Light Dark Sectors & Neutrino Mass Generation

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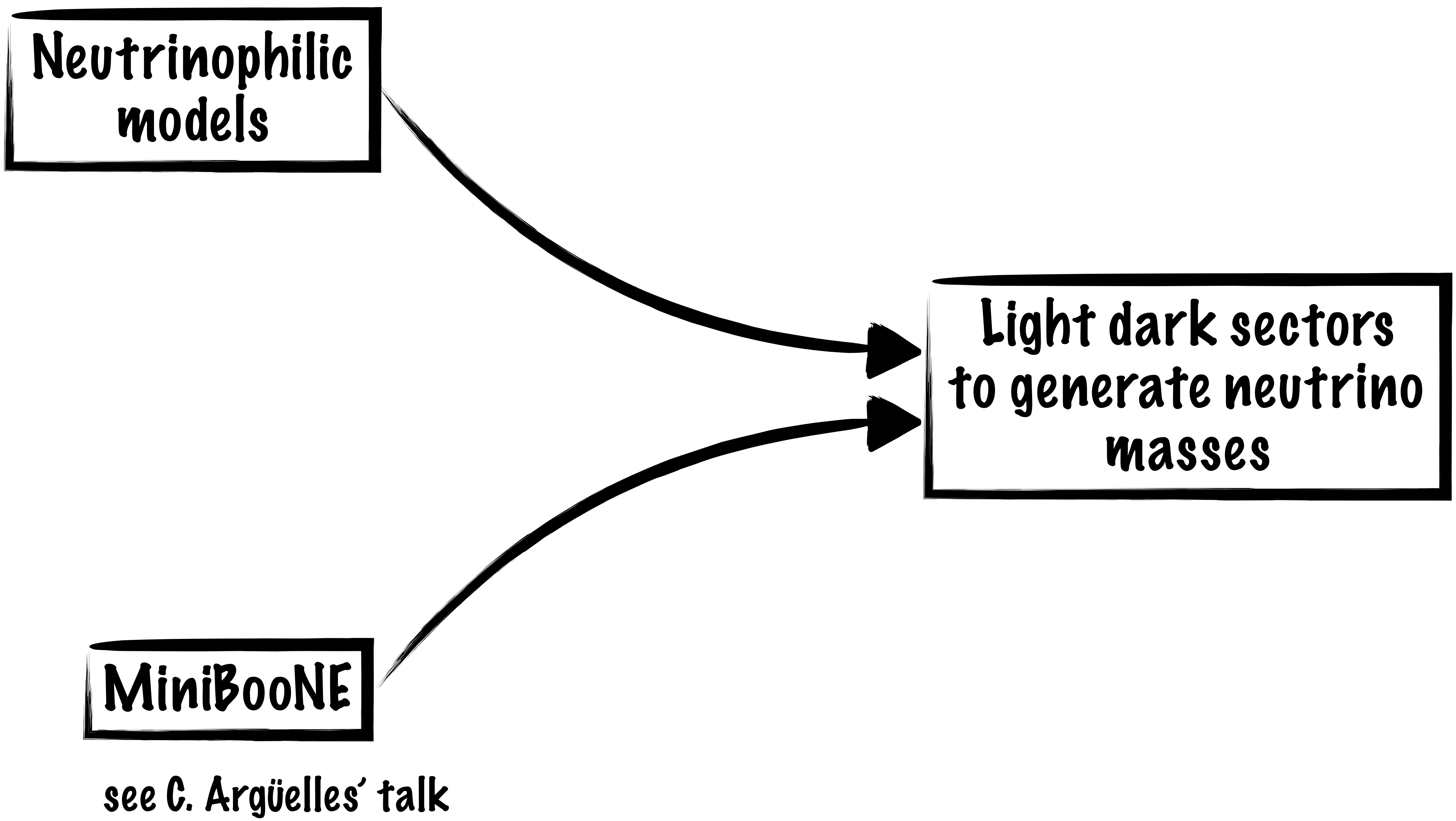
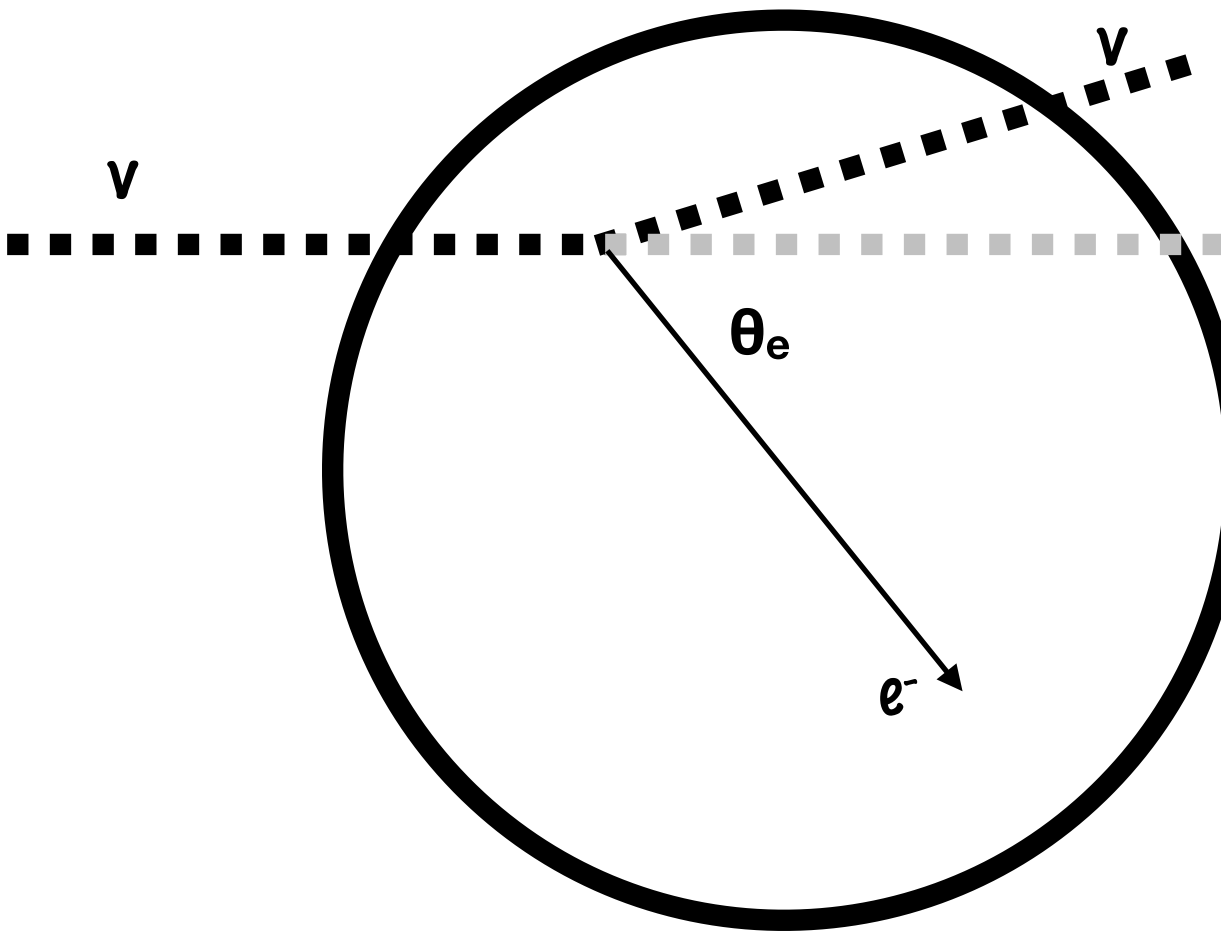
Roadmap

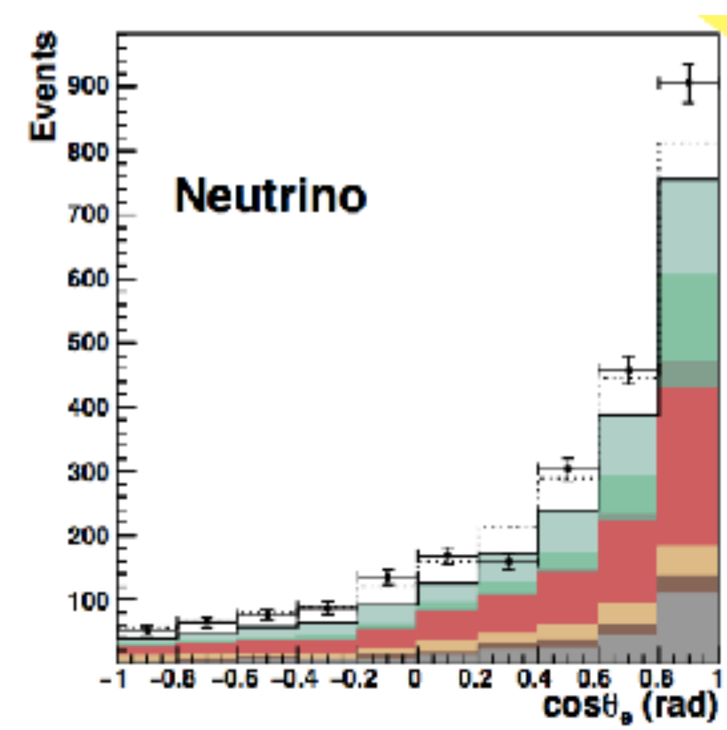

Neutrinophilic models
MiniBooNE
see C. Argüelles' talk
Light dark sectors to generate neutrino masses

MiniBooNE

Excess has a spectrum in energy but in angle as well

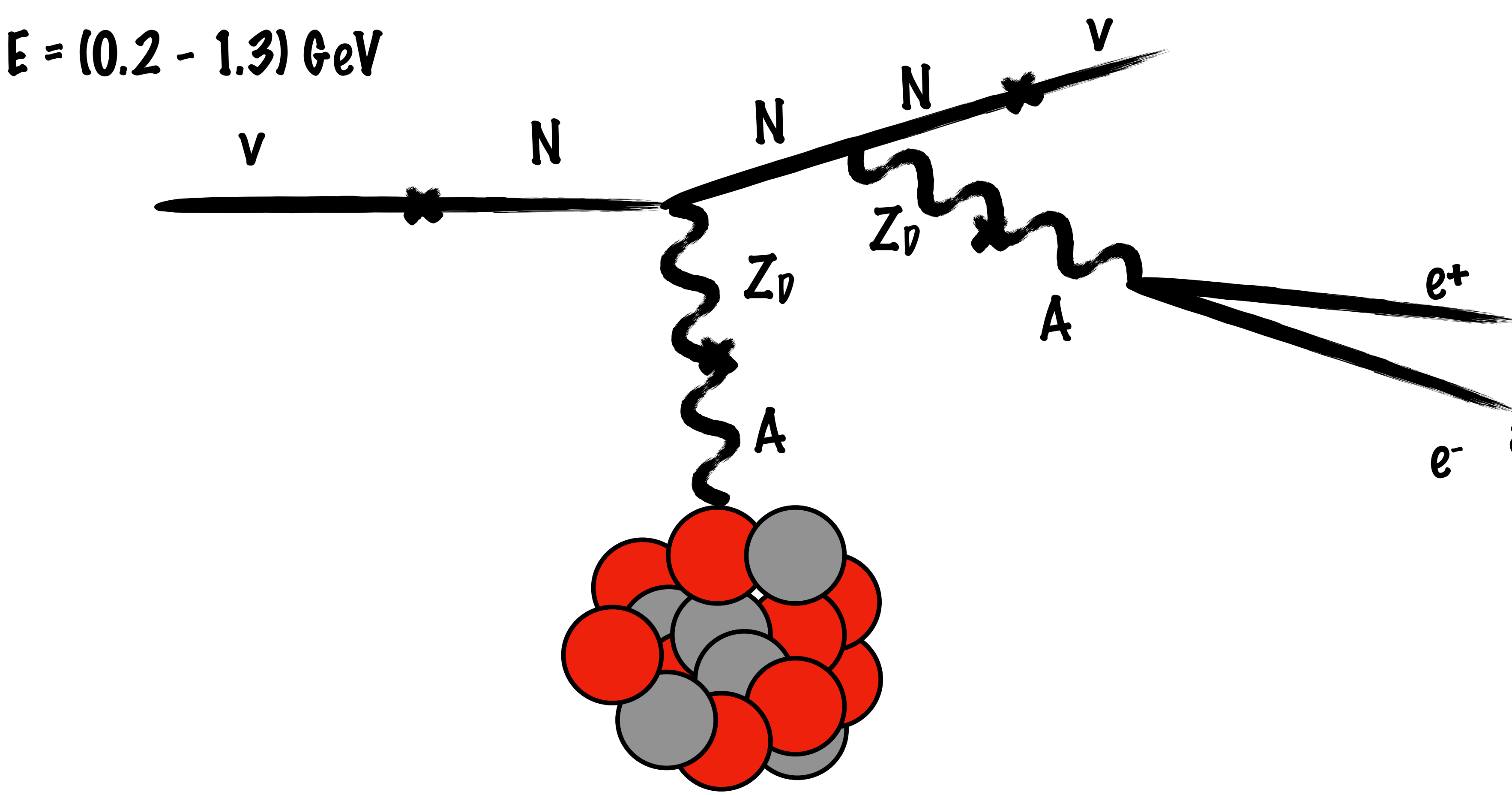


Signal is fairly isotropic



MiniBooNE

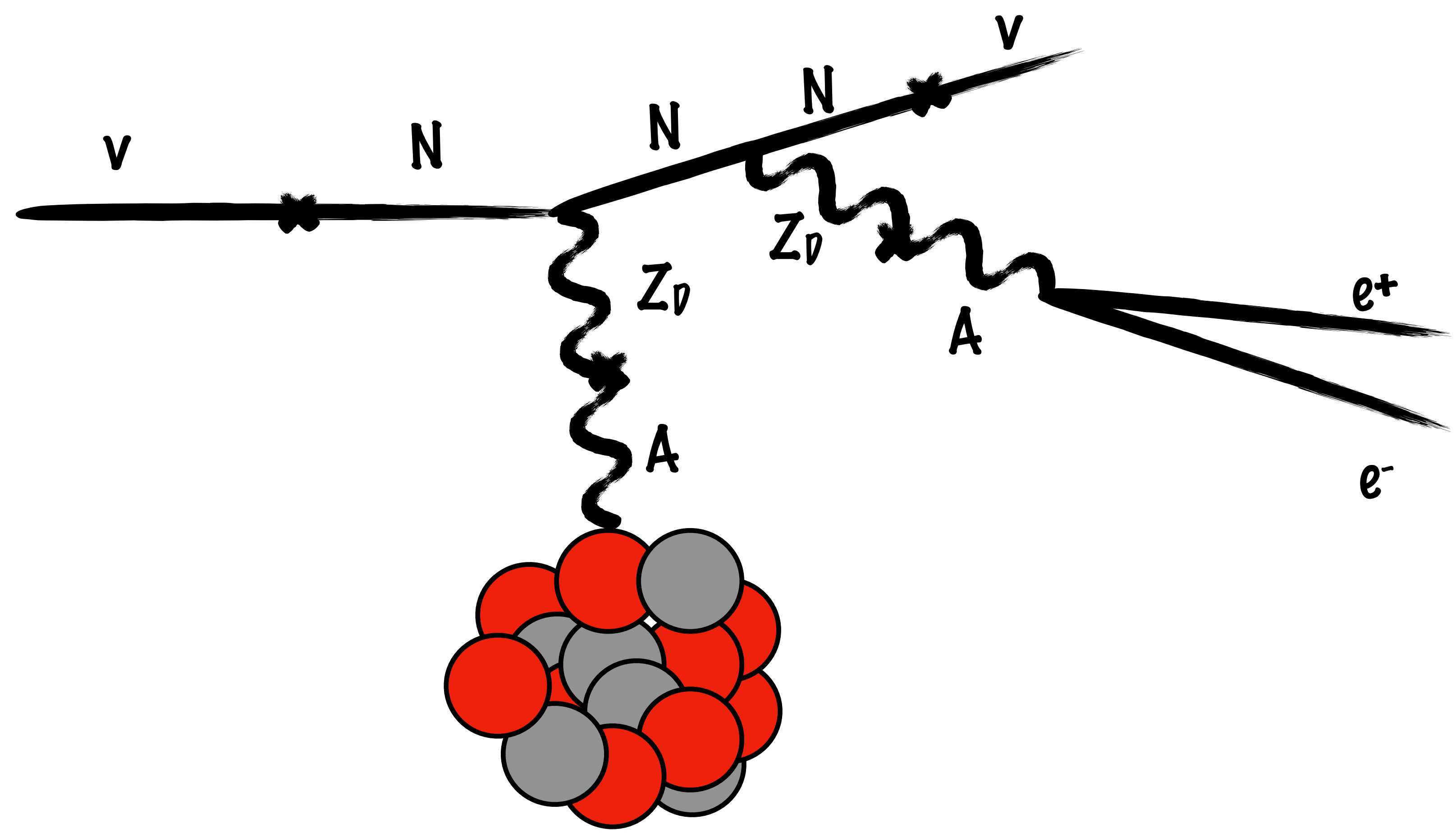
Crucial for us:
signal of two collimated electrons $\simeq$ signal of one electron



detected as one Cherenkov ring as long as angular separation is at most 12°

we need N to be heavy to have small boost ($m_N \gtrsim 100$ MeV)
and Z_D to be much lighter to be boosted ($m_{Z_D} \lesssim 60$ MeV)

MiniBooNE



Message: we want a dark sector which can accommodate

(i) a relatively heavy RH neutrino

(ii) the RH neutrino must be able to decay into a (light) dark gauge boson

(iii) the dark gauge boson should be able to decay into e^+e^-

How do we construct a model with such a dark sector?

Irreducible ingredients

(i) there must be a new gauge sector

(ii) we want the new gauge boson to mix with EM to decay into e^+e^-

$\Longrightarrow$ we'll add a $U(1)_D$

(iii) the RH neutrino must be charged under the new U(1) to allow for $Z_{D\mu}\, N^\dagger \sigma^\mu N$

(iv) we will try to avoid to use the Higgs boson to write a term L H N because N has a dark charge (we want to minimize the Z -Z_D mixing to avoid as much as possible problems with EWPM)

Point (iv) remembers

Neutrinophilic models

Gabriel, Nandi hep-ph/0610253
Davidson, Logan 0906.3335

$$\mathcal{L} = \mathcal{Y}_{ij} L_i H N_j + \frac{1}{2} M_{ij} N_i N_j + h.c.$$

Φ

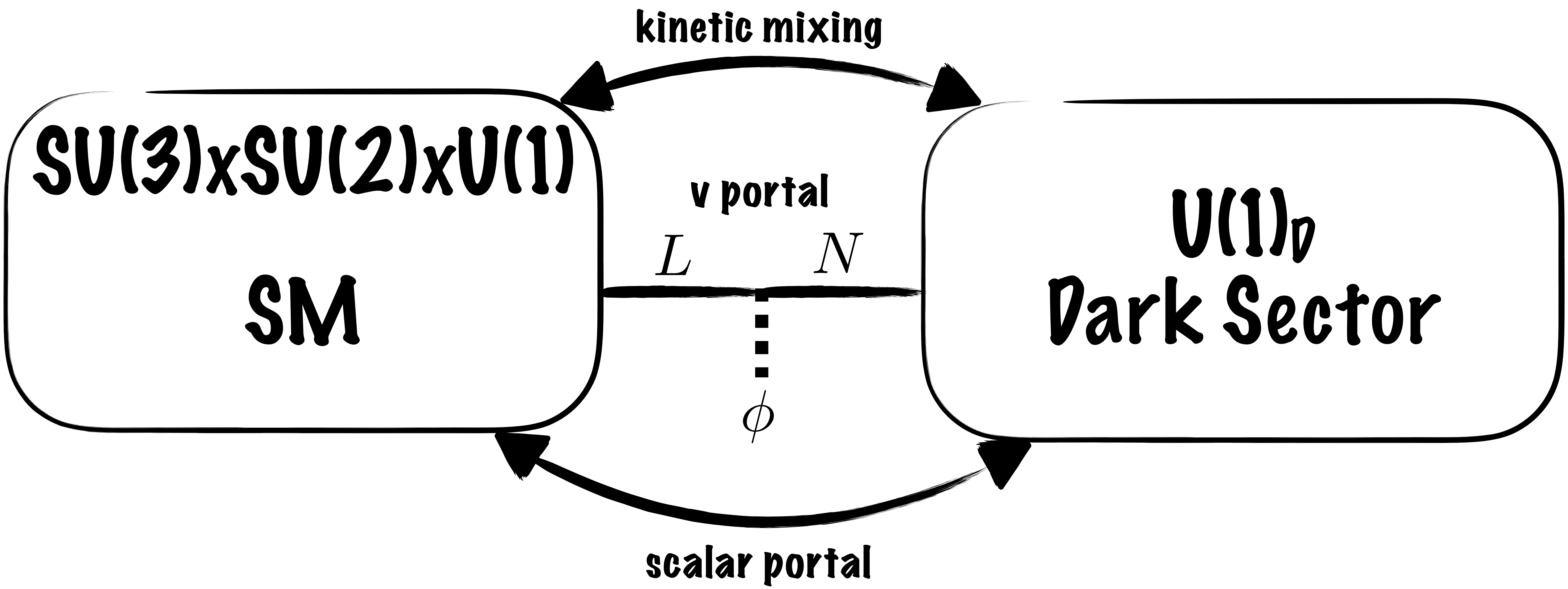
"Neutrinophilic scalar doublet",
vev O(eV) postulated

forbidden by a new global U(1) or Z_2

- Pros: (i) hierarchy between vev's radiatively stable, (ii) Y ~ 1, (iii) NP may be light
- Cons: experimentally very constrained (basically excluded)

see 1507.07550 & 1510.04284
with R. Funchal, Y. Perez & O. Sumensari

Question: can we `save' neutrinophilic models introducing the gauge symmetry we want?



see 1706.10000
with R. Funchal, P. Machado and Z. Tabrizi

More details: constructing the model

1. Dirac mass term: allowing $L\phi N$ forbidding LHN

	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{D}}$	$U(1)_\ell$	$U(1)'$
L	$\mathbf{2}$	$-1/2$	0	1	-1
ϕ	$\mathbf{2}$	$1/2$	$+1$	0	1
N	$\mathbf{1}$	0	-1	-1	0

gauged global

$$\mathcal{L} = \mathcal{Y} L \phi N$$

2. Avoiding anomalies: add new fermions N'

	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{D}}$	$U(1)_\ell$	$U(1)'$
L	$\mathbf{2}$	$-1/2$	0	1	-1
ϕ	$\mathbf{2}$	$1/2$	$+1$	0	1
N	$\mathbf{1}$	0	-1	-1	0
N'	$\mathbf{1}$	0	$+1$	$+1$	0

$$\mathcal{L} = \mathcal{Y} L \phi N + \mathcal{M} N N'$$

More details: constructing the model

3. The problem of the massless fermions: when Φ takes vet

$$\mathcal{L} = (\mathcal{Y}\langle\phi\rangle\nu + \mathcal{M}N')\,N$$

this combination gets mass, the orthogonal stays massless

add a new scalar to give a Majorana mass to N & N'

	$SU(2)_L$	$U(1)_Y$	$U(1)_\mathcal{D}$	$U(1)_\ell$	$U(1)'$
L	**2**	$-1/2$	0	1	-1
ϕ	**2**	$1/2$	$+1$	0	1
N	**1**	0	-1	-1	0
N'	**1**	0	$+1$	$+1$	0
S_2	**1**	0	$+2$	$+2$	0

$$\mathcal{L} = \mathcal{Y}L\phi N + \mathcal{M}NN' + yS_2NN + y'S_2^*N'N'$$

basically a dynamical INVERSE SEESAW ⇨

More details: constructing the model

4. The problem of the massless NGB: when <H> ≠ 0 the global U(1)′ is still a symmetry of the scalar potential, hence when <Φ> ≠ 0 the global global U(1)′ is spontaneously broken, leaving a massless NGB in the spectrum

First possibility: explicit breaking

$$\mathcal{L}_{break} = \frac{(\phi^\dagger H)^2 S_2}{\Lambda}$$

We find that the model is phenomenologically viable, although not trivial to generate this term ➪

see 1706.10000
with R. Funchal, P. Machado & Z. Tabrizi

More details: constructing the model

4. The problem of the massless NGB: when ⟨H⟩ ≠ 0 and ⟨S_2⟩ ≠ 0 the global U(1)′ is still a symmetry of the scalar potential $\Longrightarrow$ when ⟨Φ⟩ ≠ 0 the global global U(1)′ is spontaneously broken, leaving a massless NGB in the spectrum

Second possibility: add a new scalar S_1

	$SU(2)_L$	$U(1)_Y$	$U(1)_\mathcal{D}$	$U(1)_\ell$	$U(1)'$
L	**2**	$-1/2$	0	1	-1
ϕ	**2**	$1/2$	$+1$	0	1
N	**1**	0	-1	-1	0
N'	**1**	0	$+1$	$+1$	0
S_2	**1**	0	$+2$	$+2$	0
S_1	**1**	0	$+1$	0	?

see 1808.02500
with S. Jana, R. Funchal & P. Machado

More details: constructing the model

4. The problem of the massless NGB: when ⟨H⟩ ≠ 0 and ⟨S_2⟩ ≠ 0 the global U(1)′ is still a symmetry of the scalar potential ⟹ when ⟨Φ⟩ ≠ 0 the global global U(1)′ is spontaneously broken, leaving a massless NGB in the spectrum

Second possibility: add a new scalar S_1

$$V = \mu S_1(\phi^\dagger H) + \mu' S_2^* S_1^2 + \alpha(H^\dagger \phi) S_1 S_2^*$$

no consistent U(1)′ charge for S_1
hence
U(1)′ explicitly broken

μ, μ′ & α are U(1)′ spurions → technically natural to have them small ⇨

see also 1903.00006 for a similar model

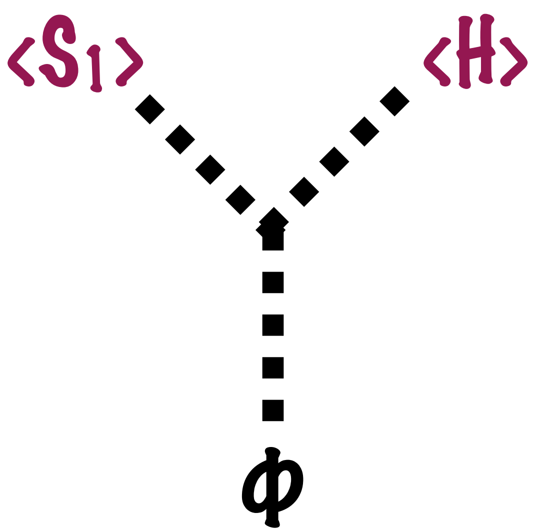
Scales in the model

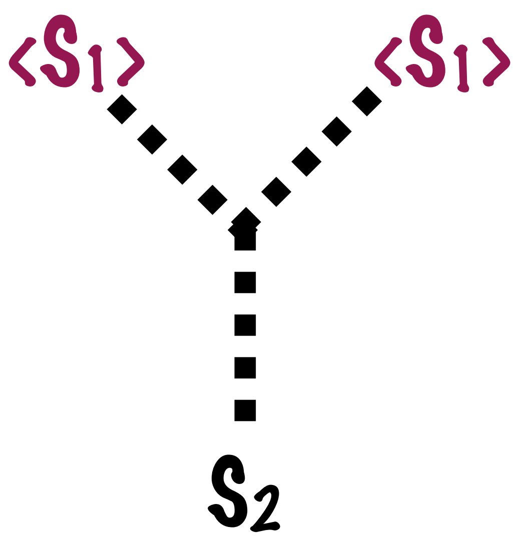
Back to $\mathcal{L} = \mathcal{Y} L \phi N + \mathcal{M} N N' + y S_2 N N + y' S_2^* N' N'$

To guarantee small nu masses we need small $\langle \Phi \rangle$ & $\langle S_2 \rangle$

Idea: generate small dynamical vev's via tadpoles

$$V = \mu S_1 (\phi^\dagger H) + \mu' S_2^* S_1^2 + \alpha (H^\dagger \phi) S_1 S_2^*$$





when μ, μ' & α vanish, no tadpole are generated, hence small vev's are technically natural

Scalar sector

More in detail:

$$V = \lambda_H \left(|H|^2 - \frac{v^2}{2}\right)^2 + \lambda_{S_2}\left(|S_1|^2 - \frac{\omega_1^2}{2}\right)^2 + \lambda_{HS_1}\left(|H|^2 - \frac{v^2}{2}\right)\left(|S_1|^2 - \frac{\omega_1^2}{2}\right)$$
$$+ m_\phi^2|\phi|^2 + \lambda_\phi|\phi|^4 + m_{S_2}^2|S_2|^2 + \lambda_{S_2}|S_2|^4$$
$$- \left[\frac{\mu}{2} S_1\left(\phi^\dagger H\right) + \frac{\mu'}{2} S_1^2 S_2^* + \frac{\alpha}{2}\left(H^\dagger \phi\right) S_1 S_2^* + \text{h.c.}\right]$$
$$+ \lambda'_{H\phi}\left|\phi^\dagger H\right|^2 + \sum_{\varphi<\varphi'}^{\{H,\phi,S_1,S_2\}} \lambda_{\varphi\varphi'}\left|\varphi\right|^2\left|\varphi'\right|^2 ,$$

Induced vev's

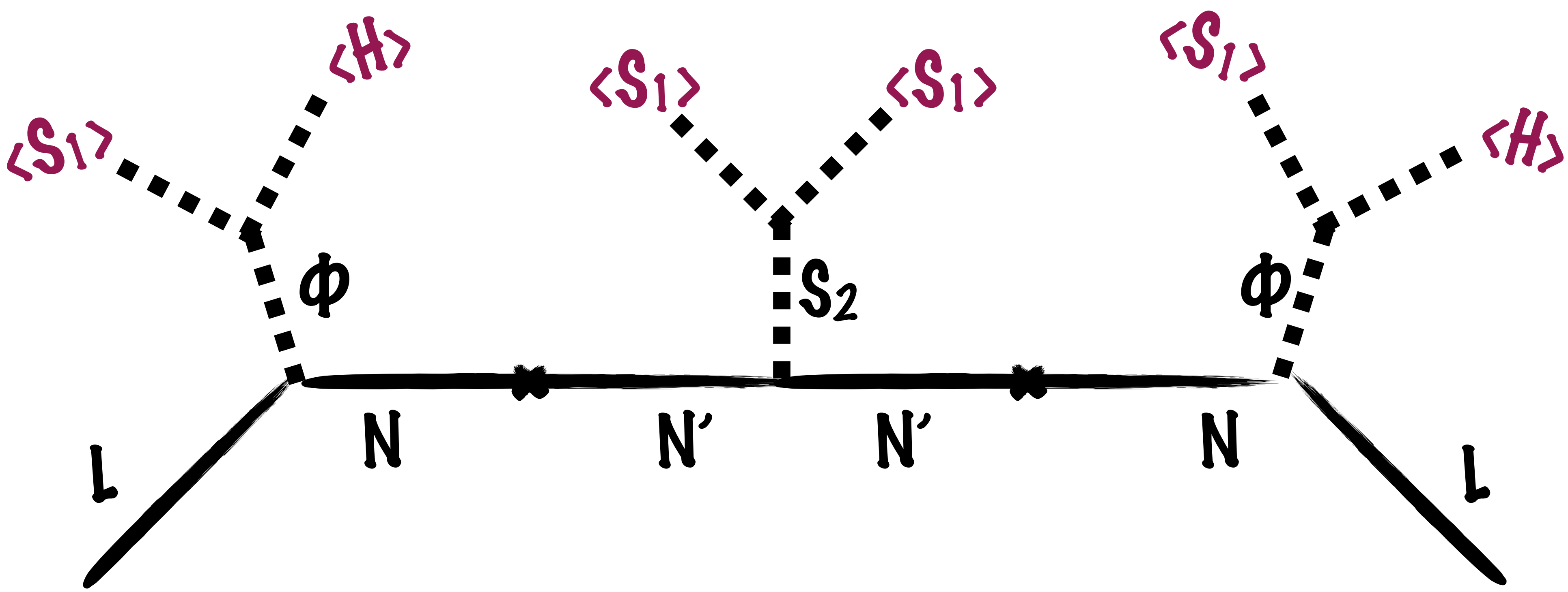
$$v_\phi \simeq \frac{1}{8\sqrt{2}}\left(\frac{\alpha\mu'\, v\omega_1^3}{M_{S'_D}^2 M_{H_D}^2} + 4\frac{\mu\,\omega_1 v}{M_{H_D}^2}\right)$$
$$\omega_2 \simeq \frac{1}{8\sqrt{2}}\left(\frac{\alpha\mu\, v^2\omega_1^2}{M_{S'_D}^2 M_{H_D}^2} + 4\frac{\mu'\,\omega_1^2}{M_{S'_D}^2}\right)$$

We need one state to be aligned to the SM Higgs $\Rightarrow$ in general we need

$\langle S_1\rangle \ll \langle H\rangle$ ("low scale realization") or $\langle S_1\rangle \gg \langle H\rangle$ ("high scale realization")

Neutrino sector -1-

Back to $\mathcal{L} = \mathcal{Y} L \phi N + \mathcal{M} N N' + y S_2 N N + y' S_2^* N' N'$



effectively a dim = 9 operator $\mathcal{L}_{mass} \sim \frac{\mathcal{Y}^2 y'}{\mathcal{M}^2} \frac{\mu^2}{M^2_{H_\mathcal{D}}} \frac{\mu'}{M^2_{S'_\mathcal{D}}} (LH)^2 |S_1|^4$

Neutrino sector -2-

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \mathcal{Y}\langle\phi\rangle & 0 \\ \mathcal{Y}\langle\phi\rangle & y\langle S_2\rangle & \mathcal{M} \\ 0 & \mathcal{M} & y'\langle S_2\rangle \end{pmatrix}$$

Light-heavy mixing $\sim Y\langle\Phi\rangle/M$

Since $\langle\Phi\rangle$ small, sterile N's can be made relatively light without introducing too much mixing

Gauge sector

$$\mathcal{L} = \frac{m_{Z_\mathcal{D}}^2}{2} Z_\mathcal{D}^2 + g_\mathcal{D} Z_\mathcal{D} \cdot J_\mathcal{D} + e\epsilon Z_\mathcal{D} \cdot J_{EM} + \frac{g}{\cos(\theta_W)} \epsilon' Z_\mathcal{D} \cdot J_Z$$

where

$$m_{Z_\mathcal{D}} \simeq g_\mathcal{D} \langle S_1 \rangle$$

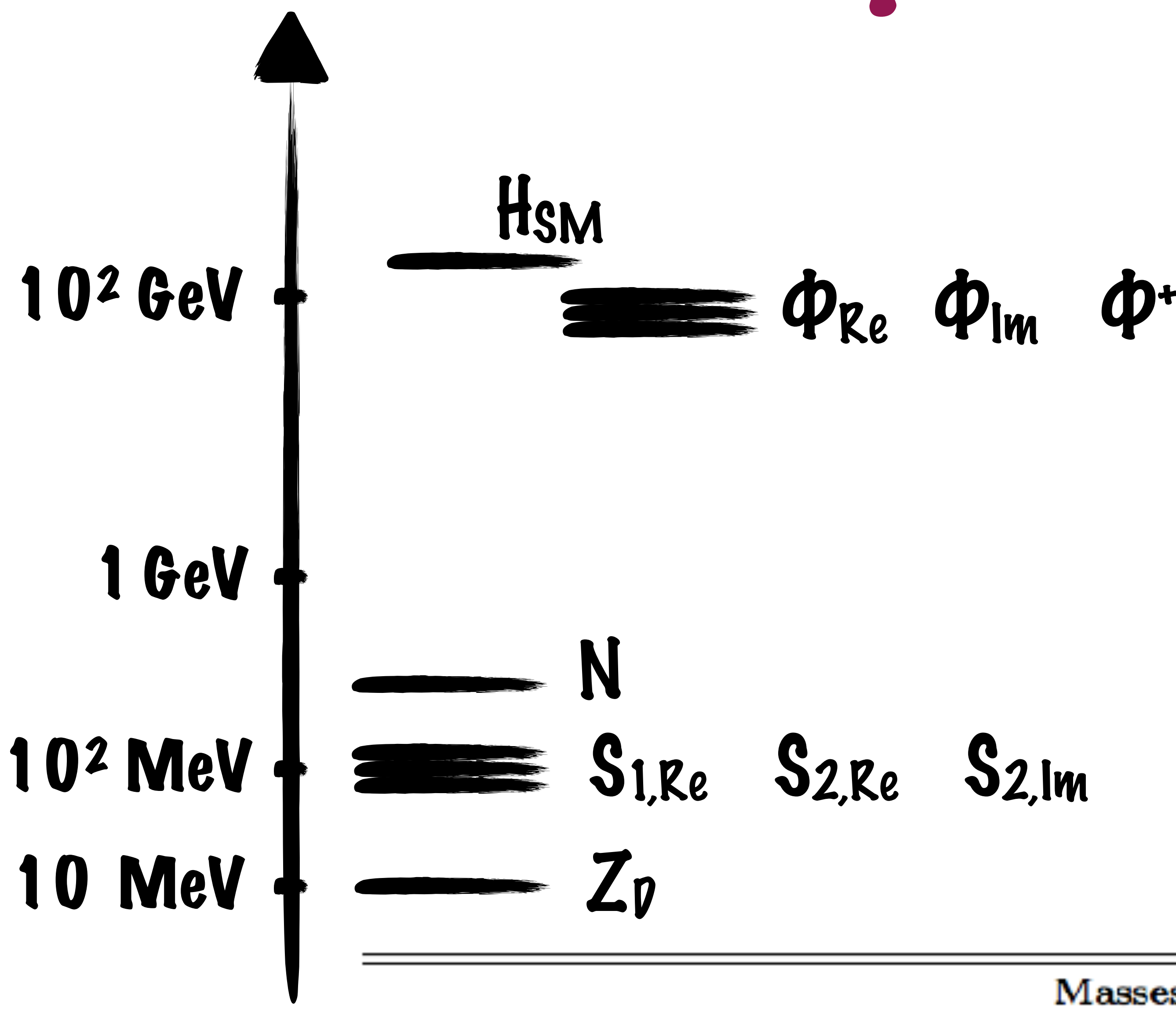
$$\epsilon' \simeq \frac{2 g_\mathcal{D}}{g/\cos(\theta_W)} \left(\frac{\langle \phi \rangle}{\langle H \rangle} \right)^2$$

$$\epsilon \gtrsim \frac{e g_\mathcal{D}}{480\pi^2} \frac{m_{Z_\mathcal{D}}^2}{m_{H_\mathcal{D}^\pm}^2}$$ **(irreducible loop contribution)**

Usual bounds apply ➪

A possible low scale spectrum

we take $\langle S_1 \rangle \ll \langle H \rangle$ to have a SM-like Higgs



Vacuum Expectation Values

v (GeV)	ω_1 (MeV)	v_ϕ (MeV)	ω_2 (MeV)
246	136	0.176	0.65

Coupling Constants

λ_H	$\lambda_{H\phi} = \lambda'_{H\phi}$	λ_{HS_1}	λ_{HS_2}
0.129	10^{-3}	10^{-3}	-10^{-3}
$\lambda_{\phi S_1}$	$\lambda_{\phi S_2}$	λ_{S_1}	$\lambda_{S_1 S_2}$
10^{-2}	10^{-2}	2	0.01
μ (GeV)	μ' (GeV)	α	g_D
0.15	0.01	10^{-3}	0.22

Bare Masses

m_ϕ (GeV)	m_2 (GeV)
100	5.51

Masses of the Physical Fields

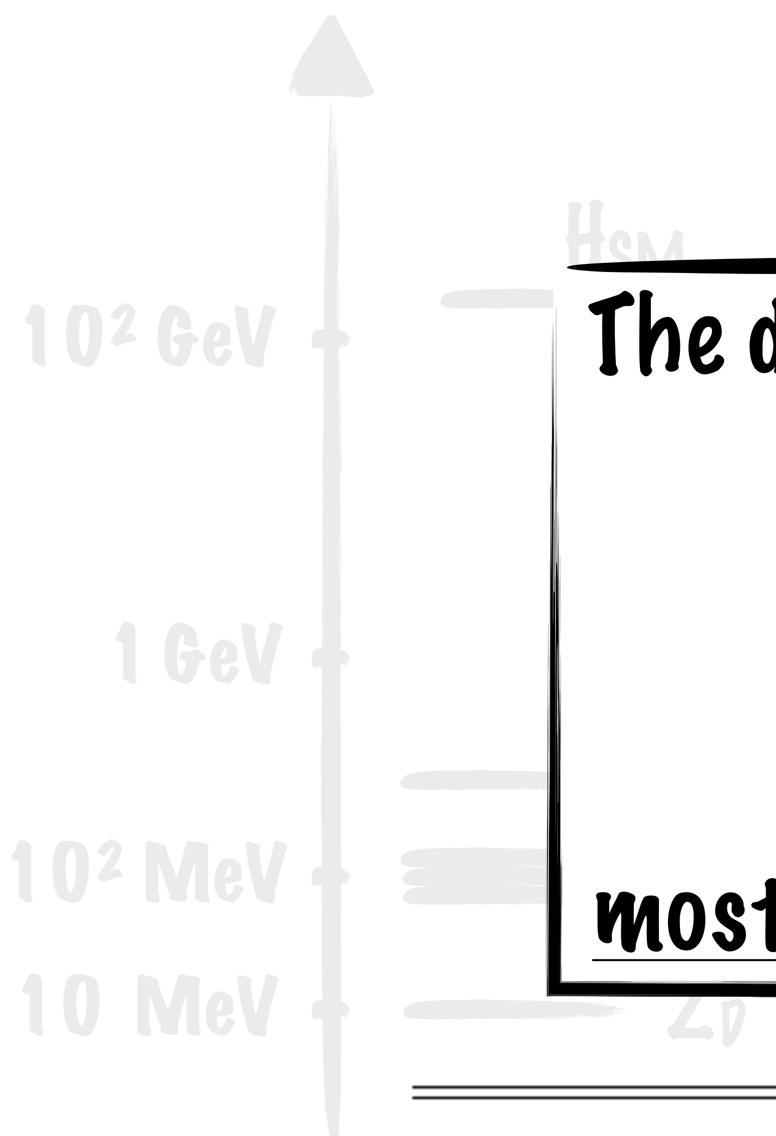
$m_{h_{SM}}$ (GeV)	m_{H_D} (GeV)	m_{S_D} (MeV)	$m_{S'_D}$ (MeV)	$m_{H^\pm_D}$ (GeV)	m_{A_D} (GeV)	m_{a_D} (MeV)	m_{Z_D} (MeV)	m_{N_D} (MeV)
125	100	272	320	100	100	272	30	150

Mixing between the Fields

$\theta_{H\phi}$	θ_{HS_1}	θ_{HS_2}	$\theta_{\phi S_1}$	$\theta_{\phi S_2}$	$\theta_{S_1 S_2}$	$\epsilon\epsilon$	ϵ'	$\lvert U_{\alpha N}\rvert^2$
1.3×10^{-6}	2.1×10^{-6}	10^{-8}	1.2×10^{-3}	8.3×10^{-7}	3.4×10^{-2}	2×10^{-4}	3.6×10^{-14}	$\mathcal{O}(10^{-6})$

A possible low energy spectrum

we take $\langle S_1 \rangle \ll \langle H \rangle$ to have a SM-like Higgs



The dark sector interacts with the SM via 3 renormalizable portals (gauge, neutrino & scalar) but with tiny mixings

$\Downarrow$

<u>mostly secluded from the visible sector</u>

Vacuum Expectation Values

MeV)	ω_2 (MeV)
76	0.65

tants

$_{S_1}$	λ_{HS_2}
$^{-3}$	-10^{-3}
$_{S_1}$	$\lambda_{S_1S_2}$
2	0.01
x	g_D
3	0.22

cs

m_2 (GeV)
5.51

Masses of the Physical Fields

$m_{h_{SM}}$ (GeV)	m_{H_D} (GeV)	m_{S_D} (MeV)	$m_{S'_D}$ (MeV)	$m_{H_D^\pm}$ (GeV)	m_{A_D} (GeV)	m_{a_D} (MeV)	m_{Z_D} (MeV)	m_{N_D} (MeV)
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Mixing between the Fields

$\theta_{H\phi}$	θ_{HS_1}	θ_{HS_2}	$\theta_{\phi S_1}$	$\theta_{\phi S_2}$	$\theta_{S_1S_2}$	$\epsilon\epsilon$	ϵ'	$\lvert U_{\alpha N}\rvert^2$
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Pheno consequences (currently under study)

- <u>Low scale realization</u>: many possible signatures in low energy experiments (APV, rare mesons decays, running weak mixing angle, NSI, CNSN...)
- <u>High energy realization</u>: interesting at colliders, although maybe too secluded (but for instance: new rare Higgs decays $h_{SM} \to Z\, Z_D$)
- <u>Dark Matter</u>: always possible to introduce a candidate, it seems hard to have a DM candidate that actually does something to the model

Takeaway

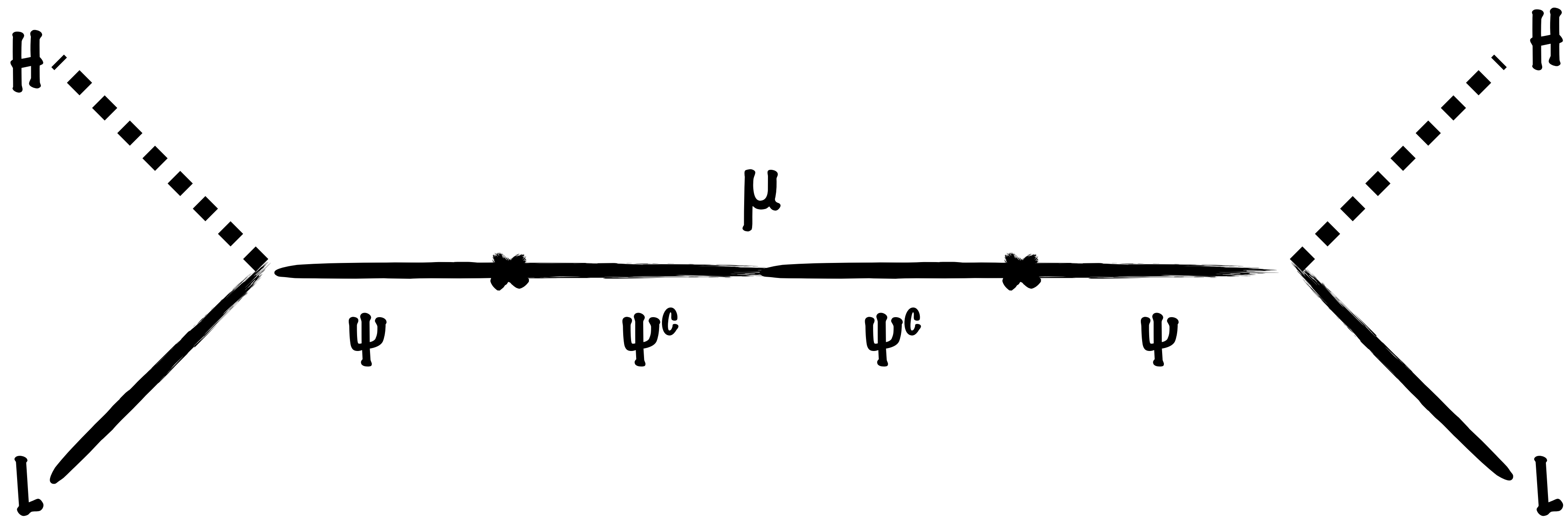
- Starting from a model motivated by MiniBooNE, we obtain a variant of neutrinophilic models with a gauged U(1)
- This model automatically gives a dynamical inverse seesaw, generating neutrino masses at the dim=9 level
- The associated dark sector is
  1. light/heavy depending on $\langle S_1 \rangle$
  2. in general very secluded from the SM
- Interesting phenomenology possible for both the low/high energy realizations, currently under study

Additional material

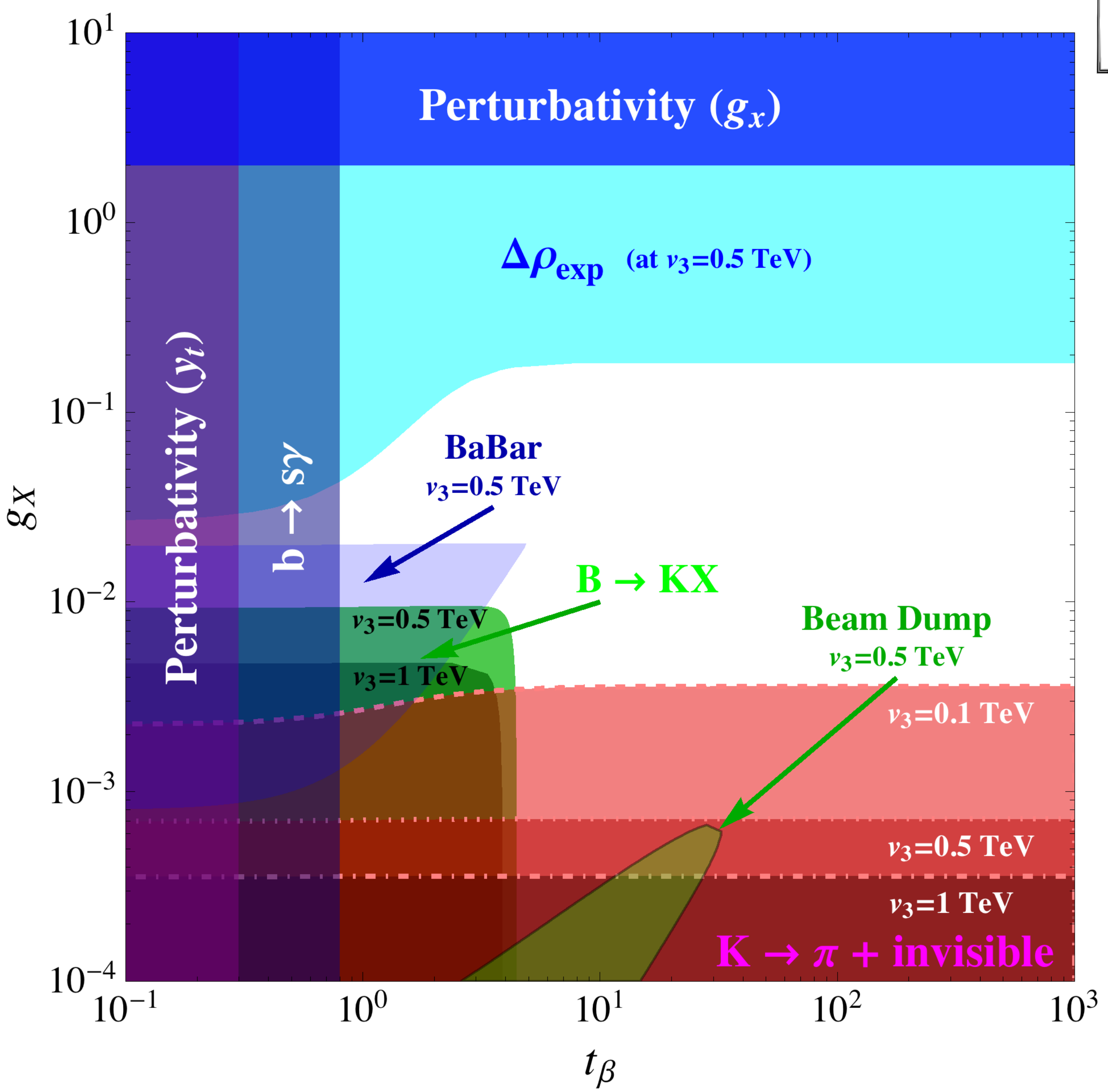
Inverse seesaw: a recap

Mohapatra '86
Mohapatra, Valle '86

$$\mathcal{L} = \mathcal{Y}(LH)\psi + m_\psi \psi\psi^c + \frac{\mu}{2}\psi^c\psi^c$$



Experimental constraints on the model with explicit breaking



see 1706.10000
with R. Funchal, P. Machado & Z. Tabrizi

Spurion analysis of global U(1)' breaking

We know that the parameters μ, μ' & α break explicitly the global U(1)' symmetry, so they can be treated as spurions with charges satisfying the following equations:

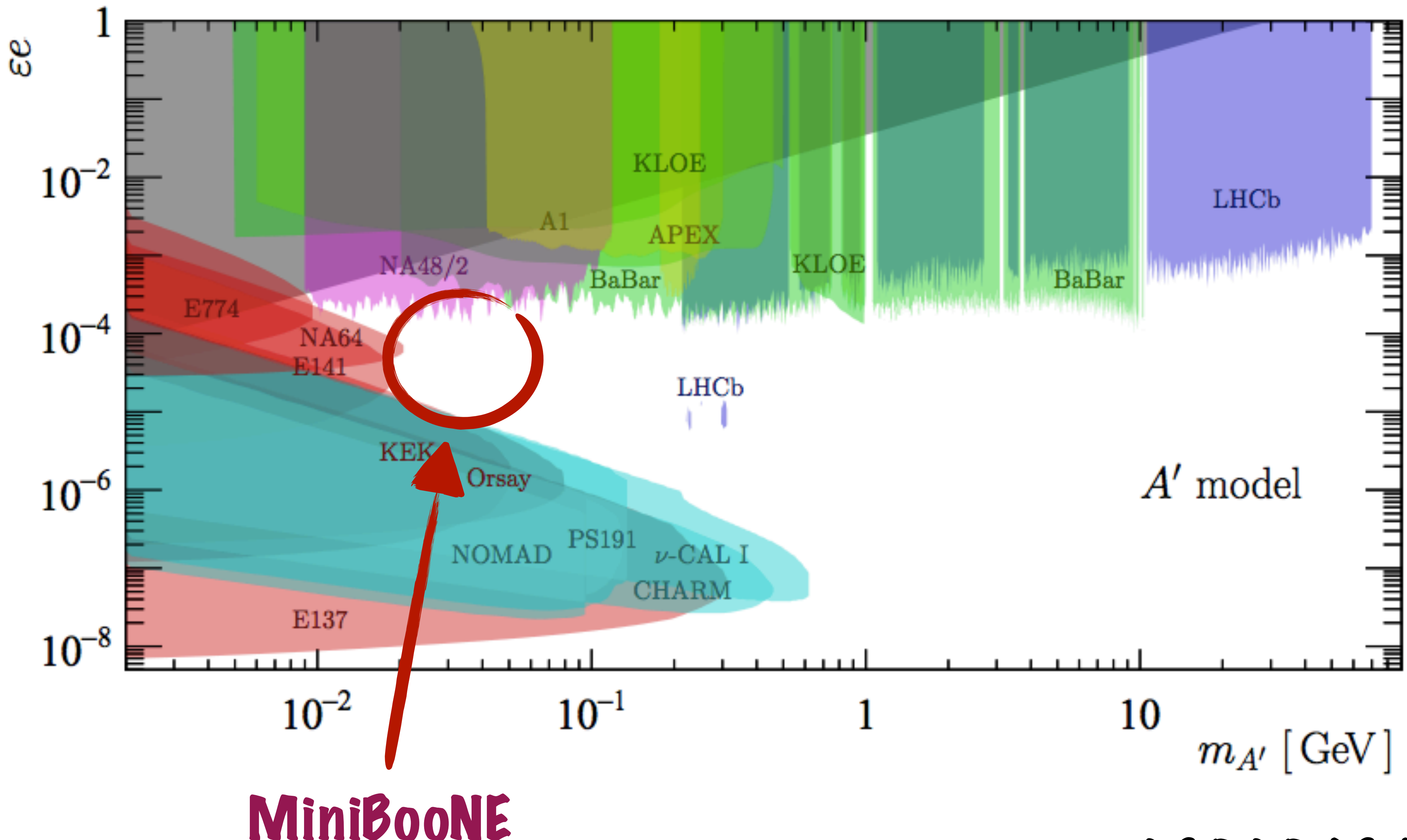
$$V = \mu S_1(\phi^\dagger H) + \mu' S_2^* S_1^2 + \alpha(H^\dagger \phi) S_1 S_2^*$$

$$q_\mu + q_{S_1} - 1 = 0, \quad q_{\mu'} + 2q_{S_1} = 0, \quad q_\alpha + 1 + q_{S_1} = 0$$

Radiatively we generate

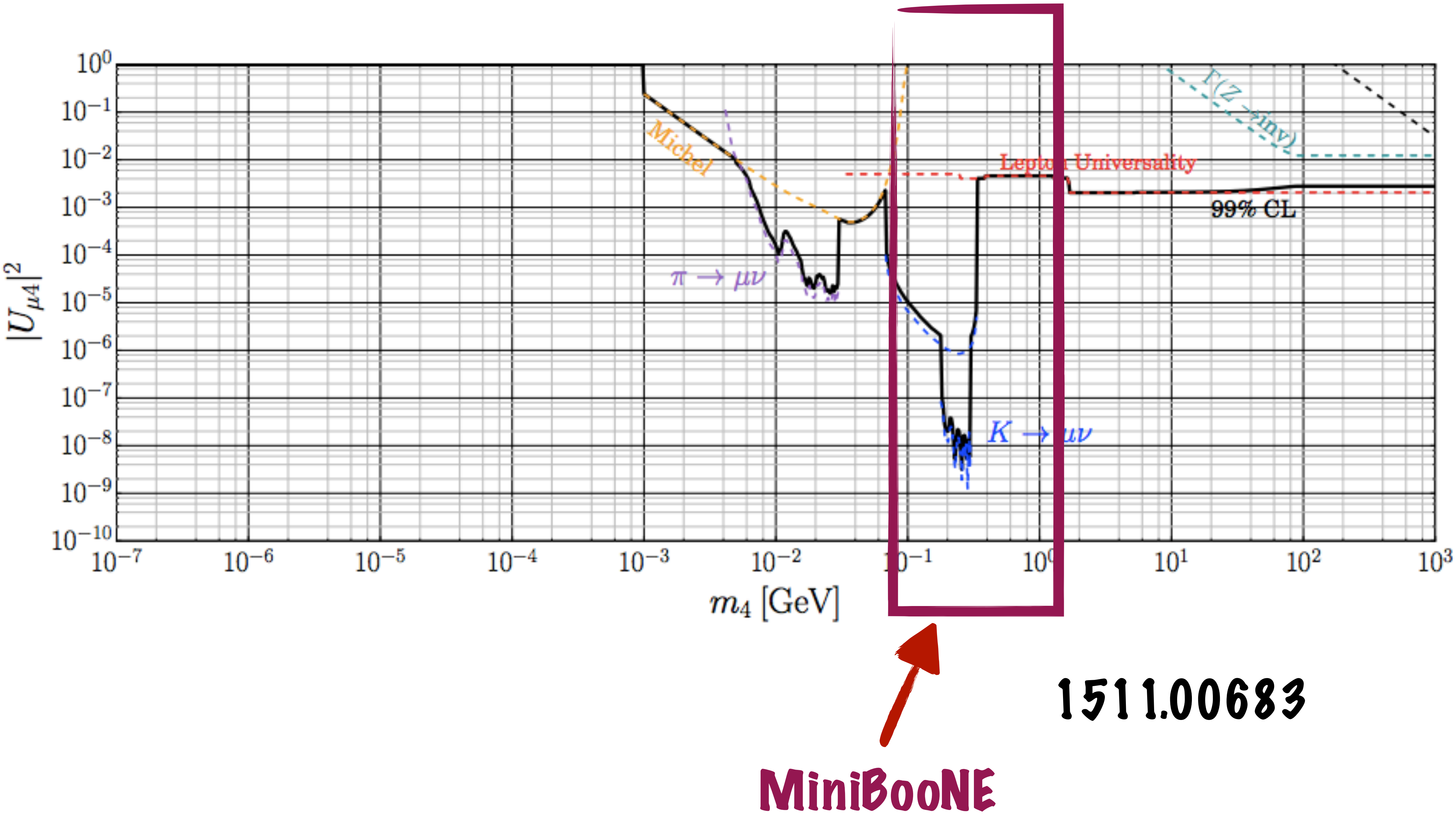
$$\Delta\mu \propto \frac{\mu' \alpha^*}{16\pi^2}$$
$$\Delta\mu' \propto \frac{\mu\alpha}{16\pi^2}$$
$$\Delta\alpha \propto \frac{\mu' \mu^*}{16\pi^2}$$

Dark Z bounds



1801.04847

Dark neutrino bounds



1511.00683

How to generate neutrino masses: common lore

If RH neutrinos exist, we can try to mimic what happens for charged fermions:

$$\mathcal{L} = \mathcal{Y}_{ij} L_i H N_j + \frac{1}{2} M_{ij} N_i N_j + h.c.$$

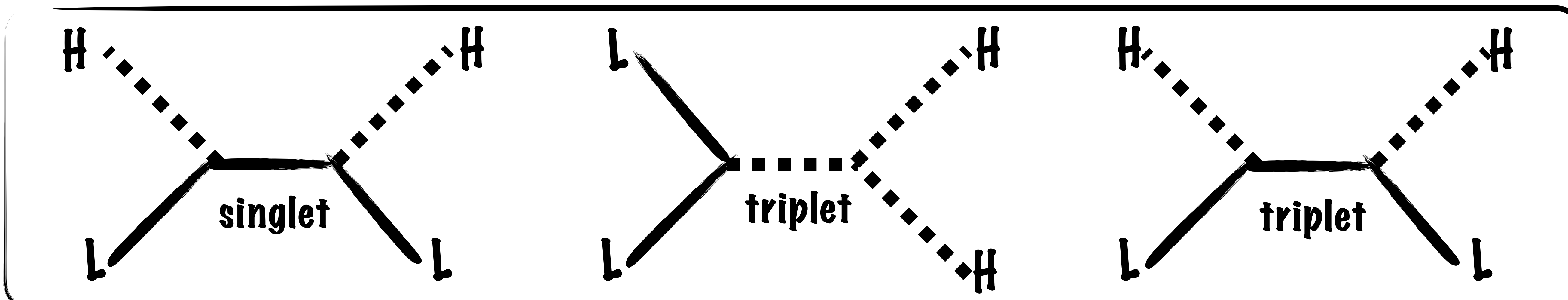
- Pros: "same" mechanism as other SM fermions
- Cons: (i) need **Y** $\sim 10^{-11}$, (ii) since **M** term is unavoidable, at most we get pseudo-Dirac ν's (i.e. ν masses not entirely coming from <H>)

How to generate neutrino masses: common lore

If M is heavier than the EW scale, then we get tiny Majorana neutrino masses

to have $m_\nu \lesssim 1$ eV $\quad \mathcal{L}_5 = \frac{c}{\Lambda}(LH)^2 \quad \Rightarrow \quad \frac{\Lambda}{c} \gtrsim 10^{13}\text{GeV}$

Other possible realizations:



- Pros: (i) simple, (ii) matter-antimatter asymmetry can be generated
- Cons: scales are too heavy to be probed (unless tiny c)