Dark matter and flavour

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IP2I – CNRS

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Outline

Introduction: from WIMP to light dark matter

Portals, flavour and dark matter targets

Focus on fermion based portals

A key DM question: stability & relic densities

What do we know about dark matter ?

→Does not interact nor decay too much *UV insensitive !*

→We know how much there is

$$\Omega h^2 \simeq 0.12$$

Planck 2018

Interesting to classify the DM candidates following how they actually reach the required density

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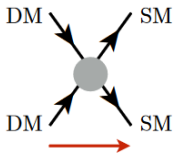
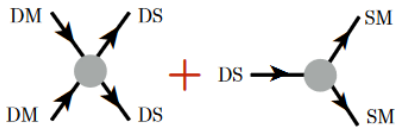


WIMP, Sub-GeV Relic, Asymmetric variants

Dark sector FO



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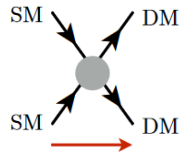
Freeze-in & friends



freeze-in, sterile-neutrino, superWIMP

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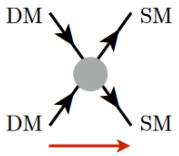

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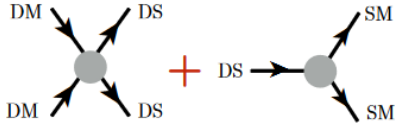

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Was it produced from the SM thermal bath ?

Abundance from another mechanism (e.g. misalignement)

No

Yes

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Yes !

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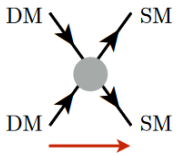

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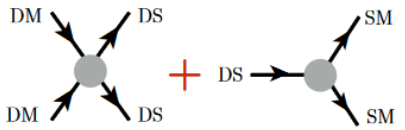

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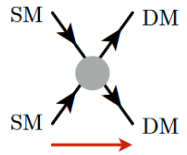

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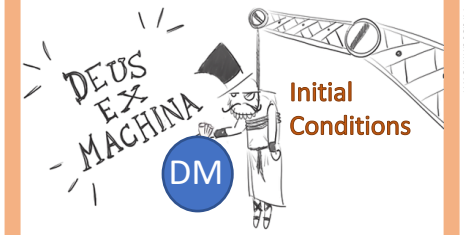
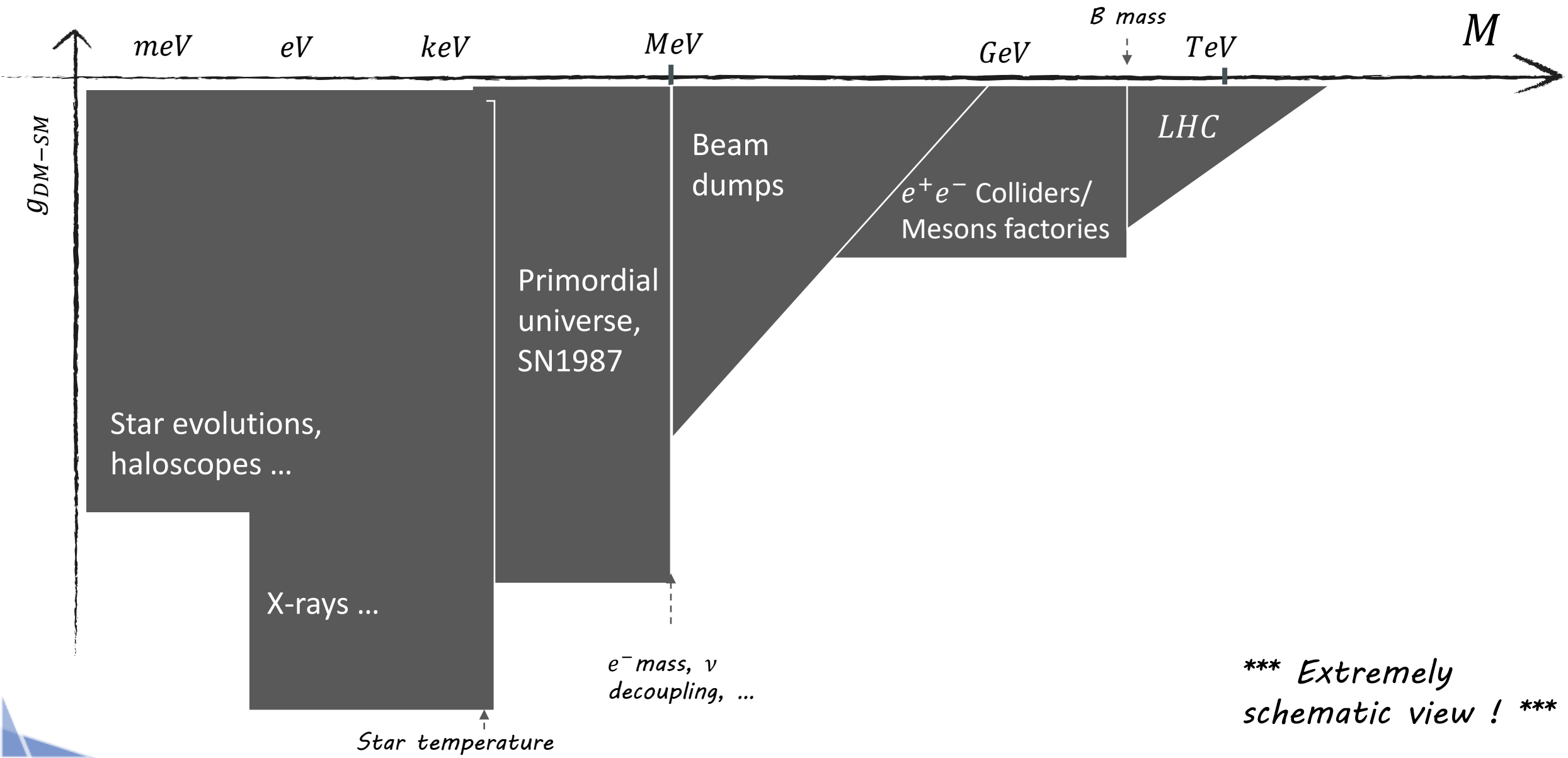
Axions & friends



QCD axion, ALP, WIMPZILLA, late decays, primordial BH

Dark matter and how to produce it



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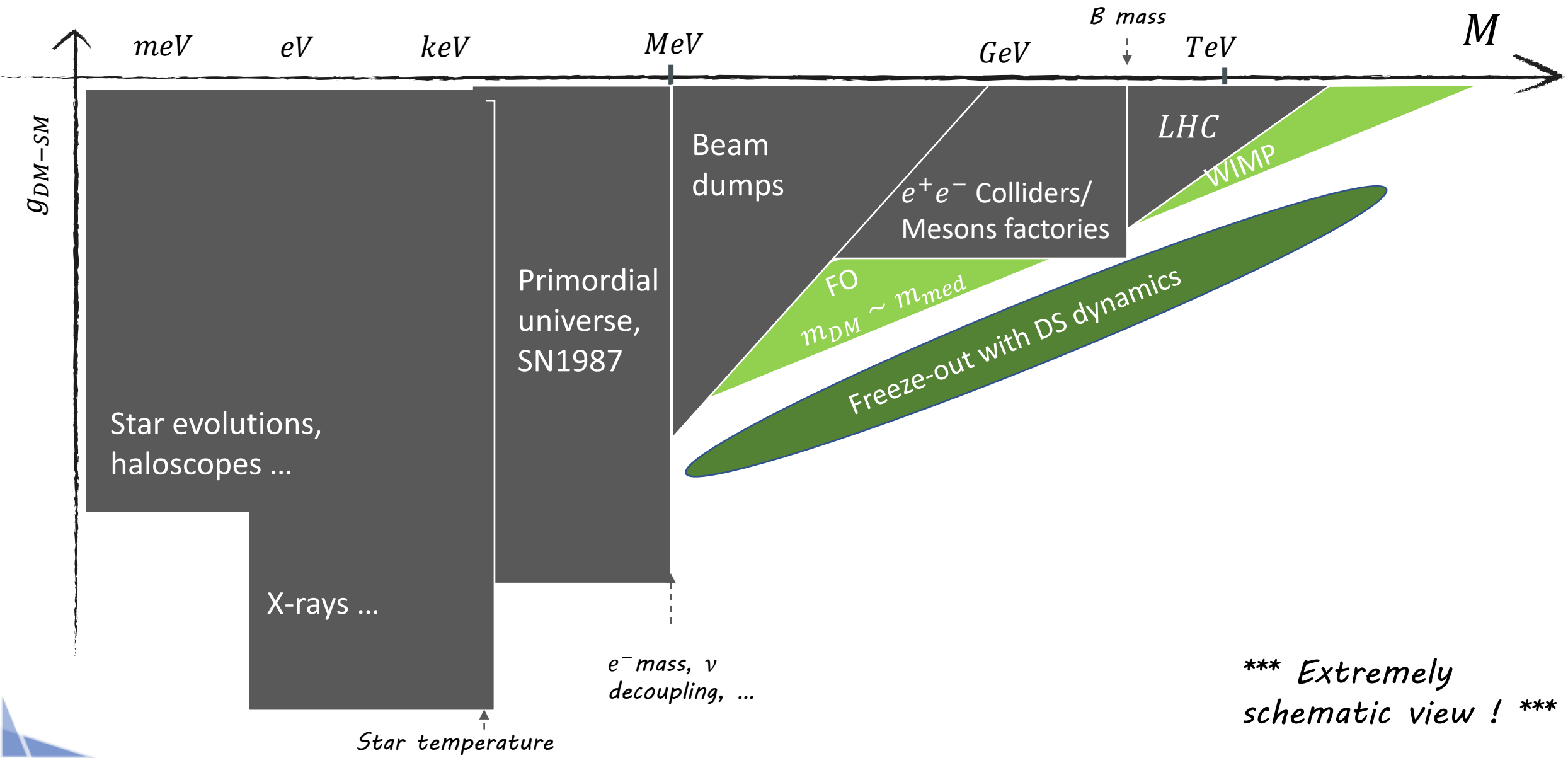

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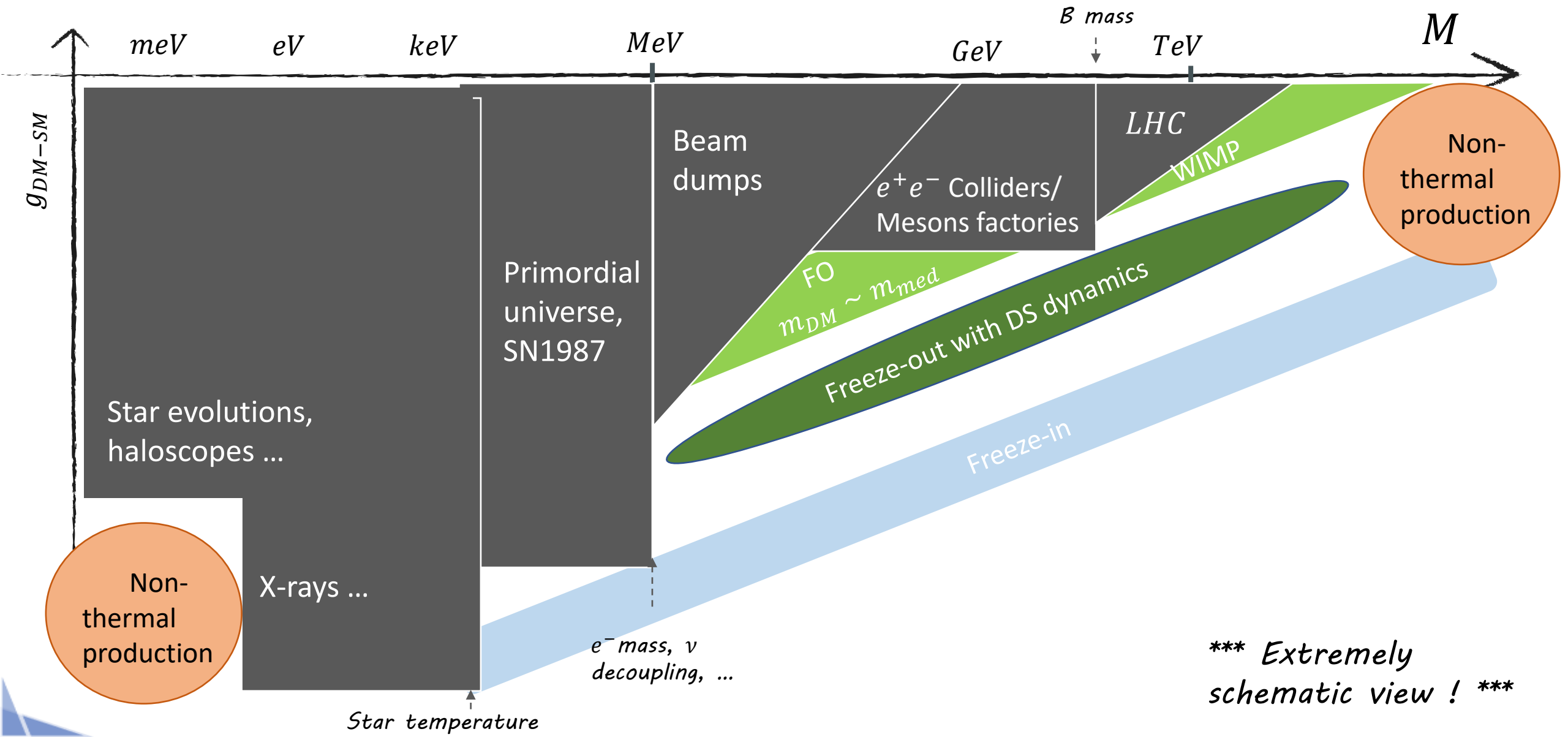

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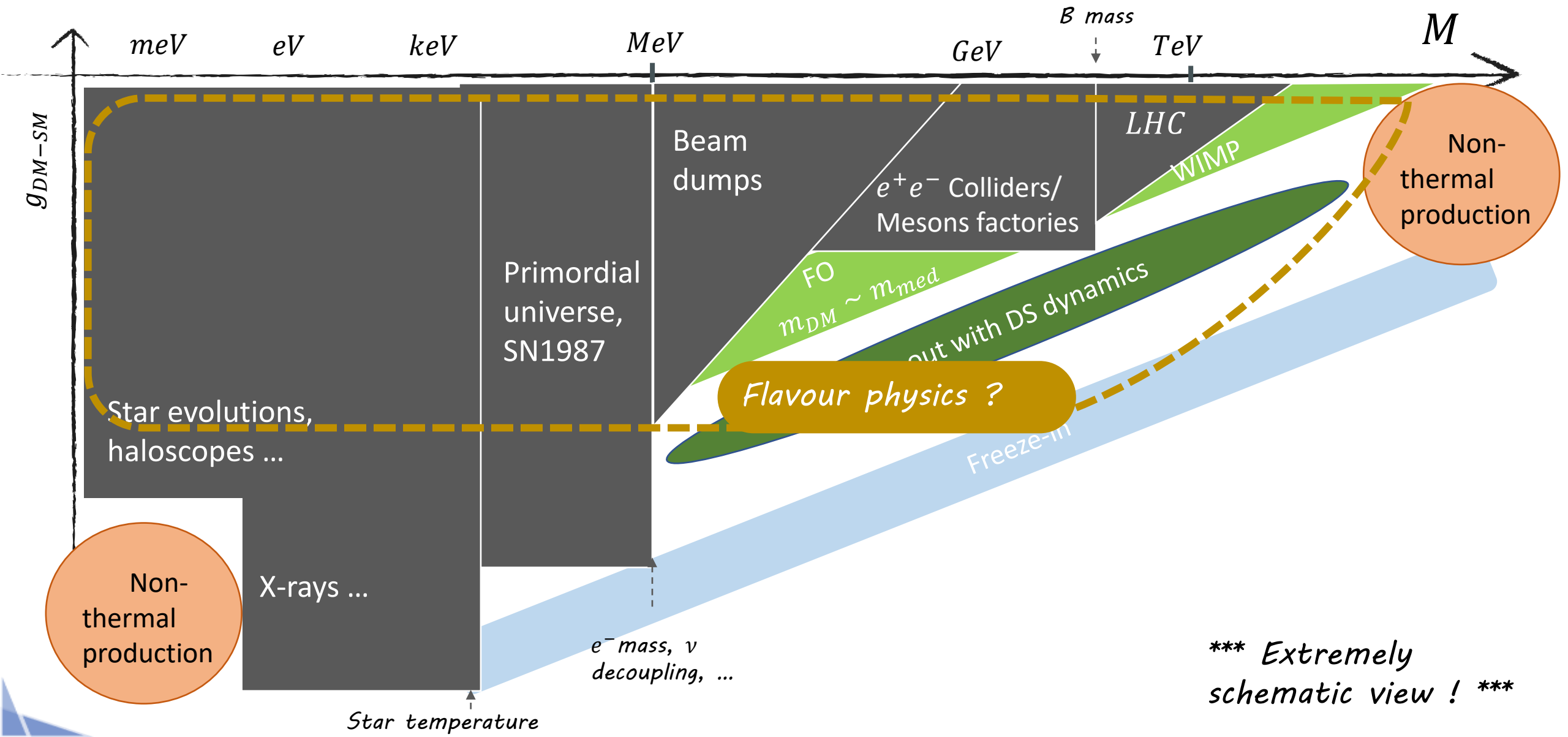
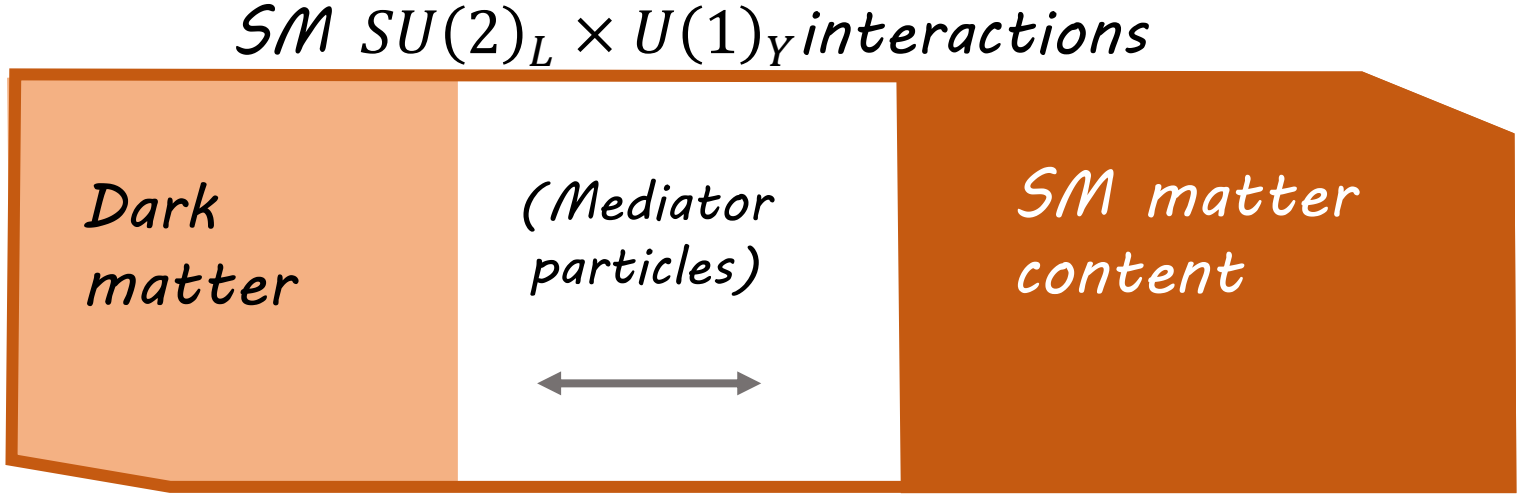


From WIMP and FDM…

- WIMP idea: DM (and other relevant particle for annihilation are at the weak scale and interact with the SM gauge groups)



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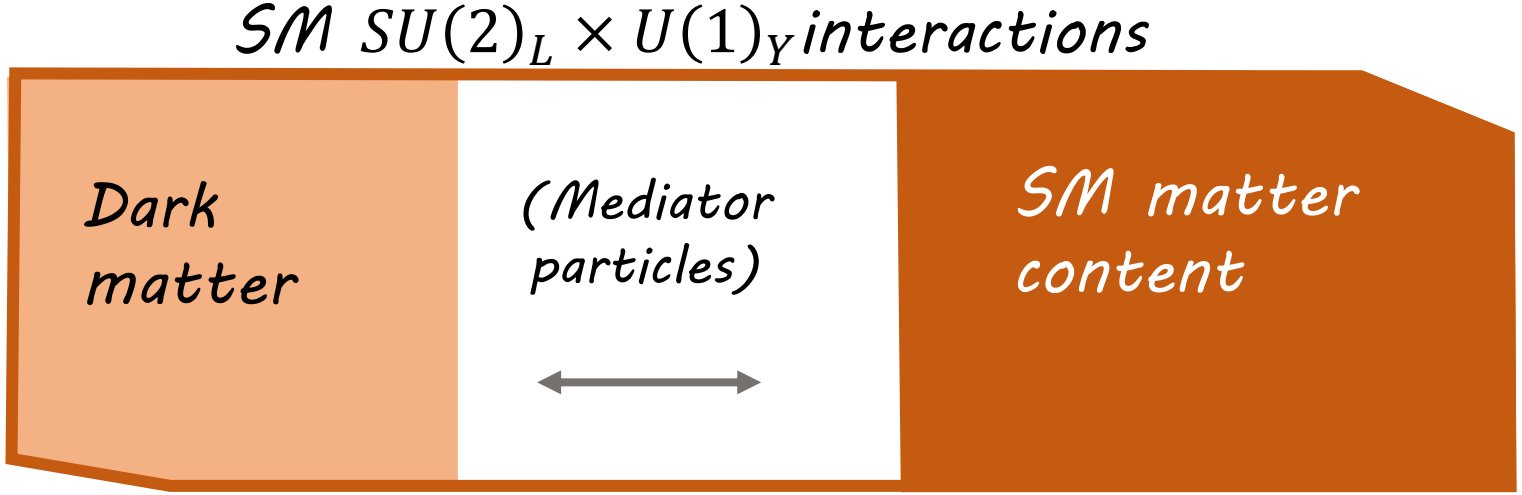


- Allow for a rich flavour structure (as relic density can be obtained from EW interaction anyway): Flavour Dark Matter (ie DM with a flavour index)

  →Typical SUSY / Composite like generalisation. WIMP with flavour index

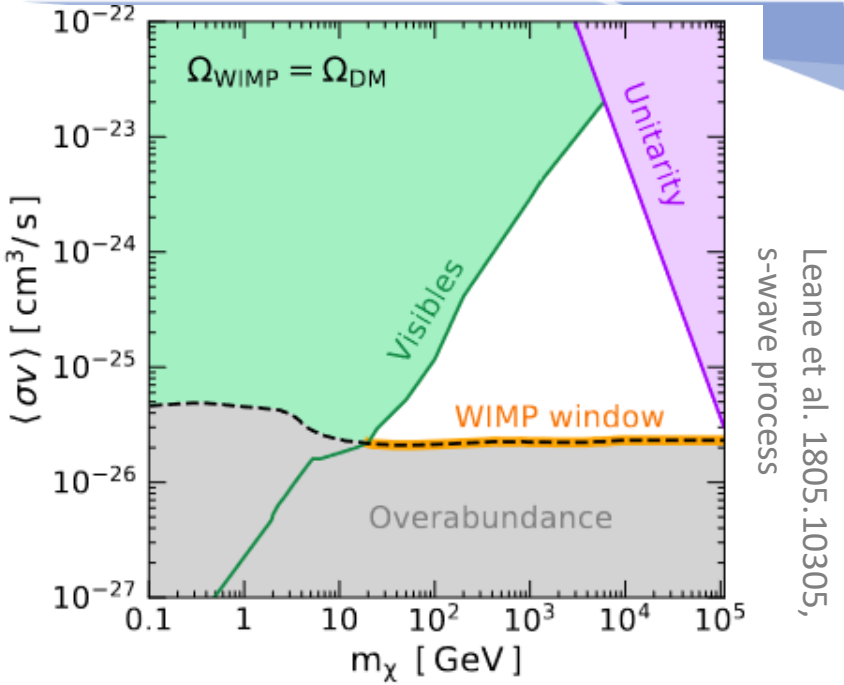
$$\mathcal{L} \supset \lambda_j{}^i \chi^j E_i^c \phi \quad \text{or} \quad \lambda_A{}^\alpha Q^A \chi_\alpha \phi \quad \ldots$$

→ Extensive works in the 2010s – 2020s (presented in previous FPCP), and rich phenomenology in flavour observables and colliders

Recent works still, by e·g· M· Blanke
2211·03809, 2212·08142, 2109·10357

…to light dark matter

- The WIMP window is constrained by, e.g. :
  - →Unitarity of its interactions
  - →Lee-Weinberg bound
  - →CMB constraints: one should not inject ionising particles at late (CMB) time



Leane et al. 1805.10305, s-wave process

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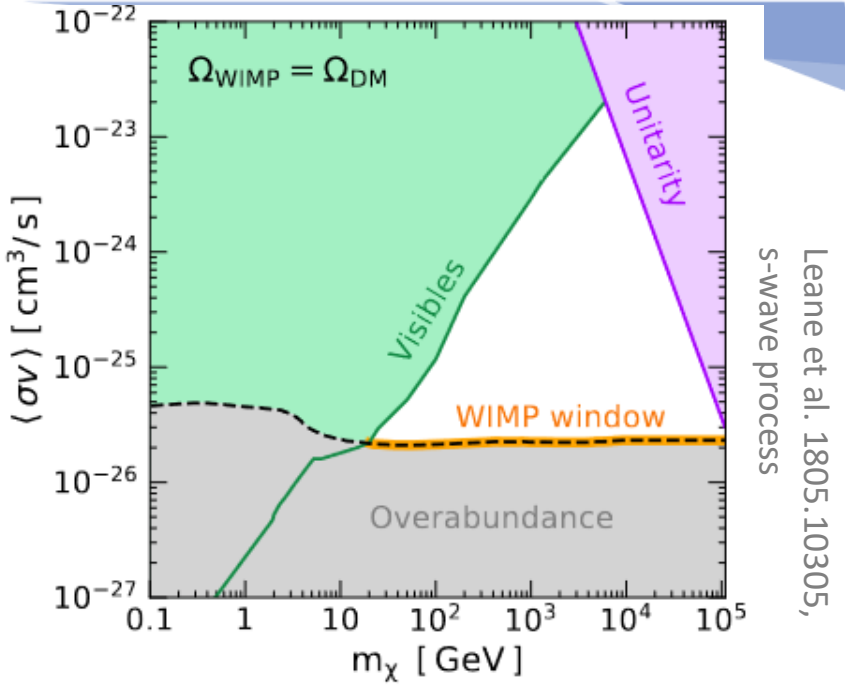
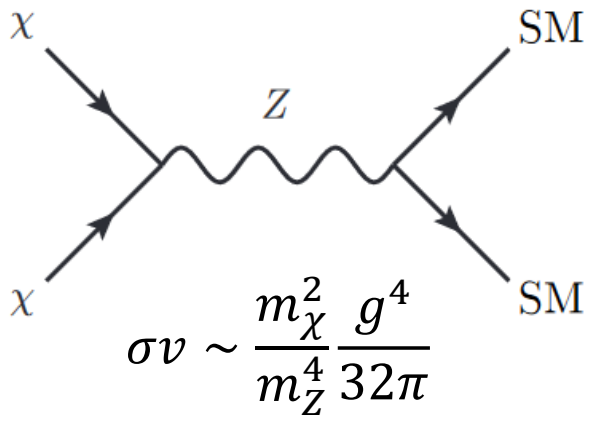
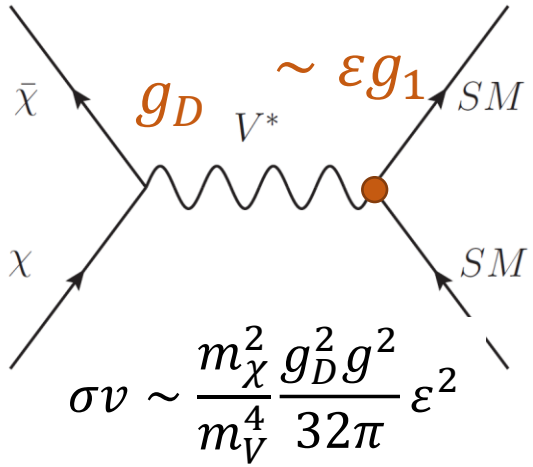


- Copying the WIMP freeze-out idea at low mass implies extending the model with a new mediator with small coupling with the SM



$(\sigma v)_{DM} \sim 4 \cdot 10^{-9}\ \mathrm{GeV}^{-2}$



Below the GeV, at $m_\chi < m_V$, need $\varepsilon < 10^{-3}$

Can be p-wave, etc…

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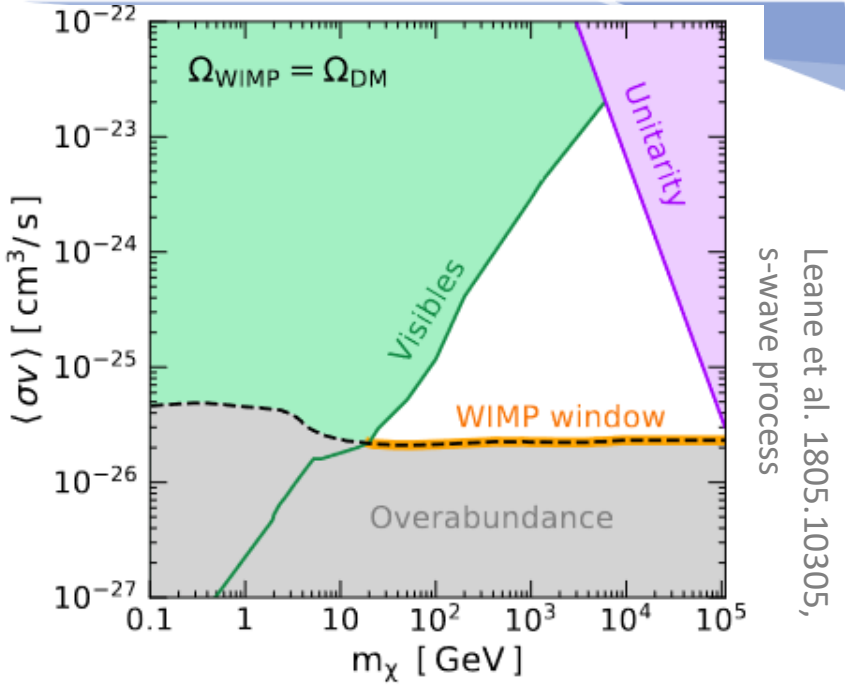

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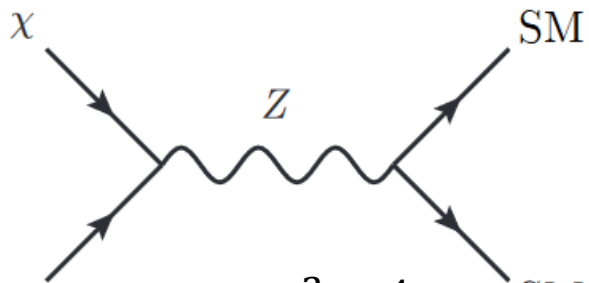

$$\sigma v \sim \frac{m_\chi^2}{m_Z^4}\frac{g^4}{32\pi}$$

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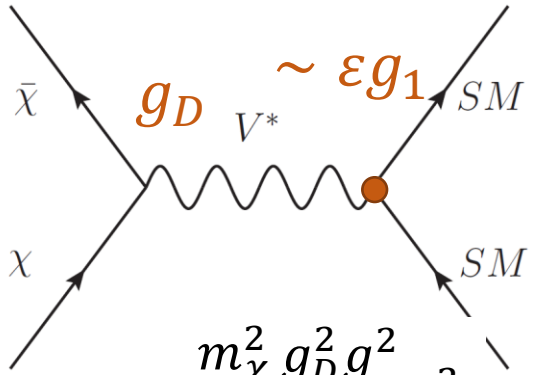
$$g_D \varepsilon \sim g \frac{m_{DM}}{m_{WIMP}}$$



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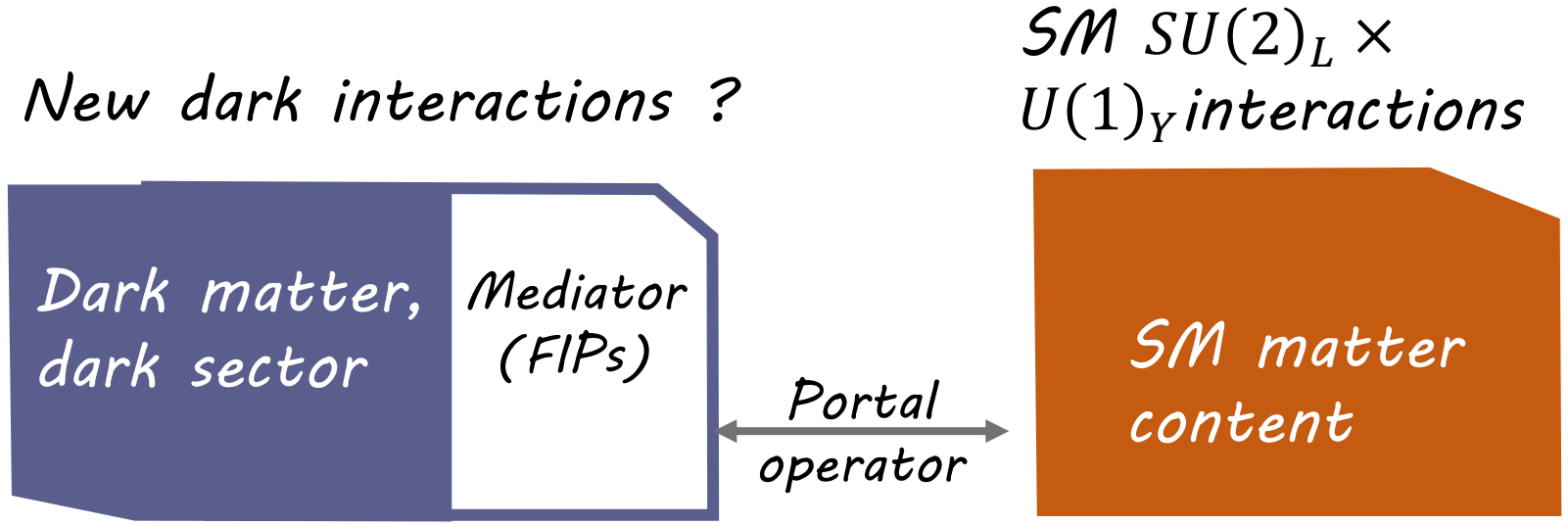
From DM properties to mediator searches

- Feebly Interacting Particles (FIPs)= "new neutral particle which interacts with the SM via suppressed new interactions"



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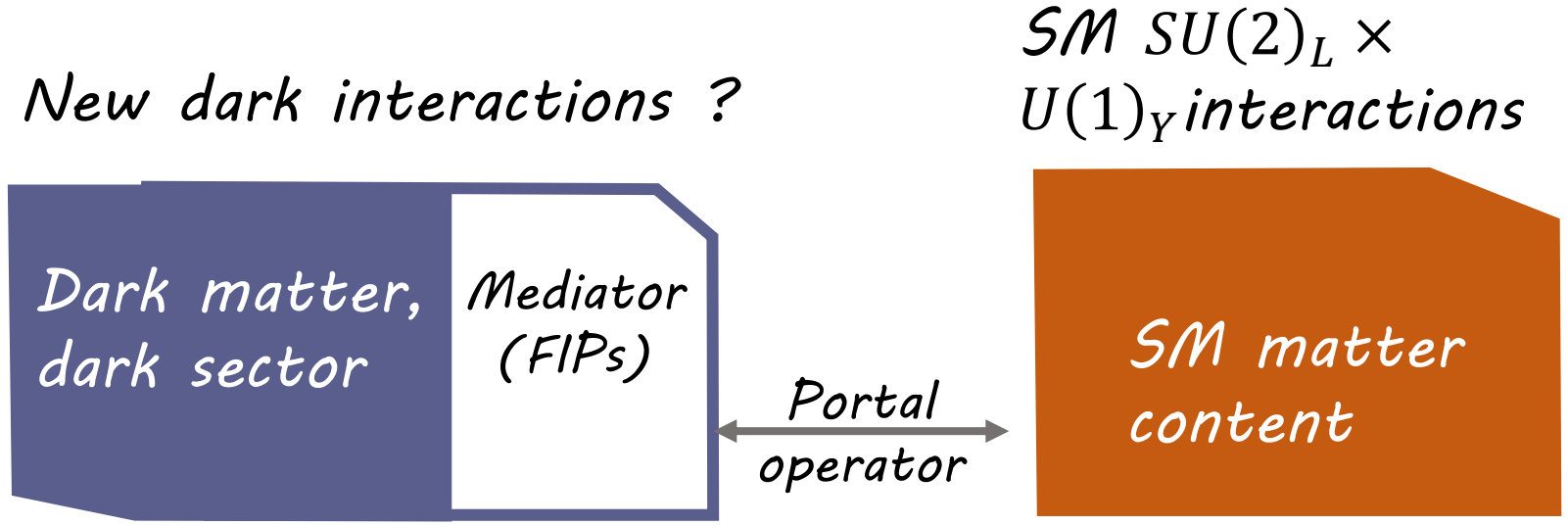
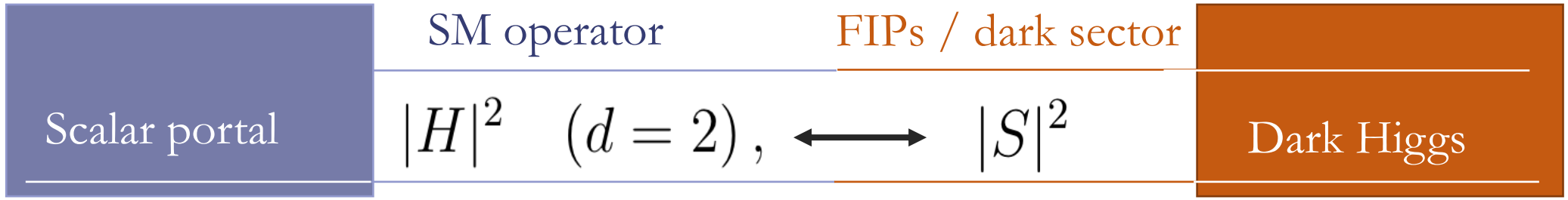


- Portal operators: parametrisation of the interactions between new neutral particle and SM (requires a gauge singlet operators built by SM fields)
- Most FIP models can be embedded in a light dark matter setup (of course with various level of complexity …)

  →Altogether an extremely rich literature of new "mechanisms" to obtain the relic density (Forbidden DM, Secluded DM, Selfish DM, Cannibal DM, etc …)

Portals, flavour and dark matter

Portal interactions: it's all about the mediator



Mixes with the standard Higgs

See Yotam Soreq's talk

DM $(\chi) \leftrightarrow S \leftrightarrow H \leftrightarrow$ SM fermions

Portal interactions: it's all about the mediator

Scalar portal	SM operator	FIPs / dark sector	Dark Higgs
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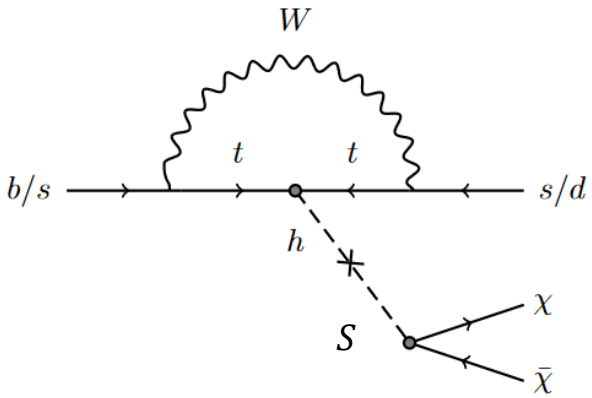
→ Light new scalars inherit the SM Higgs flavourful couplings



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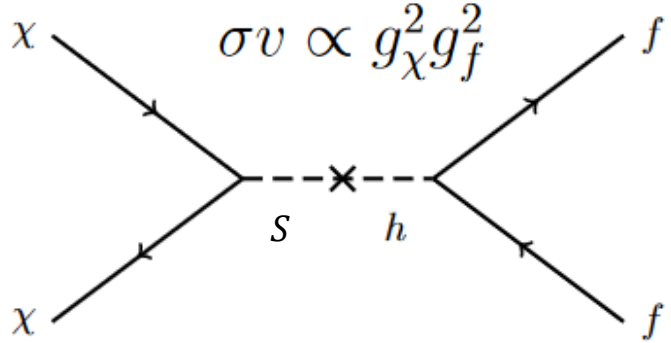

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$(m_S > m_\chi)$

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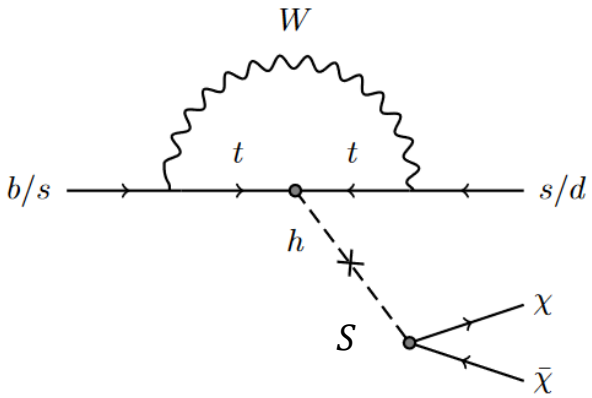

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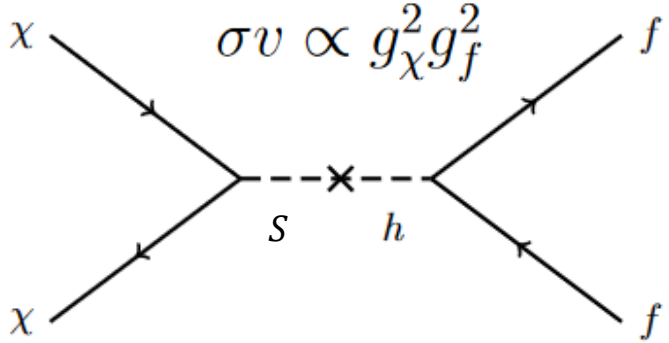

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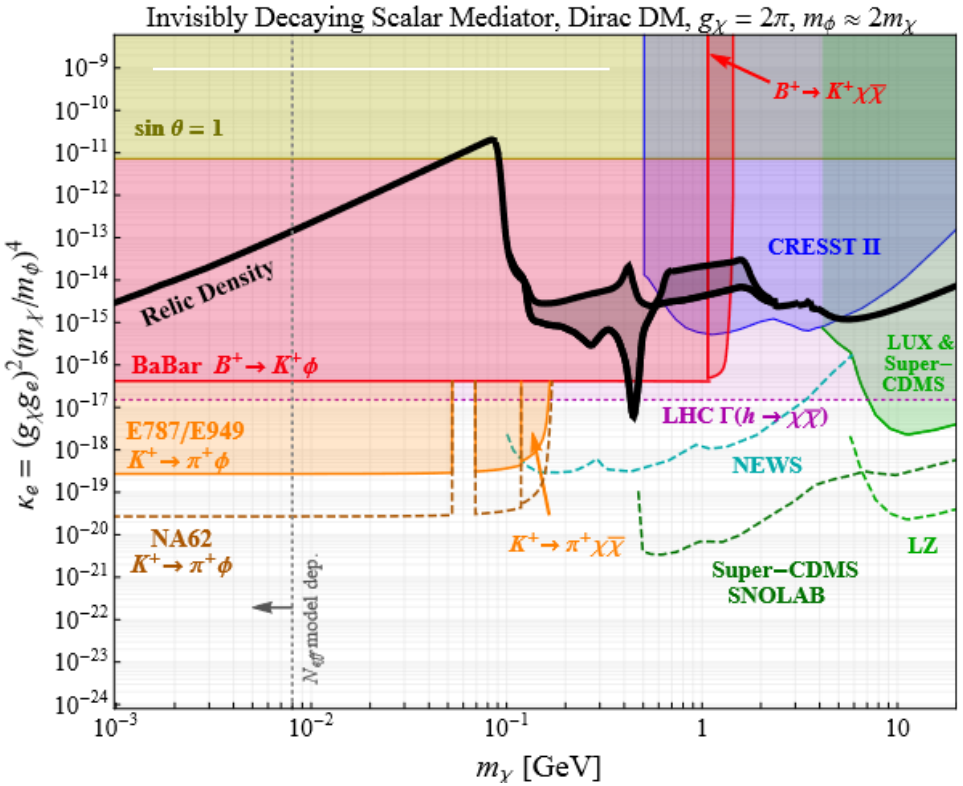

Krnjaic 1512.04119

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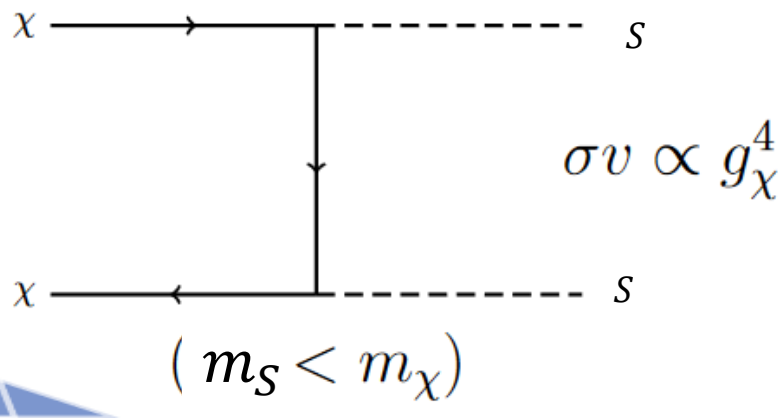

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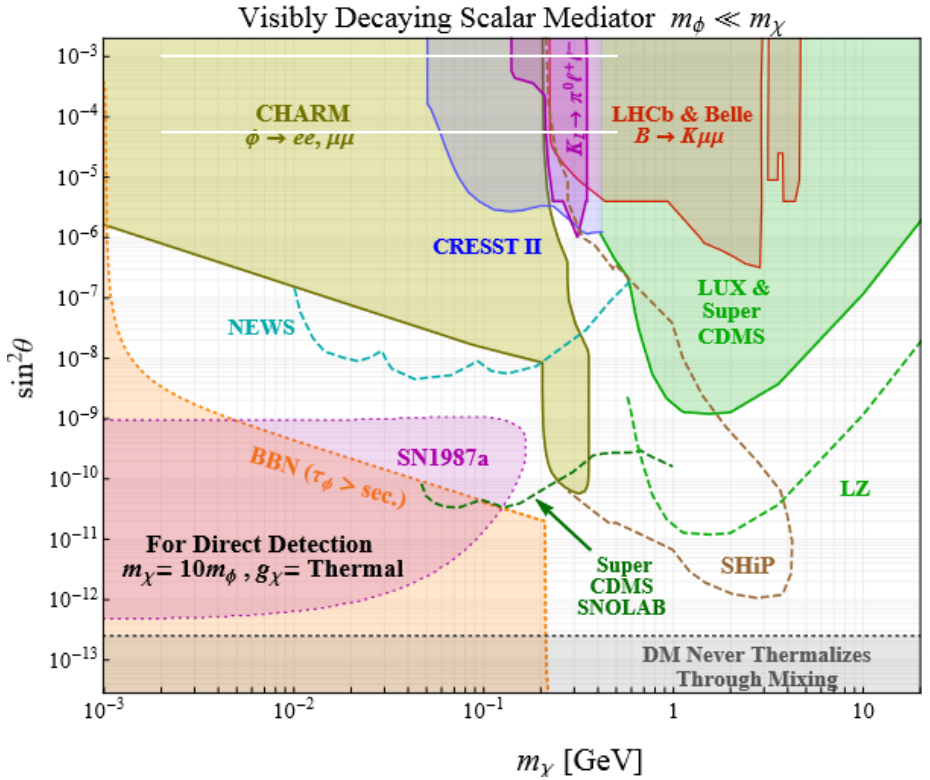
→ Or via secluded annihilation (ie into dark Higgs which later decay into SM particles)



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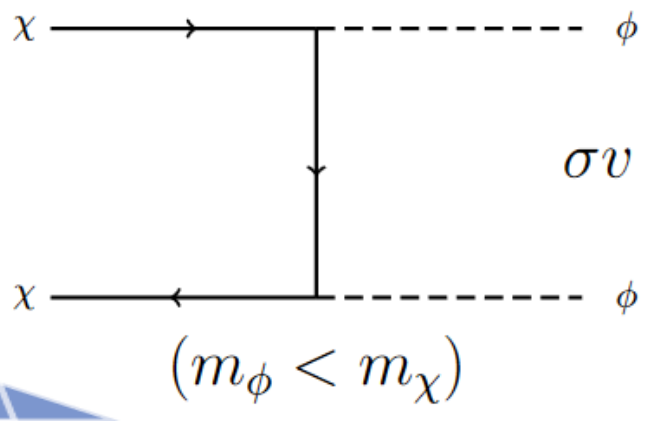

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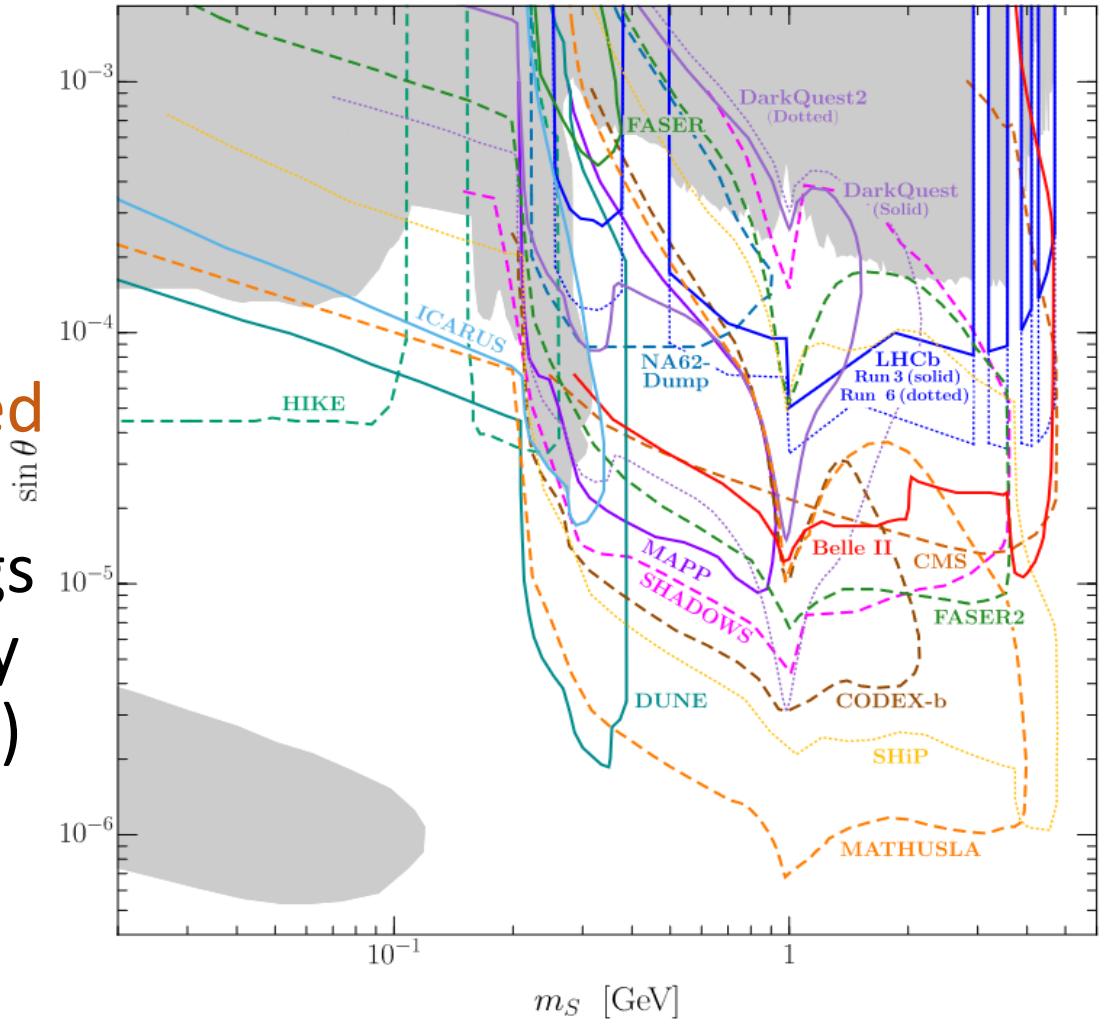


Batell et al. 2207.06905

Portal interactions - 2

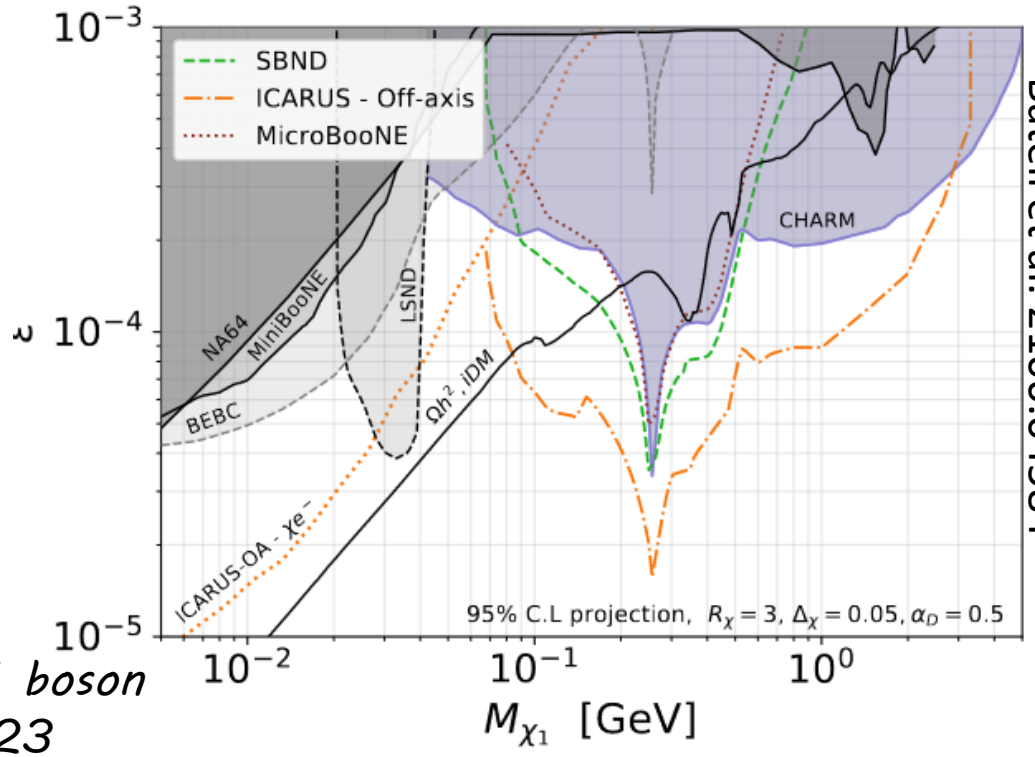
Vector portal	SM operator	FIPs / dark sector	Dark Photon
	$F_{\mu\nu} \quad (d=2)\,, \longrightarrow$	$F'^{\mu\nu}$	

Mixes with the hypercharge / photon

- No flavour dependence (only EM current interaction here)

→Yet (or maybe because of this) one of the most looked upon mediator for LDM

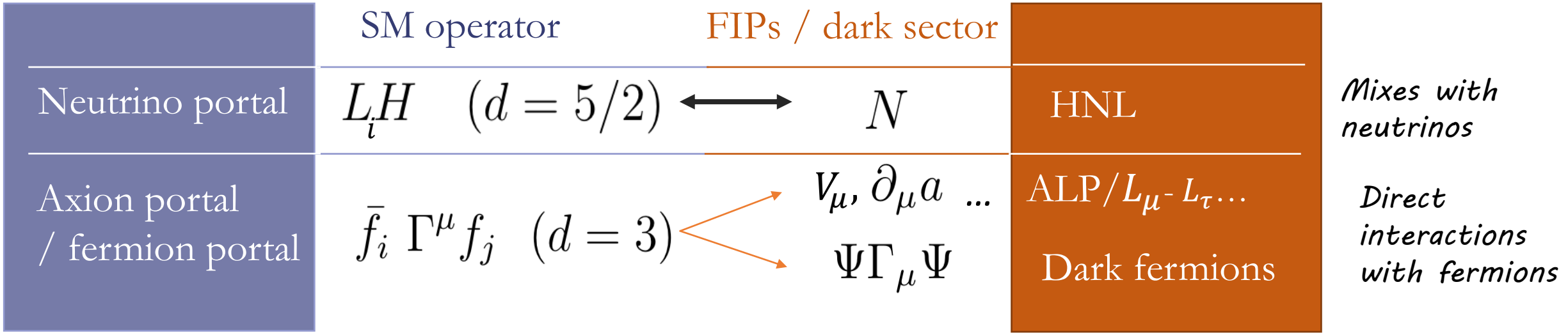
→ Still very good prospects in flavour-motivated and neutrino-motivated experiments (see Torben's talk)



Batell et al. 2106.04584

Care should be taken however for mixing with the B and Z boson in the broken phase, see e·g· Bauer, Foldenauer 2207·00023

Portal interactions - 3



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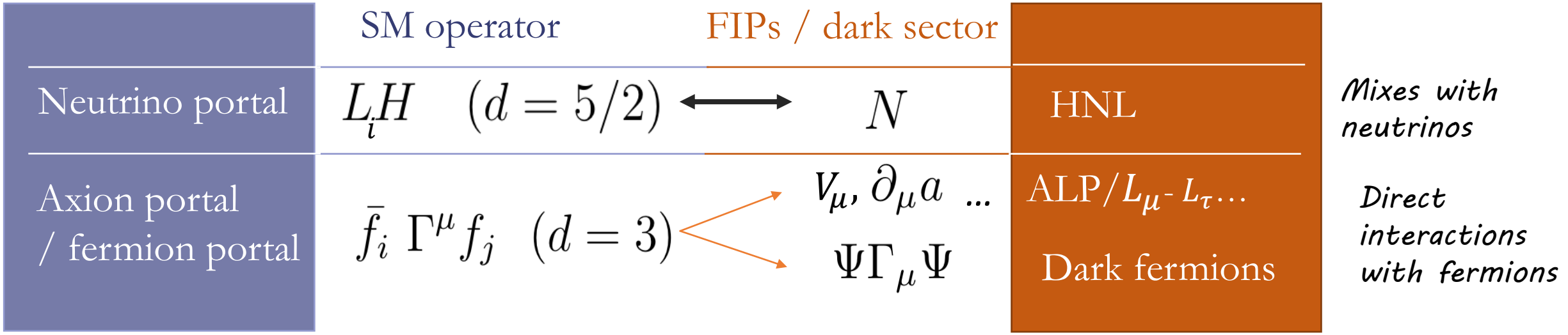

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Bolognesi , Gehrlein , Ross-Lonergan, Yáñez, neutrino session

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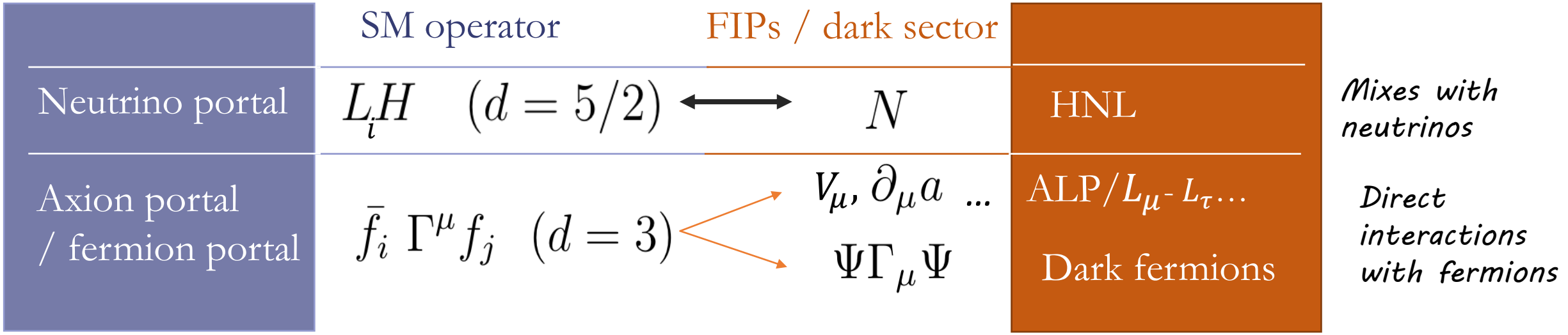

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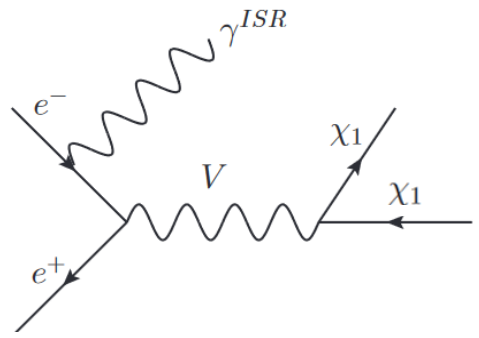
- We will discuss in more details the flavour-aspects of the "fermion pair" portal (first portal with the possibility for tree-level FV interaction)

Portals and dark matter

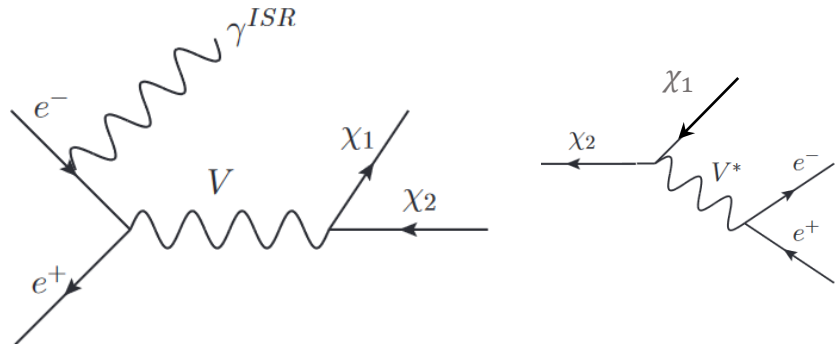
- The portal formalism relies on the assumption that there is only the SM + light particle
  → Yet some portals, such as the ALP one are effective operators and thus required an additional UV physics, which may play an important role in the production (e.g. $Z, h \to a\,\gamma$ decays at LHC, etc…)

- The presence of dark matter and/or extended dark sector motivates adding an invisible decay channel to the mediator



Purely invisible decays

Semi-visible decays



Fermion / Axion portal to dark matter and flavour

Problem: light NP & FV do not go along well

- Tree-level processes mediating FV from mesons or lepton decays are expectedly extremely constrained

  → Freeze-out from a FV fermion portal typically impossible

$$\bar{f}_i \, \Gamma^\mu f_j \quad (d = 3)$$

See Liang Sun and Gudrun Hiller's rare charm decays talks

Ann-Kathrin Perrevoor's rare lepton decays talk

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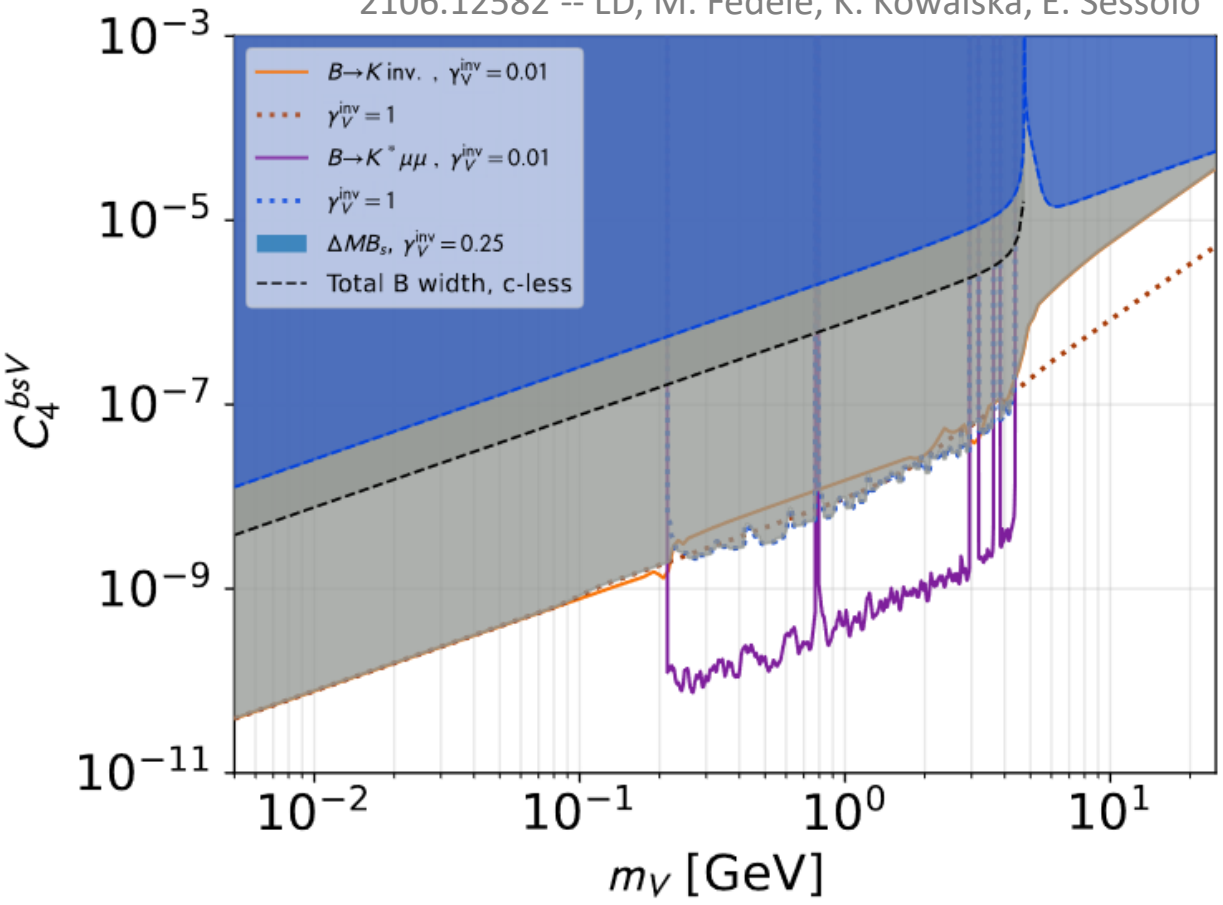
- Simple example: a new vector mediator with a pure QFV coupling between s and b quarks

$$\mathcal{Q}_4^{bsV} = (\bar{s}\gamma_\rho P_L b)\, V^\rho \,,$$

→ Including invisible decay $V \to \chi\chi$ does not help escaping constraints

2106.12582 -- LD, M. Fedele, K. Kowalska, E. Sessolo



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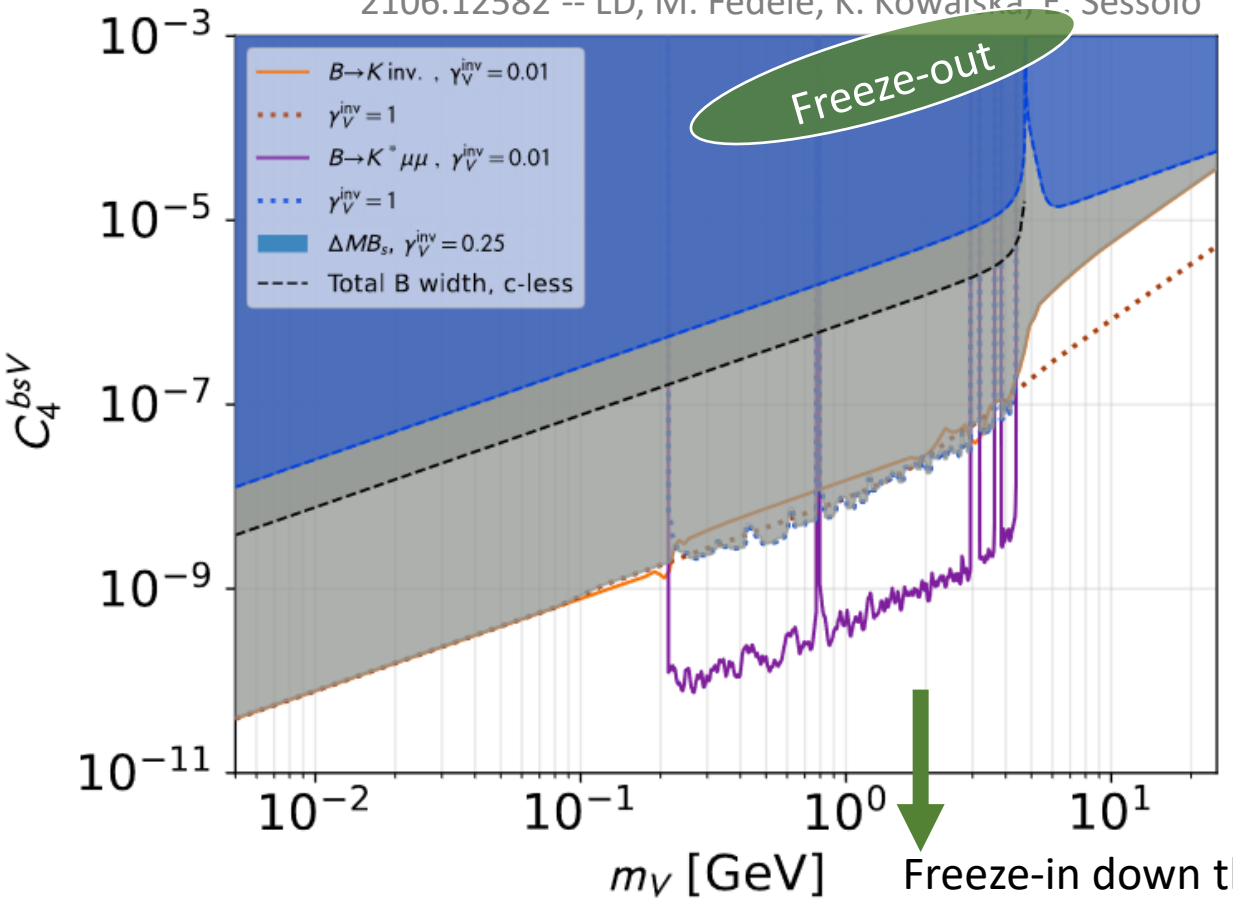

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For an axion/ALP with order one flavourful interactions

If no suppression → extremely large scales can be probed

- Similar level of constraints for ALP

e.g. Joachim Brod, Giuseppe Ruggiero Kaon decays

Sandrine Emery-Schrenk talk – BaBar $B \to Ka$

$$\mathcal{L}_{a f_i f_j} = -\frac{\partial_\mu a}{2 f_a} \left[\bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} - C^A_{f_i f_j} \gamma_5 \right) f_j \right]$$

Di Luzio et al. 2003.01100

Decay	Branching ratio	Experiment/Reference	f_a (GeV)
$K^+ \to \pi^+ a$	$< 0.73 \times 10^{-10}$	E949+E787 [593]	$> 3.4 \times 10^{11} \, \lvert C^V_{sd} \rvert$
$B^\pm \to \pi^\pm a$	$< 4.9 \times 10^{-5}$	CLEO [596]	$> 5.0 \times 10^{7} \, \lvert C^V_{bd} \rvert$
$B^\pm \to K^\pm a$	$< 4.9 \times 10^{-5}$	CLEO [596]	$> 6.0 \times 10^{7} \, \lvert C^V_{bs} \rvert$
$D^\pm \to \pi^\pm a$	< 1		$> 1.6 \times 10^{5} \, \lvert C^V_{cu} \rvert$
$\mu^+ \to e^+ a$	$< 2.6 \times 10^{-6}$	TRIUMF [598]	$> 4.5 \times 10^{9} \, \lvert C^{V(A)}_{\mu e} \rvert$
$\mu^+ \to e^+ \gamma a$	$< 1.1 \times 10^{-9}$	Crystal Box [600]	$> 1.6 \times 10^{9} \, C_{\mu e}$
$\tau^+ \to e^+ a$	$< 1.5 \times 10^{-2}$	ARGUS [604]	$> 0.9 \times 10^{6} \, C_{\tau e}$
$\tau^+ \to \mu^+ a$	$< 2.6 \times 10^{-2}$	ARGUS [604]	$> 0.8 \times 10^{6} \, C_{\tau \mu}$

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D. Redigolo's axion talk

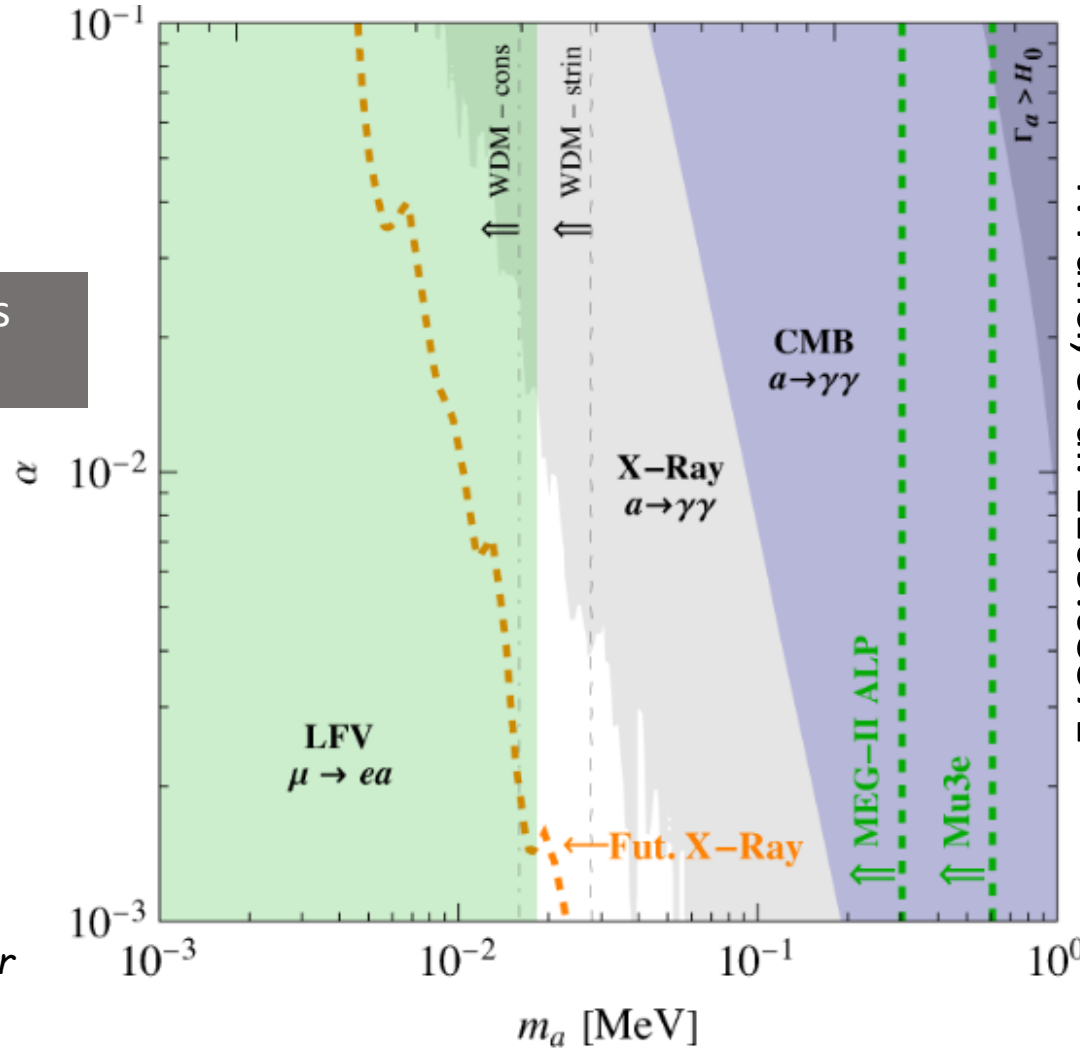
- Similar level of constraints for ALP

→Freeze-in (or non-thermal production mechanisms) can help

$$C^V_{\ell_i \ell_j} = C^A_{\ell_i \ell_j} = \begin{pmatrix} s_\alpha & c_\alpha & 0 \\ c_\alpha & -s_\alpha & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\mathcal{L}_{a f_i f_j} = -\frac{\partial_\mu a}{2 f_a} \left[\bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} - C^A_{f_i f_j} \gamma_5 \right) f_j \right]$$

Focused on Lepton Flavour Violation



P. Panci, et al. 2209.03371

Non-universality in fermion portal

- Flavour non-universal leptonic interaction can still be viable for freeze-out models: example of the $L_\mu - L_\tau$ gauge boson mediator
  - →Generated, e.g. as the τ_3-generator of a broken $SU(2)_{fL}$ flavour gauge symmetries, or just as an abelian subgroup of a bigger flavour gauge groups
  - →Anomaly-free with just the SM fermions content

$$\mathcal{L}_{\ell Z'} = q_\ell \tilde{g} \left(\bar{\mu}\gamma^\alpha \mu - \bar{\tau}\gamma^\alpha \tau + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu - \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau \right) \hat{Z}'_\alpha,$$

- One of the simplest $U(1)_X$ model still standing for the $(g-2)_\mu$ anomaly

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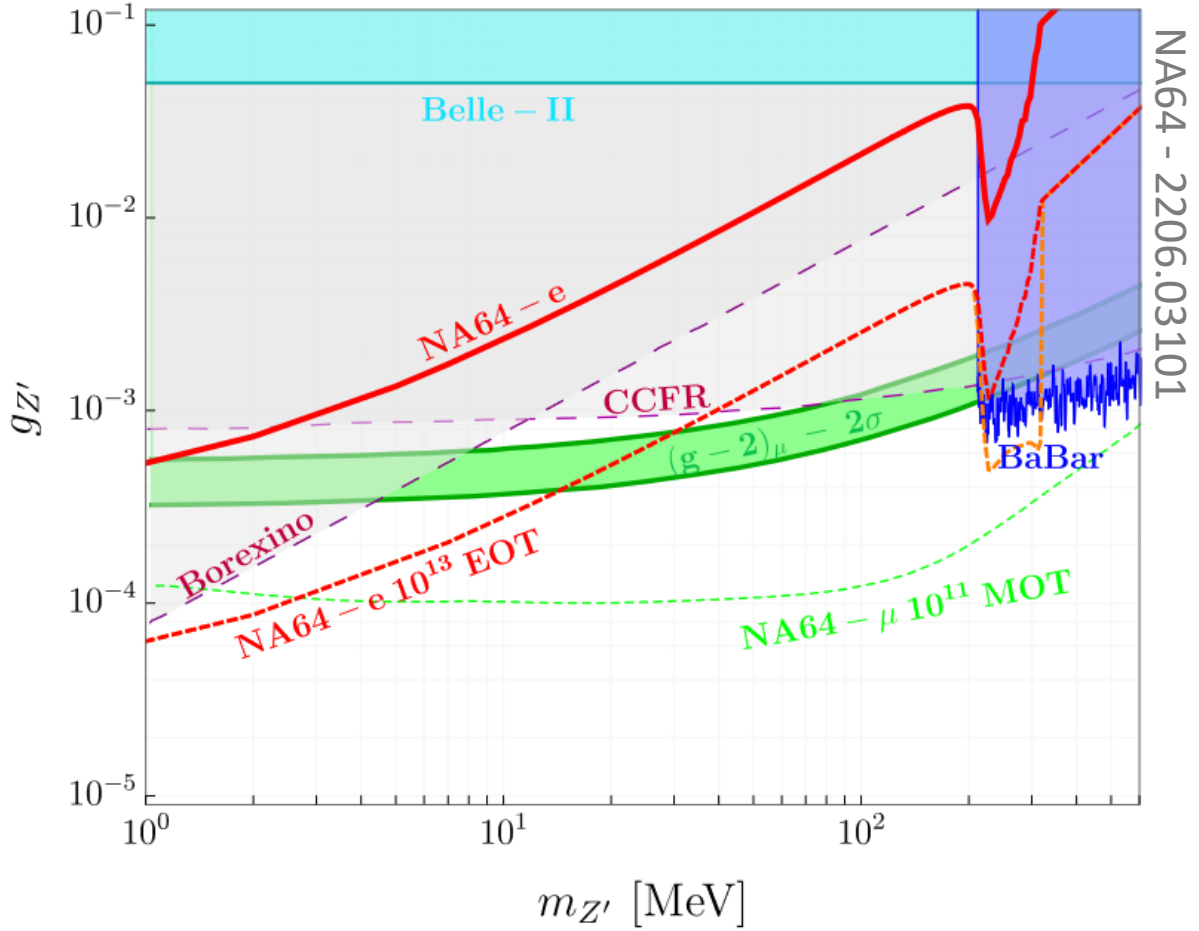


Géraldine Räuber, dark sector at Belle-II

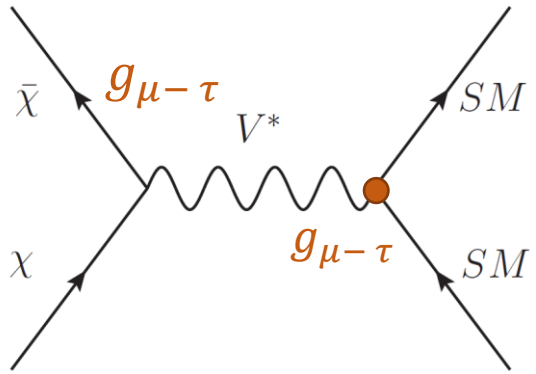
Jan Jerhot, NA62 in beam-dump mode

Freeze-out example – non-universality

- Annihilation into neutrinos can lead to a viable LDM candidate
  → Explored in a range of paper, from basic DM pheno to NS and SN related works

- Main limitation here is that coupling to DM is assumed to be of the same order as the SM one

$g_D \varepsilon g \rightarrow g^2_{\mu-\tau}$



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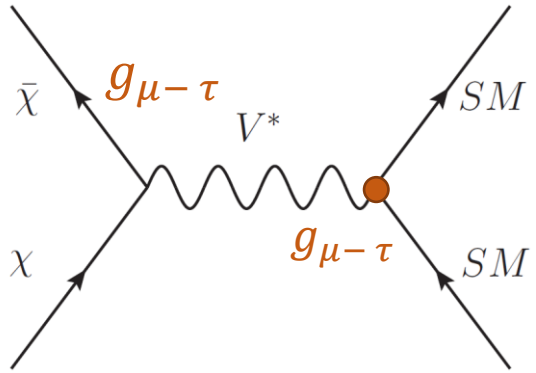
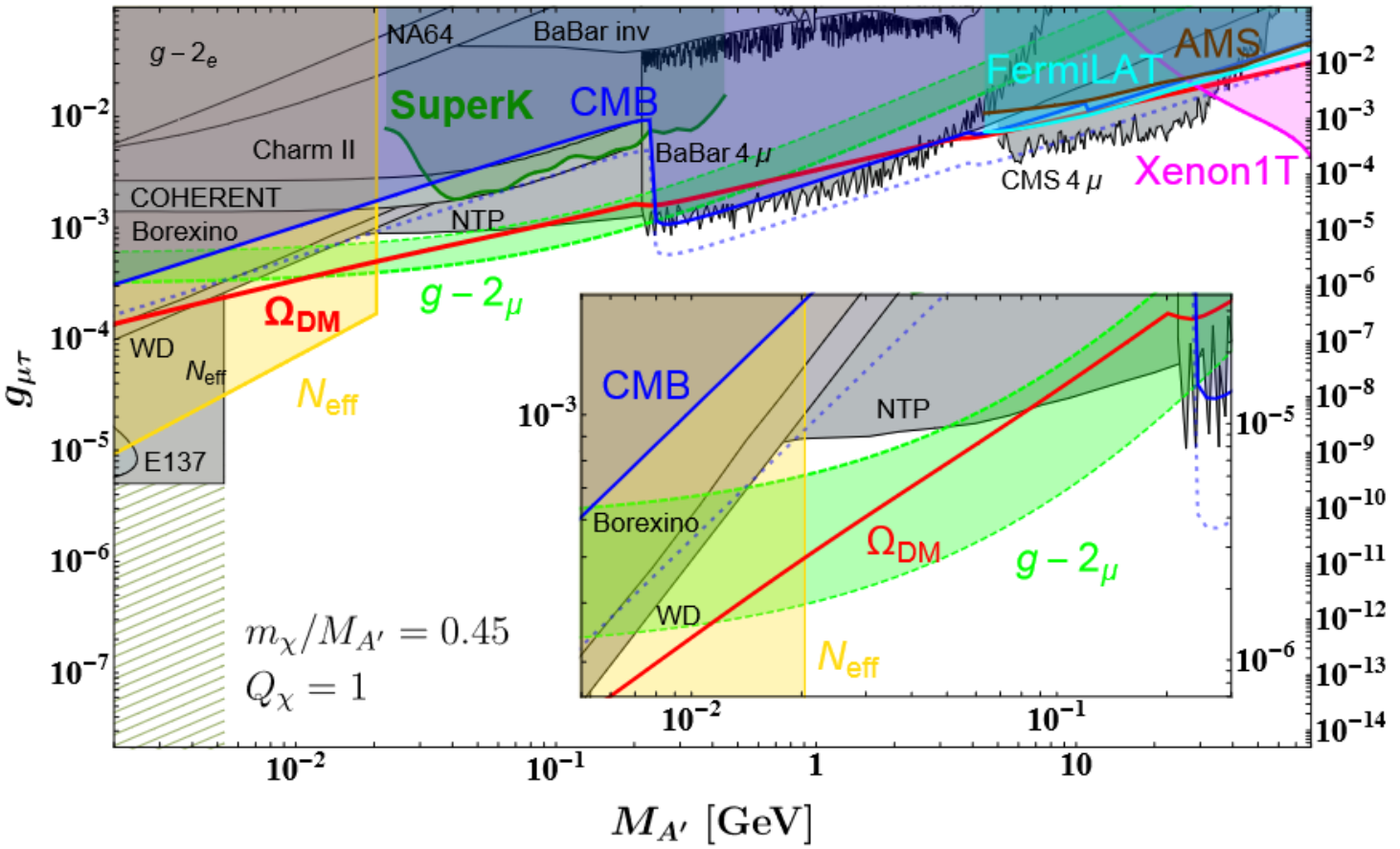


→ Interestingly, secluded types of freeze-out do not help here

Foldenauer 1808.03647



Radiative generation of mediator couplings

- In general, FIP interactions will have an RGE evolution

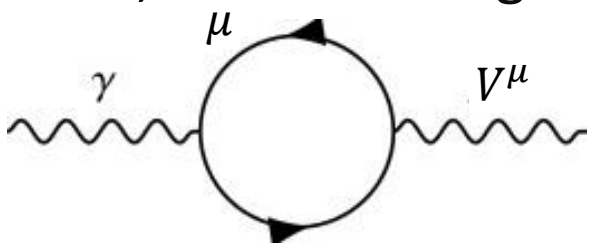
  → This is particularly important for model which try to avoid flavour-violation and/or first generation fermion interactions for pheno reasons

- For a vector FIP, kinetic mixing typically arises back from SM fermions loop, critical for experimental searches !

  → Barring tuning with new UV states, kinetic mixing reappears with a loop factor

Holdom 1985

$$\varepsilon \sim \frac{e\, g_{V\ell}}{6\pi^2}\, log$$



Stability and RG of vector couplings: Bauer et al. 2020, 2022; Greljo et al. 2022, Dror et al. 2020, 2018, Di Luzio 2022

- Similarly for an ALP, most couplings re-appear radiatively

$$\delta g_{a\gamma} = \frac{\alpha_{\rm em} g_{ae}}{\pi} B_1\left(\frac{4m_e^2}{m_a^2}\right) \qquad B_1(\tau) \to 1 \text{ for } \tau \to 0$$

Stability and RG of ALP couplings: Bauer et al. 2017,2021; Chala et al. 2021, Choi et al. 2021; Di Luzio 2023, 2022; Arina et al. 2021; Jerhot 2022

Altogether, one therefore must be careful when dealing with, e·g· large FIP coupling to second and third generations

Conclusion

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- Increasing interest toward light dark matter models in recent years
- Dark matter models below the EW scale are very sensitive to flavour physics
  - →At the very least, leveraging the precision of the system (e.g. Belle-II dark photon search)
  - →At best, triggering rare FV invisible decays for mesons/leptons

- The key question is the mediator between the DM (or dark sector) and the SM
  - → Classification in portals is definitely practical and is now widely used in both theory and experiments – still be careful about its limits
  - →Flavourful interactions are expected in many cases, leading to a rich phenomenology

- Flavour physics and flavour experiments are key players in probing these scenarios !

Backup

The troubles with non-conserved currents…

- In general, the interaction between a vector FIP and SM can be represented via a "current" J_V^μ $\quad \mathcal{L}_{\text{int}} \supset V_\mu \mathcal{J}_V^\mu$

Pospelov, Dror, Lasenby

- Non-conserved SM currents leads to strong signatures at small vector masses (Goldstone equivalence, high-energy processes scale as $\frac{E^2}{M_V^2}$)

$$V_\mu \to \frac{1}{M_V}\partial_\mu V_L$$

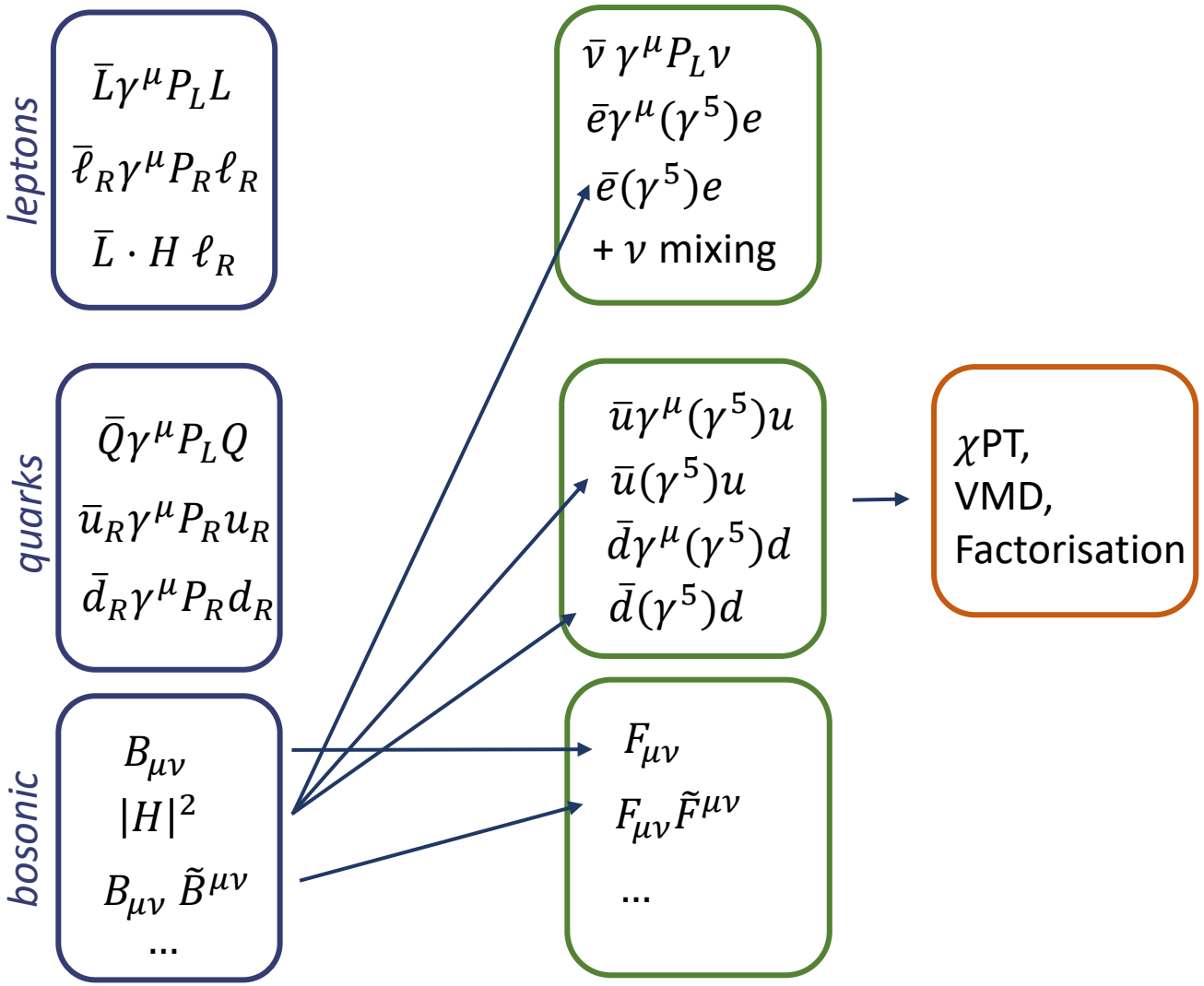
$$\mathcal{L}_{\text{int}} \supset V_\mu \mathcal{J}_V^\mu \quad \Rightarrow \quad \mathcal{L}_{\text{int}} \supset \frac{V_L}{M_V}\partial_\mu J_V^\mu$$

If the current does not correspond to a SM global symmetry, $\partial_\mu J_V^\mu \neq 0$

Note that applying the full Ward identities also leads to anomalous boson interactions

- For instance, the following are orange flags (ie, you need to be careful)…
  - → Tree-level flavour violation, both critical to the anomalies and very strongly constrained
    - B_s -mixing, $\mathrm{B_s} \to \mu\mu, B \to K^{(*)}V$ on-shell processes, with subsequent visible/invisible V decay
  - →Weak-isospin violation (no coupling to neutrinos)
    - Strong flavour-dependent modification of W decay rates
  - →Axial-coupling interaction to the SM fermions

EW scale vs low scale portals…



- Below the EW scale, the decoupling of the top quark and of the EW gauge bosons reduces the number of DoF
- BUT: QCD confinement + less gauge protections adds a layer of complexity
- Some interaction are naturally flavourful