Dark Sectors

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ICFA Seminar
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What is a Dark Sector?

Key idea: A new force may be essential to the physics of Dark Matter!

Analogy w/ Nuclear structure & hadron spectrum –
*Puzzles about structure of **matter** led to prediction of **new forces** & related symmetries up to 40 years ahead of their time*


x17

The idea of dark forces motivates qualitatively new parameter space, where important targets can be explored by small experiments

WIMPs: Confluence of Motivations

Simple, familiar Particle Content:

New Standard-Model-like matter at Standard-Model-like scales

in particular, weak-scale matter with weak interactions

particularly motivated by hierarchy problem – why is the gravitational force between fundamental particles so weak?

A simple, predictive explanation for origin of dark matter:

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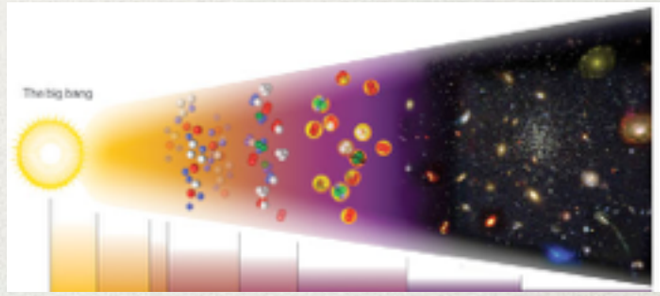

Prediction from common history + measured abundance:

Assume TeV-scale mass

$\longleftrightarrow$

Weak-ish interaction strength

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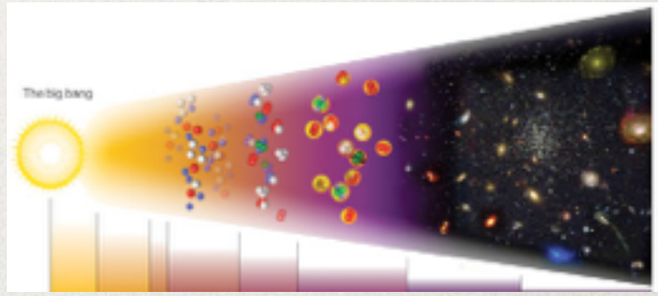

Prediction from common
history + measured

Constraints on WIMPs and TeV-scale physics more generally motivate a modest generalization of this picture

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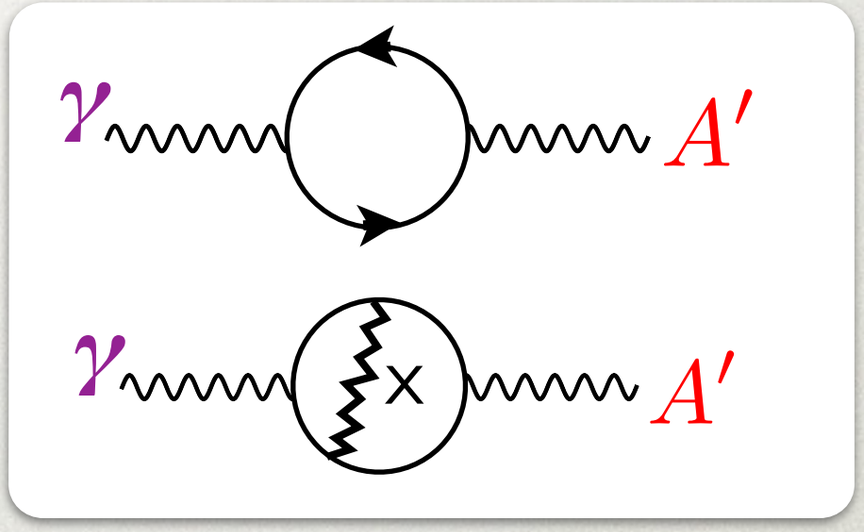
Familiar matter must be neutral under these forces – so how would we test it?

Residual interactions from quantum corrections:



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Weak enough to be missed experimentally so far

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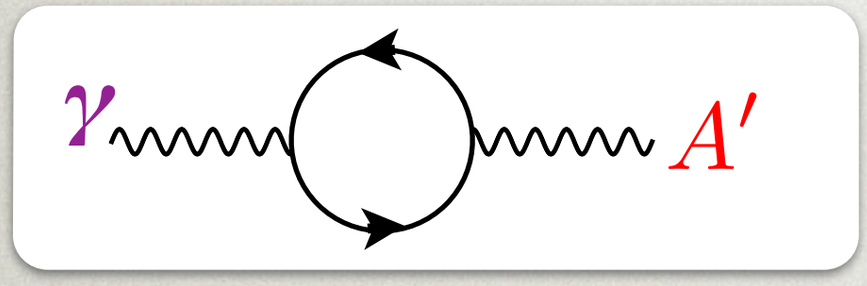

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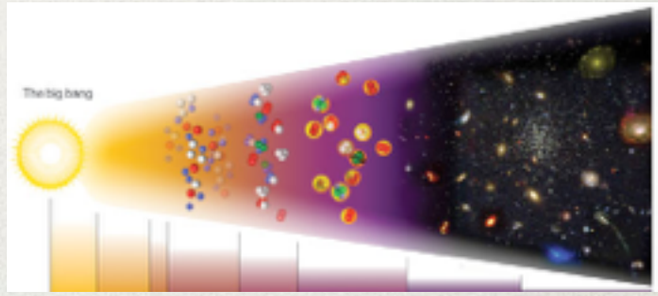

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Very weak coupling

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Lower (MeV-GeV) mass

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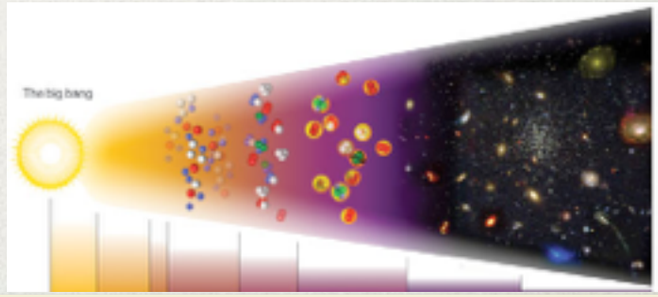

A simple & motivated extension of WIMP paradigm

$g_{\rm eff} \sim (10^{-6} - 10^{-2})e$

Weak enough to be missed experimentally so far

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- Unlocking a dark sector will open up a wealth of new questions about nature
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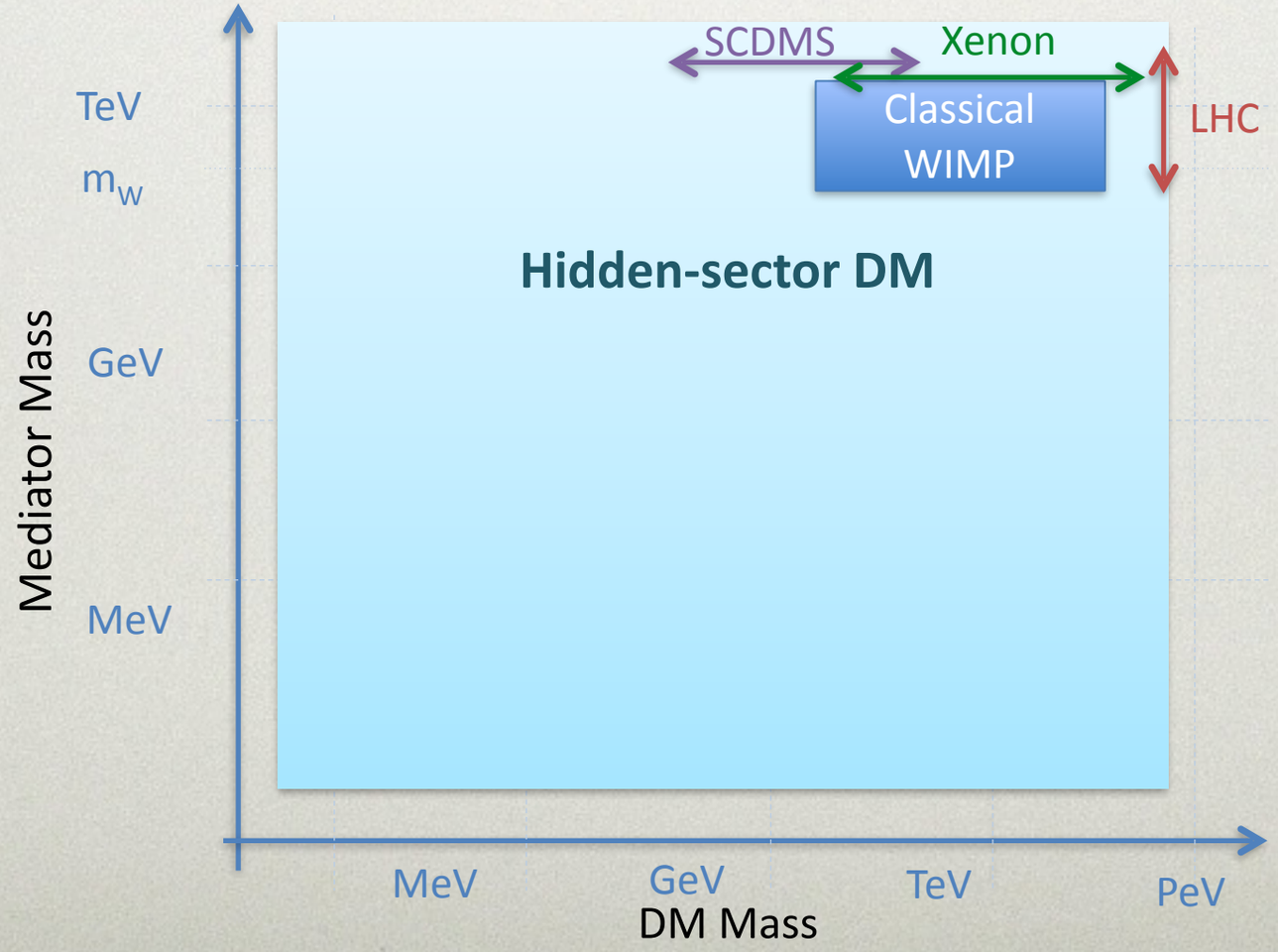

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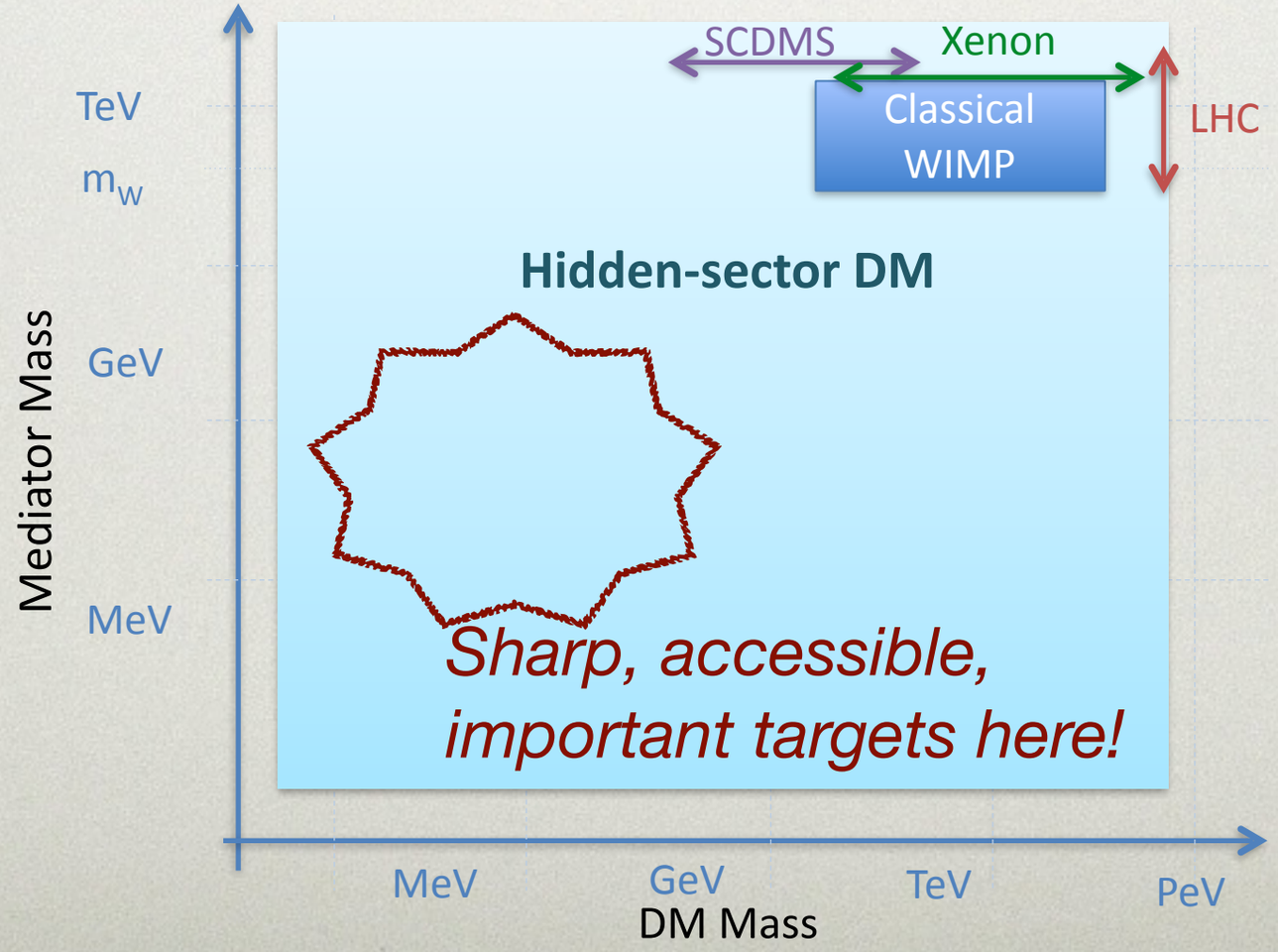
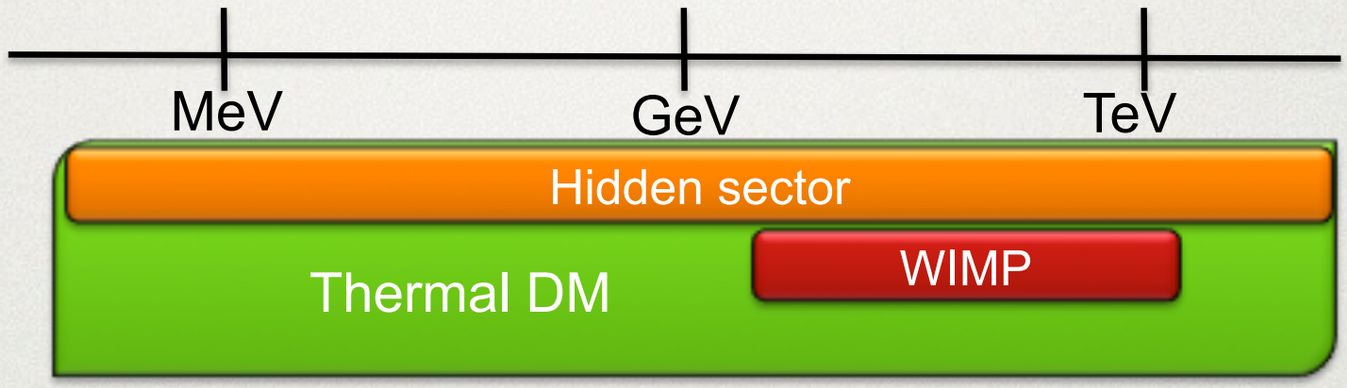


Outline

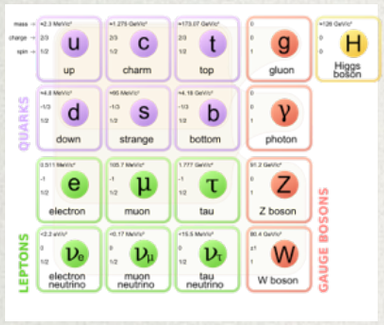
- Hidden sector DM **extends thermal DM** to sub-GeV mass range, maintaining WIMP motivation of **SM-like matter at SM-like scales**



- Framework for systematic exploration, where these motivations lead to new, predictive milestones
- Opportunities to test this hypothesis with new small experiments

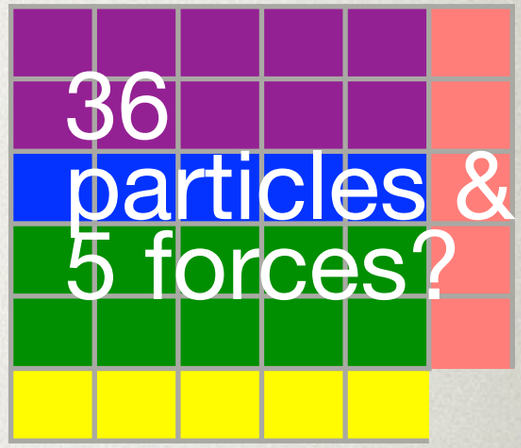
Defined Possibilities

- Whether dark sector is simple … or complex,



+ …

a DM particle +force?



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- Standard Model symmetries restrict its **interactions with us** to two types

Defined Possibilities

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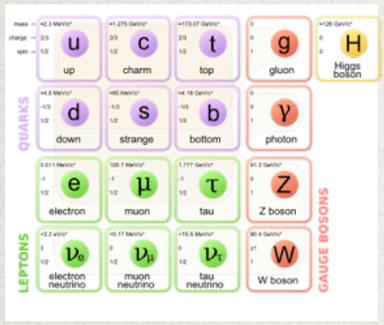

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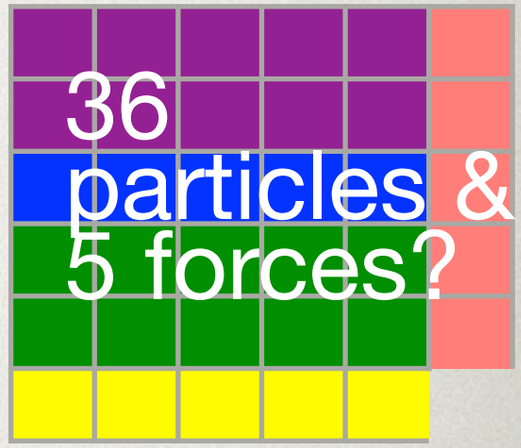

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✦ Standard Model symmetries restrict its **interactions with us** to two types

Vector Portal $\frac{1}{2}\epsilon_Y F'^{\mu\nu} F^Y_{\mu\nu}$

New spin-1 "dark photon" mixes with photon → couples to electric charge

Conserved charge can also explain dark matter's stability

Higgs Portal $\epsilon_h |\phi|^2 |h|^2$

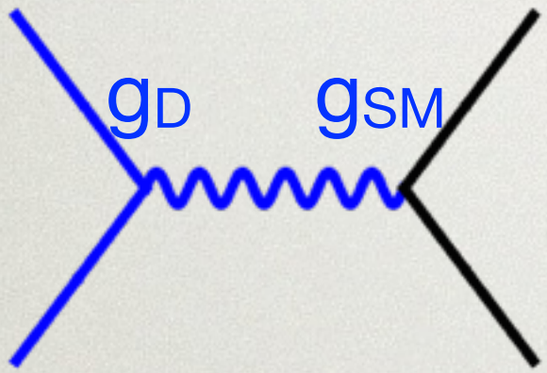
New spin-0 "dark Higgs" mixes with SM Higgs → couples to lepton & quark masses

New TeV-scale matter or other SM extensions allow related possibilities, with different charge assignments

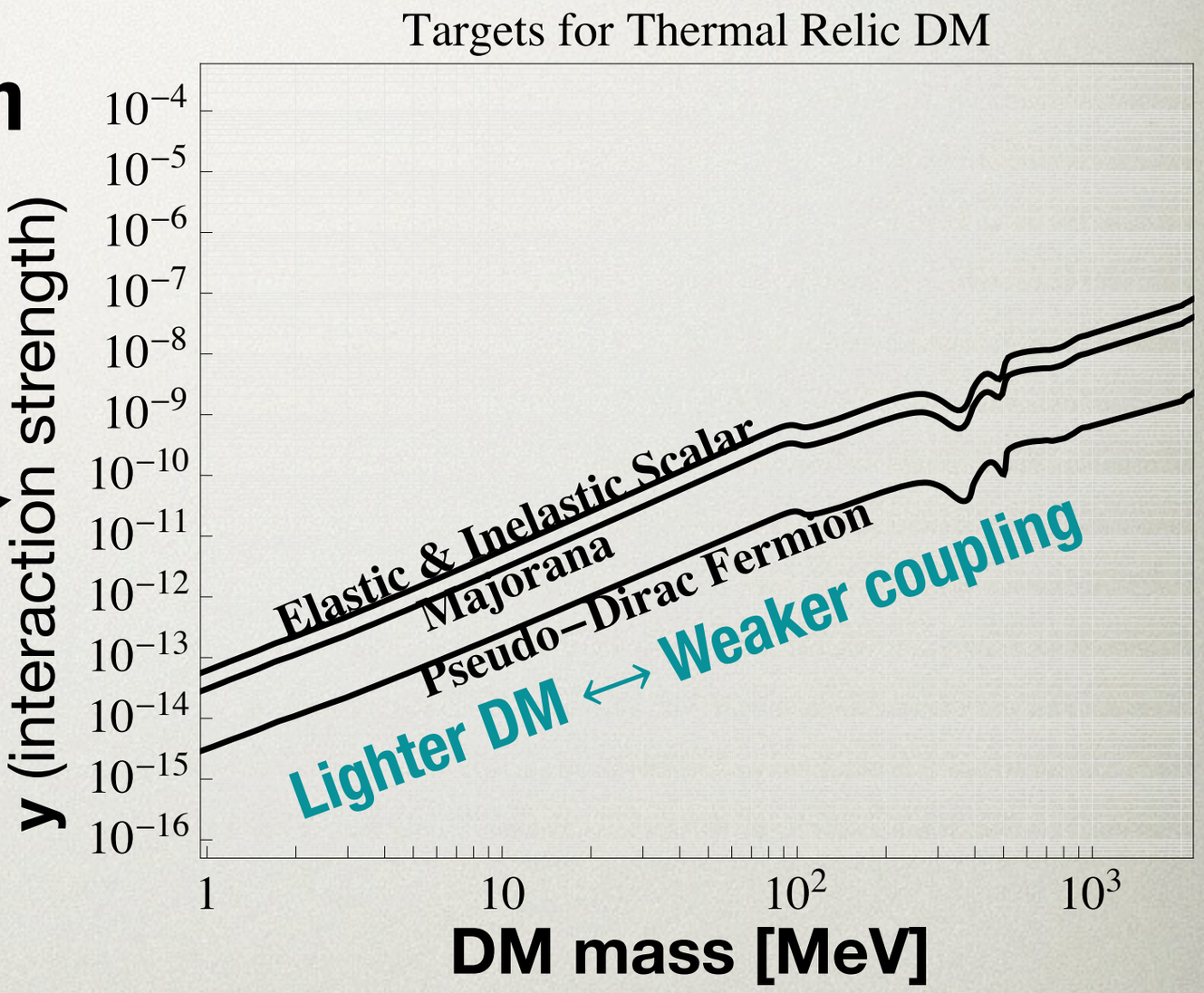
Sharp Targets for Coupling

✦ Follow directly from the motivations above

(1) Annihilation rate of thermal dark matter fixes a combination of DM and SM charges



$$y \equiv g_{SM}^2\, g_D^2\, m_{DM}^4 / m_{Med}^4$$



predicted interaction rate depends mildly on dark matter particles' spin

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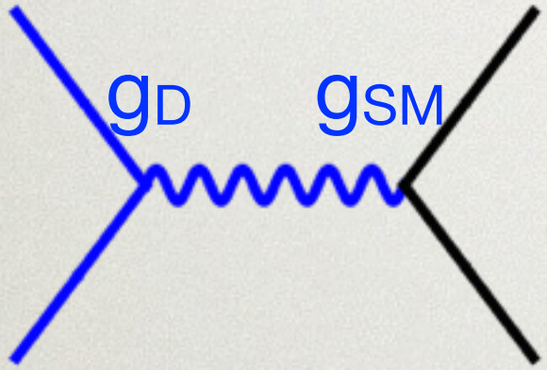

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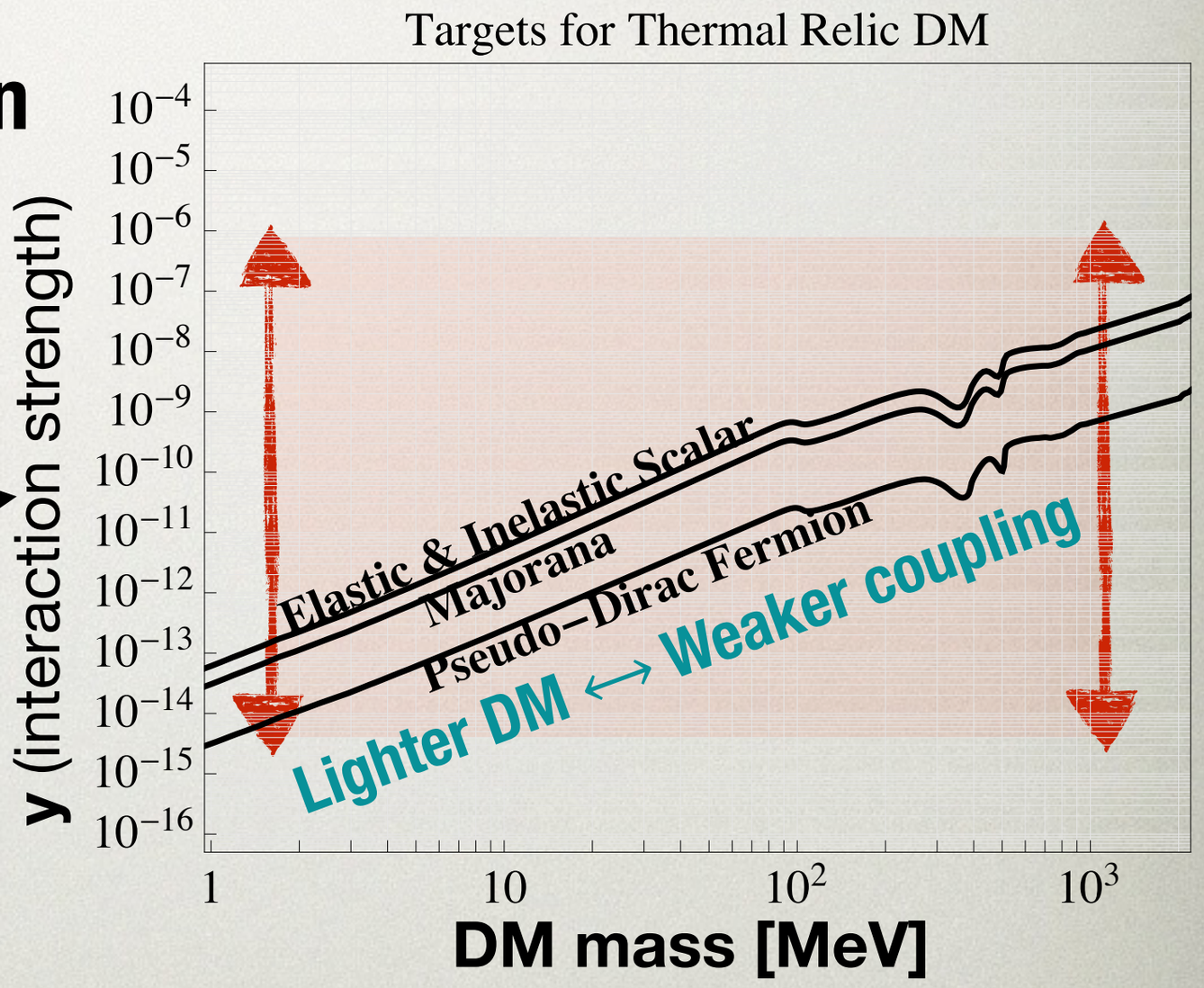
(2) Expected strength of interactions generated by quantum corrections (assume SM-like couplings and O(1) mass ratios in dark sector)



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Lessons for Experiment

- Hidden-Sector Dark Matter is highly motivated and predictive, but experimentally elusive

- Standard Model-like dark matter could be much lighter than WIMPs suggest
  - Thermal origin motivates sharp coupling vs. mass milestone
  - Look for **scattering** → lower energy threshold
  - Look for **laboratory production** → modest energy sufficient, but need high intensity and/or precision

- Look directly for new force!
  - High-precision measurements
  - **Resonant mediator production** in particle collisions → again need intensity

Vibrant, World-Wide Program

Light DM production

Light DM scattering

Resonant mediator searches

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

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 Ess[illegible] an L. Feng (WG4 Conv[illegible] Convener),[3] Peter Gra[illegible]ik (SAC member),[3] [illegible]or),[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

Dark Sectors 2016 Workshop: Community Report

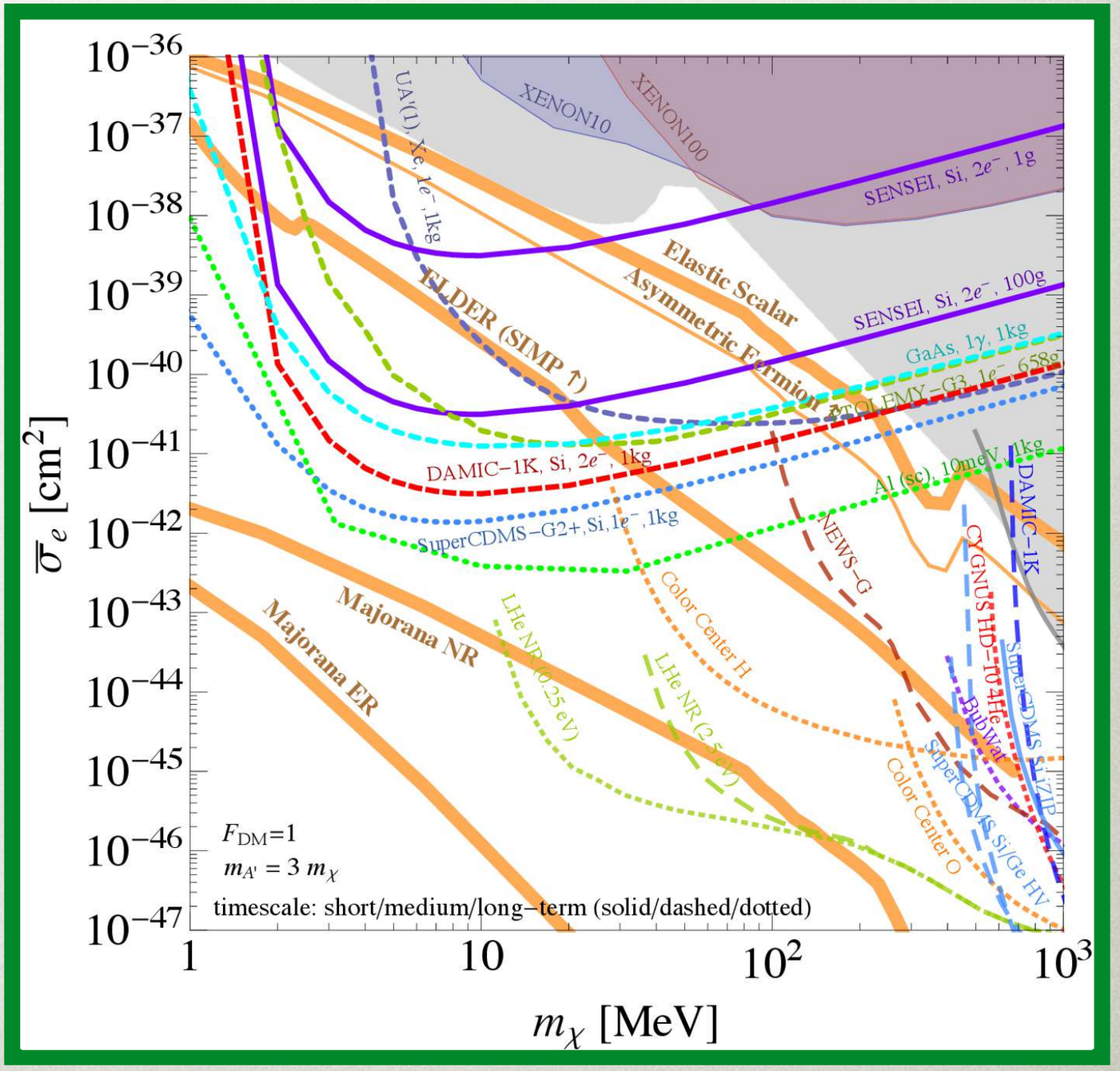
Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] [illegible] (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan Krnjaic (DM[illegible] rissey (RDS Convener),[9] T[illegible]),[1] Matt Pyle (DD Convener[illegible] er),[5,6,¶] Brian Shuve (RDS Convener),[5] Natalia Toro (Organizer),[5,6,**] Richard G Van De Water (DMA Convener),[12] Daniel Akerib,[5,13] Haipeng An,[3] Konrad Aniol,[14] Isaac J. Arnquist,[15] David M. Asner,[15] Henning O. Back,[15] Keith Baker,[16] Nathan Baltzell,[17] Dipanwita Banerjee,[18] Brian Batell,[19] Daniel Bauer,[7] James Beacham,[20] Jay Benesch,[17] James Bjorken,[5] Nikita Blinov,[5] Celine Boehm,[21] Mariangela Bondí,[22] Walter Bonivento,[23] Fabio Bossi,[24] Stanley J. Brodsky,[5] Ran Budnik,[25] Stephen Bueltmann,[26] Masroor H. Bukhari,[27] Raymond Bunker,[15] Massimo Carpinelli,[28,29] Concetta Cartaro,[5] David Cassel,[1,5] Gianluca Cavoto,[30] Andrea Celentano,[2] Animesh Chaterjee,[31] Saptarshi Chaudhuri,[8] Gabriele Chiodini,[24] Hsiao-Mei Sherry Cho,[5] Eric D. Church,[15] D. A. Cooke,[18] Jodi Cooley,[32] Robert Cooper,[33] Ross Corliss,[34] Paolo Crivelli,[18] Francesca Curciarello,[35] Annalisa

Vibrant, World-Wide Program

Light DM production

Light DM scattering

Resonant mediator searches



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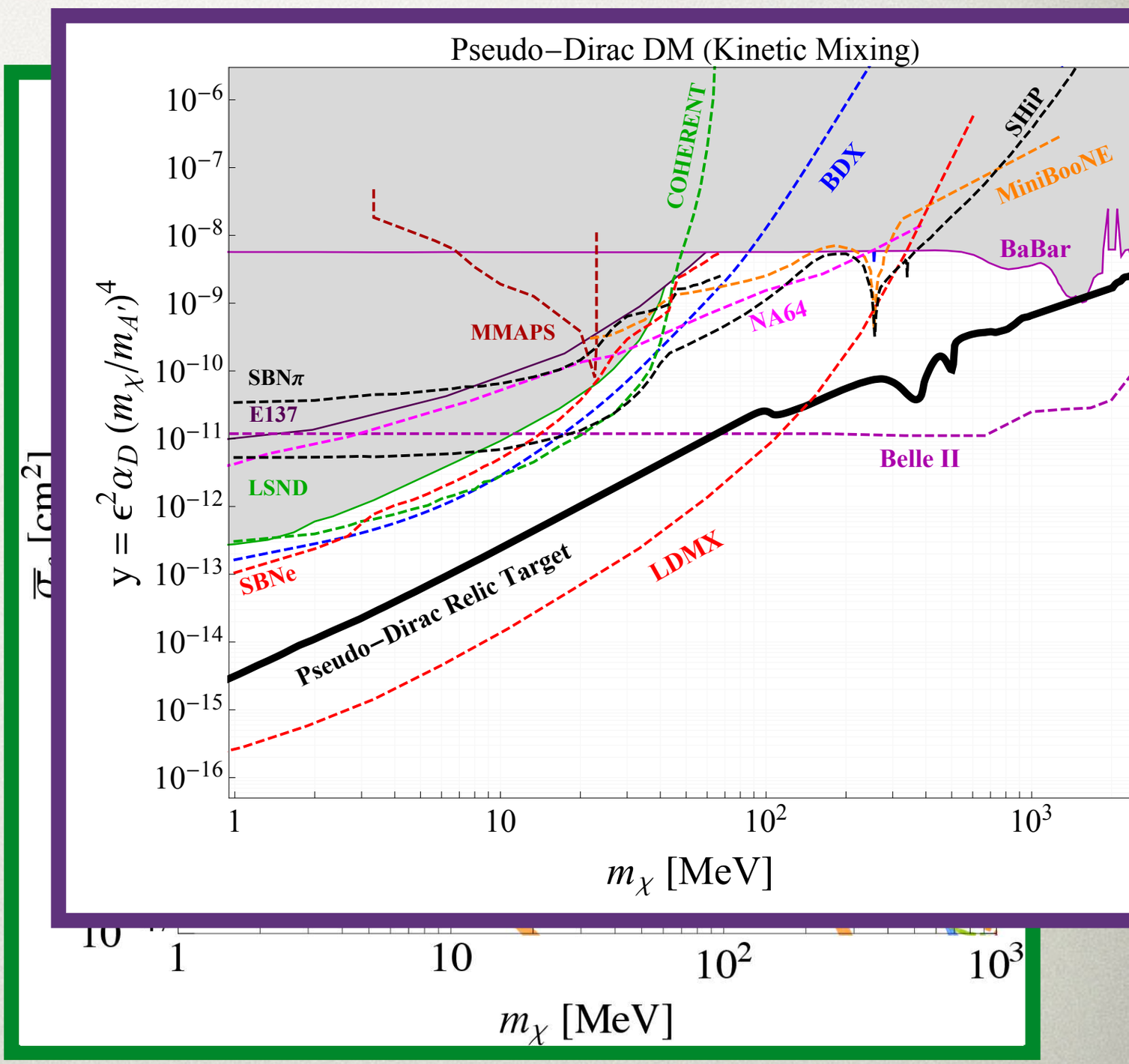

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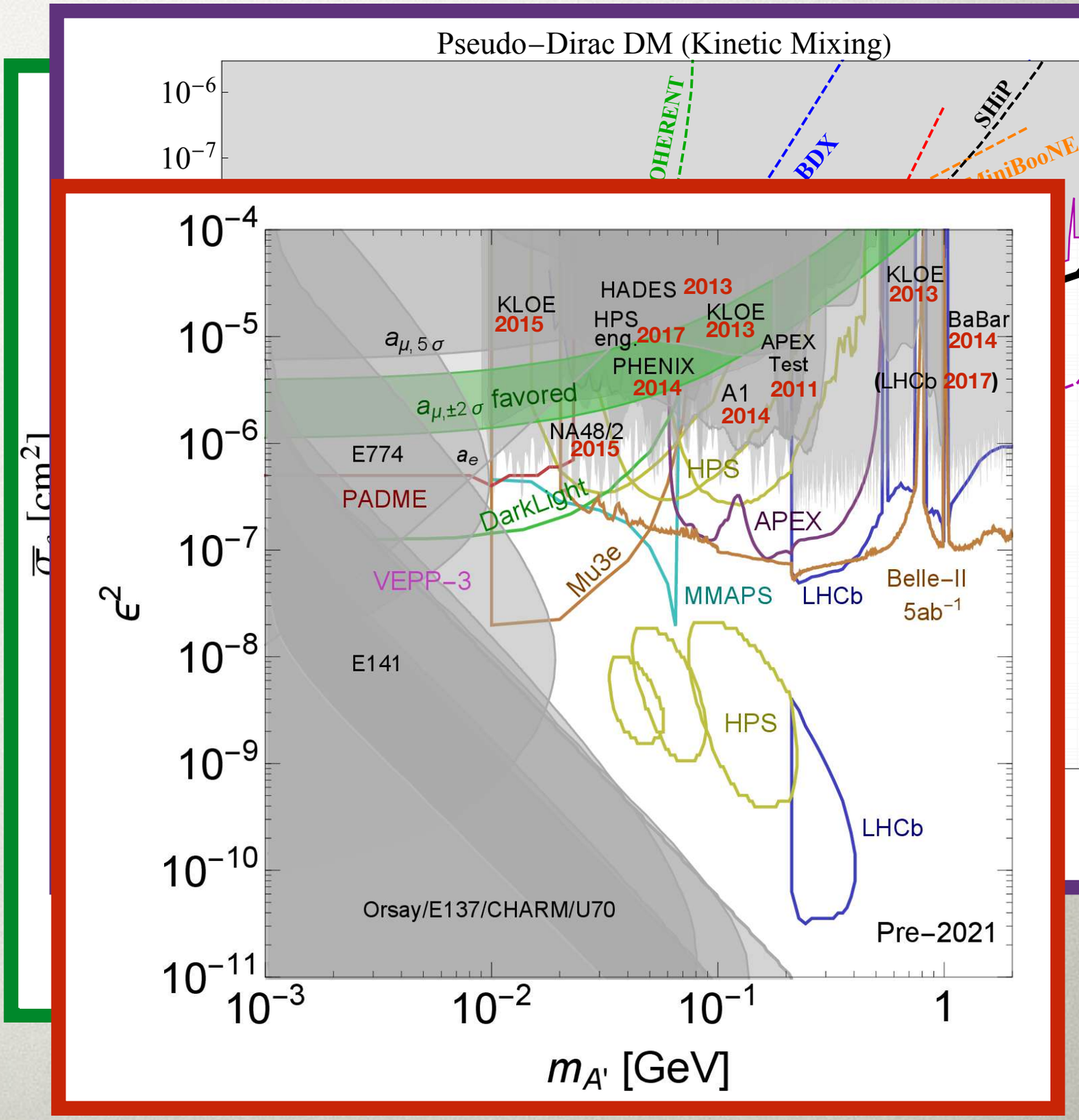


Resonant mediator searches

Need for Multi-Pronged Search

Fully explore the simple thermal models motivated earlier

Light DM production

Where multiple searches explore the same candidate, they give complementary insights

Light DM scattering

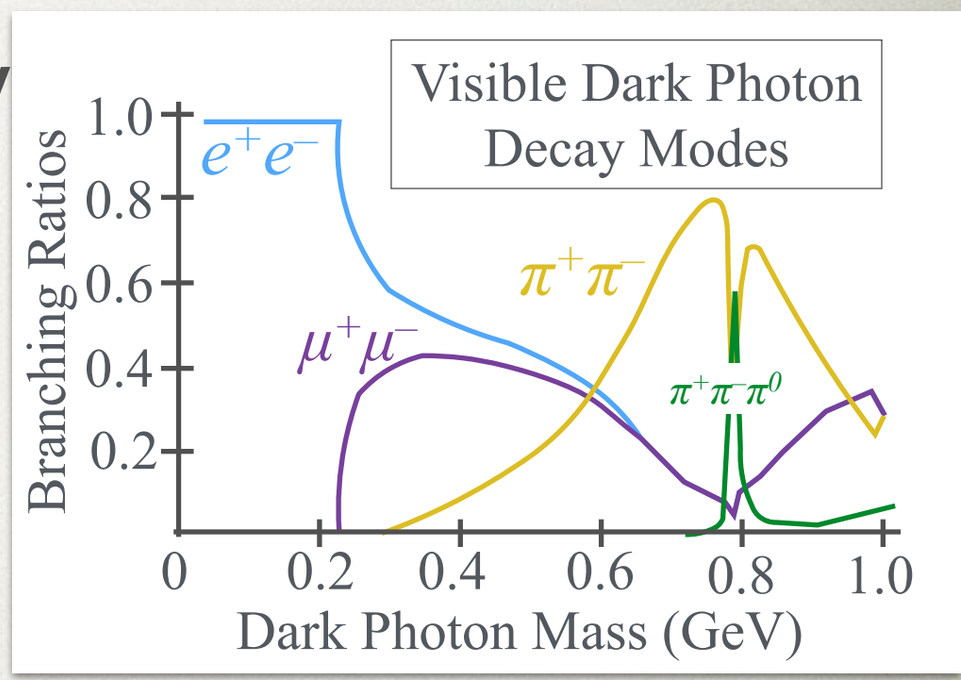
Unique sensitivity to models with very light (sub-keV-scale) mediators

Resonant mediator searches

Probe models with mediator lighter than dark matter (even if DM is heavy)

Mediator Searches

- If mediator too light to decay into DM, will instead decay to visible matter
- Searches exploit several production modes
  - bremsstrahlung
  - meson decays
  - e^+e^- annihilation
  - Drell-Yan



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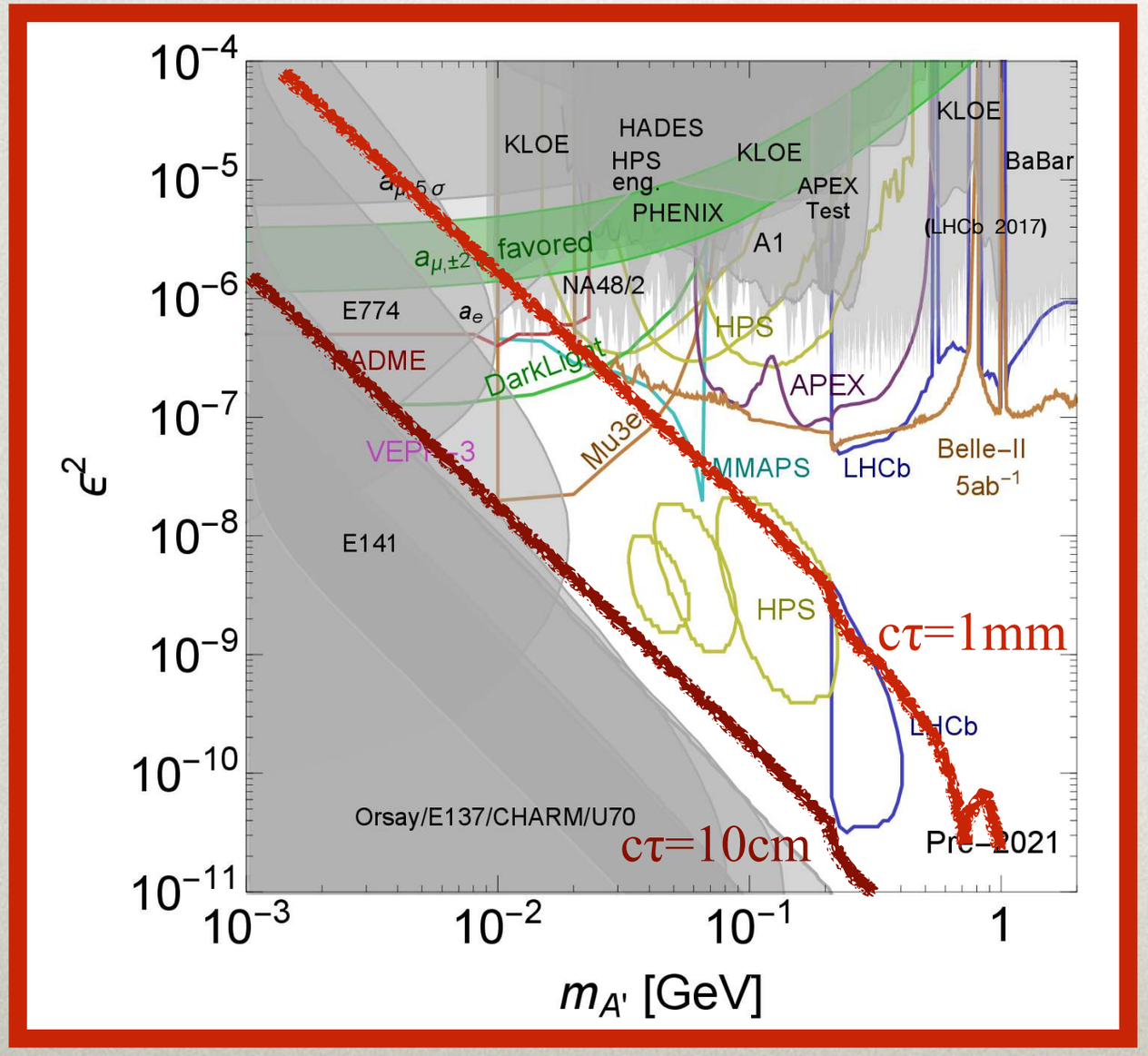

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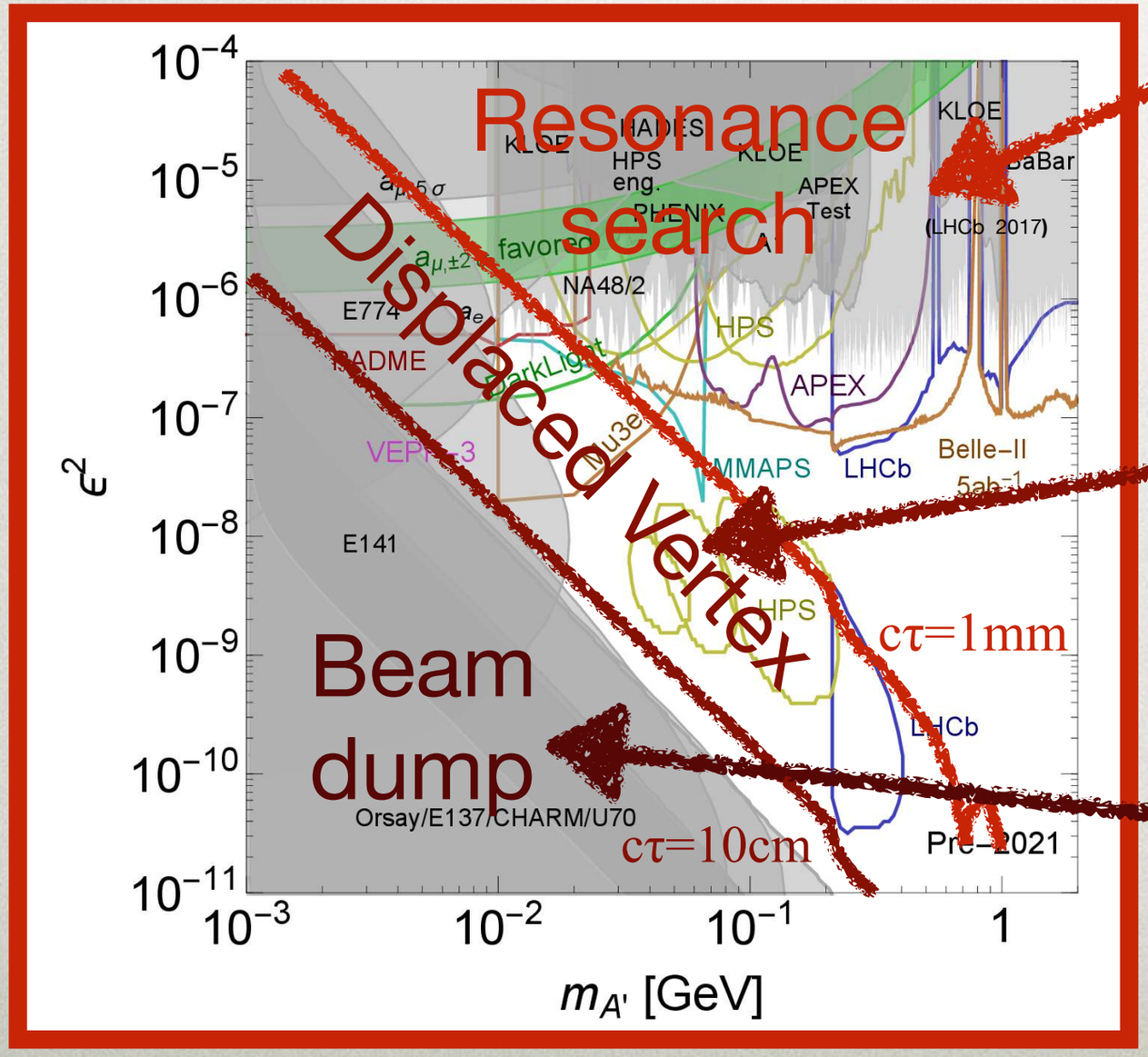
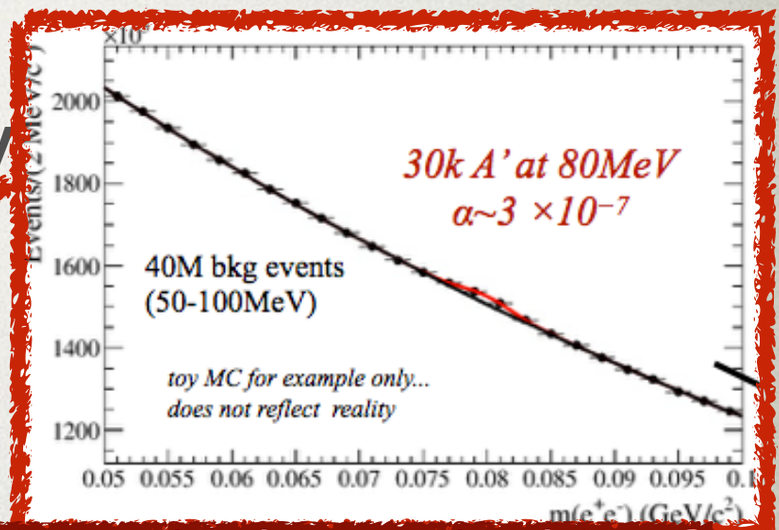
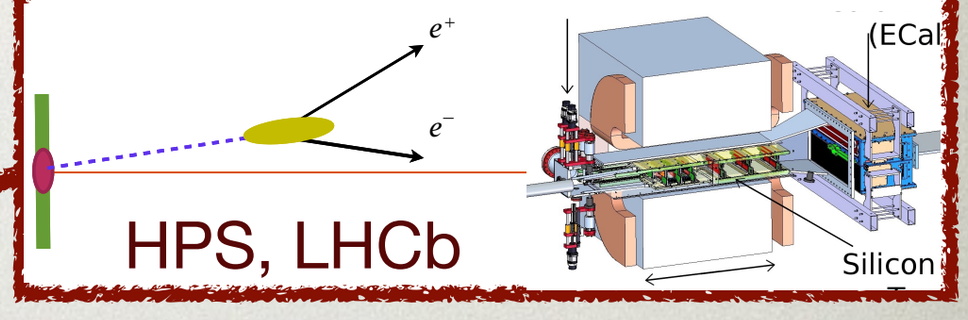
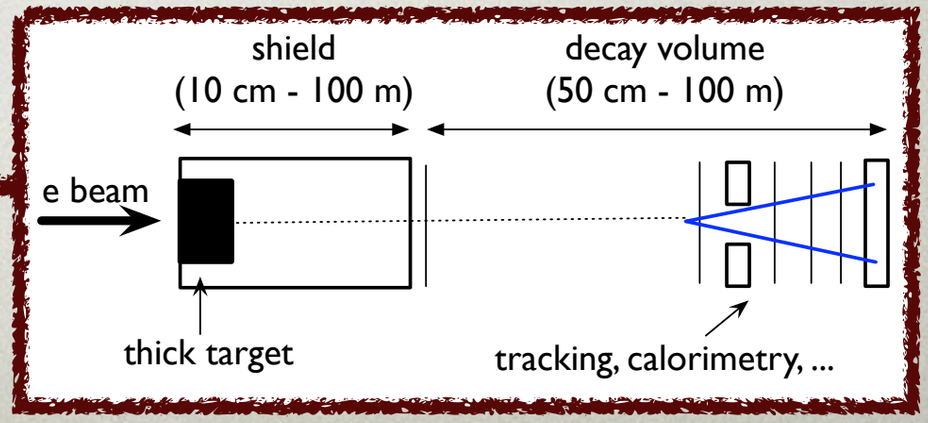


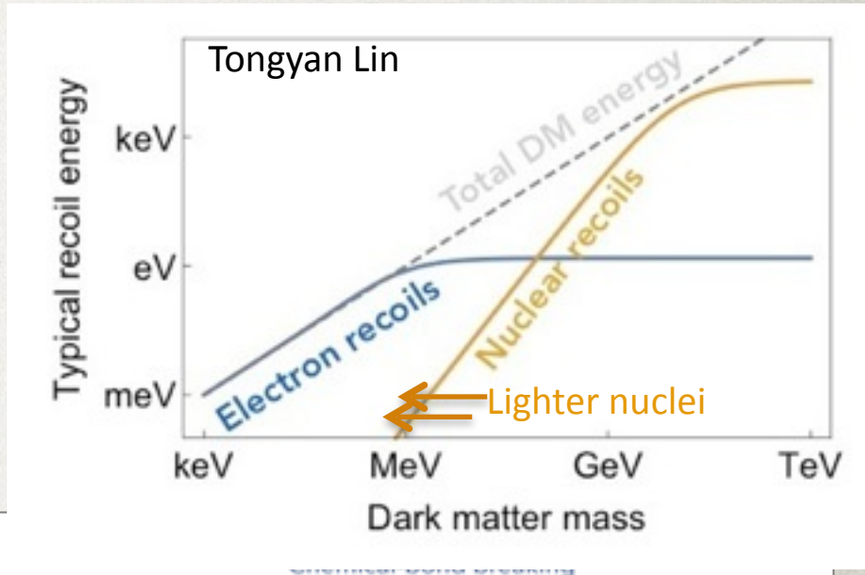




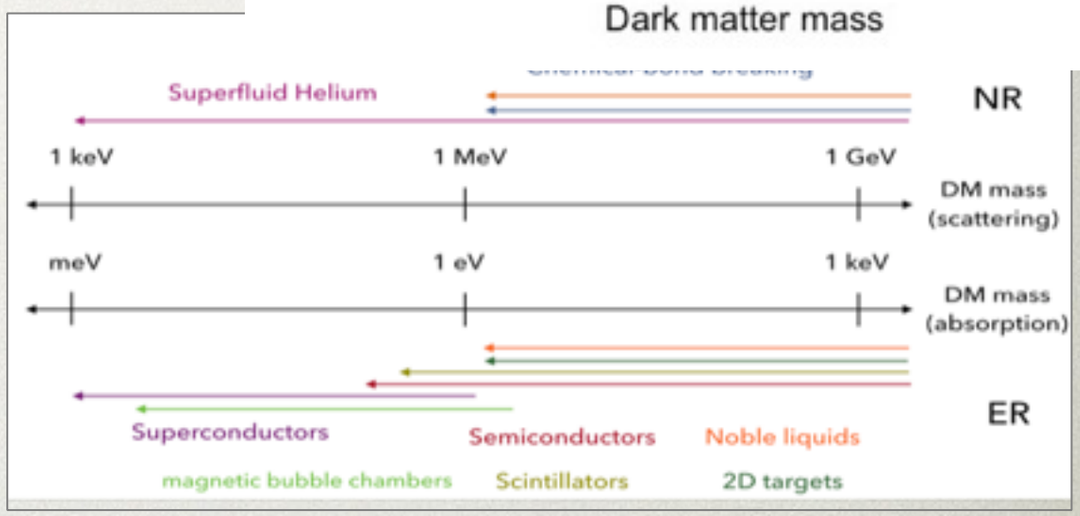


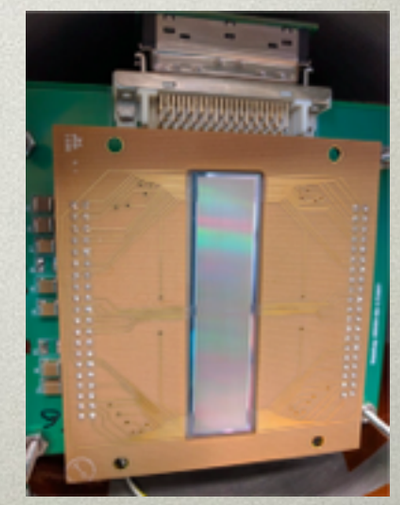
Low-Threshold Direct Detection

- **Challenge**: light dark matter gives lower-energy recoils **– but dramatic gains achievable with sub-kg detectors**



- Calls for
  - Detecting DM scattering off electrons or low-mass nuclei
  - Exploiting low-threshold processes and new readout technologies
- Examples
  - SuperCDMS in high-voltage mode can explore ≳400 MeV mass via Silicon recoil
  - SENSEI using eV-scale electron recoils in skipper CCDs to probe ≳2 MeV dark matter
  - Longer-term R&D ideas: magnetic bubble chambers, superfluid He, superconductor, … to reach ~keV DM masses





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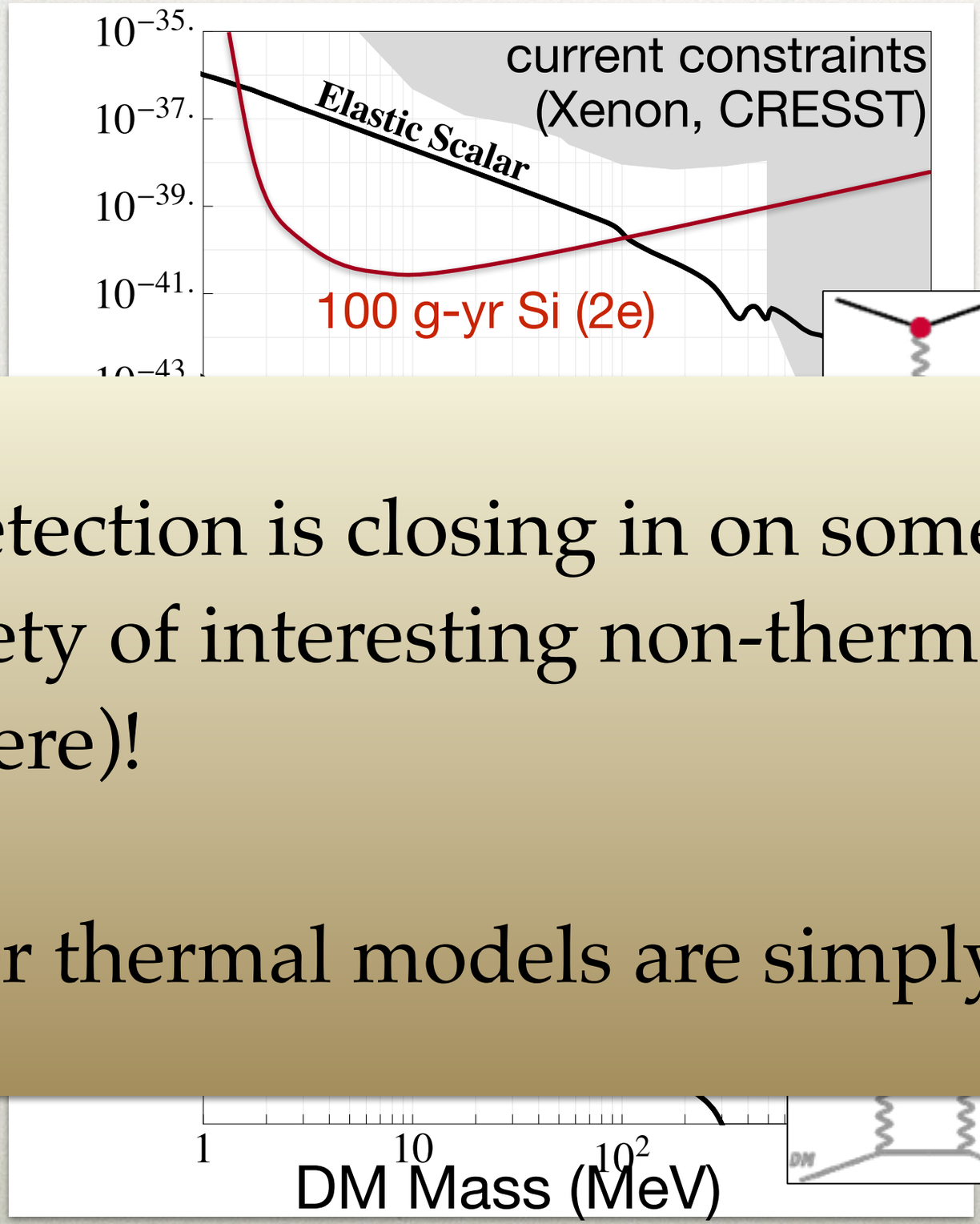
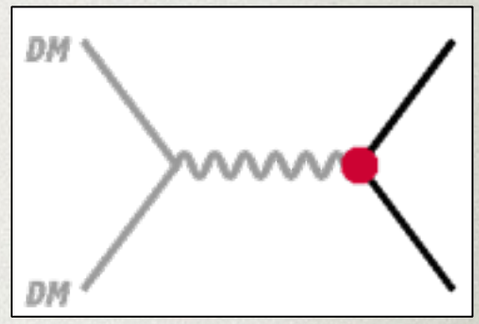


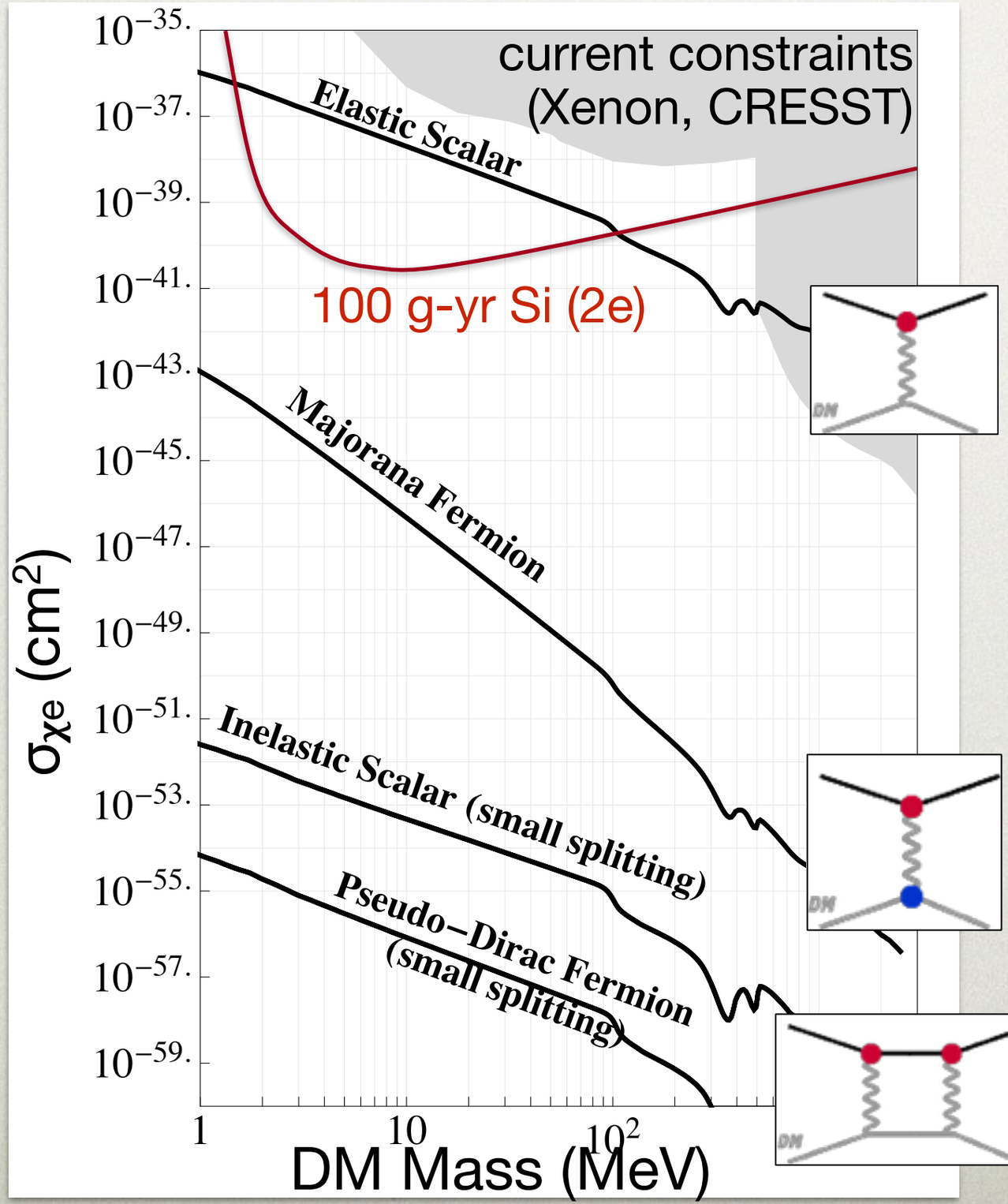


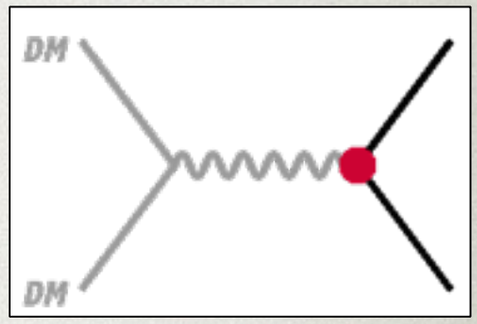
Direct detection is closing in on some thermal models (+ a variety of interesting non-thermal ones, not shown here)!

But other thermal models are simply unreachable.

- Velocity-suppression

Low-Threshold Direct Detection





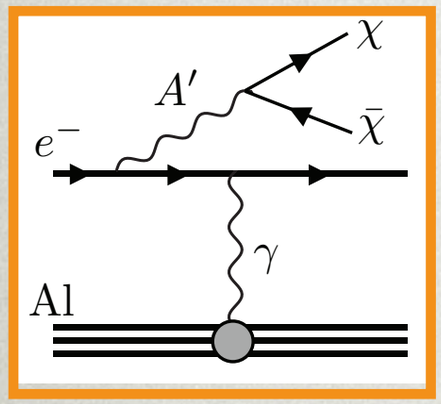
Dark matter halo is non-relativistic! (10^{-3} c) ⇒

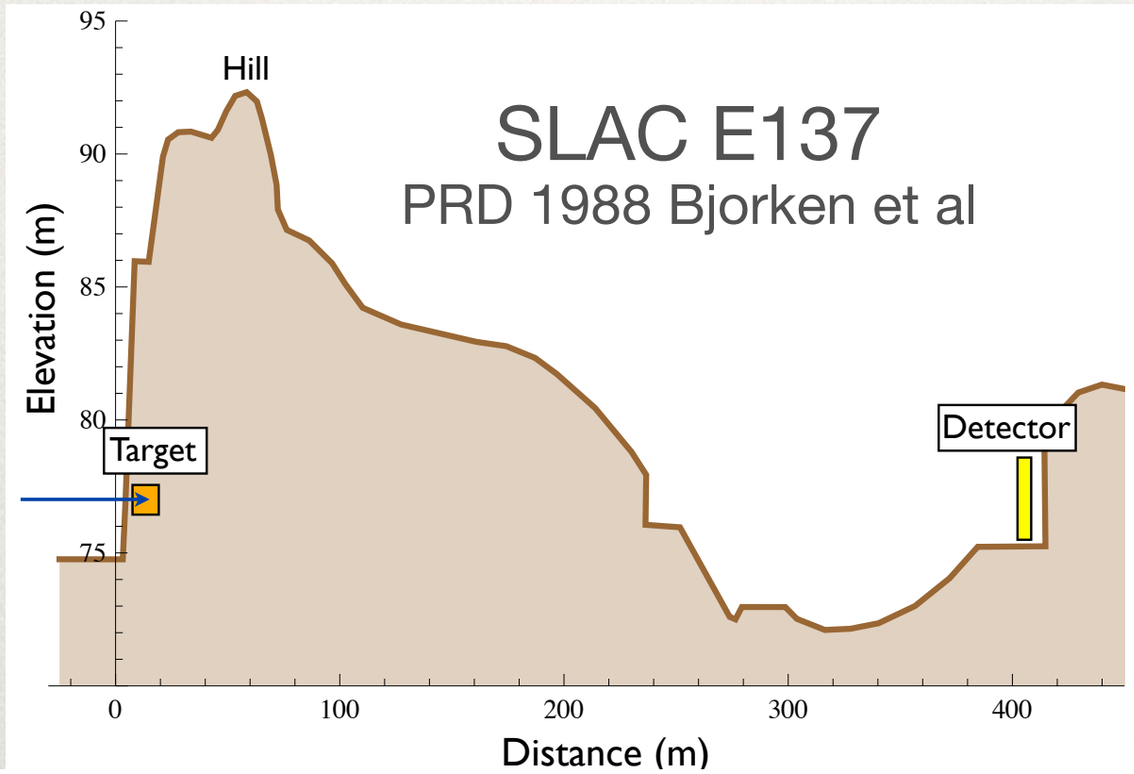
Xsec predictions spread over tens of decades, much like for WIMPs!

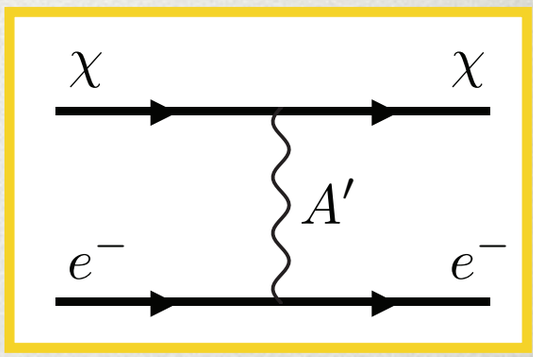
- Small DM-SM coupling
- Velocity-suppression

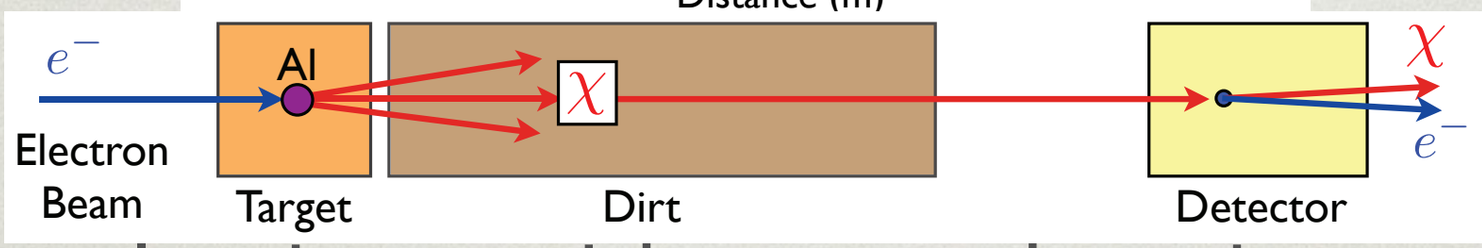
Dark-Matter Production I

- **Remedy:** make relativistic dark matter!
  - there are already powerful constraints on such production from experiments >30 years ago









  - Accelerator neutrino experiments can do this too
  - Powerful & cost-effective (parasitic) new proposals use both electron and proton beams – but hard to scale up!

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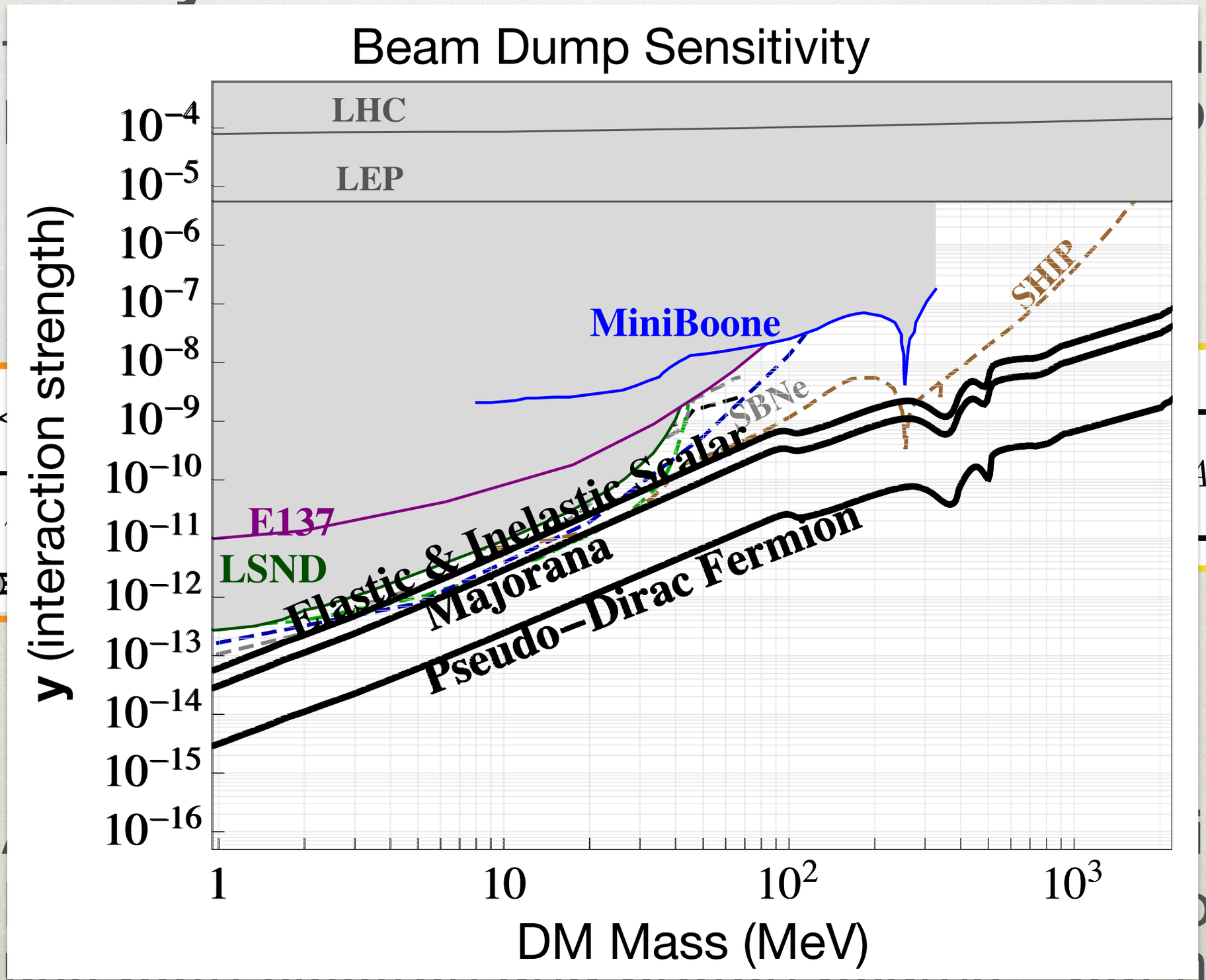
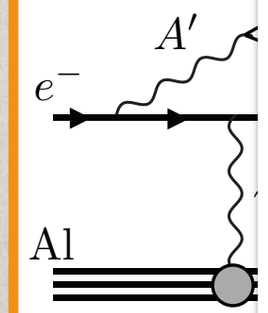
✦ **Remedy:** make relativistic dark matter!

– …ich …





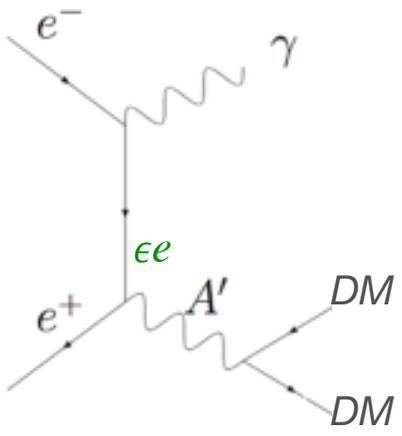
– …is too

– …oposals …ard to scale up!

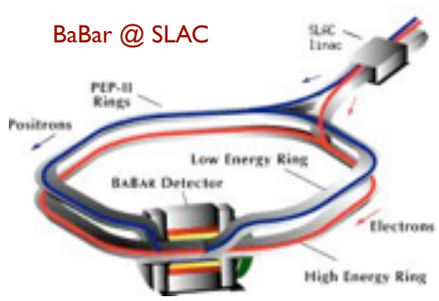
Dark-Matter Production II

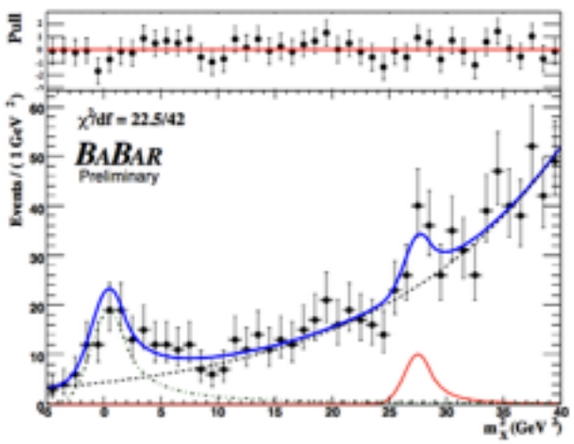
- To beat this scaling, must detect dark matter production via kinematics of visible final states
  - need signal yield∝y and low background

Missing Mass (e^+e^- colliders)
= full kinematic reconstruction



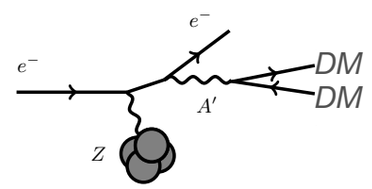
BaBar @ SLAC



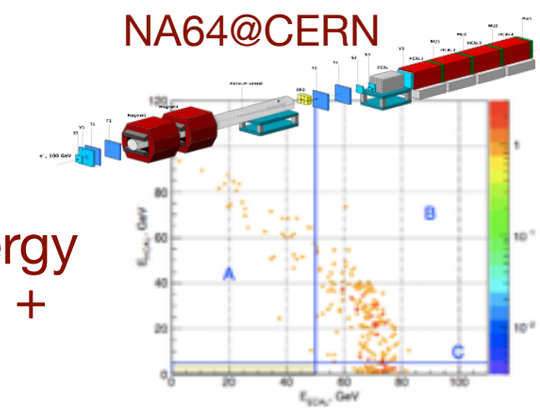


Belle II

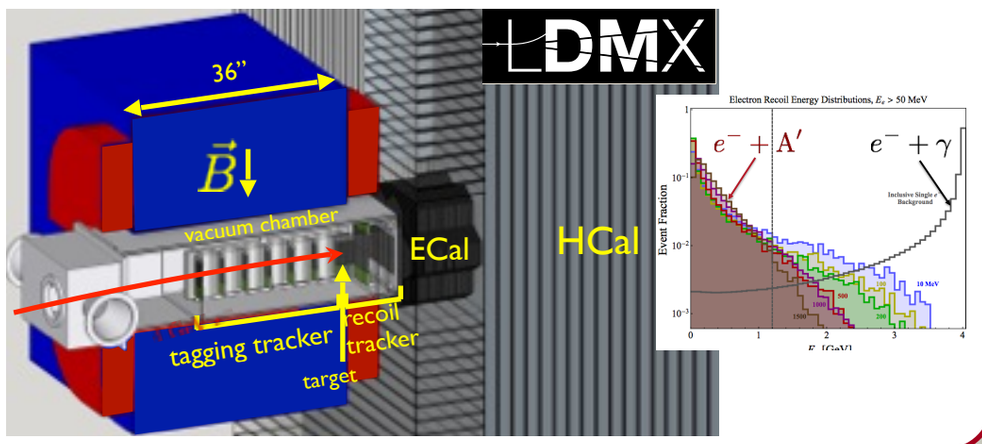
Missing Energy/Momentum
(e^- fixed target)
= partial kinematic reconstruction



NA64@CERN



Signal: low-energy recoil electron + nothing else

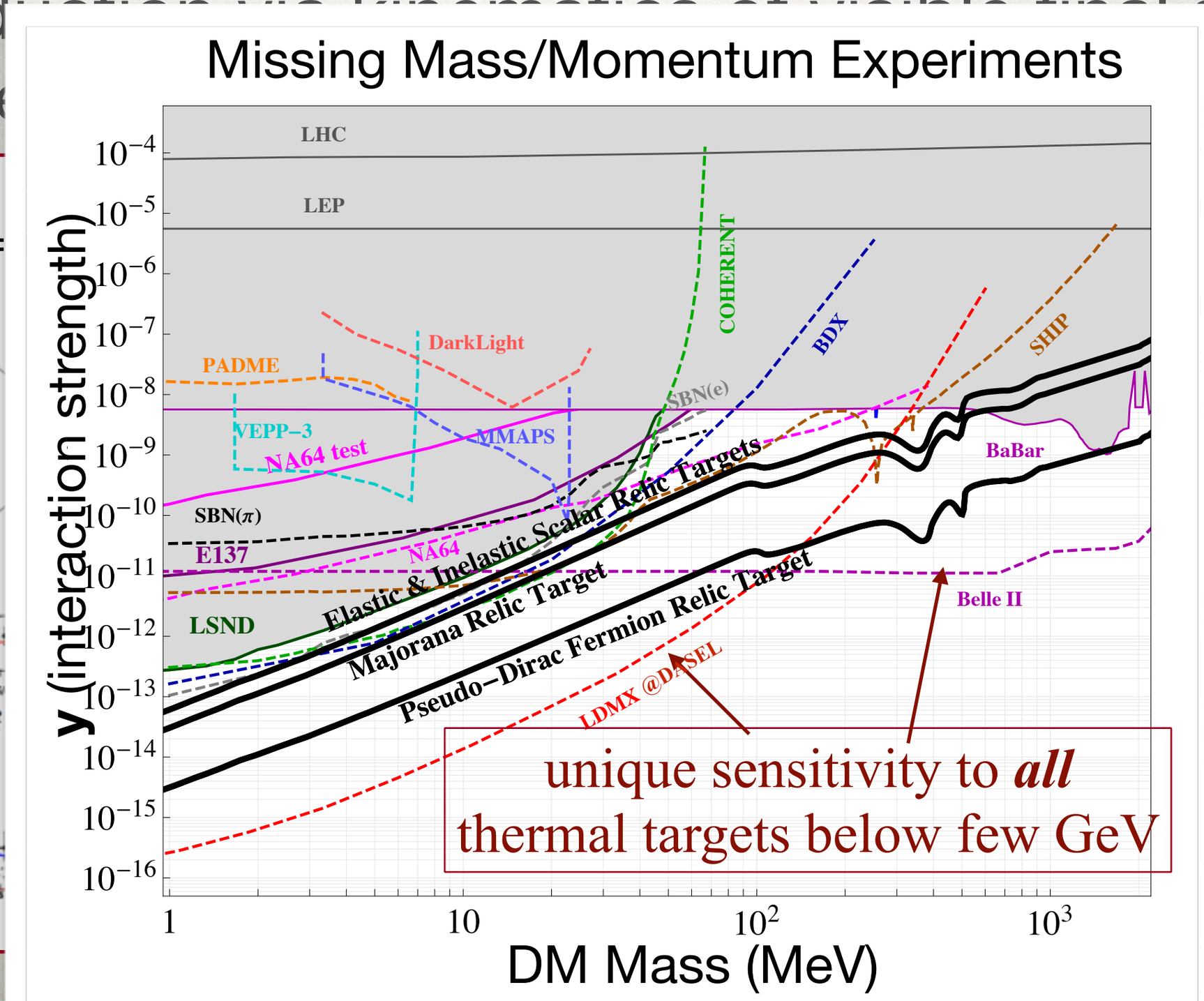


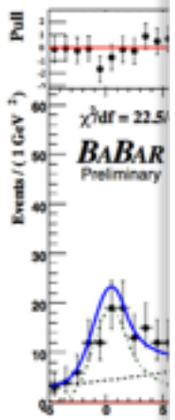
~0.1 – 10 GeV Dark Matter
(ongoing projects)

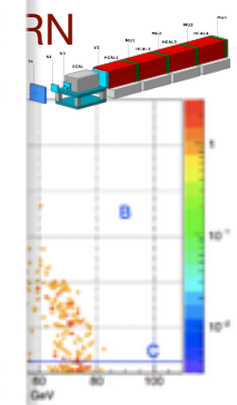
MeV–GeV Dark Matter
(small-experiment proposals)

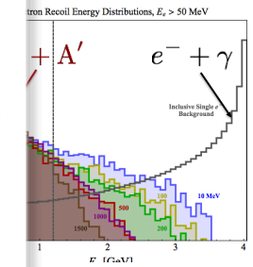
Dark-Matter Production II

- To beat this scaling, must detect dark matter prod… …states
  – nee…







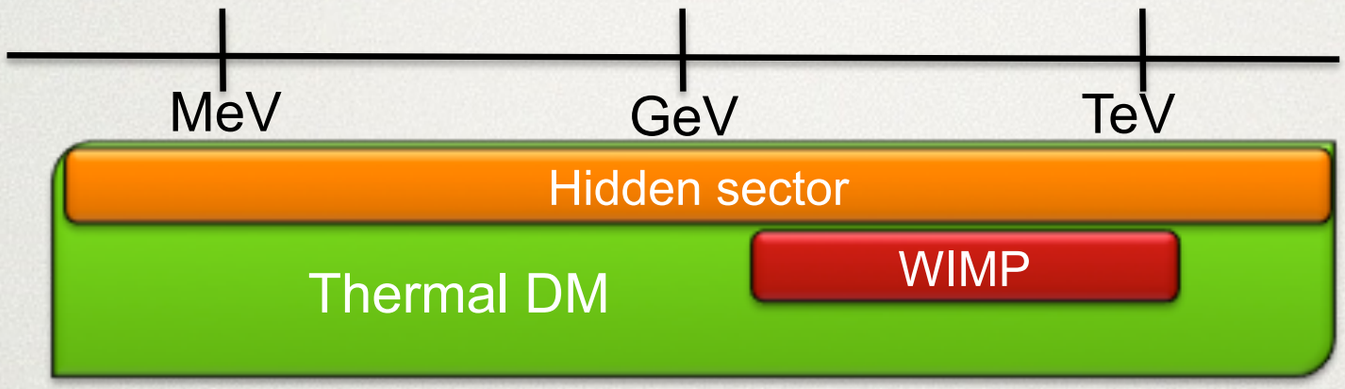


~0.1 … (ongoing projects)

… (small-experiment proposals)

Conclusions

- Hidden sector DM **extends thermal DM** to sub-GeV mass range, maintaining WIMP motivation of **SM-like matter at SM-like scales**



- Can systematically explore DM couplings to familiar matter
  - Thermal abundance motivates important target in parameter-space
- Together, upcoming projects and proposed small experiments can test this hypothesis
  - Active international community
  - Very high impact for low cost