UK Annual Theory Meeting 2019 - IPPP, Durham U

Light Dark Sectors

Adam Ritz

University of Victoria

Looking for new physics where we can see it…

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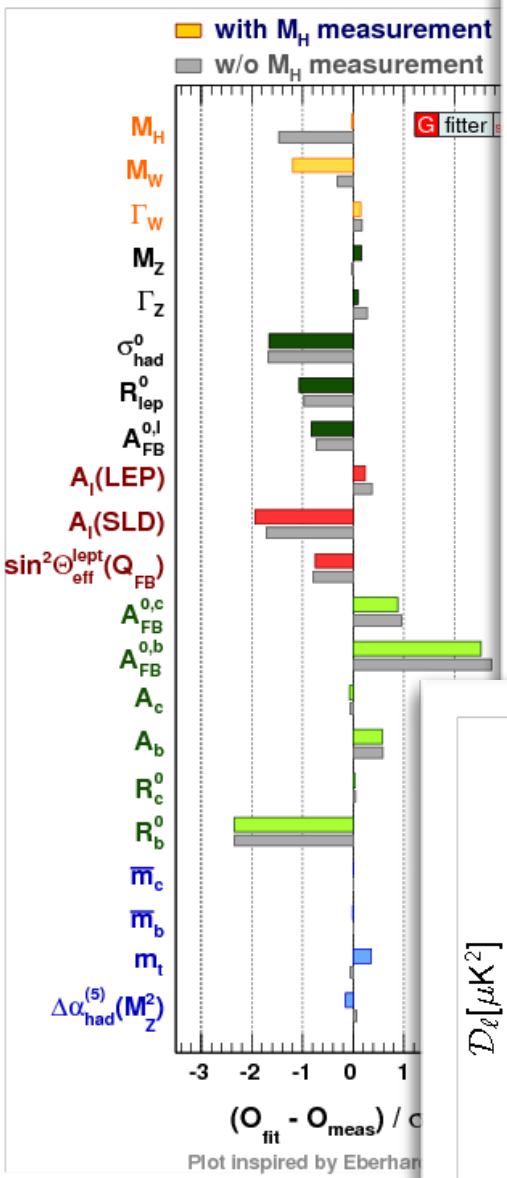
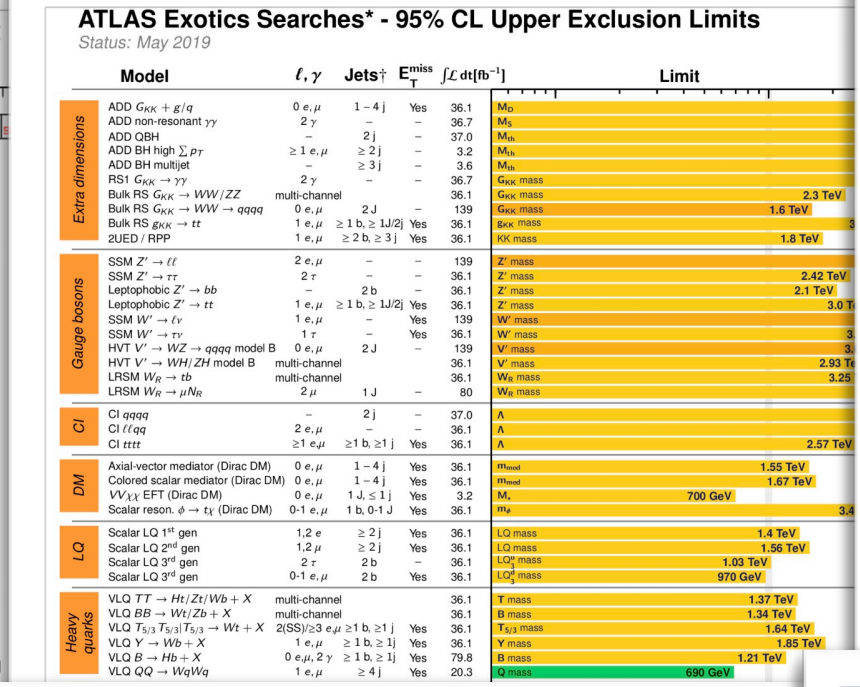
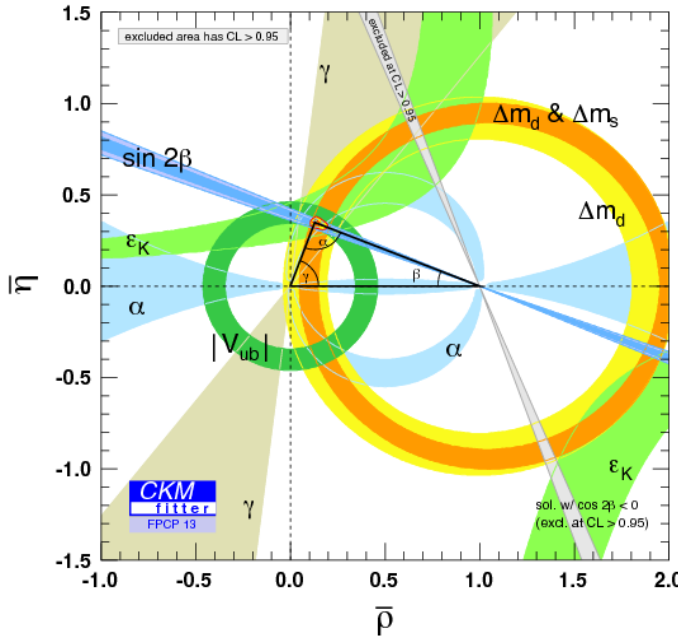
Electroweak



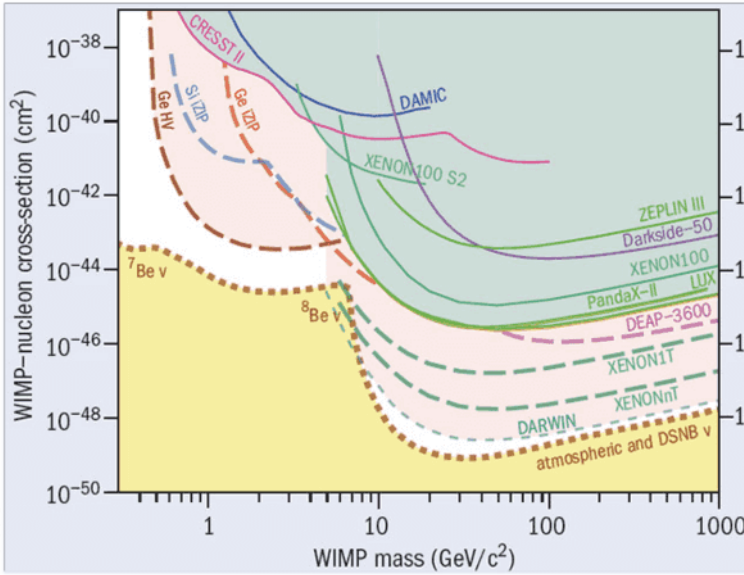
Energy frontier



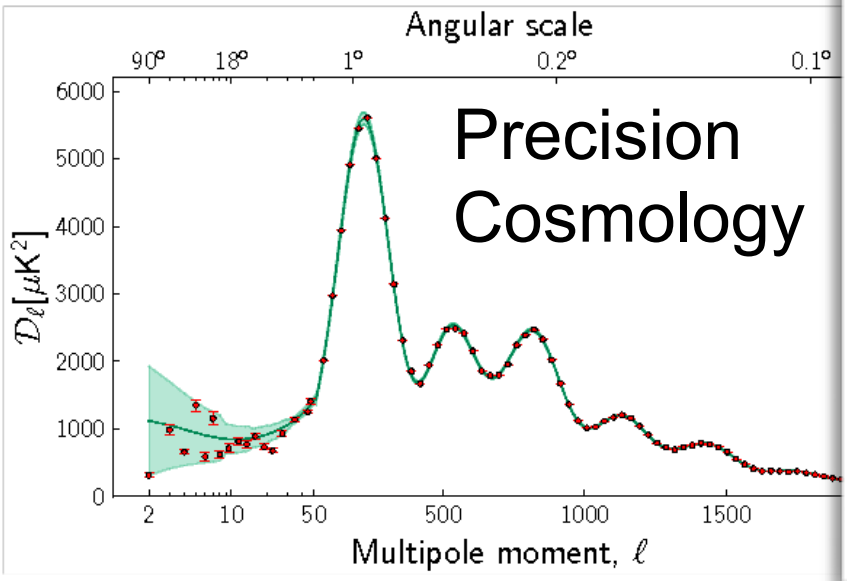
Flavour



DM direct detection



Precision Cosmology



Looking for new physics where we can see it…

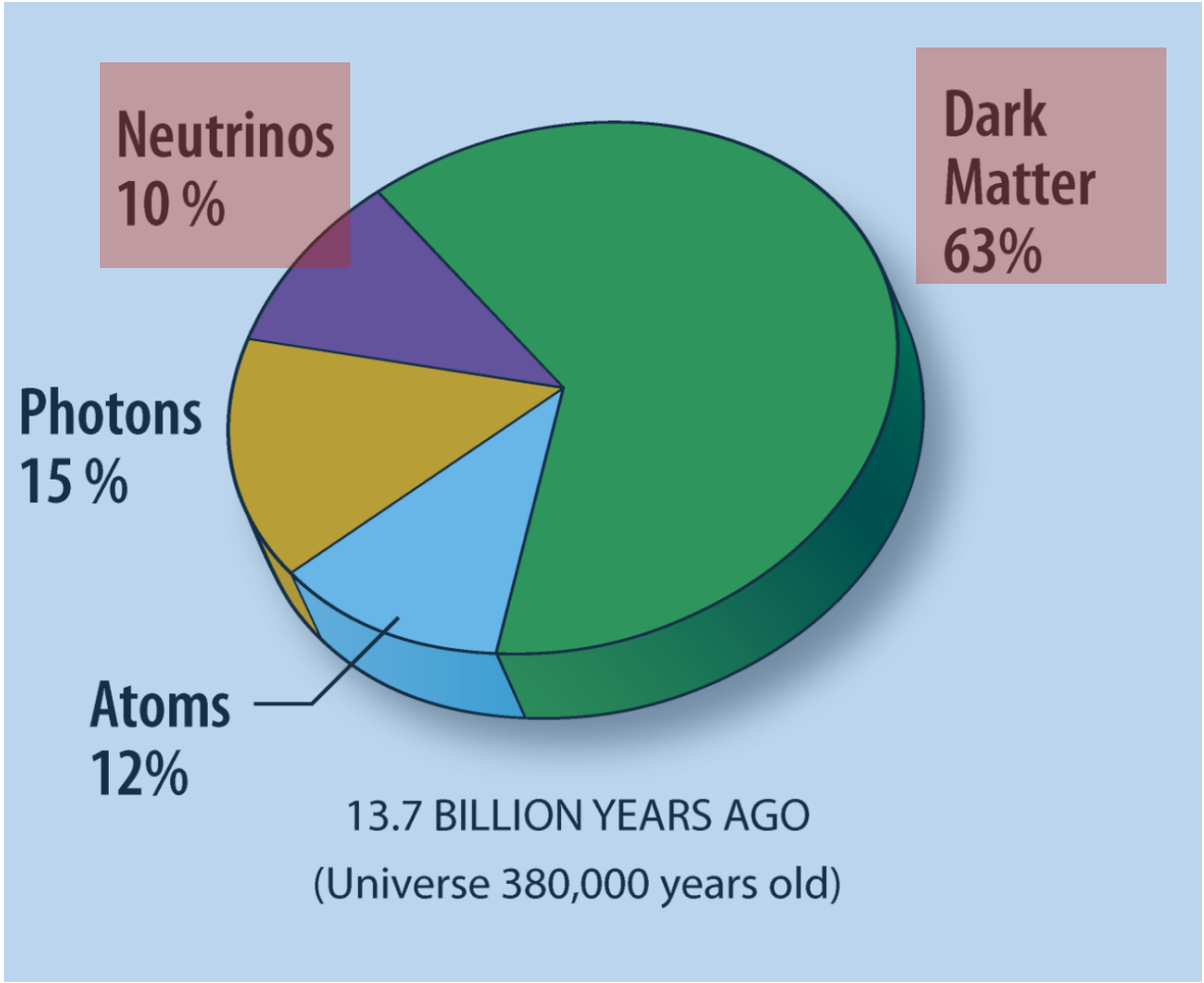
Precision ΛCDM cosmology + lack of evidence for new weak scale physics…

(Also various data-driven anomalies…)

A pragmatic approach - loosening of theoretical priors over the past decade, focusing on the strongest empirical evidence for new physics, and all observational channels (“lamps”)

Questions…

The Standard Model is highly successful, but there is sharp empirical evidence for new physics…



Neutrino mass?

What is DM?

What we do(n't) know about DM

Citation: K. Nakamura et al. (Particle Data Group), JPG **37**, 075021 (2010) (URL: http://pdg.lbl.gov)

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u}+d\overline{d})+c_2(s\overline{s})$

$\pi^\pm$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^\pm \to \ell^\pm \nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70

[Ibarra]

DARK MATTER

$J =$?

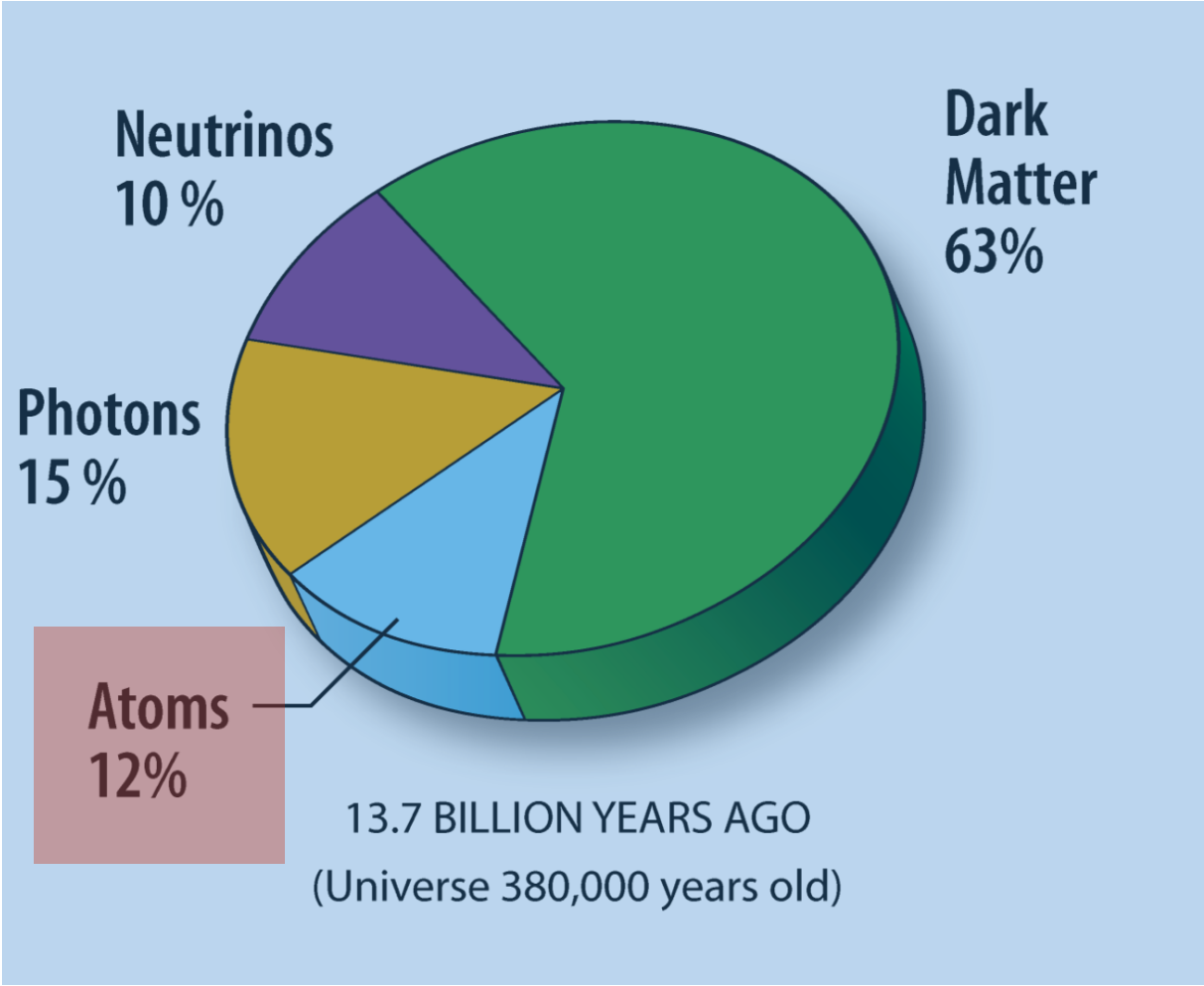
Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

- Relic density ~ 5 x baryons
- Cold enough…
- Dark enough…
- Vast theoretical scope…

Questions…

The Standard Model is highly successful, but there is sharp empirical evidence for new physics…



Baryonic sector is "known", but still requires new physics for baryogenesis…

Questions…

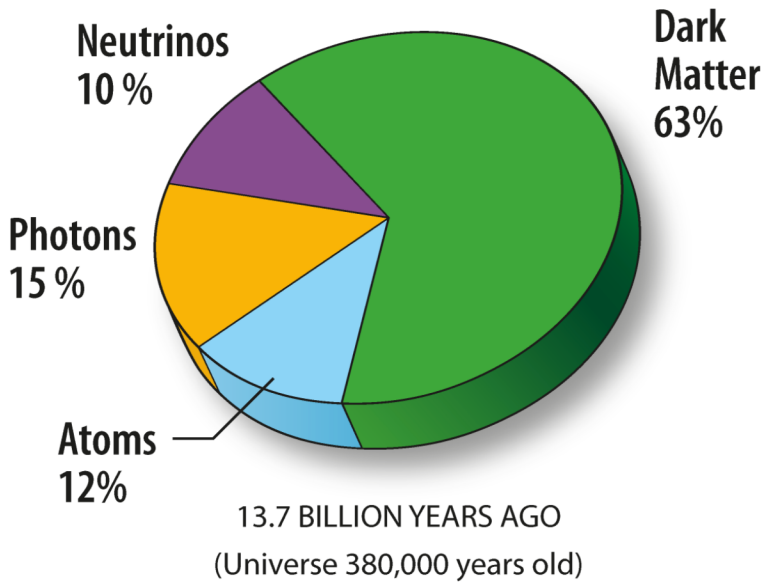
Sakharov's criteria for generating a baryon asymmetry are over 50 years old!

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…

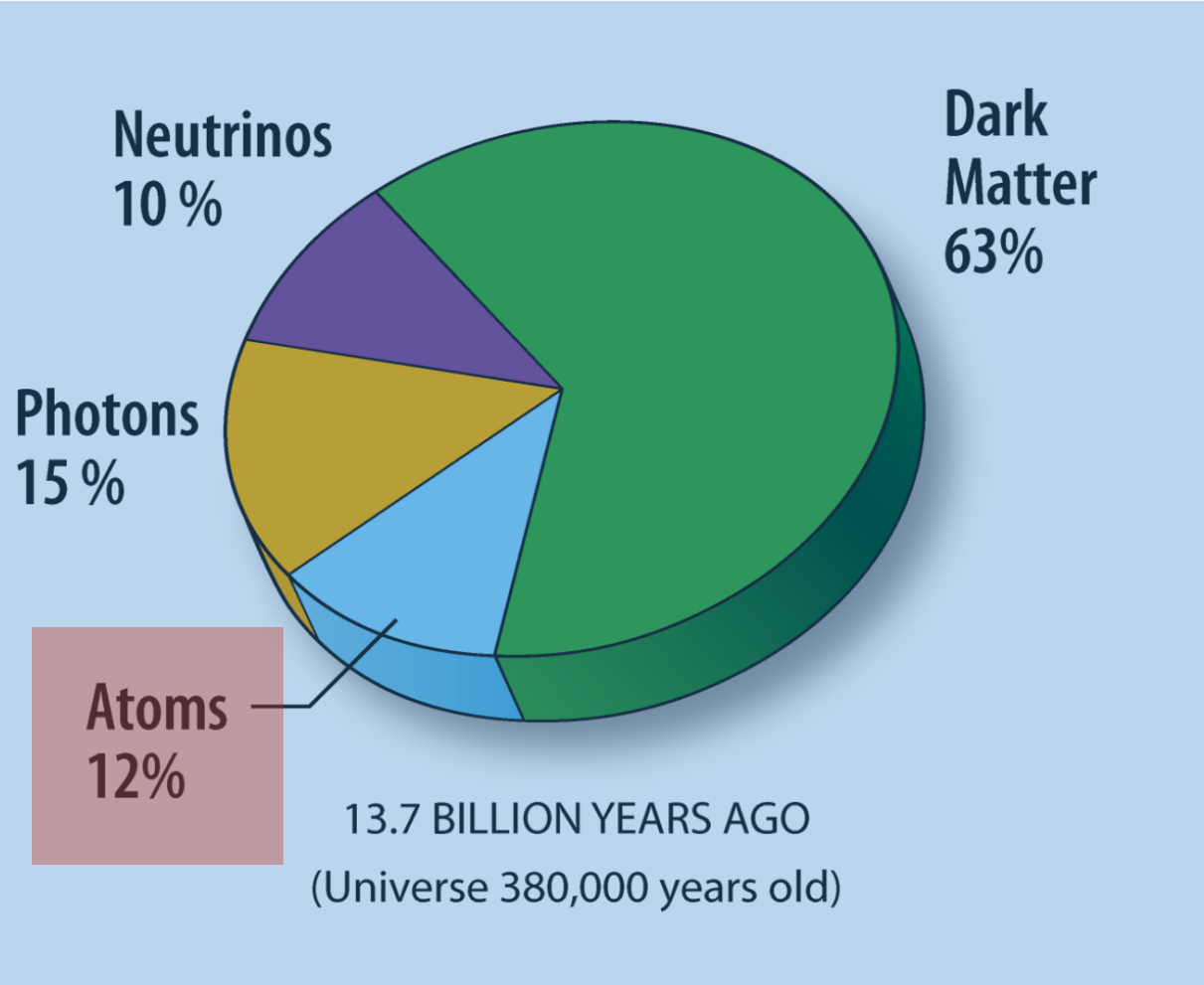


Questions

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

Questions…

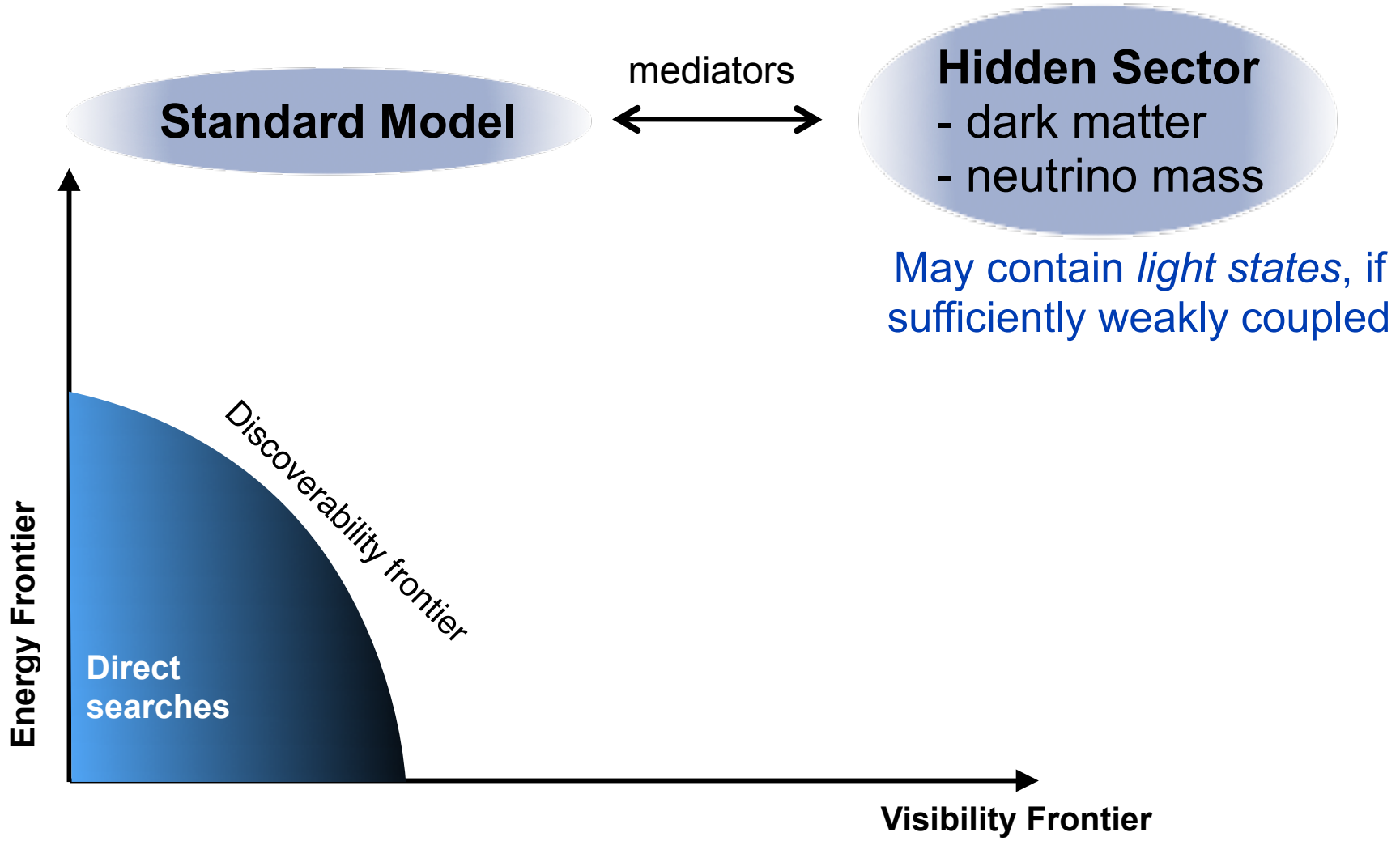
The Standard Model is highly successful, but there is sharp empirical evidence for new physics…



Baryonic sector is complex. Is it special, or should we also expect the DM sector (dark sector) to be complex also?

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 mass scale



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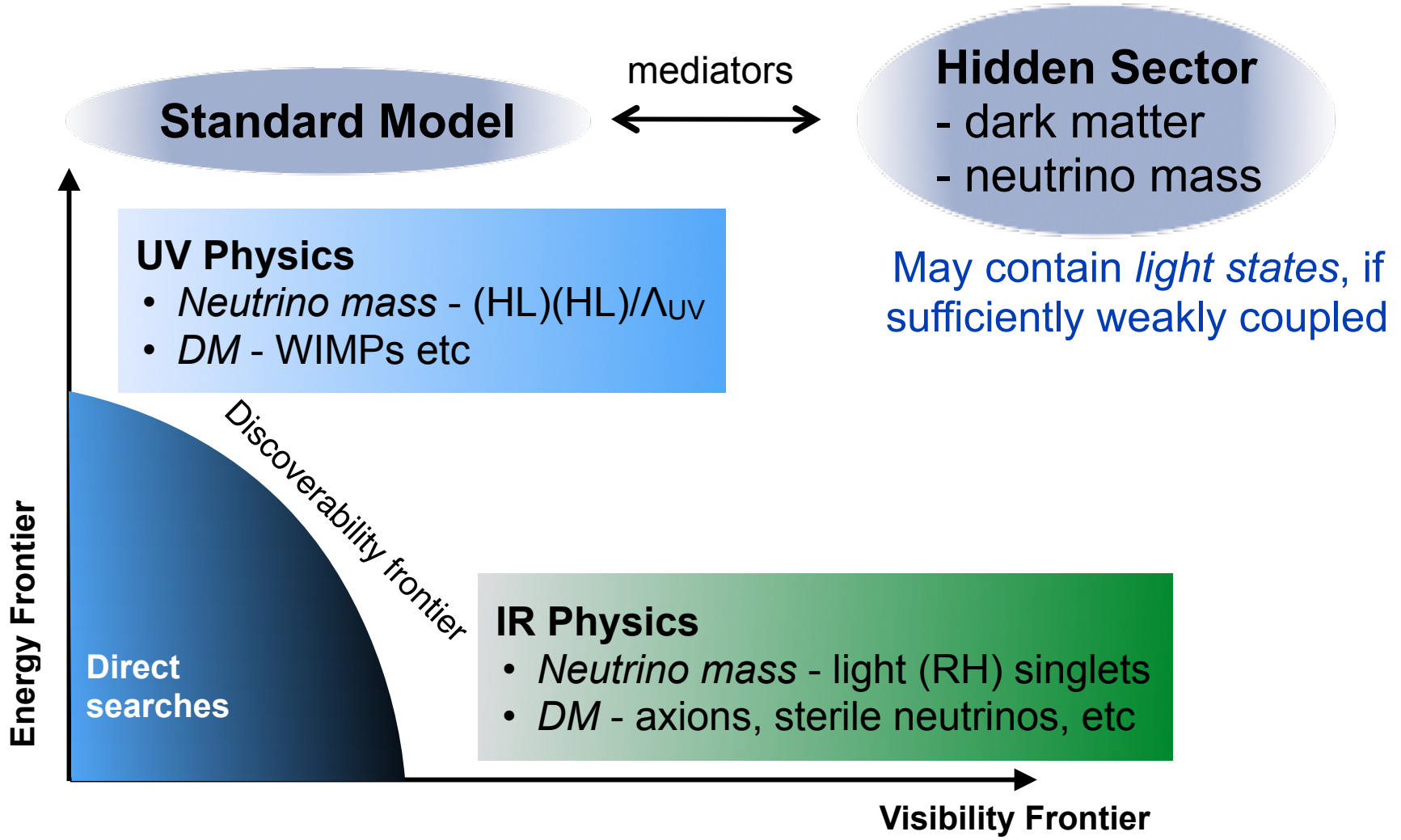
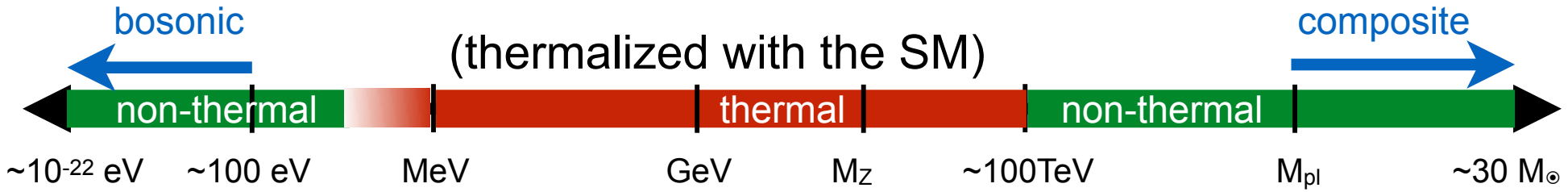


➠ a huge parameter space a priori, so what theoretical guidance is there?

Cold DM Landscape

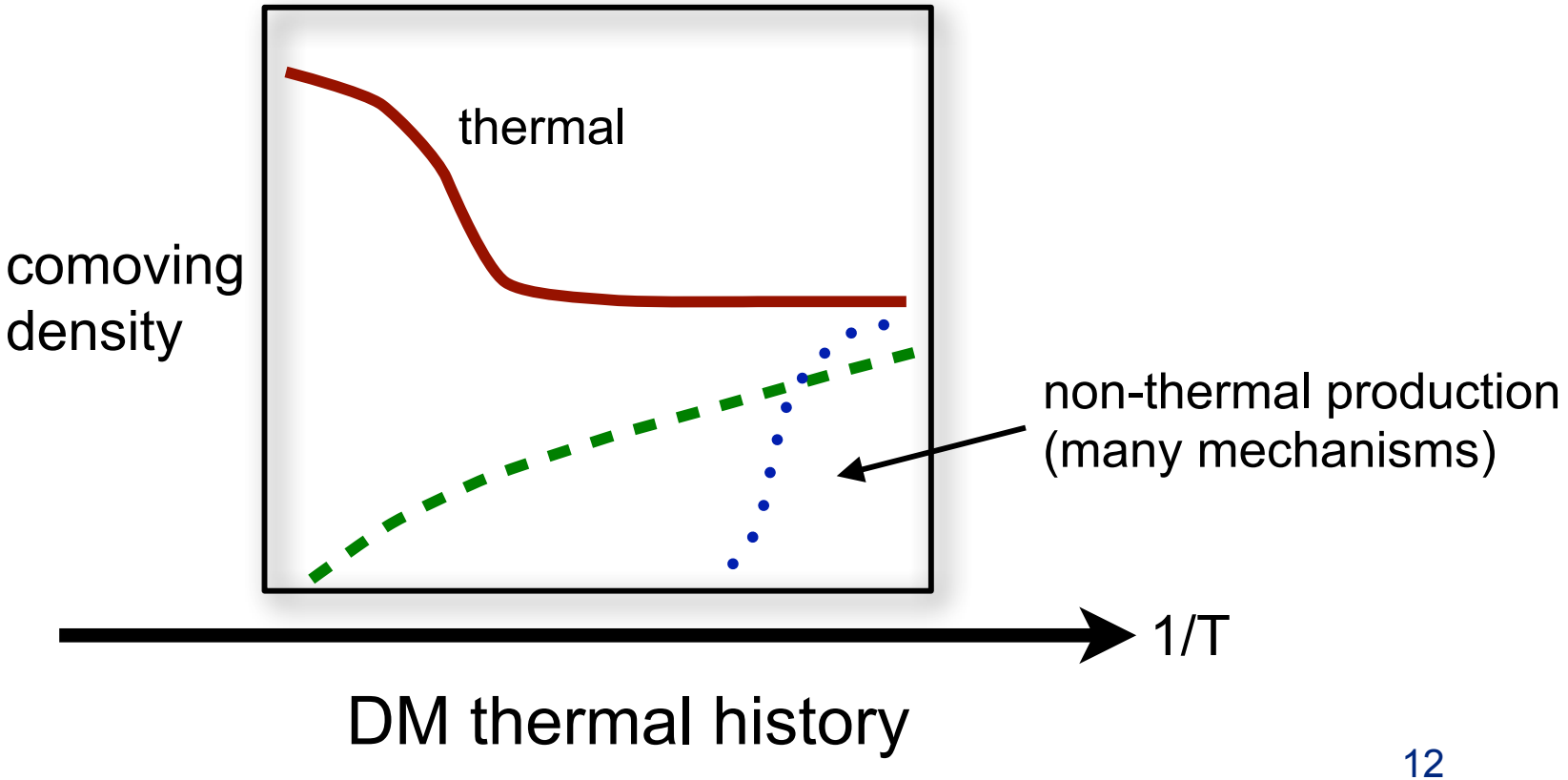
Classify models according to their thermal history in the early universe



e.g. sterile neutrinos, axions, etc

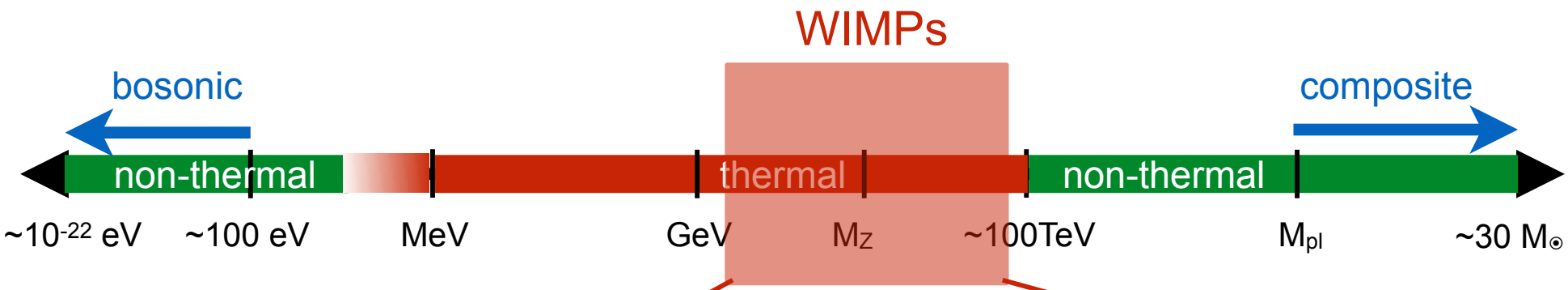
e.g. WIMPs

e.g. primordial BHs



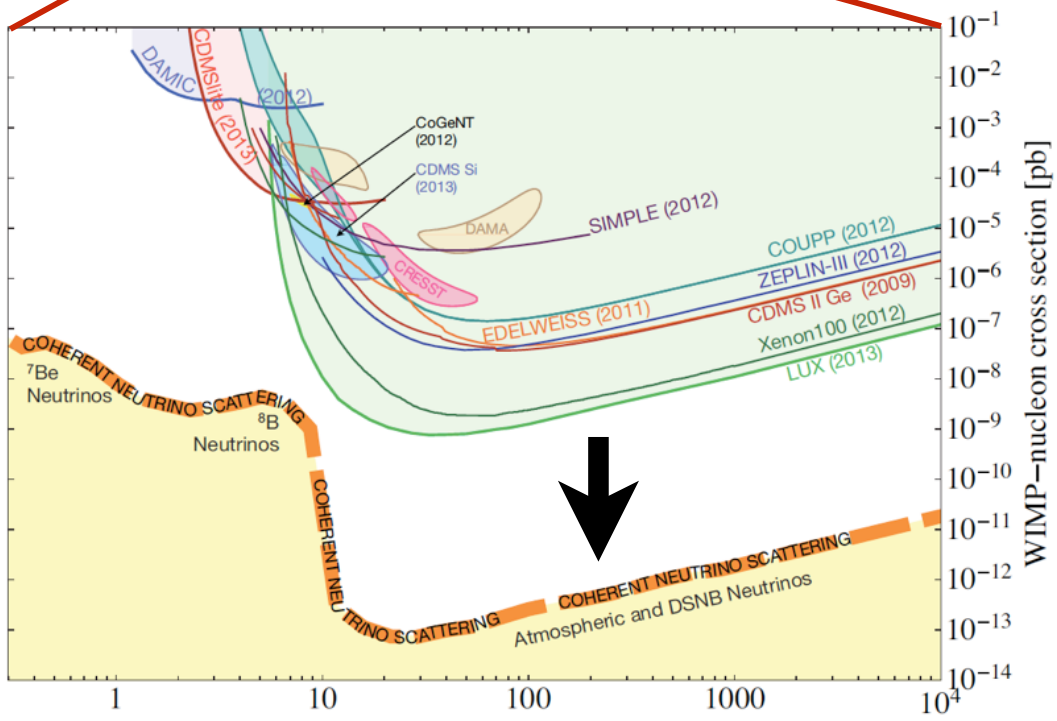
DM thermal history

Cold DM Landscape



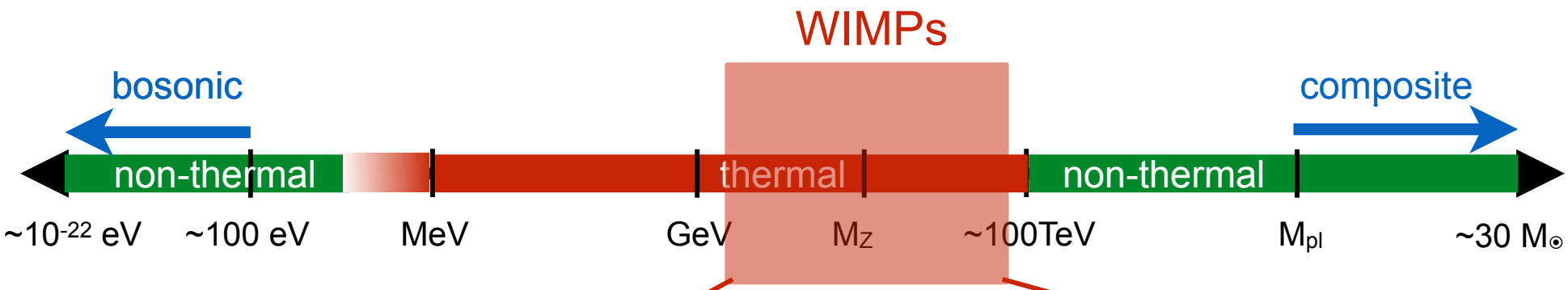
Natural starting point:

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

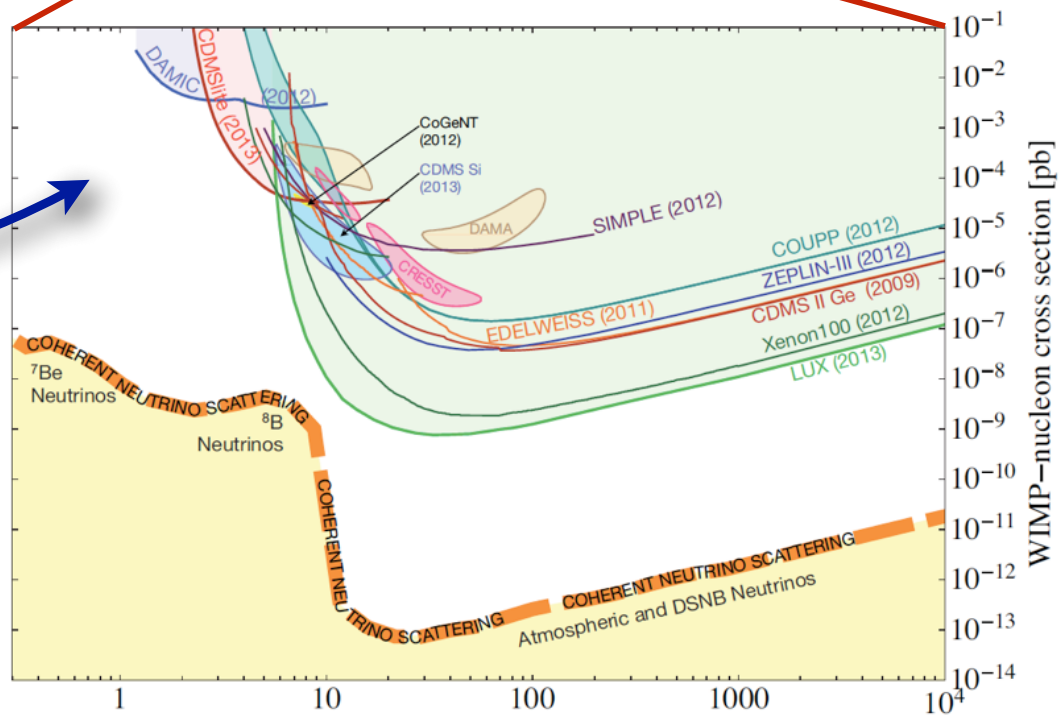


[Billard et al '13]

Cold DM Landscape



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



[Billard et al '13]

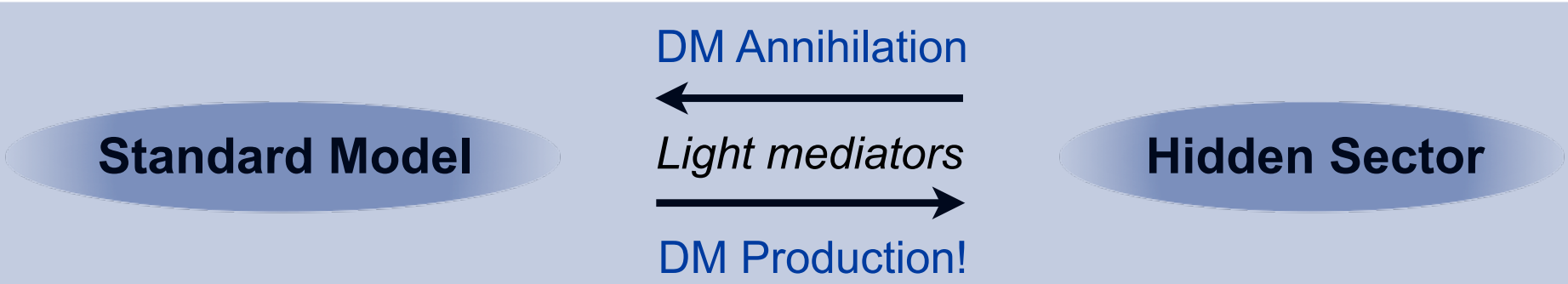
Light (thermal relic) DM

The Lee-Weinberg bound (WIMP mass ≥ few GeV) applies if annihilation in the early universe is via SM forces.

$$\sigma_{\rm ann} \propto \frac{m_{\rm DM}^2}{M_{\rm mediator}^4}$$

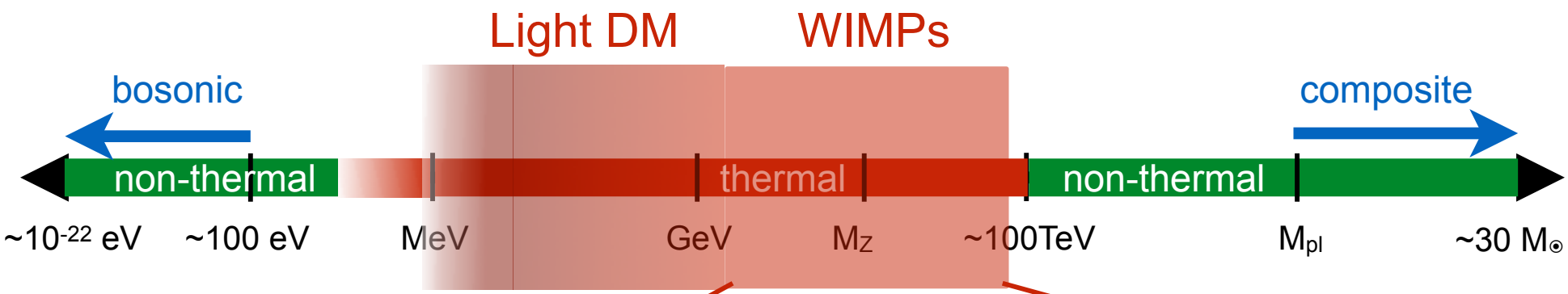
⇒ viable thermal relic density for a sub-GeV WIMP requires new annihilation channels through light states, i.e. light DM as part of a hidden sector.

[Boehm et al '03, Fayet '04,'06; Pospelov, AR, Voloshin '07; Hooper & Zurek '08]



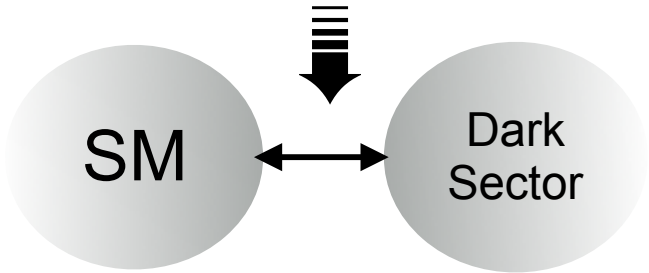
➪ by inversion, light mediators allow direct production of DM at ***low energy!***

Cold DM Landscape

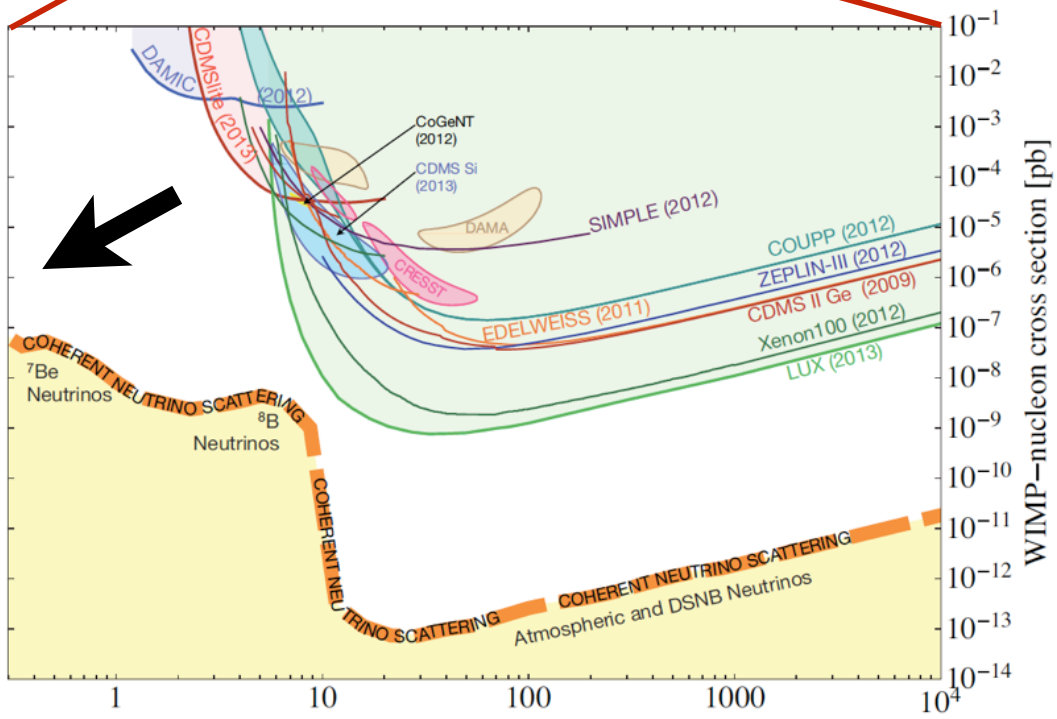


WIMP-like thermal relic

- requires light mediators to thermalize with SM



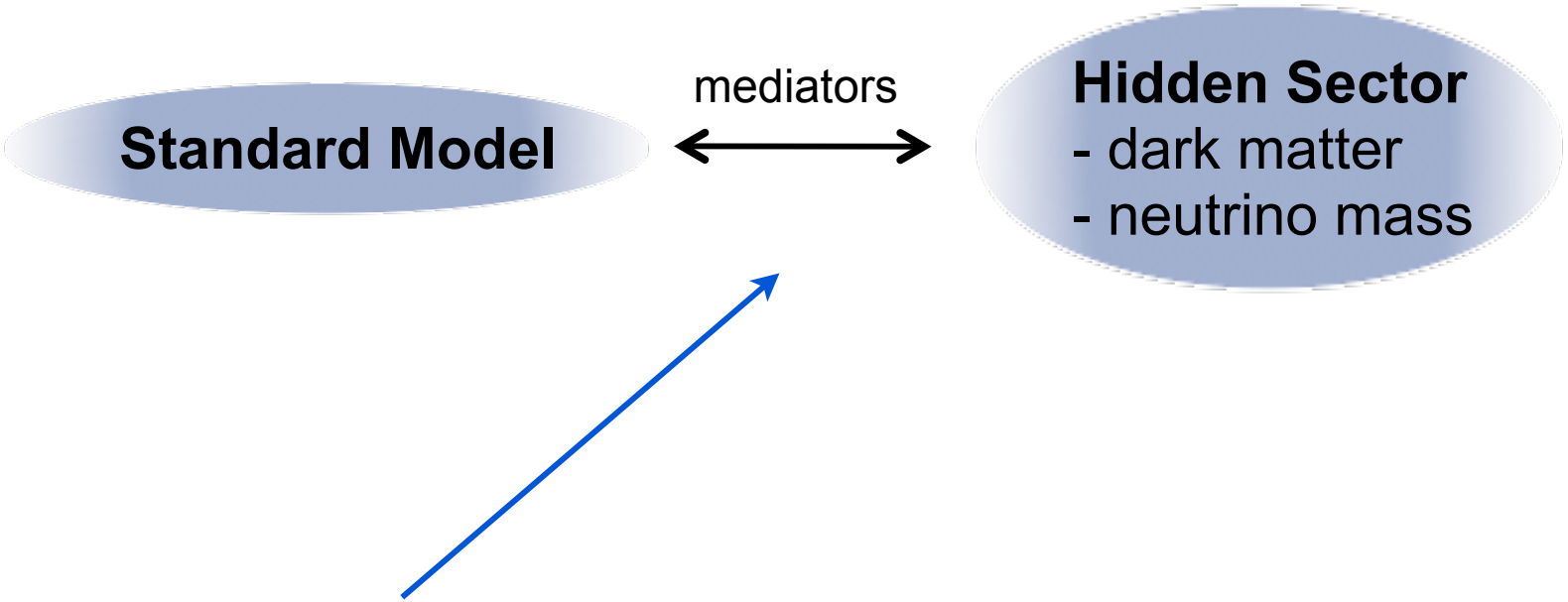
Necessarily requires a more complex dark sector



[Billard et al '13]

EFT for a (neutral) hidden sector

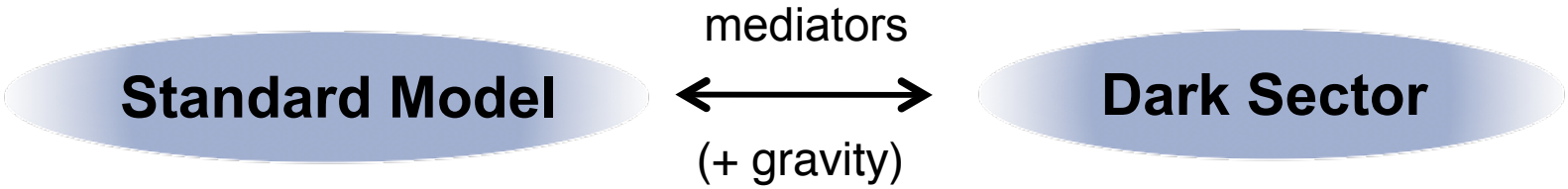
Given a very large ‘model-space’ a priori, its useful to develop an EFT expansion, assuming the hidden sector is *SM-neutral*



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



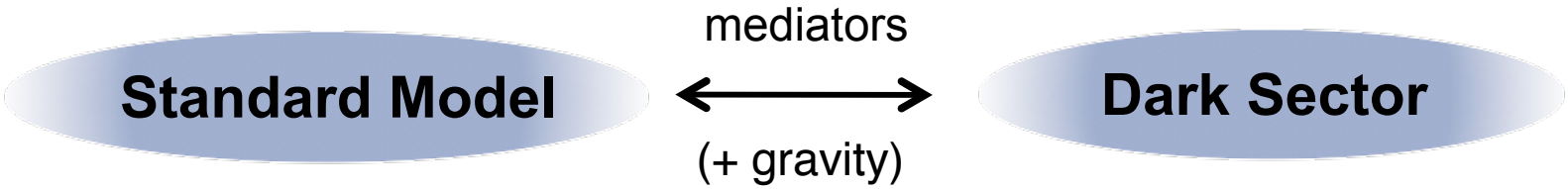
Generic interactions are irrelevant (dimension > 4), but there are three ***UV-complete relevant or marginal "portals"*** to a ***neutral hidden sector***, unsuppressed by the (possibly large) NP scale Λ

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

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

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

EFT for a (neutral) hidden sector



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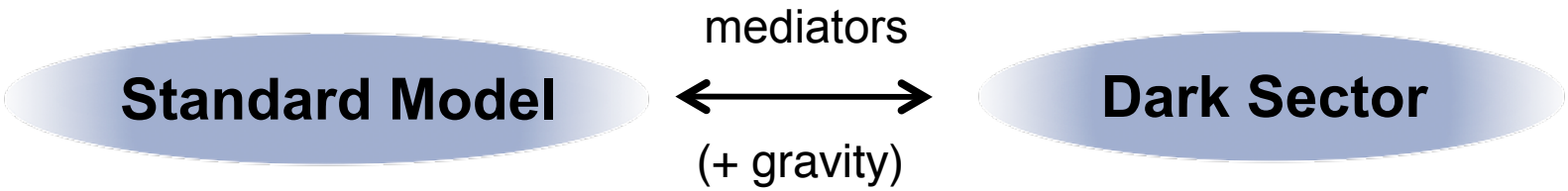
Vector portal
[Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal
[Patt & Wilczek]

Neutrino portal

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]

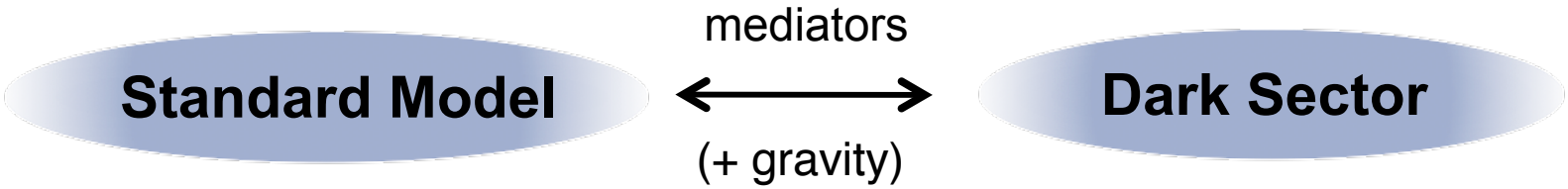
Higgs portal
[Patt & Wilczek]

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]

EFT for a (neutral) hidden sector



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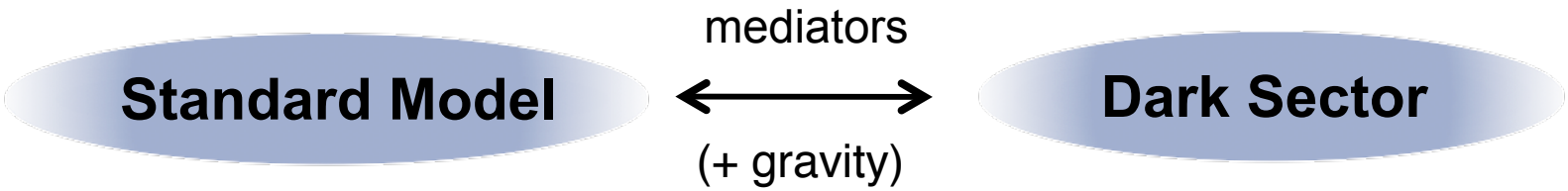
Vector portal **Higgs portal** **Neutrino portal**

Naturally incorporates minimal models of neutrino mass, and leptogenesis

EFT for a (neutral) hidden sector



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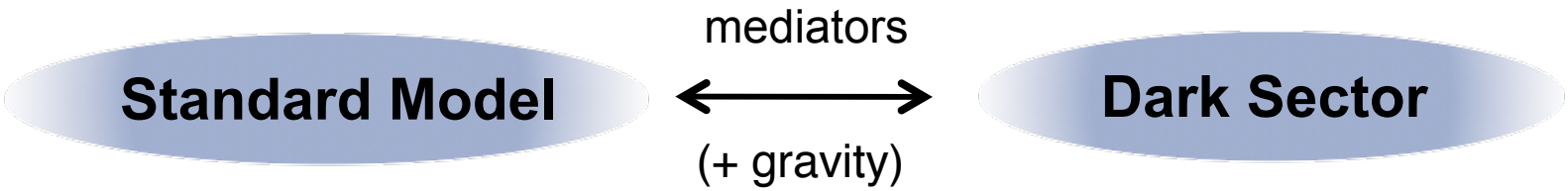
Vector portal **Higgs portal** **Neutrino portal**

Non-thermal DM candidates

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

EFT for a (neutral) hidden sector



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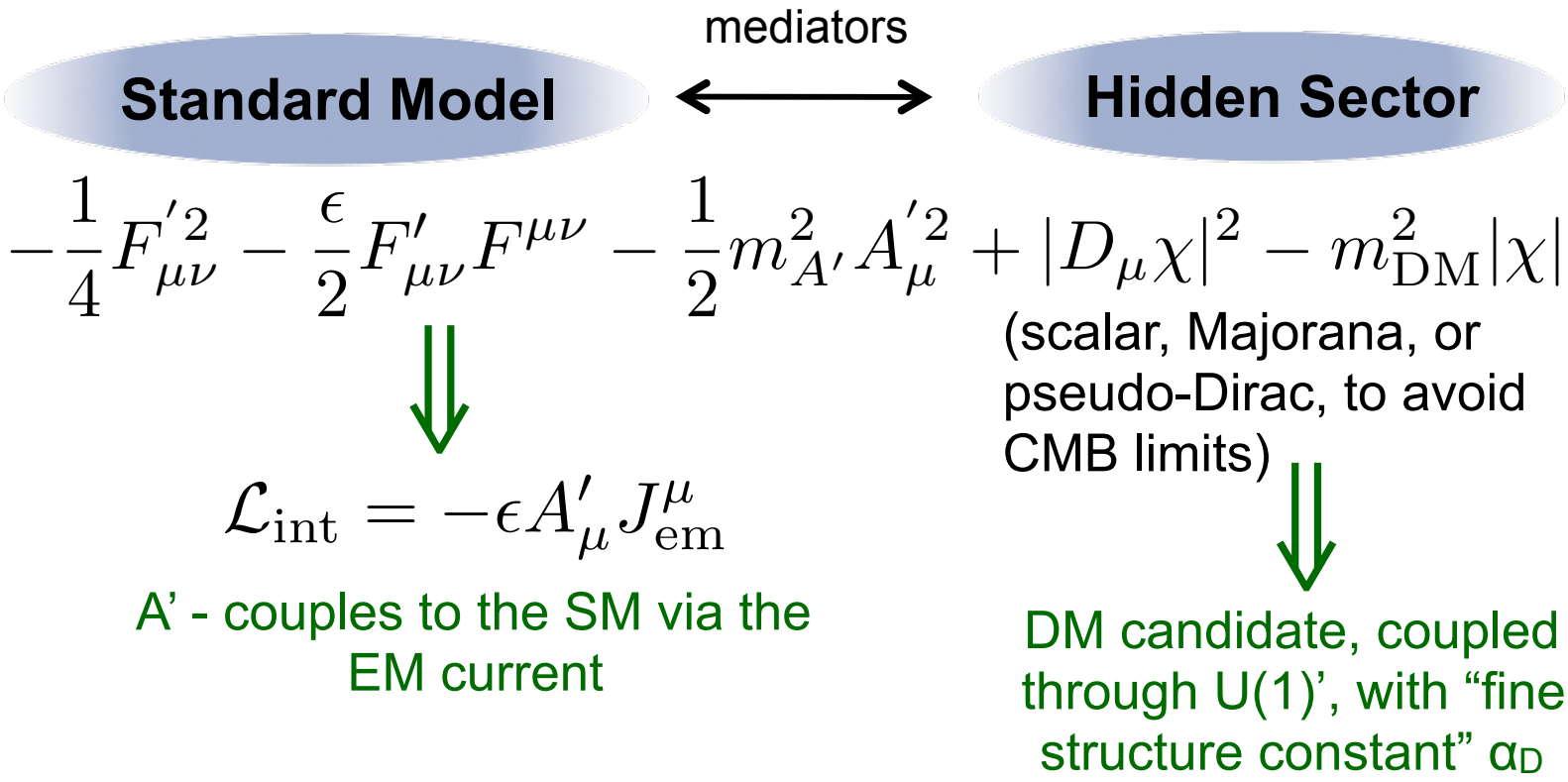
Vector portal **Higgs portal** **Neutrino portal**

Dark Forces

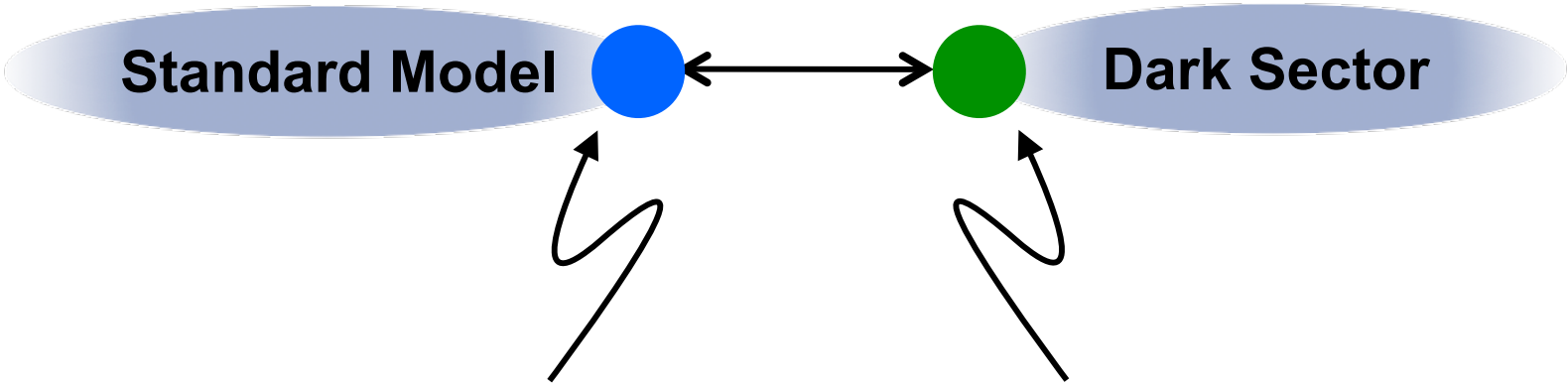
More generally, they can provide new `dark force' mediators enabling sufficient annihilation of MeV-GeV (hidden sector) dark matter in the early universe

(Minimal) Vector portal DM model



- Allows viable sub-GeV thermal relic DM candidates [Boehm et al '03, Fayet '04,'06; Pospelov, AR, Voloshin '07; Hooper & Zurek '08,…].
- For $m_{DM} < m_V$, the correct relic density fixes a specific relation between $\{\varepsilon, \alpha_D, m_V, m_{DM}\}$

Signatures of Dark Sectors



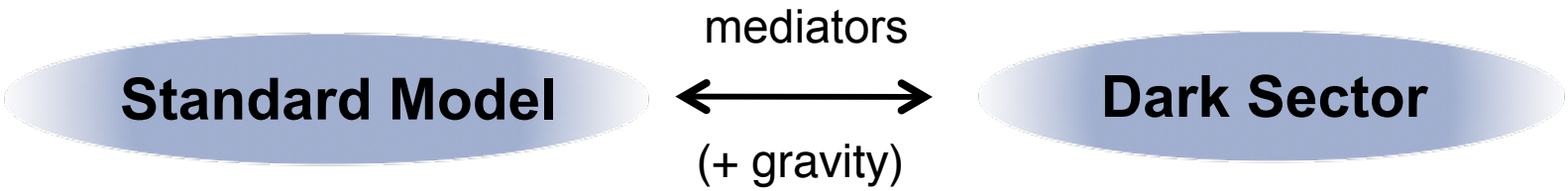
"Visible" and "hidden" signatures

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

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

Significant complementarity
between precision & intensity

EFT for a (neutral) hidden sector



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

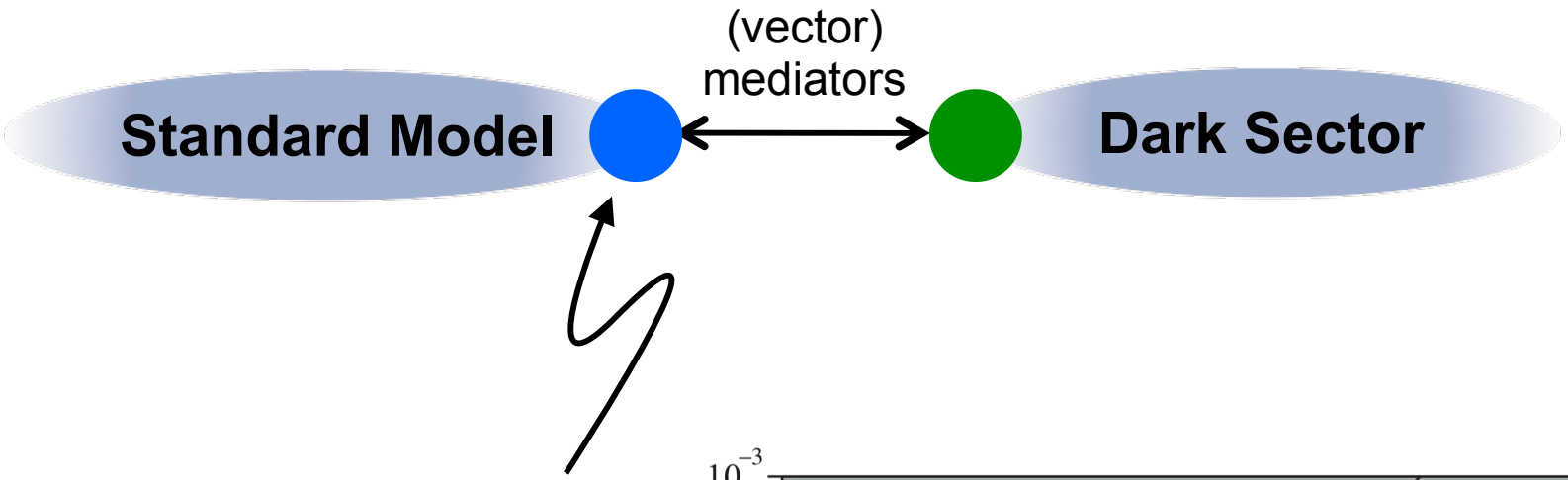
$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

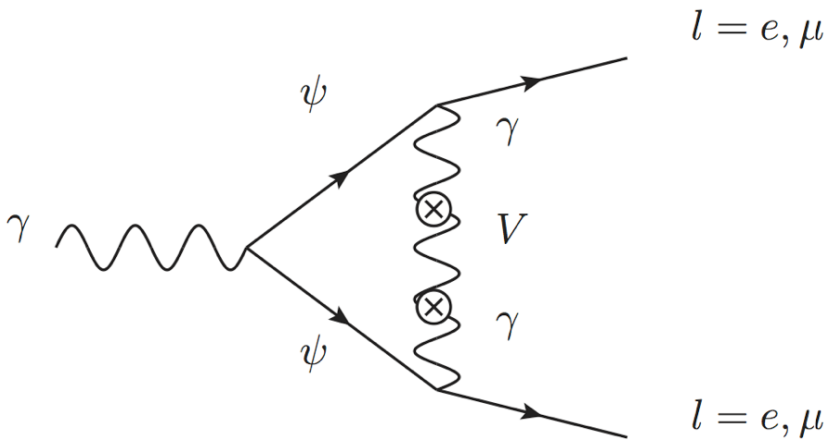
$$\downarrow \qquad \downarrow \qquad \downarrow$$

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

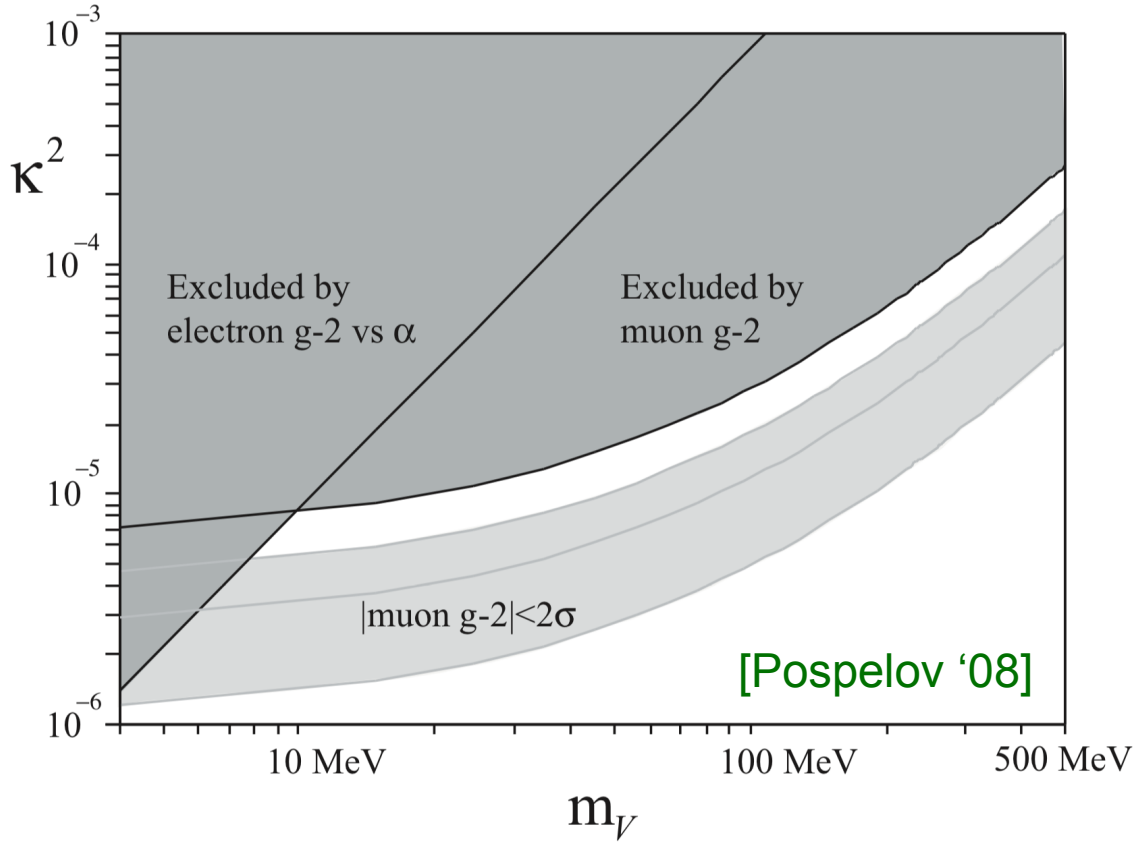
Universal couplings to EM/scalar currents at low energy, so hidden sector models have correlated observable effects

Precision corrections (g-2)

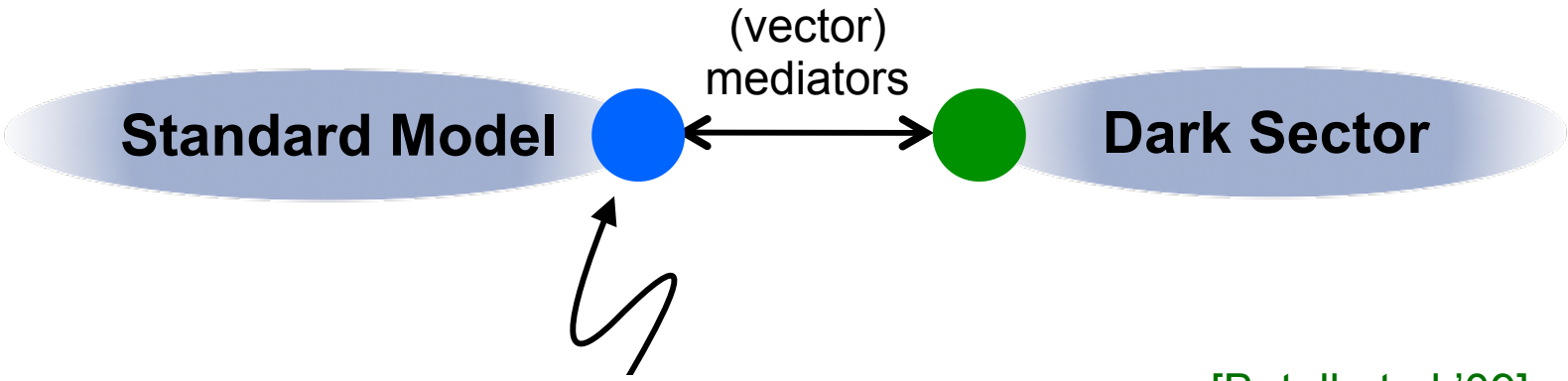




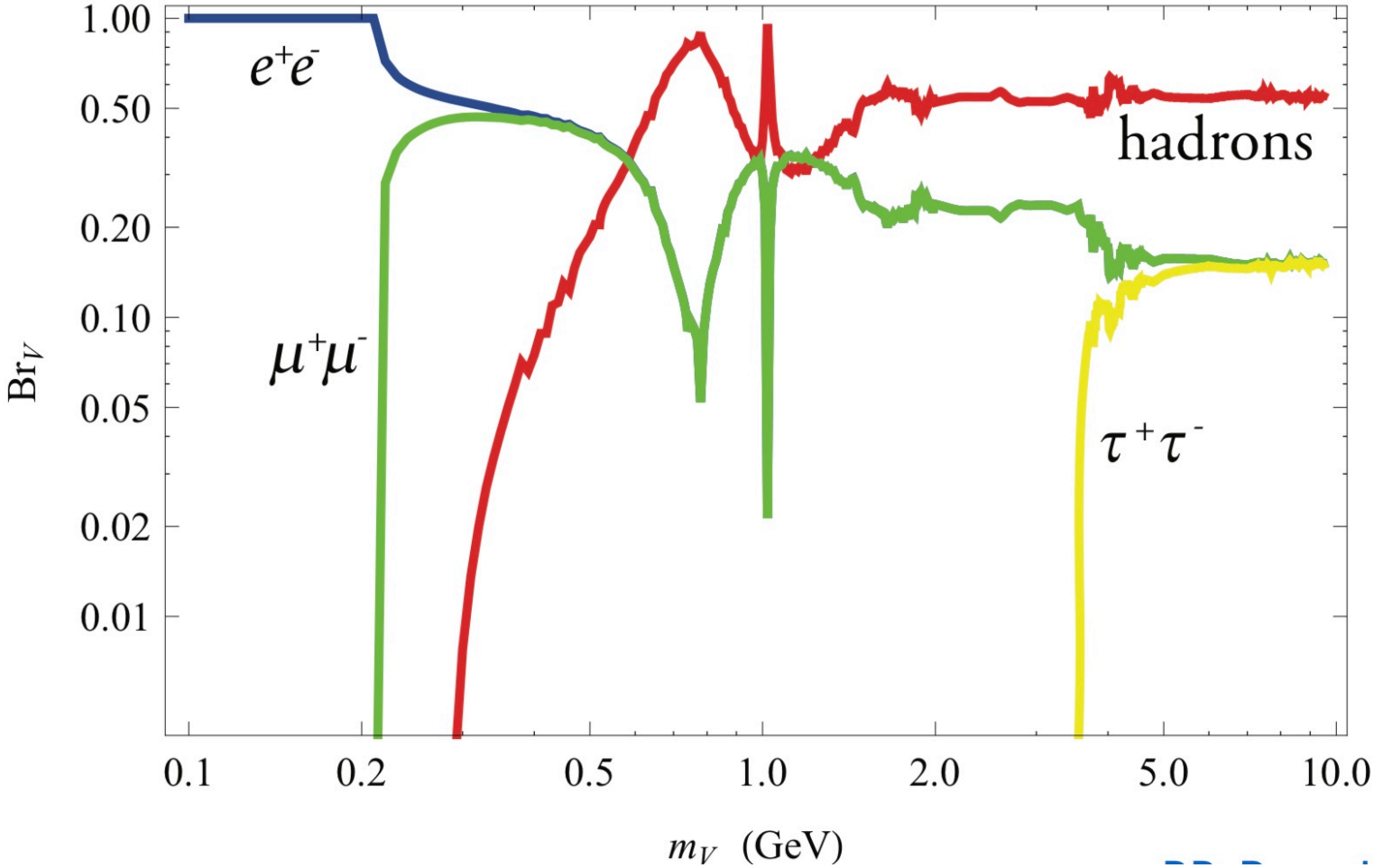
$$a_l^V = \frac{\alpha\kappa^2}{2\pi} \times \begin{cases} 1 & m_l \gg m_V \\ 2m_l^2/(3m_V^2) & m_l \ll m_V \end{cases}$$



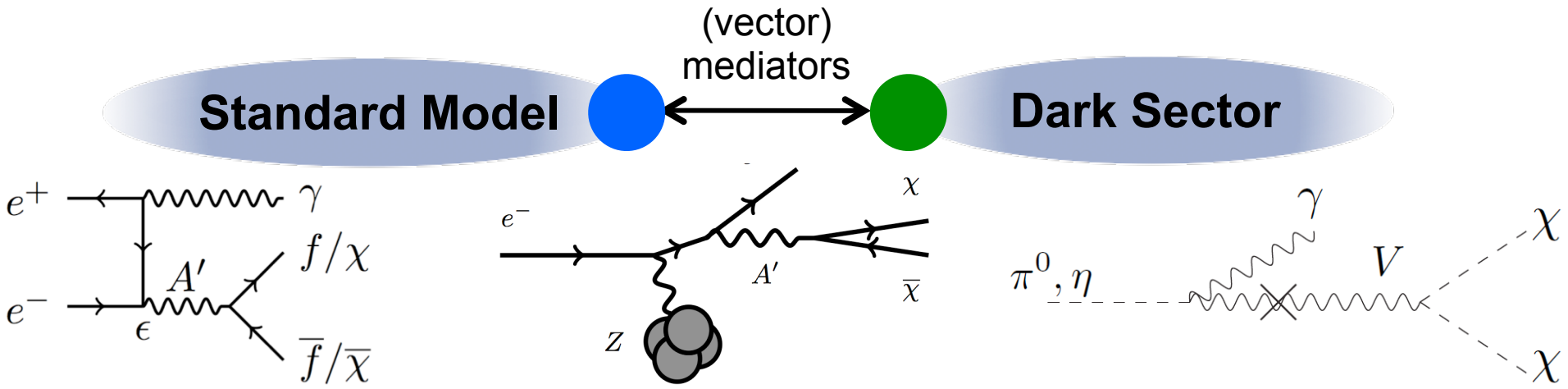
Precision corrections (g-2)

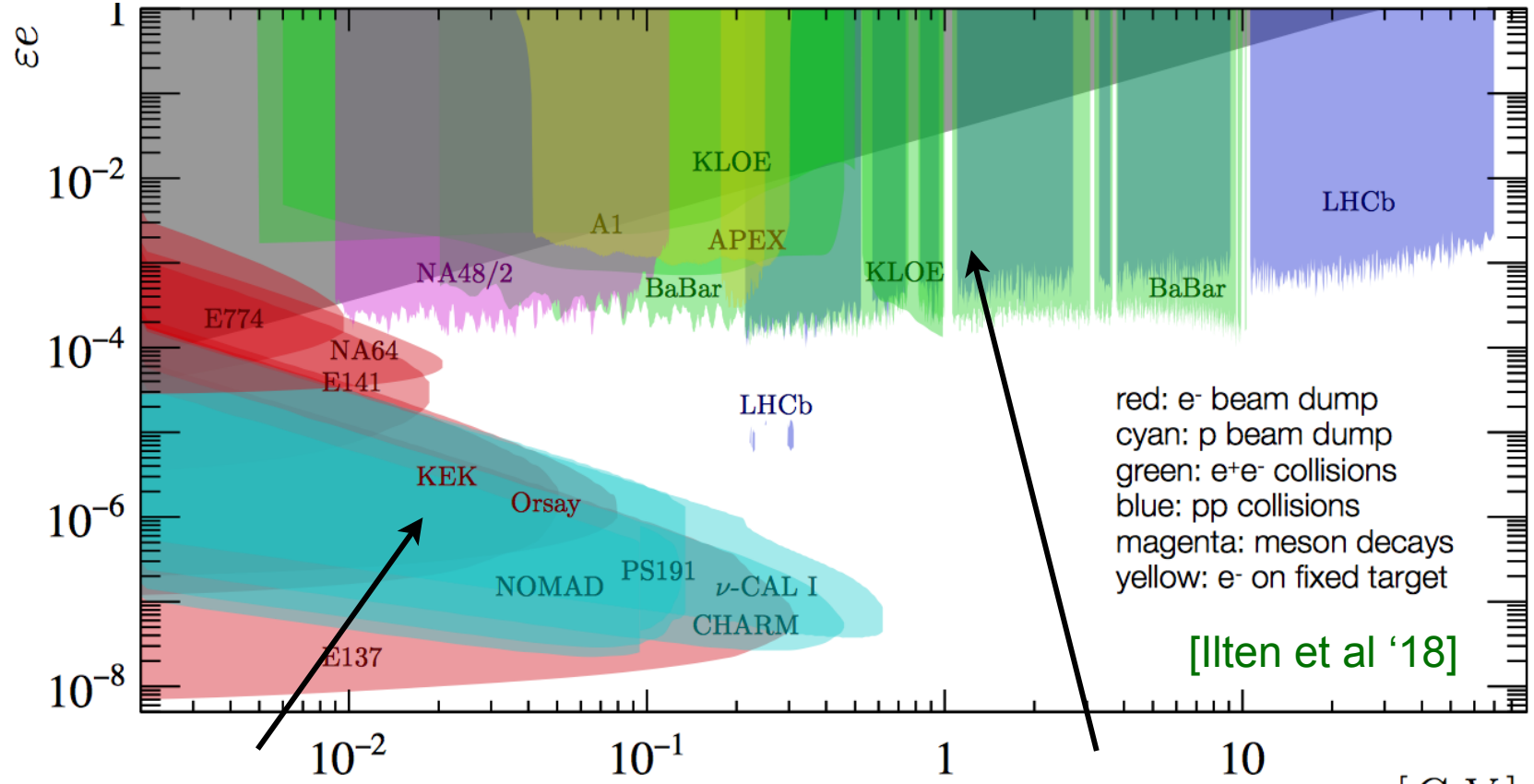


[Batell et al '09]



Rare visible decays

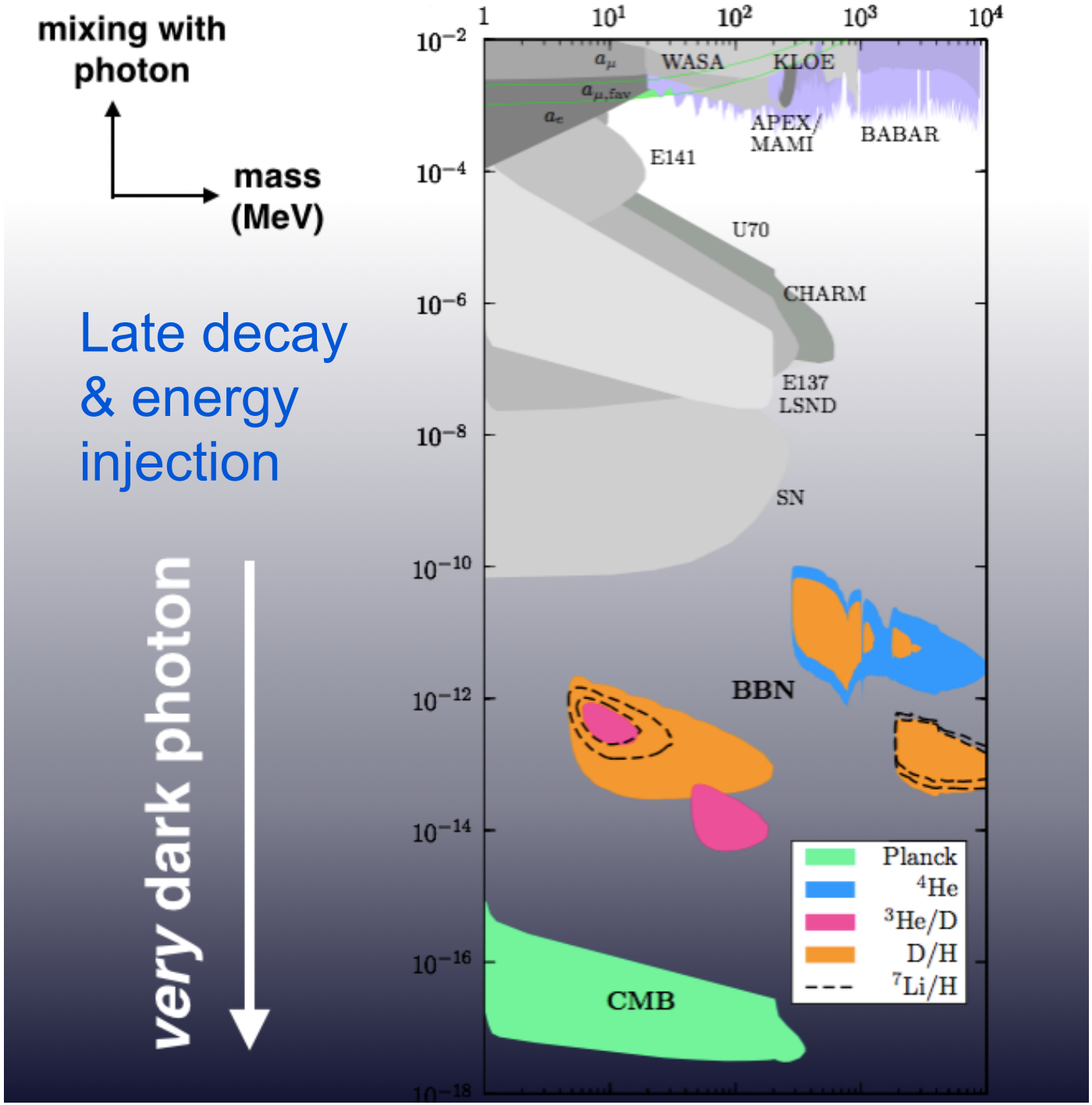




decay and EM shower

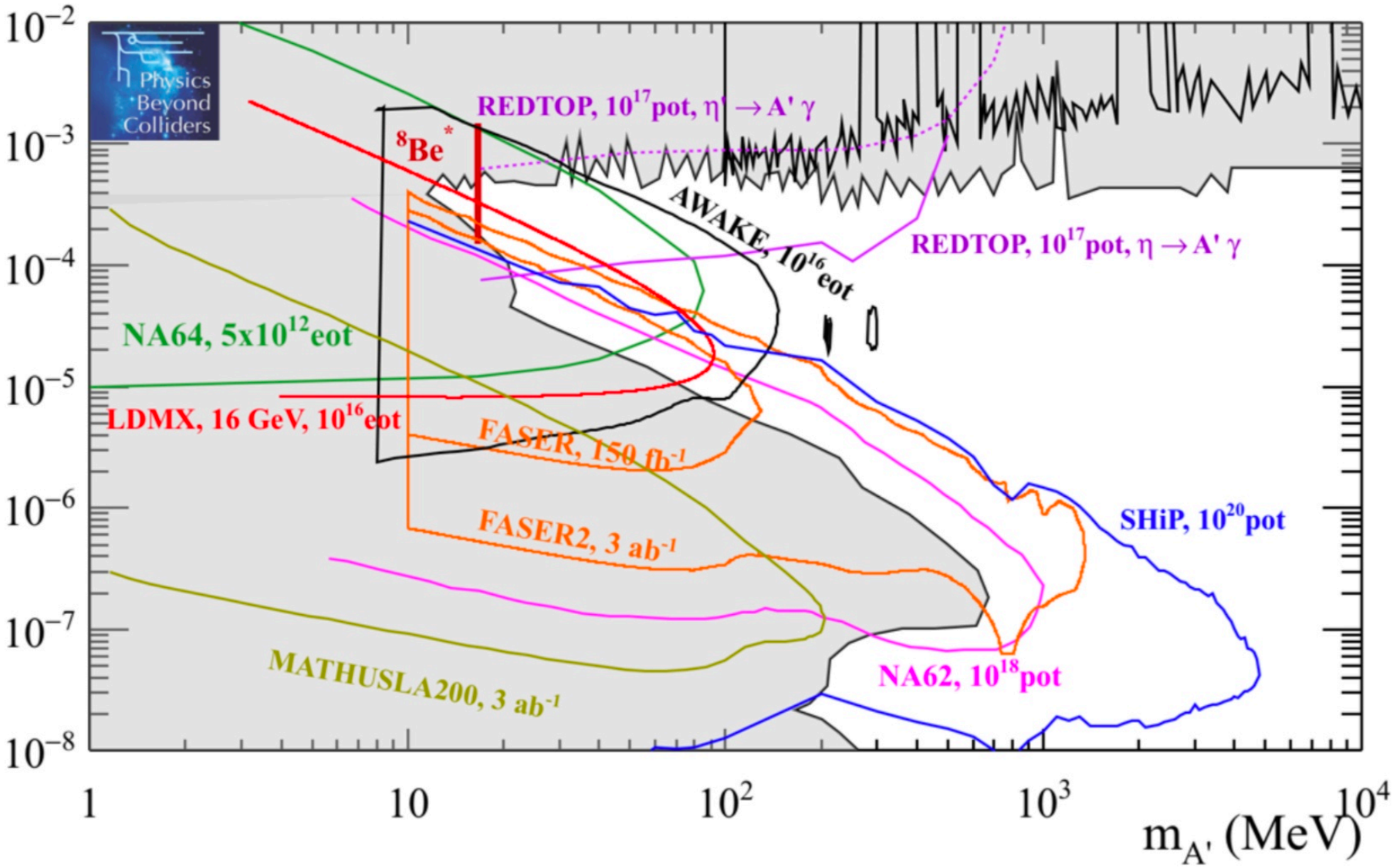
$e^+e^- \rightarrow l^+l^- \gamma$

Ultra weak coupling - BBN/CMB



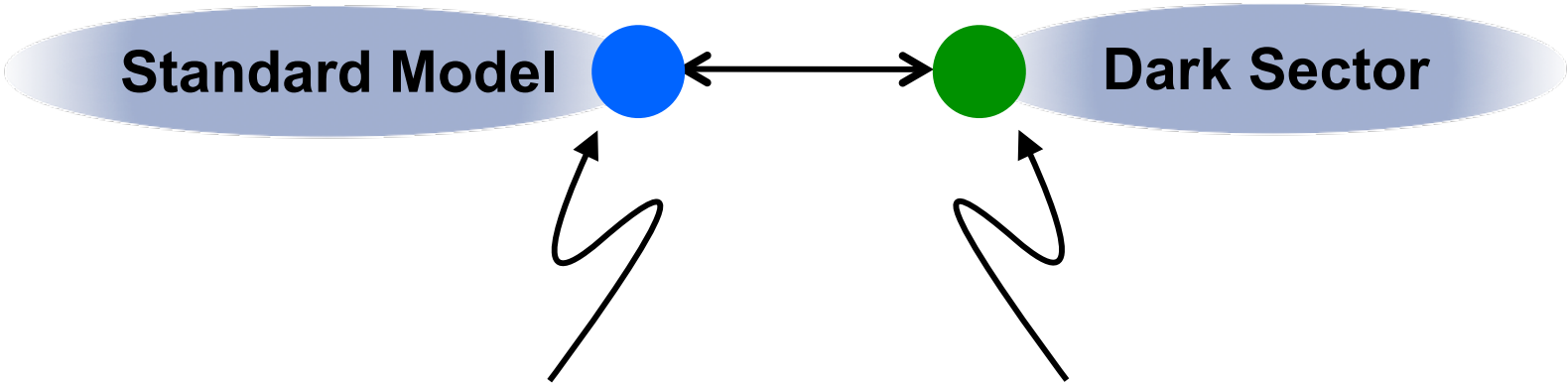
Rare visible decays - future sensitivity

Rare visible decays - future sensitivity



Plus Belle II, LHCb, SeaQuest, HPS, …

Signatures of Dark Sectors



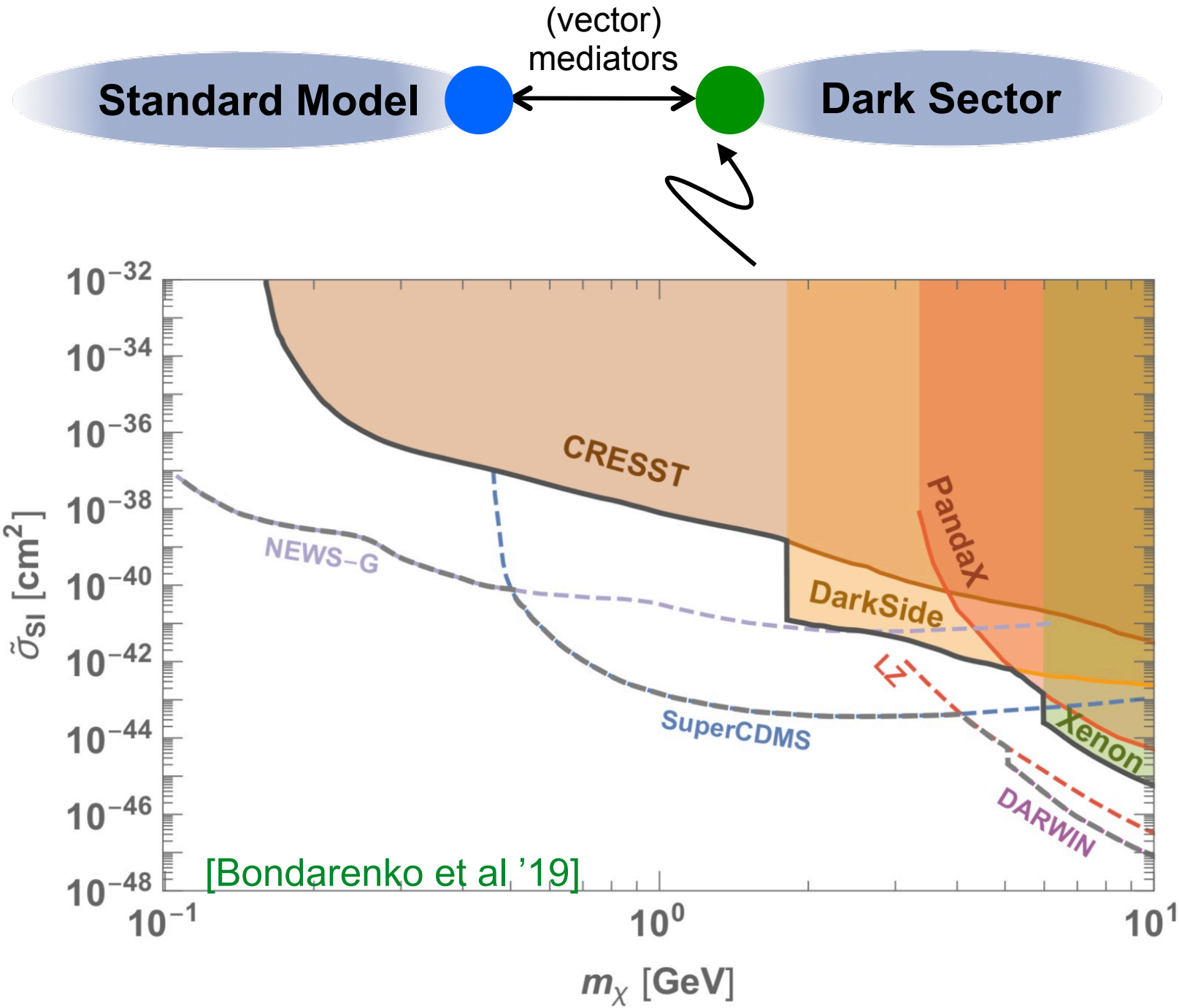
"Visible" and "hidden" signatures

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

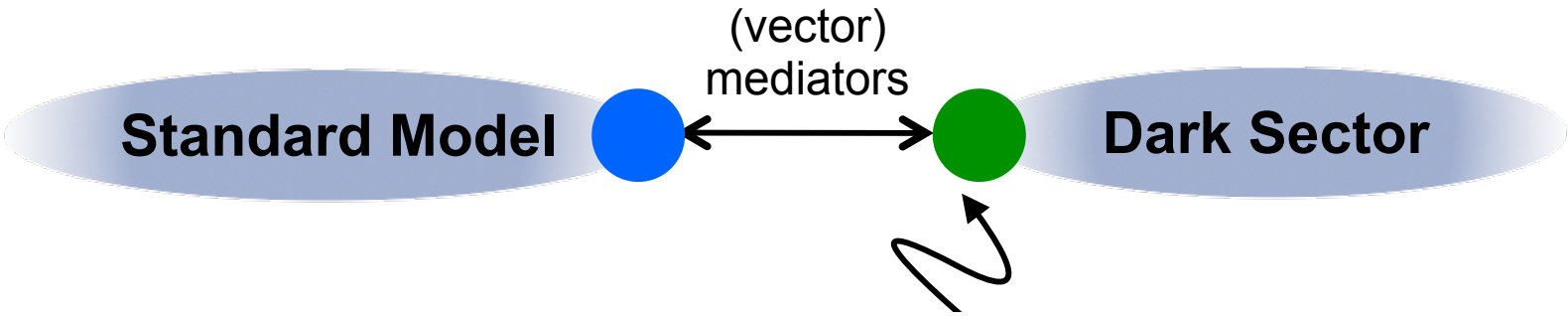
- Rare (invisible) decays/E_{miss}
- Anomalous NC-like scattering
- Astrophys/cosmology

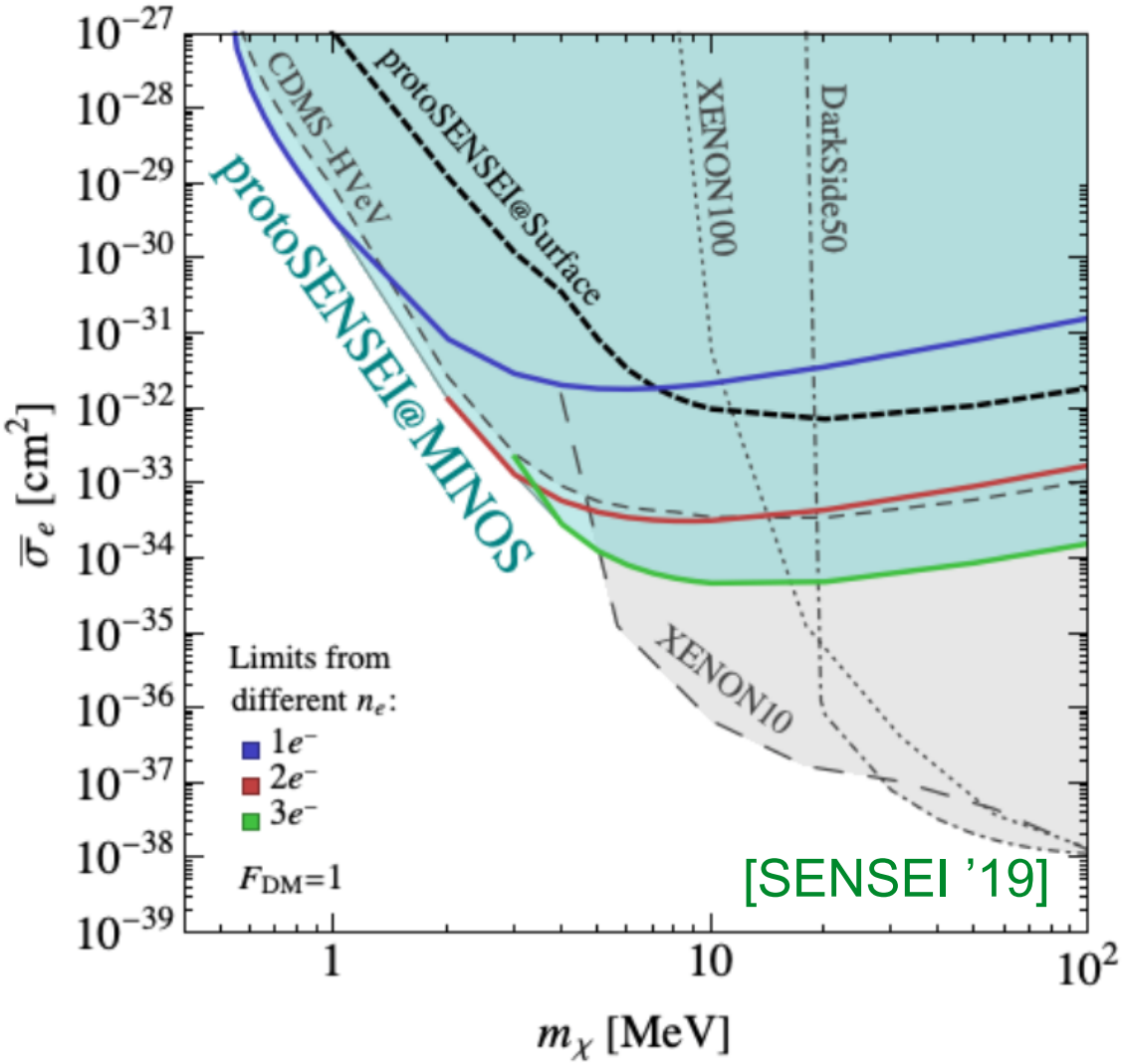
DM Models!

Low mass direct detection - N-scattering



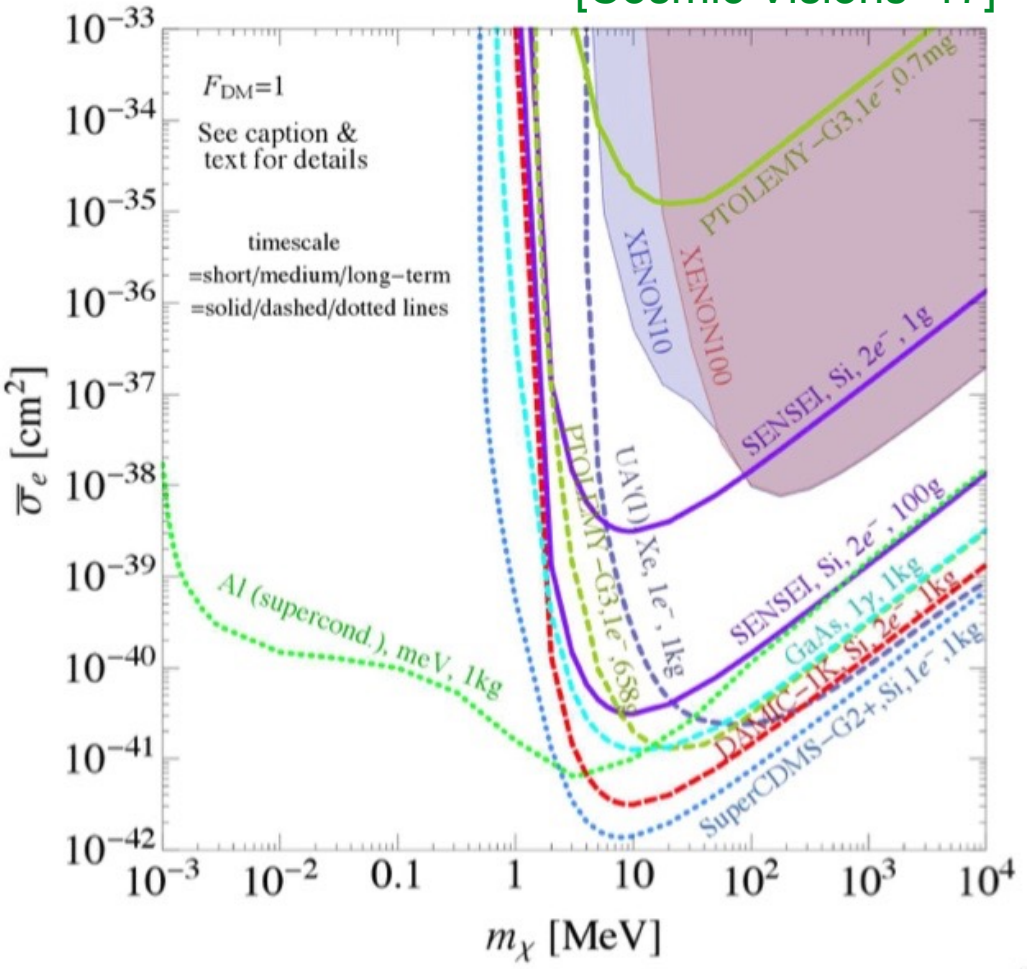
Low mass direct detection - e-scattering





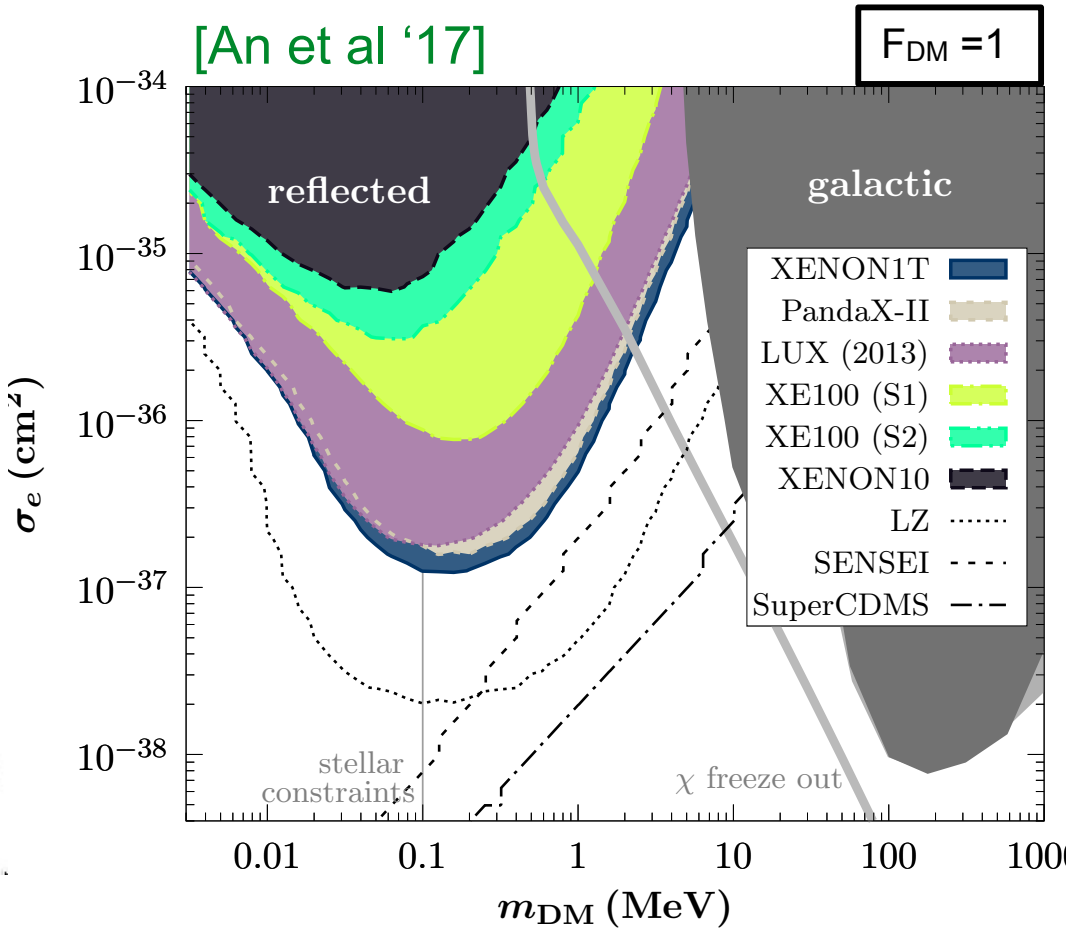
Future Sensitivity (e-scattering)

[Cosmic Visions '17]

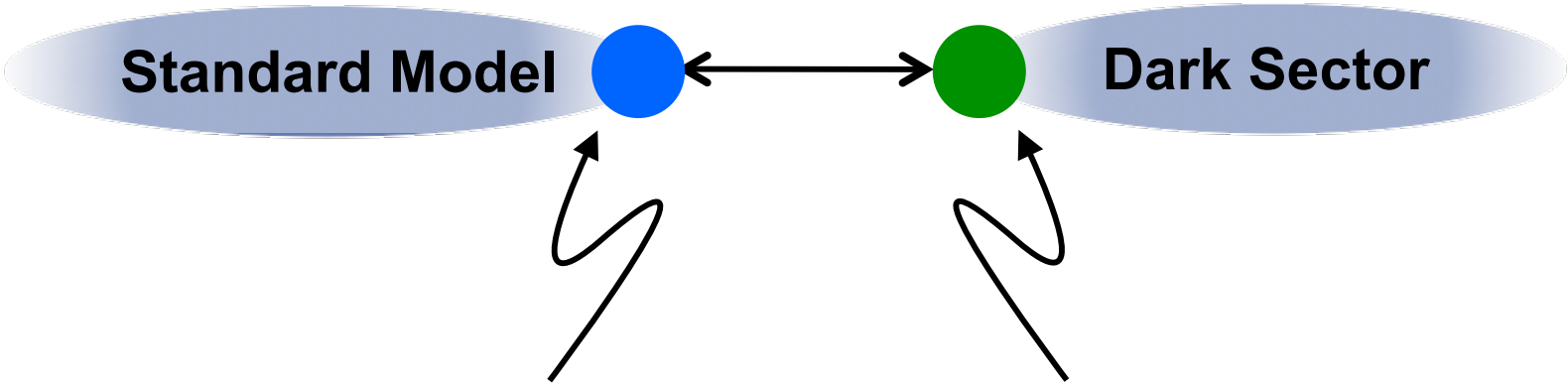


DM re-scattered by T~keV electrons in the Sun

[An et al '17]



Some experimental signatures



"Visible" and "hidden" signatures

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

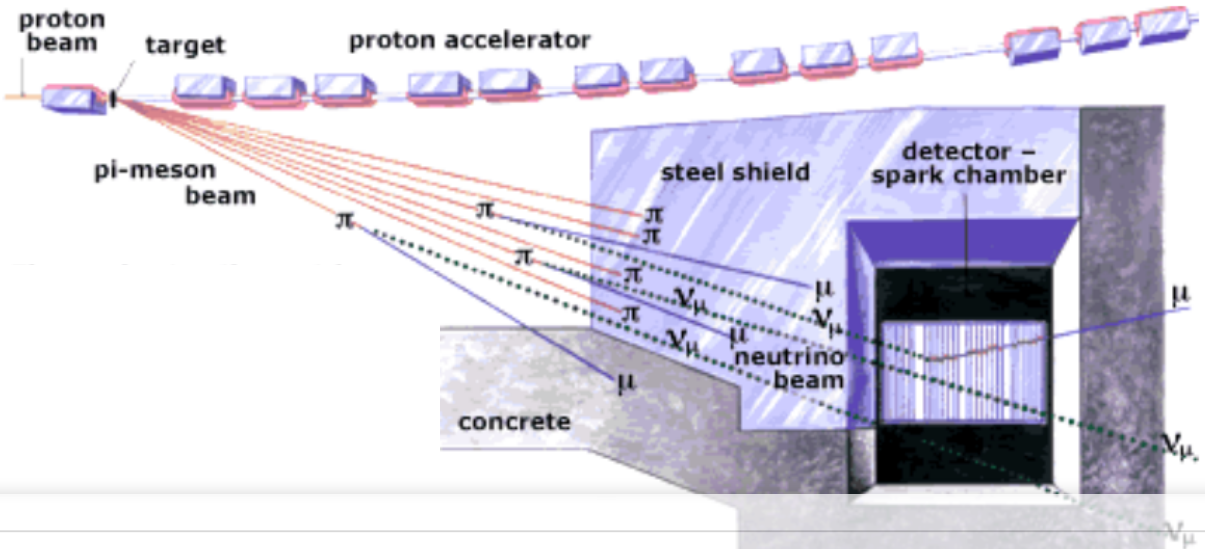
- Rare (invisible) decays/E_{miss}
- Anomalous NC-like scattering
- Astrophys/cosmology

Sensitivity at the luminosity frontier

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

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



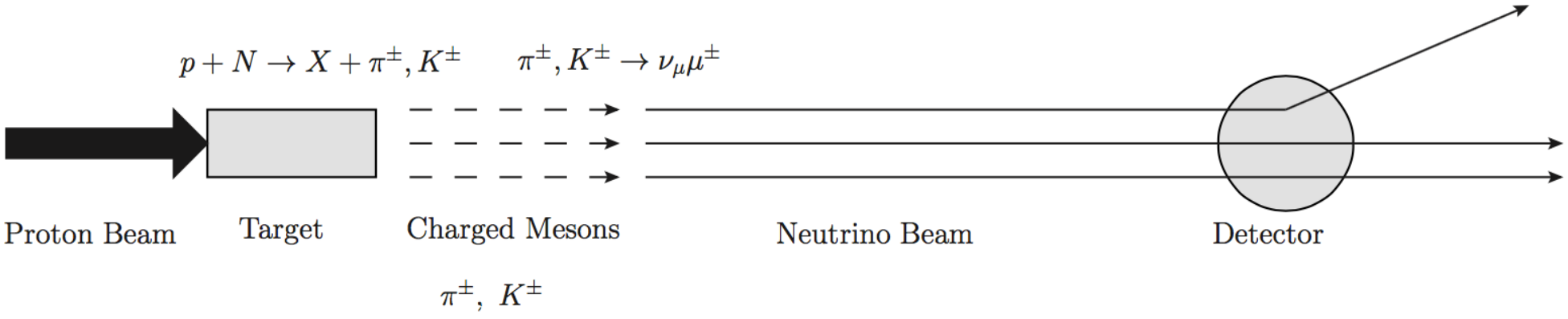
OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

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

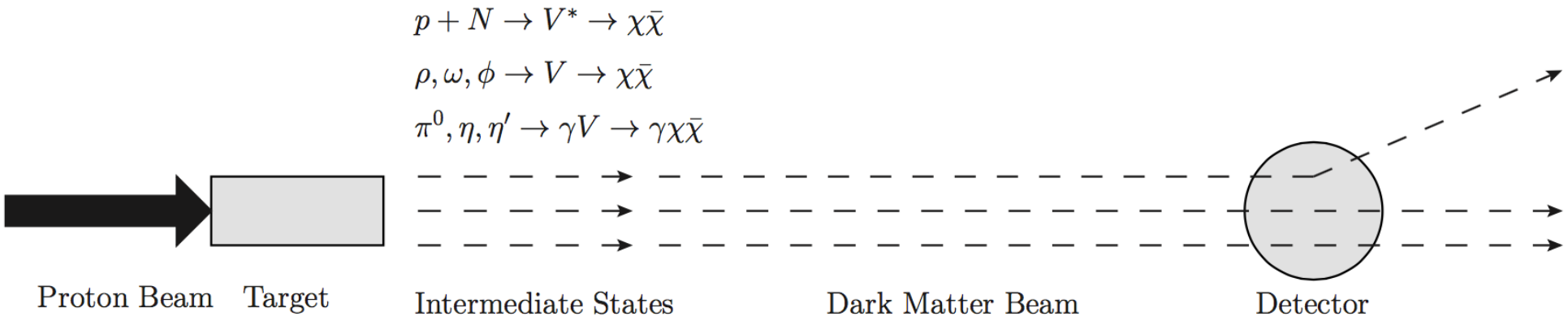
Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

Fixed target - e.g. Neutrino Beams



Basic idea: use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam.

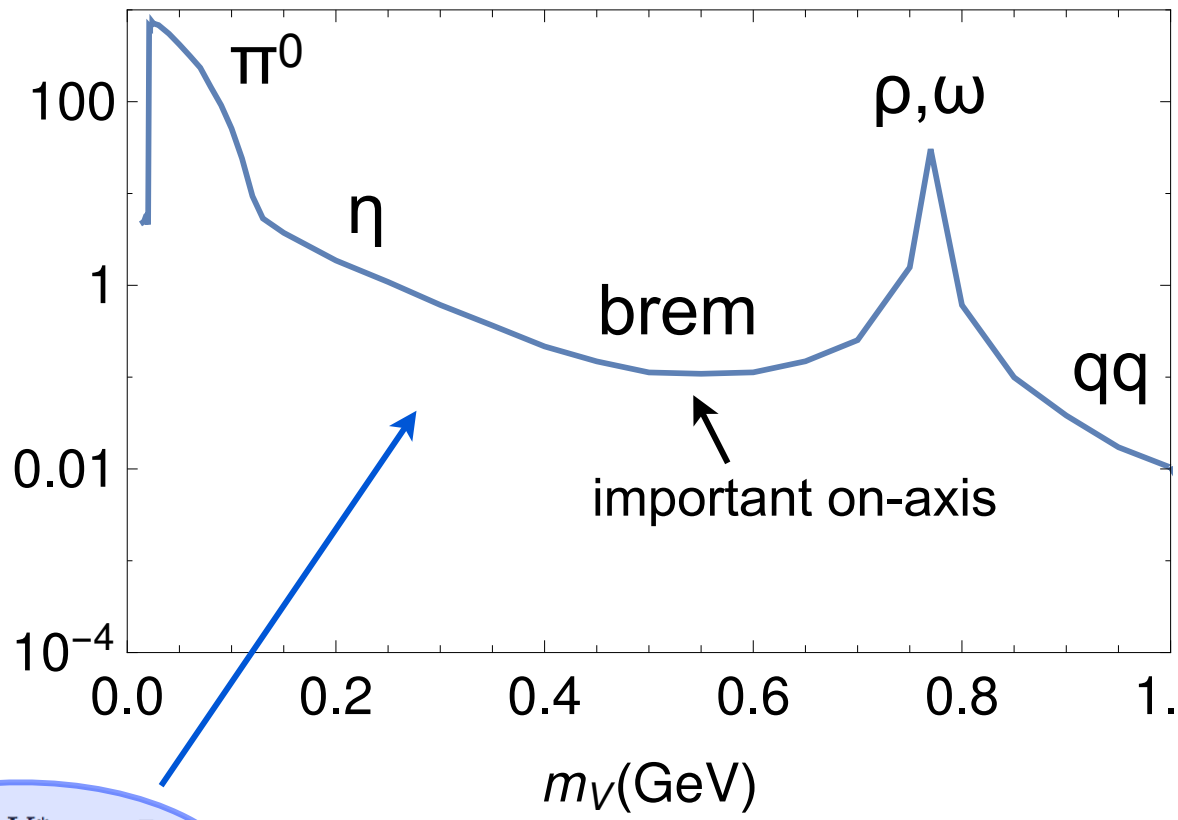


Fixed target - e.g. Neutrino Beams

[deNiverville et al '16]

Unnormalized production rate at e.g. MiniBooNE (vector mediator)

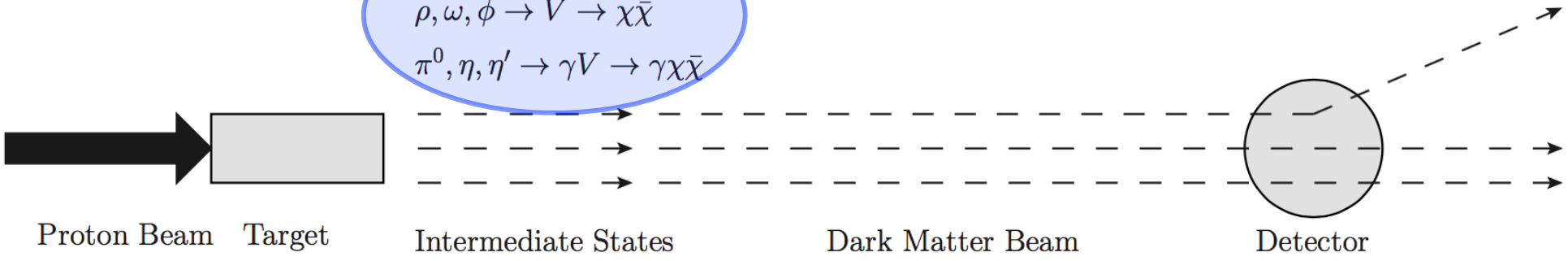
- NB: some components of production model can be validated with data, but not all...



$p + N \to V^* \to \chi\bar{\chi}$

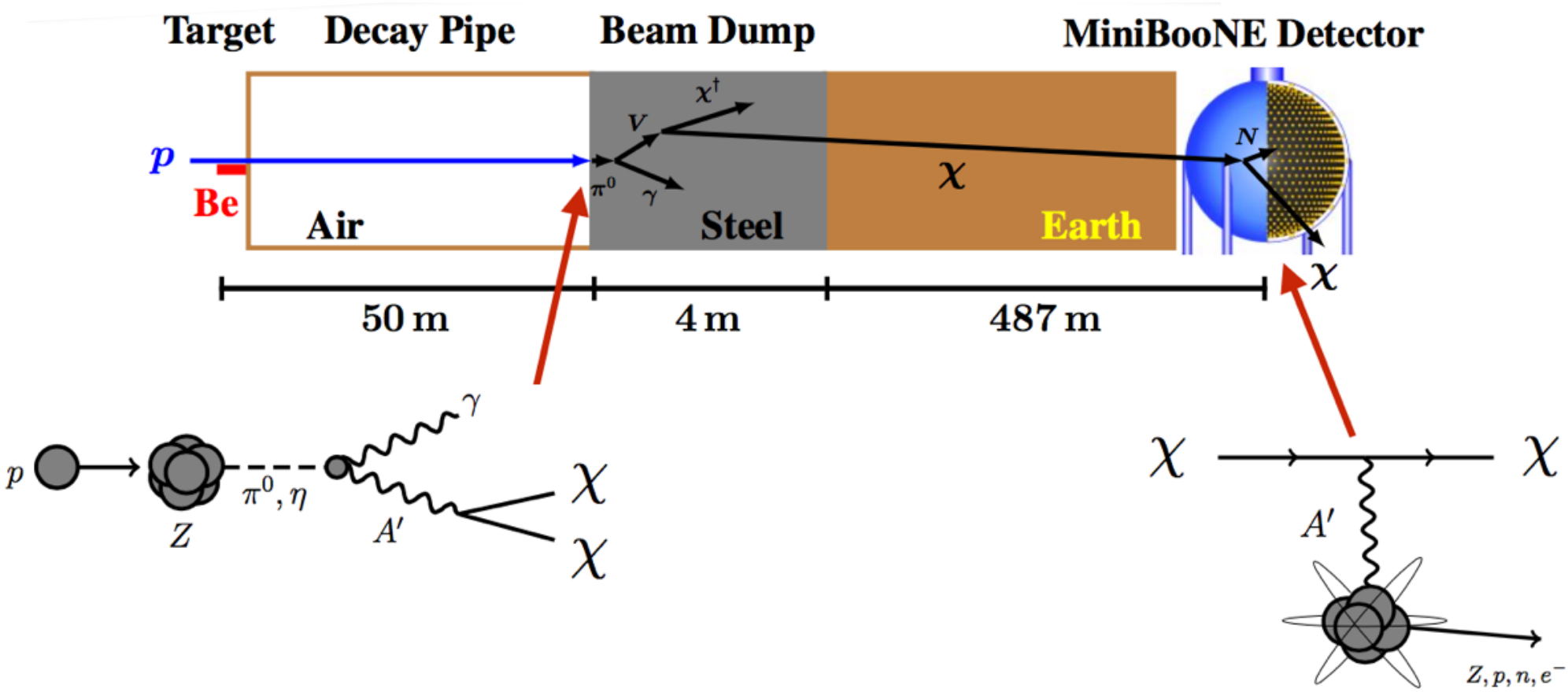
$\rho, \omega, \phi \to V \to \chi\bar{\chi}$

$\pi^0, \eta, \eta' \to \gamma V \to \gamma\chi\bar{\chi}$



Fixed target - Neutrino Beams

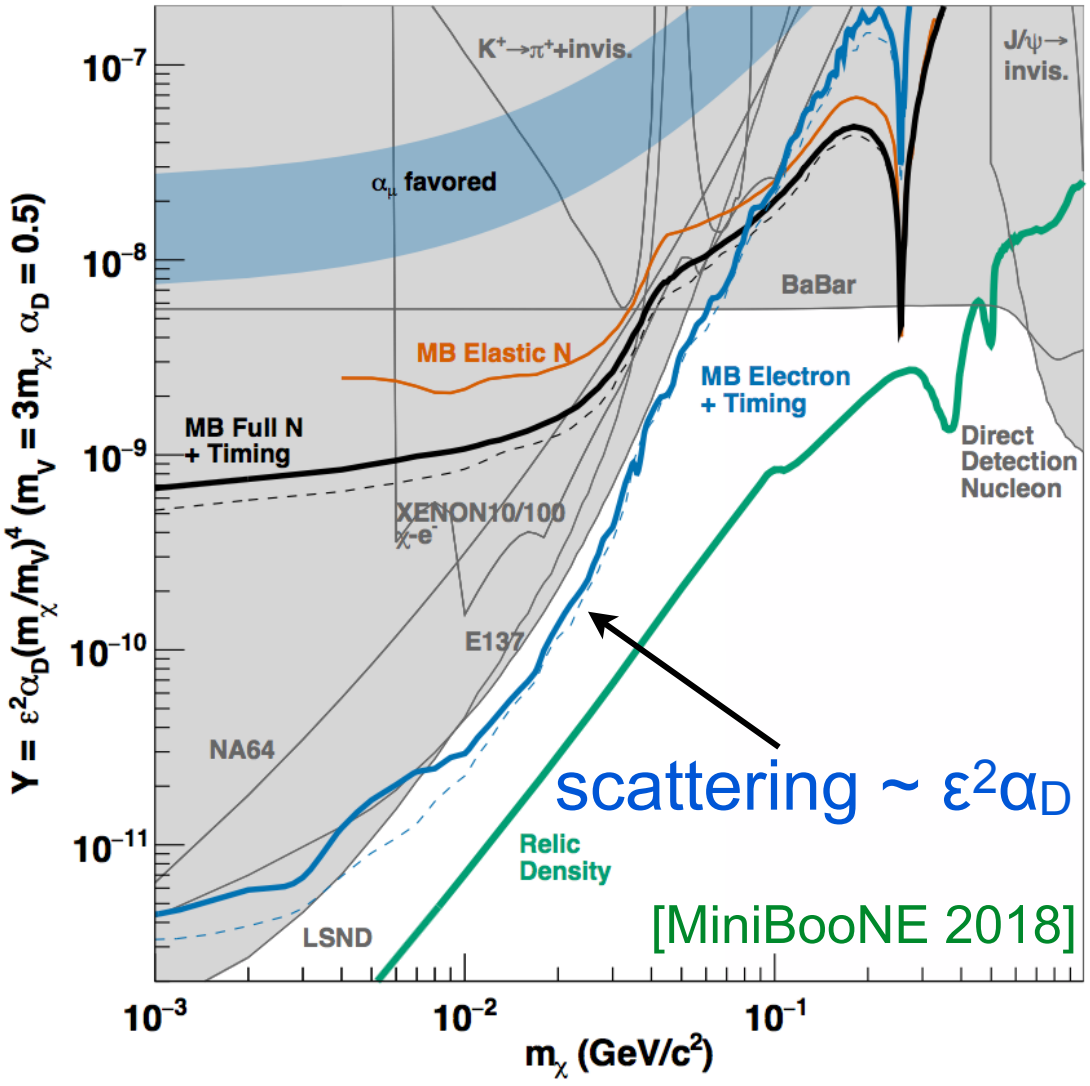
First focused DM search - MiniBooNE in “beam dump” mode



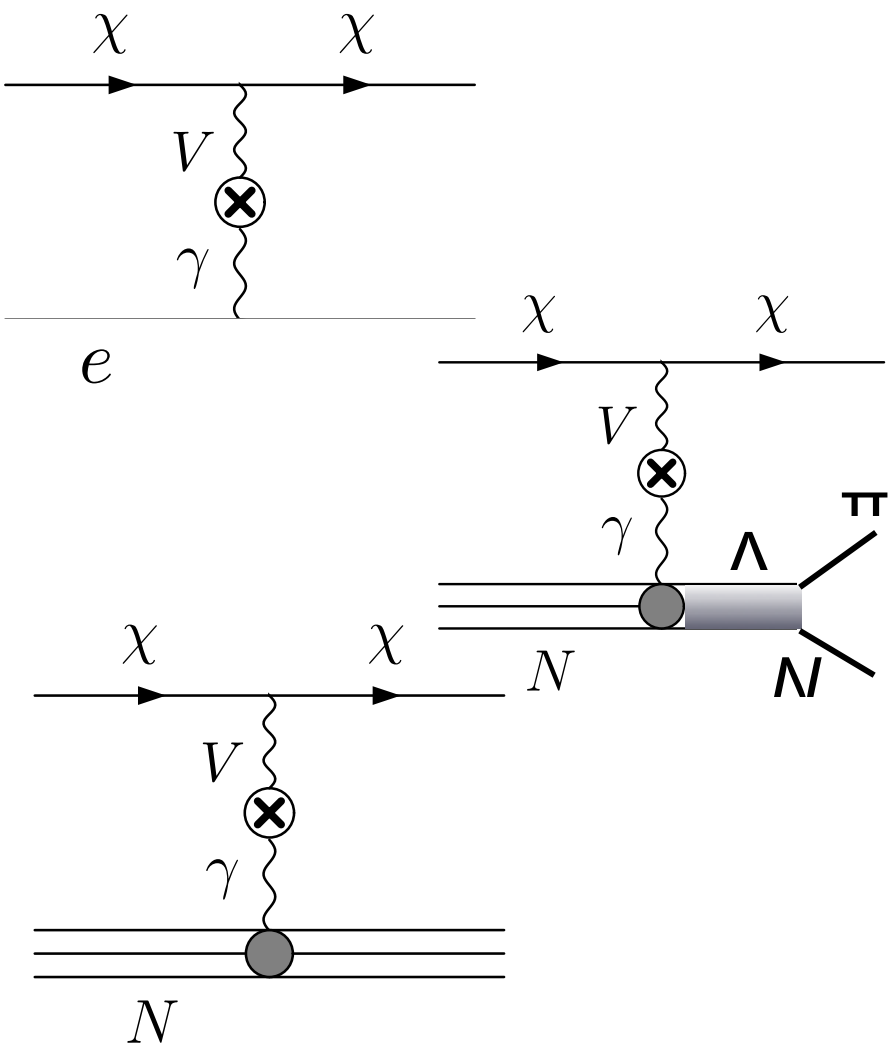
Align the beam off-target, to minimize the neutrino background

[Batell et al ’09, deNiverville et al ’11, ’12, ’16, + MiniBooNE ’12, MiniBooNE ’17, ’18]

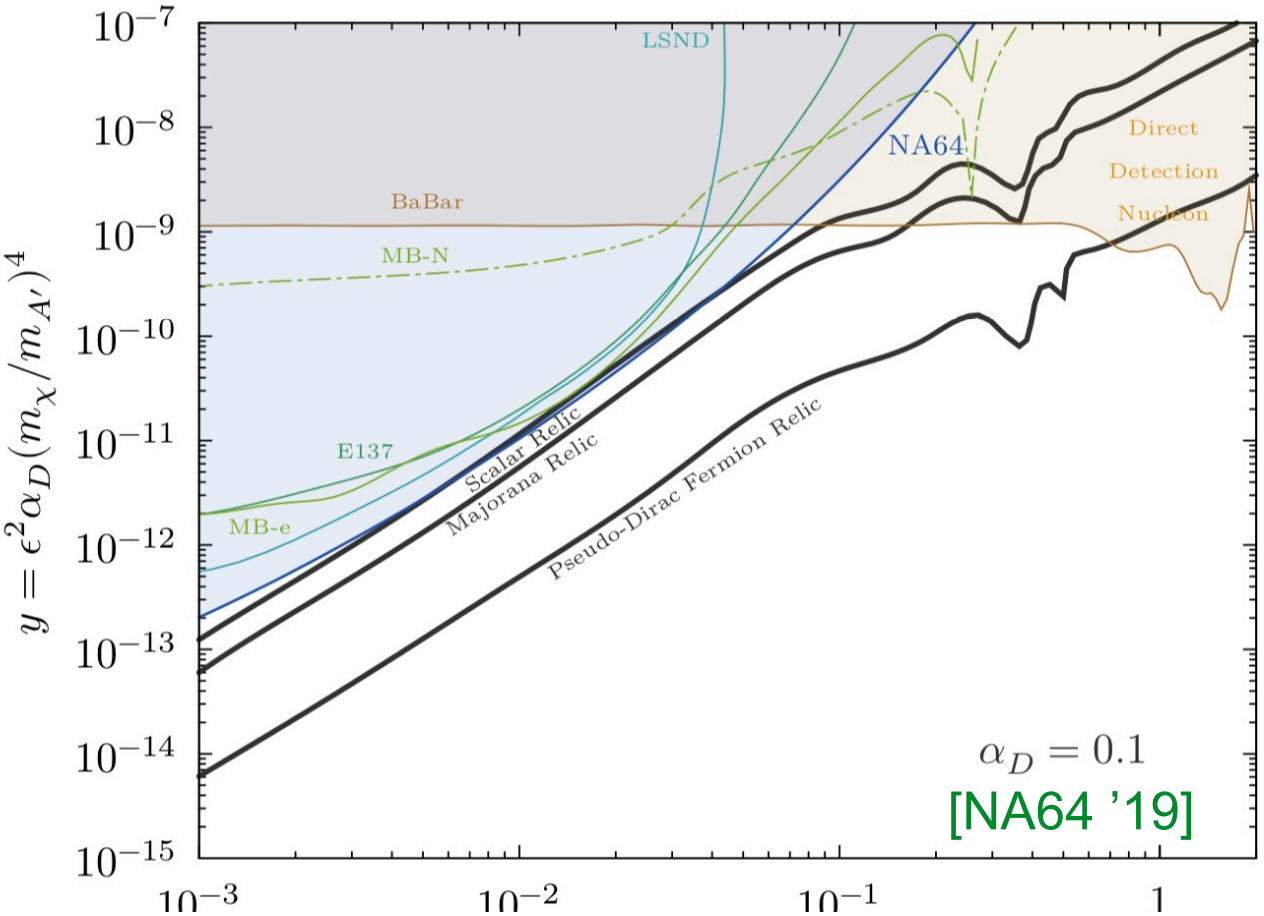
Fixed target - Neutrino Beams



Production via A'(*) → χχ

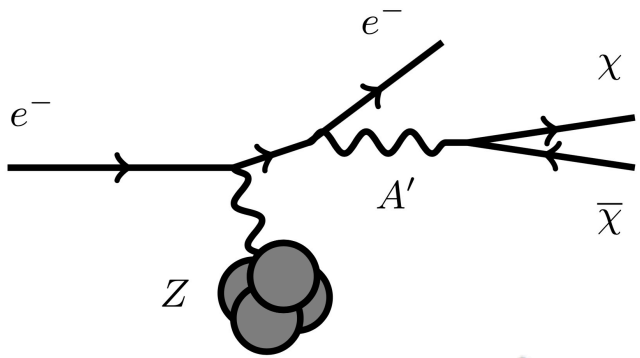


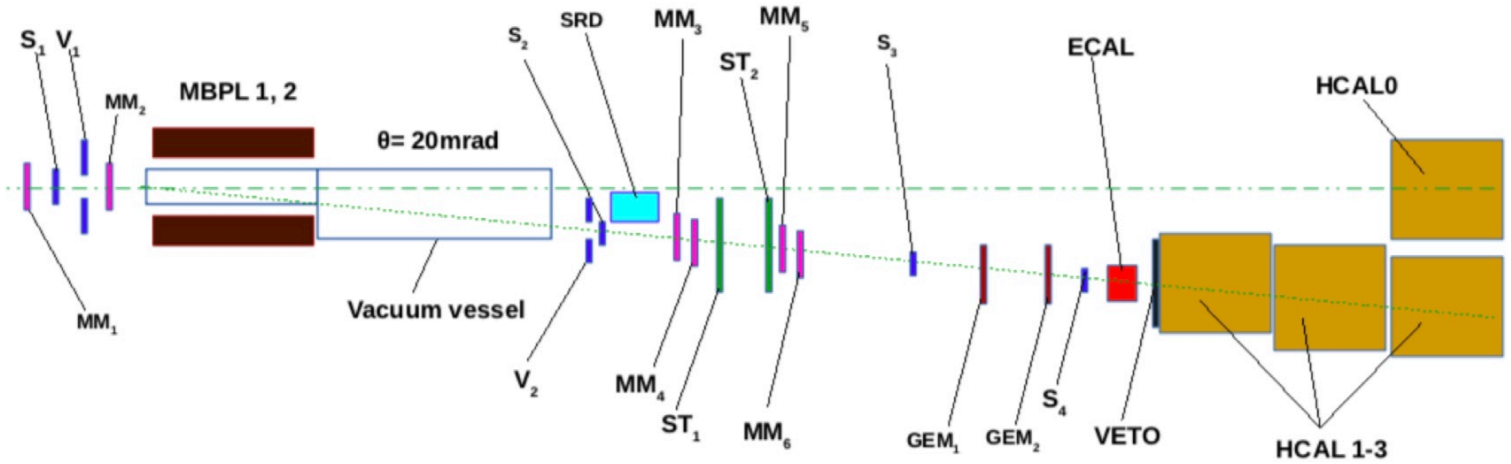
Fixed targets - NA64 missing energy search



[NA64 '19]

Production via bremsstrahlung

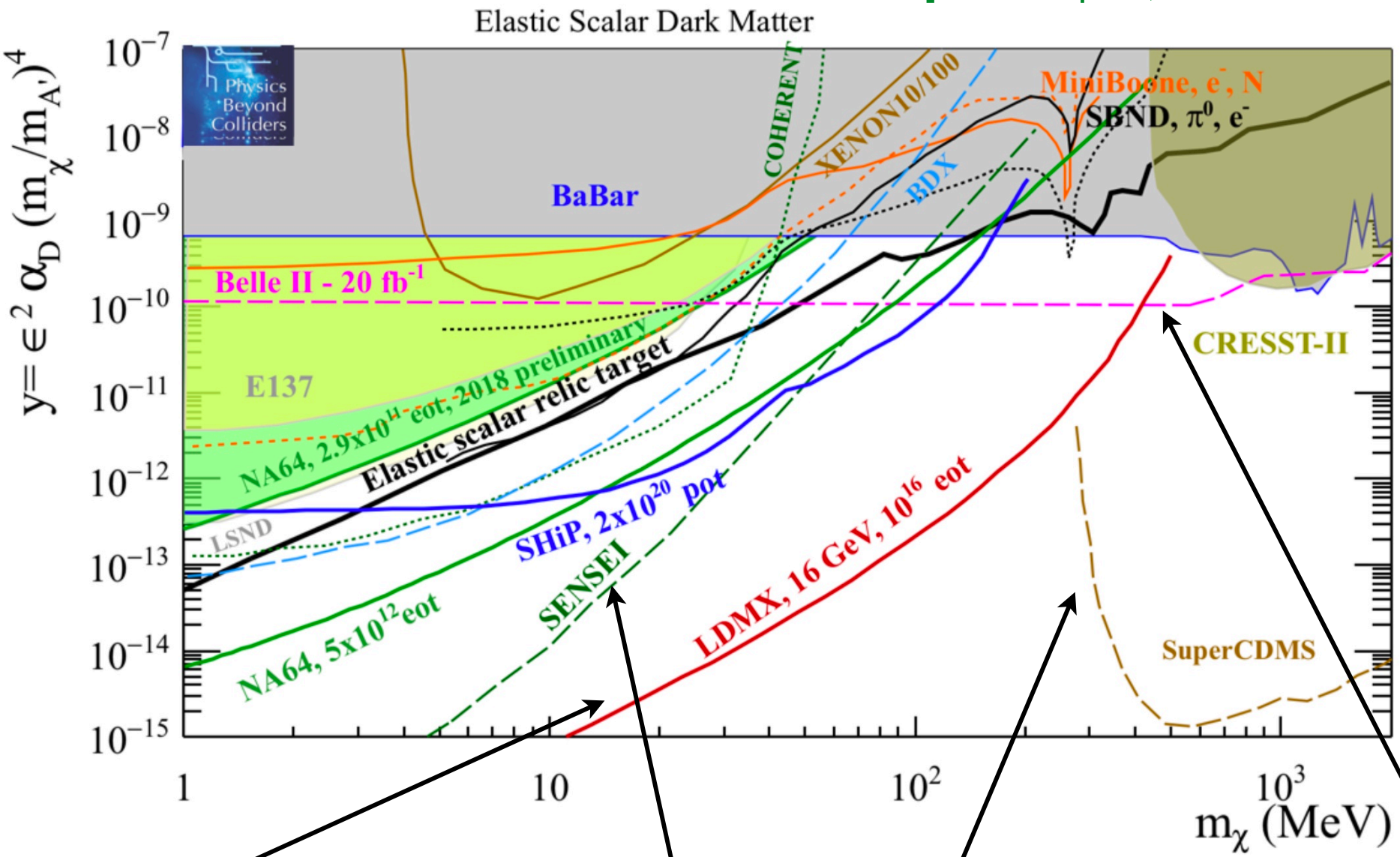




Fixed target probes - future sensitivity

Future sensitivity

[PBC Report, Beacham et al '19]



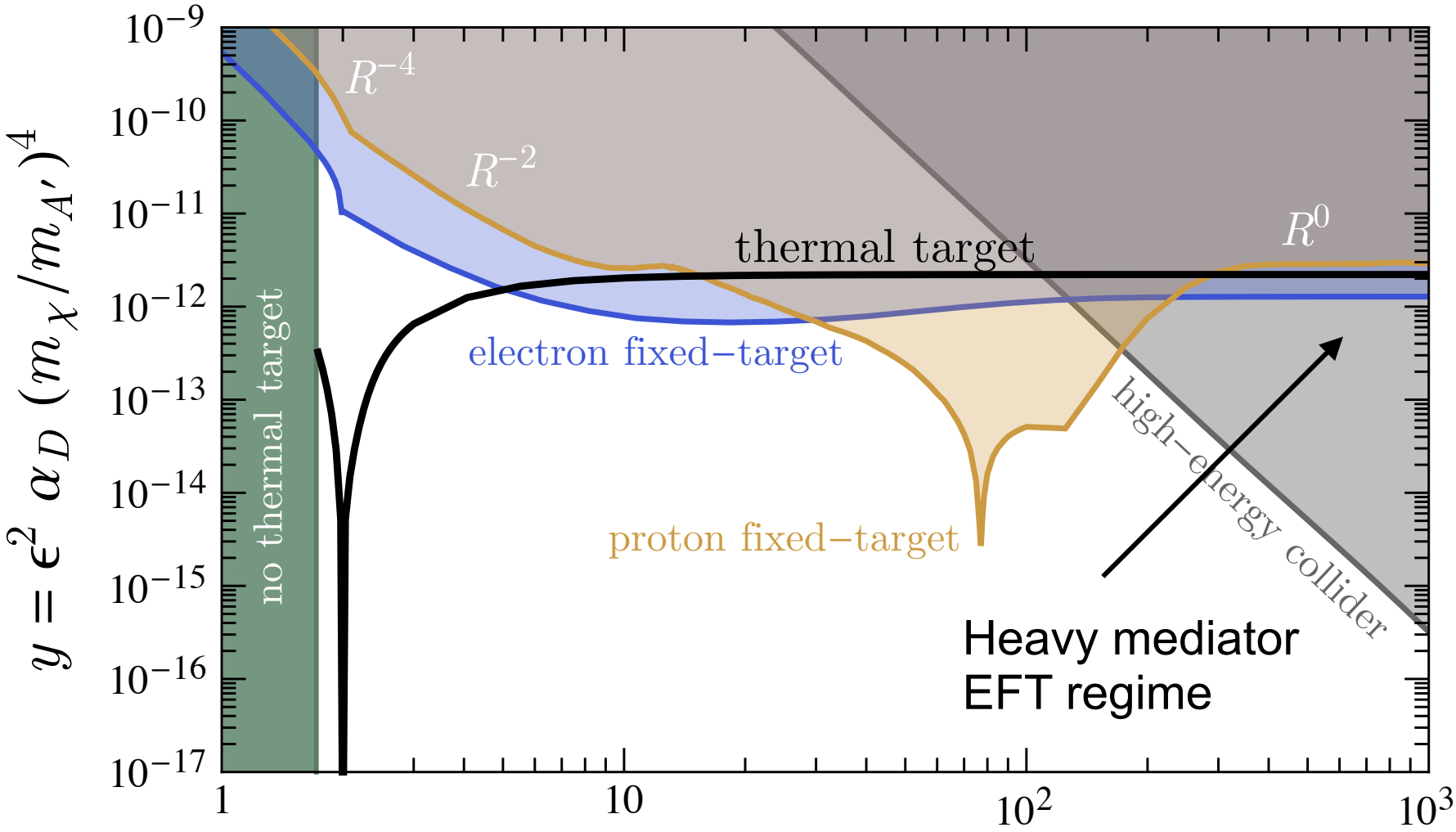
p_{miss} (LDMX)

Direct detection (e/N scattering)

E_{miss} (Belle II)

Generic fixed target sensitivity

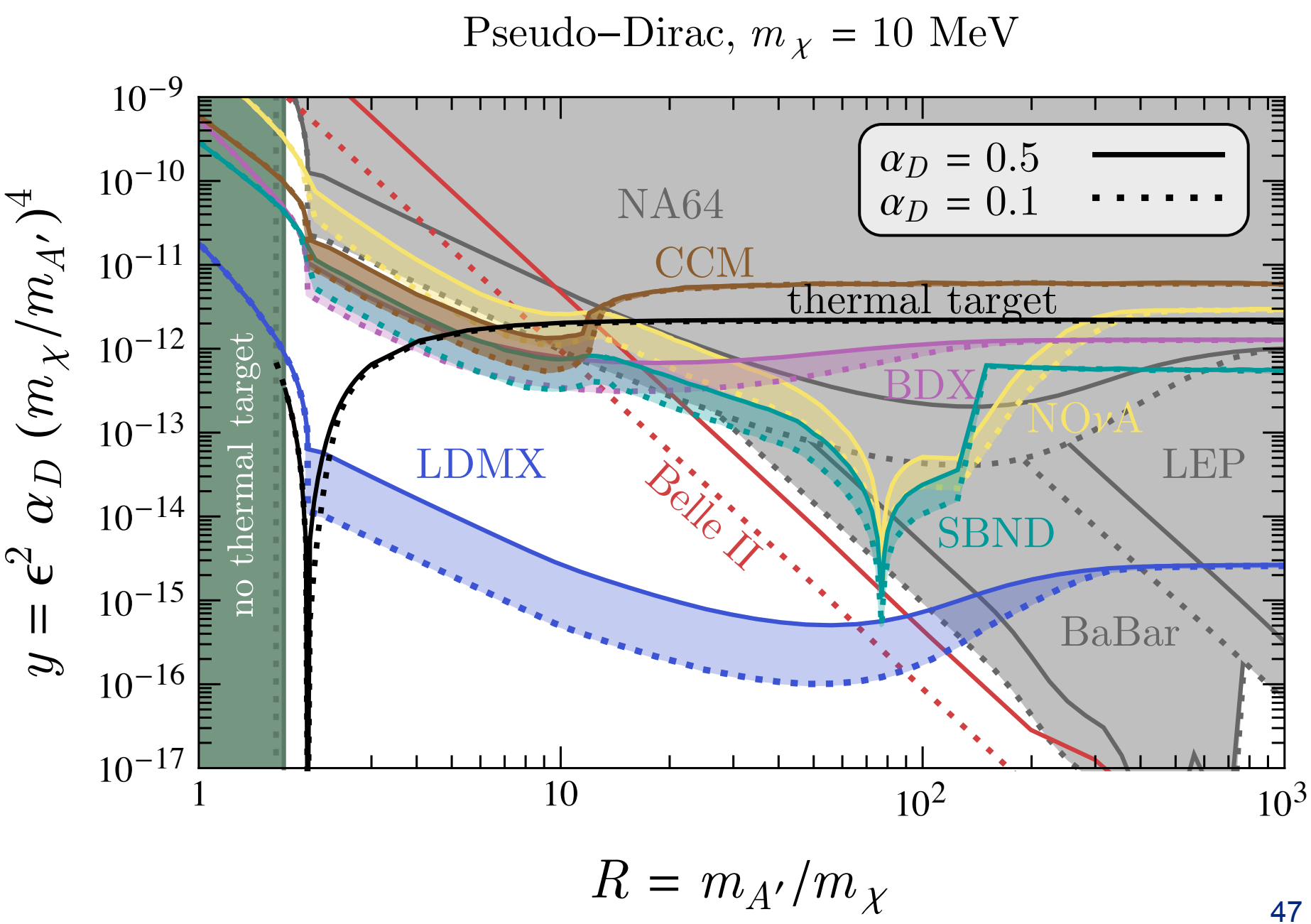
Can we explore the full parameter space $\{\varepsilon, \alpha_D, m_V, m_{DM}\}$?



[Berlin, deNiverville, AR, Schuster, Toro, to appear]

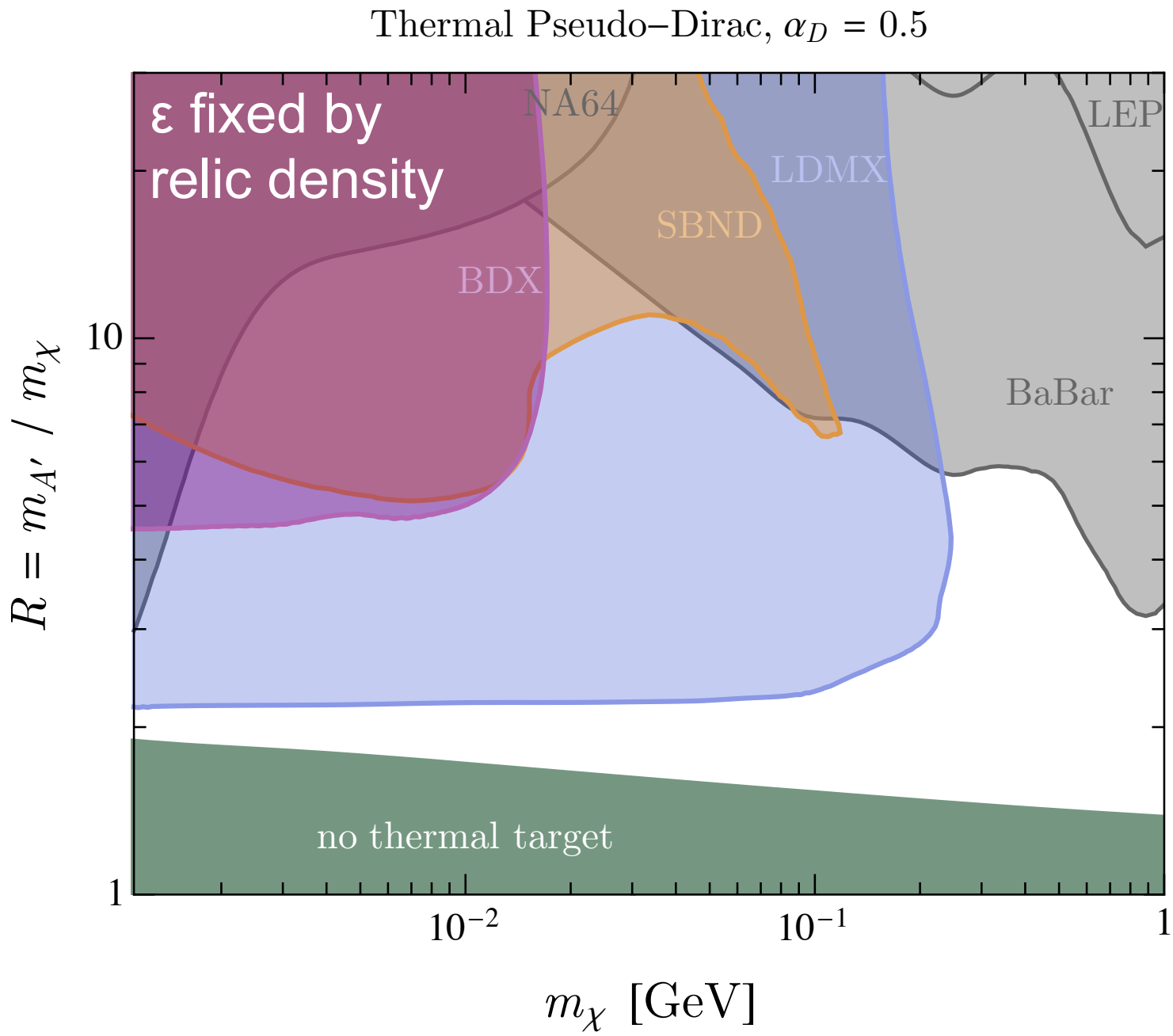
Generic fixed target sensitivity

[Berlin, deNiverville, AR, Schuster, Toro, to appear]

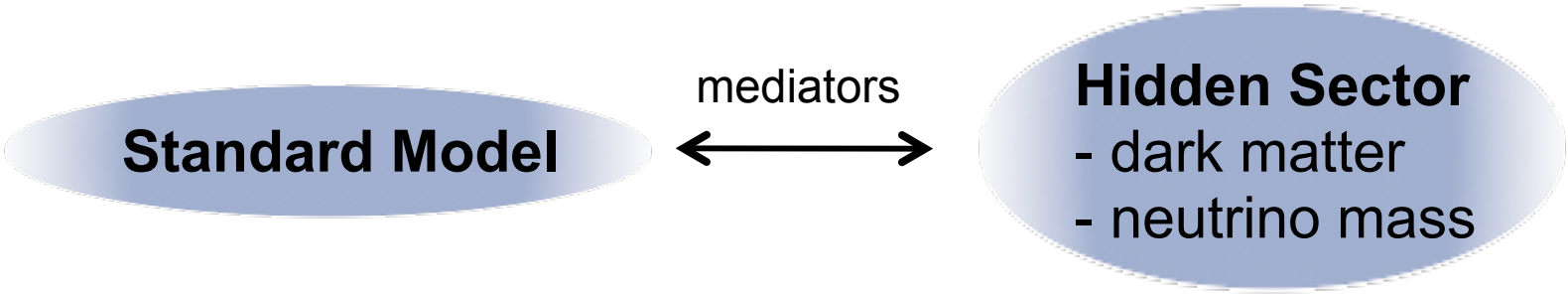


Generic fixed target sensitivity

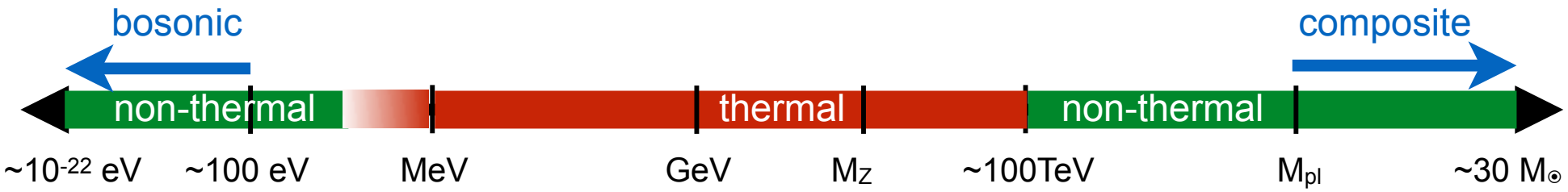
[Berlin, deNiverville, AR, Schuster, Toro, to appear]

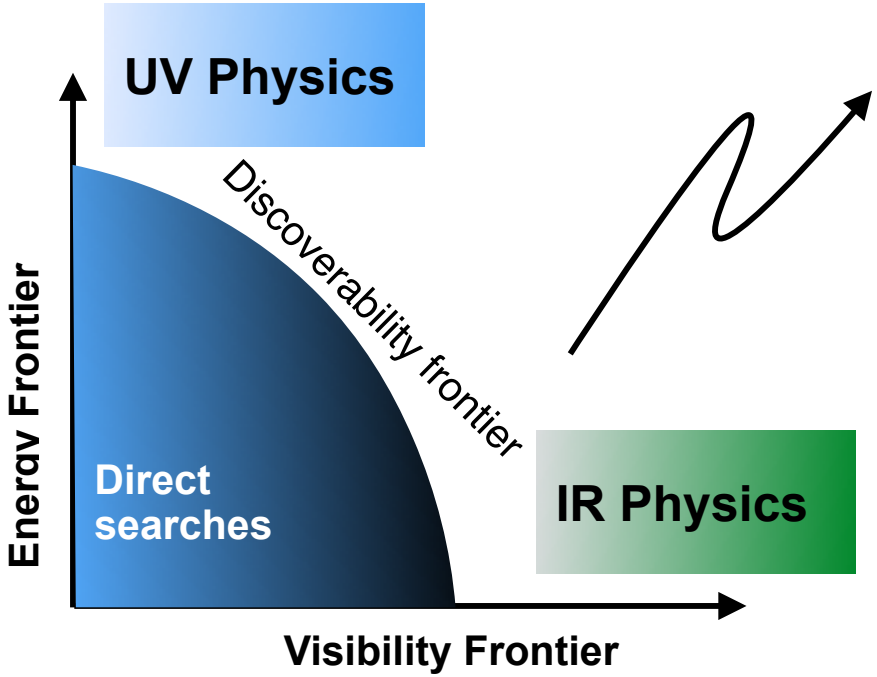


Summary



Empirical motivations for new physics suggest dark/hidden sectors:





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

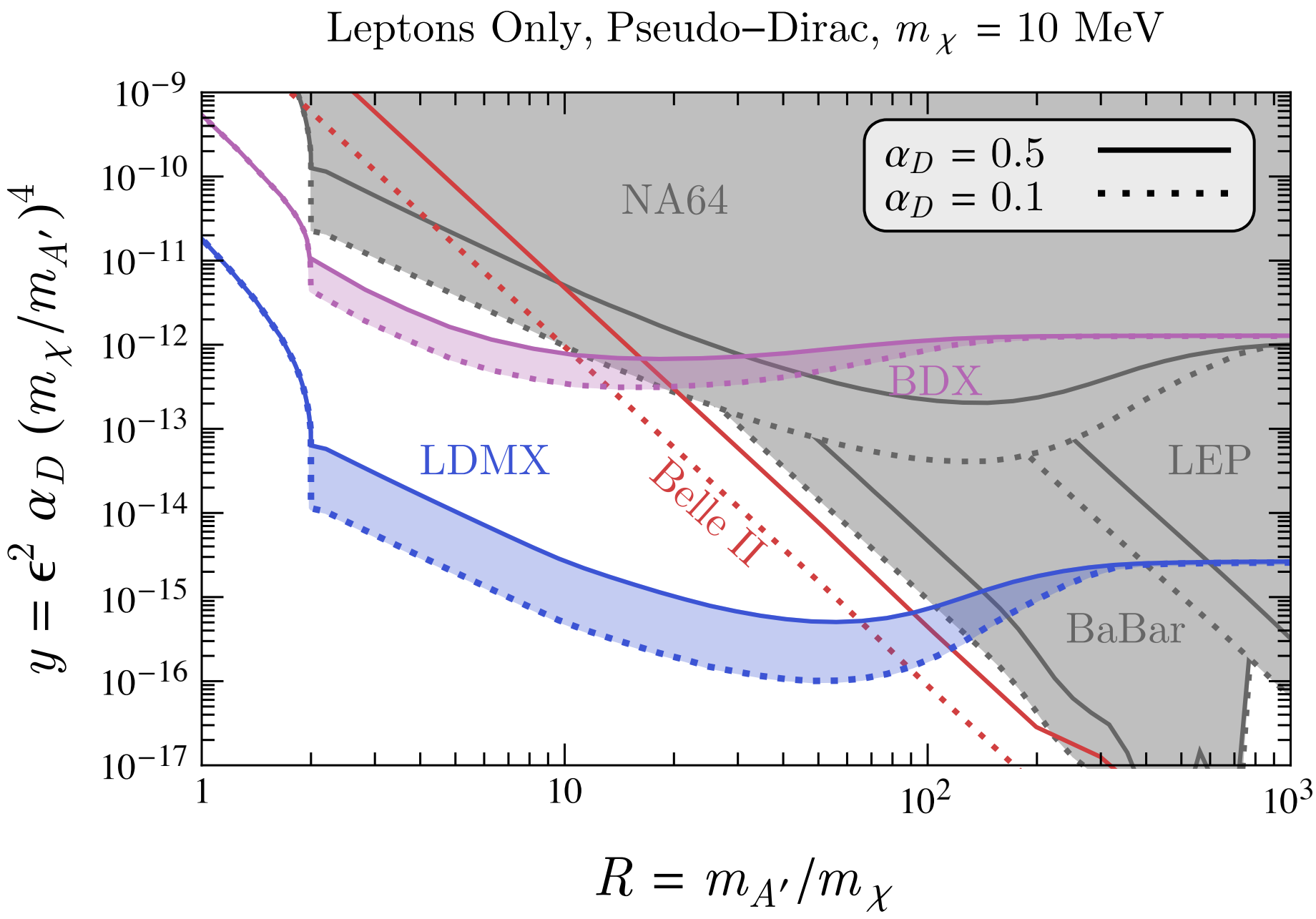
  ➡ Expanded theoretical landscape e.g. for (low mass) particle DM

  ➡ Expanded complementary search strategies, with experimental efforts at the precision and intensity frontier over the past decade

  ➡ Viable path to cover “most” of the thermal relic DM parameter space.

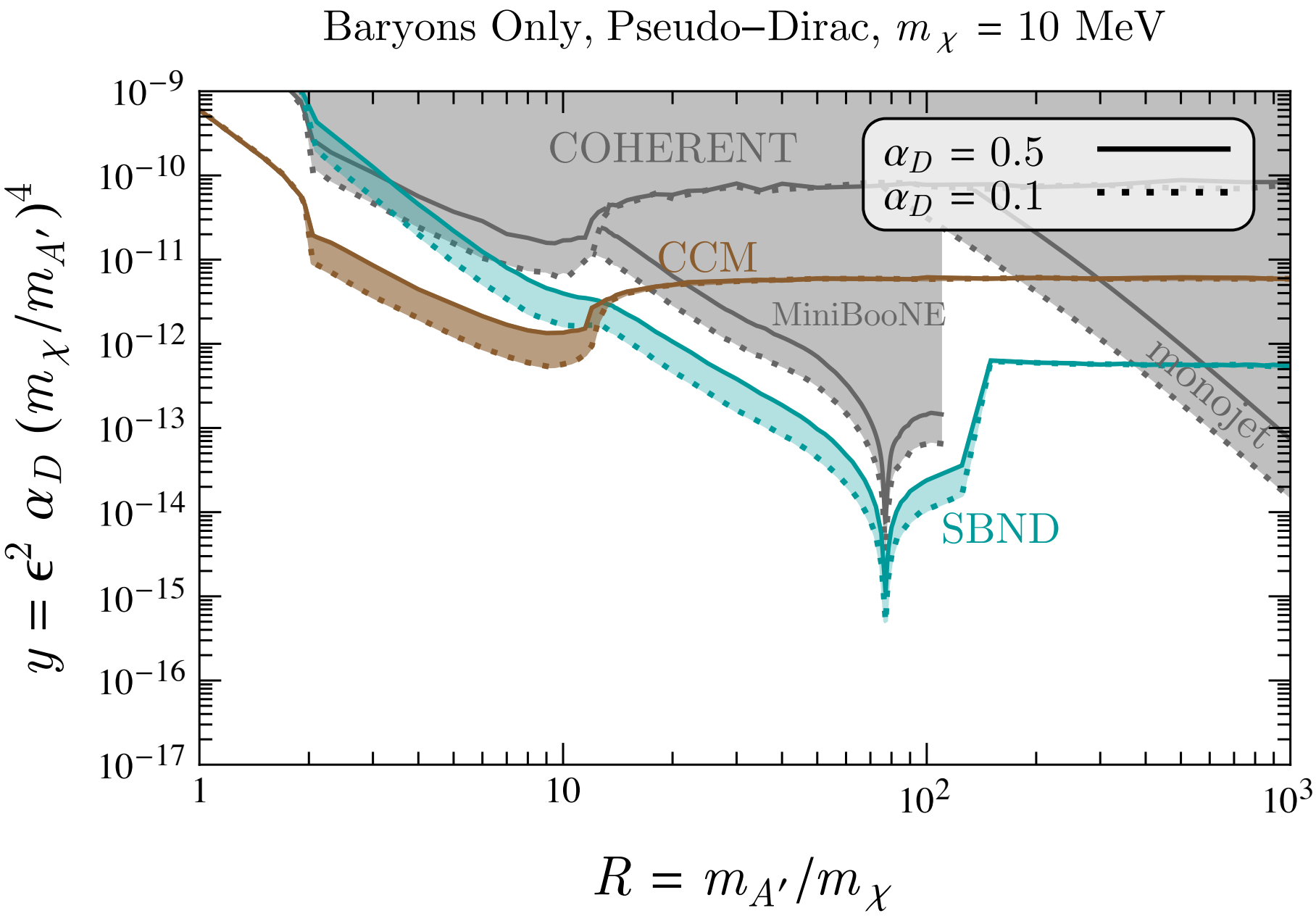
Additional slides
(including Higgs, neutrino portals)

Vector portal DM - leptonic coupling sensitivity



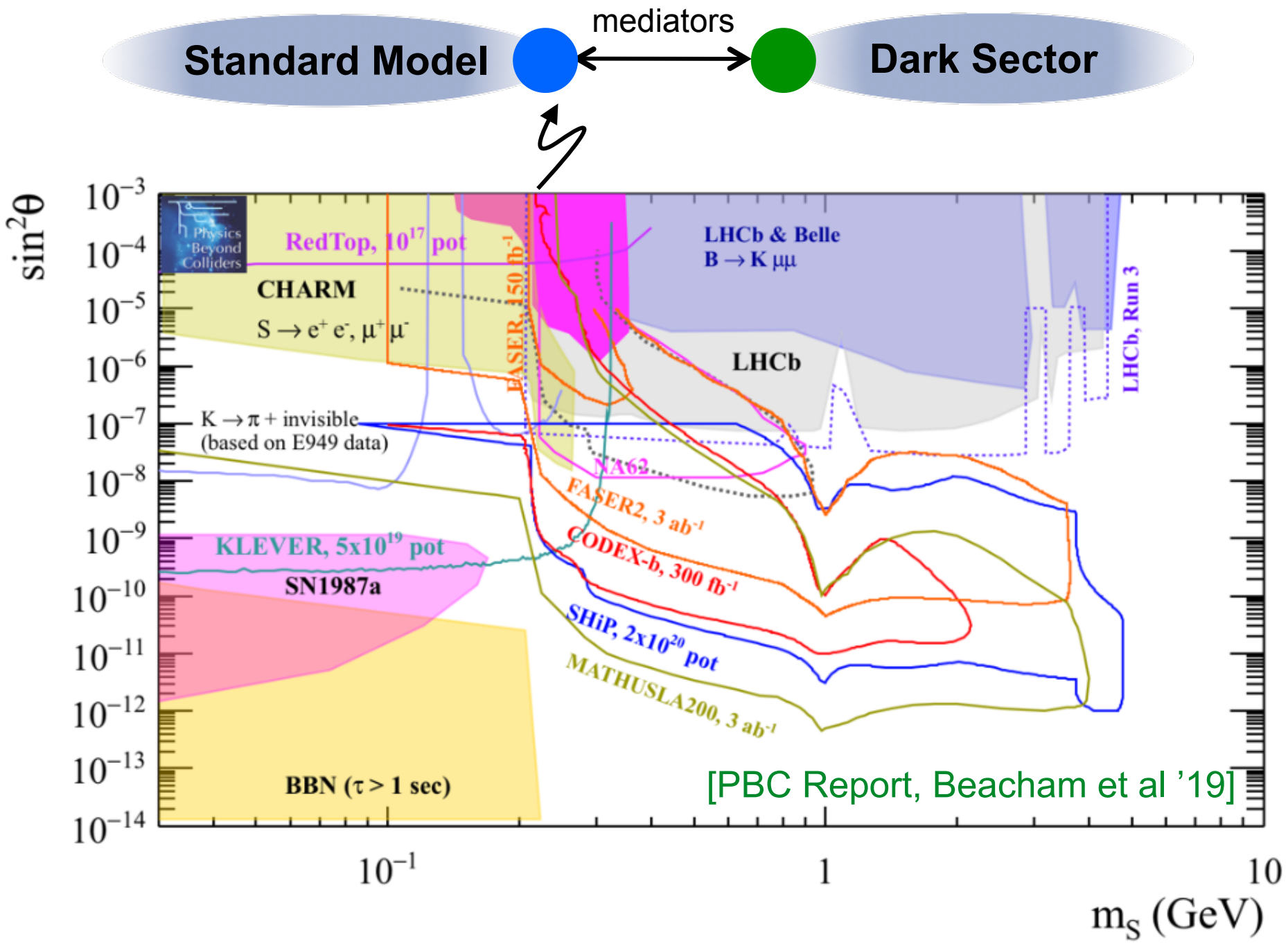
[Berlin, deNiverville, AR, Schuster, Toro, to appear]

Vector portal DM - baryonic coupling sensitivity

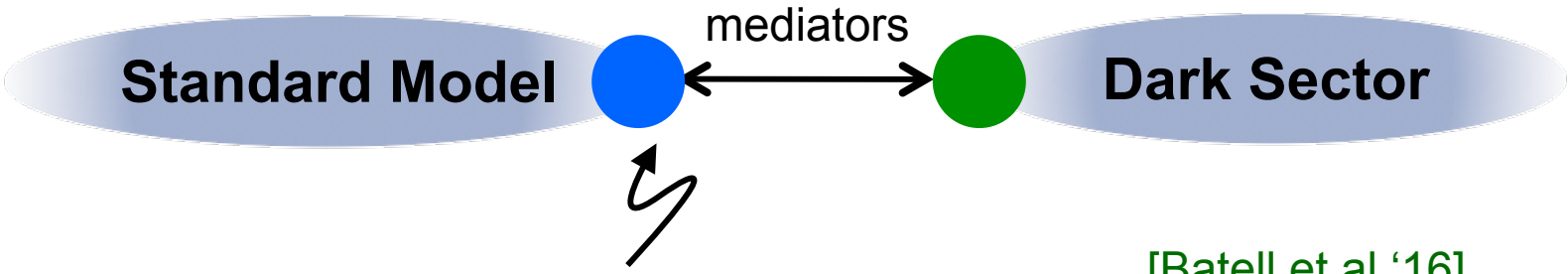


[Berlin, deNiverville, AR, Schuster, Toro, to appear]

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

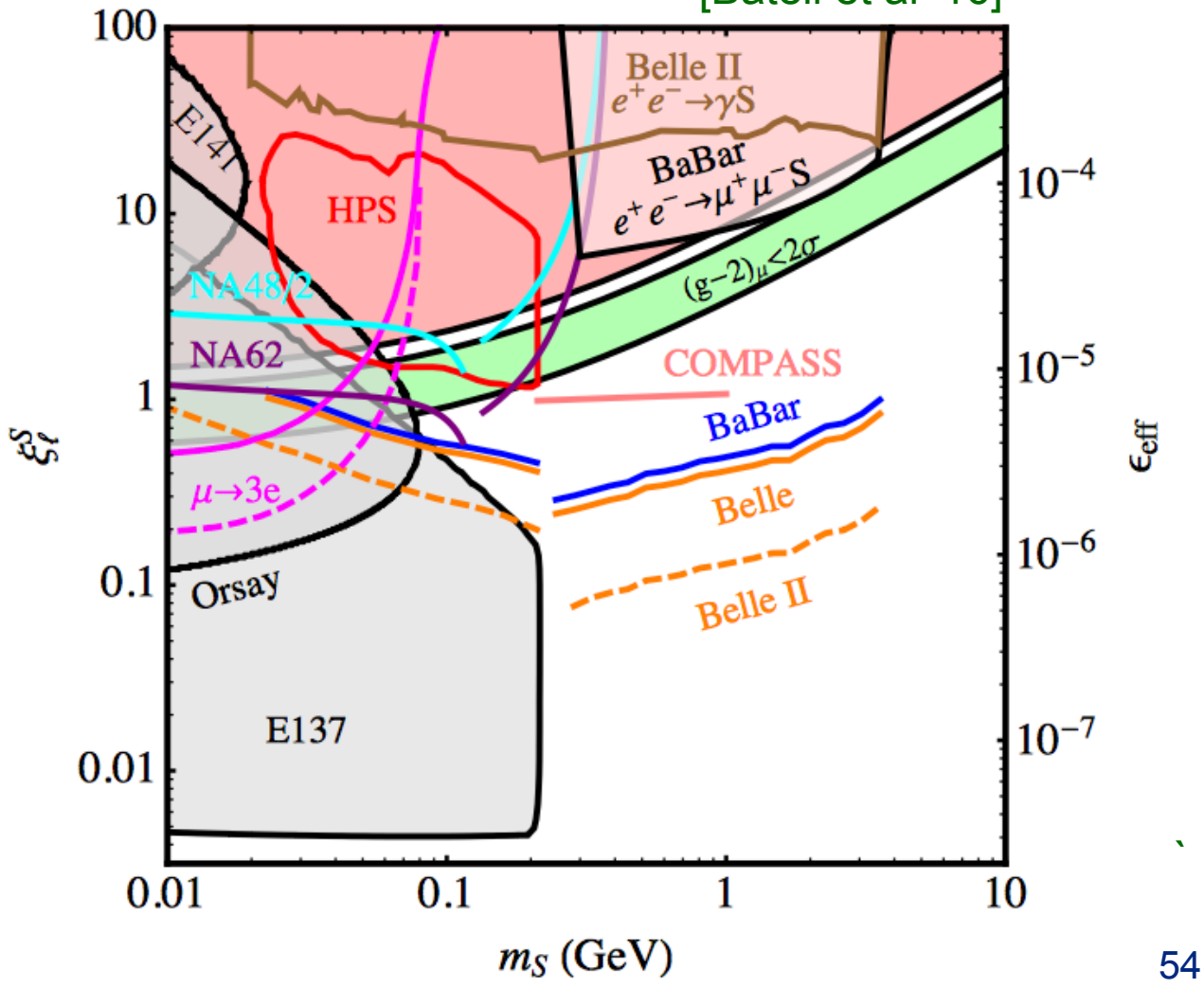


E.g. precision/rare decays (Higgs portal)

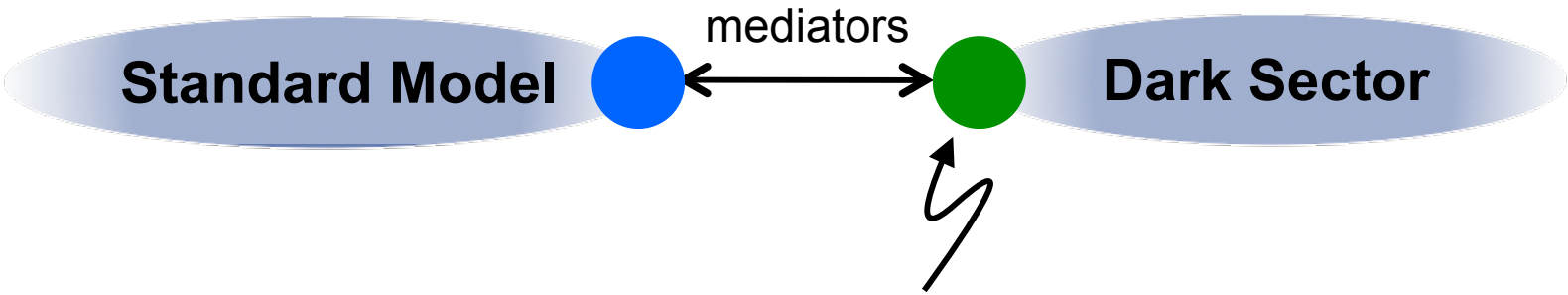


Minimal Higgs portal
➠ strong constraints due to (b → s+S) mediated transitions. The "leptonic Higgs portal" g_lSII, requires UV completion, but can be more viable

[Batell et al '16]

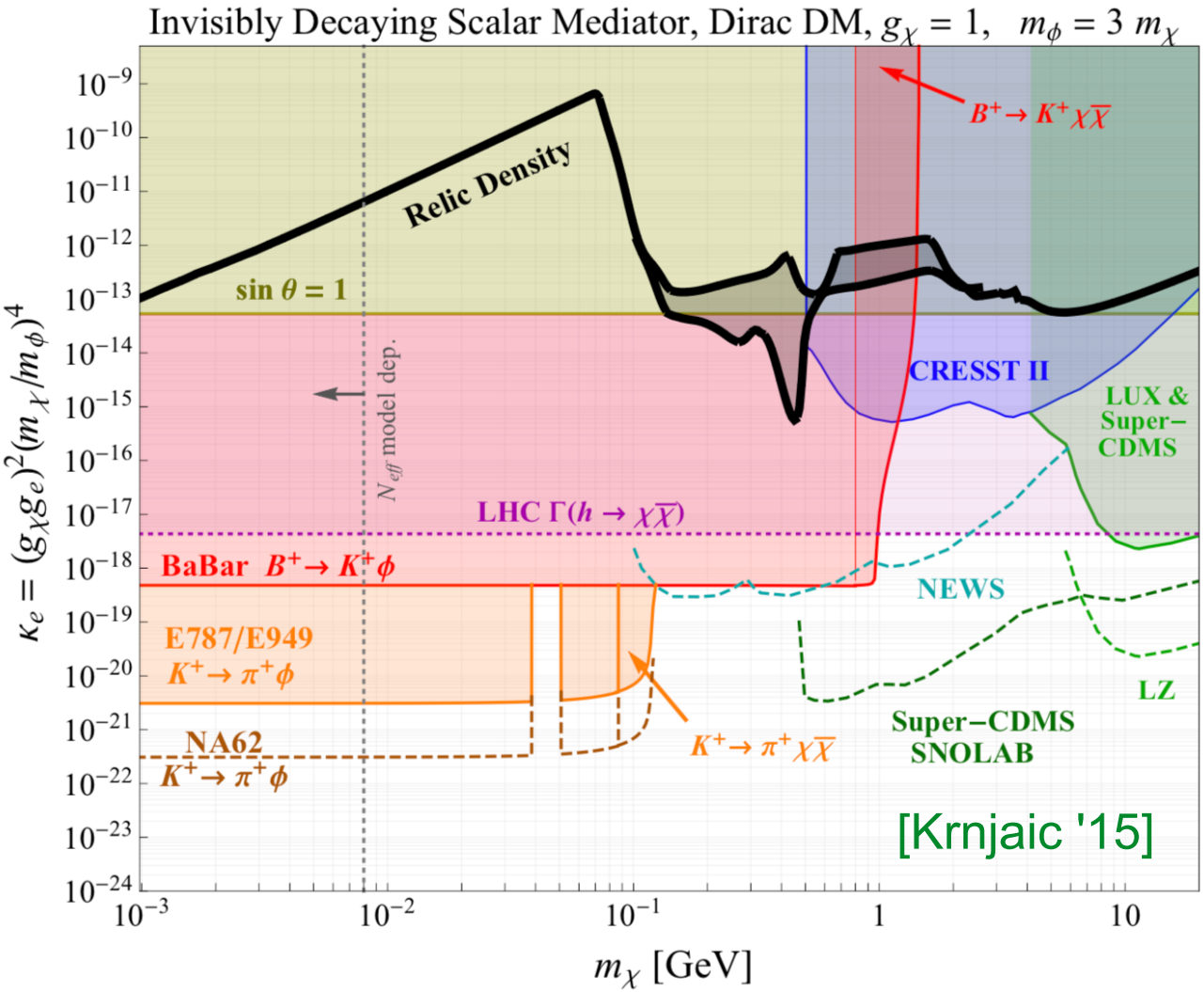


Light DM (Higgs portal)

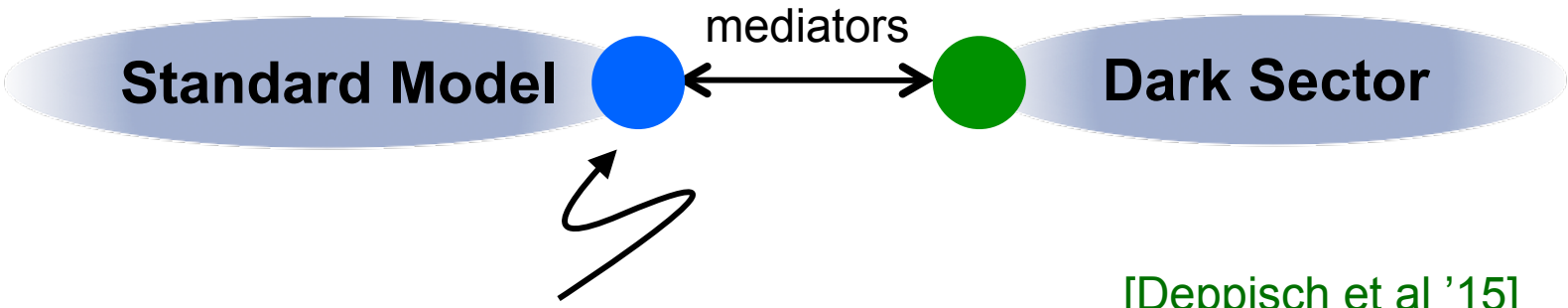


Highly constrained, due to constraints on B, K decays

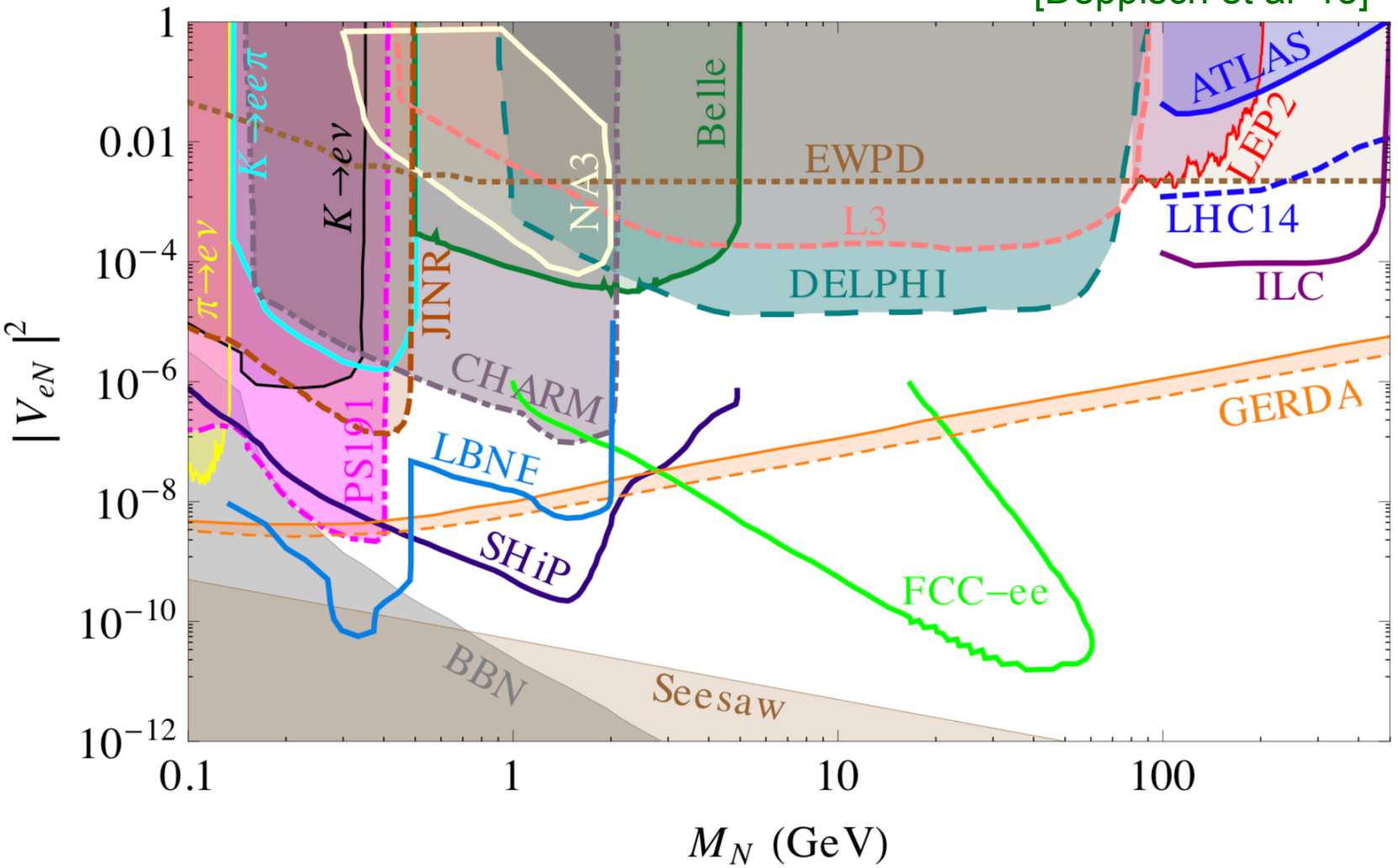
[Boehm & Fayet; deNiverville et al '12; Krnjaic '15]



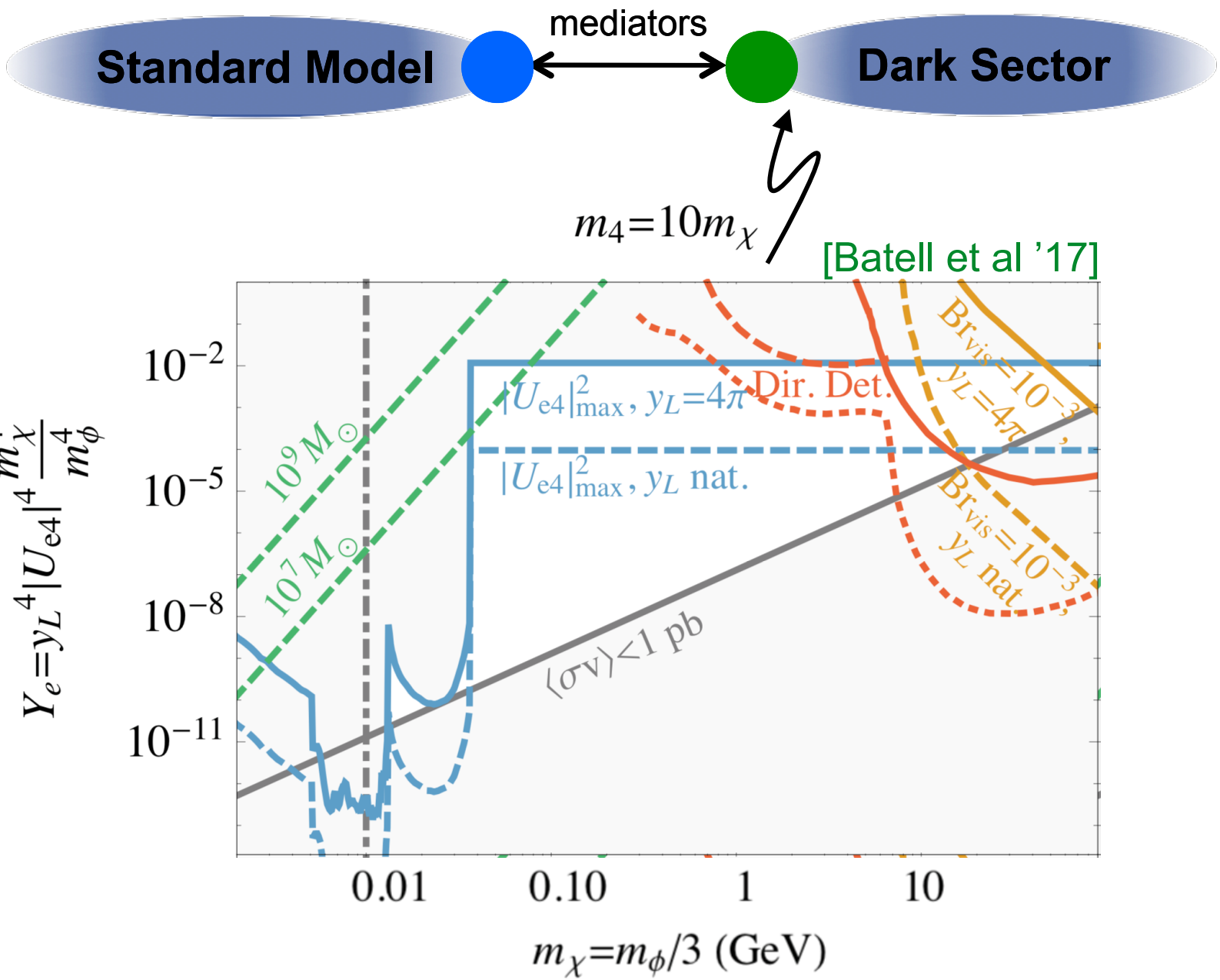
E.g. precision/rare decays (neutrino portal)



[Deppisch et al '15]



Light DM (Dirac Neutrino portal)

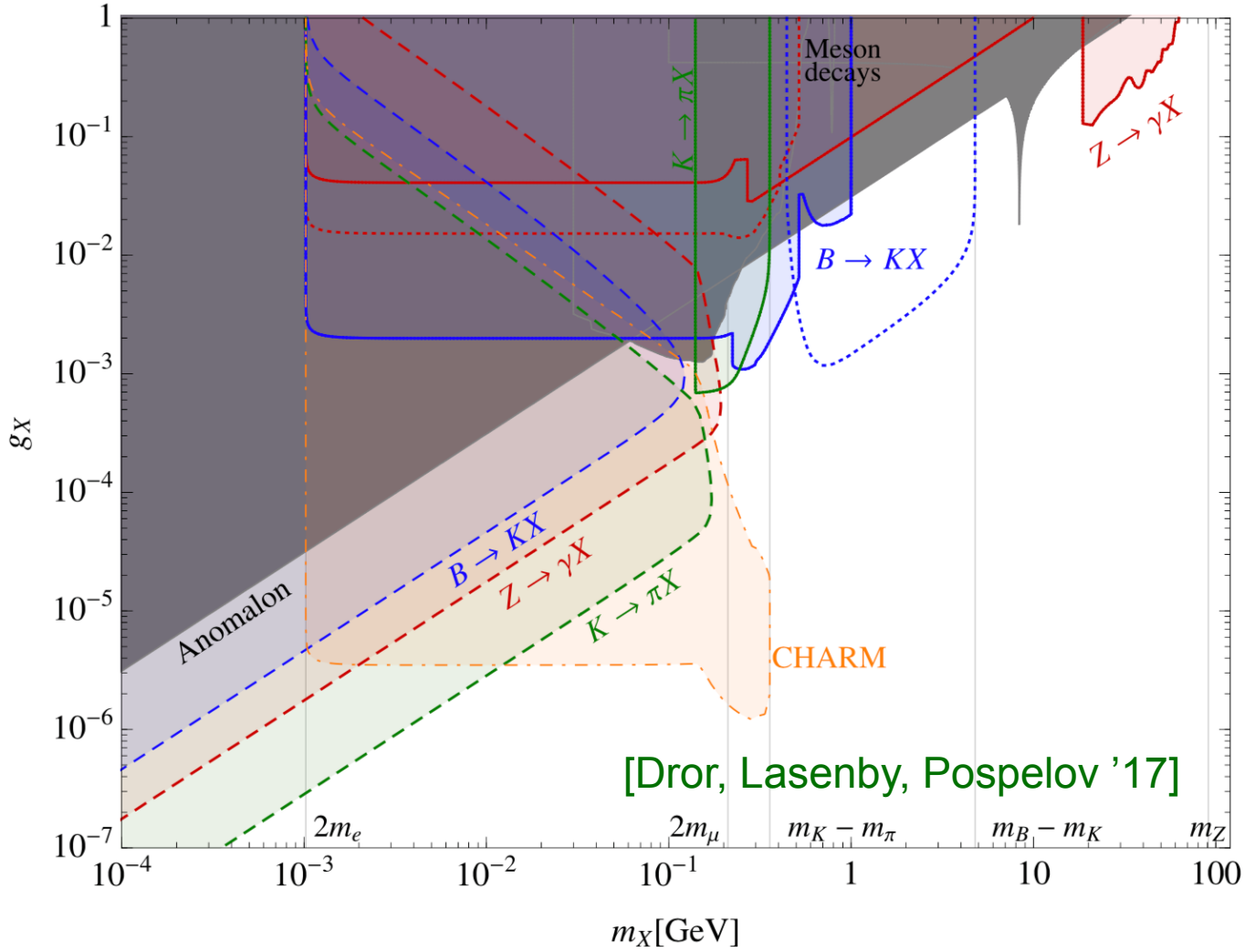


[Bertoni et al '14; Batell et al '17]

Beyond (dim ≤ 4) portals…

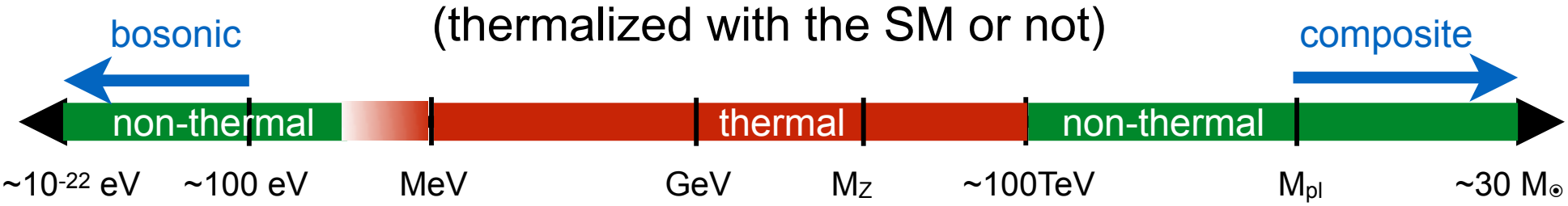
Other light dark forces, e.g. coupled to anomalous currents, generally inherit extra constraints, e.g. for a baryonic U(1)'

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



Cold DM Landscape

Classify models according to their thermal history in the early universe



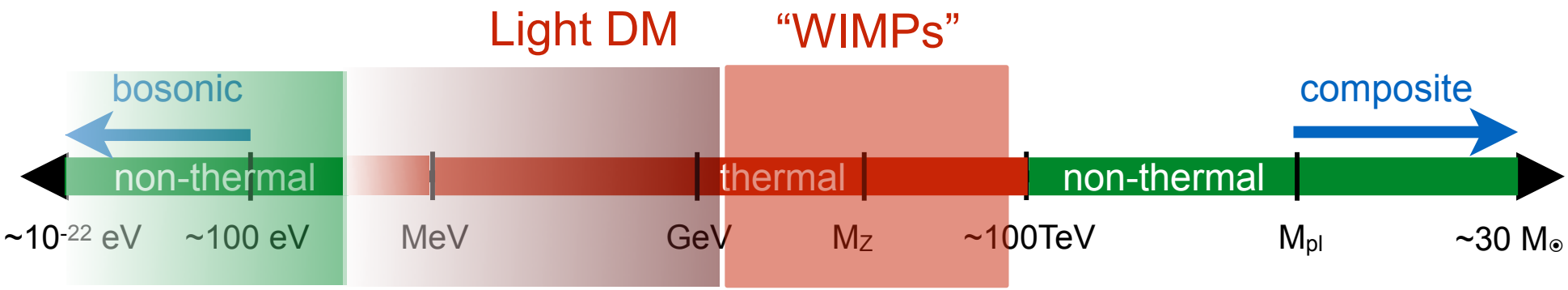
e.g. sterile neutrinos, axions, etc

e.g. primordial BHs

“Lamp posts” = Astrophysics, Direct detection via absorption, AMO technology

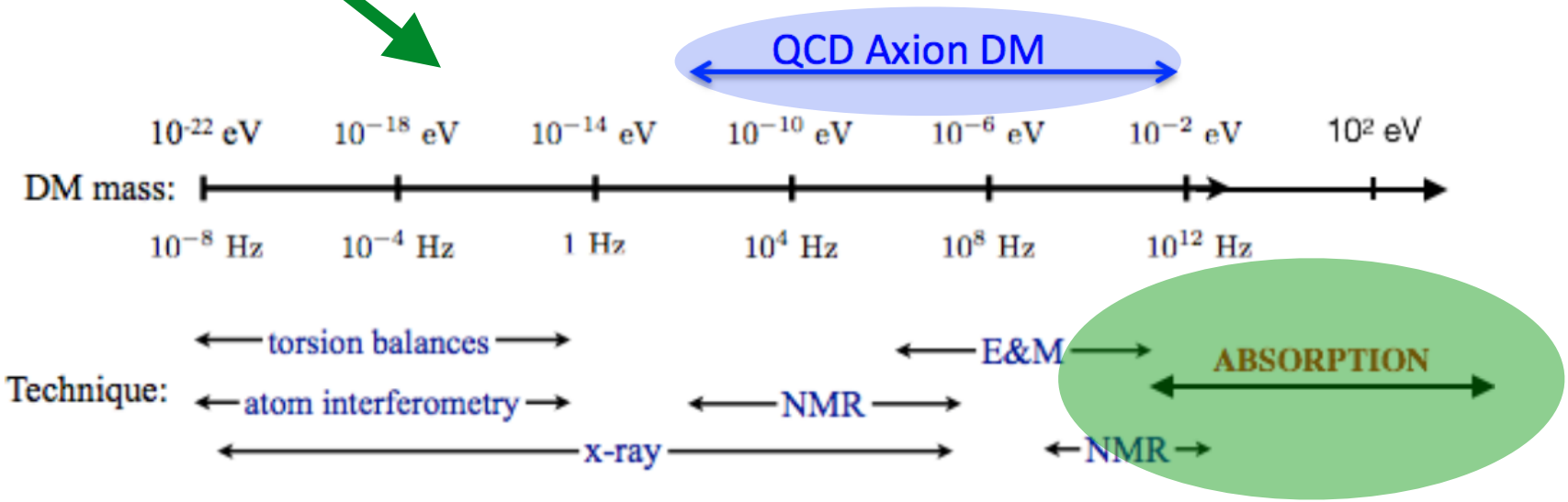
“Lamp posts” = Astrophysics, Microlensing, Grav waves

Cold DM "Landscape"



ultralight bosonic DM

Range of new low energy precision detection techniques



[Cosmic Visions 2017]

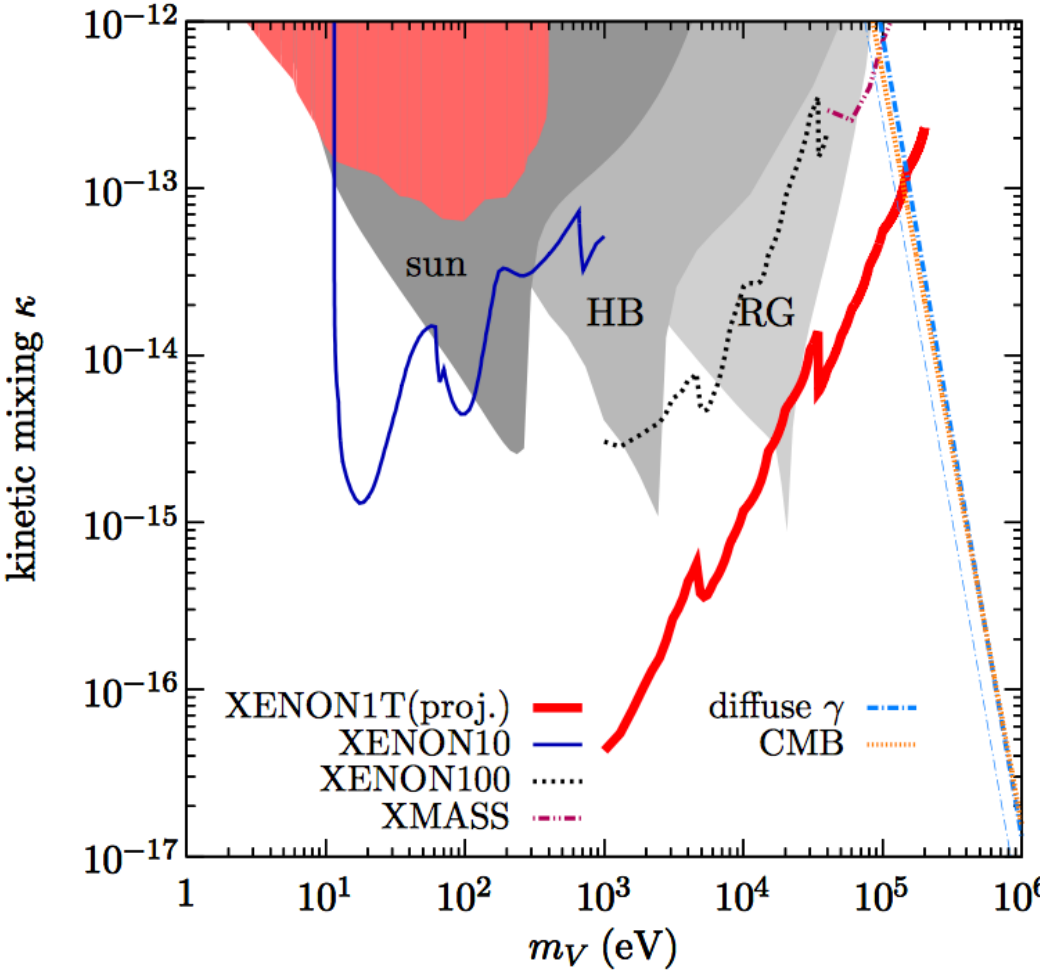
Dark photon DM - sensitivity (projections)

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

Dark photon DM: long lifetime if $m < 2m_e$ ($A' \to 3\gamma$ or 2ν)

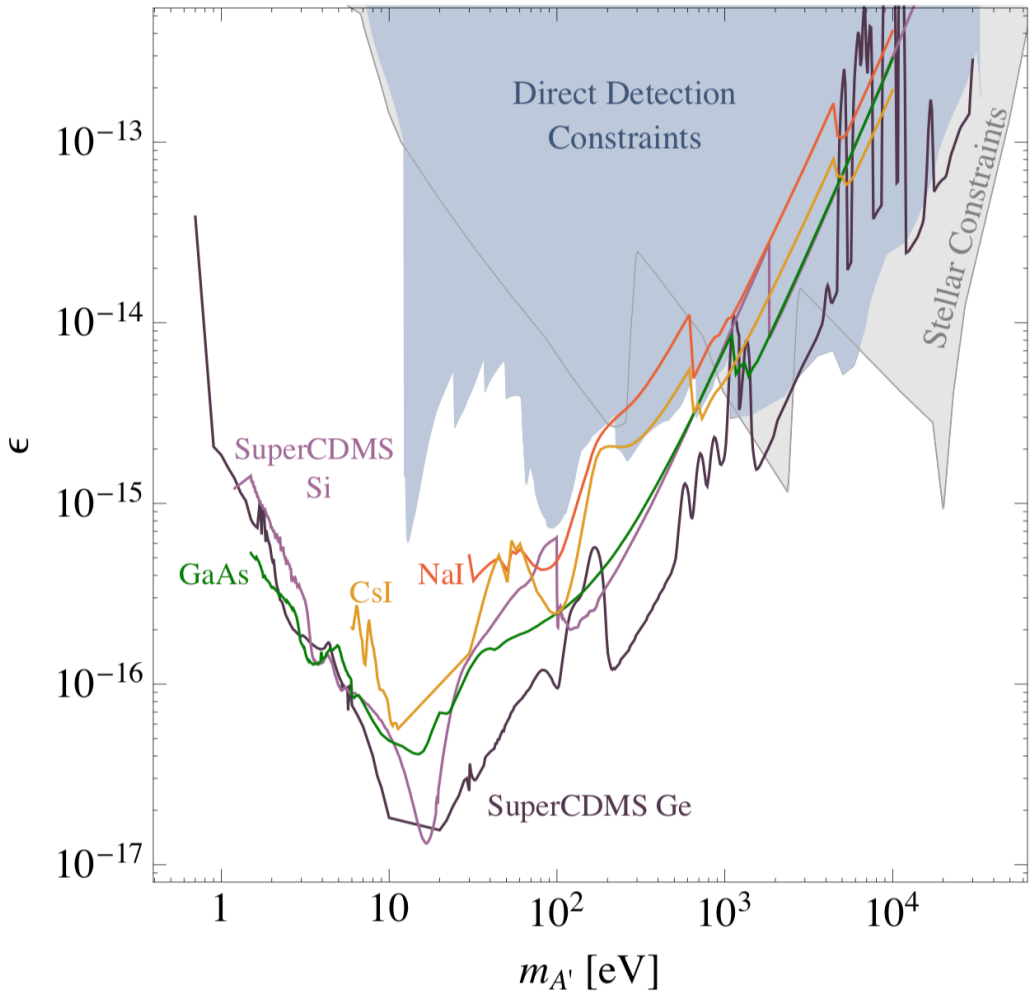
[Pospelov, AR, Voloshin '08, Redondo & Postma '08]

[An et al '15]



Sensitivity via atomic ionization

[Bloch et al '17]



[also Hochberg et al '17]