Neutrinos and rich dark sectors: the quest for the origin of neutrino masses

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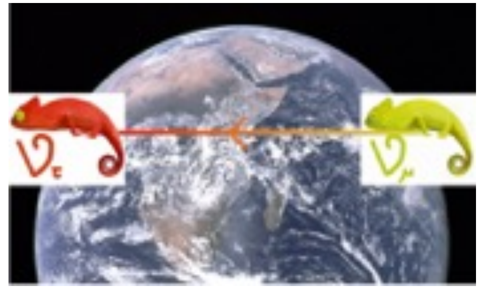
Neutrino masses



Where do they come from?

Physics BSM

Low E BSM: Dark sectors

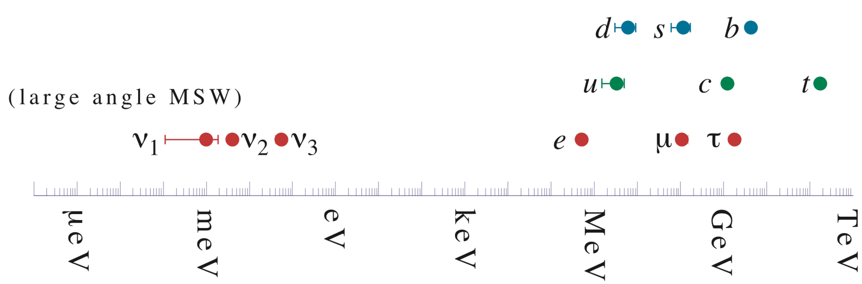
High E BSM (GUT)

Special role of neutrinos in uncovering physics BSM.

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?

What is the new physics scale?

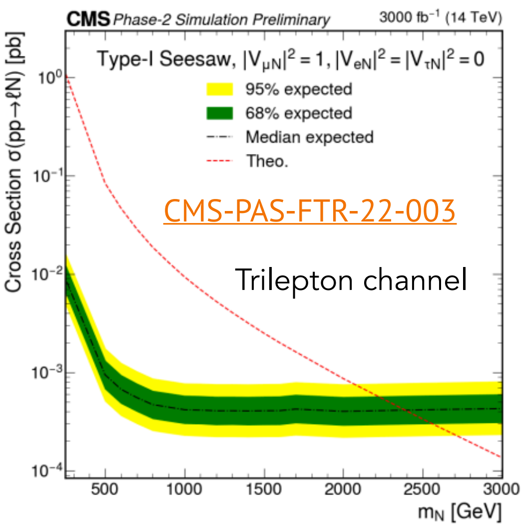
Are there new:
symmetries?
particles?
interactions?

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

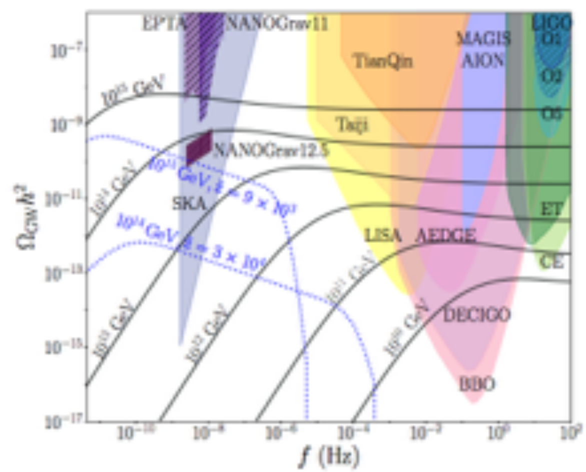
LLP searches

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…

Sterile nu oscillations

light DM

Leptogenesis

HNL searches: peak, kinks, decays,

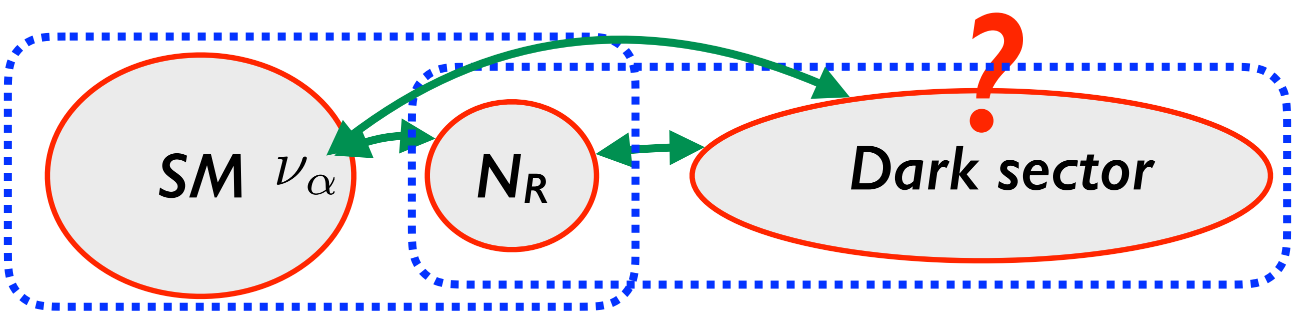
Recently, a strong theoretical effort has been done together with a blooming of experimental opportunities at the intensity frontier.

See e.g. Artuso et al., 2210.04765, S. Gori et al, 2209.04671, FIPs 2023 report, 2305.01715

The dark sector can interact with SM via portals:

- the kinetic mixing portal (dark photons);
- the scalar portal (dark scalar);
- the neutrino portal (heavy neutral leptons);
- the axion portal (axion).

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	$y_N LHN$



After symmetries breaking, the dark neutral fermions, HNLs and SM neutrinos will mix.

Neutrino masses BSM at low scales

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

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

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

In see-saw models, lowering the Yukawa couplings it is possible also to lower the N mass scale, making it exp reachable.

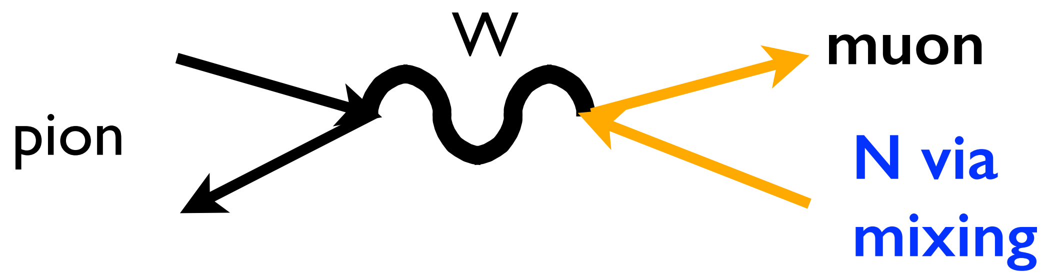
The mixing angle remains rather small:

$$\sin^2\theta \sim \frac{m_D^2}{M_N^2} \sim \frac{m_\nu}{M_N}$$

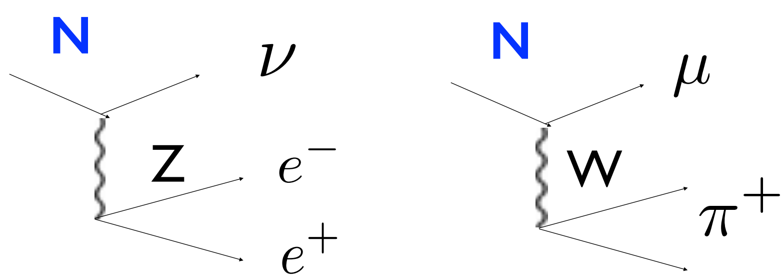
making searches very challenging.

In minimal models, HNL production and decay is controlled by the mixing with SM neutrinos.

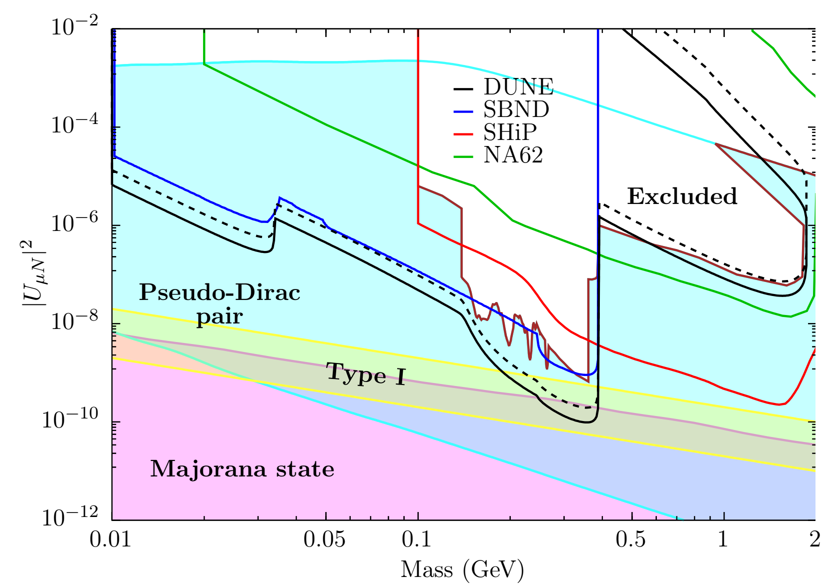
Production in e.g. neutrino experiments:



Decays:

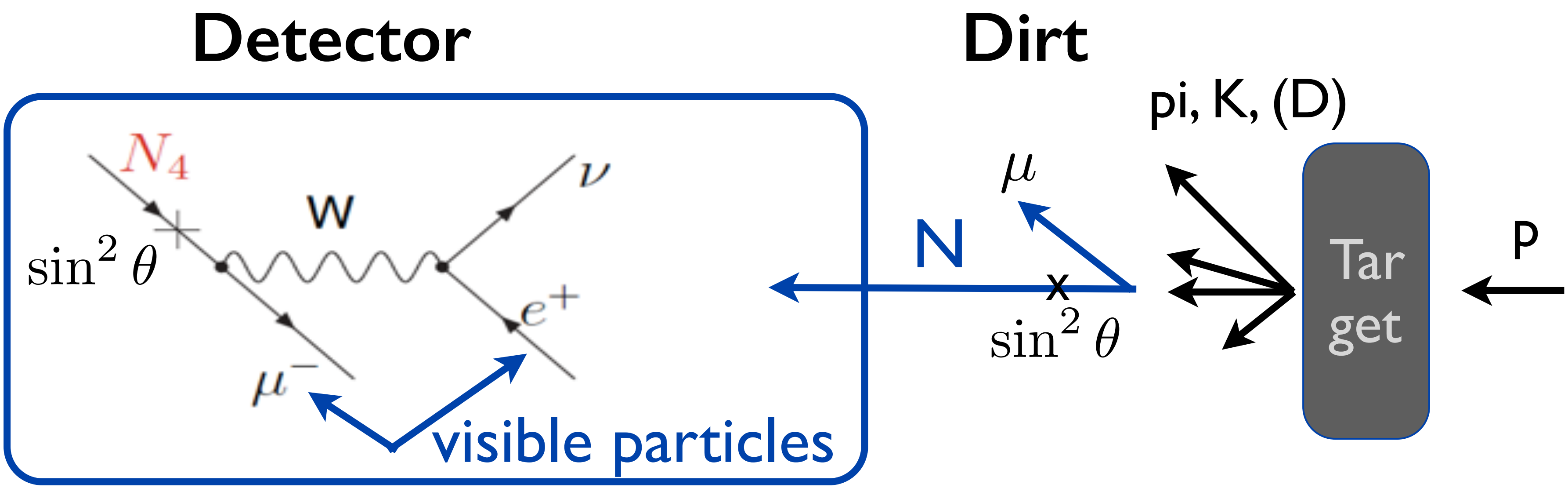


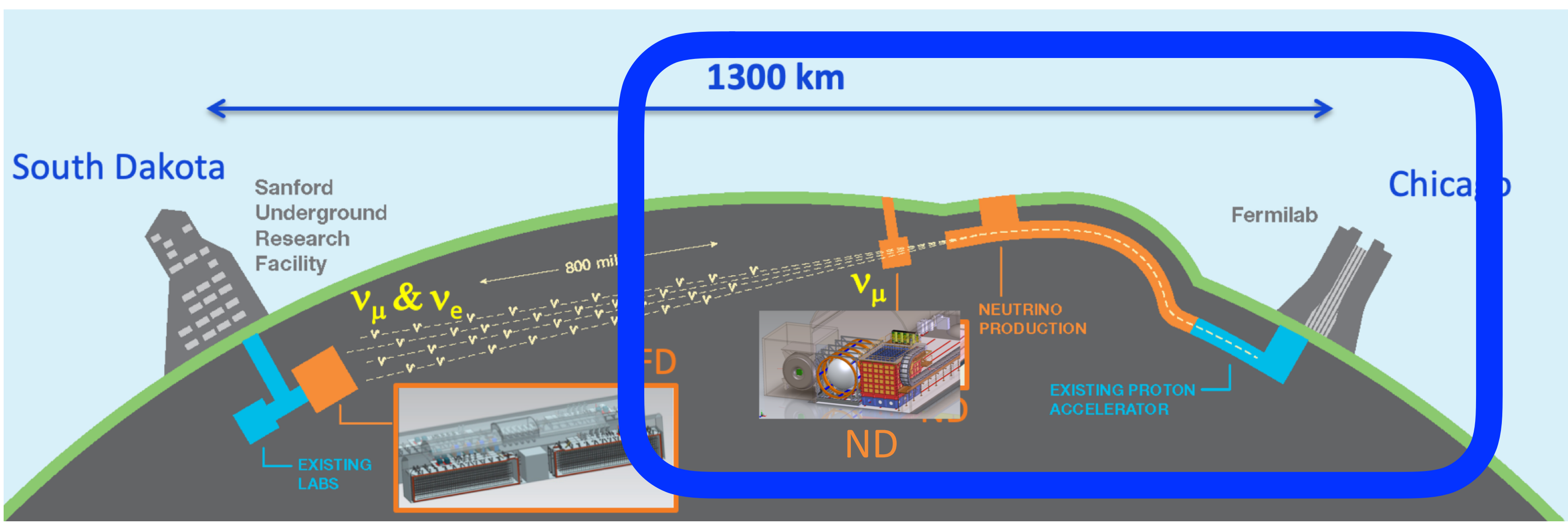
As the mixing is small and the Z, W very heavy, decays are typically very slow.

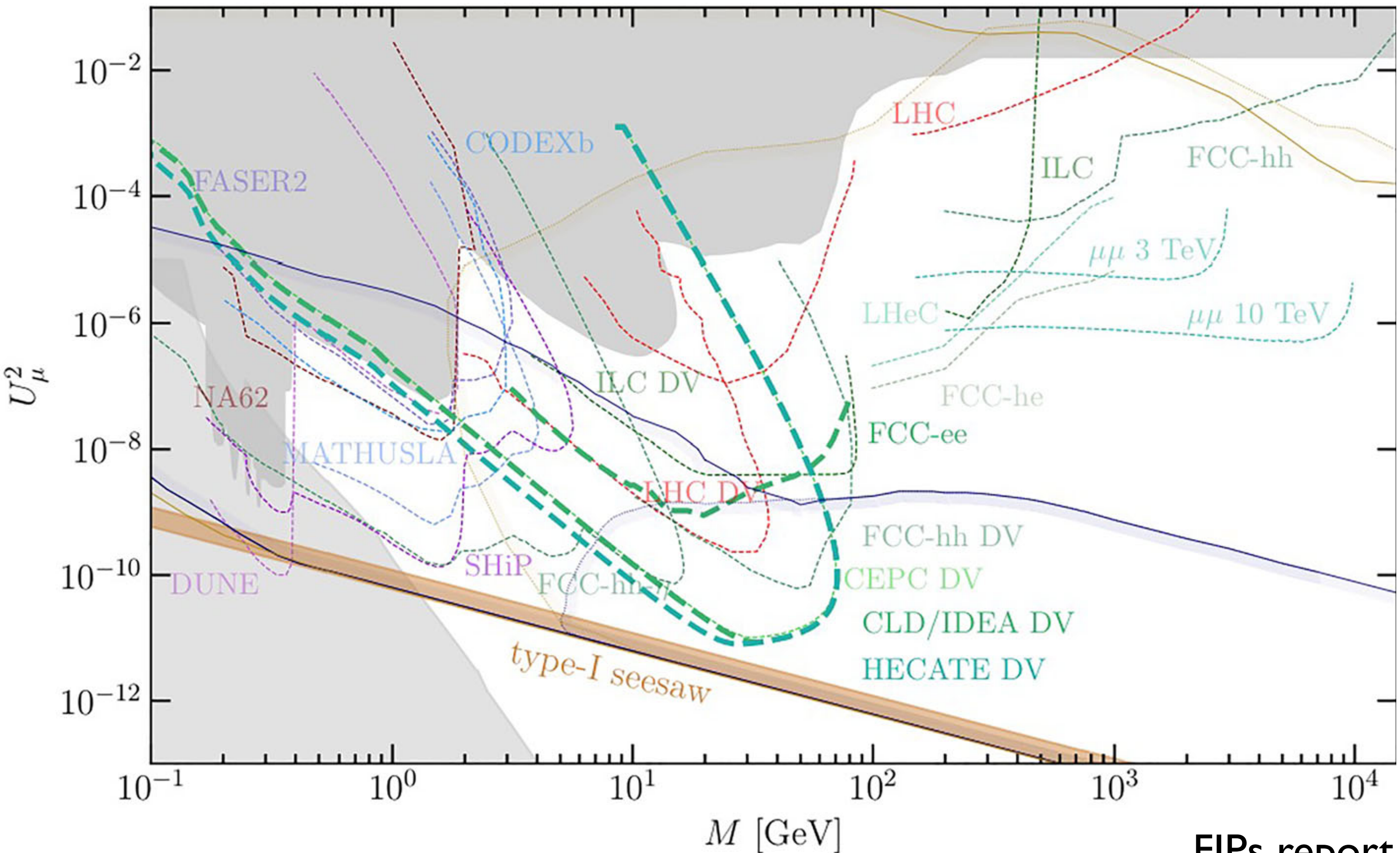


Ballett, Boschi, SP, 1905.00284

“A la beam dump” or fixed target experiments







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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.

Extensions of the see saw mechanism

Models in which it is possible to lower the mass scale, keeping large Yukawa couplings have been studied.

Let's introduce two right-handed singlet neutrinos.

$$\mathcal{L} = Y\bar{L}\cdot H N_1 + Y_2 \bar{L}\cdot H N_2^c + \Lambda \bar{N}_1 N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2$$

$$\begin{pmatrix} 0 & Yv & Y_2 v \\ Yv & \mu' & \Lambda \\ Y_2 v & \Lambda & \mu \end{pmatrix}$$

See e.g. Gavela et al., 0906.1461; Ibarra, Molinaro, Petcov, 1103.6217; Kang, Kim, 2007; Majee et al., 2008; Mitra, Senjanovic, Vissani, 1108.0004; Malinsky, Romao, Valle, 2005

$$m_{tree} \simeq -m_D^T M^{-1} m_D \simeq \frac{v^2}{2(\Lambda^2 - \mu'\mu)} \left(\mu Y_1^T Y_1 + \epsilon^2 \mu' Y_2^T Y_2 - \Lambda\epsilon(Y_2^T Y_1 + Y_1^T Y_2)\right)$$

Small neutrino masses emerge due to cancellations between the contributions of the two sterile neutrinos (typically associated to small breaking of some L).

Two limits:

- Inverse see-saw: $\Lambda \gg \mu, Y_2 v, \mu'$

Gavela et al., 0906.1461; Ibarra, Molinaro, Petcov, 1103.6217

Two quasi-Dirac neutrinos with large mixing:

$$m_4 \approx -m_5 \approx \tilde{M}_1 \approx -\tilde{M}_2 \approx \Lambda, \qquad U_{e4} \approx U_{e5} \approx Y_{1e} v / 2\Lambda,$$

$$\Delta\tilde{M} \equiv |\tilde{M}_2| - |\tilde{M}_1| \approx \mu',$$

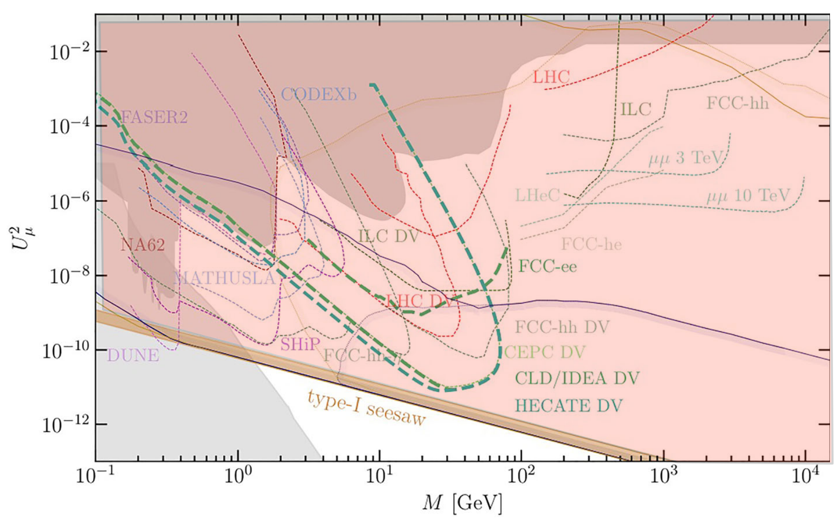
- Extended see-saw: $\mu' \gg \Lambda, \mu$

Kang, Kim, 2007; Majee et al., 2008; Mitra, Senjanovic, Vissani, 1108.0004

One light and one heavy sterile neutrino:

$$m_4 \approx \tilde{M}_1 \approx -\Lambda^2/\mu', \qquad U_{e4} \approx Y_{1e} v / \sqrt{2}\Lambda$$

$$m_5 \approx \tilde{M}_2 \approx \mu', \qquad U_{e5} \approx Y_{1e} v / \sqrt{2}\mu'$$



The all parameter space for larger U^2 becomes theoretically viable.

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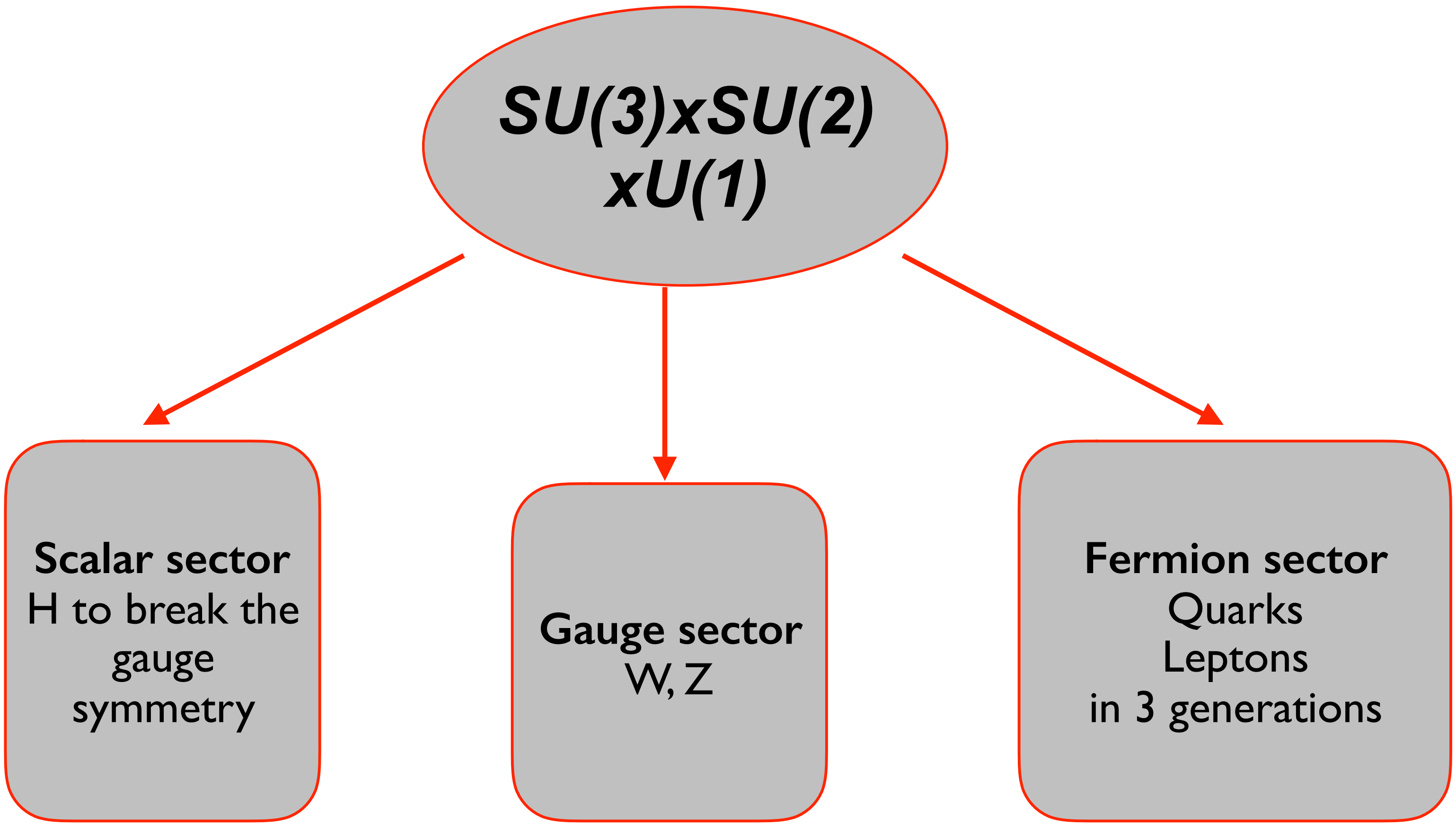
Changing the paradigm

Rich dark sectors

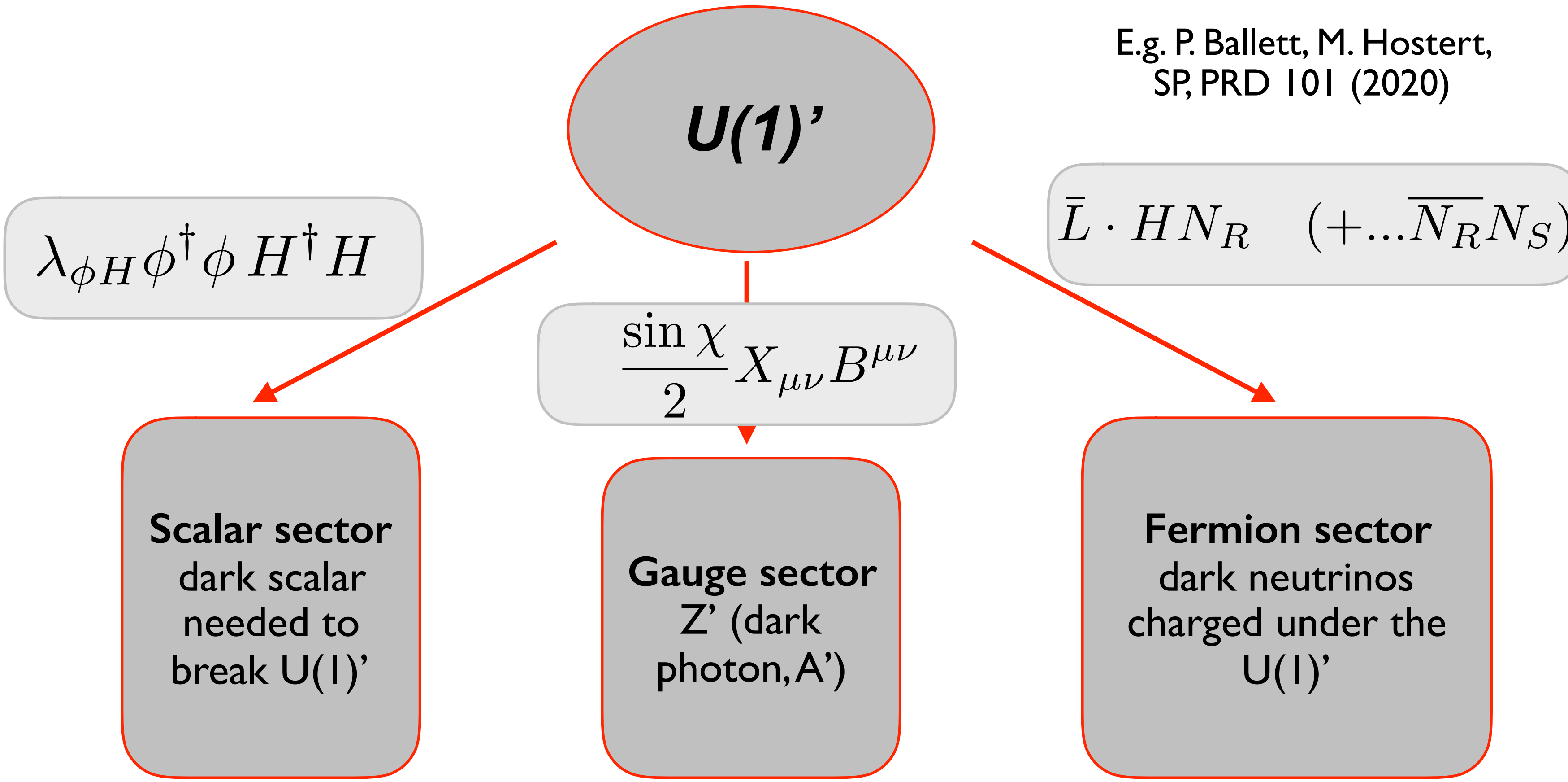
Two contrasting approaches can be taken:
Minimality: the fewest ingredients -> predictivity
Richness: connections, new signatures

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)



This type of structure is typical of rich dark sectors, that contain multiple particles and interactions.

A concrete example: the 3-portal model

The Lagrangian is given by

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

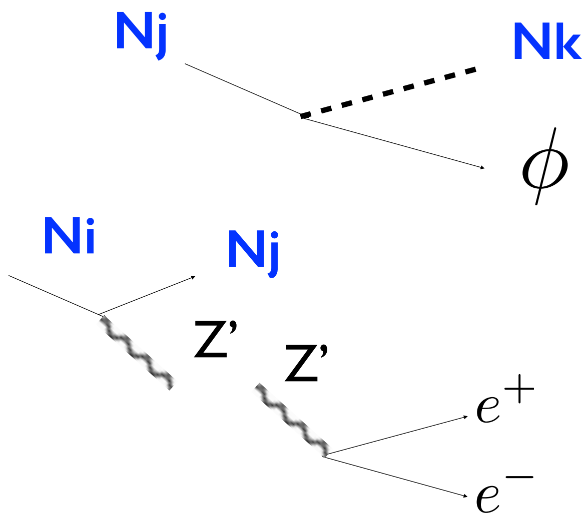
A. Abdullahi, M. Hostert, SP, 2007.11813

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

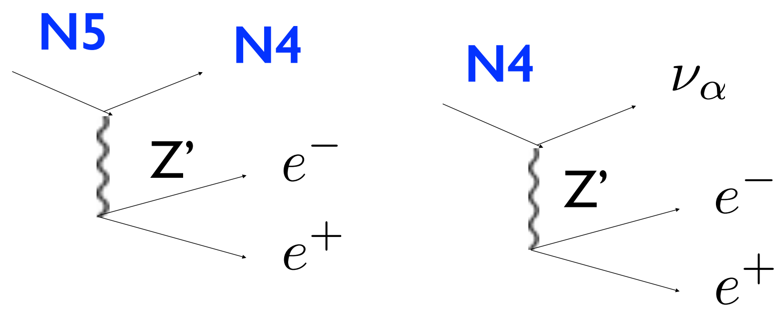
Neutrino masses emerge as discussed earlier.

New HNL phenomenology

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.

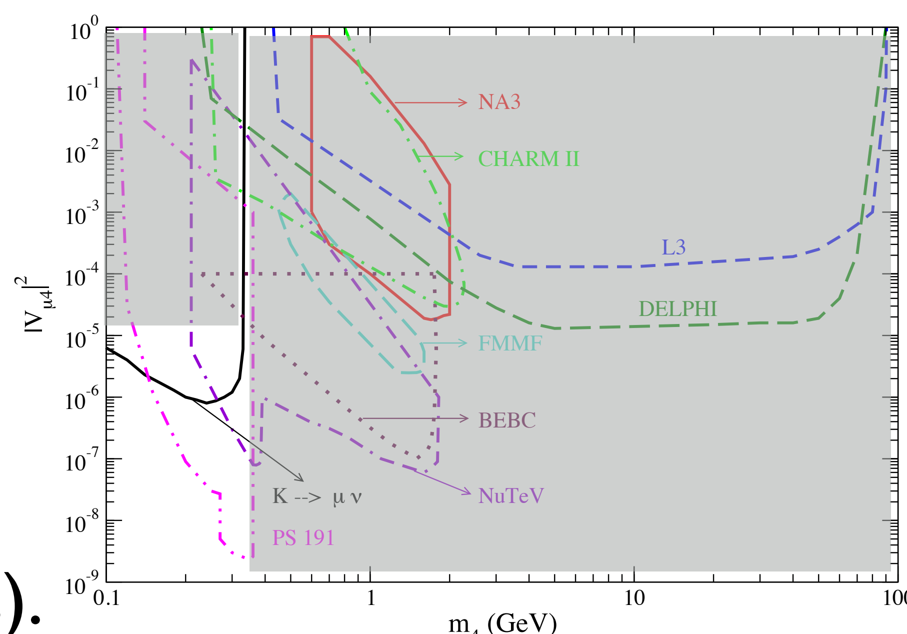


Fast visible and invisible decays



decay chains

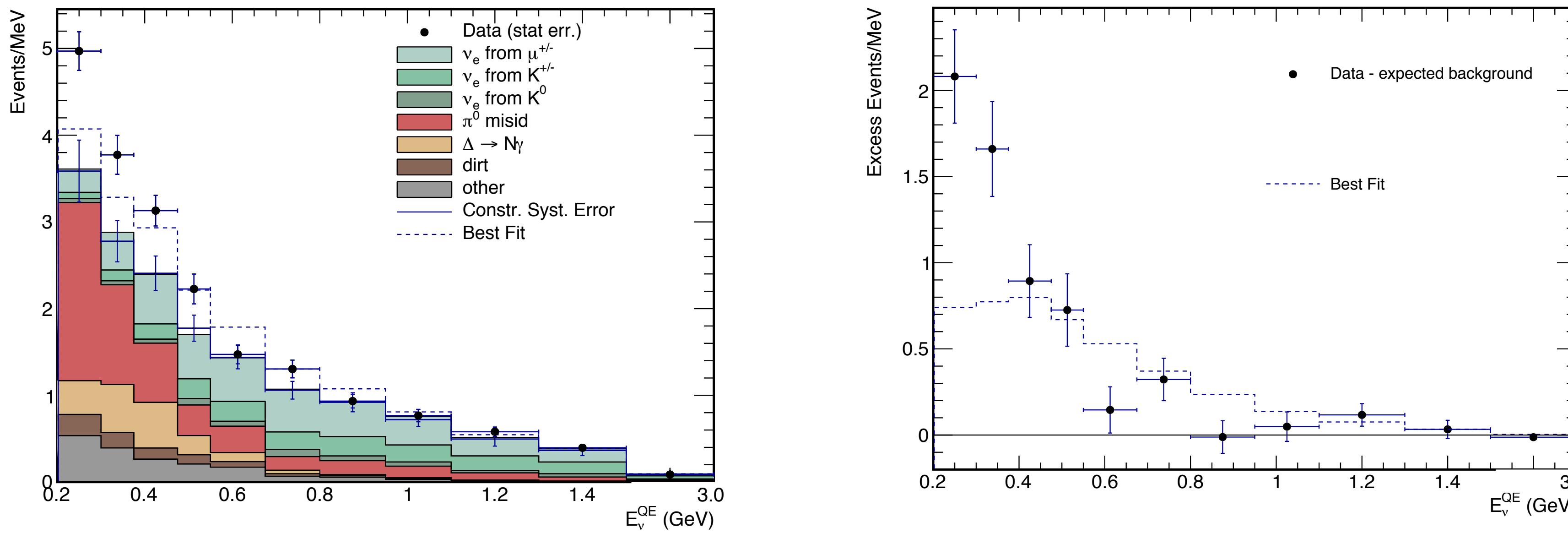
HNL decay bounds need to be reevaluated and they may not apply (e.g. beam dump experiments).



Adapted from Atre et al. 2009

New exp signatures

MiniBooNE low-E excess: due to the WC nature of MB, single electrons can be mimicked by photons and by electron-positron pairs (if overlapping or asymmetric).



MiniBooNE Coll., PRL 121 (2018)

Up-scattering of an HNL N in the detector and its decay into ee nu can provide a possible explanation.

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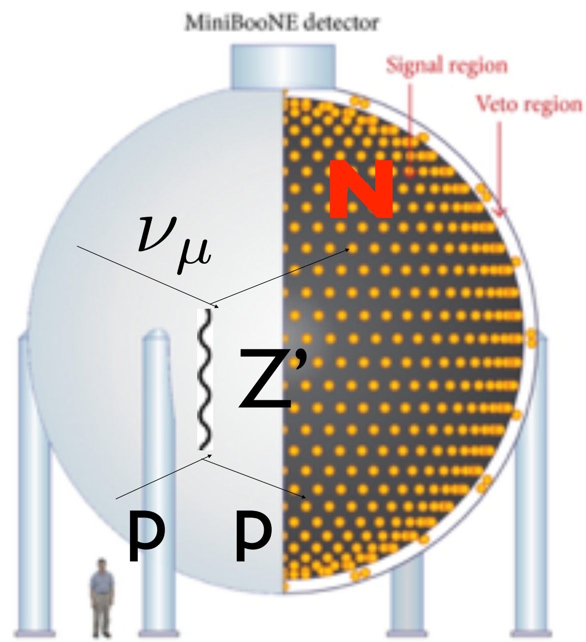
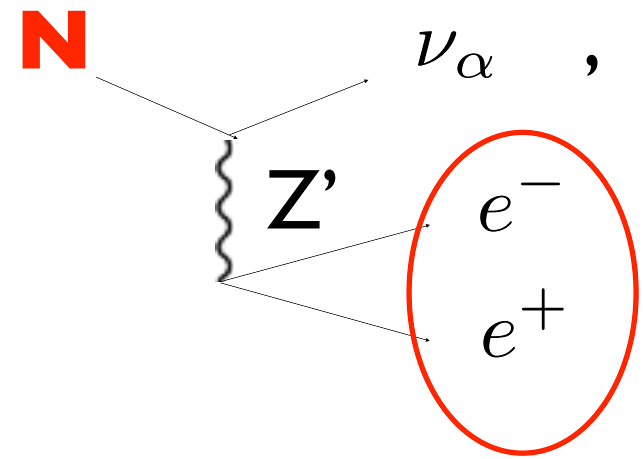
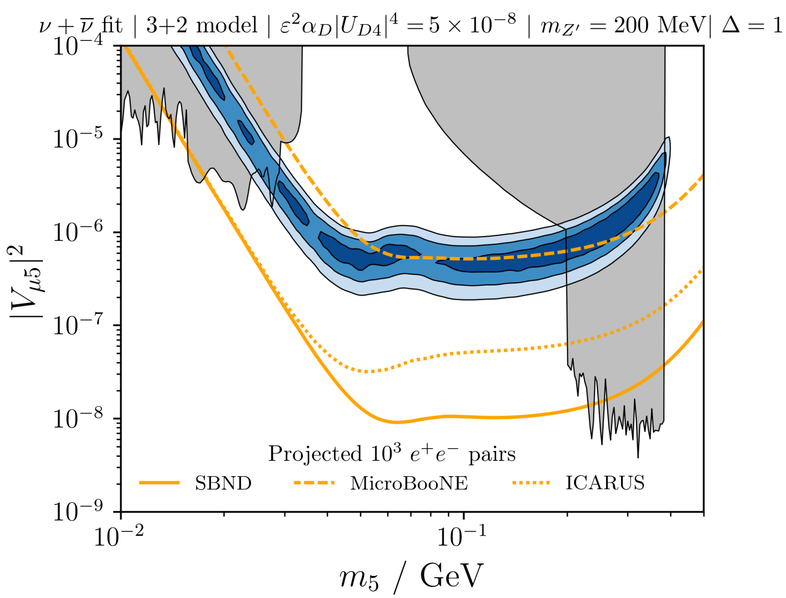
See also S. Gnineko, PRL 103 (2009), E. Bertuzzo et al., PRL 121 (2018).

ν_μ



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



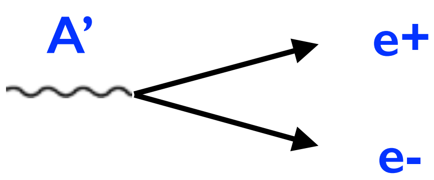


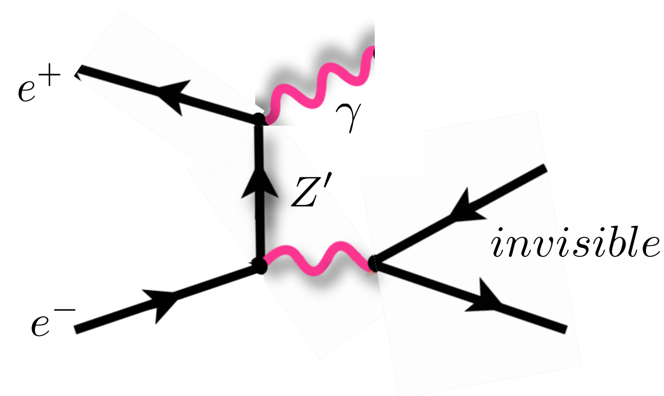
Potentially, strong bounds from ND280 in T2K. New results from MicroBooNE which disfavour part of the parameter space.

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

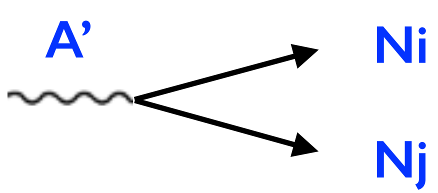
New dark photon phenomenology

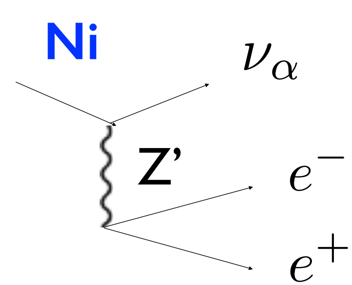
The bounds on A' are from collider (BaBar, Belle), electron and proton beam dump experiments and fixed-target ones, for visible or invisible decays.



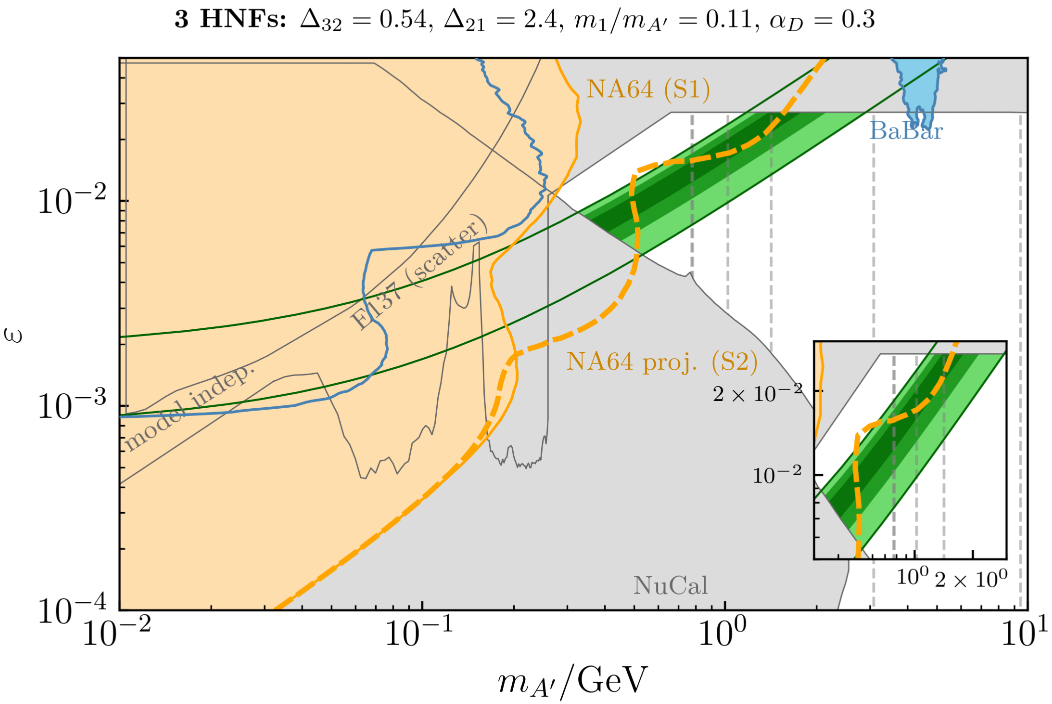


In RDS models, typically dark photons decay fast in the dark particles that subsequently decay semivisibly.





Cuts on visible and invisible energy hide the signal.



Bounds need to be reconsidered.

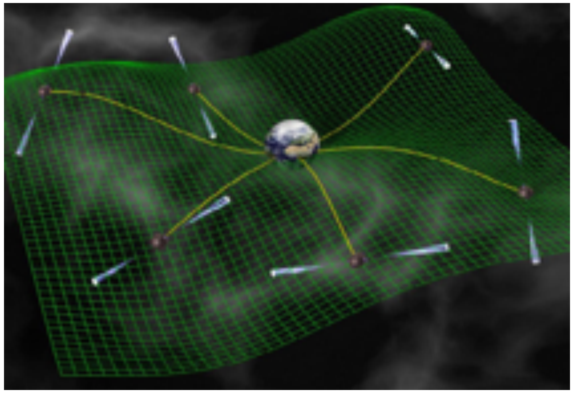
Abdullahi, Hostert, Massaro, SP, 2302.05410

See also, G. Mohlabeng, PRD99 (2019)

Our current FIPs/DS programme may not be well suited for this type of searches and might miss a dark sector which is non-minimal.

Crucial: Add to standard case also these additional type of searches, exploiting the rich exp facilities.

New dark scalar phenomenology

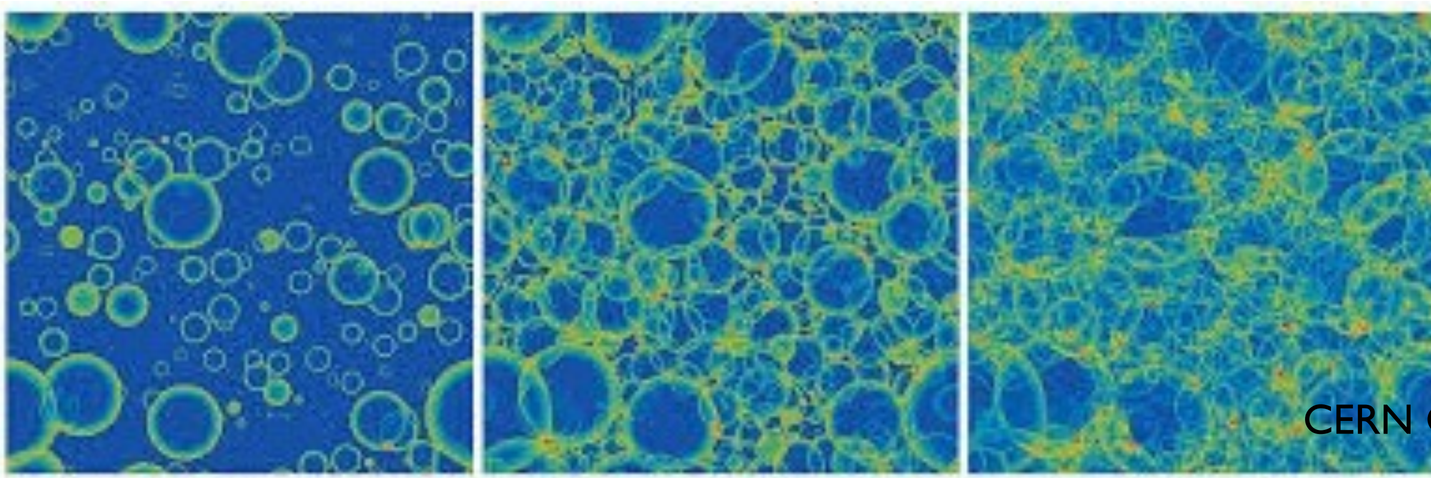


Dark scalars and photons: FOPT and PTA GWs

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

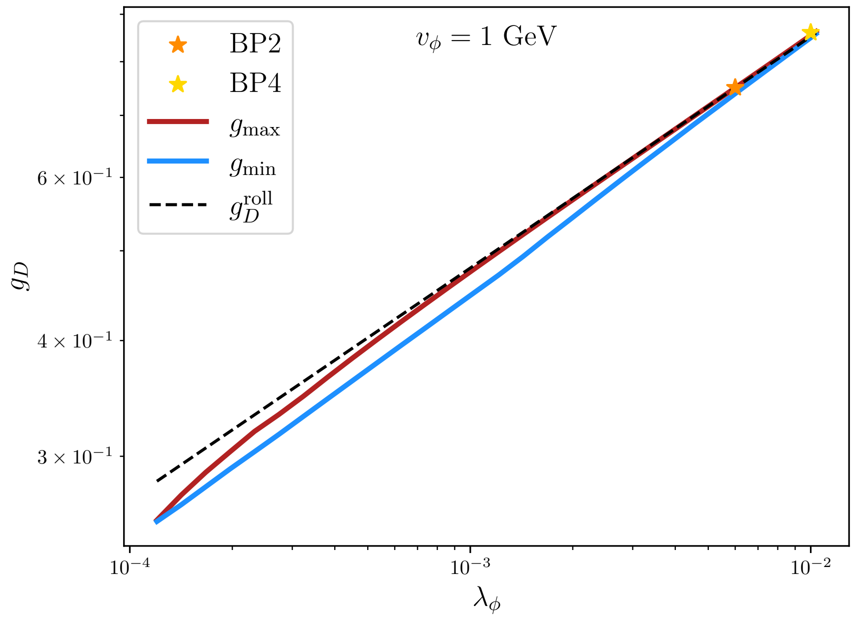
A FOPT proceeds via nucleation of bubble of true vacuum. They grow ultimately filling all the Universe.

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



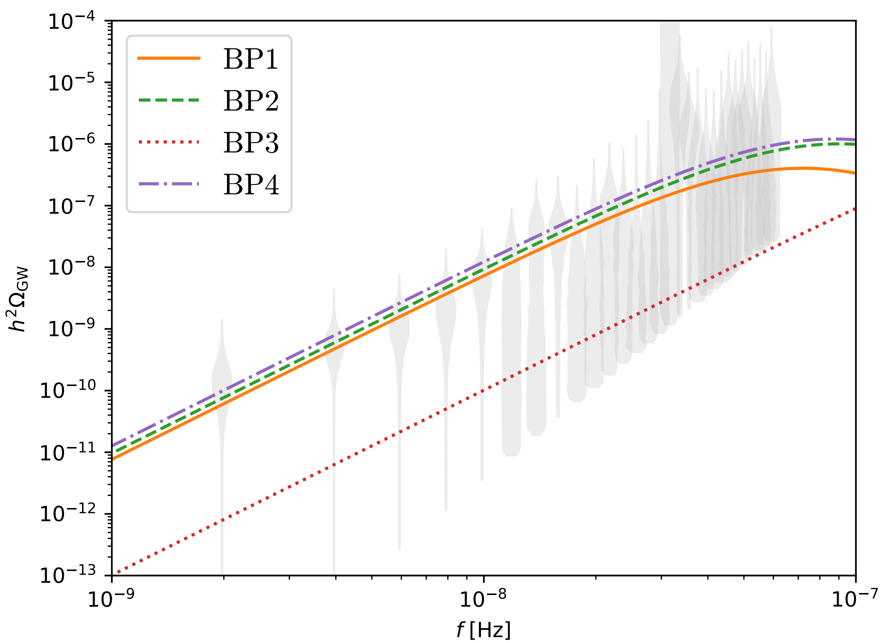
$$g_D^{\rm roll} = \left\{ \frac{16\pi^2 \lambda_\phi}{3} \left[1 - \frac{\lambda_\phi}{8\pi^2} (5 + 2\log 2) \right] \right\}^{1/4}$$

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

Between $g_{\rm max}$ and $g_{\rm min}$ 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

Neutrinos are the most elusive and mysterious of the known particles. Neutrino masses are so far the only particle physics evidence BSM.

Current status: precise knowledge of most of neutrino properties. Key questions open (nature, CPV) due to be answered in the next decade. Thriving experimental programme.

The key question is: What is the origin of neutrino masses?

What is the new physics scale? This BSM can be as high as GUT or as low as the eV. Are neutrinos pointing towards a new understanding of particles: rich dark sectors?