# Light Dark Matter at LDMX

*Dipole Emission and Global Fits*

**Taylor R. Gray**

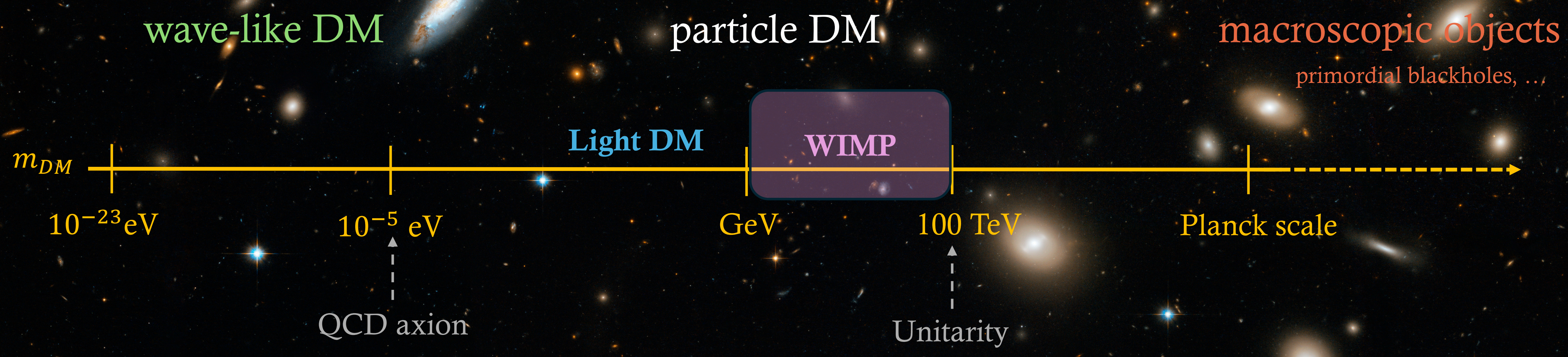
Supervisor: Riccardo Catena

Based on: JCAP01(2025)053 and arXiv:2502.13635

Knut and Alice Wallenberg Foundation

CHALMERS UNIVERSITY OF TECHNOLOGY

# What is the *Dark Matter* made of?



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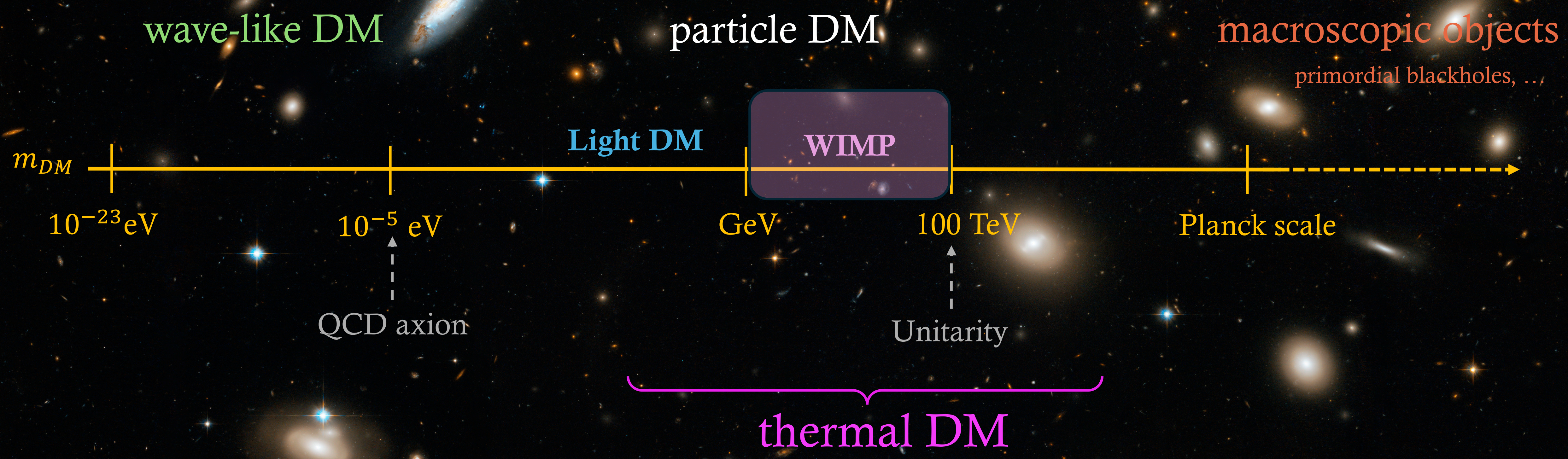
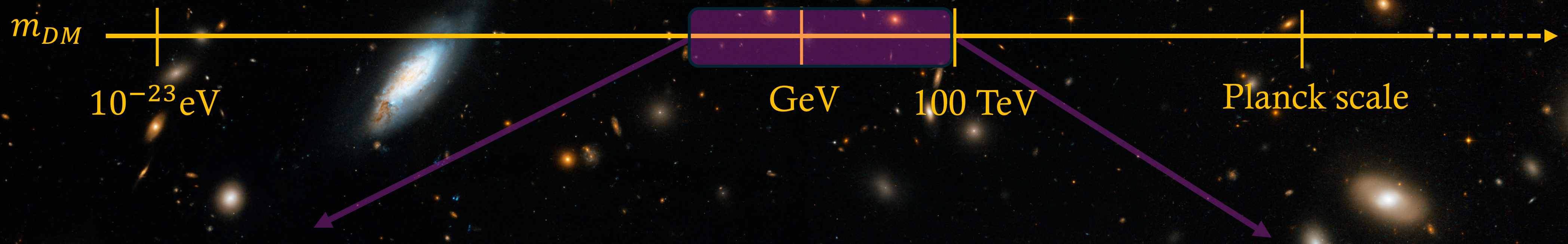


# Thermal Dark Matter Window

Thermal equilibrium between DM and SM in the early universe.



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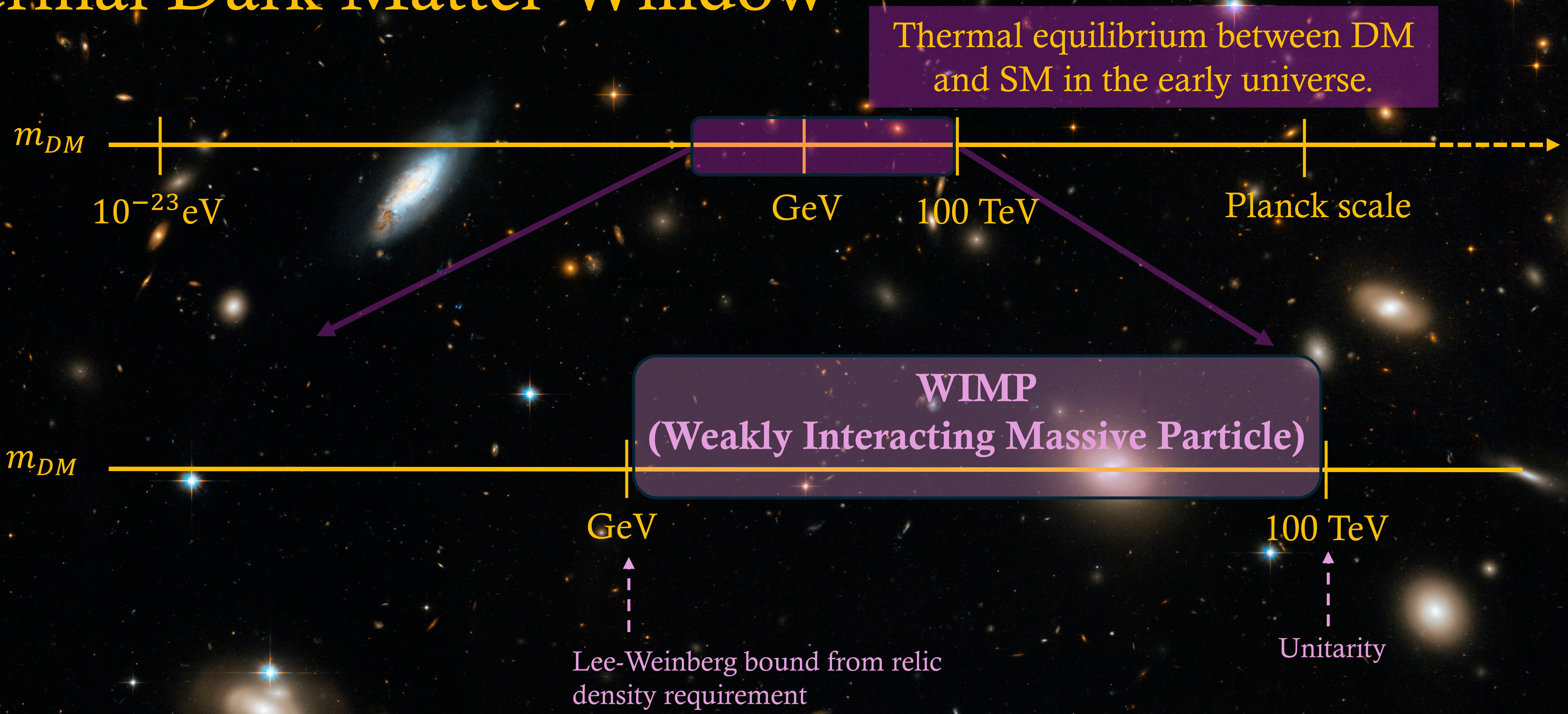
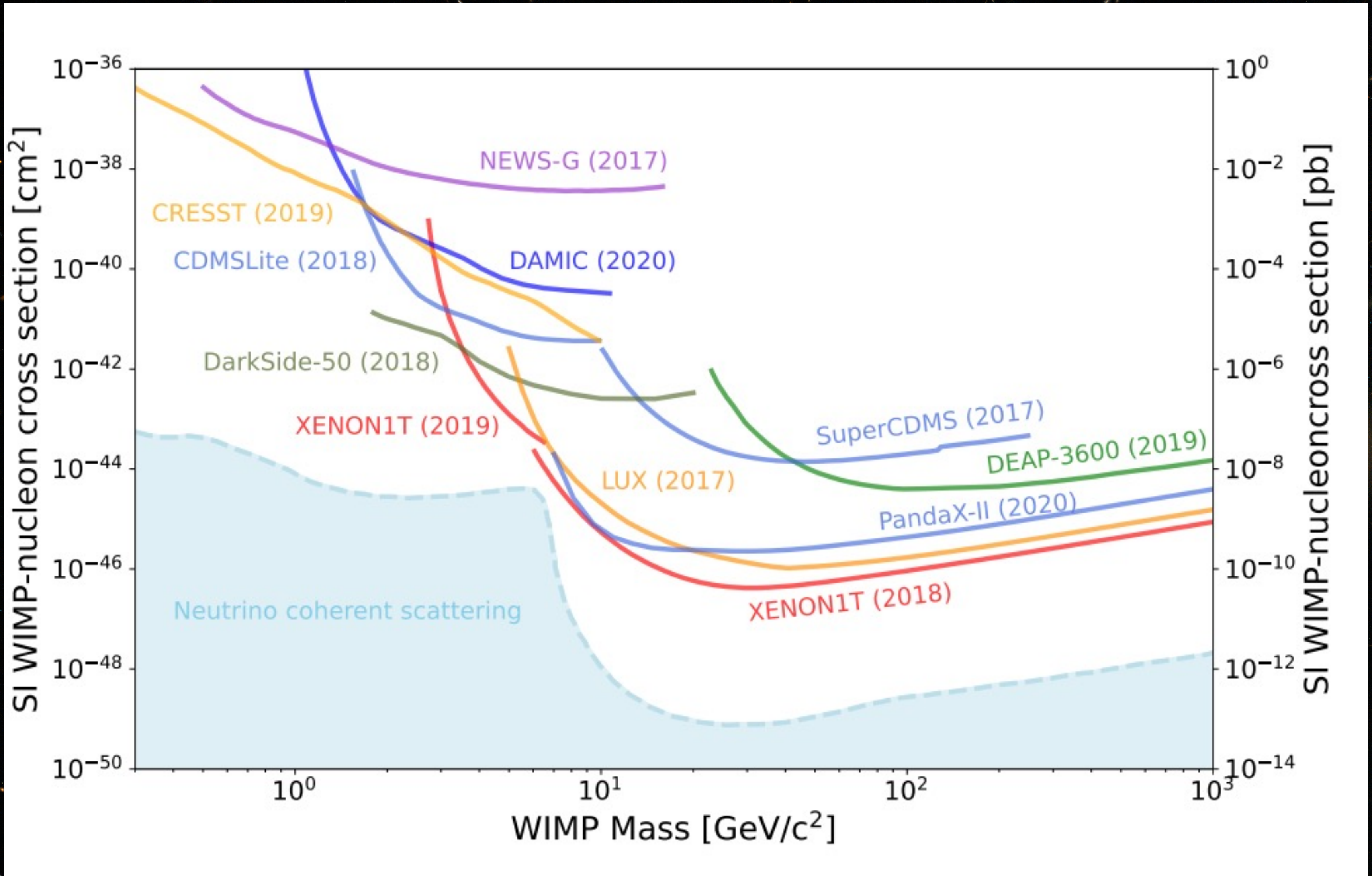
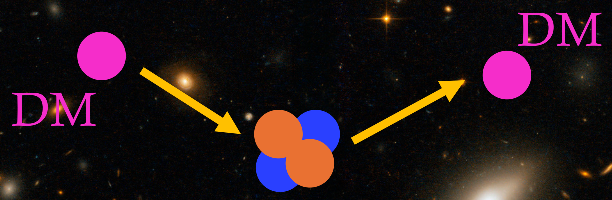



- DM interacts via the weak force near the weak scale
- Widely tested by direct detection experiments

# Nuclear Recoil Direct Detection Status



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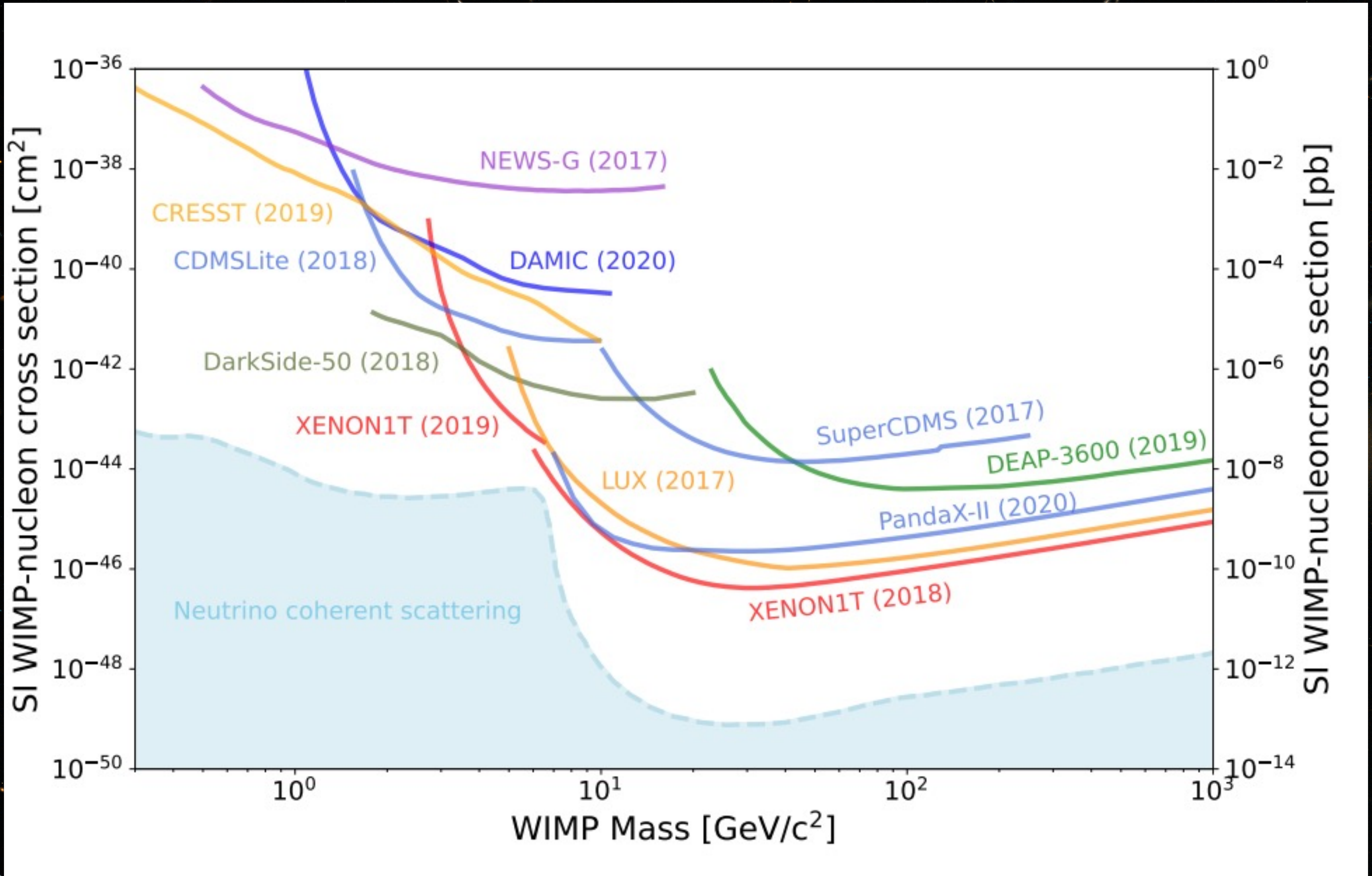
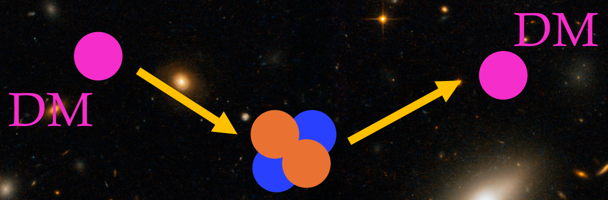



No conclusive signal found yet ☹

# Thermal Dark Matter Window

**WIMP**
**(Weakly Interacting Massive Particle)**

$m_{DM}$

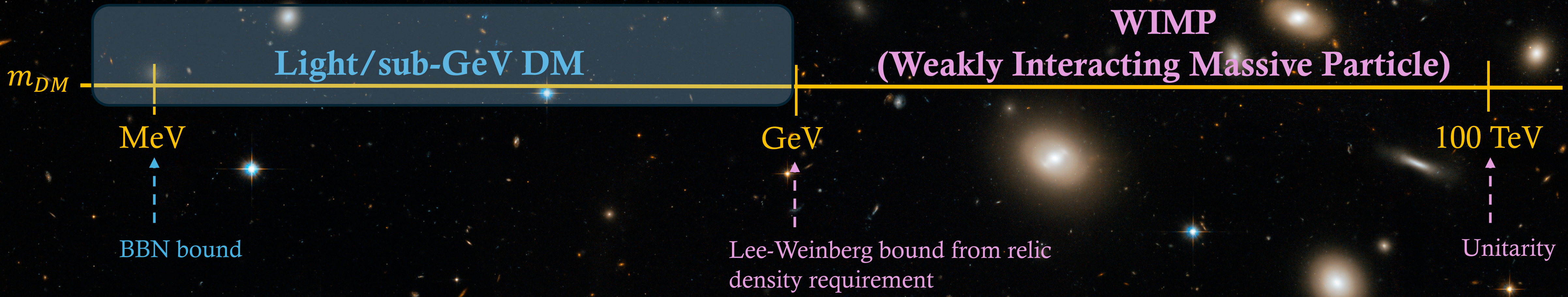
MeV GeV 100 TeV

Lee-Weinberg bound from relic density requirement

Unitarity

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

# Thermal Dark Matter Window




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

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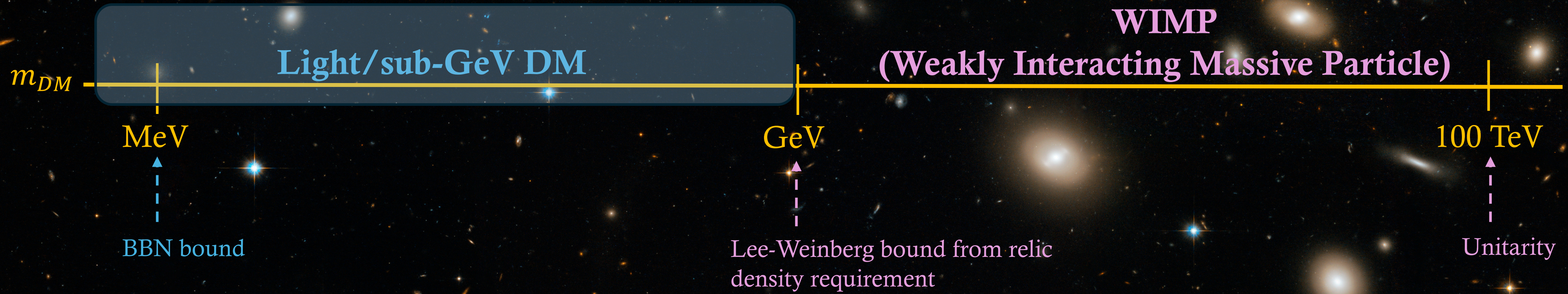


- Evade LW bound by introducing a **new mediator**
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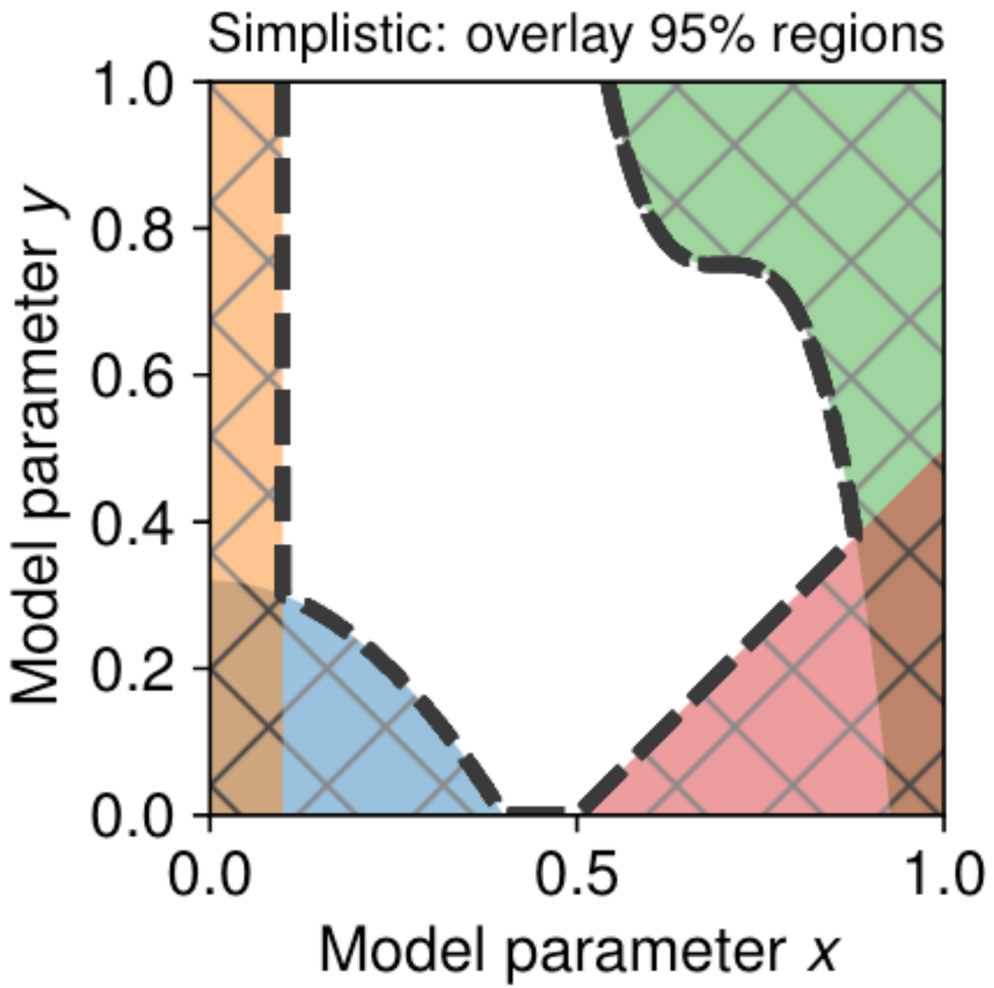
**What experiments/observations probe light DM?**

# Resonant or asymmetric:
## *The status of sub-GeV dark matter*

JCAP01(2025)053

In collaboration with:
**Sowmiya Balan**, Csaba Balazs, Torsten Bringmann, Christopher Cappiello, Riccardo Catena, Timon Emken, Tomás E. Gonzalo, Will Handley, Quan Huynh, **Felix Kahlhoefer**, and Aaron C. Vincent

# Global Fits



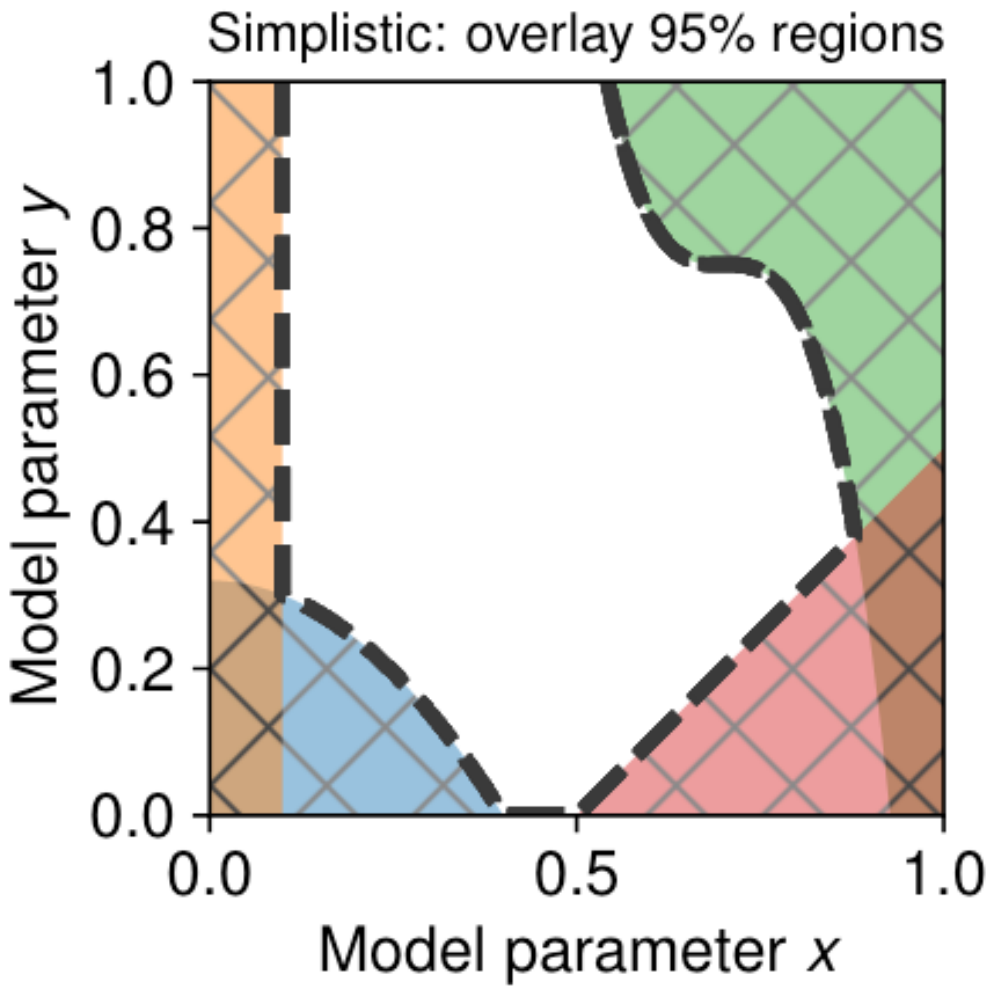

**95% confidence exclusion bound**: rate at which the true parameter values are excluded is limited to 5%

GAMBIT arXiv:2012.09874

# Global Fits

The intersection,

$$\text{Error rate} = 1 - 0.95^n$$

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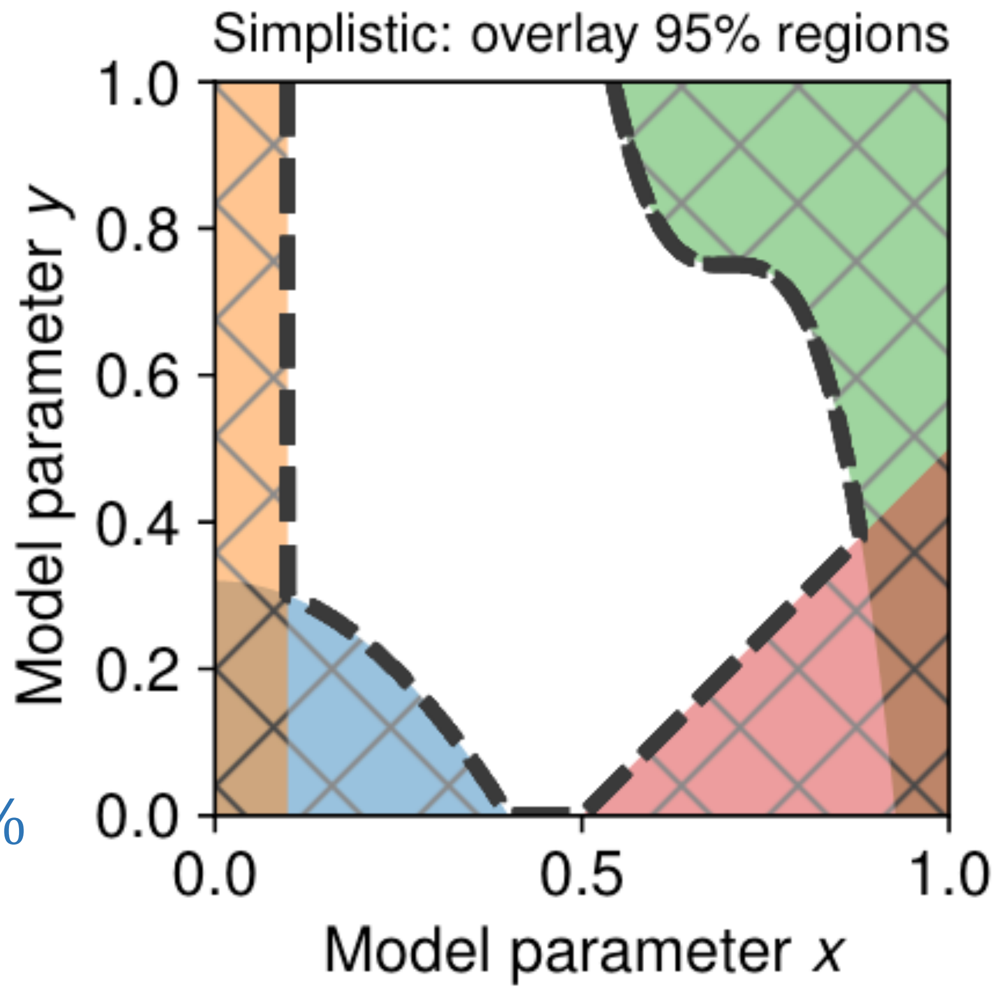


The intersection,

$\text{Error rate} = 1 - 0.95^n$

Ex: 5 experiments

- error rate $= 1 - 0.95^5 = 23\%$
- **falsely reporting** 95% C.L.

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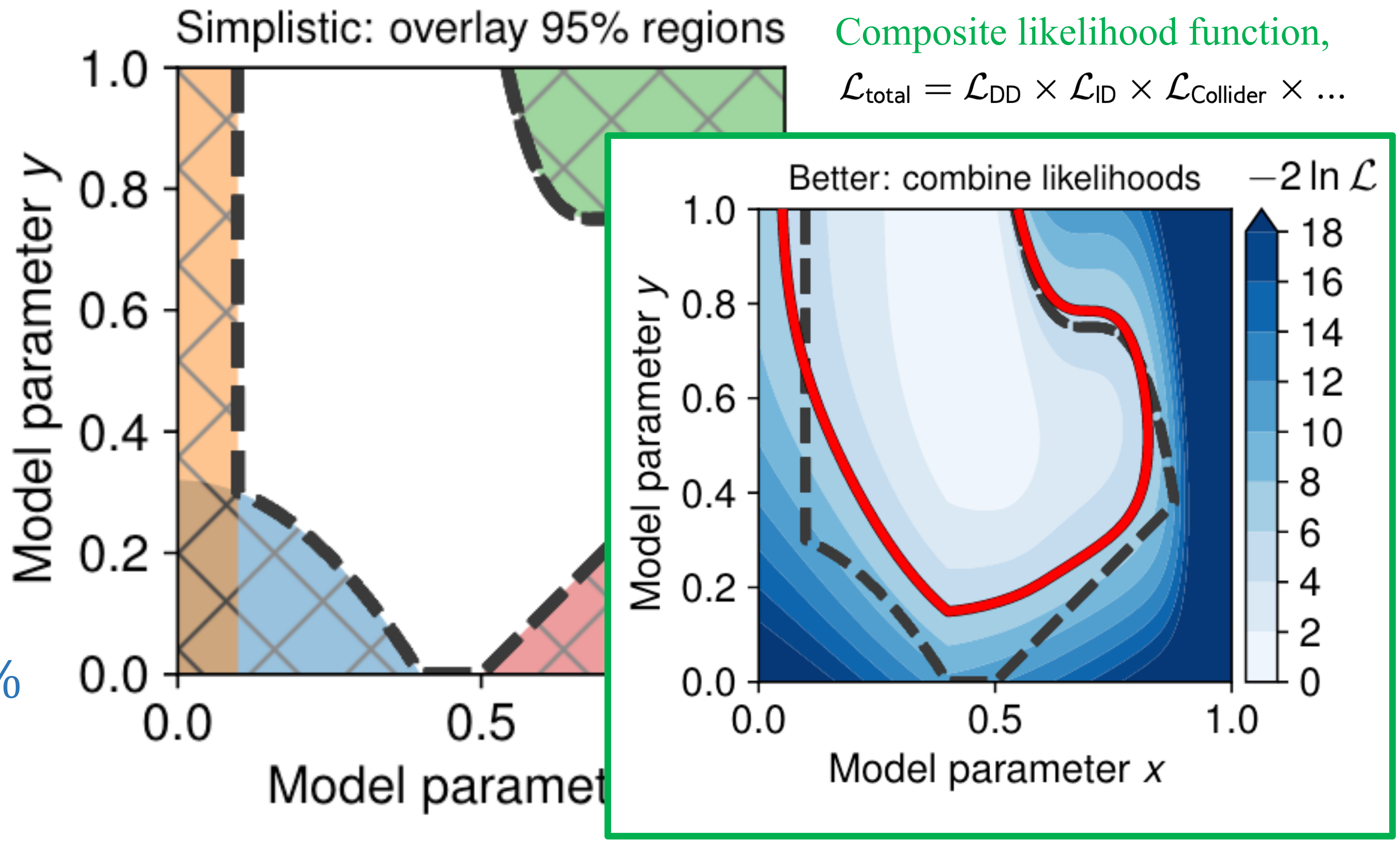


Composite likelihood function,

$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{DD}} \times \mathcal{L}_{\text{ID}} \times \mathcal{L}_{\text{Collider}} \times \ldots$

GAMBIT arXiv:2012.09874

# Global Fits of sub-GeV DM

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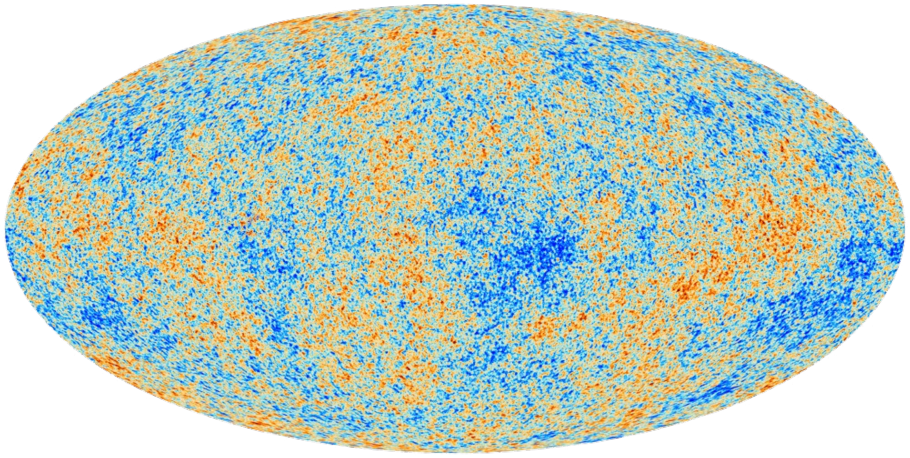
## *Cosmological Constraints*



### Relic Density (freeze-out)

$\Omega_{DM,obs}h^2 \leq \ 0.120 \pm 0.001$

*Planck 2018 results. VI. Cosmological parameters*

full-component DM OR sub-component DM

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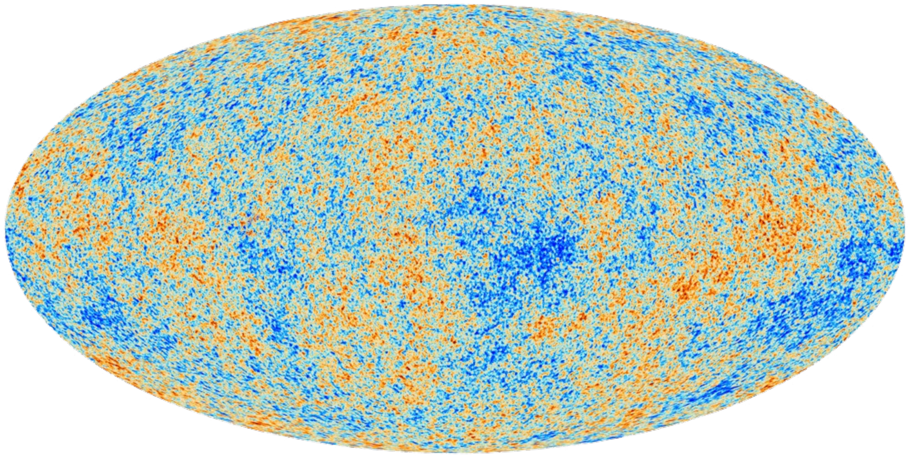

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$DM\ DM \rightarrow SM\ SM$

constrained by CMB measurements

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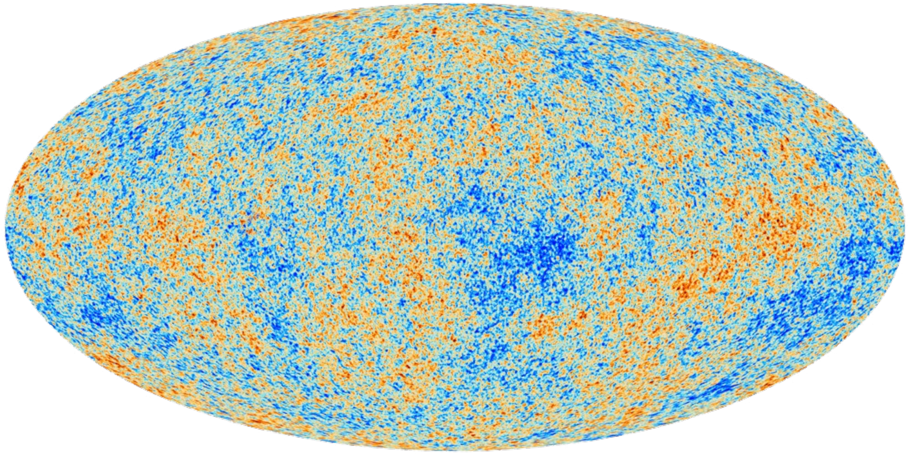

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## Big Bang Nucleosynthesis

$DM\ DM \rightarrow SM\ SM$

- Alters $N_{eff} = 2.99 \pm 0.17$
- Light element abundances

# Global Fits of sub-GeV DM

## *Astrophysical Constraints*

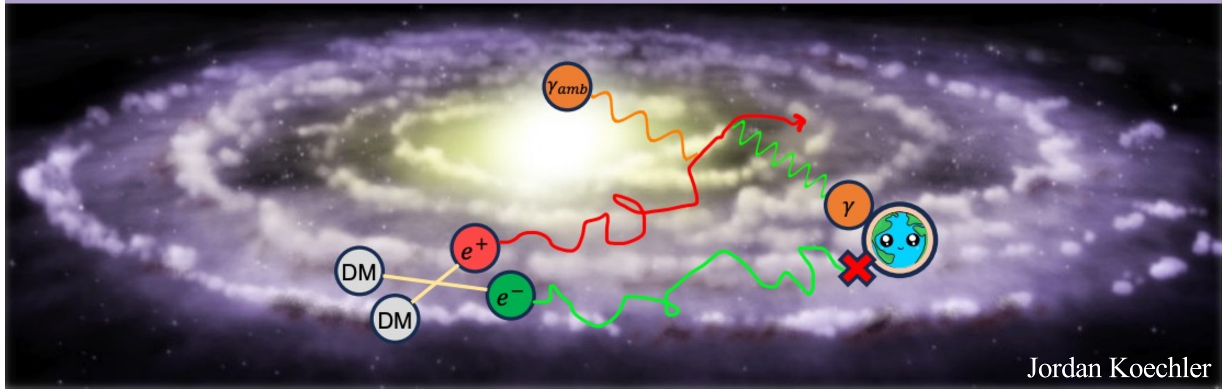
X-Rays

arXiv:2303.08854

$DM\ DM \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

$e^-\gamma \rightarrow e^-\gamma$ (Inverse Compton Scattering)

*up-scatter the low energy photons of the ambient light*



# Global Fits of sub-GeV DM

## *Astrophysical Constraints*

### Bullet Cluster

$DM\ DM \rightarrow DM\ DM$

- **subcluster survival rate**
- DM/galaxy offset

### X-Rays

arXiv:2303.08854

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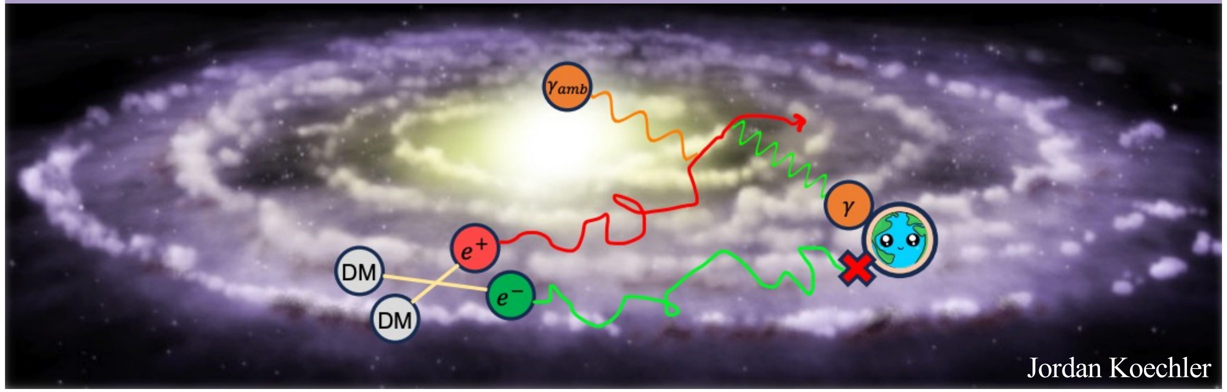


# Global Fits of sub-GeV DM

*Laboratory Experiment Constraints*

## Accelerators

**…more on this later**

**Monophoton searches**

$e^+e^- \to \gamma A', A' \to XX$

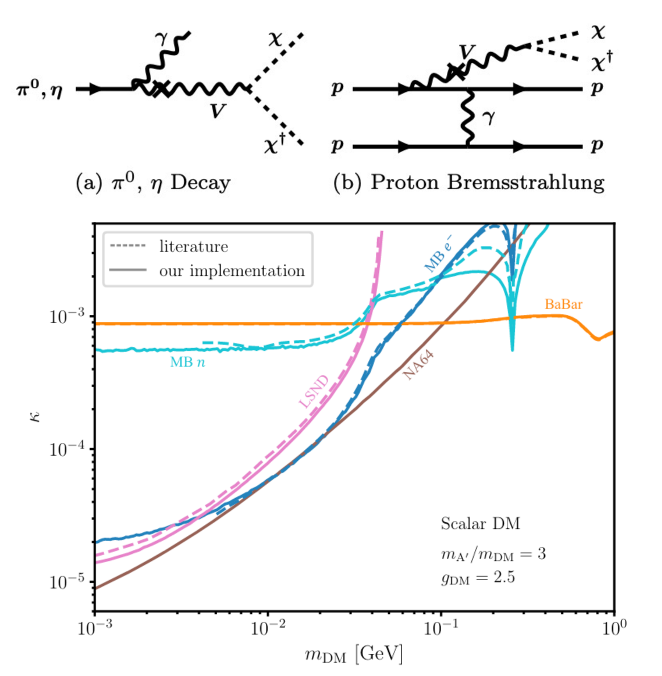
- BaBar

**Fixed Targets**

Dark photon production

$A' \to DM$

- LSND
- Mini-BooNE
- NA64



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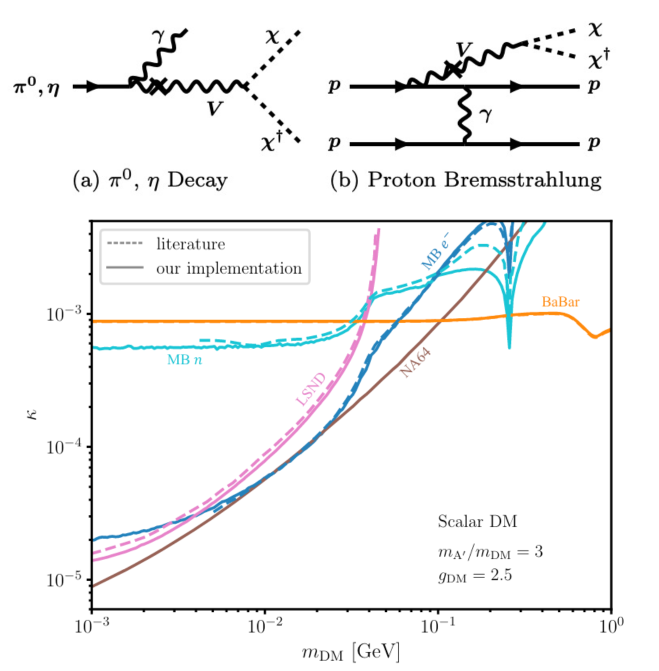
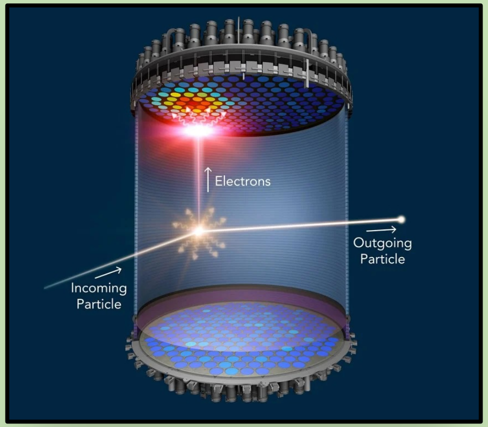



### Direct Detection arXiv:2210.07305

**obscura** software for direct DM searches via nuclear and electron recoils

- XENON1T
- SENSEI
- CRESST-III
- and more..



# Sub-GeV DM Models

Benchmark models with a $A'$ mediator

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Benchmark models with a $A'$ mediator

## Complex Scalar DM

$$\mathcal{L}_\phi = \left|\partial_\mu \phi\right|^2 - m_{DM}^2|\phi|^2 + i g_{DM} A'^\mu\left[\phi^*\left(\partial_\mu \phi^*\right)\phi\right]$$

NOT subject to indirect detection and energy injection

- $\langle \sigma v \rangle_{DM\,DM \to SM\,SM} \sim v^2$ (p-wave dominant)
- s-wave forbidden

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## Dirac Fermion DM

$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - m_{DM})\psi + g_{DM} A'^\mu \bar{\psi}\gamma_\mu \psi$$

subject to strong indirect detection and energy injection constraints

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subject to strong indirect detection and energy injection constraints

- $\langle \sigma v \rangle_{DM\ DM \to SM\ SM} \sim v^0$ (s-wave dominant)

How to evade indirect detection constraints?

1. Resonance enhancement: $\epsilon_R \equiv \frac{m_{A'}^2 - 4m_{DM}^2}{4m_{DM}^2} \ll 1$

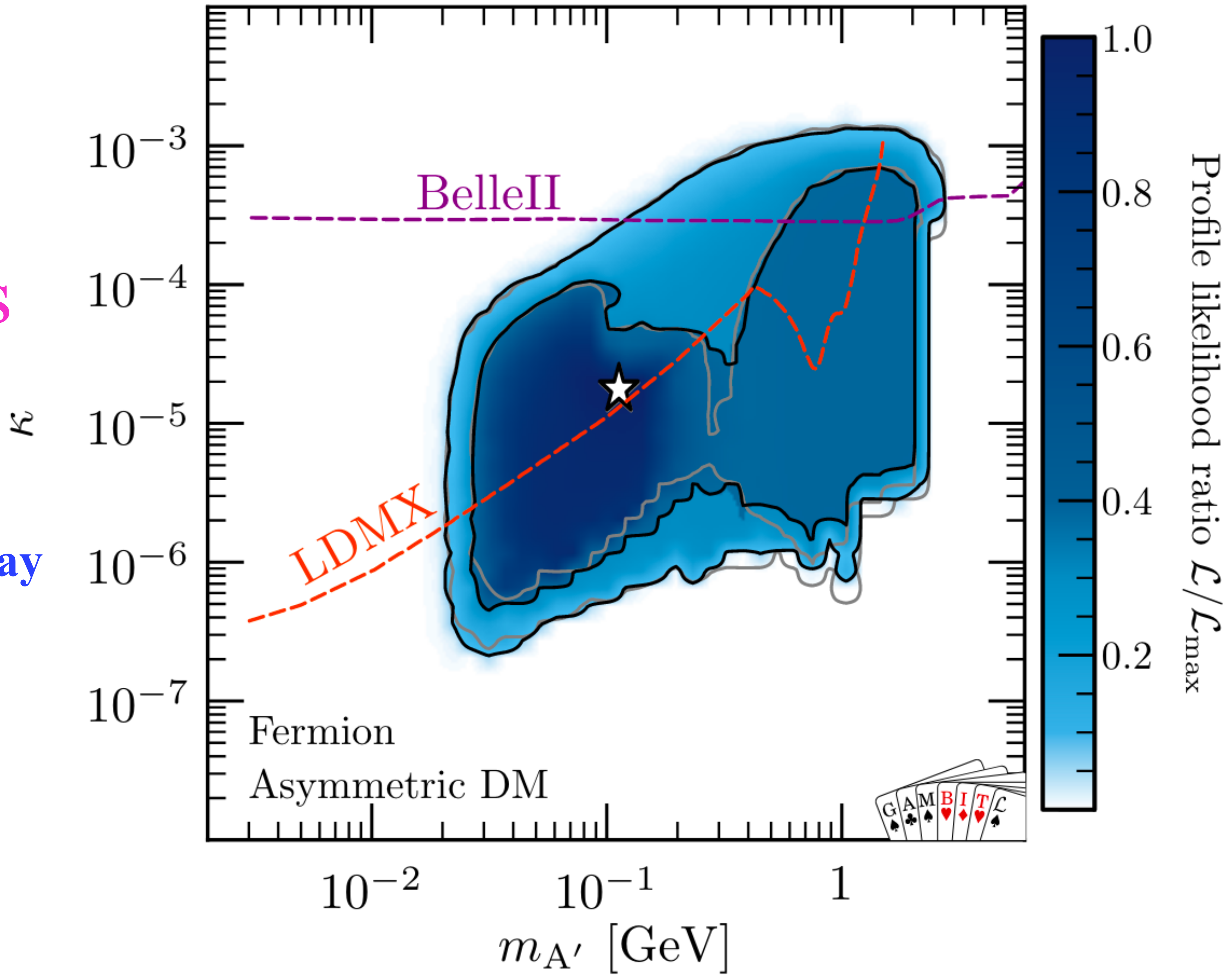
2. Assymetric: $\eta \equiv \frac{n_{DM} - n_{\overline{DM}}}{s} > 0$

3. Sub-component: $f \equiv \frac{\Omega_{DM} h^2}{\Omega_{DM,obs} h^2} < 1$

# Global Fits of sub-GeV DM: Frequentist analysis

Dirac DM subject to **strong constraints** from **CMB** and **X-ray** observations

- Requires tuning of $m_A'/m_{DM}$
  → Relax with **asymmetry**



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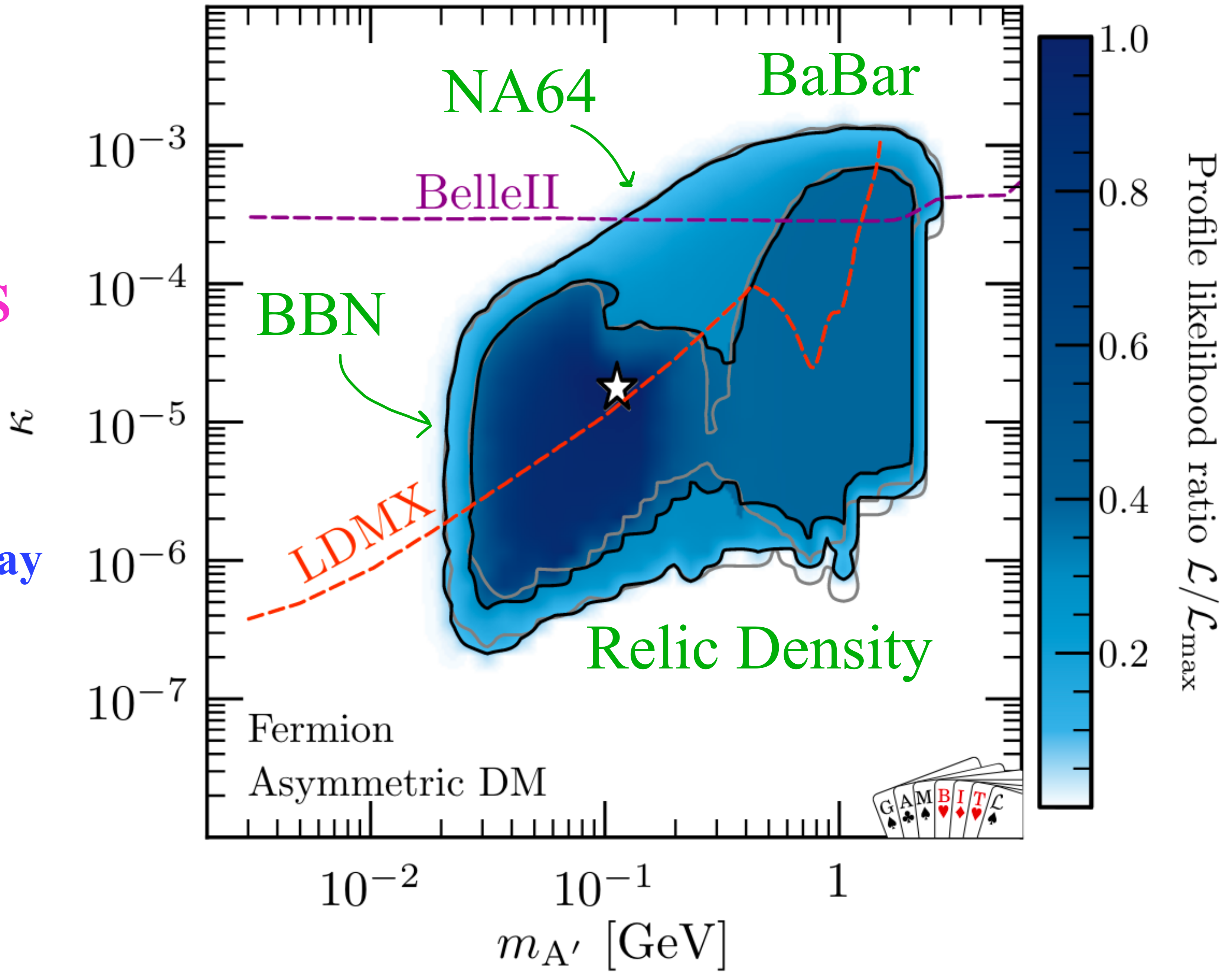

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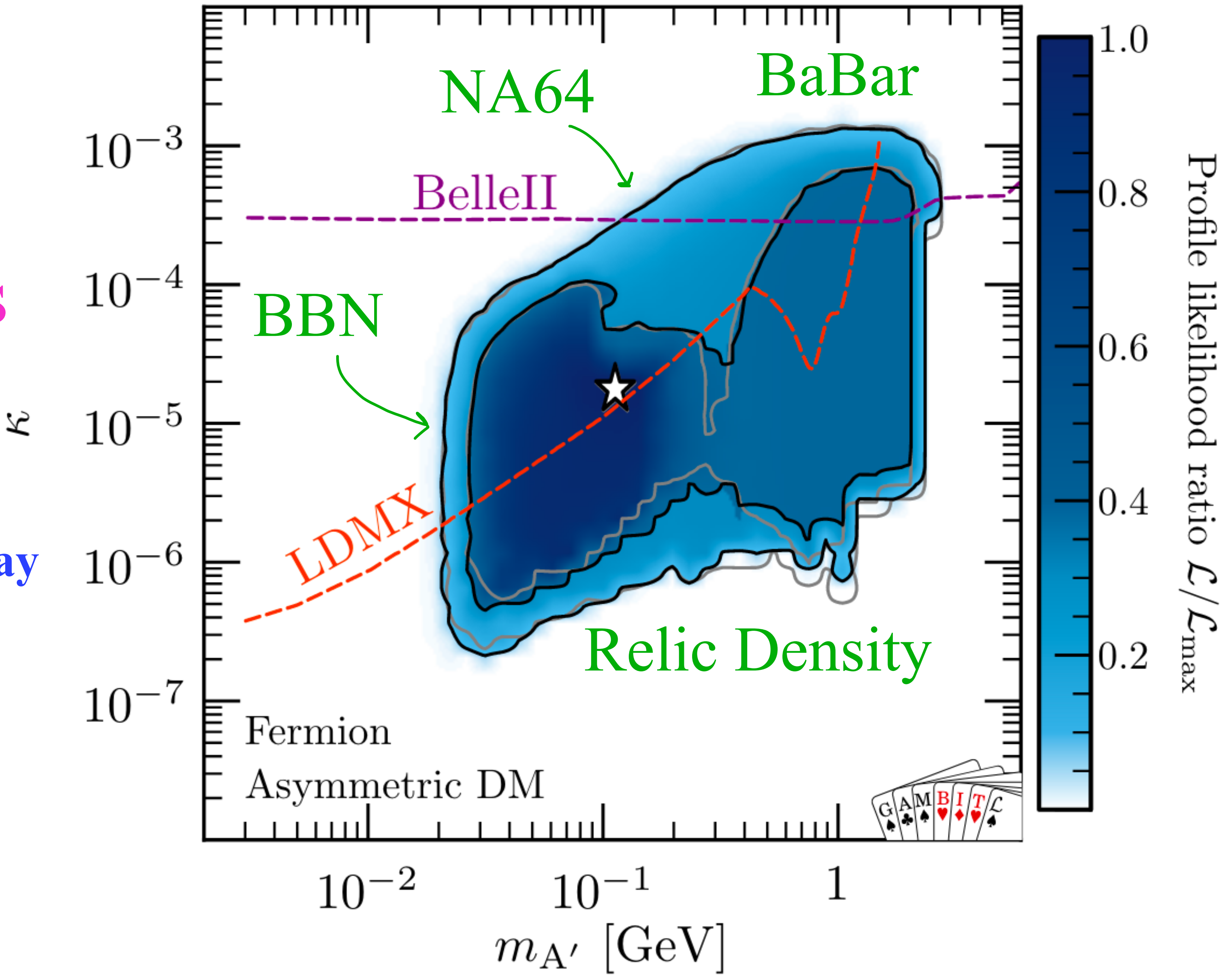
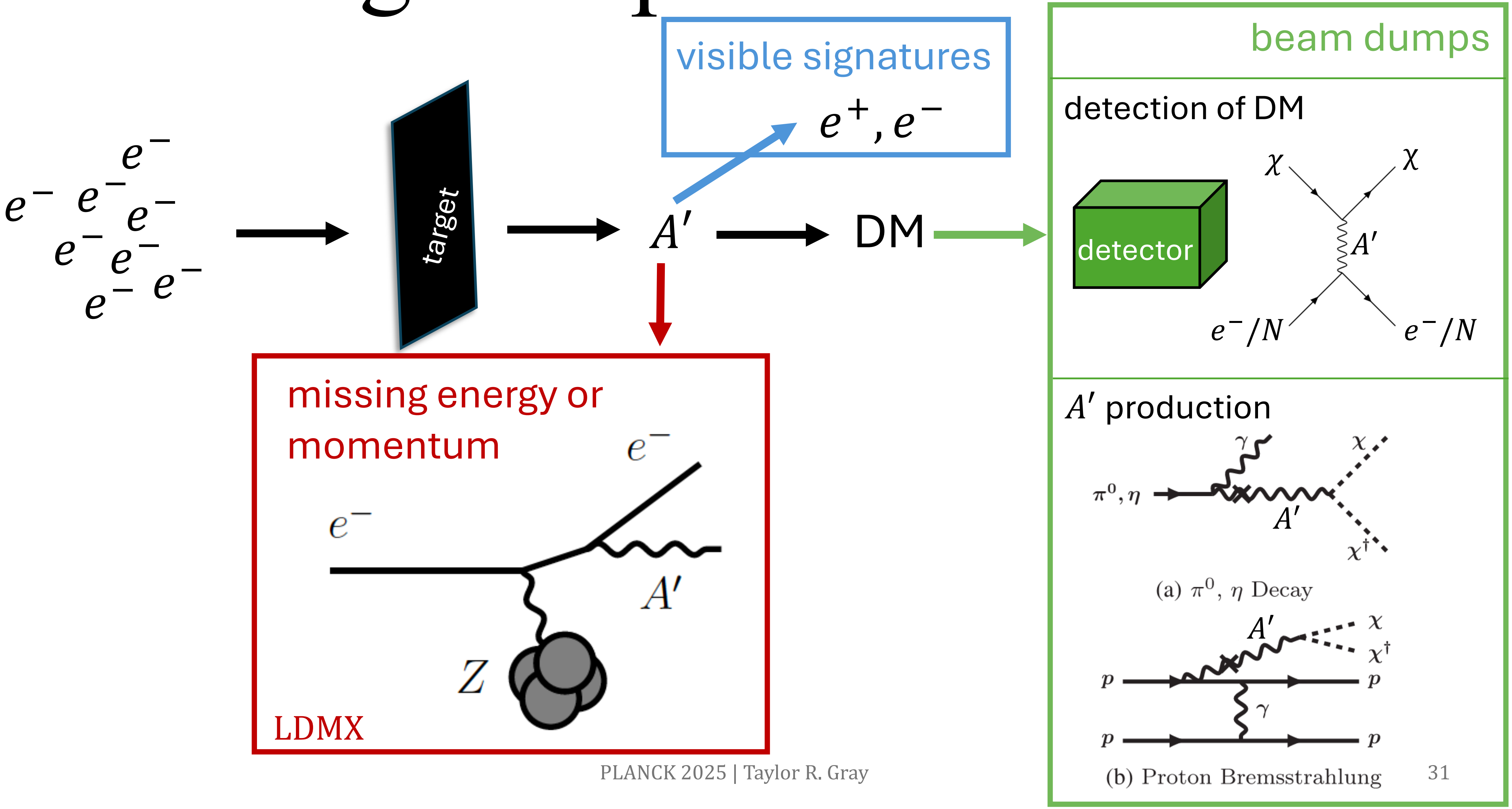
**LDMX** will probe **64%** of the posterior volume!



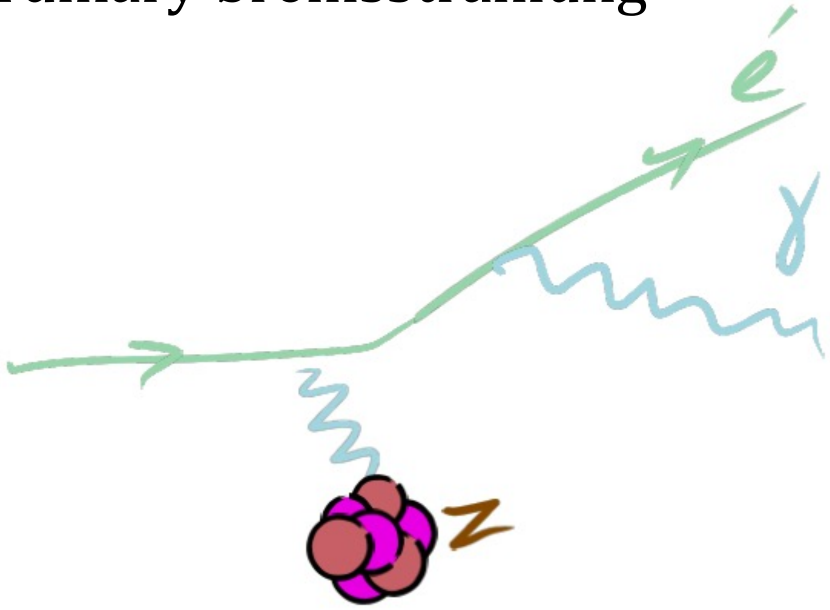
# Fixed Target Experiments



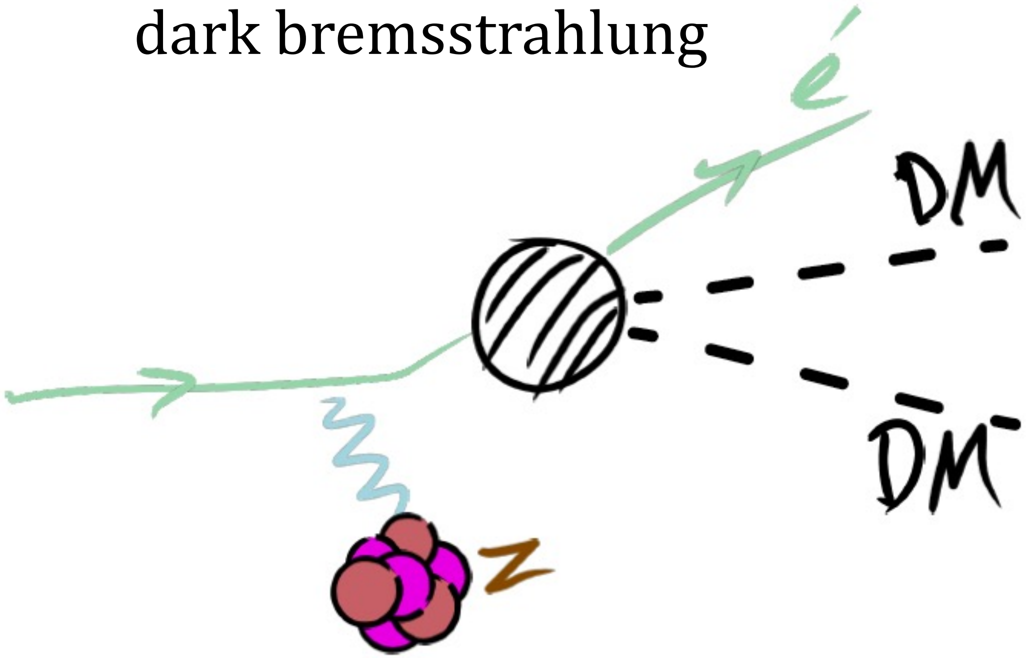
# Missing Momentum Experiment

*such as LDMX*

ordinary bremsstrahlung




dark bremsstrahlung




Einar Elen

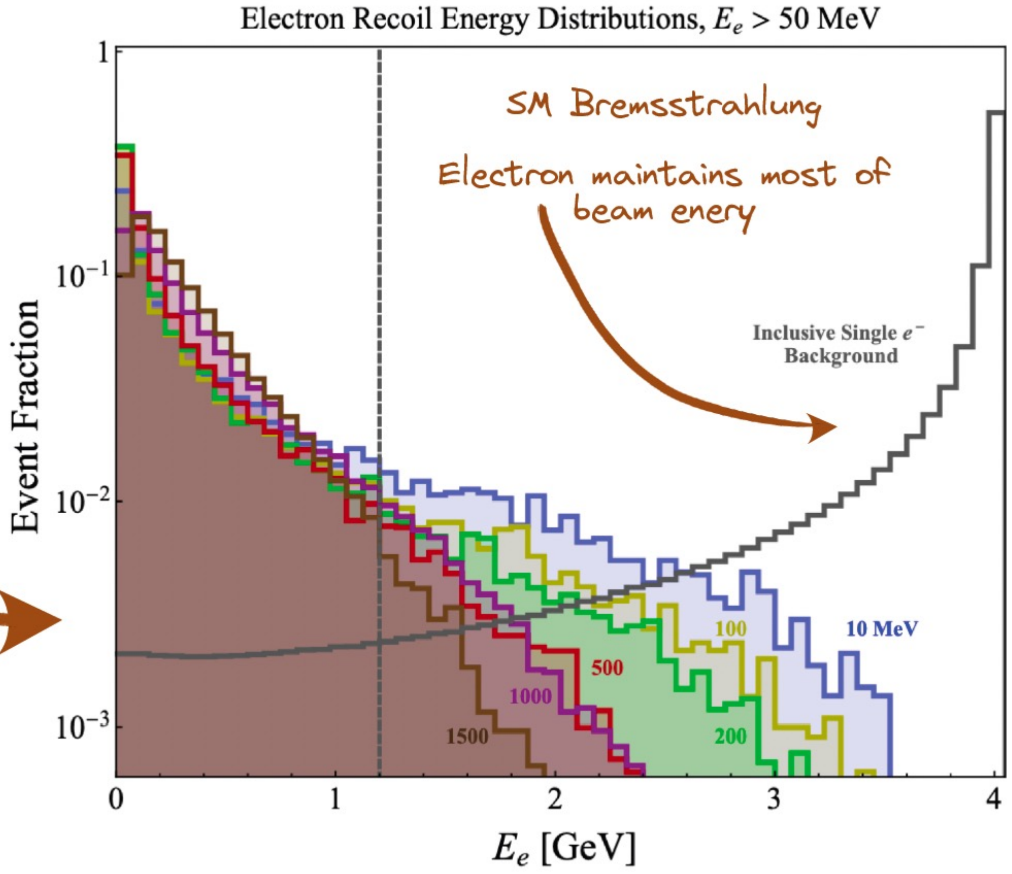
# Missing Momentum Experiment

*such as LDMX*

- How does $eA \to eA + \gamma$ differ from $eA \to eA + \chi\bar{\chi}$
- Key difference:
  - Dark object has mass
  - Fundamentally different kinematics, regardless of model

DM Bremsstrahlung

Dark object carries most of beam enery




Einar Elen

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*such as LDMX*

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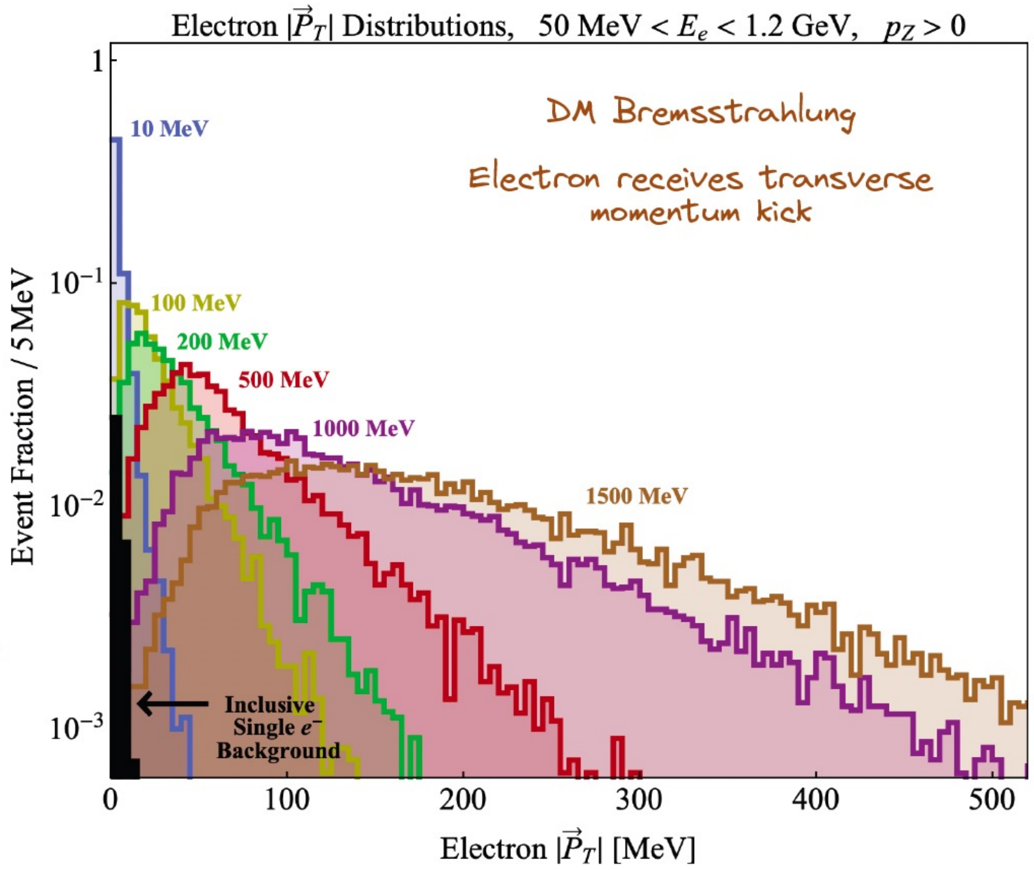
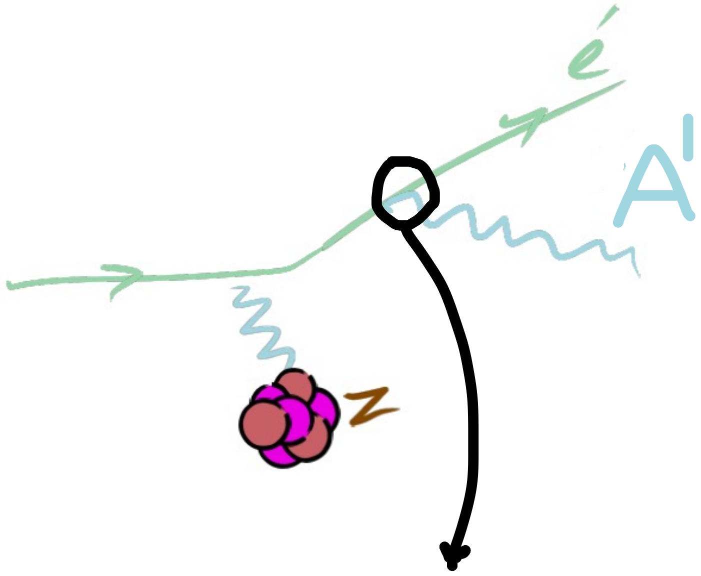
SM Bremsstrahlung

Electron continues with small scattering angle

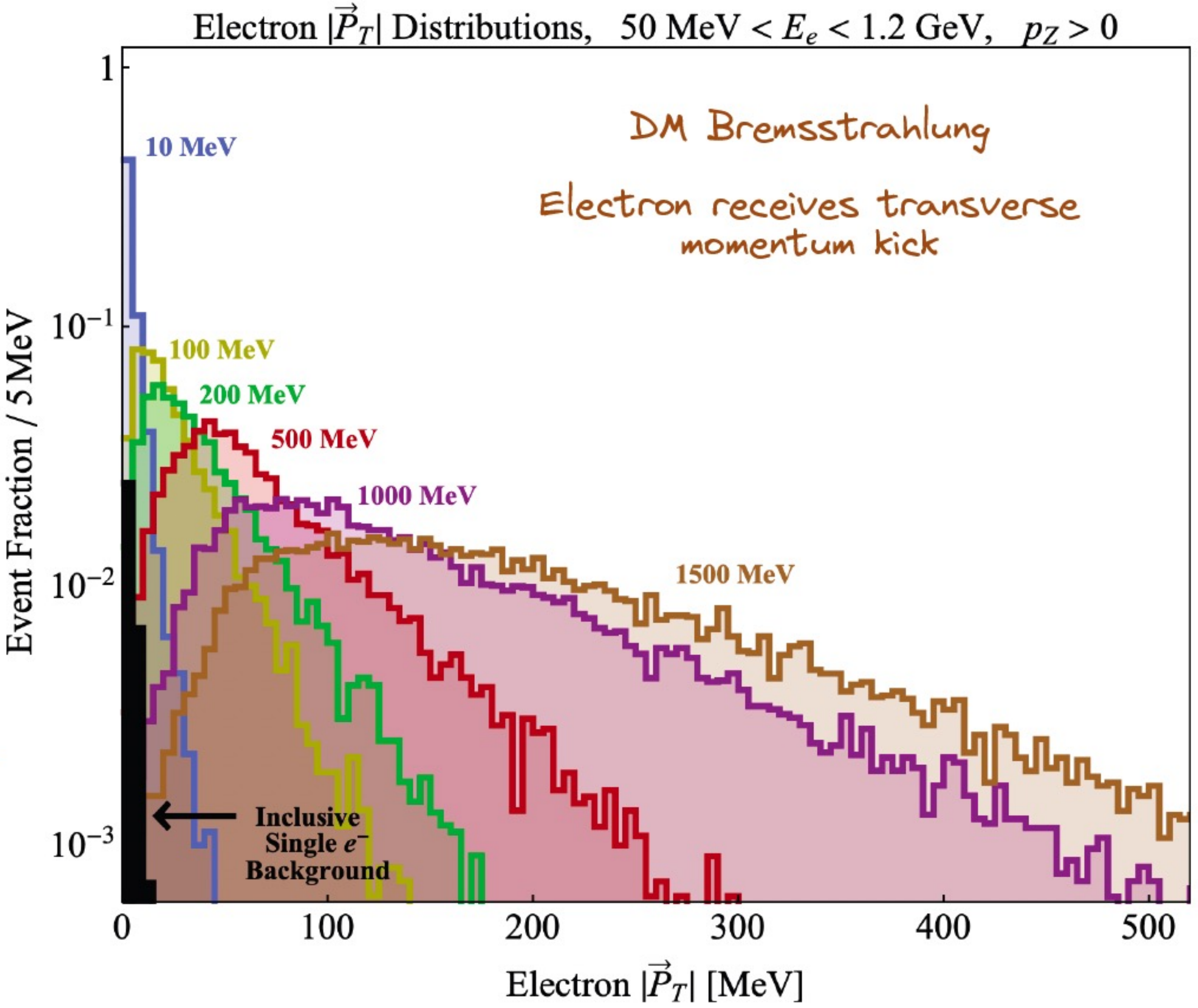


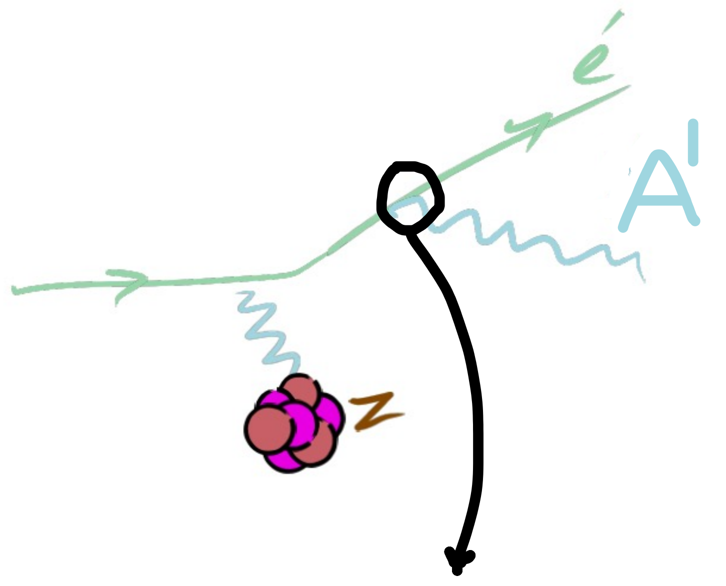

Einar Elen




**Standard Kinetic Mixing:**

$$\mathscr{L}_{A'f} = -\, e\varepsilon Q_f \bar{f}\gamma^{\mu} f A'_{\mu}$$

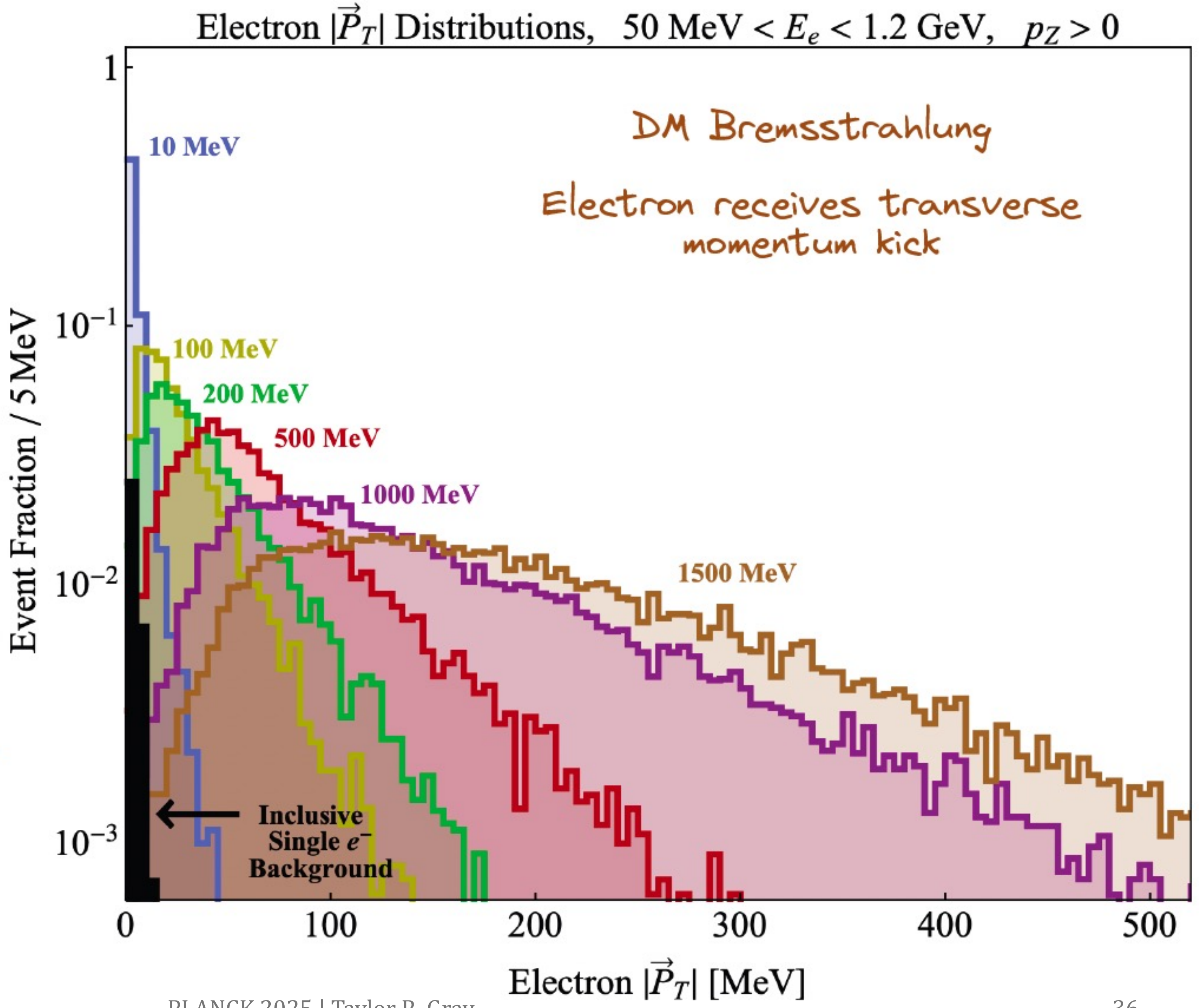





**Standard Kinetic Mixing:**

$$\mathscr{L}_{A'f} = -\,e\varepsilon Q_f \bar{f}\gamma^{\mu} f A'_{\mu}$$

+ other interactions?



# Production of Dark Photons through Higher Electromagnetic Moments at LDMX:

*Simulations and Model Discrimination*

In collaboration with:
Riccardo Catena and Thomas Jerkvall

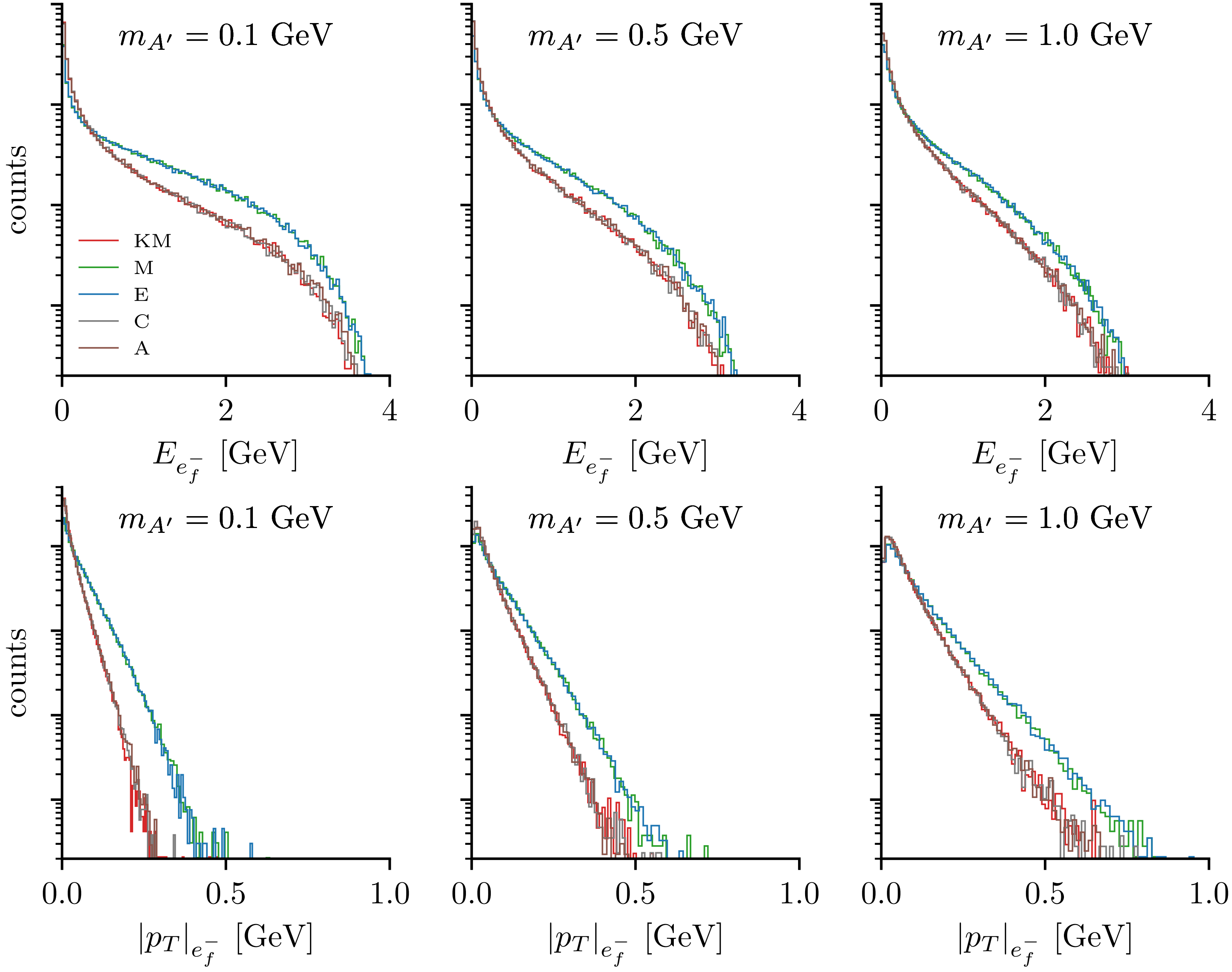
$$
\begin{aligned}
\mathscr{L}_{A'f} = & -\boxed{e\varepsilon Q_f \bar{f}\gamma^\mu f A'_\mu} - \boxed{i\mu_f \partial_\nu \left(\bar{f}\sigma^{\mu\nu} f\right) A'_\mu} + \boxed{d_f \partial_\nu \left(\bar{f}\sigma^{\mu\nu}\gamma^5 f\right) A'_\mu} \\
& - \boxed{b_f \left[\partial^\nu \partial_\nu \left(\bar{f}\gamma^\mu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

T. Rizzo arXiv:2106.11150

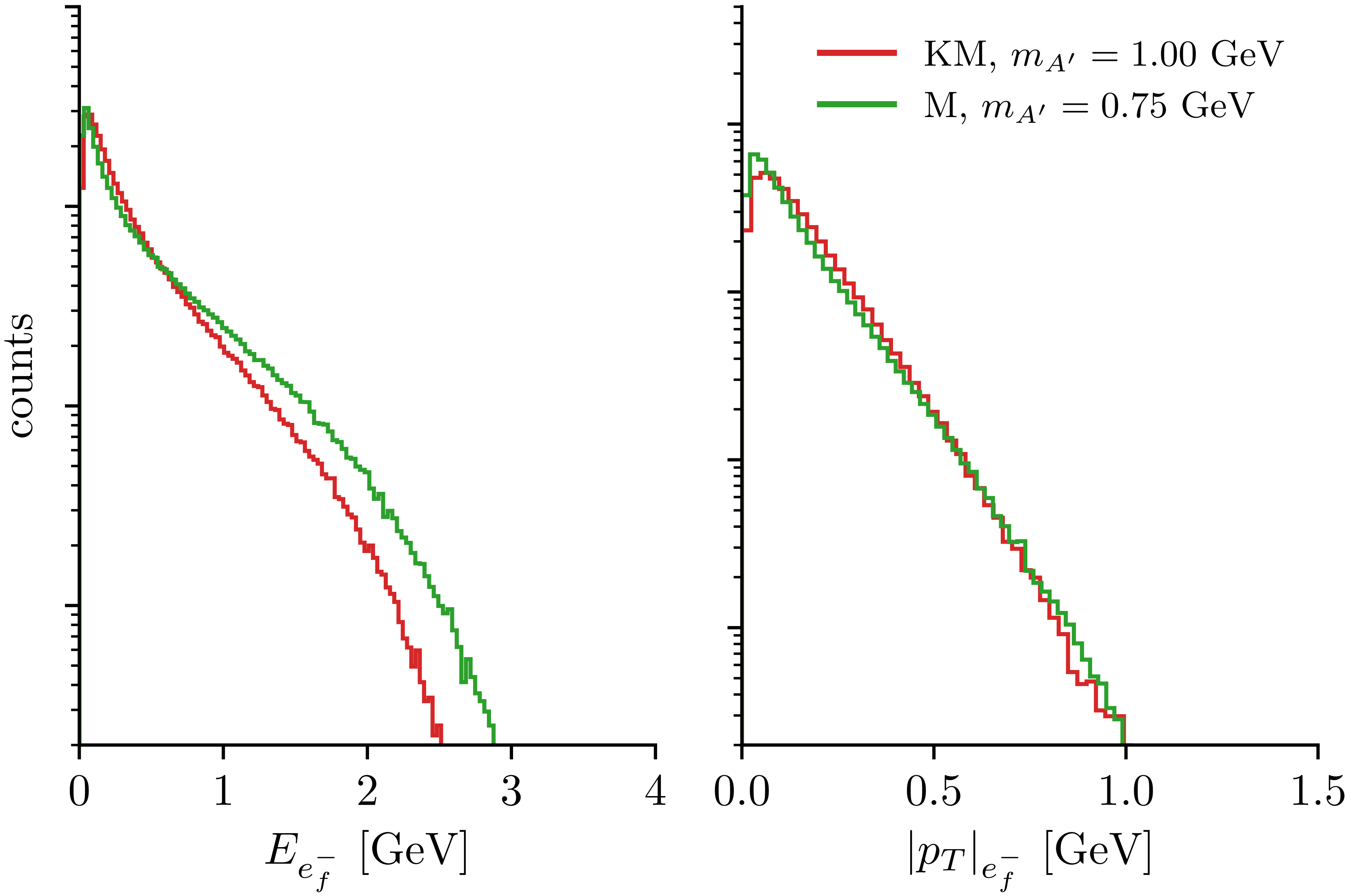
- ordinary kinetic mixing (KM)
- magnetic dipole (M)
- electric dipole (E)
- charge radius (C)
- anapole moment (A)

# Kinematic Distributions at LDMX

- 3 groups
- Characterized by **overall cross section size** and **momentum dependence in Lorentz structures** of models

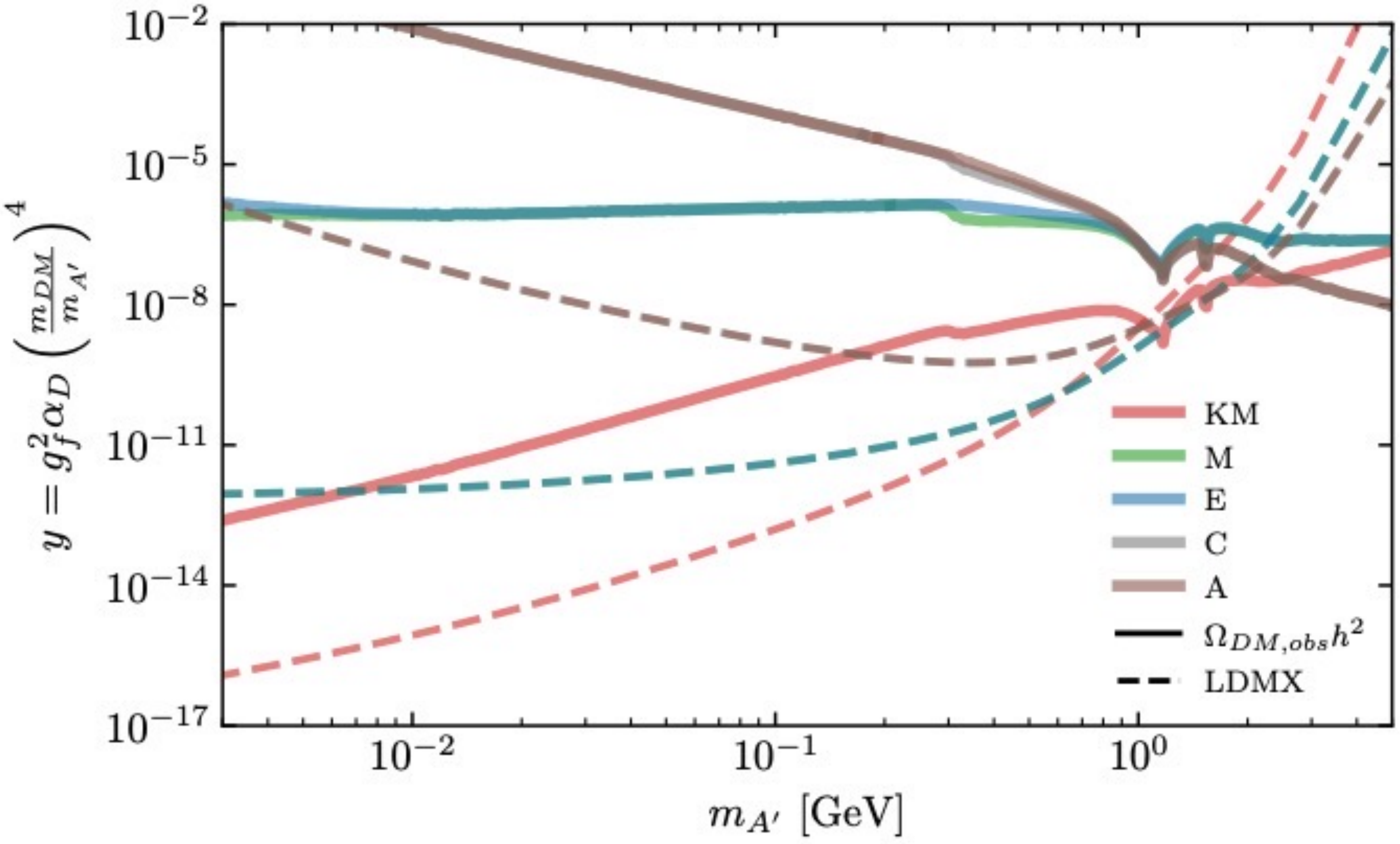


# Degeneracy between mass and model




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

# LDMX phase II projected exclusion bounds

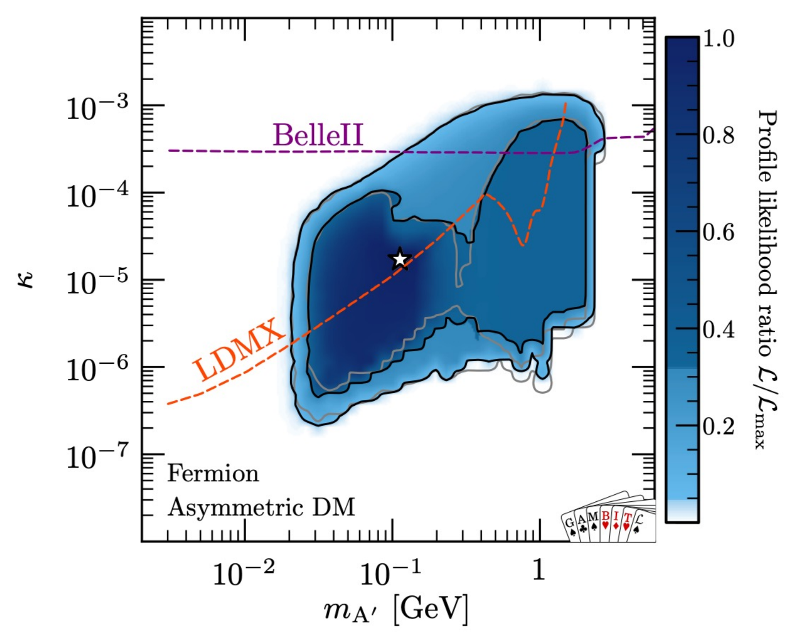


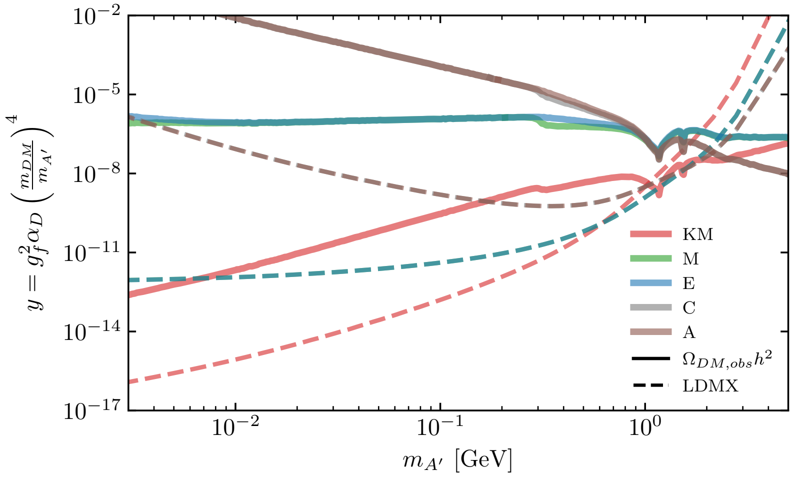
# Summary

- Frequentist and Bayesian global fits of 2 **sub-GeV DM** models using **GAMBIT**
  - Fermionic DM
    - Preferred region is resonant freeze-out
    - Or, introduce asymmetry
  - Scalar DM
    - Weak indirect detection constraints
    - Subject to constraints from fixed target/collider experiments

- Extending the theoretical landscape of fixed target experiments
  - *Higher Electromagnetic Moment* DP model
    - Model dependent signatures at **LDMX**
    - Degeneracy between $m_{A'}$ and model

Thank you for listening : )

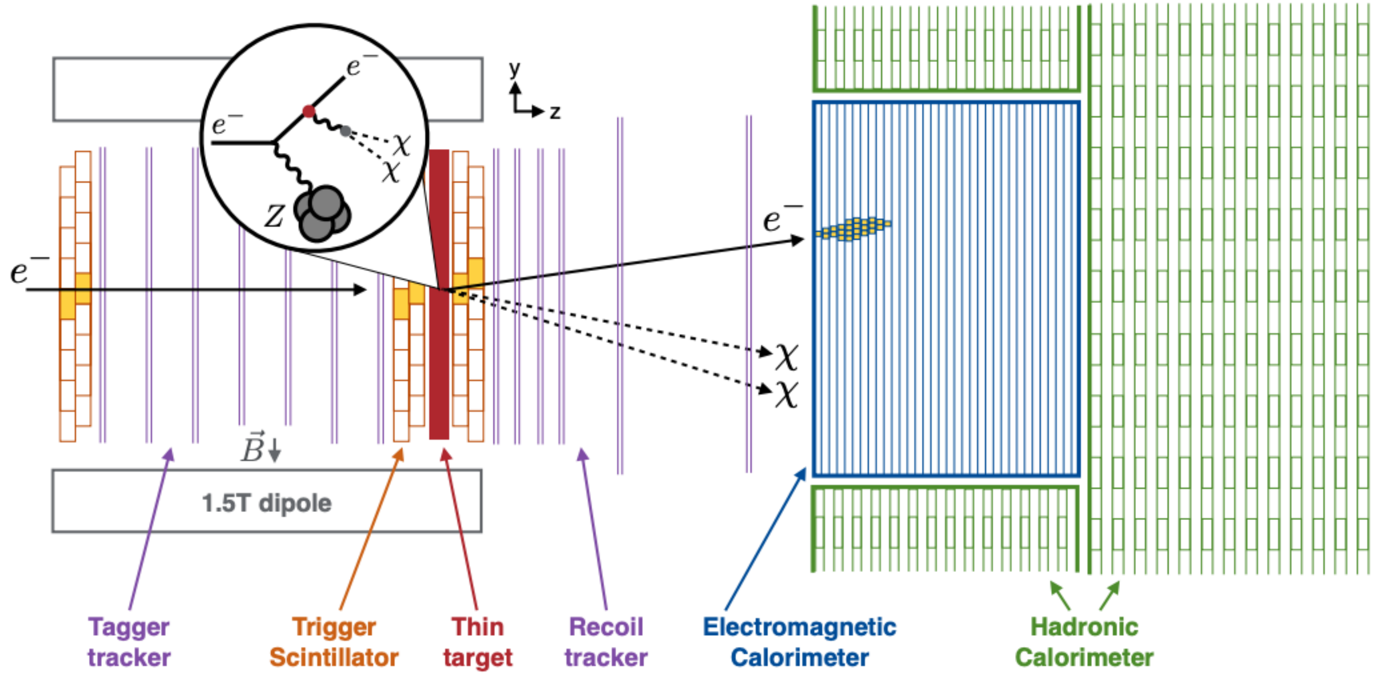


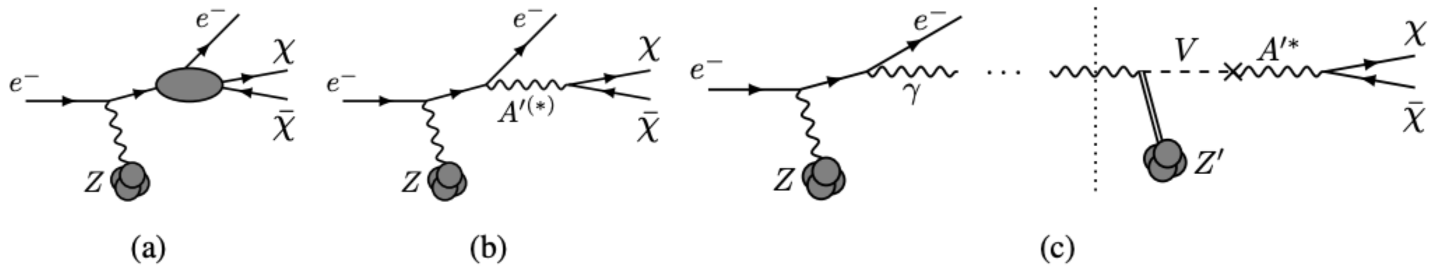



# Additional Material

# Light Dark Matter eXperiment (LDMX)

- Future fixed target missing momentum exp
  - 2025: LESA delivers beam to LDMX allowing $4\times10^{14}$ 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



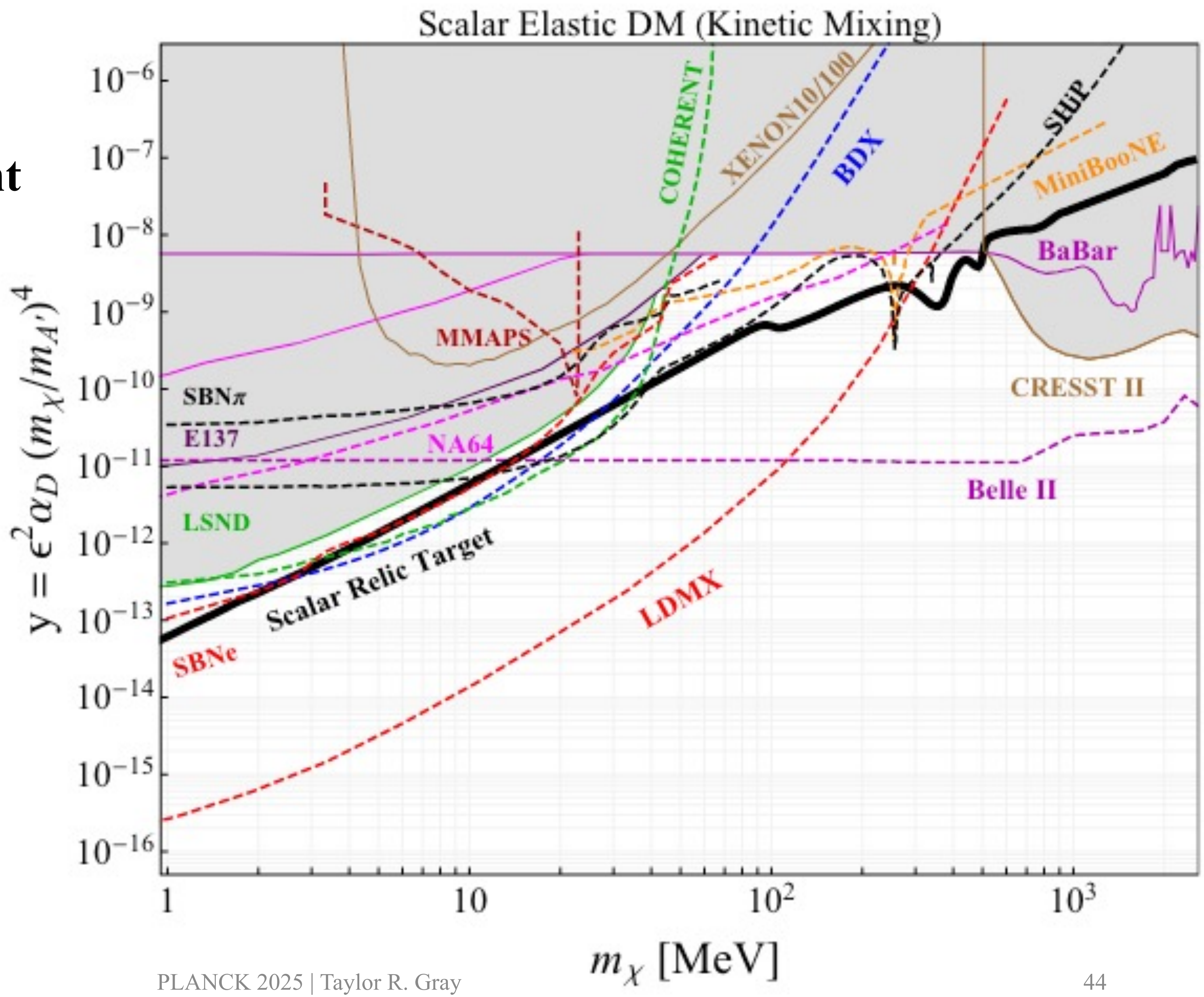




**STATUS**

- testing properties of the beam upstream
- late 2025 – preparing vertical slice test
- 2026 -- begin construction (approx 3 years)

# LDMX

a future **fixed target experiment**



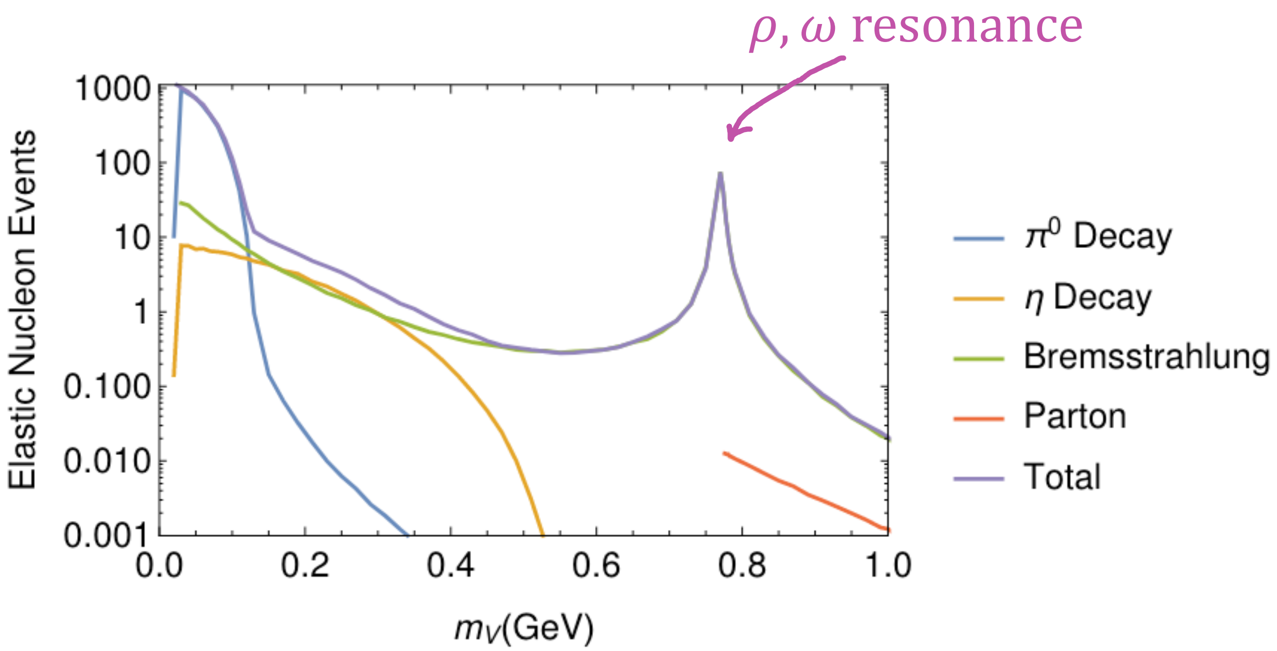
# Beam Dumps (Electron and Proton)

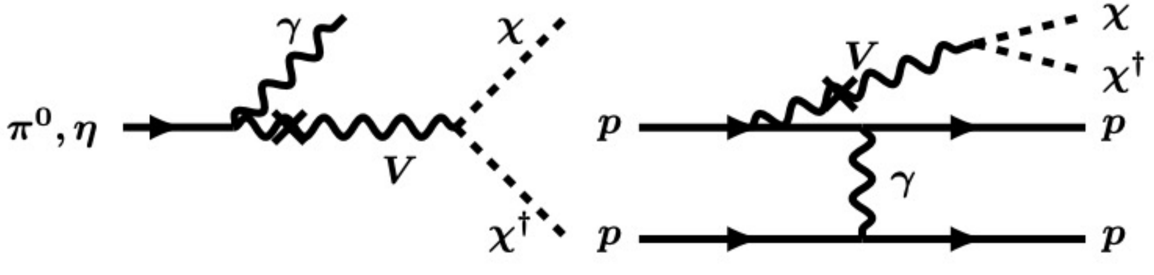
## Dark Photon/DM Production

i. Mesons from proton beam – nucleon target interactions
   *i.* $\pi^0, \eta \to \gamma A', A' \to \chi\chi$

ii. Proton/electron dark bremsstrahlung
   *i.* $pN \to pNA'$
   ii. resonant vector meson mixing

iii. Direct production through parton level processes
   i. relevant for $m_{A'} > 1$ GeV



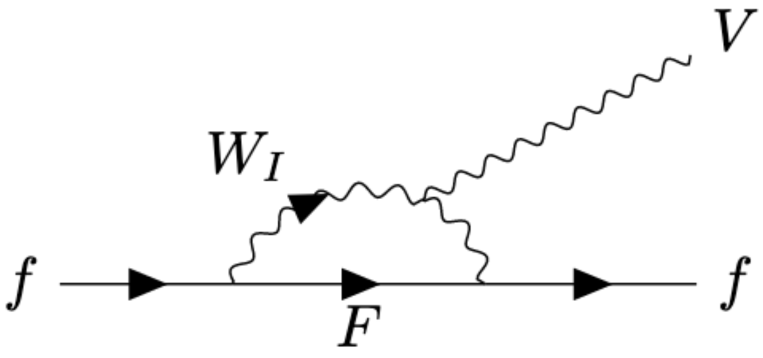

(a) $\pi^0$, $\eta$ Decay (b) Proton Bremsstrahlung

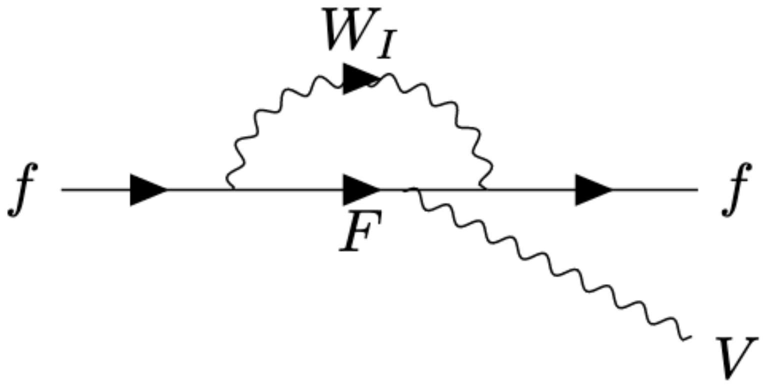
# Dark moment models

- Diagrams with loops of portal matter (PM) fields
  - PM fields: set of fields carrying both SM and dark charges, vector-like fermions

- Consider a group G under which PM fields occur in the same representation
- G becomes broken at some scale > U(1)D
- New massive gauge bosons
  - Which generate new loop diagrams/interactions

# Dark magnetic dipole model:



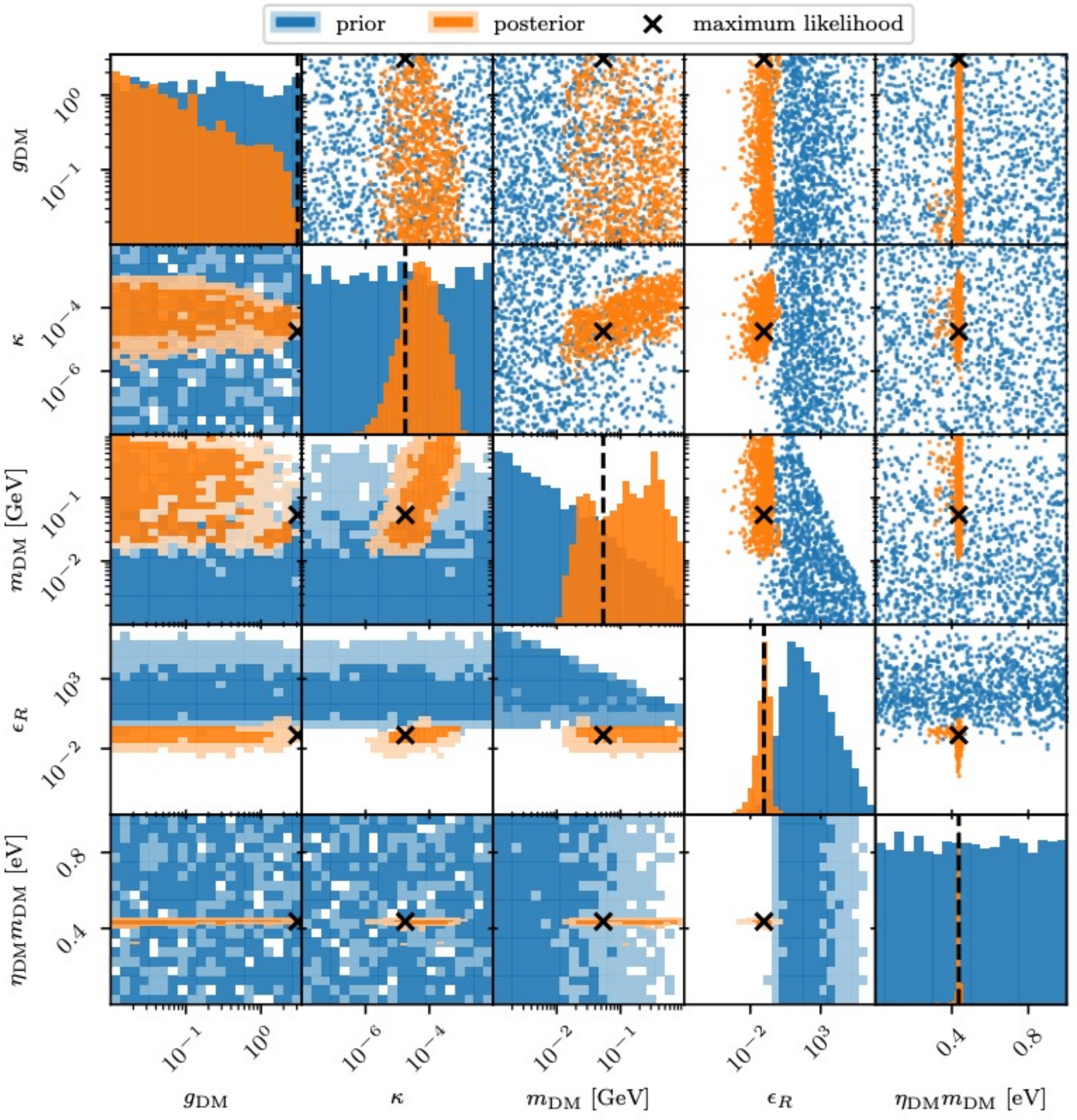




- **Dark SU(2)xU(1), fully broken**
- We have PM fermion fields (F) and new gauge bosons ($W_I$)
  - Masses at or above TeV scale to evade LHC
- SM and PM fermion fields in doublet rep. of SU(2) -> carrying same quantum numbers

# Global Fits of sub-GeV DM: Bayesian analysis

Asymmetric full component Dirac fermion DM

- Fine tuning is penalized
- Highly asymmetric is preferred
    - Relaxes other constraints



# GAMBIT Priors

**Table 1**. List of model parameters and their ranges. For frequentist scans, the prior is only used to determine the sampling strategy. Our scans also include several nuisance parameters as discussed in the text. The likelihoods that we consider are presented in section 3 and summarized in appendix E.

| **Parameter name** | **Symbol** | **Unit** | **Range** | **Prior** |
|---|---|---|---|---|
| Kinetic mixing | $\kappa$ | – | $[10^{-8}, 10^{-2}]$ | logarithmic |
| Dark sector coupling | $g_{\mathrm{DM}}$ | – | $[10^{-2}, \sqrt{4\pi}]$ | logarithmic |
| Asymmetry parameter | $\eta_{\mathrm{DM}}$ | – | $[0, 10^{-9}\,\mathrm{GeV}/m_{\mathrm{DM}}]$ | linear |
| Dark matter mass | $m_{\mathrm{DM}}$ | MeV | [1,1000] | logarithmic |
| Dark photon mass | $m_{A'}$ | MeV | [2,6000] with $m_{A'} \geq 2m_{\mathrm{DM}}$ | logarithmic |
| *or* | | | | |
| Resonance parameter | $\epsilon_R$ | – | $[10^{-3},8]$ | logarithmic |

# Samplers

## Frequentist:

arXiv:1705.07959

- Differential evolution sampler
- Profile likelihood
  - (Computationally more expensive)

## Bayesian: PolyChord

arXiv:1502.01856

- Nested sampling algorithm
- Posterior distribution of parameters given the prior