Origin of Neutrino Masses

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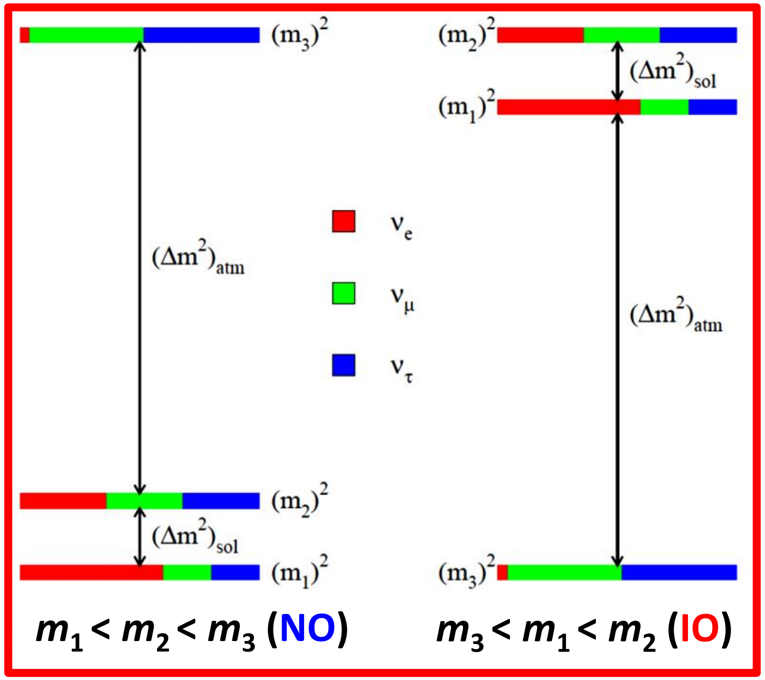
Open Questions in Neutrino Physics

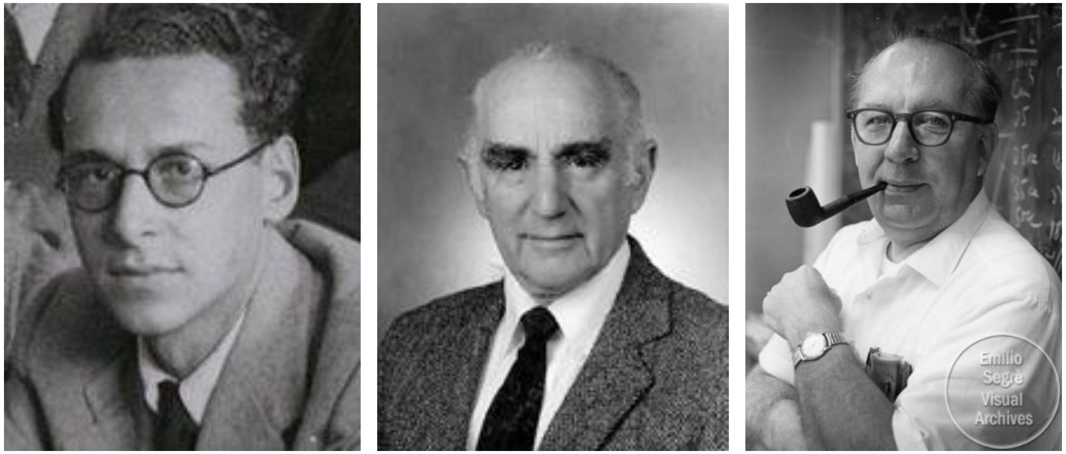
- Normal or Inverted (sign of Δm^2_{32}?)
- Leptonic CP Violation (δ = ?)
- Octant of θ_{23} (> or < 45°?)
- Absolute Neutrino Masses ($m_{\text{lightest}} = 0$?)
- Majorana or Dirac Nature ($\nu = \nu^c$?)
- Majorana CP-Violating Phases (how?)



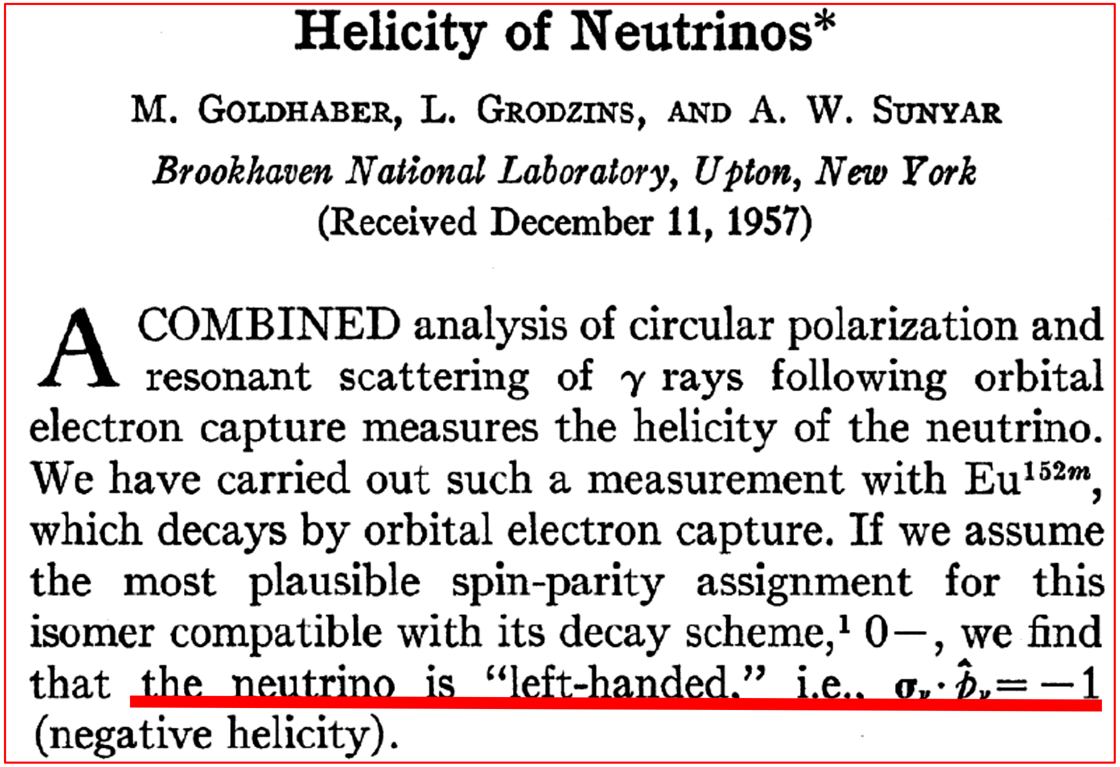
- Extra Neutrino Species
- Exotic Neutrino Interactions
- Other LNV & LFV Processes
- Leptonic Unitarity Violation

- Origin of Neutrino Masses
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM, BAU, or NP

Why Massless Neutrinos in the SM?



- Discovery of parity violation in weak interactions
- Two-component theory (Lee-Yang/Salam/Landau, 57)
- Determination of the helicity of neutrinos



Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Maximal parity violation (V-A)

Chirality: LH for ν RH for $\overline{\nu}$

$$\nu_{\mathrm{L}} \qquad \overline{\nu}_{\mathrm{R}}$$

Helicity: LH for ν RH for $\overline{\nu}$

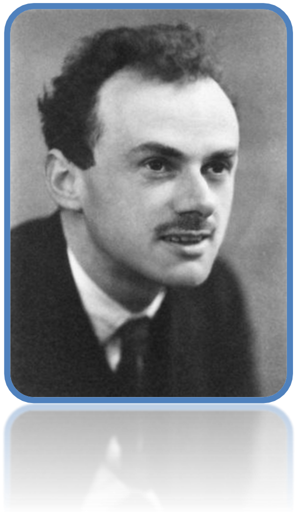
$$\boxed{\lambda(\nu) = -1} \qquad \boxed{\lambda(\overline{\nu}) = +1}$$

Just to simply identify them:

Massless Weyl Fermions

Massive Neutrinos: Dirac vs. Majorana

Now that neutrinos are massive particles, either Dirac or Majorana



Dirac Neutrinos

	LH	RH
Particle	ν_L	ν_R
Antiparticle	ν_R^C	ν_L^C

Active components

	LH	RH
Particle	ν_L	
Antiparticle		ν_L^C

Majorana (1937)

Majorana Neutrinos

$$\nu = \nu_L + \nu_L^C$$

	LH	RH
Particle	ν_L	ν_L^C

L is violated

$$\boxed{\nu = \nu^C}$$

- Massive Dirac neutrinos:

  Lepton number conservation

  four degrees of freedom

- Massive Majorana Neutrinos:

  Lepton number violation

  two degrees of freedom

Baryon and Lepton Number Violation

Unified Electroweak Theory with the $SU(2)_L xU(1)_Y$ gauge symmetry

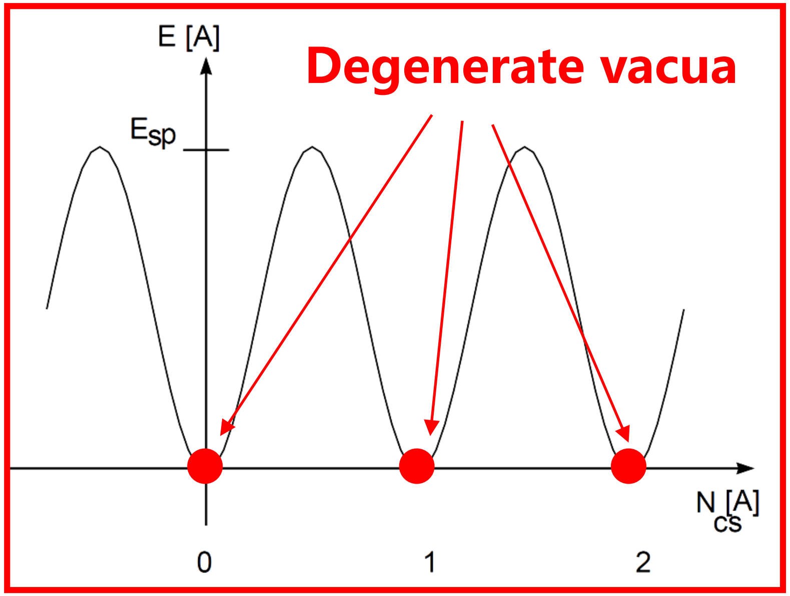
- **Particle content**
  minimality
- **Symmetries**
  SU(2)xU(1)
- **Renormalizability**
  predictive

Particle content	Weak isospin I^3	Hypercharge Y	Electric charge Q
$Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$	$+1/6$	$\begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix}$
$\ell_L \equiv \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$	$-1/2$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
$U_R \equiv u_R,\ c_R,\ t_R$	0	$+2/3$	$+2/3$
$D_R \equiv d_R,\ s_R,\ b_R$	0	$-1/3$	$-1/3$
$E_R \equiv e_R,\ \mu_R,\ \tau_R$	0	-1	-1

B and L are accidentally conserved in the SM at the classical level, but are violated at the quantum level (‘t Hooft, 76)

Only $B-L$, L_e-L_μ, $L_\mu-L_\tau$ can be conserved

Global symmetries are likely to be only approximate, as in black hole physics/ quantum gravity (Witten, 1710.01791)



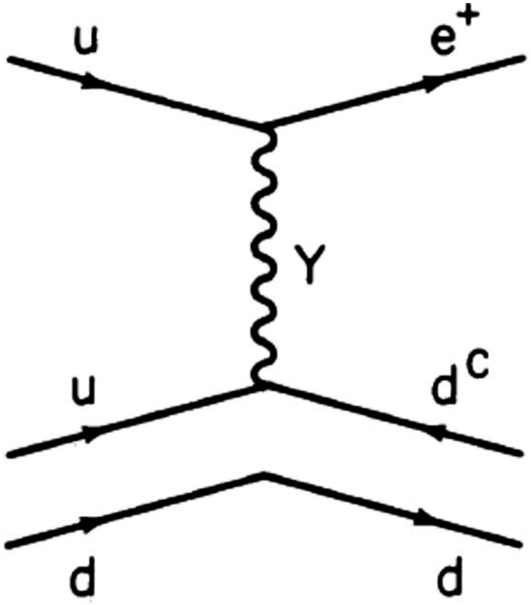
Baryon and Lepton Number Violation

Grand Unified Theories: SU(3)$_C$xSU(2)$_L$xU(1)$_Y$ gauge symmetries
Unification of quarks and leptons

SU(5) GUT: Georgi & Glashow, 1974

$$\begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ e^+ \\ \nu^c \end{pmatrix}_R \qquad \begin{pmatrix} 0 & u_3^c & u_2^c & u_1 & d_1 \\ & 0 & u_1^c & u_2 & d_2 \\ & & 0 & u_3 & d_3 \\ & & & 0 & e^+ \\ & & & & 0 \end{pmatrix}_L$$

Proton decay: $p \rightarrow e^+ + \pi^0$



Both B and L are violated by one unit in the minimal SU(5) GUTs, and B-L can be either conserved or violated (Mohapatra, 1986)

SO(10) GUTs naturally accommodate RH neutrinos and Majorana neutrino masses (Georgi, 1975; Fritzsch & Minkowski, 1975)

SM: An Effective Theory @ Low Energies

Weinberg (1979): The SM is a low-energy effective theory for electroweak interactions

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \kappa_\nu \frac{\left(\overline{\ell_{\rm L}}\widetilde{H}\right)\cdot\left(\widetilde{H}^{\rm T}\ell^{\rm C}_{\rm L}\right)}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

$$v \sim 10^2\ {\rm GeV}$$

$$M_\nu = \kappa_\nu \frac{v^2}{\Lambda} \sim 0.1\ {\rm eV} \quad \Rightarrow \quad \Lambda \sim 10^{10\cdots 14}\ {\rm GeV}$$

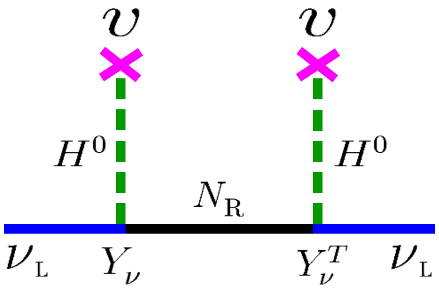
Unique dimension-5 operator for neutrino masses

Extremely high energy scale!!!

Several dimension-6 operators for proton decays (Wilczek & Zee, 79)

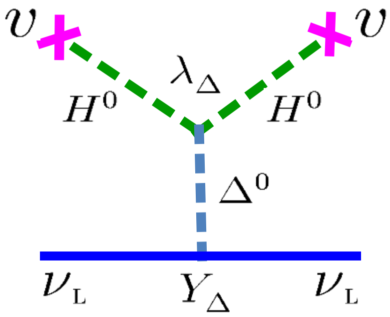
Realization of the Weinberg operator in renormalizable theories

Type-I Seesaw



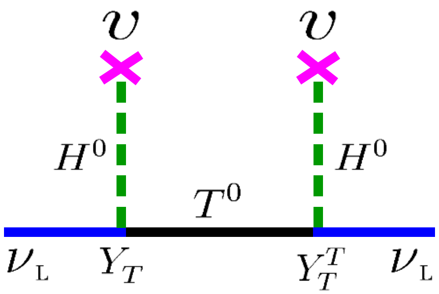
$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_{\rm R}} Y_\nu^T$$

Type-II Seesaw



$$M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

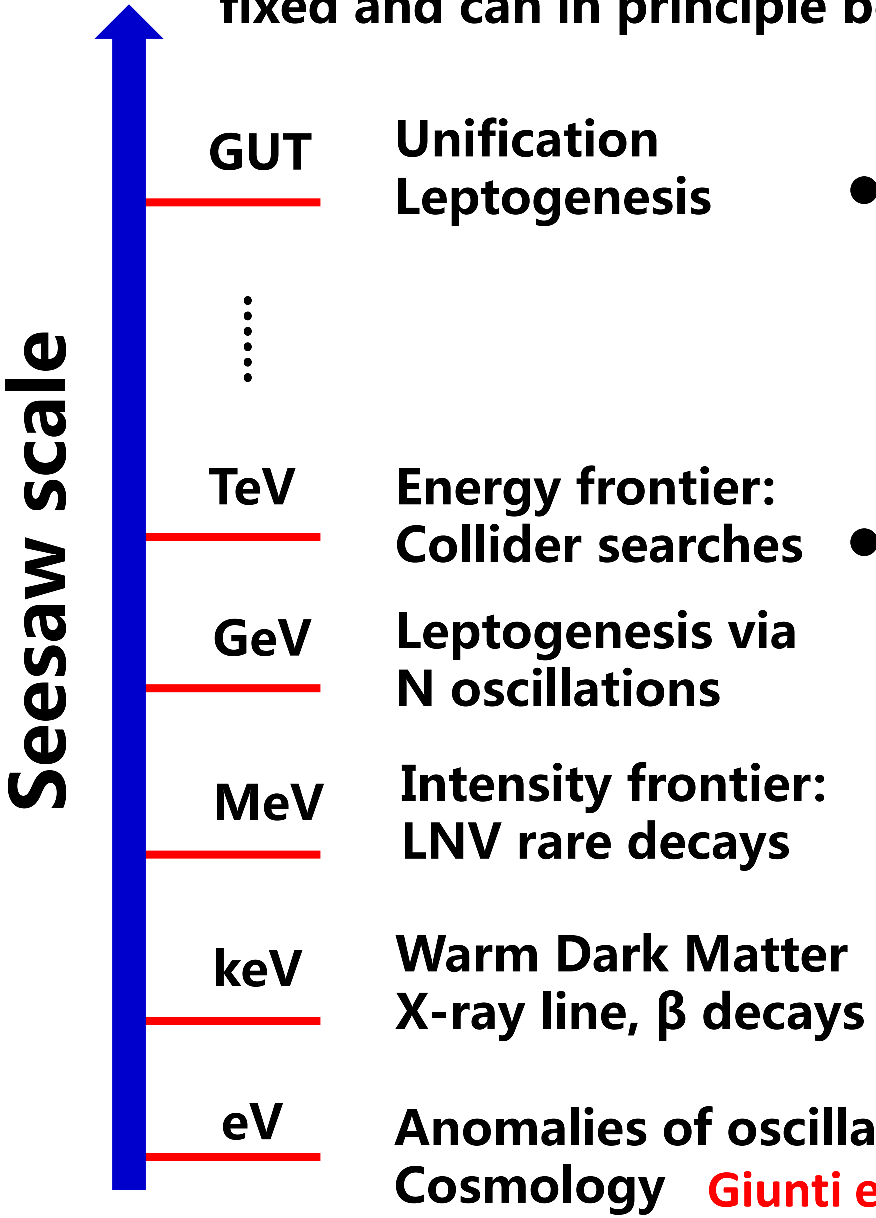
Type-III Seesaw



$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

Where is the Seesaw Scale?

In the type-I seesaw models, the scale of RH neutrino masses is not fixed and can in principle be a very wide range



Seesaw scale

GUT — **Unification**
Leptogenesis

TeV — **Energy frontier:**
Collider searches

GeV — **Leptogenesis via**
N oscillations

MeV — **Intensity frontier:**
LNV rare decays

keV — **Warm Dark Matter**
X-ray line, β decays

eV — **Anomalies of oscillation experiments**
Cosmology **Giunti et al., 18**

Xing, 09

- **Criteria for a reasonable seesaw scale?**

Testability **Naturalness**

Uniqueness **Hierarchy**

- **Close to a fundamental energy scale**

GUT scale: **heavy Majorana νs**
(only indirect tests)
hierarchy problem

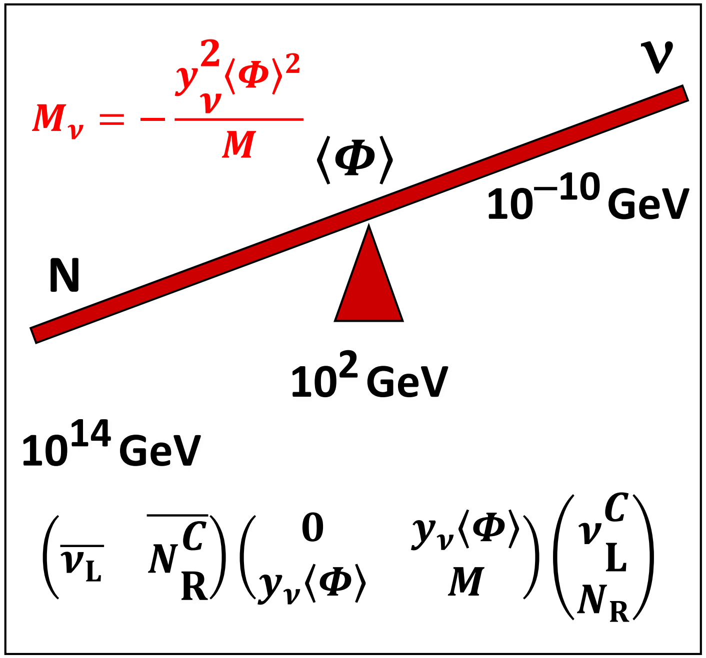
TeV scale: **heavy Majorana νs**
(direct collider searches)
fine-tuning in couplings

- **Exp. Discoveries**
- **Other new ideas**

High-scale Seesaw Models

A natural seesaw scale (e.g., type-I)

- Close to an energy scale of fundamental physics: the GUT scale 10^{16} GeV



$$M_\nu = -\frac{y_\nu^2\langle\Phi\rangle^2}{M}$$

$$\begin{pmatrix}\overline{\nu_L} & \overline{N_R^C}\end{pmatrix}\begin{pmatrix}0 & y_\nu\langle\Phi\rangle\\ y_\nu\langle\Phi\rangle & M\end{pmatrix}\begin{pmatrix}\nu_L^C\\ N_R\end{pmatrix}$$

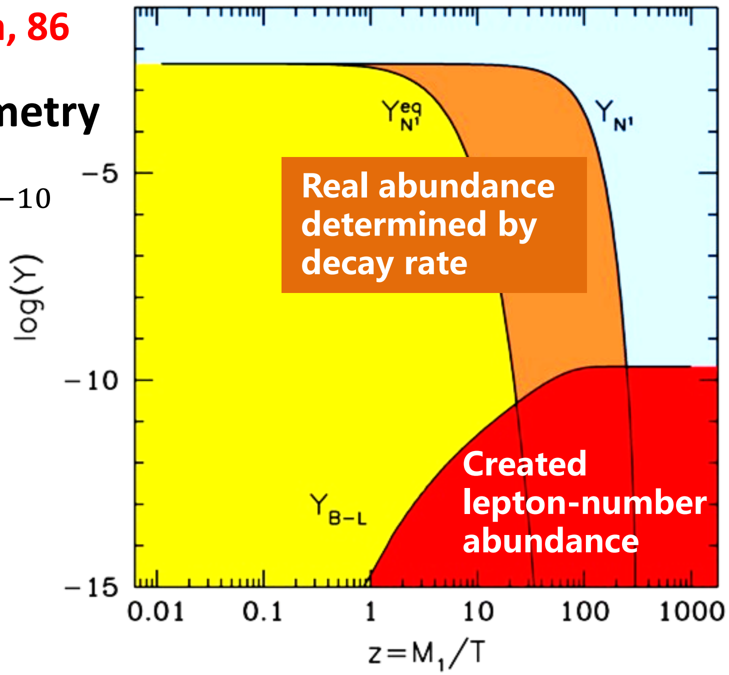
Fukugita, Yanagida, 86

B-number Asymmetry

$$\eta_B = \frac{n_B}{n_\gamma} \simeq 6\times 10^{-10}$$

Leptogenesis

- CP violation
- B-L violation
- Out-of-equili.
- Sphaleron



Seesaw-induced hierarchy problem Vissani, 98; Casas et al., 04; Abada et al., 07

$$\delta M_H^2 = \begin{cases} -\dfrac{y_i^2}{8\pi^2}\left(\Lambda^2 + M_i^2 \ln\dfrac{M_i^2}{\Lambda^2}\right) & \text{(Type I)}\\ \dfrac{3}{16\pi^2}\left[\lambda_3\left(\Lambda^2 + M_\Delta^2 \ln\dfrac{M_\Delta^2}{\Lambda^2}\right) + 4\lambda_\Delta^2 M_\Delta^2 \ln\dfrac{M_\Delta^2}{\Lambda^2}\right] & \text{(Type II)}\\ -\dfrac{3y_i^2}{8\pi^2}\left(\Lambda^2 + M_i^2 \ln\dfrac{M_i^2}{\Lambda^2}\right) & \text{(Type III)}\end{cases}$$

In type-I seesaw models:

$$M_i \lesssim 10^7\ \text{GeV}\left(\frac{0.2\ \text{eV}}{m_i}\right)^{1/3}$$

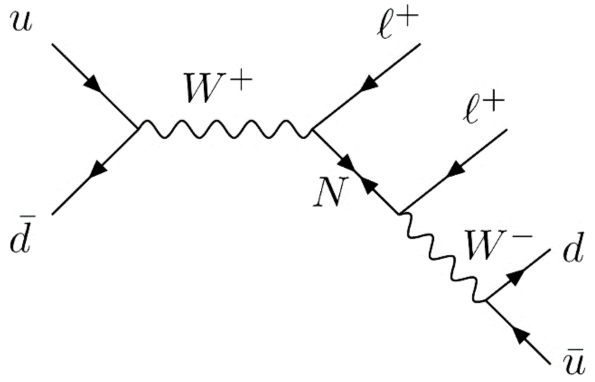
for $\delta M_H^2 \sim 0.1\ \text{TeV}^2$

Low-scale Seesaw Models

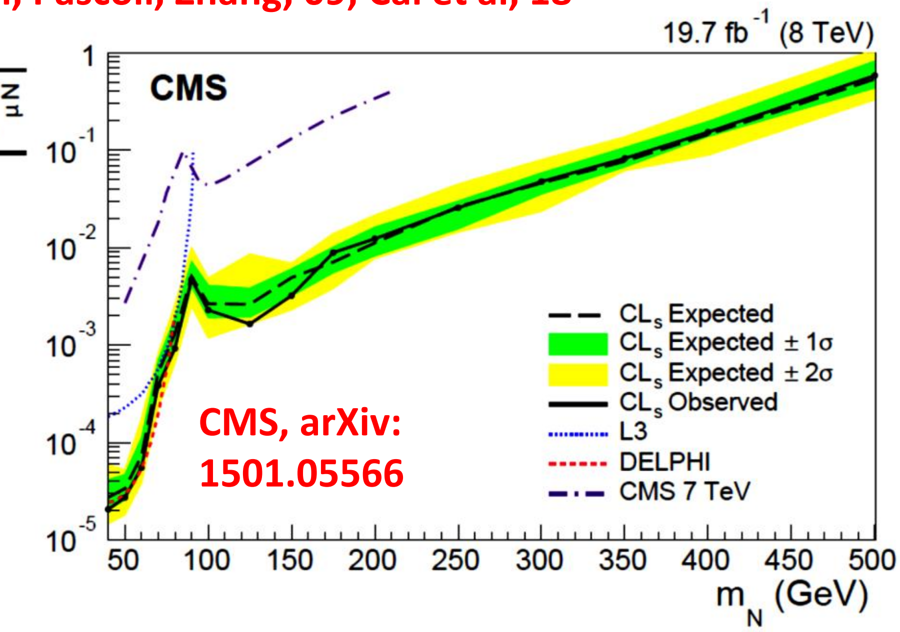
Seesaw models at the EW or TeV scales

- **motivated by the naturalness and testability problems of conventional seesaws**

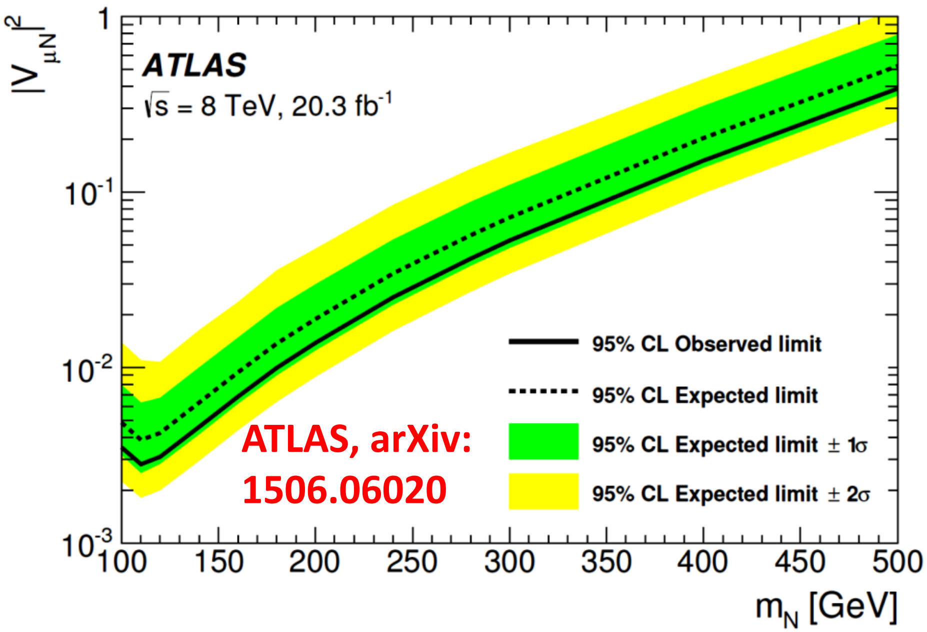
Han, Zhang, 06; Atre, Han, Pascoli, Zhang, 09; Cai et al, 18



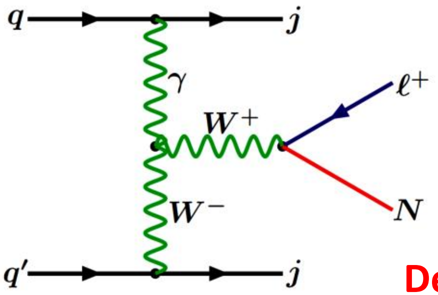
Signals:
same-sign dileptons



CMS, arXiv: 1501.05566



ATLAS, arXiv: 1506.06020



For M_N > 600 GeV, t-channel γ-mediated production dominates over Drell-Yan process

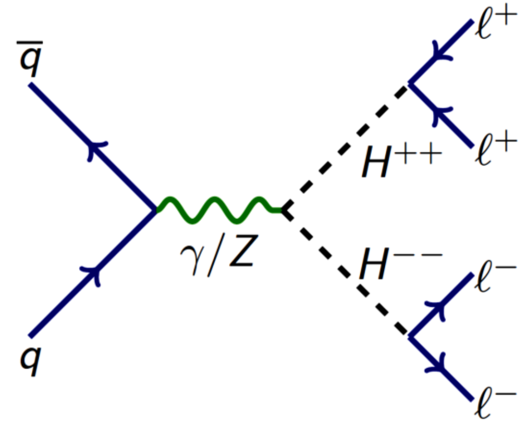
Dev et al., 14; Alva et al., 16

Type-II: 1207.2666 (CMS), 1412.0237 (ATLAS)
Type-III: 1506.01291 (CMS), 1506.01839 (ATLAS)

Low-scale Seesaw Models

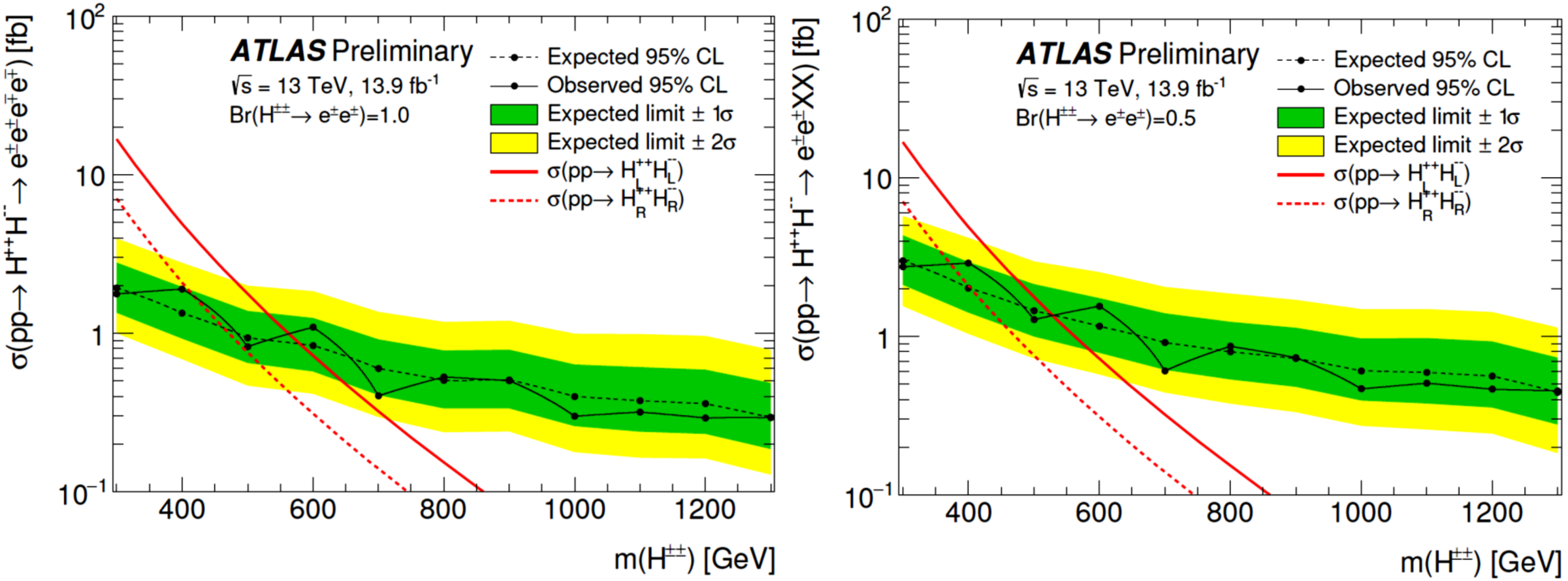
Searches for doubly-charged Higgs bosons

Chun et al., 03; Han et al., 05; Raidal et al., 07; Perez et al., 08; Cai et al., 18



- Depending on the triplet vev, the dominant decay channel is either leptons or W’s
- Couplings directly related to neutrino masses and flavor mixing parameters
- Current constants on masses depend on branching ratios of doubly-charged Higgs decays

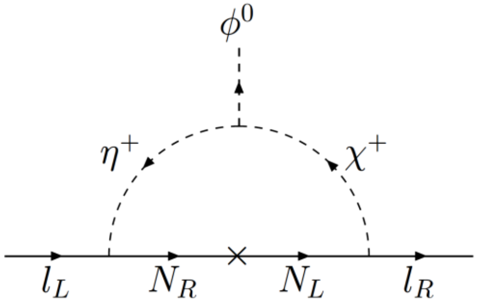
ATLAS-CONF-2016-051

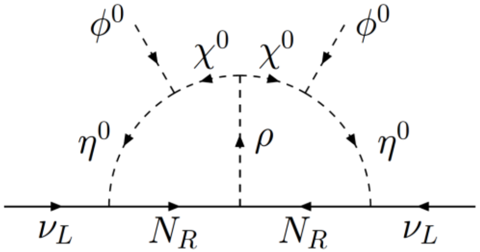


Beyond the Seesaw

Radiative mechanism

Zee, 80; Babu, 88; Ma, 98, 13





Model with A_4 x $U(1)_D$ symmetries

- **Tree-level mass forbidden by A_4 flavor symmetry**
- **Symmetry also responsible for flavor structure**
- **New fermions as DM**

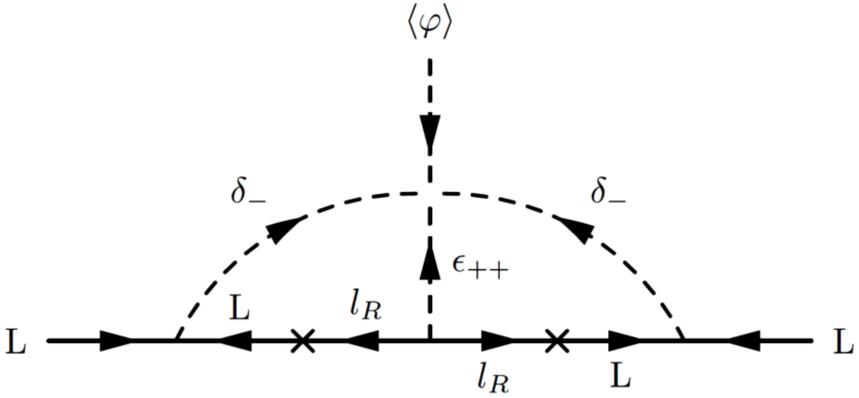
Scale-invariant extension of the SM

Coleman, E. Weinberg, 73

- **Remove mass terms of scalar fields**
- **Radiative symmetry breaking**
- **Solve the hierarchy problem of SM**

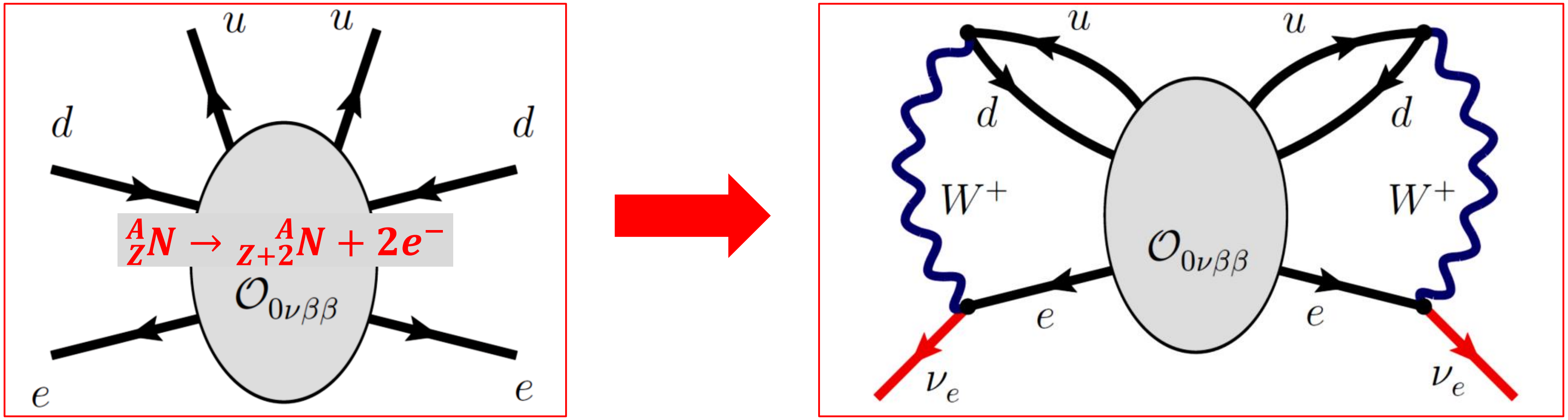
Fermion-Scalar vertex **4-Scalar**

Generation of neutrino masses



Lindner, Schmidt, Smirnov, 14

Majorana vs. Dirac



Schechter-Valle Theorem (82): If the 0νββ decay happens, there must exist an effective Majorana neutrino mass term.

Quantitatively, the 4-loop Majorana mass from the butterfly diagram is EXTREMELY small:

$$\boxed{\delta m_\nu < O(10^{-28}\ \mathrm{eV})}$$

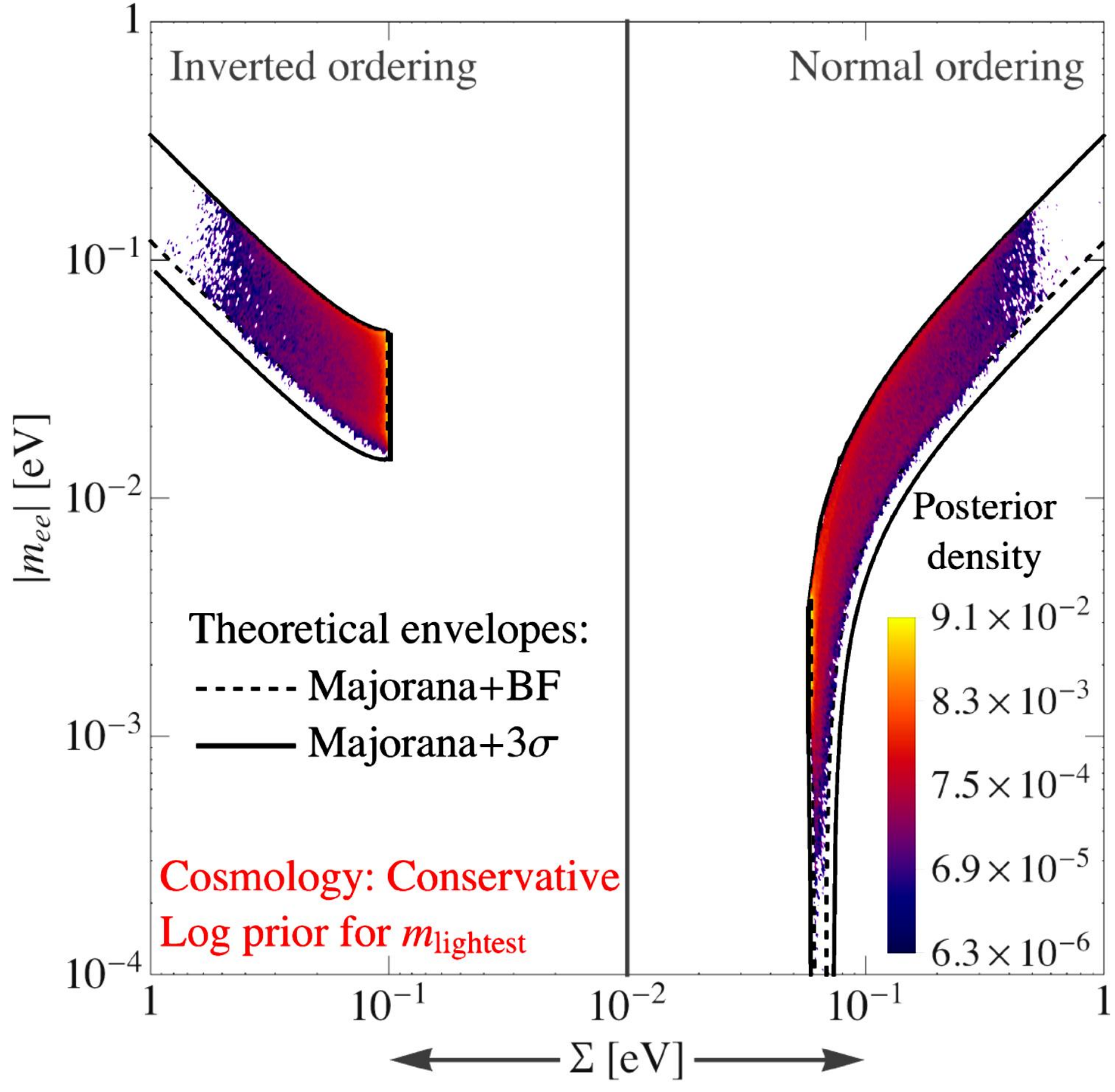
(Duerr, Lindner, Merle, 11; Liu, Zhang, Zhou, 16)

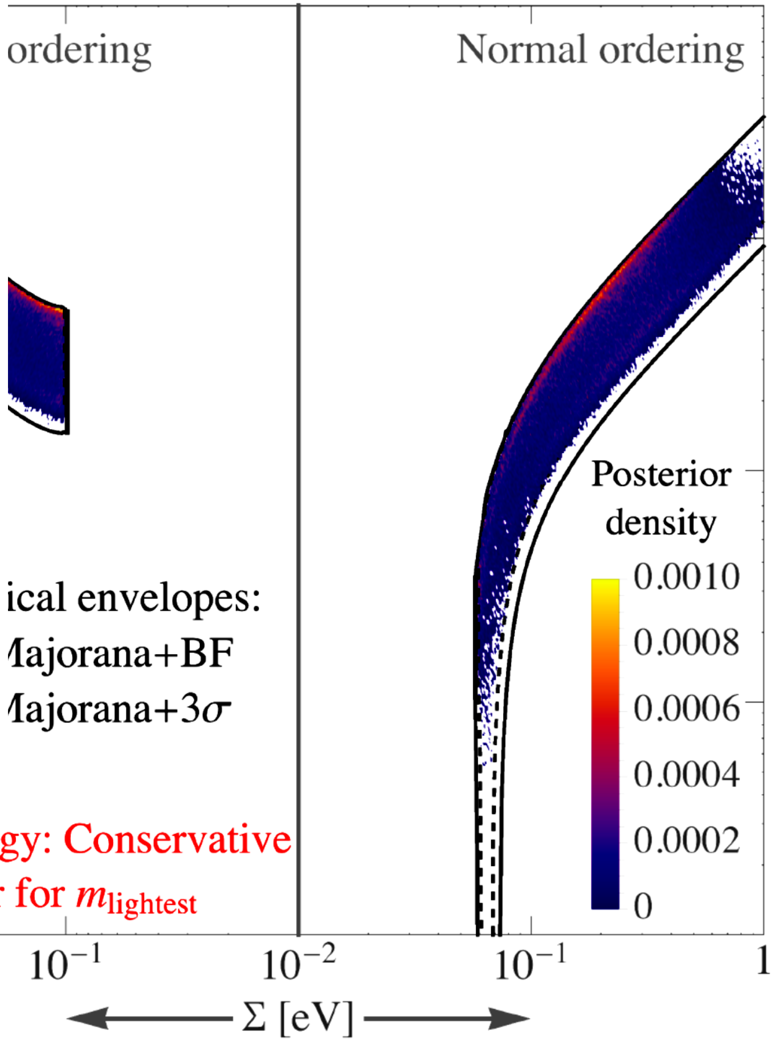
- **Assume 0νββ decays are governed by short-distance operators**
- **The Schechter-Valle (Black Box) theorem is qualitatively correct, but the induced Majorana masses are too small to be relevant for neutrino oscillations**
- **Other mechanisms are needed to generate neutrino masses**

The Effective ν Mass for 0νββ Decays

- ☐ **A global Bayesian analysis**

Caldwell et al., 1705.01945;
Agostini et al., 1705.02996





- ☐ **Log prior for the lightest ν mass leads to a shift to the region of smaller effective masses**

Majorana vs. Dirac

When the temperature *T* ~ 1 MeV, neutrinos became decoupled from the thermal bath, and formed a ν background in the Universe. Today relic neutrinos are nonrelativistic, and their number density is 56 cm^{-3} per flavor, as predicted by the standard model of cosmology.

Temperature today

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K}$$

Mean momentum today

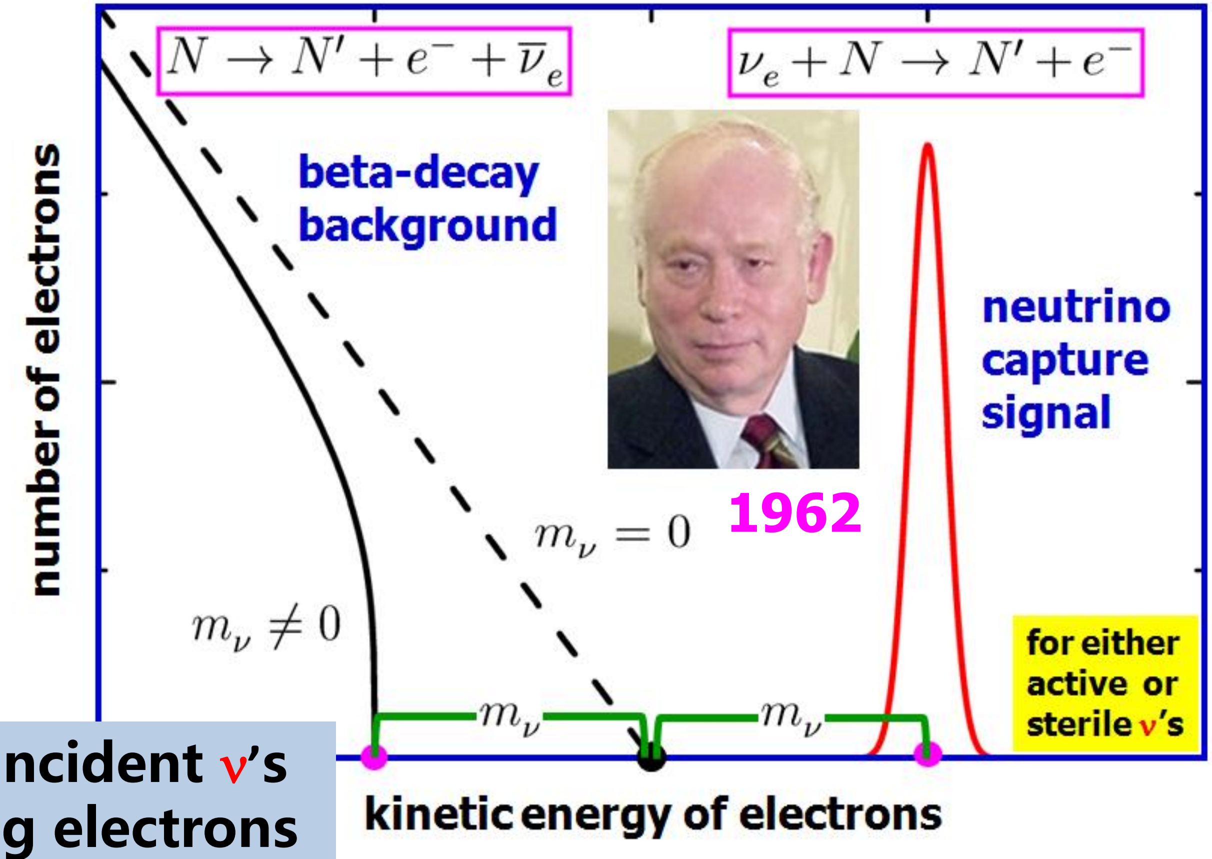
$$\langle p_\nu \rangle \simeq 3.151 T_\nu$$
$$\simeq 5.281 \times 10^{-4}\ \mathrm{eV}$$

At least 2 ν's cold today

NON-relativistic ν's!

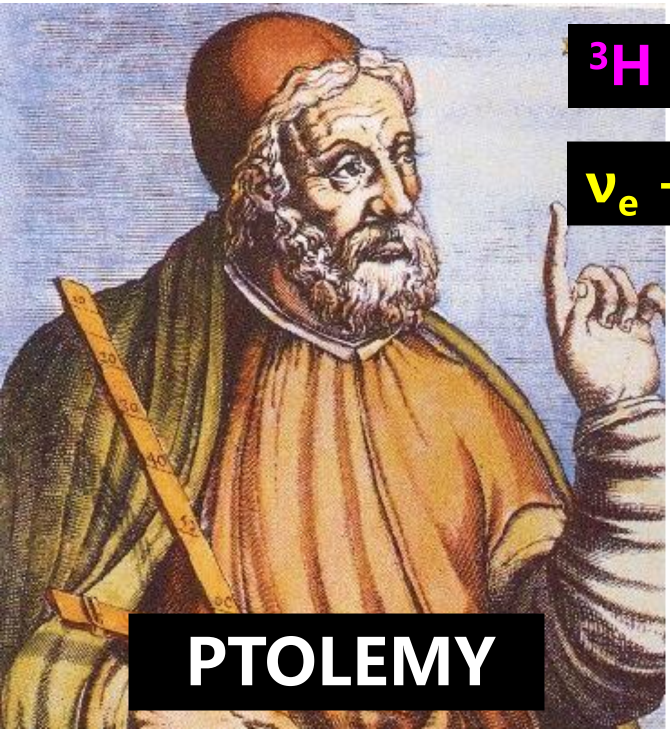
(Irvine & Humphreys, 83)

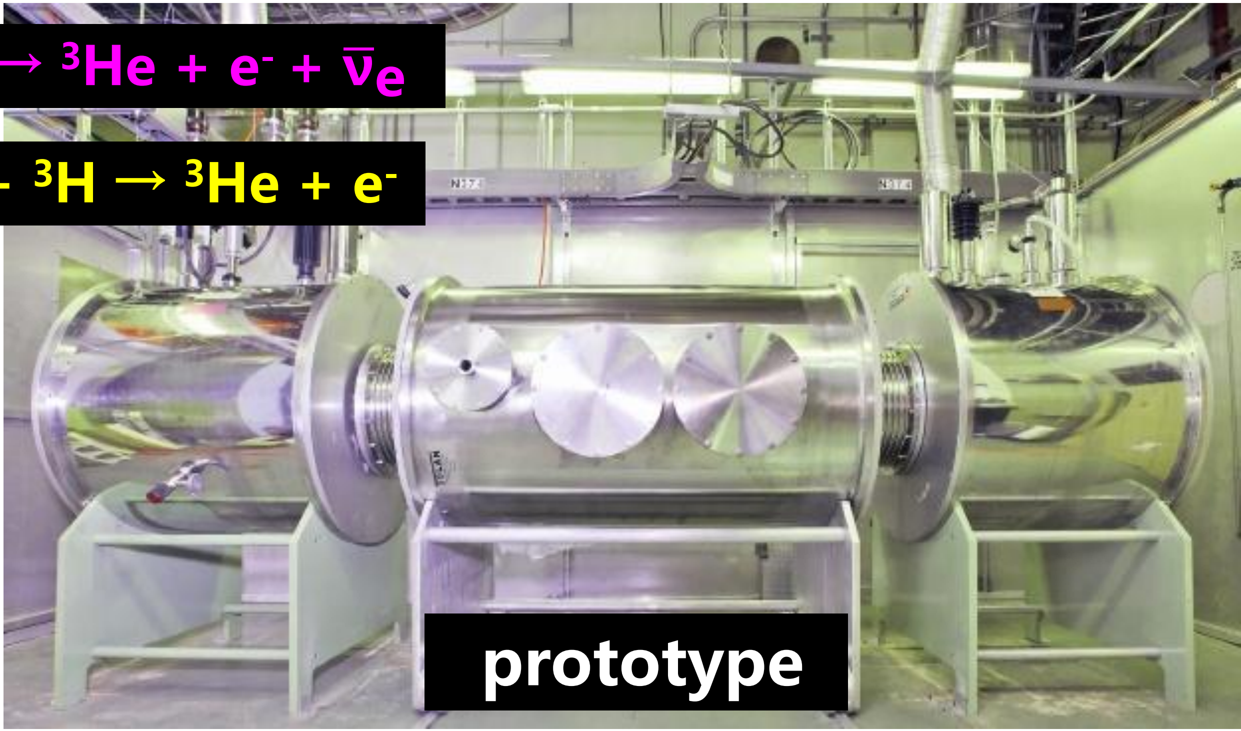
Relic neutrino capture on β-decaying nuclei



no energy threshold on incident ν's
mono-energetic outgoing electrons

Majorana vs. Dirac





$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

$\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$

- ★ first experiment
- ★ 100 g of tritium
- ★ graphene target
- ★ planned energy resolution 0.15 eV

★ **CνB capture rate**

$$\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}} \sim 4\ \mathrm{yr}^{-1}$$

$$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} \sim 8\ \mathrm{yr}^{-1}$$

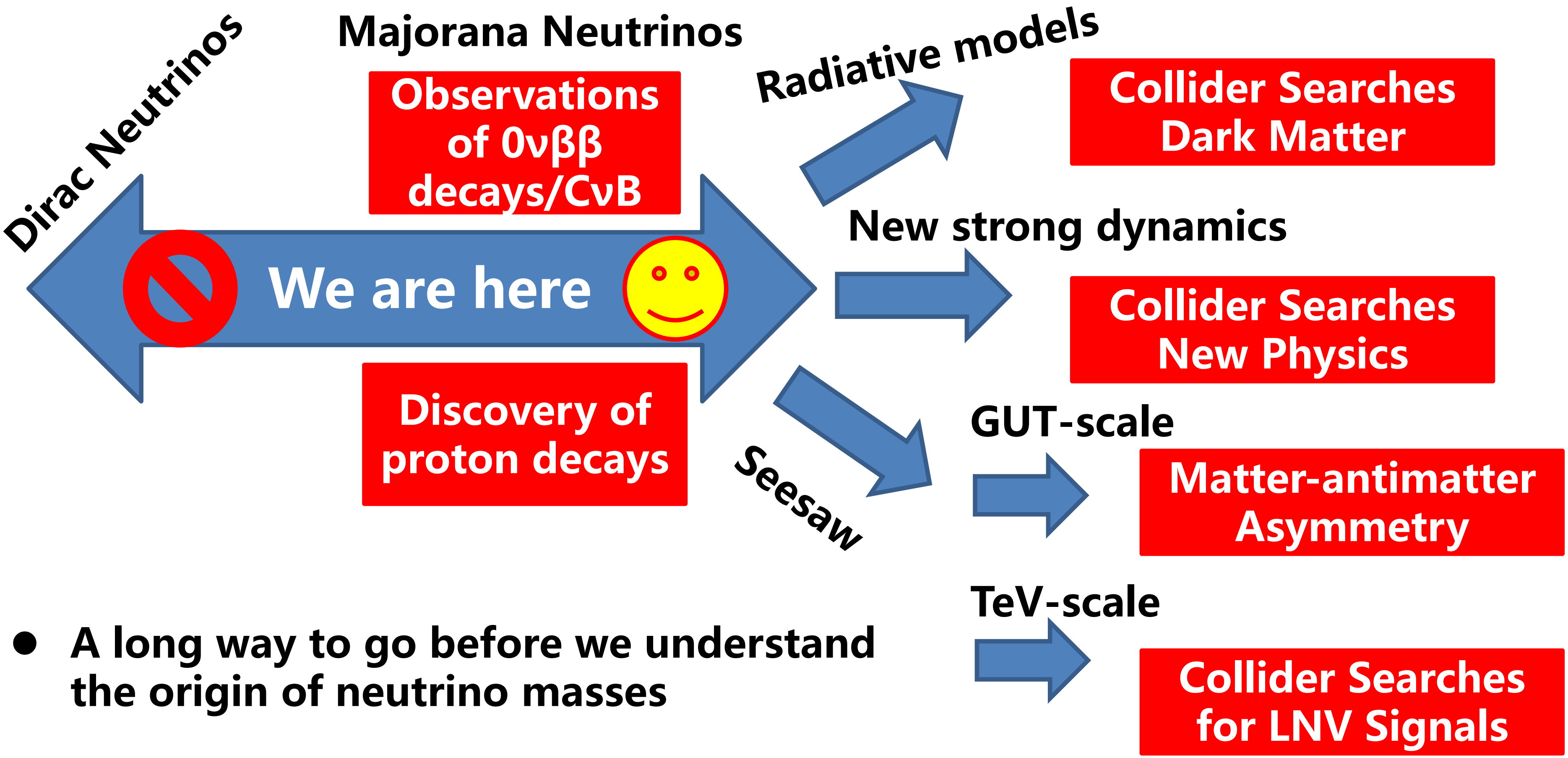
D = Dirac

M = Majorana

PTOLEMY

Princeton (**P**on-)
Tritium (**T**ecorvo)
Observatory for
Light,
Early-Universe,
Massive-Neutrino
Yield (Betts et al, arXiv:1307.4738)

Exploring the Origin of Neutrino Masses



Dirac Neutrinos

Majorana Neutrinos

Observations of 0νββ decays/CνB

We are here

Discovery of proton decays

Radiative models

Collider Searches Dark Matter

New strong dynamics

Collider Searches New Physics

Seesaw

GUT-scale

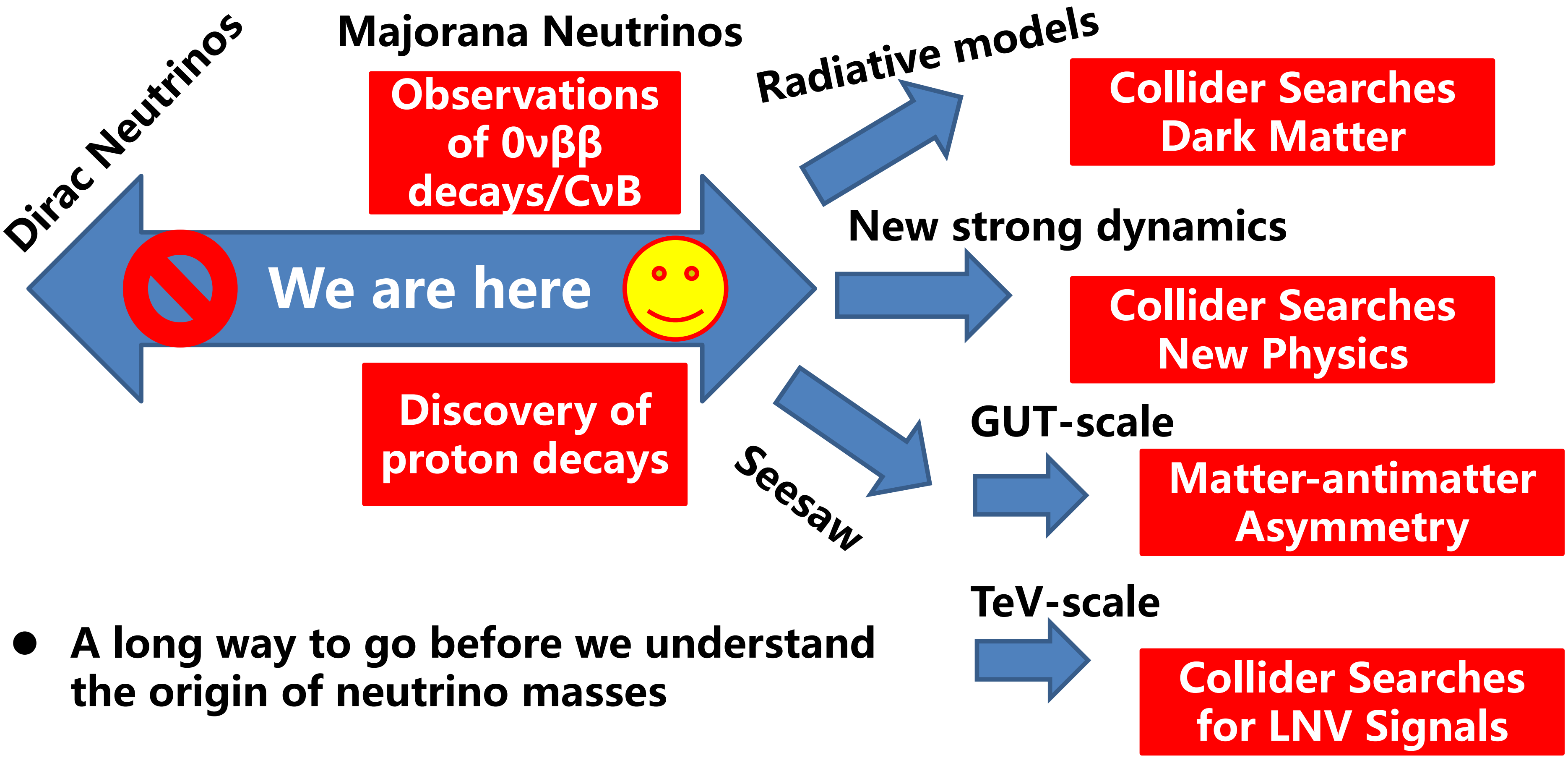
Matter-antimatter Asymmetry

TeV-scale

Collider Searches for LNV Signals

- **A long way to go before we understand the origin of neutrino masses**
- **A decisive signal will be the discovery of B and L number violation (e.g., nucleon decays & 0νββ decays)**
- **Try different ideas, such as the detection of CνB and atomic/molecular systems**

Exploring the Origin of Neutrino Masses



Dirac Neutrinos

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Thanks a lot for your attention!