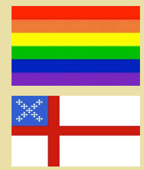
Lectures I : Neutrino Theory Basics

M.J. Ramsey-Musolf

U Mass Amherst



AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

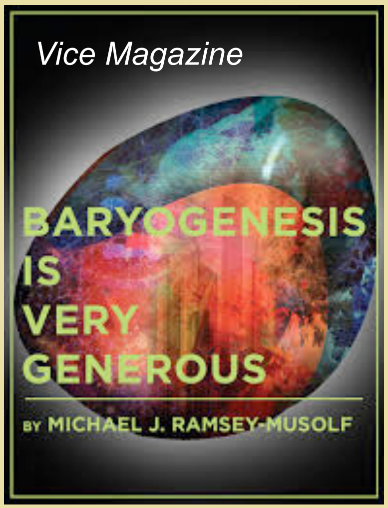
University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

NNPSS, Wright Laboratory
Yale 6/18-29/18

About MJRM

Theoretical Physics



- *Why does the Universe contain more matter than antimatter ?*
- *What are the laws of nature beyond those of the Standard Model & General Relativity ?*
- *How do quantum field theories work ?*

My pronouns: he/him/his

Fundamental Symmetries & Neutrinos

EDM searches: *BSM CPV, Origin of Matter*	*$0\nu\beta\beta$ decay searches:* *Nature of neutrino, Lepton number violation, Origin of Matter*
Electron & muon prop's & interactions: *SM Precision Tests, BSM "diagnostic" probes*	*Radioactive decays & other tests* *SM Precision Tests, BSM "diagnostic" probes*

Fundamental Symmetries & Neutrinos

EDM searches: *BSM CPV, Origin of Matter* *Lecture III*	*$0\nu\beta\beta$ decay searches:* *Nature of neutrino, Lepton number violation, Origin of Matter* *Lectures I & II*
Electron & muon prop's & interactions: *SM Precision Tests, BSM "diagnostic" probes*	*Radioactive decays & other tests* *SM Precision Tests, BSM "diagnostic" probes*

Lecture I Goals

- *Review the basic theoretical formulation of neutrino oscillation phenomenology*
- *Review some of the open questions in neutrino physics*
- *Provide a simple overview of classes of neutrino mass models with example illustrations*
- *Invite questions !*

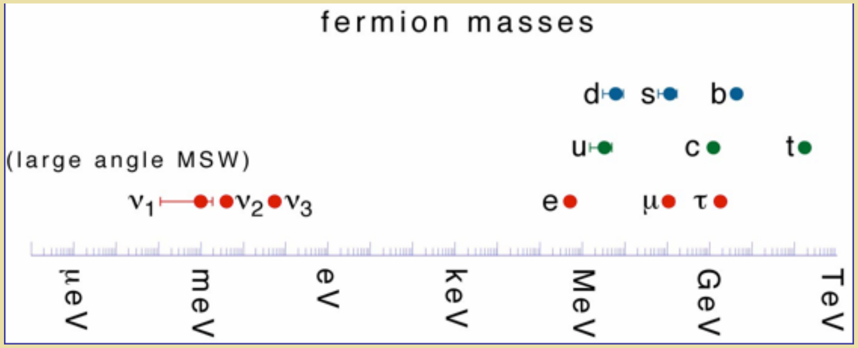
Lecture I Outline

I. *Overview*
II. *Neutrino oscillations imply non-zero m_ν*
III. *Open questions*
IV. *Neutrino Mass Models*
V. *Discussion questions*

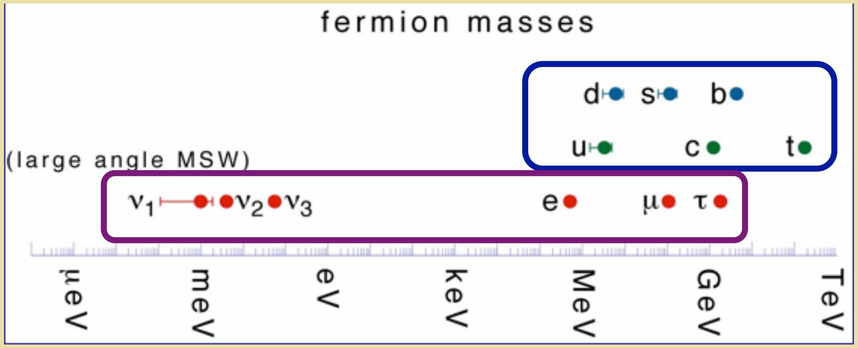
I. Overview

Theoretical complement to D. Parno's excellent experimental overview

Neutrino Masses



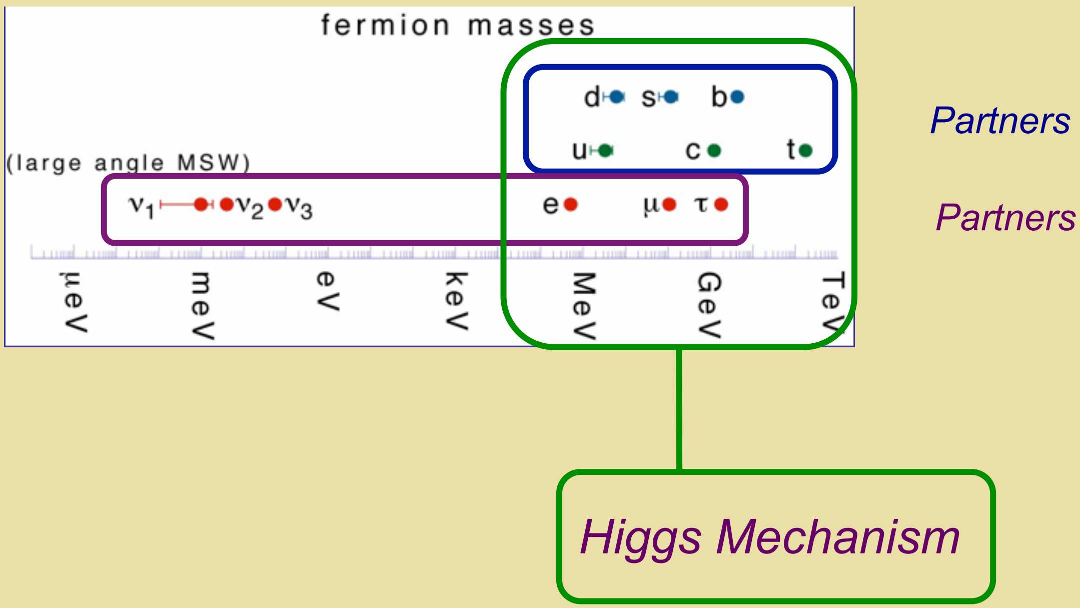
Neutrino Masses



Partners

Partners

Neutrino Masses



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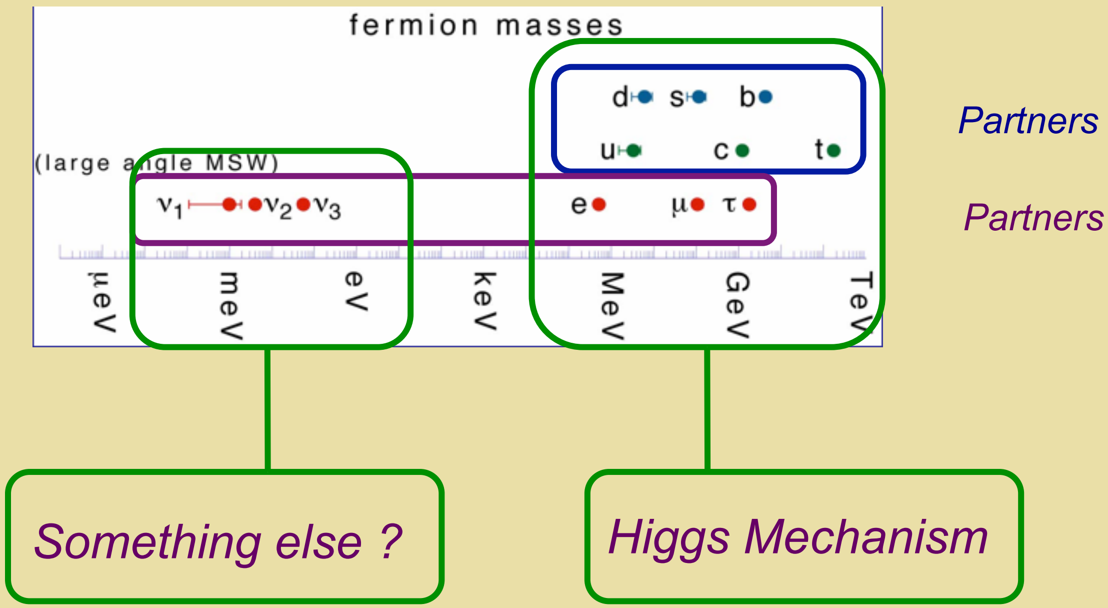
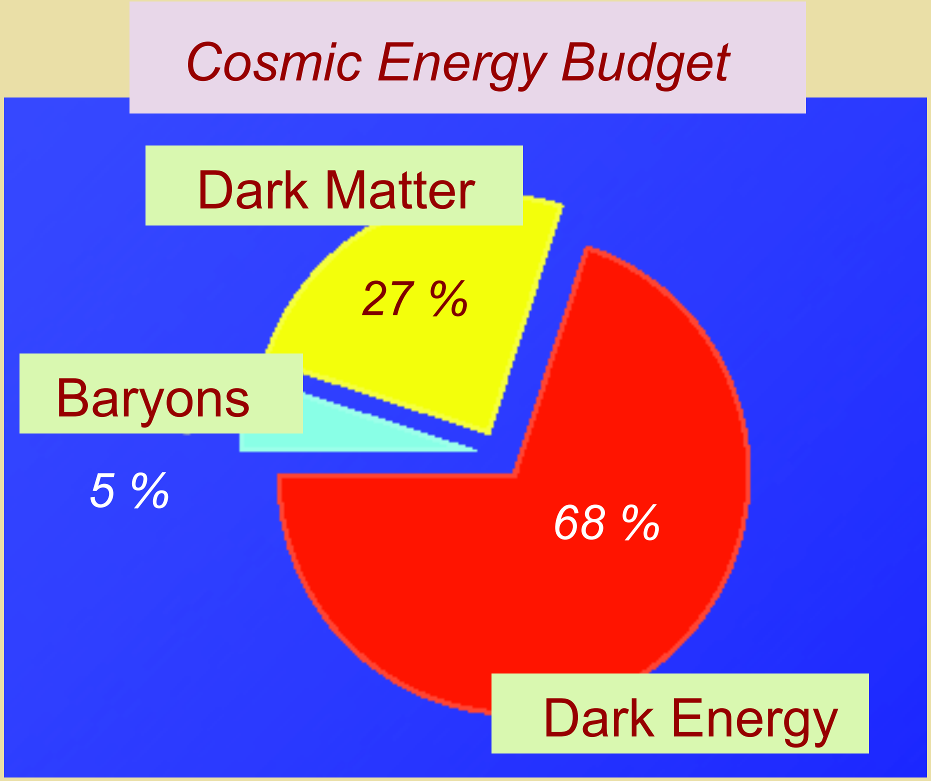


The Origin of Matter



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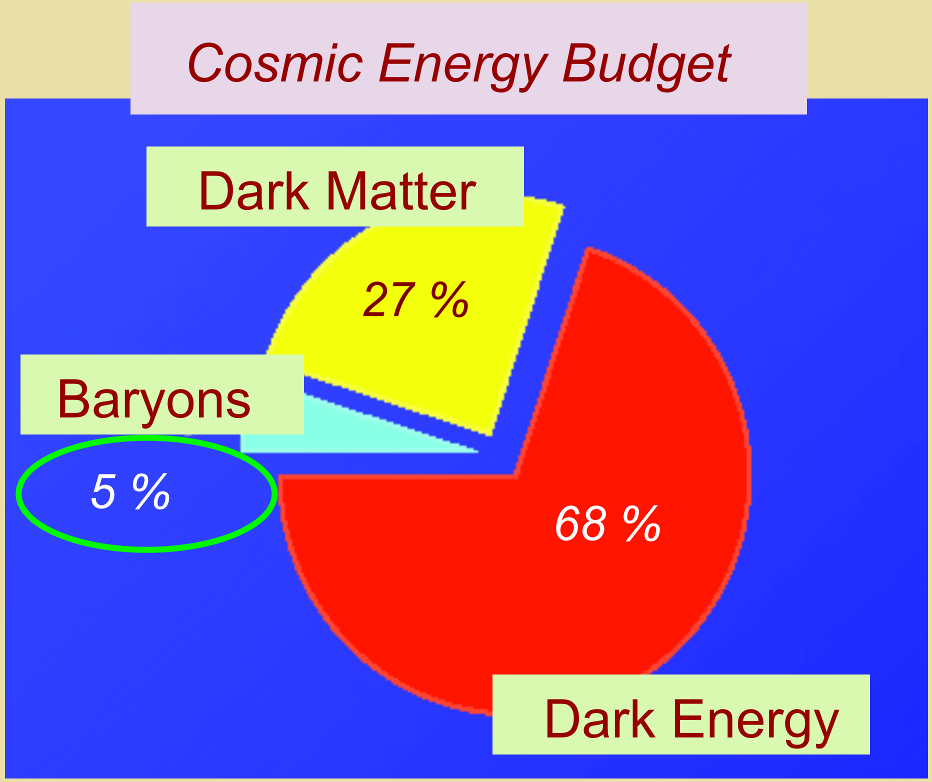

Ingredients for Baryogenesis

- *B violation (sphalerons)*
- *C & CP violation*
- *Out-of-equilibrium or CPT violation*

Ingredients for Baryogenesis

	Standard Model	BSM
• B violation (sphalerons)	✔	✔
• C & CP violation	✖	✔
• Out-of-equilibrium or CPT violation	✖	✔

Ingredients for Baryogenesis

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	BSM
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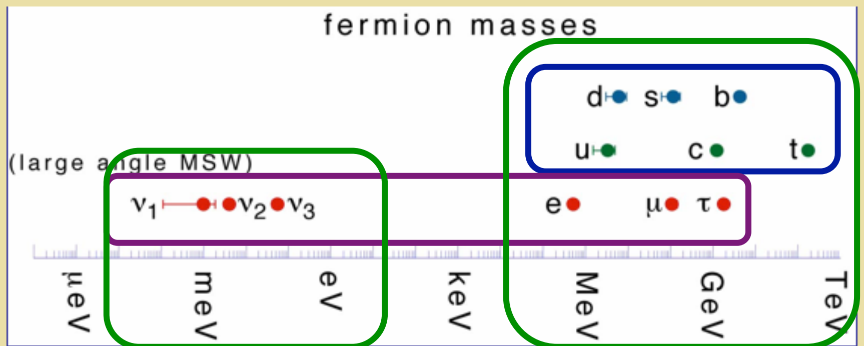
Fermion Masses & Baryon Asymmetry



Partners

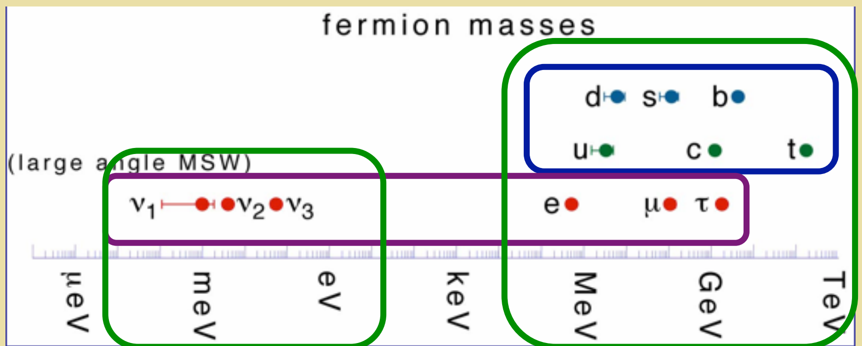
Partners

Something else ?

Higgs Mechanism

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

Fermion Masses & Baryon Asymmetry



Partners

Partners

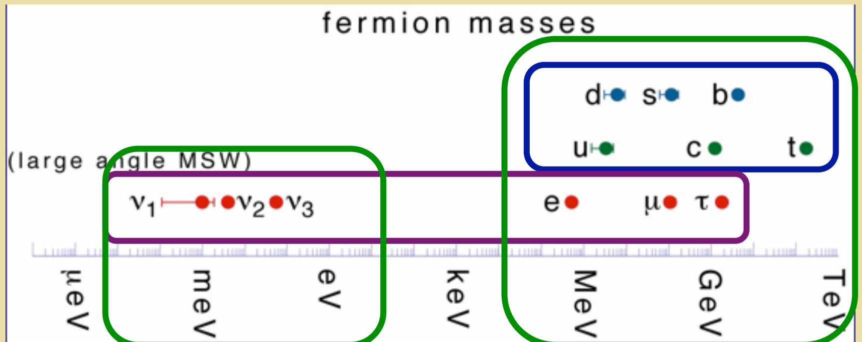
Something else ?

Higgs Mechanism

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

Lecture III

Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

Higgs Mechanism

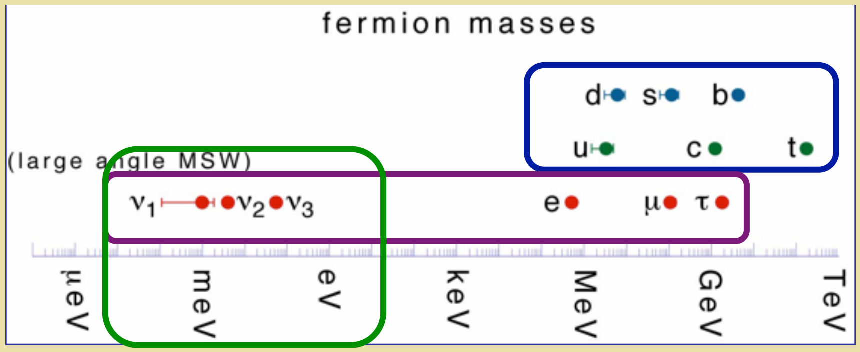
Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

Lecture II

Lecture III

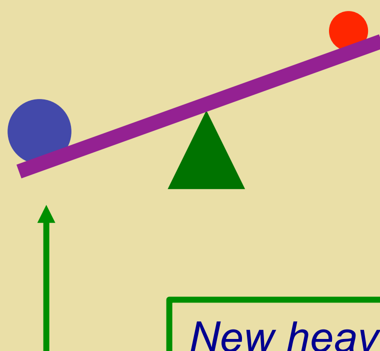
Neutrino Masses



Partners

Partners

"See saw mechanism"



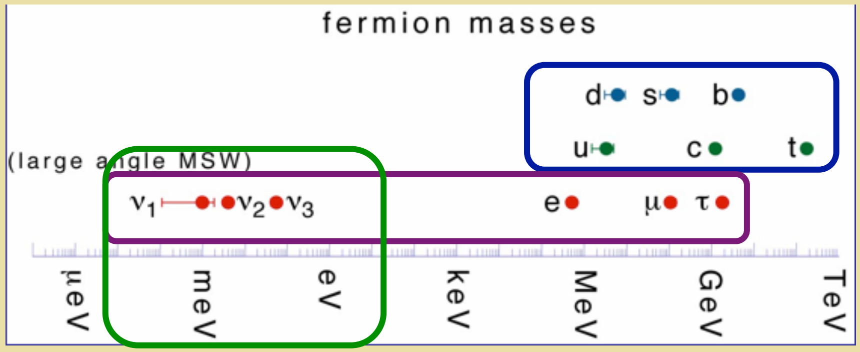
Physical state masses

$$m_1 \approx \frac{m_D^2}{M_N}$$ *~ eV*

$$m_2 \approx M_N$$ *~ 10^{12} – 10^{15} GeV*

New heavy neutrino-like particle = its own anti-particle

Neutrino Masses



Partners

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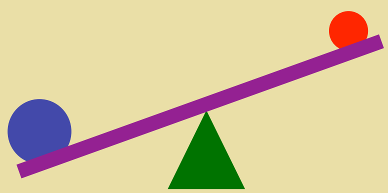

"Leptogenesis"

Heavy neutrino decays in early universe generate baryon asym

New heavy neutrino-like particle = its own anti-particle

II. Neutrino Oscillations Implies $m_\nu \neq 0$

A. Two Level System

Flavor (weak interaction) eigenstates:

$$|\nu_A\rangle \ , |\nu_B\rangle$$

Mass eigenstates:

$$|\nu_1\rangle \ , |\nu_2\rangle$$

Unitary transformation:

$$\begin{pmatrix} |\nu_A\rangle \\ |\nu_B\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

V

A. Two Level System

Initial state, created by weak interaction (e.g. β-decay):

$$|\psi(0)\rangle = |\nu_A\rangle = \cos\theta_{12}\,|\nu_1\rangle + \sin\theta_{12}\,|\nu_2\rangle$$

e.g., $\nu_A = \nu_e$

Time evolution:

$$|\psi(t)\rangle = e^{-iE_1 t}\,\cos\theta_{12}\,|\nu_1\rangle + e^{-iE_2 t}\,\sin\theta_{12}\,|\nu_2\rangle$$

What is probability of being in state $|\nu_A\rangle$ at time t after creation ?

$$\mathcal{P}(\nu_A \to \nu_A)$$

"Survival probability"

A. Two Level System

Survival amplitude:

$$\langle \nu_A | \psi(t) \rangle = e^{-iE_1 t} \cos\theta_{12} \langle \nu_A | \nu_1 \rangle + e^{-iE_2 t} \sin\theta_{12} \langle \nu_A | \nu_2 \rangle$$

$$= e^{-iE_1 t} \left[\cos^2\theta_{12} + \sin^2\theta_{12} e^{-i(E_2 - E_2)t} \right]$$

Survival probability:

$$\mathcal{P}(\nu_A \to \nu_A) = 1 - 4\cos^2\theta_{12}\sin^2\theta_{12}\sin^2\left[(E_2 - E_1)t/2\right]$$

A. Two Level System

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Massive, relativistic neutrinos (why ?)

$$E_2 - E_1 = \sqrt{p^2 + m_2^2} - \sqrt{p^2 + m_1^2} \approx \frac{m_2^2 - m_1^2}{2p} \approx \frac{m_2^2 - m_1^2}{2E} \qquad t = L/v \approx L$$

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$$\begin{aligned} \mathcal{P}(\nu_A \to \nu_A) &= 1 - 4\cos^2\theta_{12}\sin^2\theta_{12}\sin^2\left[\frac{(m_2^2 - m_1^2)L}{4E}\right] \\ &= 1 - \sin^2 2\theta_{12}\sin^2\left[\frac{(m_2^2 - m_1^2)L}{4E}\right] \end{aligned}$$

A. Two Level System

$$\mathcal{P}(\nu_A \to \nu_A) = 1 - 4\cos^2\theta_{12}\sin^2\theta_{12}\sin^2\left[\frac{(m_2^2 - m_1^2)L}{4E}\right]$$

$$= 1 - \sin^2 2\theta_{12}\sin^2\left[\frac{(m_2^2 - m_1^2)L}{4E}\right]$$

- *Two massless neutrinos:* $\theta_{12} = 0$
- *At least one massive neutrino:* $\theta_{12} \neq 0$ *and* $\mathcal{P}(\nu_A \to \nu_A) < 1$
- *Dependence on* Δm^2 *x (L/E)*
- *Transition probability:* $\mathcal{P}(\nu_A \to \nu_B) = 1 - \mathcal{P}(\nu_A \to \nu_A)$

B. Three Light Neutrinos

Lepton mixing:

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}N_R \; + \; \text{h.c.}$$

$$\tilde{H}_a = \epsilon_{ab}H_b^*$$

$$\begin{aligned} \nu^I_{Li} &= (S_\nu)_{ij}\,\nu^{\text{diag}}_{Lj} \\ N^I_{Ri} &= (T_N)_{ij}\,N^{\text{diag}}_{Rj} \\ \ell^I_{Li} &= (S_\ell)_{ij}\,\ell^{\text{diag}}_{Lj} \\ \ell^I_{Ri} &= (T_\ell)_{ij}\,\ell^{\text{diag}}_{Rj} \end{aligned}$$

Pontecorvo-Maki-Nakagawa-Sakata

$$V_{\text{PMNS}} = S_\ell^\dagger S_\nu$$

$$J_\mu^{W-} = \bar{L}\,\gamma_\mu \tau^- V_{\text{PMNS}}\,L$$

B. Three Light Neutrinos

Pontecorvo-Maki-Nakagawa-Sakata

V_{PMNS} =

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$
$$\times \,\mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"Atmospheric" *"Reactor"* *"Solar"*

B. Three Light Neutrinos

Oscillation probability (vacuum)

$$\mathcal{P}(\nu_\alpha \to \nu_\beta) =$$

$$\delta_{\alpha\beta} - 4\sum_{i>j} \Re\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2\left(\Delta m^2_{ij} \frac{L}{4E}\right)$$
$$+ 2\sum_{i>j} \Im\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin\left(\Delta m^2_{ij} \frac{L}{2E}\right)$$

$V_{PMNS} = U$

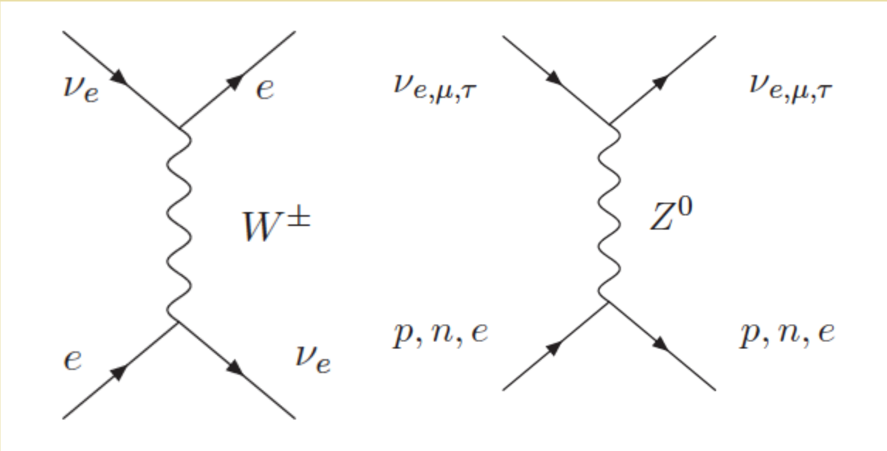
C. Oscillations in Matter

References:

- *P. Hernandez, CERN-2016-005*

Matter Effects: MSW

Forward scattering in matter



CC Hamiltonian

$$\mathcal{H}_{CC} = 2\sqrt{2}G_F\ [\bar{e}\gamma_\mu P_L \nu_e]\ [\bar{\nu}_e \gamma^\mu P_L e]$$

Fierz transf

$$= 2\sqrt{2}G_F\ [\bar{e}\gamma_\mu P_L e]\ [\bar{\nu}_e \gamma^\mu P_L \nu_e]$$

$$\langle \bar{e}\gamma_\mu P_L e\rangle_{\text{unpol. med.}} = \delta_{\mu 0}\frac{N_e}{2} \qquad \langle \mathcal{H}_{\text{CC}} + \mathcal{H}_{\text{NC}}\rangle_{\text{unpol. med.}} = \bar{\nu} V_m \gamma^0 (1-\gamma_5)\nu$$

$$V_m = \begin{pmatrix} \frac{G_F}{\sqrt{2}}\left(N_e - \frac{N_n}{2}\right) & 0 & 0 \\ 0 & \frac{G_F}{\sqrt{2}}\left(-\frac{N_n}{2}\right) & 0 \\ 0 & 0 & \frac{G_F}{\sqrt{2}}\left(-\frac{N_n}{2}\right) \end{pmatrix}$$

Matter Effects: MSW

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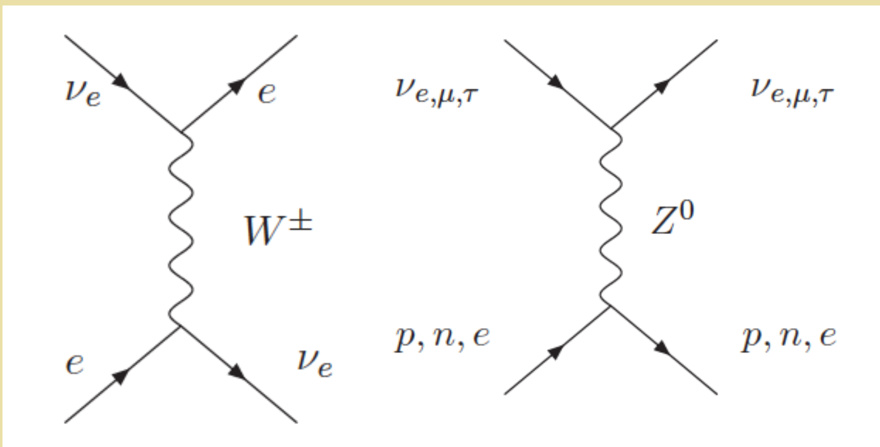

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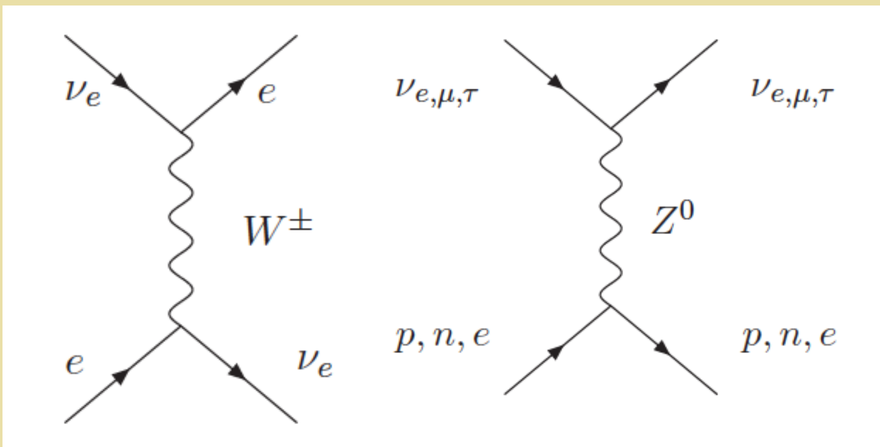
Neutral current contribution

Matter Effects: MSW

Forward scattering in matter



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Q: why no e,p NC contributions ?

Matter Effects: MSW

Forward scattering in matter

$$\langle \mathcal{H}_{\rm CC} + \mathcal{H}_{\rm CC} \rangle_{\text{unpol. med.}} = \bar{\nu} V_m \gamma^0 (1 - \gamma_5) \nu$$

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Dirac Eq: Effective mass = f(E, h)

Helicity

$$\tilde{M}_\nu^2 = M_\nu^2 \pm 4 E V_m$$

Matrices

Δm^2 & mixing angles depend on E & N_e

Matter Effects: MSW

Δm^2 & mixing angles depend on E & N_e

Two-flavor example:

$$\Delta\tilde{m}^2 = \sqrt{\left(\Delta m^2 \cos 2\theta \mp 2\sqrt{2}E\, G_F\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2},$$

$$\sin^2 2\tilde{\theta} = \frac{\left(\Delta m^2 \sin 2\theta\right)^2}{(\Delta\tilde{m}^2)^2}$$

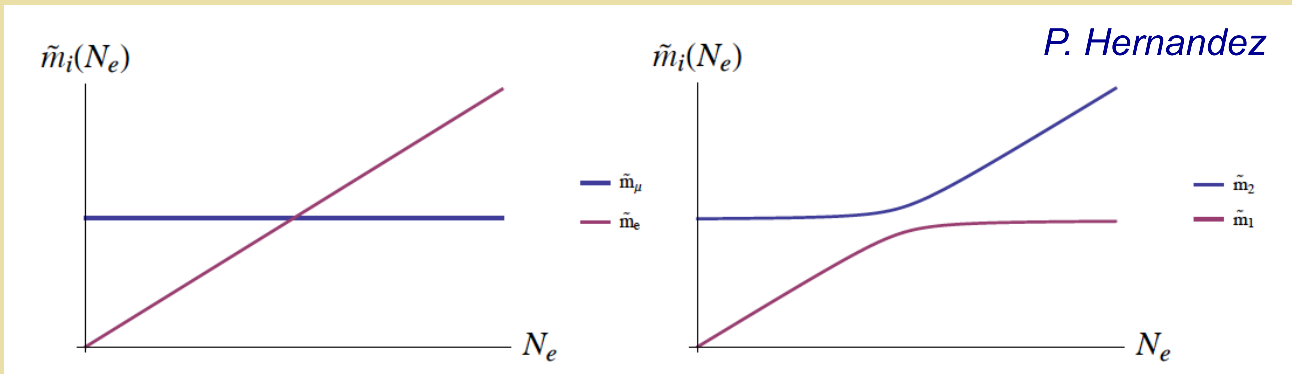
Resonance:

$$\sin^2 2\tilde{\theta} = 1$$

$$\sqrt{2}\, G_F\, N_e \mp \frac{\Delta m^2}{2E} \cos 2\theta = 0$$

Matter Effects: MSW

Resonance: would be level crossing



Matter Effects: MSW

Variable matter density (sun)

Consider adiabatic variation of N_e

$$|\tilde{\nu}_1\rangle = |\nu_e\rangle \cos\tilde{\theta} - |\nu_\mu\rangle \sin\tilde{\theta},$$
$$|\tilde{\nu}_2\rangle = |\nu_e\rangle \sin\tilde{\theta} + |\nu_\mu\rangle \cos\tilde{\theta}.$$

Electron neutrino produced at center of sun

$$2\sqrt{2}G_F N_e(0) E \gg \Delta m^2 \cos 2\theta$$

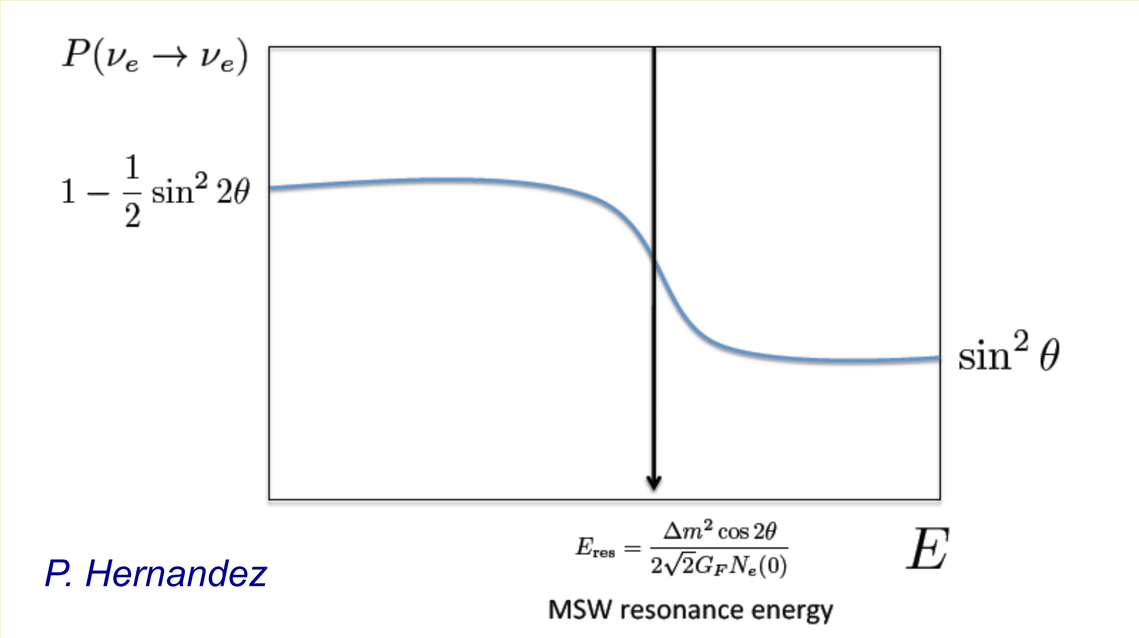
$$\tilde{\theta} \simeq \frac{\pi}{2} \Rightarrow |\nu_e\rangle \simeq |\tilde{\nu}_2\rangle$$

Exiting sun: $N_e = 0$

$$\tilde{\theta} \to \theta_{\text{vac}}$$

$$\nu_e \to \nu_\mu$$

Matter Effects: MSW



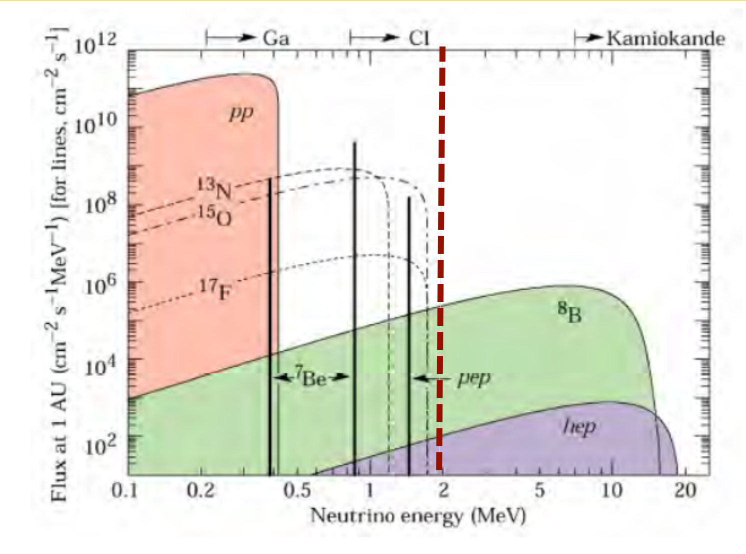
$$\mathcal{P}(\nu_A \to \nu_A) = 1 - \sin^2 2\theta_{12} \sin^2\left[\frac{(m_2^2 - m_1^2)L}{4E}\right]$$

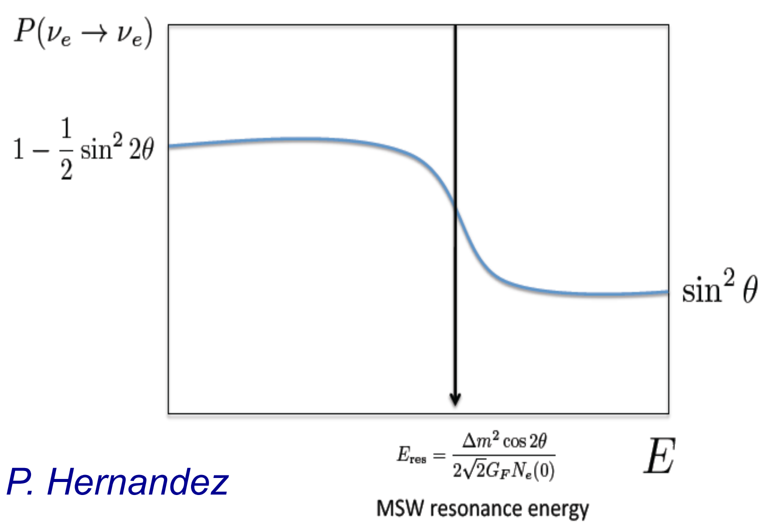
L/E >> 1 : average to 1/2

Neutrino spectrum includes both regions: need to take the "MSW effect" into account

Solar Neutrinos

Standard Solar Model (SSM)



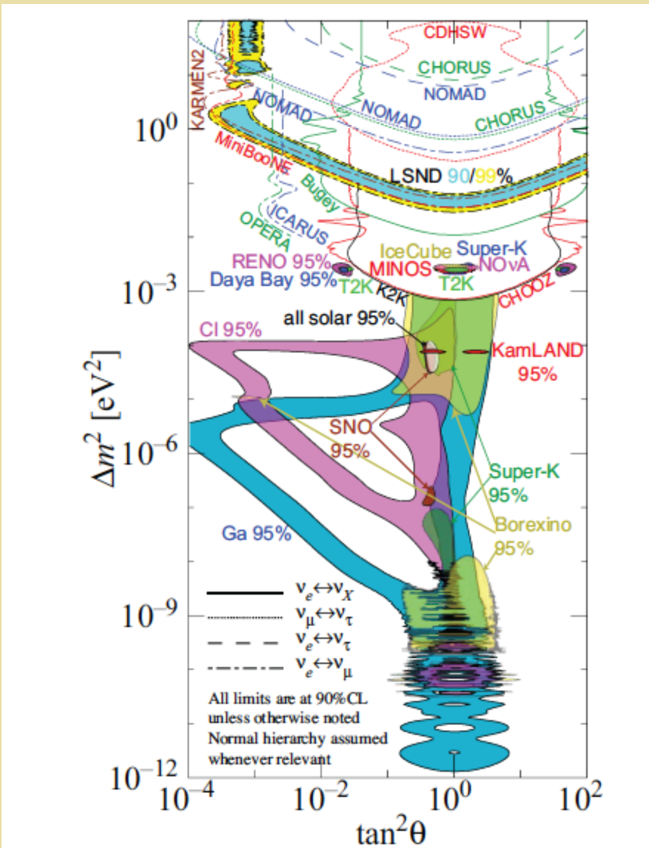


P. Hernandez

- *Analysis of terrestrial spectrum requires convolution of SSM predictions w/ MSW effect*

Oscillation Parameters

Particle Data Group & H. Murayama



Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Oscillation Parameters

See D. Parno slides

https://globalfit.astroparticles.es/

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50±0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

relative 1σ uncertainty

deSalas et al, 1708.01186 (May 2018)

III. Open Questions

- *Majorana or Dirac ?*
- *Mass hierarchy ?*
- *Absolute mass ?*
- *CPV ?*
- *Light sterile neutrinos ?*
- *Neutrino vs. quark mixing ?*
- *Theoretical origin of m_ν*

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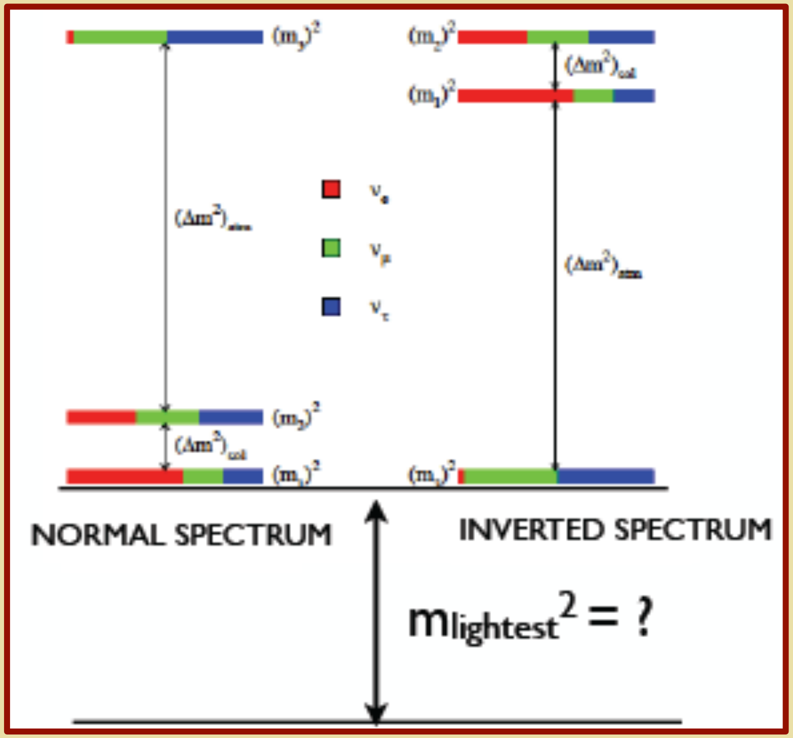
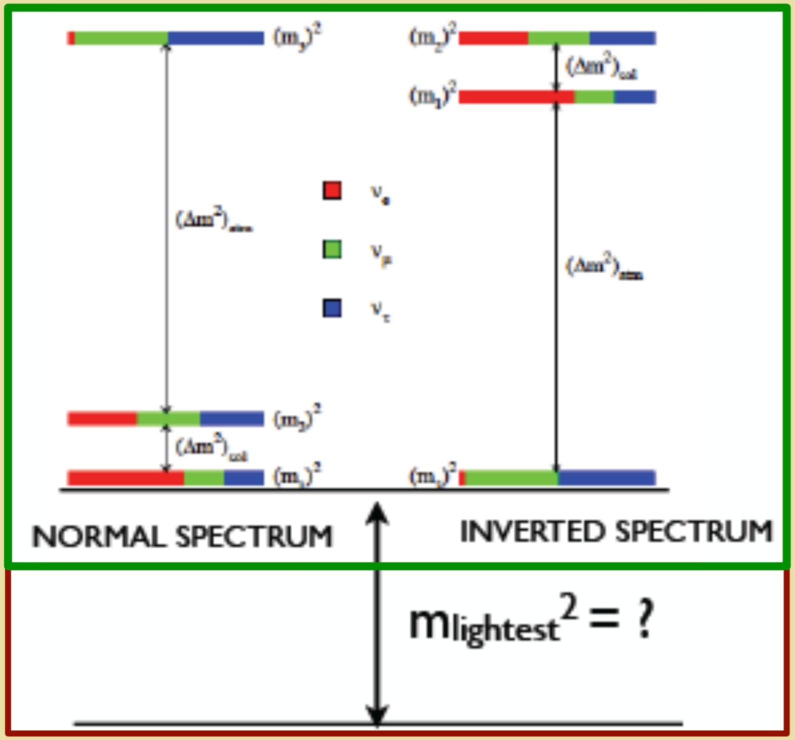
Absolute Mass & Mass Hierarchy

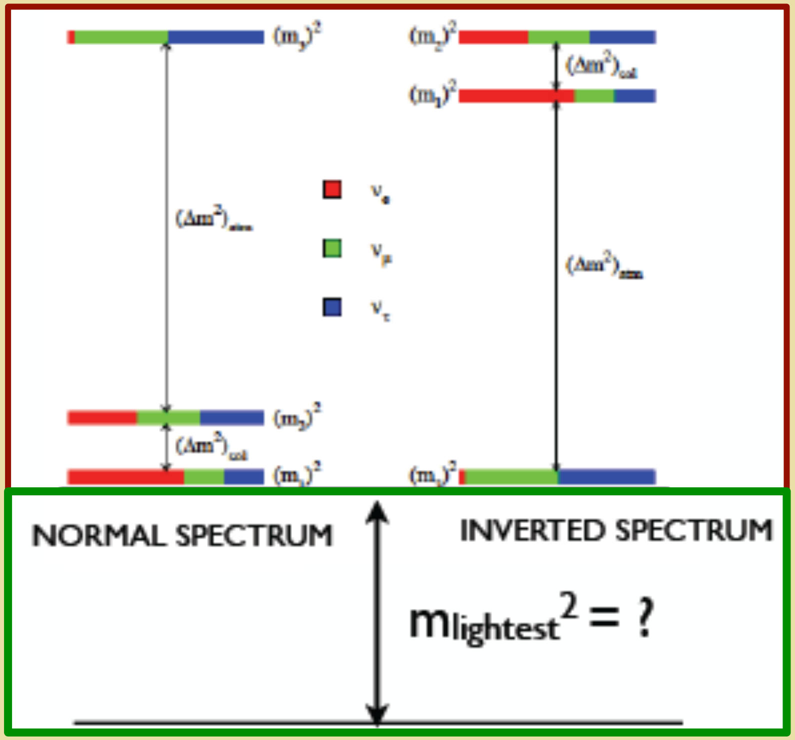


Absolute Mass & Mass Hierarchy



Oscillation Expts

Absolute Mass & Mass Hierarchy

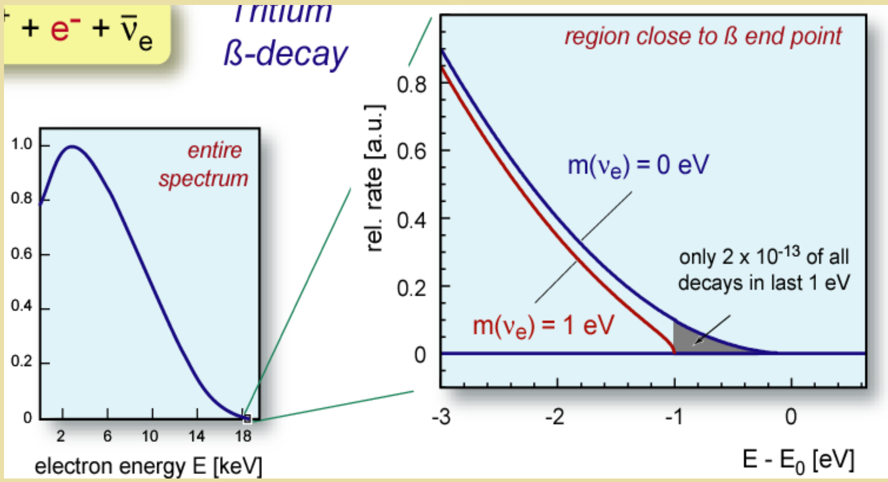


- *^3H β-decay*
- *Cosmology & astrophysics*

Kinematic Neutrino Mass Measurements

$^3H \rightarrow {}^3He \; e^- \; \bar{\nu}$

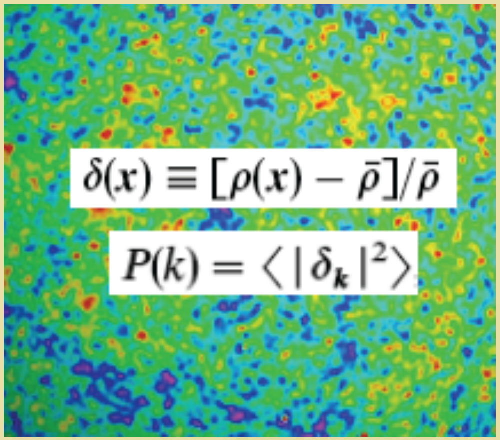
KATRIN

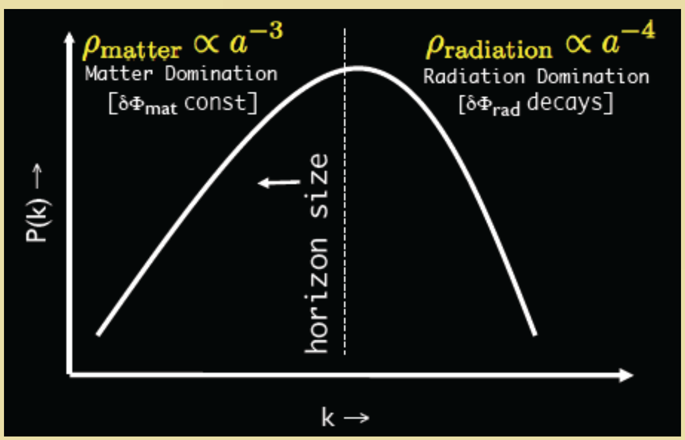


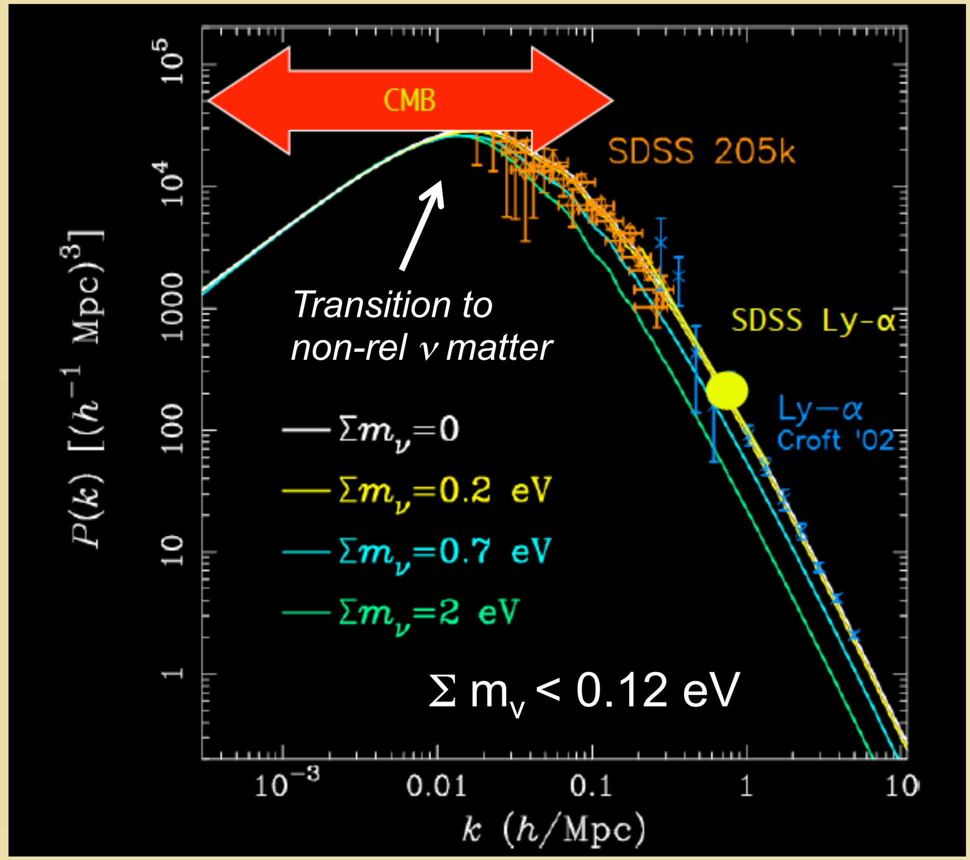
$$\frac{dN}{dp_e} \propto (E_0 - E_e)^2 \left[1 - \frac{m_\nu^2}{(E_0 - E_e)^2} \right]$$

Neutrino Mass & Cosmology

Matter Power Spectrum





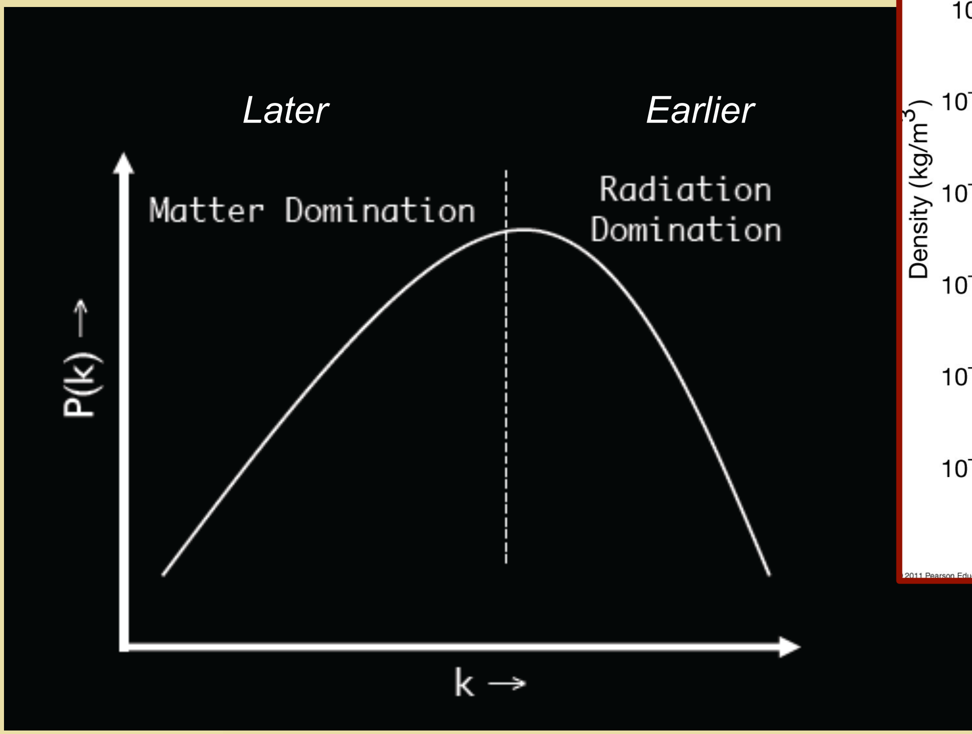


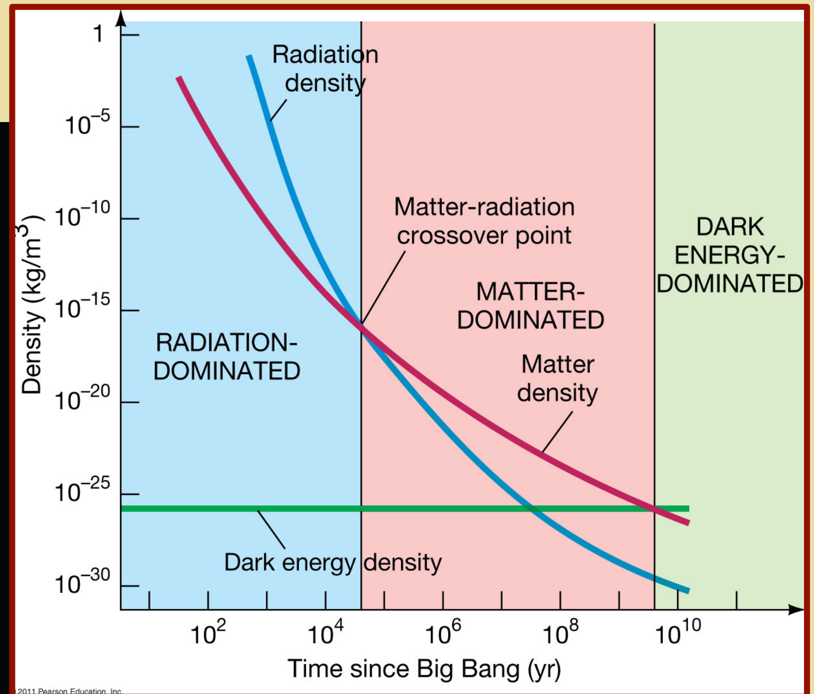
Massive neutrinos suppress power (relative to large scale power) at scales below free streaming scale

K. Abazajian ACFI neutrino mass workshop

Neutrino Mass & Cosmology

Matter Power Spectrum

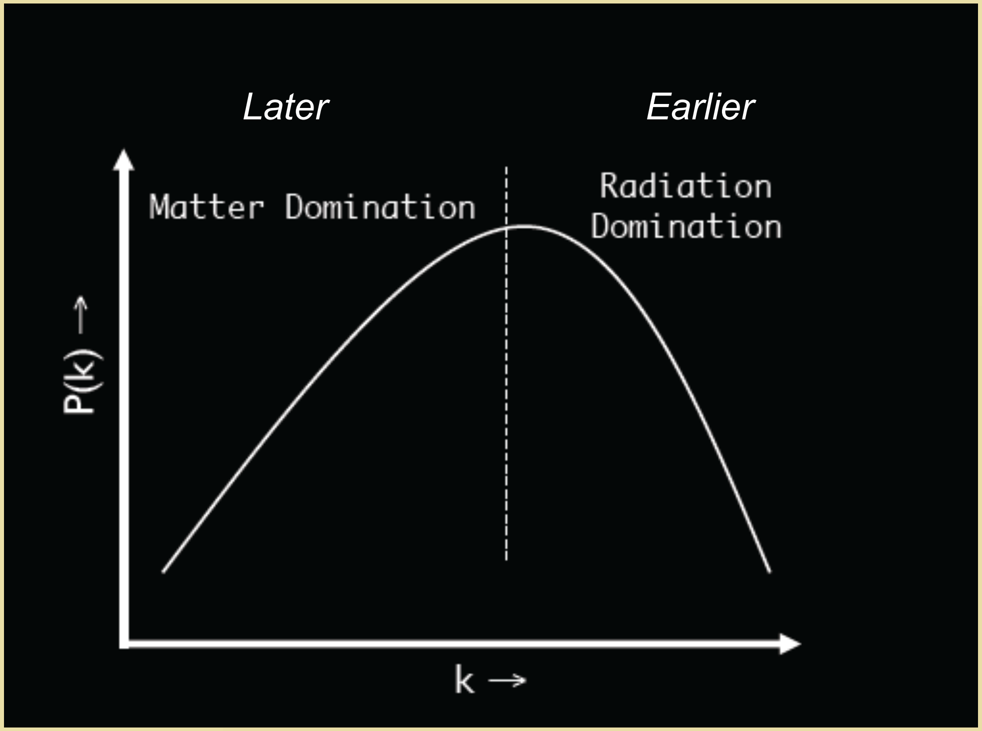




J. Brau, U. Oregon

Neutrino Mass & Cosmology

Matter Power Spectrum



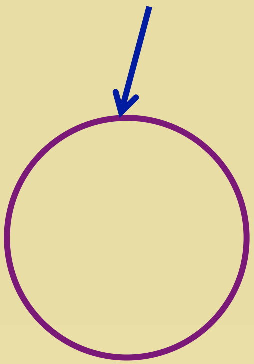
Neutrino Free Streaming

$$\Omega_M = \Omega_\nu + \Omega_{DM} + \Omega_B$$

$$\delta\rho_\nu \longleftrightarrow \delta\rho_{DM}$$

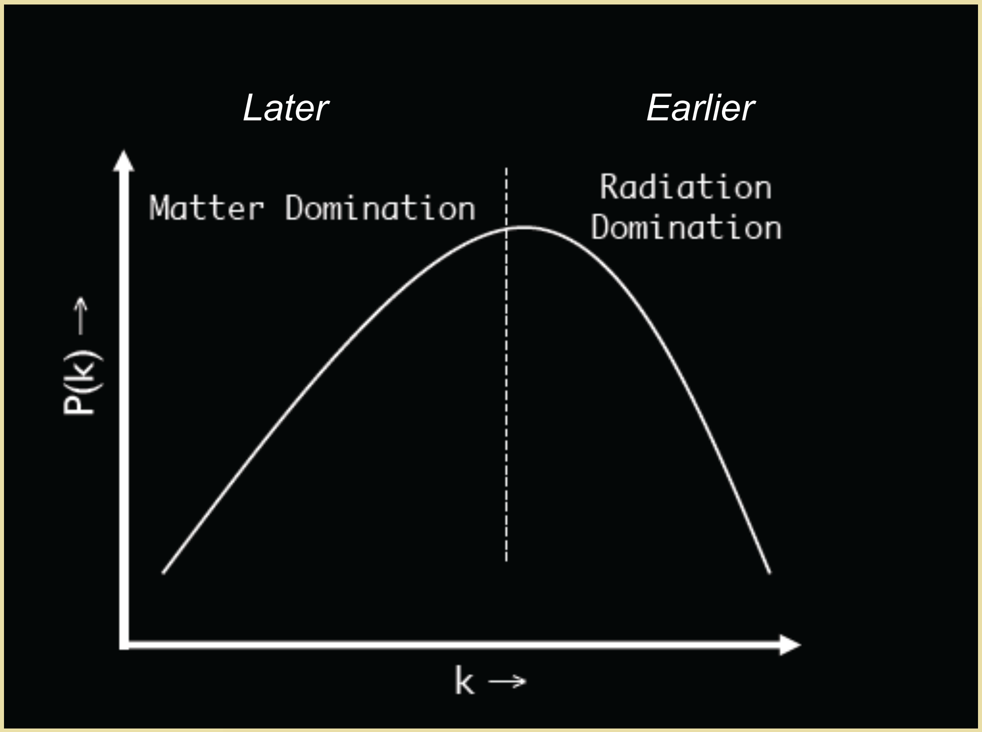
Free Streaming Scale

$$L_{\rm fs} \propto m_\nu^{-1/2}$$



Neutrino Mass & Cosmology

Matter Power Spectrum



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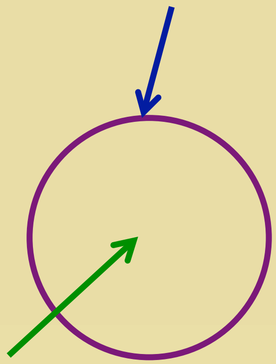
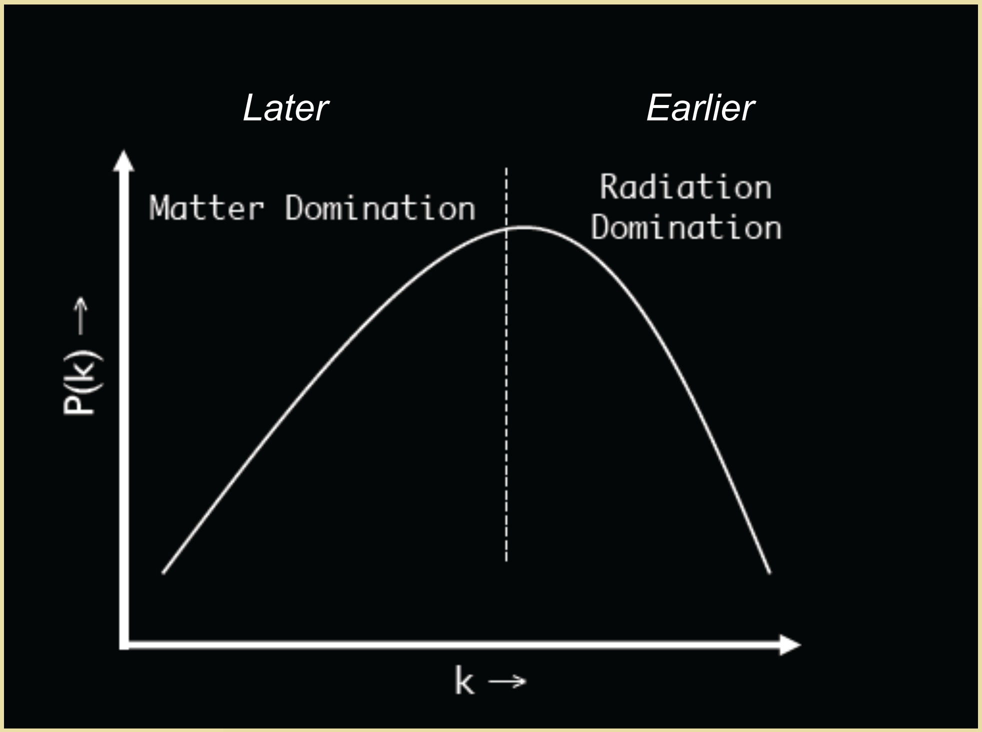


$\delta\rho_\nu$ (power) suppressed
for $L < L_{fs}$

Neutrino Mass & Cosmology

Matter Power Spectrum



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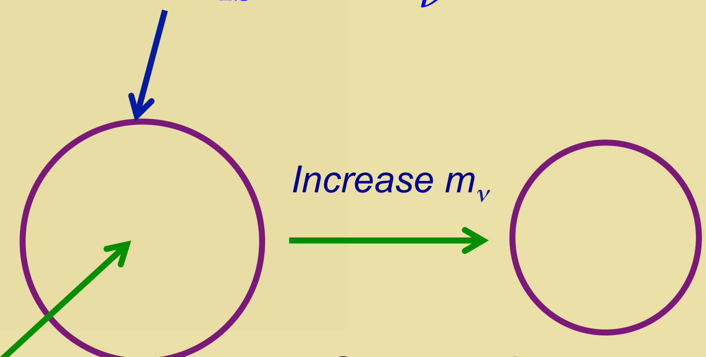


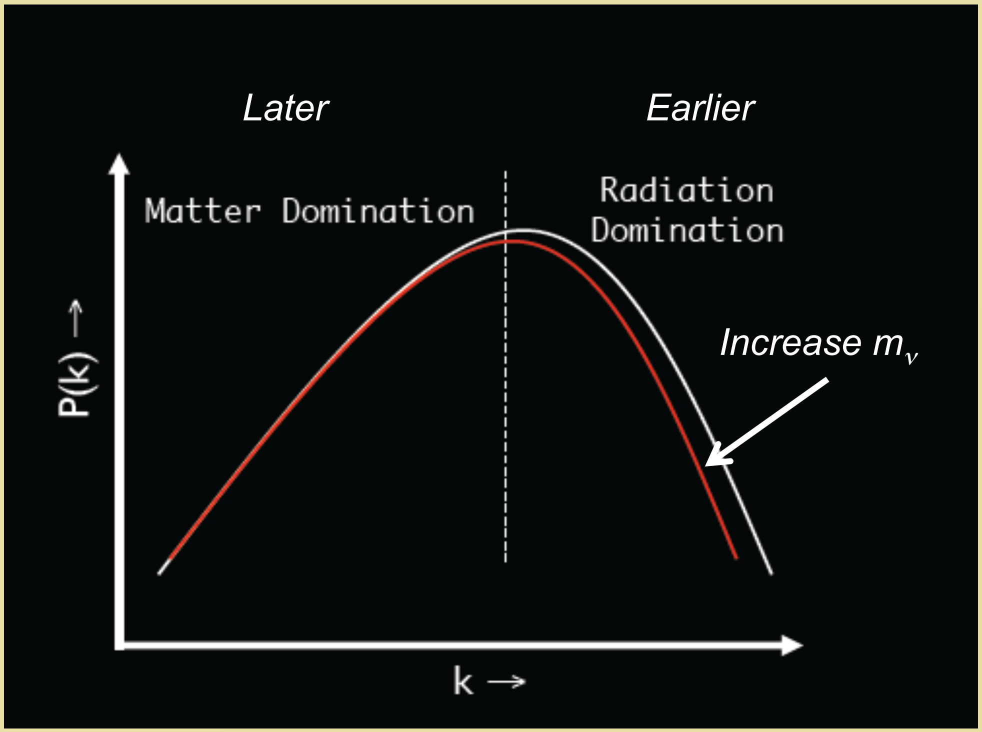
Increase m_ν

$\delta\rho_\nu$ (power) suppressed for $L < L_{fs}$

Suppression moves to smaller scales $\rightarrow$ Larger k

Neutrino Mass & Cosmology

Matter Power Spectrum



$\Sigma\, m_\nu < 0.12$ eV

Palanque-Dalabrouille '15

Neutrino Free Streaming

$$\Omega_M = \Omega_\nu + \Omega_{DM} + \Omega_B$$

$$\delta\rho_\nu \leftrightarrow \delta\rho_{DM}$$

Free Streaming Scale

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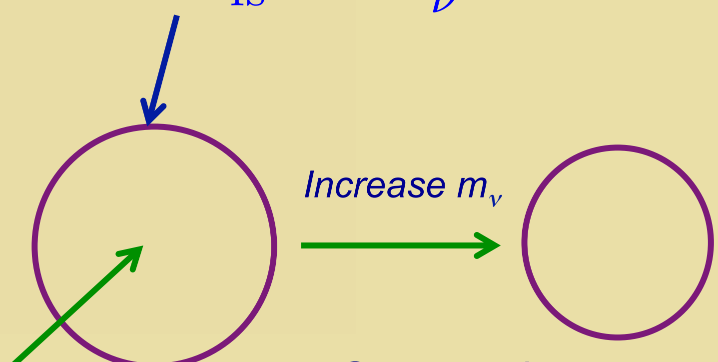
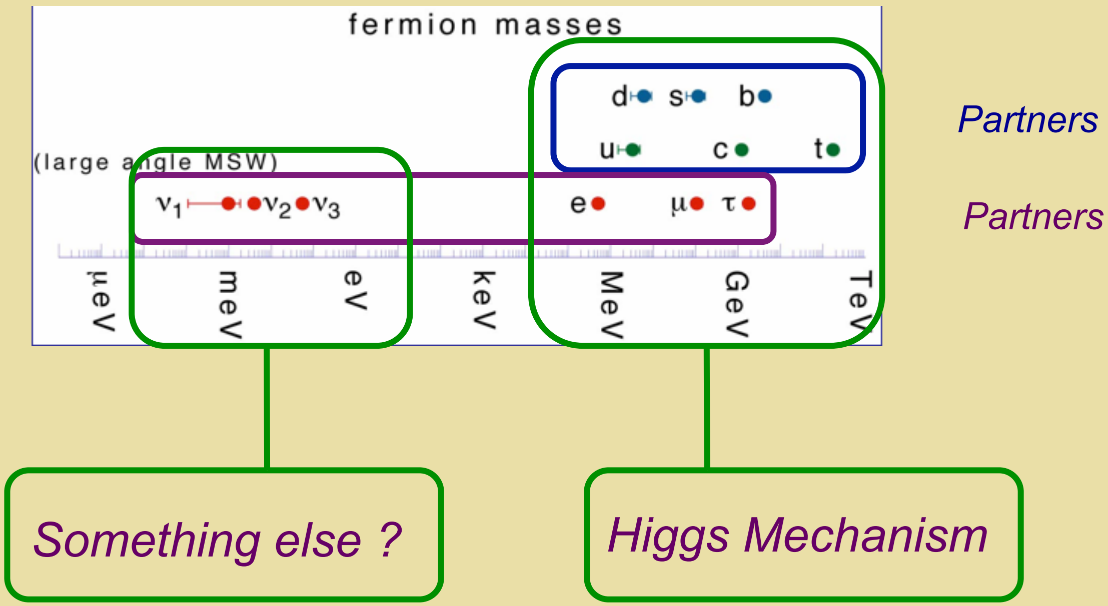


$\delta\rho_\nu$ *(power) suppressed for* $L < L_{fs}$

Suppression moves to smaller scales → Larger k

IV. Neutrino Mass Models



How do we understand the origin of m_ν theoretically ?

IV. Neutrino Mass Models

• *Type I see-saw*	*"νSM", "νMSSM"*
• *Type II see-saw*	*LRSM*
• *Type III see-saw*	*GUTs*
• *Inverse see-saw*	*LRSM*
• *Radiative*	*MSSM*

+ combinations & many other examples

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Mass Term?

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

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Lepton number violating

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+ combinations & many other examples

Type I See-Saw

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

One generation: SM + one N_R

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}N_R \ + \ \text{h.c.} + M_N \bar{N}_R^C N_R$$

⬇

$$\mathcal{L}_{\rm mass} = \begin{pmatrix} \bar{\nu}_L & \bar{N}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

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Lepton number violating

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}N_R \; + \; \text{h.c.} + M_N \bar{N}_R^C N_R$$

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Eigenvalues

$$m_1 \approx \frac{m_D^2}{M_N}$$

$$m_2 \approx M_N$$

Type I See-Saw

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

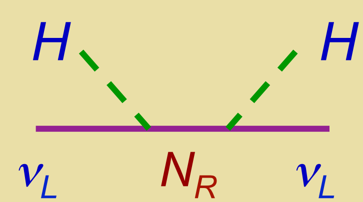
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

Low-energy eff theory

$\Lambda = m_N$



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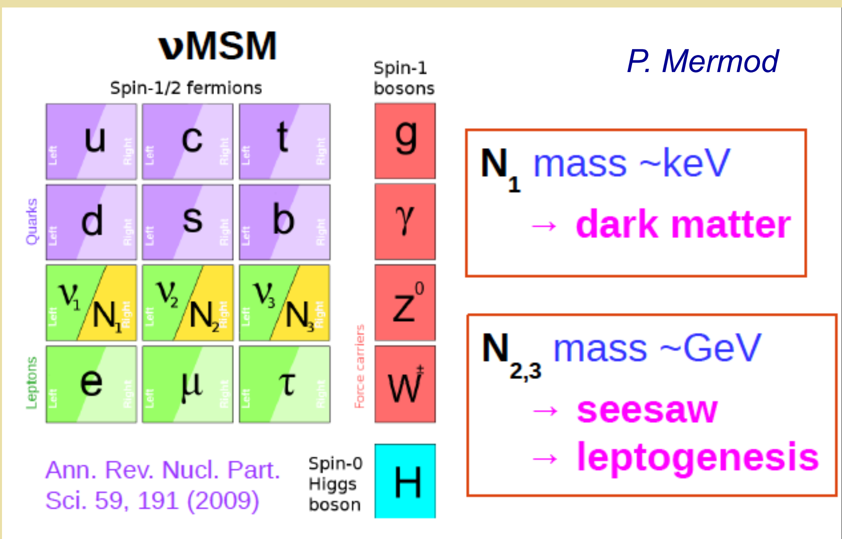
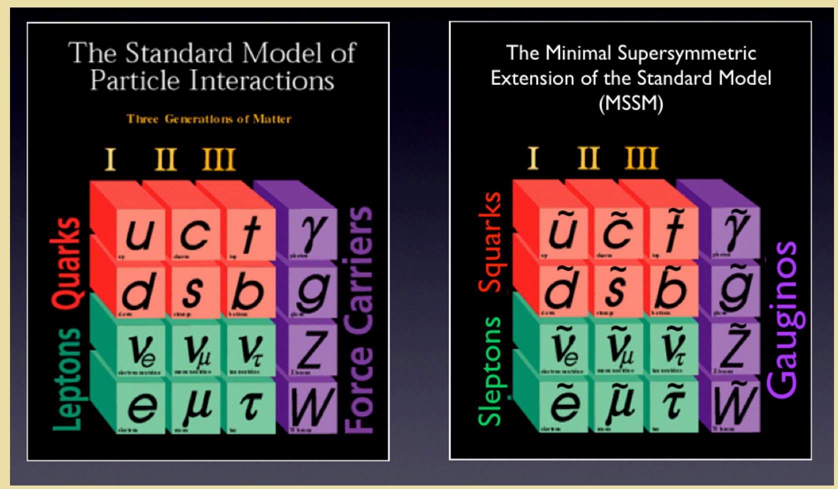
Majorana

"ν MSM"



"ν MSSM"



$$+ \quad \left(N_R, \; \tilde{N}_R\right)$$

Neutrino Mass Models

• Type I see-saw	"νSM", "νMSSM"
• Type II see-saw	LRSM
• Type III see-saw	GUTs
• Inverse see-saw	LRSM
• Radiative	MSSM

+ combinations & many other examples

Type II See-Saw

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

Introduce "Complex Triplet": Δ_L ~ (1, 3, 2)

$$\Delta_L = \begin{pmatrix} \Delta^+\sqrt{2} & \Delta^+ \\ \Delta^0 & -\Delta^+\sqrt{2} \end{pmatrix}$$

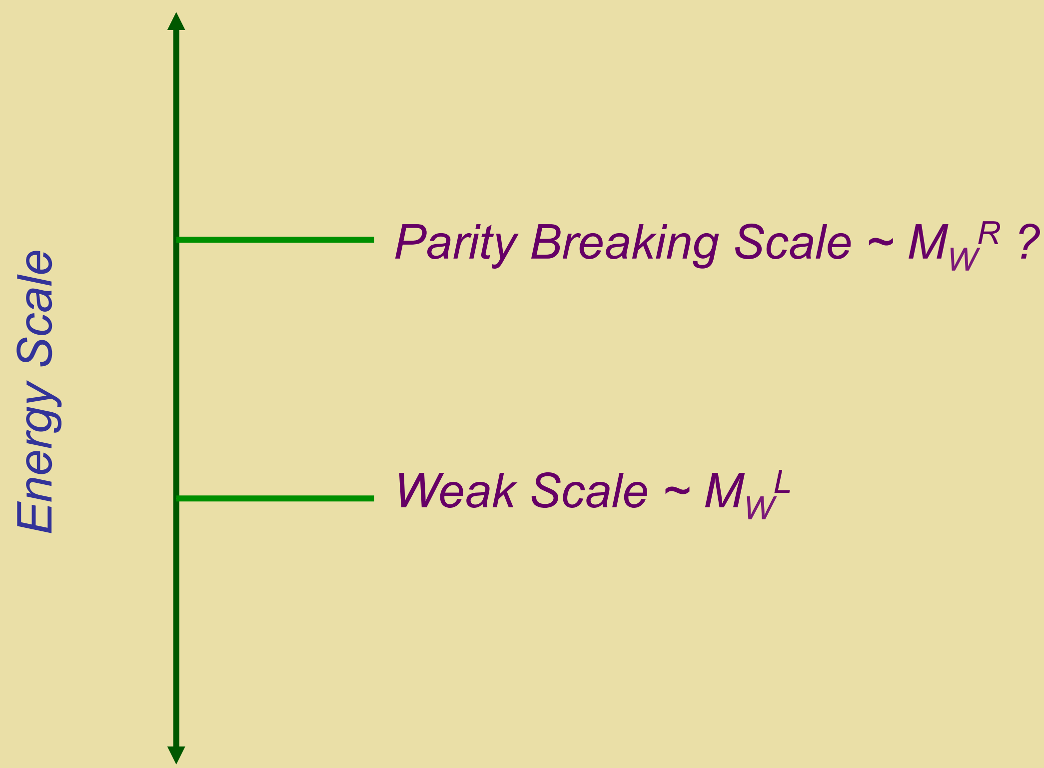
Δ^0 vev $\rightarrow$ Majorana m_ν

$$\mathcal{L} = \frac{g}{2}h_{ij}\left[\bar{L}^{C_i}\varepsilon\Delta_L L^j\right] + \text{h.c.}$$

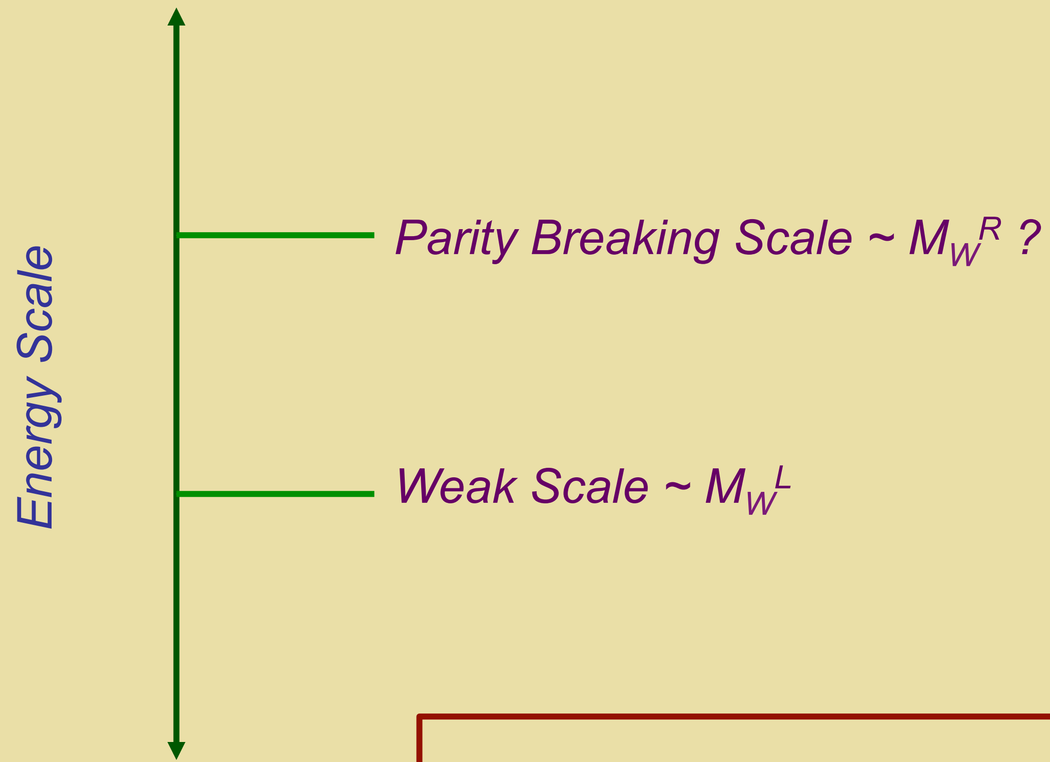
Lepton number violating

Types I & II: Left-Right Symmetric Model

BSM Mass Scale

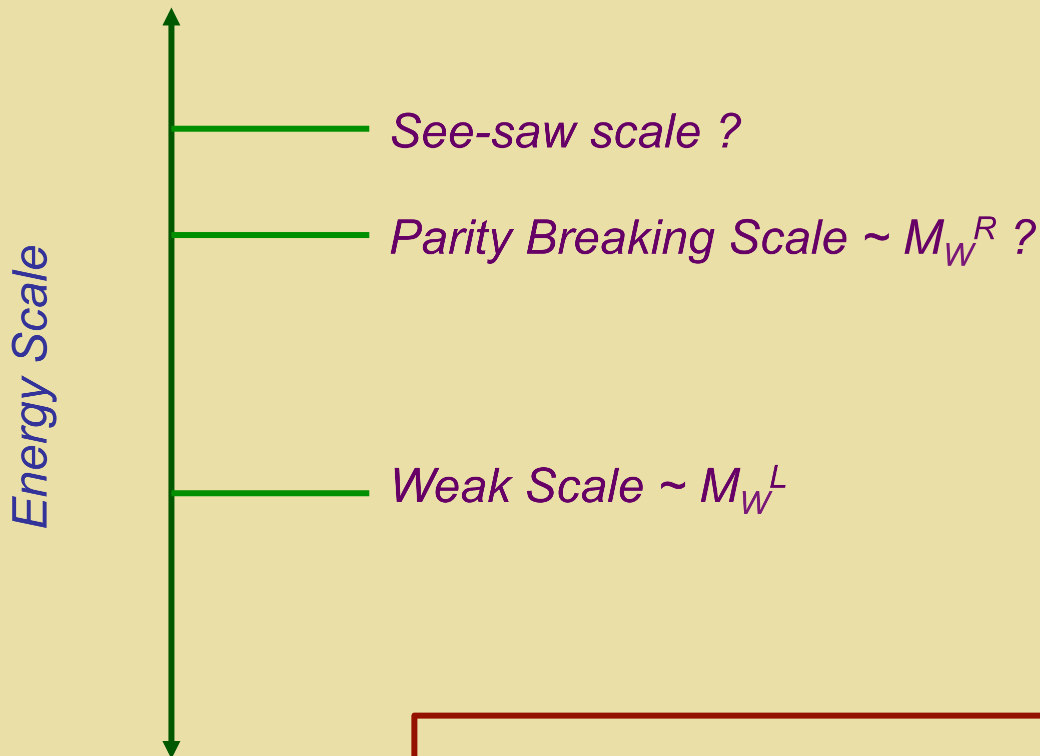


Left-Right Symmetric Model



$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Left-Right Symmetric Model



$$SU(2)_L \text{ x } SU(2)_R \text{ x } U(1)_{B-L}$$

Left-Right Symmetric Model

Gauge boson mass eigenstates

$$W_1^+ = \cos\xi \, W_L^+ + \sin\xi \, e^{-i\alpha} \, W_R^+$$
$$W_2^+ = -\sin\xi \, e^{i\alpha} \, W_L^+ + \cos\xi \, W_R^+$$

CKM Matrices for LH & RH sectors: quarks

$$\begin{aligned} u^I_{Li} &= (S_u)_{ij} \, u^{\rm mass}_{Lj} \\ u^I_{Ri} &= (T_u)_{ij} \, u^{\rm mass}_{Rj} \\ d^I_{Li} &= (S_d)_{ij} \, d^{\rm mass}_{Lj} \\ d^I_{Ri} &= (T_d)_{ij} \, d^{\rm mass}_{Rj} \end{aligned} \quad \longrightarrow \quad \begin{aligned} V^L_{\rm CKM} &= S_u^\dagger S_d \\ V^R_{\rm CKM} &= T_u^\dagger T_d \end{aligned}$$

Left-Right Symmetric Model

Gauge boson mass eigenstates

$$W_1^+ = \cos\xi\, W_L^+ + \sin\xi\, e^{-i\alpha}\, W_R^+$$
$$W_2^+ = -\sin\xi\, e^{i\alpha}\, W_L^+ + \cos\xi\, W_R^+$$

PMNS Matrices for LH & RH sectors: leptons

$$\begin{aligned} \nu^I_{Li} &= (S_\nu)_{ij}\, \nu^{\rm diag}_{Lj} \\ N^I_{Ri} &= (T_N)_{ij}\, N^{\rm diag}_{Rj} \\ \ell^I_{Li} &= (S_\ell)_{ij}\, \ell^{\rm diag}_{Lj} \\ \ell^I_{Ri} &= (T_\ell)_{ij}\, \ell^{\rm diag}_{Rj} \end{aligned}$$

→

$$V^L_{\rm PMNS} = S_\nu^\dagger S_\ell$$

Left-Right Symmetric Model

Two sources of m_ν :

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \text{h.c.}$$

Type I see-saw *Type II see-saw*

$$\mathcal{L}_{\text{mass}} = \begin{pmatrix} \bar{\nu}_L & \bar{N}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix} + m_L \bar{\nu}_L^C \nu_L$$

$$m_N \sim g h_R \langle \Delta_R^0 \rangle$$

$$m_L \sim g h_L \langle \Delta_L^0 \rangle$$

Neutrino Mass Models

- *Type I see-saw* — *"νSM", "νMSSM"*
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+ combinations & many other examples

Type II See-Saw

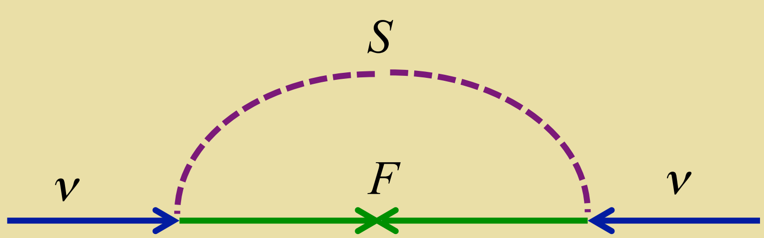
$$\mathcal{L}_{\mathrm{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \mathrm{h.c.}$$

Dirac

$$\mathcal{L}_{\mathrm{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \mathrm{h.c.}$$

Majorana

Introduce new scalars (S) & Majorana fermions (F): "mediators"



Attach Higgs lines as appropriate to get Weinberg operator

Recent mini-review: H. Sugiyama, 1505.01738

Type II See-Saw

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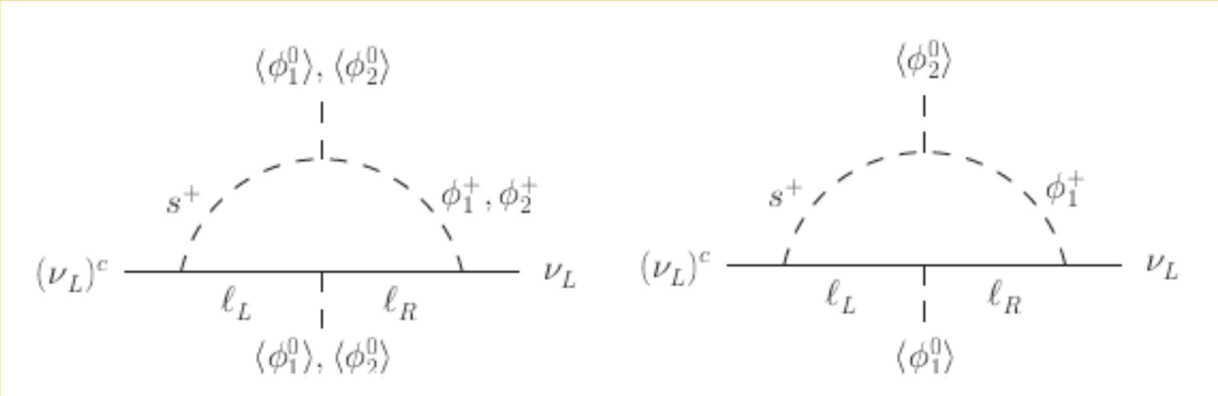

"Zee Model"

Recent mini-review: H. Sugiyama, 1505.01738

Type II See-Saw

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Dirac

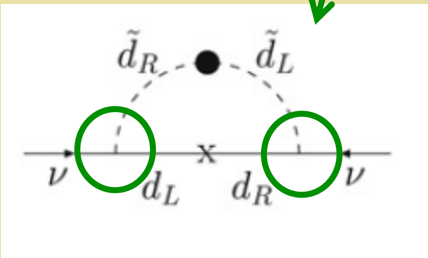
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

SUSY with "R parity" violation $P_R = (-1)^{2S+3(B-L)}$

"Superpotential"

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k + \mu'_iL_iH_u,$$



V. Discussion Questions

- *What is the see-saw scale (M_N)?*
- *What might the comparison of m_ν from terrestrial & astrophysical determinations teach us?*
- *How do we know $N_\nu = 3$?*
- *How might we determine the correct neutrino mass model ?*