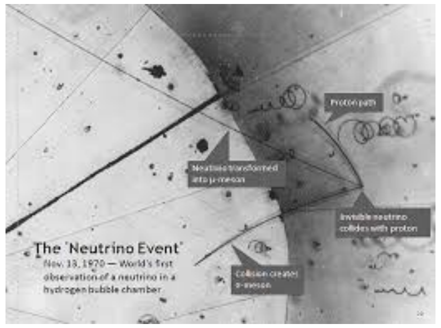
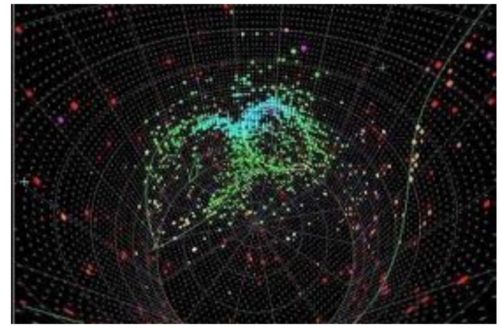
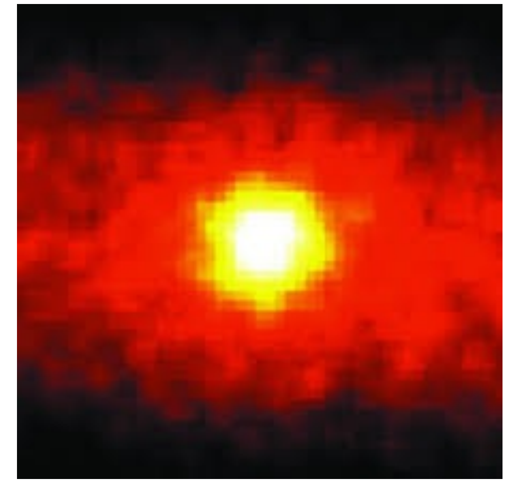
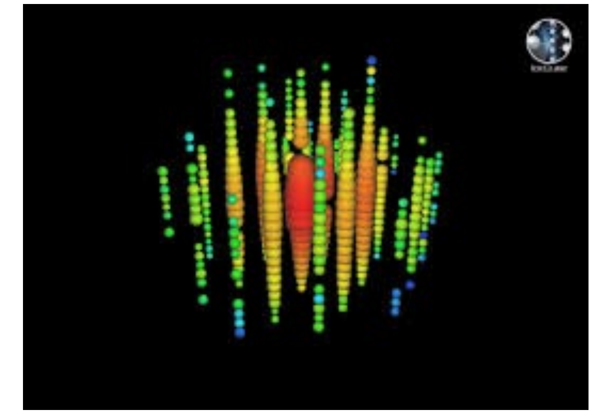


ν *Beyond the Standard Model*

Ann Nelson
"Pre SUSY" lecture 1
August 18, 2015

Today: Basics
Tommorrow: Recent Developments in ν BSM

"We have a Limited Palette"

-Sidney Coleman, Quantum Field Theory

Parameters

- *At low energy/long distance* **renormalizable** *terms dominate. With Particle/Field content of Standard Model, 19 renormalizable terms*
  - *6 quark masses, 3 quark mixing angles, 1 CP violating phase, determined by Higgs couplings*
  - *3 charged lepton masses*
  - *3 gauge couplings, 1 strong CP violating phase*
  - *2 parameter Higgs potential gives Higgs vev, Higgs self-coupling (Higgs mass)*
- *Sufficient for length scales to 10^{-33} cm (if we neglect dark matter, gravity and* **ν masses***), tested to 10^{-17} cm*

Searching for Physics Beyond

- New particles (allow new interactions)
- virtual effects (suppressed by powers of E/M)

Why is ν special?

- *ν mass is BSM, window into GUTs, hidden sectors…*
- *ν and ν mass important for cosmology*
    - *structure formation*
    - *nucleosynthesis*
    - *baryogenesis*
    - *dark matter(?)*
    - *dark energy(?)*
- *ν and ν mass important for astrophysics*
    - *stars, supernovae, heavy element nucleosynthesis*
- *Hints of anomalies*
- *History of surprises*

Physics of mass

- mass:allow particle to rest
- spinning massless particles have no rest frame,
  - need only 1 helicity (+ CPT conjugate)
- spinning massive particles in complete spin multiplet
- spin 1/2: mass connects different chiralities (potentially with different properties, as in SM)
  - (helicity=chirality in massless limit only)

ν mass in the Standard Model

- SM formulated with no "ν_R"

➡ No Renormalizable ν mass

Why?

Why no ν_R?

- seemed like a good idea to explain why ν massless
- ν_R not "necessary"
- ν_R is "sterile"

➡ $\nu_R \nu_R$ mass term allowed

➡ GUT/Planck scale?

Two ν standard models

- Model I: Dirac mass: 4 states/momentum mode
- Lepton number conserved
  - weak doublets: $\nu_L \overset{CP}{\Longleftrightarrow} \bar{\nu}_R$
  - "Sterile" weak singlets: $\bar{\nu}_L \overset{CP}{\Longleftrightarrow} \nu_R$

Two ν models cont.

- II: Majorana mass: 2 states/momentum mode
- Lepton number violated $\nu=\bar{\nu}$, no light sterile ν
- mass term $\nu\nu$ breaks lepton number
- appears to break electroweak gauge invariance
- “seesaw model”

Seesaw Majorana mass

- ν_R is gauge singlet field
- $\nu_R\ \nu_R$ Majorana mass term is gauge and Lorentz invariant
- If both Majorana and Dirac terms are present the ν mass terms may be written as a Majorana *mass matrix*:

$$\begin{array}{c|cc} & \nu_L & \overline{\nu_R} \\ \hline \nu_L & 0 & m \\ \overline{\nu_R} & m & M \end{array}$$

- m is just like the Dirac mass term and could have been written in usual way for Dirac term
- M is a Majorana mass term, breaking lepton number

Seesaw continued

$$\begin{array}{c|cc} & \nu_L & \overline{\nu_R} \\ \hline \nu_L & 0 & m \\ \overline{\nu_R} & m & M \end{array}$$

- Consider limit $M \gg m$ (motivated by GUTs)
- Diagonalize matrix perturbatively
- just like 2 state quantum system
- approximate eigenvalues: $M + \frac{m^2}{M}, \frac{-m^2}{M}$
  - ➡ sign of fermion mass does not matter
  - ➡ as M gets bigger, small eigenvalue gets smaller!
    - ★ $m_\nu \approx 0.1$ eV, $m \approx 100$ GeV $\Rightarrow M \approx 10^{14}$ GeV!
      - (at low energy, we can only determine $|m^2/M|$)

Both ν Models

- New degrees of freedom! (sterile ν)
- Dirac: light sterile ν
- Majorana seesaw: light ν *is partly sterile*

Important note about "left" and "right"

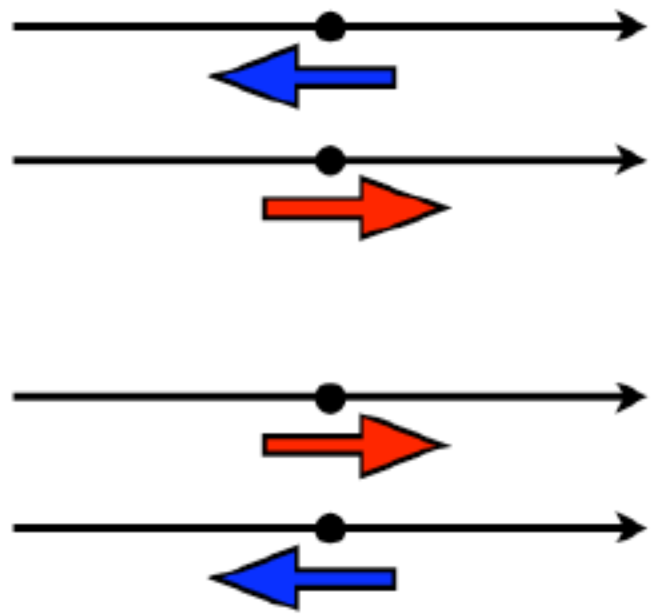
- When referring to ***fields*** "L" and "R" refer to ***chirality***
- When referring to ***particles***, "L" and "R" refer to ***helicity***
- chirality and helicity coincide for massless particles and are opposite for massless antiparticles.
- Neutrinos are so ultra relativistic, so close to massless, that chirality and helicity almost coincide.

Dirac v Majorana

Dirac

ν $L = 1$

$\bar{\nu}$ $L = -1$

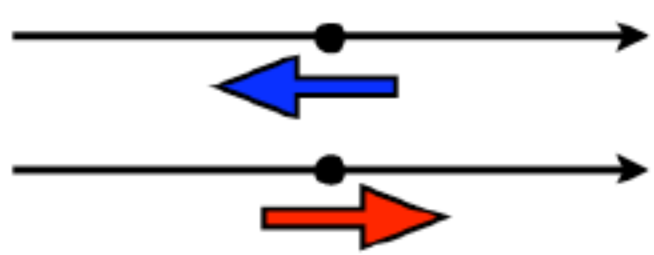


helicity	l^-	l^+
L	1	0
R	$(\frac{m_\nu}{E})^2$	0
R	0	1
L	0	$(\frac{m_\nu}{E})^2$

Majorana

ν

$\bar{\nu}$



helicity	l^-	l^+
L	1	$(\frac{m_\nu}{E})^2$
R	$(\frac{m_\nu}{E})^2$	1

$$\boldsymbol{\nu = \bar{\nu}}$$

$$(\frac{m_\nu}{E})^2 = (\frac{1eV}{1GeV})^2 = 10^{-18}$$

S. Parke Neutrino 2010

Kinematic Effects of mass

- Usually we observe effects of mass through the kinematic relation $E=\sqrt{p^2+m^2}$
- Produce ν with $E >>$ MeV
- m<eV

➡ $p \approx E - m^2/(2E)$

➡ $\Delta p < 10^{-15}$ MeV

➡ $\Delta x > 100$ m ! classical kinematic effects of mass not observable

"All the News That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179 · Copyright © 1998 The New York Times · FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

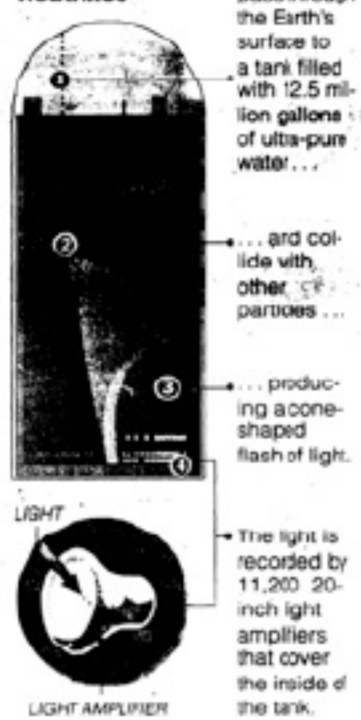
Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos



And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

ν98, @Takayam
June 1998

Atmospheric neutrino results from Super-Kamiokande & Kamiokande

— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo
for the {Kamiokande, Super-Kamiokande} Collaborations

http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/

PMNS matrix in Lepton sector

- lepton doublets: $\begin{pmatrix} \nu_{Le} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{L\mu} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{L\tau} \\ \tau_L \end{pmatrix}$
- lepton weak eigenstates are not mass eigenstates
- lepton mixing:
- $U=U_{PMNS}$
- $UU^{\dagger}=1$

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

- mixing requires neutrinos to be massive, and have nondegenerate masses
- observing mixing requires observing effects of nondegenerate neutrino mass

Quantum Mechanical Effects of ν mass

- Neutrino wave packet is so ultra relativistic that it propagates with $\omega \cong k$
  - essentially no dispersion, distance traveled $x \cong t$
  - effect of mass on overall phase of wave packet: $e^{-i\frac{m^2 t}{2E}}$
  - flavor eigenstate produced in coherent superposition of mass eigenstates which acquire different phases as they travel
  - If only 2 ν's mix (e.g. ν_{μ}, ν_e) simple formula for probability of flavor transition

$$P_{\mu \to e} = \sin^2(2\theta)\sin^2\left(\frac{(m_1^2 - m_2^2)x}{4E}\right)$$

mass vs flavor eigenstates

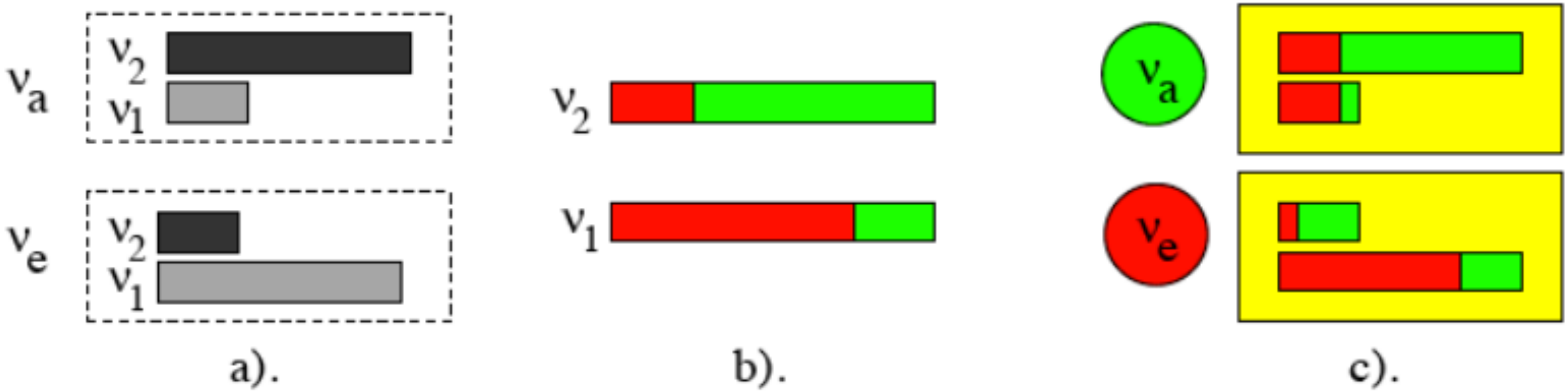


Figure 1: a). Representation of the flavor neutrino states as the combination of the mass eigenstates. The length of the box gives the admixture of (or probability to find) corresponding mass state in a given flavor state. (The sum of the lengths of the boxes is normalized to 1. b). Flavor composition of the mass eigenstates. The electron flavor is shown by red (dark) and the non-electron flavor by green (grey). The sizes of the red and green parts give the probability to find the electron and non-electron neutrino in a given mass state. c). Portraits of the electron and non-electron neutrinos: shown are representations of the electron and non-electron neutrino states as combinations of the eigenstates for which, in turn, we show the flavor composition.

from Smirnov
hep-ph/0305106

> 2 flavor mixing

- Probability of producing flavor *a* in a beam of flavor *b* at a distance *x* from the source

$$P_{ab} = \left| \sum_{j=1}^{n} U_{aj} U_{bj}^{*} e^{-i\frac{m_j^2 x}{2E}} \right|^2$$

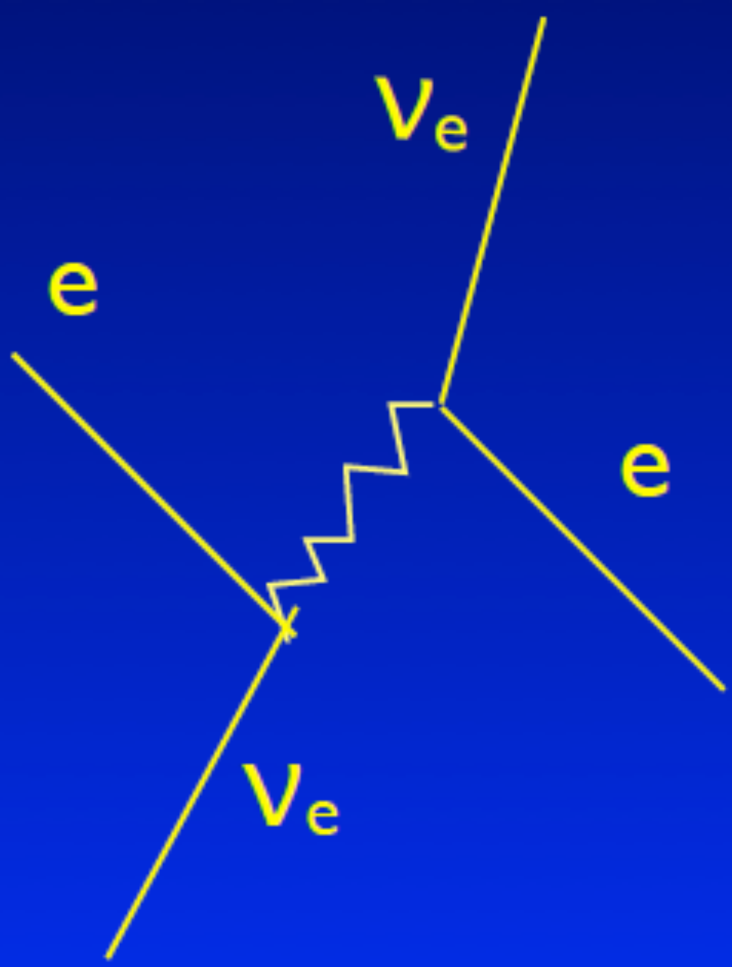
UU†=1⇒no flavor change at *x=0*

- With >2 flavors, *U* can have a CPV phase, just like in quark mixing. For antineutrinos:

$$\overline{P}_{ab} = \left| \sum_{j=1}^{n} U_{aj}^{*} U_{bj} e^{-i\frac{m_j^2 x}{2E}} \right|^2 = P_{ba} \neq P_{ab}$$

The MSW mechanism: effects of propagating though matter

- neutrinos propagate through matter
- matter is full of electrons
- forward scattering of electron neutrino
- additional phase for ν_e



Effective $\mathcal{H}$ for ν propatin

- in flavor basis: (simplified case of 2 neutrinos)
- ignore terms $\propto 1$, only can see $\Delta m^2 = m_2^2 - m_1^2$

$$H_{eff} = \begin{pmatrix} -\left(\frac{\Delta m^2}{4E}\right)\cos(2\theta) + V & \left(\frac{\Delta m^2}{4E}\right)\sin(2\theta) \\ \left(\frac{\Delta m^2}{4E}\right)\sin(2\theta) & \left(\frac{\Delta m^2}{4E}\right)\cos(2\theta) \end{pmatrix} \quad (+\ \text{terms} \propto 1\ )$$

- V is matter effect for electron neutrinos from electrons
- $V \propto$ density of electrons
- when diagonal terms are equal, resonant enhancement of mixing

Level crossing in the sun

- adiabatic conversion "start heavy, stay heavy"

from Smirnov
hep-ph/0305106

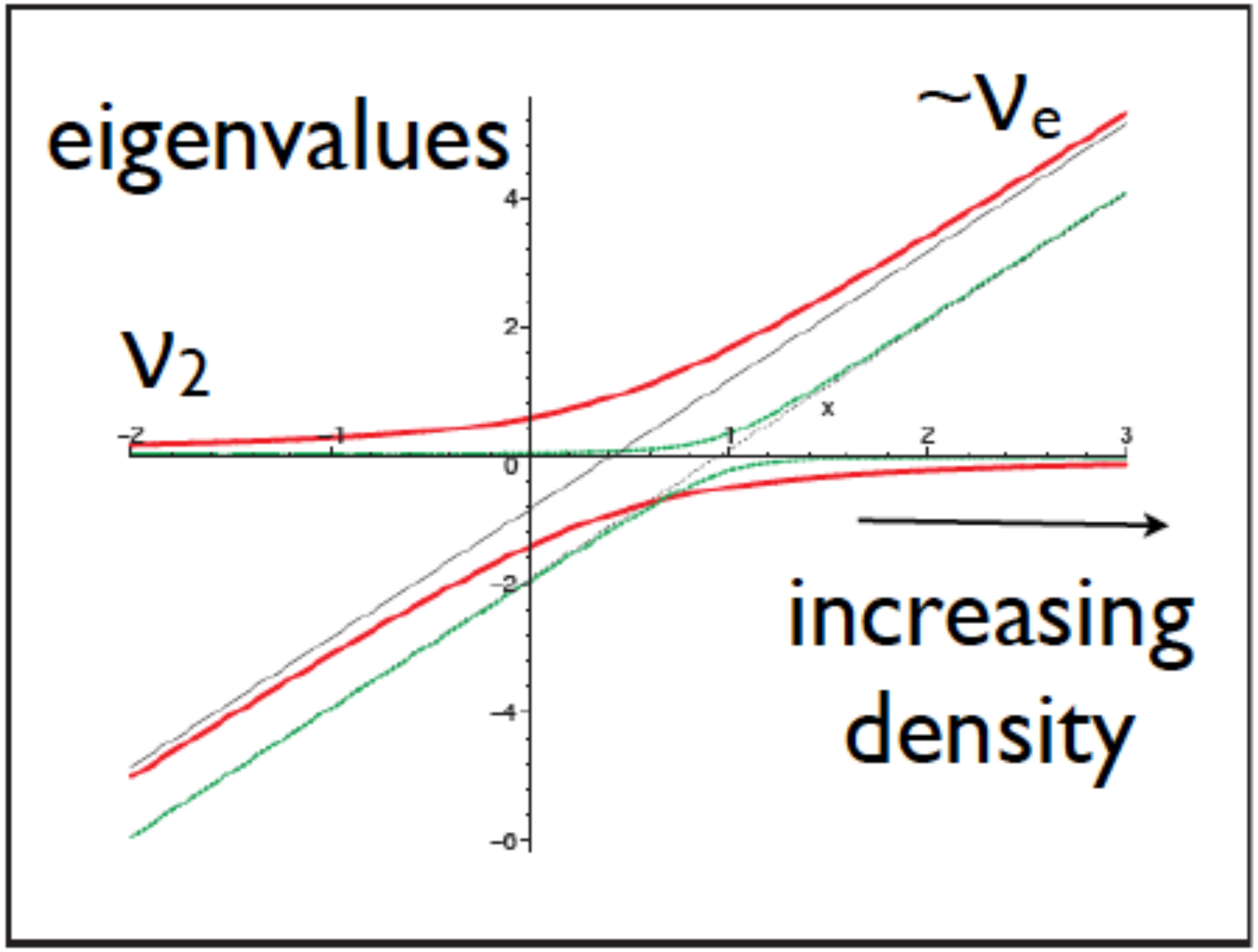


Figure 3: Level crossing scheme. Dependence of the eigenvalues of the Hamiltonian in matter, H_{1m} and H_{2m}, on the ratio $x \equiv l_\nu / l_0$ for two different values of vacuum mixing $\sin^2 2\theta = 0.825$ (solid, blue lines) and $\sin^2 \theta = 0.08$ (dashed, red lines).

Mixing angles

not observabl[e] in oscillation[s]

Mixing Matrix:

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ — Atmos. L/E $\mu \leftrightarrow e$ — Solar L/E $e \to \mu, \tau$ — $0\nu\beta\beta$ decay

500km/GeV — 15km/MeV

SNO/KamLAND $|U_{e2}|^2$

Reactor/LBL $|U_{e3}|^2(1 - |U_{e3}|^2)$

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

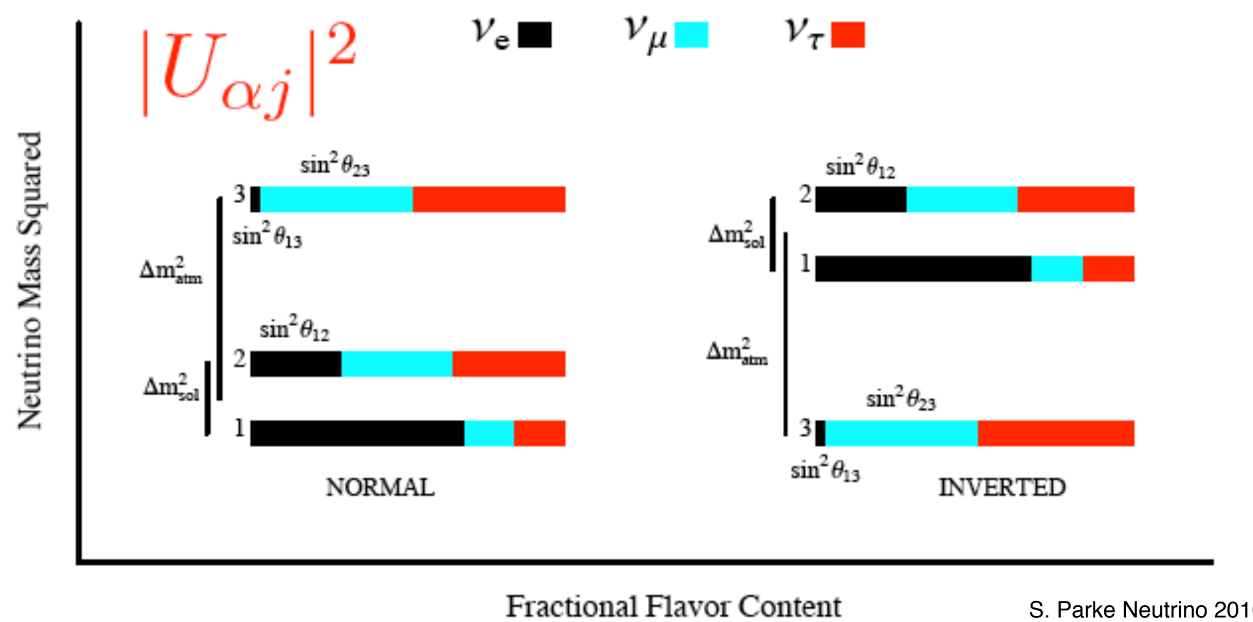
Atm Nus/LBL $|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)$

S. Parke Neutrino 2010

$$\frac{CC}{NC}\Big|_{sno} \approx |U_{e2}|^2$$

Open questions

- Majorana or Dirac?
- CP?
- ν mass hierarchy?
- absolute ν mass scale?



- Are there light “sterile ν” s?
- Do ν’s have other interactions (besides weak, gravitational?)

Who cares ?

Neutrino mass is physics "beyond the Standard Model", but . . .

we can account for neutrino mass with right handed neutrinos and/or lepton number violating nonrenormalizable interactions in

"the ν Standard Model(s)"

no revision of sacred principles needed either way

Usual reasons to care about Neutrino mass/mixing

- Window into GrandUnifiedTheorieS
- May be related to Leptogenesis/Baryogenesis
- Affects structure formation in Universe
- May affect supernovae dynamics
- Neutrino astronomy affected by mixing
- Use of neutrinos as probe, e.g. geophysical, requires knowledge of mixing parameters

Exotic Physics beyond the ν standard model

- Visible oscillations are affected by tiny GUT scale suppressed operators ('standard' seesaw) and weak force(s)
- Neutrinos can mix with "dark" (sterile) fermions
- Neutrinos can thus experience "dark forces" much more strongly than other known particles
- matter effect on oscillations is sensitive to new forces
- Neutrinos are Special!
  Neutrino physics great place to search for exotica!
  Window on the Dark Sector!

The ν portal

- (Beyond) The ν Standard Model
- Sectors and the theoretical terrain

PORTALS TO NEW SECTORS

ν portal: sterile ν's , ν anomalies, ν forces….

What is a 'portal' ???

- in science fiction and virtual 'reality': a useful short cut to another sector.
- in particle theory???
- Better than a "window". You don't just see the indirect effects of the hidden sector, you can go there. (make new kinds of particles)
- Two useful ingredients of a portal

1. Dimensional analysis: possibility of a term in an effective theory which connects two sectors
2. A long lived particle associated with the operator which can use the connection to oscillate or decay into the hidden sector

Portal to hidden sector

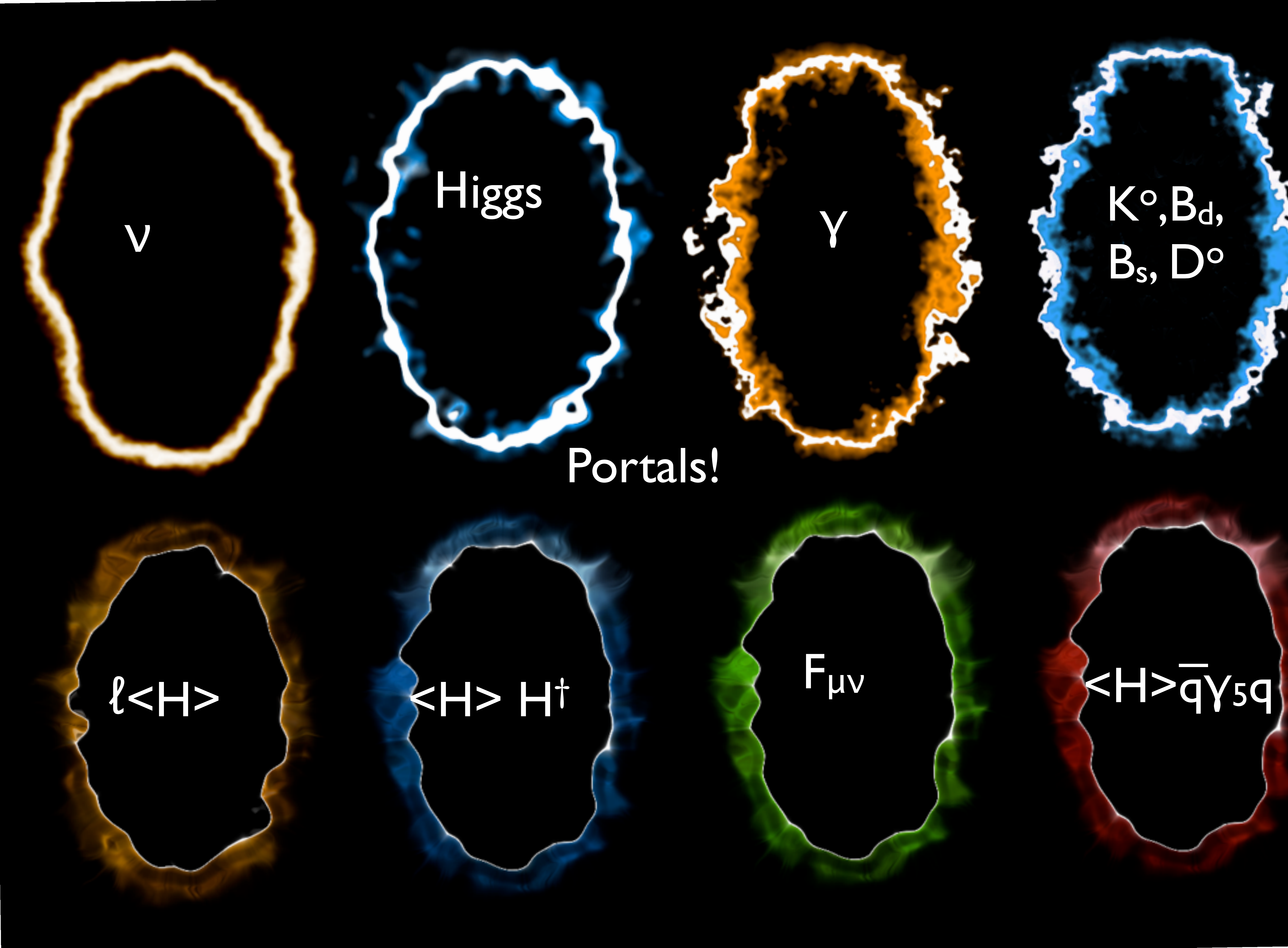
$$\frac{\mathcal{O}_{\text{hidden}}\mathcal{O}_{SM}}{M^d}$$

$\mathcal{O}_{SM} =$ standard model operator

$\mathcal{O}_{\text{hidden}} =$ hidden sector operator

$$d = \dim(\mathcal{O}_{SM}\mathcal{O}_{\text{hidden}}) - 4$$

$M =$ scale of “messenger physics”


ν
Higgs
γ
$K^o, B_d,$
B_s, D^o
Portals!
ℓ<H>
<H> H†
$F_{\mu\nu}$
<H>$\bar{q}\gamma_5 q$

ν mixing, ν force

$$\mathcal{L} \supset -m_{ij}\frac{H^2}{v^2}\ell_i\ell_j - MN_1N_2 - \lambda_i N_1 H\ell_i - y_1\phi^* N_1\chi - y_2\phi N_2\chi$$

- first term gives tiny Majorana ν masses
- last four terms conserve lepton number
- mass matrix from first three terms:

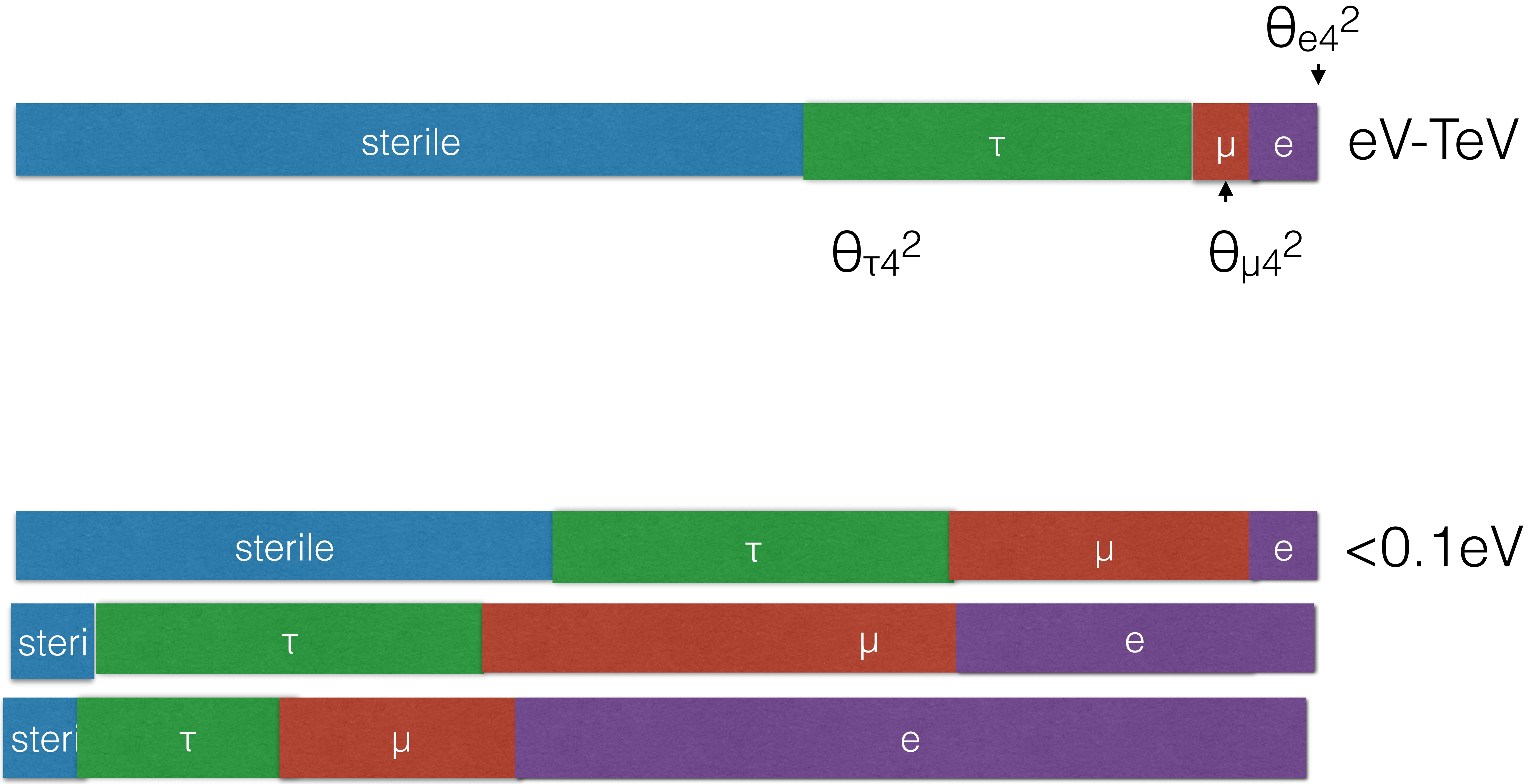
$$\begin{pmatrix} m_{ij} & \lambda_j v & 0 \\ \lambda_i v & 0 & M \\ 0 & M & 0 \end{pmatrix}.$$

- 3 very light Majorana ν's, mass from first term
- 1 heavy (e.g. eV—TeV) Dirac ν, mass $\sqrt{M^2 + \sum_i \lambda_i^2 v^2}$
- 4x4 ν mixing matrix

$$\nu_i = U_{ij}\hat{\nu}_j,$$

$$\nu_i = U_{ij}\hat{\nu}_j,$$

3+1 heavy



ν force

- N's could carry new gauge charges (broken by ϕ)
- ϕ scalar is a new force
- light ν are part N, experience new forces
- anomalous MSW matter effects: N has no weak neutral current

What good is ν portal ???

- Dark Energy
- Dark Matter (will discuss ν connection)

Summary and Outlook

- ν mass
    - tiny, inferred via flavor oscillations
    - is physics beyond the standard model, probably involving a new fermion with no standard gauge interactions
- Beyond the "standard" neutrino model
    - Does ν interact with Dark Matter? (stay tuned)
    - Non standard ν interactions via ν portal (mixing with nonstandard fermion)
    - Are (fractions of) the ν part of a dark sector?