Exploring Hidden Sector Physics with an Electron Beam Facility

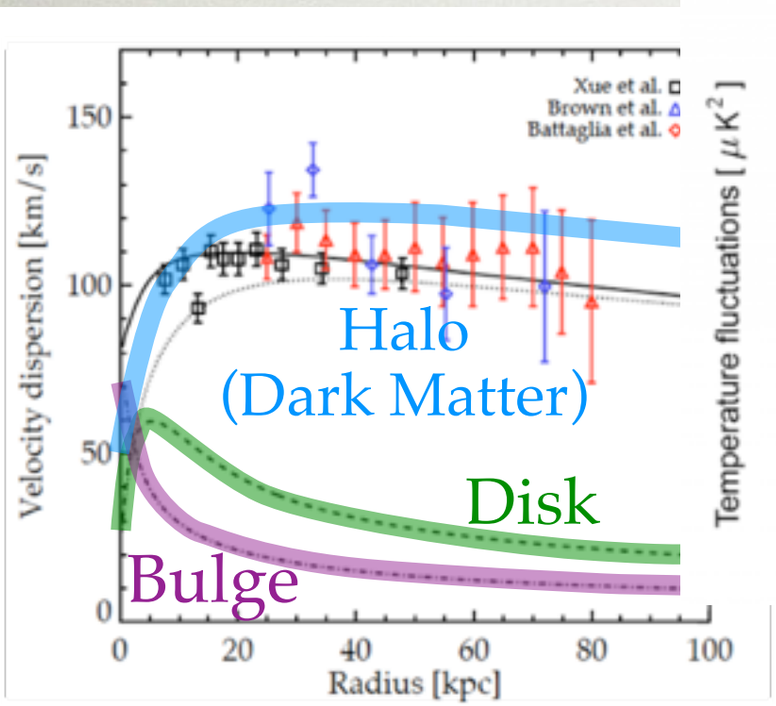
Part I: Impact on Dark Matter

Philip Schuster (SLAC)

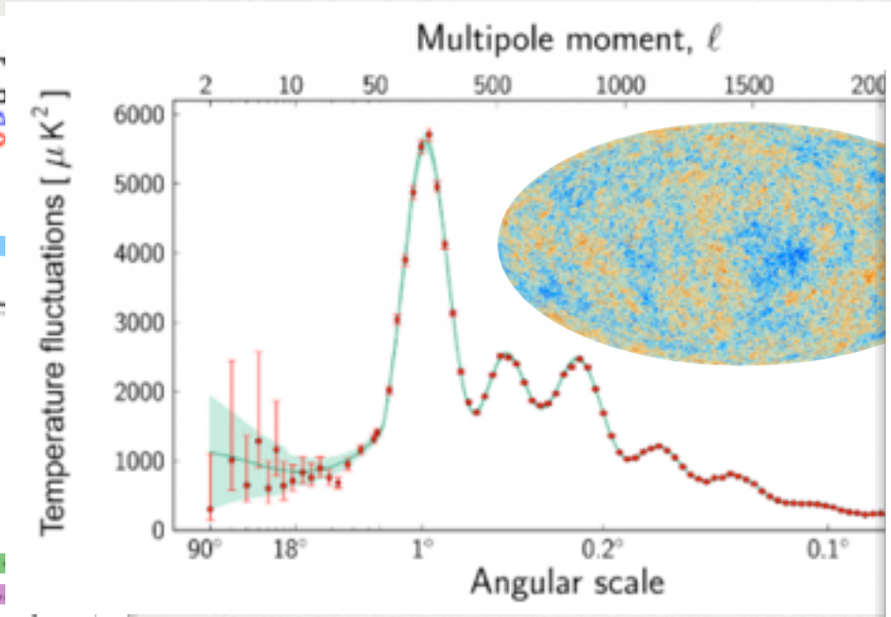
Part II: Electron Beam Facility
(Wednesday afternoon: Steinar Stapnes)

Physics Beyond Colliders, CERN
November 21, 2017

Dark Matter



Rotation curves

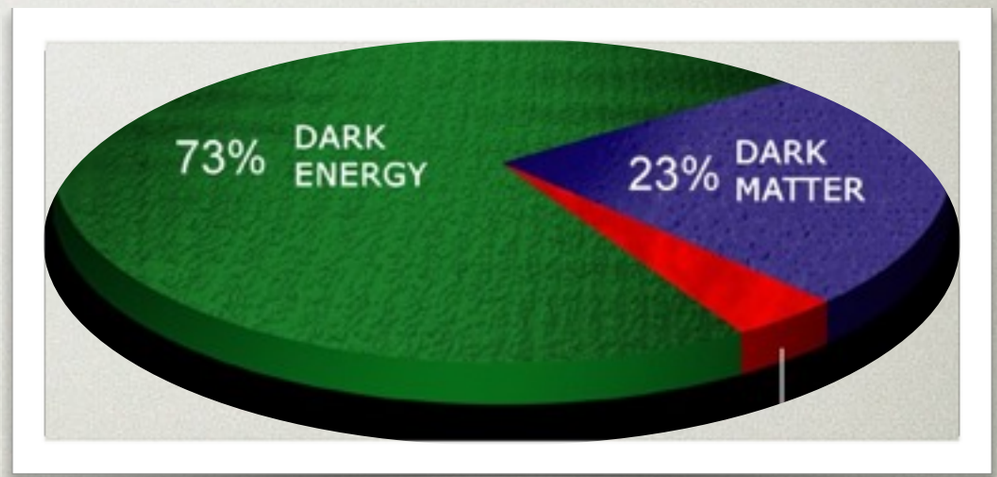


CMB Power Spectrum

Lensing

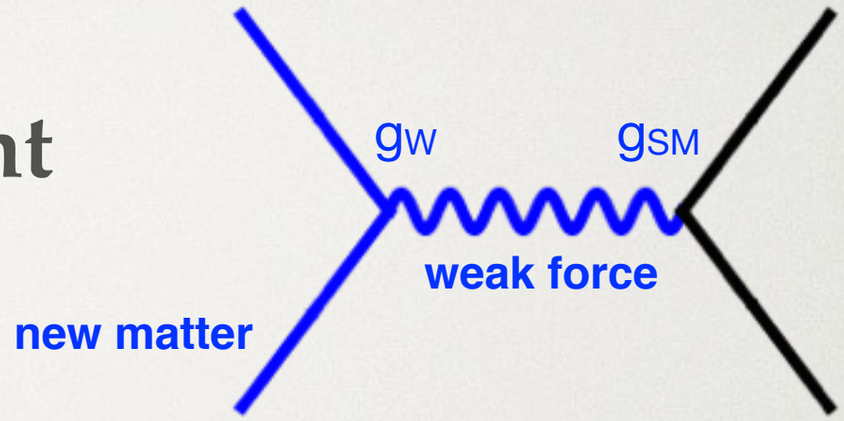
We know there is new physics in the form of dark matter!

<u>But what is it?</u>



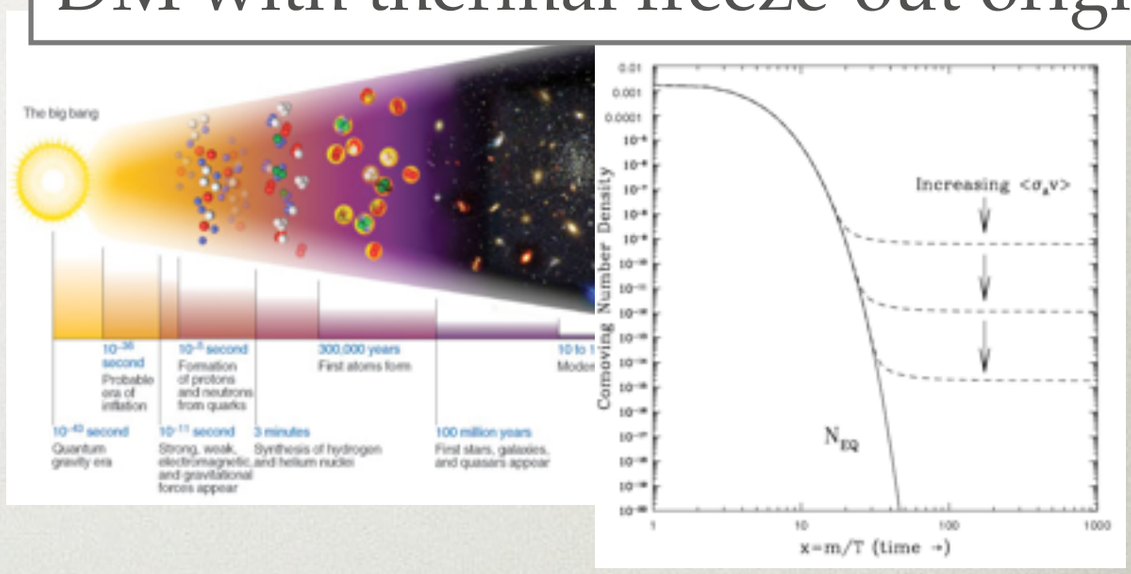
A Strong Candidate: WIMP DM

Simple, familiar particle content

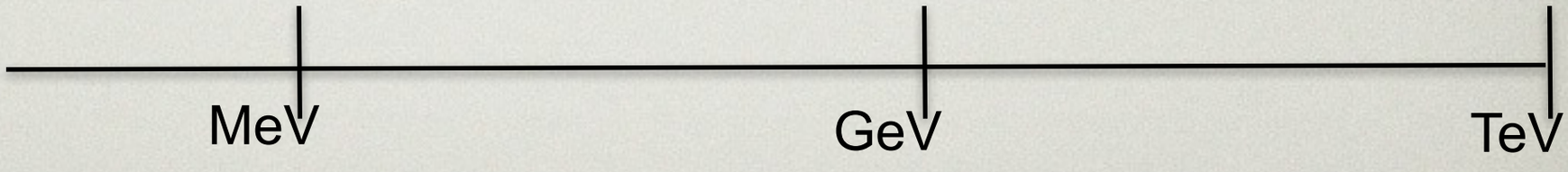


Simple, predictive cosmology

DM with thermal freeze-out origin



Motivated mass range



WIMP

Compelled to Move Beyond WIMPs

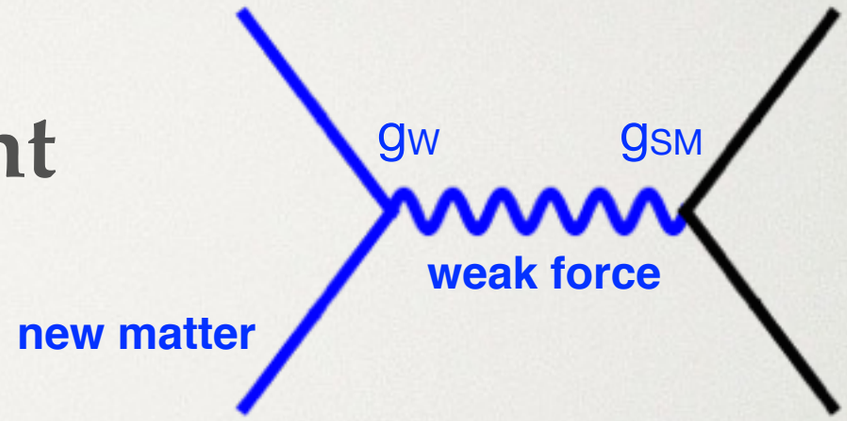
Basic weak-scale DM scenarios have been significantly constrained by the LHC, direct & indirect detection

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

What are we missing?

Logical Next Step Beyond WIMPs?

Simple, familiar particle content



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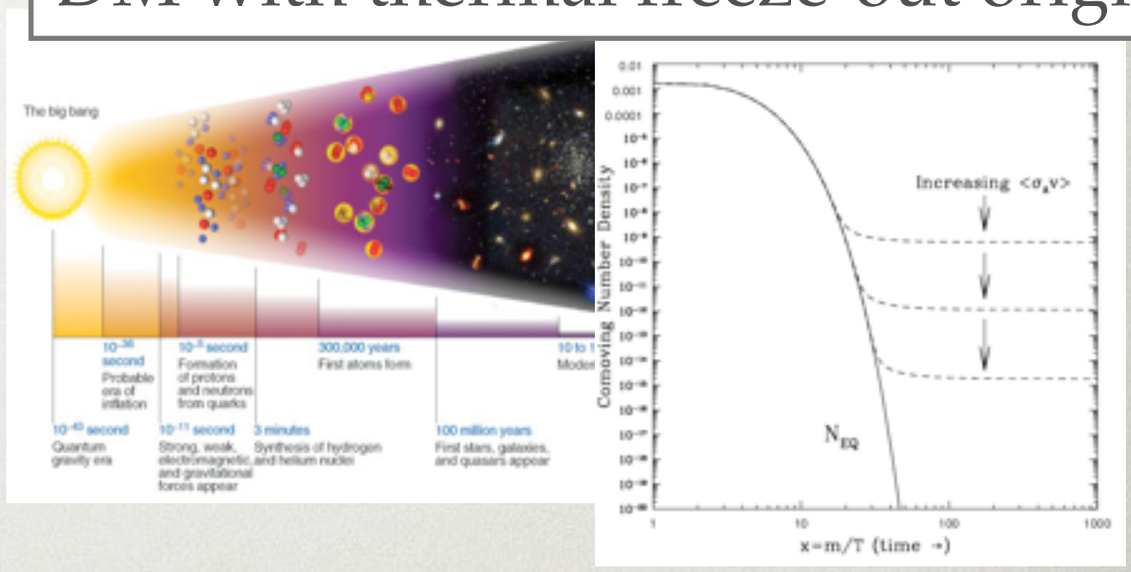


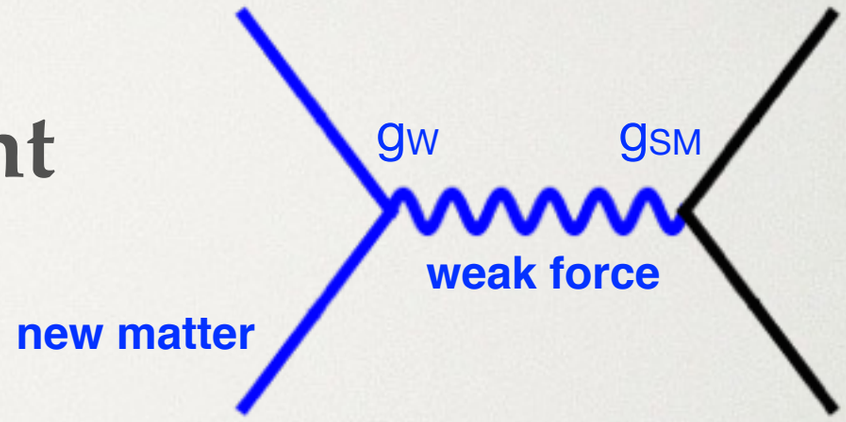
Motivated mass range

WIMP

What attractive features can remain?

Lessons From Data

Simple, familiar particle content



The ingredient most at odds with data underlying WIMPs is that interactions are mediated by W/Z bosons.

Lessons From Data

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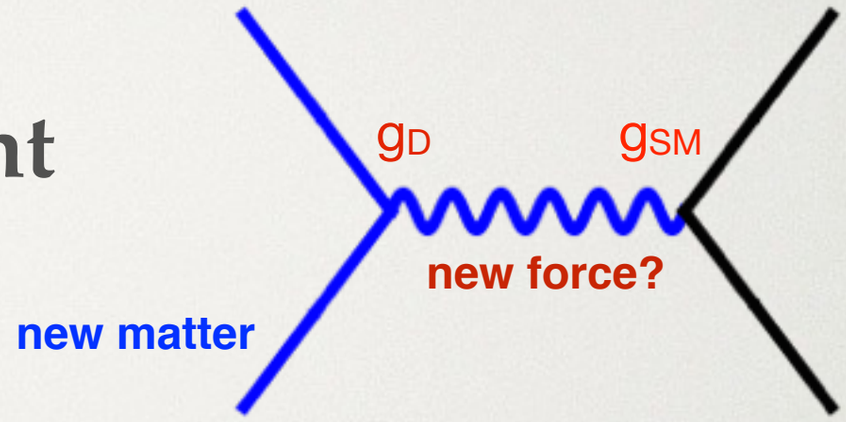


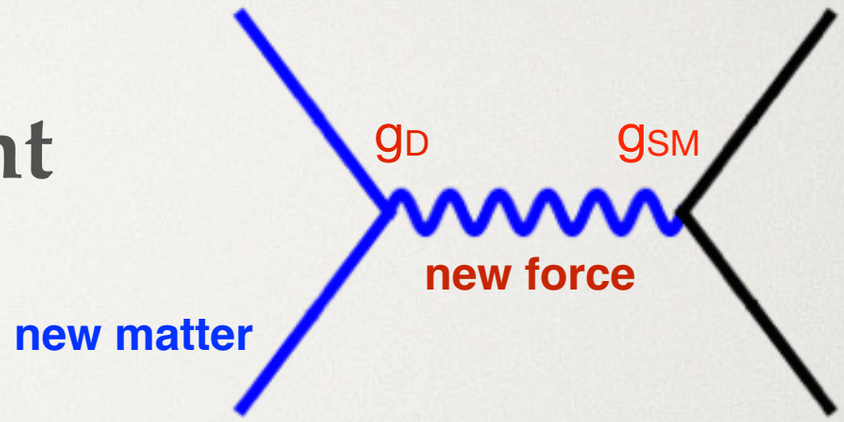
The principle most at odds with data underlying WIMPs is that interactions are mediated by W/Z bosons.

Dark matter could be charged under a new force!

(in keeping with the history of particle physics)

New Forces Interacting with The Standard Model

Simple, familiar particle content



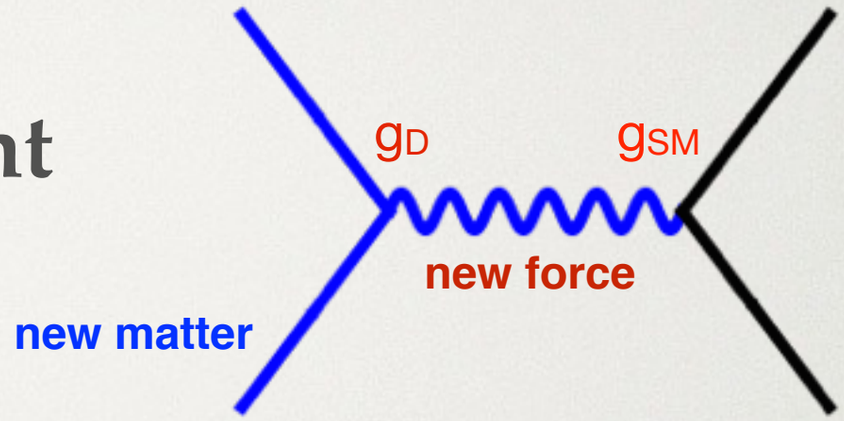
Standard Model symmetries allow two interactions with new force carriers at low-energy

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

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

New Forces Interacting with The Standard Model

Simple, familiar particle content



Standard Model symmetries allow two interactions with new force carriers at low-energy

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

Most compatible with cosmology & simple dark matter models…

focus of this talk

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

↑

Increasingly constrained by LHC

New Forces Interacting with The Standard Model

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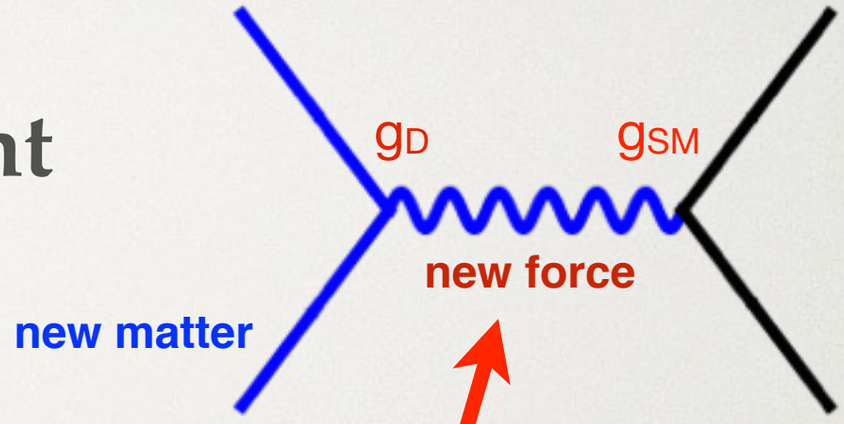

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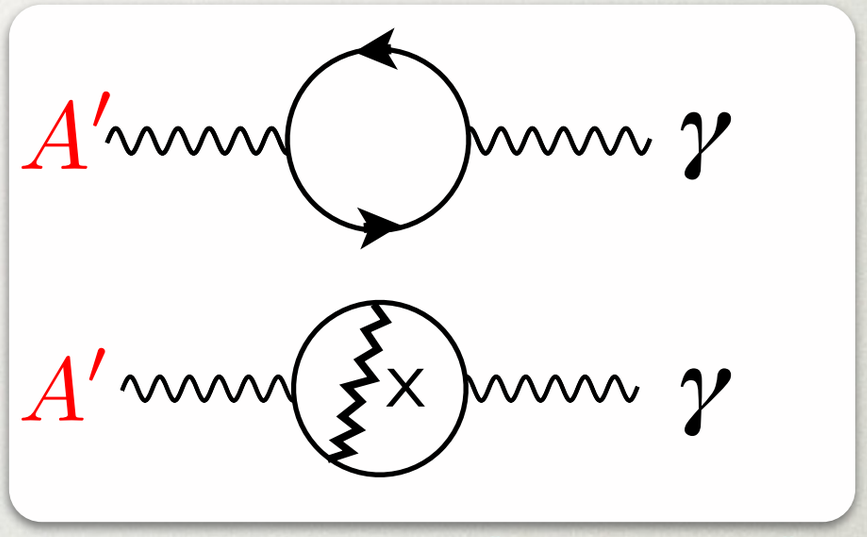
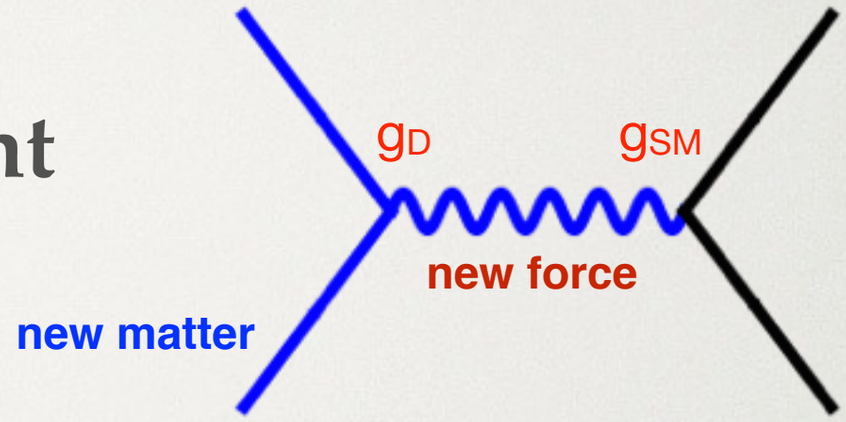


$g_{\rm SM} \sim (10^{-6} - 10^{-2})e$

Mediator particle with naturally small (loop-level) Standard Model couplings...would have missed such physics without dedicated search!

Hidden Sector Dark Matter

Simple, familiar particle content



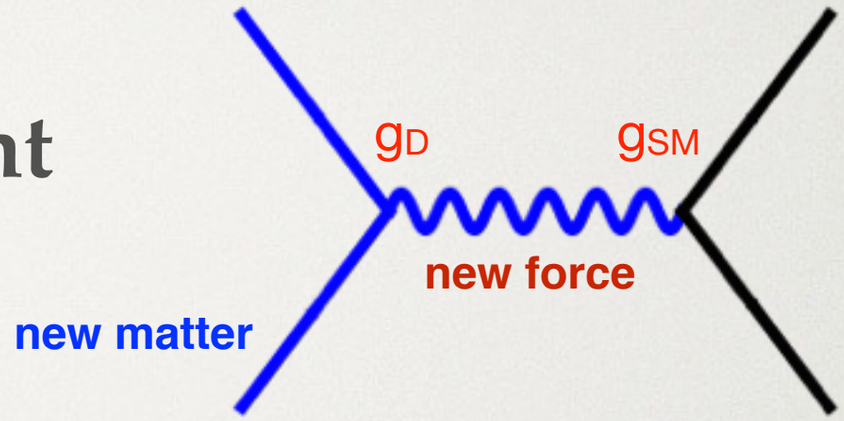
Dark Matter charged under a new force

Provides a familiar and simple explanation for dark matter stability (i.e. lightest charged particle is stable!)

Mediator mixing gives interaction with Standard Model

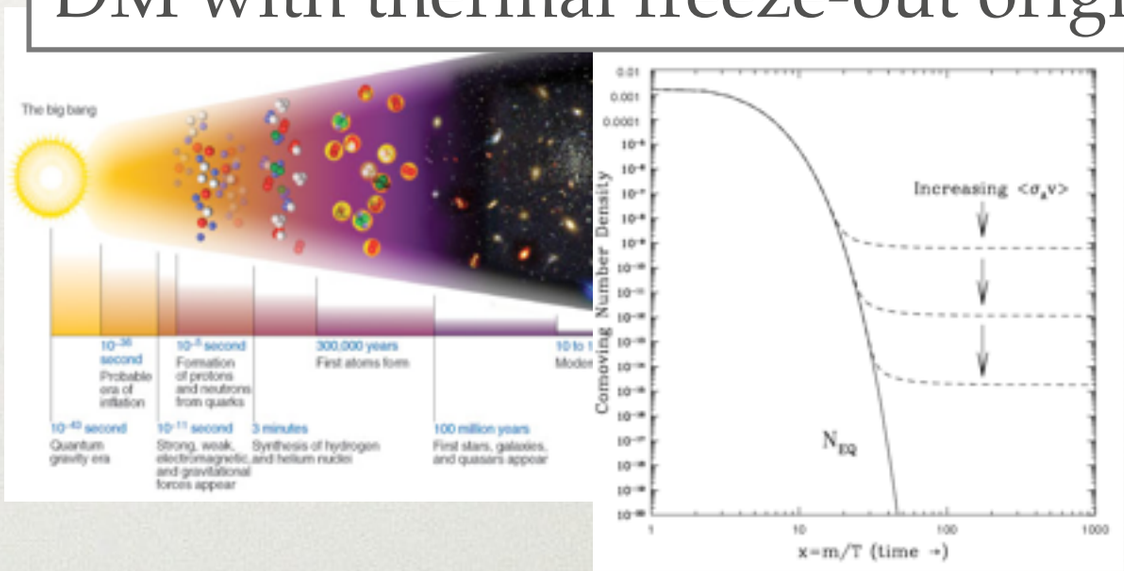
A Strong Candidate: Hidden Sector DM

Simple, familiar particle content



Simple, predictive cosmology

DM with thermal freeze-out origin



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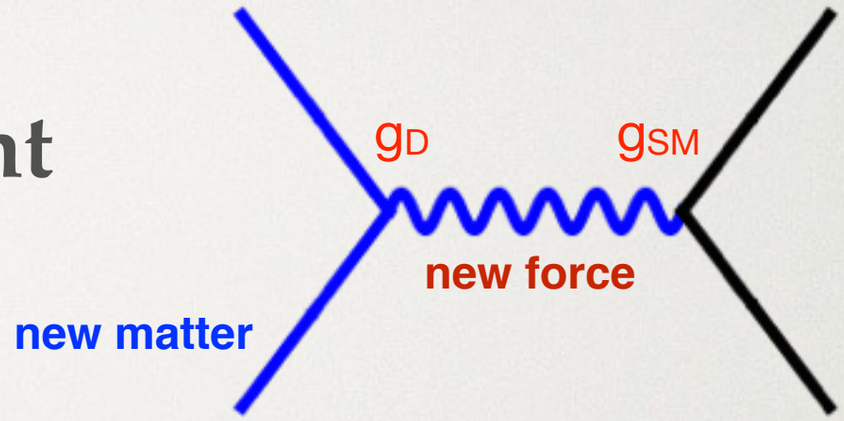

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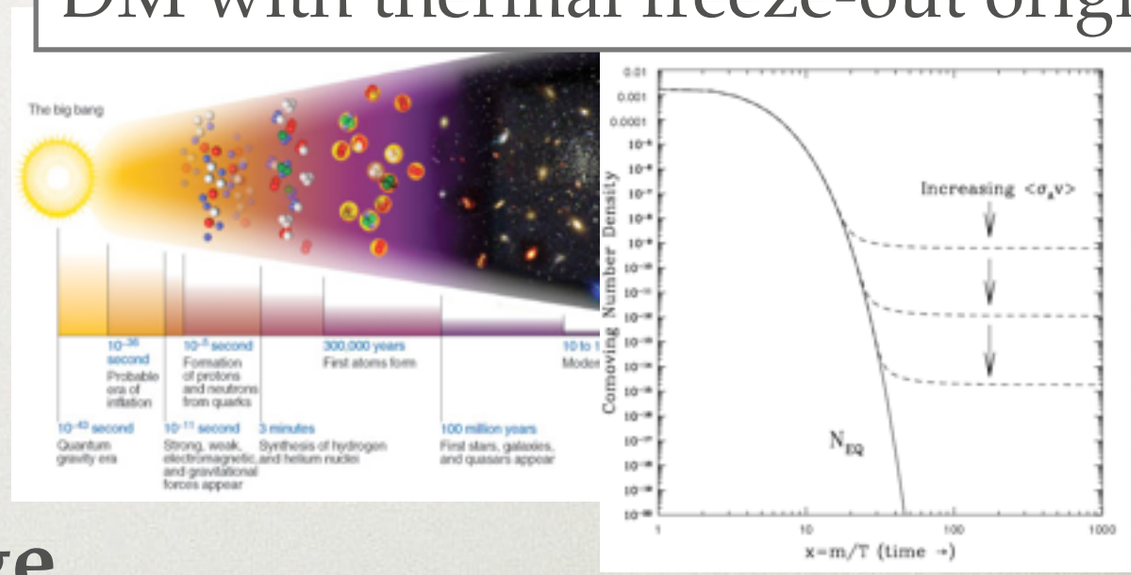
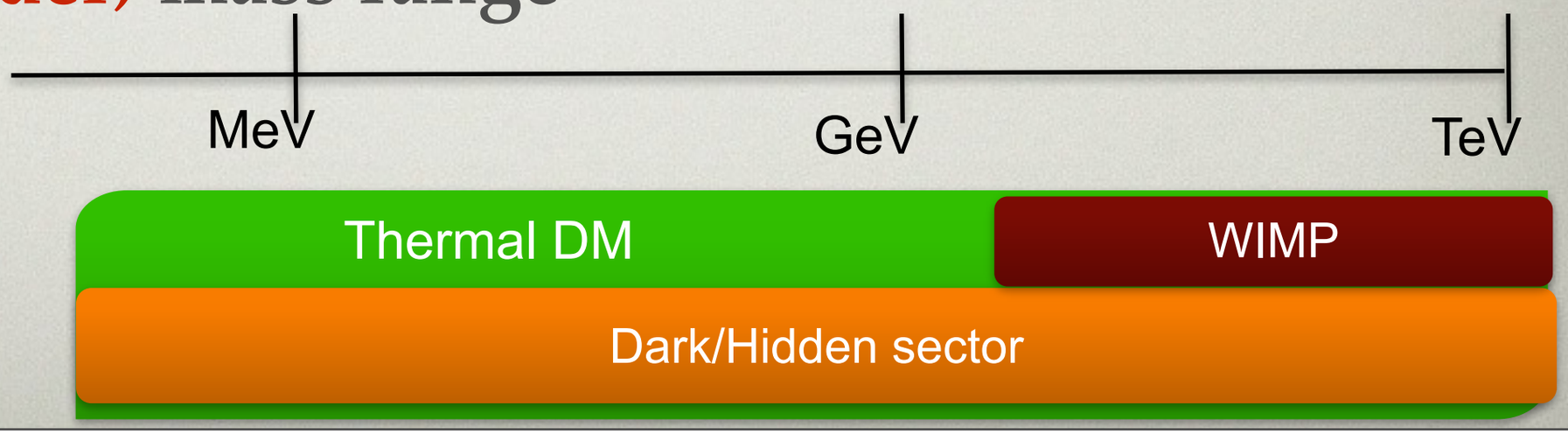
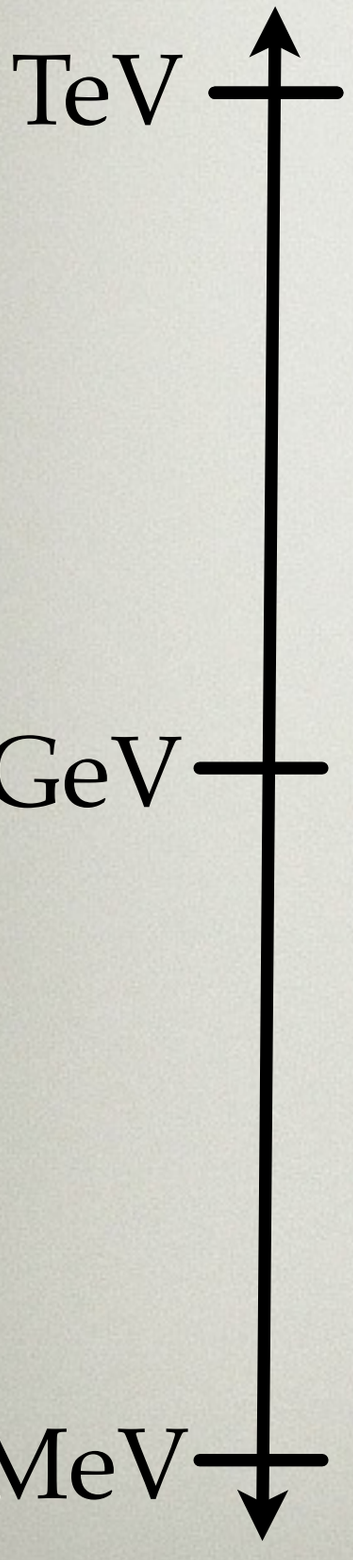


Motivated (broader) mass range



The Vicinity of the Weak Scale



SM Matter

Dark Matter?

For decades: look here!

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

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

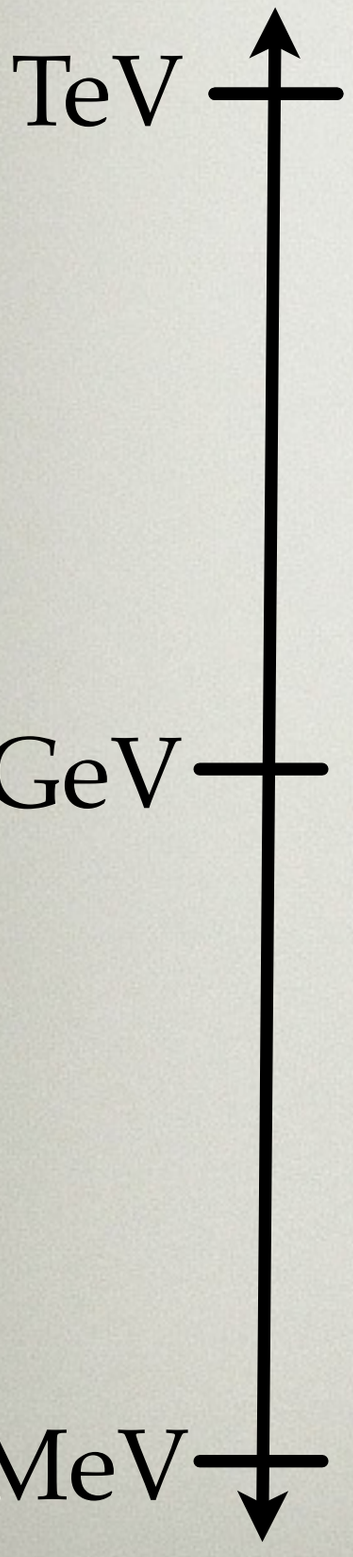
(accidentally close to weak scale)

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

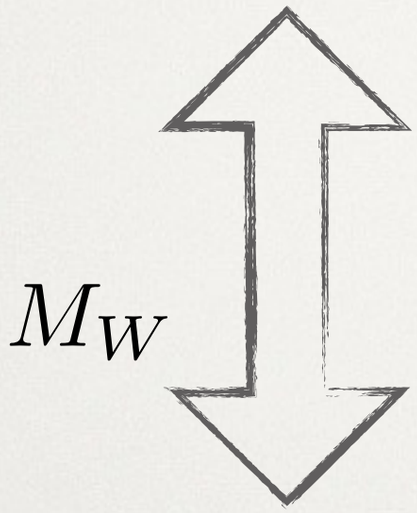
$$m_e \sim \text{small } \# \times M_W$$

(derived from weak scale)

The Vicinity of the Weak Scale



SM Matter



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

(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)

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

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

The Vicinity of the Weak Scale

SM Matter

Dark Matter?

TeV

GeV

MeV

Moving beyond WIMPs, the broad 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!**

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

(derived from weak scale)

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

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 Es… (WG4 Conv… Peter Gra… member),[3] …an L. Feng Convener),[3] …nik (SAC 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,†] …(DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan Krnjaic (DM… …issey (RDS Convener),[9] T… …),[1] Matt Pyle (DD Convener… …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

Unlocking the sub-GeV Dark Matter Frontier

Light DM Scattering

- Upcoming direct detection

Light DM Production

- New beam dump, missing momentum & energy experiments

Resonant Mediator Searches

- Accelerator searches for mediator particles

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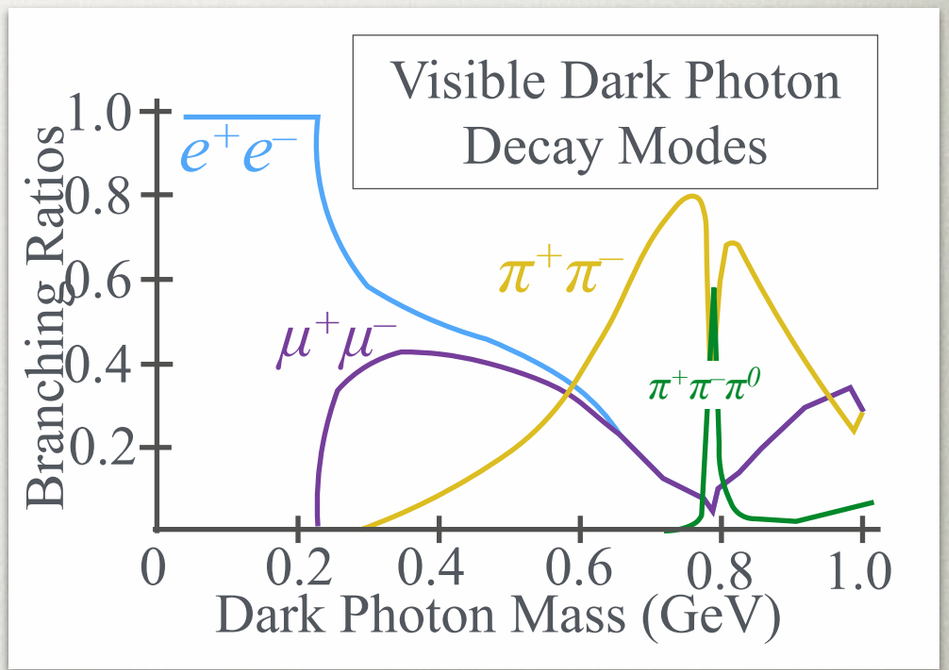
LHC@CERN !

Resonant (GeV-Scale) Mediator Searches

- Mediator might decay to visible final state
- Lifetime and decay mode dictates search strategy
- Searches can exploit several production modes
  - bremsstrahlung
  - meson decays
  - e^+e^- annihilation
  - Drell-Yan

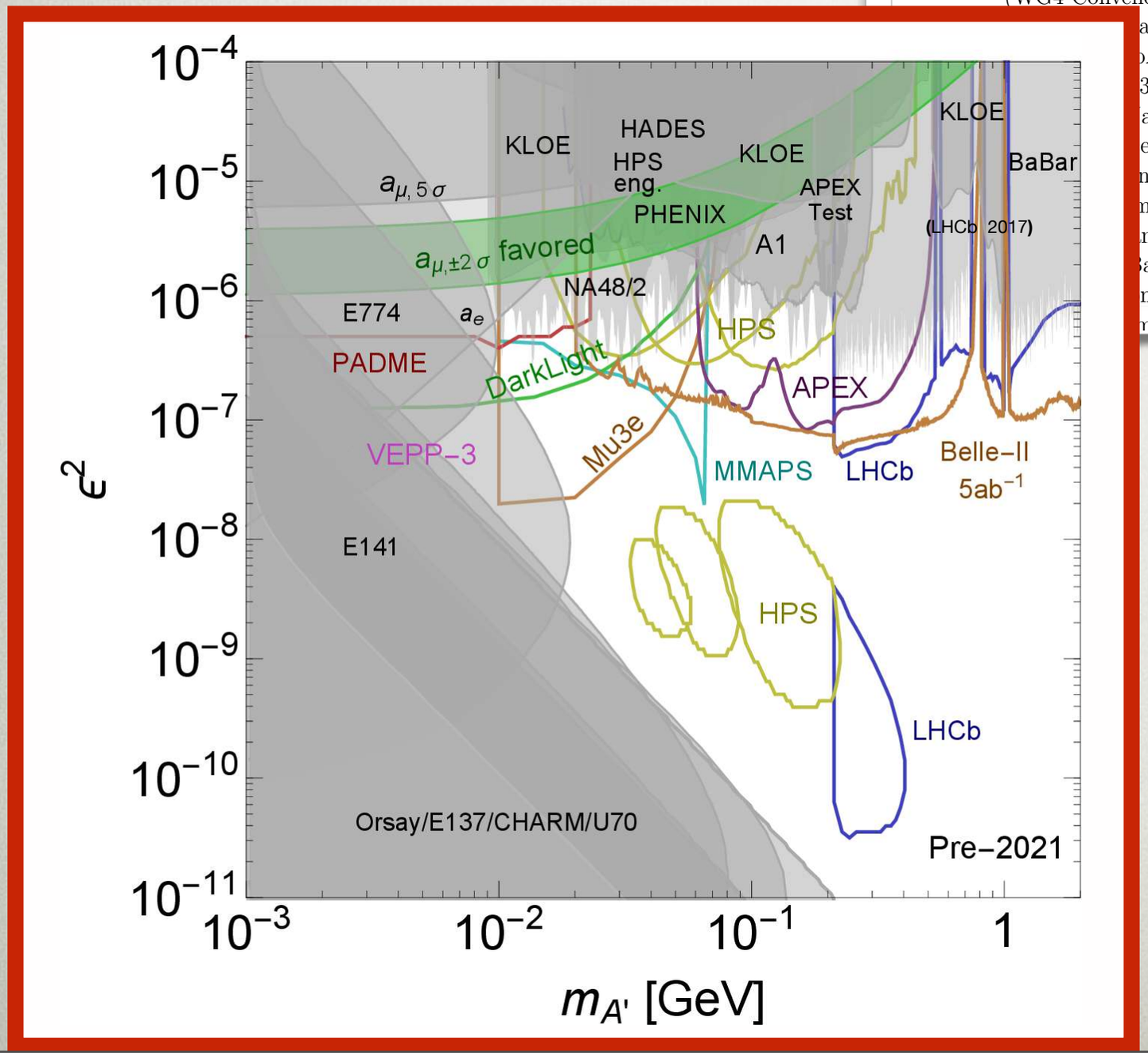


- **ATLAS, CMS, LHCb all have active searches for "dark photons" decaying to visible final states**

See community reports arXiv:1608.08632 and arXiv:1707.04591 for a summary of results

Resonant (GeV-Scale) Mediator Searches

Summary plot from US Cosmic Visions



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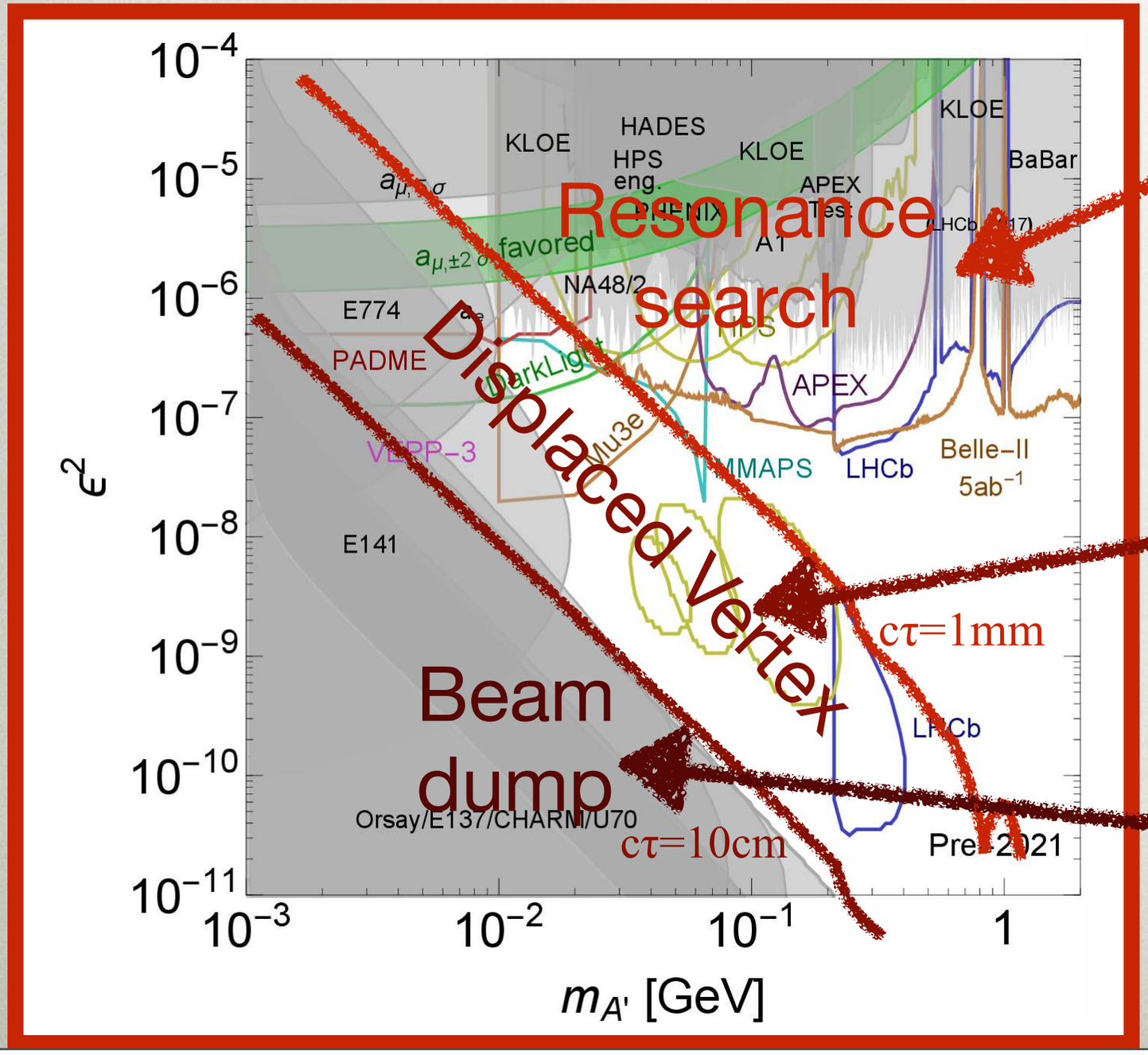
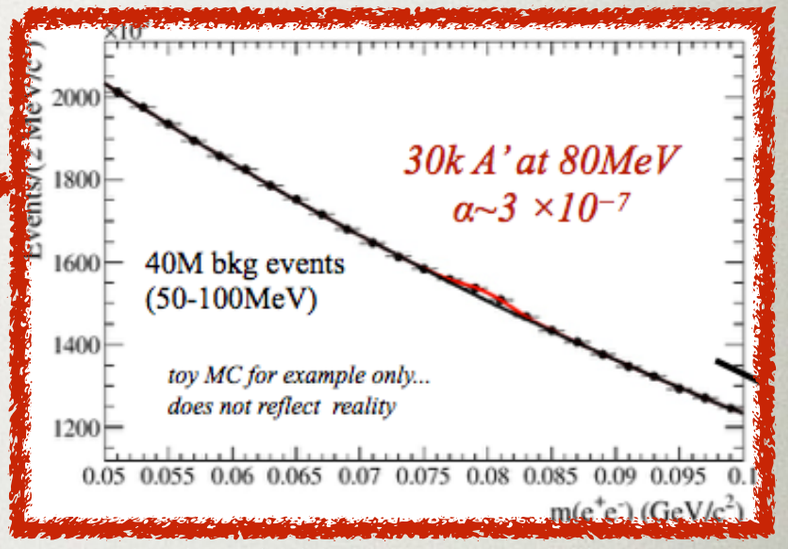
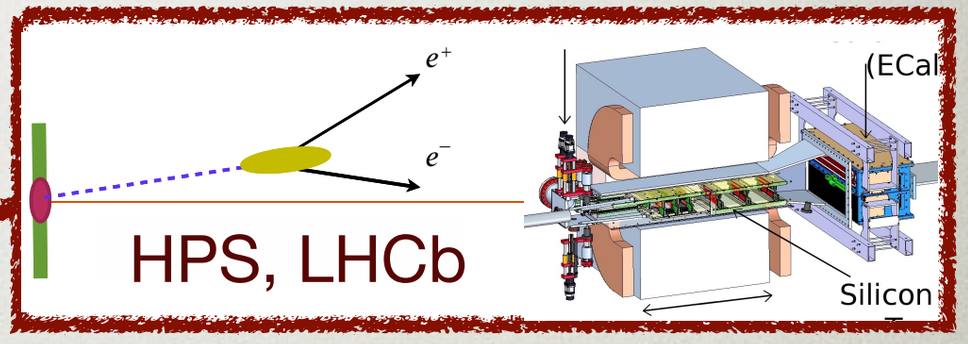
Tremendous international activity over next ~4-5 years!

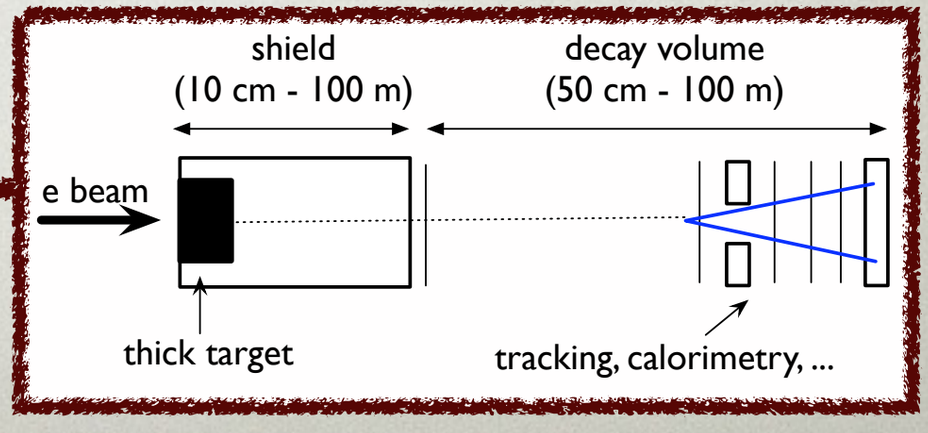
Resonant (GeV-Scale) Mediator Searches

- Resonance & Displaced Decays
- Lifetime and decay mode dictates search strategy









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Light Dark-Matter Scattering

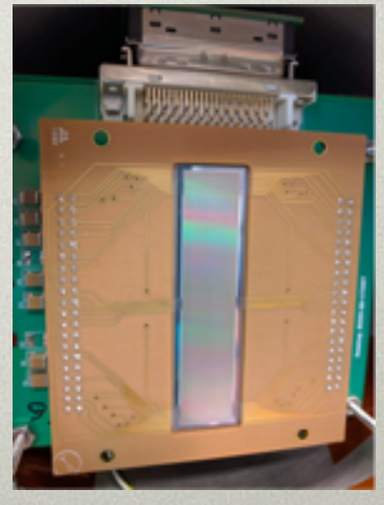
Main challenge is light dark matter deposits unusually small recoil energy in detector

Energy transfer of sub-GeV DM collision with heavy nuclear target is kinematically suppressed

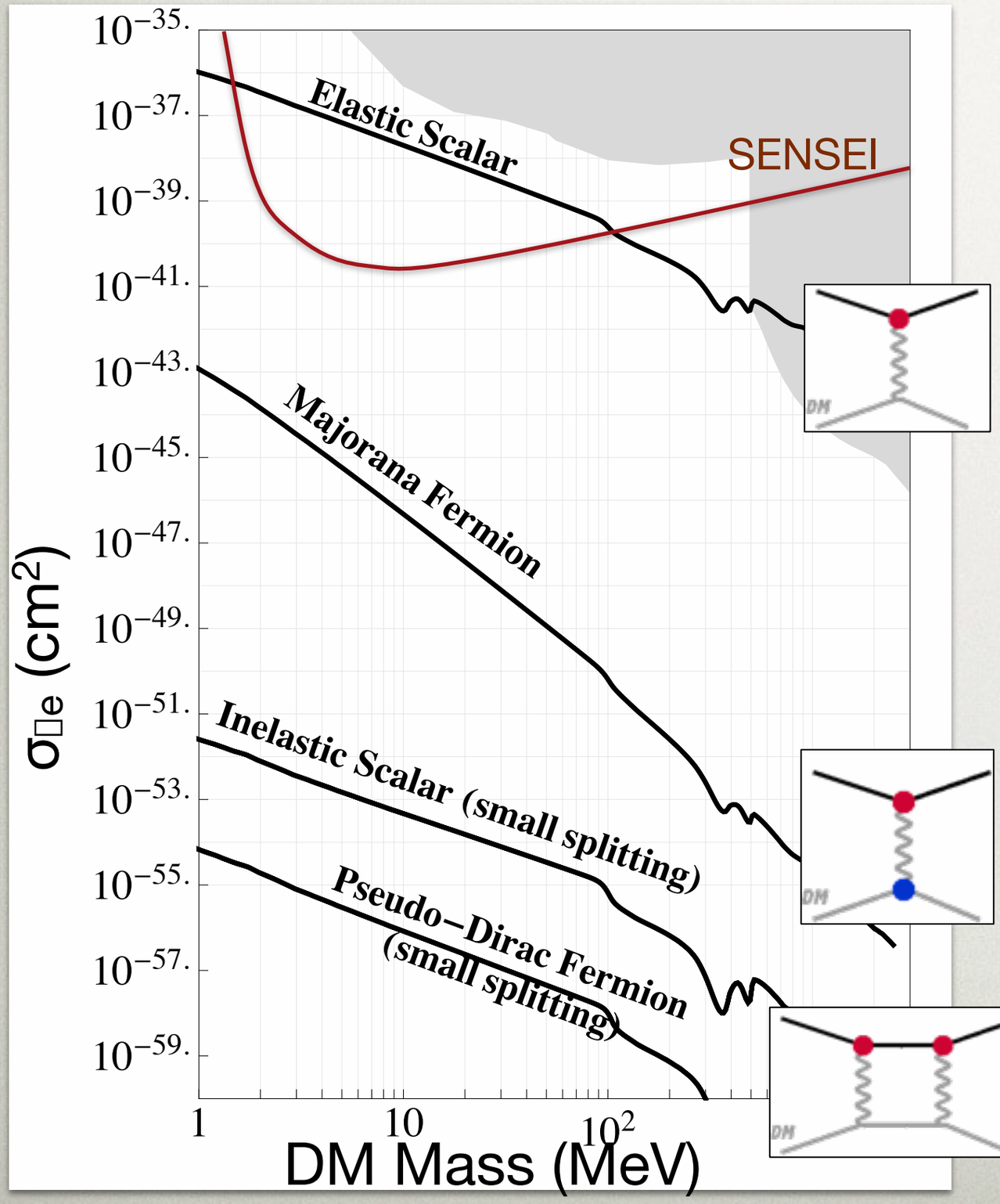
New dedicated experiments aim to see **electron** recoils at **lower** energy than typical backgrounds (radiogenic, etc)

e.g. SENSEI:

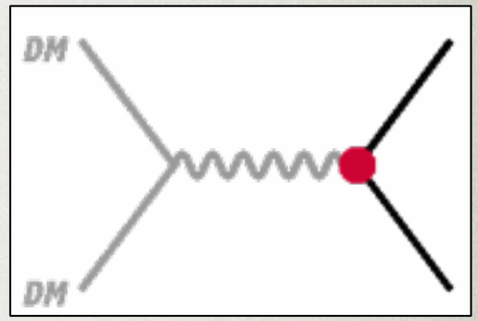
1–100g detector made from low-noise skipper CCDs



Dark-Matter-Electron Scattering: **Limitations**



Black lines correspond to "thermal freeze-out" predictions to obtain correct DM abundance!



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

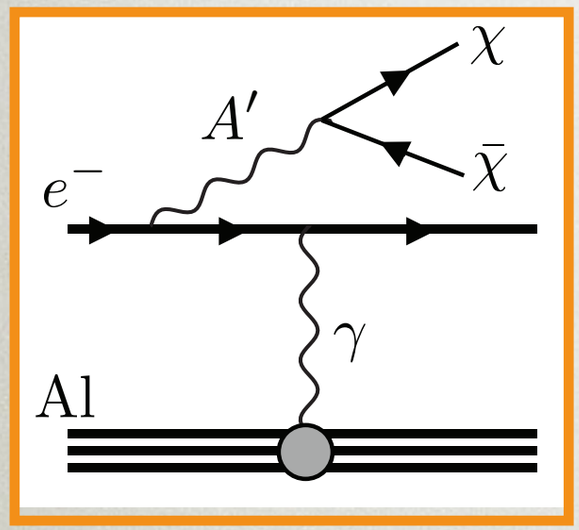
Xsec predictions spread over tens of decades (much like for WIMPs!) — a familiar and very general limitation

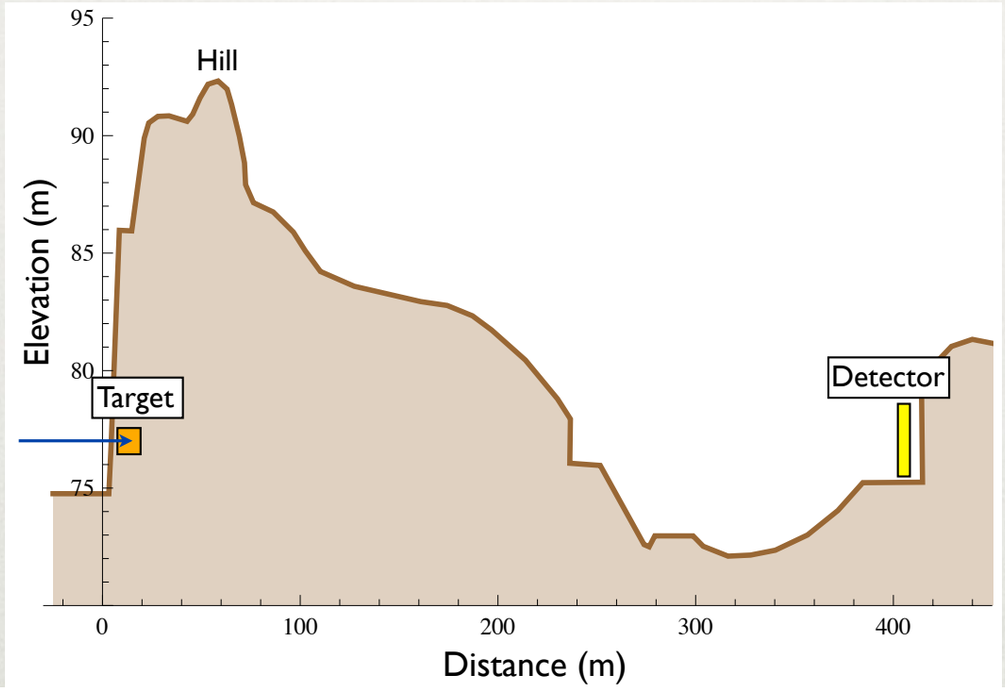
- Small DM-SM coupling
- Velocity-suppression

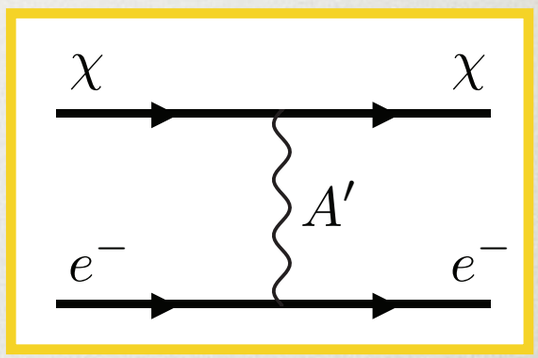
New territory, and other models, will be explored, **but <u>different approach</u> is clearly needed**

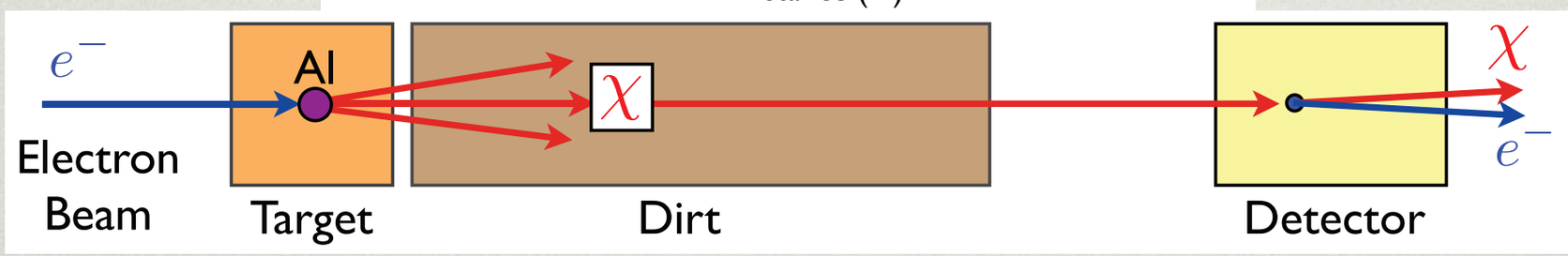
Light Dark-Matter Production

- At low mass, **relativistic** DM is readily produced in particle beam collisions! In fact, there are already powerful constraints on such production from experiments >30 years ago



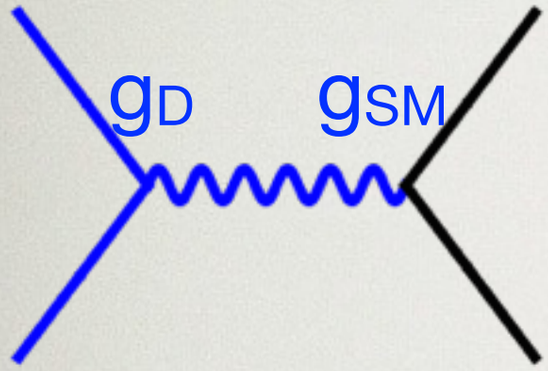






- Calls for high current electron (or proton) beams operating in a dump mode

Light Dark-Matter Production



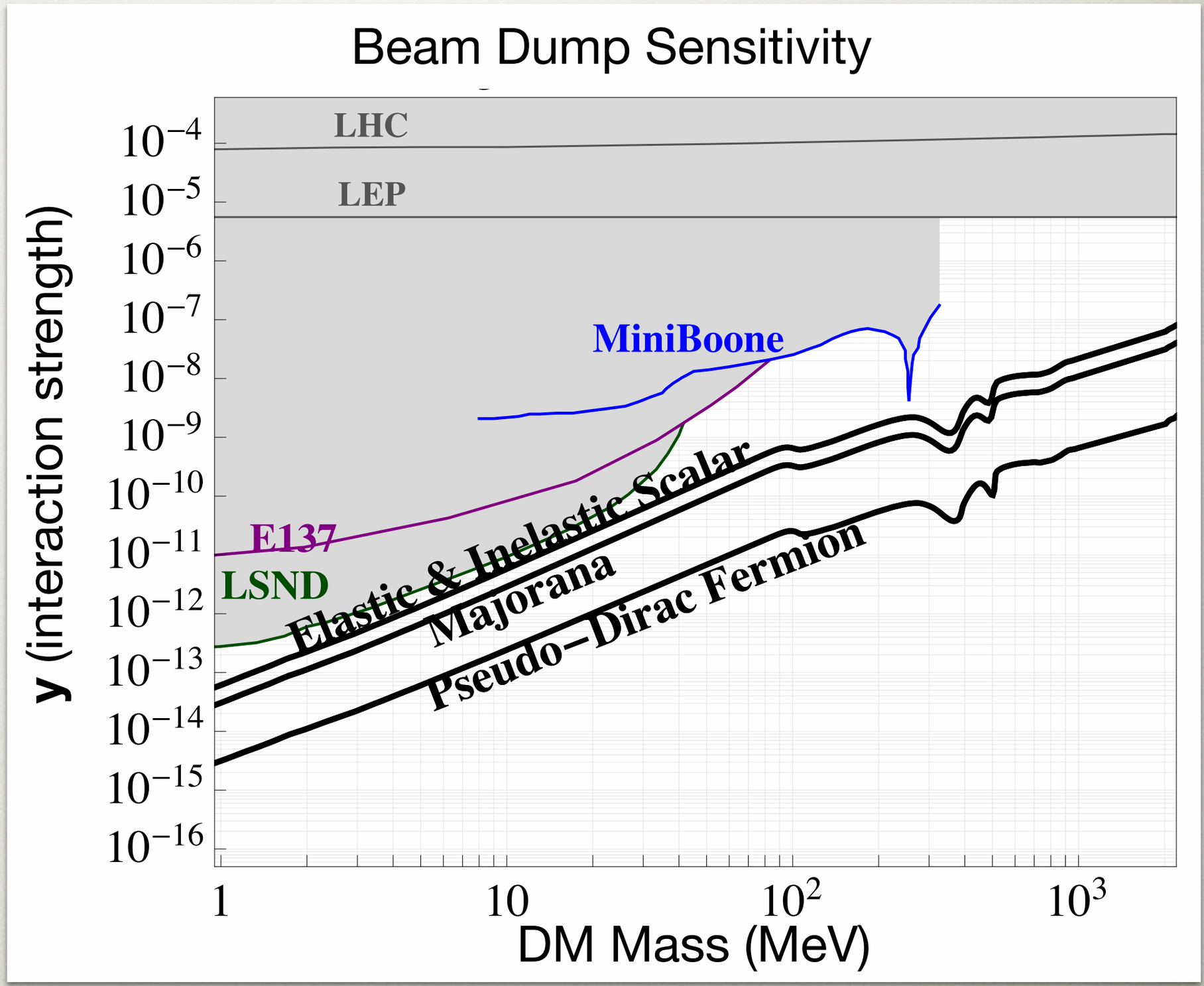
$\sigma \sim$

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

$\equiv y / m_{DM}^2$

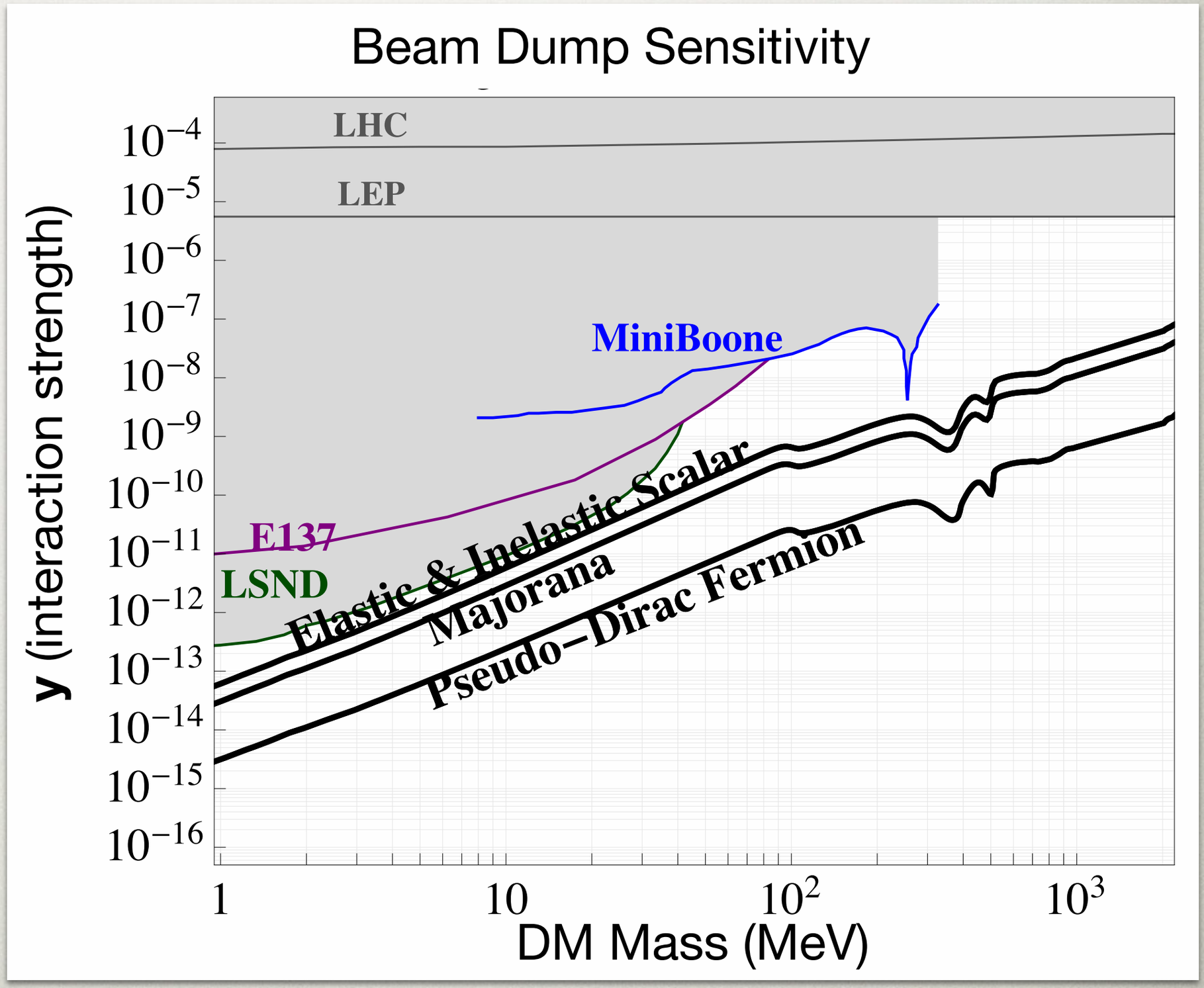
Production $\propto g_{SM}^2$ – infer **worst-case y** sensitivity from physical upper limits on g_D and m_{DM}/m_{Med}

Detection $\propto$ another **y**



Light Dark-Matter Production

- Models are more accessible with *relativistic* accelerator production
- Strongest existing sensitivity is from accelerator exp.
- Only a few orders of magnitude improvement needed to reach key milestones!

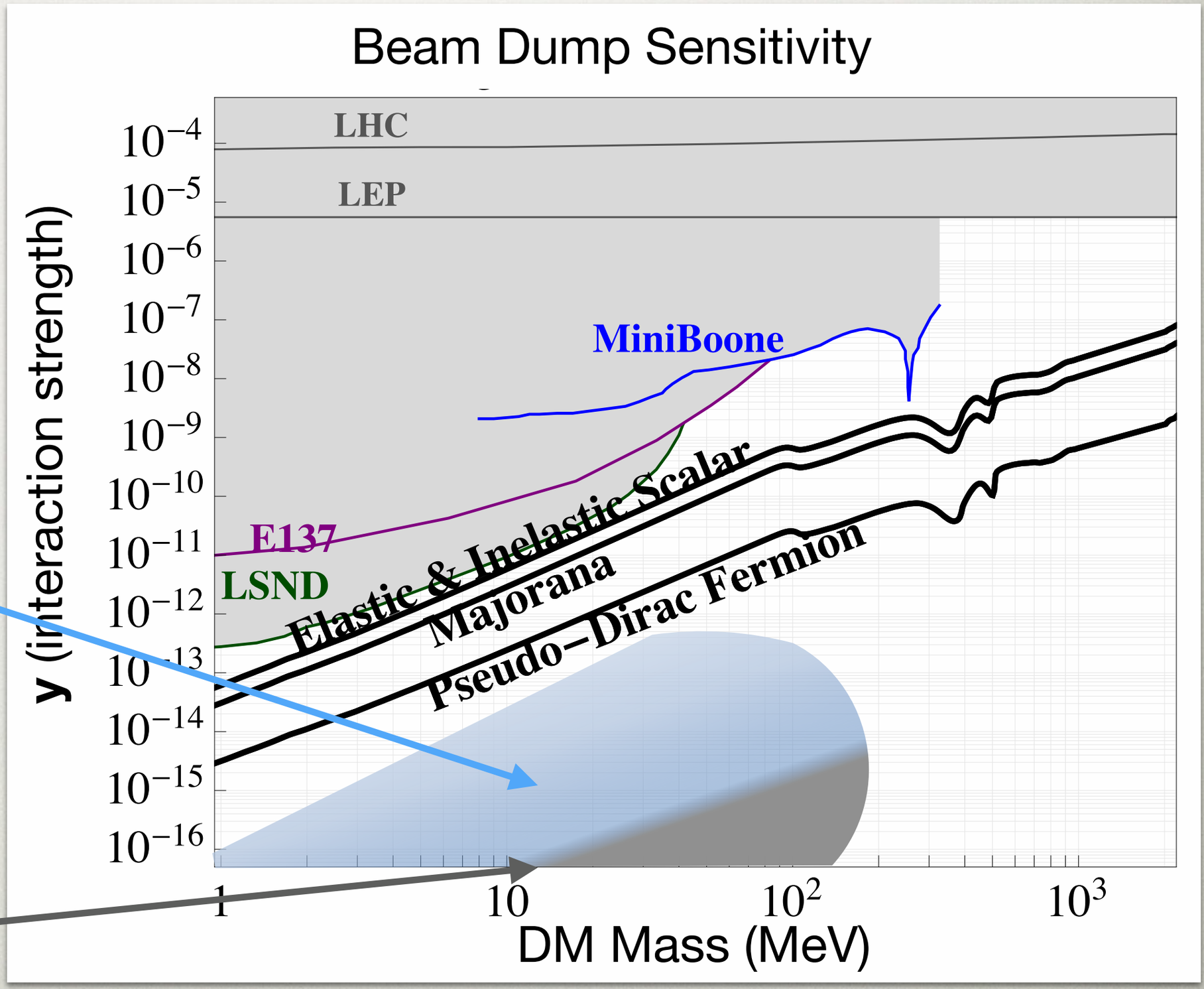


Light Dark-Matter Production

There is a data-driven "floor" to the parameter space

Future Large-scale direct detection can search for semi-relativistic DM produced in SN
(paper from Stanford/ Berkeley group to appear)

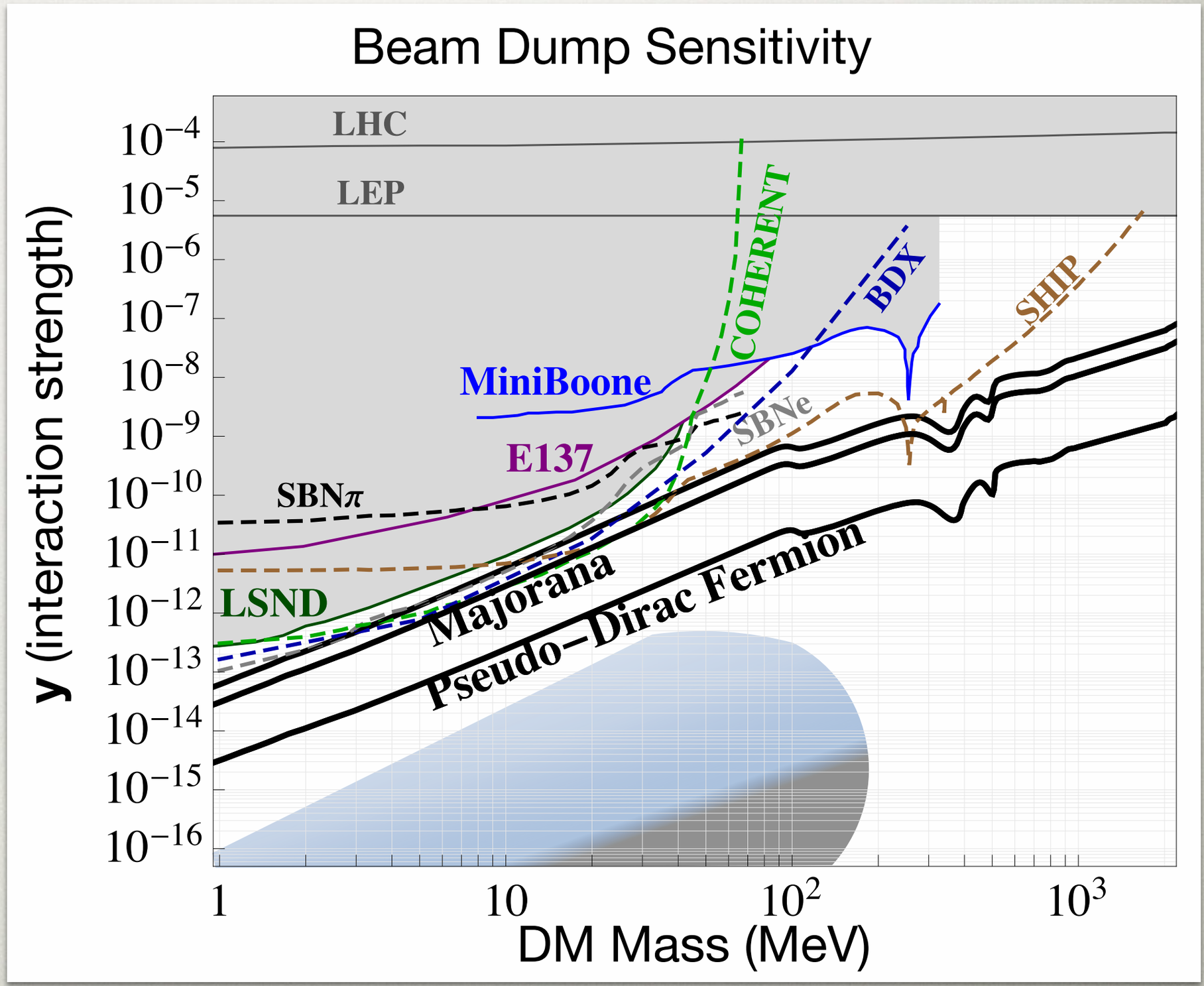
Supernovae cooling constrains ultra-small coupling



Light Dark-Matter Production

Future beam dump proposals can open up new light DM territory

…but not all key sensitivity milestones will be reached

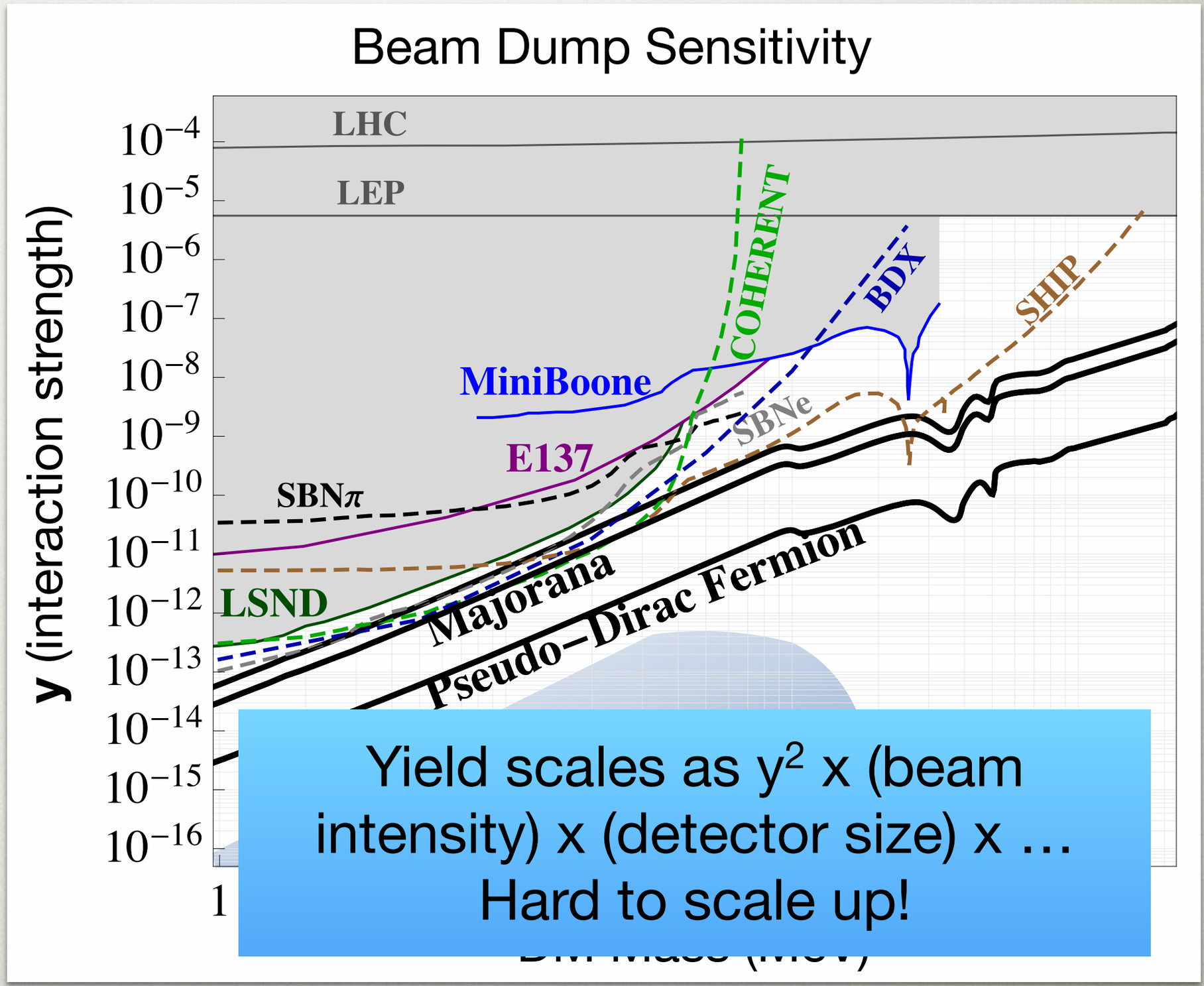


Light Dark-Matter Production

Future beam dump proposals can open up new light DM territory

…but not all key sensitivity milestones will be reached

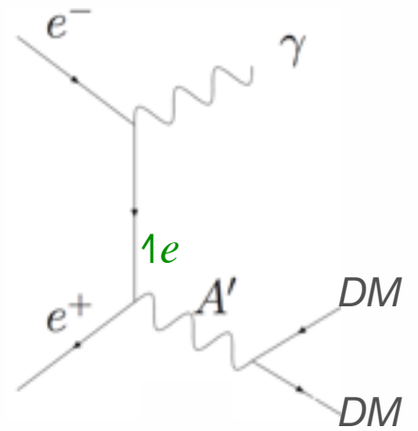
Difficult yield scaling makes future beam dump improvements difficult

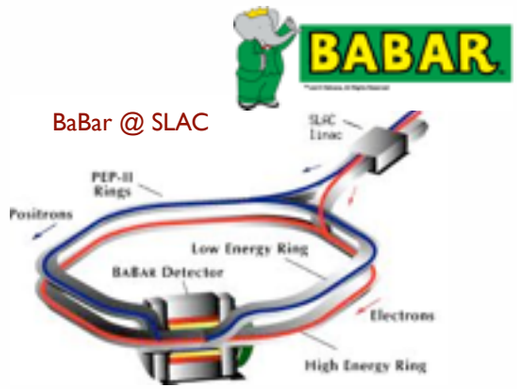


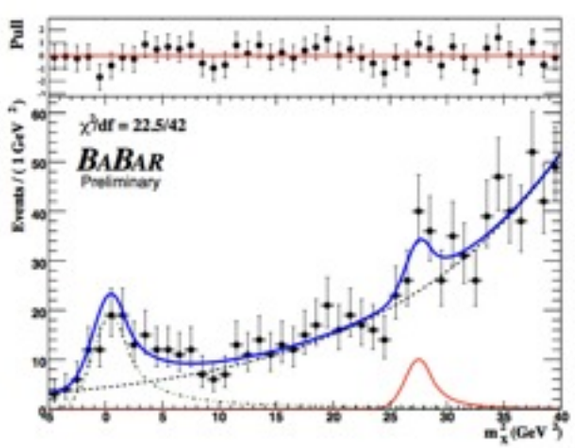
Light Dark-Matter Production

- 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

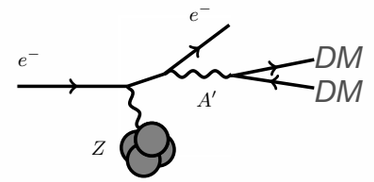




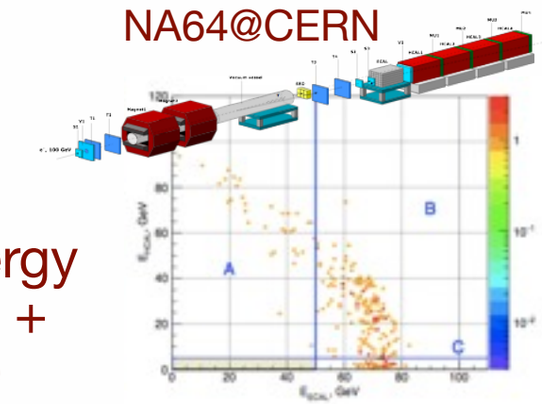


Belle II

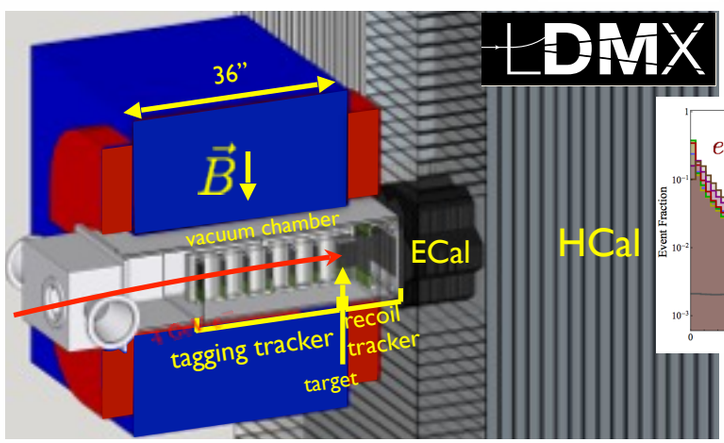
Missing Energy/Momentum
(e^- fixed target)
= partial kinematic reconstruction



NA64@CERN



Signal: low-energy recoil electron + nothing else



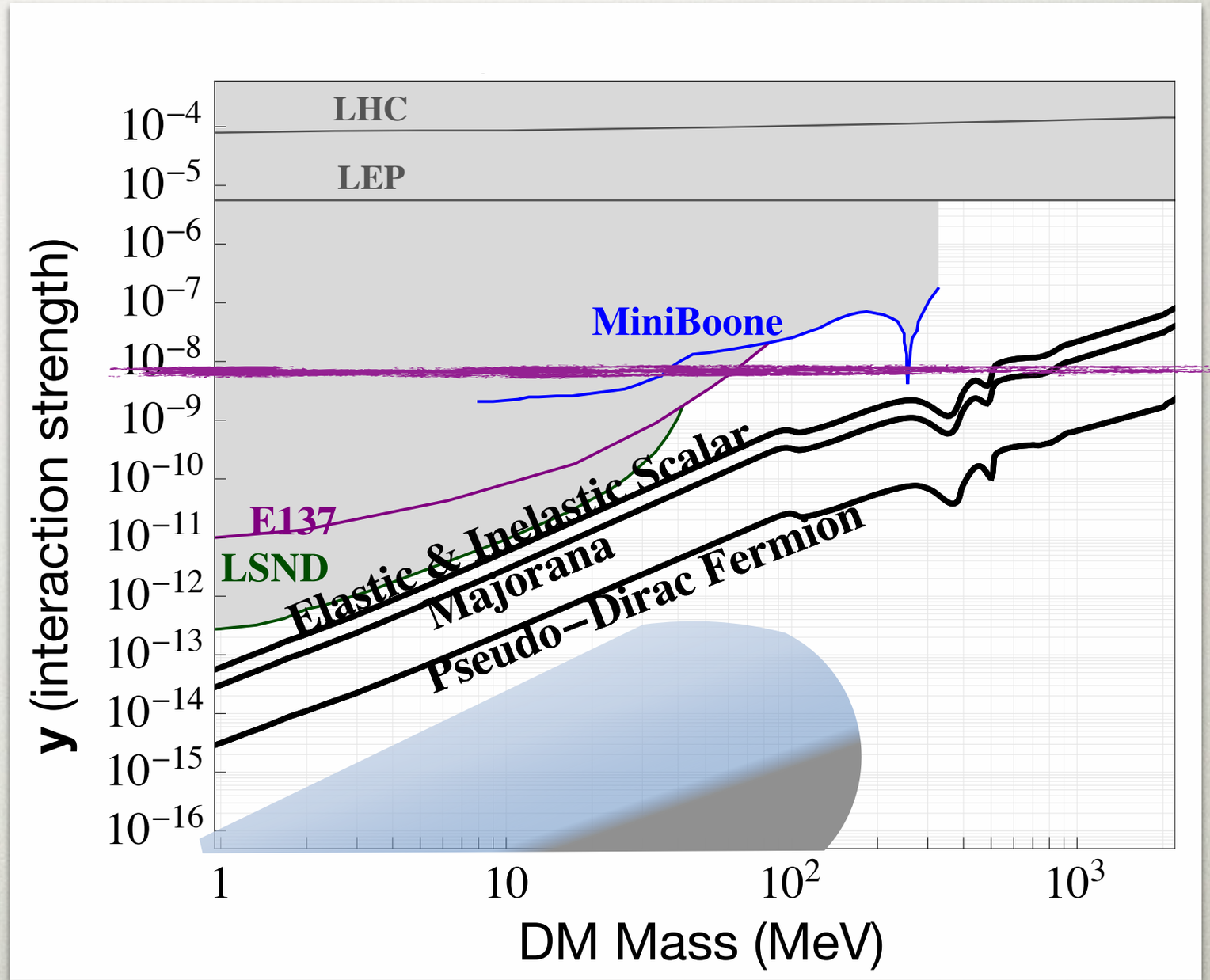
~0.1 – 10 GeV Dark Matter

MeV–GeV Dark Matter

Light Dark-Matter Production: B-factories

Colliders:

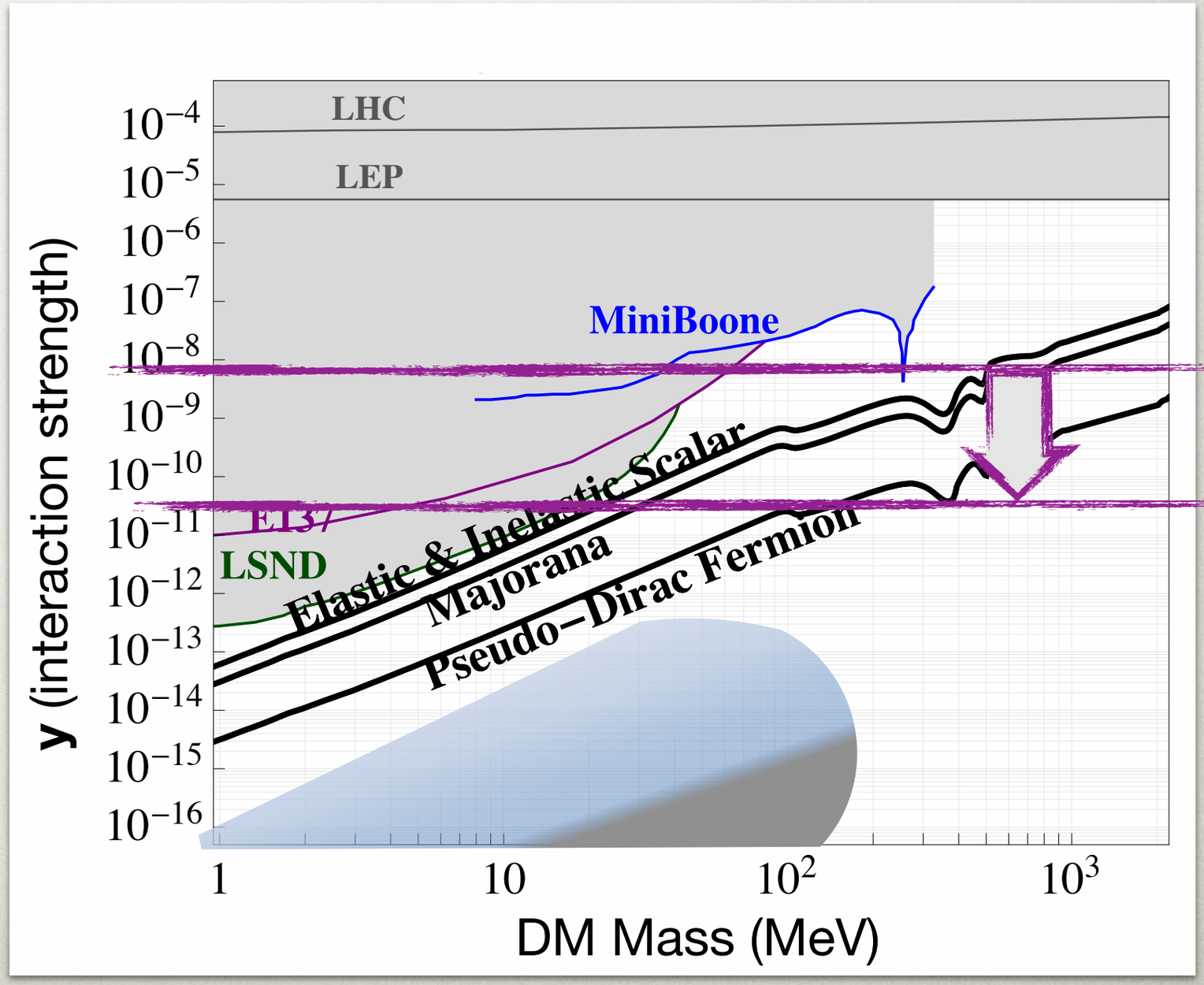
Rate ~ $\mathbf{y}\mathscr{L}/E_{CM}^2$



Light Dark-Matter Production: B-factories

Colliders:

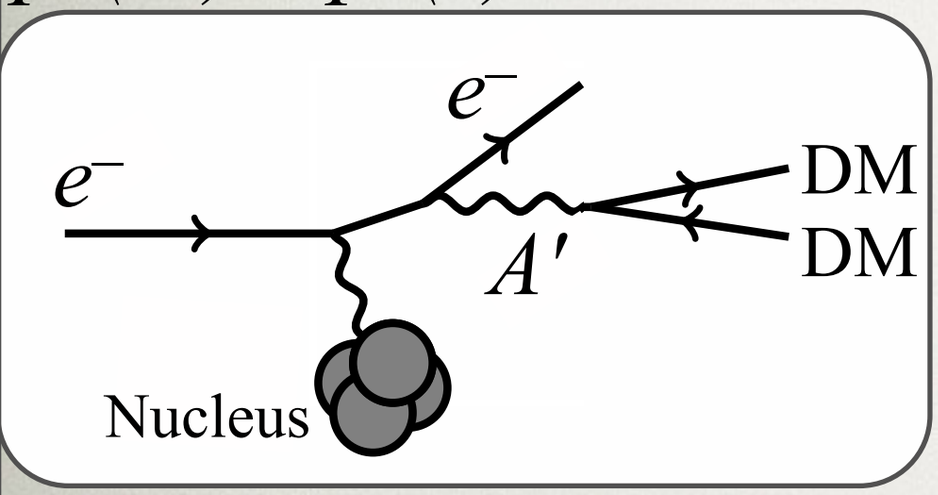
Rate ~ $\mathbf{y}\mathscr{L}/E_{CM}^2$



Fixed-Target Dark Matter Production

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

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



Exploit distinctive kinematics

Active at CERN: NA64

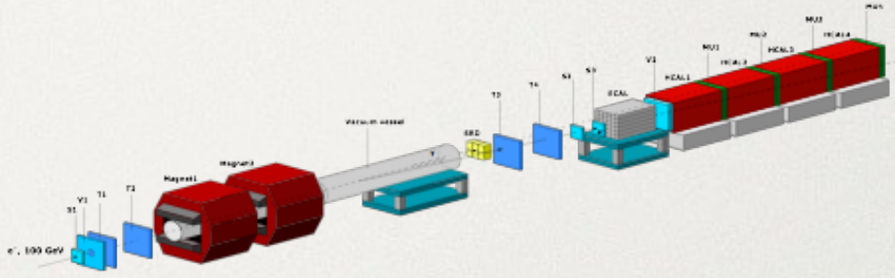
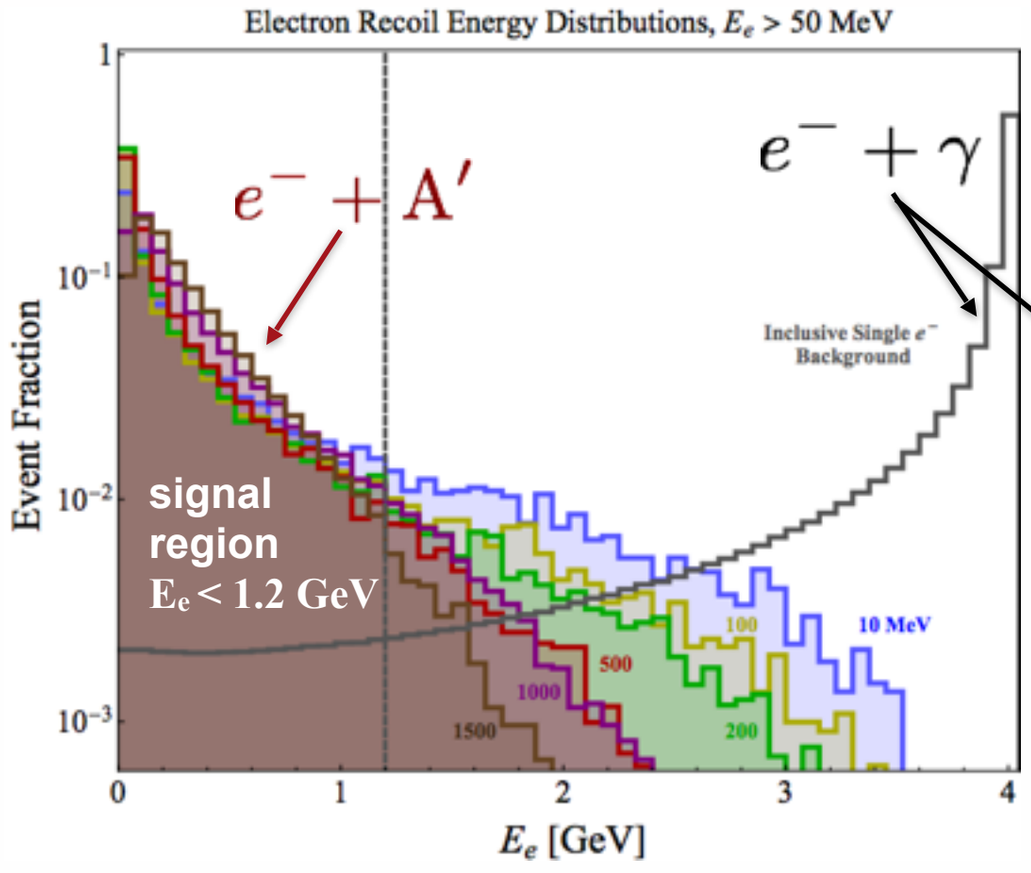
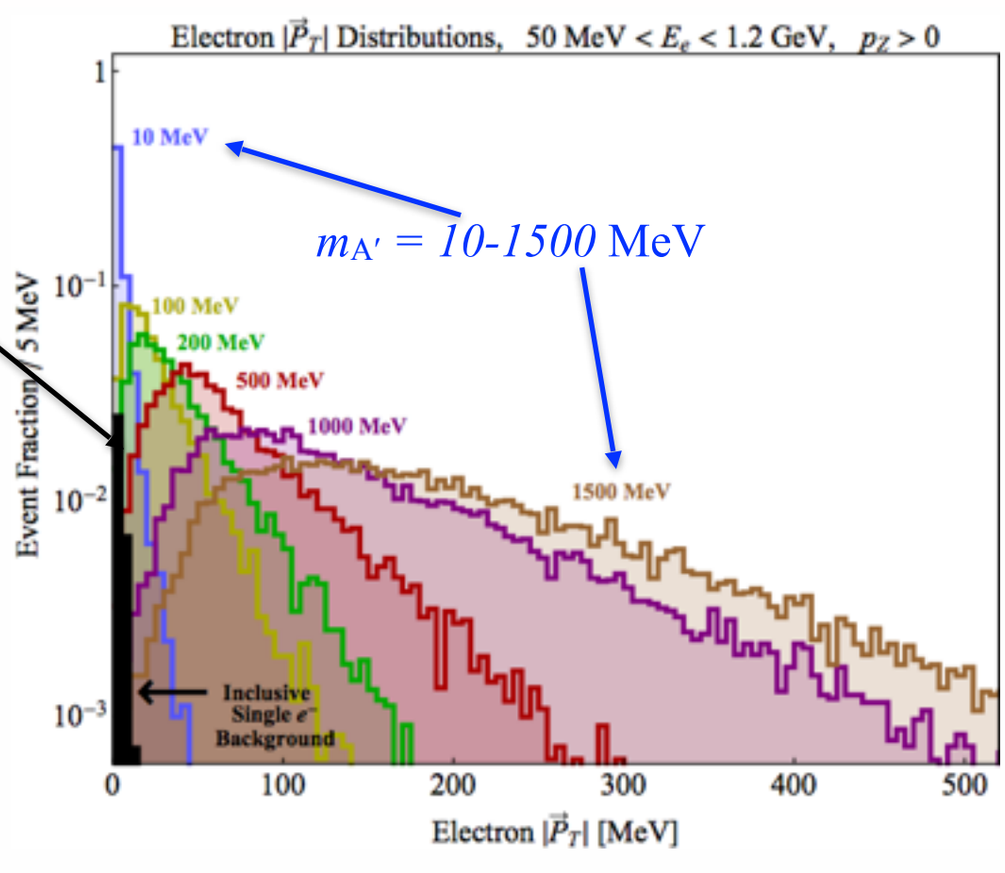


Illustration of distinctive kinematics for 4 GeV electrons on 10% target

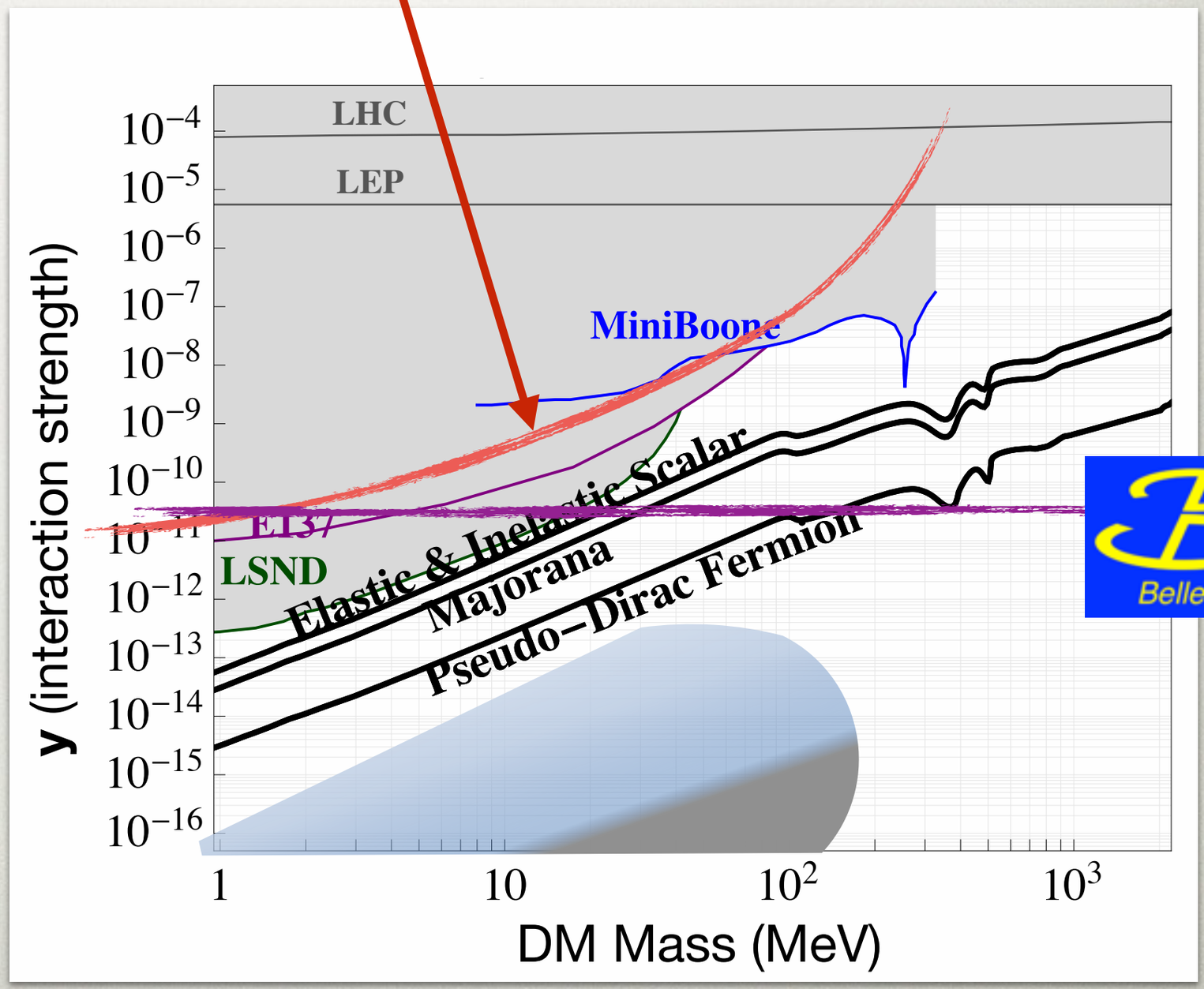




Light Dark-Matter Production
Fixed-Target Missing Energy/Momentum

Fixed target:

Rate ~ $y N_e m_e^2/m_{DM}^2$

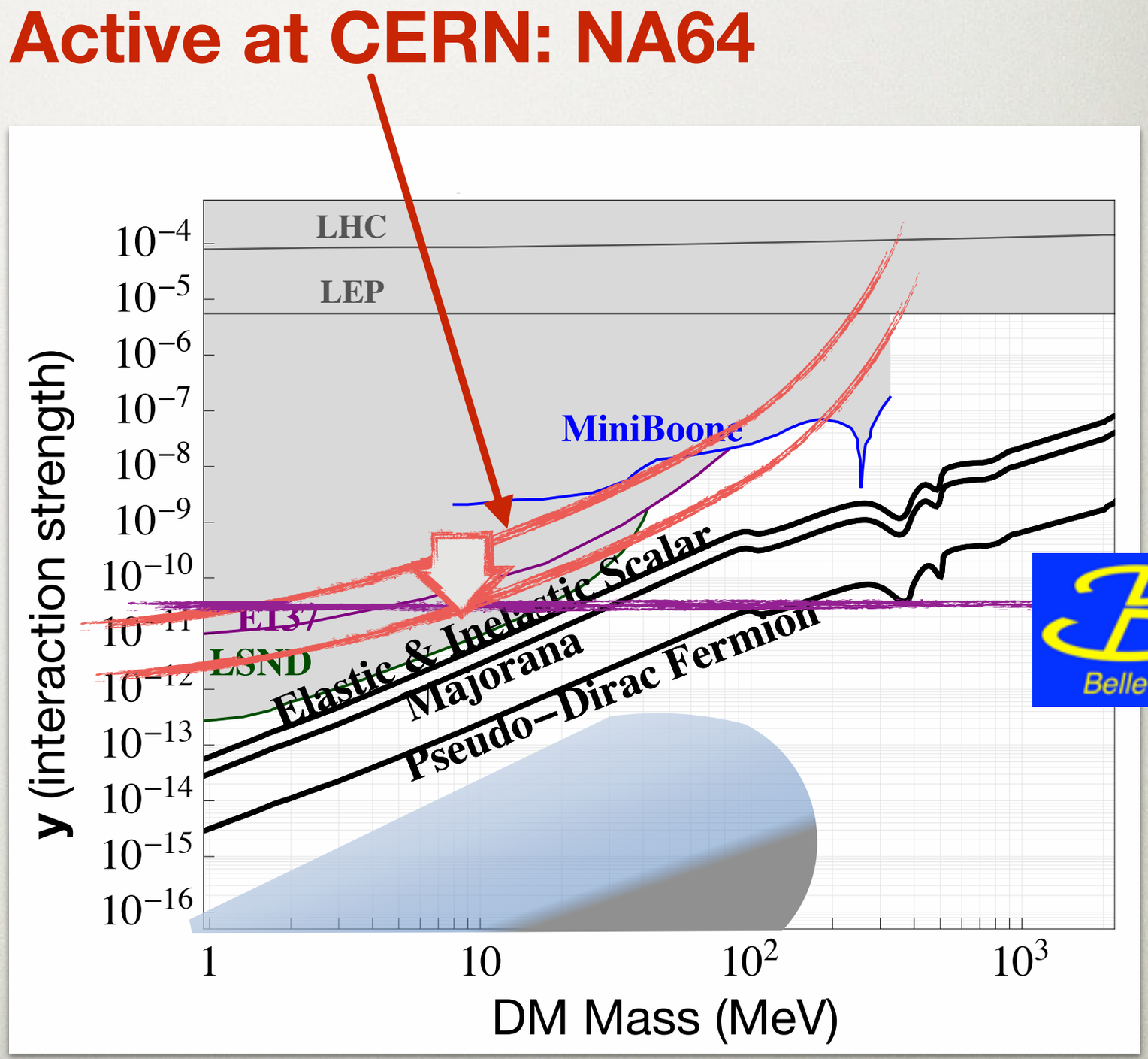


Light Dark-Matter Production
Fixed-Target Missing Energy/Momentum

Fixed target:

Rate ~ $y N_e m_e^2/m_{DM}^2$

NA64 limited by beam luminosity and not designed for high-luminosity in any case



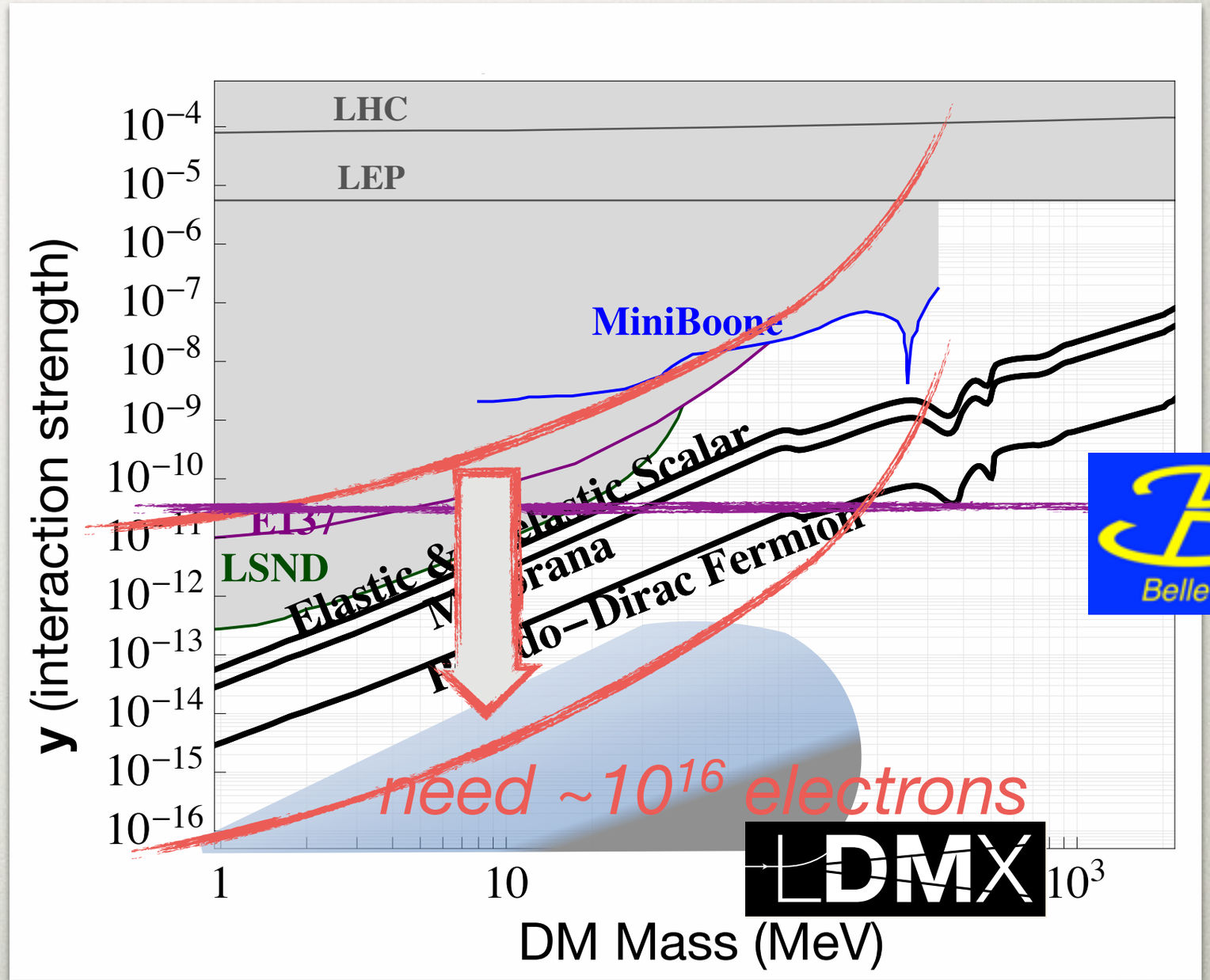
Light Dark-Matter Production
Fixed-Target Missing Energy/Momentum

Fixed target:

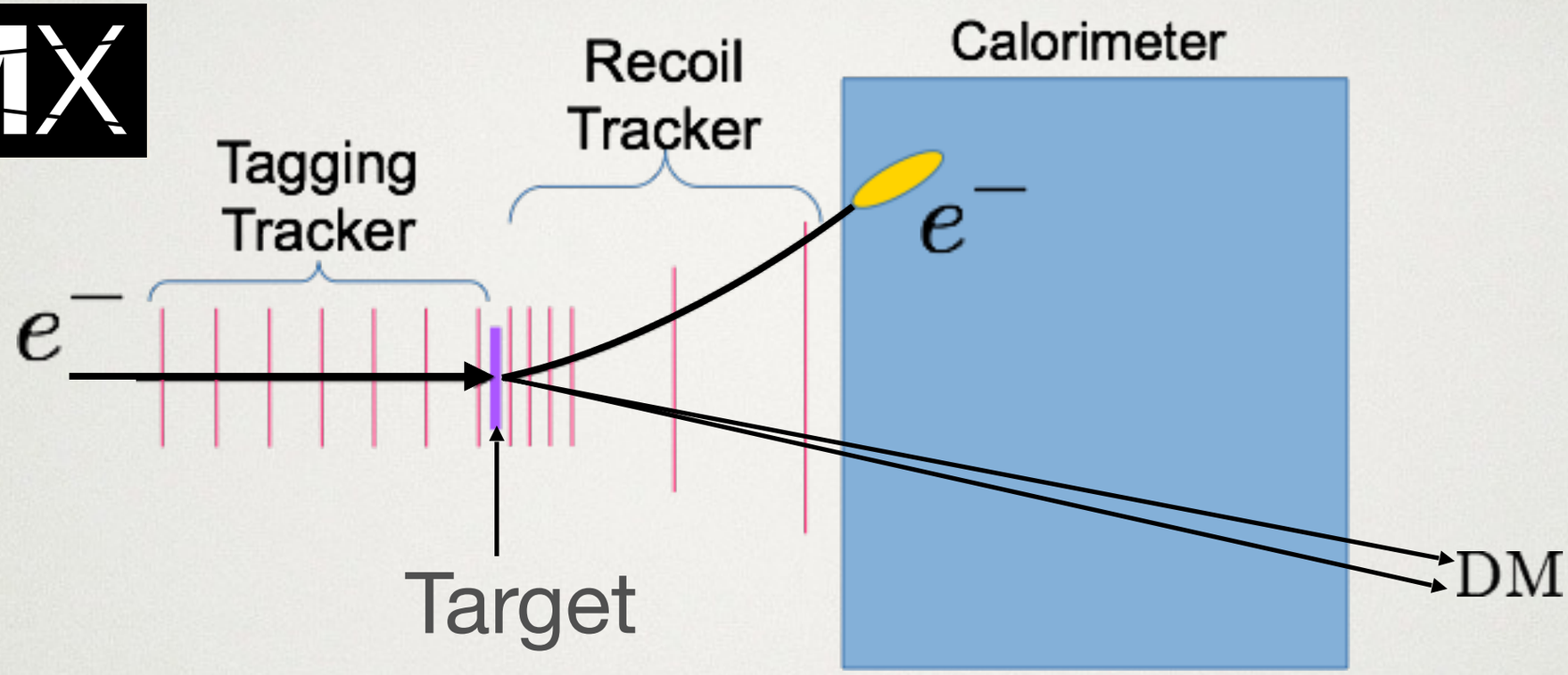
Rate ~ **$y N_e m_e^2/m_{DM}^2$**

Dedicated high-rate & high luminosity missing momentum experiment **Light Dark Matter eXperiment (LDMX)**

(next few slides elaborate)



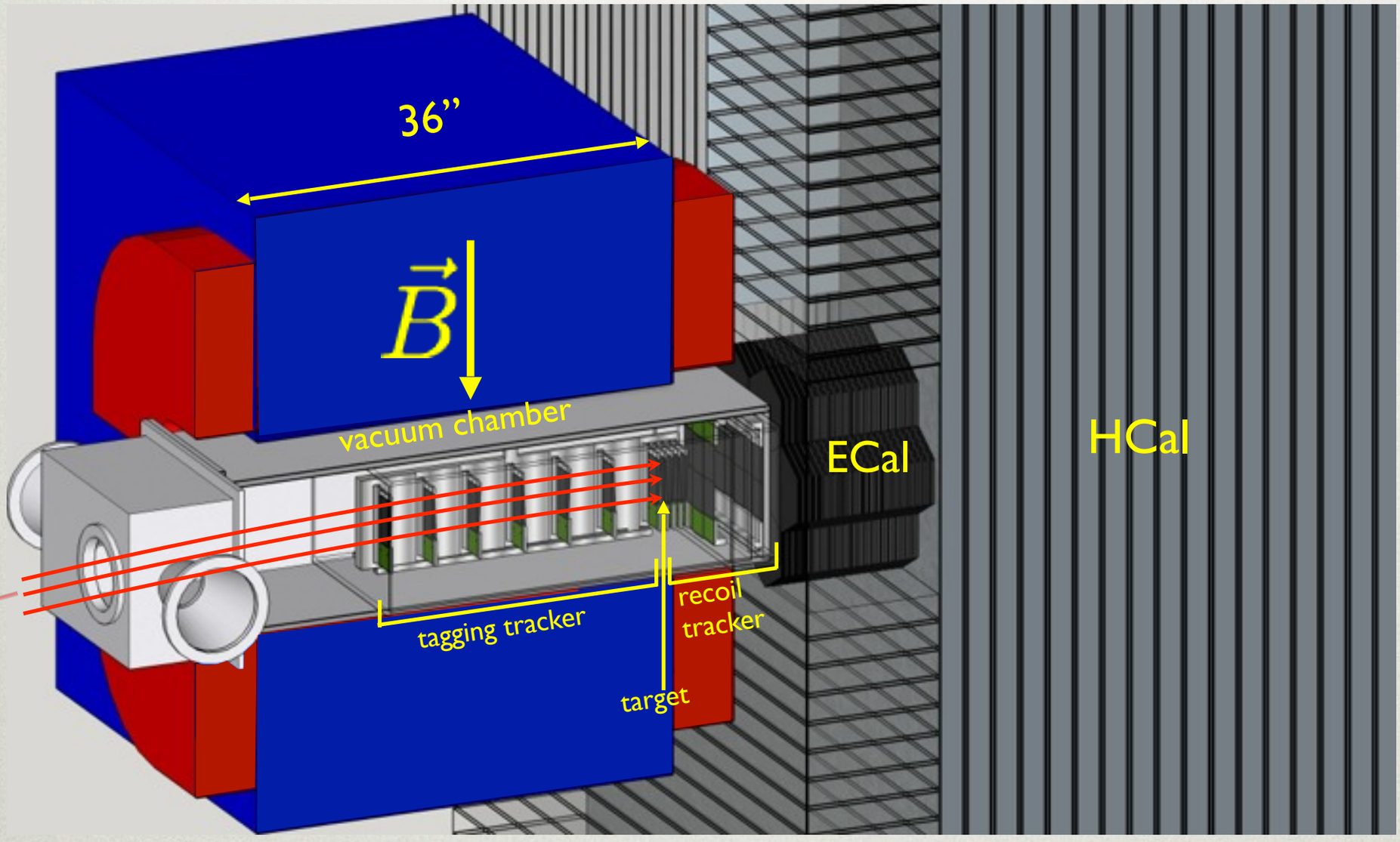
Basic Concept & Beam Requirements



- Electron beam impinging on target:
  - multi-GeV electrons
  - 1-200 MHz bunch spacing
  - Ultra-low O(1-5) electrons per bunch
- 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

LDMX Light Dark Matter eXperiment

Phase I Detector Concept and (growing) Collaboration



SLAC NATIONAL ACCELERATOR LABORATORY

UCSB

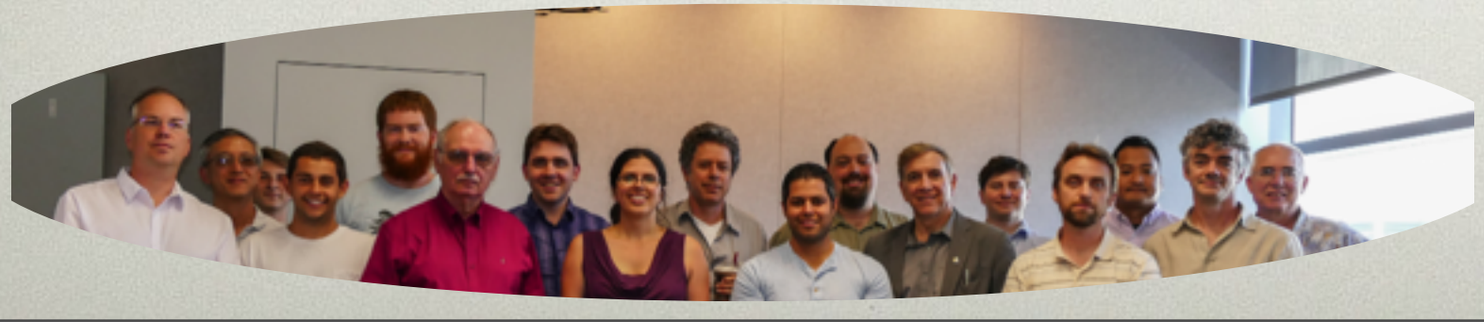
UNIVERSITY OF MINNESOTA

Fermilab

Caltech

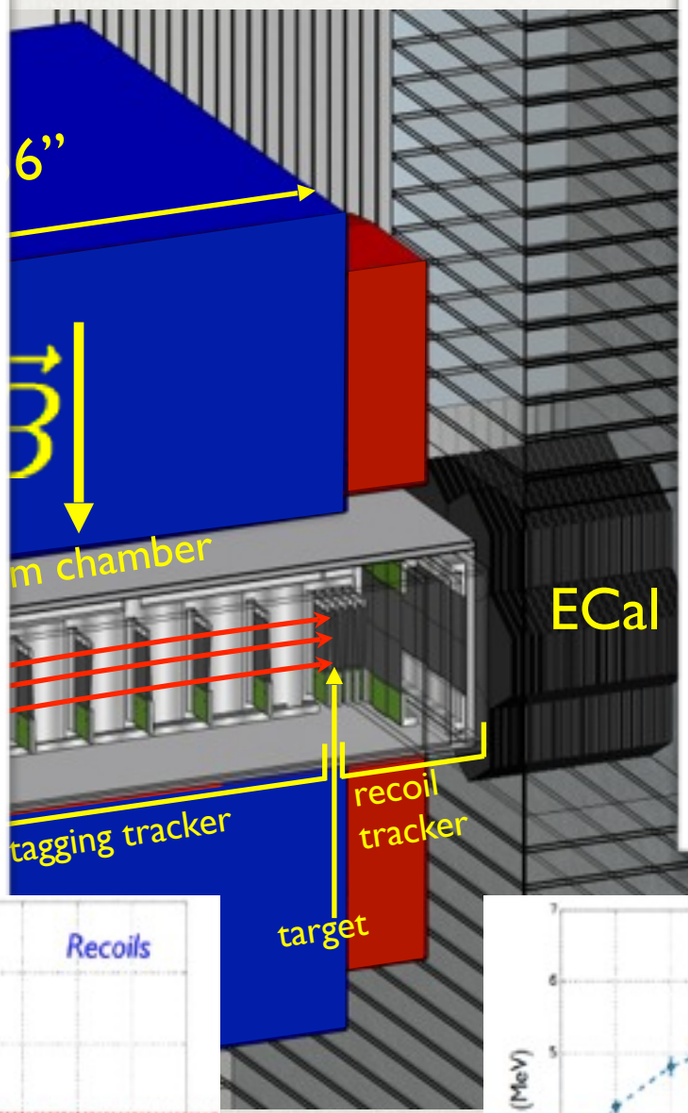
UC SANTA CRUZ

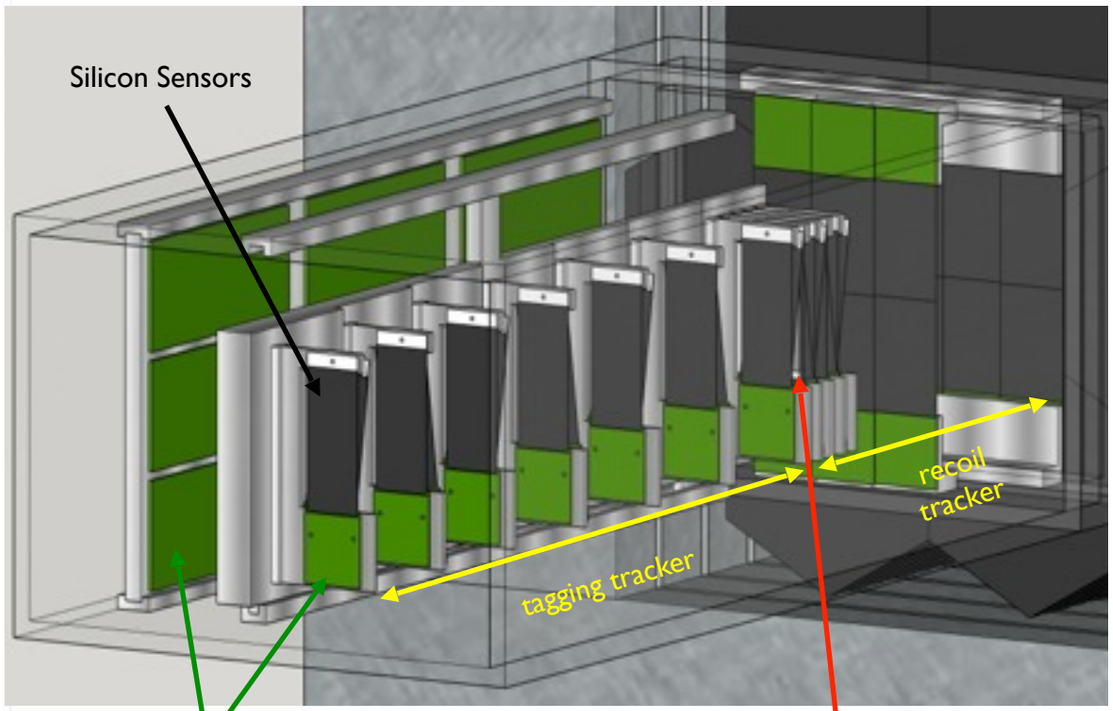
LUND UNIVERSITY

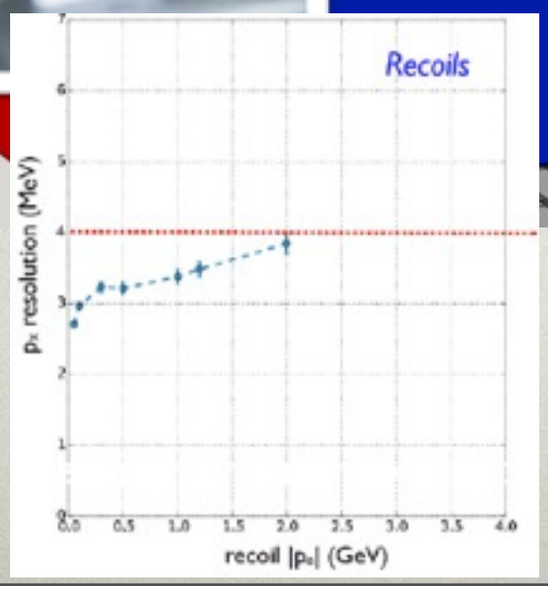


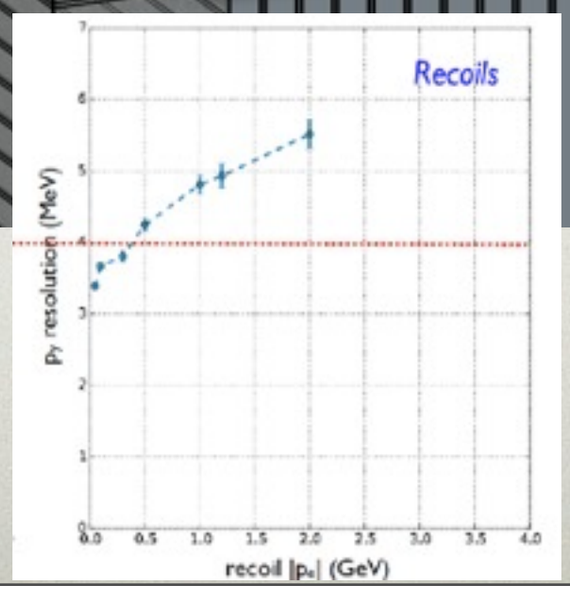
LDMX Light Dark Matter eXperiment

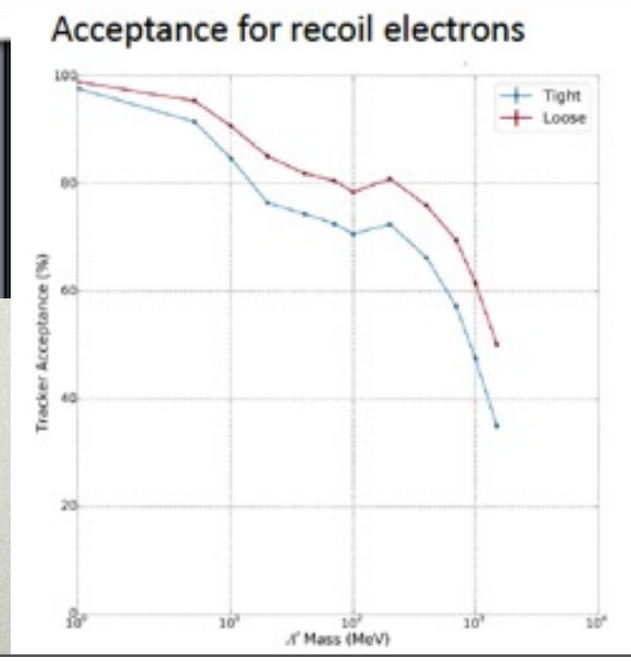
Tracking technology and experience from Heavy Photon Search Experiment







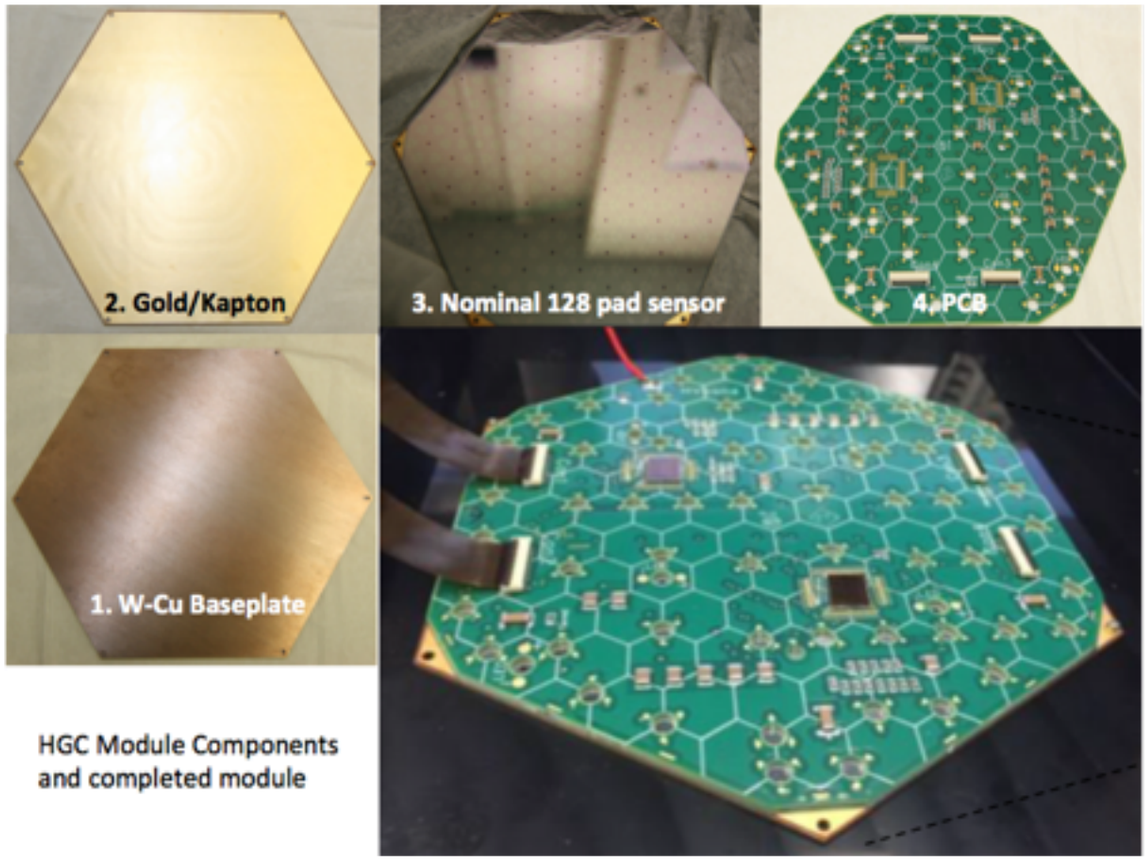




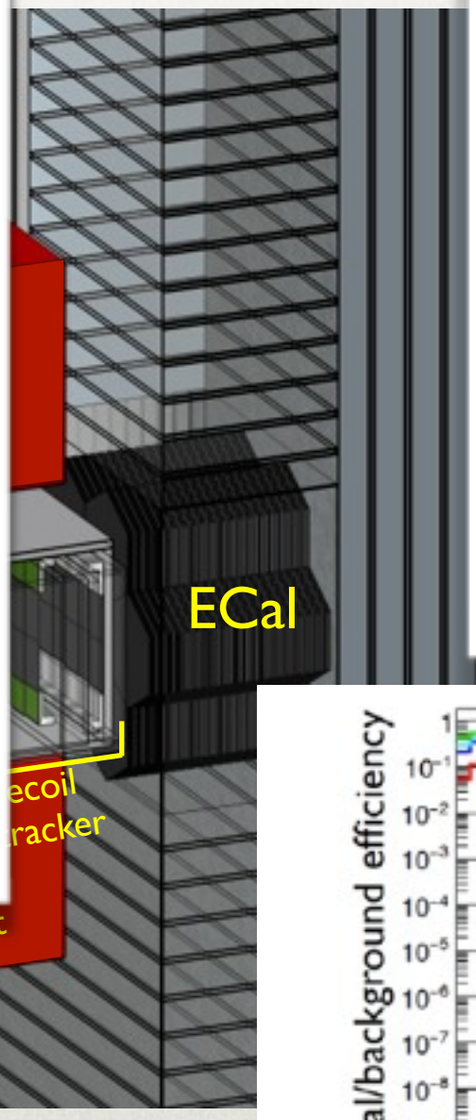
LDMX Light Dark Matter eXperiment

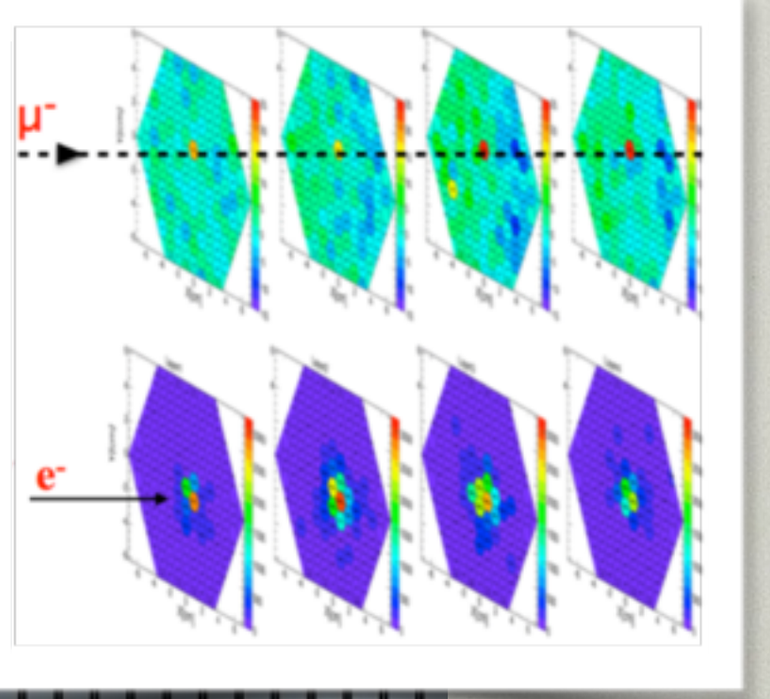
ECal is based on CMS HGC upgrade technology: radiation hard, fast, and granular

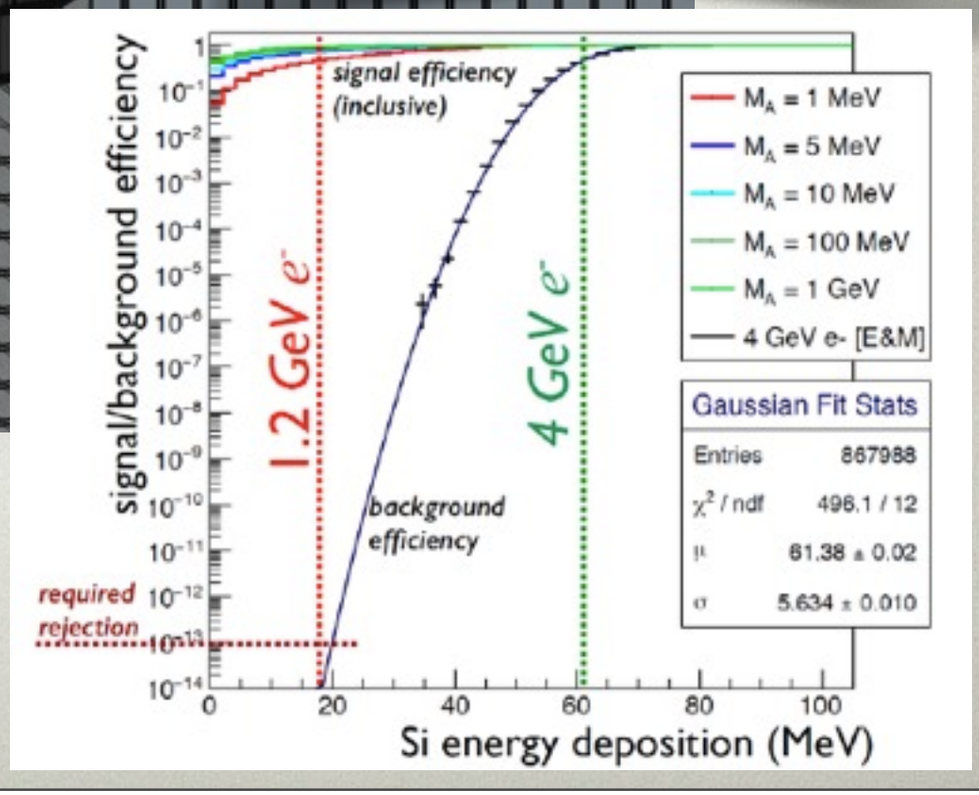
CMS upgrade Si-W EM Calorimetry

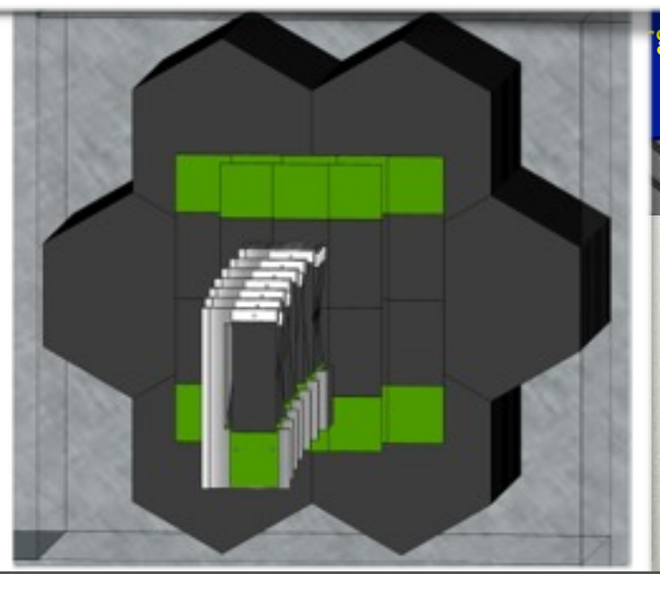


HGC Module Components and completed module



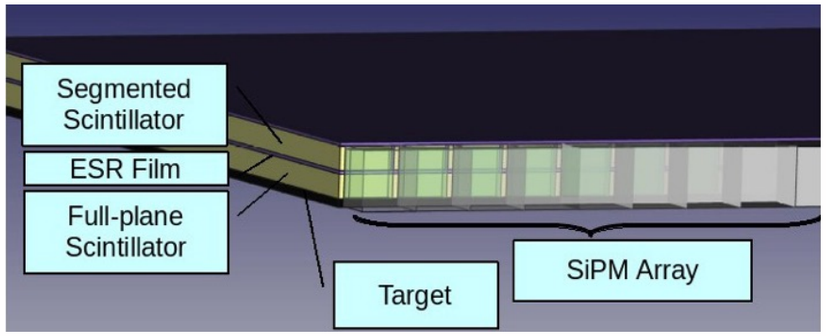


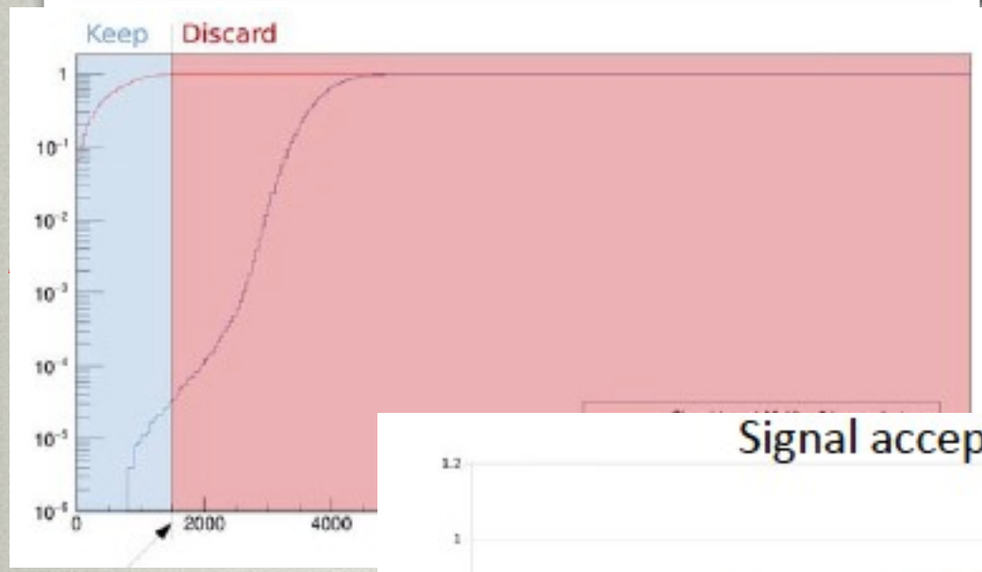


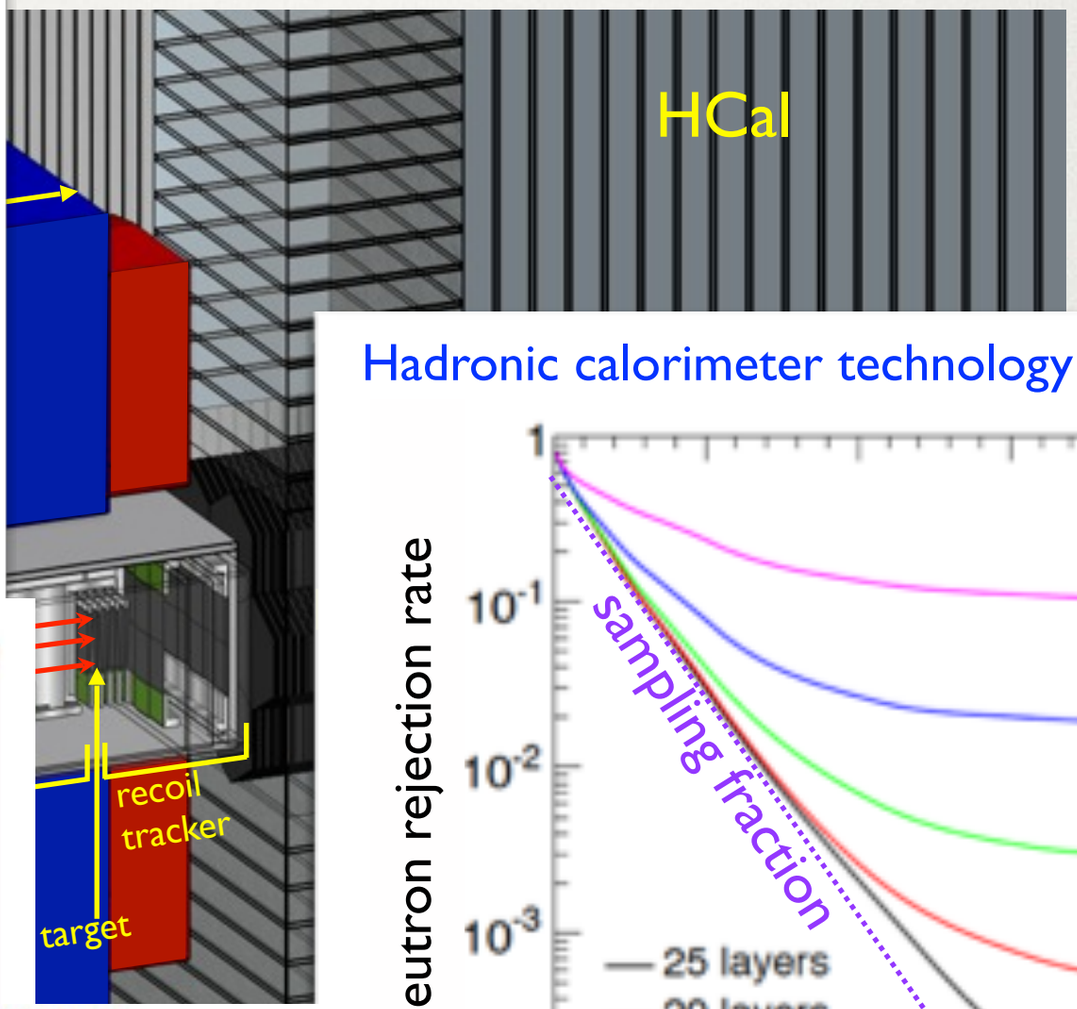


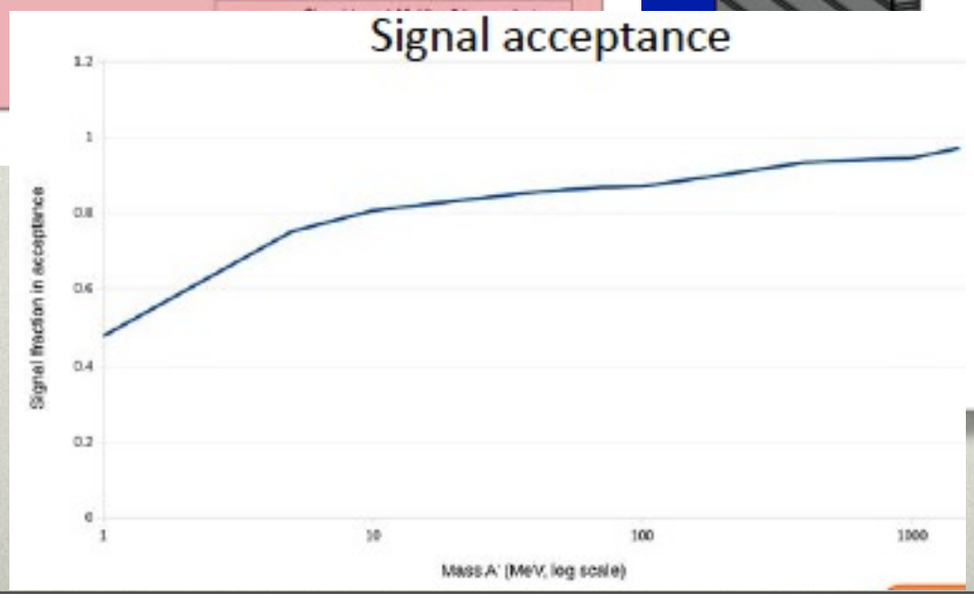
LDMX Light Dark Matter eXperiment

Trigger: Low energy deposition in ECAL + hits in scintillator pad near target

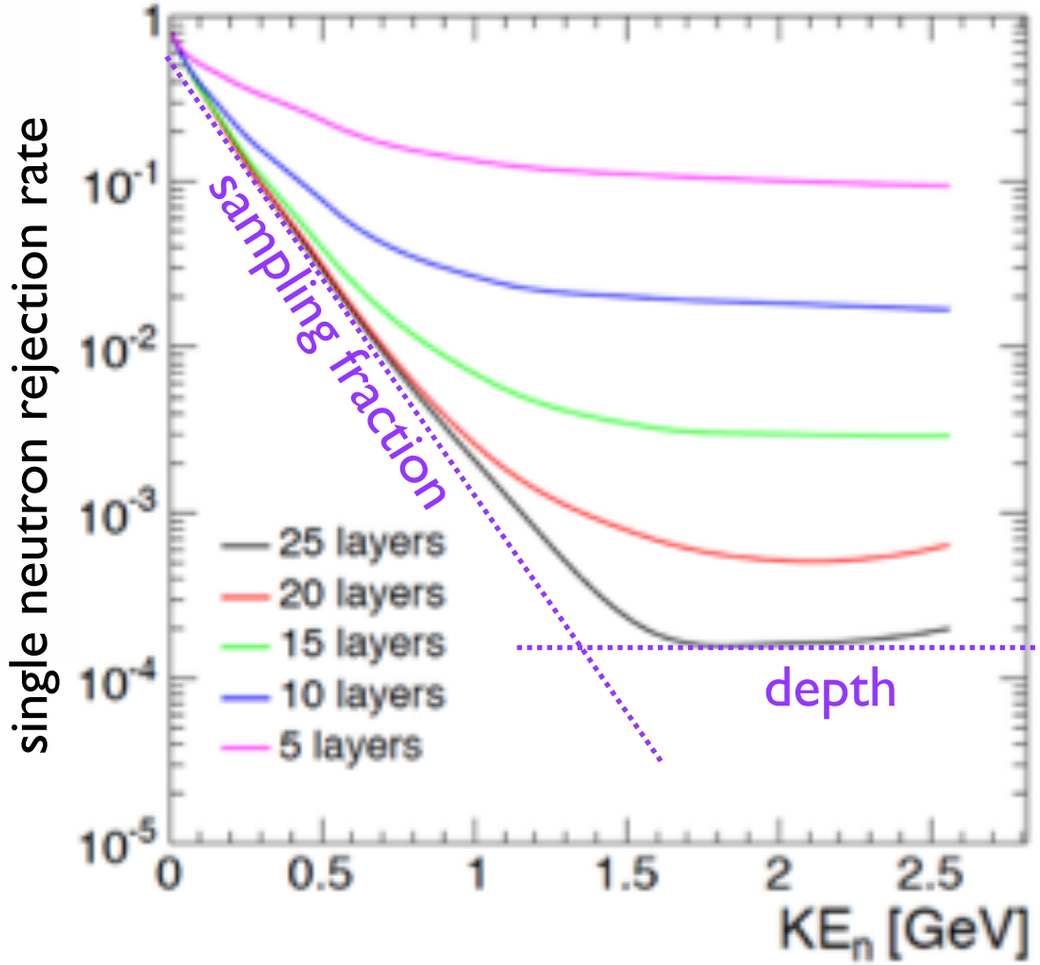








Hadronic calorimeter technology from CMS upgrade

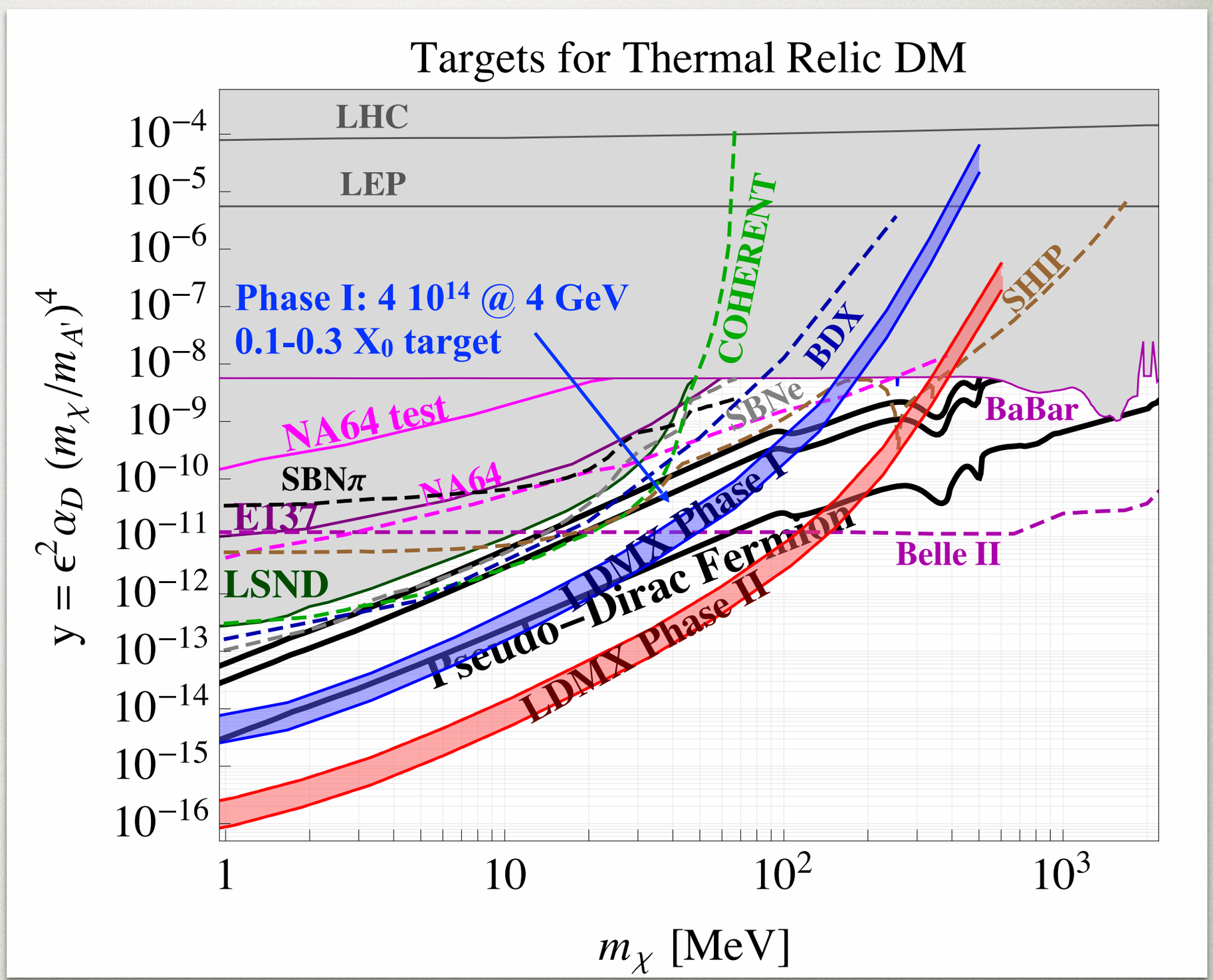


LDMX Sensitivity

Phase I: Based on 40 MHz "single electron" rate

Phase II: Based on handling O(5) electrons per bunch, fully exploit granularity and faster detectors + requires new trigger

Designing for 4-8 GeV (proposed) DASEL beam at SLAC, or 11 GeV beam at Jefferson Lab. See backup.



Unique potential to reach all thermal DM milestones at masses below ~200 MeV

Vibrant, World-Wide Program

Unlocking the sub-GeV Dark Matter Frontier

Light DM production

Light DM scattering

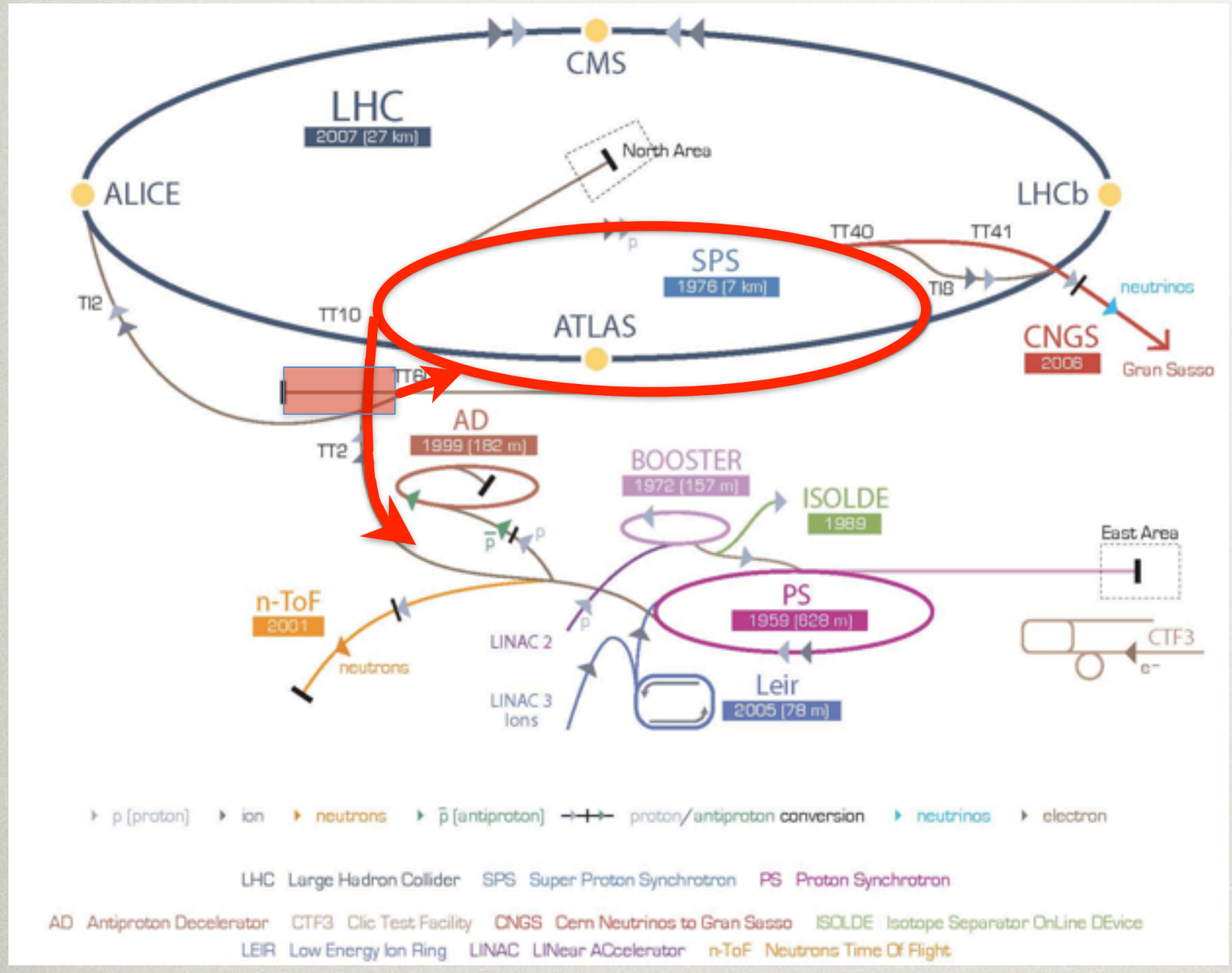
Resonant mediator searches

Dedicated electron beam required for fixed-target missing momentum, beam-dump, and direct mediator experiments!

- **multi-GeV energy**
- **pA to uA currents**
- **10-500 MHz (high rep. rate) bunch spacing**

Accelerator Talk Preview

See talk by Steinar Stapnes Wednesday afternoon!



Accelerator implementation at CERN of LDMX type of beam

X-band based 60m LINAC to 3 GeV in TT4-5.

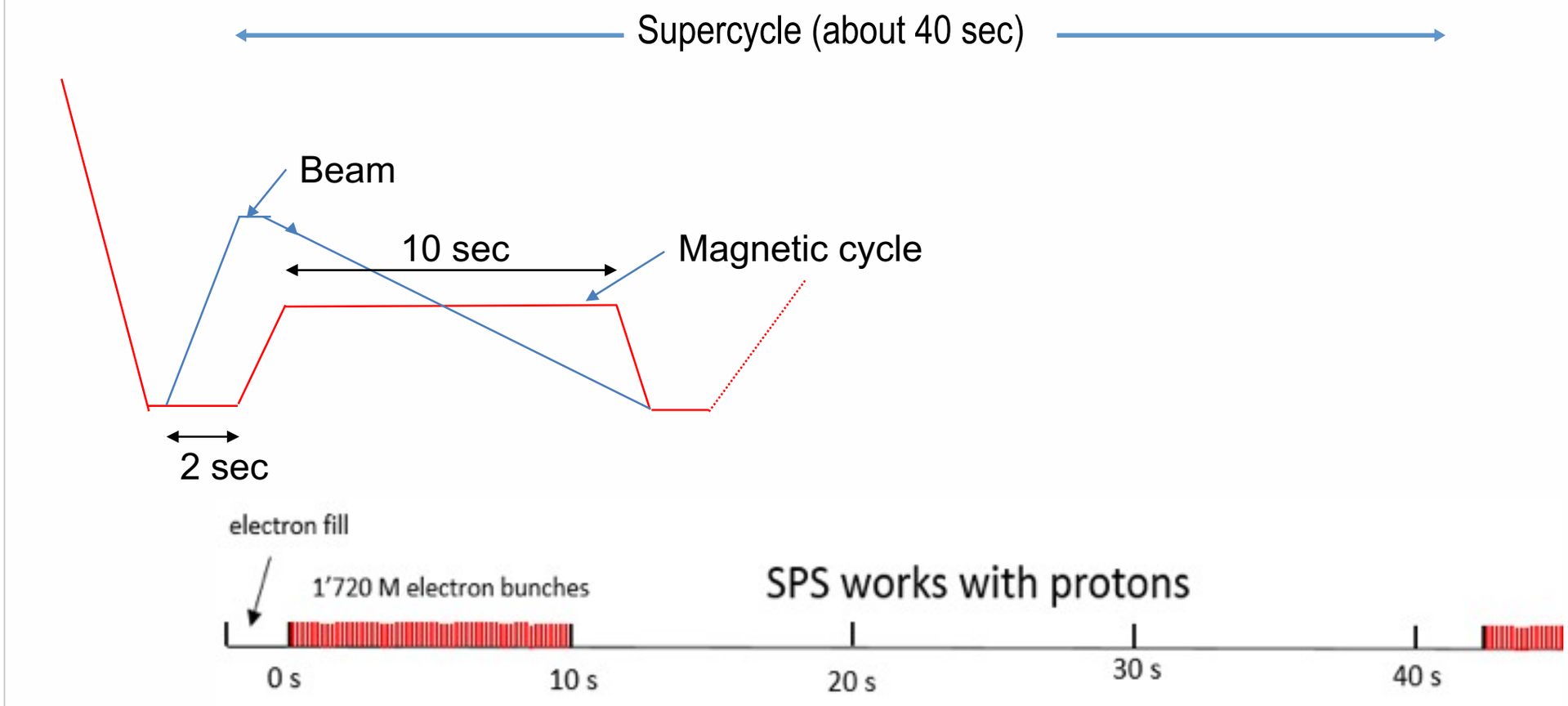
- Fill the SPS in 2s (bunches 5ns apart) via TT60
- Accelerate to ~10 GeV in the SPS
- Slow extraction to experiment in 10s as part of the SPS super-cycle
- Experiment(s) considered in UA2 area or – better - bring beam back on Meyrin site using TT10/ TT2, East Hall an option ?

Other experiments - including beam-dump experiments - can be considered
Several other possible uses of linac and SPS beams.

Accelerator Talk Preview

See talk by Steinar Stapnes Wednesday afternoon!

SPS beam for “LDMX” like experiment



With 1.7 10^9 bunches on target (5ns bunch separation), 1-10e extracted/bunch, 4x10^5 super-cycles: ~$10^{15\text{-}16}$ electrons per year at ~10 GeV

Conclusions

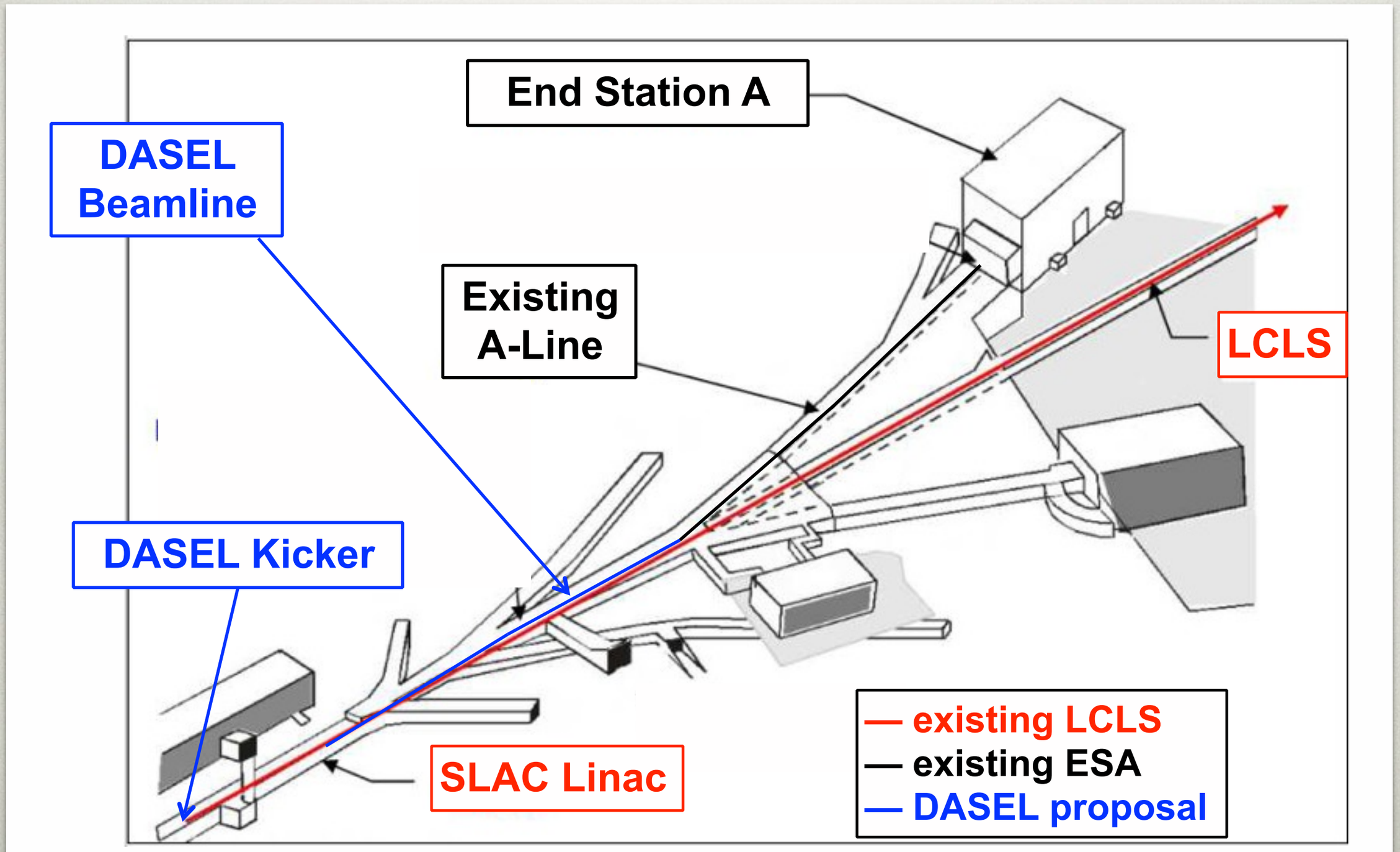
Potential for CERN to have pivotal impact on dark matter science

- Leverage existing infrastructure
- small fixed-target dark matter experiments
- decisive sensitivity to sub-GeV hidden sector DM
- need multi-GeV, high rep rate primary electron beam

Backup

DASEL Beamline @ SLAC

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



DASEL Beamline @ SLAC

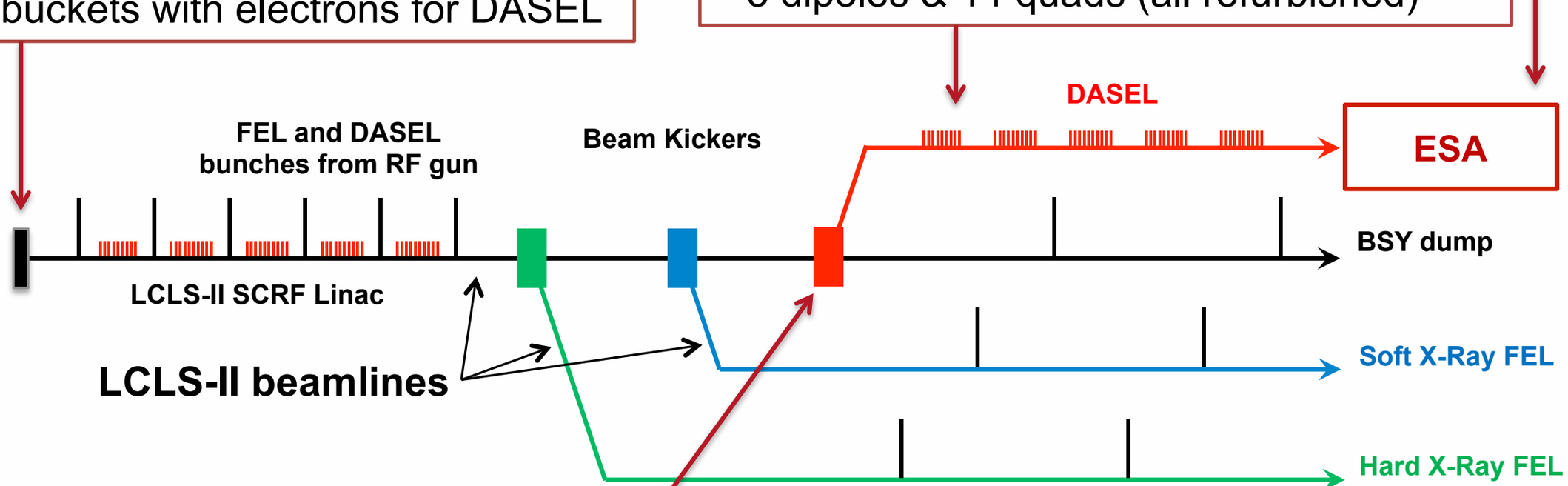
Low-current but “continuous” multi-GeV beam needed for LDMX can be delivered parasitically!

A multi-GeV, CW electron beam parasitic to LCLS-II

Laser system to fill “unused” buckets with electrons for DASEL

Experimental Facilities
- Small upgrades to ESA systems

DASEL Beamline connecting to ESA line
- 3 dipoles & 14 quads (all refurbished)



DASEL kicker/septum system downstream of FEL kickers to eliminate interference
- Based on LCLS-II design