Exploring the Dark Sector

Discovery Opportunities at Familiar Mass Scales

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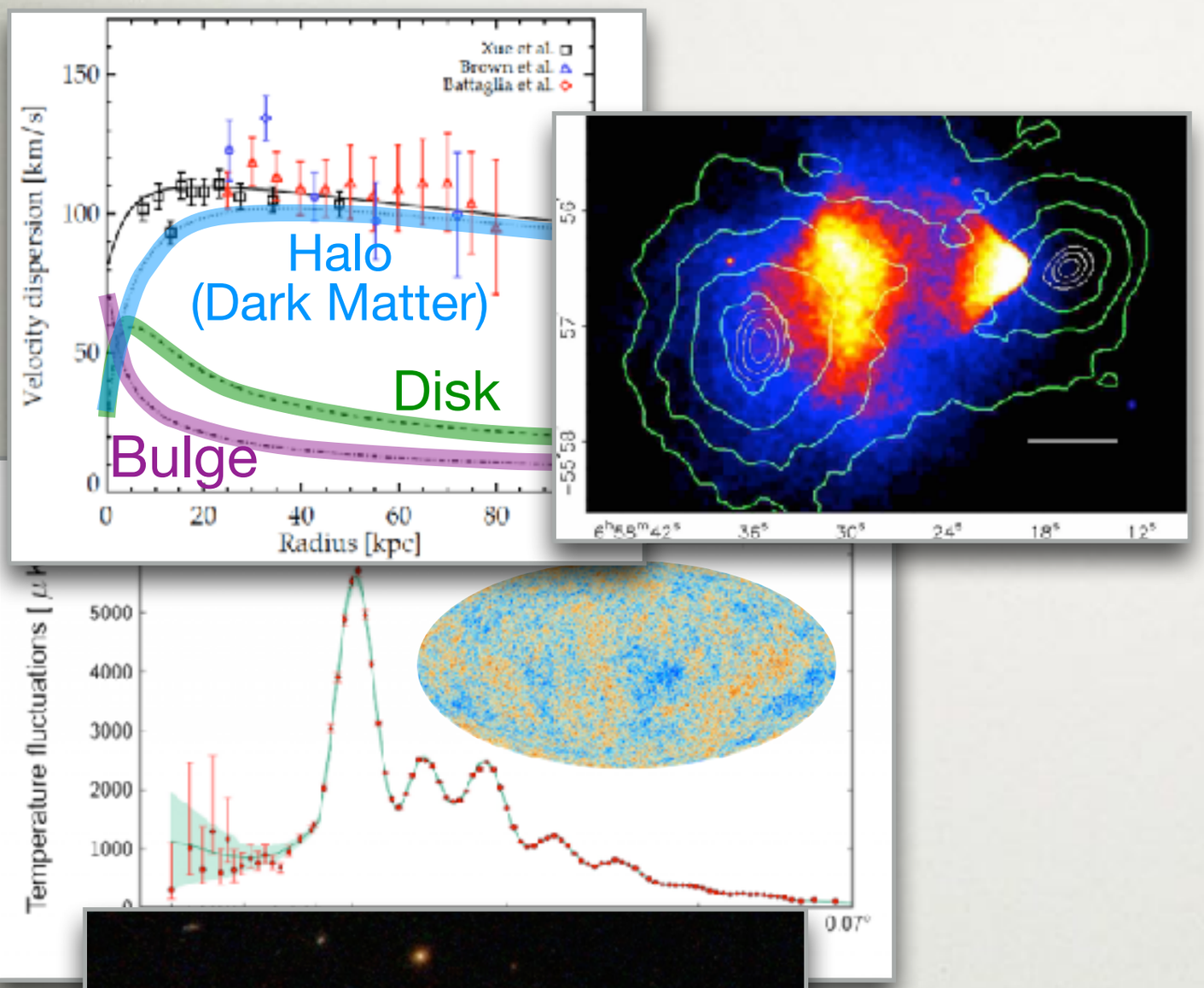
SLAC

Outline

- ✦ Motivation: Completing the WIMP Story
- ✦ Key Building Block: New Forces
- ✦ Search Challenges and Opportunities
  - (brief perspective) Low-Mass Direct Detection
  - New Forces
  - Dark Matter Production

Dark Matter



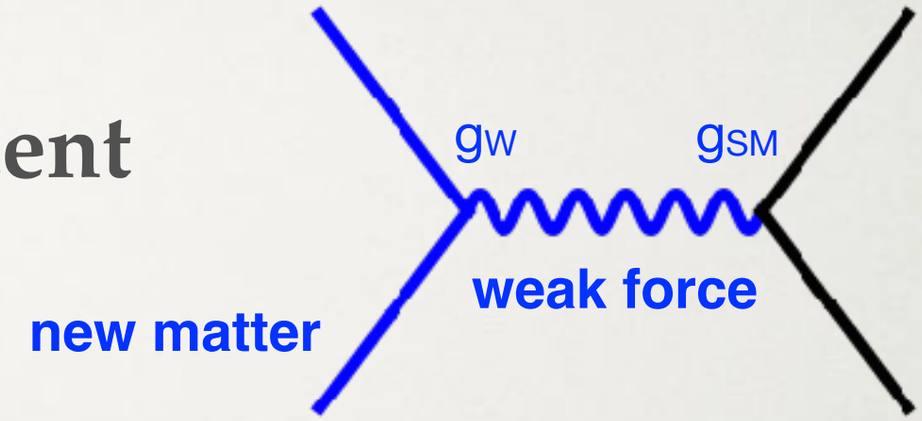
Visible Matter Mass

Total Mass

has been discovered many times over, but we still don't know what it's made of

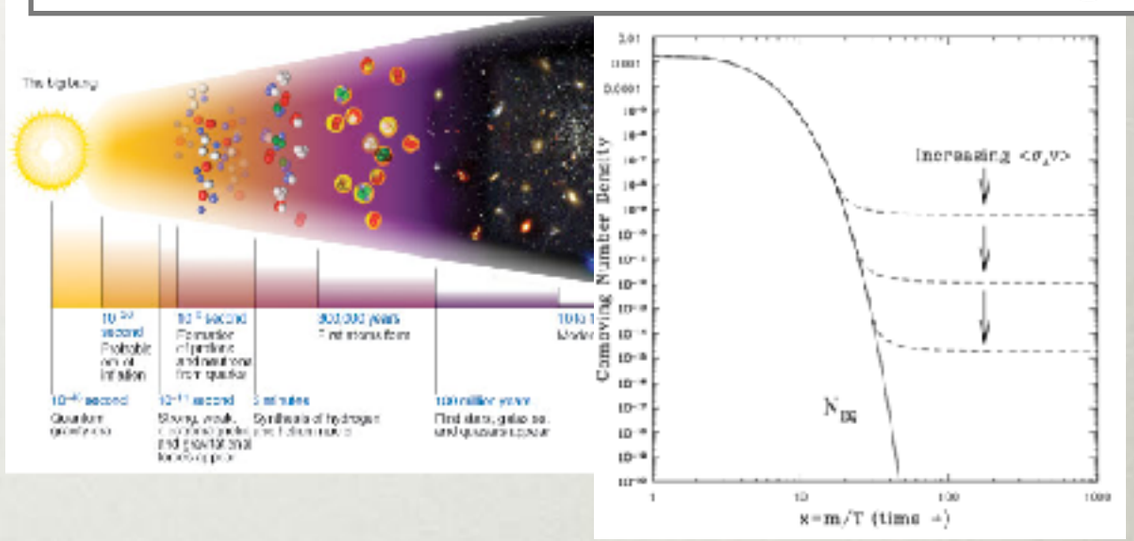
A Strong Candidate: WIMP DM

Simple, familiar particle content

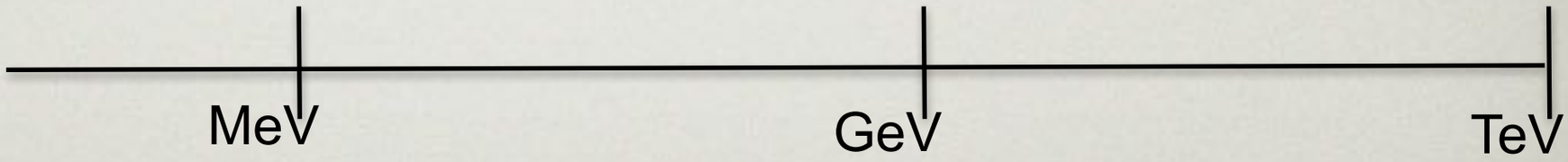


Simple, predictive cosmology

DM with thermal freeze-out origin



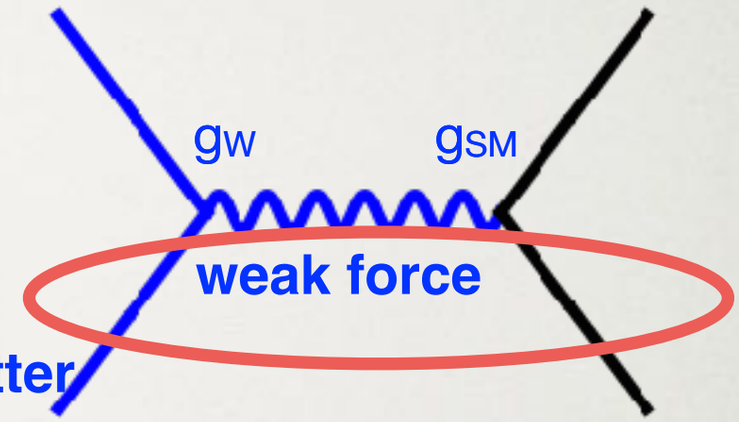
Physics-rich mass range



WIMP

A Strong Candidate: WIMP DM

Simple, familiar particle content



main source of tension

→ direct detection – naive tree-level scattering excluded by direct detection

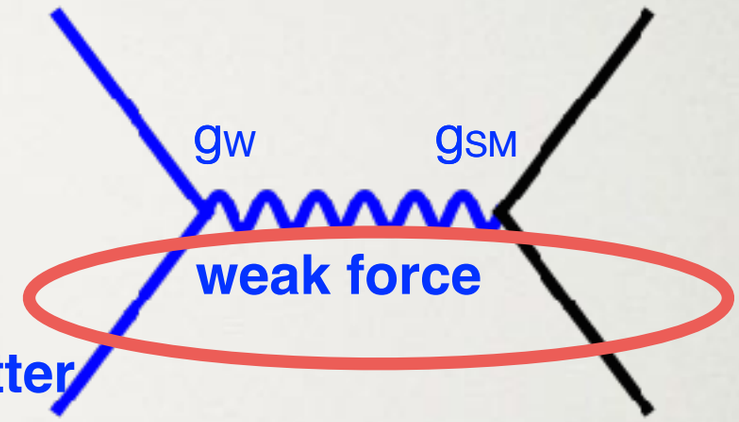
→ production of DM and related particles at colliders

→ Heavy thermal wino constrained by indirect detection

A Strong Candidate: WIMP DM

Simple, familiar particle content

main source of tension → new matter



Next steps in WIMP search are important!

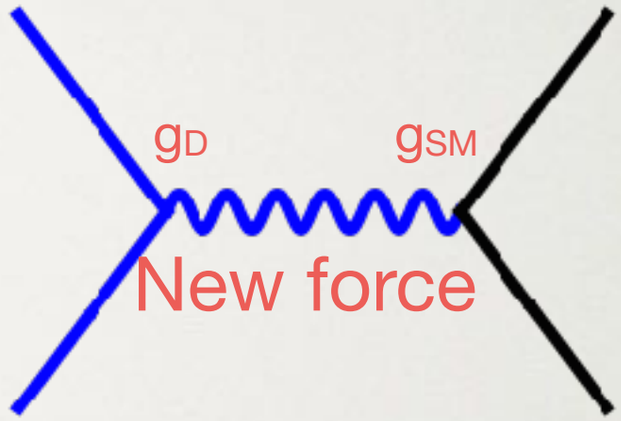
But also time to broaden the lamppost – what uncharted territory can we reach by loosening assumptions?

colliders

→ Heavy thermal wino constrained by indirect detection

A Small Step: Hidden Sector DM

Simple, familiar particle content



Dark matter could be charged under a new force!

(in keeping with the history of particle physics)

Immediate reward for this assumption:
– dark matter can be stabilized by new charge
– preserve & extend much of the WIMP story

Immediate perils:
– why haven't we seen the force yet?
maybe because it doesn't couple very strongly to us

The Portals

If DM is Standard Model neutral, what kinds of relevant interactions can it have with SM fields?

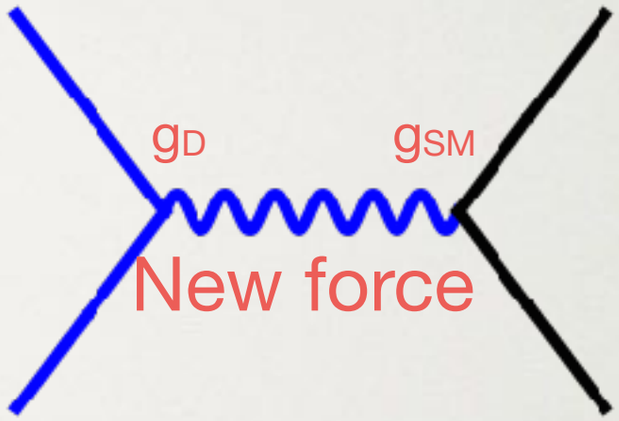
Vector Portal	$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$
Higgs portal[1]	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$
Higgs portal$^{\text{singlet}}$	$A_h \lvert h\rvert^2 \phi$
Neutrino Portal	$\epsilon_\nu (hL)\psi$
Any currents	$\epsilon_V \bar{f}\gamma^\mu q_f f V_\mu$

Great working example: Compatible with cosmology in simple models, illustrative – focus here for most of my talk

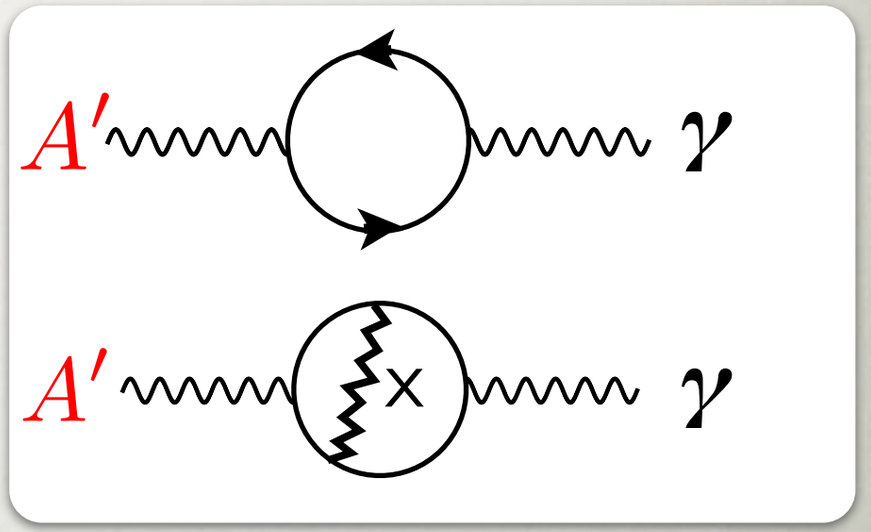
A Small Step: Hidden Sector DM

Simple, familiar particle content

Dark matter could be charged under a new force!

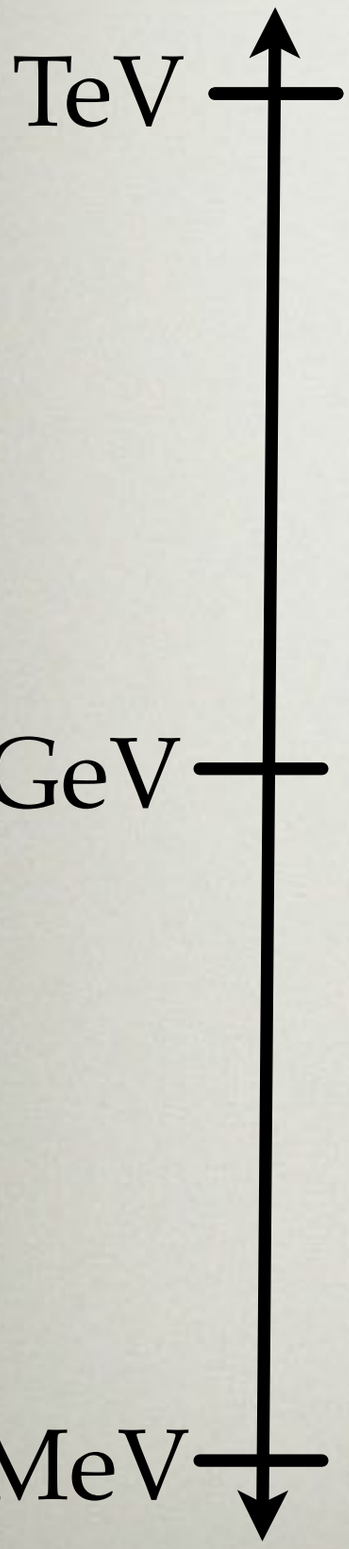


Vector Portal $\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$



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

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

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

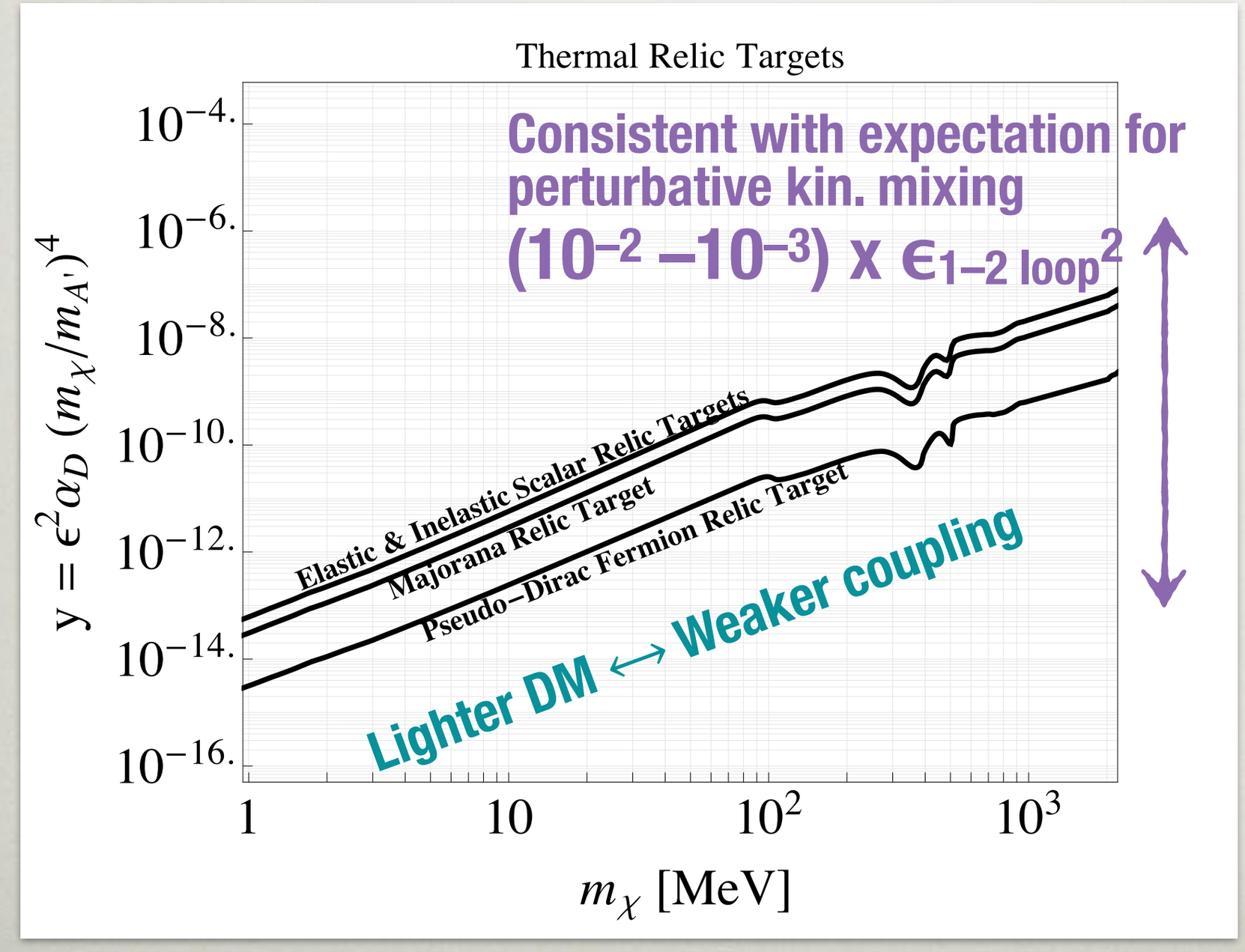
(accidentally close to weak scale)

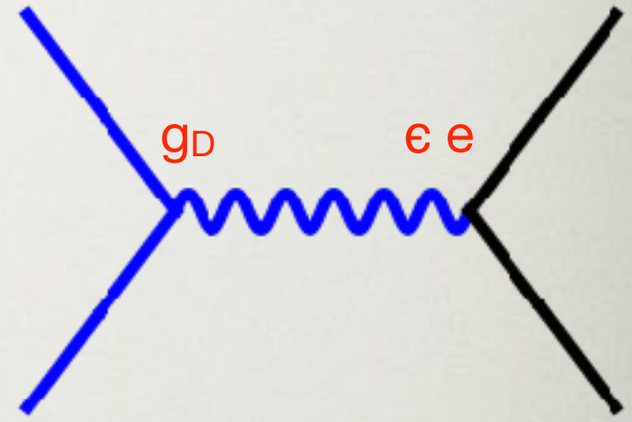
...but hidden sector matter weakly coupled to SM could well be here (similar origins to electron or proton masses)

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

(derived from weak scale)

Light Thermal Dark Matter



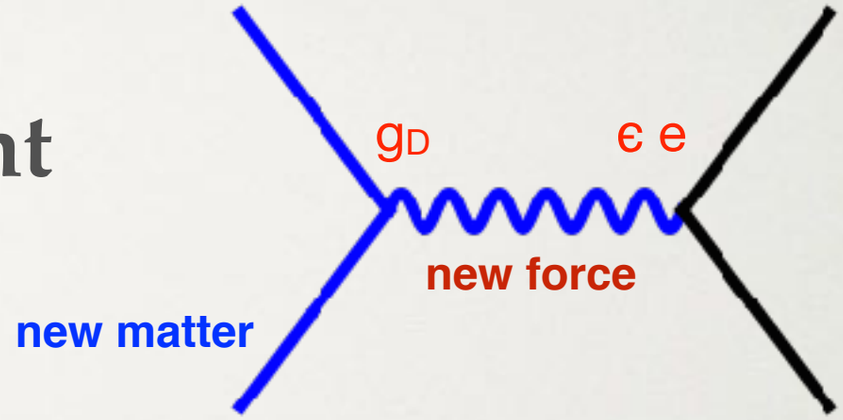


$$\sigma v \sim \frac{\epsilon^2 \alpha \alpha_D m_{DM}^2}{m_W^4}$$

$\sim 3\ 10^{-26}\ cm^3/s$

A Strong Candidate: Hidden Sector DM

Simple, familiar particle content



Simple, predictive cosmology

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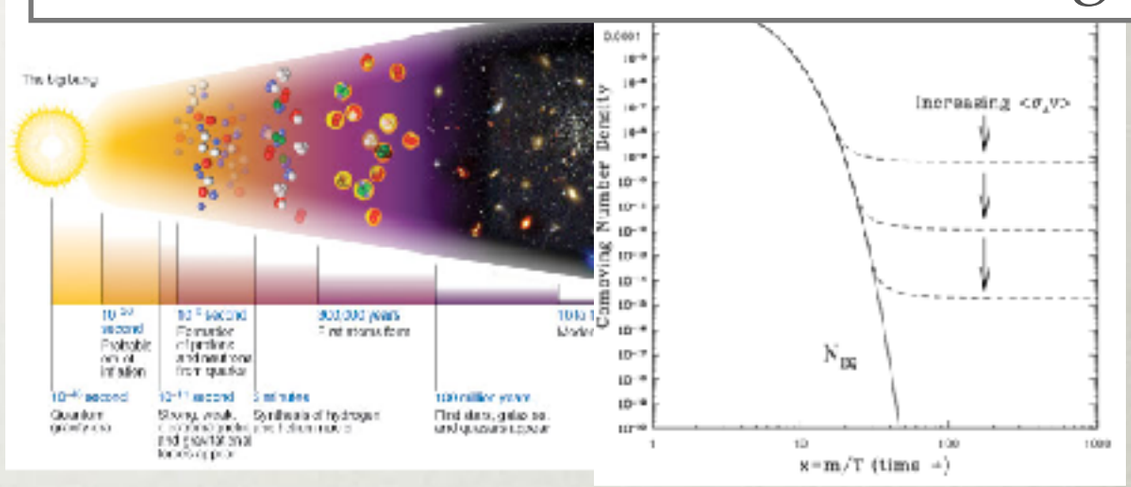
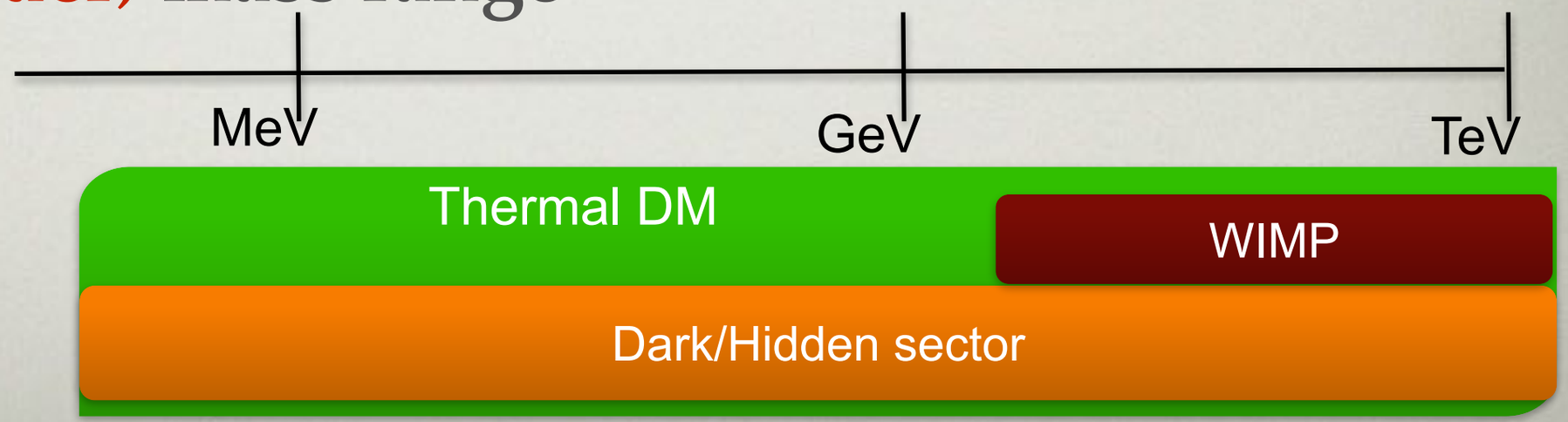


Motivated **(broader)** mass range

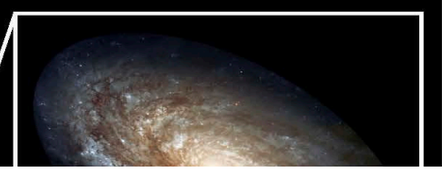


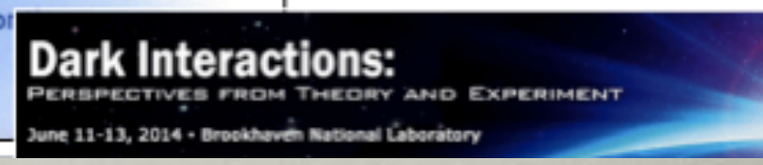
Three New Search Directions

Light DM production

Light DM scattering – K. Morå

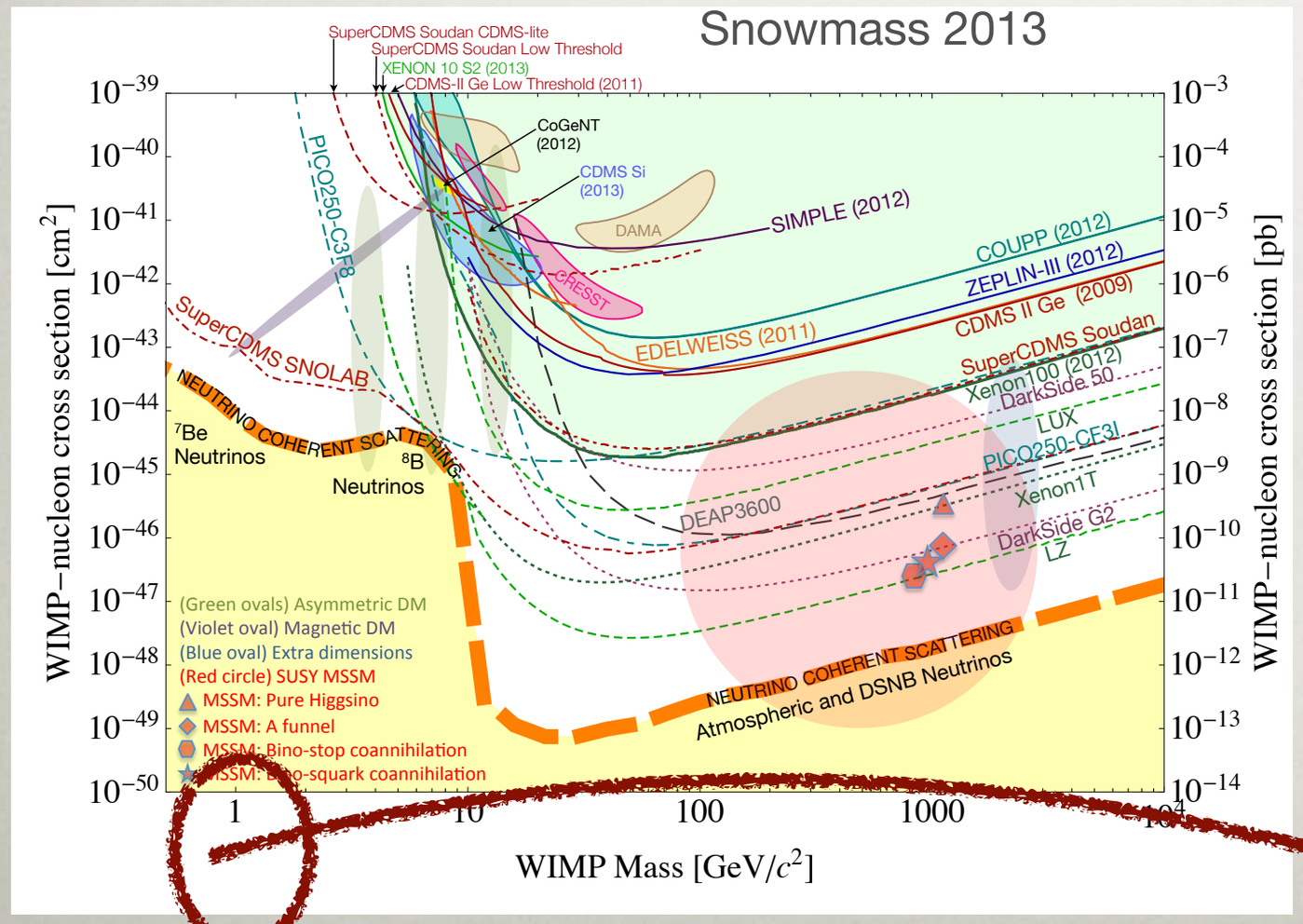
New force searches

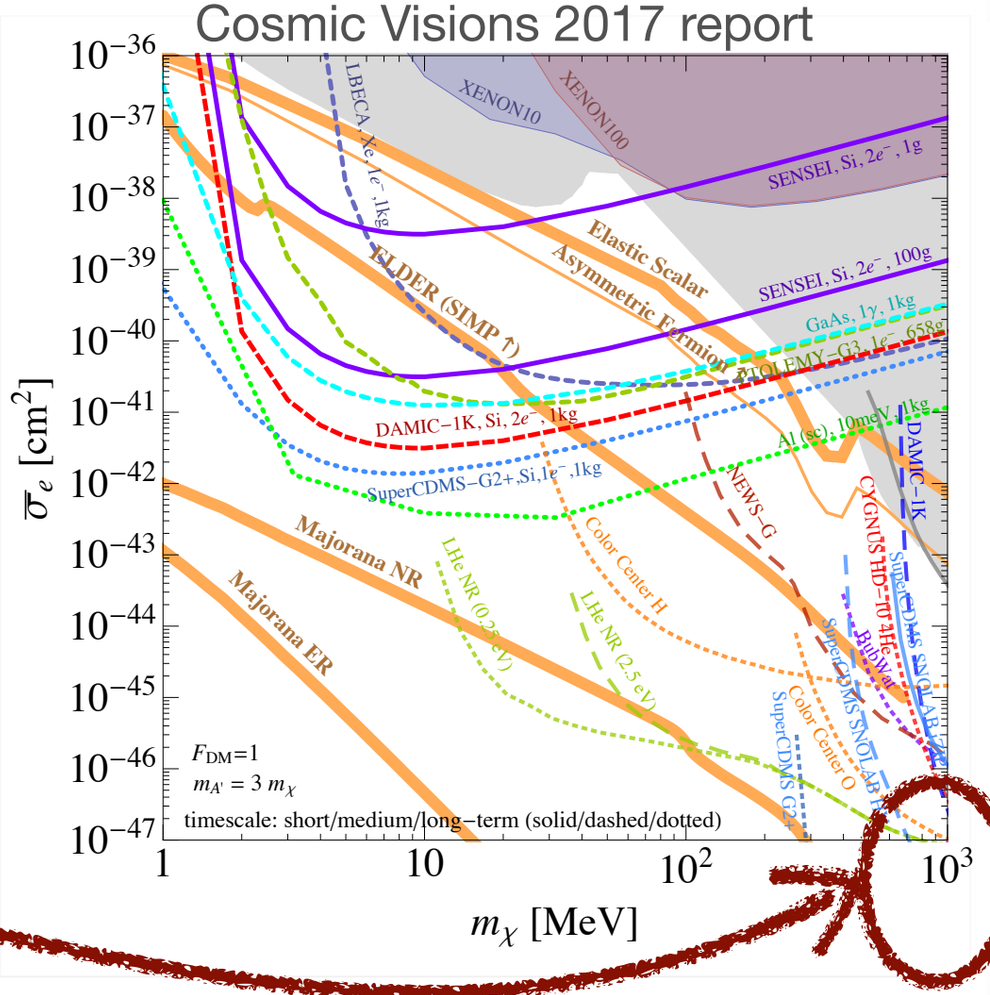




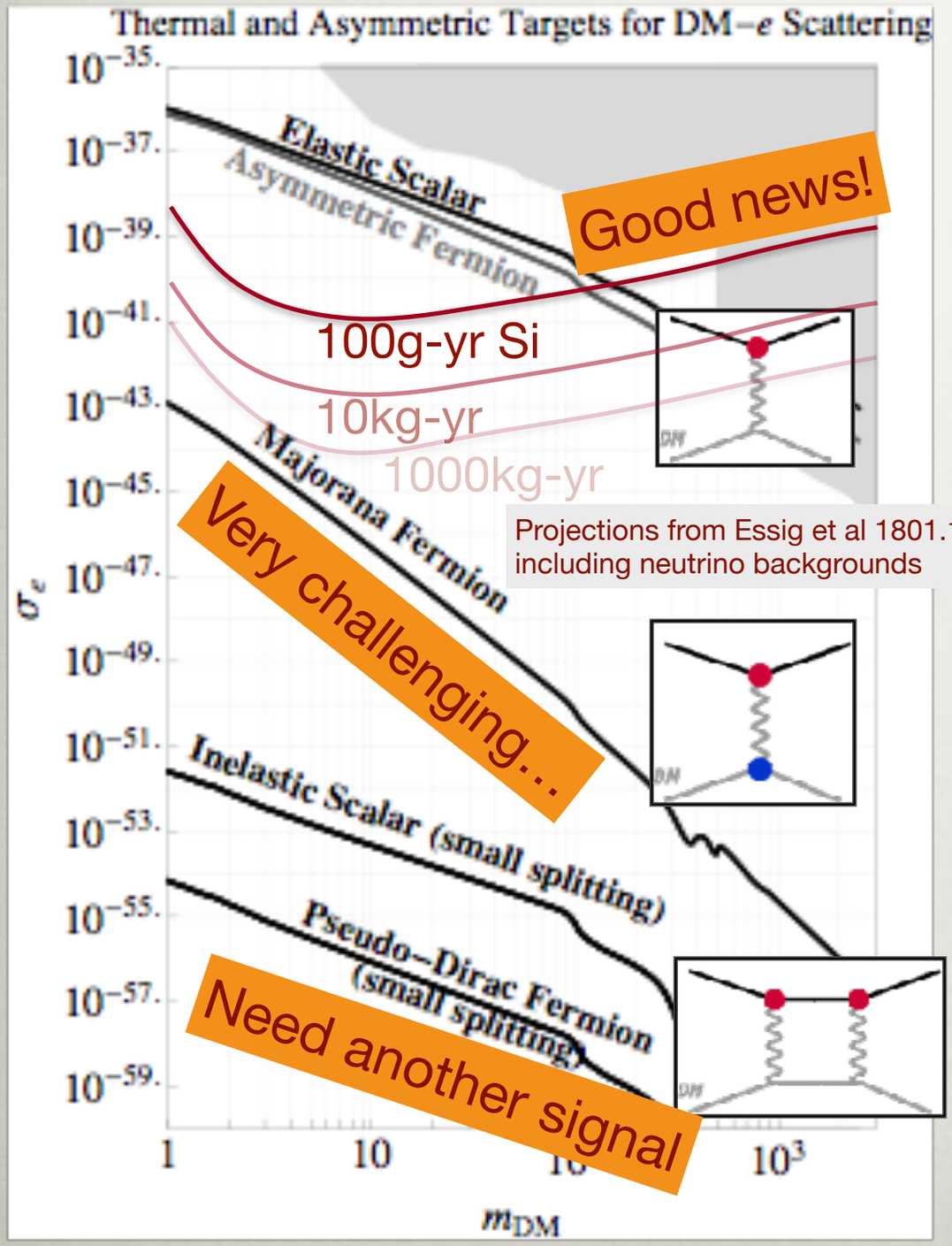
Sub-GeV Direct Detection

Extension of direct detection to <GeV masses – e.g. through electron recoils, Migdal effect, LHe detectors, advanced materials – has been an exciting and remarkable growth area over the last decade. (I won't talk about the experiments because Knut Morå just did)



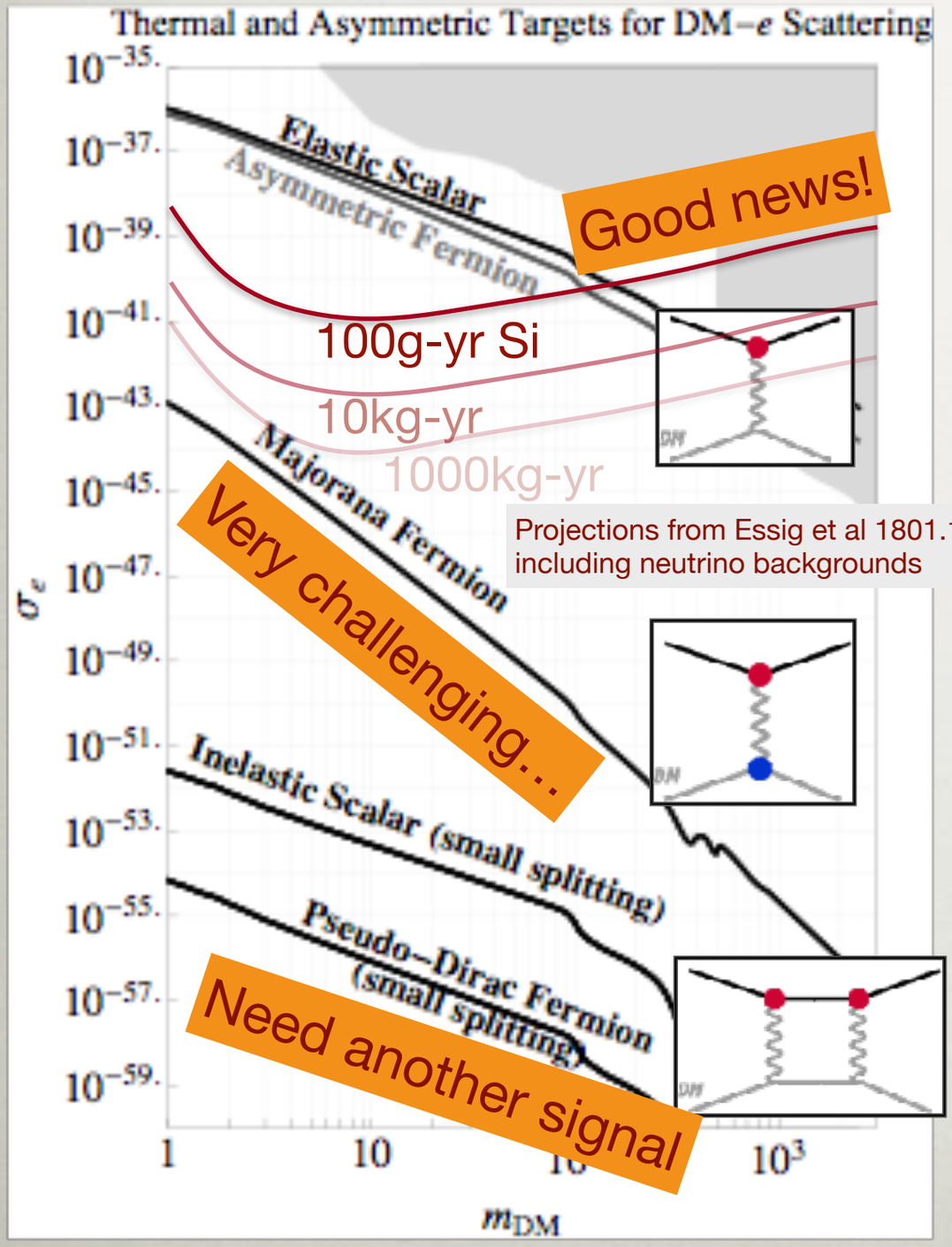


Direct Detection and Light Thermal DM



- Small DM-SM coupling
- Velocity-suppression

Direct Detection and Light Thermal DM



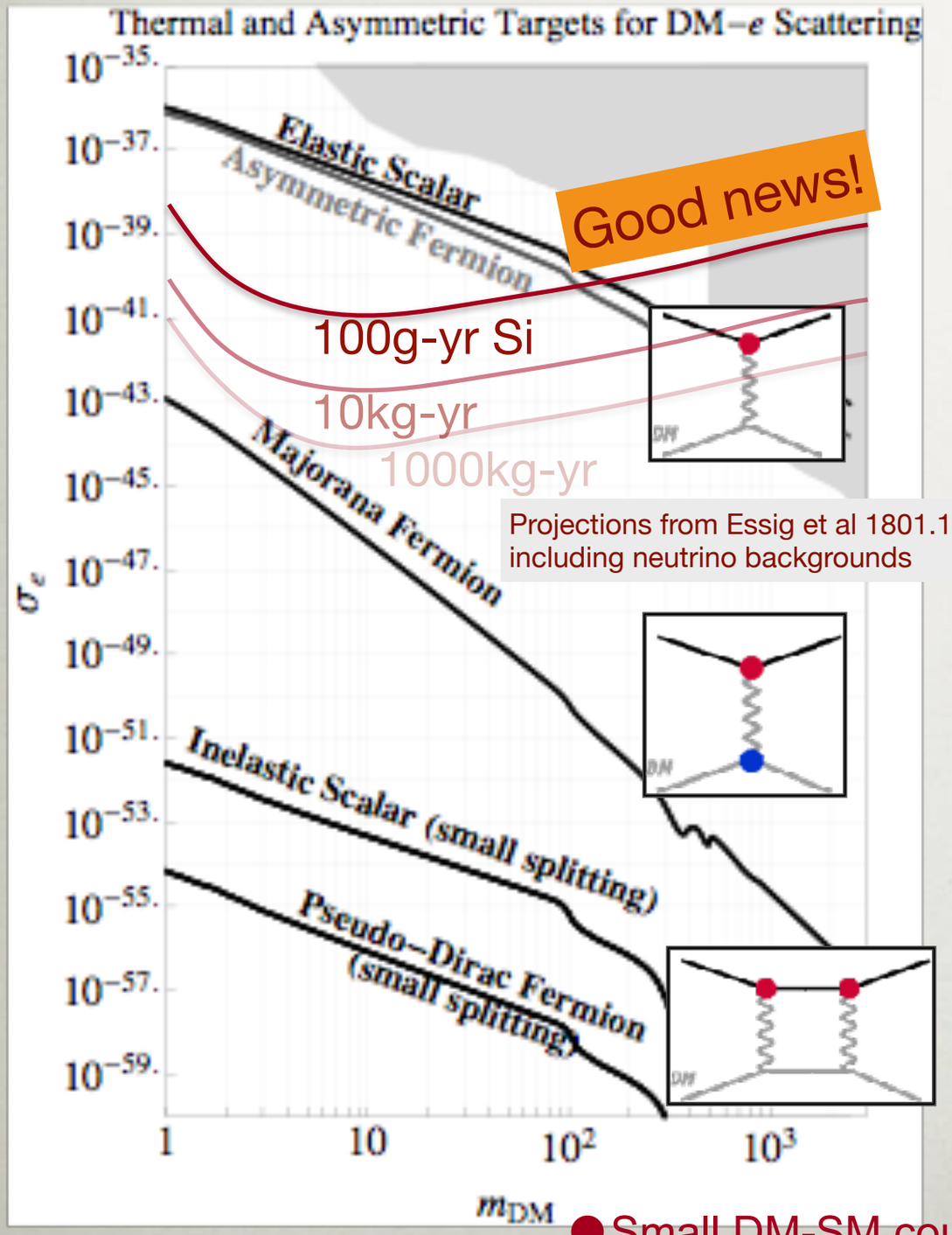
Elastic scalar thermal DM will be explored very soon! But many other simple models are nearly impossible to reach through elastic scattering!

Interesting direction: there "direct-detection-adjacent" signals of these models – are any of them robust?
(But not for this talk…)

Of course, there are other models outside thermal class that could be discovered here, too!

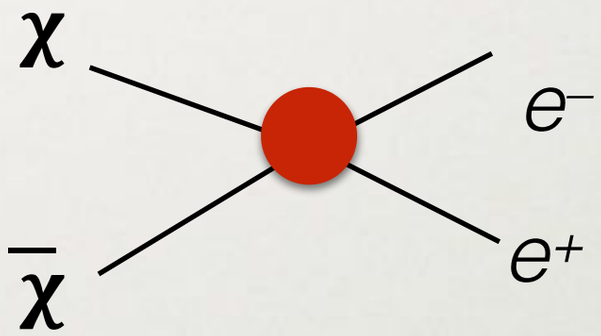
- Small DM-SM coupling
- Velocity-suppression

Direct Detection and Light Thermal DM



● Small DM-SM coupling
● Velocity-suppression

One lesson: Can be hard to explore physics of DM semi-relativistic annihilation

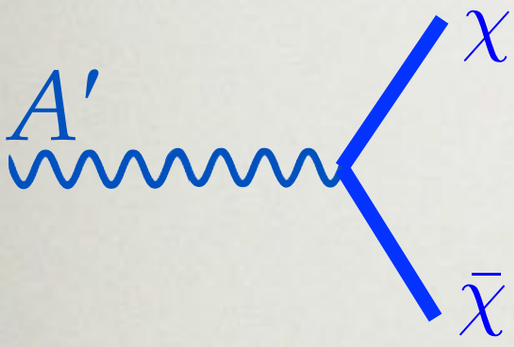


$v_{DM} \sim c$

with very non-relativistic ($v \sim 10^{-3}$ c) halo DM. **Accelerator-based searches for DM and related particles are an essential tool to explore this idea broadly.**

Organizing the Physics

(Vector Mediators as an example — most models work similarly)



DM and Mediator Production

Dark photon mass

heavy

Contact operator DM production

Mediator decays to DM
Visible decays negligible

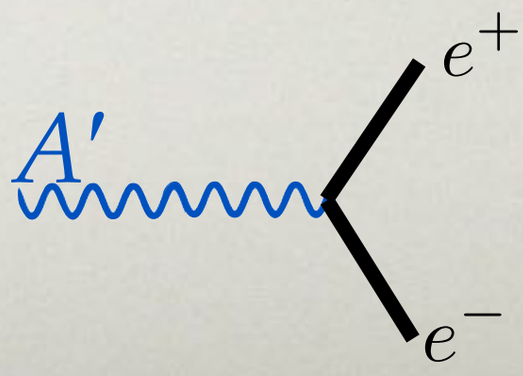
$m_{A'} = 2\, m_{DM}$

Mediator decays visibly
DM can be produced near threshold

(+DM from off-shell A')

Dark matter mass

Search for both the mediator and DM itself!



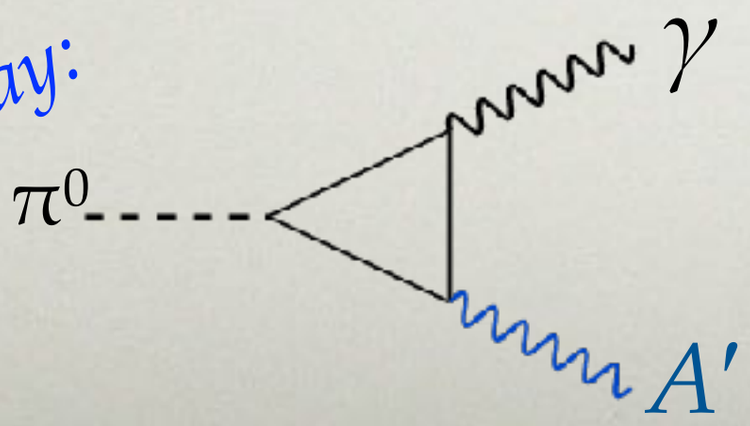
Dark Photon Production

Kinetic mixing effectively gives matter of electric charge qe an A' coupling $\propto q\varepsilon e$

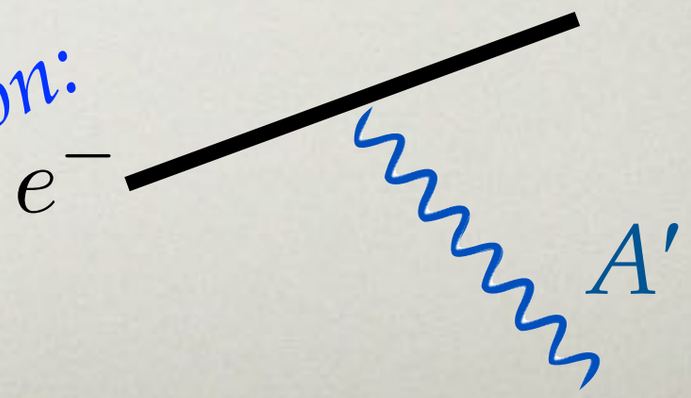
$\Rightarrow$ *Wherever there are photons (and sufficient phase space), there are dark photons*

Annihilation:

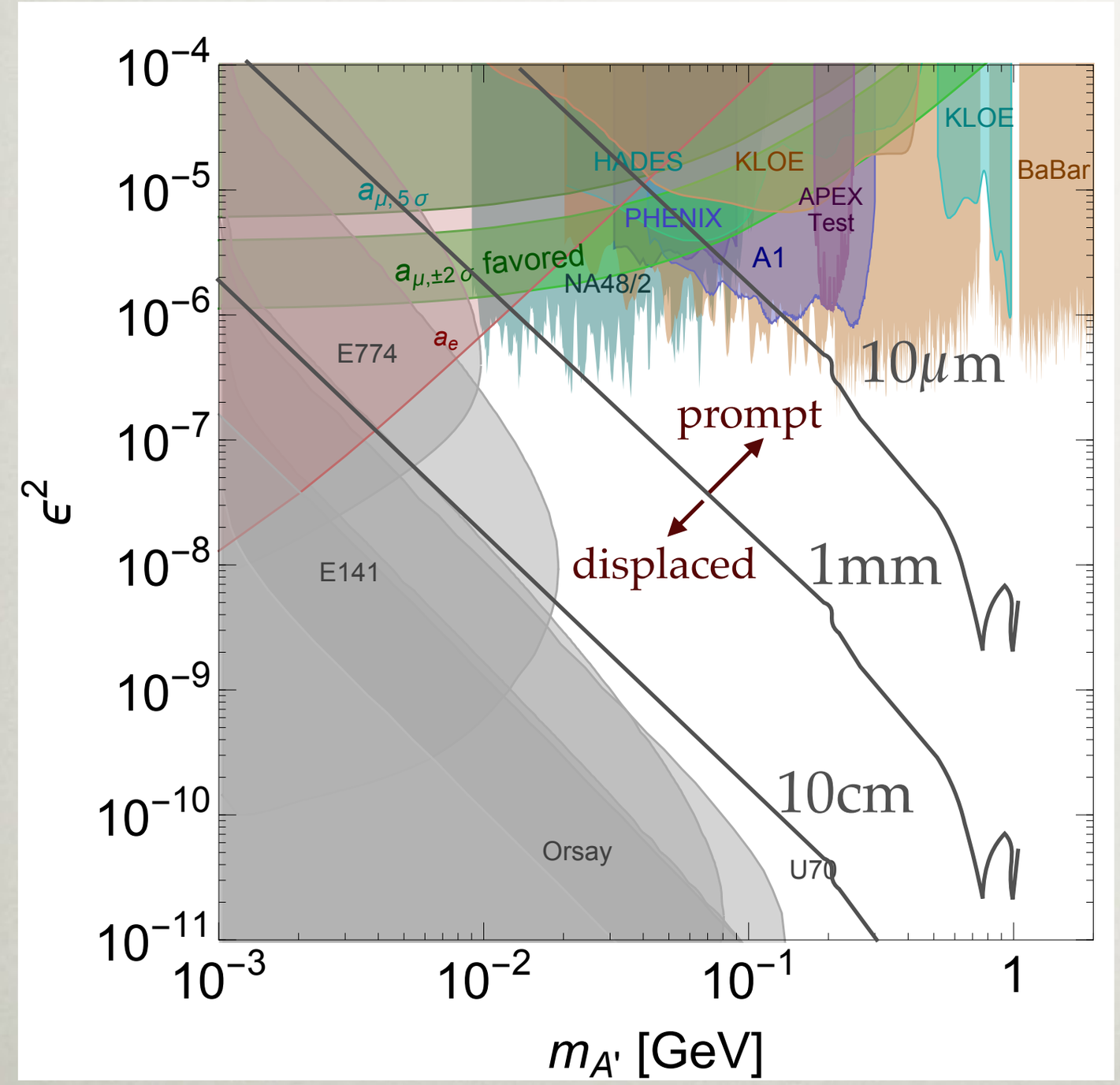
Decay:



Radiation:

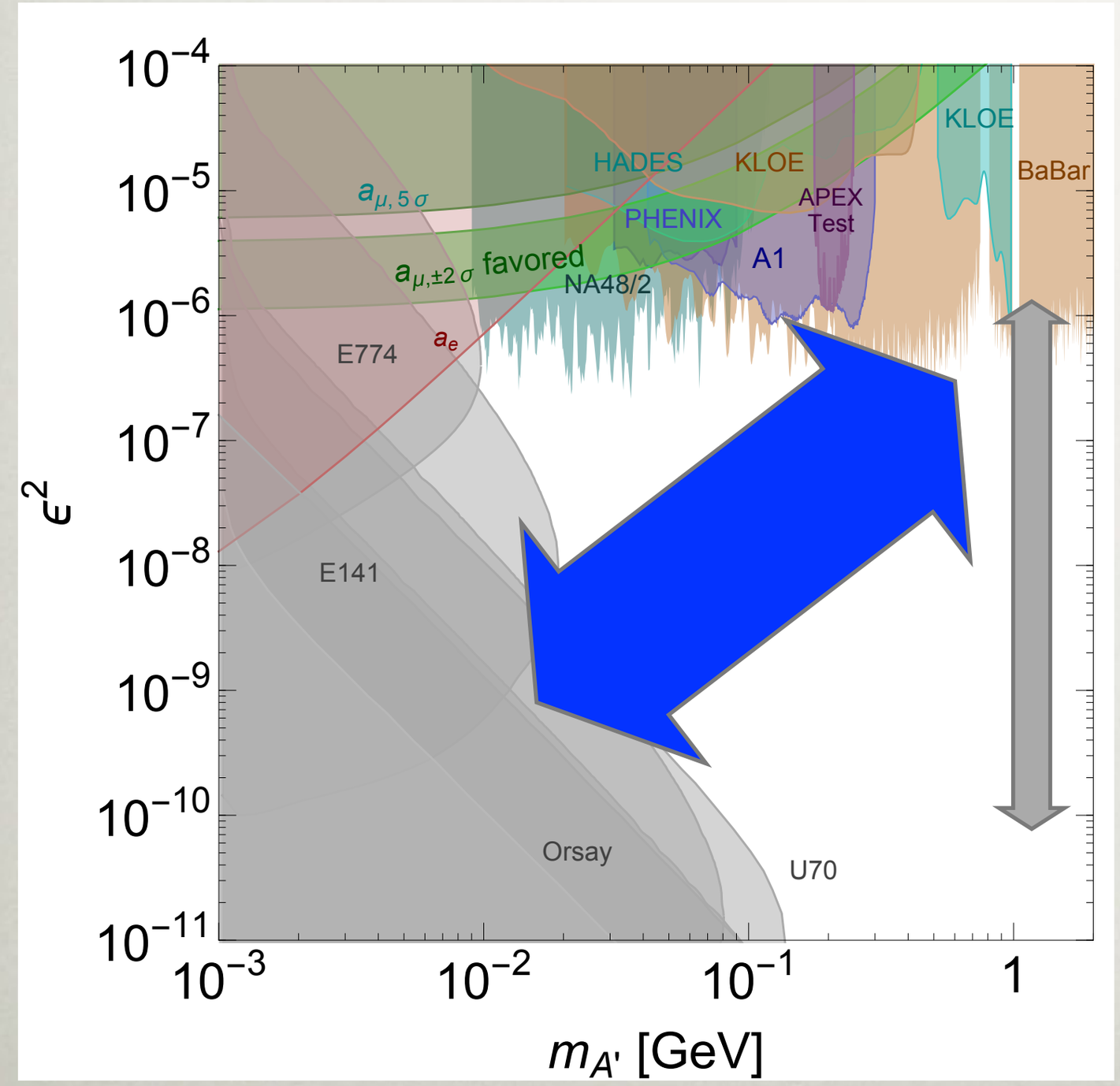


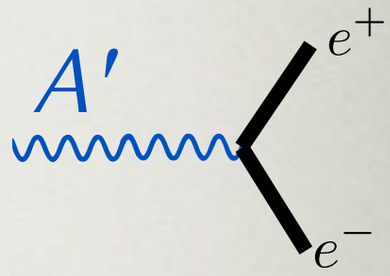
Visible Dark Photons



Natural parameter space has wide range of production rates & lifetimes

Visible "Dark Photons"

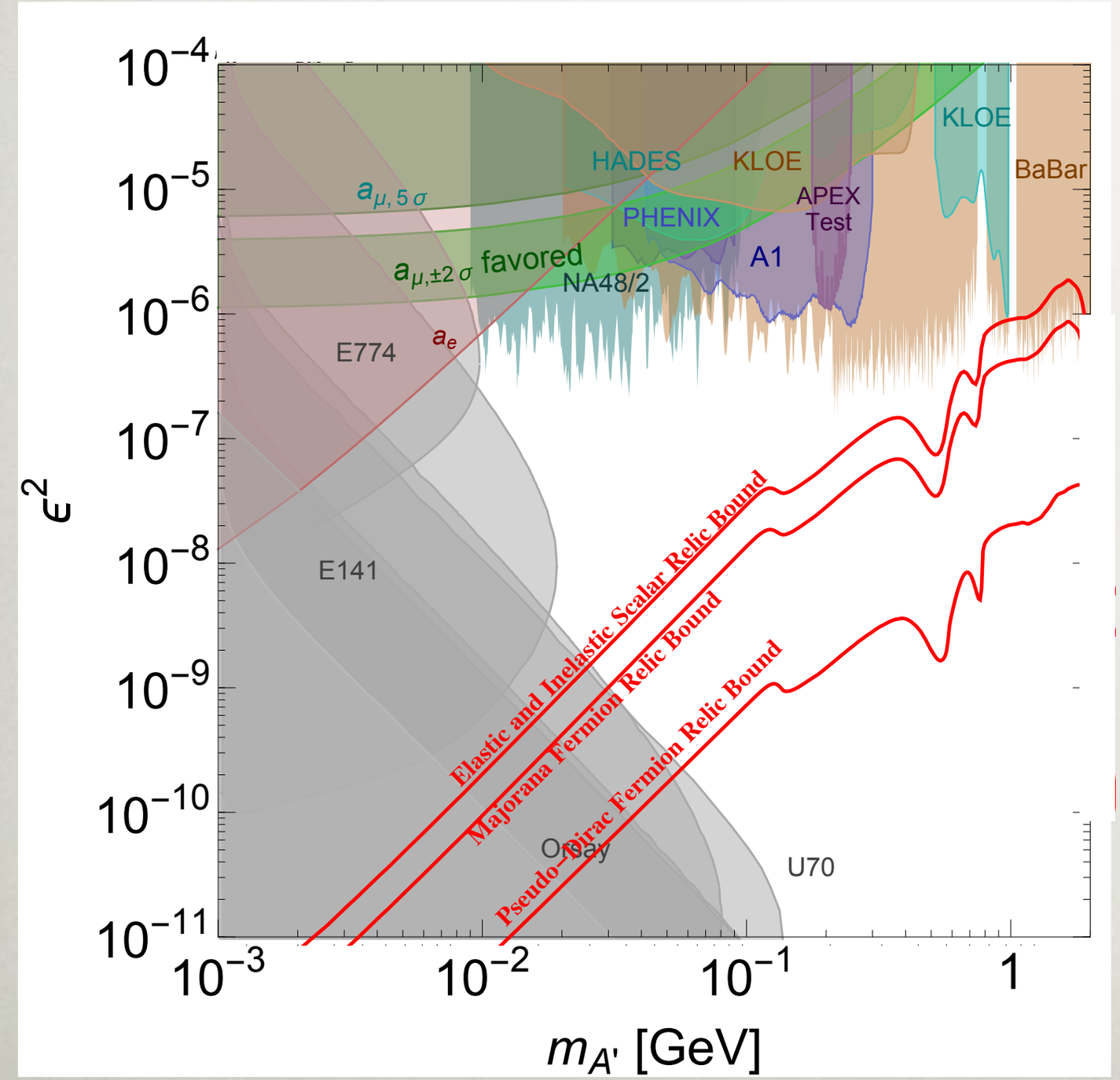


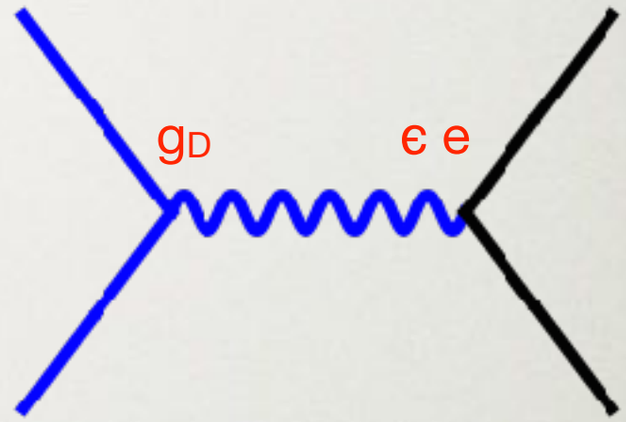


Mixing in Grand Unified Theories

sub-GeV mass scale compatible with radiative Higgs mixing or hidden valley

Visible “Dark Photons”

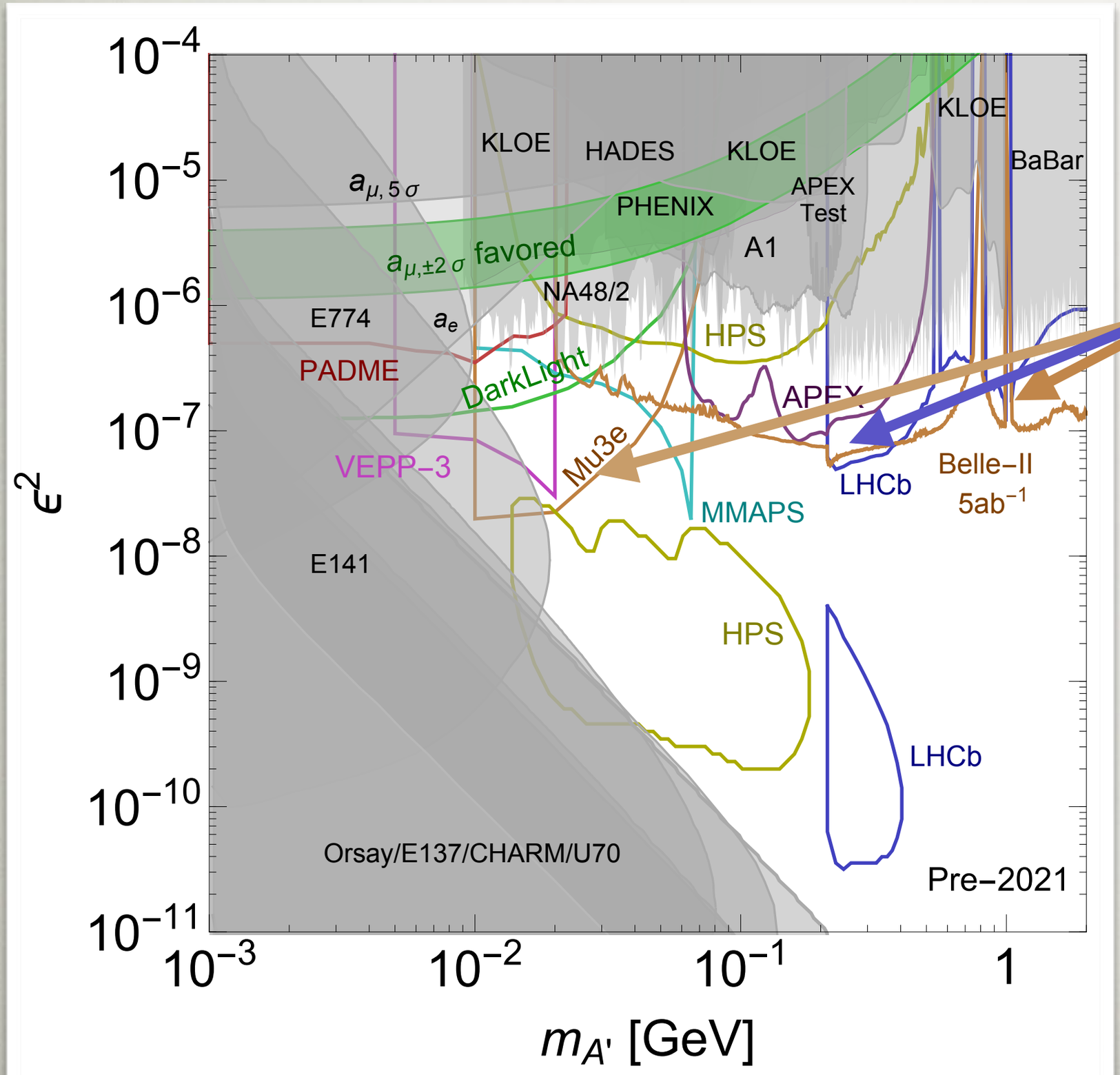




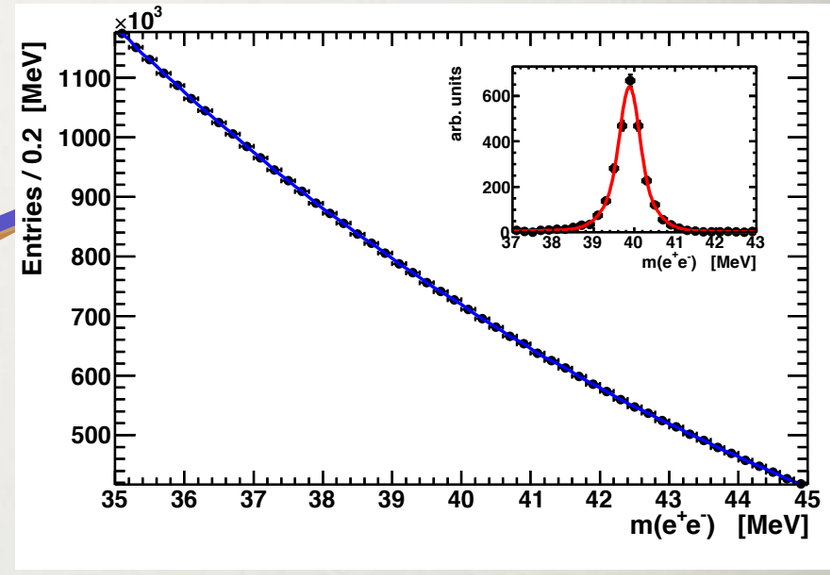
For part of DM-A’ mass range where this process controls freeze-out, provides a lower limit on mediator coupling vs mass!

at low mass, other reactions dominate: see e.g. https://arxiv.org/abs/2011.01240)

Small Bumps



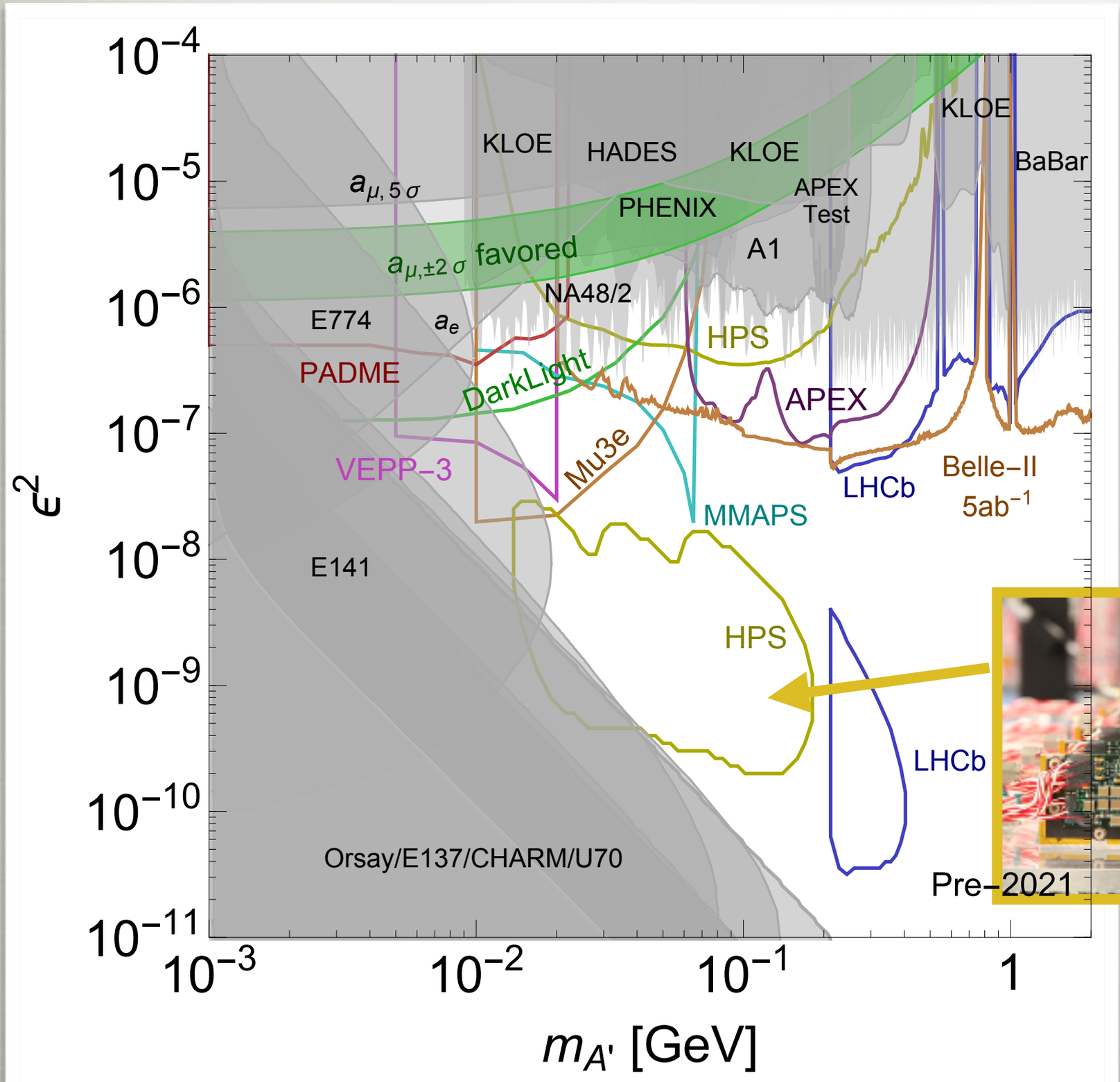
Look for tiny resonance on very high-statistics background

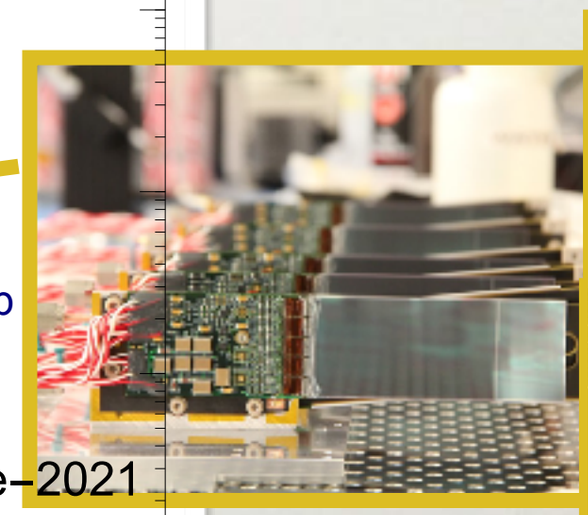


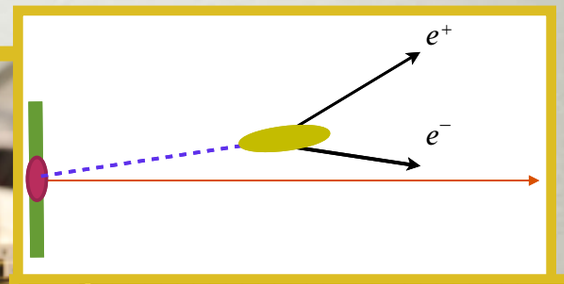
Echenard, Essig, Zhong 1411.1770

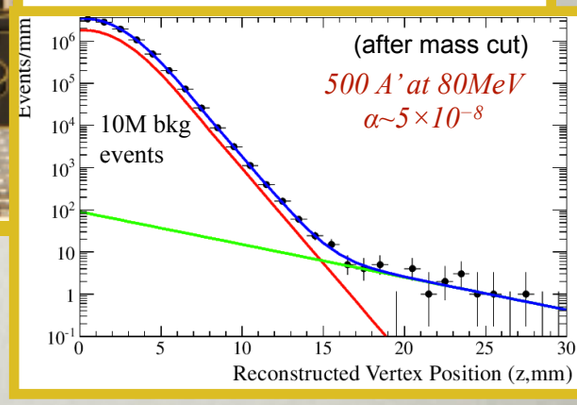
This approach has closed dark photon window for g-2 anomaly!

Turning Weakness into Strength

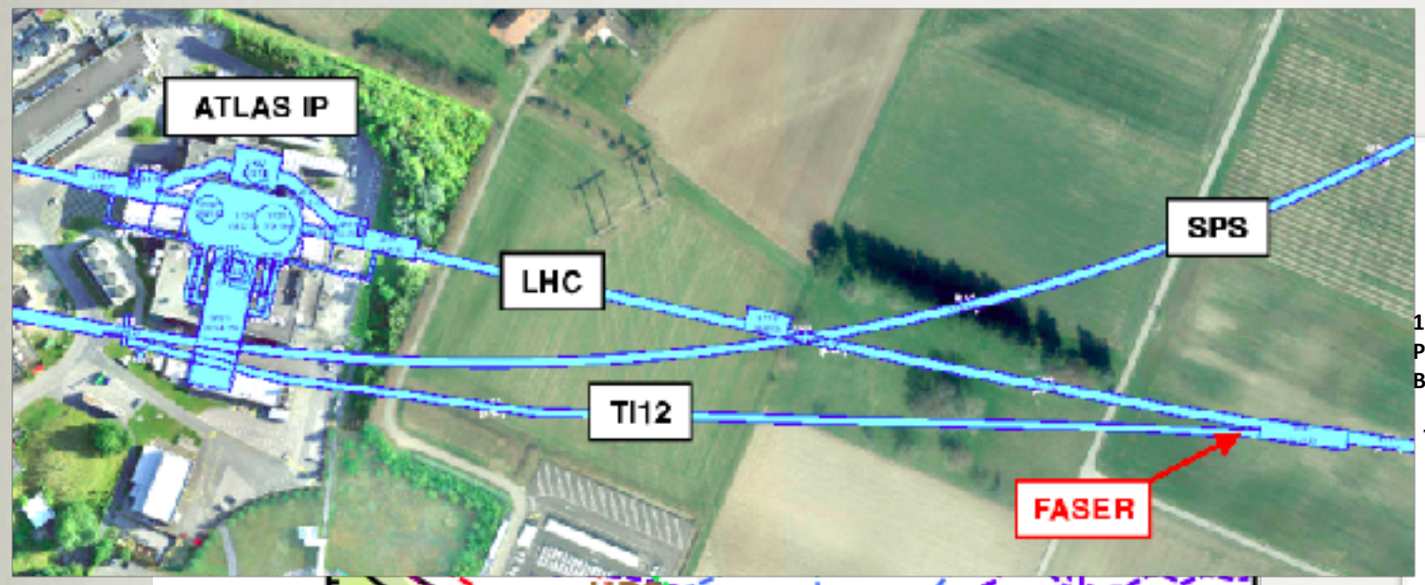




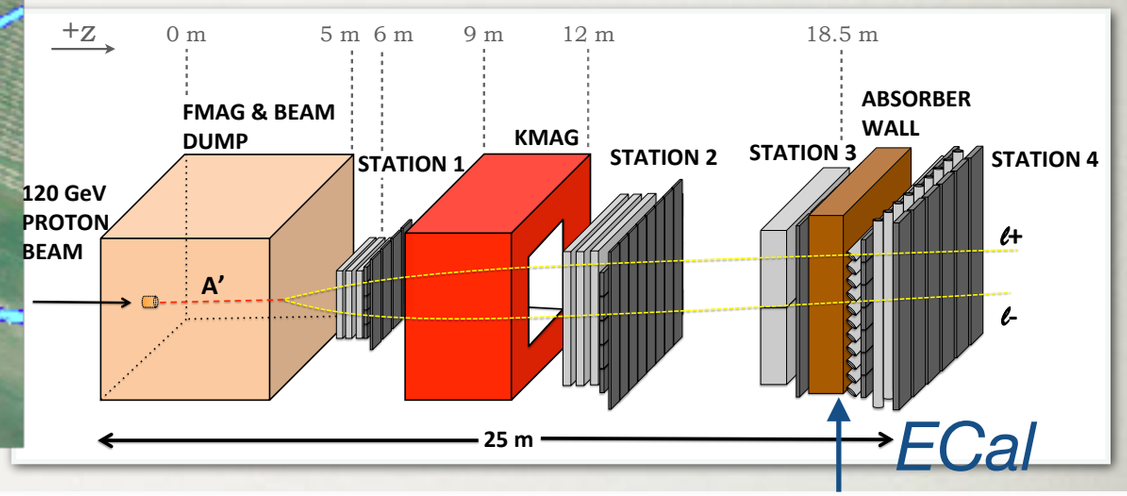


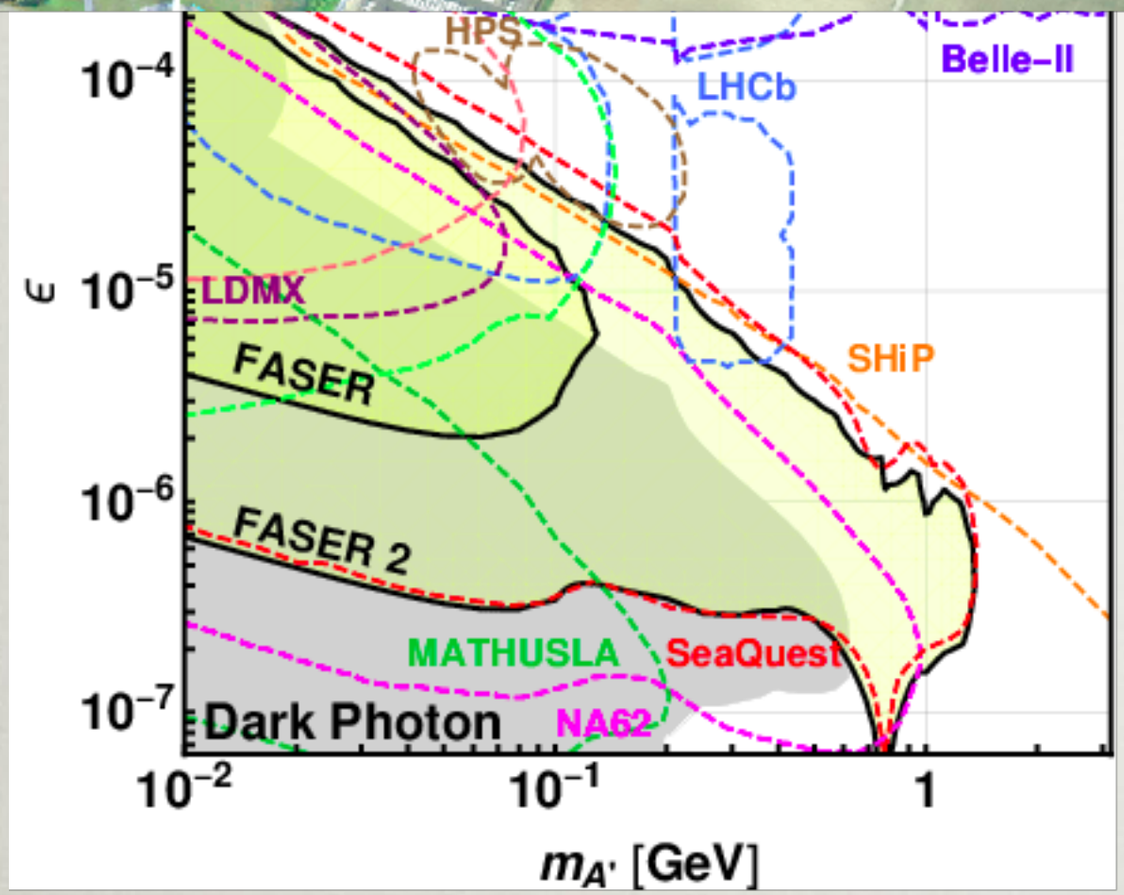


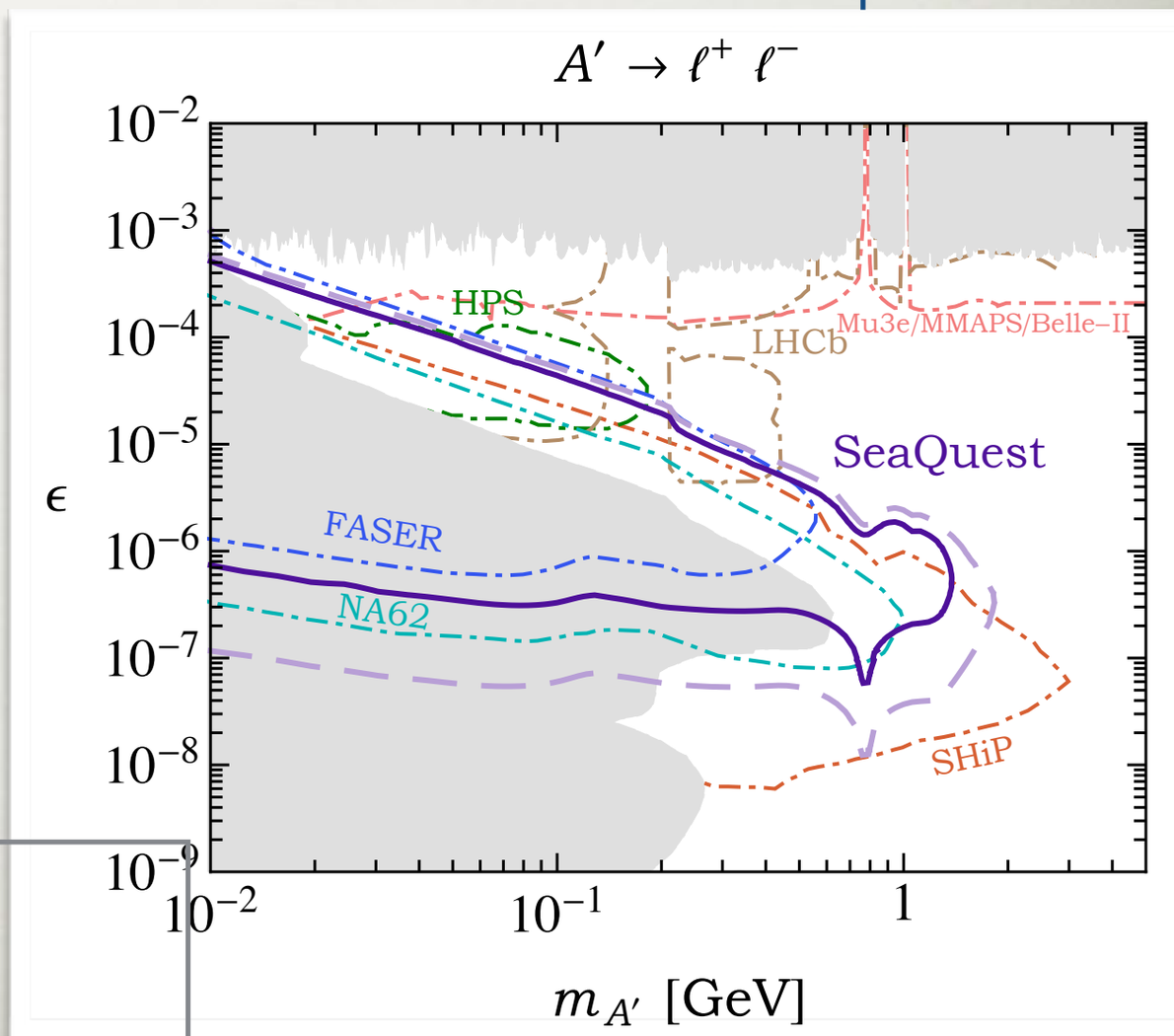
Proton Dumps and New LHC Detectors



SeaQuest→DarkQuest



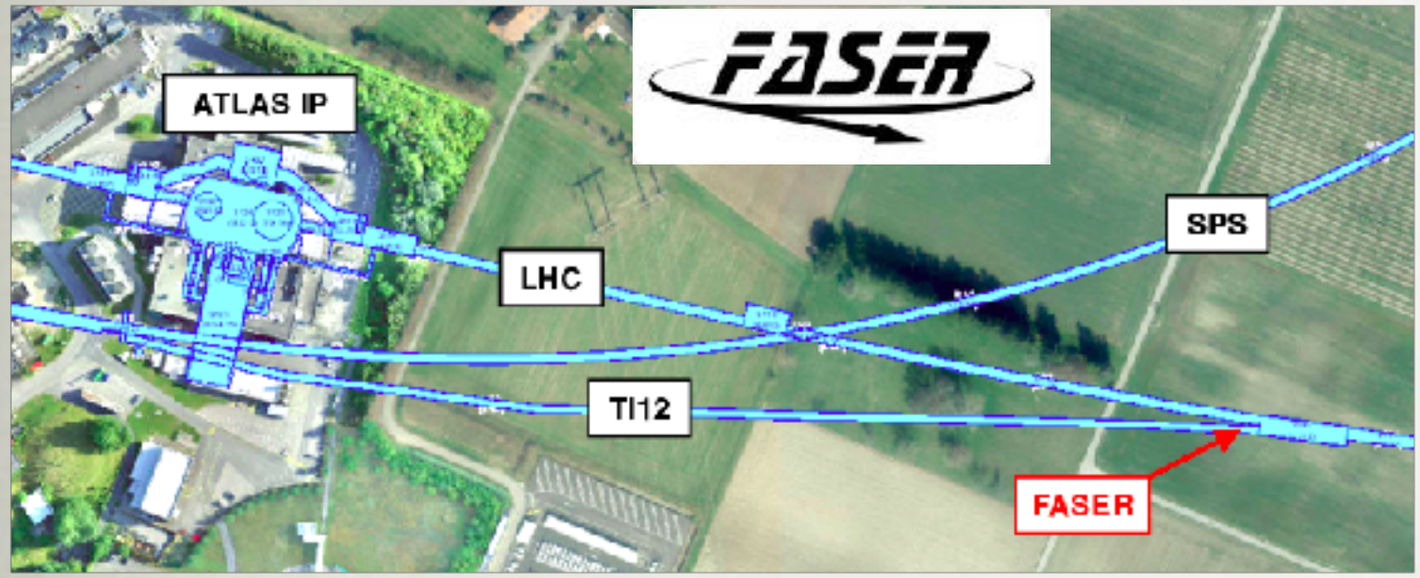


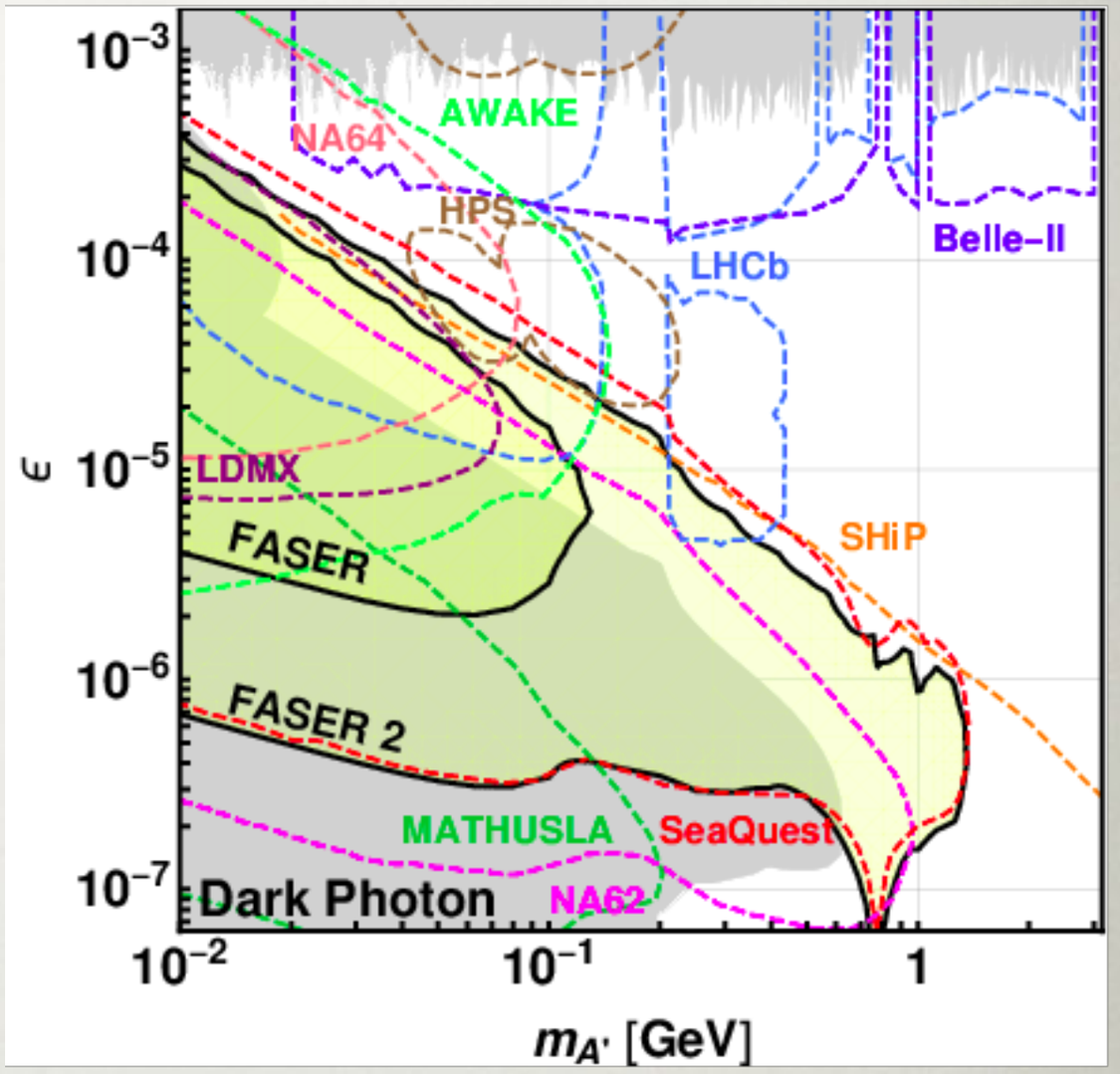


Advantages: boost, high luminosity, improved sensitivity to Higgs-mixed particles

Collider-auxiliary LLP detectors

Take advantage of boost and large interaction rates at LHC





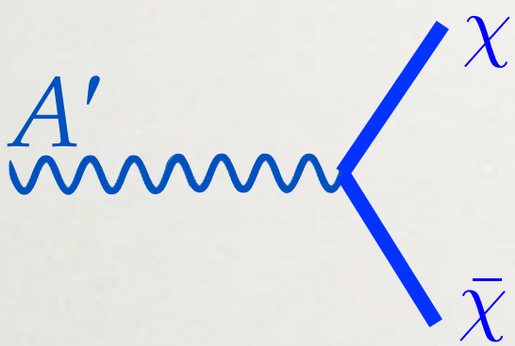
Also:

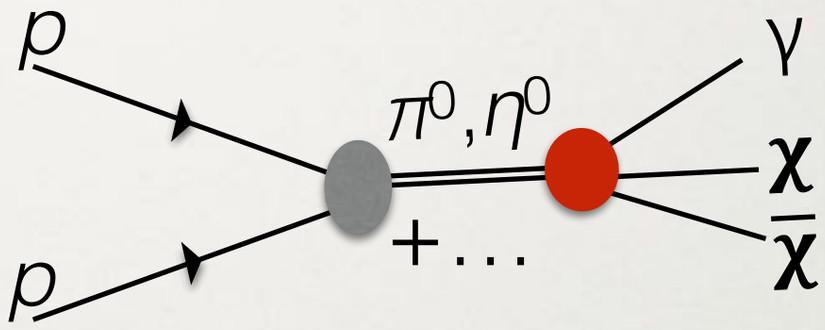
MATHUSLA, CODEXb (also at LHC)

Millicharge detector proposals

GAZELLE proposal at Belle-II

Dark Matter Production



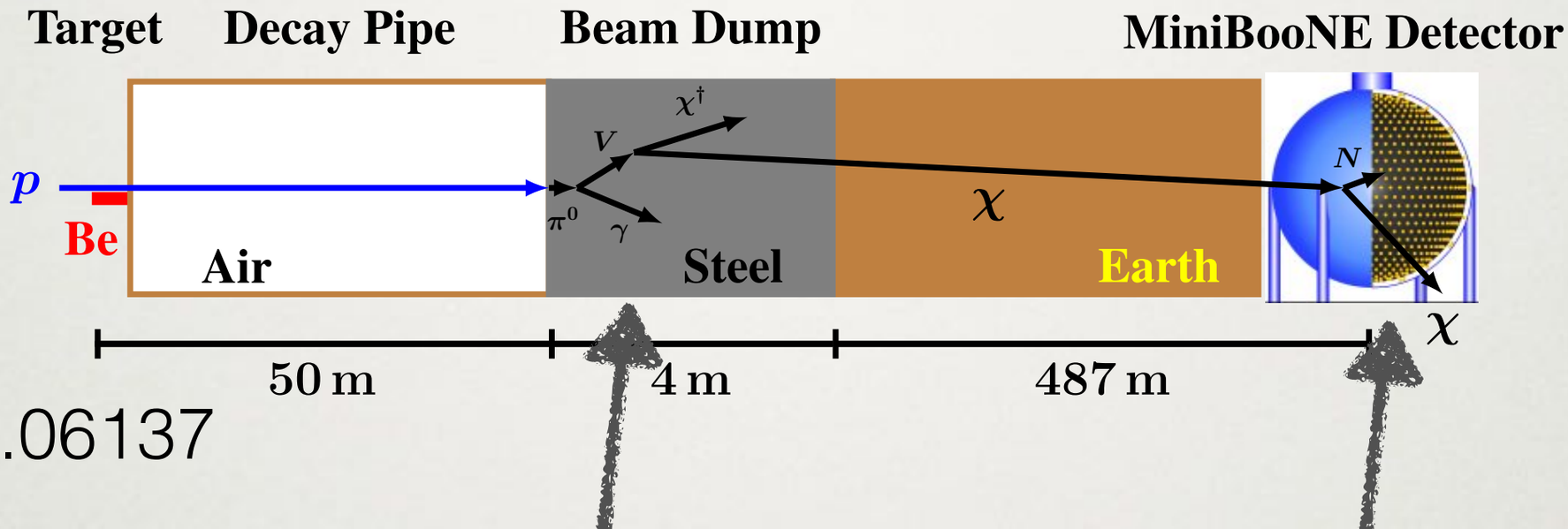


from mediator decay or via off-shell mediator

Dark Matter interacts very weakly and in these models is comparable in mass to light SM particles – how do we know when we've produced it?

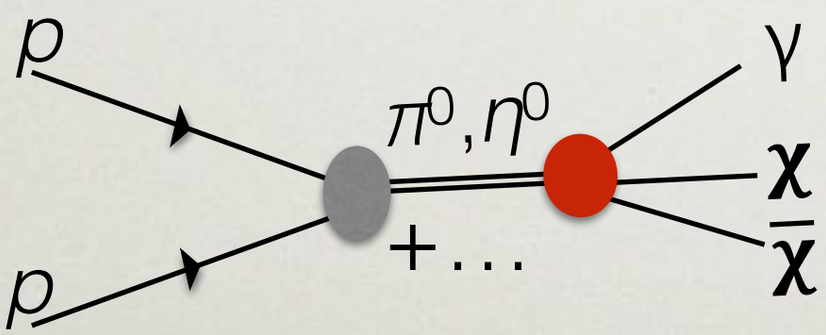
Dark Matter Beams

Already set powerful constraints!

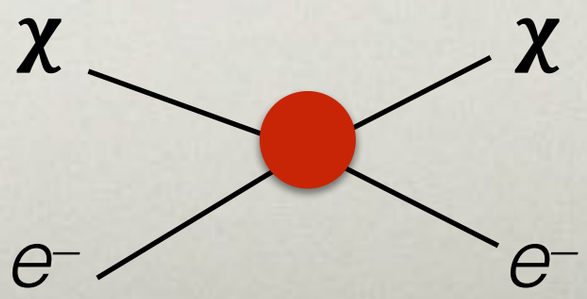


arXiv:1807.06137

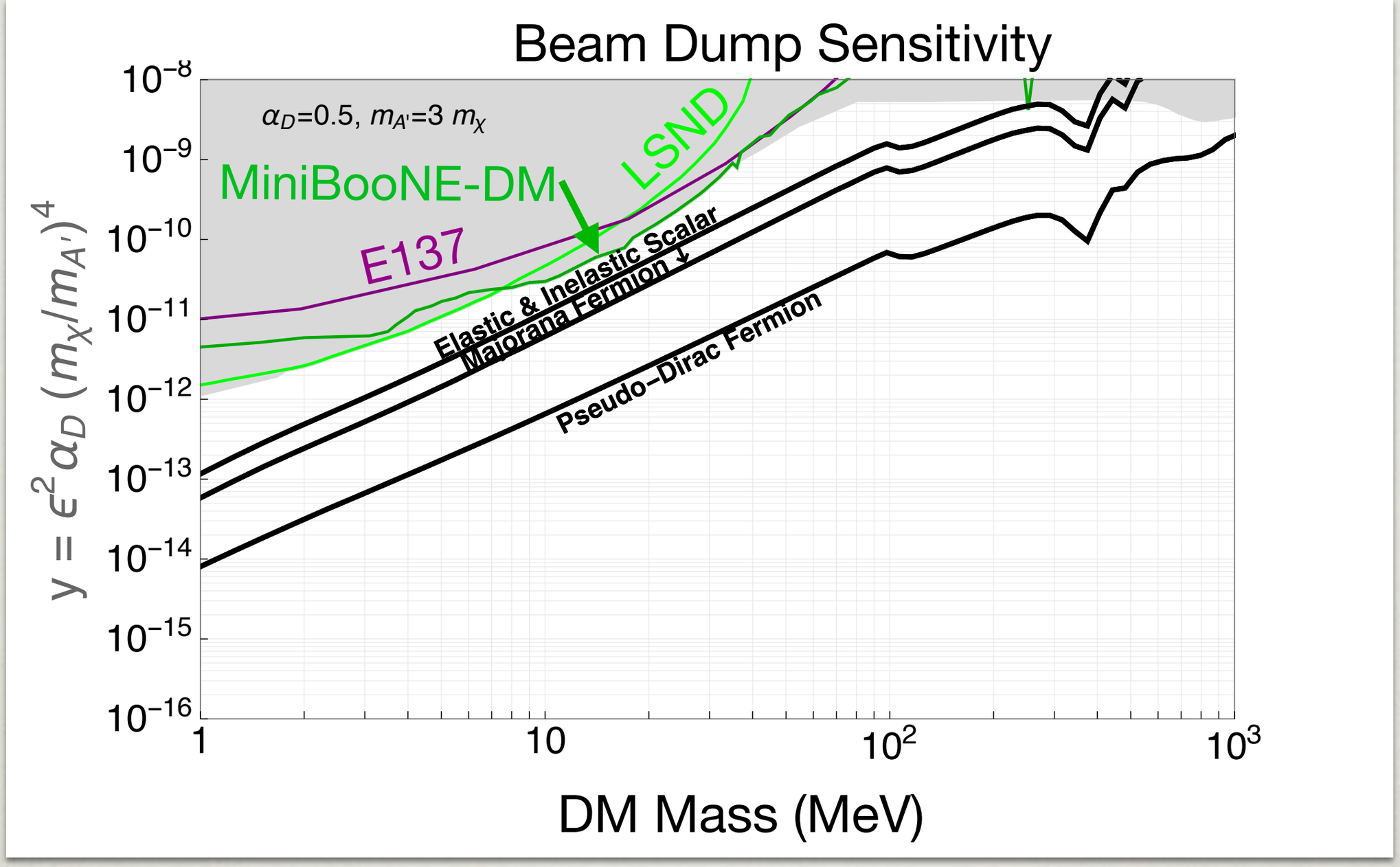
Produce dark matter in dump



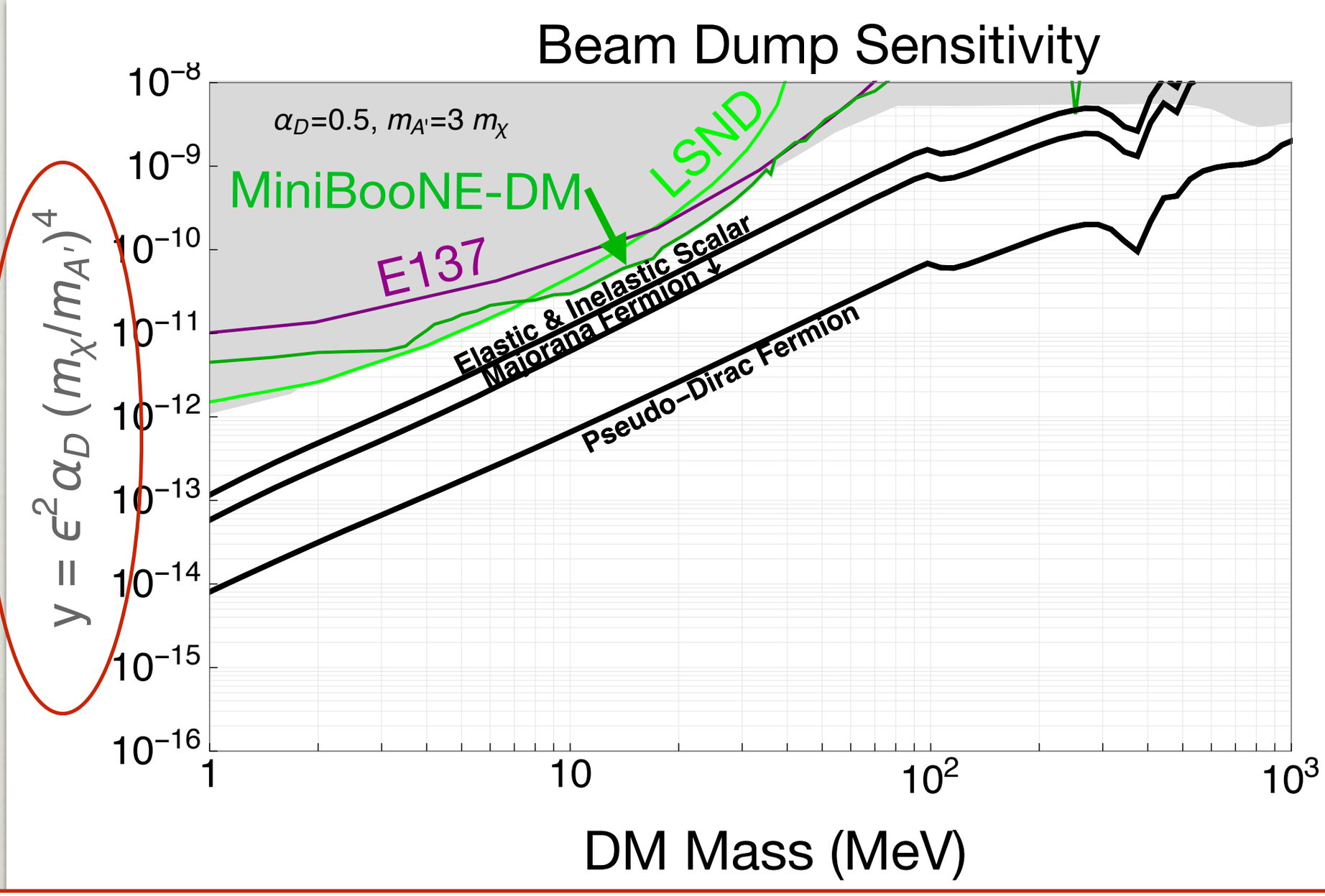
Look for (relativistic) scattering in detector



Dark Matter Beams

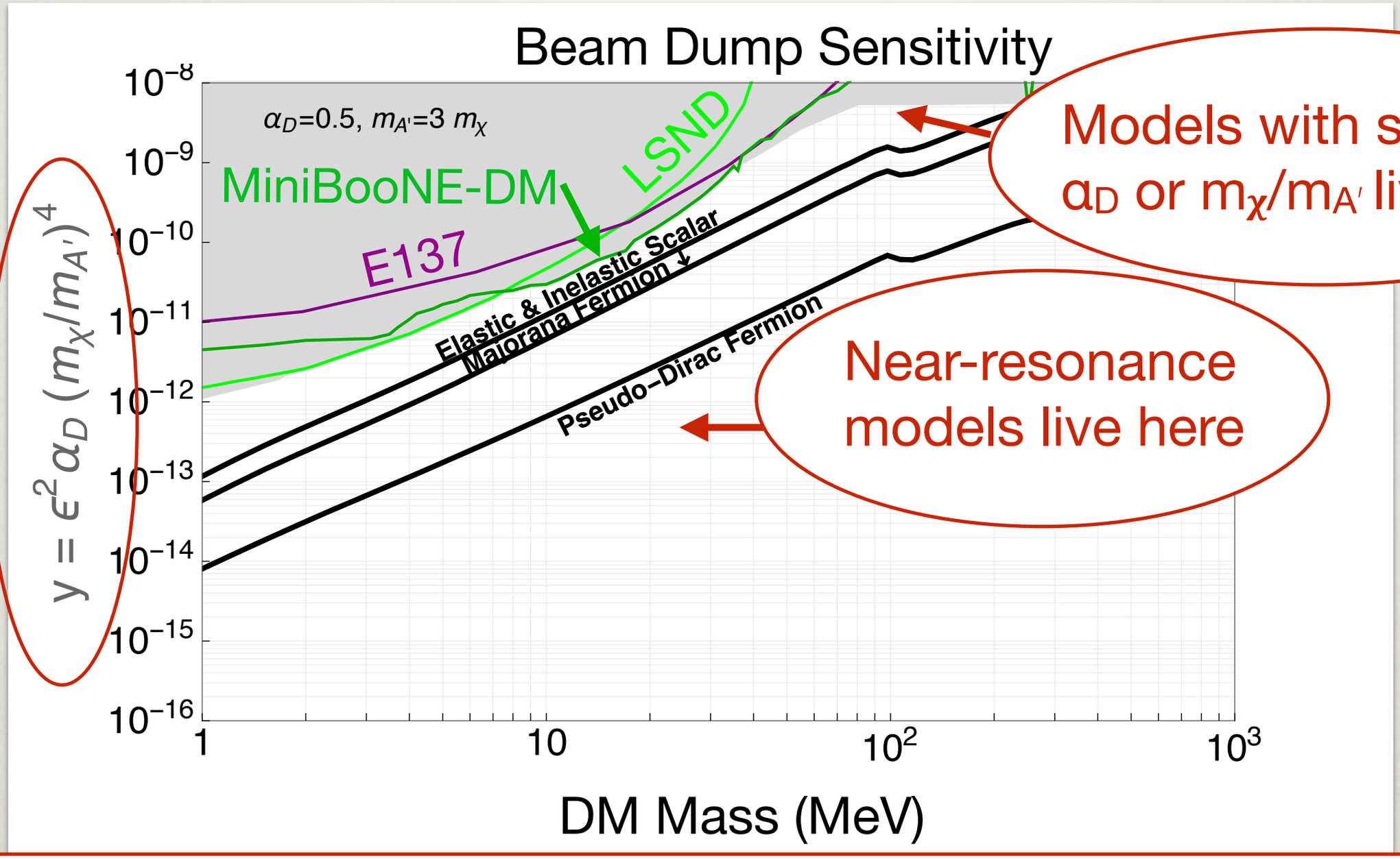


Dark Matter Beams



At given y, yields are **minimized** for large α_D and mass ratio, so take them near model limits → Near-worst-case sensitivity: α_D=0.5, , $m_\chi/m_{A'}$=3

Dark Matter Beams

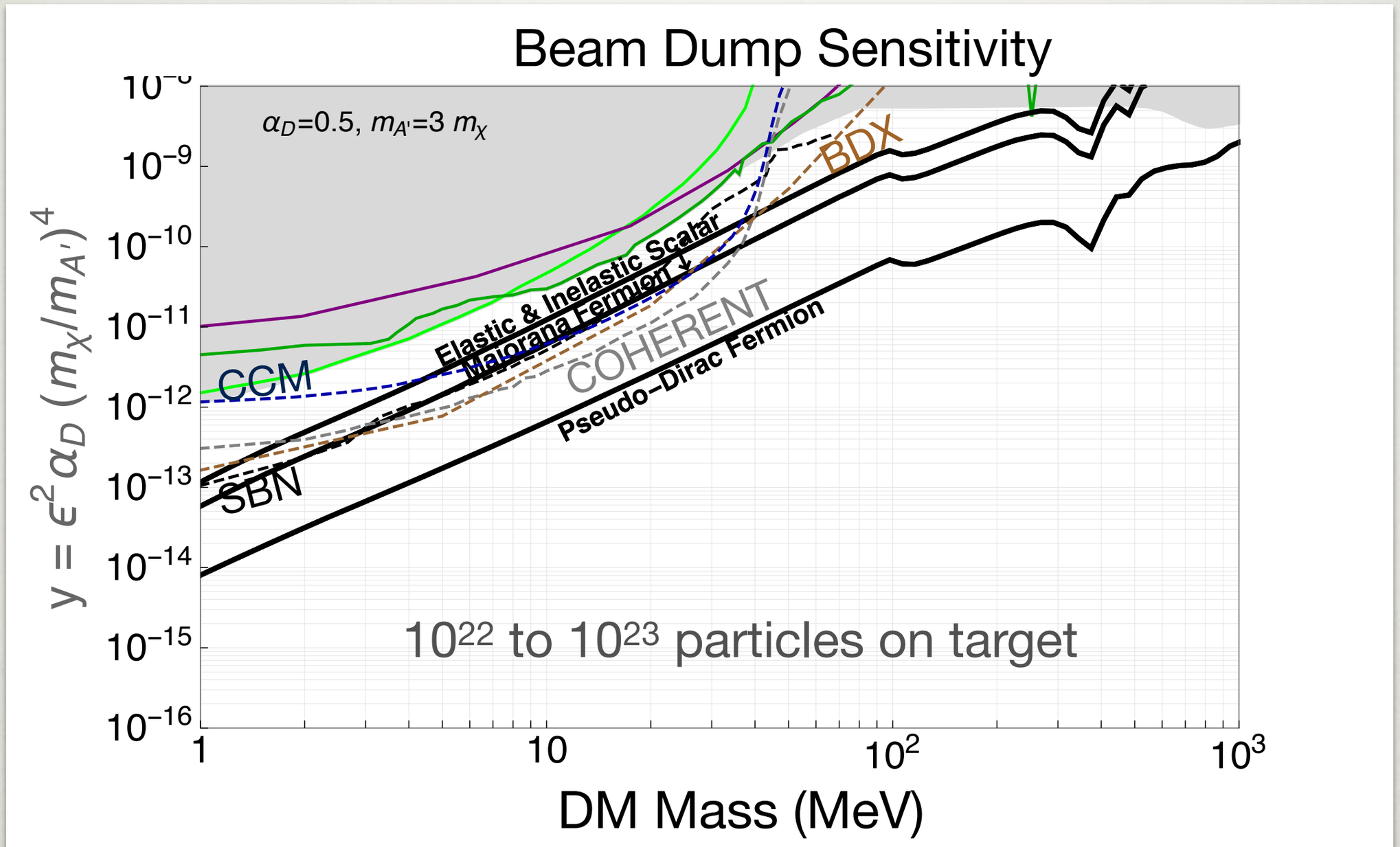


Models with smaller α_D or $m_\chi/m_{A'}$ live here

Near-resonance models live here

At given y, yields are **minimized** for large α_D and mass ratio, so take them near model limits → Near-worst-case sensitivity: α_D=0.5, , $m_\chi/m_{A'}$=3

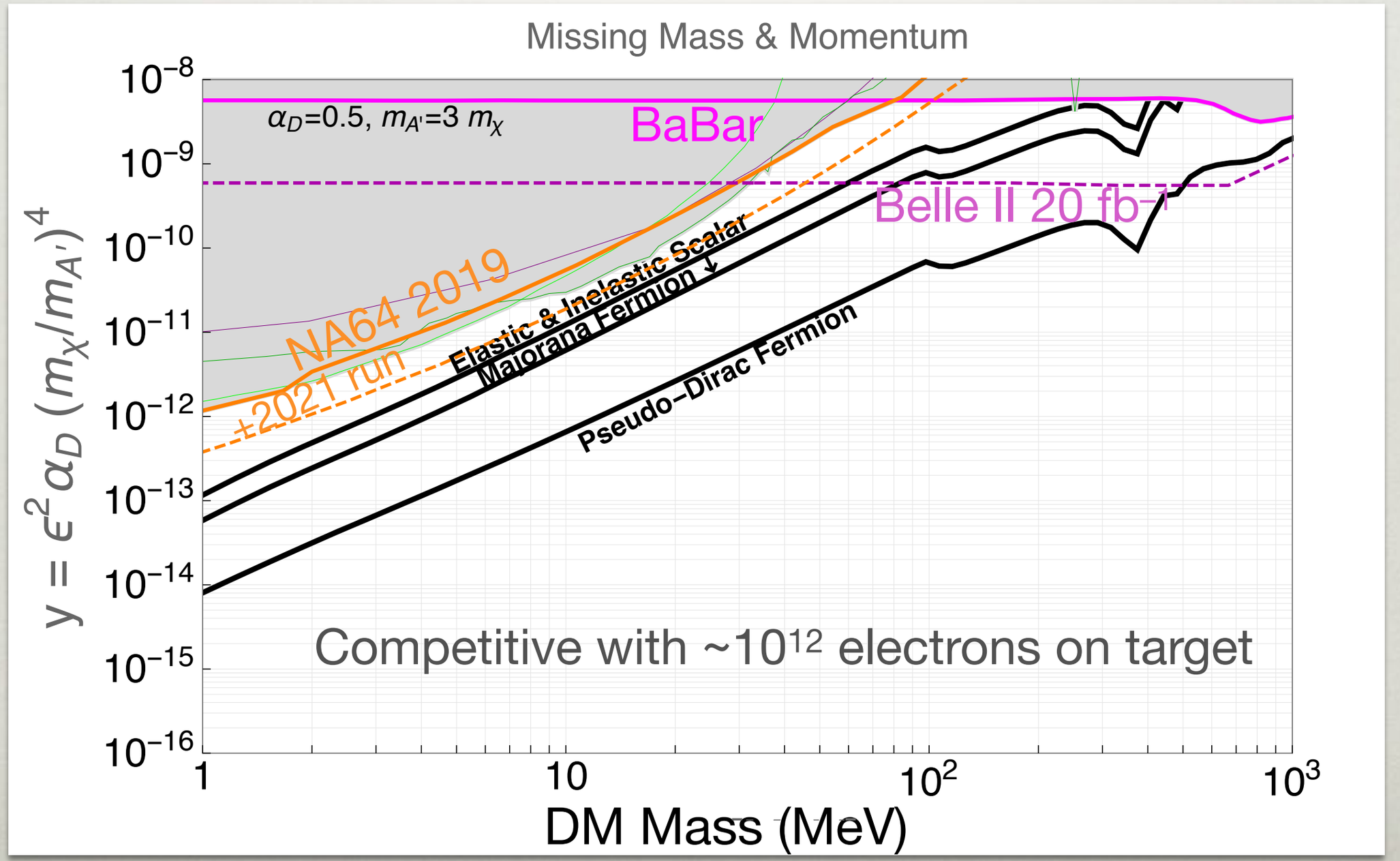
Dark Matter Beams



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

Dark-Matter Production II

- To beat this scaling, must detect O(1) fraction of dark matter production reactions – only possible via **kinematics** of visible final states



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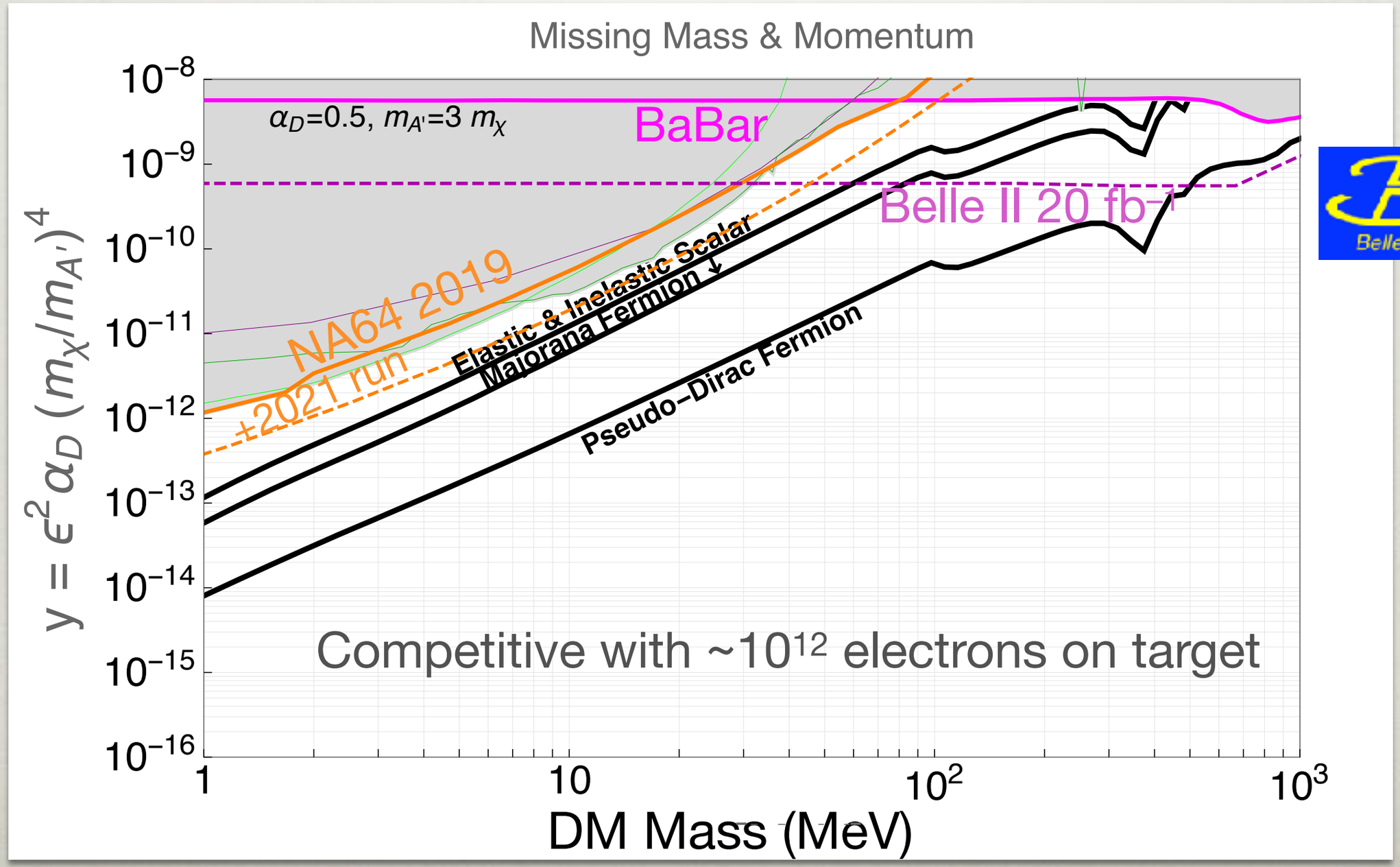

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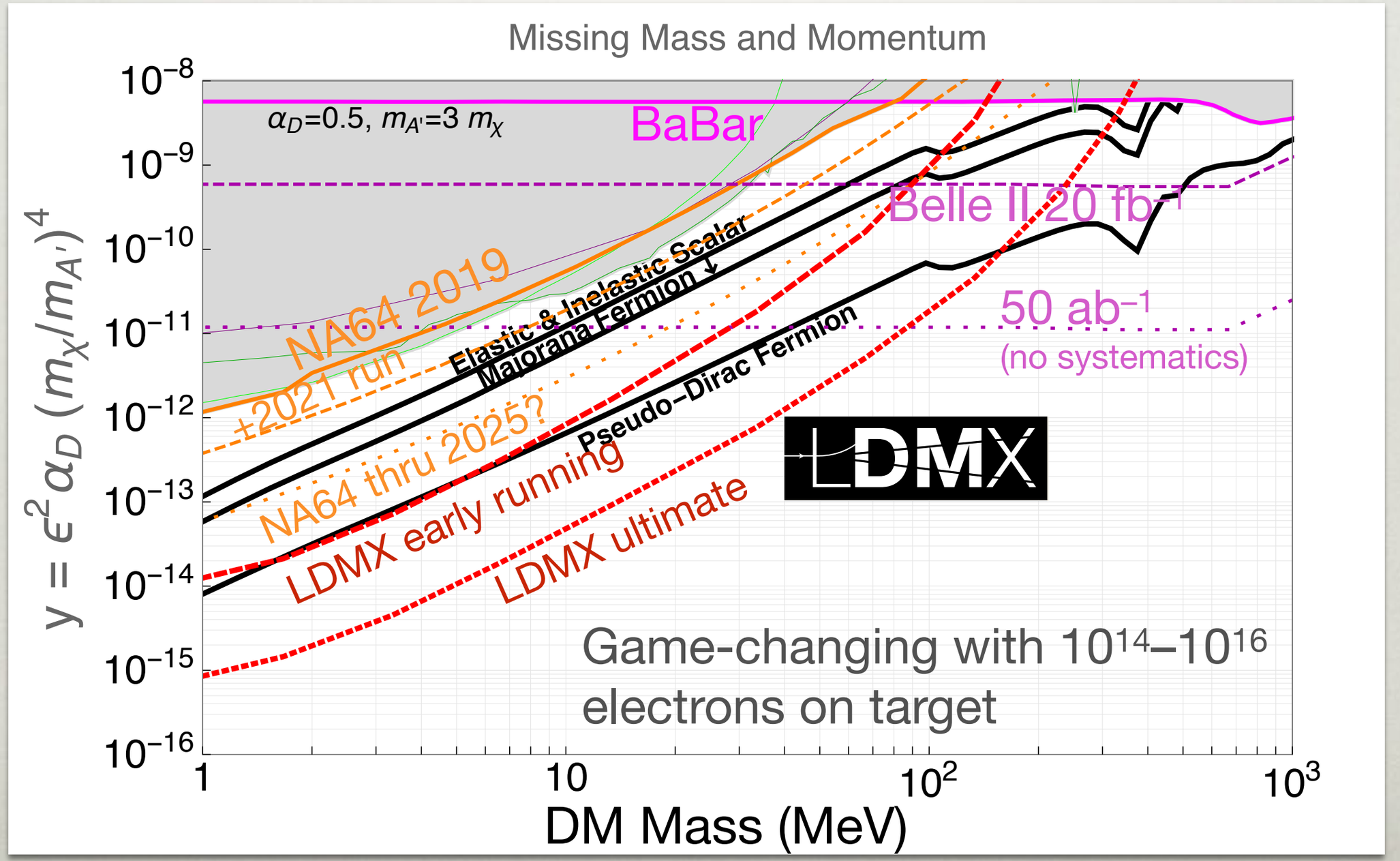

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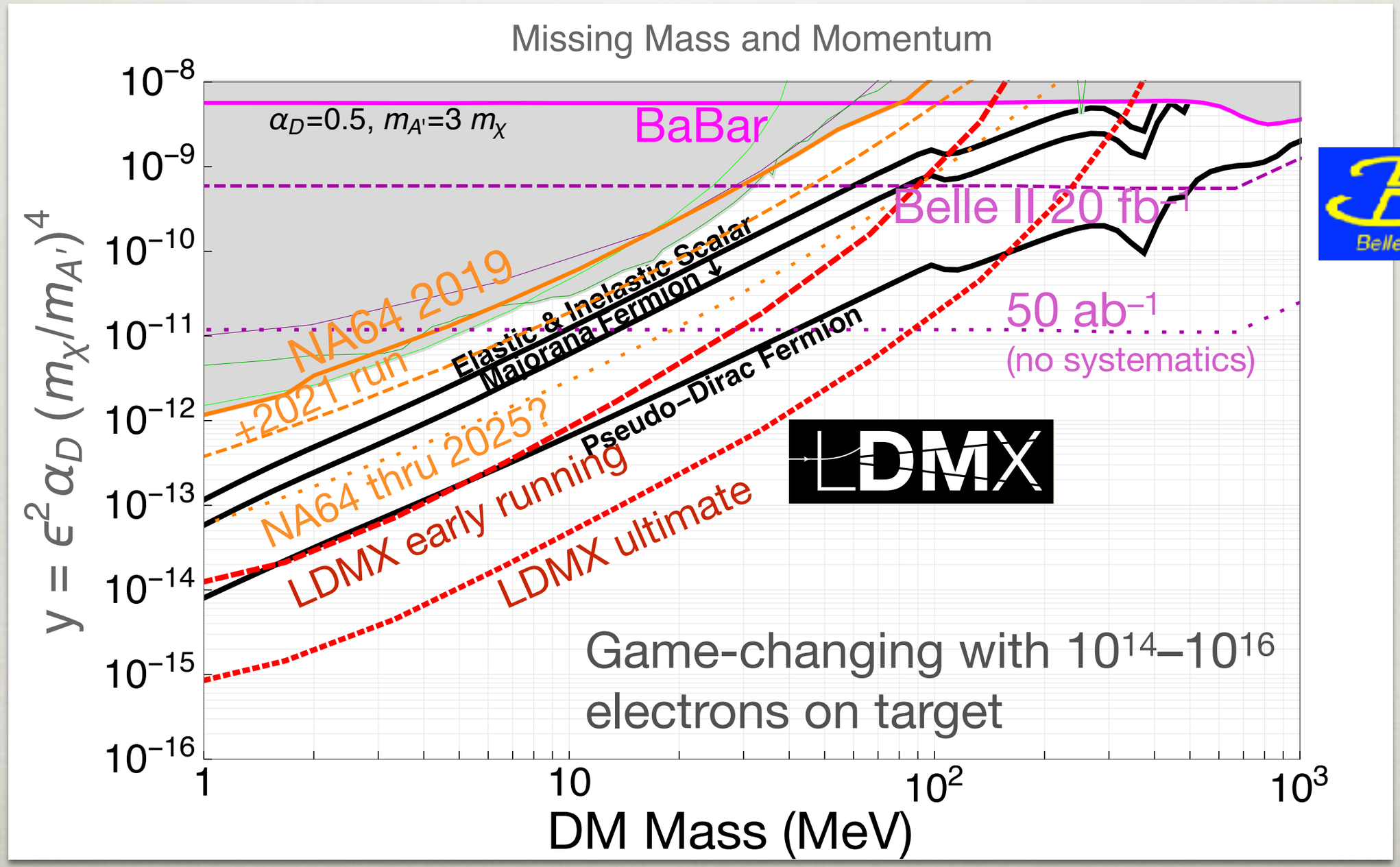
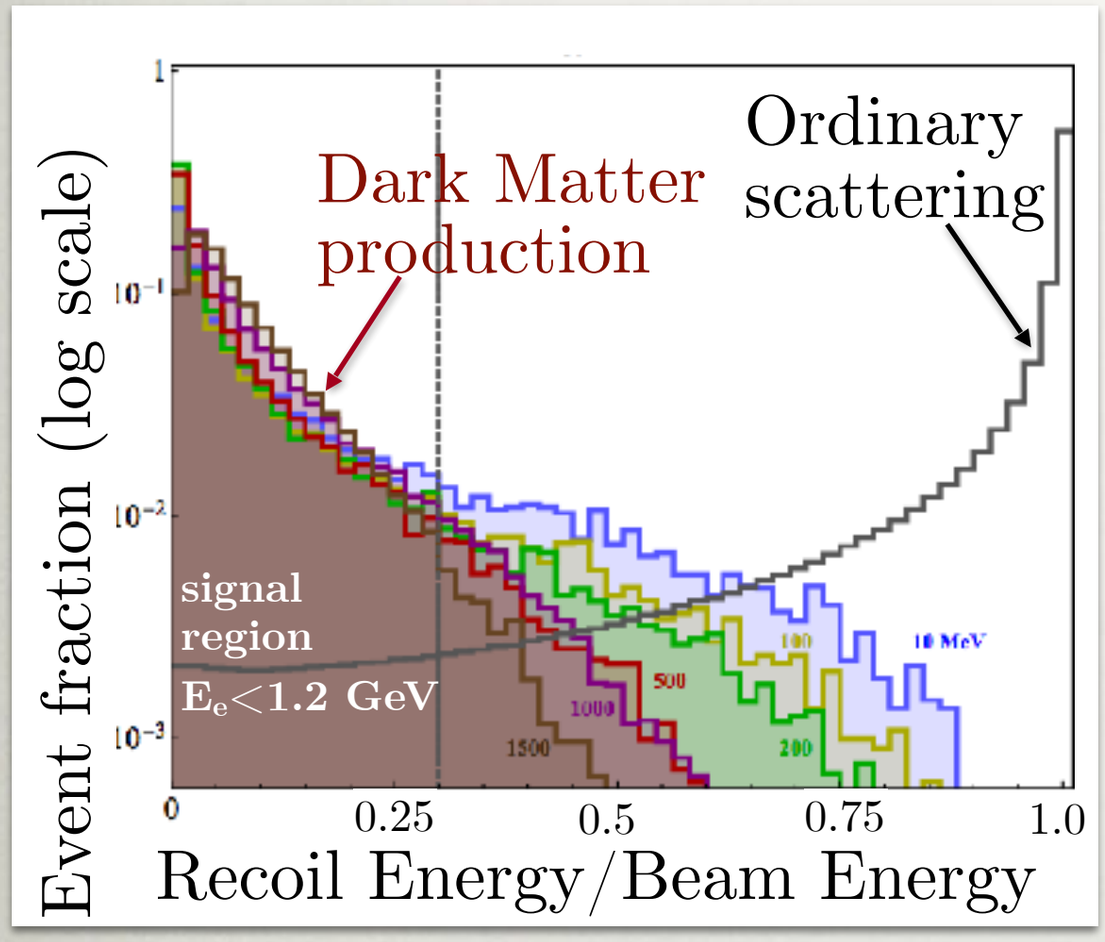
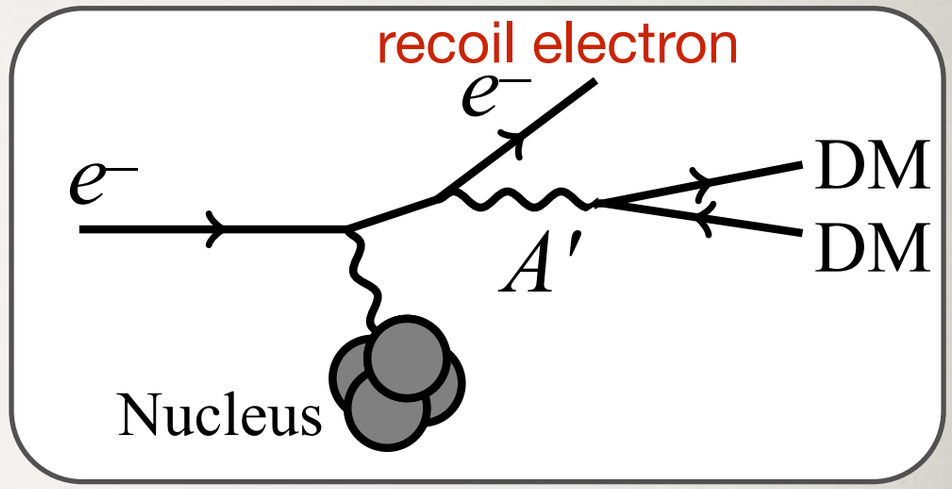
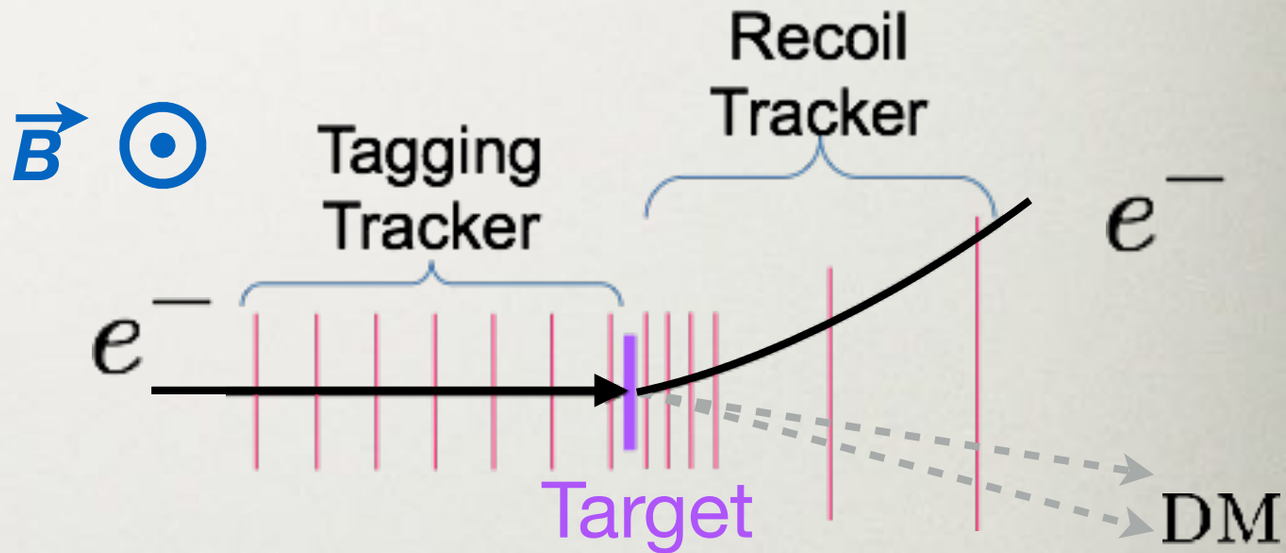


Kinematics

Typically dark matter carries most of the energy, while recoil electron carries little







Tracker design similar to HPS experiment

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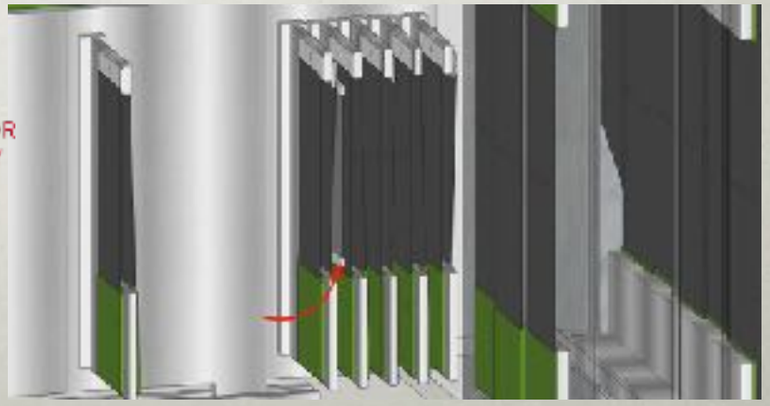

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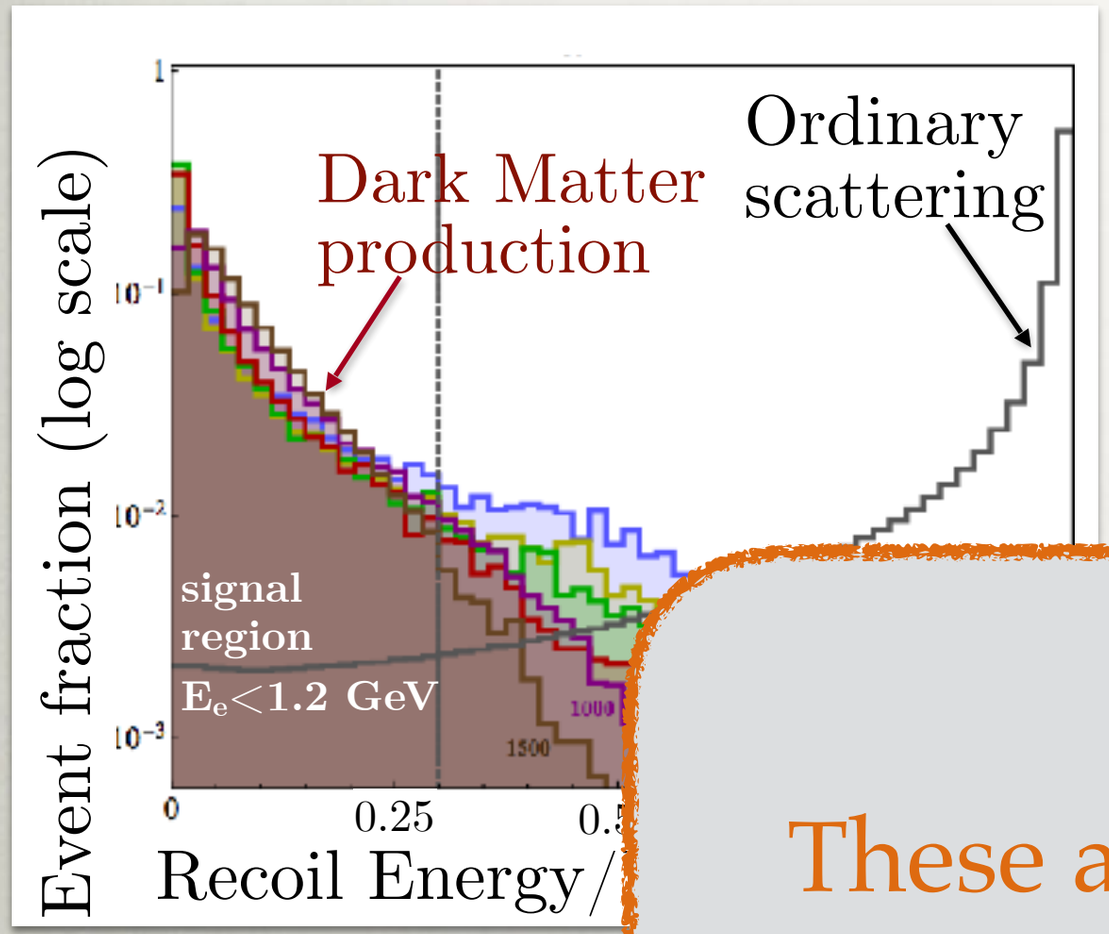
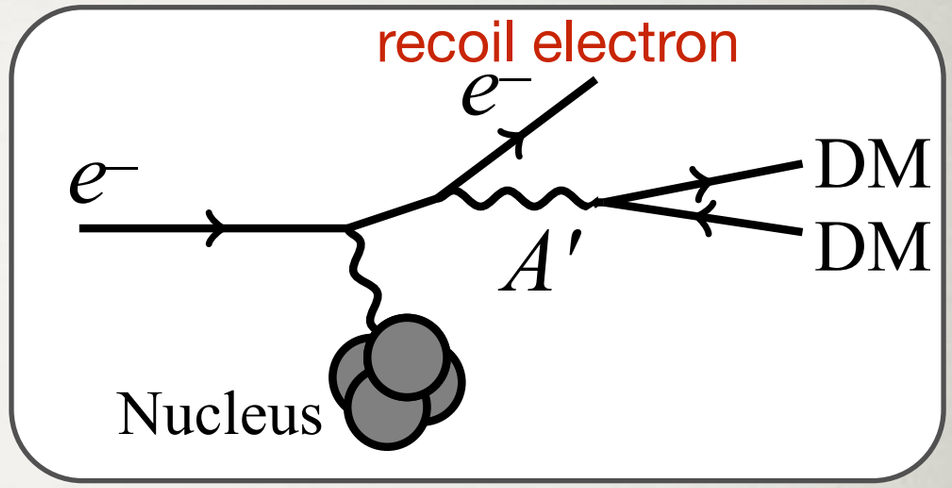
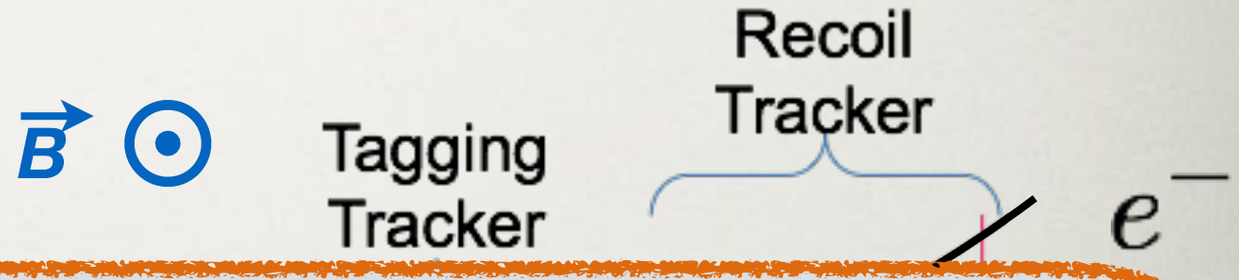


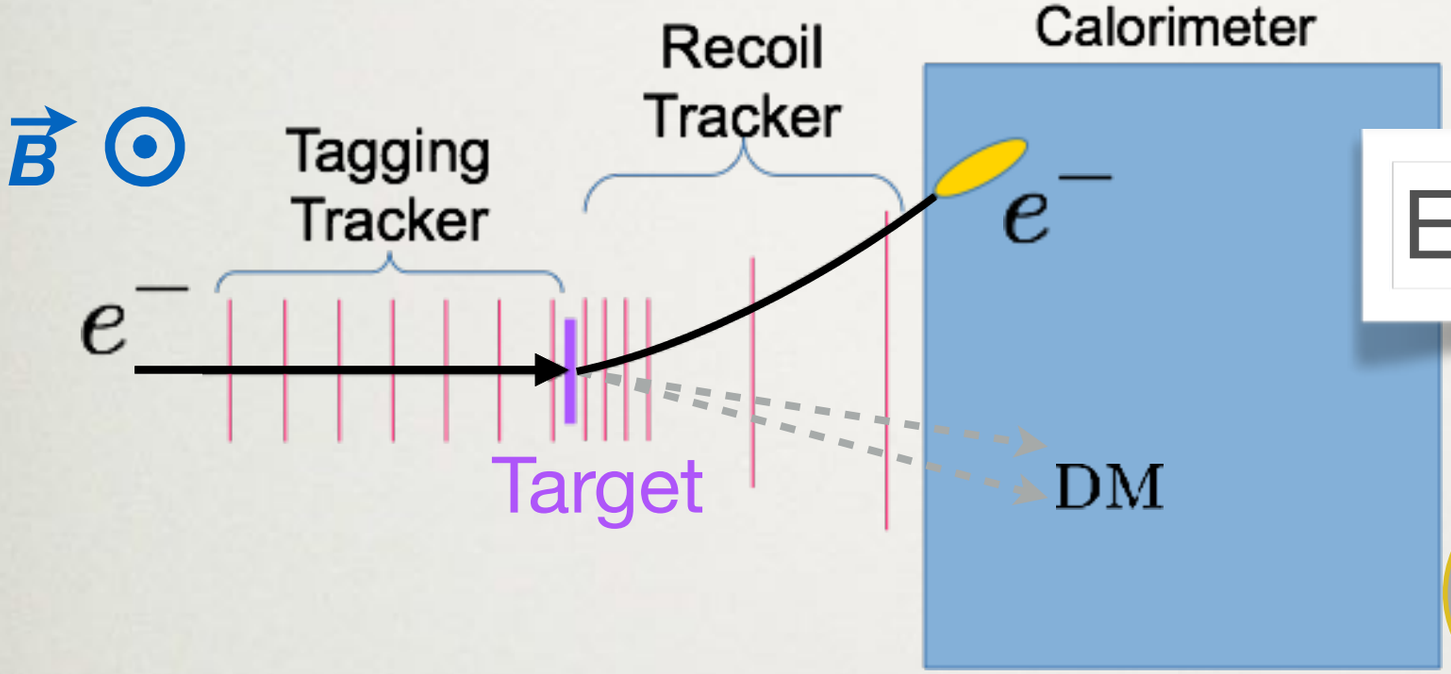




These are fractions – **not** scaled to relative event rates!

LDMX Using Total Energy

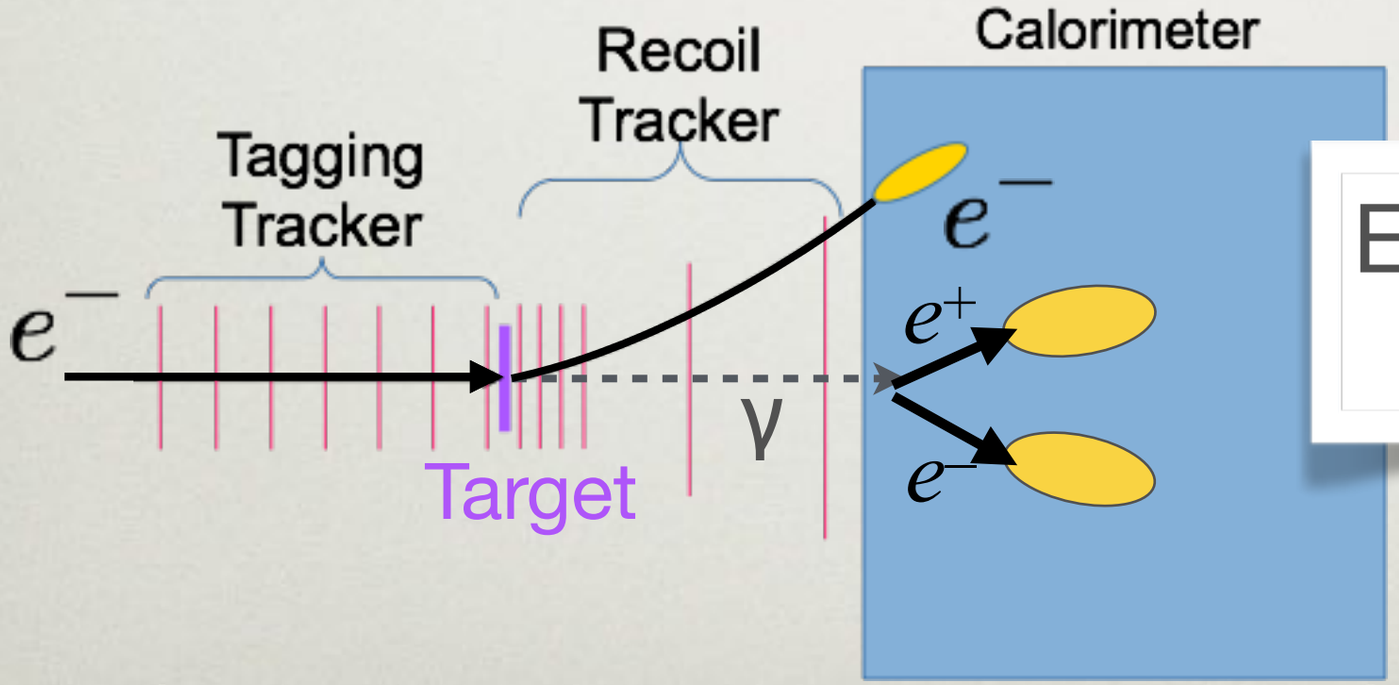
Further filter events by measuring **total energy** of visible products



$E_{total} = E_{recoil} \ll E_{beam}$

Note: transverse separations can be much smaller than shown!

vs.



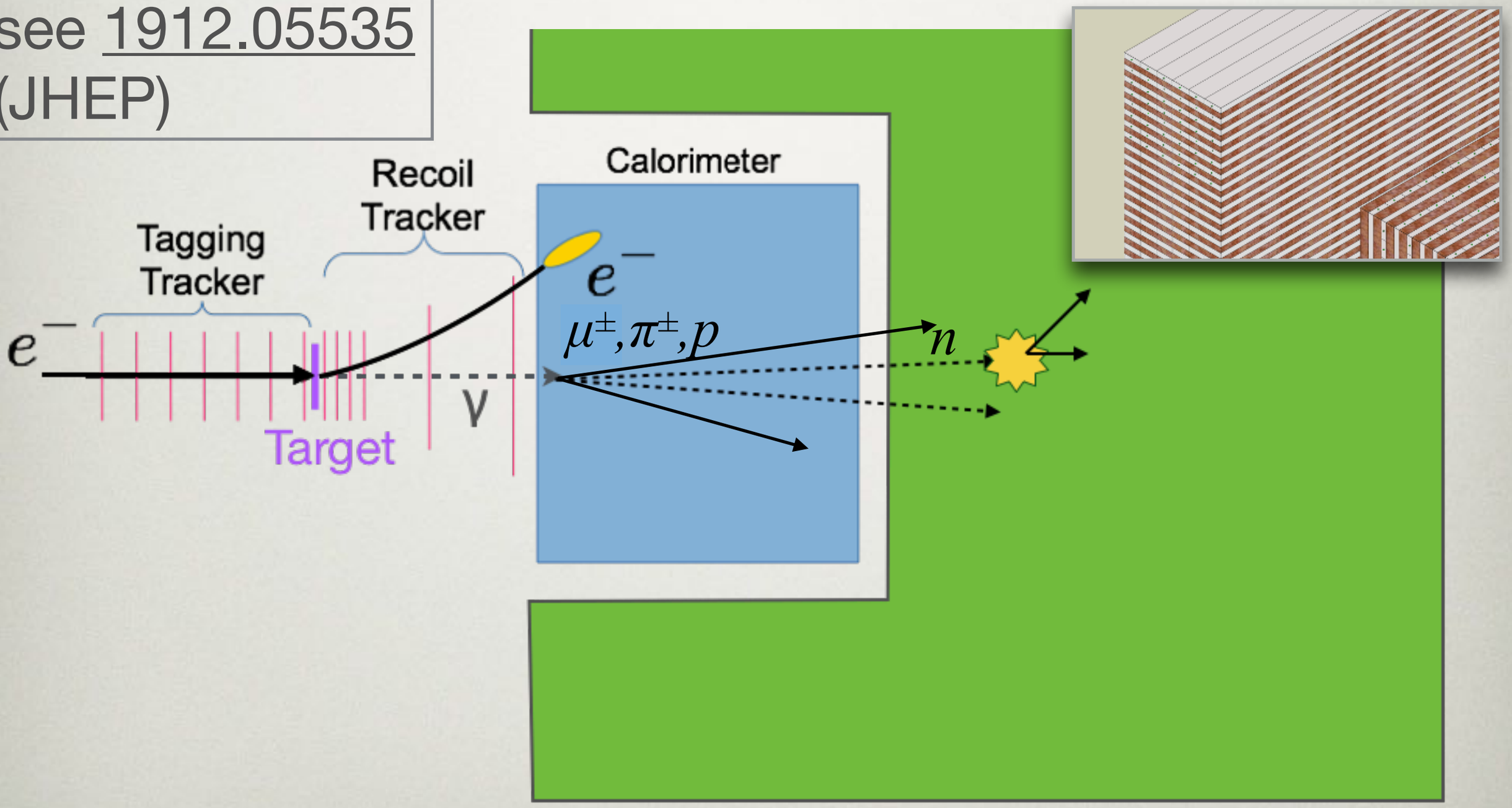
$E_{total} = E_{recoil} + E_{\gamma} \approx E_{beam}$

Trigger on low energy deposition → ~400 Hz of DM-like events from ~25 MHz of bunches.

LDMX Finding Rare Reactions

Low-energy events due to rare photon reactions (photonuclear or conversion to muons) that transfer energy to hadrons or muons

see 1912.05535 (JHEP)



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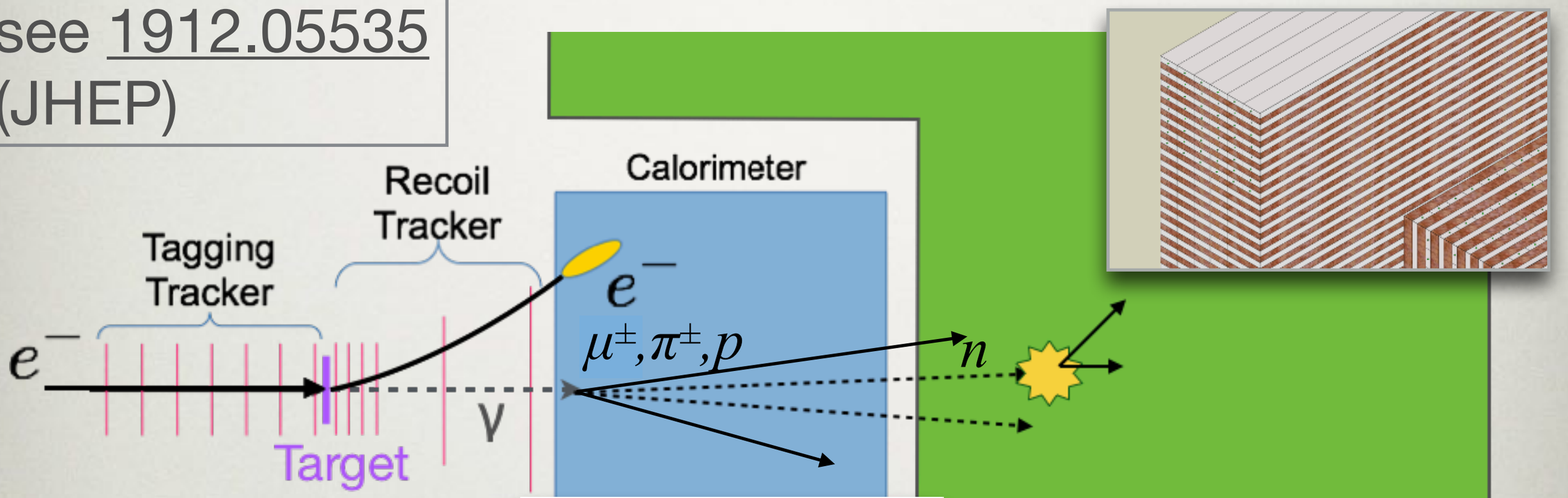
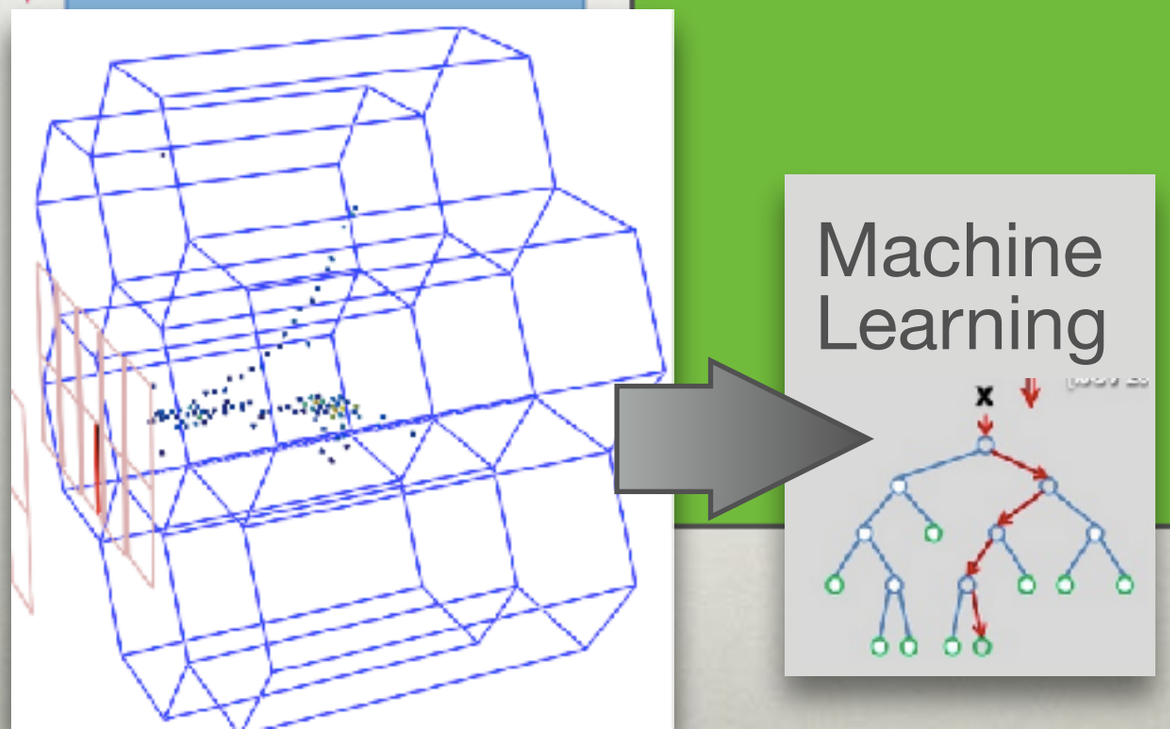


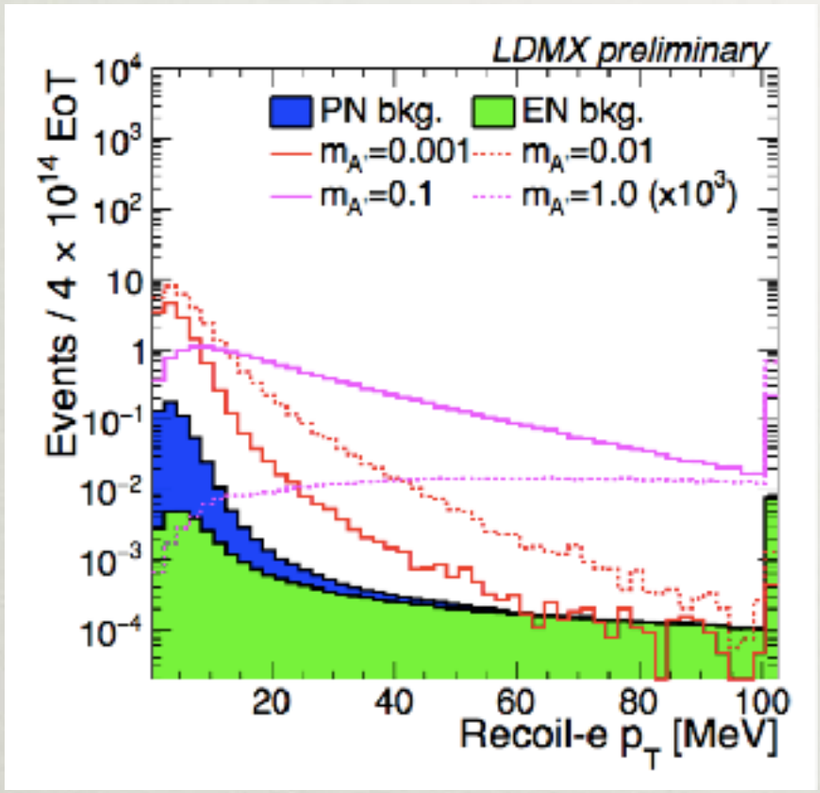
Granular ECal rejects such events based on distinctive features, e.g. tracks, “wide” or “long” showers



A Final Handle

Built into LDMX is the idea that it should be more than a counting experiment.

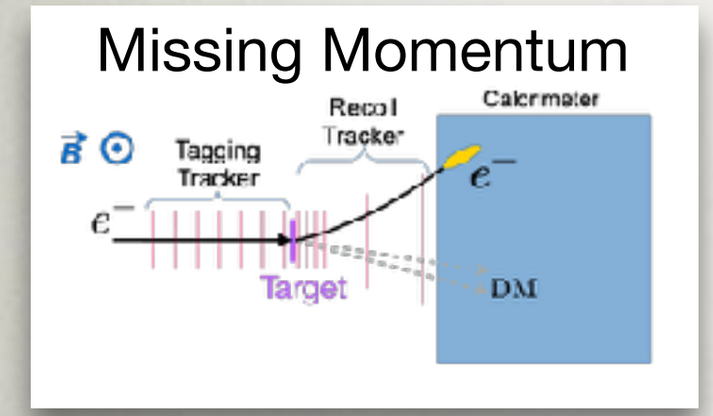
A key final measurement is the “transverse momentum” (perpendicular to beam) of the recoil electron



Gives confidence in signal, and an estimate of mass scale for dark matter physics!

Towards Precision Dark Matter Science

Very real possibility of studying the physics of the dark sector – especially with multi-experiment program.



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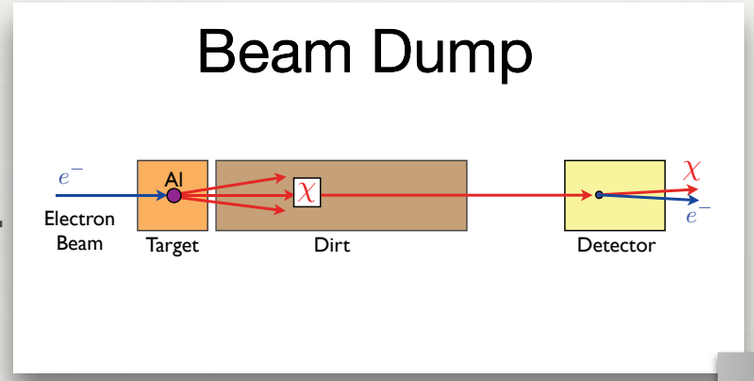

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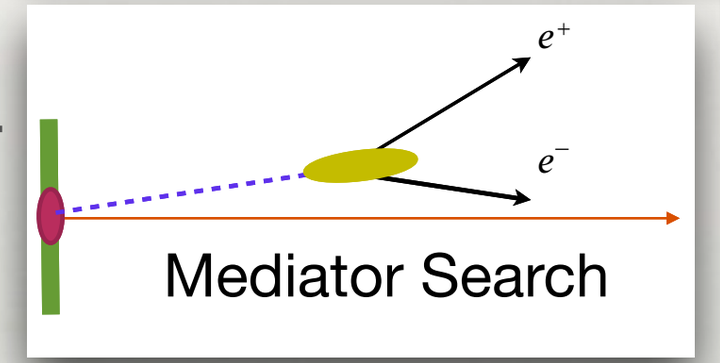
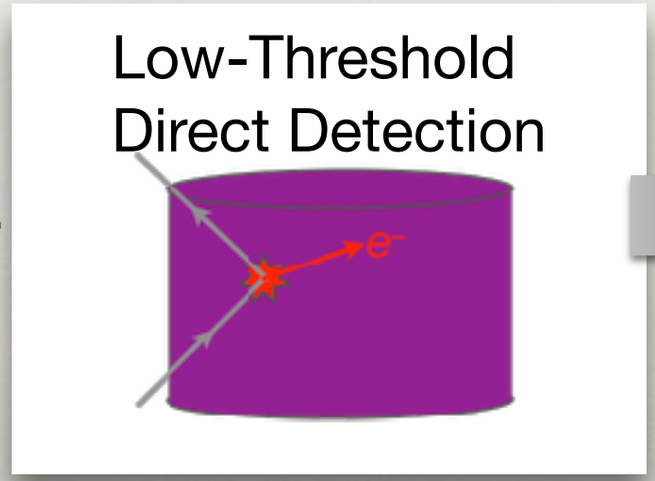


- Dark Matter and force-carrier mass
- Effective charges of Dark Matter and ordinary matter

+



- Abundance
- Cosmological lifetime
- Spin

Conclusions

- The identity of dark matter is a stark open question in fundamental physics
- Hidden sector DM modestly extends WIMP dark matter, offers sharp science case to explore new physics at familiar scales with unprecedented precision
- Powerful discovery potential for several complementary experimental approaches
- Motivates new experiments underground, at colliders, and at fixed-target facilities