Cosmic Visions: Dark Matter

Philip Schuster (SLAC)

45th SLAC Summer Institute
August 18, 2017

My thoughts on exciting new directions in dark matter science…from the perspective of a particle theorist

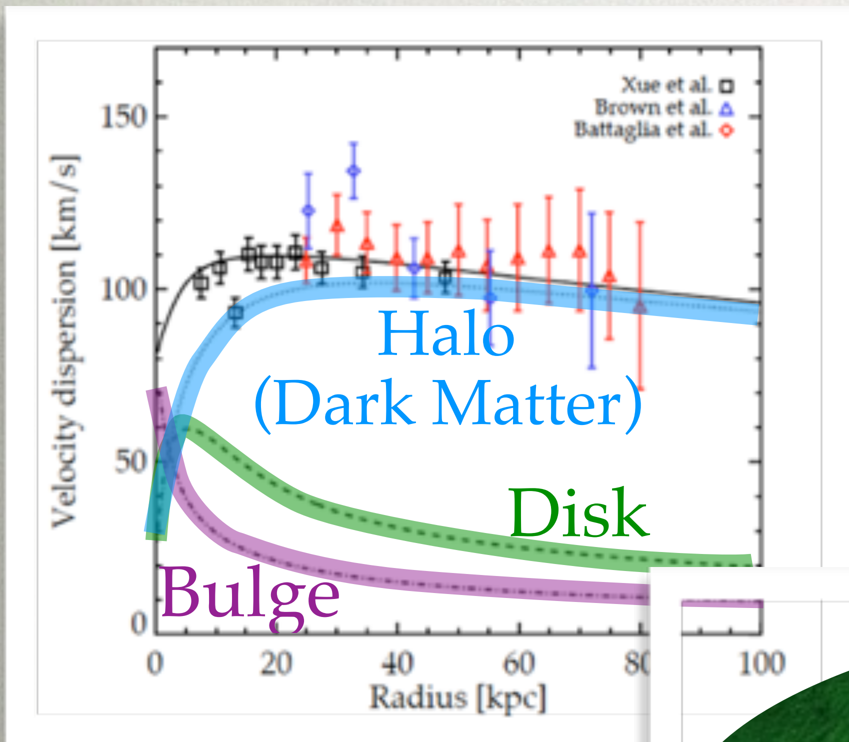
The New Era of Elementary Physics

What the Standard Model **is** has become increasingly sharp with the discovery of the Higgs

The challenge now is to **understand** how the SM fits into the grand scheme of things, and **what we are missing**

An era of exploration and rethinking basic questions...

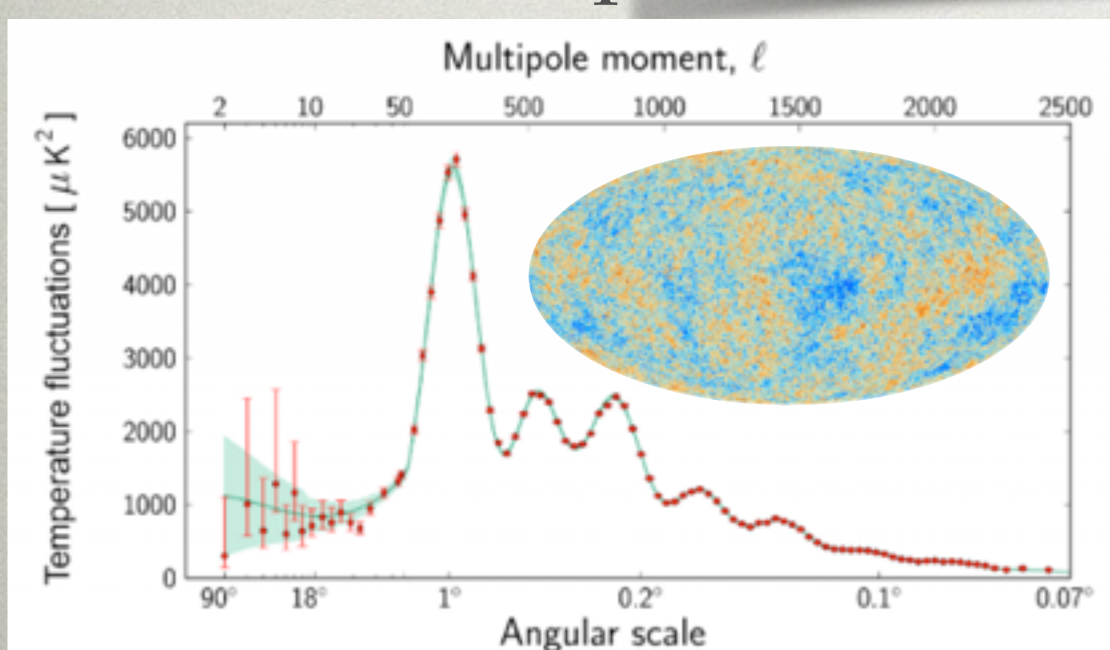
The Dark Sector



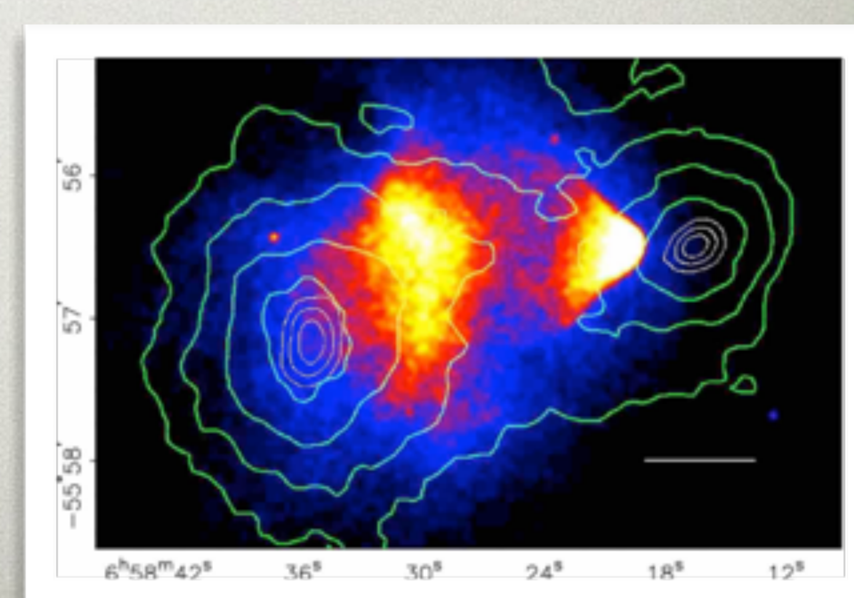
Rotation Curves

Gravitational lensing

CMB Power Spectrum



Cluster collisions



Dark Sector Science

There is new matter to discover and understand:

What is it?

Where did it come from?

How does it interact?

New forces?

Efforts to explore answers to these questions is still relatively young!

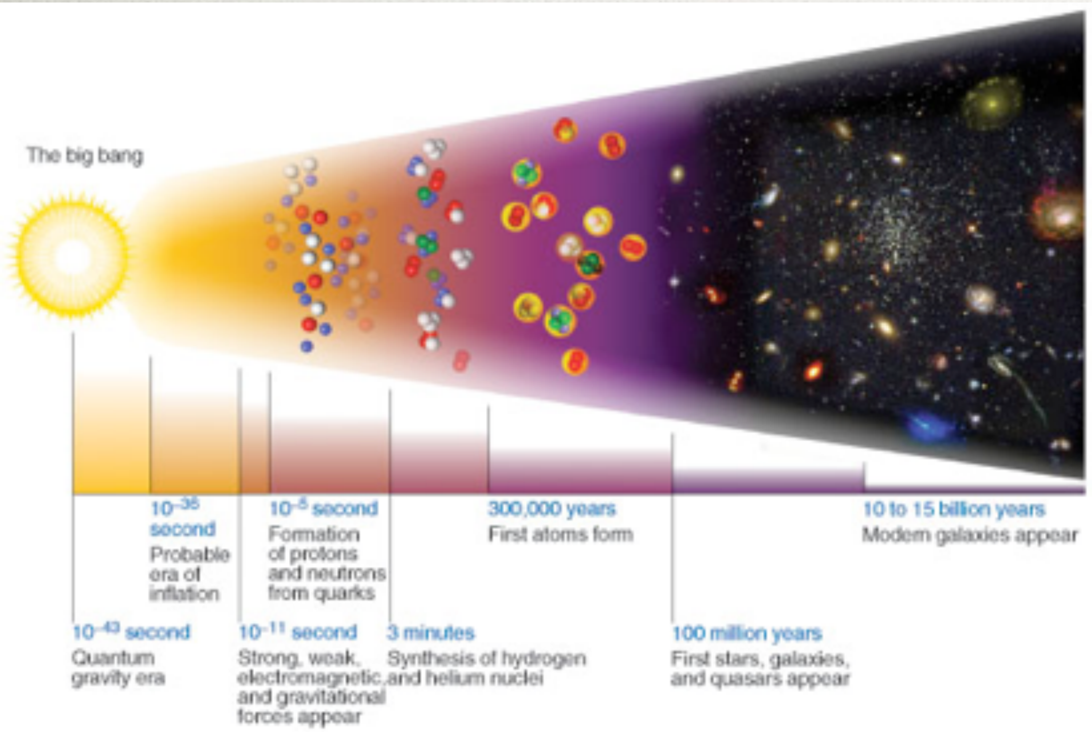
Dark Sector Science: Starting Points

A natural first guess is that dark matter is part of the solution to an existing Standard Model puzzle

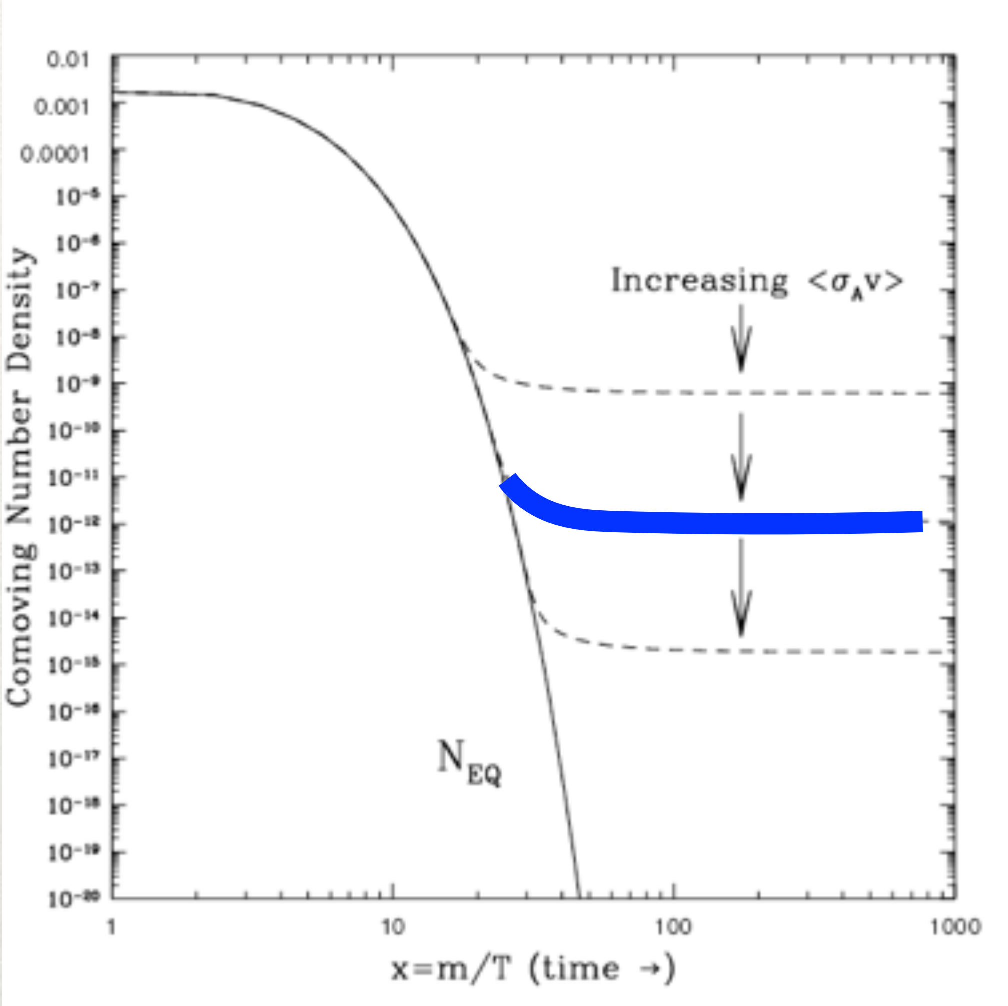
- **Hierarchy problem and weak-scale physics**

- The strong CP problem, neutrino masses, baryon asymmetry…etc

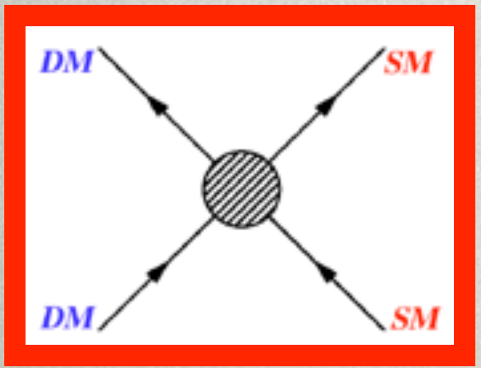
WIMPs and a Thermal Origin?



Eventually dark matter particles can't find each other to annihilate



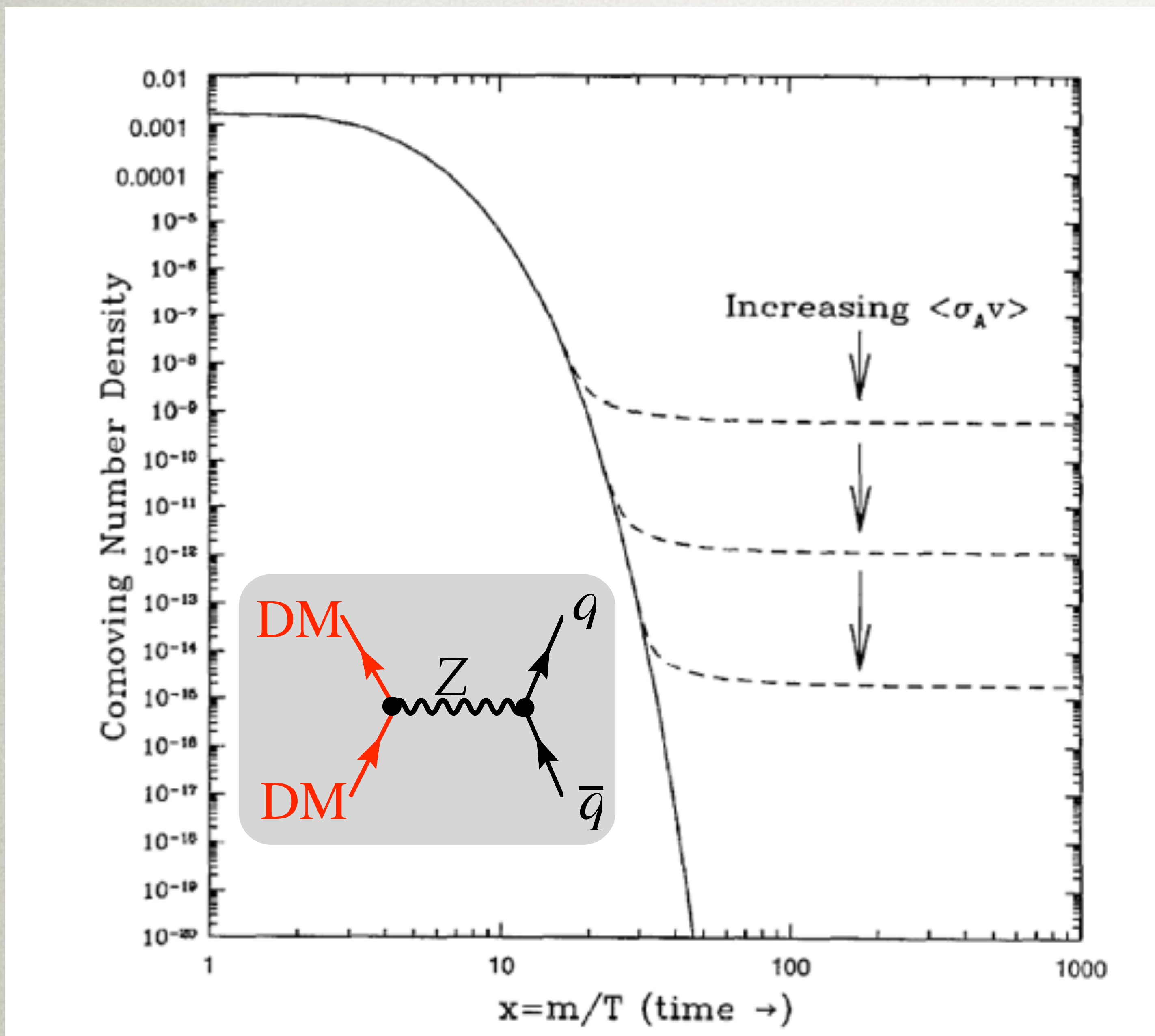
As Universe cools below DM mass, density decreases as $e^{-m/T}$



Dark Matter interacts with SM to stay in equilibrium…

and a (minimal) DM abundance is left over to the present day

WIMPs and a Thermal Origin?



Larger cross-section
⇒ later freeze-out
⇒ lower density

Correct DM density for:

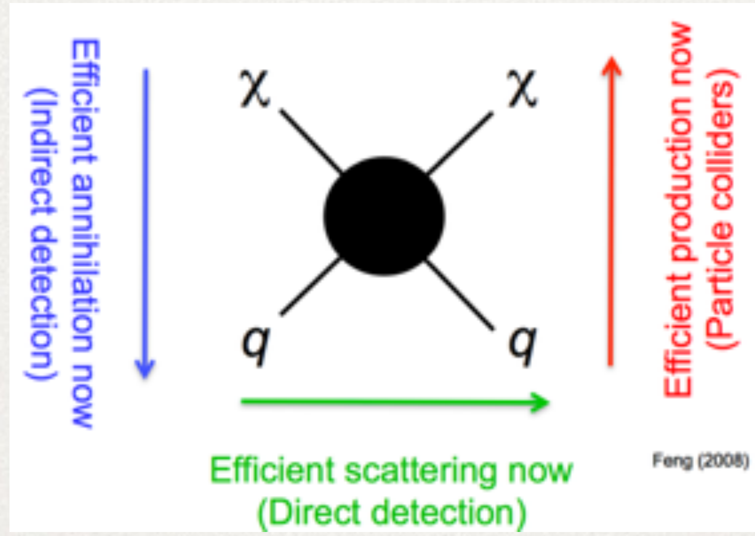
$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

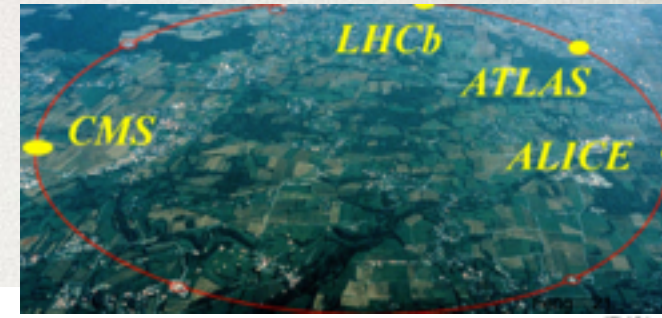
$$\simeq \frac{1}{(20\ \mathrm{TeV})^2}$$

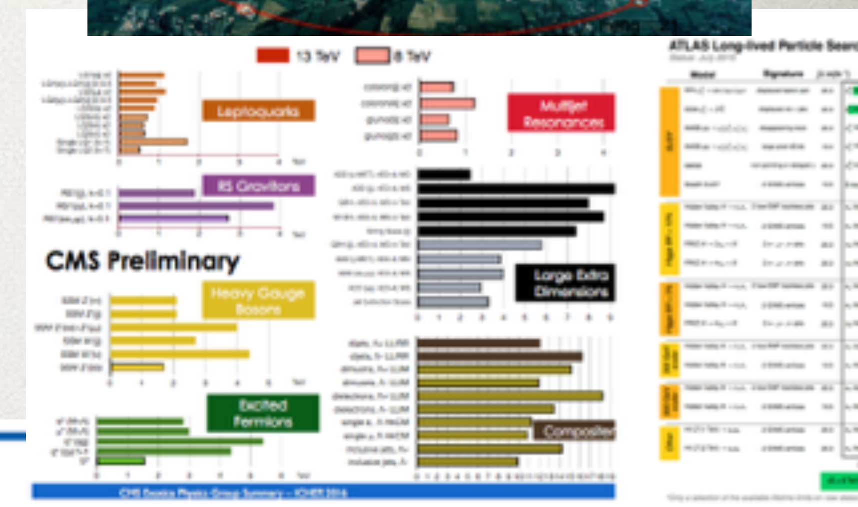
Thermal origin suggests <u>Dark Sector interactions</u> and mass in the vicinity of the weak-scale

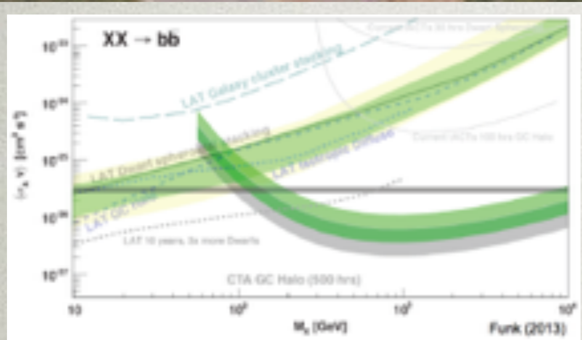
THE WIMP SEARCH EFFORT

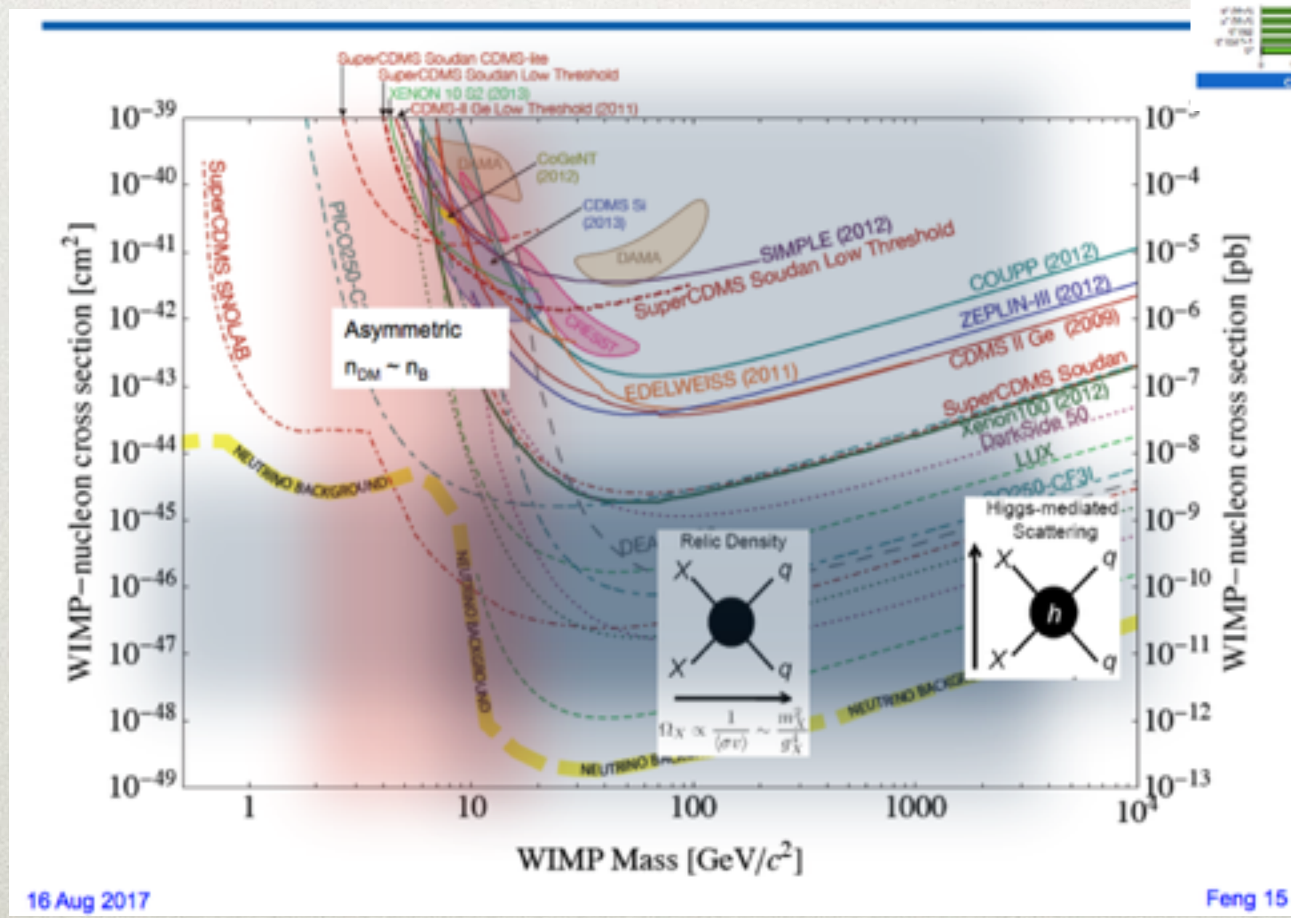
See overview talks by
Jonathan Feng and Sarah Eno











Powerful sensitivity over broad range of mass!

Compelled to Move Beyond WIMPs

Basic weak-scale DM scenarios have been significantly constrained by the LHC, direct & indirect detection

Existing experimental program will corner remaining WIMP models over the next few years

What are we missing?

First Steps Beyond WIMPs

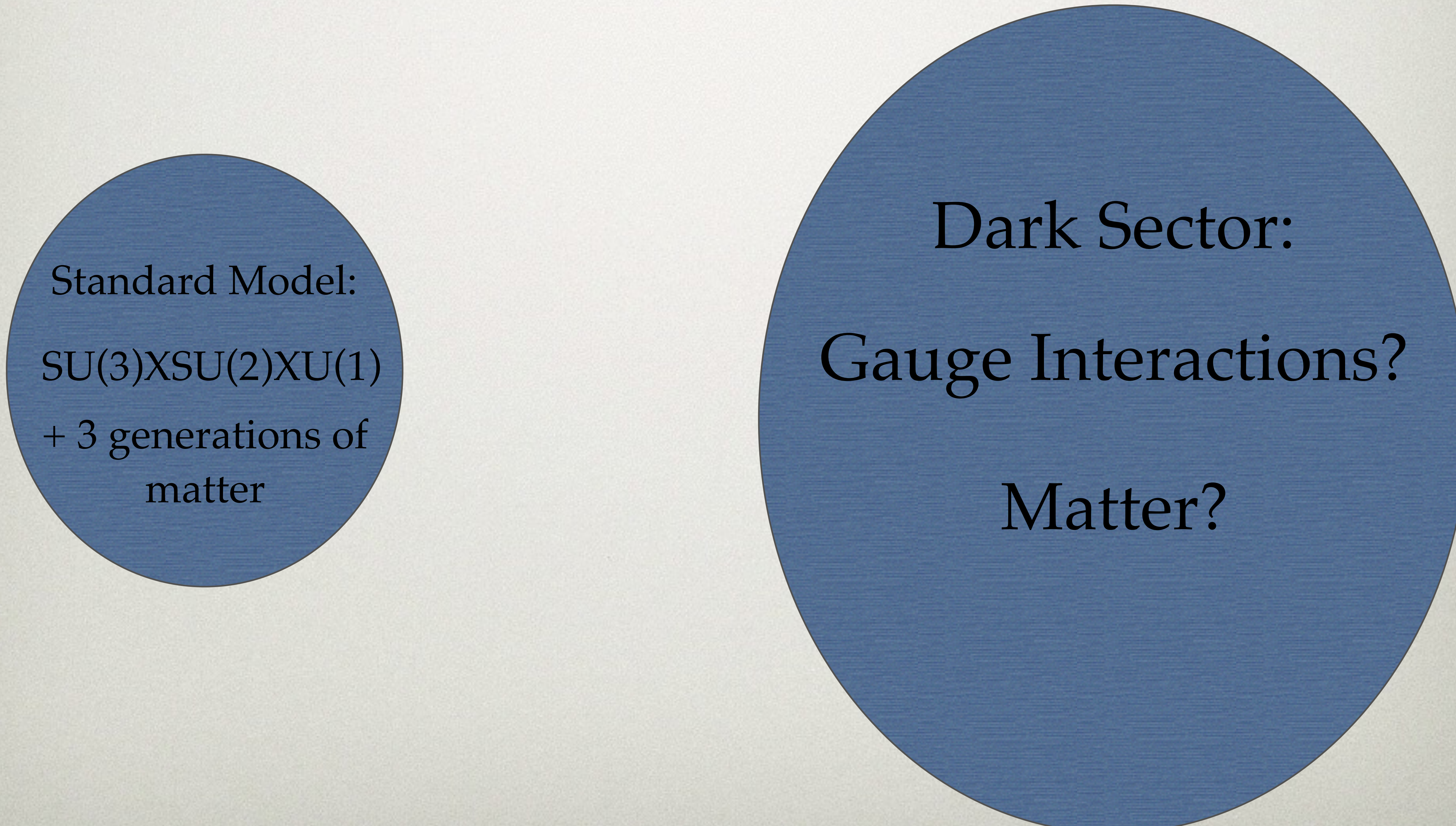
Thermal origin is a simple and compelling idea for the origin of dark matter

No need to toss out all of the nice and simple features of WIMPs

Natural first step exploring beyond WIMPs is to ask what kinds of models realize a thermal freeze-out origin

First Steps Beyond WIMPs

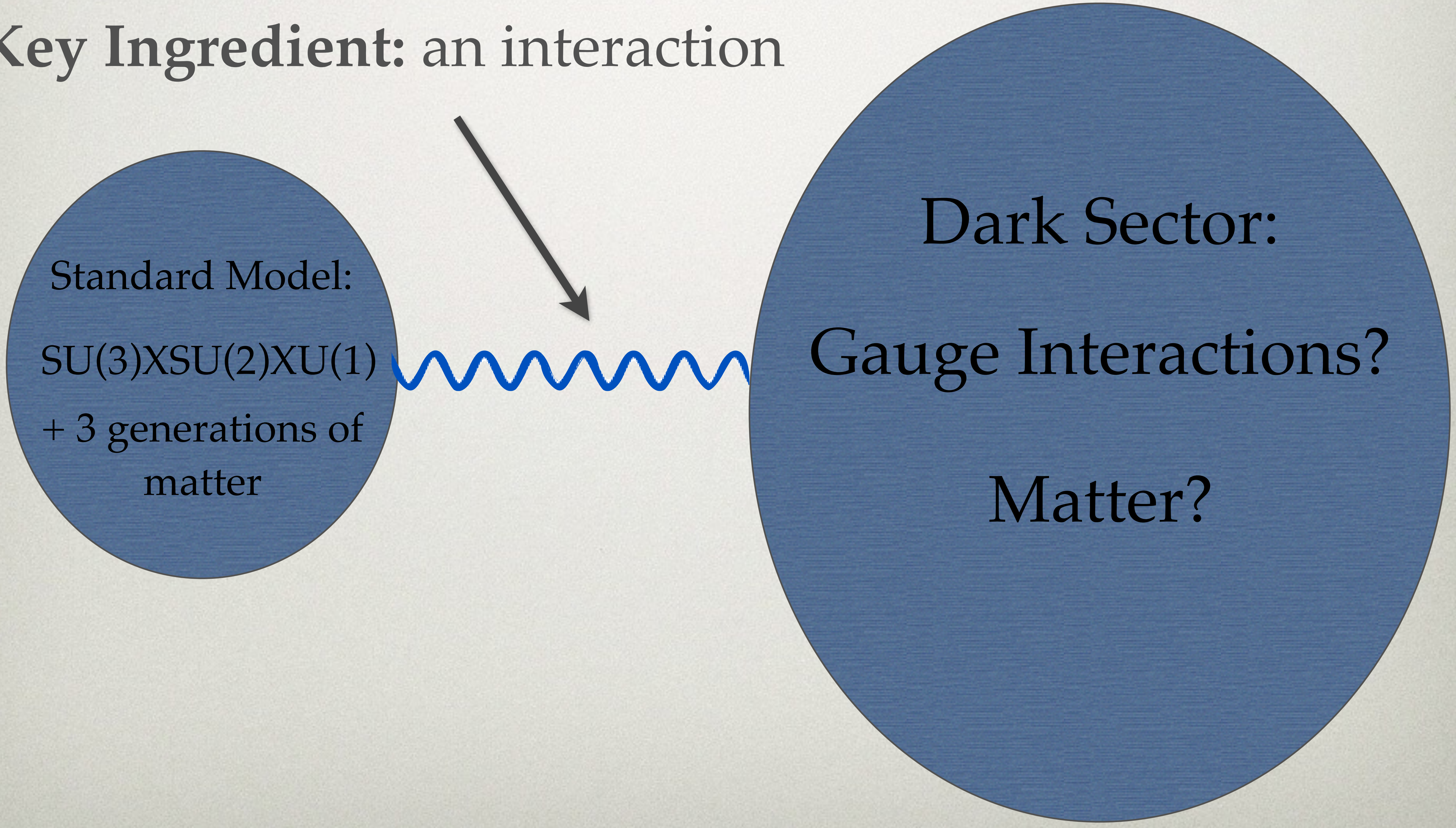
Natural next guess beyond a WIMP is that dark matter belongs to a genuinely new sector of interactions and matter!



First Steps Beyond WIMPs

Dark matter can still have a thermal origin!

Key Ingredient: an interaction



Three Interaction Types

Only three sizeable (i.e. not mass suppressed) interactions allowed by Standard Model symmetries:

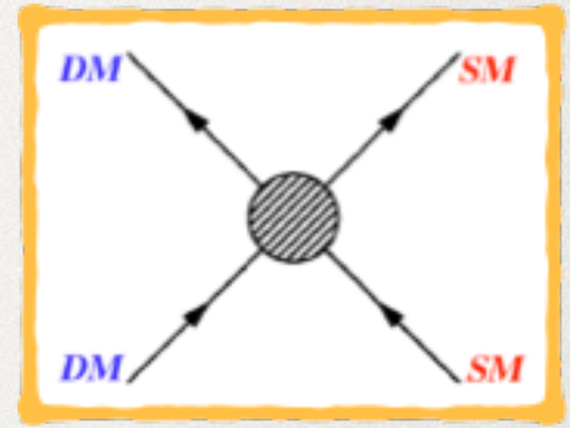
Least constrained for thermal dark matter

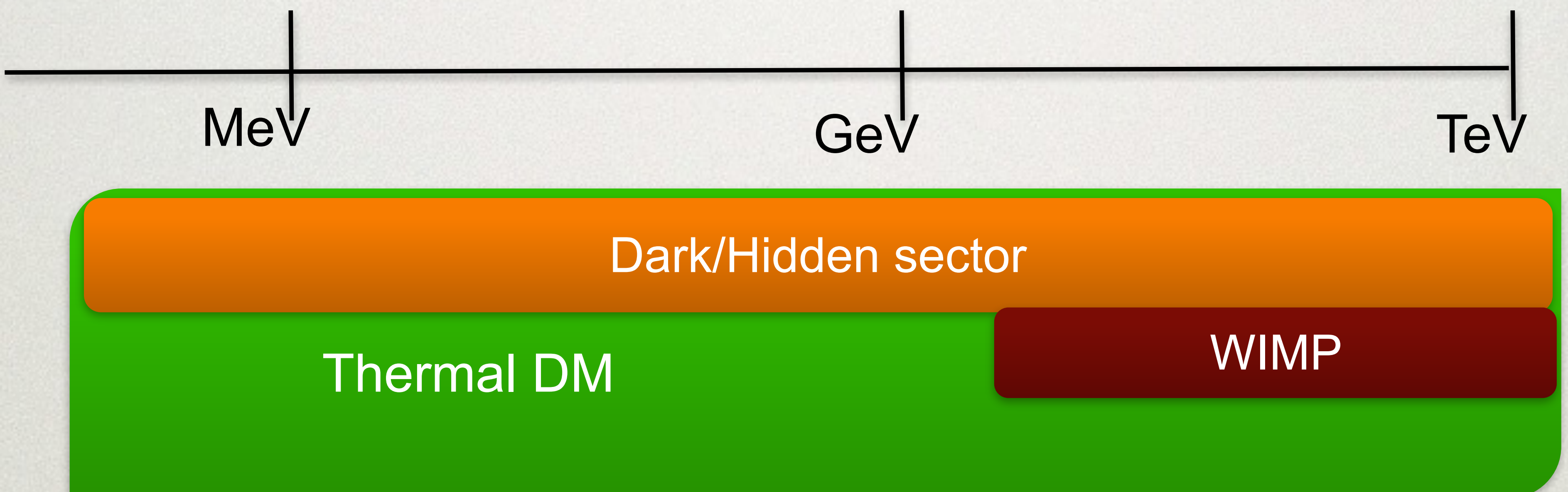
Vector Mixing	$\frac{1}{2}\epsilon_Y\, F^Y_{\mu\nu} F'^{\mu\nu}$	Very weakly coupled forces
Higgs Mixing	$\epsilon_h\, \lvert h\rvert^2 \lvert\phi\rvert^2$	exotic rare Higgs decays rare meson decays
Neutrino Mixing	$\epsilon_\nu\, (hL)\psi$	not-so-sterile neutrinos

All of these can be generated at a radiative level, so it's natural for these to be small...

Dark Sectors and Thermal Freeze-out

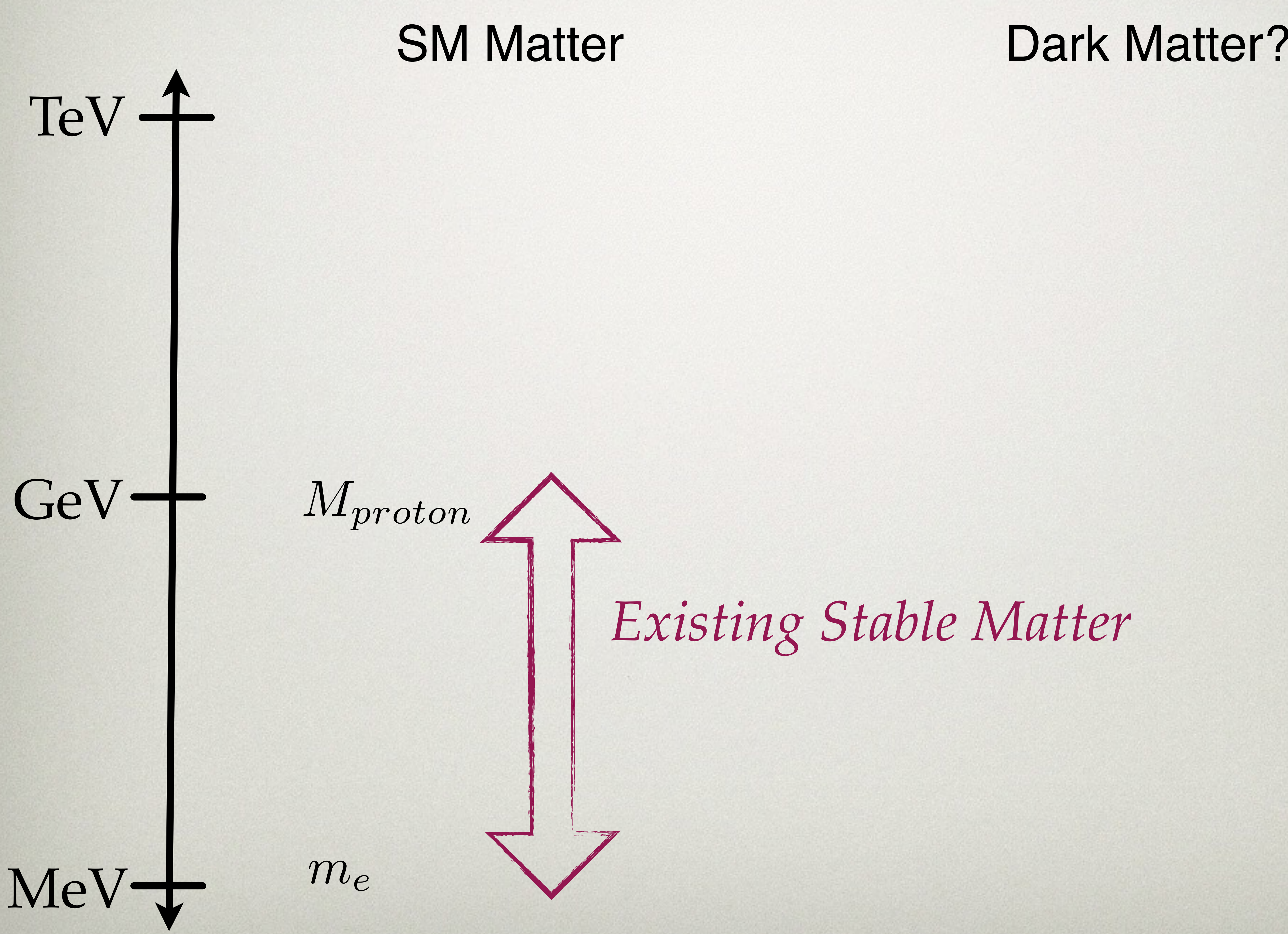
Interaction provides natural freeze-out channel into Standard Model final states



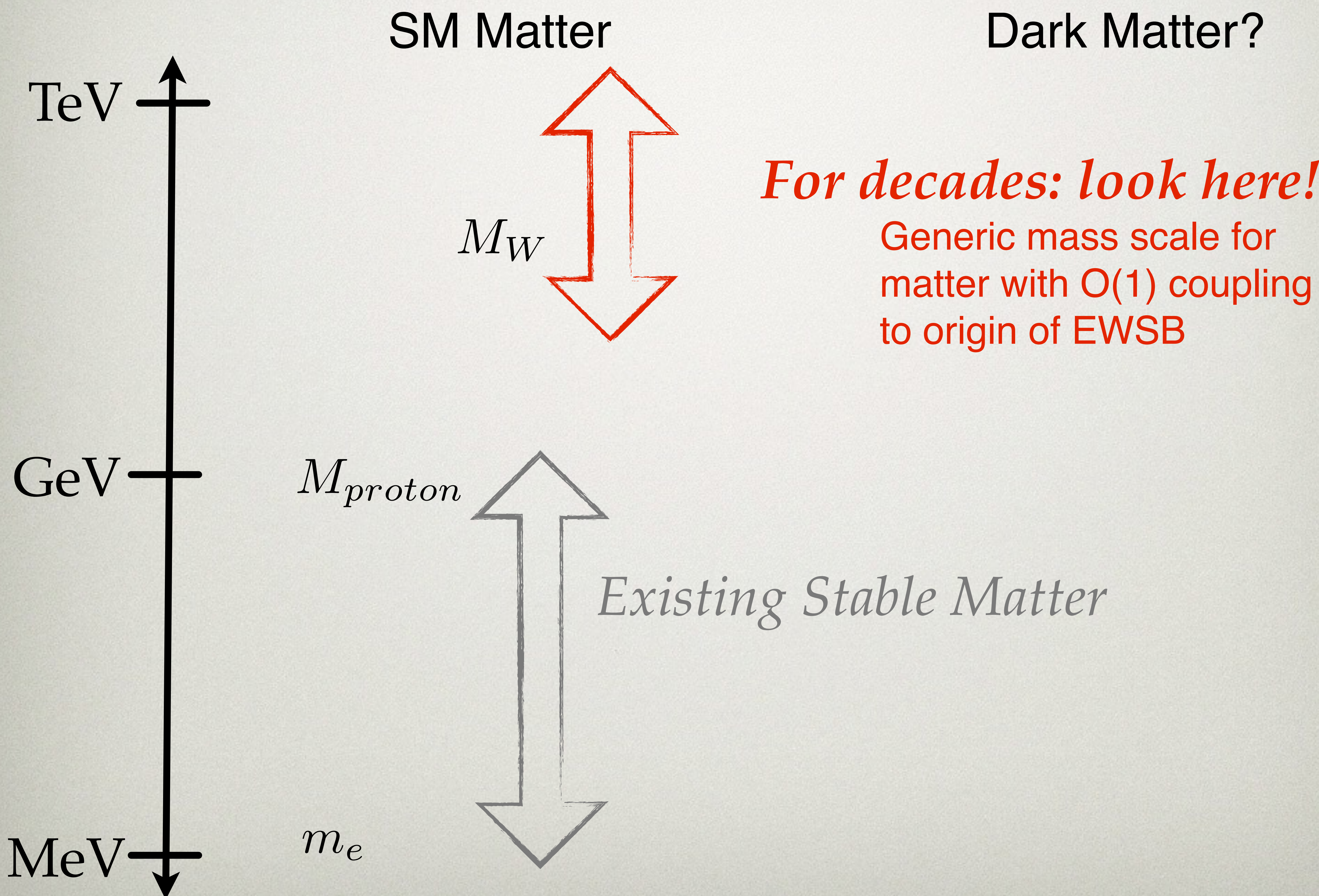


Thermal origin “dark sector” dark matter (with mediator) is viable over the entire MeV-TeV range!

Dark Sectors in the Vicinity of the Weak Scale



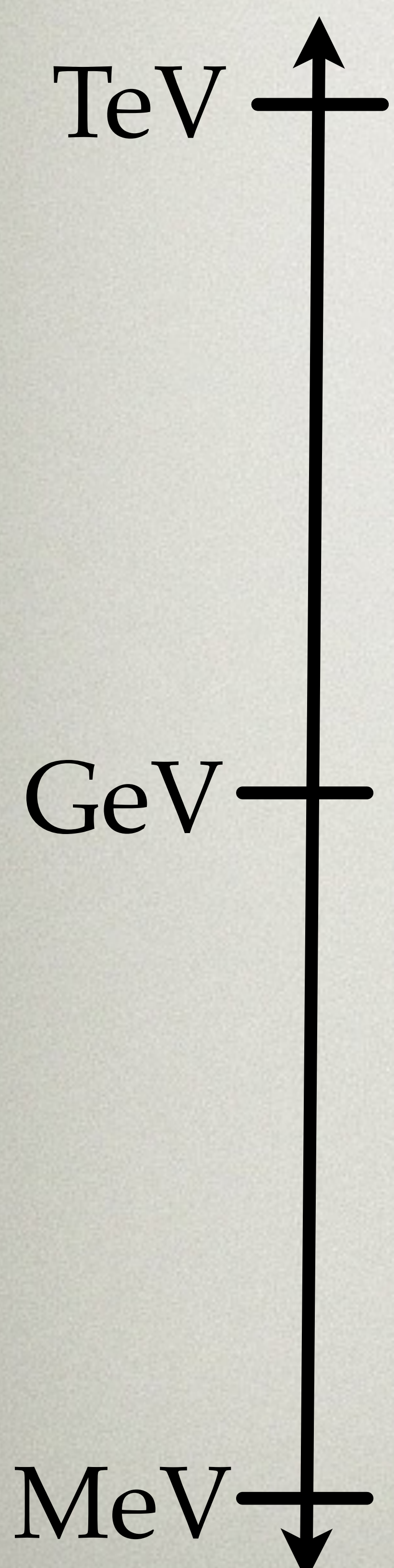
Dark Sectors in the Vicinity of the Weak Scale



Dark Sectors in the Vicinity of the Weak Scale

SM Matter

Dark Matter?



M_W

For decades: look here!

Generic mass scale for matter with O(1) coupling to origin of EWSB

$M_{proton} \sim M_{large} e^{-\#}$

(accidentally close to weak scale)

...but where do we expect hidden sector matter – with only small couplings to SM matter (generated radiatively)?

$m_e \sim \text{small}\ \# \times M_W$

(derived from weak scale)

Dark Sectors in the Vicinity of the Weak Scale

TeV

GeV

MeV

SM Matter

M_W

$M_{proton} \sim M_{large} e^{-\#}$

(accidentally close to weak scale)

$m_e \sim \text{small } \# \times M_W$

(derived from weak scale)

Dark Matter?

Generic mass scale for matter with O(1) coupling to origin of EWSB

Where do we expect hidden-sector matter?

(e.g. dark sector scalar mixing with SM higgs)

$\text{small } \# \times M_W$

Dark Sectors in the Vicinity of the Weak Scale

TeV

GeV

MeV

SM Matter

M_W

$M_{proton} \sim M_{large} e^{-\#}$

(accidentally close to weak scale)

$m_e \sim \text{small } \# \times M_W$

(derived from weak scale)

Dark Matter?

Generic mass scale for matter with O(1) coupling to origin of EWSB

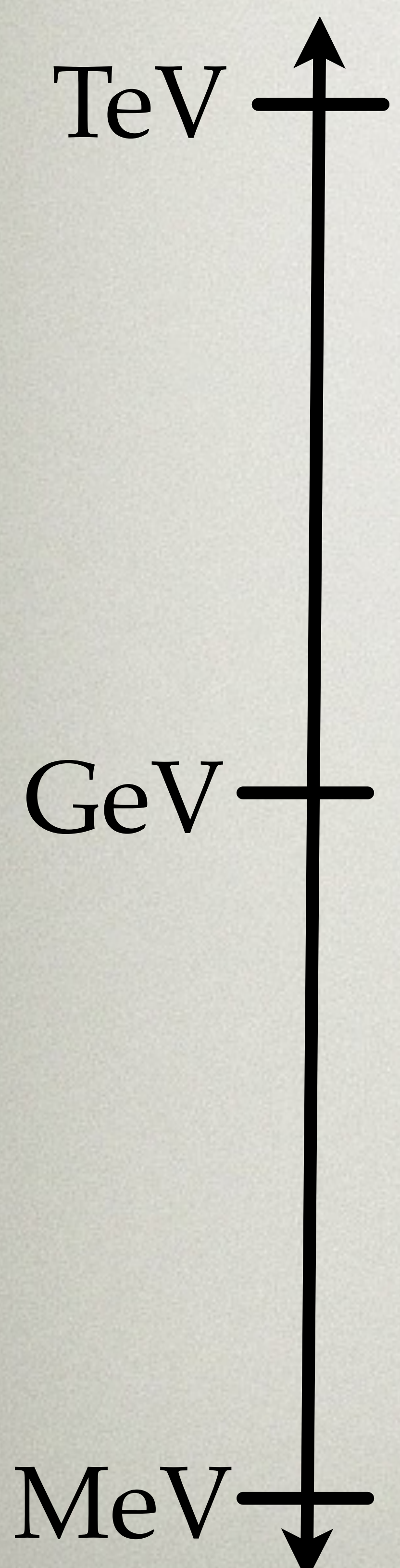
Where do we expect hidden-sector matter?

$\sim M_W \times e^{-\#}$

(e.g. "hidden valley" scenario: ~conformal to weak scale, then confining)

$\text{small } \# \times M_W$

Dark Sectors in the Vicinity of the Weak Scale



SM Matter

M_W

$M_{proton} \sim M_{large} e^{-\#}$

(accidentally close to weak scale)

$m_e \sim \text{small } \# \times M_W$

(derived from weak scale)

Dark Matter?

Generic mass scale for matter with O(1) coupling to origin of EWSB

$\sim M_W \times e^{-\#}$

Look here for hidden-sector matter!

$\text{small } \# \times M_W$

Dark Sectors in the Vicinity of the Weak Scale

SM Matter

Dark Matter?

TeV

Moving beyond WIMPs, the <u>broad</u> vicinity of the weak scale is still an excellent place to focus on:

- **An important scale!**
- **Familiar stable matter resides here!**
- **Thermal DM works well here!**

GeV

MeV

(derived from weak scale)

A New Frontier

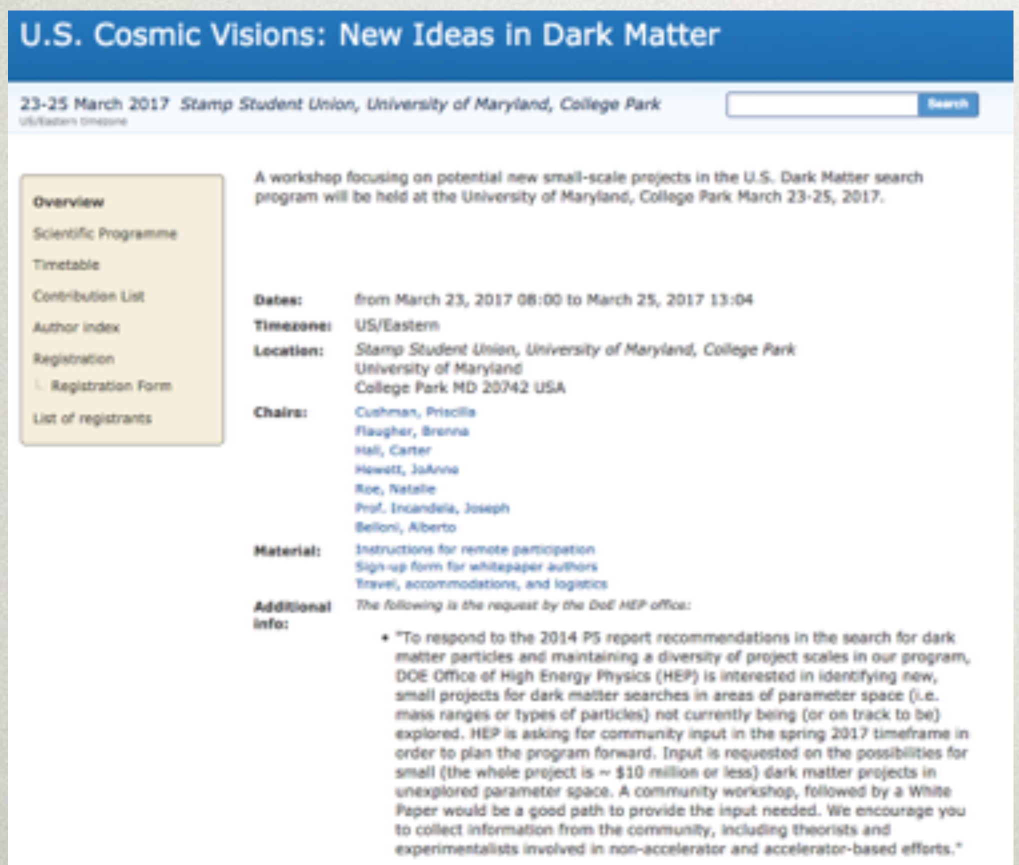
Extend sensitivity to "WIMP-like" Dark Matter in the sub-GeV Range? (light dark matter, LDM)

In a broader context, this frontier is one of two main pushes to generalize traditional dark matter scenarios, WIMPs & the QCD axion

Defining New Frontiers

Over the last few years, a strong science case for moving beyond WIMPs & axions has been put forth, and concepts for new small experiments have been proposed

See for example the U. Maryland Workshop
US Cosmic Visions: New Ideas in Dark Matter
https://indico.fnal.gov/conferenceDisplay.py?confId=13702



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

23-25 March 2017 *Stamp Student Union, University of Maryland, College Park*

US/Eastern timezone

Search

- Overview
- Scientific Programme
- Timetable
- Contribution List
- Author index
- Registration
  - Registration Form
- List of registrants

A workshop focusing on potential new small-scale projects in the U.S. Dark Matter search program will be held at the University of Maryland, College Park March 23-25, 2017.

Dates: from March 23, 2017 08:00 to March 25, 2017 13:04

Timezone: US/Eastern

Location: *Stamp Student Union, University of Maryland, College Park*
University of Maryland
College Park MD 20742 USA

Chairs: Cushman, Priscilla
Flaugher, Brenna
Hall, Carter
Hewett, JoAnne
Roe, Natalie
Prof. Incandela, Joseph
Belloni, Alberto

Material: Instructions for remote participation
Sign-up form for whitepaper authors
Travel, accommodations, and logistics

Additional info: *The following is the request by the DoE HEP office:*

- "To respond to the 2014 P5 report recommendations in the search for dark matter particles and maintaining a diversity of project scales in our program, DOE Office of High Energy Physics (HEP) is interested in identifying new, small projects for dark matter searches in areas of parameter space (i.e. mass ranges or types of particles) not currently being (or on track to be) explored. HEP is asking for community input in the spring 2017 timeframe in order to plan the program forward. Input is requested on the possibilities for small (the whole project is ~ $10 million or less) dark matter projects in unexplored parameter space. A community workshop, followed by a White Paper would be a good path to provide the input needed. We encourage you to collect information from the community, including theorists and experimentalists involved in non-accelerator and accelerator-based efforts."

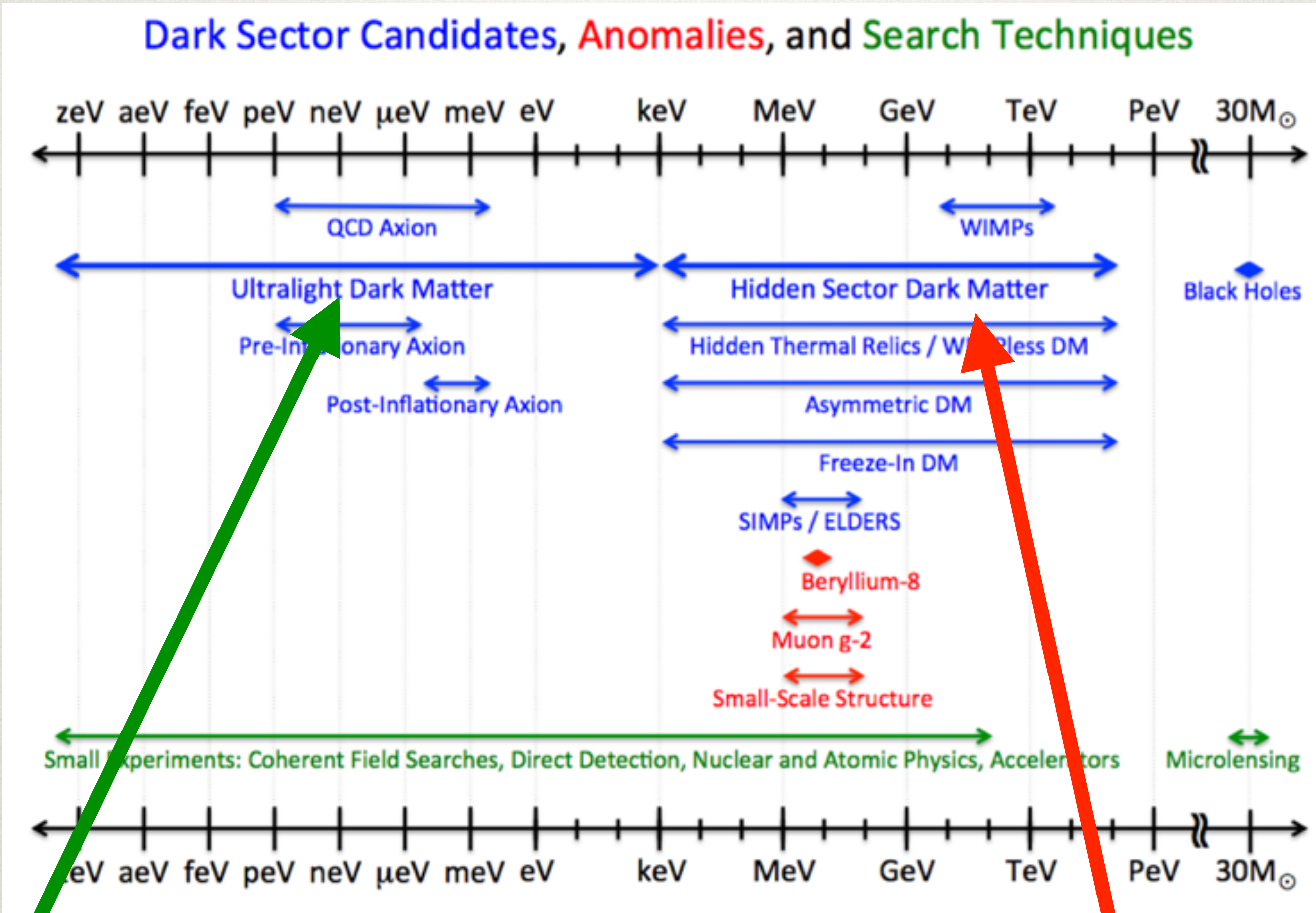
US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng (WG4 Convener),[7] Brenna Flaugher (Coordinator),[3] Patrick J. Fox (WG4 Convener),[3] Peter Graham (WG2 Convener),[8] Carter Hall (Coordinator),[2] Roni Harnik (SAC member),[3] JoAnne Hewett (Coordinator),[9,8] Joseph Incandela (Coordinator),[10] Eder Izaguirre (WG3 Convener),[11] Daniel McKinsey (WG1 Convener),[12] Matthew Pyle (SAC member),[12] Natalie Roe (Coordinator),[13] Gray Rybka (SAC member),[14] Pierre Sikivie (SAC member),[15] Tim M.P. Tait (SAC member),[7] Natalia Toro (SAC co-chair),[9,16] Richard Van De Water (SAC member),[17] Neal Weiner (SAC member),[18] Kathryn Zurek (SAC member),[13,12] Eric Adelberger,[14] Andrei Afanasev,[19] Derbin Alexander,[20] James Alexander,[21] Vasile Cristian Antochi,[22] David Mark Asner,[23] Howard Baer,[24] Dipanwita Banerjee,[25] Elisabetta Baracchini,[26] Phillip Barbeau,[27] Joshua Barrow,[28] Noemie Bastidon,[29] James Battat,[30] Stephen Benson,[31] Asher Berlin,[9] Mark Bird,[32] Nikita Blinov,[9] Kimberly K. Boddy,[33] Mariangela Bondi,[34] Walter M. Bonivento,[35] Mark Boulay,[36] James Boyce,[37,31] Maxime Brodeur,[38] Leah Broussard,[39] Ranny Budnik,[40] Philip Bunting,[12] Marc Caffee,[41] Sabato Stefano Caiazza,[42] Sheldon Campbell,[7] Tongtong Cao,[43] Gianpaolo Carosi,[44] Massimo Carpinelli,[45,46] Gianluca Cavoto,[22] Andrea Celentano,[1] Jae Hyeok Chang,[6] Swapan Chattopadhyay,[3,47] Alvaro Chavarria,[48] Chien-Yi Chen,[49,16] Kenneth Clark,[50] John Clarke,[12] Owen Colegrove,[10] Jonathon Coleman,[51] David Cooke,[25] Robert Cooper,[52] Michael Crisler,[23,3] Paolo Crivelli,[25] Francesco D'Eramo,[53,54] Domenico D'Urso,[45,46] Eric Dahl,[29] William Dawson,[44] Marzio De Napoli,[34] Raffaella De Vita,[1] Patrick DeNiverville,[55] Stephen Derenzo,[13] Antonia Di Crescenzo,[56,57] Emanuele Di Marco,[58] Keith R. Dienes,[59,2] Milind Diwan,[11] Dongwi Handiipondola Dongwi,[43] Alex Drlica-Wagner,[3] Sebastian Ellis,[60] Anthony Chigbo Ezeribe,[61,62] Glennys Farrar,[18] Francesc Ferrer,[53] Enectali Figueroa-Feliciano,[64] Alessandra Filippi,[65] Giuliana Fiorillo,[66] Bartosz Fornal,[67] Arne Freyberger,[31] Claudia Frugiuele,[40] Cristian Galbiati,[68] Iftah Galon,[7] Susan Gardner,[69] Andrew Geraci,[70] Gilles Gerbier,[71] Mathew Graham,[9] Edda Gschwendtner,[72] Christopher Hearty,[73,74] Jaret Heise,[75] Reyco Henning,[76] Richard J. Hill,[16,3] David Hitlin,[5] Yonit Hochberg,[21,77] Jason Hogan,[8] Maurik Holtrop,[78] Ziqing Hong,[29] Todd Hossbach,[23] T. B. Humensky,[79] Philip Ilten,[80] Kent Irwin,[8,9] John Jaros,[9] Robert Johnson,[53] Matthew Jones,[41] Yonatan Kahn,[68] Narbe Kalantarians,[81] Manoj Kaplinghat,[7] Rakshya Khatiwada,[14] Simon Knapen,[13,12] Michael Kohl,[43,31] Chris Kouvaris,[82] Jonathan Kozaczuk,[83] Gordan Krnjaic,[3] Valery Kubarovsky,[31] Eric Kuflik,[21,77] Alexander Kusenko,[84,85] Rafael Lang,[41] Kyle Leach,[86] Tongyan Lin,[12,13] Mariangela Lisanti,[68] Jing Liu,[87] Kun Liu,[17] Ming Liu,[17] Dinesh Loomba,[88] Joseph Lykken,[3] Katherine Mack,[89] Jeremiah Mans,[4] Humphrey Maris,[90] Thomas Markiewicz,[9] Luca Marsicano,[1] C. J. Martoff,[91] Giovanni Mazzitelli,[26] Christopher McCabe,[92] Samuel D. McDermott,[6] Art McDonald,[71] Bryan McKinnon,[93] Dongming Mei,[87] Tom Melia,[13,85] Gerald A. Miller,[14] Kentaro Miuchi,[94] Sahara Mohammed Prem Nazeer,[43] Omar Moreno,[9] Vasiliy Morozov,[31]

Defining New Frontiers

See Figure 1 of arXiv: 1707.04591



See talks by Karl van Bibber and Peter Graham

This talk
Also see talk by Jonathan Feng, Matt Pyle, Natalia Toro,

A New Frontier

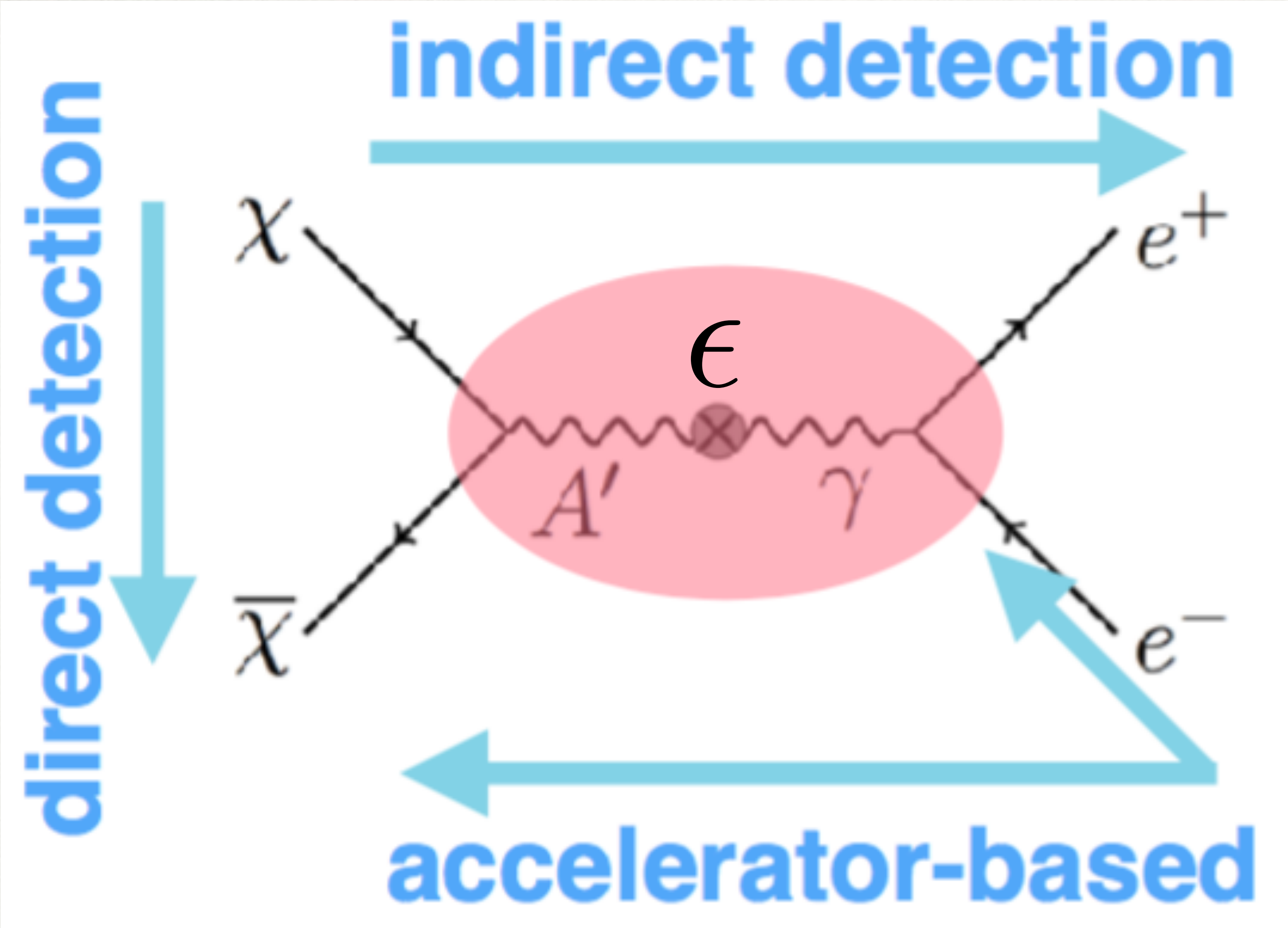
Extend sensitivity to "WIMP-like" Dark Matter in the sub-GeV Range? (light dark matter, LDM)

Need experiments that can explore the MeV-GeV "WIMP"-like scenarios, analogous to the Direct Detection, LEP, and LHC efforts to test WIMPs in the GeV-TeV range.

What are the experimental ingredients of a robust effort?

Look to the 30-yr WIMP effort for lessons.
Many similarities and a few critical differences…

WIMP & Thermal LDM Experimental Effort: Phenomenology Similarities



+ other modes

Experimental strategies similar to WIMP program, but new challenges and opportunities arise from the lower mass scales

WIMP & Thermal LDM Experimental Effort: Basic Model Similarities

Phenomenology of WIMP scenarios carries over to MeV-GeV WIMP-like scenarios:

Particle Type **Dark Matter Current** **Different Low-Energy Phenomenology!**

Model	Mass terms	J^μ_D	scattering $\mathcal{M} \propto$	scattering $\sigma \propto$	Annilhilation $\sigma v \propto$	CMB-viable?
Fermion DM – Direct Annihilation						
Majorana	$\not{U}(1)_D$	$\bar{\Psi}\gamma^\mu\gamma_5\Psi$	$\vec{\sigma}\cdot\vec{v}$	v^2	p-wave $\propto v^2$	Y
Dirac	$U(1)_D$-inv.	$\bar{\Psi}\gamma^\mu\Psi$	1	1	s-wave $\propto v^0$	N
Pseudo-Dirac	$U(1)_D$-inv. & $\not{U}(1)_D$	$\bar{\Psi}_L\gamma^\mu\Psi_H$	1 (inelastic)	kin. forbidden [a]	kin. forbidden	Y
Scalar DM – Direct Annihilation						
Complex	$U(1)_D$-inv.	$\phi^*\partial^\mu\phi - \phi\partial^\mu\phi^*$	1	1	p-wave $\propto v^2$	Y
Pseudo-complex	$U(1)_D$-inv. & $\not{U}(1)_D$	$\phi_L\partial^\mu\phi_H - \phi_H\partial^\mu\phi_L$	v^2 (inelastic)	kin. forbidden	kin. forbidden [b]	Y

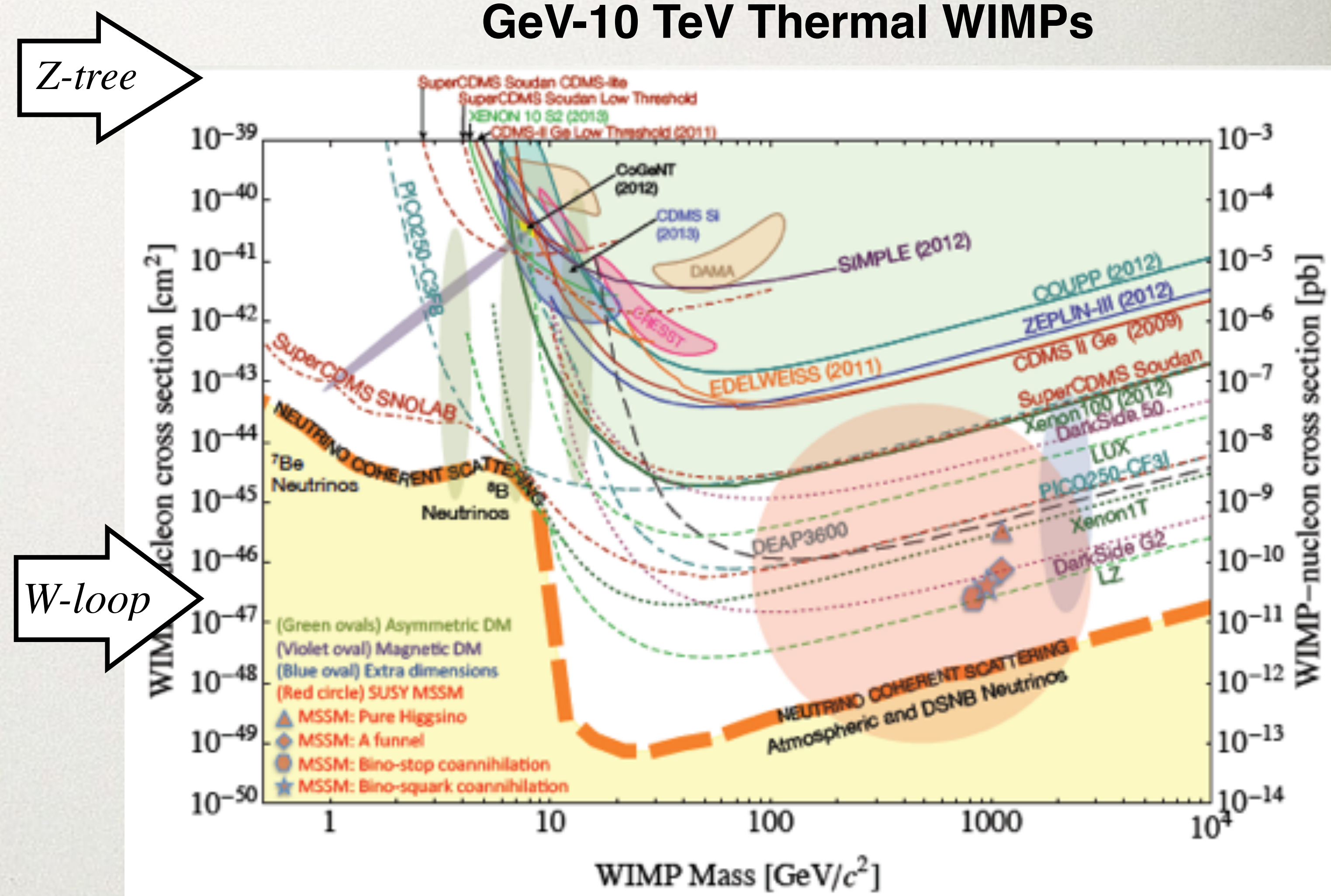
Just like neutralino WIMP candidates

Just like sneutrino or Dirac neutrino WIMP candidate

WIMP & Thermal LDM Experimental Effort: Direct Detection Similarities

Key Thermal Targets Span Large Range.

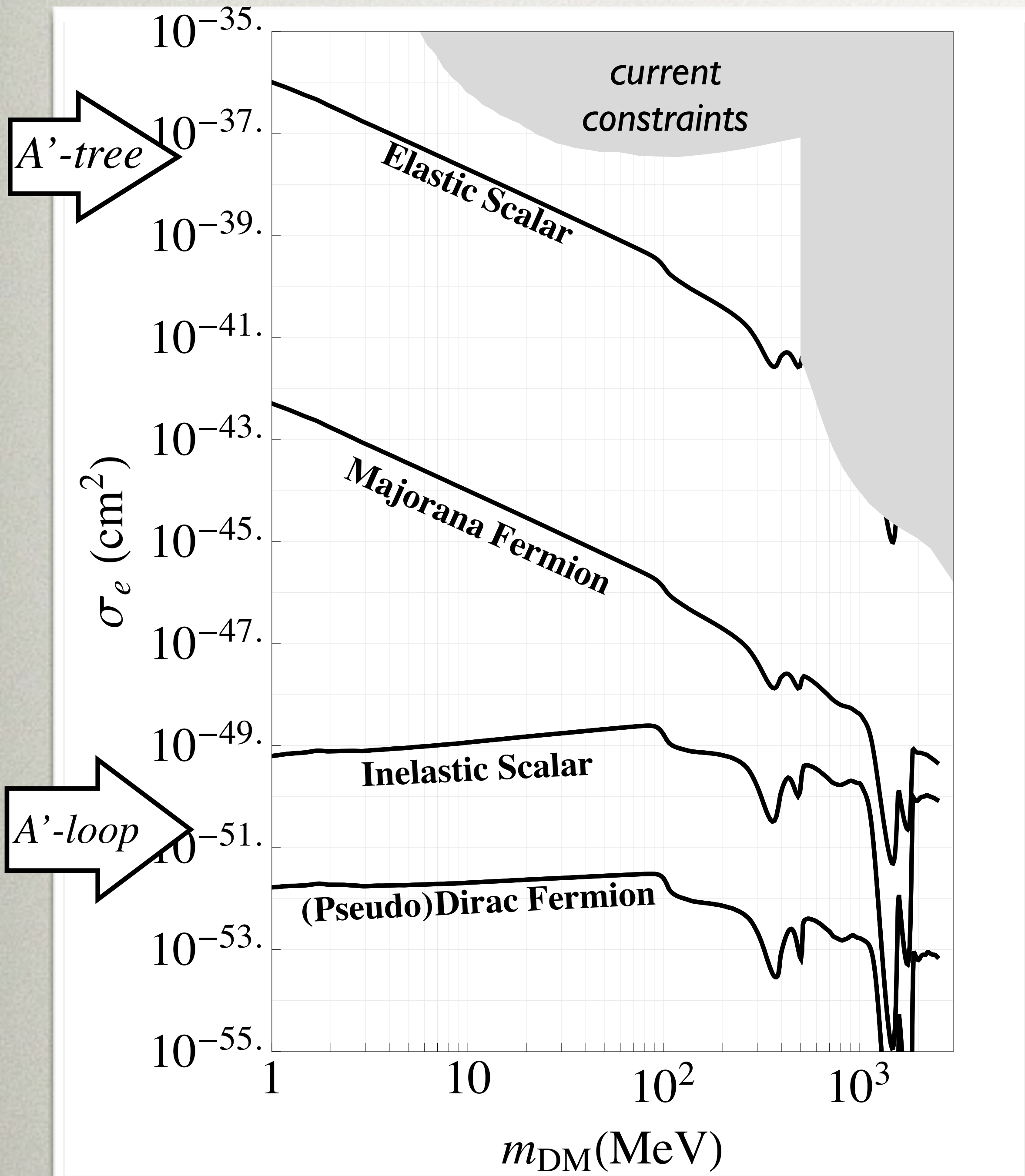
GeV-10 TeV Thermal WIMPs



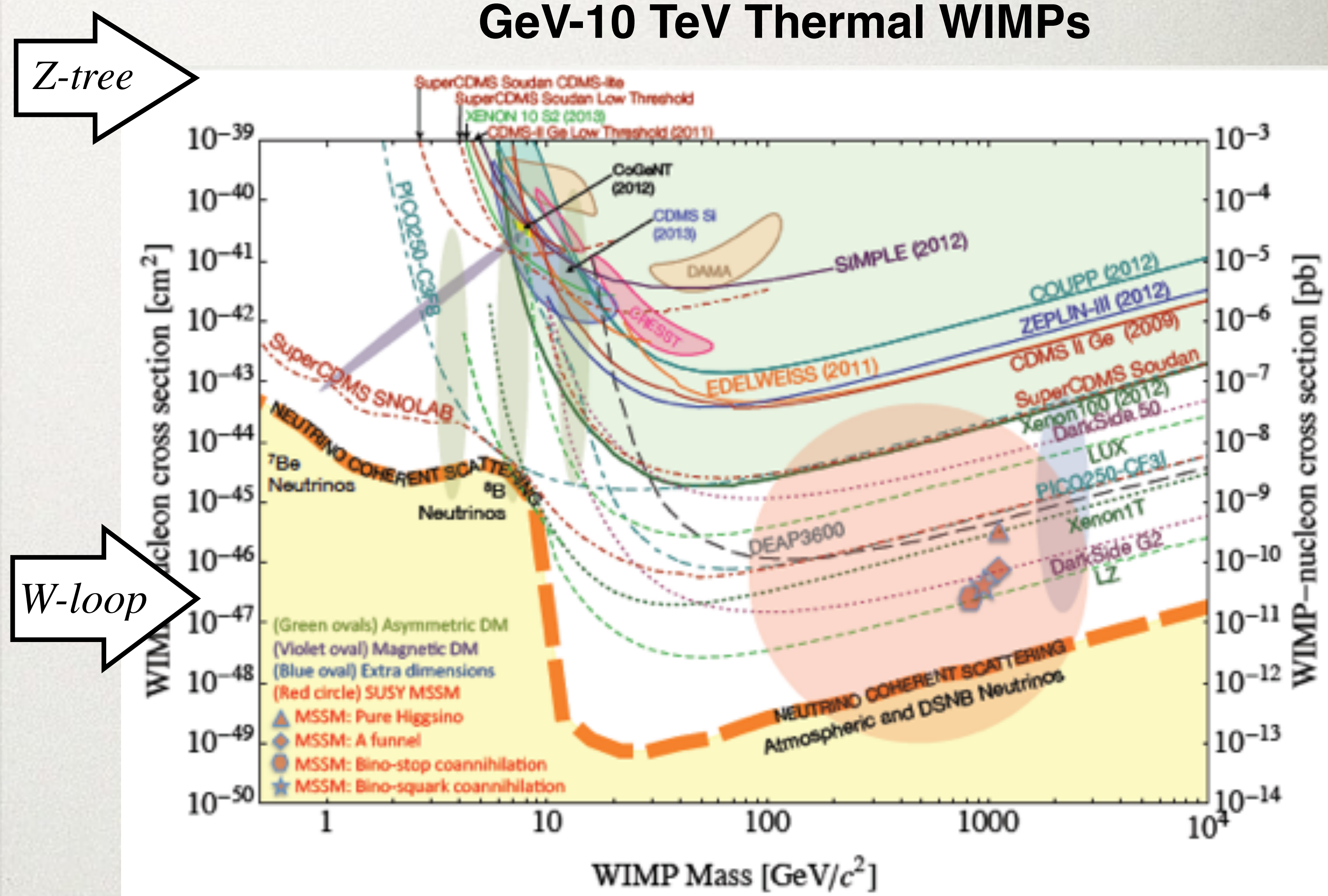
WIMP & Thermal LDM Experimental Effort: Direct Detection Similarities

Key Thermal Targets Span Large Range.

MeV-GeV Thermal LDM



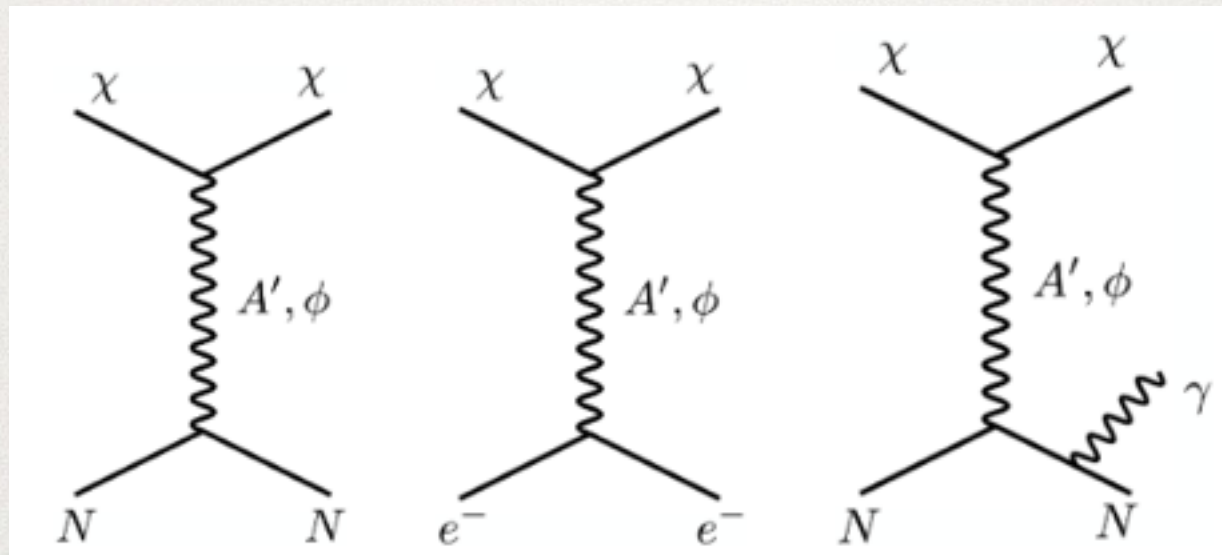
GeV-10 TeV Thermal WIMPs



Similar to WIMPs: thermal LDM motivates large range of direct detection cross-section

Direct Detection Challenges & Opportunities

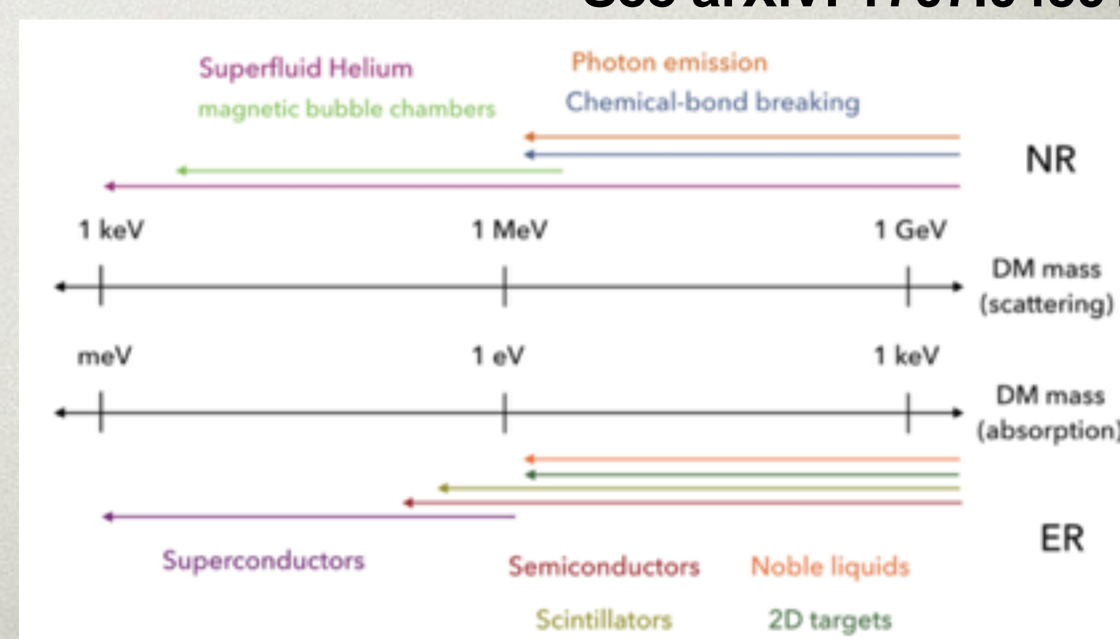
Basic difficulty: non-relativistic scattering of sub-GeV particles deposits eV-keV of energy



electron scattering has easiest to detect energy deposition

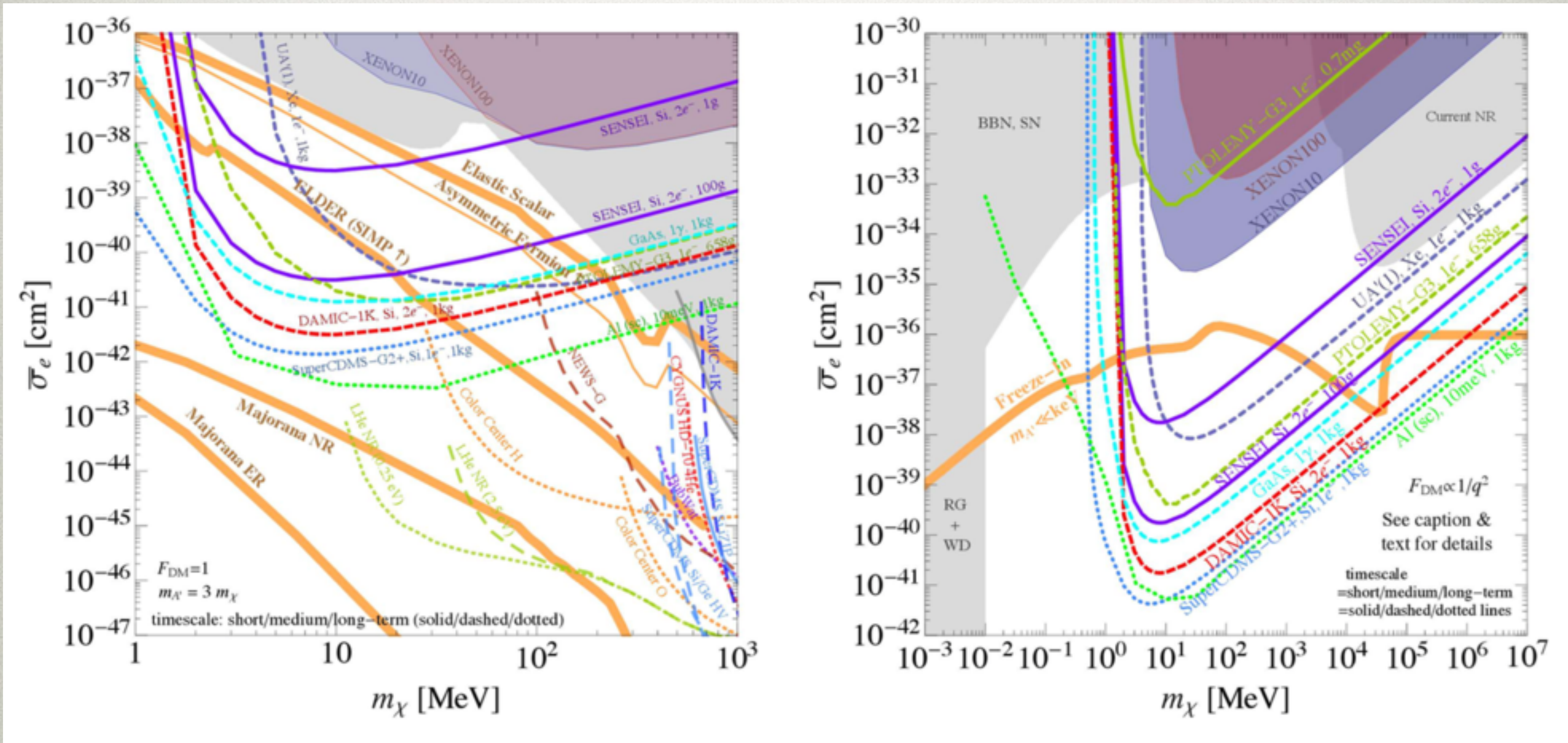
Range of technologies proposed to detect very low energy deposition of LDM scattering

See arXiv: 1707.04591



Direct Detection Challenges & Opportunities

See arXiv: 1707.04591



Excellent ideas for experiments to provide new sensitivity to LDM parameter space over the next 10 years

(many of them discussed in Matt Pyle's talk)

WIMP & Thermal LDM Experimental Effort: Radically Different Story for Accelerators

TeV-scale electro-weak states were not easily accessible to accelerators when WIMP effort started!

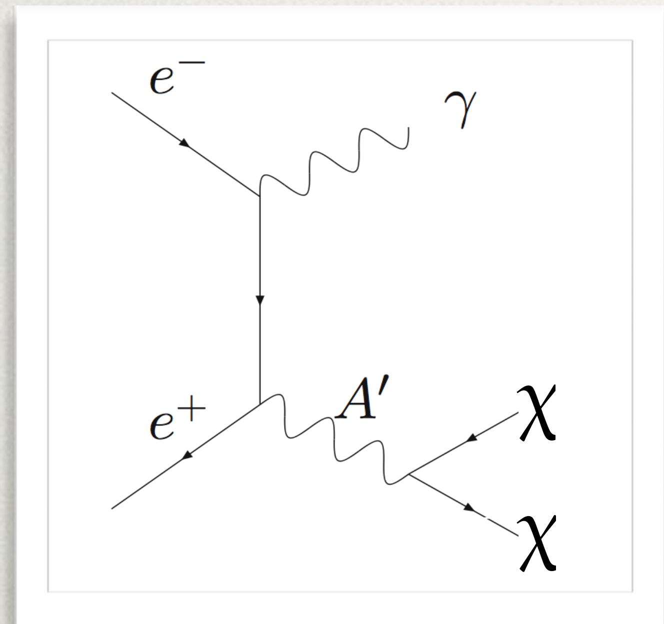
Decades of development of mid- to high-energy accelerator infrastructure and impressively powerful particle detector technology has now taken place...

Whereas sub-GeV weakly coupled particles readily accessible to accelerators

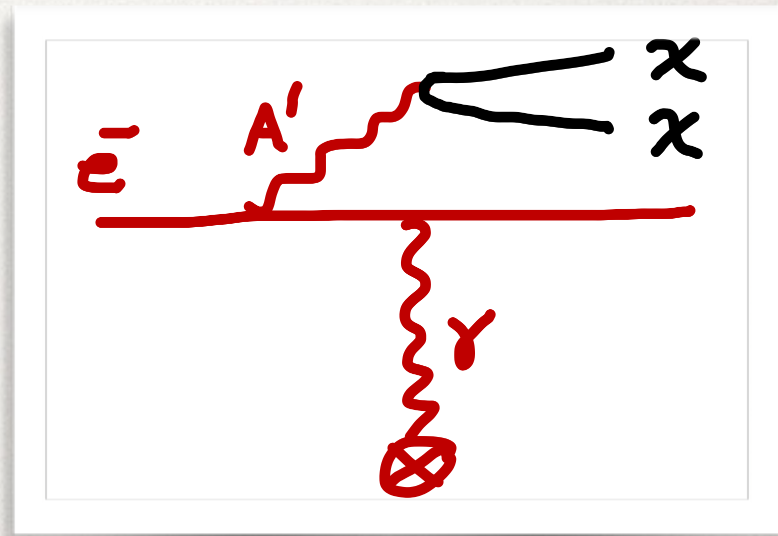
Accelerator Exp. Challenges & Opportunities

Easy to produce light dark matter

Collider production



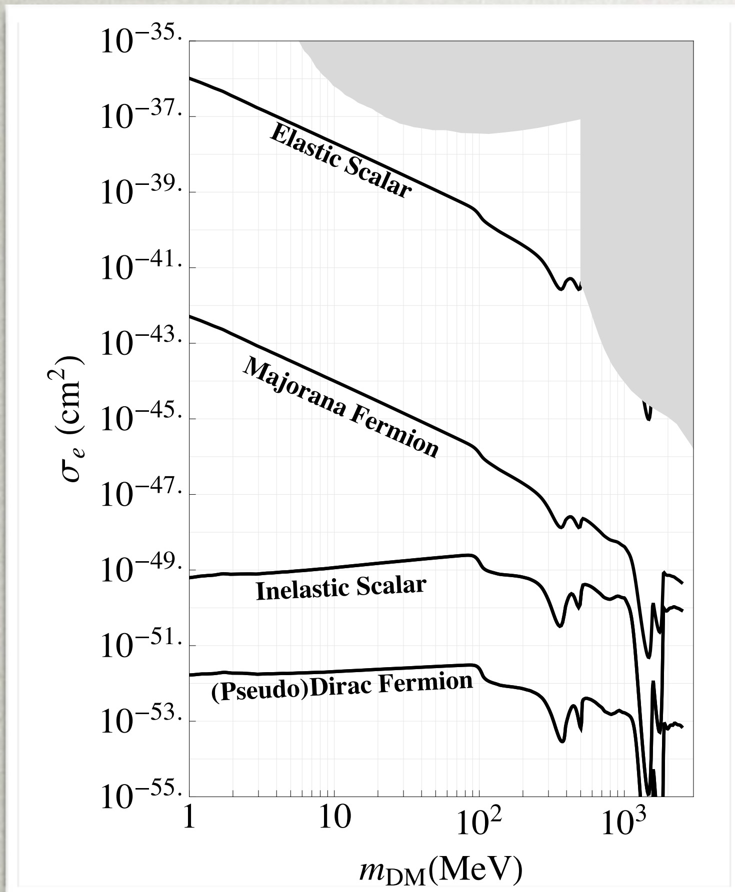
Fixed-Target production

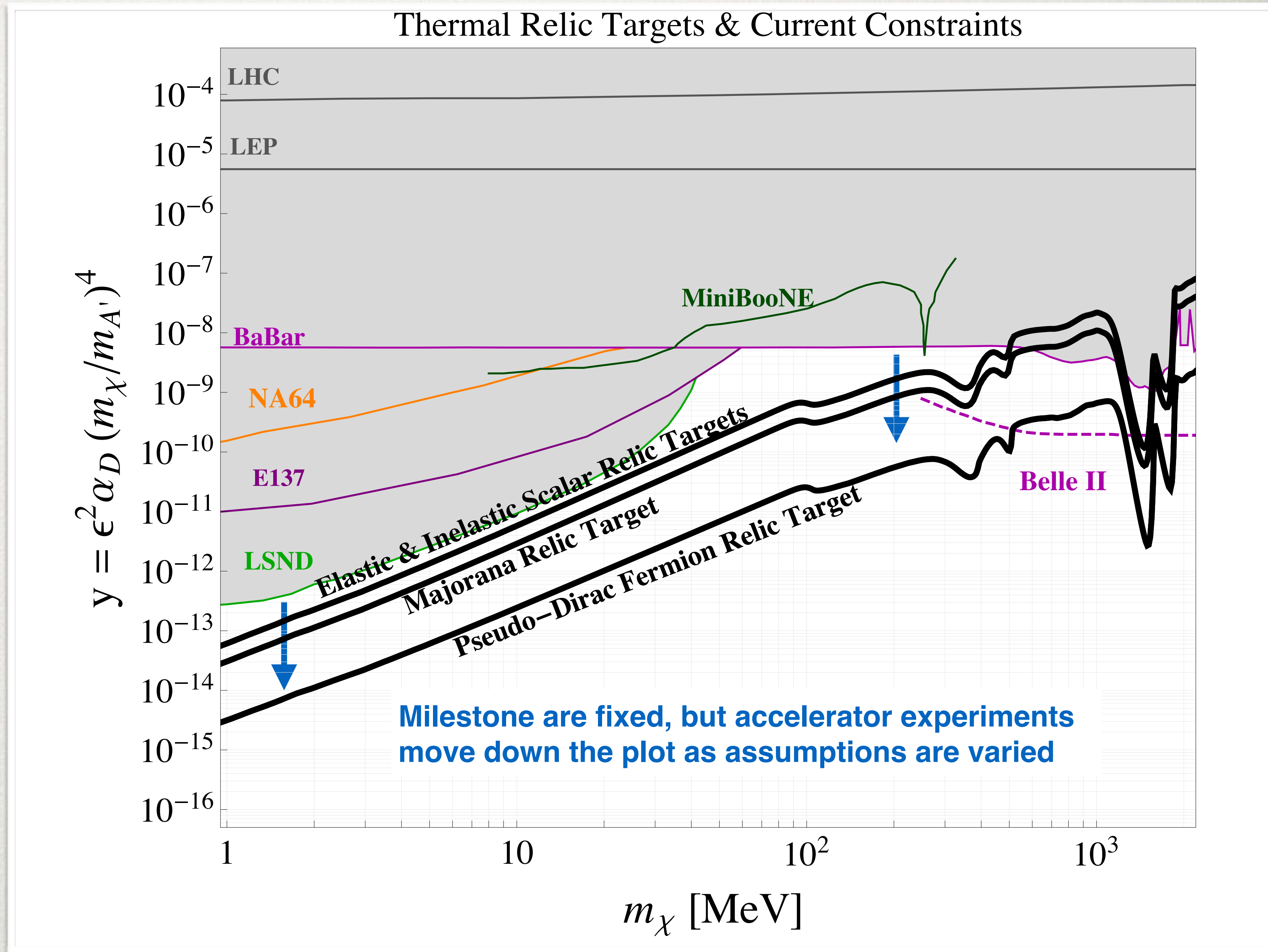


The challenge is isolating the production signature in a low background manner

But this is a well studied problem at this point!
(see talk by Natalia Toro)

Accelerator Exp. Challenges & Opportunities

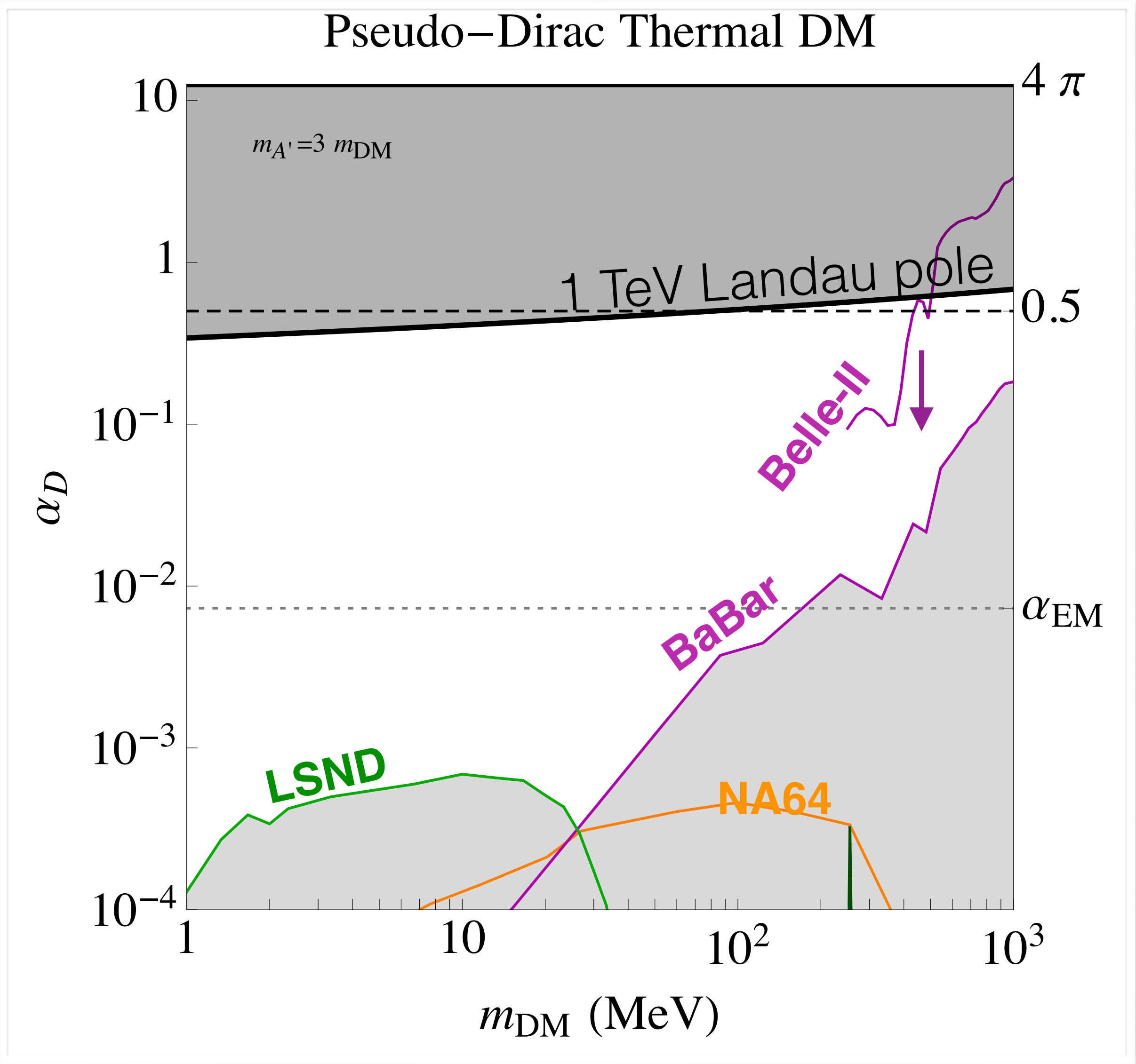


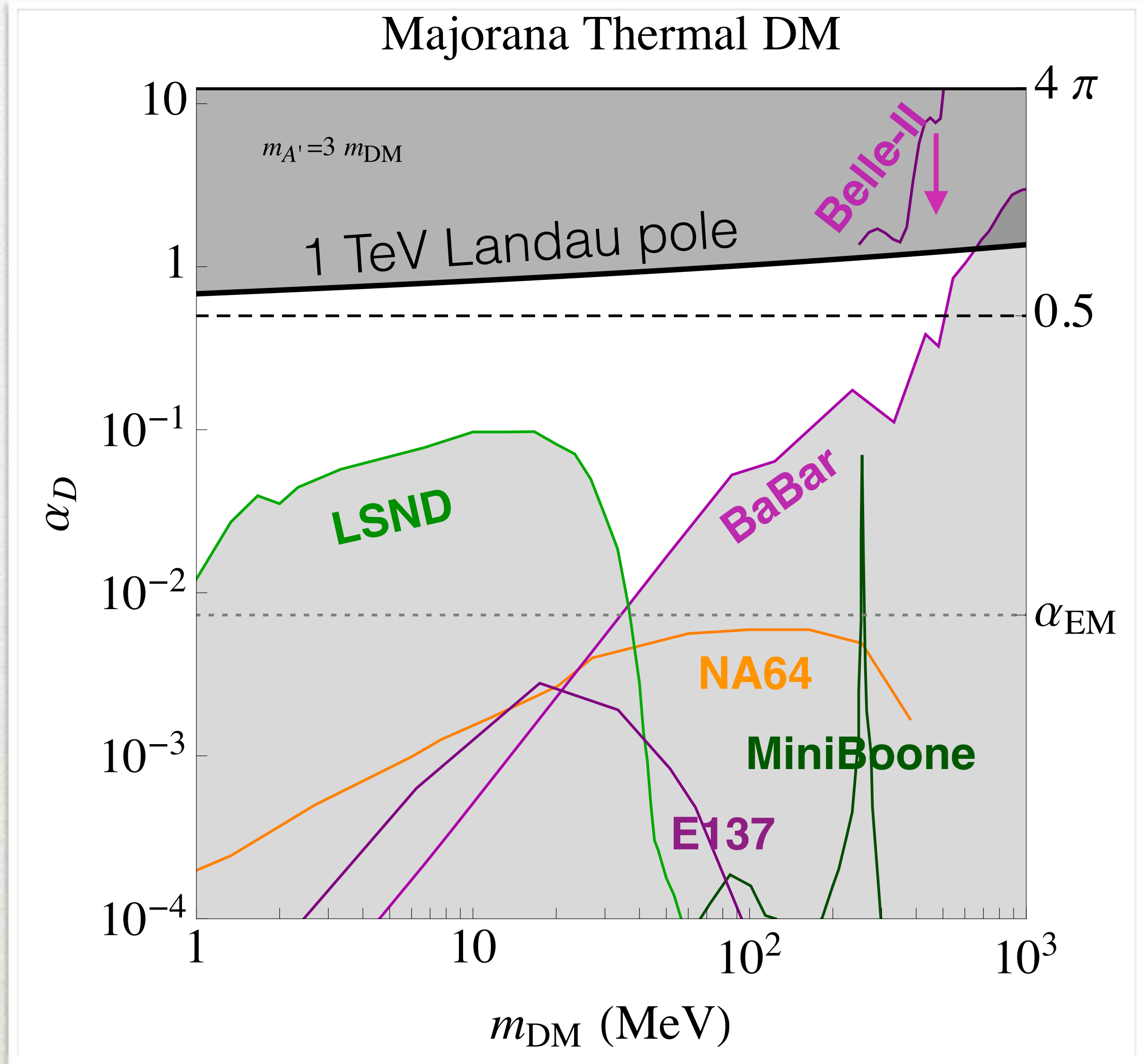


- Accelerators probe DM interactions at the same momentum scales governing freeze-out: **much tighter set of coupling vs. mass milestones**

Accelerator Experiments Have Cornered Thermal LDM

Assuming thermal abundance to fix ϵ

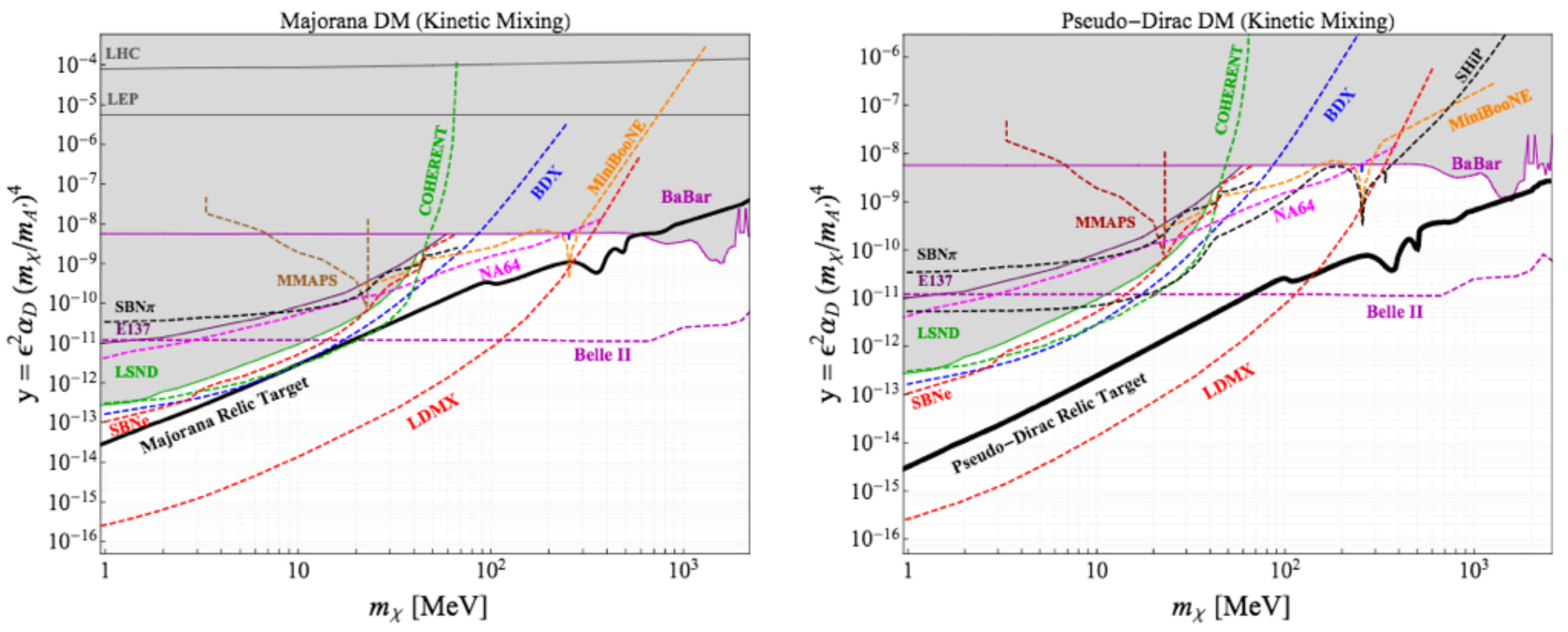




Remaining 1-3 orders of magnitude represent some of the best motivated parameter space. An amazing opportunity!

Accelerator Exp. Challenges & Opportunities

See arXiv: 1707.04591

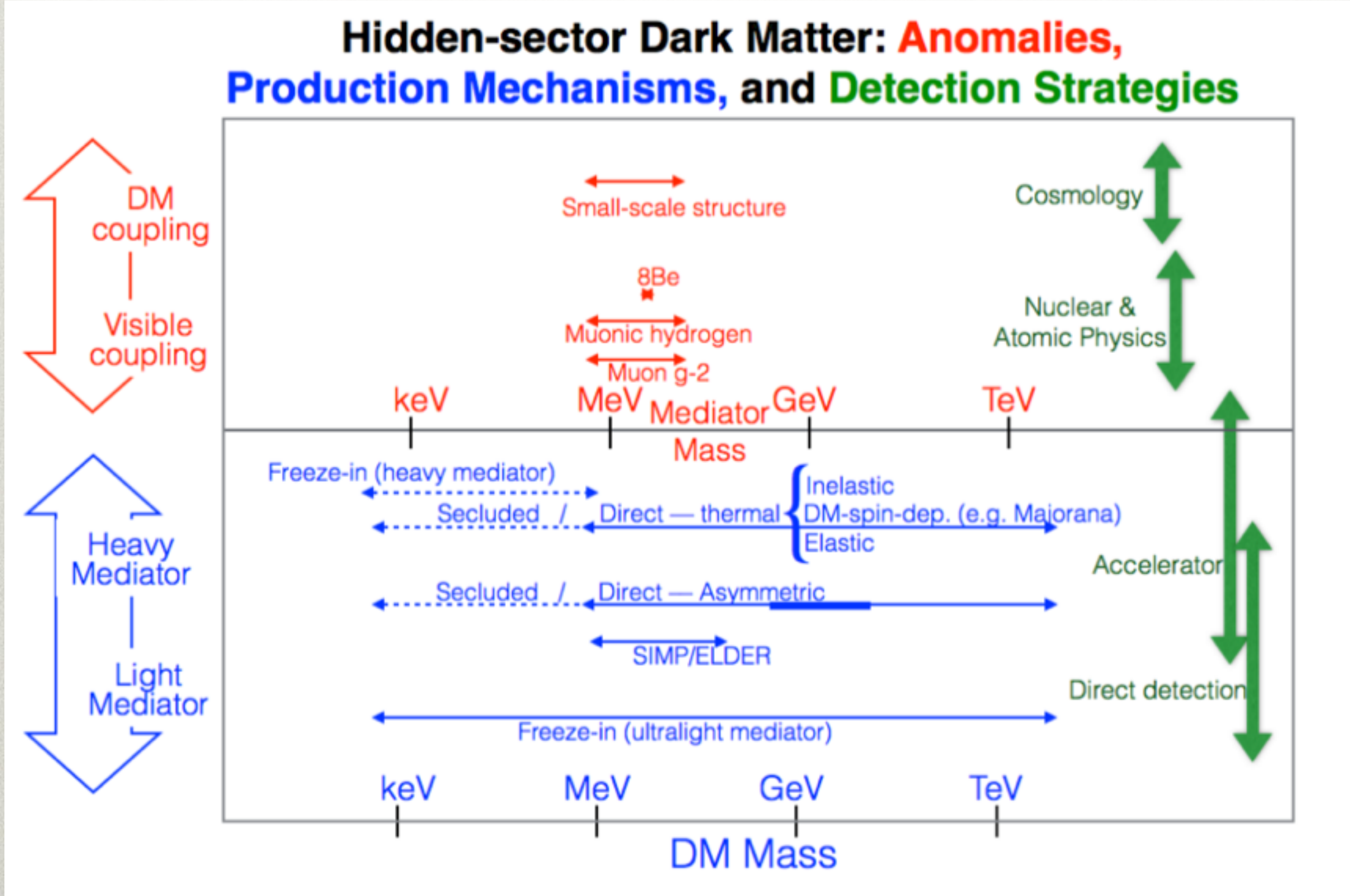


Excellent prospects for experiments to provide milestone sensitivity to LDM parameter space over the next 10 years

(many of them discussed in Natalia Toro's talk)

Powerful Complementarity

See arXiv: 1707.04591



Conclusions

The search for dark matter is sharpening into a broad and robust effort, building on the achievements of the WIMP and QCD axion program

I'm more confident than ever that this will allow us to discover the fundamental physics of dark matter

Best of luck to all of you!