UNIVERSITY OF Southampton
School of Physics and Astronomy

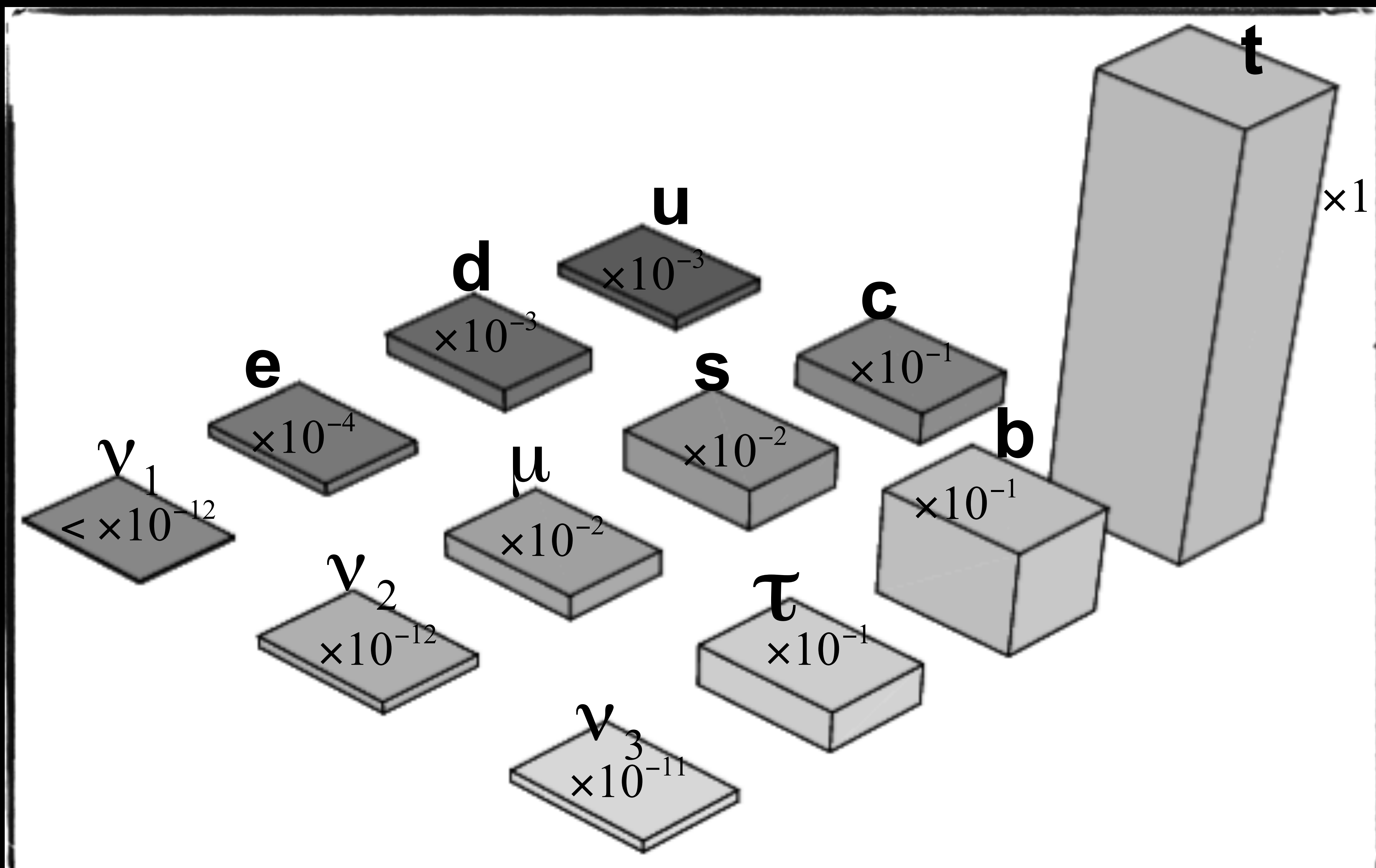
elusives invisiblesPlus
neutrinos, dark matter & dark energy physics

Flavour and Neutrinos

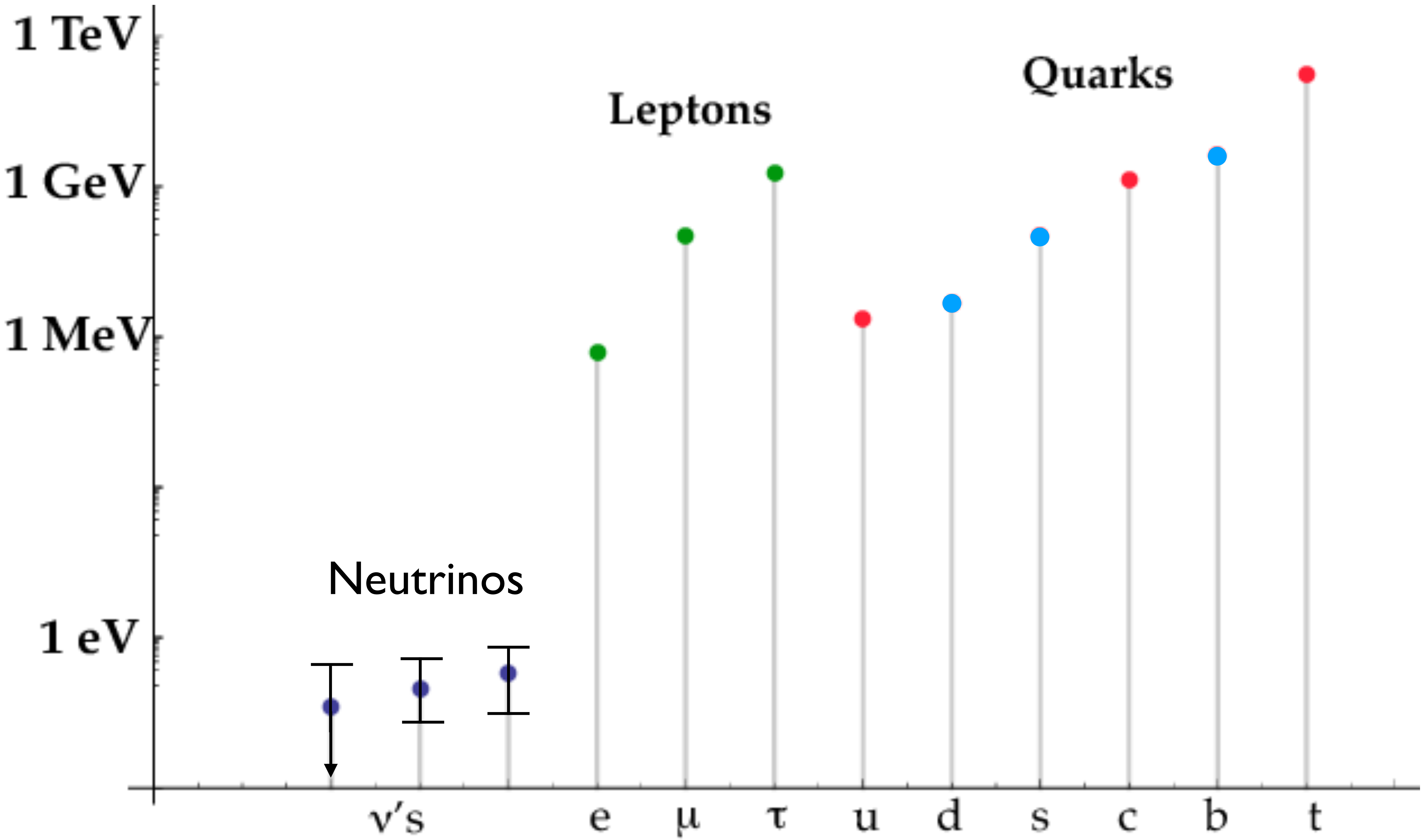
Steve King

Introduction to Flavour

Quark and Lepton Mass

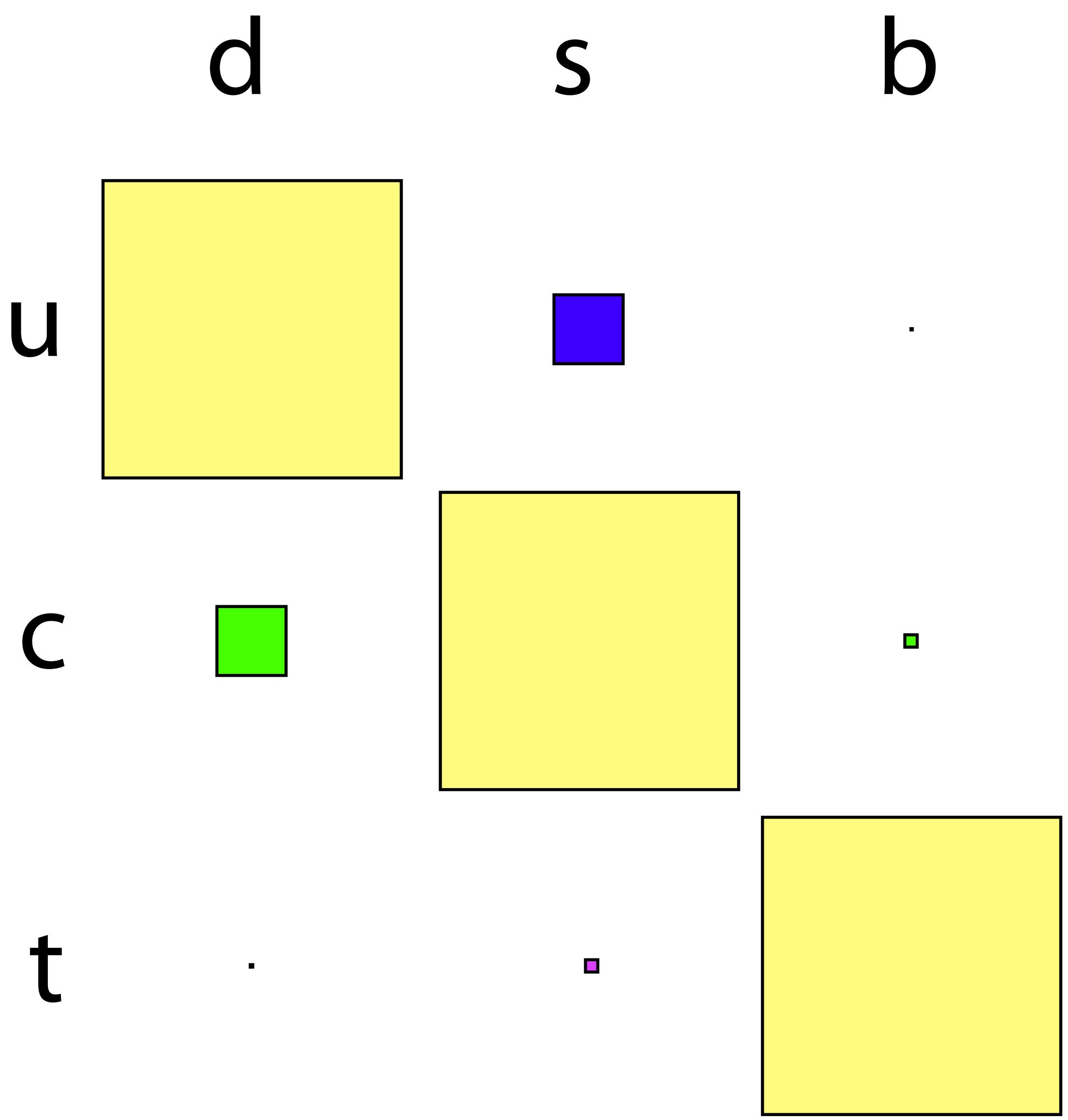


Masses

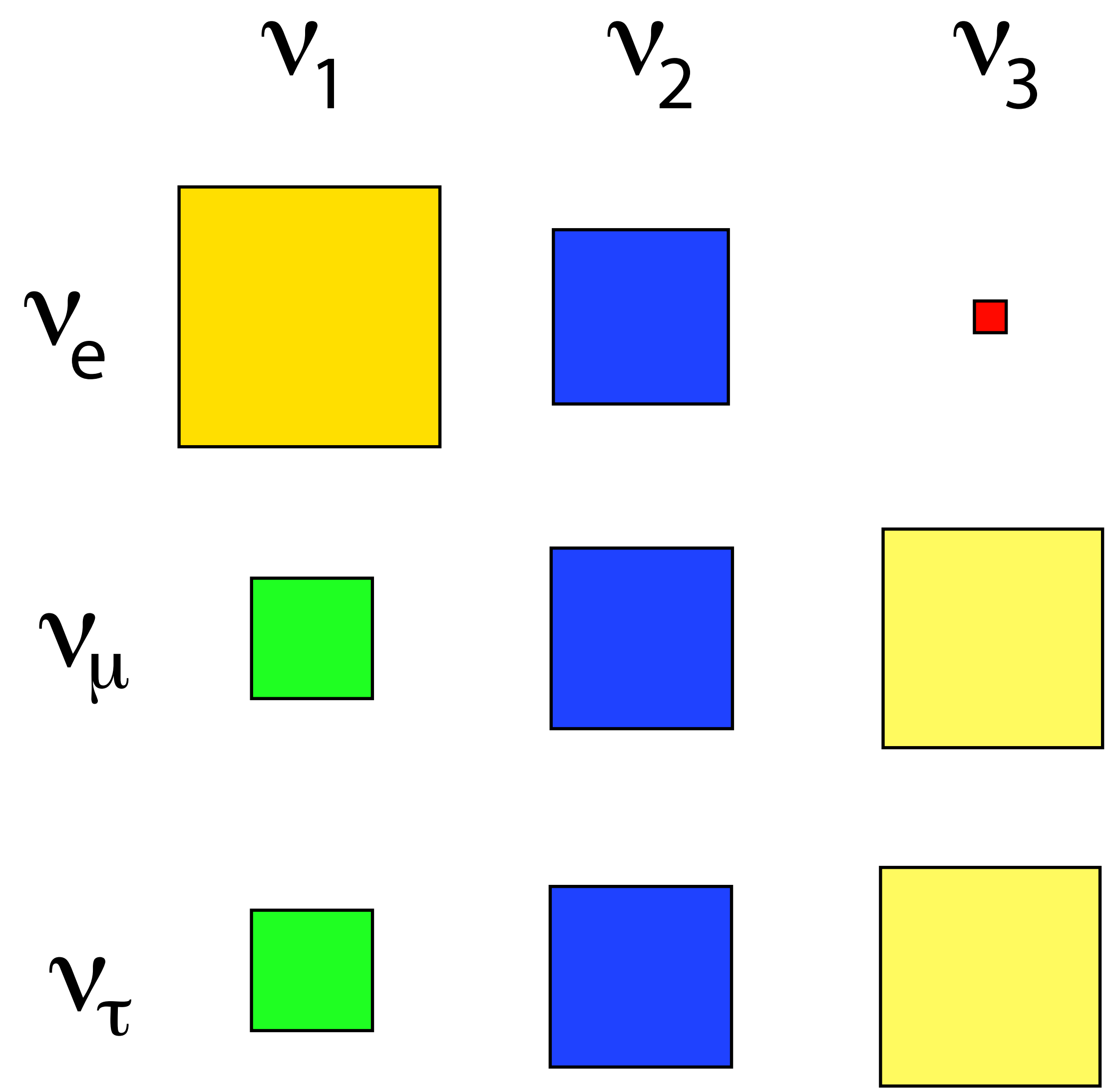


Mixing

CKM



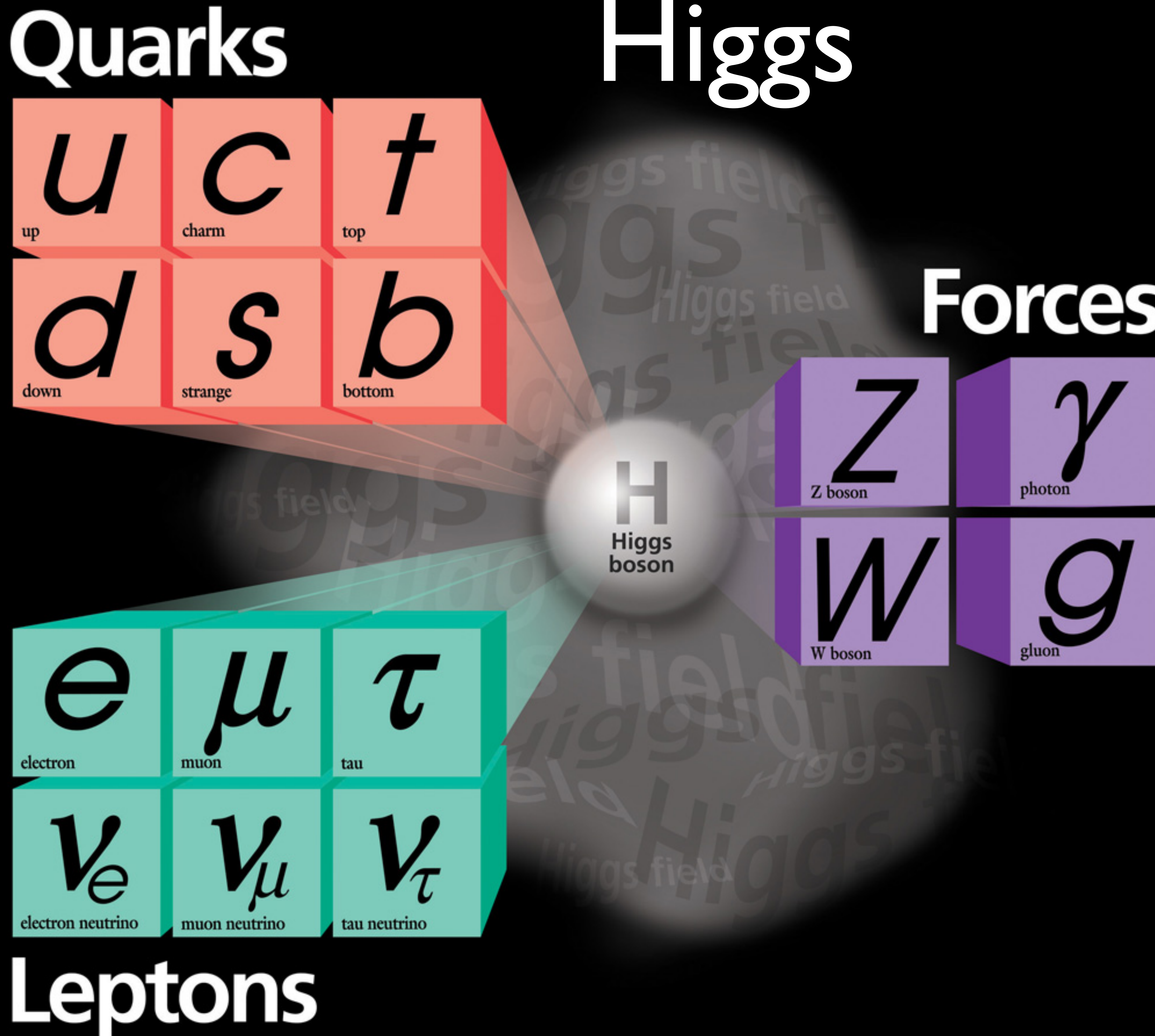
PMNS



Angles and CP

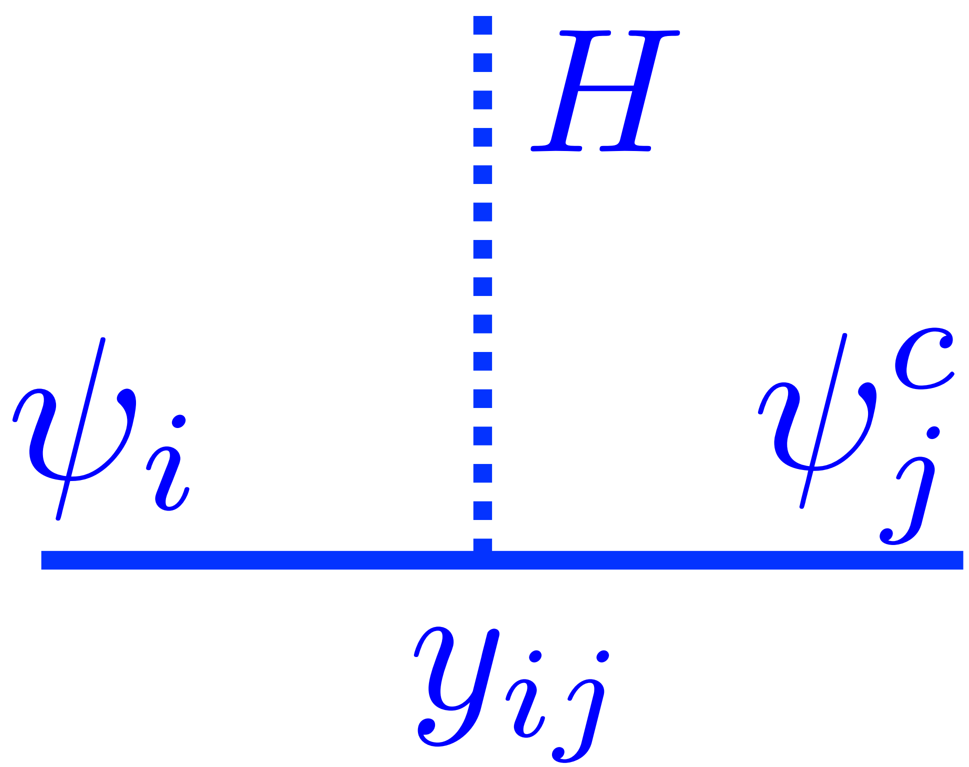
	θ_{12}	θ_{23}	θ_{13}	δ
Quarks	13° $\pm 0.1^\circ$	2.4° $\pm 0.1^\circ$	0.2° $\pm 0.05^\circ$	70° $\pm 5^\circ$
Leptons	34° $\pm 1^\circ$	45° $\pm 5^\circ$	8.5° $\pm 0.15^\circ$	-90° $\pm 50^\circ$

Higgs


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons

Yukawa couplings

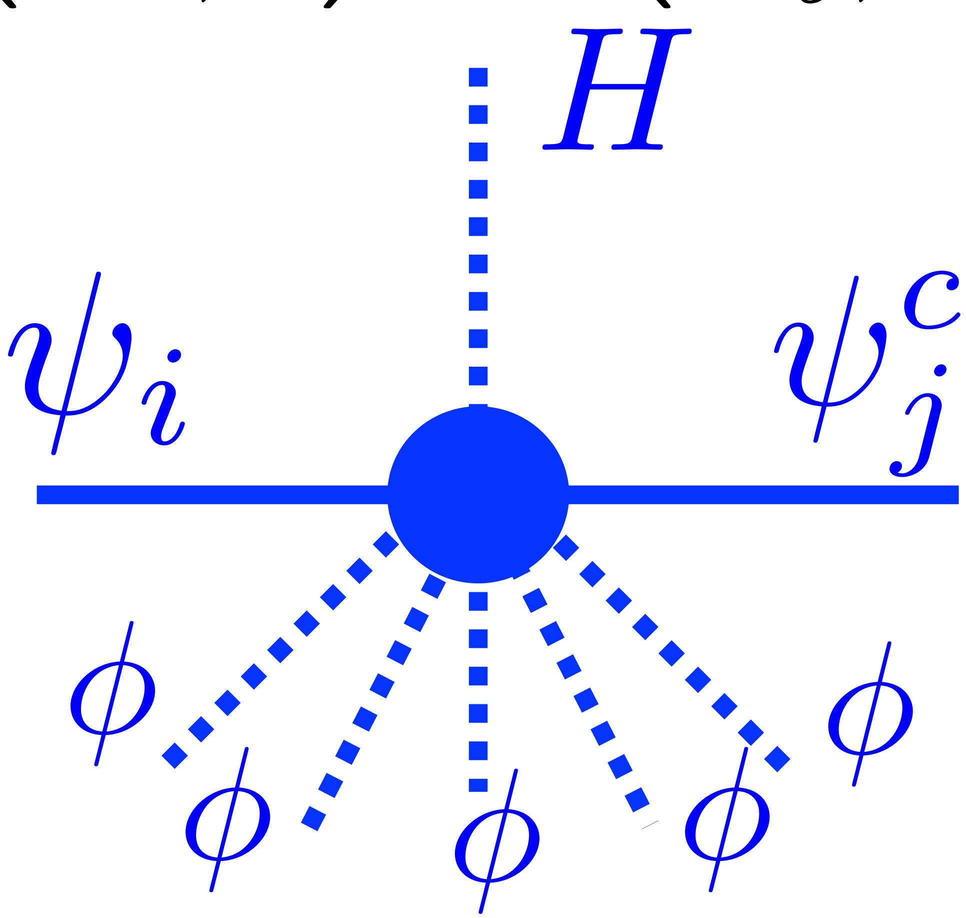
$$y_{ij} H \psi_i \psi_j^c$$



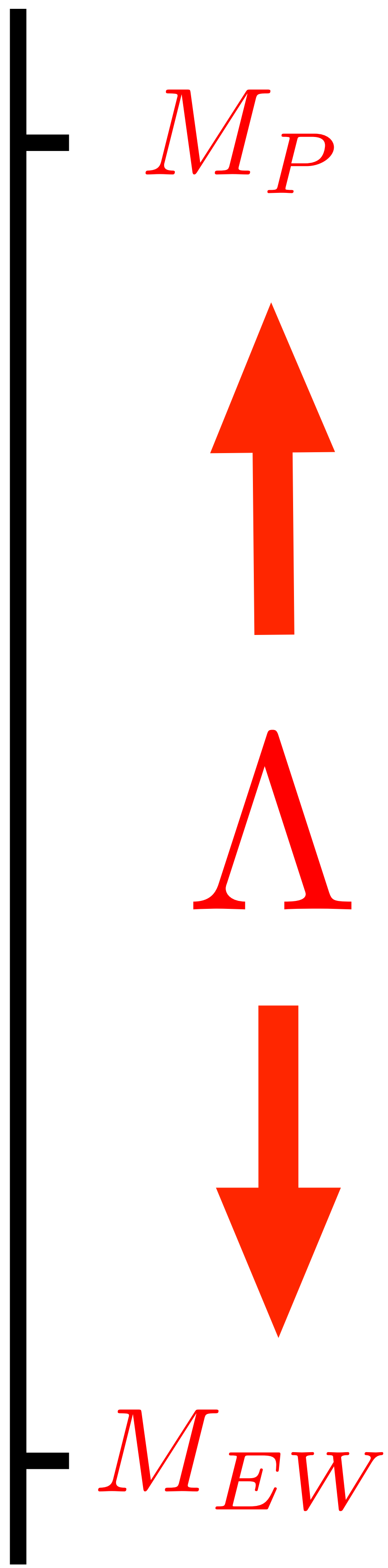
Why so small (apart from top quark)?

BSM idea: Effective Yukawa couplings

$$\left(\frac{\langle\phi_i\rangle}{\Lambda^{\psi}_{i,n}}\right)^n \left(\frac{\langle\phi_j\rangle}{\Lambda^{\psi^c}_{j,m}}\right)^m H\psi_i\psi^c_j$$



Yukawas small due to powers of ratios $\frac{\langle\phi\rangle}{\Lambda}$

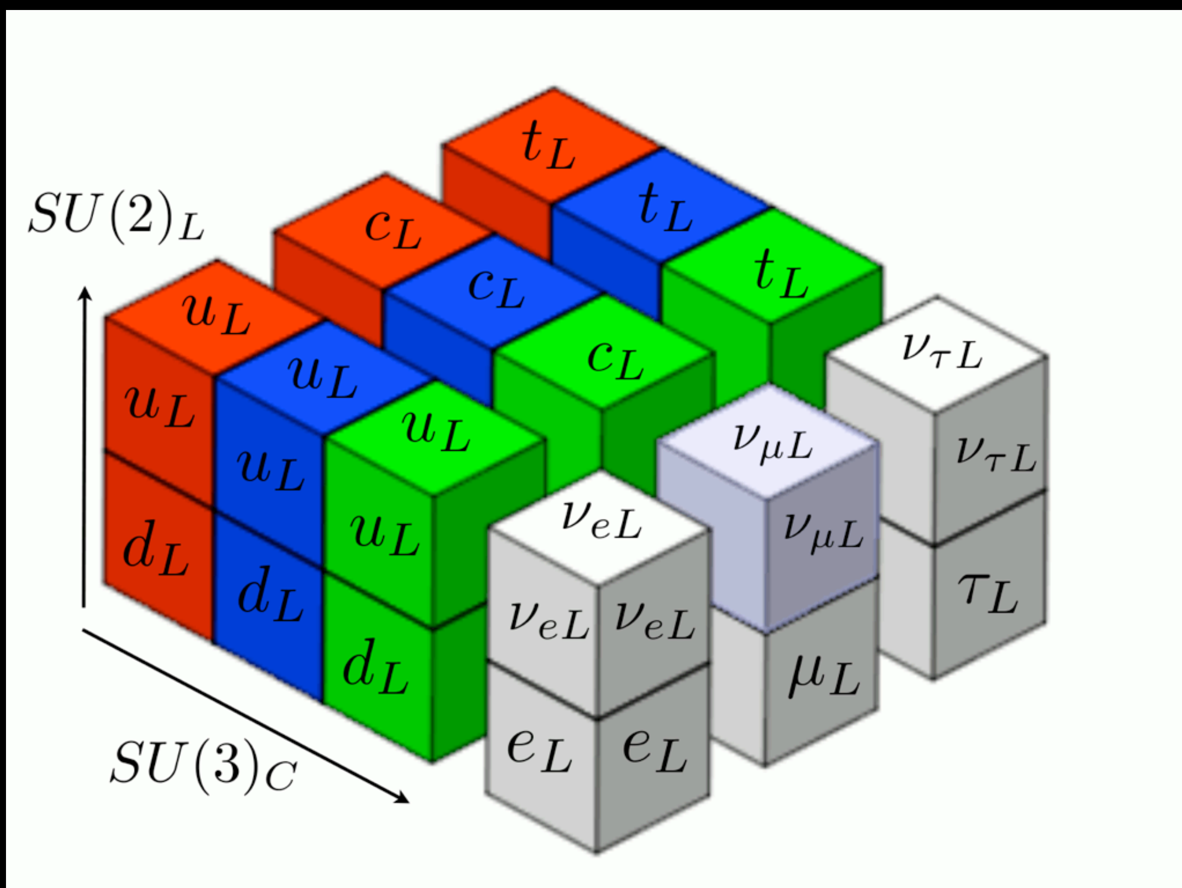


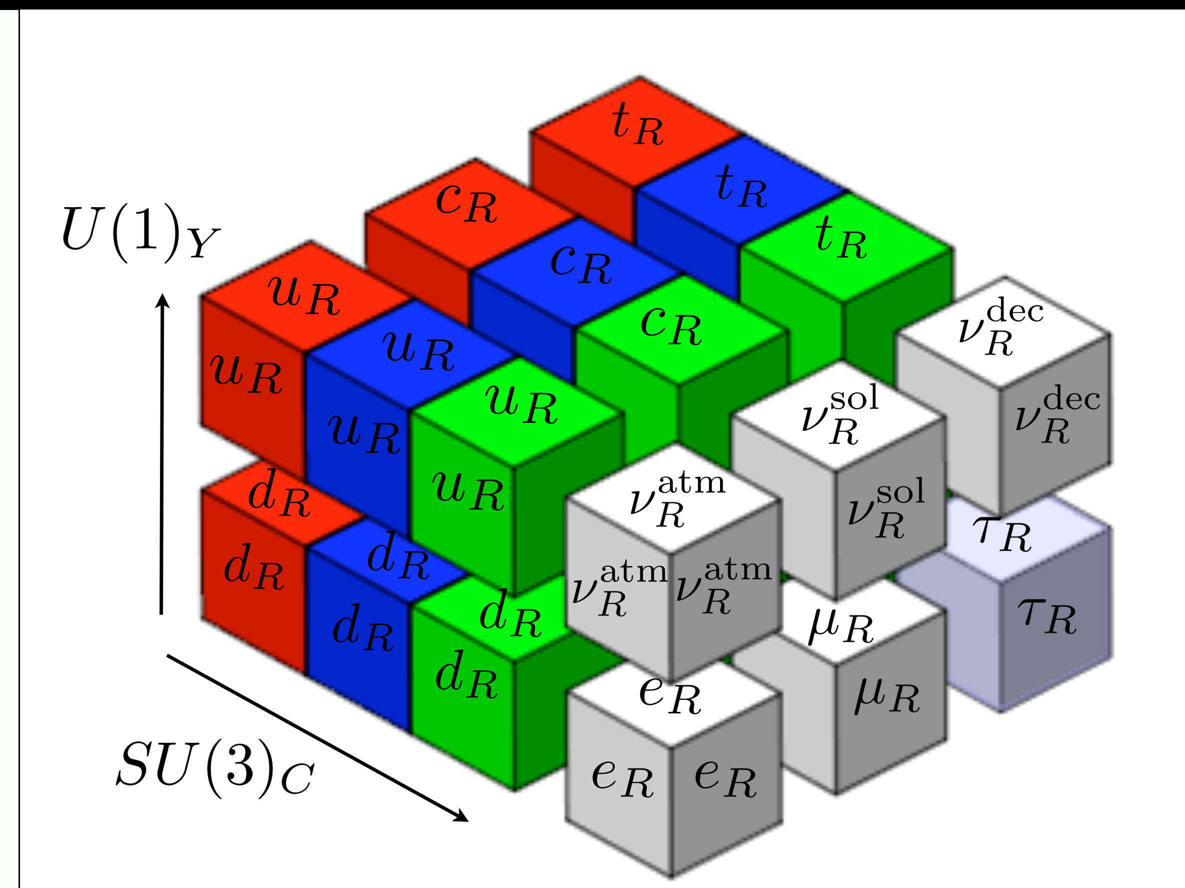
Flavour scales can be from the Planck scale to electroweak scale

Keeping fixed ratios $\frac{\langle \phi \rangle}{\Lambda}$

The Standard Model

The Standard Model





SM gauge group and fermions

$$G_{\rm SM} \equiv {\rm SU}(3)_{\rm C} \times {\rm SU}(2)_{\rm L} \times {\rm U}(1)_{\rm Y}$$

$q_{iL} \equiv \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L$	$(3, 2, 1/6)$
u_{iR}	$(3, 1, 2/3)$
d_{iR}	$(3, 1, -1/3)$
$\ell_{iL} \equiv \begin{pmatrix} \nu_i \\ e_i^- \end{pmatrix}_{\rm L}$	$(1, 2, -1/2)$
$e_i^-{}_R$	$(1, 1, -1)$

$$Y \equiv Q - T_3$$

$$Y_{u_L} = \frac{2}{3} - \frac{1}{2} = \frac{1}{6},$$

$$Y_{d_L} = -\frac{1}{3} + \frac{1}{2} = \frac{1}{6}$$

Family universal couplings of gauge bosons to fermions

$$D_\mu q_L = \left(\partial_\mu - i\frac{g_s}{2}\lambda_k G_\mu^k - i\frac{g}{2}\tau_j W_\mu^j - i\frac{g'}{6}B_\mu \right) q_L ,$$

$$D_\mu u_R = \left(\partial_\mu - i\frac{g_s}{2}\lambda_k G_\mu^k - i\frac{2g'}{3}B_\mu \right) u_R ,$$

$$D_\mu d_R = \left(\partial_\mu - i\frac{g_s}{2}\lambda_k G_\mu^k + i\frac{g'}{3}B_\mu \right) d_R ,$$

$$D_\mu \ell_L = \left(\partial_\mu - i\frac{g}{2}\tau_j W_\mu^j + i\frac{g'}{2}B_\mu \right) q_L ,$$

$$D_\mu e_L^- = \left(\partial_\mu + igB_\mu \right) e_R^- .$$

Spot the deliberate mistake?

Higgs mechanism

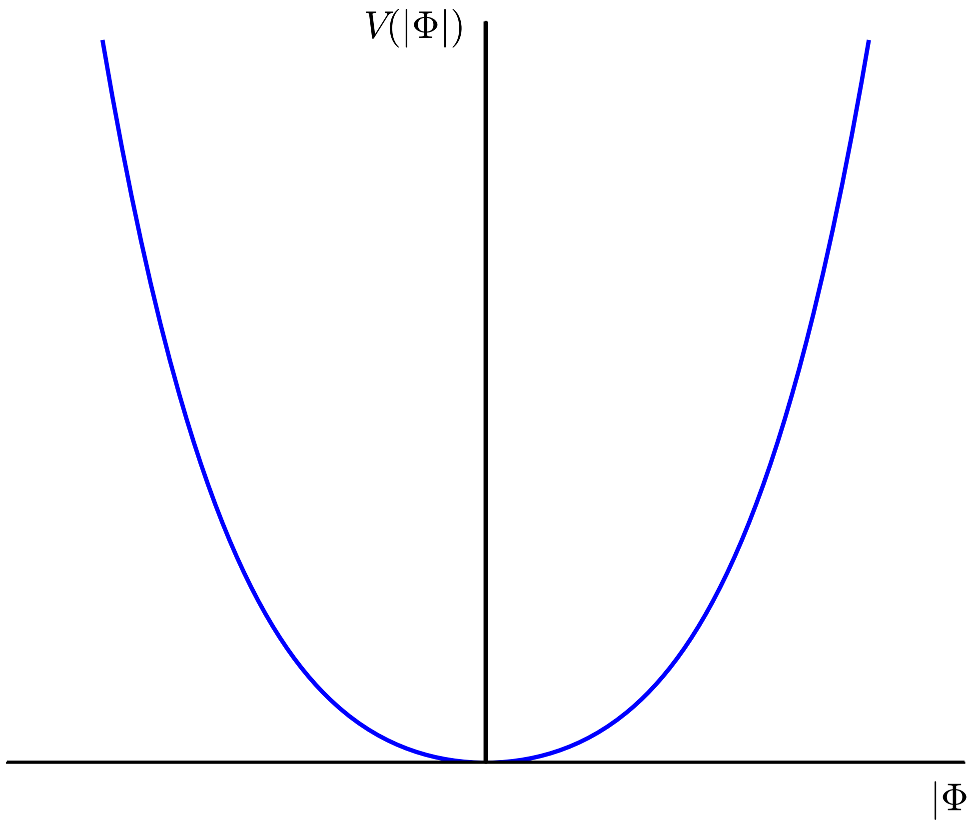
$$SU(3)_C \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_C \times U(1)_{e.m.}$$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \sim (1, 2, 1/2)$$

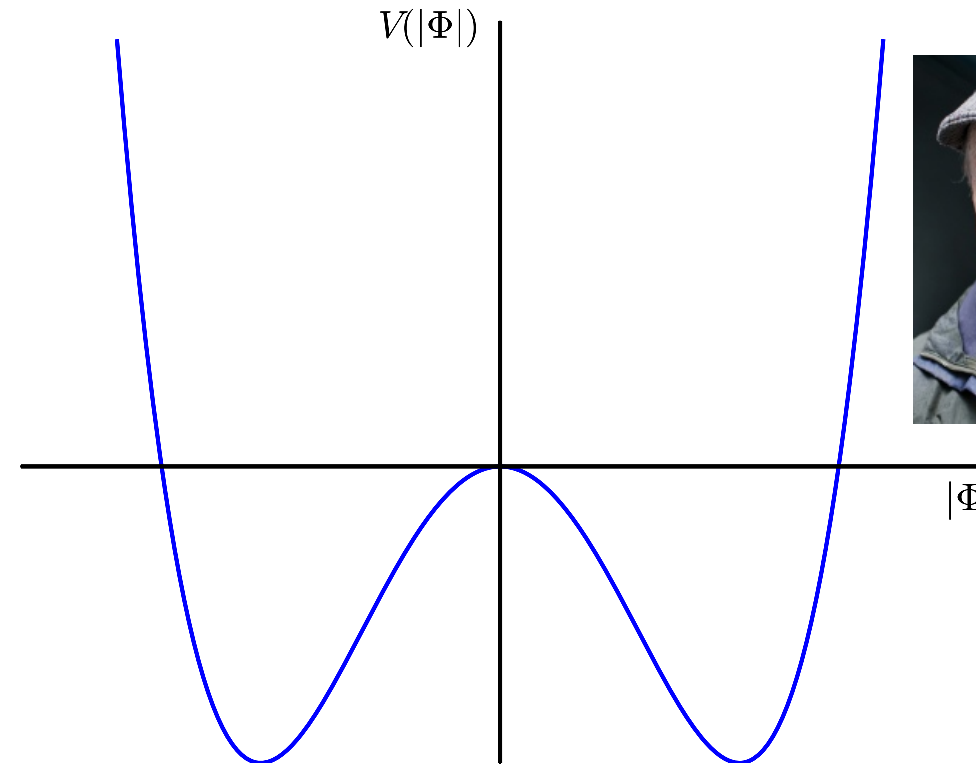
$$Q = T_3 + Y$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

$$\langle 0|\phi|0\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v \end{pmatrix}$$



(a) $\lambda > 0,\ \mu^2 > 0$



(b) $\lambda > 0,\ \mu^2 < 0$

W and Z masses

$$W^a_\mu\,,\,B_\mu \;\longrightarrow\; W^+_\mu\,,\,W^-_\mu\,,\,Z_\mu\,,\,A_\mu$$

$$M_W = \frac{g\,v}{2} \qquad\qquad \tan\theta_W \equiv \frac{g'}{g}$$

$$Z_\mu = \cos\theta_W\,W^3_\mu - \sin\theta_W\,B_\mu$$

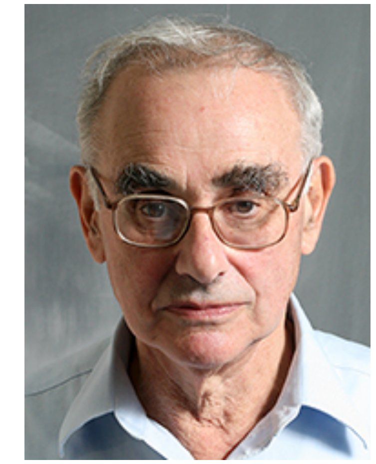
$$M_Z = \sqrt{g^2+g'^2}\,\frac{v}{2} = \frac{M_W}{\cos\theta_W}$$

Massless photon

$$A_\mu = \cos\theta_W\,B_\mu + \sin\theta_W\,W^3_\mu$$

$$e = \frac{g\,g'}{\sqrt{g^2+g'^2}} = g\sin\theta_W = g'\cos\theta_W$$

Yukawa couplings



$$-\mathscr{L}_Y = (Y_u)_{ij}\,\overline{q_{iL}}\,\tilde{\phi}\,u_{iR} + (Y_d)_{ij}\,\overline{q_{iL}}\,\phi\,d_{iR} + (Y_\ell)_{ij}\,\overline{\ell_{iL}}\,\phi\,e_{iR} + \text{H.c.}$$

$$\phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + H + i\,G_0) \end{pmatrix}$$

G are Goldstone bosons eaten by W and Z
H is the physical Higgs boson
v is the vacuum expectation value

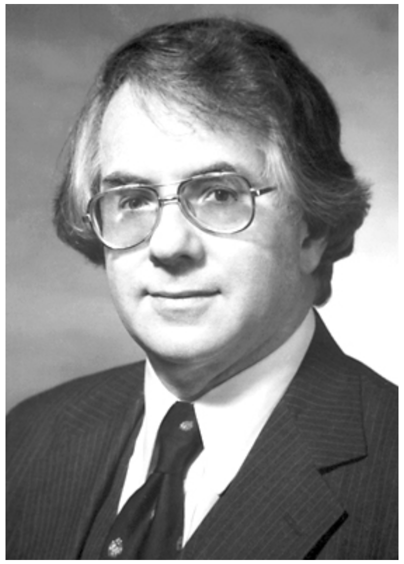
$$\tilde{\phi} \equiv i\tau_2\,\phi^\dagger$$

$$-\mathscr{L}_Y = \frac{v}{\sqrt{2}}\,(Y_u)_{ij}\,\overline{u}_{iL}\,u_{iR} + \frac{v}{\sqrt{2}}\,(Y_d)_{ij}\,\overline{d}_{iL}\,d_{iR} + \frac{v}{\sqrt{2}}\,(Y_\ell)_{ij}\,\overline{e}_{iL}\,e_{iR}$$

$$+ \frac{(Y_u)_{ij}}{\sqrt{2}}\,\overline{u}_{iL}\,u_{iR}\,H + \frac{(Y_d)_{ij}}{\sqrt{2}}\,\overline{d}_{iL}\,d_{iR}\,H + \frac{(Y_\ell)_{ij}}{\sqrt{2}}\,\overline{e}_{iL}\,e_{iR}\,H$$

Note: Higgs boson H couplings are proportional to Yukawa couplings

W and Z couplings



$$-\mathscr{L}_{\rm CC} = \frac{g}{\sqrt{2}} \left[\overline{u}_{iL}^{0}\, \gamma^\mu\, d_{iL}^{0} + \overline{\nu}_{iL}^{0}\, \gamma^\mu\, e_{iL}^{0}\right] W_\mu^+ + \text{H.c.}\,.$$

$$\mathscr{L}_{\rm NC} = \frac{g}{\cos\theta_W} \left[\overline{u}_L^0\, \gamma^\mu\, u_L^0 - \overline{d}_L^0\, \gamma^\mu\, d_L^0 + \overline{\nu}_L^0\, \gamma^\mu\, \nu_L^0 - \overline{e}_L\, \gamma^\mu\, e_L^0 - 2\sin^2\theta_W\, J^\mu_{\rm e.m.}\right] Z_\mu$$

$$J^\mu_{\rm e.m.} = \frac{2}{3}\left[\overline{u}_L^0\, \gamma^\mu\, u_L^0 + \overline{u}_R^0\, \gamma^\mu\, u_R^0\right] - \frac{1}{3}\left[\overline{d}_L^0\, \gamma^\mu\, d_L^0 + \overline{d}_R^0\, \gamma^\mu\, d_R^0\right] - \left[\overline{e}_L^0\, \gamma^\mu\, e_L^0 + \overline{e}_R^0\, \gamma^\mu\, e_R^0\right]$$

The zero superscripts remind us that the Yukawa matrices are not yet diagonal

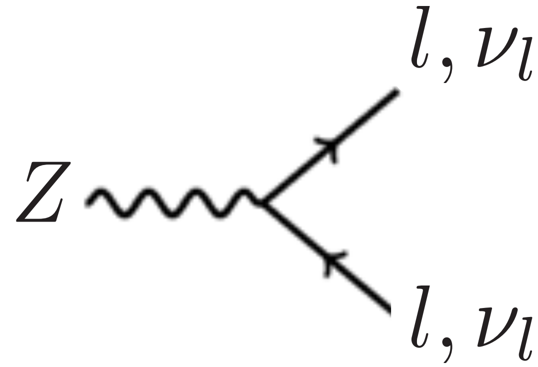
BUT even when diagonal the neutral current retains the same form:

$$\mathscr{L}'_{\rm NC} = \frac{g}{\cos\theta_W} \left[\overline{u}_L\, \gamma^\mu\, u_L - \overline{d}_L\, \gamma^\mu\, d_L + \overline{\nu}_L\, \gamma^\mu\, \nu_L - \overline{e}_L\, \gamma^\mu\, e_L - 2\sin^2\theta_W\, J^\mu_{\rm e.m.}\right] Z_\mu$$

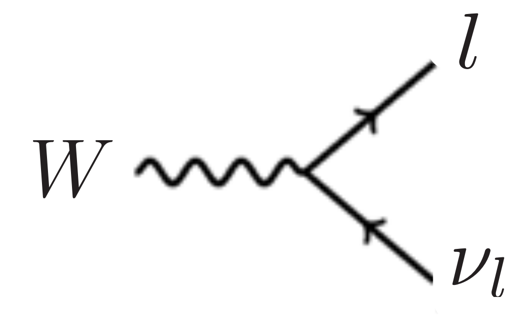
Hence no Flavour Changing Neutral Currents (GIM mechanism)

In the Standard Model, **lepton couplings** to the gauge bosons are **identical**:

Neutral current: $l = e, \mu, \tau$



Charged current: $l = e, \mu, \tau$



Lepton Flavour Universality : couplings equal for e, mu, tau

Lepton Flavour Conservation: does not change e, mu, tau flavours

- The branching fractions (BF) to different lepton generations only differ due to **lepton masses**
  - ➤ Higgs couplings, phase space, level of helicity suppression

- Lepton Universality has been **thoroughly tested** over the years at LEP, PIENU, NA62, BES-III, CLEO, KEDR and many other experiments.
  - **Neutral Currents** measured to be universal with <2‰ precision
  - **Charged Currents** measured to be universal with <2‰ precision for the first two generations

Quark Flavour

Quark Yukawa couplings and CKM

$$\mathcal{L} = -v^u Y^u_{ij} \overline{u}^i_{\rm L} u^j_{\rm R} - v^d Y^d_{ij} \overline{d}^i_{\rm L} d^j_{\rm R} + h.c.$$

$$U_{u_{\rm L}}\, Y^u\, U^\dagger_{u_{\rm R}} = \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}, \quad U_{d_{\rm L}}\, Y^d\, U^\dagger_{d_{\rm R}} = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$

$$U_{\rm CKM} = U_{u_{\rm L}} U^\dagger_{d_{\rm L}}$$

5 phases removed

$$\mathcal{L}^{CC} = -\frac{g}{\sqrt{2}} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} U_{\rm CKM} \gamma^\mu W^+_\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

Unitary matrix $U^\dagger U = I$

Parametrising the CKM mixing matrix

$$\begin{pmatrix}\overline{u} & \overline{c} & \overline{t}\end{pmatrix}_L \gamma^\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb}\end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W_\mu^+$$

$$s_{12} = \sin\theta_{12}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb}\end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta_{13}} & 0 & c_{13}\end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1\end{pmatrix}$$

$$= \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{13}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13} e^{i\delta_{13}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13} e^{i\delta_{13}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13} e^{i\delta_{13}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13} e^{i\delta_{13}} & c_{23}\, c_{13}\end{pmatrix}$$

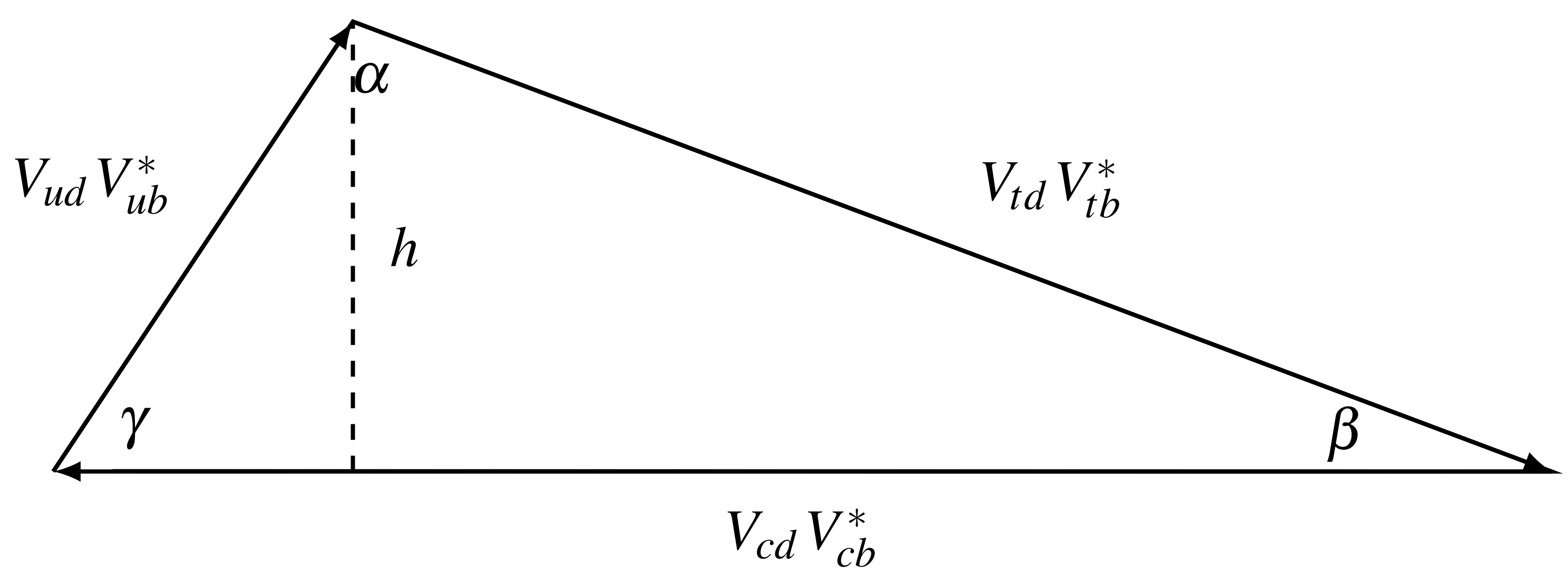
$$s_{13} = |V_{ub}|\,, \qquad s_{12} = \frac{|V_{us}|}{\sqrt{1-|V_{ub}|^2}}\,, \qquad s_{23} = \frac{|V_{cb}|}{\sqrt{1-|V_{ub}|^2}}$$

Quark CP violation

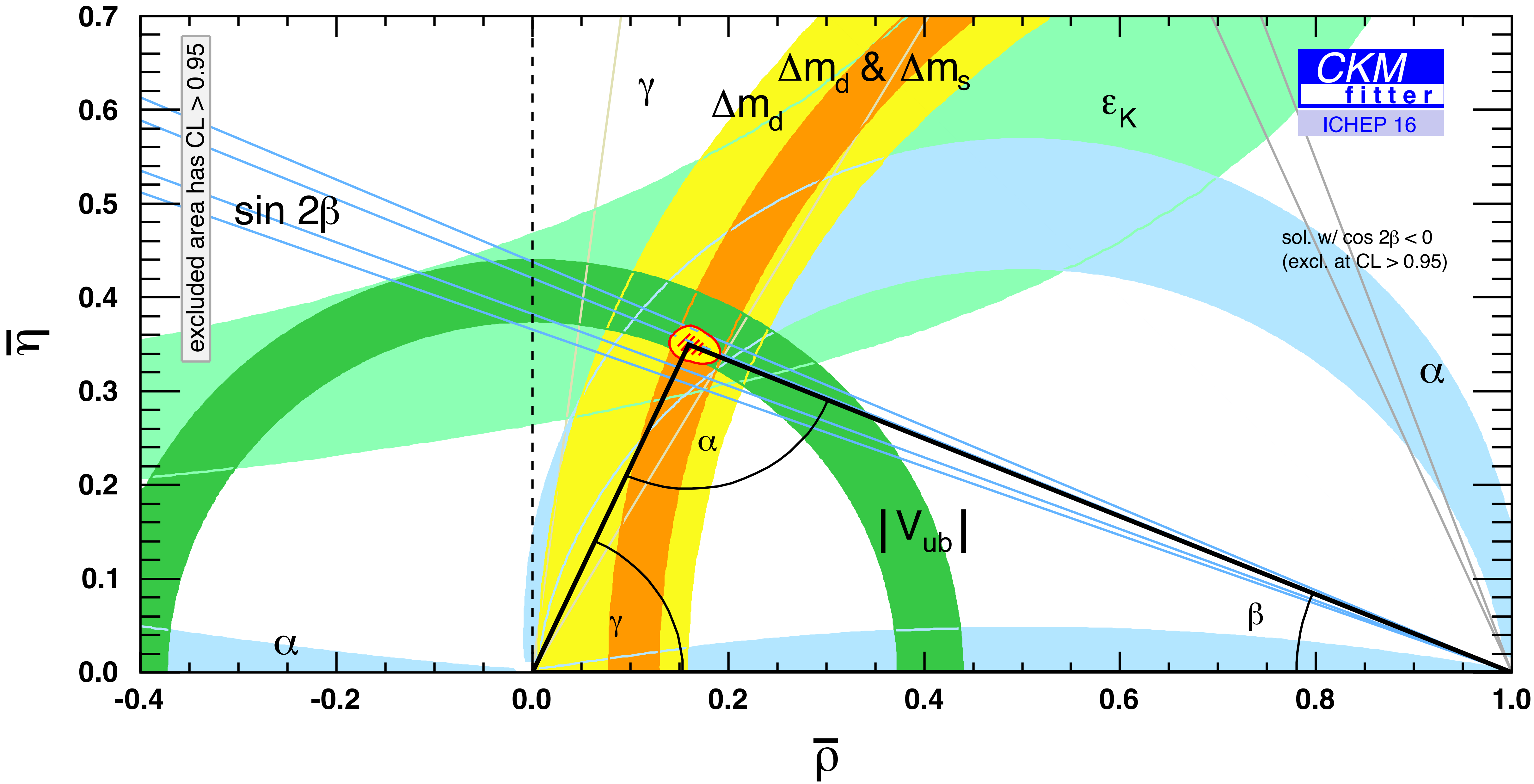
$$\begin{pmatrix}\overline{u} & \overline{c} & \overline{t}\end{pmatrix}_L \gamma^\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W_\mu^+$$

Unitarity implies for example orthogonality of 1st and 3rd columns:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Quark CP violation



CP violating phase $\gamma \approx \delta_{13} \approx 70^{\circ}$

Some flavoured mesons

charged:

$$K^+ \sim \bar{s}u, \quad D^+ \sim c\bar{d}, \quad D_s^+ \sim c\bar{s}, \quad B^+ \sim \bar{b}u, \quad B_c^+ \sim \bar{b}c,$$
$$K^- \sim s\bar{u}, \quad D^- \sim \bar{c}d, \quad D_s^- \sim \bar{c}s, \quad B^- \sim b\bar{u}, \quad B_c^- \sim b\bar{c},$$

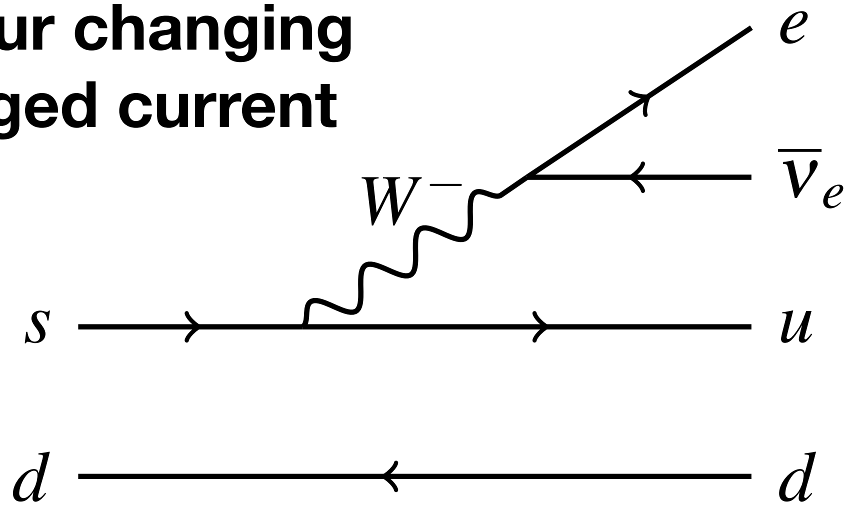
neutral:

$$K \sim \bar{s}d, \qquad D \sim c\bar{u}, \qquad B_d \sim \bar{b}d, \qquad B_s \sim \bar{b}s,$$
$$\overline{K} \sim s\bar{d}, \qquad \overline{D} \sim \bar{c}u, \qquad \overline{B}_d \sim b\bar{d}, \qquad \overline{B}_s \sim b\bar{s},$$

The neutral K, D, B_d and B_s mesons mix with their antiparticles, $\overline{K}$, $\overline{D}$, $\overline{B}_d$ and $\overline{B}_s$ thanks to the weak interaction (quantum-mechanical two-state systems).

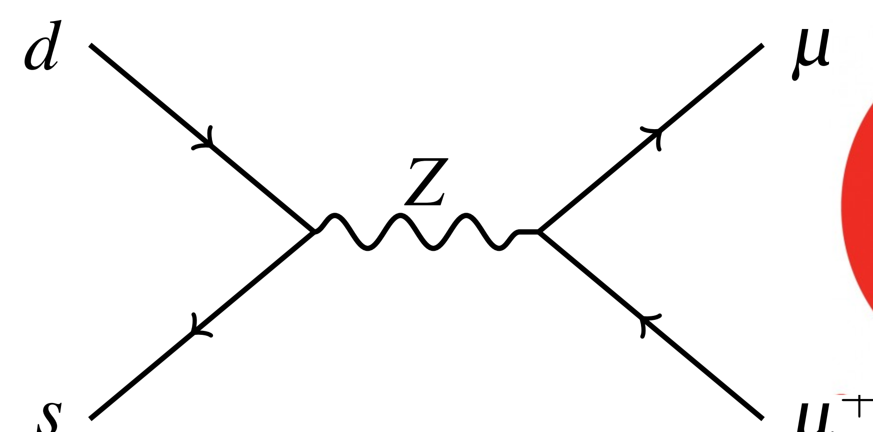
Examples of Quark Flavour Changing Processes

Flavour changing charged current



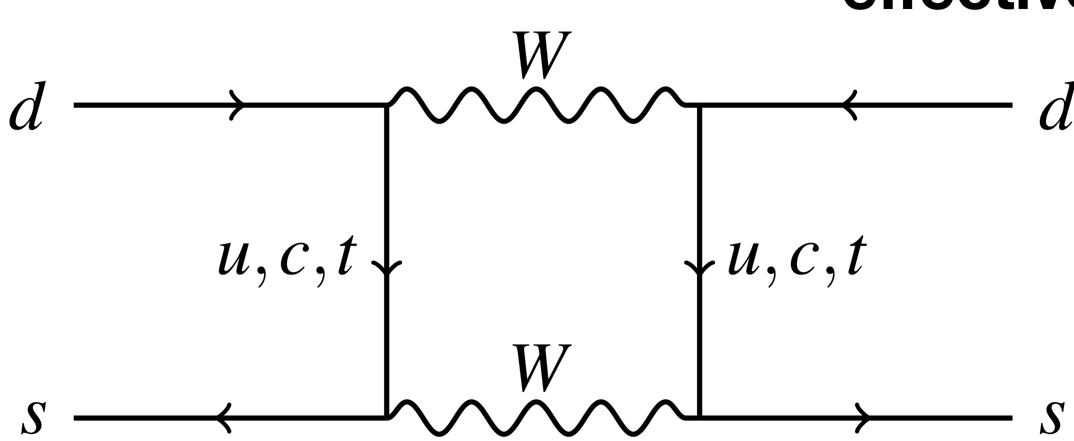
(a) $K_L^0 \longrightarrow \pi^+ e^- \nu_e$

No tree level FCNCs

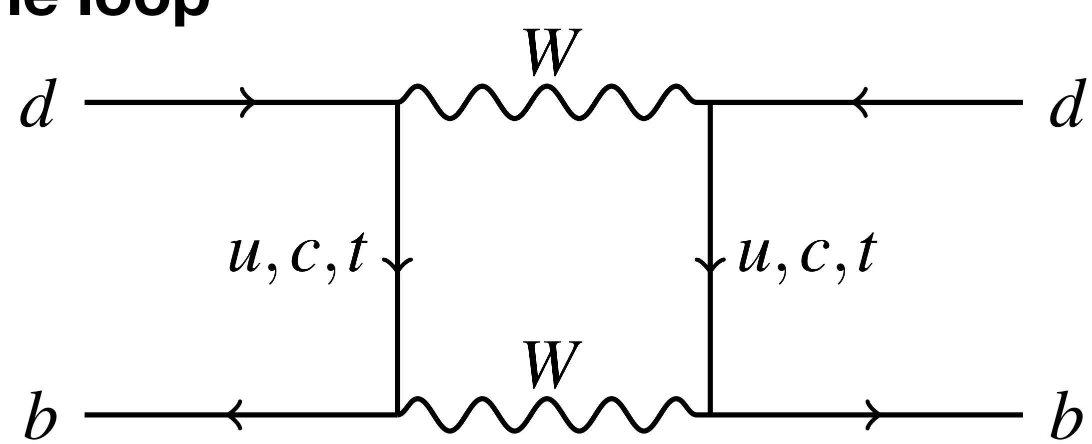


Forbidden by GIM mechanism

Flavour changing neutral currents generated effectively at one loop

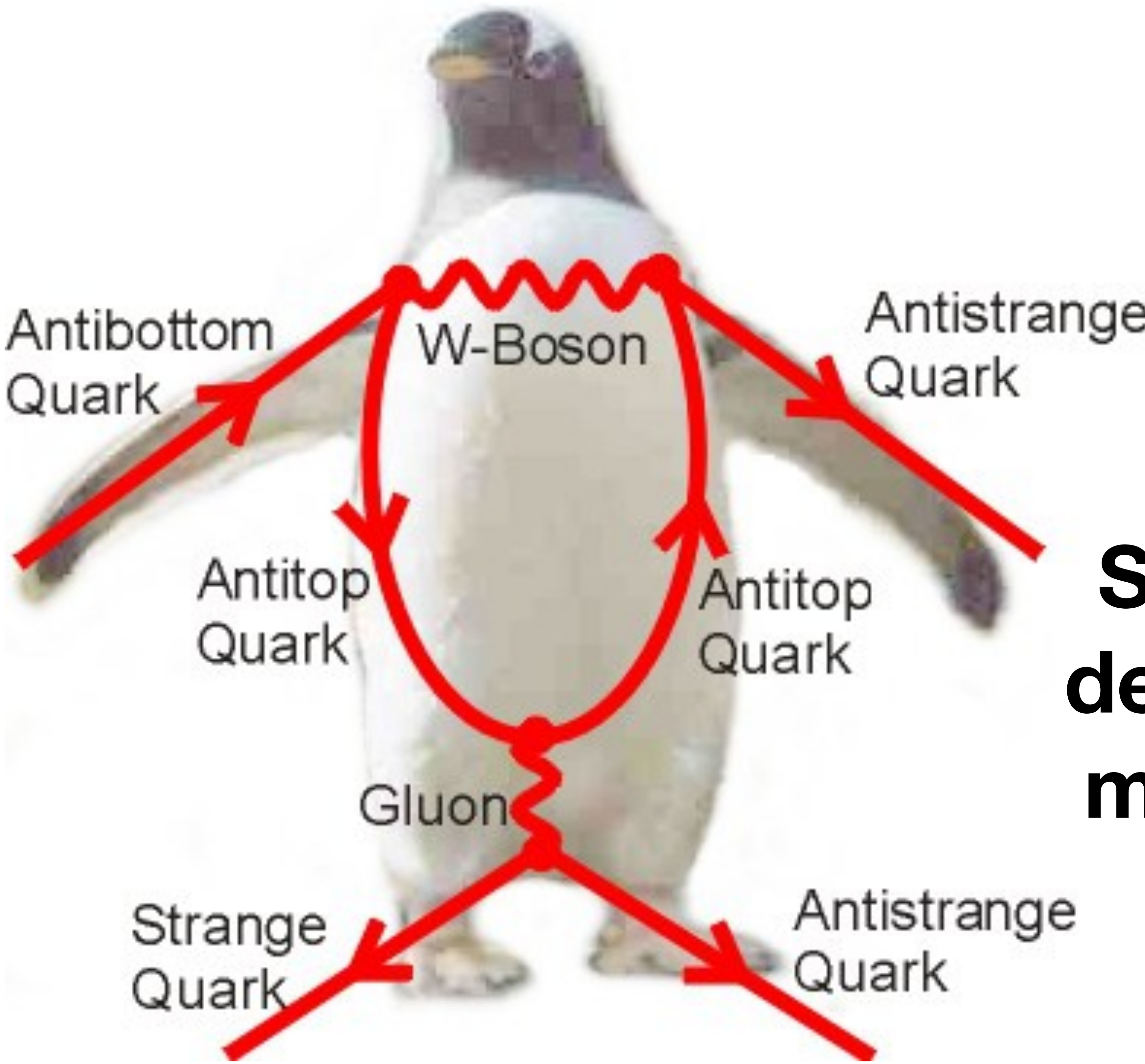


(a) $K^0 - \overline{K^0}$ mixing



(b) $B_d^0 - \overline{B_d^0}$ mixing

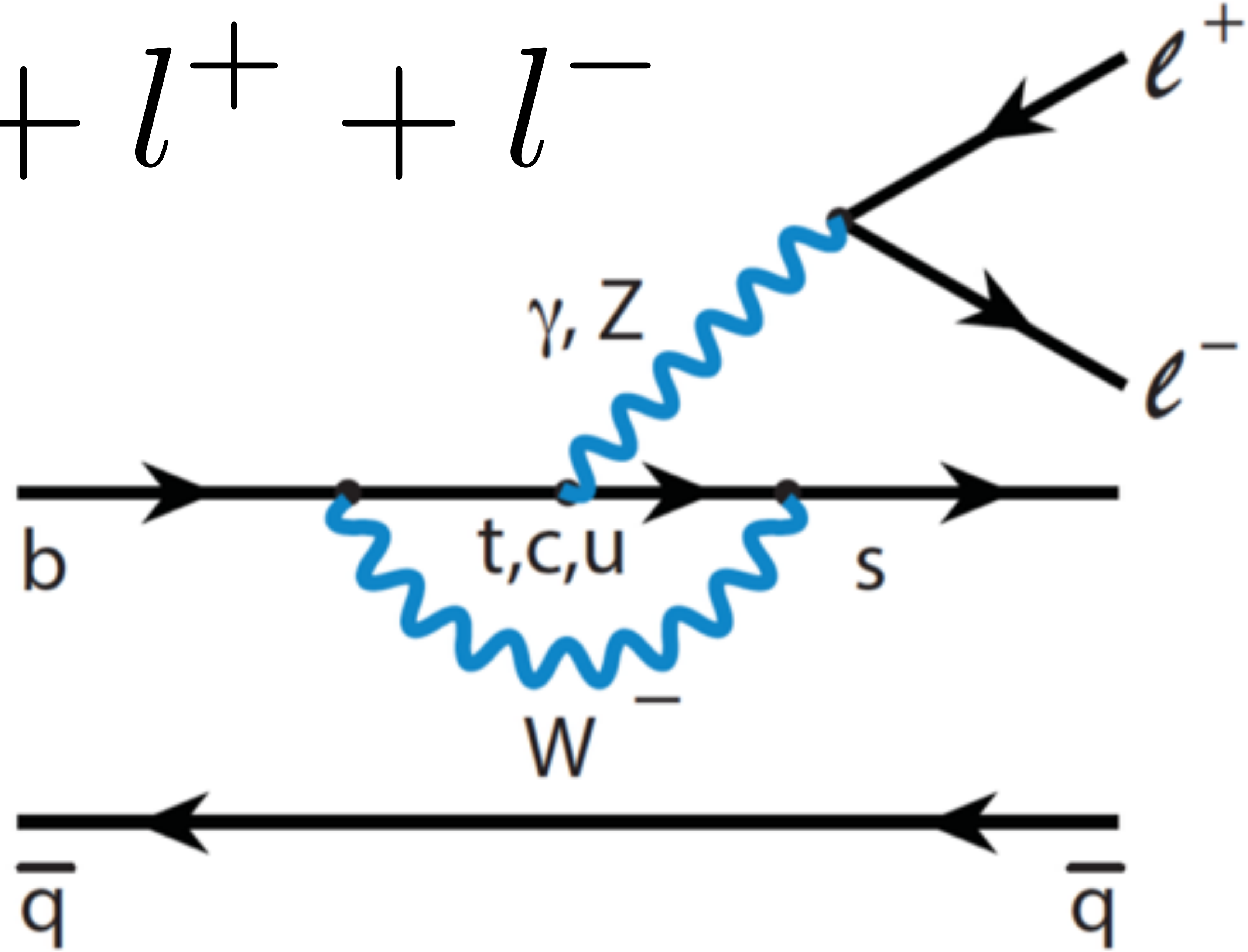
Flavour changing penguin



Spot the deliberate mistake?

$$B \to K + l^+ + l^-$$

Homework: make this look like a penguin



- $b \to s l^+ l^-$ transitions are rare in the SM (no tree level contributions: GIM, CKM, in some cases helicity suppressed)
- ideally suited for indirect New Physics searches (indirectly sensitive to energy scales O(100TeV))

Siim Tolk

Anomalies in b quark transitions

- five different **experiments**:
  ATLAS, BABAR, BELLE, CMS, LHCb
- vastly different **collision environments** requiring different analysis strategies: *hadronic (abundant) VS leptonic (clean)*
- processes with different SM contributions:
  tree level semi-leptonic decays, loop level FCNC transition
- many **clean observables**:
  angular observables, branching fraction ratios

LFU tests with B→K(*)μμ and B→K(*)ee decays: R(K) and R(K*)

- Theoretical uncertainties on the exclusive B→K(*)ll branching fractions are **reduced to a per-mille level** in ratios *(hadronic effects cancel)*:

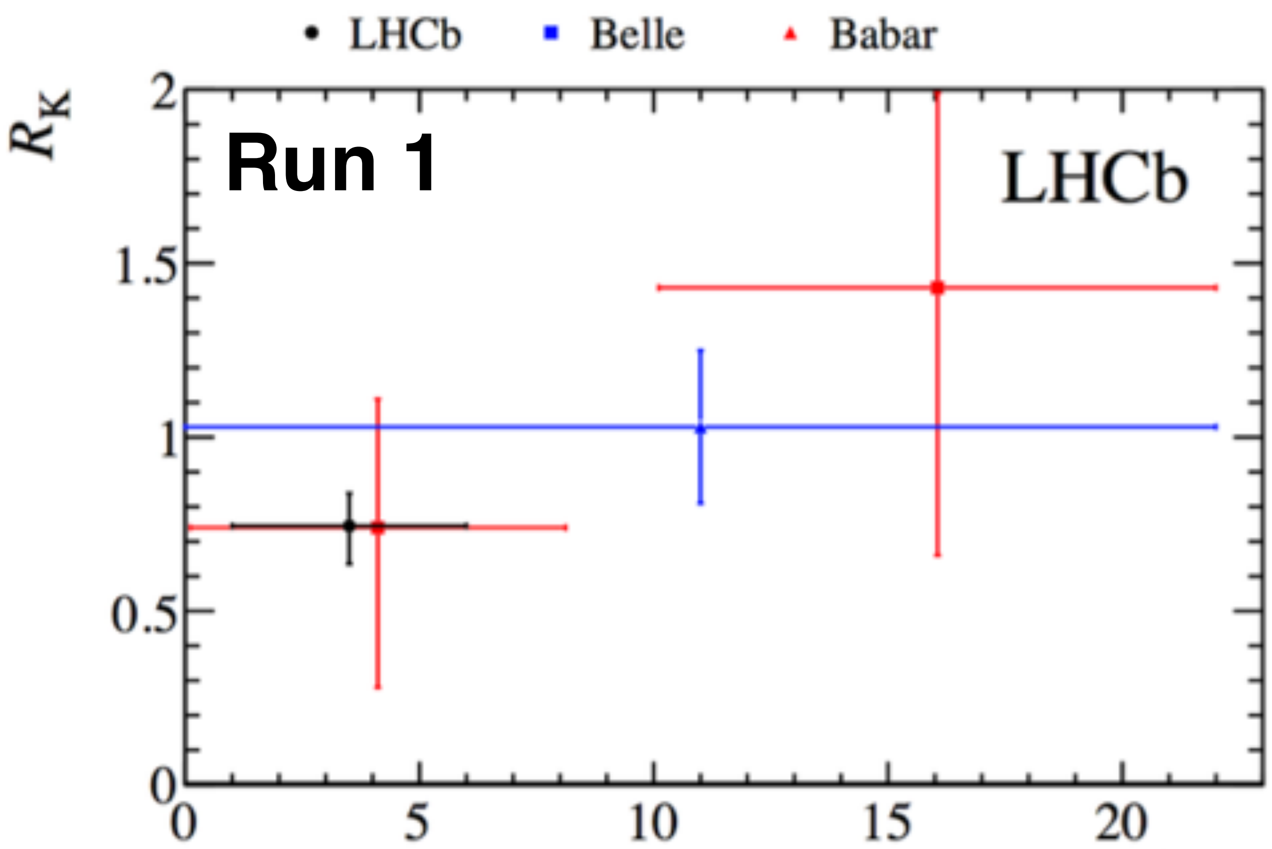
$$R(K) = \frac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-} \quad R(K^*) = \frac{B^0 \to K^{*0}\mu^+\mu^-}{B^0 \to K^{*0}e^+e^-}$$

- SM, R(K) and R(K*) expected to be close to unity.
- Sensitive to new neutral and heavy gauge bosons, lepto-quarks, Z’ models.

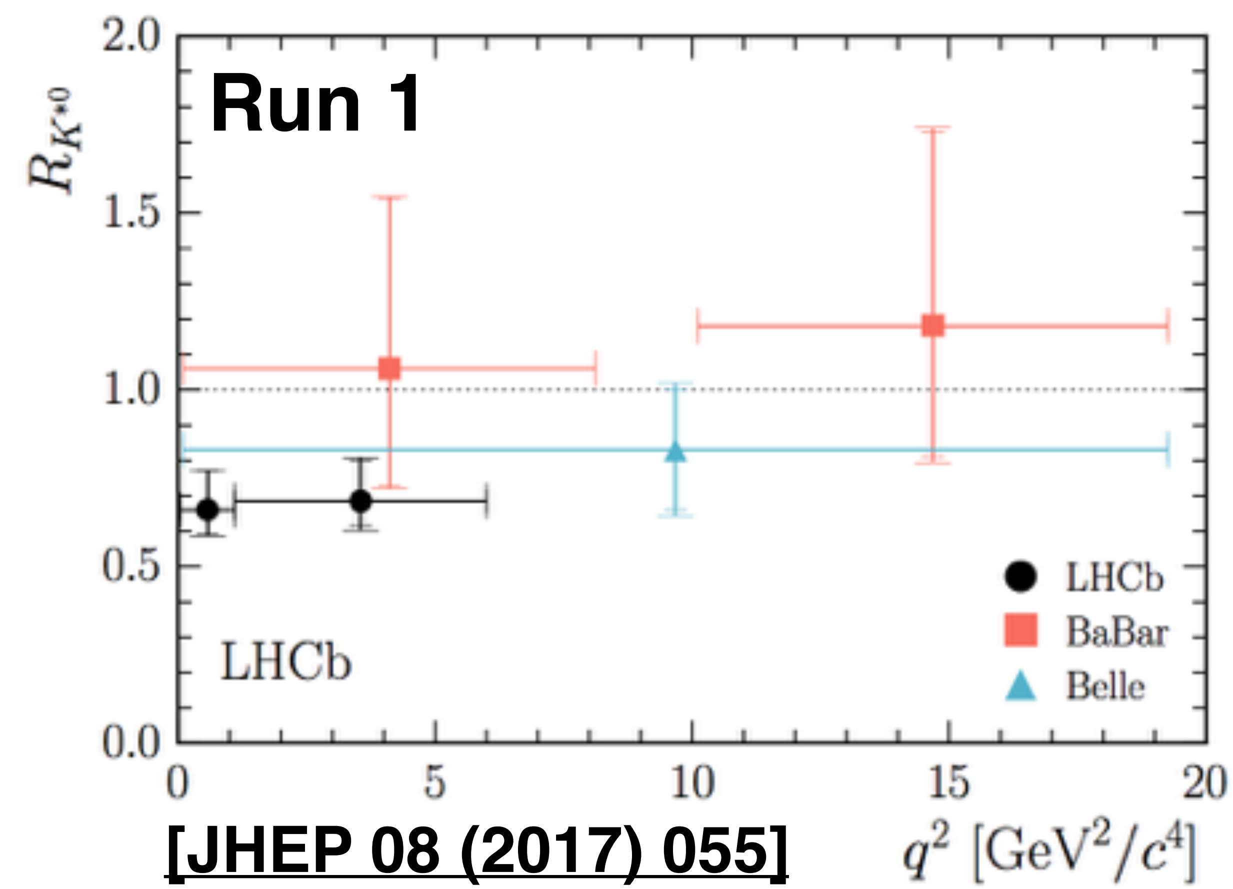
R(K) and R(K*) results

Siim Tolk

LHCb focusses on the q^2 regions with reliable theoretical predictions and small contributions from the resonant modes. Precision limited by statistics.



[PRL 113 (2014) 151601]



[JHEP 08 (2017) 055]

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst}).$$

2.6σ Deviation from Standard Model

$$R_{K^{*0}} = \begin{cases} 0.66 \, ^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \;\; \text{GeV}^2/c^4\,, \\ 0.69 \, ^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad\; < q^2 < 6.0 \;\; \text{GeV}^2/c^4\,. \end{cases}$$

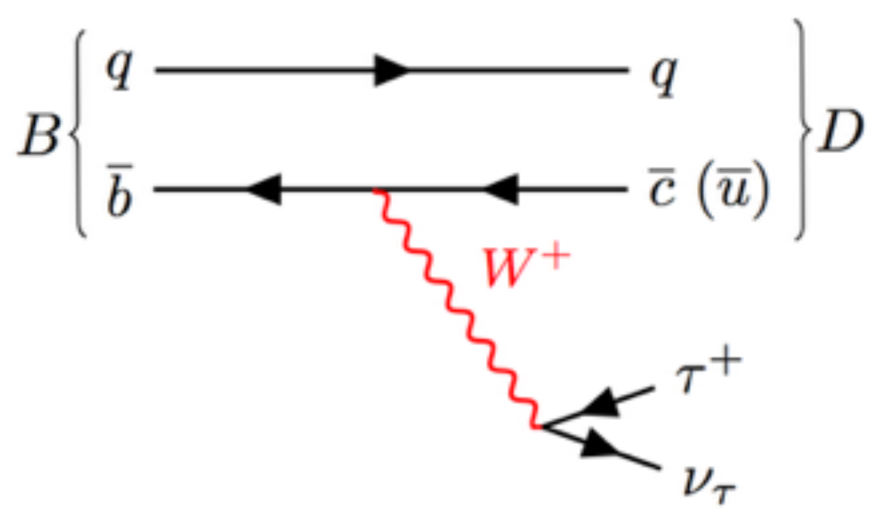
2.1 - 2.4σ

R(D*) and R(D) results

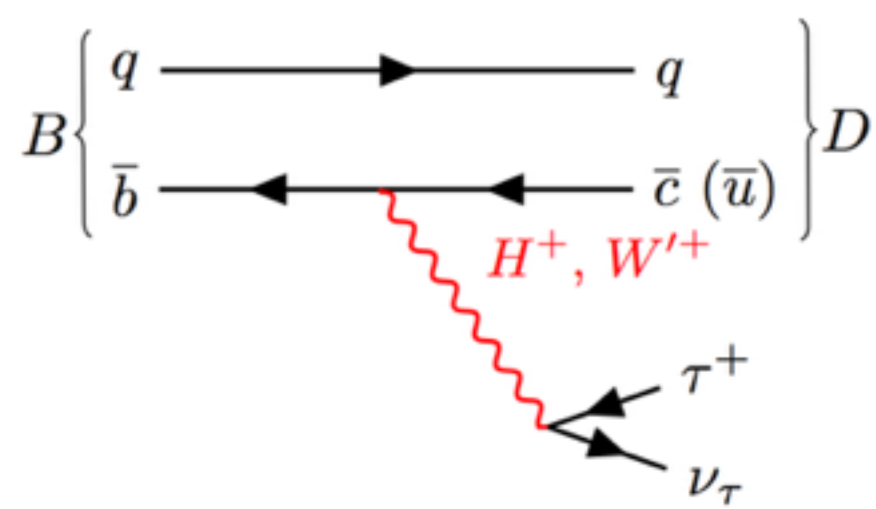
Siim Tolk

Tree level **semi-leptonic b→clν transitions** are excellent test modes for charged currents:

SM



New Physics?



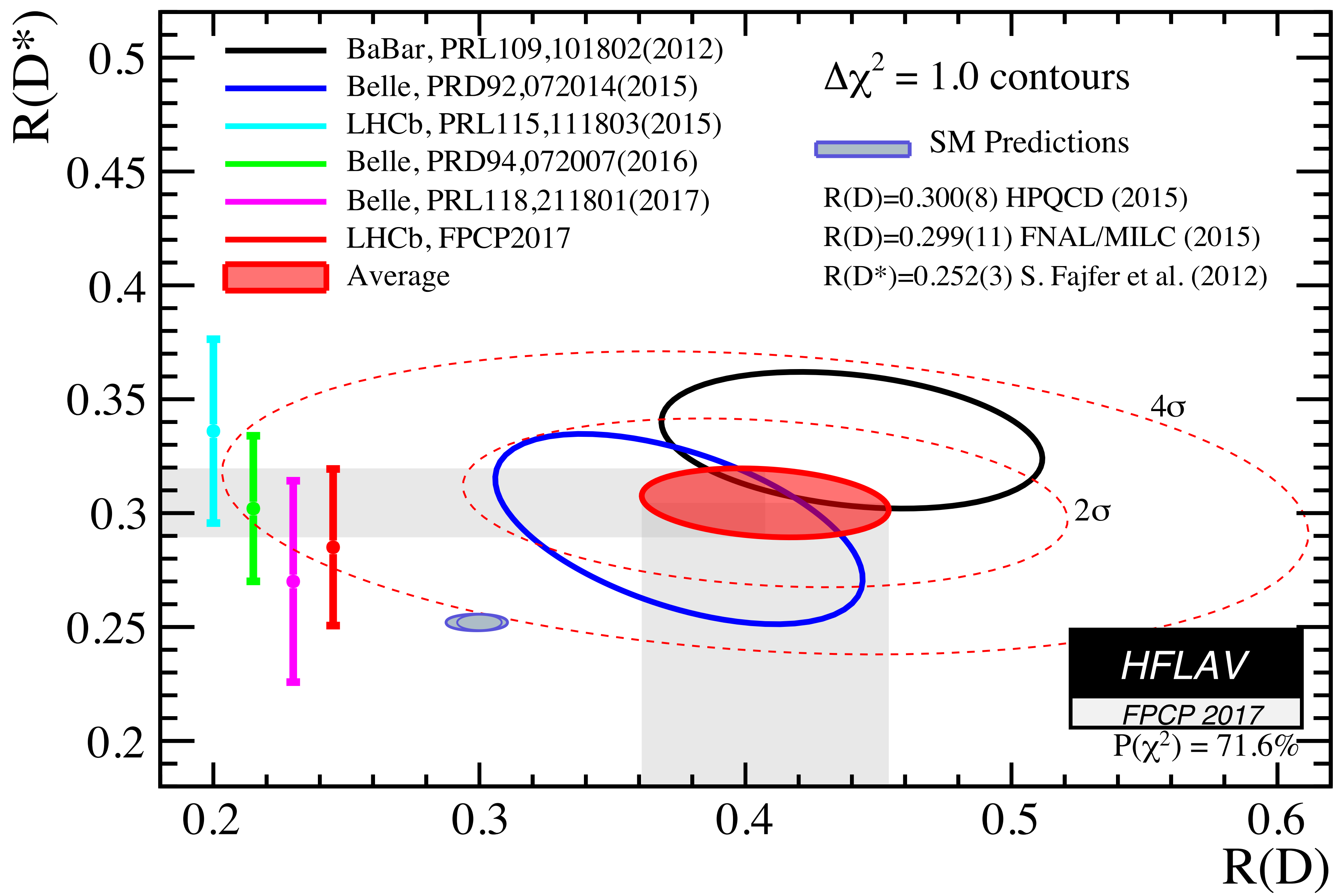
- abundant (crucial for the τ mode) and theoretically well understood
- the ratios of branching fractions are known with a **precision of a few %** and can be precisely measured:

$$\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$ **= 0.260(8)** **SM**

$R(D^*)$ and $R(D)$ results

Siim Tolk

Combined $R(D^*)$ and $R(D)$ significance is 4.1σ w.r.t SM *($R(D^*)$ alone 3.4 σ)*



NB! Updates not included (small combined effect on the tension):

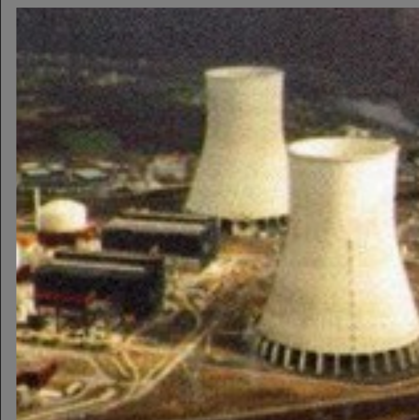
** mild change in the published LHCb R(D*) from hadronic τ channel*

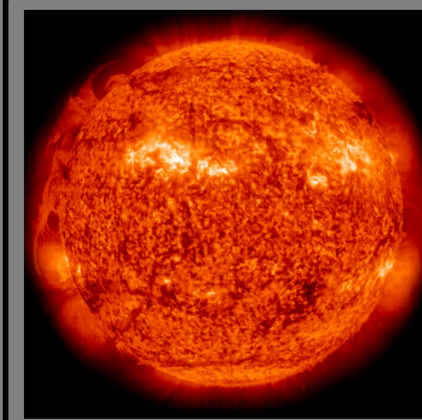
** updated SM predictions [JHEP 11 (2017) 061]*

Introduction to Neutrinos

Where do neutrinos appear in nature?

✓ Nuclear Reactors



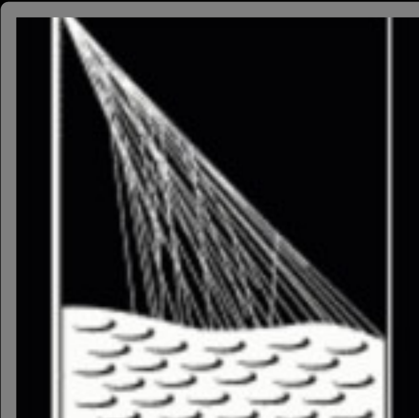


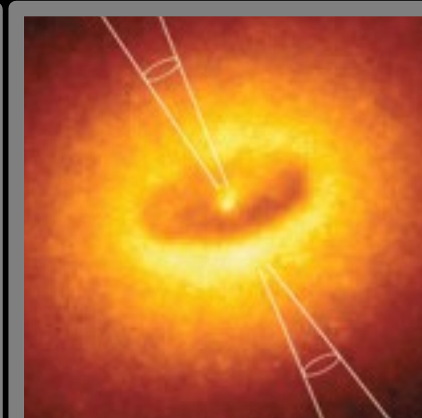
Sun ✓

✓ Particle accelerator

Supernova
(Star collapse)
SN 1987A ✓

✓ The atmosphere
(Cosmic Rays)

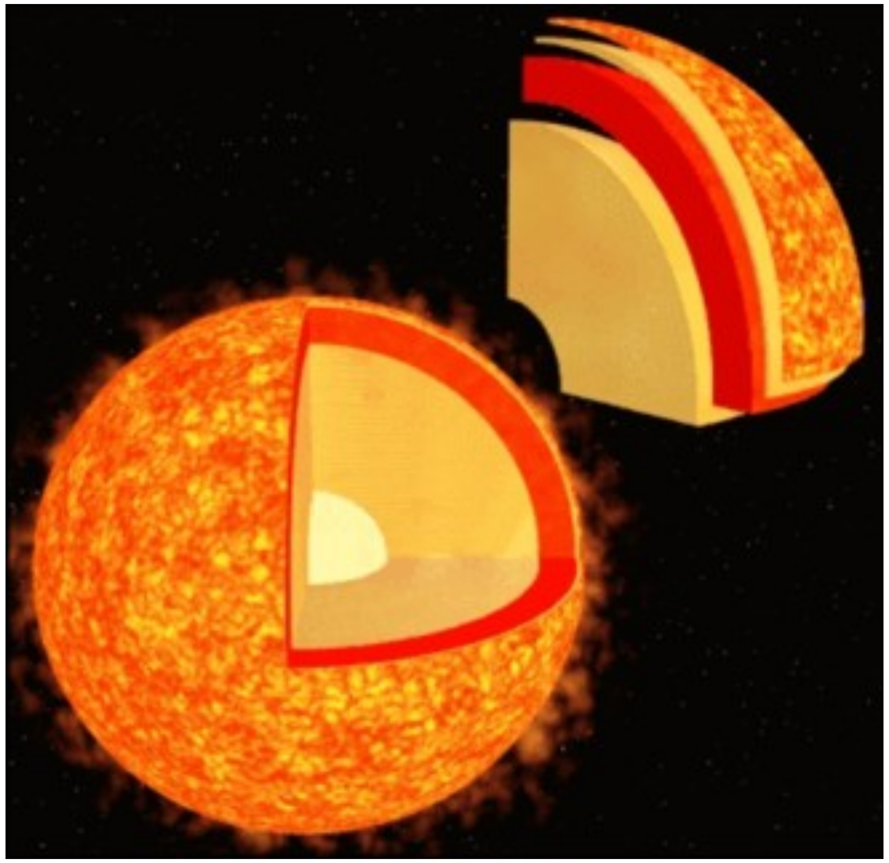


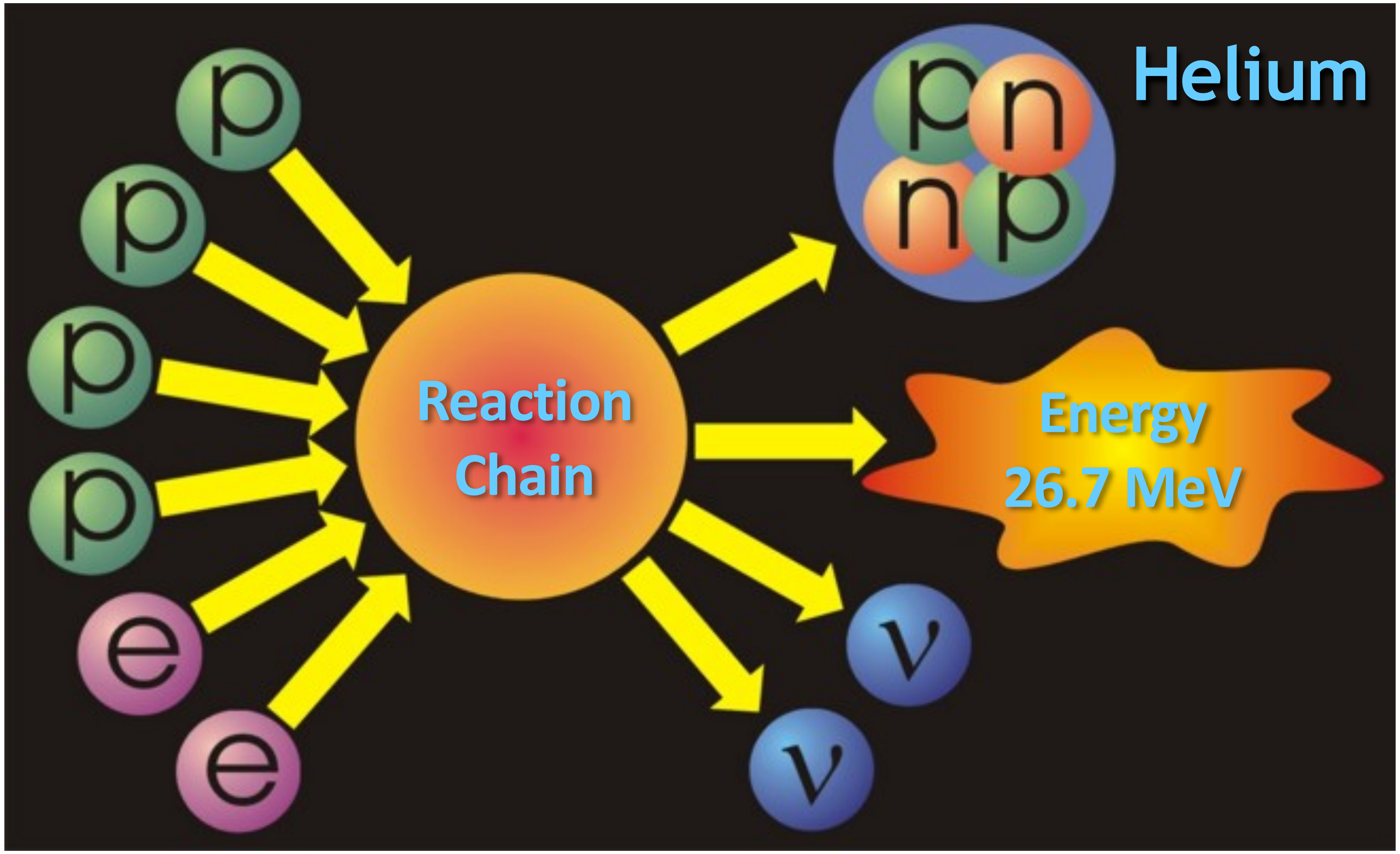


Astrophysical
accelerator

✓ Earth's crust
(Natural radioactivity)

Neutrinos from the Sun



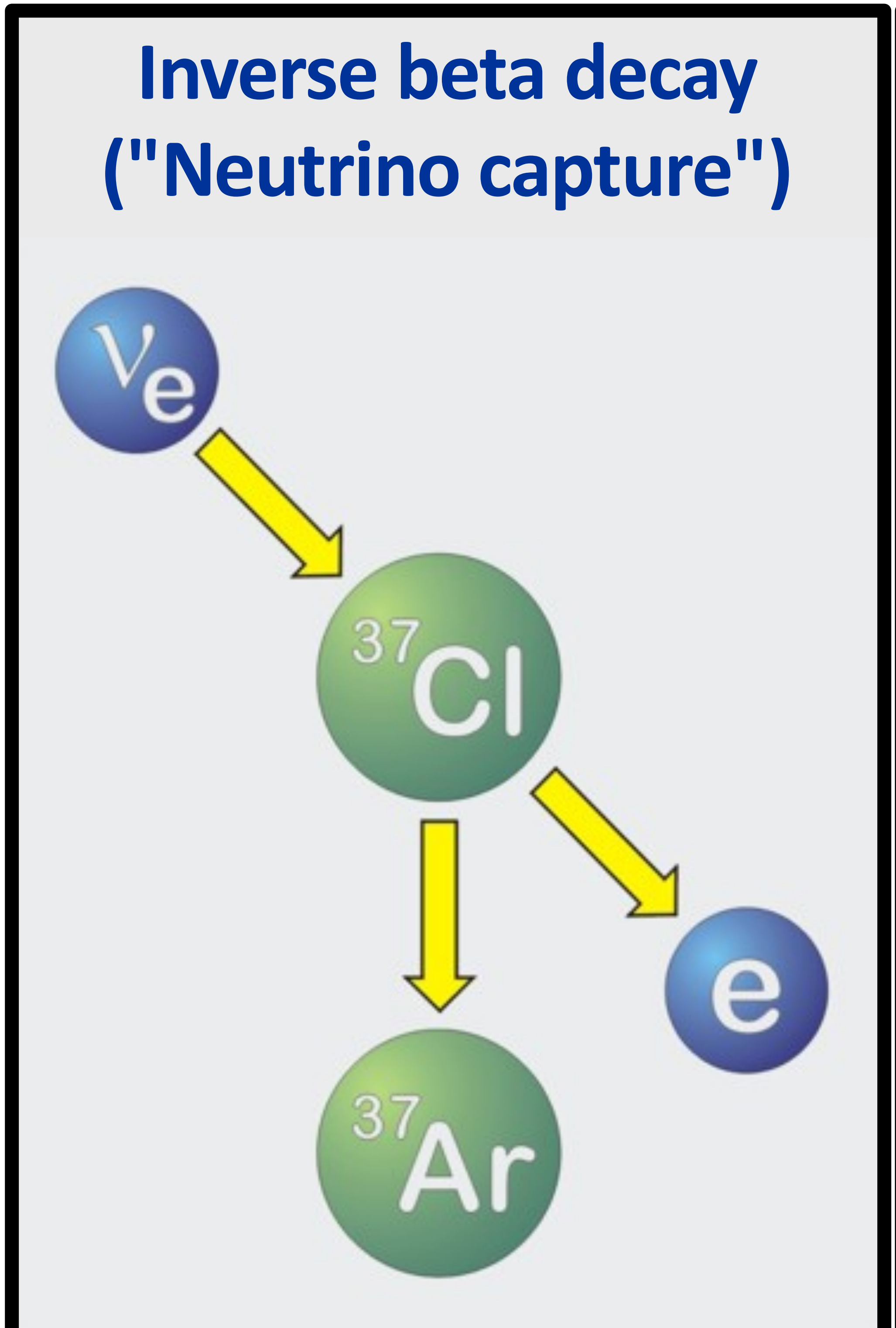


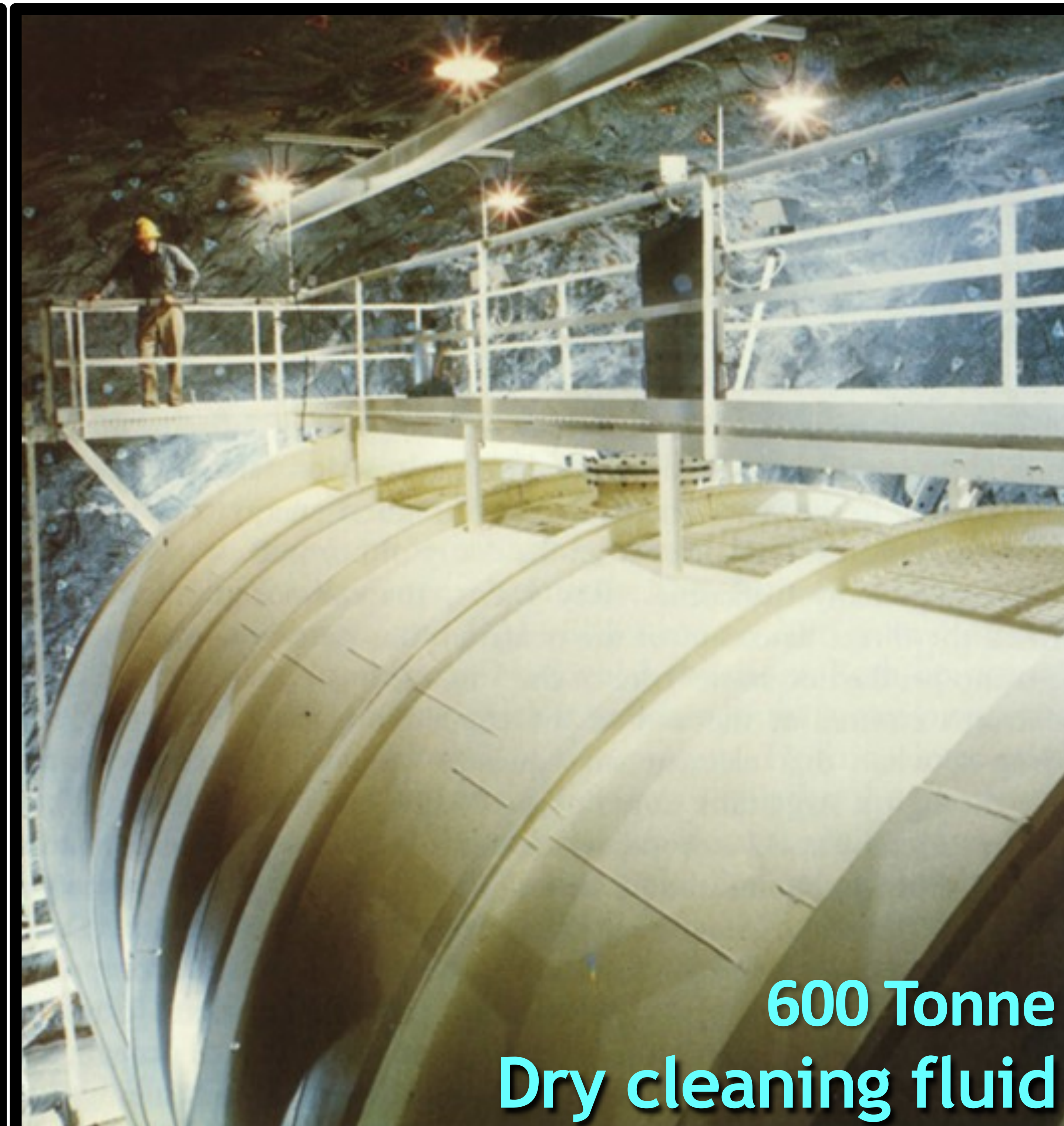
Solar radiation: 98 % Light
2 % Neutrinos

We observe: 66 Billion Neutrinos/cm²/sec

Hans Bethe (1906–2005, Nobel prize 1967)
Thermo-nuclear reaction chains (1938)

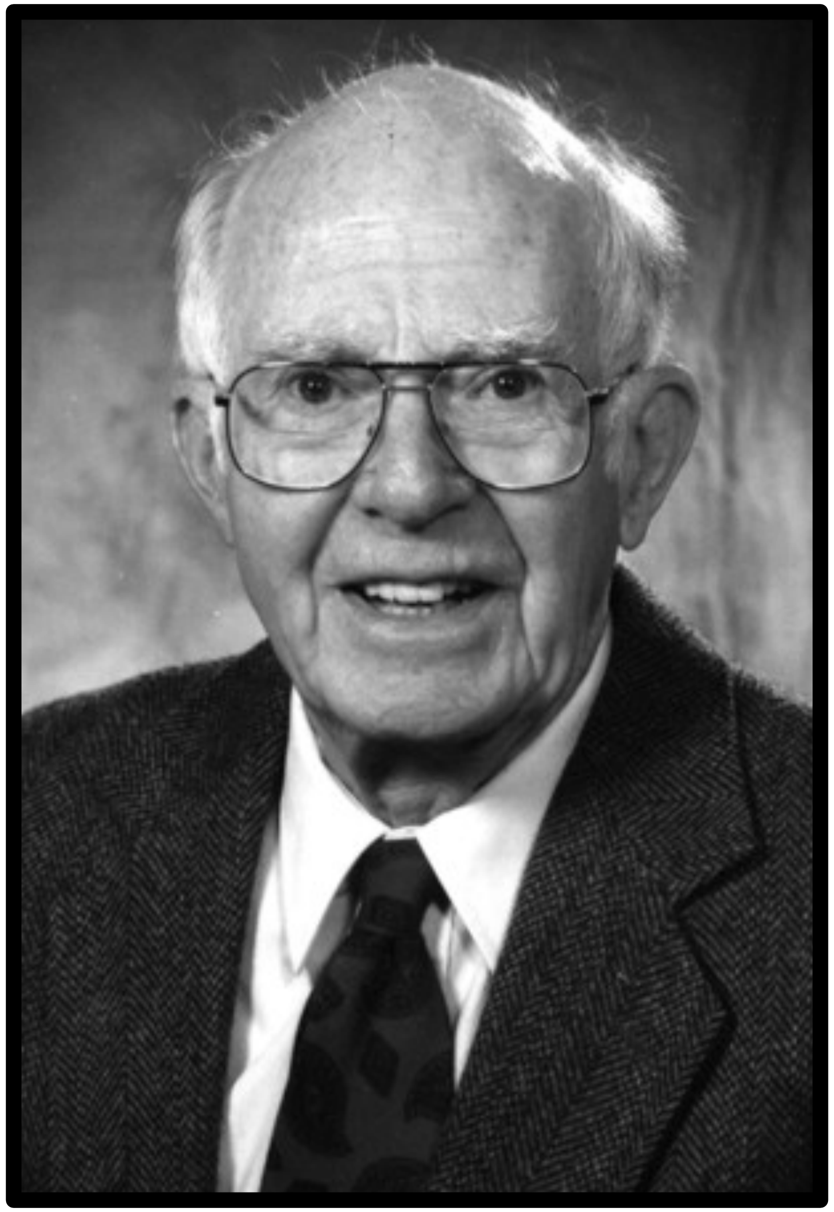
First measurement of neutrinos from the Sun





Homestake Solar neutrino-Observatory (1967–1994)

Physics Nobel Prize 2002 for Neutrino-Astronomy

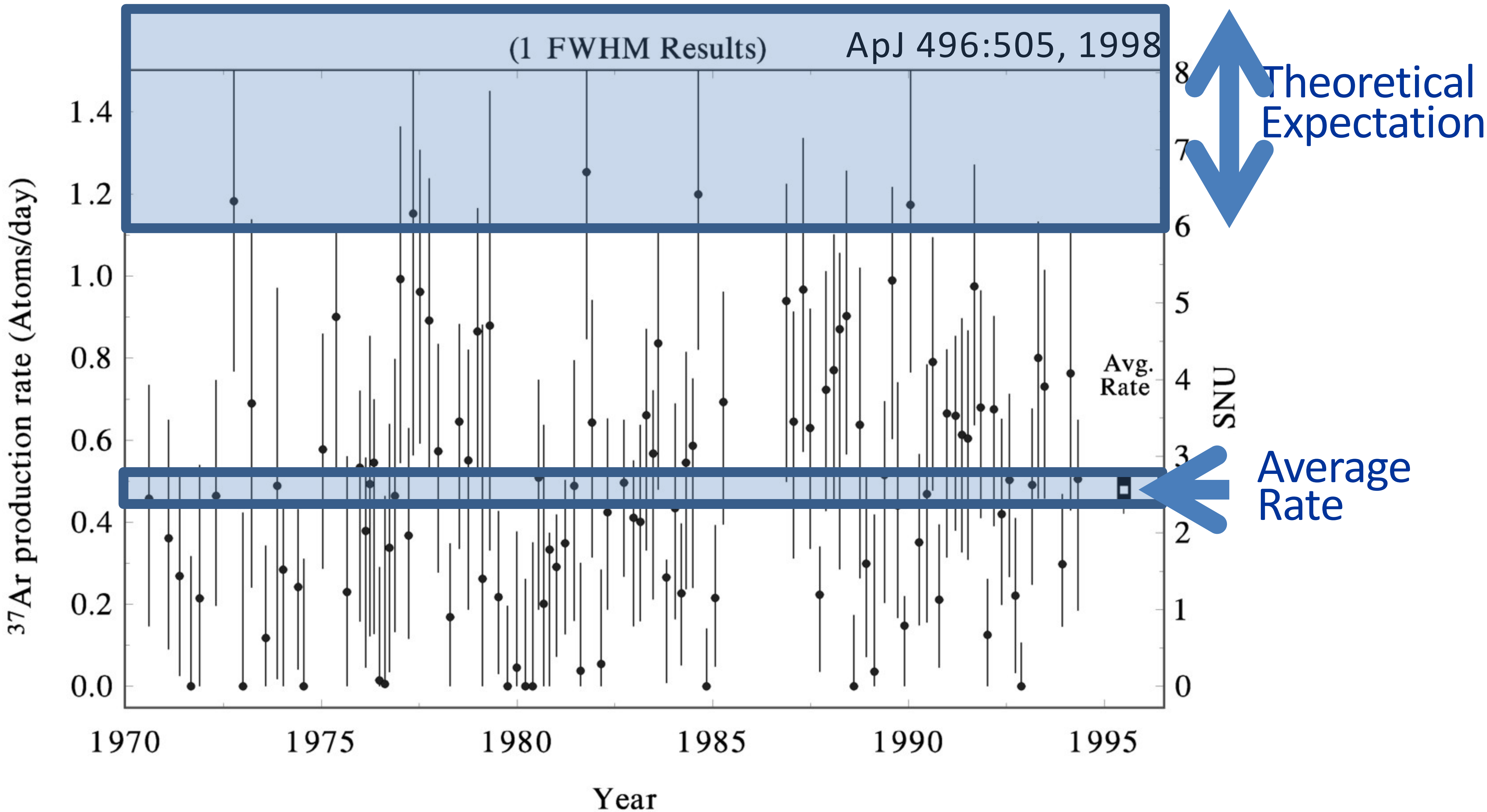


Ray Davis Jr.
(1914–2006)

Masatoshi Koshiba
(*1926)

„ for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”

Results of Chlorine Experiment (Homestake)



Average (1970–1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

Theoretical Prediction 6–9 SNU

"Solar Neutrino Problem" since 1968

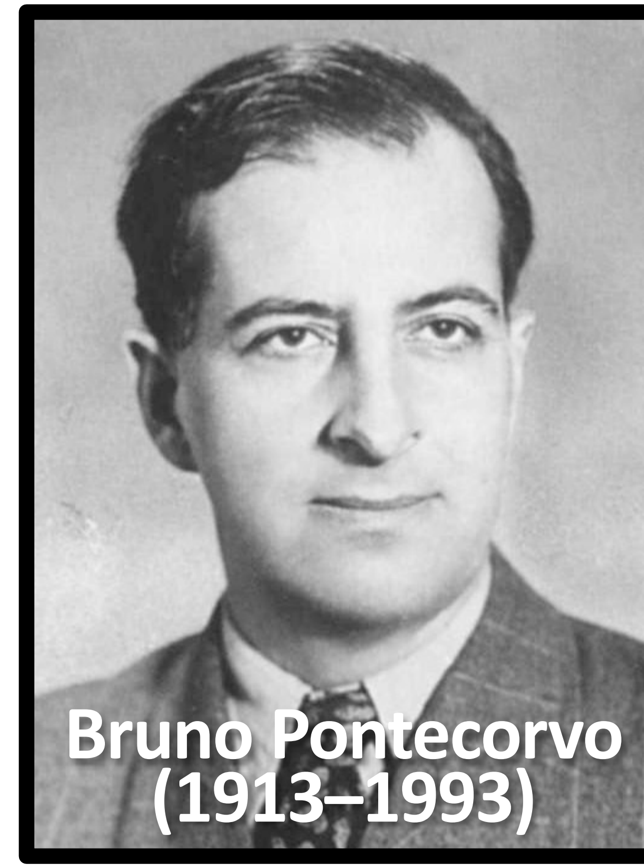
Neutrino-Oscillations

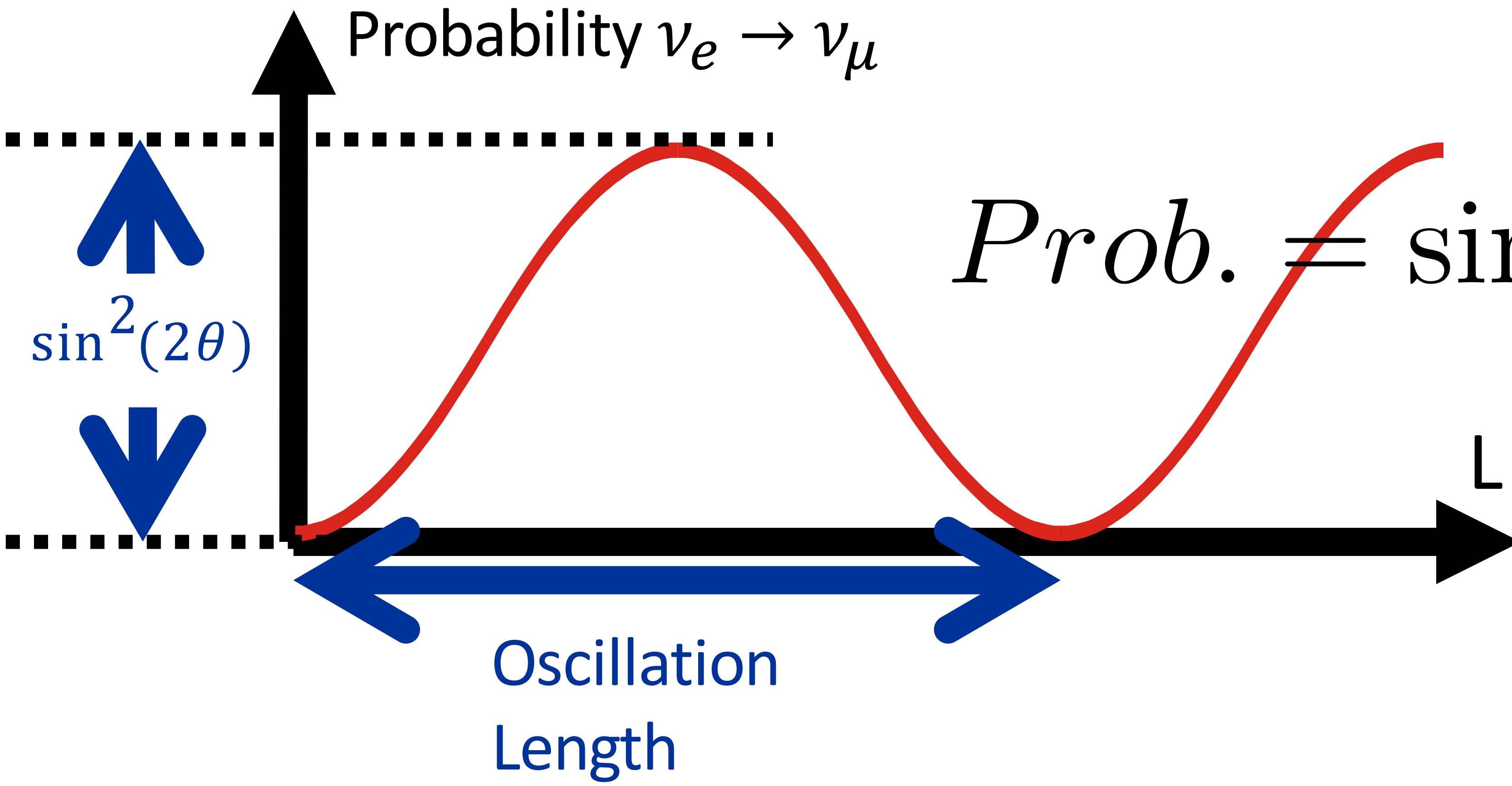
Pontecorvo & Gribov (1968 „ Solar neutrino problem“)

- Neutrinos are quantum superpositions of mass states

$$\nu_e = +\cos\Theta\ \nu_1 + \sin\Theta\ \nu_2$$
$$\nu_\mu = -\sin\Theta\ \nu_1 + \cos\Theta\ \nu_2$$

- Different propagation speeds gives neutrino oscillations



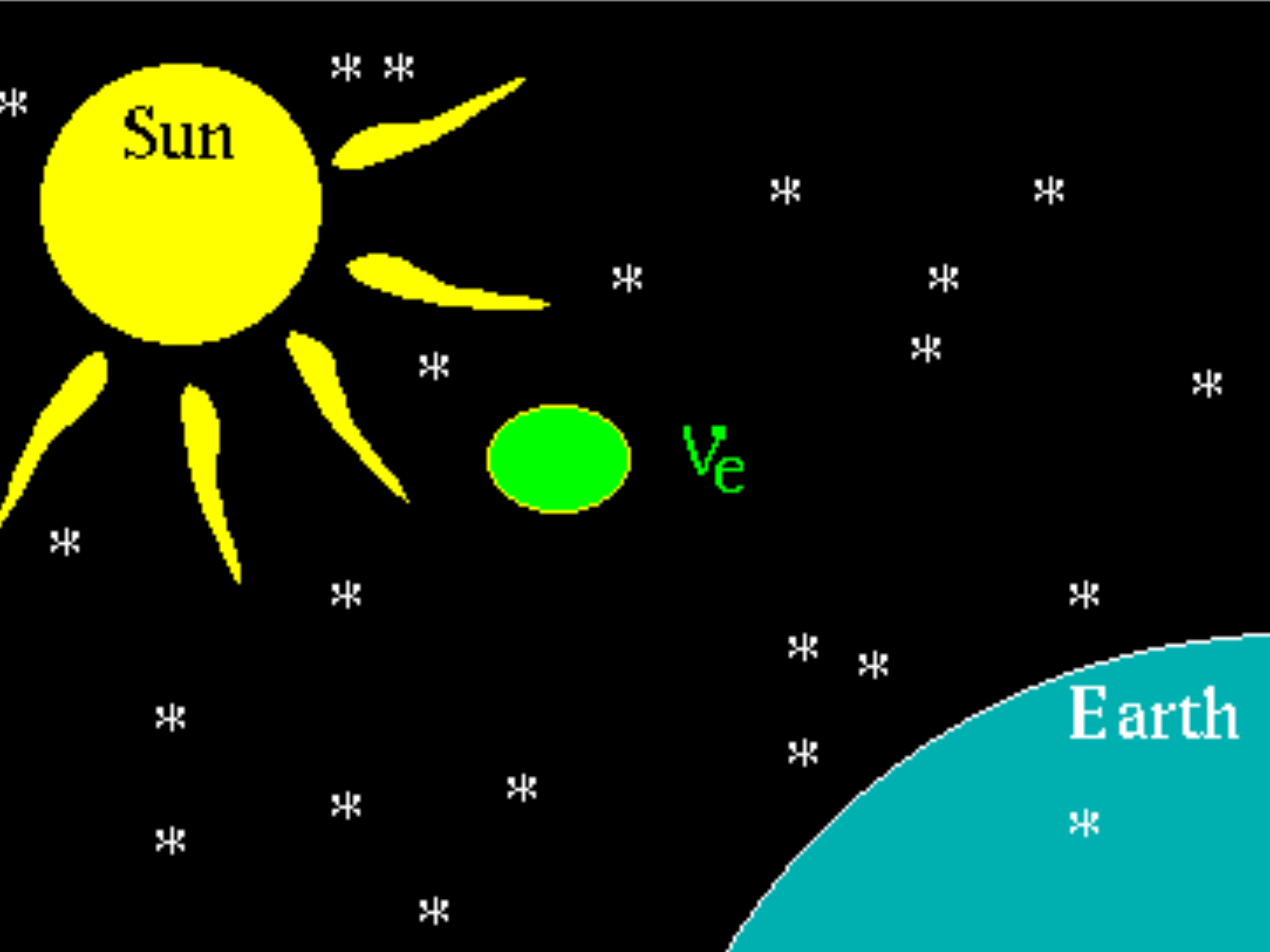


$$Prob. = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{E}$$

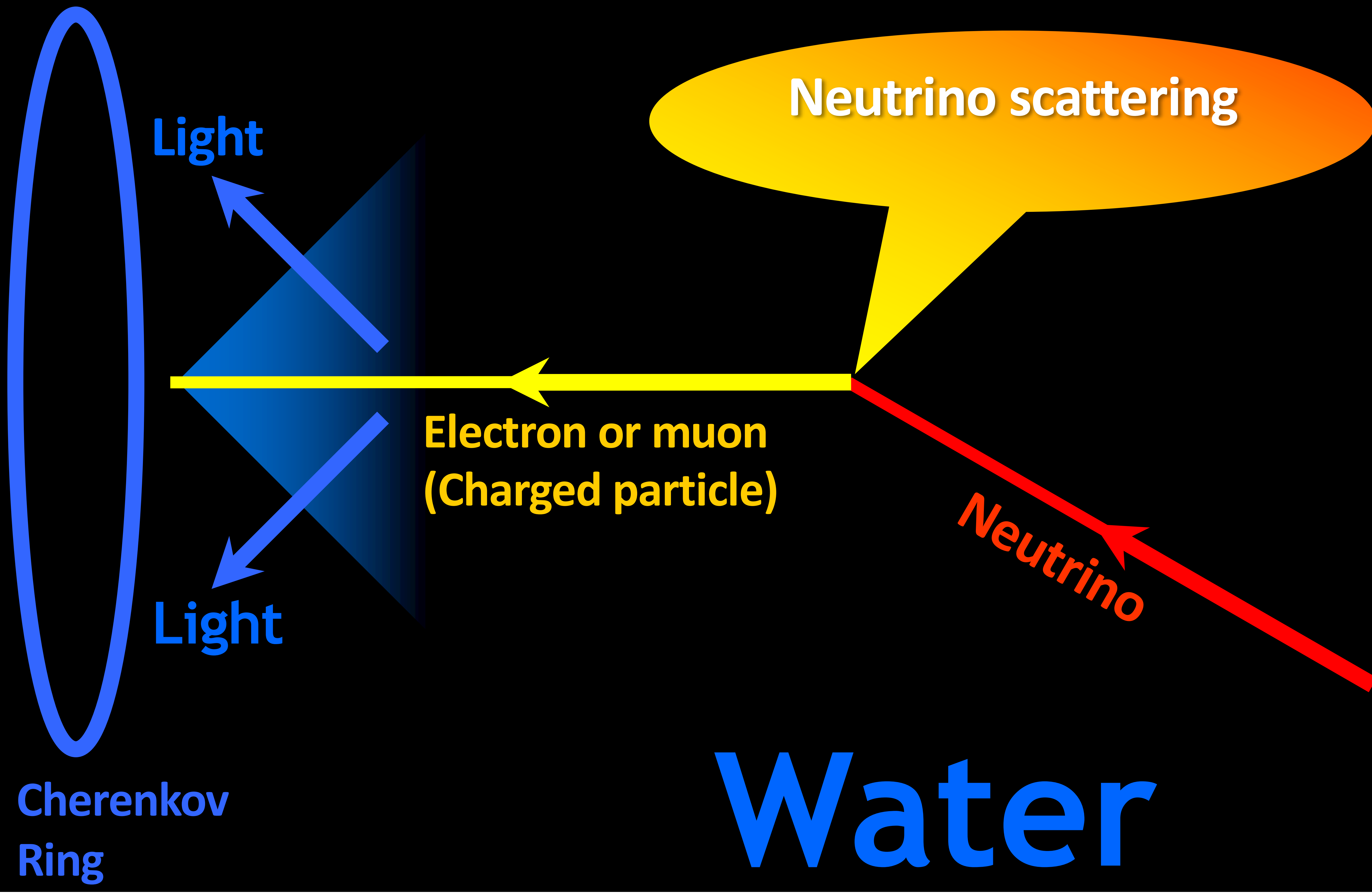
L is distance travelled

E is energy of neutrino

$$\Delta m^2 = m_2^2 - m_1^2$$


Sun
ν_e
Earth

Detecting neutrinos in water



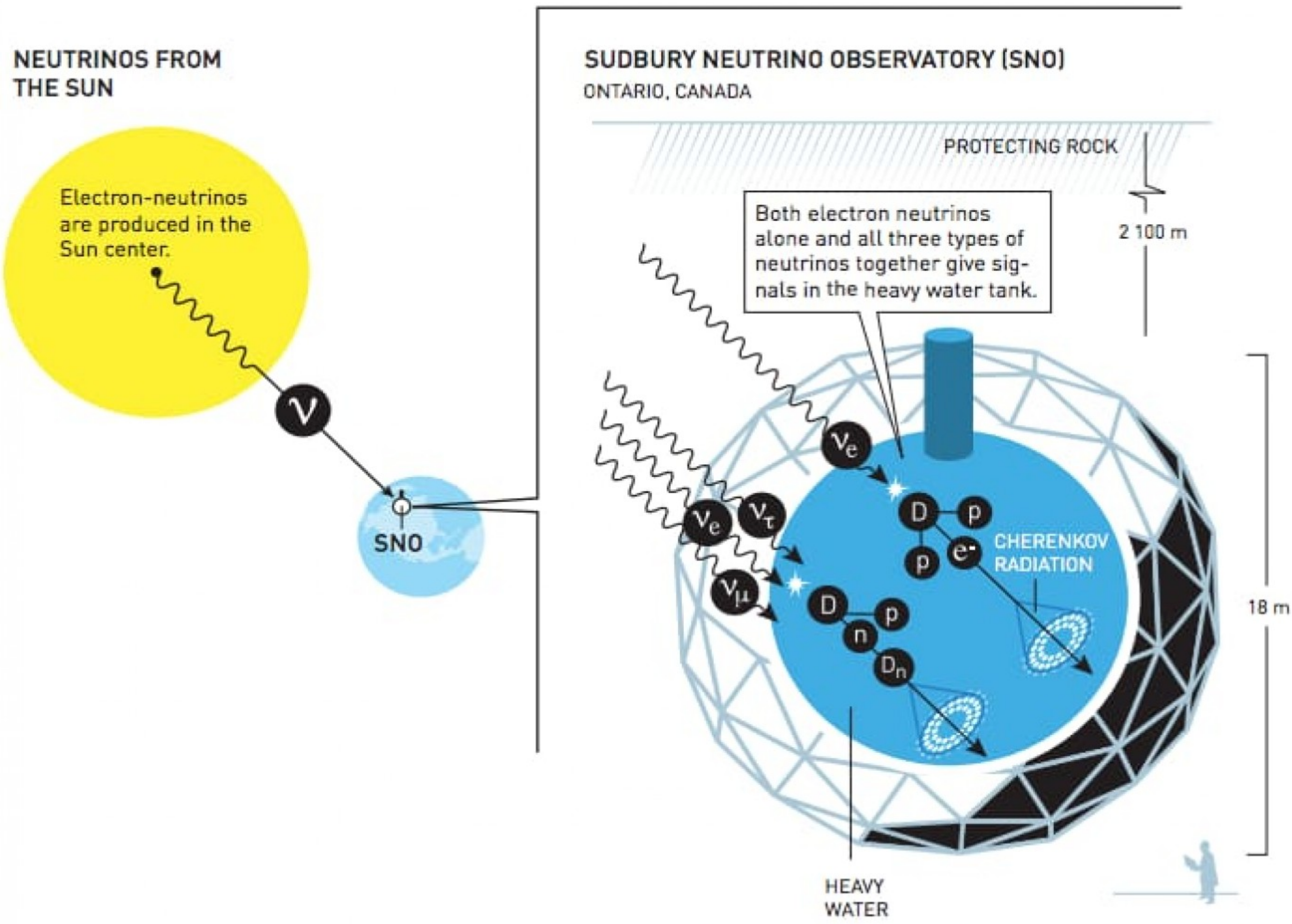
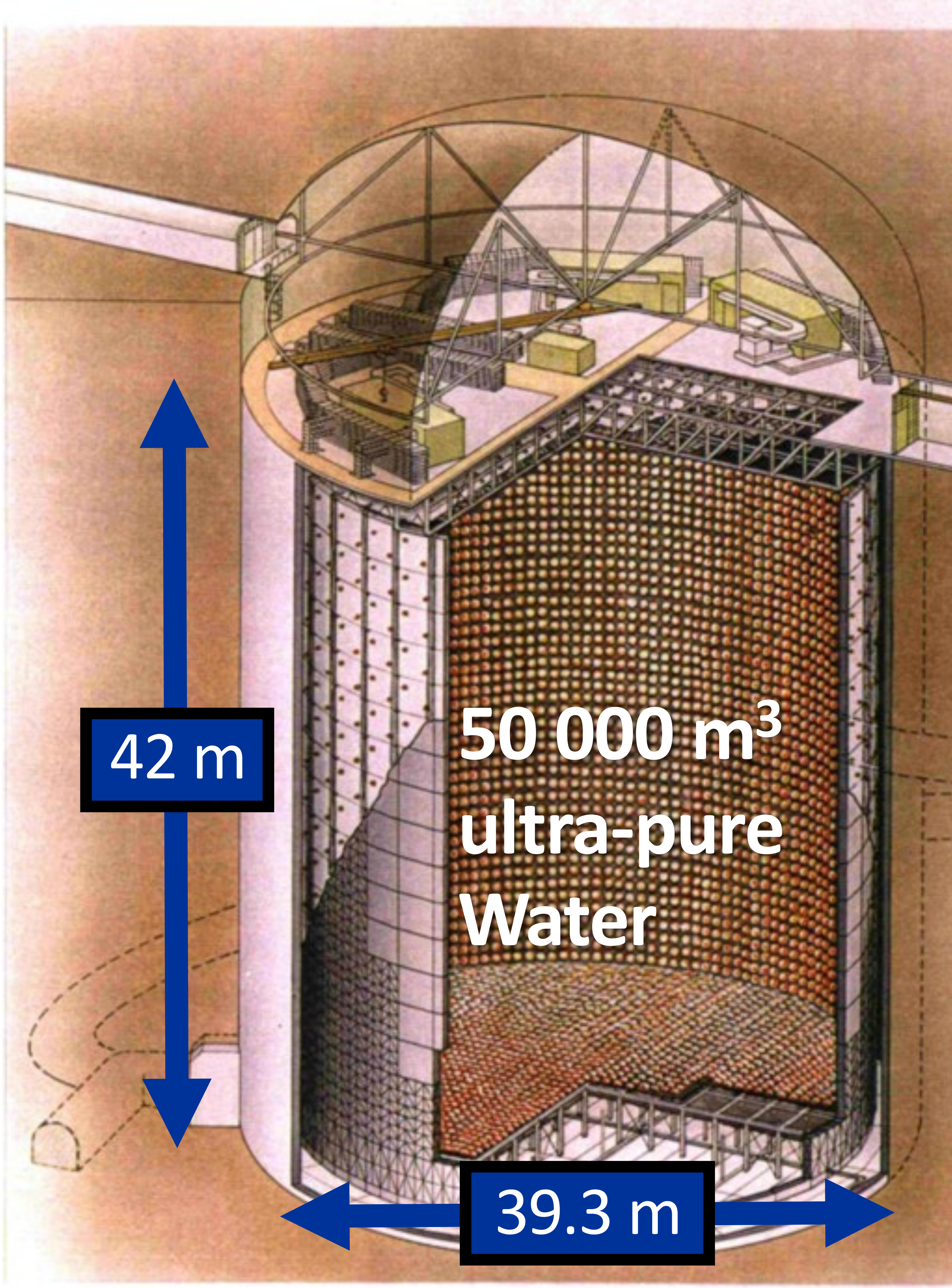
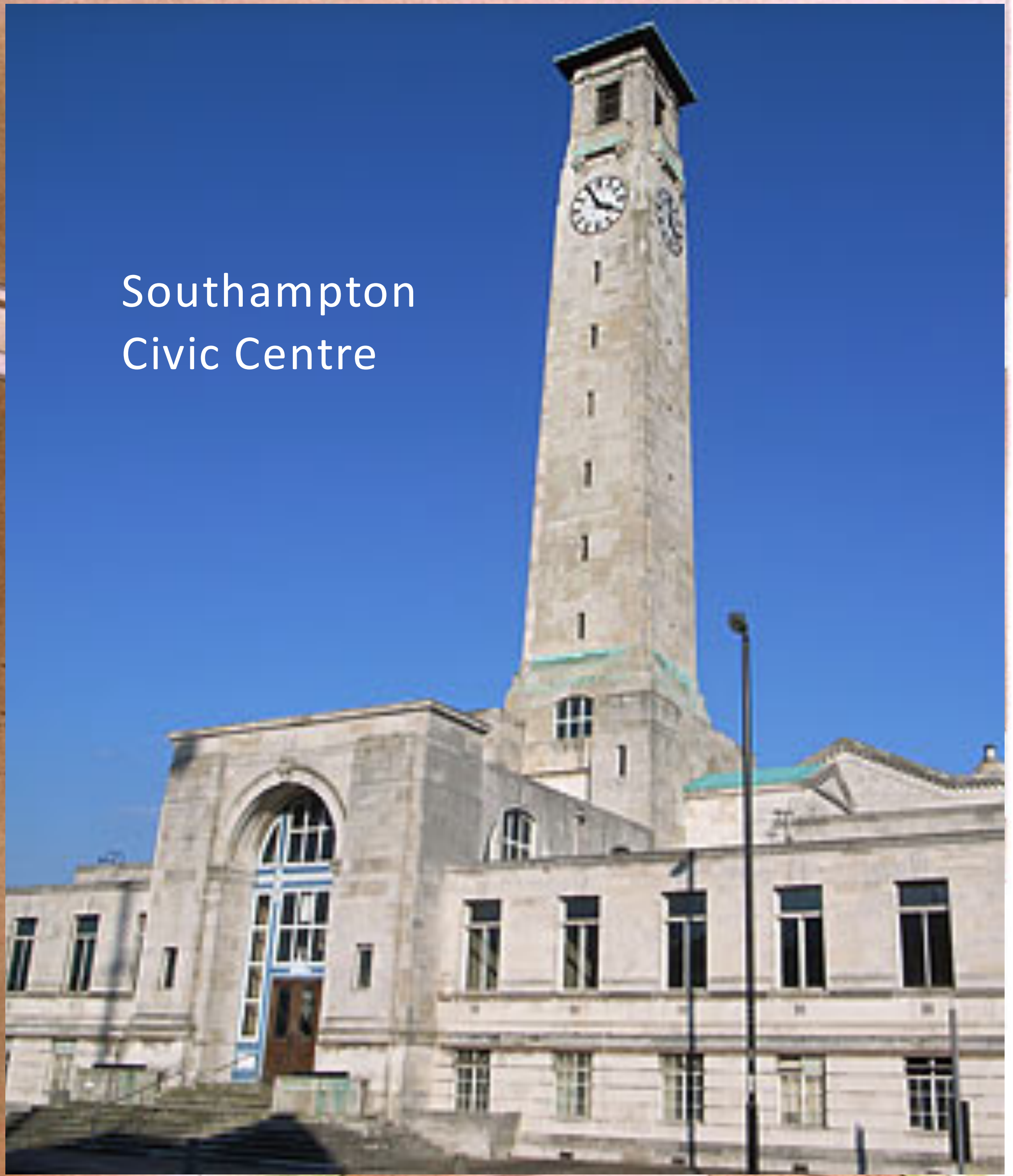


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

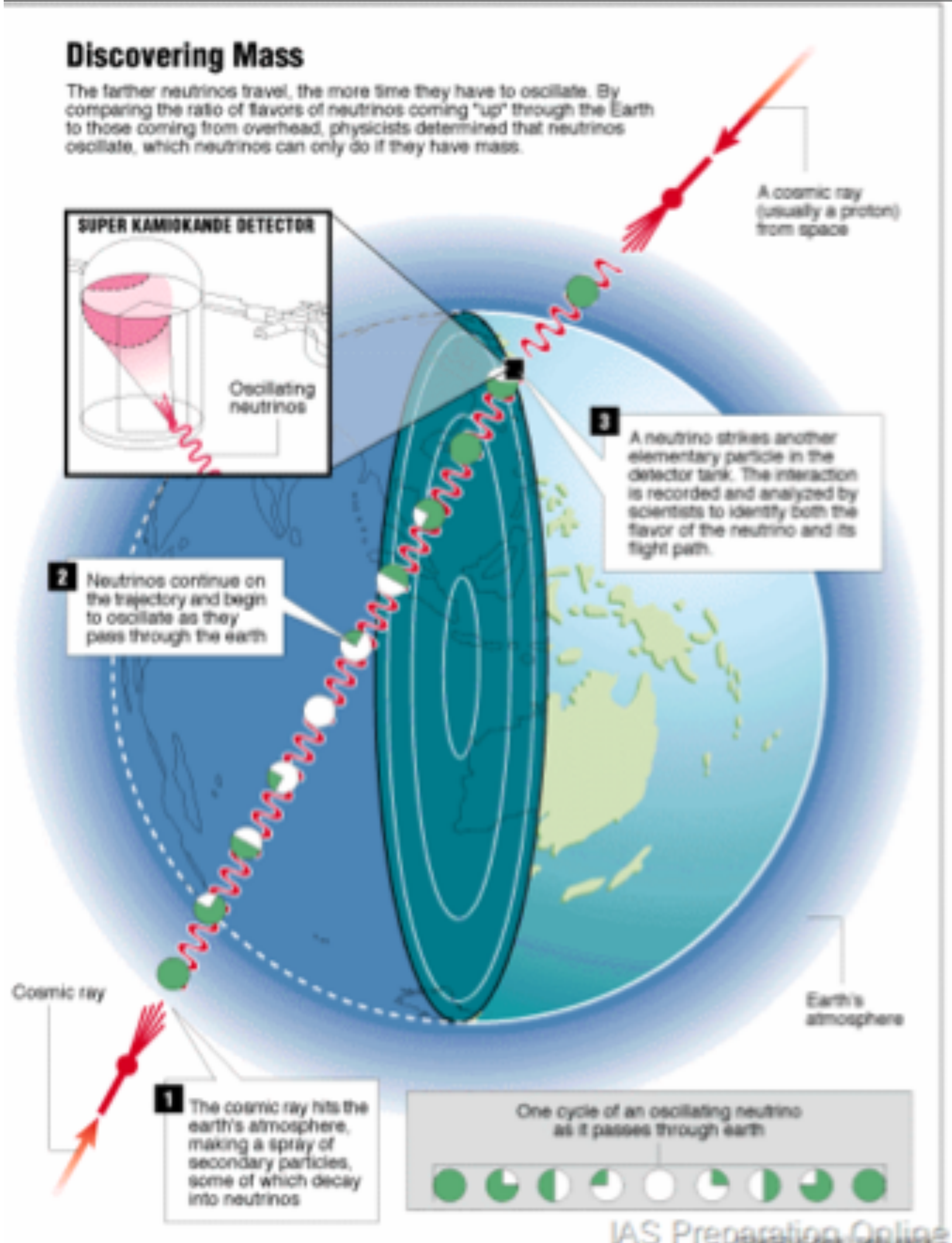
Super-Kamiokande Detector (since 1996)

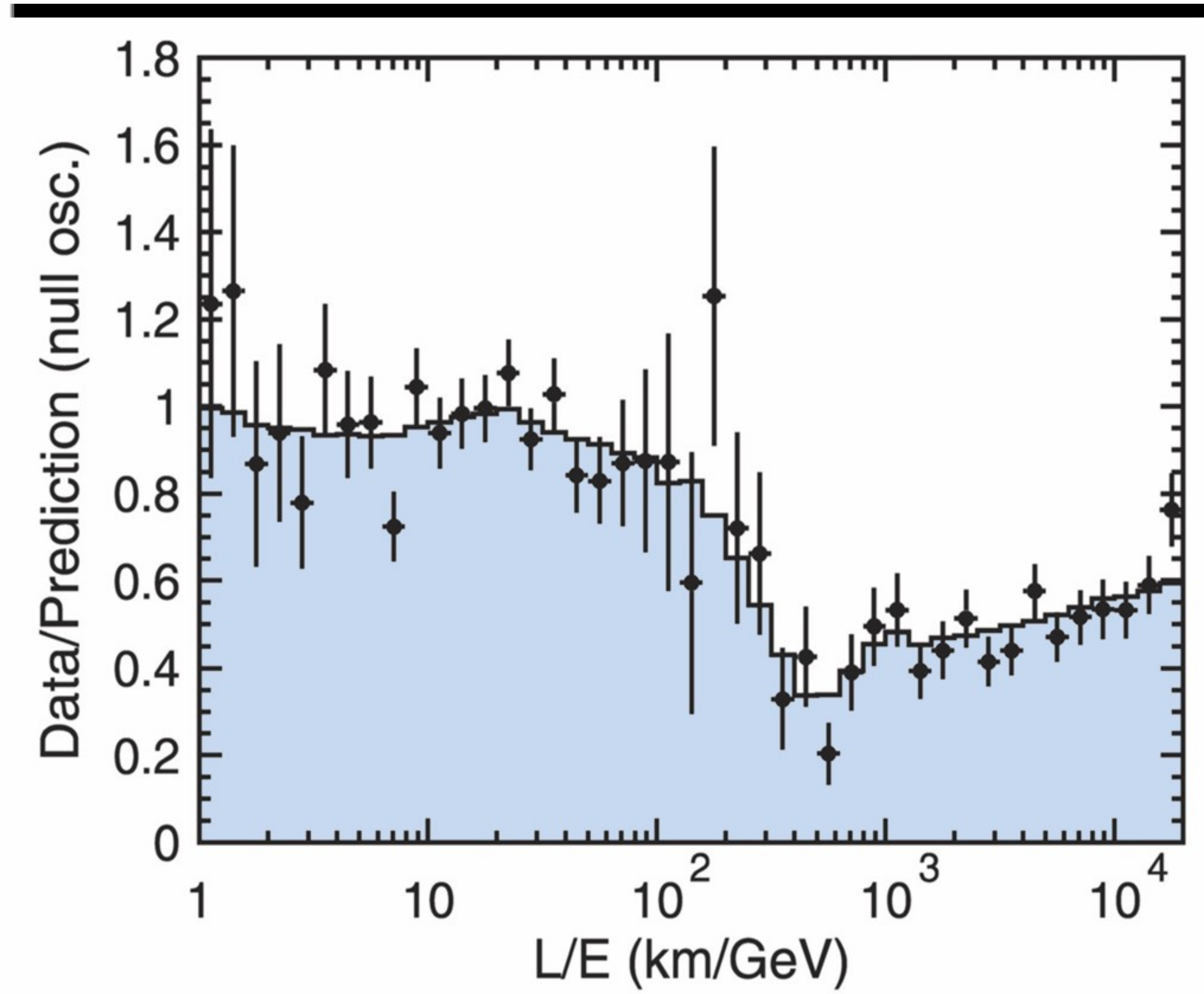





by Susana Molina Sedgewick

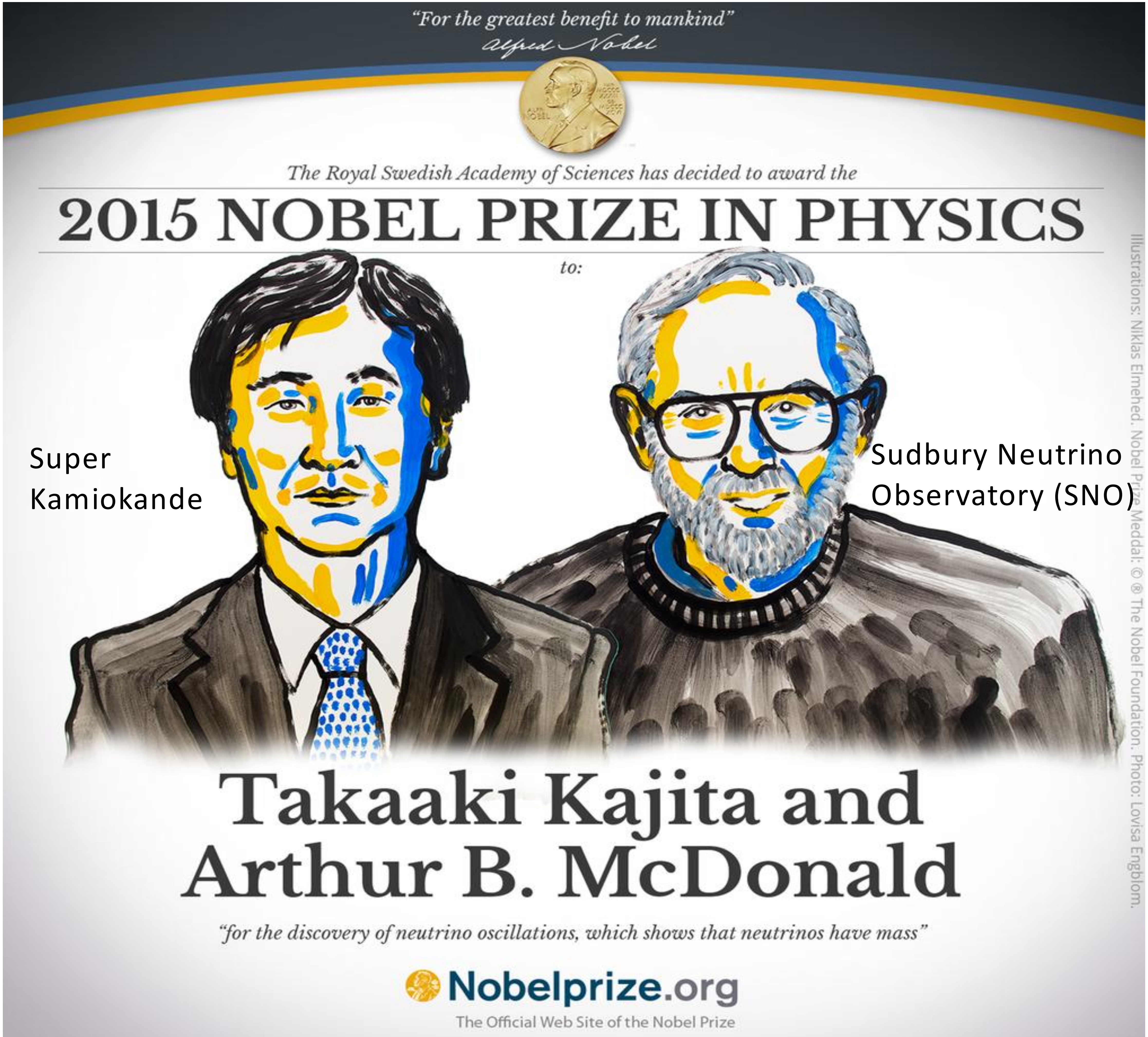
Atmospheric Neutrino Oscillations (1998)





$$Prob. = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{E}$$

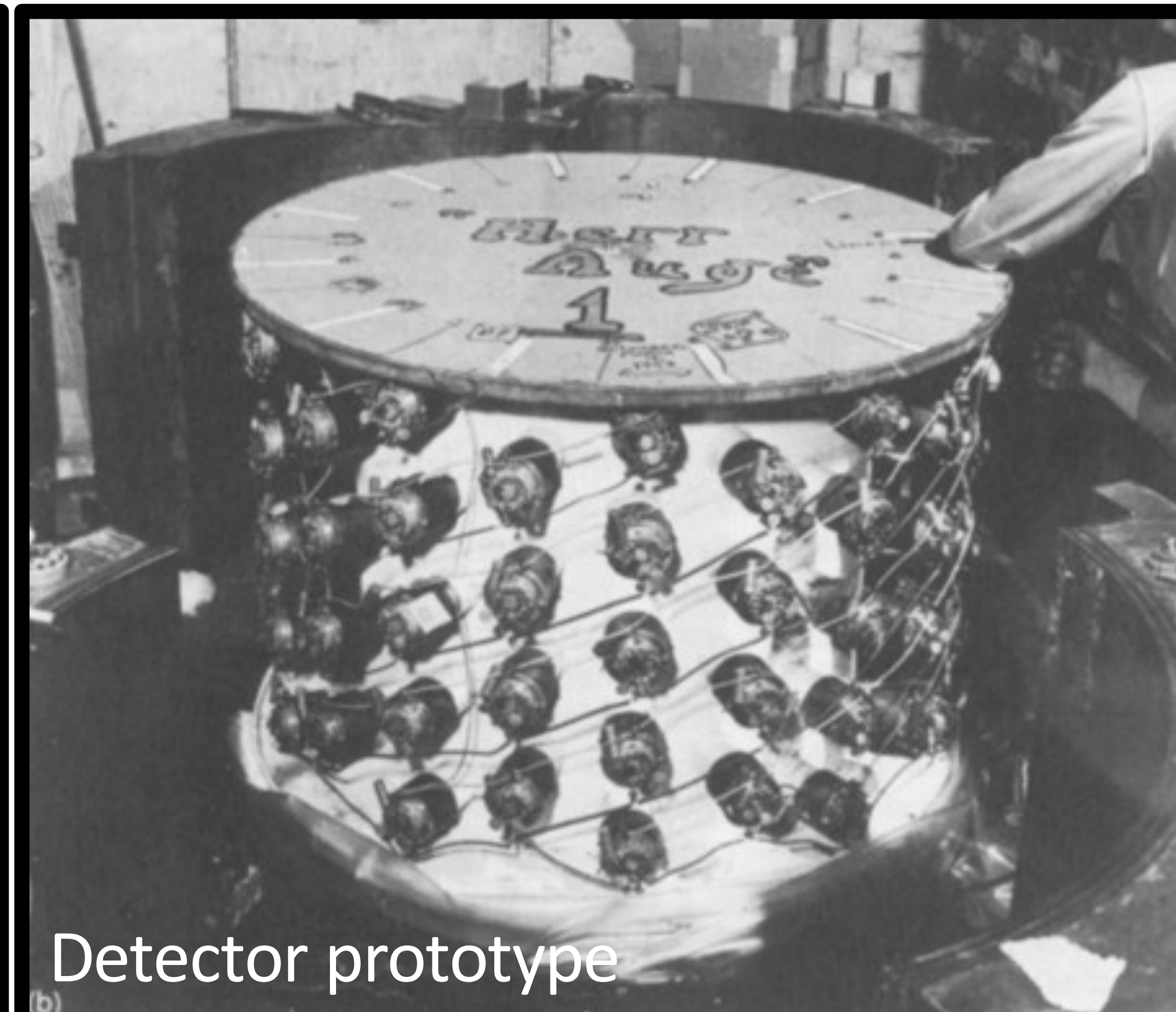
Atmospheric neutrino oscillations show characteristic L/E variation



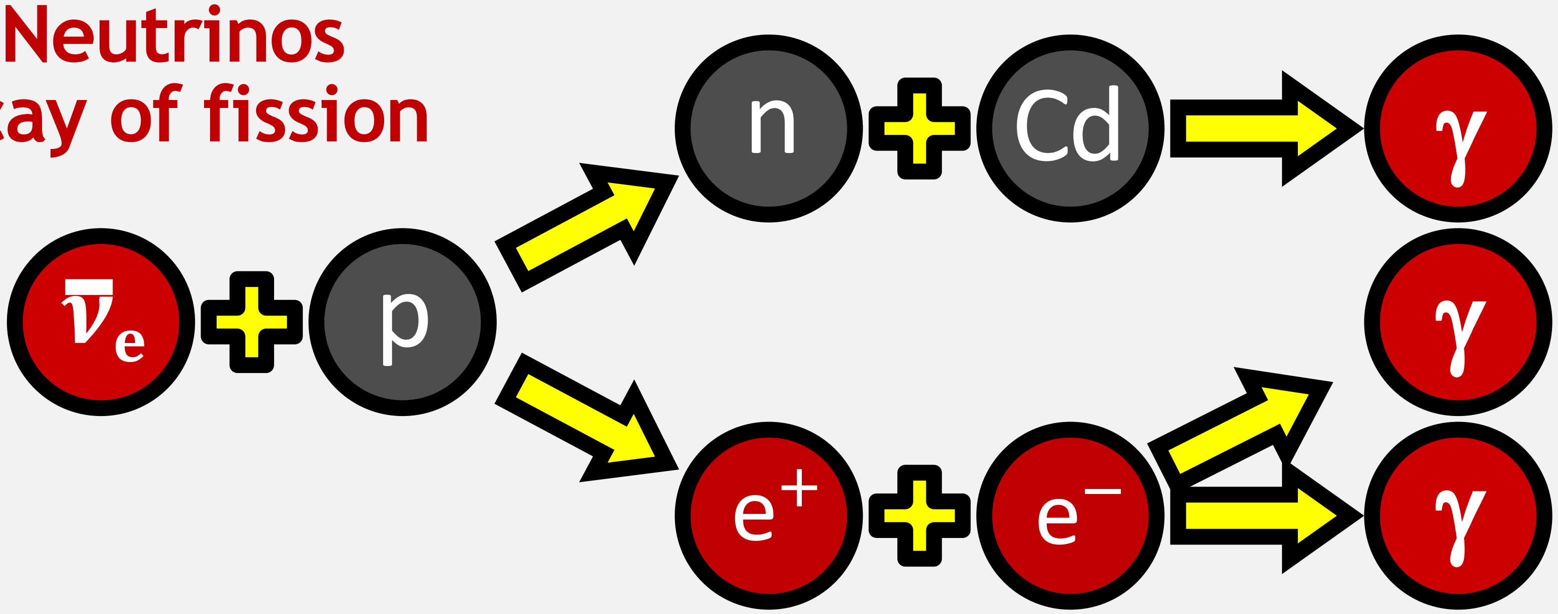
Super Kamiokande

Sudbury Neutrino Observatory (SNO)

First neutrinos from nuclear reactors (20th July 1956)



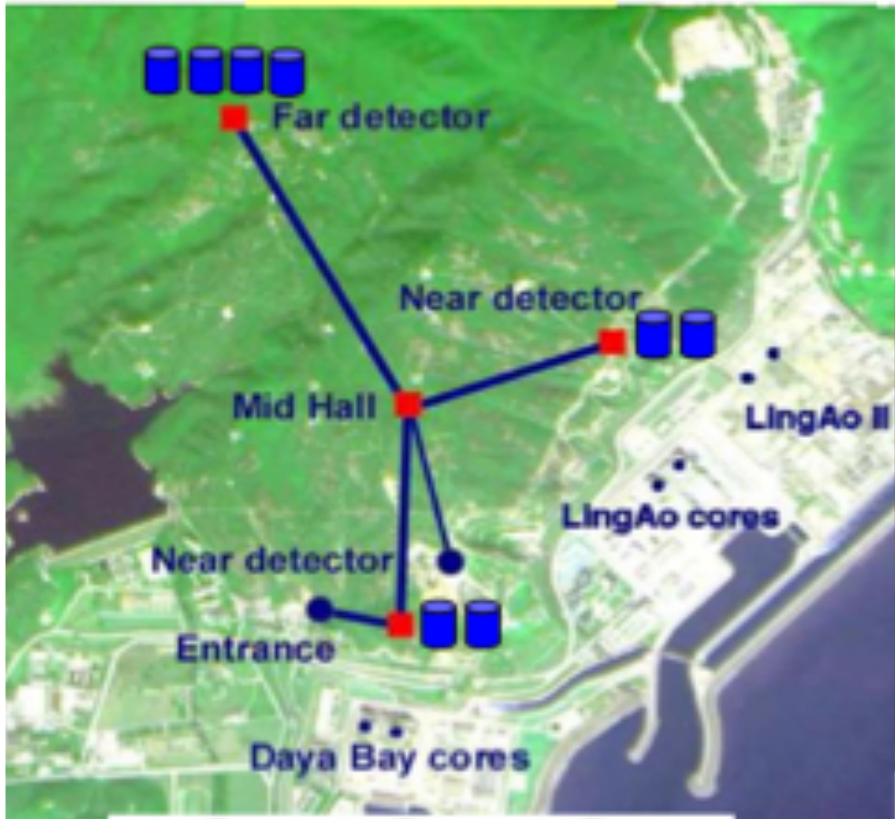
Anti-Electron Neutrinos from beta decay of fission products in Hanford Nuclear reactor



3 Gammas in coincidence

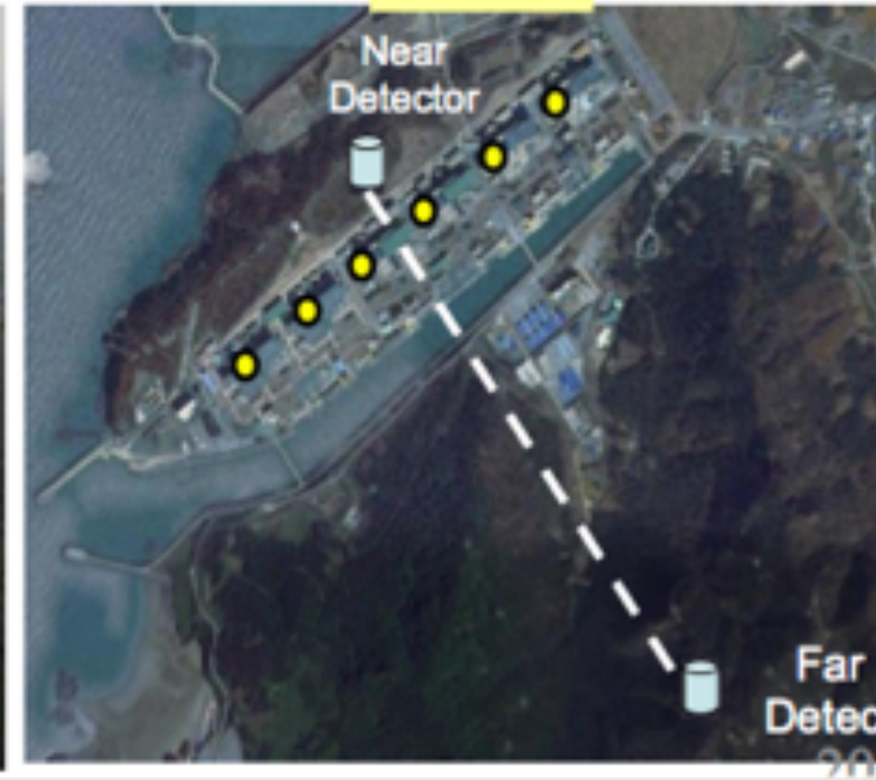
Modern Reactor Experiments

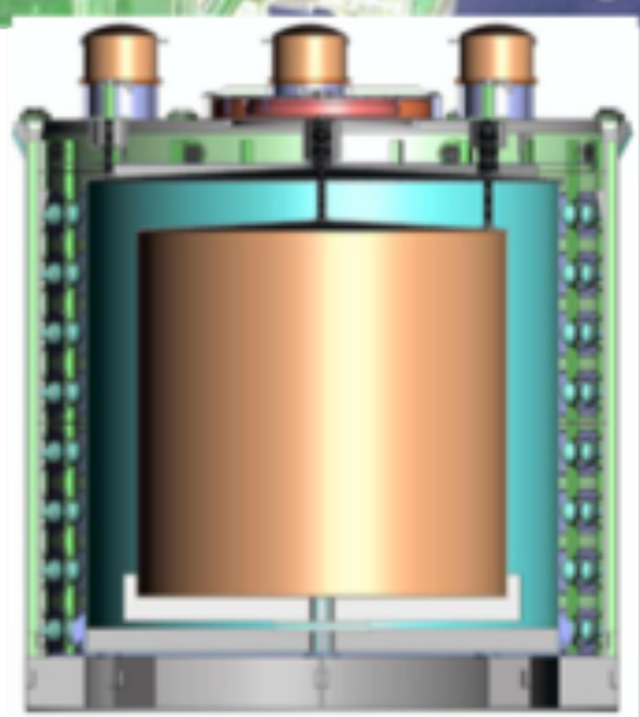
Daya Bay



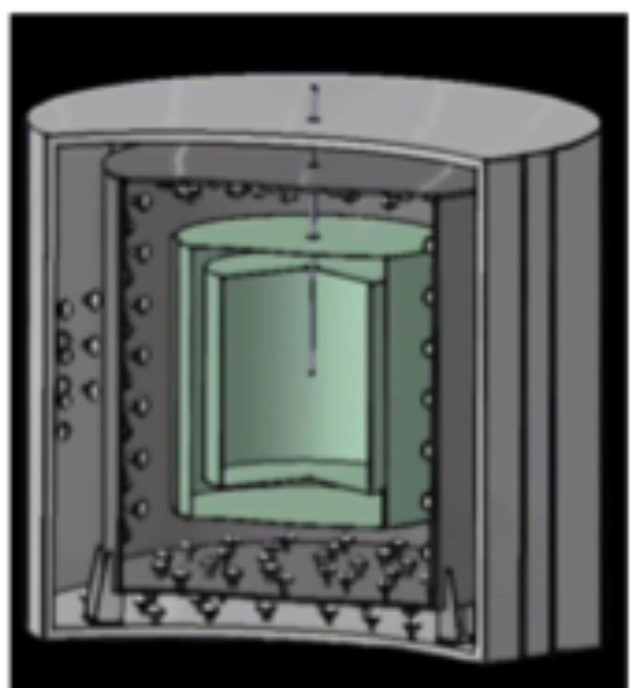
Double Chooz

Reno

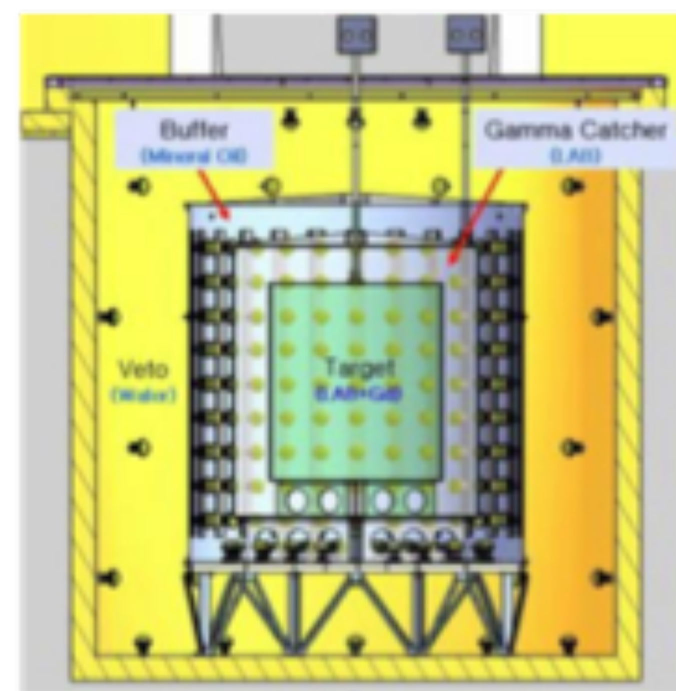




Daya Bay

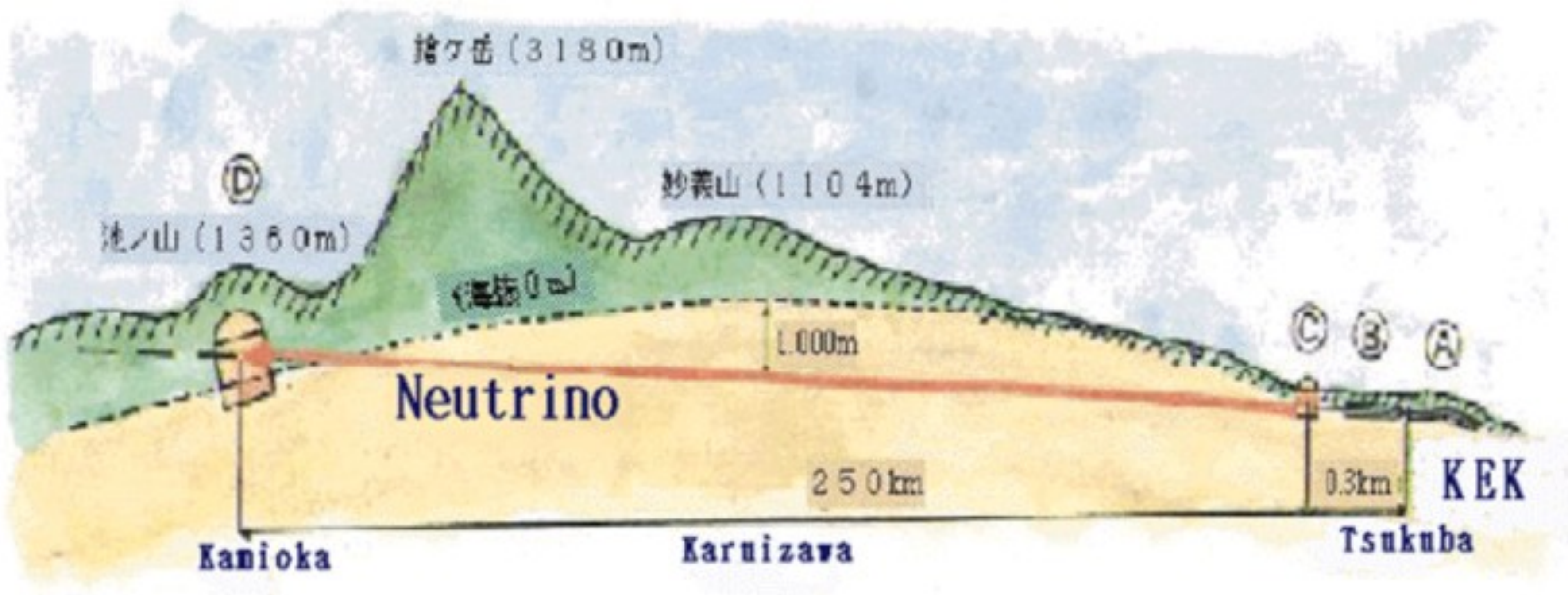


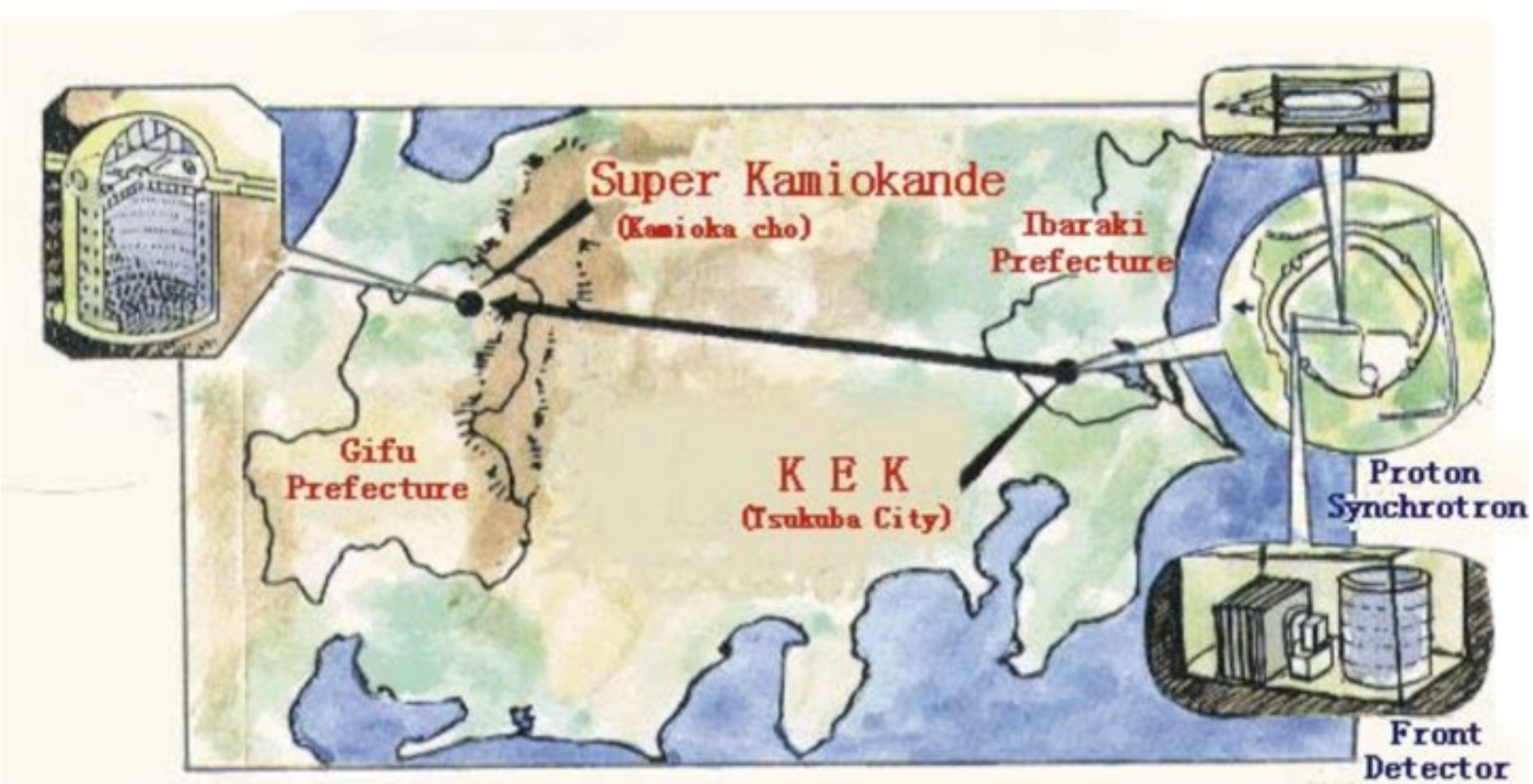
Double Chooz



RENO

Long-Baseline (LBL) Experiments





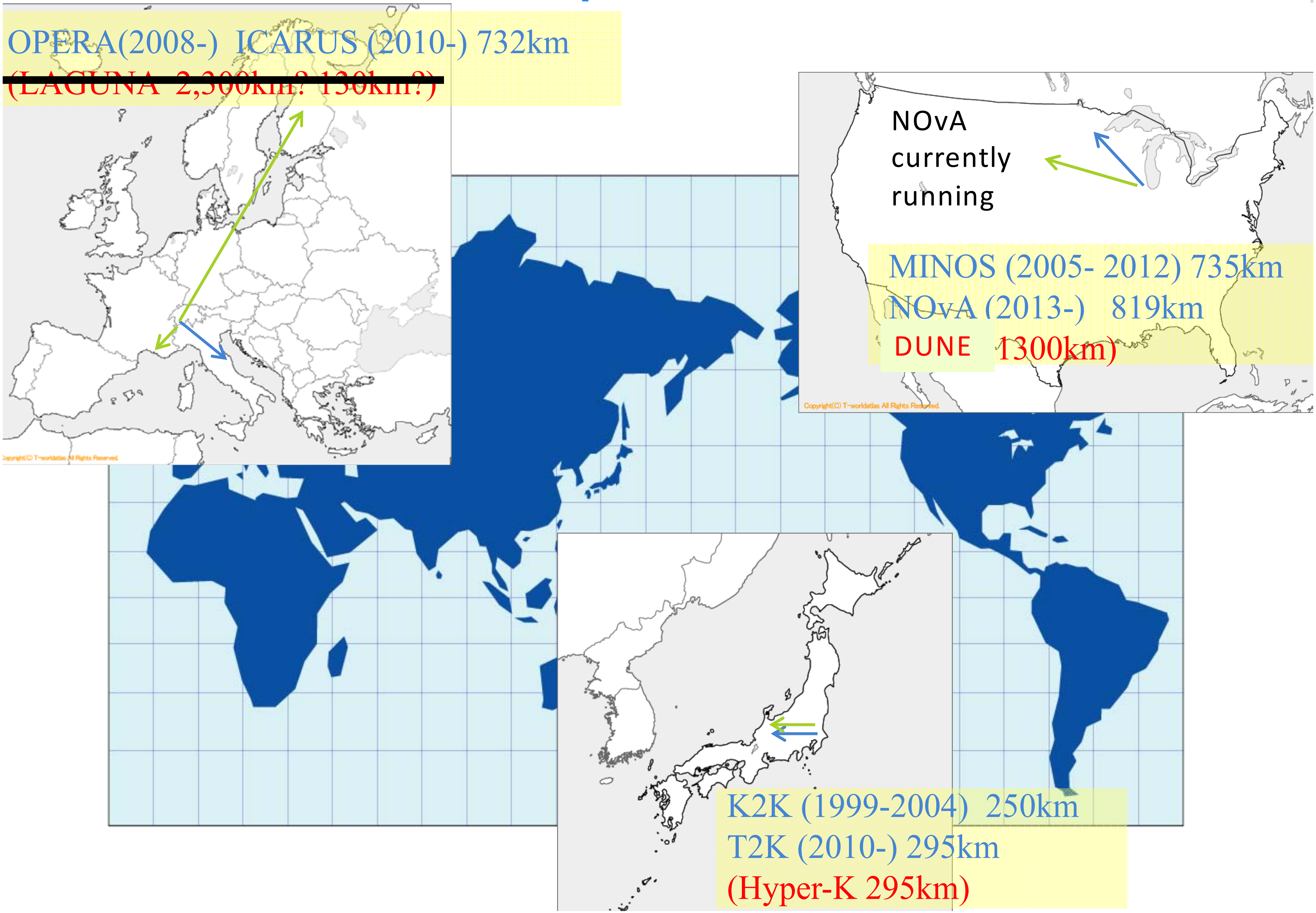
K2K Experiment (KEK to Kamiokande) measured precise neutrino oscillation parameters.

Since then other LBL Experiments:

- Minos (US)
- Opera (Europe)
- T2K (Japan)
- Nova (US)

Tsukuba to Kamioka (T2K) currently running experiment

World LBL experiments

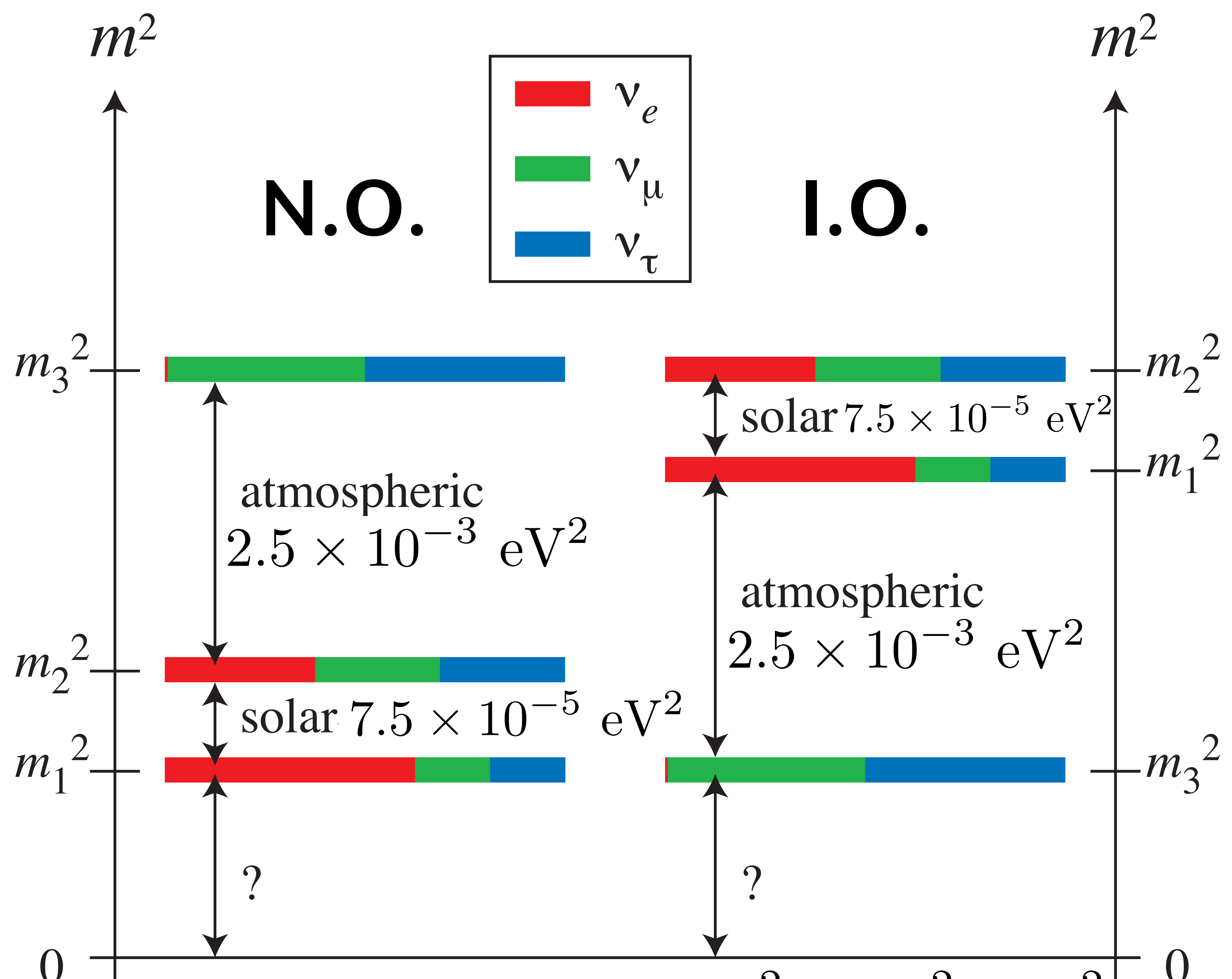


Neutrino Mass and Mixing

The 6 observables in neutrino oscillations

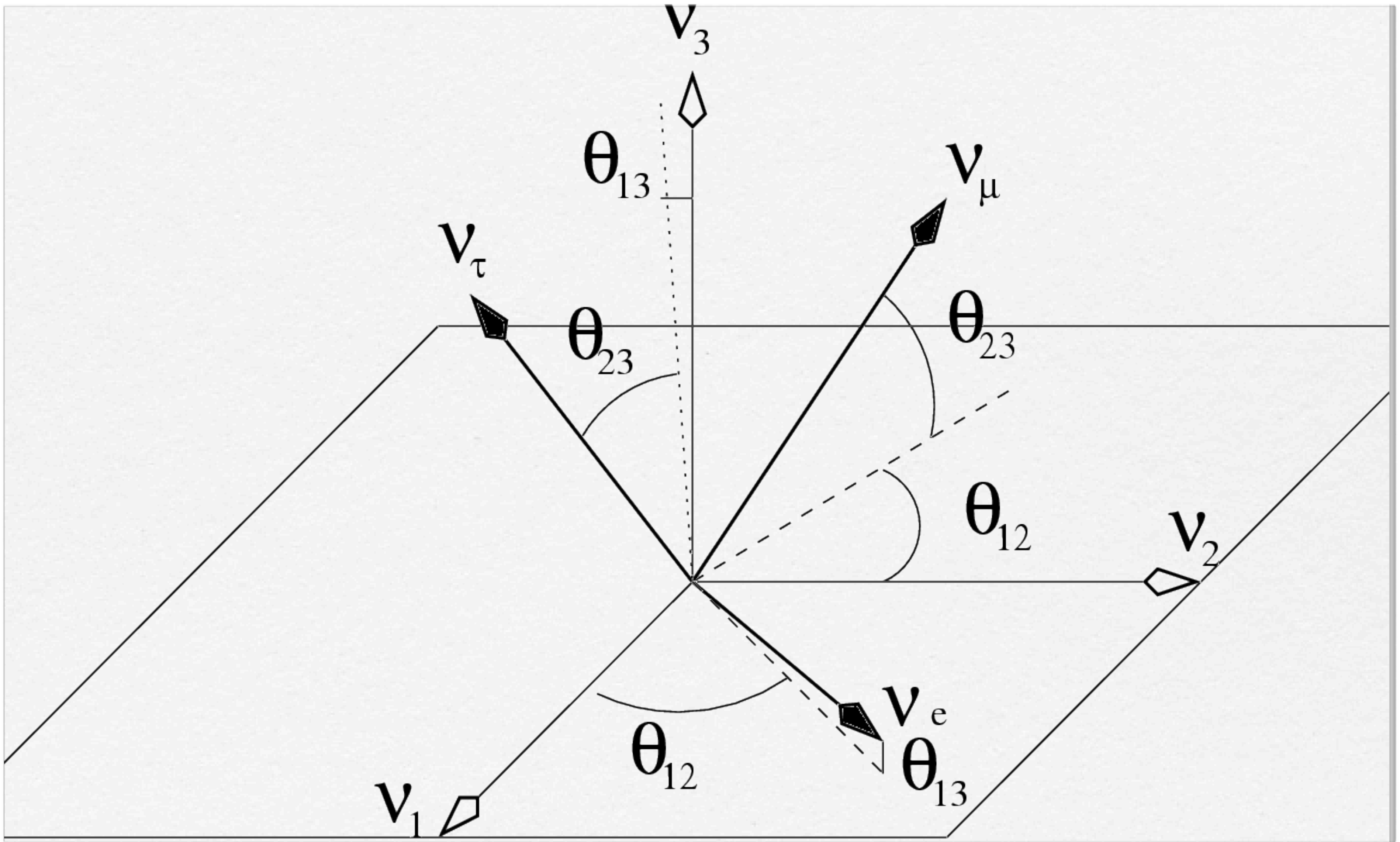
- ✳The atmospheric mass squared difference Δm^2_{31}
- ✳The solar mass squared difference Δm^2_{21}
- ✳The atmospheric angle θ_{23}
- ✳The solar angle θ_{12}
- ✳The reactor angle θ_{13}
- ✳The CP violating phase δ

Neutrino Mass Squared

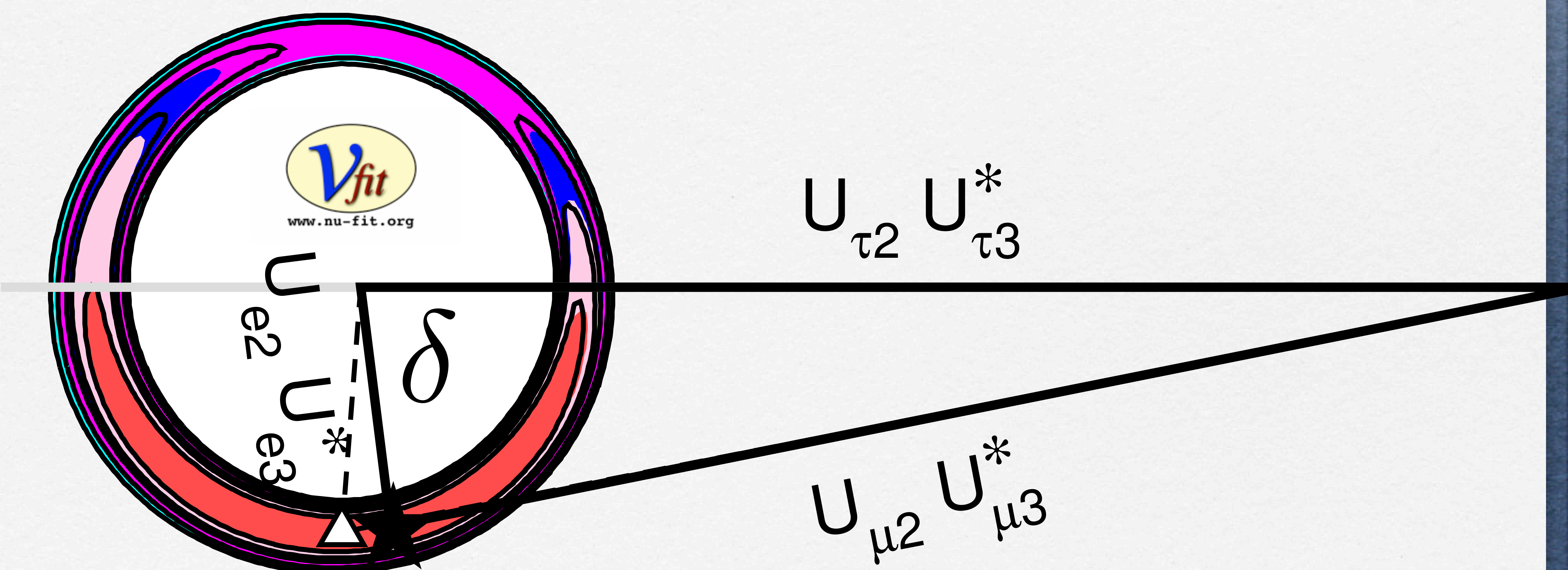


Neutrino oscillations depend on $\Delta m^2_{ij} = m^2_i - m^2_j$

Lepton Mixing Angles



CP Violating Phase



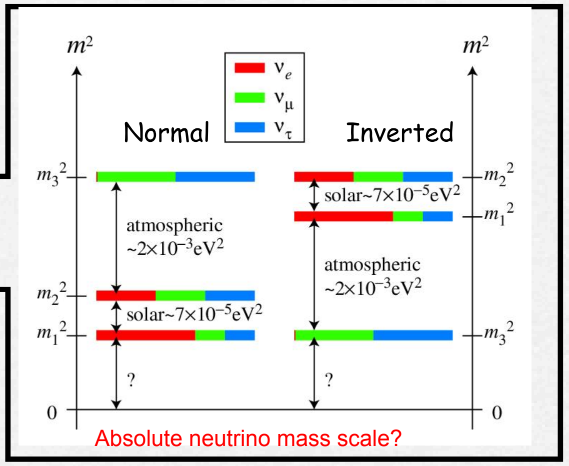
Lepton Mixing Matrix

Standard Model states

$$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}_L$$

PMNS matrix

Neutrino mass states



Pontecorvo
Maki
Nakagawa
Sakata

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

$$U = \begin{pmatrix}1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0 \\ 0 & \frac{\alpha_{21}}{2} & 0 \\ 0 & 0 & \frac{\alpha_{31}}{2}\end{pmatrix}$$

Atmospheric | **Reactor** | **Solar** | **Majorana**

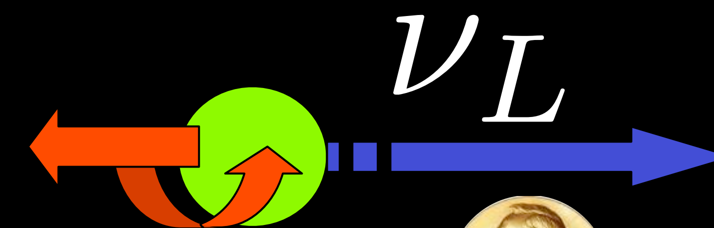
PMNS and CKM mixing

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

For Majorana neutrinos → $\times\, \mathrm{diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$

Same form for quarks and leptons
(but very different angles)

A Brief History of Progress in Neutrino Physics since 1998



- ☑ Atmospheric ν_μ disappear, large θ_{23} (1998)  SK
- ☑ Solar ν_e disappear, large θ_{12} (2002)  SK, SNO
- ☑ Solar ν_e are converted to $\nu_\mu+\nu_\tau$ (2002) SNO
- ☑ Reactor anti-ν_e disappear/reappear (2004) Kamland
- ☑ Accelerator ν_μ disappear (2006) MINOS
- ☑ Accelerator ν_μ converted to ν_τ (2010) OPERA
- ☑ Accelerator ν_μ converted to ν_e, θ_{13} hint (2011) T2K
- ☑ Reactor anti-ν_e disappear, θ_{13} meas. (2012) DB, Reno

Latest NuFIT Fit 3.2

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix}+2.399 \to +2.593 \\ -2.536 \to -2.395\end{bmatrix}$

$$\Delta m^2_{3l} = m^2_3 - m^2_1 \qquad \Delta m^2_{3l} = m^2_3 - m^2_2$$

Quark vs Lepton mixings (again)

	θ_{12}	θ_{23}	θ_{13}	δ
Quarks	13° $\pm 0.1^\circ$	2.4° $\pm 0.1^\circ$	0.2° $\pm 0.05^\circ$	70° $\pm 5^\circ$
Leptons	34° $\pm 1^\circ$	45° $41^\circ \pm 1^\circ$ $50^\circ \pm 1^\circ$	8.5° $\pm 0.15^\circ$	-90° $\pm 50^\circ$

Open Questions

 Is CP violated in the leptonic sector? (Probably)

 Is the atmospheric angle in first or second octant?

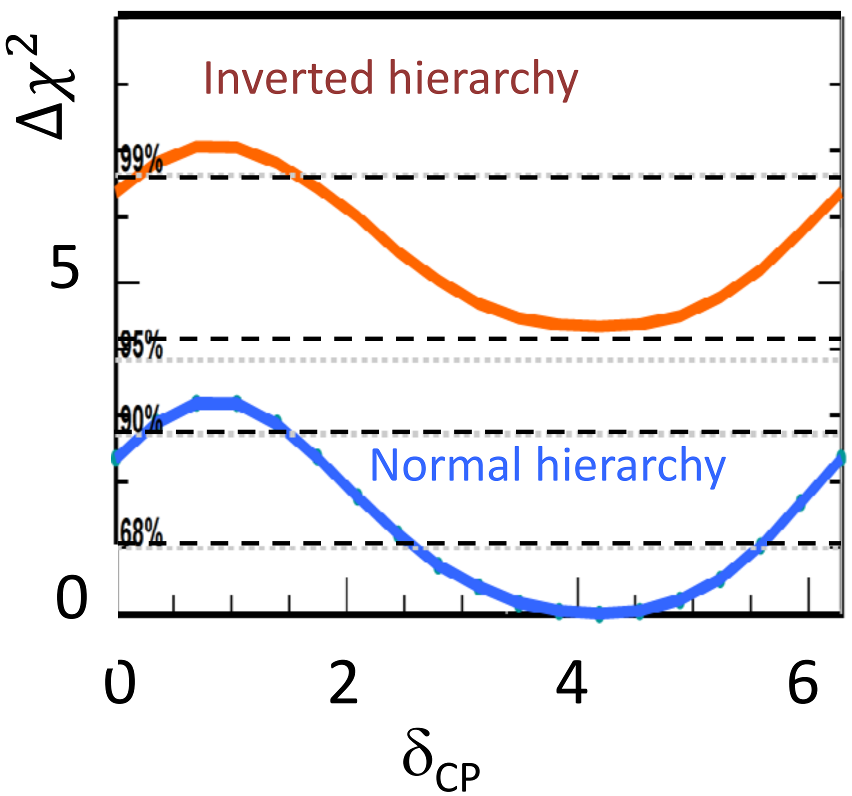
 Are neutrino masses NO or IO ? (NO preferred)

 What is the lightest neutrino mass?

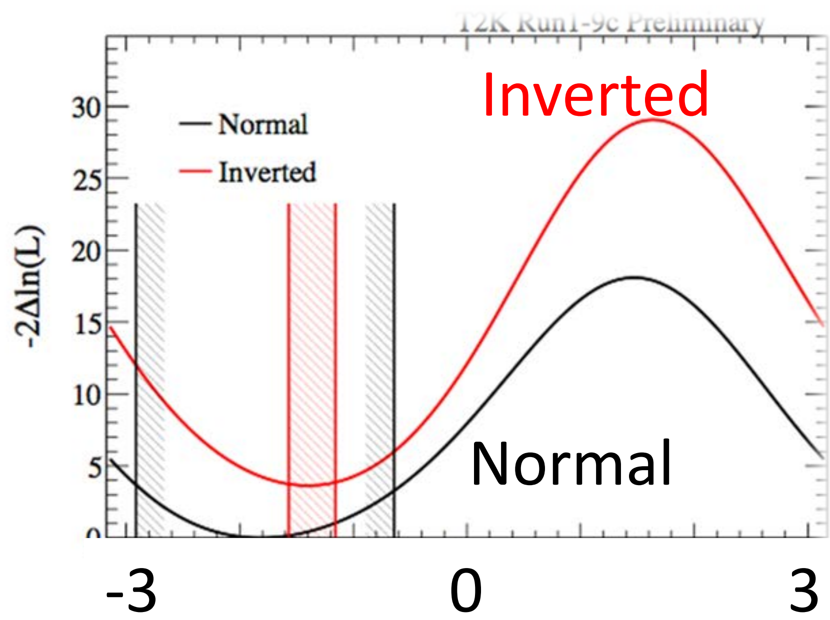
 Are neutrino masses Dirac or Majorana?

News in Neutrino 2018

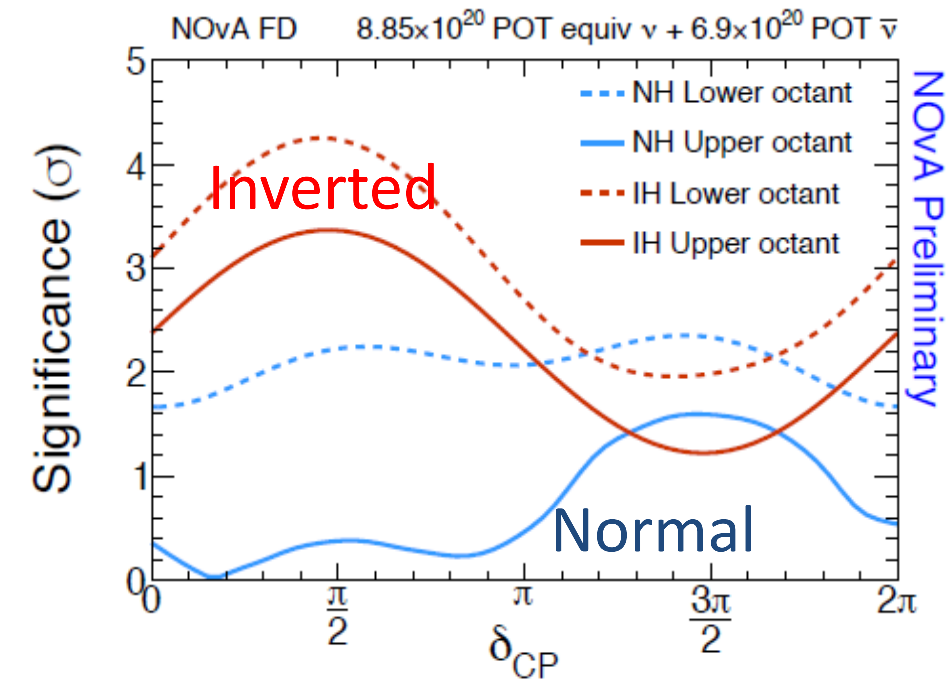
Super-K atmospheric (Y. Hayato)



T2K (M. Wascko)



NOvA (M. Sanchez)



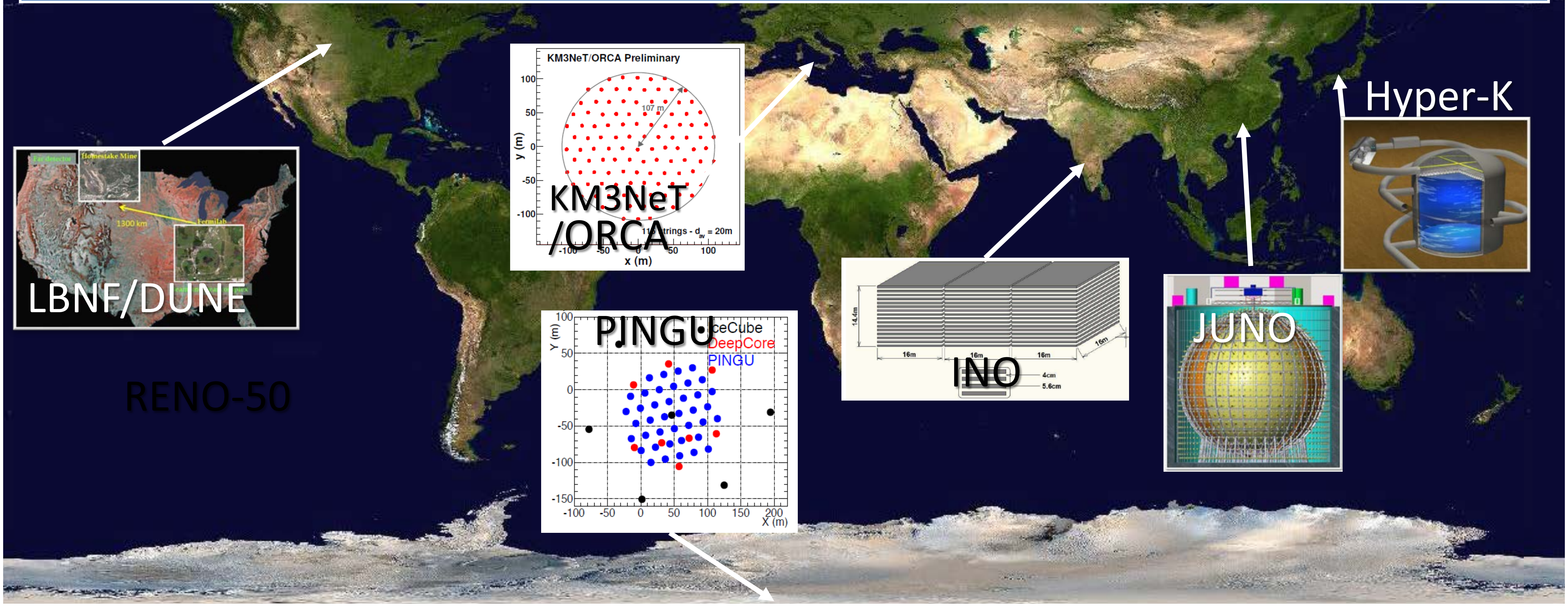
Already some interesting indications:

➔ NO favored by these 3 experiments at ~(1 ~ 2) sigma level each.

➔ These experiments give some favored δ_{CP} region(s).

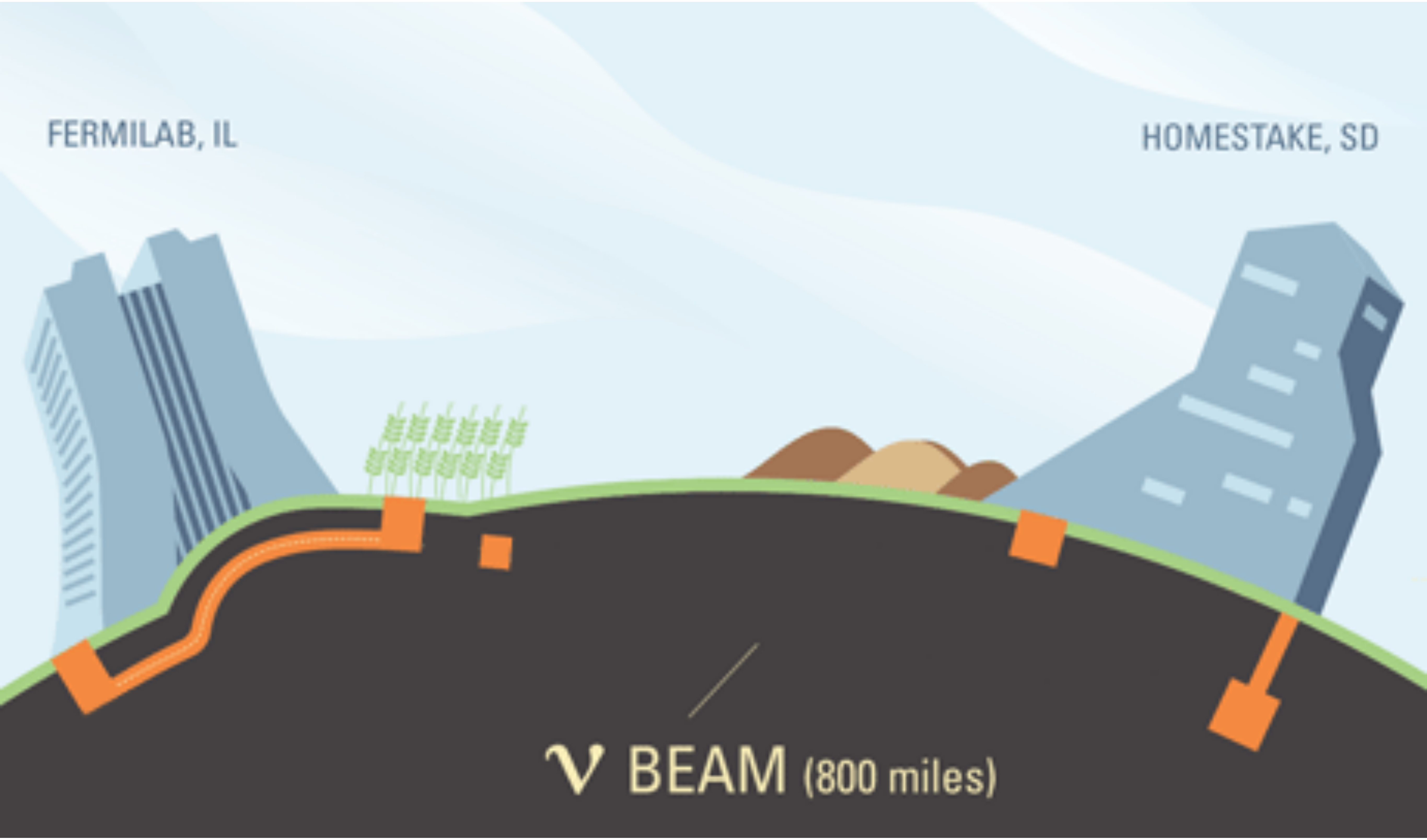
Future experiments that will tell us the neutrino masses hierarchy

We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 σ CL from each exp.



...and the LBL experiments will tell us about leptonic CP violation - important to know because it is related to leptogenesis and the origin of matter-antimatter asymmetry

Future LBL Neutrino Experiments


FERMILAB, IL
HOMESTAKE, SD
ν BEAM (800 miles)

Neutrino Oscillations in vacuum

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*})\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

$$+ 2\sum_{i>j}\mathrm{Im}(U_{\alpha i}^{*}U_{\beta i}U_{\alpha j}U_{\beta j}^{*})\sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right),$$

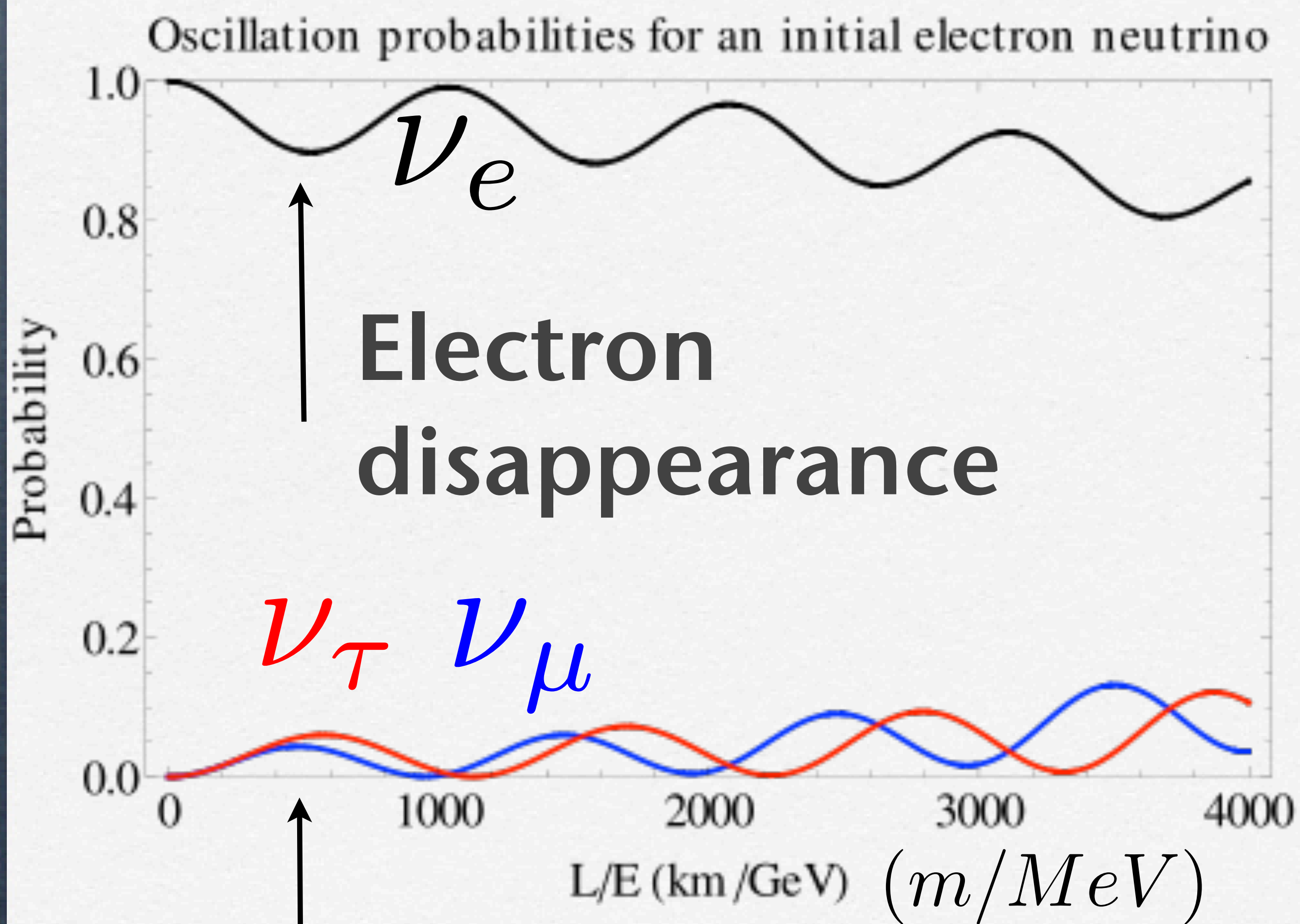
$$\frac{\Delta m^2\, c^3\, L}{4\hbar E} = \frac{\mathrm{GeV\,fm}}{4\hbar c}\times\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E}\approx 1.27\times\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E}$$

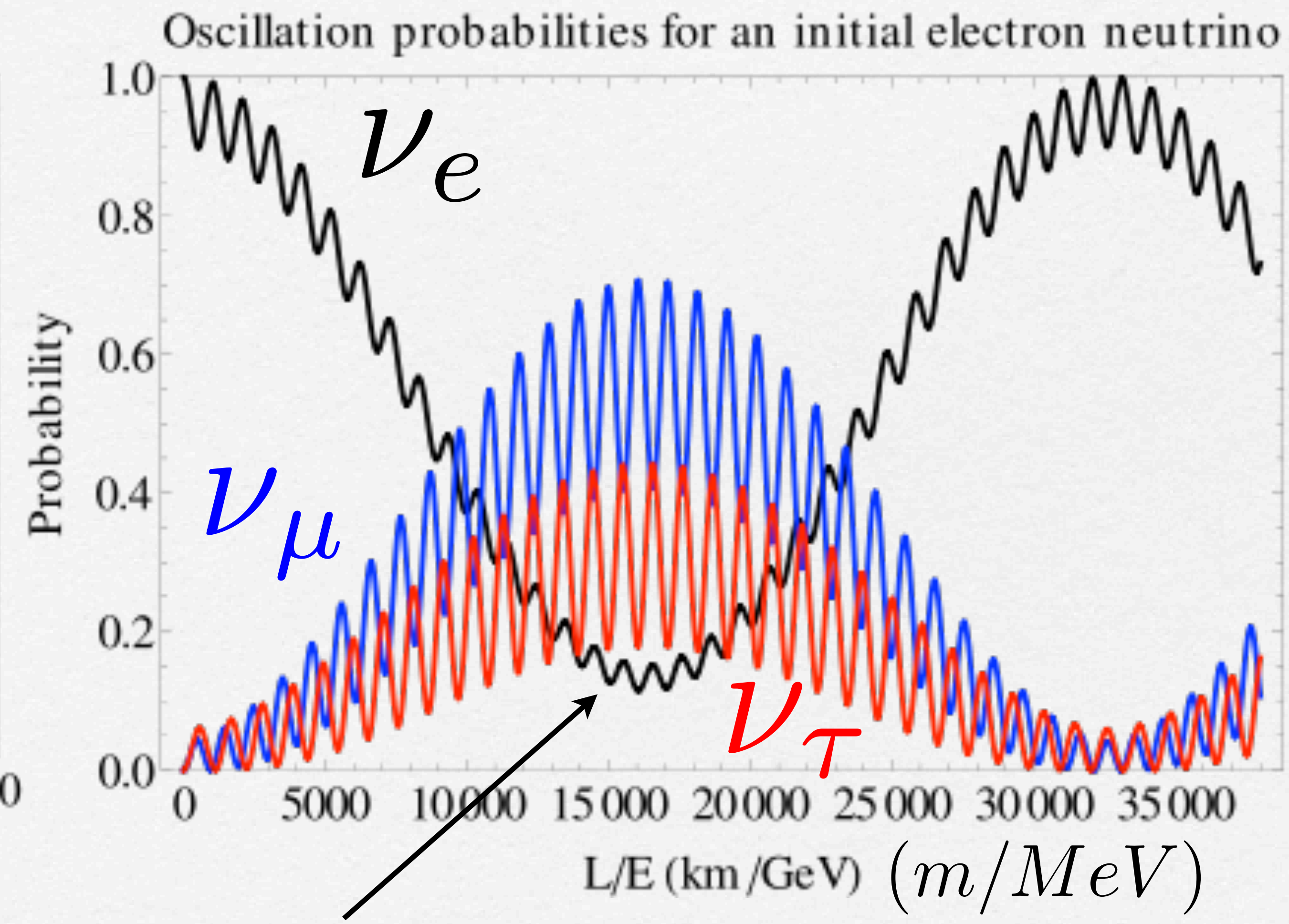
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Electron Neutrino Oscillations

$$P(\bar{\nu}_e \to \bar{\nu}_e; E, L) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$- \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$





Daya Bay
RENO
(1st atm max)

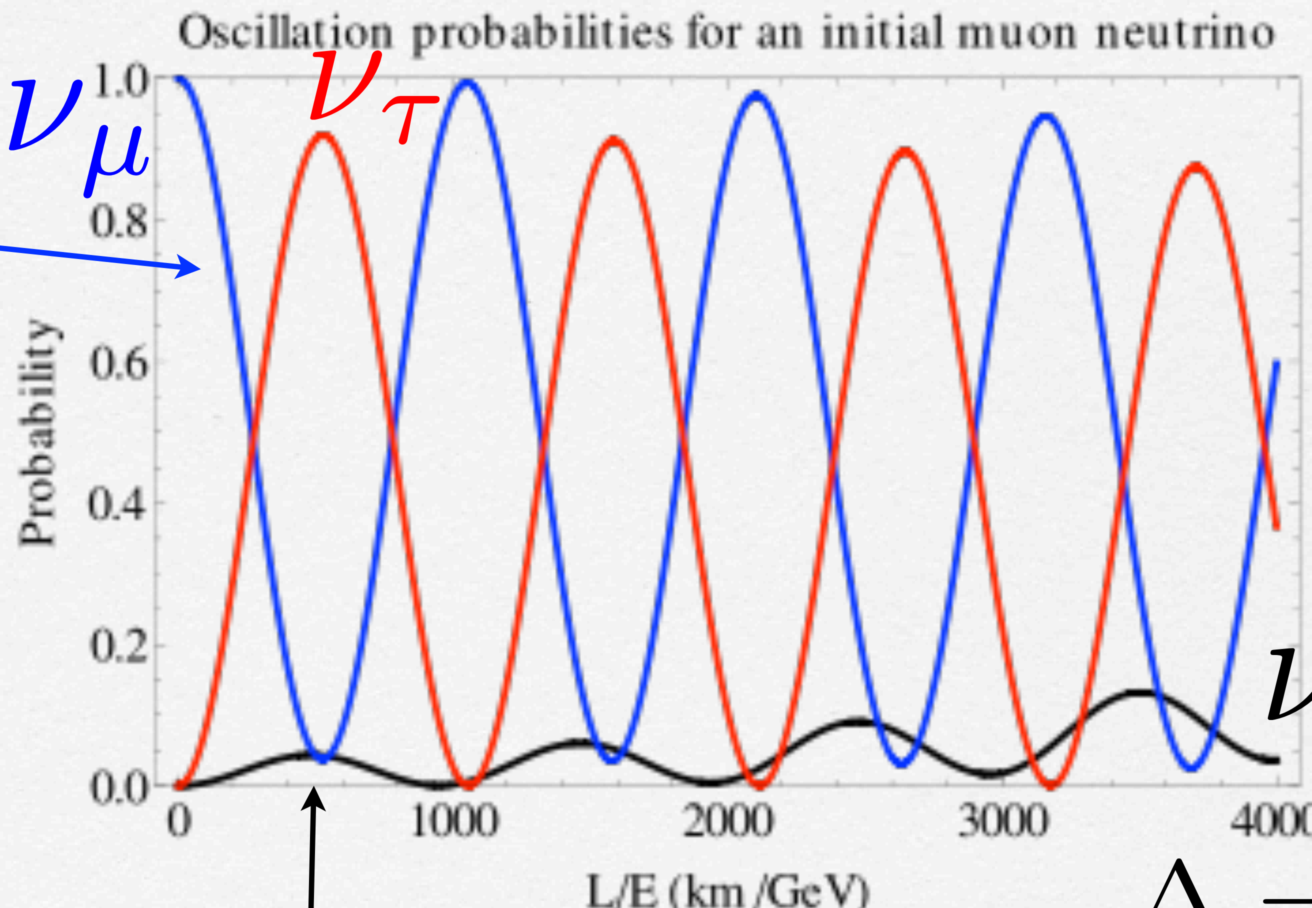
$$\frac{\Delta m^2_{31} L}{4E} = \frac{\pi}{2}$$

JUNO
RENO50km
(1st sol max)

$$\frac{\Delta m^2_{21} L}{4E} = \frac{\pi}{2}$$

Muon Neutrino Oscillations

$$P(\nu_\mu \to \nu_\mu; E, L) = 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta L}{2}\right) + \mathcal{O}(\epsilon)$$



ν_μ ν_τ ν_e

Muon disappearance

Accelerator LBL (1st atm max)

$$\frac{\Delta m^2_{31} L}{4E} = \frac{\pi}{2}$$

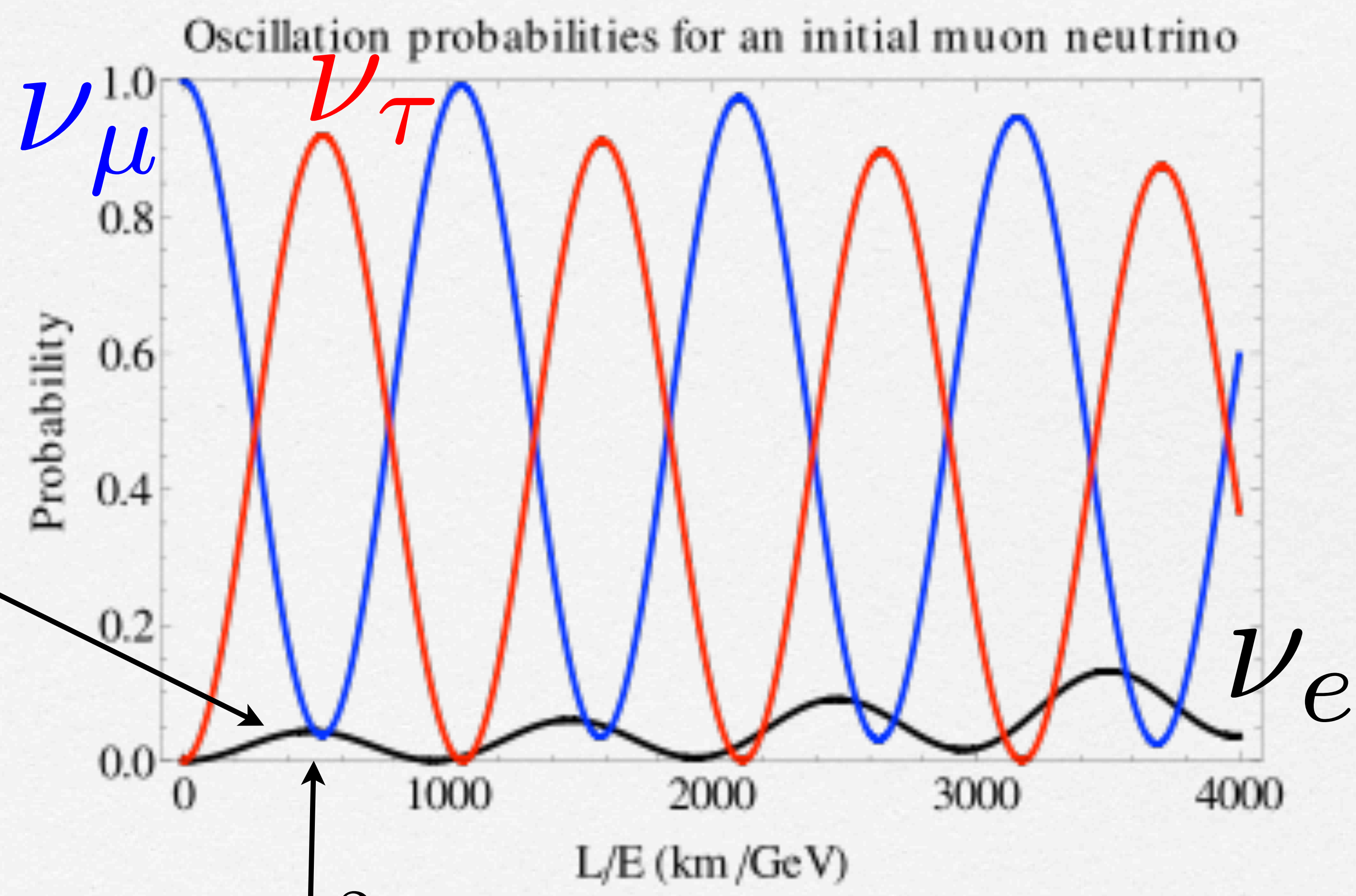
$$\Delta = \Delta m^2_{31}/2E$$

$$\epsilon \equiv \Delta m^2_{21}/\Delta m^2_{31} \approx 0.03$$

Muon Neutrino Oscillations

$$P(\nu_\mu \to \nu_e; E, L) \equiv P_1 + P_{\frac{3}{2}} + \mathcal{O}\left(\epsilon^2\right)$$

Electron appearance



Accelerator LBL (1st atm max)

$$\frac{\Delta m^2_{31} L}{4E} = \frac{\pi}{2}$$

Muon Neutrino Oscillations

$$P(\nu_\mu \to \nu_e; E, L) \equiv P_1 + P_{\frac{3}{2}} + \mathcal{O}\left(\epsilon^2\right)$$

$$P_1 = \frac{4}{(1-r_A)^2} \sin^2\theta_{23} \sin^2\theta_{13} \sin^2\left(\frac{(1-r_A)\Delta L}{2}\right),$$

$$P_{\frac{3}{2}} = 8J_r \frac{\epsilon}{r_A(1-r_A)} \cos\left(\delta + \frac{\Delta L}{2}\right) \sin\left(\frac{r_A \Delta L}{2}\right) \sin\left(\frac{(1-r_A)\Delta L}{2}\right)$$

CP phase — Matter effect

Electron appearance depends on CP phase

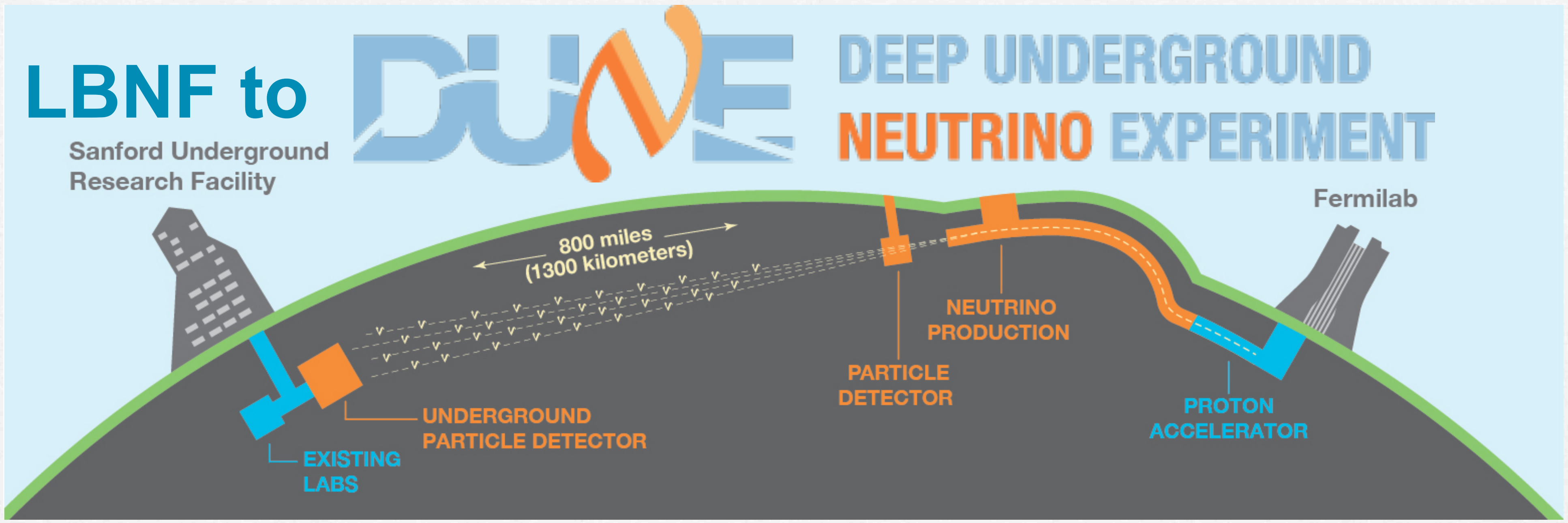
$$\Delta = \Delta m^2_{31}/2E$$

$$\epsilon \equiv \Delta m^2_{21}/\Delta m^2_{31} \approx 0.03$$

r_A, δ change sign for antineutrinos

$$J_r = \cos\theta_{12} \sin\theta_{12} \cos\theta_{23} \sin\theta_{23} \sin\theta_{13}$$

Future LBL experiments

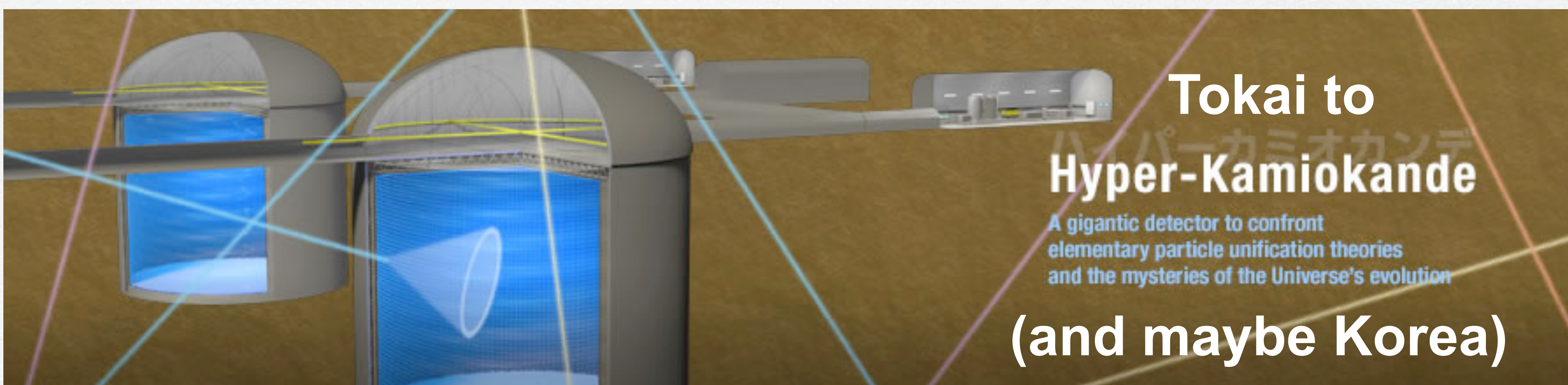


Beams of

$\nu_\mu \quad \bar{\nu}_\mu$

from

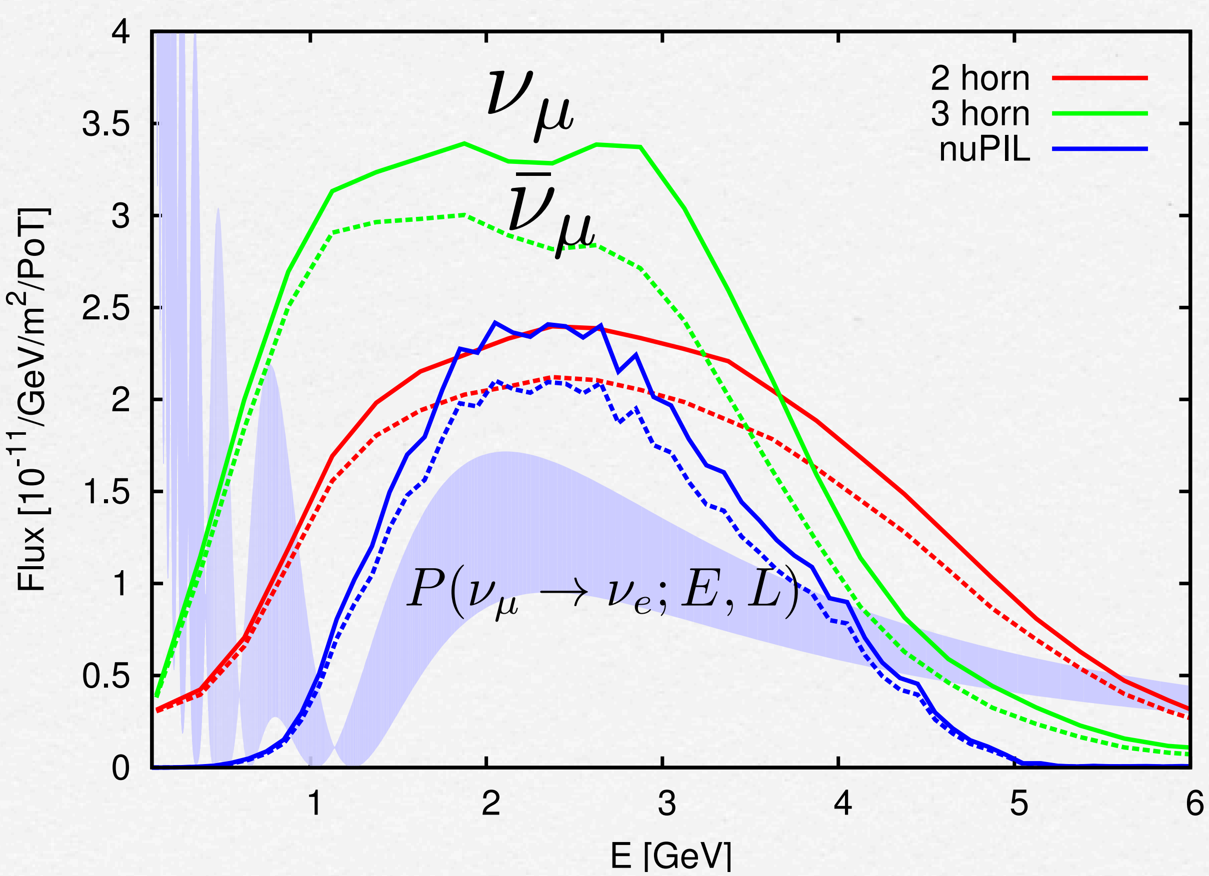
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$



Highly complementary experiments:

DUNE

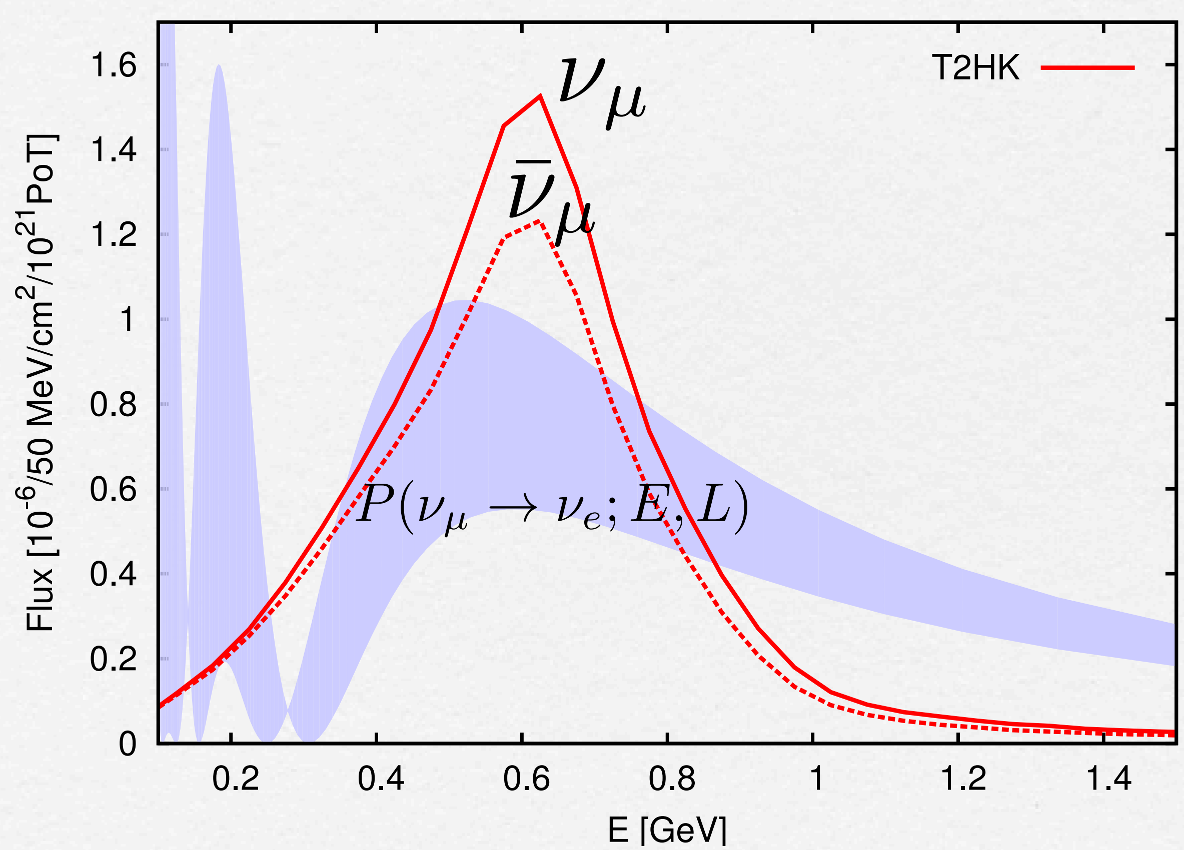
$L = 1300km$



Wide Band Beam
LAr detector

T2HK

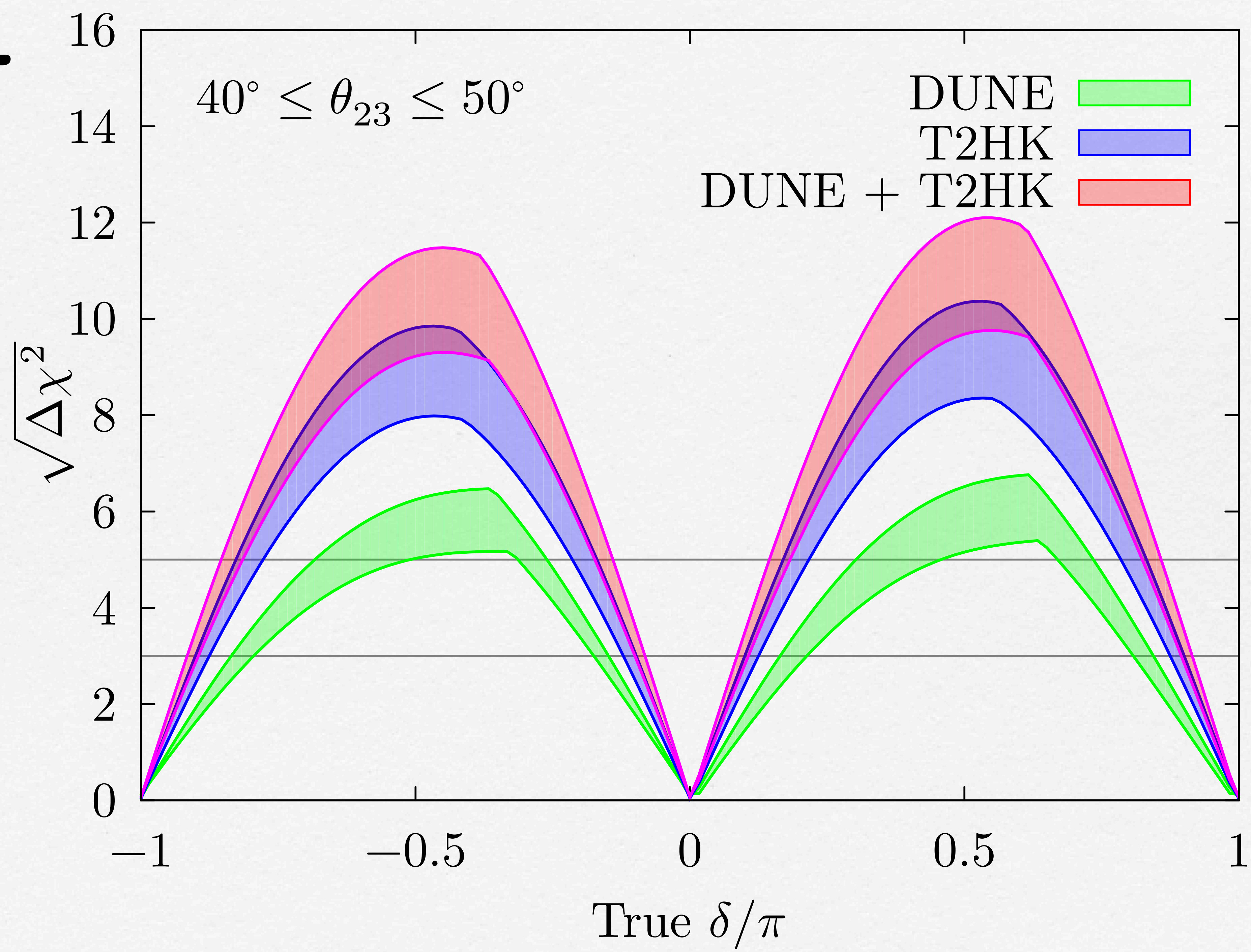
$L = 295km$



Narrow Band Beam (off-axis)
Water detector

CP violation sensitivity

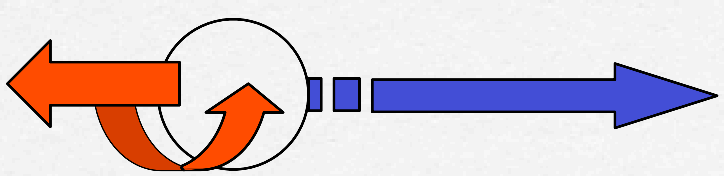
σ



Neutrino Theory

The Electron Mass

e^-_L

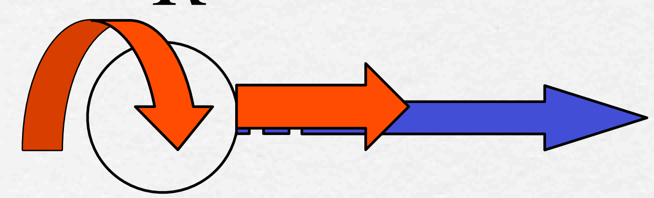


Left-handed electron

Dirac

$$m_e \overline{e_L} e_R$$

e^-_R

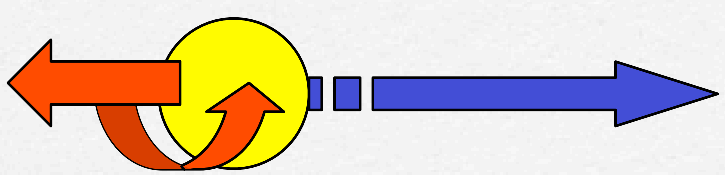


Right-handed electron

Neutrino Mass

Left-handed neutrino

ν_L

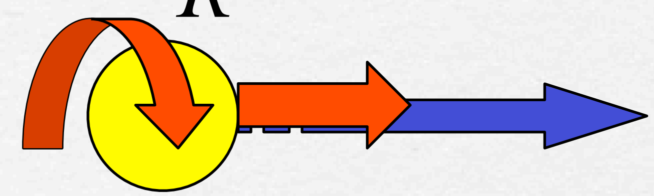


Dirac

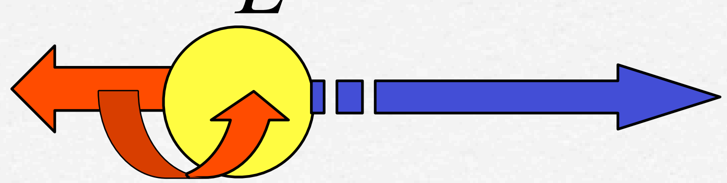
$$m_D \overline{\nu_L} \nu_R$$

Right-handed neutrino

ν_R



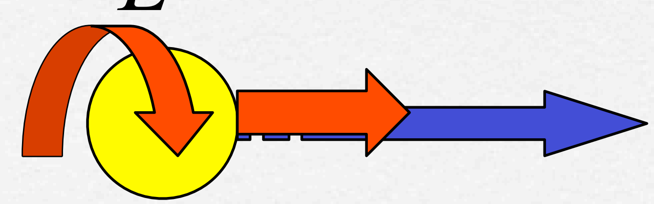
ν_L



Majorana

$$m_\nu \overline{\nu_L} \nu_L^c$$

ν_L^c



Left-handed neutrino

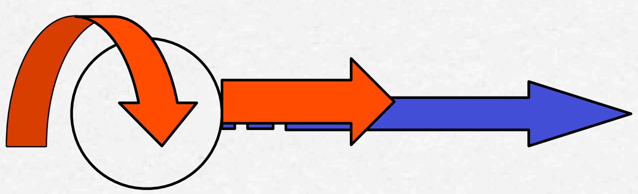
Right-handed antineutrino

Right-handed neutrino mass

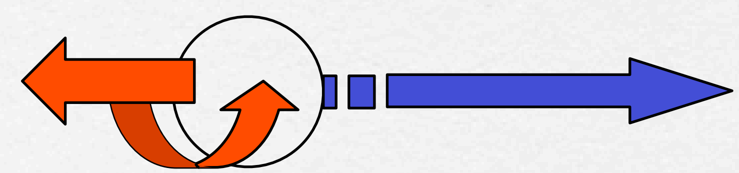
ν_R

Majorana

ν_R^c



$$M_R \overline{\nu_R} \nu_R^c$$



Right-handed neutrino

Left-handed antineutrino

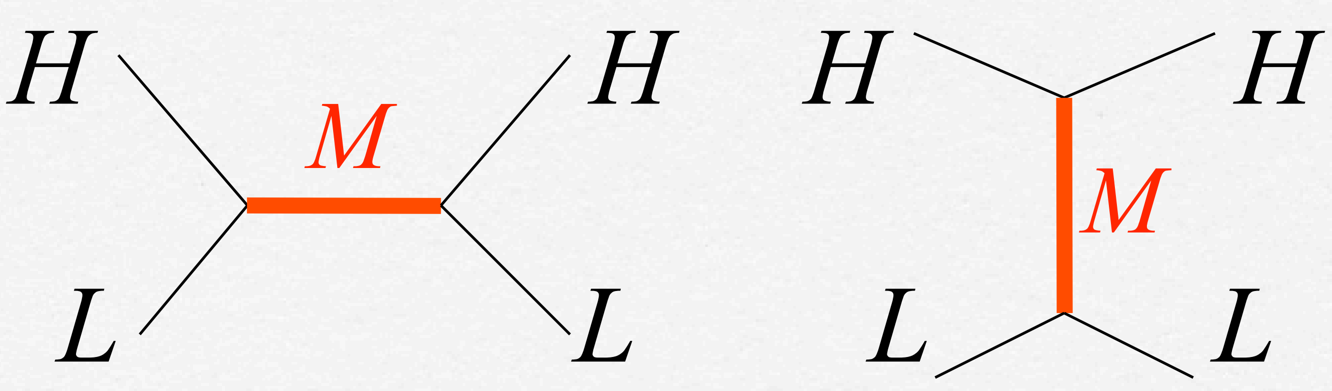
Is Majorana mass renormalisable?

Renormalisable $\Delta L = 2$ operator $\lambda_\nu LL\Delta$ where Δ is light Higgs triplet with VEV < 8GeV from ρ parameter

Non-renormalisable $\Delta L = 2$ operator $\frac{\lambda_\nu}{M} LLHH = \frac{\lambda_\nu}{M} \langle H^0 \rangle^2 \overline{\nu}_{eL} \nu_{eL}^c$ Weinberg

This is nice because it gives naturally small Majorana neutrino masses $m_{LL} \sim \langle H^0 \rangle^2 / M$ where M is some high energy scale

The high mass scale can be associated with some heavy particle of mass M being exchanged (can be singlet or triplet)



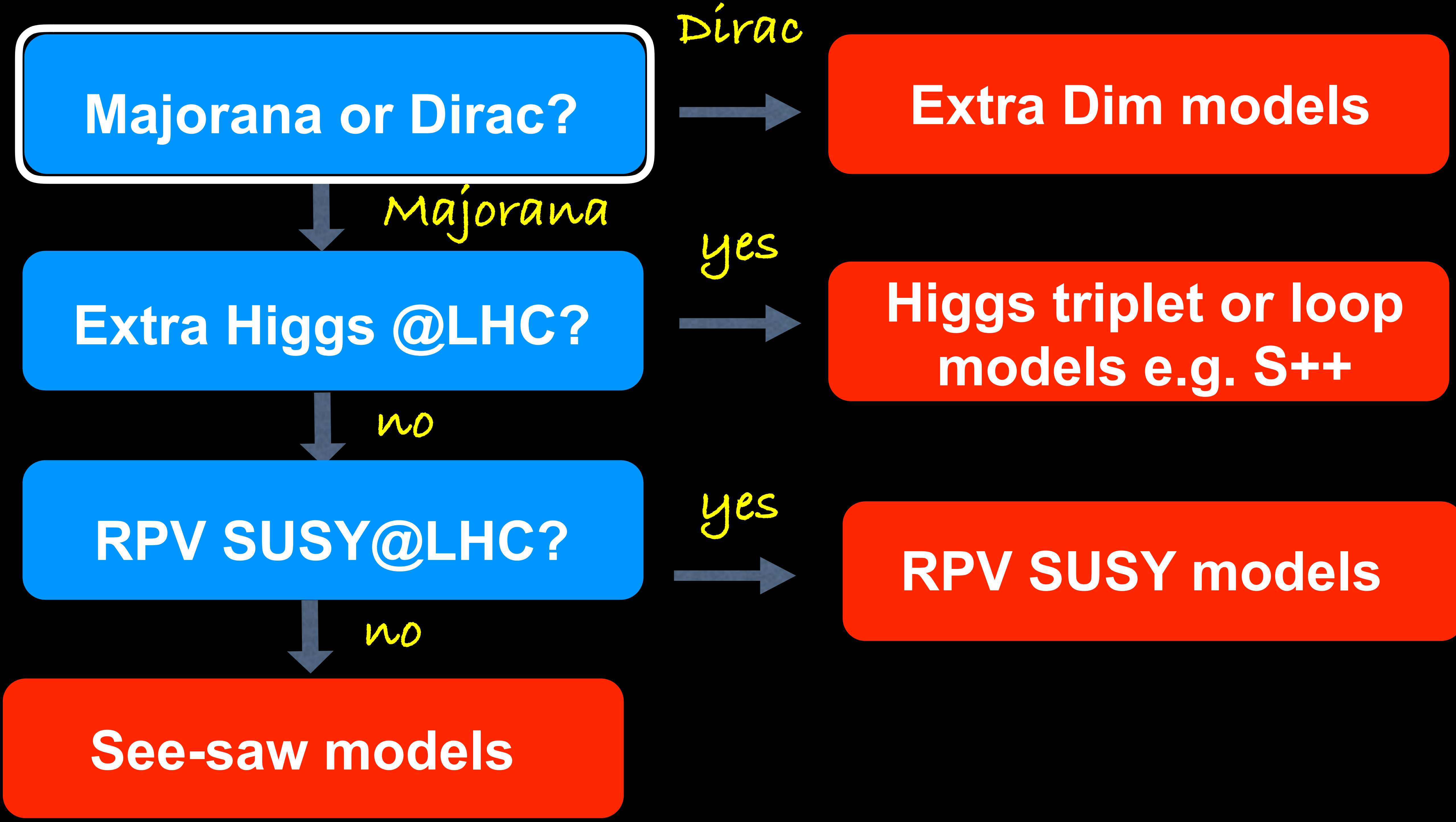
See-saw mechanisms

The three reasons for zero neutrino mass in the Standard Model

1. There are no right-handed neutrinos
2. There are no Higgs triplets of $SU(2)_L$
3. There are no non-renormalizable terms

Many (many) possibilities for the origin of neutrino mass...

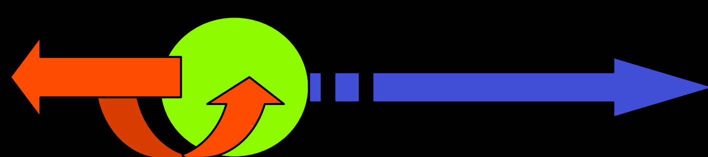
Roadmap of neutrino mass



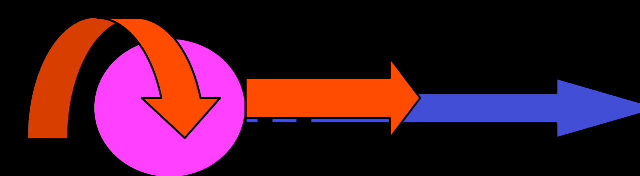
Dirac or Majorana?

SFK 0712.1750

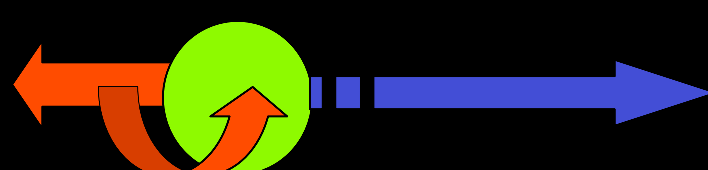
ν_L — **Dirac** — ν_R



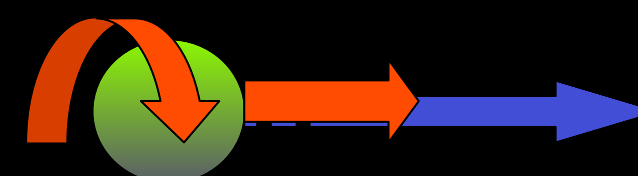
$$m_{\rm D}\bar{\nu}_L\nu_R$$



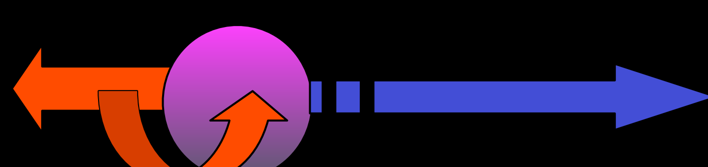
ν_L — **Majorana** — ν_L^c



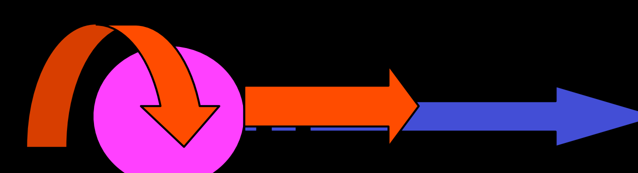
$$m_{\rm L}\bar{\nu}_L\nu_L^c$$



ν_R^c — **Majorana** — ν_R



$$M_{\rm R}\bar{\nu}_R^c\nu_R$$

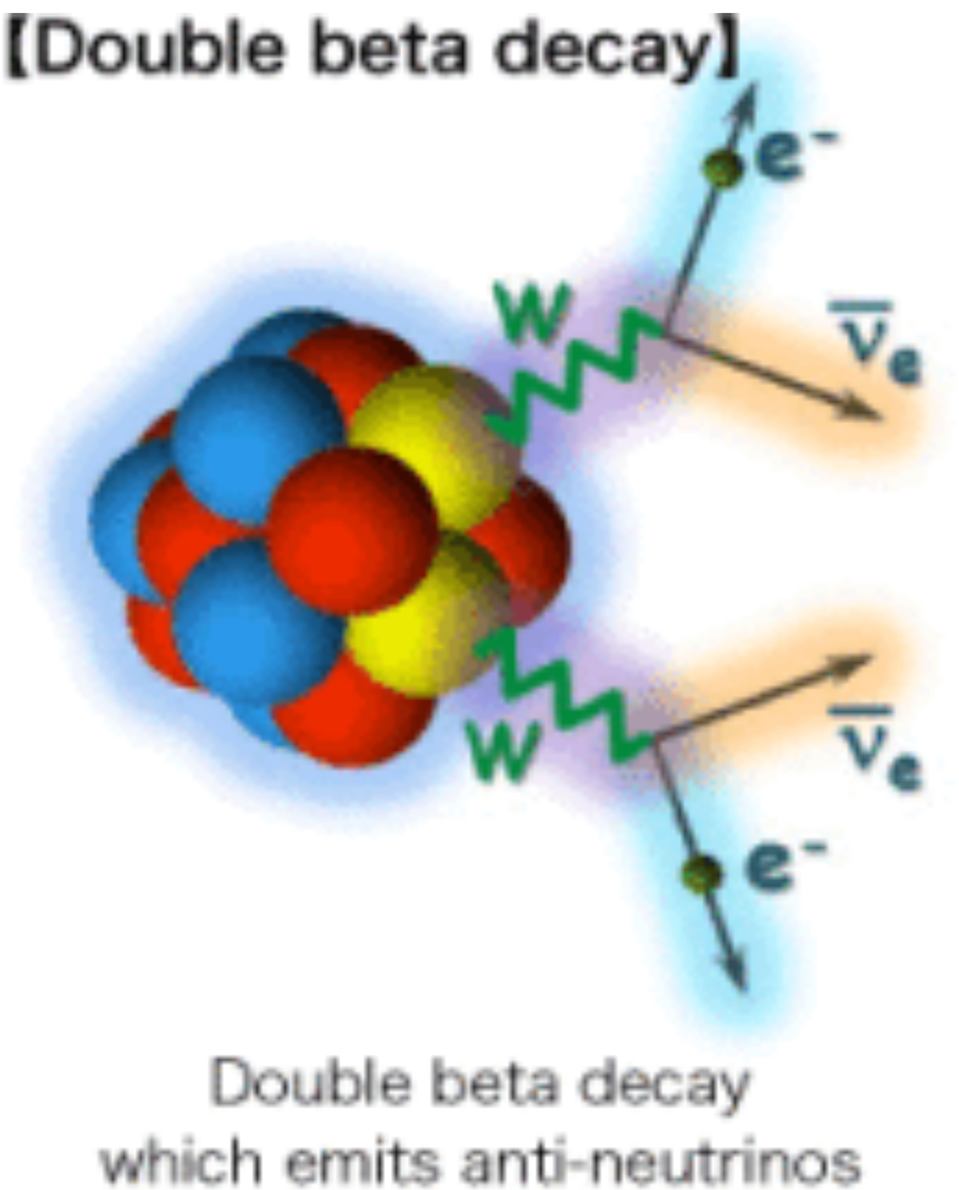


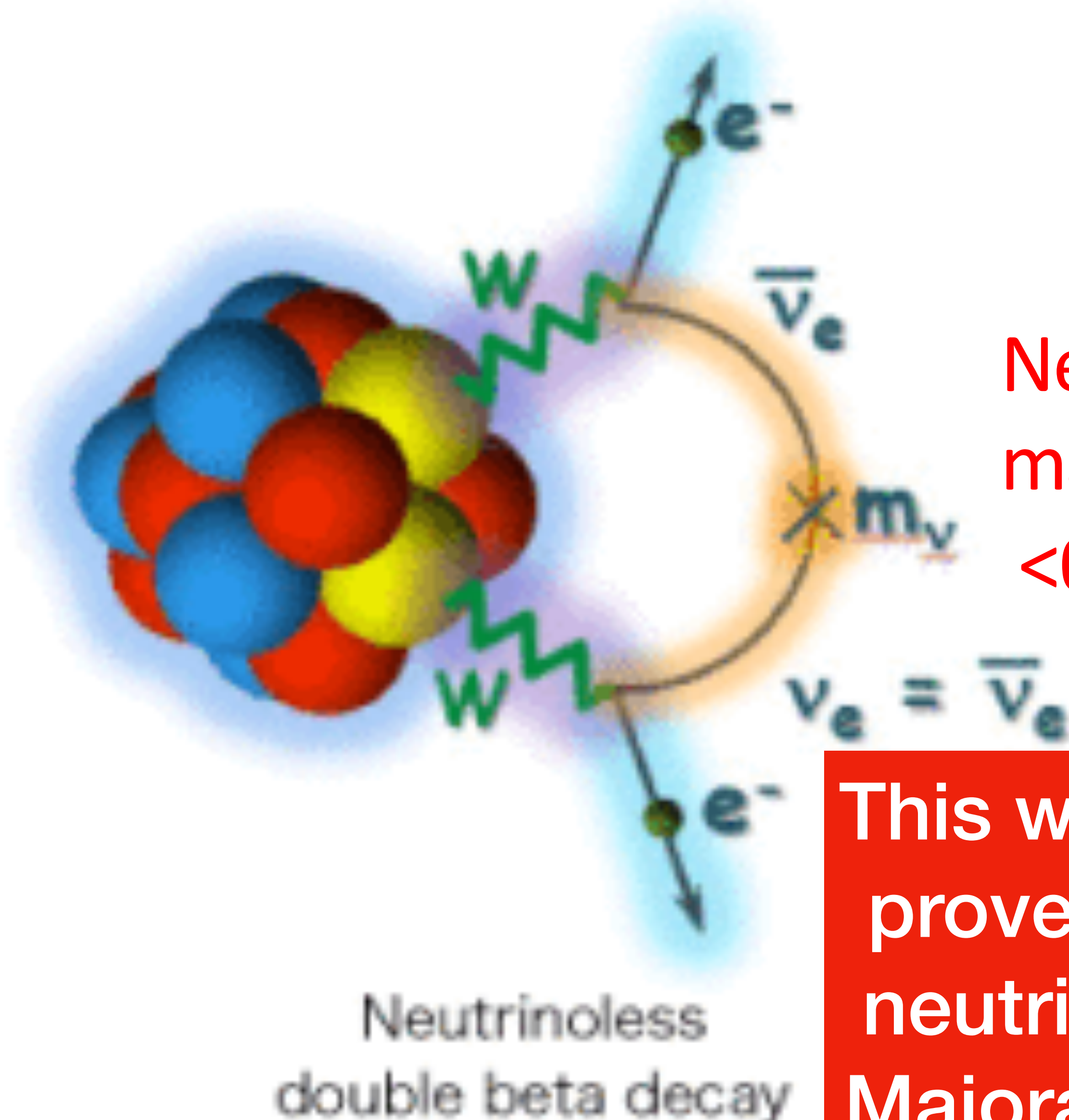
Neutrino Mass Limits from the Laboratory

Many currently running experiments: GERDA, Majorana, EXO, CUORE, Kamland-Zen

This decay (on the left) is commonly observed

The rarest form of beta decay, if observed, would give a precise mass measurement





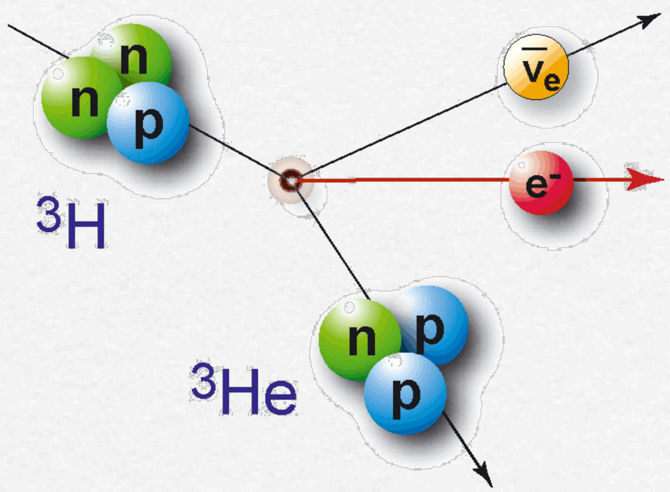
Neutrino mass <0.2 eV

This would also prove that the neutrino has a Majorana mass

Experimental determination of neutrino mass

Majorana only
(no signal if Dirac)

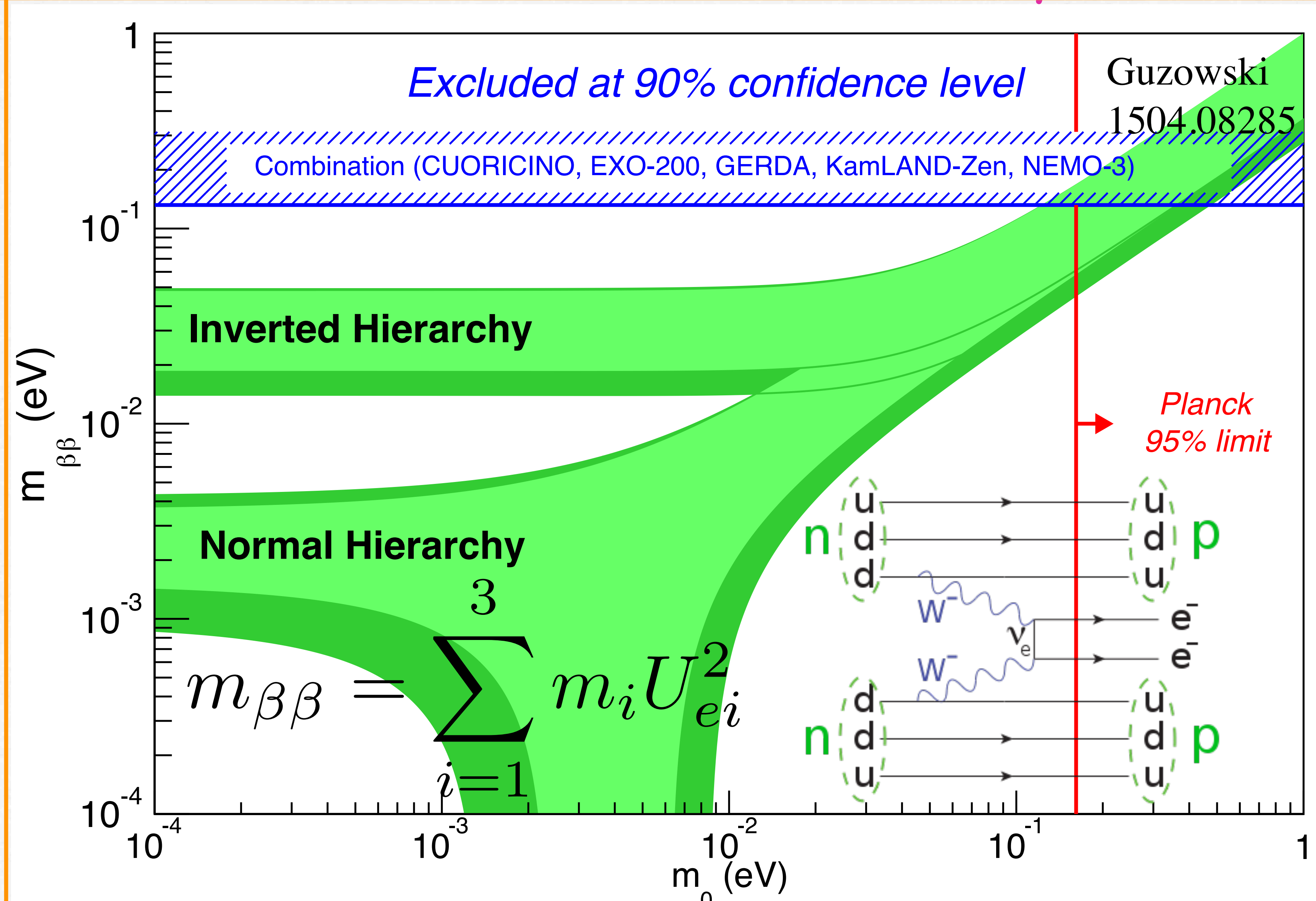
Tritium beta decay



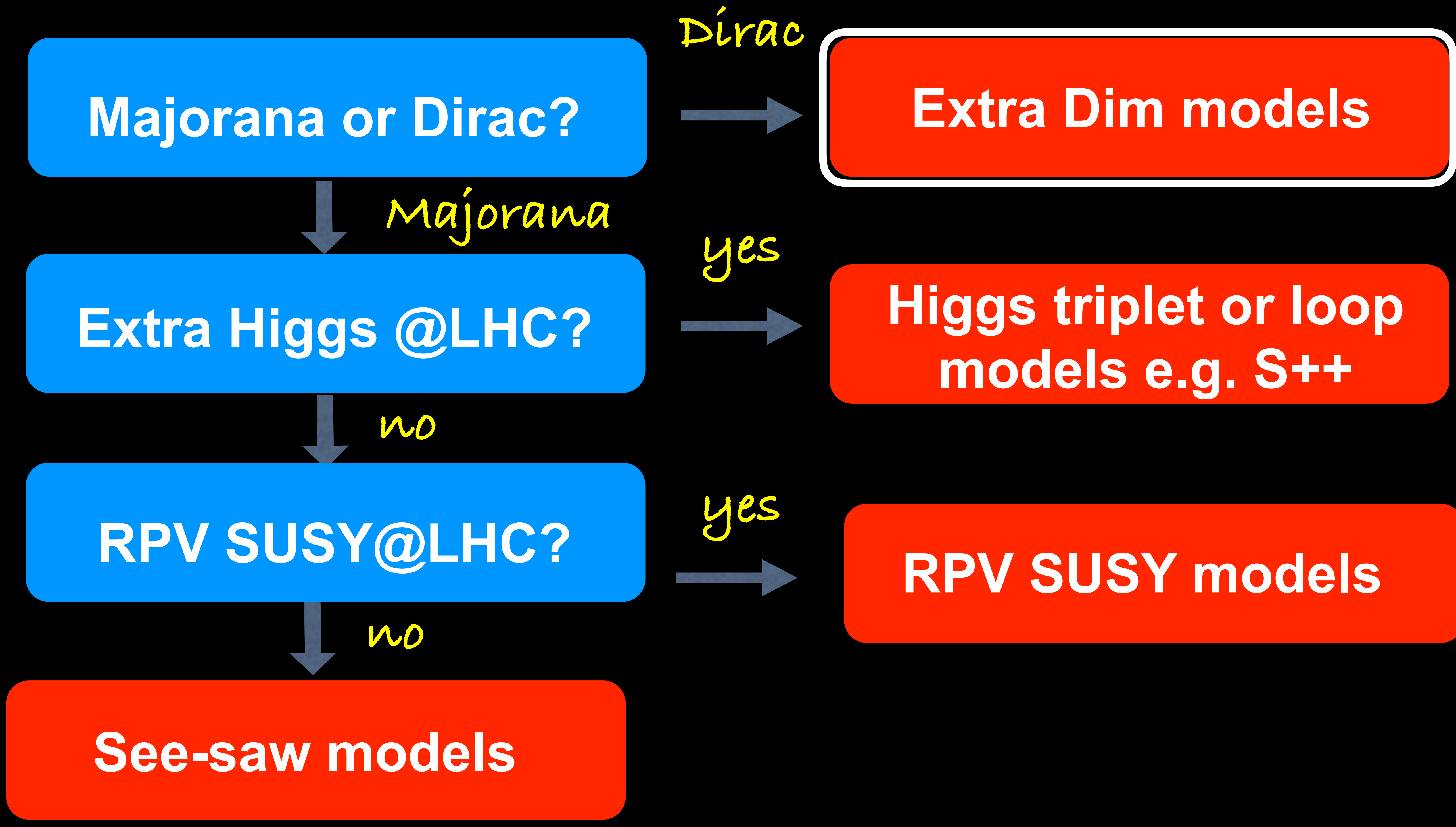
$$m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

Present Mainz	< 2.2 eV
KATRIN	~0.35eV

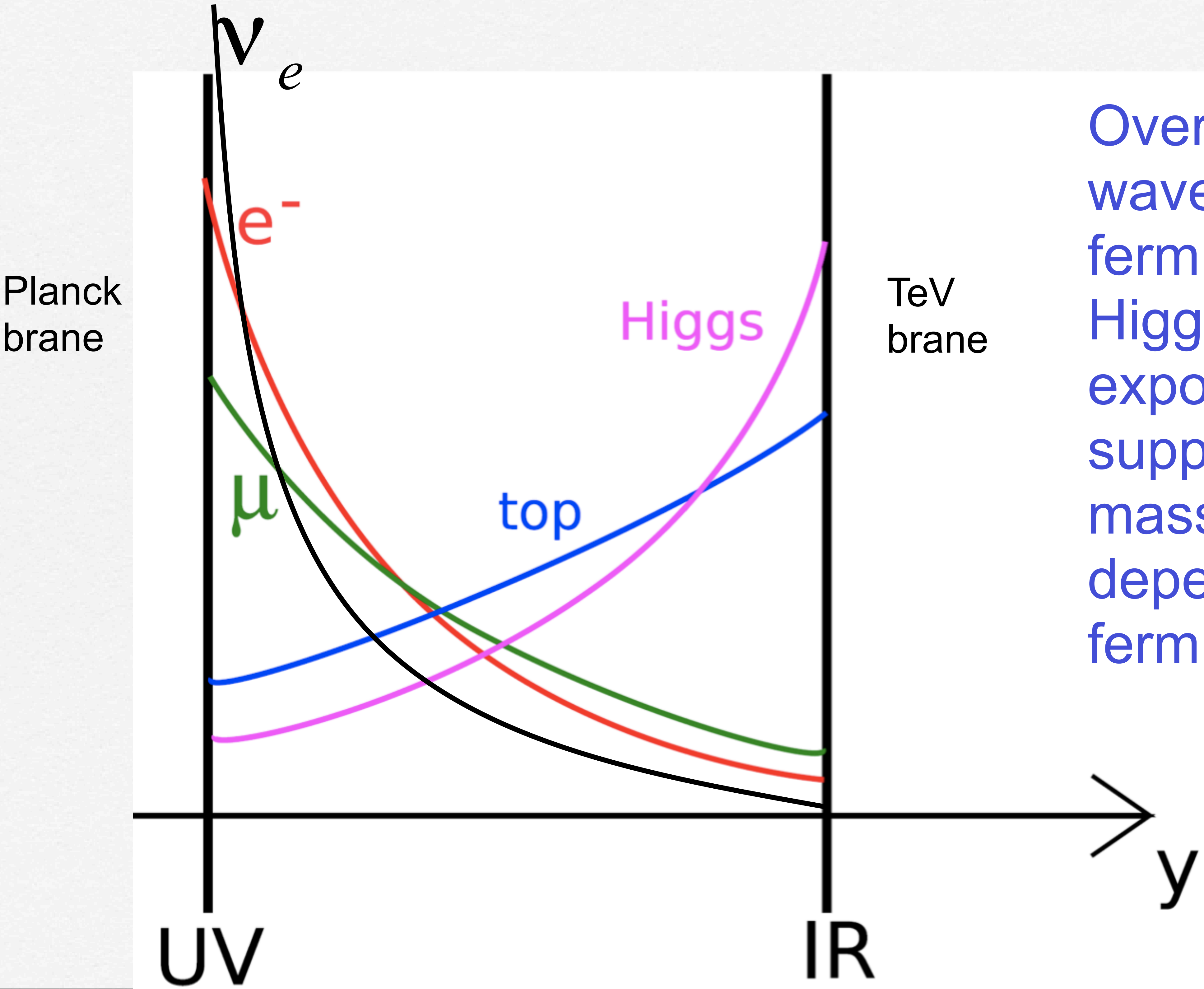
Neutrinoless double beta decay



Roadmap of neutrino mass

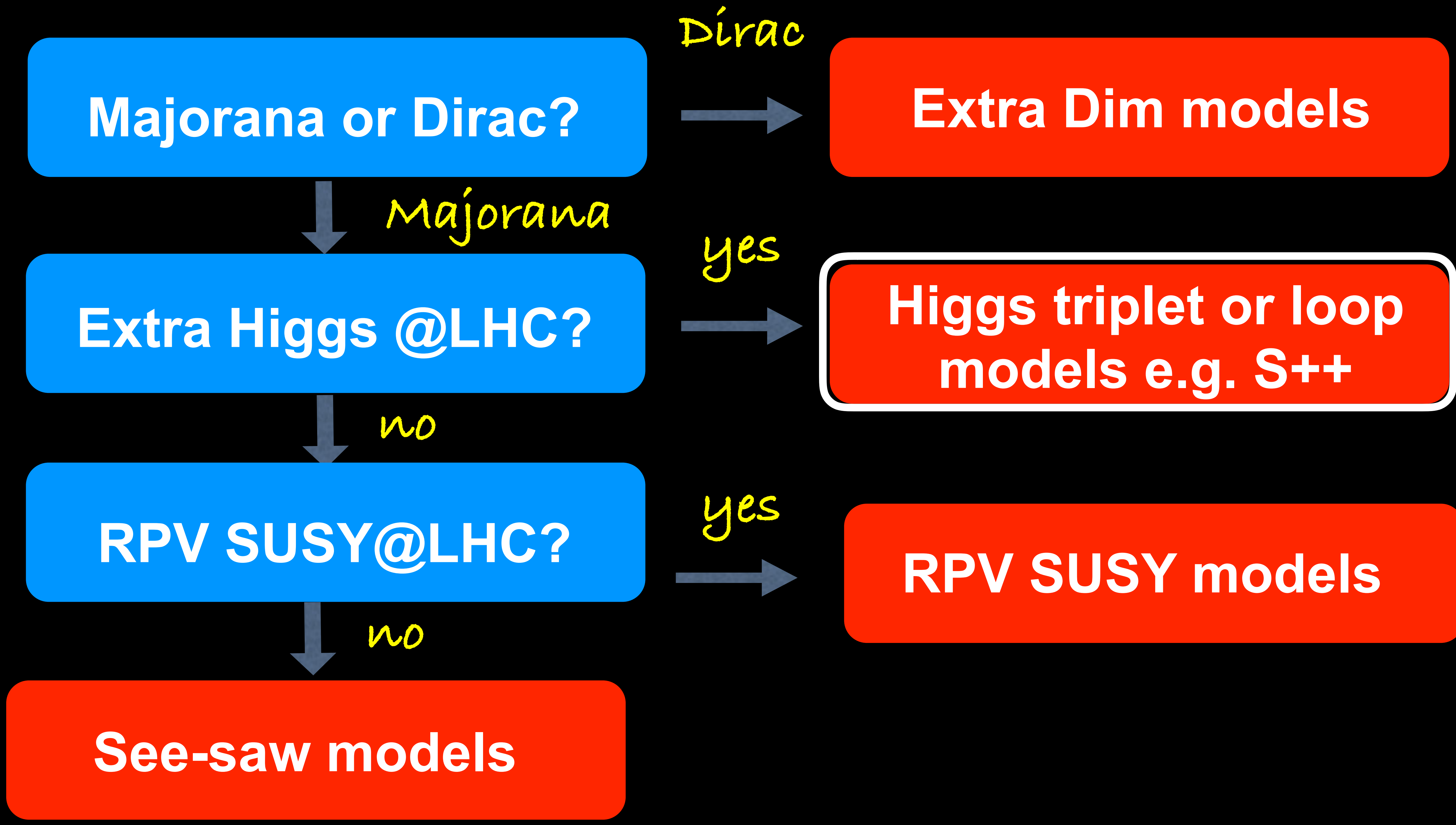


Extra dimensions

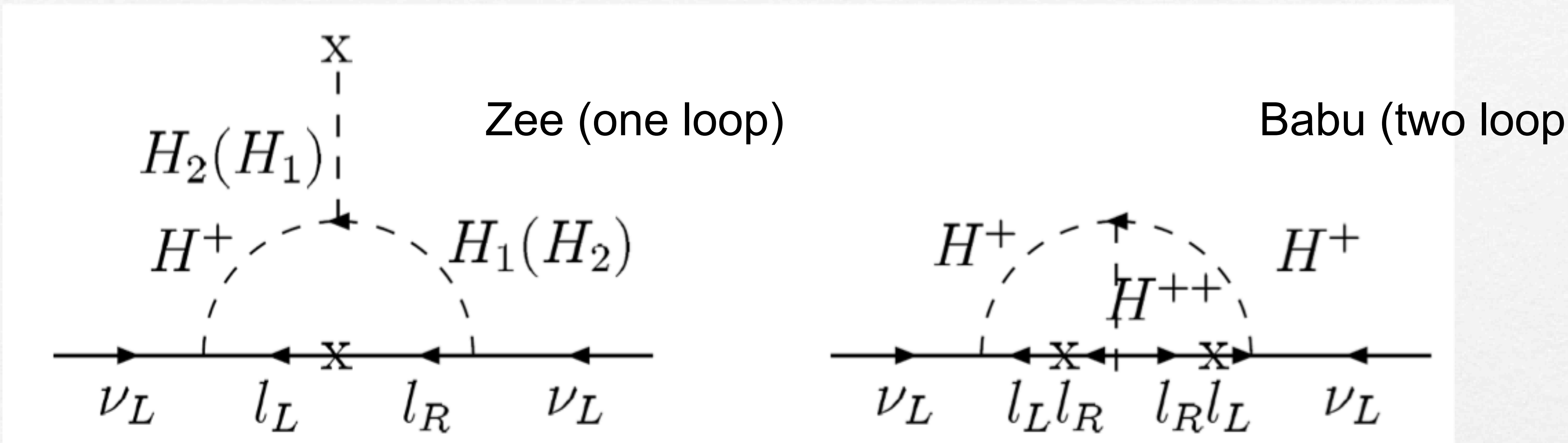


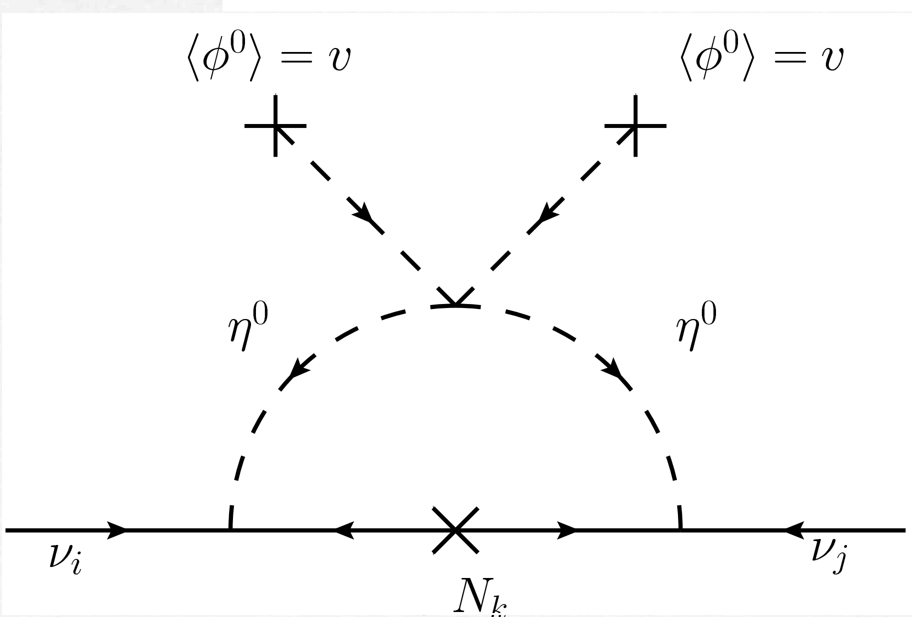
Overlap wavefunction of fermions with Higgs gives exponentially suppressed Dirac masses, depending on the fermion profiles

Roadmap of neutrino mass

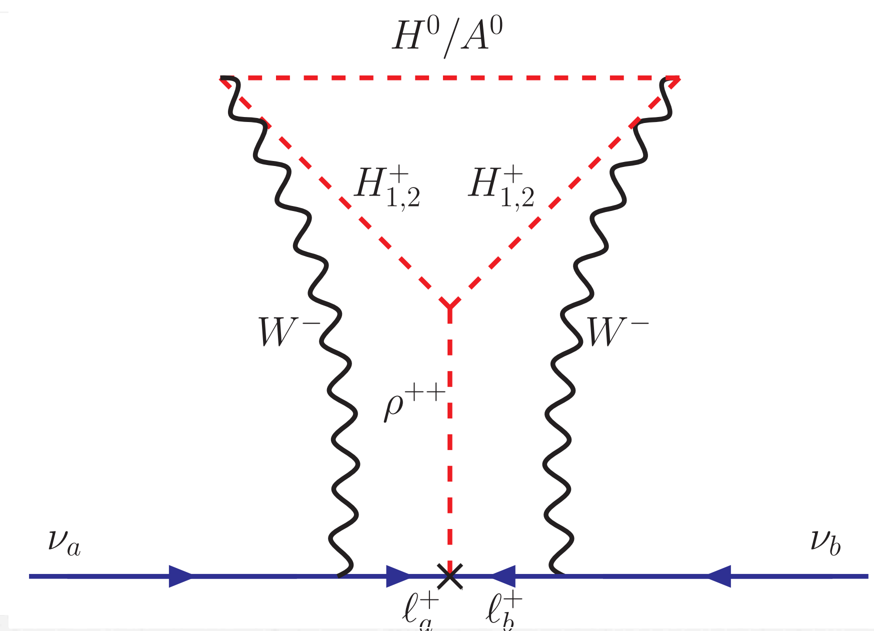


Loop Models of Neutrino Mass

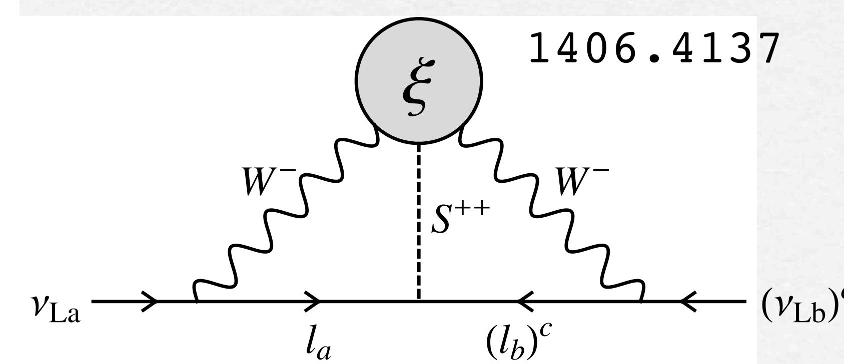




Scotogenic model

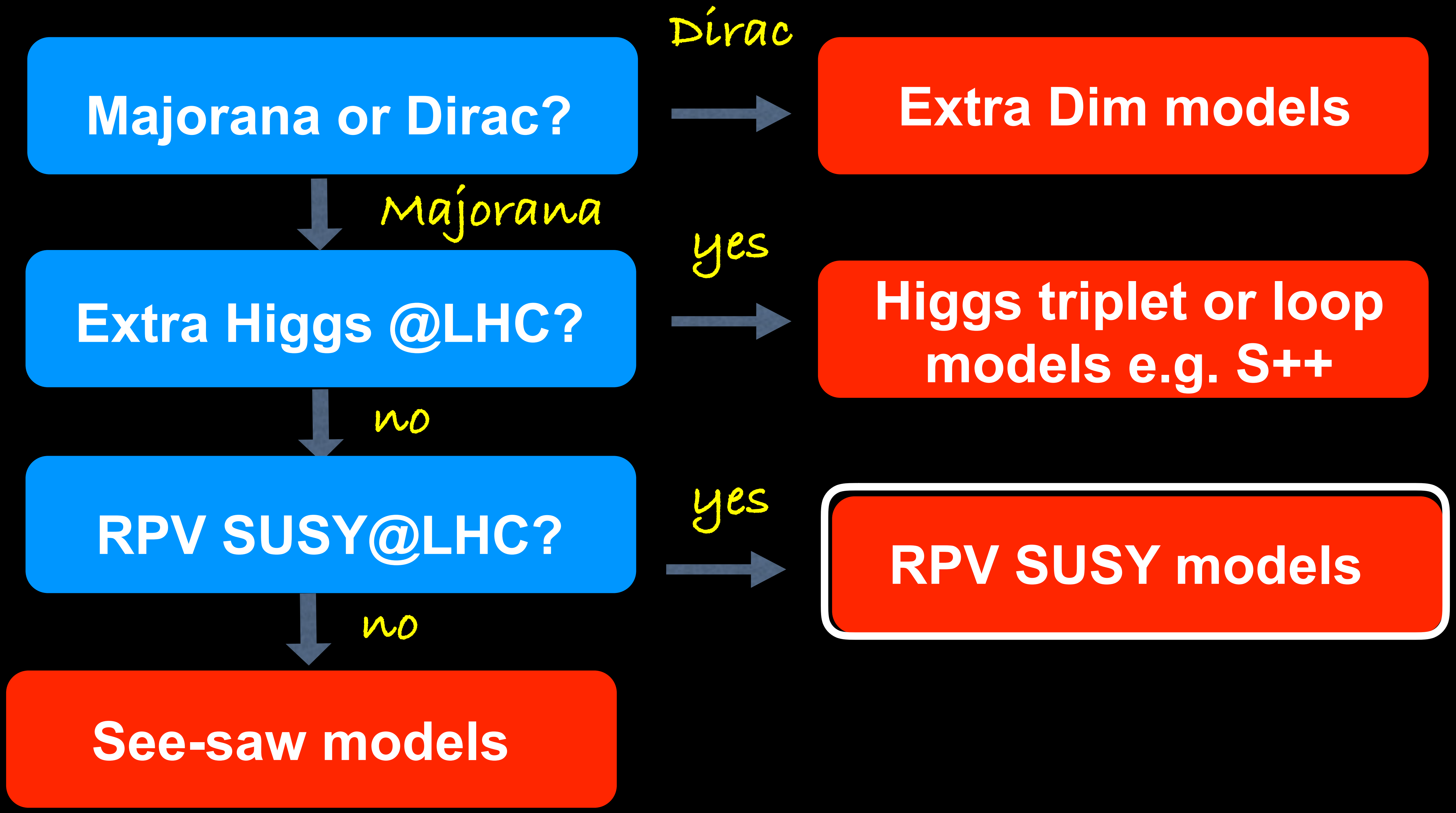


Cocktail model



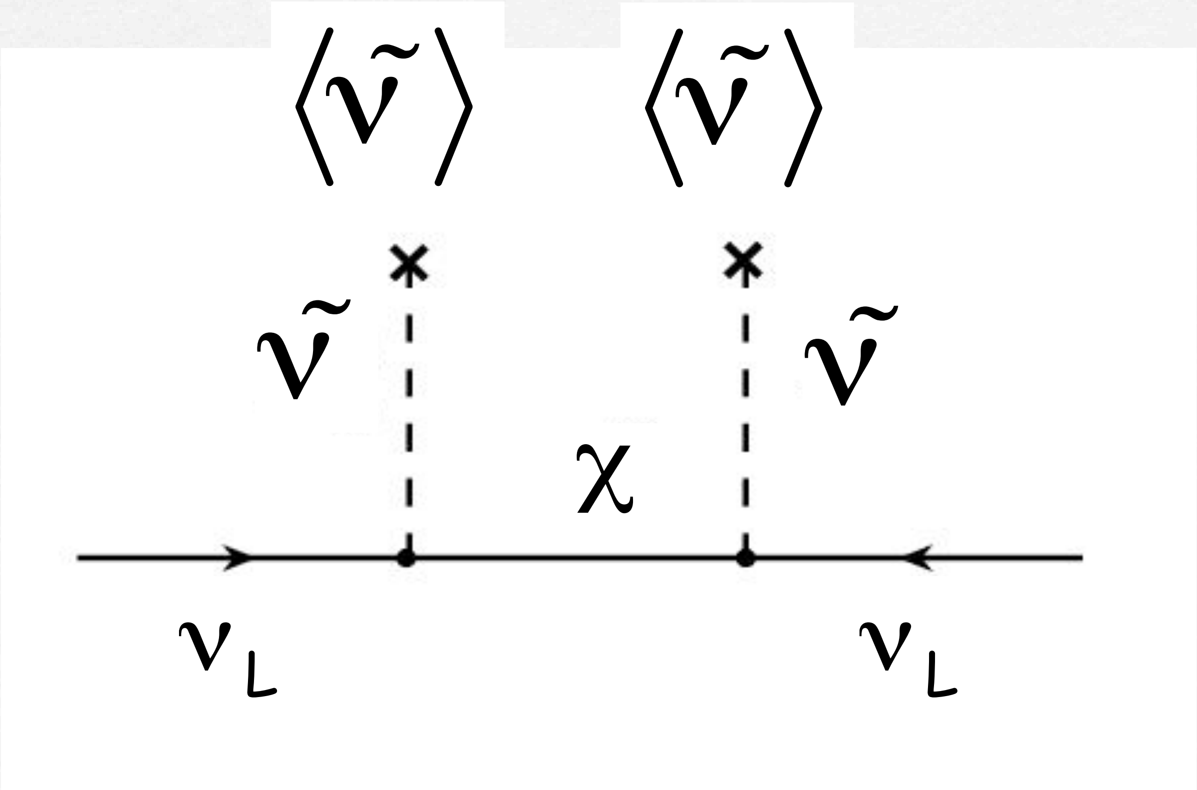
Effective theory

Roadmap of neutrino mass



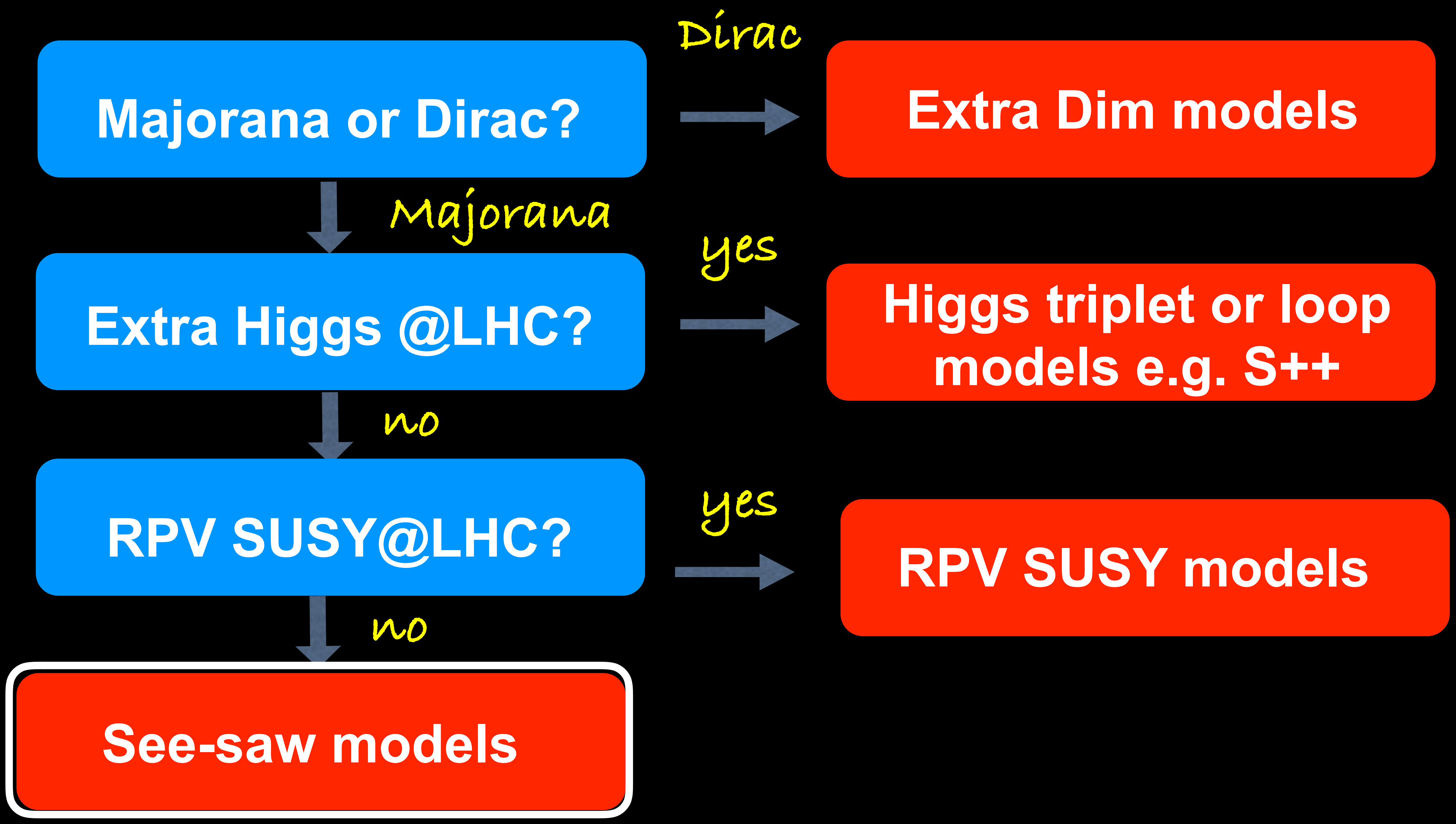
R-Parity Violating SUSY

- Majorana masses can be generated via RPV SUSY
- Scalar partners of lepton doublets (slepton doublets) have same quantum numbers as Higgs doublets
- If R-parity is violated then sneutrinos may get (small) VEVs inducing a mixing between neutrinos and neutralinos χ

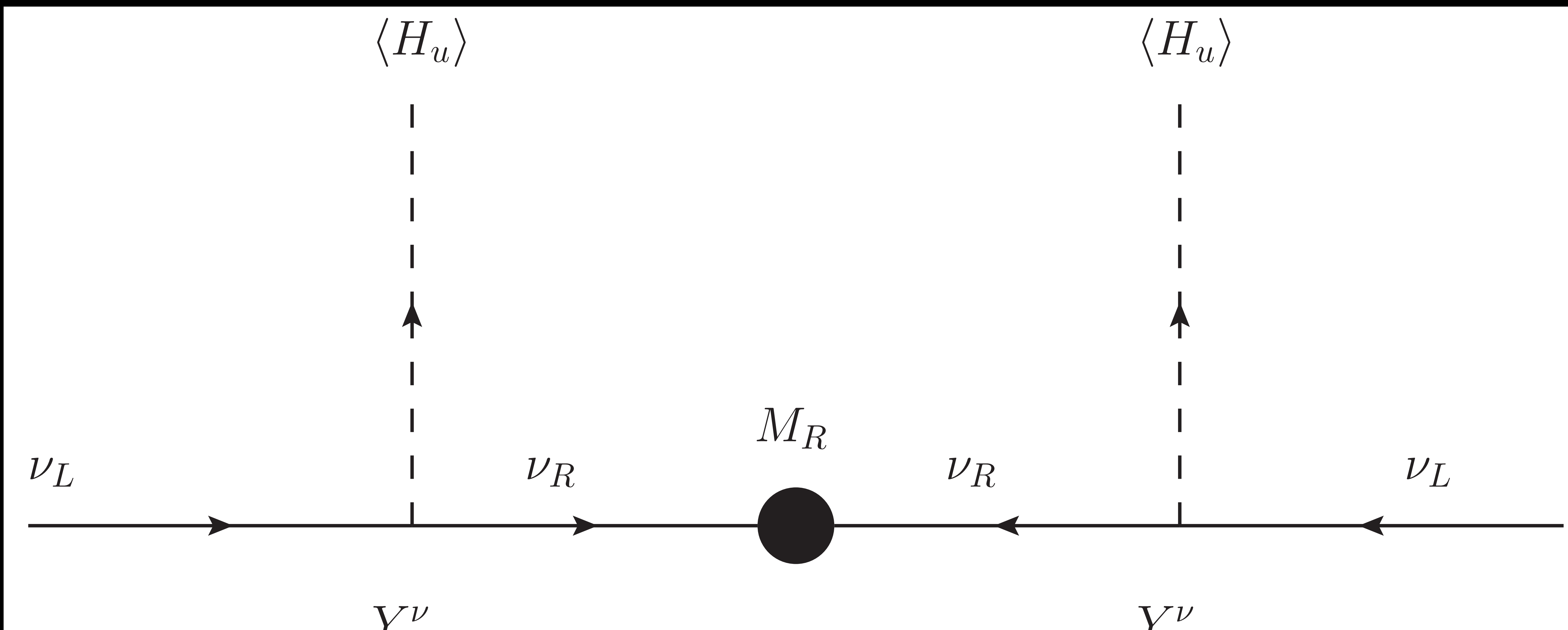


$$m_{LL}^{\nu} \approx \frac{\langle \tilde{\nu} \rangle^2}{M_\chi} \approx \frac{MeV^2}{TeV} \approx eV$$

Roadmap of neutrino mass

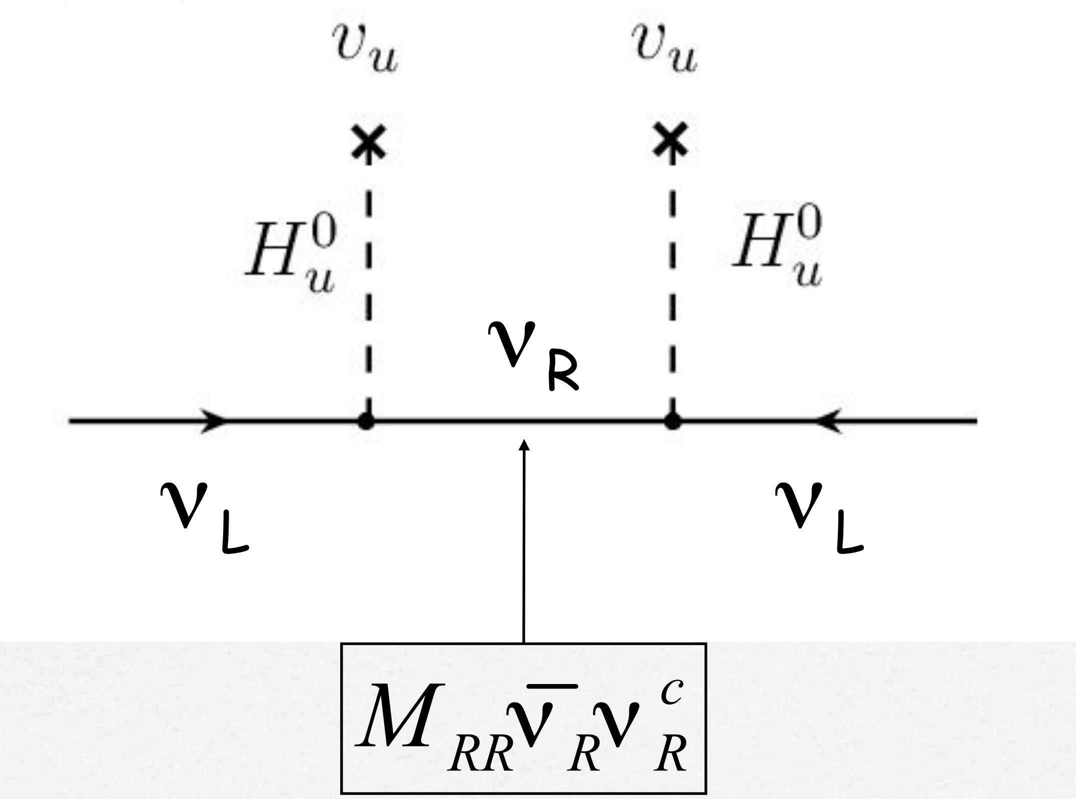


Minimal Type I seesaw



Type I see-saw mechanism

P. Minkowski (1977), Gell-Mann, Glashow, Mohapatra, Ramond, Senjanovic, Slanski, Yanagida (1979/1980), Schechter and Valle (1980)...

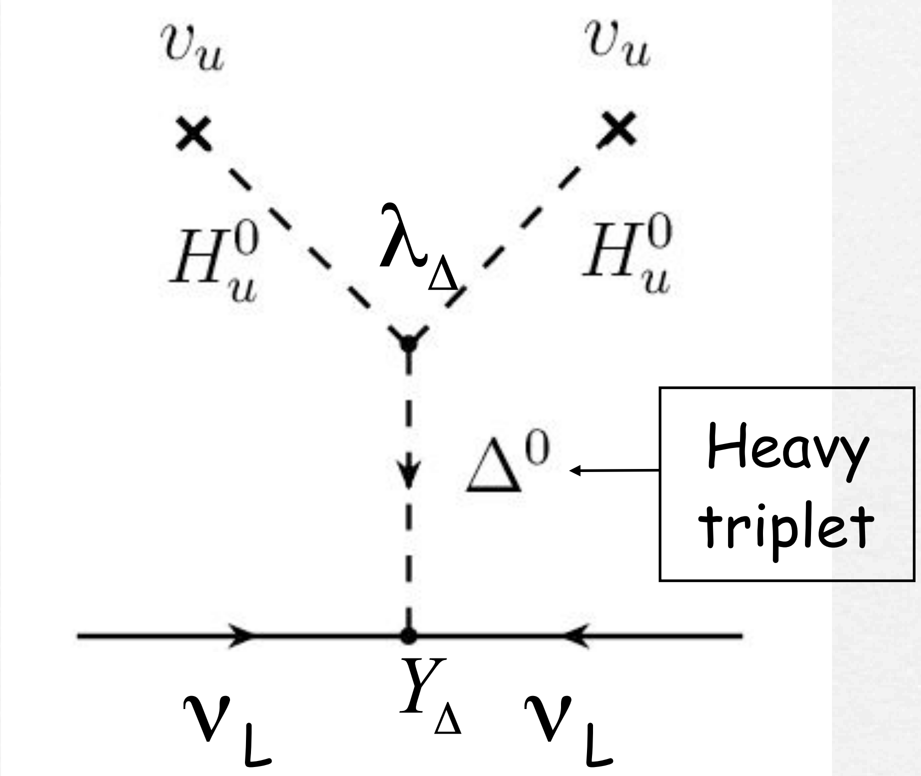


$$m_{LL}^{I} \approx -m_{LR} M_{RR}^{-1} m_{LR}^{T}$$

Type I

Type II see-saw mechanism (SUSY)

Lazarides, Magg, Mohapatra, Senjanovic, Shafi, Wetterich, Schechter and Valle...



$$m_{LL}^{II} \approx \lambda_\Delta Y_\Delta \frac{v_u^2}{M_\Delta}$$

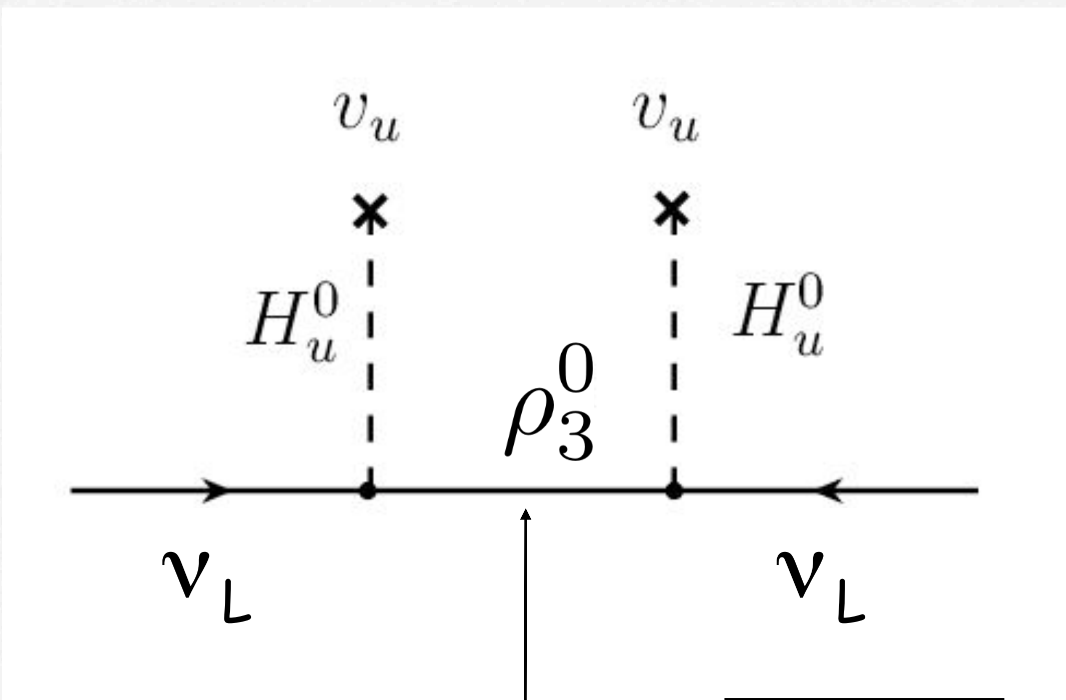
Type II

Type III see-saw mechanism

Foot, Lew, He, Joshi; Ma...

Supersymmetric adjoint SU(5)

Perez et al; Cooper, SFK, Luhn,...



$SU(2)_L$ fermion triplet

$$M_\rho \rho\rho$$

$$m_{LL}^{III} \approx -m_{LR} M_\rho^{-1} m_{LR}^T$$

Type III

See-saw w/extra singlets S

Inverse see-saw

Wyler, Wolferstein; Mohapatra, Valle

$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

M ≈ TeV ➔ LHC

$$M_\nu = M_D M^{T^{-1}} \mu M^{-1} M_D^T$$

Linear see-saw

$$\begin{pmatrix} 0 & M_D & M_L \\ M_D^T & 0 & M \\ M_L^T & M^T & 0 \end{pmatrix}$$

Malinsky, Romao, Valle

$$M_\nu = M_D (M_L M^{-1})^T + (M_L M^{-1}) M_D{}^T$$

LFV predictions

Seesaw mechanism

Minkowski; Yanagida;
Gell-Mann, Ramond,
Slansky; Glashow;
Mohapatra, Senjanivic;
Schechter, Valle;...

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

One family

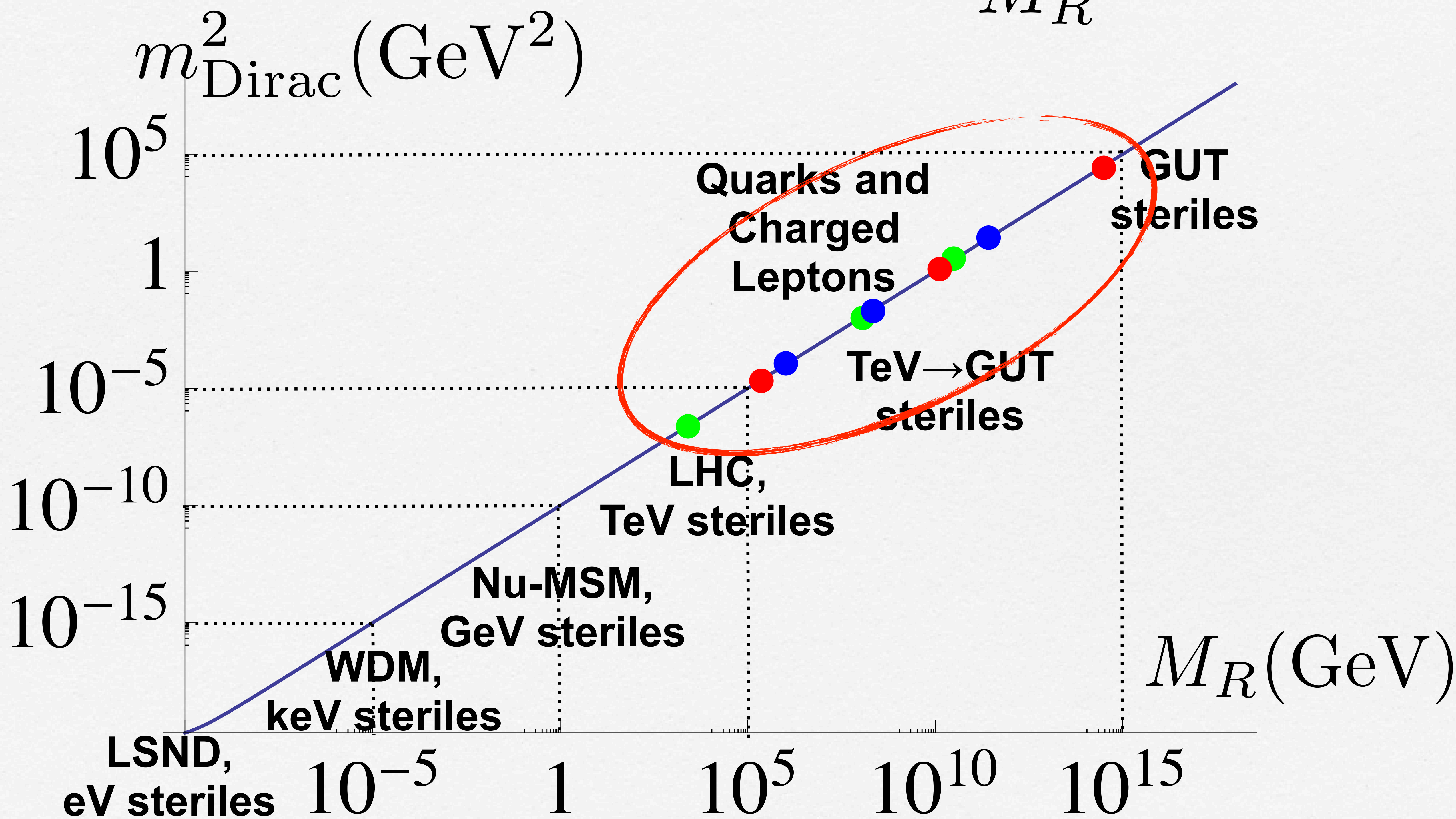
$$m_D \ll M_R$$

Seesaw assumption

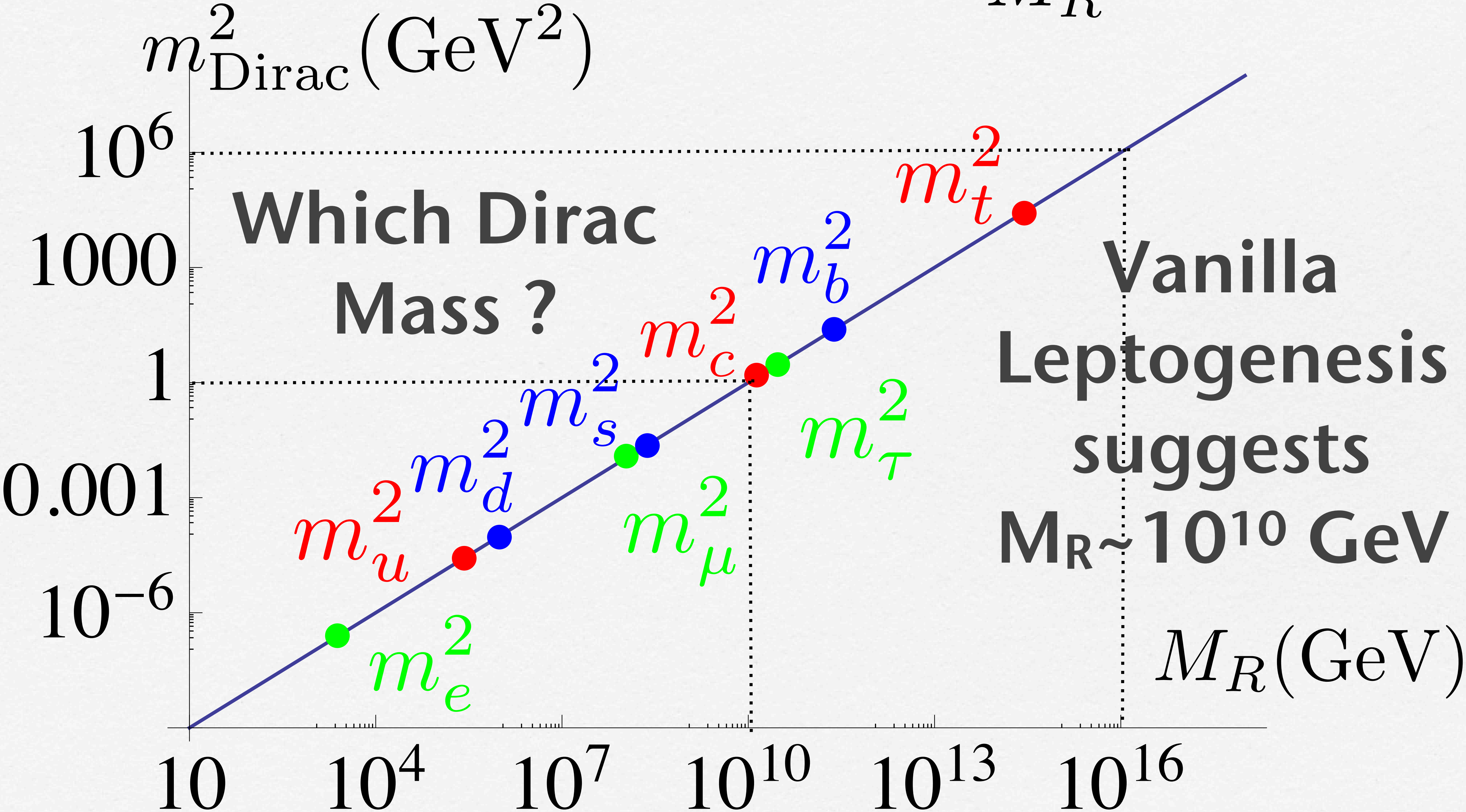
$$m_\nu \approx \frac{m_D^2}{M_R} \sim 0.1\mathrm{eV}$$

Physical neutrino mass

$$m_\nu \approx \frac{m_{\rm Dirac}^2}{M_R} = 0.1\text{eV}$$



$$m_\nu \approx \frac{m^2_{\text{Dirac}}}{M_R} = 0.1\text{eV}$$



Two right-handed neutrinos: the Littlest Seesaw

1512.07531

$$m_D = \begin{pmatrix} 0 & b \\ a & 3b \\ a & b \end{pmatrix} \qquad M_R = \begin{pmatrix} M_{\mathrm{atm}} & 0 \\ 0 & M_{\mathrm{sol}} \end{pmatrix}$$

$$m_\nu = m_D \frac{1}{M_R} m_D^T$$

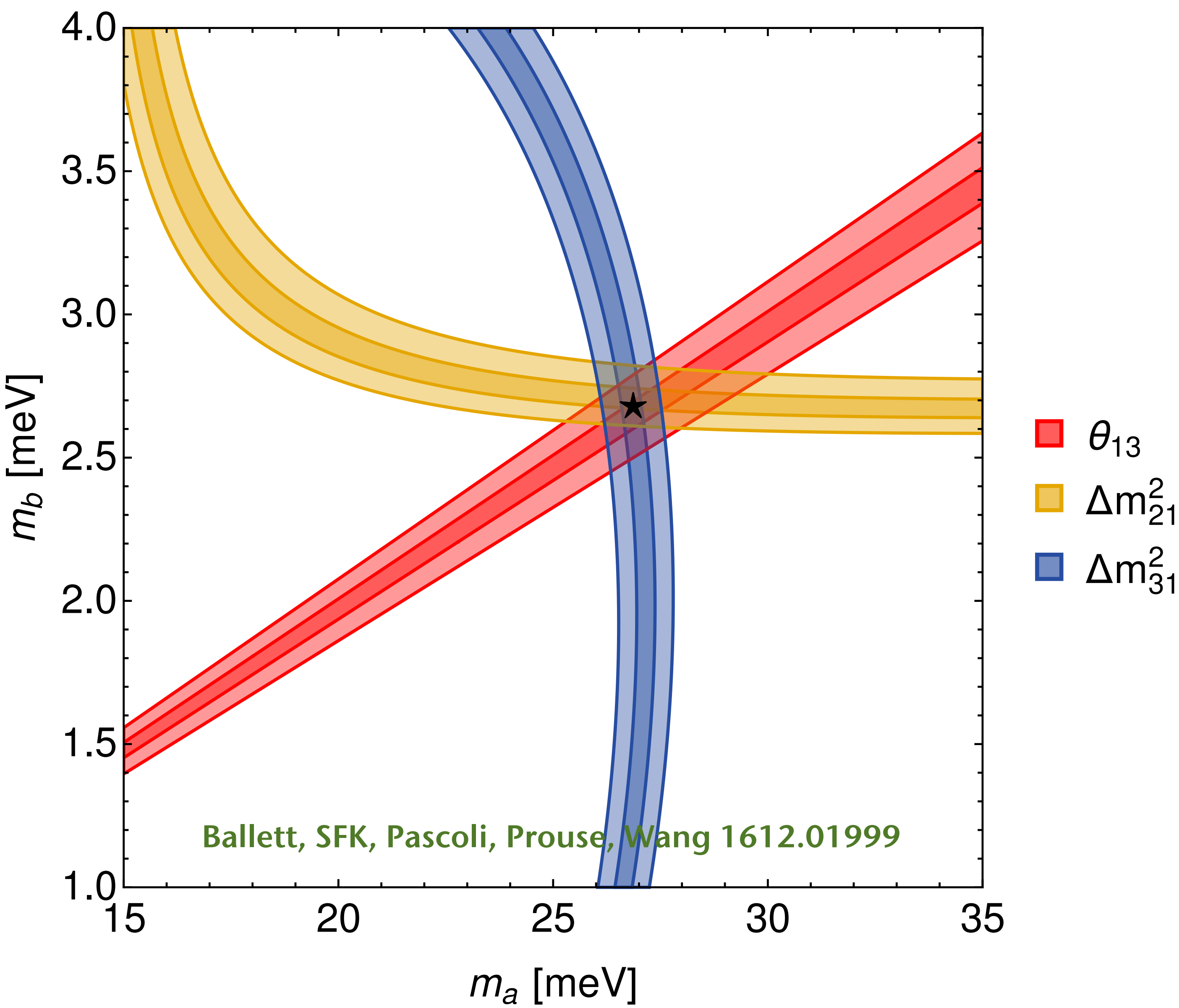
seesaw formula in matrix form

$$m_\nu = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b \begin{pmatrix} 1 & 3 & 1 \\ 3 & 9 & 3 \\ 1 & 3 & 1 \end{pmatrix}$$

$$m_a = \frac{a^2}{M_{\mathrm{atm}}} \qquad m_b = \frac{b^2}{M_{\mathrm{sol}}}$$

The Littlest Seesaw 1512.07531

$$m_\nu = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b \begin{pmatrix} 1 & 3 & 1 \\ 3 & 9 & 3 \\ 1 & 3 & 1 \end{pmatrix} e^{i2\pi/3}$$



2 input parameters

Predicts:

3 neutrino masses,
3 mixing angles,
1 Dirac CP phase,
2 Majorana phases
= 9 observables

Very predictive!

Currently measured 5 observables

Good agreement!

see talk by Sam Rowley