Can neutrinos explain *everything*?

(besides CMB photons)

Aart Heijboer - Nikhef

Topical lectures on flavour physics and CP violation, March 2022

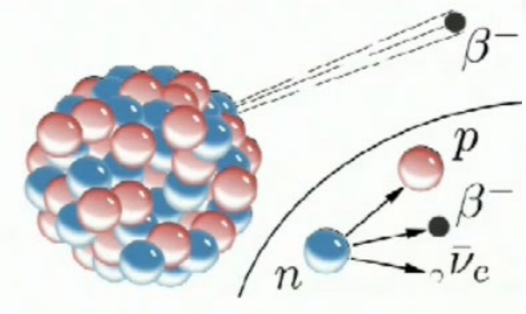
outline

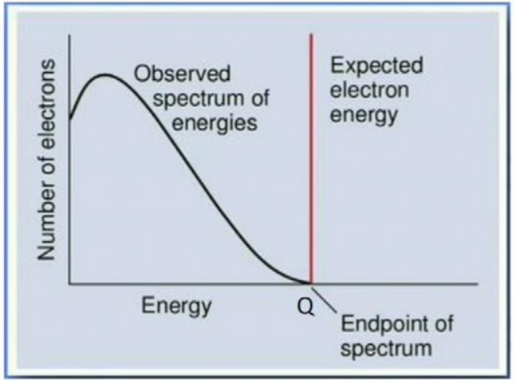
- Lecture 1 : neutrinos and oscillations (+CP)
- Lecture 2: neutrino masses & leptogenisis (1h)
- Lecture 3: hand on computer exercise (1h)

Broad overview
very loose on technicalities.

References [heavily used and screenshotted]

- [1] : P. Hernández, Lecture notes, arXiv:1708.01046v1
- [2] : PDG: ***14. Neutrino Masses, Mixing, and Oscillations***
- [3] : https://www.youtube.com/watch?v=Ml_6iNqU3HA (excellent talk on leptogenesis)





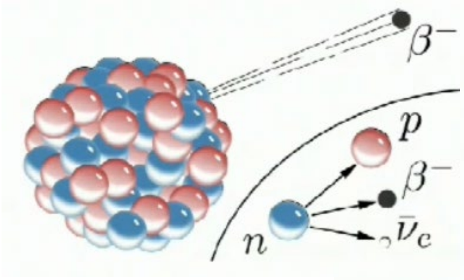
Niels Bohr

"At the present stage of atomic theory we have no arguments for upholding the concept of energy balance in the case of β-ray disintegrations."

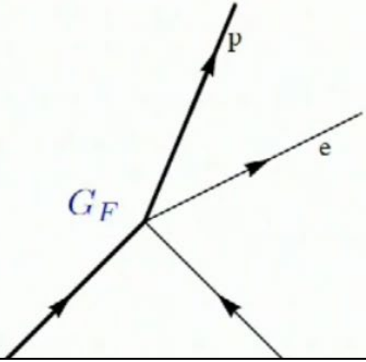
Wolfgang Pauli

"Desperate remedy….."
"I do not dare publish this idea…."
"I admit my way out may look improbable…."
"Weigh it and pass sentence…."

neutrinos

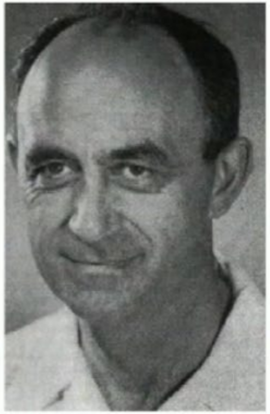


1934: Theory of beta decay



$$n + \nu \to p + e^-$$

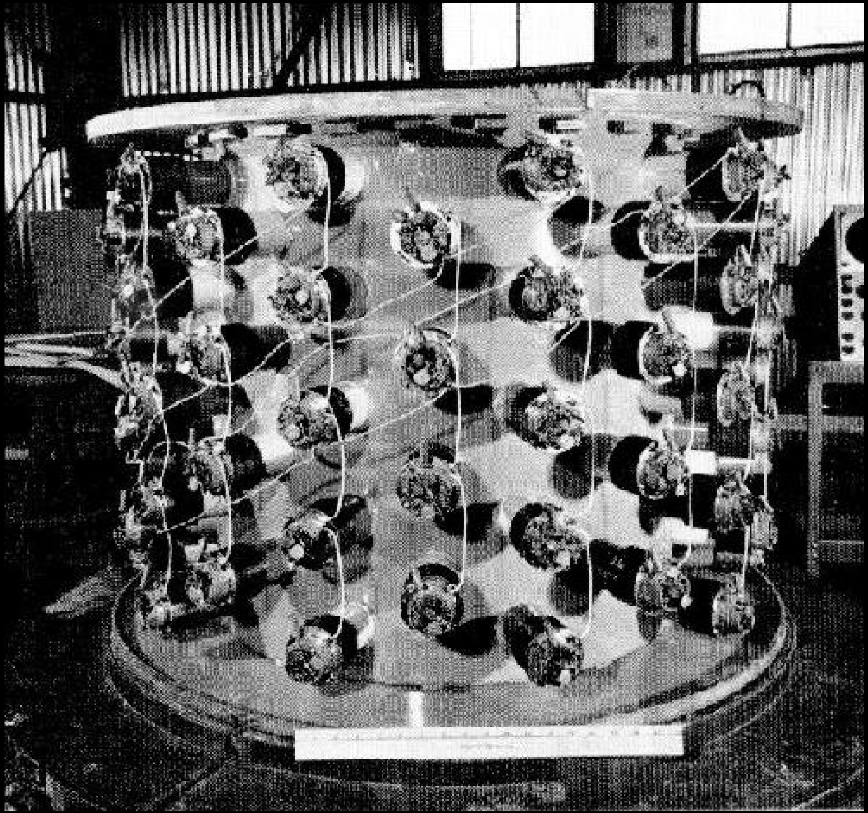
$$p + \bar{\nu} \to n + e^+$$



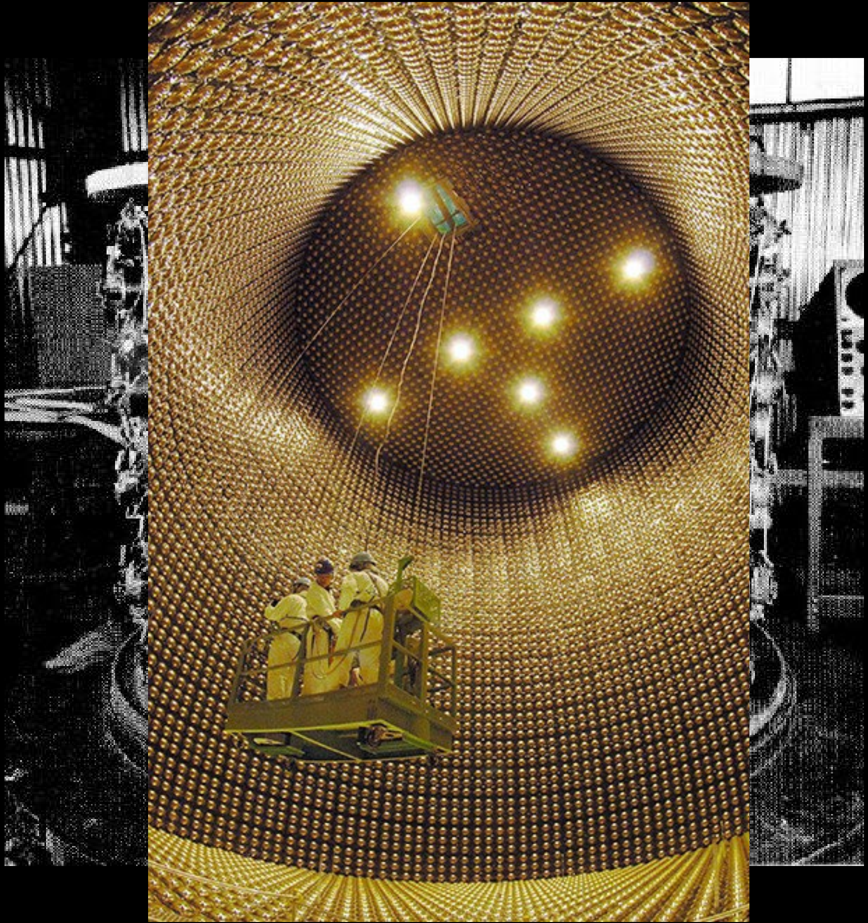
E. Fermi
(Nobel 1938)

$$G_F^0 = \frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2 c^4} = 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2}$$

Nature did not publish his article: "contained speculations too remote from reality to be of interest to the reader…"



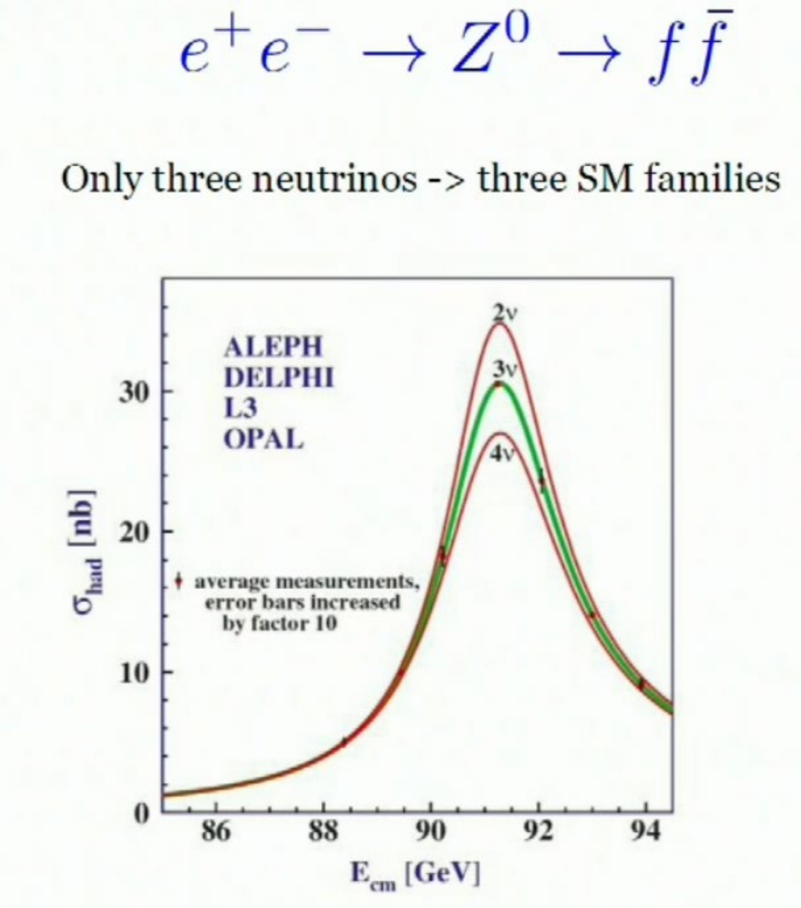
Reines & Cowan 1956

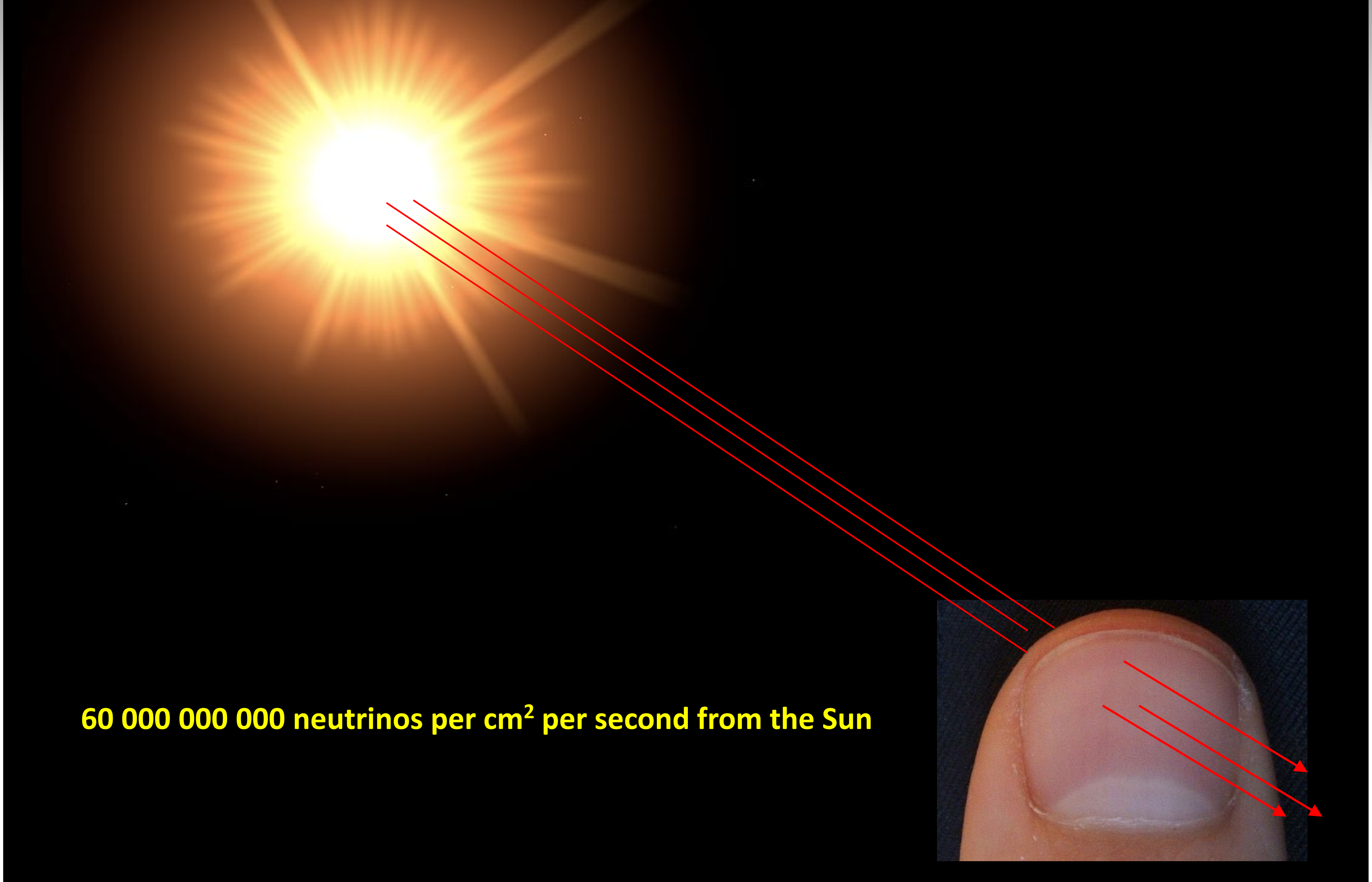


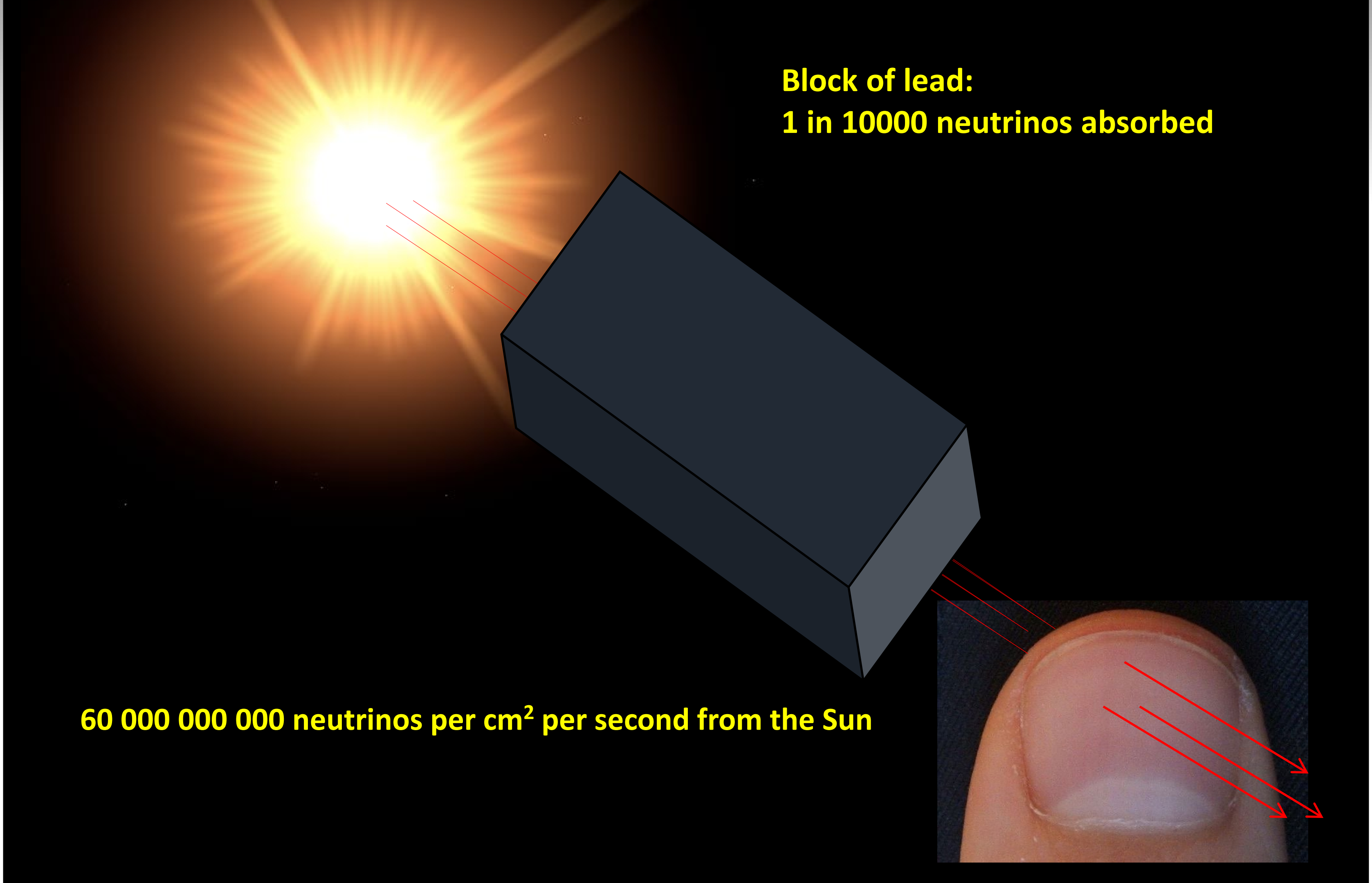
Not much has changed

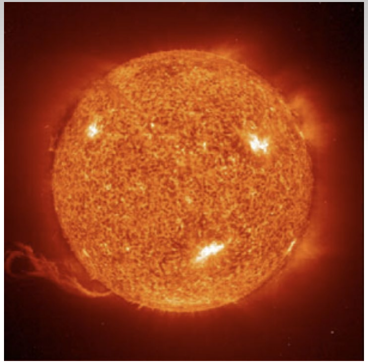
What we know..

- There are 3 of them
- They have mass (since ~2000)
- They are everywhere.

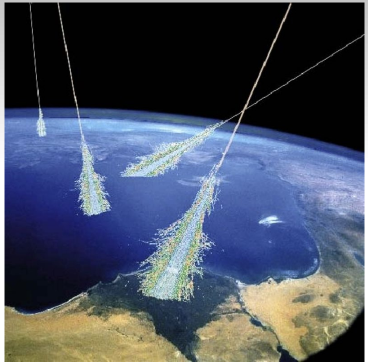



60 000 000 000 neutrinos per cm^2 per second from the Sun

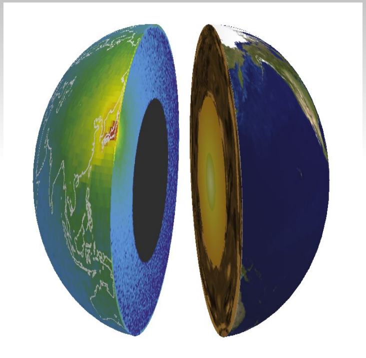

Block of lead:
1 in 10000 neutrinos absorbed
60 000 000 000 neutrinos per cm² per second from the Sun



Sun 5×10^{10}/s



Atmospheric 0.2 /s

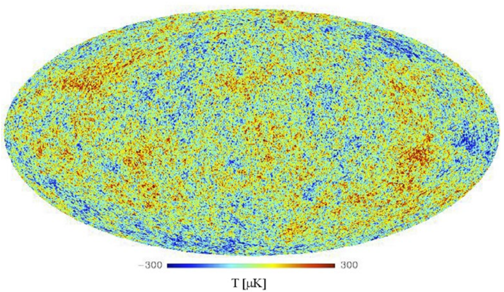


Earth 10^{7}/s

Reactor 10^{9}/s (@100m)

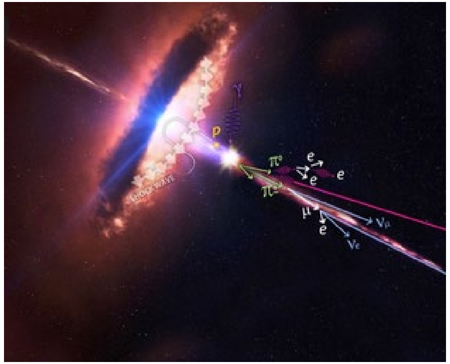
Supernova 1987: ~10^{10}/s

Standard Model



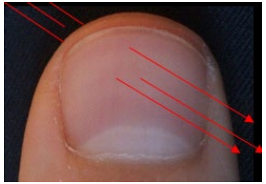
Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.

Big Bang: ~2×10^{10}/s

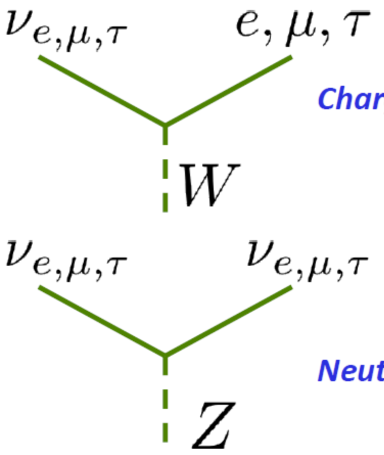


HE cosmic: 10^{-8}/s

Per cm^2



$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{matrix} \leftarrow & q = 0 \\ \leftarrow & q = -1 \end{matrix}$$

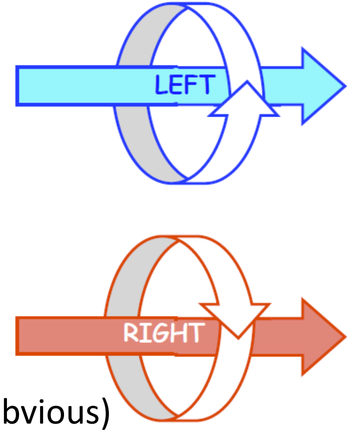


Charged Current (Δq=1)

Neutral Current (Δq=0)

Neutrinos are created in a left-handed (LH) state $\boldsymbol{\nu}$

Anti-nus are created in a right-handed (RH) state $\boldsymbol{\bar{\nu}}$



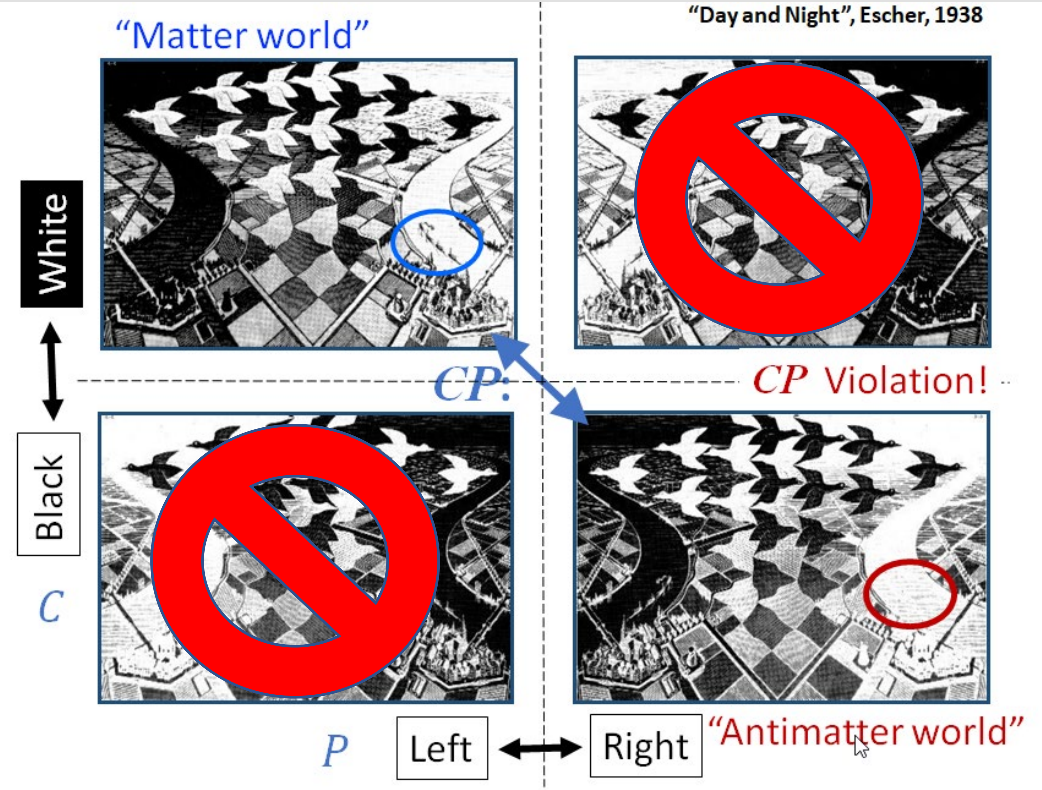
(so the P part of CP is pretty obvious)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

With neutrinos (only weak interaction):

The P-mirrored version of a *neutrino does not exist.*

The question if the CP-mirrored Interactions are subtly different remains…



mixing

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}}_{\text{Majorana phases}}$$

$$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$$

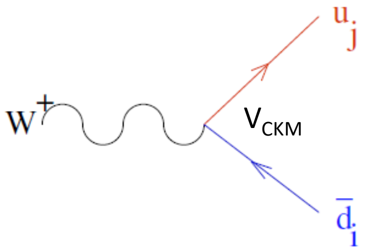
$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

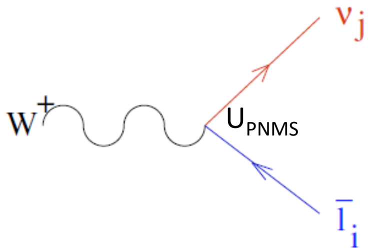
$$UU^\dagger = 1 \qquad U \to U^* \text{ for } \overline{\nu} \qquad c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

mixing

$$\mathcal{L}_{SM} - \frac{g}{\sqrt{2}} \sum_{\alpha} \bar{\nu}_\alpha \gamma_\mu P_L l_\alpha W^+_\mu$$

$$\mathcal{L}^{\text{lepton}}_{CC} = -\frac{g}{\sqrt{2}} \bar{l}'_i \gamma_\mu P_L W^+_\mu \underbrace{(U_l^\dagger U_\nu)_{ij}}_{U_{\text{PMNS}}} \nu'_j + \text{h.c.}$$





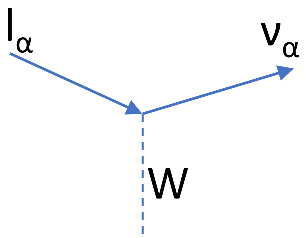
Expressed in mass-basis, the vertex would look just like the quarks.

..and you could do neutrino physics like that.

oscillations

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

Neutrinos are treated as plane waves, with equal **p.**
More rigorous treatments available [1]



$$|\nu_\alpha(t_0)\rangle = \sum_i U^*_{\alpha i}|\nu_i(\mathbf{p})\rangle$$

Decompose into mass eigenstates

$$\hat{H}|\nu_i(\mathbf{p})\rangle. = E_i(\mathbf{p})|\nu_i(\mathbf{p})\rangle, \quad E_i(\mathbf{p})^2 = \mathbf{p}^2 + m_i^2.$$

$$|\nu_\alpha(t)\rangle = e^{-i\hat{H}(t-t_0)}|\nu_\alpha(t_0)\rangle = \sum_i U^*_{\alpha i}e^{-iE_i(\mathbf{p})(t-t_0)}|\nu_i(\mathbf{p})\rangle.$$

True, but H is hard here

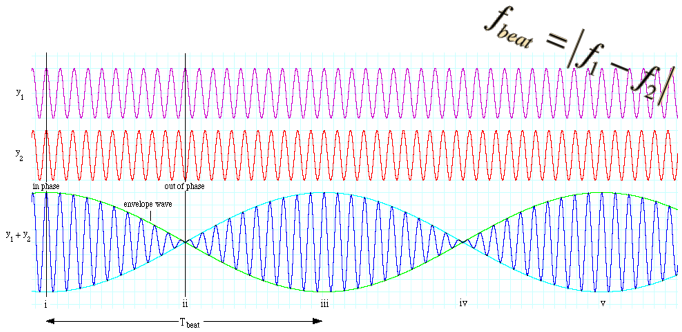
easy for mass eigenstates

Probability to find ν_β

$$P(\nu_\alpha \to \nu_\beta)(t) = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U_{\beta i}U^*_{\alpha i}e^{-iE_i(\mathbf{p})(t-t_0)}\right|^2$$

oscillations

$$P(\nu_\alpha \to \nu_\beta)(t) = \left|\langle \nu_\beta | \nu_\alpha(t)\rangle\right|^2 = \left|\sum_i U_{\beta i} U^*_{\alpha i} e^{-iE_i(\mathbf{p})(t-t_0)}\right|^2$$



$$E_i(\mathbf{p}) - E_j(\mathbf{p}) \simeq \frac{1}{2}\frac{m_i^2 - m_j^2}{|\mathbf{p}|} + \mathcal{O}(m^4)$$

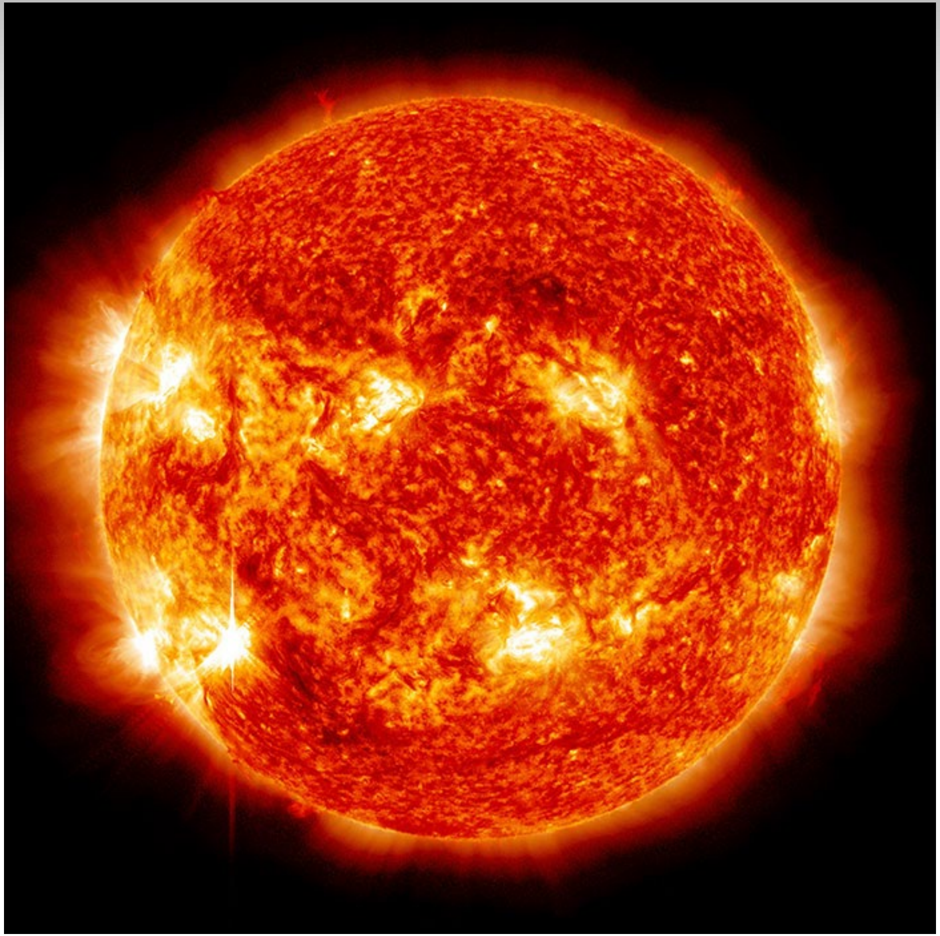
In vacuum, at E>>m

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m^2_{ji} L}{2|\mathbf{p}|}}}$$

Two flavour case

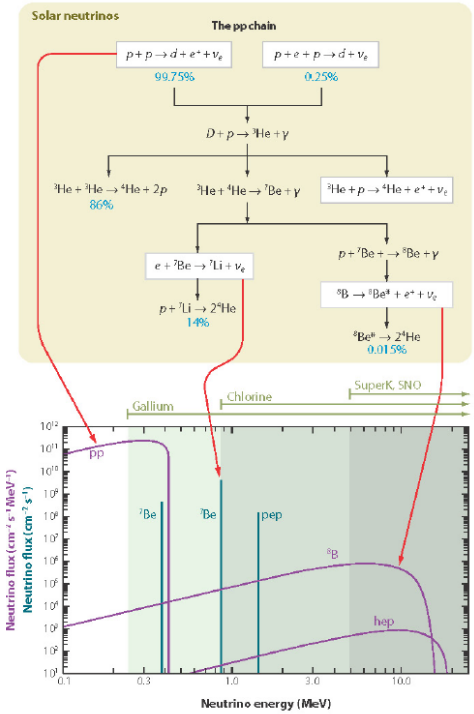
$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2/eV^2 \cdot L/km}{E_\nu/GeV}\right)$$

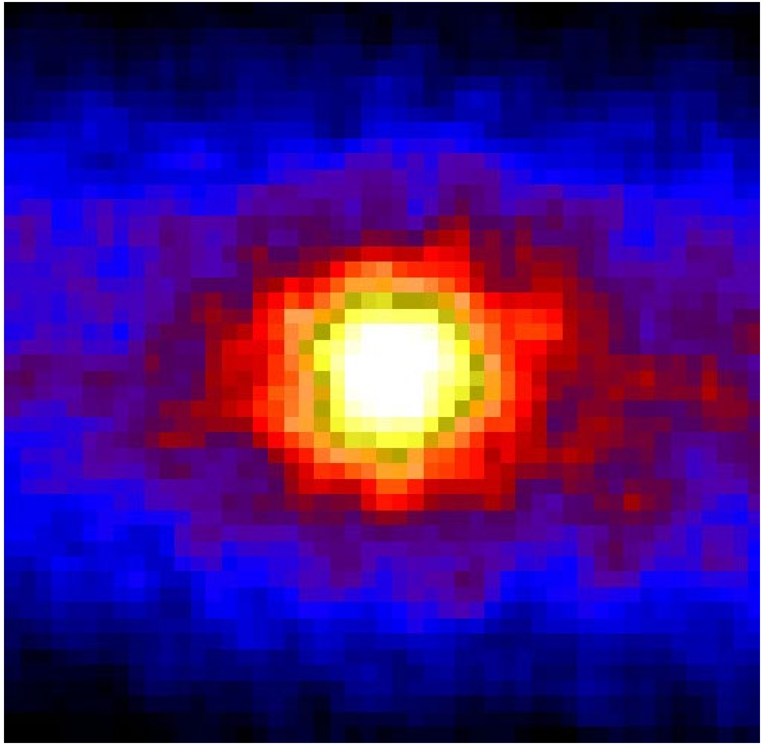
Always some combination of mixing angles, and oscillations with Δm^2 L/E



Why is the Sun hot?

$$\nu_e + e^- \rightarrow \nu_e + e^-.$$

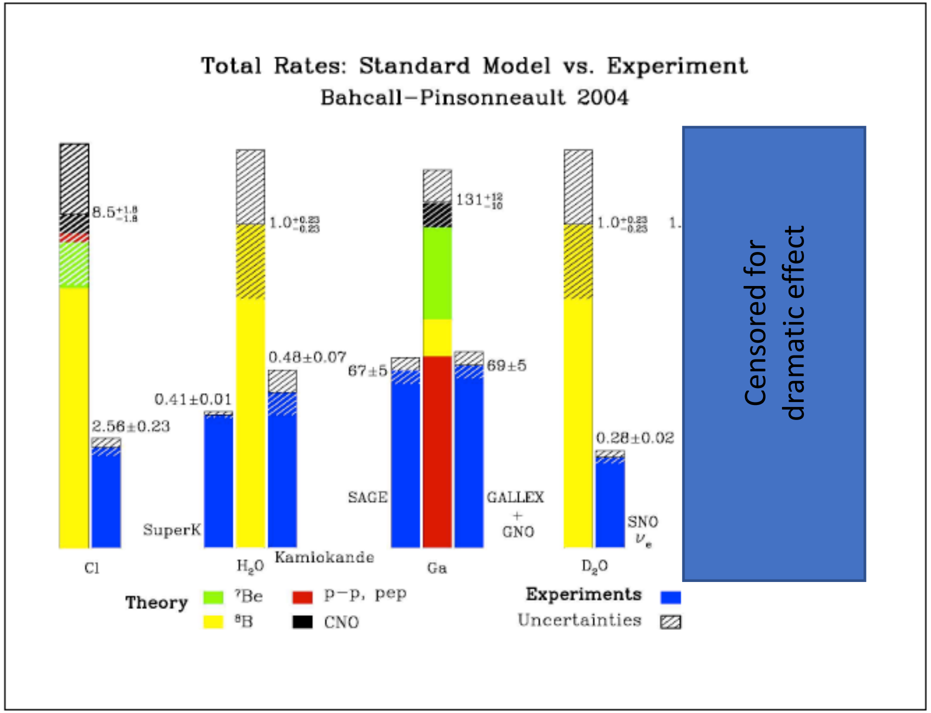




Not enough, though

“Solar neutrino problem”

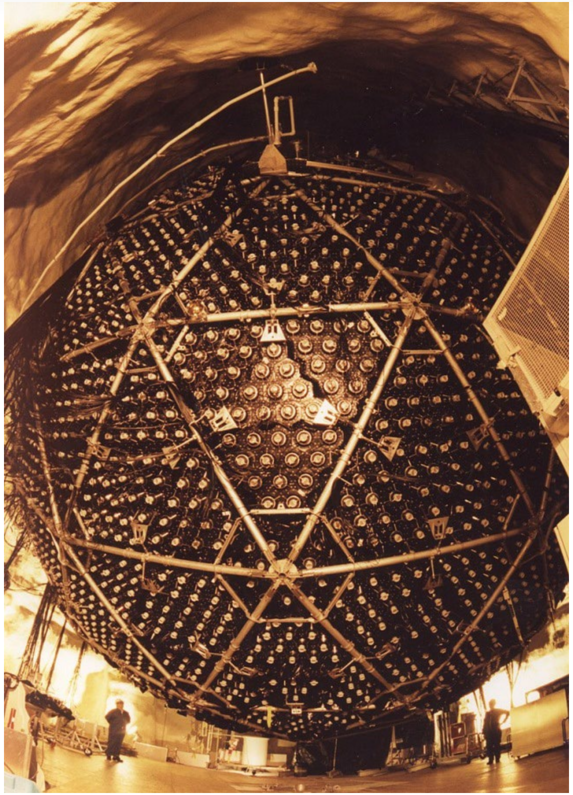
All CC-sensitive results indicated a ν_e deficit…



Only 30 to 50% of neutrinos from the Sun are detected! (as ν_e)

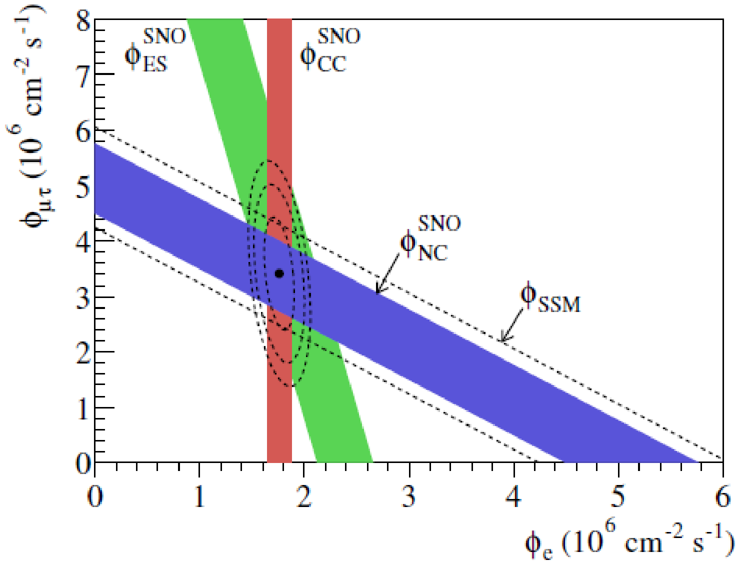
- Okay, maybe neutrino oscillations, but maybe the Solar model is wrong.
- No direct proof of oscillations (also other exotic explanations)

Solar neutrino problem (2001)



(CC) $\nu_e + d \to p + p + e^-$ $E_{\rm thres} > 5$ MeV

(NC) $\nu_x + d \to p + n + \nu_x \quad x = e, \mu, \tau$ $E_{\rm thres} > 2.2$ MeV

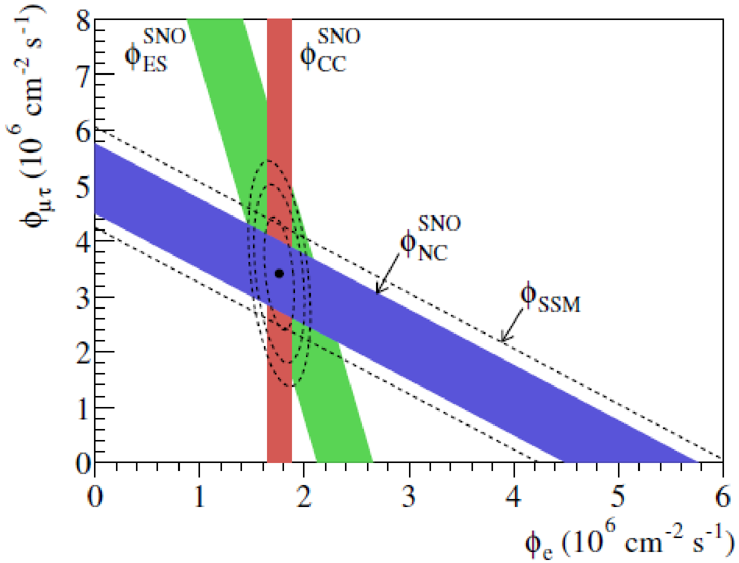


Solar neutrino problem (2001)

$$\mathrm{CC}: \quad \nu_e + d \rightarrow p + p + e$$
$$\mathrm{NC}: \nu_{e,\mu,\tau} + d \rightarrow p + n + \nu_{e,\mu,\tau}$$
$$\mathrm{ES}: \nu_{e,\mu,\tau} + e \rightarrow e + \nu_{e,\mu,\tau}$$

But mostly ν_e

- The sun shines in ν_τ and/or ν_μ
- Total flux in perfect agreement with Solar model
- Definite proof of flavour change (oscillations)



"Solar neutrino problem"

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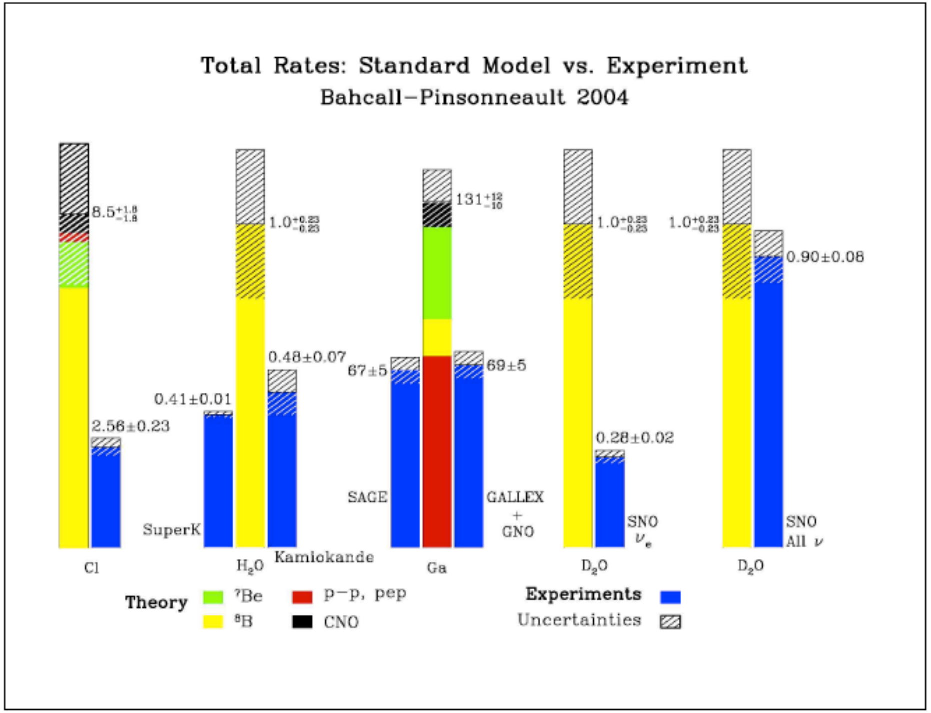


All understood now

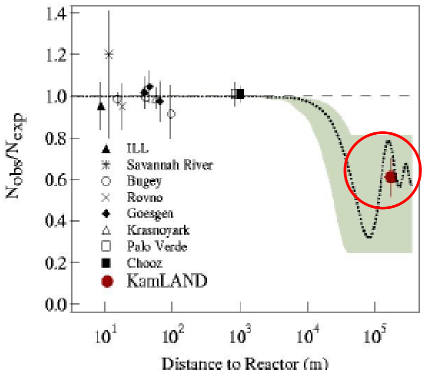

Understood since 2001

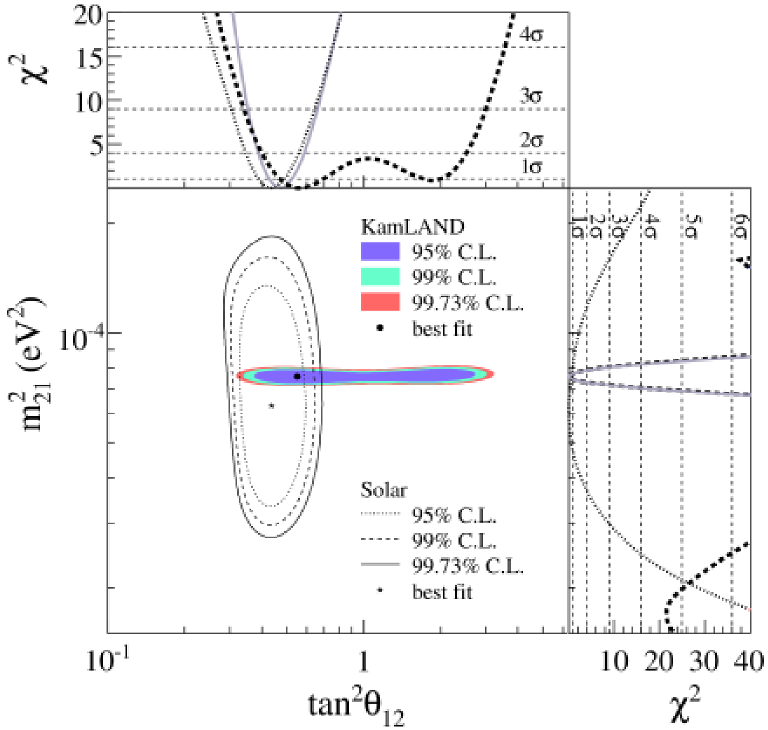
reactors

- θ_{13} is small
- At large distnance 2nd term kicks in (α=0.03)
- Kamland @ ~100 km

$$P(\overline{\nu}_e \to \overline{\nu}_e) \simeq 1 - \sin^2(2\theta_{13}) \sin^2 \Delta - \cos^4 \theta_{13} \sin^2(2\theta_{12}) \sin^2(\alpha\Delta).$$

2002: electron flavor disappearance observed





reactors

- θ_{13} is small
- At large distnance 2nd term kicks in (α=0.03)
- Kamland @ ~100 km
- Double Chooz @ 1 km

$$P(\overline{\nu}_e \to \overline{\nu}_e) \simeq 1 - \sin^2(2\theta_{13}) \sin^2 \Delta - \cos^4 \theta_{13} \sin^2(2\theta_{12}) \sin^2(\alpha\Delta).$$

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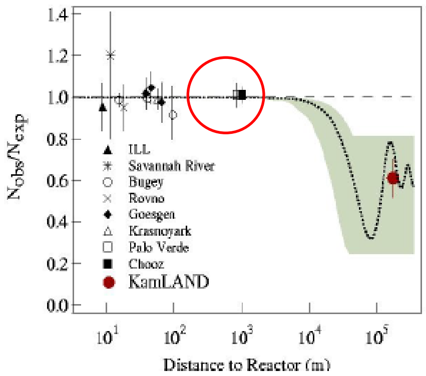
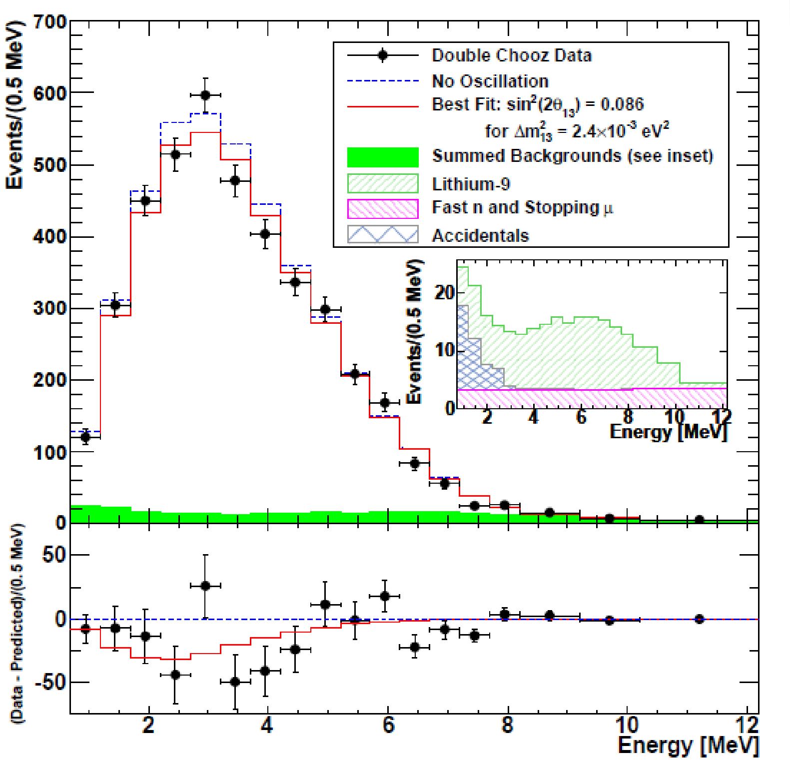
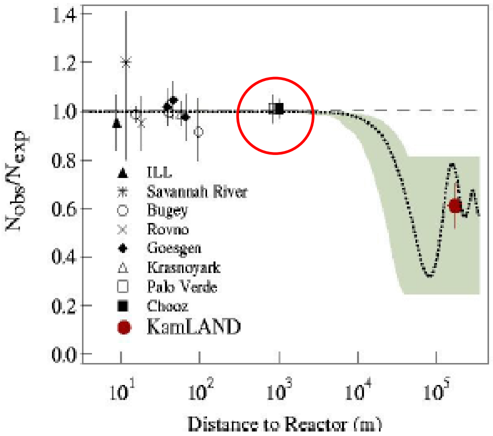


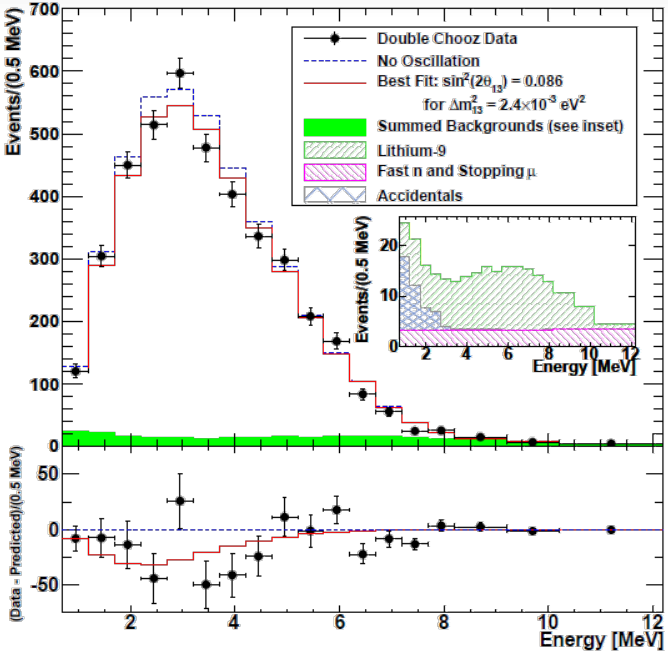
$\theta_{13}>0$!



At smaller distances.. $\theta_{13}>0$!

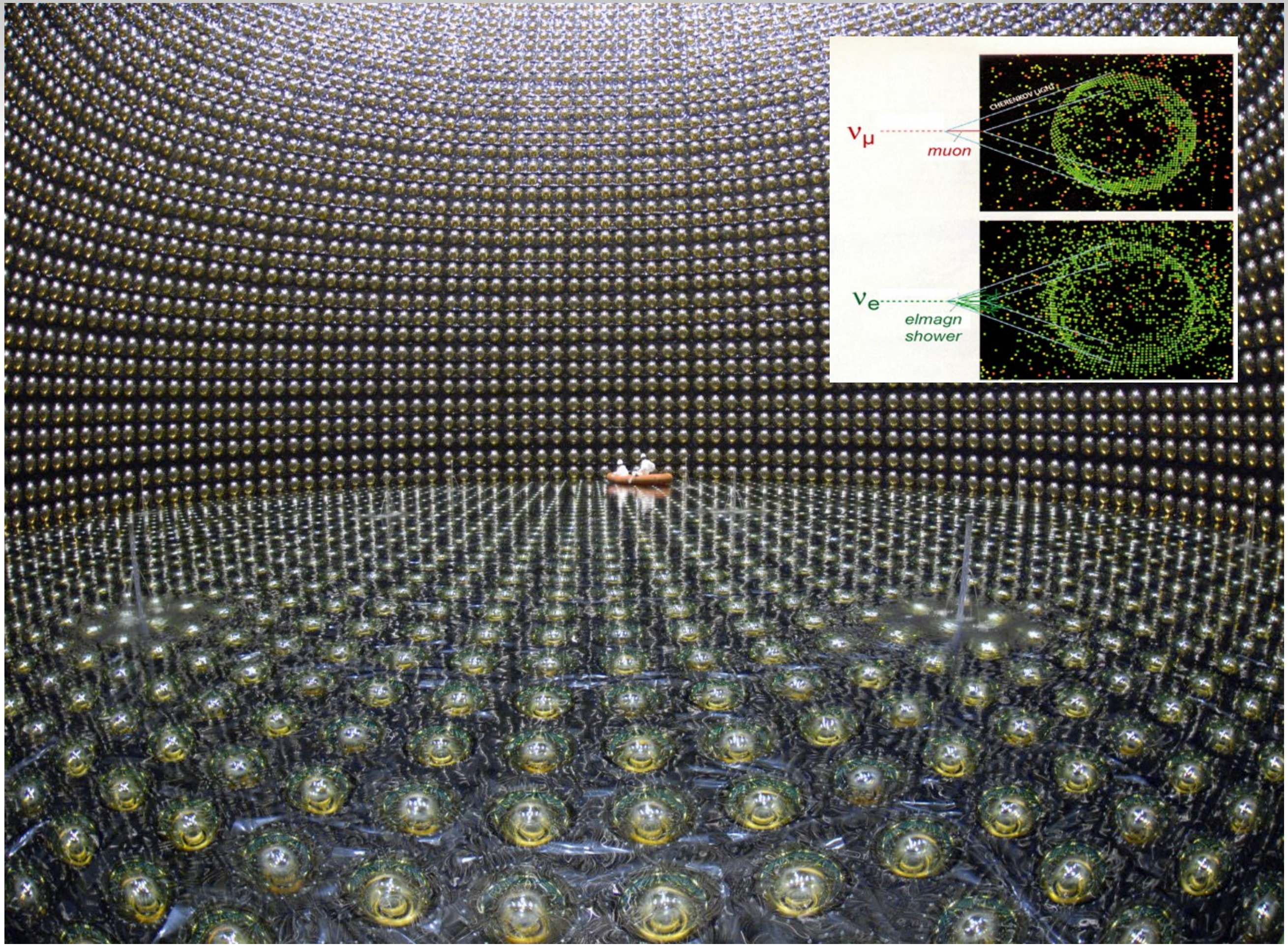
2002: electron flavor disappearance observed



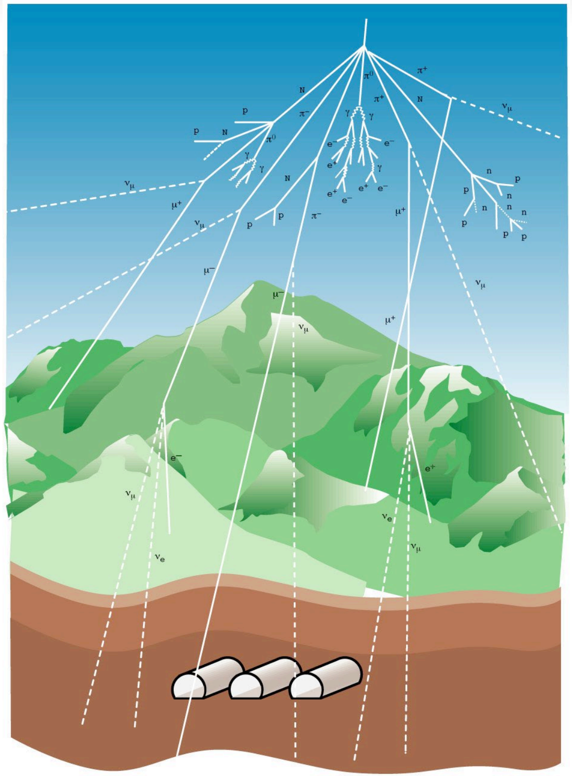


$$P(\overline{\nu}_e \to \overline{\nu}_e) \simeq 1 - \sin^2(2\theta_{13})\sin^2\Delta - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2(\alpha\Delta).$$

(1^{st} term dominant)


ν_μ
muon
CHERENKOV LIGHT
ν_e
elmagn
shower

Atmospheric neutrinos

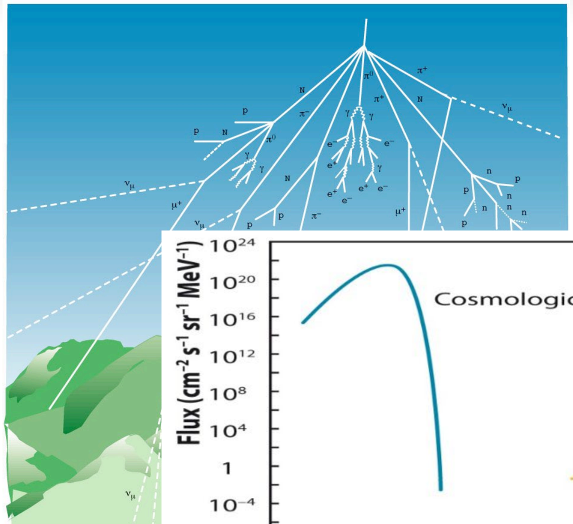


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

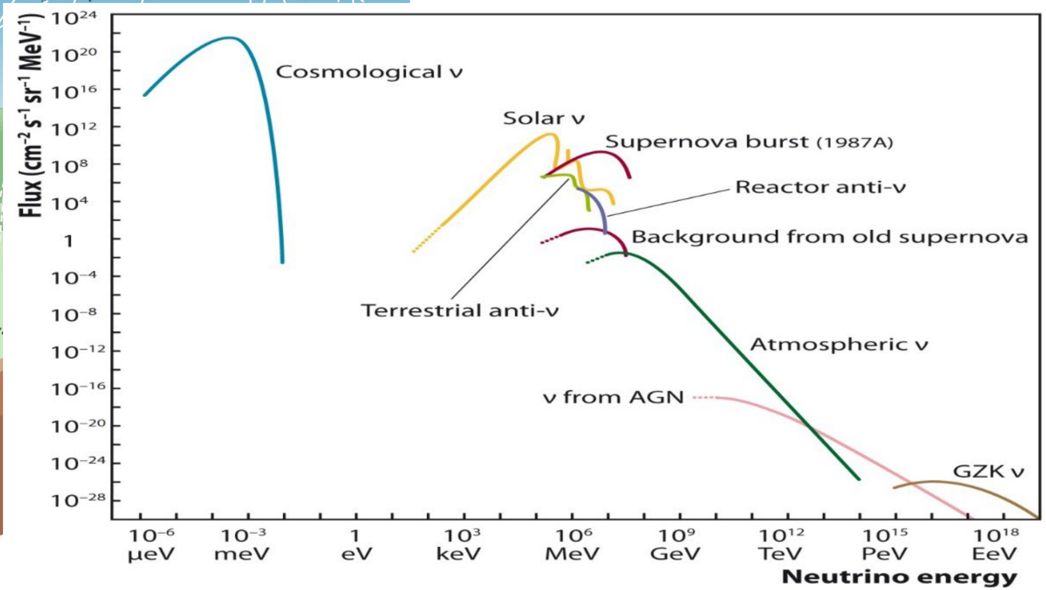
also: π^- μ^- e^- decay chain
decays of kaons K^+, K^-

flavour ratio $\nu_\mu : \nu_e = 2 : 1$

Atmospheric neutrinos



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\quad\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



Evidence neutrino oscillations

Muon-neutrinos are ‘disappearing’ At low energies.

Electron neutrinos as expcted.

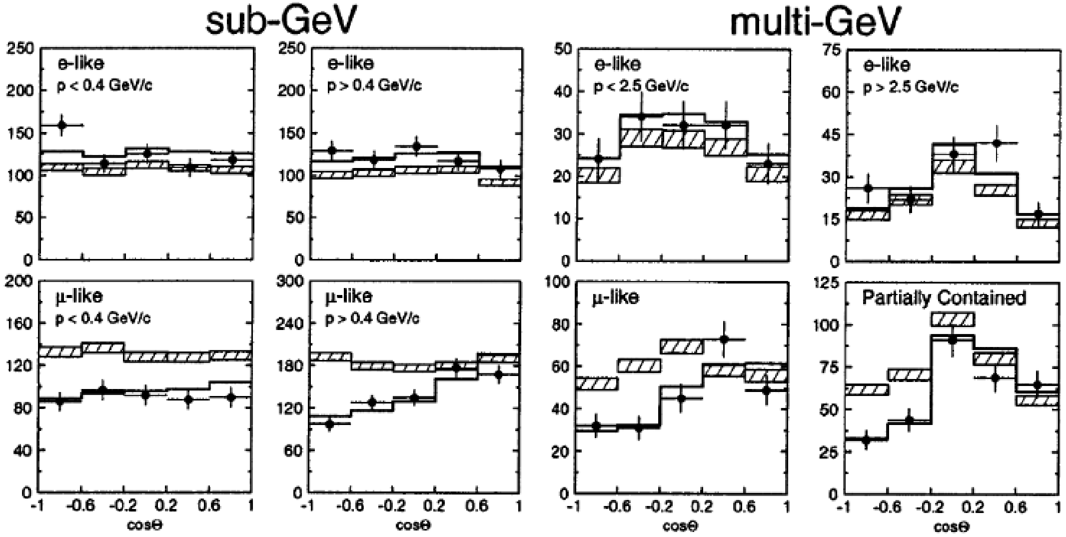


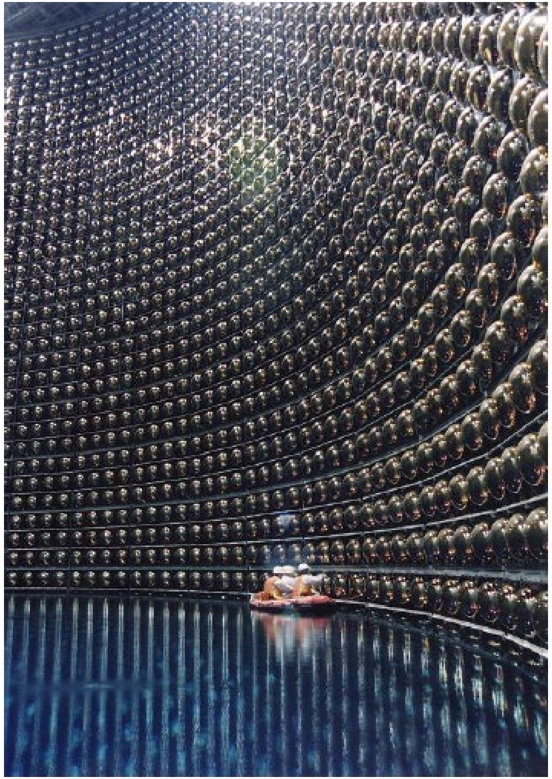
FIG. 3. Zenith angle distributions of μ-like and e-like events for sub-GeV and multi-GeV data sets. Upward-going particles have $\cos\Theta < 0$ and downward-going particles have $\cos\Theta > 0$. Sub-GeV data are shown separately for $p < 400$ MeV/c and $p > 400$ MeV/c. Multi-GeV e-like distributions are shown for $p < 2.5$ and $p > 2.5$ GeV/c and the multi-GeV μ-like are shown separately for FC and PC events. The hatched region shows the Monte Carlo expectation for no oscillations normalized to the data live time with statistical errors. The bold line is the best-fit expectation for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with the overall flux normalization fitted as a free parameter.

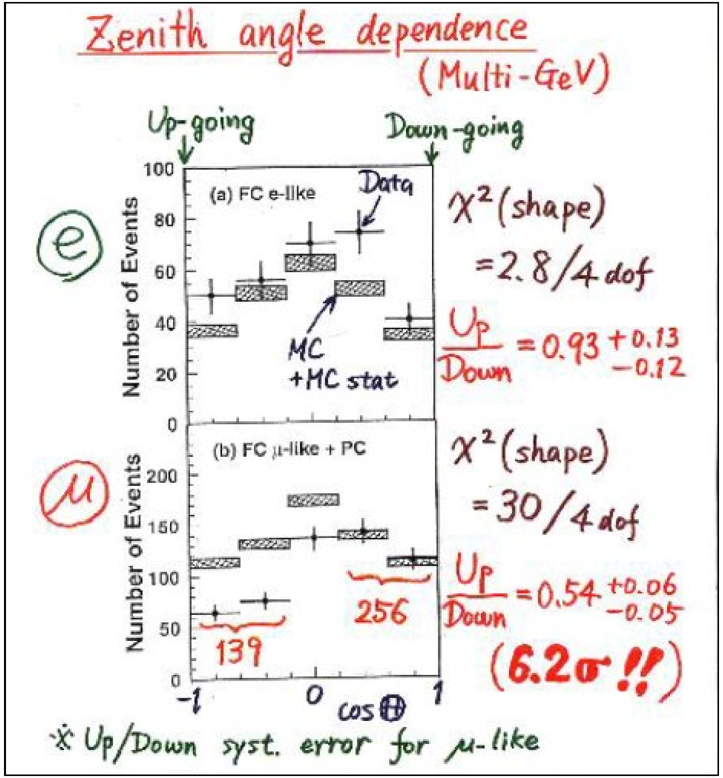
Y. Fukuda *et al.* (Super-Kamiokande Collaboration)
Phys. Rev. Lett. **81**, 1562 – Published 24 August 1998

Ev

Muon-ne
are 'disap
At low en

Electron r
as expcte

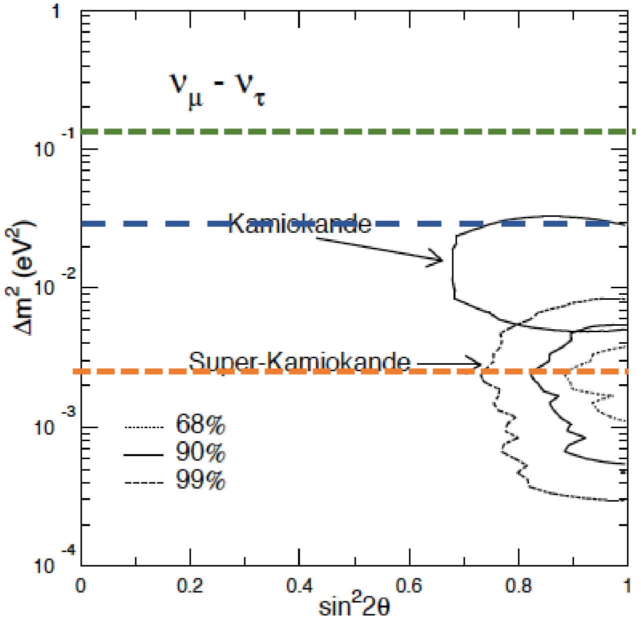




(T. Kajita at Neutrino' 98, Takayama)

One-mass-scale approximation

$$P_{\mu\tau} \approx \sin^2(2\theta_{23})\ \sin^2(\Delta m^2 L/4E)$$



This is now called, 'the large Δm^2',
The atmospheric Δm^2 , or
$\Delta m^2_{31} \approx \Delta m^2_{32}$

Corresponding mixing angle: atmospheric mixing angle, or Θ_{23}

Plot from 1998. Guess the current Best-fit value… red, blue or green?

Oscillations

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

Share this: 1.5K

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

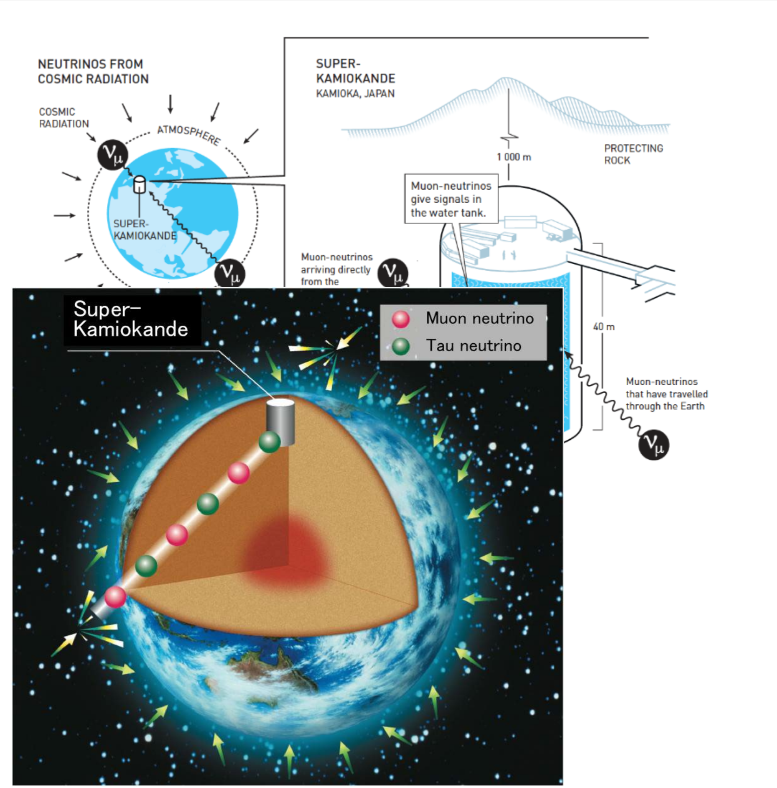
Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

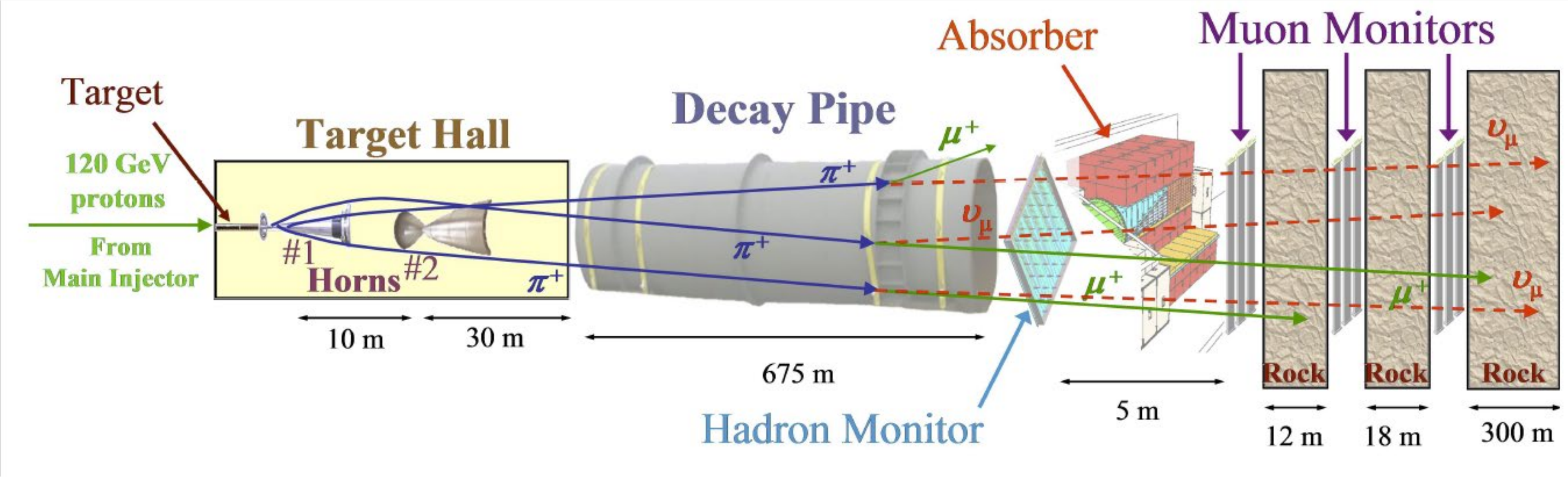
Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



Confirming ‘atmospheric’ mixing

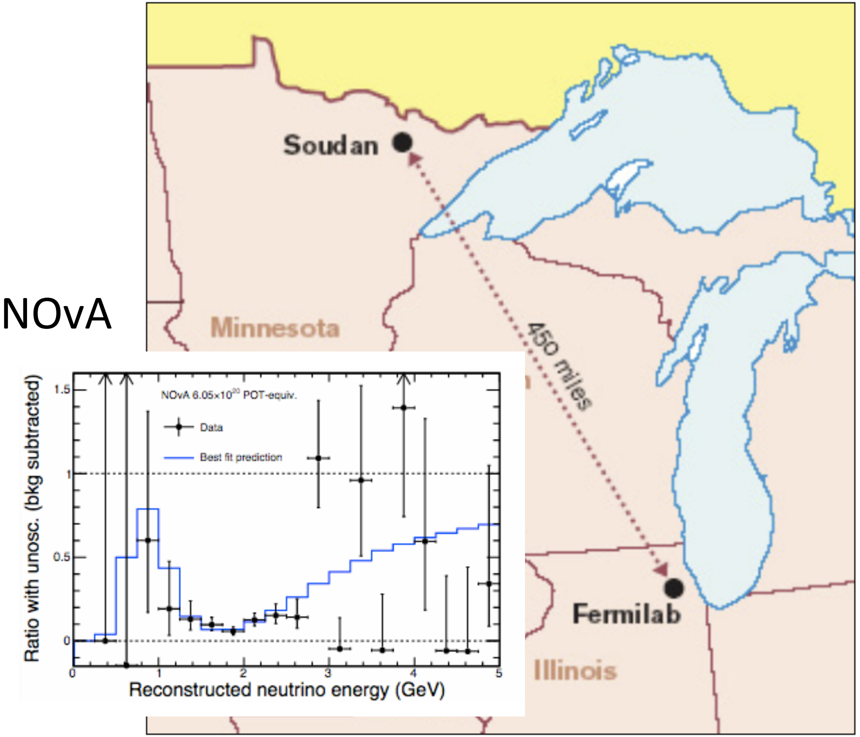


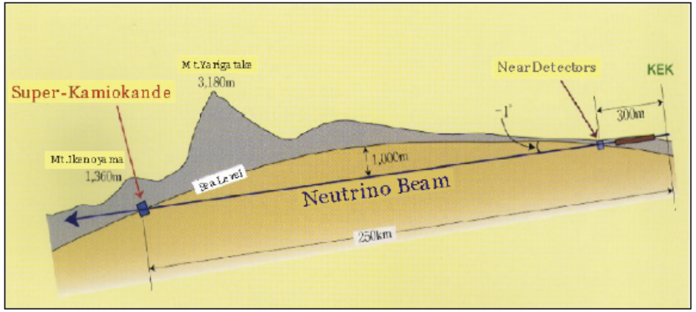
E. Lisi

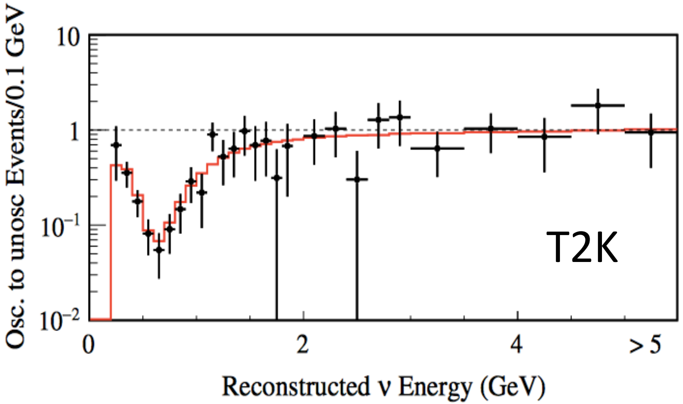
Confirming ‘atmospheric’ mixing

“Reproducing atmospheric ν_μ physics” in controlled conditions

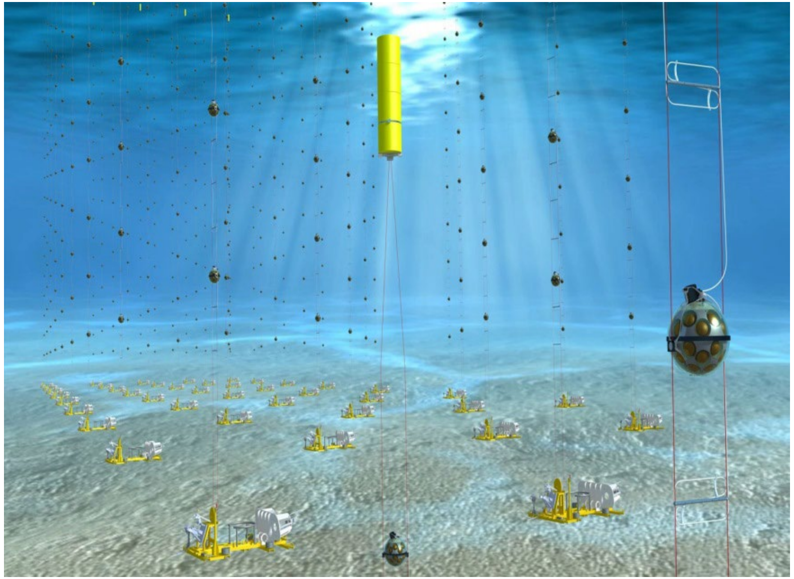
NOvA

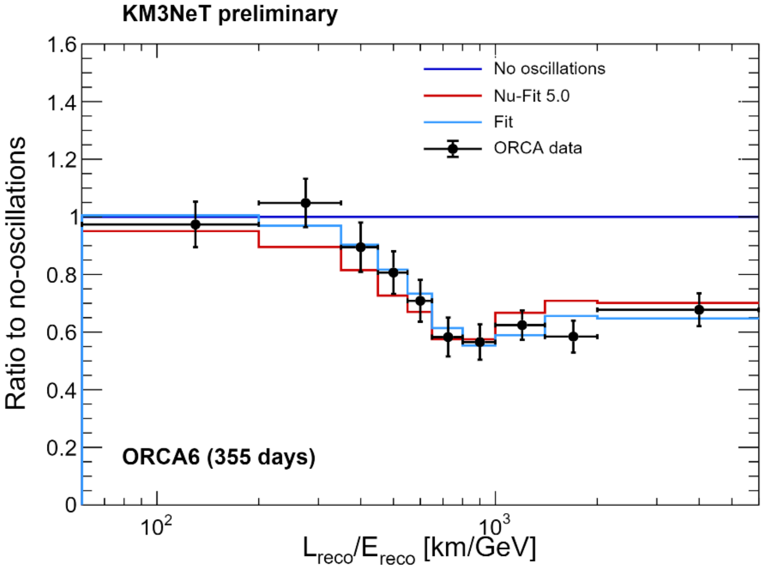






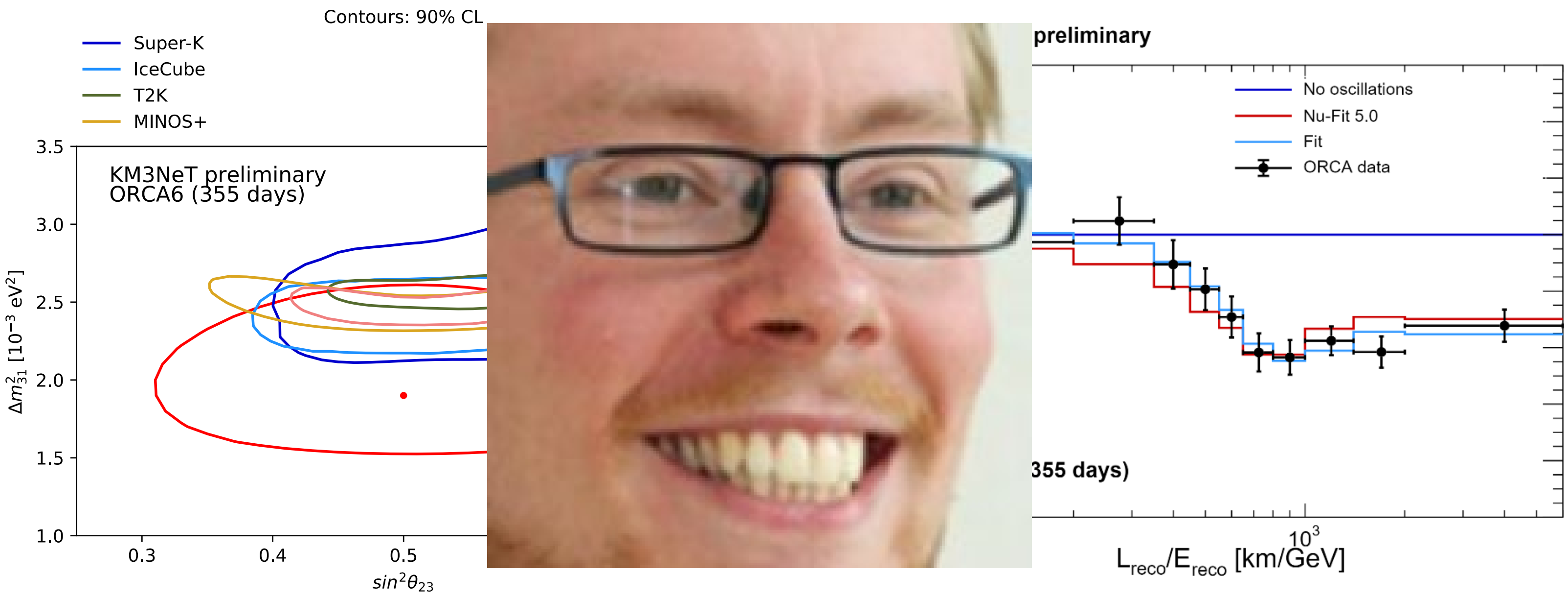
… most recent to join the game I think





6 lines of the KM3NeT/ORCA detector running for 1 year
(completed detector will have 115 lines)

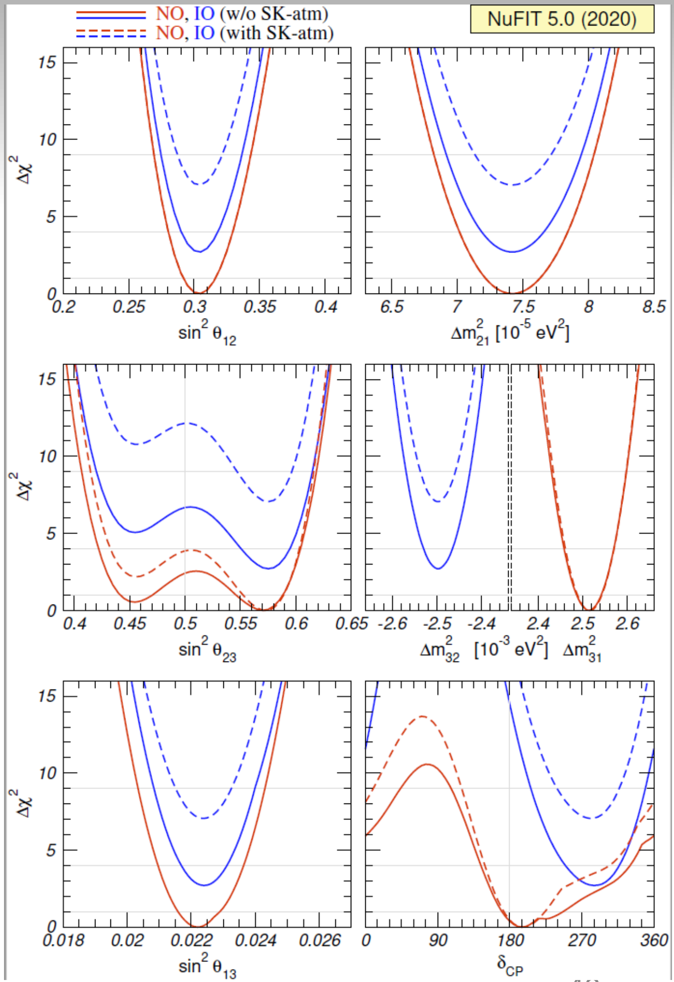
… most recent to join the game I think



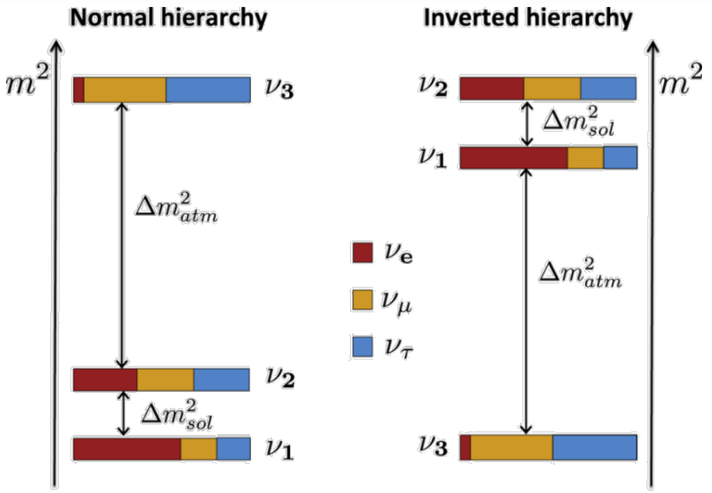
6 lines of the KM3NeT/ORCA detector running for 1 year
(completed detector will have 115 lines)

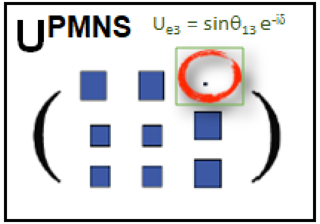
Global fits..

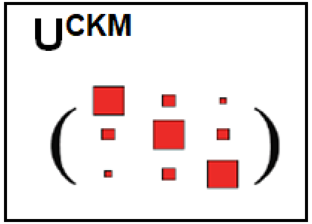
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

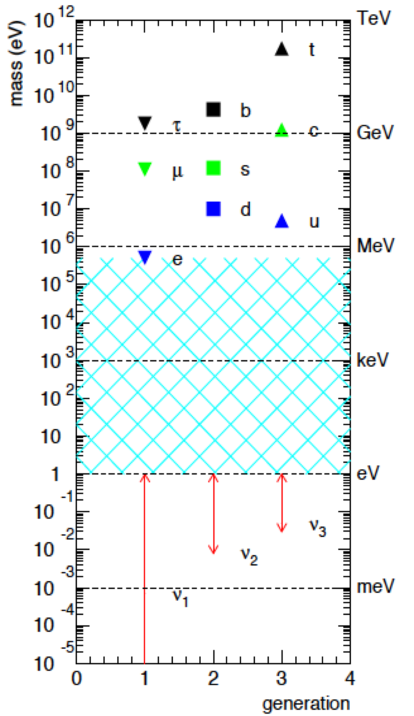


Conclusions so far..









- All mixing angles are non-zero
  - Each flavour contributes to each mass eigenstate
  - Very different from quarks
- At least two of the masses are non-zero. But tiny wrt quarks
- We know the sign of Δm_{12}

- What about CP?

What about CP? (i.e. the supposed topic of this lecture ;)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}[\mathrm{W}^{\mathrm{ij}}_{\alpha\beta}]\,\sin^2\left(\frac{\Delta \mathrm{m}^2_{\mathrm{ij}}\,\mathrm{L}}{4\mathrm{E}_\nu}\right)$$

$$\mp\; 2\sum_{j>i} \mathrm{Im}[\mathrm{W}^{\mathrm{ij}}_{\alpha\beta}]\,\sin\left(\frac{\Delta \mathrm{m}^2_{\mathrm{ij}}\,\mathrm{L}}{2\mathrm{E}_\nu}\right), \quad W^{ij}_{\alpha\beta} \equiv [U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}]$$

- 2^{nd} term above flips sign.
- Only CP if Im ≠ 0 -> δ≠0

$$A^{CP}_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$$

$$A^{\text{CP(T)-odd}}_{\nu_\alpha\nu_\beta} = \frac{\sin\delta c_{13} \sin 2\theta_{13} \overbrace{\sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E_\nu}}^{\text{solar}} \overbrace{\sin 2\theta_{23} \sin^2 \frac{\Delta m^2_{13} L}{4E_\nu}}^{\text{atmos}}}{P^{\text{CP-even}}_{\nu_\alpha\nu_\beta}}.$$

What about CP? (i.e. the supposed topic of this lecture ;)

It was not a-priori obvious CP would be observable.

δ must not be zero*
(and not 180 deg)

θ_{13} must not be zero
(okay since ~*2012*!)
..in fact no angle may be 0
And you need 3 generations, by the way!

must measure in both L/E regimes.
(both Δm^2 must be non-zero)

$$\underset{\alpha \neq \beta}{A^{\text{CP(T)-odd}}_{\nu_\alpha \nu_\beta}} = \frac{\sin\delta c_{13} \sin 2\theta_{13} \overbrace{\sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E_\nu}}^{\text{solar}} \overbrace{\sin 2\theta_{23} \sin^2 \frac{\Delta m^2_{13} L}{4E_\nu}}^{\text{atmos}}}{P^{\text{CP-even}}_{\nu_\alpha \nu_\beta}}.$$

It does not depend on the flavours.

* I guess that's why they call it the cp-phase….

Interesting factoid

You can't have CP violation in neutrino disappearance experiments.

CP violation : $$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

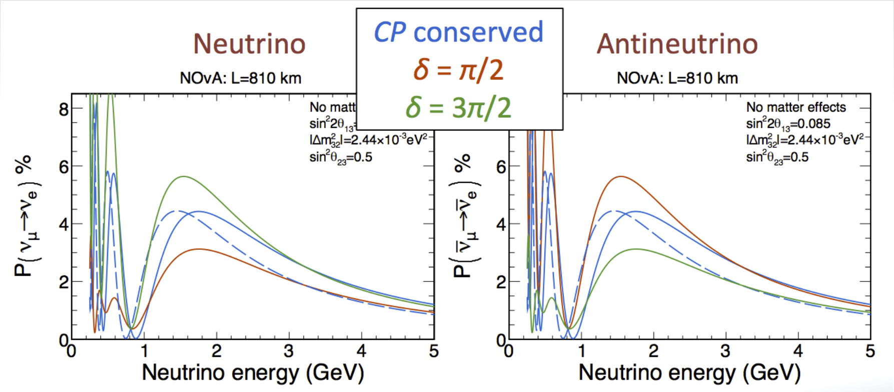
But CPT conservation says : $$P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$$

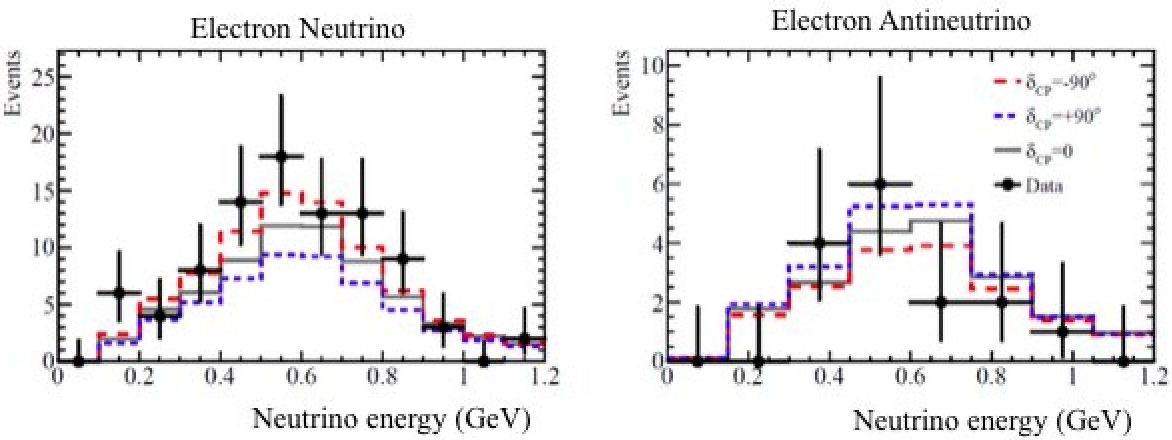
If β=α, this is a contradiction.
In other words : disappearance probability is the same when you run it backwards, and therefore it must also be the same under CP.

To measure CP, look for appearance

Measure δ

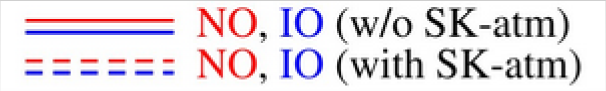
$$P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} = s_{23}^2 \sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right) + c_{23}^2 \sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right) + \tilde{J}\,\frac{\Delta_{12}}{A}\,\sin\left(\frac{AL}{2}\right)\frac{\Delta_{13}}{B_\pm}\,\sin\left(\frac{B_\pm L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right),$$

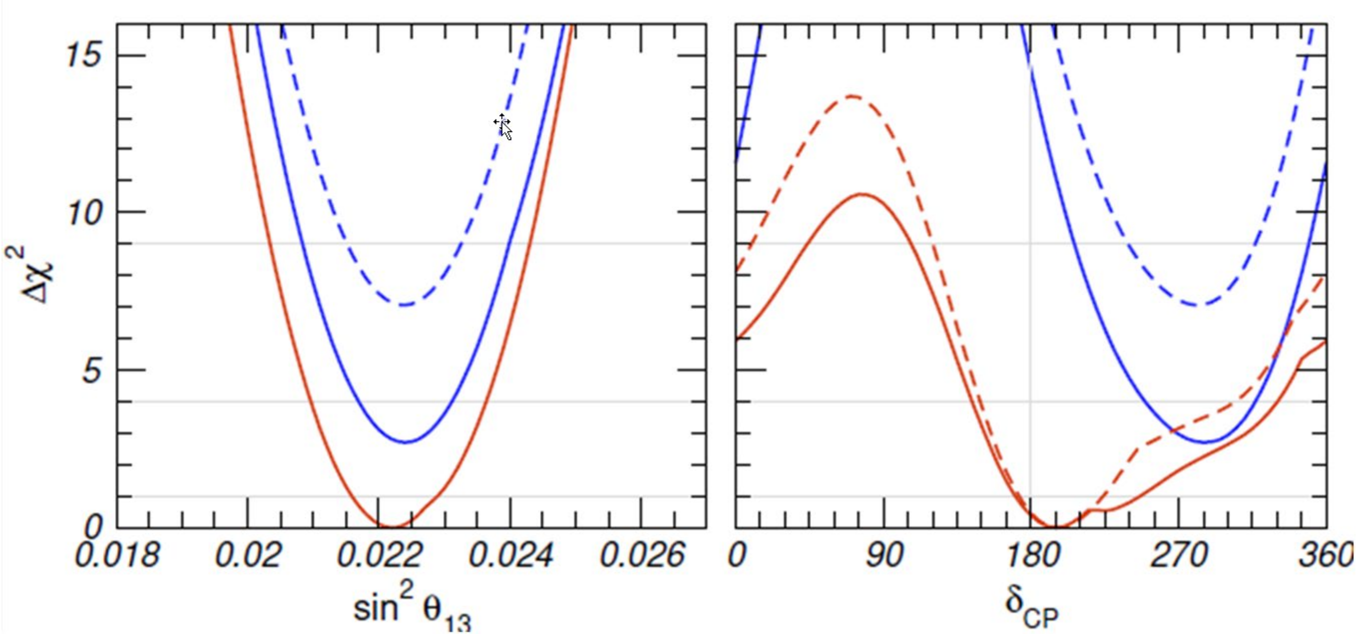




As example, data from T2K.
(NOvA also in this game)

Global fit (nufit 5.0),

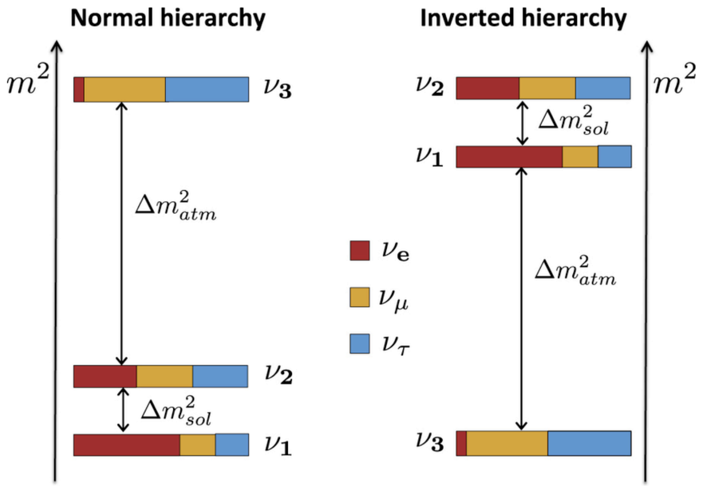


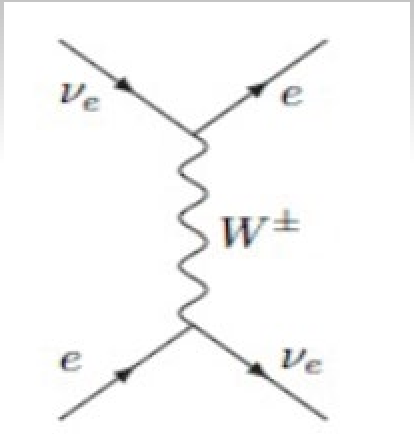


Hint for non-zero δ, and if IO, then hint for maximal CP.

..but significance limited… and would be nice to know the mass-ordering.

Mass ordering

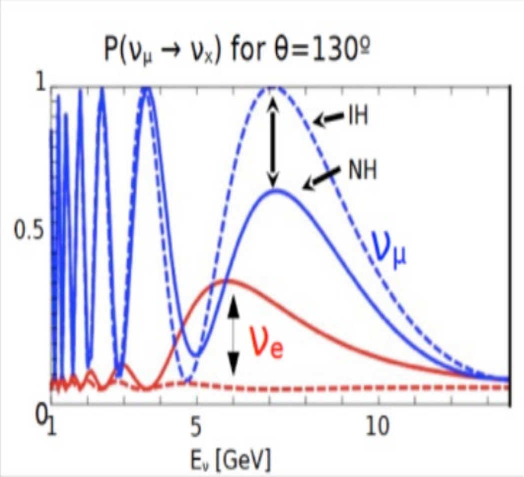




Matter effects:

The Earth is full of electrons (but no muons or taus).

The electron-



Large effect on oscillations

Nb: these matter effects must also
Be taken into account in the cp-measurements

How to compute

Exponentiate complex matrix…

Typically via diagonalization
(i.e. find the “effective-mass” eigenstates)

Or some other numerical tool.

$$i\frac{\partial}{\partial t}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} = \mathcal{H}_m(\rho)\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$\mathcal{H}_m(\rho) = \begin{bmatrix}E_1 & & \\ & E_2 & \\ & & E_3\end{bmatrix} + \mathbf{U}^{\mathrm{T}}\begin{bmatrix}A(\rho) & & \\ & 0 & \\ & & 0\end{bmatrix}\mathbf{U}$$

$$\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}_{\mathrm{end}} \equiv \mathbf{T}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} = e^{-i\mathcal{H}_m L}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}_{\mathrm{start}}$$

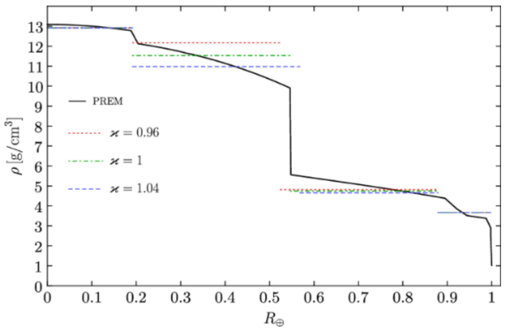
for traversing the full Earth:

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}_{\mathrm{det}} = \mathbf{U}\,\mathbf{T}_n\,\mathbf{T}_{n-1}\,\ldots\,\mathbf{T}_1\,\mathbf{U}^{\mathrm{T}}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}_{\mathrm{atm}}$$

square to get probability

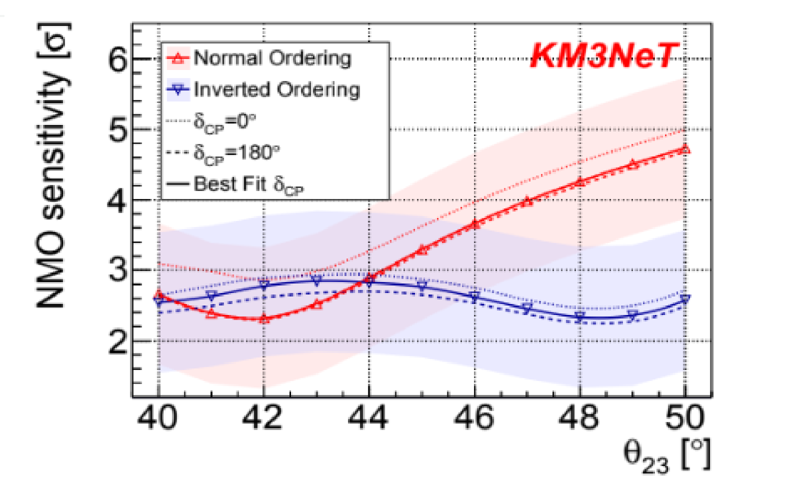
- Schro…
  the ma…
- Free p…
  basis. Matter contribution (density
  dependent) simple in flavour basis
- Propagate states through a
  layer of constant densitity
  (nb: matrix exponentiation)
- Many small layers of constant
  density. En transform to flavour
  basis at beginning and end.

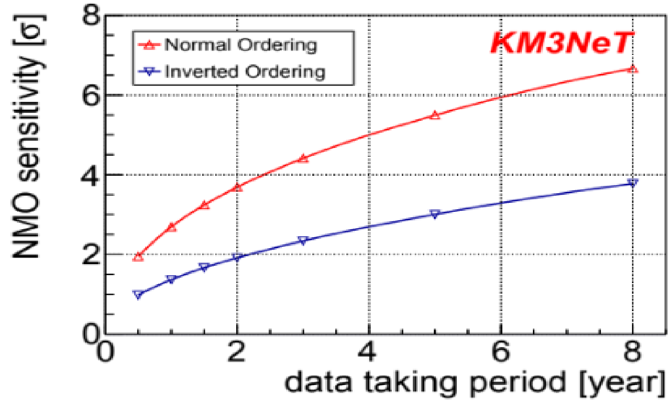
Earth density profile



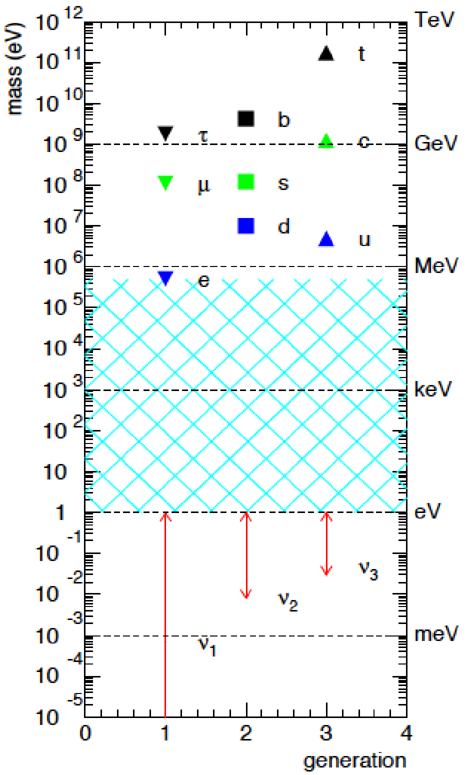
KM3NeT/ORCA

May definitely measure the mass ordering
(if we build it fast enough)





Neutrinos vs Quarks



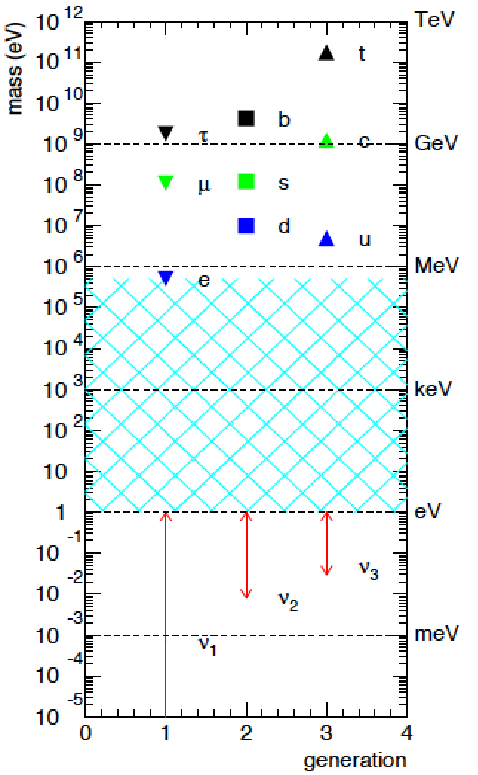
Question for the audience
(during the break)

Is it reasonable to think neutrinos are massive for the same reason as quarks & charged leptons?

Can neutrinos explain *everything*?

(besides CMB photons)

Neutrinos vs Quarks



- Is it reasonable to think neutrinos are massive for the same reason as quarks & charged leptons?

Adding neutrino masses to SM

Yukawa coupling

Higgs

$$-\mathcal{L}_m^{Dirac} = \overline{L}\,\lambda\tilde{\Phi}\,\nu_R + \text{h.c.}$$

$L = (\nu\ l)$ is the lepton doublet

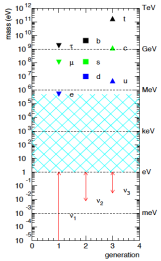
After spontaneous symmetry breaking:

$$-\mathcal{L}_m^{Dirac} \to -\overline{\nu_L}\,\lambda\frac{v}{\sqrt{2}}\nu_R + \text{h.c.}\ .$$

$$m_\nu = \lambda\frac{v}{\sqrt{2}}.$$

Okay, but…

- A right-handed neutrino that is a ‘singlet under all the gauge groups’. (theorist talk for: “it doesn’t ever do anything”).
- A ‘hierarchy’ problem: why Yukawa couplings so small for neutrinos?



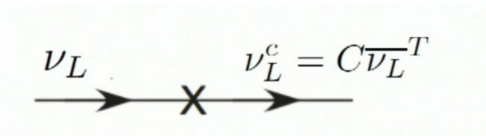
Adding neutrino masses to SM

$$-\mathcal{L}_m^{Majorana} = \bar{L}\tilde{\phi}\,\alpha C\tilde{\phi}^T\bar{L}^T + h.c.,$$

After symmetry breaking

$$-\mathcal{L}_m^{Majorana} \to \bar{\nu}_L\alpha\frac{v^2}{2}C\bar{\nu}_L^T + h.c.,$$

$$\alpha = \frac{\lambda}{\Lambda} \quad \Big| \quad m_\nu = \frac{\lambda}{\Lambda}v^2.$$



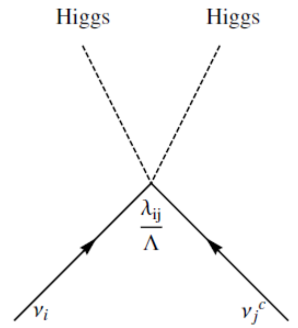


Fig. 12: Weinberg operator.

- α has units of 1/mass
- scale indicative of new physics inside the blob
- High mass scale -> low mass neutrinos
- Majorana neutrinos violate L
- Neutrinos are their own anti-particles

Interesting thought…

What if we did effective field theory, like our quark-minded colleagues?

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{\alpha_i}{\Lambda} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2} O_i^{d=6} + \ldots$$

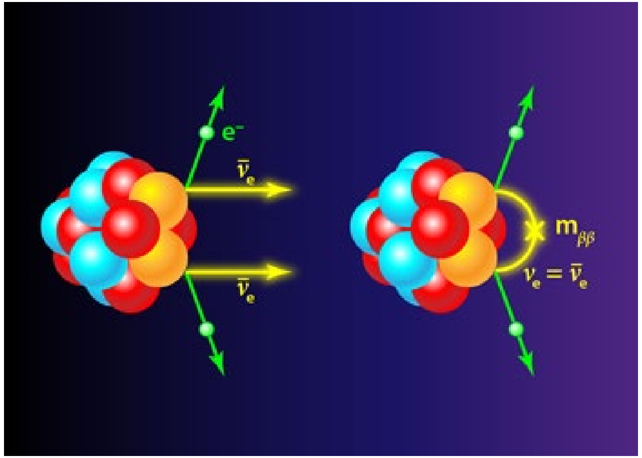
The only possible d=5 operator
is the one for Majorana neutrino masses.

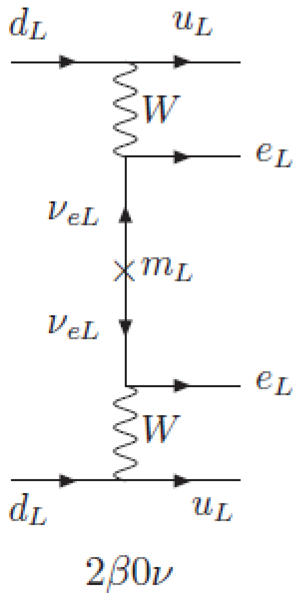
If one were to look for new physics in this way, the
first* thing one could hope to find is (majorana) neutrino masses.

Well….we did!

Majorana or not?

Best option: neutrinoless double Beta decay
- Possible if, and only if, Majorana



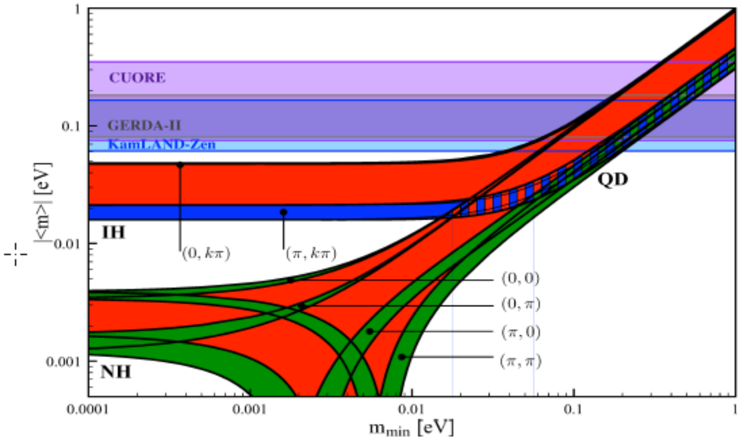


1) Make a ν

2) change helicity because he has mass.

3) W wants to know:
- helicity correct?
~~- nu/nubar correct~~

Experiments looking for ββ0ν



Many runners in the race to discover 0νββ decay...

TABLE VII. In this table, the main features and performances of some past, present and future $0\nu\beta\beta$ experiments are listed.

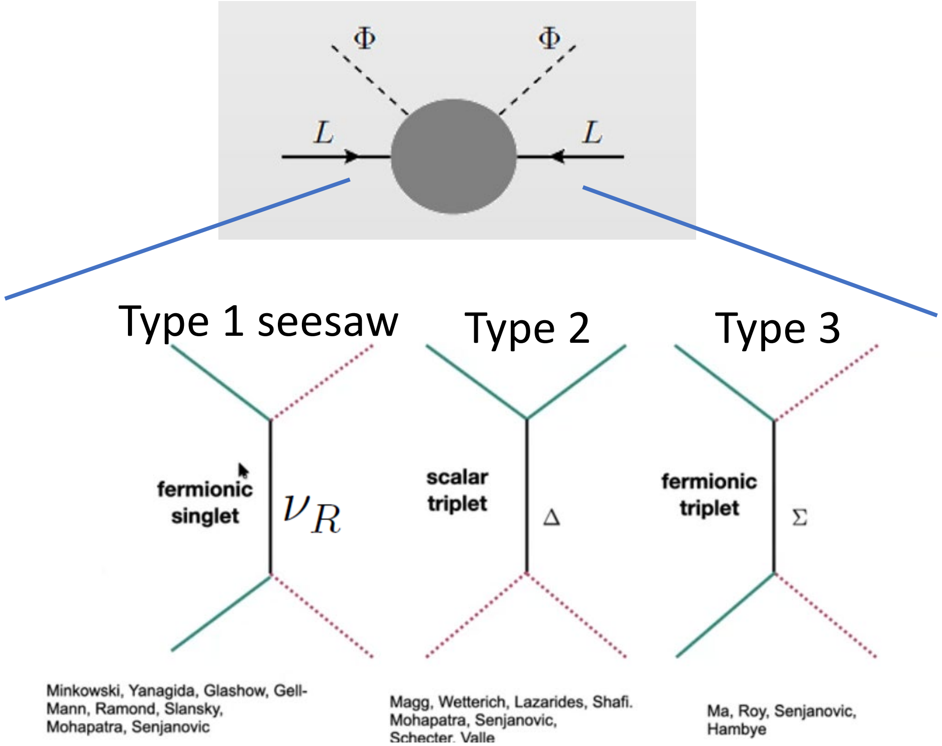
Experiment	Isotope	Techinique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% C.L.) [10^{25} yr]
Past							
Cuoricino, [179]	^{130}Te	bolometers	40.7 (TeO_2)	19.75	5.8 ± 2.1	0.153 ± 0.006	0.24
CUORE-0, [180]	^{130}Te	bolometers	39 (TeO_2)	9.8	5.1 ± 0.3	0.058 ± 0.006	0.29
Heidelberg-Moscow, [181]	^{76}Ge	Ge diodes	11 (^{enr}Ge)	35.5	4.23 ± 0.14	0.06 ± 0.01	1.9
IGEX, [182, 183]	^{76}Ge	Ge diodes	8.1 (^{enr}Ge)	8.9	~ 4	$\lesssim 0.06$	1.57
GERDA-I, [167, 184]	^{76}Ge	Ge diodes	17.7 (^{enr}Ge)	21.64	3.2 ± 0.2	~ 0.01	2.1
NEMO-3, [185]	^{100}Mo	tracker + calorimeter	6.9 (^{100}Mo)	34.7	350	0.013	0.11
Present							
EXO-200, [186]	^{136}Xe	LXe TPC	175 (^{enr}Xe)	100	89 ± 3	$(1.7 \pm 0.2) \cdot 10^{-3}$	1.1
KamLAND-Zen, [187, 188]	^{136}Xe	loaded liquid scintillator	348 (^{enr}Xe)	89.5	244 ± 11	~ 0.01	1.9
Future							
CUORE, [189]	^{130}Te	bolometers	741 (TeO_2)	1030	5	0.01	9.5
GERDA-II, [174]	^{76}Ge	Ge diodes	37.8 (^{enr}Ge)	100	3	0.001	15
LUCIFER, [190]	^{82}Se	bolometers	17 ($Zn^{82}Se$)	18	10	0.001	1.8
MAJORANA D., [191]	^{76}Ge	Ge diodes	44.8 ($^{enr/nat}Ge$)	100 [a]	4	0.003	12
NEXT, [192, 193]	^{136}Xe	Xe TPC	100 (^{enr}Xe)	300	$12.3 - 17.2$	$5 \cdot 10^{-4}$	5
AMoRE, [194]	^{100}Mo	bolometers	200 ($Ca^{enr}MoO_4$)	295	9	$1 \cdot 10^{-4}$	5
nEXO, [195]	^{136}Xe	LXe TPC	4780 (^{enr}Xe)	12150 [b]	58	$1.7 \cdot 10^{-5}$ [b]	66
PandaX-III, [196]	^{136}Xe	Xe TPC	1000 (^{enr}Xe)	3000 [c]	$12 - 76$	0.001	11 [c]
SNO+, [197]	^{130}Te	loaded liquid scintillator	2340 (^{nat}Te)	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [198, 199]	^{82}Se	tracker + calorimeter	100 (^{82}Se)	500	120	0.01	10

[a] our assumption (corresponding sensitivity from Fig. 14 of Ref. [191]).
[b] we assume 3 tons fiducial volume.
[c] our assumption by rescaling NEXT.

from 1601.07512

25

Seesaw mechanism



- Suppose the new physics is due to a right-handed neutrino

$$\nu_R$$

- Give it both a Yukawa coupling to the left-handed leptons, and Majorana mass term…

Seesaw mechanism

A Majorana mass for the New, right handed neutrino.

A 'normal' Dirac mass with λ ~ 1. generated by Yukawa coupling.

$$\mathcal{L}_{m_\nu} = -M_{\mathrm{D}}\left(\overline{\nu_{\mathrm{L}}}\nu_{\mathrm{R}} + \overline{\nu_{\mathrm{R}}}\nu_{\mathrm{L}}\right) - \frac{1}{2}M_{\mathrm{R}}\left(\overline{\nu_{\mathrm{R}}^{c}}\nu_{\mathrm{R}} + \overline{\nu_{\mathrm{R}}}\nu_{\mathrm{R}}^{c}\right).$$

$$m_\nu = \lambda\frac{v}{\sqrt{2}}.$$

$$L = \frac{1}{\sqrt{2}}\left(\nu_{\mathrm{L}} + \nu_{\mathrm{L}}^{c}\right); \qquad R = \frac{1}{\sqrt{2}}\left(\nu_{\mathrm{R}} + \nu_{\mathrm{R}}^{c}\right).$$

This is the 1-neutrino case.
For 3 generations
M are matrices that
can violate CP.

$$\mathcal{L}_{m_\nu} = -\begin{pmatrix}\overline{L} & \overline{R}\end{pmatrix}\begin{pmatrix}0 & M_{\mathrm{D}} \\ M_{\mathrm{D}} & M_{\mathrm{R}}\end{pmatrix}\begin{pmatrix}L \\ R\end{pmatrix}$$

Eigenvalues

$$M_{\mathrm{R}} \text{ and } M_{\mathrm{D}}^{2}/M_{\mathrm{R}},$$

If M_R is large, then the left-handed mass-eigenstates are very small!

Sees

for the

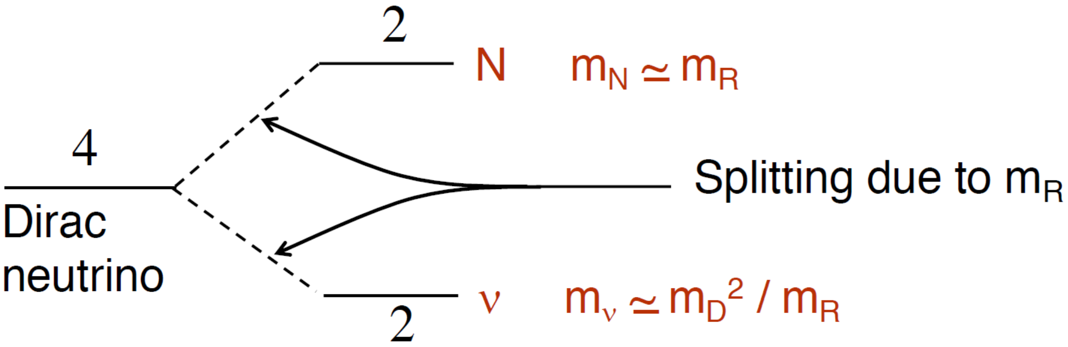
d neutrino.

A 'normal' Dirac mass with λ ~ 1. generated b Yukawa coupling.

$$m_\nu = \lambda \frac{v}{\sqrt{2}}.$$

What Happened?

The Majorana mass term split a Dirac neutrino into two Majorana neutrinos.



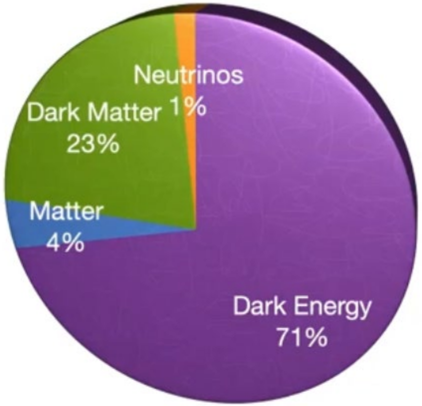
$4 = 2 + 2$

Boris Kayser

If N

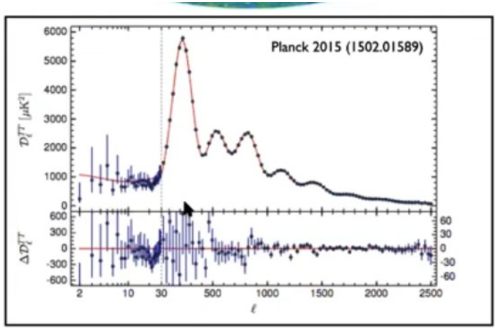
all!

(Lepto)genesis

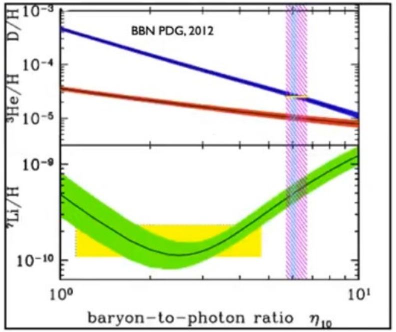


Baryon to photon ratio. Extremely well measured
From both CMB and Big Bang Nucleosynthesis.

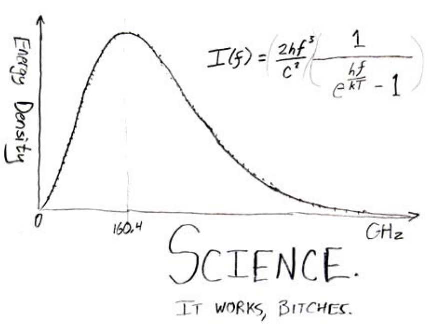
$$\eta_B = (6.02 - 6.18) \times 10^{-10}$$



$\eta_{\mathrm{CMB}} = (6.23 \pm 0.17) \times 10^{-10}$



$\eta_{\mathrm{BBN}} = (6.08 \pm 0.06) \times 10^{-10}$

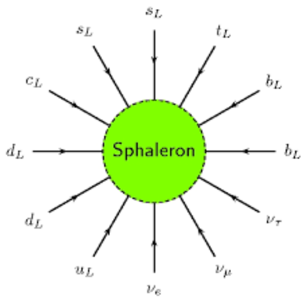


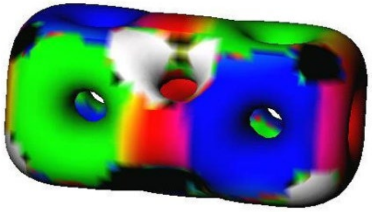
Sakharov's Conditions

- ☑ Baryon number violation
- ☑ C & CP-violation
- ☑ Departure from thermal equilibrium

Buzzword: “Sphalerons”

Non-pertubative SM process that
Conserves B-L
(but not B and not L)

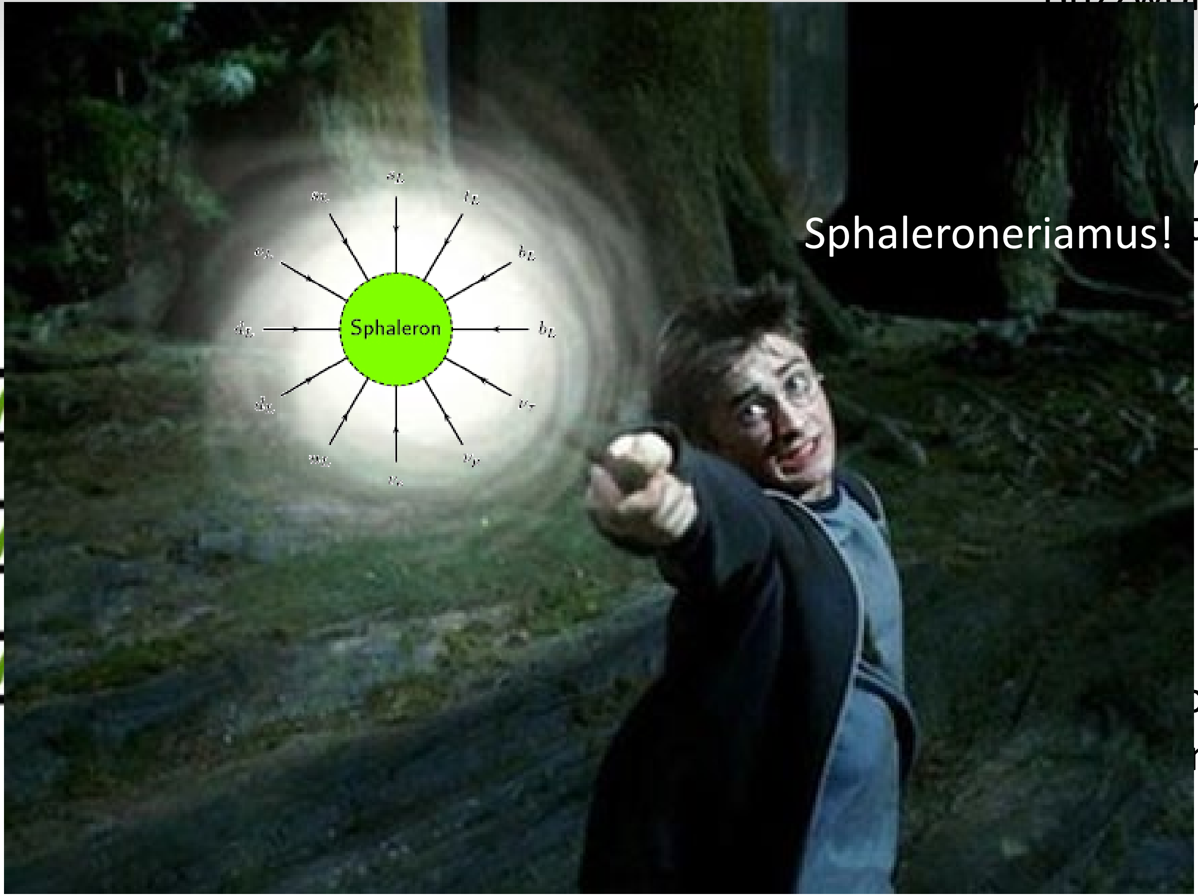


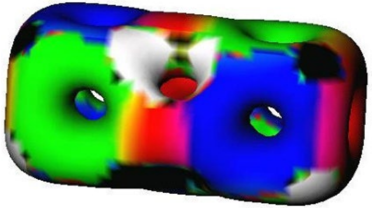


These can convert a lepton asymmetry into a Baryon one.

Buzzword: “sphalerons”

rtubative SM process that
ves B-L
B and not L)



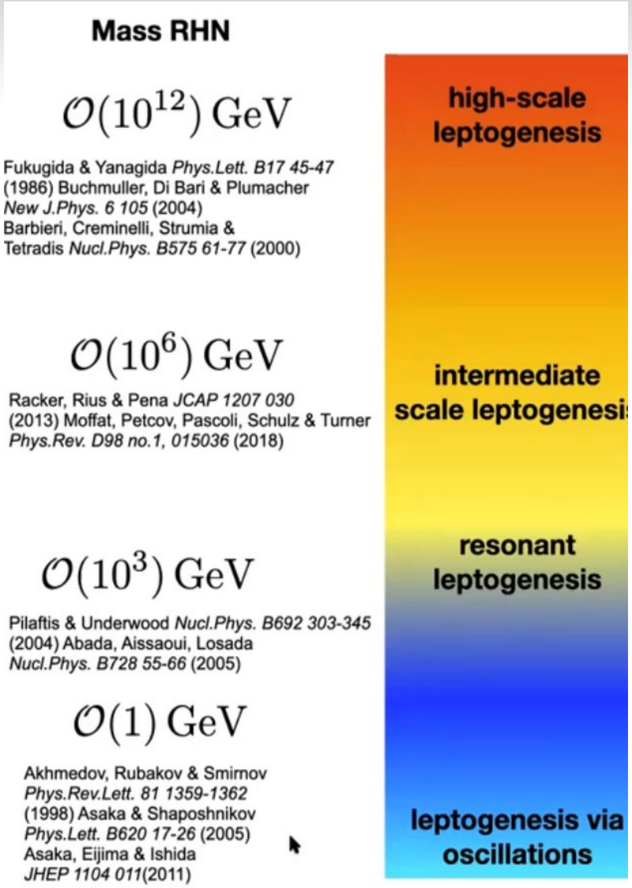


onvert a lepton asymmetry
n one.

Leptogenesis

- Dynamically generate lepton asymmetry, by *producing* N in the early universe
- They decay into leptons
- Lepton-asymmetry converted to Baryon asymmetry by SM sphaleron process
- All this while the Universe is cooling.
- See if this yields the correct Bayon number

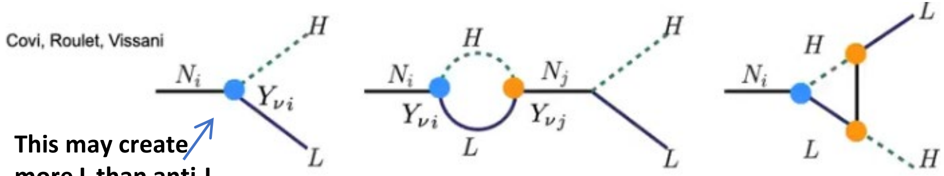
- Can be made to work, with various variations, for a huge mass-range for the right-handed neutrinos.



Leptogenesis

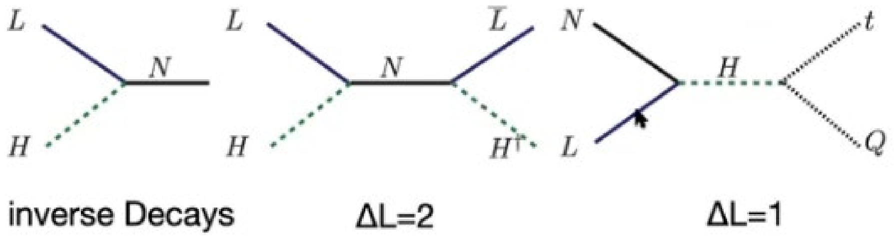
N = right handed heavy neutrino, which is its own anti-particle. M>T
L = (normal) Leptons
H = Higgs

Processes creating leptons…

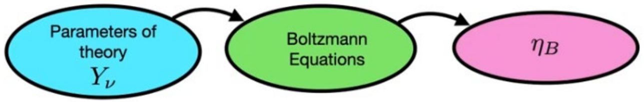


This may create more L than anti-L

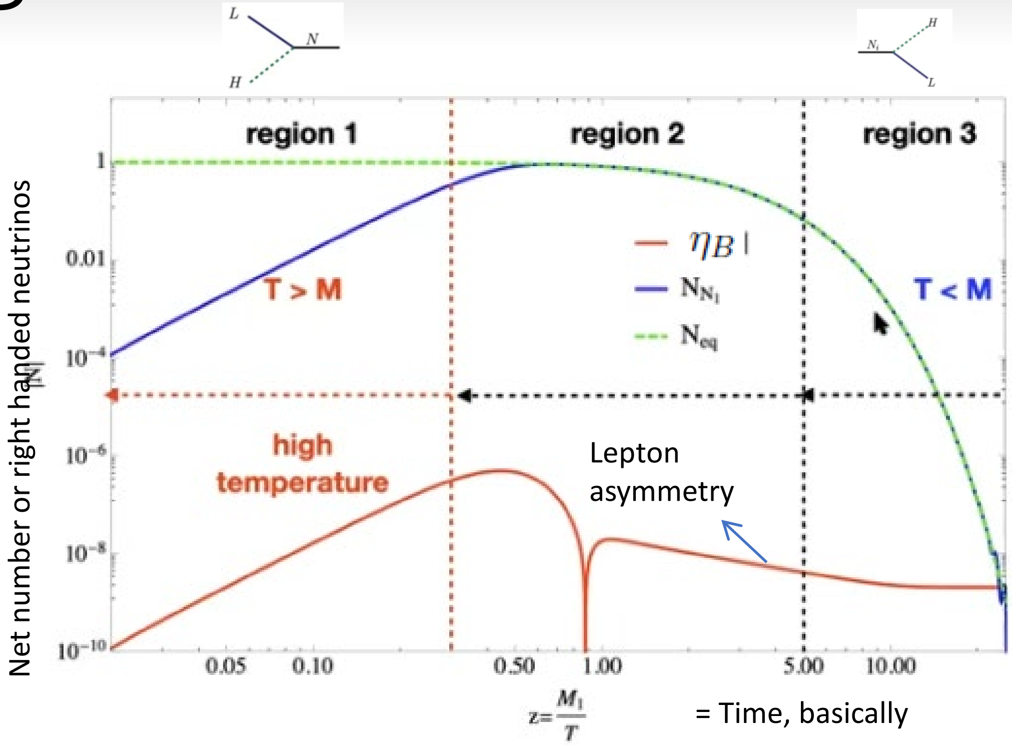
Competing with ‘destroying’ leptons …



- Set of coupled differential equations.
- Starting with no N.
- Evolve while T goes down.
- See what happens



leptogenesis



Compare with Observed Asymmetry η_B

(not order of magnitude, But the actual, measured number, within errors)

$$\eta_B \equiv \frac{N_B}{N_\gamma^{\rm rec}} = a_{\rm sph}\frac{N_{B-L}}{N_\gamma^{\rm rec}} = \frac{28}{79}\frac{1}{27}N_{B-L} = 0.013 N_{B-L}$$

leptogenesis

Okay, but we know nothing about these right handed neutrinos

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

low-energy scale: 3 phases, 3 mixing angles and 3 masses

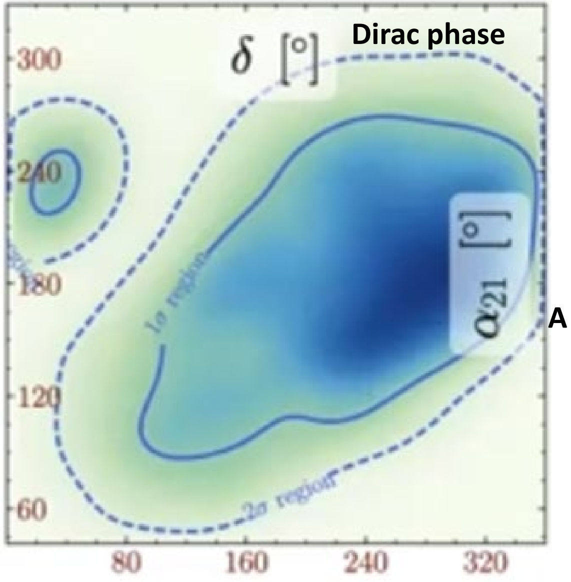
high-energy scale: 3 phases, 3 mixing angles and 3 masses

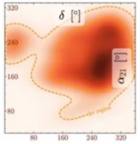
18 parameters in total; of which 6 are known (low-E angles + masses)

One fun question: What if all the CPV is from the low-energy sector?

leptogenesis

$M_1 = 3.16 \times 10^6\,\mathrm{GeV},\ M_2 = 3.5M_1,\ M_3 = 3.5M_2$





<- for inverse ordering, looks different but same conclusion

Here, at PeV masses for the RHN

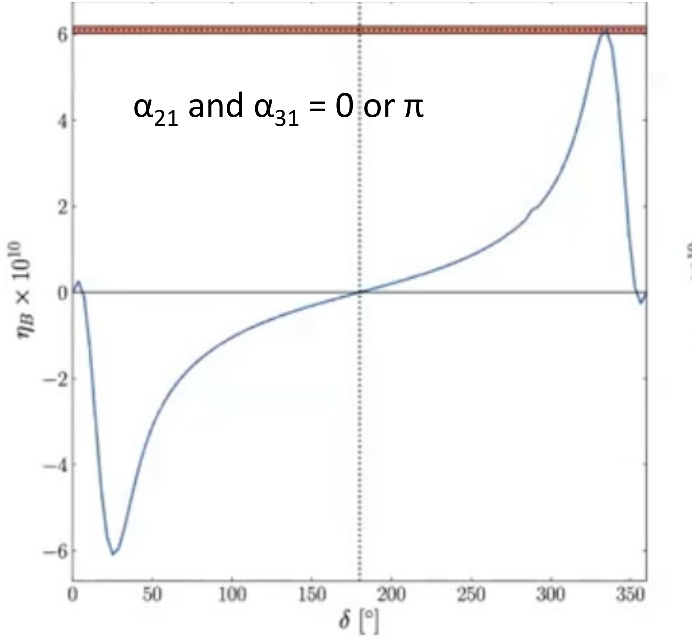
- Assume two phases
- Scan all other parameters (mixing angles of the RHNs) to yield correct Baryon asy. (while conserving CP there).
- See for which region it can work

$\Rightarrow$ It works!

While there is absolutely no reason (afaik) to suspect the CP conservation at high scale, it is ‘nice’ to know it is not needed. The low-scale CP phases can be measured(!)

leptogenesis

$$M_1 = 7.0 \times 10^8\,\text{GeV},\; M_2 = 3.5M_1,\; M_3 = 3.5M_2$$

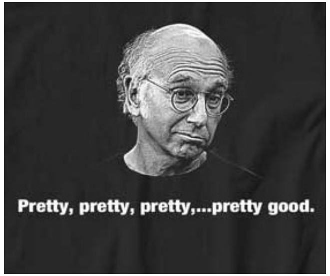


Can even do it with just the Dirac phase!
(which we are already measuring and which will be measured by Dune).

And with just the Majorana phases it works too.

In conclusion

- Leptogenesis, building on seesaw mechanism:
  - Rather minimal assumptions
    Every theory of massive neutrinos need RHN and
    no reason not to write general mass terms…
    All the rest follows.
  - *Explains why the normal neutrinos are light*
  - *Explains the matter-anti-matter asymmetry in the Universe*
  - *predicts/assumes Majorana particles -> testable.*
  - Measuring CPV in normal neutrinos would lend a lot
    of, let’s say, “psychological support”



THE END

mixing

$$-\mathcal{L}_m^{\text{Majorana}} = \frac{1}{2}\overline{\nu_L^i}\,(M_\nu)_{ij}\,\nu_L^{cj} + \overline{l_L^i}\,(M_l)_{ij}\,l_R^j + \text{ h.c.}$$

$$M_\nu = U_\nu^\dagger \text{Diag}(m_1, m_2, m_3) U_\nu^*$$

mass eigenstates $\nu_L' = U_\nu \nu_L$ 'flavour' eigenstates

Questions

Why do neutrino's behave so differently from quarks?
(do they get mass the same way??)

(why do we not even know)
Which neutrino is the heaviest?

So what if neutrinos violate CP?
(Leptogenesis?)

Do neutrinos point to new Physics?