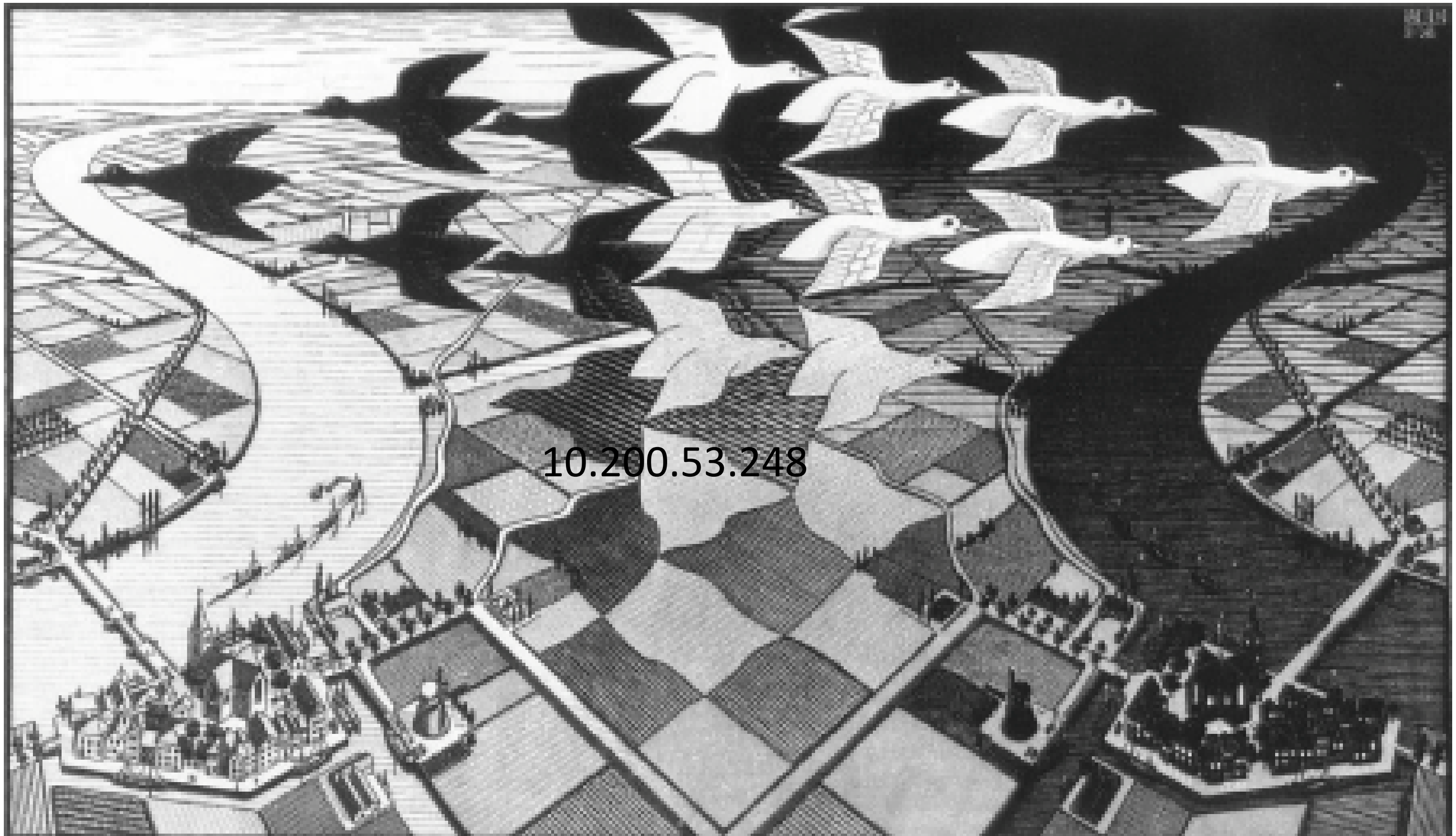
CP Violation

-- Lecture 7 --



M.C. Escher

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Summary of Lecture 6

- Measurements of ϕ_1, the phase of V_{td} agree with constraint set by measurements of $|V_{td}|$ (from B^0-$\bar{B}^0$ mixing); $|V_{ub}|$ (from $B \rightarrow \pi e^- \nu$); and ε (from CPV in K-mesons) .

- Kobayashi & Maskawa shared the 2008 Nobel prize for their 6-quark model for CPV.

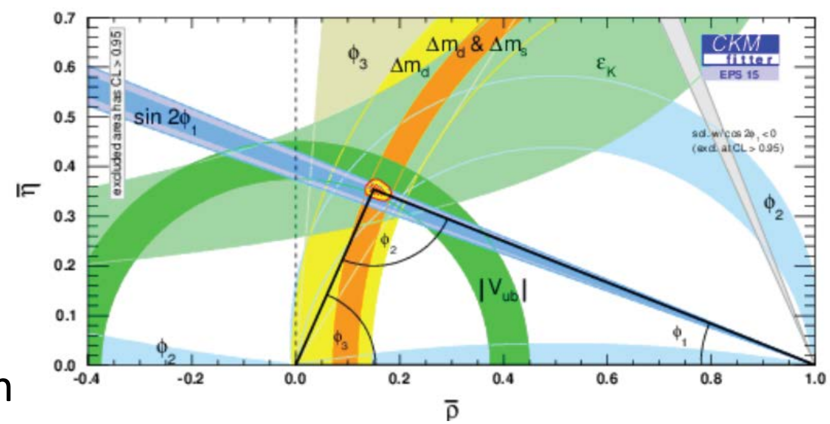
- Subsequent measurements produced a precision measurement of $\phi_1 = 21.9^o \pm 0.6^o$ and first measurements of $\phi_2 = 86.7^o \pm 3.5^o$ and $\phi_3 = 76.2^o \pm 5.0^o$.

- At current precision, $\phi_1 + \phi_2 + \phi_3 = 185.9^o \pm 6.1^o$, consistent with a closed triangle.

- Large direct CP violations are observed, such as a ~30% difference between B^0 & $\bar{B}^0 \rightarrow \pi^+\pi^-$

- All observed CP violation measurements can be attributed to the KM phase in the 6-quark flavor mixing matrix. The CP violations in the 3rd generation b-quark, t-quark are near their maximum possible values (e.g, $\sin 2\phi_1 \approx 0.68$ *vs* a maximum possible value of 1).

- All measured constraints on the ρ & η Wolfenstein parameters are consistent with each other.

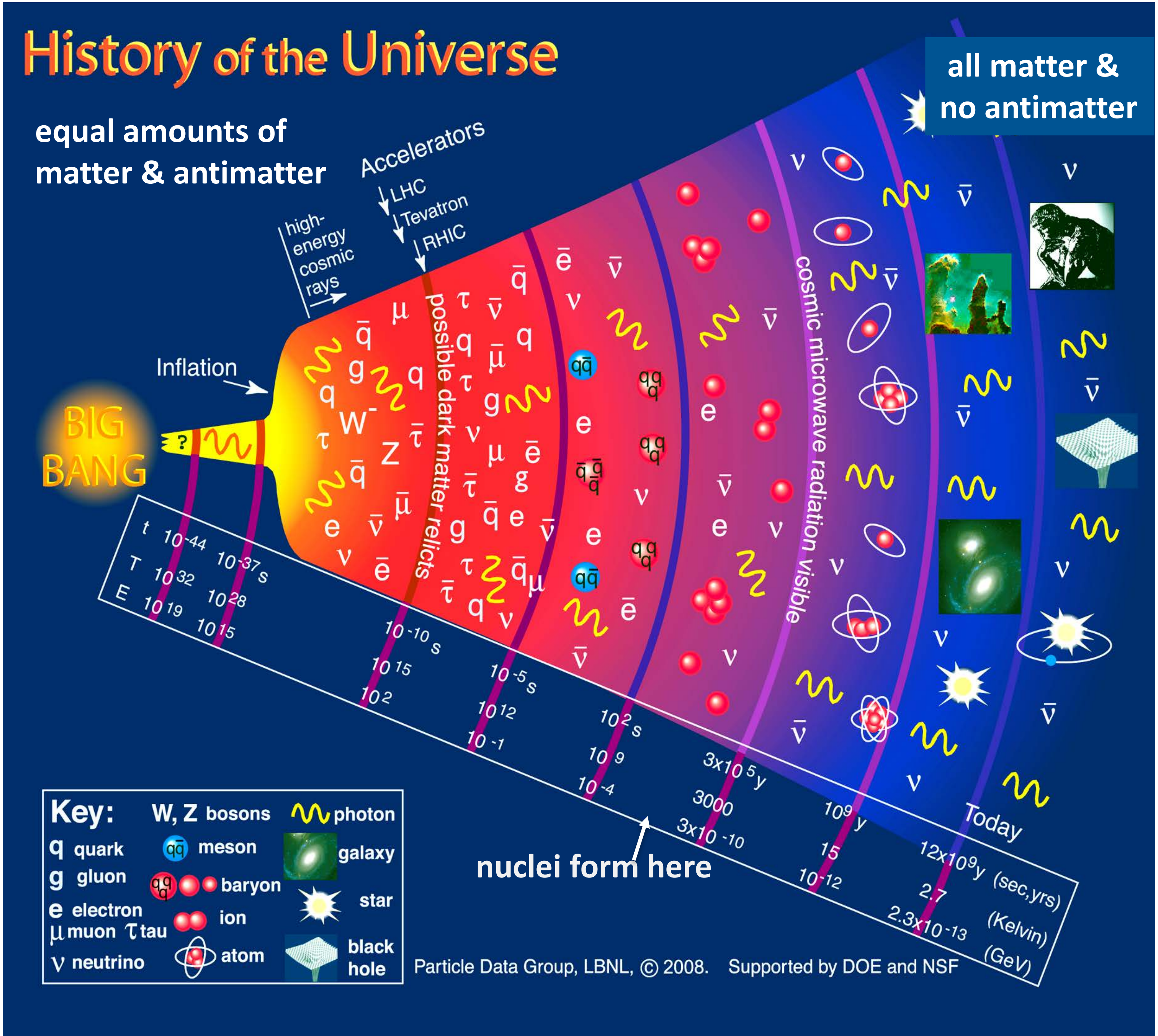


CPV and Big Bang Cosmology

Baryon Asymmetry of the Universe

"Big-Bang:" matter-antimatter symmetric

- today's universe: all matter; ~no antimatter
  - > where did all the antimatter go?
  - > $\mathcal{CP}$**V** must have played a key role



History of the Universe
equal amounts of matter & antimatter
all matter & no antimatter
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
nuclei form here
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Sakharov: CP violation is necessary to explain the Baryon Asymmetry of the Universe (BAU).

-- slide from Lecture 1 --

Sakharov: CPV, C-asymmetry & the baryon asymmetry of the Universe (1967)

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

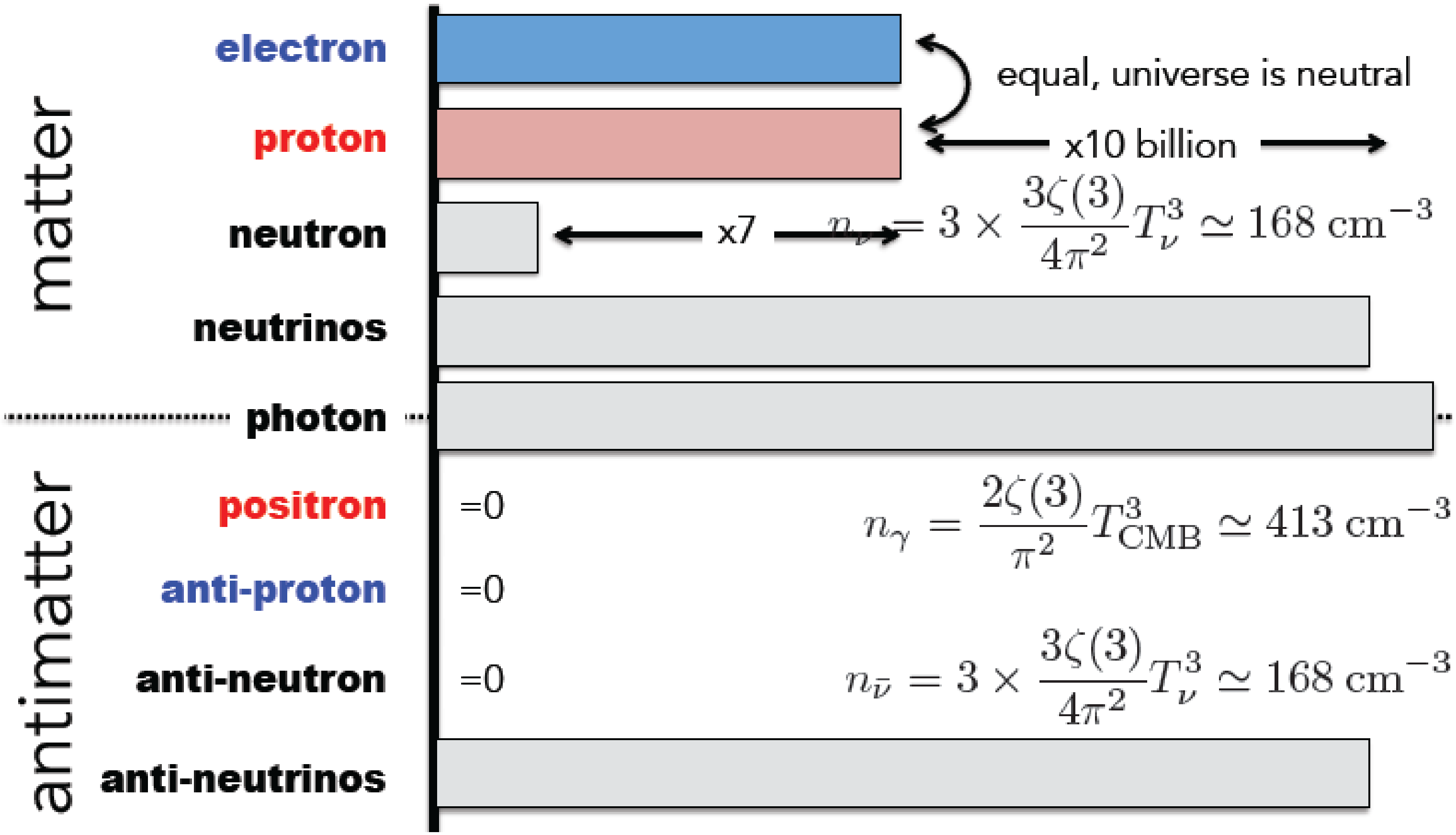
Out of S. Okubo's effect
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ
И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

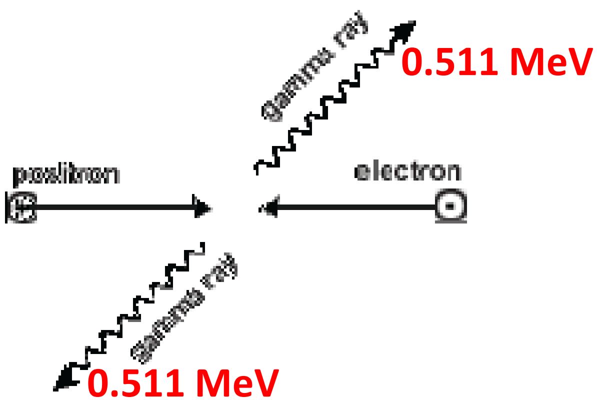
CP violation ("S. Okubo's effect") is a necessary condition for explaining why the current Universe is all matter, & not equal amounts of matter and antimatter.

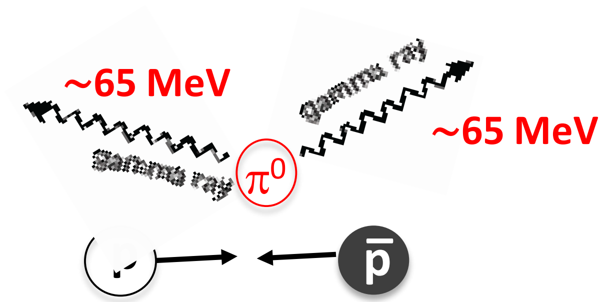
BAU: Baryon asymmetry of the Universe

The Universe is matter, and not antimatter.



How do we know that?





positrons and electrons annihilate to two ≈0.511 MeV γ's

protons and antiprotons annihilate to pions, including π^0s, which decay to two ≈65 MeV γ's

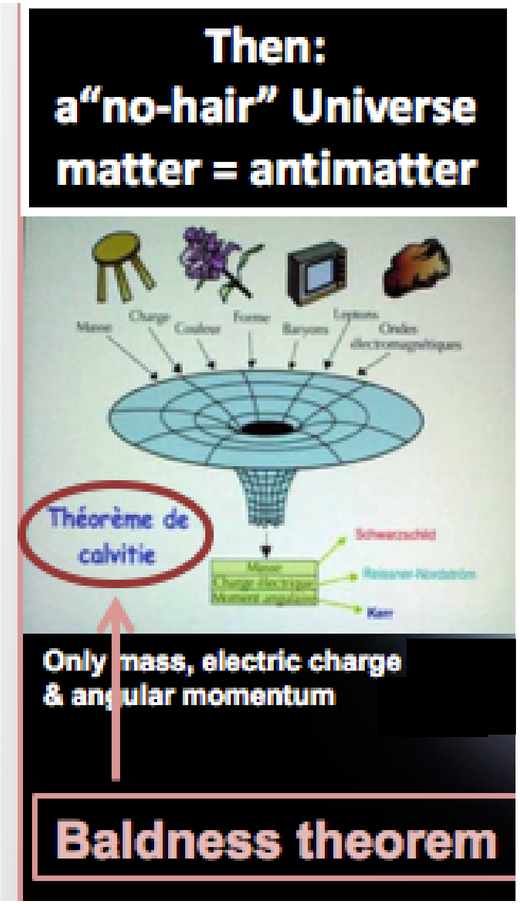
The non-observation of these gammas indicate that there are no large quantities of antimatter within a distance of $\lesssim 10^{11}$ light yrs

Steigman, Ann.Rev.Astron.Astrophys. 14 (1976) 339-372

Could the baryon excess be an initial condition?

Any initial baryon (or antibaryon) excess would have been destroyed during inflation.

Stephen Hawking's "no hair" theorem says that the initial, exploding Black Hole only had **mass, charge** and **angular momentum**

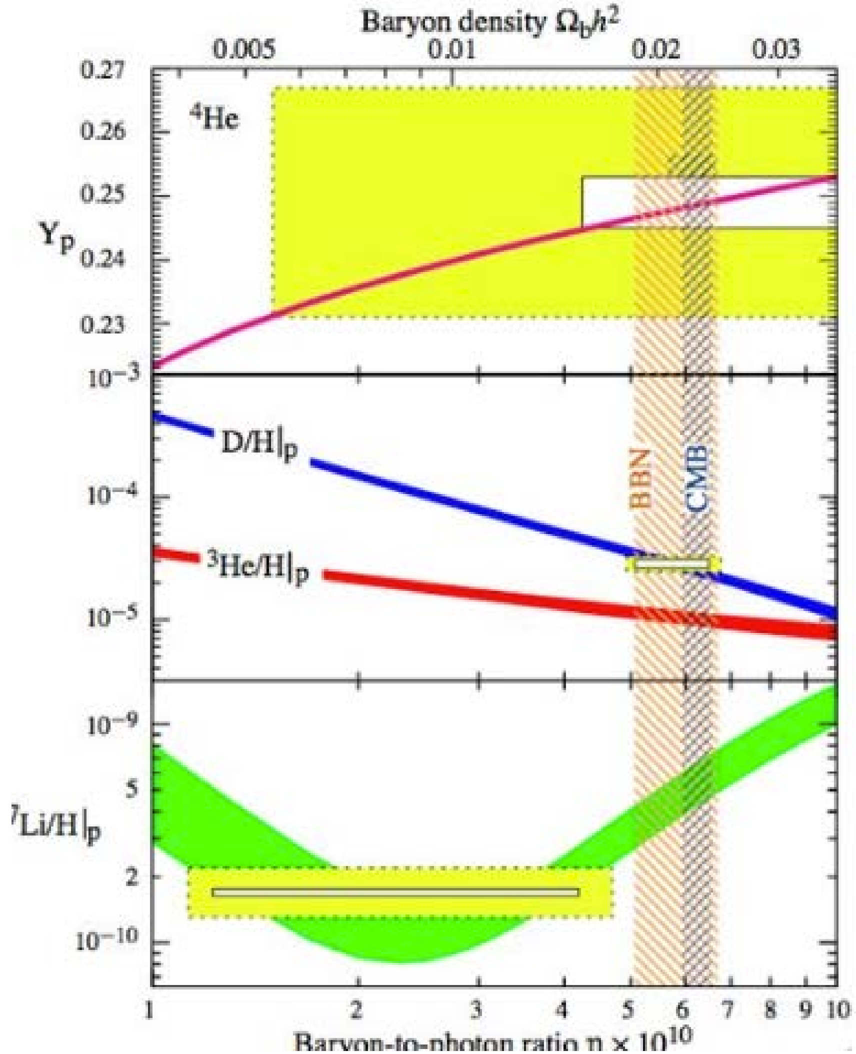


When was the baryon excess formed

nucleosynthesis models
require the matter excess
to occur for **Temp > 4.7 MeV**

Phys.Rev. D92 (2015) no.12, 123534

If the baryon excess didn't
form before **Temp≳40 MeV,**
all of the of the protons &
antiprotons would have
annihilated each other.



Sakharov’s three conditions

1) Baryon number violation

2) C violation and CP violation

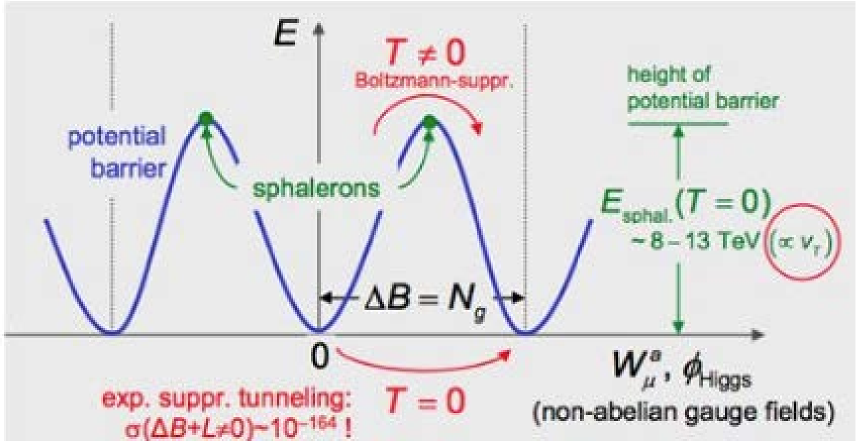
3) Deviation from thermal equilibrium

1) Baryon number violation

If we start with $N_B = N_{\bar{B}}$ & end with $N_B>0$ & $N_{\bar{B}}=0$
we obviously need a $\Delta B \neq 0$ process

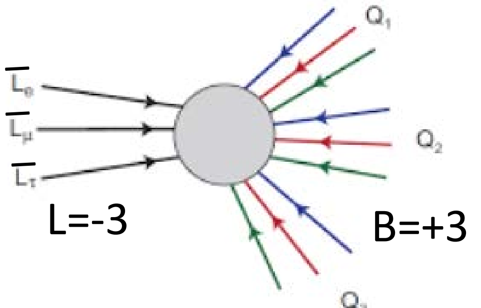
the SM theory has a $\Delta B \neq 0$ process called a Sphaleron

EW theory has different vacuum states separated by potential barriers $E_{sphaleron}$~10TeV



for energies $E<E_{spaleron}$, transitions between different vacua are unmeasurably small

for energies $E>E_{spaleron}$, transitions between adjacent vacua that violate Lepton & Baryon number, but conserve B-L can occur.
For example $\bar{L}\,\bar{L}\,\bar{L} \rightarrow$ qqq qqq qqq

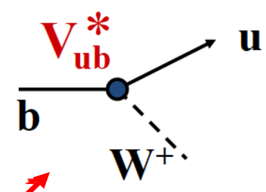


a quark has B=1/3rd

only ΔL=3 or ΔB=3 transitions occur

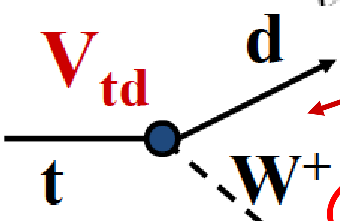
2) C violation and CP violation

as discussed at length in this class, the SM has a well documented CPV mechanism

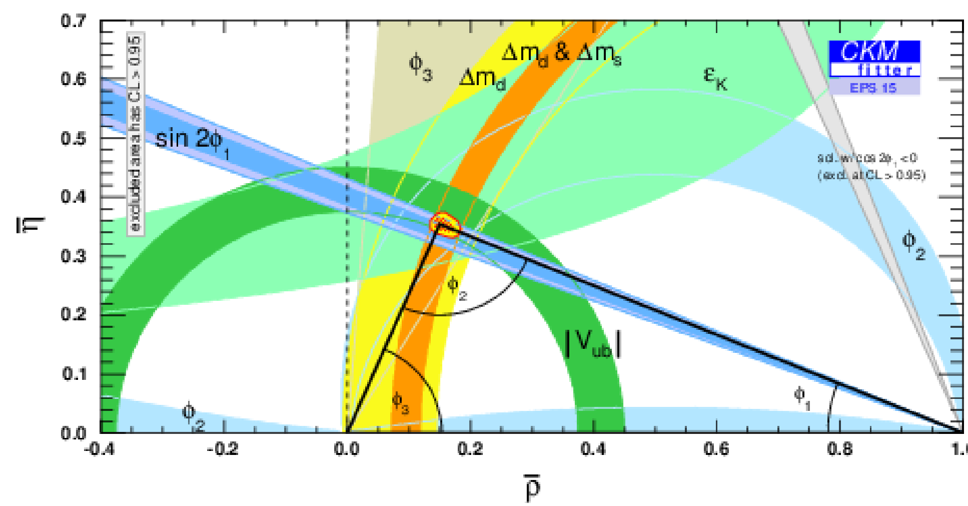


$\phi_3\ (\gamma)$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ \lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$

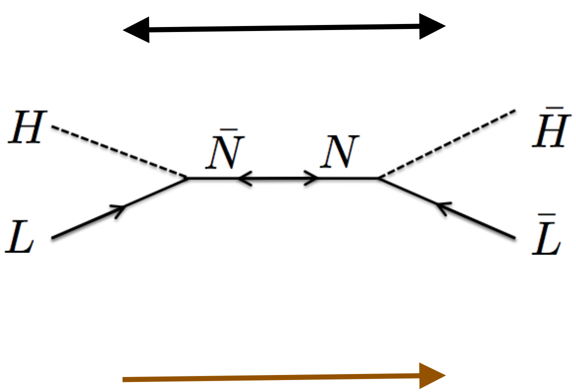


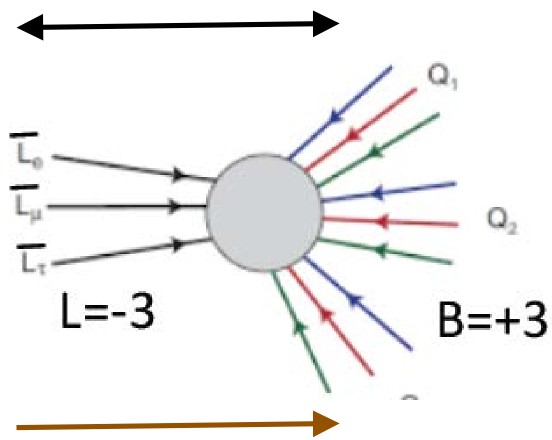
$\phi_1\ (\beta)$



3) Deviation from thermal equilibrium

For high temperatures, $\Delta B \neq 0$ and CPV processes can proceed in both directions with the net effect of "washing out" any asymmetry that might exist.





-- need to be able to distinguish "the arrow of time" --

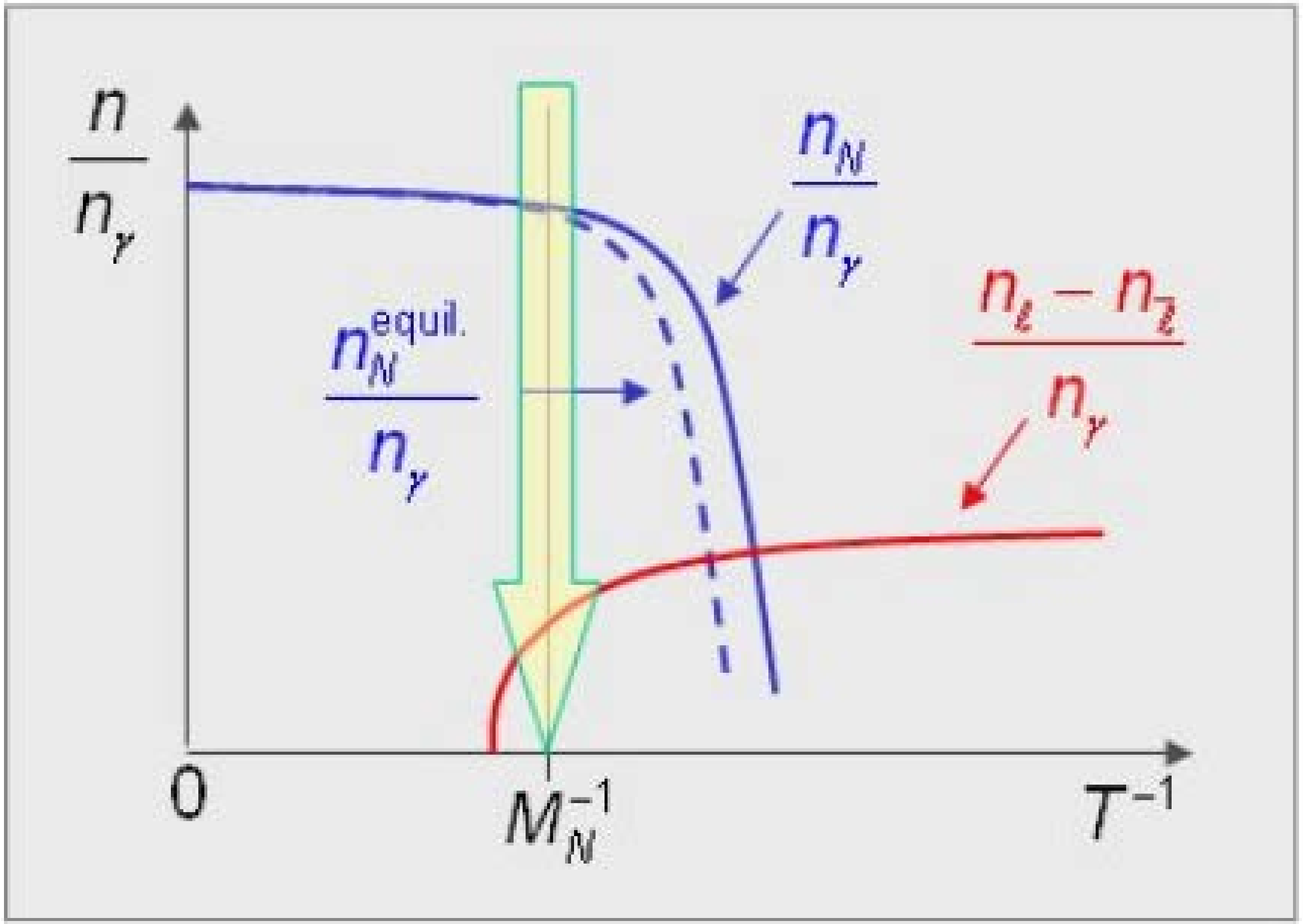
For the early universe, a process is in thermal equilibrium has a rate (i.e., Γ) that is faster than the Hubble expansion:

$$\Gamma_H = 1.8\frac{T^2}{m_{Pl}} \approx 2\left(\frac{T}{10^{12}\mathrm{GeV}}\right)^2 \times 10^4\,\mathrm{GeV}$$

$$m_{Pl} = 1.22\times 10^{19}\,\mathrm{GeV} \Leftarrow \text{Planck mass} = \sqrt{\frac{\hbar c}{G_N}}$$

What can cause non-equilibrium?

Long lifetime ($\Gamma \lesssim \Gamma_H$) or a mass threshold



Does the KM 6-quark model do this?

Baryon asymmetry of the Universe: $\left.\frac{n_{\mathcal{B}}}{n_\gamma}\right|_{\mathrm{WMAP}} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$ WMAP

Expectation from KM 6-quark model: $\left.\frac{n_{\mathcal{B}}}{n_\gamma}\right|_{SM} \approx 10^{-20}$

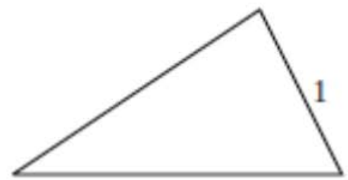
too small by
10 orders-of-mag!!

Additional source of CPV is required:

-neutrinos?
-new physics?

Why doesn't the SM CPV work?

Unitarity relations give different shaped triangles

12	$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$	$\epsilon + \epsilon + \epsilon^5 = 0$	 $\varepsilon^4 \simeq 0.002$
23	$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$	$\epsilon^4 + \epsilon^2 + \epsilon^2 = 0$	 $\varepsilon^2 \simeq 0.05$
13	$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$	$\epsilon^3 + \epsilon^3 + \epsilon^3 = 0$	

All the triangles have the same area

$$A = \tfrac{1}{2}\,\mathrm{Im}\left[V_{ud}V_{tb}V_{ub}^*V_{td}^*\right] = \tfrac{1}{2}J$$

$$J = \text{"Jarlskog Invariant"}$$

$$J_{CKM} = A^2\lambda^6(1-\lambda^2)\eta \approx 3.2\times 10^{-5}$$

J_{CKM} characterizes the size of all CPV asymmetries in the CKM model

SM CPV is too small

$$A_{CKM} \sim \frac{J_{CKM}\tilde{F}_U \tilde{F}_D}{T^{12}}$$

$$\tilde{F}_U = \left(m_t^2 - m_c^2\right) \times \left(m_t^2 - m_u^2\right) \times \left(m_c^2 - m_u^2\right)$$ ~1.5x10^9 GeV^6

$$\tilde{F}_D = \left(m_b^2 - m_s^2\right) \times \left(m_b^2 - m_d^2\right) \times \left(m_s^2 - m_d^2\right)$$ ~6 GeV^6

$$A_{CKM} \sim \frac{J_{CKM}\tilde{F}_U \tilde{F}_D}{T^{12}} \approx \frac{3\times 10^{-5} \times 10^{10}\,\mathrm{GeV}^{12}}{(100\ \mathrm{GeV})^{12}} = 3\times 10^{-19} \ll \frac{\eta_B}{\eta_\gamma} \approx 5\times 10^{-10}$$

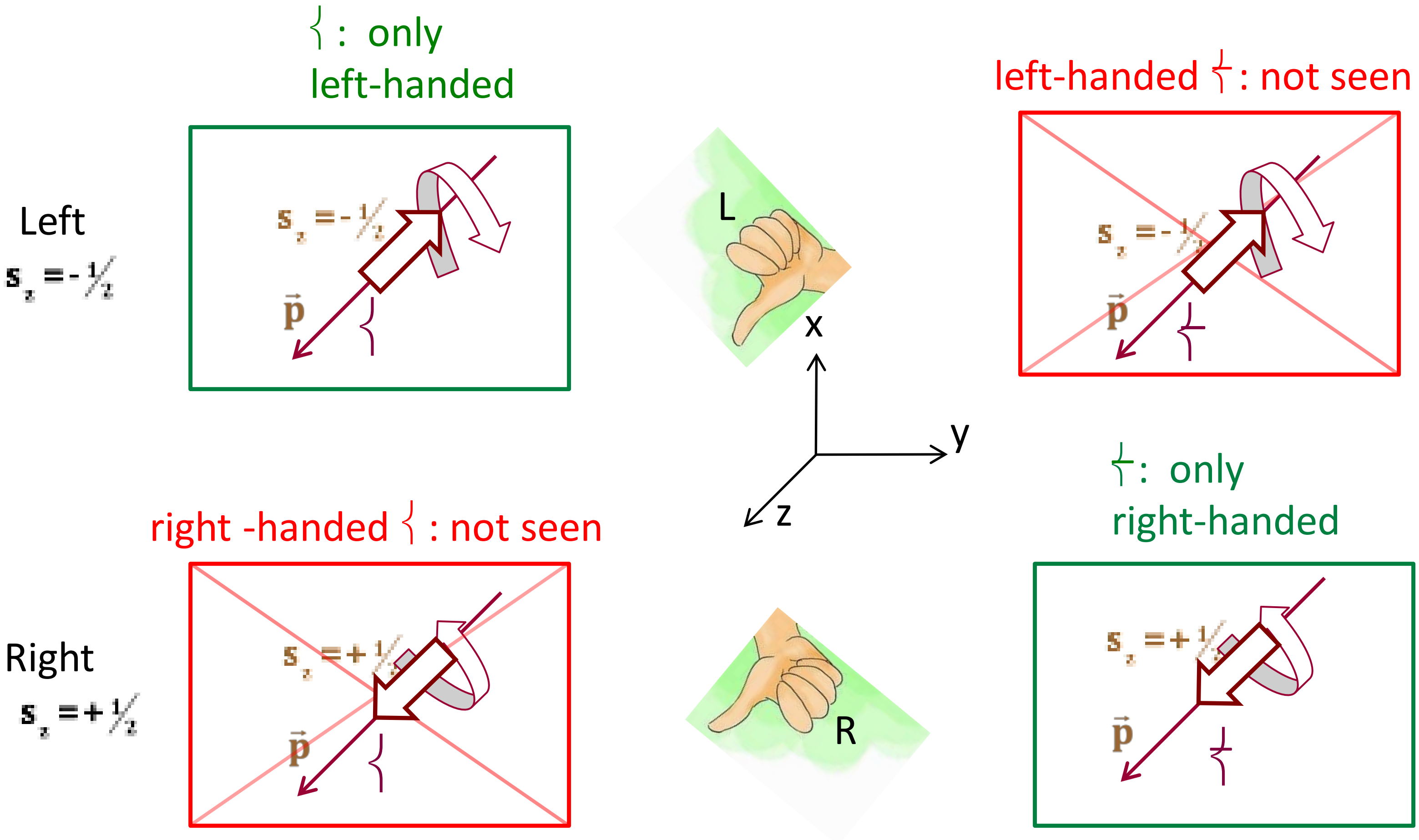
need something else

What about neutrinos?

What do we know about neutrinos?

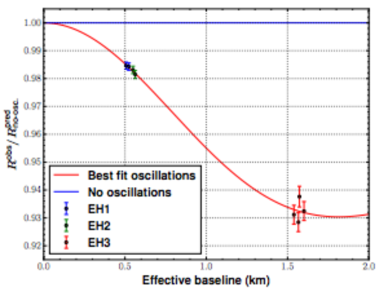
neutrinos are left-handed

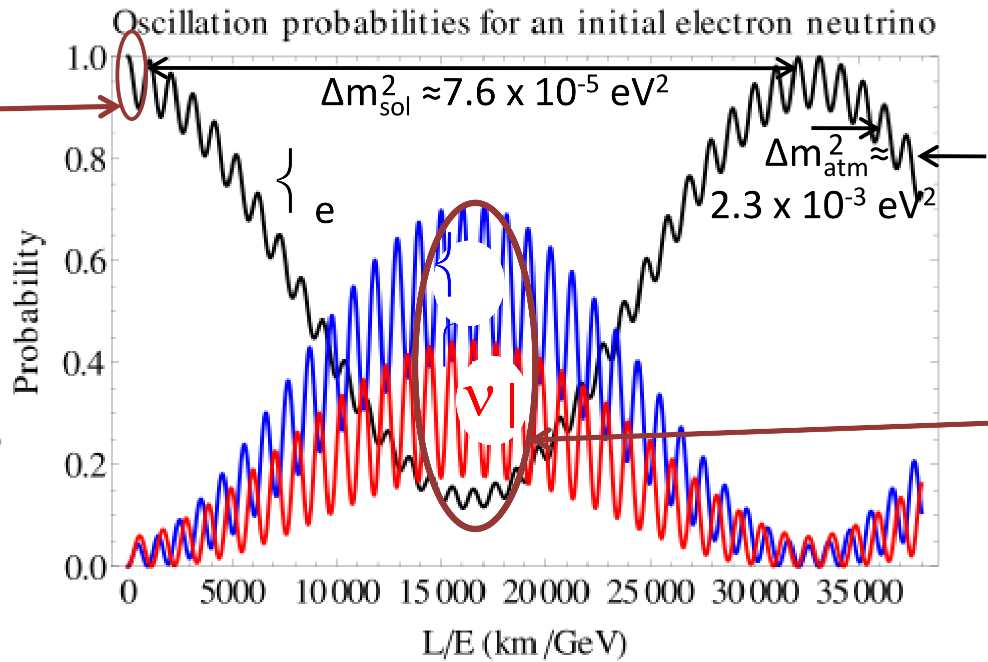
antineutrinos are right-handed



Neutrinos oscillate → they have mass

Daya Bay measured this region





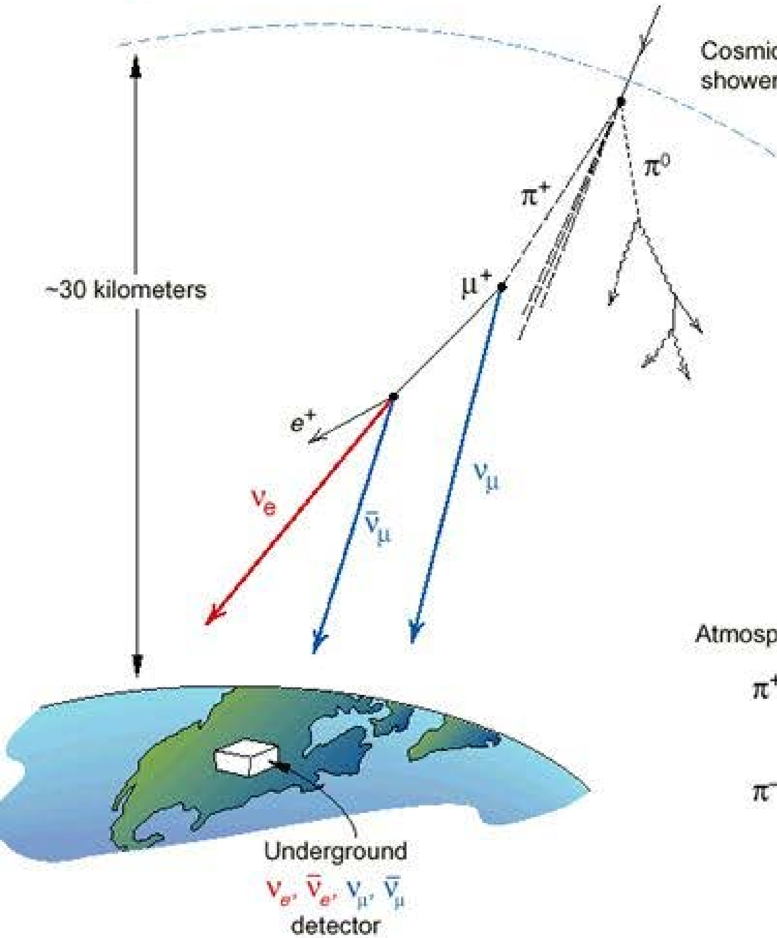
Juno will measure this region

So far we only know Δm^2 values, no absolute mass values.

~10^{-6} m_e

Cosmological measurements: $m_\nu < 0.7$ eV (95% confidence level)

Atmospheric Neutrinos

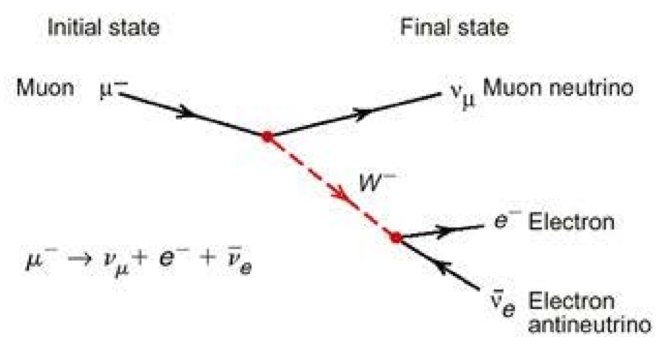


Weak decays are sources of neutrinos:

- □, K mesons decay on the way to Earth
- some muons also decay but many reach the surface (m_μ=106 MeV; cτ=659 m)

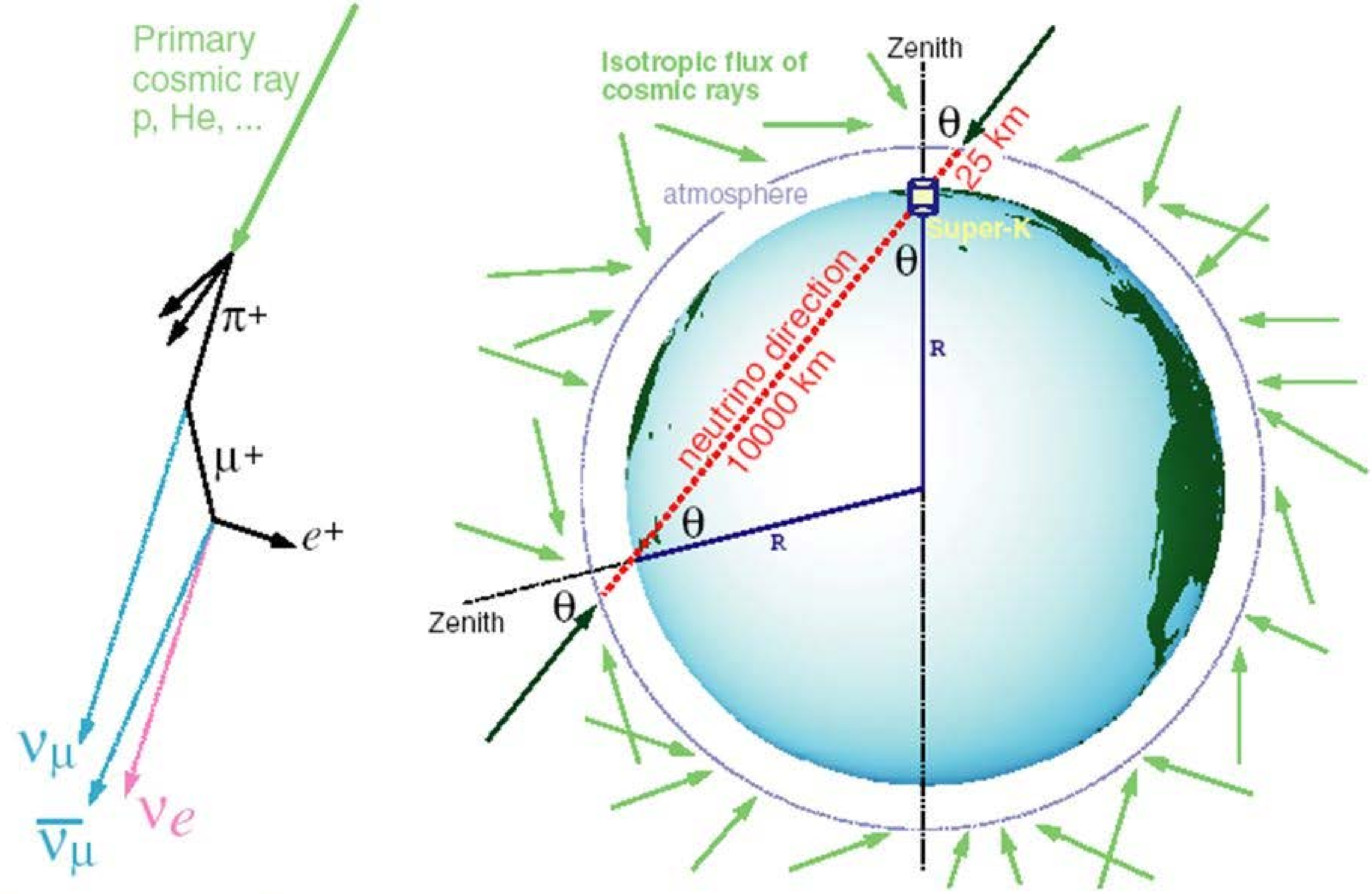
Atmospheric neutrino source

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



$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

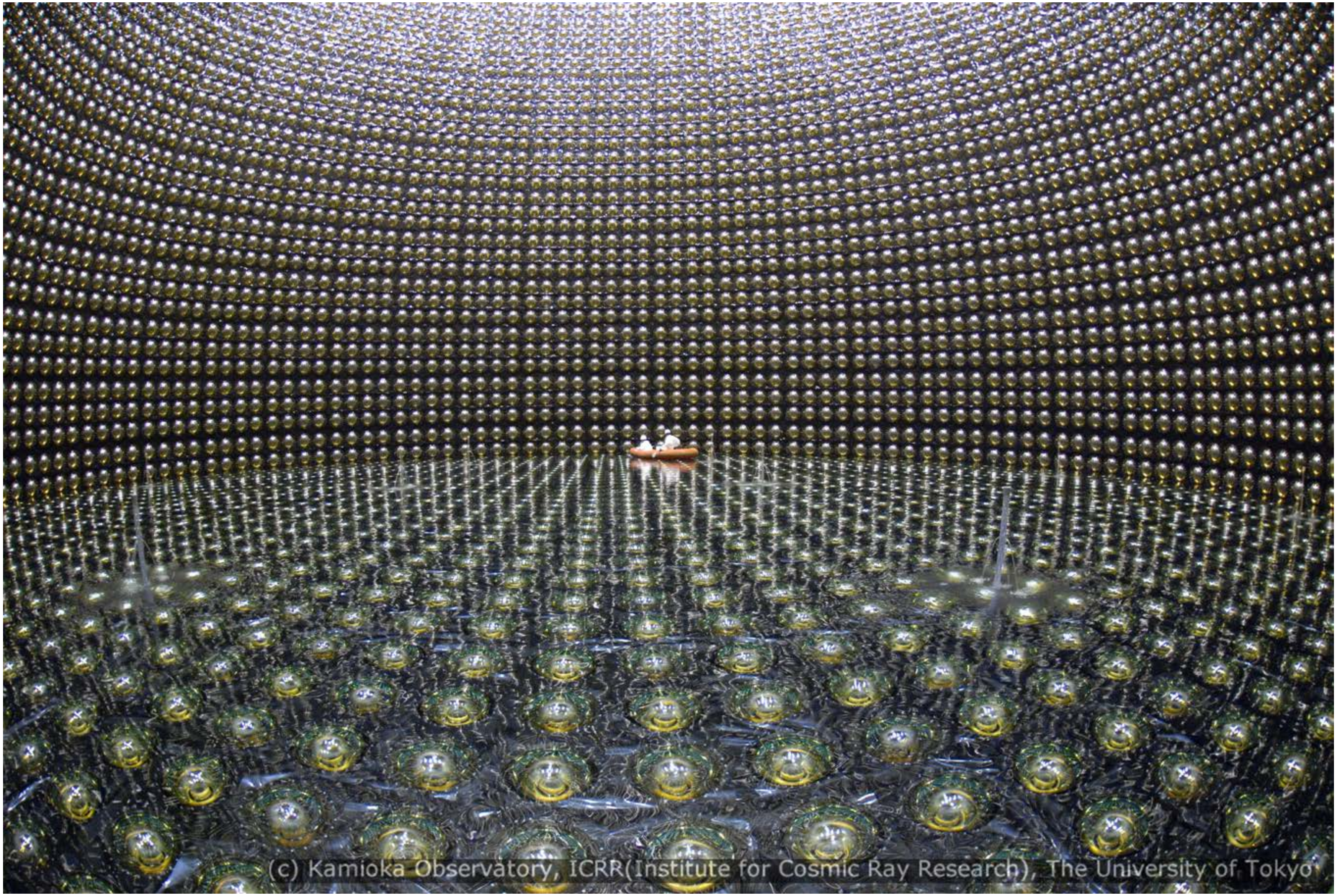
They come from all directions



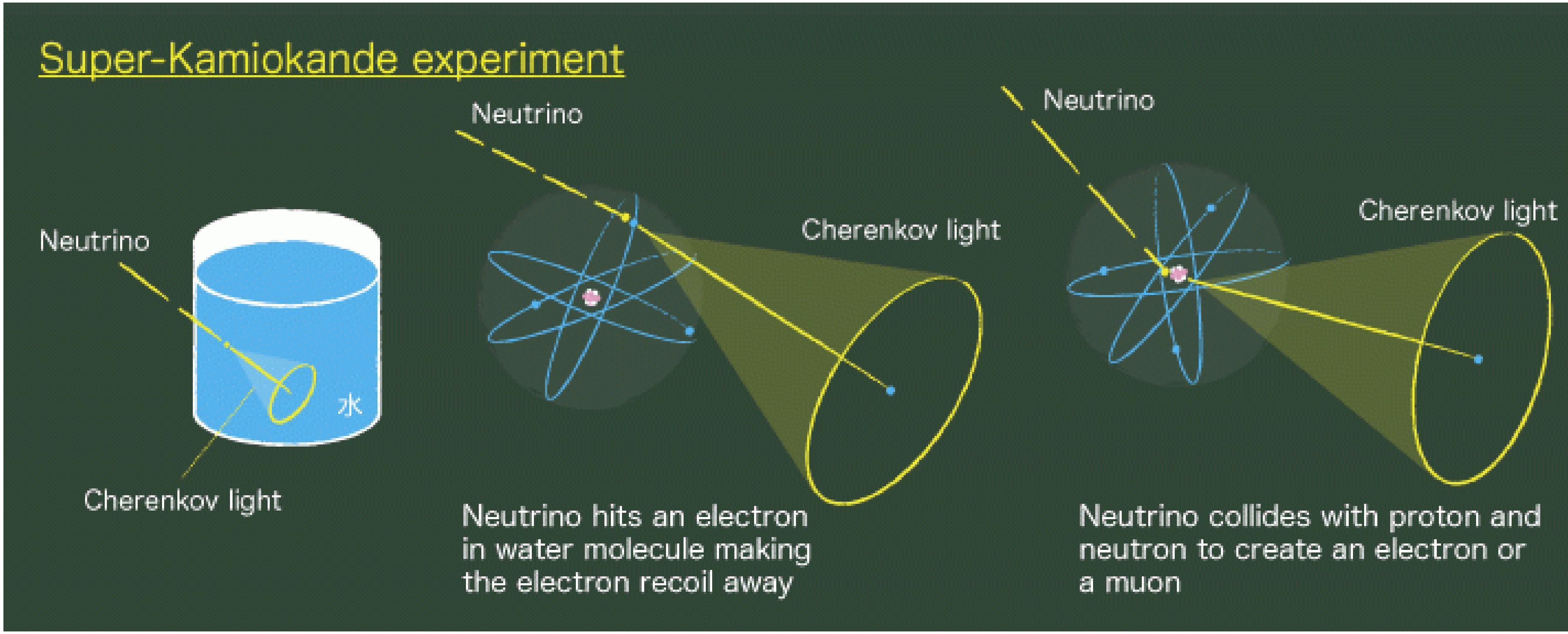
Ratio of $\nu_\mu/\nu_e \sim 2$

Up/Down Symmetric Flux

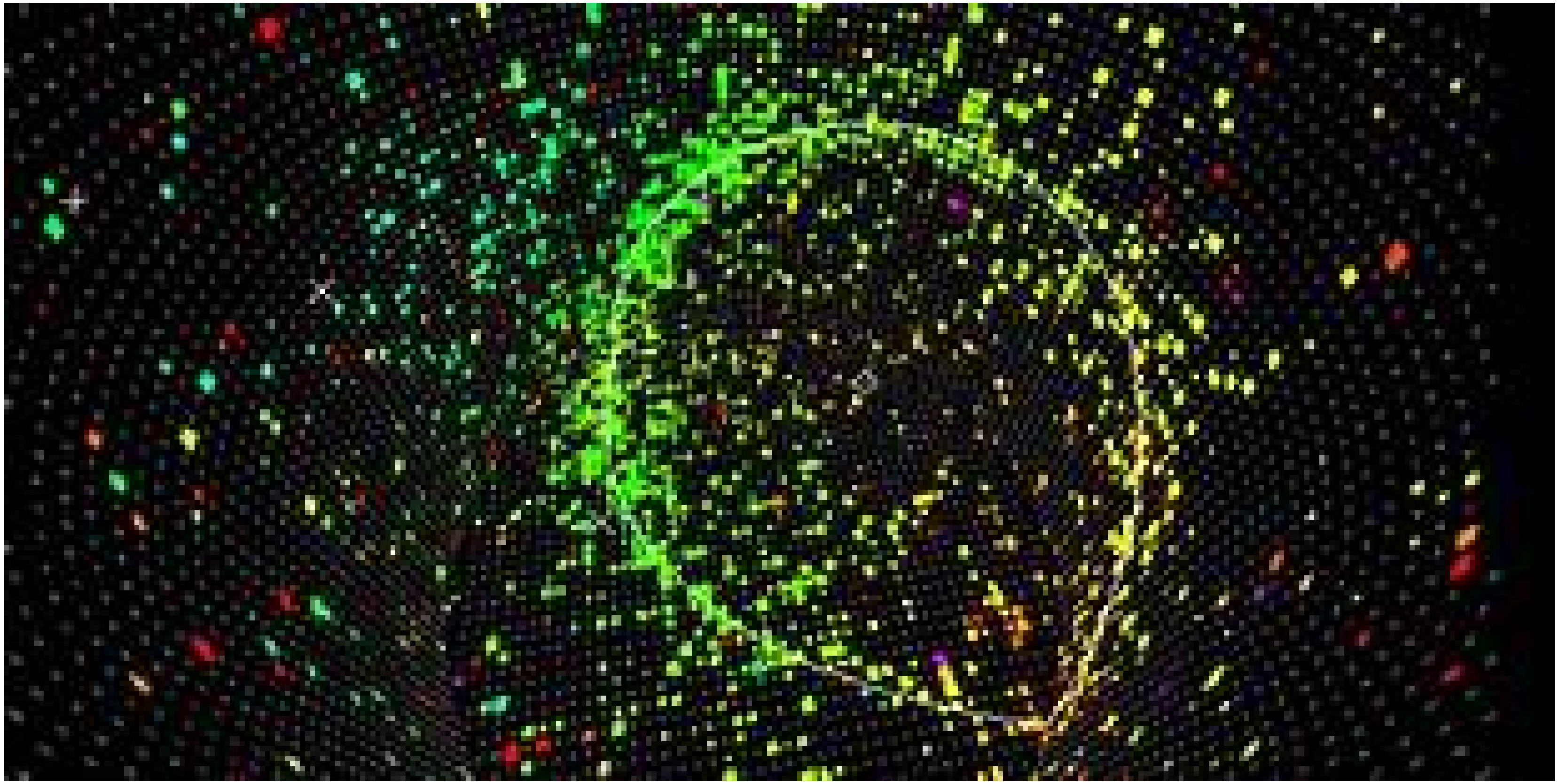
The Super Kamiokande H_2O detector



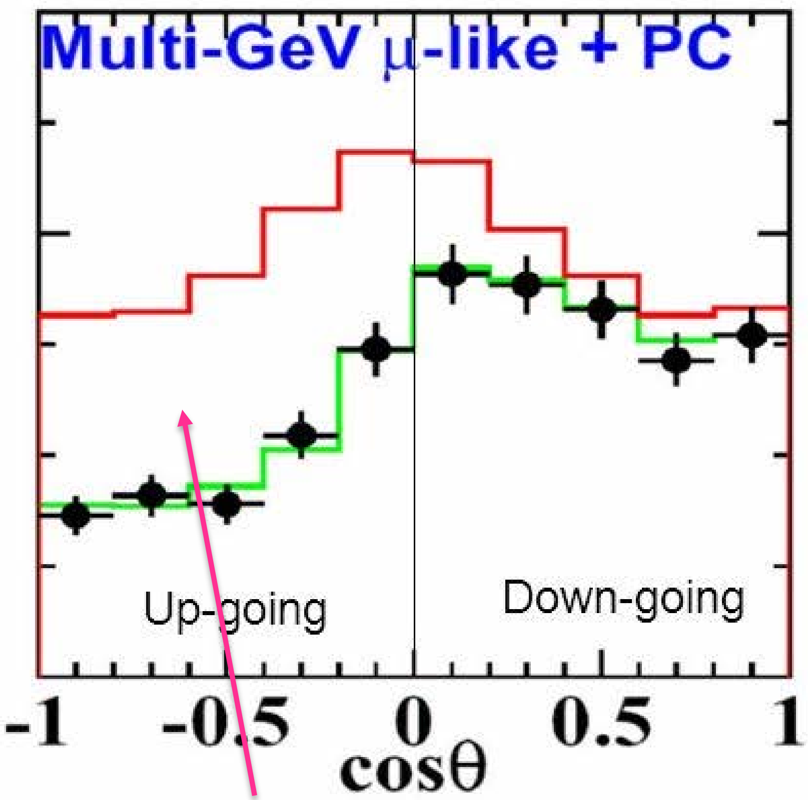
principle of detection



atmospheric neutrino event in Super-K



Discovery of neutrino oscillation
Super-Kamiokande (1998)

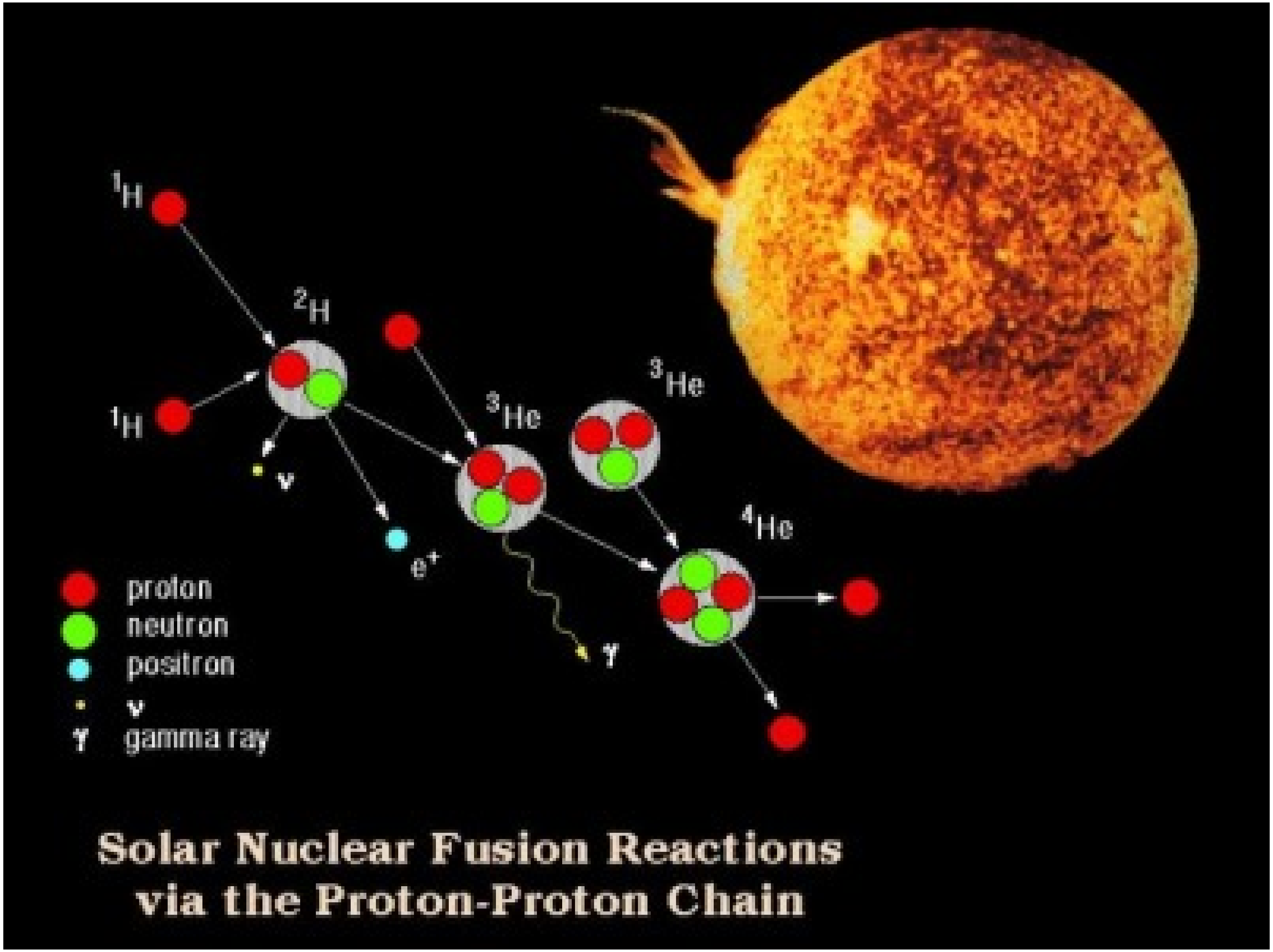


2002 Nobel Prize
Koshiba
(superK Spokesman)
shared with Davis

Half of the ν_μ are lost!
Oscillated to undetected ν_τ

oscillation frequency:
$\Delta m^2_{atm} \approx 2.3 \times 10^{-3}$ eV^2

Solar neutrinos



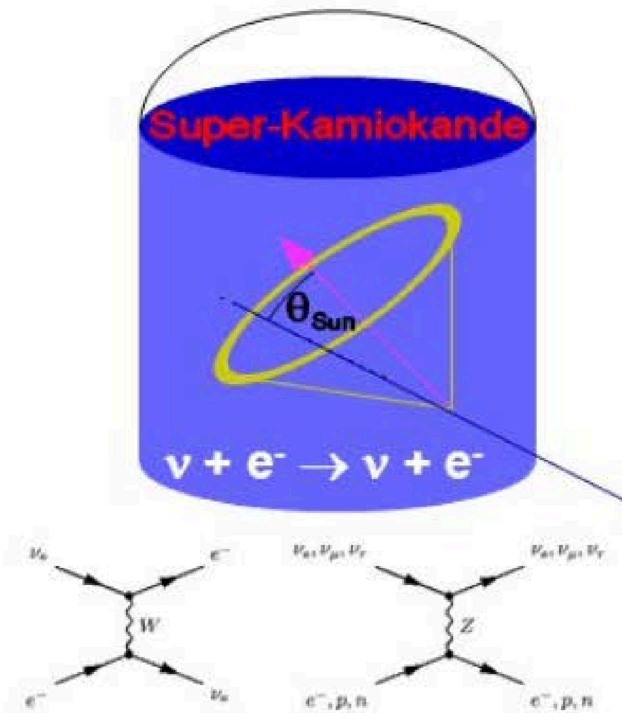
R. Davis: measuring the solar neutrino flux in a gold mine in South Dakota for 30 years (1969-1999)

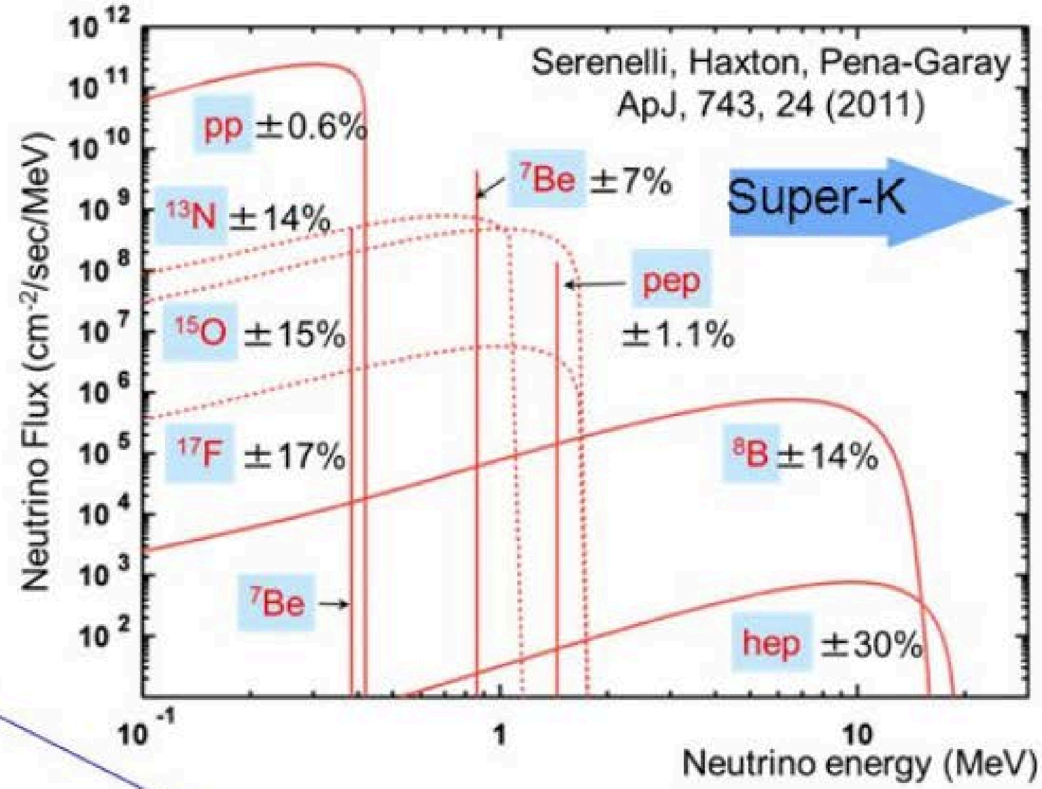
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

${}^{37}Ar$: $T_{1/2}$=35 days

R. Davis
Solar neutrinos pioneer

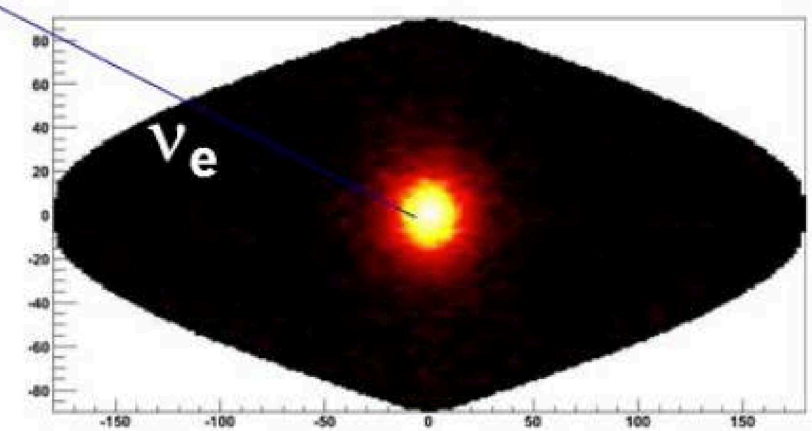
…and observing only 1/3 of the expected flux!! Why?



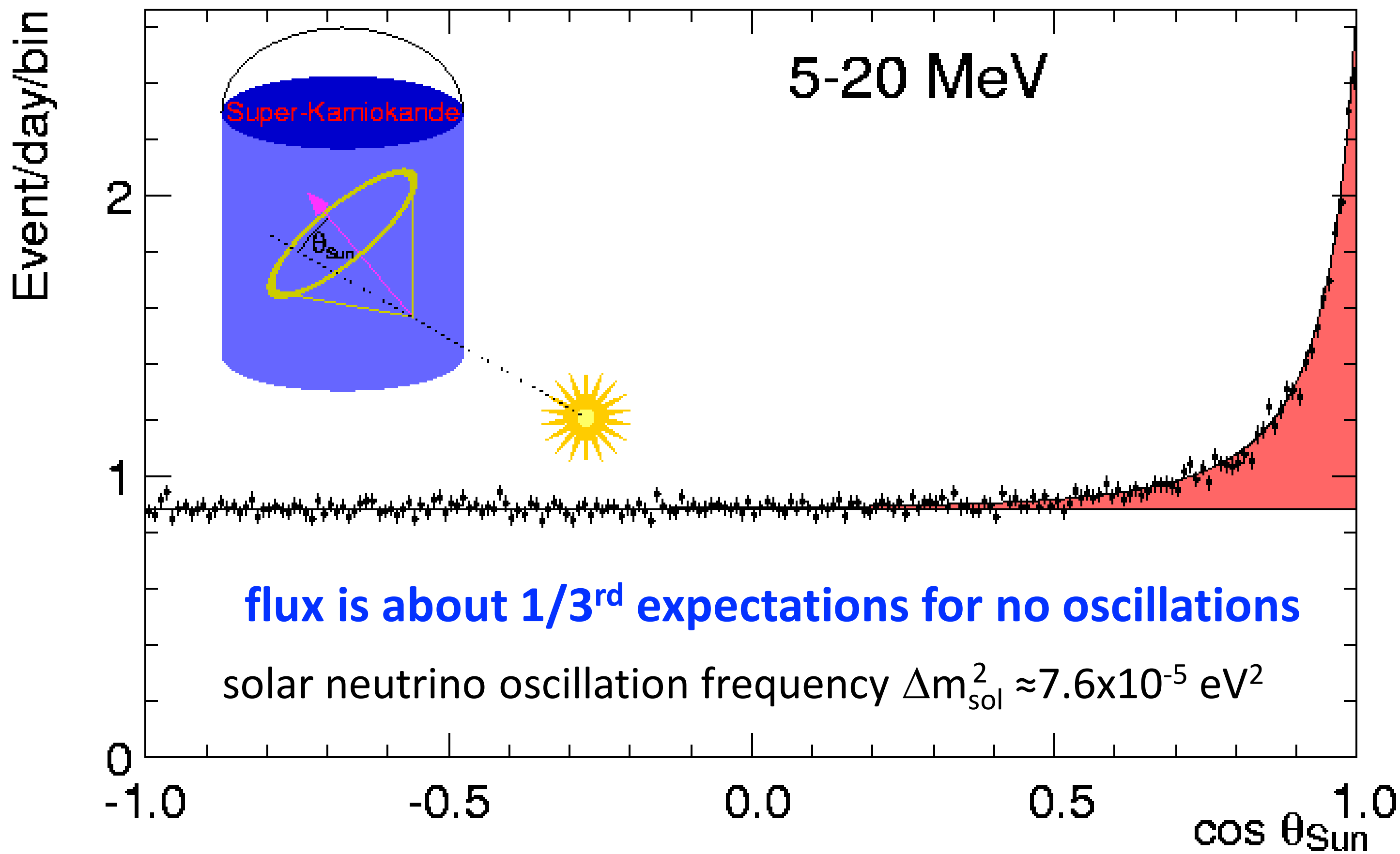


Solar neutrinos observation

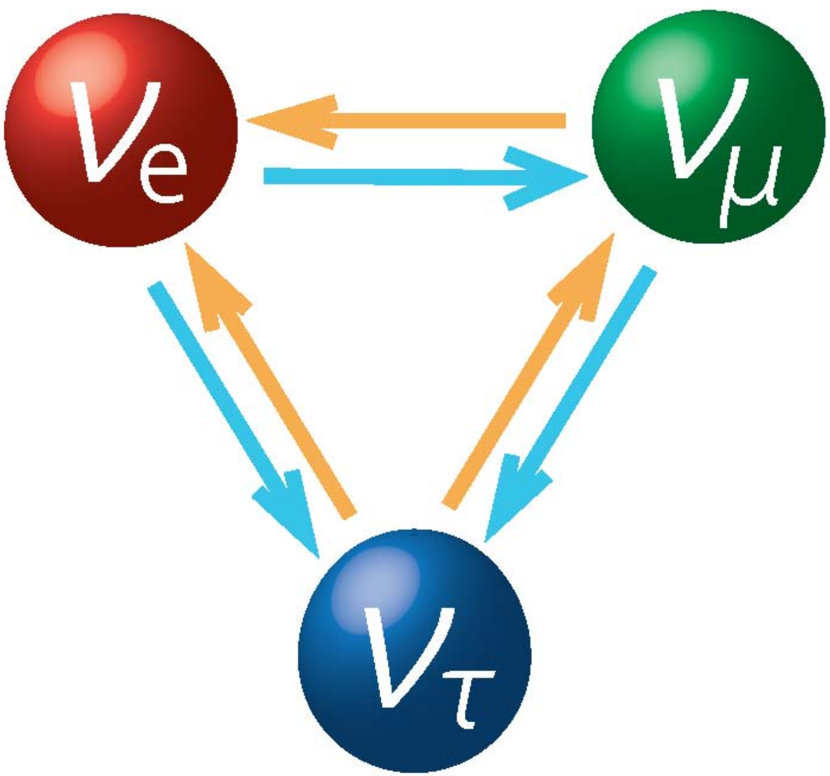
in Super-K

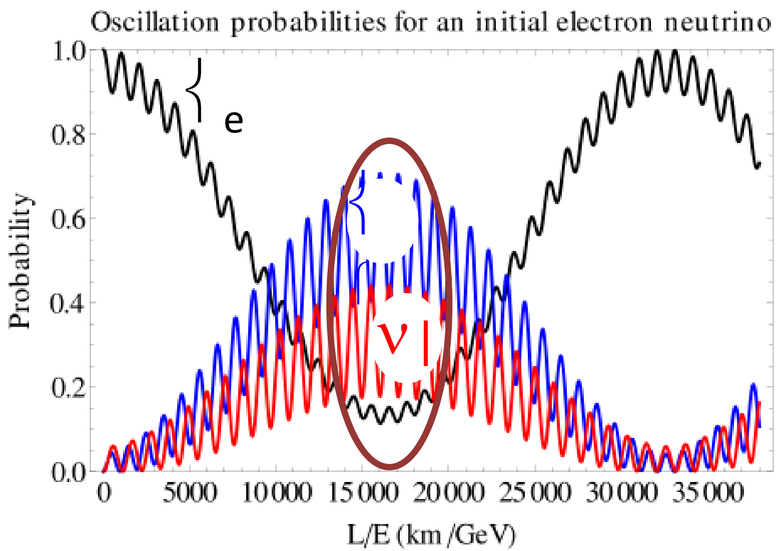


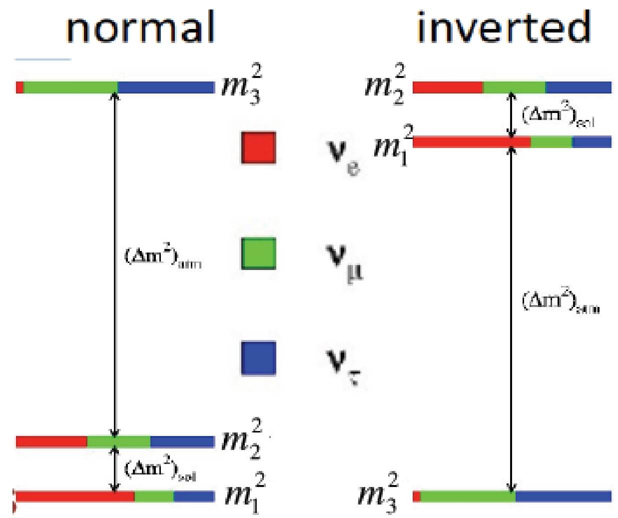
Super-K solar neutrino signal



neutrinos oscillate





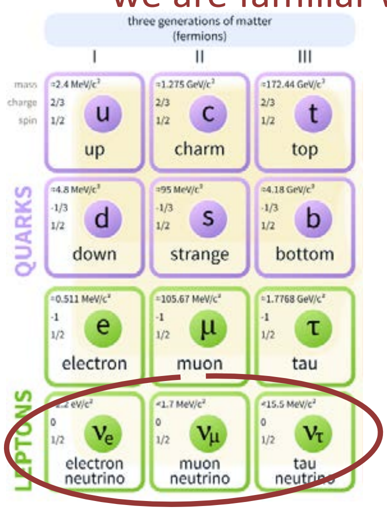


ν flavor-eigenstates and mass-eigenstates

flavor eigenstates | mass eigenstates

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

These are the ν's that we are familiar with



$$^{14}C \rightarrow {}^{14}N\, e^- \,\overline{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$D_s^+ \rightarrow \tau^+ \nu_\tau$$

flavor eigenstates

These ν's have well defined masses and frequencies

$$|\nu_1(t)\rangle = |\nu_1(0)\rangle e^{-im_1 t}$$

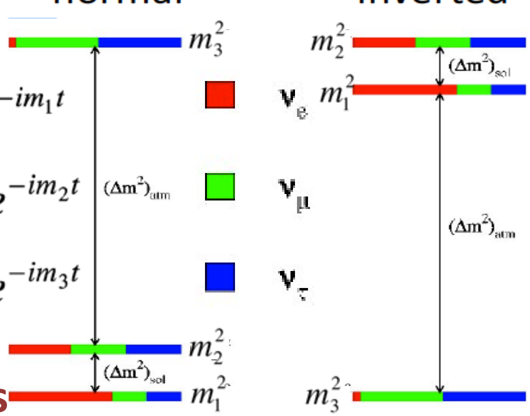
$$|\nu_2(t)\rangle = |\nu_2(0)\rangle e^{-im_2 t}$$

$$|\nu_3(t)\rangle = |\nu_3(0)\rangle e^{-im_3 t}$$

mass eigenstates

ν_e heaviest

normal | inverted



ν_e lightest

Neutrino masses are special

Hermitian conjugate

The free field-Dirac Lagrangian: $\mathcal{L} = i\overline{\Psi}\gamma^{\mu}\partial_{\mu}\Psi - m\overline{\Psi}\Psi$, where $\overline{\Psi} = \Psi^{t}\gamma^{0}$.

Here, $m\overline{\Psi}\Psi$ is the term that gives Dirac particles their masses.

Rewrite Ψ in left- and right-handed components:

Left-handed proj. oper. Right-handed proj. oper.

$$\Psi = \tfrac{1}{2}\left(\left(1+\gamma^{5}\right)\Psi + \left(1-\gamma^{5}\right)\Psi\right) = \psi_{L} + \psi_{R}$$

$$\gamma^{5} = \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

Since $\gamma^{5}\gamma^{0} = -\gamma^{0}\gamma^{5}$ & $\gamma^{5}\gamma^{5} = 1$, it is easy to show that:

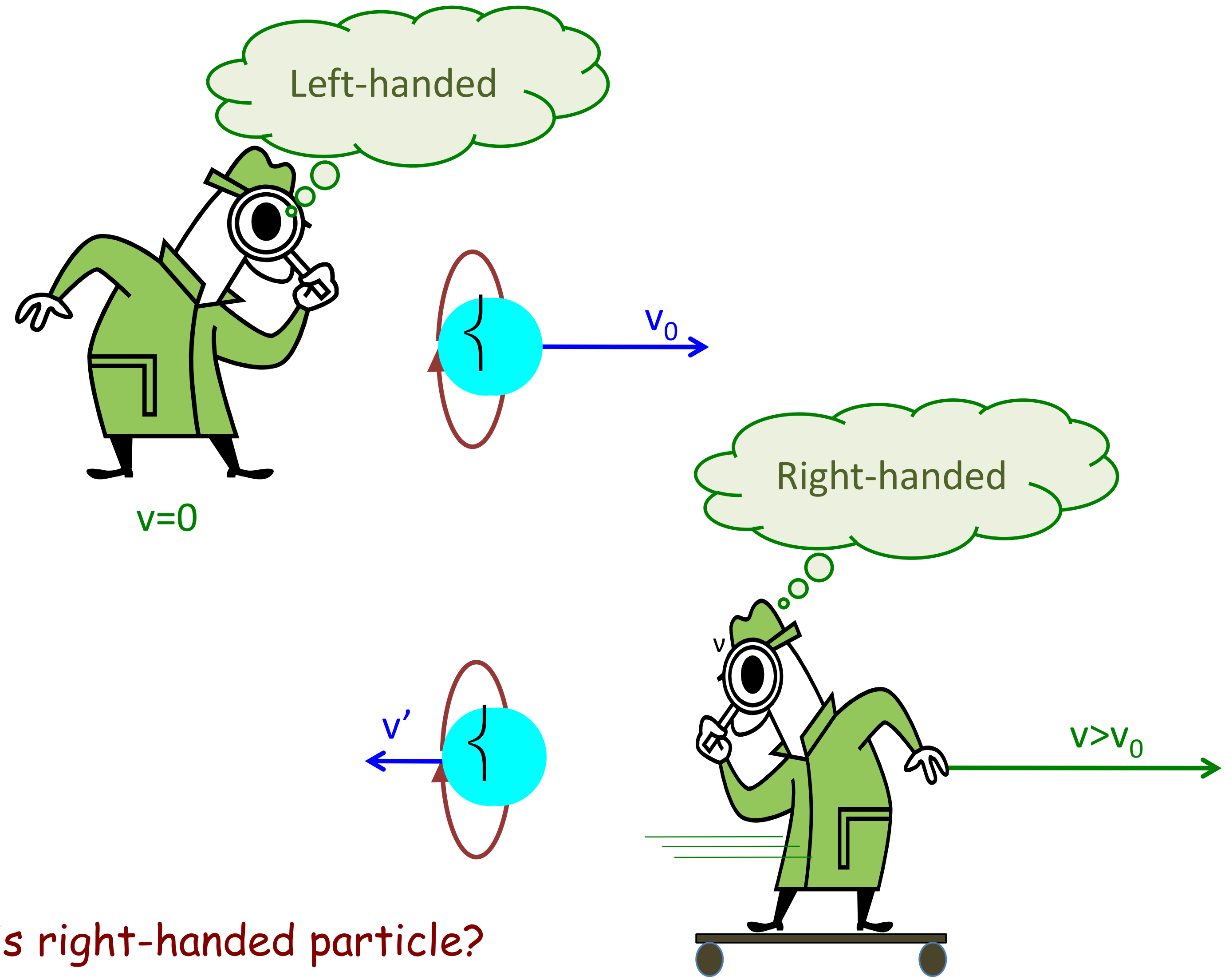
$$m\overline{\Psi}\Psi = m\left(\overline{\psi}_{R}\psi_{L} + \overline{\psi}_{L}\psi_{R}\right)$$

a Dirac fermion *must* have both right- & left-handed components to have mass

Since neutrinos have non-zero mass, there *must be* right-handed neutrinos.

-- so far, experiments only see left-handed neutrinos --

if $m_\nu \neq 0$, right-handed neutrinos must exist



What is this right-handed particle?

Neutrino masses are special

hermitian conjugate

The free field-Dirac Lagrangian: $\mathcal{L} = i\overline{\Psi}\gamma^{\mu}\partial_{\mu}\Psi - m\overline{\Psi}\Psi$, where $\overline{\Psi} = \Psi^{\dagger}\gamma^{0}$.

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Left-handed proj. oper. Right-handed proj. oper.

Rewrite Ψ in left- and right-handed components: $\Psi = \frac{1}{2}\left(\left(1+\gamma^{5}\right)\Psi + \left(1-\gamma^{5}\right)\Psi\right) = \psi_L + \psi_R$

$$\gamma^{5} = \begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

Since $\gamma^{5}\gamma^{0} = -\gamma^{0}\gamma^{5}$ & $\gamma^{5}\gamma^{5} = 1$, it is easy to show that:

$$m\overline{\Psi}\Psi = m\left(\overline{\psi}_R\psi_L + \overline{\psi}_L\psi_R\right)$$

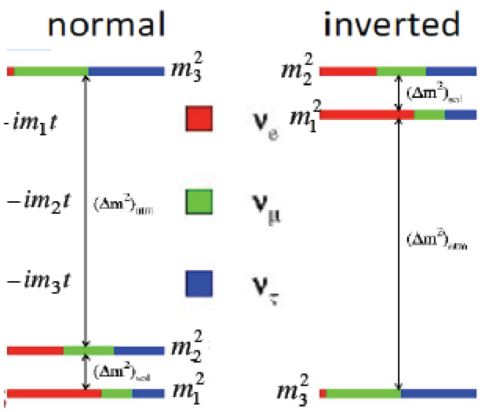
a Dirac fermion *must* have both right- & left-handed components to have mass

Since neutrinos have non-zero mass, there *must be* right-handed neutrinos.

-- so far, experiments only see left-handed neutrinos --

What we don't know about neutrinos

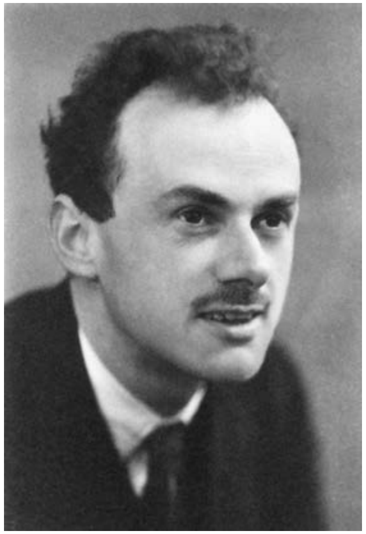
-- What is the mass hierarchy and absolute scale?



-- Are ν's "Dirac" or "Majorana" particles?

-- Do neutrinos violate CP symmetry?

4-component Dirac neutrinos



P.A.M. Dirac
1902-1984

left-handed neutrino

$$\psi_L = \sqrt{E+m}\begin{bmatrix} 0 \\ 1 \\ \frac{p_1 - ip_2}{E+m} \\ \frac{-p_3}{E+m} \end{bmatrix}$$

left-handed antineutrino

$$\bar{\psi}_L = \sqrt{E+m}\begin{bmatrix} \frac{p_1 - ip_2}{E+m} \\ \frac{-p_3}{E+m} \\ 0 \\ 1 \end{bmatrix}$$

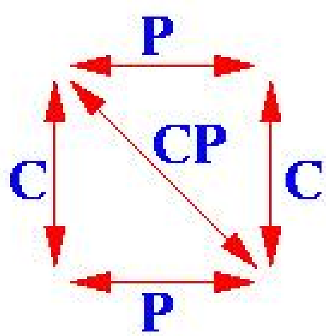
right-handed neutrino

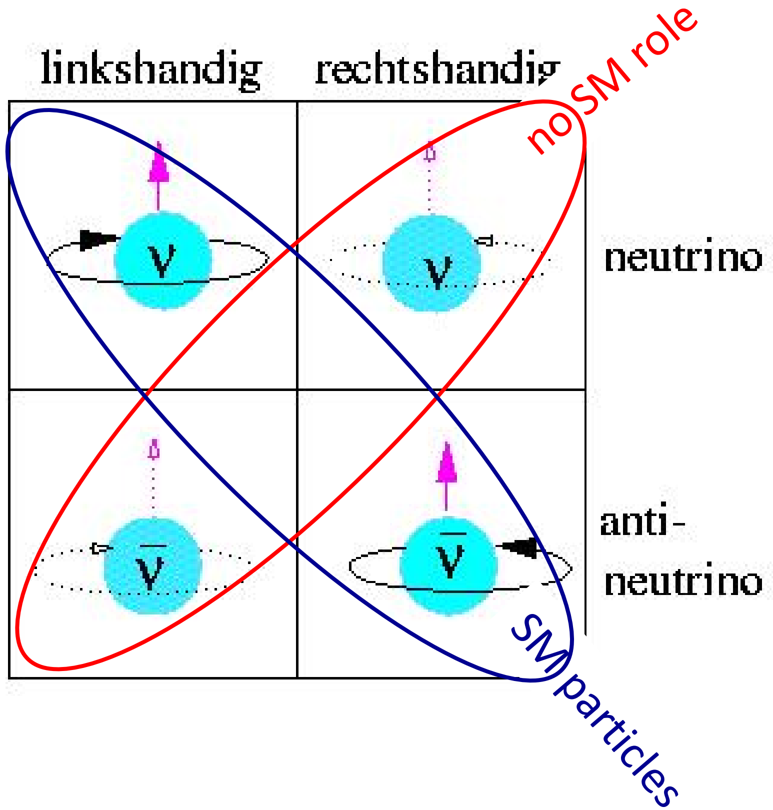
$$\psi_R = \sqrt{E+m}\begin{bmatrix} 1 \\ 0 \\ \frac{p_3}{E+m} \\ \frac{p_1 + ip_2}{E+m} \end{bmatrix}$$

right-handed antineutrino

$$\bar{\psi}_R = \sqrt{E+m}\begin{bmatrix} \frac{p_3}{E+m} \\ \frac{p_1 + ip_2}{E+m} \\ 1 \\ 0 \end{bmatrix}$$

a Dirac neutrino?





Majorana neutrinos?

Ettore Majorana
1906-????
(disappeared
In 1938)

a neutrino is it's own antiparticle: $\nu^{\text{maj}} = C\nu^{\text{maj}}$

In terms of 4-comp, Dirac spinors, *a* Majorana neutrino is:

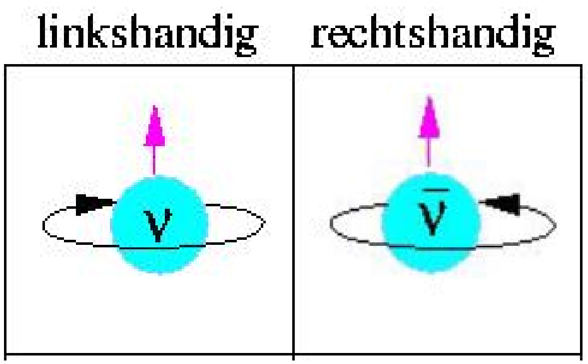
$$\nu^{\text{maj}} = \tfrac{1}{\sqrt{2}}(\psi_L + (\psi_L)^C = \bar{\psi}_R \Leftarrow \text{right-handed antineutrino}$$

$$= \psi_L + C\psi_L = \psi_L + \gamma^2\psi_L^*$$

Majorana neutrinos are 2-dimensional spinors

Majorana neutrino?

neutrino



antineutrino

R- & L-handed Majorana neutrinos

$P_L \equiv \frac{1}{2}(1+\gamma_5)$

LH proj. Oper.

$P_R \equiv \frac{1}{2}(1-\gamma_5)$

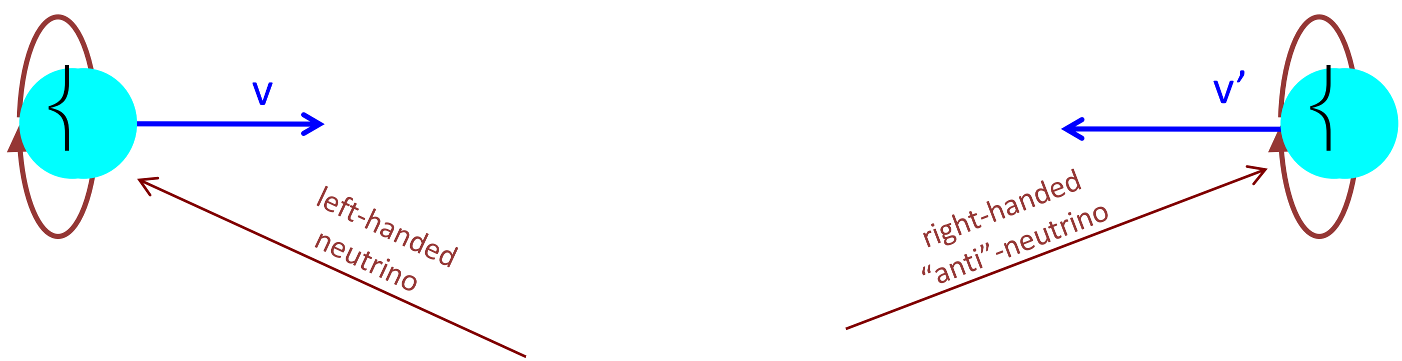
RH proj. Oper.

$$P_L \nu^{\mathrm{maj}} = \tfrac{1}{2}(1+\gamma_5)\psi_L + \tfrac{1}{2}(1+\gamma_5)\gamma_2\psi_L^* = \psi_L + \tfrac{1}{2}\gamma_2(1-\gamma_5)\psi_L^* = \psi_L$$

$P_L f_L = f_L \qquad \gamma_5\gamma_2 = -\gamma_2\gamma_5 \qquad P_R f_L^* = 0$

$$P_R \nu^{\mathrm{maj}} = \tfrac{1}{2}(1-\gamma_5)\psi_L + \tfrac{1}{2}(1-\gamma_5)\gamma_2\psi_L^* = 0 + \tfrac{1}{2}\gamma_2(1+\gamma_5)\psi_L^* = \gamma_2 P_L \psi_L^* = (\psi_L)^C$$

$P_R f_L = 0 \qquad \gamma_5\gamma_2 = -\gamma_2\gamma_5$



$$\nu^{\mathrm{maj}} = \psi_L + (\psi_L)^C$$

What happened to Ettore Majorana?

-- 80 year old, unsolved mystery --

Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Has anyone seen?

Ettore Majorana, U. of Naples physicist, mysteriously disappeared on the last day of March (1938). 31yrs old, 1.70m tall, slender, black hair, dark eyes, long scar on the back of one of his hands.
If you know something, please write to R.P.E. Marianecci, 66 Regina Margherita St, Rome.

-- Fermi's most brilliant student --

July 25-26 1938: What boat Majorana take?

lots of speculation

Scientist Majorana not kidnapped

LO SCIENZIATO MAJORANA NON FU RAPITO

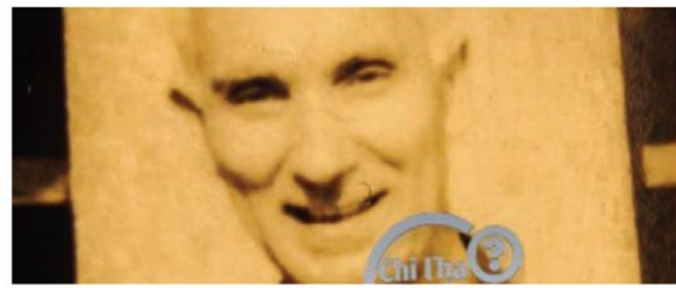
Questa è la sensazionale rivelazione del prof. Emilio Segrè, che fu il più valido collaboratore di Enrico Fermi. Per oltre vent'anni tra le ipotesi sulla scomparsa del fisico Ettore Majorana, quella del rapimento da parte di una misteriosa Potenza aveva riscosso il maggior credito

"Sei un asino"

IlFattoQuotidiano.it / Scienza

Emigrated to Venezuela?

Ettore Majorana, "the physicist alive and residing in Venezuela in the 50s"



It is the hypothesis of the Rome prosecutor on the never resolved case of the brilliant Catania physicist mysteriously disappeared in 1938. For the investigators he lived voluntarily in the Venezuelan city of Valencia

$\mathcal{CP}$V and neutrinos

Dirac neutrino mixing

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

Number of parameters:	18
Unitarity conditions:	9
6 leptons; (6-1) arb. phases:	5
# of free parameters:	4

3 Euler angles &
1 Dirac phase

Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS matrix

there is one Dirac phase:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric+LBL Daya Bay, RENO & CHOOZ solar+KamLAND

This is no more effective at generating
a BAU than the CKM phase

hierarchy of the PMNS mixing matrix

very different than that of the CKM matrix; the smallest element is U_{e3}≈0.15

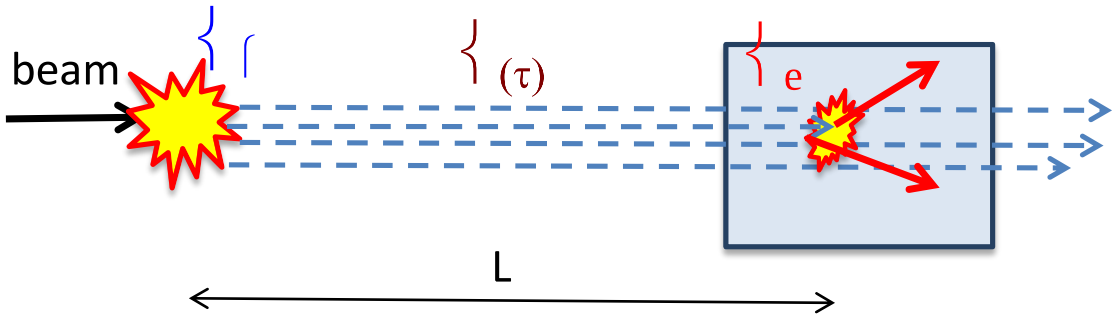
The 3 σ ranges (99.7% confidence) for the current matrix are:[9]

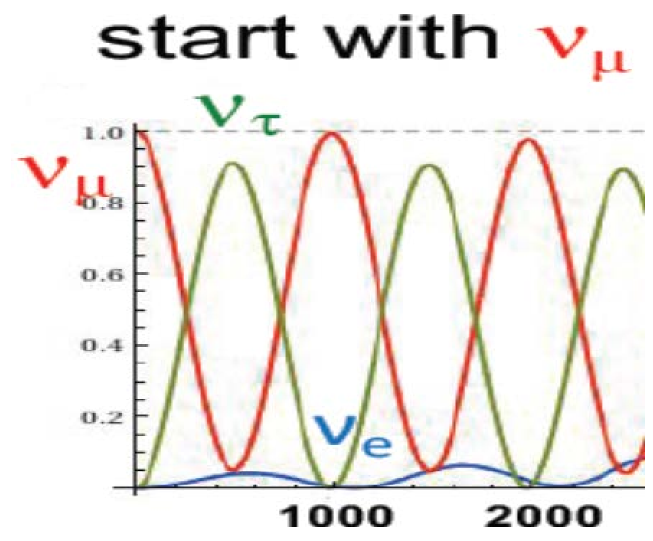
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 0.799 \ldots 0.844 & 0.516 \ldots 0.582 & 0.141 \ldots 0.156 \\ 0.242 \ldots 0.494 & 0.467 \ldots 0.678 & 0.639 \ldots 0.774 \\ 0.284 \ldots 0.521 & 0.490 \ldots 0.695 & 0.615 \ldots 0.754 \end{bmatrix}$$

for comparison:

$$V_{CKM} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

Dirac neutrino mixing





$$P_{\nu_\alpha \to \nu_\beta}(t) = \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2$$

where: $|\nu_\alpha(t)\rangle = U^D_{\alpha 1} |\nu_1\rangle e^{-im_1 t} + U^D_{\alpha 2} |\nu_2\rangle e^{-im_2 t} + U^D_{\alpha 3} |\nu_{e3}\rangle e^{-im_3 t}$

and $\langle \nu_\beta | = U^{D*}_{\beta 1} \langle \nu_1 | + U^{D*}_{\beta 2} \langle \nu_2 | + U^{D*}_{\beta 3} \langle \nu_3 |$

$$\Rightarrow P_{\nu_\alpha \to \nu_\beta}(t) = \left| U^D_{\alpha 1} U^{D*}_{\beta 1} e^{-im_1 t} + U^D_{\alpha 2} U^{D*}_{\beta 2} e^{-im2t} + U^D_{\alpha 1} U^{D*}_{\beta 1} e^{-im_3 t} \right|^2$$

$$s_{13} e^{i\delta_D}$$

$$\nu_\mu \to \nu_e \Rightarrow P_{\nu_\mu \to \nu_{des}}(t) = \left| U^D_{e1} U^{D*}_{\mu 1} e^{-im_1 t} + U^D_{e2} U^{D*}_{\mu 2} e^{-im2t} + U^D_{e3} U^{D*}_{\beta 3} e^{-im_3 t} \right|^2$$

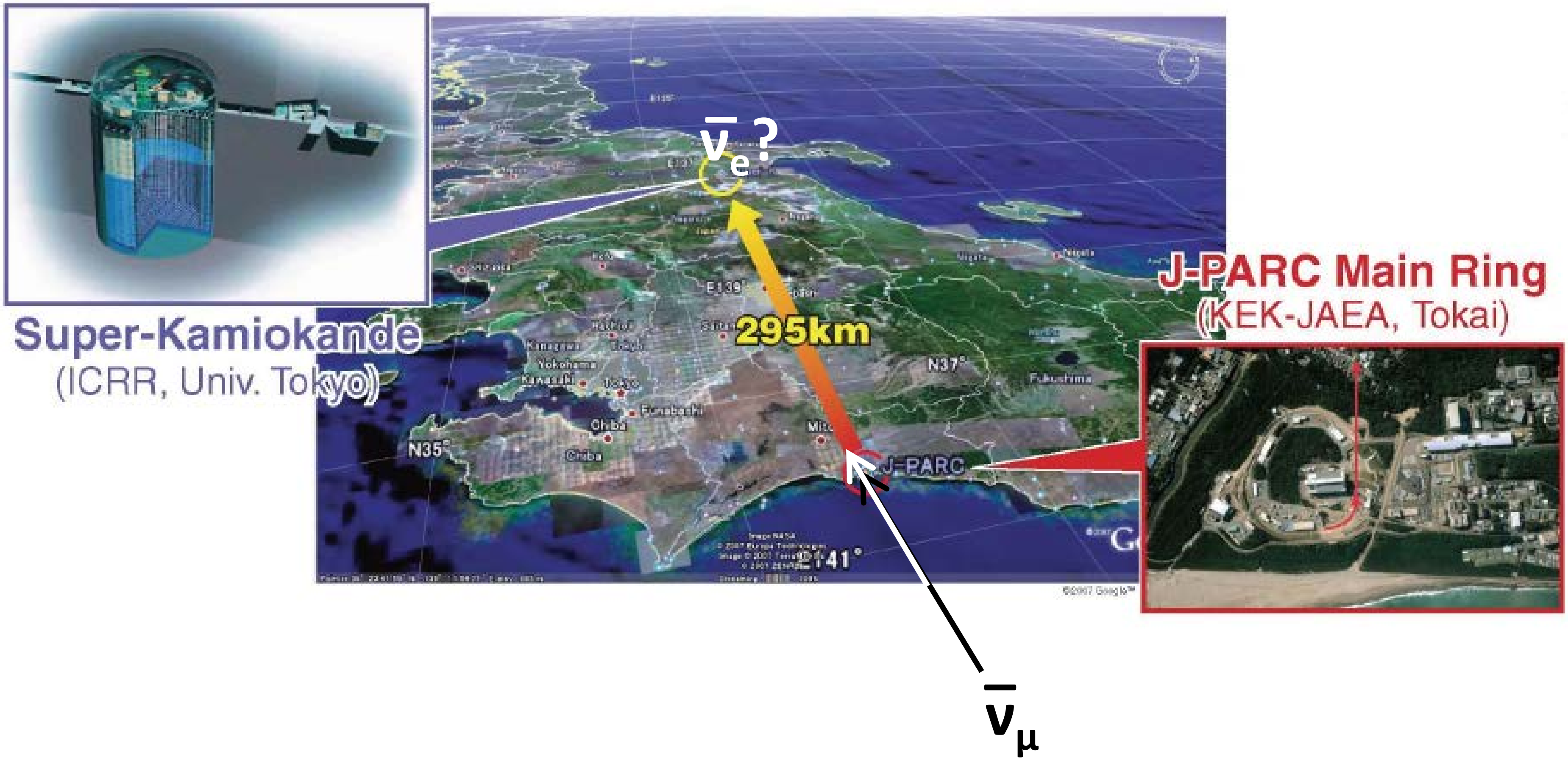
$$\bar{\nu}_\mu \to \bar{\nu}_e \Rightarrow \delta_D \to -\delta_D$$

T2K (Tokai to Kamiokande) Experiment

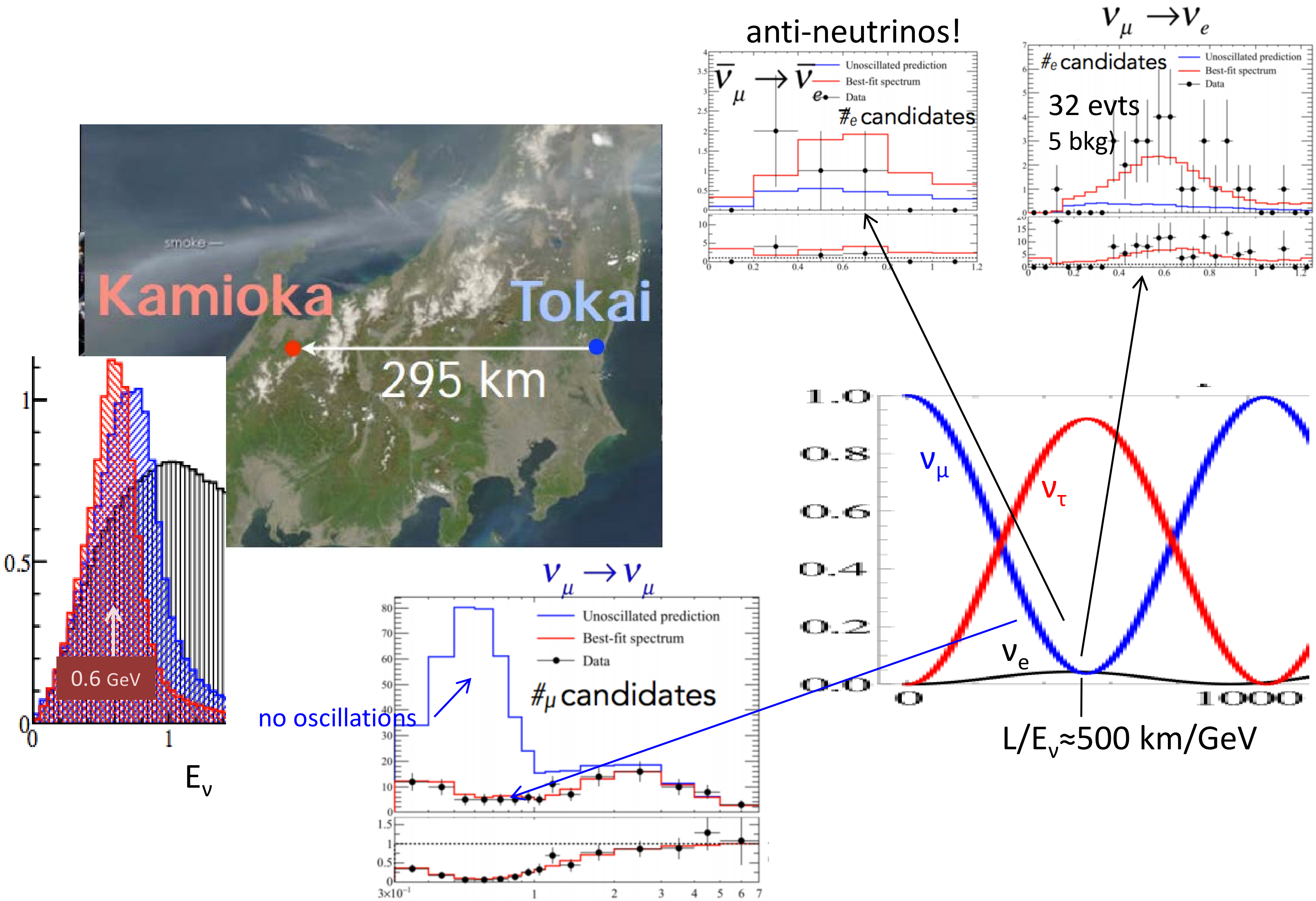
-- in Japan --

T2K (Tokai to Kamiokande) Experiment

-- in Japan --

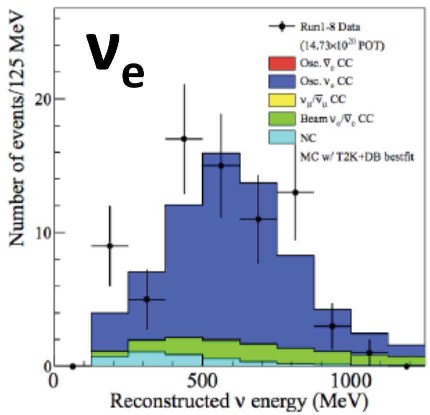


T2K experiment

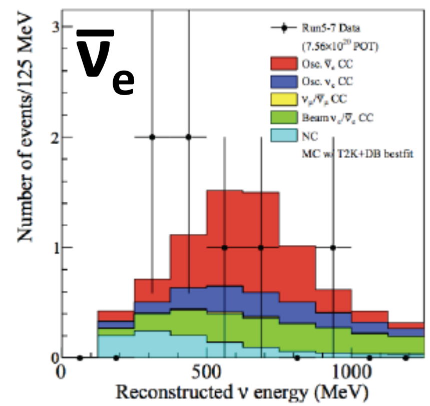


2017 T2K results

74 evts

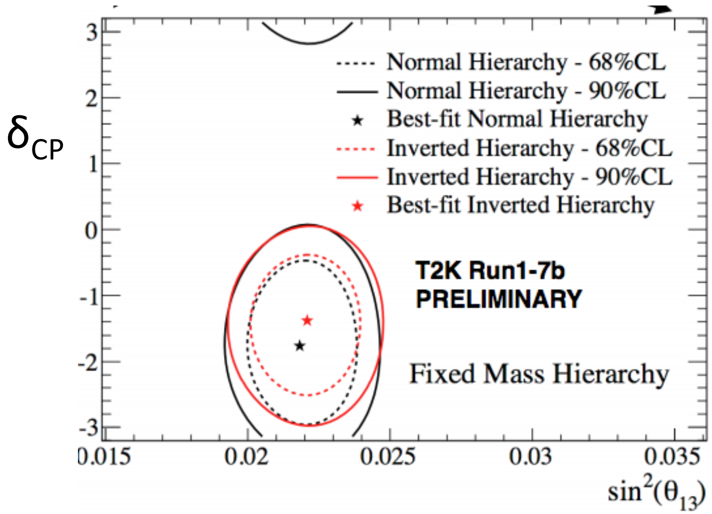


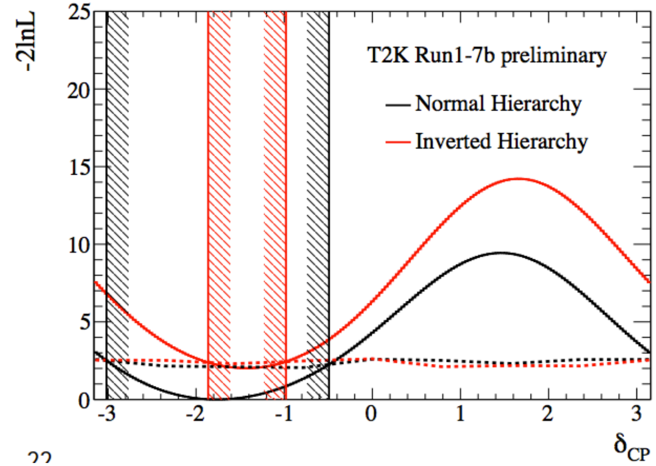
7 evts



	Predicted Rates				Observed
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
ν_e	73.5	61.5	49.9	62.0	74
	6.92	6.01	4.87	5.78	15
$\bar{\nu}_e$	7.93	9.04	10.04	8.93	7

T2K results





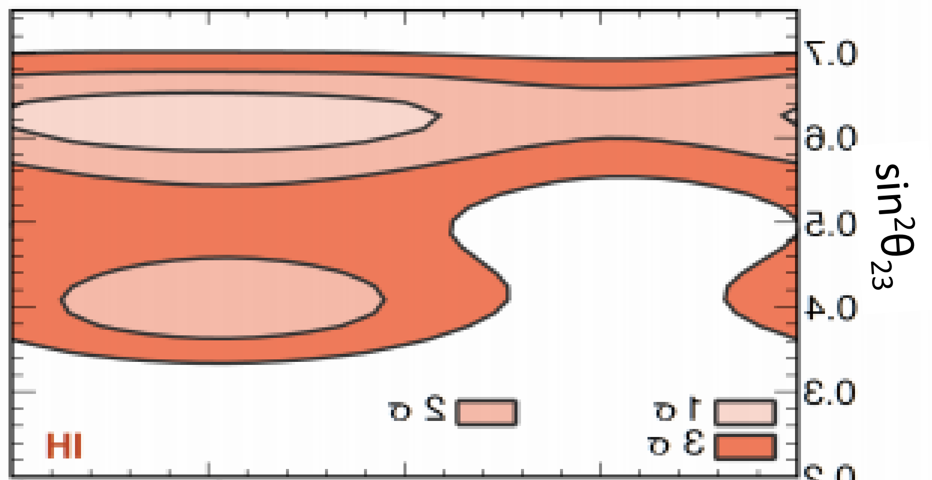
δ_{CP} = [-3.02, -0.49] (NH), [-1.87, -0.98] (IH) @90% CL

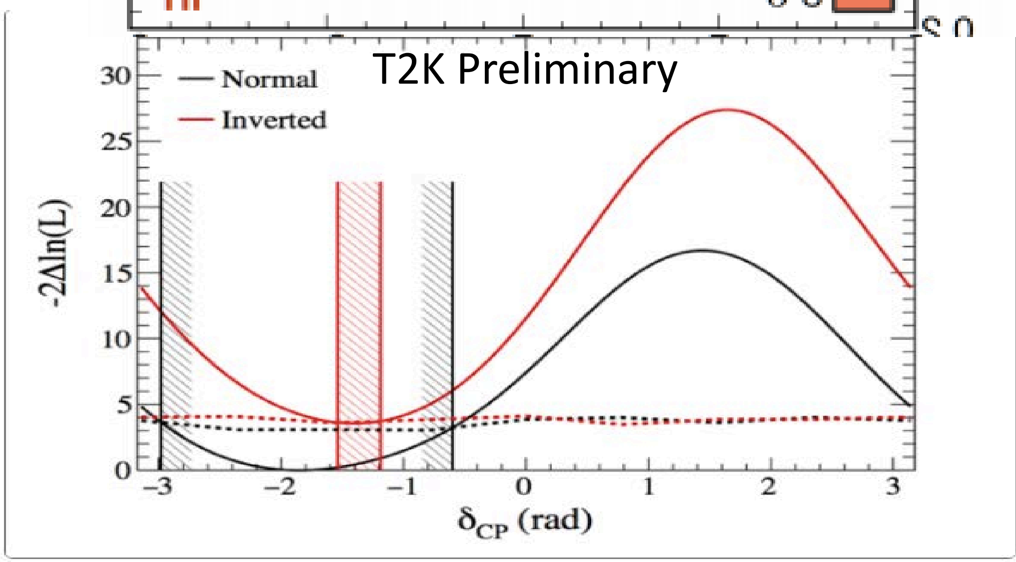
Central value (NH) $\delta_{CP} \approx -\pi/2$; equivalent to Nova's preferred (NH) value $\delta_{CP} \approx 3\pi/2$

(Nova & T2K) errors ≈ ±0.4π (≈±80°)

“Hints” of non-zero δ_D

NOνA Preliminary





neutrino hype

New Scientist

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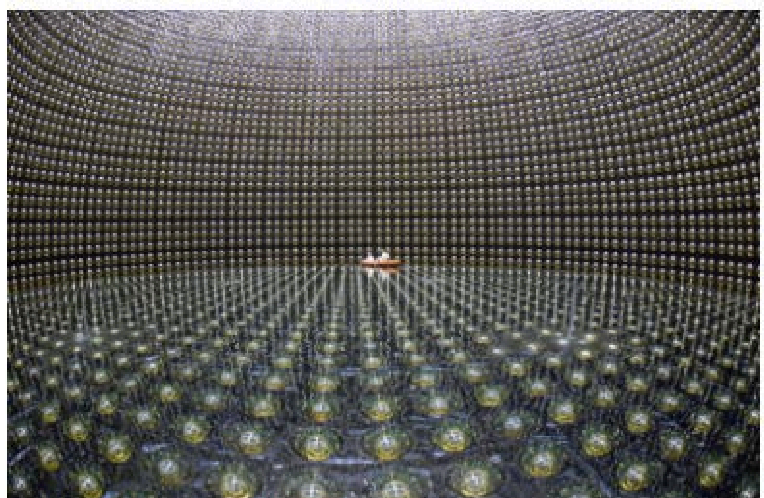
DAILY NEWS 4 July 2016

Neutrinos hint at why antimatter didn't blow up the universe



Super-Kamiokande: a huge detector looking out for tiny particles

Kamioka Observatory/ICRR(Institute for Cosmic Ray Research)/The University of Tokyo

does non-zero δ_D explain the baryon asymmetry?

Jarlskog invariant of the PMNS ν mixing matrix

$$\left|J_{PMNS}\right| = \mathrm{Im}(U_{e2}U^*_{e3}U^*_{\mu 2}U_{\mu 3}) \approx 0.033 \times \sin\delta_D$$

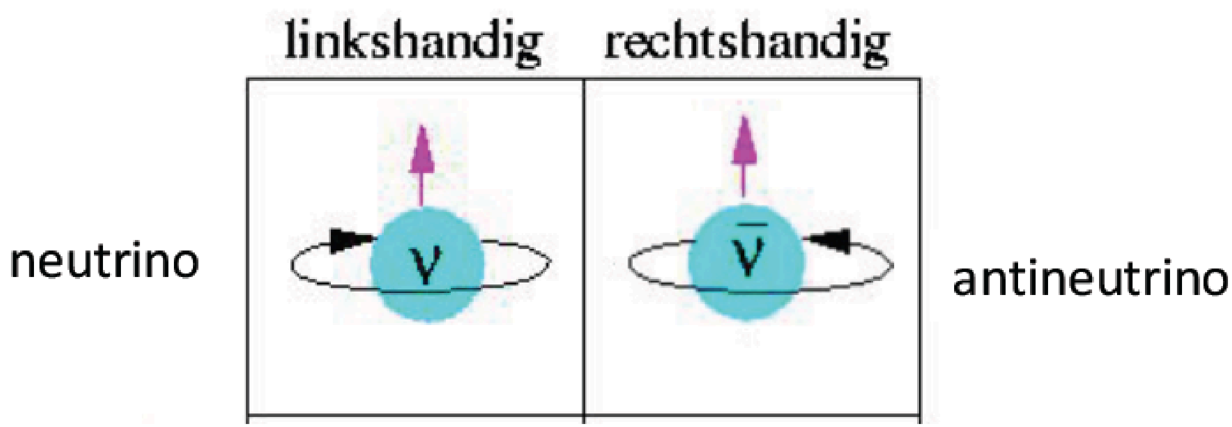
if $|\delta_D| \approx \pi/2$, as the data suggest, $|J_{PMNS}| \approx 0.03$, $10^3 \mathrm{x} |J_{CKM}|$ and be more efficient at creating CPV asymmetries.

does non-zero δ_D explain the baryon asymmetry?

No!

Since there are no relevant light neutrino thresholds, light neutinos stay in thermal equilibrium (contrary to Sakharov condition 3)
→ light neutrino CPV does not create a matter-antimatter asymmetry. instead it tends to "wash out" existing ones

What if neutrinos are Majorana particles?



Majorana neutrino mixing

lepton number isn't conserved &, so, the number of arbitrary phases is smaller:

& the number of free parameters larger:

Number of parameters:	18
Unitarity conditions:	9
arbitrary phases:	4
free parameters:	6

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 Euler angles,
1 Dirac phase and
2 Majorana phases

"Majorana phases"

Majorana neutrino mixing

lepton number isn't conserved &, so, the number of arbitrary phases is smaller:

& the number of free parameters larger:

Number of parameters:	18
Unitarity conditions:	9
arbitrary phases:	3
free parameters:	6

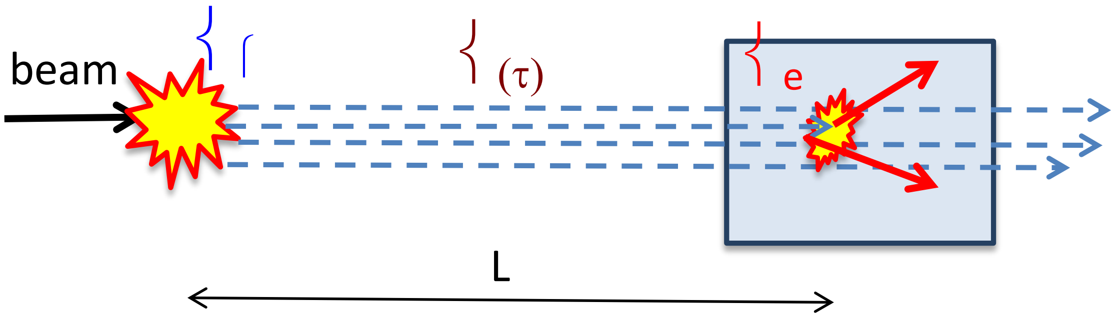
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

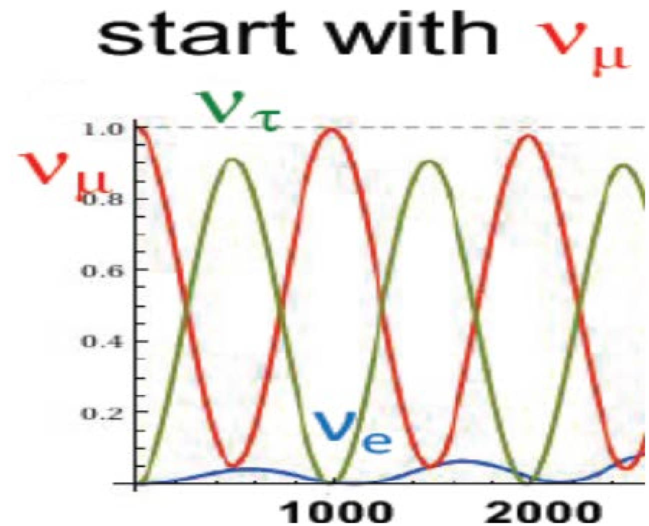
"Majorana phases"

3 Euler angles,
1 Dirac phase and
2 Majorana phases

$$U^{\text{Maj}} = \begin{pmatrix} U^{\text{D}}_{e1} e^{i\alpha_1/2} & U^{\text{D}}_{e2} e^{i\alpha_2/2} & U^{\text{D}}_{e3} \\ U^{\text{D}}_{\mu 1} e^{i\alpha_1/2} & U^{\text{D}}_{\mu 2} e^{i\alpha_2/2} & U^{\text{D}}_{\mu 3} \\ U^{\text{D}}_{\tau 1} e^{i\alpha_1/2} & U^{\text{D}}_{\tau 2} e^{i\alpha_2/2} & U^{\text{D}}_{\tau 3} \end{pmatrix}$$

Majorana neutrino mixing





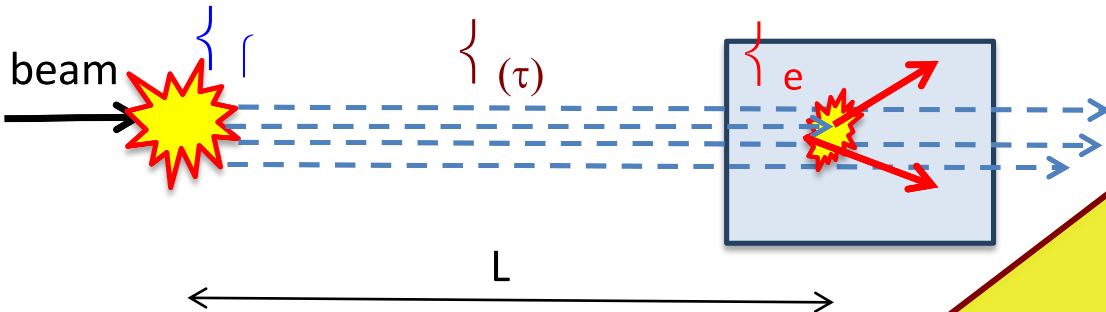
$$P_{\nu_\alpha \to \nu_\beta}(t) = \left| \left\langle \nu_\beta \middle| \nu_\alpha(t) \right\rangle \right|^2$$

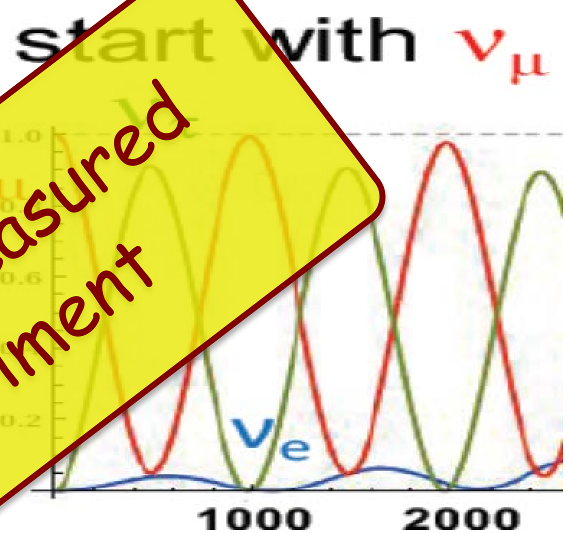
$$= \left| U^D_{\alpha 1} e^{-i\alpha_1/2} U^{D*}_{\beta 1} e^{i\alpha_1/2} e^{-im_1 t} + U^D_{\alpha 2} e^{-i\alpha_2/2} U^{D*}_{\beta 2} e^{i\alpha_2/2} e^{-im2t} + U^D_{\alpha 1} U^{D*}_{\beta 1} e^{-im_3 t} \right|^2$$

$$\Rightarrow P_{\nu_\alpha \to \nu_\beta}(t) = \left| U^D_{\alpha 1} U^{D*}_{\beta 1} e^{-im_1 t} + U^D_{\alpha 2} U^{D*}_{\beta 2} e^{-im2t} + U^D_{\alpha 1} U^{D*}_{\beta 1} e^{-im_3 t} \right|^2$$

← identical to Dirac neutrino results

Majorana neutrino mixing





$$P_{\nu_\alpha \to \nu_\beta}(t) = \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2$$

$$= \left| U^D_{\alpha 1} e^{-i\alpha_1/2} U^{D*}_{\beta 1} e^{i\alpha_1/2} e^{-im_1 t} + U^D_{\alpha 2} e^{-i\alpha_2/2} U^{D*}_{\beta 2} e^{i\alpha_2/2} e^{-im2t} + U^D_{\alpha 1} U^{D*}_{\beta 1} e^{-im_3 t} \right|^2$$

$$\Rightarrow P_{\nu_\alpha \to \nu_\beta}(t) = \left| U^D_{\alpha 1} U^{D*}_{\beta 1} e^{-im_1 t} + U^D_{\alpha 2} U^{D*}_{\beta 2} e^{-im2t} + U^D_{\alpha 1} U^{D*}_{\beta 1} e^{-im_3 t} \right|^2$$

← identical to Dirac neutrino results

Majorana phases **cannot** be measured in **any** oscillation experiment add a right-handed, but heavy neutrino

Heavy Majorana neutrinos (in 2 slides)

Majorana Neutrinos: ν_L^m is left-handed

N_R^m is right-handed

In *L-R* symmetric models: ν_L^m is in a Weak-Isospin doublet with a charged lepton

N_R^m is a Weak-Isospin singlet

The mass matrix in $\begin{pmatrix} \nu_L^m \\ N_R^m \end{pmatrix}$ space is:

$$\langle M \rangle = \begin{pmatrix} \langle \nu_L^m | M | \nu_L^m \rangle & \langle \nu_L^m | M | N_R^m \rangle \\ \langle N_R^m | M | \nu_L^m \rangle & \langle N_R^m | M | N_R^m \rangle \end{pmatrix} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix},$$

where:

-- $\boldsymbol{m_D}$ is the "Dirac mass" and is generated by the same Higgs mechanism that gives the charged leptons their masses – and has a similar value;

-- $\left\langle \nu_L^{\text{maj}} \middle| M \middle| \nu_L^{\text{maj}} \right\rangle = 0$ (input);

-- $\boldsymbol{M_R}$ is the very high mass scale where *L-R* symmetry holds

The physical neutrinos are the eigenstates of this matrix

Physical Majorana neutrino states

Eigenvalue equation:

$$\begin{vmatrix} 0-\lambda & m_D \\ m_D & M_R-\lambda \end{vmatrix} = 0$$

M_R is very large ($\sim 10^{12}$ GeV?)
m_D is a "typical" lepton mass

solutions:

heavy: $\sim 10^{12}$ GeV — right-handed

$$\lambda_{"R"} = M_R - \frac{m_D^2}{M_R}; \quad |N^m\rangle = |N_R^m\rangle + \frac{m_D}{M_R}|\nu_L^m\rangle$$

$$\lambda_{"L"} = \frac{m_D^2}{M_R}; \quad |\nu^m\rangle = |\nu_L^m\rangle - \frac{m_D}{M_R}|N_R^m\rangle$$

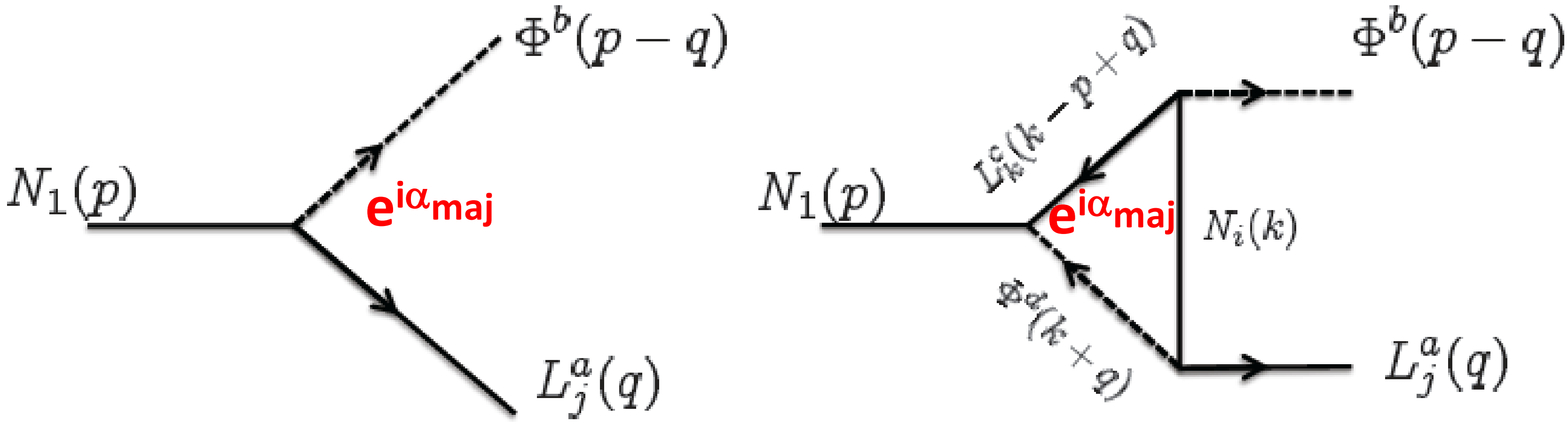
light: <1eV — left-handed

this is the famous "See-Saw Mechanism" used to explain the very low, but non-zero, ν mass values (i.e. $m_\nu \sim 10^{-3}$ eV)

If $\mathcal{CP}$ is violated: $\mathcal{A}(N^m \to \ell^- + \text{hadrons}) \neq \mathcal{A}(N^m \to \ell^+ + \overline{\text{hadrons}})$

for $m_D \sim 1$ GeV, the observed $m_\nu \lesssim 0.1$ eV requires $M_R \gtrsim 10^{11}$ GeV

Leptogenesis: CPV provided by decaying heavy neutrinos

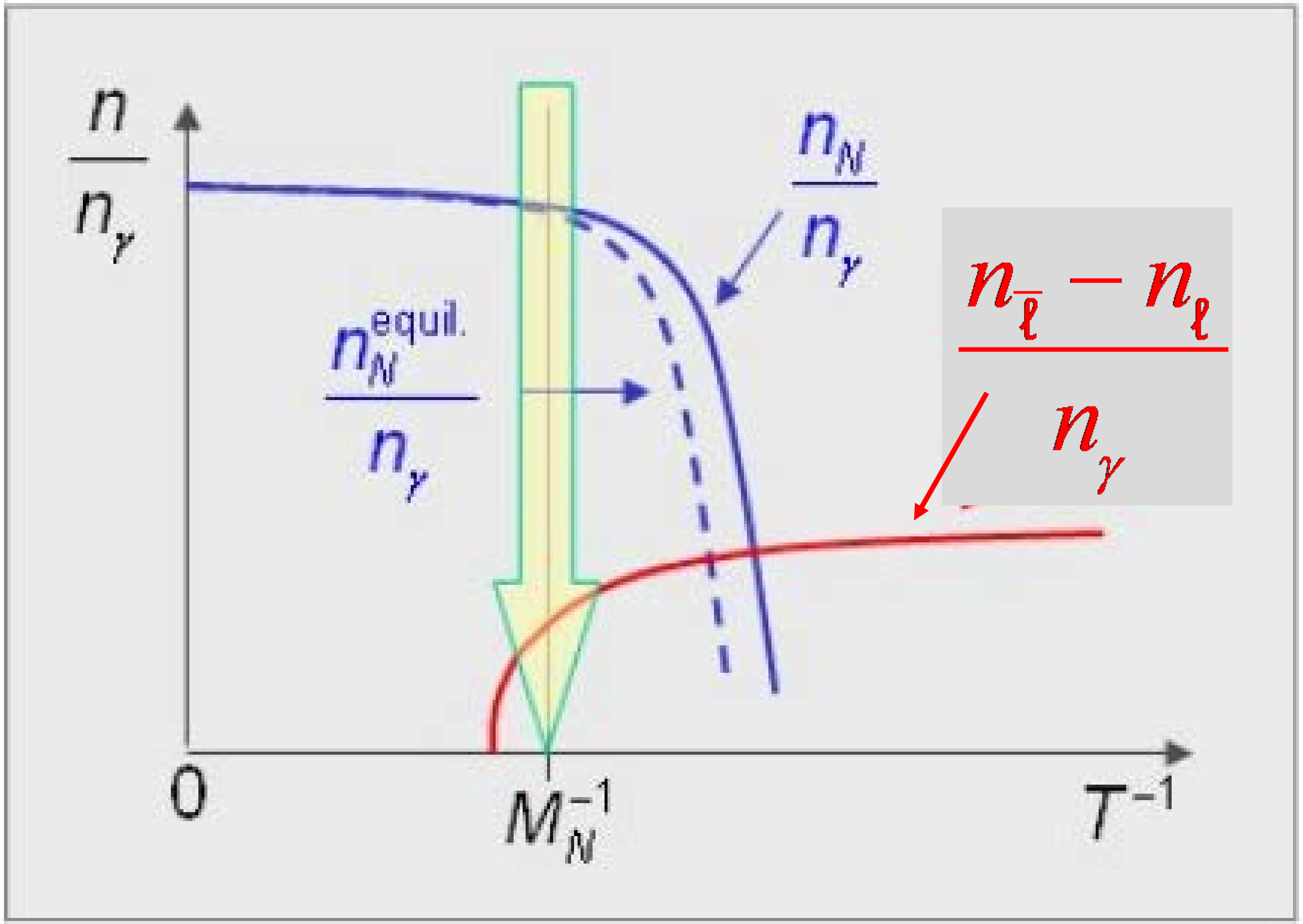


$$\Gamma(\bar{N} \to \bar{\ell}\ \bar{\Phi}) > \Gamma(N \to \ell\ \Phi) \quad \Leftarrow \text{ antilepton excess established}$$

$$n_{\bar{\ell}} - n_{\ell} > 0$$

C and CPV violation, Sakharov condition #2 is satisfied

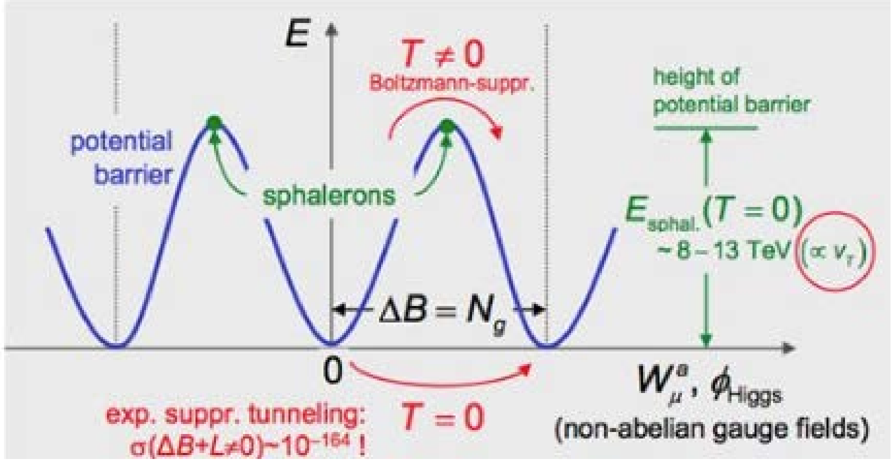
near threshold, (T~M_N) equilibrium is broken

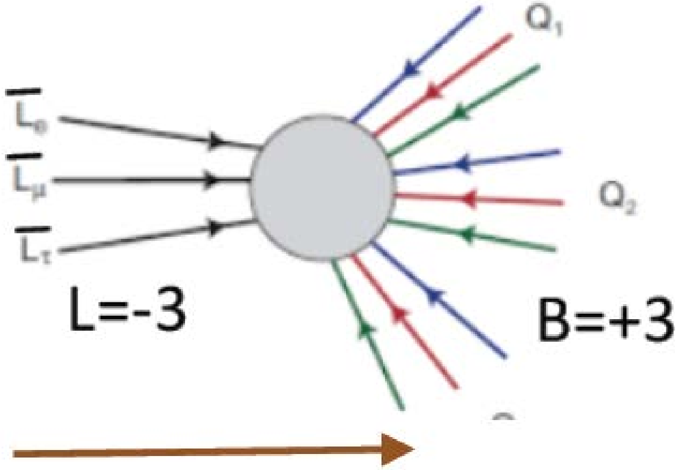


Sakharov's condition 3 is satisfied

near $E_{spaleron}$ (~10 TeV) antileptons→quarks

$$n_{\bar{\ell}} > n_{\ell} \Rightarrow n_{qqq} > n_{\overline{qqq}}$$



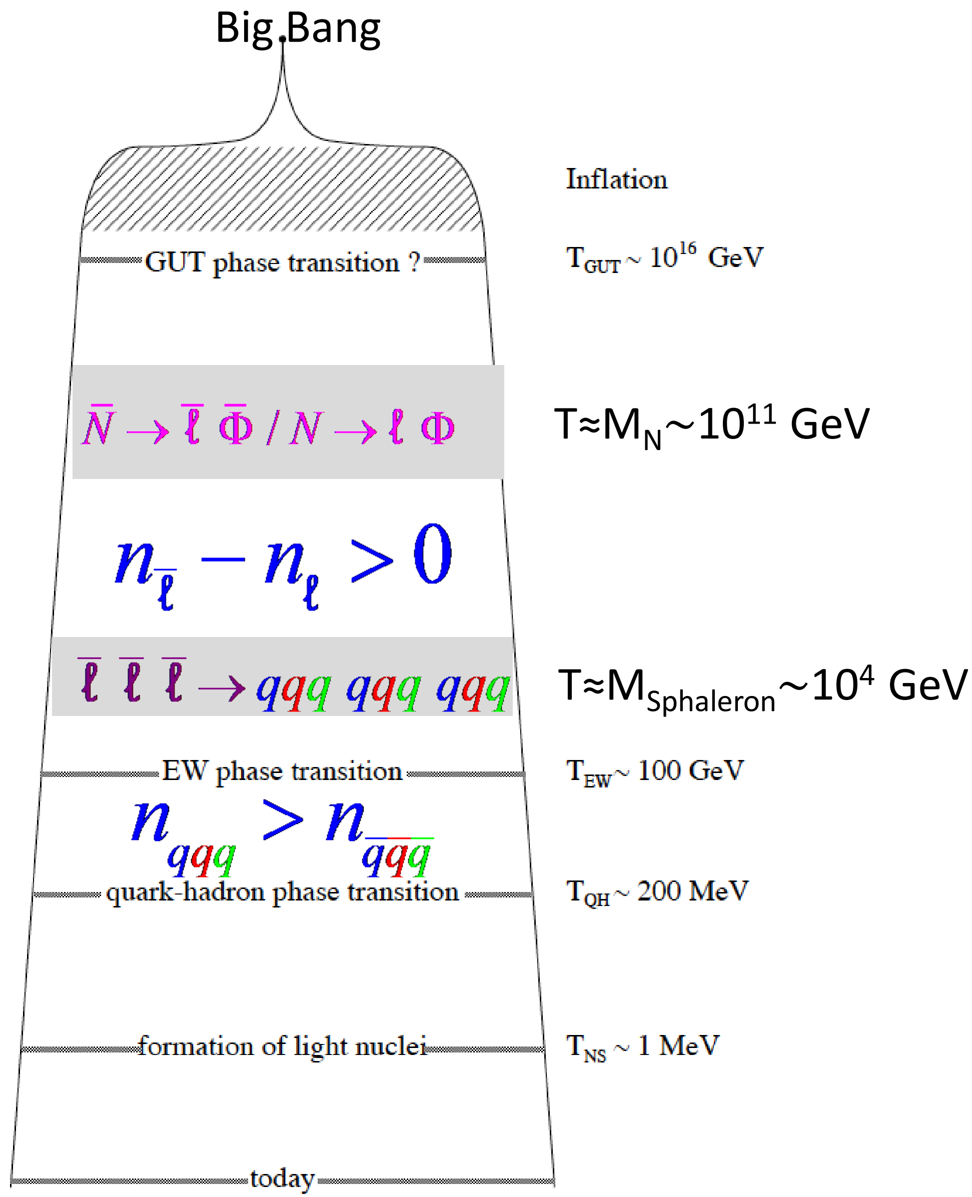


Sakharov's condition 1 is satisfied →

$$n_B \to n_B + 3$$

Baryon number conservation is violated

Matter-antimatter asymmetry timeline



Comments

Leptogenesis provides a plausible explanation for BAU.

However, the main features of the model, i.e., the heavy right-handed neutrinos, and their CPV Majorana phases are inaccessible to experiment and, thus, the essential features of this model cannot be confirmed.

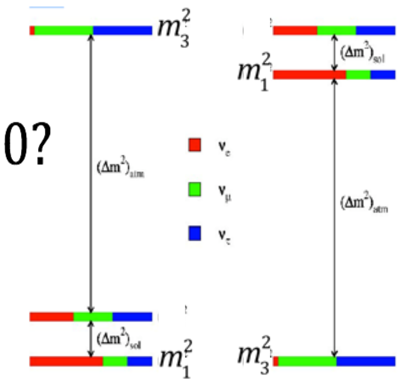
The one neutrino-sector CPV parameter that is accessible to experiment, the light neutrino Dirac phase, δ_D, has little to do with the Leptogenesis scheme for BAU.

ν oscillation experiments (Nova, T2K, T2HK, DUNE, …) do not directly address the baryon asymmetry.

What we don't know about neutrinos
-- that is addressed by ν -oscillation expts --

- Mass hierarchy:

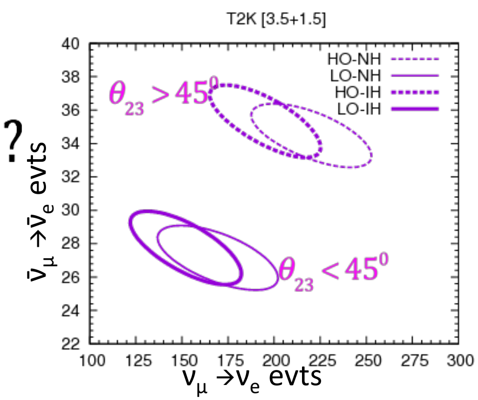
$(m_3^2 - m_1^2) > 0? ...\text{or} ... < 0?$



yes-no question; very likely will be answered by JUNO

- Octant degeneracy:

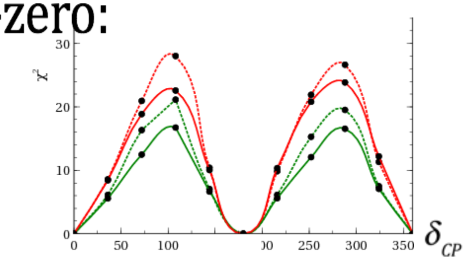
$\theta_{23} > 45^0 ?... \text{or} ... < 45^0 ?$



of major interest only to some specialists

- is the Dirac phase non-zero:

$|\delta_{CP}| \neq 0?$



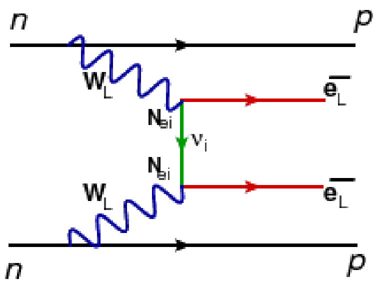
K & M taught us that (almost certainly) $\delta_{CP} \neq 0$

What we don’t know about neutrinos
-- that is ***not*** addressed by { oscillation expts --

- ν: Dirac or Majorana?

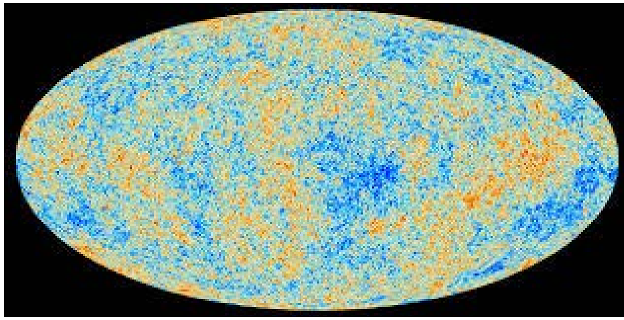
  is lepton # conserved?

  only possible with 0{ ®® decay experiments



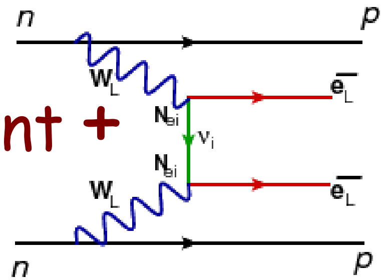
- What is the absolute neutrino mass scale?

  Katrin-like experiments and/or precision CMB measurements



- What are the Majorana phases? $\alpha_1 = ?; \alpha_2 = ?$

absolute mass msmnt +



Double beta decay process

$2\nu\ \beta\beta$ decay

2nd order beta decay

Rare nuclear decay

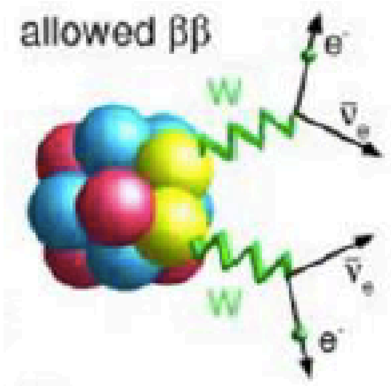
($>10^{18}$ years)

$0\nu\ \beta\beta$ decay

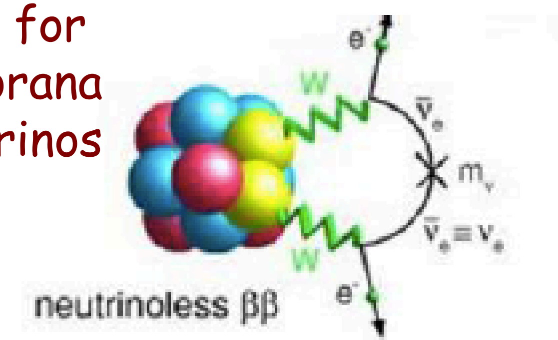
1) ν mass>0 &

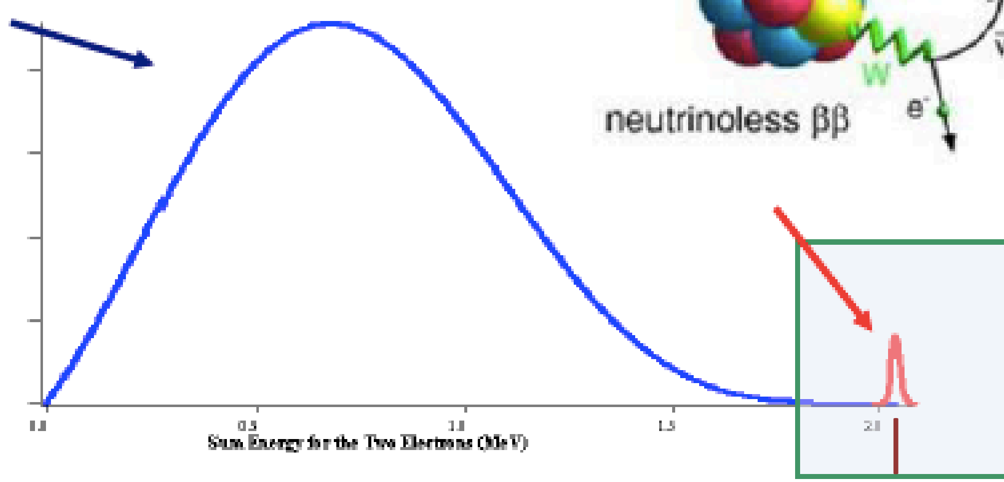
Majorana particle

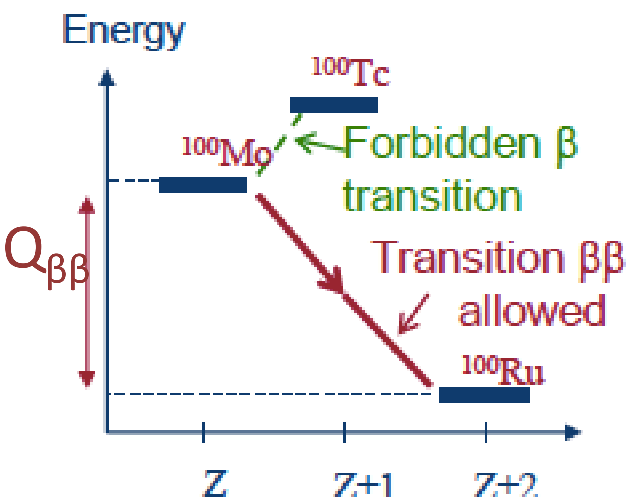
2) New Physics



only for Majorana neutrinos







$Q_{\beta\beta}(^{100}Mo)=3.034$ MeV

0ν ββ half-life

effective

ν_e mass

phase space factor

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

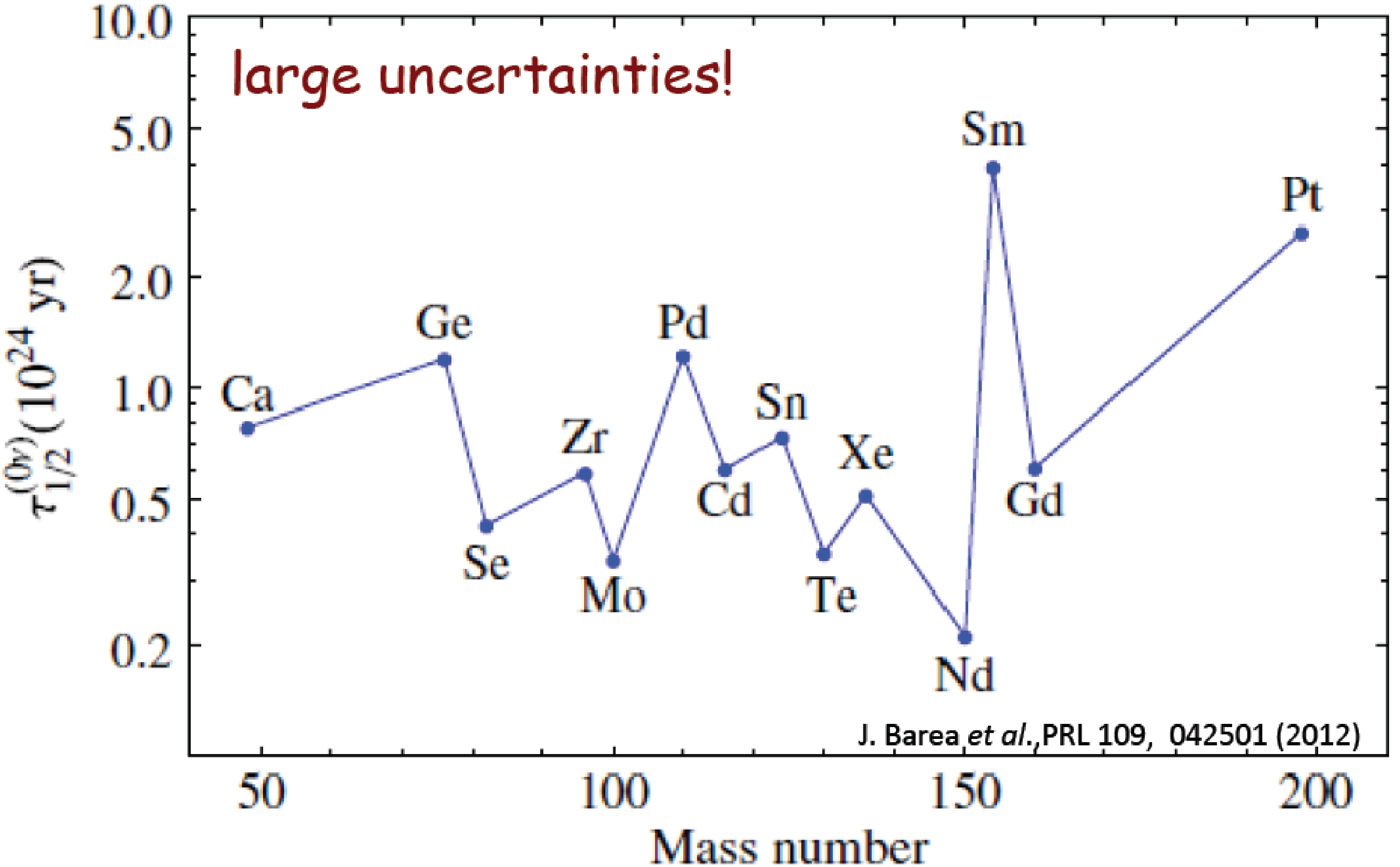
impossibly difficult nuclear Matrix Element

$$\langle m_{\beta\beta}\rangle = \sum U_{ei}^2 m_i = U_{e1}^2 m_1 e^{i\alpha_1} + U_{e2}^2 m_2 e^{i\alpha_1} + U_{e3}^2 m_3 e^{i\delta_2}$$

coherent sum

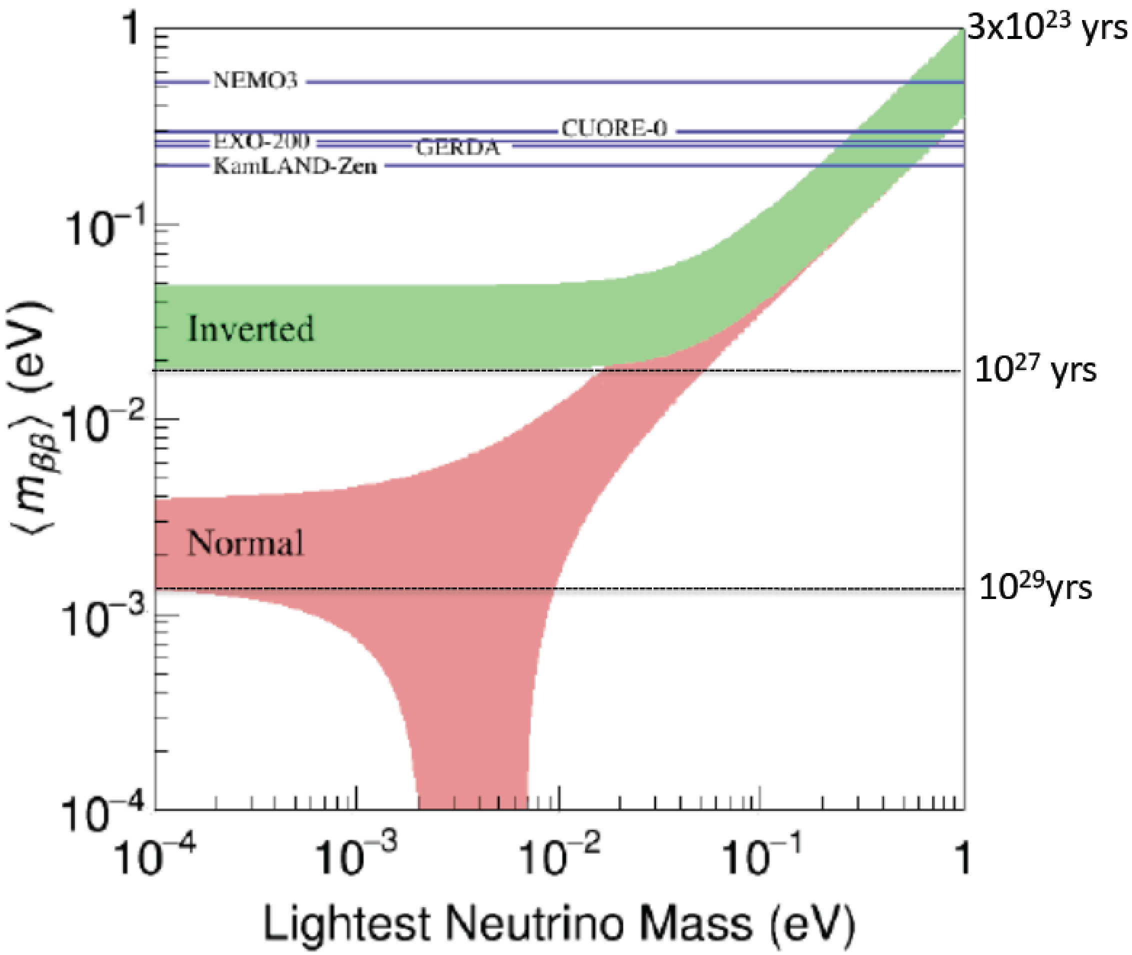
$T_{1/2}^{0\nu}$ for $\langle m_{\beta\beta} \rangle = 1\text{eV}$ for different nuclides

$$\frac{1}{G_{0\nu}\left|M_{0\nu}\right|^2}$$



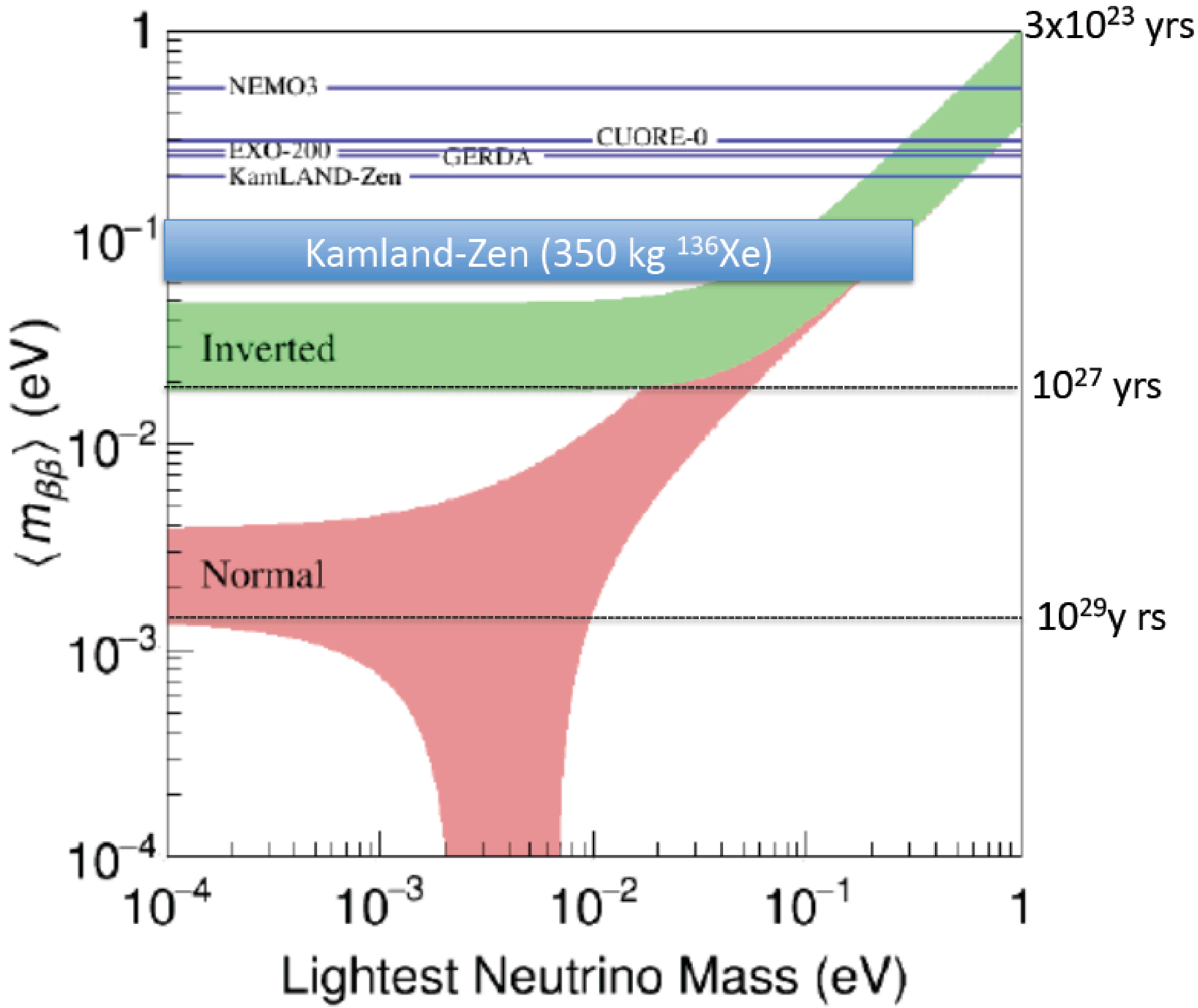
$T_{1/2}^{0\nu}$ & $\langle m_{\beta\beta} \rangle$ *versus* lightest ν mass

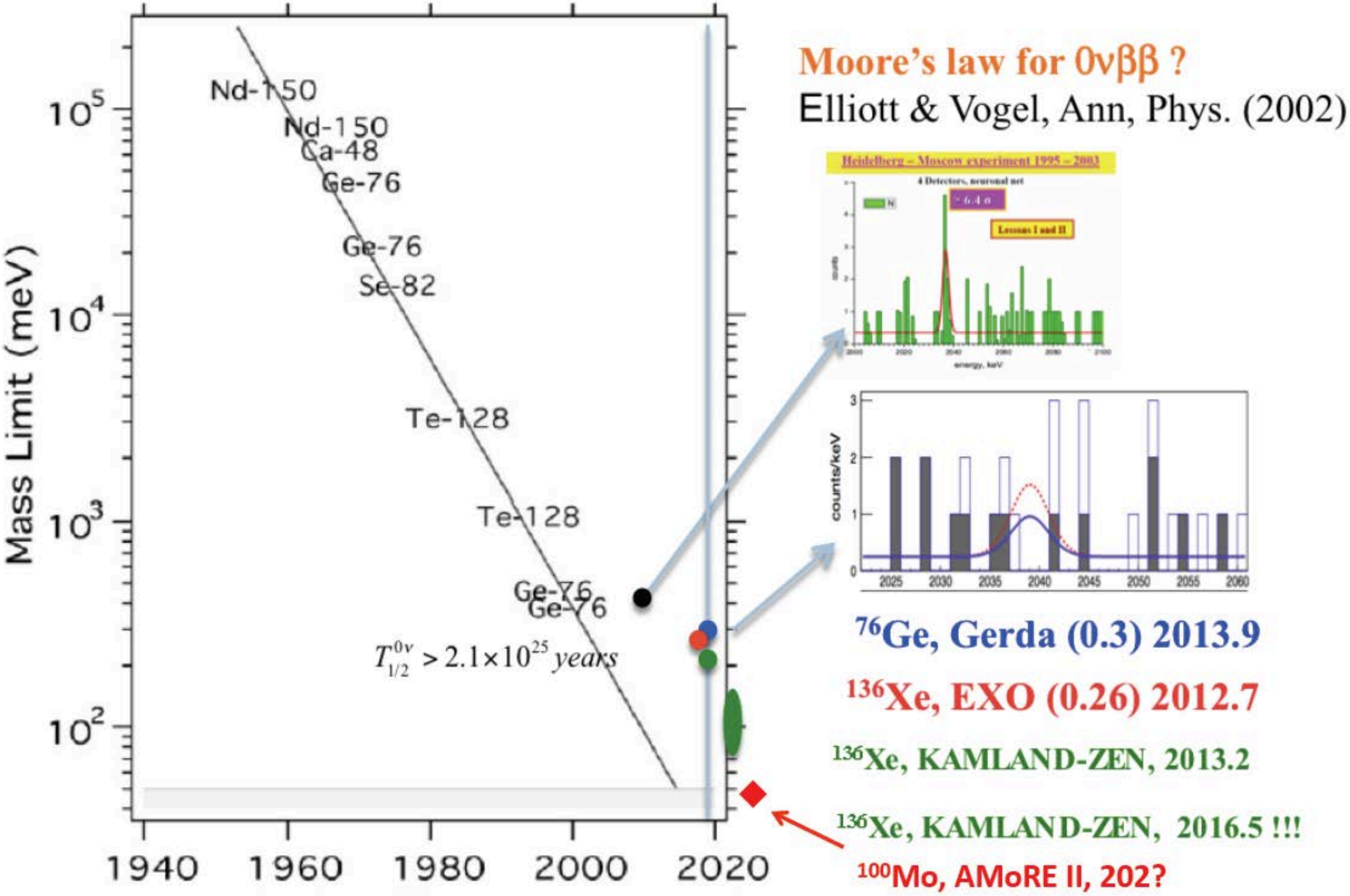
-- for ^{100}Mo --



Problem: N_A is too small

0-bkg mass for 1 ct/yr (^{100}Mo)





Moore's law for 0νββ ?
Elliott & Vogel, Ann, Phys. (2002)
Mass Limit (meV)
10^5
10^4
10^3
10^2
1940
1960
1980
2000
2020
Nd-150
Nd-150
Ca-48
Ge-76
Ge-76
Se-82
Te-128
Te-128
Ge-76
Ge-76
$T_{1/2}^{0\nu} > 2.1\times10^{25}$ years
Heidelberg – Moscow experiment 1995 – 2003
4 Detectors, neuronal net
energy, keV
counts/keV
76Ge, Gerda (0.3) 2013.9
136Xe, EXO (0.26) 2012.7
136Xe, KAMLAND-ZEN, 2013.2
136Xe, KAMLAND-ZEN, 2016.5 !!!
100Mo, AMoRE II, 202?

comments

- $0\nu\beta\beta$ decay experiments are impossibly difficult
- big payoff ➔ if you detect it, you will have established neutrinos as Majorana particles
- extracting <$m_{\beta\beta}$> will require a precision calculation of an impossibly difficult nuclear M.E.
- CPV Majorana phase information will require independent measurements of <m_ν> and even then you only get one constraint for two different phases
- establishing neutrinos as Dirac-like fermions is hopeless if the ν mass hierarchy is "normal"

Course Summary

- CP violations are interesting because they provide a unique view of what is going on in the inner workings of the Standard Model
- Mechanisms for CP violation are critical to the understanding of how the universe evolved from the matter-antimatter symmetric condition that existed shortly after the Big Bang to the decidedly matter-antimatter asymmetric condition that prevails today.
- Experiments at the start of the 21st century verified the Kobayashi-Maskawa 6-quark model for CP violation.
- All measured CP violations can be explained by the KM 6-quark model.
- CP violations are mainly confined to the b- & t-quark sector, where they occur at system are due to leakage via higher-order terms from the b-/t-quark sector.
- The KM-mechanism for CP violation is not sufficient to account for the Baryon Asymmetry of the Universe. Other sources of CPV, perhaps in the { -sector or from still undiscovered New Physics phenomena, must be at play.

謝謝