Producing Light Dark Matter at Fixed Target Experiments

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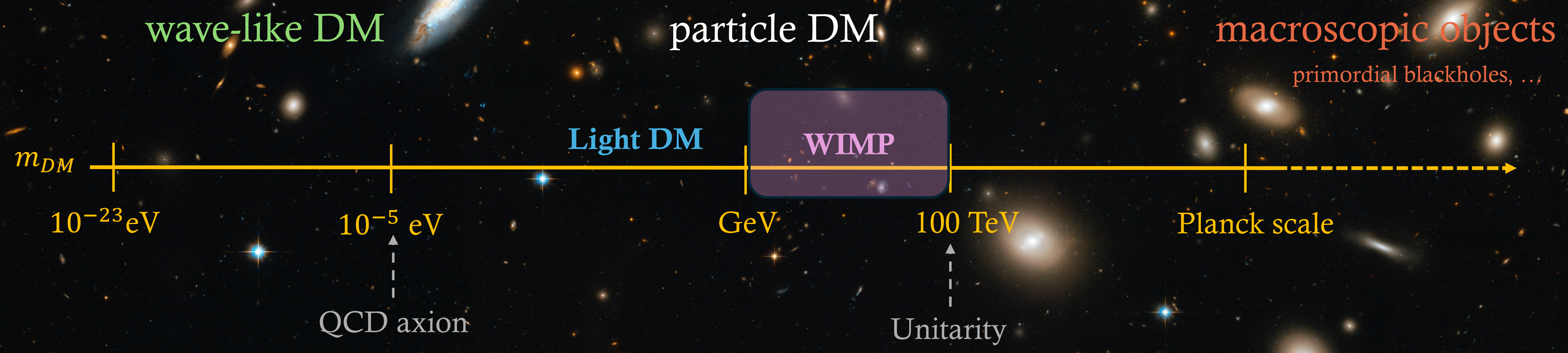
Partikeldagarna 2025

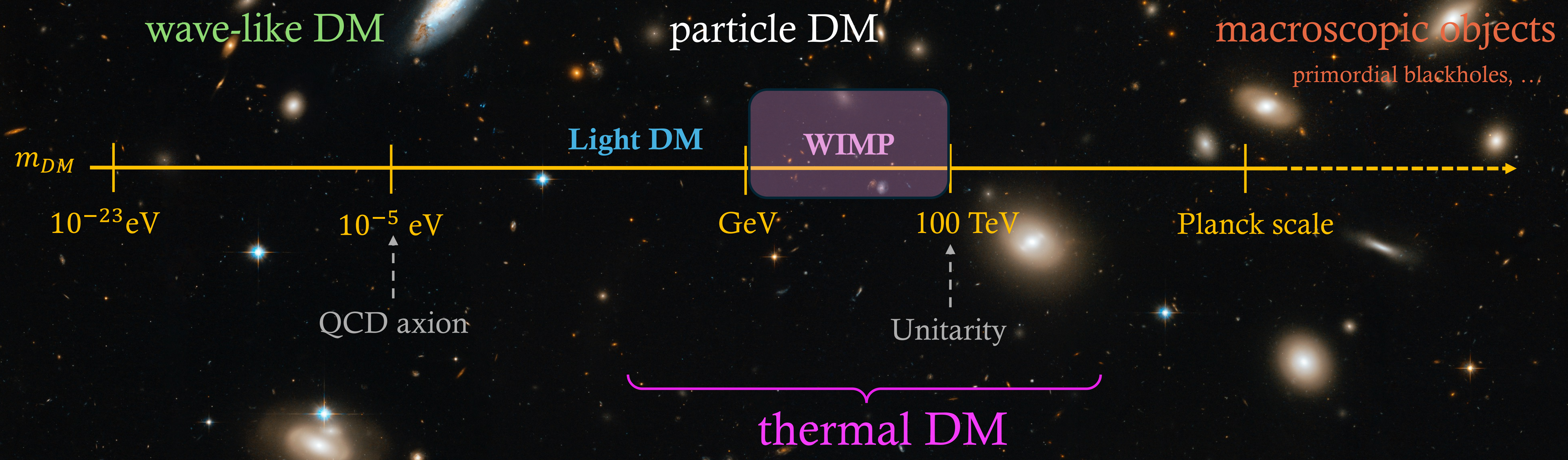
Knut and Alice Wallenberg Foundation

CHALMERS UNIVERSITY OF TECHNOLOGY

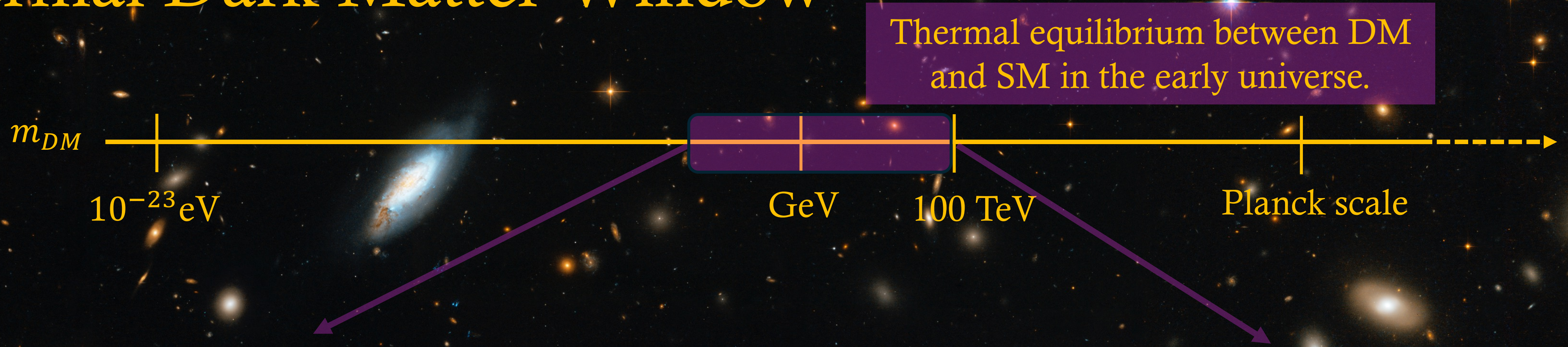
What is the *Dark Matter* made of?



What is the *Dark Matter* made of?

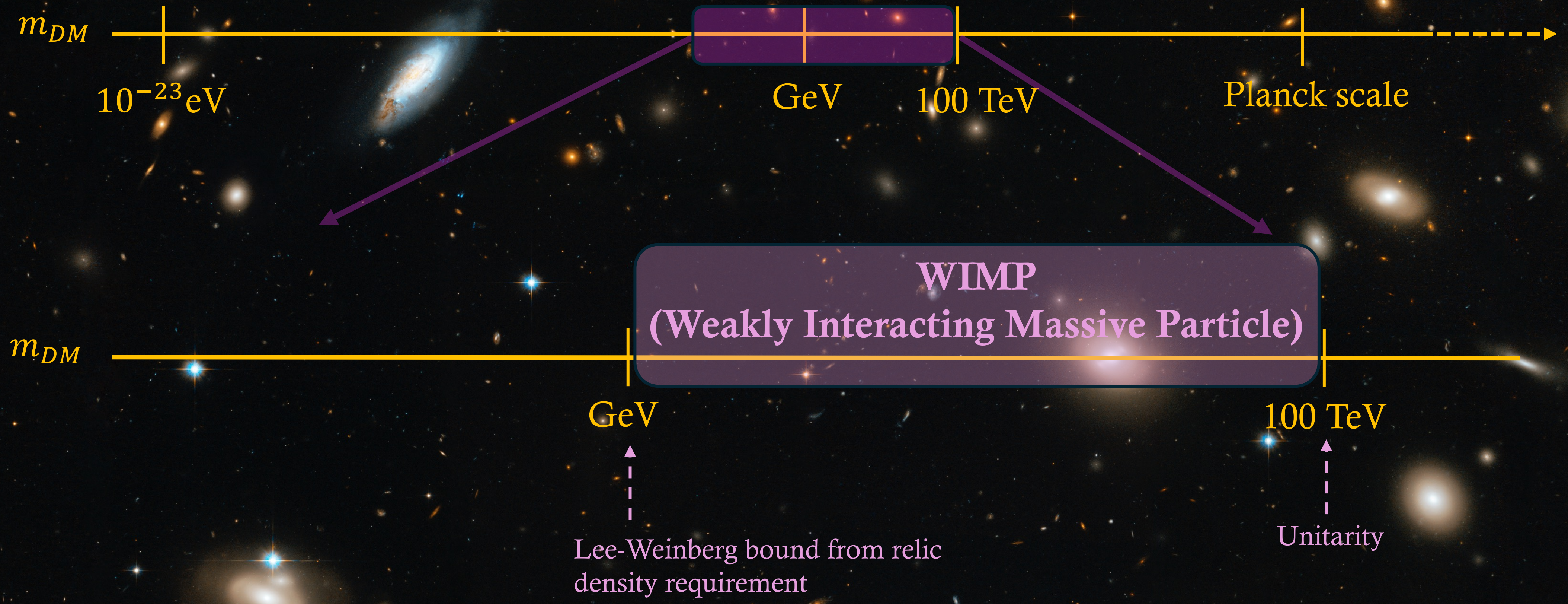


Thermal Dark Matter Window



Thermal Dark Matter Window

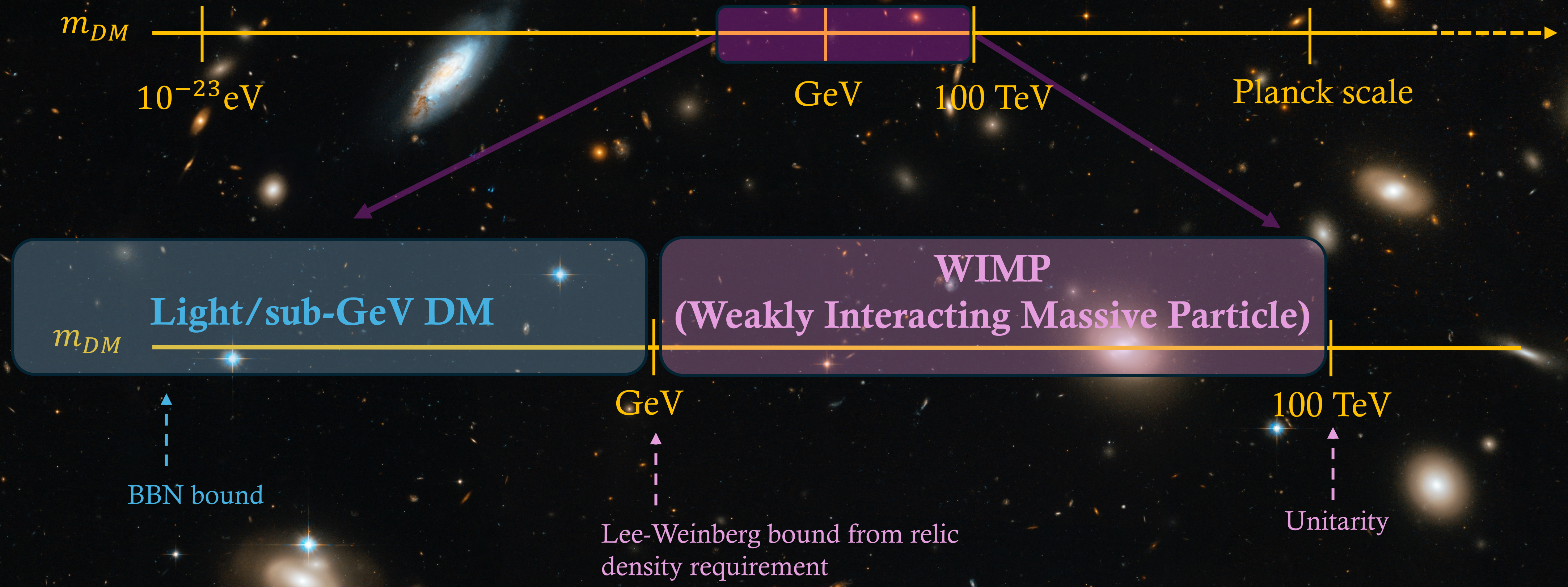
Thermal equilibrium between DM and SM in the early universe.



- DM interacts via the weak force near the weak scale
- Widely tested by direct detection experiments

Thermal Dark Matter Window

Thermal equilibrium between DM and SM in the early universe.



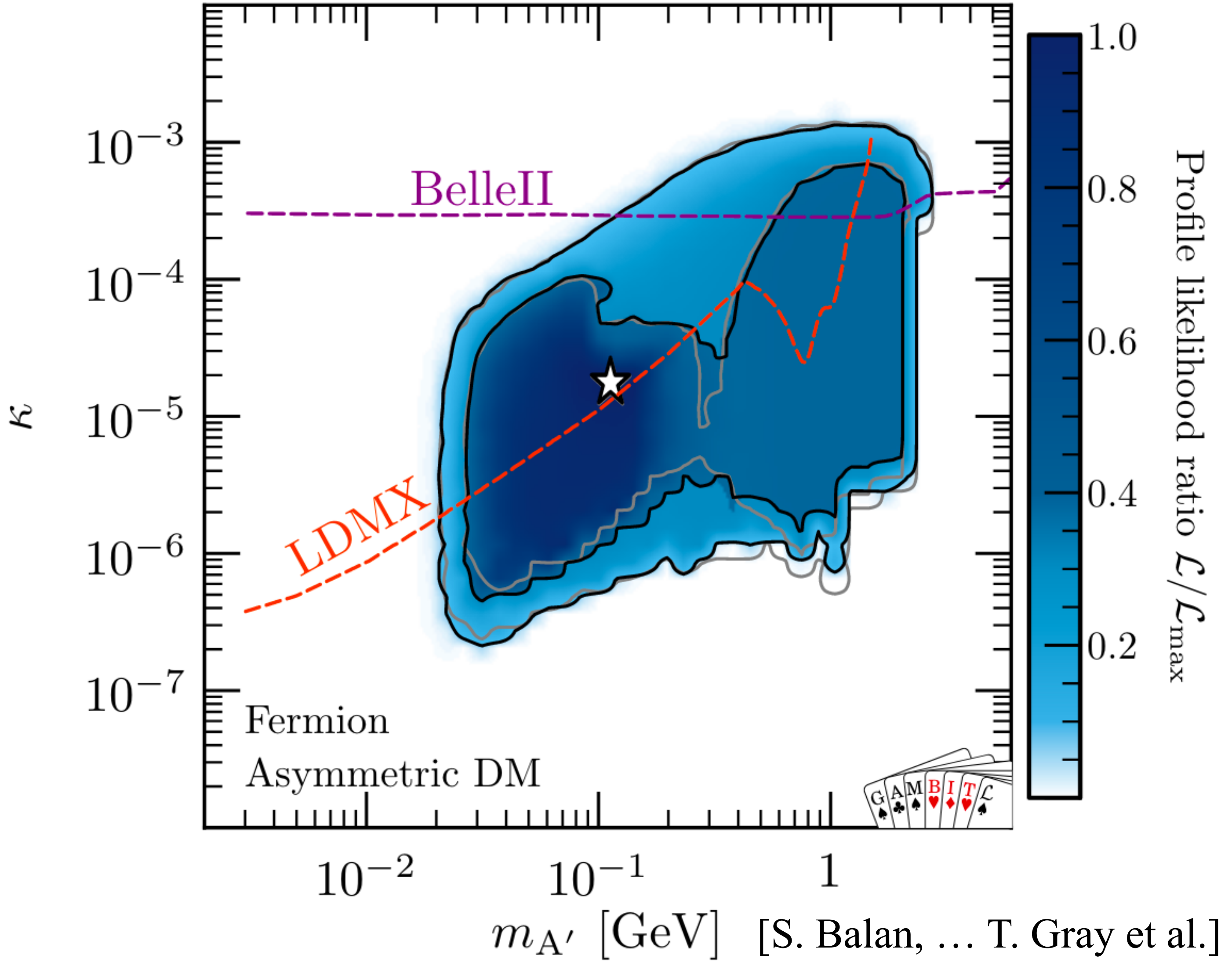
- Evade LW bound by introducing a **new mediator**
- DM too light to deposit sufficient energy in nuclear recoils

See Theresa Backes' talk!

- DM interacts via the weak force near the weak scale
- Widely tested by direct detection experiments

Light Dark Matter Status

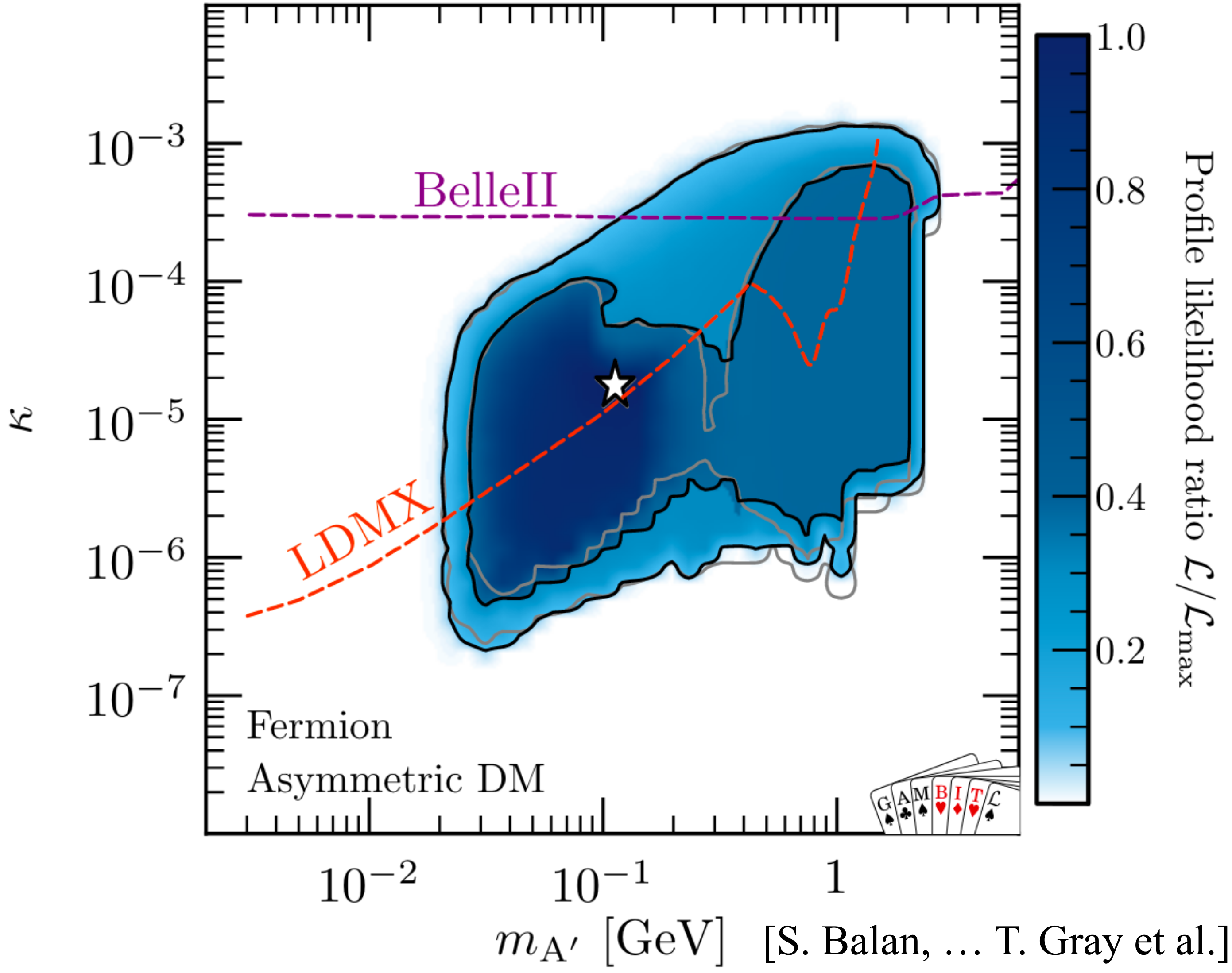
Frequentist Global Fits



[S. Balan, … T. Gray et al.]

Frequentist Global Fits

LDMX will probe **64%** of posterior volume!



[S. Balan, … T. Gray et al.]

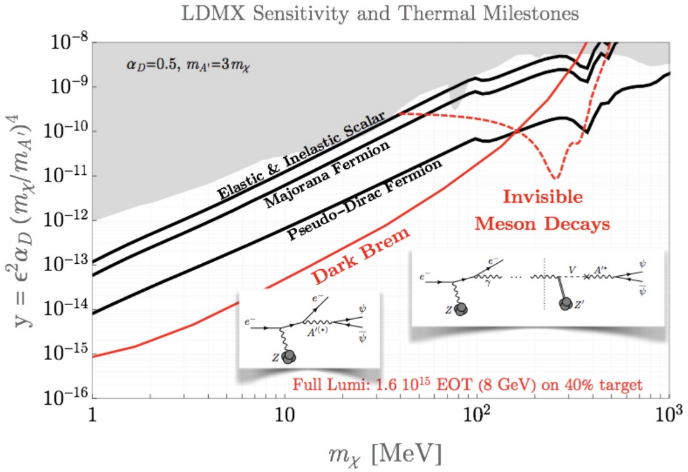
Light Dark Matter Status

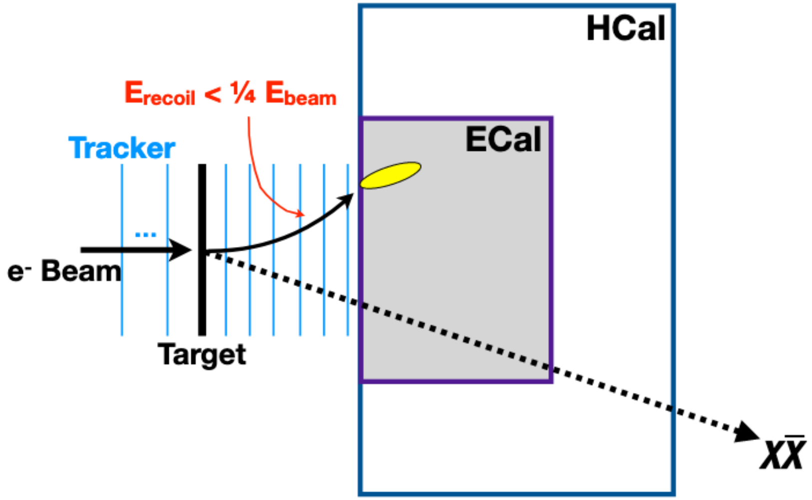
See talks by ***Clay Barton*** and ***Andreas Pettersson and Verena Hehl***!

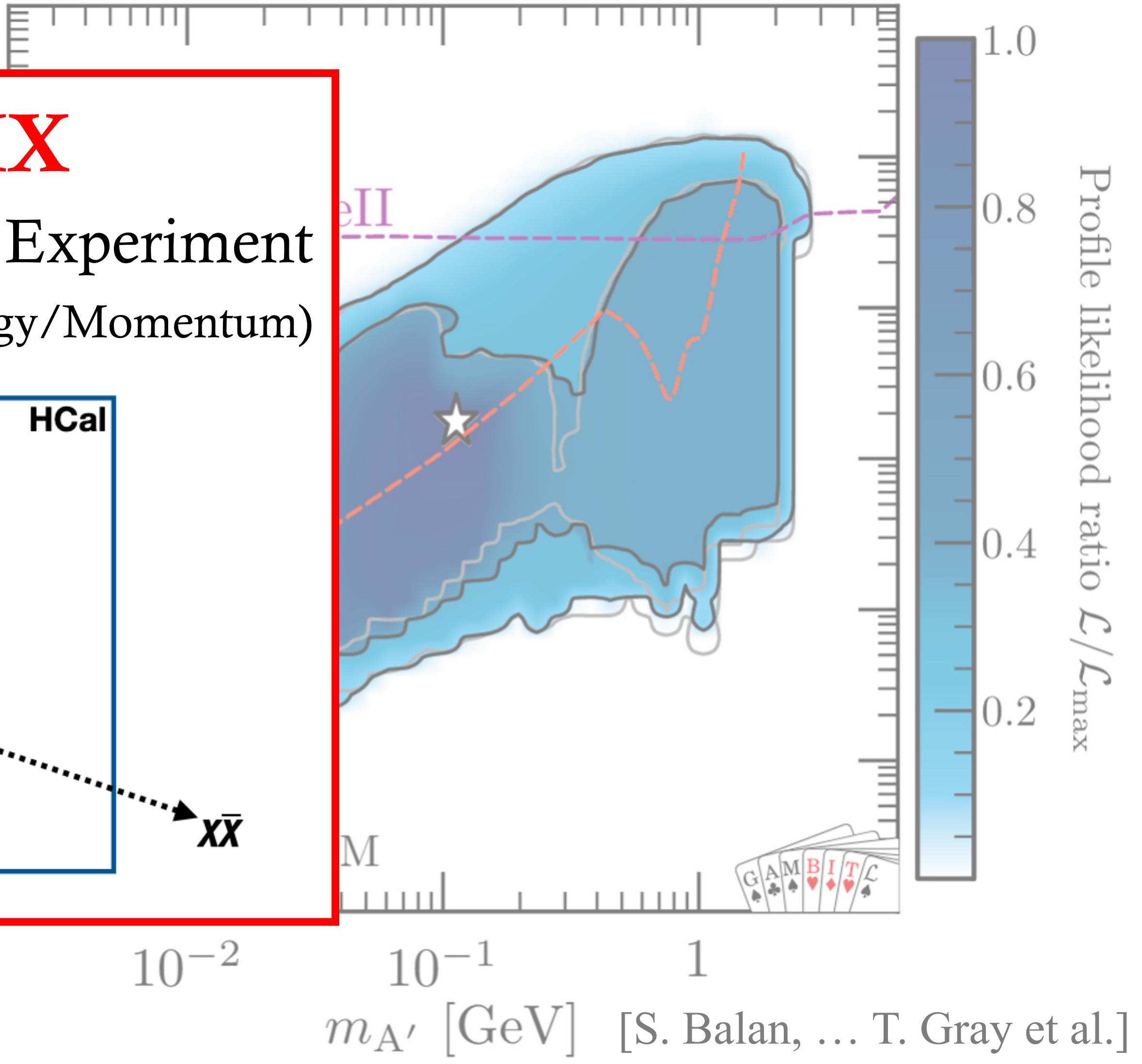
LDMX

Future Fixed-Target Experiment

(Missing Energy/Momentum)

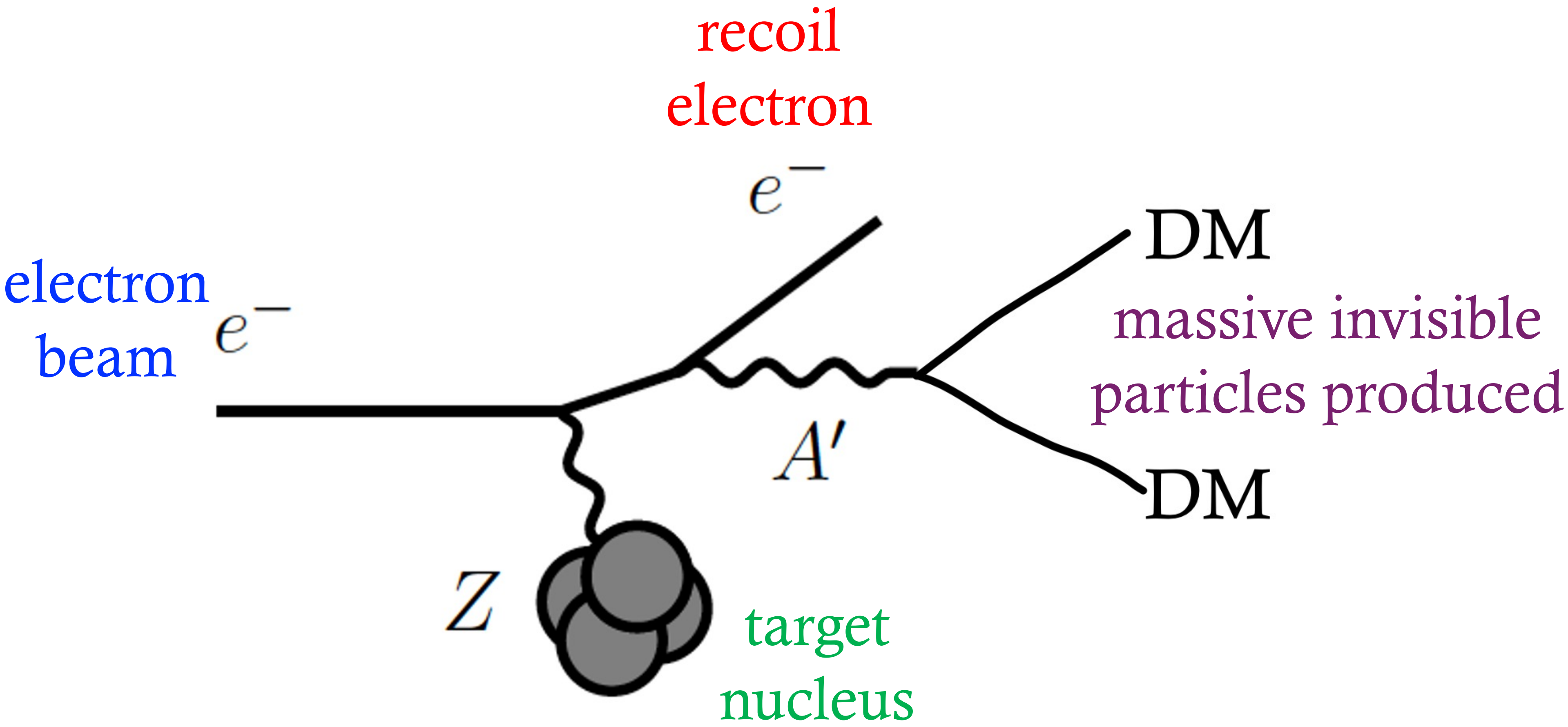






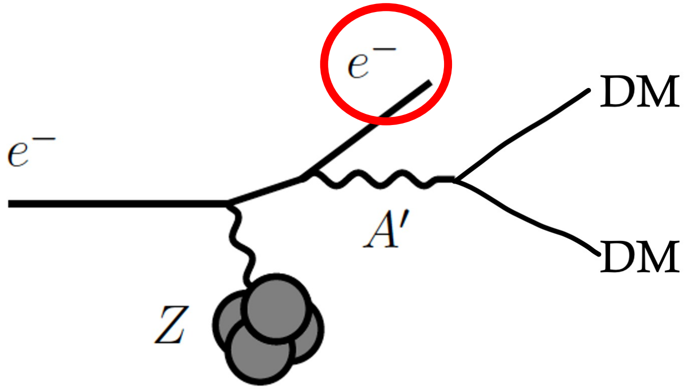
[S. Balan, … T. Gray et al.]

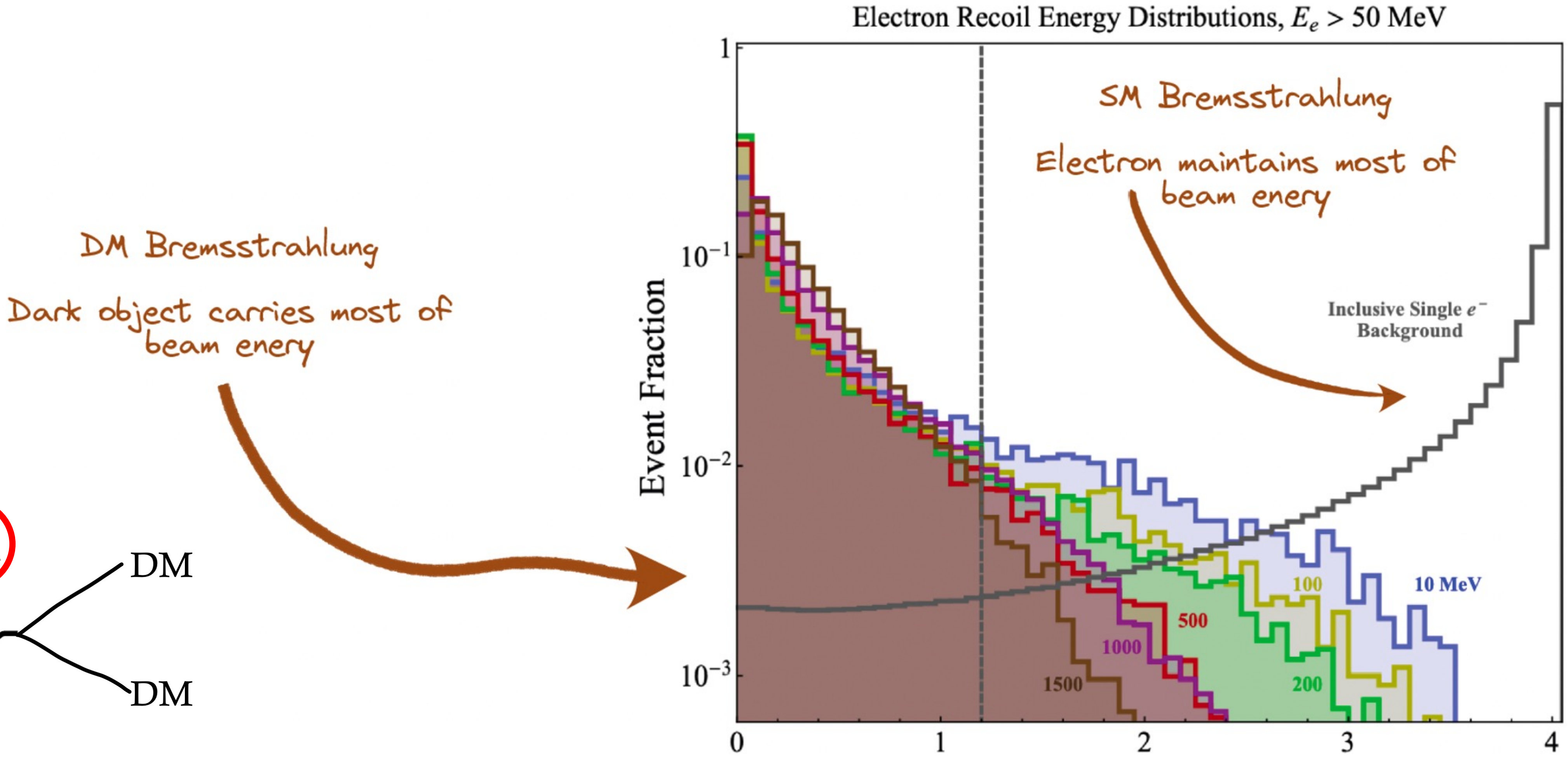
LDMX: Light Dark Matter EXperiment



LDMX: Light Dark Matter EXperiment

Recoil e^- *Energy*





[slide from E. Elén]

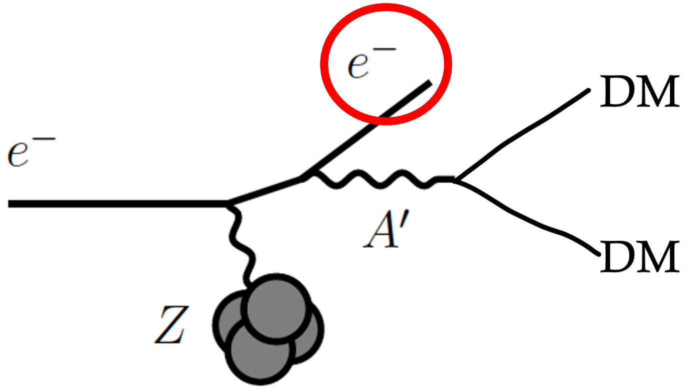
[T. Åkesson et al.]

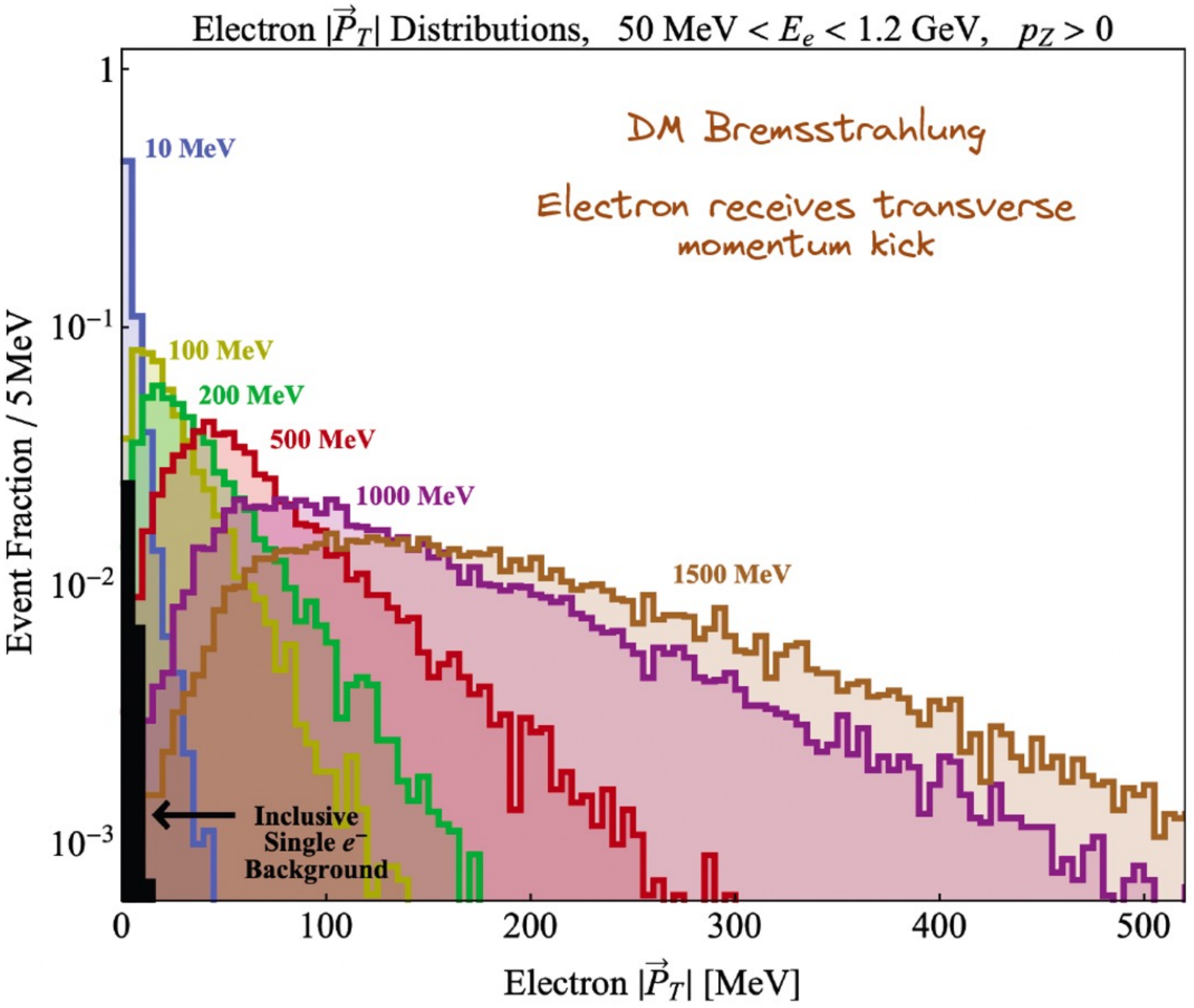
LDMX: Light Dark Matter EXperiment

Recoil e^-
Transverse Momentum p_T

SM Bremsstrahlung

Electron continues with small scattering angle





[slide from E. Elén]

[T. Åkesson et al.]

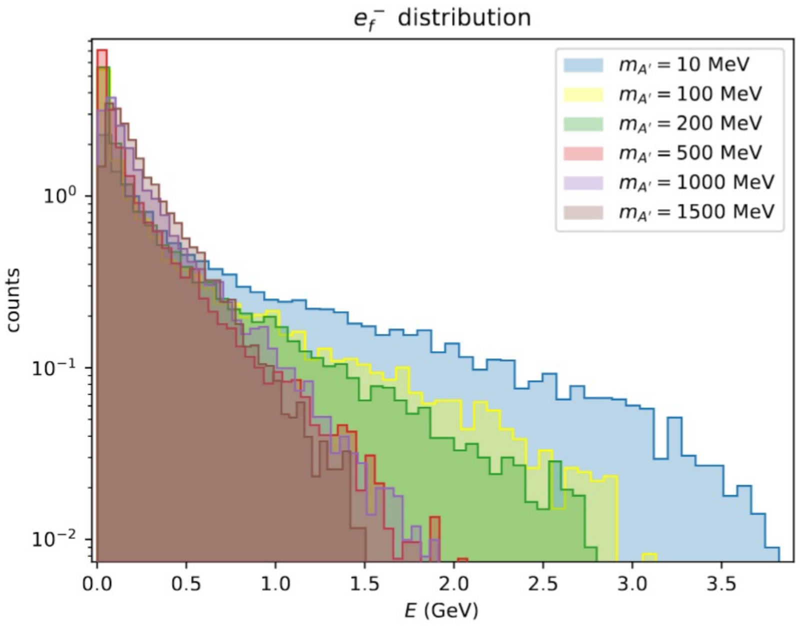
An LDMX Likelihood

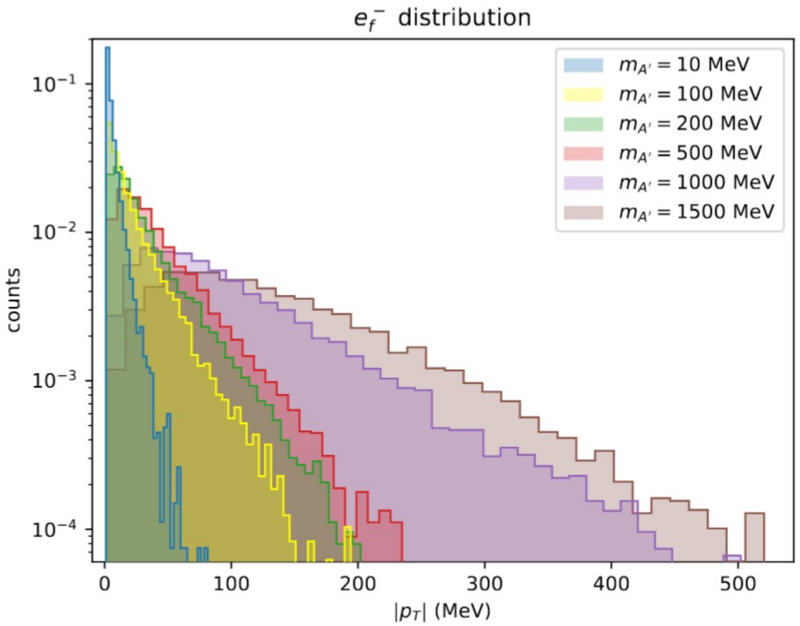
- Exclusion limits
- Discovery
  - Mass/Model determination
- Include in ***global fits***

$$\mathcal{L} = \prod_{\text{bins}} \frac{\nu_i^{d_i}}{d_i!} e^{-\nu_i}$$

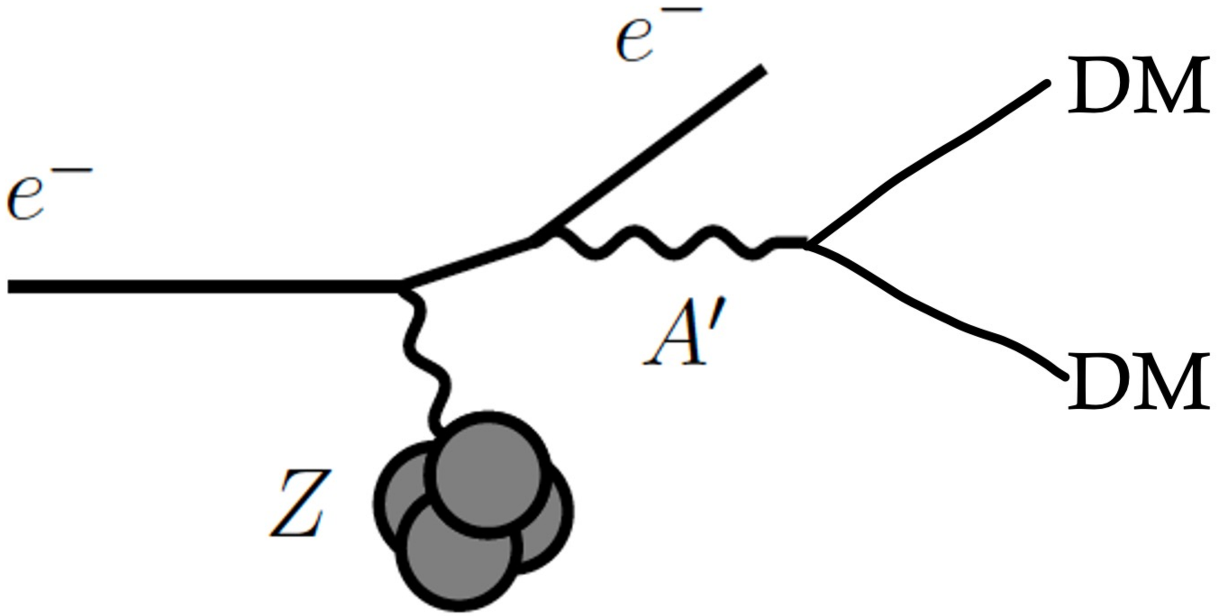
(Poisson distribution)

in energy or p_T



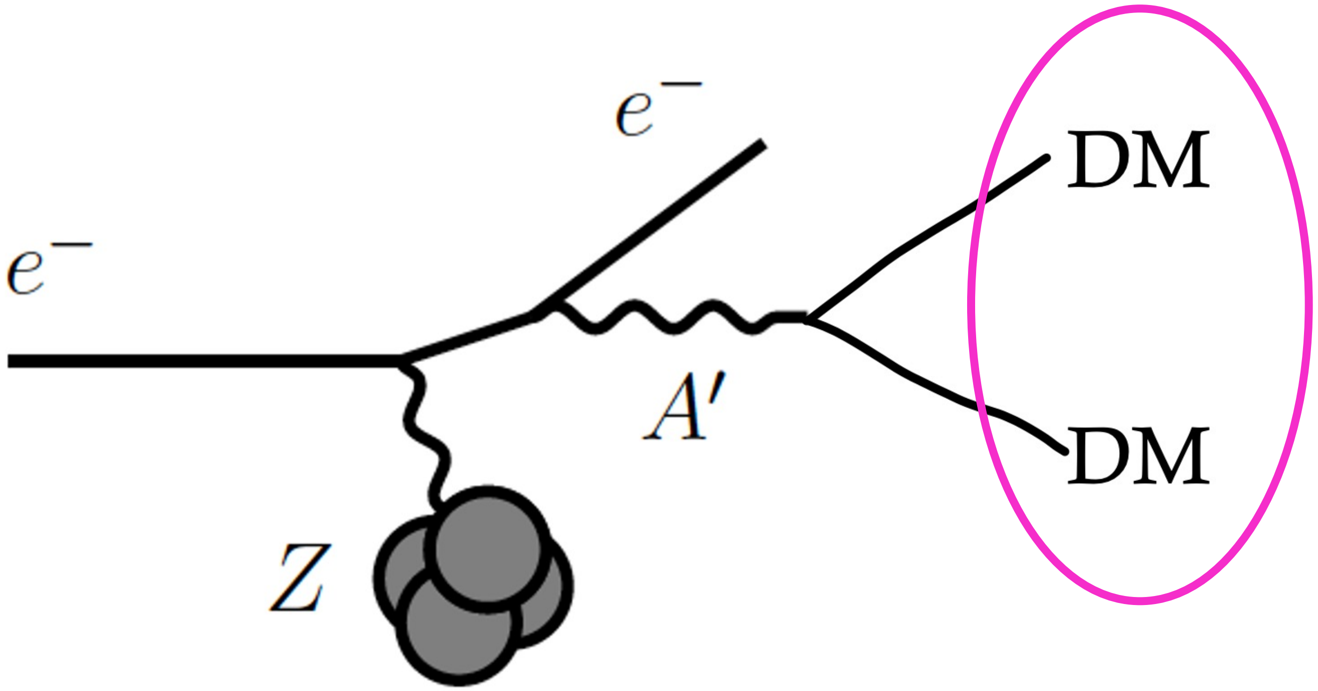


Light Dark Matter Production at Fixed Targets



Light Dark Matter Production at Fixed Targets

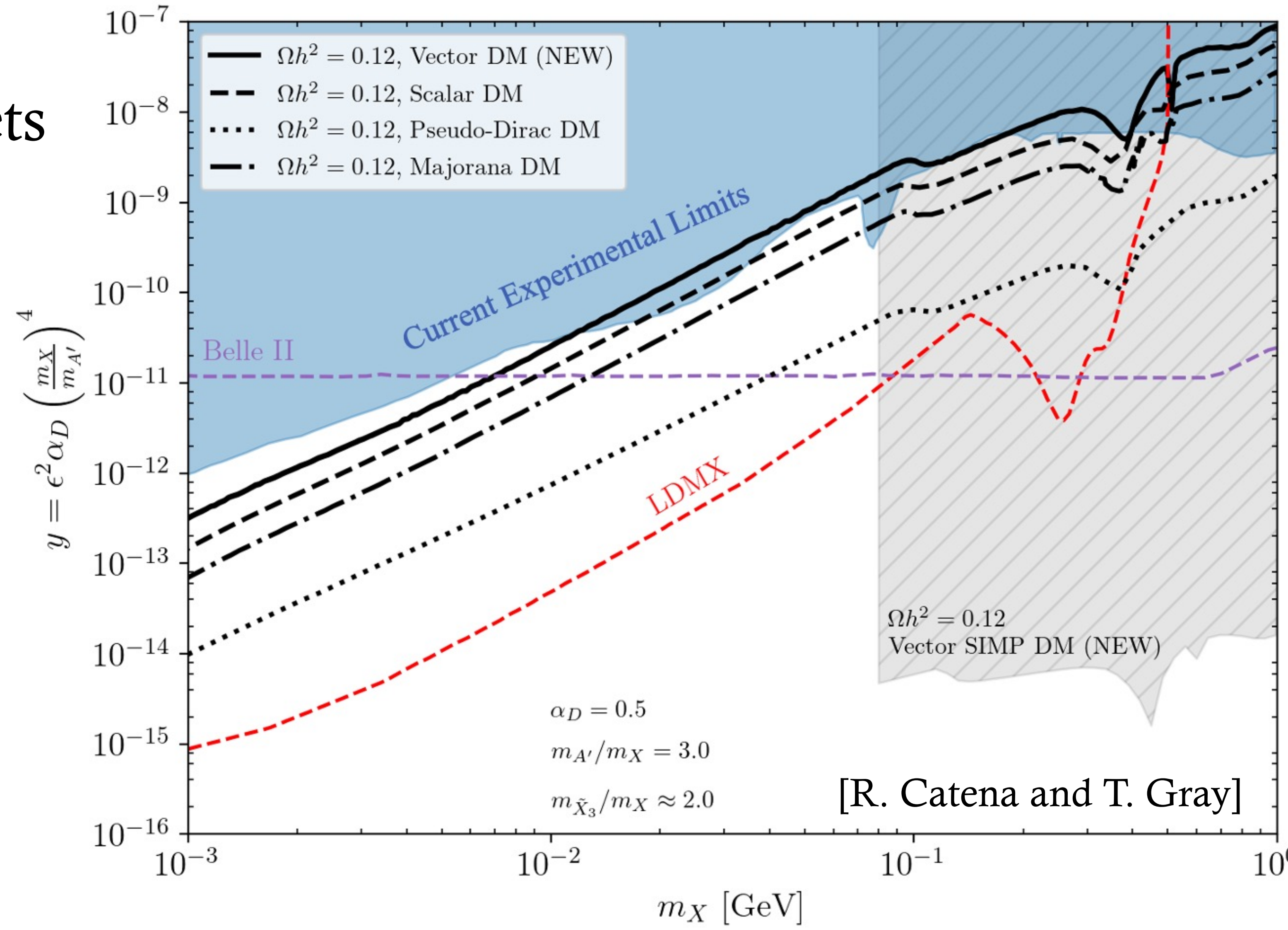
DM theory landscape



Light Dark Matter Theory Landscape

Summary of Thermal Targets

- including **vector DM**!



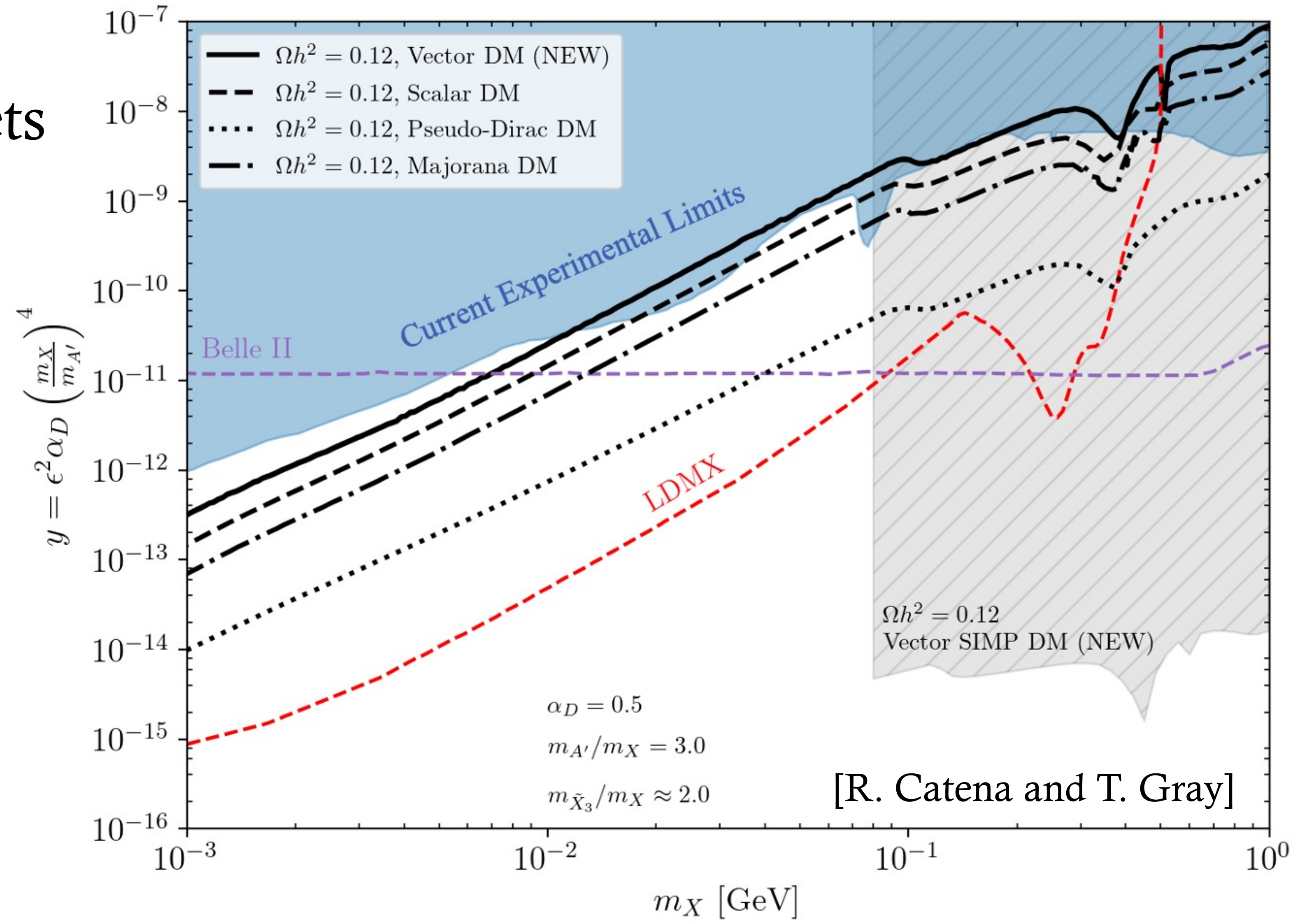
[R. Catena and T. Gray]

Light Dark Matter Theory Landscape

Summary of Thermal Targets

- including **vector DM**!

Mass Hierarchy:
$m_{DM} < m_{med}/2$



Light Vector Dark Matter Scenario

Dark SU(2) $\left\{ \begin{array}{l} X_\mu^a \longrightarrow \begin{array}{ll} X^+X^- & \textbf{Vector DM} \\ Z' & \textbf{“Dark Photon”} \end{array} \\ \\ \Phi_D \text{ (doublet)} \\ \Sigma_D \text{ (triplet)} \end{array} \right.$

gives mass to dark gauge bosons

gives more mass to the DM

Reversed Mass Hierarchy:

$m_{DM} > m_{med}/2$

[A. Banerjee, R. Catena, T. Gray, arXiv: 2512.XXXX]

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↓

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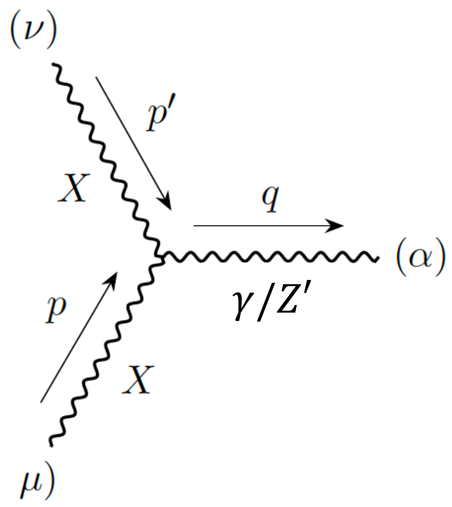
$$\mathcal{L}_{Portal} = -\frac{\sin\zeta}{v_{\Sigma_D}} Tr\left[\Sigma_D X_{\mu\nu}\right] B^{\mu\nu}$$



(Magnetic Dipole)

[A. Banerjee, R. Catena, T. Gray, arXiv: 2512.XXXX]

Light Vector Dark Matter Scenario

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- $X^a_\mu \longrightarrow$ X^+X^- **Vector DM**; Z' **"Dark Photon"**
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- Σ_D (triplet) gives more mass to the DM

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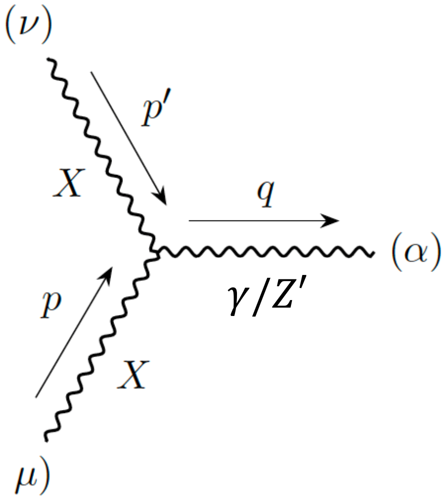
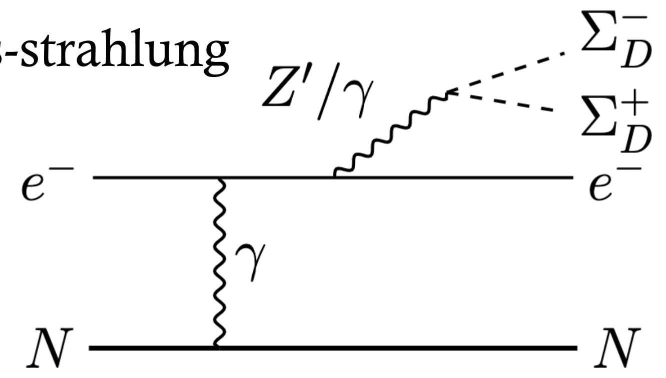


(Magnetic Dipole)

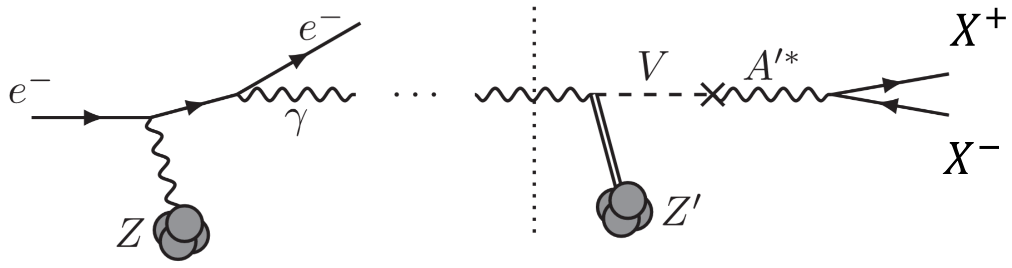
[A. Banerjee, R. Catena, T. Gray, arXiv: 2512.XXXX]

Phenomenology:

- Off-shell Dark Brem
- Dark Higgs-strahlung

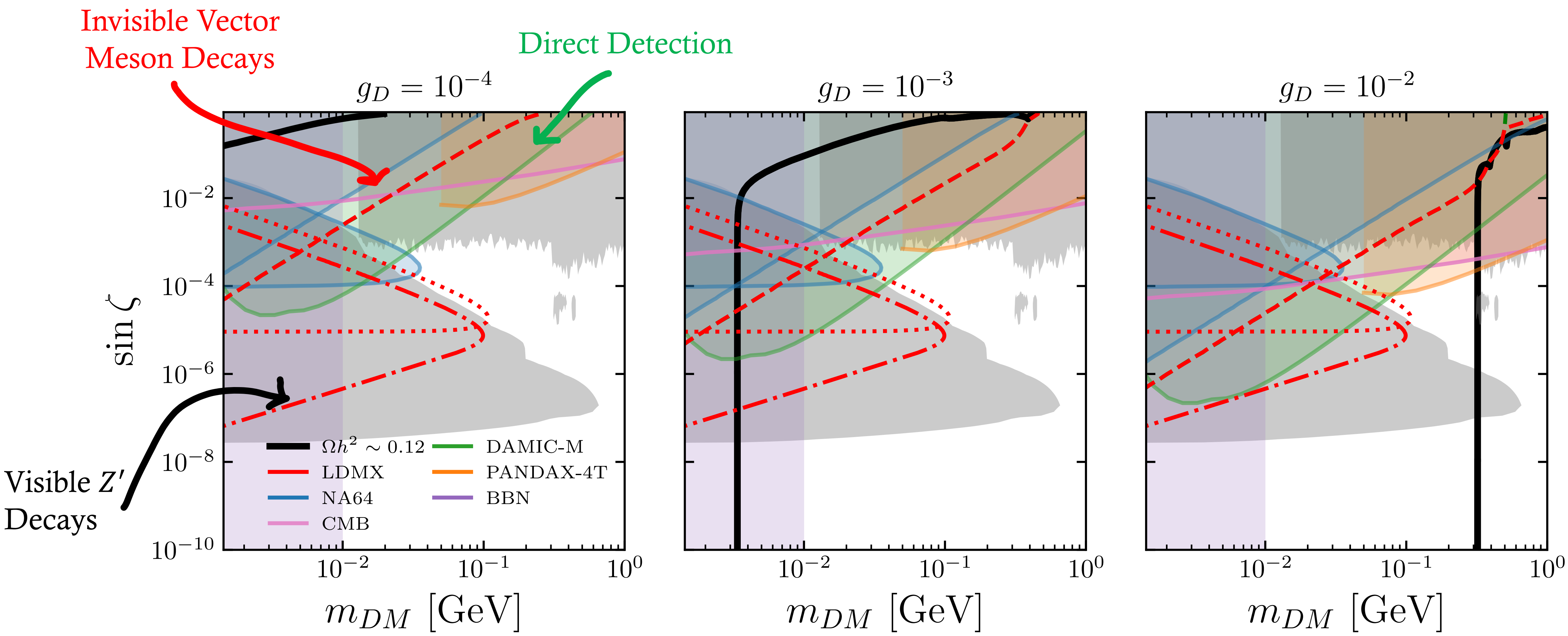


- Invisible Vector Meson Decay

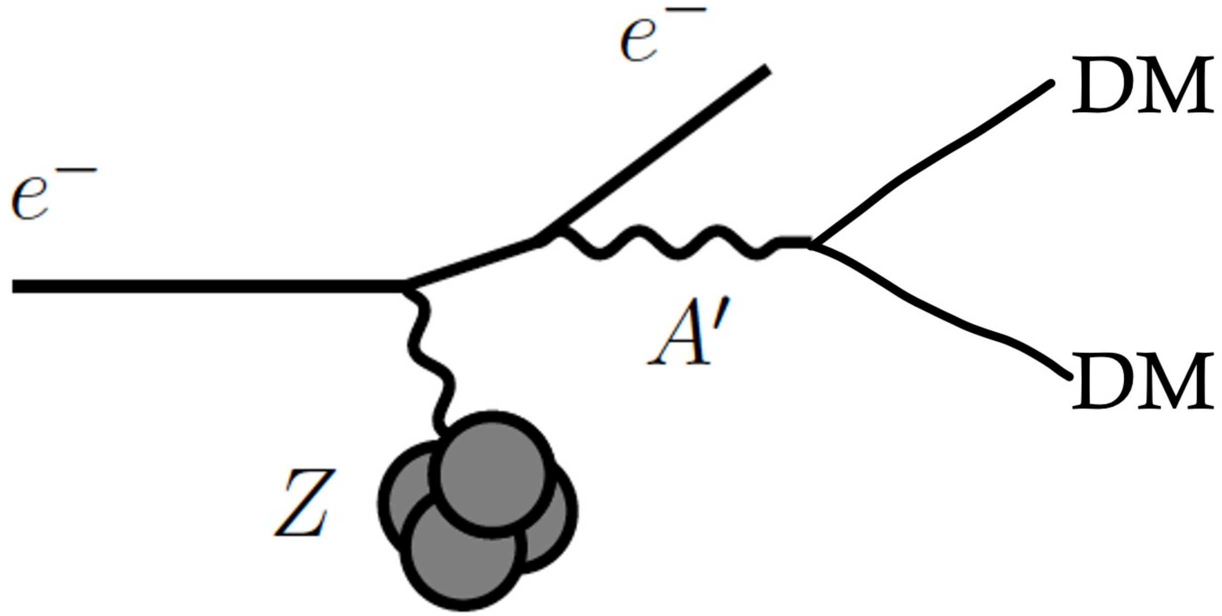


Light Vector Dark Matter Scenario

[A. Banerjee, R. Catena, T. Gray, arXiv: 2511.XXXX]

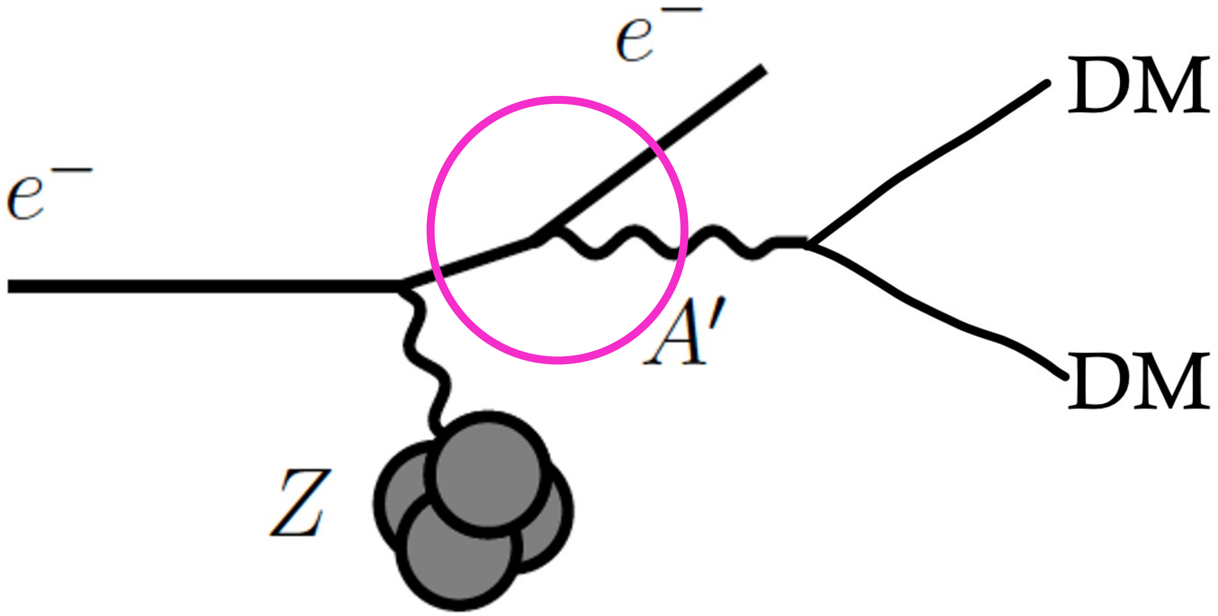


Light Dark Matter Production at Fixed Targets



Light Dark Matter Production at Fixed Targets

DM theory landscape: **Dark Photon Model**



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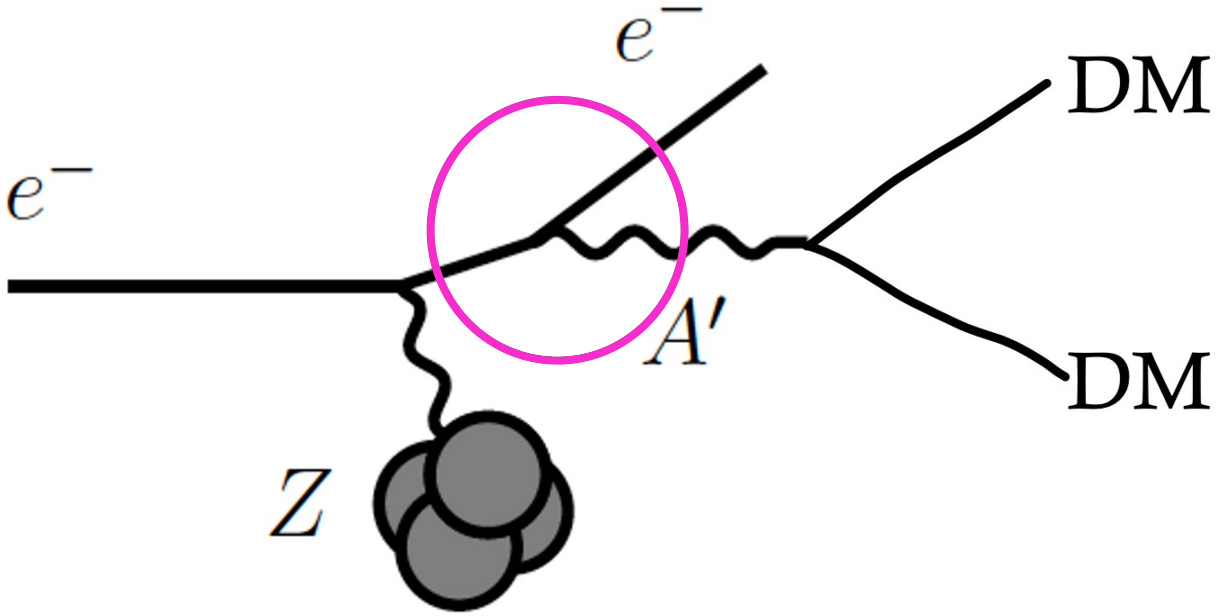

Beyond ordinary kinetic mixing!

Production of Dark Photons through Higher Electromagnetic Moments at LDMX

- ordinary kinetic mixing (KM)
- magnetic dipole (M)
- electric dipole (E)
- charge radius (C)
- anapole moment (A)

$$\begin{aligned}\mathscr{L}_{A'f} = & \boxed{- e\varepsilon Q_f \bar{f}\gamma^\mu f A'_\mu} - \boxed{i\mu_f \partial_\nu \left(\bar{f}\sigma^{\mu\nu} f\right) A'_\mu} + d_f \partial_\nu \left(\bar{f}\sigma^{\mu\nu}\gamma^5 f\right) A'_\mu \\ & - b_f \left[\partial^\nu \partial_\nu \left(\bar{f}\gamma^\mu f\right) - \partial^\mu \partial_\nu \left(\bar{f}\gamma^\nu f\right)\right] A'_\mu \\ & + a_f \left[\partial^\nu \partial_\nu \left(\bar{f}\gamma^\mu \gamma^5 f\right) - \partial^\mu \partial_\nu \left(\bar{f}\gamma^\nu \gamma^5 f\right)\right] A'_\mu ,\end{aligned}$$

[R. Catena, T. Gray, T. Jerkvall]

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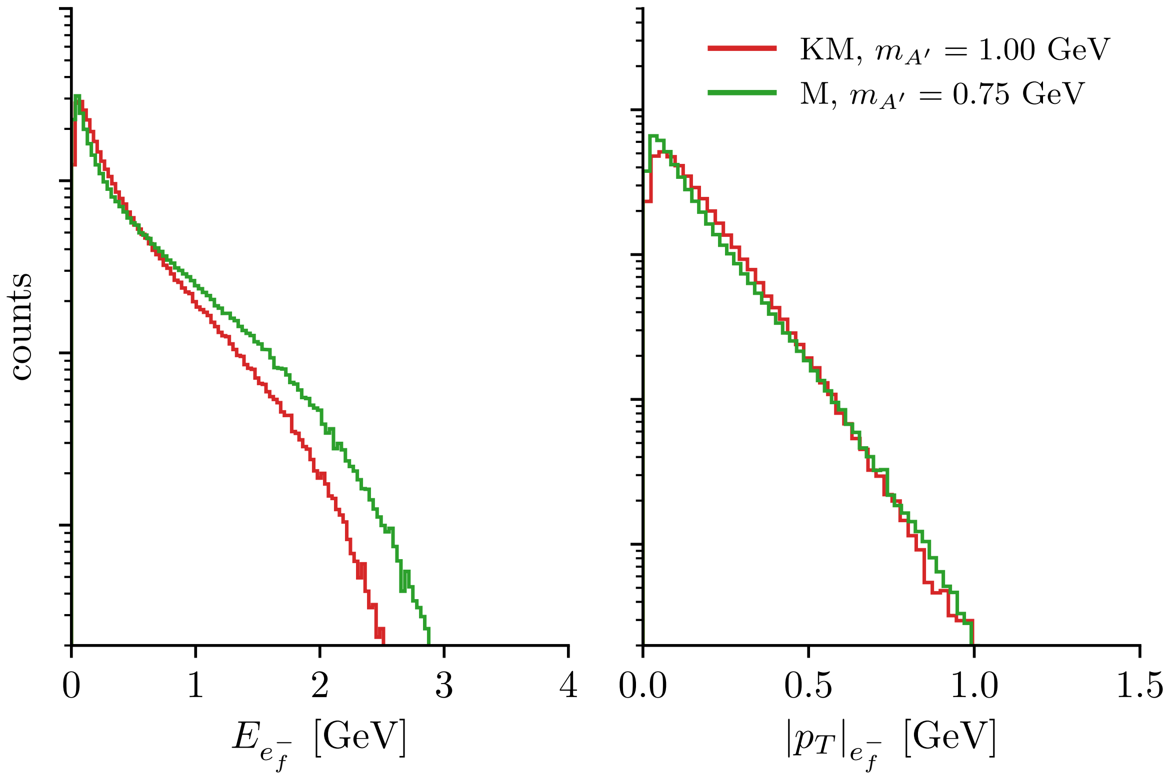
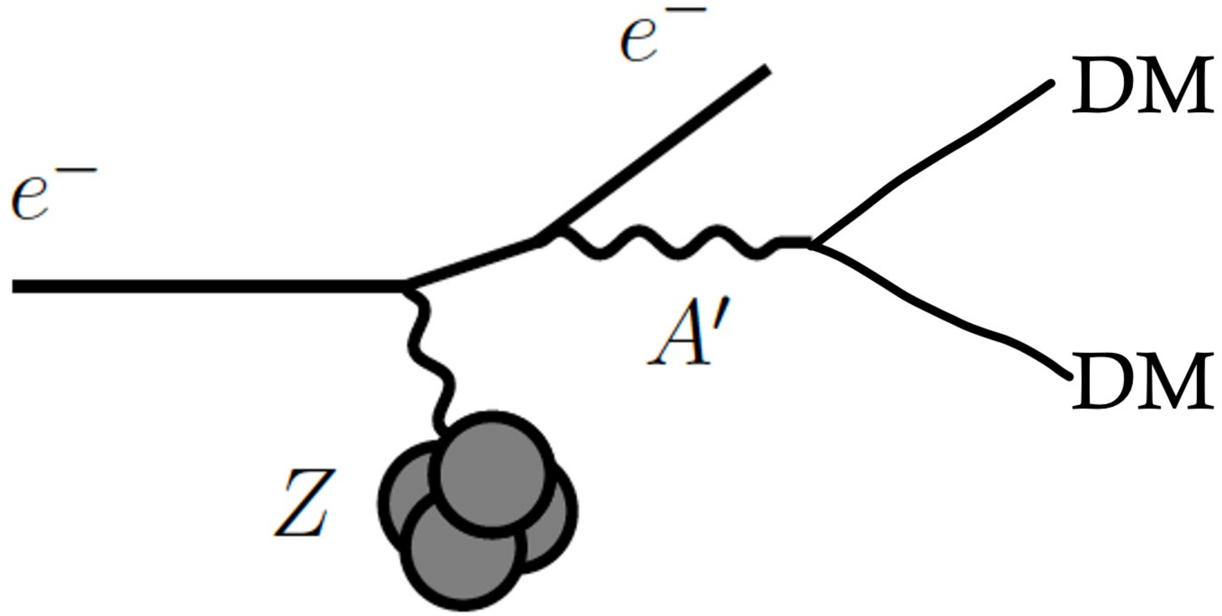
$$- b_f \left[\partial^\nu \partial_\nu \left(\bar{f}\gamma^\mu f\right) - \partial^\mu \partial_\nu \left(\bar{f}\gamma^\nu f\right)\right] A'_\mu$$
$$+ a_f \left[\partial^\nu \partial_\nu \left(\bar{f}\gamma^\mu \gamma^5 f\right) - \partial^\mu \partial_\nu \left(\bar{f}\gamma^\nu \gamma^5 f\right)\right] A'_\mu,$$



- In addition to **mass reconstruction** → DP **model reconstruction**?
- **Break degeneracy** between groups with both E_e and $|p_T|_E$

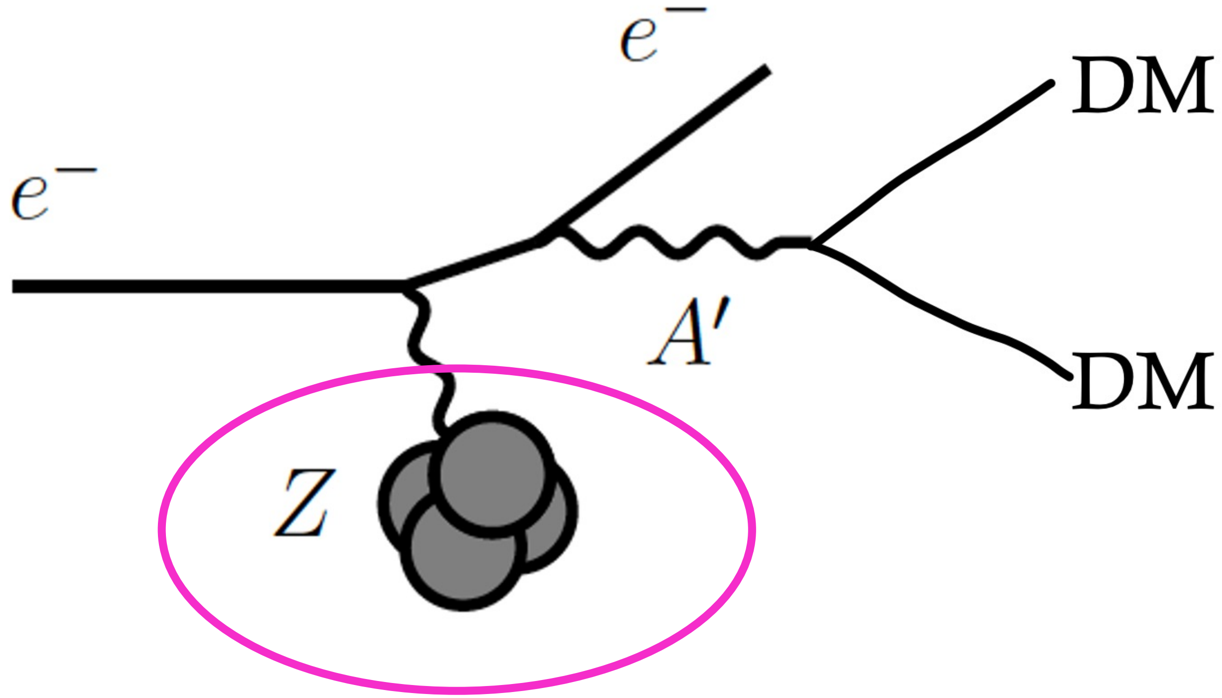
[R. Catena, T. Gray, T. Jerkvall]

Light Dark Matter Production at Fixed Targets



Light Dark Matter Production at Fixed Targets

Ab-Initio Modeling of the Target Nucleus using Many-Body Methods

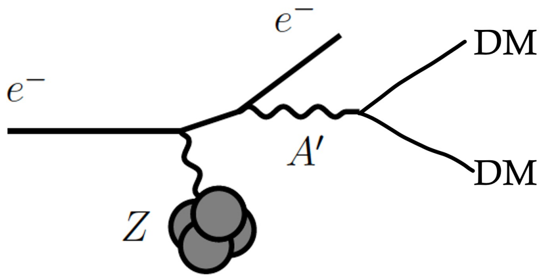


Ab-Initio Modeling of the Target Nucleus

using Many Body Methods

$$N_{\mathrm{events}} \propto \int dq \, \frac{q^2 - q^2_{\mathrm{min}}}{q^3} |F(q)|^2$$

Form Factor



[T. Gray and A. Scalesi *in preparation*]

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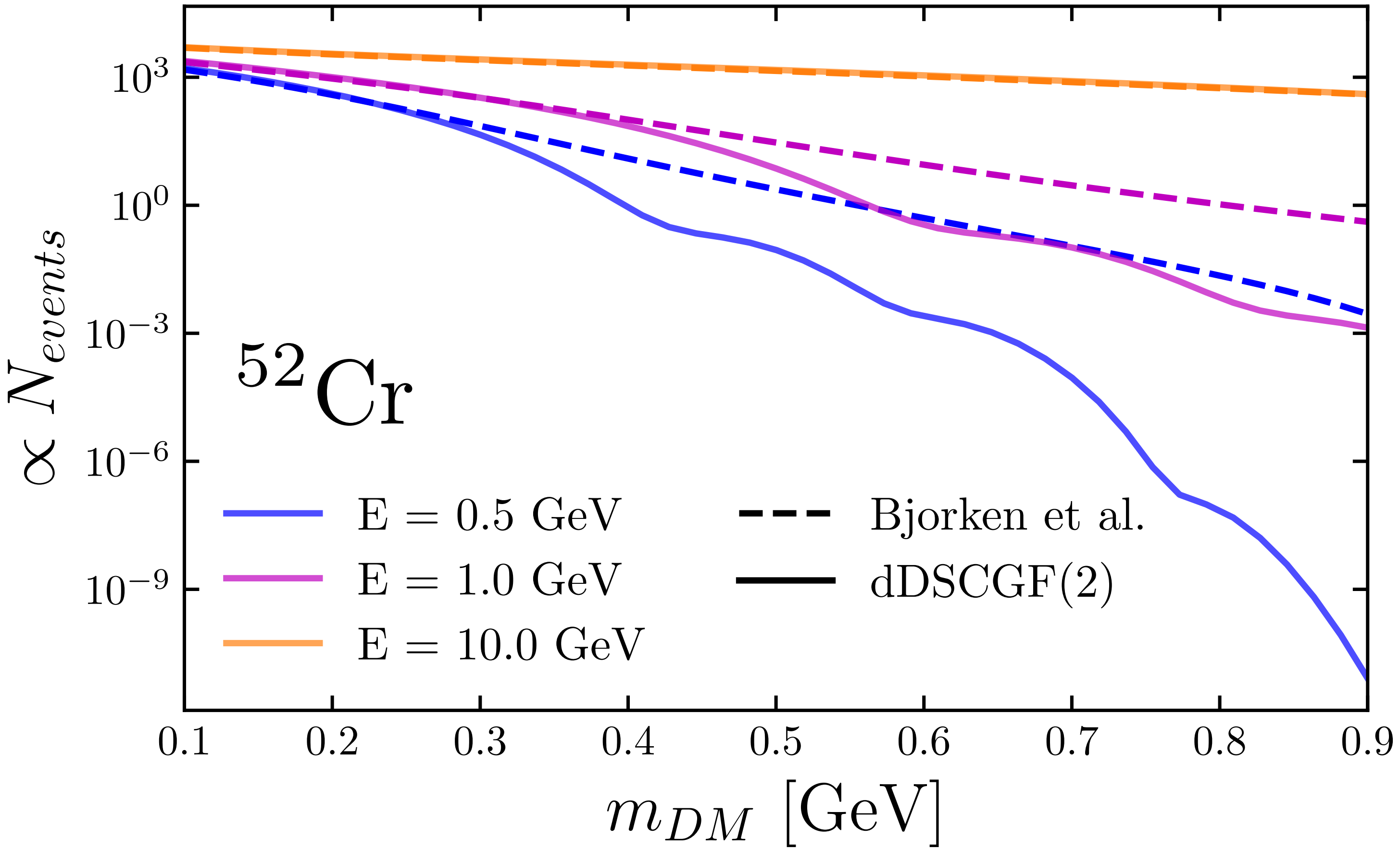

[T. Gray and A. Scalesi *in preparation*]

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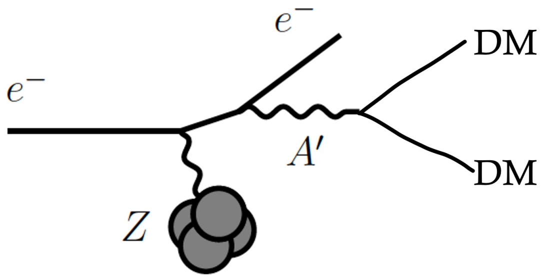
Form Factor

Experimental sensitivity depends on nuclear structure!

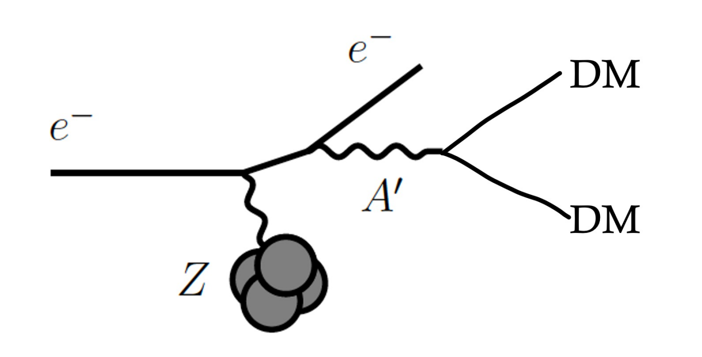


Summary

It's an exciting time for Light DM searches!

- upcoming experiments (such as **LDMX**)
- extending the sensitivity frontier for a rich array of **light DM theories**

- However, we need to:
  - Know how to deal with a **potential signal**
  - Properly model the signal + background
    - Nuclear structure can play a role!



Thank you for listening ☺

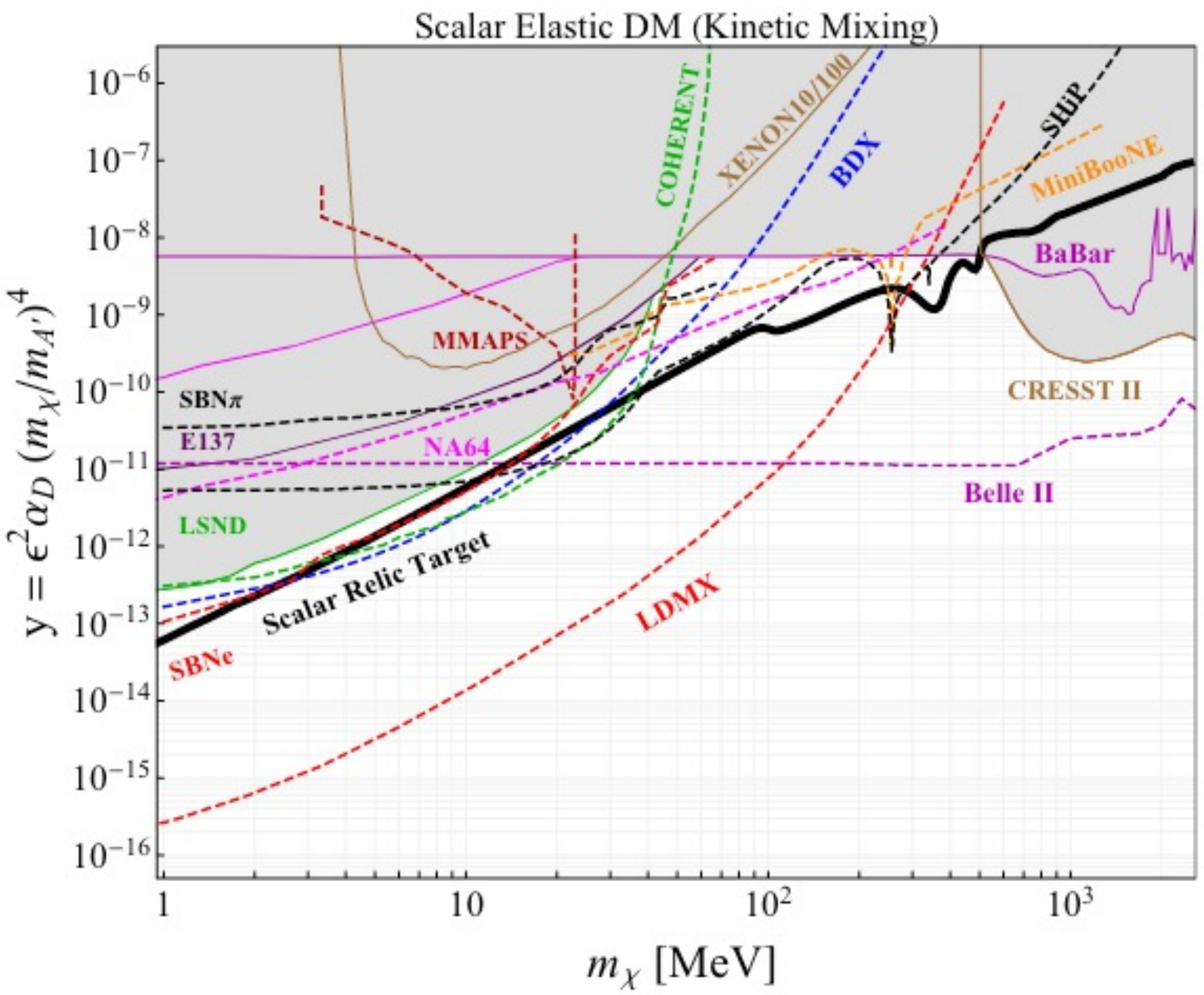
Additional Material

Light Dark Matter Status

Indirect Detection
- CMB energy injection

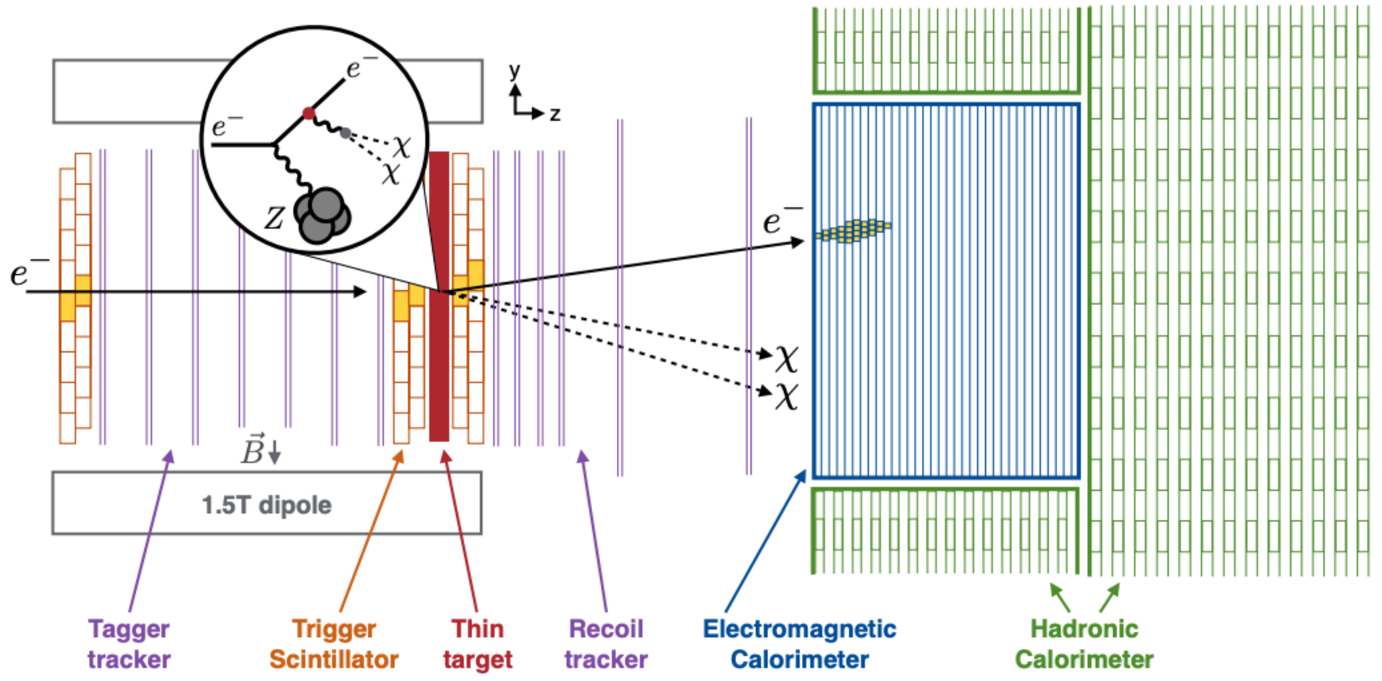
Direct Detection
- Electron recoils
- Phonon excitations

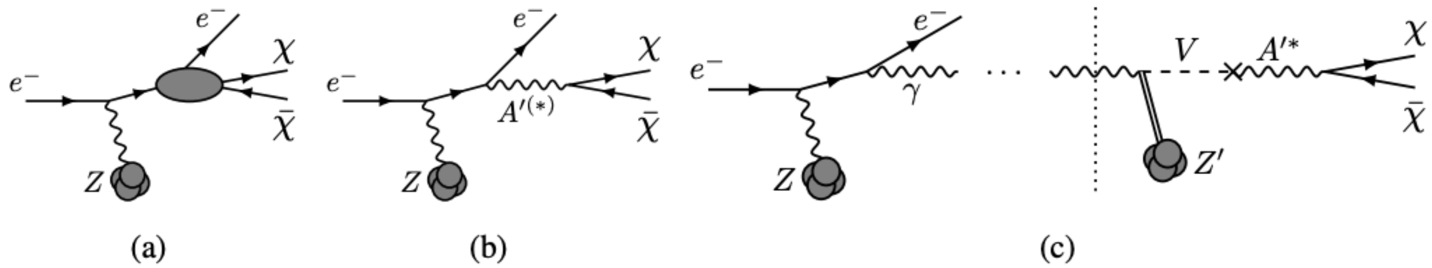
Collider
- Mono-γ
- Beam dumps
- **Fixed target**



Light Dark Matter eXperiment (LDMX)

- Future fixed target missing momentum exp
  - 2025: LESA delivers beam to LDMX allowing $4{\times}10^{14}$ EOT
  - 2027: 10^{16} EOT
- e^- incident on a thin tungsten target
- Charged particle tracker and calorimeters to measure DM signature
  - Recoil electron pT accompanied by absence of other particle activity





STATUS

- Completed tests of upstream beam (results available soon)
- LDMX beam into experimental area and the vertical slice test (This year)
- Measurements with HCal prototype in the experimental hall (early 2026)
- Begin construction in late 2026 (~3 years)