Light Thermal Dark Matter & Accelerator Complementarity

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

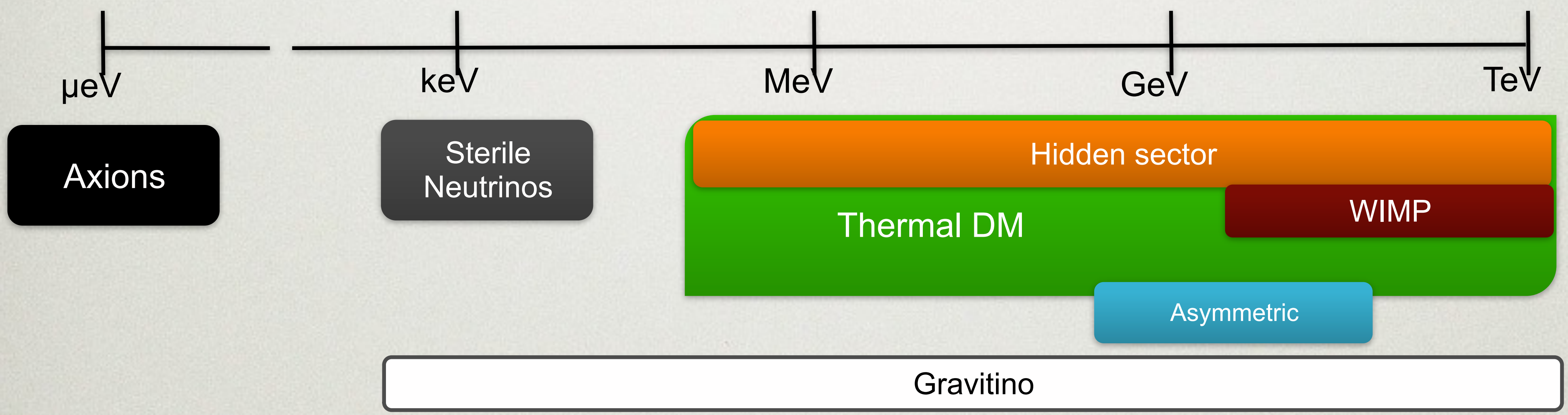
March 23, 2017

Outline

- Thermal Dark Matter is important beyond WIMPs
  - sub-GeV (i.e. Standard Model scales!) is the next obvious place to seriously explore thermal DM
- The key role of accelerator experiments in any light dark matter program
- Comments on testing or discovering LDM

Targeted Exploration

- Wide range of possibilities – even the ones highlighted by P5 span ~20 orders of magnitude in DM mass!



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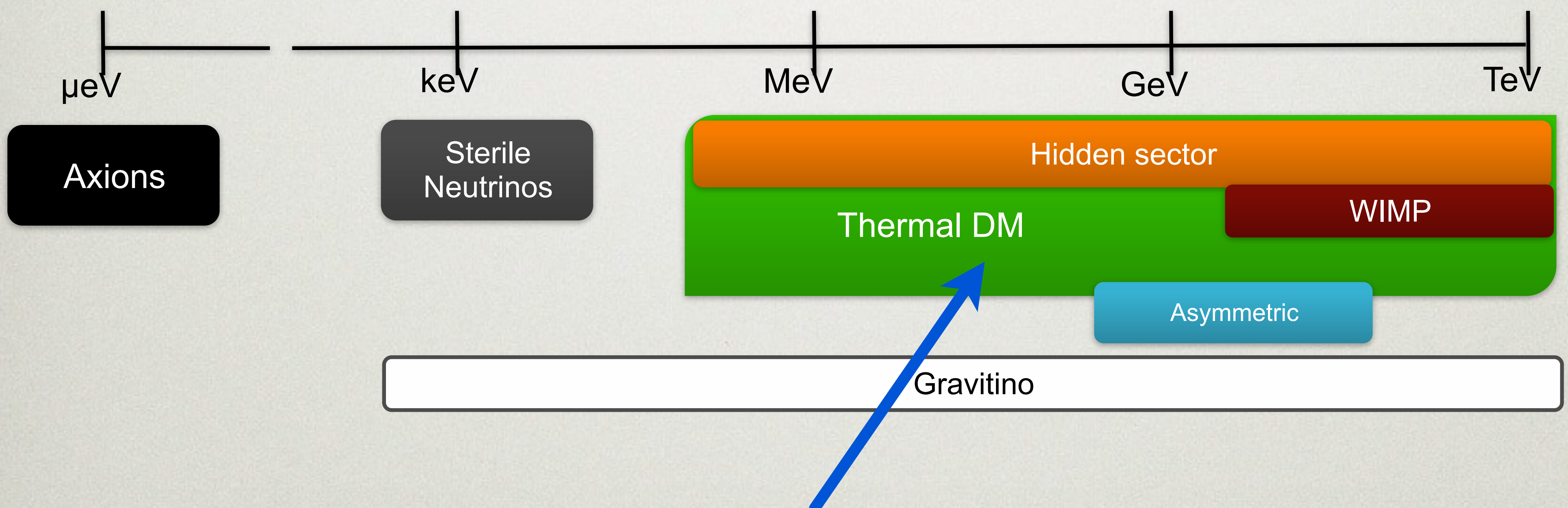
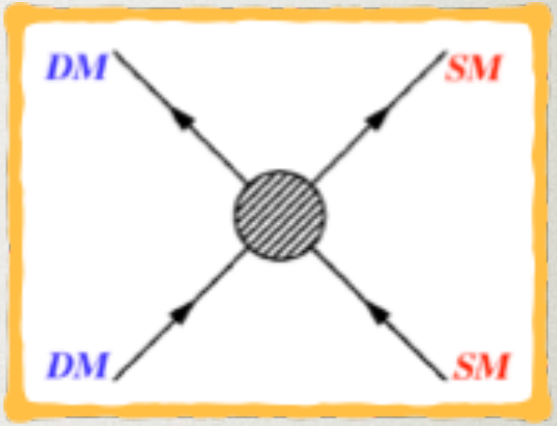


Thermal Dark Matter of particular importance

Thermal Dark Matter: A Prime Target

Simple: Interactions between dark and familiar matter maintain thermal equilibrium as Universe cools, until critical density below which dark matter annihilation "freezes out"

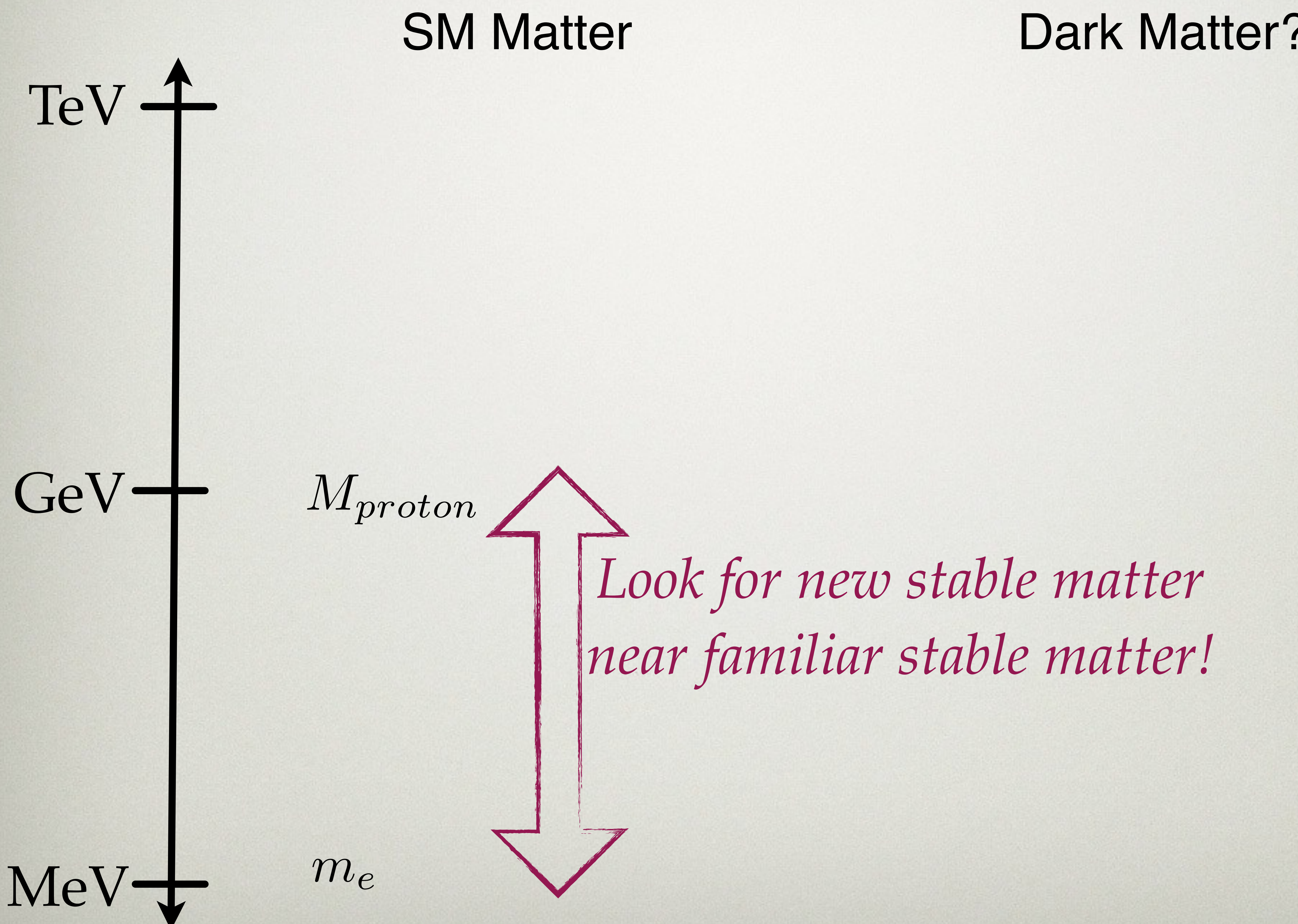


Predictive: Strength of dark matter interaction with familiar matter determines the residual abundance – so observed DM abundance predicts strength of DM interactions

Straightforward: Many well-motivated models have the ingredients to realize thermal dark matter (including, but not limited to, WIMPS)

Data Driven! Evidence from CMB and BBN for hot & dense thermal phase of Universe. We don't have to speculate (much) about thermal origin possibility.

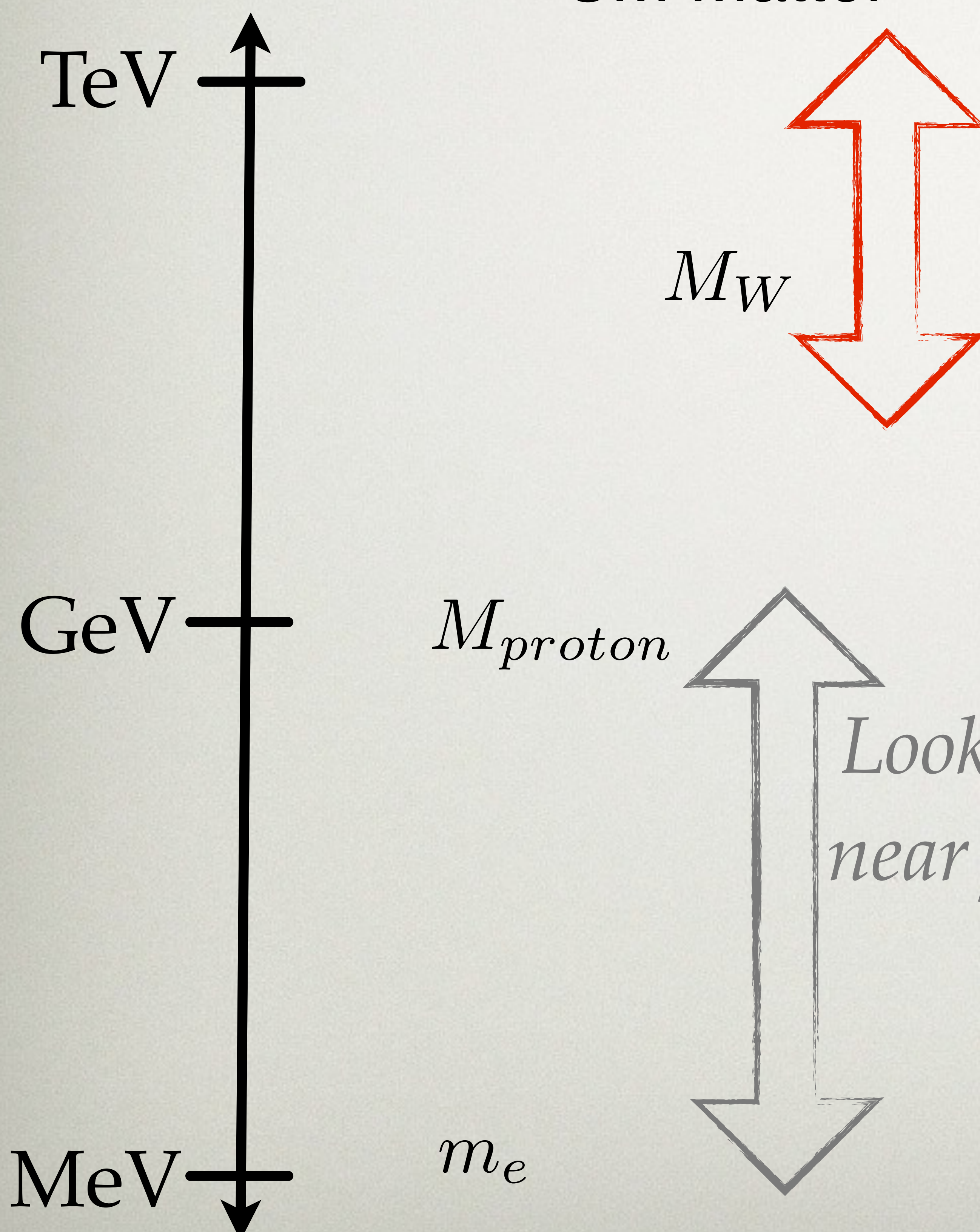
Vicinity of Weak Scale: A Prime Target



Vicinity of Weak Scale: A Prime Target

SM Matter

Dark Matter?

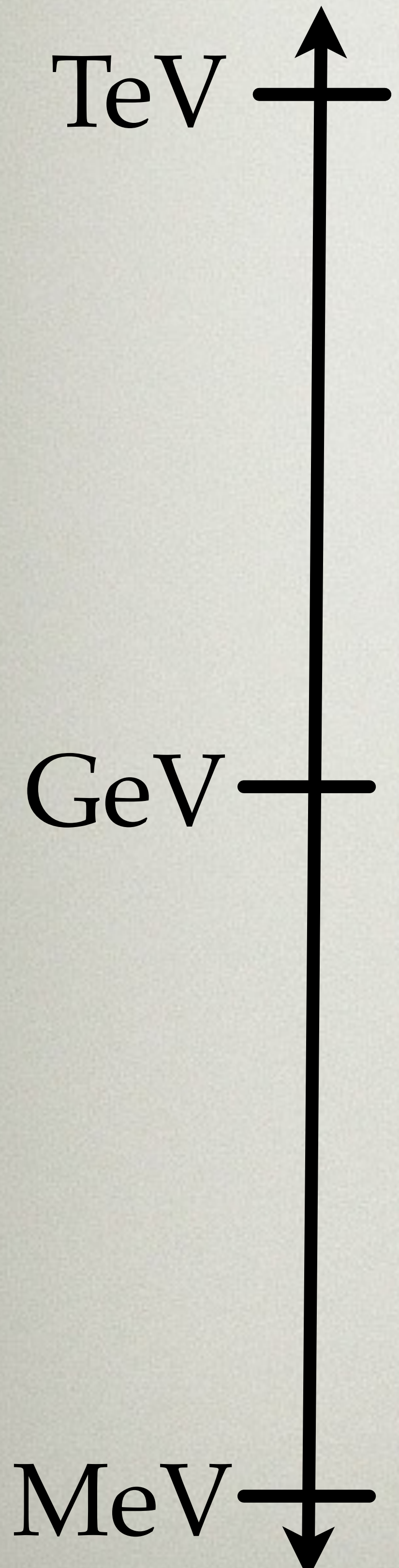


For decades: look here!

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

Look for new stable matter near familiar stable matter!

VICINITY OF WEAK SCALE: A PRIME TARGET



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)

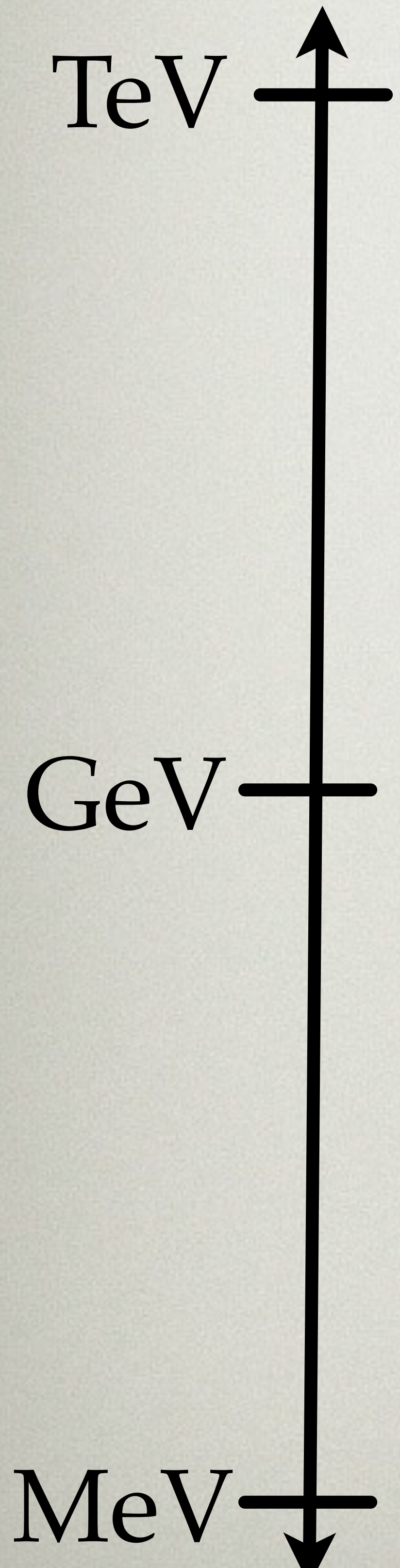
Dark Matter?

For decades: look here!

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

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

Vicinity of Weak Scale: A Prime Target



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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)

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

Vicinity of Weak Scale: A Prime Target

SM Matter

TeV

M_W

GeV

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

(accidentally close to weak scale)

MeV

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

(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)

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

Vicinity of Weak Scale: A Prime Target

SM Matter	Dark Matter?
M_W	Generic mass scale for matter with O(1) coupling to origin of EWSB
$M_{proton} \sim M_{large} e^{-\#}$ (accidentally close to weak scale)	$\sim M_W \times e^{-\#}$
$m_e \sim \text{small}\ \# \times M_W$ (derived from weak scale)	$\text{small}\ \# \times M_W$

TeV

GeV

MeV

Look here for hidden-sector matter!

Vicinity of Weak Scale: A Prime Target

SM Matter | Dark Matter?

TeV

GeV

MeV

The <u>broad</u> vicinity of the weak scale is perhaps the best motivated place to discover dark matter:

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

(derived from weak scale)

Scientific Goal

Test Thermal Dark Matter in the MeV-TeV Range

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 ingredients of a high-impact program that can address the sub-GeV mass range?

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

WIMP & Thermal LDM Programs: Improved Starting Information

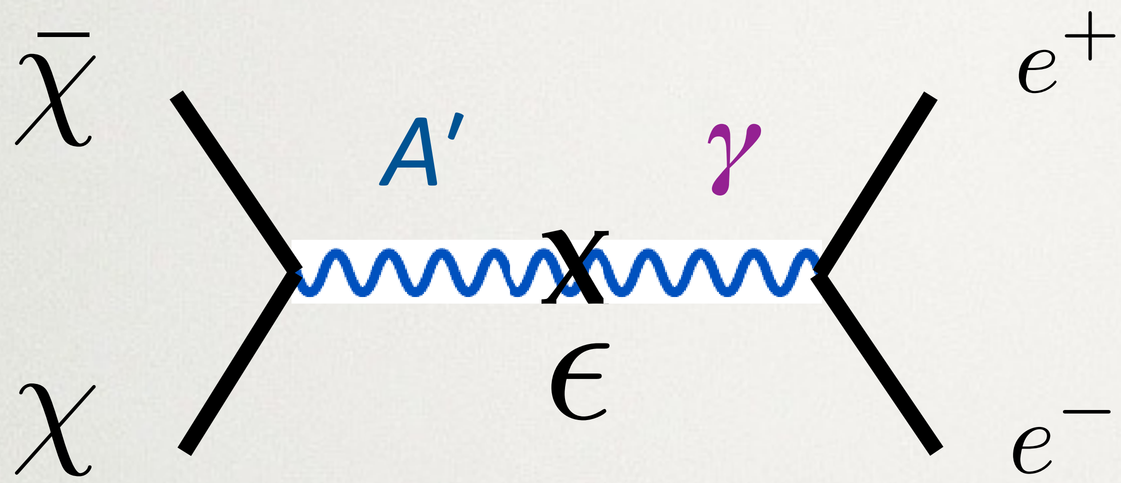
Cosmology and astrophysics is far more advanced: ***narrows the set of thermal scenarios***

…p-wave and co-annihilation scenarios preferred

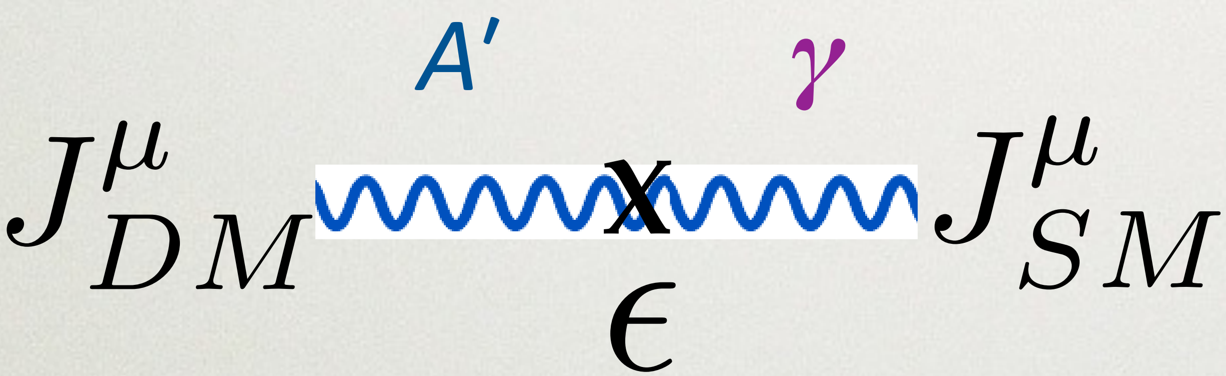
Standard Model is far better explored and understood: ***narrows the set of interactions***

…weakly coupled MeV-GeV vector mediator interactions preferred

WIMP & Thermal LDM Programs: Phenomenology Similarities



+ other modes



Characterize the "dark" current - SM current interactions mediated by a vector

WIMP & Thermal LDM Programs: Phenomenology Similarities

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

Particle Type

Dark Matter Current

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

Different Low-Energy Phenomenology!

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Different Low-Energy Phenomenology!

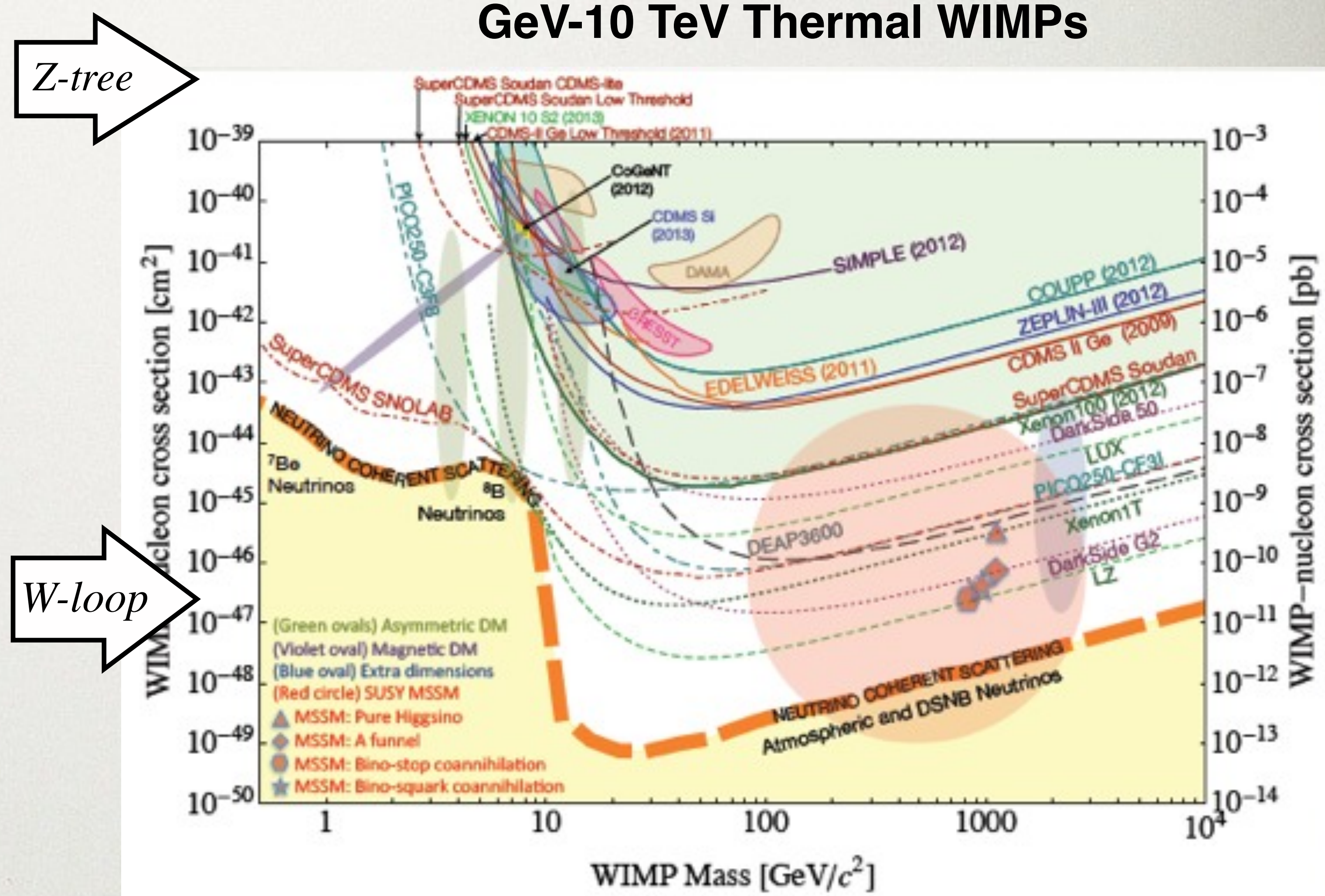
Just like neutralino WIMP candidates

Just like sneutrino or Dirac neutrino WIMP candidate

WIMP & Thermal LDM Programs: Direct Detection Similarities

Key Thermal Targets Span Large Range.

GeV-10 TeV Thermal WIMPs



WIMP & Thermal LDM Programs: Direct Detection Similarities

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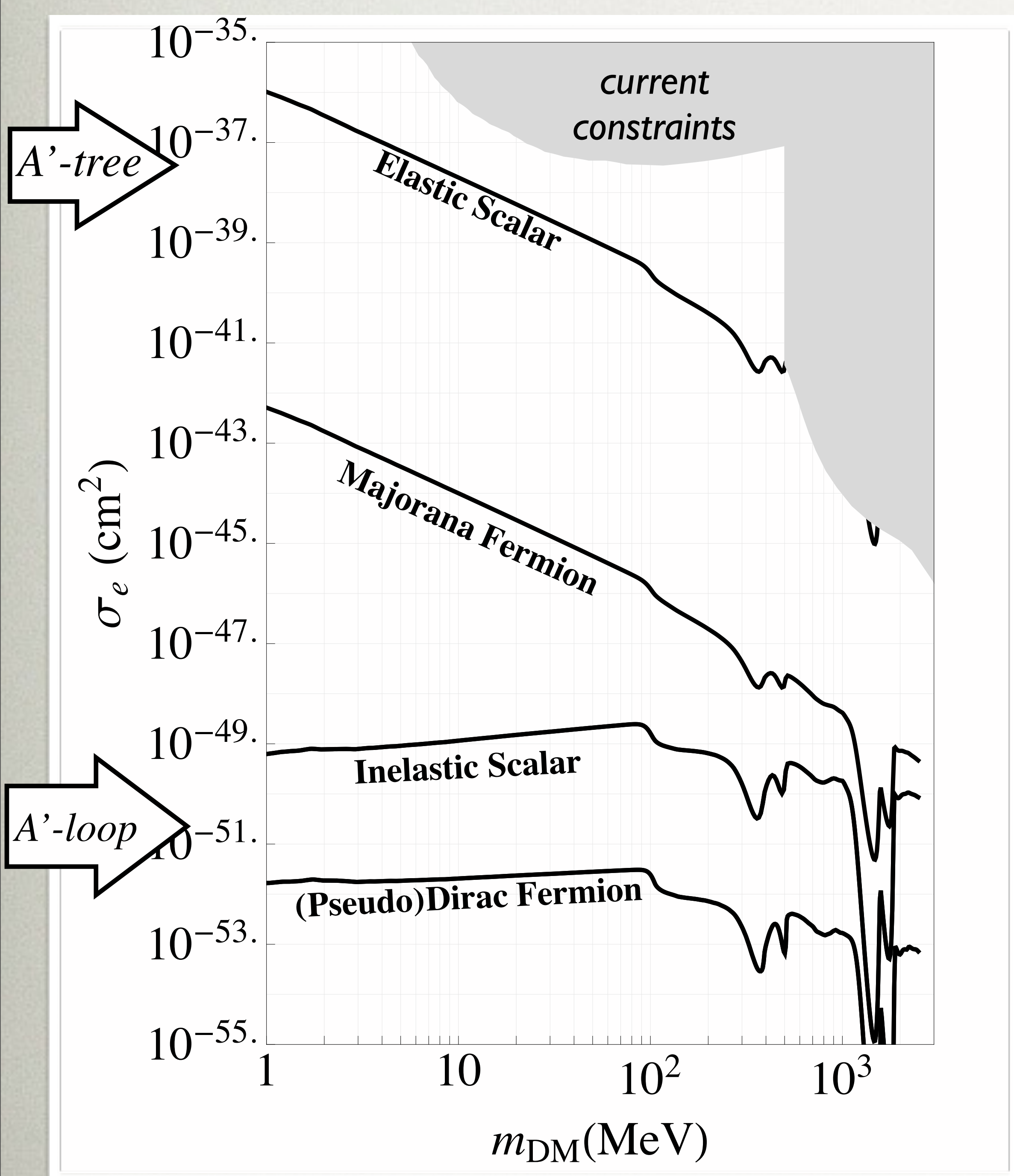
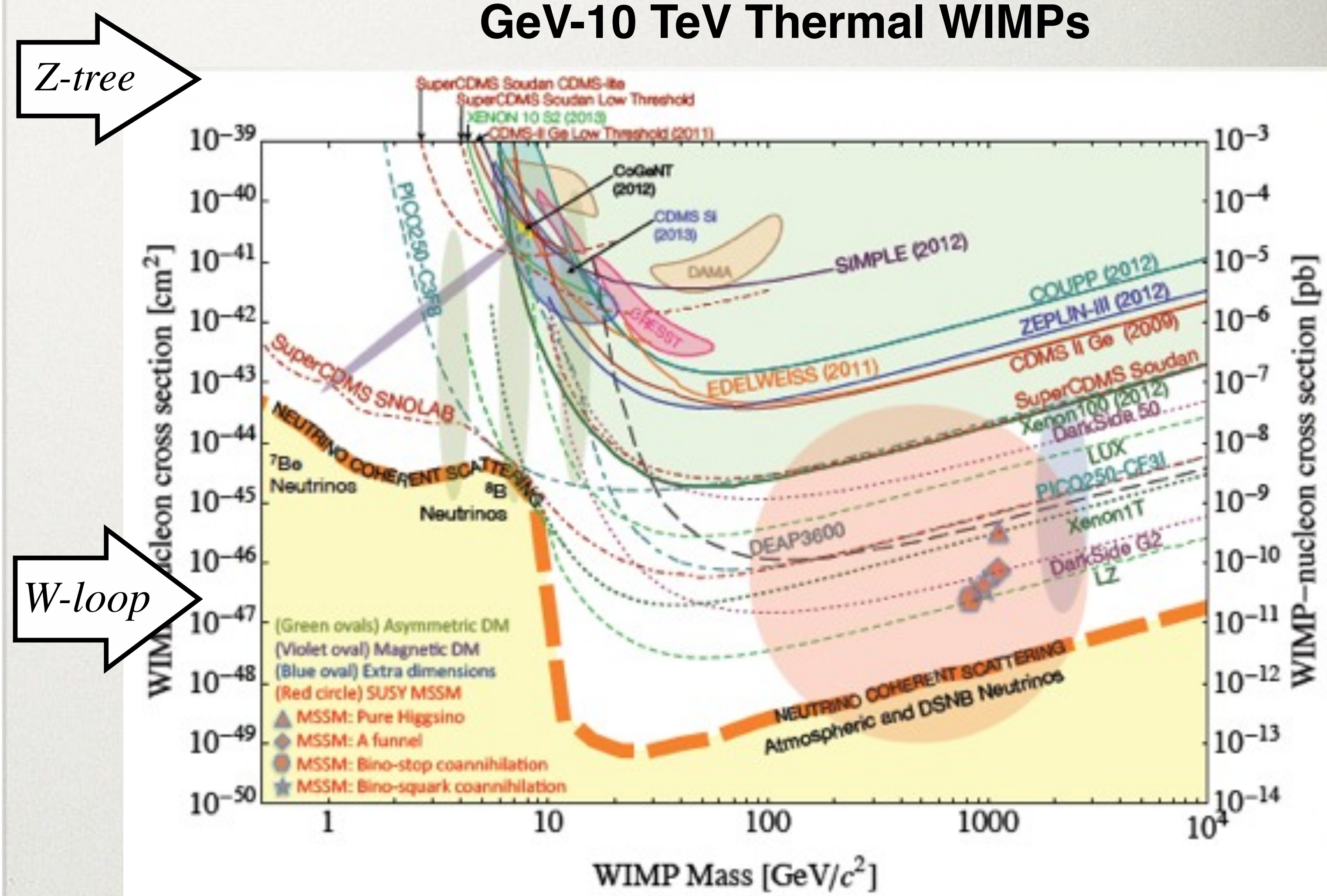
MeV-GeV Thermal LDM



GeV-10 TeV Thermal WIMPs



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

WIMP & Thermal LDM Programs: Radically Different Story for Accelerators

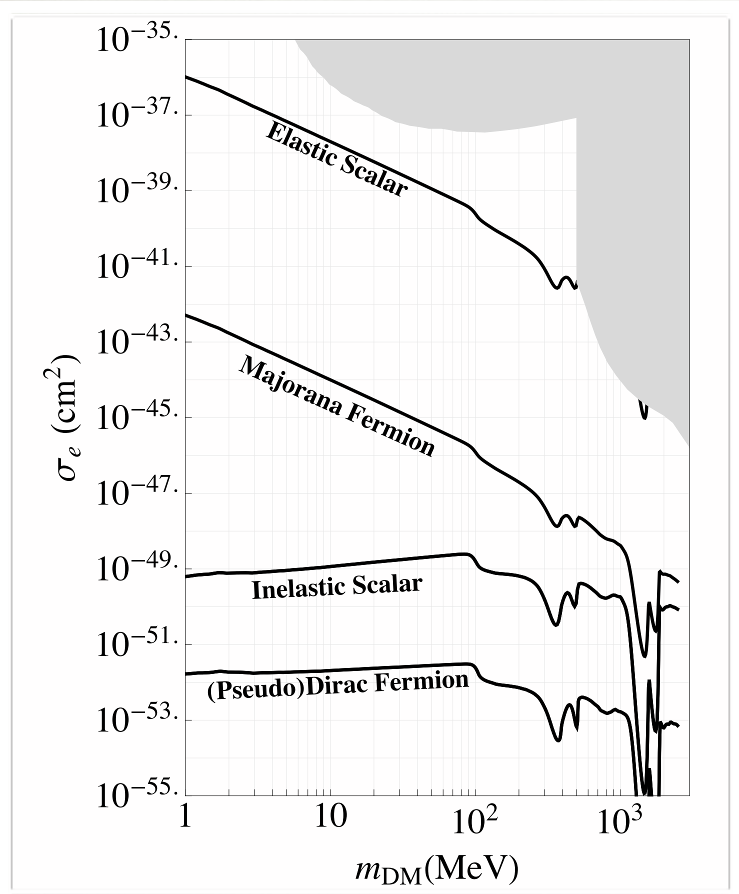
TeV-scale electro-weak states were not easily accessible to accelerators when WIMP effort started!

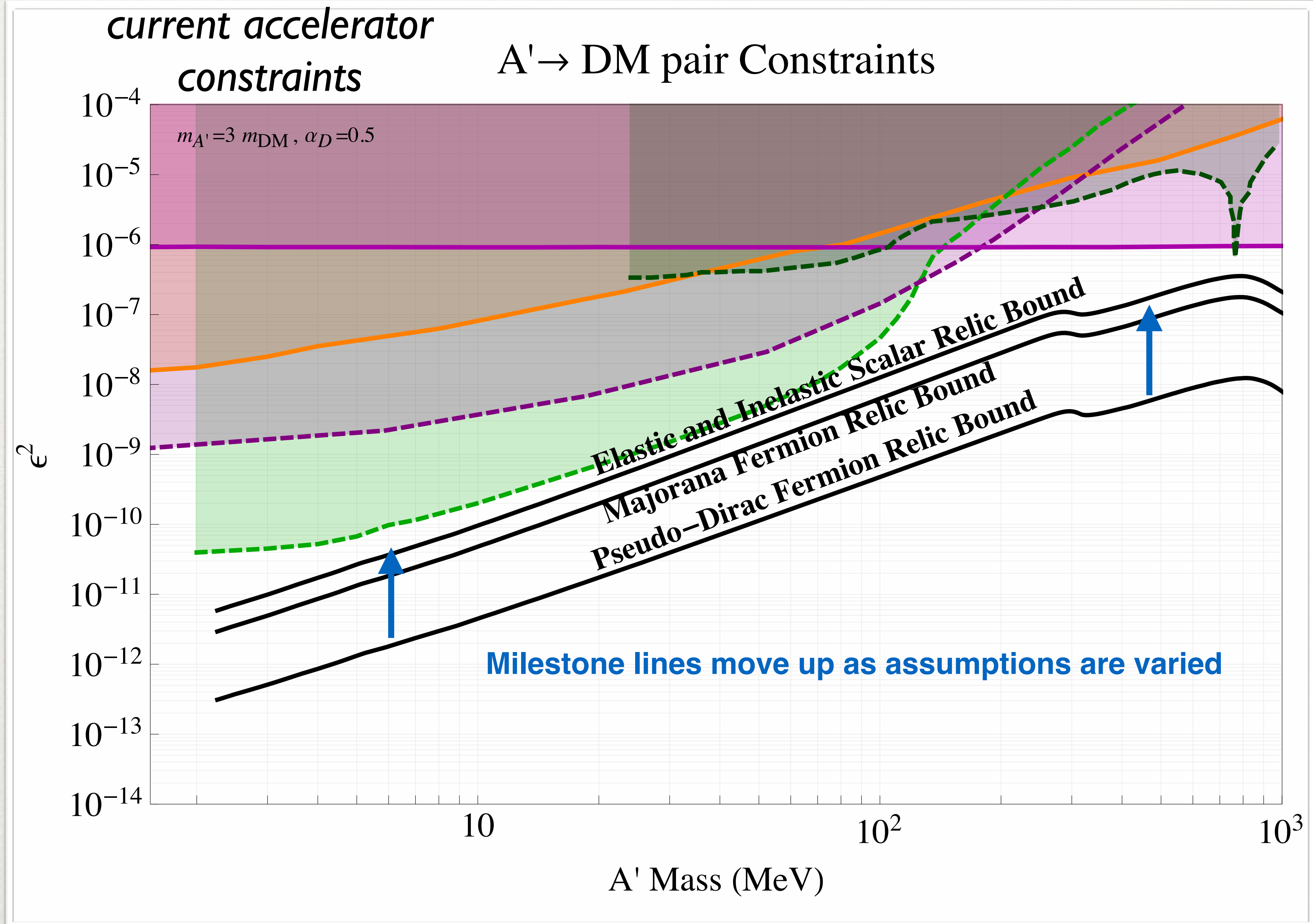
Decades of development of mid- to high-energy accelerator infrastructure and impressively powerful particle detector technology has now taken place...

Whereas sub-GeV weakly coupled particles readily accessible to accelerators as the LDM effort begins

In fact, a tremendous amount of sub-GeV parameter space has already been explored by accelerator experiments!

Accelerators: Thermal LDM Readily Accessible

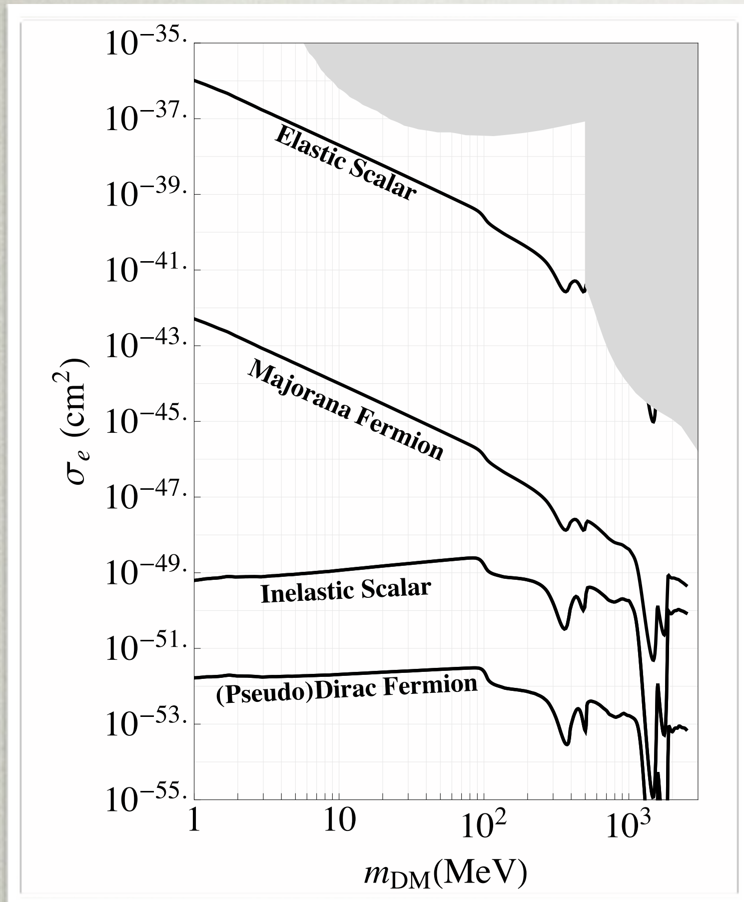




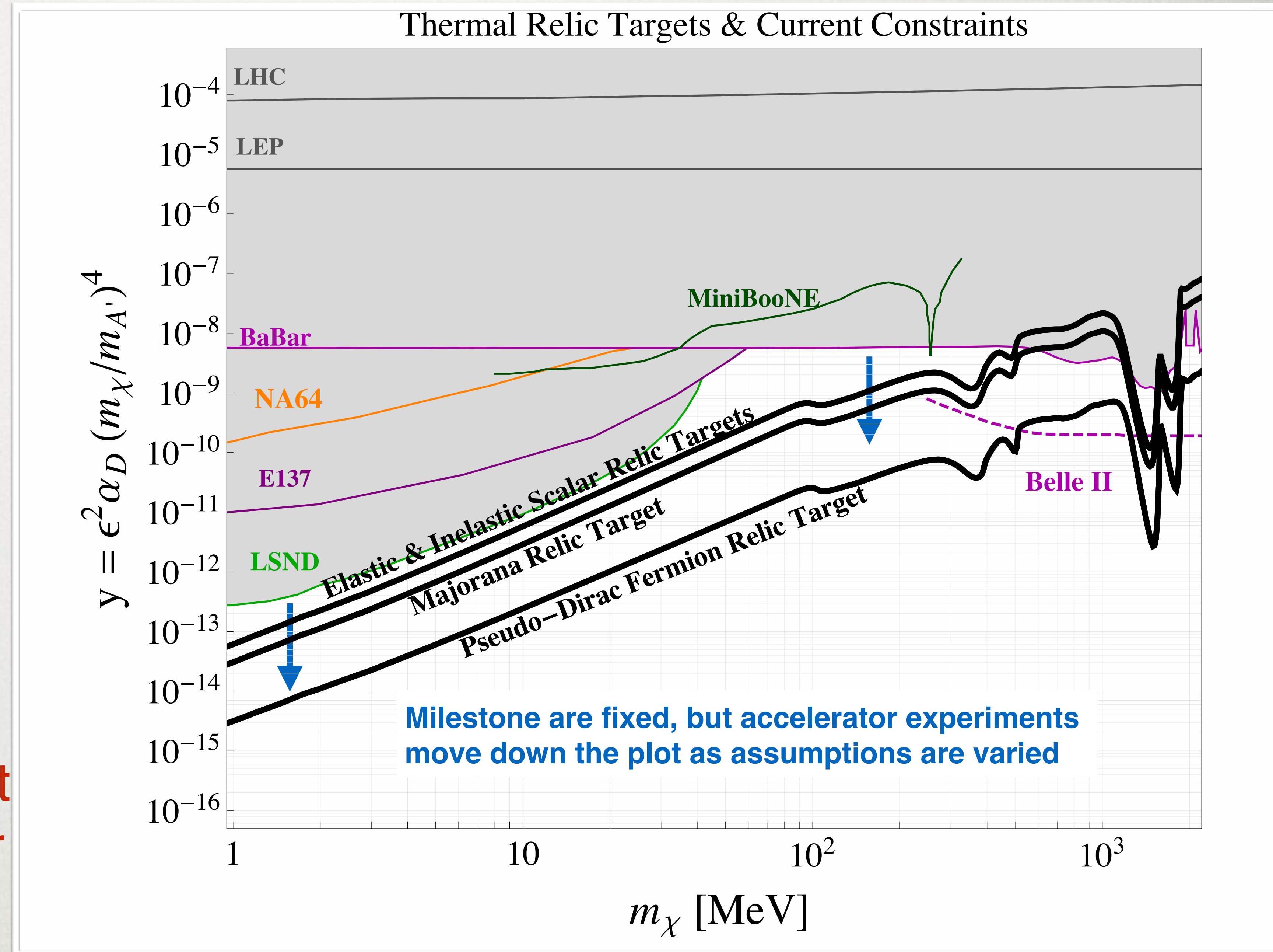
Accelerators probe coupling strength vs. mass, **not** direct detection cross section vs. mass

- Accelerators probe DM interactions at the same momentum scales governing freeze-out: **much sharper coupling vs. mass milestones**
- Plot sensitivity with unfavorable assumptions for unknown model parameters

Accelerators: Thermal LDM Readily Accessible



Can instead use variable that determines freeze-out abundance vs dark matter mass



- Accelerators probe DM interactions at the same momentum scales governing freeze-out: **much sharper coupling vs. mass milestones**
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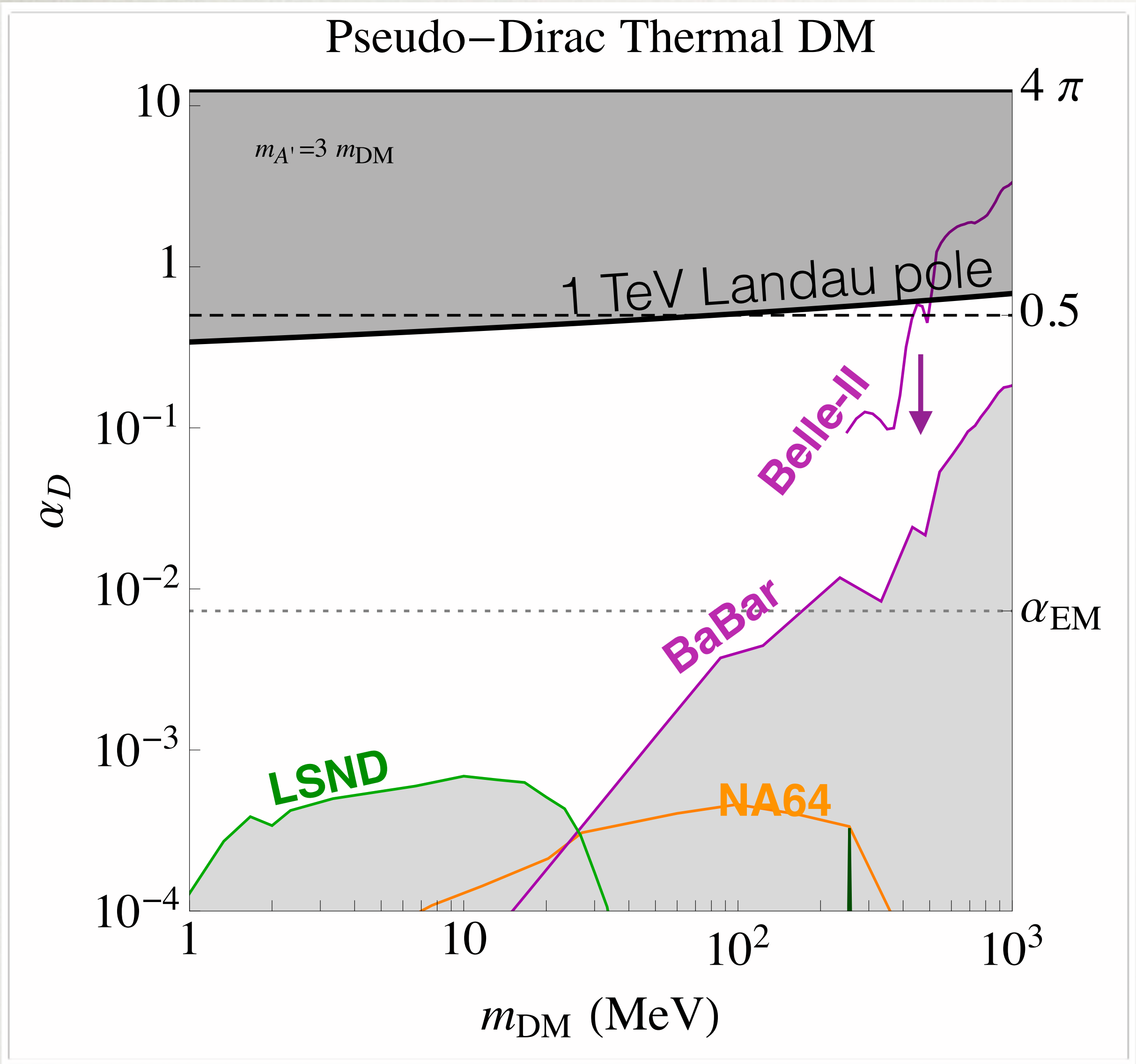
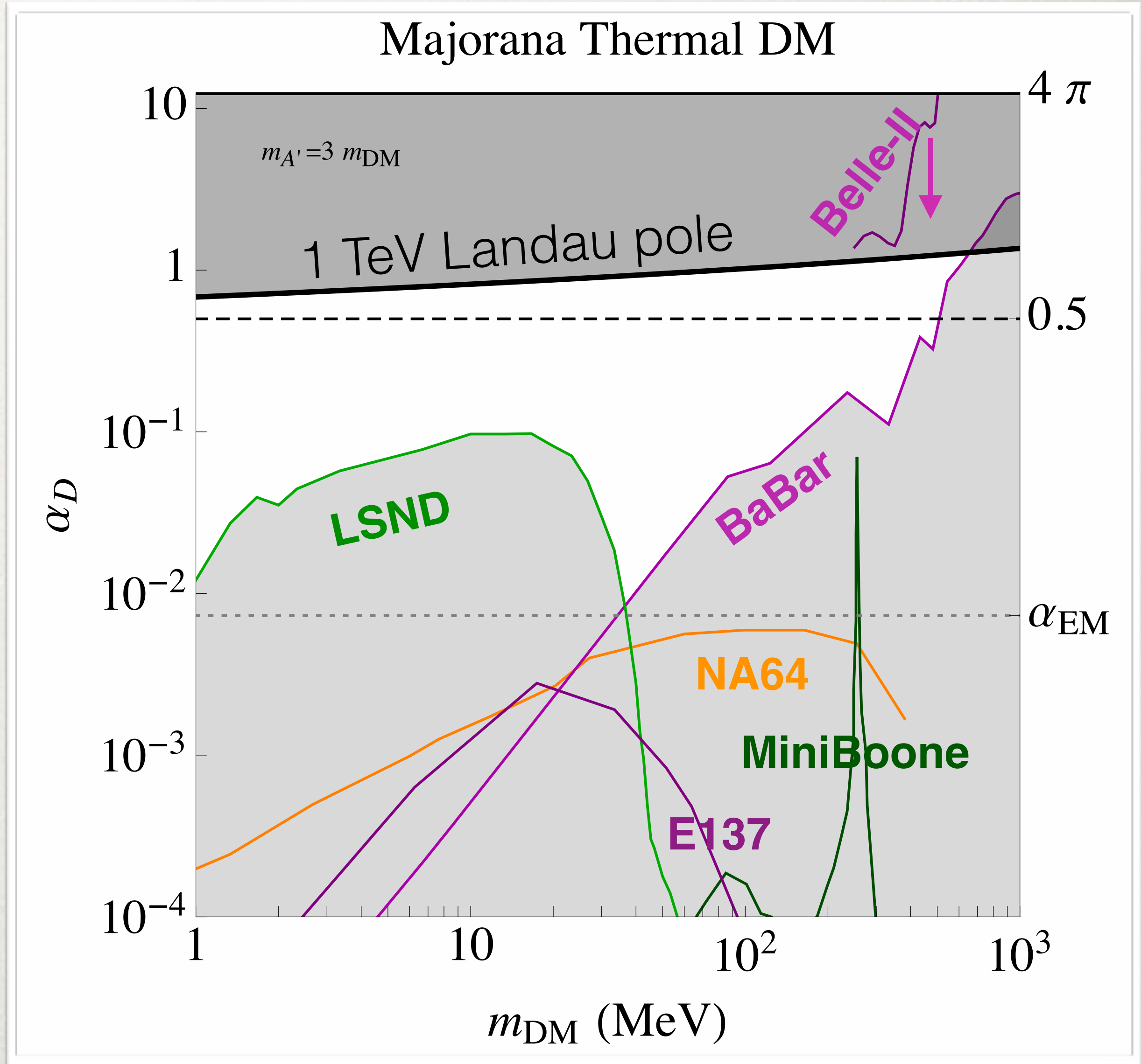
Accelerator Experiments already exploring LDM

Assuming thermal abundance to fix ϵ

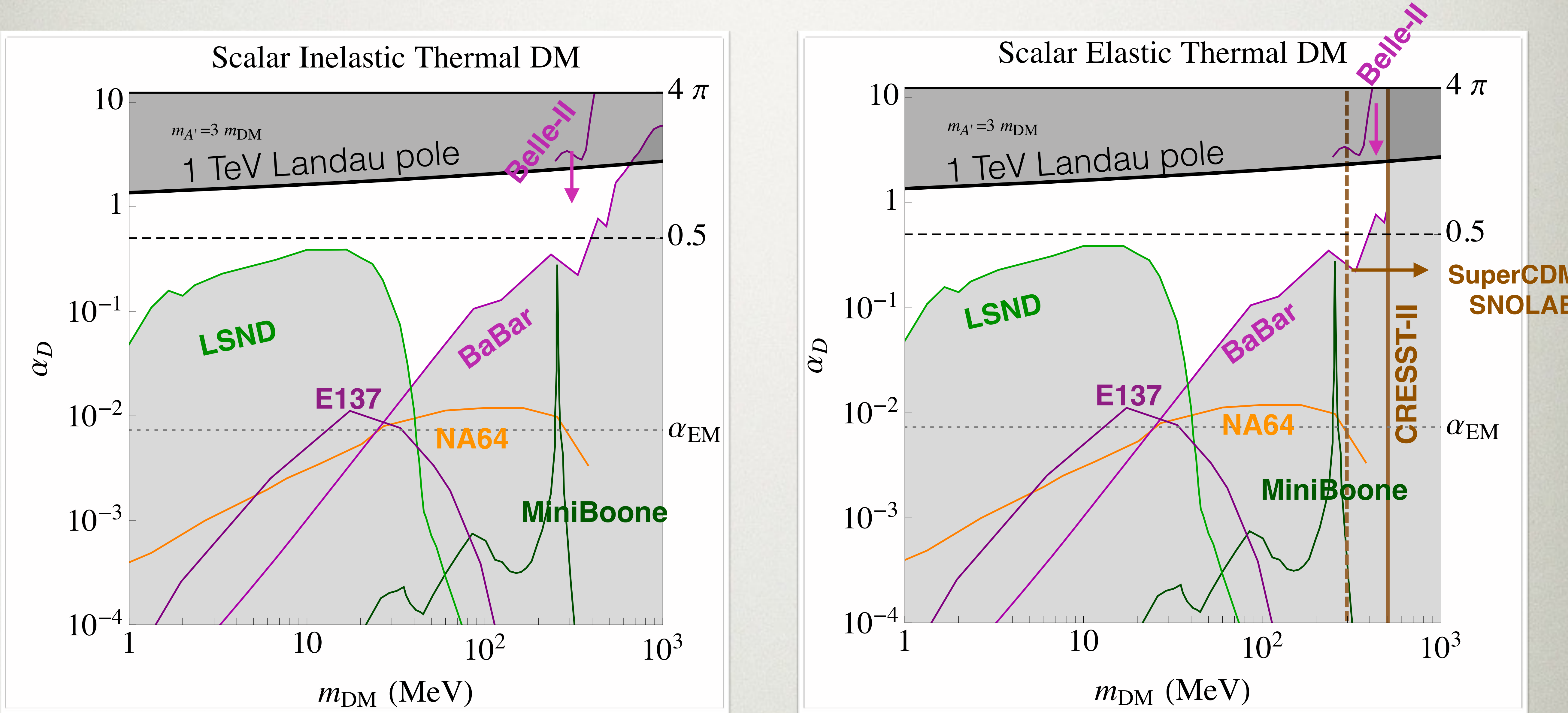




Remaining 1-3 orders of magnitude represent some of the best motivated parameter space. Accelerator efforts poised for discovery or decisive result. An amazing opportunity!

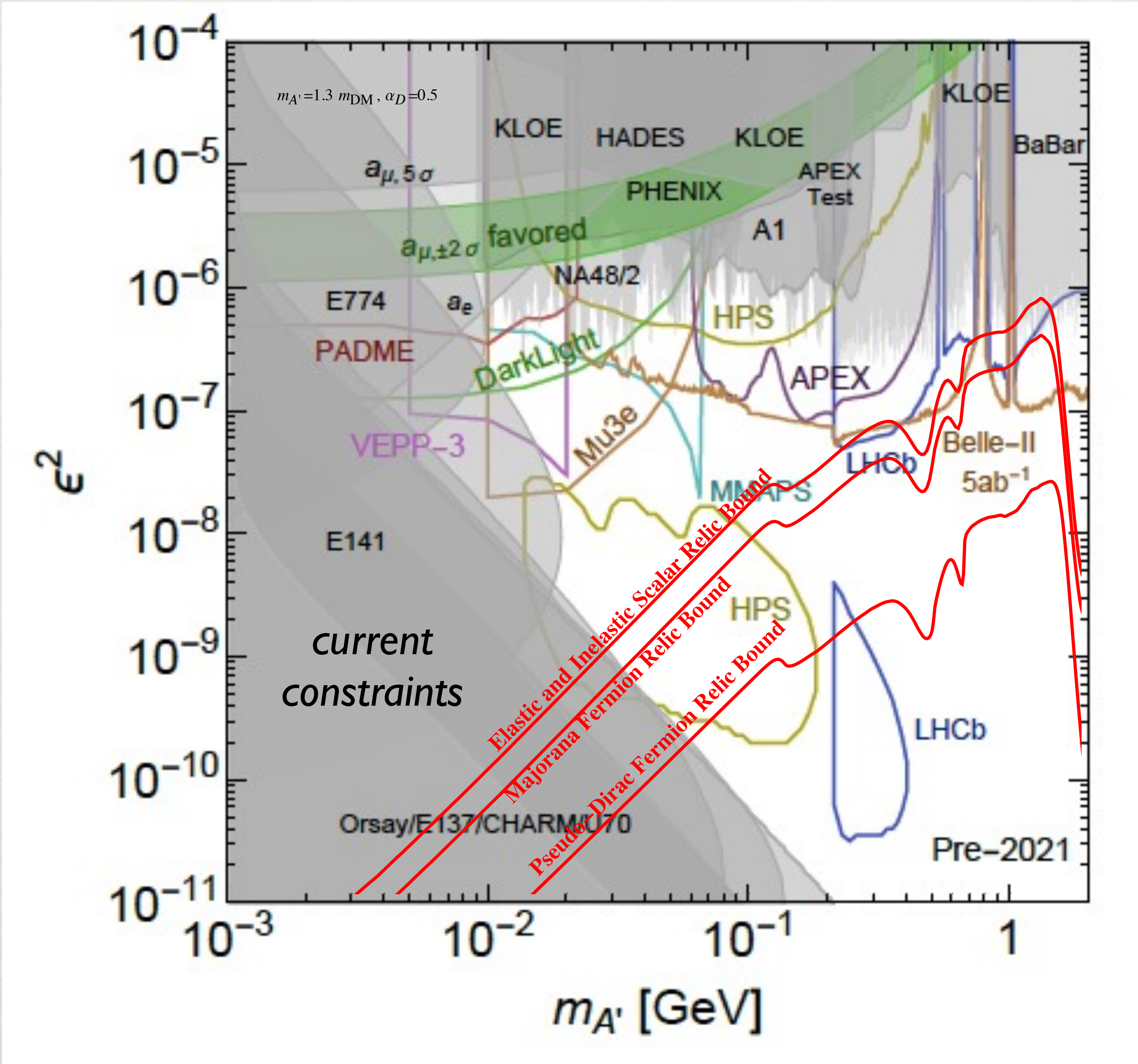
Accelerator Experiments already exploring LDM

Assuming thermal abundance to fix ϵ



Much of both scalar DM scenarios has been probed, but it's critical to close the remaining territory!

Thermal LDM: Mediator Physics Plays a Central Role



Territory above the red lines motivated by thermal DM!

Accelerator experiments leading the way exploring the possible mediator physics! This is a crucial part of the physics!

Accelerator Complementarity

Accelerator experiments are in the best position to test all GeV-scale (and below) thermal DM scenarios.

WG3: Can this be done quickly and at reasonable cost?

WG3/4: What are the important contributions from existing and already planned experiments?

WG3/4: How far do new experiments need to push for a null result to be robust (i.e. of lasting value)?

Accelerator Complementarity

Conversely, can a convincing discovery be made? After all, some of the best motivated parameter space is still unexplored!

For this purpose, a clear case can be made that multiple techniques are required:

Accelerator Missing Mass/Energy/Momentum

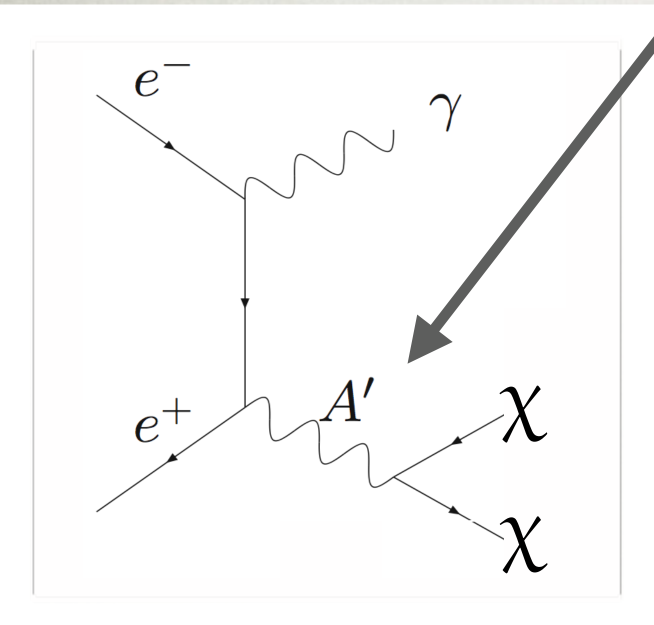
Accelerator Beam Dump Technique

Direct Detection Technique

Accelerator Complementarity

Case I: $m_\chi < m_{A'} < 2m_\chi$

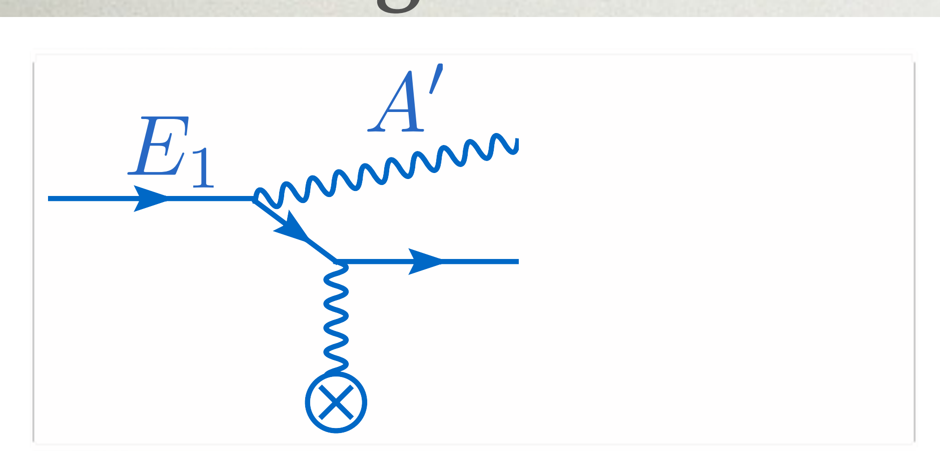
Colliders



Rate gives coupling information

$$\sigma \sim \alpha_D \epsilon^2 \frac{1}{E_{CM}^2}$$

Fixed-Target



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Missing Mass/Energy/Momentum

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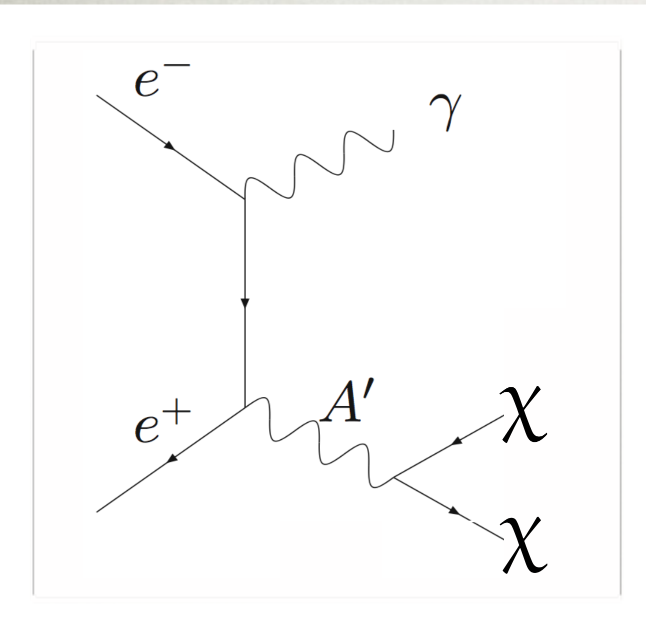
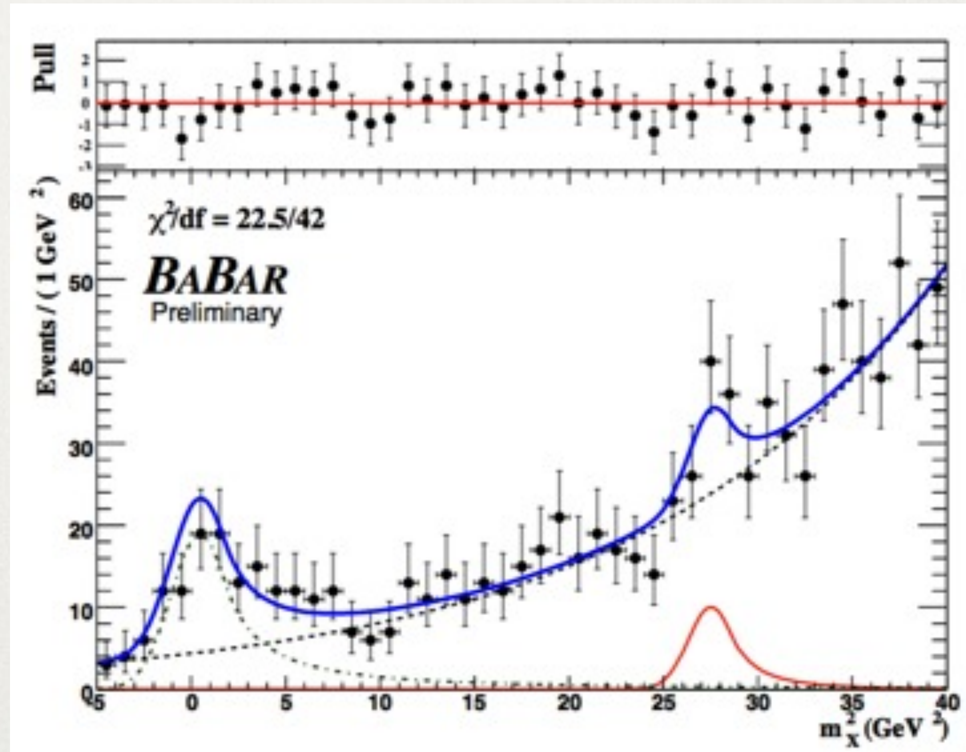
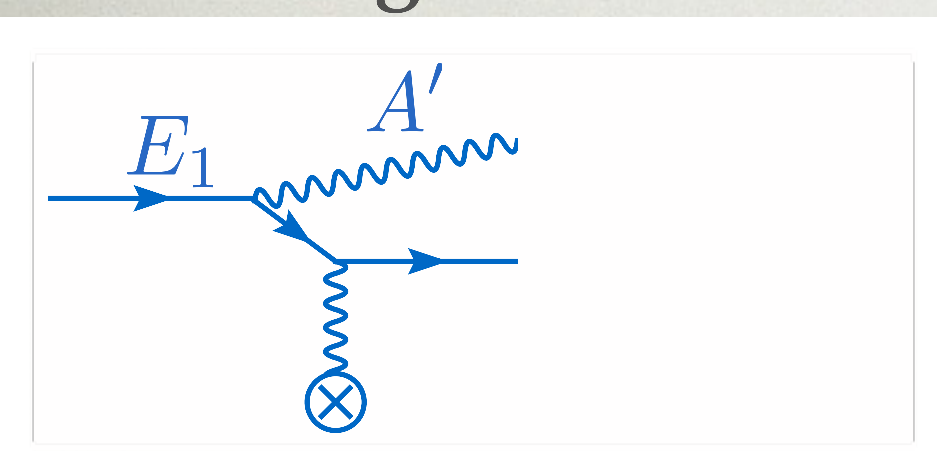
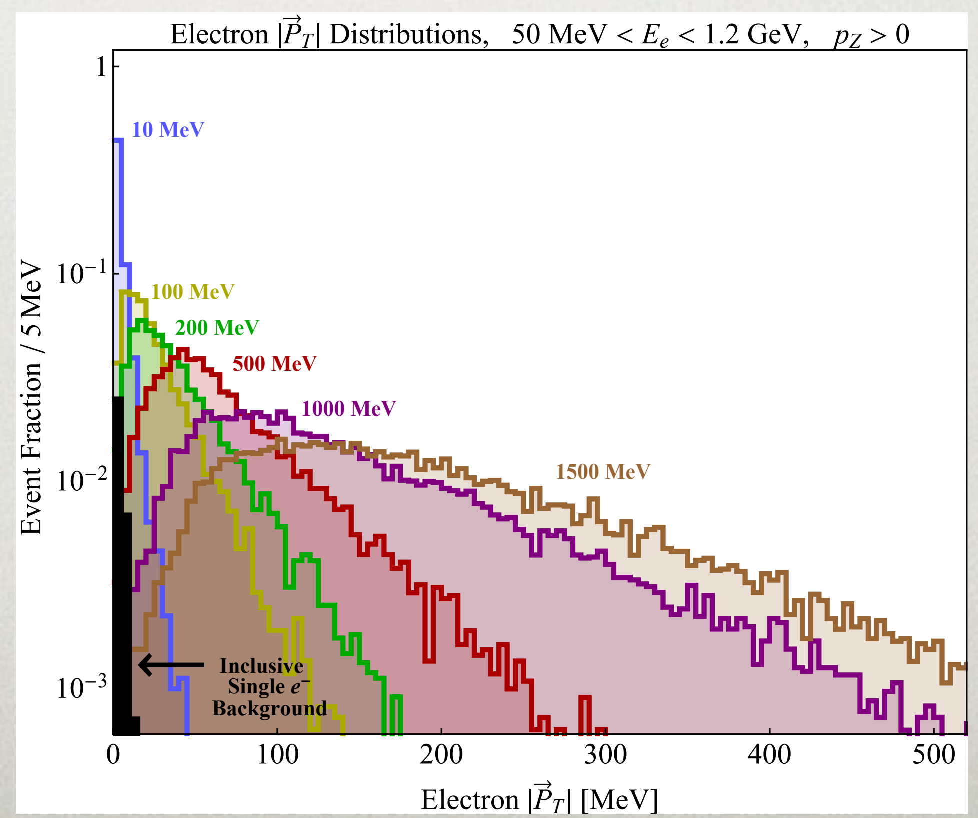




Kinematics gives m_χ

Fixed-Target





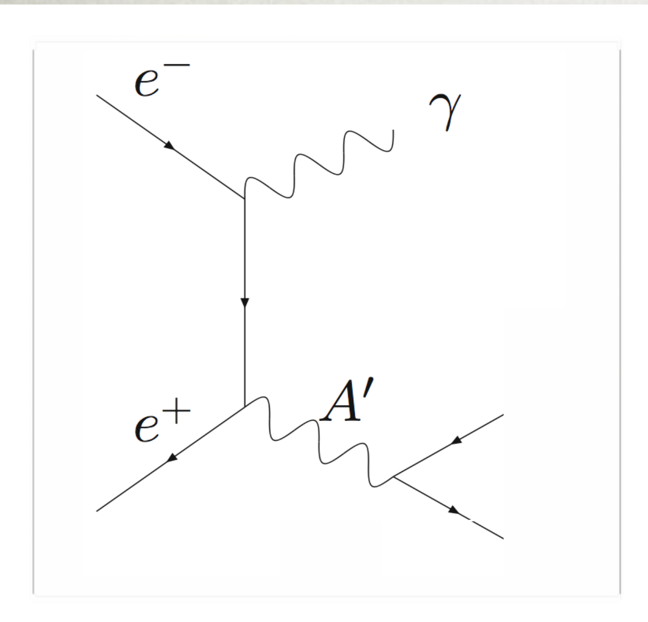
Kinematics gives m_χ

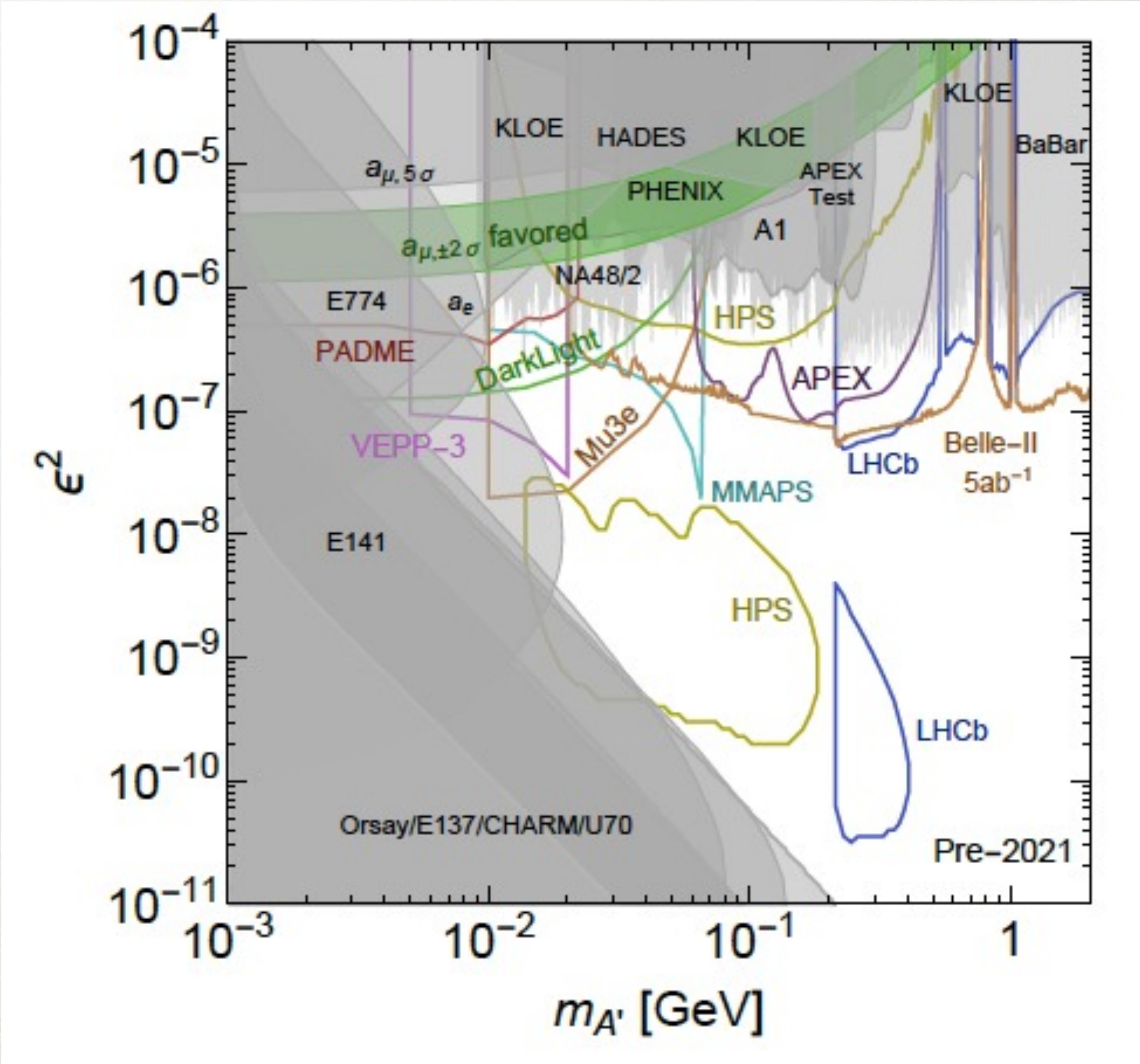
Missing Mass/Energy/ Momentum

Accelerator Complementarity

Case I: $m_\chi < m_{A'} < 2m_\chi$

Colliders





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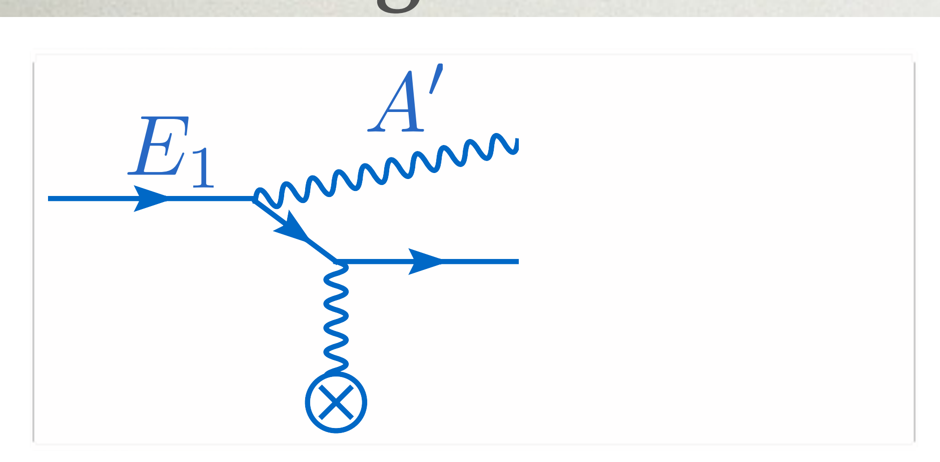


Visible A′ searches give $m_{A'}$ **and** ϵ

Missing Mass/Energy/Momentum

Accelerator Complementarity

Case I: $m_\chi < m_{A'} < 2m_\chi$

Can separately measure:

$m_{A'}$ ϵ m_χ α_D

From visible A' exp.

From missing mass/momentum exp.
(and beam dumps)

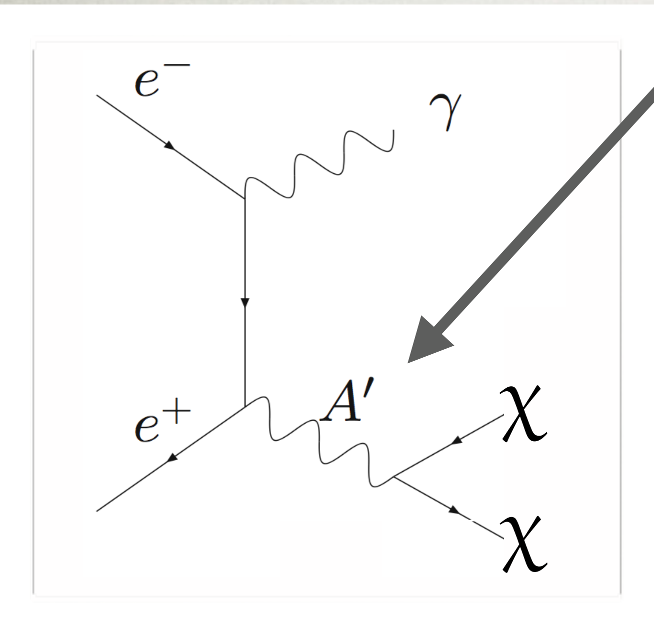
Accelerator experiments can untangle the physics in detail

Still want Direct Detection to verify cosmological stability

Accelerator Complementarity

Case II: $2m_\chi < m_{A'}$

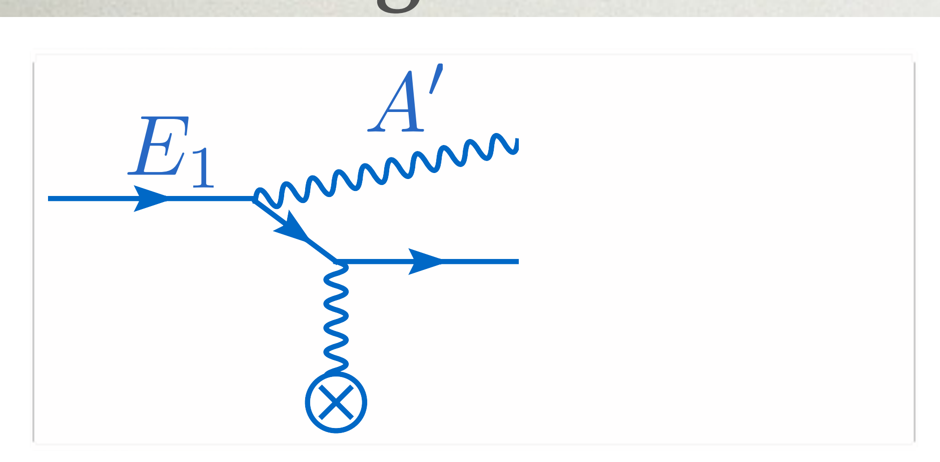
Colliders



$$\sigma \sim \epsilon^2 \frac{1}{E_{CM}^2}$$

Rate gives ϵ

Fixed-Target



$$\sigma \sim \epsilon^2 \frac{1}{m_{A'}^2}$$

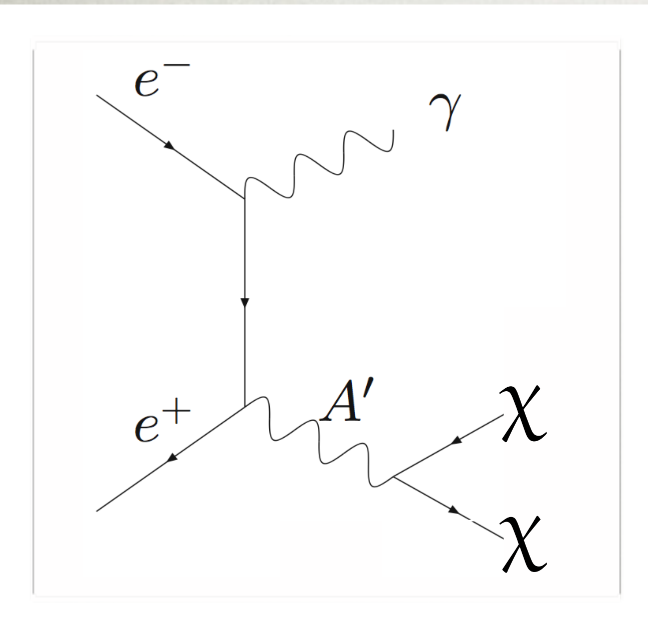
Rate gives $\dfrac{\epsilon}{m_{A'}}$

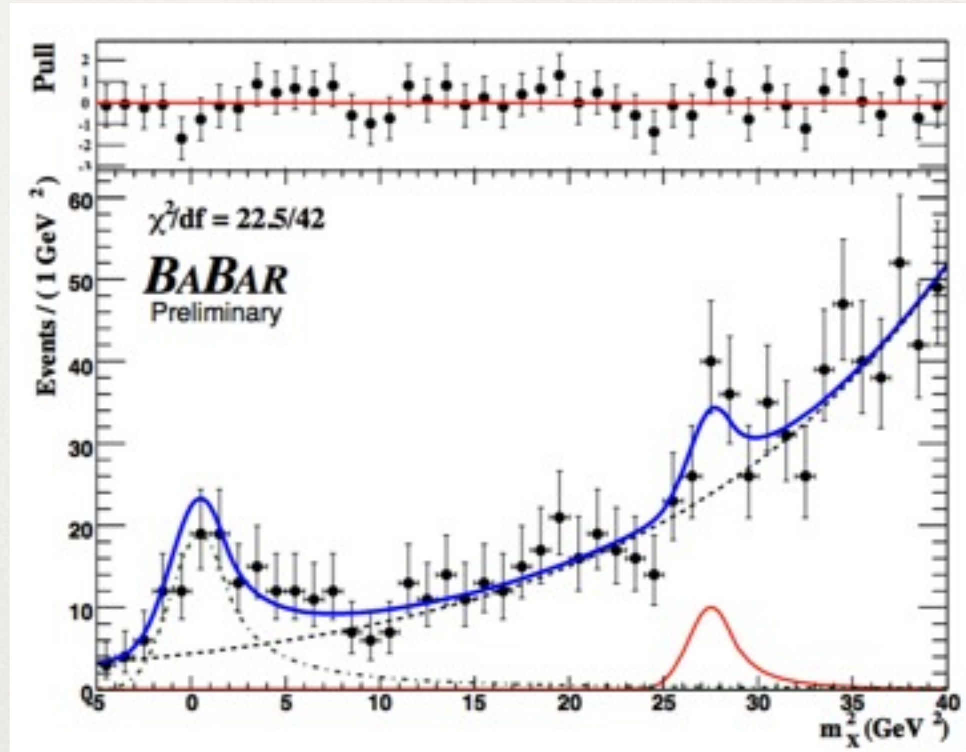
Missing Mass/Energy/Momentum

Accelerator Complementarity

Case II: $2m_\chi < m_{A'}$

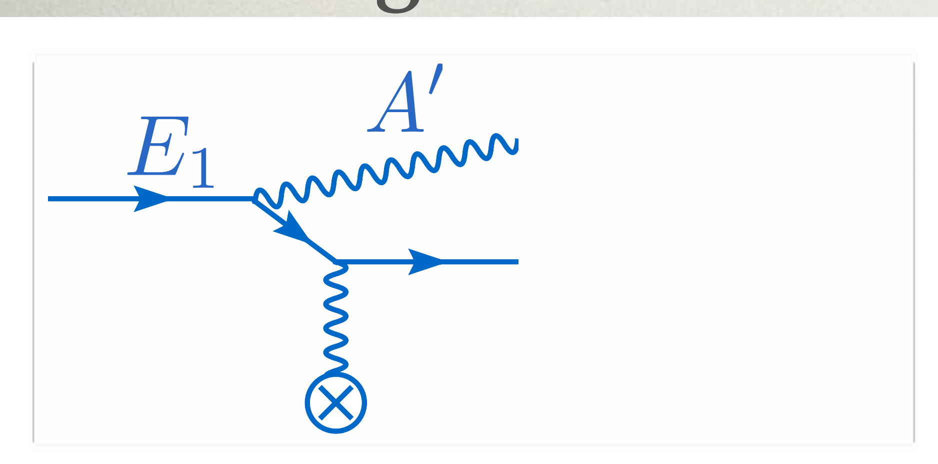
Colliders

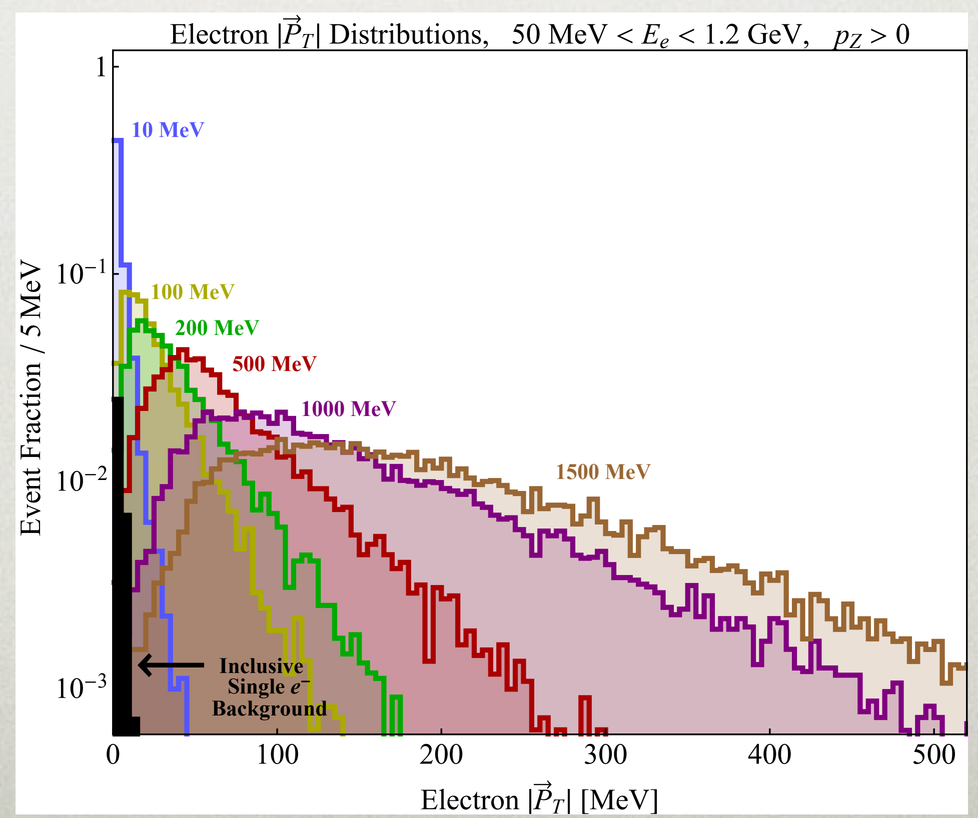




Kinematics gives $m_{A'}$

Fixed-Target





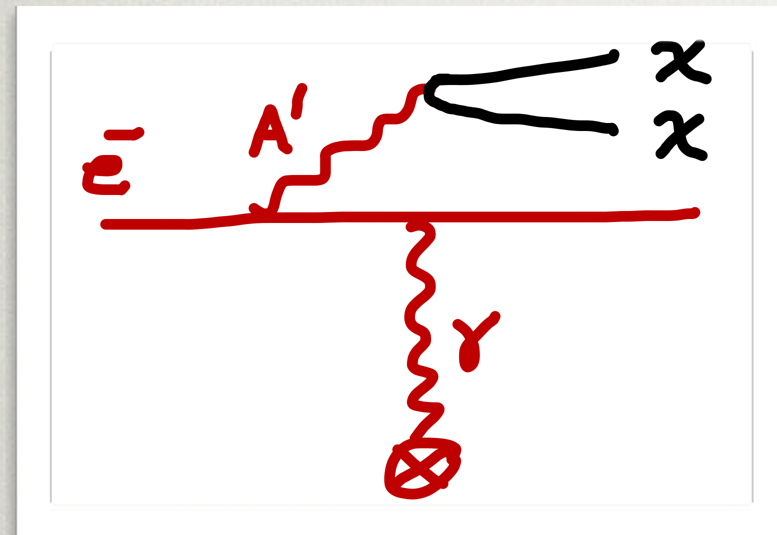
Kinematics gives $m_{A'}$

Missing Mass/Energy/ Momentum

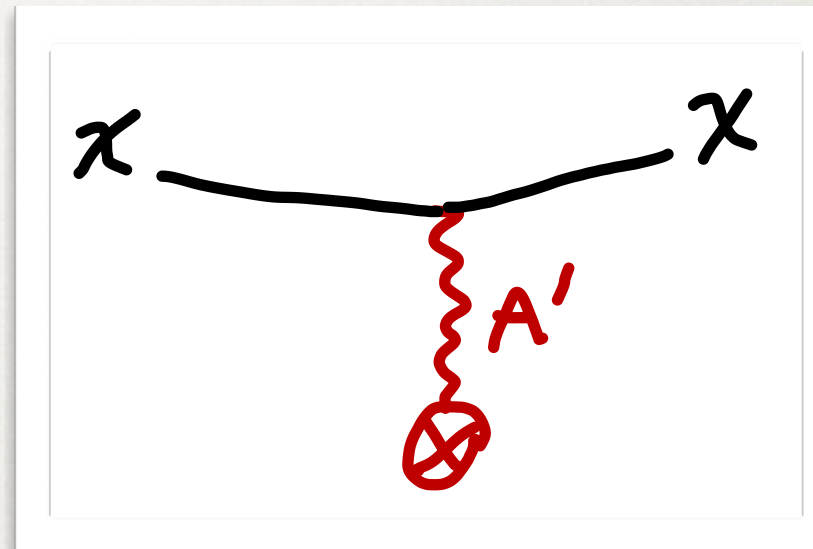
Accelerator Complementarity

Case II: $2m_\chi < m_{A'}$

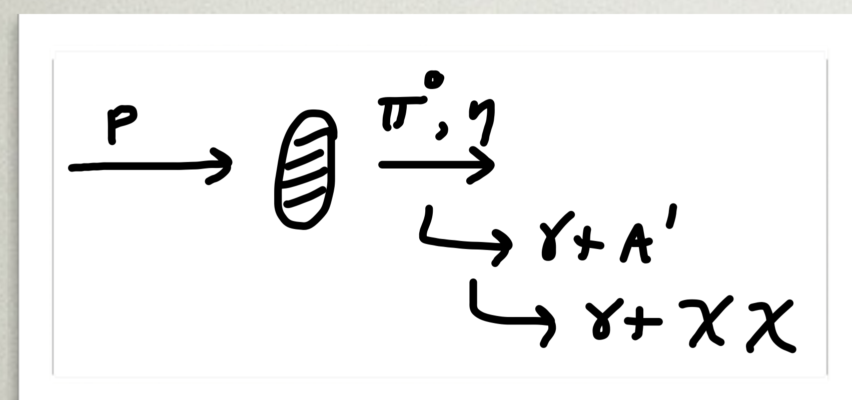
Beam Dump Technique



$$\sigma \sim \epsilon^2 \frac{1}{m_{A'}^2}$$



$$\sigma \sim \frac{\alpha_D \epsilon^2}{m_{A'}^2}$$



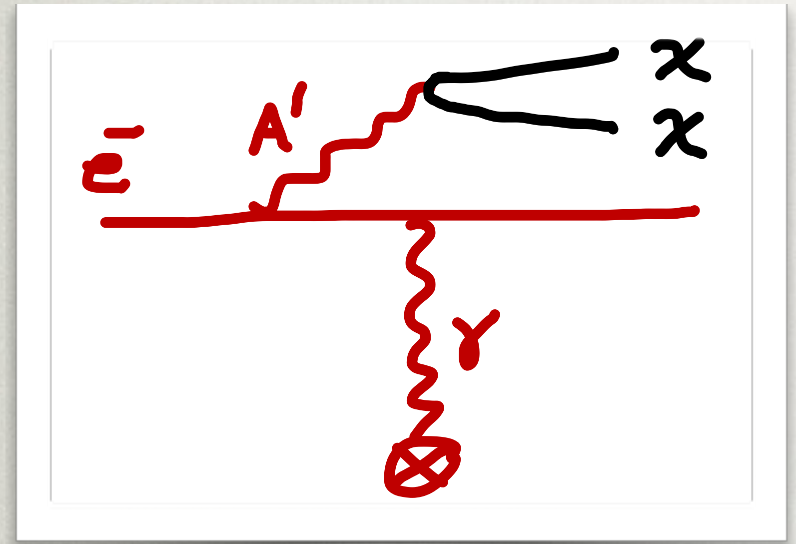
$$\sigma \sim \epsilon^2$$

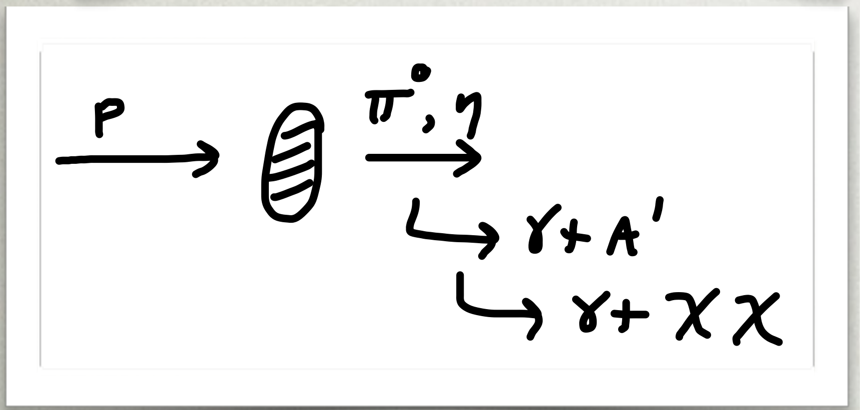
$$N \sim \frac{\alpha_D \epsilon^4}{m_{A'}^2} \quad \text{or} \quad N \sim \frac{\alpha_D \epsilon^4}{m_{A'}^4}$$

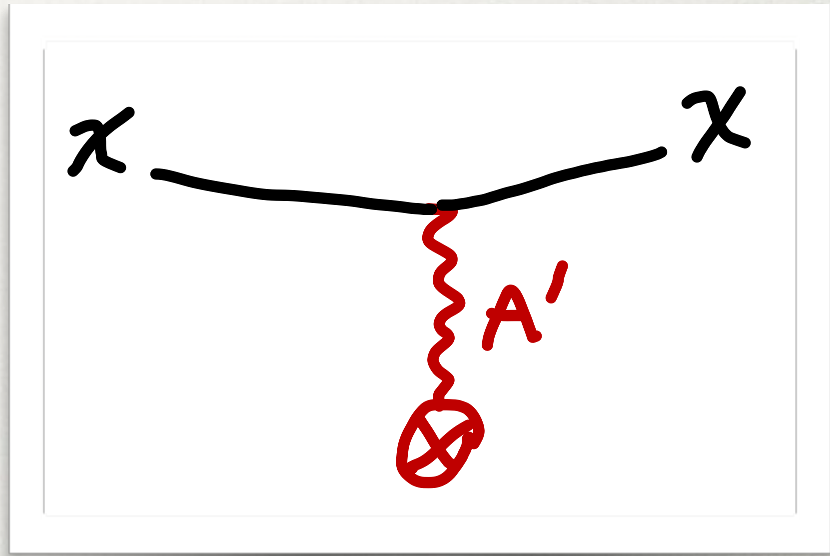
Accelerator Complementarity

Case II: $2m_\chi < m_{A'}$

Beam Dump Technique







Given info about $m_{A'}$ ϵ
provides sensitivity to α_D

Accelerator Complementarity

Case II: $2m_\chi < m_{A'}$

Can separately measure:

$m_{A'}$ ϵ α_D

From missing mass/momentum exp. From beam-dump exp.

Accelerator experiments can almost untangle the physics in detail

Need Direct Detection to measure m_χ **and verify cosmological stability**

Conclusions

- Thermal dark matter is simple, predictive, and arguably the least speculative possibility.
  If we do nothing else, we should test this idea!

- The broad vicinity of the weak scale is an excellent place to be looking — the logical extension to the WIMP program.

- Accelerator experiments are in the best position to test (i.e. rule out or discover) light thermal DM — **all** important scenarios are within 1-3 orders of magnitude of existing experiments' cross-section reach.

- Accelerator experiments can also make a decisive discovery, and combined with direct detection experiments, can reveal the underlying dark sector physics