The Search For Light Dark Matter

Philip Schuster (SLAC)

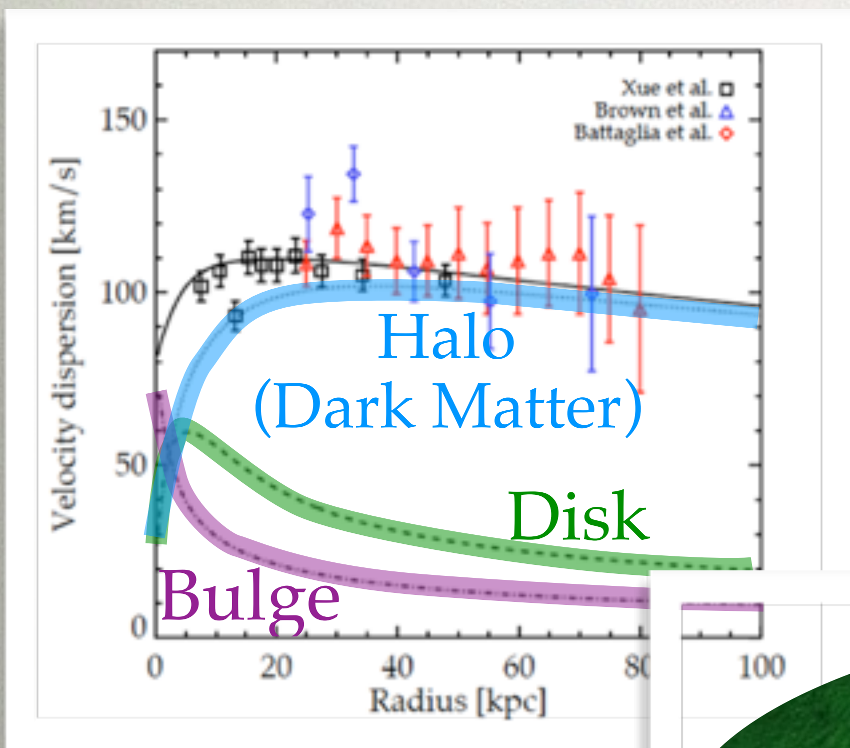
Bay Area Particle Theory Seminar
October 6, 2017

Outline

Light Dark Matter Motivations & Theory

Light Dark Matter Experiments

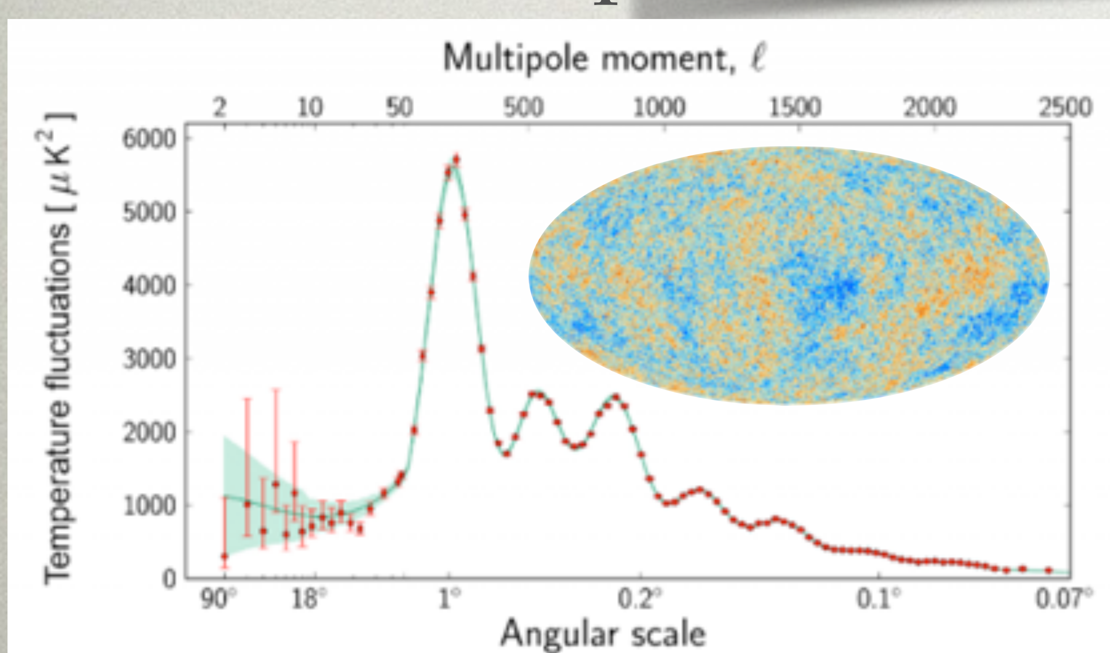
The Dark Sector



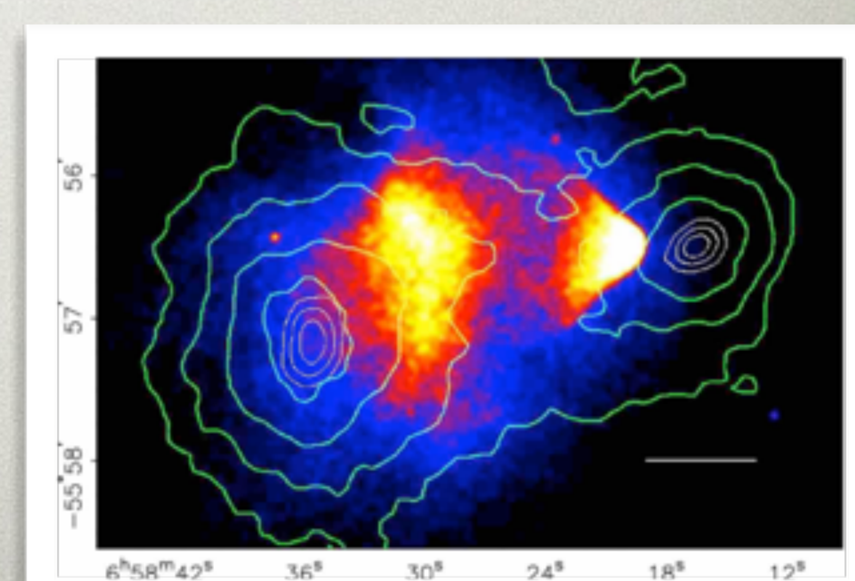
Rotation Curves

Gravitational lensing

CMB Power Spectrum



Cluster collisions



Dark Sector Science

What new particles and forces comprise dark matter?

Where did dark matter come from?

Dark Sector Science: Starting Points

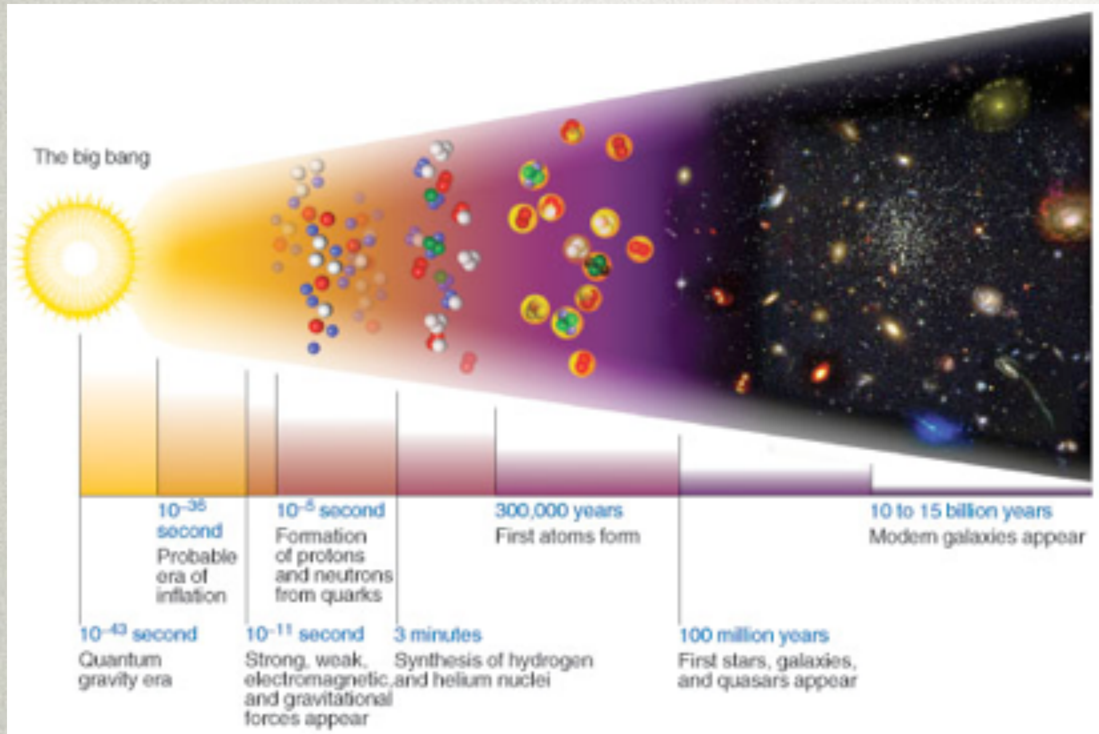
A natural first guess is that dark matter is part of the solution to an existing Standard Model puzzle

- **Hierarchy problem and weak-scale physics**
  - **Motivates new physics near the weak: dark matter could be part of this**
  - **Broad vicinity of weak-scale is already known to be interesting — familiar matter resides here!**

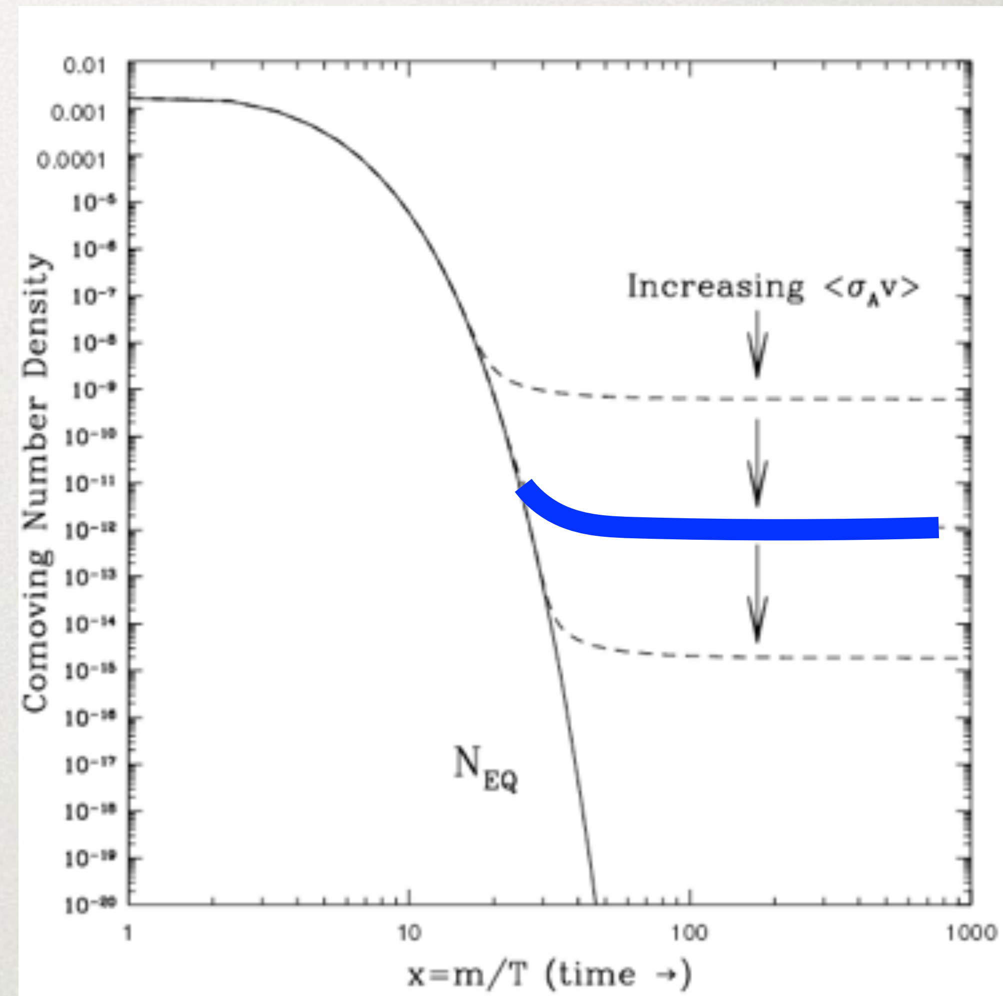
For me, this is the most compelling mass scale to understand and explore, with WIMPs as the canonical weak-scale dark matter candidate

- Strong CP, neutrino masses, baryon asymmetry…etc

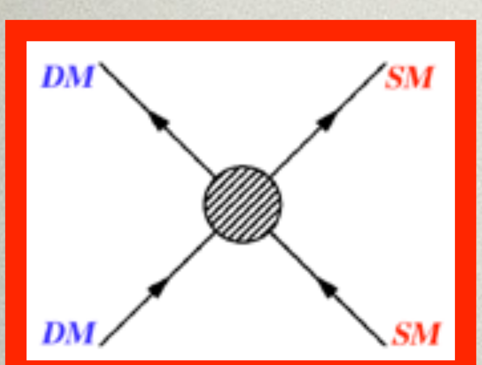
WIMPs and a Thermal Origin?



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



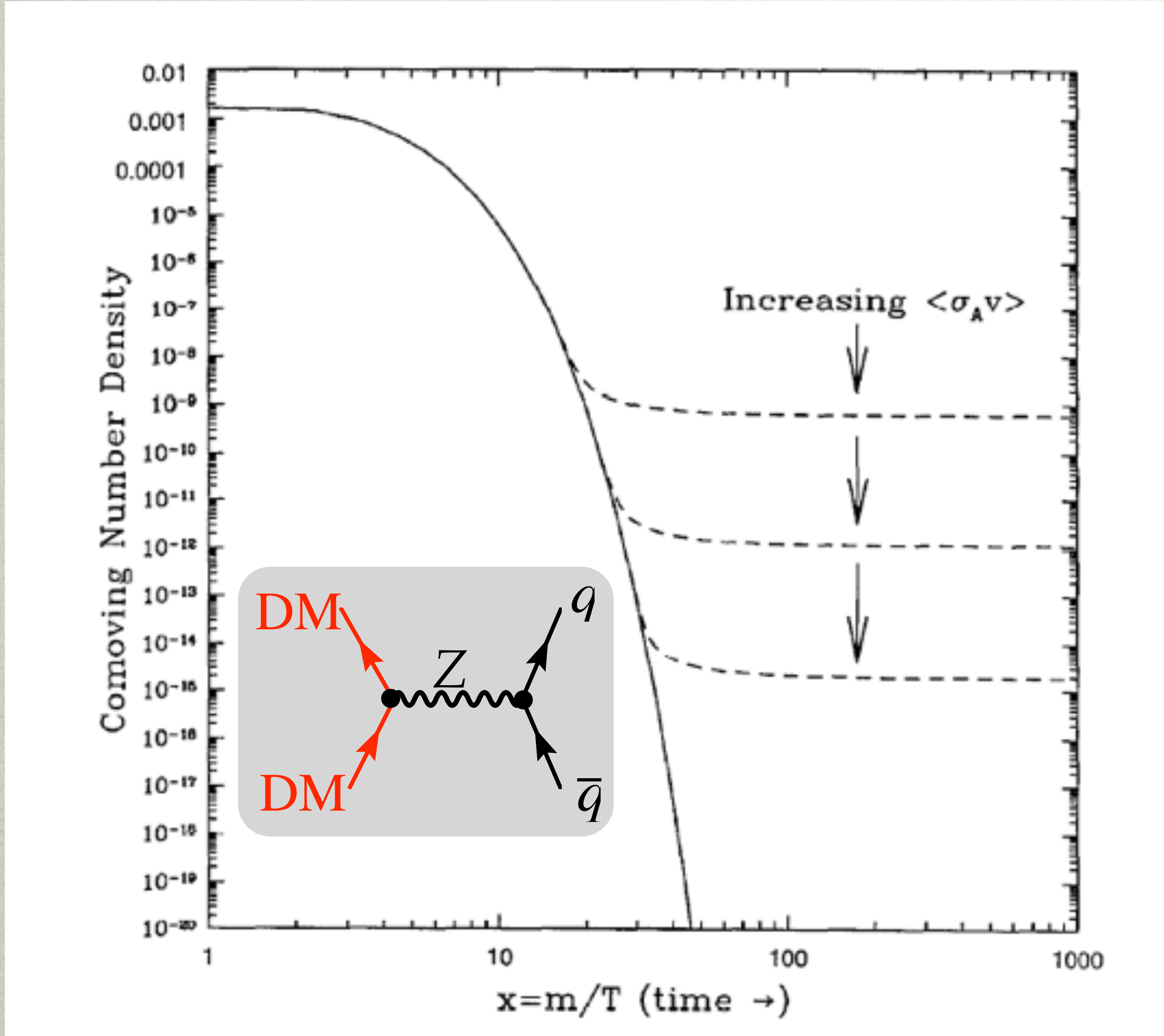
As Universe cools below DM mass, density decreases as $e^{-m/T}$



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

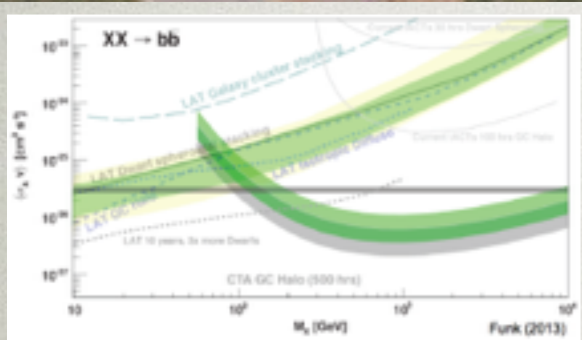
Correct DM density for:

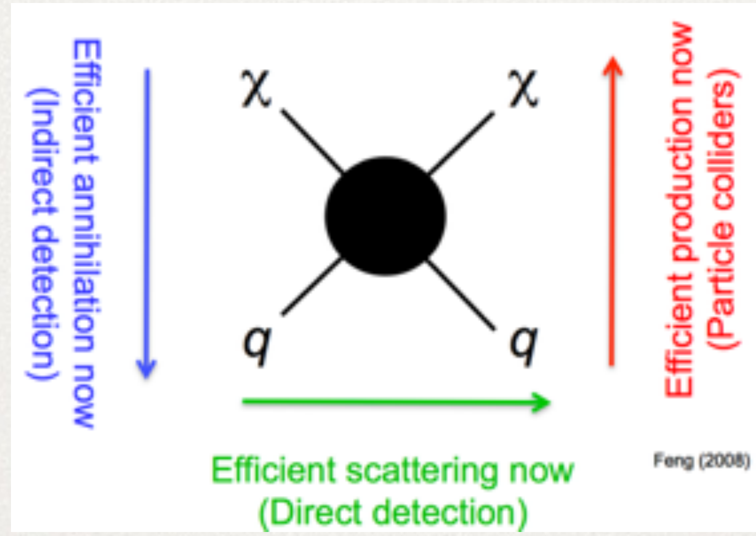
$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \text{cm}^3/\text{s}$$

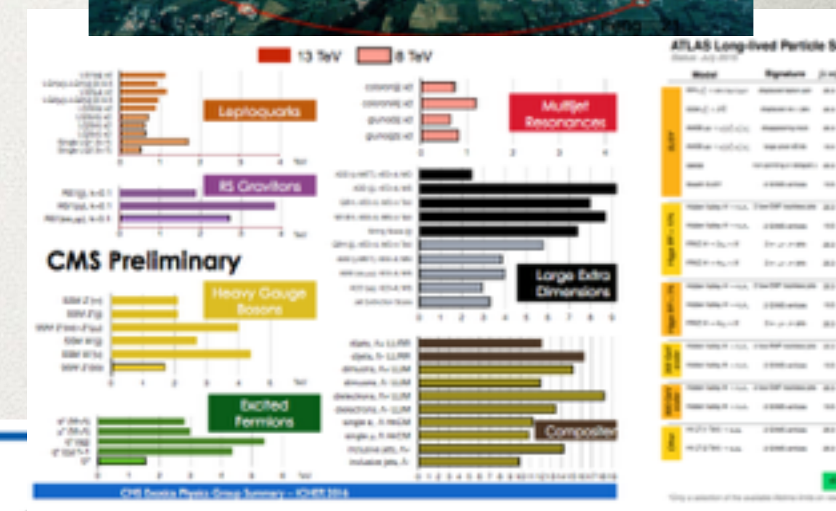
$$\simeq \frac{1}{(20\ \text{TeV})^2}$$

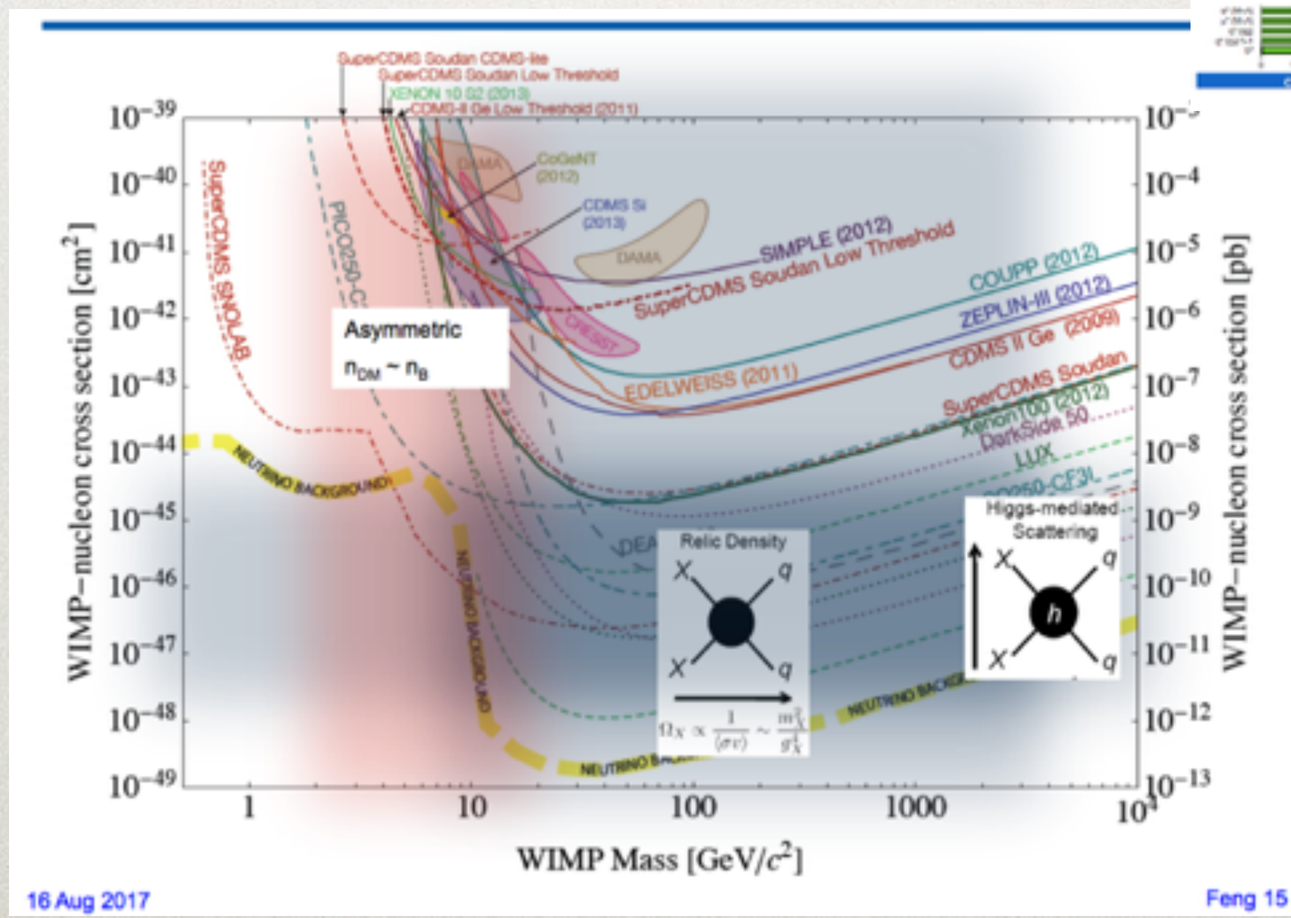
Thermal origin suggests Dark Sector interactions and mass in the vicinity of the weak-scale

THE WIMP SEARCH EFFORT









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

Vicinity of the weak-scale remains well-motivated

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

- **Thermal Origin**
- **Standard Model-like Mass**
- **Standard Model forces**

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First Steps Beyond WIMPs

- **Thermal Origin**
- **Standard Model-like Mass**
- **Standard Model-like forces**

"WIMP-like" dark matter, just not charged under SU(2) weak. Interacts via some other mediator — hidden (or dark) sector dark matter!

What are the options?

Three Interaction Types

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

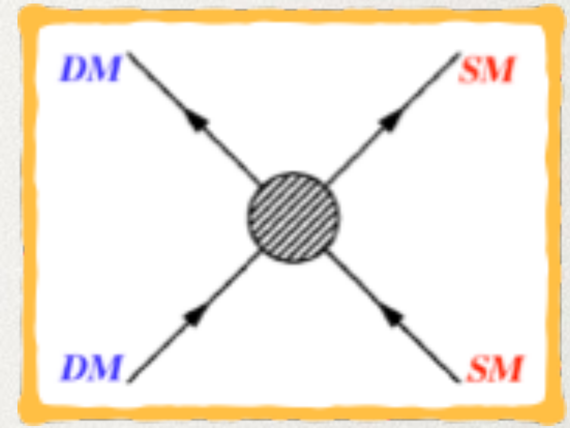
Least constrained for thermal dark matter

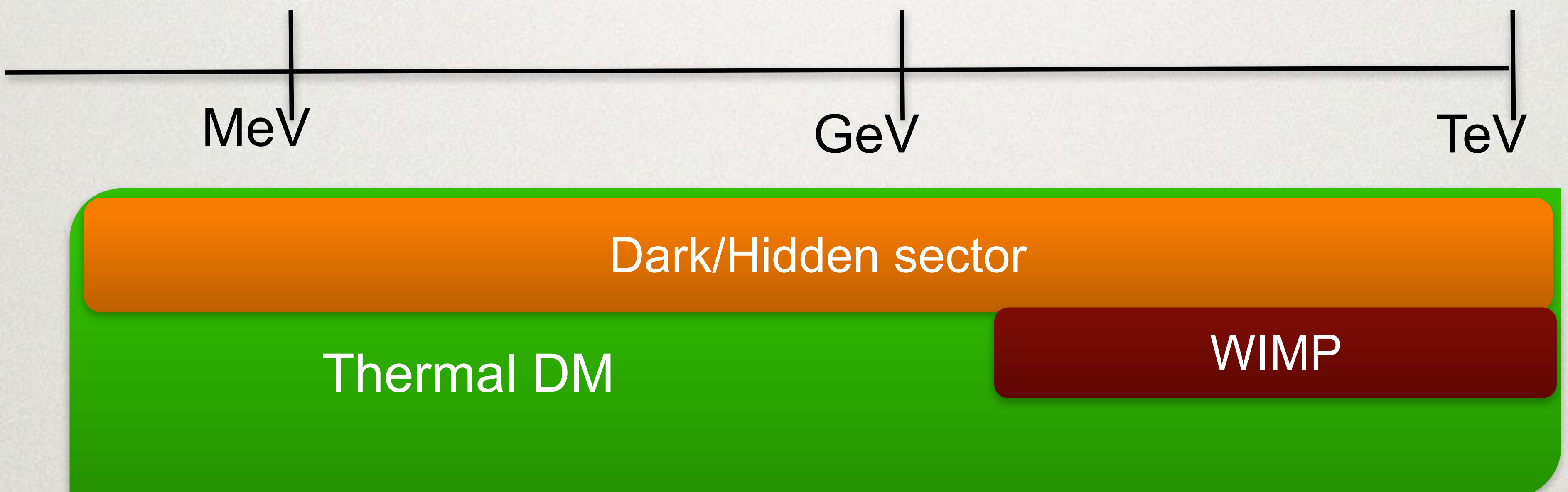
Vector Mixing	$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$	Very weakly coupled forces
Higgs Mixing	$\epsilon_h \, \lvert h \rvert^2 \lvert \phi \rvert^2$	exotic rare Higgs decays rare meson decays
Neutrino Mixing	$\epsilon_\nu \, (hL)\psi$	not-so-sterile neutrinos

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

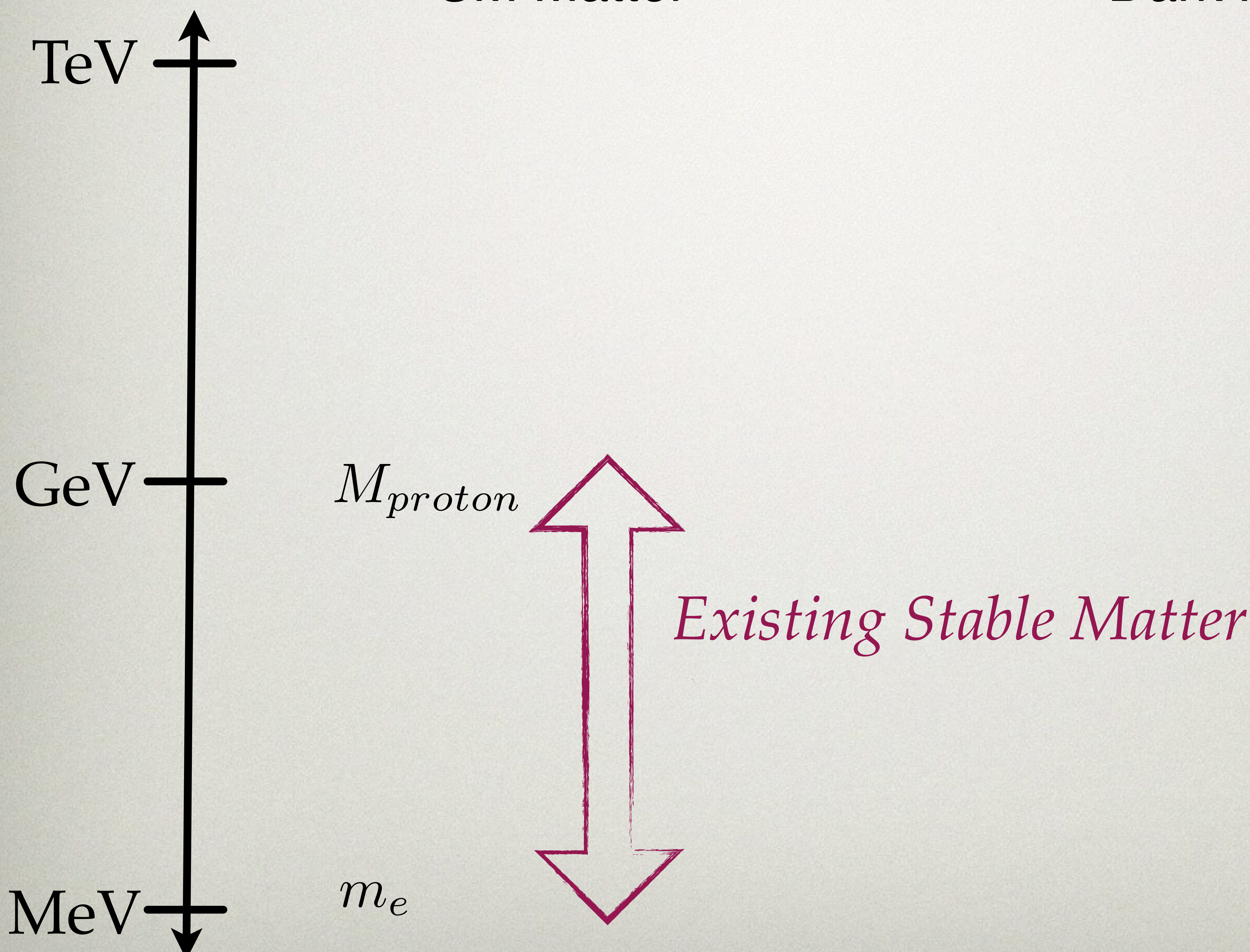




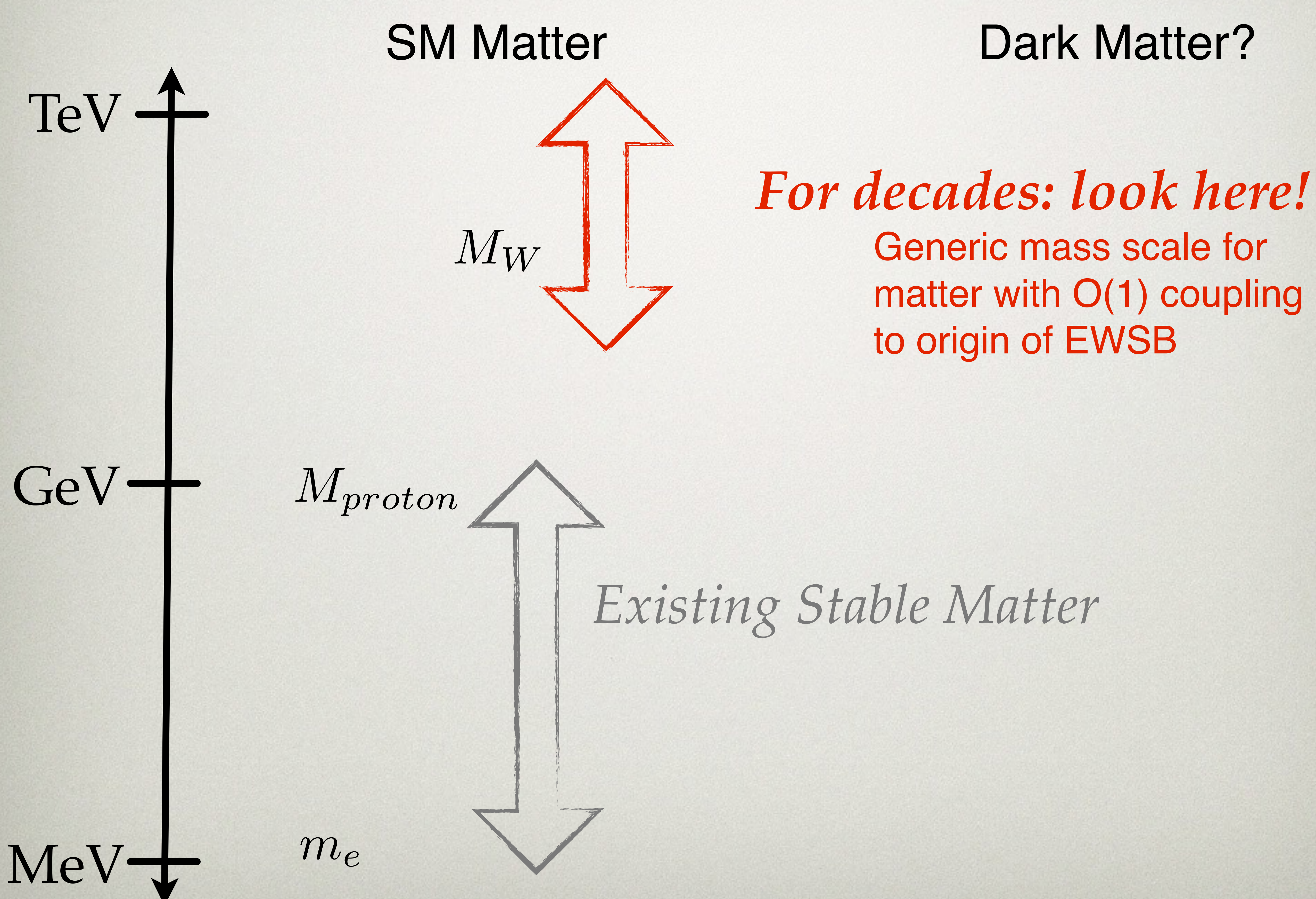
Thermal origin "dark sector" dark matter (with mediator) is viable over the entire MeV-TeV range!

Dark Sectors in the Vicinity of the Weak Scale

SM Matter | Dark Matter?



Dark Sectors in the Vicinity of the Weak Scale



Dark Sectors in the Vicinity of the Weak Scale

SM Matter

Dark Matter?

TeV

M_W

For decades: look here!

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

GeV

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

(accidentally close to weak scale)

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

MeV

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

(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

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

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(derived from weak scale)

Dark Matter?

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

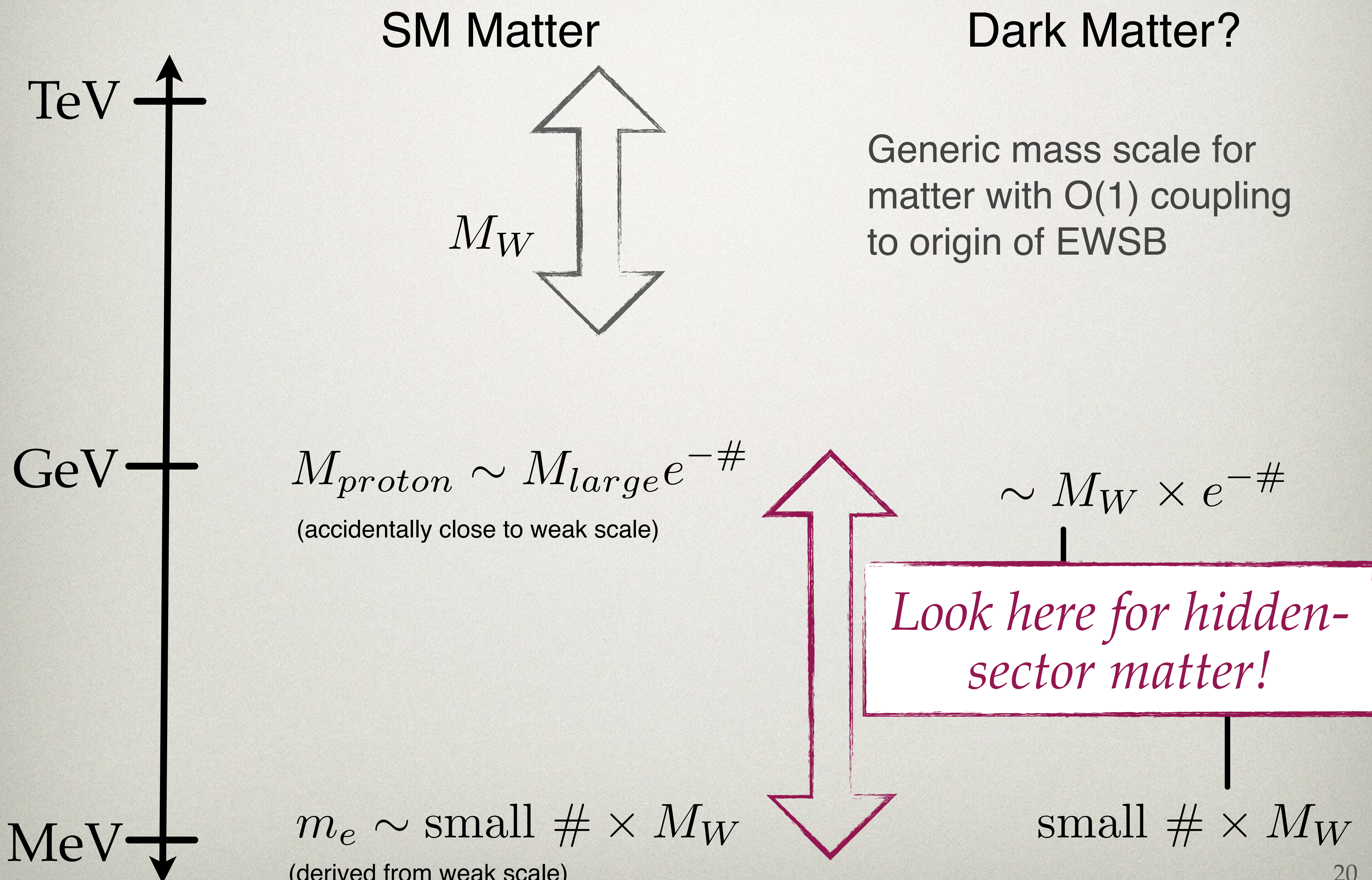
Where do we expect hidden-sector matter?

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

(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



Dark Sectors in the Vicinity of the Weak Scale

SM Matter

Dark Matter?

TeV

GeV

MeV

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

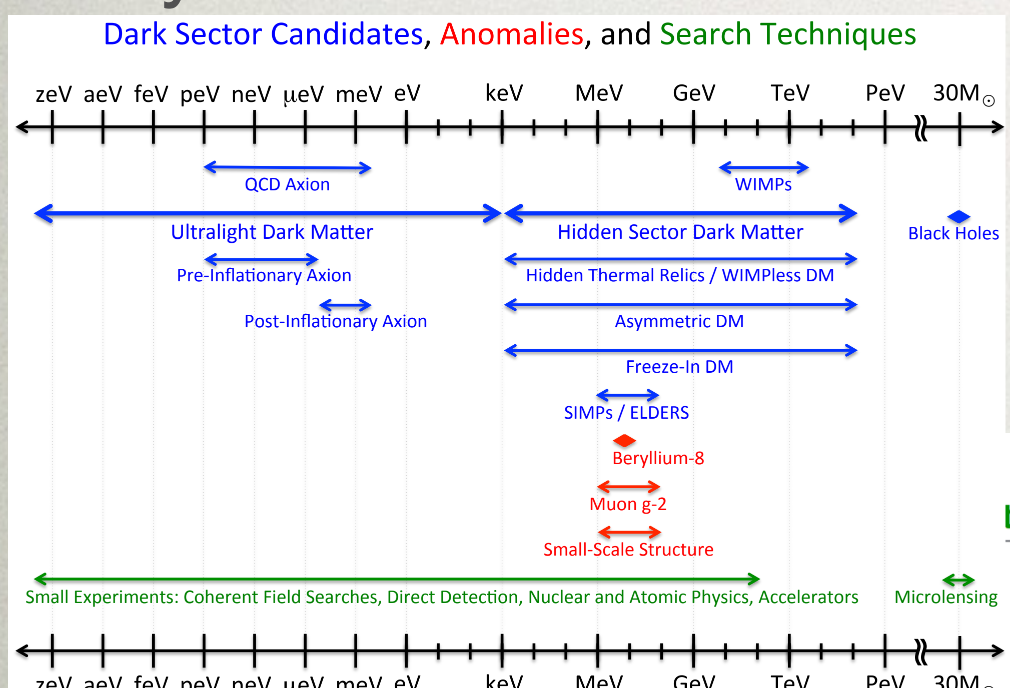
- **An important scale!**
- **Familiar stable matter resides here!**
- **Thermal DM works well here!**

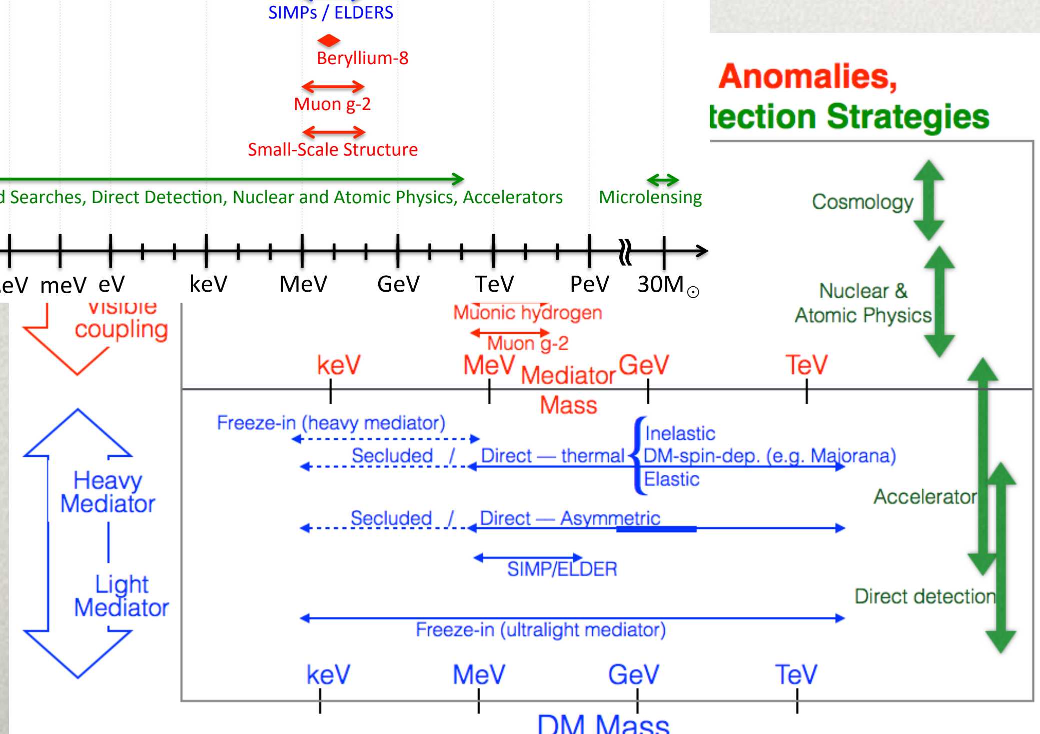
(derived from weak scale)

Defining New Frontiers

Over the last few years, a strong science case for moving beyond WIMPs has been established

Workshop and Community Report:
arXiv: 1707.04591
Light hidden-sector dark matter
a key area of focus





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

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 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 Bondì,[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,[63] 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] Frederic Mouton,[61] Holger Mueller,[12] Alexander Murphy,[95] Russell Neilson,[96] Tim

A New Frontier

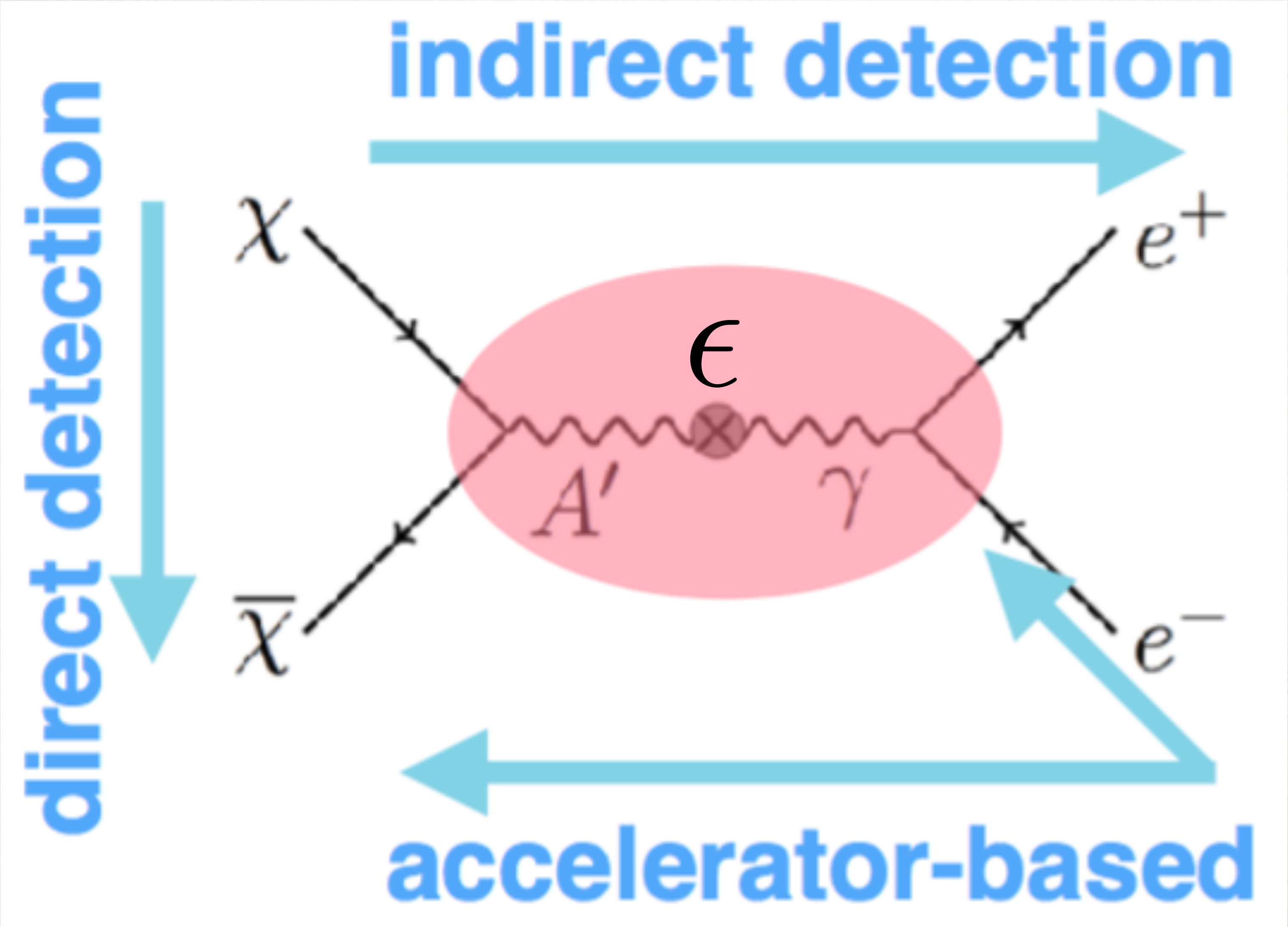
Extend sensitivity to “WIMP-like” Dark Matter in the sub-GeV Range? **(light dark matter, LDM)**

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

Thermal LDM Models

Low-energy phenomenology depends on

- DM spin (fermion or scalar)
- Mass structure ($U(1)_D$–preserving, $U(1)_D$–breaking, or both)

charged, elastic *axially coupled elastic* *inelastic*

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

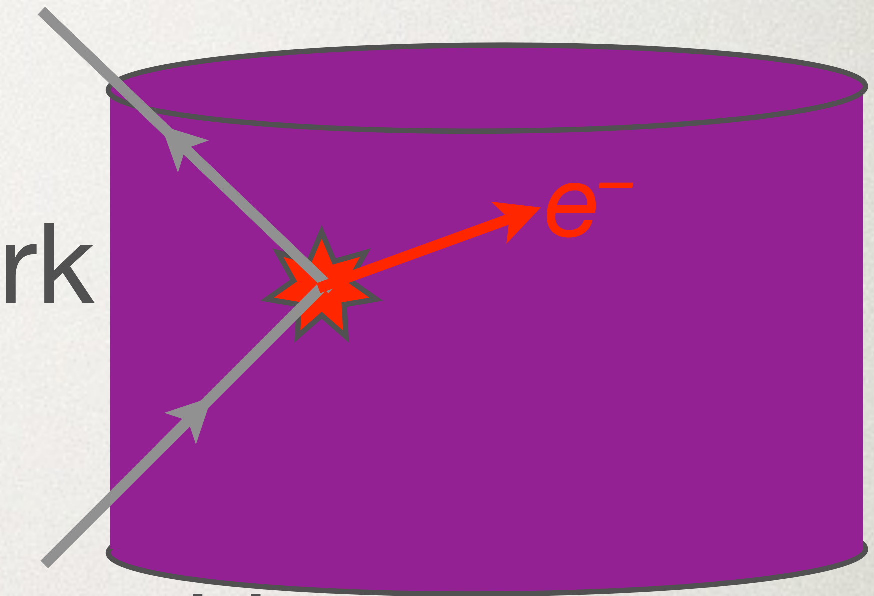
Model	Mass terms	J_D^μ	scattering $\sigma \propto$	Annilhilation $\sigma v \propto$	CMB-viable?
Fermion DM – Direct Annihilation					
Majorana	$\not{U}(1)_D$	$\bar{\Psi}\gamma^\mu\gamma_5\Psi$	v^2	p-wave $\propto v^2$	Y
Dirac	$U(1)_D$-inv.	$\bar{\Psi}\gamma^\mu\Psi$	1	s-wave $\propto v^0$	N
Pseudo-Dirac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

Like neutralino WIMP

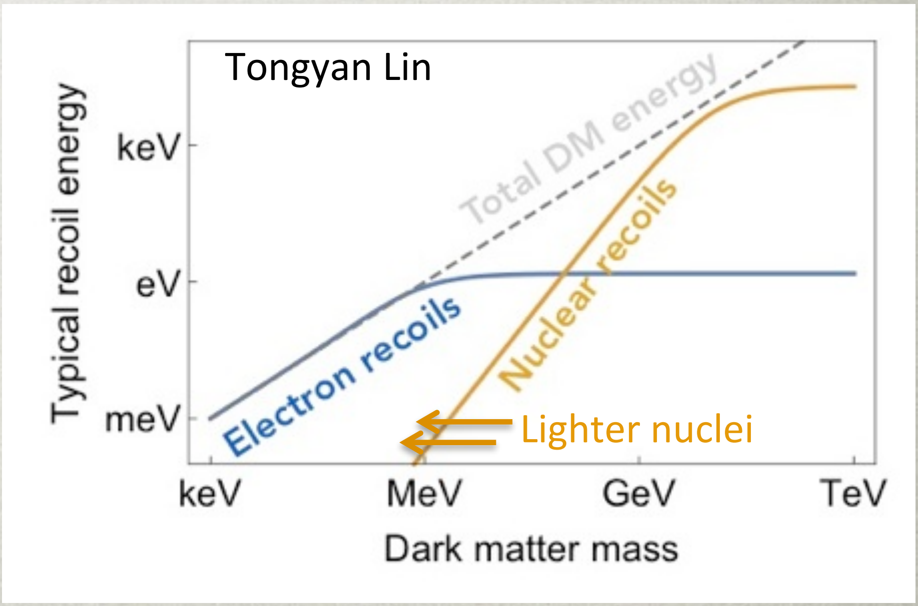
Like sneutrino or Dirac neutrino WIMP

Dark-Matter-Electron Scattering

- Use the abundance and higher charge of dark matter particles to your advantage!



- Dark matter transfers more kinetic energy when it scatters off light electron vs. heavy nucleus*
- Challenge: electron recoils are usually the background for direct detection!

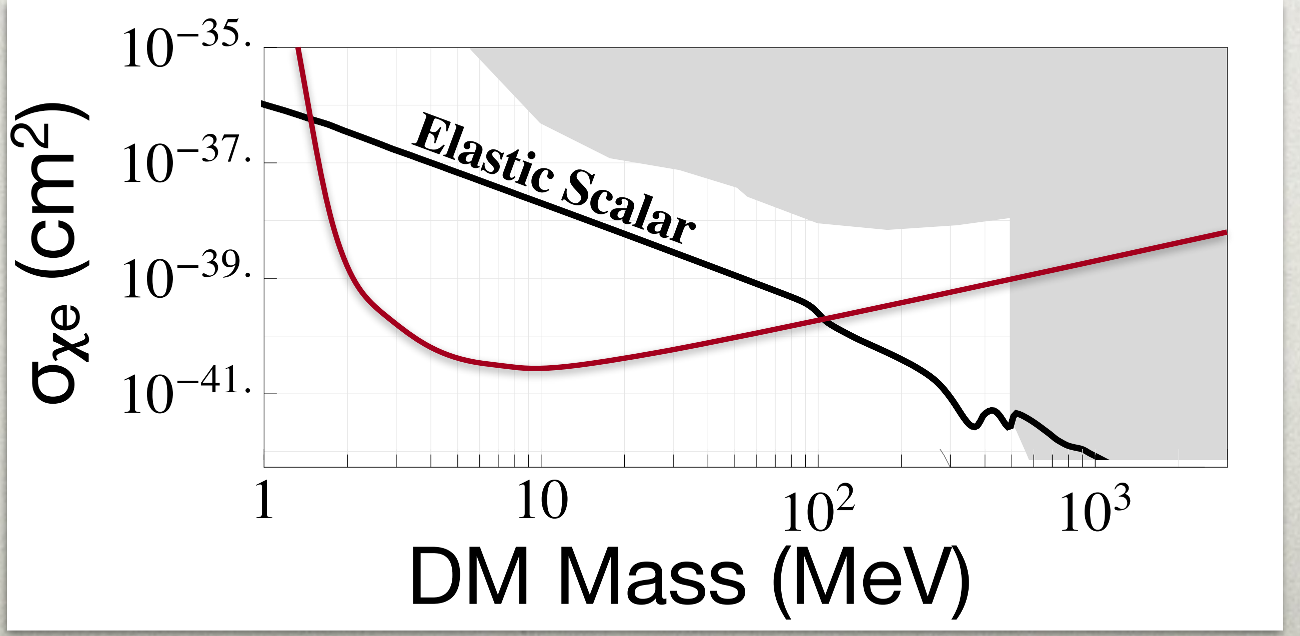


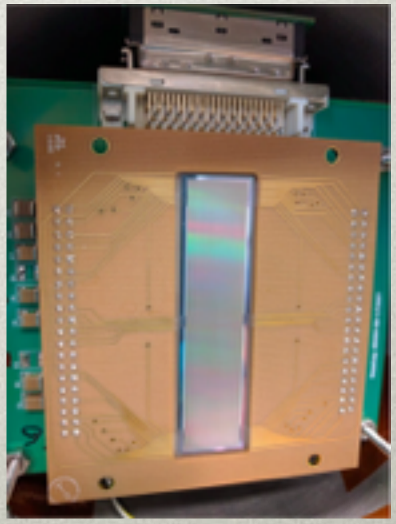
*Exciting ideas for low-threshold nuclear detection too!

Dark-Matter-Electron Scattering

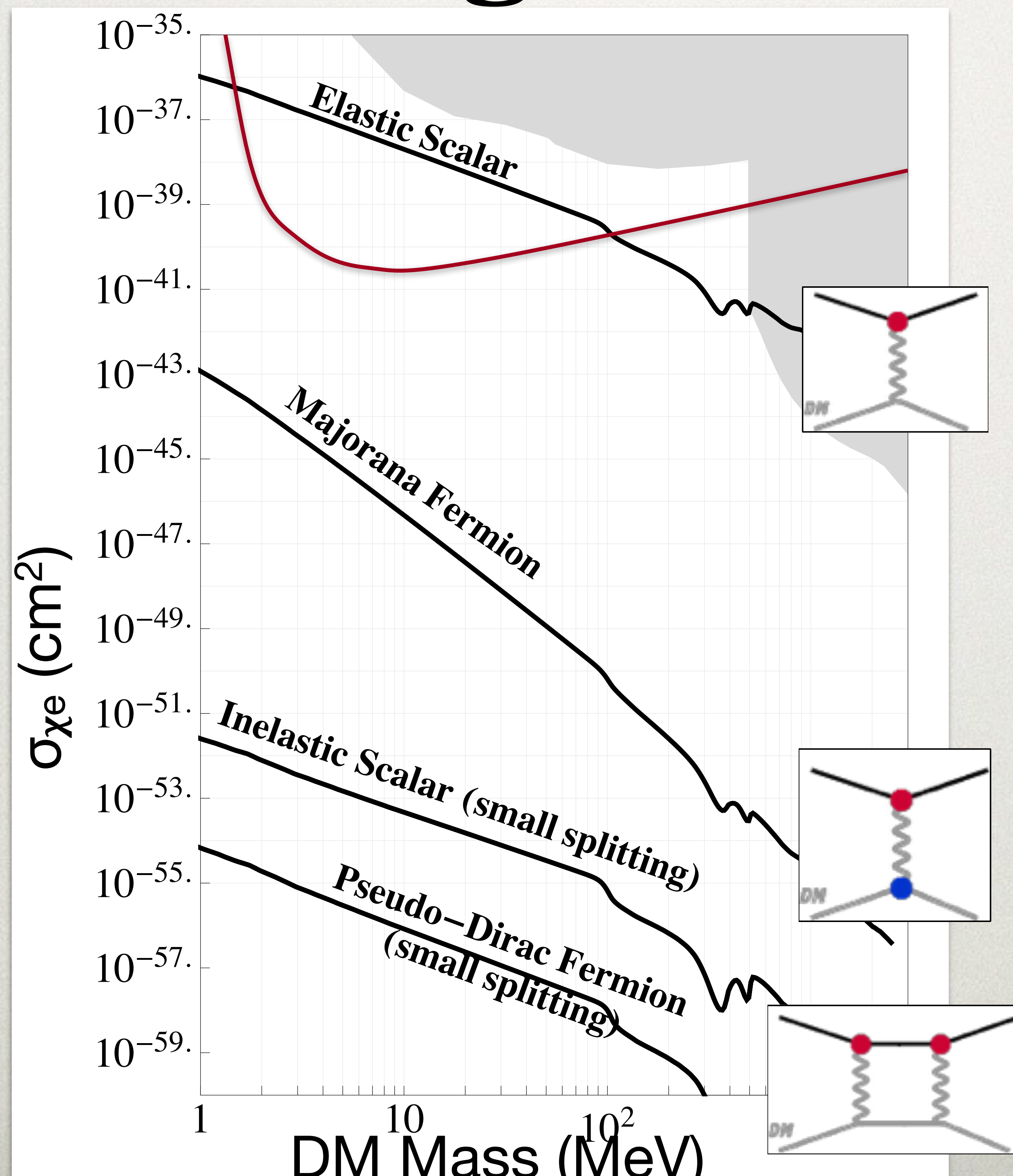
New dedicated experiments aim to see electron recoils at **lower** energy than typical backgrounds (radiogenic, etc)

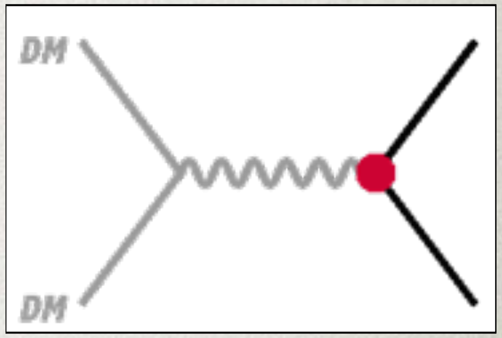
e.g. SENSEI:
1–100g detector made from low-noise skipper CCDs





Dark-Matter-Electron Scattering: Limitations





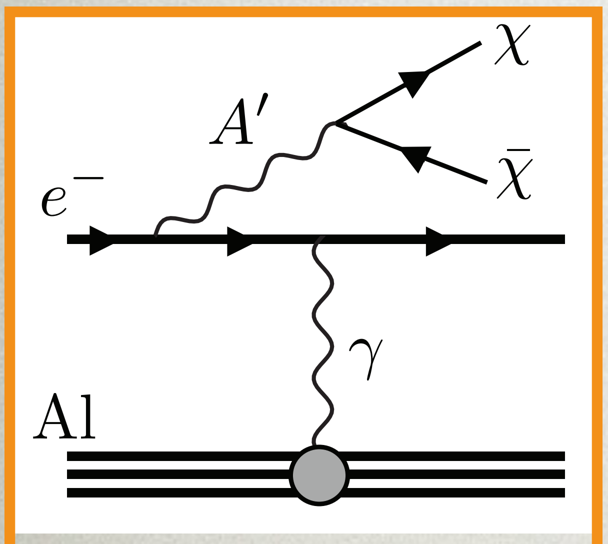
Dark matter halo is non-relativistic! (10^{-3} *c*) ⇒

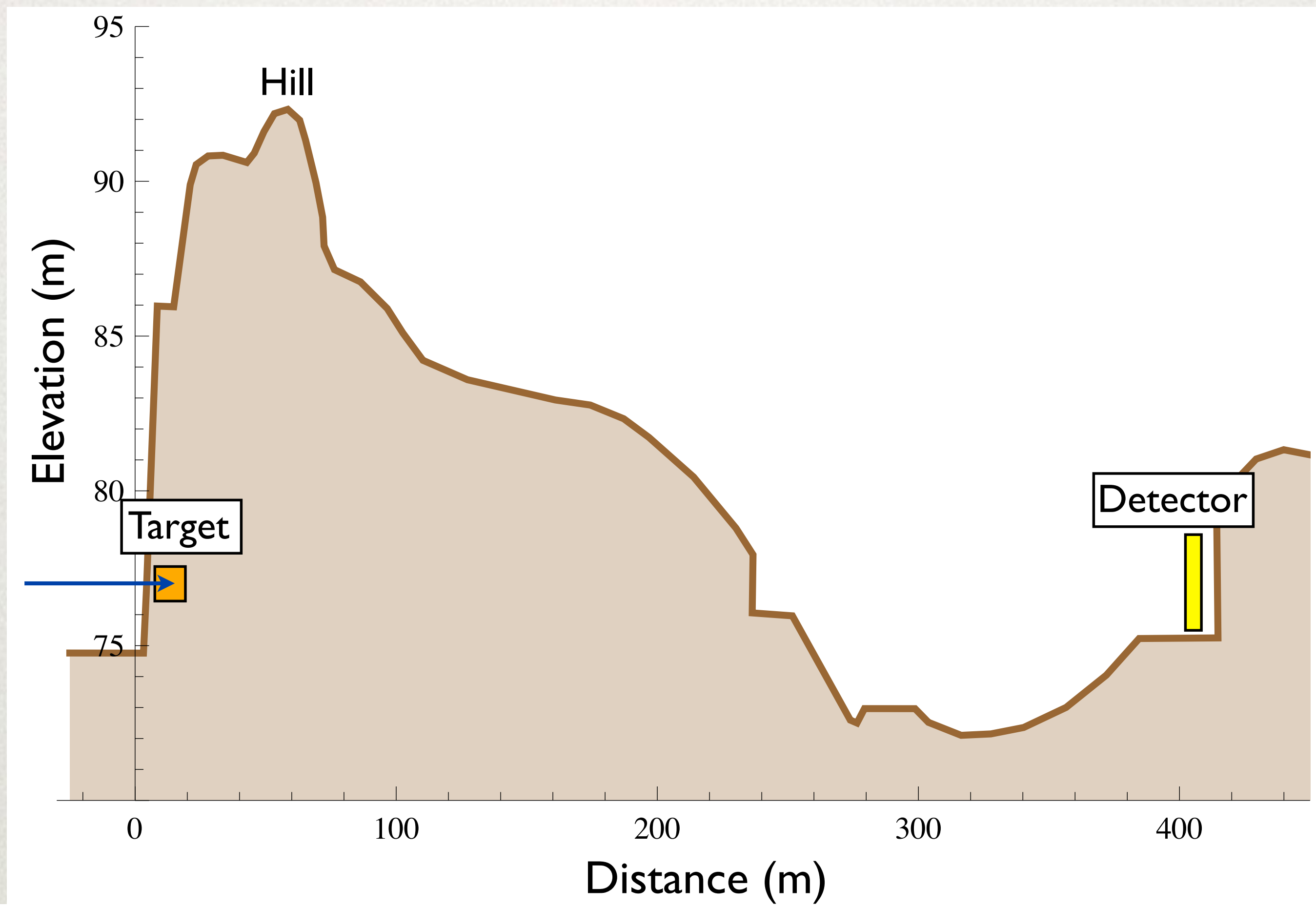
Xsec predictions spread over tens of decades, much like for WIMPs!

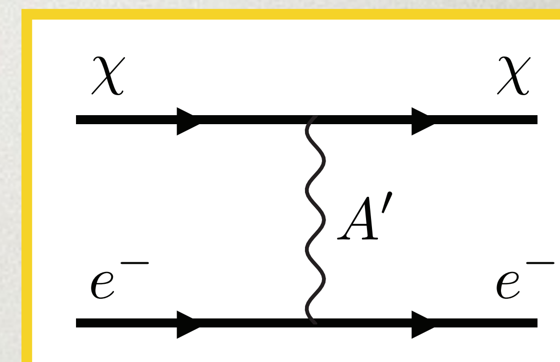
- Small DM-SM coupling
- Velocity-suppression

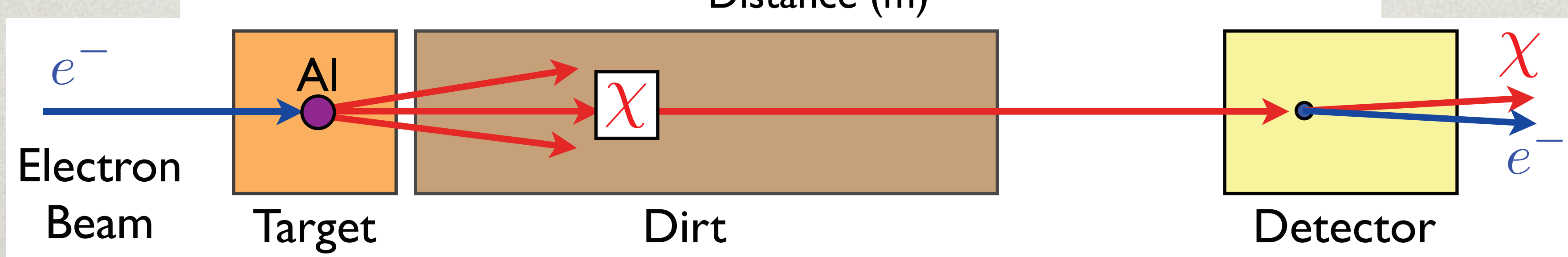
Dark-Matter Production I

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



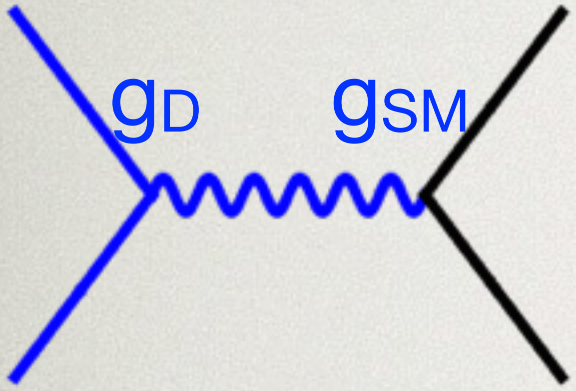






- Similarly, accelerator neutrino experiments are also Dark Matter factories

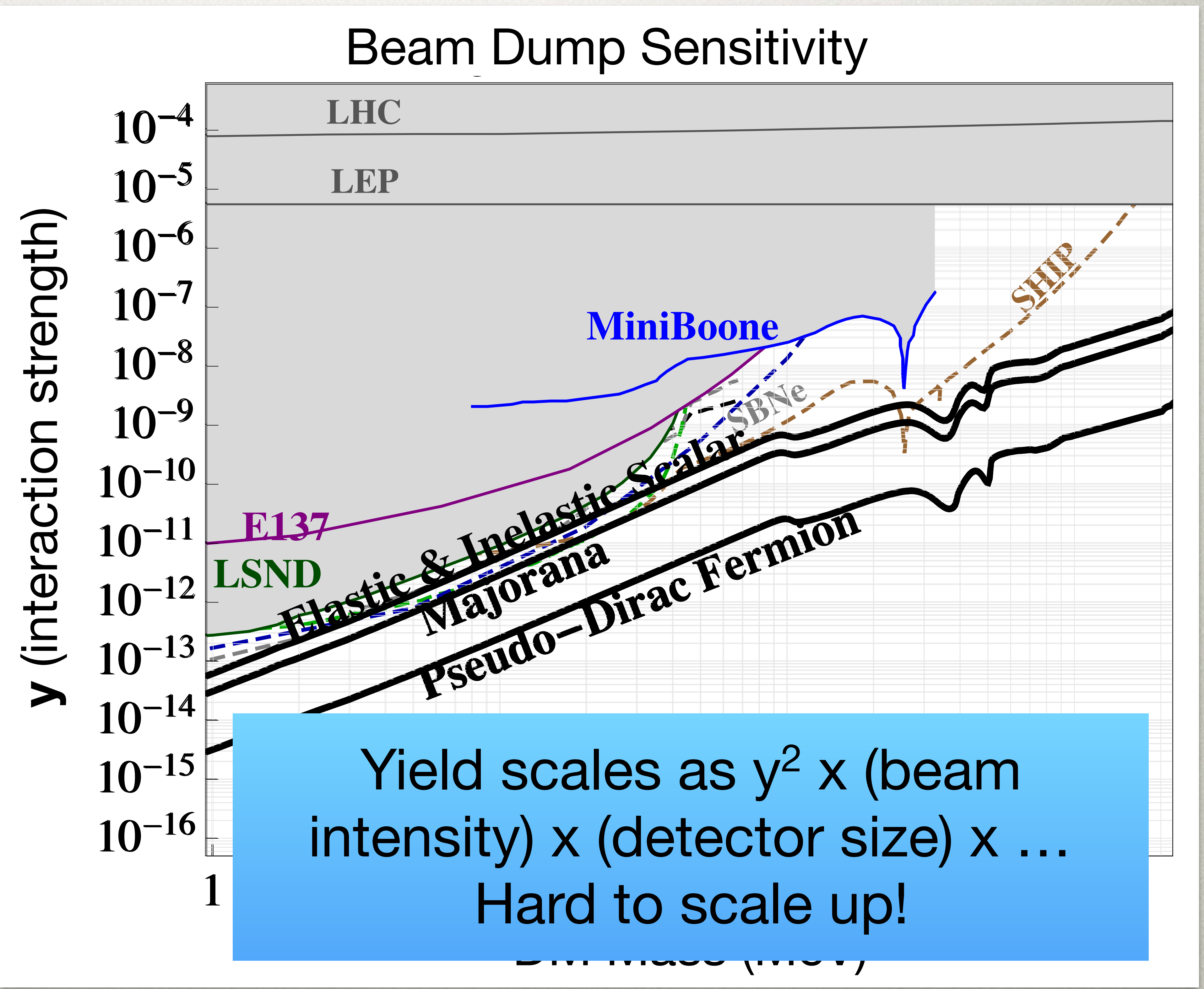
Dark-Matter Production I



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

Production $\propto g_{SM}^2$ – infer **worst-case y** sensitivity from physical upper limits on g_D and m_{DM}/m_{Med}

Detection $\propto$ another **y**

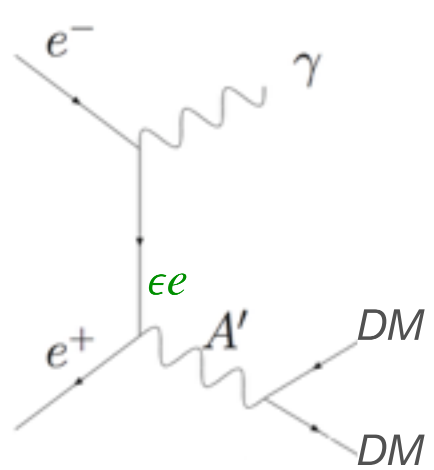


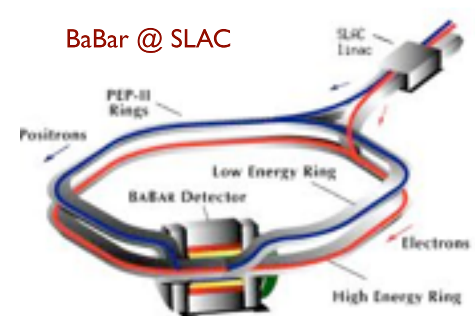
Yield scales as y^2 x (beam intensity) x (detector size) x … Hard to scale up!

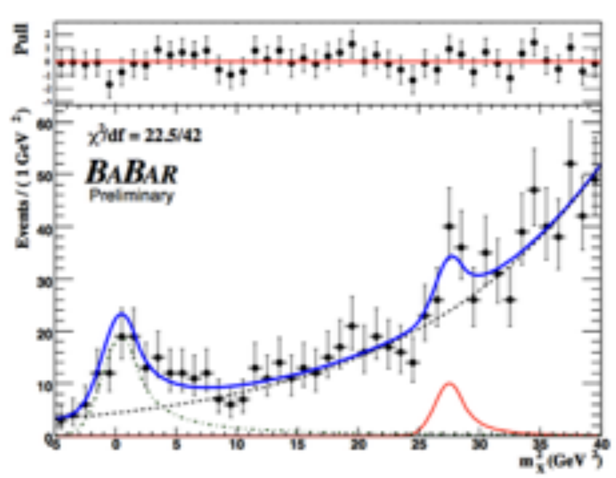
Dark-Matter Production II

- To beat this scaling, must detect dark matter production via **kinematics** of visible final states
  - gives signal yield$\propto$y; low irreducible background

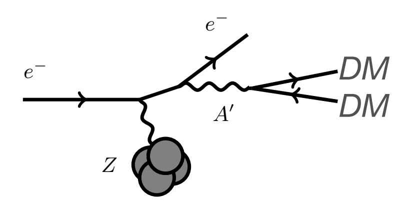
Missing Mass (e^+e^- colliders)
= full kinematic reconstruction

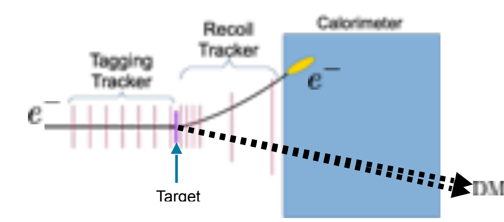


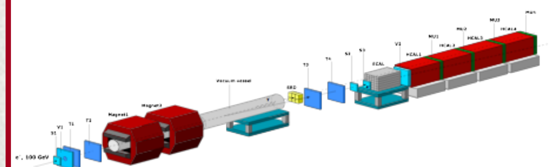


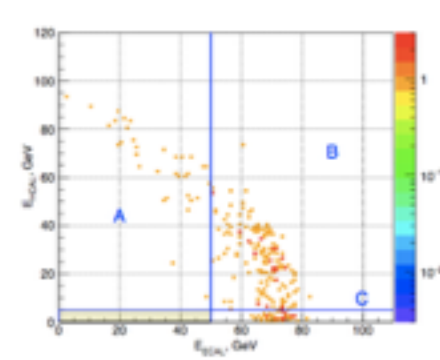


Missing Energy/Momentum
(e^- fixed target)
= partial kinematic reconstruction

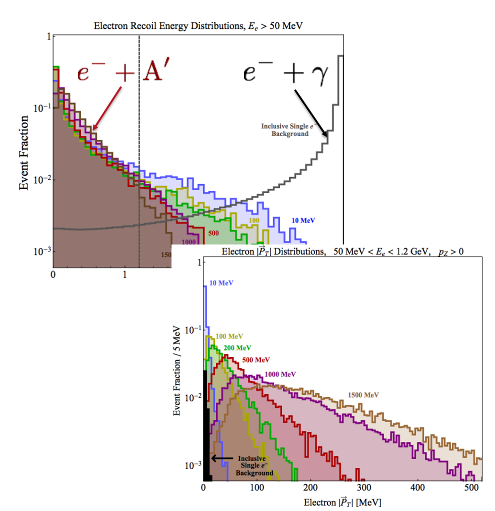








LDMX

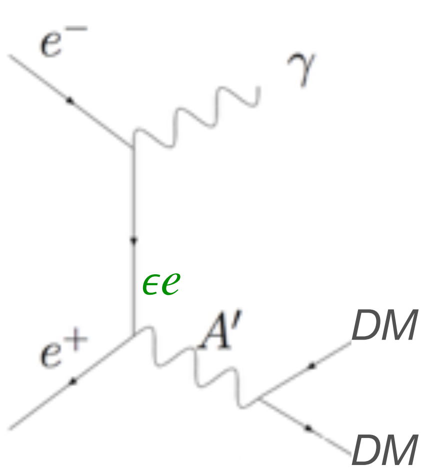


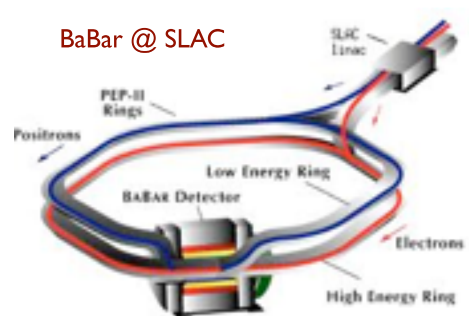
lower mass

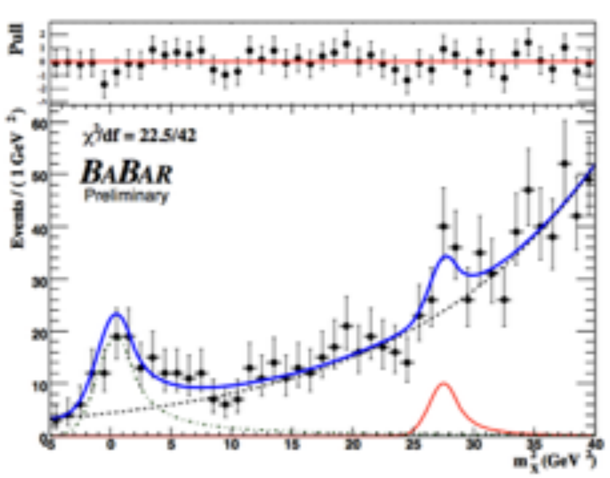
Dark-Matter Production II

- To beat this scaling, must detect dark matter production via **kinematics** of visible final states
  - – gives signal yield∝y; low irreducible background

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







Dark-Matter Production II

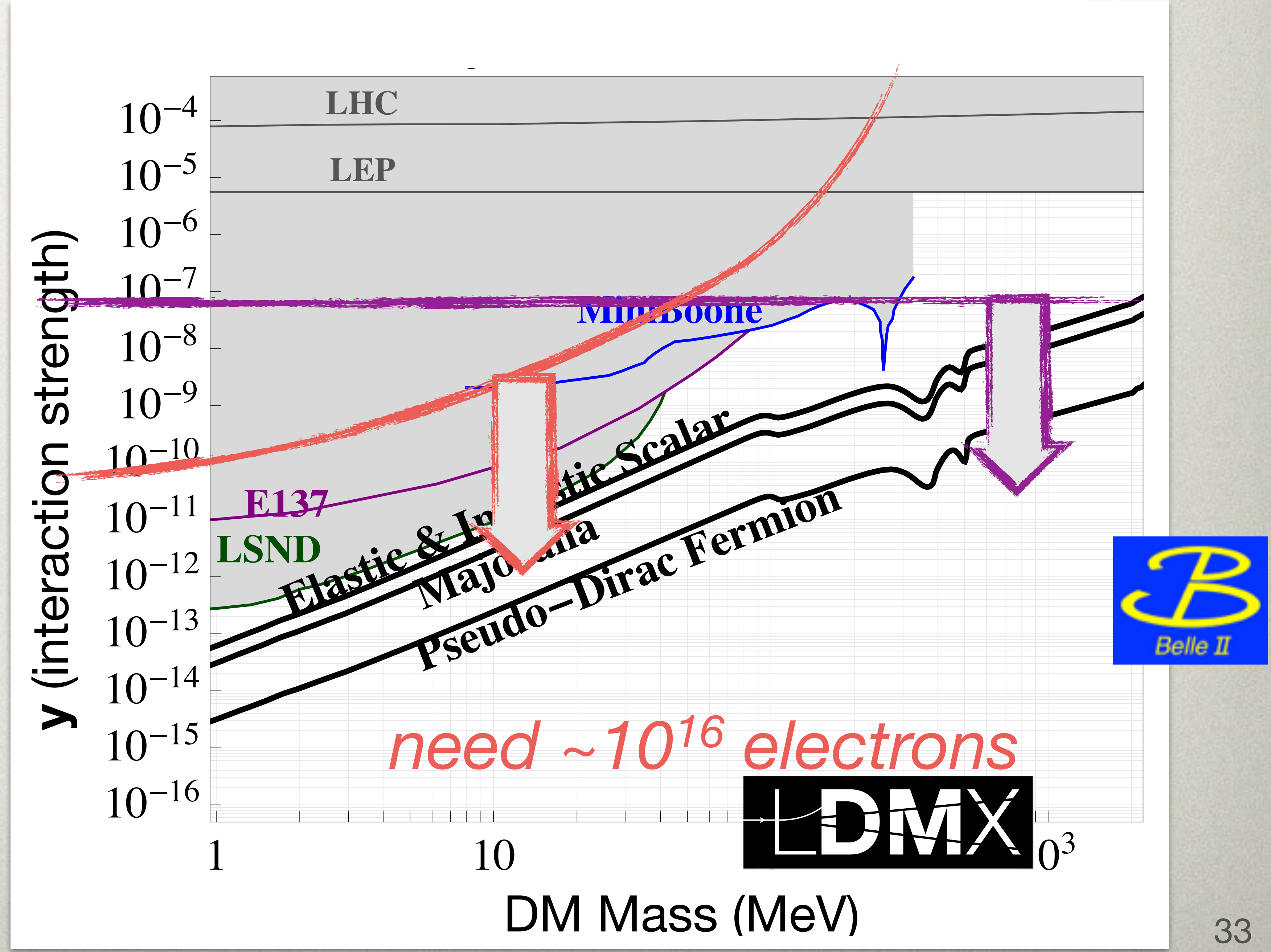
- To beat this scaling, must detect dark matter production via **kinematics** of visible final states

Colliders:

Rate ~ **y**$\mathscr{L}$ /E_{CM}^2

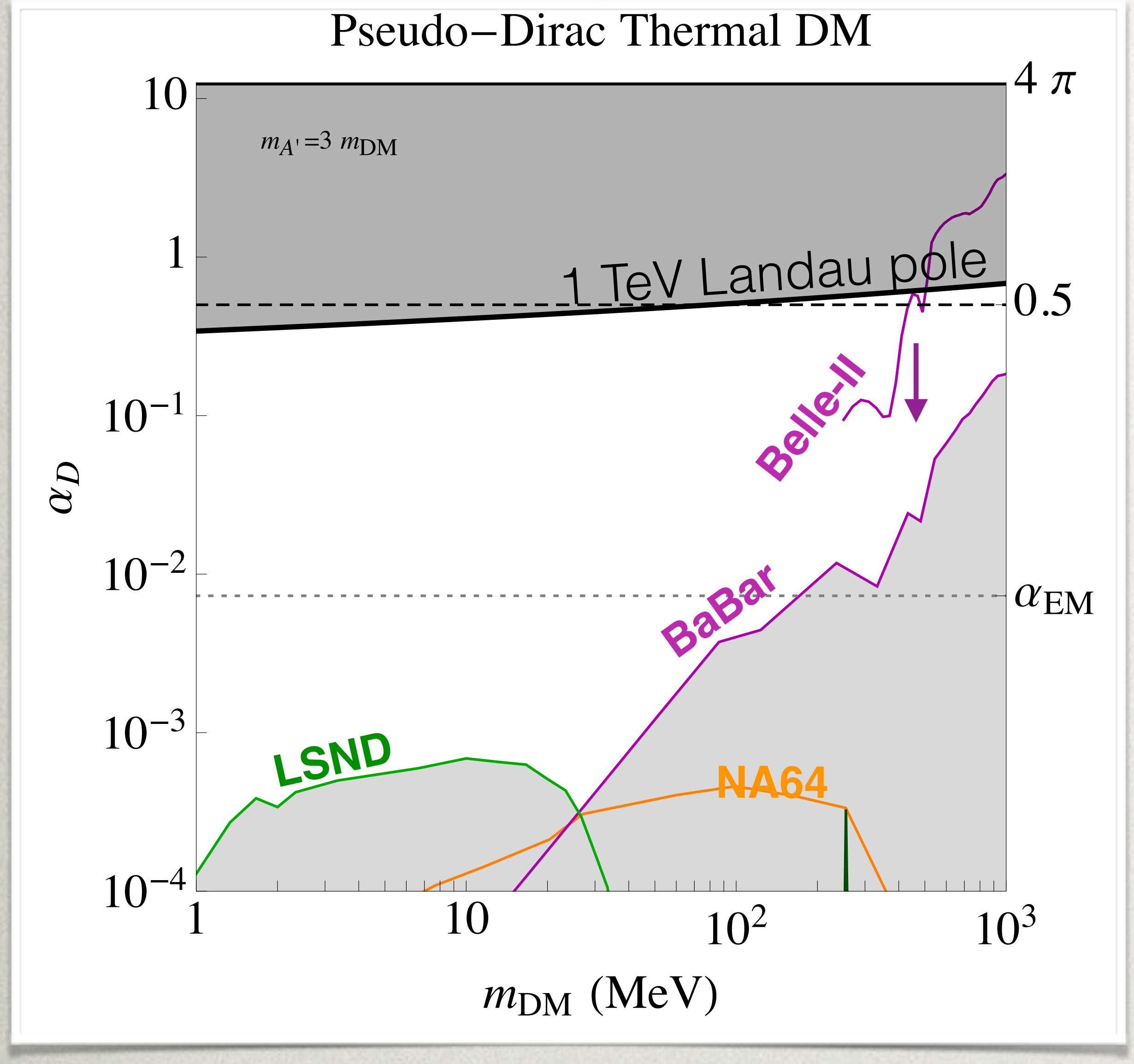
Fixed target:

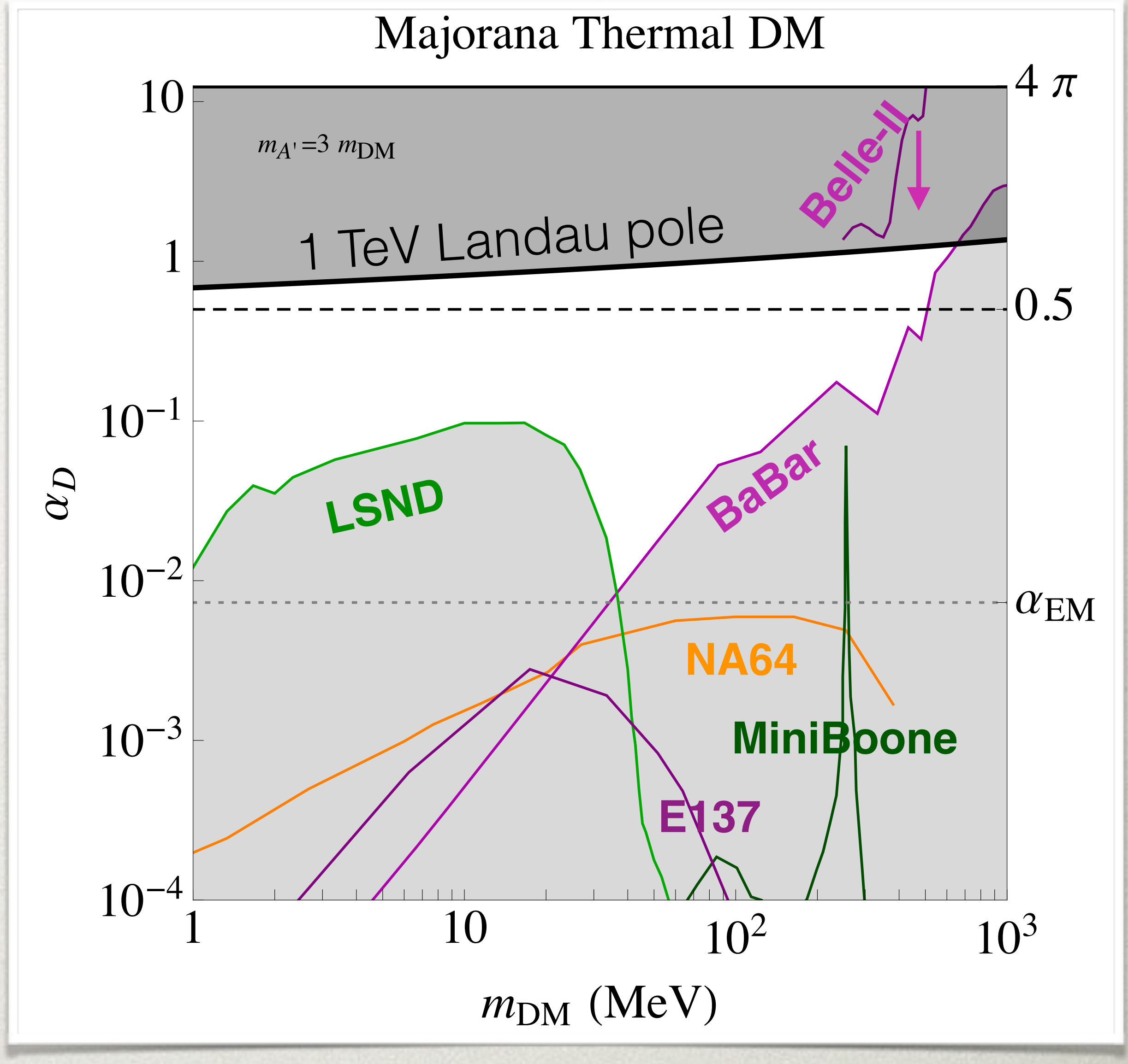
Rate ~ **y** $N_e m_e^2/m_{DM}^2$ (add'l form factor penalty @ high masses)



Accelerator Experiments Have Cornered Thermal LDM

Assuming thermal abundance to fix ϵ



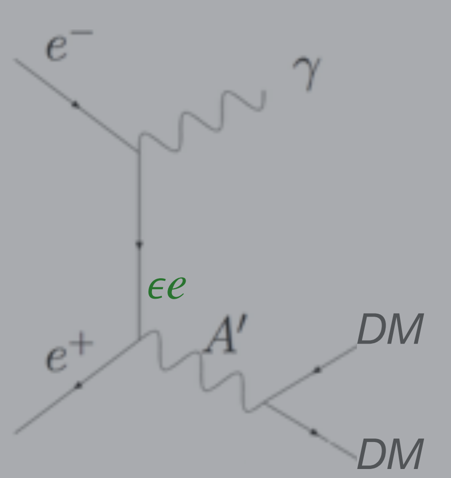


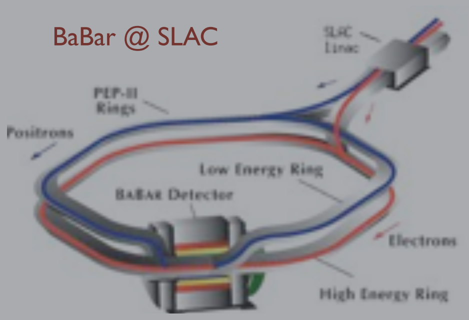
Remaining 1-3 orders of magnitude represent some of the best motivated parameter space. An amazing opportunity!

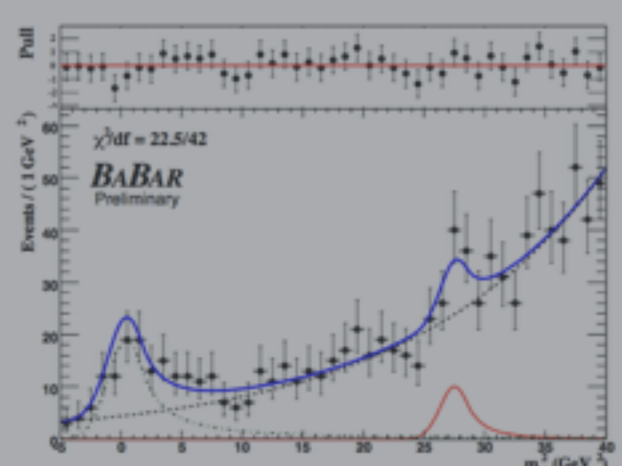
Dark-Matter Production II

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

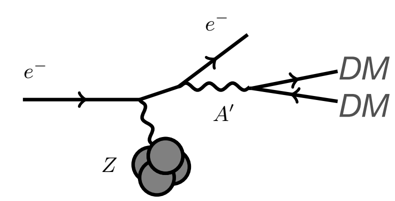
Missing Mass (e^+e^- colliders)
= full kinematic reconstruction

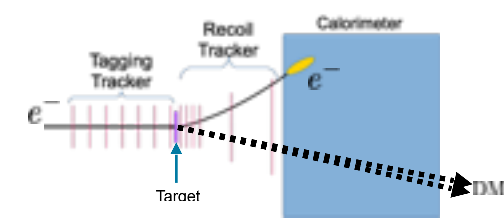


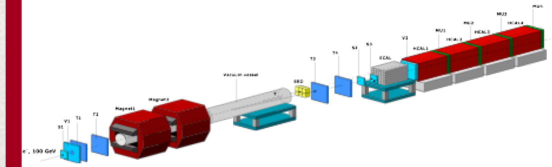


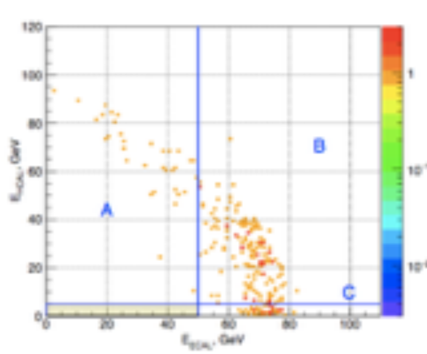


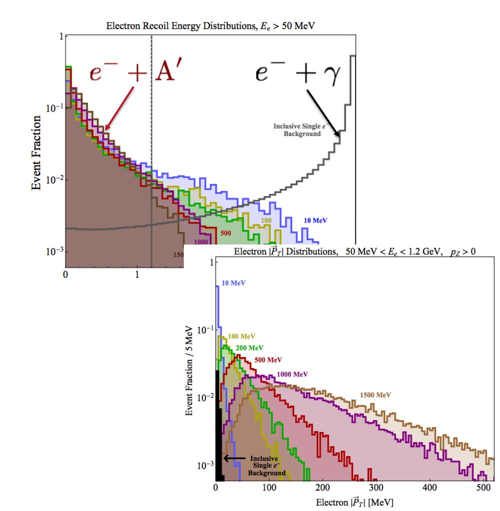
Missing Energy/Momentum
(e^- fixed target)
= partial kinematic reconstruction







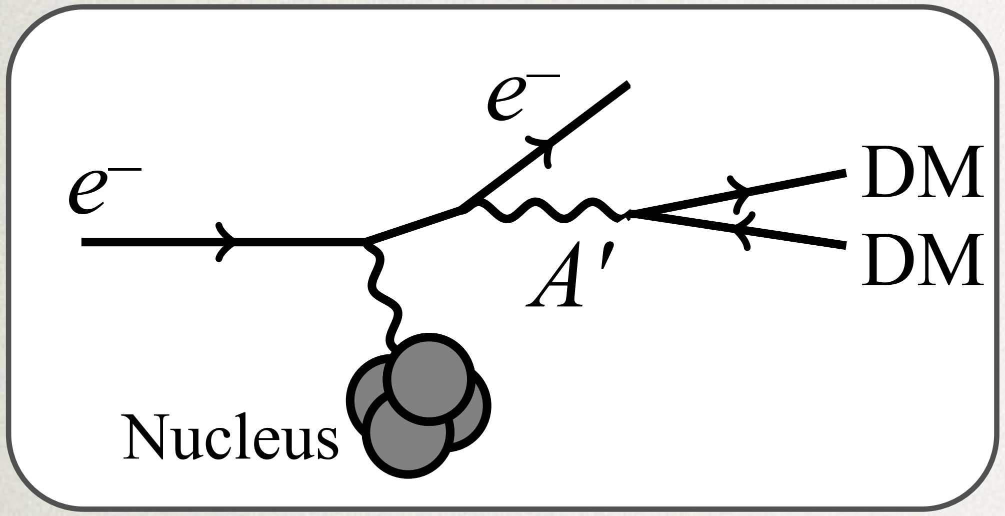




~0.1 – 10 GeV Dark Matter

MeV–GeV Dark Matter

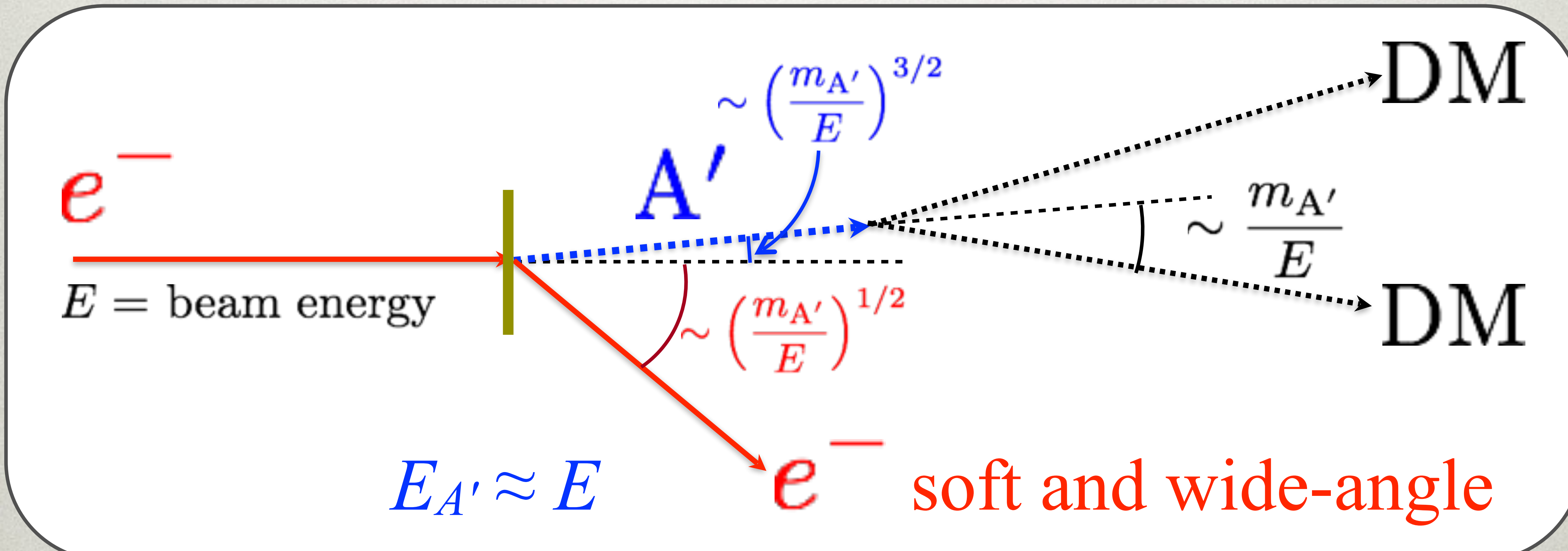
Kinematics of New-Particle Production in Electron Beams



Low-energy nucleus typically not measurable

$E(A') \approx E_{beam}$ $\quad$ $E(e) \ll E_{beam}$

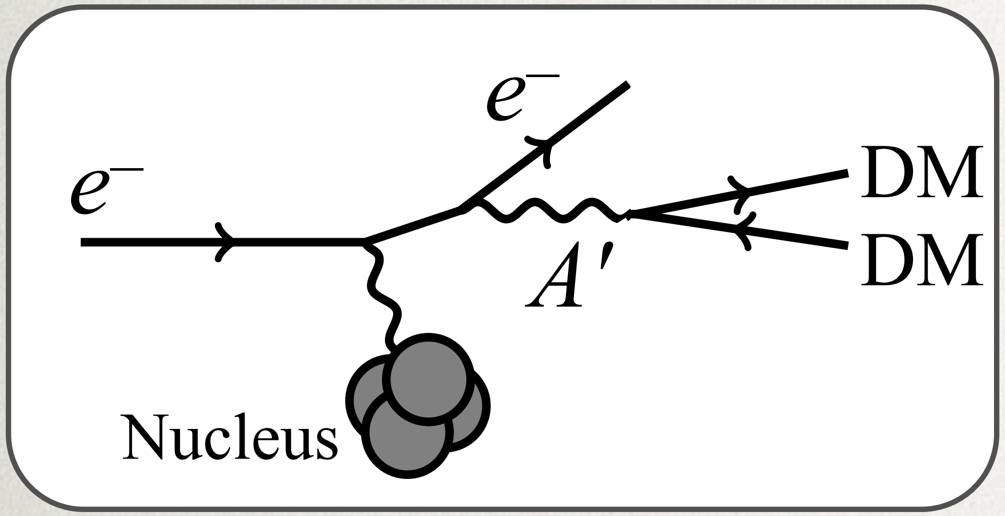
$p_T(A') \sim p_T(e) \sim m_{A'}$



Most of beam energy carried away by invisible particles

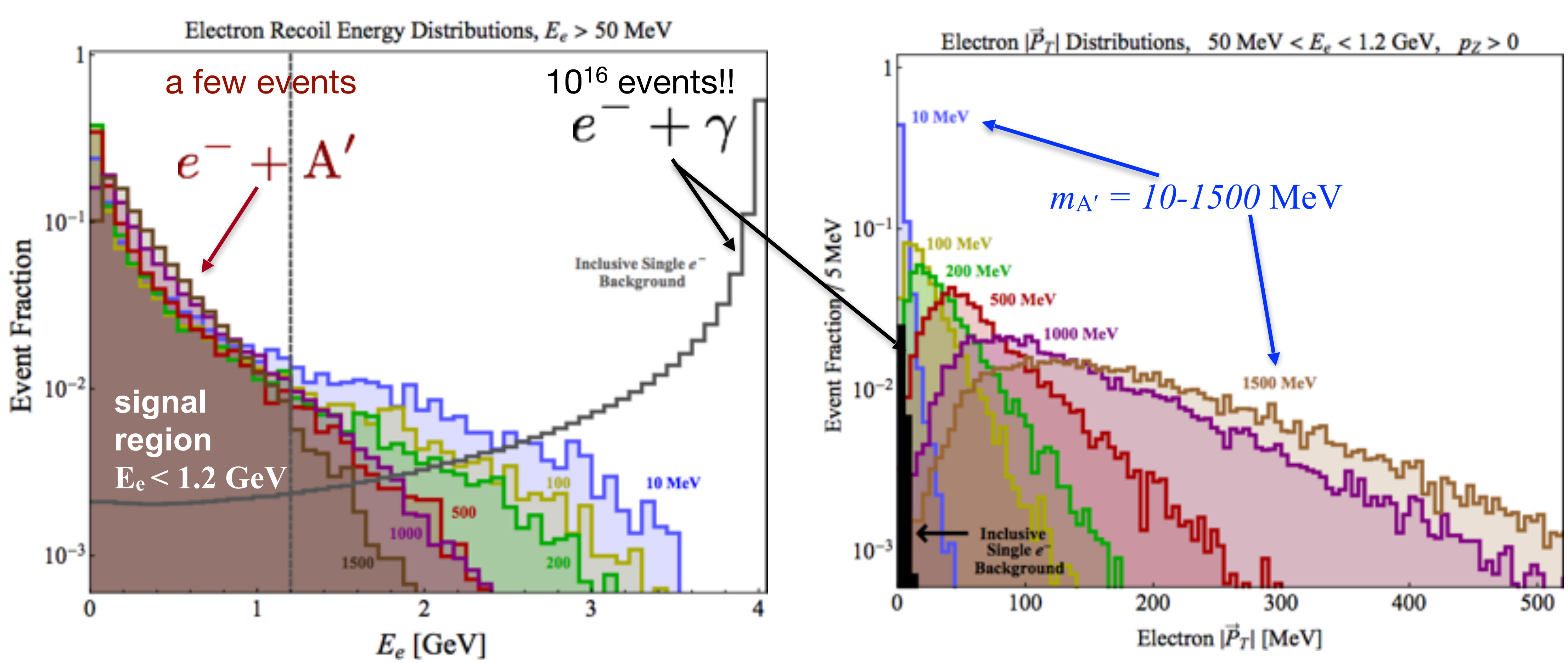
Recoil electron kinematics opposite of typical bremsstrahlung

Kinematics of New-Particle Production in Electron Beams

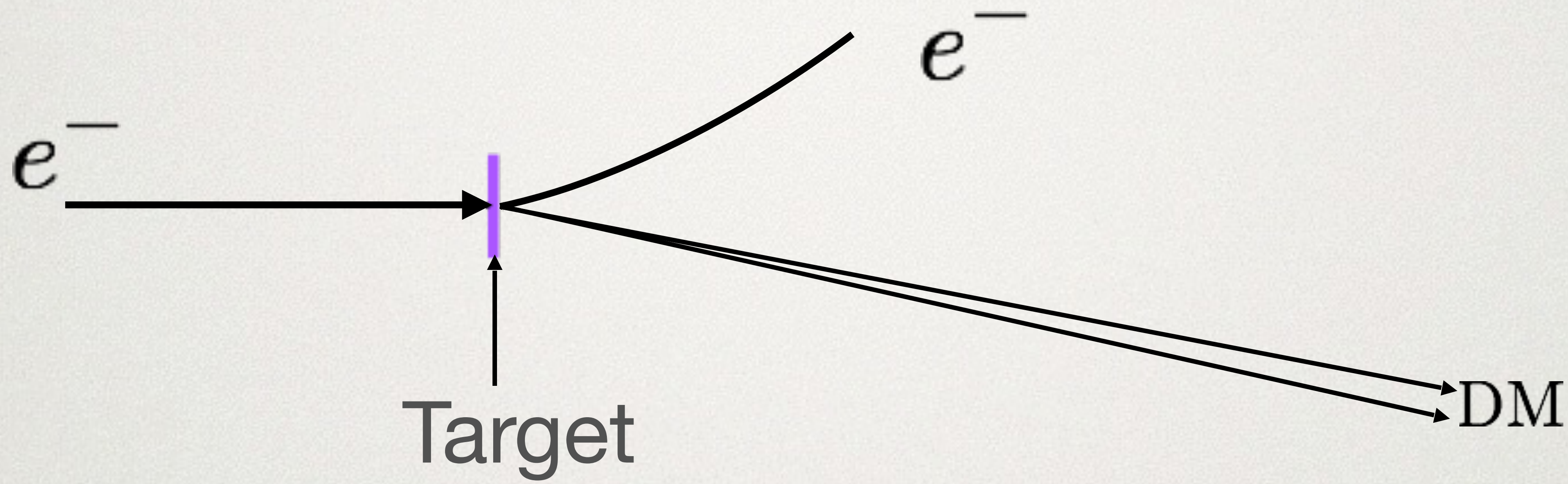


$$E(A') \approx E_{beam} \quad E(e) \ll E_{beam}$$
$$p_T(A') \sim p_T(e) \sim m_{A'}$$

recoil distributions, 4 GeV e^- on 10% X_0 target – NOT TO SCALE

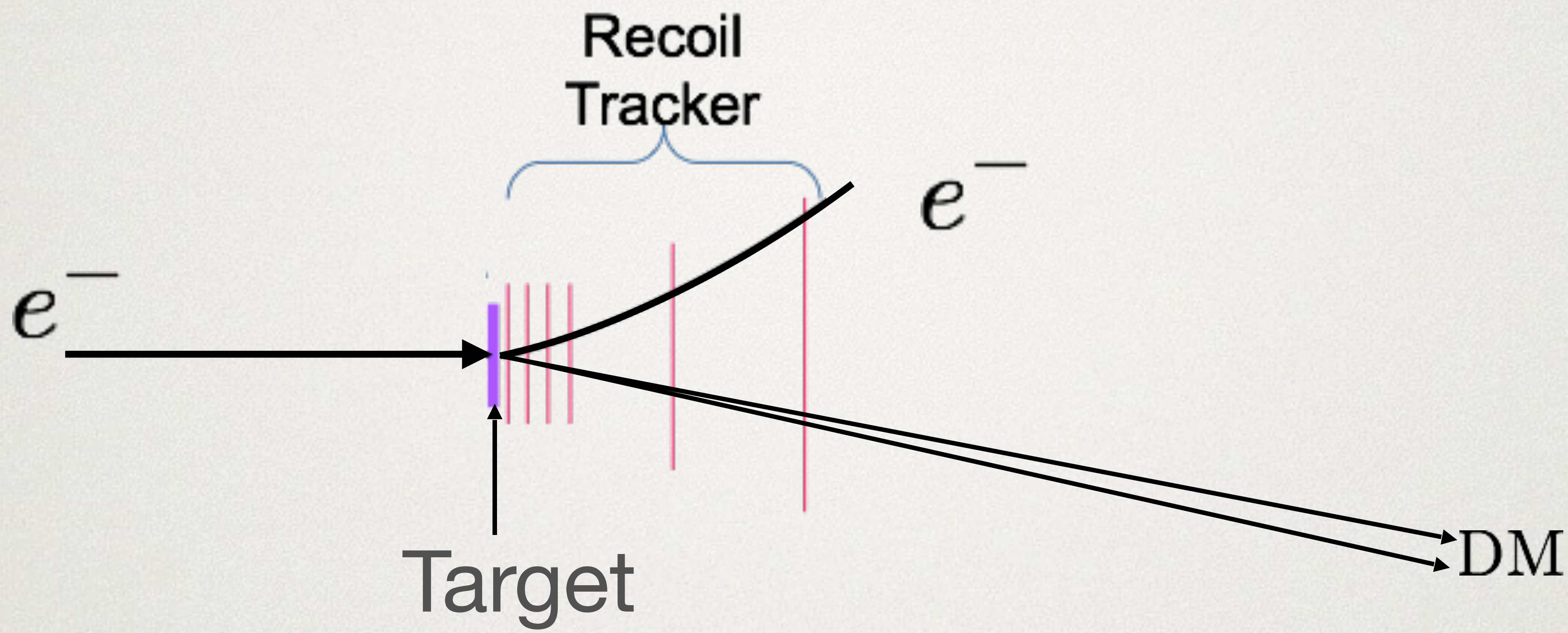


How to Identify These Events?



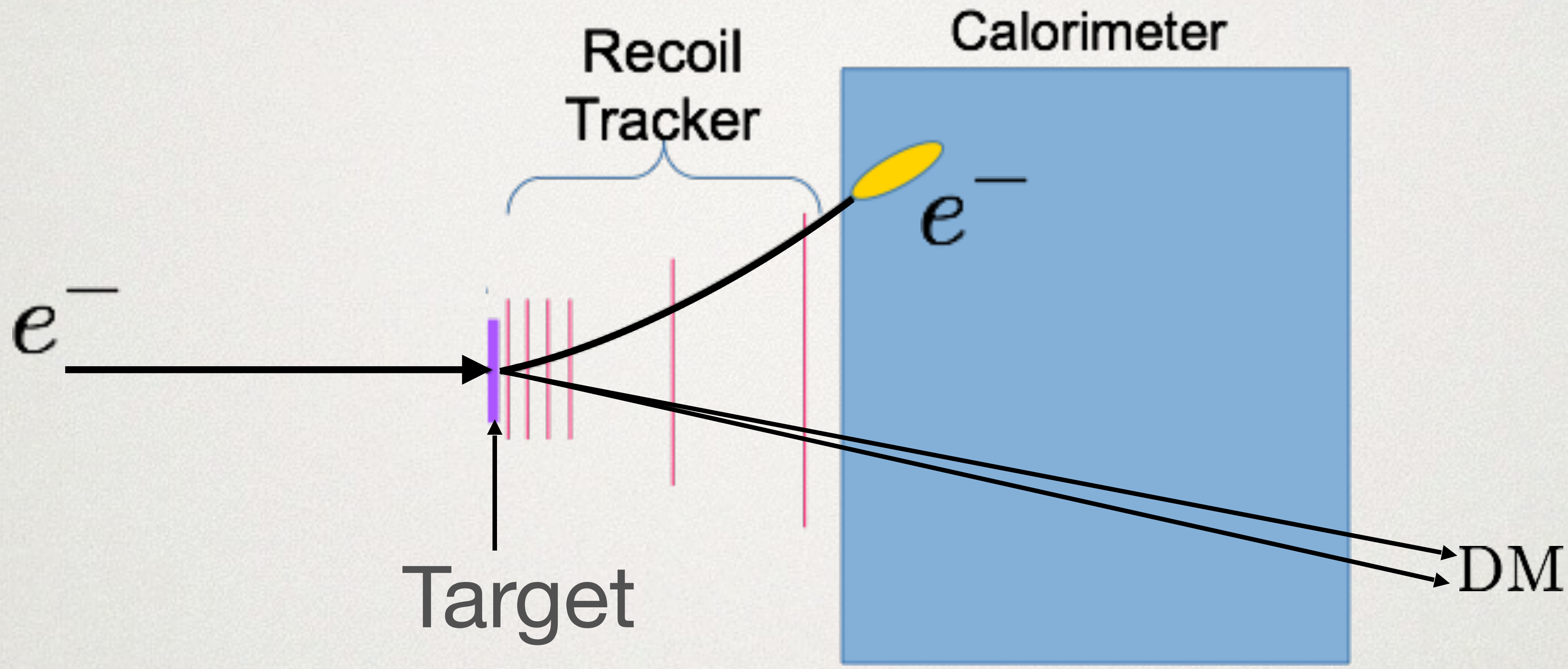
- Electron beam impinging on target

How to Identify These Events?



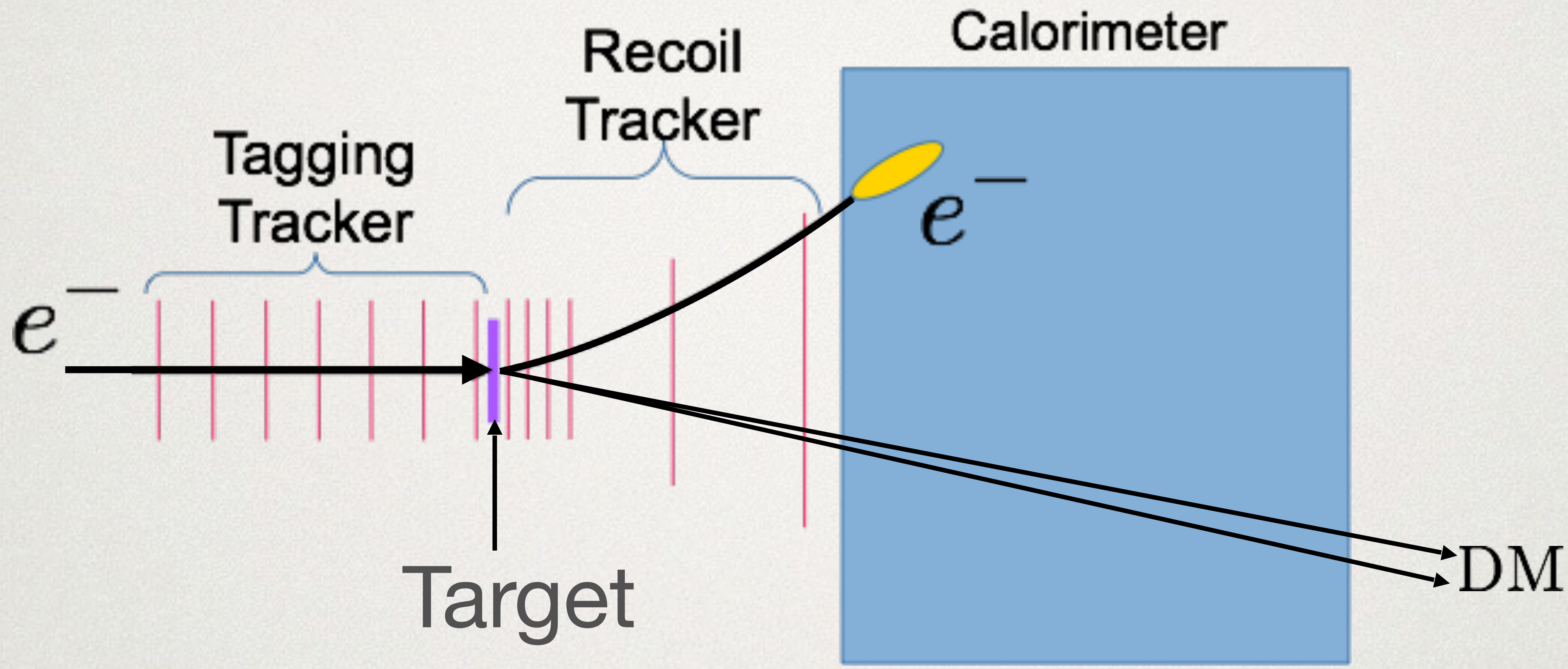
- ✦ Electron beam impinging on target
- ✦ Measure recoiling low-energy-fraction electron & its p_T
  - Forward tracking in (small) B-field

How to Identify These Events?



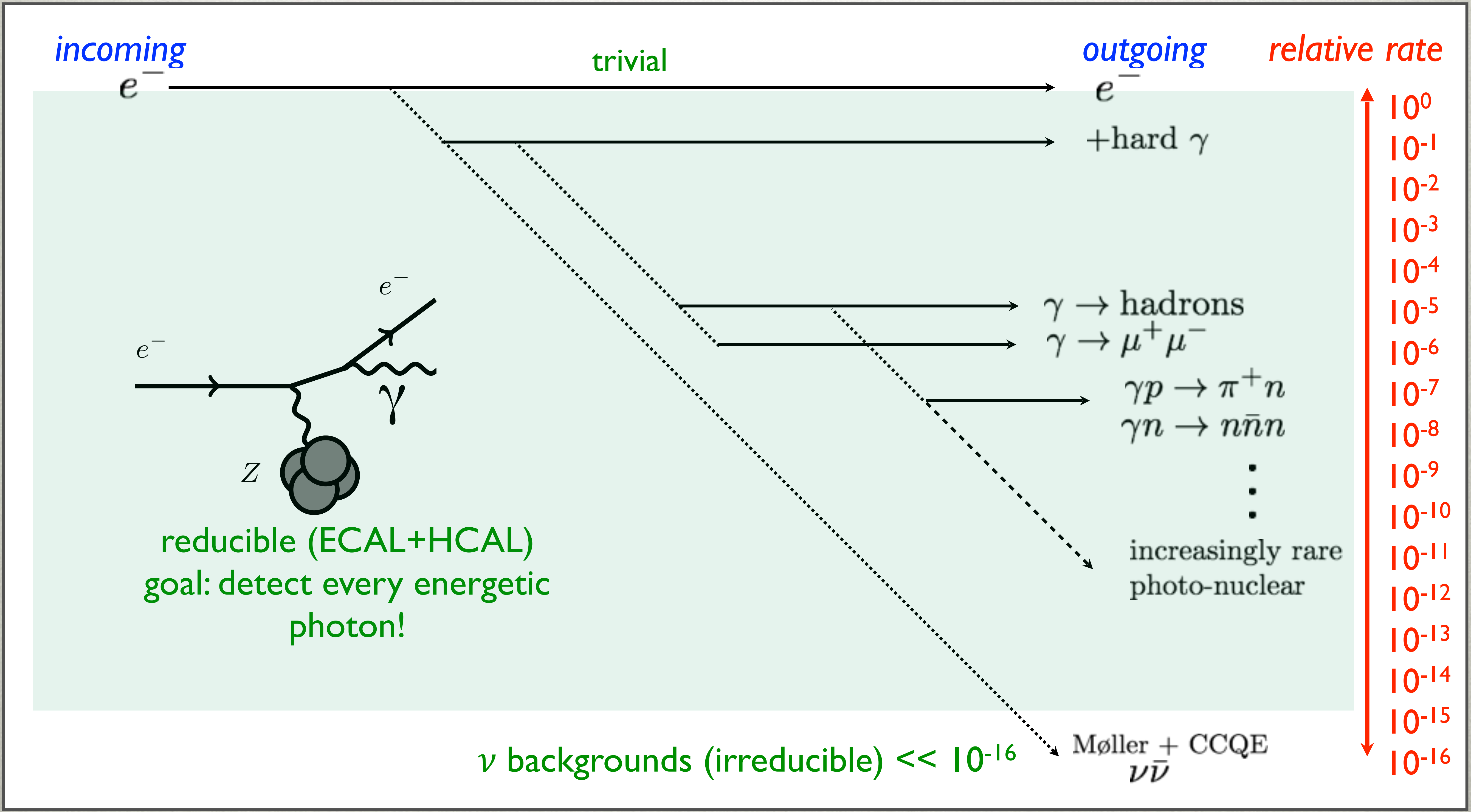
- ✦ Electron beam impinging on target ~one at a time
- ✦ Measure recoiling low-energy-fraction electron & its p_T
  - Forward tracking in (small) B-field
- ✦ Reject events with visible particles carrying remaining energy
  - Deep, highly segmented calorimeter

How to Identify These Events?

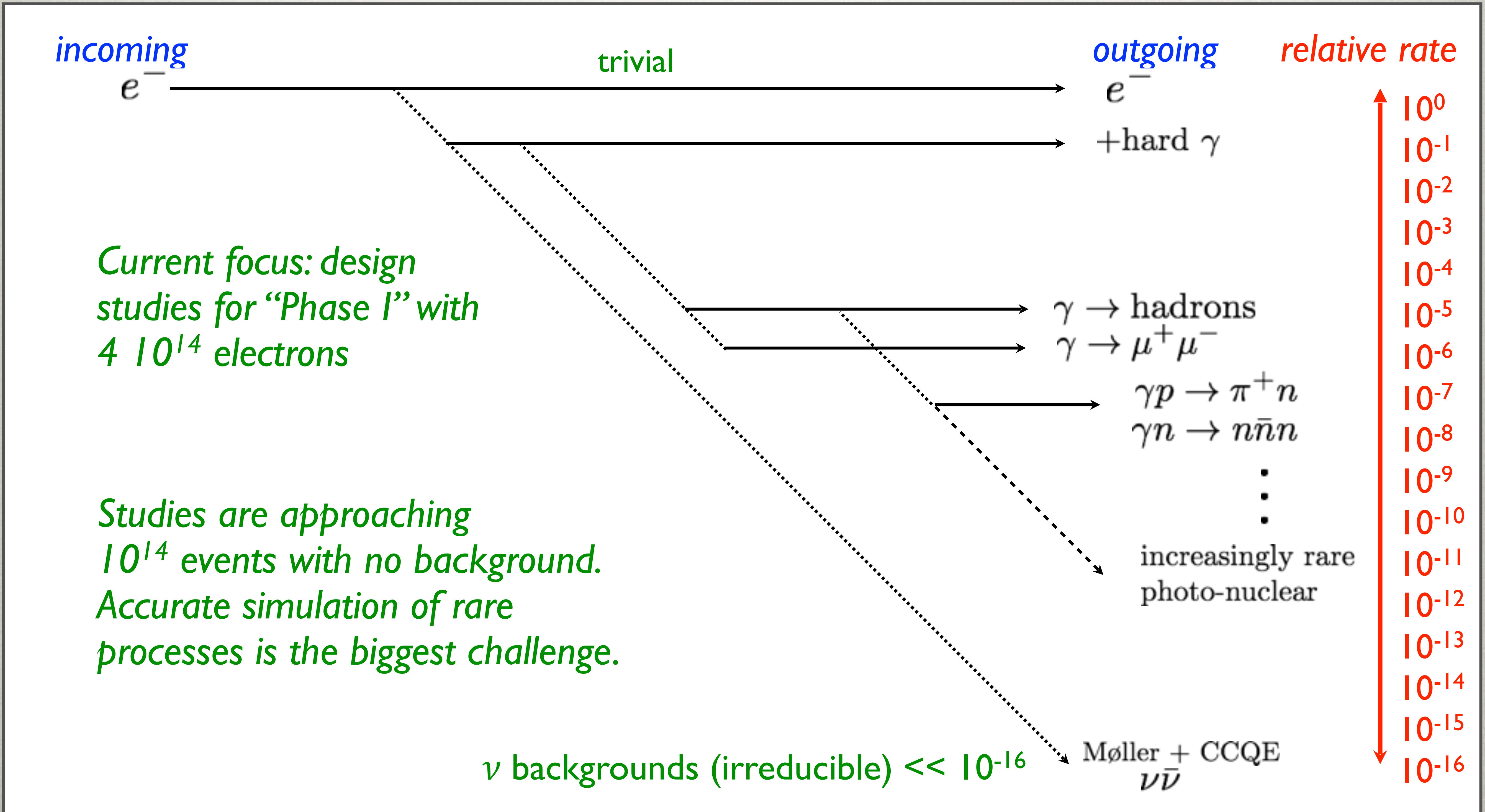


- Electron beam impinging on target
- Measure recoiling low-energy-fraction electron & its p_T
  - Forward tracking in (small) B-field
- Reject events with visible particles carrying remaining energy
  - Deep, highly segmented calorimeter
- Positively identify high-energy incident electron
  - (High-B-field) tracking upstream of target

Backgrounds!



Backgrounds!

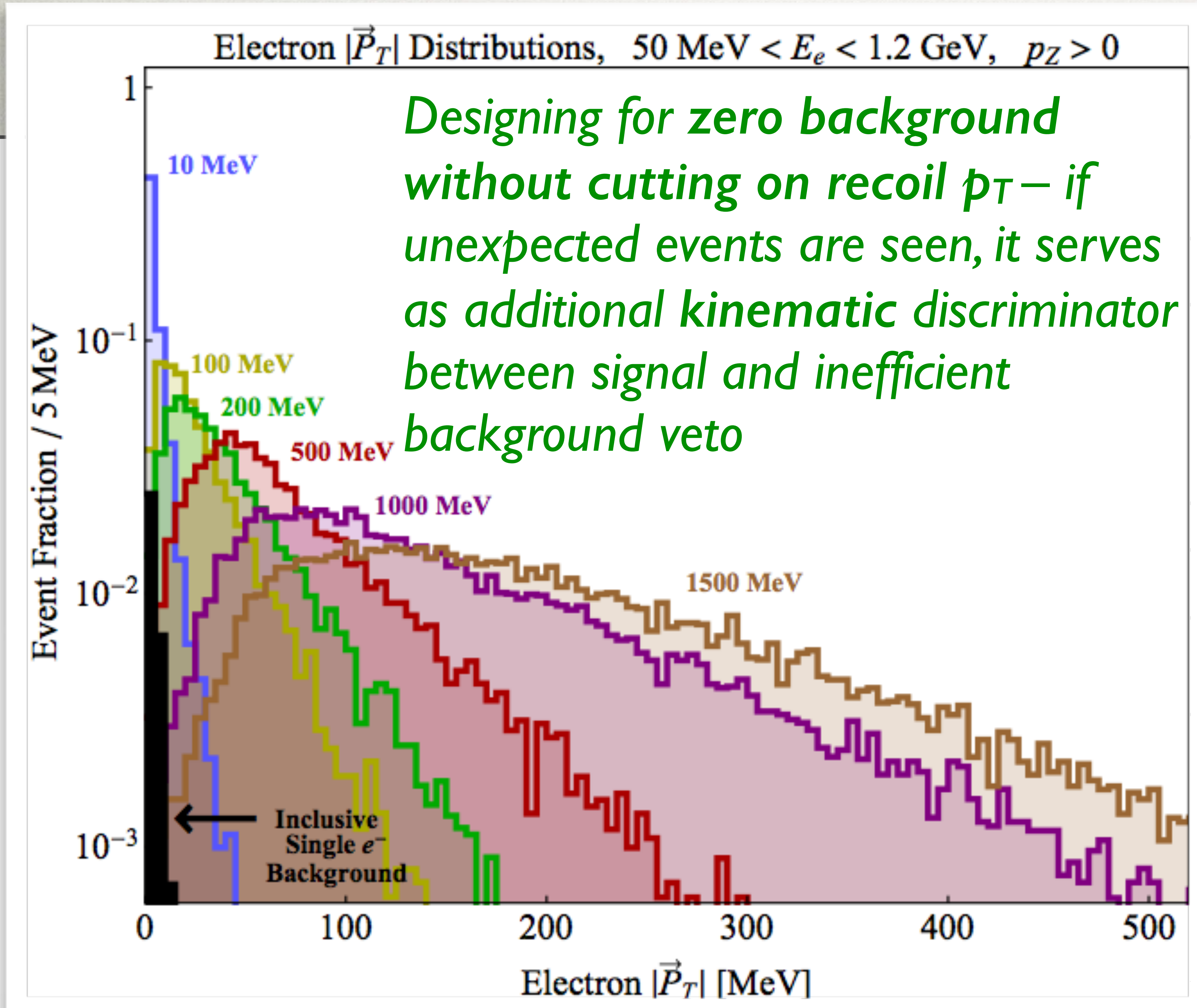


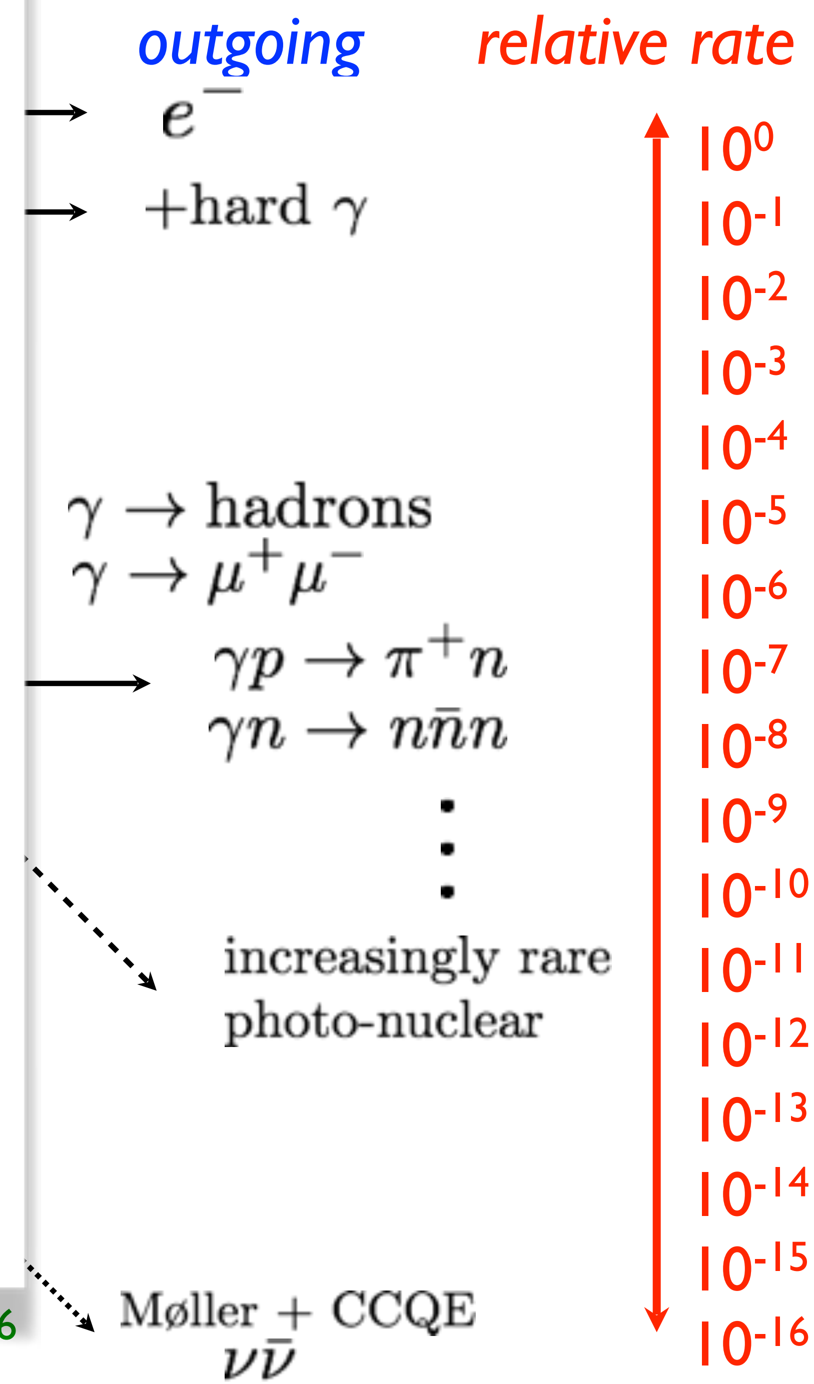
Light Dark Matter eXperiment

Phase I Detector Concept and Collaboration

Phase II may require more granularity and faster detectors (for pileup mitigation) + new trigger

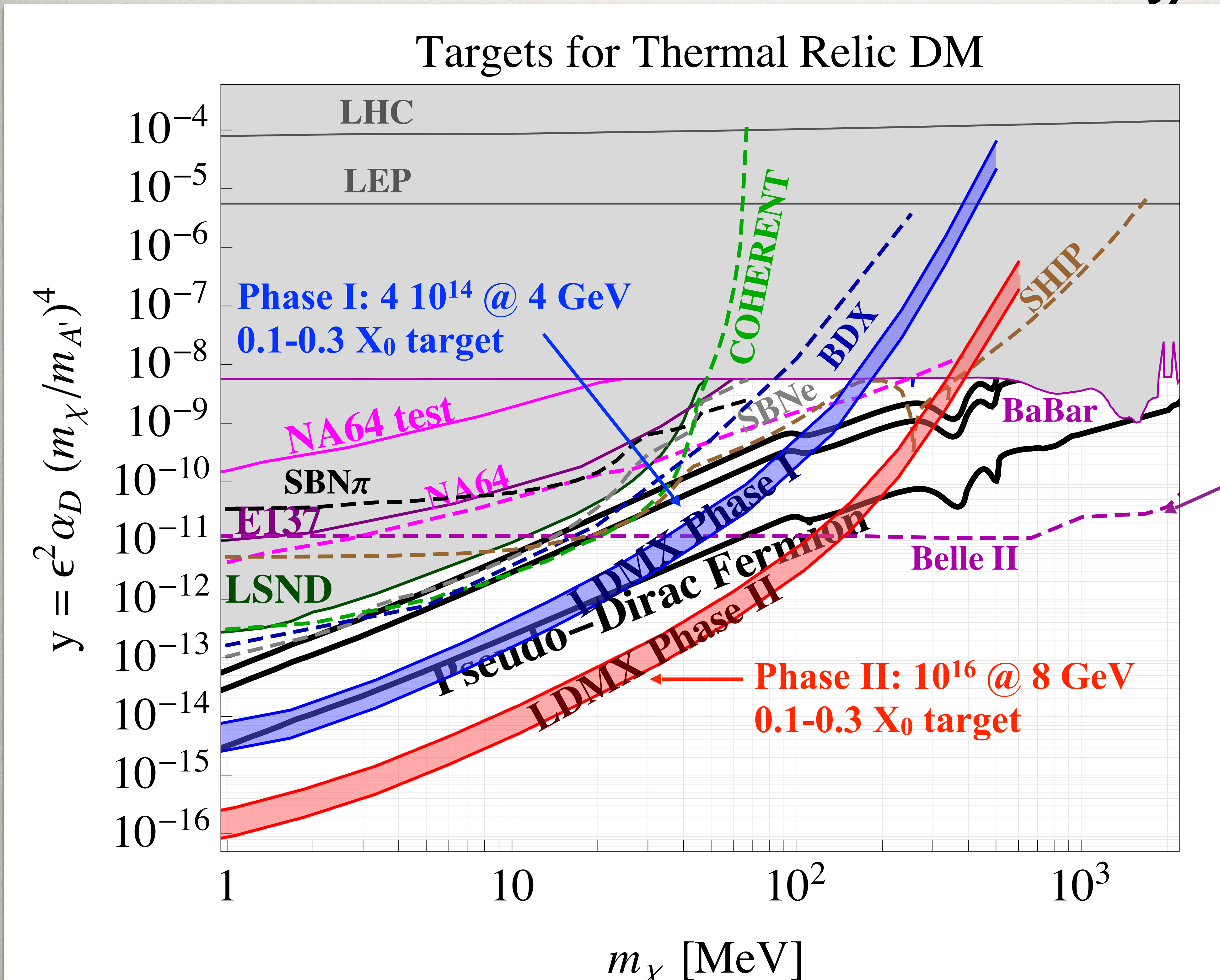
Backgrounds!





ν backgrounds (irreducible) << 10^{-16}

LDMX Sensitivity



Belle II missing mass search – complementary high-mass sensitivity

Unique potential to reach all thermal DM milestones at masses below ~100 MeV

Conclusions

WIMPs and WIMP-like dark matter near the weak-scale (MeV-TeV) remains well-motivated and important to test

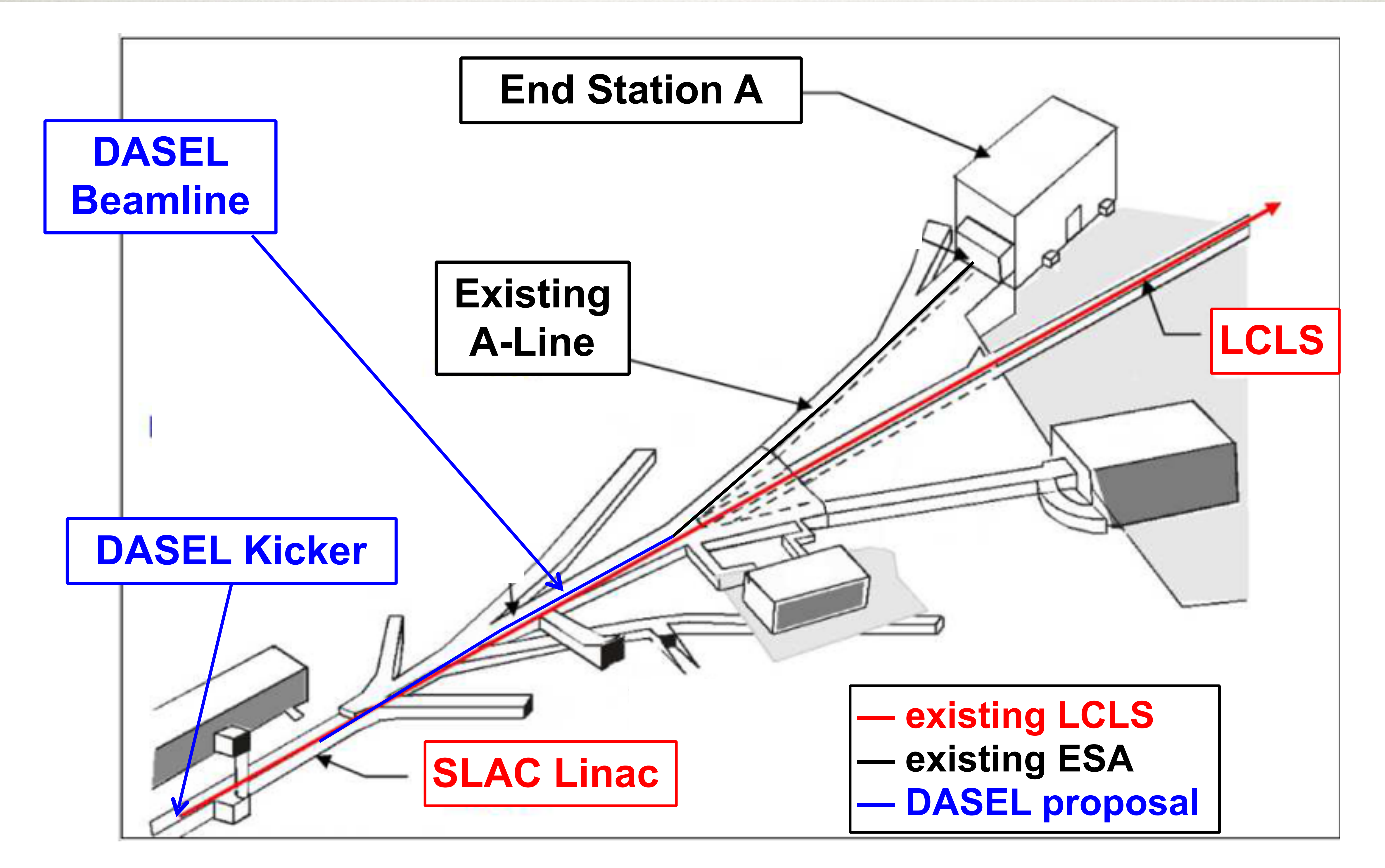
Large scale direct detection continues to define & push the boundaries above the GeV mass range

Existing and new small-scale accelerator experiments will test a broad range of scenarios below the GeV mass range

Backup

DASEL Beamline @ SLAC

Low-current but "continuous" multi-GeV beam needed for LDMX can be delivered parasitically!



DASEL Beamline @ SLAC

Low-current but "continuous" multi-GeV beam needed for LDMX can be delivered parasitically!