Neutrino Physics
and
Nuclear astrophysics

Lecture I – neutrino physics

National Nuclear Physics Summer School

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Neutrino mass/mixing is Beyond Standard Model physics

I will show that nuclear physics is a key tool in leveraging
the data from new observatories to learn about BSM neutrino physics
and
understanding neutrino physics (*e.g.*, how neutrinos change flavor)
may give insights into key nuclear physics problems
(*e.g.*, origin of the elements, high density nuclear equation of state)

The elementary particles which we know about --

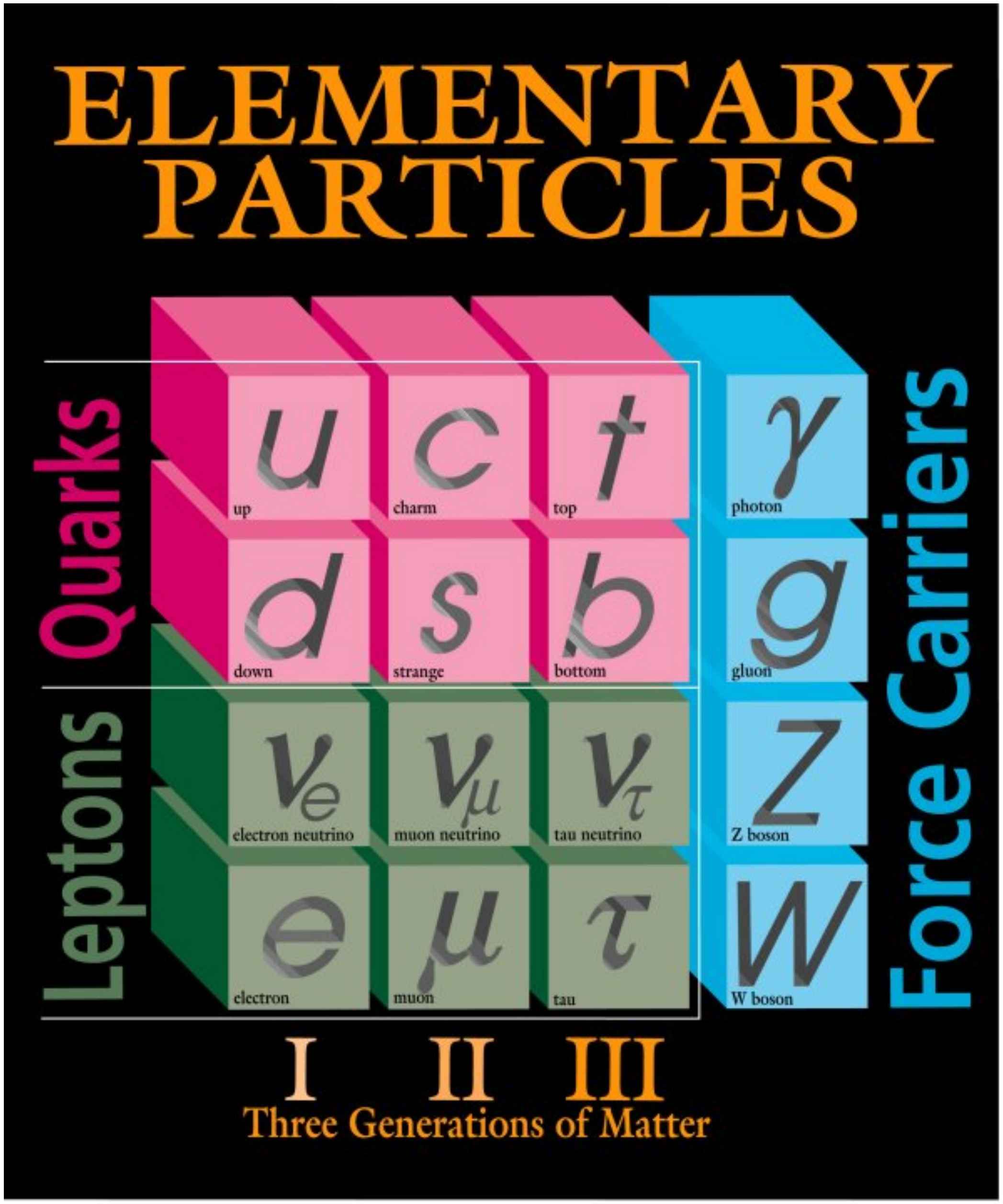
These particles are the building blocks of the *Standard Model*.

Neutrinos, like the charged leptons and quarks are spin-1/2 but, unlike those particles, neutrinos have no electric charge.

Each particle has an antiparticle, so there are six known neutrinos:

$$\underbrace{\nu_e, \bar{\nu}_e}_{\textbf{electron flavor}}, \underbrace{\nu_\mu, \bar{\nu}_\mu}_{\textbf{mu flavor}}, \underbrace{\nu_\tau, \bar{\nu}_\tau}_{\textbf{tau flavor}}$$

We know the rest masses of all the particles in this table ***EXCEPT*** for the neutrinos!



Fermilab 95-759

They don't call it the weak interaction for nothing!

Neutrinos experience only gravity and the weak interaction.

At the neutrino energies typical in stars and the early universe
the **weak** interaction is *twenty orders of magnitude* ***weaker*** (10^{-20})
than the **electromagnetic** interaction that governs how light (photons)
influences matter.

It would take a block of lead
several light years *thick*
to have a decent chance of
stopping one of these neutrinos **!**

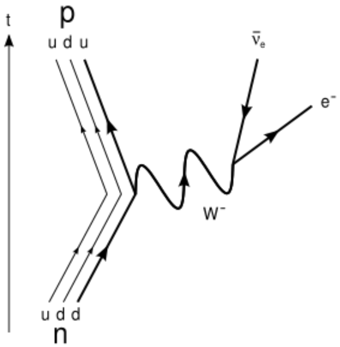
I'm never impressed by this – neutron star matter is 14 orders of magnitude denser than Pb

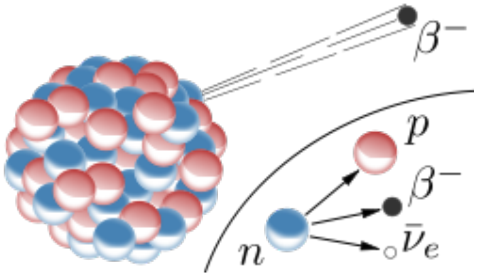
So how do we even know these particles exist?

Wolfgang Pauli's

"... *desperate remedy* ... to save the law of conservation of energy ..." 1930

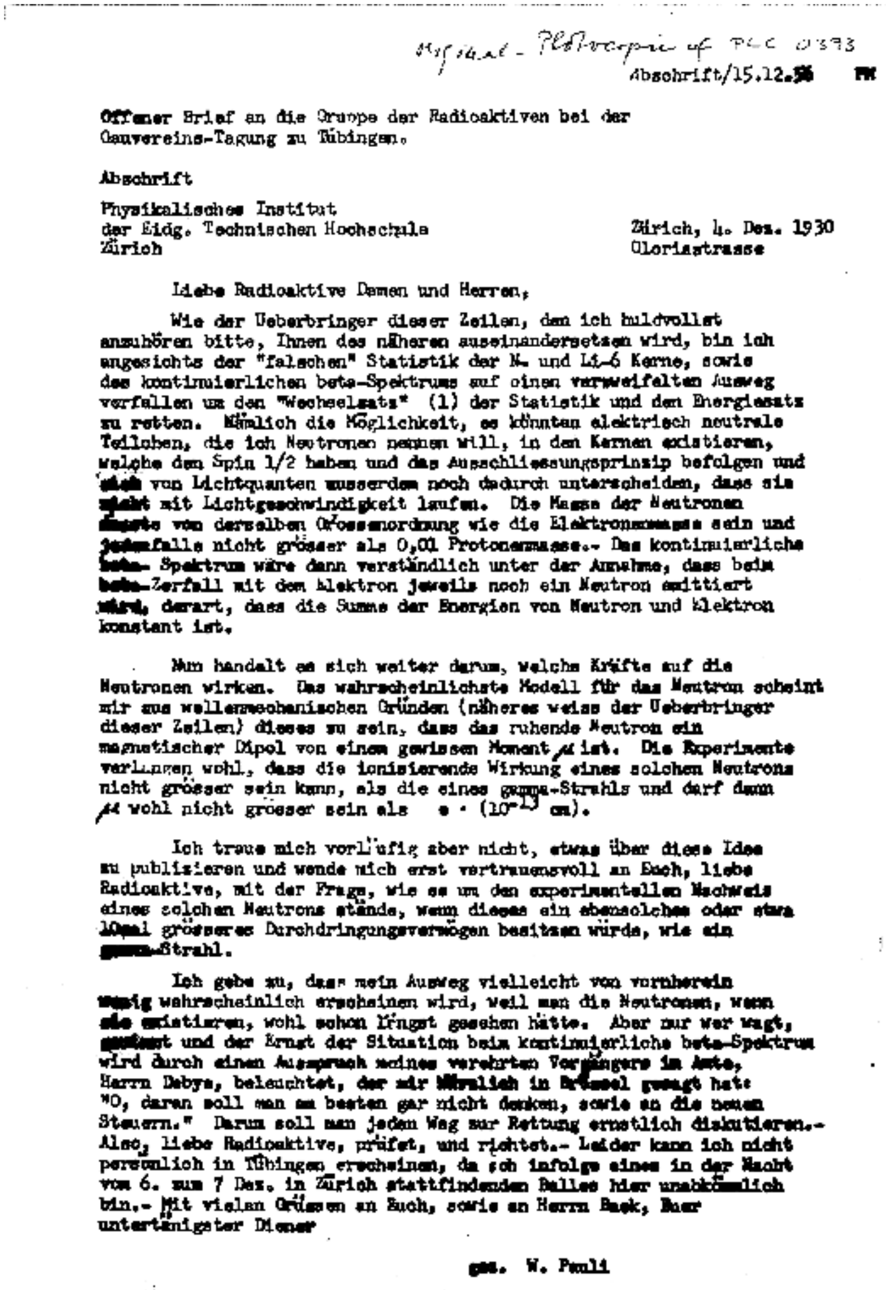
In beta decay a neutron in the nucleus changes into a proton. An electron and a neutrino (an electron antineutrino actually) are emitted.





Experimenters knew the energy of the initial and final nuclei and they could measure the energy of the electron, but they *could not* detect the neutrino. To them it looked as if energy wasn't conserved. Pauli suggested that there might be an unseen neutral, chargeless particle that takes away the missing energy - he called it a "*neutron*"!

Pauli’s letter to the participants of a meeting of experimental physicists which he could not attend.



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

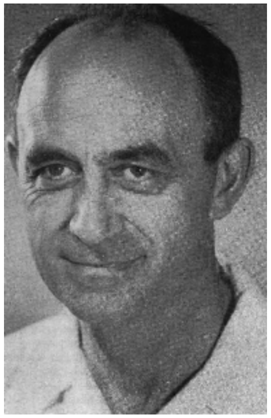
Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

from FNAL’s *Symmetry* magazine

In 1934 Enrico Fermi created a theory of the Weak Interaction that explains the experiments and has allowed us to calculate how neutrinos should behave and interact with matter.



Neutrinos are responsible
for most of the “*heavy lifting*”
in the early universe and core collapse supernovae.

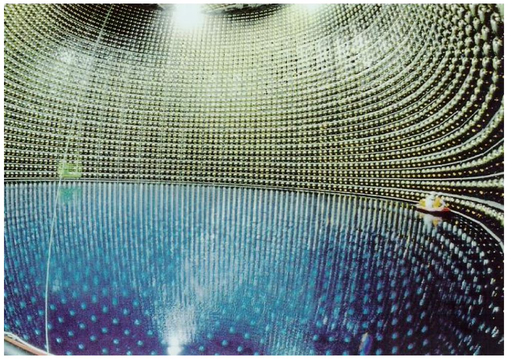
For example, they carry can a significant fraction
of the energy and entropy in these environments.

This might seem like an outrageously absurd statement given how feebly neutrinos interact with matter.

The neutrino interaction strength we typically deal with in stars and the universe is **Twenty Orders of Magnitude** (10^{-20}) ***weaker*** than the electromagnetic interaction that governs how photons (light) influence matter!

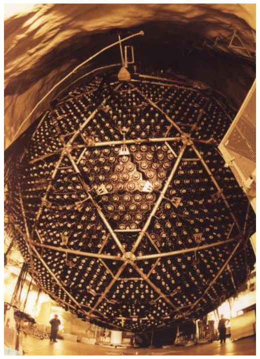
However, as we shall see, with HUGE NUMBERS, neutrinos can easily make up for their weak interactions.

Nevertheless, we need *really big detectors* to "see" reactor, accelerator, solar, and supernova neutrinos!



SuperK

100 KTons H_2O



Sudbury Neutrino Observatory

10 KTons D_2O

The Weak Interaction may be feeble, but . . .

The weak interaction is the only means for
converting neutrons into protons and *vice versa*.

If it were not for the weak interaction:
-stars would not shine (for very long anyway)
-there would be very few of some elements required for life
(e.g., because there would be no core collapse supernovae)

The Weak Interaction

changes neutrons to protons and *vice versa*

strength of the Weak Interaction: Fermi constant $G_{\mathrm{F}} \approx 1.166 \times 10^{-11}\,\mathrm{MeV}^{-2}$

$G_{\mathrm{F}} \sim 10^{-5}\ \mathrm{amu}^{-2}$

$$\nu_e + n \longrightarrow p + e^- \qquad \bar{\nu}_e + p \longrightarrow n + e^+$$

$$e^- + p \longrightarrow n + \nu_e \qquad e^+ + n \longrightarrow p + \bar{\nu}_e$$

$$\sigma_{\mathrm{weak}} \sim G_{\mathrm{F}}^2\, E_\nu^2$$

$$E_\nu = 1\,\mathrm{Mev} \Rightarrow \sigma_{\mathrm{weak}} \sim 5 \times 10^{-44}\,\mathrm{cm}^2 \left(\frac{E_\nu}{\mathrm{MeV}}\right)^2$$

typically some 20 orders of magnitude weaker than electricity (*e.g.,* Thompson cross section)

Neutrino mass physics is a theme common to both

Compact Objects (*supernovae; neutron stars; holes; etc. . .*)

Cosmology (*structure formation; dark matter, etc. . .*)

Synergy between
laboratory/observational neutrino physics
and the continuing
revolution in observational astronomy

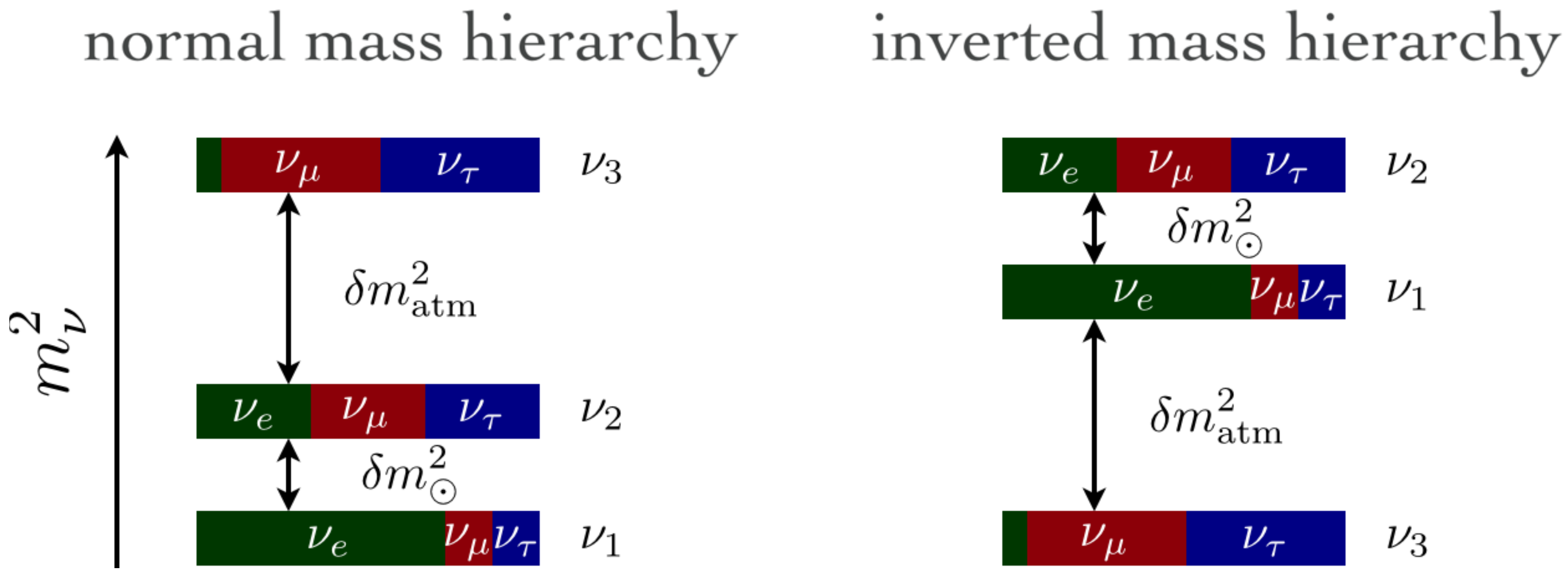
Neutrino Mass: what we know and don't know

We know the *mass-squared* differences:

$$\boxed{e.g.,\quad \delta m^2_{21} \equiv m^2_2 - m^2_1}$$

$$\begin{cases} \delta m^2_{\odot} \approx 7.6 \times 10^{-5}\,\mathrm{eV}^2 \\ \delta m^2_{\mathrm{atm}} \approx 2.4 \times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

We *do not* know the *absolute masses* or the *mass hierarchy*:


normal mass hierarchy

inverted mass hierarchy

Neutrino energy (mass) states are not coincident with the weak interaction (flavor) states

The unitary transformation that relates these states in vacuum has 4 parameters (exclusive of Majorana phases**)**

We know 2 of the 4 vacuum 3X3 mixing parameters and we have a good upper limit on a third.

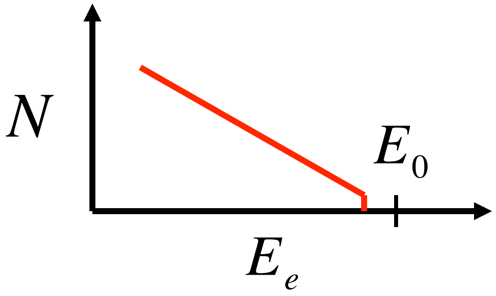
Direct Laboratory Limits on Neutrino Rest Masses

"m_{ν_τ}" < 18.2 MeV (τ - decay; Groom *et al.,* Eur. J. Phys., C15, 1, 2000.)

"m_{ν_μ}" <190 keV (π - decay)

"m_{ν_e}" < 2 eV (Tritium endpoint; KATRIN eventually down to 200 meV =.2 eV)

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e \qquad \frac{dN}{dE_e} \propto \sqrt{\left(E_e - E_0\right)^2 - \text{"}m_{\nu_e}^2\text{"}}$$



$$\text{"}m^2_{\nu_e}\text{"} \approx +0.6 \pm 2.8 \pm 2.1 \ \mathrm{eV}^2$$
$$\approx -1.6 \pm 2.5 \pm 2.1 \ \mathrm{eV}^2$$

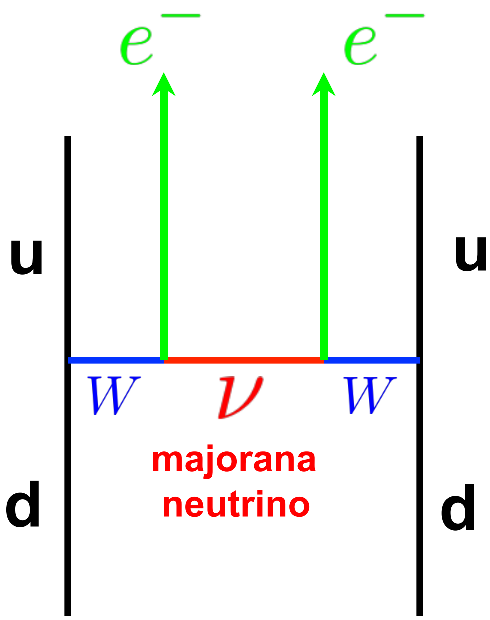
< 4 eV² with high confidence

- J. Bonn *et al.,* Nucl. Phys. B 91, 273, 2001.

In terms of matrix elements of the Unitary Transformation:

$$\text{"}m^2_{\nu_e}\text{"} = m_1^2\left|U_{e1}\right|^2 + m_2^2\left|U_{e2}\right|^2 + m_3^2\left|U_{e3}\right|^2 + \ldots + m_n^2\left|U_{en}\right|^2$$

Majorana Neutrinos: Neutrinoless Double Beta Decay

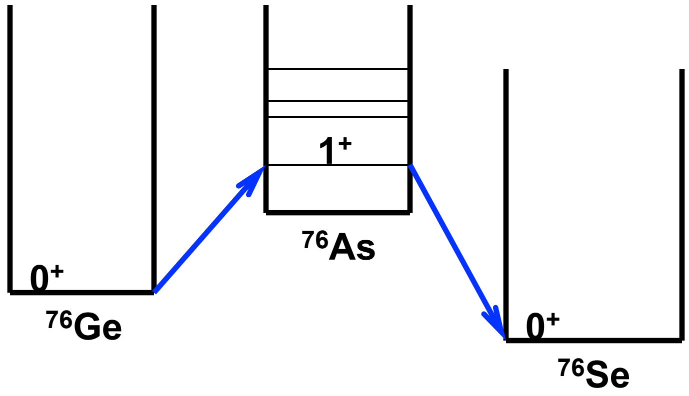


two neutrons change
into two protons

$$\Gamma_{0\nu} = \frac{1}{\tau_{\beta\beta}} = G_{0\nu}\left|M_{\rm nuc}\right|^2 m_{\beta\beta}^2$$

$$\langle m_{\beta\beta}\rangle = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Second order weak process:
coherent sum over intermediate nuclear states



experiments should get to > 10^{27} year lifetime, or

$$m_{\beta\beta} < 50\,\mathrm{meV}$$

P-Maki-Nakagawa-Sakata matrix

$$\boxed{\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}}$$

$$U_m = U_{23}\, U_{13}\, U_{12}\, M$$

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

$$U_{12} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

4 parameters

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$\theta_{12} \approx 0.59^{+0.02}_{-0.015}$$

$$\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}$$

$$\theta_{13} \approx 0.154^{+0.065}_{-0.065}$$

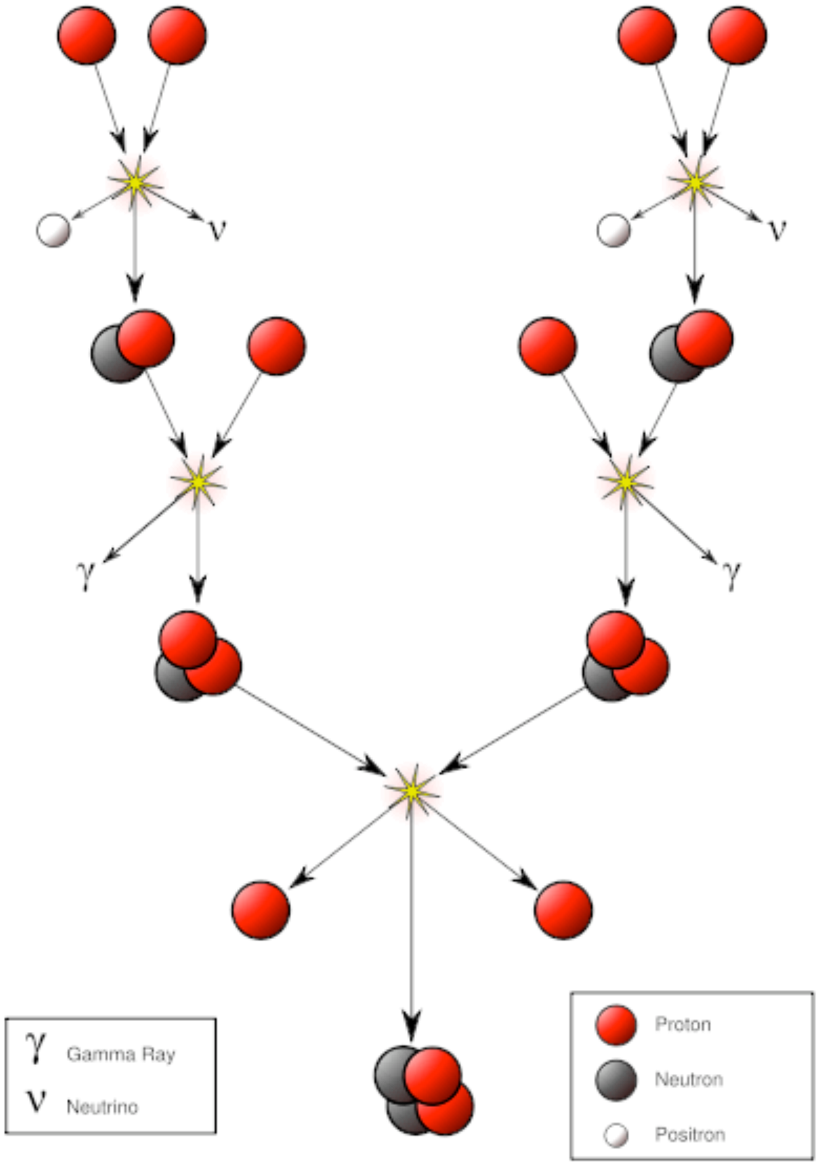
$\delta = CP$ violating phase $=?$

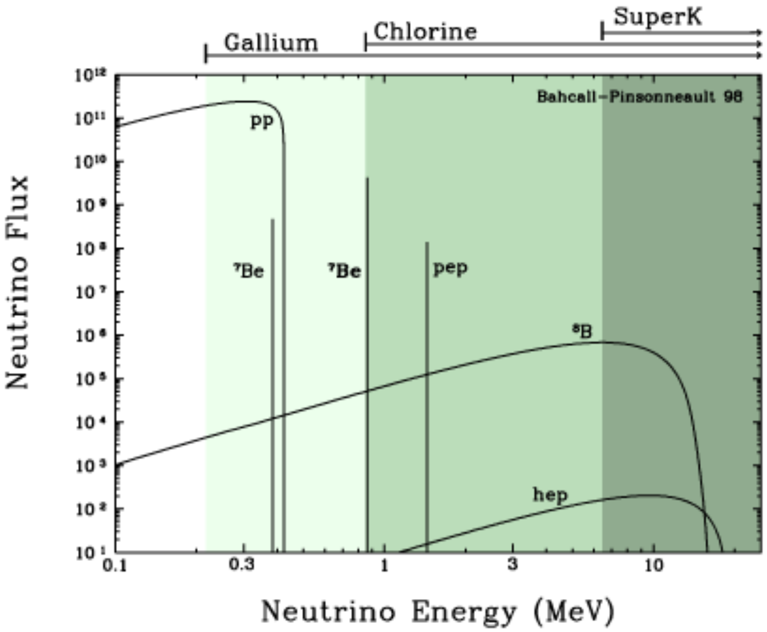
So, we *already* know from the lab a great deal about neutrino mass/mixing – this is *Beyond Standard Model* physics. There may be more surprises.

-- not including this in astrophysical models where neutrinos are import is unacceptable.

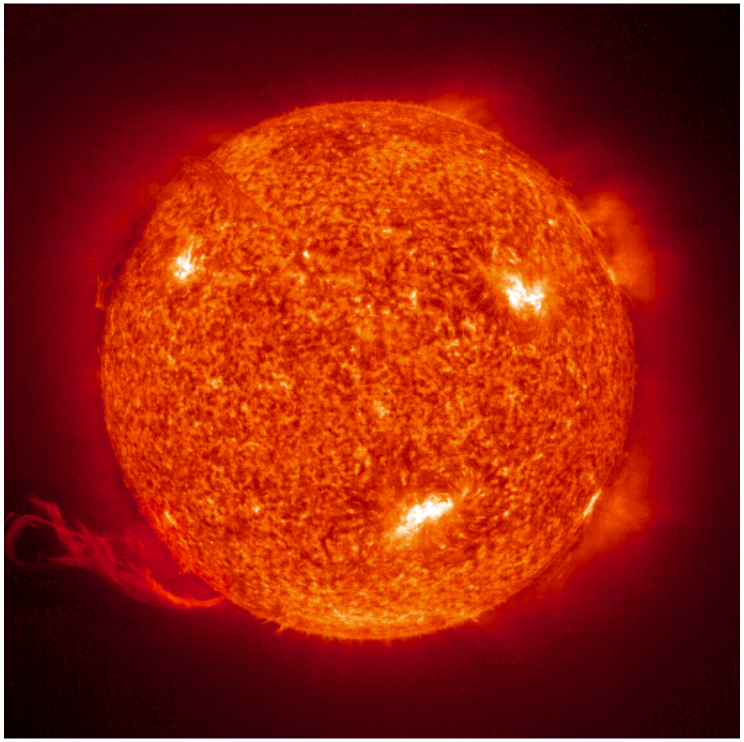
Fusion reactions power the sun

-they make, ultimately, photons and neutrinos



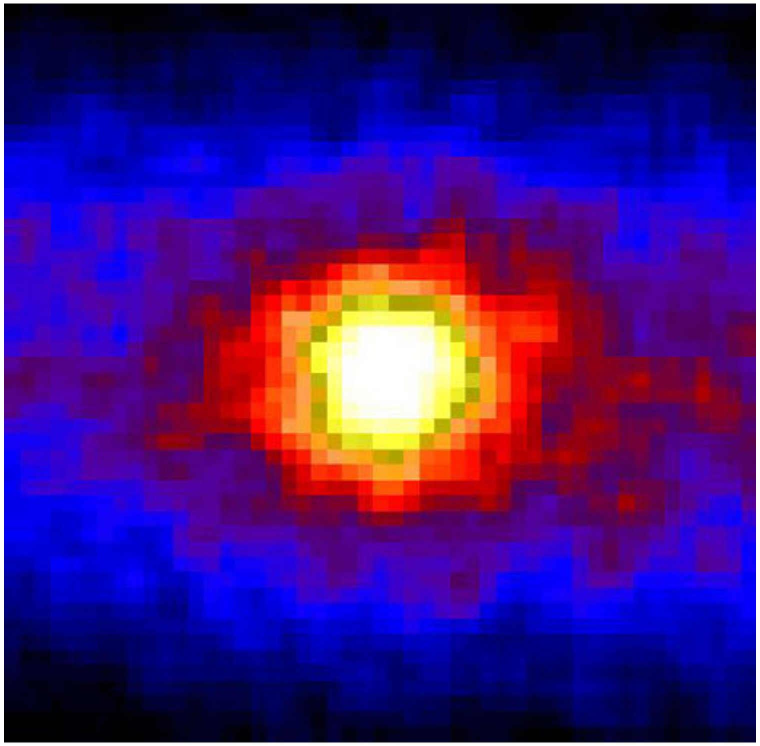


John Bahcall - solar neutrino problem



The sun in x-rays (photons)

(Cornell)

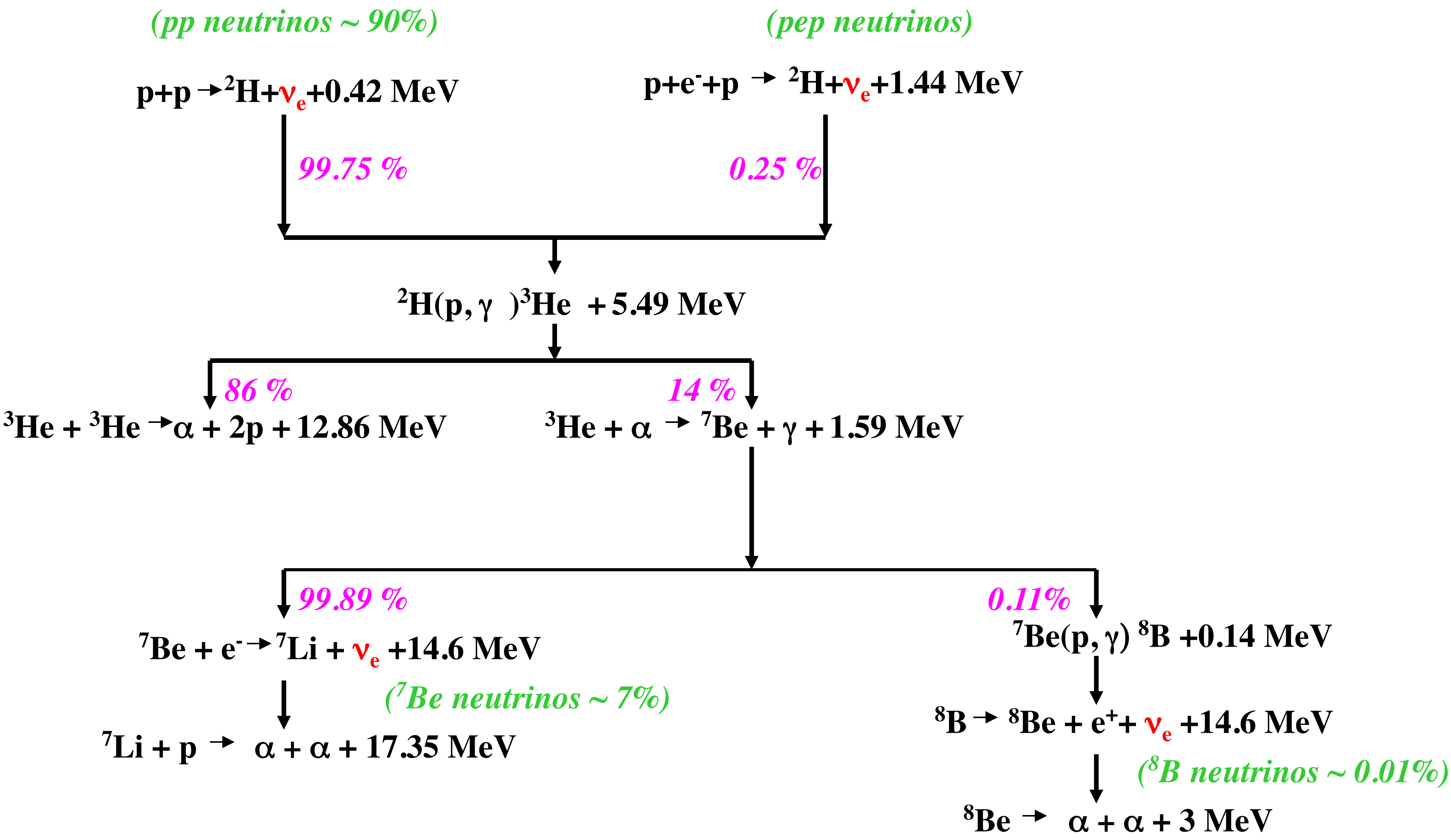


the sun in neutrinos
-composite from SuperK

(R. Svoboda, LBNL, now UCD)

But whereas neutrinos are innocent bystanders in the sun, they are the criminal masterminds in the early universe and core collapse supernovae!

Nuclear Reactions in the Sun and Associated Neutrino Production



(pp neutrinos ~ 90%)

$p+p \rightarrow {}^2H+\nu_e+0.42$ MeV

99.75 %

(pep neutrinos)

$p+e^-+p \rightarrow {}^2H+\nu_e+1.44$ MeV

0.25 %

${}^2H(p,\gamma)\,{}^3He + 5.49$ MeV

86 %

${}^3He + {}^3He \rightarrow \alpha + 2p + 12.86$ MeV

14 %

${}^3He + \alpha \rightarrow {}^7Be + \gamma + 1.59$ MeV

99.89 %

${}^7Be + e^- \rightarrow {}^7Li + \nu_e + 14.6$ MeV

(^{7}Be neutrinos ~ 7%)

${}^7Li + p \rightarrow \alpha + \alpha + 17.35$ MeV

0.11%

${}^7Be(p,\gamma)\,{}^8B + 0.14$ MeV

${}^8B \rightarrow {}^8Be + e^+ + \nu_e + 14.6$ MeV

(^{8}B neutrinos ~ 0.01%)

${}^8Be \rightarrow \alpha + \alpha + 3$ MeV

But, Two-Thirds of Neutrinos Coming from the Sun are Measured to have Mu and Tau Flavor!

Neutrinos in Medium

Medium-Enhanced/Suppressed Neutrino Flavor Transformation

Photons acquire an index of refraction from forward scattering on the atoms (electrons) in, for example, glass or air. The propagation speed of light in materials like these is reduced from the vacuum propagation speed.
It is as if the photons acquire an "*effective mass*" in medium.

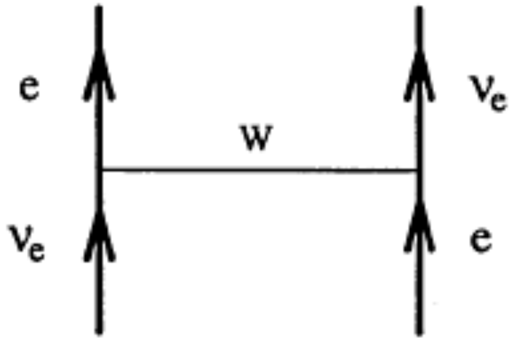
Likewise, a neutrino can acquire an index of refraction by forward scattering on any particles that carry weak charge (e.g., electrons, positrons, quarks, or other neutrinos). Again, we can think of this as an "effective mass" acquired by the neutrino in medium. Flavor mixing properties altered as well.

In optically birefringent media like calcite crystals, the index of refraction depends on the polarization state of the photon.

All media of interest in the cosmos are "optically birefringent" for neutrinos. That is, the effective mass acquired by a neutrino depends on its flavor state.

**Coherently propagating
active neutrinos acquire effective masses
(like index of refraction) via forward scattering
on particles that carry weak charge.**

Consider neutrino-electron charged current forward exchange scattering as a source of neutrino index of refraction, effective mass:



A schematic view of neutrino effective masses

The current-current Lagrangian for neutrino-electron scattering

$$\begin{cases} L_{total} = \overline{\Psi}_\nu (i\not\partial - m_\nu)\Psi_\nu + \overline{\Psi}_e (i\not\partial - m_e)\Psi_e \\ -\frac{G_F}{\sqrt{2}}(\overline{\Psi}_\nu \gamma^\mu (1-\gamma_5)\Psi_\nu)(\overline{\Psi}_e \gamma_\mu (1-\gamma_5)\Psi_e) \end{cases}$$

From this we can define a potential stemming from the electron background:

$$\Big\{ A^\mu \equiv \frac{G_F}{\sqrt{2}}\left[\overline{\Psi}_e \gamma^\mu (1-\gamma_5)\Psi_e\right] = (\varphi, \mathbf{A})$$

The neutrino Lagrangian is then:

$$\Big\{ L_\nu = \overline{\Psi}_\nu \left(i\not\partial - \not{A}(1-\gamma_5) - m_\nu\right)\Psi_\nu$$

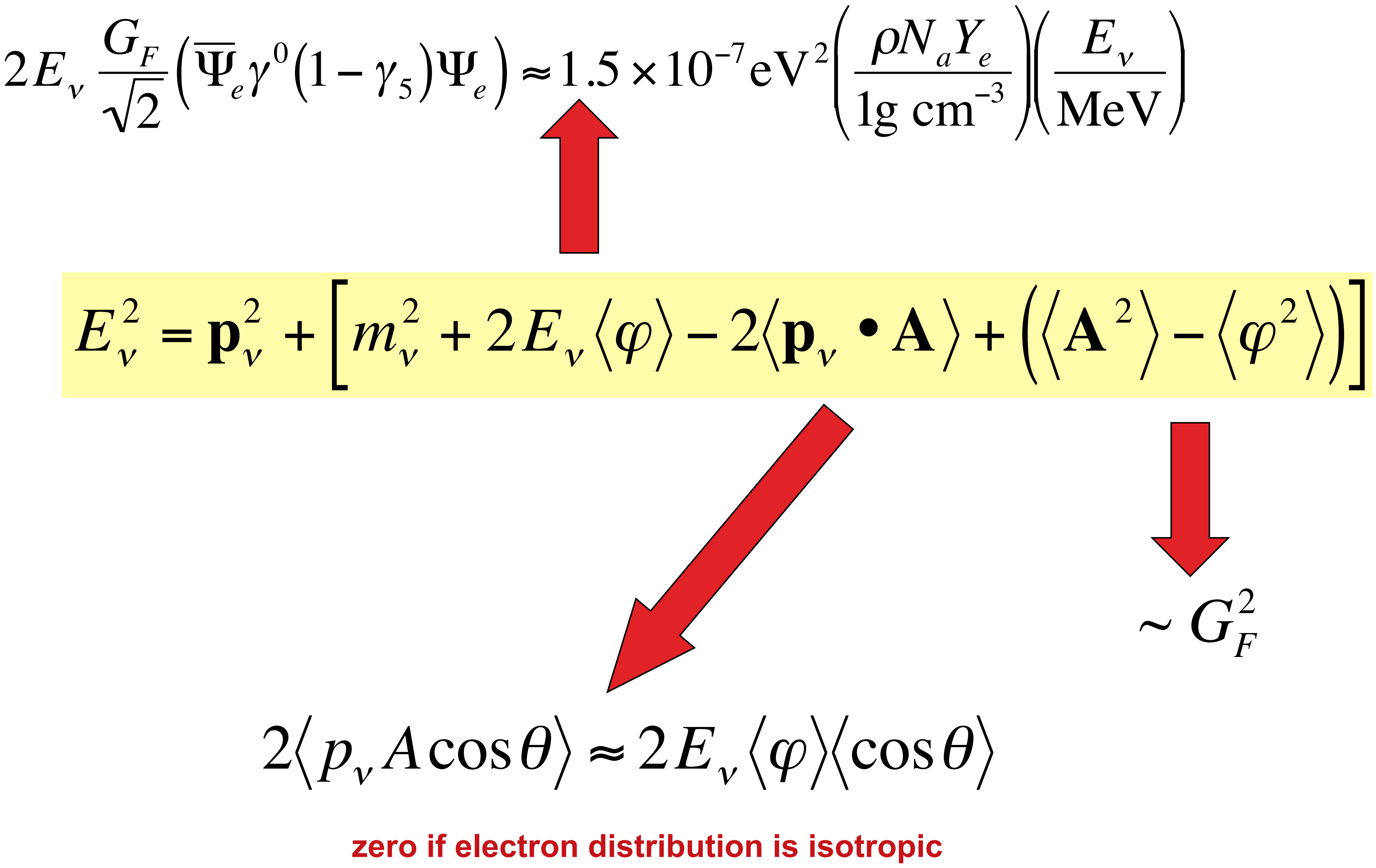
The equation of motion (Dirac equation) corresponding to this is . . .

$$\Big\{ \underbrace{\left(i\frac{\partial}{\partial t} - \varphi\right)\Psi_\nu = \left[\boldsymbol{\alpha} \bullet \left(\tfrac{1}{i}\nabla - \mathbf{A}\right) + \beta m_\nu\right]\Psi_\nu}$$

and the dispersion relation is . . .

$$\left(E_\nu - \varphi\right)^2 = \left(\mathbf{p}_\nu - \mathbf{A}\right)^2 + m_\nu^2$$

$$E_\nu^2 = \mathbf{p}_\nu^2 + \left[m_\nu^2 + 2E_\nu\varphi - 2\mathbf{p}_\nu \bullet \mathbf{A} + \left(\mathbf{A}^2 - \varphi^2\right)\right]$$



$$2E_\nu \frac{G_F}{\sqrt{2}}\left(\overline{\Psi}_e\gamma^0(1-\gamma_5)\Psi_e\right) \approx 1.5\times10^{-7}\,\mathrm{eV}^2\left(\frac{\rho N_a Y_e}{1\mathrm{g\ cm}^{-3}}\right)\left(\frac{E_\nu}{\mathrm{MeV}}\right)$$

$$E_\nu^2 = \mathbf{p}_\nu^2 + \left[m_\nu^2 + 2E_\nu\langle\varphi\rangle - 2\langle\mathbf{p}_\nu \bullet \mathbf{A}\rangle + \left(\langle\mathbf{A}^2\rangle - \langle\varphi^2\rangle\right)\right]$$

$$\sim G_F^2$$

$$2\langle p_\nu A\cos\theta\rangle \approx 2E_\nu\langle\varphi\rangle\langle\cos\theta\rangle$$

zero if electron distribution is isotropic

Consider a simple 2X2 example: the classic
Mikheyev-Smirnov-Wolfenstein (MSW) flavor transformation

vacuum

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

$$|\nu_{\mu,\tau}\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

where θ is an effective 2×2 vacuum mixing angle, and we assume the normal mass hierarchy

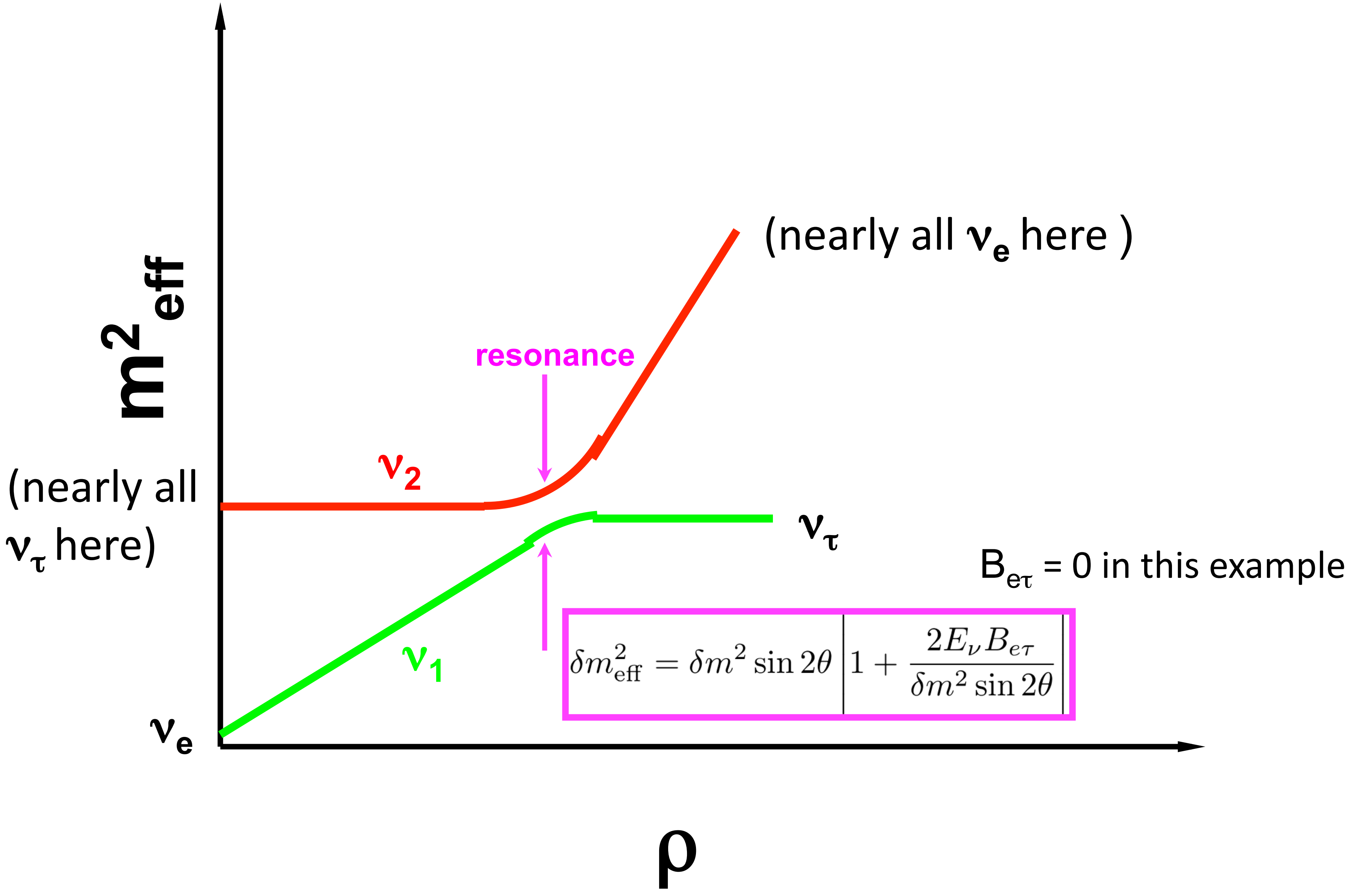
in medium

$$|\nu_e\rangle = \cos\theta\,(t)\;|\nu_1\,(t)\rangle + \sin\theta\,(t)\;|\nu_2\,(t)\rangle$$

$$|\nu_{\mu,\tau}\rangle = -\sin\theta\,(t)\;|\nu_1\,(t)\rangle + \cos\theta\,(t)\;|\nu_2\,(t)\rangle$$

where $\theta\,(t)$, $|\nu_{1,2}\rangle$ are effective in medium mixing angle, mass states, respectively

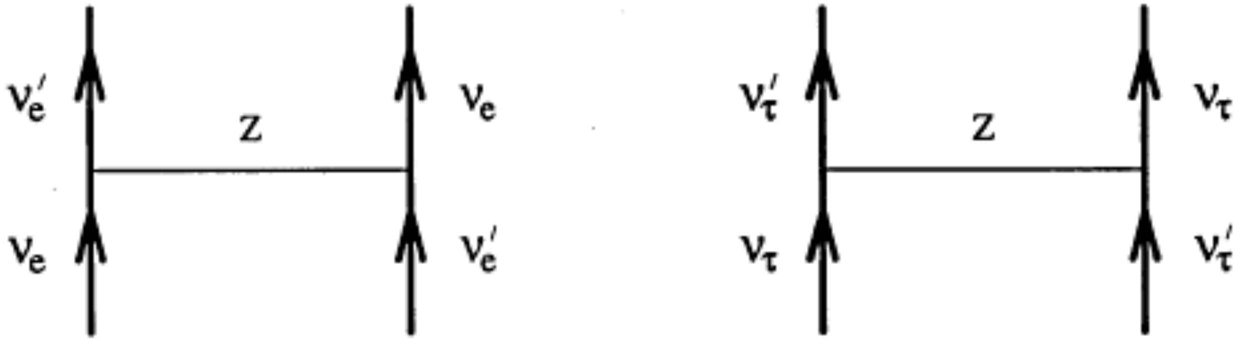
Neutrino Mass Level Crossing (MSW Resonance)



$B_{e\tau}$ = 0 in this example

$$\delta m^2_{\rm eff} = \delta m^2 \sin 2\theta \left| 1 + \frac{2E_\nu B_{e\tau}}{\delta m^2 \sin 2\theta} \right|$$

Analogous potentials arise from neutrino-neutrino neutral current forward exchange scattering, e.g.,



flavor diagonal potential B

flavor off-diagonal potential $B_{e\tau}$

Low-Temperature Neutrino Forward Scattering Potentials

$$H(\nu_s) \approx 0$$

$$H(\nu_e) = \sqrt{2}G_F\left(n_e - \tfrac{1}{2}n_n\right) + \sqrt{2}G_F\left[2\left(n_{\nu_e} - n_{\bar{\nu}_e}\right) + \left(n_{\nu_\mu} - n_{\bar{\nu}_\mu}\right) + \left(n_{\nu_\tau} - n_{\bar{\nu}_\tau}\right)\right]$$

$$H(\nu_\mu) = \sqrt{2}G_F\left(-\tfrac{1}{2}n_n\right) + \sqrt{2}G_F\left[\left(n_{\nu_e} - n_{\bar{\nu}_e}\right) + 2\left(n_{\nu_\mu} - n_{\bar{\nu}_\mu}\right) + \left(n_{\nu_\tau} - n_{\bar{\nu}_\tau}\right)\right]$$

$$H(\nu_\tau) = \sqrt{2}G_F\left(-\tfrac{1}{2}n_n\right) + \sqrt{2}G_F\left[\left(n_{\nu_e} - n_{\bar{\nu}_e}\right) + \left(n_{\nu_\mu} - n_{\bar{\nu}_\mu}\right) + 2\left(n_{\nu_\tau} - n_{\bar{\nu}_\tau}\right)\right]$$

Neutrino Flavor Transformation in Core Collapse Supernovae and Early Universe

Coherent Limit

– neutrino elastic forward scattering

(appropriate for most low density media: the sun, outer envelope of supernovae)

De-Coherent Limit

-neutrino inelastic/direction changing scattering dominated

-(high density: dense supernova environments, early universe)

Quantum Kinetic Equations

A. Vlasenko, G.M.F., V. Cirigliano (2012)

$$i p_\mu \partial^\mu f\,(x,\vec{p}) - [m^2, f\,(x,\vec{p})] - p_\mu [\Sigma_V^\mu(x), f\,(x,\vec{p})] = I_{\rm col}(f,\bar{f})$$

$$i p_\mu \partial^\mu \bar{f}\,(x,\vec{p}) - [m^2, \bar{f}\,(x,\vec{p})] - p_\mu [\Sigma_V^\mu(x), \bar{f}\,(x,\vec{p})] = \bar{I}_{\rm col}(f,\bar{f})$$

Schroedinger-like

@ low density where
neutrinos propagate coherently

Boltzmann equation

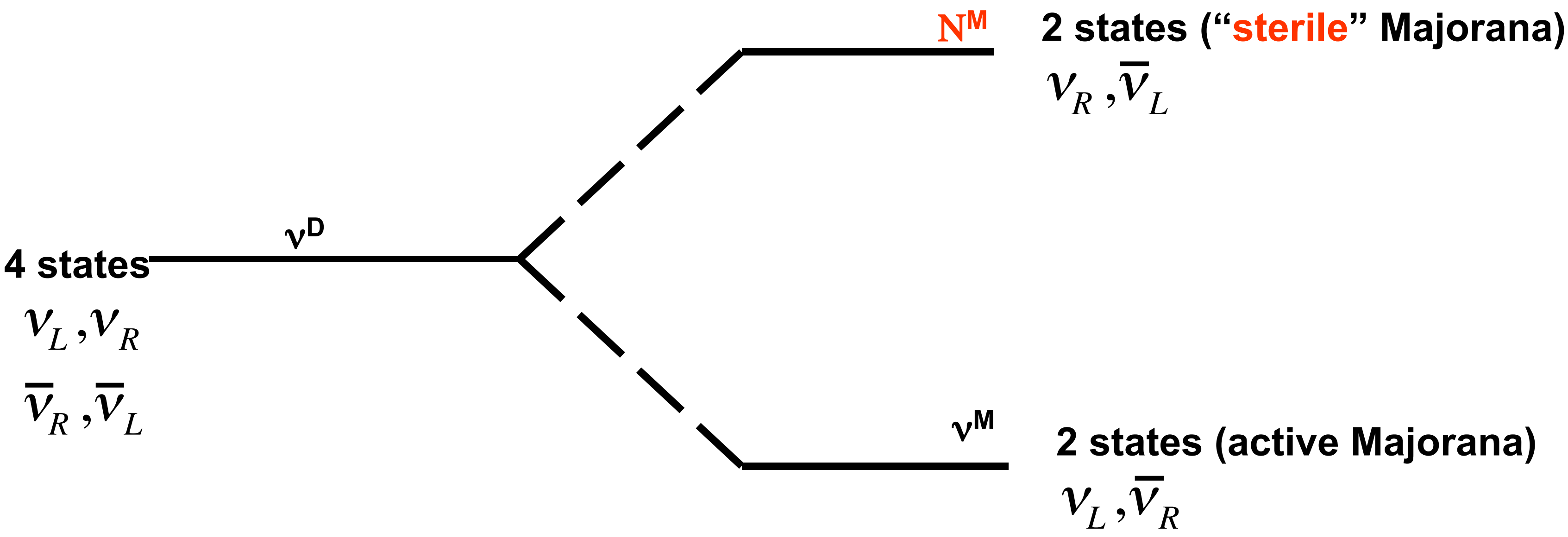
@ high density where
inelastic scattering dominates

see Alexey Vlasenko's talk here

Why Are Neutrinos So Light?

Dirac Neutrinos $\nu \neq \overline{\nu}$ $\nu + \overline{\nu} = 4$ **states**

Majorana Neutrinos $\nu = \overline{\nu}$ $\nu + \overline{\nu} = 2$ **states**



4 states ν_L, ν_R $\overline{\nu}_R, \overline{\nu}_L$

ν^D

N^M **2 states ("sterile" Majorana)** $\nu_R, \overline{\nu}_L$

ν^M **2 states (active Majorana)** $\nu_L, \overline{\nu}_R$

See-Saw Relation for the Product of Neutrino Masses: (m_N)(m_ν) ~ (Really Big Mass Scale)^2

↑ **Unification Scale?**

Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra & Senjanovic

(after a slide by Boris Kayser)

Experiment tells us that neutrinos have mass.

This fact begs the question:

Are there other neutrinos, perhaps with higher masses?

If there are, the Z^0 width measurement implies that these neutrinos must have interaction strengths which are *SMALLER THAN THE WEAK INTERACTION* !!!

“Sterile Neutrinos.” ?????

(not really *sterile* because of vacuum mixing with active neutrinos)

Three “hints” for light sterile neutrinos?

mini-BooNE neutrino oscillation experiment at FNAL

$$\nu_\mu \to \; \nu_s \to \nu_e \quad \text{appearance with } \delta m^2 \sim 1\,\mathrm{eV}^2$$

neutrino reactor anomaly:

$$\bar{\nu}_e \text{ deficit from } \bar{\nu}_e \to \bar{\nu}_s \text{ (???) -- a disappearance experiment}$$

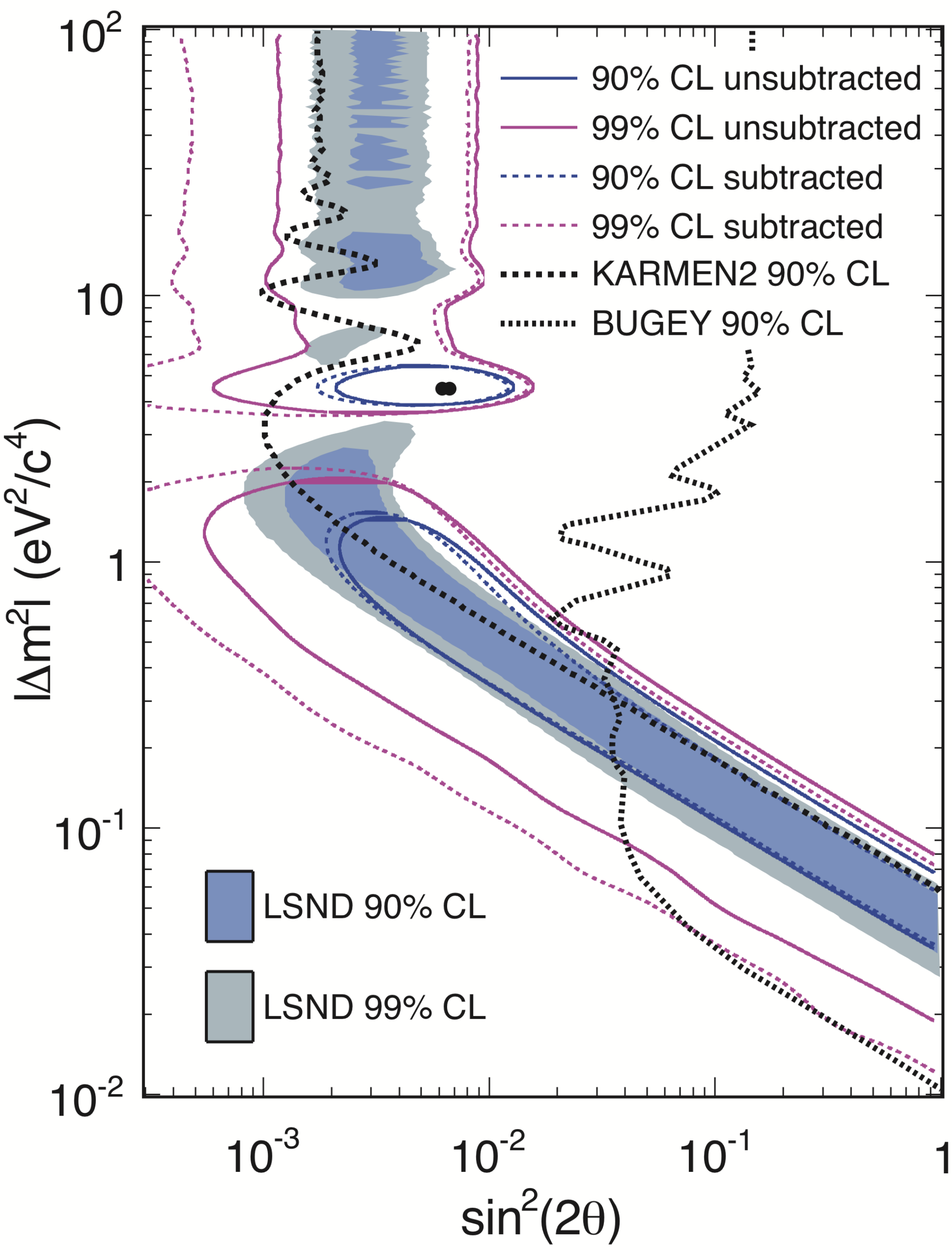
Extra radiation at photon-decoupling (N_{eff})

– Cosmic Microwave Background observations

MiniBooNE Oscillation Fit

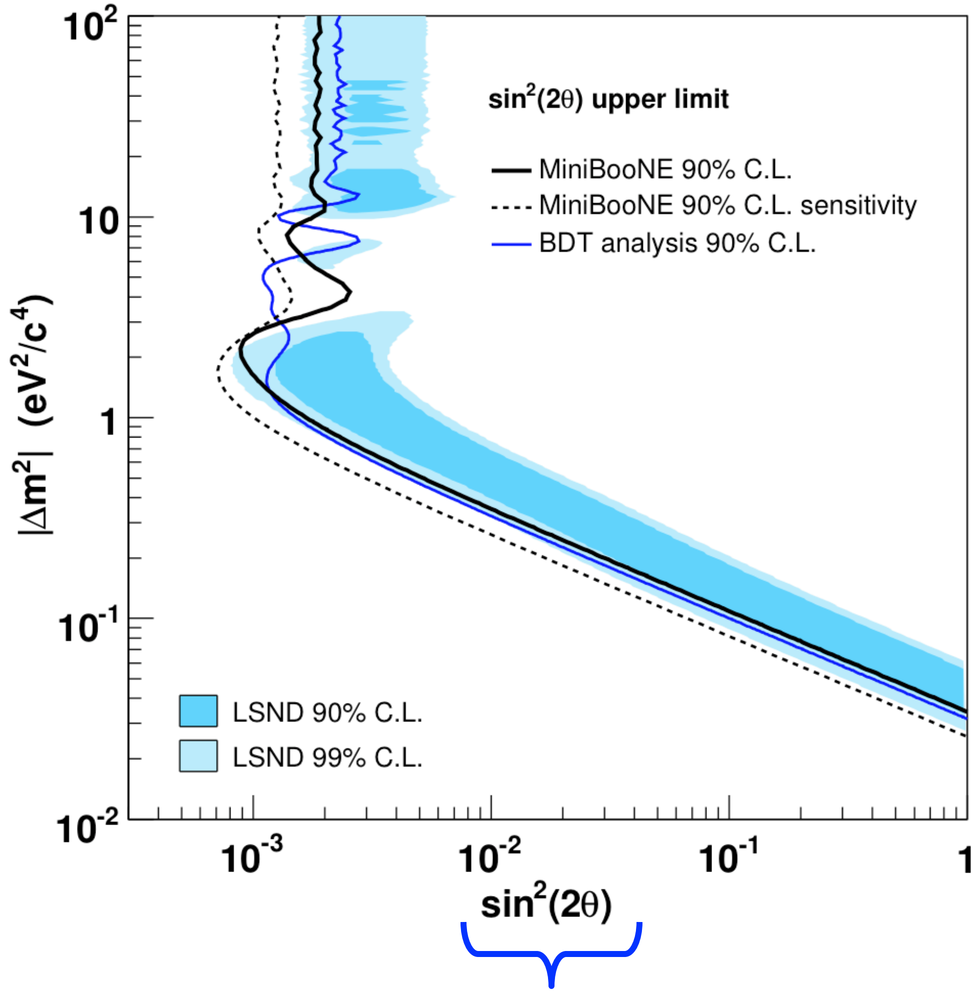
E>200 MeV

$\bar{\nu}_\mu$->$\bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed



W. Louis 2011

MiniBooNE



Consistent with the LSND signal.

At the very least it is a constraint on active-sterile mixing. As we will see, it does not eliminate much of the astrophysically interesting parameter space.

Why?

Watch out! This refers to an effective 2X2 vacuum mixing angle satisfying (for, *e.g.*, "3+1")

$$\sin^2 2\theta \approx 4|U_{e4}|^2|U_{\mu 4}|^2$$

$$\nu_\mu \longrightarrow \nu_s \longrightarrow \nu_e$$

But for astrophysics we want , *e.g.*, just

$$\nu_e \rightarrow \nu_s \quad \& \quad |U_{e4}|^2$$

“Sterile” neutrinos are *not sterile* by virtue of their vacuum mixing with active neutrinos

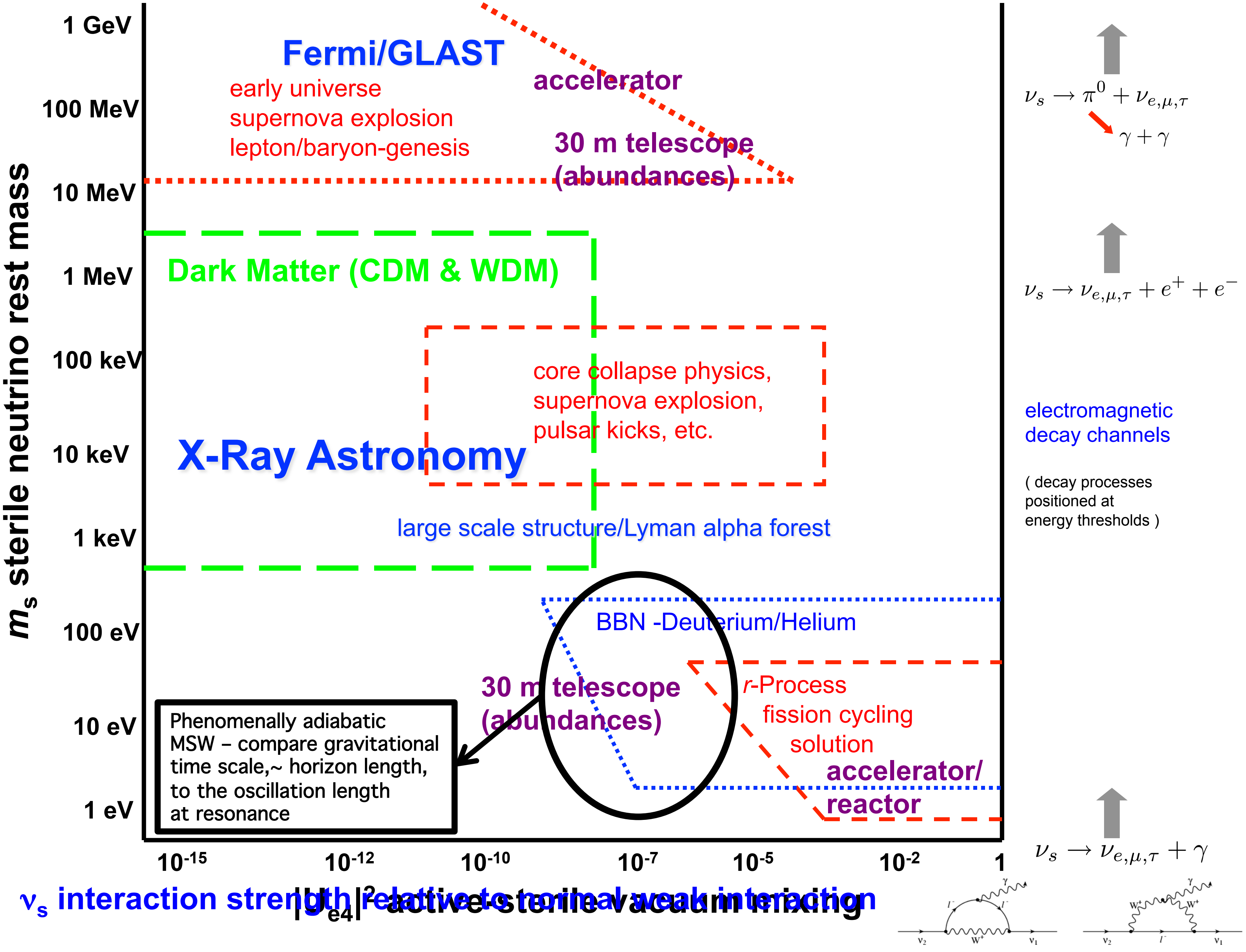
$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$$\sin^2 2\theta \left\{ \right.$$

Gives effective interaction strength of the sterile neutrino relative to the standard ***Weak Interaction***

It is by virtue of these tiny interactions that sterile neutrinos can be produced in the early universe or in supernovae


1 GeV
100 MeV
10 MeV
1 MeV
100 keV
10 keV
1 keV
100 eV
10 eV
1 eV
m_s sterile neutrino rest mass
Fermi/GLAST
early universe
supernova explosion
lepton/baryon-genesis
accelerator
30 m telescope
(abundances)
Dark Matter (CDM & WDM)
core collapse physics,
supernova explosion,
pulsar kicks, etc.
X-Ray Astronomy
large scale structure/Lyman alpha forest
BBN -Deuterium/Helium
30 m telescope
(abundances)
r-Process
fission cycling
solution
accelerator/
reactor
Phenomenally adiabatic
MSW – compare gravitational
time scale,~ horizon length,
to the oscillation length
at resonance
10^{-15}
10^{-12}
10^{-10}
10^{-7}
10^{-5}
10^{-2}
1
$|U_{e4}|^2$ active-sterile vacuum mixing
ν_s interaction strength relative to normal weak interaction
$\nu_s \to \pi^0 + \nu_{e,\mu,\tau}$
$\gamma + \gamma$
$\nu_s \to \nu_{e,\mu,\tau} + e^+ + e^-$
electromagnetic
decay channels
(decay processes
positioned at
energy thresholds)
$\nu_s \to \nu_{e,\mu,\tau} + \gamma$
γ
l^-
W^+
ν_2
ν_1
W^+
W^+
γ
ν_2
l^-
ν_1