Learning about New Physics with Neutrinos

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Why New Physics with Neutrinos?

Lots of sources:
natural and artificial

Lots of sensitive detectors
and detection techniques

Neutrino mass and mixing
are physics beyond SM

Weak interactions

Huge energy range

Many (possible) connections
to other
particles/phenomena

Sensitivity to many
new physics scenarios

Neutrino mass and mixing are 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

$\longrightarrow$ 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)

    $\longrightarrow$ deviations are negligibly small
  - observable corrections possible in many models (more later)
- ultimately observational question

Lots of sources: natural and artificial and in huge energy range

Natural:		Artificial:	
• CνB (Chris Tully)	< meV	• Reactor	MeV
• Geoneutrinos	< MeV	• Accelerator/collider	MeV-TeV
• Sun	~ MeV	• …	
• Supernovae	~ 10 MeV		
• Atmospheric	~ MeV-PeV		
• (other)Astrophysical	~ GeV-EeV		
• …			

Lots of sensitive detectors and detection techniques

- many complementary 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

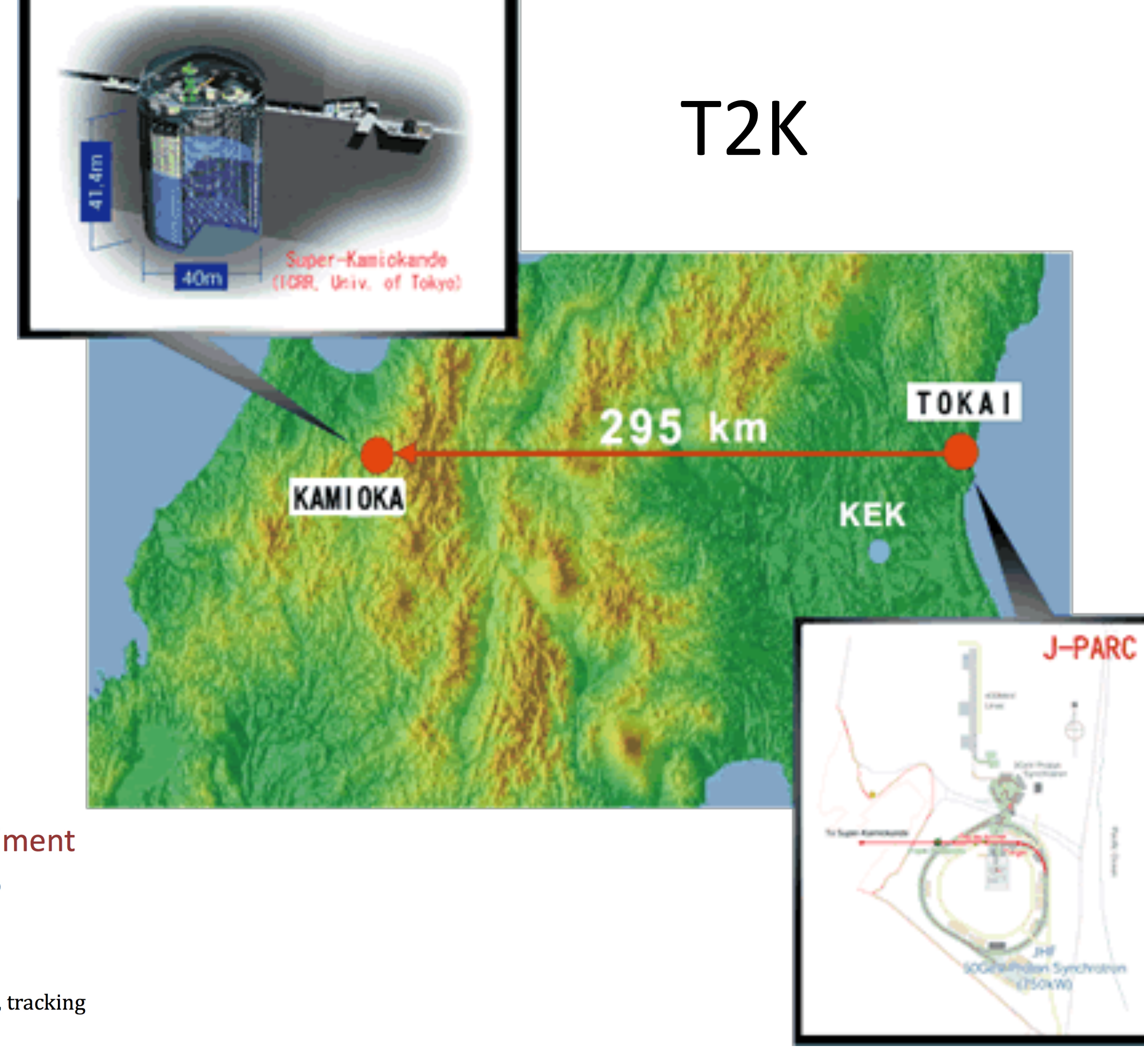
- extreme/unexplored energies/densities/distances

  e.g. astrophysical neutrinos in IceCube, CνB

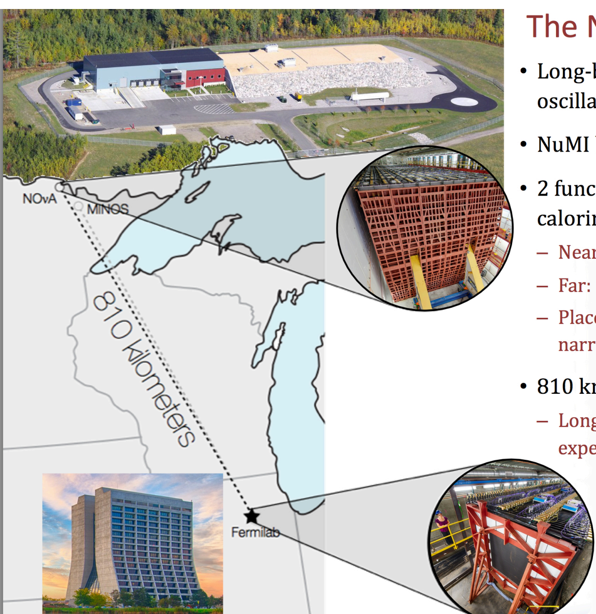
  small effects accumulate over long distances or get amplified because of environment

  unique to neutrinos

T2K



Long Baseline Experiments



The NOvA Experiment

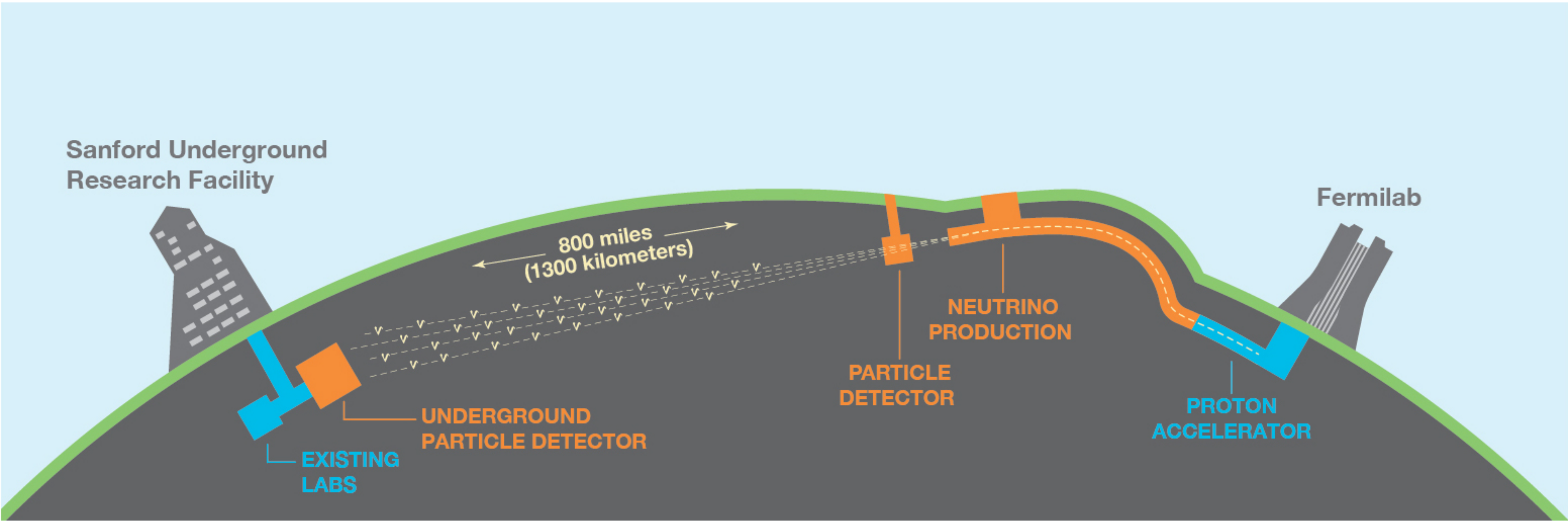
- Long-baseline neutrino oscillation experiment
- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

Take a tour in VR!

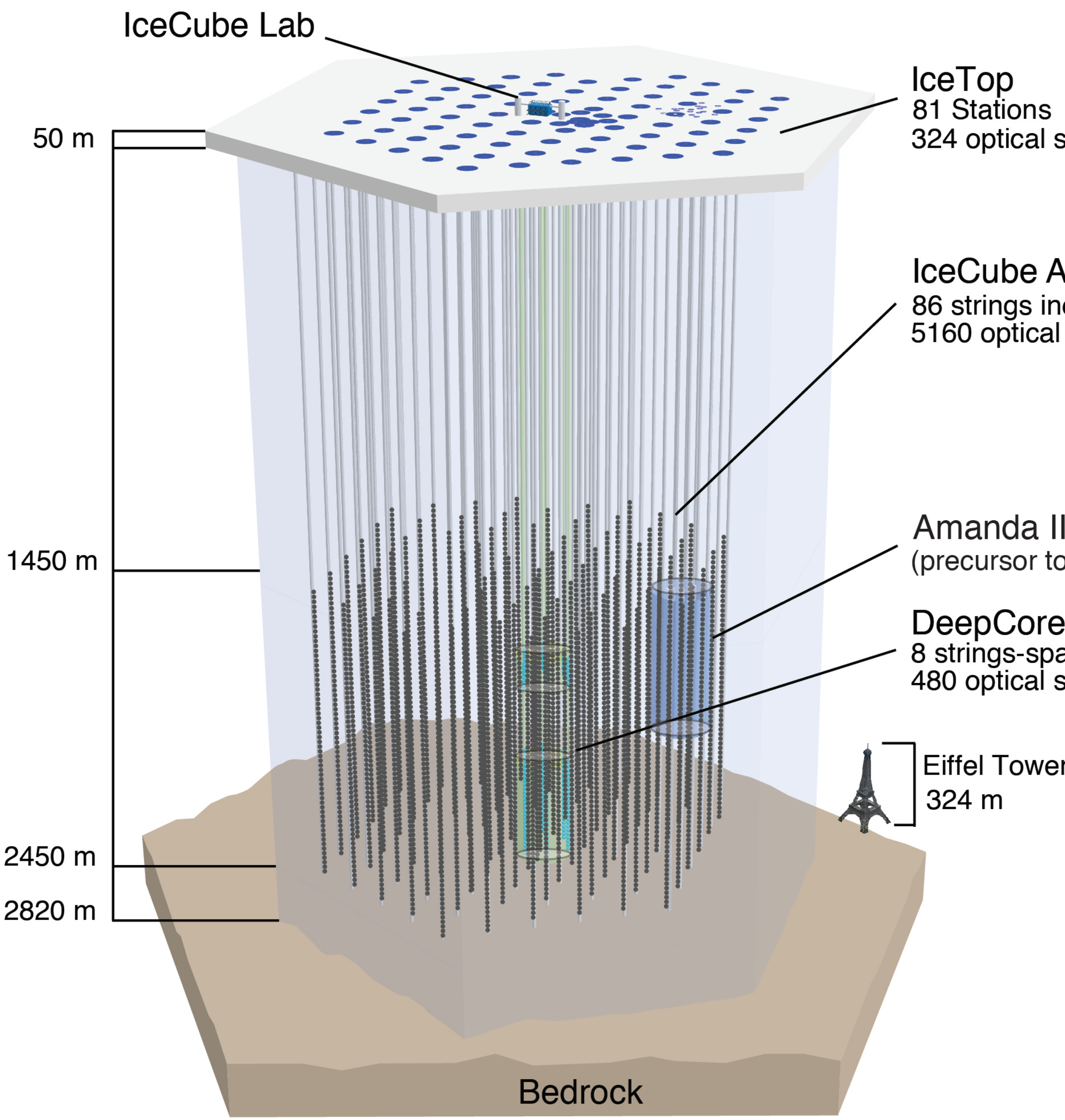
Himmel, Nu2020

Long Baseline Experiments

DUNE

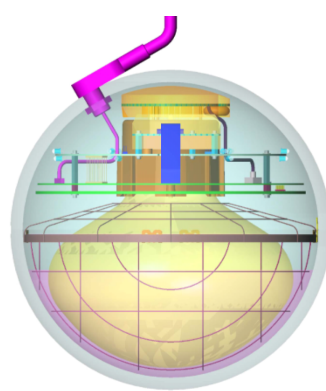


The IceCube Neutrino Observatory



Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



Digital Optical Module (DOM)

Why New Physics with Neutrinos?

Weak interactions

- can escape extreme environments: Sun, supernovae,
  extreme astrophysical objects (AGN, GRB, etc.)

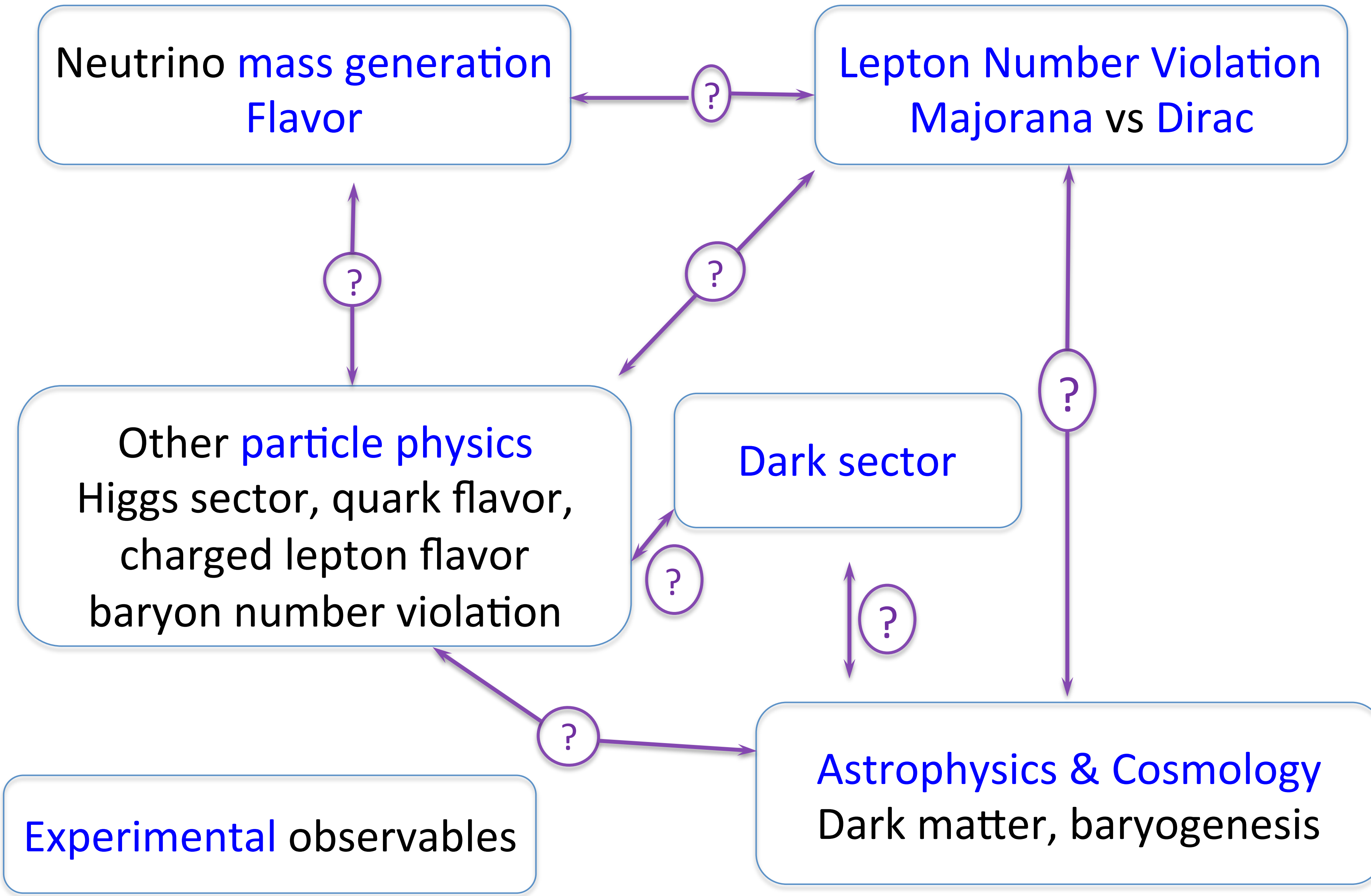
- can do astronomy (point back to source)

- relative effects of new physics can be large
  new physics: $\mathcal{O}(1)$ effects for weak scale new physics
  $\%$ level effects: un-probed regime

Many complementary observables

Large model parameter space for new physics effects

Many (possible) connections to other particles/ phenomena



New Physics with Neutrinos

- high precision determination of standard neutrino properties

- sensitivity to new neutrino properties and other new physics require:
  1. precision measurements of many types
  2. high precision theoretical understanding of many issues
     (e.g. interaction cross sections, analysis framework)

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

Three-flavor neutrino oscillations

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

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

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

$$\Delta m^2_{21} = \Delta m^2_{sol} \qquad \Delta m^2_{32} = \Delta m^2_{atm}$$

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

NuFIT 5.1 (2021)

without SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

Esteban I., Gonzalez-Garcia M.C., Maltoni M., Schwetz T., Zhou A.
JHEP 09 (2020) 178 [arXiv:2007.14792]
NuFIT 5.1 (2021), 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

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?

New Physics?

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

?

Experimental observables

Bishai

Neutrino interactions

New interactions
predicted in specific models
explored in “effective theory”

New states

Fleming

“directly” observable

Shoemaker
Hostert

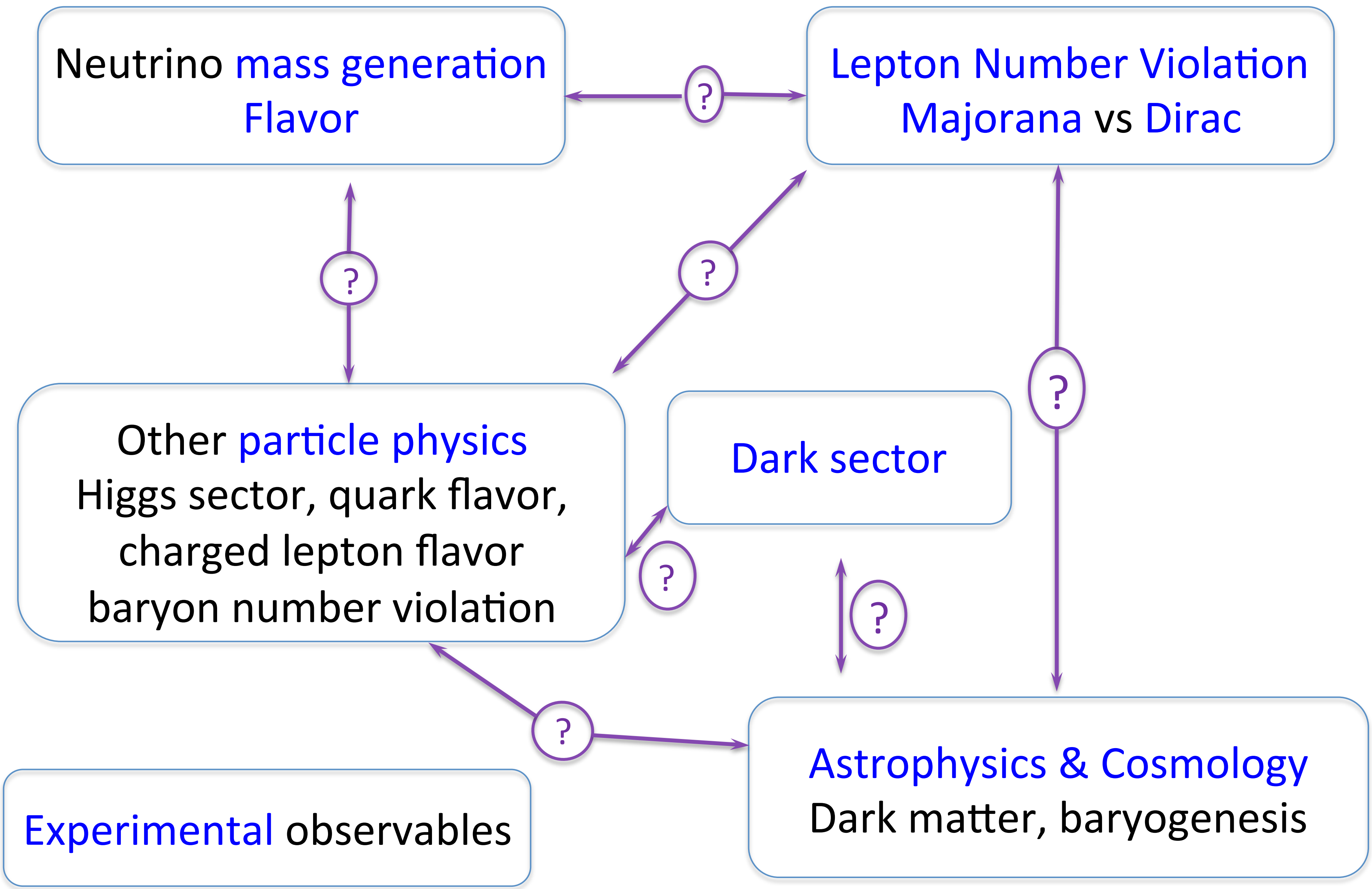
Non-unitary lepton mixing

Gehrlein

Other neutrino properties

e.g. decay length,
electromagnetic prop., LIV

Many (possible) connections to other particles/ phenomena



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

Sharma, Subhash, Zhou, Narayan

Neutrino interactions:

Standard Model

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

Gu

Non-Standard Interactions (NSI)

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

Neutrino interactions

- Many types of processes and observables at different energies
- E.g.
  - Coherent elastic neutrino nucleus scattering
  - 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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(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.

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

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 $\epsilon_{\alpha\beta}$

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

- 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 effects

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

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

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

NSI: constraints

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

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 $\longrightarrow$ 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 (e.g. CEvNS) are complementary

  $\longrightarrow$ need overall consistency
  - current and future sensitivity: 10% to under 1% of G_F

  $\longrightarrow$ probing relevant, unexplored physics scales
- construct model $\longrightarrow$ 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

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

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

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

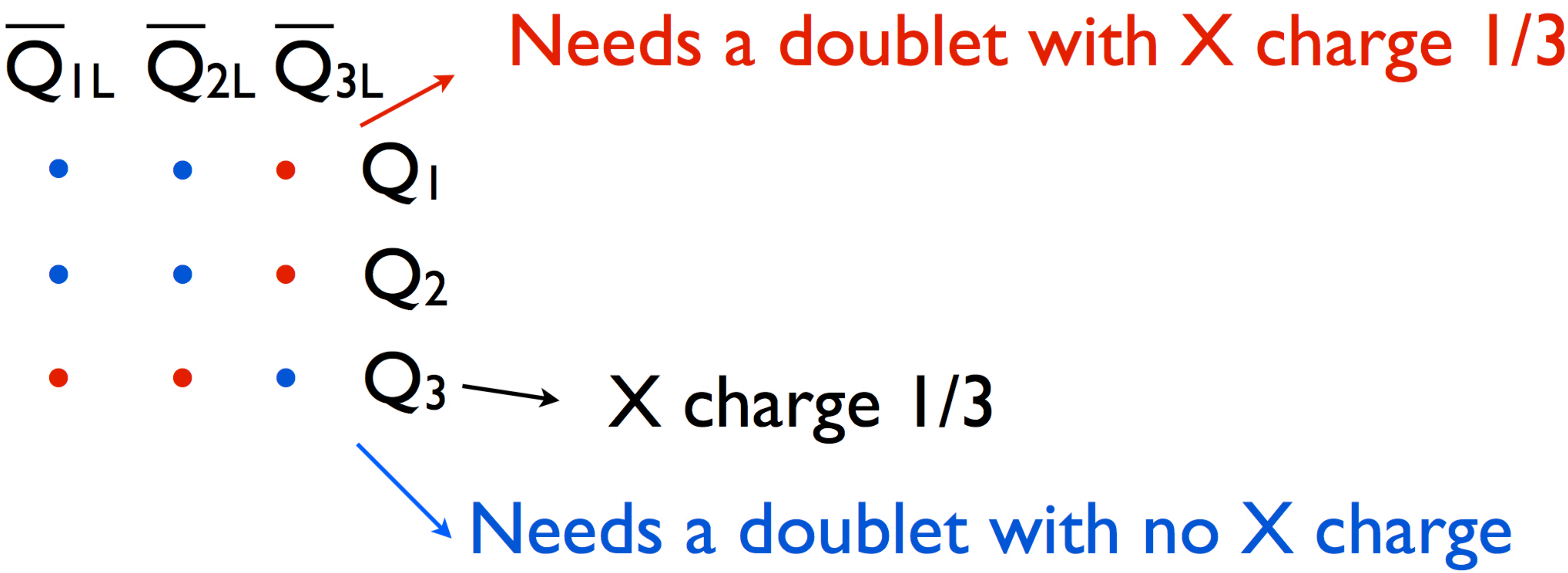
Synergy between vastly different physics:

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

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

- 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

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

Quarks

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

$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\begin{pmatrix} m^0_u & 0 & V^0_{ub} m^0_t \\ 0 & m^0_c & V^0_{cb} m^0_t \\ 0 & 0 & m^0_t \end{pmatrix} \qquad \begin{pmatrix} m^0_d & 0 & 0 \\ 0 & m^0_s & 0 \\ a m^0_b & b m^0_b & m^0_b \end{pmatrix}$$

$$V_{\text{CKM}} = V^L_u V^{L\dagger}_d$$

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

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

Mass generation in neutrino sector less constrained

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

No flavor changing interactions in the lepton sector!

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

Scalars

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

The flavor symmetry is broken by a Higgs doublet

its "natural" scale is approximately electroweak

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

Gauge Sector

M_Z^2 Mixing between X and Z

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

M_X^2

$$Z_\mu \simeq -s_w B_\mu + c_w W^3_\mu - s_X X^0_\mu,$$
$$X_\mu \simeq s_X(-s_w B_\mu + c_w W^3_\mu) + X^0_\mu,$$

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

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

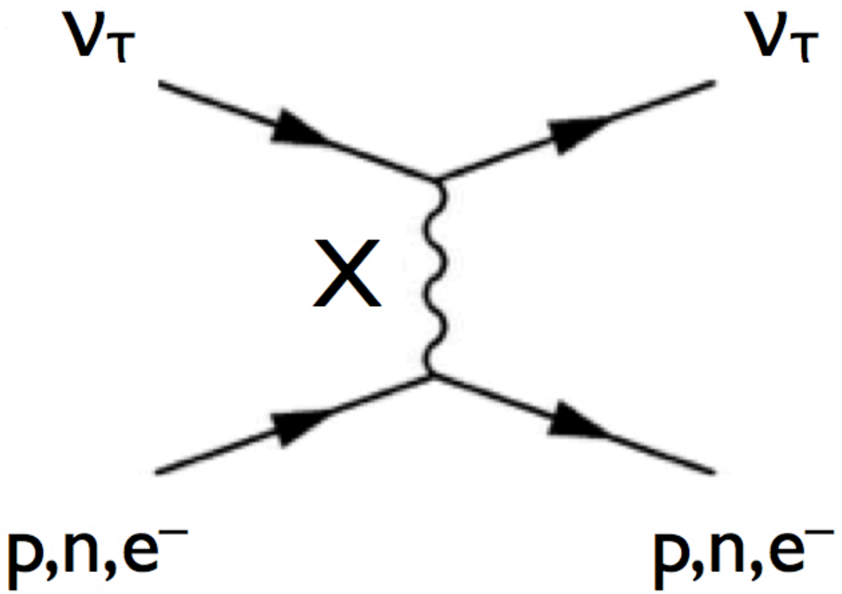
Small X-Z mixing suggests small g_X and M_X below weak scale

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

$M_X = 100MeV \sim 1GeV$

Phenomenology

New contribution to neutrino matter potential

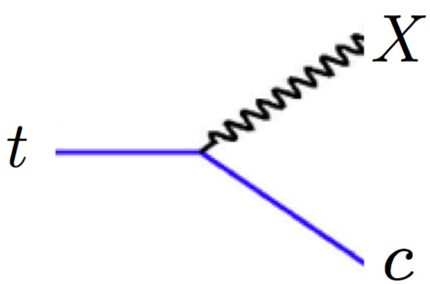


$\epsilon_{\tau\tau}$

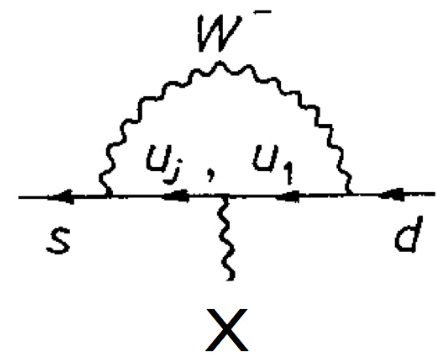
Phenomenology

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

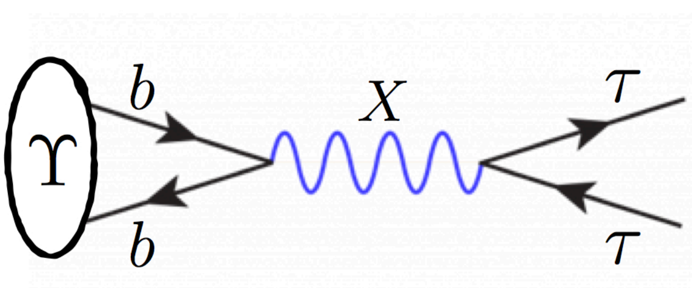


$D^0 - \overline{D^0}$

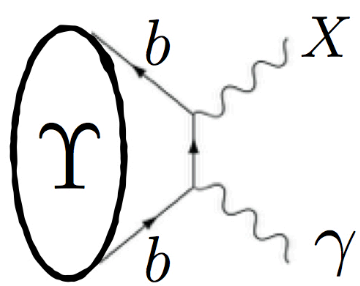


X couples to third family

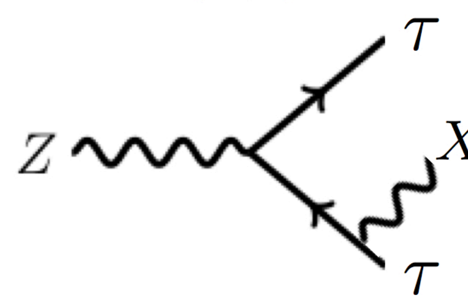
$\Upsilon \to \tau^+\tau^-$



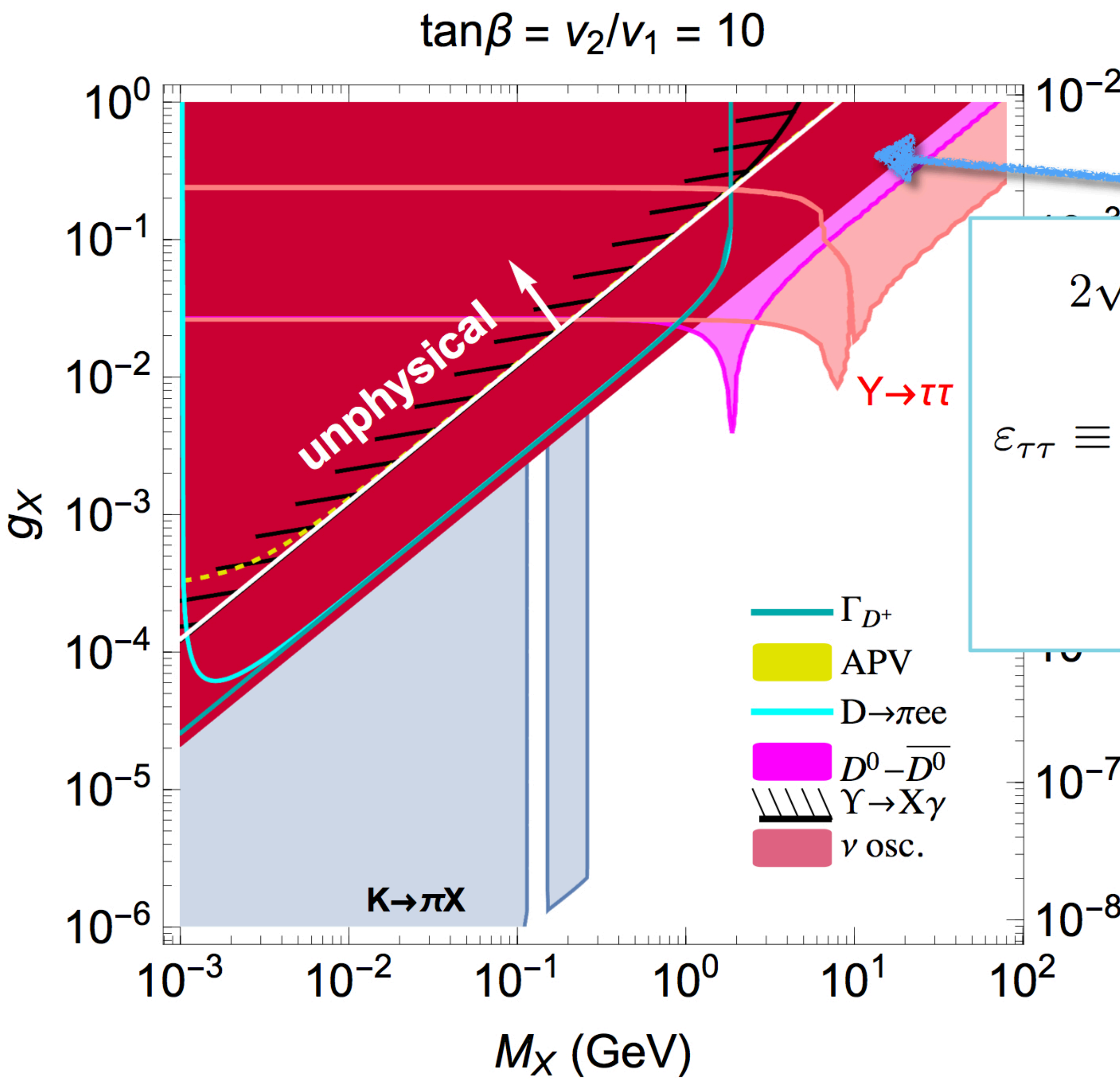
$\Upsilon \to \gamma X$



$Z \to \tau\tau X$



Phenomenology



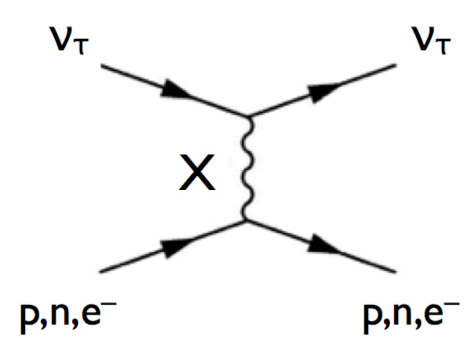
Neutrino oscillations

Probing the vevs

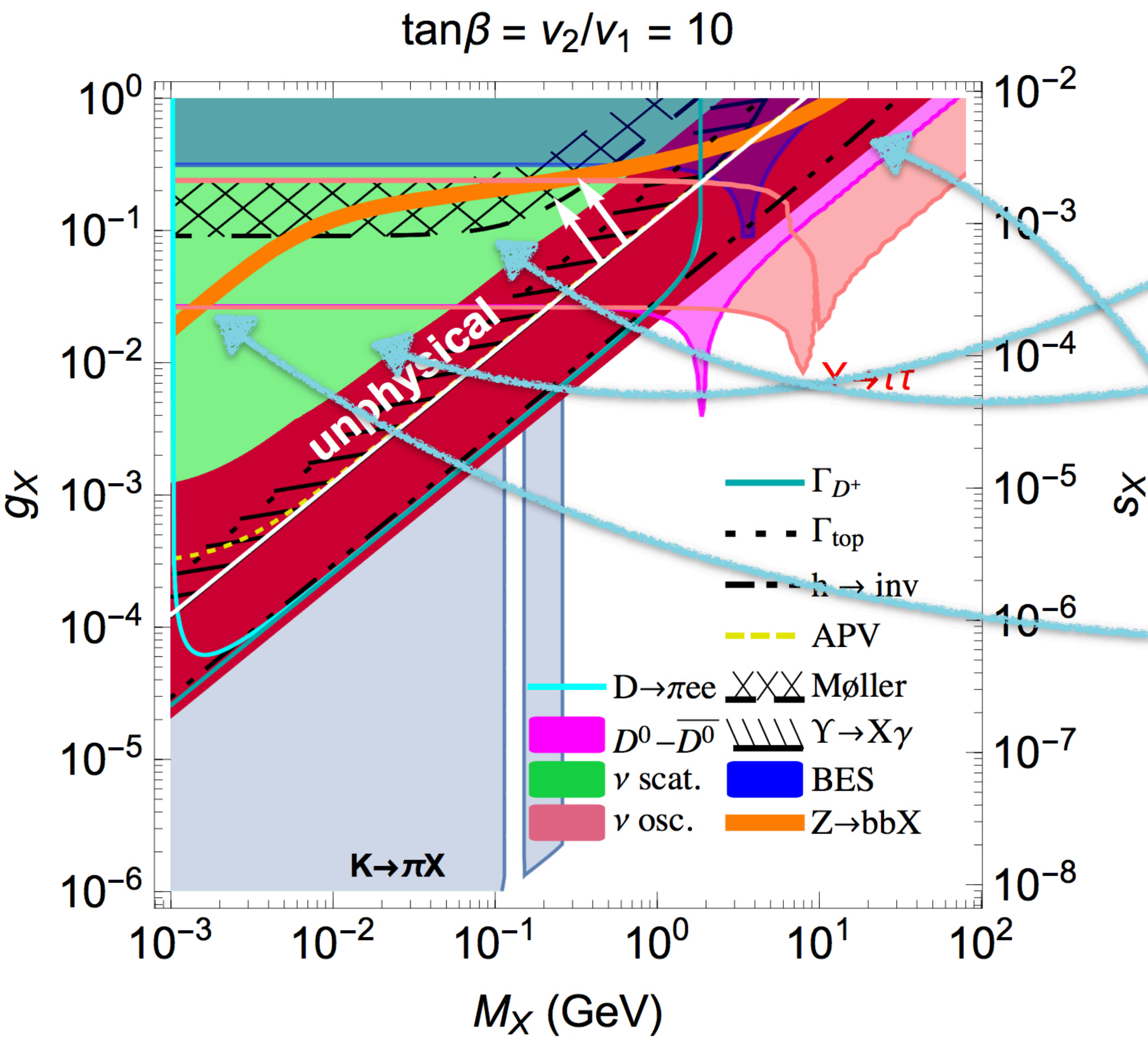
$$2\sqrt{2}G_F\varepsilon^{f}_{\alpha\alpha}\left(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L}\right)\left(\bar{f}\gamma^\mu f\right)$$

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

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



Phenomenology



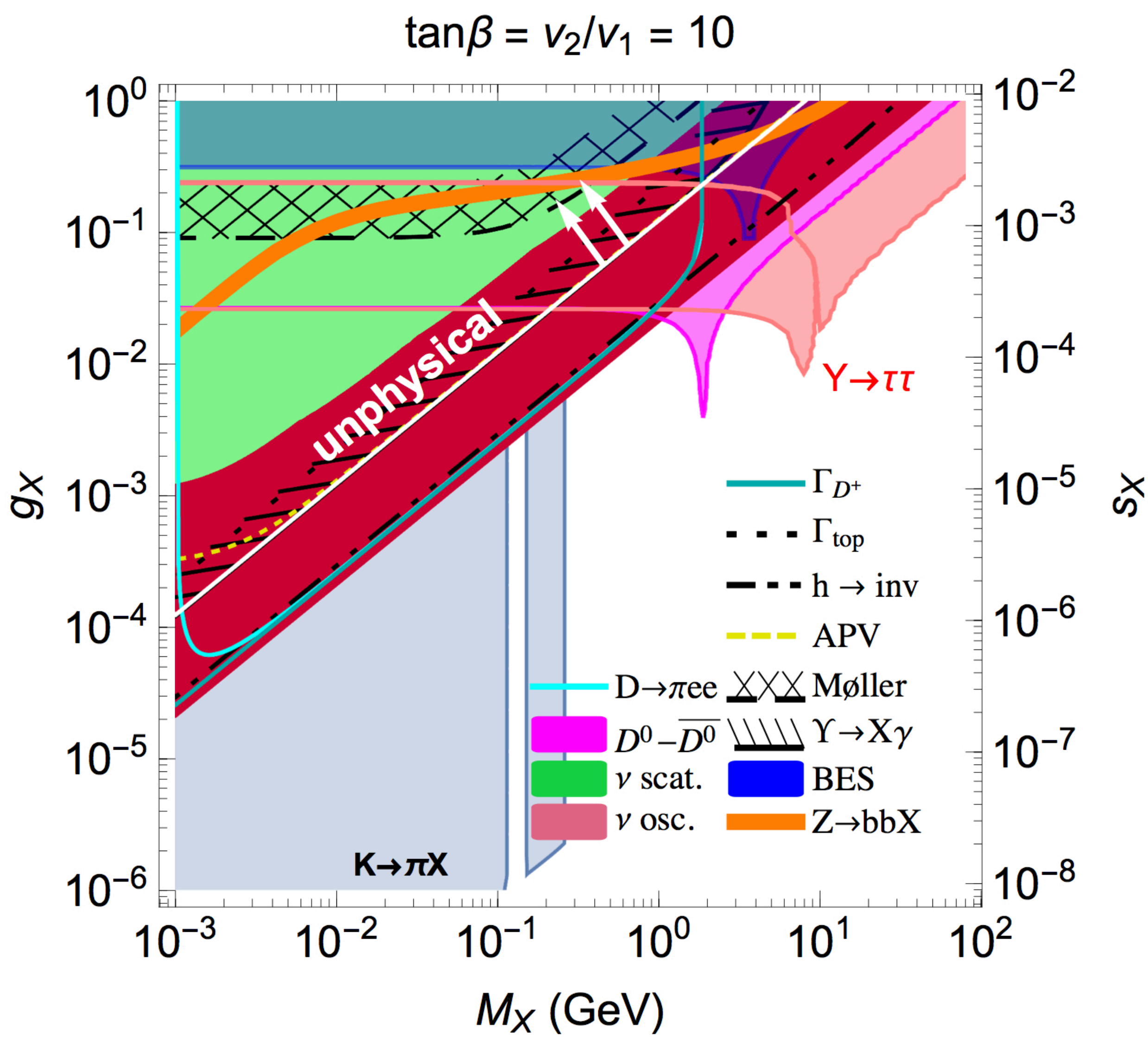
Neutrino scattering
X-Z mixing

Møller scattering
X-Z mixing

h invisible decays
Longitudinal enhancement

Z to bbX, ττX
Transverse mode

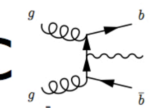
Phenomenology



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 $\tau^+\tau^-$

$(g\text{-}2)_\mu$
Does not decouple, but weak

Beam dump exps
X decays invisibly

W to τ ν X
longitudinal + transverse

LEP direct searches
Coupling to e^-

New Physics with Neutrinos

- high precision determination of standard neutrino properties

- sensitivity to new neutrino properties and other new physics require:
    1. precision measurements of many types
    2. high precision theoretical understanding of many issues
       (e.g. interaction cross sections, analysis framework)

- many complementary observables

- many new signatures to search for

Neutrino mass

Simplest scenario:

right-handed neutrino

Majorana mass $M > v$ $\longrightarrow$ see-saw mechanism

$$m_1 \sim M \qquad m_2 \sim \frac{Y^2 v^2}{M}$$

$$Y_t \sim 1 \qquad M \sim M_{GUT}$$

$$Y_e \sim 10^{-6} \qquad M \sim TeV$$

Other scenarios:

see-saw like: $m \sim \dfrac{Y'^2 v'^2}{M'}$

v' and M' can both be much smaller

Different scenarios

keV, MeV, GeV discussed in different contexts

(hidden sectors, dark matter connections, etc.)