neutrino masses and baryogenesis

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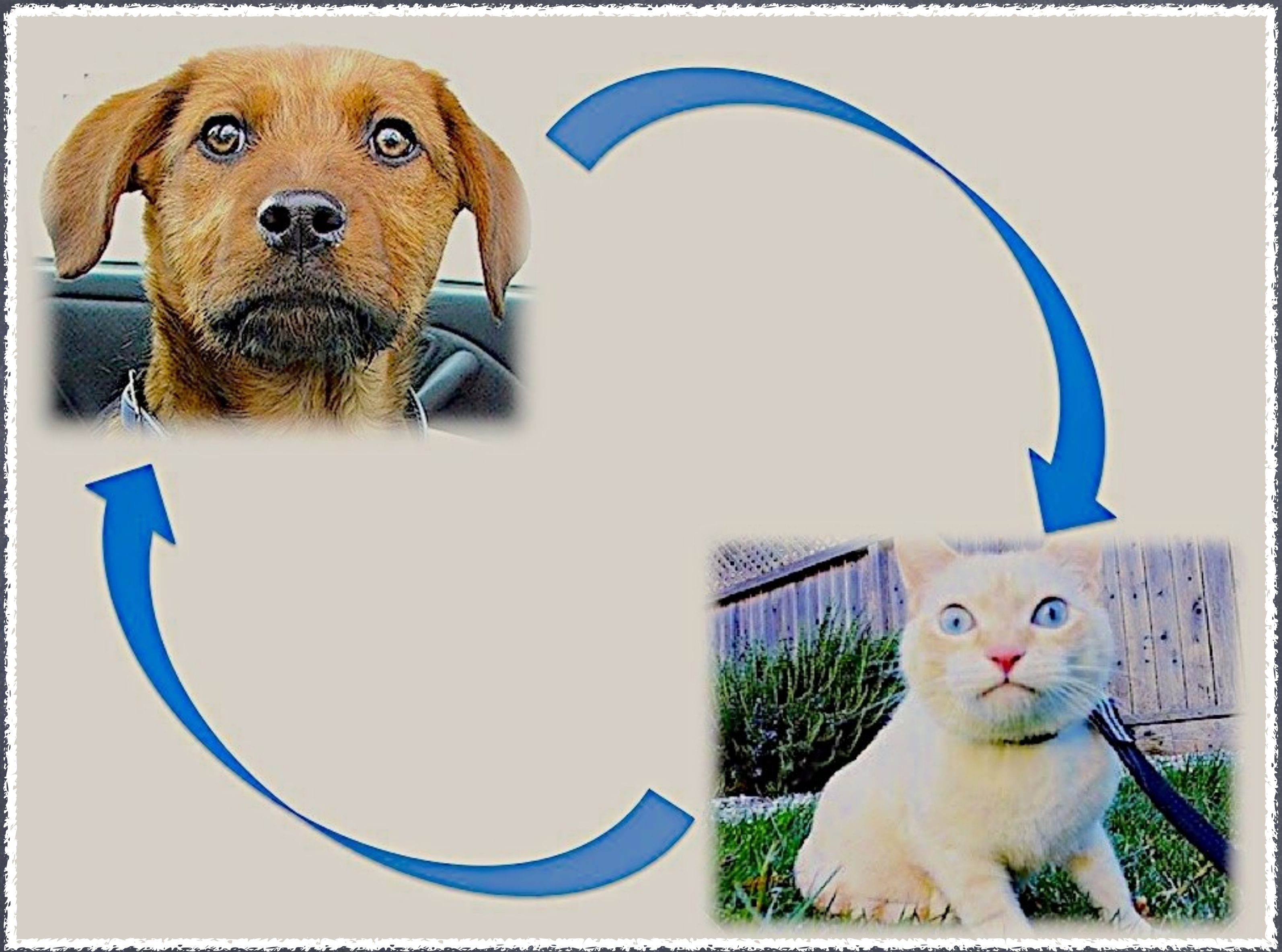
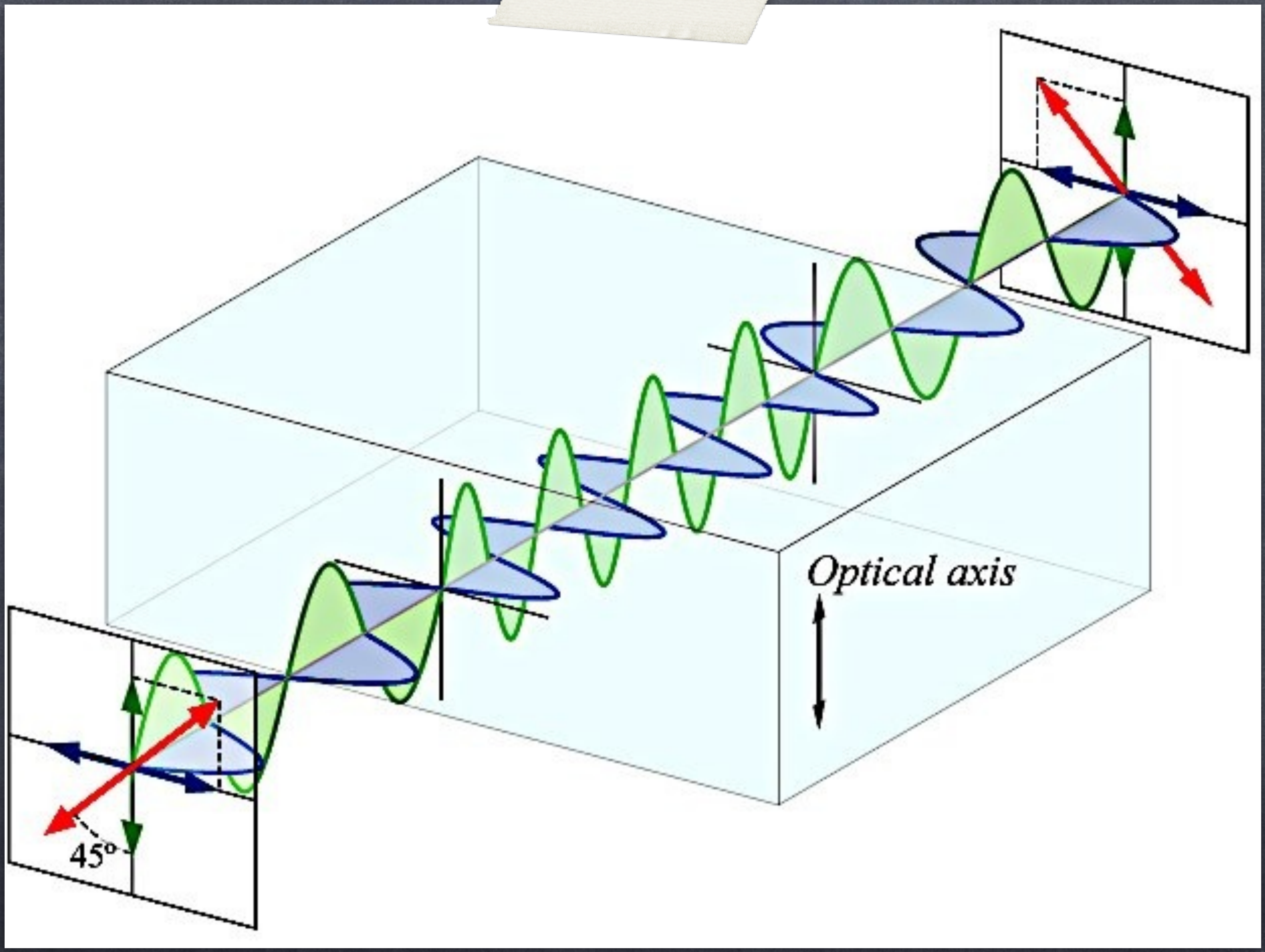
ISSS School, L'Aquila; April 24, 2014



Neutrino oscillations

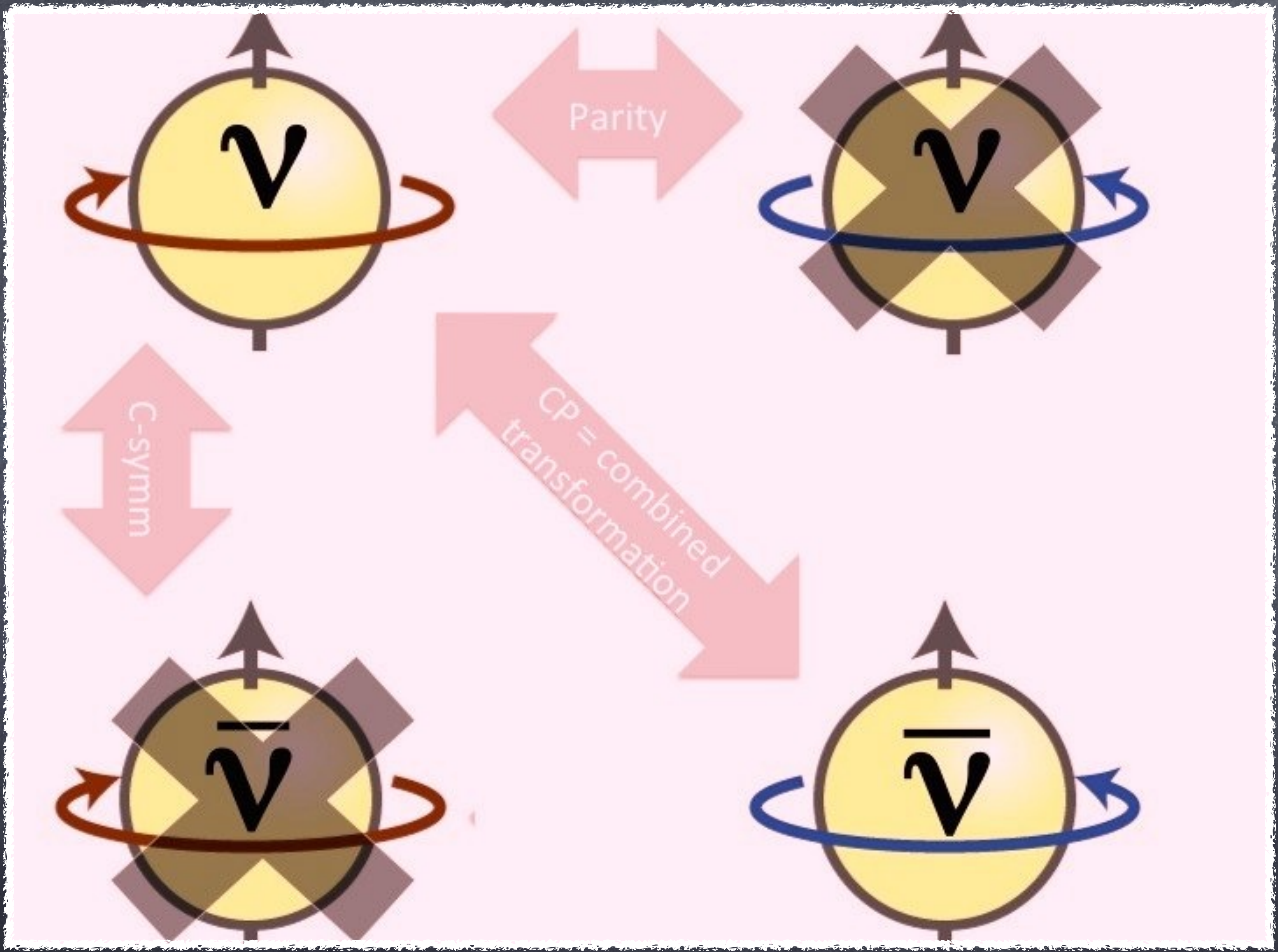
often presented with a prejudice: they belong to the deep mysteries of quantum mechanics and, as such, they should not be explained to a wide public

Waves are subject to transformations

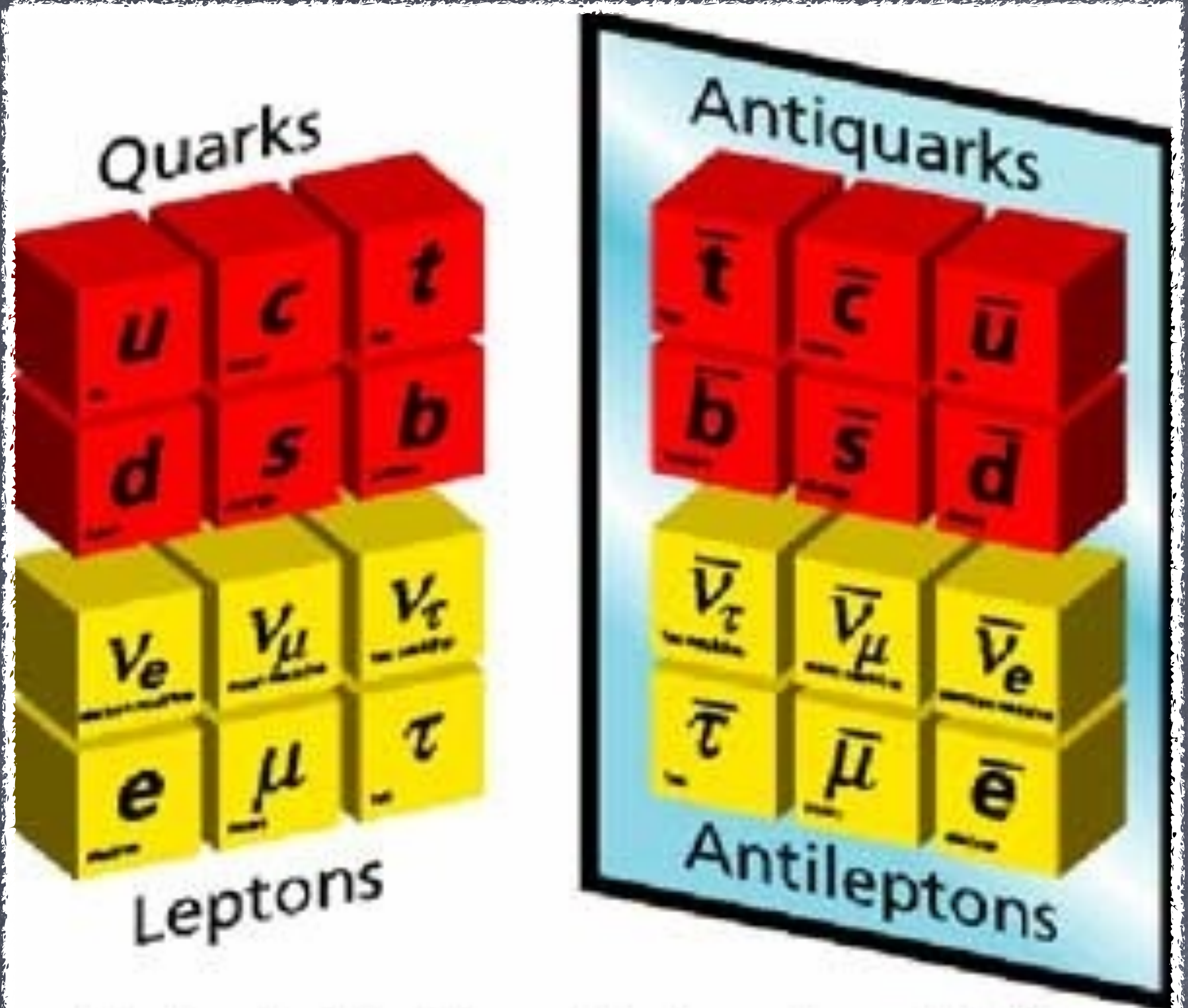


An anisotropic crystal arranged to flip the polarization of a wave.
We can say that photons change their state completely.

Neutrinos

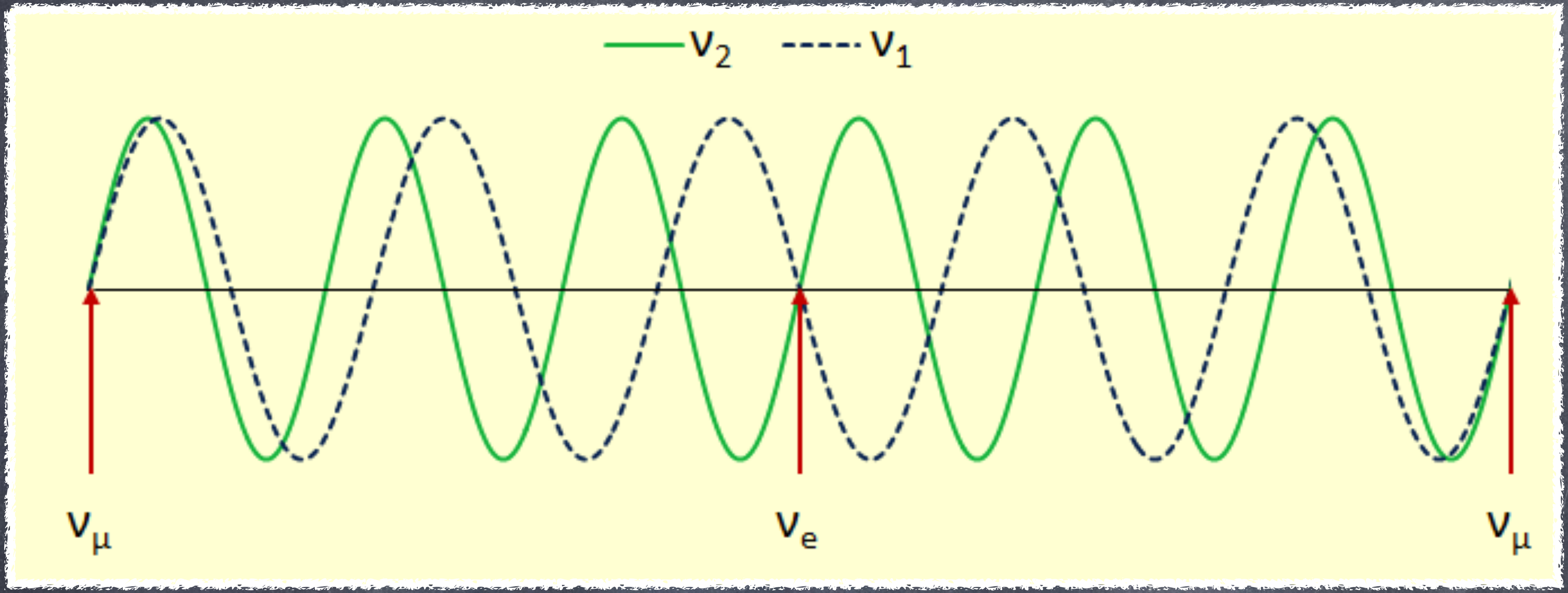


have only one polarization state



The Standard Model contains 3 neutrinos of definite flavor, and a set of corresponding anti-particles.

There is one "flavor" (i.e., type) of neutrino for each charged lepton: we have electronic, muonic, tau neutrinos



Flavor changes during propagation

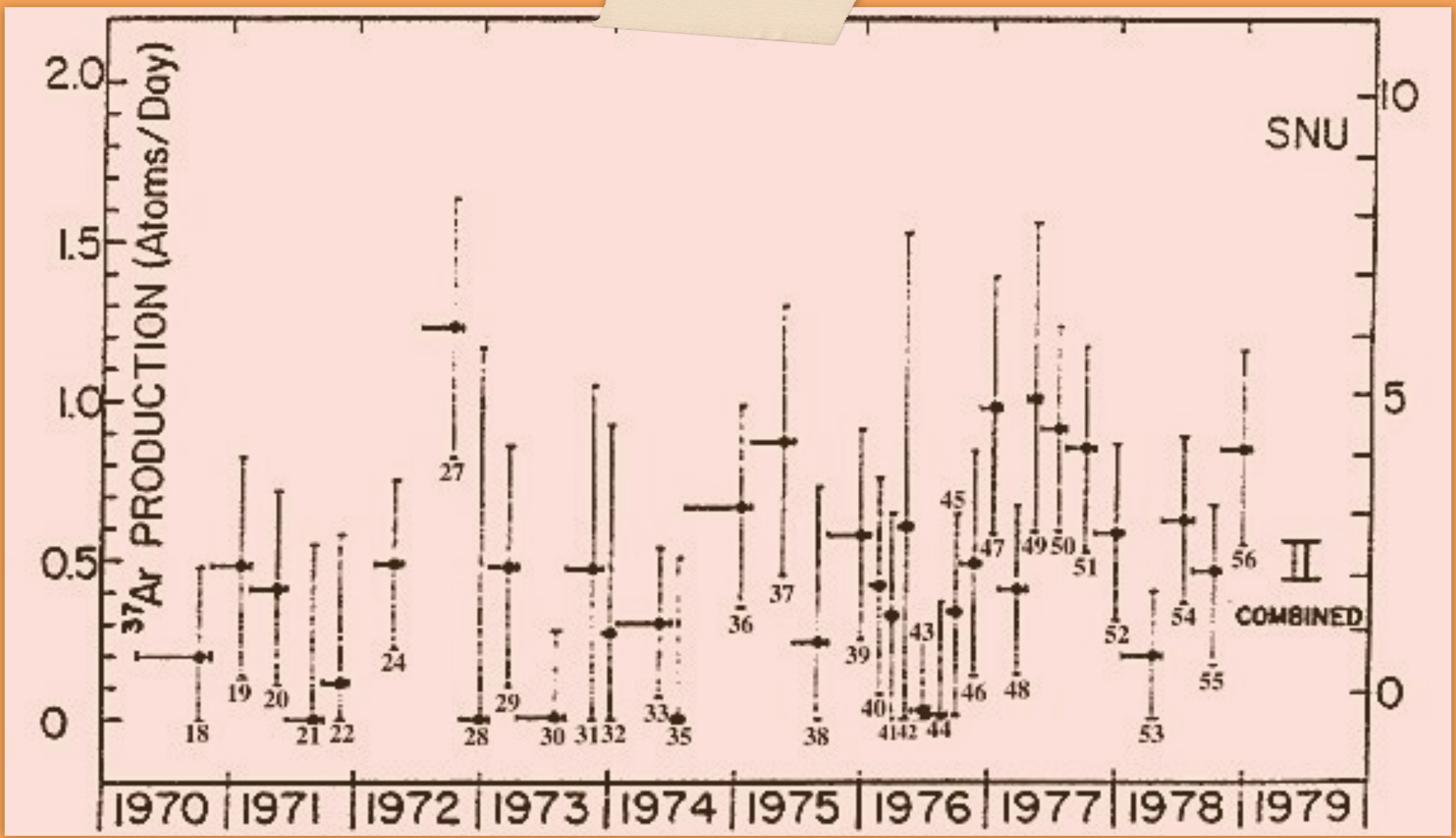
if muonic and electronic neutrinos are superpositions of two states with different phase velocity (Pontecorvo; Sakata et al.)

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_j\rangle \sim \exp\left[i\frac{px - E_j t}{\hbar}\right], \quad \text{with } j = 1, 2$$

$$\frac{(E_1 - E_2)t}{\hbar} = \frac{(m_1^2 - m_2^2)c^4 t}{(E_1 + E_2)\hbar} \approx \frac{(m_1^2 - m_2^2)L}{E} \times \frac{c^3}{2\hbar}$$

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \times \sin^2\left[1.27\frac{m_1^2 - m_2^2}{\text{eV}^2/c^4}\frac{L}{\text{km}}\frac{\text{GeV}}{E}\right]$$

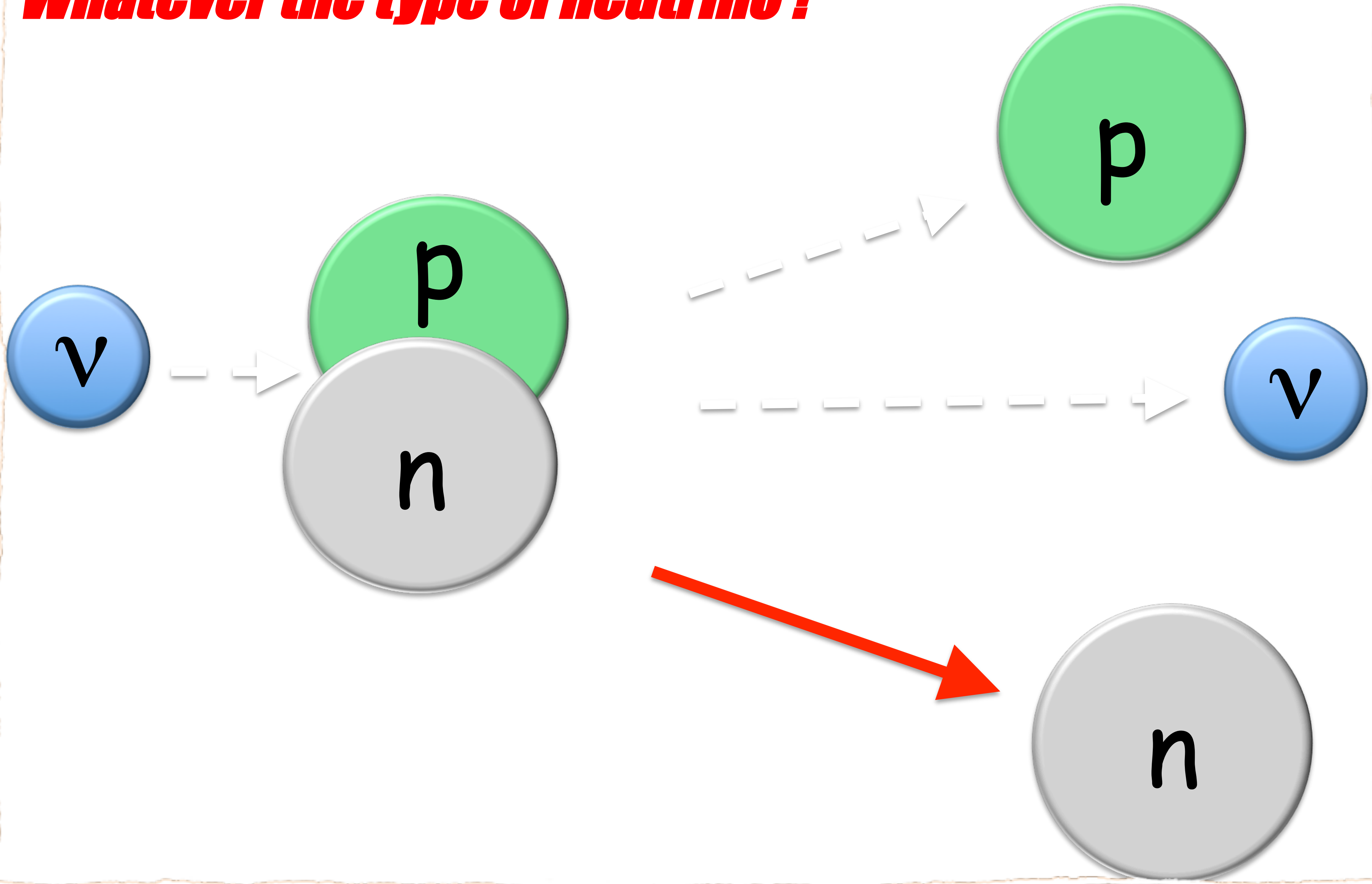


The electron neutrinos from the sun disappear

as observed since late 60's (Homestake)

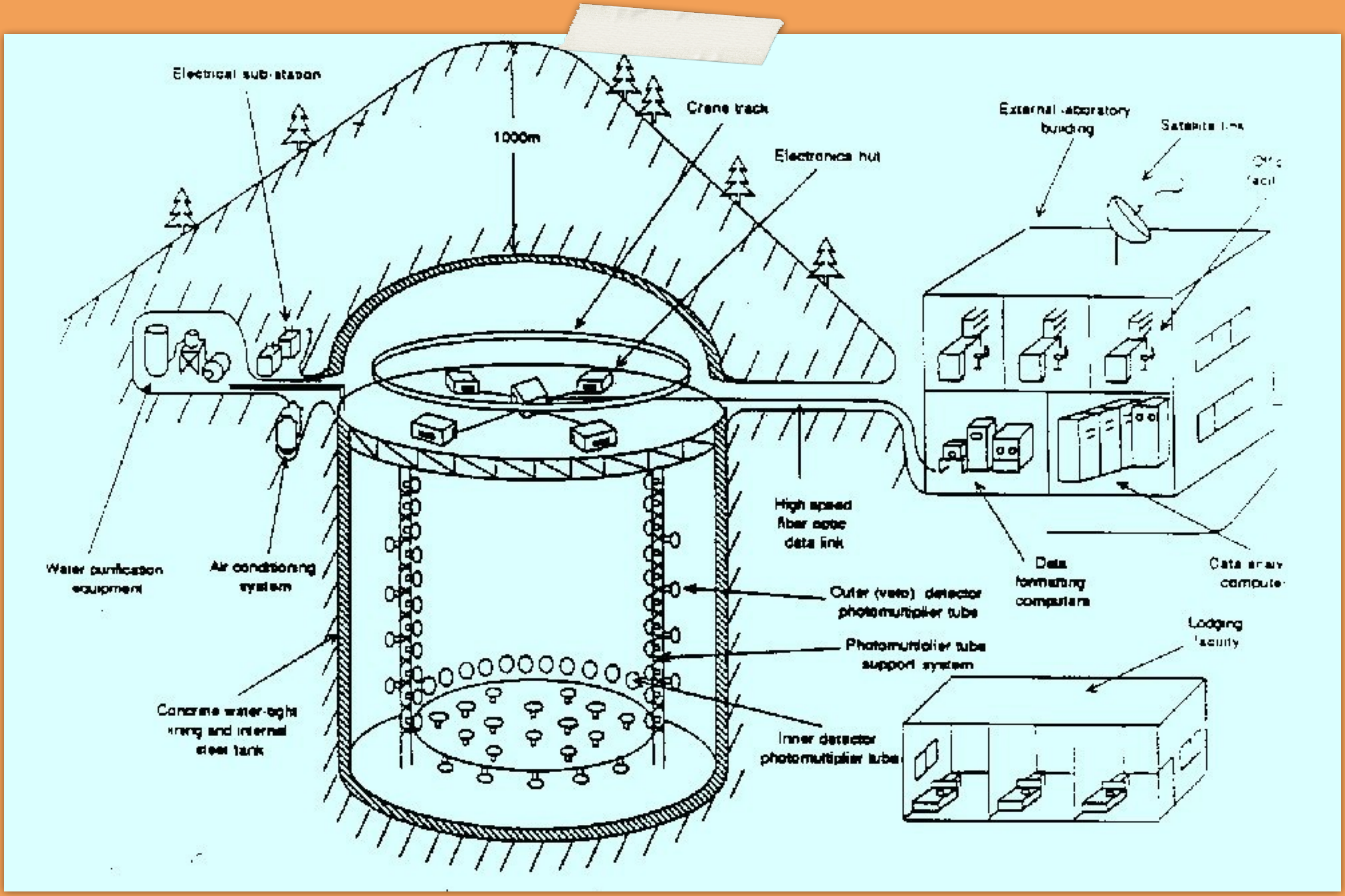
From Deuterium dissociation we obtain an observable neutron...

Whatever the type of neutrino !



The total number of solar neutrinos is <u>just as expected</u> (SNO)

Muon atmospheric neutrino disappear as known since 80's (KamiokaNDE)

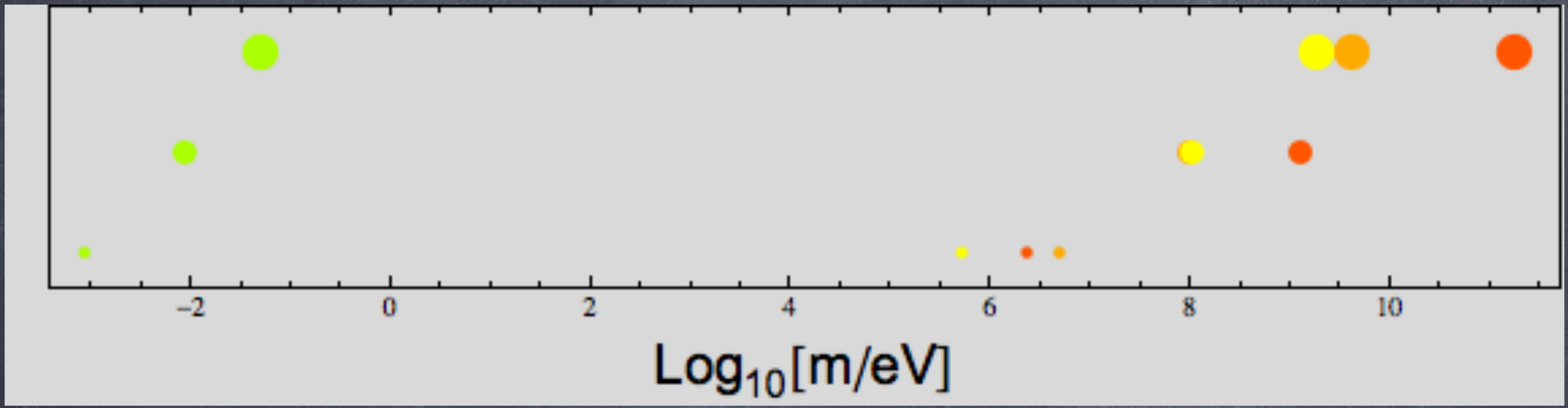


They <u>become tau neutrinos</u>

as was checked directly (OPERA)

Fermion masses

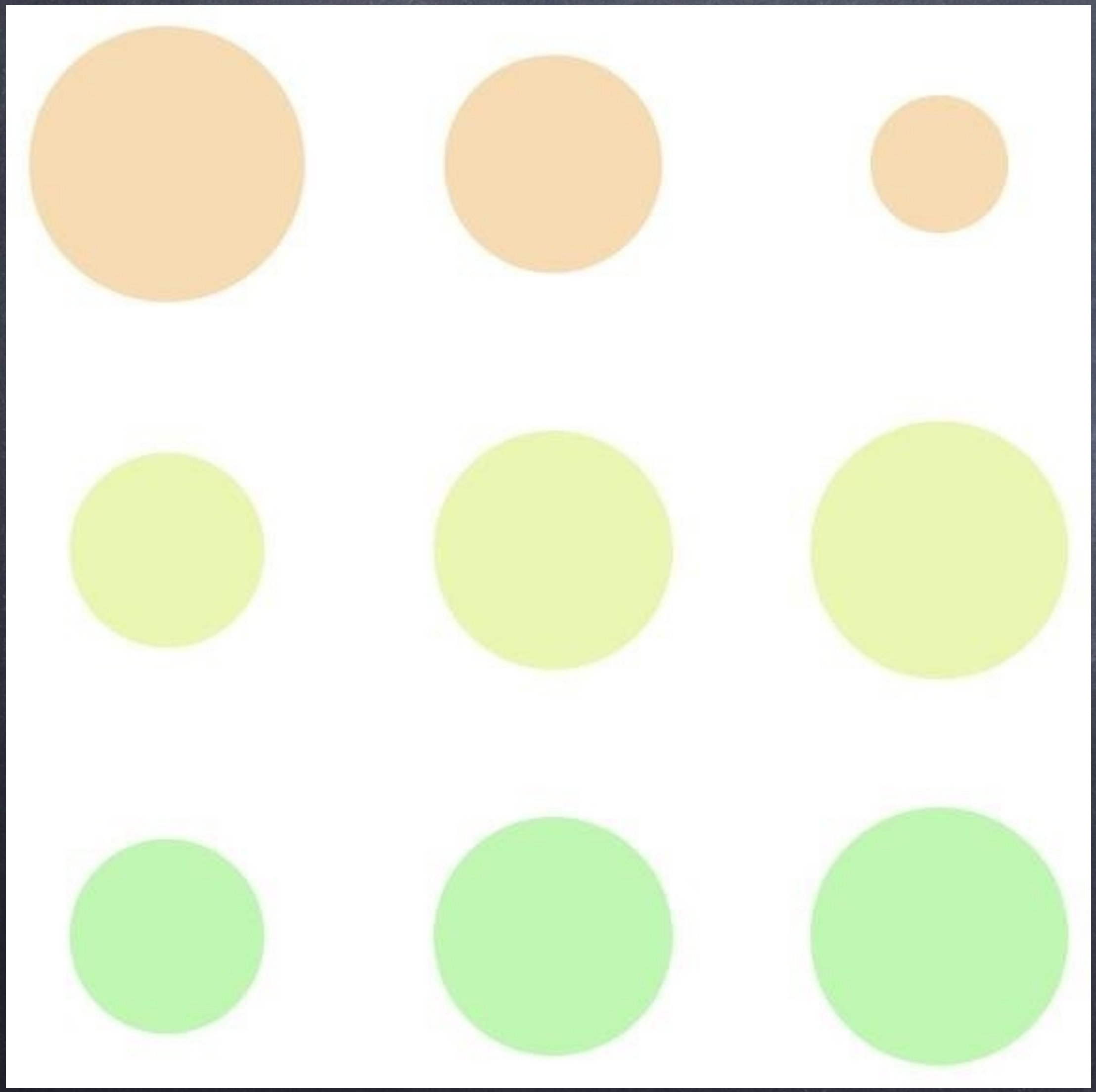
Green=neutrinos; Yellow=charged leptons;
Orange=down quarks; Red=up quarks.



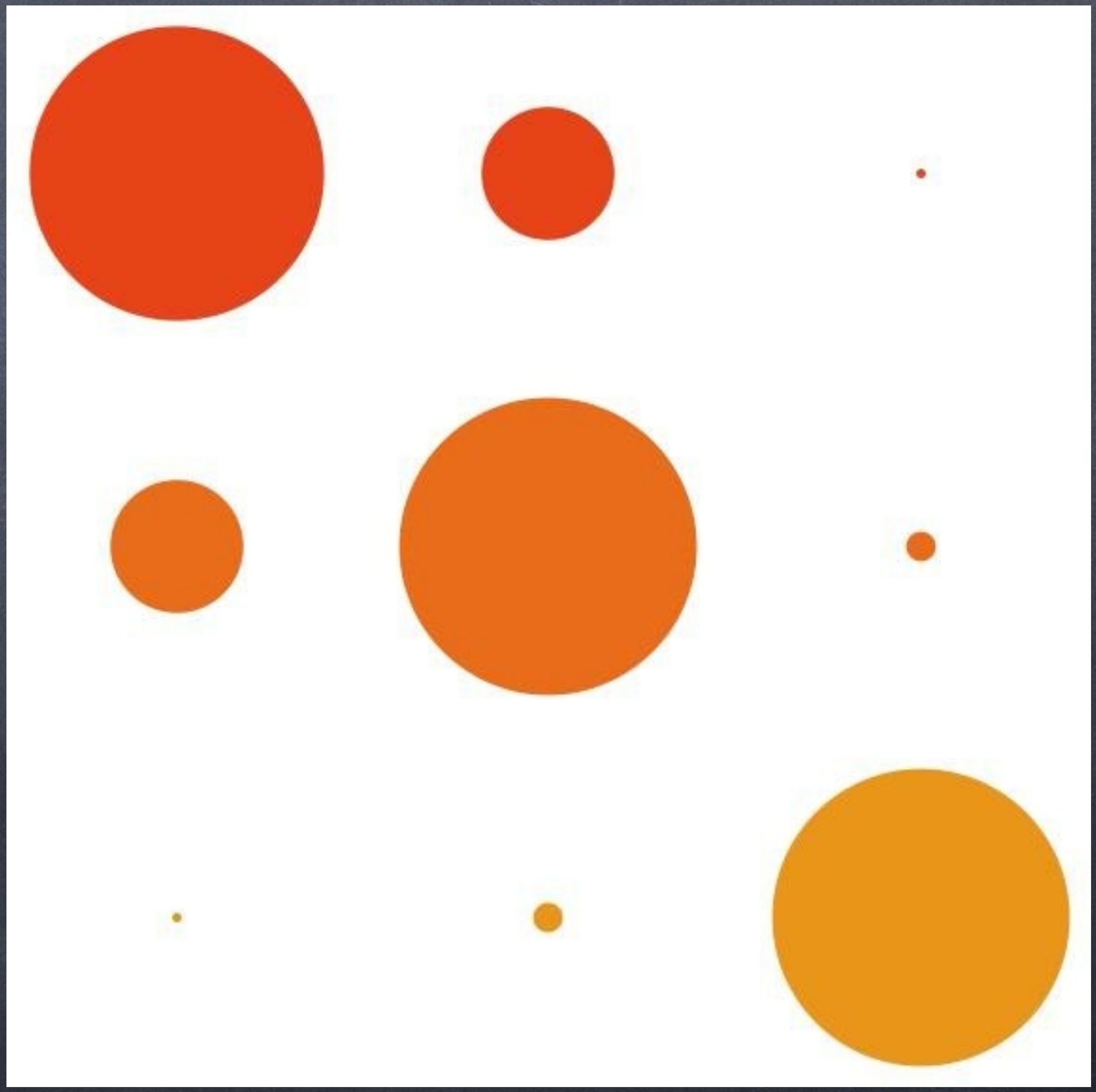
For neutrinos, I plot square root of $m^2_j - m^2_i$

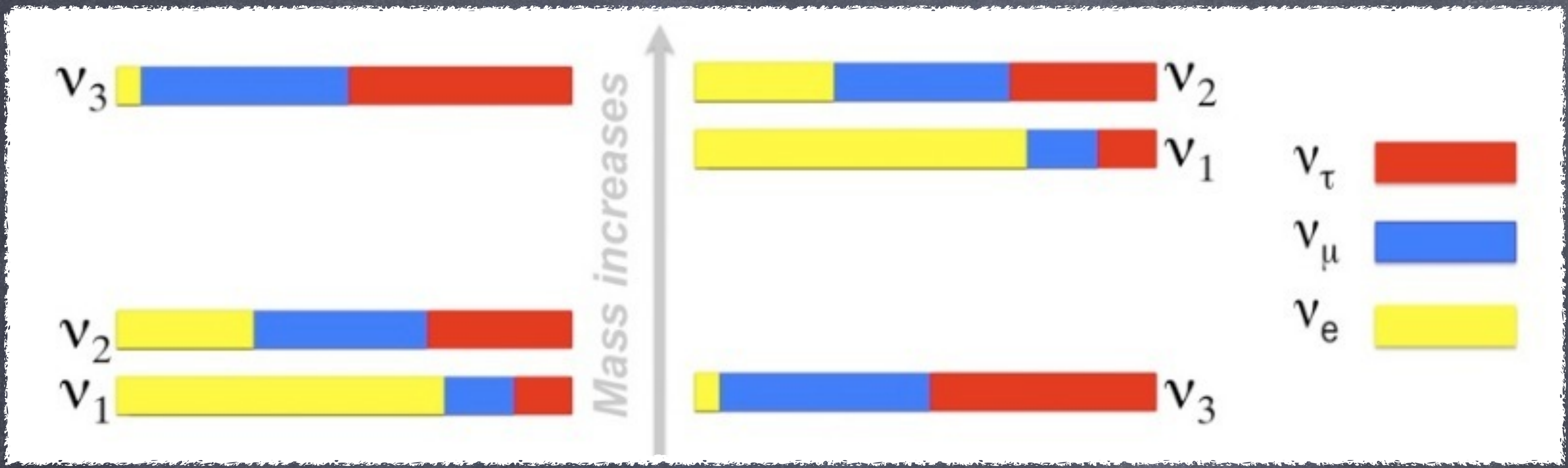
Area of the circles = Size of the mixing elements of leptons, $|U_{e1}|$, $|U_{e2}|$, $|U_{e3}|$, $|U_{\mu 1}|$,... and of quarks, $|V_{ud}|$, $|V_{us}|$, $|V_{ub}|$, $|V_{cs}|$ ...

LEPTONS



QUARKS





The data are compatible with two hierarchies of mass –i.e., spectra

indeed, oscillations probe only the differences of the squared masses; and on top of that, they cannot probe the absolute mass scale…

http://pcbat1.mi.infn.it/~battist/cgi-bin/oscil/index.r

Neutrino Oscillations Simulator

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Vasilis Vlachoudis CERN
23 Apr 2014 12:17:46

Plot Options

Energy Range: 0.2 - 10.0 GeV Bins: 100 bins

Probability Range: 0.0 - 1.0

Plot Reset

#1 Case

Oscillation Parameters

Θ_{12} 34.0 deg Θ_{13} 9.0 deg

Θ_{23} 42.0 deg Δ 270 deg

$\Delta m_{12}{}^2$ 7.5E-5 eV^2 $\Delta m_{23}{}^2$ 2.4E-3 eV^2

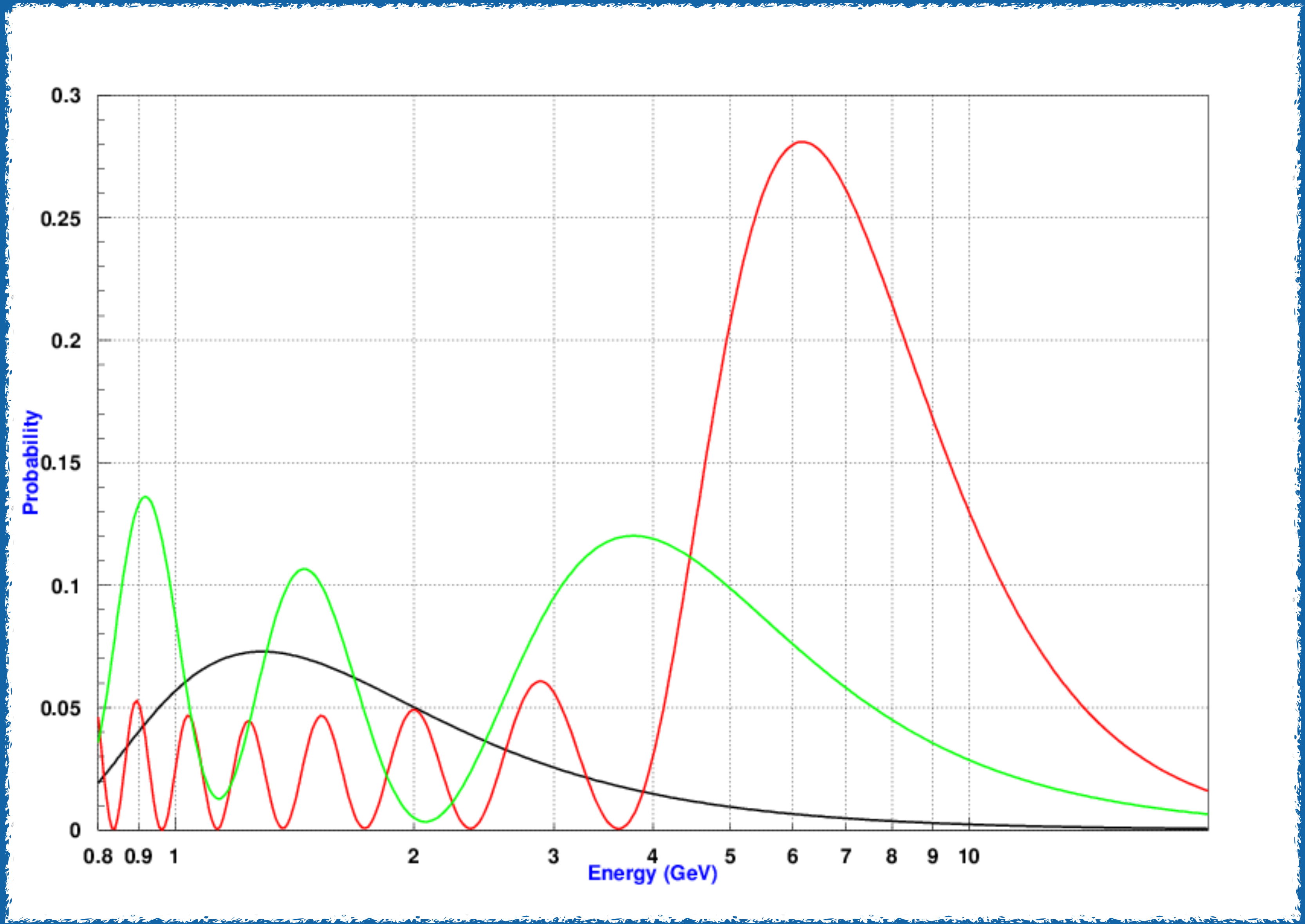
Hierarchy Normal   Matter Effects Activated

Distance: 730. km

An additional effect acts on neutrinos that propagate in the matter (here, Earth matter)

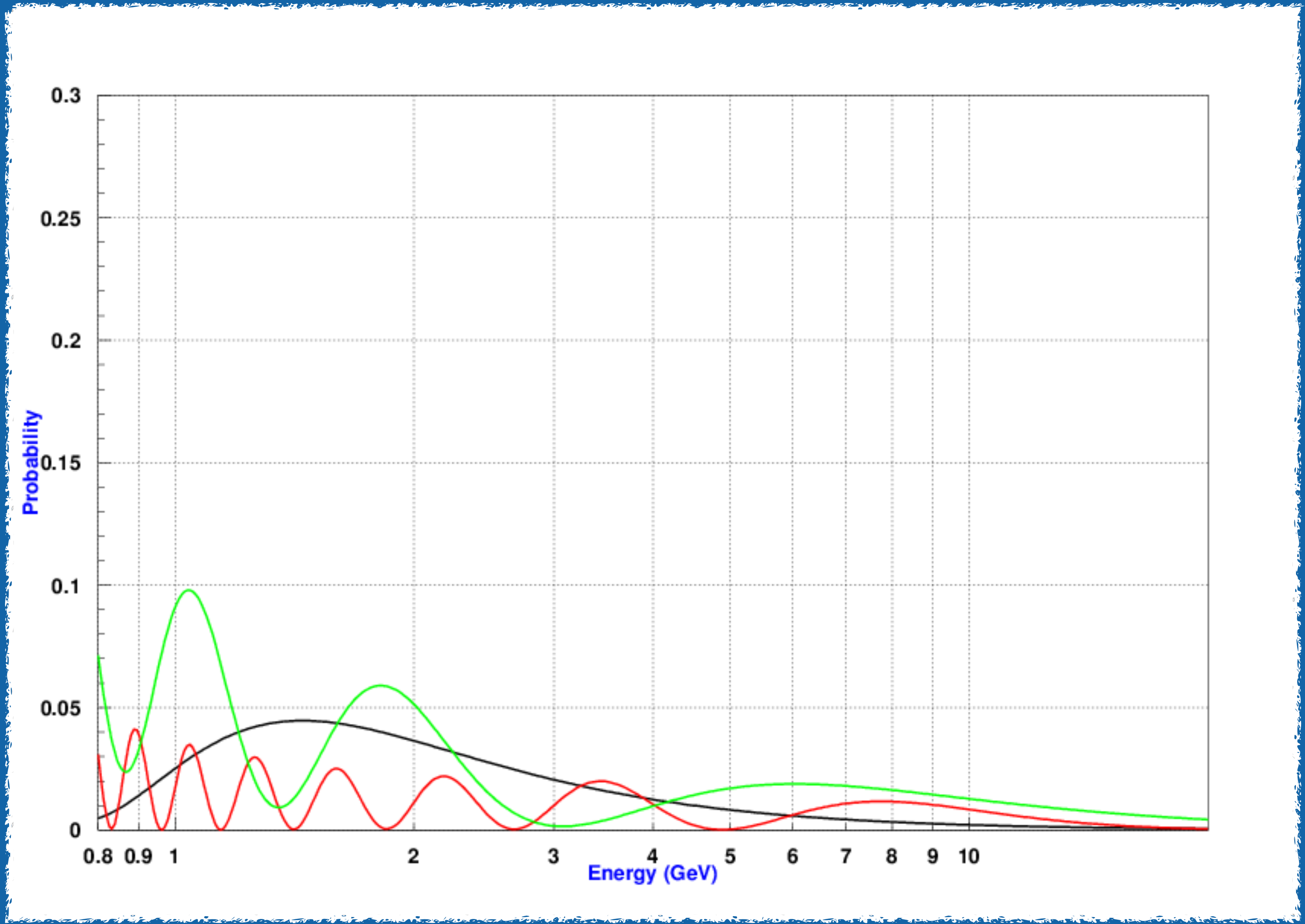
Plot

$\nu_e \Rightarrow \nu_e$ $\nu_\mu \Rightarrow \nu_e$ $\nu_\tau \Rightarrow \nu_e$



oscillations of muon to electron neutrinos

for a distance of 730 (black), 2500 (green), 6371 (red) km



oscillations of muon to electron anti-neutrinos

for a distance of 730 (black), 2500 (green), 6371 (red) km

Non-oscillation measurements of the mass?

Barker et al., 2013; Dell'Oro et al, 2014

- Kinematic limits from SN1987a: <5.8 eV
- Search in tritium spectrum: <2 eV
- Majorana mass from $0\nu2\beta$: <0.2-0.9 eV
- Cosmology: <0.07 eV (or = 0.11 eV?)

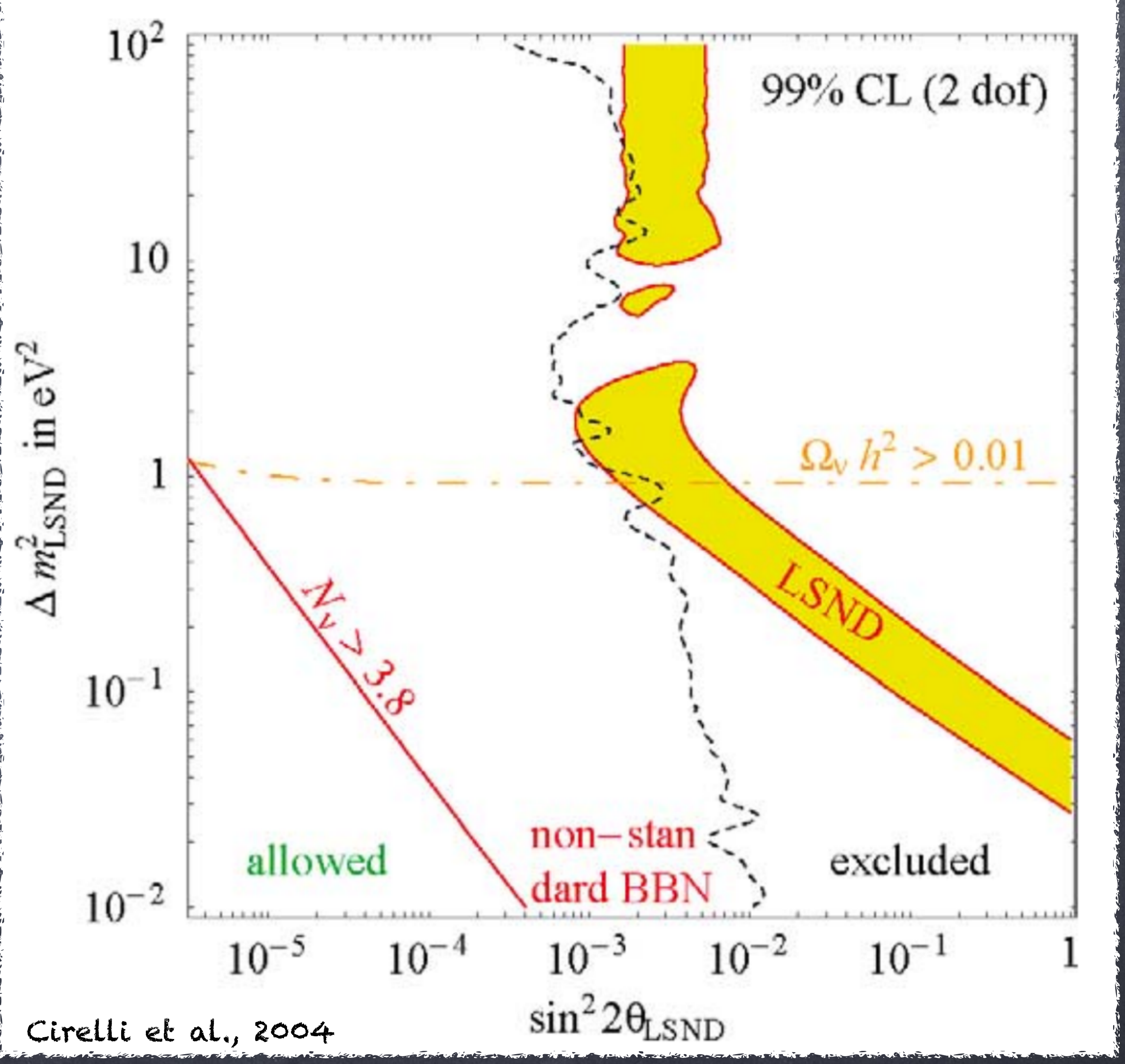
remind that oscillations do not probe the absolute mass scale and note we assume only 3 light neutrinos here

Other neutrinos?

- The Z^0 width indicates 3 neutrinos
- One can postulate non-interacting light neutrinos to address anomalies, e.g., LSND
- Cosmology? (see Melchiorri's lecture and Verde et al., arXiv:1404.5950)

A global approach to the data

LSND observations can be attributed to oscillations of new neutrinos, but at the price of tension with other data

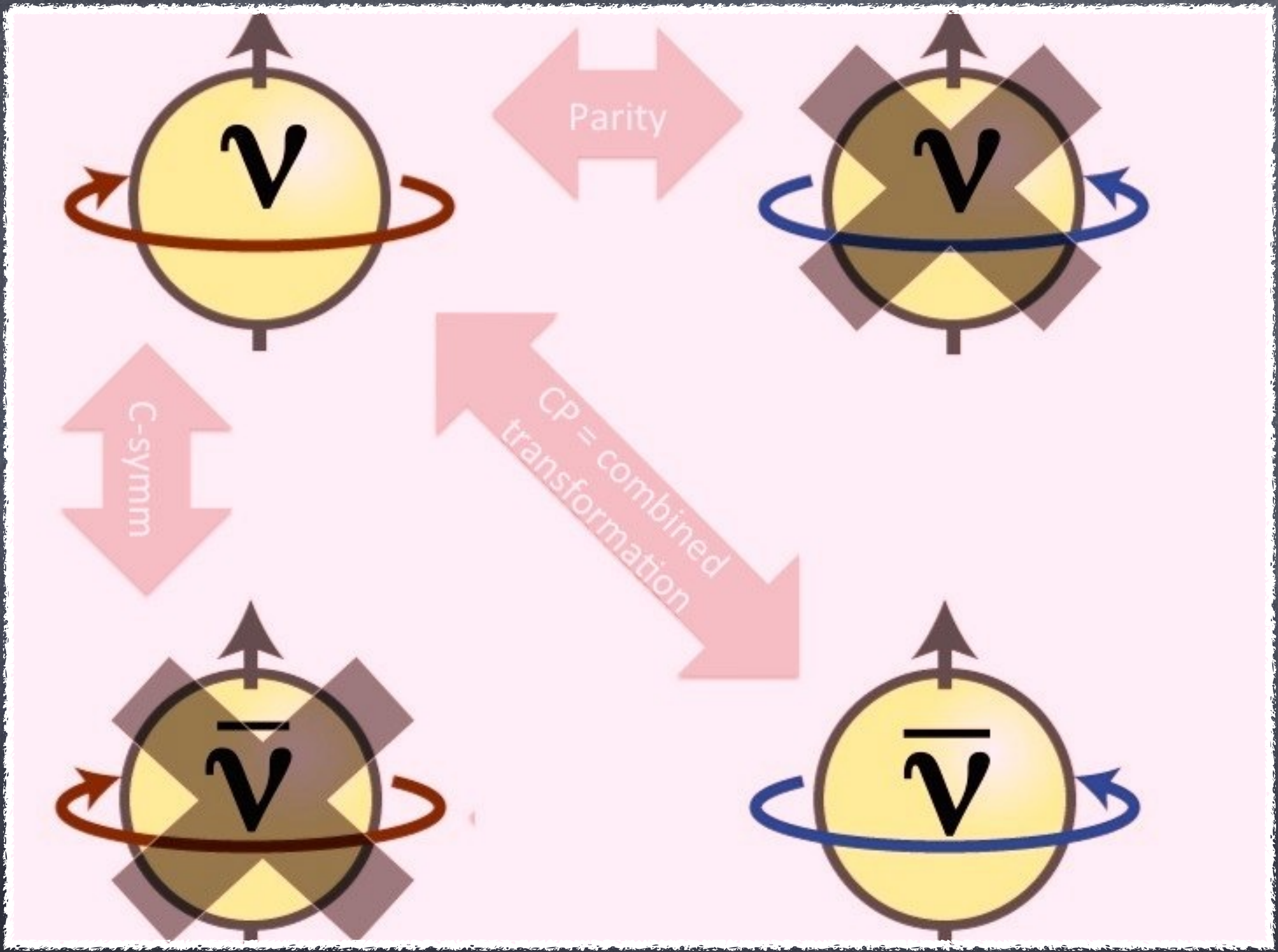


Cirelli et al., 2004

Neutrino masses in particle physics

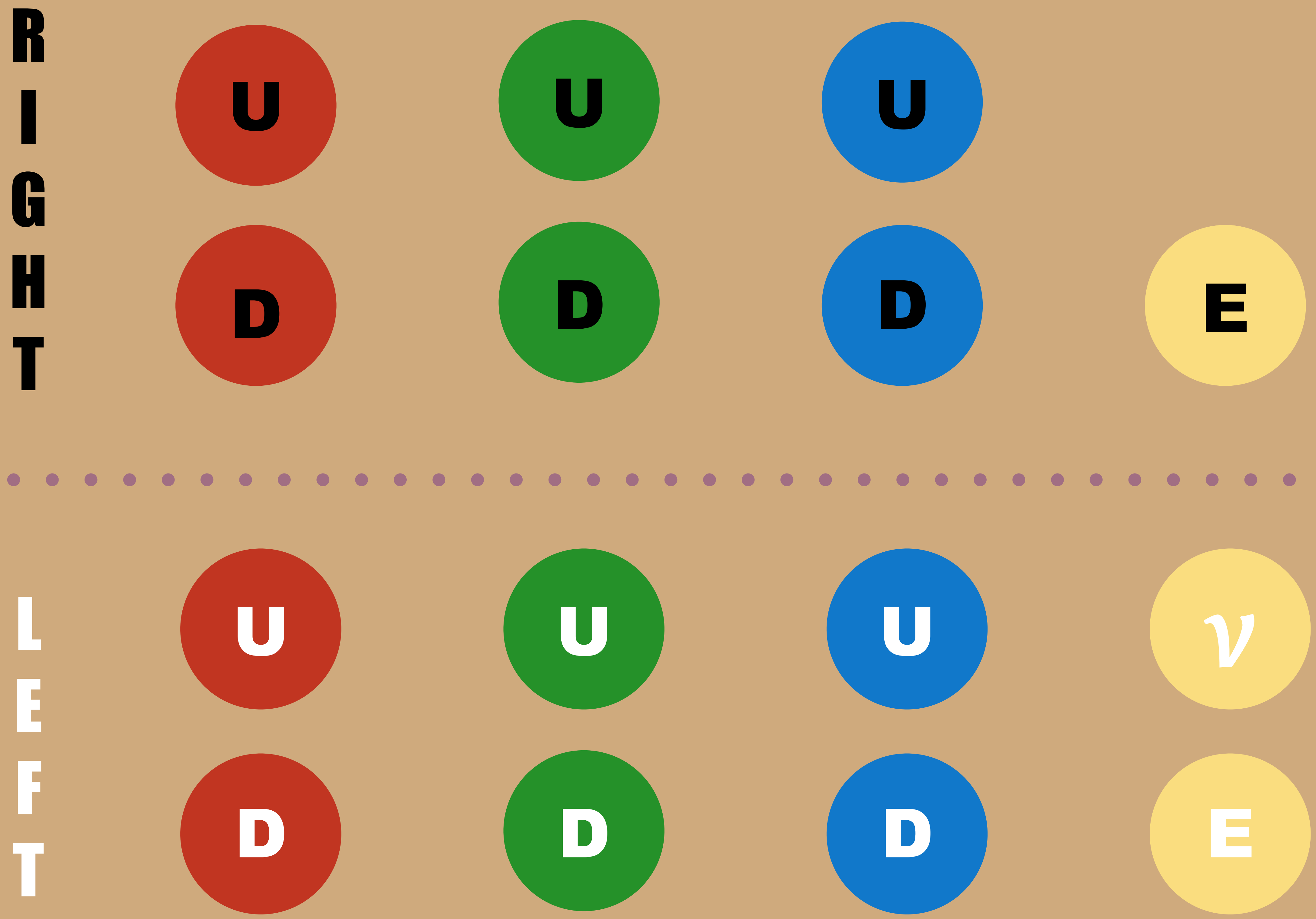
- Observation of the Higgs particle: a triumph of standard model (SM).
- All known particles get mass from this one.
- Except neutrinos, that are massless. Thus we know that SM is incomplete!

remind: Neutrinos



have only one polarization state (in the SM)

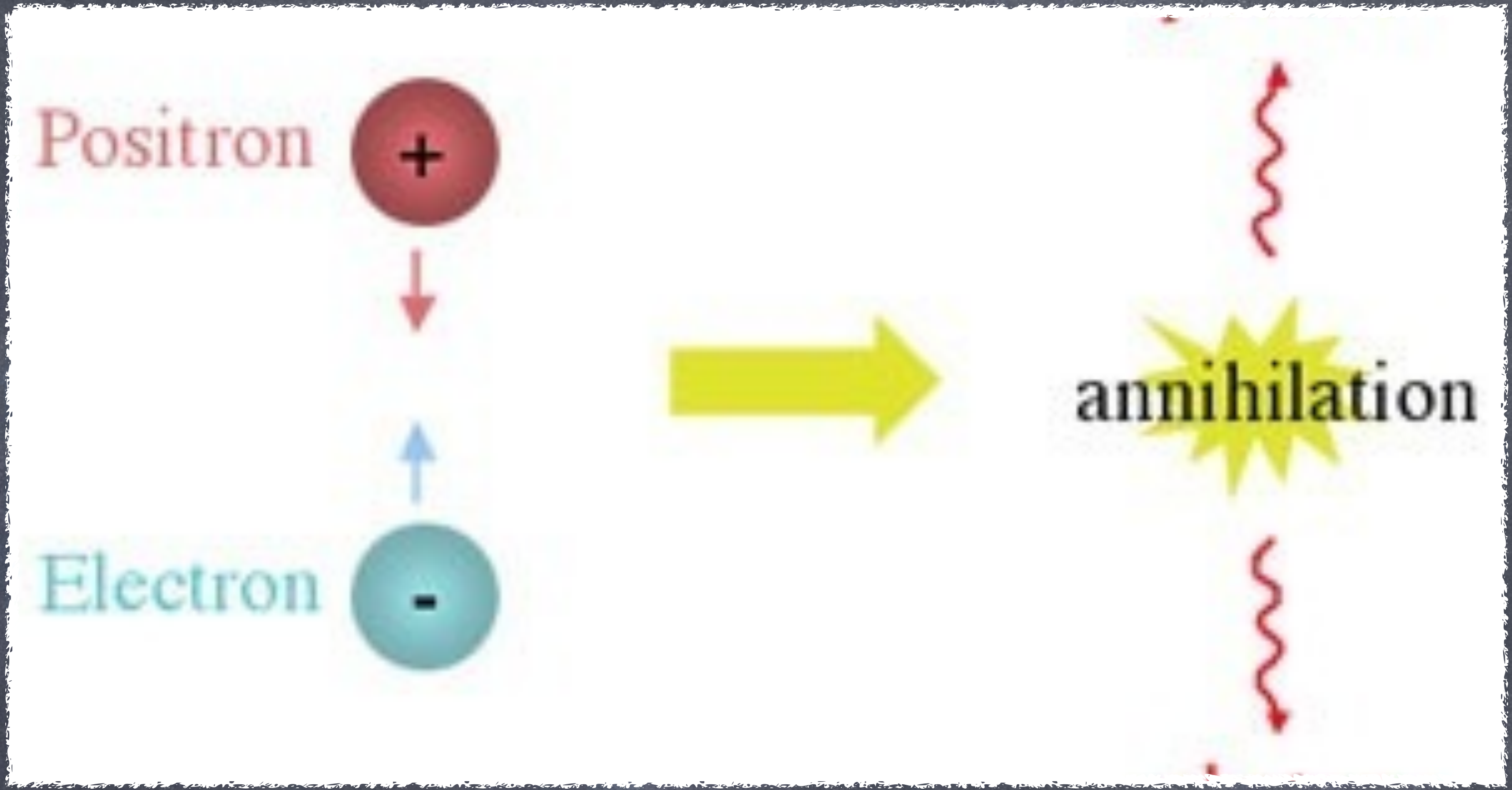
15 particles per family



Modifying the SM?

- It is quite natural to add a "right" neutrino to the spectrum: a non-interacting neutrino.
- This provides us with an explanation for neutrino masses.
- But it means a new mass scale, unrelated with the SM scale (i.e., with the Higgs mass).

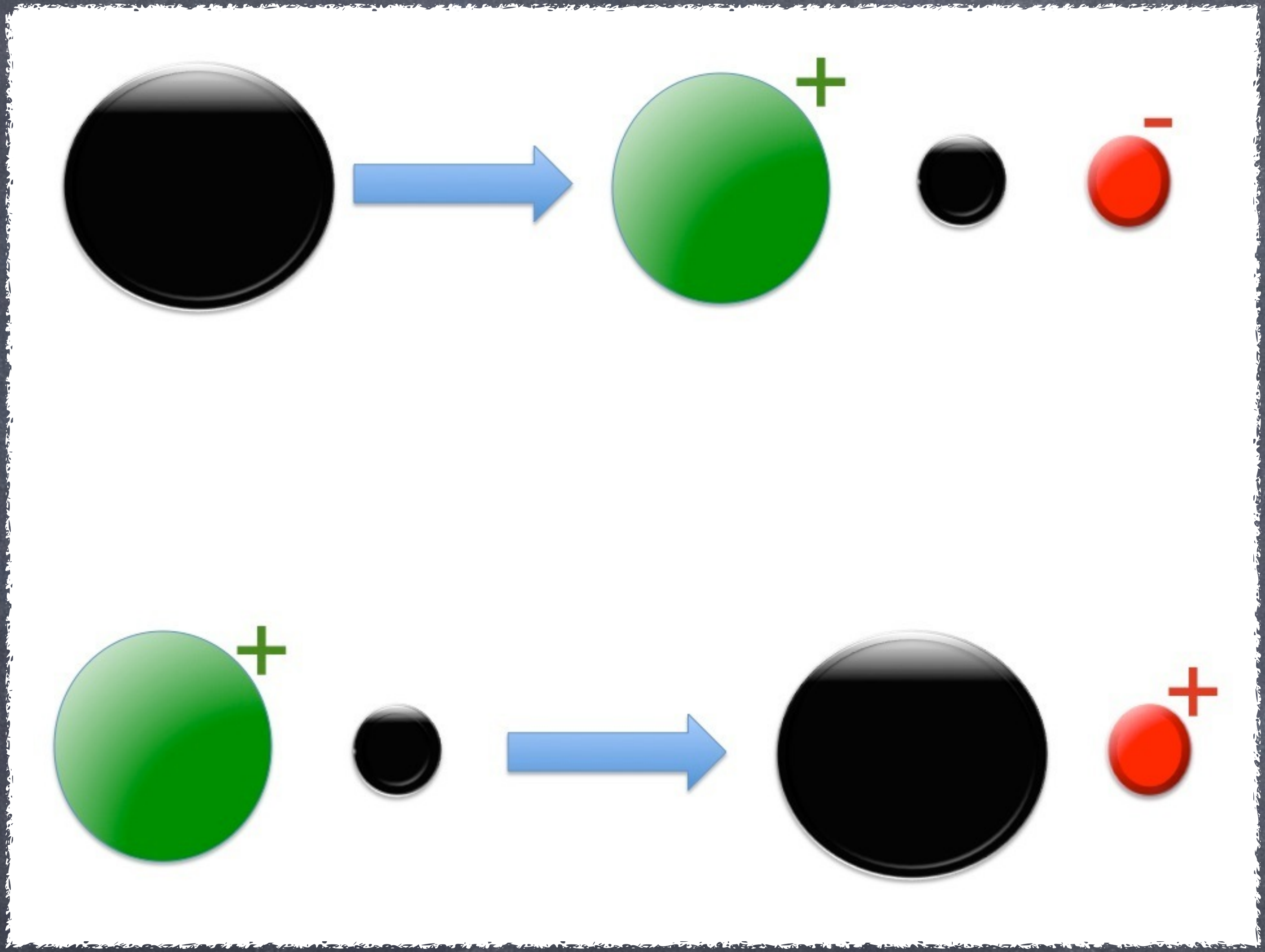
Baryogenesis



antimatter does exist

and it manifests itself, e.g., in high-energy astrophysics

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



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

the (anti)neutrino cross section is connected to the beta decay rate; this was used to observe the (anti)neutrino from nuclear reactors.

Sakharov '67

- In the early Universe, matter & antimatter annihilate
- If we want to explain the predominance of matter ...
- ... we need baryon-, C- and T-violation

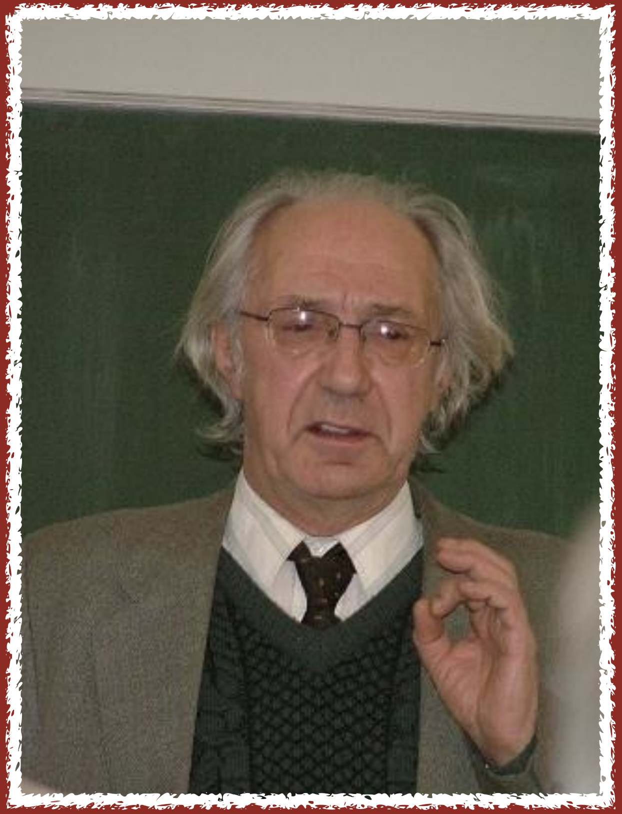
What about the SM?

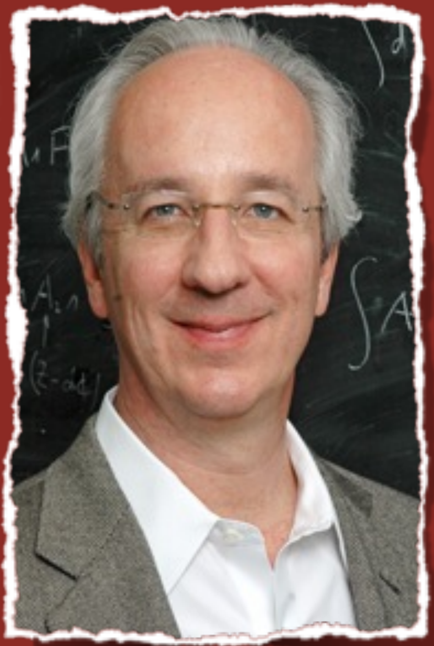
- Weak interaction violate C maximally
- CP is violated, albeit mildly, in hadronic interactions (e.g., $K_L \to \pi^+ \pi^-$)
- However baryon and lepton numbers are conserved ... arent they?

to be sure...

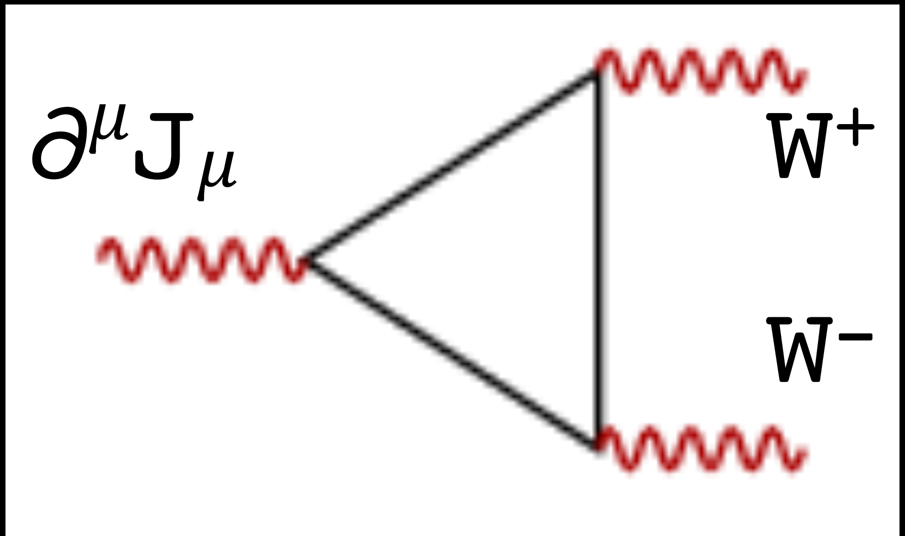
- We have never observed any variation of the number of baryons or of leptons
- E.g., $p \to e^{+} \pi^{0}$ is allowed by energy conservation, but has never been seen
- Also, $(A,Z) \to (A,Z+2) + 2\, e^{-}$ (neutrinoless double beta decay) has not been observed
- Regarding the SM as a classical theory we can prove: baryon and lepton numbers do not change

but the SM has a surprise!



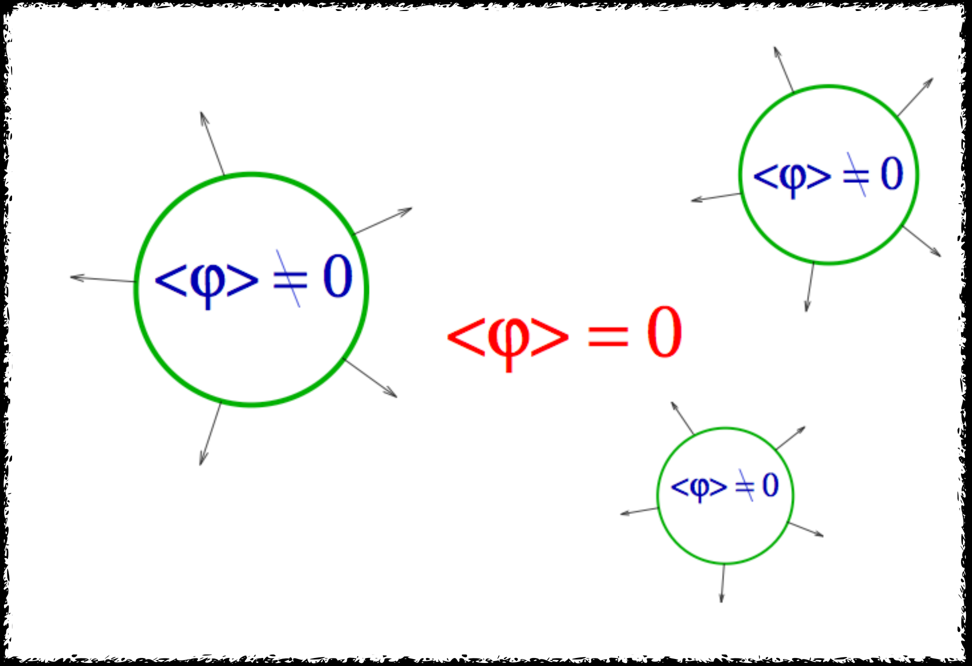


- The baryon and the lepton numbers are conserved in the classical theory.
- But not in quantum field theory: see Figure.
- Therefore, one expects transitions that change B and L, when W are in thermal equilibrium.

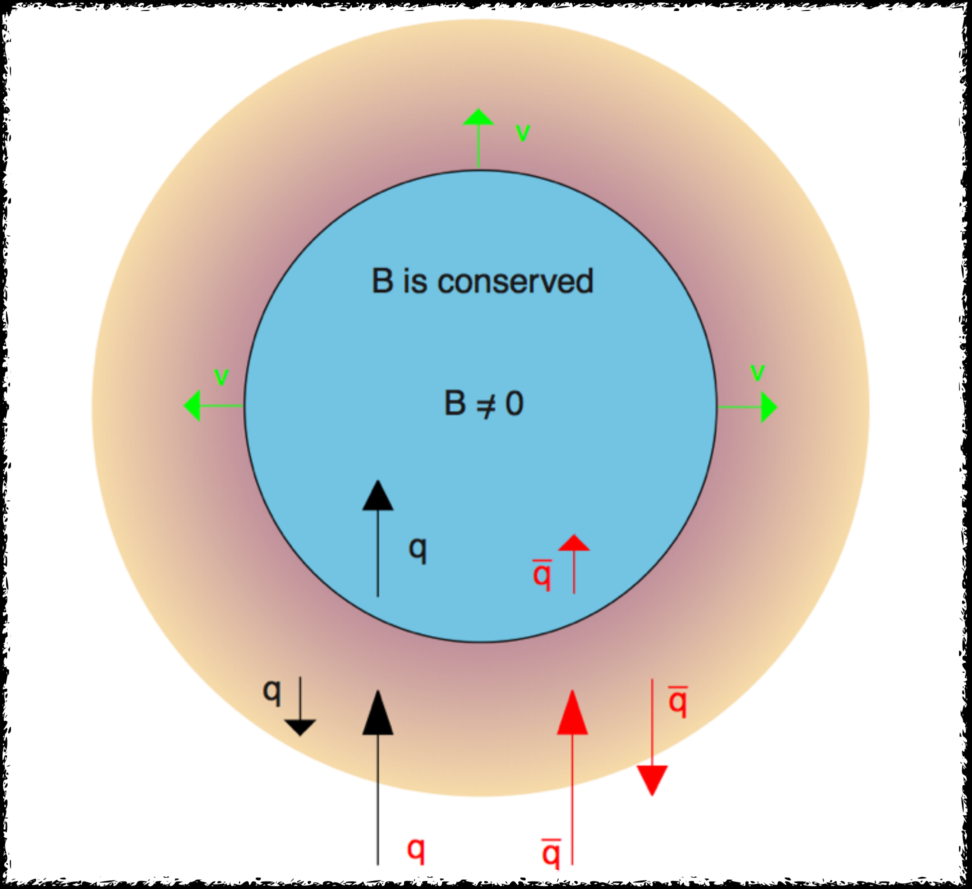


$$\partial^\mu B_\mu = \partial^\mu L_\mu = \frac{3}{32\pi^2}\,\mathrm{Tr}\Big[F_{\mu\nu}\,\tilde{F}^{\mu\nu}\Big]$$

- EW baryogenesis: the attempt to see whether the SM is enough



- The answer: SM alone does not work, just for quantitative (not for principle) reasons



With Fukugita & Yanagida

neutrino masses enter the stage

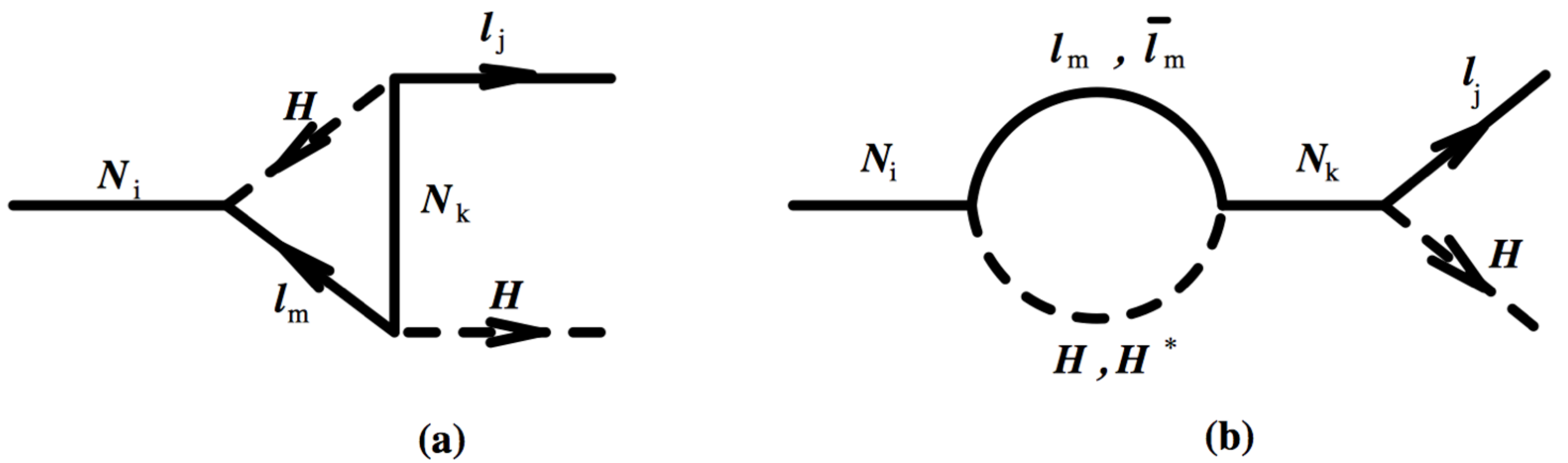


Figure 1: Diagrams contributing to the vertex (Fig. 1a) and wave function (Fig. 1b) CP violation in the heavy singlet neutrino decay.

Covi et al. '96

Heavy RH neutrinos

can prefer to decay into antileptons; then, converted into baryons

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

Shaposhnikov '09

too many mechanisms!

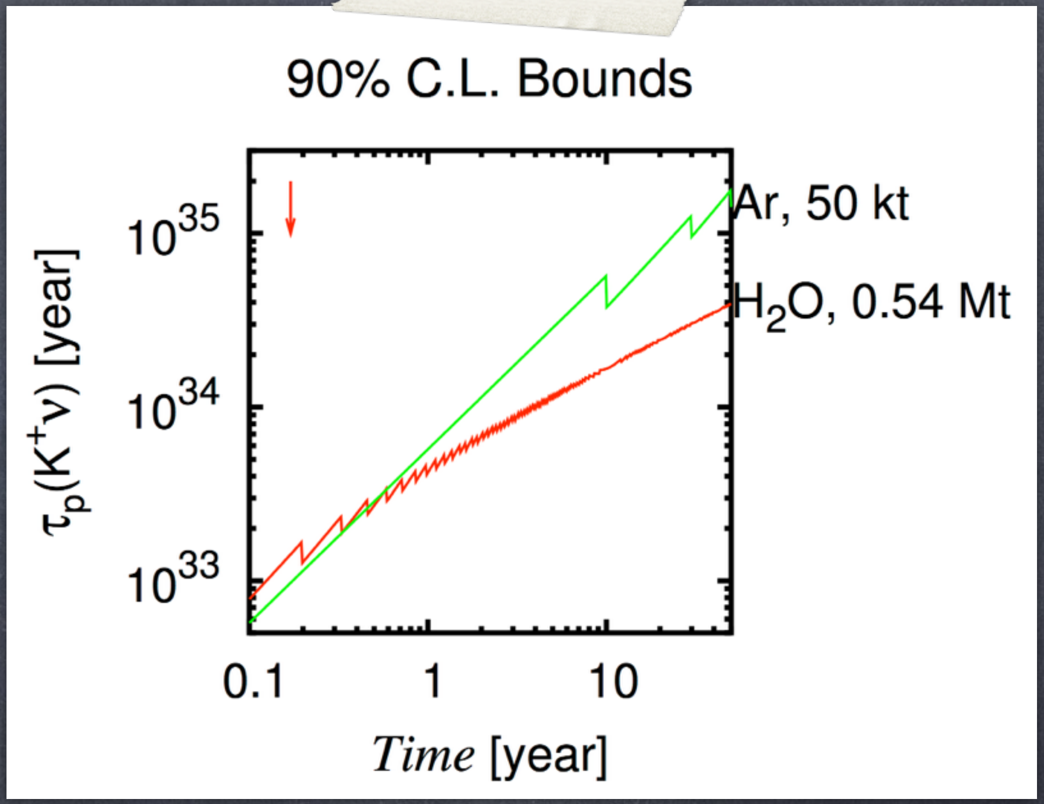
those testable in the lab can be regarded with favour

Shaposhnikov strikes again

- take full advantage of the 3 RH neutrinos
- one of them can be dark matter of ~10 keV
- the other ones, with mass ~GeV, can make lepto-genesis

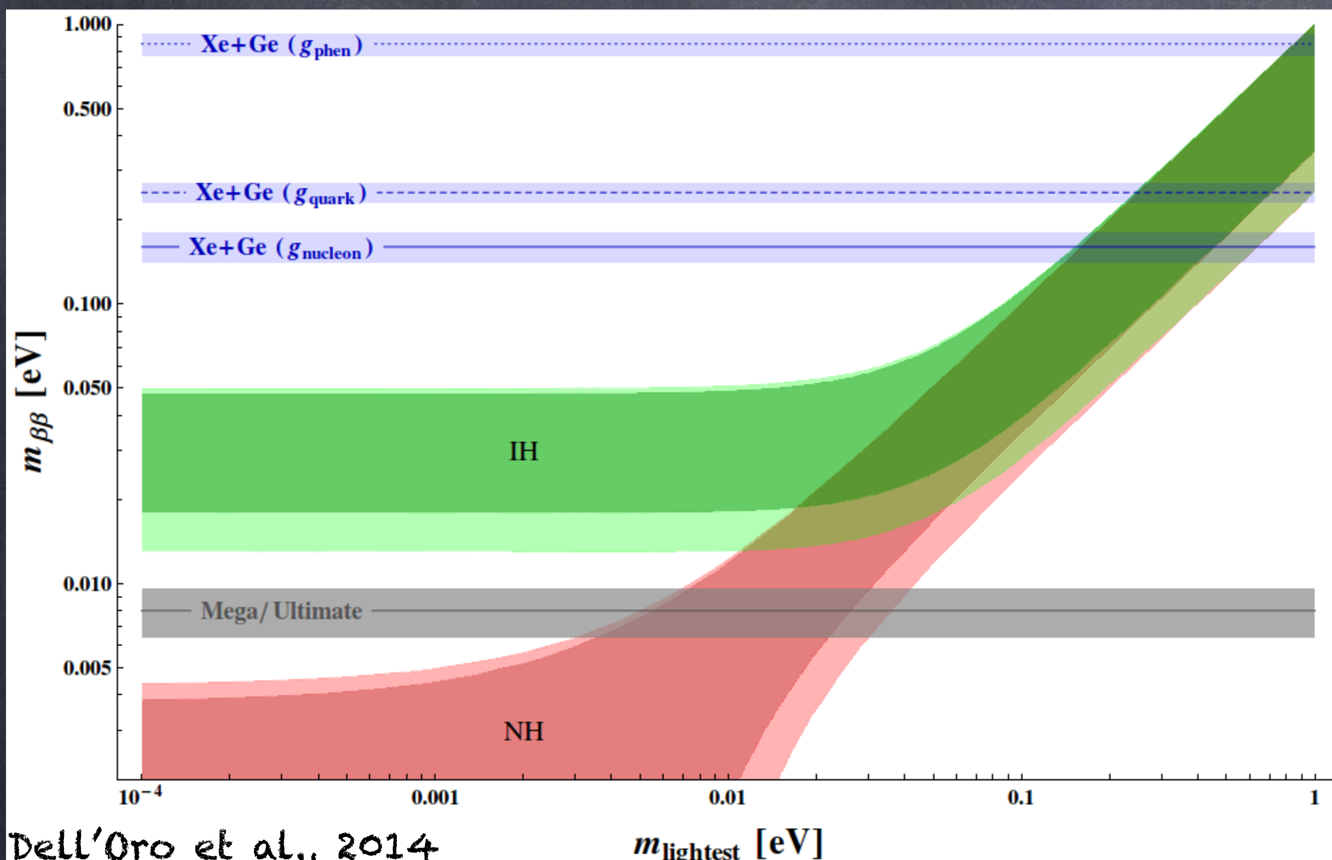
if nothing new is seen at accelerators, what else can we do to proceed?

we can search for matter instability (proton decay)

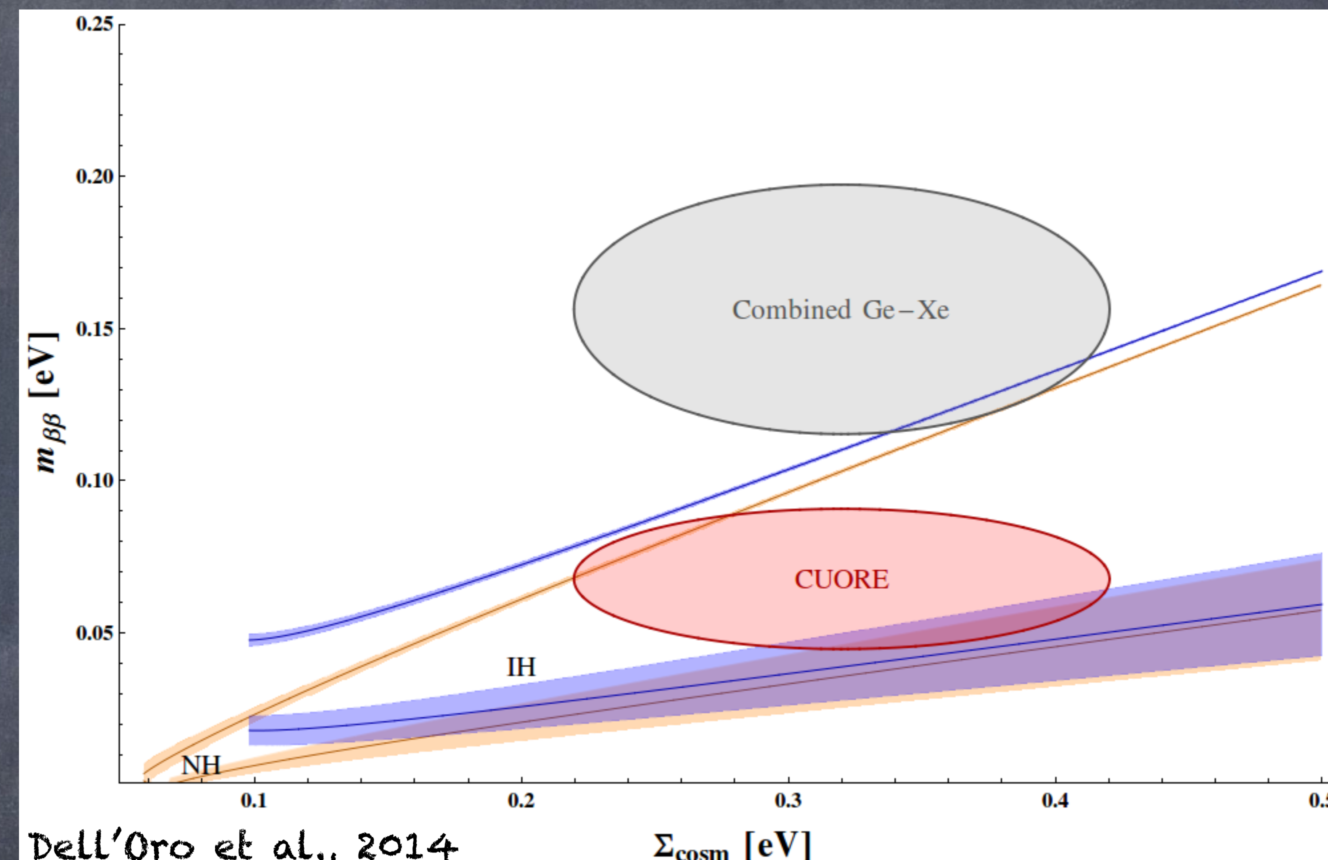


monitoring many 10 kton x year of matter, we have not seen any event yet.
In principle it is still interesting to continue to search for it and we would know how to do; but we have no clear theoretical clue where to find it.

we can search for the creation of electrons in a nuclear transition



Dell'Oro et al., 2014

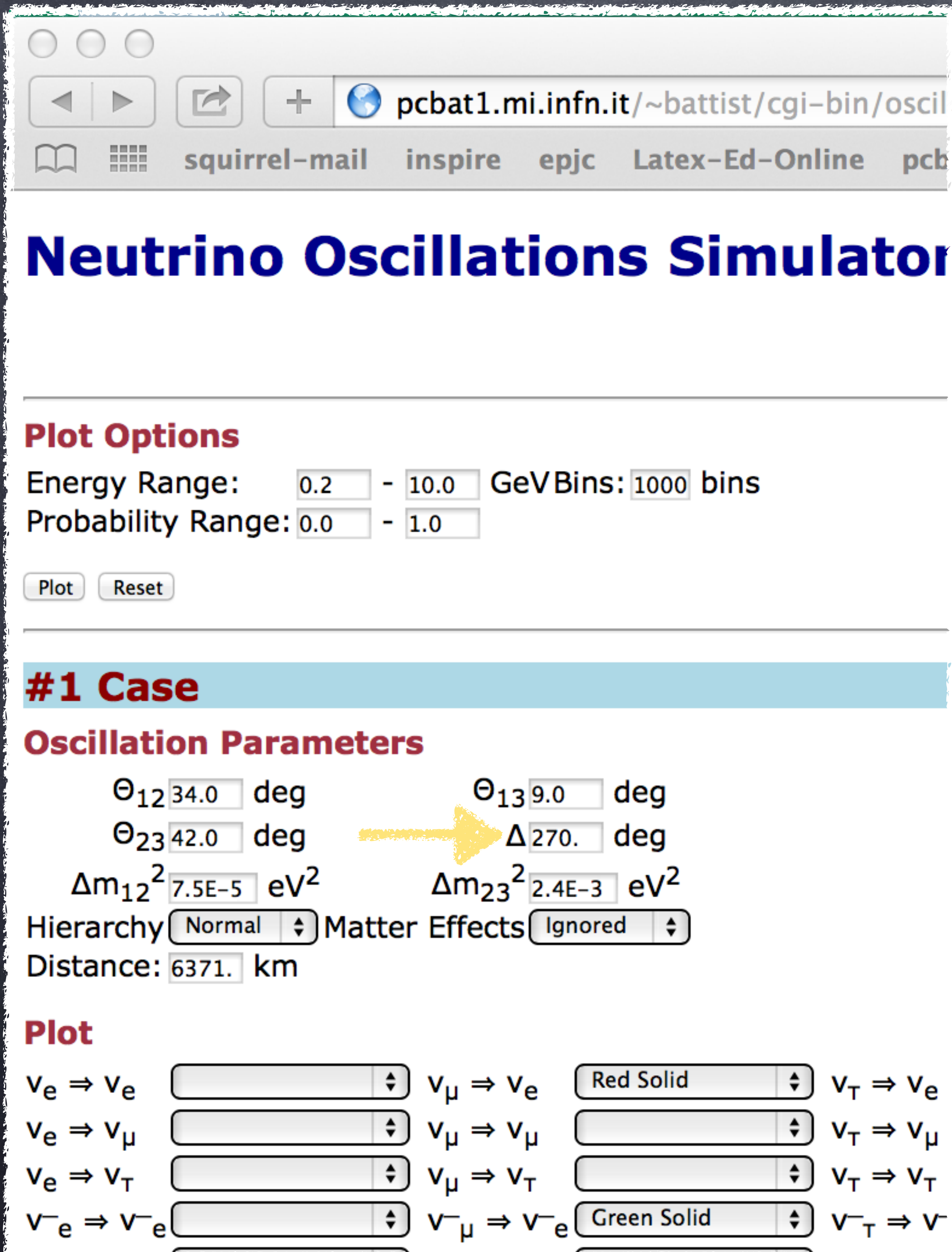


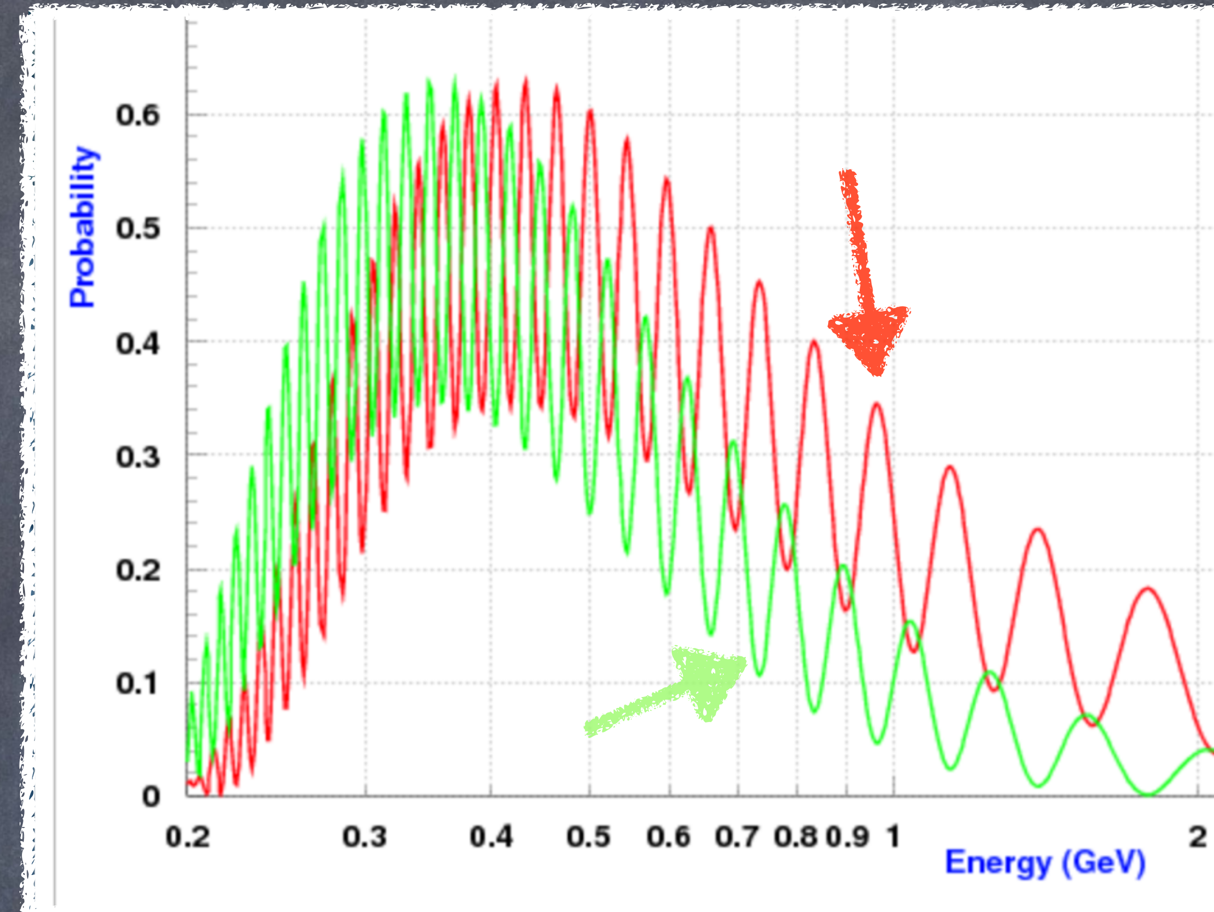
Dell'Oro et al., 2014

i.e., neutrinoless double beta decay

whose rate is linked with (Majorana) neutrino masses

we can search for leptonic CP violation





with CP violation, oscillations of a muon neutrino into an electron neutrino (red) differs from the same for antineutrinos (green) even in vacuum.