Rich dark sectors: from the neutrino portal to gravitational waves

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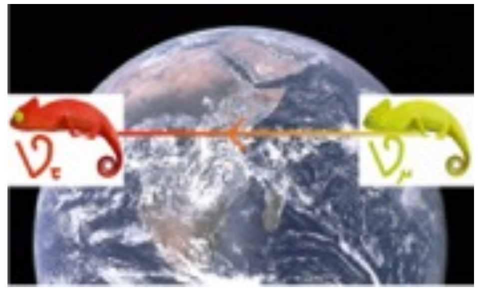
Evidence beyond the SM

There is evidence that the Standard Model is incomplete: three pillars (plus maybe GW?).

Neutrino masses



Dark Matter


@Symmetry magazine

Baryon asymmetry

Symmetry magazine

The ultimate goal is to unveil the New SM that would explain these pieces of evidence.

What is the new physics scale?

I will focus on neutrinos as our guide.

Neutrino have masses

Neutrinos oscillate

Mixing between flavour and mass basis is described by the *Pontecorvo-Maki-Nakagawa-Sakata* matrix:

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

Flavour field

Mass field

which enters in the CC interactions

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{k\alpha} \left(U^*_{\alpha k} \bar{\nu}_{kL} \gamma^\rho l_{\alpha L} W_\rho + \text{h.c.} \right)$$

The probability of oscillation is

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{i \frac{\Delta m^2_{i1} L}{2E}} \right|^2}$$

Neutrino oscillations imply that **neutrinos have mass and mix.**

NuFIT 6.0 (2024)

	Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
$\delta_{\rm CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$

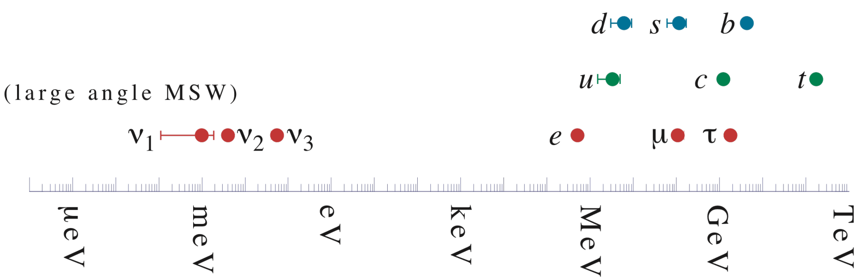
- 2 mass squared differences
- 3 sizable mixing angles,
- mild hints of CPV
- mild indications in favour of NO

M. C. Gonzalez-Garcia et al., 2410.05380
http://www.nu-fit.org/

Neutrinos: Open window on Physics BSM

Neutrinos give a new perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass?
and why are they so much lighter than the other fermions?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

Neutrino masses Beyond SM

In the SM, neutrinos do not acquire mass and mixing.

Dirac Masses

If we introduce a right-handed neutrino, then an interaction with the Higgs boson emerges.

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.} \longrightarrow m_D = y_\nu v = V m_{\text{diag}} U^\dagger$$

This term is SU(2) invariant and respects lepton number.

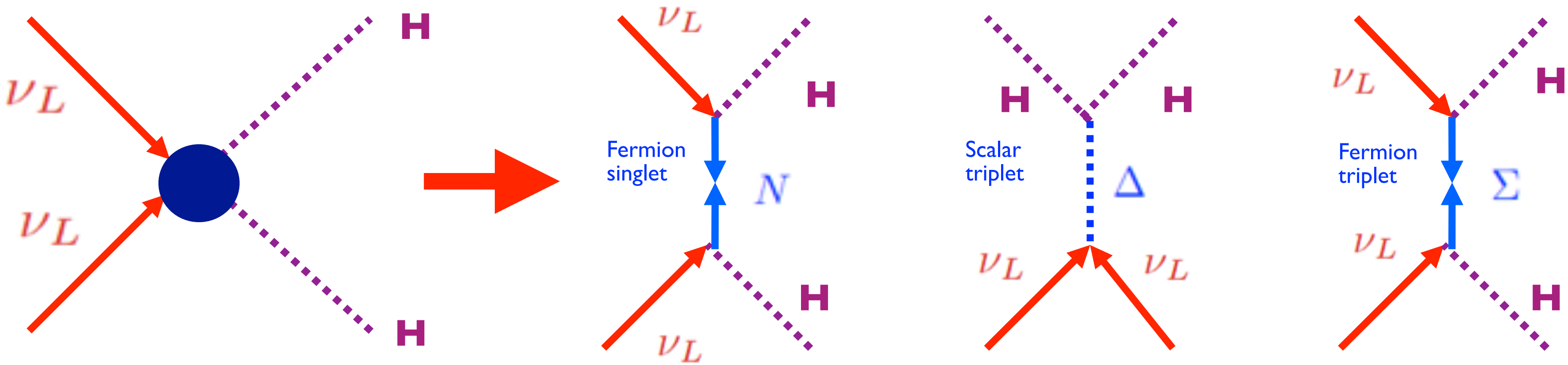
- why the coupling is so small??? $y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$
- why the leptonic mixing angles are large?
- why neutrino masses have at most a mild hierarchy?
- why no Majorana mass term for RH neutrinos? We need to impose L as a fundamental symmetry.

Majorana Masses

Introduce a Dimension 5 operator (or allow new scalar fields, e.g. a triplet):

$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

Weinberg operator, PRL 43



Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Ma, Mohapatra, Senjanovic, Magg, Wetterich, Lazarides, Shafi, Schecter, Valle, Hambye…

This term breaks lepton number and induces Majorana masses and Majorana neutrinos. It can be induced by a high energy theory (see-saw mechanism).

Neutrino masses BSM:
“vanilla” see saw mechanism type I

Symmetry magazine

- Introduce a right handed neutrino **N**
- It couples to the Higgs and has a Majorana mass

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

As a result, neutrinos can have naturally small masses and are Majorana particles.

What is the new physics scale?

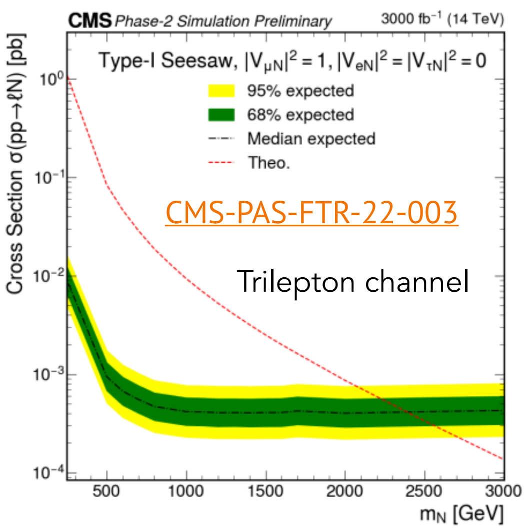
Are there new:
symmetries?
particles?
interactions?

New physics scale: High Energy frontier and above

eV keV MeV GeV **TeV** **Intermediate scale** **GUT scale**

At TeV SUSY MSSM, split SUSY, Composite Higgs, Technicolor….

GUT theories



LHC new particle searches

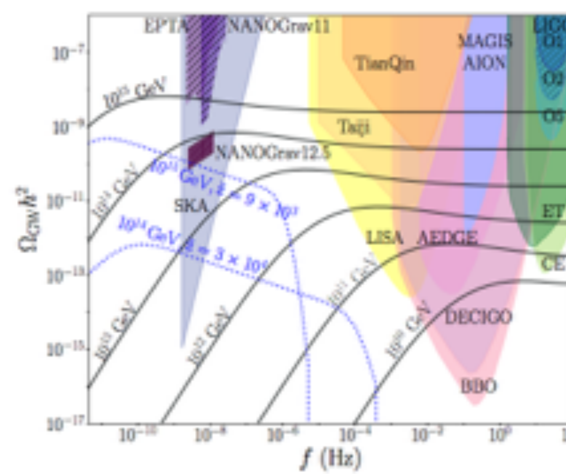
LLP searches

CLFV

Leptogenesis/EW baryogenesis

GW from U(1)$_L$ breaking

Proton decay Leptogenesis



S. King et al., PRL 126 (2021)

Despite intense searches in colliders, flavour and DM exp, no hints of TeV new physics have been found.

Going low in energy: Dark sectors

A change of paradigm might be needed: new physics may be light but hidden because too weakly interacting (dark or hidden sectors).

eV keV MeV GeV TeV Intermediate scale GUT scale

Low E See-saw models, NuMSM, extended see-saw…

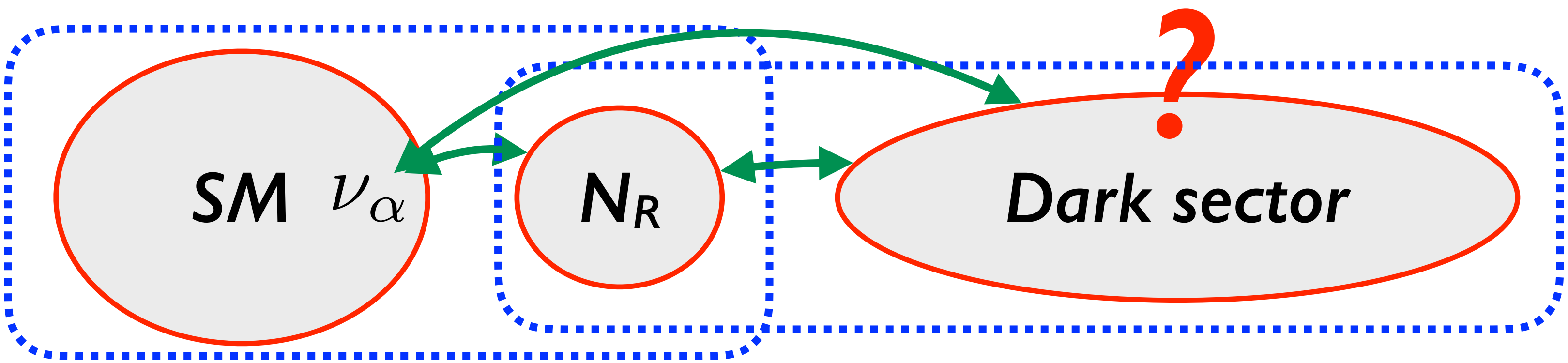
$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{keV}^2}{10\ \mathrm{MeV}} \sim 0.1\ \mathrm{eV}$$

Lowering the Yukawa couplings or imposing L quasi-conservation in extended models, it is possible to lower the N (HNL) mass scale.

The dark sector can interact with SM via portals:

Portal	Coupling
Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Axion-like particles, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Dark Higgs, S	$(\mu S + \lambda_{\rm HS} S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$
milicharged particle, χ	$\epsilon A^\mu \bar{\chi}\gamma_\mu \chi$

See e.g. Artuso et al., 2210.04765, S. Gori et al, 2209.04671, FIPs 2022 report, 2305.01715

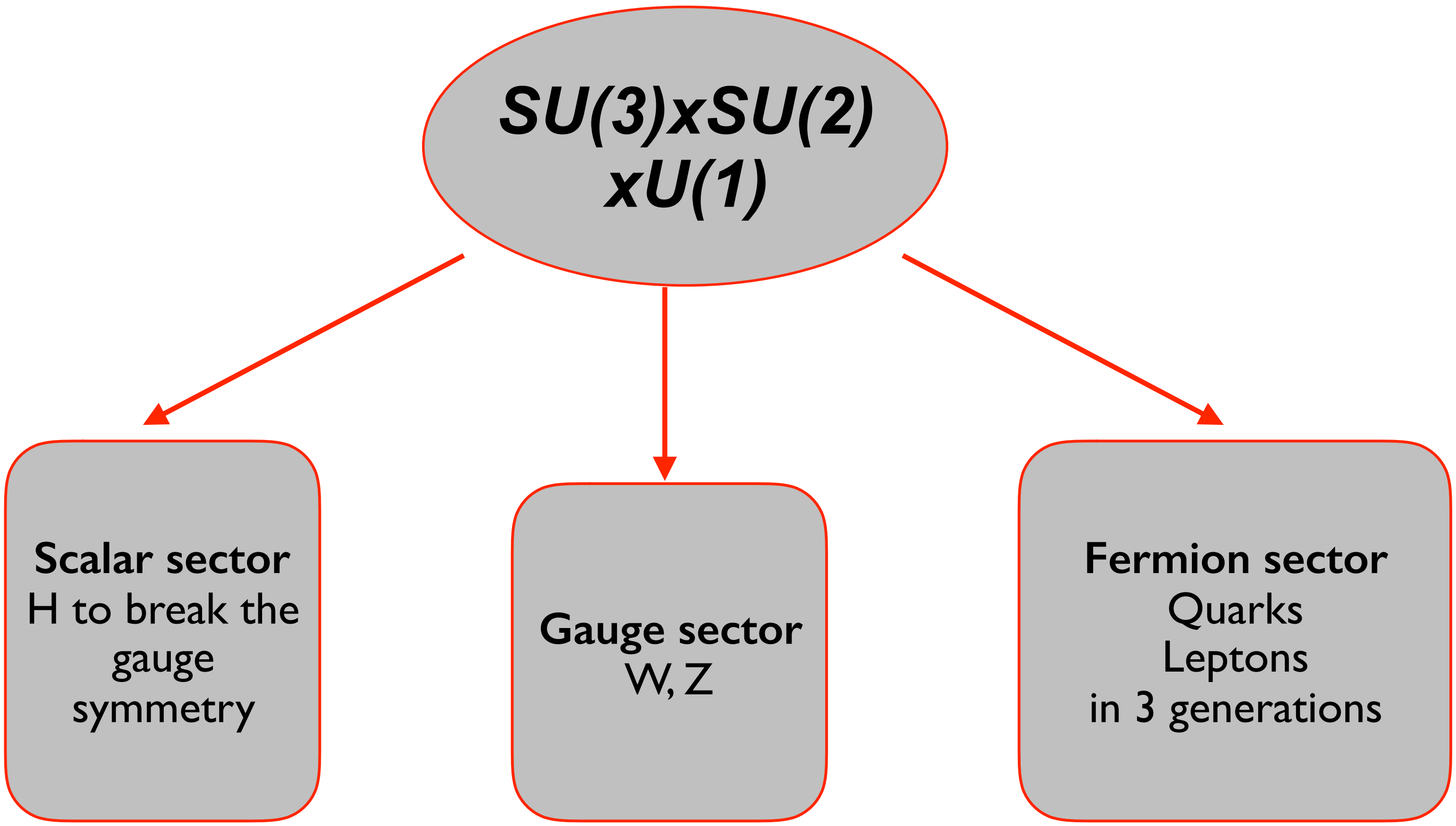


After symmetry breakings, neutrinos can mix with HNLs and dark fermions.

Changing the paradigm

Rich dark sectors

Non-minimality is strongly motivated: the SM is highly non-minimal and it exists.



A rich dark sector

E.g. P. Ballett, M. Hostert, SP, PRD 101 (2020)

U(1)'

$$\lambda_{\phi H}\phi^\dagger\phi\, H^\dagger H$$

$$\frac{\sin\chi}{2}X_{\mu\nu}B^{\mu\nu}$$

$$\bar{L}\cdot H N_R \quad (+\ldots\overline{N_R}N_S)$$

Scalar sector
dark scalar needed to break U(1)'

Gauge sector
Z' (dark photon, A')

Fermion sector
dark neutrinos charged under the U(1)'

Where does the new mass scale come from?

It can be generated dynamically from a scalar that acquires a vev, possibly induced by EW SSB.

A concrete example: the 3-portal model

The Lagrangian is given by

$$\begin{aligned}\mathcal{L} \supset \mathcal{L}_{\rm SM} &- \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\sin\chi}{2}X_{\mu\nu}B^{\mu\nu} \\ &+ (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi) - \lambda_{\Phi H}|H|^2|\Phi|^2 \\ &+ \overline{\widehat{\nu}_N} i\partial\!\!\!/ \widehat{\nu}_N + \overline{\widehat{\nu}_D} i D\!\!\!\!/_X \widehat{\nu}_D - \Big[(\overline{L}\widetilde{H})Y\widehat{\nu}_N^c + \overline{\widehat{\nu}_N} Y_L \widehat{\nu}_{D_L}^c \Phi \\ &+ \overline{\widehat{\nu}_N} Y_R \widehat{\nu}_{D_R} \Phi^* + \frac{1}{2}\overline{\widehat{\nu}_N} M_N \widehat{\nu}_N^c + \overline{\widehat{\nu}_{D_L}} M_X \widehat{\nu}_{D_R} + \text{h.c.}\Big]\end{aligned}$$

A. Abdullahi, M. Hostert, SP, 2007.11813

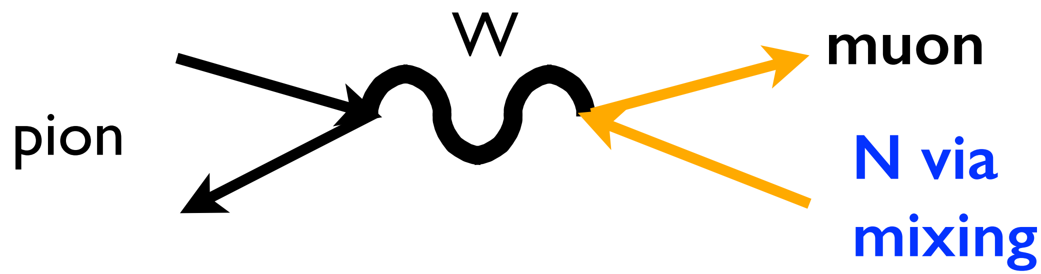
The model is anomaly free thanks to the inclusion of two dark neutrinos with opposite charges. Other possibilities can also be considered (adding sub-GeV DM).

Focus on a scale of MeV-GeV: $v_\phi, m_{Z'} \sim \text{GeV}.$

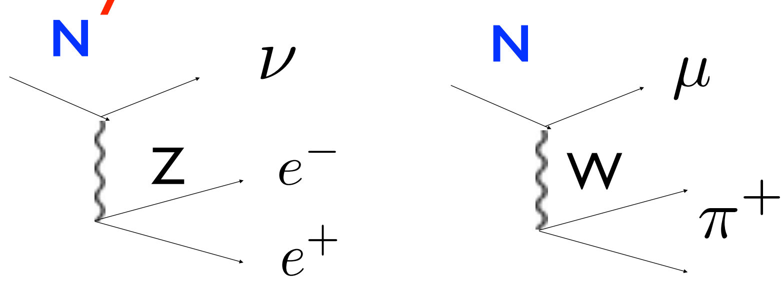
Tests of dark sectors: HNL searches

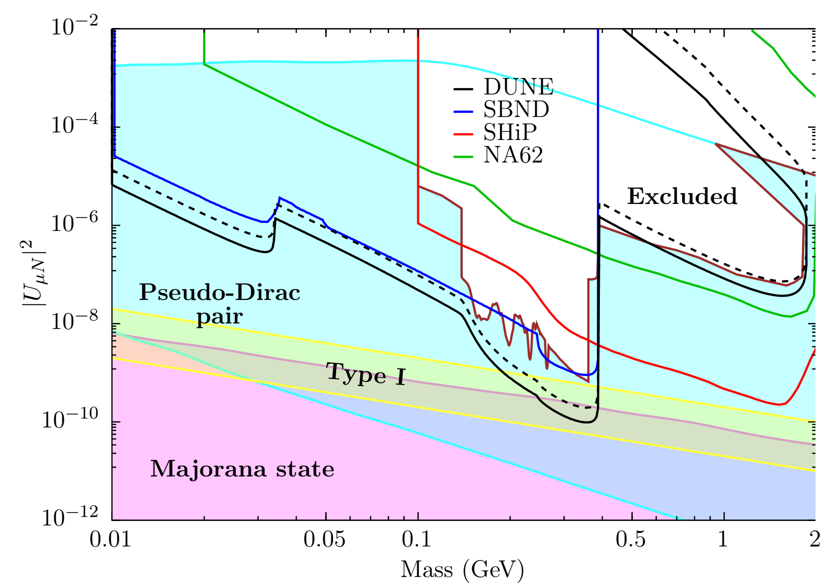
In minimal models, HNL production and decay is controlled by the mixing with neutrinos: $\sin^2 \sim m_\nu / M$.

Production in e.g. neutrino experiments:



Decays:

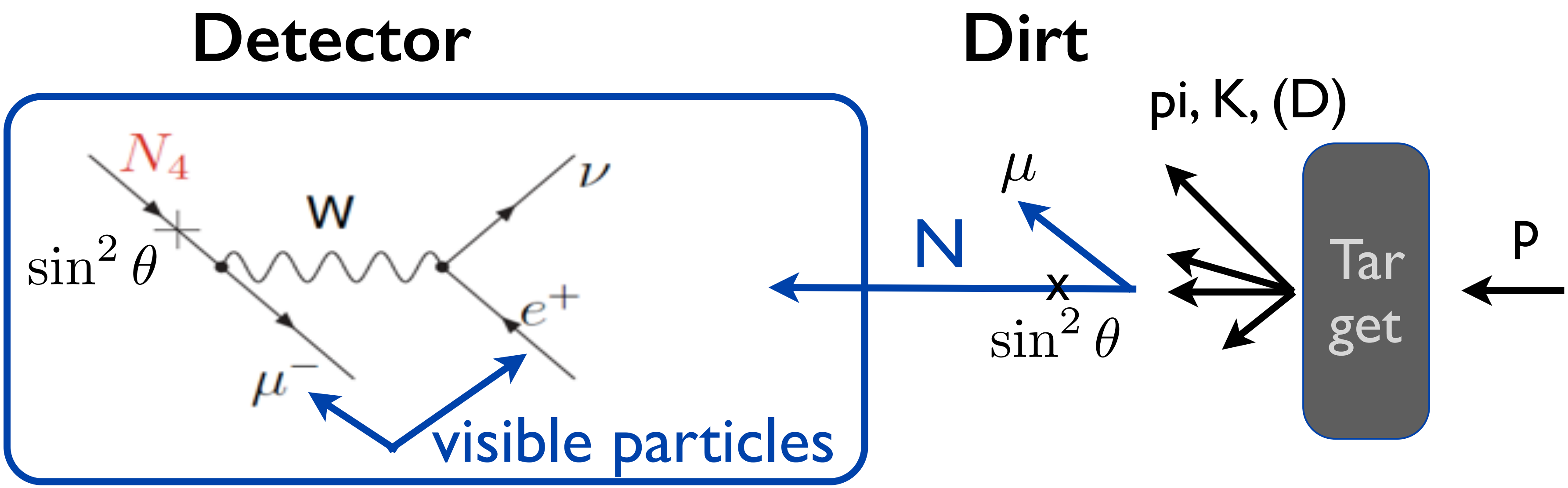


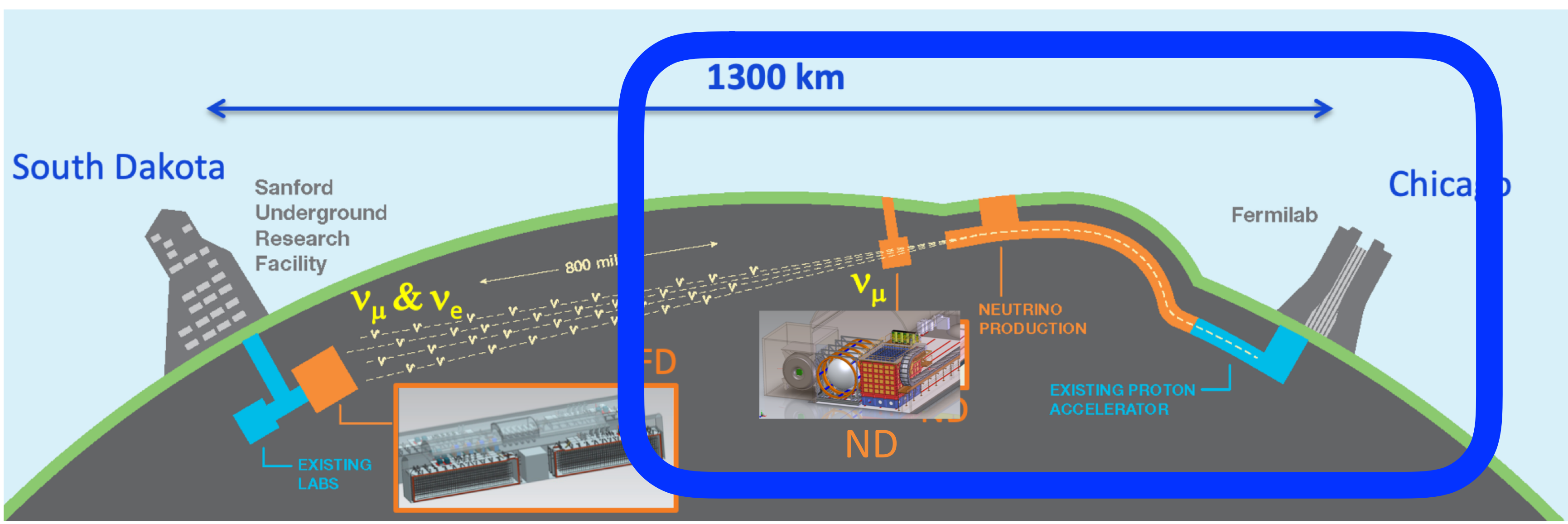


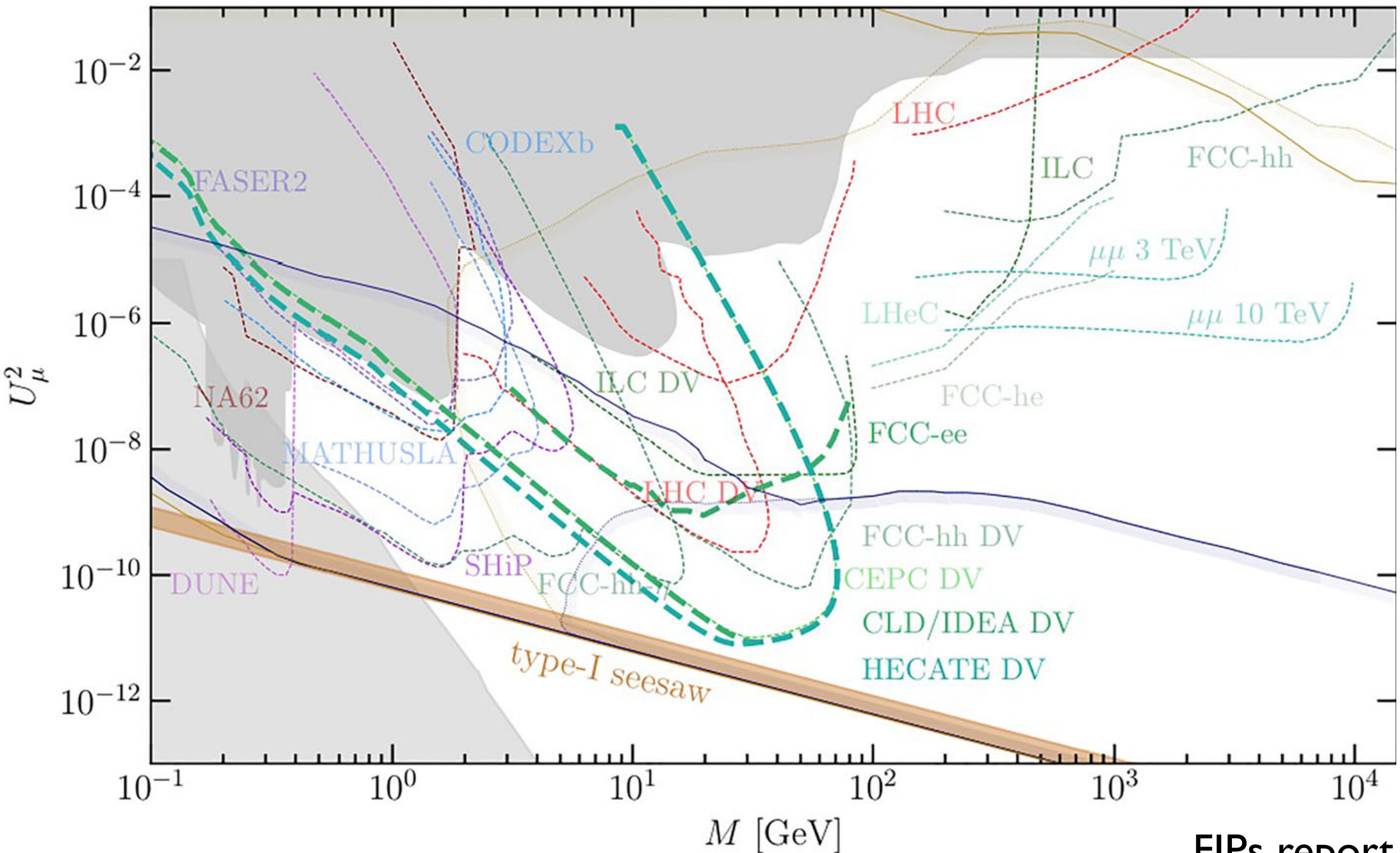
Ballett, Boschi, SP, 1905.00284

As the mixing is small and the Z, W very heavy, decays are typically very slow.

Search for these HNL? “A la beam dump” experiments



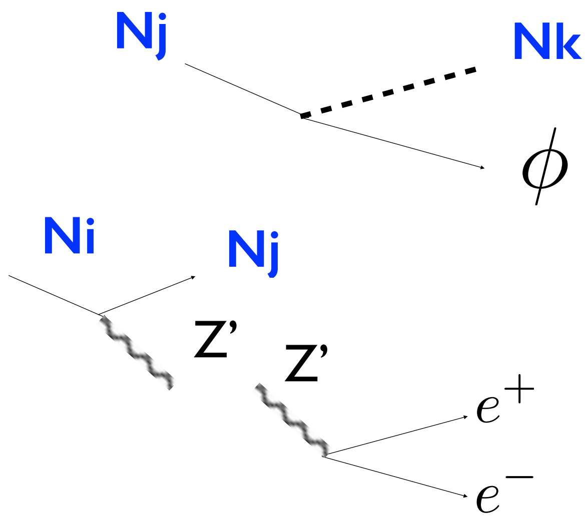


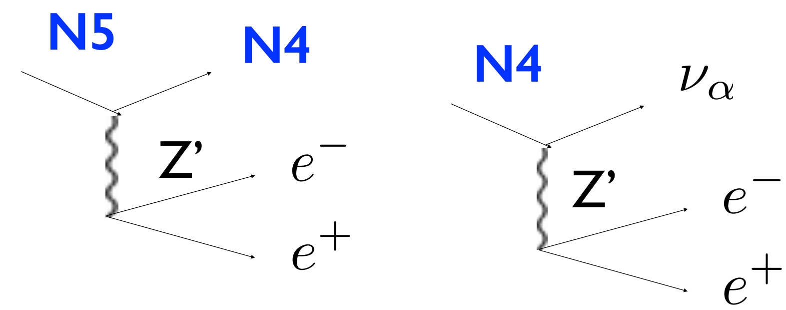


FIPs report 2022

Future exp such as DUNE ND, SHiP, FCC might approach the "see-saw region" in certain mass ranges. The typical search is for displaced vertices.

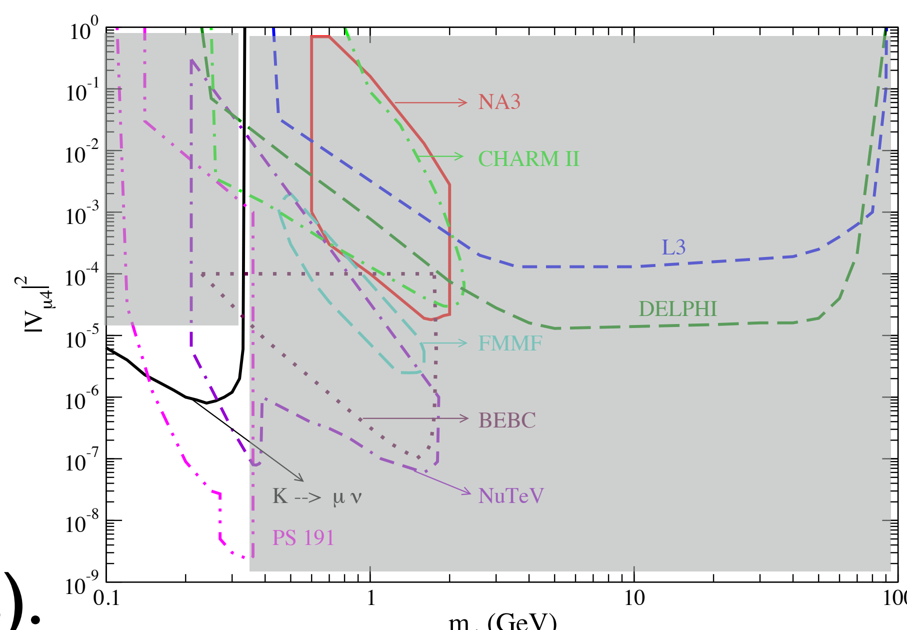
In RDS models, HNL production is controlled by mixing or other portal (e.g. B-L gauge coupling) and decay can be fast due to the internal DS dynamics.





decay chains

Fast visible and invisible decays

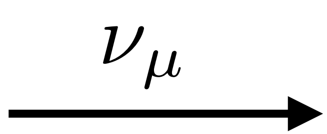


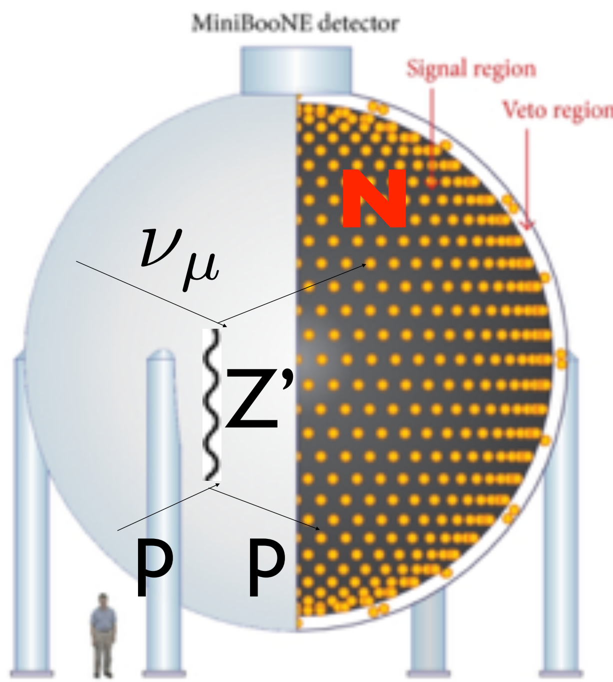
HNL decay bounds need to be reevaluated and they may not apply (e.g. beam dump experiments).

Adapted from Atre et al. 2009

New exp signatures

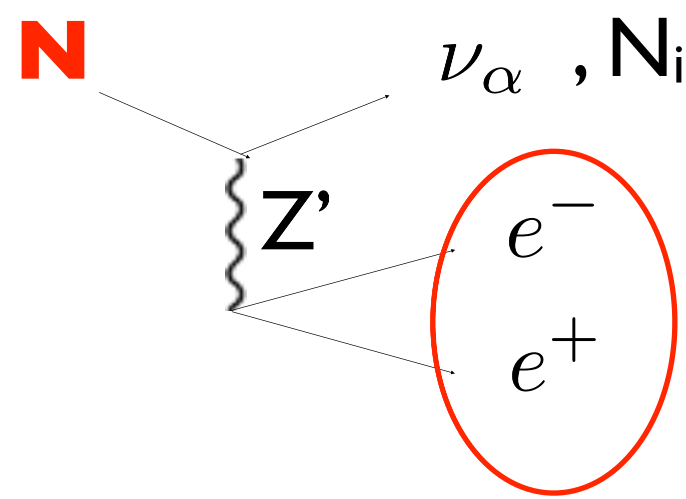
Up-scattering of an HNL N in the detector and its decay into ee (mumu) nu.





P. Ballett, S. Pascoli, M. Ross-Lonergan, PRD 99 (2019)

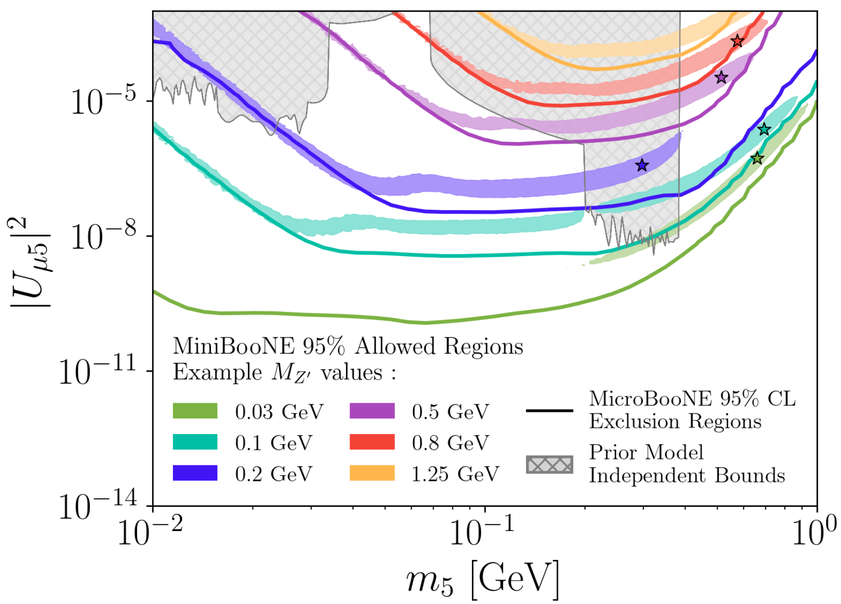
See also S. Gnineko, PRL 103 (2009), E. Bertuzzo et al., PRL 121 (2018).



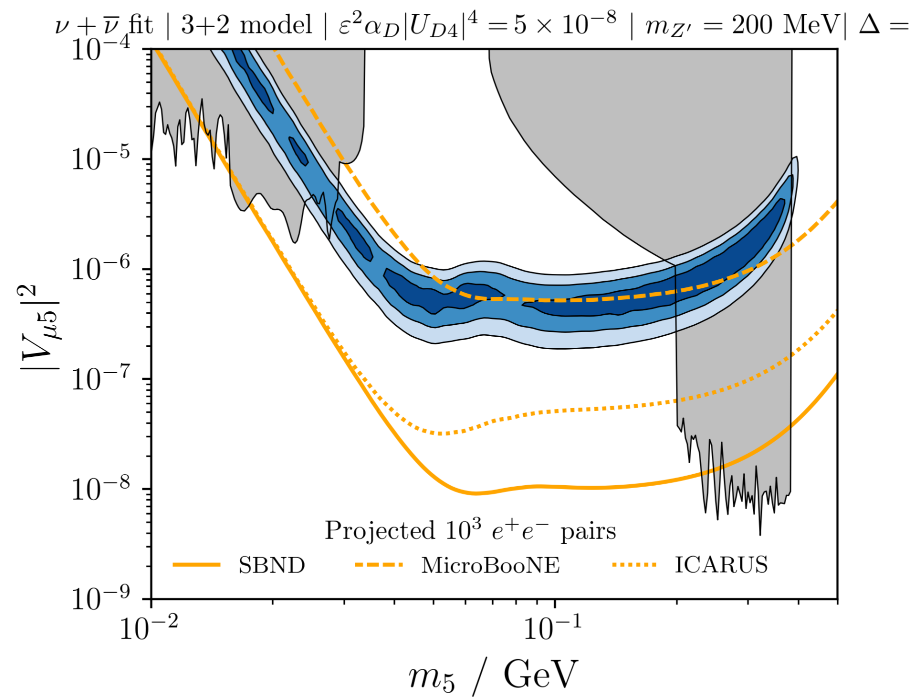
This can provide an explanation of the MiniBooNE low-E excess.

Current (microBooNE, SBN, T2K) and future (T2HK, DUNE) neutrino facilities can explore the corresponding parameter space.

https://www.bo.infn.it/gruppo2/sbn-it/

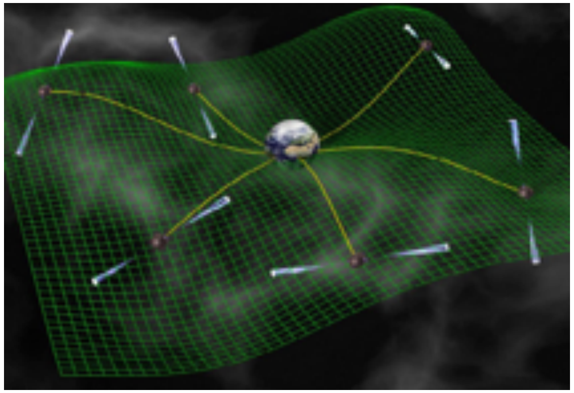


(b) Dual dark neutrino scenario, $\Delta = 1$, $\varepsilon = 8 \times 10^{-4}$.



MicroBooNE collaboration, 2502.109000

Abdullahi, Hostert, Hoefken Zink, Massaro, SP, 2308.02543

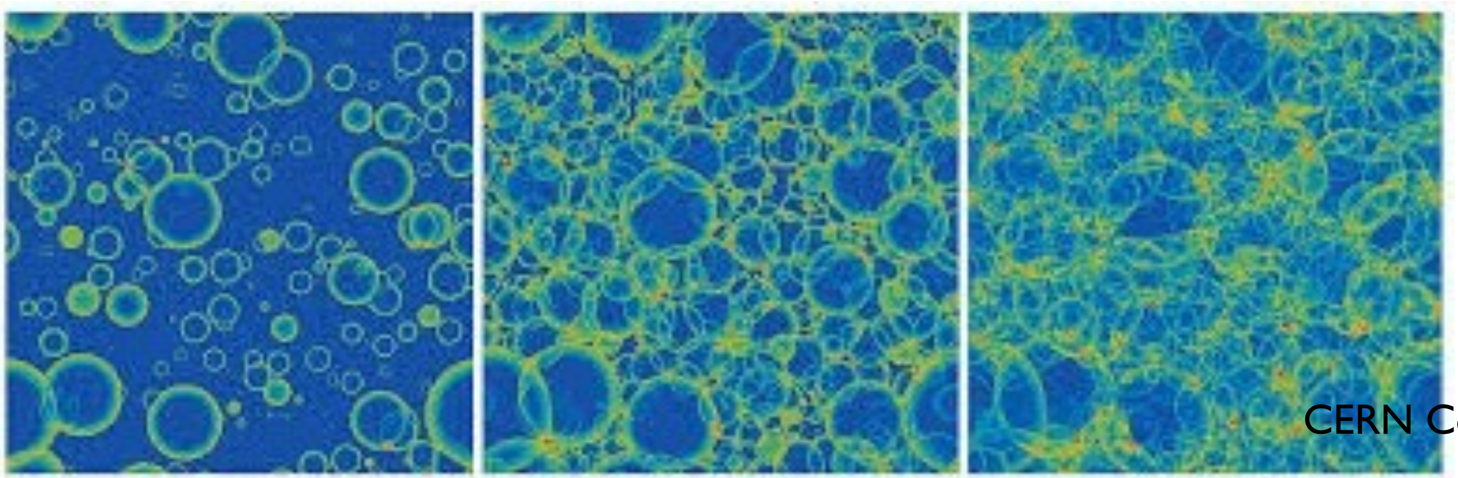


Dark scalars and photons: FOPT and PTA GWs

G. Agazie et al. (NANOGrav), 2306.16213; J. Antoniadis et al. (EPTA, InPTA:), 2306.16214; D. J. Reardon et al., 2306.16215; H. Xu et al., 2306.16216.

In 2023, evidence was reported of nanoHertz stochastic GW background by PTA experiments. A FOPT provides a possible explanation.

See also, S. Balan et al., 2502.19478; J. Goncalves et al., 2501.11619



CERN Courier

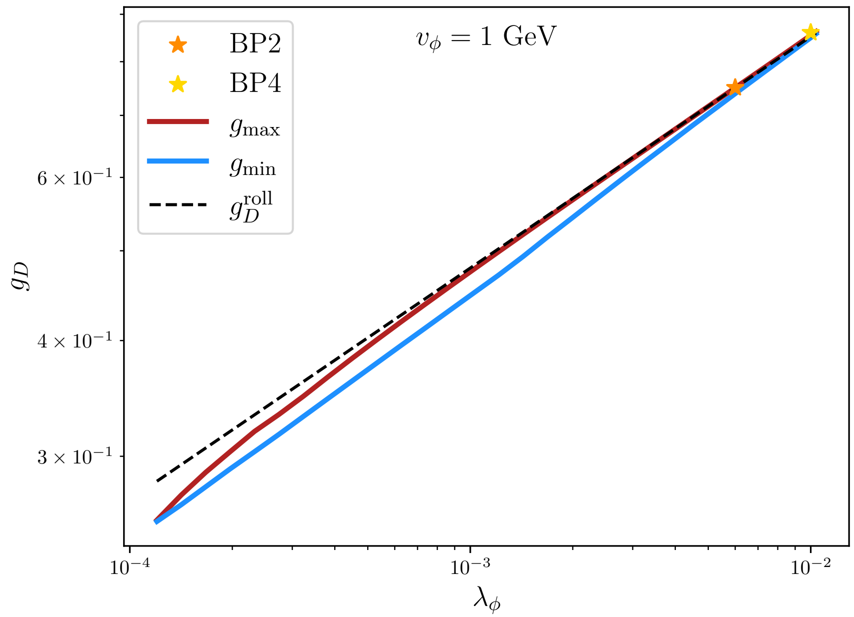
A FOPT proceeds via nucleation of bubble of true vacuum. They grow ultimately filling all the Universe.

The evolution of the PT needs to be very slow (supercooled PT) and this sets important requirements on the parameters of the model.

We consider a U(1) extension with scalar for SBB:

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) - V(\phi^*\phi) - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} \qquad V = -\mu_\phi^2 \phi^*\phi + \lambda_\phi (\phi^*\phi)^2$$

Costa et al., 2501.15649



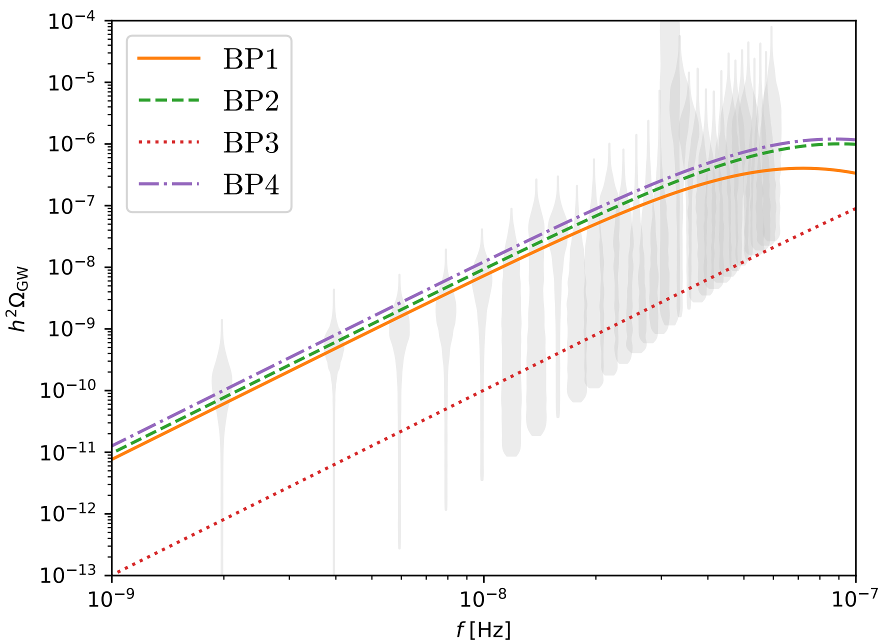
$$g_D^{\rm roll} = \left\{ \frac{16\pi^2 \lambda_\phi}{3} \left[1 - \frac{\lambda_\phi}{8\pi^2} (5 + 2\log 2) \right] \right\}^{1/4}$$

For $g_{\rm roll}$ there is a barrier between the two vacua at zero T.

Between $g_{\max}$ and $g_{\min}$ the FOPT completes.

We have identified BP for which the FOPT can reproduce the PTA data as well as lead to completion of the PT.

	v_ϕ [GeV]	λ_ϕ	g_D	T_p [MeV]	$H_* R_*$	α	m_φ [GeV]	$m_{Z'}$ [GeV]
BP1	0.5	0.006	0.75	12.54	0.4771	342.34	0.055	0.375
BP2	1	0.006	0.75	22.54	0.7729	522.85	0.110	0.750
BP3	10	0.006	0.75	193.87	1.399	463.12	1.10	7.50
BP4	1	0.010	0.86	38.03	0.8804	102.16	0.144	0.862



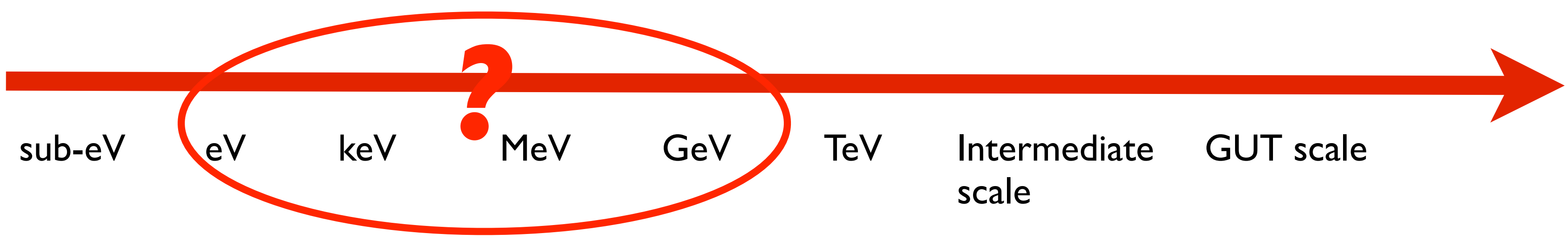
Costa et al., 2501.15649

There is a distinct phenomenology associated: the dark scalar is much lighter than the dark photon with important exp implications.

Conclusions

We know that the SM incomplete (3 pillars+ GW?). What is the New SM?

Many new ideas exploring different mass scales: neutrino masses, sterile neutrinos, DM, axions, dark sectors,…



Conclusions

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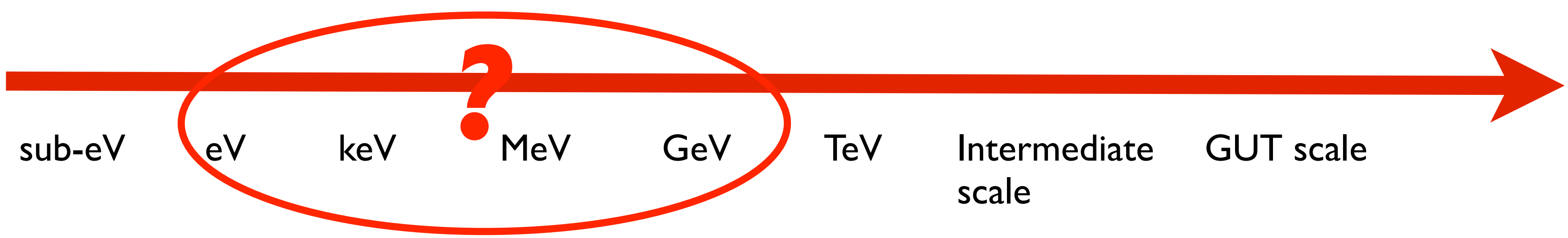

Maybe the new physics is just round the corner and might have a complex structure as the SM, with important phenomenological implications for their searches.
Neutrinos play a key role in their exploration.