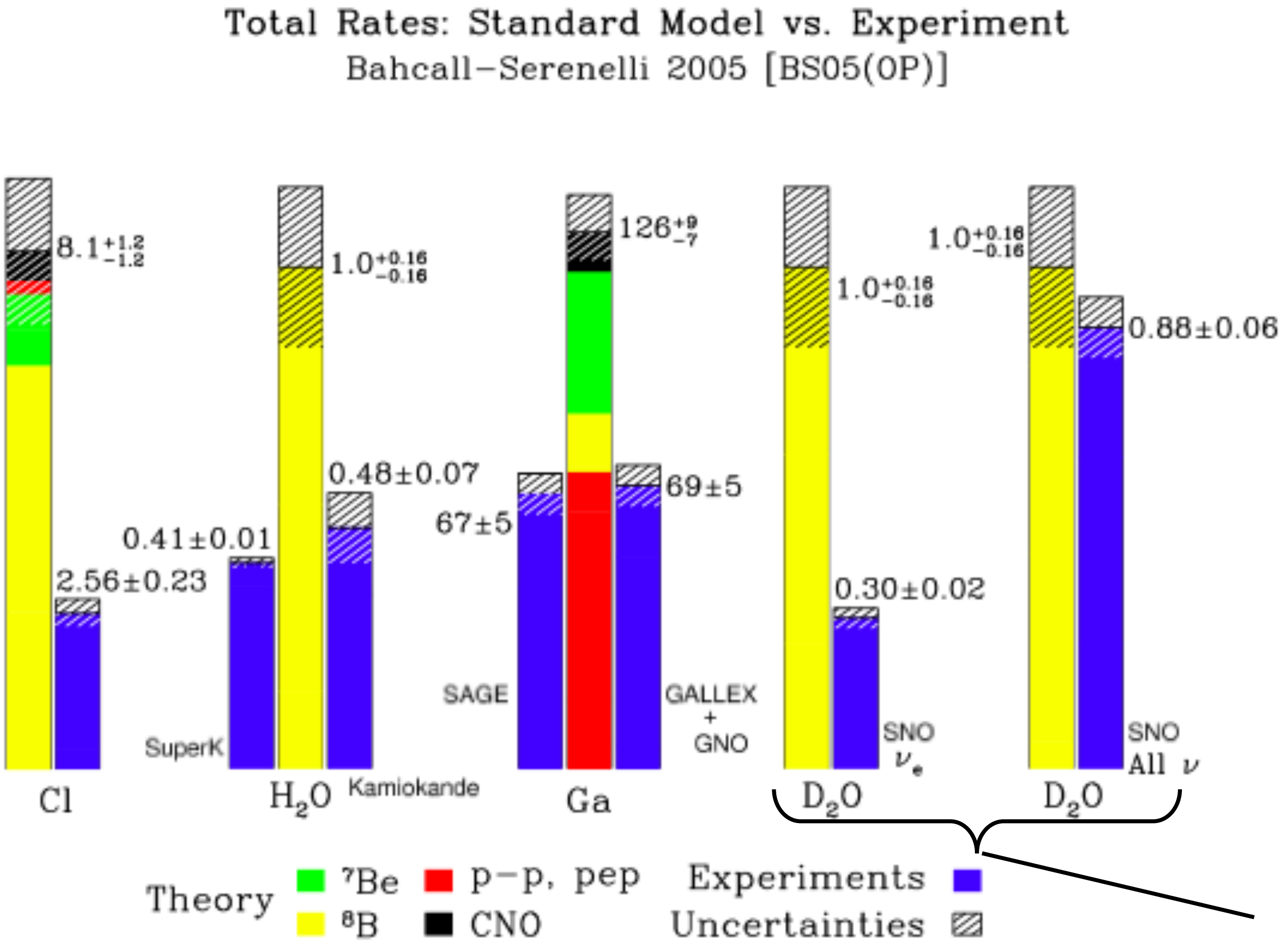


Elastic scattering of neutrinos on electrons
Charged lepton produces Cherenkov radiation
CC contribution 6.8 x NC contribution
→ much enhanced for ν_e



Different
ν energy
thresholds
with different
techniques

The solar neutrino problem



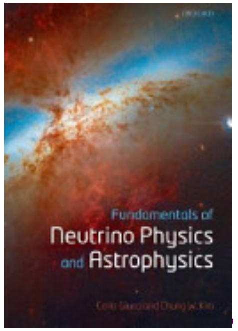
http://www.sns.ias.edu/~jnb

Solved in 2002 by SNO
More in Lecture 2

Recap and outlook

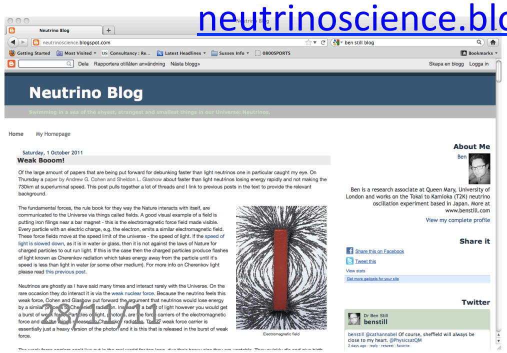
- The neutrino is the least understood of our fundamental particles, but may hold the answer to many exciting questions about the universe as well as particle physics
- Neutrinos oscillate between different flavours because they have non-zero mass AND their mass eigenstates are different from their flavour eigenstates
- The study of neutrinos from the sun showed an apparent deficit of neutrinos – we know now that it is due to oscillations
- More on neutrino oscillations tomorrow!

Suggested reading



- C. Giunti and C. W. Kim, Fundamentals of Neutrino Physics and Astrophysics, Oxford University Press 2007

- F. Close, Neutrino, Oxford University Press 2010
- Derivation of neutrino oscillations: PhD theses, .e.g., B. Still, T2K ND280 π_0 Electromagnetic Calorimeter, University of Sheffield 2009
  - Ben also runs a neutrino blog: http://neutrinoscience.blogspot.com/



Neutrino Blog

Swimming in a sea of the shyest, strangest and smallest things in our Universe: Neutrinos.

Home My Homepage

Saturday, 1 October 2011

Weak Booom!

Of the large amount of papers that are being put forward for debunking faster than light neutrinos one in particular caught my eye. On Thursday a paper by Andrew G. Cohen and Sheldon L. Glashow about faster than light neutrinos losing energy rapidly and not making the 730km at superluminal speed. This post pulls together a lot of threads and I link to previous posts in the text to provide the relevant background.

The fundamental forces, the rule book for they way the Nature interacts with itself, are communicated to the Universe via things called fields. A good visual example of a field is putting iron filings near a bar magnet - this is the electromagnetic force field made visible. Every particle with an electric charge, e.g. the electron, emits a similar electromagnetic field. These force fields move at the speed limit of the universe - the speed of light. If the speed of light is slowed down, as it is in water or glass, then it is not against the laws of Nature for charged particles to out run light. If this is the case then the charged particles produce flashes of light known as Cherenkov radiation which takes energy away from the particle until it's speed is less than light in water (or some other medium). For more info on Cherenkov light please read this previous post.

Electromagnetic field

Neutrinos are ghostly as I have said many times and interact rarely with the Universe. On the rare occasion they do interact it is via the weak nuclear force. Because the neutrino feels this weak force, Cohen and Glashow put forward the argument that neutrinos would lose energy by a similar process to Cherenkov radiation. Instead of a burst of light however you would get a burst of weak force. Particles of light, photons, are the force carriers of the electromagnetic force and are the things released in Cherenkov radiation. The Z^0 weak force carrier is essentially just a heavy version of the photon and it is this that is released in the burst of weak force.

About Me

Ben

Ben is a research associate at Queen Mary, University of London and works on the Tokai to Kamioka (T2K) neutrino oscillation experiment based in Japan. More at www.benstill.com

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Dr Ben Still
benstill

benstill @cathannabel Of course, sheffield will always be close to my heart. @PhysicsatQM
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