Family of Dark Matter Particles

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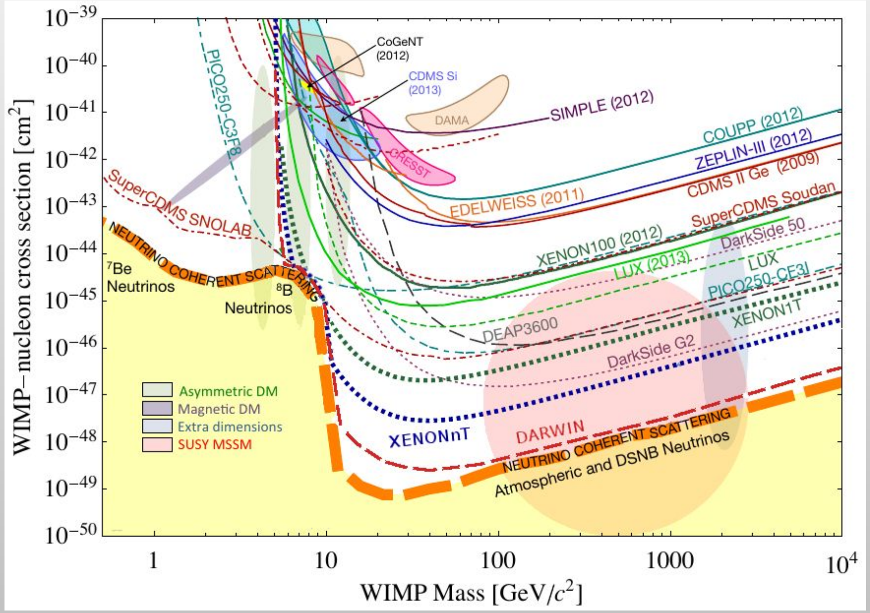
SSI 2018

Introduction

- Evidence for the DM is gravitational :
    - Rotation curves,
    - Bullet cluster,
    - CMB power spectrum, LSS, …
- Minimal models like WIMP have probed a wide range of the parameter space
- 5% of the Universe today is described by the SM
- 27% is Dark Matter
    - Why should DM be described by only 1 particle?

    - motivates exploration of broader set of DM candidates with more particles.

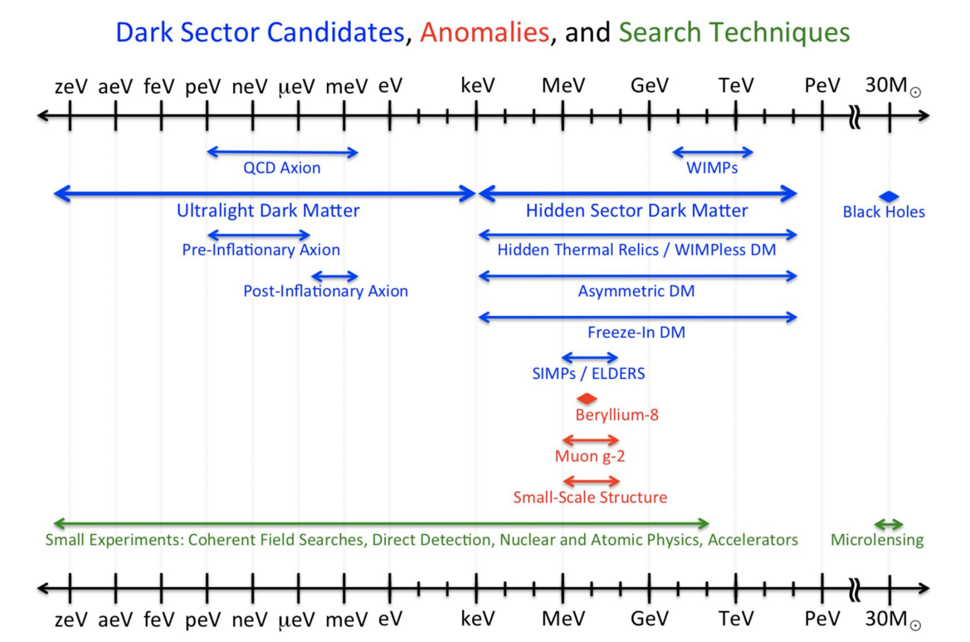
Summary for spin-independent
WIMP-nucleon scattering results
Baudis(2014)



Introduction

- The on-going particle physics experiments probe possible portals into a dark sector at various scales. They will not necessarily probe the dark sector structure.
- To dig deeper into the dark sector, we could study the cosmological signatures.

- We want to survey some DM models mimicking different aspects of the SM and look into their signatures.



Composite Dark Matter

Composite DM

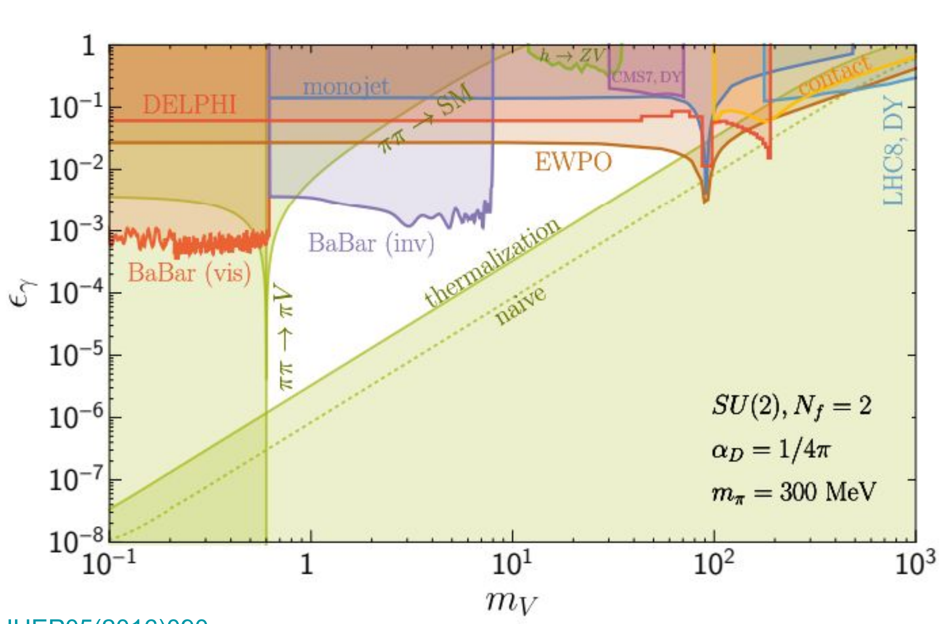
- ~20% of the Universe matter is made of bound states. Can the remaining ~80% be made of them too?
- Idea: have a stable bound state as DM
- Motivation:
  - Stability in a natural way
  - Neutrality
  - Suppressed interactions
  - New observables
- Types:
  - QCD-like with dark hadrons, mass comes from non perturbative effects:
    - Pion-like
    - Baryon-like
    - Others: quarkonium, glueball-like, ...
  - QED-like with dark atoms

Example of Pion-like DM

1. Light Q_u, Q_d confined with gauge $SU(2)_E$
2. $SU(4)_F$ symmetry with (anti)ectoquarks
3. $SU(4)_F$ spontaneously broken pseudo-Goldstone bosons.
4. $U(1)_X$ (Ectobaryon number) protects the lightest composite **N=Q_uQ_d**.
5. Dark Photon connects with the Standard Model through ϵ_γ

$$\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$$

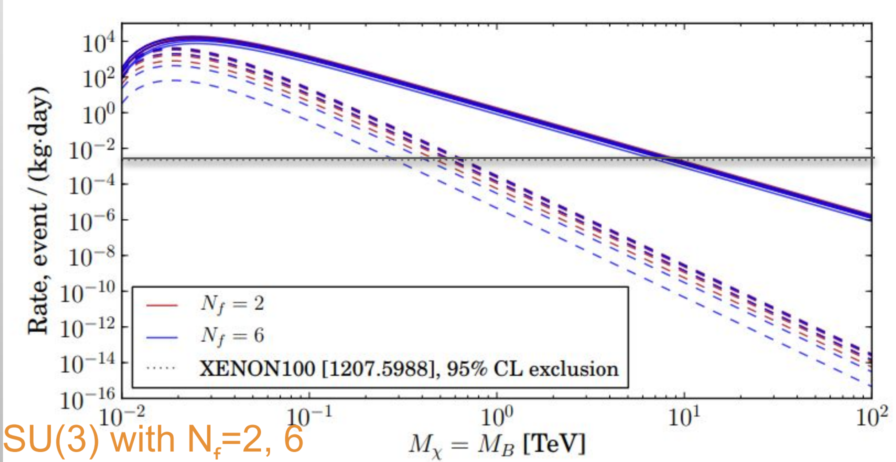
	$SU(2)_E$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
Q_u	**2**	**1**	**1**	$+1/2$	$+1/2$
Q_d	**2**	**1**	**1**	$-1/2$	$+1/2$



JHEP05(2016)090

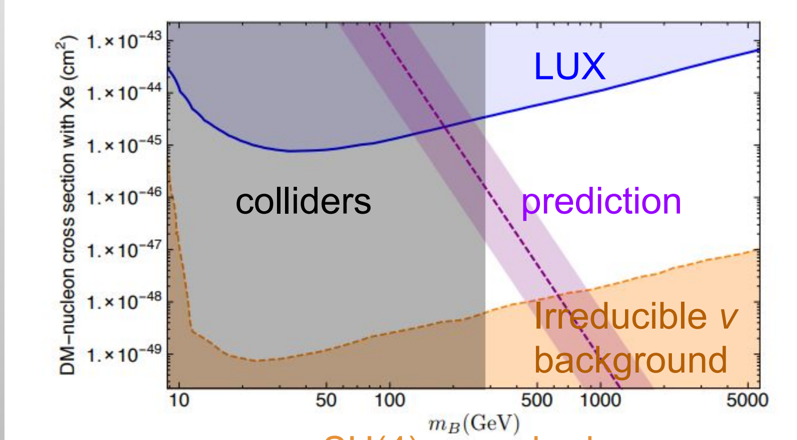
Example of Baryon-like DM

- Stability is easily included
- Interactions suppressed by dim-6 operators (at least)
- Many possibilities, lattice explorations (LSD collaboration)



SU(3) with N_f=2, 6

Phys. Rev. D88, 014502 (2013)



SU(4) quenched

Phys. Rev. Lett. 115, 171803 (2015)

Intro. **Model I** Model II Summary

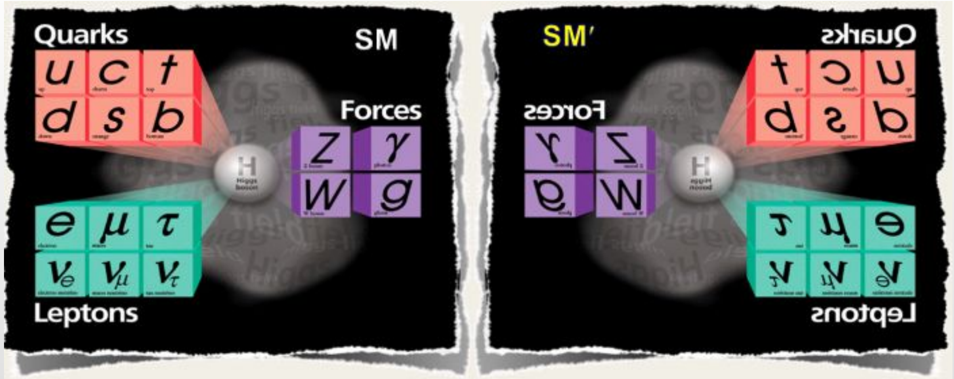
Mirror Dark Matter

Mirror DM

- Composite DM models are indeed a step away from minimal models toward resembling the SM.
- Something more similar to the SM : Another copy of the SM.
- The abundance of the visible and the dark sectors are in the same ballpark, motivating possibility of similar structure.
- Can a sector almost exactly similar to the SM be part of the DM?

- If viable, what are its smoking gun signatures?

Mirror DM



- The model
  - Exact field content as the SM.
  - Exact coupling. Or not!
  - Possible to introduce non-gravitational interactions.
  - Possible portals : [arXiv:0304260]
    - U(1) gauge mixing.
    - Scalar portal.
    - Neutrinos.

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

- DM candidate : the same particles as our sector (p’,n’,e’). In various form, e.g. ions’, gas’, compact objects’.
- Should study the cosmology to discern them from minimal models.

Cosmo Constraints on the MDM

- The BBN bound forces a temperature difference. This means the mirror sector goes out of equilibrium earlier.
- $x=T'/T$, energy density goes like fourth power of T.

$$\Delta N_\nu \simeq 6.14\, x^4$$

- BBN constraints : **$x<0.6$.**
- The source of temperature difference can be an asymmetric reheating.

- $x<1$ is why despite the similar micro-physics, these sectors have different macro-physics.
- That changes the chemical composition of that universe drastically. [arXiv:0809.0668]

Cosmo Constraints on the MDM

- LSS and CMB put similar constraints.

  They imply for 0.2<x<0.6, only part of the DM can be from MDM. For x<0.2, all of the DM can be MDM. [arXiv:0507153]

- Very different temperature puts bound on the possible kinetic mixing.

	$\mathbf{x=0.1}$	$\mathbf{x=0.3}$	$\mathbf{x=0.5}$	$\mathbf{x=0.7}$
^4He	0.8051	0.6351	0.5035	0.4077
$D/H\,(10^{-5})$	$1.003 \cdot 10^{-7}$	$4.838 \cdot 10^{-4}$	$6.587 \cdot 10^{-3}$	$3.279 \cdot 10^{-2}$
$^3He/H\,(10^{-5})$	0.3282	0.3740	0.4172	0.4691
$^7Li/H\,(10^{-10})$	$1.996 \cdot 10^3$	$3.720 \cdot 10^2$	$1.535 \cdot 10^2$	$0.7962 \cdot 10^2$

	standard	$\mathbf{x=0.1}$	$\mathbf{x=0.3}$	$\mathbf{x=0.5}$	$\mathbf{x=0.7}$
^4He	0.2483	0.2483	0.2491	0.2538	0.2675
$D/H\,(10^{-5})$	2.554	2.555	2.575	2.709	3.144
$^3He/H\,(10^{-5})$	1.038	1.038	1.041	1.058	1.113
$^7Li/H\,(10^{-10})$	4.549	4.548	4.523	4.356	3.871

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

$$\epsilon < 2 \times 10^{-10}$$

MDM Predictions in Cosmology

- Smoking gun :
  - Higher star evolution rate thanks to the Helium abundance. Due to this high star-evolution rate, there are many mirror supernovae and, hence, MACHOS.
  - Additional supernovae mean GW without correlated luminous signal.
  - Usual minimal model detection prospects, e.g. that of the milli-charged particles.

All of them do not necessitate an exact copy of the SM; yet, they imply complex sectors with similar structure as the SM.

- Add-ons
  - The Core-Cusp Problem.
  - EDGES 21cm line : if you like dark ambulances.

Summary

- Various composite DM Models are tightly constrained by the particle physics experiments. They are not dead though!
- An exact copy of the SM (MDM) with lower enough temperature can be a reliable DM model.
- They are constrained by different particle physics experiments or cosmological observations.
- Some small-scale structure observables or gravitational waves can be the potential signatures of MDM.

Back Up

The Question

The Dark Sector may be more complex than just a single dark matter state; some authors postulate that it may consist of an almost **exact copy of the Standard Model** but with somewhat different particle masses and couplings. Discuss this possibility in detail from the **astrophysics and cosmology perspective**.

What **differences in parameters** would be necessary to make this scenario work? What are the corresponding constraints and describe a **set of experiments** than could be performed to detect such a possibility.

The Question II

The Dark Sector may be more complex than just a minimal DM. Discuss a few of non-minimal models **resembling different aspects of the SM**. Discuss this possibility in detail from the **astrophysics and cosmology perspective**.

What **differences in parameters** would be necessary to make these scenario work? What are the corresponding constraints and describe a **set of experiments** than could be performed to detect such a possibility.

Constraints on different portals

Model independent constraints

- *Vector portal:* constrained by mu & e magnetic dipole moments for sub-GeV mediators and by precision ew-physics for heavier mediators
- *Higgs portal:* constraints from heavy meson decays, but specific to minimal model. Orders of magnitude weaker for non-minimal models
- Benchmark from coupling to a SM global symmetry like baryon or lepton number. → Interactions from elec. Neutral particles imply more constraints (e-nu scattering and low E neutron scattering data) on new bosons coupled to lepton and baryon number.

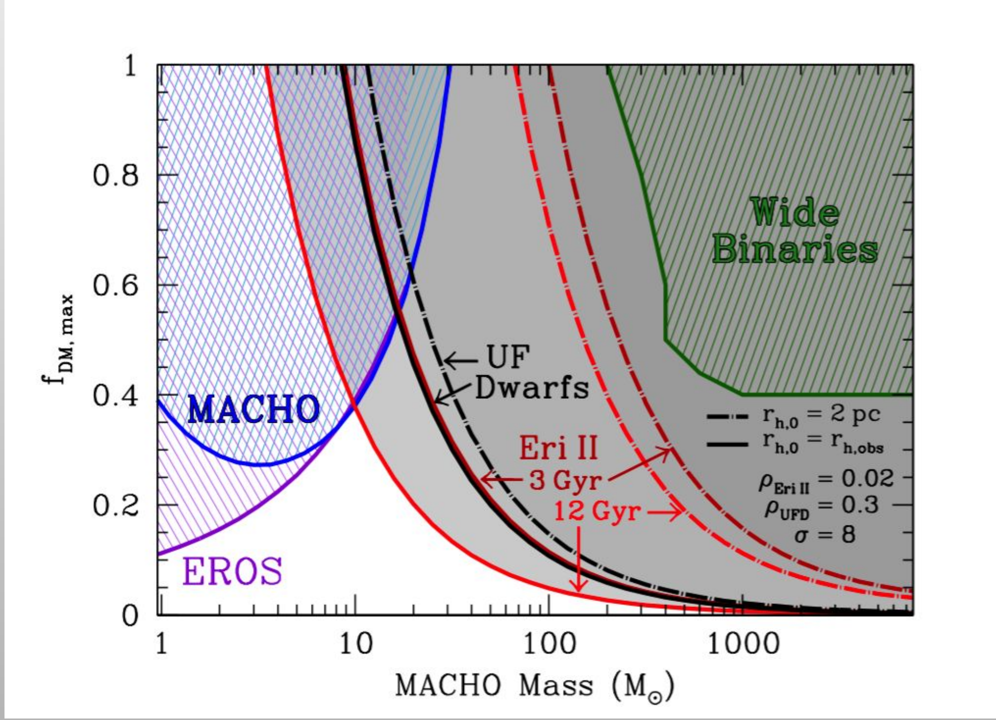
The next gen of DM interaction searches will probe viable and motivated parameter space for all portal interactions. Global symmetry couplings motivates separate exploration of DM couplings to leptons and hadrons

Why no collapse

- The collapse happens when the gravity pull overcomes the kinetic energy.
- Ample evidence for the DM to be in a halo around the galaxies; not collapsed to disks.
- Given the different chemical composition, specially the Helium abundance, the star evolutions are happening faster in the Mirror sector.
- Hence, higher supernovae rate that prevents the gravitational collapse.

Bounds on MACHOs

[arXiv:1605.03665]

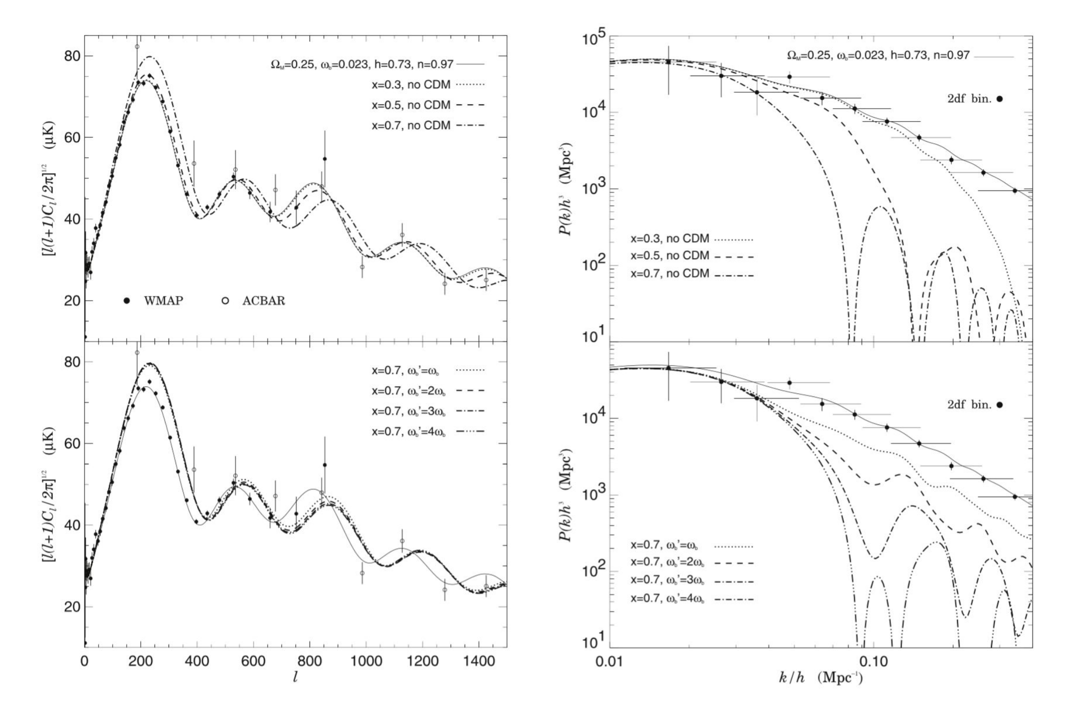


CMB/LSS bounds on MDM

- The two relevant epochs for the structure formation are MRE and MRD.
- MRE is common between the two sectors. [arXiv:0809.0668]
- The perturbations should not grow before MRD.
- For small enough x, mirror photon decouples before matter-radiation equality.
- For $x>0.3$, MDM behaves like a WDM.
- For $x<0.3$, MDM is the same as CDM:[arXiv:1401.3965]
    - Faster evolution of the Mirror world implies most of the DM is in form of neutral atoms
    - They do not interact frequently, i.e. collisionless.
- Signatures should be looked for on small scales.

CMB/LSS bounds on MDM

[arXiv:0809.0668]



Twin DM

In the Twin Higgs scenario there is also a Higgs-Higgs’ coupling that provides a portal between the sectors.

Constraints:

- Precision electroweak measurements.
- CMB data that puts limits on Neff at BBN

Signatures MDM [arXiv:1305.4939]

- Direct detection

- Indirect detection

- Collider signatures: Look for missing energy in processes like $pp \to ZZ' \to \ell^+\ell^-$(or γ) + E_T^{miss}

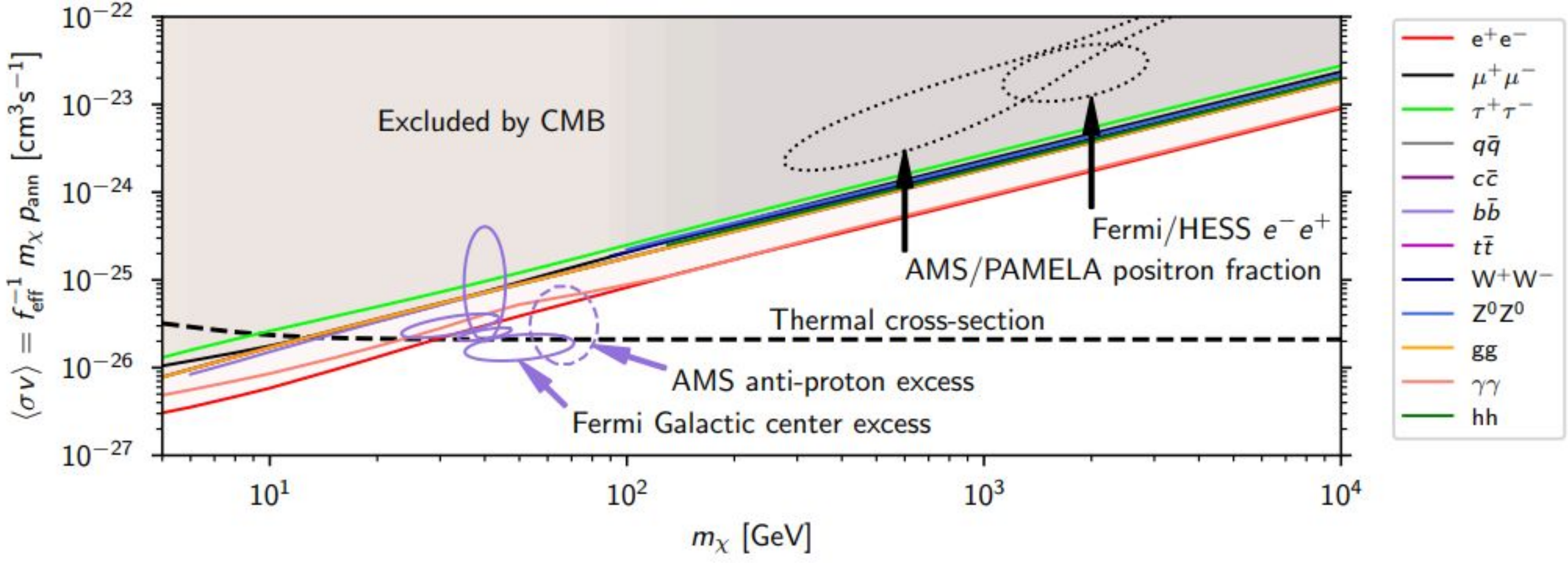


Fig. 46. *Planck* 2018 constraints on DM mass and annihilation cross-section. Solid straight lines show joint CMB constraints on several annihilation channels (plotted using different colours), based on $p_{\rm ann} < 3.2 \times 10^{-28}\,\mathrm{cm^3\,s^{-1}\,GeV^{-1}}$. We also show the $2\,\sigma$ preferred region suggested by the AMS proton excess (dashed ellipse) and the *Fermi* Galactic centre excess according to four possible models with references given in the text (solid ellipses), all of them computed under the assumption of annihilation into $b\bar{b}$ (for other channels the ellipses would move almost tangentially to the CMB bounds). We additionally show the $2\,\sigma$ preferred region suggested by the AMS/PAMELA positron fraction and *Fermi*/H.E.S.S. electron and positron fluxes for the leptophilic $\mu^+\mu^-$ channel (dotted contours). Assuming a standard WIMP-decoupling scenario, the correct value of the relic DM abundance is obtained for a "thermal cross-section" given as a function of the mass by the black dashed line.