

Neutrino Theory Overview

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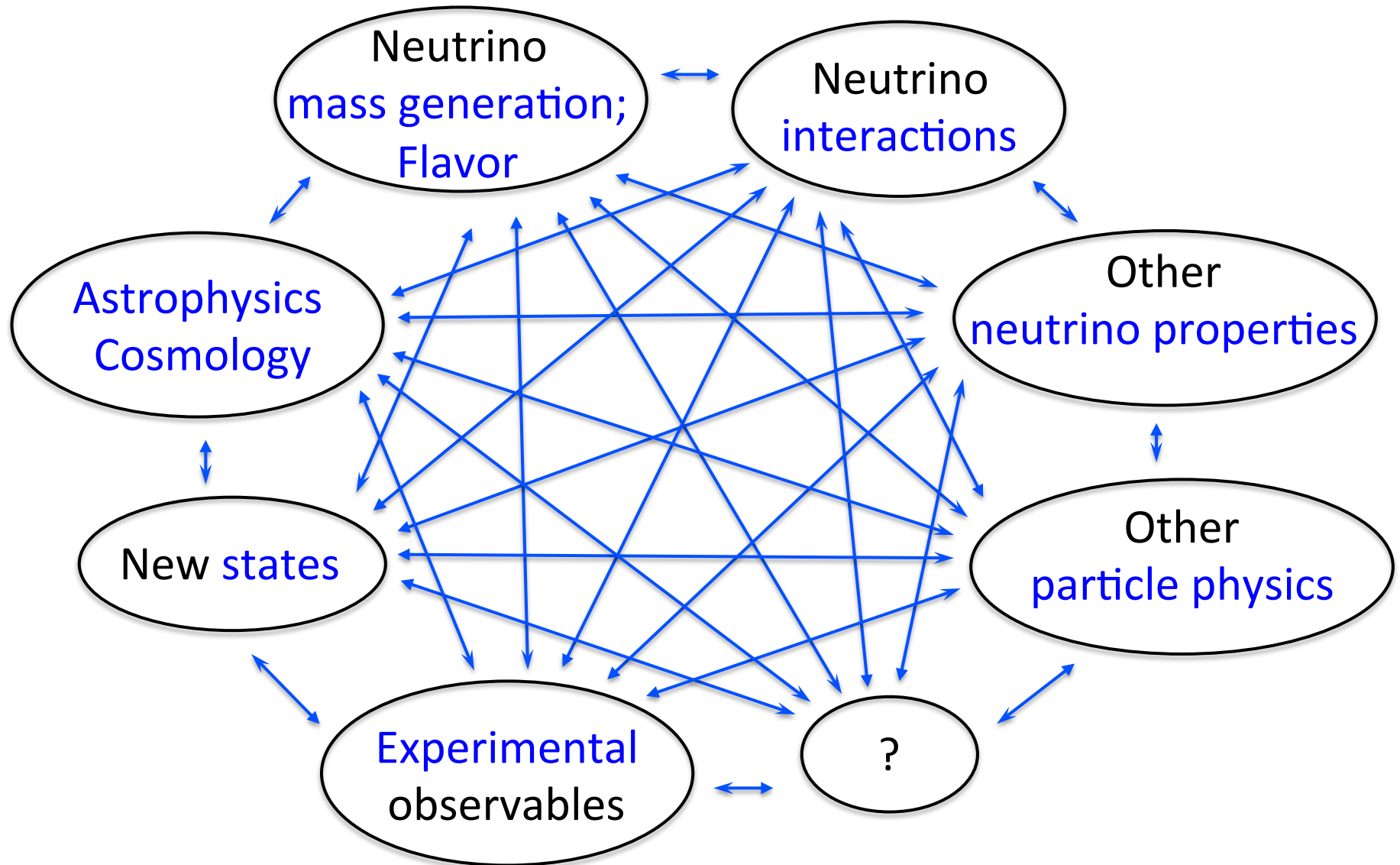
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What is Neutrino Theory?



What is Neutrino Theory?

Neutrino mass generation
Flavor

- ▶ Generic ideas: see-saw
- ▶ Explicit model building
 - grand unification
 - radiative mechanisms
 - flavor symmetries
- ▶ What is the scale?
 - GUT
 - TeV
 - Sub-eV

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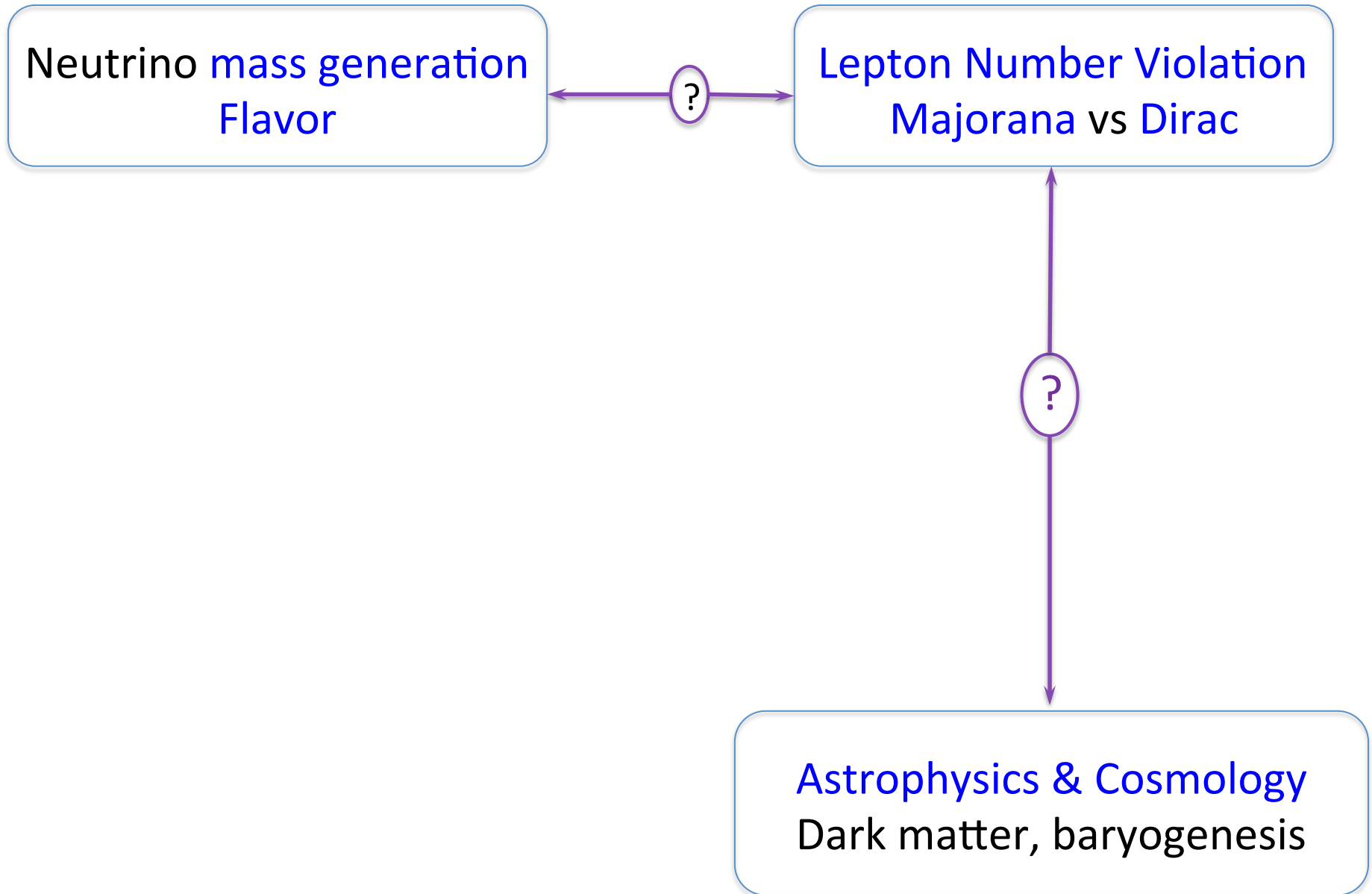
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?

Lepton Number Violation
Majorana vs Dirac

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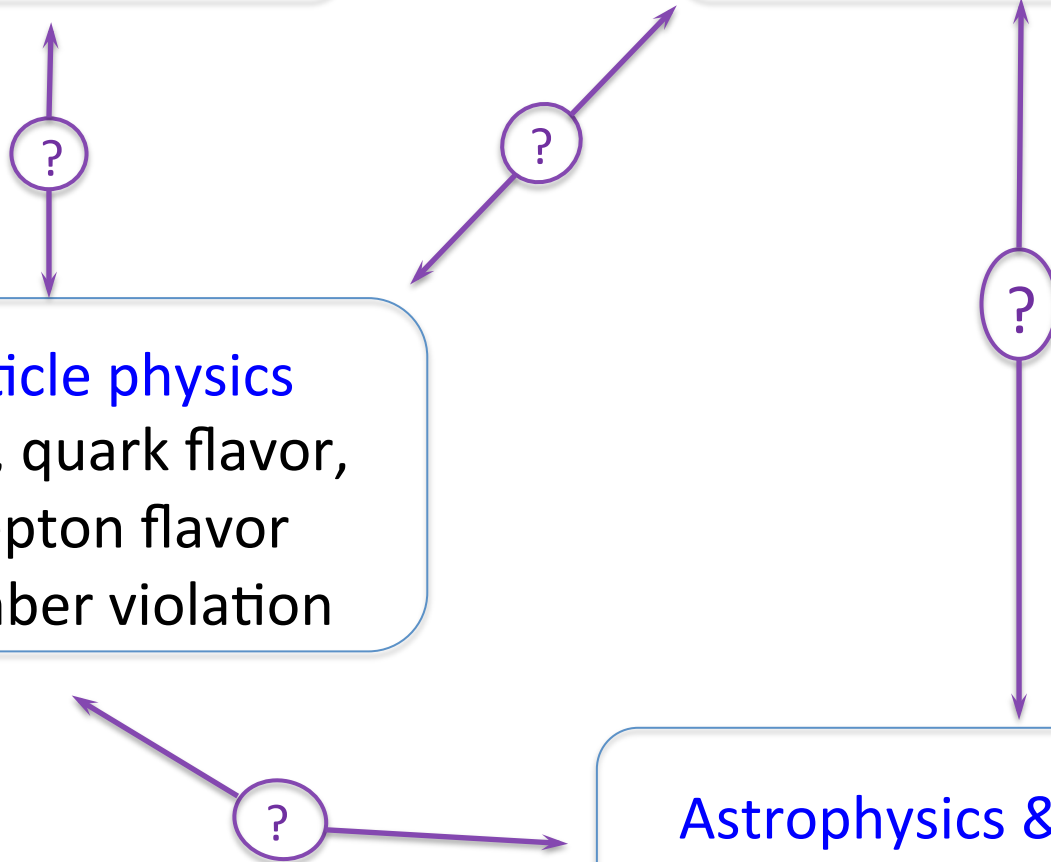
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Lepton Number Violation
Majorana vs Dirac

Other particle physics
Higgs sector, quark flavor,
charged lepton flavor
baryon number violation

Astrophysics & Cosmology
Dark matter, baryogenesis




What is Neutrino Theory?

Astrophysics and Cosmology

- ▶ Neutrinos in early universe
- ▶ Supernovae
 - Both astrophysics and neutrino physics
 - Neutrinos carry out most of energy
 - Neutrino oscillations very complex, including self-interactions
- ▶ Connections between neutrinos and dark matter, baryogenesis
- ▶ Very high energy neutrinos
 - Interesting astrophysical sources – extreme environments
 - Energies beyond those accessible in labs
 - Propagation over large distance sensitive to particle properties

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Experimental observables

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Neutrino interactions

New interactions
predicted in specific models

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Light: observable
Non-unitary lepton mixing

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Other neutrino properties

e.g. decay length,
electromagnetic prop.

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Neutrino mass generation
Flavor

Neutrino interactions

New interactions
predicted in specific models

Other particle physics

e.g.

- Higgs sector
- Charged lepton flavor
- Quark flavor
- Baryon number violation

New states

Light: observable
Non-unitary lepton mixing

Experimental observables

Other neutrino properties

e.g. decay length,
electromagnetic prop.

Neutrino interactions:

► Standard Model

- many energy ranges MeV- EeV
- many types of processes
- many not understood/measured with sufficient precision

► Non-Standard Interactions (NSI)

- many types of processes
- models can predict them
- model-independent phenomenological parametrizations useful to connect to experimental observables

Three-flavor neutrino oscillations

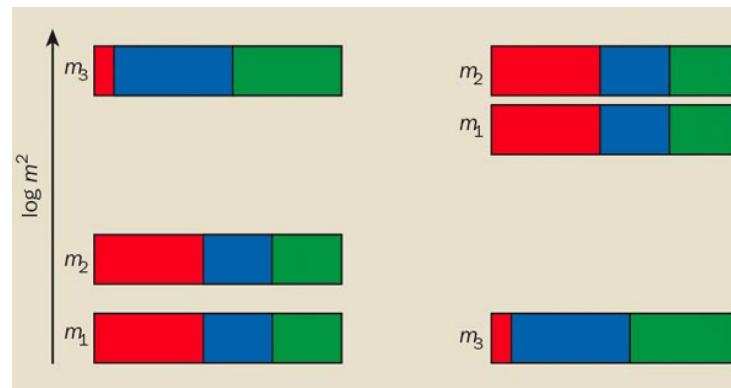
- solar, atmospheric, accelerator, reactor experiments
- Three-flavor mixing matrix

$$U = R_{23} K R_{13} K^* R_{12}$$

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

$$\Delta m_{21}^2 = \Delta m_{sol}^2 \quad \Delta m_{32}^2 = \Delta m_{atm}^2$$

$$\theta_{12} = \theta_{sol} \quad \theta_{13} = \theta_{reactor} \quad \theta_{23} = \theta_{atm} \quad \delta$$



with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2 \theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \rightarrow 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \rightarrow 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \rightarrow 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \rightarrow 35.87$
	$\sin^2 \theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \rightarrow 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \rightarrow 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \rightarrow 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \rightarrow 51.8$
	$\sin^2 \theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \rightarrow 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \rightarrow 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \rightarrow 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \rightarrow 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \rightarrow 369$	282^{+26}_{-30}	$193 \rightarrow 352$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \rightarrow +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \rightarrow -2.414$

Esteban I., Gonzalez-Garcia M.C., Maltoni M.,
 Schwetz T., Zhou A.
[JHEP 09 \(2020\) 178 \[arXiv:2007.14792\]](#)
[NuFIT 5.0 \(2020\), www.nu-fit.org.](#)

Three flavor neutrino oscillations (the new - or ν - standard model)

- Weak interactions (W & Z exchange) are the *only* neutrino interactions
- There are no additional neutrino states that can mix with the three SM flavors

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Specific Questions

- What are the 3 flavor oscillation parameters?
2 mass square differences, 3 mixing angles
Is 2-3 mixing maximal? if not, what is the octant, ...
- Is there CP violation in the lepton sector?
measure phase
- What is the mass ordering?

Neutrinos in the Standard Model and beyond

- Neutrino mass and mixing: physics **beyond** SM
- **Non**-trivial extension:
 - add right handed neutrino to SM (like for other SM fermions)
 - add Yukawa coupling to Higgs $Y_\nu \bar{L} H N_R$
(like for other SM fermions)
 - **BUT** Majorana mass term $M_R \overline{N_R^c} N_R$ allowed by SM symmetries
(unlike for other SM fermions)

Need to consider at least:

new implications of **Majorana** neutrinos

or

new symmetry to forbid Majorana mass term

-> **new interactions, new phenomena, etc.**

Three flavor neutrino oscillations (the new - or ν - standard model)

- Weak interactions (W & Z exchange) **are** the *only* neutrino interactions
- There are **no additional neutrino states** that can **mix with the three SM flavors**
- **Only an “effective theory”**
- **additional states and/or interactions *needed***
to generate neutrino masses and mixing
may or may not connect to observed “anomalies”
- other interactions and new light states possible
- do not know correct scale/model
 - *if all* new physics is at high scale (e.g. GUT models)
→ all deviations are negligibly small
 - observable corrections possible in many models
- ultimately **observational question**

Experimental observables

- experiments designed for high precision measurements
e.g. DUNE, short baseline program at Fermilab, etc.
- very high statistics data
e.g. atmospheric neutrinos in IceCube Deep Core/PINGU
- high precision determination of standard neutrino properties
- sensitivity to new neutrino properties and other new physics

require high precision measurements as well as
high precision theoretical understanding of many issues
(e.g. interaction cross sections, analysis framework)

Neutrino interactions

- Many types of processes and observables at different energies
- E.g.
 - Coherent elastic neutrino nucleus scattering: see Louis Strigari's talk
 - Neutrinoless double beta decay
 - Majorana vs Dirac answered by detection
 - Quantitative connections to neutrino mass, CP phases, etc.: need nuclear matrix elements
 - DIS at extremely high energies (astrophysical neutrinos)
 - QCD beyond parameter space probed by colliders
 - Relative effects of new physics can be large
 - Neutrino interactions at few GeV :
 - many processes can contribute to one observable signature
 - hadronic physics effects large
 - ...

Non-Standard neutrino Interactions (NSI)

PHYSICAL REVIEW D

VOLUME 17, NUMBER 9

1 MAY 1978

Neutrino oscillations in matter

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Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{L} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha\gamma^\rho\nu_\beta)(\bar{f}\gamma_\rho Pf)$$

Non-Standard neutrino Interactions (NSI)

- Standard Model can be treated as an effective low energy theory of some high energy completion at scale M
 - Write down all effective higher-dimensional operators involving SM fields and respecting SM symmetries
 - Dimension 5 ($1/M$) : Majorana mass
 - Dimension 6 ($1/M^2$): lots of operators, with and without Higgs
 - **new neutrino interactions**, smaller than SM ones
- (suppressed by high scale M)
can be parametrized as $\epsilon_{\alpha\beta}$

$$\mathcal{L} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha\gamma^\rho\nu_\beta)(\bar{f}\gamma_\rho Pf)$$

- **Effective** low-energy **parametrization** in terms of $\epsilon_{\alpha\beta}$ **very general**: can come **from different types of underlying physics**
- E.g.: effects of a sterile neutrino at energies much lower than its mass look like $\epsilon_{\alpha\beta}$; leptoquarks
- If you can constrain general $\epsilon_{\alpha\beta}$, many models can map their parameters onto $\epsilon_{\alpha\beta}$

NSI: matter effect

$$H_{I,NSI} = V_{cc} \begin{pmatrix} 1 + \epsilon_{ee} & |\epsilon_{e\mu}|e^{i\delta_{e\mu}} & |\epsilon_{e\tau}|e^{i\delta_{e\tau}} \\ |\epsilon_{e\mu}|e^{-i\delta_{e\mu}} & \epsilon_{\mu\mu} & |\epsilon_{\mu\tau}|e^{i\delta_{\mu\tau}} \\ |\epsilon_{e\tau}|e^{-i\delta_{e\tau}} & |\epsilon_{\mu\tau}|e^{-i\delta_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta} \equiv \sum_{\substack{f=e,u,d \\ P=L,R}} \epsilon_P^{\alpha\beta,ff} \frac{n_f}{n_e}$$

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\bar{\nu}_\alpha\gamma_\mu\nu_\beta \left(\epsilon_L^{\alpha\beta,ij} \bar{f}_L^i\gamma^\mu f_L^j + \epsilon_R^{\alpha\beta,ij} \bar{f}_R^i\gamma^\mu f_R^j \right) + h.c.$$

NSI: constraints

OSC			+COHERENT		
	LMA	LMA \oplus LMA-D		LMA	LMA \oplus LMA-D
$\varepsilon_{ee}^u - \varepsilon_{\mu\mu}^u$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$	ε_{ee}^u	$[-0.008, +0.618]$	$[-0.008, +0.618]$
$\varepsilon_{\tau\tau}^u - \varepsilon_{\mu\mu}^u$	$[-0.005, +0.130]$	$[-0.152, +0.130]$	$\varepsilon_{\mu\mu}^u$	$[-0.111, +0.402]$	$[-0.111, +0.402]$
$\varepsilon_{e\mu}^u$	$[-0.060, +0.049]$	$[-0.060, +0.067]$	$\varepsilon_{\tau\tau}^u$	$[-0.110, +0.404]$	$[-0.110, +0.404]$
$\varepsilon_{e\tau}^u$	$[-0.292, +0.119]$	$[-0.292, +0.336]$	$\varepsilon_{e\mu}^u$	$[-0.060, +0.049]$	$[-0.060, +0.049]$
$\varepsilon_{\mu\tau}^u$	$[-0.013, +0.010]$	$[-0.013, +0.014]$	$\varepsilon_{e\tau}^u$	$[-0.248, +0.116]$	$[-0.248, +0.116]$
$\varepsilon_{ee}^d - \varepsilon_{\mu\mu}^d$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$	$\varepsilon_{\mu\tau}^u$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon_{\tau\tau}^d - \varepsilon_{\mu\mu}^d$	$[-0.005, +0.095]$	$[-0.013, +0.095]$	ε_{ee}^d	$[-0.012, +0.565]$	$[-0.012, +0.565]$
$\varepsilon_{e\mu}^d$	$[-0.061, +0.049]$	$[-0.061, +0.073]$	$\varepsilon_{\mu\mu}^d$	$[-0.103, +0.361]$	$[-0.103, +0.361]$
$\varepsilon_{e\tau}^d$	$[-0.247, +0.119]$	$[-0.247, +0.119]$	$\varepsilon_{\tau\tau}^d$	$[-0.102, +0.361]$	$[-0.102, +0.361]$
$\varepsilon_{\mu\tau}^d$	$[-0.012, +0.009]$	$[-0.012, +0.009]$	$\varepsilon_{e\mu}^d$	$[-0.058, +0.049]$	$[-0.058, +0.049]$
$\varepsilon_{ee}^p - \varepsilon_{\mu\mu}^p$	$[-0.041, +1.312]$	$\oplus[-3.327, -1.958]$	$\varepsilon_{e\tau}^d$	$[-0.206, +0.110]$	$[-0.206, +0.110]$
$\varepsilon_{\tau\tau}^p - \varepsilon_{\mu\mu}^p$	$[-0.015, +0.426]$	$[-0.424, +0.426]$	$\varepsilon_{\mu\tau}^d$	$[-0.011, +0.009]$	$[-0.011, +0.009]$
$\varepsilon_{e\mu}^p$	$[-0.178, +0.147]$	$[-0.178, +0.178]$	ε_{ee}^p	$[-0.010, +2.039]$	$[-0.010, +2.039]$
$\varepsilon_{e\tau}^p$	$[-0.954, +0.356]$	$[-0.954, +0.949]$	$\varepsilon_{\mu\mu}^p$	$[-0.364, +1.387]$	$[-0.364, +1.387]$
$\varepsilon_{\mu\tau}^p$	$[-0.035, +0.027]$	$[-0.035, +0.035]$	$\varepsilon_{\tau\tau}^p$	$[-0.350, +1.400]$	$[-0.350, +1.400]$
			$\varepsilon_{e\mu}^p$	$[-0.179, +0.146]$	$[-0.179, +0.146]$
			$\varepsilon_{e\tau}^p$	$[-0.860, +0.350]$	$[-0.860, +0.350]$
			$\varepsilon_{\mu\tau}^p$	$[-0.035, +0.028]$	$[-0.035, +0.028]$

Esteban, M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. Salvado
arXiv:1805.04530, *JHEP* 08 (2018) 180, *JHEP* 12 (2020) 152 (addendum)

Non-Standard Neutrino Interactions (NSI)

- **any** interaction beyond weak (W , Z exchange)
- **pheno** approach: parametrize most general interaction i.t.o. known particle content \rightarrow explore observational consequences
 - long baseline neutrino oscillations
 - matter effects sensitive to any new **vector**-type interactions
propagation effects large
 - source/detector effects smaller, but can include other types of interactions (scalar, pseudo-scalar, axial, tensor)
 - other types of experiments (scattering) are **complementary**
 \rightarrow **need overall consistency**
 - current and future sensitivity: 10% to under 1% of G_F
 \rightarrow probing **relevant, unexplored physics scales**
- construct **model** \rightarrow explore observational consequences in all relevant experiments (ν , collider, flavor, etc.)

NSI & New Flavor Physics

- In the SM each family consistent on its own (anomalies cancel, etc.)
- 3 families?
- Mixing?
- Why such small mixing for third family quarks?
- Maybe third family is special: we gauge B-L for 3rd generation

$$U(1)_{B-L}^{(3)}$$

Babu, Friedland, Machado, Mocioiu, JHEP 1712 (2017) 096

Low scale flavor models: there could be flavor dependent physics below the electroweak scale

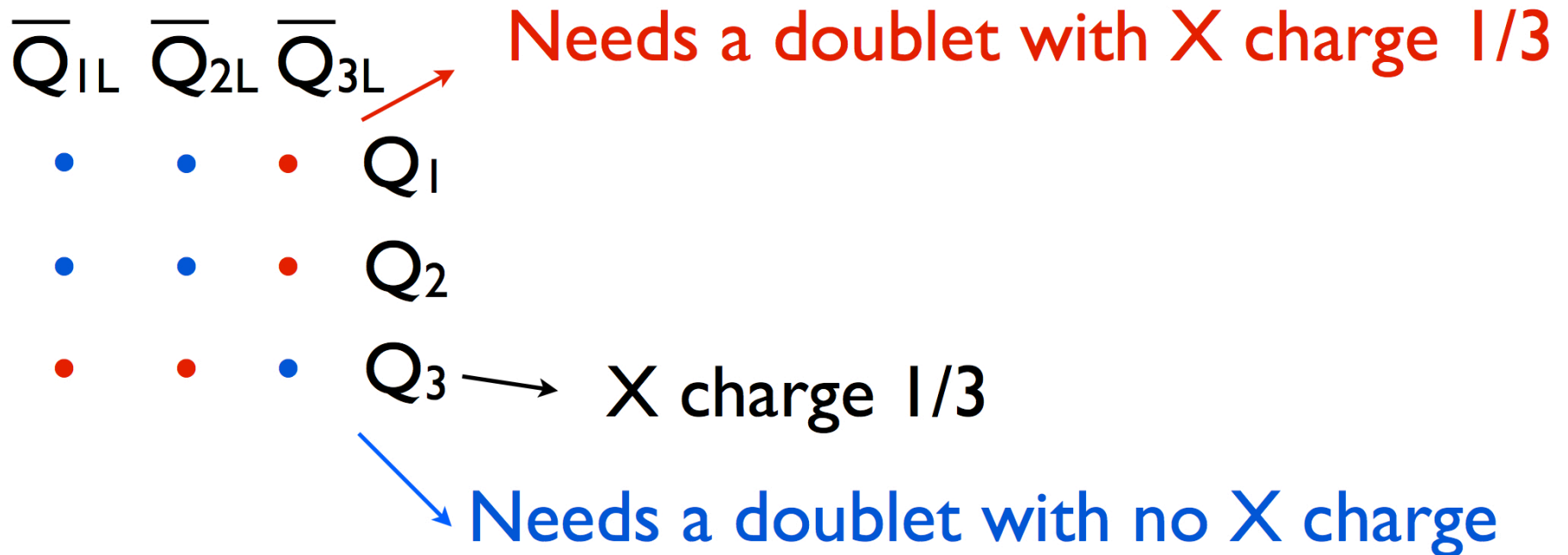
Synergy between vastly different physics:

neutrino oscillations, Higgs decays, b-physics, APV, meson oscillation and decays...

$$U(1)_{B-L}^{(3)}$$

- First and second family have no charge
- Third family is charged $(Q_{3L}, u_{3R}, d_{3R}) : 1/3, (\ell_{3L}, e_{3R}, \nu_{3R}) : -1,$

Need two Higgs doublets to generate CKM mixing



Also need a SM singlet with X charge 1/3

$$U(1)_{B-L}^{(3)}$$

Quarks

$$\mathcal{L}_{yuk}^q = \overline{\mathbf{Q}}_L \begin{pmatrix} y_{11}^u \tilde{\phi}_2 & y_{12}^u \tilde{\phi}_2 & y_{13}^u \tilde{\phi}_1 \\ y_{21}^u \tilde{\phi}_2 & y_{22}^u \tilde{\phi}_2 & y_{23}^u \tilde{\phi}_1 \\ 0 & 0 & y_{33}^u \tilde{\phi}_2 \end{pmatrix} \mathbf{u}_R + \overline{\mathbf{Q}}_L \begin{pmatrix} y_{11}^d \phi_2 & y_{12}^d \phi_2 & 0 \\ y_{21}^d \phi_2 & y_{22}^d \phi_2 & 0 \\ y_{31}^d \phi_1 & y_{32}^d \phi_1 & y_{33}^d \phi_2 \end{pmatrix} \mathbf{d}_R + \text{h.c.}$$



$$\begin{pmatrix} m_u^0 & 0 & V_{ub}^0 m_t^0 \\ 0 & m_c^0 & V_{cb}^0 m_t^0 \\ 0 & 0 & m_t^0 \end{pmatrix}$$



$$\begin{pmatrix} m_d^0 & 0 & 0 \\ 0 & m_s^0 & 0 \\ am_b^0 & bm_b^0 & m_b^0 \end{pmatrix}$$

$$V_{\text{CKM}} = V_u^L V_d^{L\dagger}$$

Generates flavor changing interactions in the quark sector

$$U(1)_{B-L}^{(3)}$$

Leptons

13 and 23 off-diagonal couplings forbidden by
charge assignments and minimal Higgs sector

Can only generate θ_{12} here

$$\mathcal{L}_{yuk}^{\ell} = y_{ij}^{\ell} \bar{L}_i \phi_2 \ell_{Rj} \quad y_{ij} = 0 \text{ for } ij = 13, 23, 31, 32.$$

Mass generation in neutrino sector less constrained

$$\frac{1}{\Lambda} \left(\bar{L}_{1,2} \tilde{\phi}_2 \right) \left(\phi_2^{\dagger} \tilde{L}_{1,2} \right), \quad \frac{1}{\Lambda^2} \left(\bar{L}_3 \tilde{\phi}_1 \right) \left(\phi_1^{\dagger} \tilde{L}_{1,2} \right) s^*$$

No flavor changing interactions in the lepton sector!

$$U(1)_{B-L}^{(3)}$$

Scalars

	ϕ_1	ϕ_2	s
$SU(2)_L$	2	2	1
$U(1)_Y$	+1	+1	0
$U(1)_{B-L}^{(3)}$	+1/3	0	+1/3

The flavor symmetry is broken by a Higgs doublet
 its “natural” scale is \sim electroweak

$U(1)_{B-L}^{(3)}$

Gauge Sector

 M_Z^2

Mixing between X and Z

$$M_{\text{gauge}}^2 = \frac{1}{4} \begin{pmatrix} (g^2 + g'^2)v^2 & -2\sqrt{g^2 + g'^2}g_X v_1^2/3 \\ -2\sqrt{g^2 + g'^2}g_X v_1^2/3 & 4g_X^2(v_1^2 + v_s^2)/9 \end{pmatrix}$$

M_X^2

$$Z_\mu \simeq -s_w B_\mu + c_w W_\mu^3 - s_X X_\mu^0,$$

$$X_\mu \simeq s_X (-s_w B_\mu + c_w W_\mu^3) + X_\mu^0,$$

$$s_X \equiv \frac{2}{3} \frac{g_X}{\sqrt{g^2 + g'^2}} \frac{v_1^2}{v^2}$$

$$M_X^2 = \frac{1}{9} g_X^2 \left(\frac{v_1^2 v_2^2}{v^2} + v_s^2 \right)$$

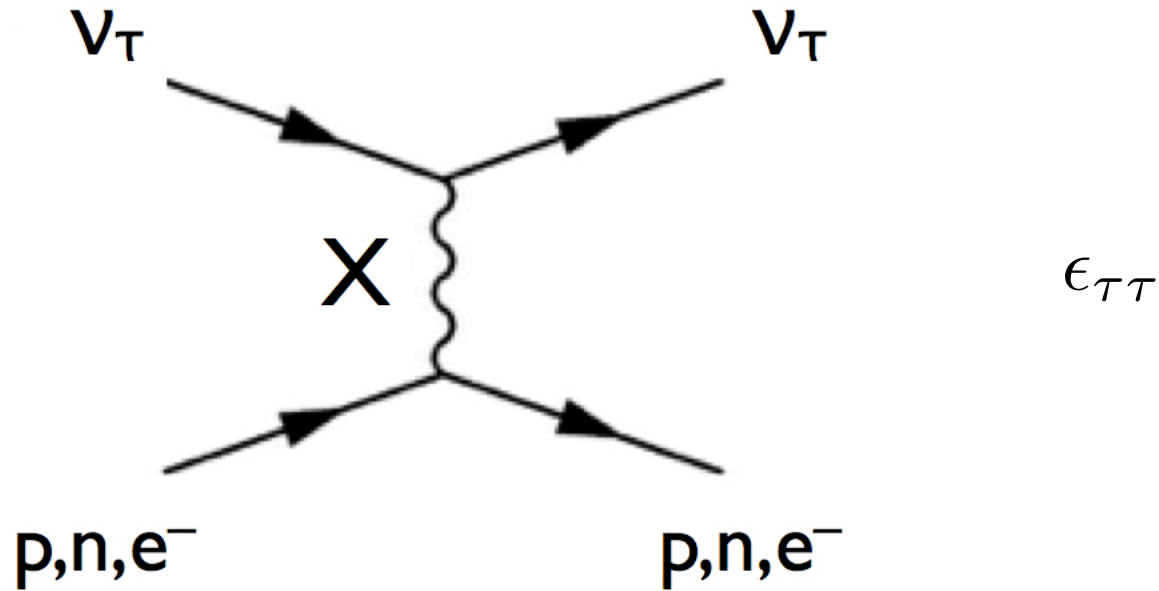
Small X-Z mixing suggests small g_X and M_X below weak scale

$g_X = 10^{-3} \sim 10^{-2}$ would correspond to

$$M_X = 100 \text{ MeV} \sim 1 \text{ GeV}$$

Phenomenology

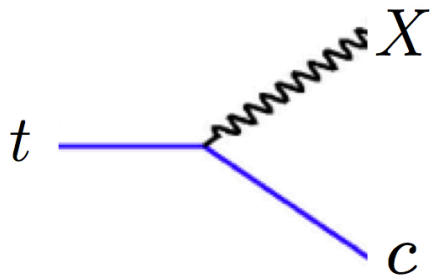
New contribution to neutrino matter potential



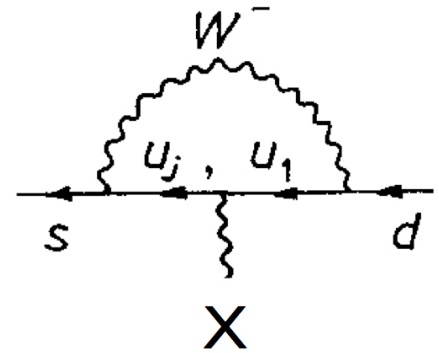
Phenomenology

Flavor changing: D oscillations, top, K and D decays

Generation of V_{ub} and V_{cb} in up sector leads to small u-c FC

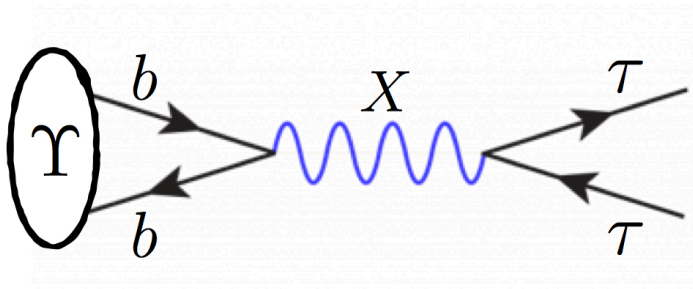


$$D^0 - \overline{D}^0$$

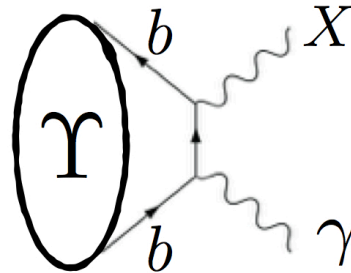


X couples to third family

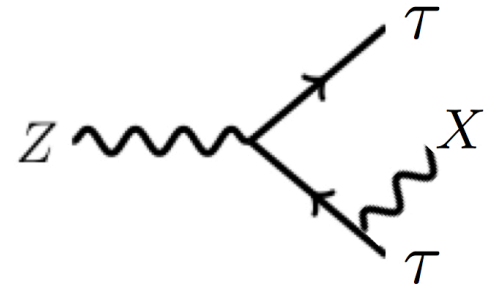
$$\Upsilon \rightarrow \tau^+ \tau^-$$



$$\Upsilon \rightarrow \gamma X$$

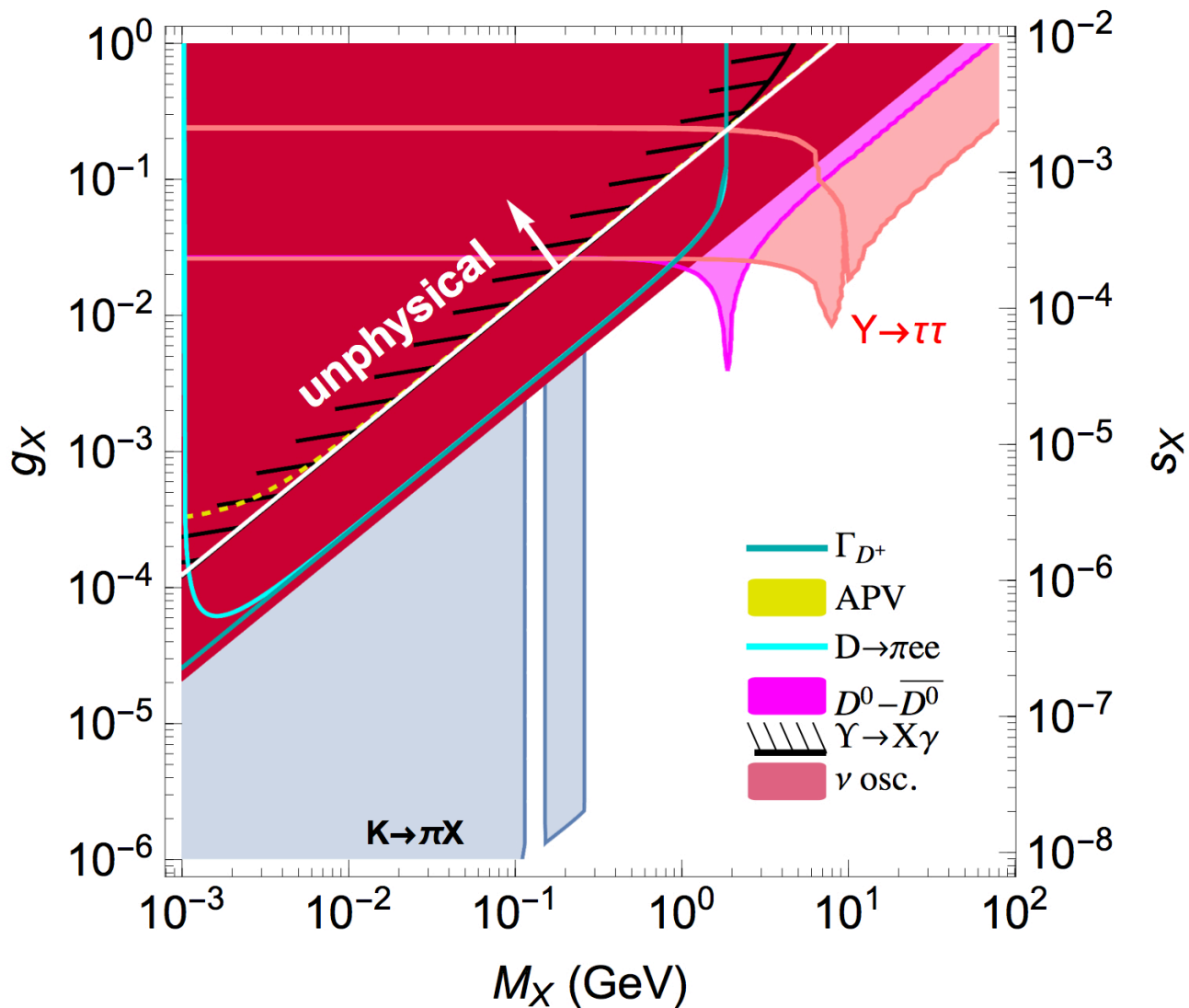


$$Z \rightarrow \tau \tau X$$



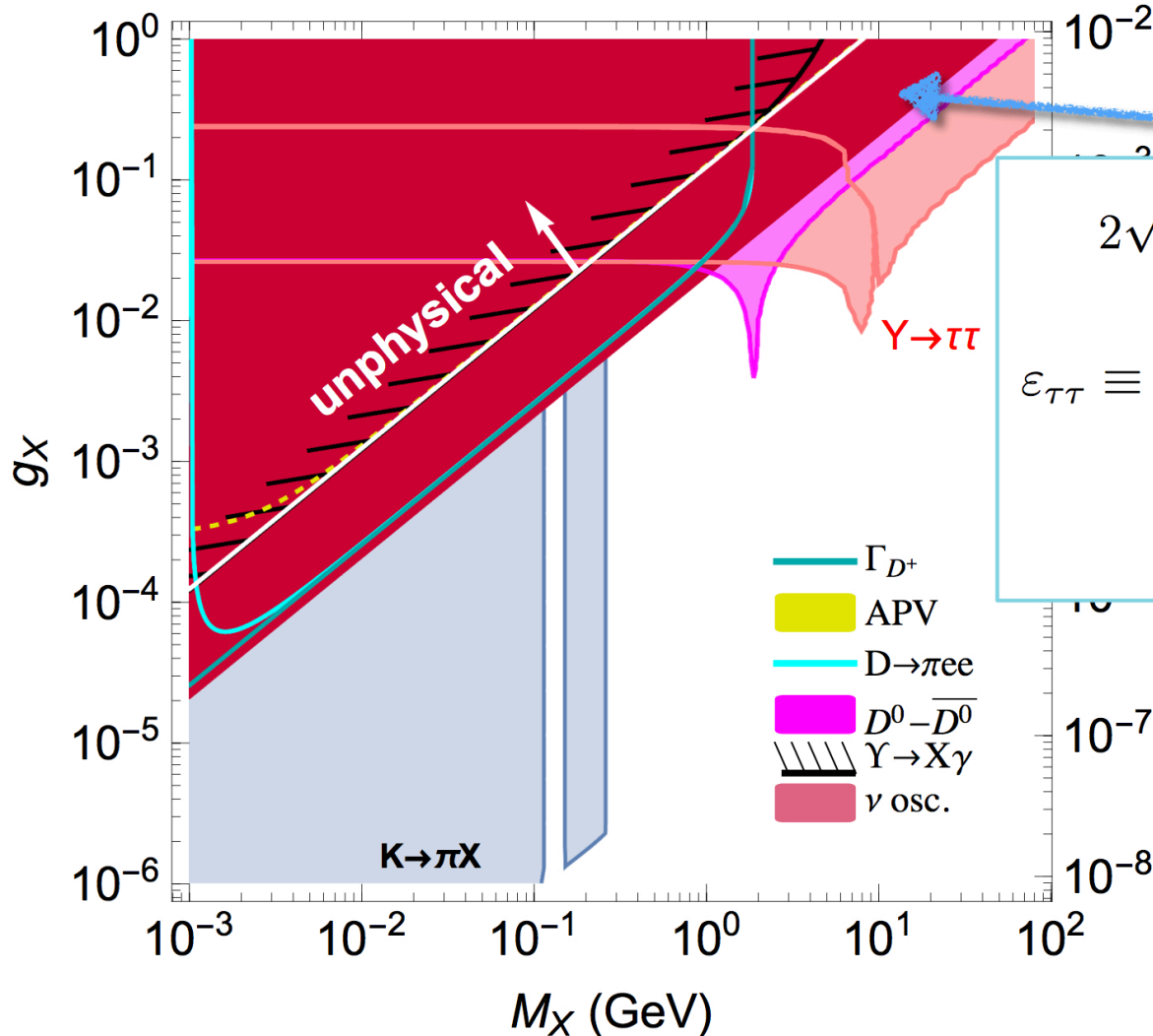
Phenomenology

$$\tan\beta = v_2/v_1 = 10$$



Phenomenology

$$\tan\beta = v_2/v_1 = 10$$

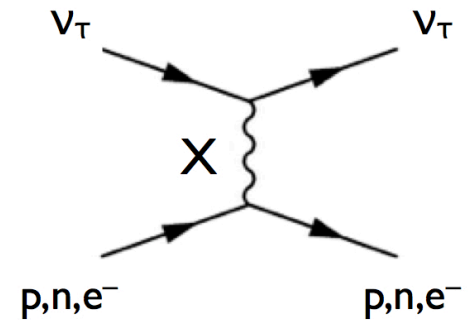


Neutrino oscillations
Probing the vevs

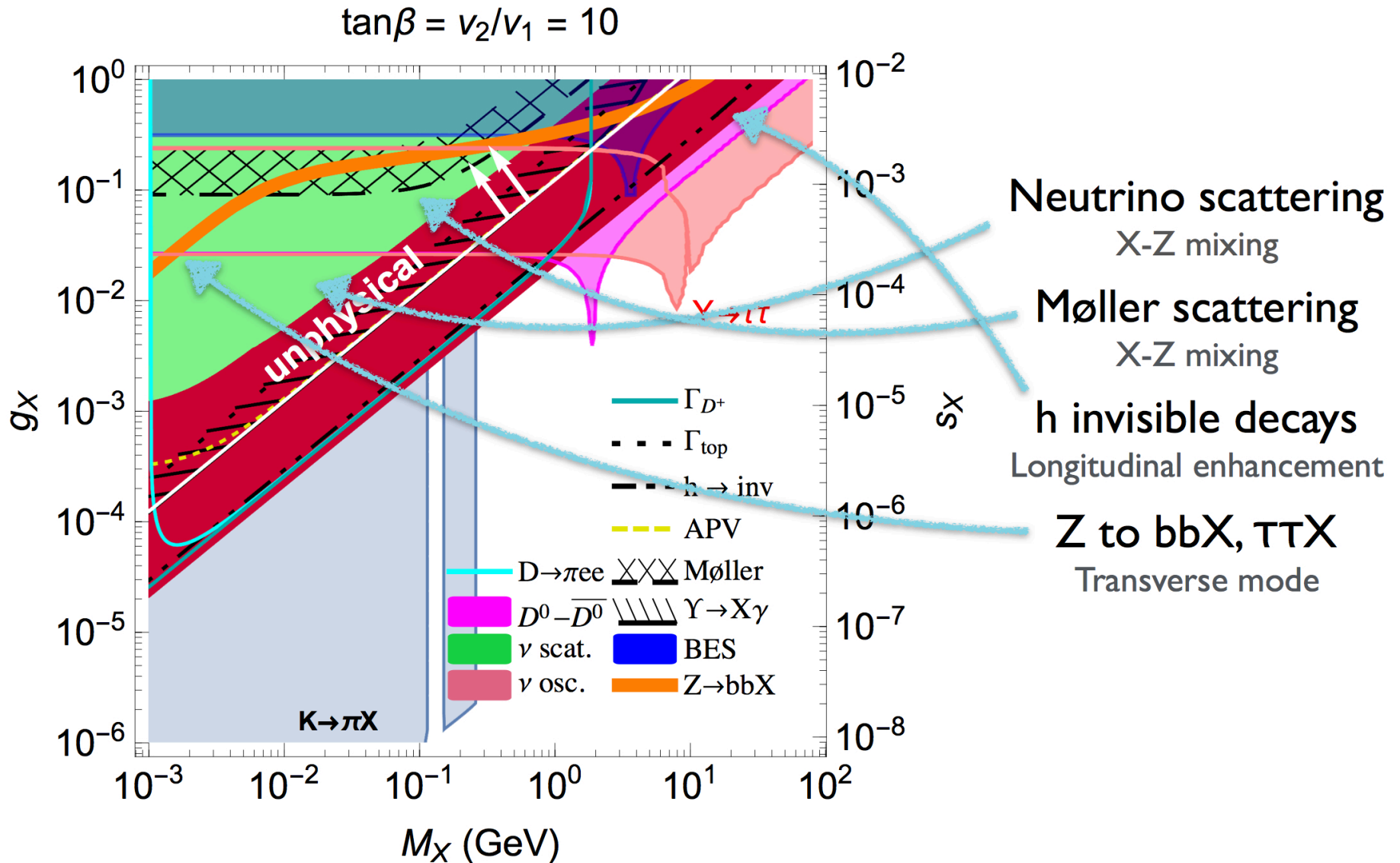
$$2\sqrt{2}G_F \varepsilon_{\alpha\alpha}^f (\bar{\nu}_{\alpha L} \gamma_\mu \nu_{\alpha L}) (\bar{f} \gamma^\mu f)$$

$$\varepsilon_{\tau\tau} \equiv \varepsilon_{\tau\tau}^p + \varepsilon_{\tau\tau}^n + \varepsilon_{\tau\tau}^e = 3 \frac{v_1^2 v^2}{v_1^2 v_2^2 + v_s^2 v^2}$$

$$|\varepsilon_{\tau\tau}| < 0.09$$

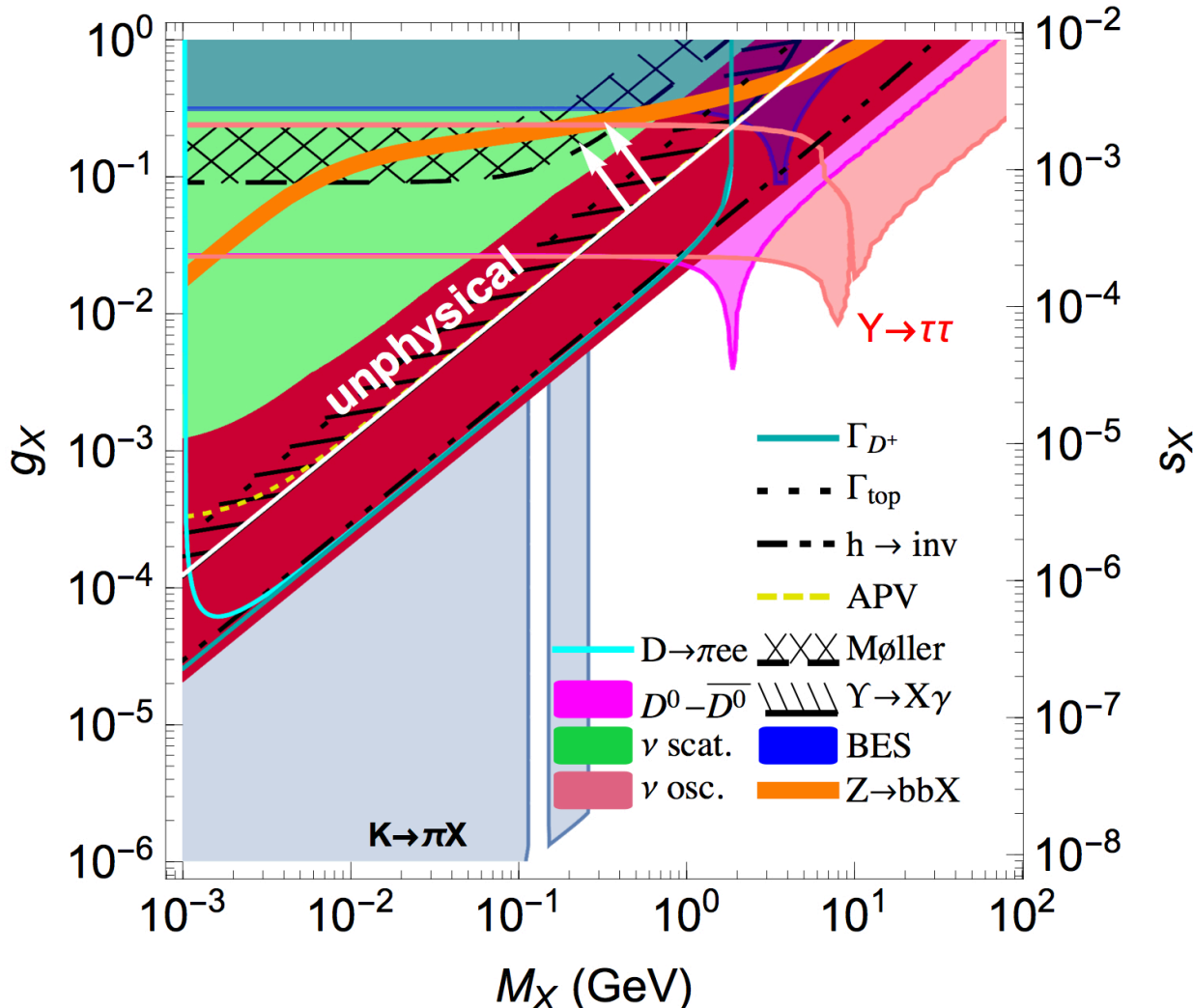


Phenomenology



Phenomenology

$$\tan\beta = v_2/v_1 = 10$$



Top decays ✓

longitudinal enhancement

Z to f f X ✓

longitudinal + transverse

X at the LHC

Non-standard Z' search

Meson oscillation ✓

Probing FCNCs

BES-III ✓

e^+e^- to $\tau^+\tau^-$

$(g-2)_\mu$ ✓

Does not decouple, but weak

Beam dump exps 👍

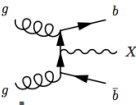
X decays invisibly

W to $\tau \nu X$ ✓

longitudinal + transverse

LEP direct searches ✓

Coupling to e^-



Neutrino Theory Overview

