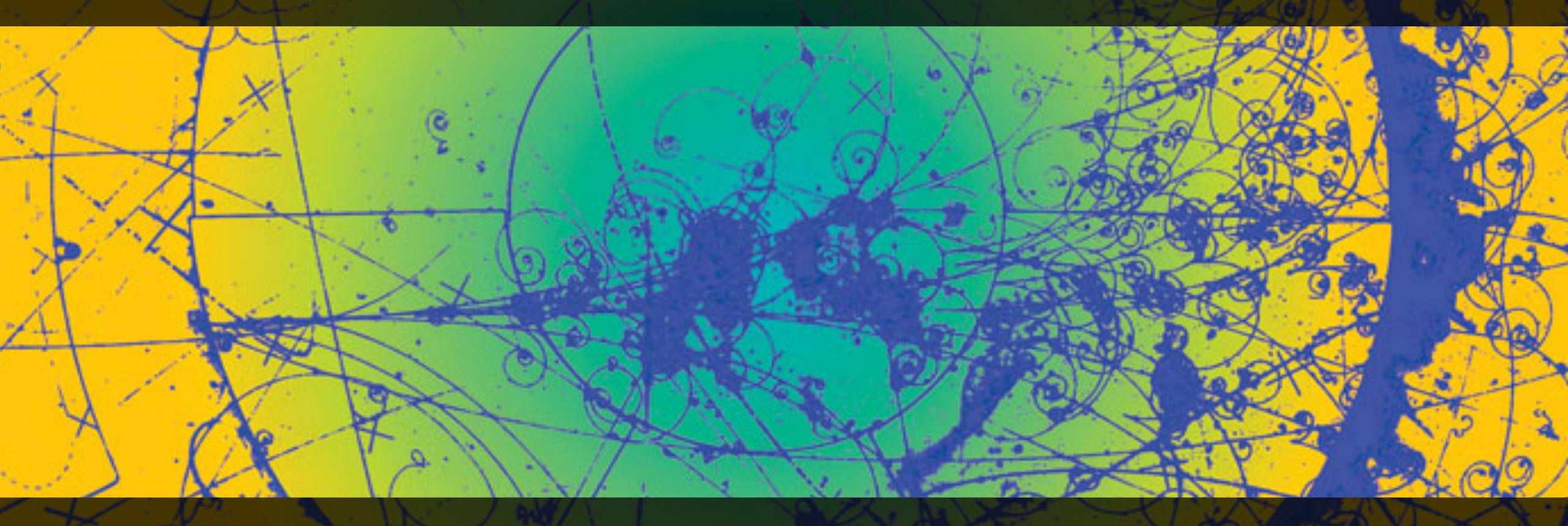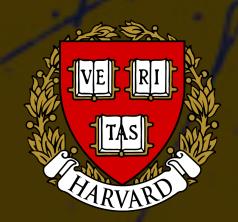# Neutrinos: physics beyond the Standard Model

Neutrino University, July 23, 2025

Matheus Hostert mhostert@g.harvard.edu

Harvard University → University of Iowa

New Physics with Neutrinos: way more than I can cover in one lecture

References to other lectures series for those interested in phenomenology/theory**:**

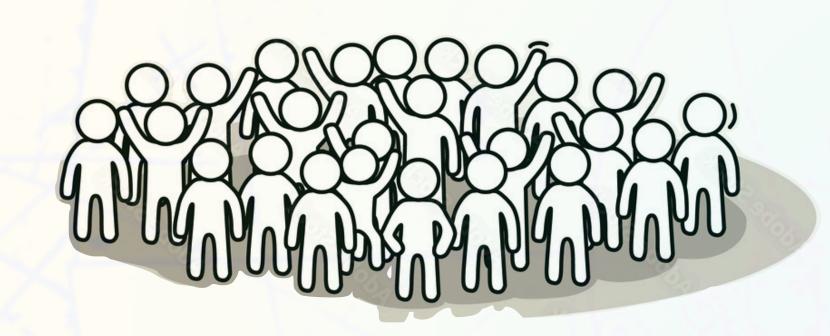**https://npc.fnal.gov/neutrino-university-past-series/**

1) Mainz lectures on Lab probes of DM and neutrinos — Brian Batell

2) TASI lectures on neutrino mass models — André de Gouvea

3) ICTP lectures on neutrino physics — Pedro Machado

4) TASI lectures on neutrino physics — Shirley Li

+ many others…

Much more at the International Neutrino Summer School (INSS) 2025

We hope to record the INSS lectures, stay tuned!
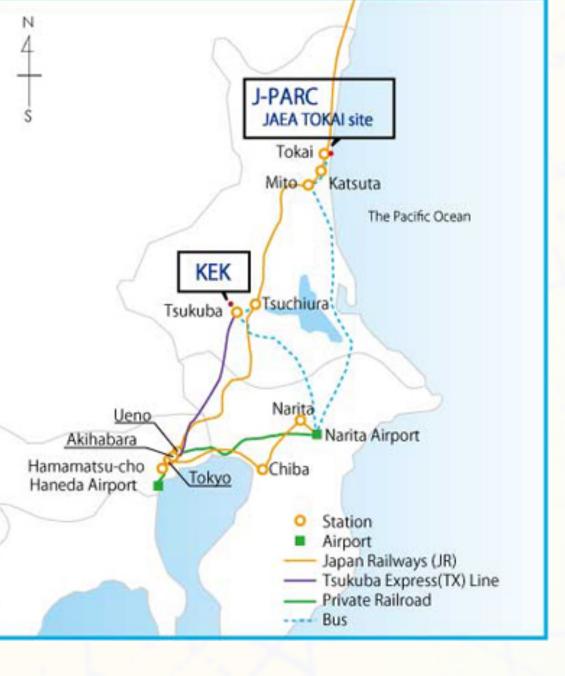
By the way… what does phenomenology mean?

Theory:

Ideas to answer conceptual and empirical puzzles. Make sense of data.

Experiment:

Measurements of known and unknown phenomena, expansion of our empirical boundaries.

Phenomenology

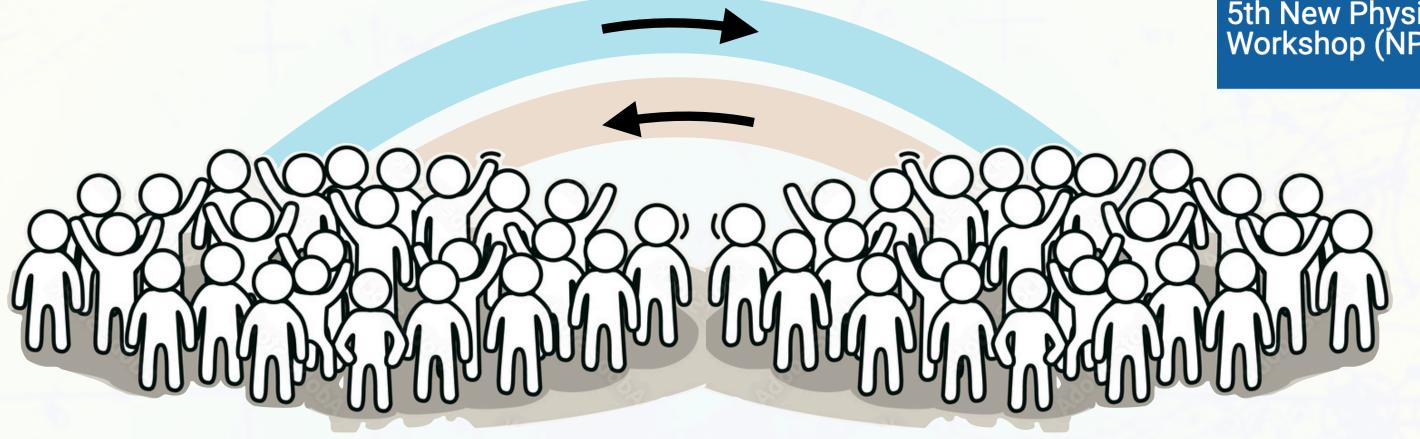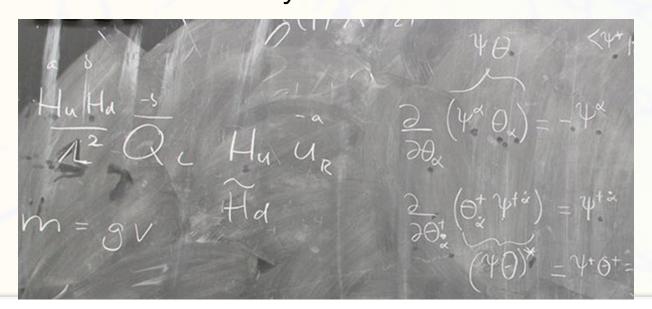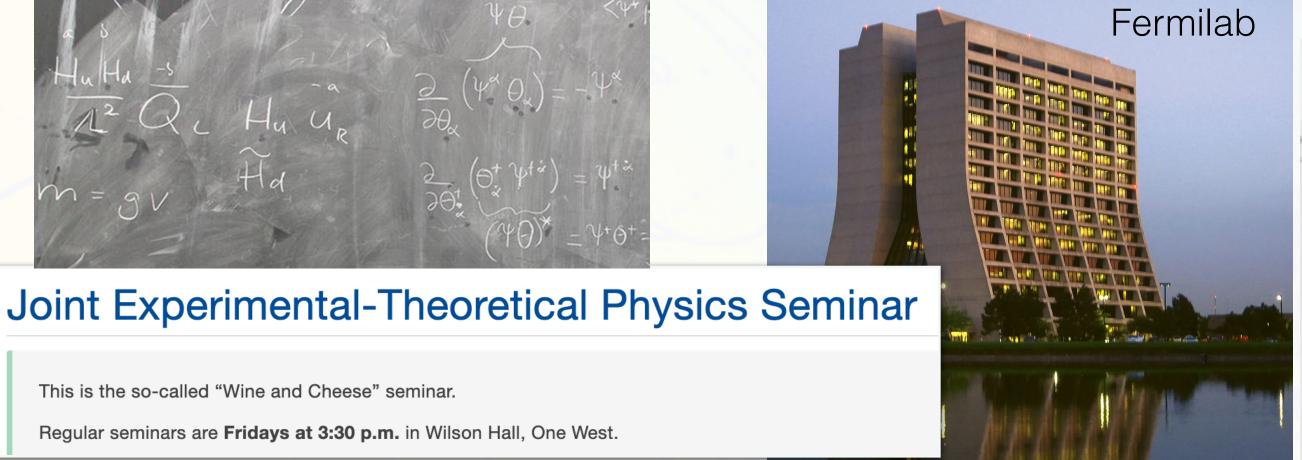**The interface or transition between the two worlds.**

Interprets and predicts measurements using existing or proposed theories.

Fermilab Theory division

Fermilab

CERN theory division

CERN

Joint Experimental-Theoretical Physics Seminar

This is the so-called "Wine and Cheese" seminar.

Regular seminars are **Fridays at 3:30 p.m.** in Wilson Hall, One West.

This Lecture / Talk

1) Neutrinos in the Standard Model — do they fit?

The Higgs and fermion masses: Dirac? Majorana? Both?

A taste of neutrino mass theories.

2) Neutrinos as probes of new fundamental physics

New forces and particles.

Neutrinos as portals to dark matter.

Note: I will take lots of shortcuts and will have to talk about things superficially.
Please ask questions!

This Lecture / Talk

1) Neutrinos in the Standard Model — do they fit?

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New forces and particles.

Neutrinos as portals to dark matter.

The Standard Model
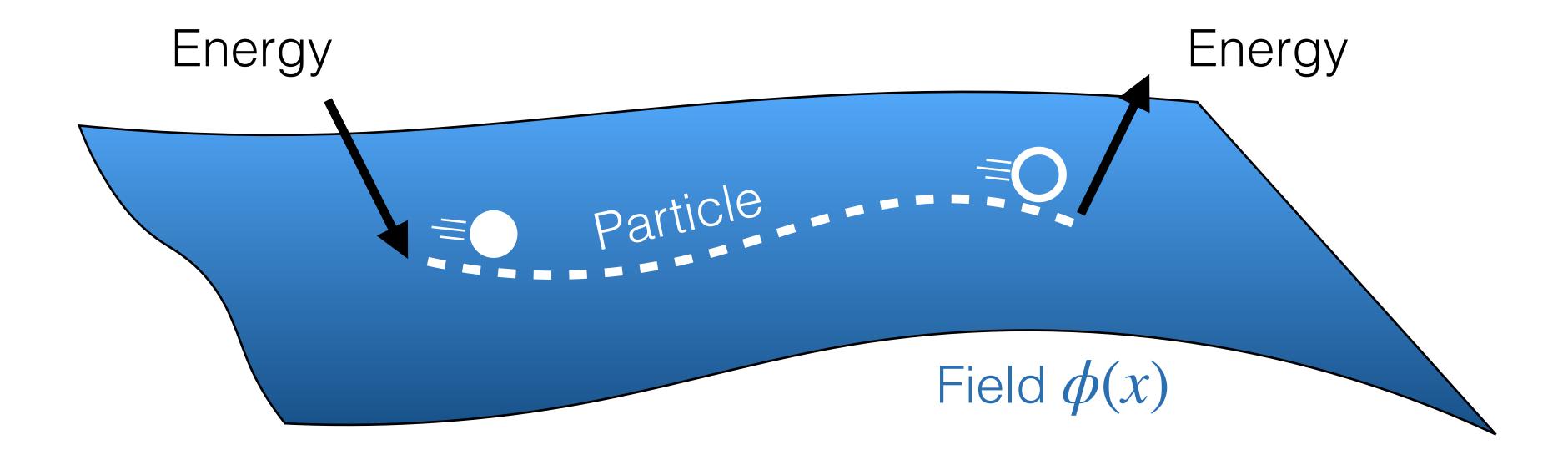
Particles and Fields

Particles are the smallest excitations of "**quantum field**"

Each particle is associated with its own field

The Standard Model (actually)

The Higgs

The Higgs Boson

(Spin-0)

The Standard Model (actually)

The Higgs

Dynamics

(Symmetries)

Strong Force

$SU(3)$

H

g

The Higgs Boson

(Spin-0)

The Standard Model (actually)

The Higgs

Dynamics

(Symmetries)

Strong Force

Electroweak Force

$\mathrm{SU}(3)$

$\mathrm{SU}(2) \times \mathrm{U}(1)$

H

g

W^+

W^-

Z

γ

The Higgs Boson

(Spin-0)

The "two" forces and their mediators

Bosons (Spin-1)

The Standard Model (actually)

Matter Content

u_L d_L u_R d_R

Left and right-handed quarks

The Higgs

H

The Higgs Boson

(Spin-0)

Dynamics

(Symmetries)

Strong Force

SU(3)

g

Electroweak Force

$SU(2) \times U(1)$

W^+

W^-

Z

γ

The "two" forces and their mediators

Bosons (Spin-1)

The Standard Model (actually)

Matter Content

u_L d_L u_R d_R
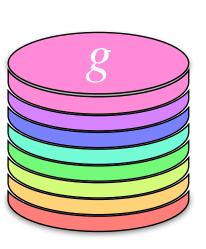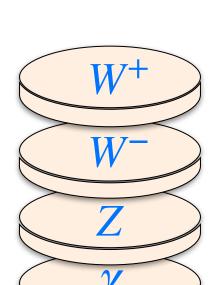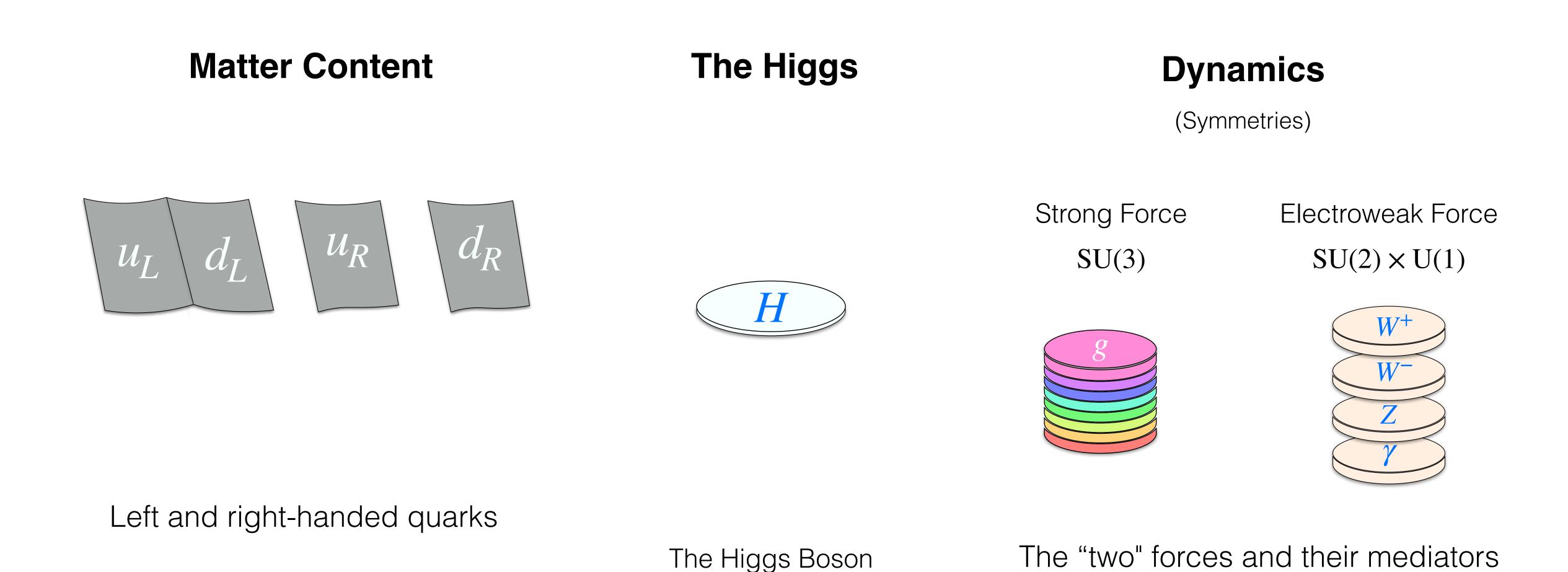
Left and right-handed quarks

with 3 colors

The Higgs
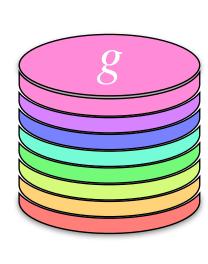
H

The Higgs Boson

(Spin-0)

Dynamics

(Symmetries)

Strong Force

SU(3)

g

Electroweak Force

SU(2) × U(1)

W^+

W^-

Z

γ

The "two" forces and their mediators

Bosons (Spin-1)

The Standard Model (actually)

Matter Content
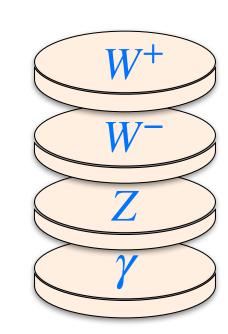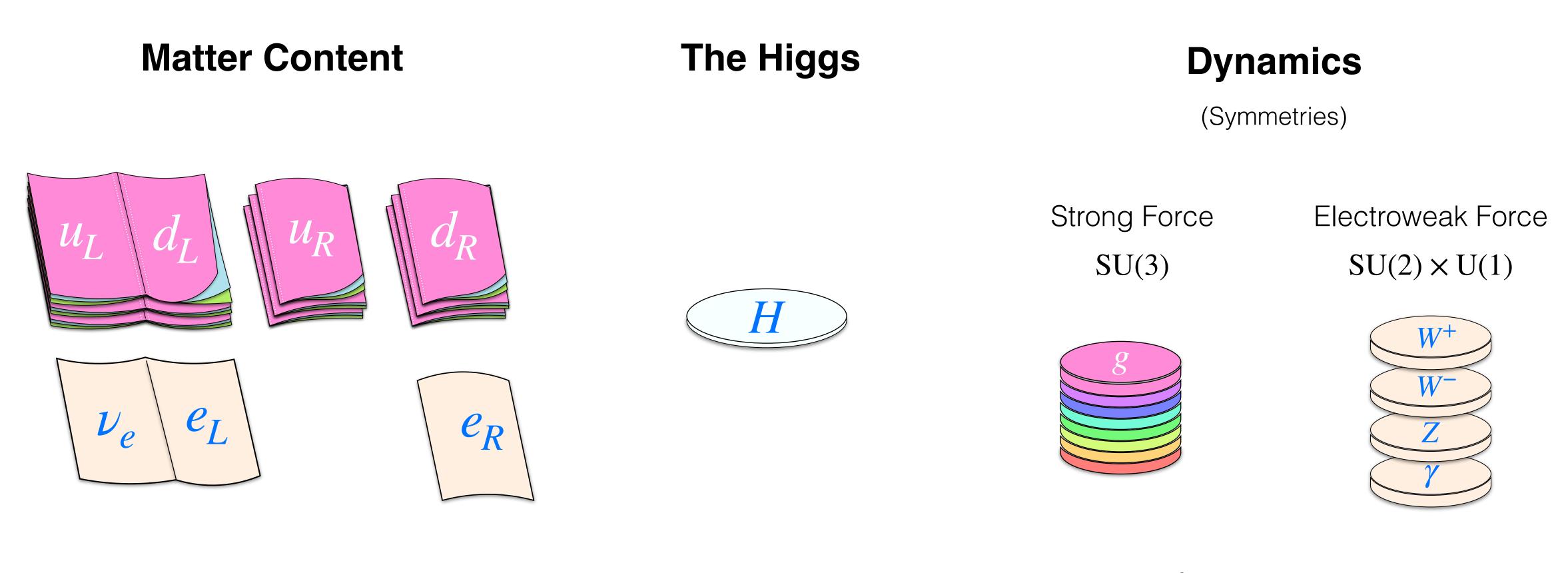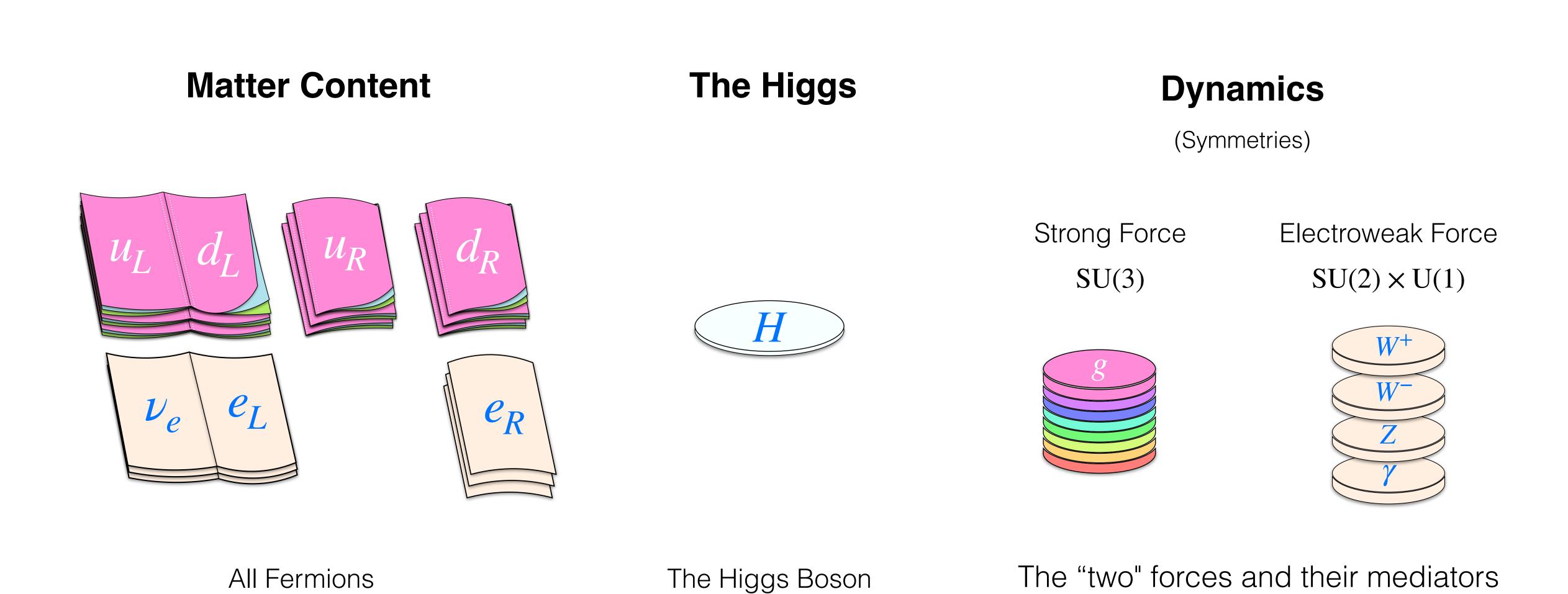
Left and right-handed quarks

with 3 colors

and 3 generations (u, c, t and d, s, b)

The Higgs

The Higgs Boson

(Spin-0)

Dynamics

(Symmetries)

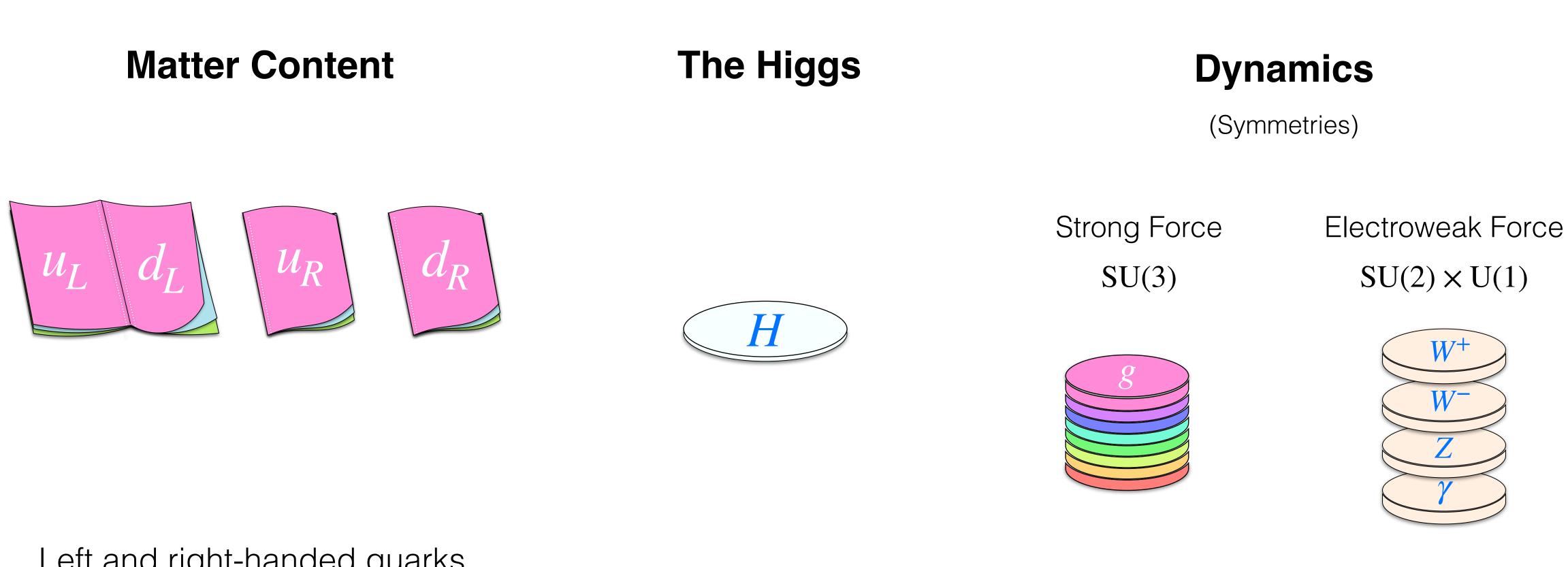Strong Force

$SU(3)$

Electroweak Force

$SU(2) \times U(1)$

The "two" forces and their mediators

Bosons (Spin-1)

The Standard Model (actually)

Matter Content

u_L d_L u_R d_R

ν_e e_L e_R

Leptons

The Higgs

H

The Higgs Boson

(Spin-0)

Dynamics

(Symmetries)

Strong Force

SU(3)

g

Electroweak Force

$SU(2) \times U(1)$

W^+

W^-

Z

γ

The "two" forces and their mediators

Bosons (Spin-1)

The Standard Model (actually)

Matter Content

u_L d_L u_R d_R

ν_e e_L e_R

All Fermions

(Spin-1/2)

The Higgs

H

The Higgs Boson

(Spin-0)

Dynamics

(Symmetries)

Strong Force

$SU(3)$

Electroweak Force

$SU(2) \times U(1)$

g

W^+

W^-

Z

γ

The "two" forces and their mediators

Bosons (Spin-1)

The Standard Model (actually)

Matter Content

u_L d_L u_R d_R

ν_e e_L ν_R e_R

All Fermions

(Spin-1/2)

The Higgs

H

The Higgs Boson

(Spin-0)

Dynamics

(Symmetries)

Strong Force

SU(3)

g

Electroweak Force

$SU(2) \times U(1)$

W^+

W^-

Z

γ

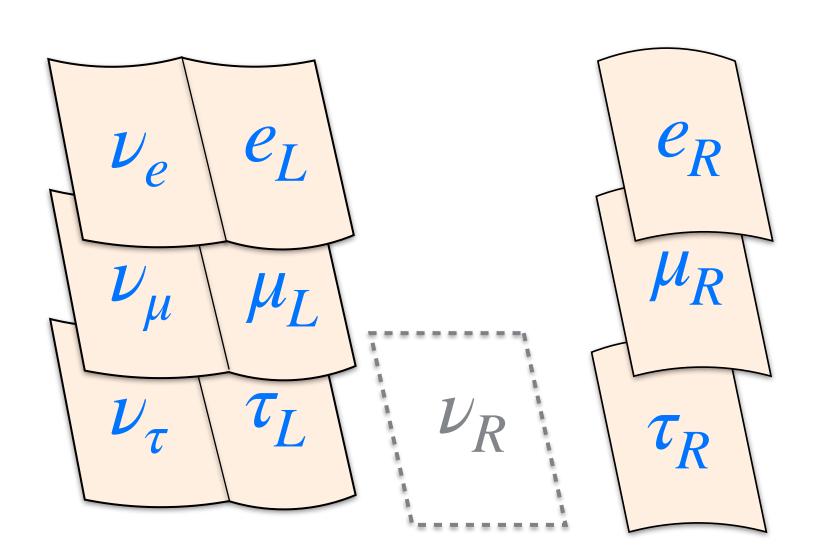The "two" forces and their mediators

Bosons (Spin-1)

How many neutrinos?

Usual lepton flavors.

How many neutrinos?

Usual lepton flavors.

"Sterile" or "right-handed" neutrinos.

ν_e e_L

ν_μ μ_L

ν_τ τ_L

ν_R

e_R

μ_R

τ_R

ν_R ?

**If they exist, ν_R neutrinos
would not interact with any known force**

Fermion Masses

Dirac Mass

$$m_D$$
$$\psi_L \longrightarrow\!\!\times\!\!\longrightarrow \psi_R$$

Couples two chiral particles

Majorana Mass

$$m_L$$
$$\psi_L \longrightarrow\!\!\times\!\!\longrightarrow \overline{\psi_L}$$

Going from particle to antiparticle

Put in "by-hand": a mass is an intrinsic property of the field.

It should be Lorentz-invariant, so I need to associate it with a combination that has "no spin":

$$\psi_L \psi_R \quad \text{or} \quad \psi_L \overline{\psi_L}$$

Fermion Masses

Dirac Mass

$$m_D$$

$$\psi_L \ \rule[0.5ex]{1cm}{0.4pt}\!\!\times\!\!\rule[0.5ex]{1cm}{0.4pt} \ \psi_R$$

$$Q_{\mathrm{EM}} \qquad\qquad Q_{\mathrm{EM}}$$

Majorana Mass

$$m_L$$

$$\psi_L \ \rule[0.5ex]{1cm}{0.4pt}\!\!\times\!\!\rule[0.5ex]{1cm}{0.4pt} \ \overline{\psi_L}$$

$$Q_{\mathrm{EM}} \qquad\qquad -Q_{\mathrm{EM}}$$

Any quantum number associated with the fermion is violated by a Majorana mass

Reason why all other SM fermions can only have a Dirac mass.

Electromagnetic charge Q_{EM} conservation is incompatible with a Majorana mass

What about neutrinos?

Dirac Mass

$$m_D$$

$$\nu_L \longmapsto \nu_R$$

$$Q_{\text{EM}} = 0 \qquad Q_{\text{EM}} = 0$$

Majorana Mass

$$m_L$$

$$\nu_L \longmapsto \overline{\nu_L}$$

$$Q_{\text{EM}} = 0 \qquad -Q_{\text{EM}} = 0$$

Neutrinos carry no electromagnetic charge, so **Majorana masses are allowed.**

The only fundamental fermion we know of that can do this.

What about neutrinos?

Dirac Mass

$$\nu_L \overset{m_D}{\rule{2em}{0.4pt}\times\rule{2em}{0.4pt}} \nu_R$$

$Q_{\mathrm{W}} \neq 0 \qquad\qquad Q_{\mathrm{W}} = 0$

Majorana Mass

$$\nu_L \overset{m_L}{\rule{2em}{0.4pt}\times\rule{2em}{0.4pt}} \overline{\nu_L}$$

$Q_{\mathrm{W}} \qquad\qquad -Q_{\mathrm{W}}$

However!
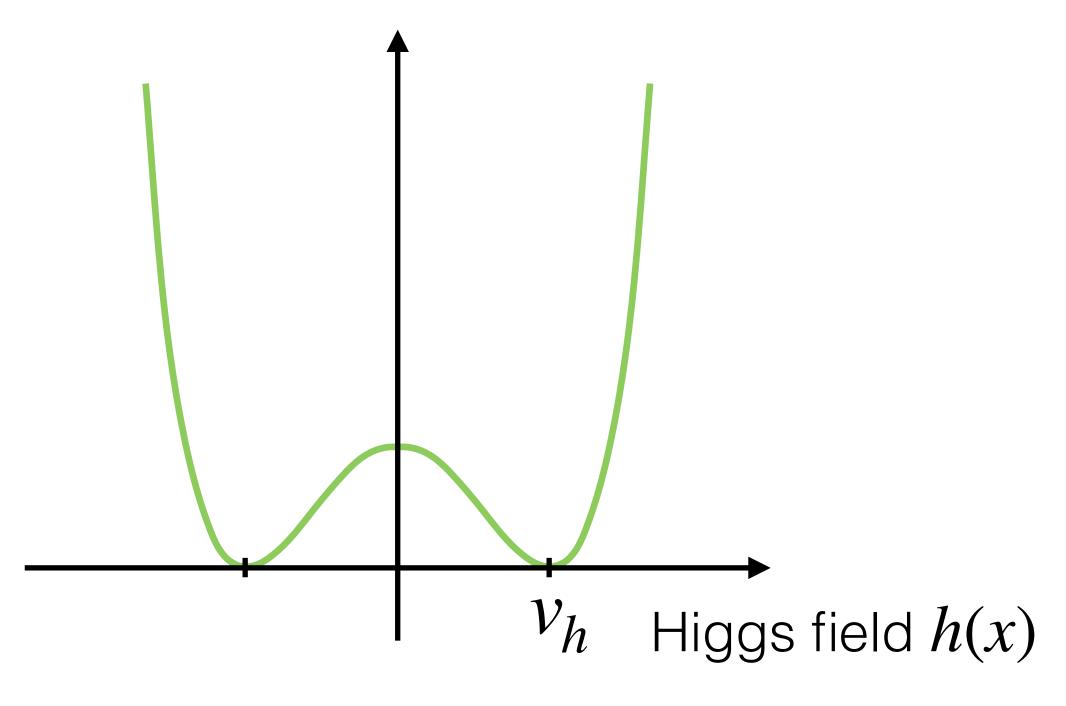
Left- and right-handed particles carry different charges ("Q_{W}") under the Weak force
(the charge responsible for weak Z and $W^{\pm}$ interactions).

Shouldn't "Q_{W}" also be conserved?

Q_W is actually a combination of the fermion charge under the $SU(2)_L \times U(1)_Y$ gauge symmetries.
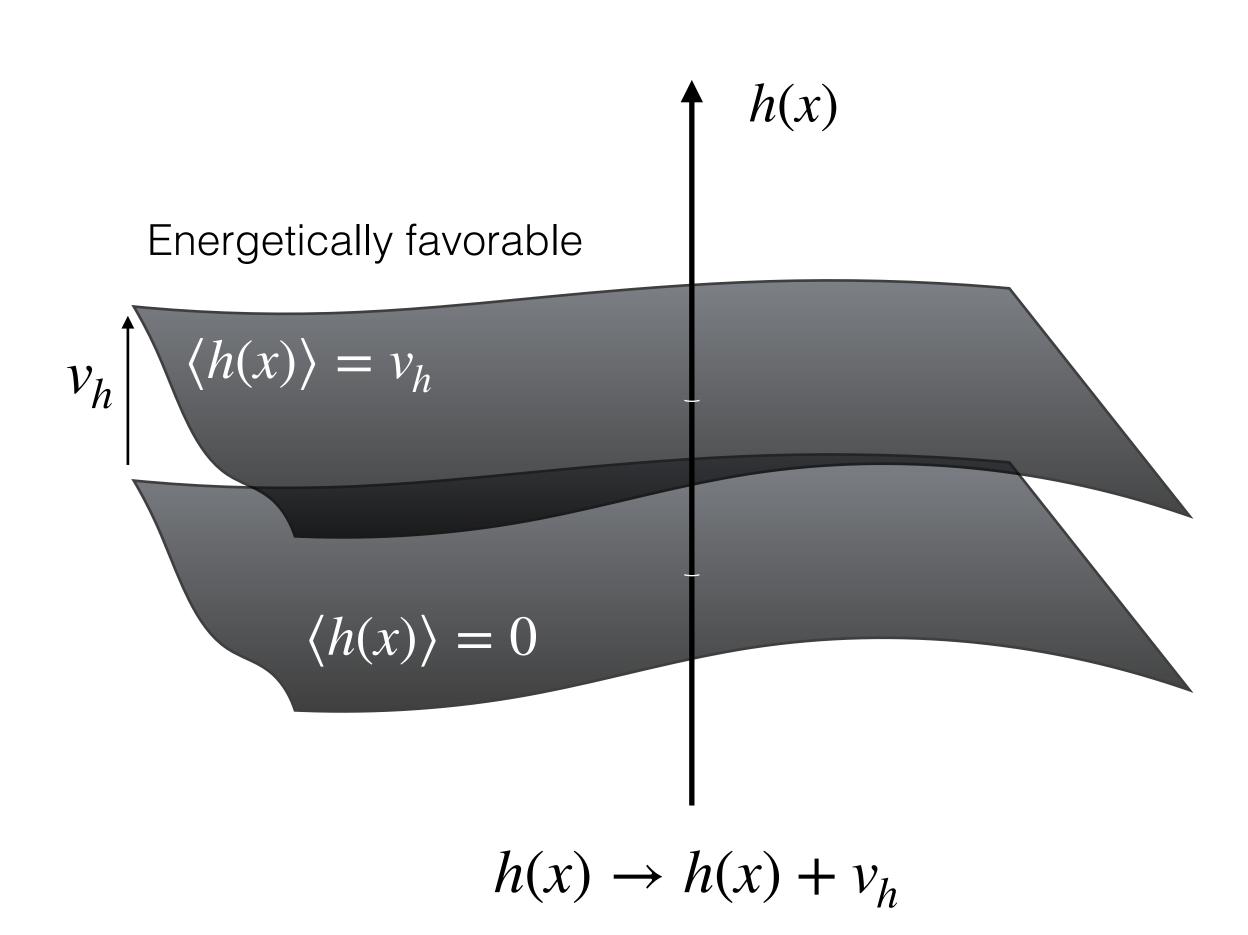
The Higgs Mechanism
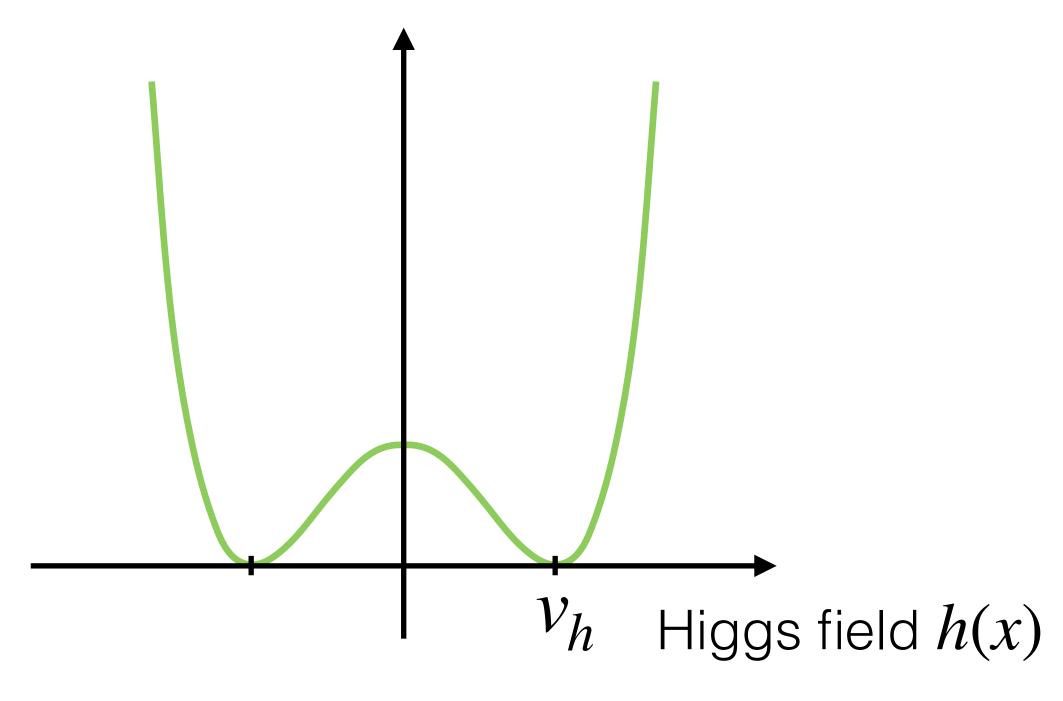
Potential energy $V(x)$

v_h

Higgs field $h(x)$

$$V(x) \sim \left(h^2 - v_h^2 \right)^2$$

The Higgs Mechanism

Potential energy $V(x)$

Higgs field $h(x)$

v_h

$$V(x) \sim \left(h^2 - v_h^2 \right)^2$$

$h(x)$

Energetically favorable

v_h

$\langle h(x) \rangle = v_h$

$\langle h(x) \rangle = 0$

$$h(x) \rightarrow h(x) + v_h$$
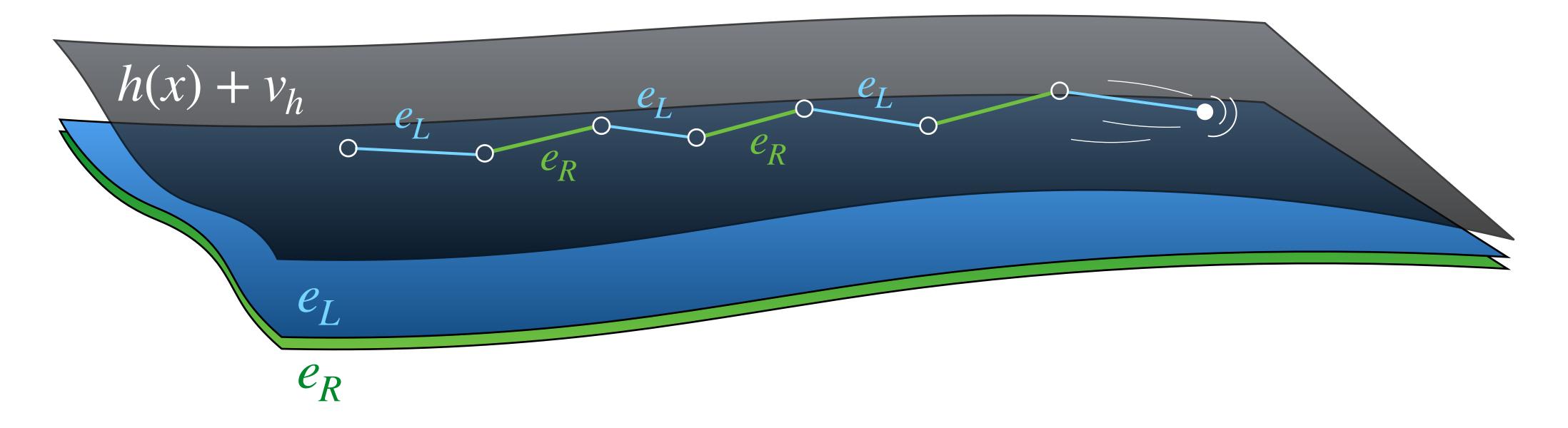
Higgs develops a non-zero "vacuum expectation value" (v.e.v.)
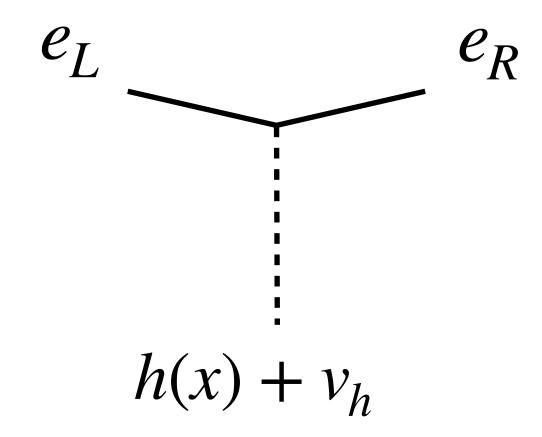
Cartoonish picture fermion masses from the Higgs field

Electron-Higgs interactions give rise to the electron mass.
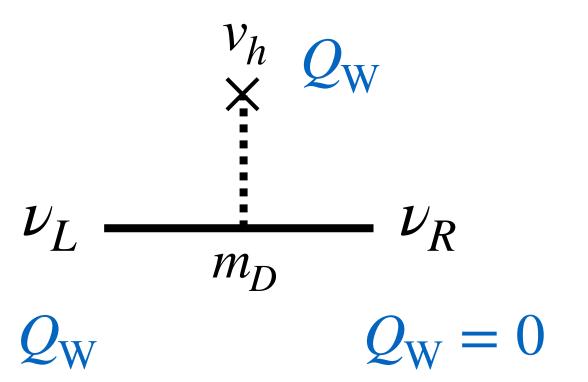
As we will see, "e_L" and "e_R" are two sides of the same coin:
the Dirac fermion "e"

This is a "phib" (a physics fib): see this nice discussion by M. Strassler
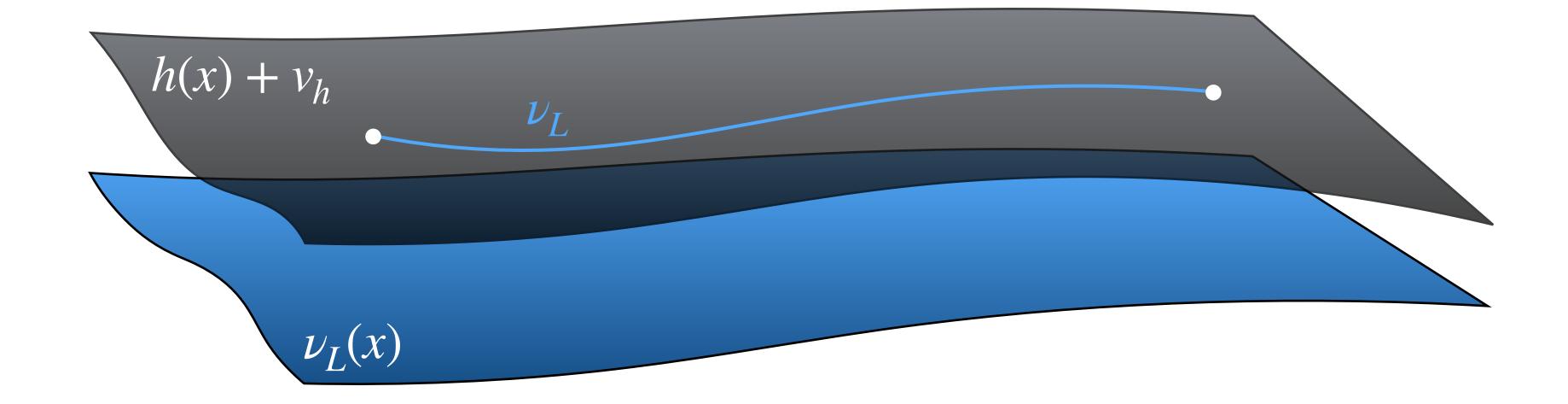
"**Dirac** Mass"

$$v_h$$
$$\times \quad Q_{\mathrm{W}}$$

$$\nu_L \overline{\qquad\qquad} \nu_R$$
$$m_D$$

$$Q_{\mathrm{W}} \qquad\qquad Q_{\mathrm{W}} = 0$$

$$m_D = y \times v_h$$

y Is called the Yukawa coupling
(Typically between 0 and 1)

It turns out that the Higgs background allows this charge to be *effectively* violated.

The Higgs acts to **"store"** and **"lend"** any leftover "Q_W".

m_D and m_L are now no longer intrinsic properties of the field, but the result of **the Higgs (background)** interacting with **fermions, conserving Q_W overall.**

The problem with neutrinos
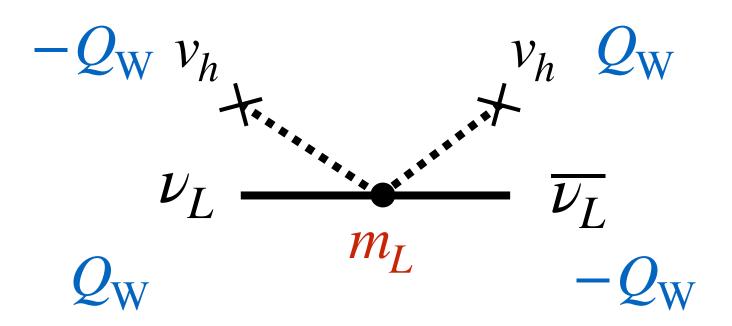
Without ν_R, the Standard Model predicts massless neutrinos.

As you know, this is **not** compatible with the fact that neutrinos oscillate!

What about Majorana masses?

"**Majorana** Mass"

$$-Q_{\mathrm{W}} \; v_h \qquad\qquad v_h \; Q_{\mathrm{W}}$$

$$\nu_L \quad\rule{1cm}{0.4pt}\bullet\rule{1cm}{0.4pt}\quad \overline{\nu_L}$$

$$m_L$$

$$Q_{\mathrm{W}} \qquad\qquad -Q_{\mathrm{W}}$$

$$m_L = \mathrm{coupling}' \times \frac{v_h^2}{\Lambda}$$
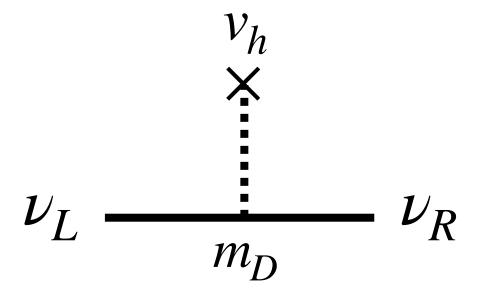
m_L implies the existence of a new energy scale Λ that is different from v_h

The SM is then an **effective theory** and recognize the existence of **new physics at scale** Λ.

Not a solution on its own, but a useful framework.

What about right-handed neutrinos?

"**Dirac** Mass"

$$\nu_L \underset{m_D}{\overset{\overset{v_h}{\times}}{\rule{6em}{0.4pt}}} \nu_R$$

Majorana Mass

$$\nu_R \overset{m_R}{\underset{\times}{\rule{6em}{0.4pt}}} \overline{\nu_R}$$

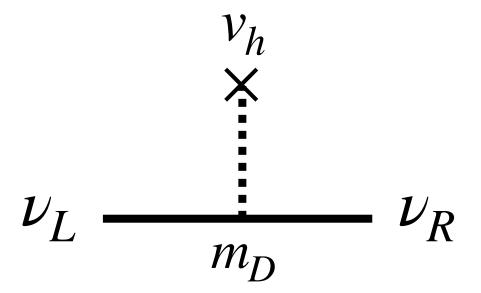ν_R is "sterile" — it need not carry any (conserved) quantum number.

Unless new symmetries exist in nature, ν_R should have a Majorana mass.

This can now be a genuine fundamental parameter.

What about right-handed neutrinos?

"Dirac Mass"

$$v_h$$
$$\times$$
$$\nu_L \rule{2cm}{0.4pt} \nu_R$$
$$m_D$$

Majorana Mass

$$m_R$$
$$\nu_R \rule{2cm}{0.4pt}\times\rule{1cm}{0.4pt} \overline{\nu_R}$$

One such symmetry could be Lepton Number:

$$L(\nu_L) = L(\nu_R) = +1$$

If conserved, $m_R = 0$ and $m_L = 0$, and neutrinos are simply Dirac particles.

Neutrino Masses (seesaw)

Mass matrix of ν_L and ν_R:

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

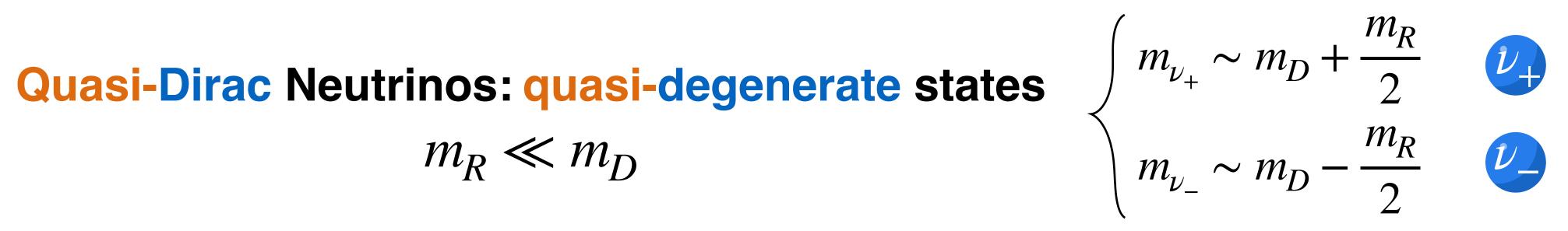# Neutrino Masses (seesaw)

Interaction (flavor) basis

$$(\nu_L \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Diagonalize to mass basis

$\longrightarrow$

Mass (physical) states

$$(\nu_1 \quad \nu_2) \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

General 2 neutrino picture:
$$\left\{ m_{1,2} \sim \frac{m_R^2 \pm \sqrt{4m_D^2 + m_R^2}}{2m_R} \right.$$

Weakly-interacting neutrino (standard)

$$|\nu_L\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

Sterile neutrino (new physics, not observed)

$$|\nu_R\rangle = -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle$$

Let's investigate a few regimes

Neutrino Masses (seesaw)

Interaction (flavor) basis

$$(\nu_L \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D & 0 \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$
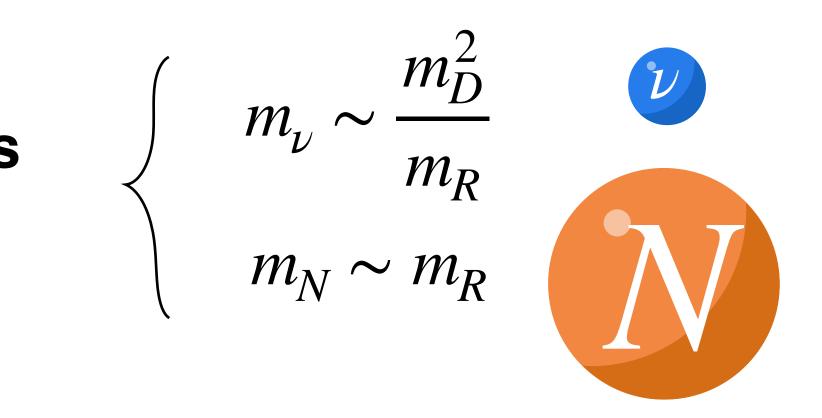
Diagonalize to
mass basis

$\longrightarrow$

Mass (physical) states

$$(\nu_- \quad \nu_+) \begin{pmatrix} m_{\nu_-} & 0 \\ 0 & m_{\nu_+} \end{pmatrix} \begin{pmatrix} \nu_- \\ \nu_+ \end{pmatrix}$$

Dirac Neutrinos: **degenerate** states

$$m_R = 0$$
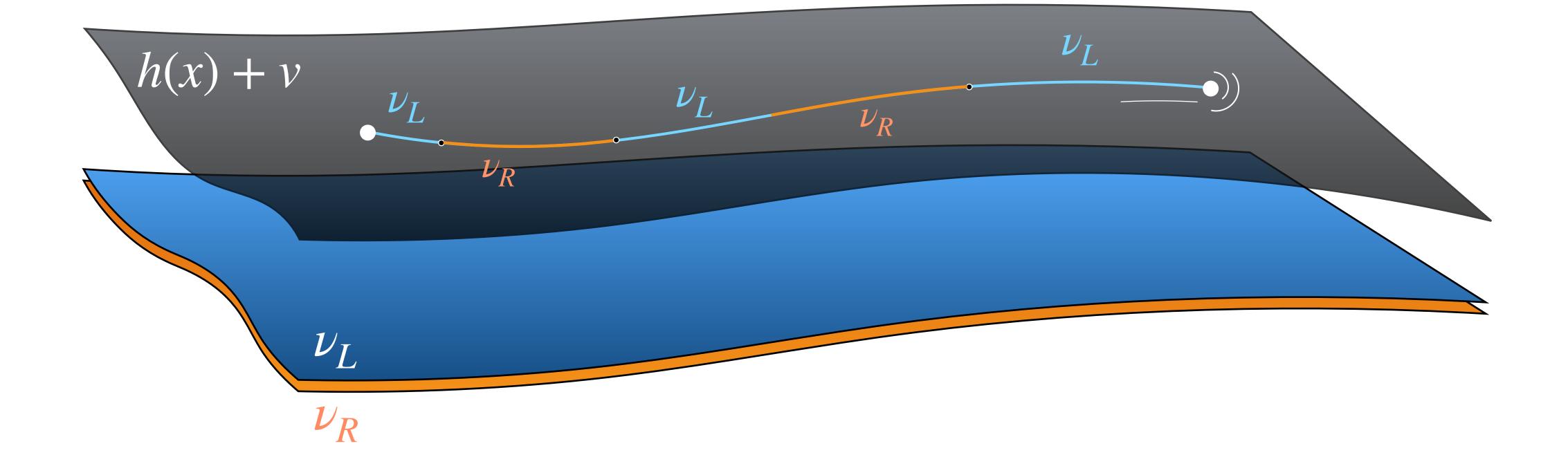
$$\begin{cases} m_{\nu_+} = m_D \quad \nu_+ \\ \\ m_{\nu_-} = m_D \quad \nu_- \end{cases}$$

Weakly-interacting neutrino (standard)

$$|\nu_L\rangle = \frac{|\nu_+\rangle + |\nu_-\rangle}{\sqrt{2}}$$

$$\theta = \frac{\pi}{4}$$

Sterile neutrino (new physics, not observed)

$$|\nu_R\rangle = \frac{|\nu_+\rangle - |\nu_-\rangle}{\sqrt{2}}$$

Neutrino Masses (seesaw)

Interaction (flavor) basis

$$(\nu_L \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Diagonalize to
mass basis

$\longrightarrow$

Mass (physical) states

$$(\nu_- \quad \nu_+) \begin{pmatrix} m_{\nu_-} & 0 \\ 0 & m_{\nu_+} \end{pmatrix} \begin{pmatrix} \nu_- \\ \nu_+ \end{pmatrix}$$

Quasi-Dirac Neutrinos: quasi-degenerate states

$$m_R \ll m_D$$

$$\begin{cases} m_{\nu_+} \sim m_D + \dfrac{m_R}{2} & \nu_+ \\[2em] m_{\nu_-} \sim m_D - \dfrac{m_R}{2} & \nu_- \end{cases}$$

Weakly-interacting neutrino (standard)

$$|\nu_L\rangle \sim \frac{|\nu_+\rangle + |\nu_-\rangle}{\sqrt{2}}$$

$$\theta \sim \frac{\pi}{4}$$

Sterile neutrino (new physics, not observed)

$$|\nu_R\rangle \sim \frac{|\nu_+\rangle - |\nu_-\rangle}{\sqrt{2}}$$

Neutrino Masses (seesaw)

Interaction (flavor) basis

$$(\nu_L \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Diagonalize to
mass basis
$\longrightarrow$

Mass (physical) states

$$(\nu \quad N) \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

Seesaw Mechanism: large Majorana masses

$$m_R \gg m_D$$

$$\begin{cases} m_\nu \sim \dfrac{m_D^2}{m_R} \\ m_N \sim m_R \end{cases}$$

Weakly-interacting neutrino (standard)

$$|\nu_L\rangle \sim |\nu\rangle + \theta |N\rangle$$

$$\theta \ll 1$$

Sterile neutrino (new physics, not observed)
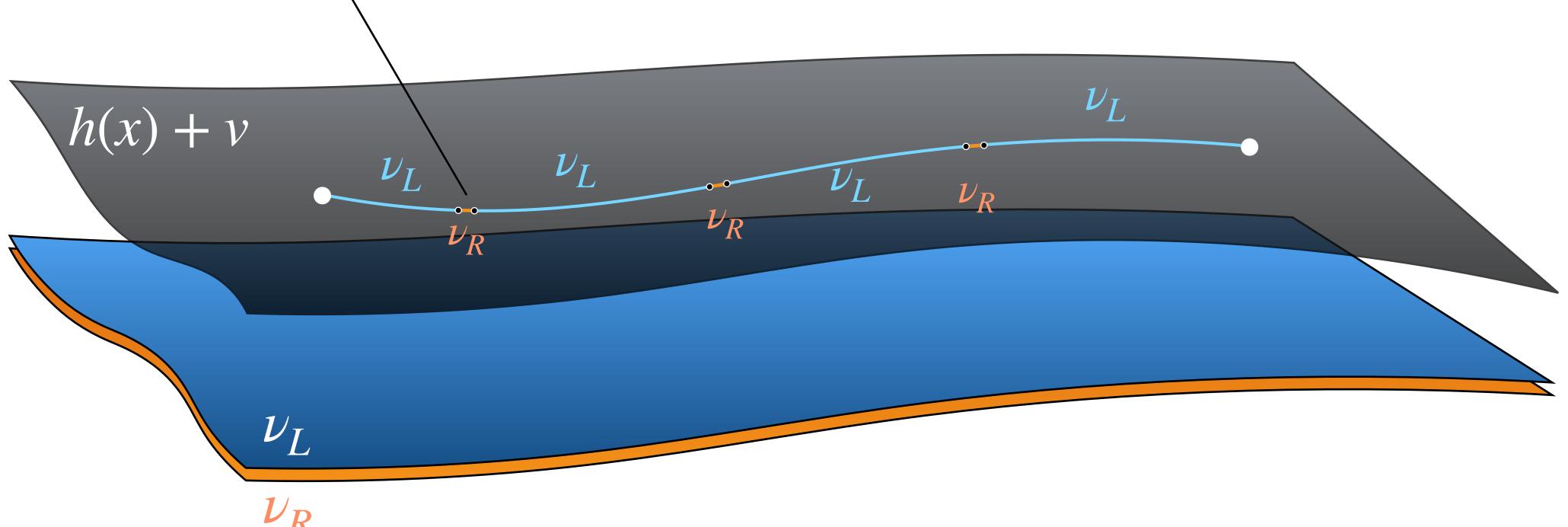
$$|\nu_R\rangle \sim |N\rangle - \theta |\nu\rangle$$

Yet another cartoon: the seesaw mechanism

$$\delta t \delta E > \frac{\hbar}{2} \implies \delta t \sim \frac{1}{m_R}$$

"The larger m_R is, the less time ν_R has to fluctuate into existence"

Again, just a cartoon, don't take this too seriously!

Neutrino Masses (seesaw)

Interaction (flavor) basis

$$(\nu_L \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Diagonalize to
mass basis

$\longrightarrow$

Mass (physical) states

$$(\nu \quad N) \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

Let's put some numbers in

(assuming "couplings" = 1 so that $m_D \sim v_h$)

What we want: $m_\nu \sim 0.1$ eV

Physicists

What we get: $m_\nu \sim \dfrac{m_D^2}{m_R} = 0.1 \text{ eV} \left(\dfrac{v_h}{100 \text{ GeV}} \right)^2 \left(\dfrac{10^{14} \text{ GeV}}{m_N} \right)$ and $\theta^2 \sim 10^{-24}$

Neutrino Masses (seesaw)

Interaction (flavor) basis   **Mass (physical) states**

$$\begin{pmatrix} \vec{\nu}_L & \vec{\nu}_R \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix} \begin{pmatrix} \vec{\nu}_L \\ \vec{\nu}_R \end{pmatrix}$$

$\xrightarrow{\text{Diagonalize to mass basis}}$

$$\begin{pmatrix} \vec{\nu} & \vec{N} \end{pmatrix} \begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ \vec{N} \end{pmatrix}$$

In reality, this is a matrix multiplication problem:

(3x3)   (3x?) (?x?) (?x3)

$$M_\nu \sim M_D \textcolor{red}{M_R^{-1}} M_D^T$$

We know nothing about the matrix M_N:
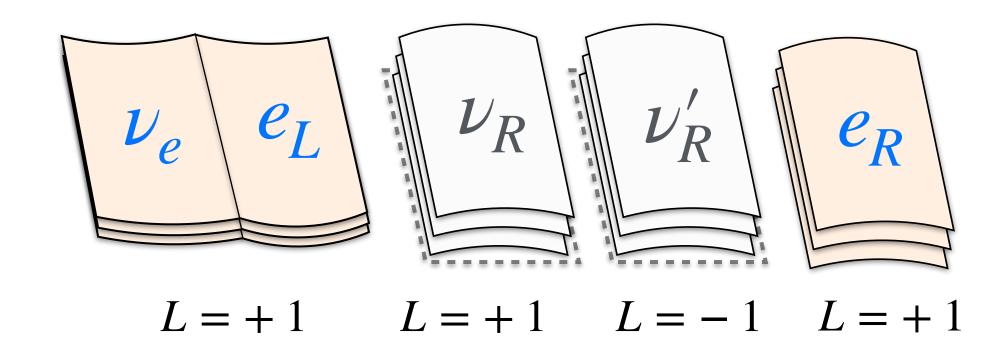
How many right-handed neutrinos (how many entries in $\vec{\nu}_R$)?

Do they respect new kinds of symmetries?

Do they feel new interactions?

Neutrino Masses (the *inverse* seesaw)

Interaction (flavor) basis

Now there are two kinds of RH neutrinos for a single ν_L

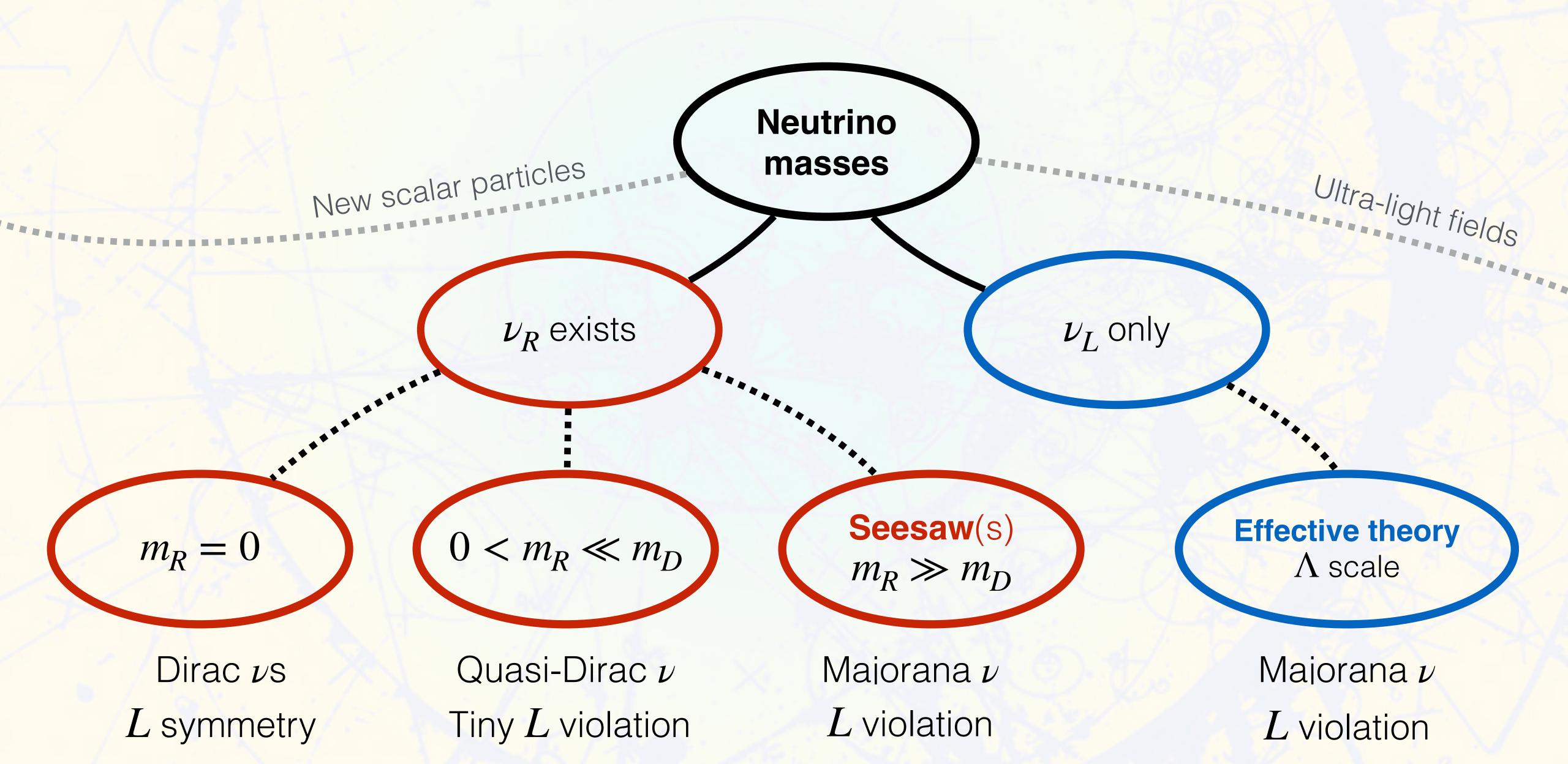$$\begin{pmatrix} \nu_L & \nu_R & \nu_R' \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \\ \nu_R' \end{pmatrix}$$

ν_e e_L ν_R ν_R' e_R

$L = +1$ $L = +1$ $L = -1$ $L = +1$
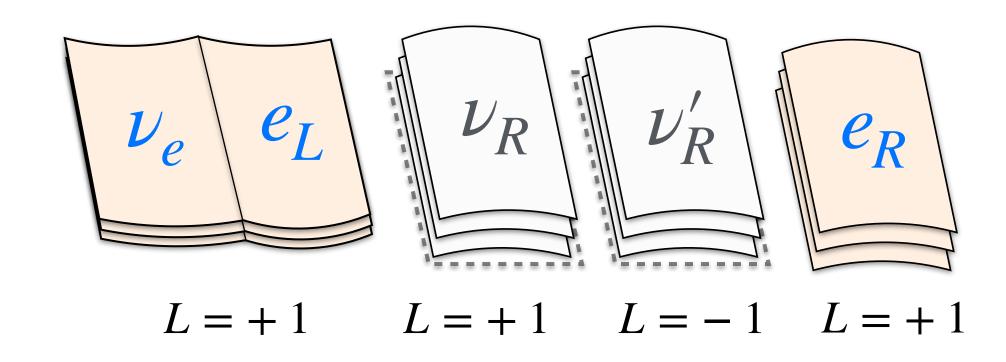
"Left for the reader": Diagonalize this mass matrix assuming $m_D \ll M$ and $m_R \ll M$.

Neutrino Masses (the *inverse* seesaw)

Interaction (flavor) basis

$$\begin{pmatrix} \nu_L & \nu_R & \nu'_R \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \\ \nu'_R \end{pmatrix}$$

Now there are two kinds of RH neutrinos for a single ν_L

$$L = +1 \qquad L = +1 \qquad L = -1 \qquad L = +1$$

You should find:

$$m_1 = \frac{m_D^2}{M^2} m_R \text{ (Majorana particle) and } m_{2,3} \sim M \pm \frac{m_R}{2} \text{ (quasi-Dirac pair)}.$$

A "seesaw", but the smaller the "Majorana" mass m_R is, the lighter neutrinos are.
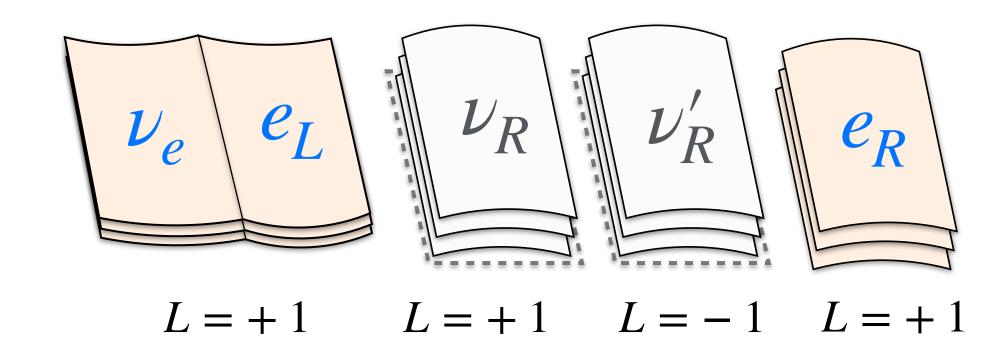
Lepton number is almost a good symmetry (it is exact if $m_R = 0$ and "lightest" neutrinos are massless)

Neutrino Masses (the *inverse* seesaw)

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$$\begin{pmatrix} \nu_L & \nu_R & \nu'_R \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \\ \nu'_R \end{pmatrix}$$

Now there are two kinds of RH neutrinos for a single ν_L

$L = +1 \qquad L = +1 \qquad L = -1 \qquad L = +1$

Heavy neutrinos can be within experimental reach:

Summary

This Lecture / Talk

1) Neutrinos in the Standard Model — do they fit?

The Higgs and fermion masses: Dirac? Majorana? Both?

A taste of neutrino mass theories.

2) Neutrinos as probes of new fundamental physics

New forces and particles.

Neutrinos as portals to dark matter.
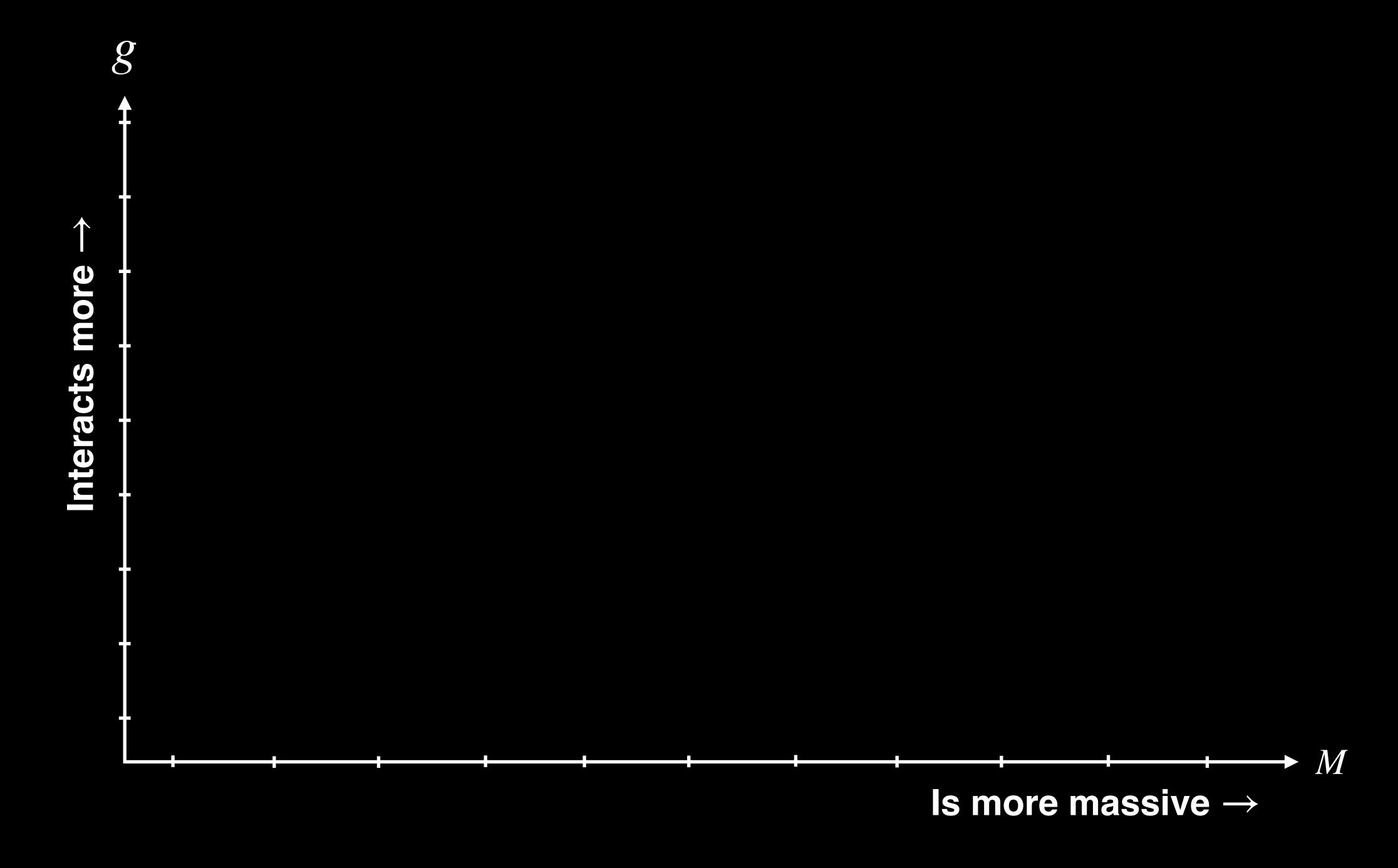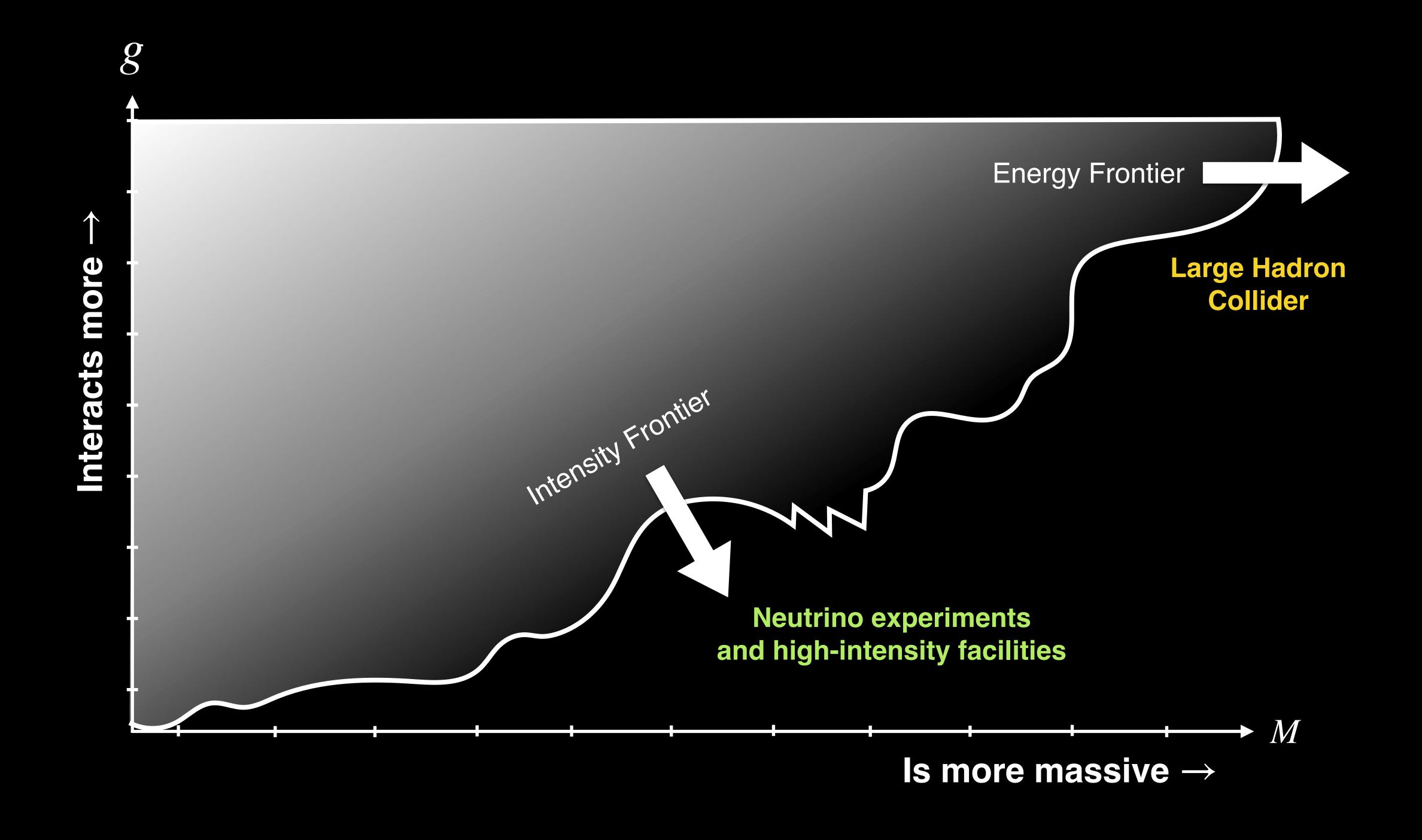
**STANDARD
MODEL**

DARK SECTOR

New particles carry no SM charge
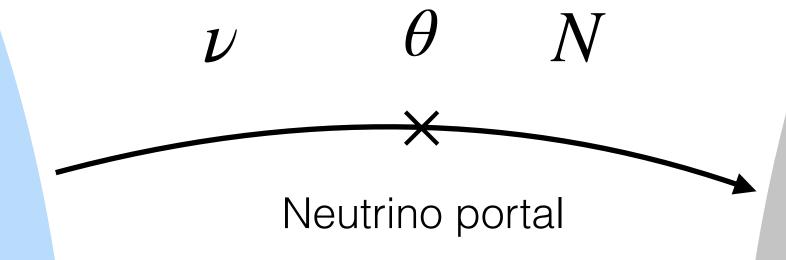
New fundamental mass scales

New particles can be light

Testable at low energies!

STANDARD MODEL

DARK SECTOR

$$\nu \quad \theta \quad N$$

Neutrino portal

Heavy Neutrinos

$$G_F$$

$$\mu^+ \quad \nu_\mu \quad \nu_e \quad e^+$$
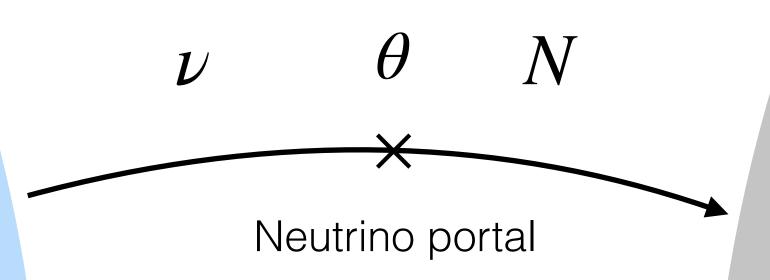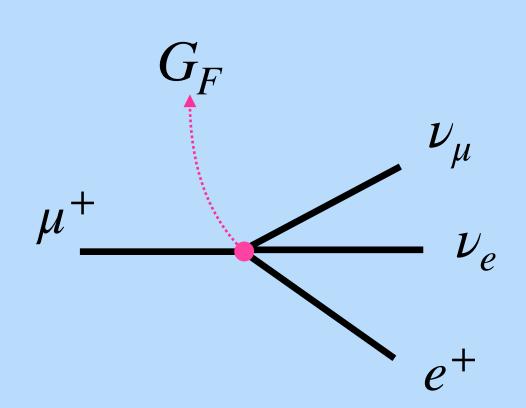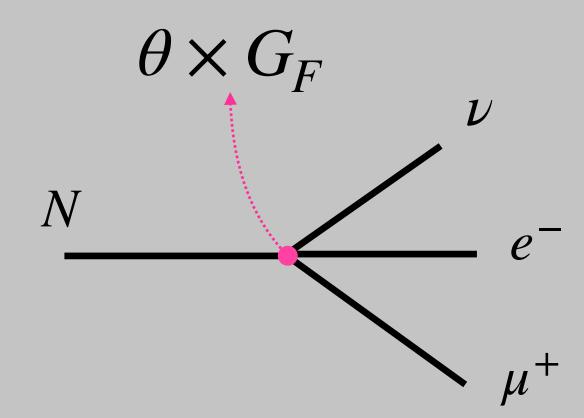
Weak interaction

$$G_F \sim \frac{1}{m_W^2}$$

$$\theta \times G_F$$

$$N \quad \nu \quad e^- \quad \mu^+$$

Weaker-than-Weak interactions ($\theta \ll 1$)
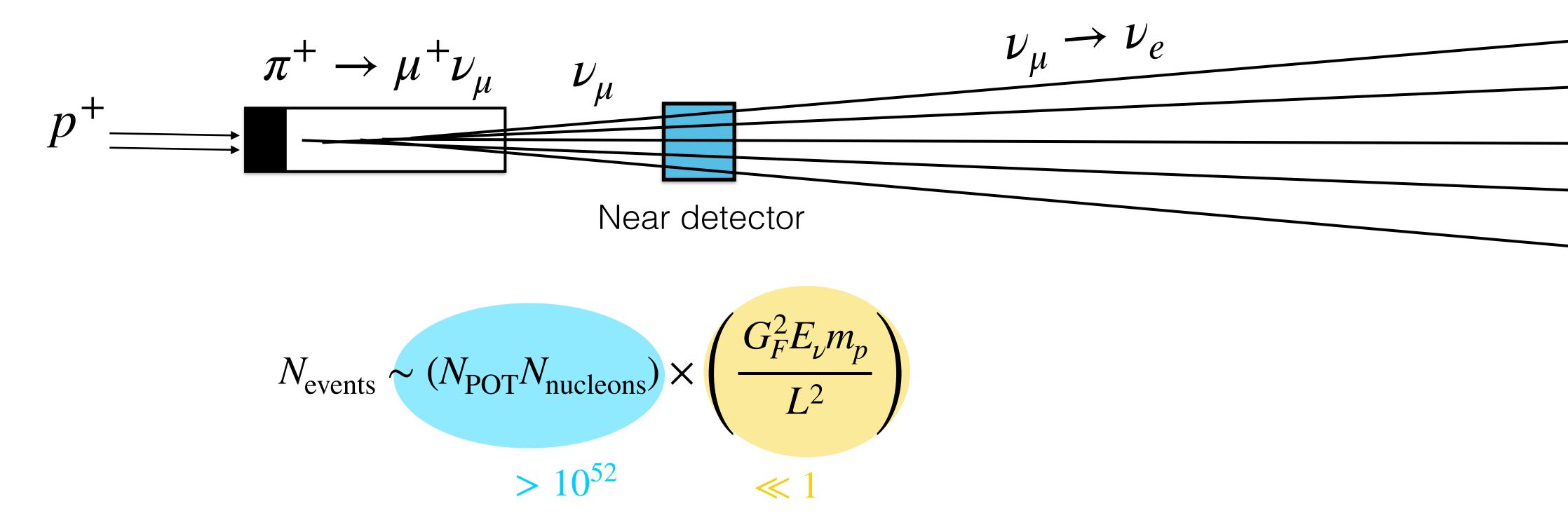
$$\frac{\tau_N}{\tau_{\text{muon}}} \sim \left(\frac{m_\mu}{m_N}\right)^5 \times \frac{1}{\theta^2}$$

Accelerator neutrino experiments

Accelerator neutrino experiments
(the near detector — largest intensity of neutrinos)

$$N_{\text{events}} \sim (N_{\text{POT}} N_{\text{nucleons}}) \times \left(\frac{G_F^2 E_\nu m_p}{L^2} \right)$$

$$> 10^{52} \qquad \ll 1$$
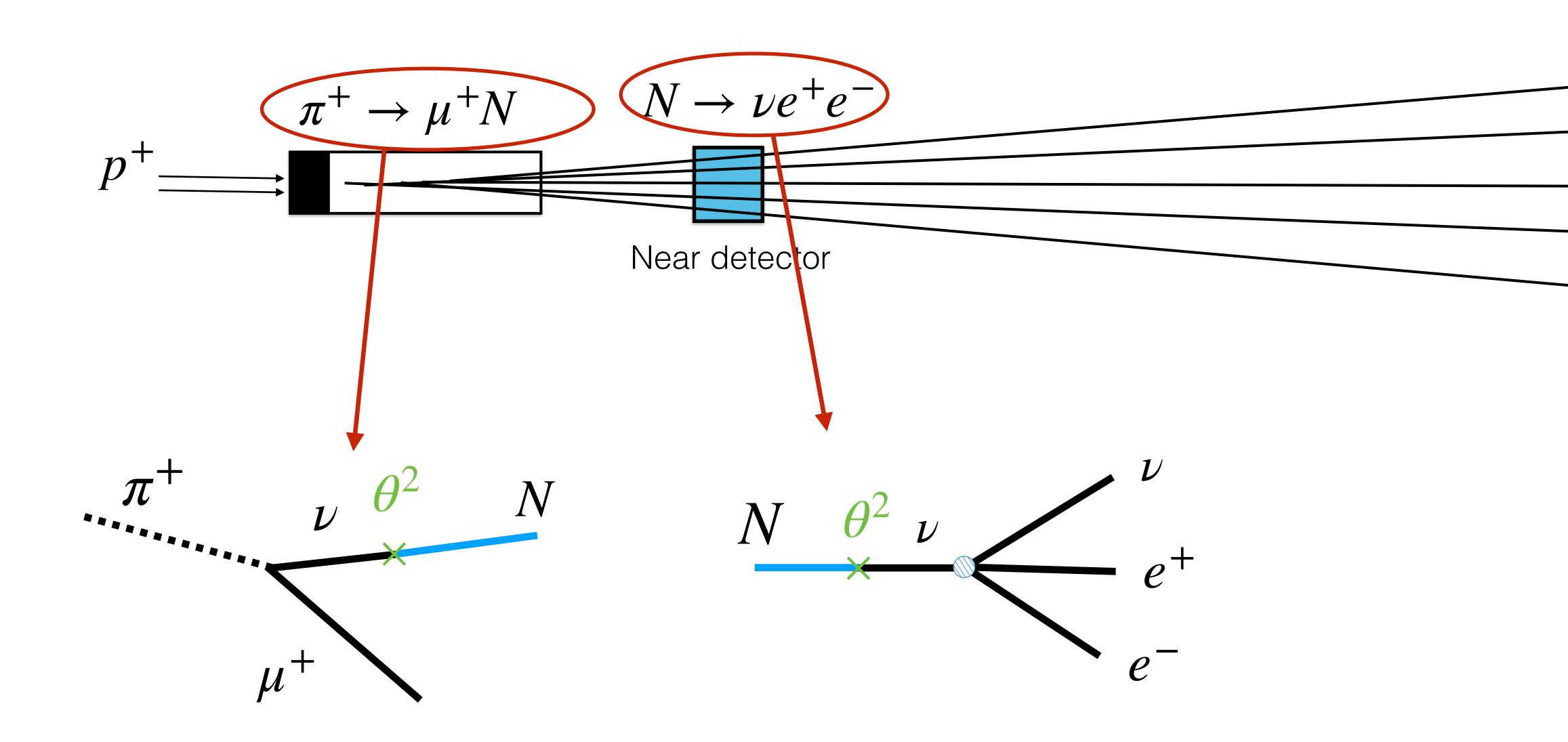
Neutrino experiments are, by construction, sensitive to very rare phenomena.

Really good at searching for new effects that compete with the weak force.
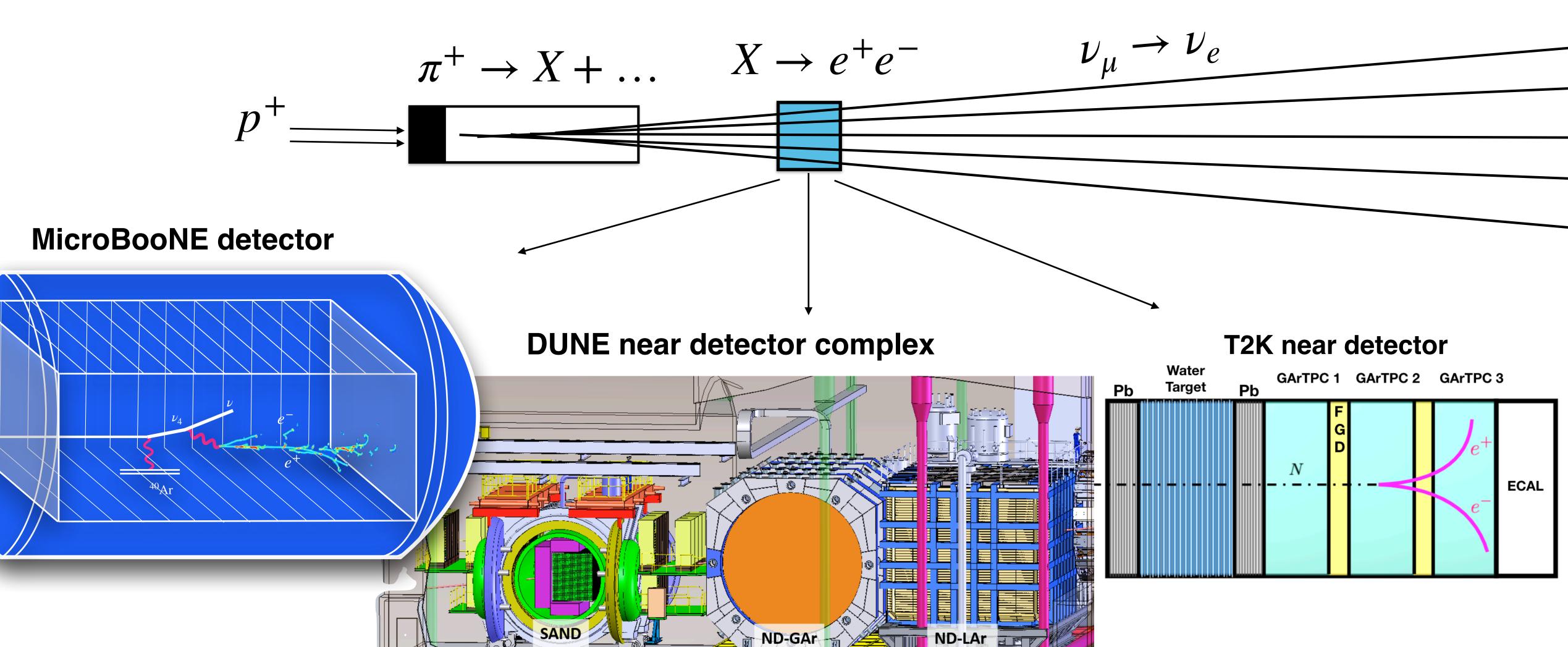
Accelerator neutrino experiments
(the near detector — largest intensity of new particles?)
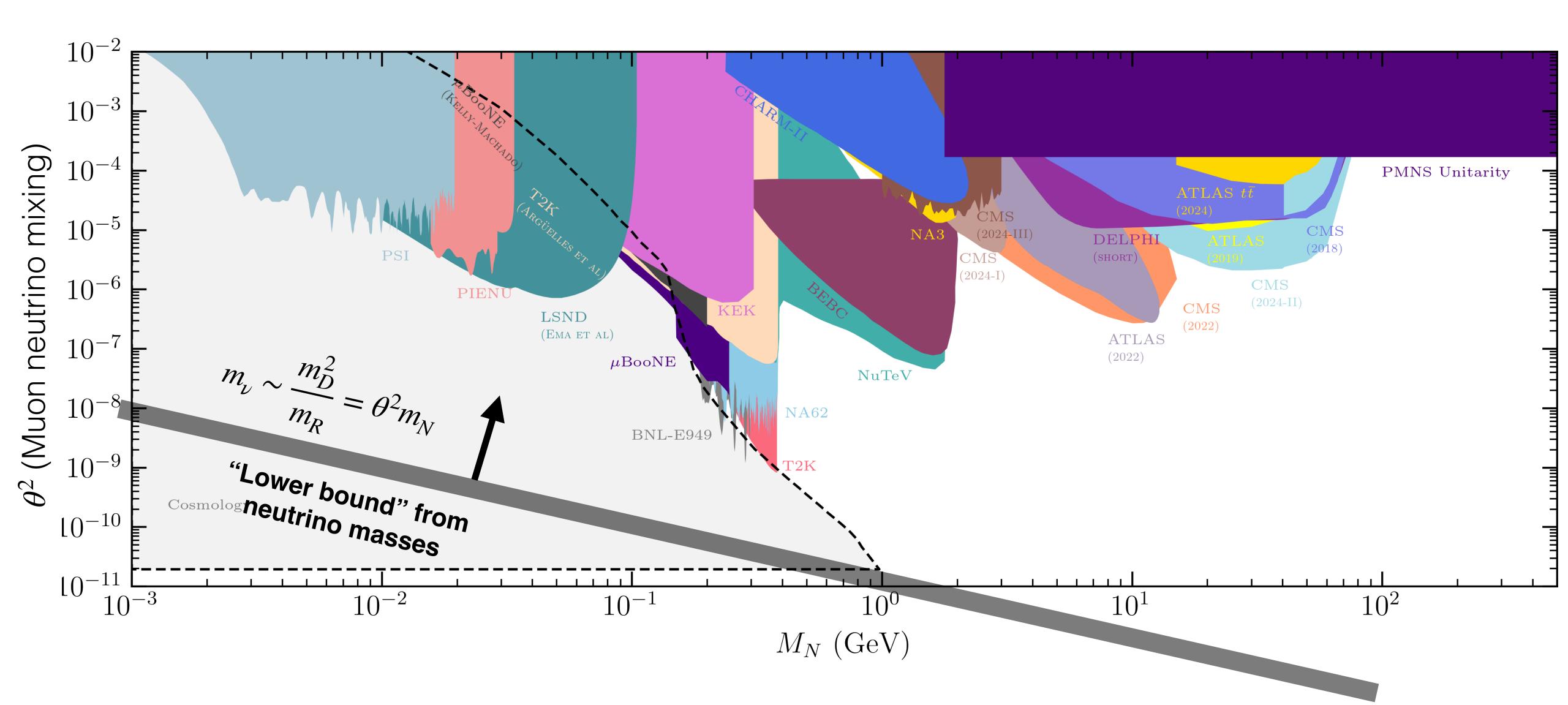
Near Detector and Short-Baseline Experiments
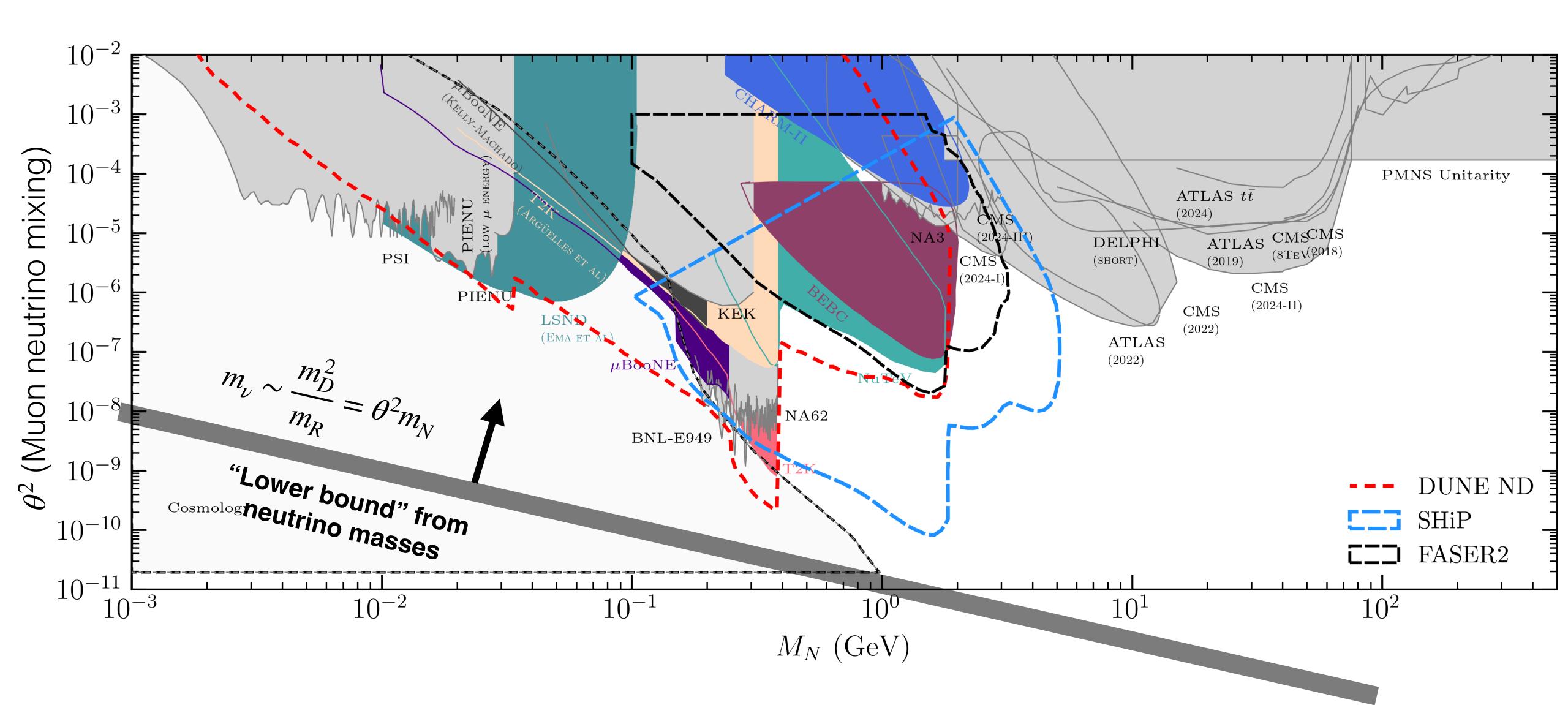
1) as close to the source as possible (high intensity & not interested in standard oscillations)

2) have good particle identification (neutrino vs other BSM phenomena).

$$\pi^+ \to X + \dots \qquad X \to e^+ e^- \qquad \nu_\mu \to \nu_e$$

$$p^+$$

MicroBooNE detector

DUNE near detector complex

T2K near detector

Parameter Space of Hypothetical Heavy Neutrinos

$$m_\nu \sim \frac{m_D^2}{m_R} = \theta^2 m_N$$

"Lower bound" from neutrino masses

Parameter Space of Hypothetical Heavy Neutrinos

$$m_\nu \sim \frac{m_D^2}{m_R} = \theta^2 m_N$$

"Lower bound" from neutrino masses

Cosmology

Legend:
- DUNE ND (red dashed)
- SHiP (blue dashed)
- FASER2 (black dashed)

Axis labels: θ^2 (Muon neutrino mixing), M_N (GeV)

STANDARD MODEL

DARK SECTOR

ν N

Neutrino portal

Heavy Neutrinos — Weaker-than-Weak force

γ γ_d

Photon portal

Dark photons — Weaker-than-EM force

h h_d

Higgs portal

Dark Higgs — Weaker-than-Yukawa force

Axions

Axions and Axion-like-particles

STANDARD MODEL

DARK SECTOR

ν N

Neutrino portal

γ γ_d

Photon portal

h h_d

Higgs portal

Axions and Axion-like-particles

Heavy Neutrinos

Dark photons

Dark Higgs

Axions

STANDARD MODEL

DARK SECTOR

ν　　　N

Neutrino portal

Heavy Neutrinos

Just the "starter" portals.
Many possibilities to be explored.

γ　　　γ_d

Photon portal

Dark photons

h　　　h_d

Higgs portal

Dark Higgs

Choose wisely!
...

Axions and Axion-like-particles

Axions
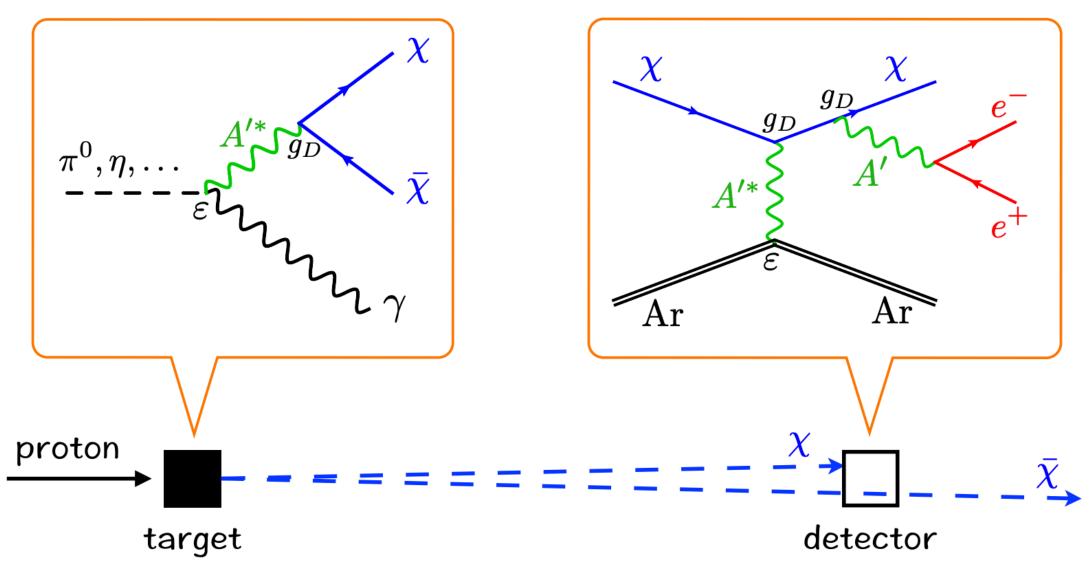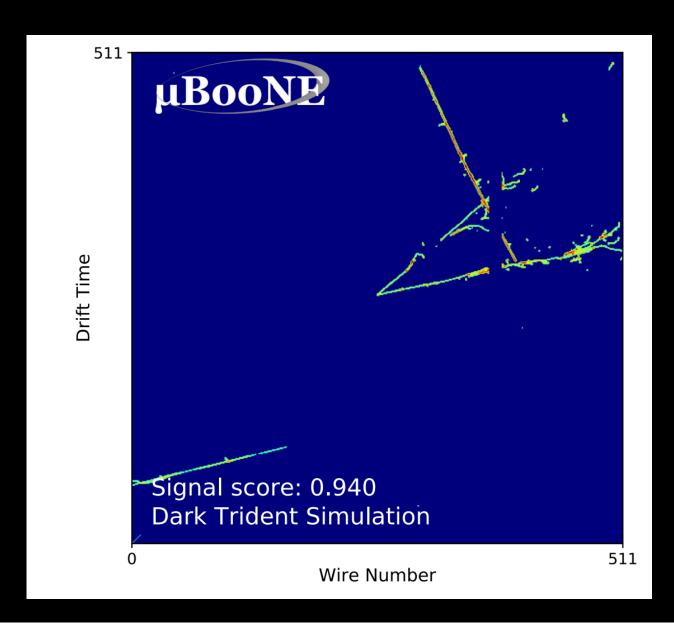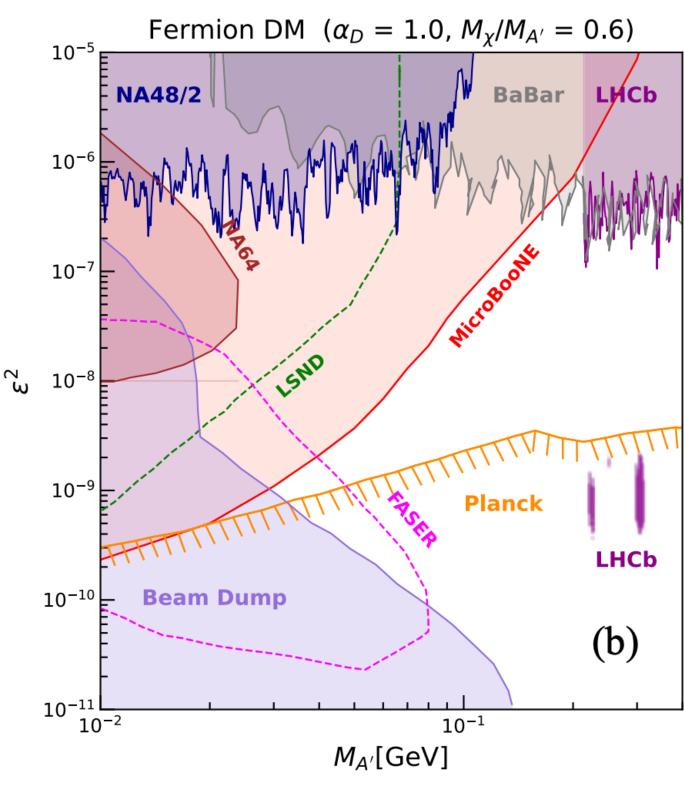
dark matter?

Light dark matter example:
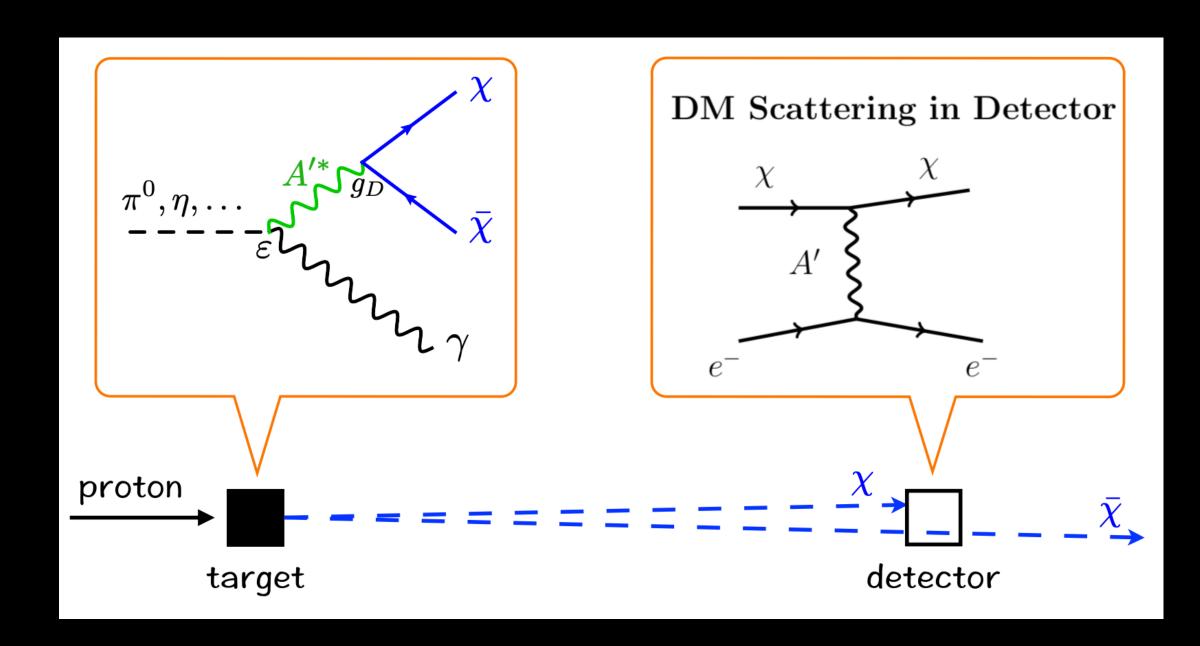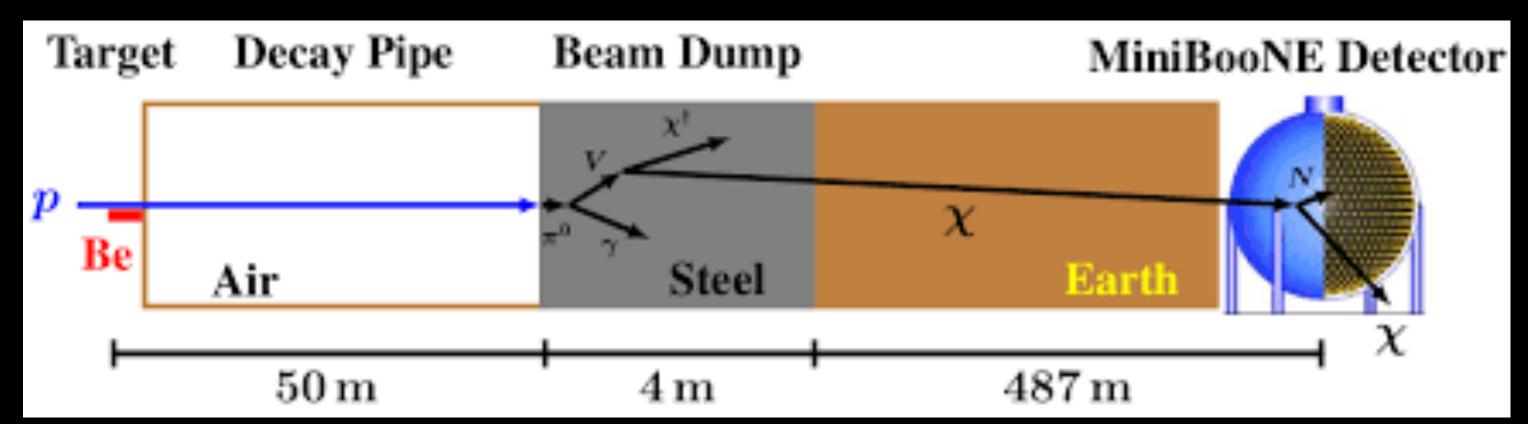
Idea in A. de Gouvea, P. J. Fox, R. Harnik, K. J. Kelly, and Y. Zhang (2018)
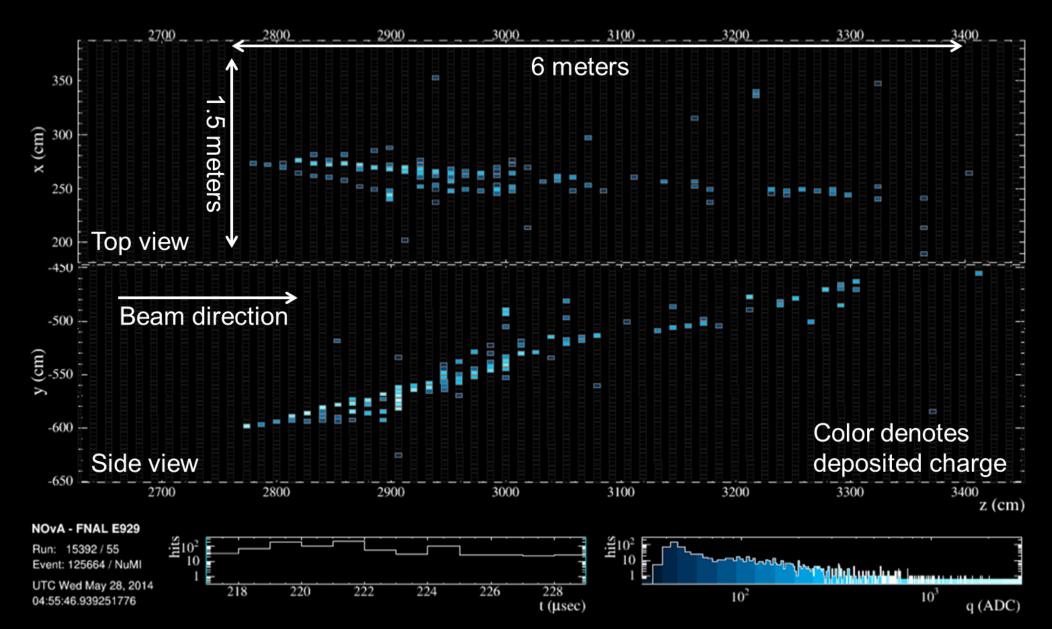
Results from MicroBooNE collaboration (2024)

Light dark matter example:

NOvA Experiment

Light Dark Matter
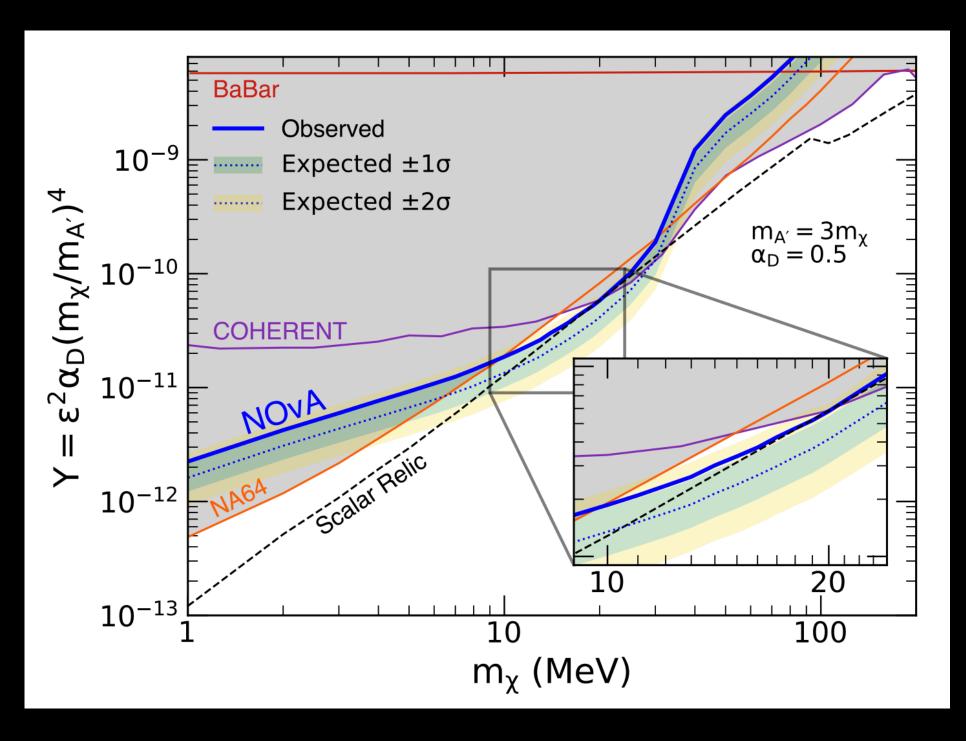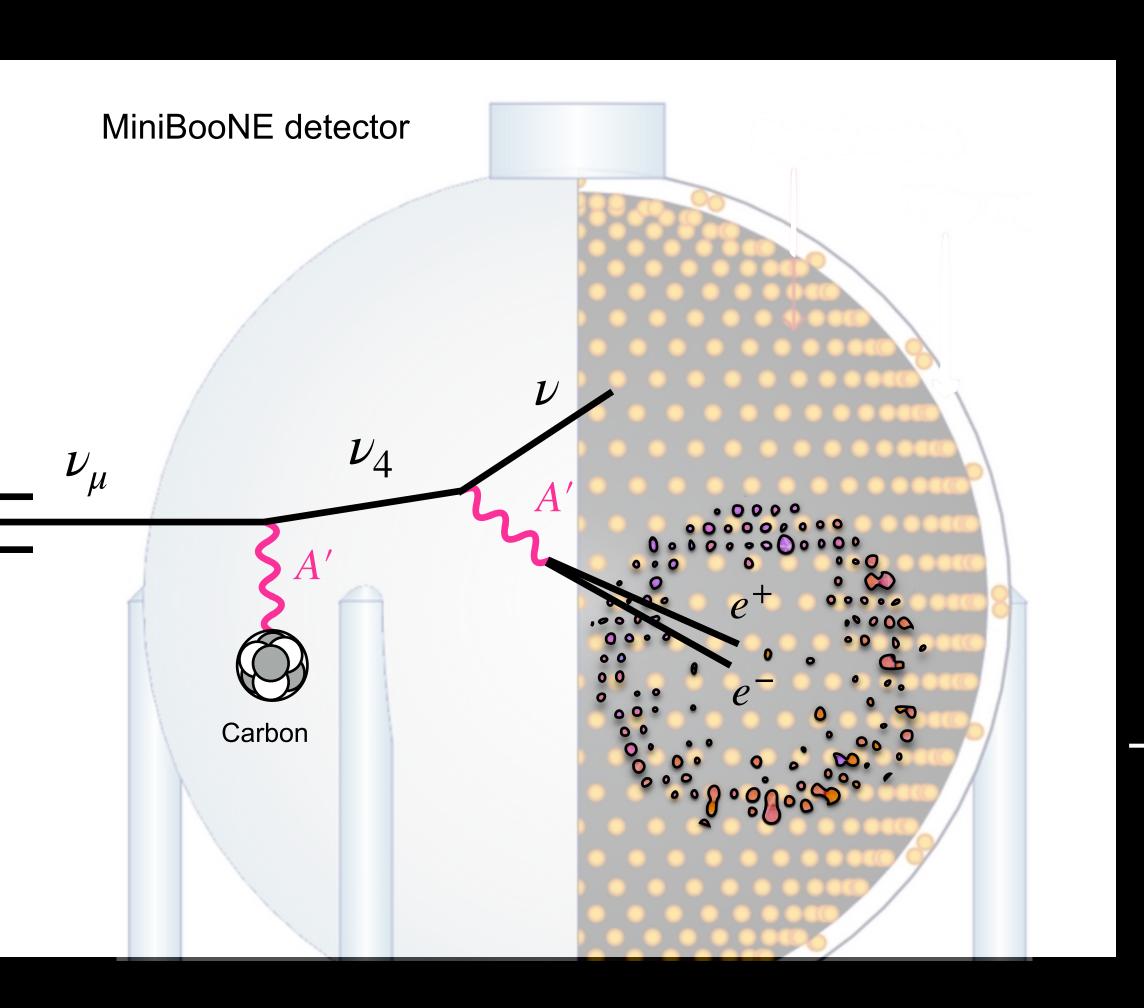
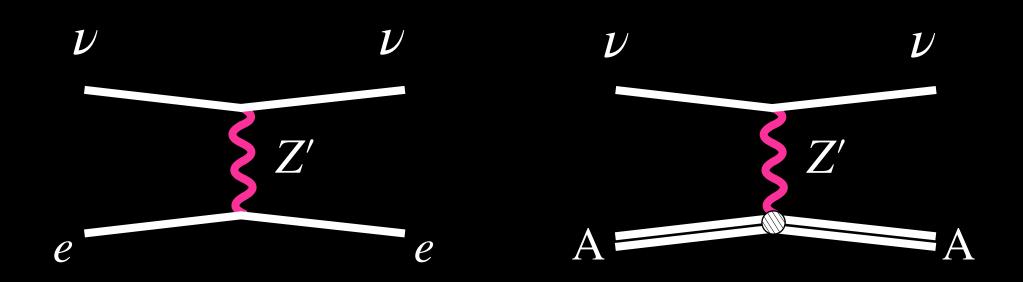# "Dark" heavy neutrino example:
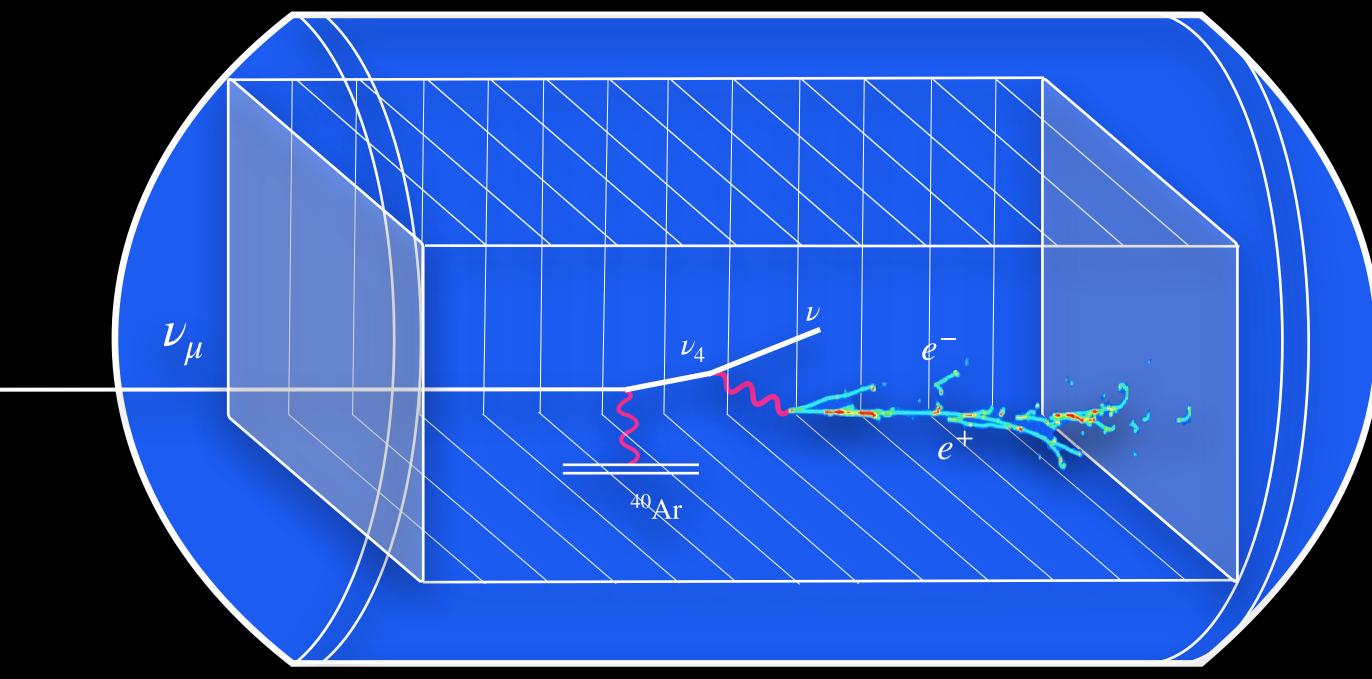
Neutrino upscattering as a source of heavy neutrinos

Decay $N \to \nu A'$ and $A' \to e^+ e^-$ mimic electron and photon signals at Cherenkov detectors.
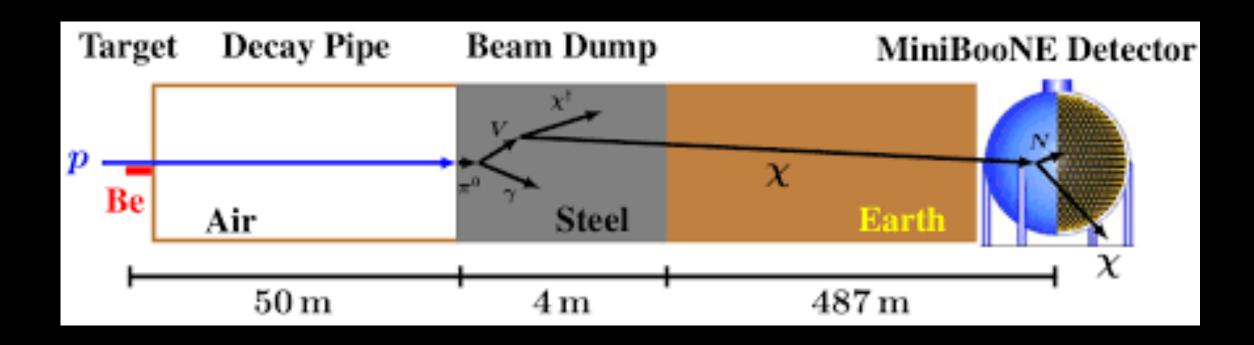

MicroBooNE LArTPC

MiniBooNE detector

ν_μ

ν_4

ν

A'

A'

e^+

e^-

Carbon

ν_μ

ν_4

ν

e^-

e^+

^{40}Ar

Other examples of beyond-the-Standard Model applications:

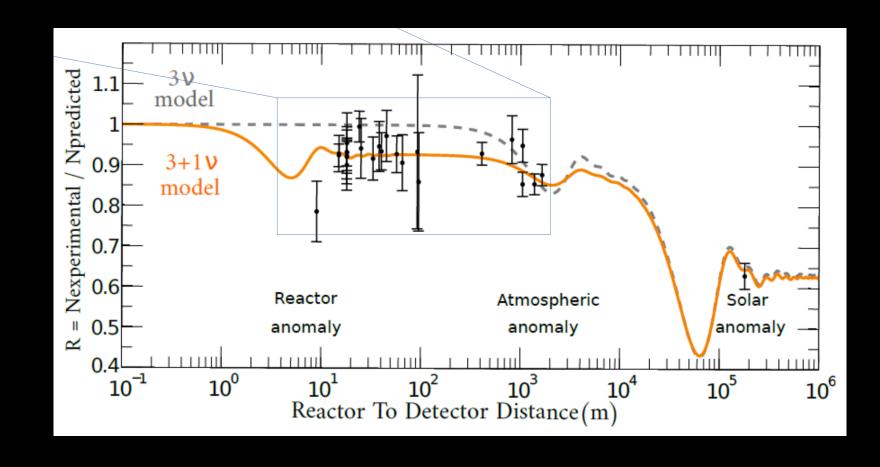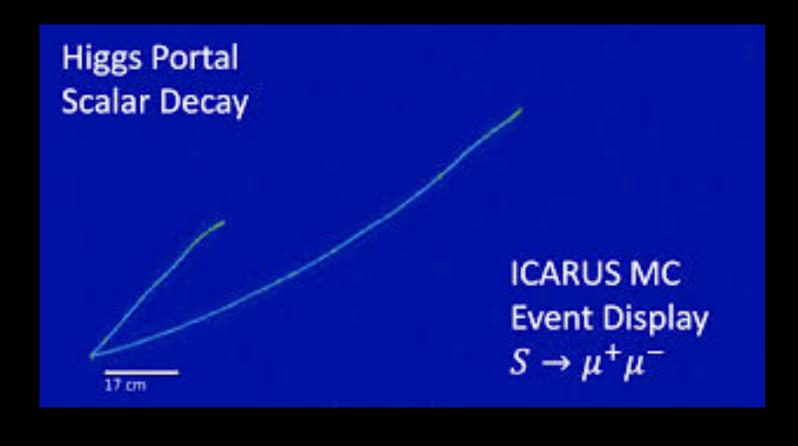## New Forces

Non-Standard Interactions (NSIs)

Light Dark Matter

Sterile Neutrino Oscillations

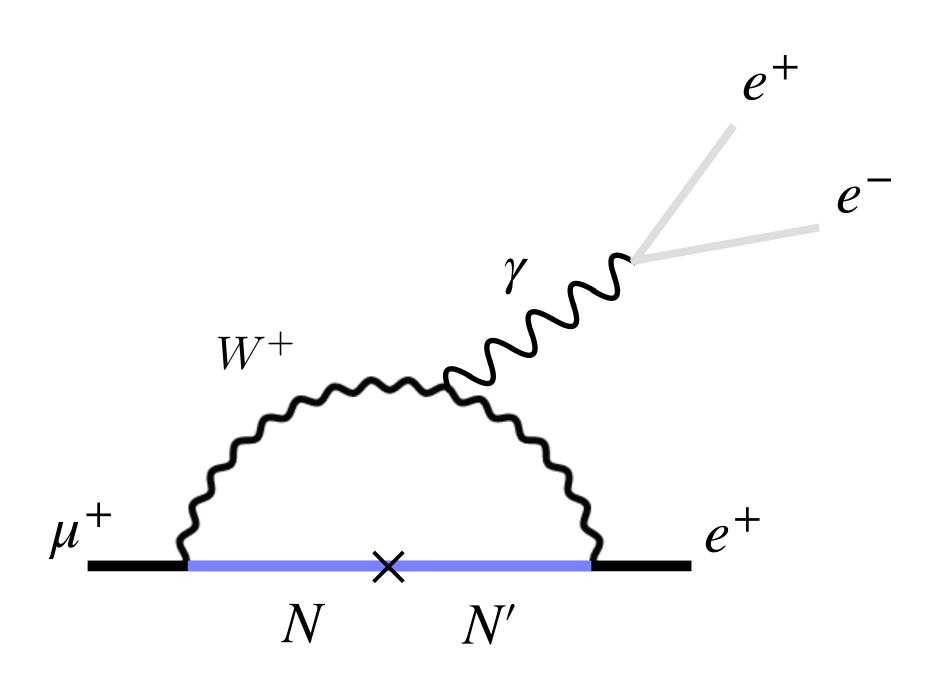
Long-Lived Particles

Take Home

Neutrino masses gives us **"reasonable doubt"** that the SM is incomplete.

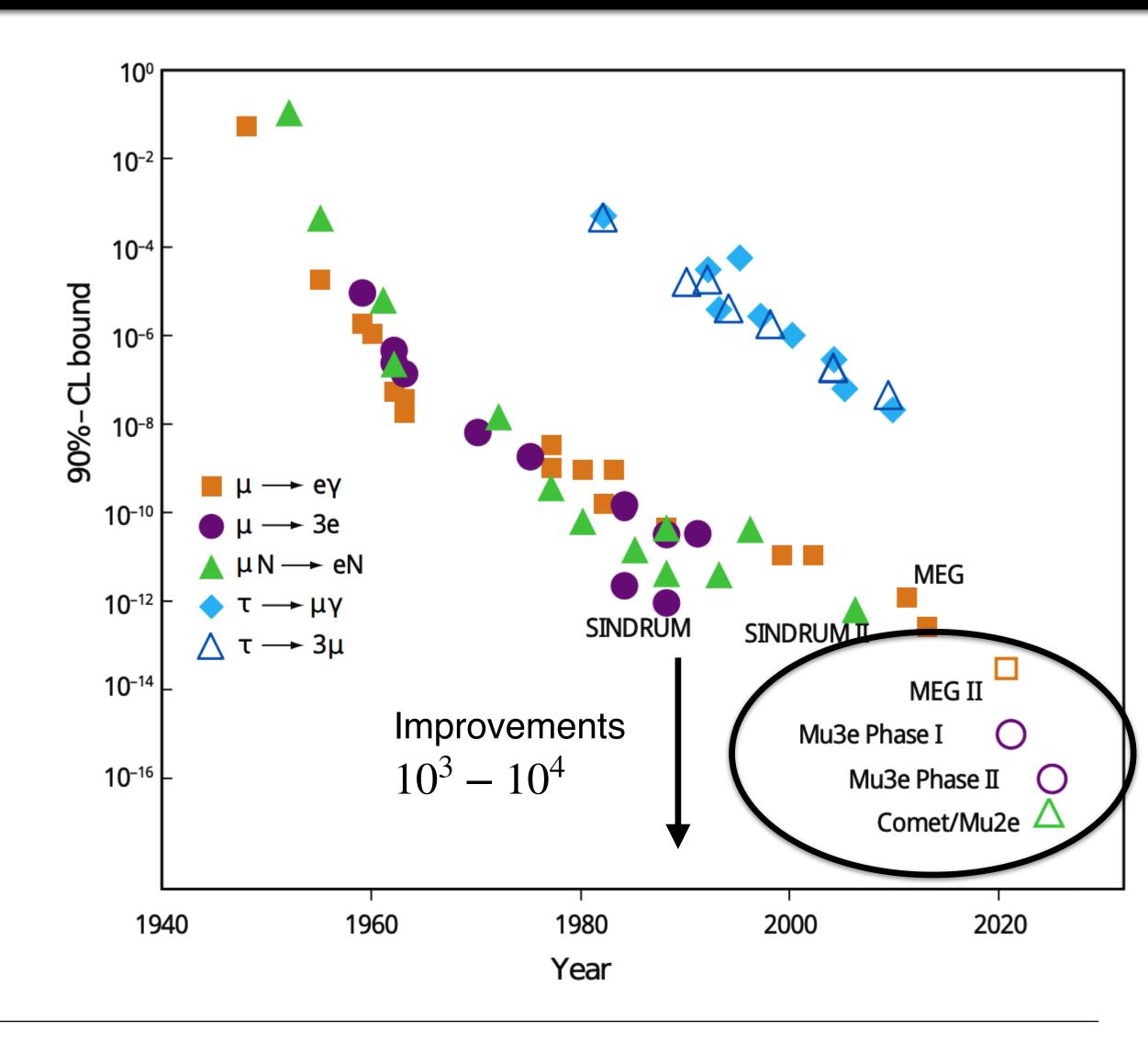Many explanations: challenge is in testing them. **Need data!**

Particle physics entered a new era of studying **rare phenomena** and neutrino experiments can help us navigate it

This is a fertile ground for **phenomenology**!

Indirect probes of neutrino mass physics