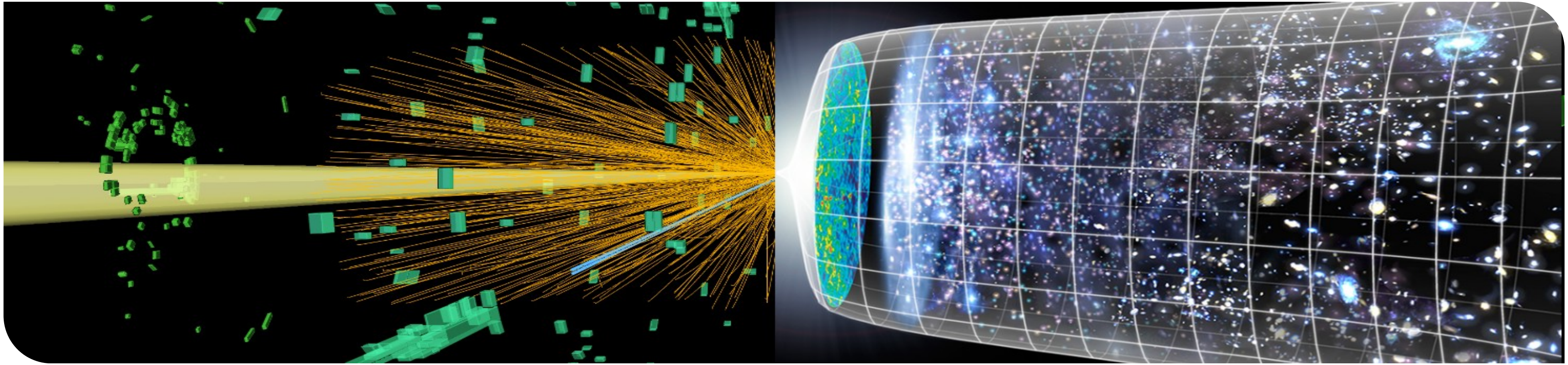
Resonant or asymmetric?
The status of sub-GeV dark matter

Felix Kahlhoefer

Light Dark World 2024

KAIST, Daejeon, 14 August 2024



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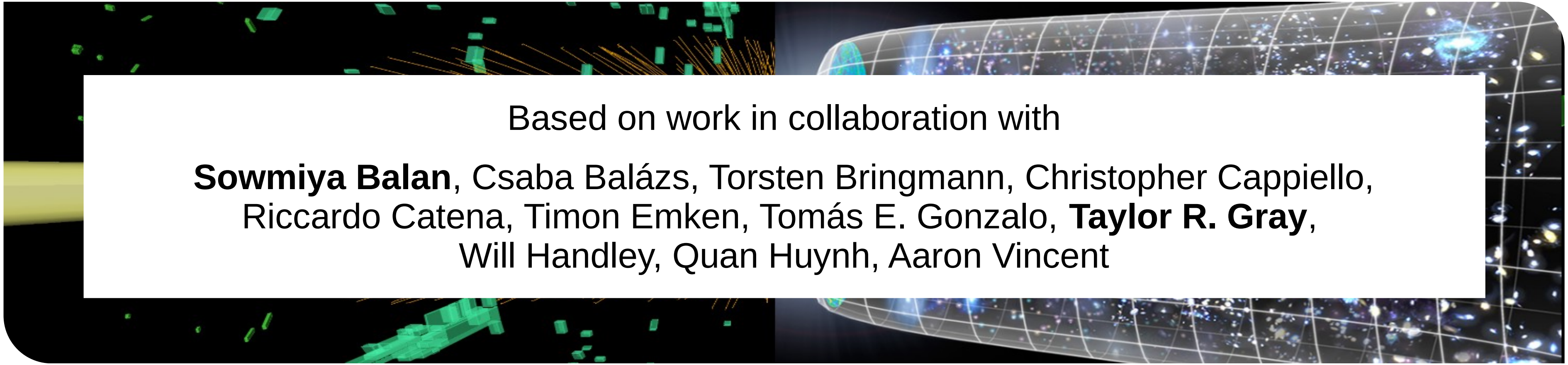

Based on work in collaboration with

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

What is the dark matter mass?

10^{-22} eV $100\ M_\odot$

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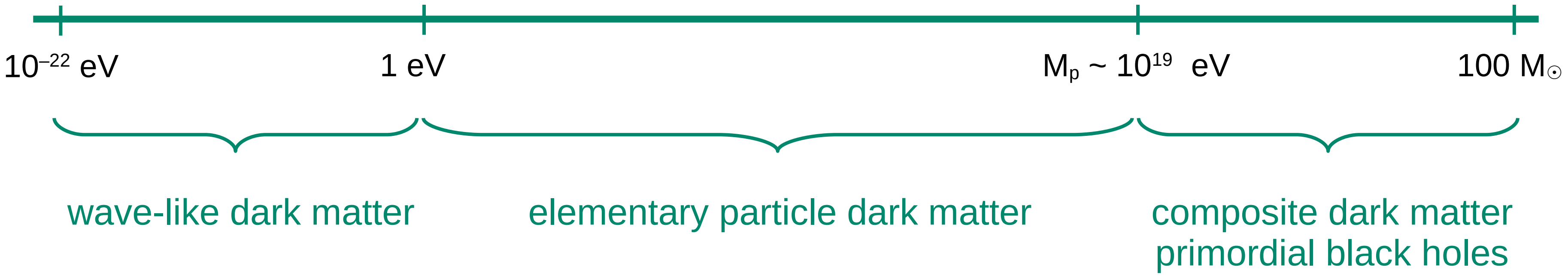

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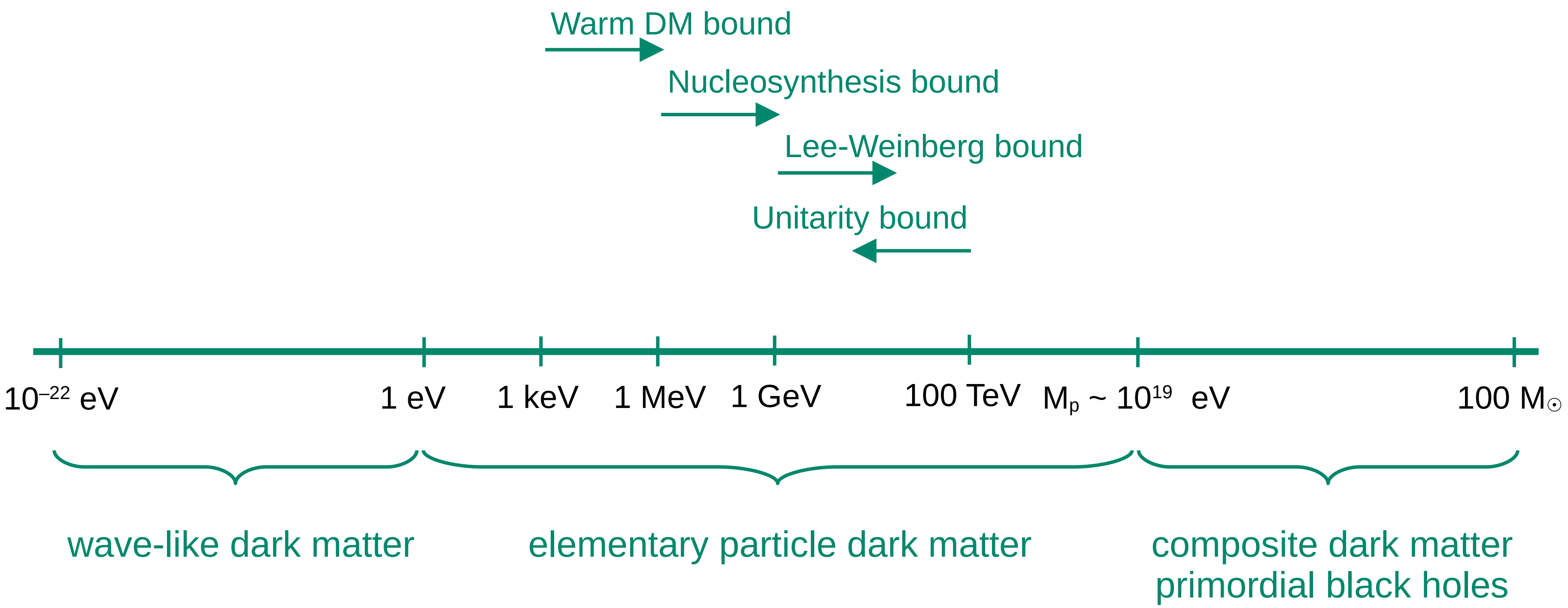

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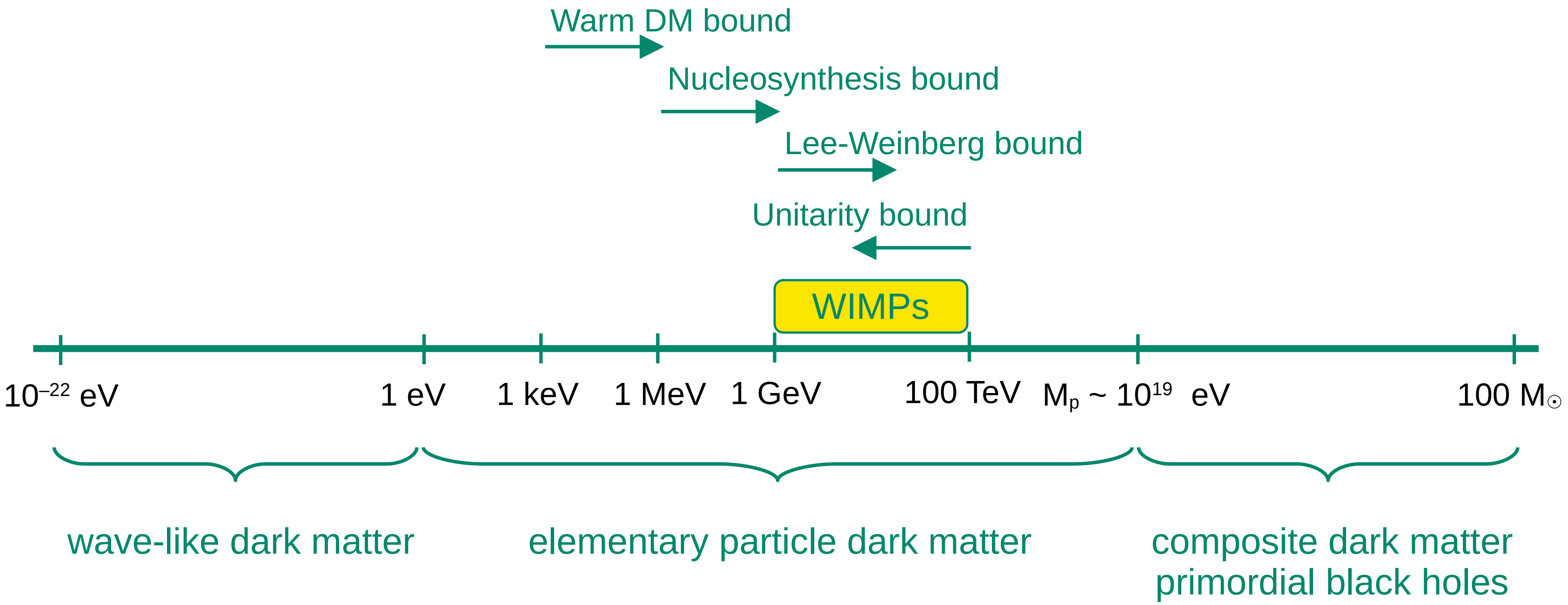

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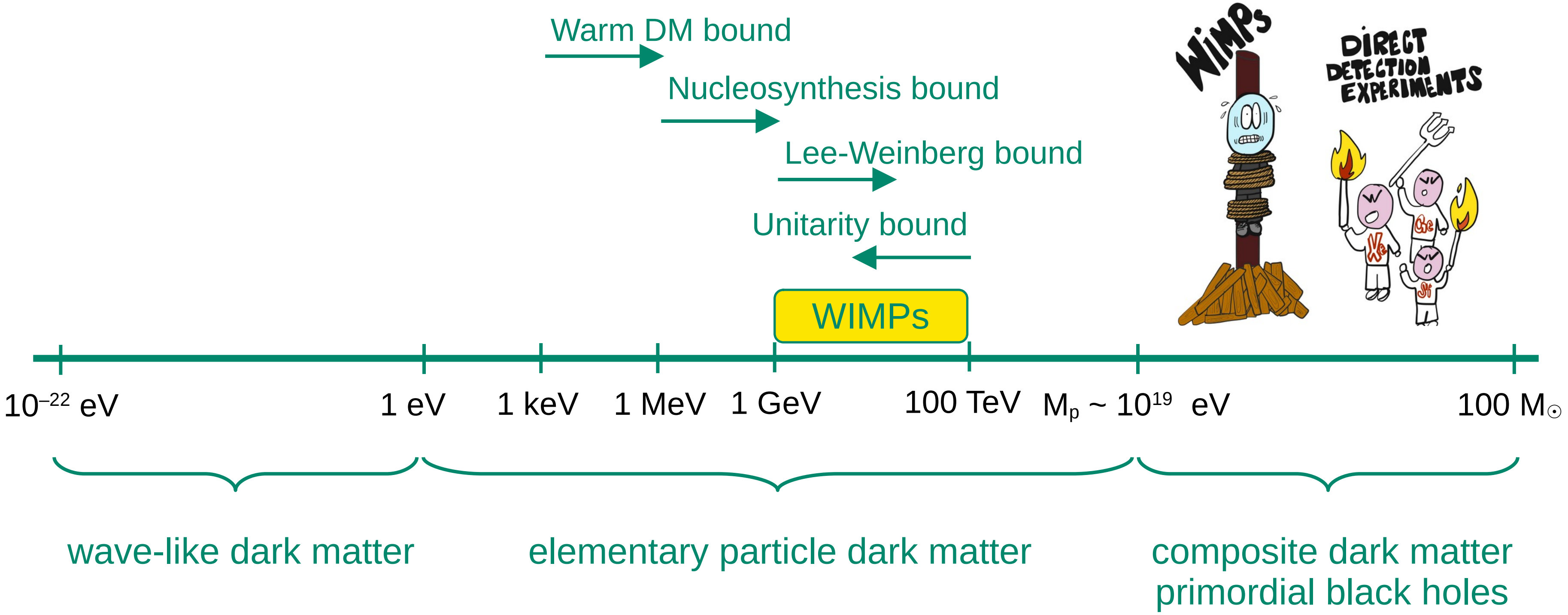

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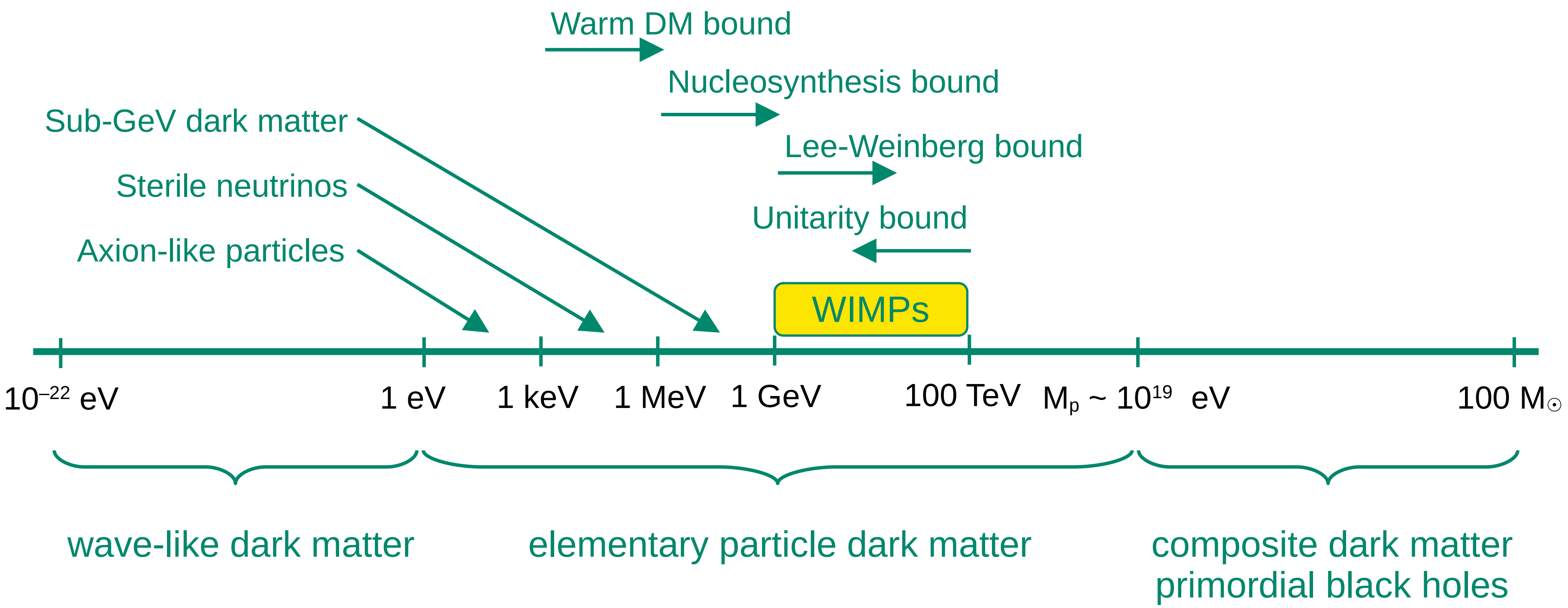

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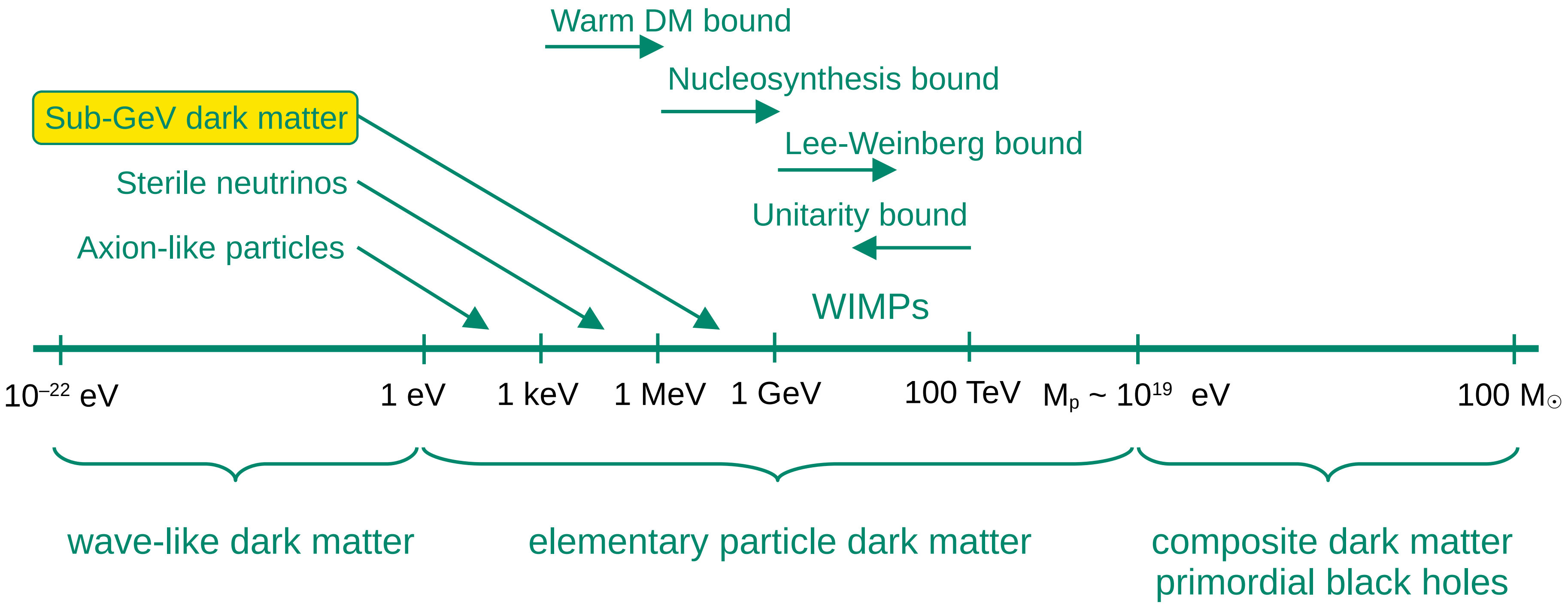

Definition: Sub-GeV dark matter

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

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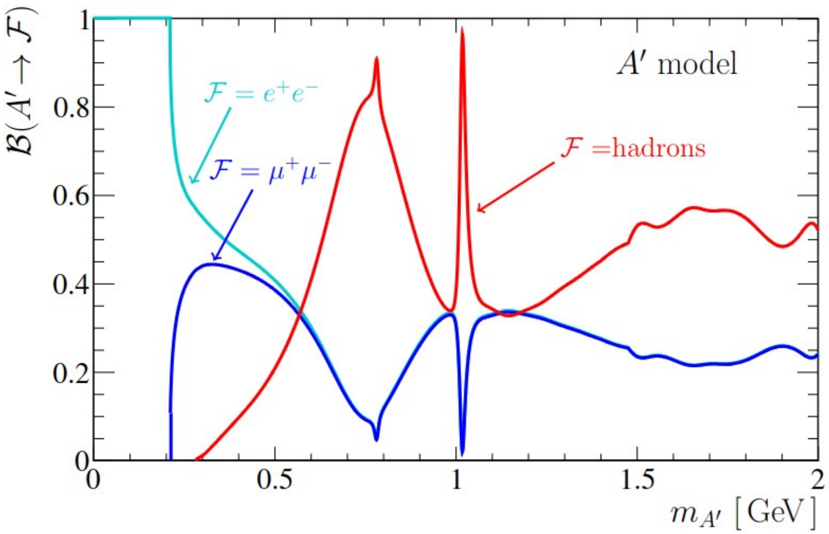
Implication 1: Sub-GeV dark matter requires a new type of interactions

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



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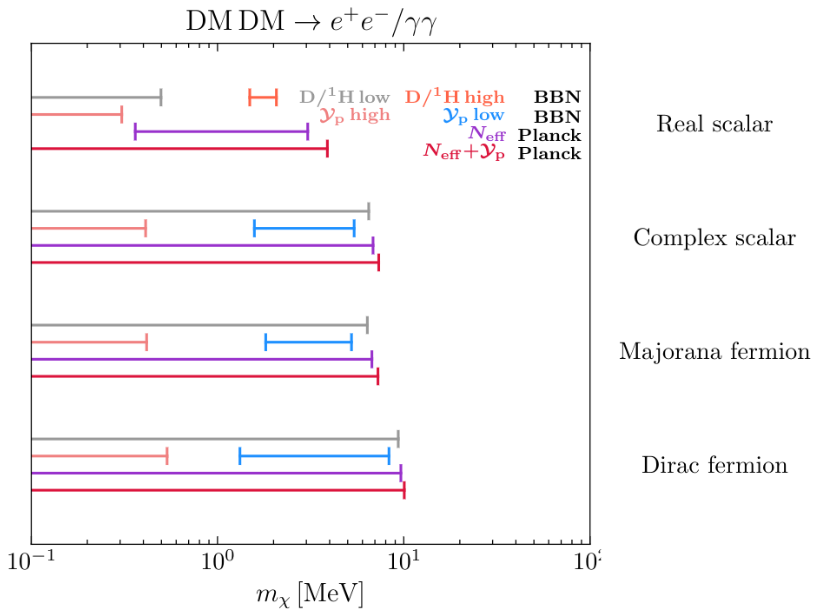
Cosmological constraints (I)

- 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



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Definition: Sub-GeV dark matter

Karlsruhe Institute of Technology

Institute for Theoretical Particle Physics

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

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

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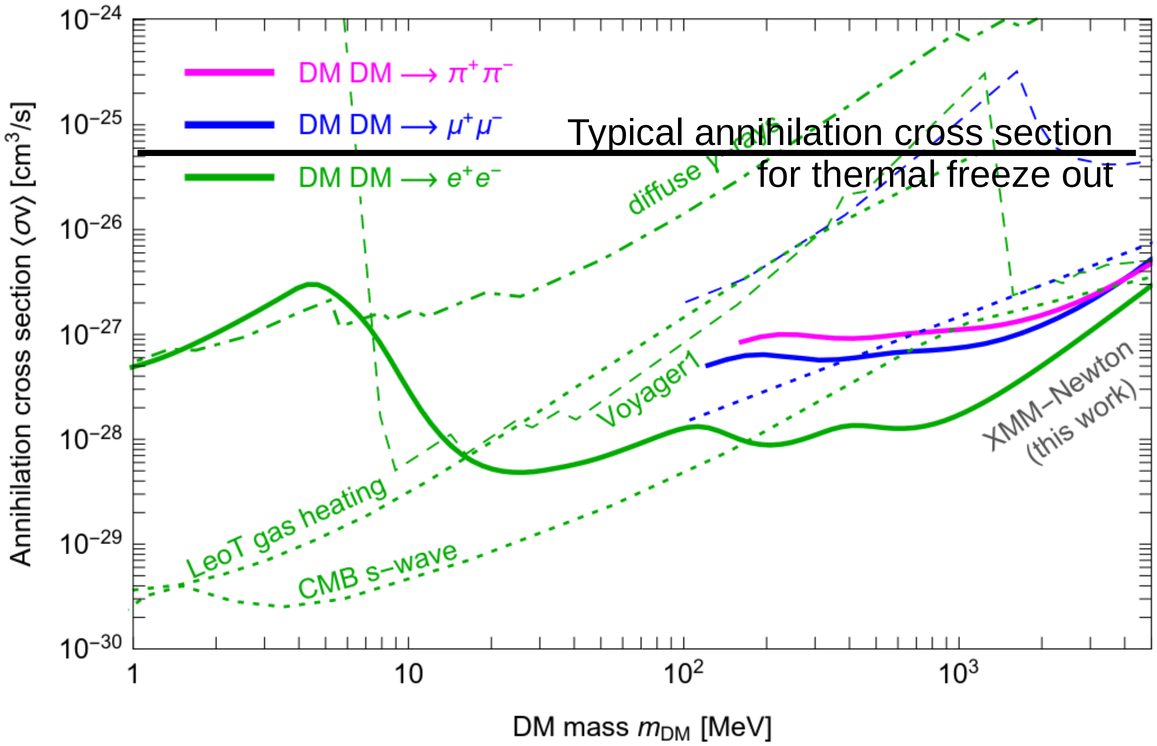
Cosmological constraints (II)

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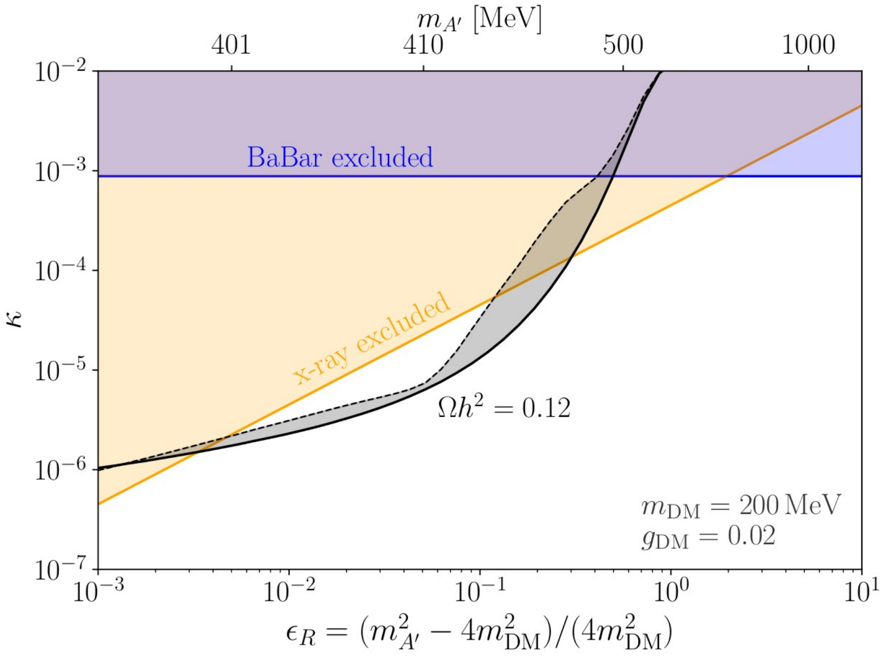
Implication 3: Sub-GeV dark matter must suppress late-time annihilations

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



Possibility 2: Particle-antiparticle asymmetry

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- DM asymmetry given by

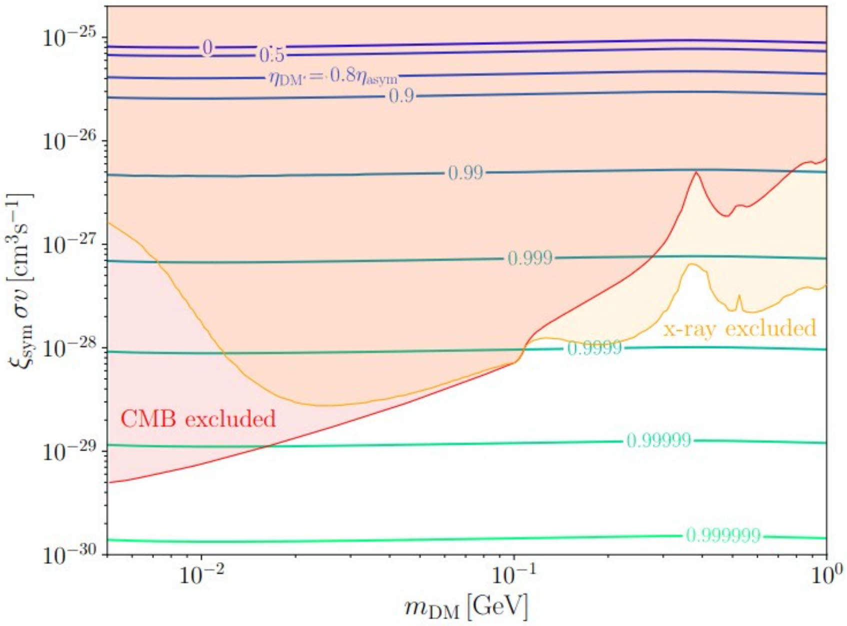
$$\eta_{\rm DM} \equiv \frac{n_\chi - n_{\overline{\chi}}}{s}$$

- Observed relic abundances implies

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

- 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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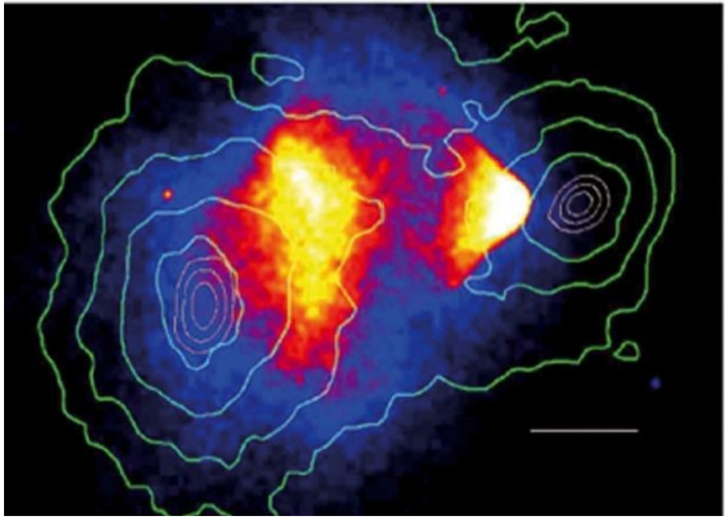
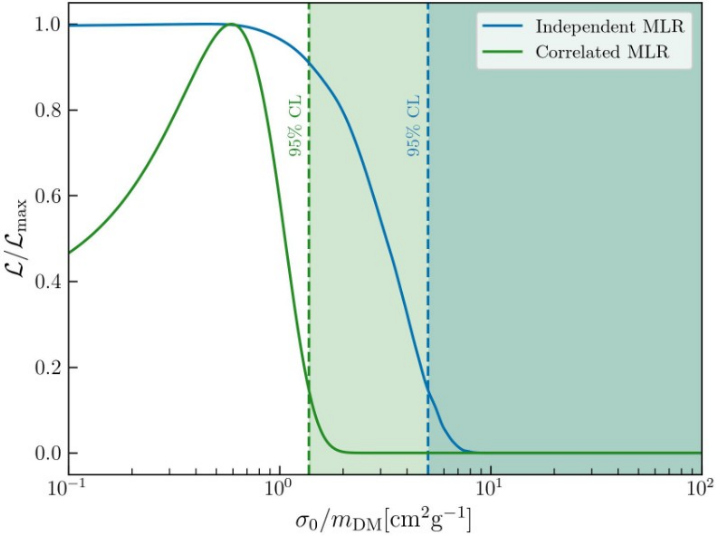
Model summary

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

Constraints: Self-interactions

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





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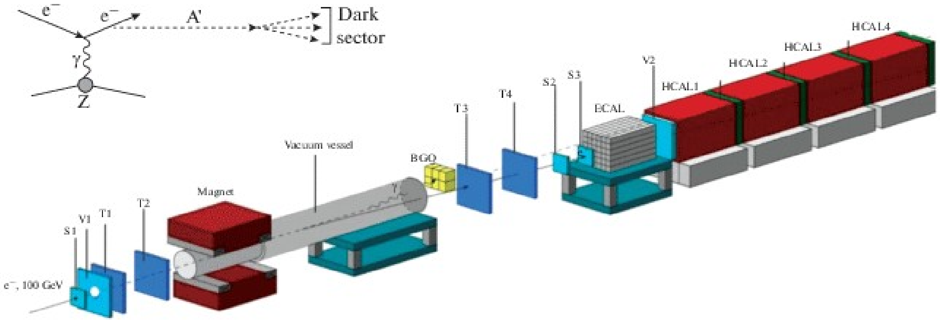
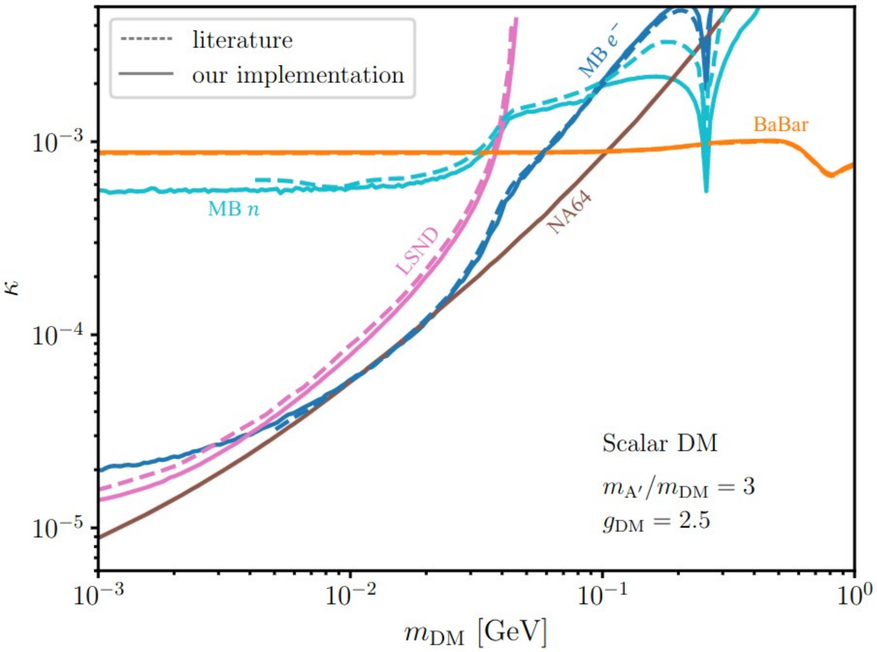
Constraints: Accelerator experiments

- Missing energy searches:
  - BaBar and NA64

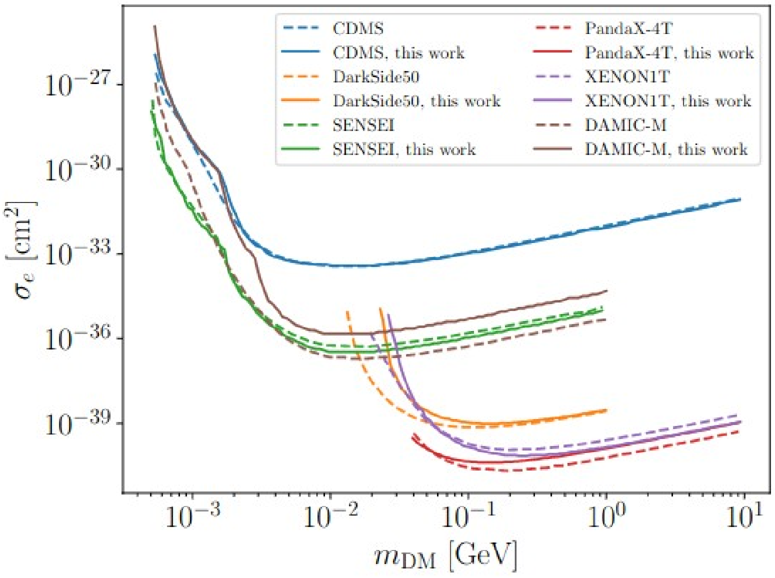




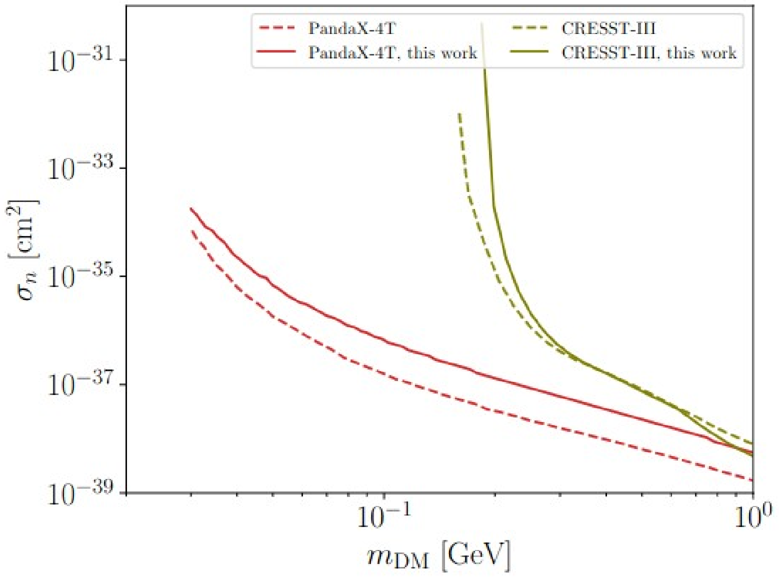
- Searches for DM scattering:
  - LSND and MiniBooNE

Constraints: Direct detection

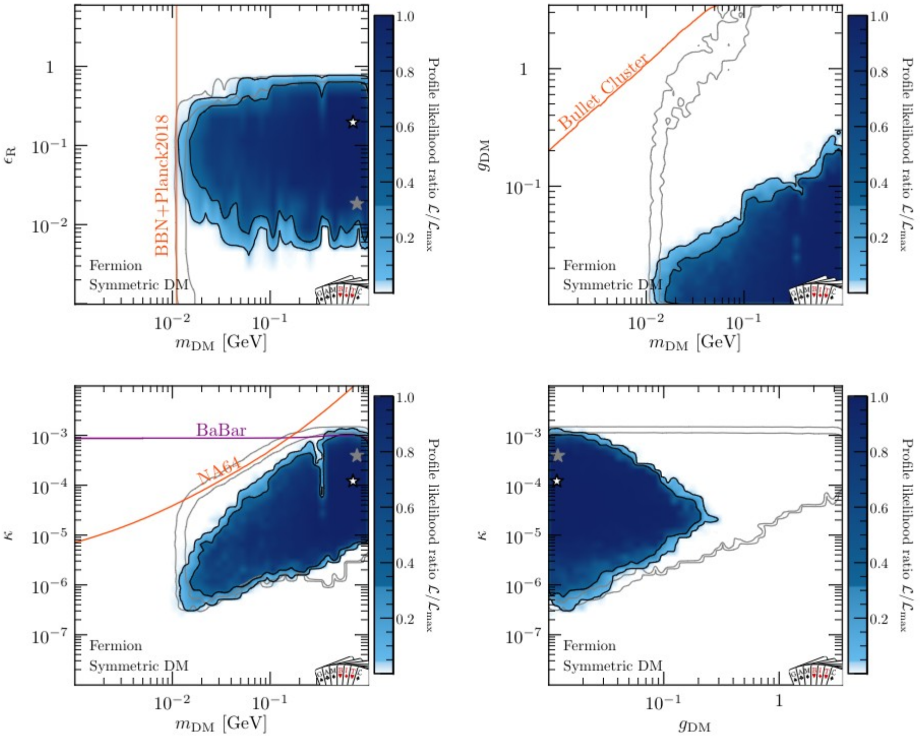
DM-electron scattering



DM-nucleus scattering (including Migdal effect)

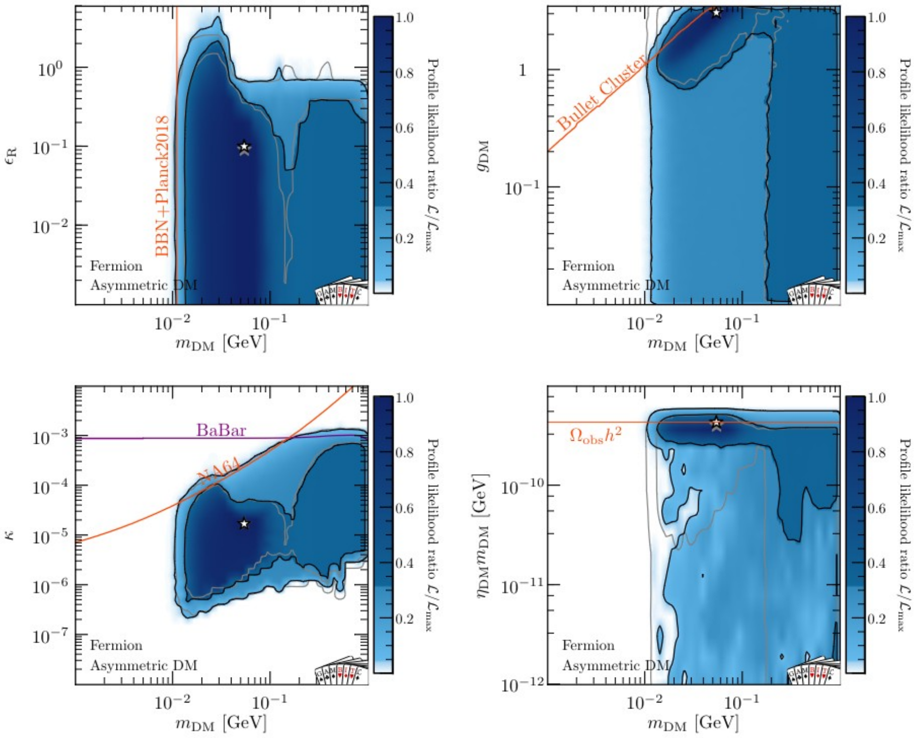


Results: Symmetric fermionic DM



- 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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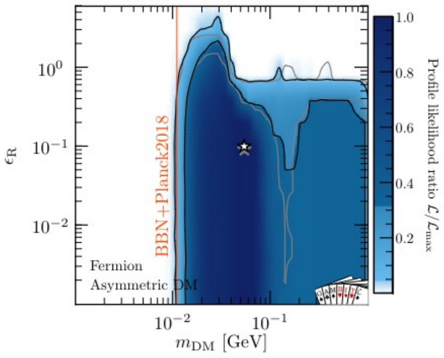
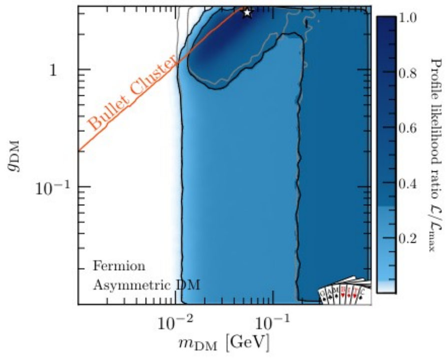
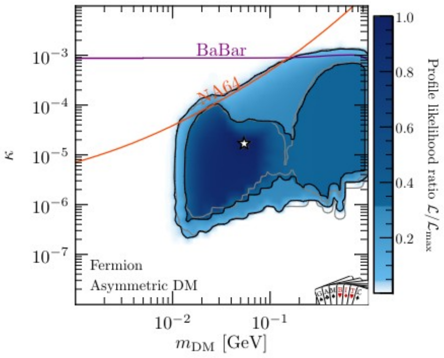
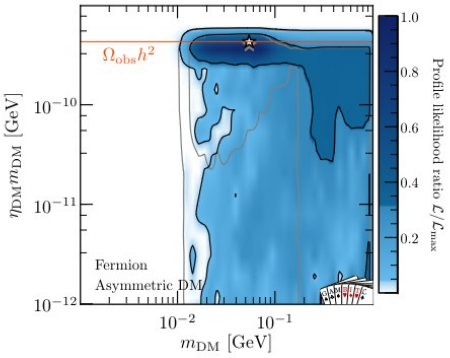
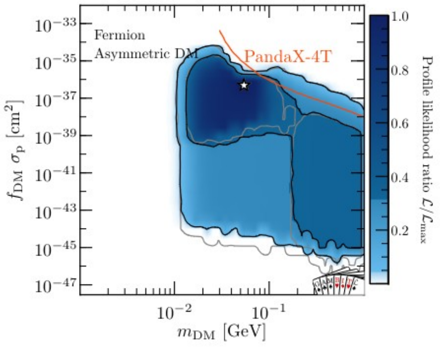


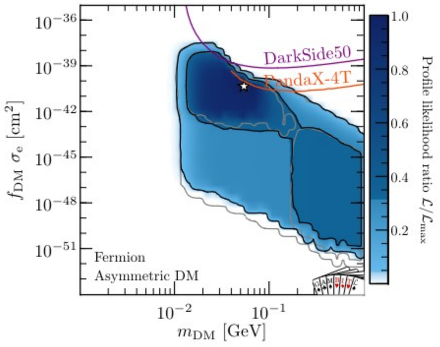


- Viable parameter space determined by combination of cosmological, astrophysical, laboratory and collider likelihoods









Preference for asymmetric DM?

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

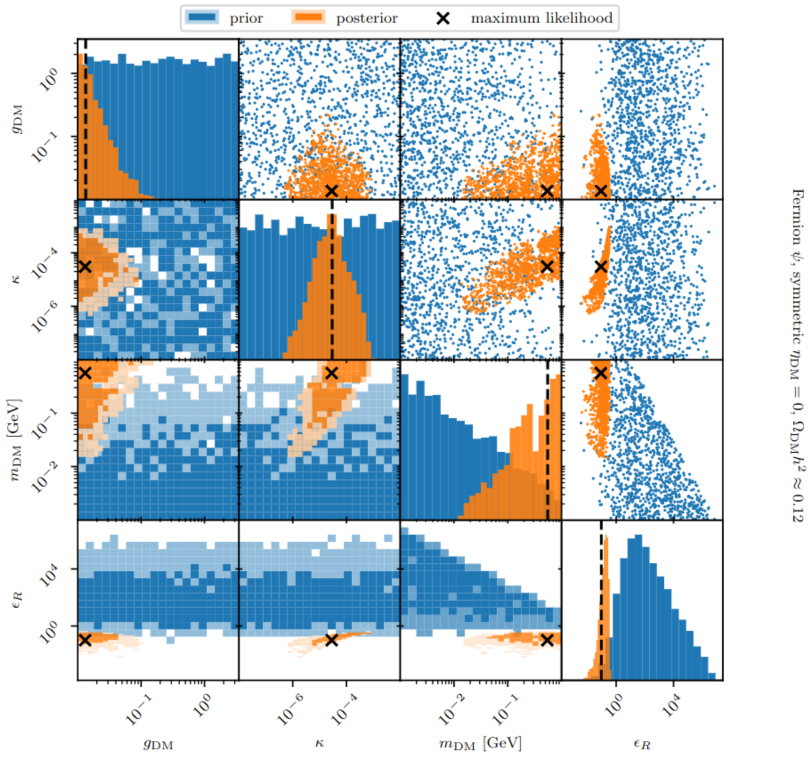
  → $-2\,\Delta \log L = 2.2$ (~1σ)

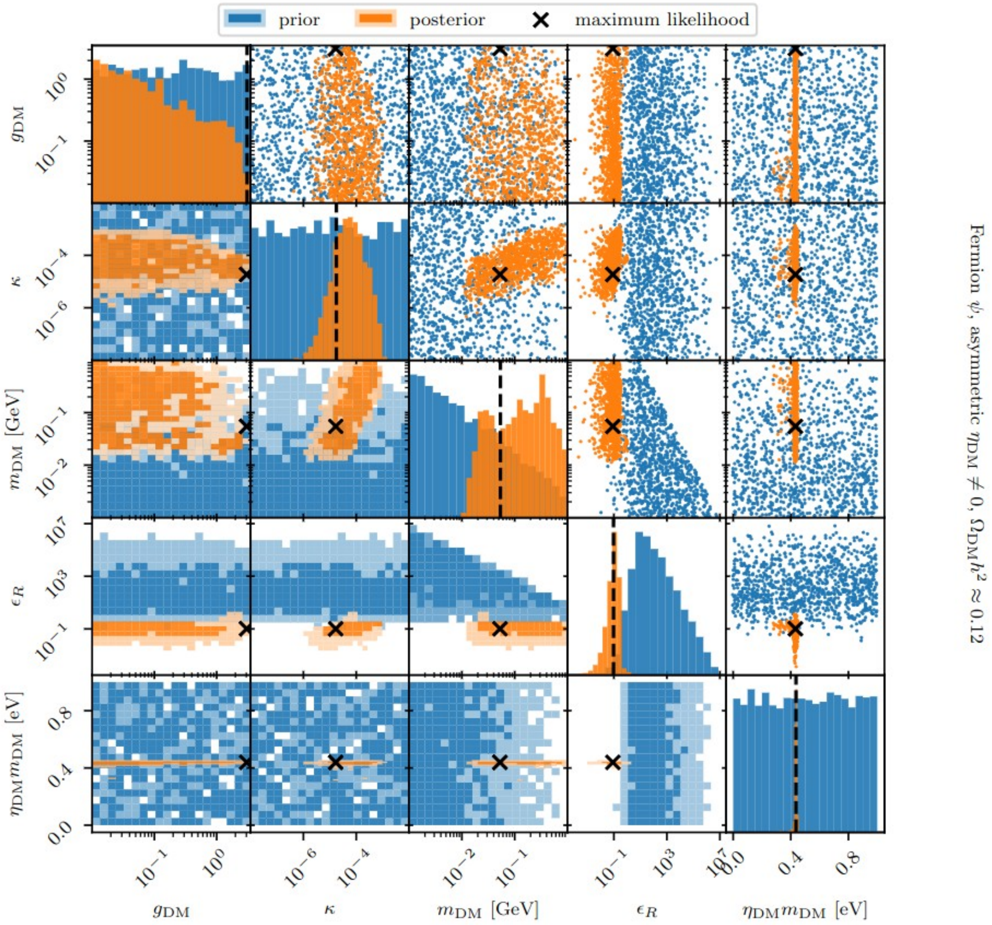
- But it also substantially reduces the required fine-tuning in parameter space
- Can be quantified using Bayesian evidence

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

  → Size of parameter region with large likelihood

Results: Bayesian scans





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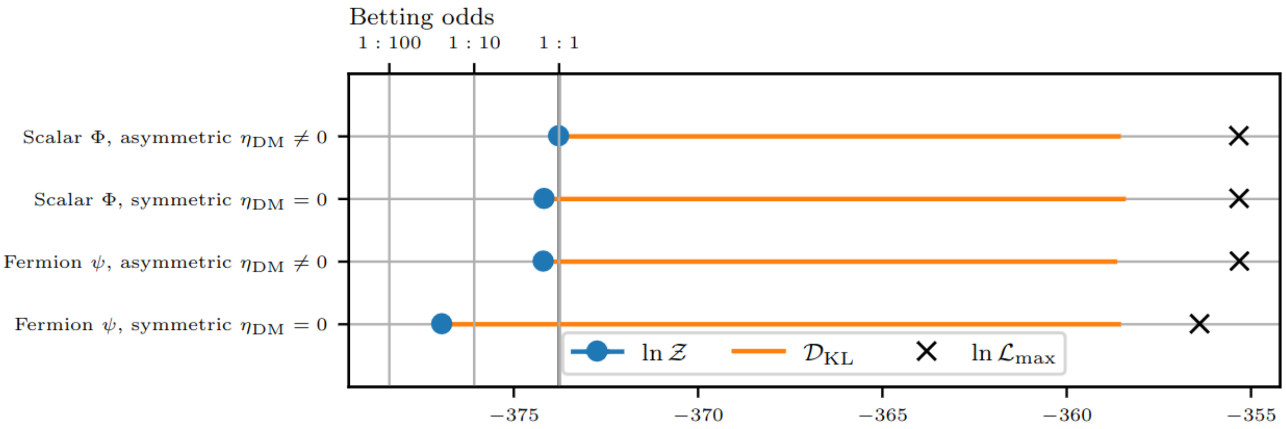
Results: Bayes factors



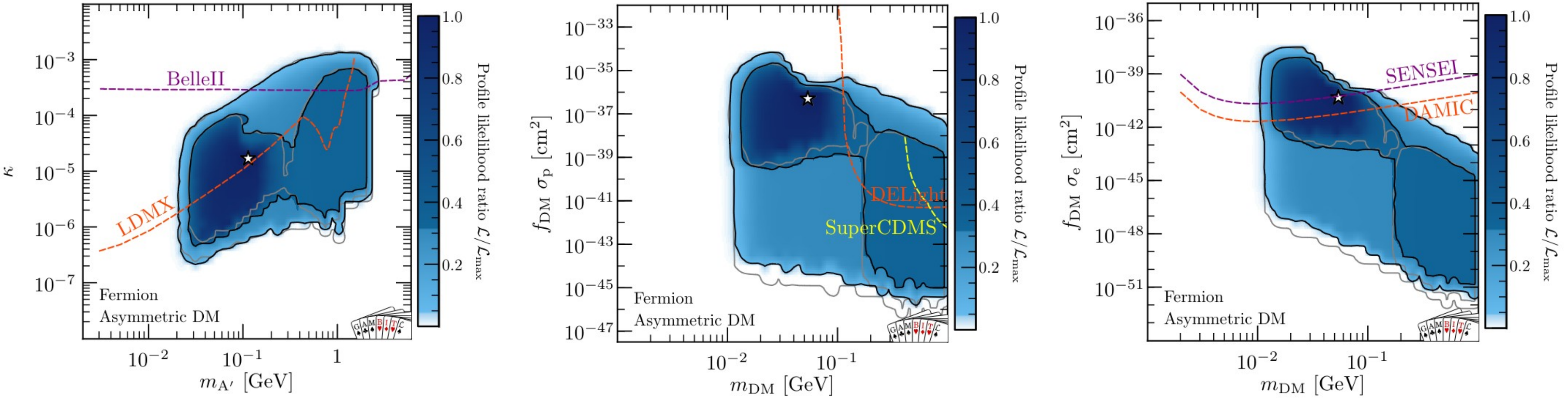
- Fine-tuning penalty quantified by Kulback-Leibler divergence:

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

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

Projections

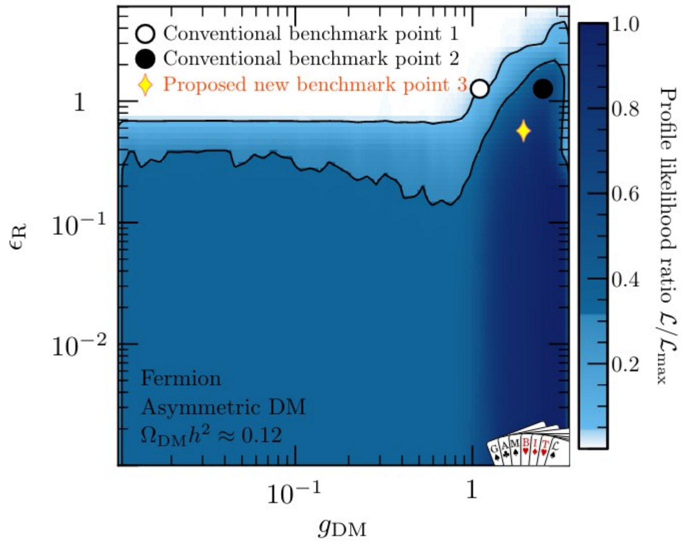
- Allowed regions of parameter space can be probed with various proposed experiments



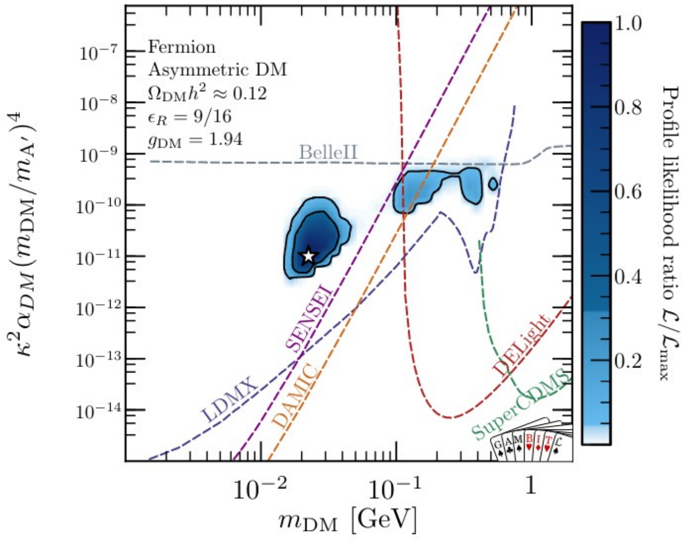
- Most impactful: LDMX (64% of posterior volume probed)

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:
$m_{A'} = 2.5m_{DM}$
$g_{DM} = 1.9$



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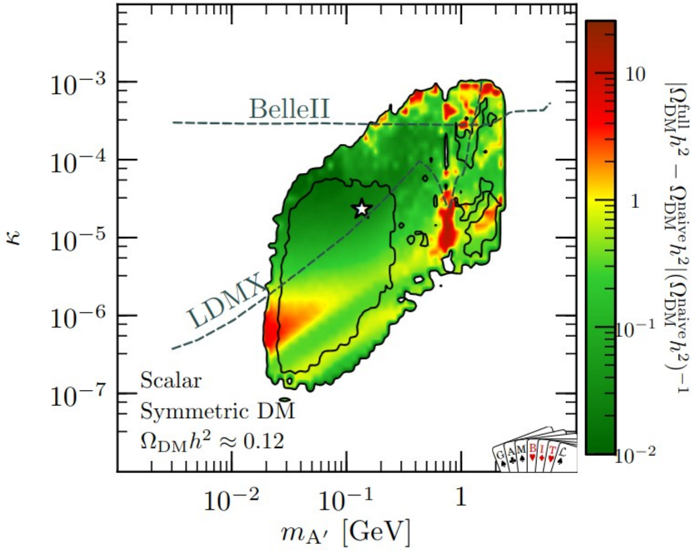
Outlook (part 1)

- 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



Outlook (part 2)

- Upcoming: A closer look at mass generation
- Consider dark Higgs mechanism for dark photon and DM particle
  - Possibility to have additional Majorana mass term

    → Dirac fermion splits into two Majorana states with off-diagonal couplings

    → Additional long-lived particle & exotic experimental signatures
  - Possibility to have no tree-level mass terms at all (conformal dark sector)

    → Spontaneous symmetry breaking via strong 1st order phase transition

    → Possibility for a sizeable gravitational wave signal in the nHz region

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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!