

Light Dark Sectors

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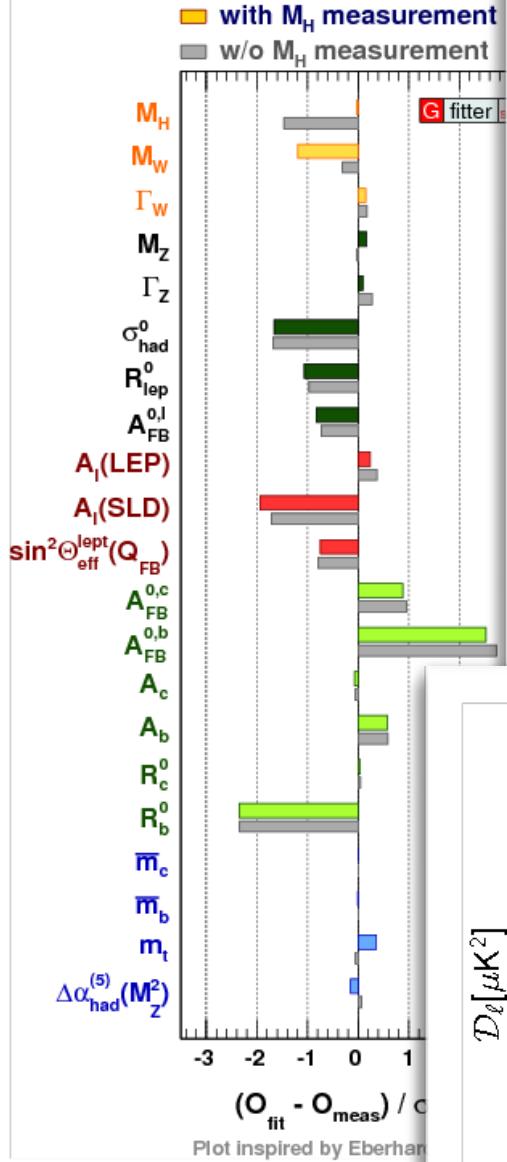
Looking for new physics where we can see it...



Opportunity

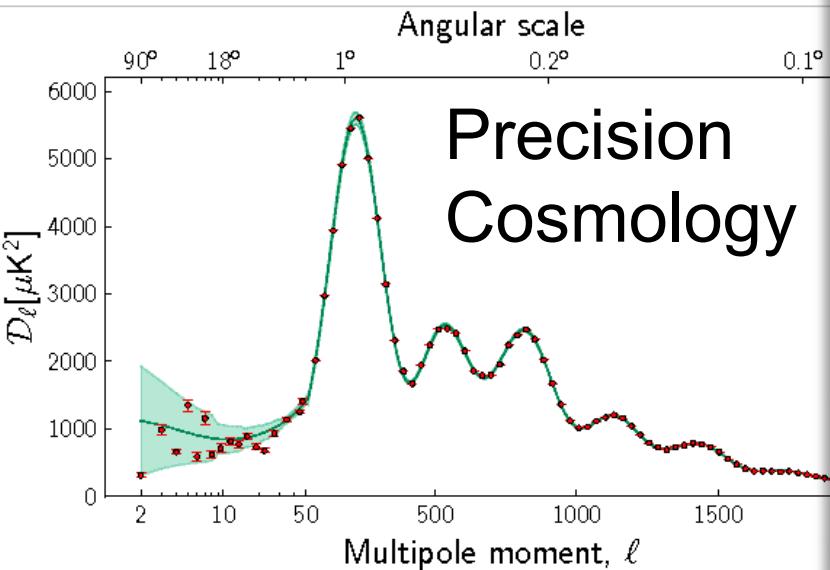
Looking for new physics where we can see it...

Electroweak

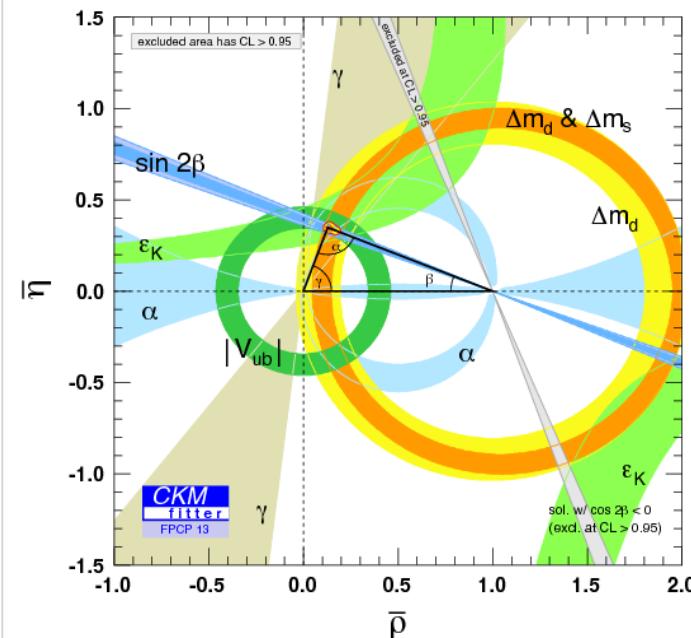


Energy frontier

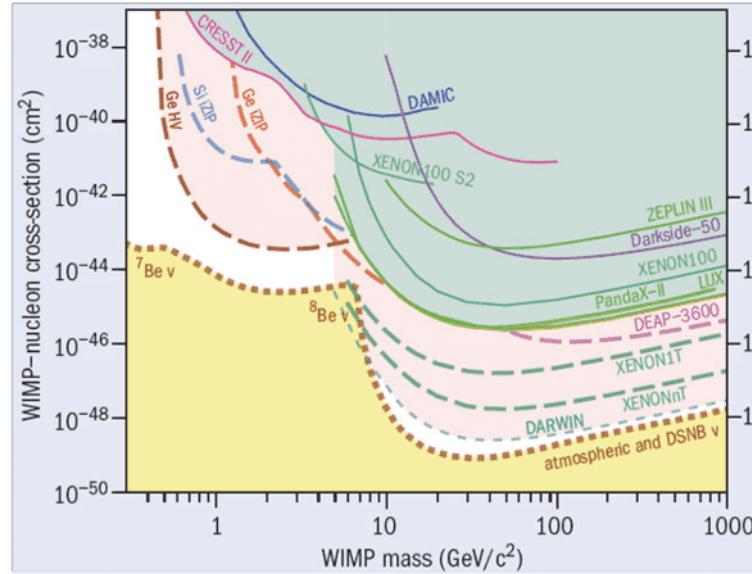
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits						
		ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 - 4 j	Yes	36.1	M_0
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_5
	ADD OBH	-	2 j	-	37.0	M_{bh}
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	M_{bh}
	ADD BH multi-jet	-	$\geq 3 j$	-	3.6	M_{bh}
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	G_{KK} mass
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	2.3 TeV
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qqqq$	0 e, μ	2 J	-	139	1.6 TeV
	Bulk RS $G_{KK} \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1 J/2$	Yes	36.1	G_{KK} mass
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	139	Z' mass
	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1	Z' mass
	Leptophobic $Z' \rightarrow bb$	-	2 b	-	36.1	Z' mass
	Leptophobic $Z' \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1 J/2$	Yes	36.1	Z' mass
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	-	36.1	W' mass
	SSM $W' \rightarrow \tau\nu$	1 τ	-	-	36.1	W' mass
	HVT $V \rightarrow WZ \rightarrow qqqq$ model B	0 e, μ	2 J	-	139	V mass
	HVT $V \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V mass
	LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	W_R mass
	LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	-	80	W_R mass
CI	CI $qqqq$	-	2 j	-	37.0	A
	CI $\ell'\ell q\bar{q}$	2 e, μ	-	-	36.1	A
	CI $\ell'\ell qq$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	2.57 TeV
	DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 - 4 j	Yes	36.1
	DM	Colored scalar mediator (Dirac DM)	0 e, μ	1 - 4 j	Yes	m_{mod}
	DM	Color scalar DM (Dirac DM)	0 e, μ	$1 J, \leq 1 J$	Yes	3.2
	DM	V _{CKM} EFT (Dirac DM)	0 e, μ	1 b, 0 - 1 J	Yes	700 GeV
	DM	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	0 - 1 e, μ	1 b, 0 - 1 J	Yes	3.4
	LQ	Scalar LQ 1 st gen	1, 2 e	$\geq 2 j$	Yes	36.1
	LQ	Scalar LQ 2 nd gen	1, 2 μ	$\geq 2 j$	Yes	36.1
Heavy quarks	LQ	Scalar LQ 3 rd gen	2 τ	2 b	-	36.1
	VLO	Scalar LQ 3 rd gen	0 - 1 e, μ	2 b	Yes	36.1
	VLO	$T T \rightarrow H/\tau/\tau b/Wb + X$	multi-channel	-	36.1	T mass
	VLO	$BB \rightarrow Wt/Zb + X$	multi-channel	-	36.1	B mass
	VLO	$T_{2/3}T_{5/3}S_1T_{2/3} \rightarrow Wt + X$	$2(SS)/3$ e, μ	$\geq 1 b, \geq 1 j$	Yes	$T_{2/3}S_1$ mass
Heavy quarks	VLO	$Y \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1
	VLO	$B \rightarrow Hb + X$	0 e, $\mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8
	VLO	$QQ \rightarrow WqWq$	1 e, μ	$\geq 4 j$	Yes	20.3
	VLO					690 GeV



Flavour



DM direct detection



Looking for new physics where we can see it...



Precision Λ CDM cosmology + lack of evidence for new weak scale physics...

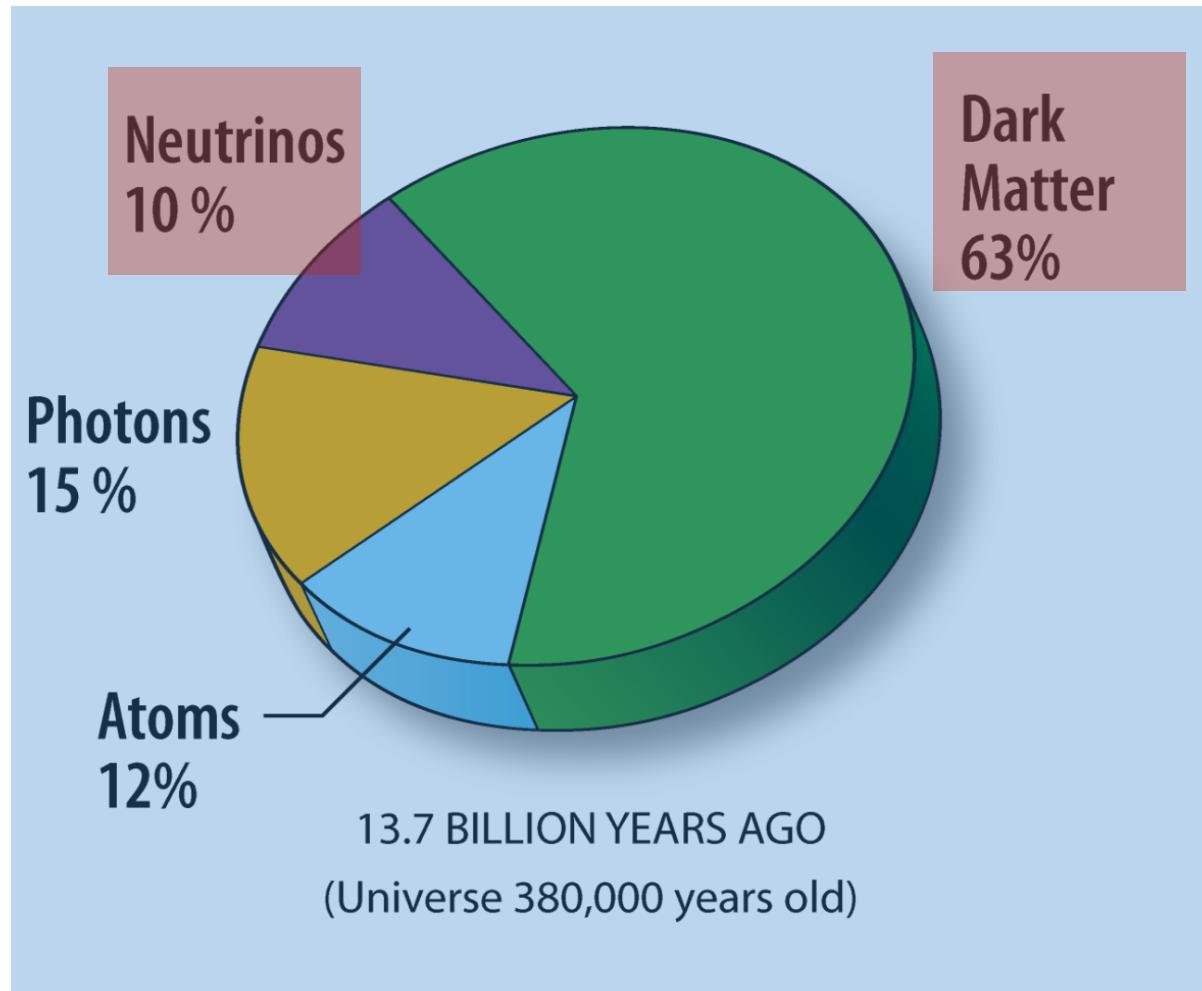


(Also various data-driven anomalies...)

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): $u\bar{d}, (u\bar{u} - d\bar{d})/\sqrt{2}, d\bar{u}$;
for $I = 0$ ($\eta, \eta', h, h', \omega, \phi, f, f'$): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

π^\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

$\pi^\pm \rightarrow e^\pm \nu \gamma$ 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 ($\frac{\rho}{MeV/c}$)
$\mu^+ \nu_\mu$	[b] $(99.98770 \pm 0.00004) \%$	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
$e^+ \nu_e \nu \bar{\nu}$	$< 5 \times 10^{-6}$ 90%	70

[lbarra]

DARK MATTER

$J = ?$

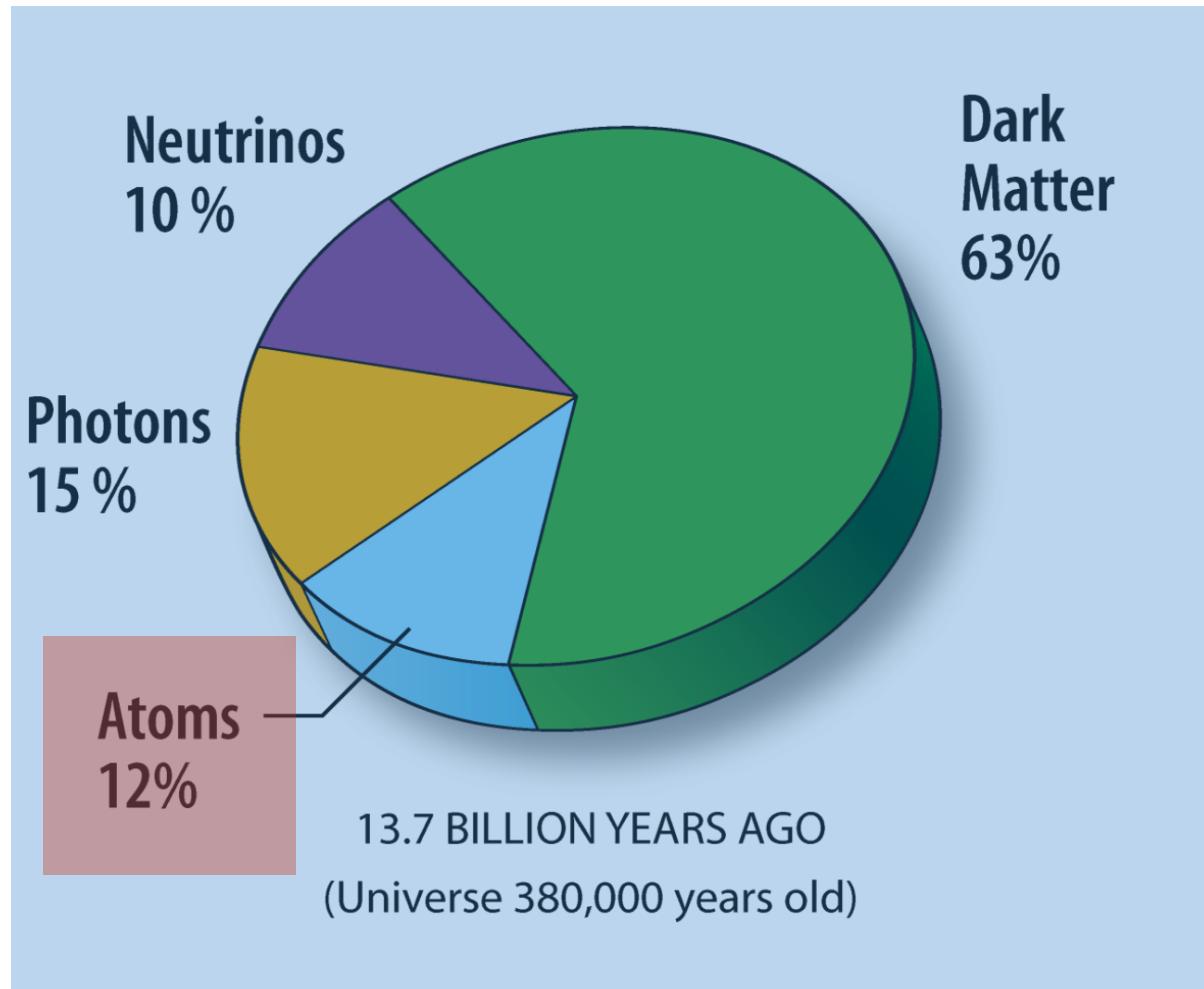
Mass $m = ?$
Mean life $\tau = ?$

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level ($\frac{\rho}{MeV/c}$)
?	?	?

- Relic density $\sim 5 \times$ 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

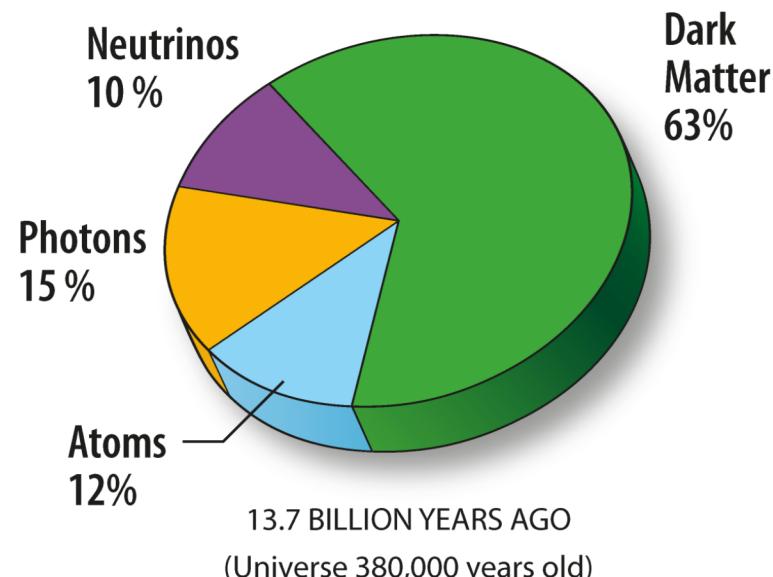
A. D. Sakharov

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 antimatter; 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...

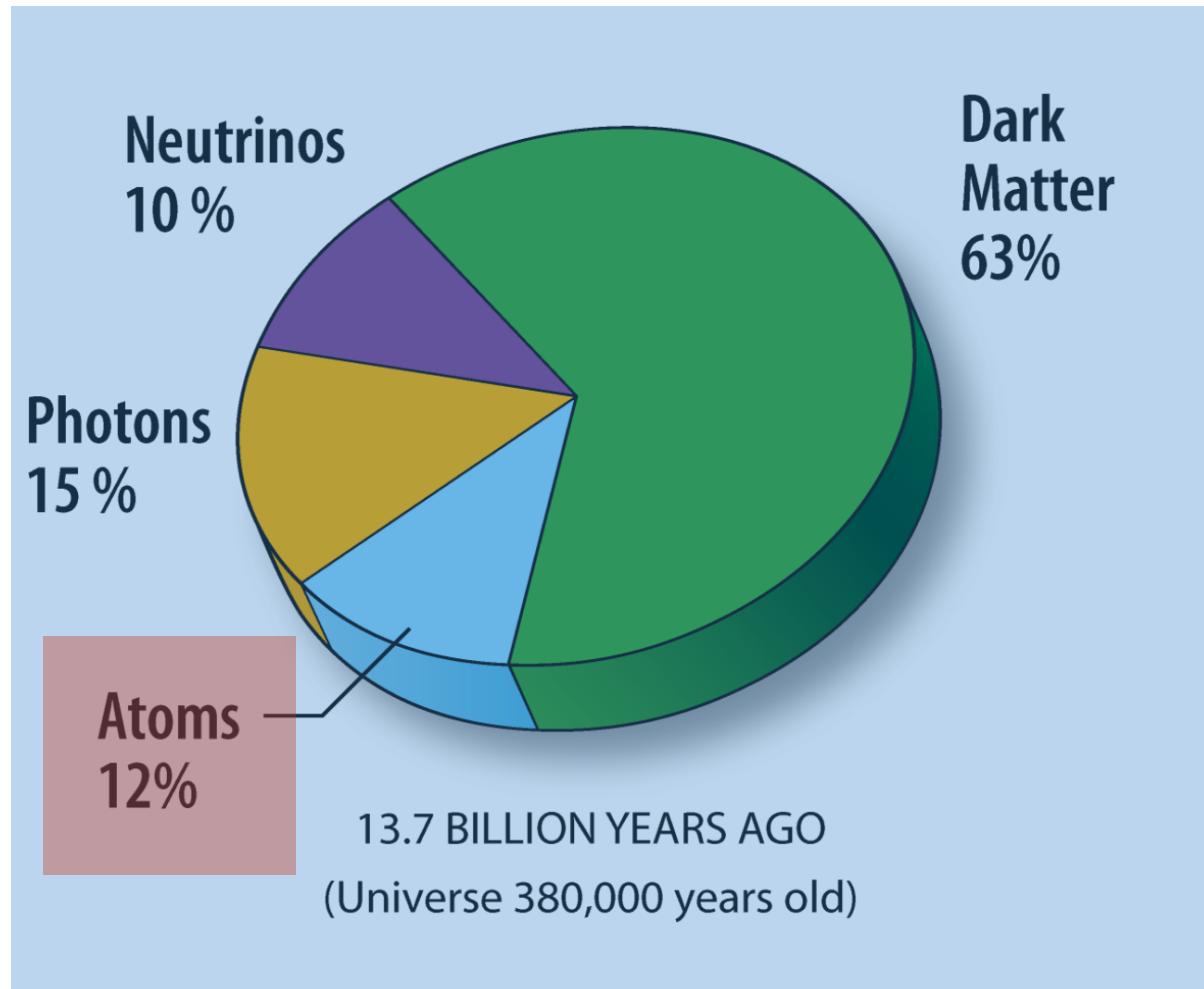


Questions

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

Questions...

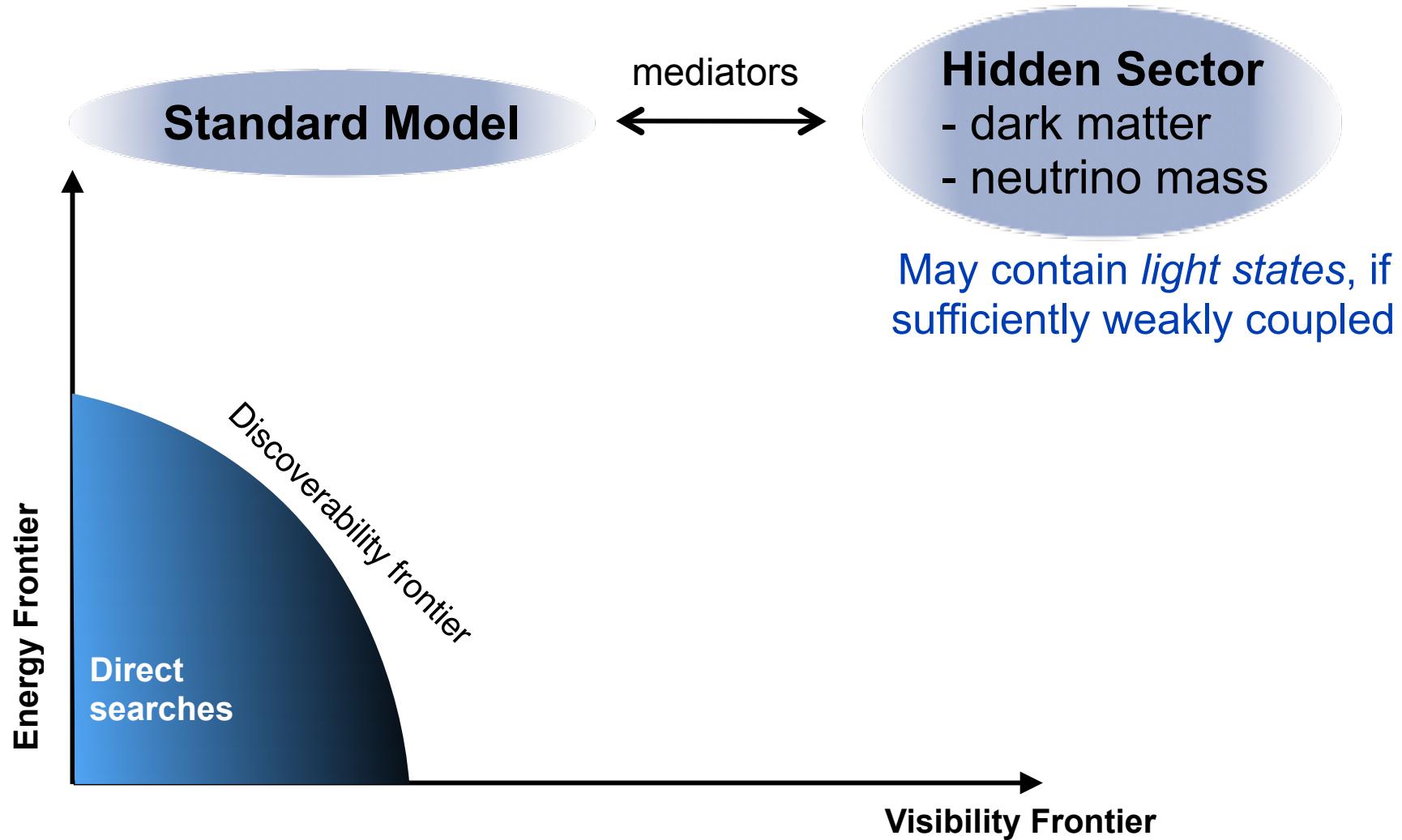
The Standard Model is highly successful, but there is sharp empirical evidence for new physics...



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

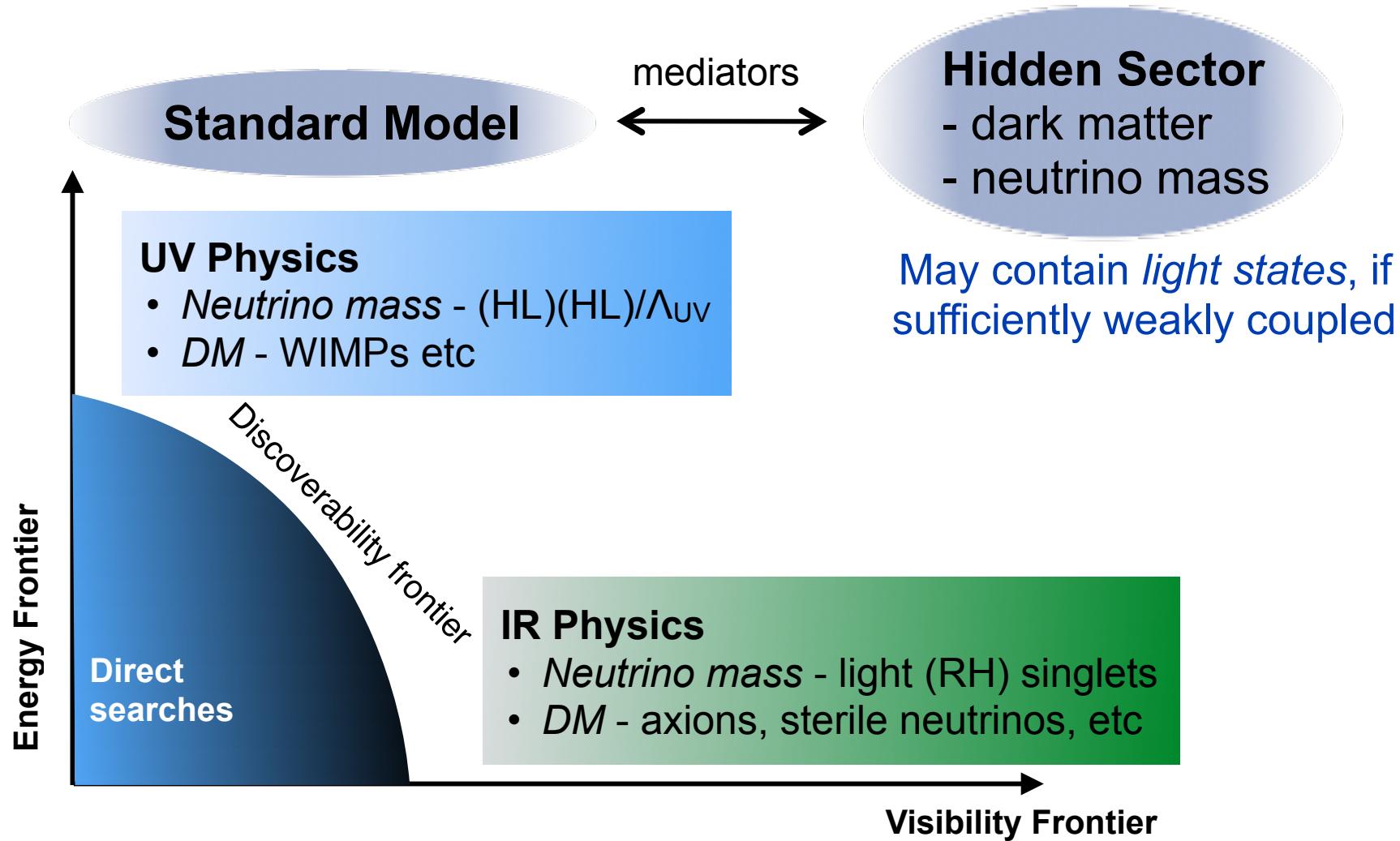
New physics in a dark/hidden sector

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



New physics in a dark/hidden sector

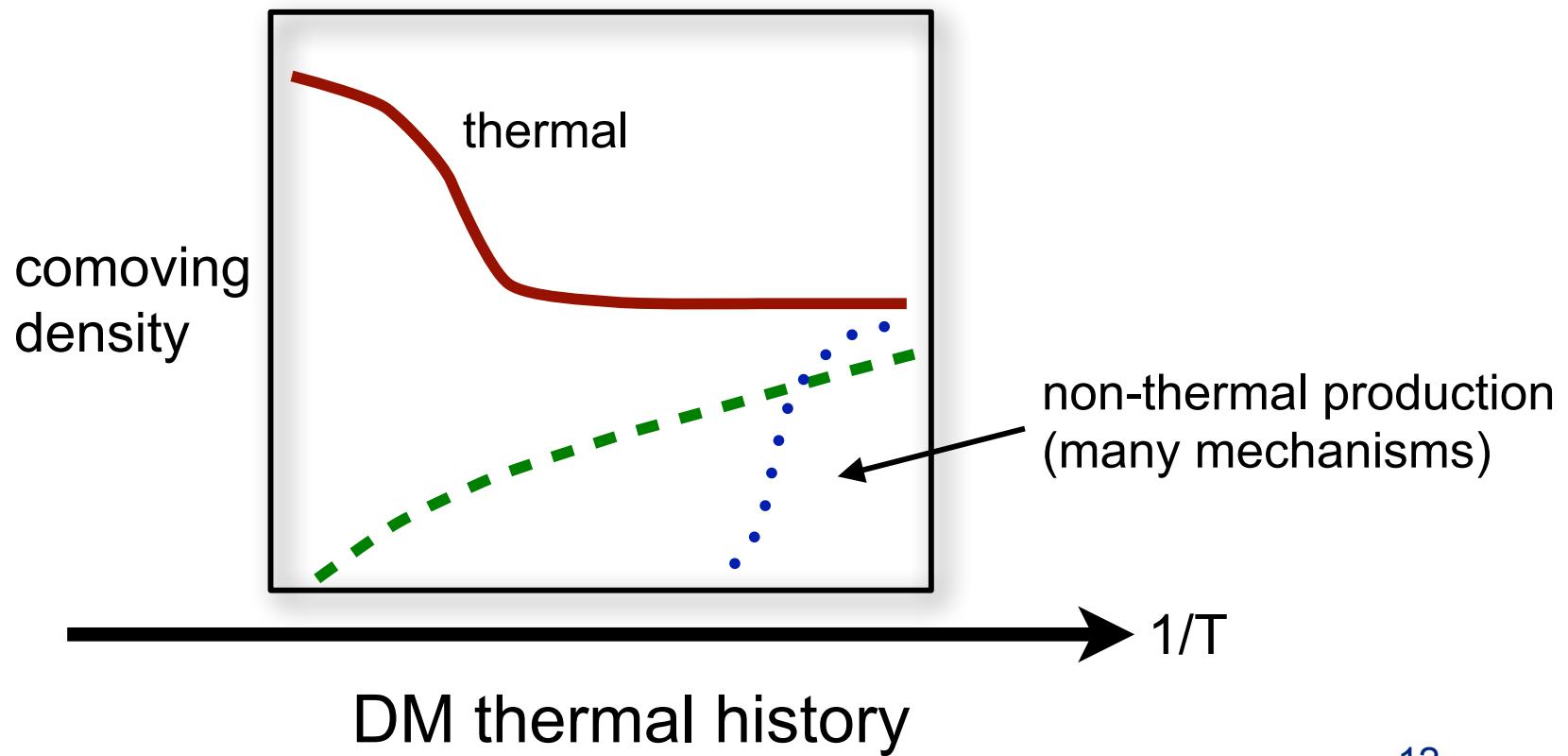
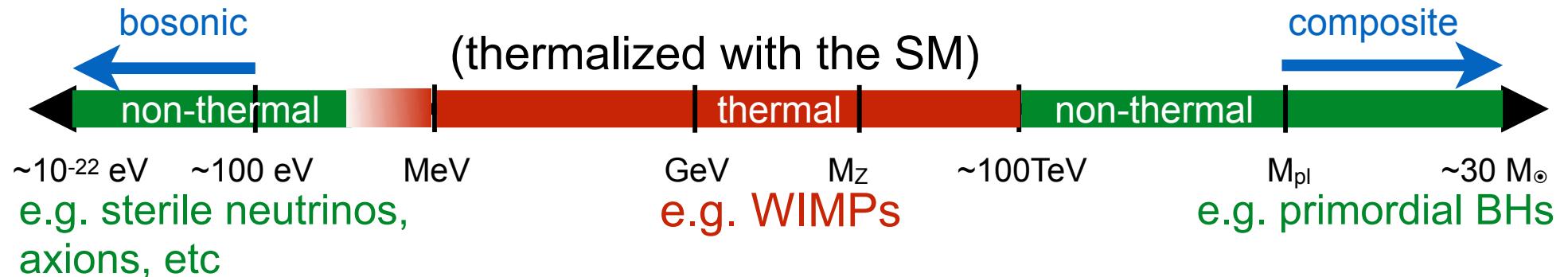
Empirical evidence for new physics (e.g. *neutrino mass, dark matter*) arguably points to a hidden/dark sector, but not directly to a mass scale



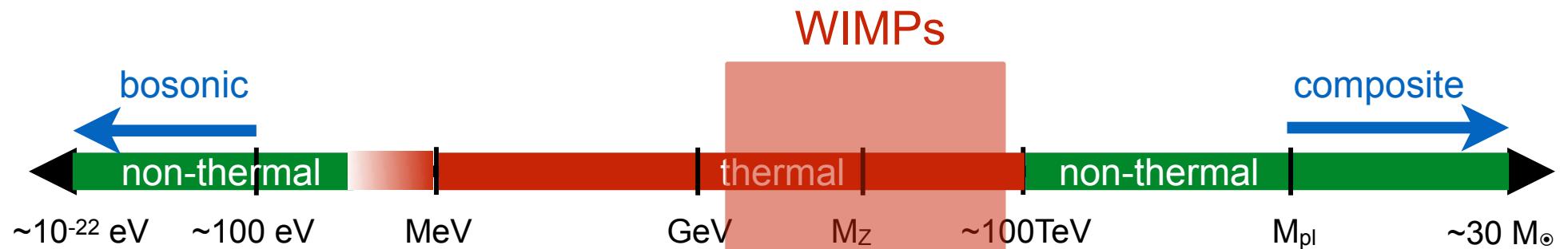
➡ a huge parameter space a priori, so what theoretical guidance is there?

Cold DM Landscape

Classify models according to their thermal history in the early universe

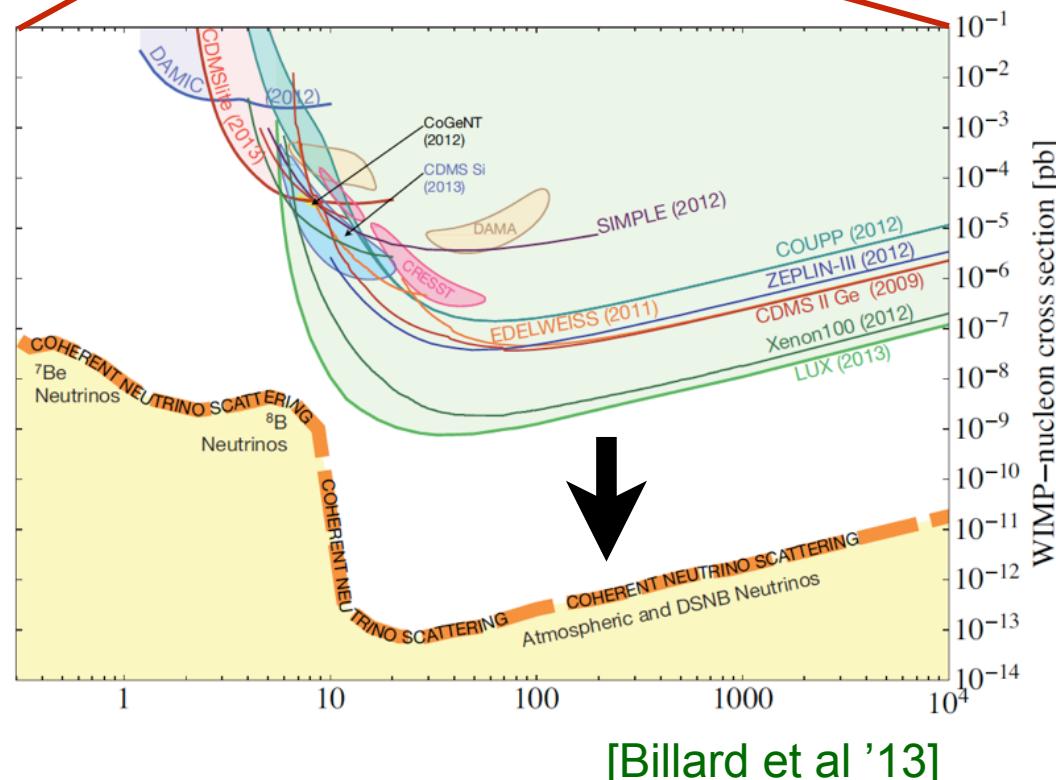


Cold DM Landscape

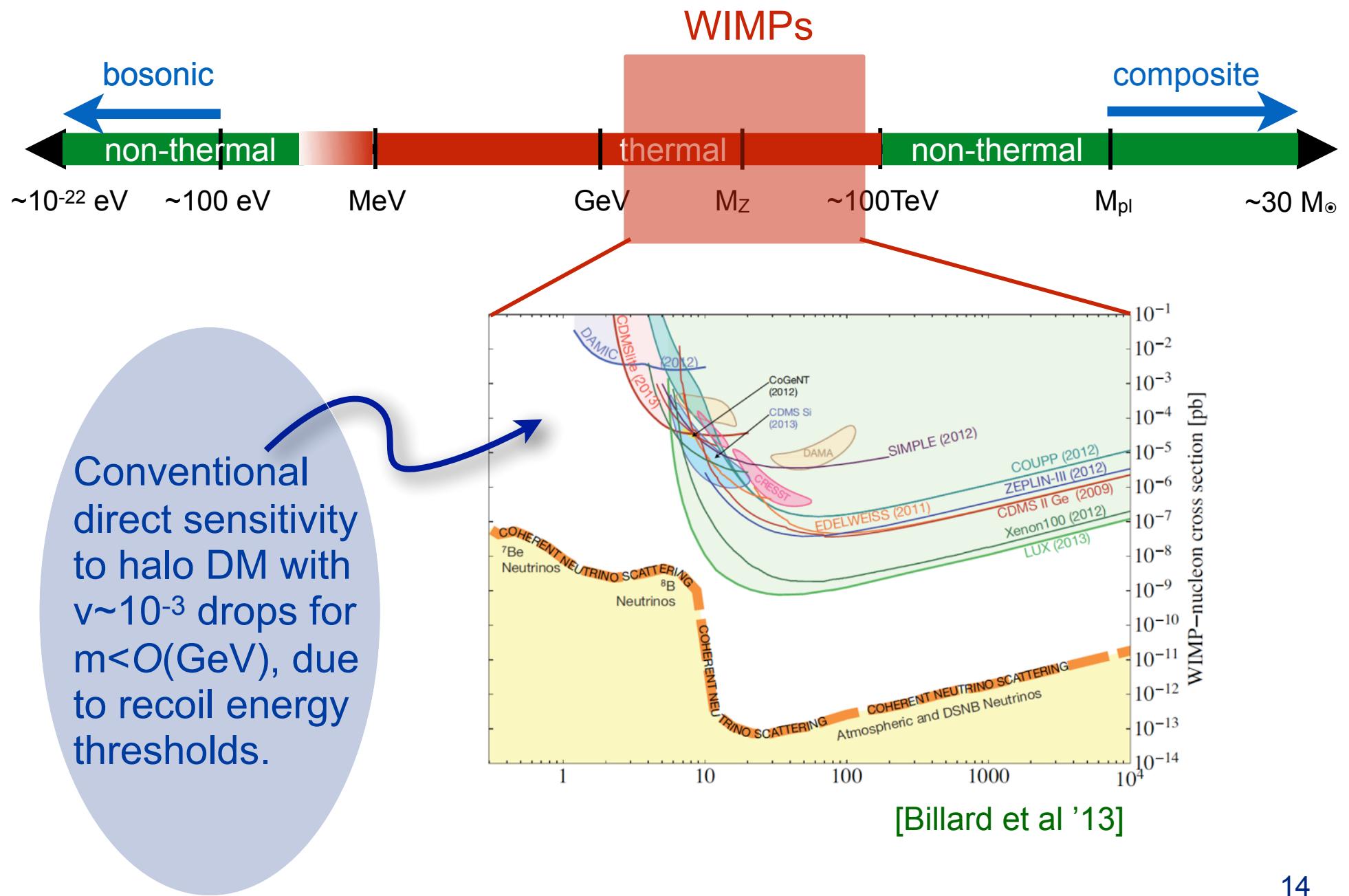


Natural starting point:

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



Cold DM Landscape



Light (thermal relic) DM

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

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

⇒ 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]

Standard Model

DM Annihilation

←

Light mediators

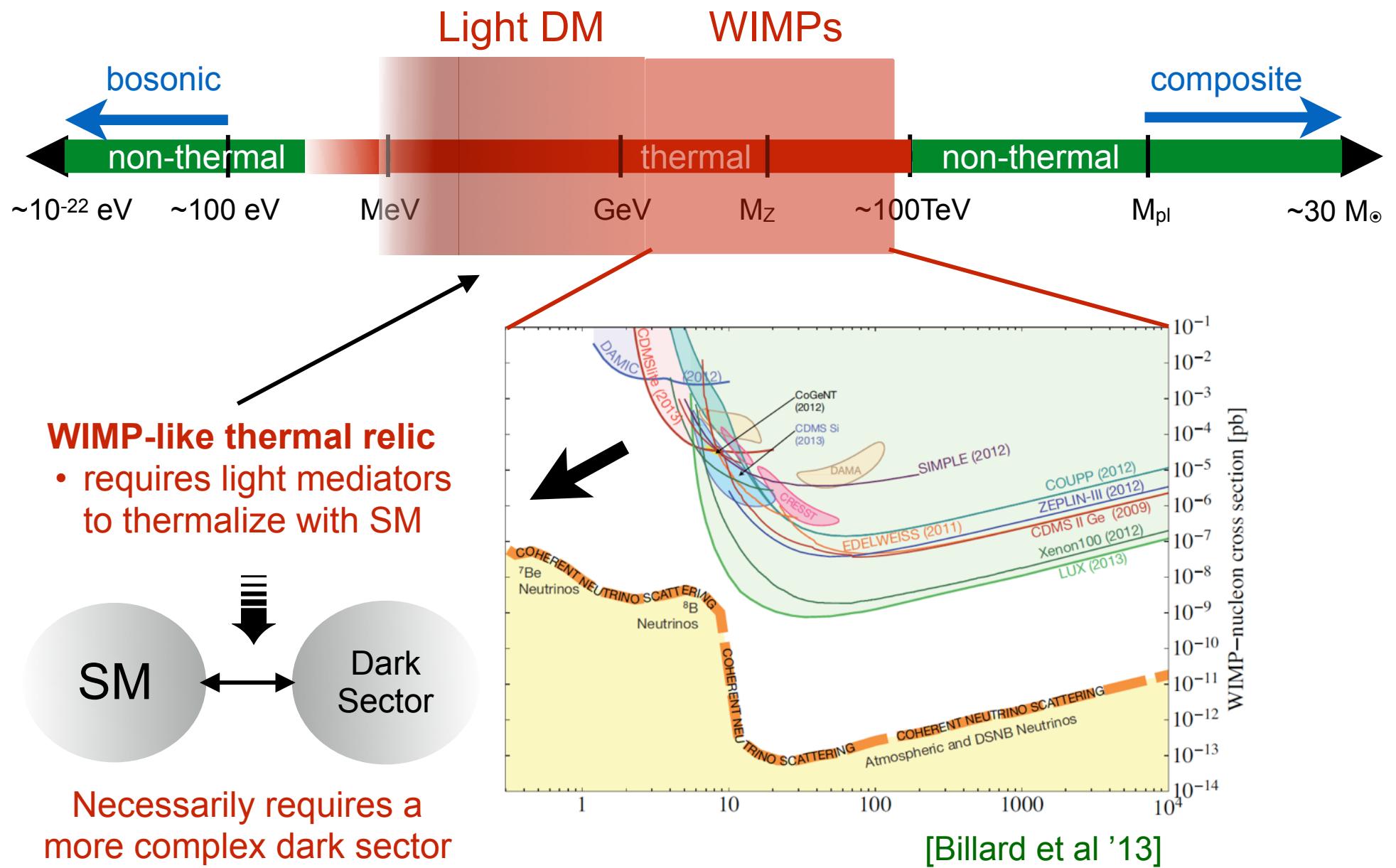
→

DM Production!

Hidden Sector

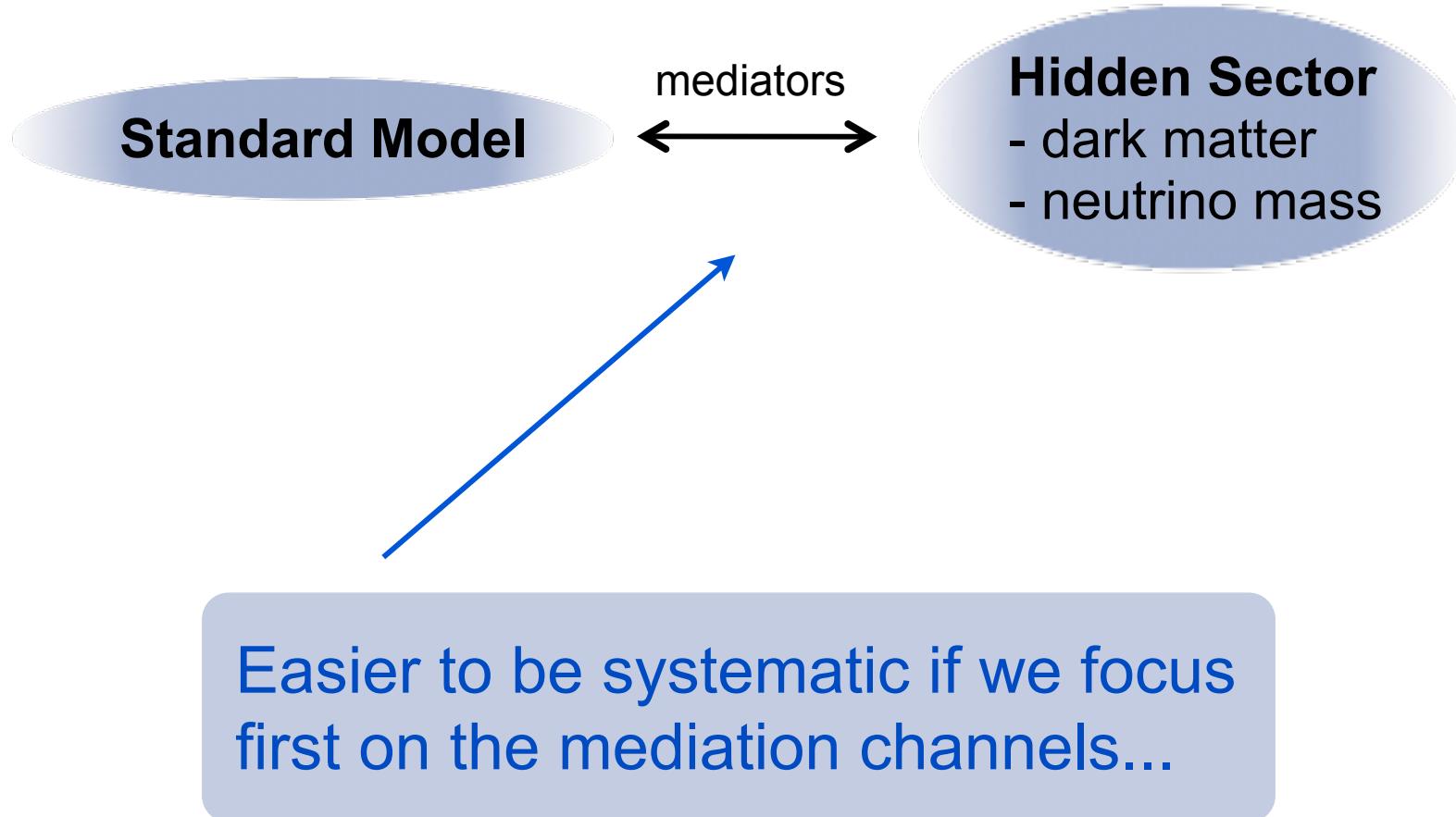
⇒ by inversion, light mediators allow direct production of DM at **low energy!**

Cold DM Landscape



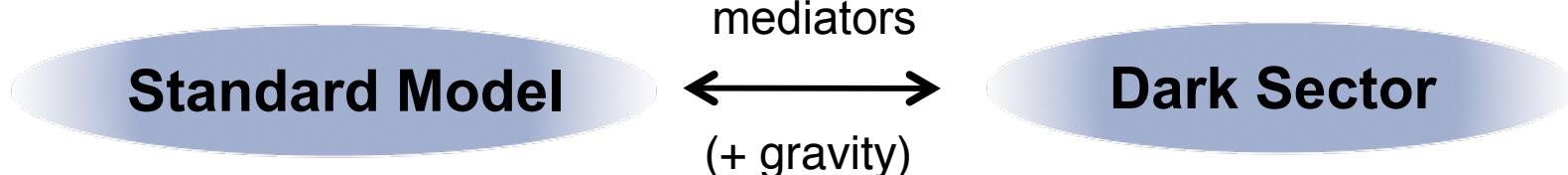
EFT for a (neutral) hidden sector

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



Substantial research effort over the past decade....

EFT for a (neutral) hidden sector



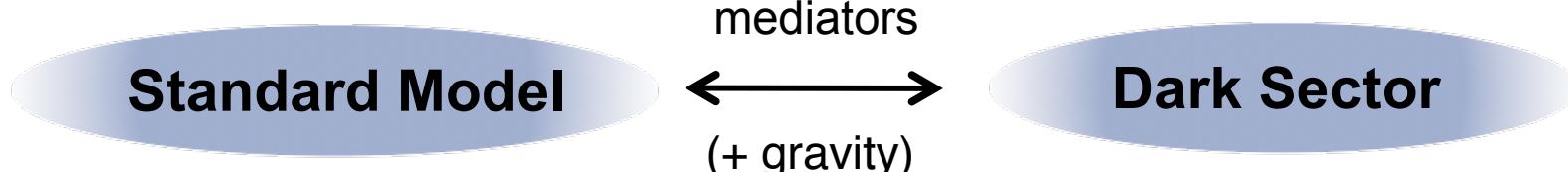
Generic interactions are irrelevant (dimension > 4), but there are three ***UV-complete relevant or marginal “portals”*** to a ***neutral hidden sector***, unsuppressed by the (possibly large) NP scale Λ

$$\begin{aligned} \mathcal{L} &= \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\text{SM})} \mathcal{O}_l^{(\text{med})} = \mathcal{L}_{\text{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right) \\ &= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right) \end{aligned}$$

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

An arrow points from the term $B^{\mu\nu} A'_{\mu\nu}$ in the second equation to the expression $\epsilon_{(1-\text{loop})}$ in the third equation.

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

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Vector portal

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

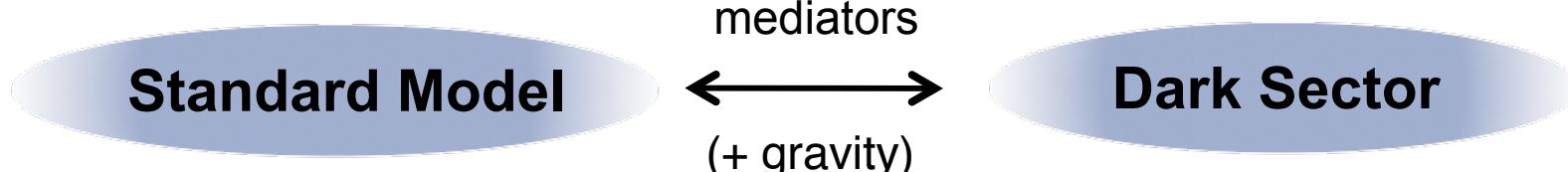
Higgs portal

[Patt & Wilczek]

Neutrino portal

Many more UV-sensitive interactions at $\text{dim} \geq 5$

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

$$\begin{aligned} \mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\text{SM})} \mathcal{O}_l^{(\text{med})} &= \mathcal{L}_{\text{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right) \\ &= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j \\ &\quad \text{Vector portal [Okun; Galison & Manohar; Holdom; Foot et al]} \quad \text{Higgs portal [Patt & Wilczek]} \quad \text{Neutrino portal} \\ &\quad + \frac{1}{f_a} \left(\text{tr}(G\tilde{G}) + c_F F\tilde{F} \right) a + \mathcal{O}(\dim \geq 5) \\ &\quad \text{Axion portal [Weinberg, Wilczek, KSVZ, DFSZ]} \end{aligned}$$

EFT for a (neutral) hidden sector

Standard Model

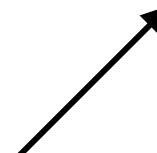
mediators
 \longleftrightarrow
 (+ gravity)

Dark 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

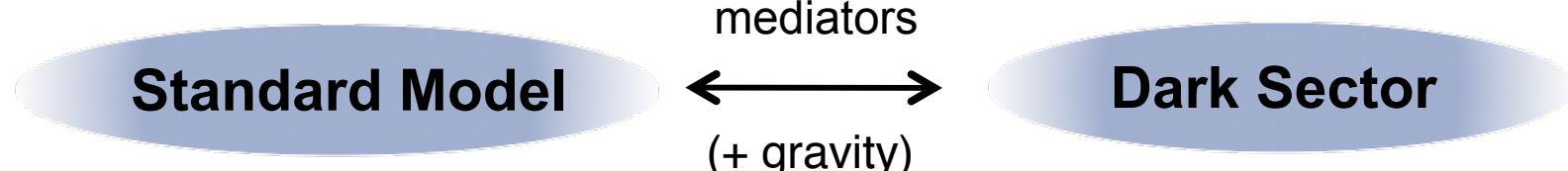
$$\begin{aligned} \mathcal{L} &= \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\text{SM})} \mathcal{O}_l^{(\text{med})} = \mathcal{L}_{\text{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right) \\ &= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right) \end{aligned}$$

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



Naturally incorporates minimal models of neutrino mass, and leptogenesis

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

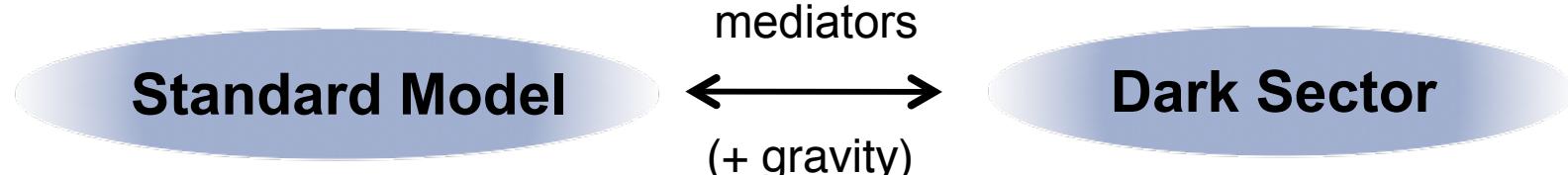
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Vector portal
 Higgs portal
 Neutrino portal

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



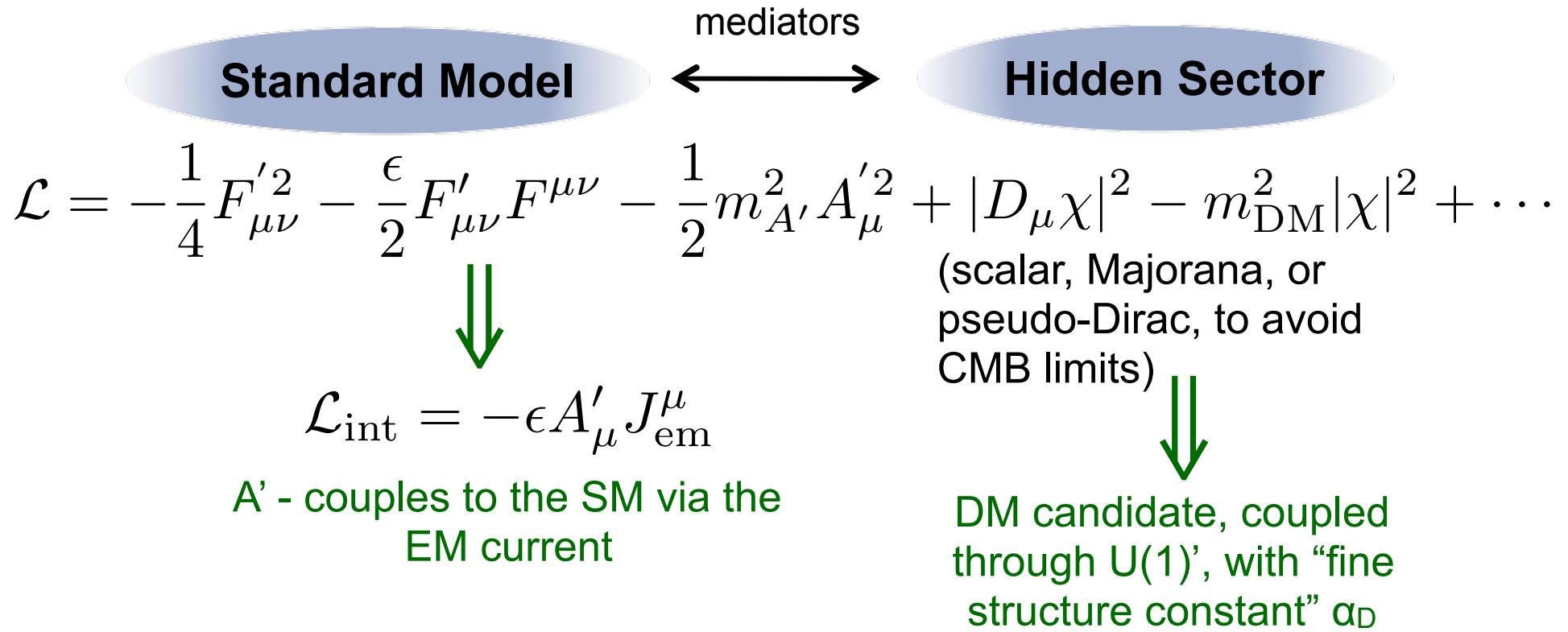
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Vector portal Higgs portal Neutrino portal

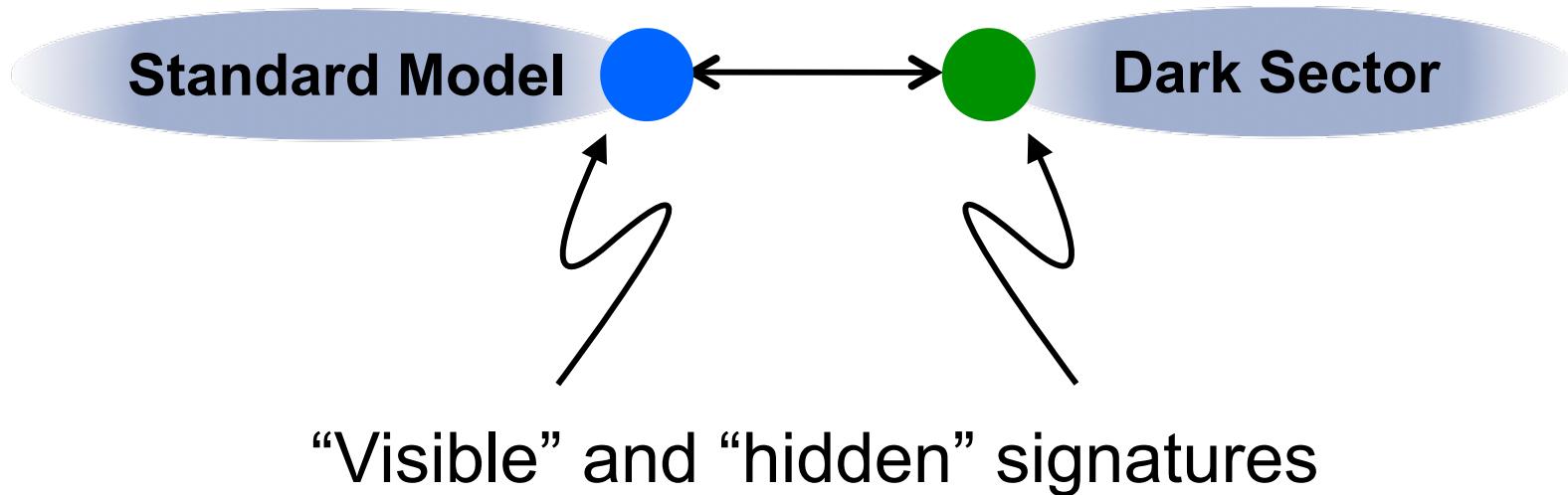
More generally, they can provide new ‘dark force’ mediators enabling sufficient annihilation of MeV-GeV (hidden sector) dark matter in the early universe

(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 $m_{\text{DM}} < m_V$, the correct relic density fixes a specific relation between $\{\epsilon, \alpha_D, m_V, m_{\text{DM}}\}$

Signatures of Dark Sectors



- 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

Standard Model

mediators
↔
(+ gravity)

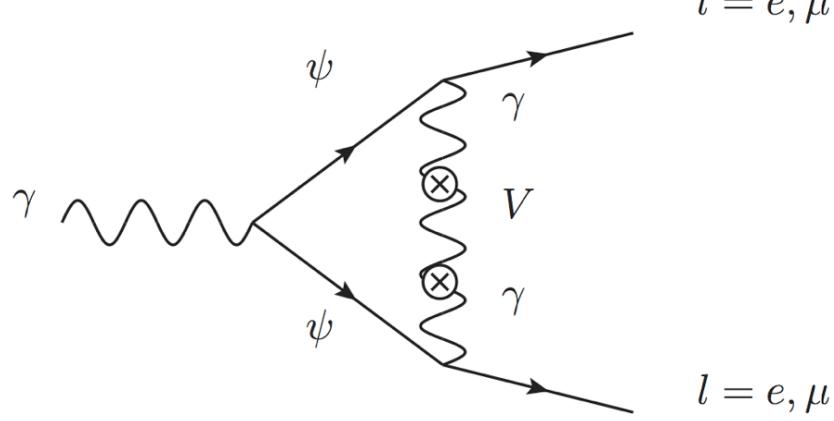
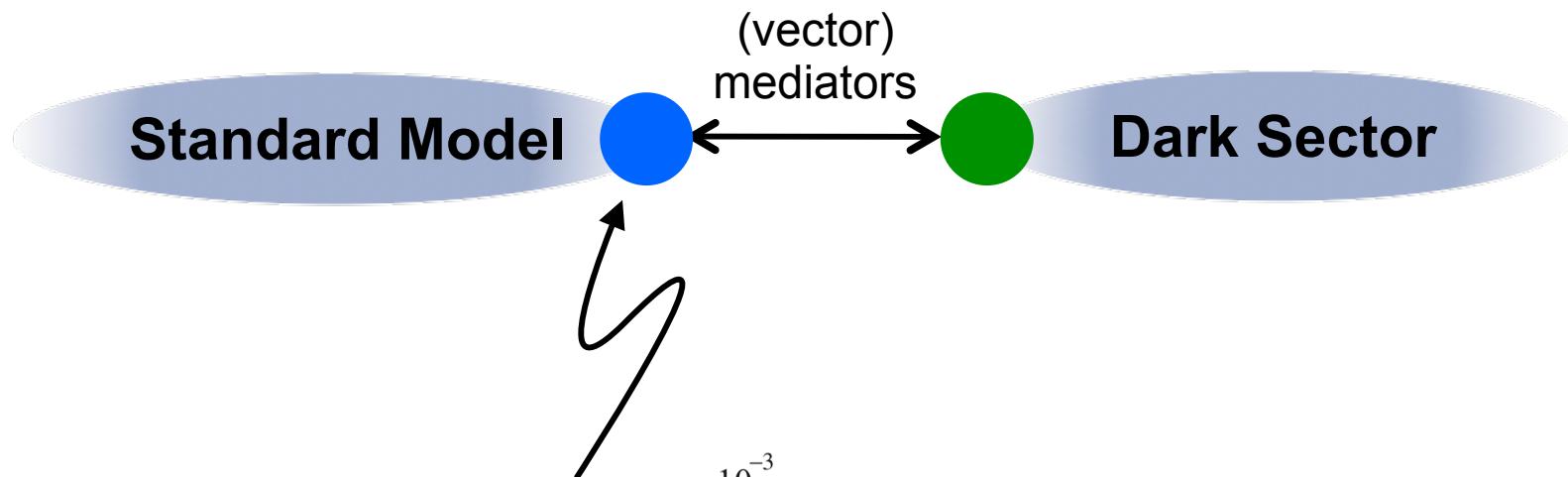
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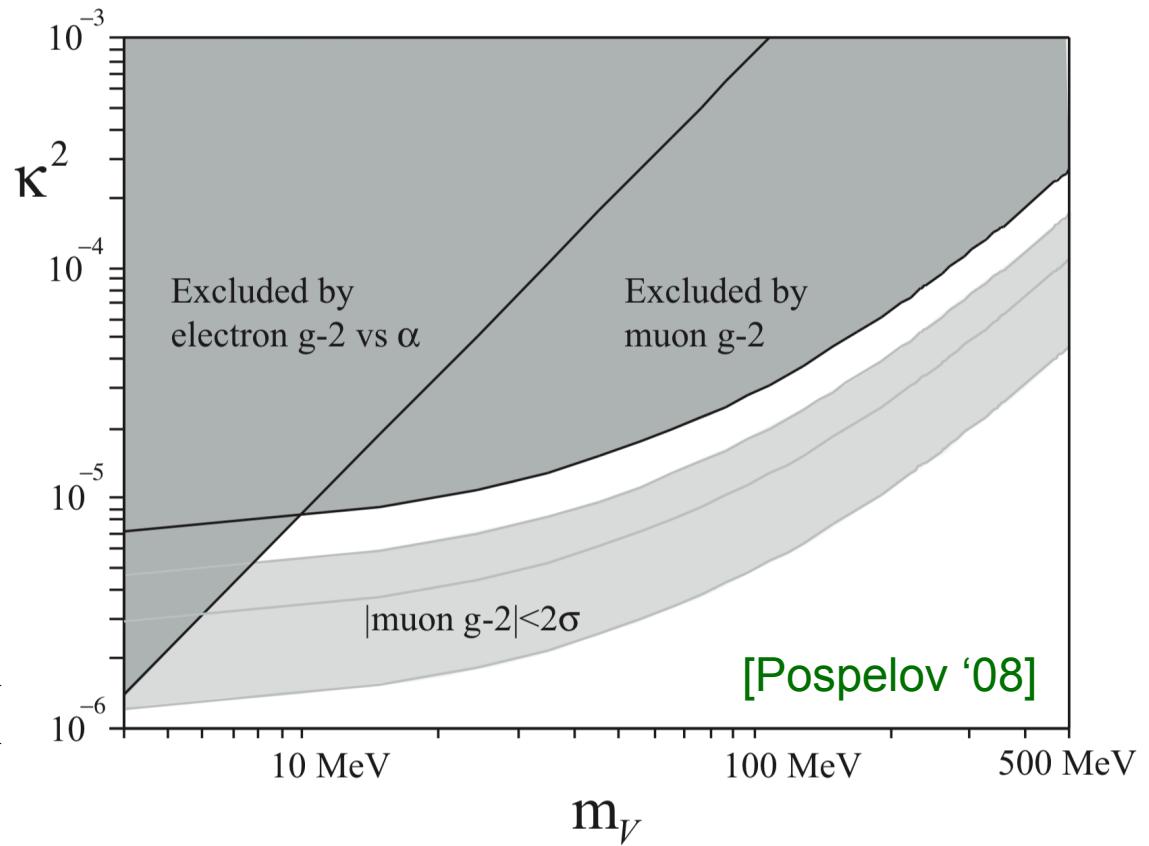
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Universal couplings to EM/scalar currents at low energy, so hidden sector models have correlated observable effects

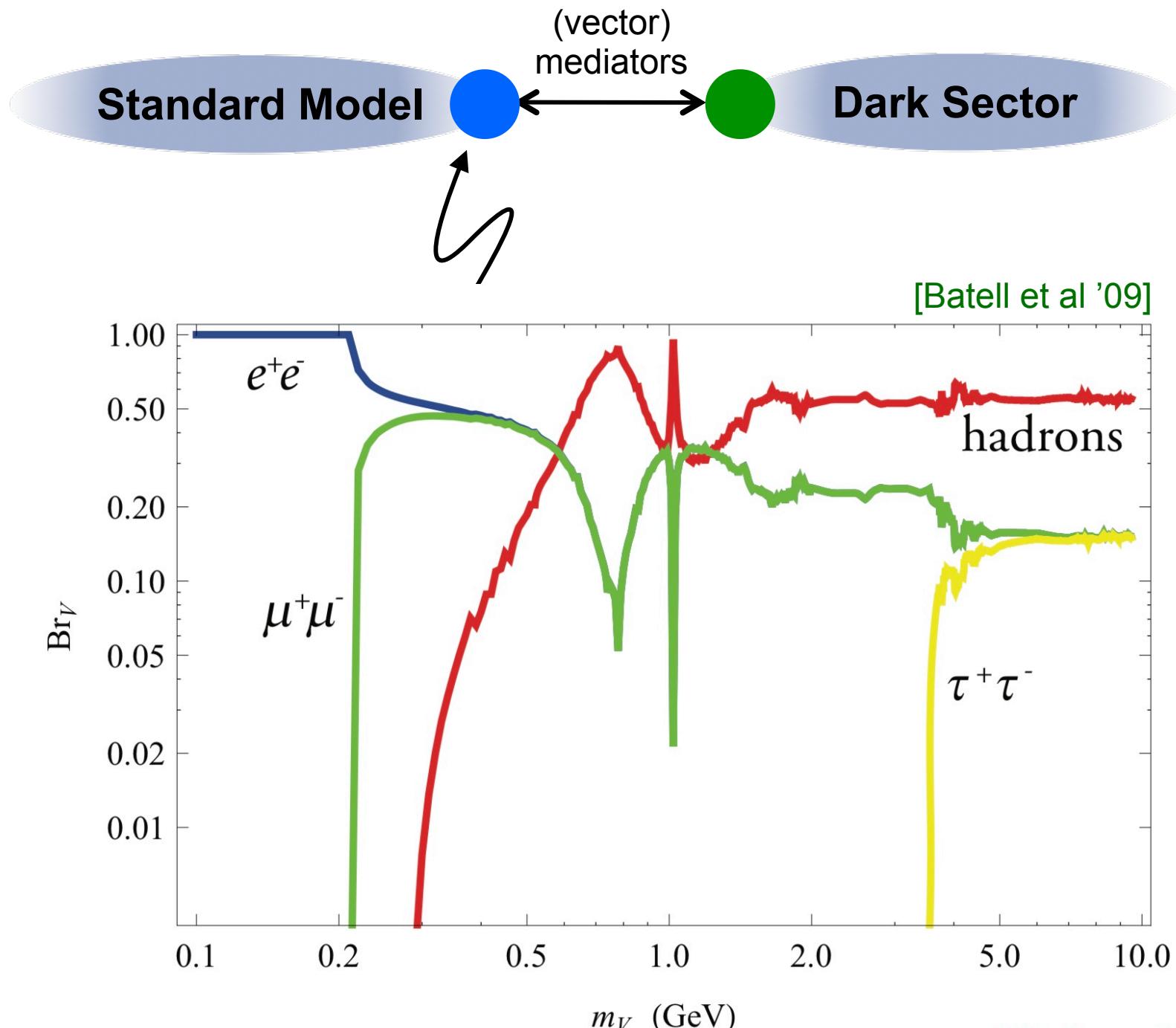
Precision corrections ($g-2$)



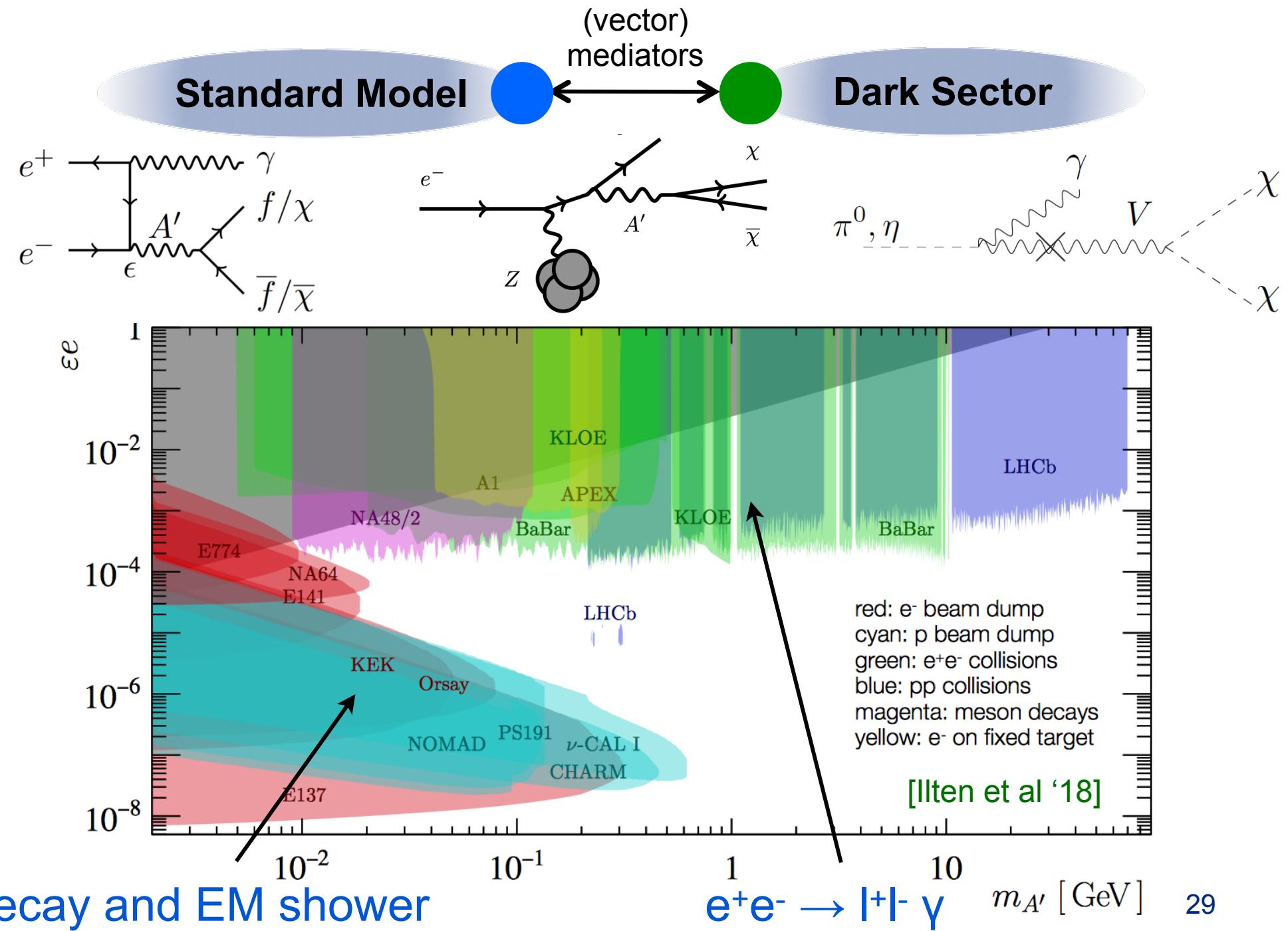
$$a_l^V = \frac{\alpha \kappa^2}{2\pi} \times \begin{cases} 1 & m_l \gg m_V \\ 2m_l^2/(3m_V^2) & m_l \ll m_V \end{cases}$$



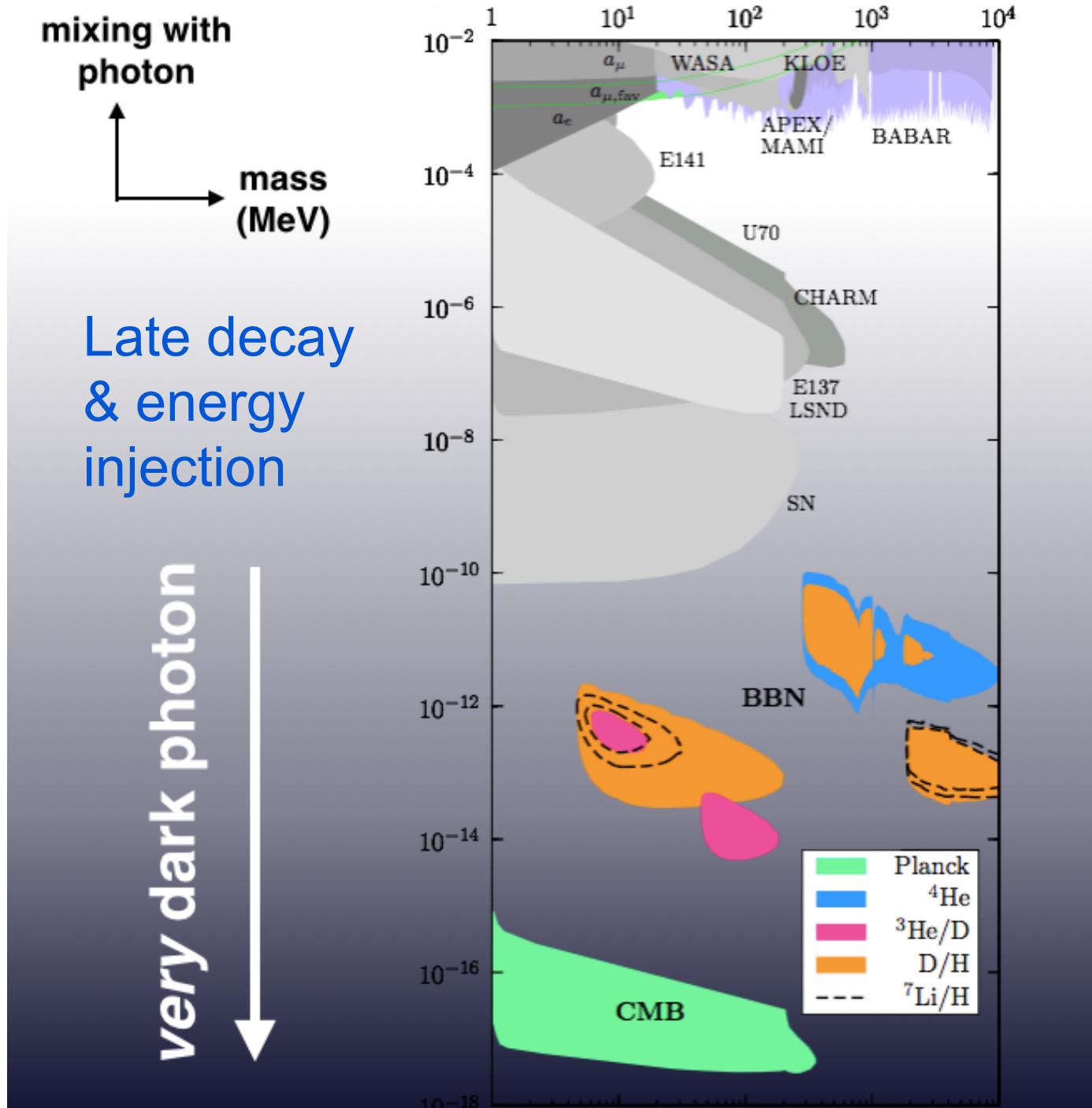
Precision corrections (g-2)



Rare visible decays



Ultra weak coupling - BBN/CMB



Rare visible decays - future sensitivity

Dark Sectors Workshop 2016

FUTURE OPPORTUNITIES TO EXPLORE LIGHT DARK MATTER

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WORKSHOP ON



U.S. Cosmic Visions: New Ideas in Dark Matter

23-25 March 2016
Stamp Student
US/Eastern timezone

CERN Accelerating science



ABOUT NEWS SCIENCE

News > News > Topic: Accelerators

CERN launches Physics Beyond Colliders study group

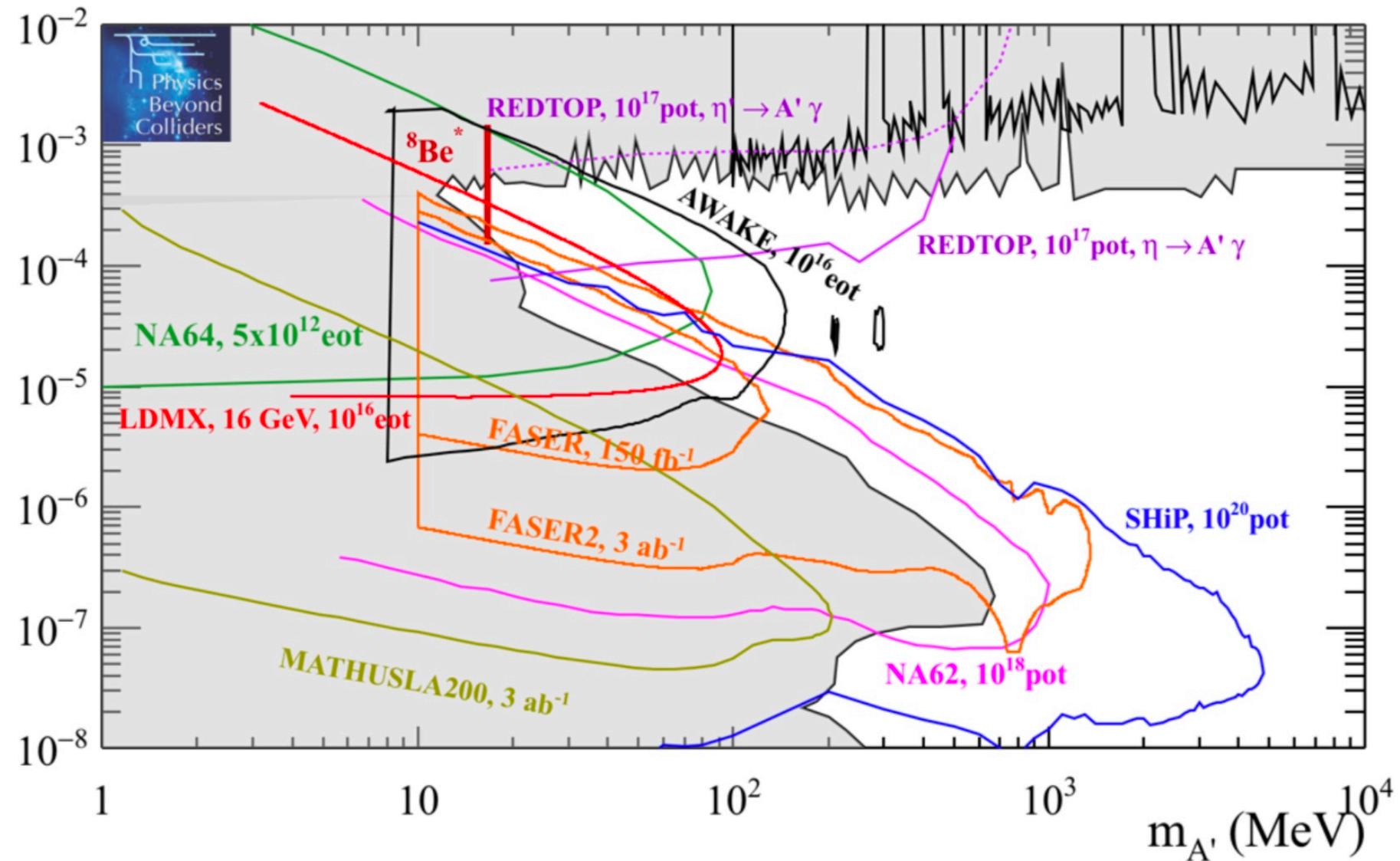
CERN invites abstract applications for the workshop, which will investigate how CERN's accelerators can help solve questions of particle physics

24 MAY, 2016

We are pleased to announce the kick-off workshop of the "Physics Beyond Colliders" Study Group which has recently been set up by CERN Management. The workshop will be held at CERN, Geneva, on September 6-7, 2016.

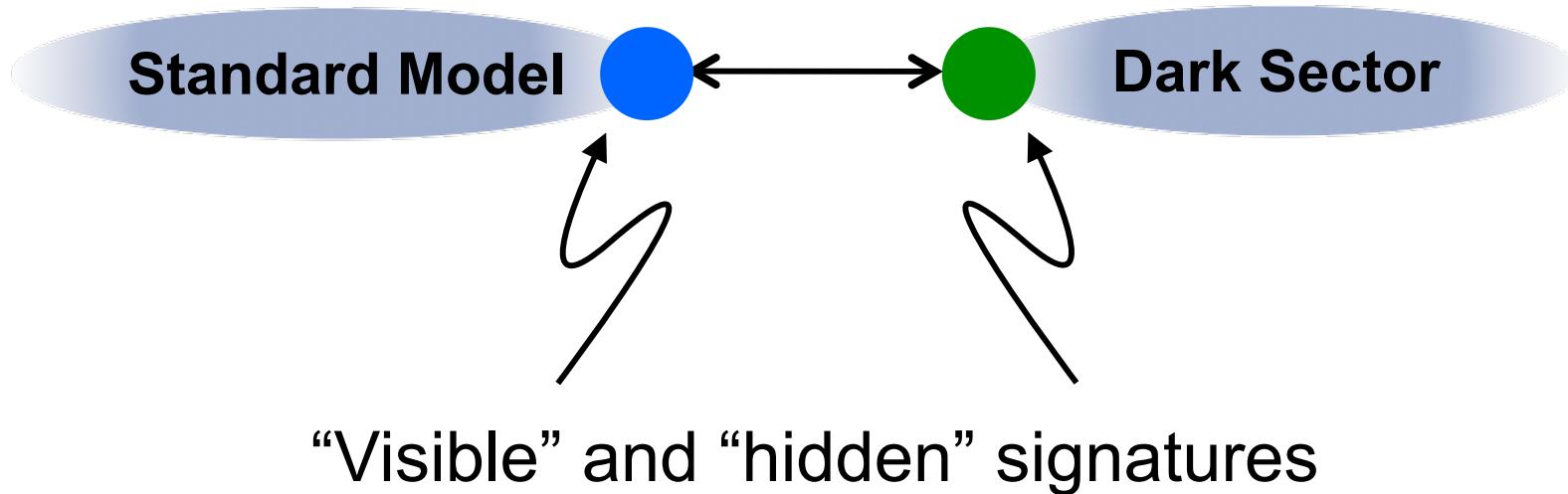
Rare visible decays - future sensitivity

Dark Physics Beyond Colliders
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Plus Belle II, LHCb, SeaQuest, HPS, ...

Signatures of Dark Sectors

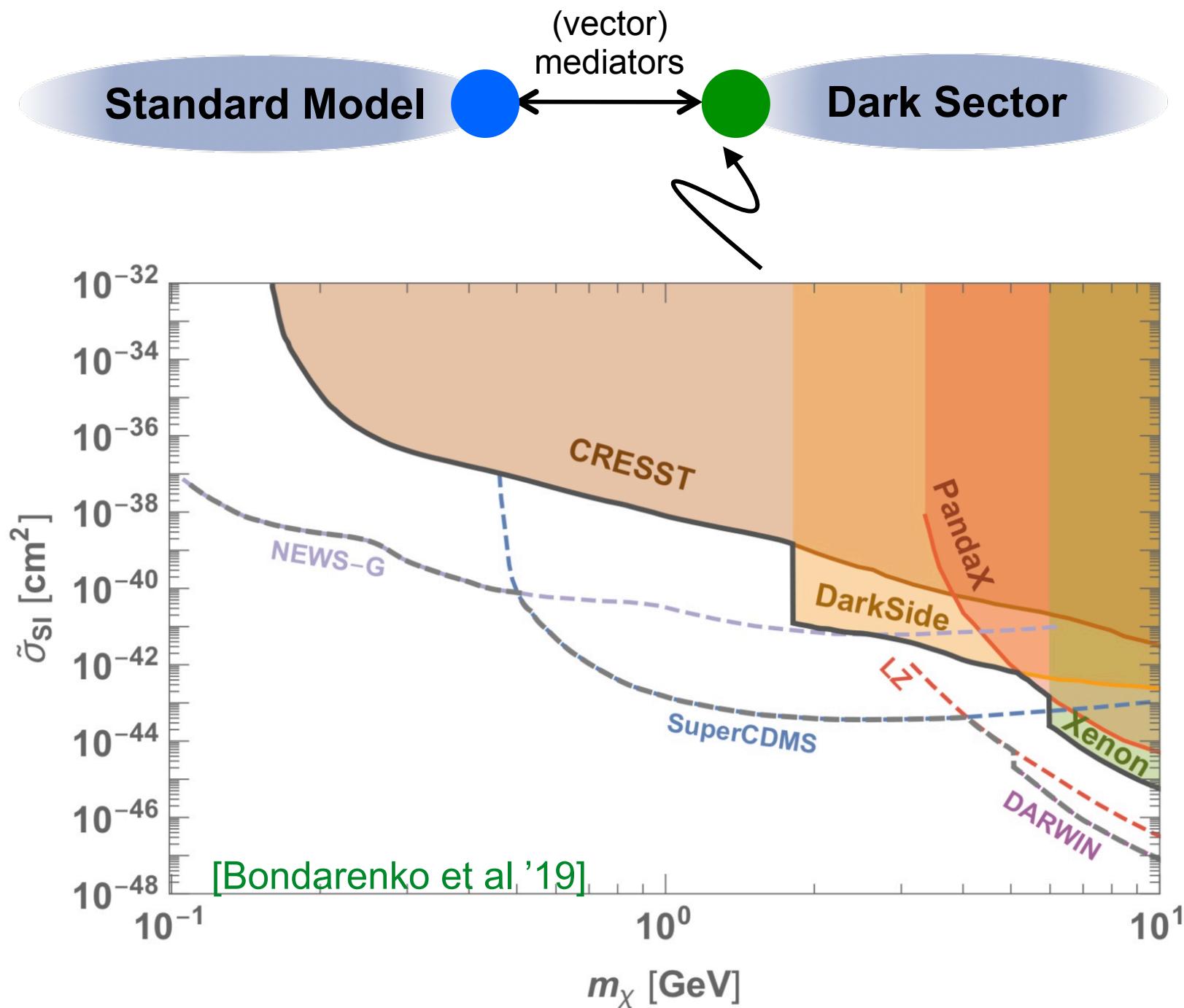


- Precision corrections
- Rare (visible) decays
- Astrophys/cosmology

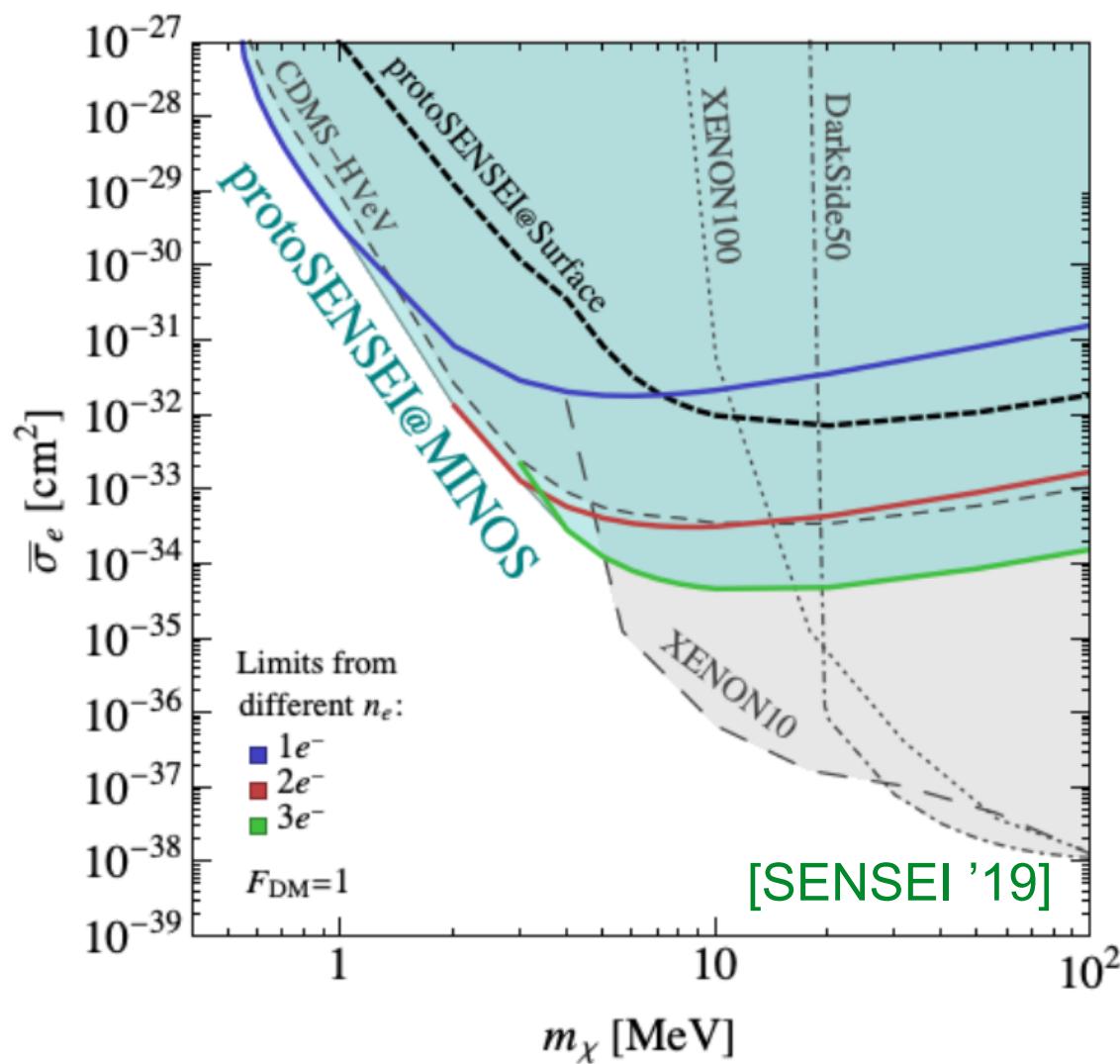
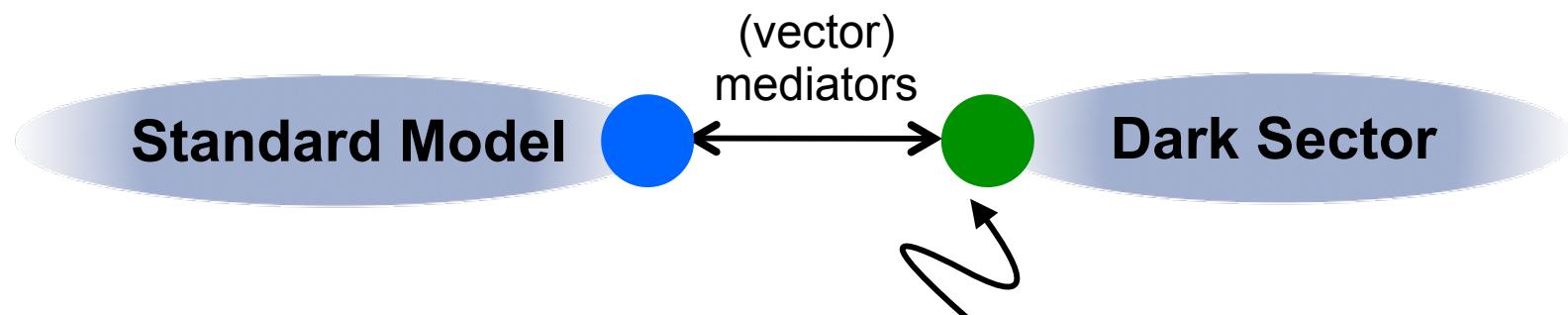
- Rare (invisible) decays/ E_{miss}
- Anomalous NC-like scattering
- Astrophys/cosmology

DM Models!

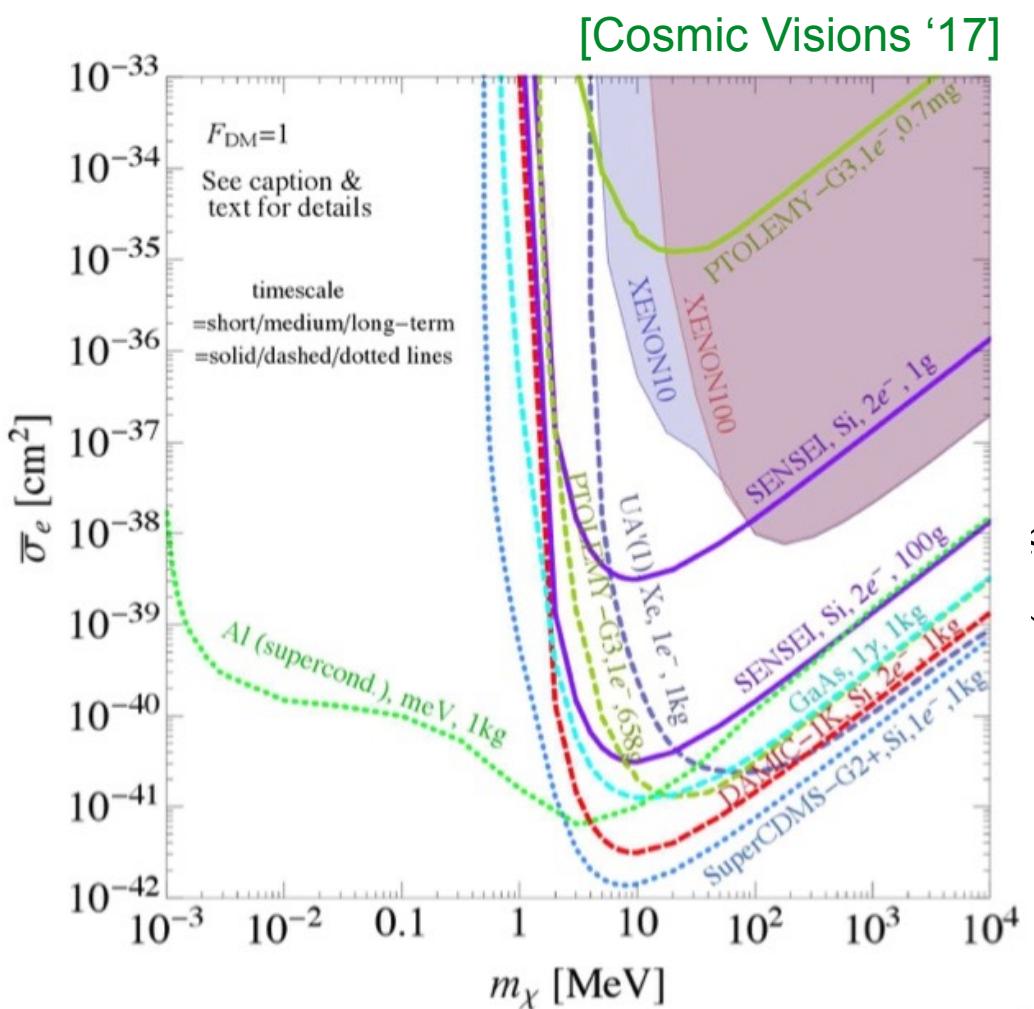
Low mass direct detection - N-scattering



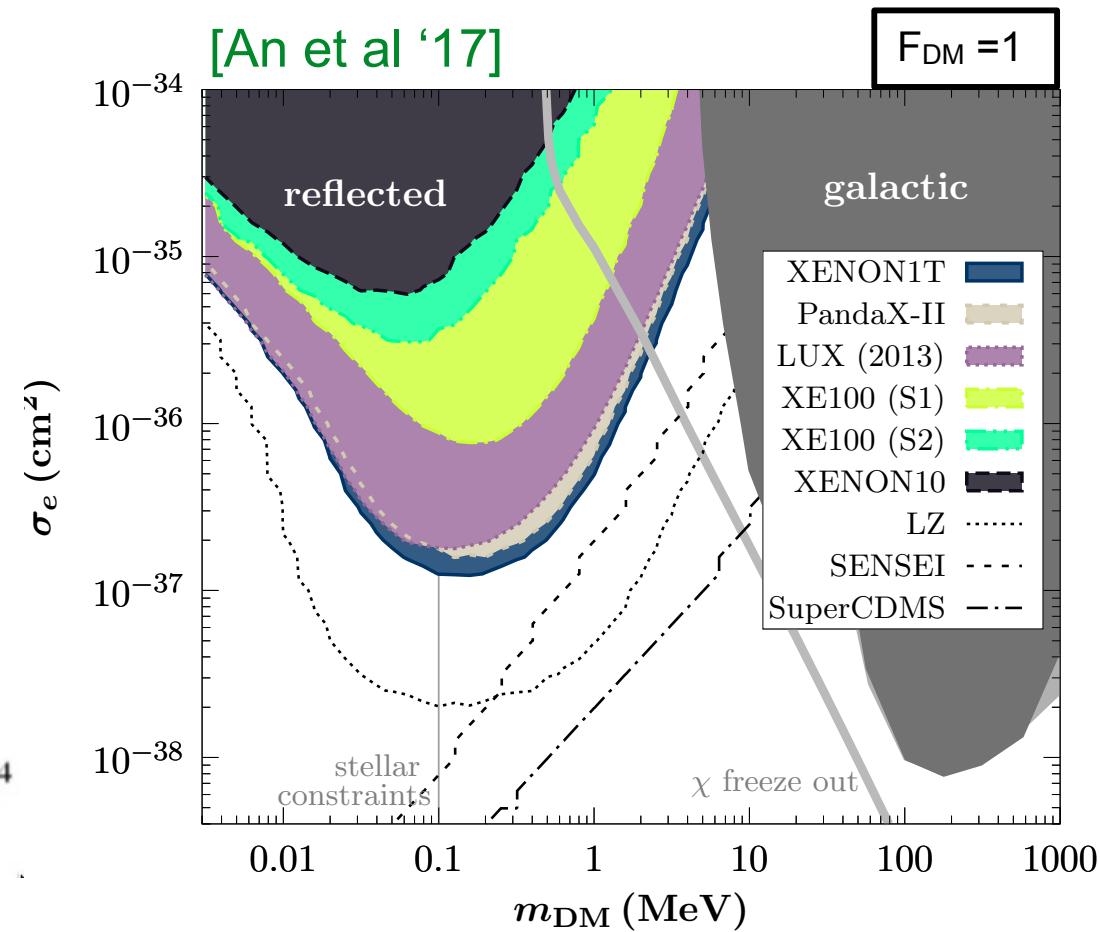
Low mass direct detection - e-scattering



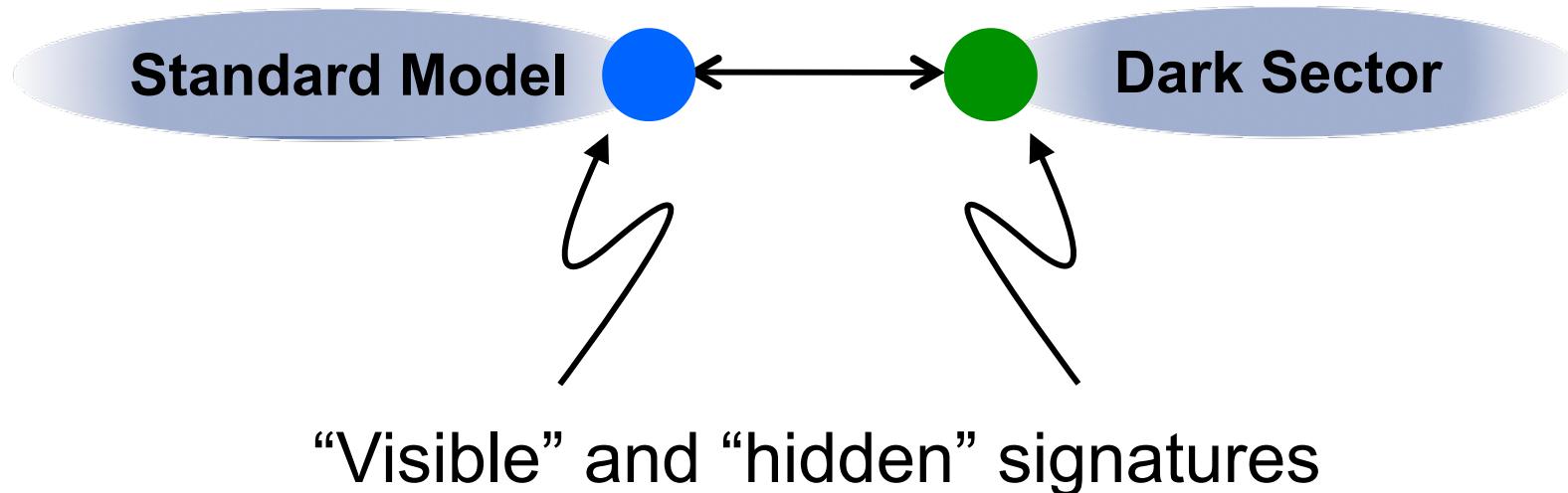
Future Sensitivity (e-scattering)



DM re-scattered by $T \sim \text{keV}$
electrons in the Sun



Some experimental signatures



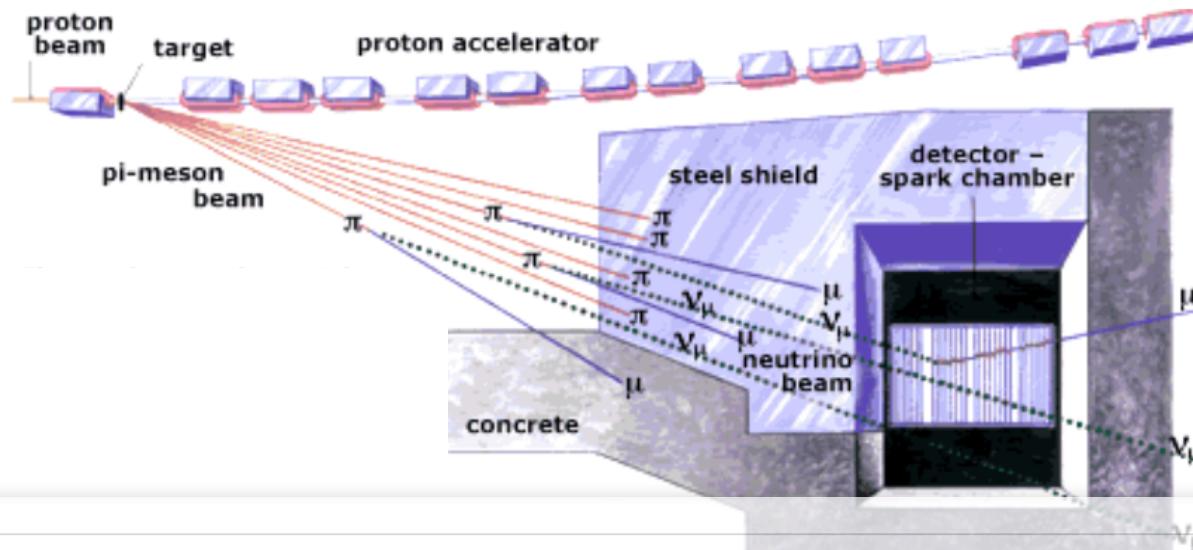
- Precision corrections
- Rare (visible) decays
- Astrophys/cosmology

- 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 $\sim \text{O}(100/\text{cm}^3)$, but are not currently visible in direct detection due to low mass, since $\text{KE} \sim 10^{-4} \text{ eV}$
- ⇒ BUT muon neutrino discovery (**at BNL**) involved production via meson decays (large rate), and detecting the (weak) scattering of the relativistic neutrino beam

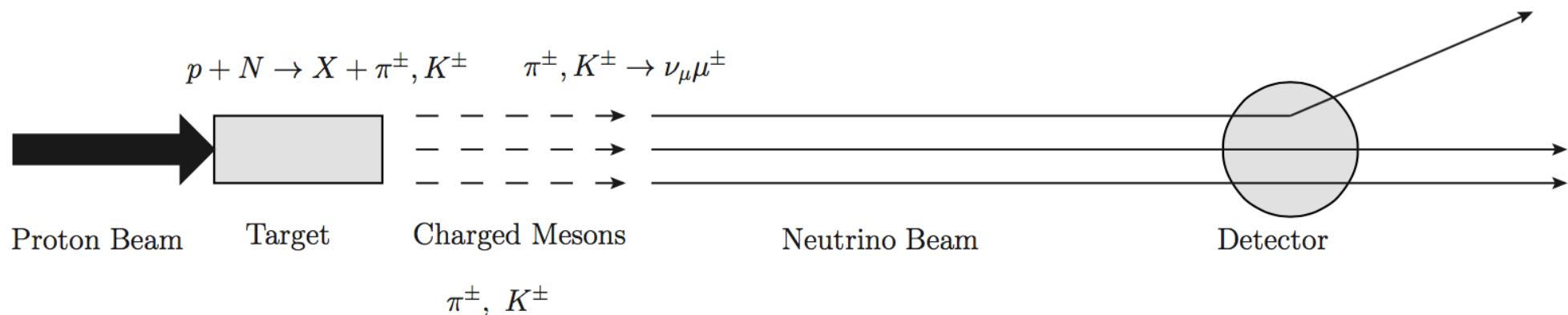


OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

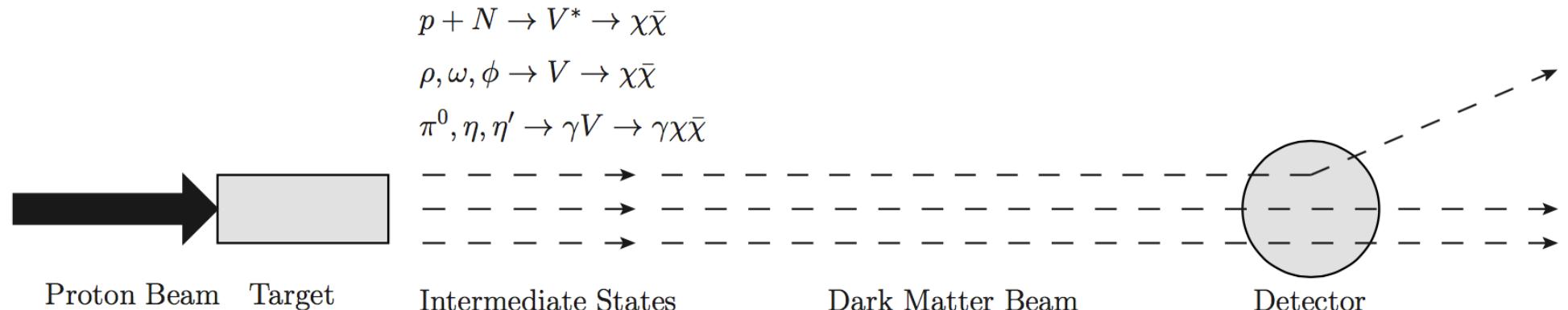
G. Danby, J.-M. Gaillard, K. Goulian, L. M. Lederman, N. Mistry,
M. Schwartz,[†] and J. Steinberger[†]

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.

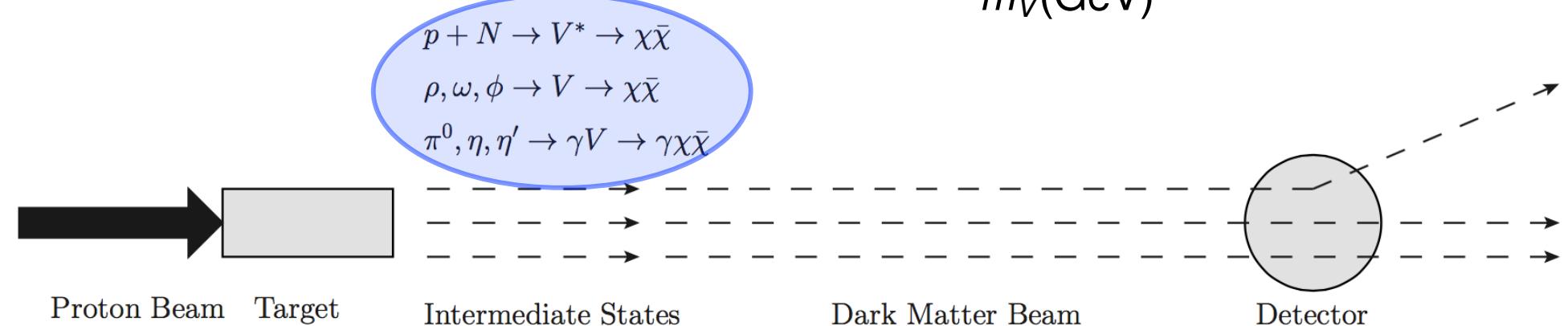


Fixed target - e.g. Neutrino Beams

[deNiverville et al '16]

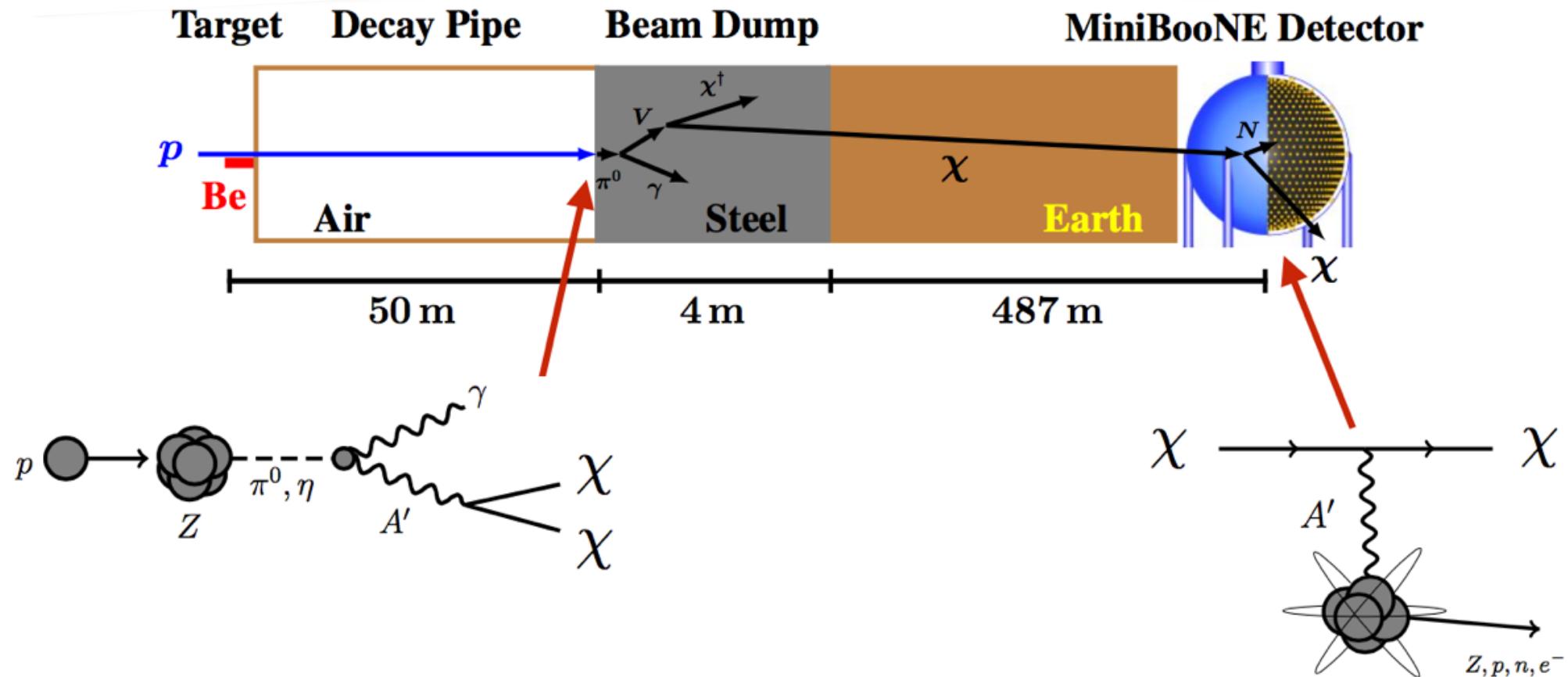
Unnormalized production rate at e.g. MiniBooNE (vector mediator)

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



Fixed target - Neutrino Beams

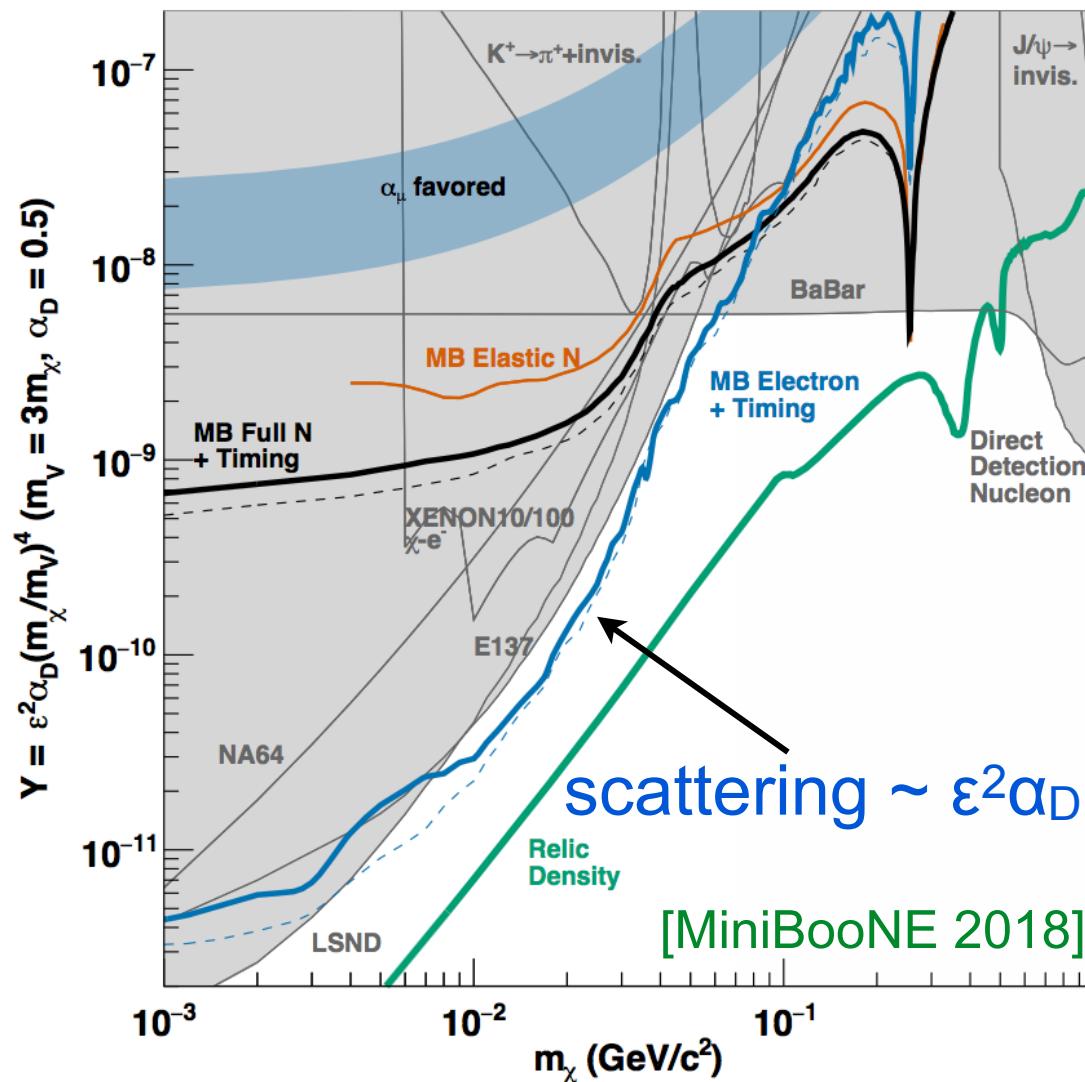
First focused DM search - MiniBooNE in “beam dump” mode



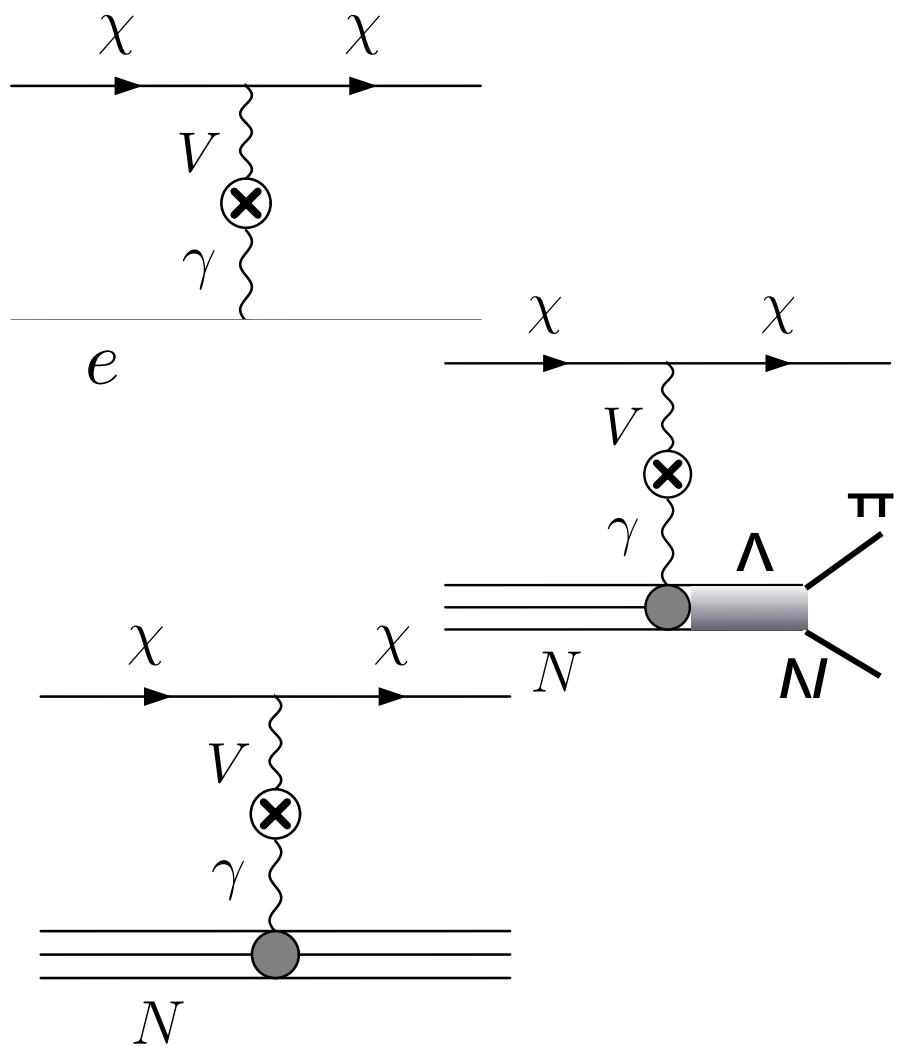
Align the beam off-target, to minimize the neutrino background

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

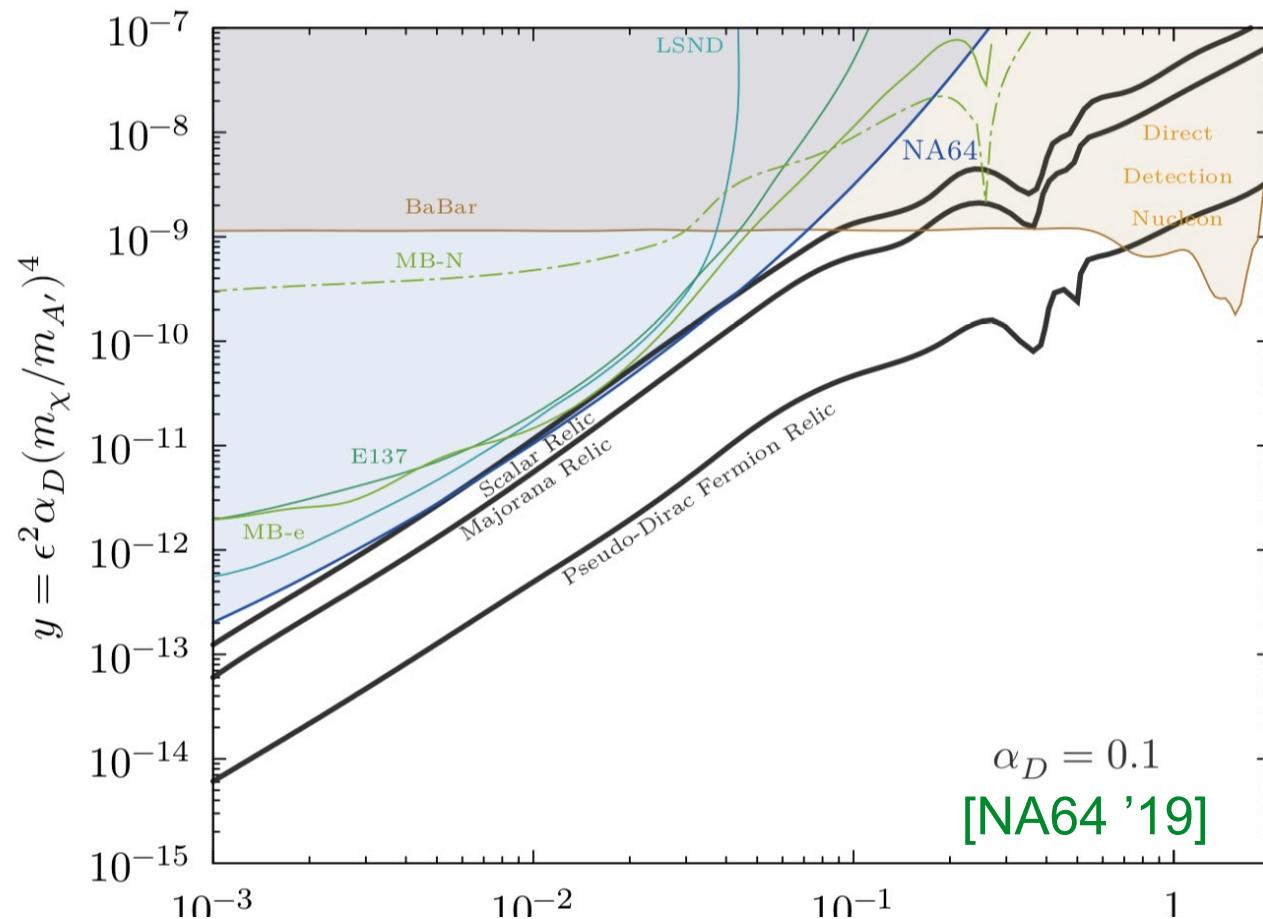
Fixed target - Neutrino Beams



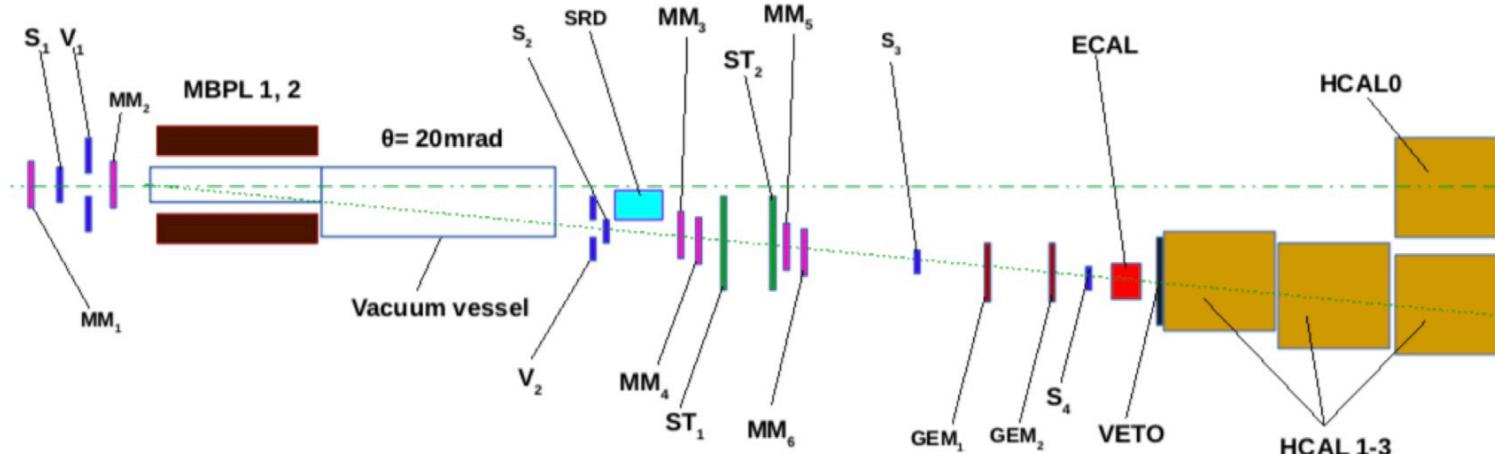
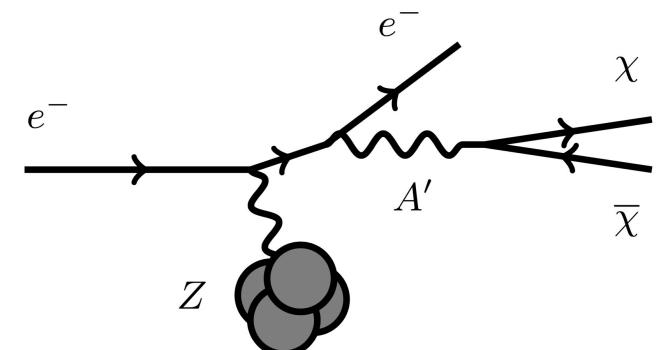
Production via $A'(*) \rightarrow \chi\chi$



Fixed targets - NA64 missing energy search



Production via
bremsstrahlung



Fixed target probes - future sensitivity

U.S. Cosmic Visions: New Ideas in Dark Matter

The screenshot shows a news article from the ENERGY.GOV website. The header features the ENERGY.GOV logo and navigation links for SCIENCE & INNOVATION, ENERGY ECONOMY, SECURITY & SAFETY, and SAVE ENERGY, SAVE MONEY. A search icon is also present. The main title of the article is "Department of Energy to Provide \$24 Million to Study Dark Matter", dated APRIL 18, 2019. The article discusses projects to take advantage of recent theory and technology advances. A sidebar on the left includes social media sharing icons for email, Facebook, Twitter, LinkedIn, and Pinterest.

ENERGY.GOV

SCIENCE & INNOVATION

ENERGY ECONOMY

SECURITY & SAFETY

SAVE ENERGY, SAVE MONEY

Department of Energy

Department of Energy to Provide \$24 Million to Study Dark Matter

APRIL 18, 2019

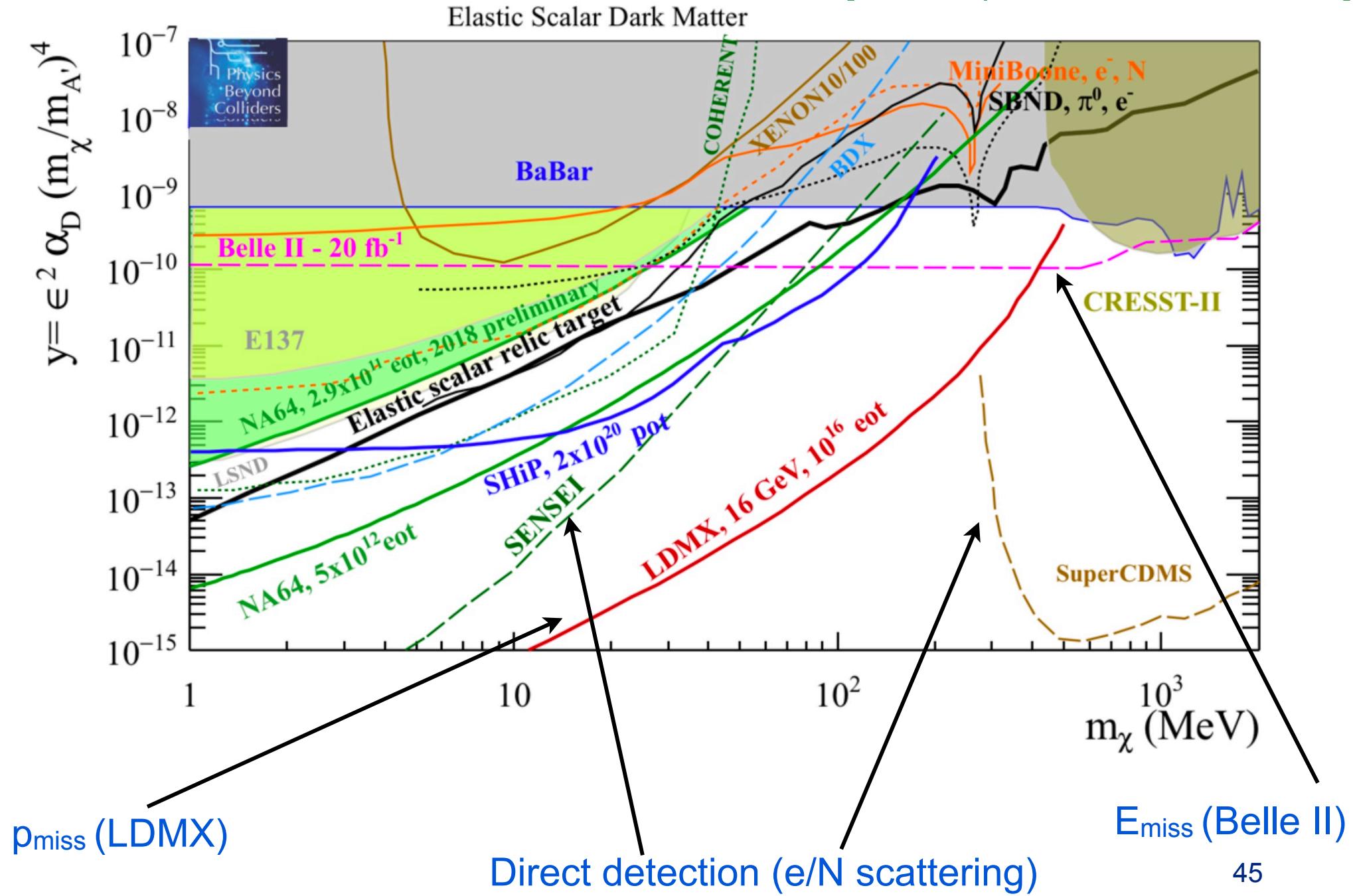
Home » Department of Energy to Provide \$24 Million to Study Dark Matter

Projects to Take Advantage of Recent Theory and Technology Advances

WASHINGTON, D.C. - Today, the U.S. Department of Energy (DOE) announced a plan to provide \$24 million for the development of new projects to study dark matter.

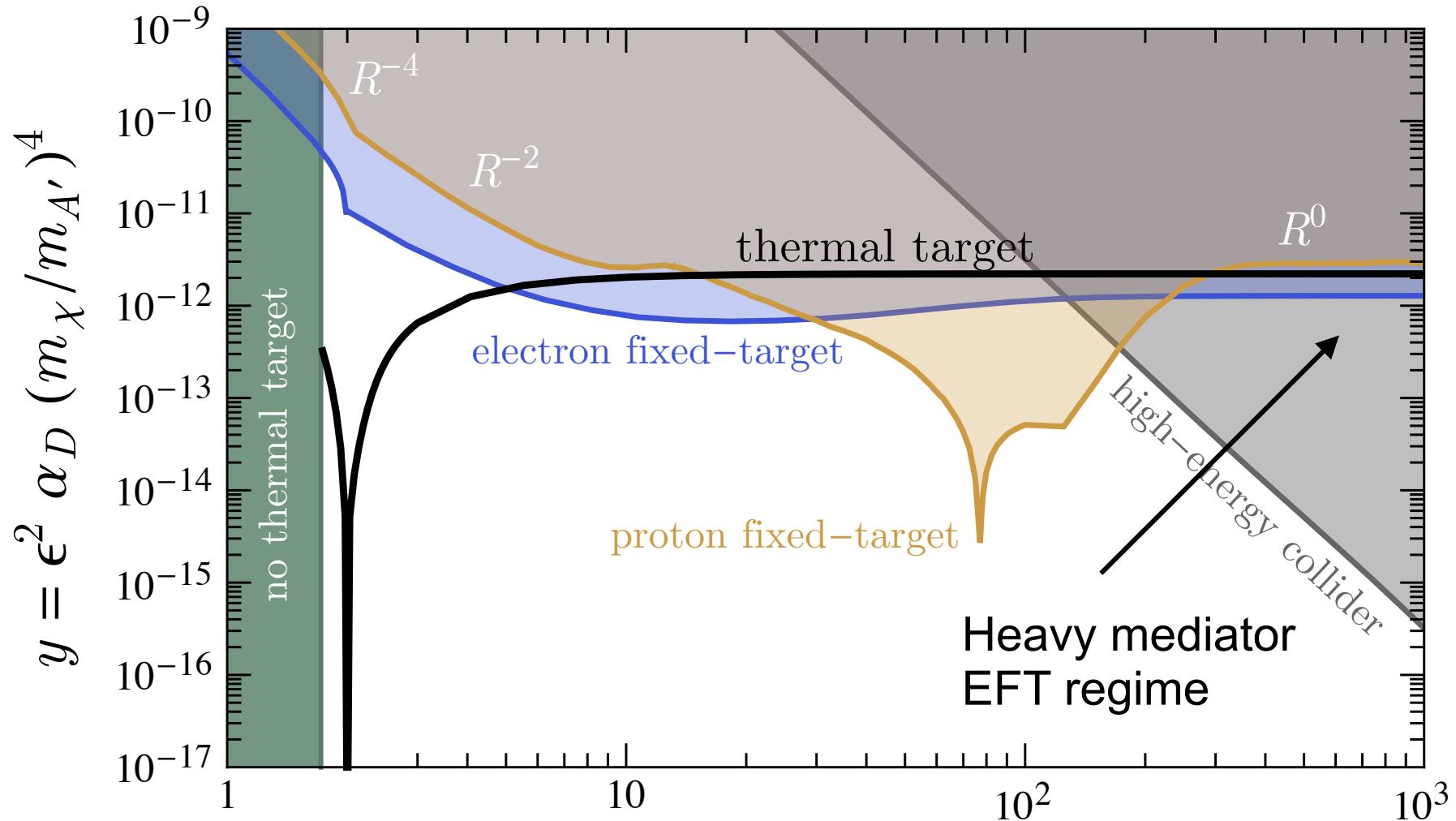
Future sensitivity

[PBC Report, Beacham et al '19]



Generic fixed target sensitivity

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

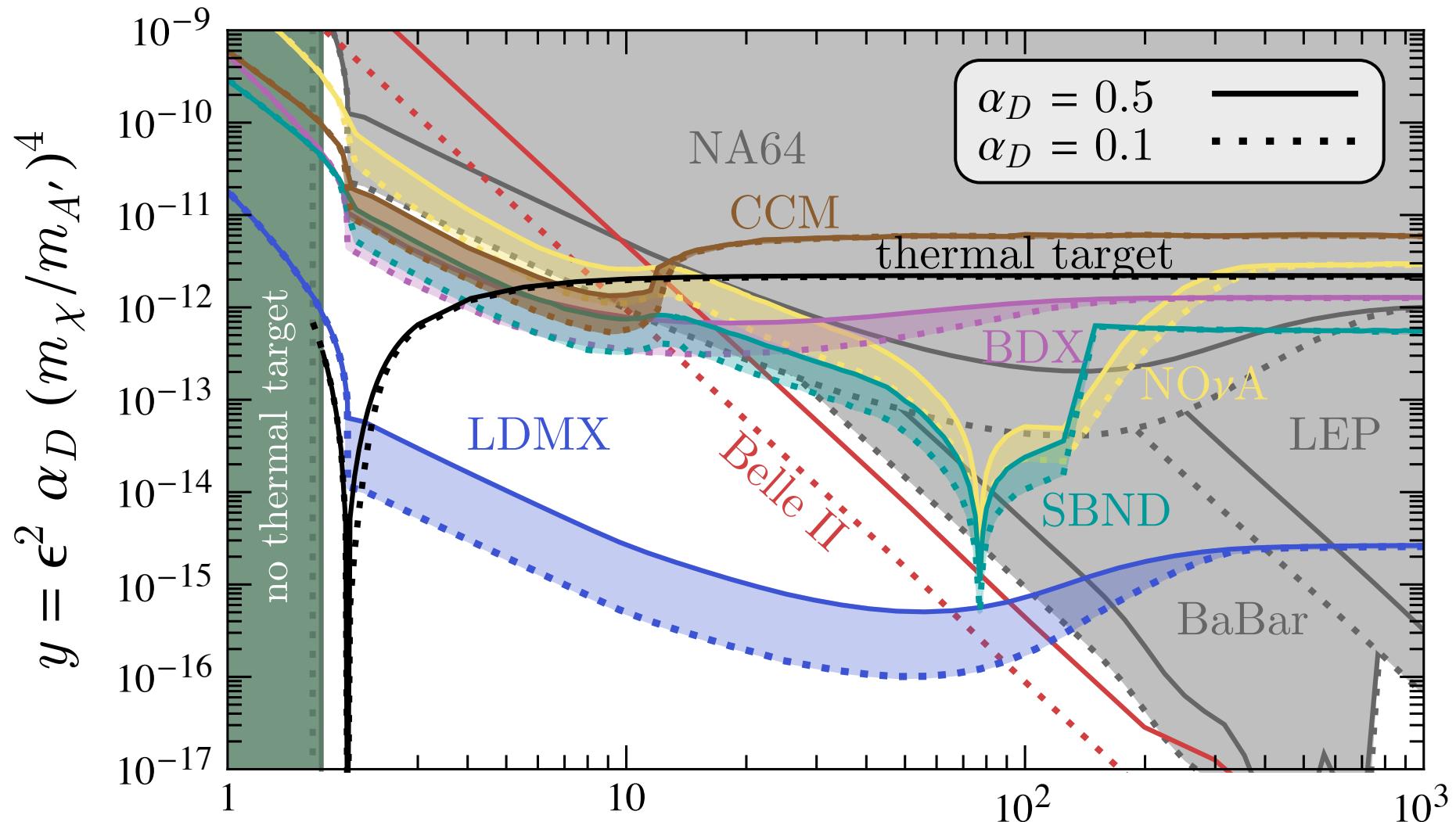


$$R = m_{A'} / m_\chi$$

Generic fixed target sensitivity

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

Pseudo-Dirac, $m_\chi = 10$ MeV

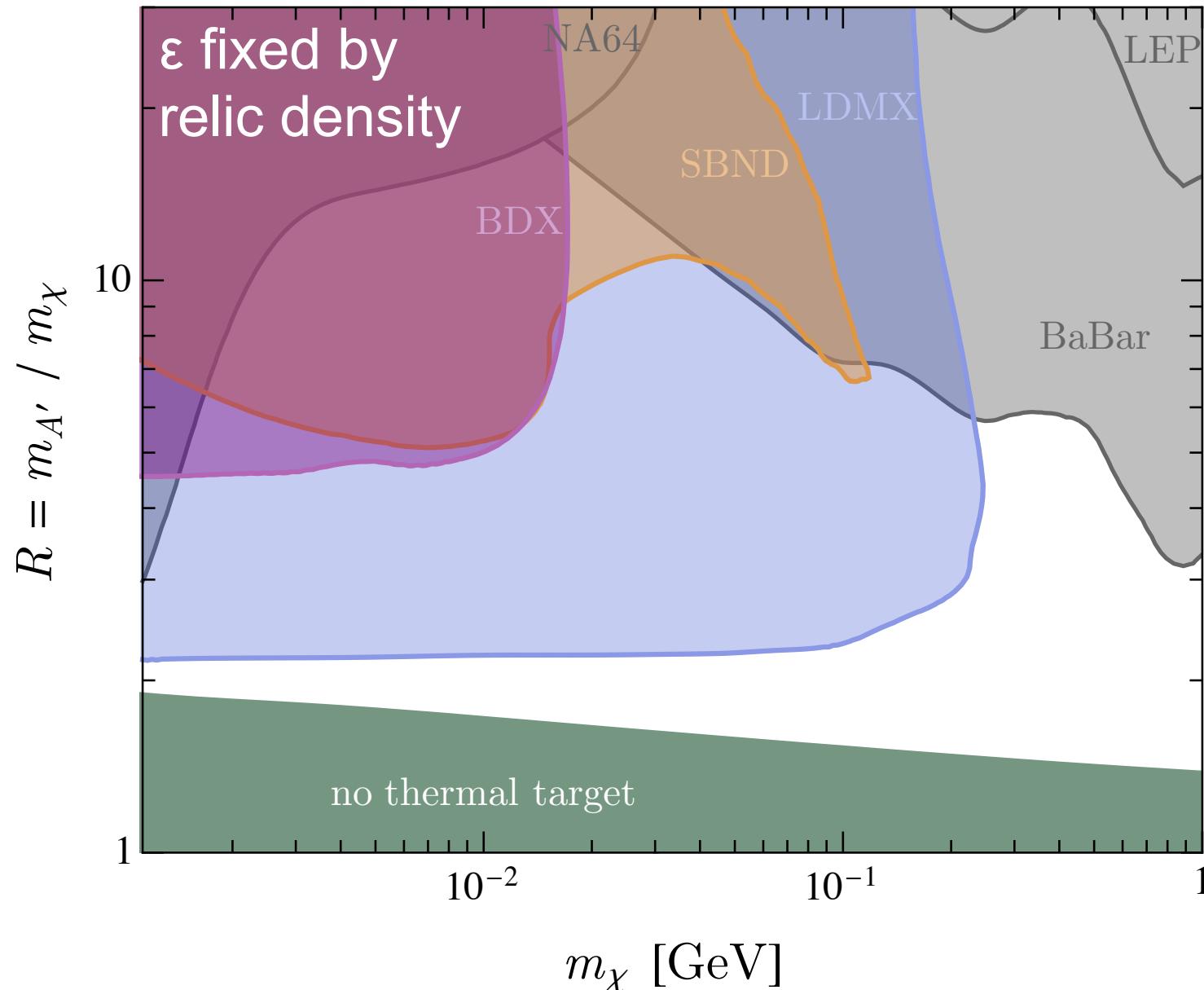


$$R = m_{A'}/m_\chi$$

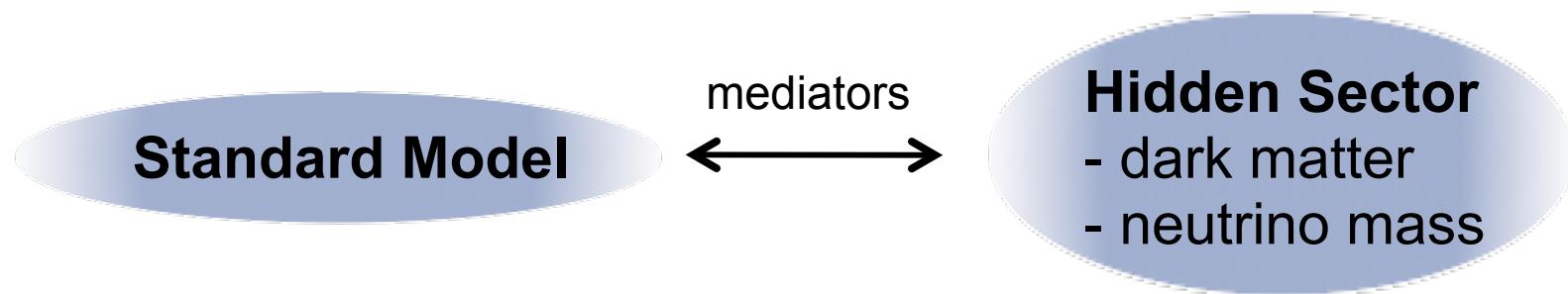
Generic fixed target sensitivity

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

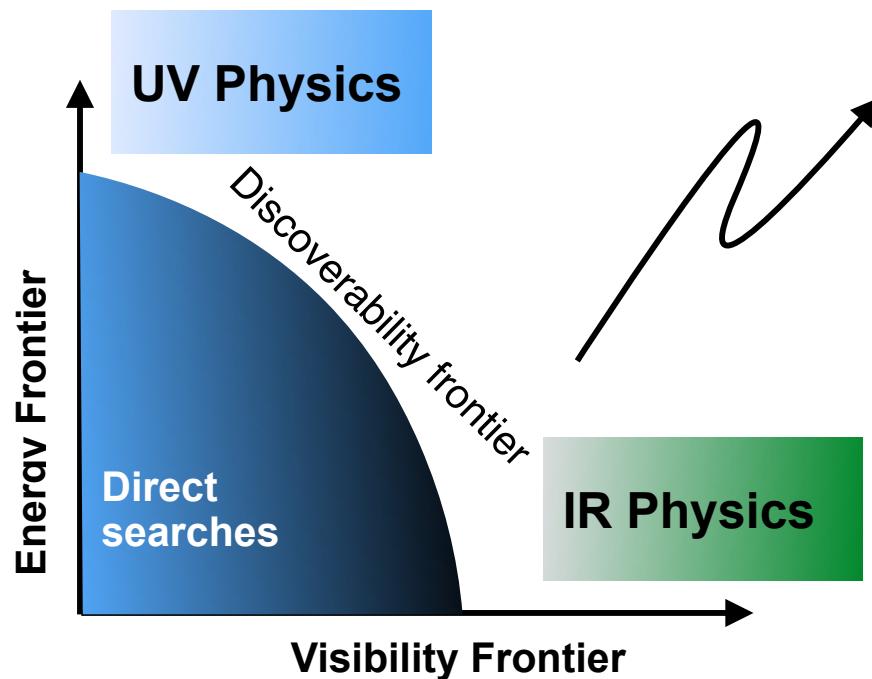
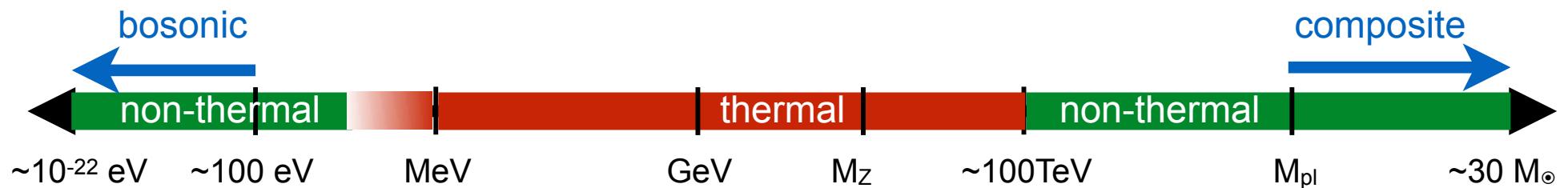
Thermal Pseudo–Dirac, $\alpha_D = 0.5$



Summary



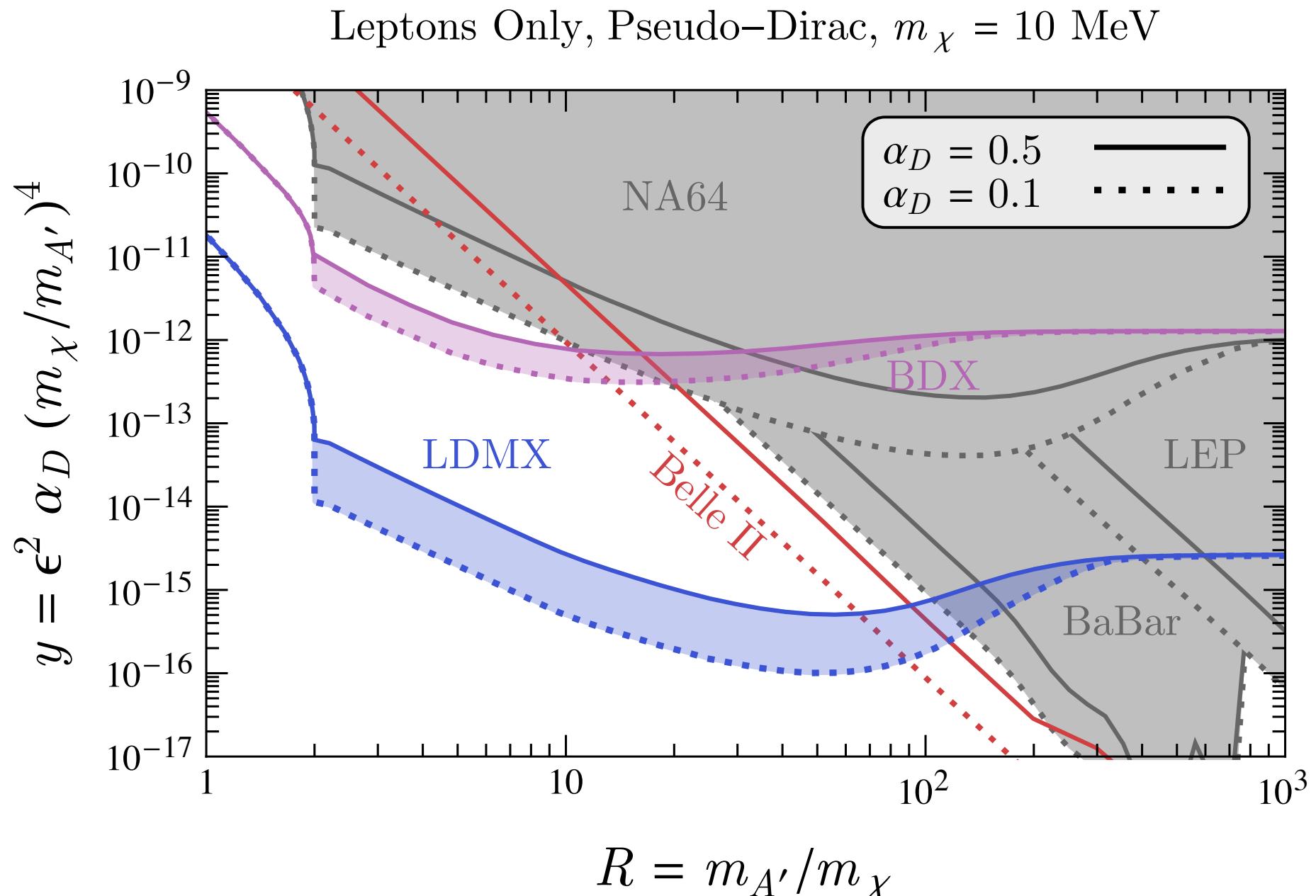
Empirical motivations for new physics suggest dark/hidden sectors:



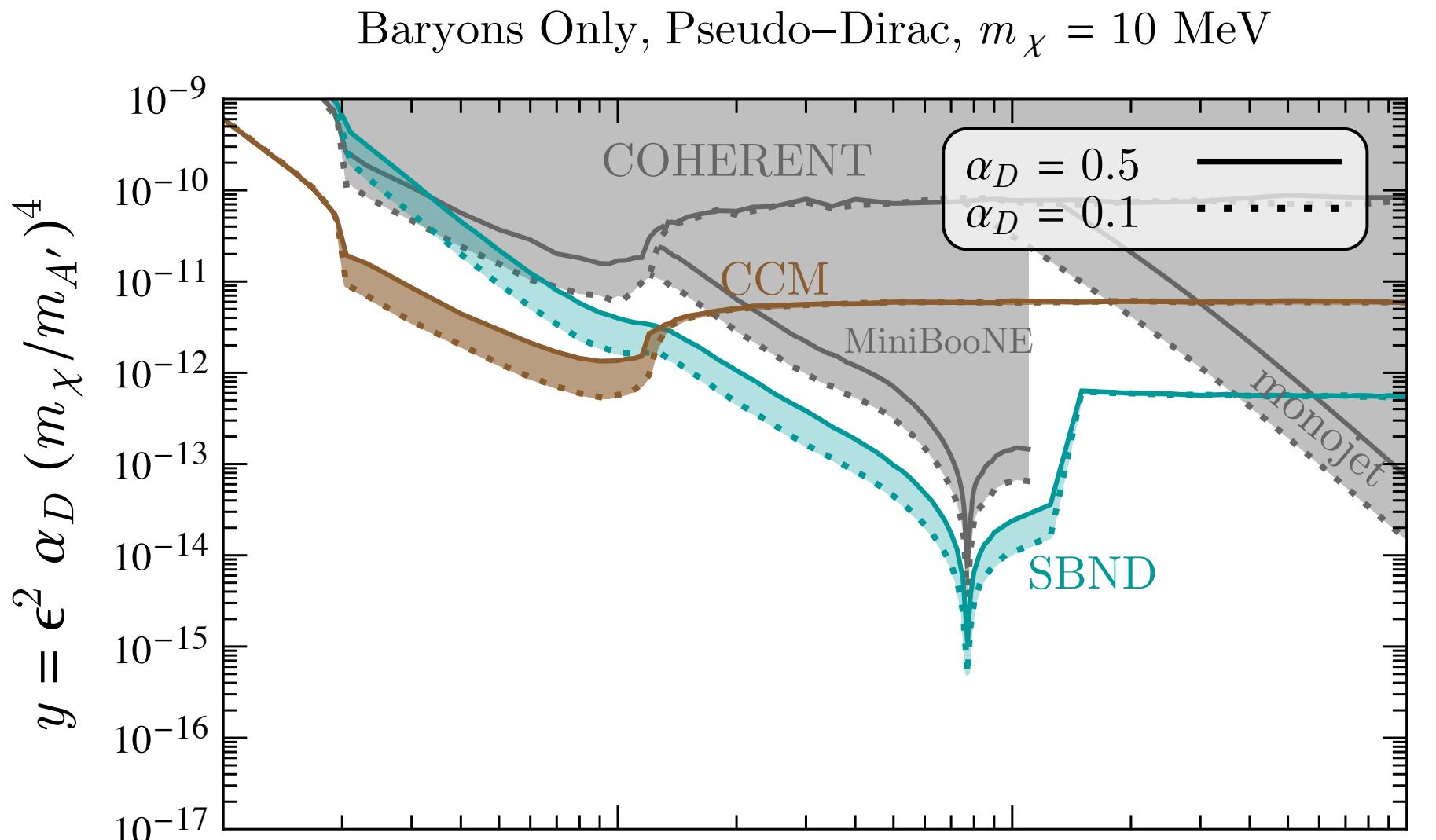
- EFT arguments focus attention on the UV-complete *portal interactions*
 - Expanded theoretical landscape e.g. for (low mass) particle DM
 - Expanded complementary search strategies, with experimental efforts at the precision and intensity frontier over the past decade
 - Viable path to cover “most” of the thermal relic DM parameter space.

Additional slides (including Higgs, neutrino portals)

Vector portal DM - leptonic coupling sensitivity

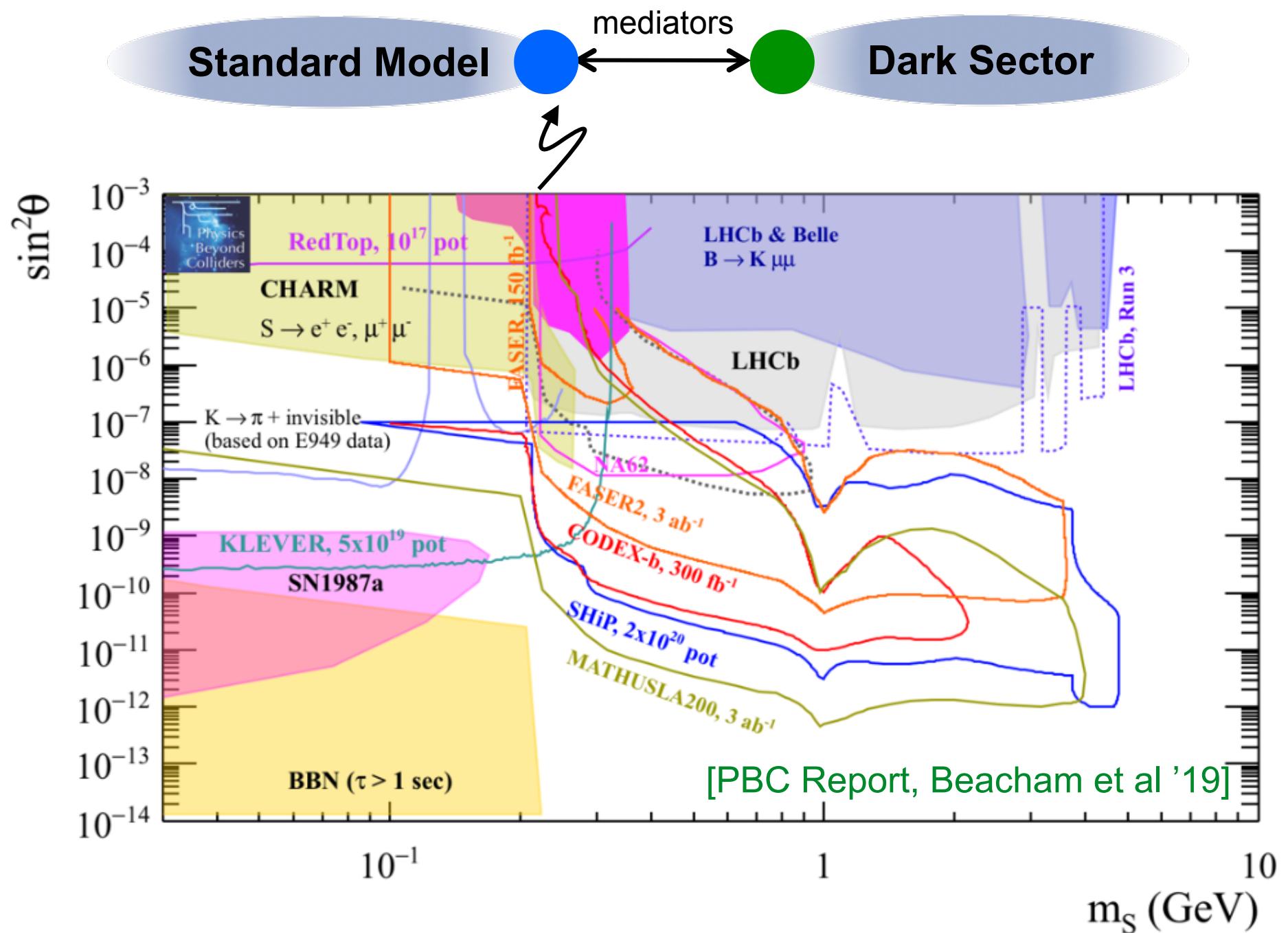


Vector portal DM - baryonic coupling sensitivity



$$R = m_{A'}/m_\chi$$

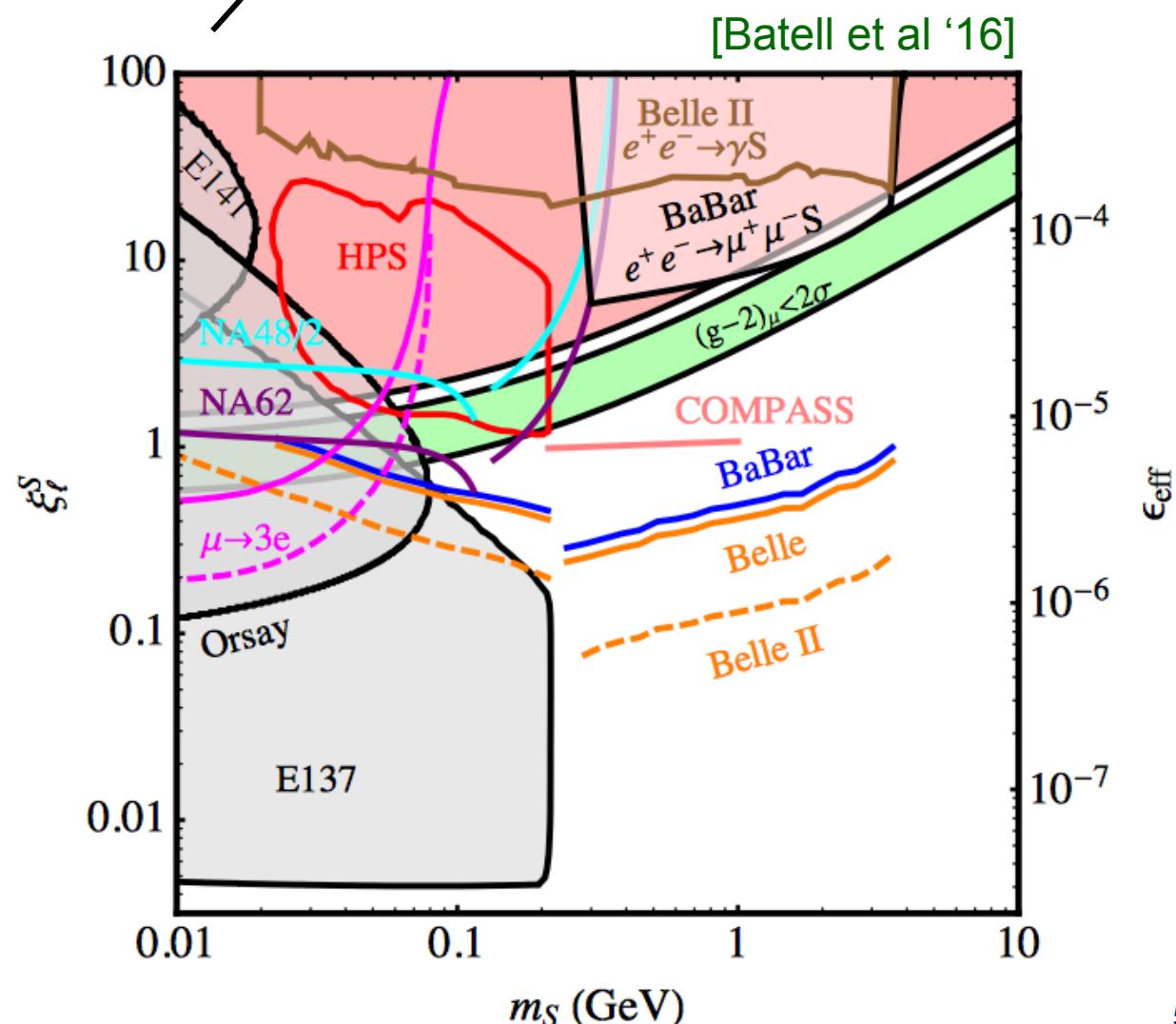
E.g. precision/rare decays (Higgs portal)



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



Minimal Higgs portal
➡ strong constraints
due to $(b \rightarrow s + S)$
mediated transitions.
The “leptonic Higgs
portal” $g_1 S II$, requires
UV completion, but
can be more viable



Light DM (Higgs portal)

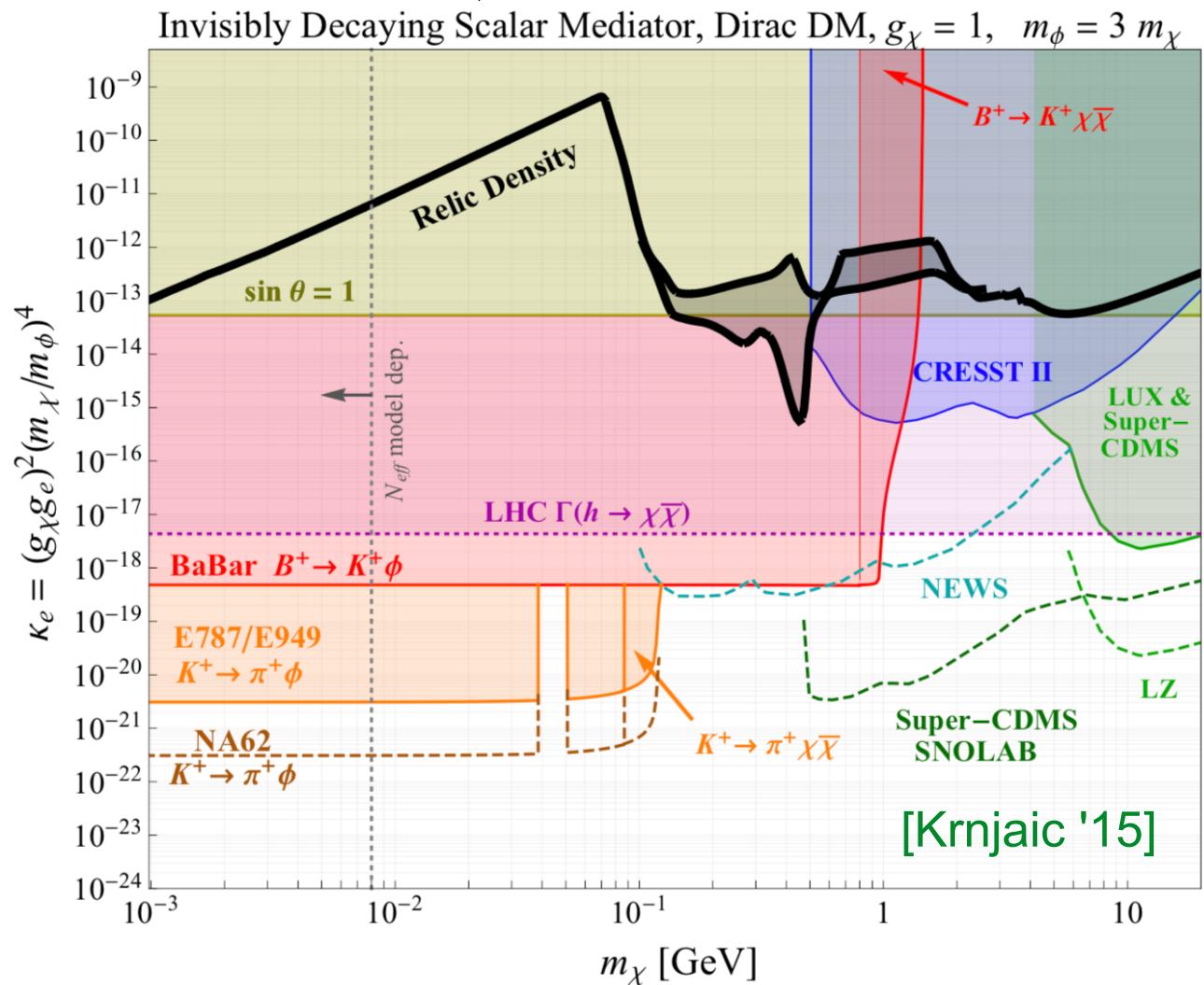
Standard Model

Dark Sector

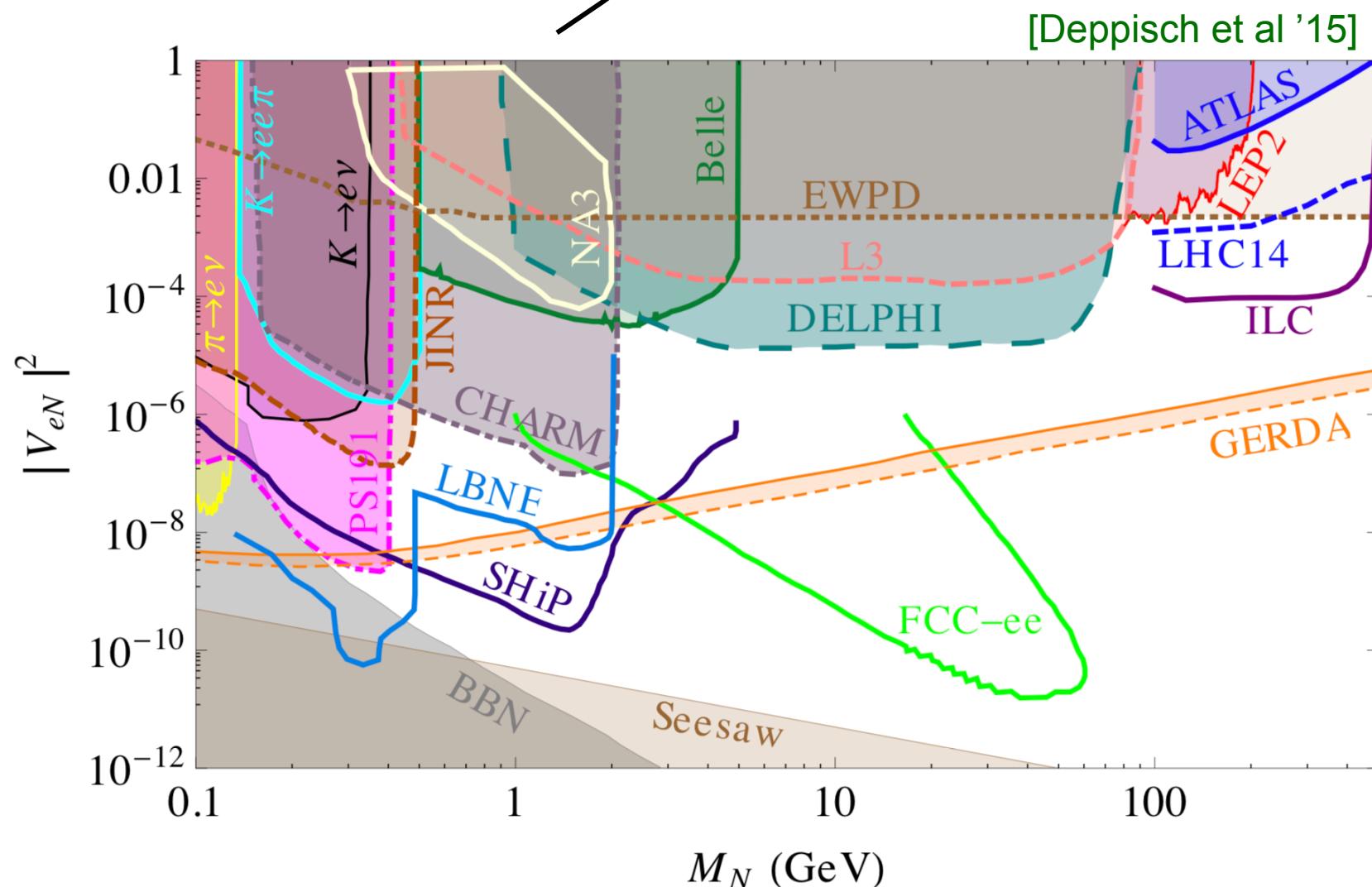
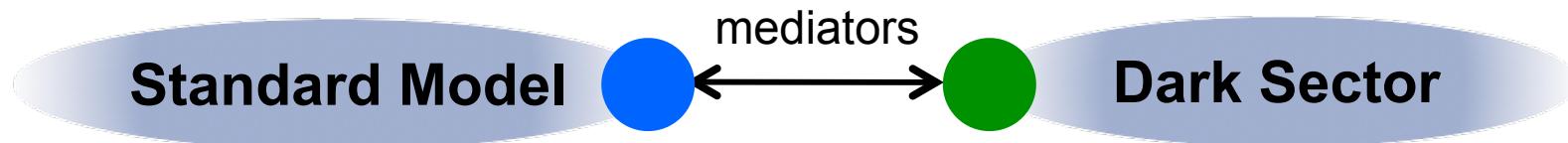
mediators

Highly constrained,
due to constraints
on B, K decays

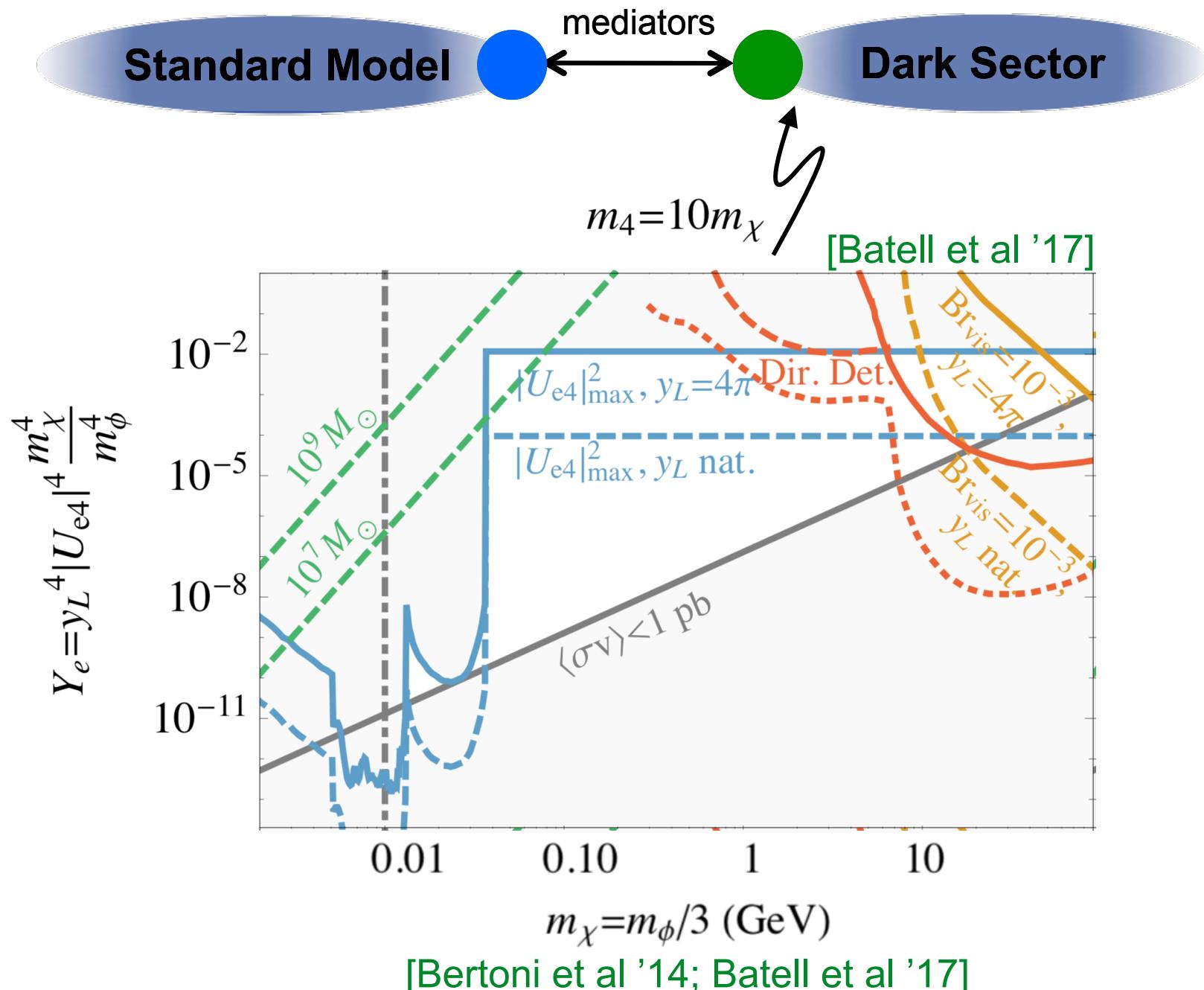
[Boehm & Fayet;
deNiverville et al
'12; Krnjaic '15]



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



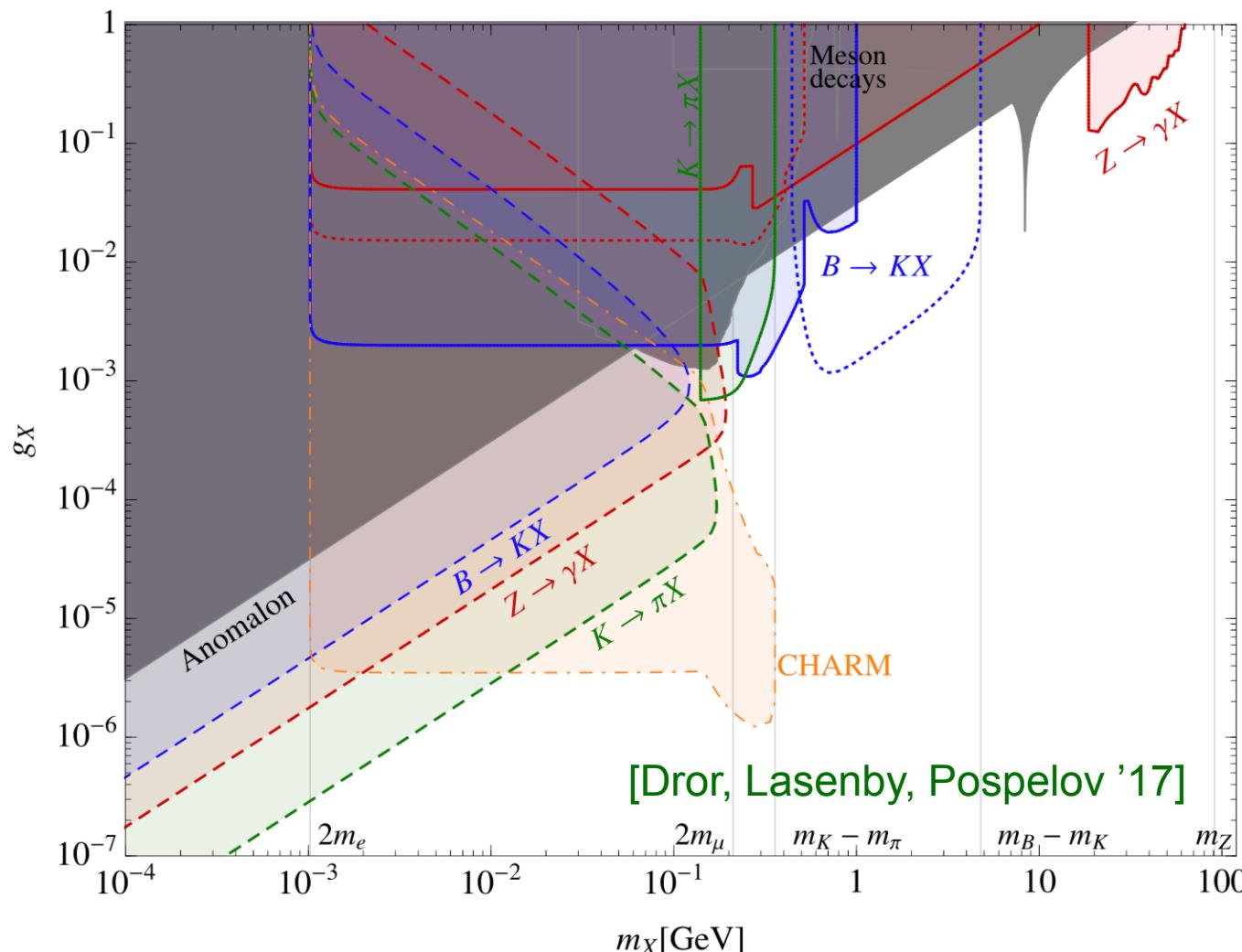
Light DM (Dirac Neutrino portal)



Beyond ($\dim \leq 4$) portals...

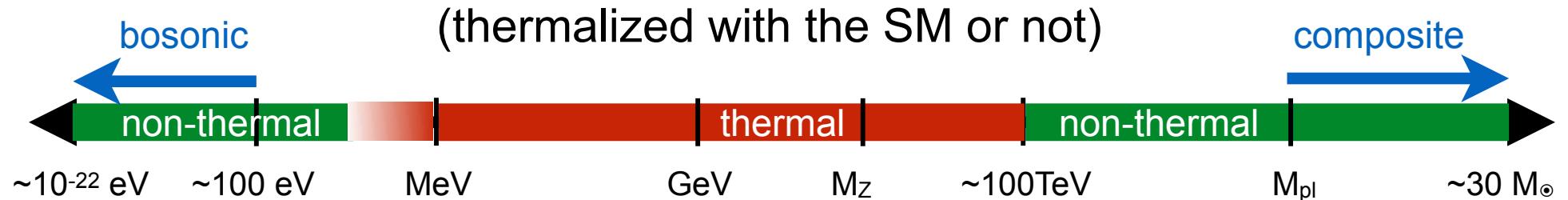
Other light dark forces, e.g. coupled to anomalous currents, generally inherit extra constraints, e.g. for a baryonic U(1)'

$$\begin{aligned} \mathcal{L} \supset & C_B g_X g'^2 \epsilon^{\mu\nu\rho\sigma} X_\mu B_\nu \partial_\rho B_\sigma \\ & + C_W g_X g^2 \epsilon^{\mu\nu\rho\sigma} X_\mu (W_\nu^a \partial_\rho W_\sigma^a + \frac{1}{3} g \epsilon^{abc} W_\nu^a W_\rho^b W_\sigma^c) \end{aligned}$$



Cold DM Landscape

Classify models according to their thermal history in the early universe



e.g. sterile neutrinos,
axions, etc

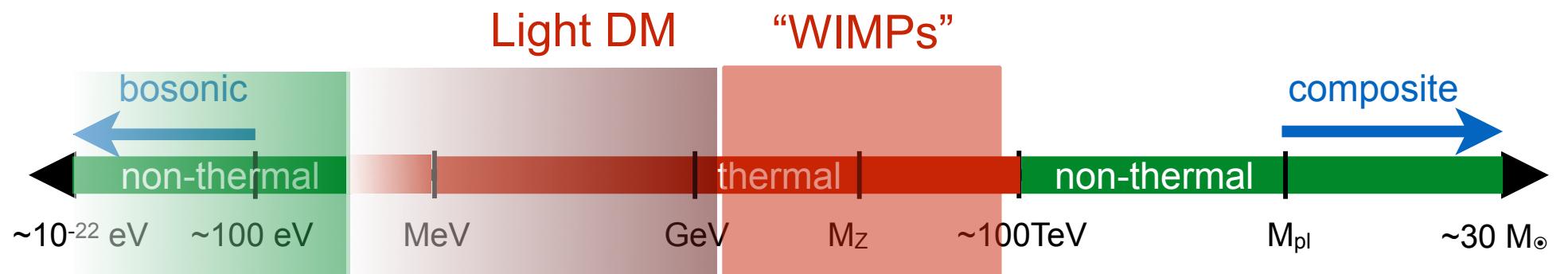
e.g. primordial BHs



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

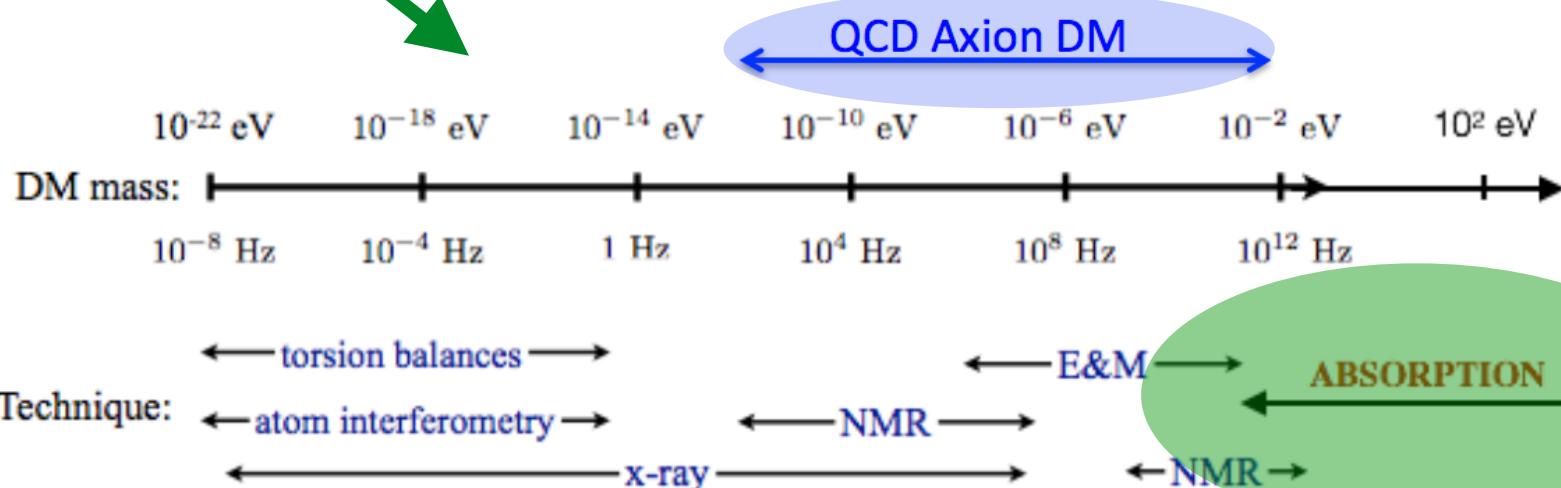
“Lamp posts” = Astrophysics,
Microlensing, Grav waves

Cold DM “Landscape”



ultralight bosonic DM

Range of new low energy precision detection techniques



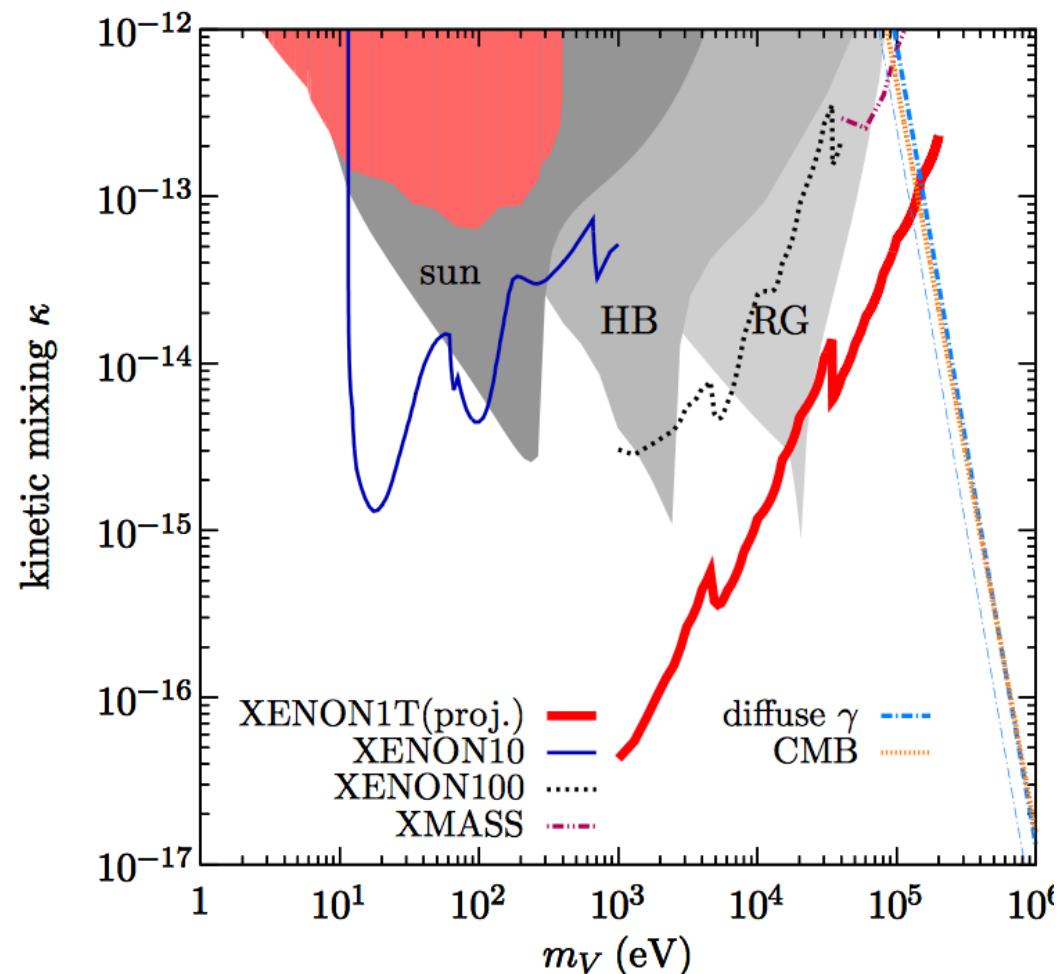
Dark photon DM - sensitivity (projections)

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

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

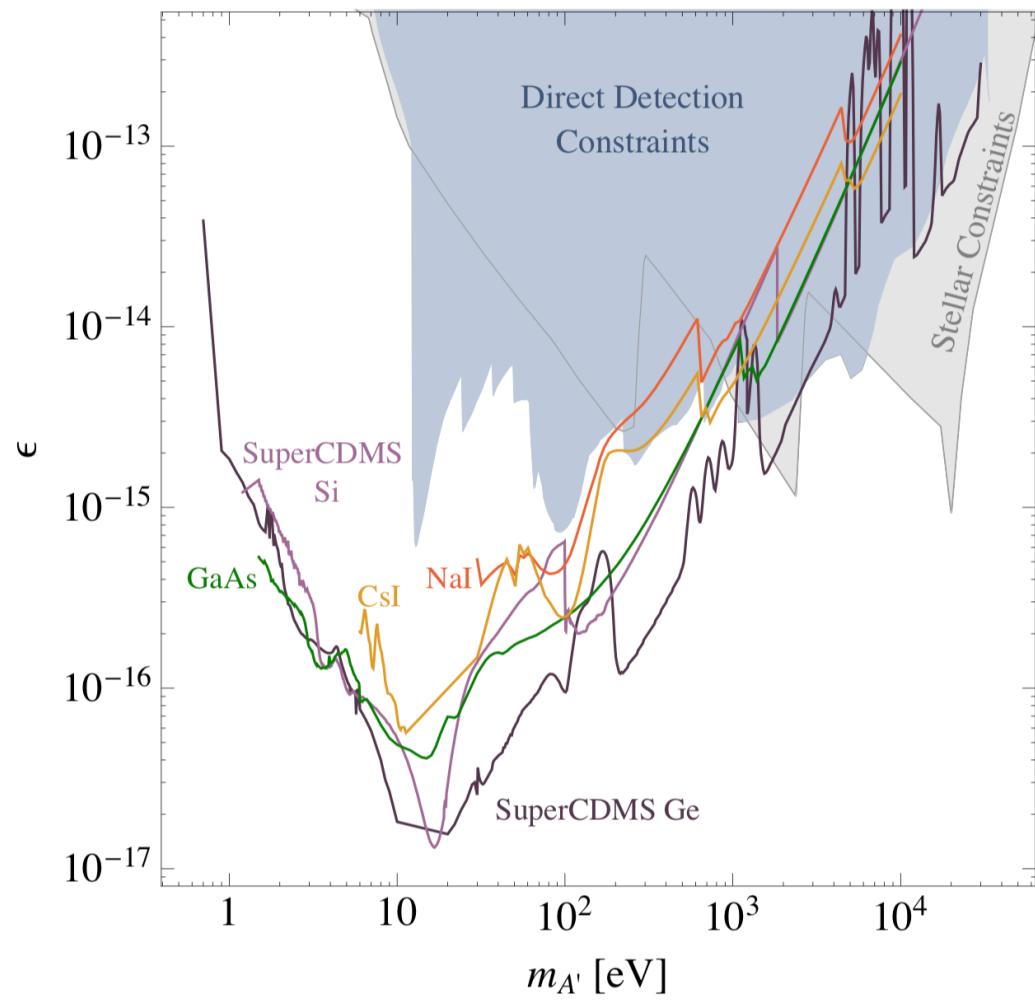
[Pospelov, AR, Voloshin '08, Redondo & Postma '08]

[An et al '15]



Sensitivity via atomic ionization

[Bloch et al '17]



[also Hochberg et al '17]