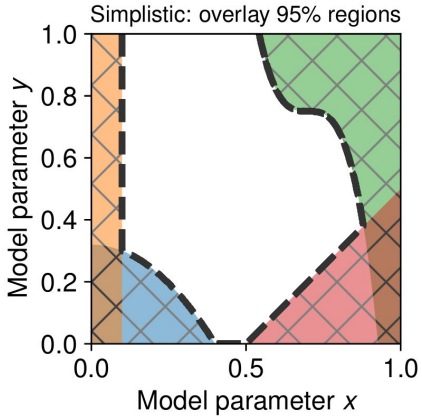
Global fits of sub-GeV dark matter models with GAMBIT

Sowmiya Balan

With Taylor R. Gray, Felix Kahlhoefer, Torsten Bringmann, Jonas Matuszak, Carlo Tasillo and others

JCAP01(2025)053, arXiv:2502.19478

Global Fits



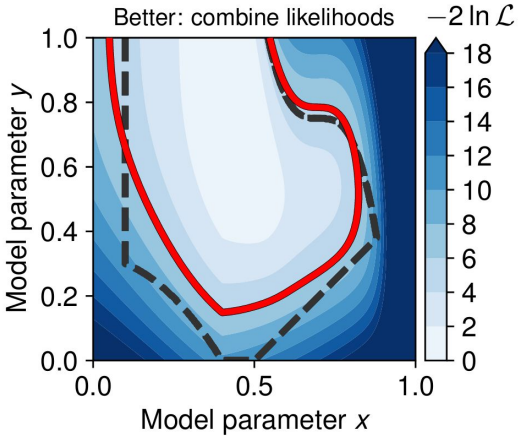
AbdusSalam et al, arXiv:2012.09874

- Simple overlay of constraints → no proper statistical interpretation
- Global fits: combined likelihood

$$\mathcal{L} = \mathcal{L}_{Collider}\ \mathcal{L}_{DD}\ \mathcal{L}_{ID}$$

- Global fits with GAMBIT

Global And Modular Beyond the standard model Inference Tool (GAMBIT)



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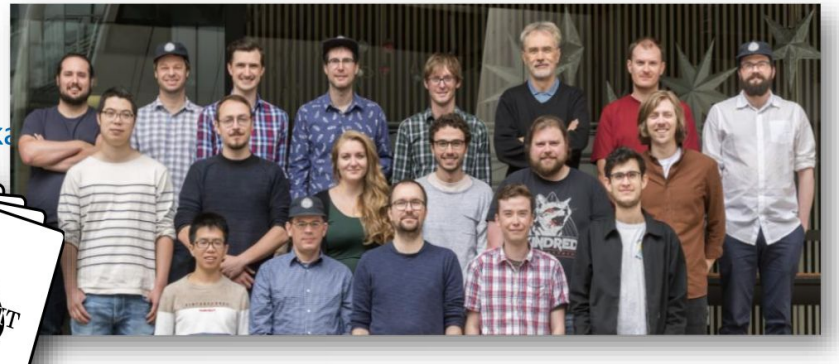
GAMBIT: The Global And Modular BSM Inference Tool

gambitbsm.org github.com/GambitBSM EPJC 77 (2017) 784 arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packa
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source



Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, SuperIso, SUSY-AI, xsec, Vevacious, WIMPSim

Recent collaborators: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, LL Braseth, T Bringmann, A Buckley, J Butterworth, JE Camargo-Molina, C Chang, J Cornell, M Danninger, A Fowlie, T Gonzalo, W Handley, S Hoof, A Jueid, F Kahlhoefer, A Kvellestad, M Lecroq, C Lin, M Lucente, FN Mahmoudi, DJE Marsh, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, R Ruiz, A Scaffidi, P Scott, W Shorrock, C Sierra, P Stöcker, W Su, J Van den Abeele, A Vincent, M White, A Woodcock, Y Zhang ++

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

Sowmiya Balan,[a,*] **Csaba Balázs**,[b] **Torsten Bringmann**,[c,*] **Christopher Cappiello**,[d,e,f] **Riccardo Catena**,[g] **Timon Emken**,[h] **Tomás E. Gonzalo**,[a] **Taylor R. Gray**,[g,*] **Will Handley**,[i,j] **Quan Huynh**,[b] **Felix Kahlhoefer**[a,*] **and Aaron C. Vincent**[d,e,f]

Model - Sub-GeV fermionic DM

- Dirac fermion stable due to U(1)' gauge symmetry

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

- Portal to SM through dark photon A' with kinetic mixing

$$\frac{\kappa}{2} F_{\mu\nu}F'^{\mu\nu} \longrightarrow \kappa e A'^{\mu} \sum_{f} q_f \overline{f}\gamma_{\mu} f$$

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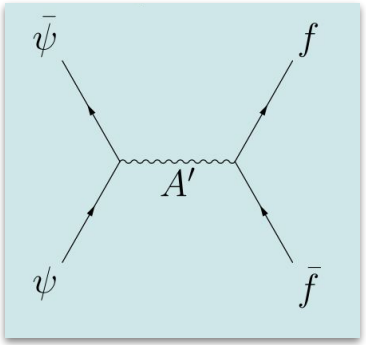

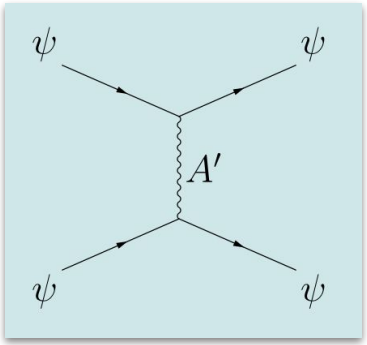

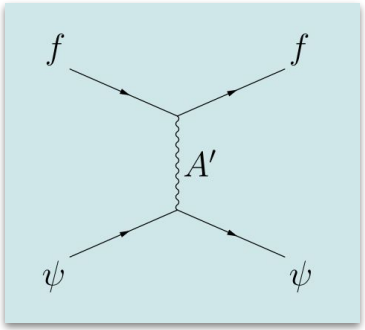

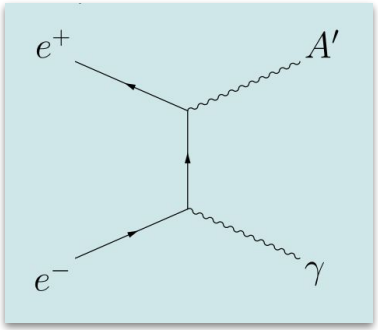

Status of sub-GeV dark matter

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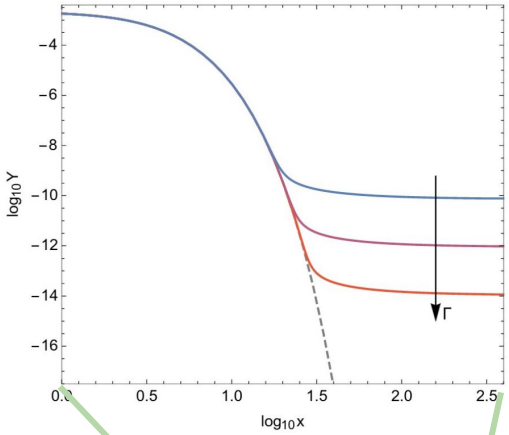
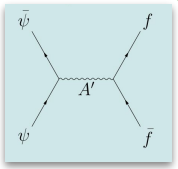
JCAP01(2025)053

Challenges to freeze-out





Freeze-out

$1/T$

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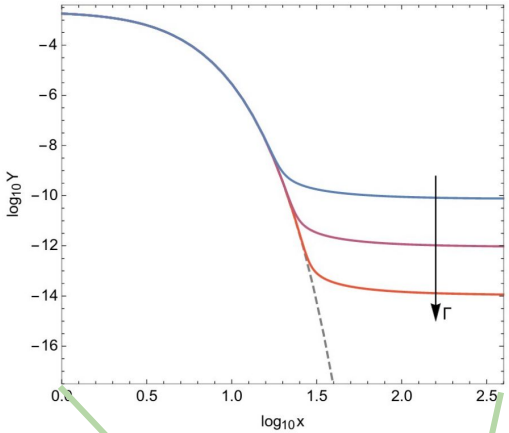
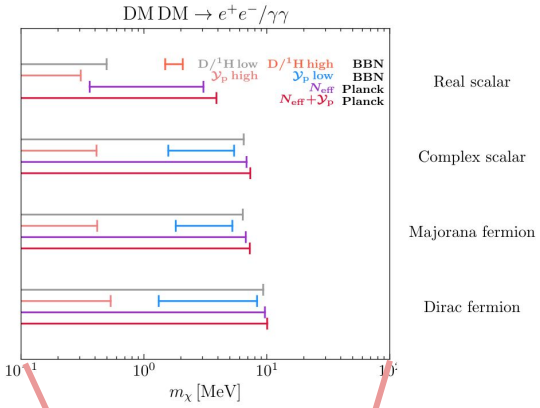
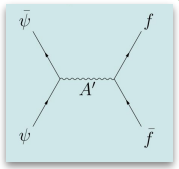


Depta et al, arXiv:1901.06944





Freeze-out

BBN

$1/T$

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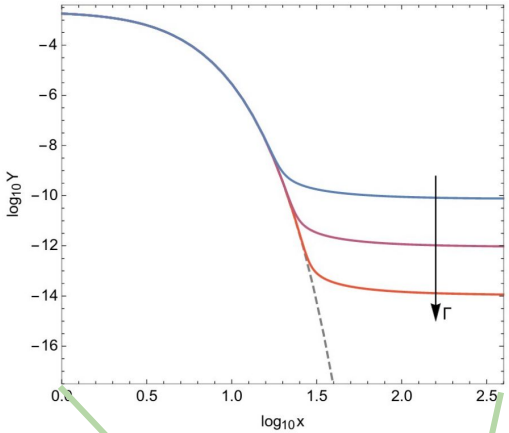
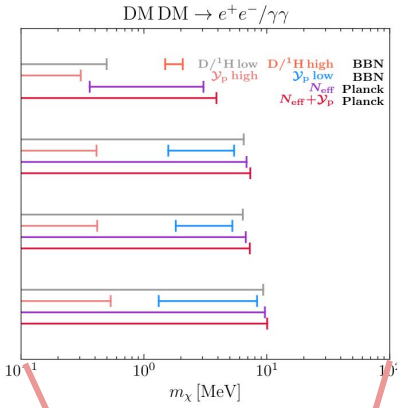
Depta et al, arXiv:1901.06944

Cirelli et al, arXiv:2303.08854



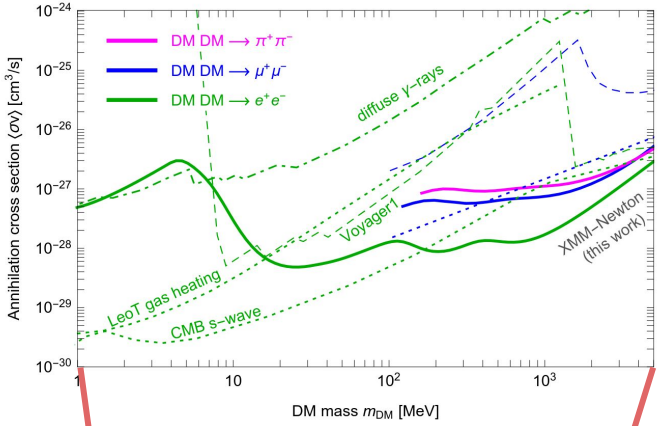


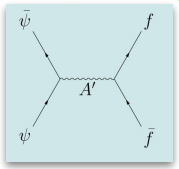
Real scalar

Complex scalar

Majorana fermion

Dirac fermion



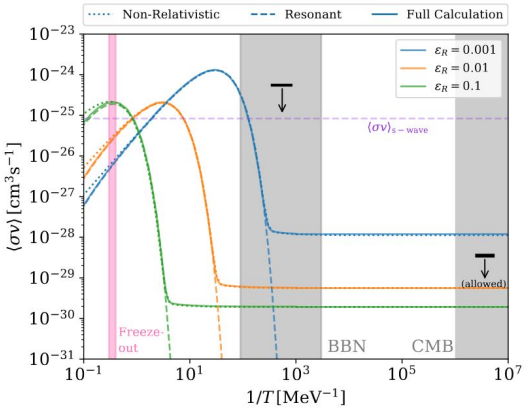


Freeze-out → BBN → CMB → X-ray → $1/T$

Possible solutions

- Resonance,

$$\epsilon_R \equiv \frac{m_{A'}^2 - 4m_{\rm DM}^2}{4m_{\rm DM}^2} \ll 1$$



Bernreuther et al, arXiv:2010.14522

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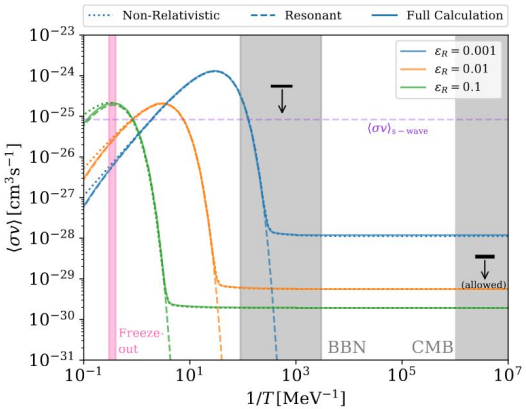
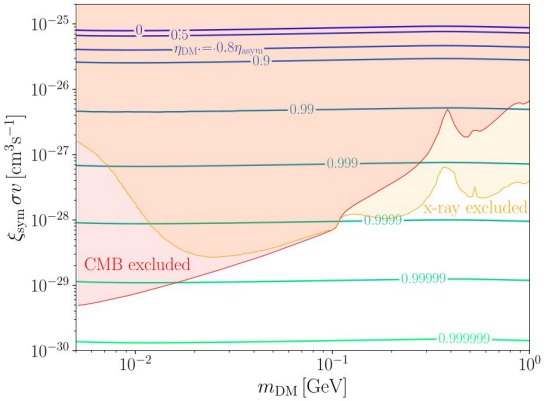


- Asymmetry,

$$\eta_{\rm DM} \equiv \frac{n_\chi - n_{\overline{\chi}}}{s} \neq 0$$



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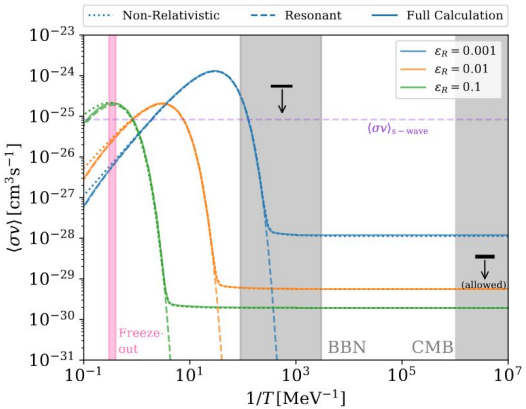

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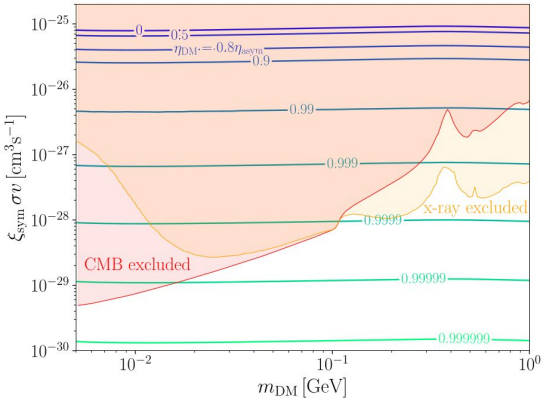
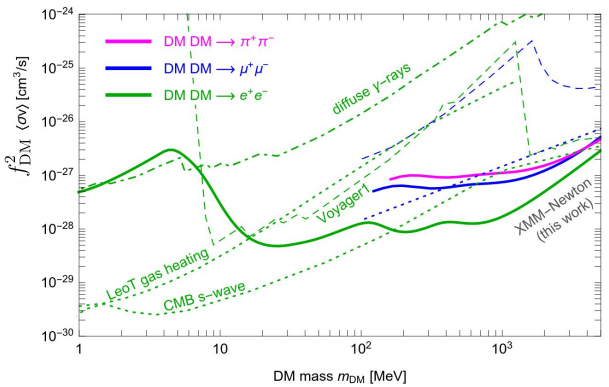


- Sub-dominant DM,

$$f_{\rm DM} = \frac{\Omega_{\rm DM} h^2}{\Omega_{\rm obs} h^2} \leq 1$$



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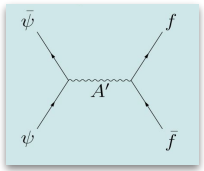

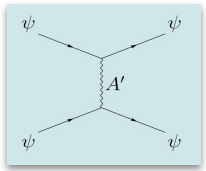

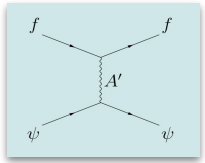

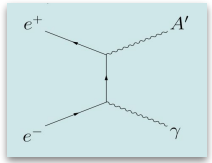

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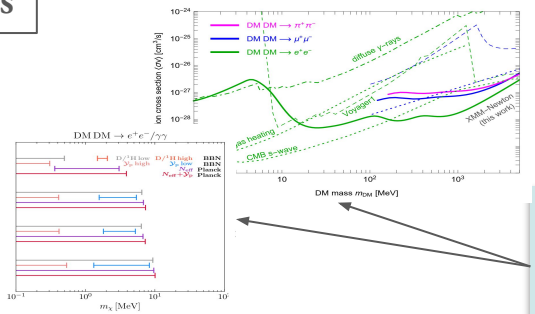
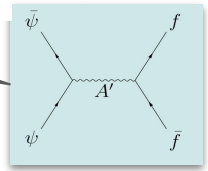
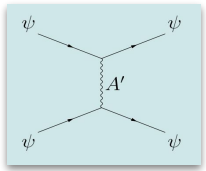
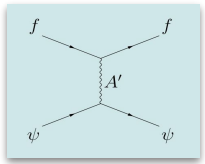
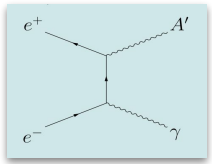


Indirect detection + Cosmology









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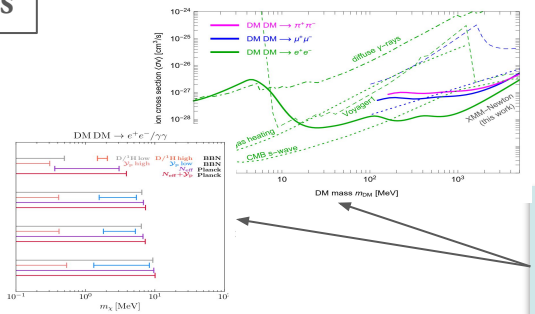

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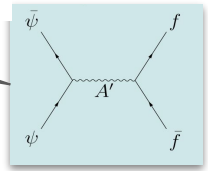
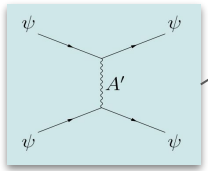
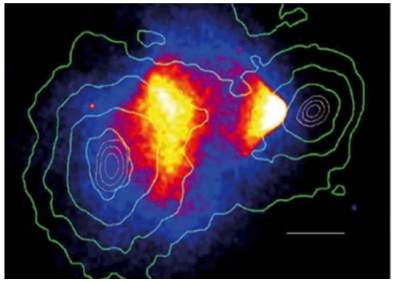
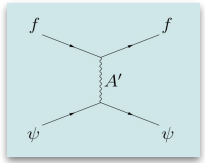
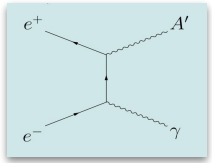






Bullet Cluster





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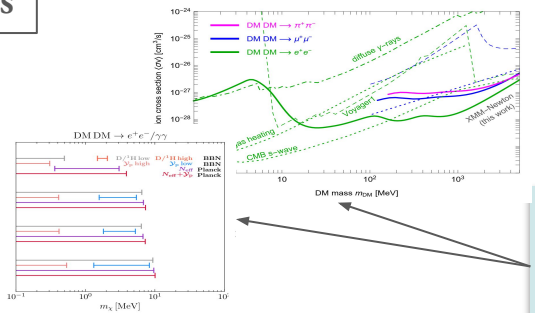

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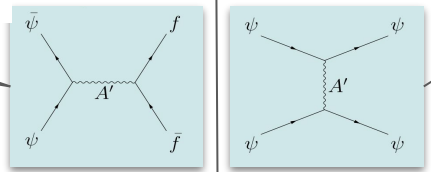

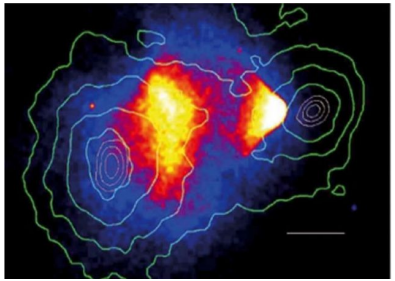

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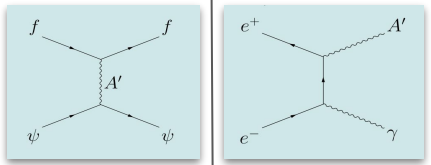

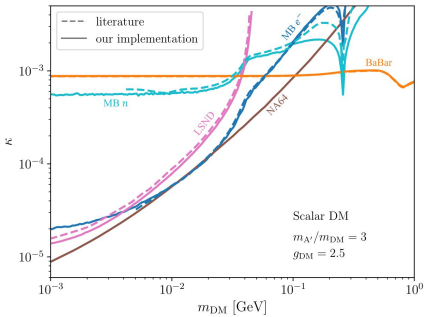

Accelerator experiments

Status of sub-GeV dark matter

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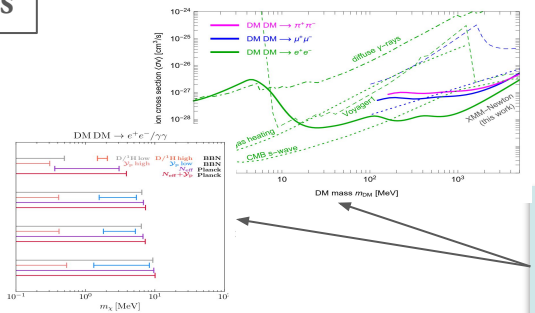

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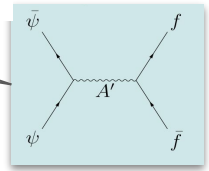

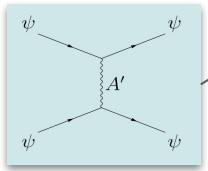

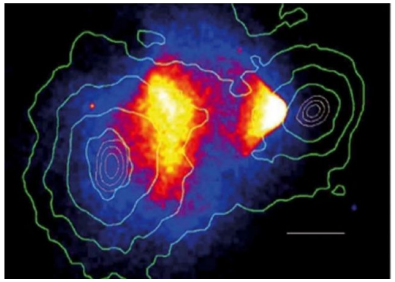

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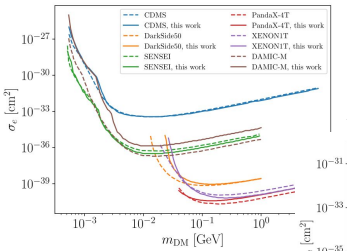
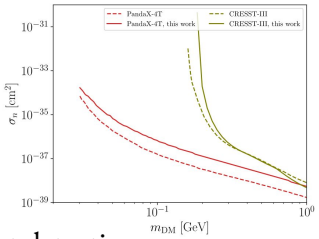
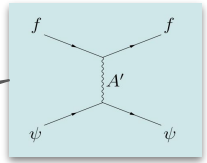
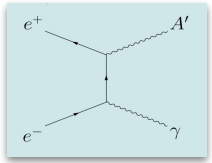
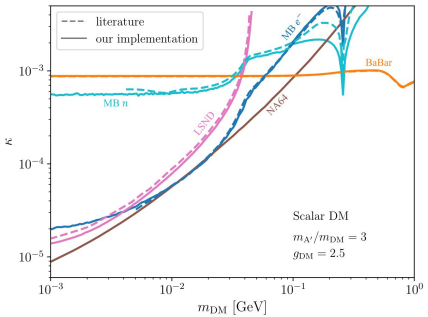




Direct detection







Accelerator experiments

Status of sub-GeV dark matter

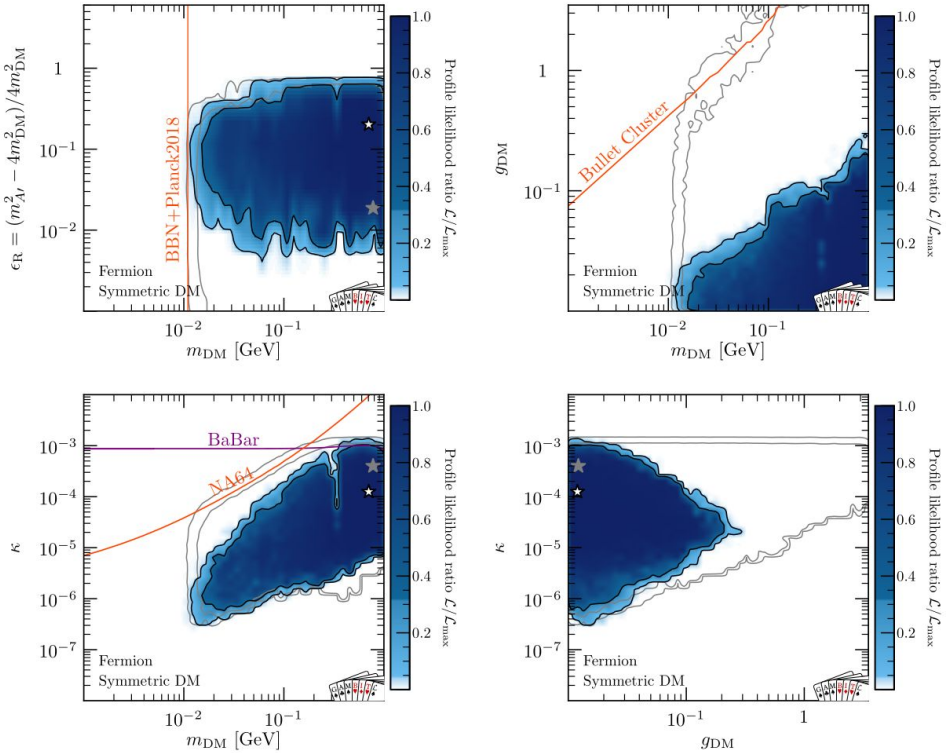
Sowmiya Balan, Taylor R. Gray, Felix Kahlhoefer, Torsten Bringmann and others

JCAP01(2025)053

Results: Symmetric dark matter

$$\eta_{\rm DM} = 0$$

- Sub-dominant DM: $\Omega_\psi h^2 \leq 0.12$
  - Allows small resonance parameter, large couplings and masses
- All DM: $\Omega_\psi h^2 = 0.12$
  - Does not allow large couplings, fine-tuned parameter regions



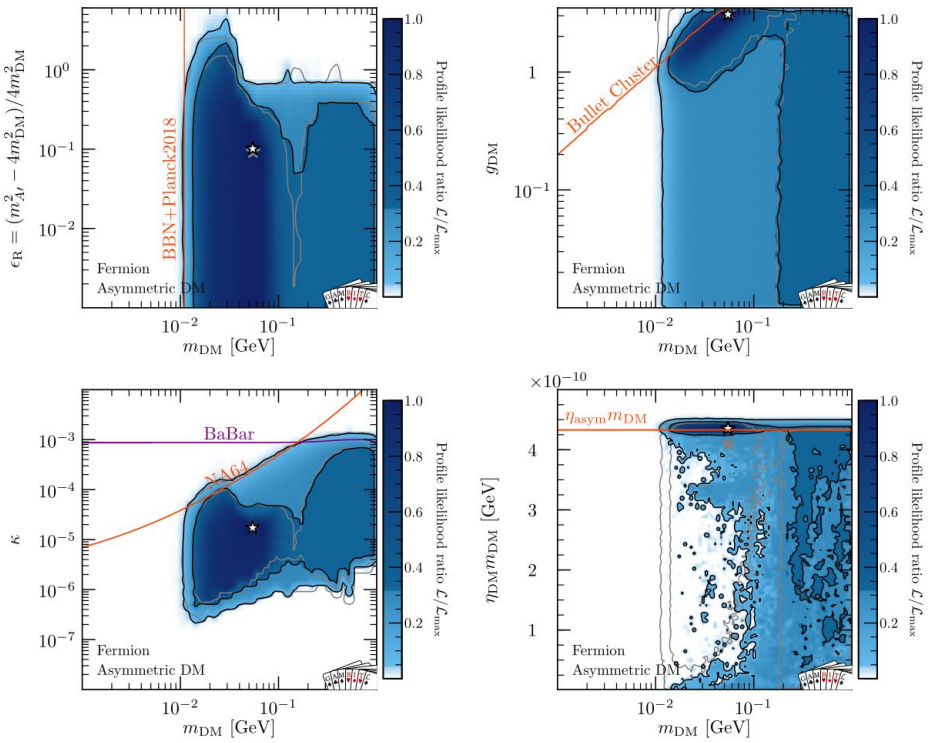
sowmiya.balan@kit.edu

Karlsruhe Institute of Technology

Results: Asymmetric dark matter

$$\eta_{\rm DM} \neq 0$$

- All DM: $\Omega_\psi h^2 = 0.12$
  - Large couplings allowed
  - Large asymmetry preferred
  - Contours coincide with sub-dominant DM



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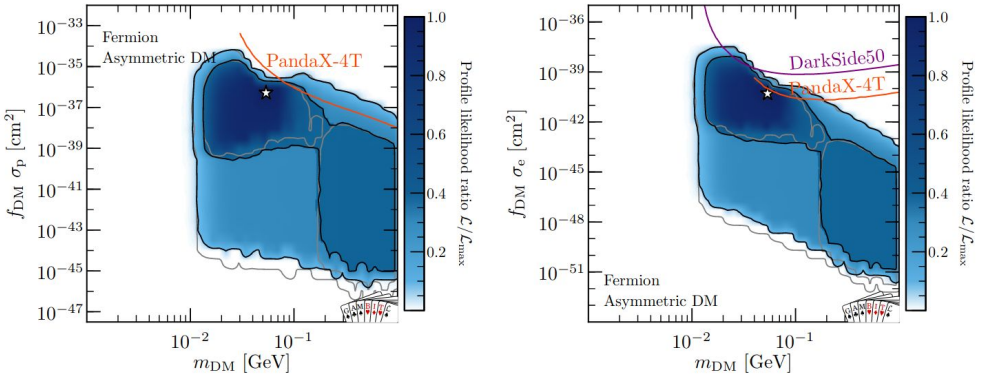

⇒Asymmetric fermionic DM - discoverable!

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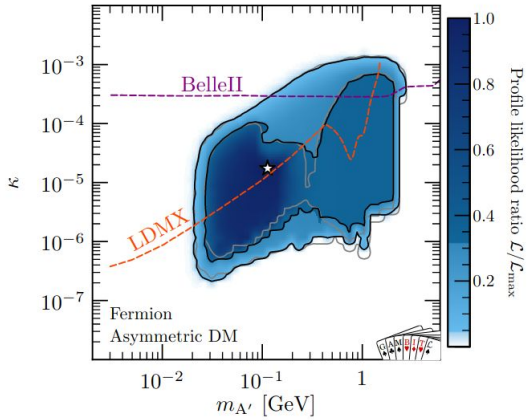


⇒Asymmetric fermionic DM - discoverable!

Prepared for submission to JCAP

Sub-GeV dark matter and nano-Hertz gravitational waves from a classically conformal dark sector

Sowmiya Balan,[a] **Torsten Bringmann,**[b] **Felix Kahlhoefer,**[a,c] **Jonas Matuszak,**[a] **and Carlo Tasillo**[d,e]

Model - Sub-GeV fermionic DM

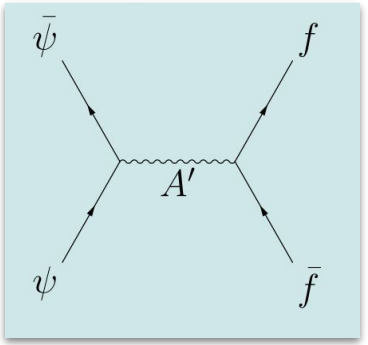
- Dirac fermion stable due to U(1)' gauge symmetry

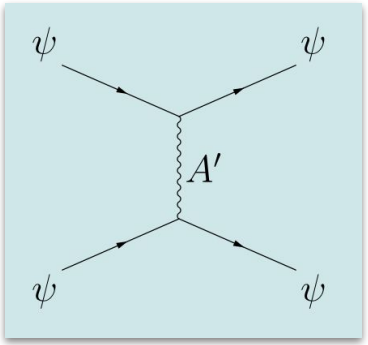
$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - m_{\rm DM})\psi + g_{\rm DM} A'^\mu \bar{\psi}\gamma_\mu\psi$$

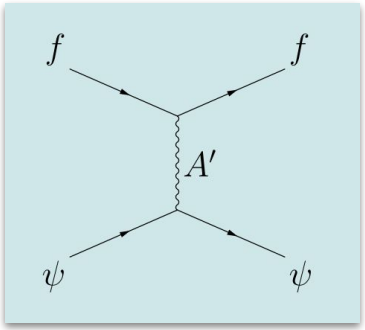
- Portal to SM through dark photon A' with kinetic mixing

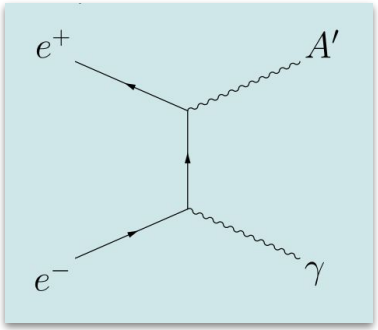
$$\mathcal{L}_{\rm int} = -\frac{1}{2} m_{A'}^2 A'^\mu A'_\mu - \frac{1}{4} A'^{\mu\nu} A'_{\mu\nu} - \kappa e A'^\mu \sum_f q_f \bar{f}\gamma_\mu f$$

?









Model - Sub-GeV fermionic DM

- Dirac fermion DM + dark photon + dark Higgs

$$\mathcal{L}_{\text{int}} \supset -\lambda v\phi^3 - \frac{\lambda}{4}\phi^4 + g^2 v A'_\mu A'^\mu \phi + \frac{g^2}{2}\phi^2 A'_\mu A'^\mu$$

$$+ \frac{g}{2}\bar{\chi}\gamma^\mu\gamma^5\chi A'_\mu - \frac{y}{\sqrt{2}}\phi\bar{\chi}\chi$$

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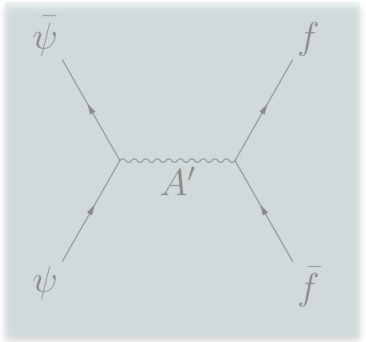

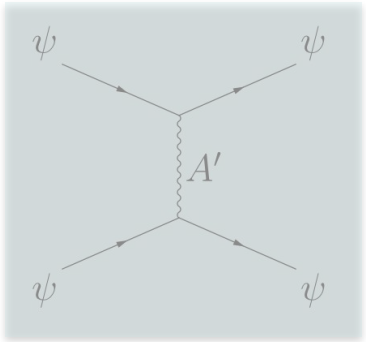

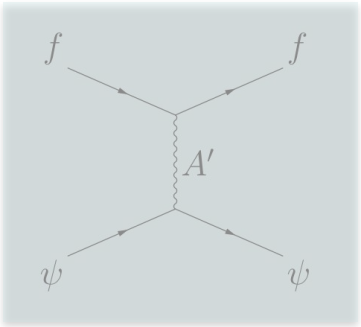

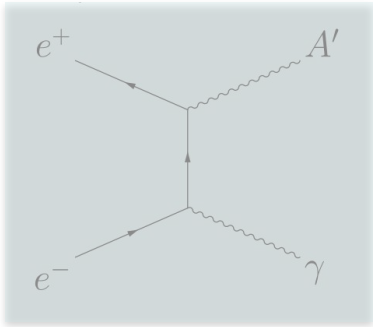

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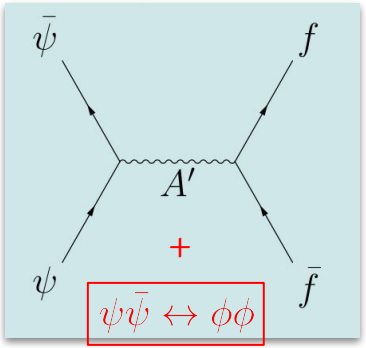
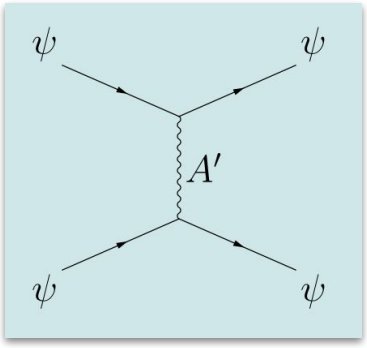
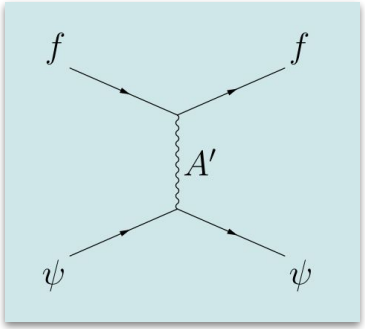
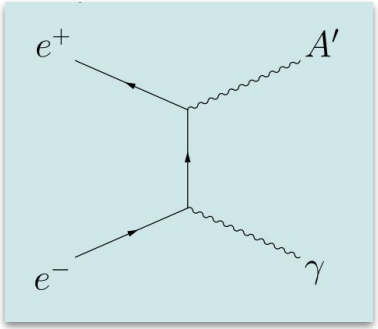








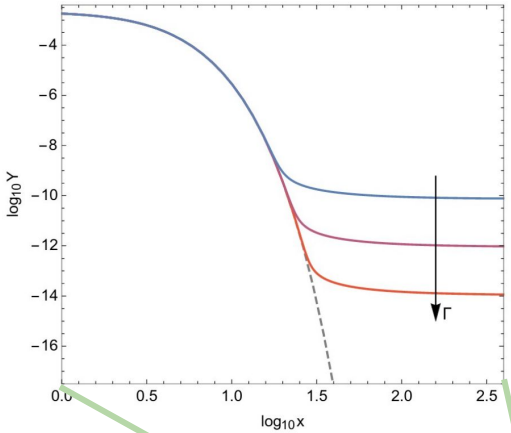
\+ Loop-induced dark Higgs decays

Sub-GeV dark matter and nHz gravitational waves

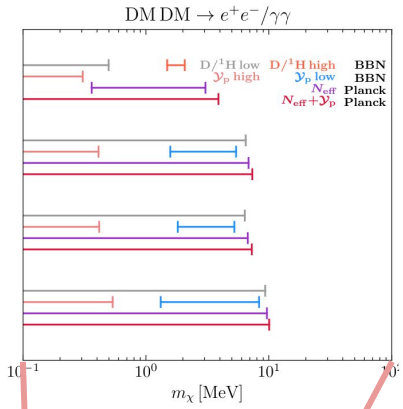
Sowmiya Balan, Felix Kahlhoefer, Torsten Bringmann, Jonas Matuszak and Carlo Tasillo

2502.19478

Cosmology of our dark sector



Depta et al, 1901.06944



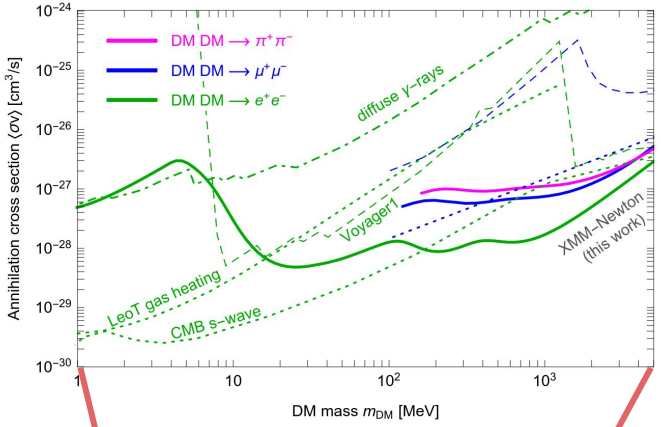
Real scalar

Complex scalar

Majorana fermion

Dirac fermion

Cirelli et al, 2303.08854



Annihilations

Freeze-out

BBN

CMB

X-ray

$1/T$

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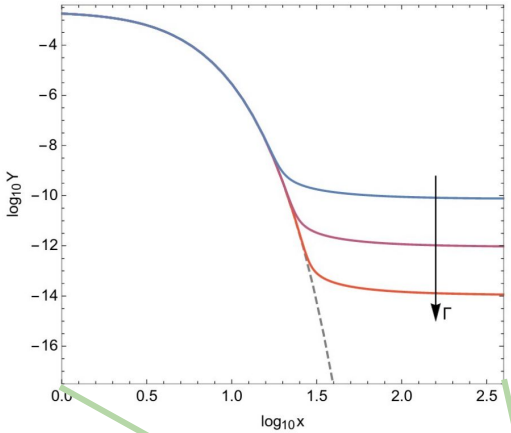

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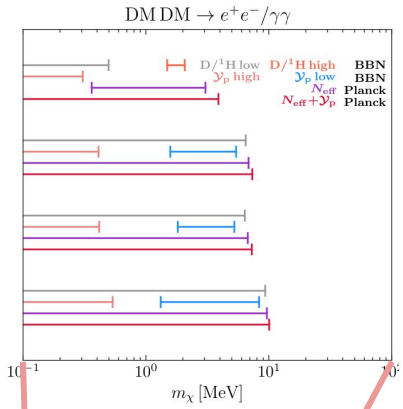

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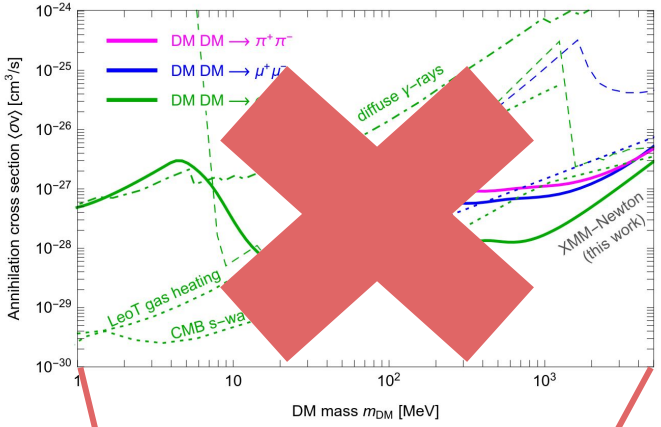

Velocity-suppression

Annihilations

Freeze-out

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CMB

X-ray

$1/T$

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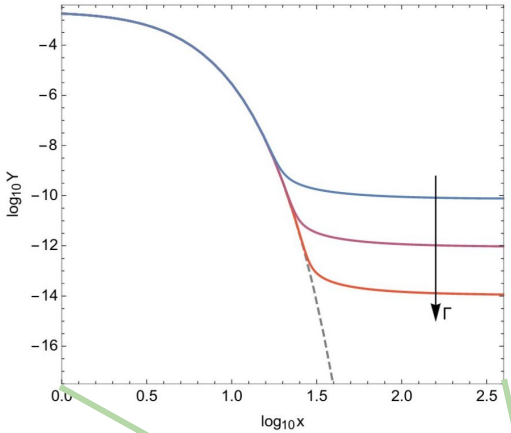
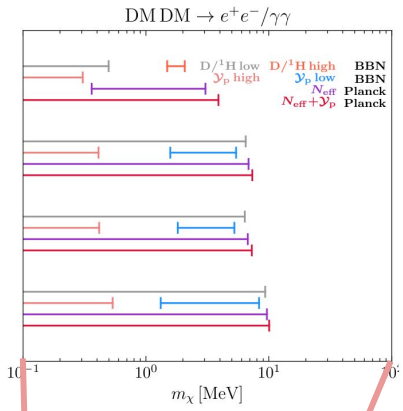


Depta et al, 1901.06944



Dark Higgs decays

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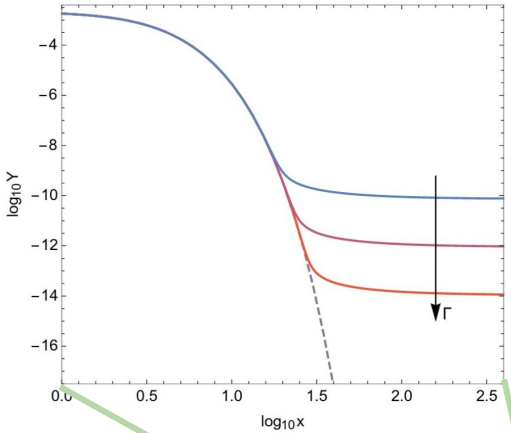

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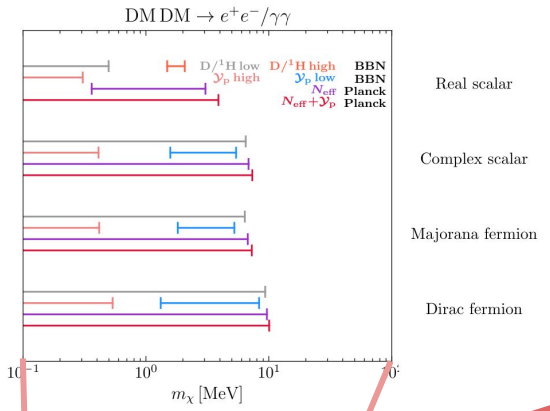
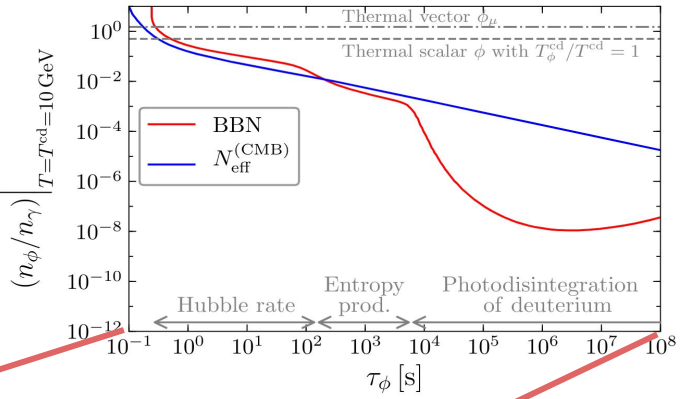


Hufnagel et al, 1808.09324



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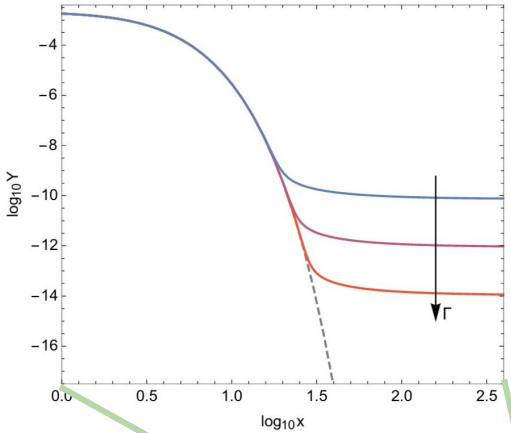

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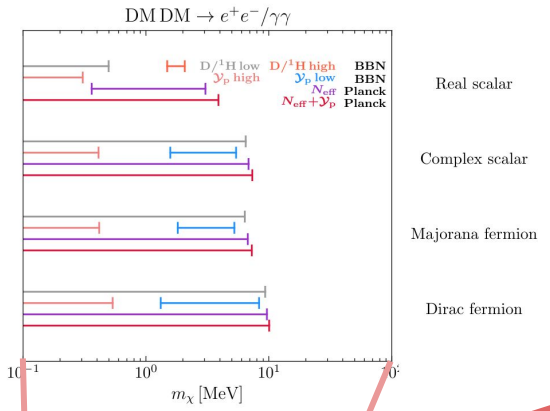

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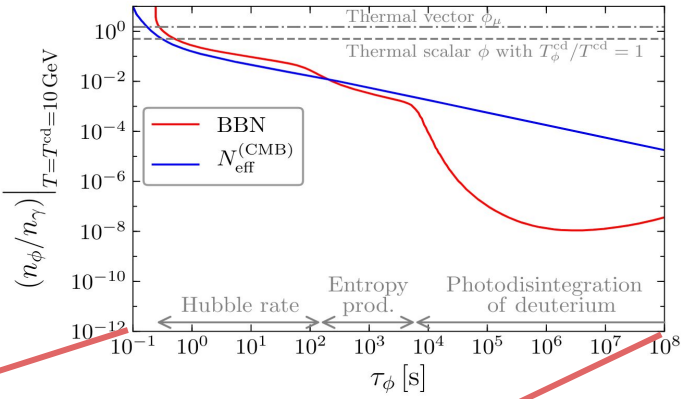

Dark Higgs decays

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?

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Sub-GeV dark matter and nHz gravitational waves

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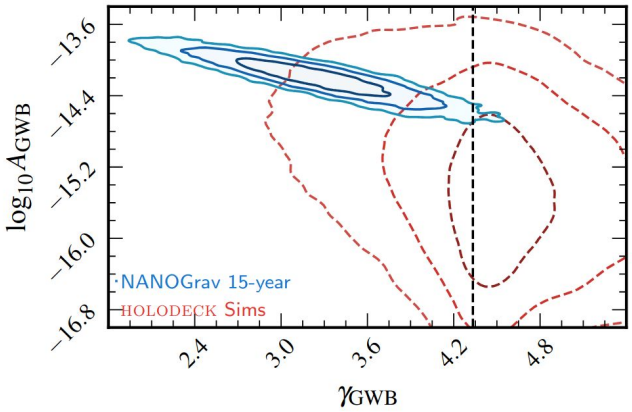
Gravitational waves from phase transition

- Phase transition → gravitational waves
- PTAs observed evidence for nHz stochastic gravitational wave background
- Astrophysical explanation: supermassive black hole binary (SMBHB) mergers; in tension with realistic astrophysical simulations



NANOGrav, 2306.16213

Sub-GeV dark matter and nHz gravitational waves

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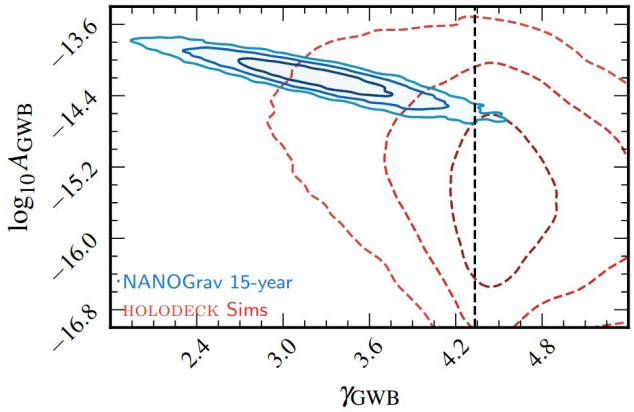
2502.19478

Gravitational waves from phase transition

- First Order Phase transition (FOPT) → gravitational waves
- PTAs observed evidence for nHz stochastic gravitational wave background
- Astrophysical explanation: supermassive black hole binary (SMBHB) mergers; in tension with realistic astrophysical simulations

⇒ PTA signal = GW from phase transition + SMBHB ?



NANOGrav, 2306.16213

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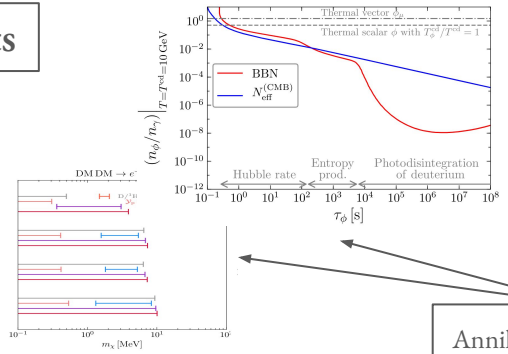
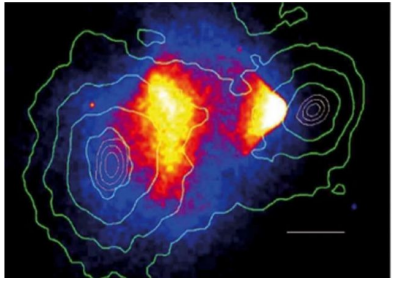
Constraints



Cosmology

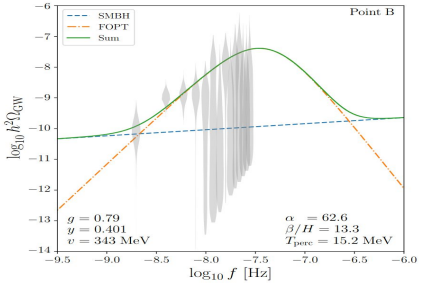
Annihilations and decays

Self-interactions



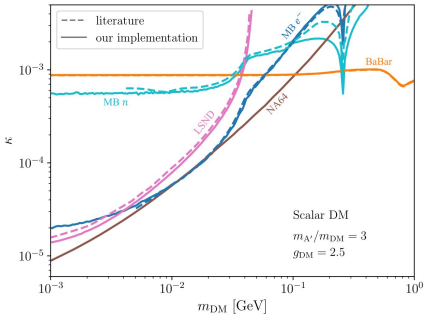
Bullet Cluster

GW from FOPT



NANOGrav Signal

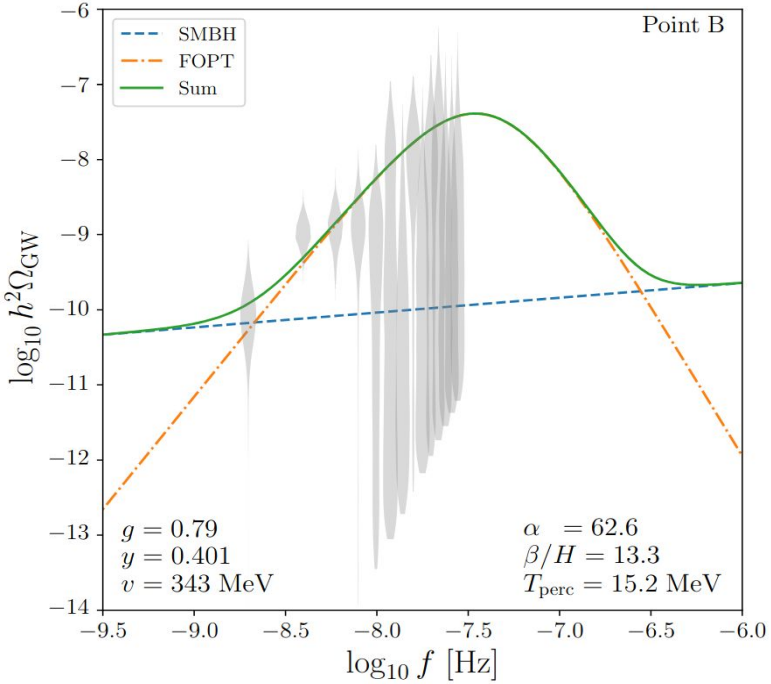
Invisible dark photon decays



Accelerator experiments

Global fit results

- Strong phase transition +SMBH background consistently fit PTA signal
- Observed DM relic abundance reproduced
- Viable interval in kinetic mixing parameter testable with LDMX

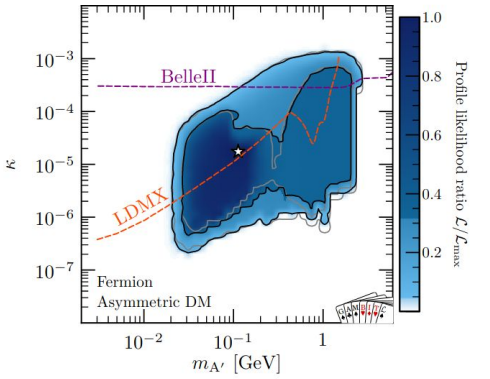


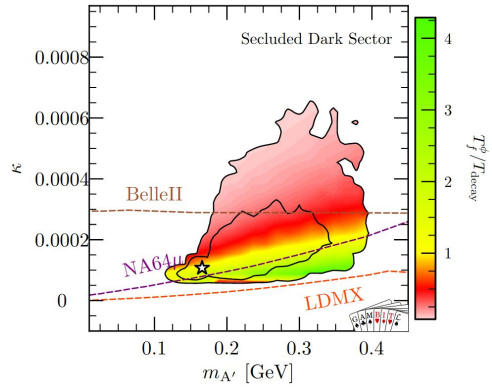
Summary

Sowmiya Balan, Felix Kahlhoefer, Torsten Bringmann, Jonas Matuszak and Carlo Tasillo

2502.19478

- GAMBIT is cool!
- Viable sub-GeV thermal relics: Asymmetric fermion DM, fermion DM in dark sector with dark Higgs
- Dark sector phase transition → nHz gravitational waves
- Viable regions in both models consistent with current constraints
- Discoverable!





BACKUP

Sub-GeV dark matter and nHz gravitational waves

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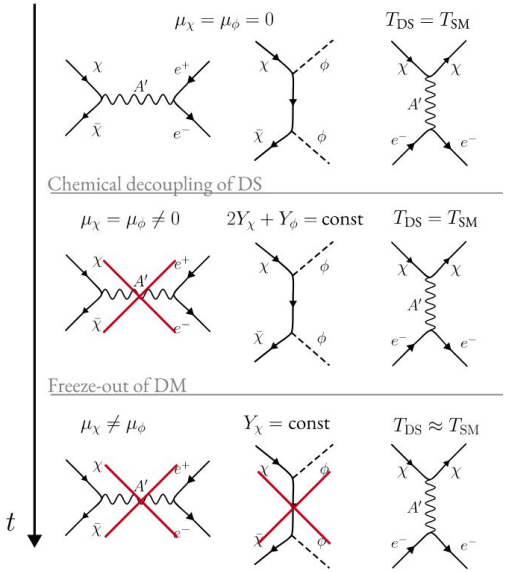
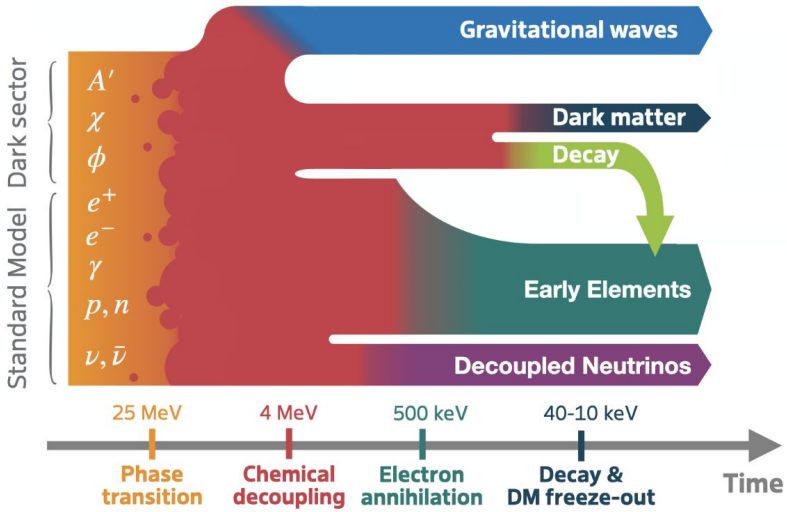
Secluded Dark Sector





Sub-GeV dark matter and nHz gravitational waves

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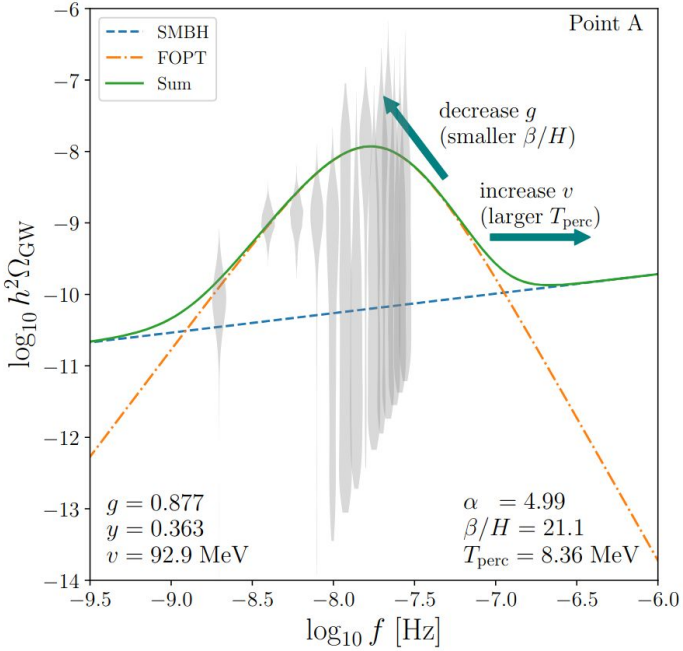
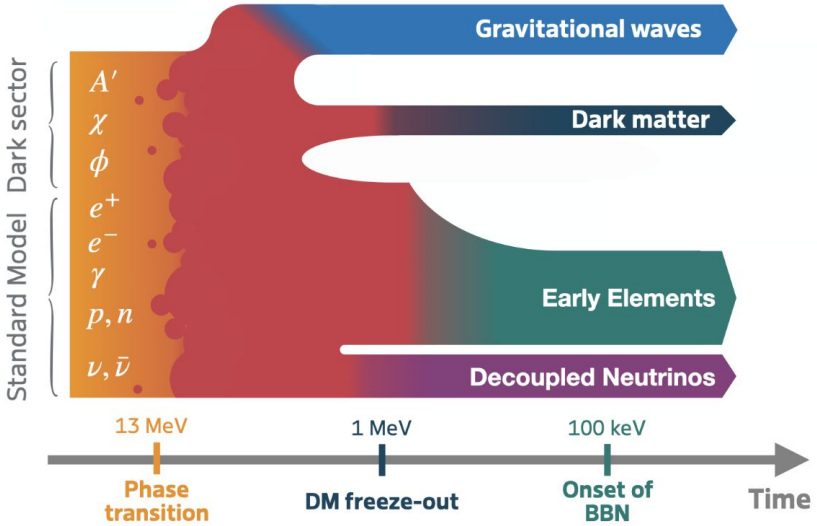
2502.19478

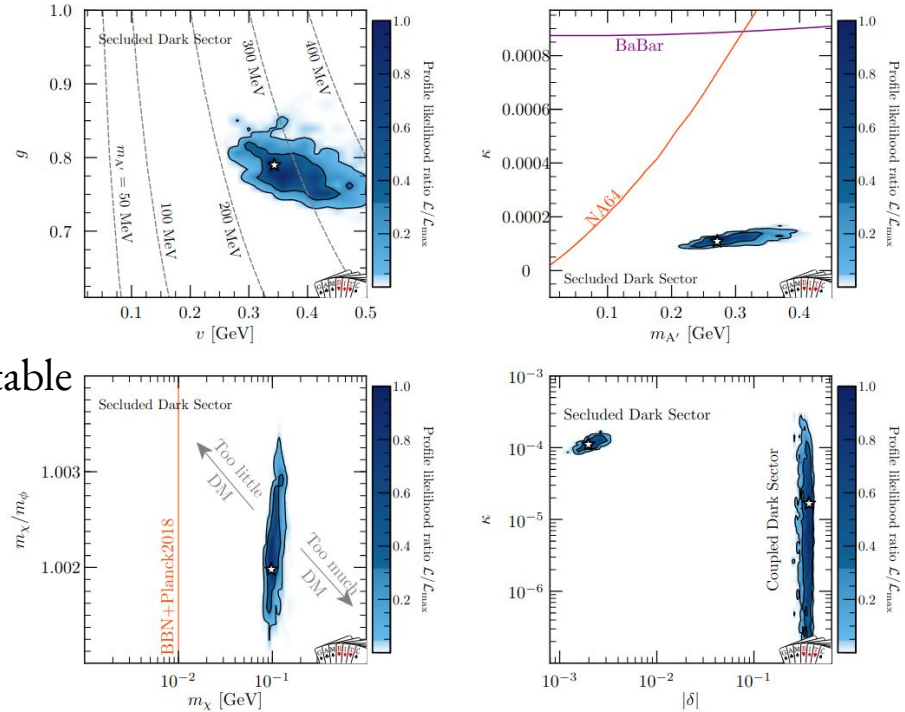
Coupled Dark Sector





Global fit results

- Strong phase transition +SMBH background consistently fit PTA signal
- Observed DM relic abundance reproduced
- Viable interval in kinetic mixing parameter testable with LDMX

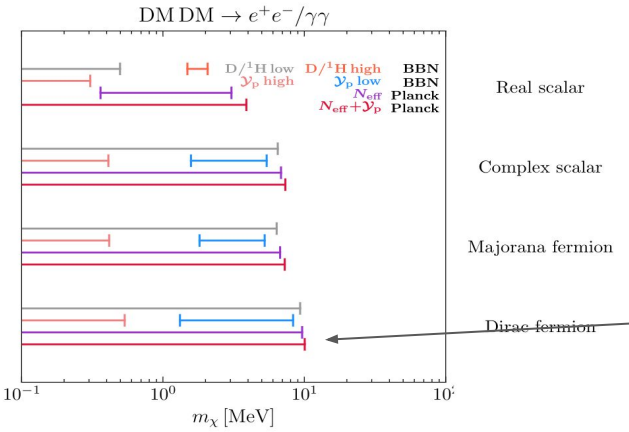


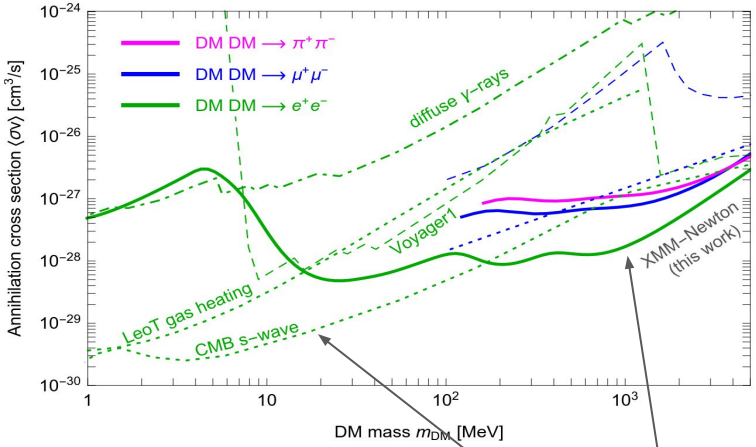
Status of sub-GeV Dark Matter

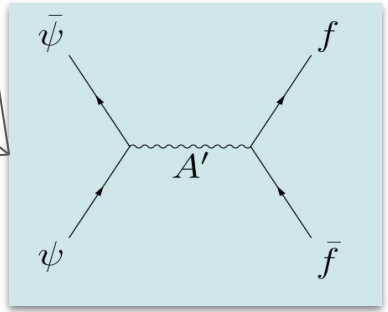
Cosmological and ID constraints

arXiv:2405.17548

- BBN: $m_{\rm DM} \gtrsim 10\,{\rm MeV}$
- CMB + X-ray: strong late universe annihilation constraints







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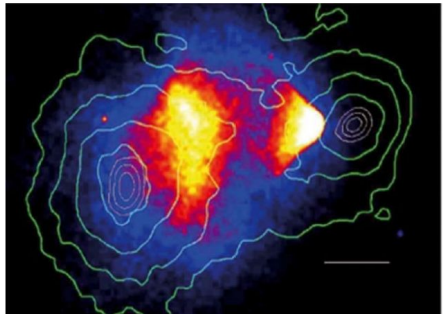
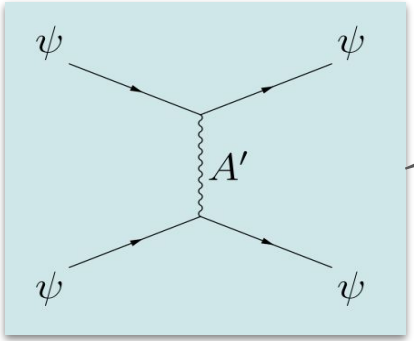
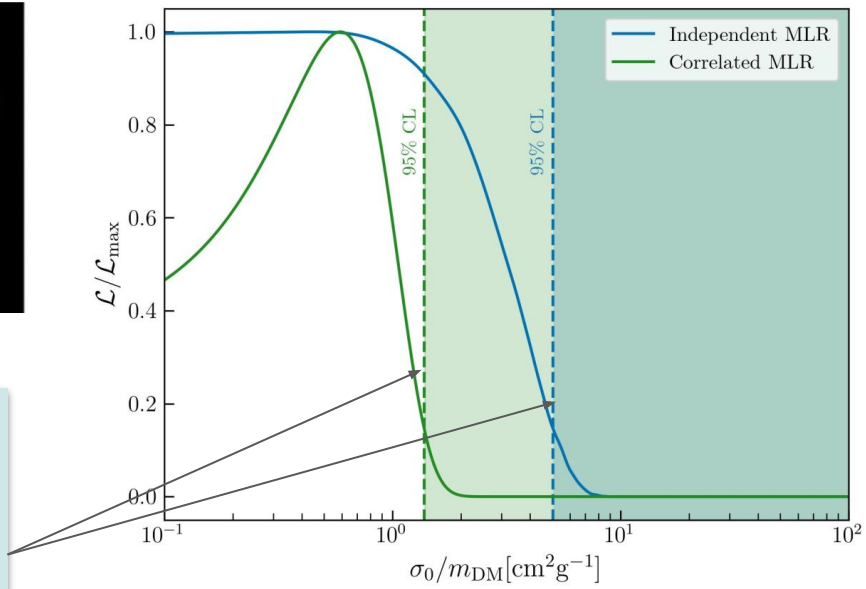
Bullet Cluster constraints

arXiv:2405.17548







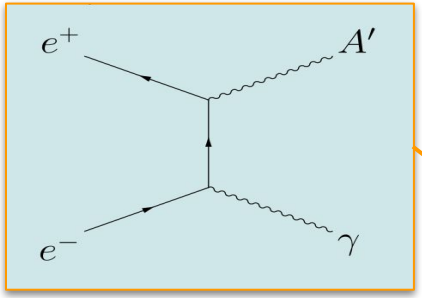
- Based on sub-cluster survival in Bullet Cluster
- Symmetric DM + isotropic, velocity-independent cross-section:

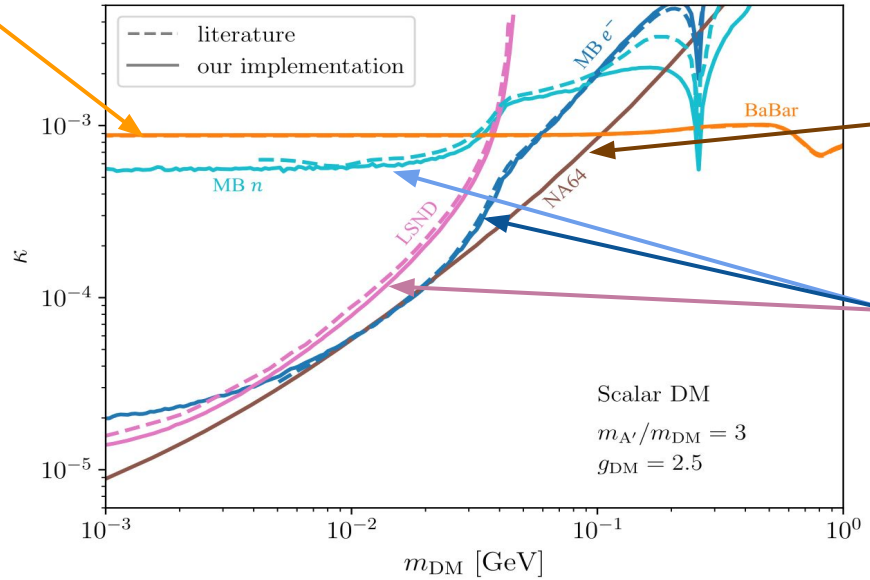
$$\sigma_0/m_{\rm DM} \; < \; 1.4\,{\rm cm}^2{\rm g}^{-1}$$

Status of sub-GeV Dark Matter

Accelerator experiments

arXiv:2405.17548





- Missing energy events

$e^- Z \to e^- Z A'$

- DM scattering events

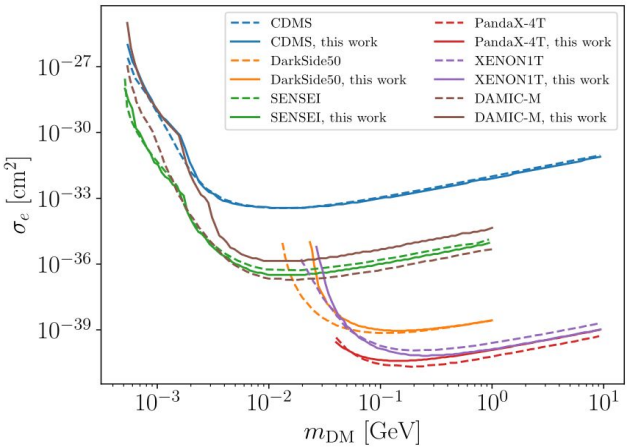
$\pi^0, \eta \to \gamma + A',\ A' \to \chi\bar{\chi}$

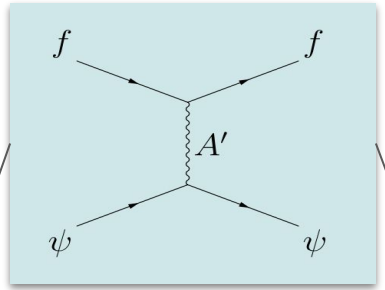
Status of sub-GeV Dark Matter

Direct detection

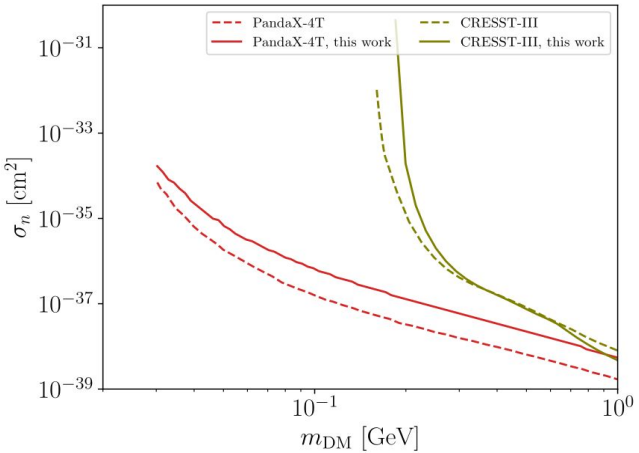
arXiv:2405.17548

- DM - electron scattering





- DM - nucleus scattering



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Status of sub-GeV Dark Matter

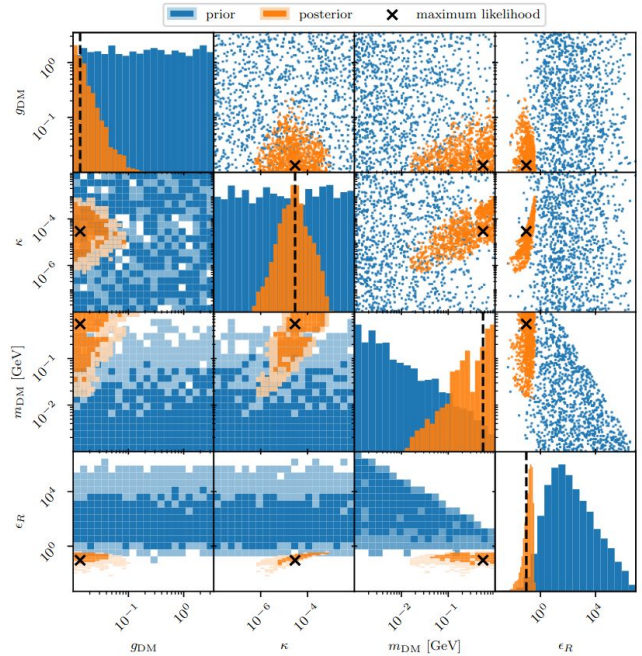
Bayesian model comparison

arXiv:2405.17548

$\eta_{\rm DM} = 0$

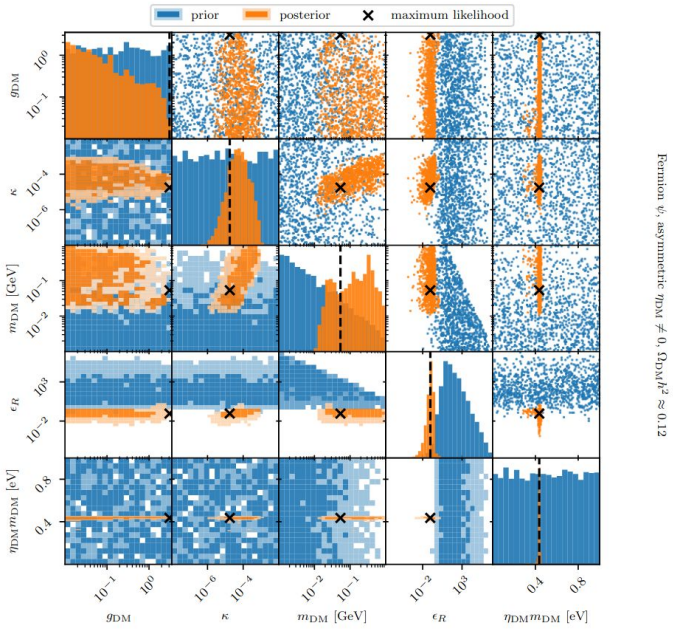
$\Omega_{\rm obs} h^2 = 0.12$

$\eta_{\rm DM} \neq 0$



Bayes factor:

$$\frac{\mathcal{Z}_{\rm asym}}{\mathcal{Z}_{\rm sym}} = 15.6$$



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Status of sub-GeV Dark Matter

Sensitivities

arXiv:2405.17548

- Allowed parameter regions can be probed by future laboratory experiments