中微子理论与唯象学

周顺
（高能所&国科大）

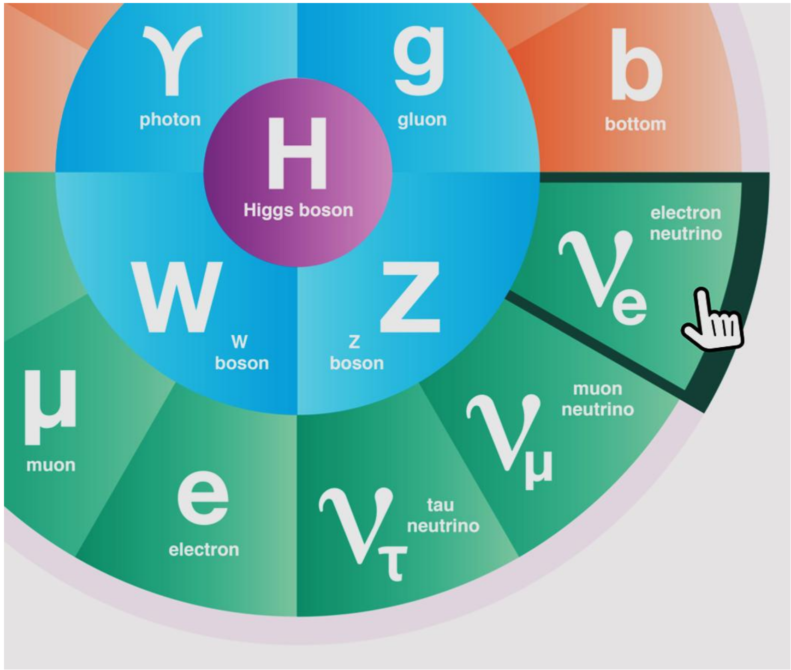
■ 中微子质量：基本属性、质量顺序与绝对大小

■ 质量的起源：理论模型、唯象分析与实验探测

高能物理分会非加速器物理研讨会，北京，2021-05-15

中微子物理学：尚未解决的基本问题

- Normal or Inverted (sign of Δm^2_{31}?)
- 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
- Various LNV & LFV Processes
- Leptonic Unitarity Violation
- Origin of Neutrino Masses
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM, BAU, or NP

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

PDG 2020

LEPTONS

Basic properties:

① Spin
② Mass
③ Electric charge
④ Lifetime
⑤ EM dipole moments

e

$J = \frac{1}{2}$

Mass $m = (548.579909070 \pm 0.000000016) \times 10^{-6}$ u

Mass $m = 0.5109989461 \pm 0.0000000031$ MeV

$\left|m_{e^+} - m_{e^-}\right|/m < 8 \times 10^{-9}$, CL = 90%

$\left|q_{e^+} + q_{e^-}\right|/e < 4 \times 10^{-8}$

Magnetic moment anomaly

$(g-2)/2 = (1159.65218091 \pm 0.00000026) \times 10^{-6}$

$(g_{e^+} - g_{e^-}) \,/\, g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$

Electric dipole moment $d < 0.11 \times 10^{-28}$ e cm, CL = 90%

Mean life $\tau > 6.6 \times 10^{28}$ yr, CL = 90% [a]

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Magnetic moment anomaly

Basic properties:
1. Spin
2. Mass
3. Electric charge
4. Lifetime
5. EM dipole moments

Neutrino Properties

$$\frac{\tau}{m} > 7 \times 10^9\ \mathrm{s/eV} \xrightarrow{m \approx 0.1\ \mathrm{eV}} \tau > 20\ \mathrm{yr}$$

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m < 1.1$ eV, CL = 90% (tritium decay)
Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV (solar)
Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% (accelerator)
Magnetic moment $\mu < 0.28 \times 10^{-10}\ \mu_B$, CL = 90% (solar + radiochemical)

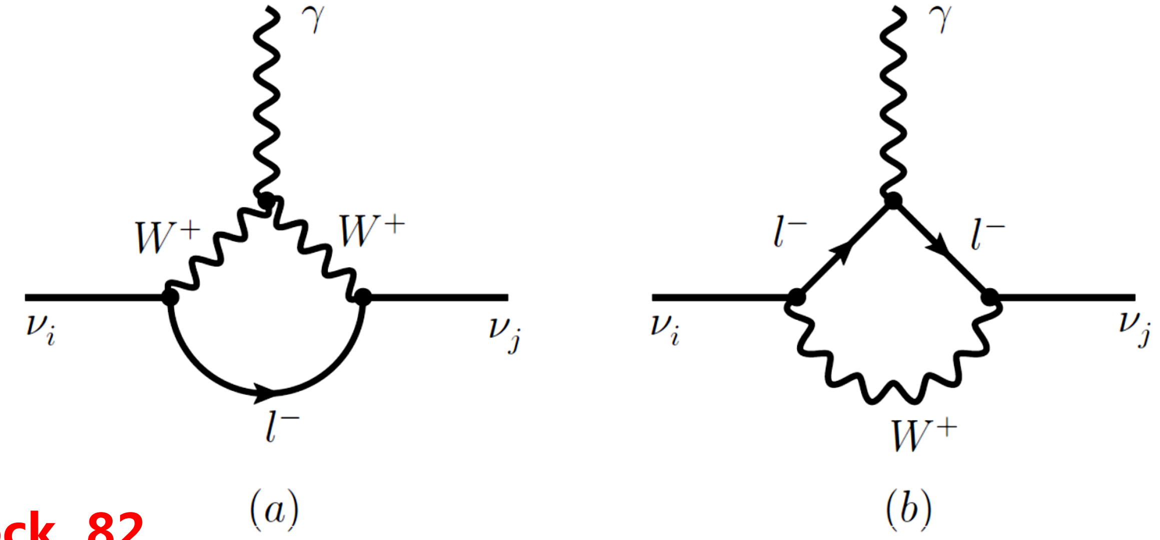
◆ Massive neutrinos can decay but their lifetimes are extremely long

◆ Massive neutrinos can have electric and magnetic dipole moments

Neutrino decays are NOT exotic!!

Standard Model with Massive Neutrinos

$$\nu_i \to \nu_j + \gamma$$



Fujikawa & Shrock, 80; Shrock, 82

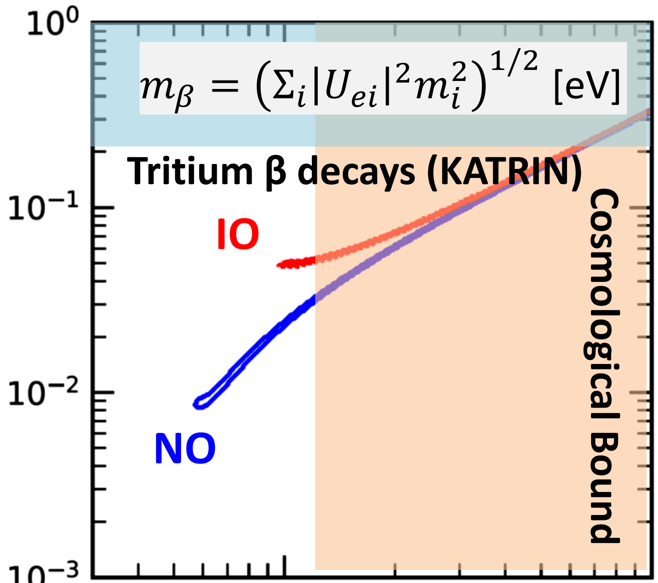
$$\Gamma_{ij} = \frac{(m_i^2 - m_j^2)^3}{8\pi m_i^3}\left(|\mu_{ij}|^2 + |\epsilon_{ij}|^2\right) \approx 5.3 \times \left(1 - \frac{m_j^2}{m_i^2}\right)^3 \left(\frac{m_i}{1\ \mathrm{eV}}\right)^3 \left(\frac{\mu_{\mathrm{eff}}}{\mu_{\mathrm{B}}}\right)^2\ \mathrm{s}^{-1}$$

Given current neutrino oscillation data and cosmological bound on ν mass

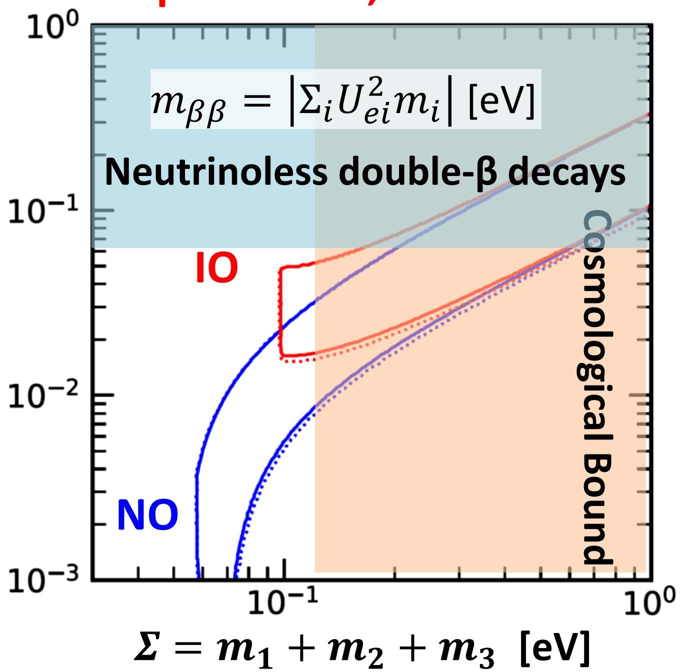
$$\mu_{\mathrm{eff}} \lesssim 10^{-24}\ \mu_{\mathrm{B}} \qquad \tau_i \gtrsim 10^{43}\ \mathrm{years}$$

Sensitive to New Physics

中微子质量：属性、顺序和大小



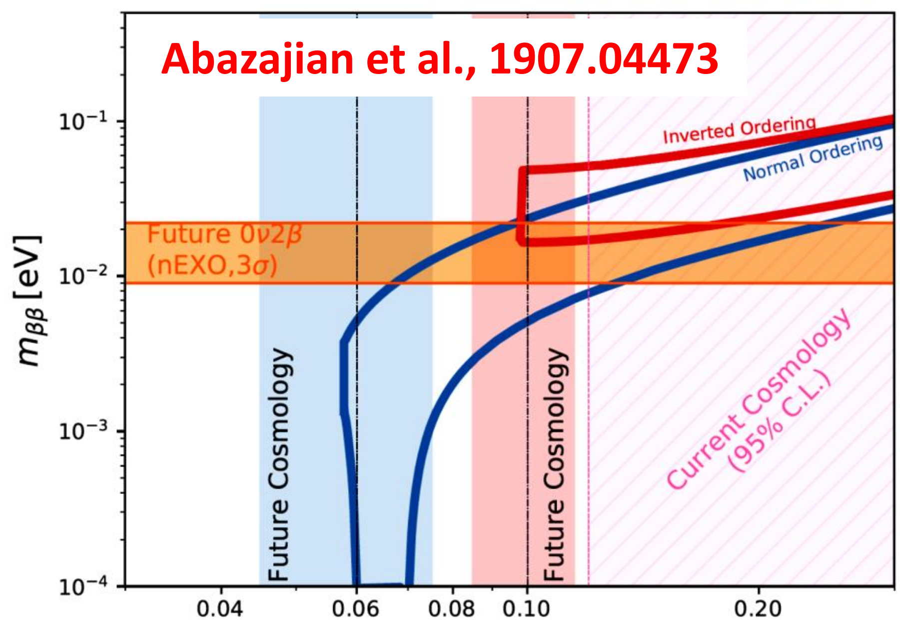
Capozzi et al., 2003.08511



$m_1 < m_2 < m_3$ (NO) or $m_3 < m_1 < m_2$ (IO)

Constraints on absolute neutrino masses

- **Tritium β decays (95% C.L.)**
  $m_\beta < 1.1$ eV (KATRIN)
  2.1 eV (Mainz & Troitzk)
- **Neutrinoless double-β decays (90% C.L.)**
  $m_{\beta\beta} < (0.06 \sim 0.16)$ eV (KamLAND-Zen)
  $(0.19 \sim 0.45)$ eV (EXO-200)
  $(0.22 \sim 0.64)$ eV (GERDA)
- **Cosmological observations (95% probability)**
  $\Sigma < 0.12$ eV (Planck)



中微子质量：基本属性

★ Discovery of lepton number violation: **neutrinoless double-β decay**

- **Dirac Neutrinos**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\nu_{\rm R}} {\rm i} \partial\!\!\!/ \nu_{\rm R} - \left[\overline{\ell_{\rm L}} Y_\nu \tilde{H} \nu_{\rm R} + {\rm h.c.} \right]$$

Generate Dirac ν masses in a similar way to that for quarks and charged leptons, after the spontaneous gauge symmetry breaking

$$M_\nu = Y_\nu v$$

M_ν: $O(0.1~{\rm eV})$; Y_ν: $O(10^{-12})$; v: $\sim 10^2$ GeV

- Need to introduce additional symmetries to the SM to forbid a Majorana mass for right-handed neutrino singlets
- Need to explain strong hierarchies among the Yukawa couplings of the SM fermions

- **Majorana Neutrinos**

$$- \left[\frac{1}{2} \overline{\nu^{\rm C}_{\rm R}} M_{\rm R} \nu_{\rm R} + {\rm h.c.} \right]$$

Generate tiny Majorana ν masses via the so-called seesaw mechanism

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

M_ν: $O(0.1~{\rm eV})$; $M_{\rm R}$: $O(10^{14}~{\rm GeV})$

- Retain the SM symmetries
- GUT or TeV energy scale?

Guide theorists to build up a model for tiny ν masses

中微子质量：正序vs.倒序

★ **After the discovery of 0νββ decays: Massive Majorana Neutrinos**

Mass ordering: (1) first step to fix ν masses; (2) a model discriminator

Tri-bimaximal Mixing

$$U = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Harrison, Perkins & Scott, 02; Xing, 02; He & Zee, 03

Flavor Structure

$$M_\nu = U \widehat{M}_\nu U^T$$

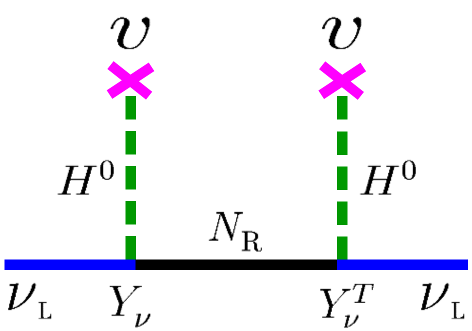
Neutrino Mass Spectrum

	NO	**IO**	**QD**
$\widehat{M}_\nu \approx$	$m_3 \begin{pmatrix} \varepsilon^2 & & \\ & \varepsilon & \\ & & 1 \end{pmatrix}$	$m_2 \begin{pmatrix} 1 & & \\ & 1 & \\ & & \varepsilon \end{pmatrix}$	$m_3 \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$
	$m_1 < m_2 < m_3$	$m_3 < m_1 < m_2$	$m_1 \sim m_2 \sim m_3$
$M_\nu \approx$	$m_3 \begin{pmatrix} \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{pmatrix}$	$m_2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$	$m_3 \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$

In specific ν mass models, MO is correlated with the octant of θ_{23} and CP phase δ; and relevant for model building with flavor symmetries and connections to quarks

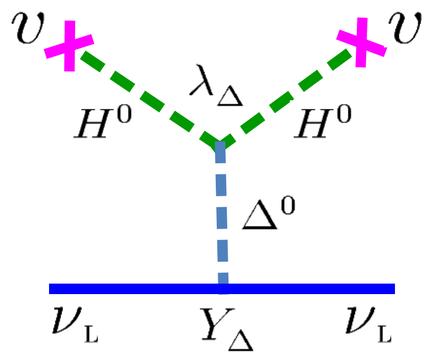
★ **Theoretical models: Absolute masses indicate the new-physics scale**

a natural way to understand neutrino masses



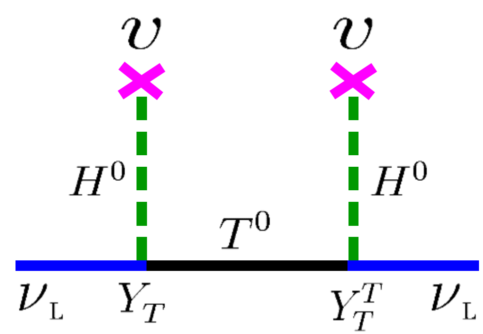
$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$

Minkowski, 77;…



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

Magg, Wetterich 80;…



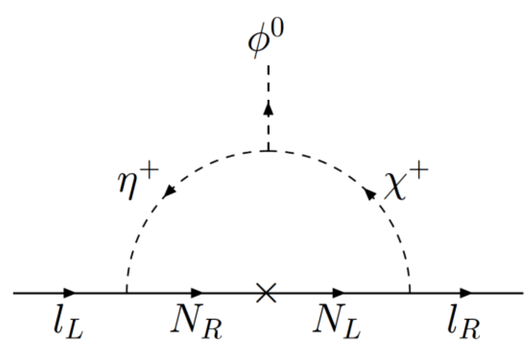
$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

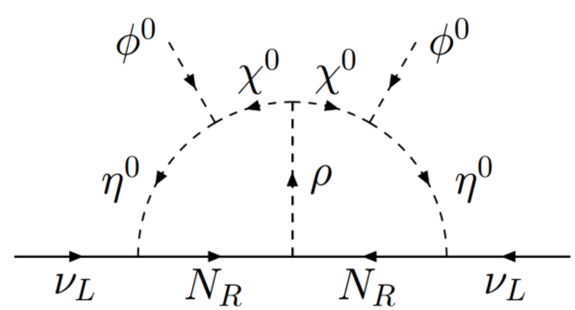
Foot, Lew, He, Joshi, 89

$$M_\nu = v^2 Y_\nu M_R^{-1} Y_\nu^T$$

M_ν: $\boldsymbol{O}(0.1\ \mathrm{eV})$ M_R: $\boldsymbol{O}(10^{14}\ \mathrm{GeV})$

High- vs. Low-scale models



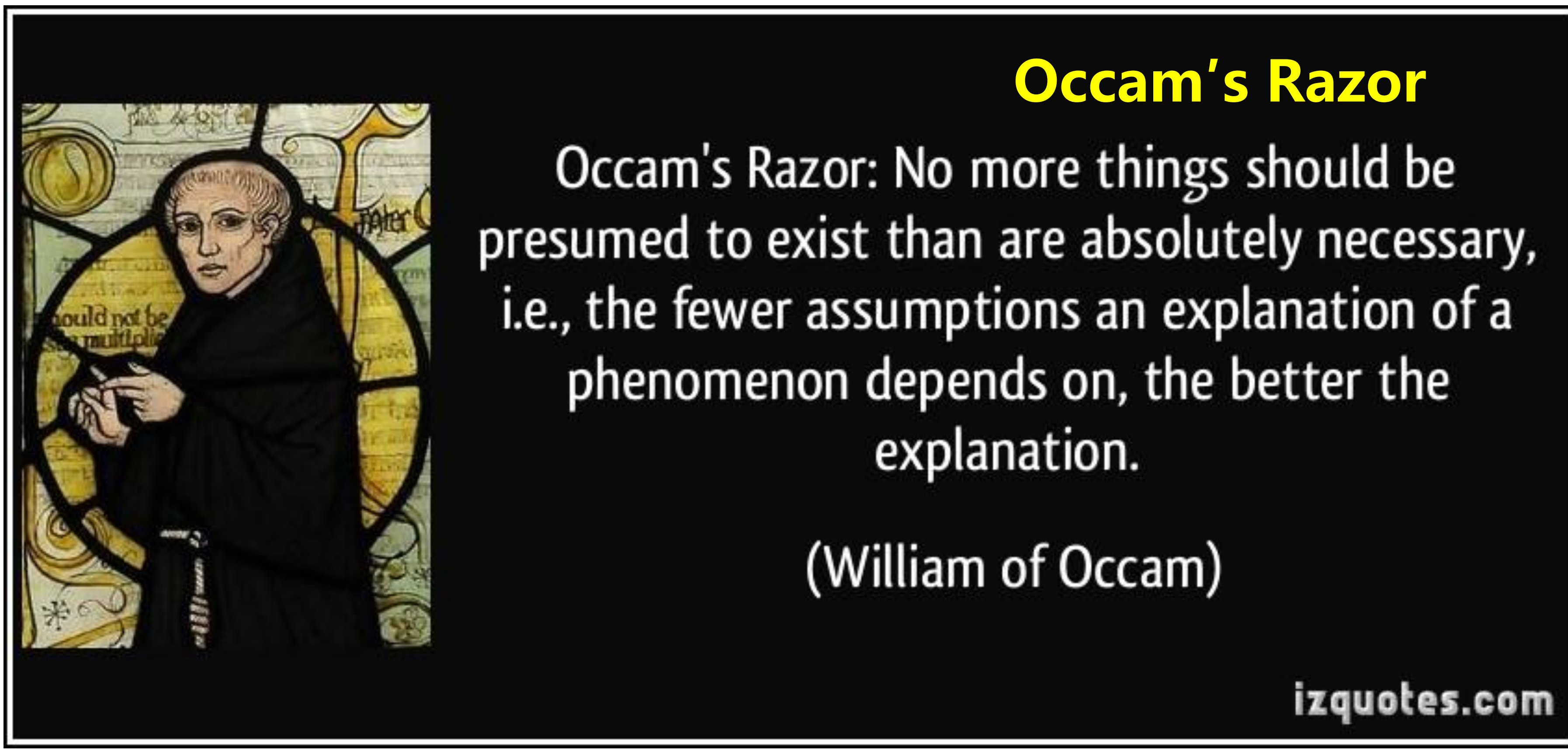


Radiative models: Zee, 80; Babu, 88; Ma, 98, 13

★ **Example**: the minimal type-I seesaw predicts one **massless** neutrino

The vanishing of lightest ν mass is consistent with ν oscillations, so two right-handed neutrinos in the type-I seesaw model are enough:

$$M_\nu = -\kappa \langle H \rangle^2 = -M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T \qquad \text{of rank two}$$

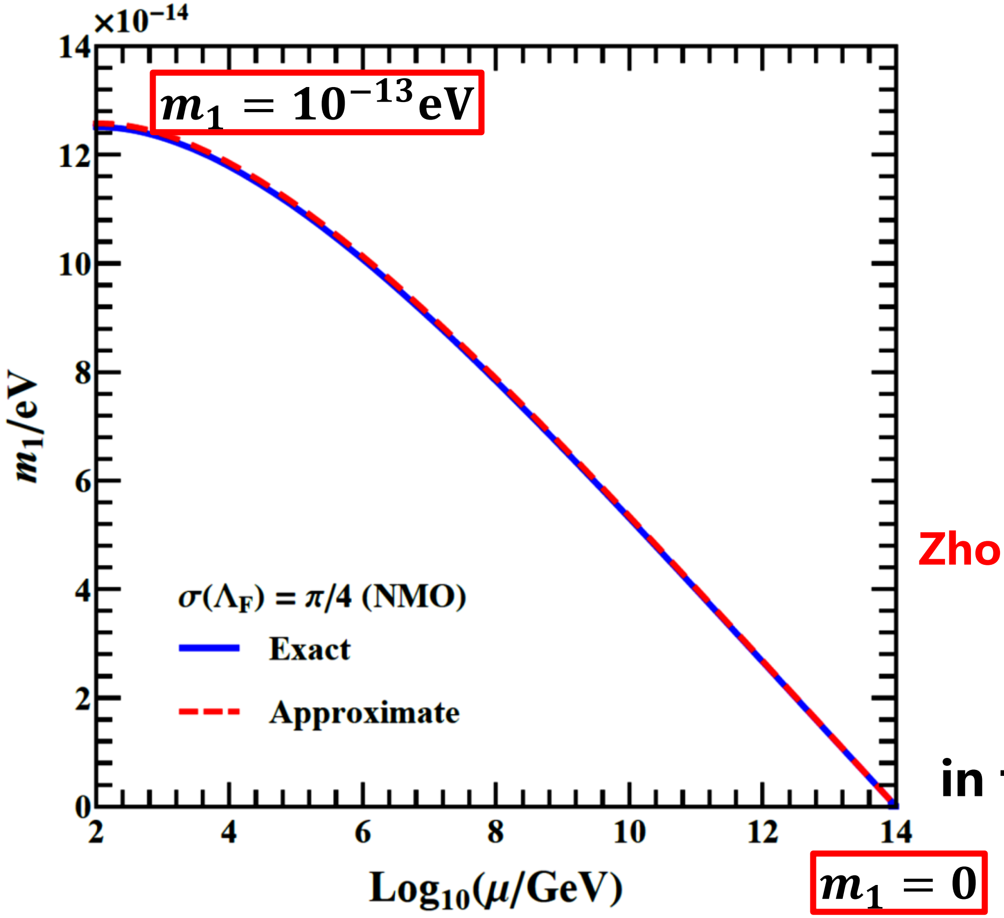


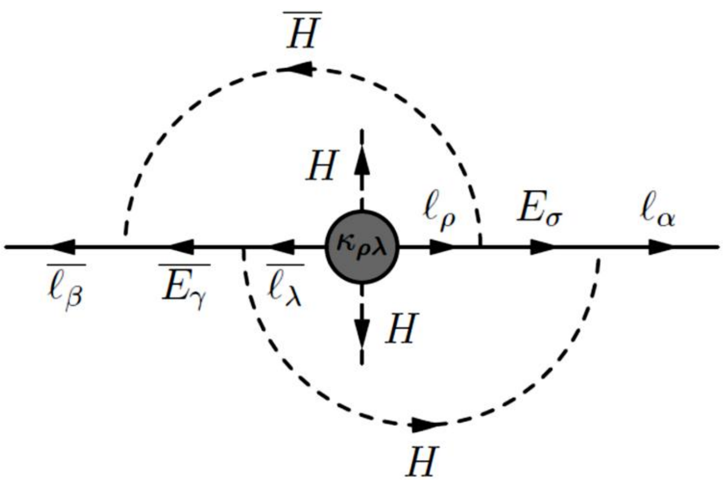
★ **Example**: the minimal type-I seesaw predicts one **massless** neutrino

Davidson, Isidori & Strumia, 07; Xing & Zhang, 20

Two-loop RG running

$$16\pi^2 \frac{\mathrm{d}\kappa}{\mathrm{d}t} = \alpha_\kappa \kappa - \frac{3}{2}\left[\left(Y_l Y_l^\dagger\right)\kappa + \kappa\left(Y_l Y_l^\dagger\right)^T\right] + \frac{1}{8\pi^2}\left(Y_l Y_l^\dagger\right)\kappa\left(Y_l Y_l^\dagger\right)^T$$





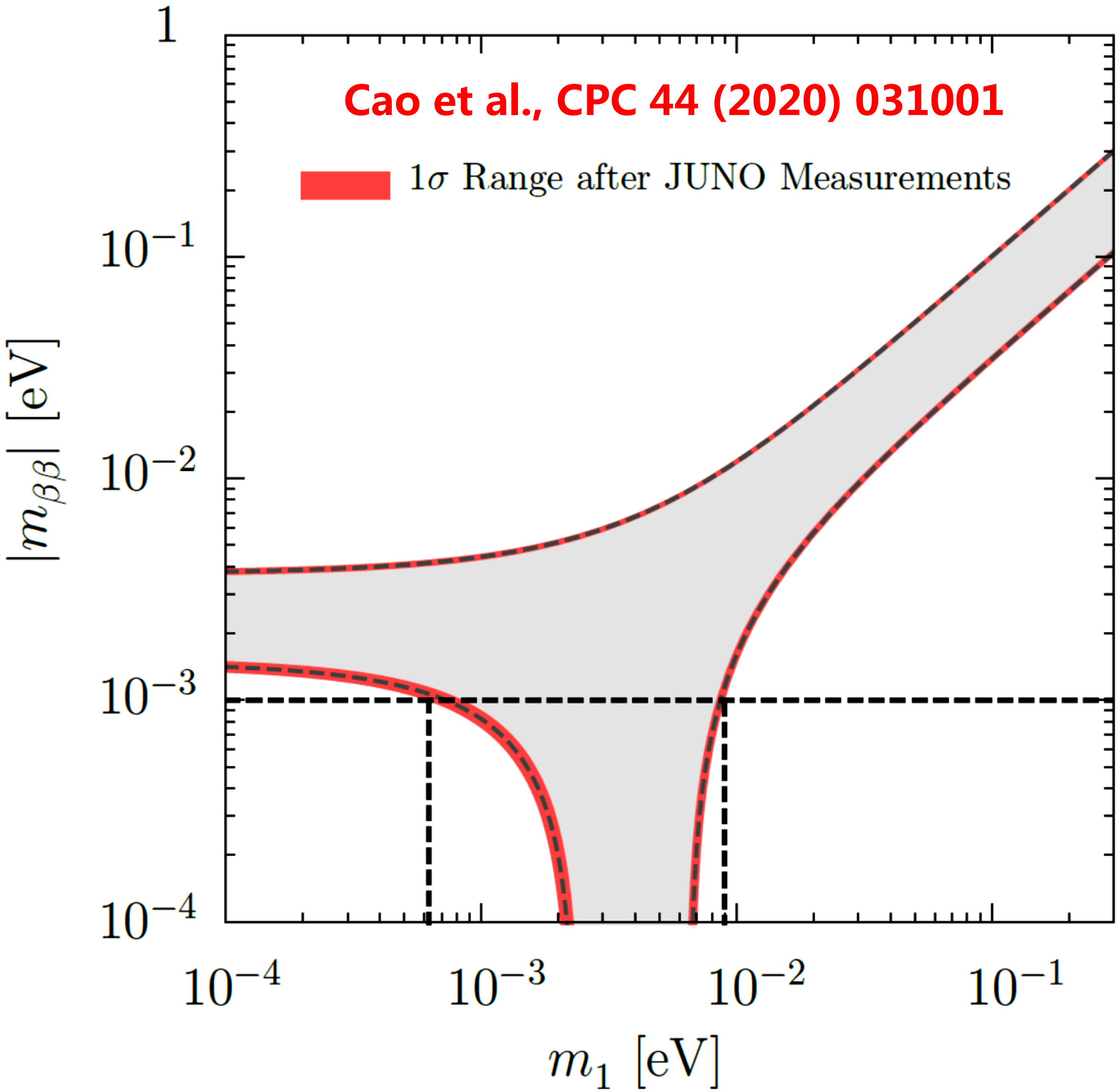
Zhou, 21 **One-loop matching condition**

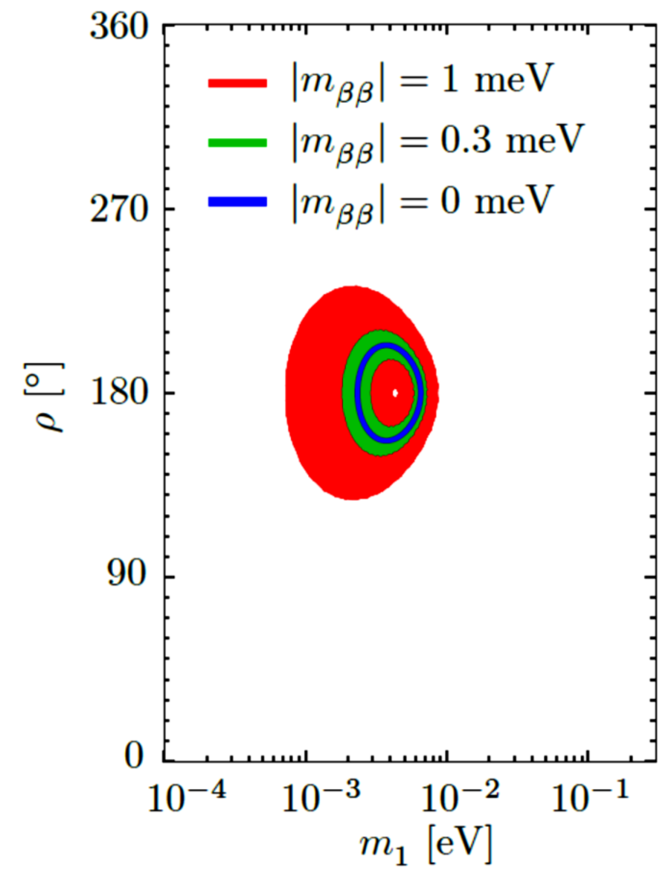
$$m_1(\Lambda_{\rm SUSY}) \approx 6.7 \times 10^{-10}\ {\rm eV}$$

in the SUSY version of minimal seesaw

中微子绝对质量：实验探测

★ 0νββ-decays: toward the 1 meV sensitivity of the effective ν mass



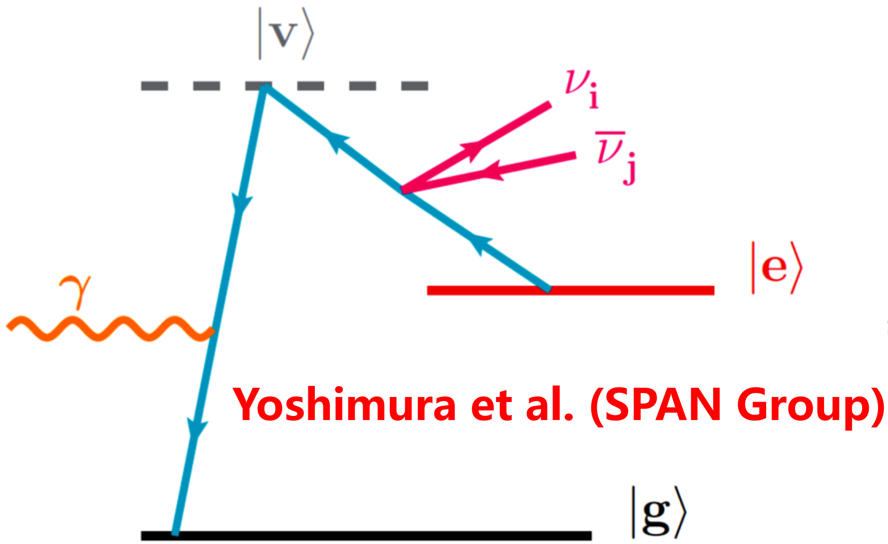


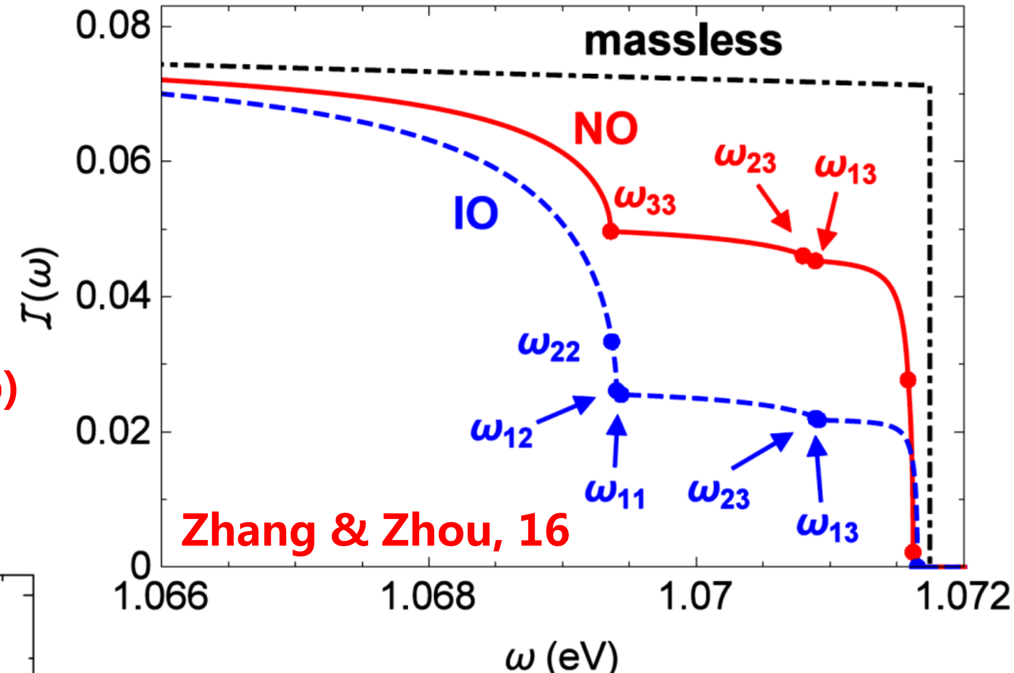
Precise determination of the lightest neutrino mass

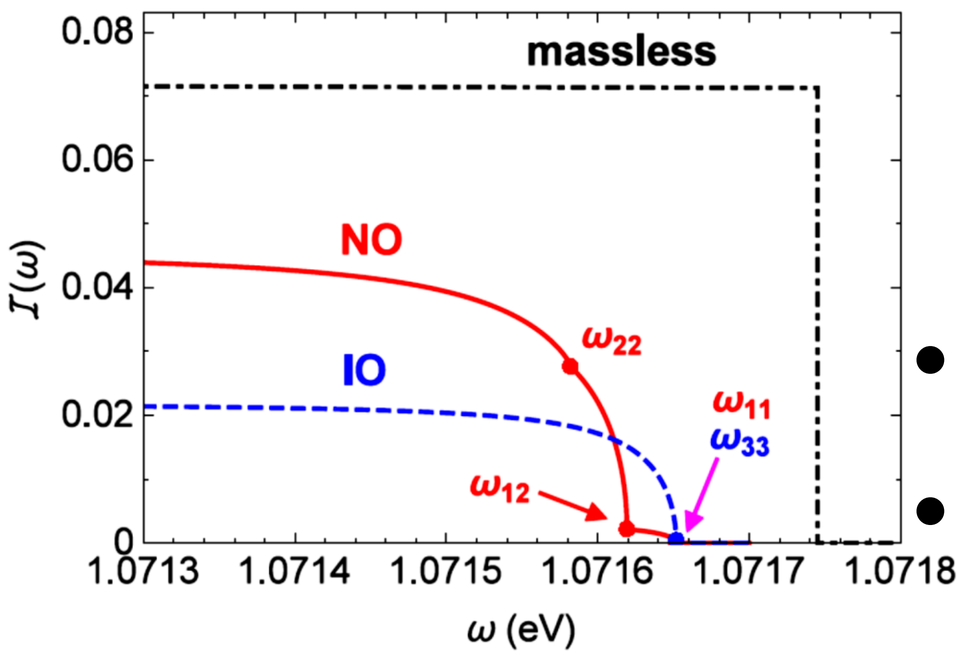
$m_1 \in [0.7, 8]$ meV

中微子绝对质量：实验探测

★ **Radiative Emission of Neutrino Pair (RENP): superradiant atoms/molecules**







$$\omega_{ij} = \frac{\epsilon_{\rm eg}}{2} - \frac{(m_i + m_j)^2}{2\epsilon_{\rm eg}}$$

- **Macro coherent emission of neutrino pairs (to compensate weak rates)**
- **Irreducible EM backgrounds/ further effects needed (soliton-condensate)**

总结与展望

- 中微子振荡实验进入精确测量时代，中微子理论和唯象学研究以基于**味对称性**的质量模型构造为主线，解释轻子味混合模式

- 中微子Majorana属性、质量顺序和绝对质量的实验测量对探究中微子质量起源问题至关重要，尤其是**无中微子双贝塔衰变**

- 有质量中微子的基本性质还包含**寿命、电/磁偶极矩**，结合大型暗物质实验探测器、天文和宇宙学观测

- 关注粒子物理、核物理、原子物理、量子光学等交叉研究方向，探索全新的中微子探测技术的基本原理