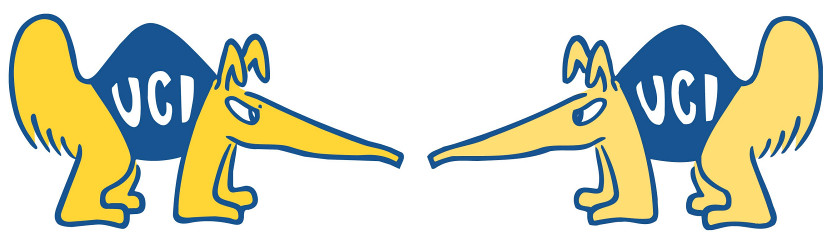
Neutrino Physics Introduction

Mu-Chun Chen, University of California at Irvine



Flavor Physics Conference, ICISE, Quy Nhon, Vietnam, August 18, 2022

Neutrino Physics Post-1998

1998: evidence for neutrino mass from SuperK ($\nu_\mu \rightarrow \nu_\tau$)

first solid evidence of beyond the Standard Model Physics

Massive Neutrinos

2002: evidence for neutrino mass from SNO ($\nu_e \rightarrow \nu_{\mu,\tau}$)

2003: KamLand confirmed Large Mixing Angle solution to solar ν problem

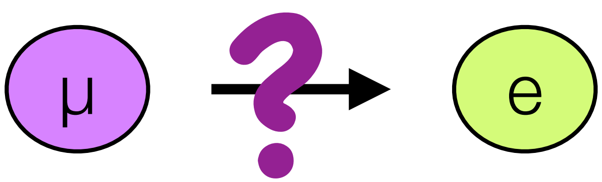
2011: hints for non-zero θ_{13} from T2K, MINOS, and Double Chooz

2012: evidences of non-zero θ_{13} from Daya Bay and RENO

for some parameters: discovery phase into precision phase;
and yet, many great discoveries to come

Neutrino Oscillation ⇒ Massive Neutrinos

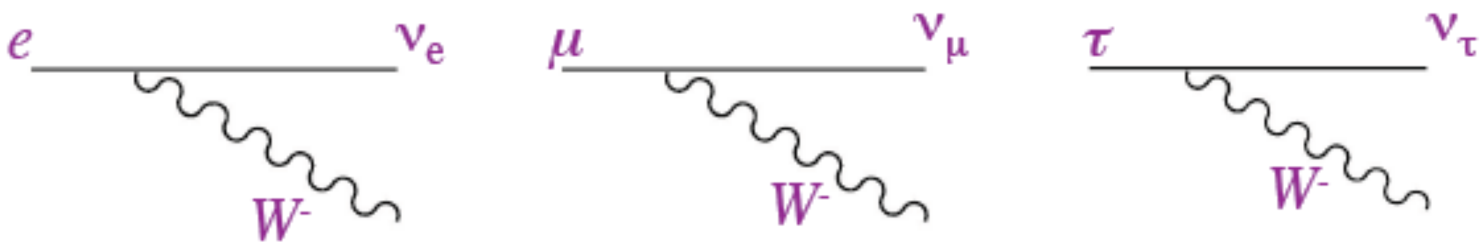
- Neutrino Masses are non-degenerate (at least two are non-zero)
  - mass eigenstates ≠ weak eigenstates
- Accidental symmetries in SM
  - Broken lepton flavor numbers: L_e, L_μ, L_τ
  - Processes cross family lines in lepton sector now possible
    - As a result
      - neutrino oscillation ✔
      - lepton flavor violation decays?



- total lepton number? $L \stackrel{?}{=} L_e + L_\mu + L_\tau$ ↔

What if Neutrinos Have Mass?

- Similar to the quark sector, there can be a mismatch between mass eigenstates and weak eigenstates
- weak interactions eigenstates: ν_e, ν_μ, ν_τ



- mass eigenstates: ν_1, ν_2, ν_3
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

Maki, Nakagawa, Sakata, 1962 ; Pontecorvo, 1967

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\text{PMNS}} = V^\dagger_{e,L} V_{\nu,L}$$

3 mixing angles
+ 1 (3) phase(s) for
Dirac (Majorana)
neutrinos

Leptonic Mixing Matrix

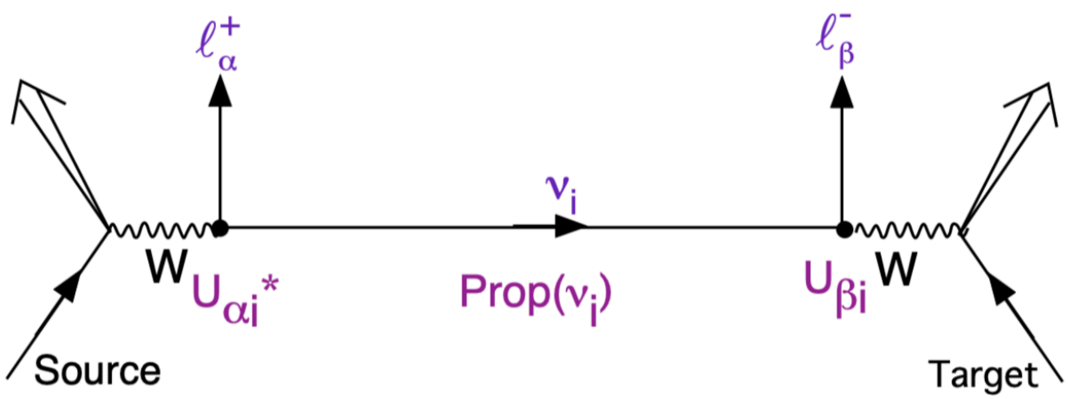
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

$$U_{\text{PMNS}} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_a & s_a \\ 0 & -s_a & c_a \end{bmatrix}}_{\text{atm}} \underbrace{\begin{bmatrix} c_x & 0 & s_x e^{-i\delta} \\ 0 & 1 & 0 \\ -s_x e^{i\delta} & 0 & c_x \end{bmatrix}}_{\text{reactor}} \underbrace{\begin{bmatrix} c_s & s_s & 0 \\ -s_s & c_s & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{solar}} \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\left(\frac{1}{2}\phi_{12}\right)} & 0 \\ 0 & 0 & e^{i\left(\frac{1}{2}\phi_{13}+\delta\right)} \end{bmatrix}}_{\text{Majorana phases}}$$

- three mixing angles: $c_a, \; c_s, \; c_x$
- three CP phases (if Majorana): $\delta, \; \phi_{12}, \; \phi_{13}$
  - 1 CP phase (if Dirac): δ
- Oscillation experiments: sensitive only to δ

Neutrino Oscillation: Macroscopic Quantum Mechanics

- production: neutrinos of a definite flavor produced by weak interaction
- propagation: neutrinos evolve according to their masses
- detection: neutrinos of a different flavor composition detected



$$P(\nu_\alpha \to \nu_\beta)$$

$$P\left[\nu_\mu \to \nu_e\right] = \sin^2 2\theta \sin^2\left[1.27\Delta m_{32}^2\left(\frac{(\text{eV})^2}{c^2}\right)\frac{L(\text{km})}{E(\text{GeV})}\right]$$

Classes of Experiments

Oscillation Experiments:

Atmospheric, solar, reactor, accelerator neutrinos

- mass ordering, CP phases, precision measurements
- Searches for BSM physics

Weak Decay Kinematics:

- Absolute mass scale
- Precision cosmology

Neutrino cross sections, CEνNS:

- Interpretation of data
- BSM

Neutrinoless Double Beta Decay:

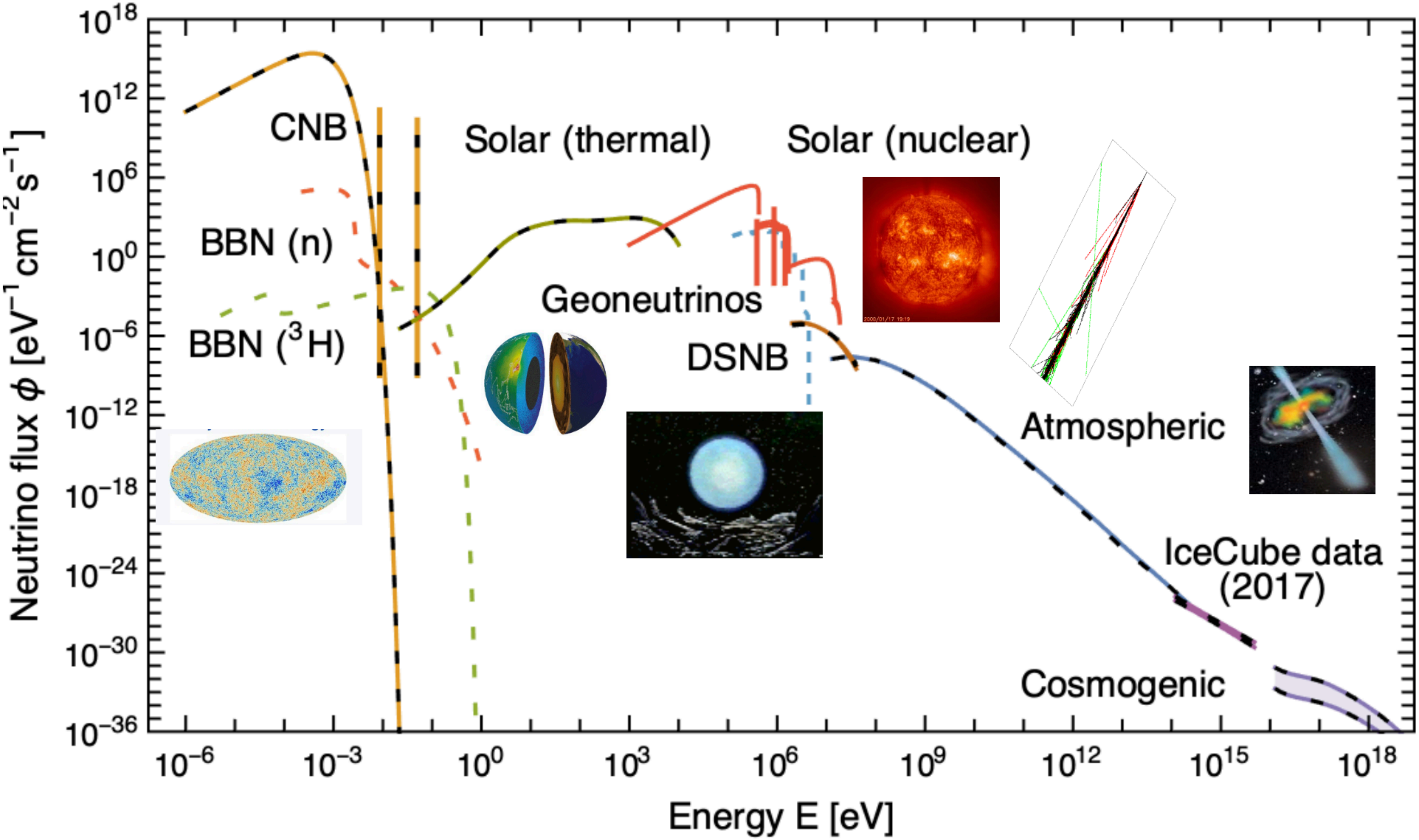
- Majorana vs Dirac

Astrophysical Neutrinos:

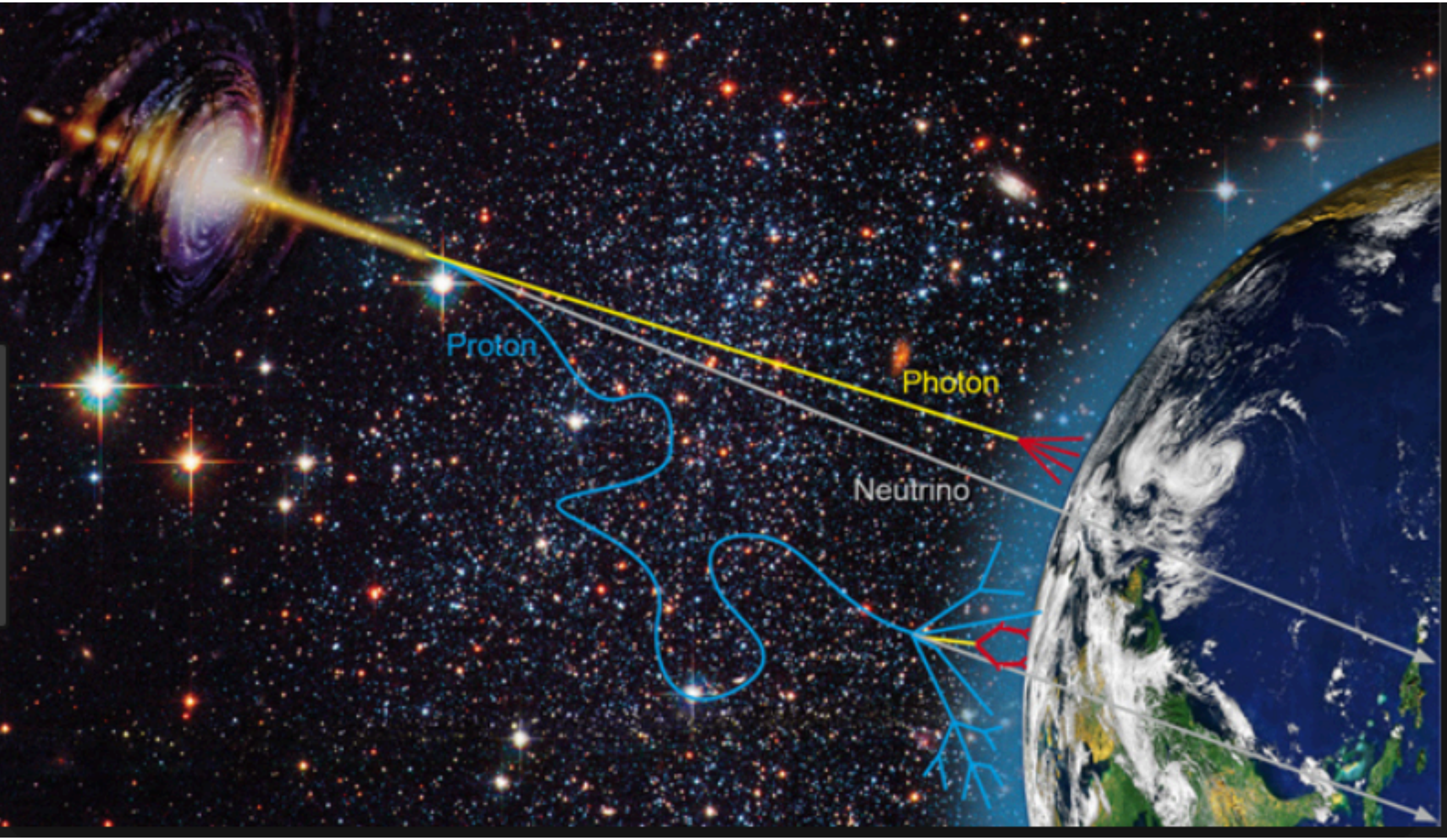
SN, GRBs, AGNs, mergers

- Possible BSM physics

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF



[Slide Curtesy: Kate Scholberg, Snowmass CSS 2022]



[Photo credit: Astroparticle Physics - DESY]

Neutrinos as messengers

IceCube: Talk by Juan Pablo Yanez

Where Do We Stand?

- Latest 3 neutrino global analysis:

Gonzalez-Garcia, Maltoni, Schwetz (NuFIT), 2111.03086

with SK atmospheric data

	Normal Ordering (Best Fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

➡ hints of $\theta_{23} \neq \pi/4$

➡ expectation of Dirac CP phase δ

➡ slight preference for normal mass ordering

Neutrino Mass Measurements

- search for absolute mass scale:
  - end point kinematic of tritium beta decays $\text{Tritium} \rightarrow He^3 + e^- + \overline{\nu}_e$

$m_{\nu_e} < 2.2 \text{ eV } (95\% \text{ CL})$ Mainz

$m_{\nu_\mu} < 170 \text{ keV}$

$m_{\nu_\tau} < 15.5 \text{ MeV}$

KATRIN: current limit ~ 0.8 eV
Future sensitivity ~ 0.2 eV

Other ideas: Project 8, ECHO, Holmes

  - neutrinoless double beta decay

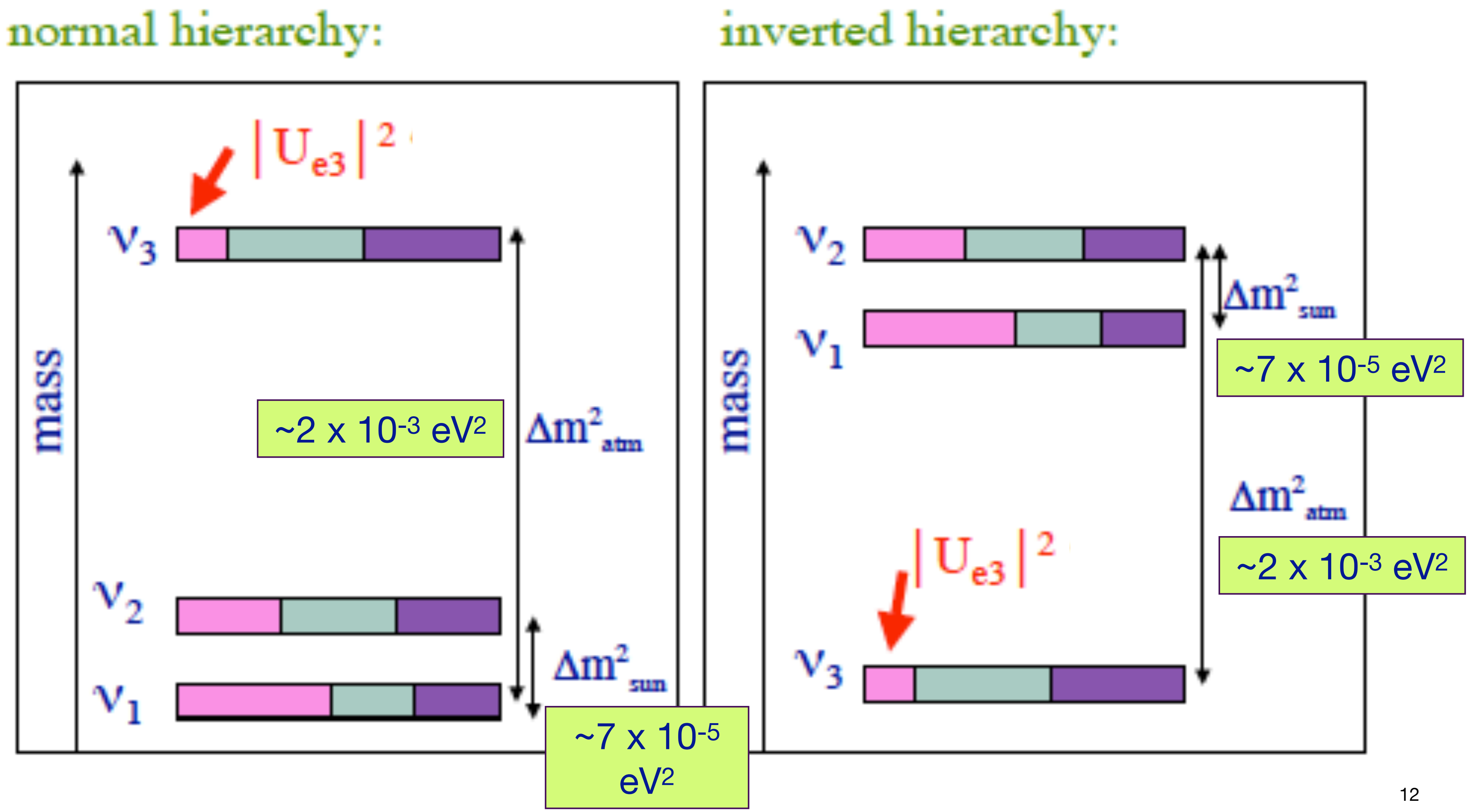
current bound: $|\langle m \rangle| \equiv \left| \sum_{i=1,2,3} m_i U_{ie}^2 \right|$ < (0.061-0.165) eV (Kamland-Zen, 2016)

  - Cosmology $\Sigma(m_{\nu_i}) < 0.12$ eV

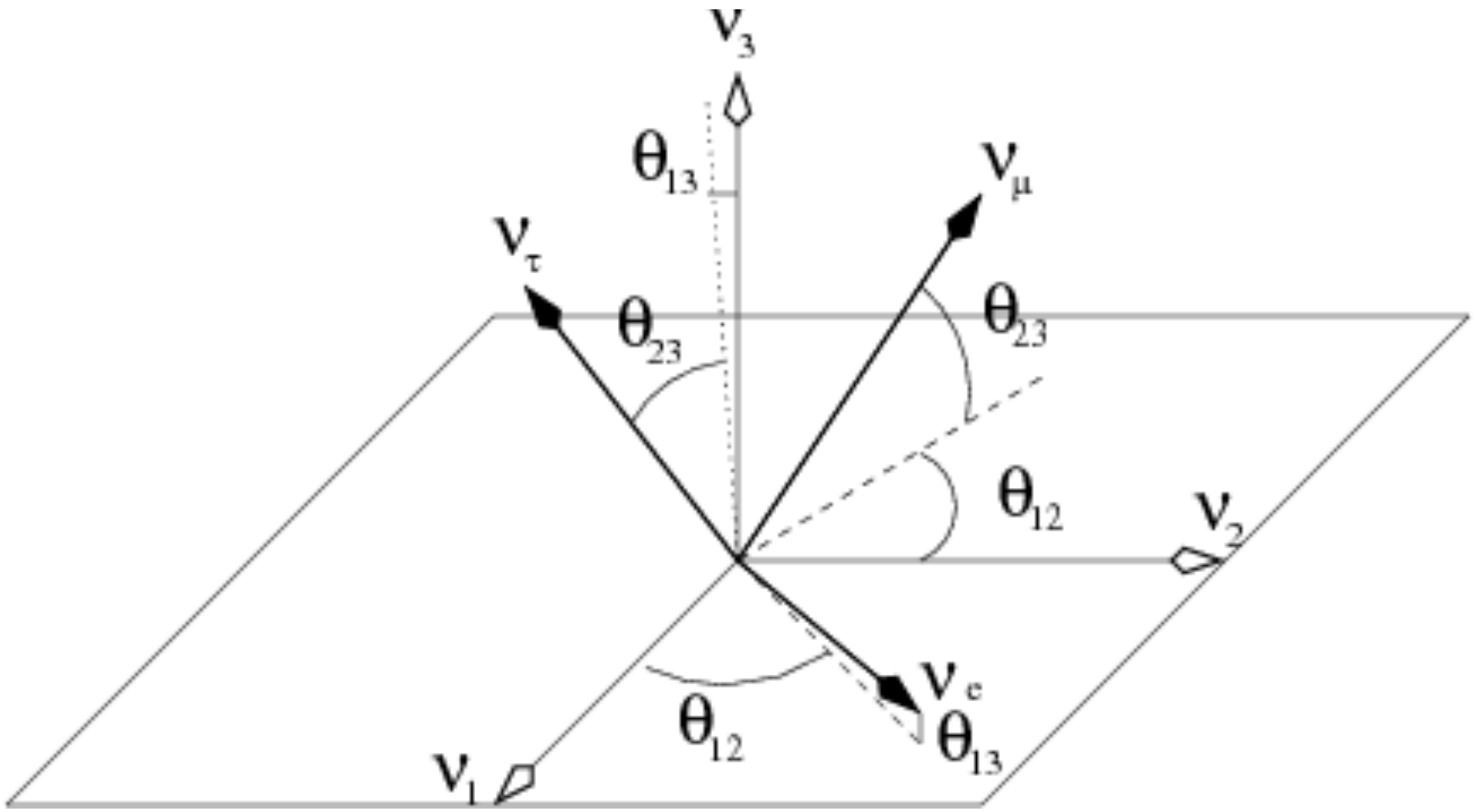
$N_{eff} = 2.99 \pm 0.17$ [Planck 2018] $\Rightarrow$ fully thermalized sterile neutrino disfavored

How are masses ordered?

The known knowns:



The Known Knowns



NuFIT (2022)

[θ^{lep}_{23} ~ 42°] [θ^{lep}_{12} ~ 33°] [θ^{lep}_{13} ~ 9°]

Open Questions - Neutrino Properties

☞ **CP** violation in lepton sector?

☞ **Mass ordering**: sign of (Δm_{13}^2)?

☞ **Precision:** $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?

CP Violation in Neutrino Oscillation

- With leptonic Dirac CP phase δ ≠ 0 ➜ leptonic CP violation
- Predict different transition probabilities for neutrinos and antineutrinos

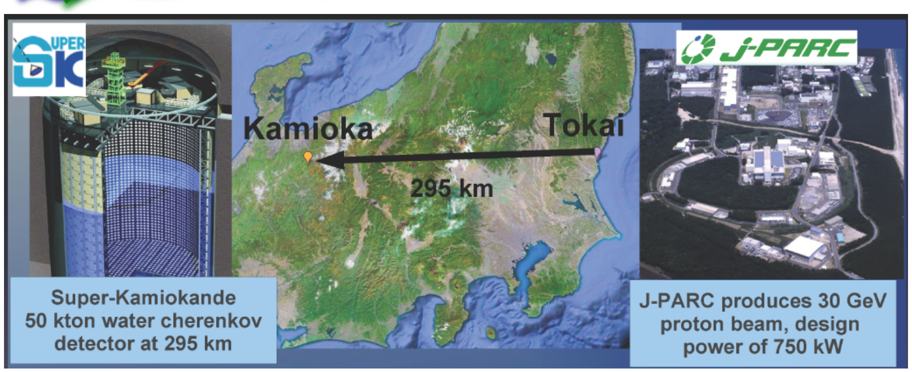
$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu_\alpha} \to \overline{\nu_\beta})$$

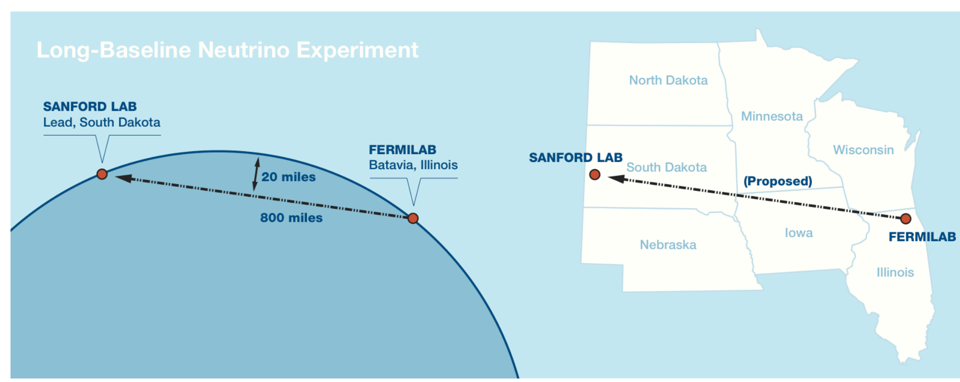
- One of the major scientific goals at current and planned neutrino experiments

T2K

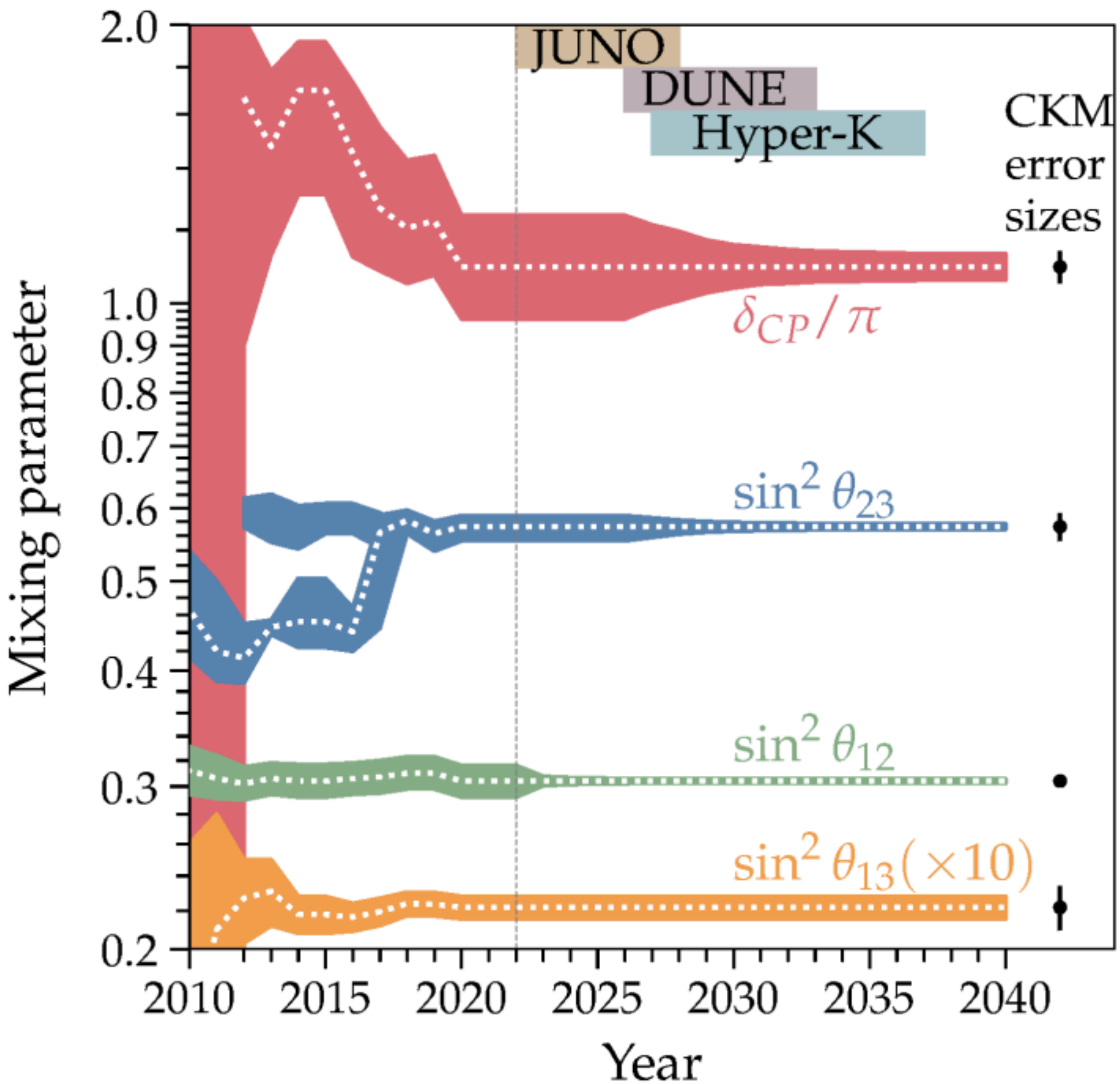
Hyper-Kamiokande

DUNE





Experimental Precision: Oscillation Parameters



NoVA: Talk by Ashley Back

T2K: Talk by Alexander Izmaylov

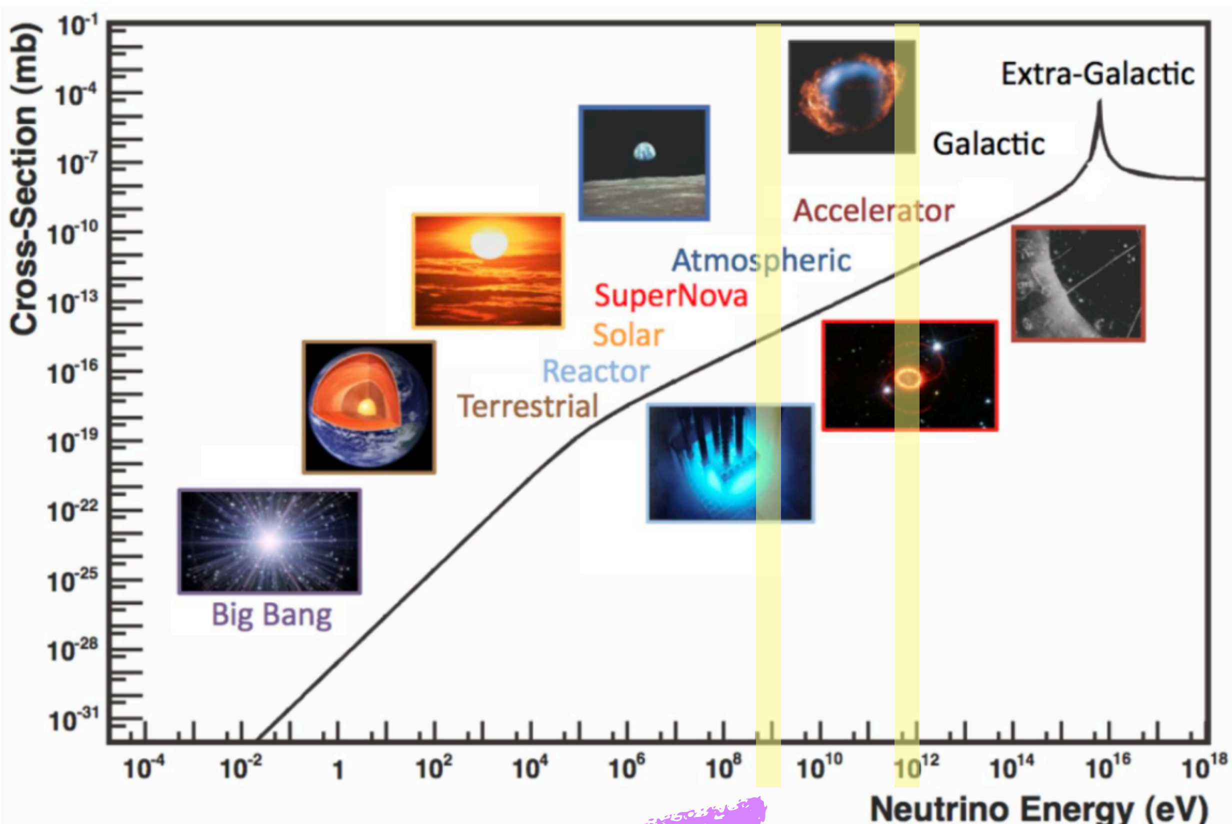
DUNE: Talk by Pip Hamilton

Hyper-K: Talk by Stephane Zsoldos

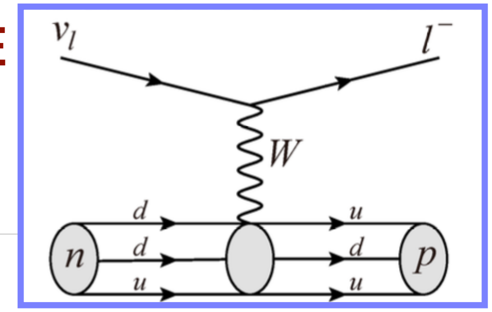
JUNO: Talk by Giuseppe Andronico

Figure from Song, Li, Argüelles, Bustamante, Vincent (2020)

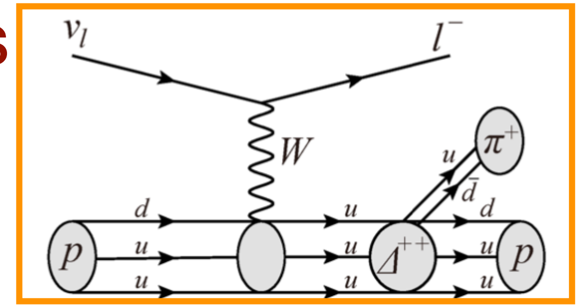
Neutrino Interactions



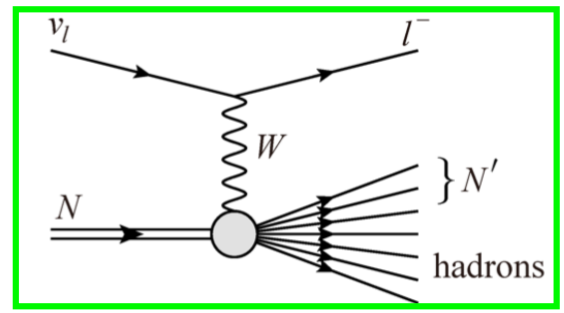
CCQE



CC RES



CC DIS



MicroBooNE: Talk by Melissa Uchida

@GeV: Needed to understand oscillation data

SND@CERN: Talk by Albert De Roeck

(TeV) Neutrinos at LHC

Some Anomalies are
more anomalous
than others.

Neutrino Anomalies

Neutrinos Travel Faster Than Light, According to One Experiment

Others doubt the mind-boggling claim, which would overturn Einstein's theory of special relativity

22 SEP 2011 • BY ADRIAN CHO (Science)

Common origin of superluminal neutrinos and DAMA annual modulation

Neutrino A…

Superluminal neutri… domain w…

Multiple Lorentz Groups - A Toy Model for Superluminal Muon Neutrinos

Neut… …ight, According … Experiment

Others doubt the mind… would overturn Einstein's theory of special relativit…

…11 • BY ADRIAN CHO

Superluminal Neutrinos in the Minimal Standard Model Extension

Superluminal Neutrinos without Revolution

Tachyonic neutrinos and the neutrino mas…s

A model of superluminal neutrinos

Common origin ...

Once Again, Physicists Debunk Faster-Than-Light Neutrinos

Five different groups agree that the elusive particles obey Einstein's speed limit after all

8 JUN 2012 • BY ADRIAN CHO (Science)

Multipl...

Superlum...

Superluminal Neutrinos in the Minimal Standard Model Extension

Superluminal Neutrinos without Revolution

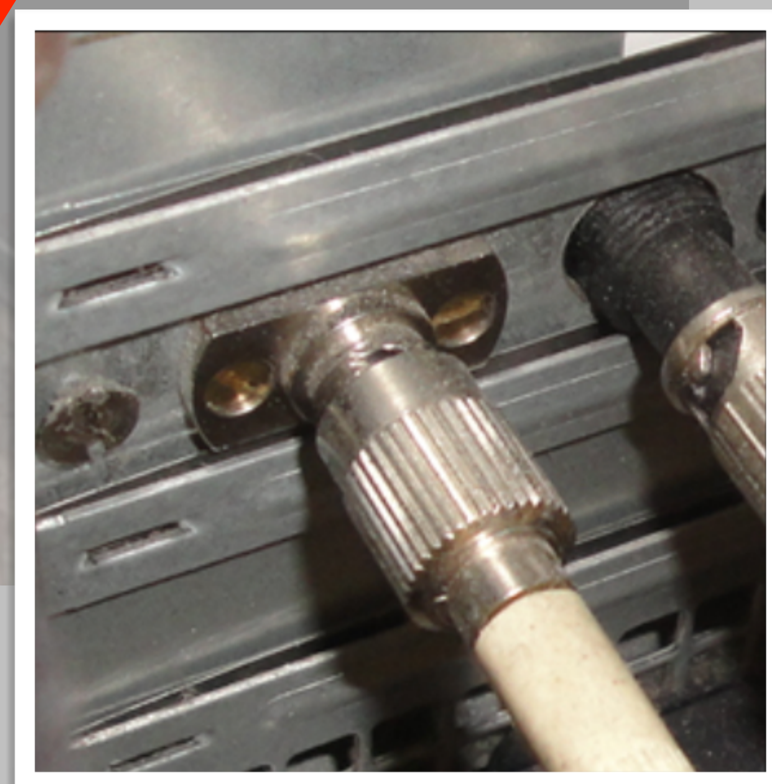
Tachyonic neutrinos and the neutrino mas...s

A model of superluminal neutrinos

N... Experiment

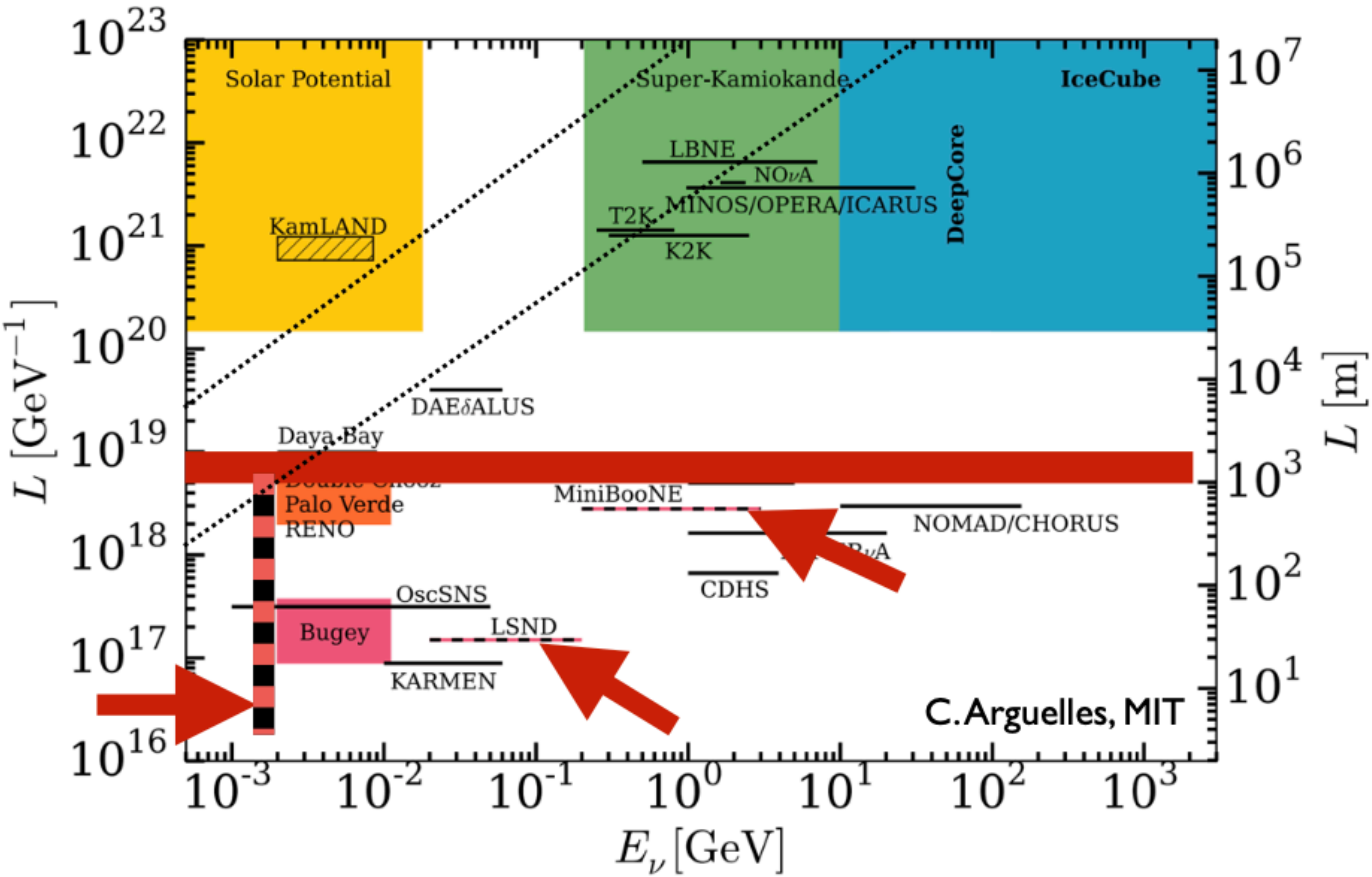
...thers doubt the mind-... would overturn Einstein's theory of special relativity

...11 • BY ADRIAN CHO

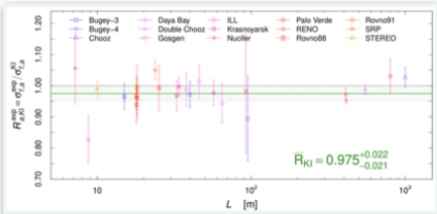


Neutrino Anomalies

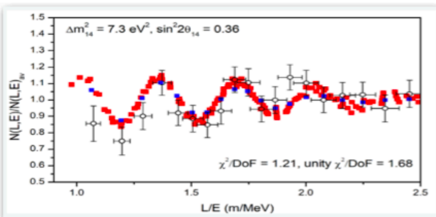
Measurements at < km disagree with state-of-the-art neutrino predictions



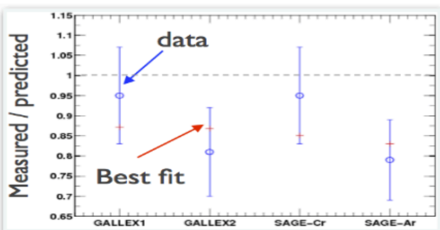
Neutrino Anomalies



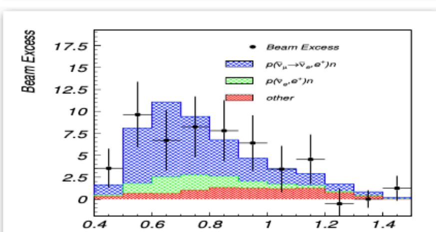
reactor flux anomaly
resolved with new input data to flux calculation



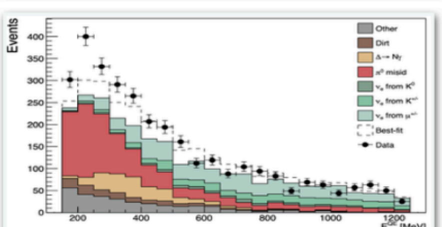
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



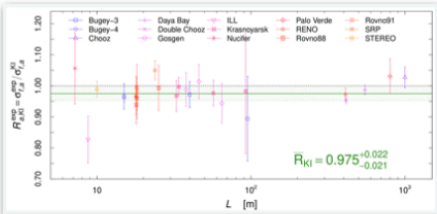
LSND
unresolved



MiniBooNE
unresolved

[Slide Curtesy: Joachim Kopp @ Neutrino 2022]

Are there sterile neutrinos?



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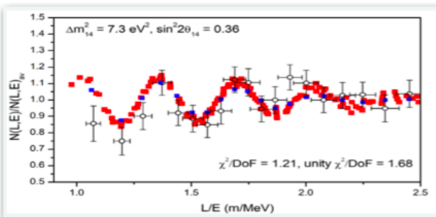

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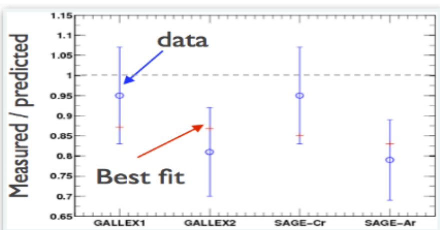

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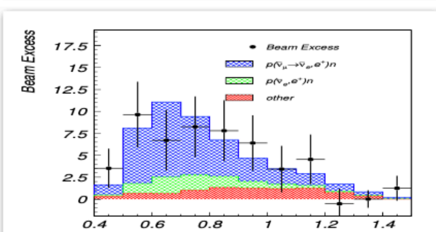
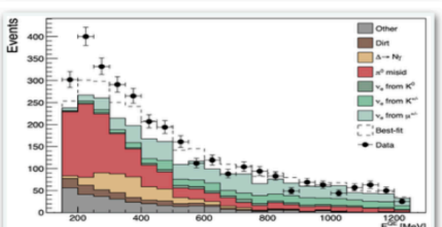


LSND
unresolved



MiniBooNE
unresolved

[Slide Curtesy: Joachim Kopp @ Neutrino 2022]

New neutrino mass states (eV)?

Sterile neutrinos

DANSS: Talk by Eduard Samigullin

MicroBooNE: Talk by Melissa Uchida

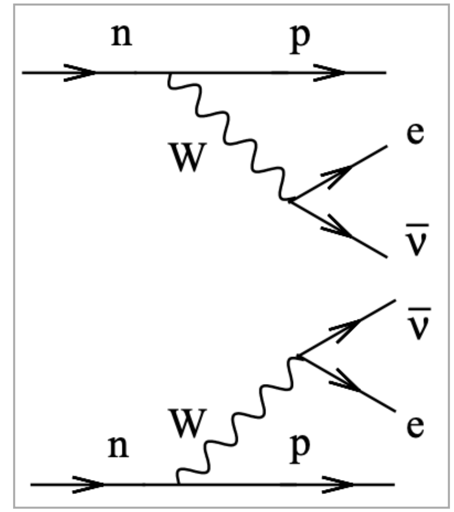
IceCube: Talk by Juan Pablo Yanez

(NoVA: Talk by Ashley Back)

Are Neutrinos their Own Antiparticles?

Two-neutrino double-β decay

Maria Goeppert-Mayer, 1935



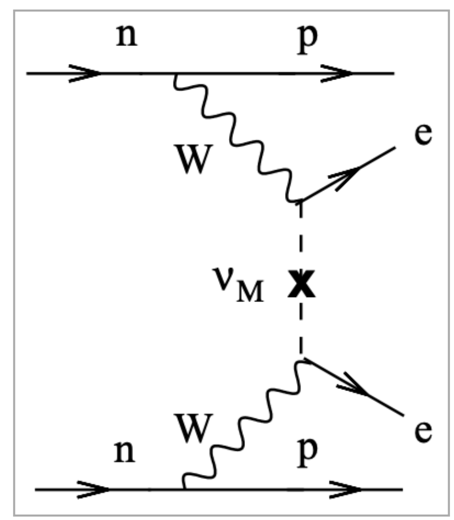
LN conserved

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

First observed in 1987

Neutrinoless double-β decay

Wendell Furry, 1939



$$\Delta L = 2$$

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

Required massive Majorana neutrinos;

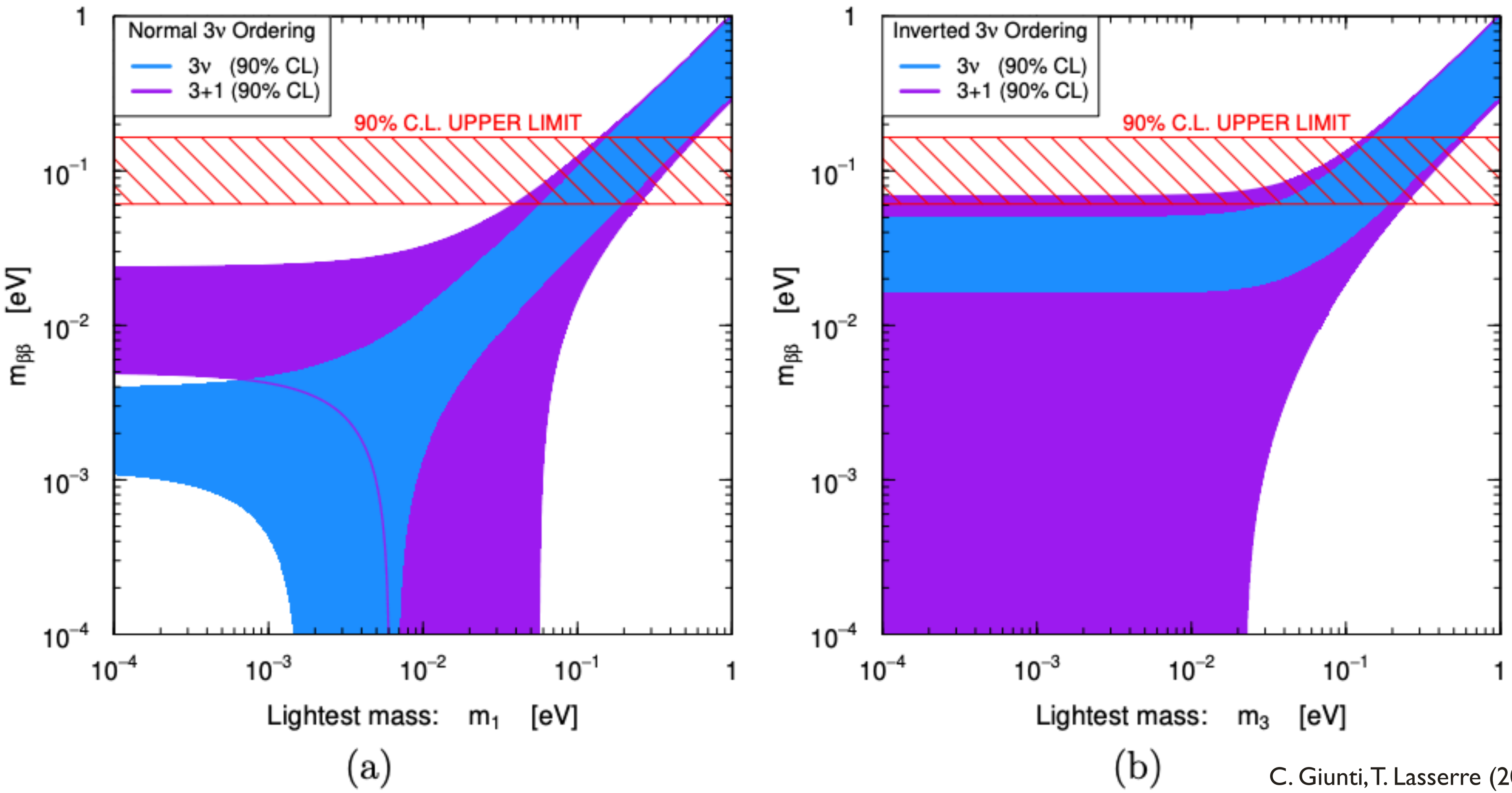
Not yet observed

Neutrinoless Double Beta Decay

$$|m_{\beta\beta}| = \left|\sum_{k=1}^{4} U_{ek}^2 \, m_k\right|$$

3ν: IO fully covered by 2035

4ν: NO can be probed



C. Giunti, T. Lasserre (2019)

Open Questions - Neutrino Properties

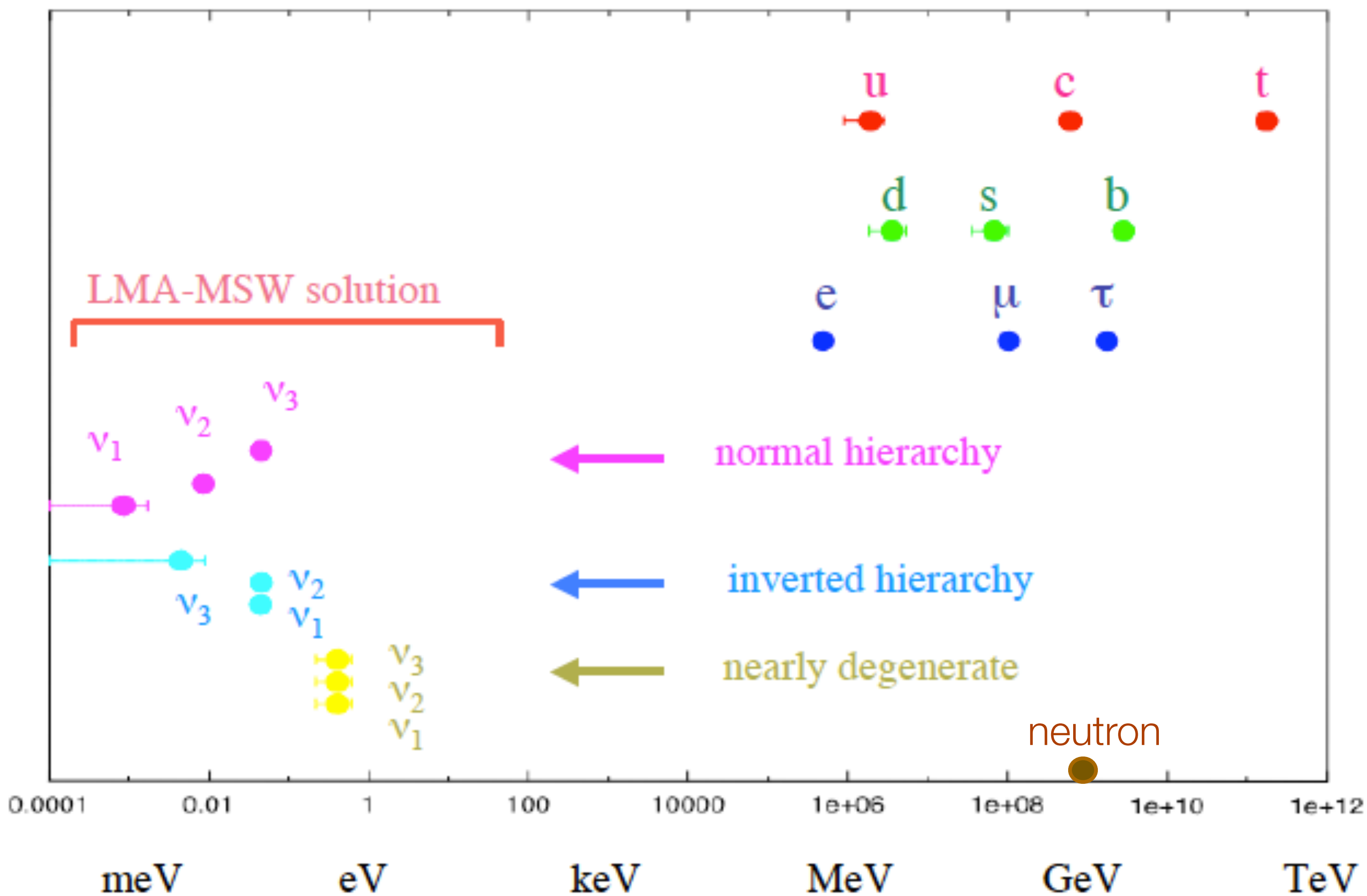
- ☞ Majorana vs Dirac?
- ☞ CP violation in lepton sector?
- ☞ Absolute mass scale of neutrinos?
- ☞ Mass ordering: sign of (Δm_{13}^2)?
- ☞ Sterile neutrino(s)?
- ☞ Precision: $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?
- ☞ Additional Neutrino Interactions?

To understand some of these properties
⇒ BSM Physics

a suite of current and upcoming experiments to address these puzzles

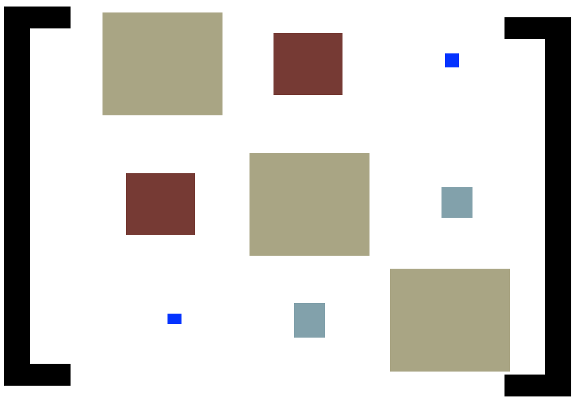
Open Questions - Theoretical

☞ Smallness of neutrino mass: $m_\nu \ll m_{e,u,d}$

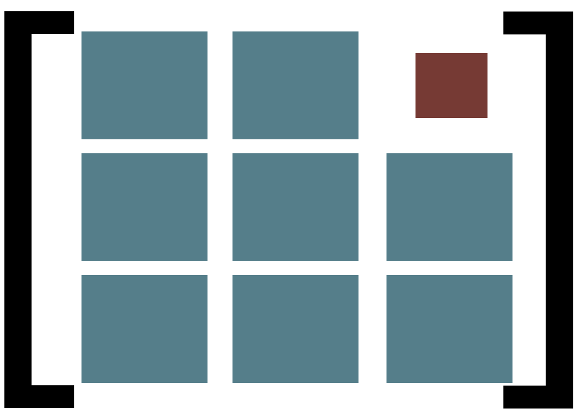


Open Questions - Theoretical

☞ Flavor structure:



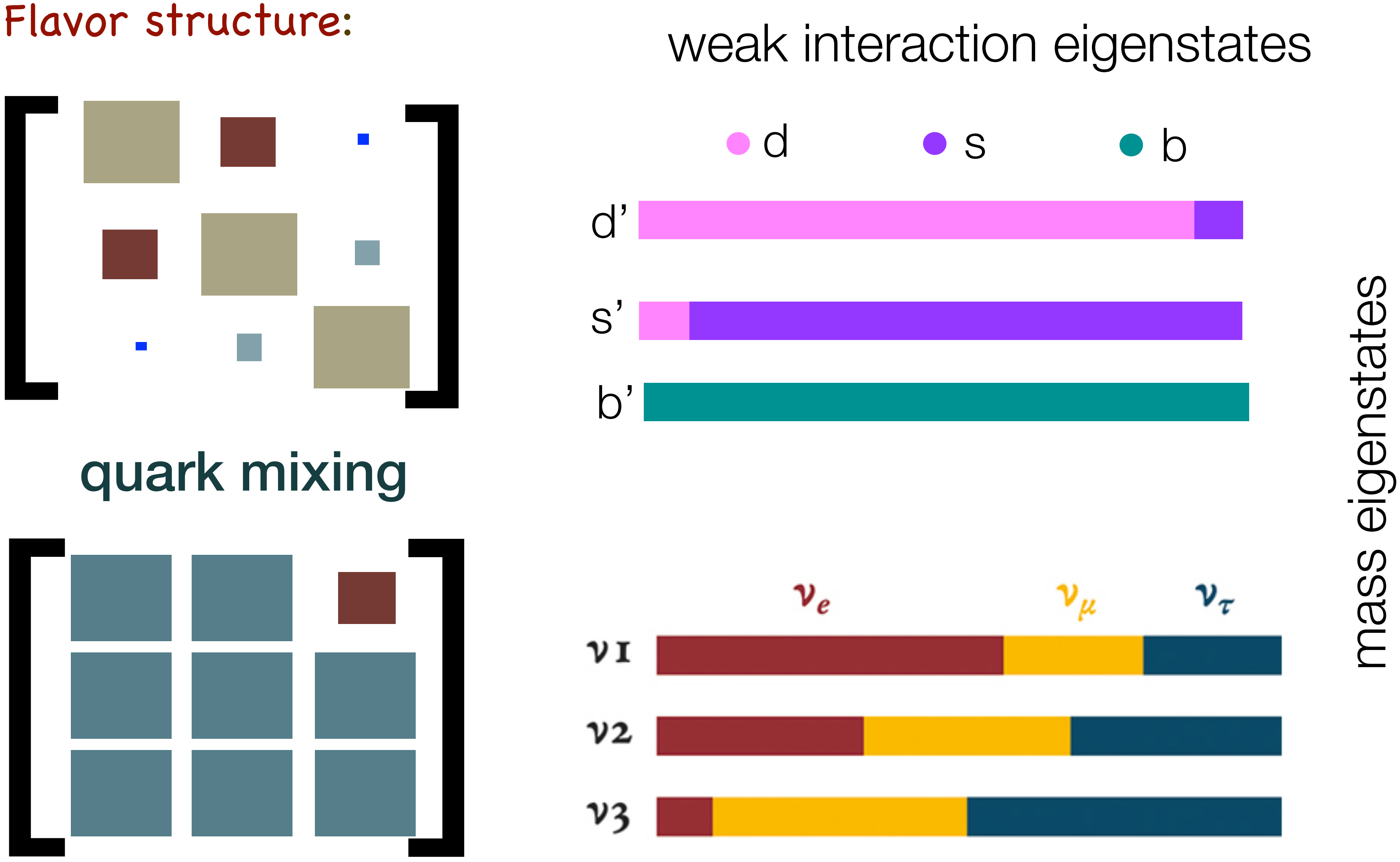
quark mixing



leptonic mixing

Open Questions - Theoretical

☞ Flavor structure:



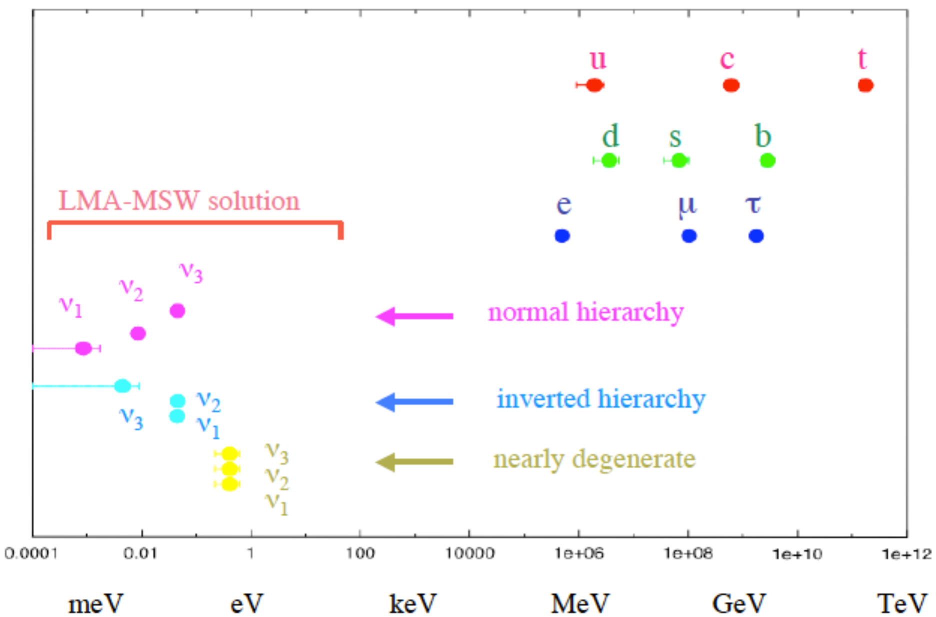
quark mixing

leptonic mixing

Open Questions - Theoretical

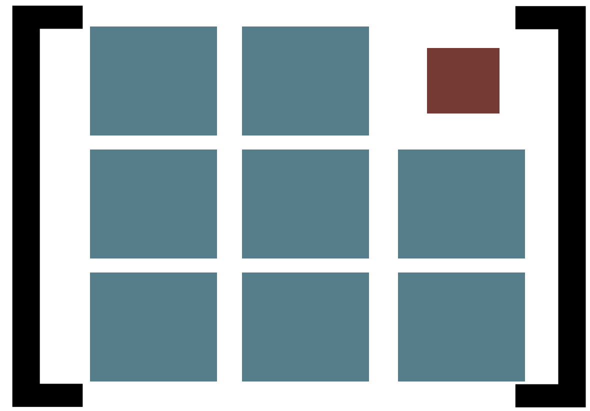
☞ Smallness of neutrino mass:

$$m_\nu \ll m_{e,\,u,\,d}$$

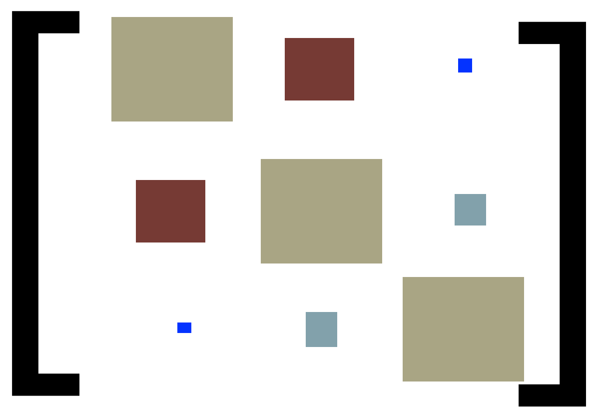


Fermion mass and hierarchy problem ➟ Many free parameters in the Yukawa sector of SM

☞ Flavor structure:



leptonic mixing



quark mixing

Why Should We Care?

- Understanding a wealth of data, fundamentally
- SM flavor sector: no understanding of significant fraction (22/28) of SM parameters; (c.f. SM gauge sector)
- Neutrinos as window into BSM physics
  - neutrino mass generation unknown (suppression mechanism, scale)
  - Uniqueness of neutrino masses ➜ connections w/ NP frameworks
- **Neutrinos affords opportunities for new explorations**
  - New Tools
  - May address other puzzles in particle physics
    - Window into early Universe
  - UV connection

e.g. stability of Dark Matter: Talk by Ricardo Cepedello

e.g. modular symmetries: Talk by Michael Ratz

Smallness of neutrino masses

What is the operator for neutrino mass generation?

- Majorana vs Dirac
- scale of the operator
- suppression mechanism

Neutrino Mass beyond the SM

- SM: effective low energy theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\mathcal{O}_{5D}}{M} + \frac{\mathcal{O}_{6D}}{M^2} + \ldots$$

→ new physics effects

- only one dim-5 operator: most sensitive to high scale physics

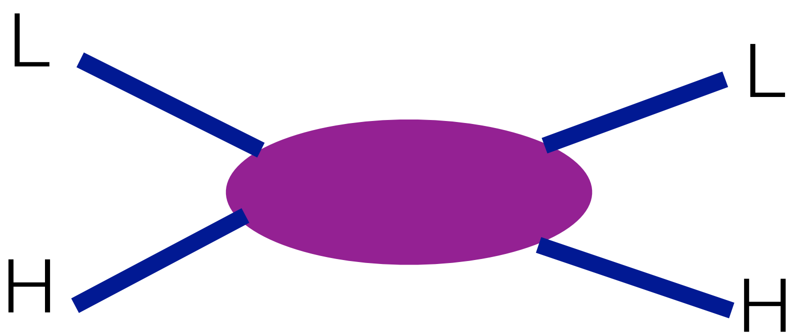
$$\frac{\lambda_{ij}}{M} H H L_i L_j \quad \Rightarrow \quad m_\nu = \lambda_{ij} \frac{v^2}{M}$$

Weinberg, 1979

- $m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.1$ eV with $v \sim 100$ GeV, $\lambda \sim O(1) \Rightarrow M \sim 10^{14}$ GeV
- Lepton number violation $\Delta L = 2$ ⇨ Majorana fermions

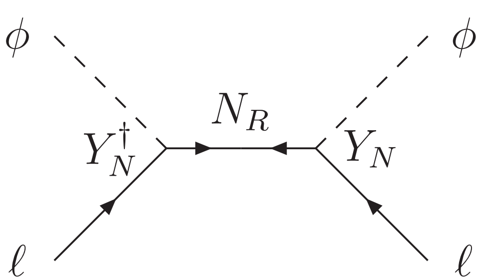
↕ GUT scale

Neutrino Mass beyond the SM



3 possible portals

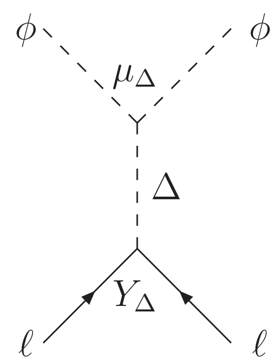
Type-I seesaw



N_R: $SU(3)_c \times SU(2)_w \times U(1)_Y \sim (1,1,0)$

Minkowski, 1977; Yanagida, 1979; Glashow, 1979;
Gell-mann, Ramond, Slansky,1979;
Mohapatra, Senjanovic, 1979;

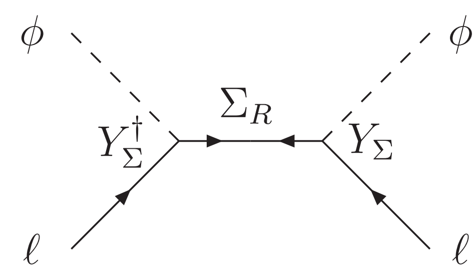
Type-II seesaw



Δ: $SU(3)_c \times SU(2)_w \times U(1)_Y \sim (1,3,2)$

Lazarides, 1980; Mohapatra, Senjanovic, 1980

Type-III seesaw



$$\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$$

Σ_R: $SU(3)_c \times SU(2)_w \times U(1)_Y \sim (1,3,0)$

Foot, Lew, He, Joshi, 1989; Ma, 1998

Why are neutrinos light? (Type-I) Seesaw Mechanism

- Adding the right-handed neutrinos:

Minkowski, 1977; Yanagida, 1979; Gell-Mann, Ramond, Slansky, 1979; Mohapatra, Senjanovic, 1981

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$m_\nu \sim m_{light} \sim \frac{m_D^2}{M_R} << m_D$$

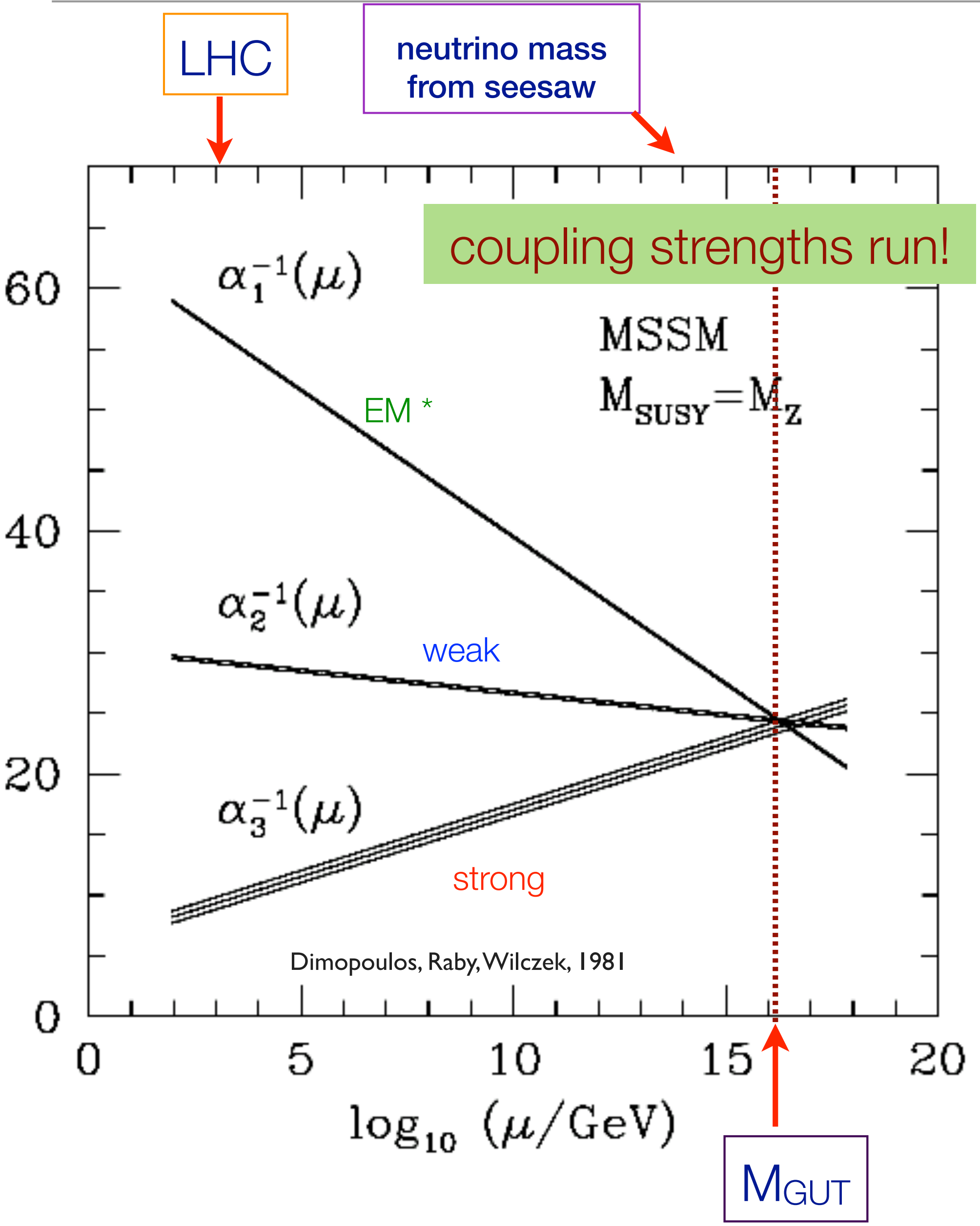
$$m_{heavy} \sim M_R$$

For $m_{\nu_3} \sim \sqrt{\Delta m^2_{atm}}$

If $m_D \sim m_t \sim 180 \ \ GeV$

$\Rightarrow$ $M_R \ \sim \ 10^{15} \ GeV \ \text{(GUT !!)}$

Grand Unification Naturally Accommodates Seesaw



- ☞ origin of the heavy scale ⇒ $U(1)_{B-L}$
- ☞ exotic mediators ⇒ predicted in many GUT theories, e.g. SO(10)

$$16 = (3, 2, 1/6) \sim \begin{bmatrix} u & u & u \\ d & d & d \end{bmatrix}$$
$$+ (3^*, 1, -2/3) \sim (u^c \; u^c \; u^c)$$
$$+ (3^*, 1, 1/3) \sim (d^c \; d^c \; d^c)$$
$$+ (1, 2, -1/2) \sim \begin{bmatrix} \nu \\ e \end{bmatrix}$$
$$+ (1, 1, 1) \sim e^c$$
$$+ (1, 1, 0) \sim \nu^c$$

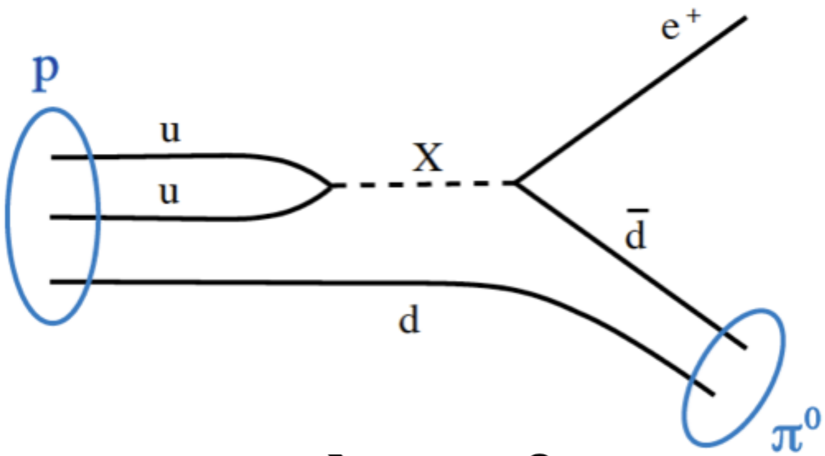
Fritzsch, Minkowski, 1975

Grand Unification: Proton Decay

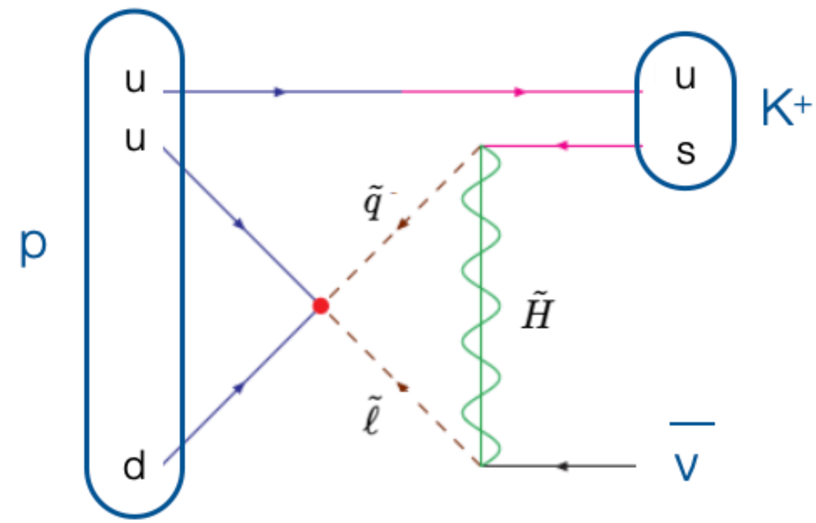
- GUT predicts proton decay

SUSY GUTs: additional contributions mediated by superpartners

$\Delta(B-L) = 0$



$p \to e^+\pi^0$



$p \to \overline{\nu} K^+$

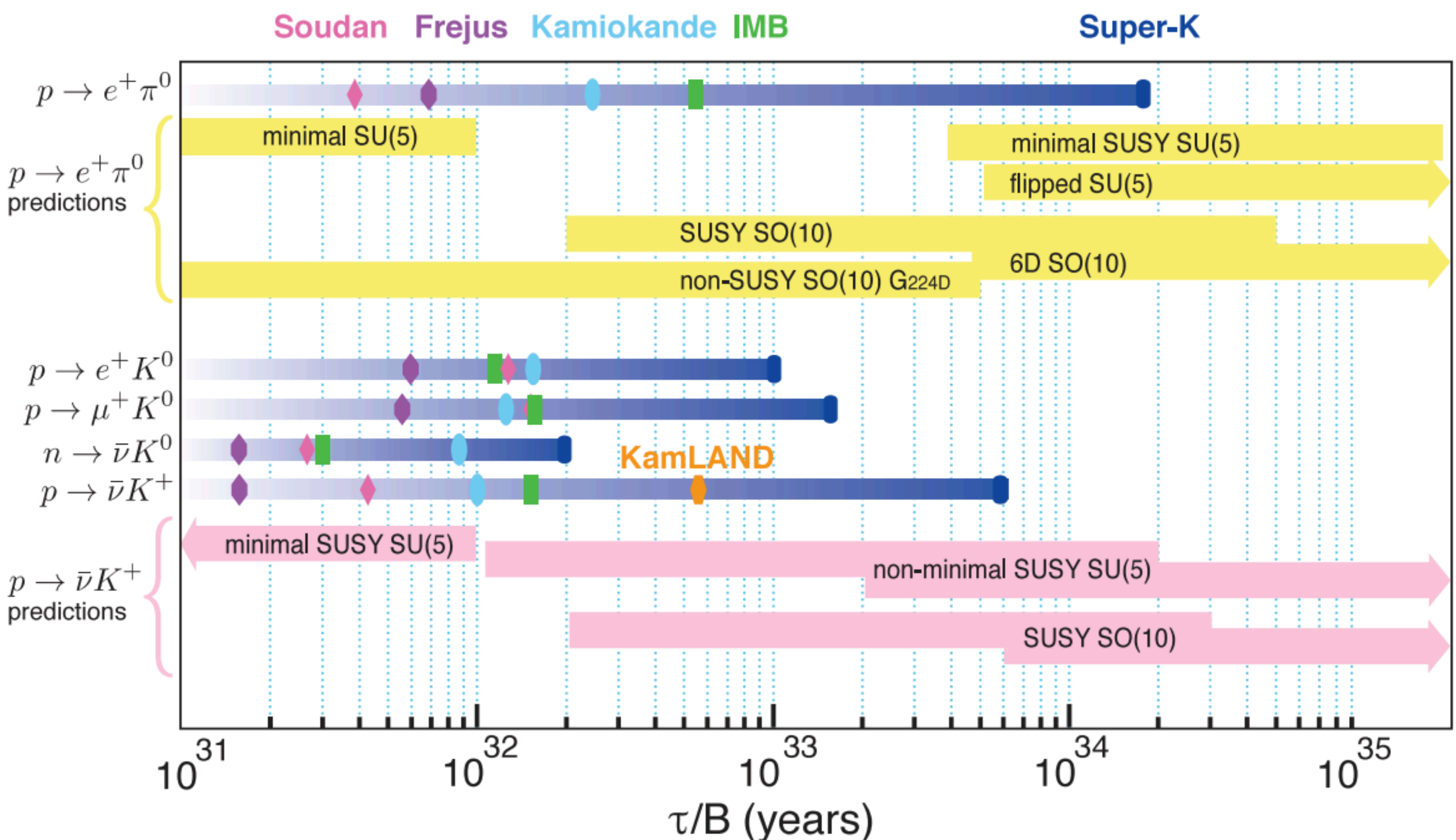
X: exotic heavy force carriers

$\tilde{H}$ **: color-triplet Higgsinos**

$$\tau_p \propto M_X^4$$

$$\tau_p \propto M_{\tilde{H}}^2$$

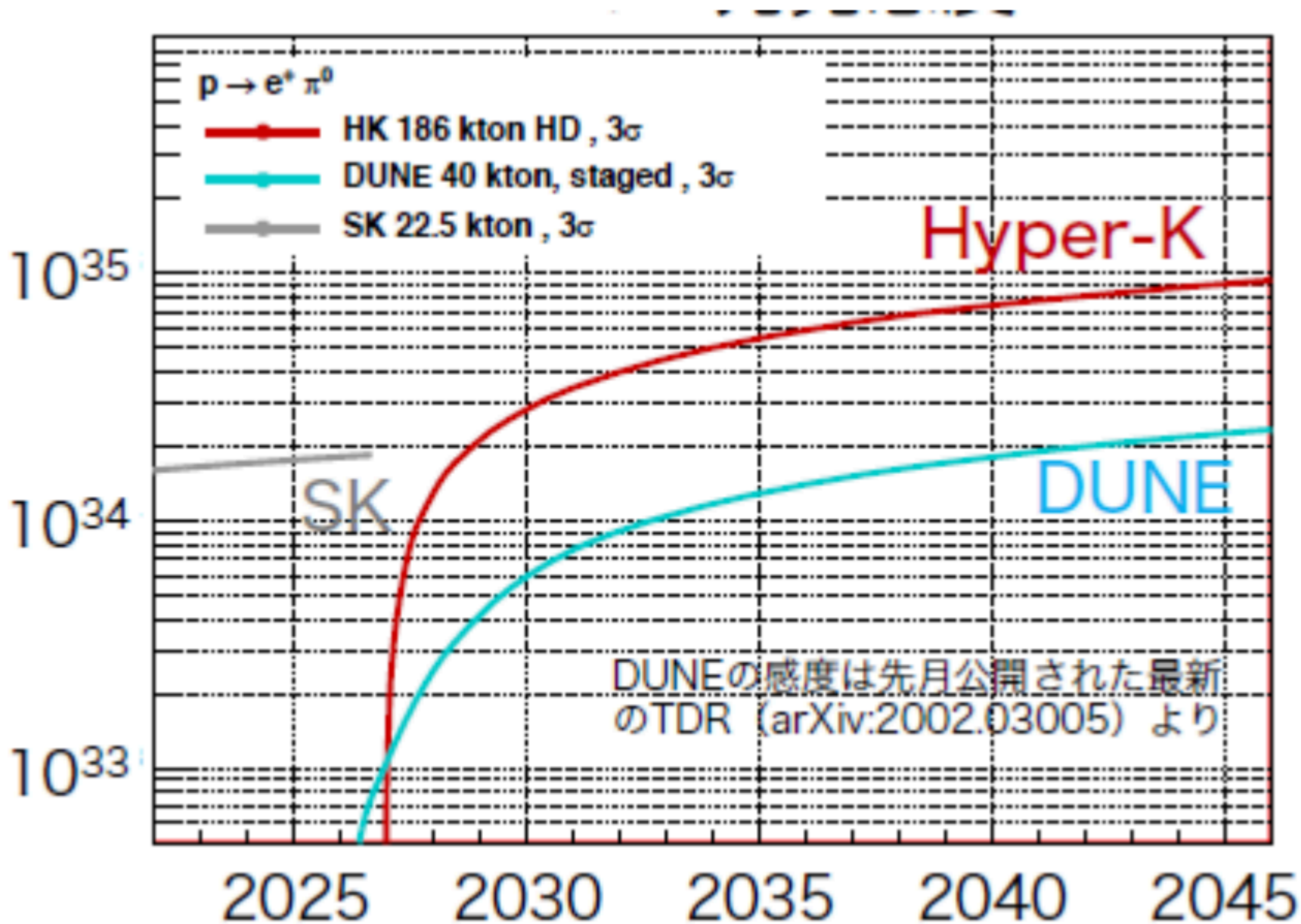
Grand Unification: Proton Decay



[K.S. Babu et al, arXiv:1311.5285]

Grand Unification: Proton Decay

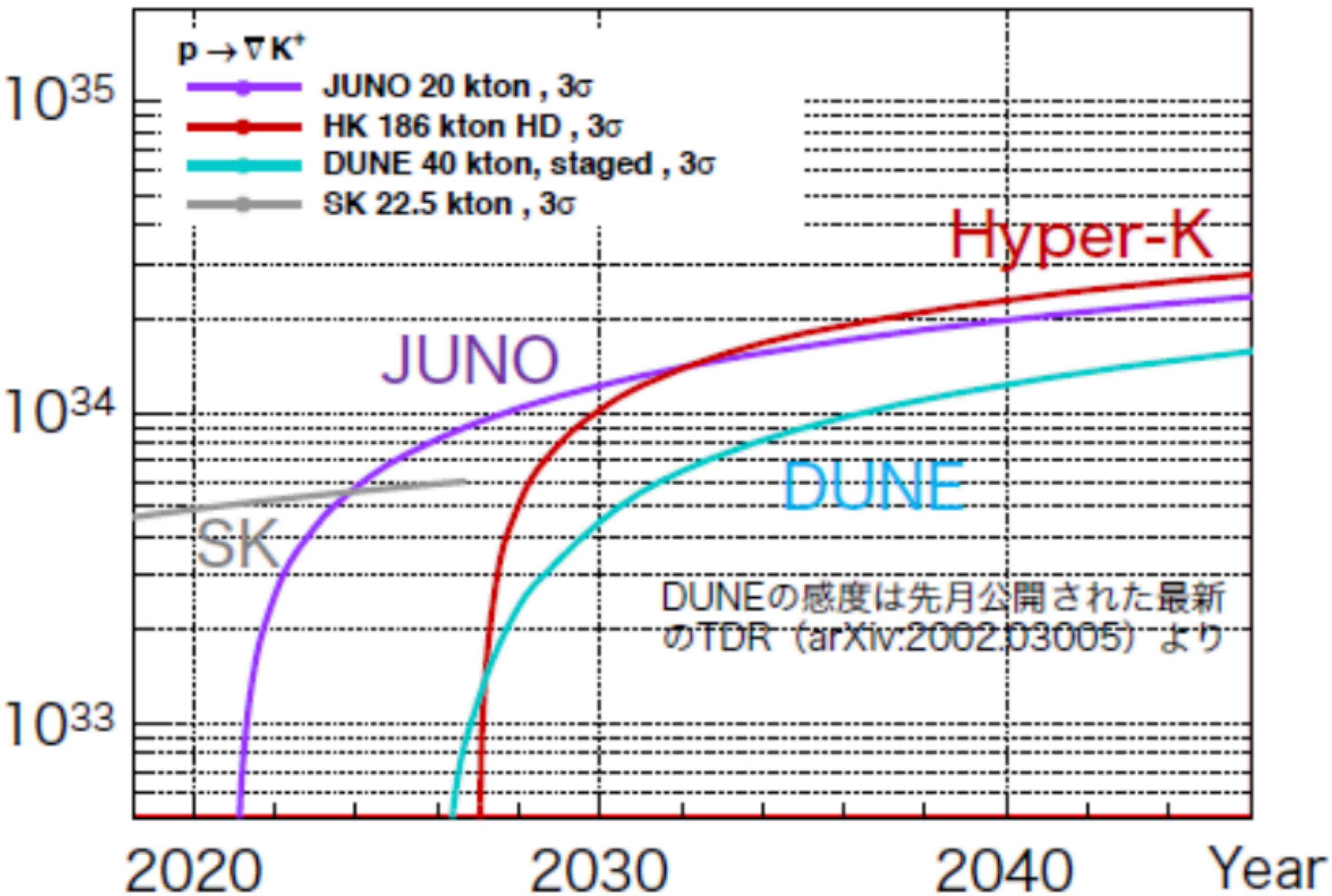
3σ discovery potential $p \to e^+\pi^0$



[M. Miura @ ICISE 2021]

Grand Unification: Proton Decay

3σ discovery potential $p \to \nu K^+$



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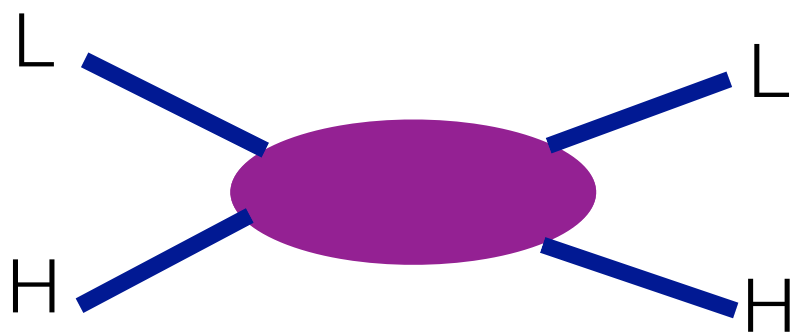

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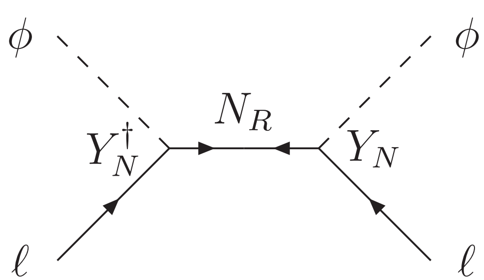

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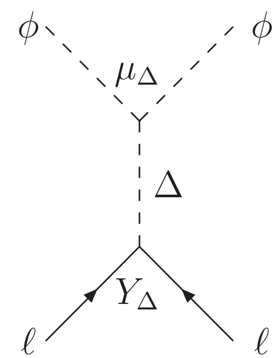

Δ: $SU(3)_c \times SU(2)_W \times U(1)_Y \sim (1,3,2)$

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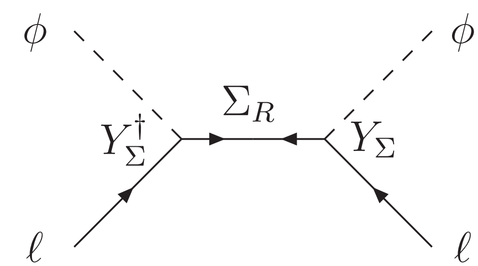
Type-III seesaw



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Σ_R: $SU(3)_c \times SU(2)_W \times U(1)_Y \sim (1,3,0)$

Foot, Lew, He, Joshi, 1989; Ma, 1998

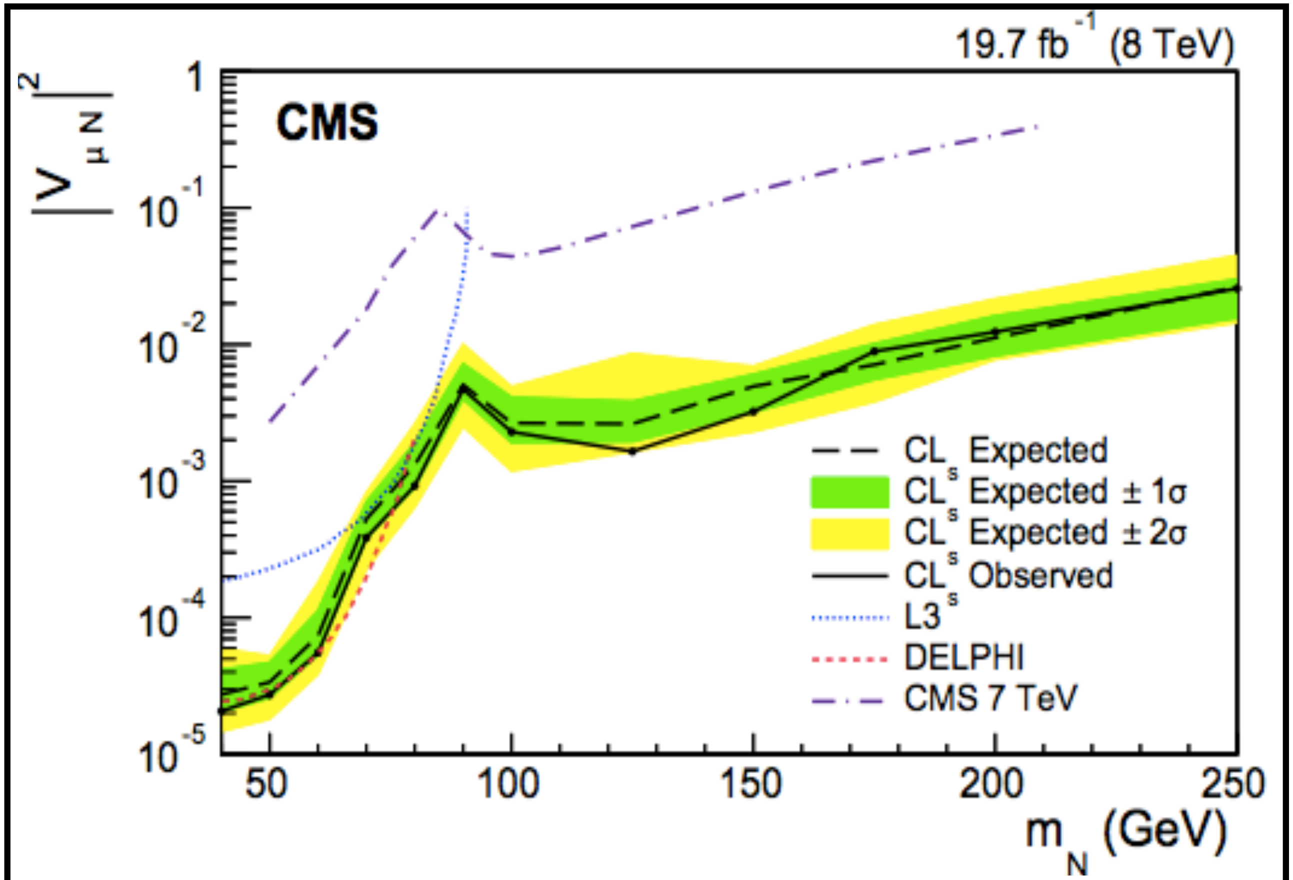
Low Scale Seesaws

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.1$ eV with $v \sim 100$ GeV, $\lambda \sim 10^{-6}$
$\Rightarrow$ M ~ 10^2 GeV

- New particles:
  - Type I seesaw: generally decouple from collider experiments
  - Type II seesaw: $\Delta^{++} \to e^+ e^+, \mu^+ \mu^+, \tau^+ \tau^+$
  - Type III seesaw: observable displaced vertex, dark matter candidate
  - inverse seesaw: non-unitarity effects
  - radiative mass generation: model dependent - singly/doubly charged SU(2) singlet, even colored scalars in loops, dark matter candidate
- New interactions:
  - LR symmetric model: W_R
  - R parity violation: $\tan^2 \theta_{\mathrm{atm}} \simeq \frac{BR(\tilde{\chi}_1^0 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}_1^0 \to \tau^\pm W^\mp)}$

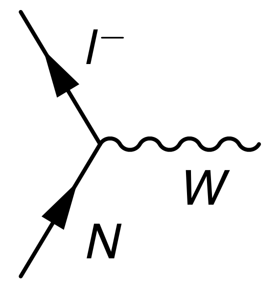
[References see e.g. Review: M.-C. C., J. Huang, 1105.3188]

Cautions!!! Is it really the ν_R in Type I seesaw?



Expanded view of the region:
40 GeV < m_N < 250 GeV

RH neutrino production thru active-sterile mixing:



$$\propto V = \frac{m_D}{M_R} \sim \frac{10^{-4}\ \text{GeV}}{100\ \text{GeV}} = 10^{-6}$$

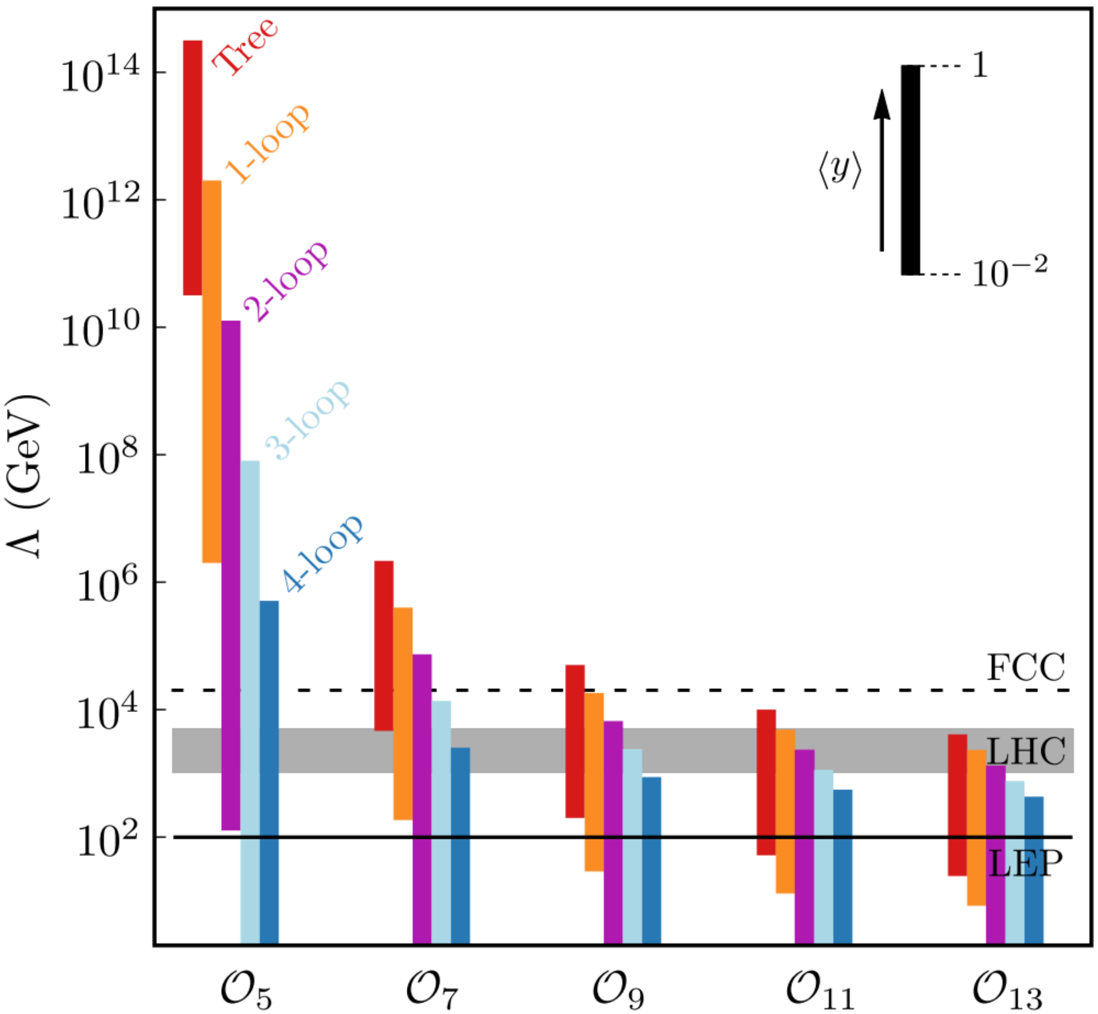
RH neutrino relevant for ν mass generation

⇨ $|V_{\mu N}|^2 = 10^{-12}$

unless extremely fine-tuned

Kersten, Smirnov (2007)

Higher Dimensional Neutrino Masses



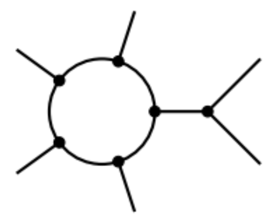
Anamiati, Castillo-Felisola, Fonseca, Helo, Hirsch (2019)

$$m_\nu \propto \epsilon \cdot \left(\frac{1}{16\pi^2}\right)^n \cdot \left(\frac{v}{\Lambda}\right)^{d-5} \cdot \frac{v^2}{\Lambda}.$$

Babu, Leung (2001); de Gouvea, Jenkins (2007); …..

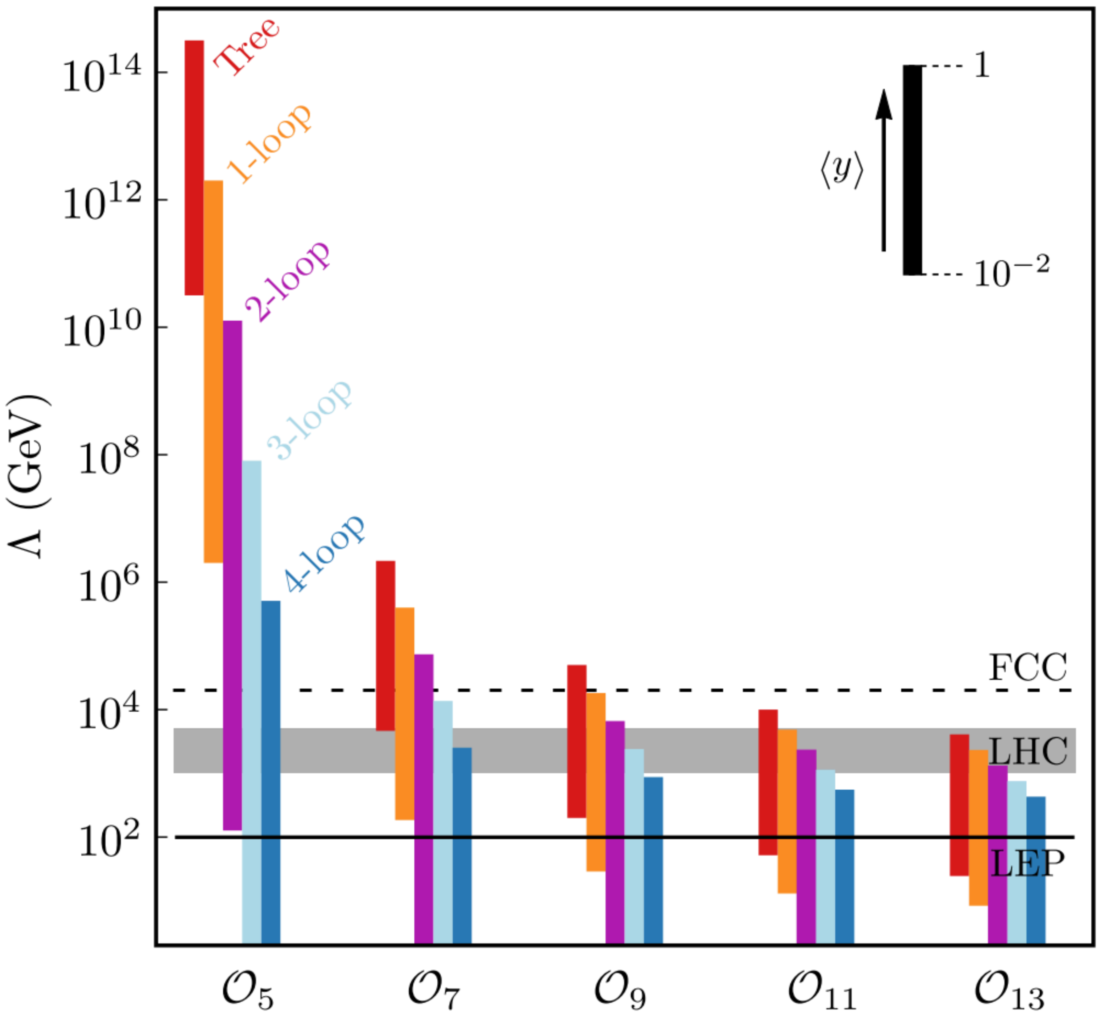
e.g. at dim-7, 1-loop

$$O_1' = LLHH(H^\dagger H)$$



For an excellent review on Radiative Neutrino Mass Generation: Cai, Herrero-García, Schmidt, Vincente, Volkas, 1706.08524

Higher Dimensional Neutrino Masses



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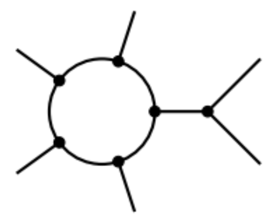


For an excellent review on Radiative Neutrino Mass Generation: Cai, Herrero-García, Schmidt, Vincente, Volkas, 1706.08524

Need a lot of work to have realistic mixing

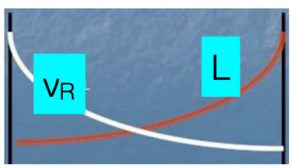
What if neutrinos are Dirac?

Small Masses - Dirac Neutrinos

Randall-Sundrum warped extra dimensions

$$\psi_{(0)} \sim e^{(1/2-c)ky}$$

UV



SM (us)

Grossman, Neubert (2000); Huber, Shafi (2001)

Clockwork Seesaw Mechanism

S.C. Park, C.S. Shin (2017); Hong, Kurup, Perelstein (2019); Babu, Saad (2020) …

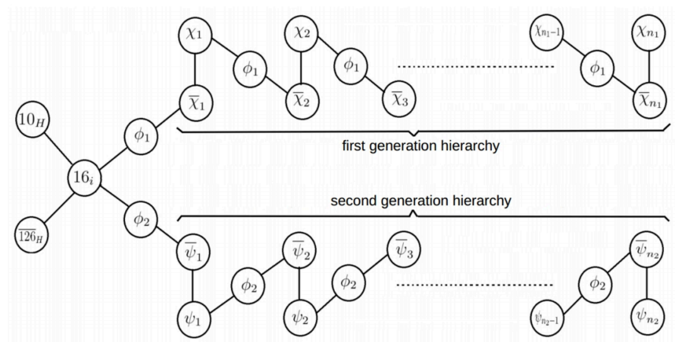
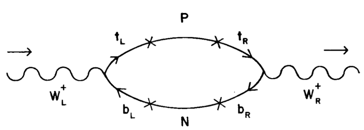


Figure from Babu, Saad (2020)

Radiative Mass Generation



Cheng, Li (1978); …..

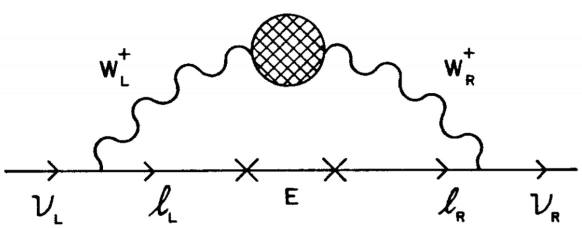
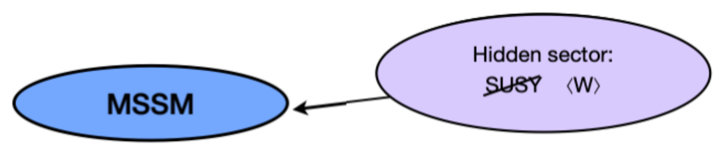


Figure from Babu, He (1988);

For clarifications of radiative Dirac neutrino mass generation: see e.g. Farzan, Pascoli, Schmidt (2012)

SUSY Breaking

Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner (2001)



$$Y_\nu \sim \frac{m_{3/2}}{M_P} \sim \frac{\mu}{M_P}$$

Flavor structure

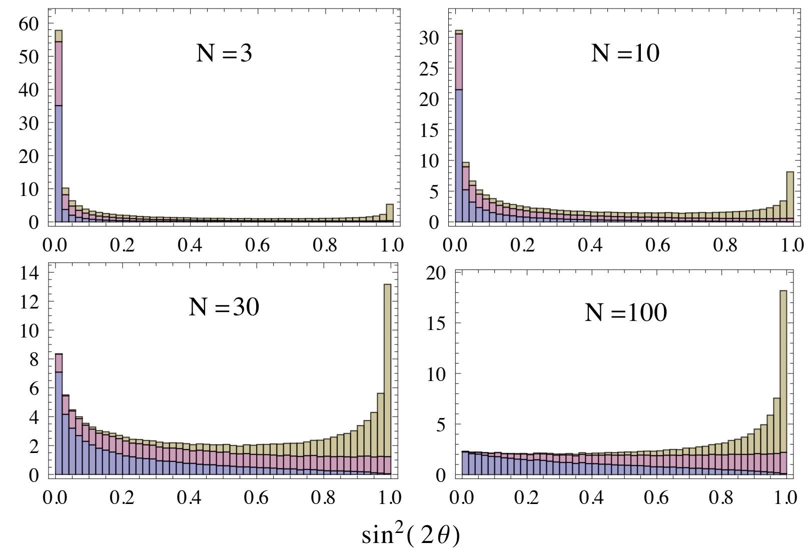
anarchy vs symmetry

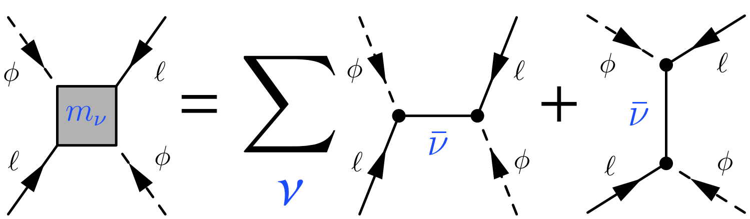
Flavor Structure - Anarchy

- there are no parametrically small numbers   Hall, Murayama, Weiner (2000); de Gouvea, Murayama (2003);
- large mixing angle, near mass degeneracy statistically preferred
- UV theory prediction can resemble anarchy
  - warped extra dimensions
  - heterotic string models: O(100) RH neutrinos   Buchmüller, Hamaguchi, Lebedev, Ramos-Sánchez, Ratz (2007)

- statistical expectations with large N (= # of RH neutrinos)

Feldstein, Klemm (2012)





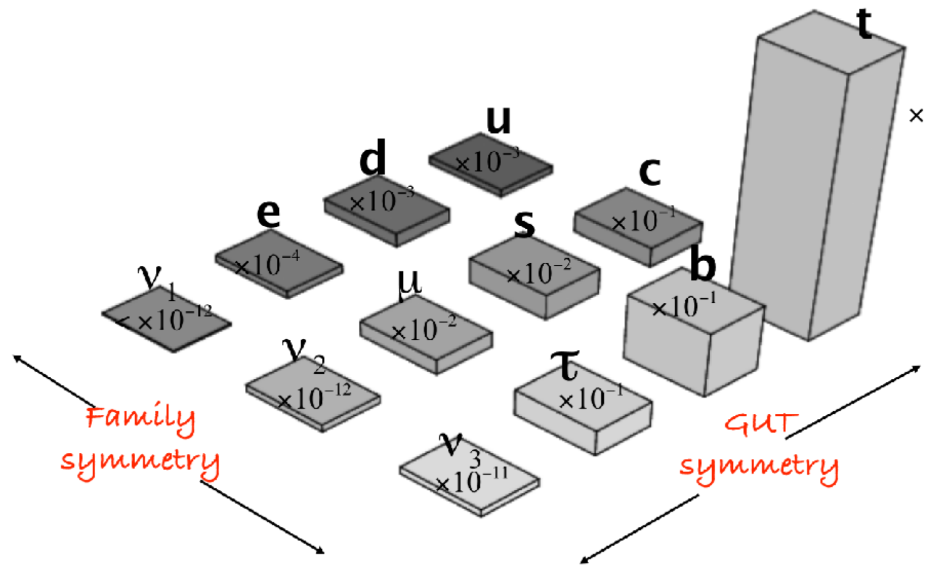
$$m_\nu \sim \frac{v^2}{M_*}$$

$$M_* \sim \frac{M_{\rm GUT}}{10 \ldots 100}$$

Flavor Structure from Symmetries

Grand Unified Theories: GUT symmetry

Quarks ↔ Leptons



[Figure Credit: arXiv:1301.1340]

Family Symmetry:

e-family ↔ muon-family ↔ tau-family

Symmetry Relations

Symmetry $\Rightarrow$ relations among parameters

$\Rightarrow$ reduction in number of fundamental parameters

Symmetry Relations

Symmetry $\Rightarrow$ relations among parameters

$\Rightarrow$ reduction in number of fundamental parameters

Symmetry $\Rightarrow$ experimentally testable

correlations among physical observables

Testing Symmetry Relations ⇒ Precision

Symmetry ⇒ experimentally testable correlations among physical observables

mass hierarchy

CP phase

$0\nu\beta\beta$

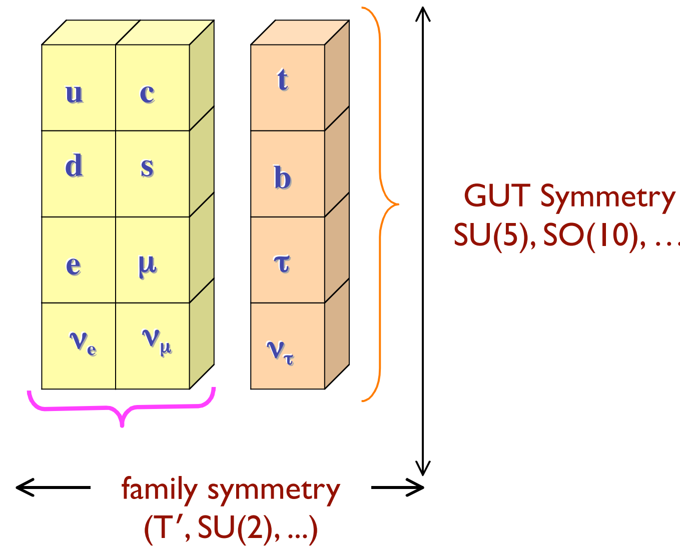
cLFV

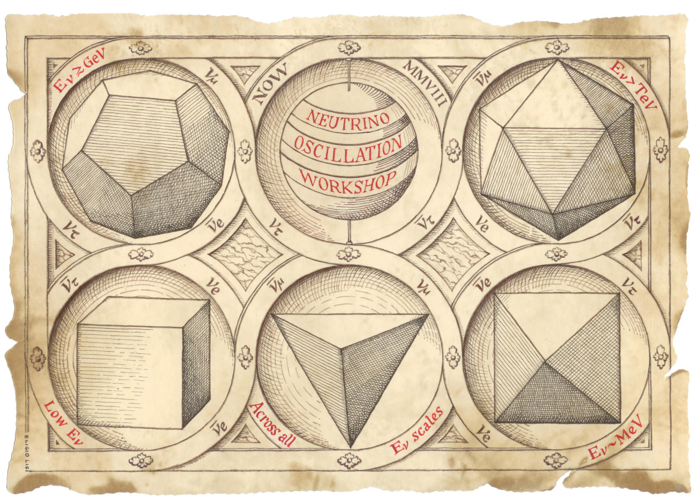
mixing angles

Testing correlations ⇒ Precision

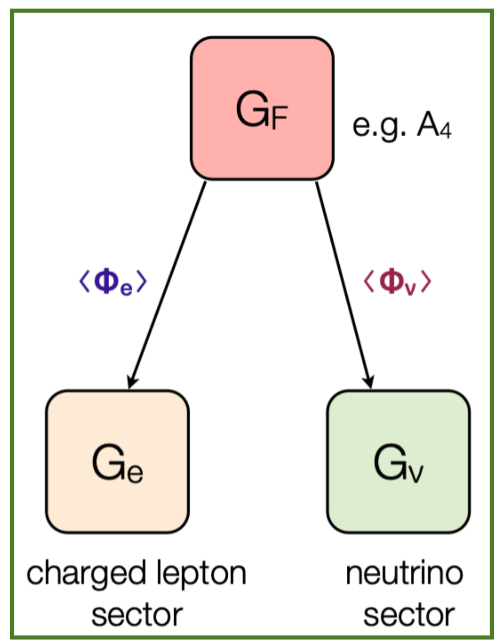
Non-Abelian Discrete Flavor Symmetries

- Large neutrino mixing motivates discrete flavor symmetries
  - A_4 (tetrahedron)
  - T´ (double tetrahedron)
  - S_3 (equilateral triangle)
  - S_4 (octahedron, cube)
  - A_5 (icosahedron, dodecahedron)
  - Δ_{27}
  - Q_6
  - .....





[Eligio Lisi for NOW2008]



Tri-bimaximal Neutrino Mixing

- **Latest Global Fit (3σ)**

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou (2020)

$$\sin^2\theta_{23} = 0.437\ (0.374 - 0.626)$$ $[\theta^{lep}_{23} \sim 49.2°]$

$$\sin^2\theta_{12} = 0.308\ (0.259 - 0.359)$$ $[\theta^{lep}_{12} \sim 33.4°]$

$$\sin^2\theta_{13} = 0.0234\ (0.0176 - 0.0295)$$ $[\theta^{lep}_{13} \sim 8.57°]$

- **Tri-bimaximal Mixing Pattern**

Harrison, Perkins, Scott (1999)

$$U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

$$\sin^2\theta_{\mathrm{atm,\,TBM}} = 1/2 \qquad \sin^2\theta_{\odot,\mathrm{TBM}} = 1/3$$

$$\sin\theta_{13,\mathrm{TBM}} = 0.$$

Neutrino Mass Matrix from A4

- Imposing A4 flavor symmetry on the Lagrangian

Ma, Rajasekaran (2001); Babu, Ma, Valle (2003); Altarelli, Feruglio (2005)

- A4 spontaneously broken by flavon fields

2 free parameters

$$M_\nu = \frac{\lambda v^2}{M_x} \begin{pmatrix} 2\xi_0 + u & -\xi_0 & -\xi_0 \\ -\xi_0 & 2\xi_0 & u - \xi_0 \\ -\xi_0 & u - \xi_0 & 2\xi_0 \end{pmatrix}$$

relative strengths
$\Rightarrow$ CG's

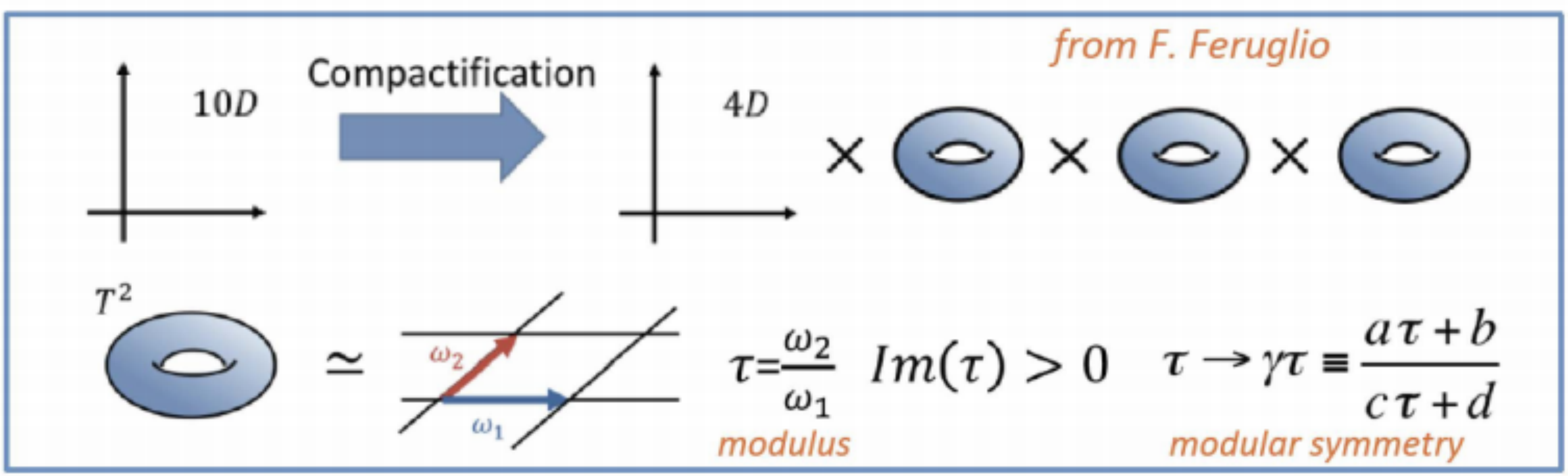
- always diagonalized by TBM matrix, independent of the two free parameters

$$U_{\rm TBM} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -\sqrt{1/6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -\sqrt{1/6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Neutrino Mixing Angles from Group Theory

Modular Flavor Symmetries

- Extra dimensional origin of non-Abelian discrete symmetries
- Modular symmetries   Altarelli, Feruglio (2005); Feruglio (2017), ...
  - Inspired by string theories
  - Imposing modular invariance $Y = Y(\tau)$
  - Highly predictive models



A Toy Modular A_4 Model

Feruglio (2017)

- Weinberg Operator $$\mathscr{W}_\nu = \frac{1}{\Lambda}[(H_u \cdot L)\ Y\ (H_u \cdot L)]_1$$
- Traditional A4 Flavor Symmetry
  - Yukawa Coupling Y → Flavon VEVs (A_4 triplet, 6 real parameters)

$$Y \to \langle\phi\rangle = \begin{pmatrix} a \\ b \\ c \end{pmatrix} \quad \Longrightarrow \quad m_\nu = \frac{v_u^2}{\Lambda}\begin{pmatrix} 2a & -c & -b \\ -c & 2b & -a \\ -b & -a & 2c \end{pmatrix}$$

- Modular A4 Flavor Symmetry
  - Yukawa Coupling Y → Modular Forms (A4 triplet, 2 real parameters)

$$Y \to \begin{pmatrix} Y_1(\tau) \\ Y_2(\tau) \\ Y_3(\tau) \end{pmatrix} \quad \Longrightarrow \quad m_\nu = \frac{v_u^2}{\Lambda}\begin{pmatrix} 2Y_1(\tau) & -Y_3(\tau) & -Y_2(\tau) \\ -Y_3(\tau) & 2Y_2(\tau) & -Y_1(\tau) \\ -Y_2(\tau) & -Y_1(\tau) & 2Y_3(\tau) \end{pmatrix}$$

A Toy Modular A_4 Model

Feruglio (2017)

- Input Parameters:

$$\tau = 0.0111 + 0.9946i \qquad v_u^2/\Lambda$$

- Predictions:

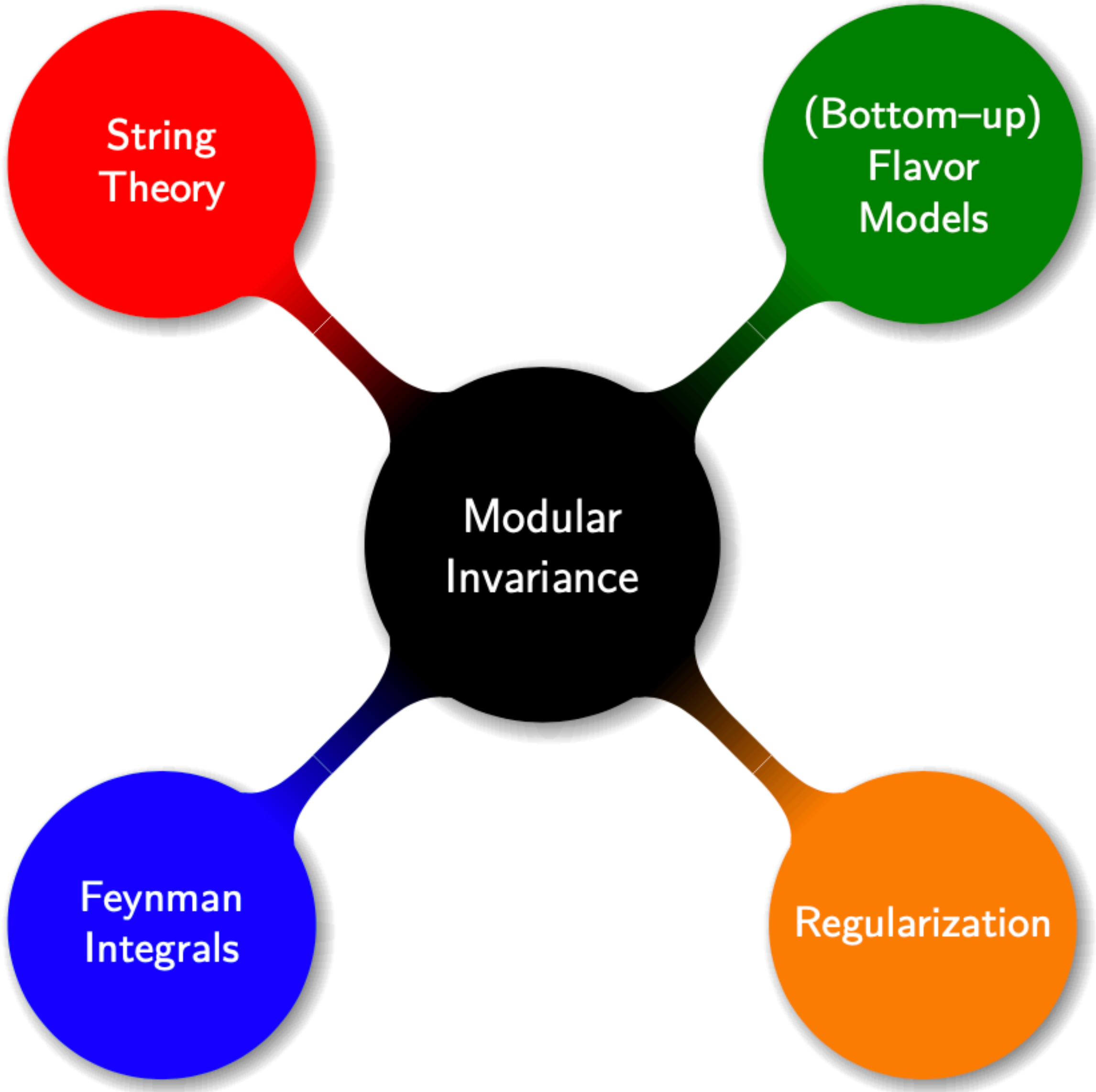
$$\frac{\Delta m^2_{sol}}{|\Delta m^2_{atm}|} = 0.0292$$

$$\sin^2\theta_{12} = 0.295 \qquad \sin^2\theta_{13} = 0.0447 \qquad \sin^2\theta_{23} = 0.651$$

$$\frac{\delta_{CP}}{\pi} = 1.55 \qquad \frac{\alpha_{21}}{\pi} = 0.22 \qquad \frac{\alpha_{31}}{\pi} = 1.80 \quad .$$

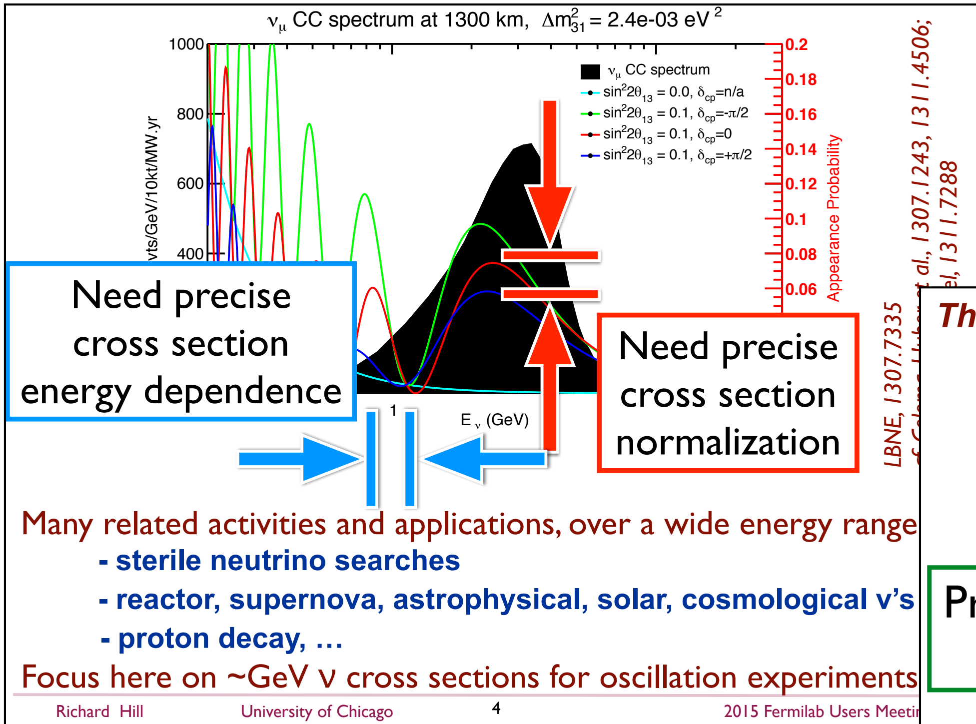
$$m_1 = 4.998 \times 10^{-2}\ eV \qquad m_2 = 5.071 \times 10^{-2}\ eV \qquad m_3 = 7.338 \times 10^{-4}\ eV$$

Modular Invariance Beyond Neutrino Flavor

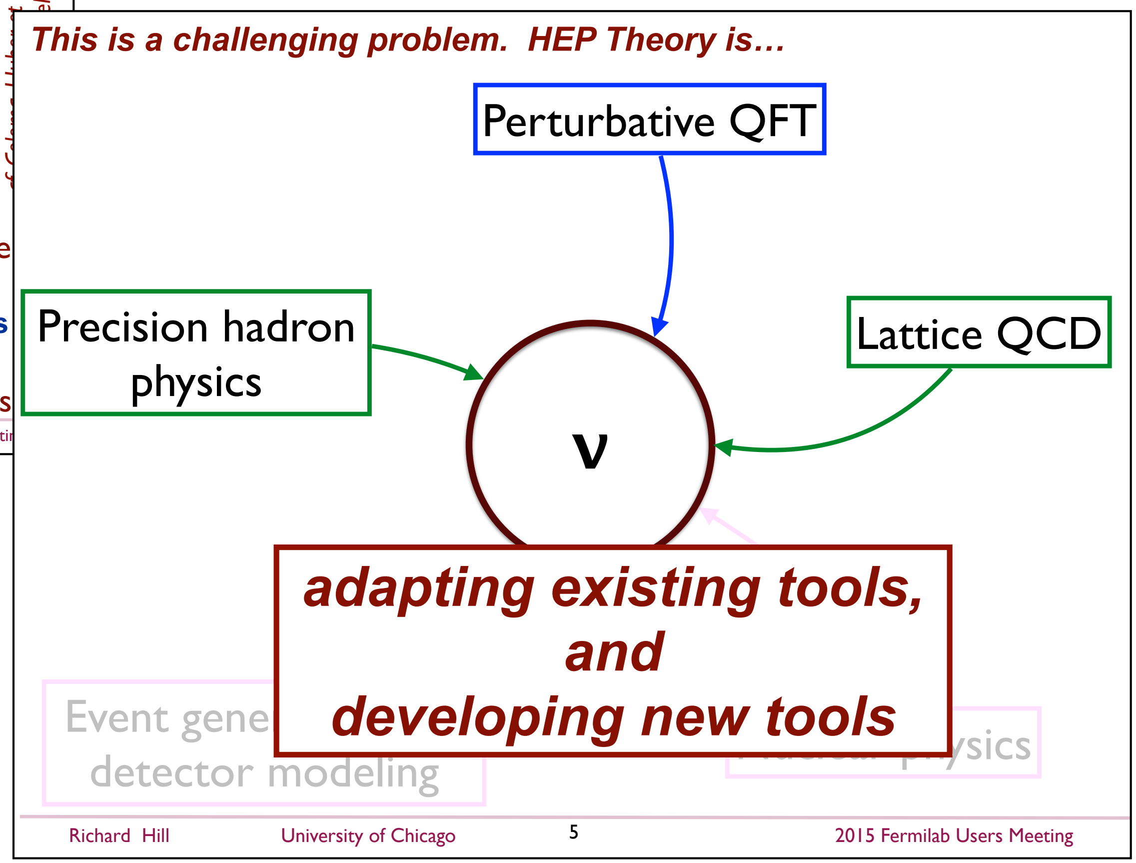


Precision

Experimental Precision

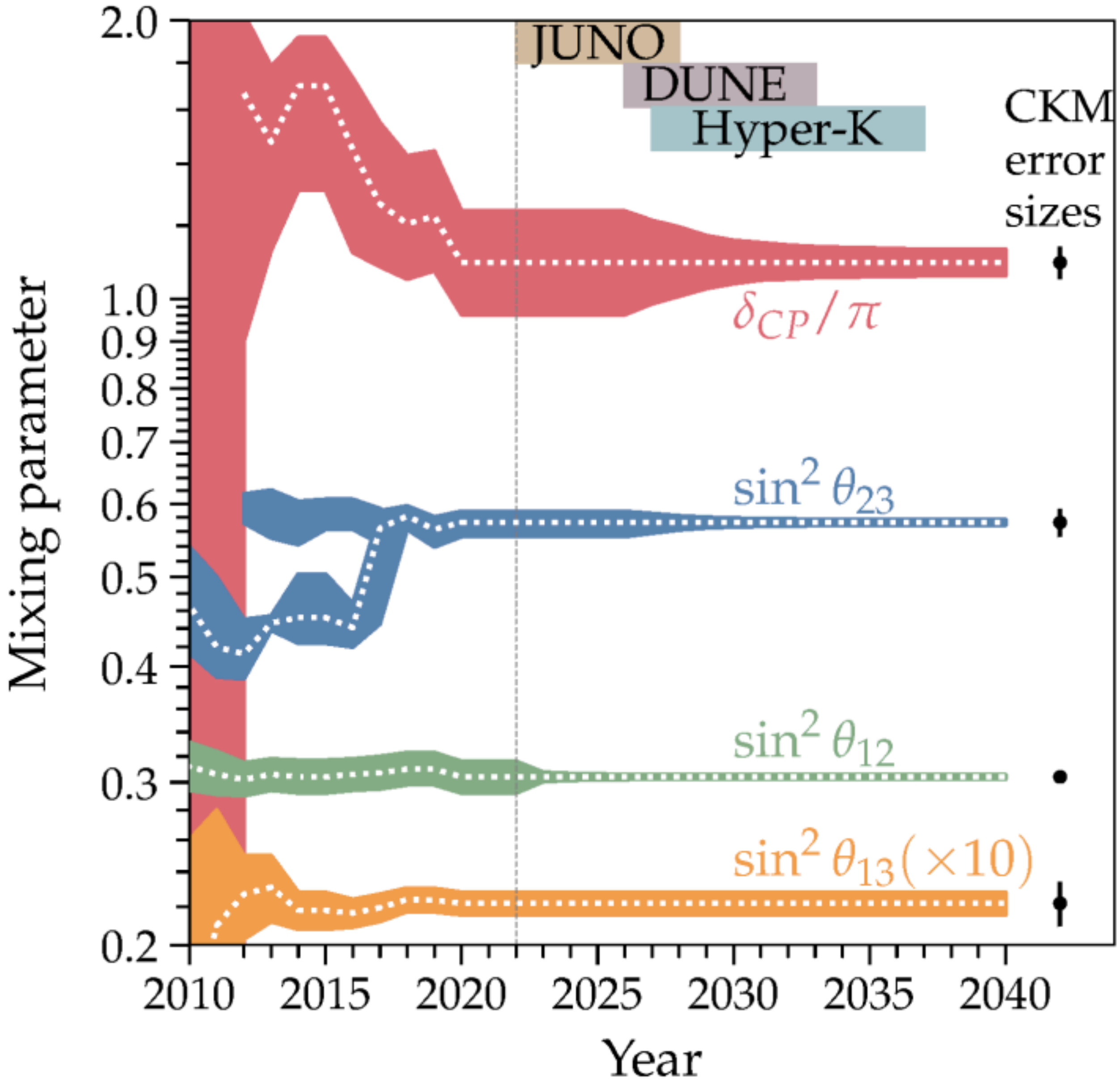


HEP Theory can contribute!



[Slide curtesy: Richard Hill @ 2015 Fermilab Users Meeting]

Precision of Theory Predictions



Are precision in model predictions compatible with experimental precision?

Talk by Michael Ratz

Figure from Song, Li, Argüelles, Bustamante, Vincent (2020)

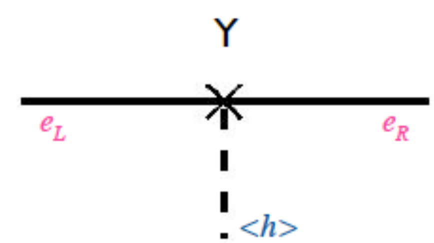
CP Violation

Origin of CP Violation

- CP violation ⇔ complex mass matrices

$$\overline{U}_{R,i}(M_u)_{ij}Q_{L,j} + \overline{Q}_{L,j}(M_u^\dagger)_{ji}U_{R,i} \xrightarrow{\mathcal{CP}} \overline{Q}_{L,j}(M_u)_{ij}U_{R,i} + \overline{U}_{R,i}(M_u)^*_{ij}Q_{L,j}$$

- Conventionally, CPV arises in two ways:
  - Explicit CP violation: complex Yukawa coupling constants Y
  - Spontaneous CP violation: complex scalar VEVs <h>



- **Complex CG coefficients in certain discrete groups ⇒ explicit CP violation**
  - CPV in quark and lepton sectors purely from complex CG coefficients

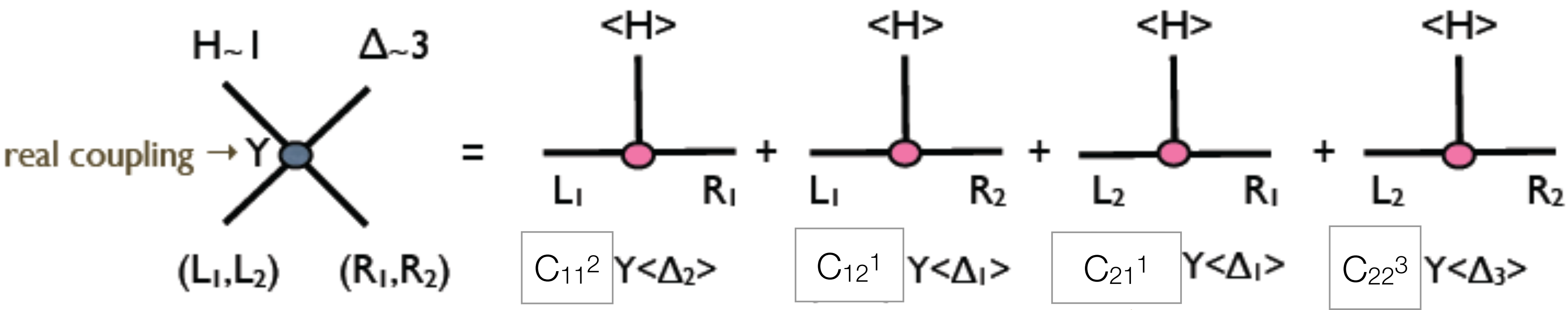
CG coefficients in non-Abelian discrete symmetries
➪ relative strengths and phases in entries of Yukawa matrices
➪ mixing angles and phases (and mass hierarchy)

Group Theoretical Origin of CP Violation

M.-C.C., K.T. Mahanthappa
Phys. Lett. B681, 444 (2009)

Basic idea

Discrete symmetry ***G***



$C_{ij}{}^{k}$: complex CG coefficients of ***G***

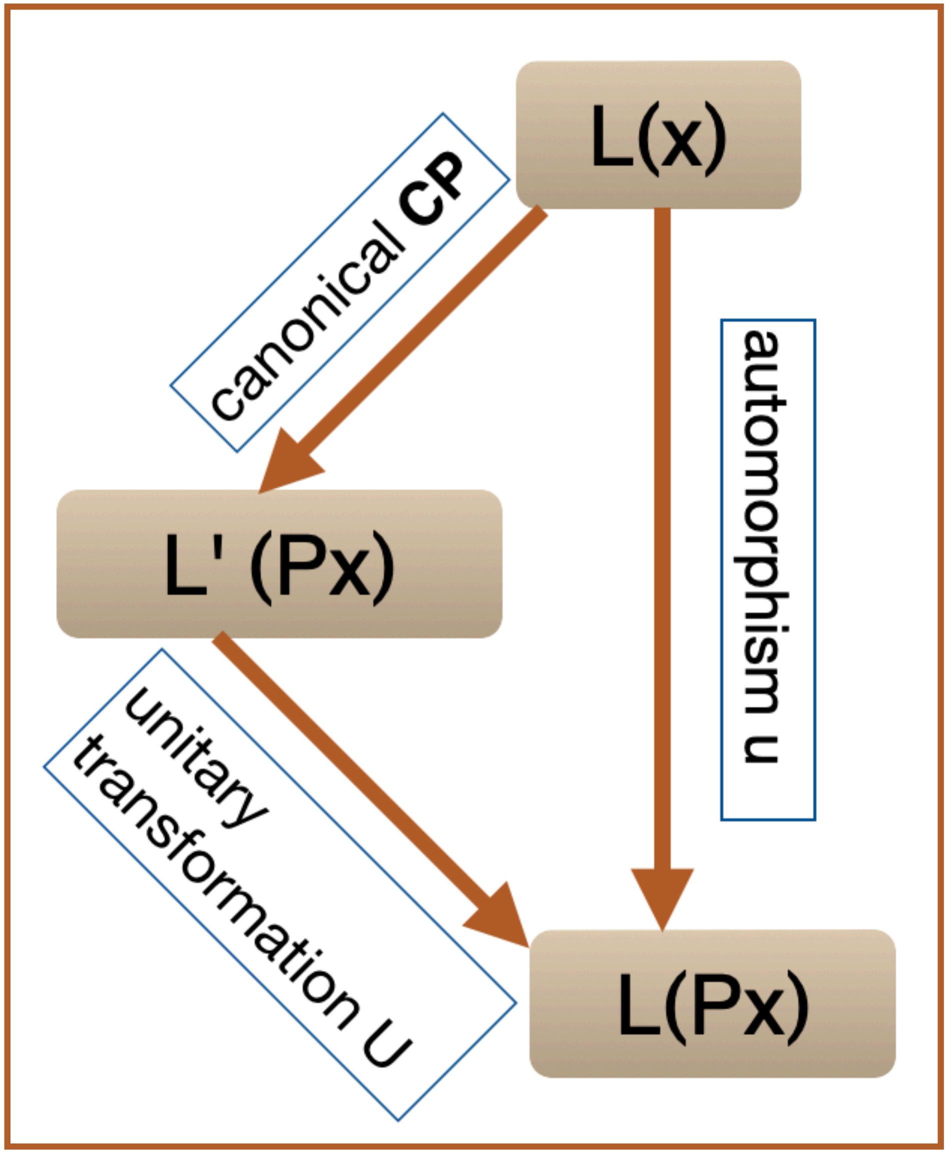
- if Z_3 symmetric $\Rightarrow$ $\langle\Delta_1\rangle = \langle\Delta_2\rangle = \langle\Delta_3\rangle \equiv \langle\Delta\rangle$ real
- Complex effective mass matrix: **phases determined by group theory**

$$\begin{matrix} & (L_1 & L_2) & & \end{matrix}$$

$$M = \begin{pmatrix} C_{11}{}^{2} & C_{21}{}^{1} \\ C_{12}{}^{1} & C_{22}{}^{3} \end{pmatrix} Y \langle\Delta\rangle \quad \begin{pmatrix} R_1 \\ R_2 \end{pmatrix}$$

Group Theoretical Origin of CP Violation

M-CC, Mahanthappa (2009); M.-C.C, M. Fallbacher, K.T. Mahanthappa, M. Ratz, A. Trautner, NPB (2014)



complex CGs ⇨ G and physical CP transformations do not always commute

Class-inverting outer automorphism

⇕

Physical CP

Outlook

History of the Universe

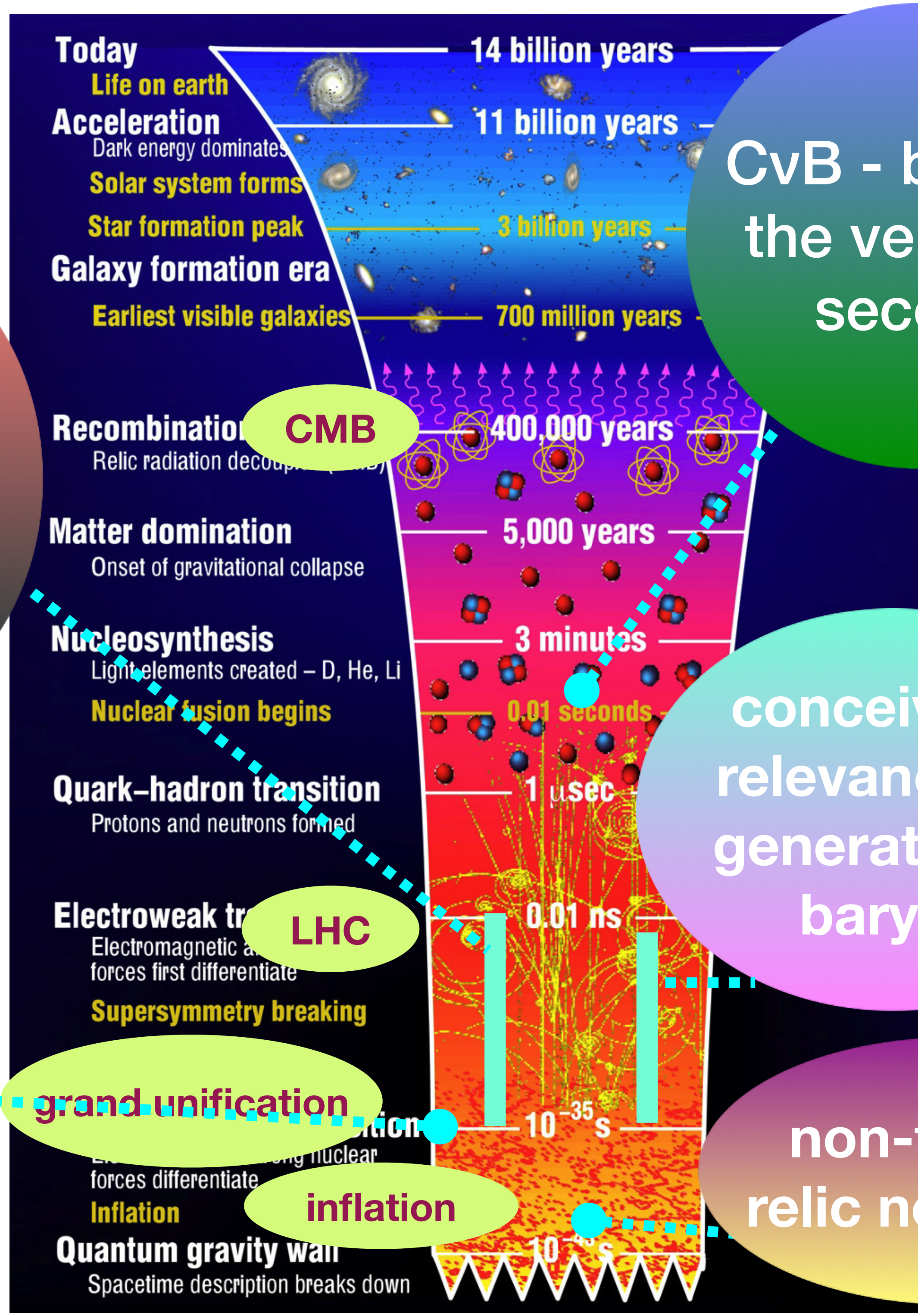
CvB - back to the very first second

physics for ν mass generation unknown

unique window into GUT scale physics

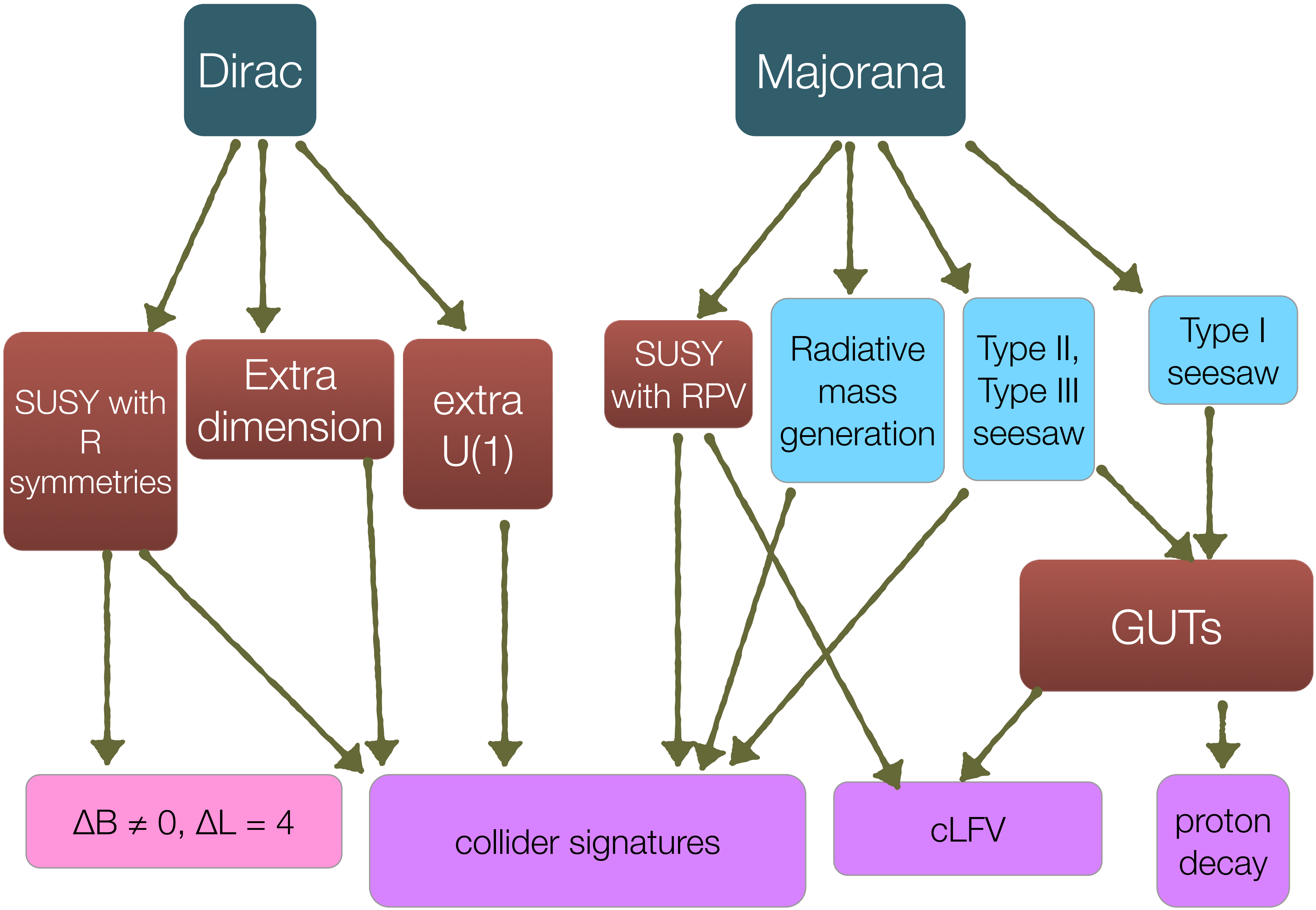
conceivable relevance for generation of baryon

non-thermal relic neutrinos?



Outlook

- Fundamental origin of fermion mass & mixing patterns still unknown
  - It took decades to understand the gauge sector of SM
- Uniqueness of Neutrino masses offers exciting opportunities to explore BSM Physics
  - Many NP frameworks; addressing other puzzles
  - Early Universe (baryogengesis thru leptogenesis, non-thermal relic neutrinos)
- New Tools/insights:
  - Non-Abelian Discrete Flavor Symmetries ⇒ **origin of CP**
    - Deep connection between outer automorphisms and **CP**
  - **Modular Flavor Symmetries**
    - Enhanced predictivity of flavor models
    - Possible connection to more fundamental physics



Dirac
Majorana
SUSY with R symmetries
Extra dimension
extra U(1)
SUSY with RPV
Radiative mass generation
Type II, Type III seesaw
Type I seesaw
GUTs
ΔB ≠ 0, ΔL = 4
collider signatures
cLFV
proton decay