Dark Interactions 2018 - BNL

Light Dark Sectors
Motivations & Signatures

Adam Ritz
University of Victoria

Into the dark…

[Symmetry ’18, Artwork by Sandbox Studio]

Motivating Questions…

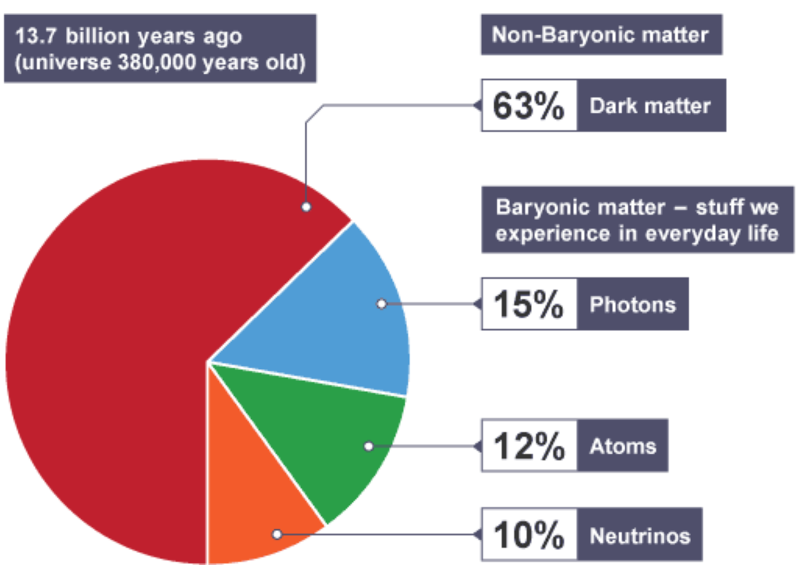
Sakharov's criteria for generating a baryon asymmetry are 50 years old!

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from anti-matter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the

- *Developed at a time before there was clear evidence for dark matter or neutrino mass. Now, given that evidence, there are even more questions…*

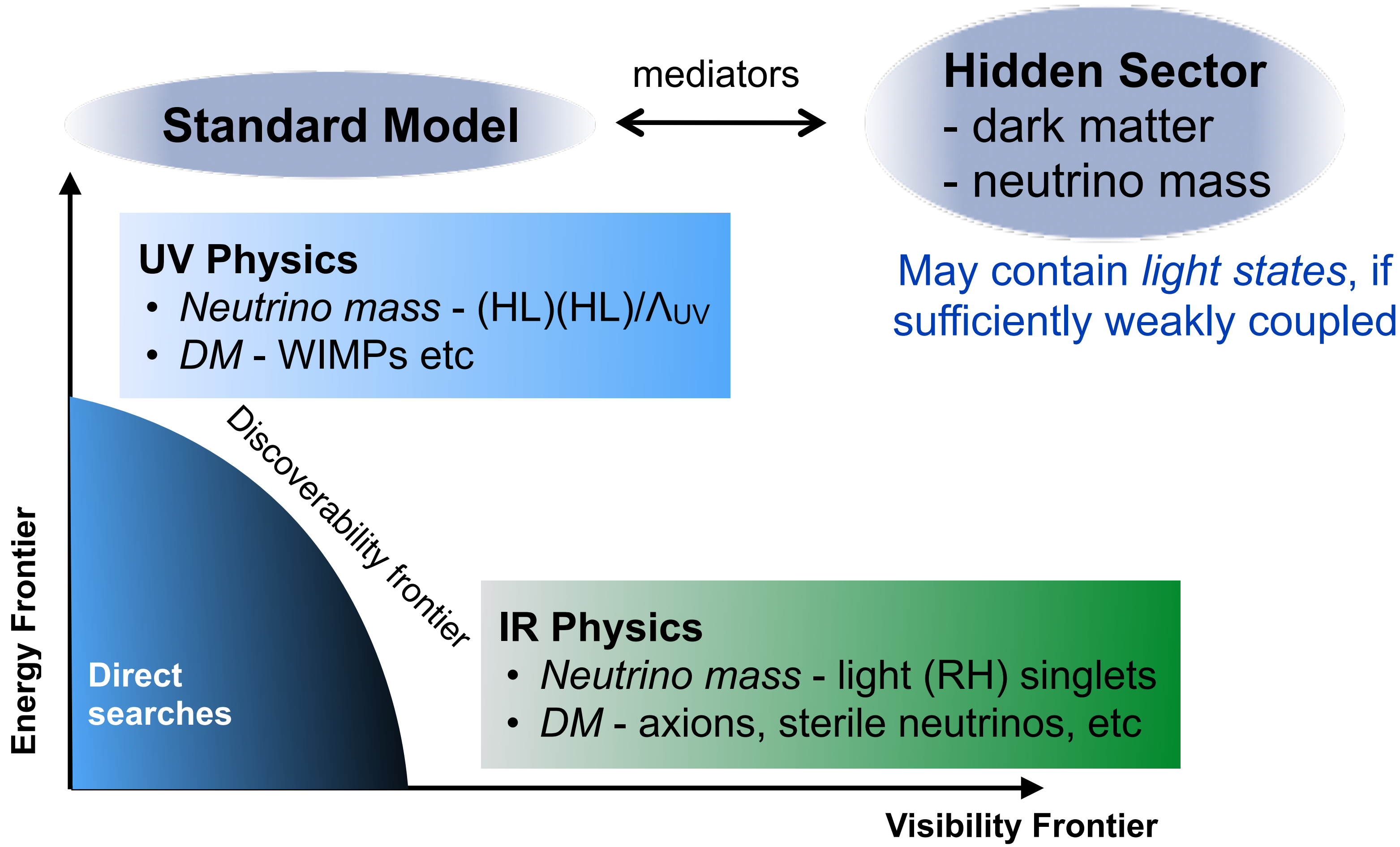


Questions

- Baryon asymmetry?
  and
- Identity of Dark Matter?
- DM-genesis?
- Neutrino mass?
- Lepton asymmetry?

New physics in a dark/hidden sector

E*mpirical* evidence for new physics (e.g. *neutrino mass, dark matter*) arguably points to a hidden/dark sector, but not directly to a specific mass scale

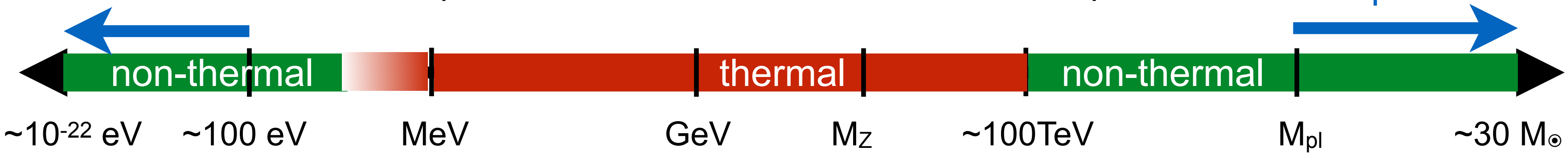


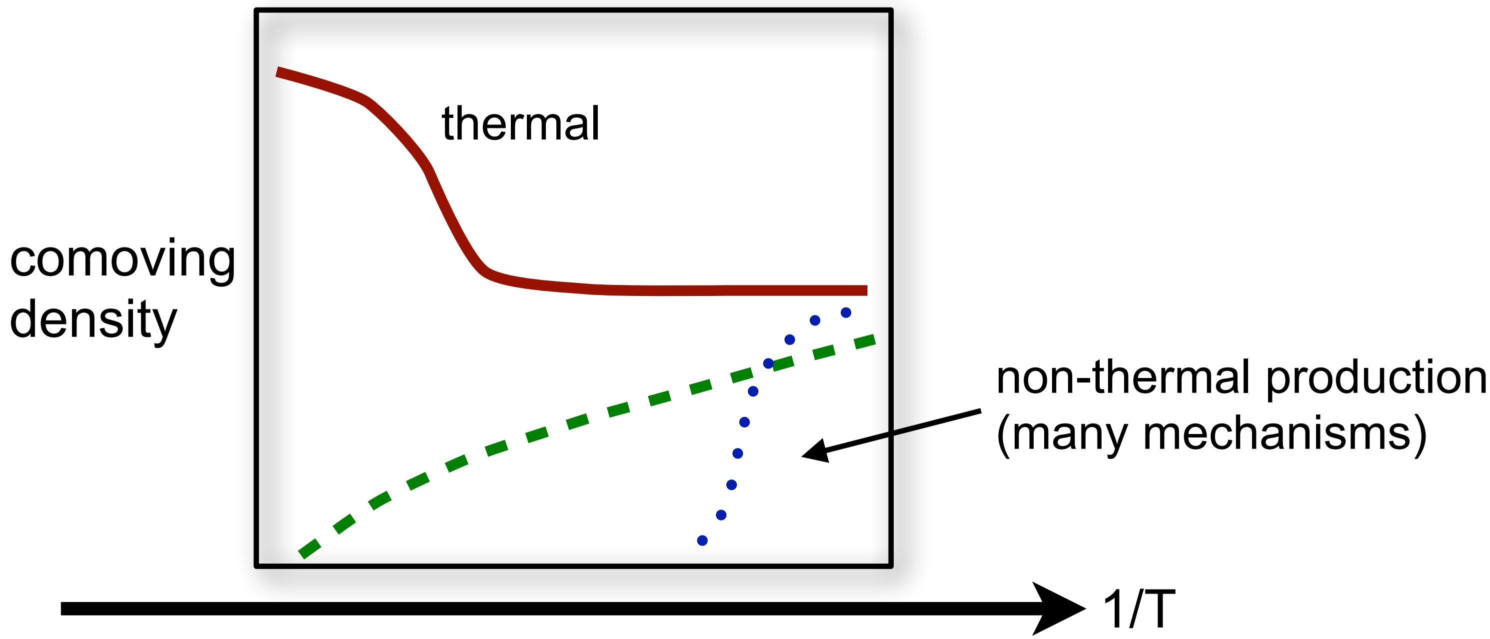
➠ a huge parameter space a priori, so what theoretical guidance is there?

Cold DM "Landscape"

Classify models according to their thermal history in the early universe

(thermalized with the SM or not)

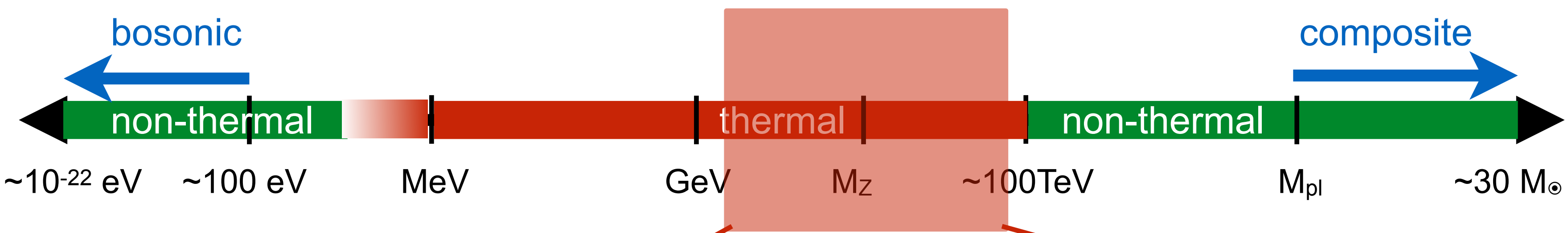




DM thermal history

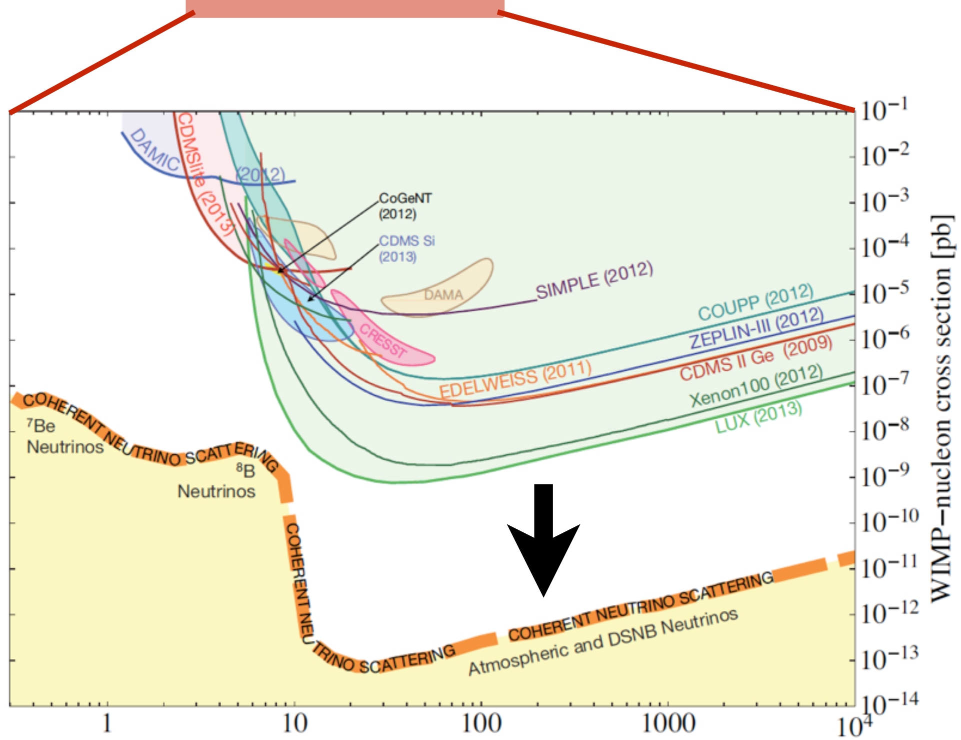
Cold DM "Landscape"

Classify models according to their thermal history in the early universe



Natural starting point:

- Minimal, linked to EWSB…
- But no evidence thus far from direct detection, or the LHC…



[Billard et al '13]

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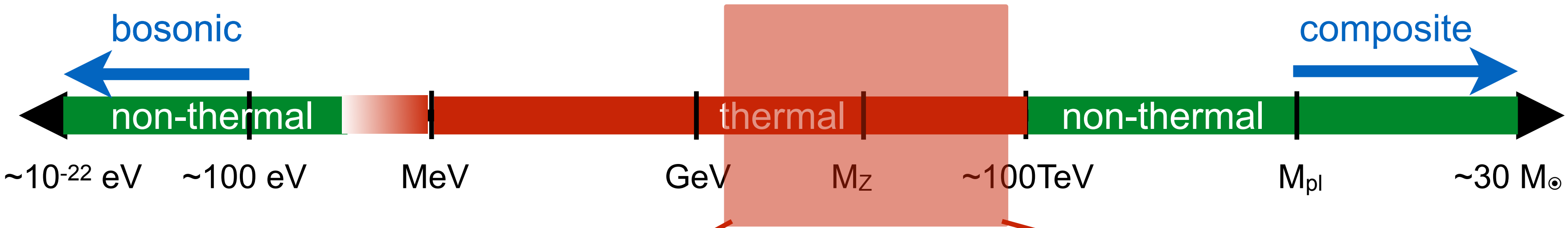
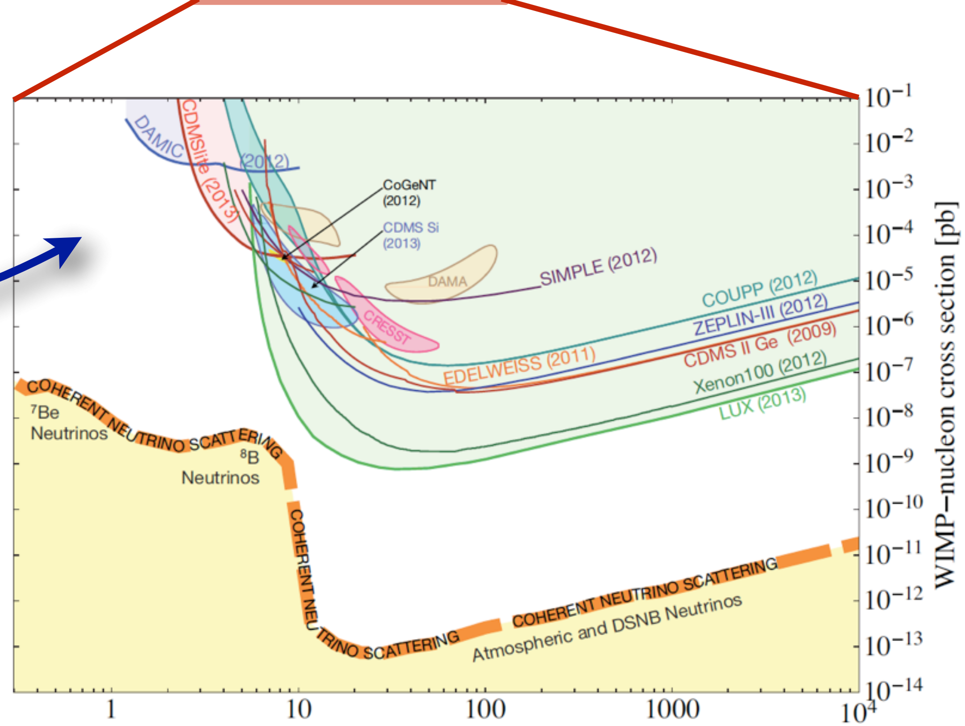


Conventional direct sensitivity to halo DM with v~10^{-3} drops for m<O(GeV), due to recoil energy thresholds.



[Billard et al '13]

Maybe CDM is more like the CvB…

- SM neutrinos are a (small) component of (hot) dark matter
- very abundant ~ O(100/cm^3), but are not currently visible in direct detection due to low mass, since KE~10^{-4} eV

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ([illegible] eV), however. We examine a

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses [illegible]

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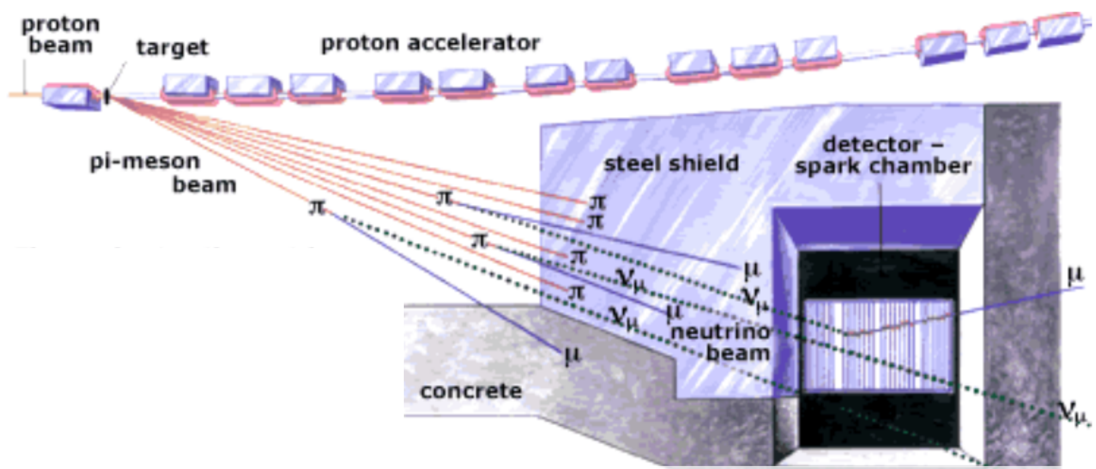
- SM neutrinos are a (small) component of (hot) dark matter
- very abundant ~ O(100/cm^3), but are not currently visible in direct detection due to low mass, since KE~10^{-4} eV

➠ BUT muon neutrino discovery ***(at BNL)*** involved production via meson decays (large rate), and detecting the (weak) scattering of the relativistic neutrino beam



OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

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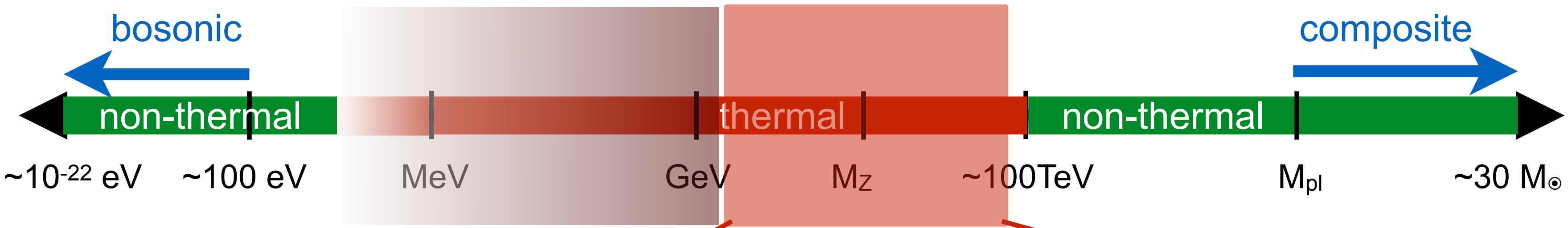
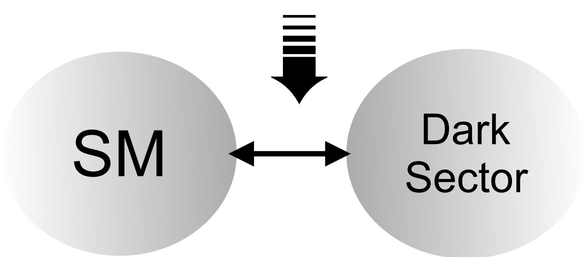
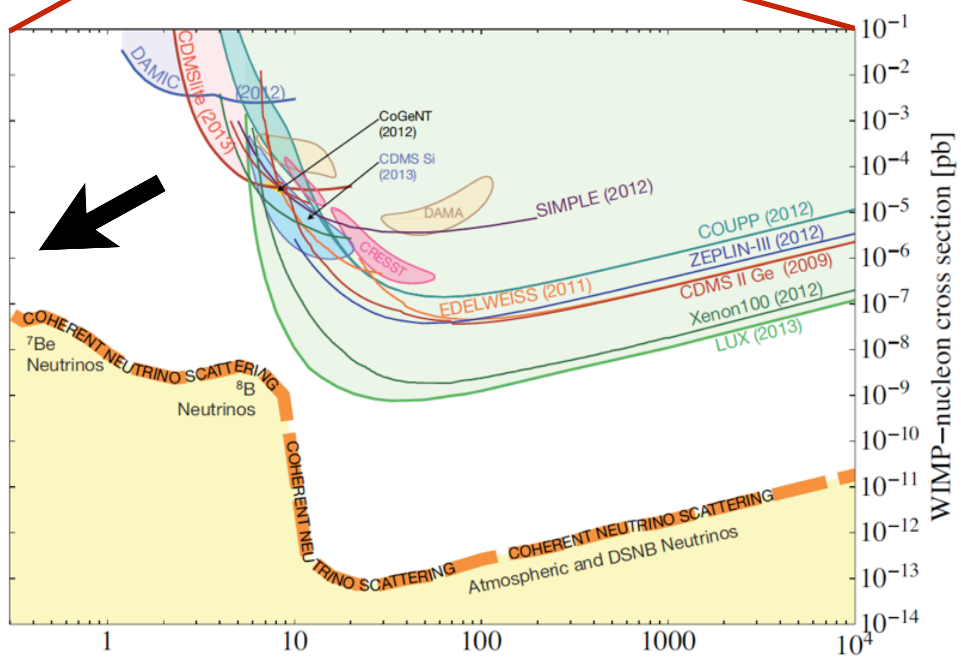


WIMP-like thermal relic

- $\sigma_{ann} \propto m_{DM}^2/m_{med}^4$ so Lee-Weinberg bound ➠ light mediators are required for freeze out with the required relic abundance

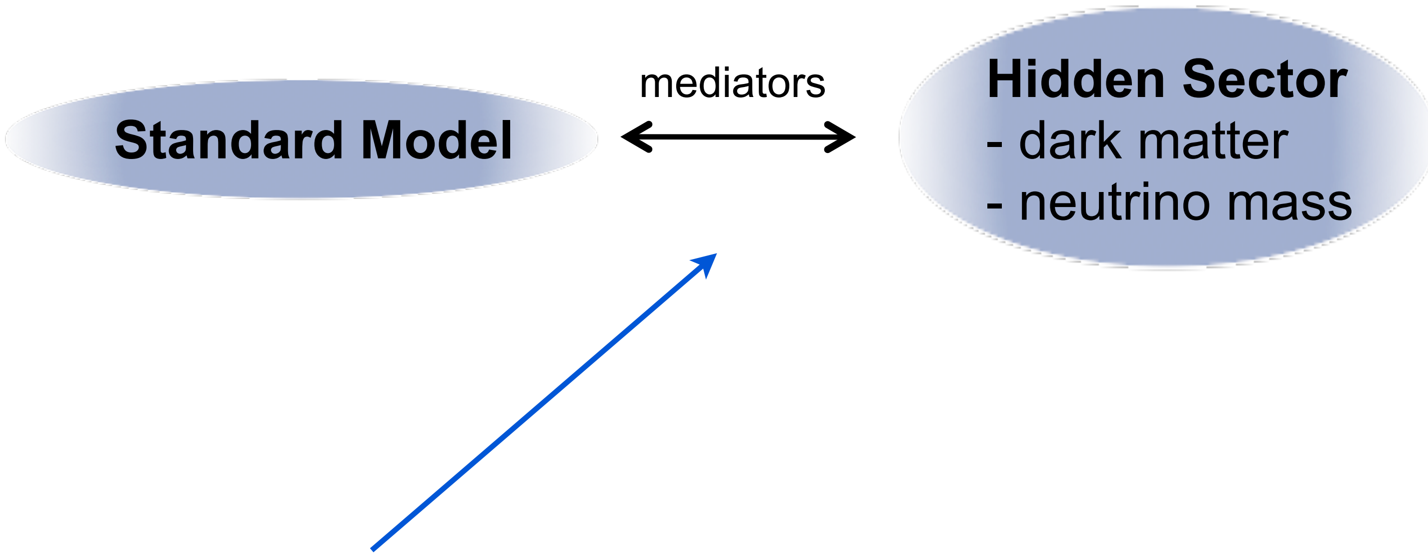




[Billard et al '13]

EFT for a (neutral) hidden sector

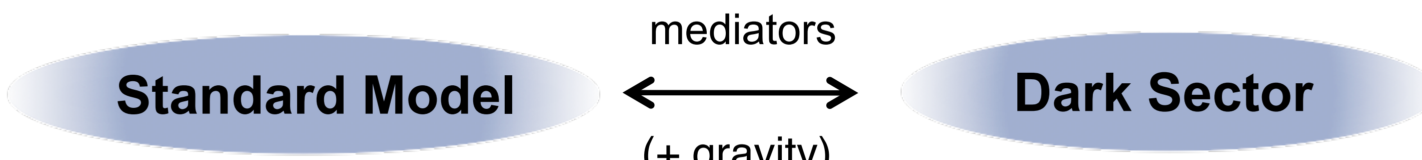
Given a very large ‘model-space’ a priori, its useful to develop an EFT expansion, assuming the hidden sector is *SM-neutral*



Easier to be systematic if we focus first on the mediation channels...

Substantial research effort over the past decade….

EFT for a (neutral) hidden sector



Generic interactions are irrelevant (dimension > 4), but there are three ***UV-complete relevant or marginal "portals"*** to a ***neutral hidden sector***, unsuppressed by the (possibly large) NP scale Λ

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

e.g. $\epsilon_{(1-\mathrm{loop})} \sim \frac{ee'}{12\pi^2} \ln\left(\frac{\Lambda_{\mathrm{UV}}}{\Lambda}\right)$

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Standard Model $\xleftrightarrow[\text{(+ gravity)}]{\text{mediators}}$ **Dark Sector**

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Vector portal
[Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal
[Patt & Wilczek]

Neutrino portal

Many more UV-sensitive interactions at dim ≥ 5

EFT for a (neutral) hidden sector

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Vector portal
[Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal
[Patt & Wilczek]

Neutrino portal

$$+\frac{1}{f_a}\left(\mathrm{tr}(G\tilde{G}) + c_F F\tilde{F}\right) a + \mathcal{O}(\mathrm{dim} \geq 5)$$

Axion portal
[Weinberg, Wilczek, KSVZ, DFSZ]

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Vector portal **Higgs portal** **Neutrino portal**

Naturally incorporates minimal models of neutrino mass, and leptogenesis

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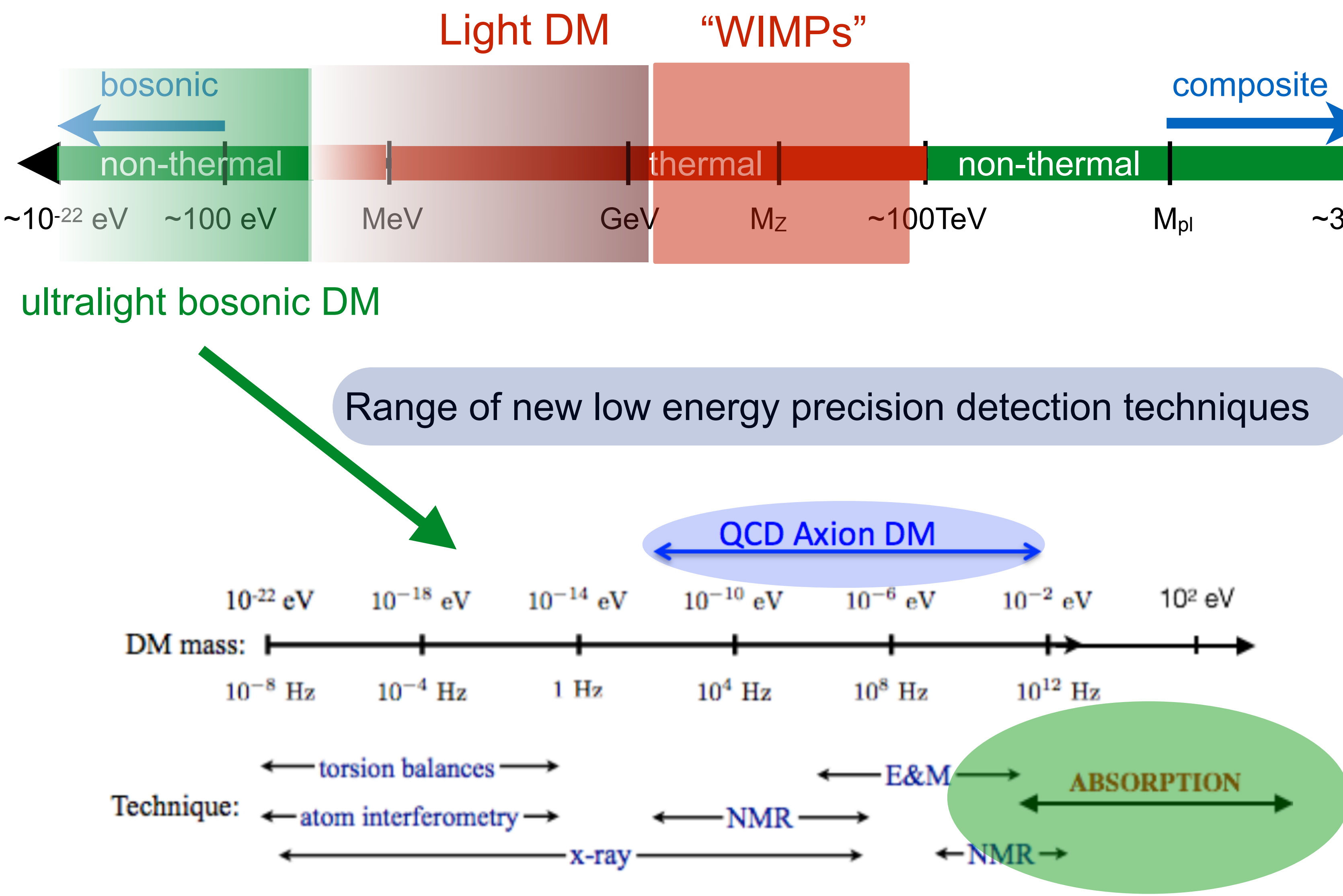
Vector portal **Higgs portal** **Neutrino portal**

If sufficiently light, A', N and S can be viable (and minimal) *nonthermal* cold DM candidates

Cold DM "Landscape"



[Cosmic Visions 2017]

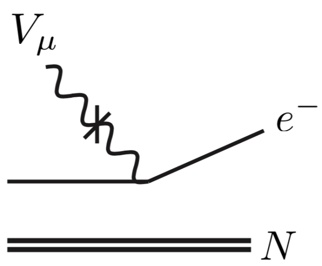
EG: keV-scale vector portal DM

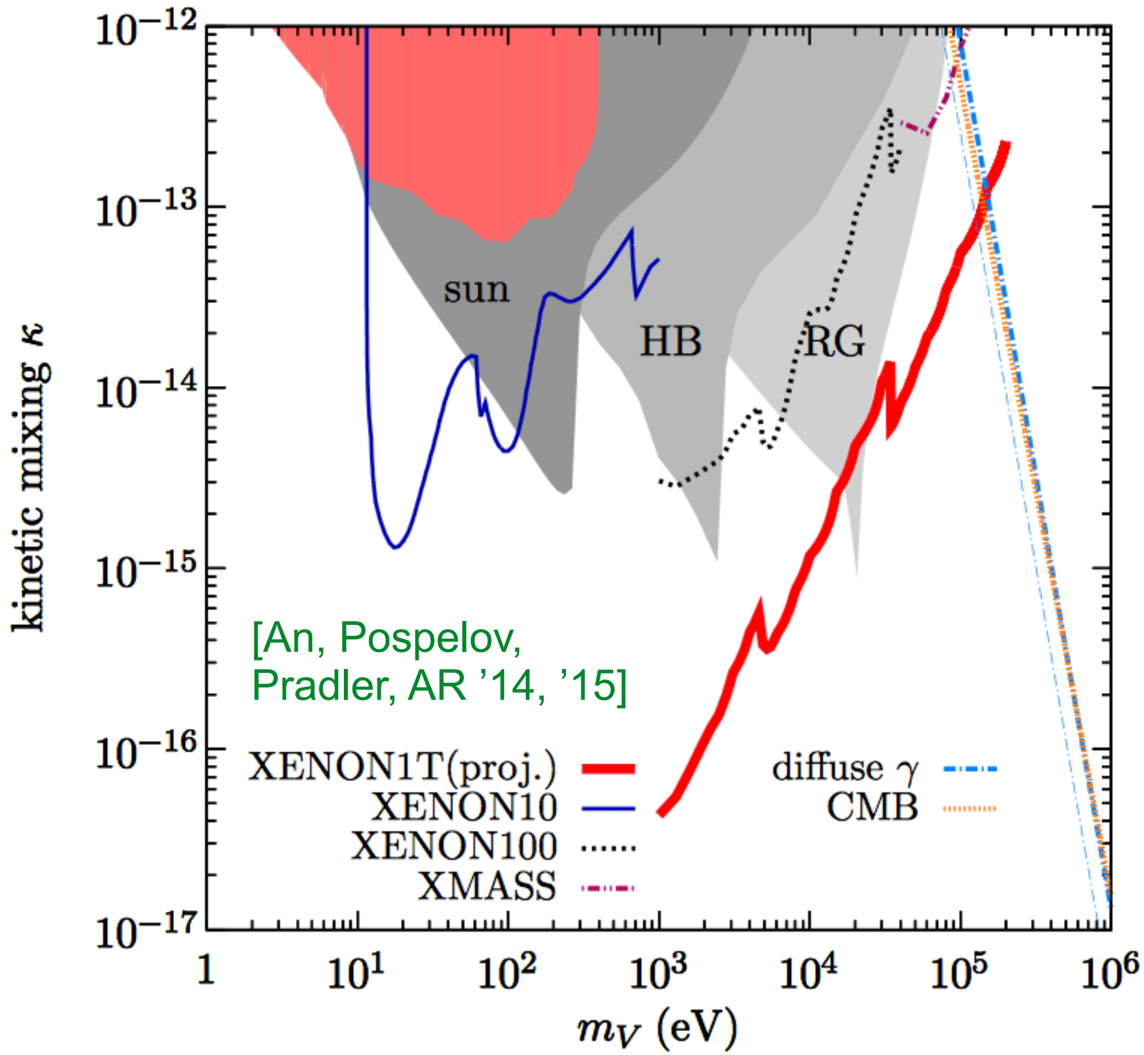
$$\mathcal{L} = -\frac{1}{4}F'^2_{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2_{A'}A'^2_{\mu} + \cdots$$

Dark photon DM: long lifetime if m < $2m_e$ (A' → 3γ or 2ν)

[Pospelov, AR, Voloshin '08, Redondo & Postma '08]

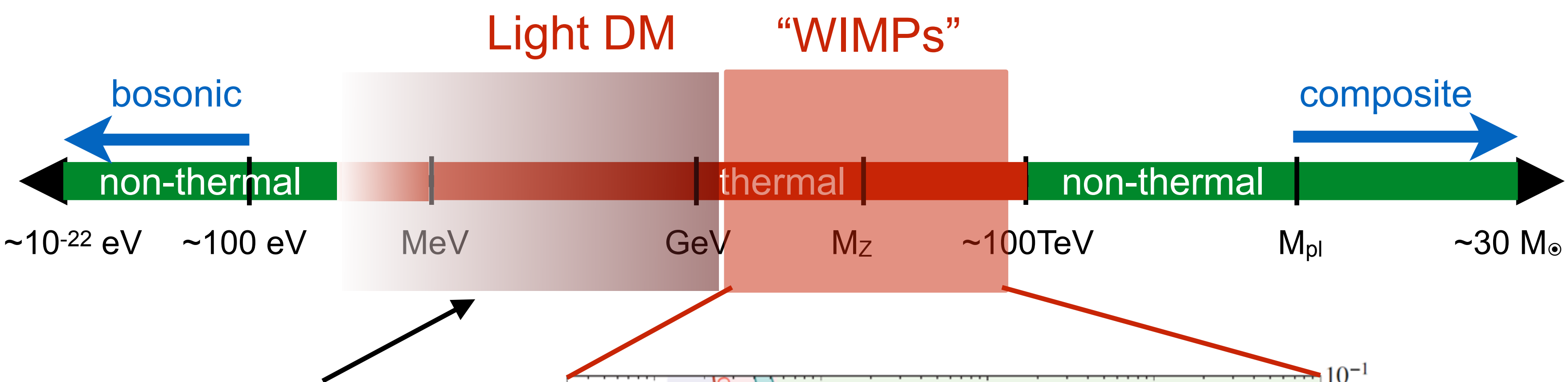
Sensitivity via atomic ionization





[An, Pospelov, Pradler, AR '14, '15]

Cold DM “Landscape”



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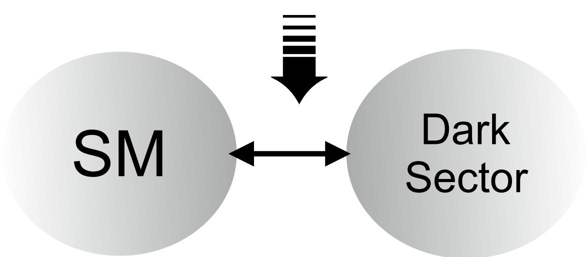

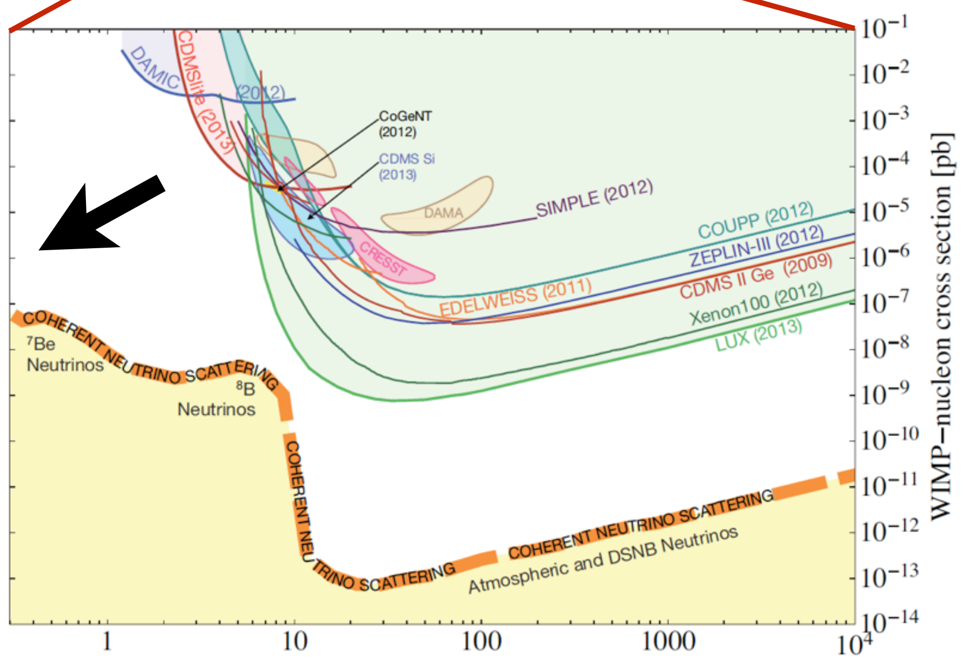

[Billard et al ’13]

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Vector portal **Higgs portal** **Neutrino portal**

A', S can provide new `dark force' mediators enabling sufficient annihilation of MeV-GeV (hidden sector) dark matter in the early universe

EFT for a (neutral) hidden sector - IR mediation

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Vector portal | **Higgs portal** | **Neutrino portal**

$$= -\frac{\epsilon}{2} B^{\mu\nu} \boxed{A'_{\mu\nu}} - H^\dagger H \boxed{(AS + \lambda S^2)} - Y_N^{ij} \bar{L}_i H \boxed{N_j} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$\epsilon \boxed{A'_\mu J^\mu_{\mathrm{EM}}} \qquad \frac{Av^2}{m_h^2} \boxed{S J_S} \qquad v Y_N^{ij} \boxed{\bar{\nu}_i N_j}$$

Universal couplings to EM/scalar currents at low energy, so hidden sector models have correlated observable effects

EFT for a (neutral) hidden sector - IR mediation

$$\text{Standard Model} \xleftrightarrow[\text{(+ gravity)}]{\text{mediators}} \text{Dark Sector}$$

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Vector portal — **Higgs portal** — **Neutrino portal**

$$= -\frac{\epsilon}{2} B^{\mu\nu} \boxed{A'_{\mu\nu}} - H^\dagger H \boxed{\left(AS + \lambda S^2\right)} - Y_N^{ij} \bar{L}_i H \boxed{N_j} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

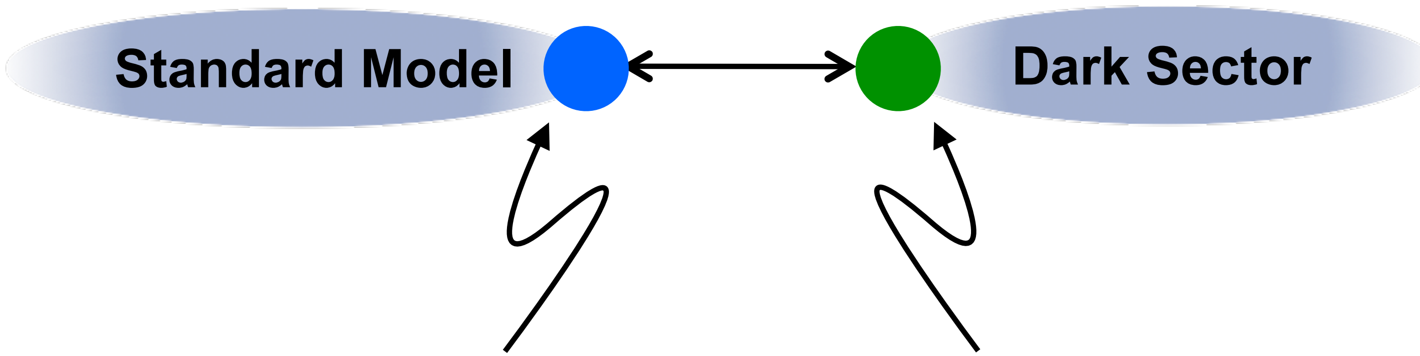
$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$\epsilon \boxed{A'_\mu J^\mu_{\mathrm{EM}}} \qquad \frac{Av^2}{m_h^2} \boxed{S J_S} \qquad v Y_N^{ij} \boxed{\bar{\nu}_i N_j}$$

$$\downarrow \qquad\qquad \downarrow$$

$$J_{\mathrm{EM},\,\mu} J^\mu_{\mathrm{dark}} + \cdots \qquad J_{\mathrm{S}} J_{\mathrm{S,dark}} + \cdots$$

Some experimental signatures



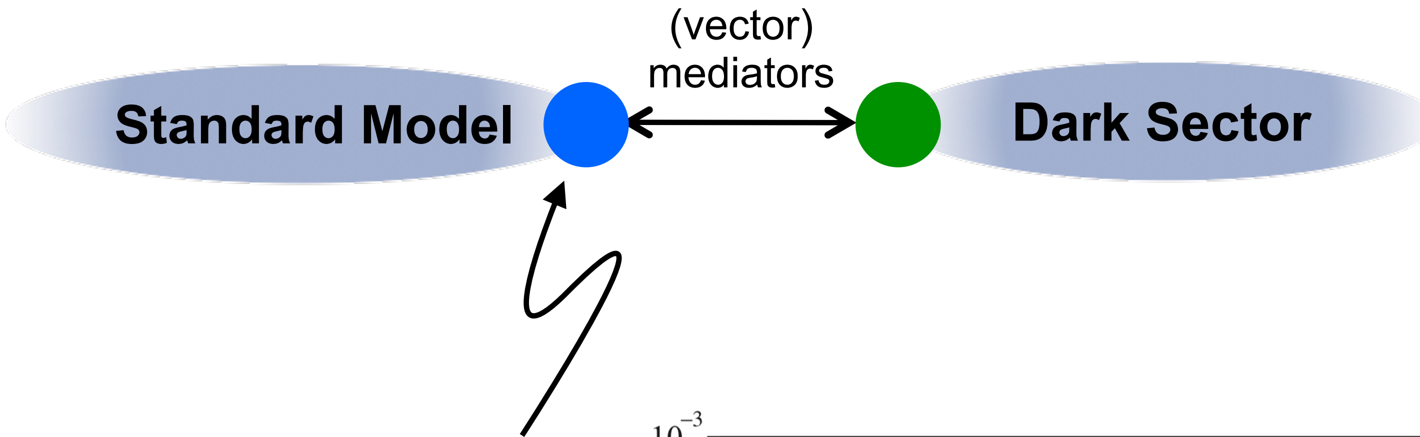
"Visible" and "hidden" signatures

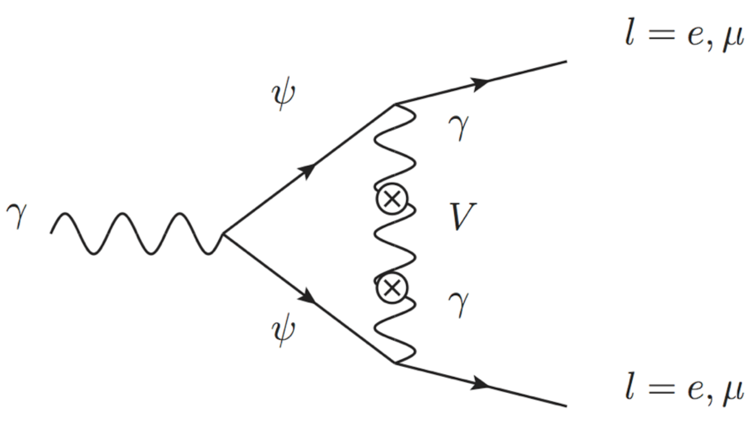
- Precision corrections
- Rare (visible) decays
- Astrophys/cosmology

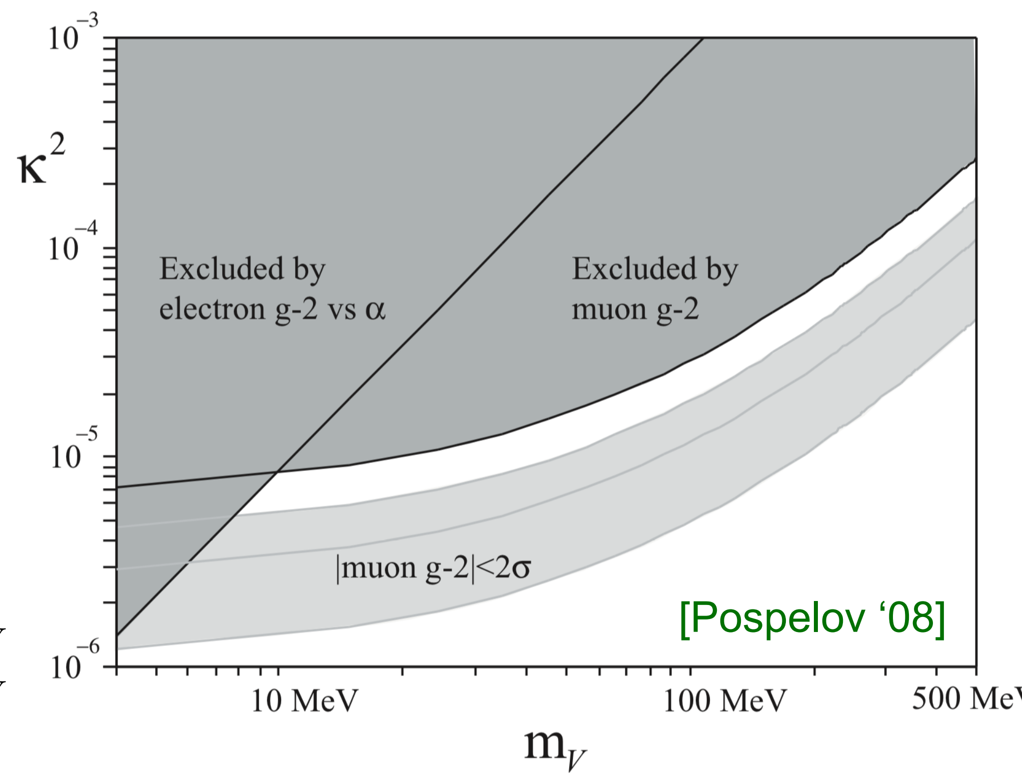
- Rare (invisible) decays/E_{miss}
- Anomalous NC-like scattering
- Astrophys/cosmology

Significant complementarity
between precision & intensity

E.g. precision corrections (vector portal)

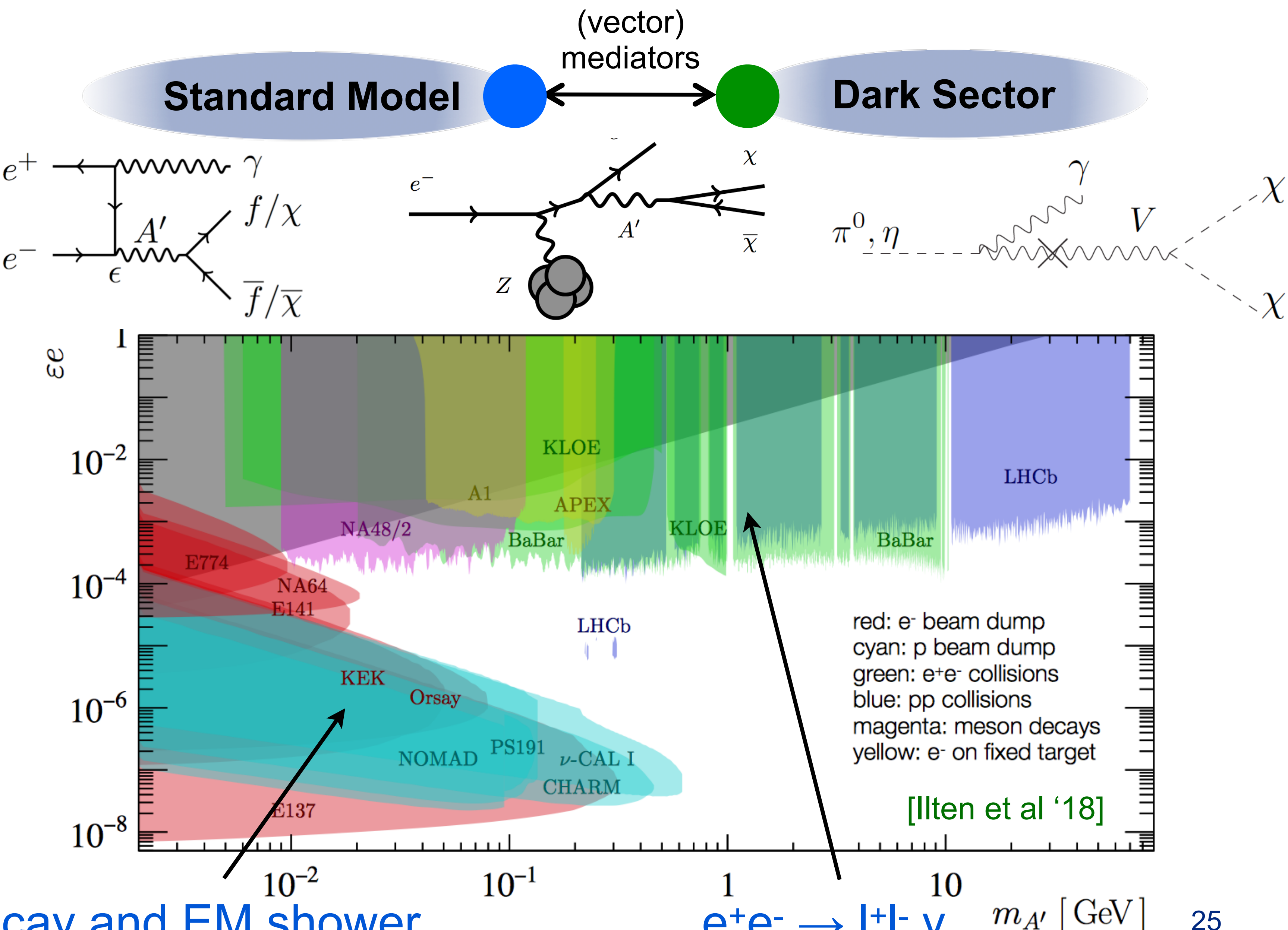






$$a_l^V = \frac{\alpha\kappa^2}{2\pi} \times \begin{cases} 1 & m_l \gg m_V \\ 2m_l^2/(3m_V^2) & m_l \ll m_V \end{cases}$$

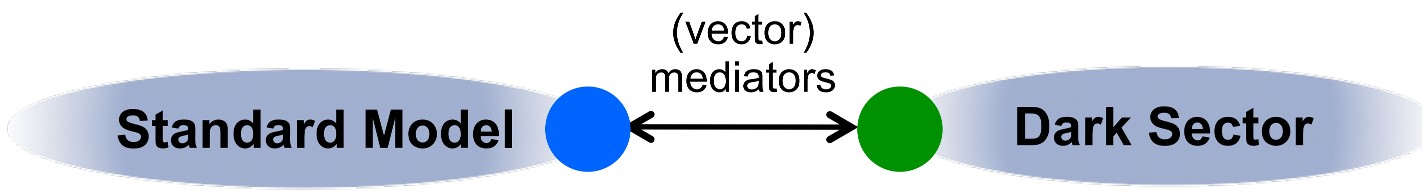
E.g. rare visible decays (vector portal)

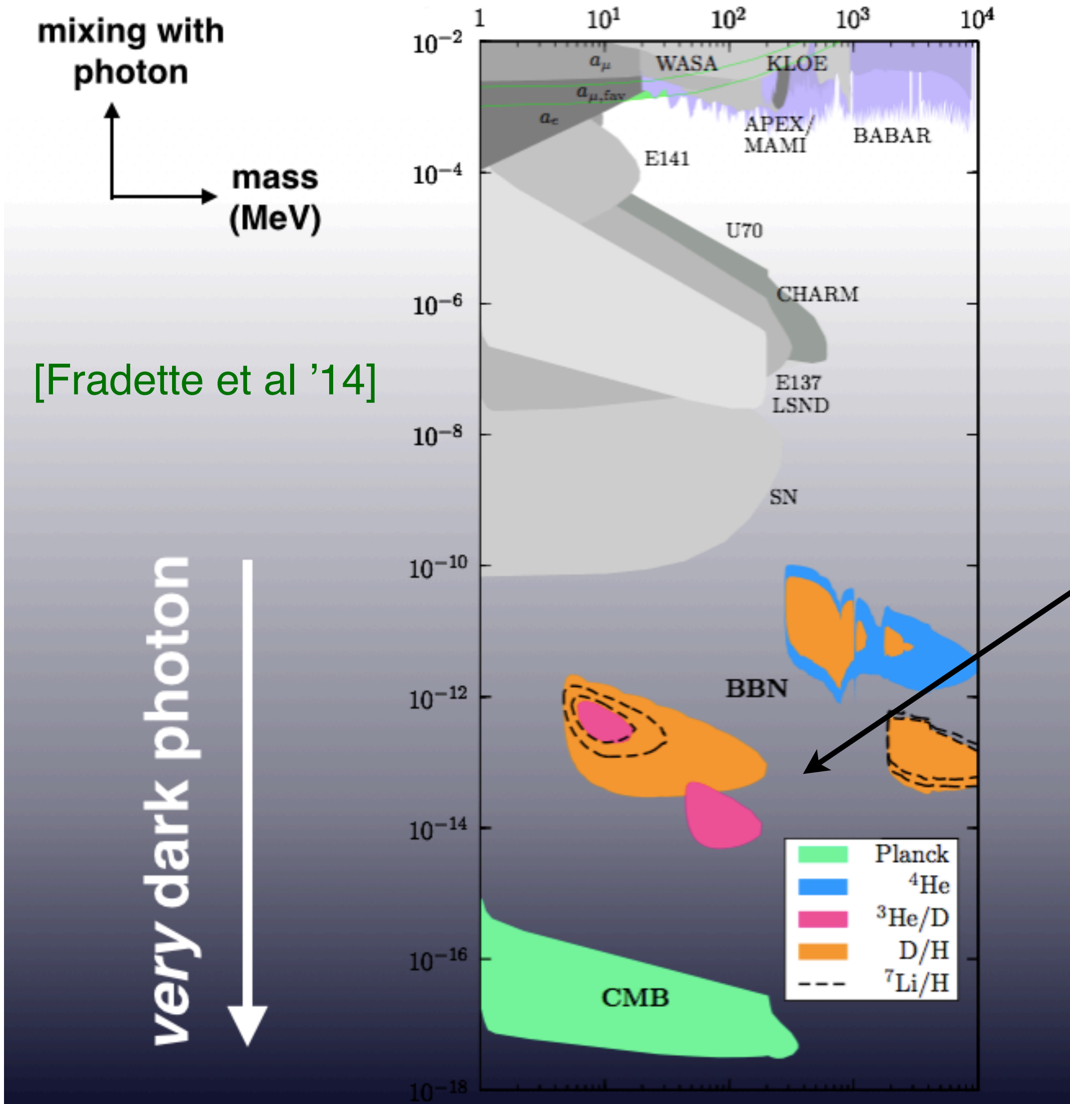


decay and EM shower

$e^+e^- \rightarrow l^+l^- \gamma$

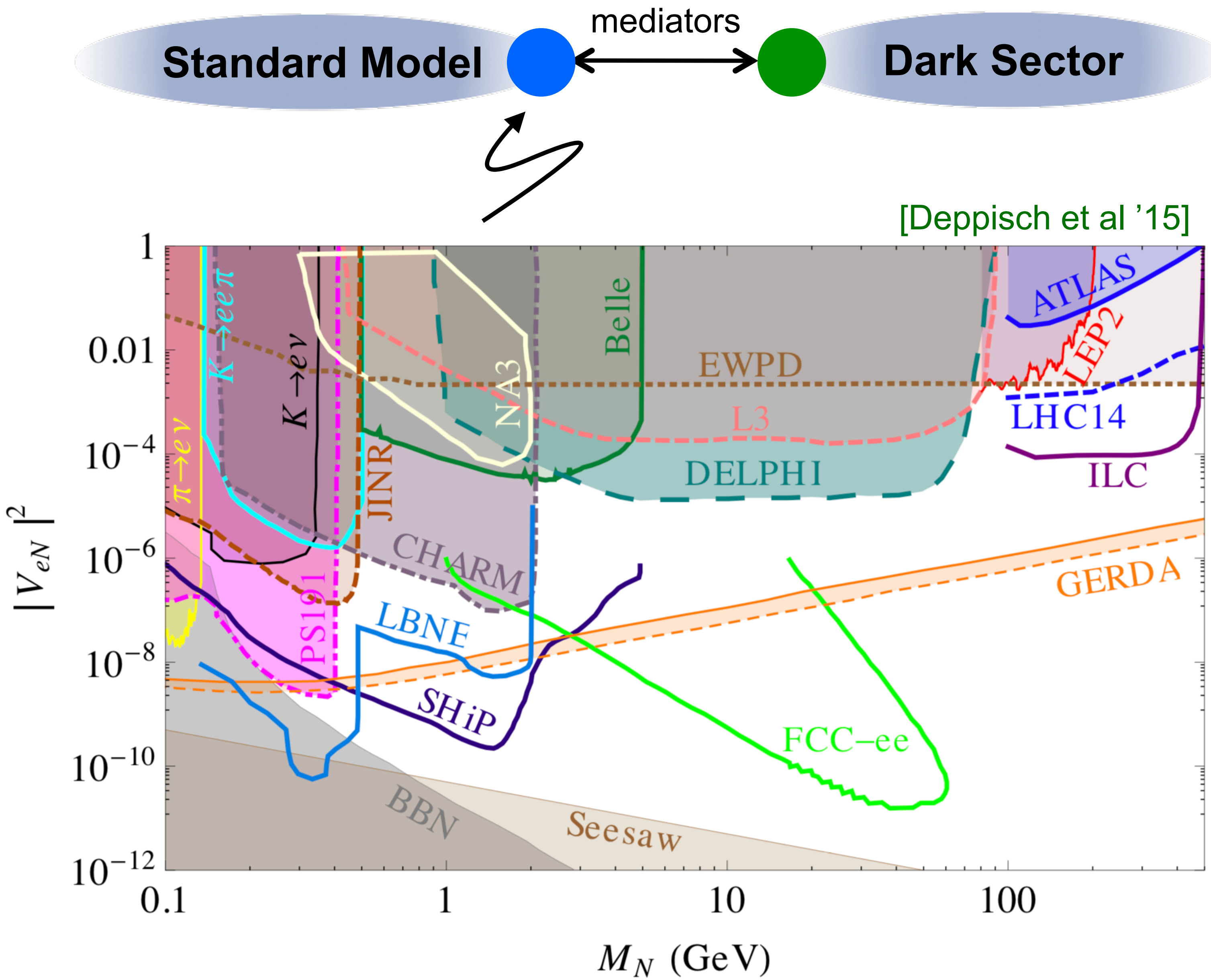
E.g. BBN/CMB (vector portal)



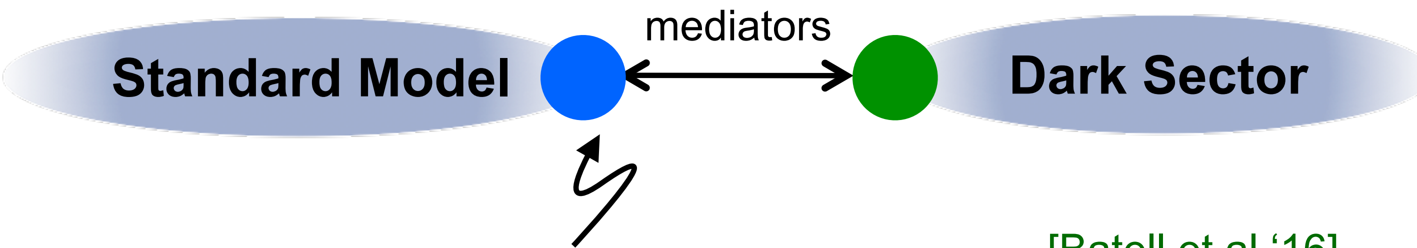


Late decay
& energy
injection

E.g. precision/rare decays (neutrino portal)

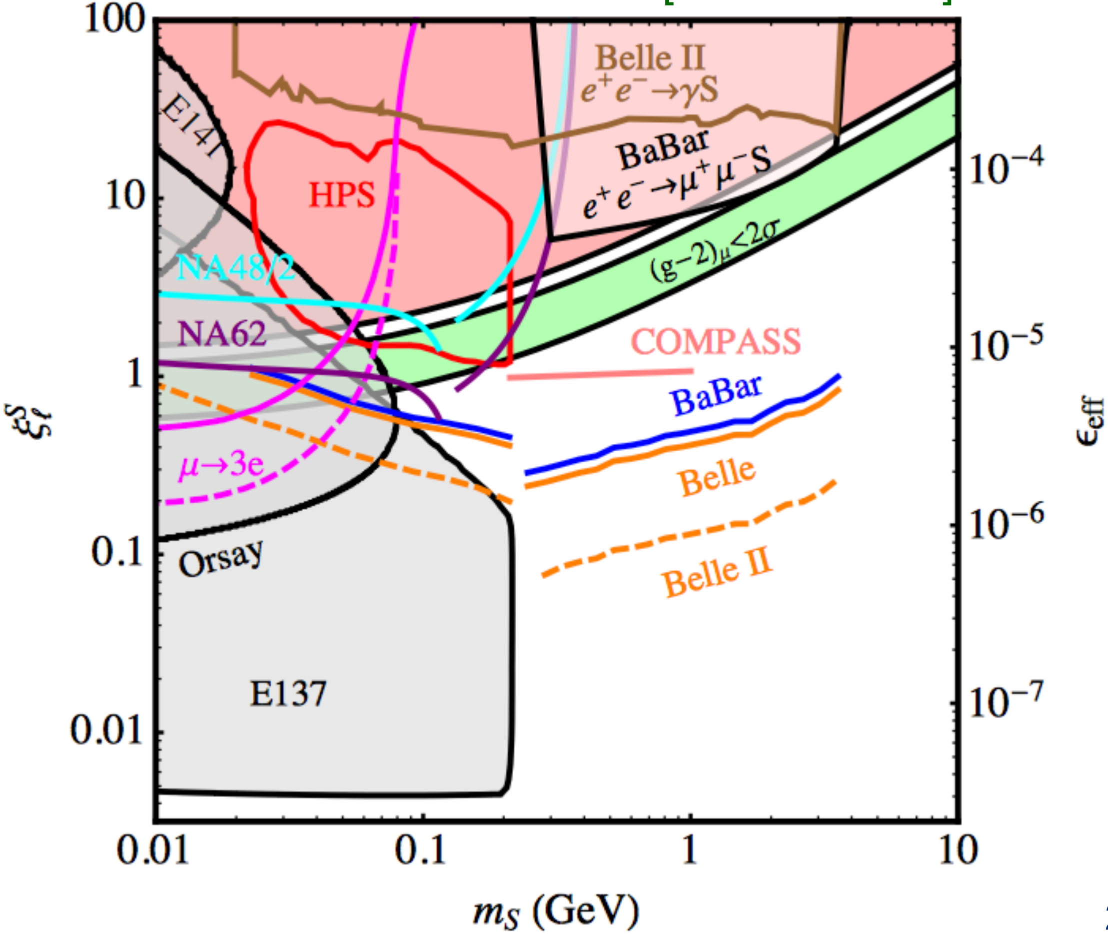


E.g. precision/rare decays (Higgs portal)



Minimal Higgs portal ➠ strong constraints due to ($b \rightarrow s+S$) mediated transitions. The "leptonic Higgs portal" $g_l S l l$, requires UV completion, but can be more viable

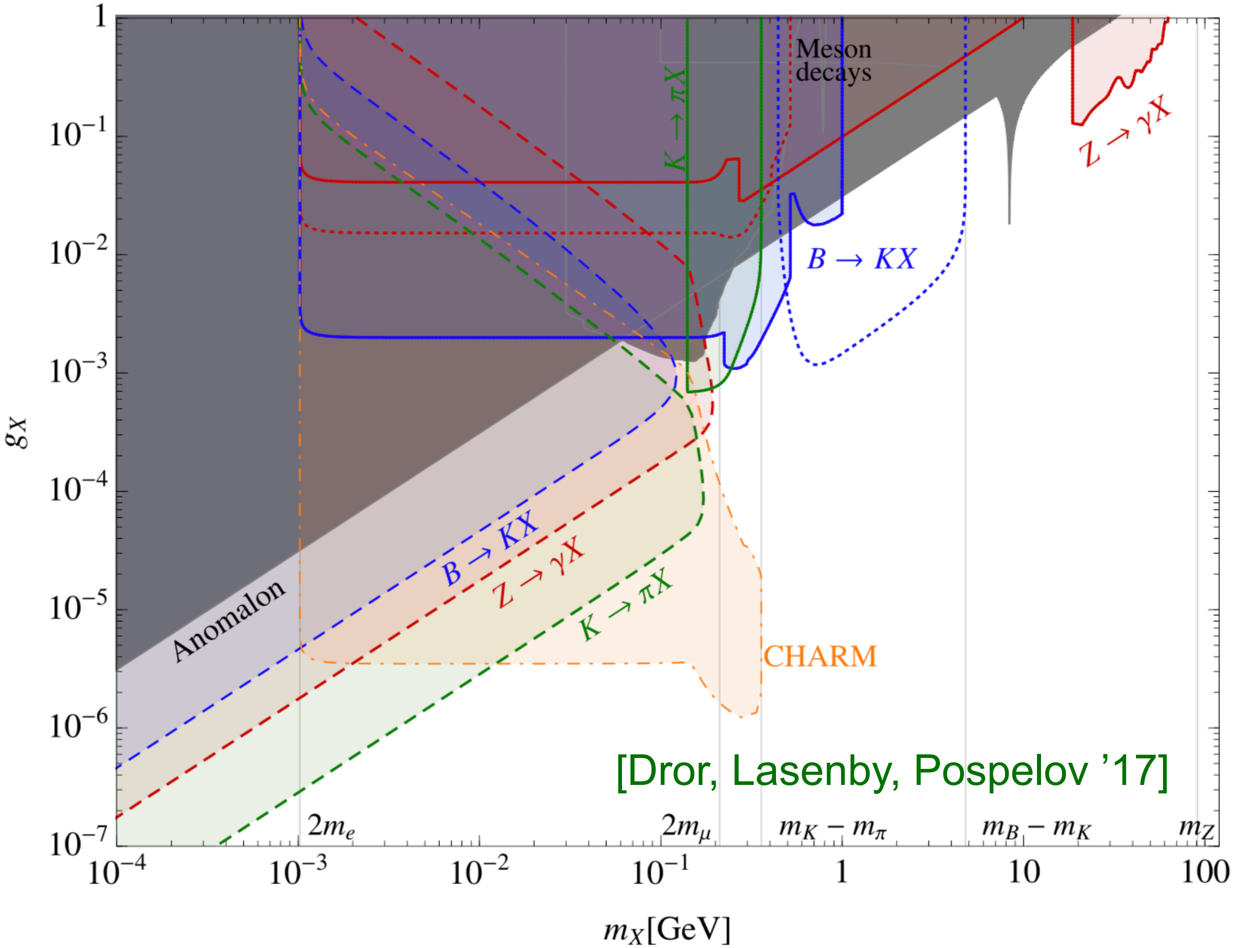
[Batell et al '16]



Beyond (dim ≤ 4) portals…

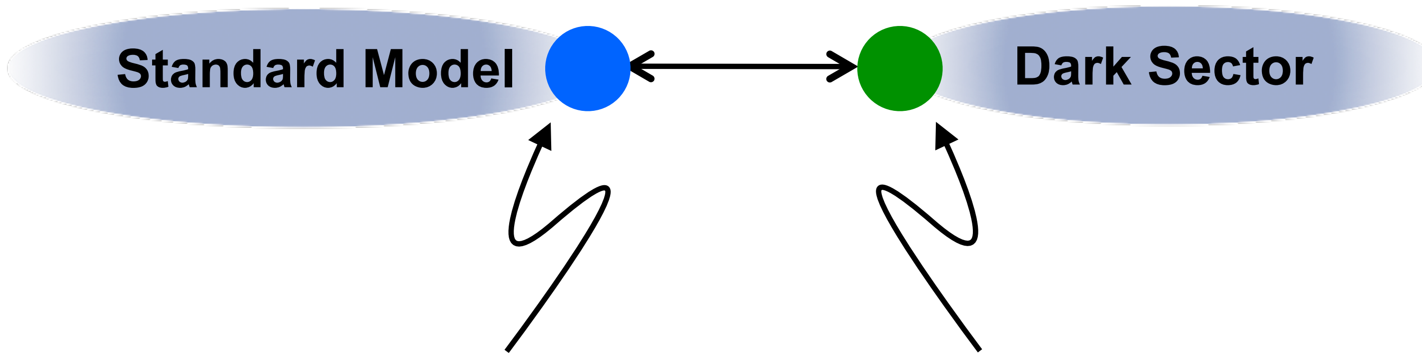
Other light dark forces, e.g. coupled to anomalous currents, generally inherit extra constraints, e.g. for a baryonic U(1)'

$$\mathcal{L} \supset C_B g_X g'^2 \epsilon^{\mu\nu\rho\sigma} X_\mu B_\nu \partial_\rho B_\sigma$$
$$+ C_W g_X g^2 \epsilon^{\mu\nu\rho\sigma} X_\mu (W^a_\nu \partial_\rho W^a_\sigma + \frac{1}{3} g \epsilon^{abc} W^a_\nu W^b_\rho W^c_\sigma)$$



[Dror, Lasenby, Pospelov '17]

Some experimental signatures



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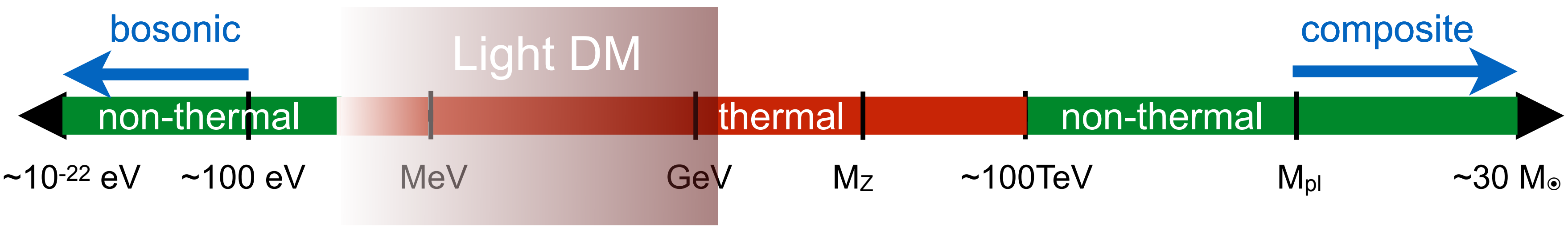
DM Models!

DM detection signatures



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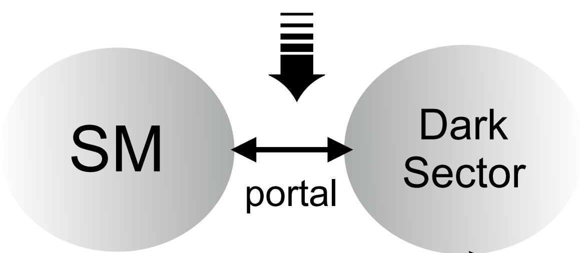
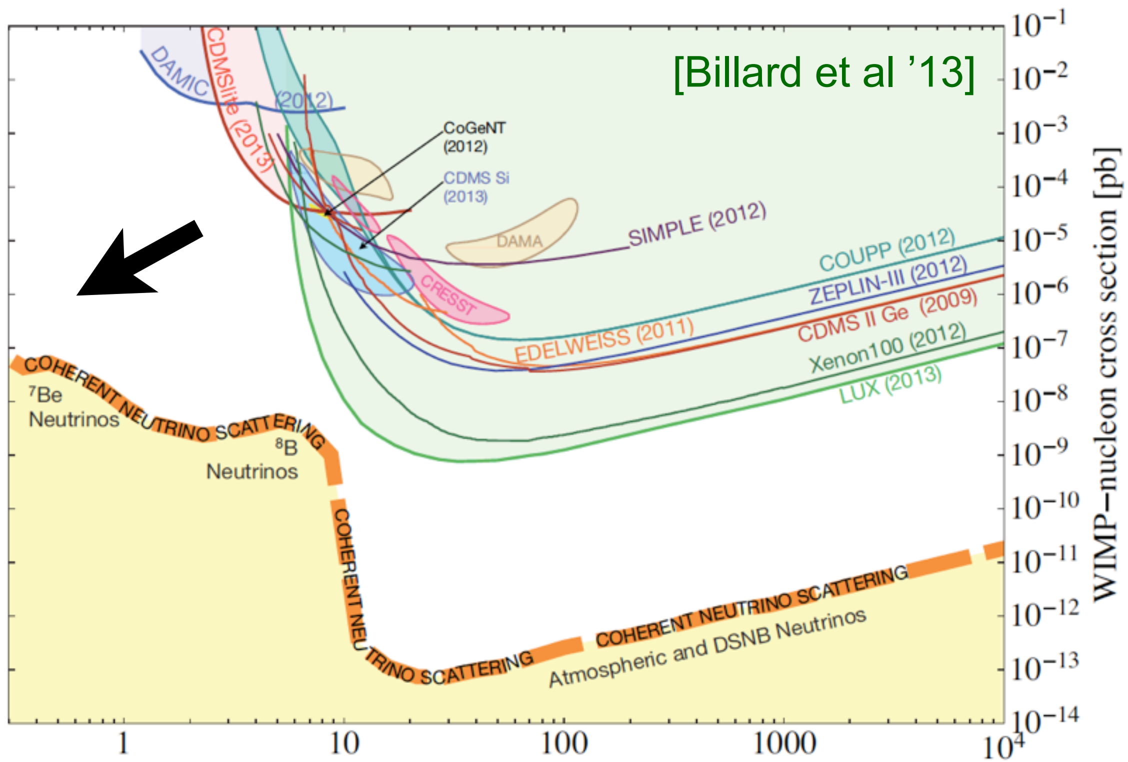
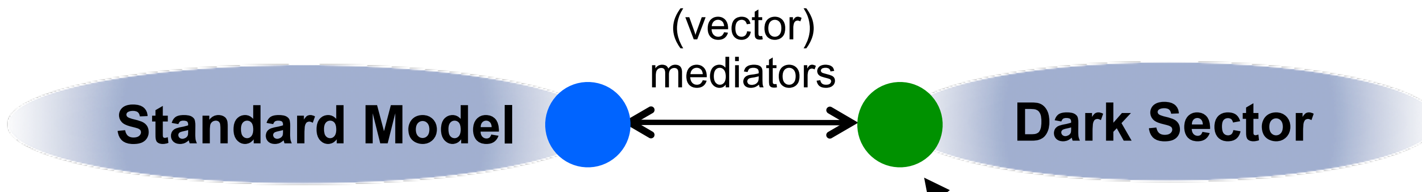
- $\sigma_{ann} \propto m_{DM}^2/m_{med}^4$ so Lee-Weinberg bound ➠ light mediators are required for freeze out with the required relic abundance



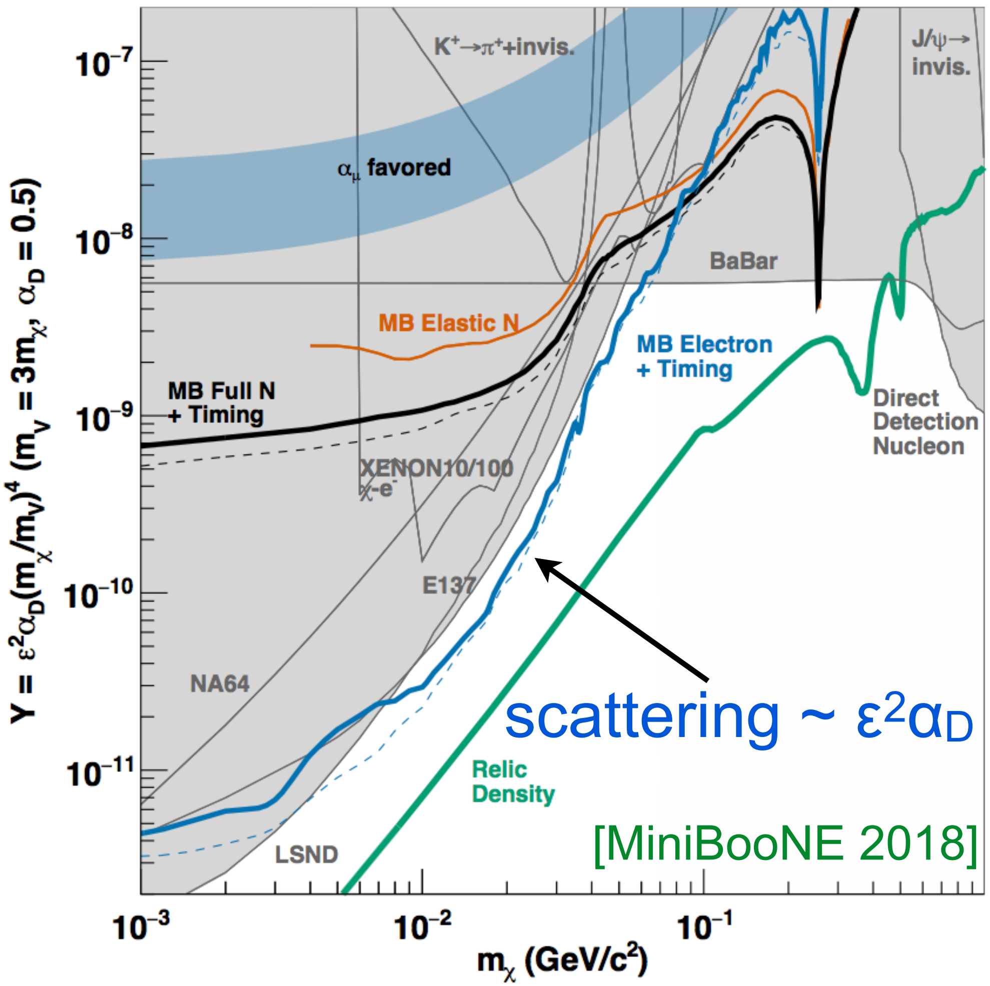


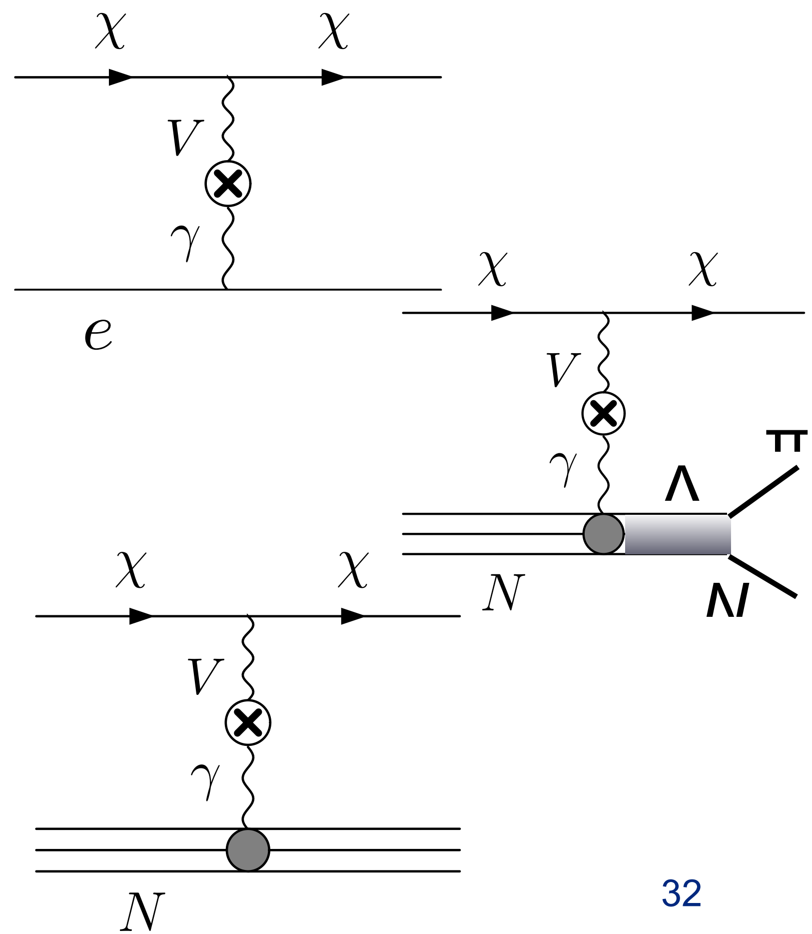
sub-GeV DM benchmark - scalar/pseudo-Dirac fields charged under a dark U(1)' [Boehm & Fayet, Batell, Pospelov, AR, deNiverville, McKeen, Essig, Schuster, Toro, Izaguirre, Krnjaic, Kahn, Morrissey, Zurek, …]

Light DM (vector portal mediator)

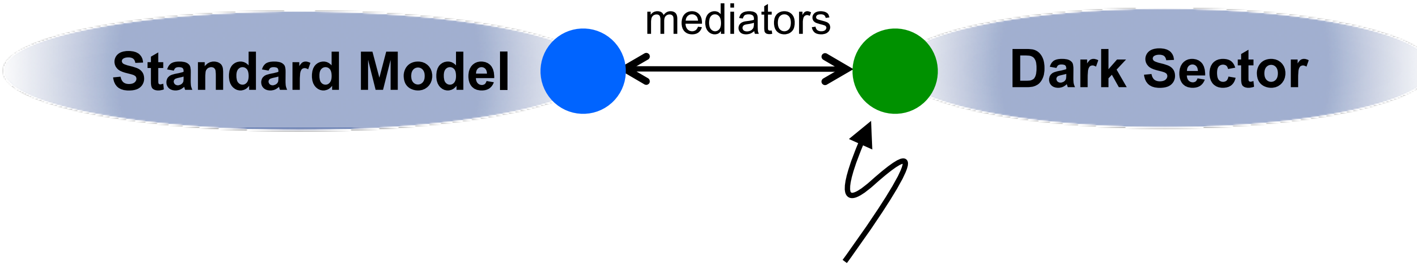


Production via A'(*) → χχ



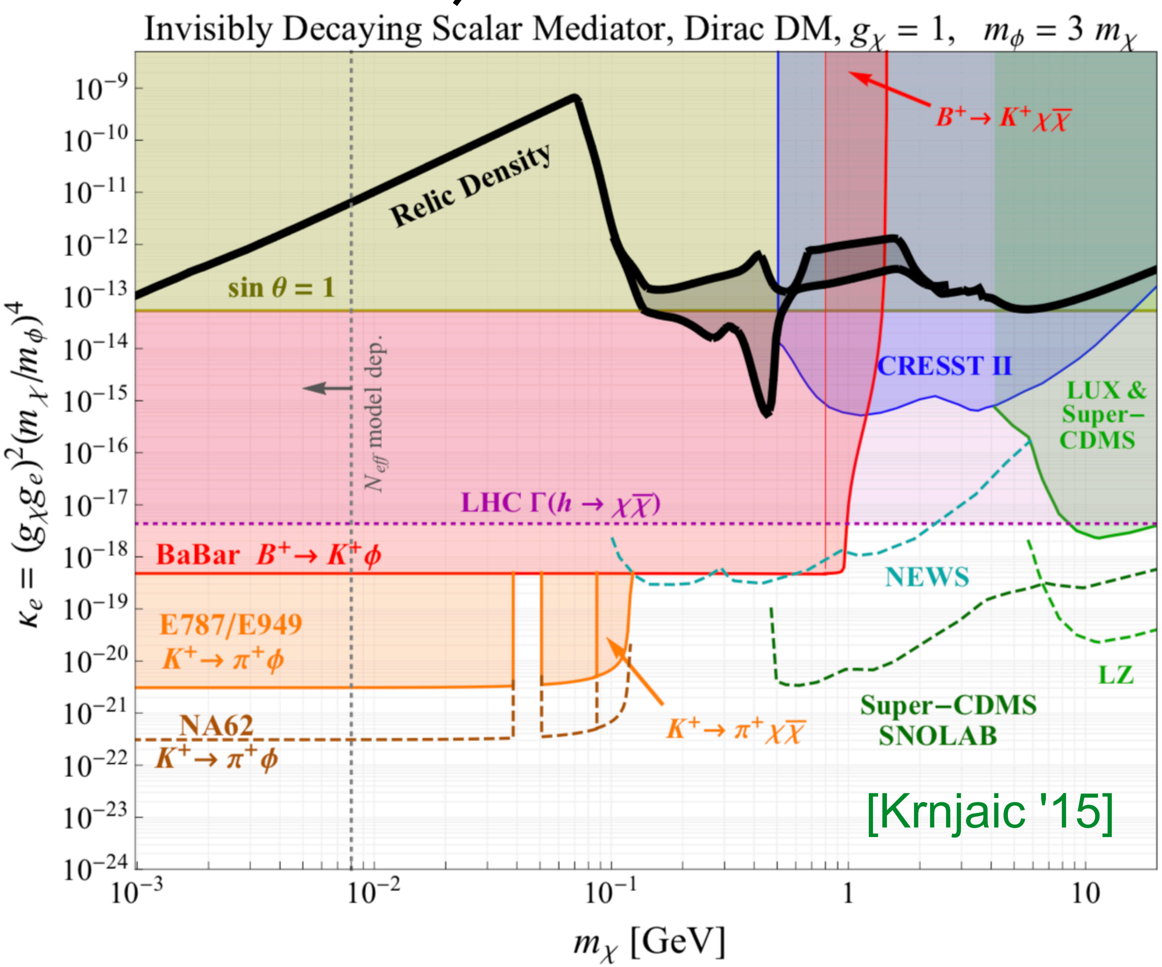


Light DM (Higgs portal)

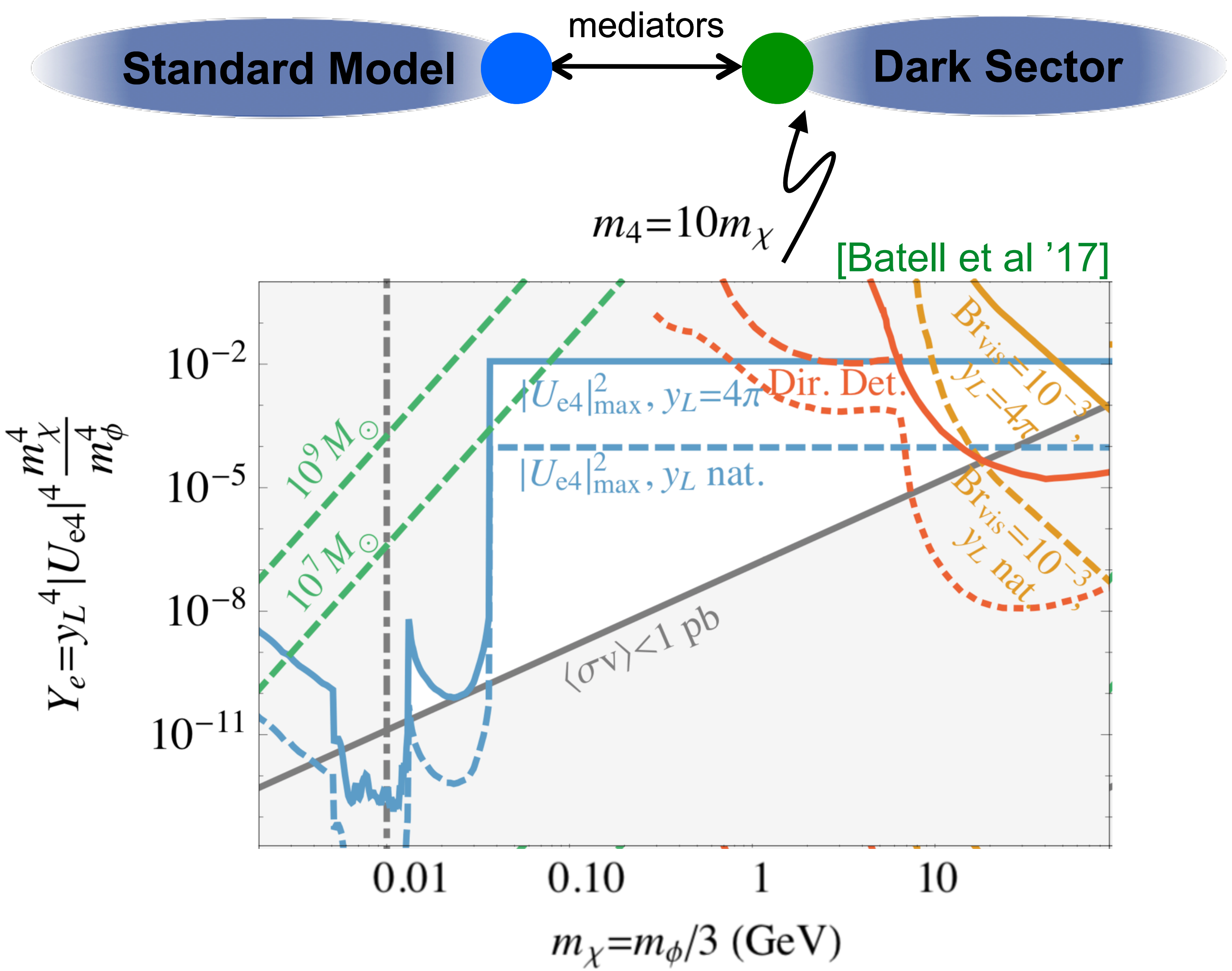


Highly constrained, due to constraints on B, K decays

[Boehm & Fayet; deNiverville et al '12; Krnjaic '15]

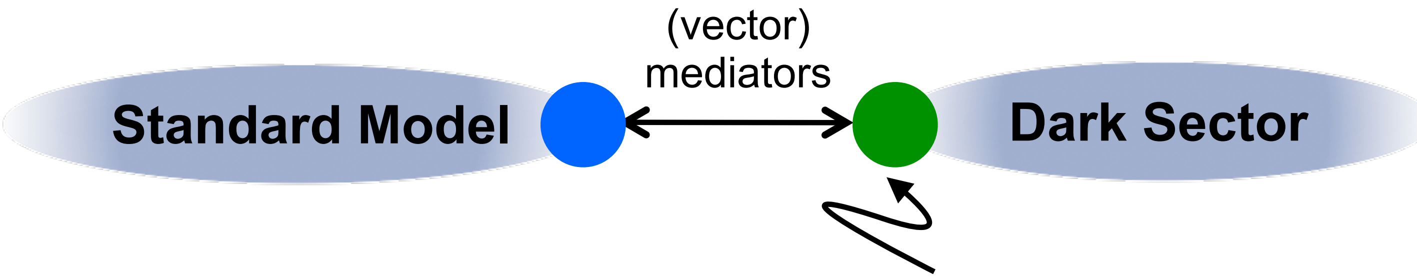


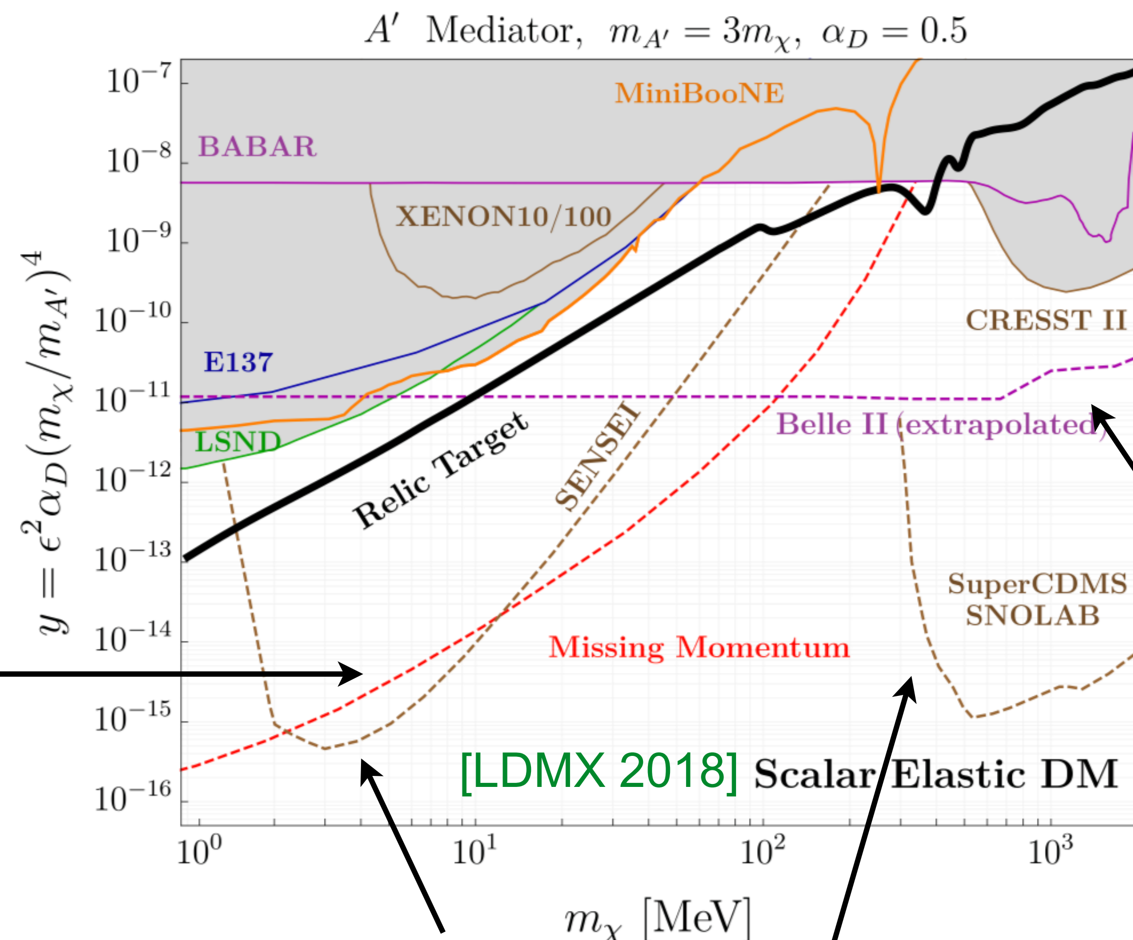
Light DM (Dirac Neutrino portal)



[Bertoni et al '14; Batell et al '17]

Prospects - vector portal DM





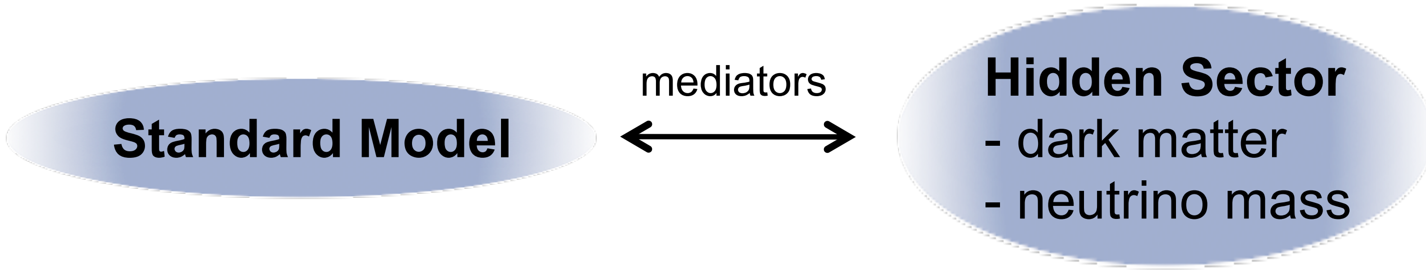
[LDMX 2018]

p_{miss} (LDMX)

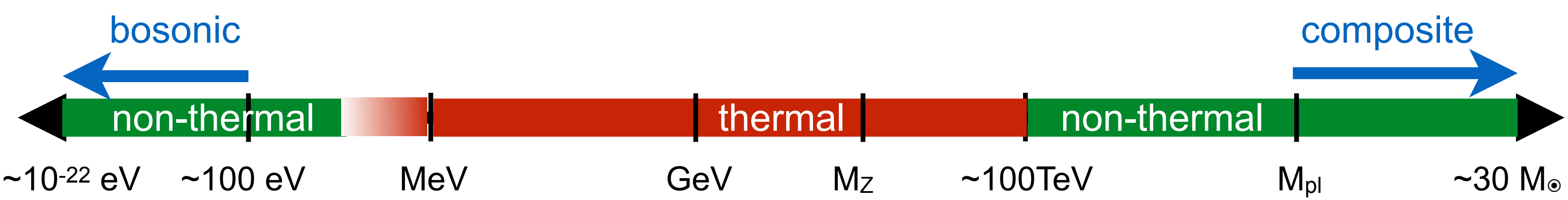
E_{miss} (Belle II)

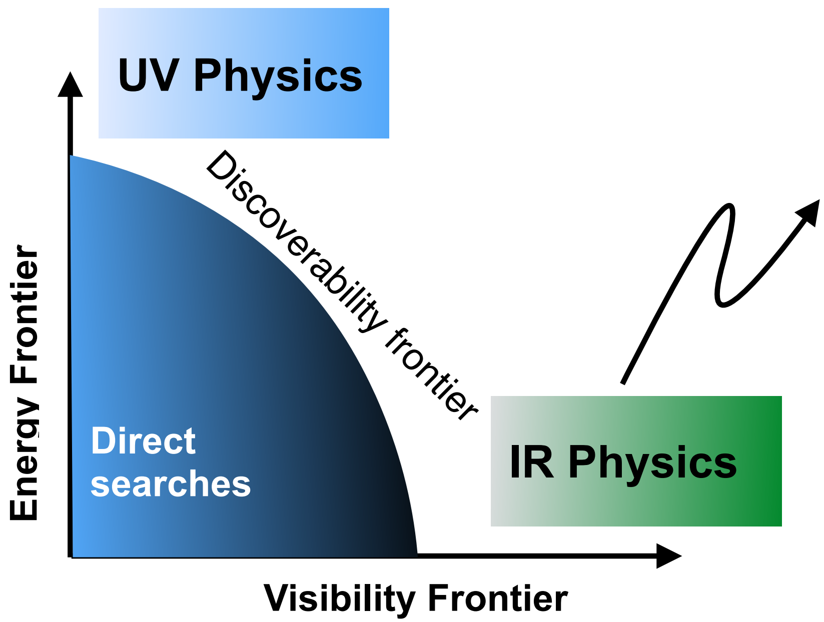
Direct detection (e/N scattering)

Summary



Empirical motivations for new physics suggest dark/hidden sectors, which can contain light (sub-EW scale) degrees of freedom:





- EFT arguments focus attention on the UV-complete *portal interactions*

  ➡ Expanded theoretical landscape e.g. for (low mass) particle DM, requiring new complementary search strategies, with growing experimental efforts at the precision and intensity frontier over the past decade