Light Long-Lived Particles: Synergies between EF and RF

Stefania Gori
UC Santa Cruz

Snowmass Energy Frontier Workshop
April 1, 2022

RF6: dark sectors at high intensities

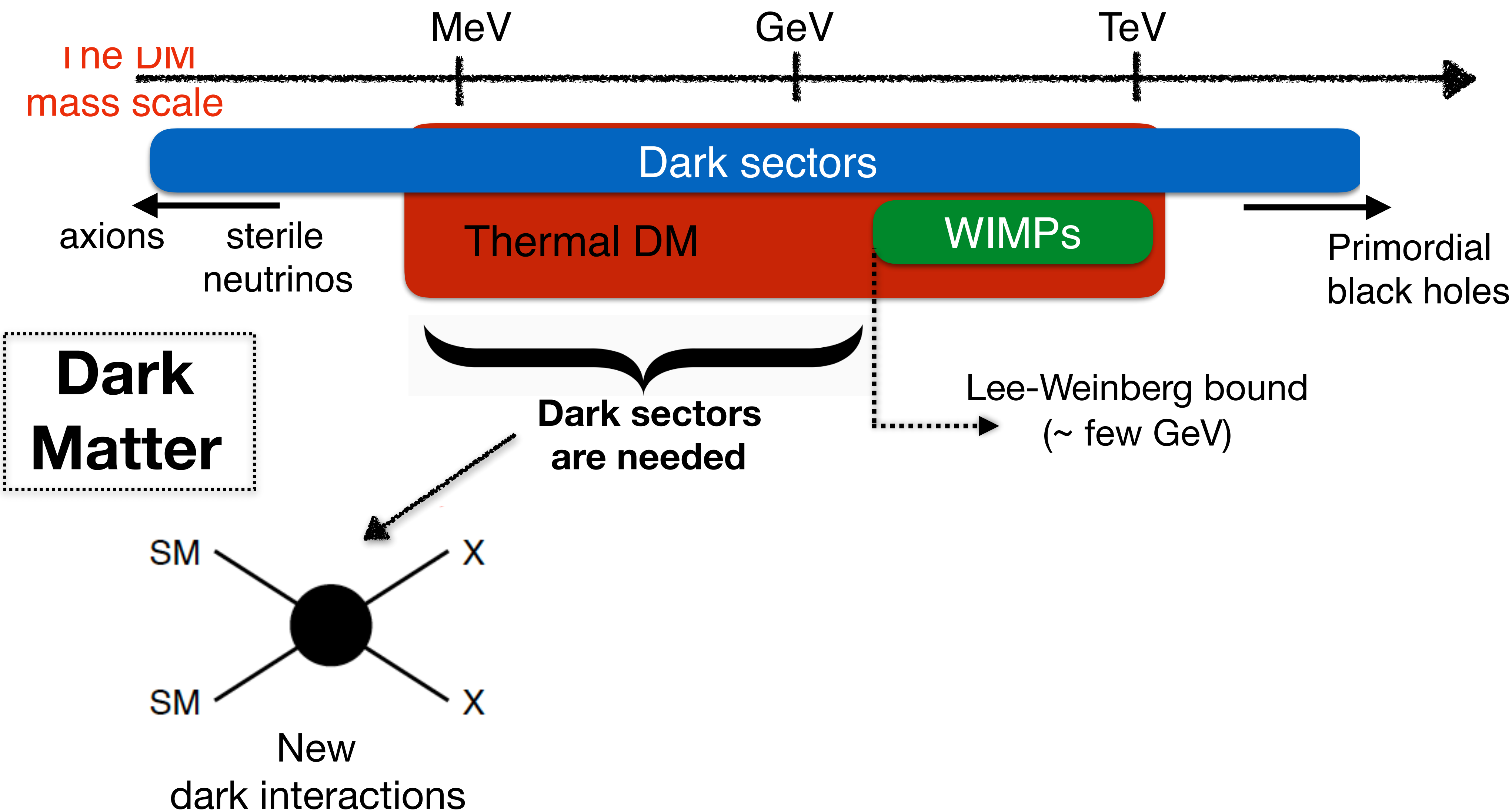
Conveners: Stefania Gori (sgori@ucsc.edu), Mike Williams (mwill@mit.edu)

- mailing list (SNOWMASS-RPF-06-DARK-SECTOR@fnal.gov)
- SLACK channel (#rpf-06-dark-sector)
- webpage: https://snowmass21.org/rare/dark

Key questions:

- Why are dark sectors a compelling opportunity for the next decade?
- What are the needed theoretical developments to guarantee a broad exploration of the dark sector?
- Which set of benchmark models comprehensively covers the interesting signatures we can look for?
- How will experiments confront the dark sector landscape? (RF6 involves experiments from small to large, both dedicated and multi-purpose).

Why a dark sector? (@ or below the GeV scale)



1. Thermal experimental targets

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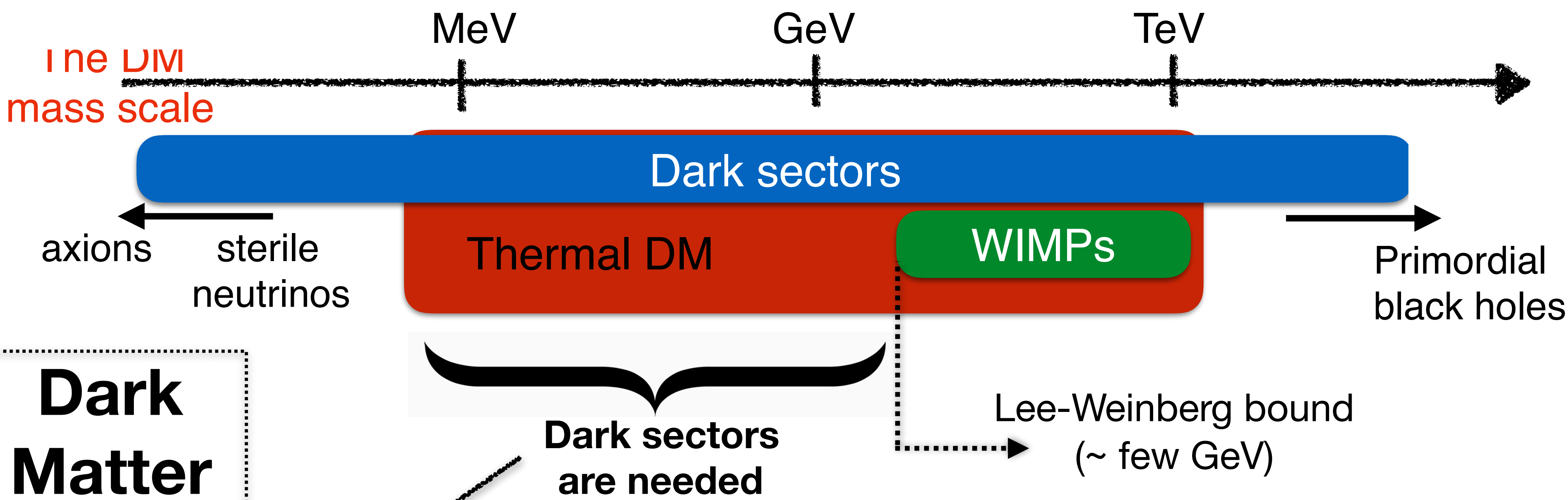
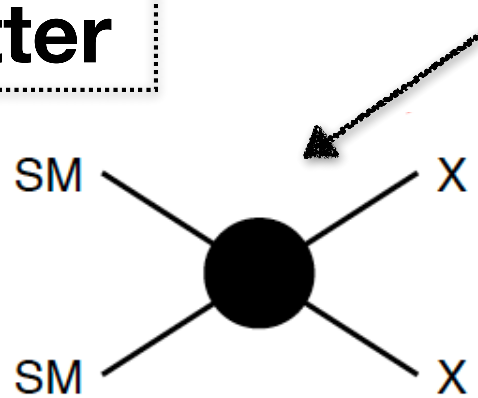


Dark Matter



New
dark interactions

1. Thermal experimental targets

Dark sectors can also address

- Strong CP problem (axion (-like particles));
- Gauge hierarchy problem (relaxion);
- Neutrino mass generation (sterile neutrinos);
- Anomalies in data ← **2. Anomaly-based experimental targets**

Approximate symmetry can protect their mass

RF6 "Big ideas" solicited papers

- Organization around science goals/questions.
- Arrange the breadth of RF6 science so that all the main techniques have a chance to shine.
- Span $\gtrsim$95% of white-paper interests

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1. Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.
Editors: Gordan Krnjaic, Natalia Toro

2. Explore the structure of the dark sector by producing and detecting unstable dark particles: Minimal Portal Interactions.
Editors: Brian Batell, Chris Hearty

3. New Flavors and Rich Structures in Dark Sectors.
Editors: Phil Harris, Philip Schuster, Jure Zupan

4. Experiments/facilities/tools
Editors: Phil Ilten, Nhan Tran

More details: https://docs.google.com/document/d/1R0O23wjGLxRzsc93a4pJIFn17yW9TCTq
(in our google drive folder, https://drive.google.com/drive/folders/1sMn1cWl2ddqzu46Yi4TcMIX7Cm2GUxO_)

Deadline: April 15

Long lived dark particles

Many dark sector models predict the presence of LLPs:

The "mediator"

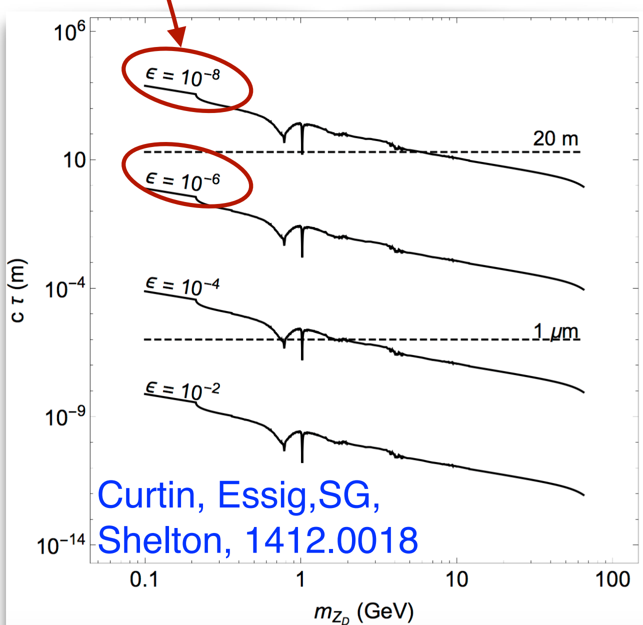
$\epsilon B^{\mu\nu} A'_{\mu\nu}$

$\kappa |H|^2 |S|^2$

$y H L N$

$g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

If the portal coupling is small and the mediator does not decay to other dark particles:



Often the production rate and decay length depend on the same coupling

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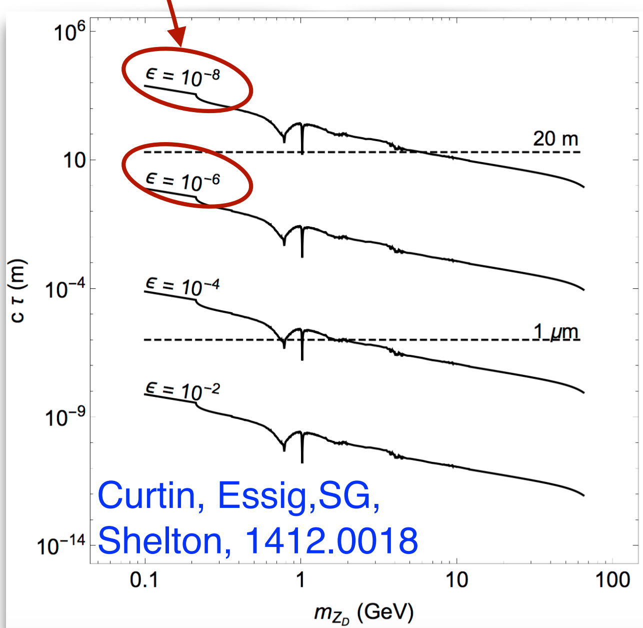


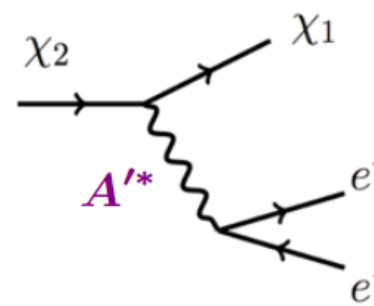
Often the production rate and decay length depend on the same coupling

"Rich dark sectors"

Dark sectors can contain several dark particles (in addition to a DM state and a mediator)

The width of the dark particles can be suppressed by:

- small mass splitting
  example: inelastic DM



$$\Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \frac{4\epsilon^2\, \alpha_{em}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

- multi-body phase space and / or loop suppression

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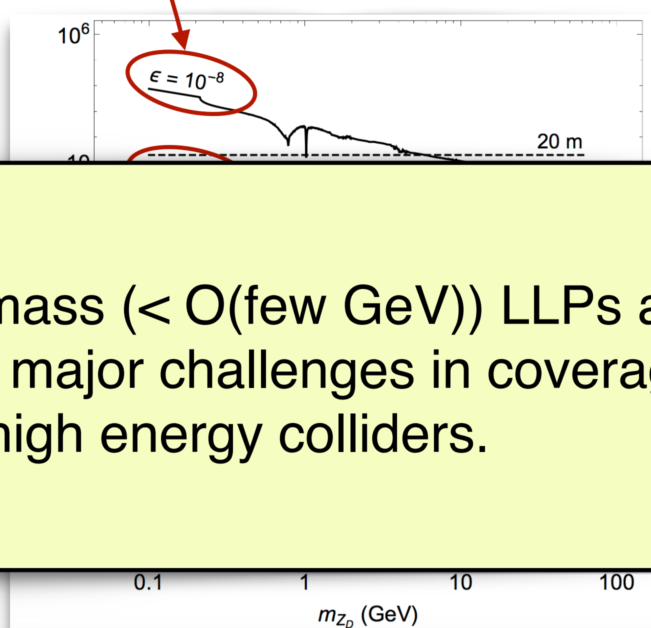

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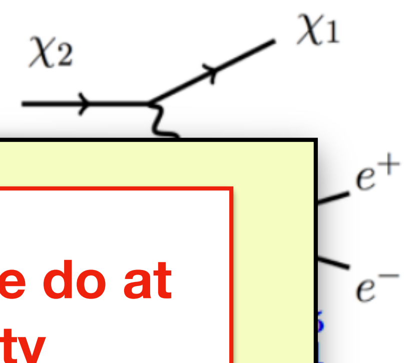


loop suppression

Low-mass (< O(few GeV)) LLPs are one of the major challenges in coverage at the LHC/high energy colliders.

What can we do at high-intensity experiments? (RF6)

From 4. Experiments/facilities/tools
Editors: Phil Ilten, Nhan Tran

Experiments

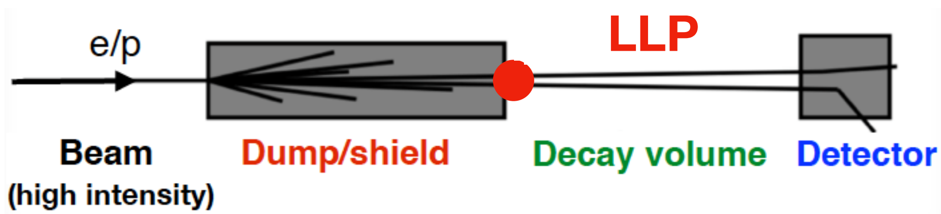
Contents

Please fill out the form https://docs.google.com/forms/d/e/1FAIpQLSfGJA2LUo6s7h7yvXaqDYr5k9ZB39v0mI0zmKj_sn0l2_9LJQ/viewform if your experiment is missing!

+ auxiliary detectors
FACET @ LHC

Complementarity of strategies for LLPs

Fixed target/ beam dump experiments



$\sqrt{s} < \mathcal{O}(50\ \mathrm{GeV})$

Longer decay volume ⟶ smaller couplings can be probed
Shorter dump (backgrounds?) ⟶ larger couplings can be probed

High-intensity colliders/ meson factories

- Meson → LLP + SM
- LLP production through bremsstrahlung, Primakoff production, …

Auxiliary detectors

LLP production at main IP and decay in the detector

Possible benchmarks

initiated by N.Toro

Benchmarks in Final State x Portal Organization

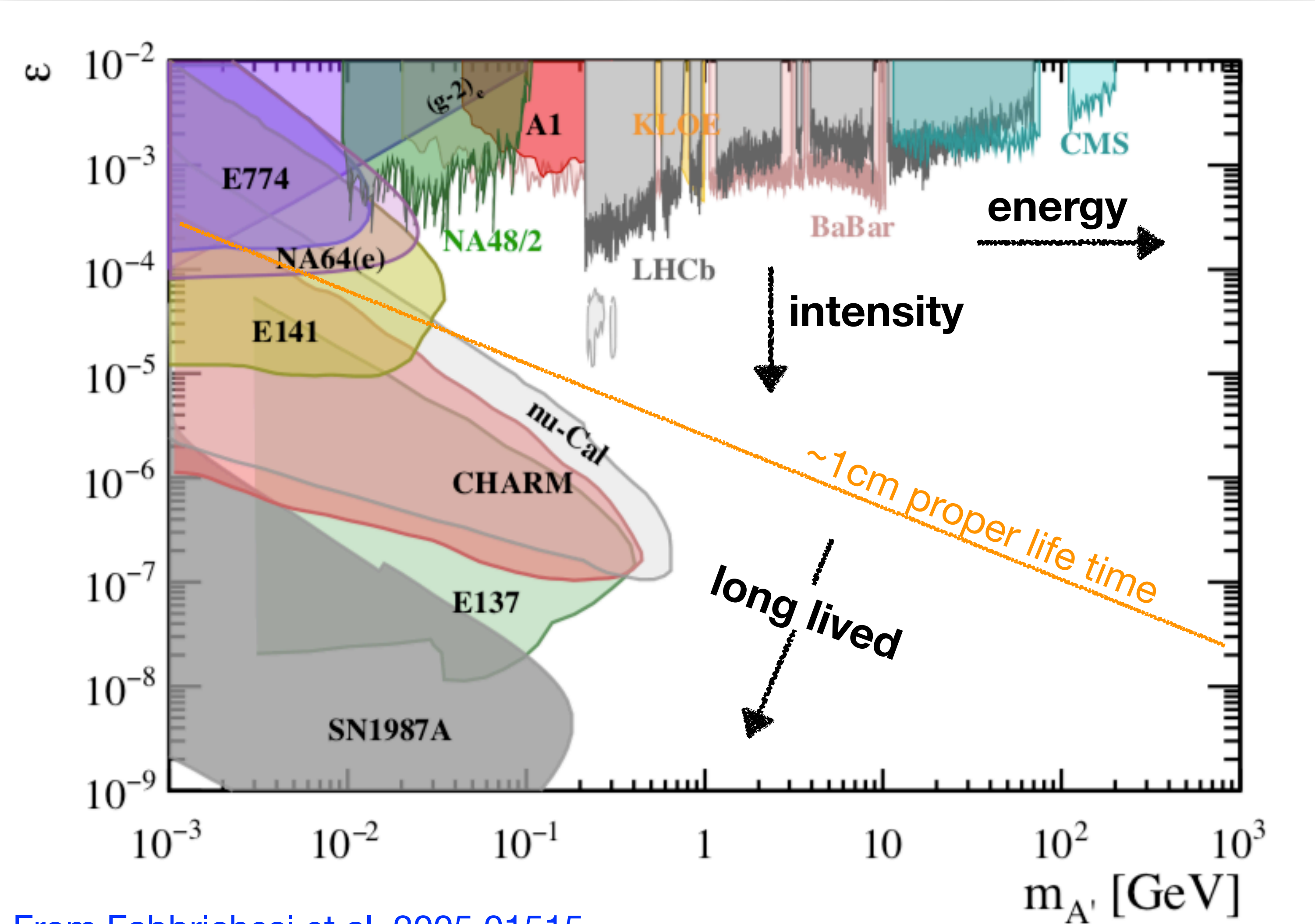
	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [$m_{A'}/m_\chi=3, \alpha_D=.5$]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] m_χ vs. α_D [$m_{A'}/m_\chi=3$, $y=y_{fo}$] m_χ vs. m_A [α_D=0.5, $y=y_{fo}$] *Millicharge m vs. q*	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi=3, \alpha_D=.5$] (anom connection)** **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L\,/\,\mu-\tau\,/\,B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. $\sin\theta$ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. $\sin\theta$* [λ=0] *m_S vs. $\sin\theta$* [λ=s.t. Br(H→ss ~10^{-2})]?	Dark Higgsstrahlung (w/vector) scalar SIMP models Leptophilic/leptophobic dark Higgs
Neutrino	e/μ/τ a la1709.07001 Batell, Han, McKeen, Es Haghi	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasonable flavor structures	Sterile neutrinos with new forces
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* *m_a vs. f_w*	FV axion couplings
	Big idea 1	**Big idea 2**	**Big idea 3**

Focus: both the DM and the **mediator** are light (O(GeV) or less)

Bold = BRN benchmark, italic = PBC benchmark, others are new suggestions

BRN = basic research needs for DM small projects

Complementary reach on a long-lived dark photon



From Fabbrichesi et al, 2005.01515

Direct production of a dark photon, A'

$$\boxed{\epsilon B^{\mu\nu} A'_{\mu\nu}}$$

Complementarity high energy - high intensity

→ a huge mass range can be covered!

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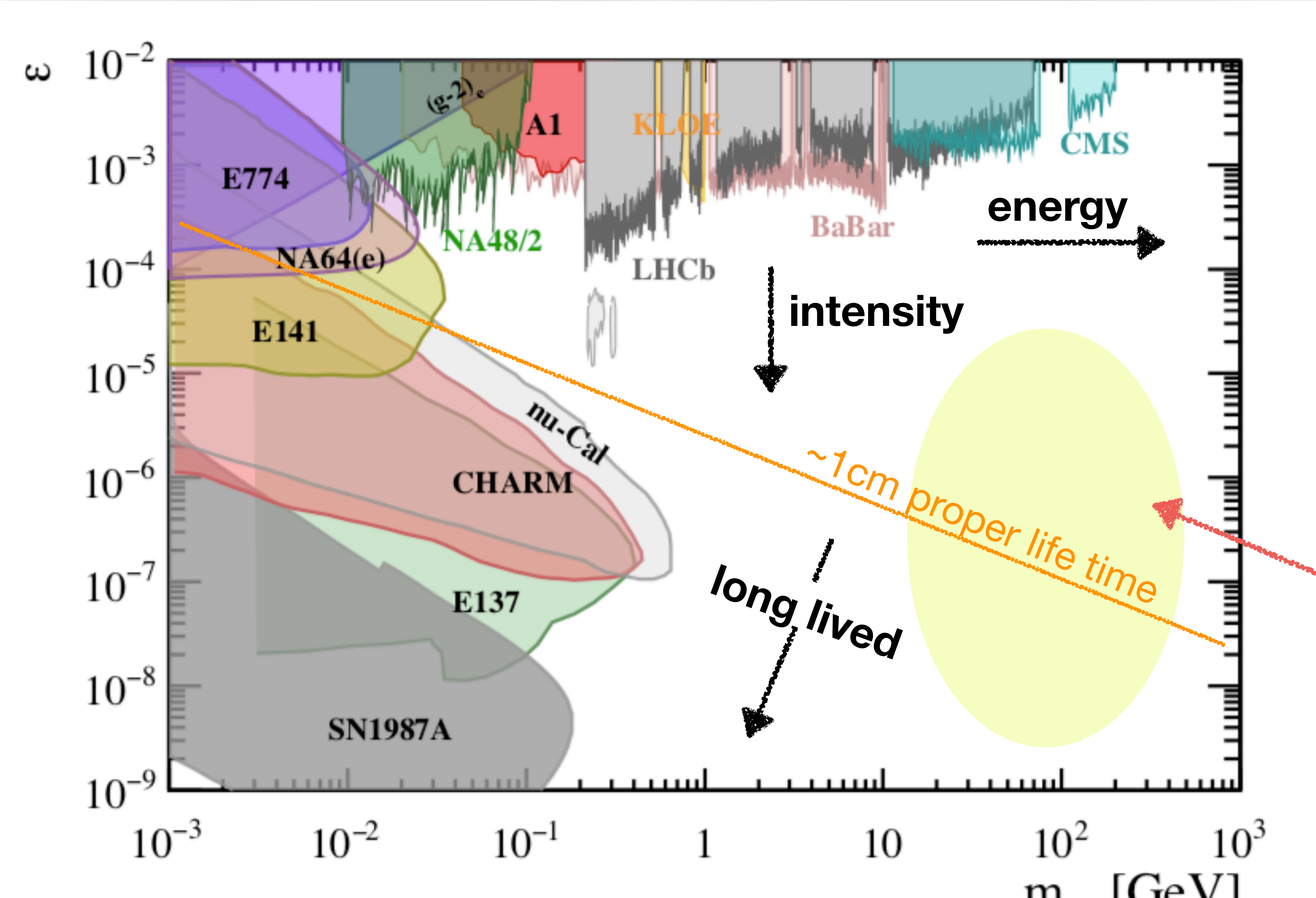

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High-energy:

Complementarity with Higgs exotic decays:
h → ZA'

If the A' mass arises from a dark Higgs, mixing with the SM Higgs,
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with a long-lived A'

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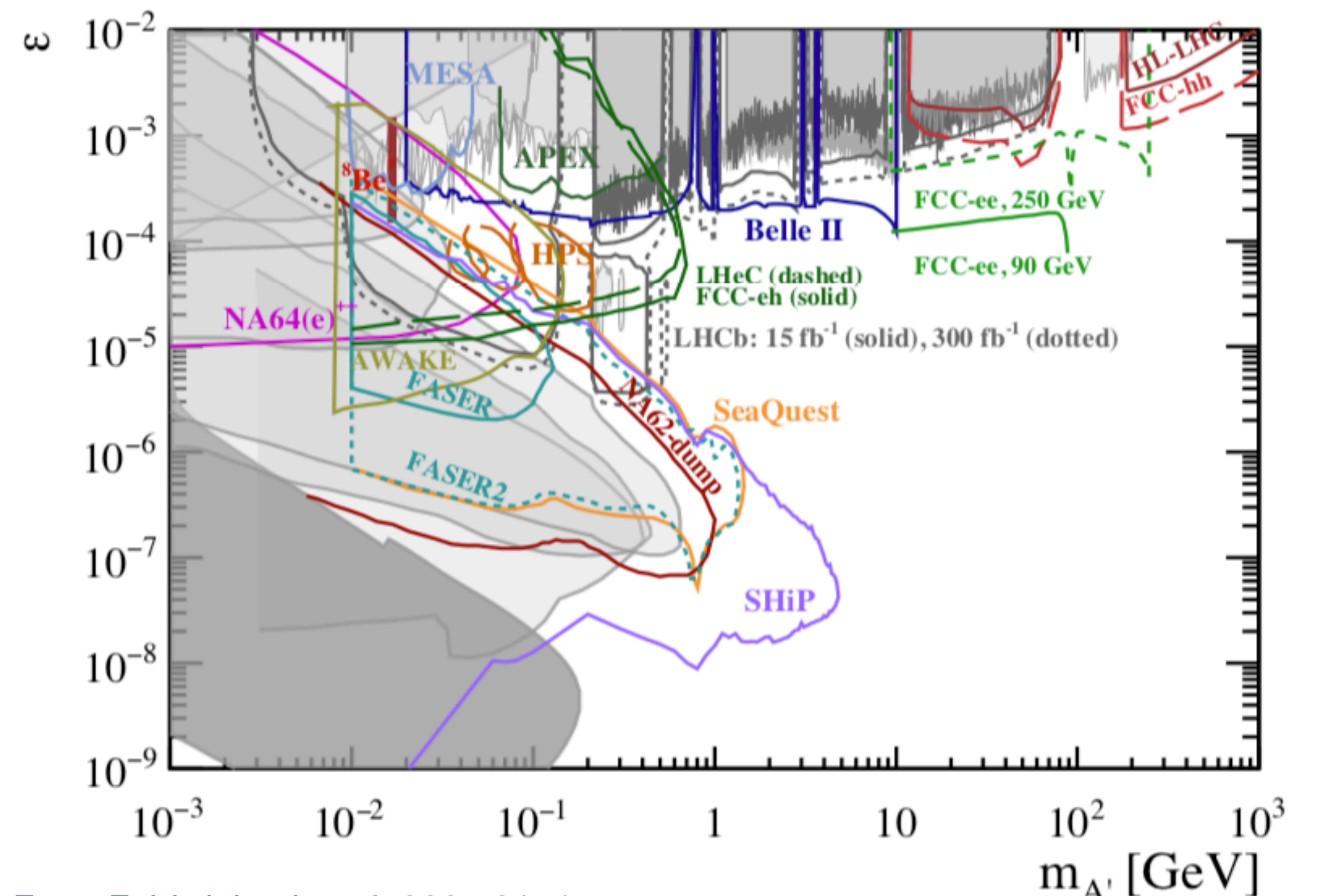

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The additional states can have a production and a decay width that depend on different parameters (as opposed to minimal portal scenarios)

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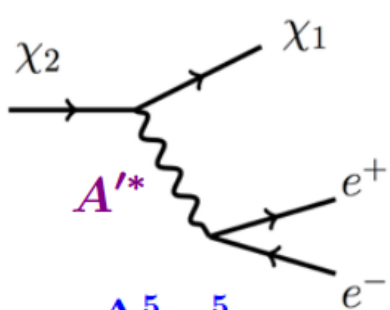
An interesting example: Inelastic Dark Matter (IDM) models

$$-\mathcal{L} \supset m_D\, \eta\, \xi + \frac{1}{2}\, \delta_\eta\, \eta^2 + \frac{1}{2}\, \delta_\xi\, \xi^2 + \text{h.c.}$$

2-component Weyl spinors with opposite charge under U(1)’

$$\mathcal{L} \supset \frac{i e_D\, m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}} A'_\mu\, (\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1)$$

Small mass splitting between X_1 and X_2



* Signatures in our labs:

$$\begin{cases} A' \to \chi_2 \chi_1 \\ \Gamma(\chi_2 \to \chi_1 e^+ e^-) \simeq \dfrac{4\epsilon^2\, \alpha_{\rm em}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4} \end{cases}$$

X_2 is typically long lived

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fixed target exp. testing missing momentum
(Big idea 1)

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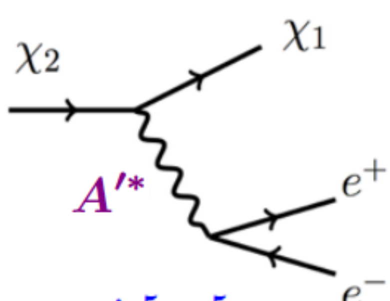

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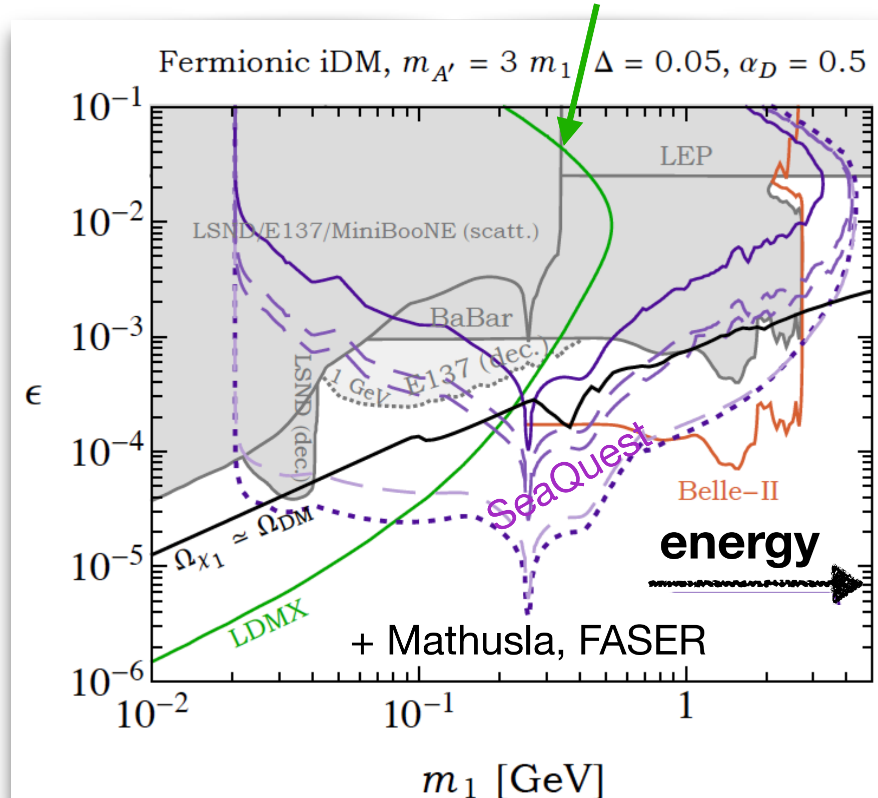


Berlin, SG, Schuster, Toro, 1804.00661

Conclusions & outlook

* Dark Sectors represent a broad arena for new physics, with dark matter as powerful motivation (+ strong CP problem, baryogenesis, neutrino masses, …);
* Plenty of recent developments on the theory side;
* Much is unexplored;
* Bounded, reachable and motivated regions of parameter space represent exciting directions for near-term experiments.

Dark sector models often predict LLPs.

How do we achieve “comprehensive” coverage of LLP parameter space?

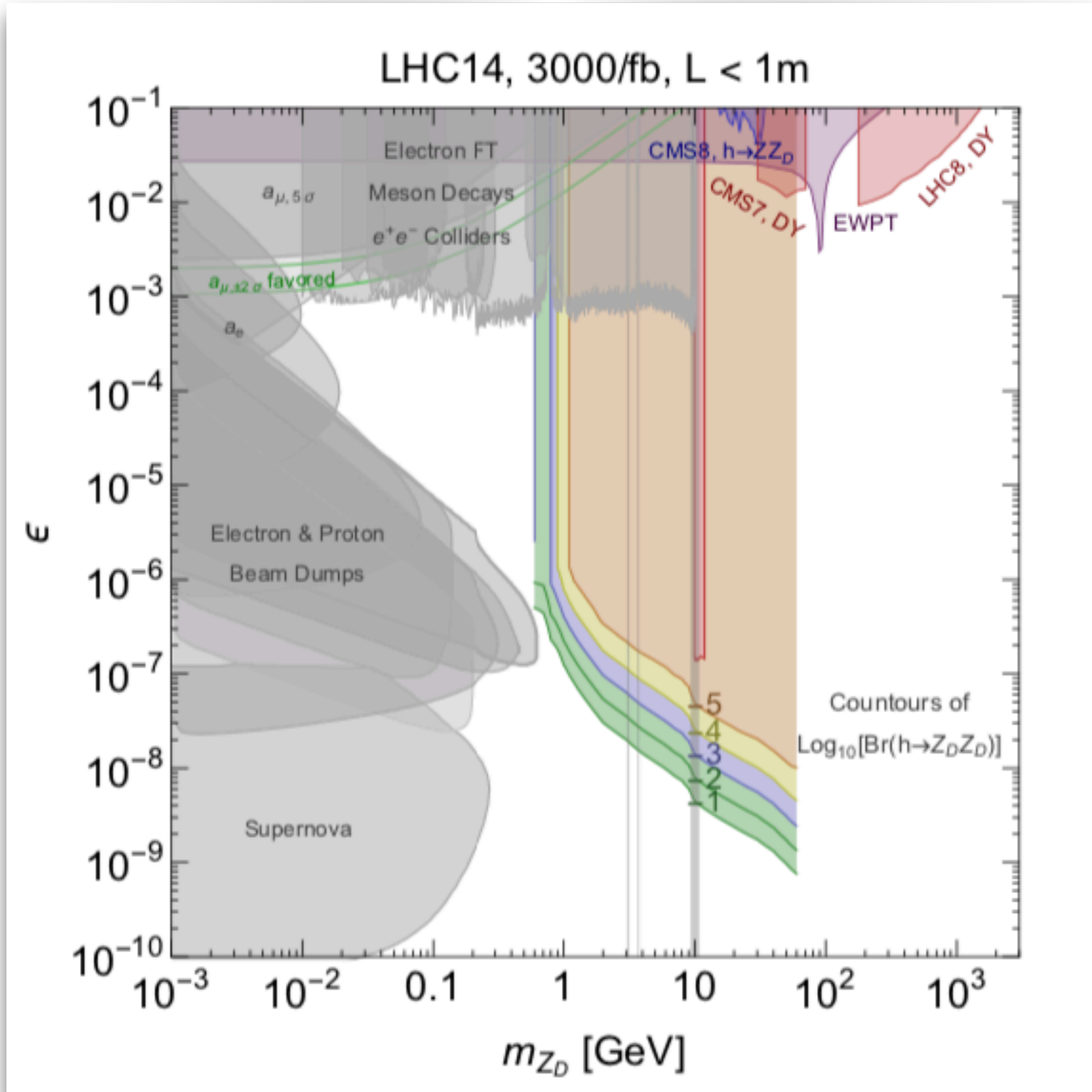
Low- and high-energy experiments, as well as small and multi-purpose experiments, complement each other because they have different strengths.
When the low- and high-mass focused physics join without gaps, considering both together allows a more powerful, robust scientific conclusion than considering them separately

Working with EF9 & 10 to bridge the GeV-to-TeV Gap

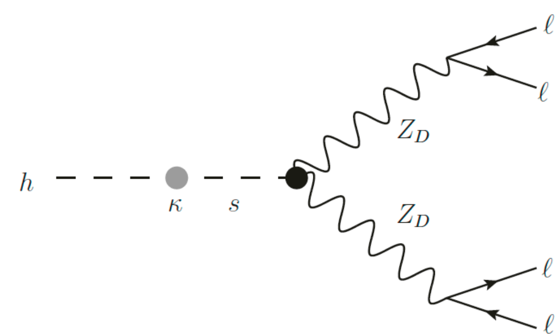
Complementarity with invisible Dark Matter searches (big idea 1)

<u>Next rare frontier meeting</u>: May 16-19 in Cincinnati.

Higgs exotic decays and long-lived dark photons



Curtin, Essig, SG, Shelton, 1412.0018

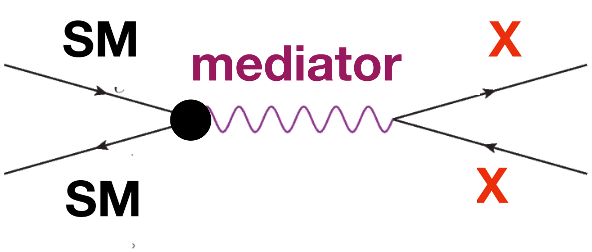


Final states to look for

a. **Invisible, non-SM**

Dark Matter production

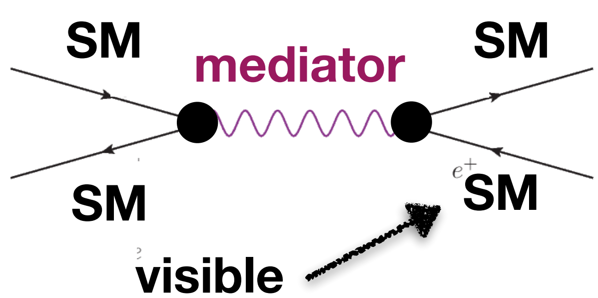
Producing stable particles that could be (all or part of) Dark Matter



b. **Visible, SM**

Production of portal-mediators that decay to SM particles

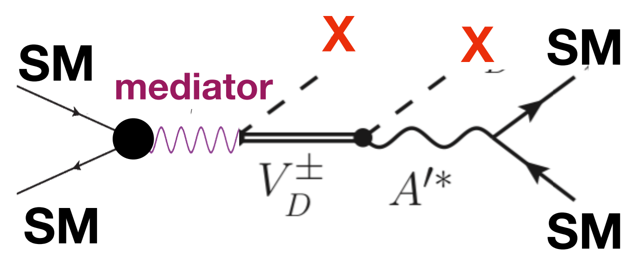
Systematically exploring the portal coupling to SM particles



c. **Mixed visible-invisible**

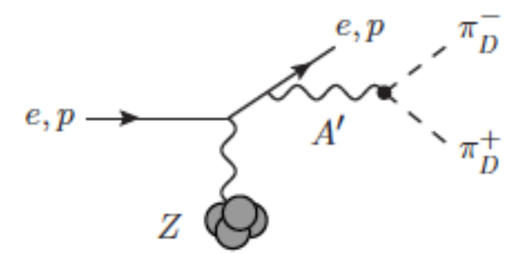
Production of "rich" dark sectors

Testing the structure of the dark sector

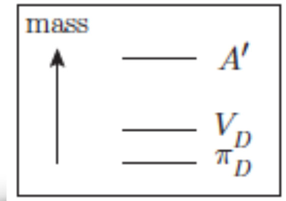


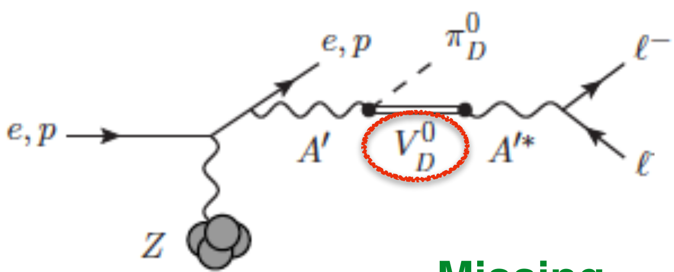
SIMP decays of the dark photon

$A' \to \pi_D^+ \pi_D^-$ (DM)



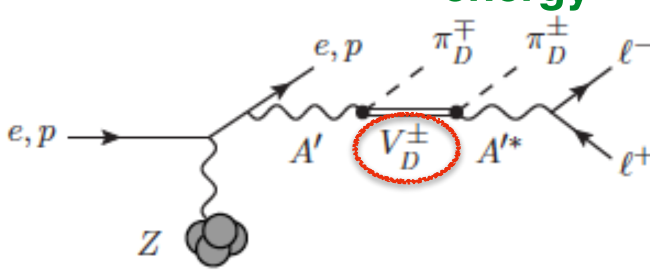
Invisible
A' decay





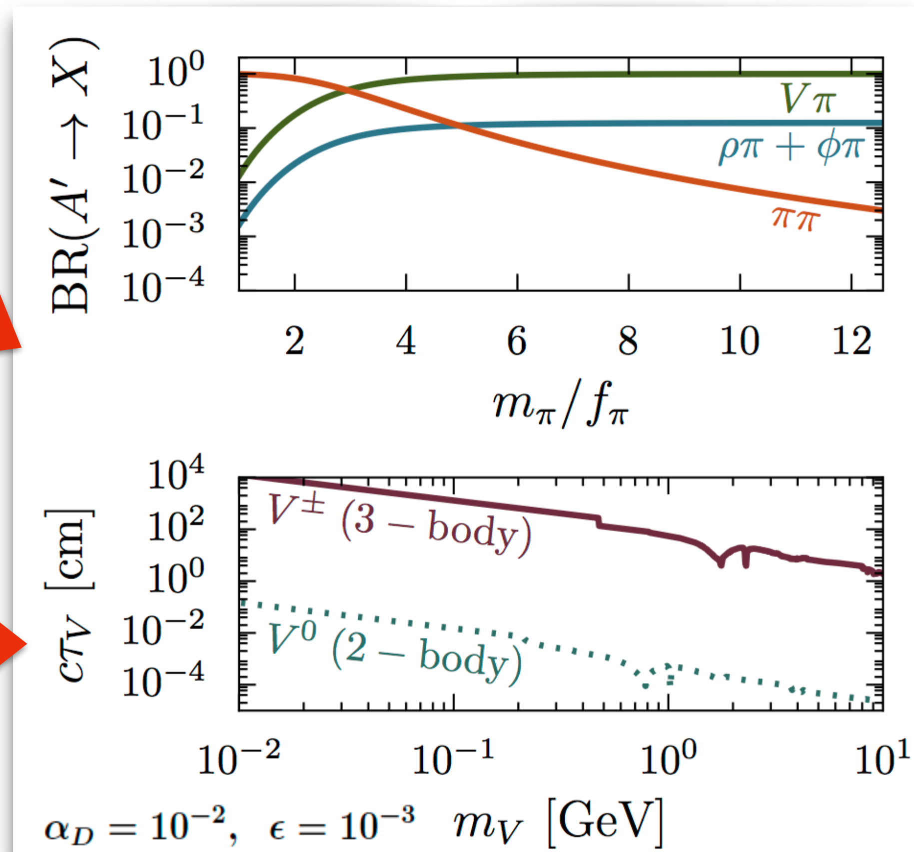
Missing energy

Visible
A' decay



$A' \to \pi_D V_D$

Berlin, Blinov, SG, Schuster, Toro, 1801.05805

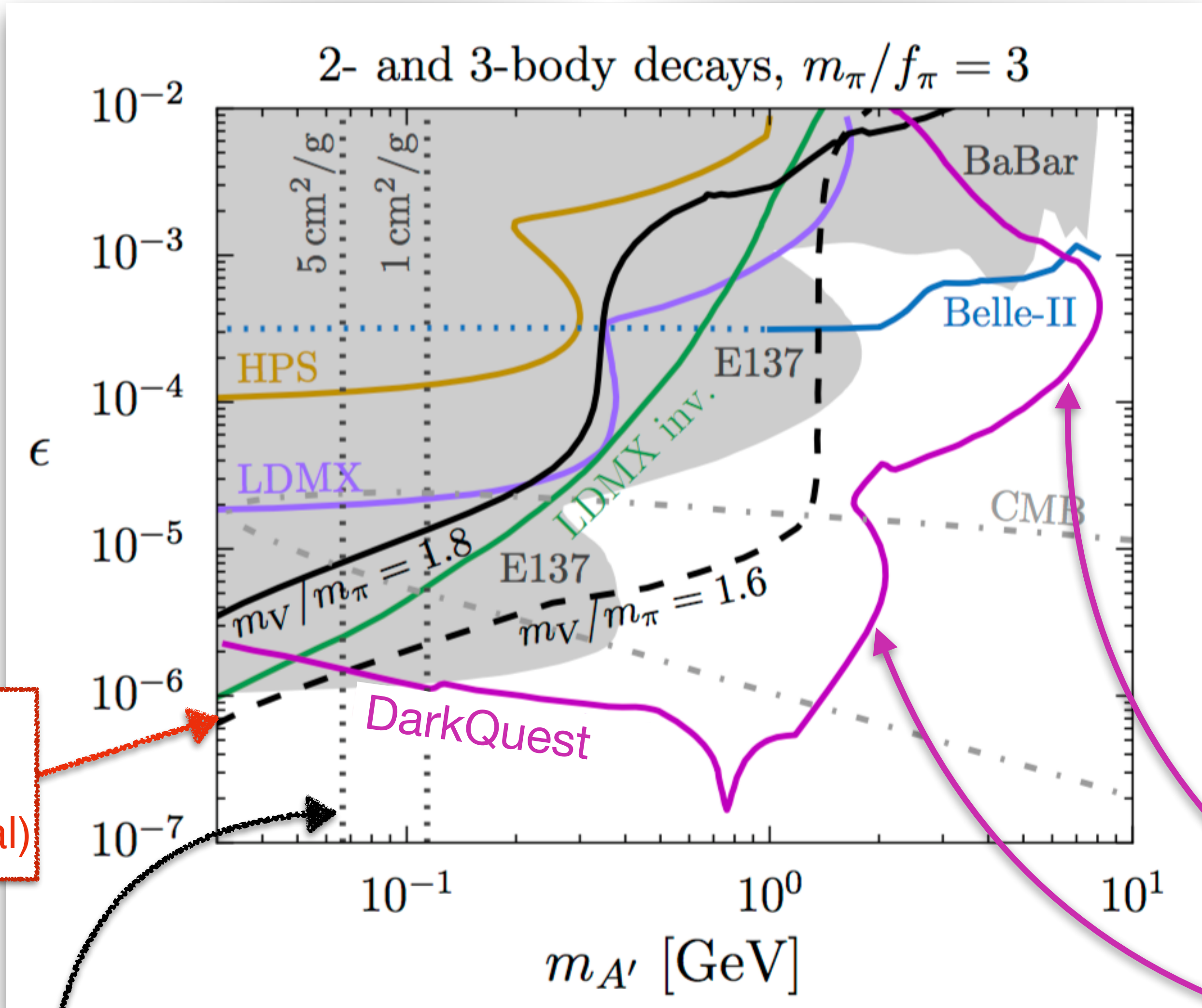


Displaced decays of the dark vector

Good for beam dumps!

The reach for SIMPs (2+3 body decays)

Berlin, Blinov, SG, Schuster, Toro, 1801.05805



Relic line (our goal)

Bound from DM self-interaction

$\alpha_D = 10^{-2}$, $m_{A'}/m_\pi = 3$

In color:

reach of past experiments:

- Belle II: (same Babar signature)

$e^+e^- \to \gamma A', \quad A' \to \mathrm{inv}$

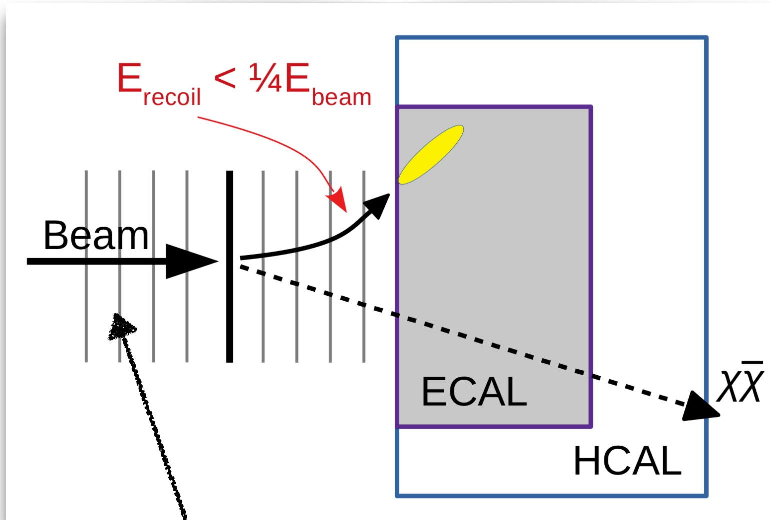
- LDMX: invisible A'
- LDMX: visible A'
- HPS: electron beam dump experiment. Search for visibly decaying A' **(*)**
- DarkQuest

$A' \to \pi_D V_D$

$V_D^0 \to \ell^+\ell^-$

$V_D^\pm \to \pi_D^\pm \ell^+\ell^-$

Missing energy/momentum searches for DM



e⁻ beam for the LDMX experiment,
Akesson et al., 1808.05219

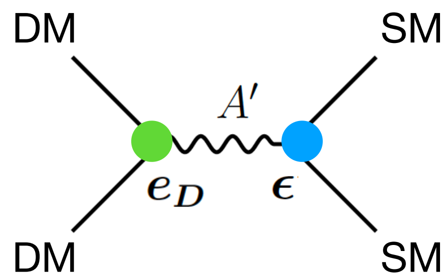
μ⁻ beam for the M³ experiment,
Kahn et al. 1804.03144

$$\mathrm{Majorana}: J_D^\mu = \frac{1}{2}\bar{\chi}\gamma^\mu\gamma_5\chi$$

$$\mathrm{PseudoDirac}: J_D^\mu = i\bar{\chi}_1\gamma^\mu\chi_2$$

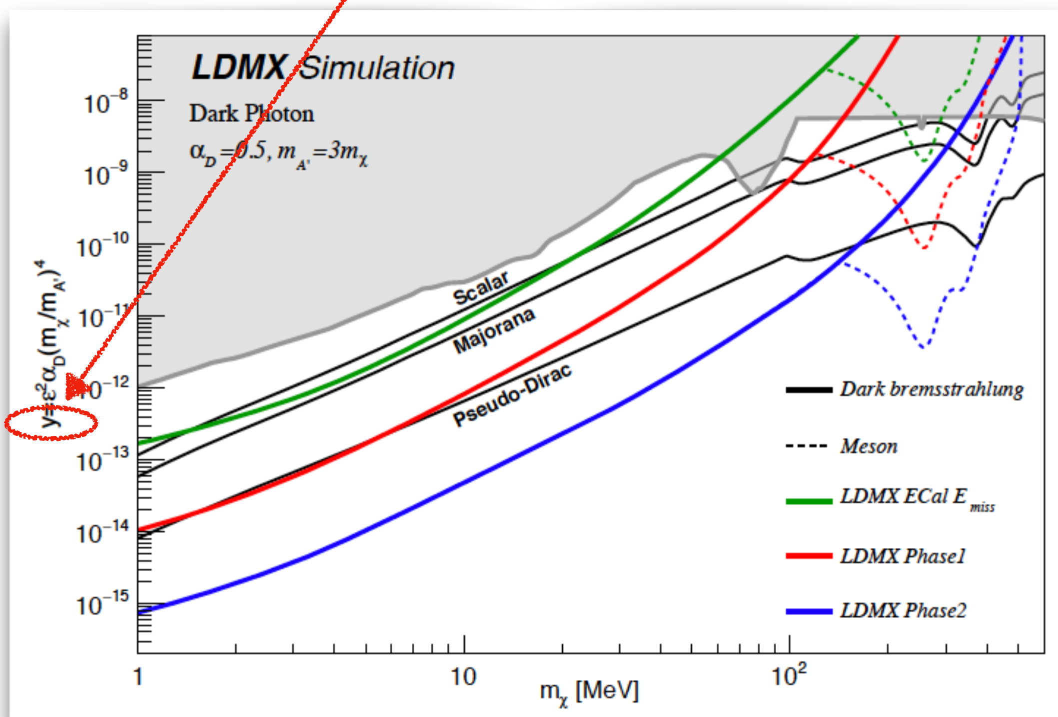
$$\mathrm{Scalar}: J_D^\mu = i(\chi^*\partial^\mu\chi - \chi\partial^\mu\chi^*)$$

DM thermal targets

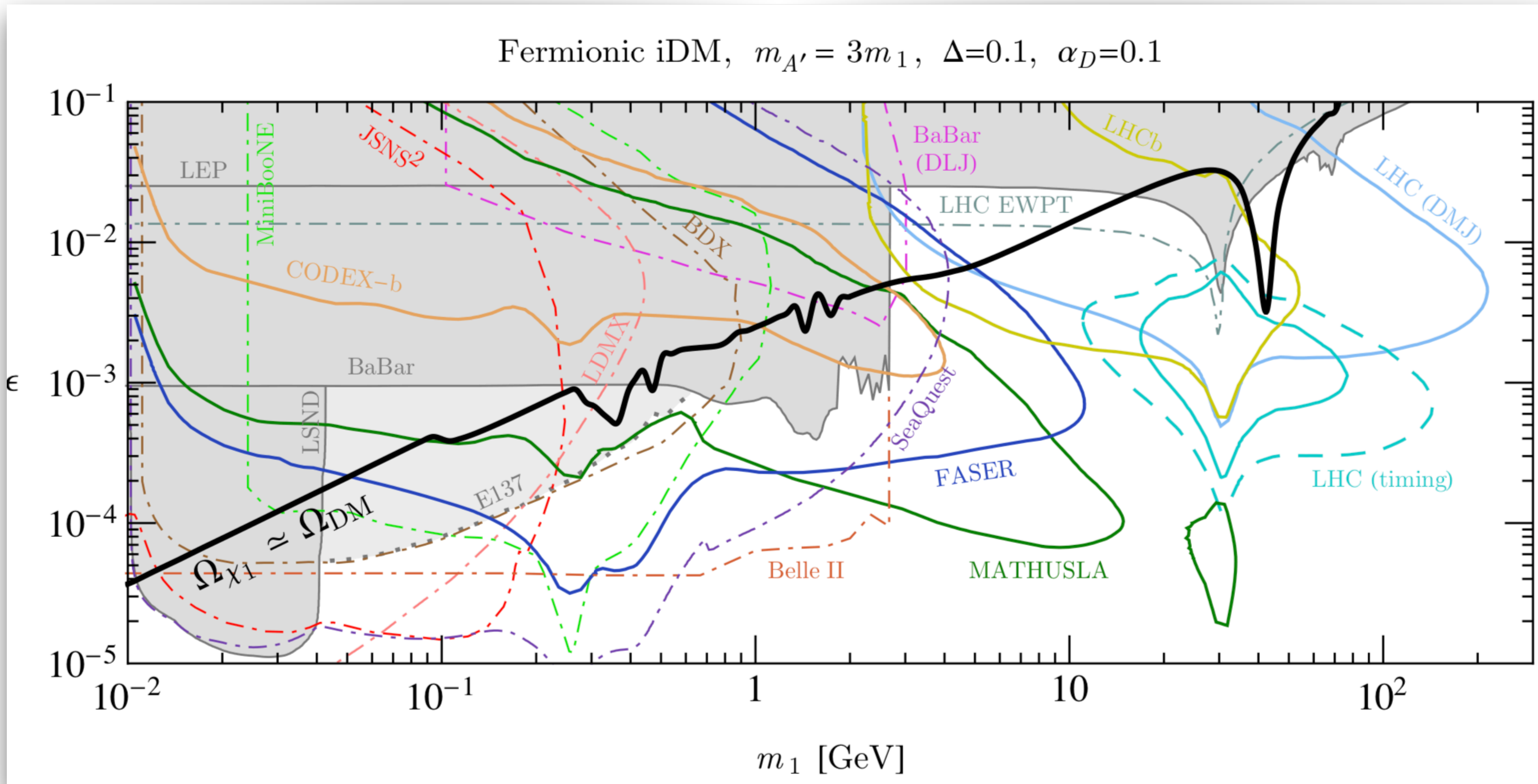


$$\sigma \propto \frac{y}{m_{\mathrm{DM}}^2}, \quad y \equiv \epsilon^2\alpha_D\left(\frac{m_{\mathrm{DM}}}{m_{A'}}\right)^4$$

Snowmass contribution, Akesson et al., 2203.08192



IDMs at high intensity and high energy



Berlin, Kling, 1810.01879