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

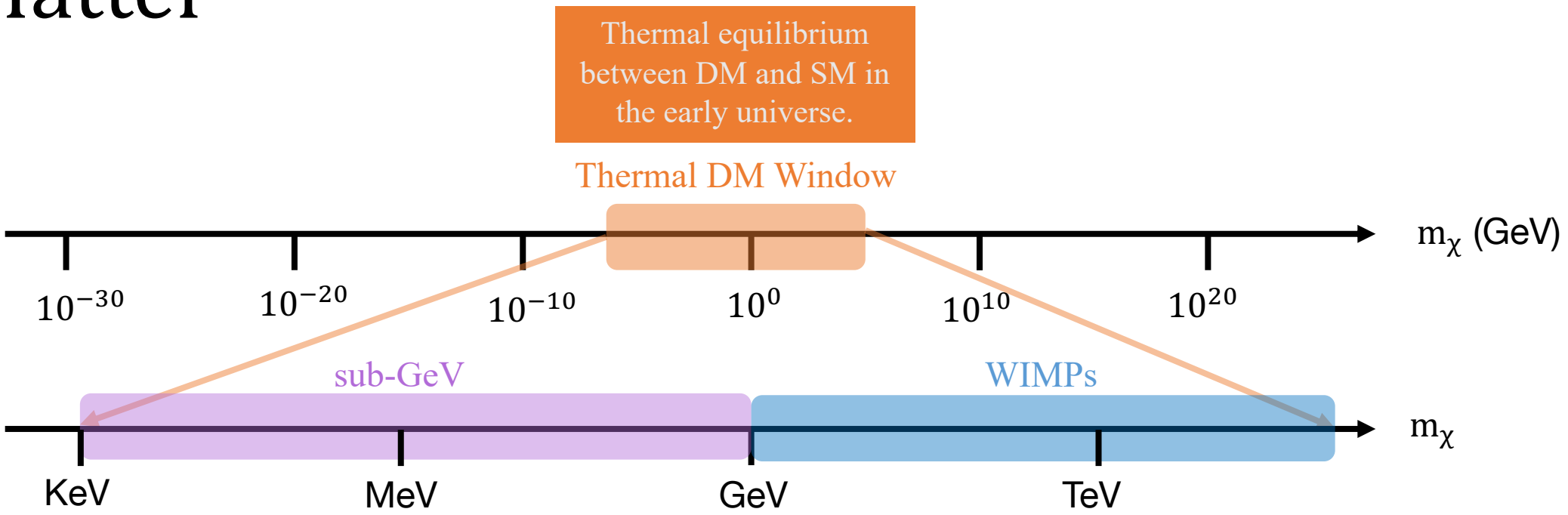
arXiv:2405.17548

Taylor R. Gray

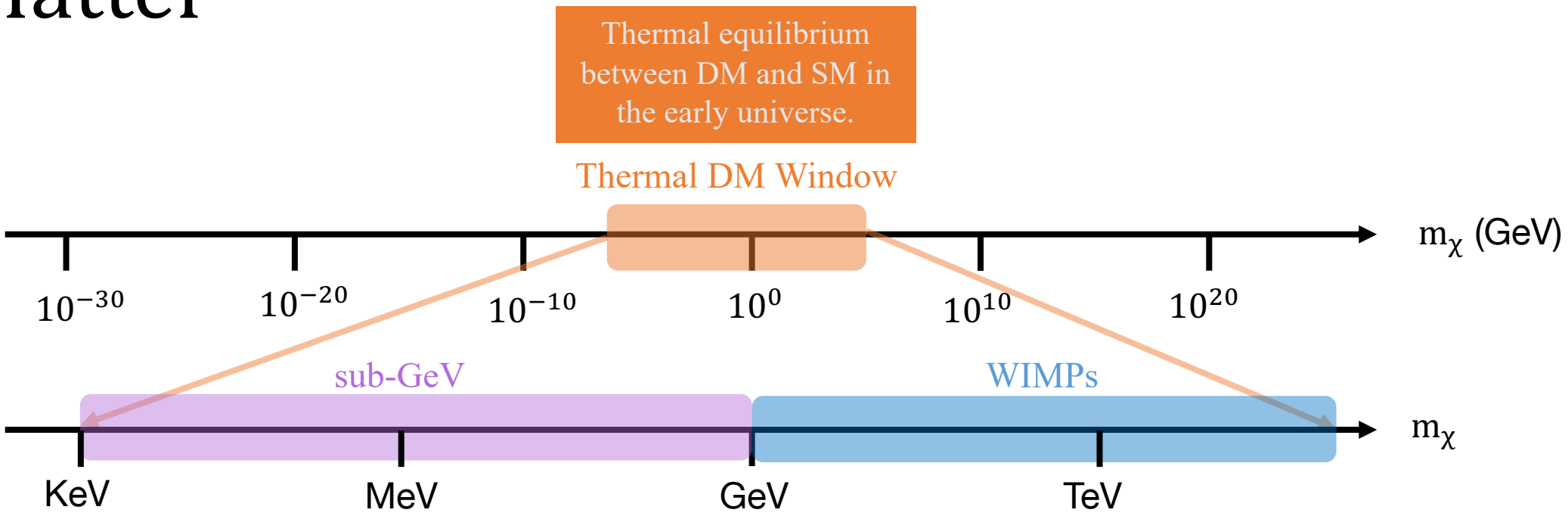
In collaboration with:
Sowmiya Balan, Csaba Balazs, Torsten Bringmann, Christopher Cappiello, Riccardo Catena, Timon Emken, Tomás E. Gonzalo, Will Handley, Quan Huynh, **Felix Kahlhoefer**, and Aaron C. Vincent

Partikeldagarna 2024

Sub-GeV Dark Matter



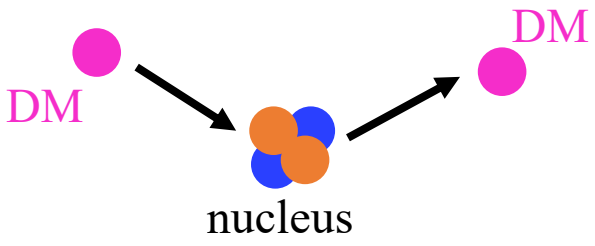
Sub-GeV Dark Matter



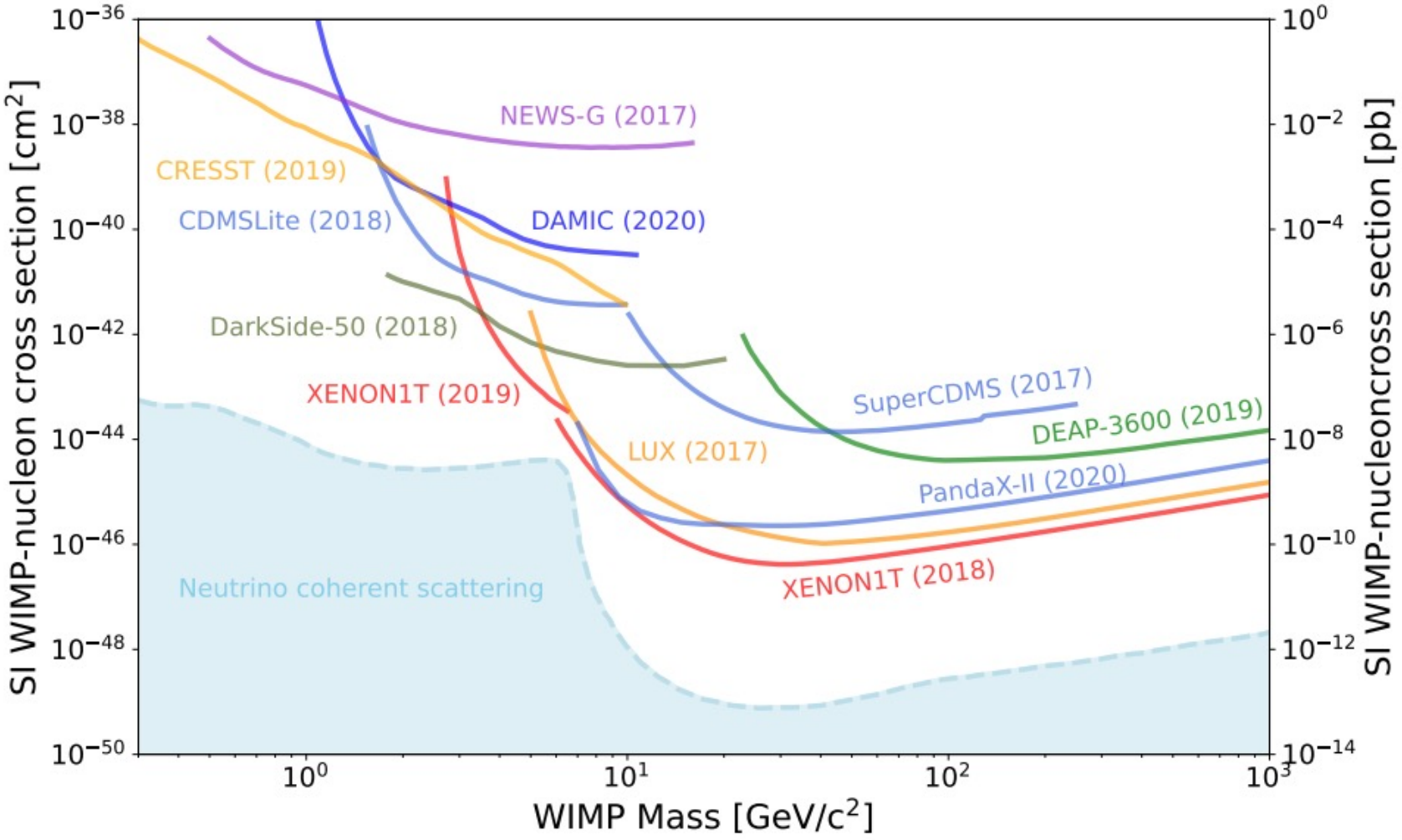
- DM produced through freeze-out near weak scale
- GeV-TeV scale thermal DM already widely tested

Nuclear Recoil Direct Detection Status

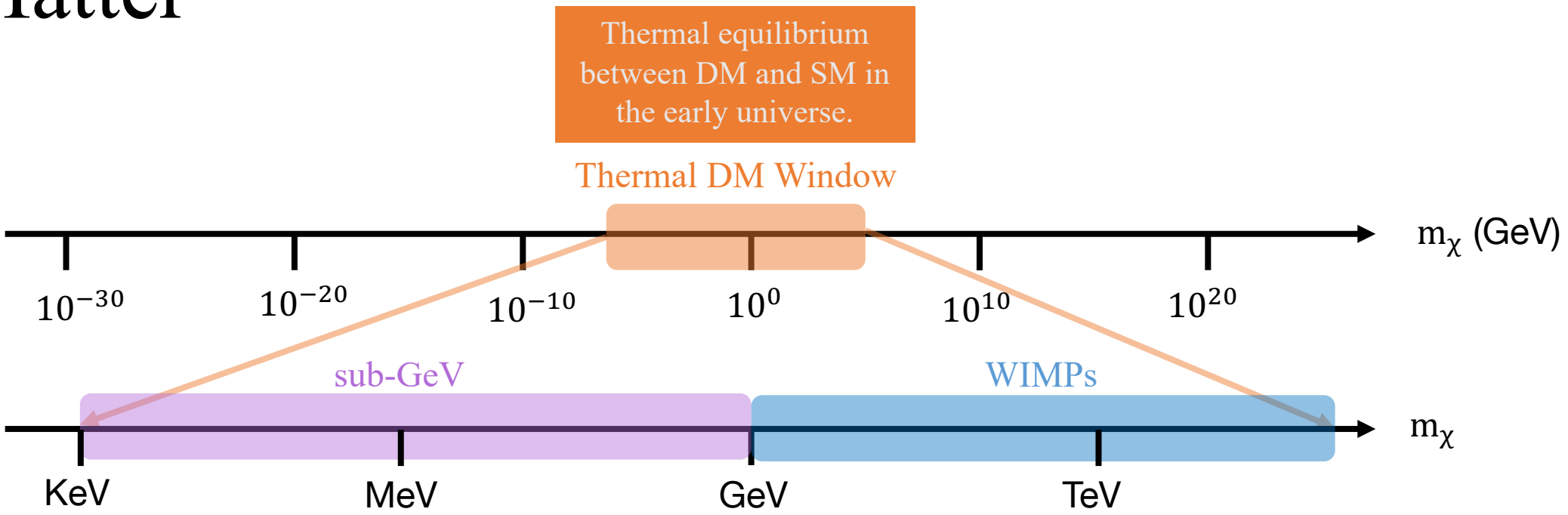
- Sensitive to GeV-TeV scale DM masses
- Approaching neutrino "fog"



PDG



Sub-GeV Dark Matter



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  - Evade Lee-Weinberg bound by introducing new mediator

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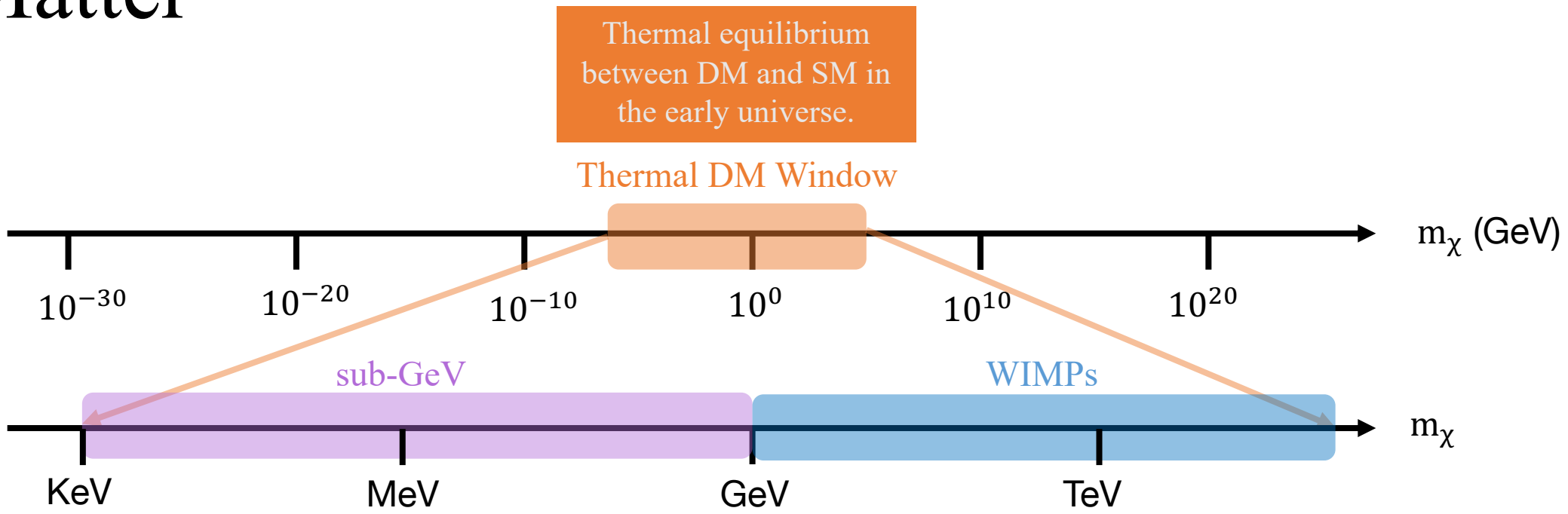
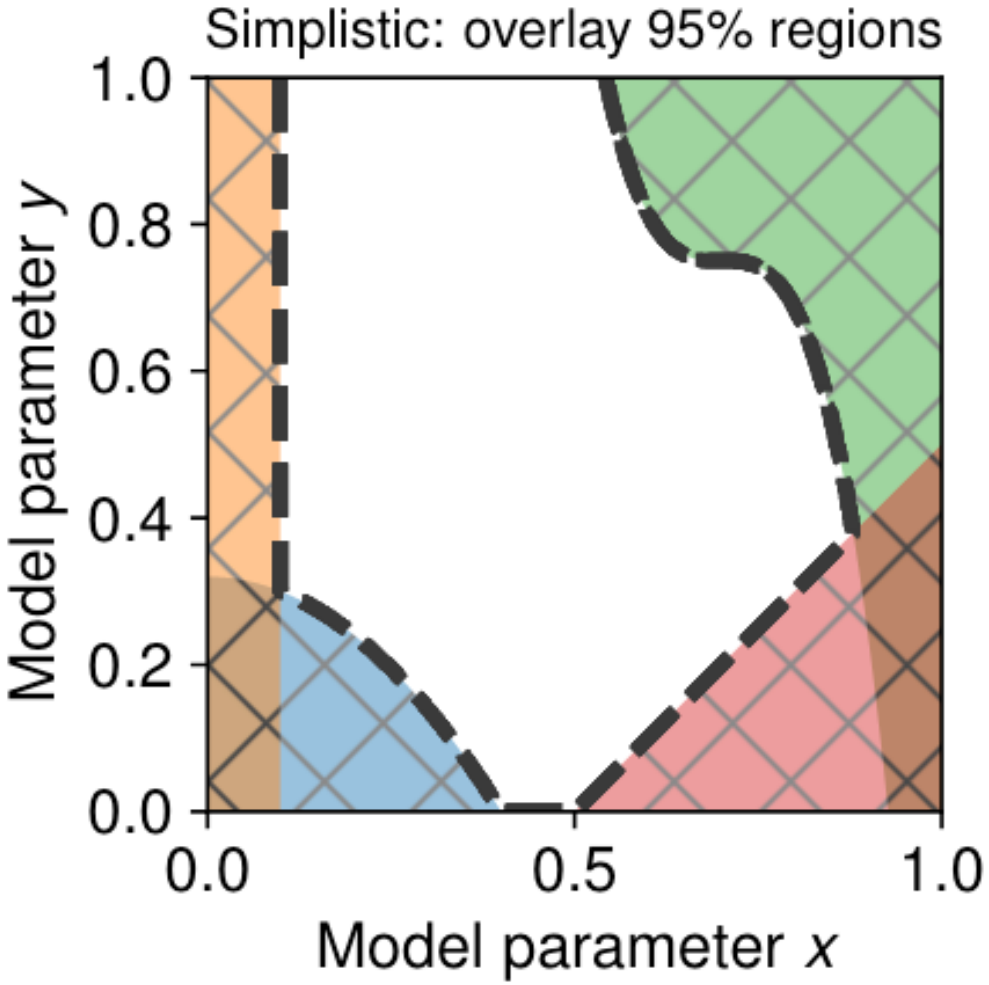


- Also can be produced through freeze-out
  - Evade Lee-Weinberg bound by introducing new mediator
- Escapes nuclear recoil direct detection exps
  - Largely experimentally **unexplored**..
  - Electron recoils or **accelerator exps**

- DM produced through freeze-out near weak scale
- GeV-TeV scale thermal DM already widely tested

See Michał's talk!!

Global Fits



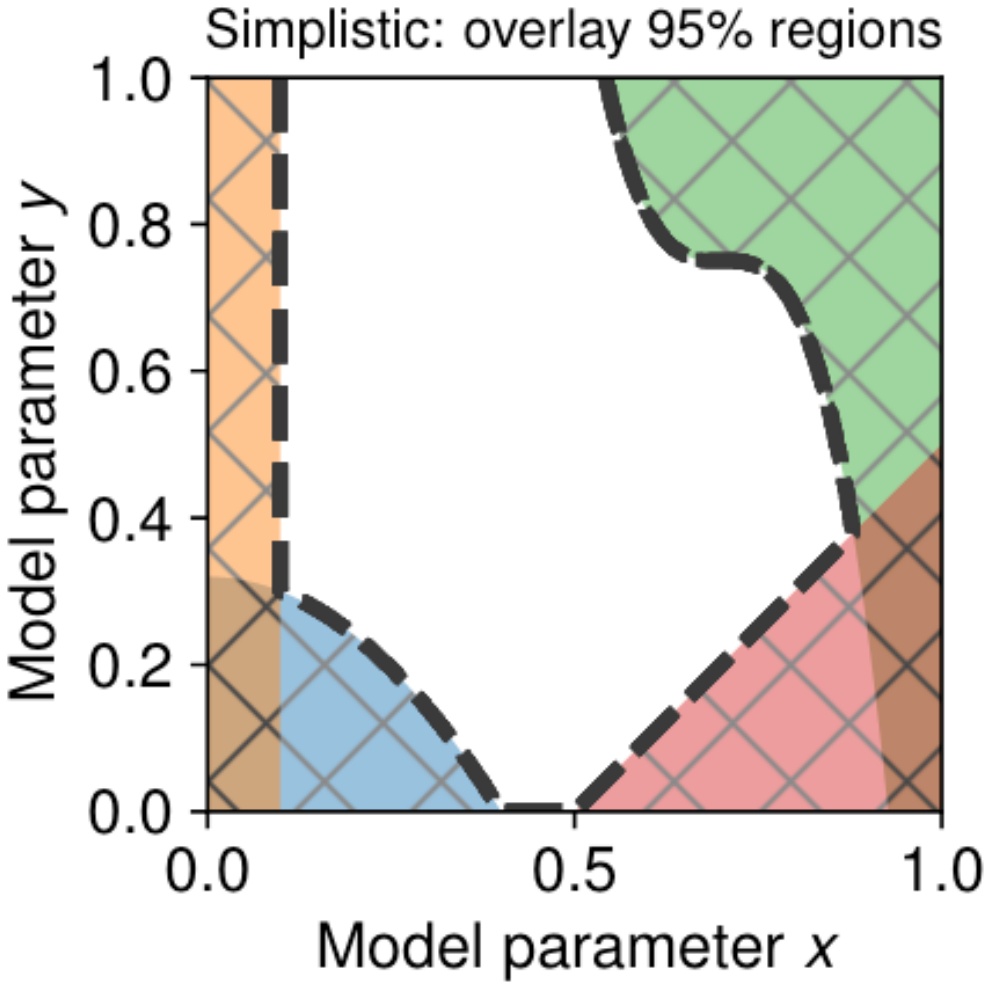
95% confidence exclusion bound: rate at which the true parameter values are excluded is limited to 5%

GAMBIT arXiv:2012.09874

Global Fits

The intersection,

Error rate = $1 - 0.95^n$



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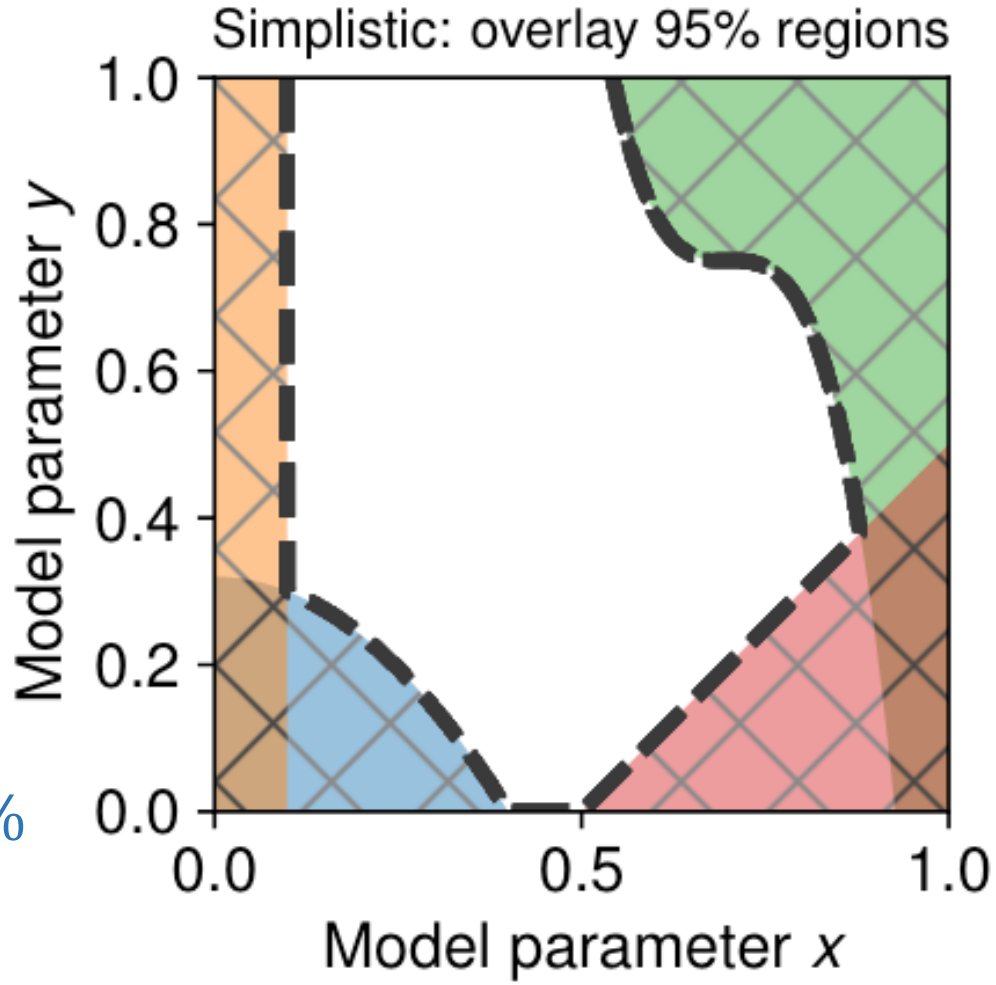
Ex: 5 experiments

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



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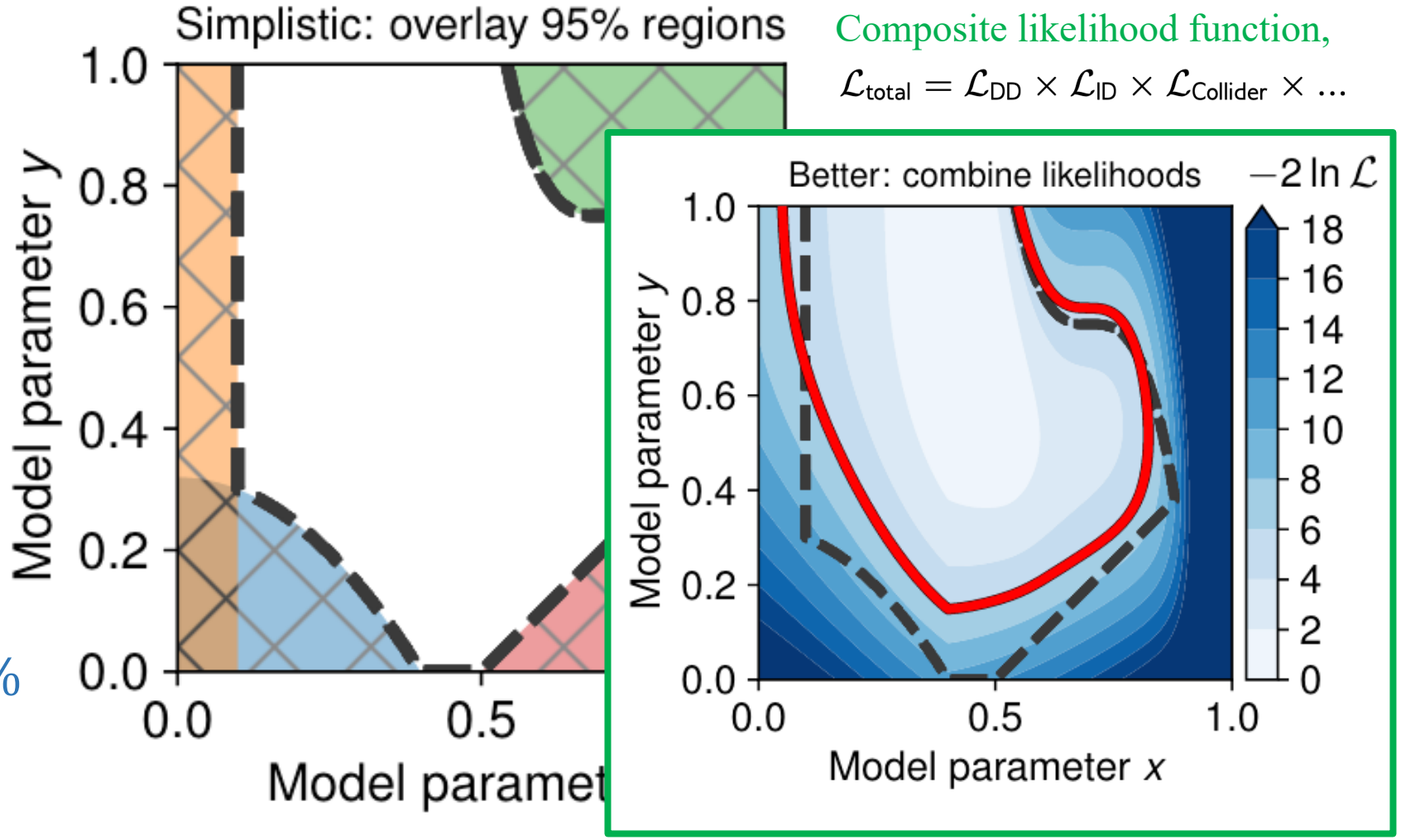

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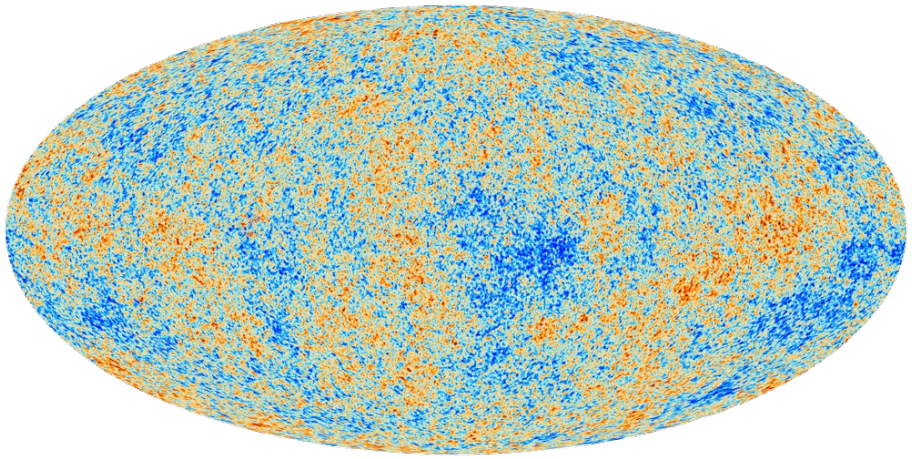
Global Fits of sub-GeV DM

Cosmological Constraints



Relic Density (freeze-out)

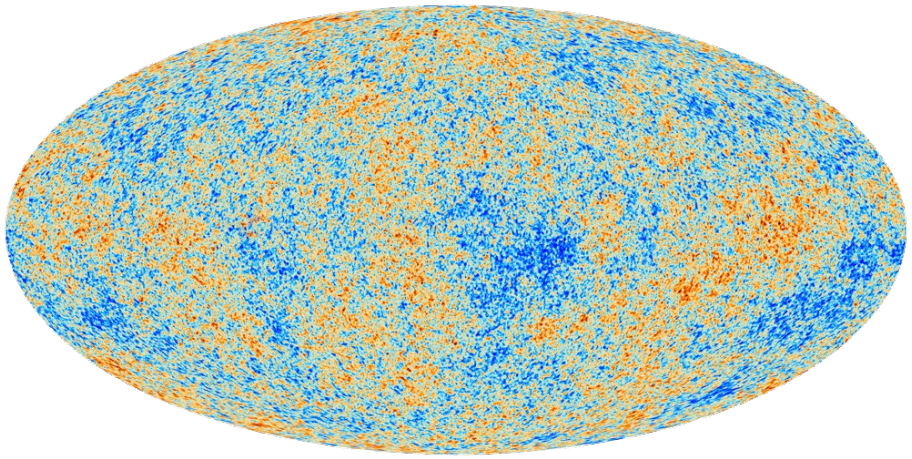
$\Omega_{DM,obs}h^2 \leq 0.120 \pm 0.001$

Planck 2018 results. VI. Cosmological parameters

full-component DM OR sub-component DM

Global Fits of sub-GeV DM

Cosmological Constraints



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$DM\ DM \rightarrow SM\ SM$

constrained by CMB measurements

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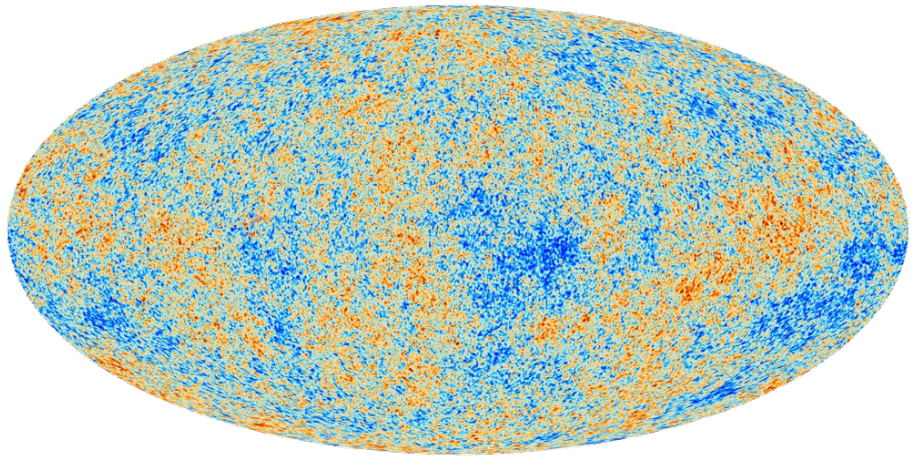

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Big Bang Nucleosynthesis

$DM\ DM \rightarrow SM\ SM$

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

Global Fits of sub-GeV DM

Astrophysical Constraints

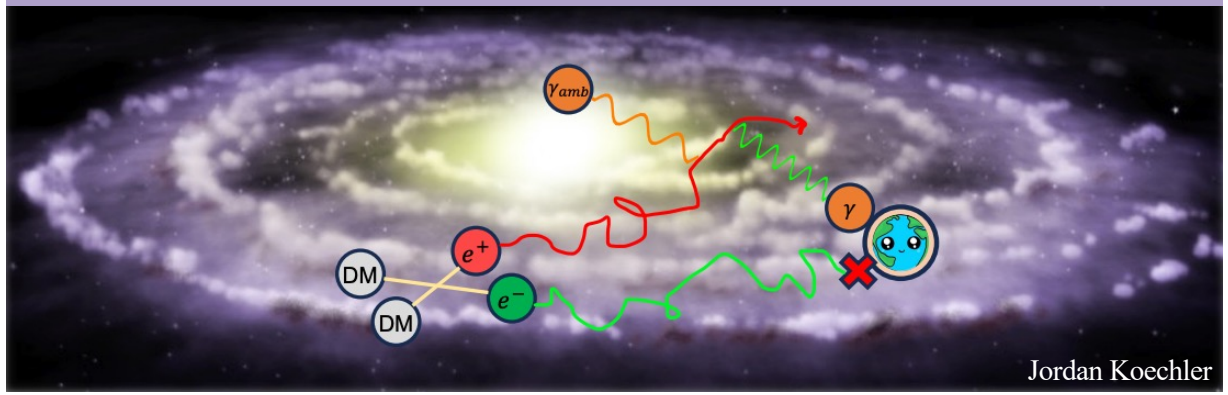
X-Rays

arXiv:2303.08

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

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

up-scatter the low energy photons of the ambient light



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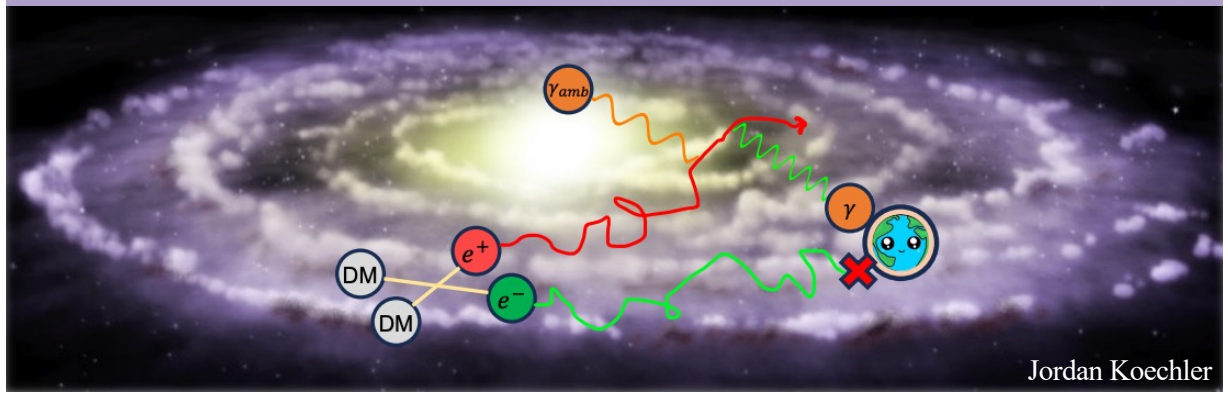


Global Fits of sub-GeV DM

Laboratory Experiment Constraints

Accelerators

Monophoton searches

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

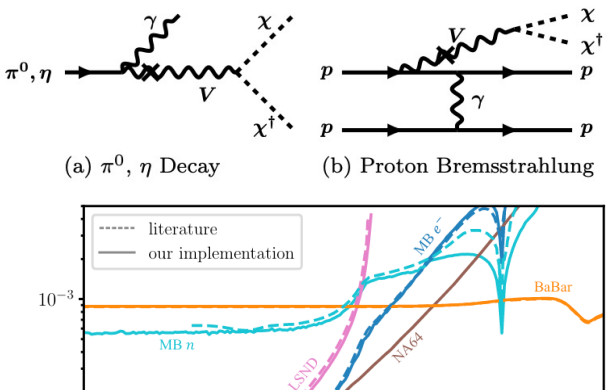
- BaBar

Fixed Targets

Dark photon production

$A' \to DM$

- LSND
- Mini-BooNE
- NA64



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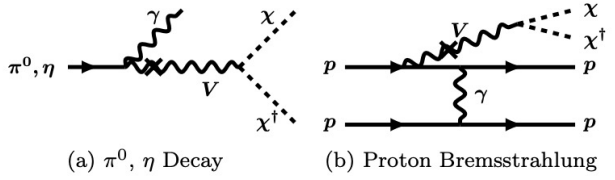
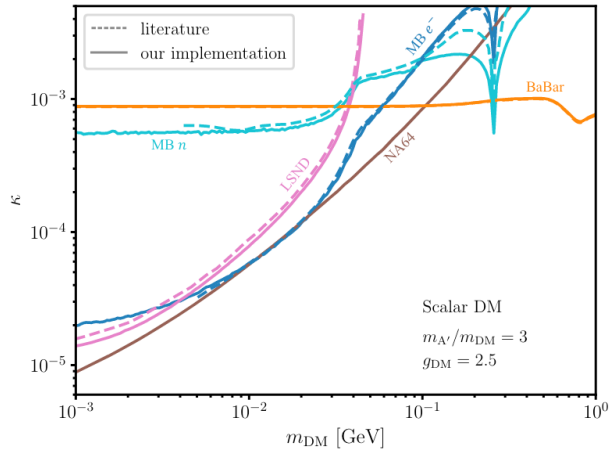


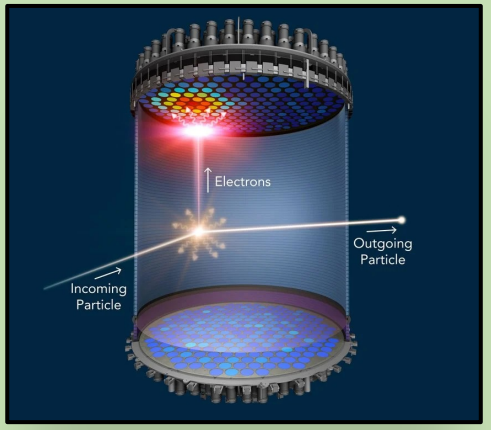
(a) π^0, η Decay (b) Proton Bremsstrahlung



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

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

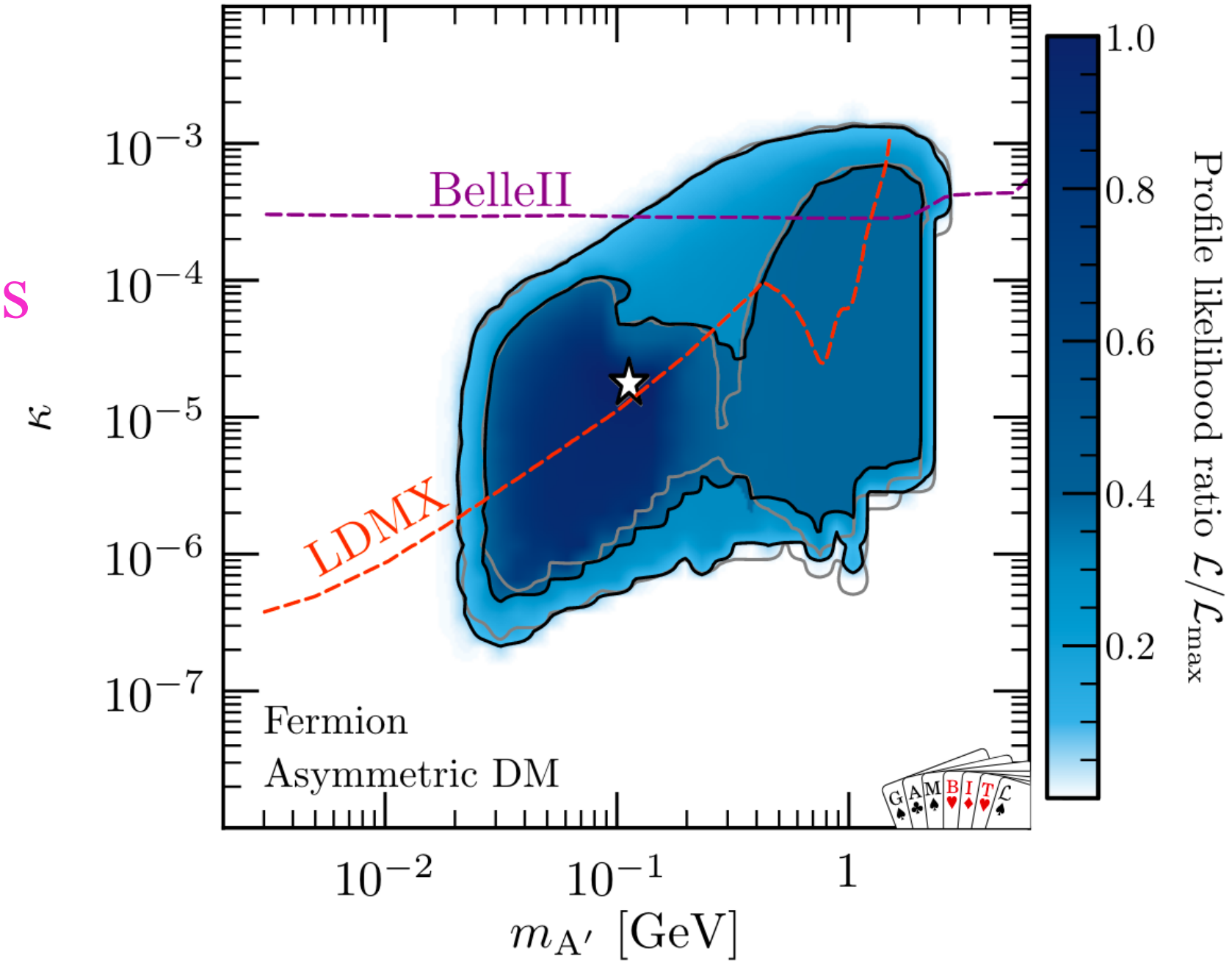
How to evade indirect detection constraints?

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: $f \equiv \frac{\Omega_{DM} h^2}{\Omega_{DM,obs} h^2} < 1$

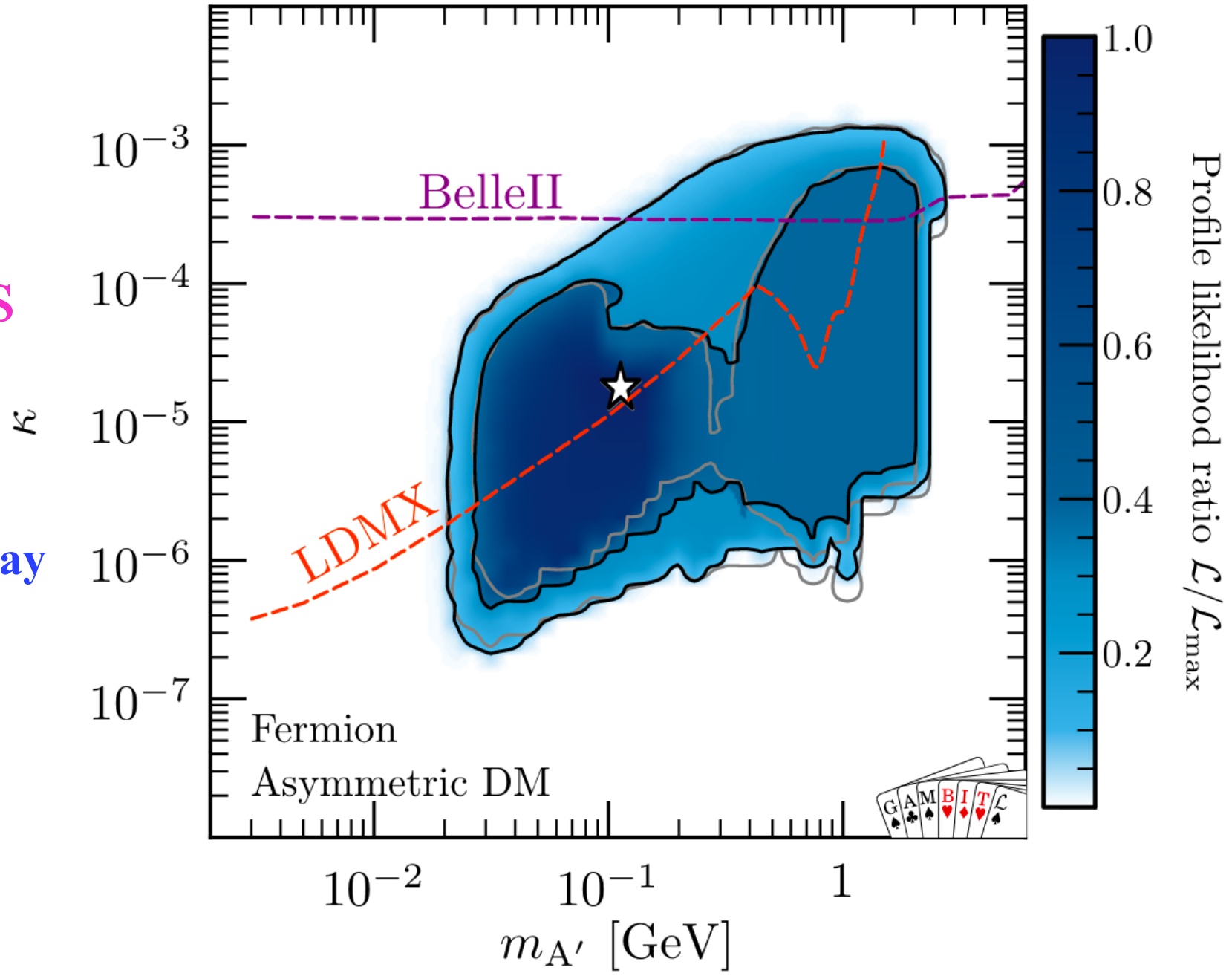
Global Fits of sub-GeV DM:
Frequentist analysis



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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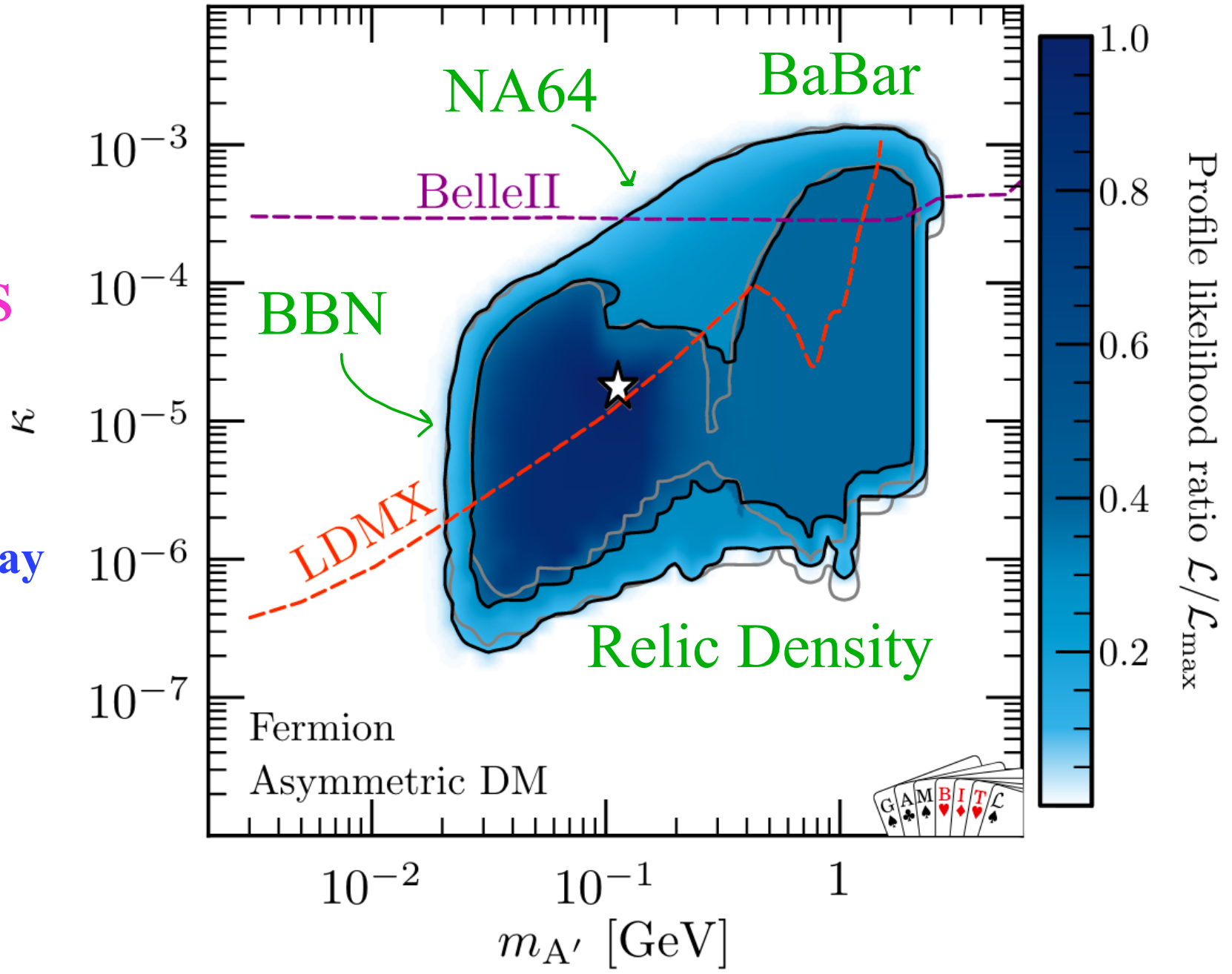

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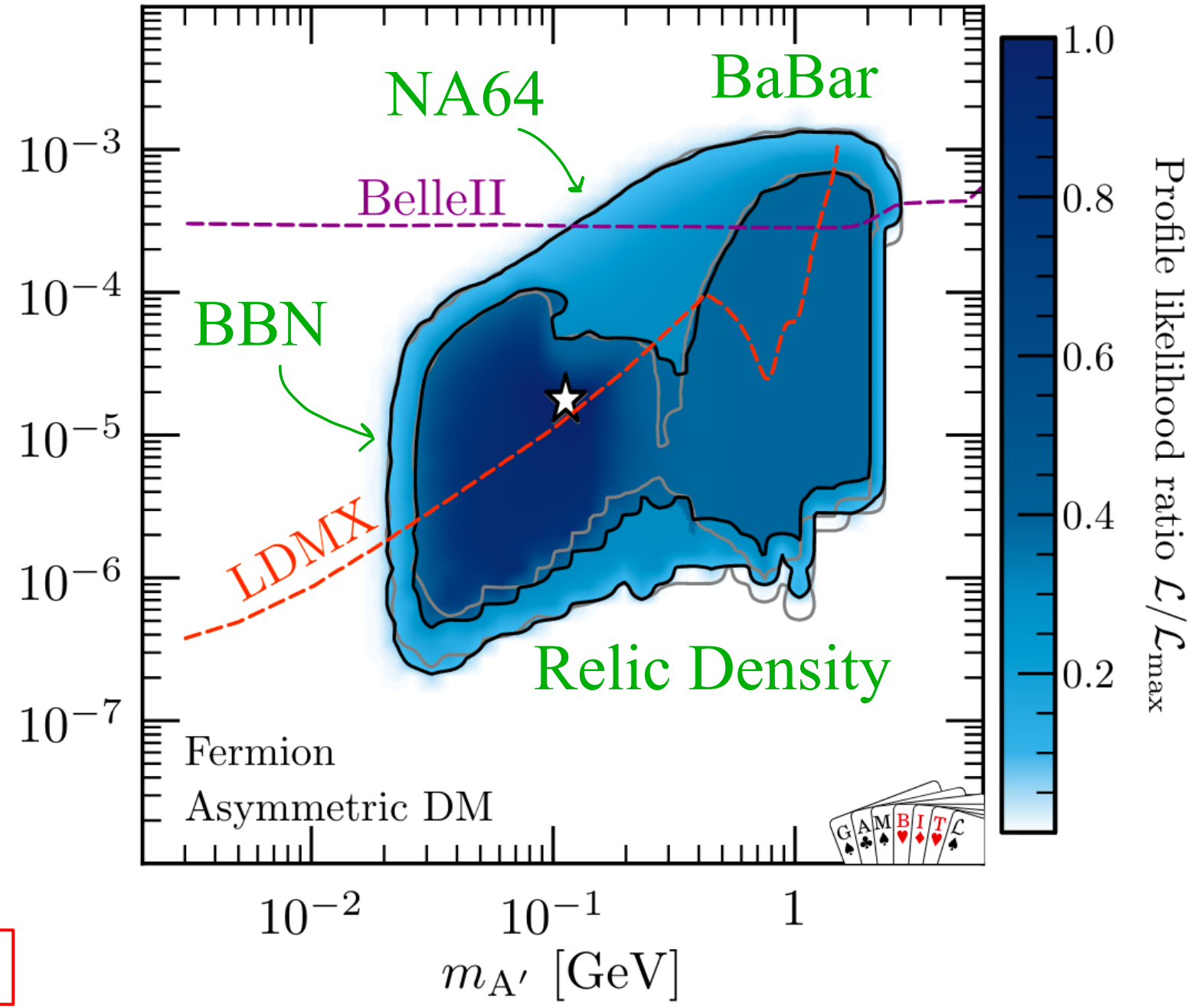
See Hannah's talk

And Andreas' talk!

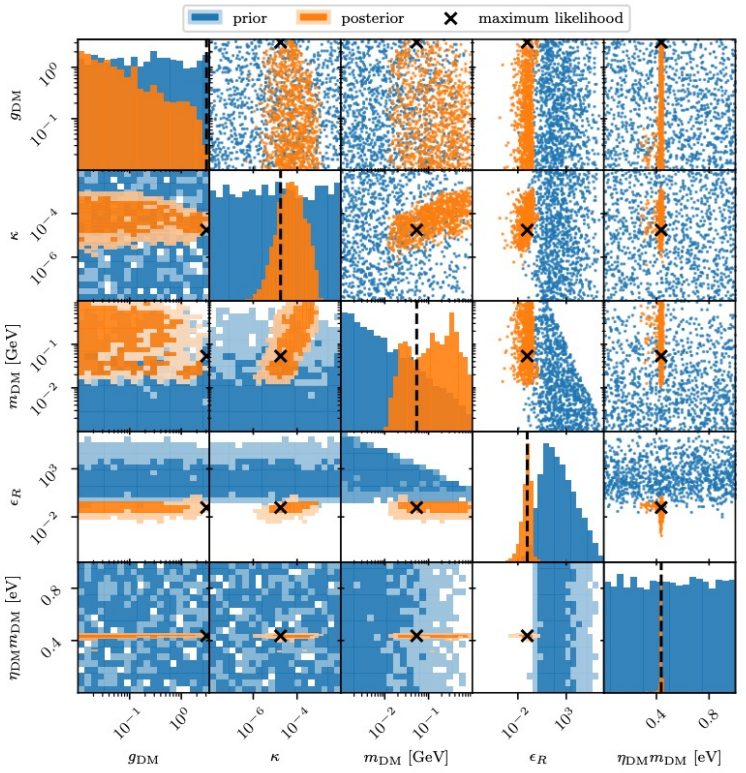


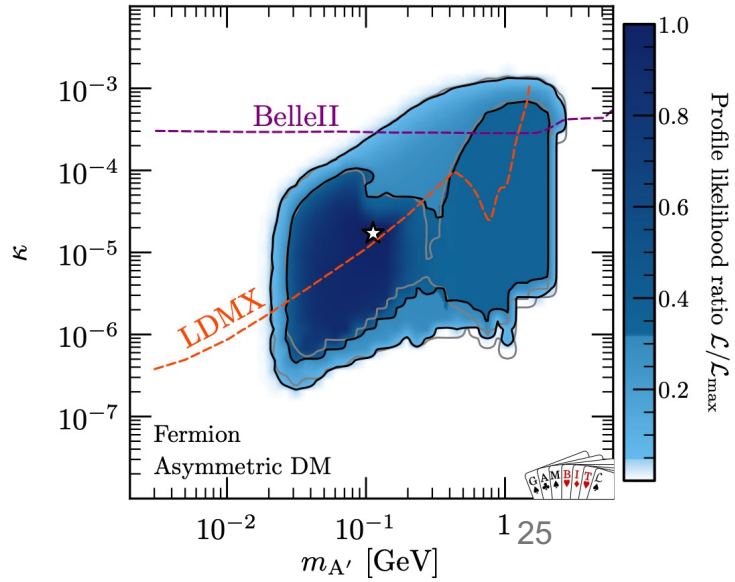
Summary

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

Thank you for listening!





Additional Material

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	κ	–	$[10^{-8}, 10^{-2}]$	logarithmic
Dark sector coupling	$g_{\rm DM}$	–	$[10^{-2}, \sqrt{4\pi}]$	logarithmic
Asymmetry parameter	$\eta_{\rm DM}$	–	$[0, 10^{-9}\,{\rm GeV}/m_{\rm DM}]$	linear
Dark matter mass	$m_{\rm DM}$	MeV	[1,1000]	logarithmic
Dark photon mass	$m_{A'}$	MeV	[2,6000] with $m_{A'} \geq 2m_{\rm DM}$	logarithmic
or				
Resonance parameter	ϵ_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

Frequentist vs Bayesian

- Parameters are fixed quantities
- Only likelihood matters

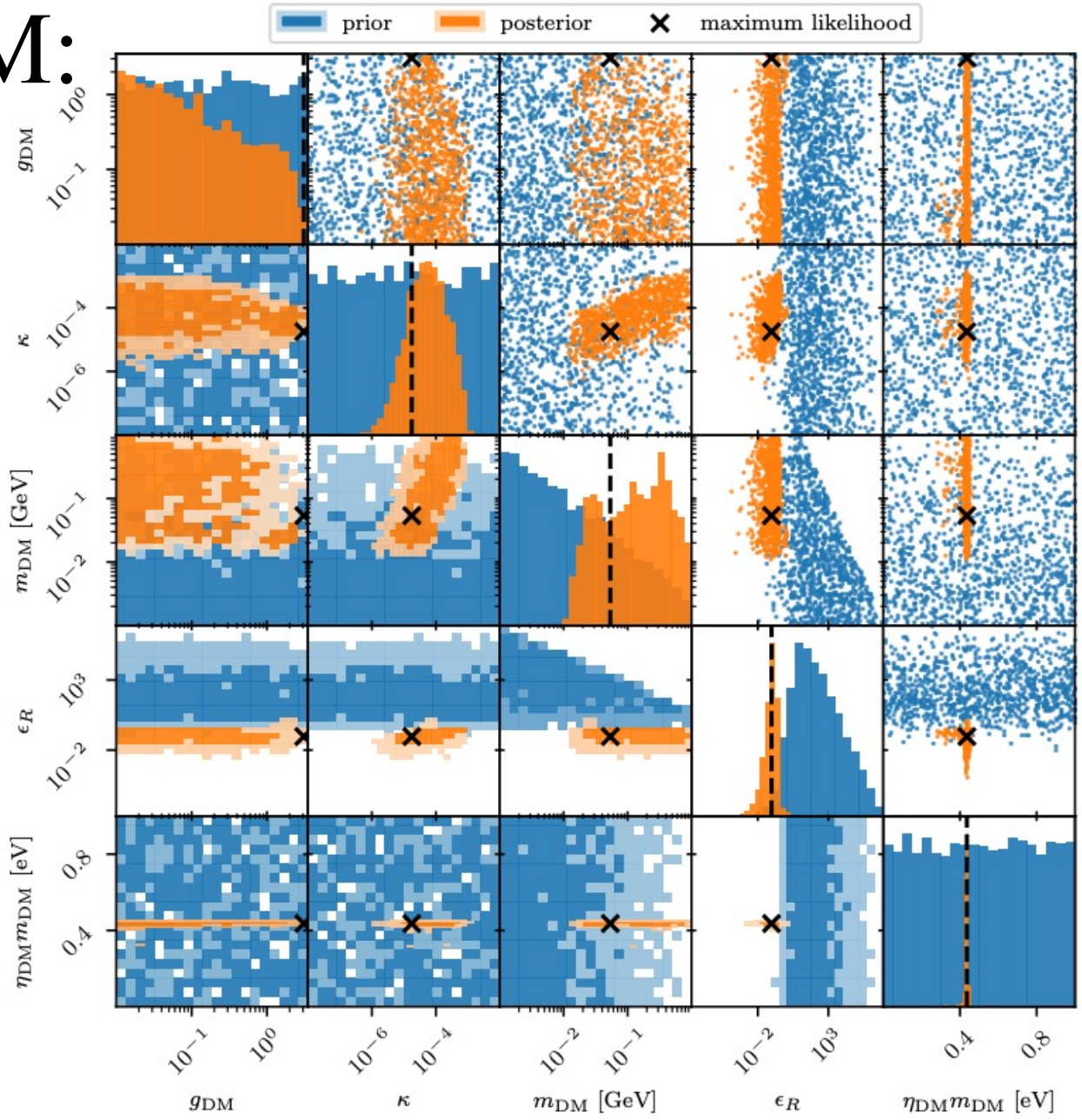
- Parameters are random variables w distributions
- Volume of allowed parameter space

(Fine-tuning is penalized)

  - For example:
    - η parameter
    - smaller g_{DM} and larger m_{DM}

Global Fits of sub-GeV DM: Bayesian scans

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



Asymmetric full component Dirac fermion DM