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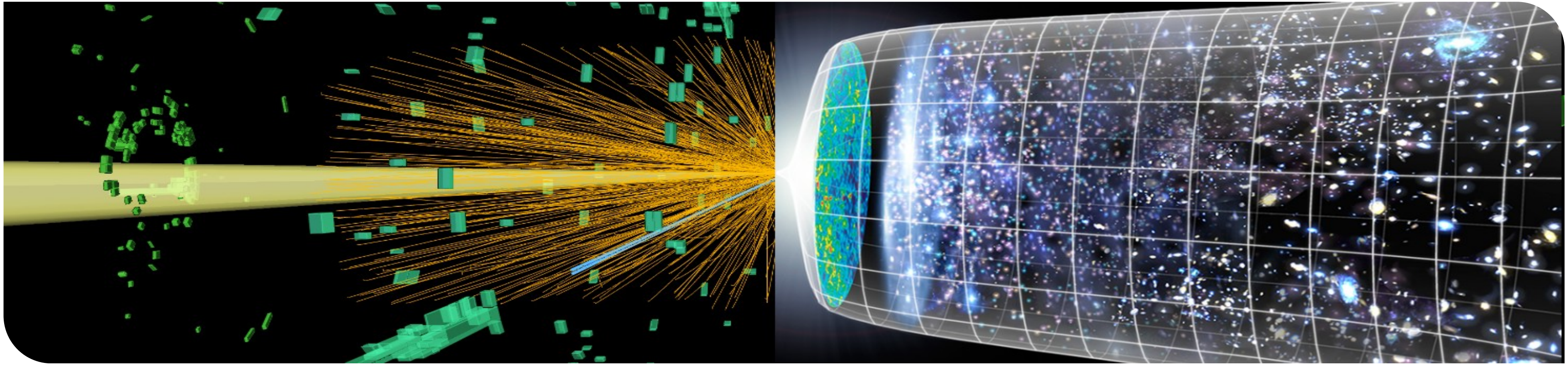
Resonant or asymmetric?
The status of sub-GeV dark matter

Felix Kahlhoefer

GUINEAPIG 2024 Workshop on Light Dark Matter
University of Toronto & online, 20-22 August 2024



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Resonant or asymmetric?
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Based on **arXiv:2405.17548** in collaboration with

Sowmiya Balan, Csaba Balázs, Torsten Bringmann, Christopher Cappiello,
Riccardo Catena, Timon Emken, Tomás E. Gonzalo, **Taylor R. Gray**,
Will Handley, Quan Huynh, Aaron Vincent

Definition: Sub-GeV dark matter

Particles with mass below the GeV scale that are in thermal equilibrium in the early universe and obtain their relic abundance via the freeze-out mechanism

Definition: Freeze-out mechanism

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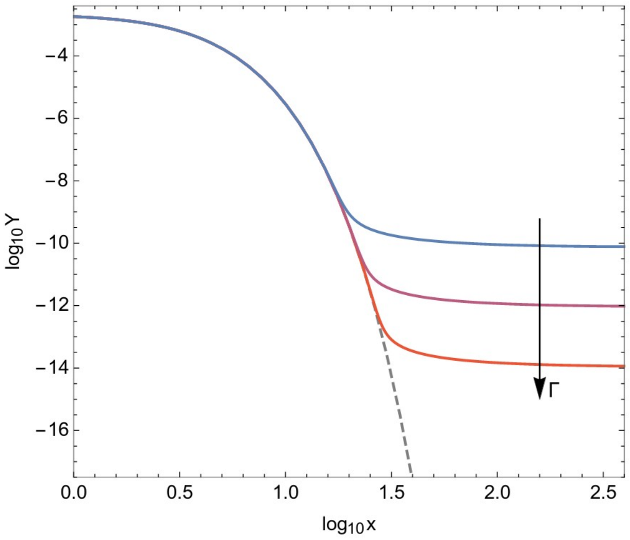
- DM production and annihilation processes are in equilibrium in early universe
- As universe cools down, DM particles depart from equilibrium (freeze-out)
- DM abundance set by freeze-out temperature



- **Lee-Weinberg bound:** For a GeV-scale particle with weak interactions one finds

$$\Omega h^2 \sim (2\ \mathrm{GeV} / m_{DM})^2 < 0.12 \rightarrow \mathrm{mDM} > 5\ \mathrm{GeV}$$

Definition: Sub-GeV dark matter

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Particles with mass below the GeV scale that are in thermal equilibrium in the early universe and obtain their relic abundance via the freeze-out mechanism

Implication 1: Sub-GeV dark matter requires a new type of interactions

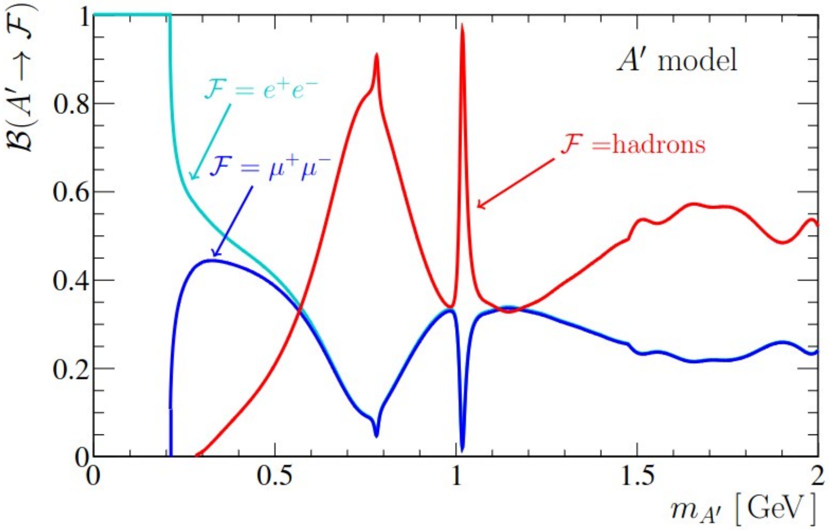
Dark photons

- Simple and attractive possibility: Consider a new U(1)' gauge symmetry
- Gauge symmetry spontaneously broken (or Stueckelberg mechanism)

  → Massive gauge boson

- Interactions with SM through kinetic mixing
- Couplings proportional to charge
- Decay modes can be inferred from data

Ilten et al., arXiv:1801.04847



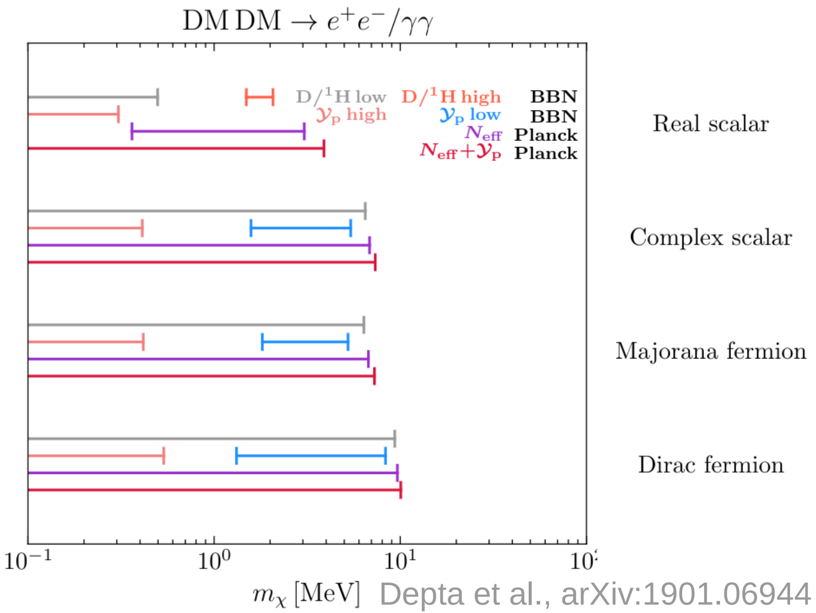
Cosmological constraints (I)

- In the MeV-range dark photons decay dominantly into leptons

- Effects on cosmological observables:
  - Heating of electron-photon plasma after neutrino decoupling

    → modification of effective relativistic degrees of freedom (N_{eff})
  - Photodisintegration of heavier elements

    → modification of element abundances



Depta et al., arXiv:1901.06944

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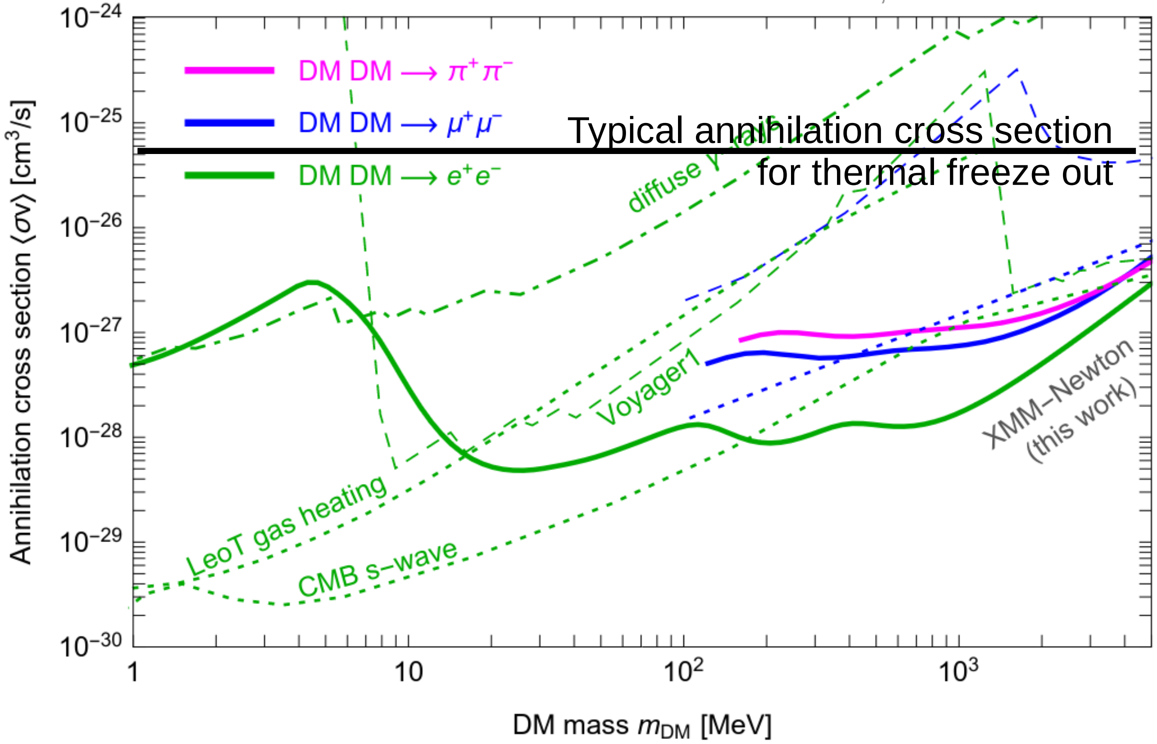
Implication 1: Sub-GeV dark matter requires a new type of interactions

Implication 2: Sub-GeV dark matter must have a mass above ~10 MeV

Cosmological constraints (II)

Cirelli et al., arXiv:2303.08854

- DM annihilations during recombination leave an imprint on the CMB
- DM annihilations in the present universe lead to observable x-ray signals
- Constraints many orders of magnitude stronger than thermal cross section



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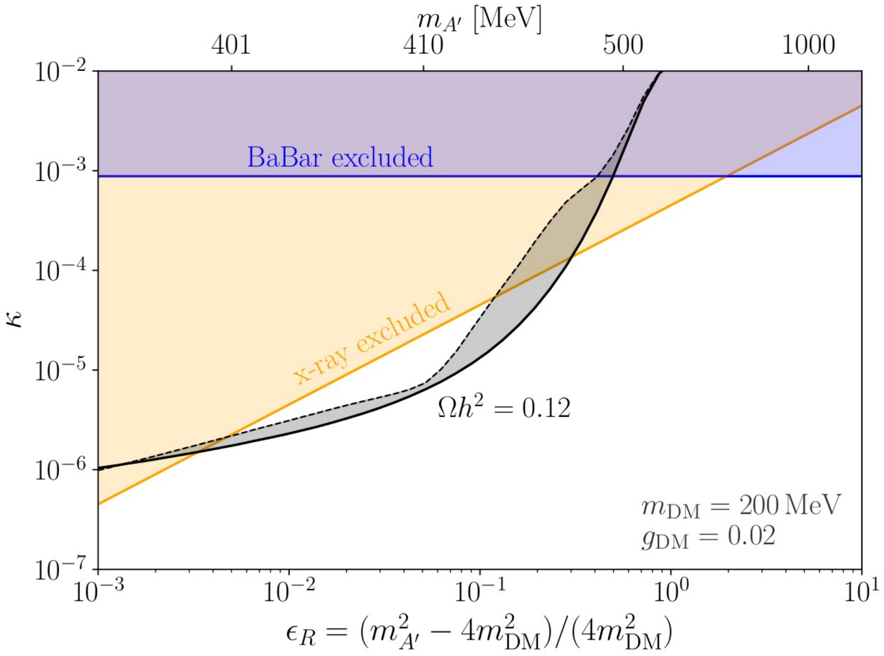
Implication 3: Sub-GeV dark matter must suppress late-time annihilations

Possibility 1: Velocity-dependent annihilation

- Simplest solution: Consider p-wave annihilation ($\sigma v \sim v^2$)
- Automatically guaranteed for scalar DM
- For fermionic DM, consider resonance parameter

$$\epsilon_R = \frac{m_{A'}^2 - 4m_\chi^2}{4m_\chi^2}$$

- For $\varepsilon_R \ll 1$, annihilations are enhanced during freeze-out and suppressed at later times



Possibility 2: Particle-antiparticle asymmetry

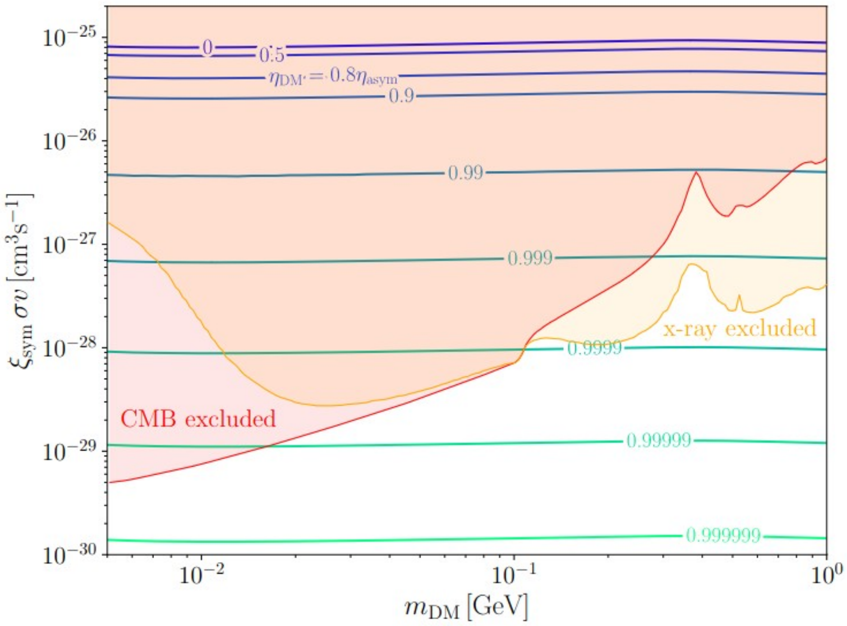
- DM asymmetry given by

$$\eta_{\rm DM} \equiv \frac{n_\chi - n_{\overline{\chi}}}{s}$$

- Observed relic abundances implies

$$\eta_{\rm DM} \leq \frac{4.33 \times 10^{-10}\,{\rm GeV}}{m_{\rm DM}} \equiv \eta_{\rm asym}(m_{\rm DM})$$

- For $\eta_{\rm DM}$ close to $\eta_{\rm asym}$ almost no anti-particles remain in the present universe
  → late-time annihilations are suppressed



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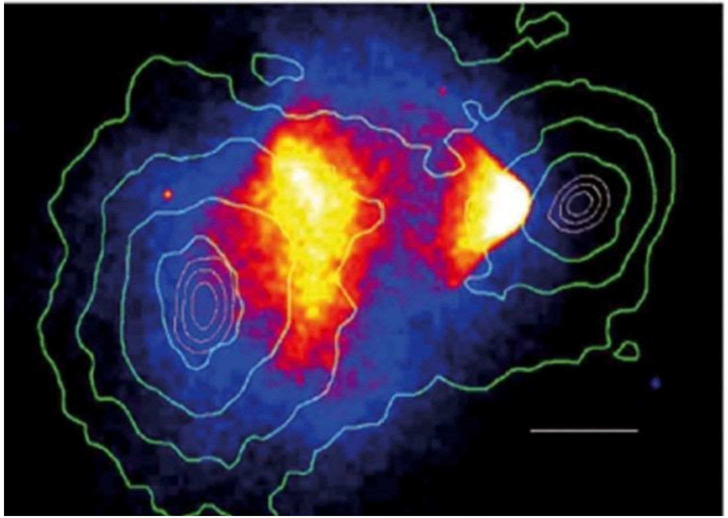
Model summary

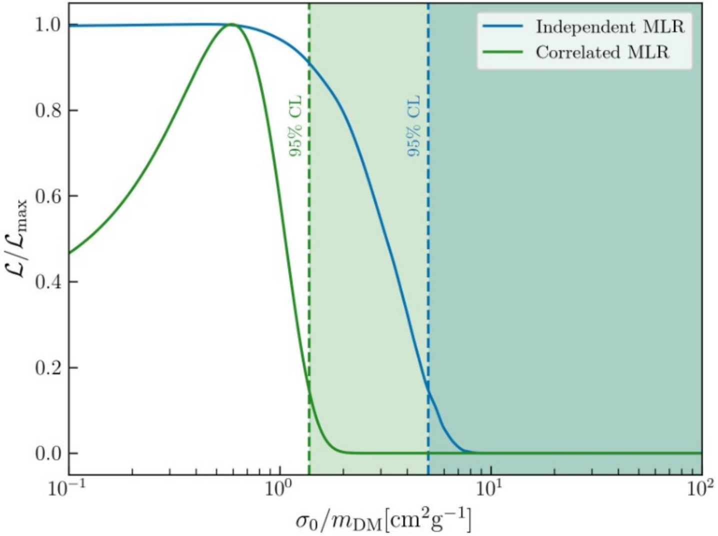
- Four model parameters:
  - Dark matter mass m_{DM} → consider range [1 MeV, 1 GeV]
  - Dark photon mass $m_{A'}$ → replaced by resonance parameter $\epsilon_R = \frac{m_{A'}^2 - 4m_\chi^2}{4m_\chi^2}$
  - Dark gauge coupling g_{DM} → perturbativity bound $g_{DM} < \sqrt{4\pi}$
  - Kinetic mixing κ → electroweak precision tests: $\kappa < 10^{-2}$

- For fermionic DM consider also $\eta_{\mathrm{DM}} \equiv \frac{n_\chi - n_{\overline{\chi}}}{s}$

Constraints: Self-interactions

- Further bound on g_{DM} from Bullet Cluster (non-evaporation of sub-cluster)
- Symmetric DM: Bound approximately given by $\sigma_0/m_{DM} < 1.4\ \text{cm}^2\ \text{g}^{-1}$





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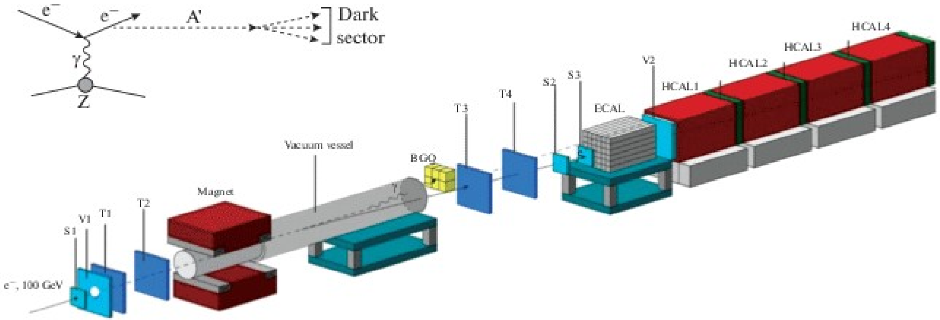
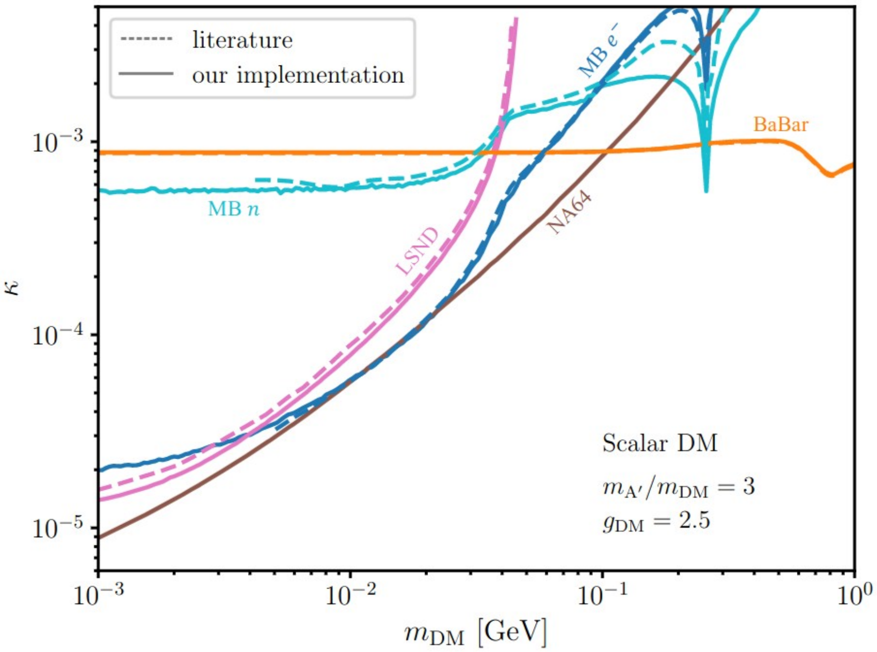
Constraints: Accelerator experiments

- Missing energy searches:
  - BaBar and NA64



- Searches for DM scattering:
  - LSND and MiniBooNE



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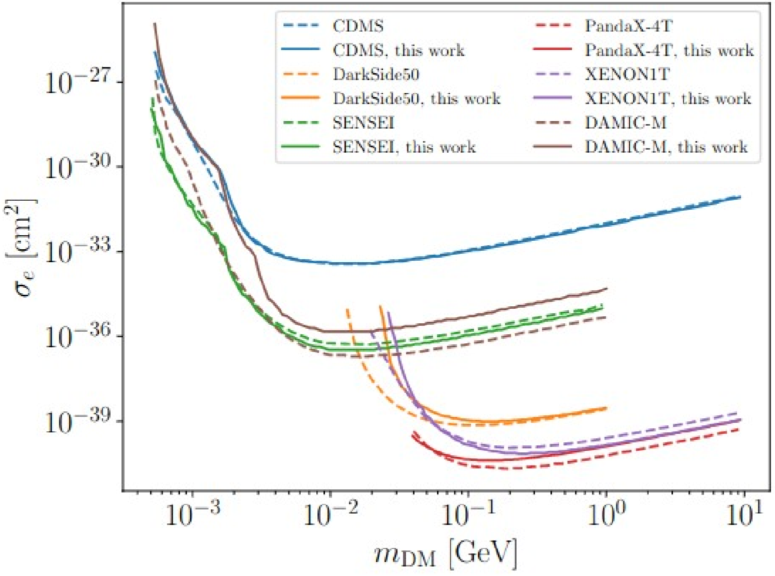
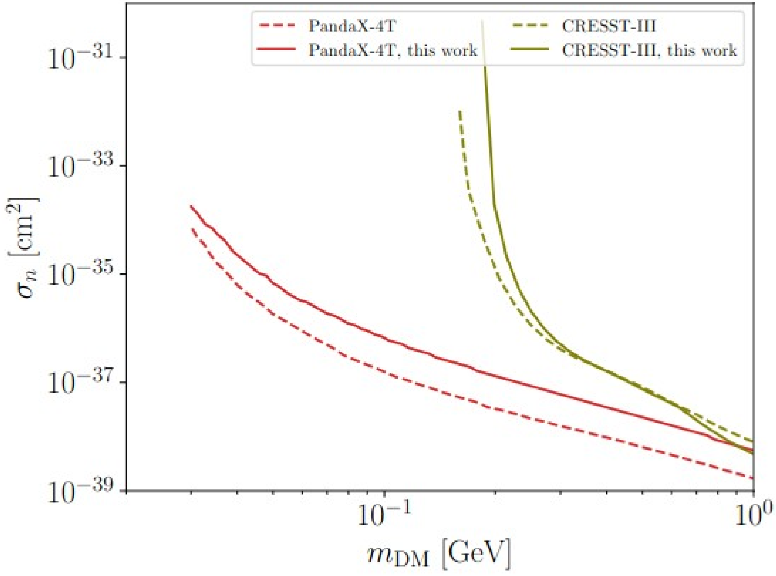
Constraints: Direct detection

DM-electron scattering



DM-nucleus scattering (including Migdal effect)



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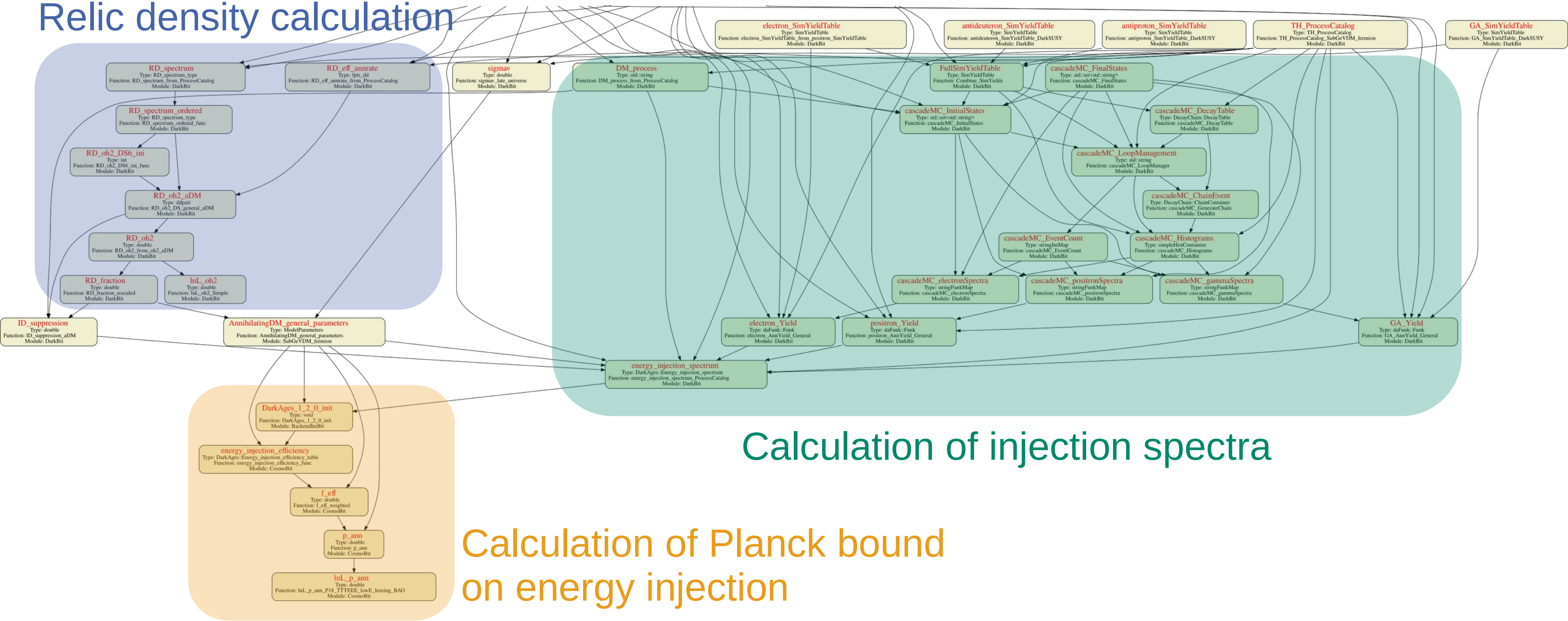
GAMBIT:
The Global And Modular BSM Inference Tool

- An international community with 50+ collaborators (experiments + theorists)
- A software framework for global fits developed over the past decade
  - Automated construction of composite likelihoods for a given model
  - Efficient scans of multi-dimensional parameter space
  - Consistent treatment of uncertainties and nuisance parameters
  - Maximum of flexibility and modularity in terms of data sets and models
  - Optimized for parallel computing & fully open source

Part of the GAMBIT dependency tree



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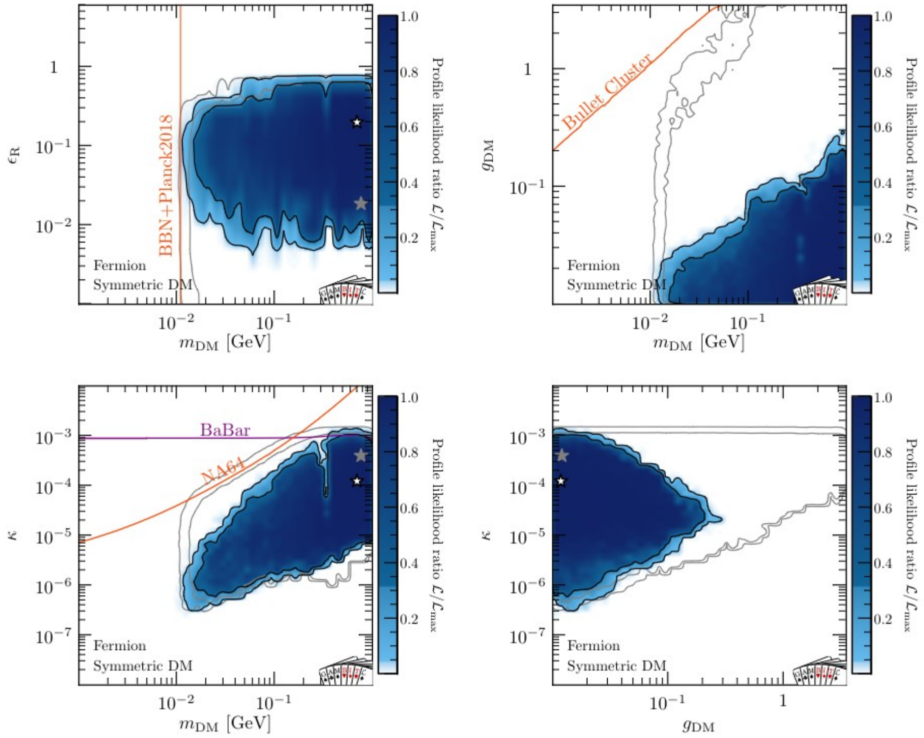
Results: Symmetric fermionic DM



- Blue regions: Allowed parameter space ($\Omega h^2 \approx 0.12$)
- Grey lines: Allowed parameter space ($\Omega h2 \leq 0.12$)
- White star: Best-fit point

Results: Asymmetric fermionic DM

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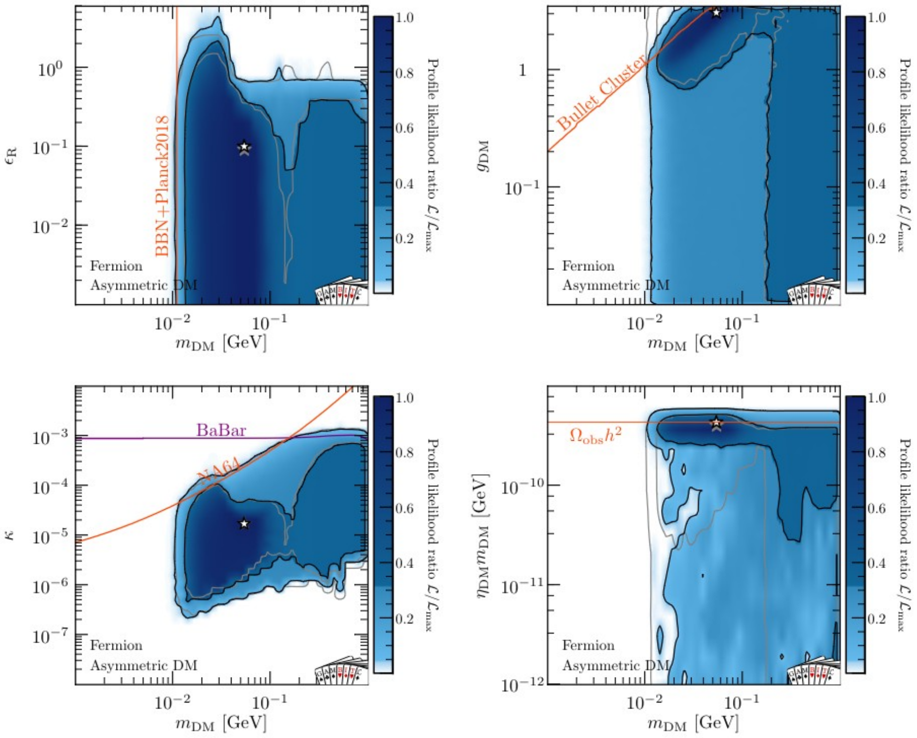

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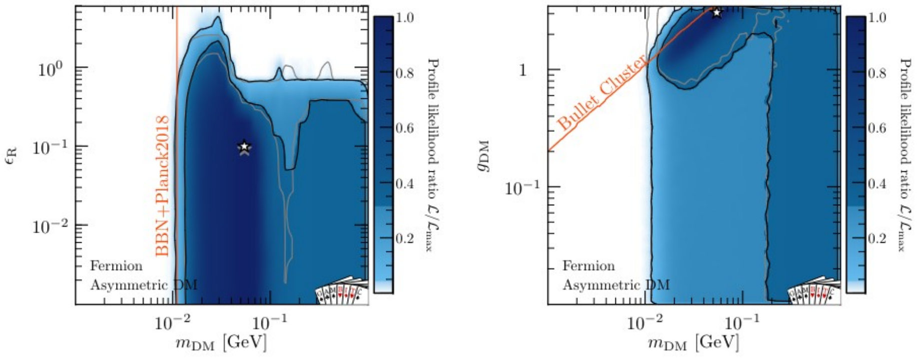
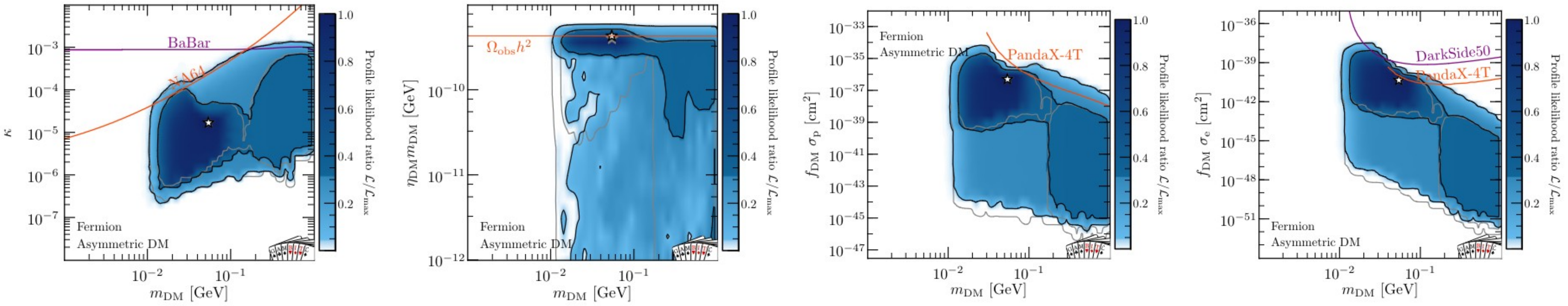
Results: Asymmetric fermionic DM



- Viable parameter space determined by combination of cosmological, astrophysical, laboratory and collider likelihoods



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Preference for asymmetric DM?

- Asymmetric DM model can fit slight preference for non-zero self-interaction cross section from Bullet Cluster

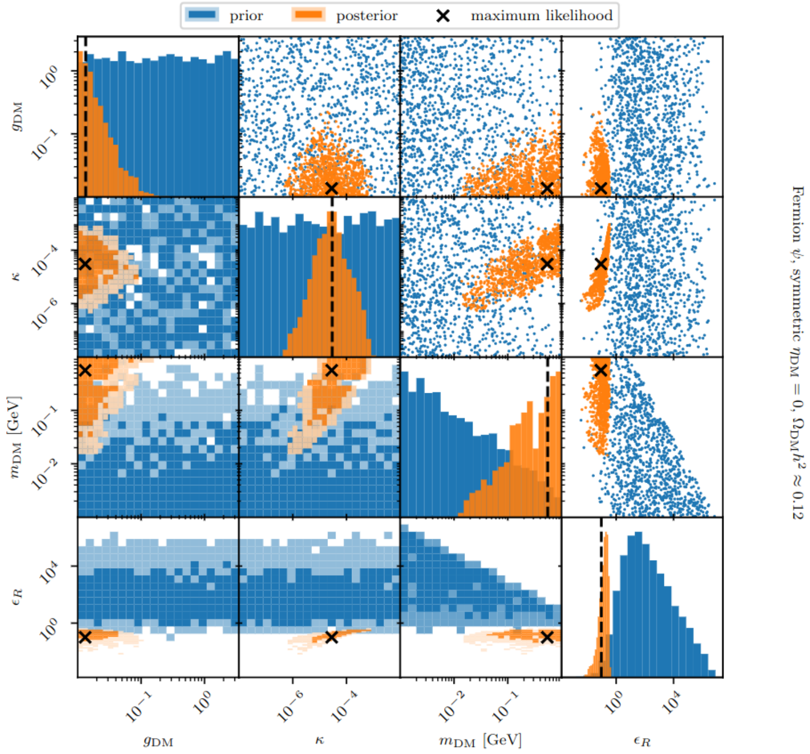
  → $-2\,\Delta \log L = 2.2$ (~1σ)

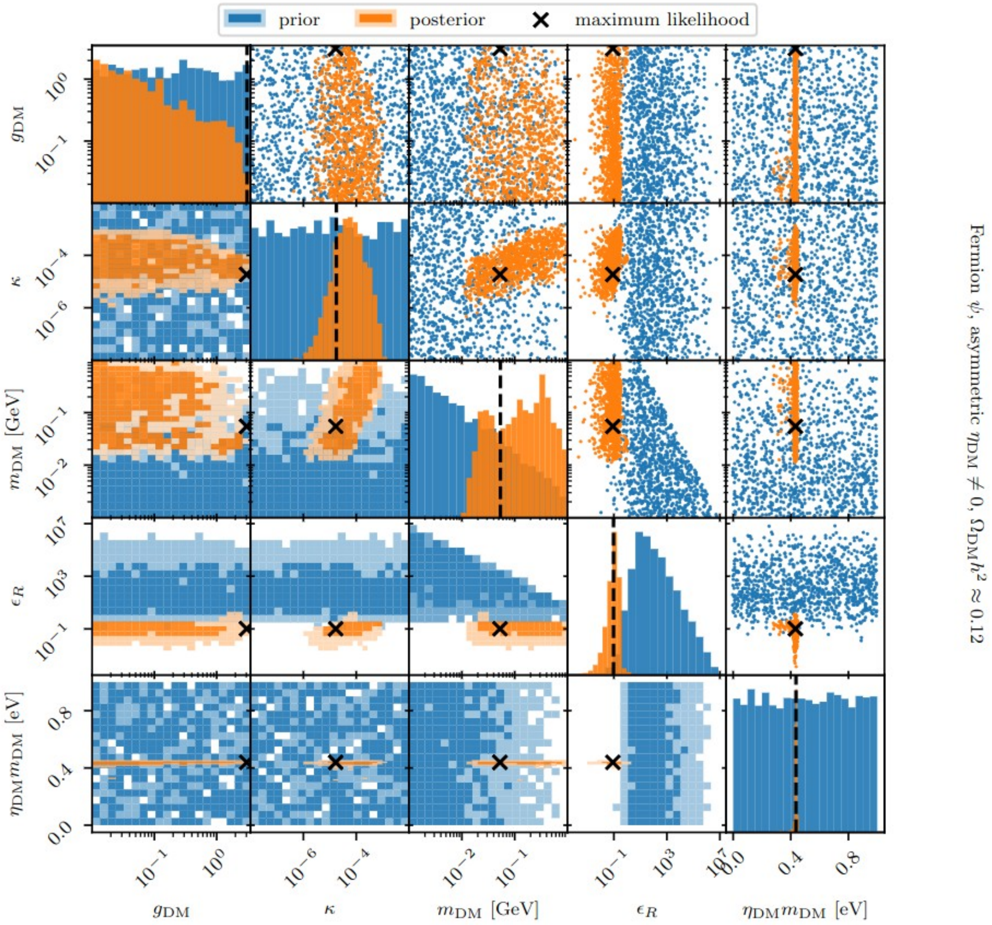
- But it also substantially reduces the required fine-tuning in parameter space
- Can be quantified using Bayesian evidence

$$\mathcal{Z} = \int \mathcal{L}(\theta)\pi(\theta)\mathrm{d}\theta$$

  → Size of parameter region with large likelihood

Results: Bayesian scans





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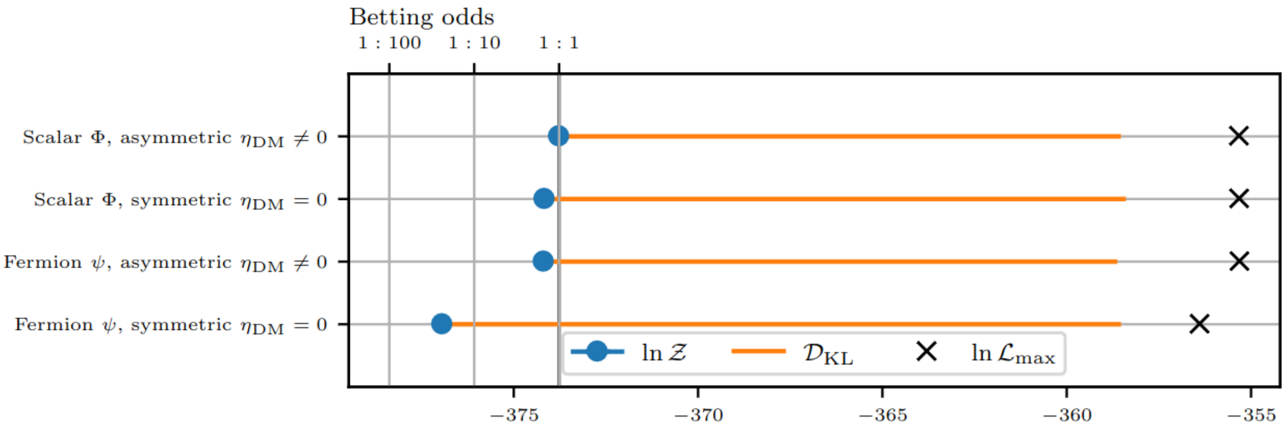
Results: Bayes factors



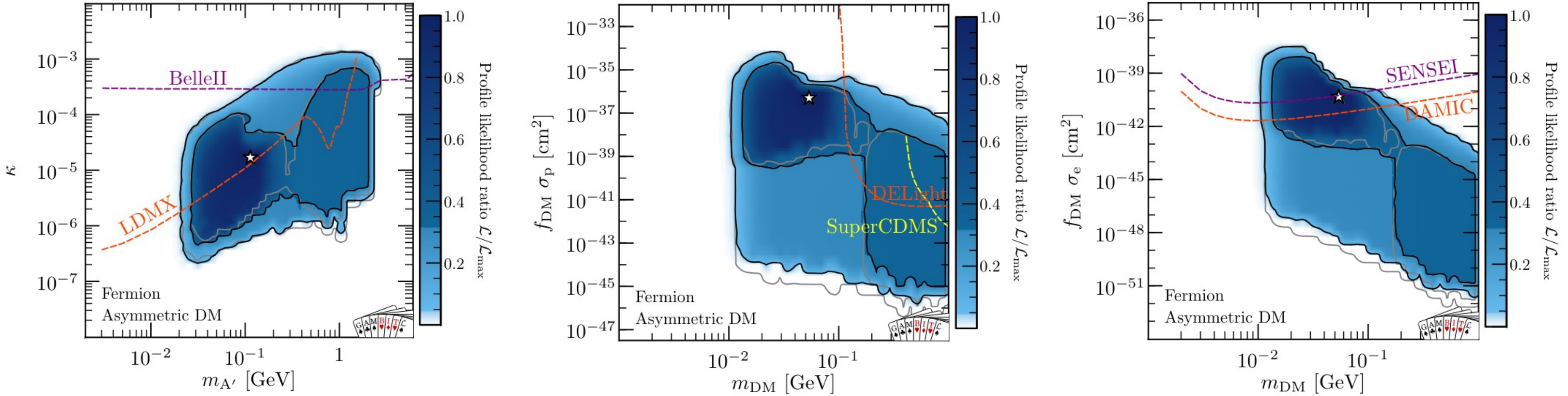
- Fine-tuning penalty quantified by Kulback-Leibler divergence:

$$\mathcal{D}_{KL} = \int \mathcal{P}(\theta) \log \frac{\mathcal{P}(\theta)}{\pi(\theta)} d\theta$$

- Result: Symmetric fermionic DM disfavoured with $Z_{asym}/Z_{sym} \sim 15$
- No preference between asymmetric fermionic DM and scalar DM

Projections

- Allowed regions of parameter space can be probed with various proposed experiments



- Most impactful: LDMX (64% of posterior volume probed)

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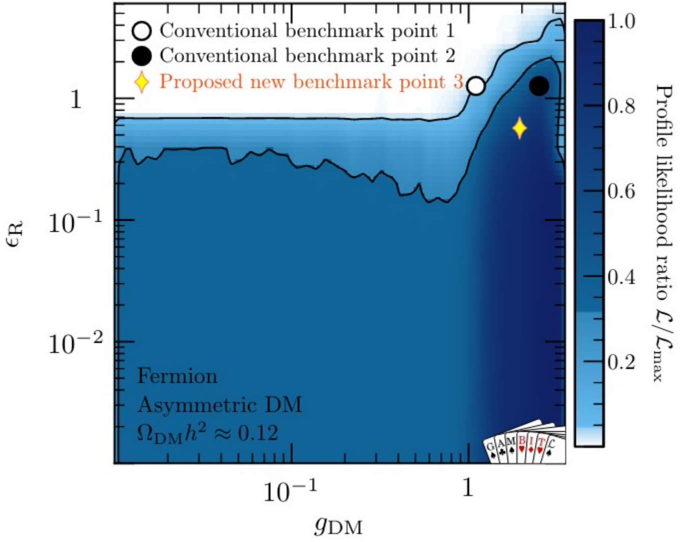
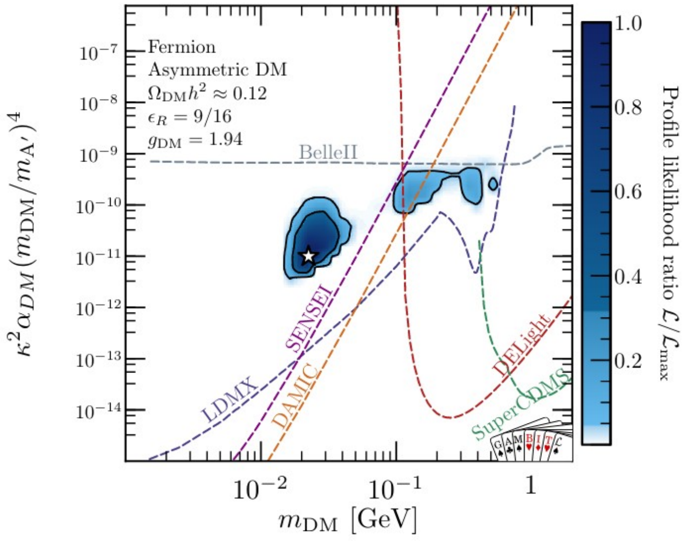
A new benchmark scenario

- To optimise experimental searches, useful to define benchmark points
- Current benchmark point: $m_{A'} = 3m_{DM}$ and either $g_{DM} = 1.1$ or 2.5 → Tension!



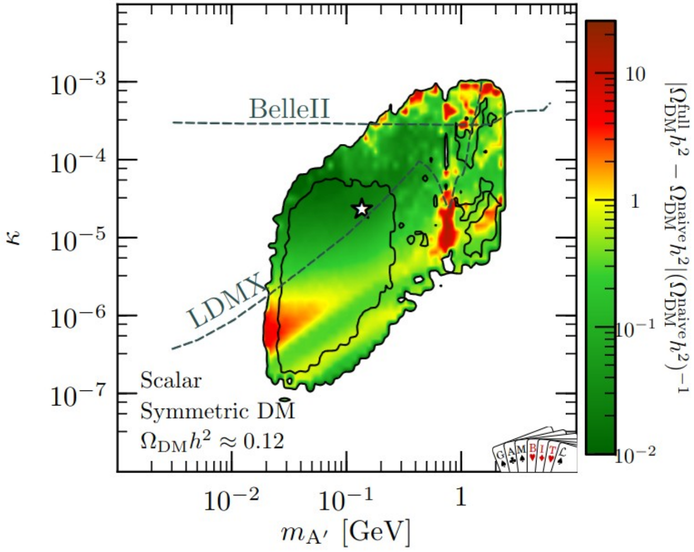
New bench-mark point:
$m_{A'} = 2.5m_{DM}$
$g_{DM} = 1.9$



Outlook

- Upcoming: A closer look at resonant enhancement
  - Kinetic equilibrium not guaranteed during freeze-out. True relic density may be larger than naive result from Boltzmann equation
  - For strong resonant enhancement there are additional constraints from CMB (spectral distortions) and BBN (photodisintegration)
  - Dark photon may obtain non-negligible visible branching ratio

  → Need reinterpretation of many more experiments



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Conclusions

- Mass range for thermal DM: 10 MeV < m_{DM} < 100 TeV
- Sub-GeV DM evades Lee-Weinberg bound by introducing dark photon mediator
- Velocity-independent annihilation rate in strong tension with data

→ Velocity-dependent annihilations
→ Particle-antiparticle asymmetry

} Many constraints: Some tuning required!
Fermionic DM: Preference for asymmetry
New benchmark point with $m_{A'} = 2.5 m_{DM}$

- Excellent prospects for next-generation experiments!