Dark matter phenomenology

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What's new with dark matter?

(A recurrent question by Serguey when meeting him in an informal environment, most often an overcrowded bus on the line between the Trieste city center and SISSA)

The era of precision cosmology has been shaping in the last two decades, showing overwhelming evidence for dark matter, or - actually - within the standard model for cosmology, for a classical, cold, pressure-less fluid subject to gravitational interactions only (no coupling to ordinary matter or photons, no self-coupling).

Tests of such gravitational coupling determine, e.g., its mean density with exquisite accuracy:

$$\Omega_c h^2 = 0.120 \pm 0.001$$ *[Planck +, arXiv:1807.06209]*

as well as the spectrum of its perturbations (nearly scale invariant, as expected from inflation), to be followed in an (almost) fully consistent pattern from an early snapshot (the CMB) to the late-time and today's structures in the Universe.

… so, what's new with dark matter?

Unfortunately, from a particle physics perspective, reformulating the DM puzzle in terms of elementary particles, possibly in the dilute limit (two-body interactions dominating over multi-body interactions) remains **an assumption**, and not the only possible extrapolation!

The realm of prejudices, mostly referring to (blaming) two guidelines:

1) we need a "natural" mechanism to generate dark matter in the early Universe

2) there are some aspects which are not satisfactory in the standard model of particle physics, addressing such open issues will lead to an extension of the standard model embedding dark matter as well.

The bet I made with somebody else's money

The standard attitude some years ago:

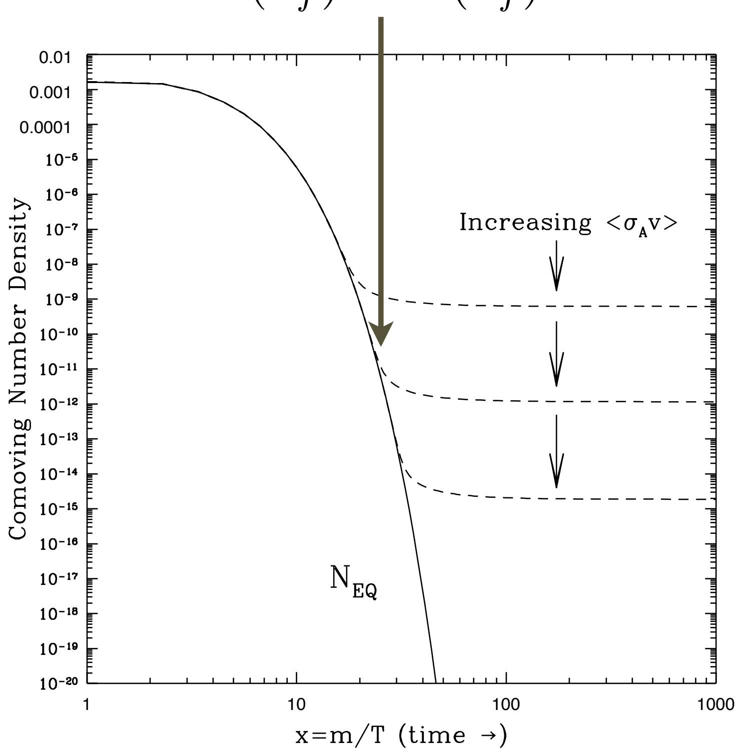
i) A new particle will be found at colliders

ii) Direct detection experiments will demonstrate that it makes the dark matter

A trigger from naturalness versus the hierarchy problem, and thermal relic **WIMPs** as natural dark matter candidates.

Thermal relics directly coupled to the baryon/photon primordial bath: $\chi\,\bar{\chi} \leftrightarrow \mathrm{SM}\,\overline{\mathrm{SM}}$ (with SM is some lighter Standard Model state)

$\Gamma(T_f) \simeq H(T_f)$



$$\Omega_\chi h^2 \simeq \frac{3 \cdot 10^{-27}\mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle \sigma_A v \rangle_{T=T_f}}$$

WIMP miracle: "fixed" DM pair annihilation cross section into "visible" particles.

A recipe that can work below about **100 TeV** (unitarity limit *[Griest & Kamionkowski 1990]*; in realistic models up to about 15 TeV) and gets inefficient below about **1 GeV**.

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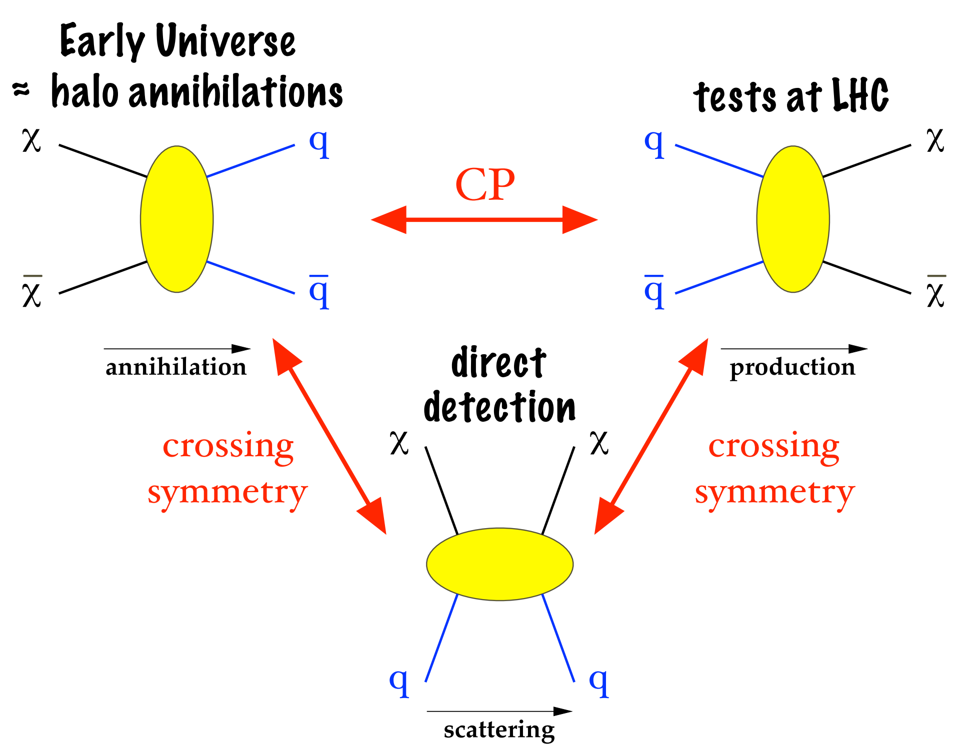
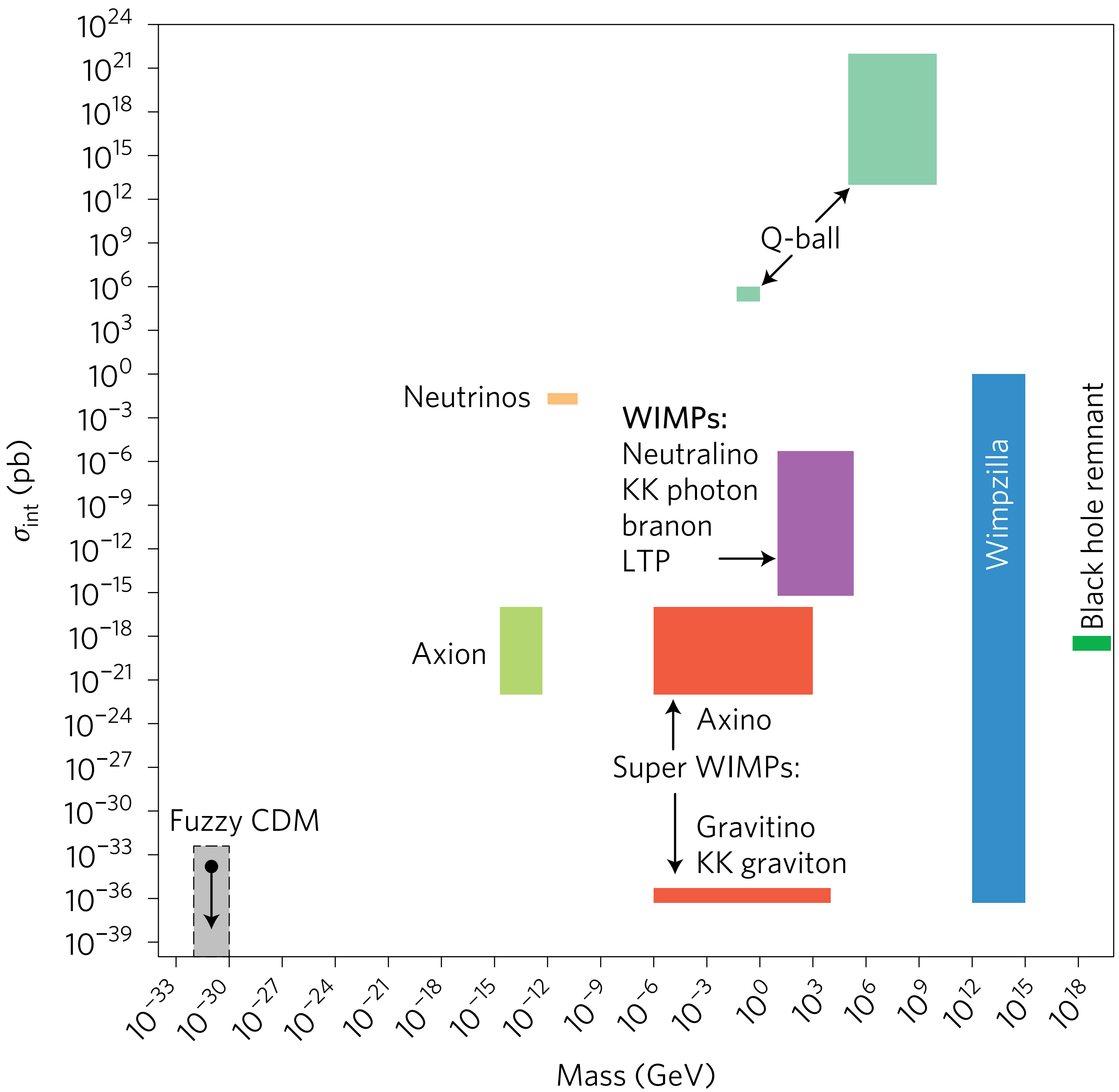
Thermal relics: the familiar and beloved scheme



A scheme which has not paid so far: the WIMP paradigm is well alive (and it will be hard to kill it), however it is getting less popular with bettors.

Avoid betting is the best bet

Today's attitude: let's be inclusive!



Viable particle frameworks span huge ranges in masses and interaction scales.

(not to mention the revival of non-particle frameworks, such as the case for primordial black holes as dark matter).

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At some early cosmological epoch (temperature much larger than the particle mass) the abundance of the DM candidates relative to SM particles also spans huge ranges, e.g.:

- It is order 1 for **WIMPs** (since the sizeable interaction ensures thermal equilibrium)

- It is very small for **super-WIMPs** (never in thermal equilibrium because of their tiny interactions, e.g. they leak out the thermal bath through the freeze-in mechanism)

- It is very large for **super-cold DM** (very light bosons, almost non interacting, with huge occupation numbers of their lowest momentum state, e.g.: axion DM)

Natural matching $\Omega_\chi \sim \Omega_{CDM}$??? Fine, *my* model is potentially ugly, but consider how ugly is *your* model !!!

Maybe something new with dark matter

The $\Lambda\mathrm{CDM}$ model under extreme scrutiny may show, on top of the astonishing successes, also some discordance. Most relevantly for dark matter:

- A small-scale crisis of the CDM paradigm? (observational cores versus predicted cusps in the density profile of small dark-matter-dominated galaxies; missing satellites, in particular in the count for the most massive sub-halos in the Milky Way and the Local Group - the too-big-to-fail problem; …)

- Tensions in cosmological parameters? (indirect versus direct measurements of H_0 - $5\,\sigma$ discrepancy between Planck CMB and SH0ES SNIa + much more; early Universe versus late Universe determination of the normalisation of the power spectrum - $\sim 3\,\sigma$ discrepancy between CMB and weak lensing measurements of S_8)

First insights on the “true nature” of dark matter and dark energy?

Maybe something new with dark matter

The small-scale crisis pointing to an excess of power on small scales (or maybe to baryonic components/baryonic feedback not properly treated in the simulations). Remove power by introducing a new physical scale associated to DM particles: a free-streaming scale (e.g. warm dark matter); a self-interaction scale; a macroscopic "quantum" scale (e.g. dark matter as a BEC); a large DM-baryon or DM-photon interaction scale; …

Suppressing S_8 at late times, letting dark matter decay or cannibalise itself? Play with subdominant components which again dump power (self-interacting DM, very light axion-like DM, …)?

Steadily moving towards a scenario in which, rather than the SM + a DM particle, you have SM + a multicomponent dark sector in which address the dark matter problem and much more (e.g. the H_0 tension with some early dark energy component???).

Still dealing with this damned lamppost cartoon…

Waiting for super-precision cosmology to solve it all (but on small scales and the difficulties in modelling baryons, it is not expected to happen very soon), the dark matter phenomenologist faces hard times, running the risk of getting trapped by the infamous “streetlight effect”. (Not to mention all the times he will be blamed for “chasing ambulances”)

However sometimes there is a lot of fun going on under lampposts (and discoveries would be amazing…)

Recent under-lamppost analyses

Blazer Boosted Dark Matter *[Wang, Granelli, P.U., PRL 2022]*

The galactic component of DM particles has non-relativistic velocities, $v \sim 10^{-3}c$. Their recoil energy in direct detection experiments $E_{rec} \sim (m_\chi^2 v^2)/M_N$ is typically below threshold if the DM particle mass m_χ is lighter than $\sim 1\,\mathrm{GeV}$.

[Bringmann & Pospelov, PRL 2019]:

galactic cosmic rays (mainly protons) may up-scatter a fraction of the DM galactic population to high energies making sub-GeV dark matter candidates potentially detectable.

Is there in Nature a potentially more powerful and/or more efficient dark matter booster?

Recent under-lamppost analyses

Blazer Boosted Dark Matter

[Wang, Granelli, P.U., PRL 2022]

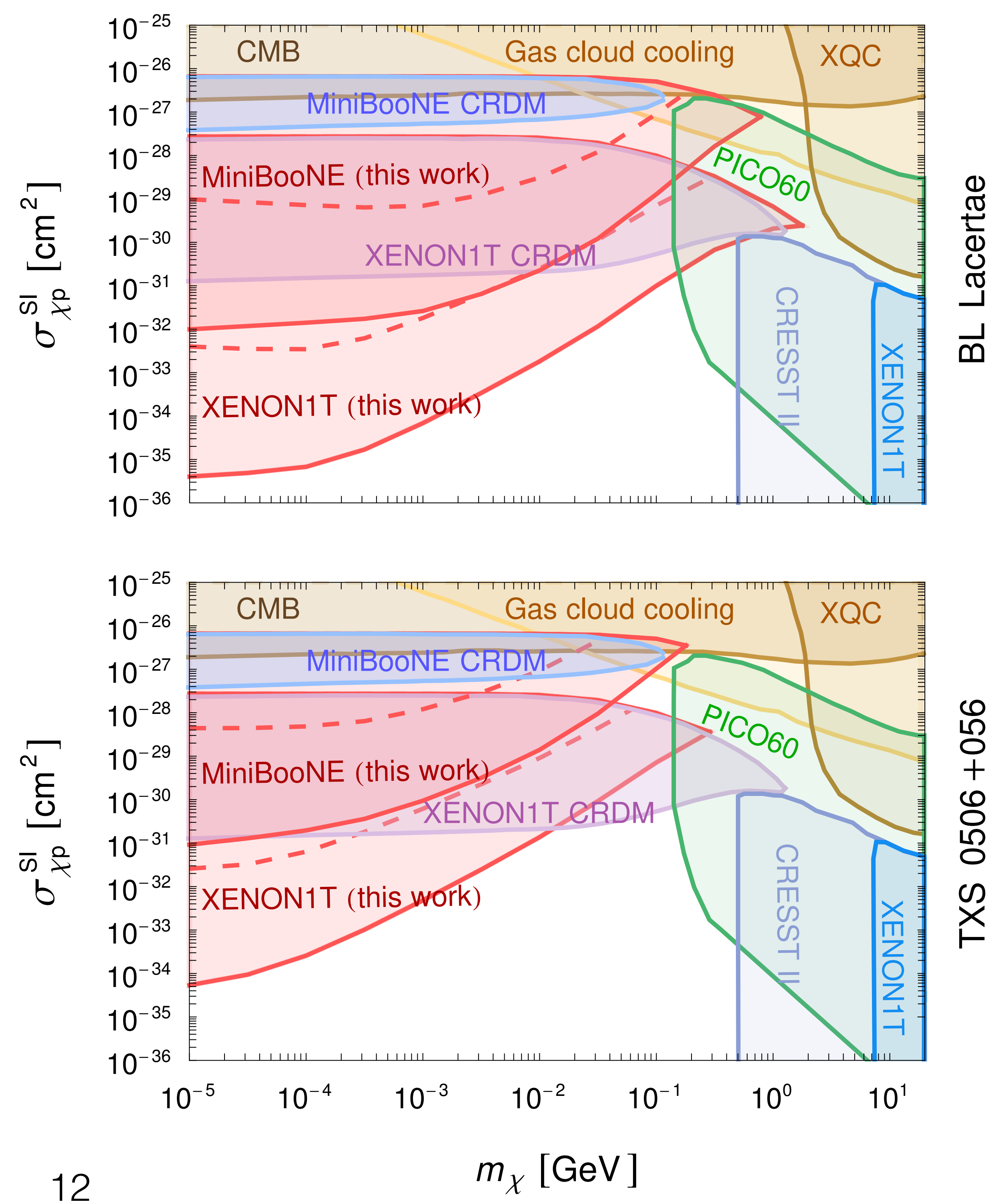
Blazers are the ideal case:

Extremely powerful flux of protons (electrons) through an extremely dense dark matter environment (dark matter spike accreted around the blazer black hole engine)

Tightest limits/best discovery potential for light dark matter

See also:

[Granelli, P.U., Wang, JCAP 2022]

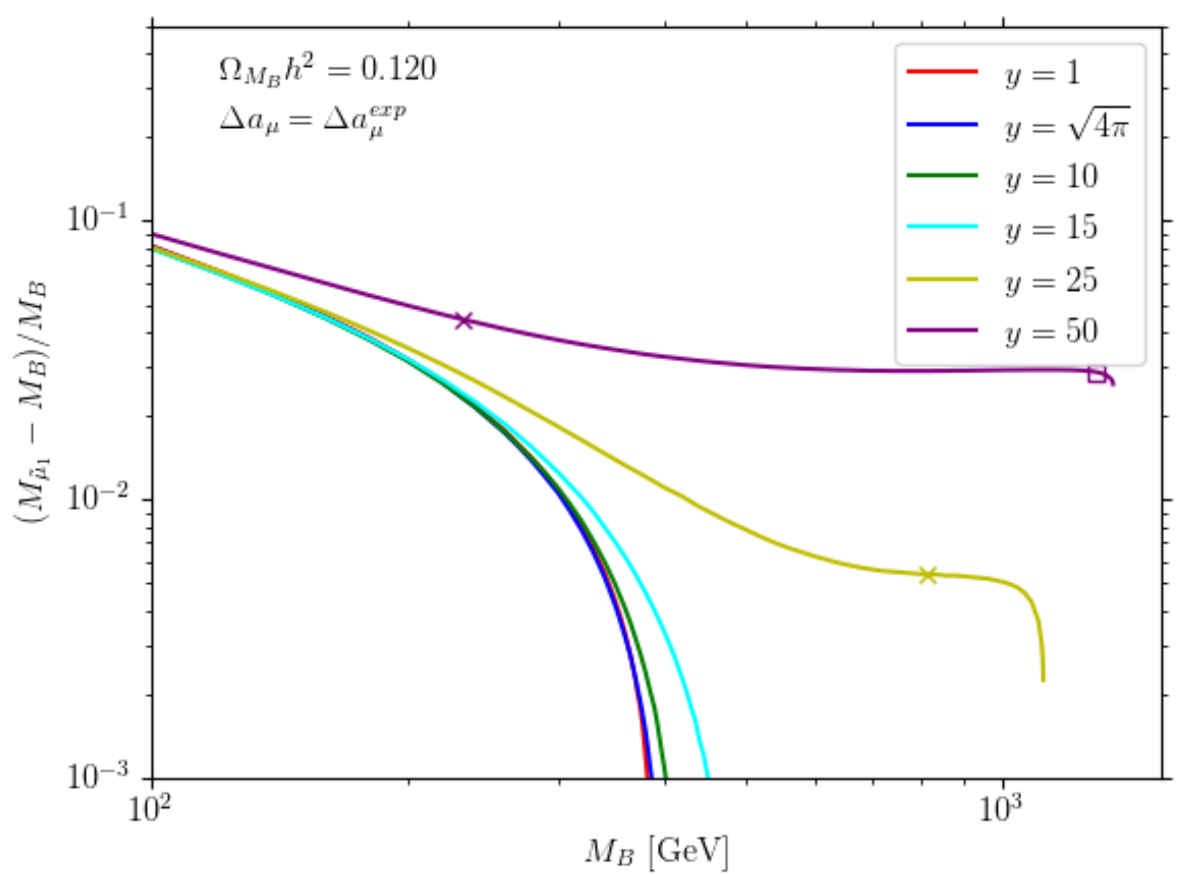


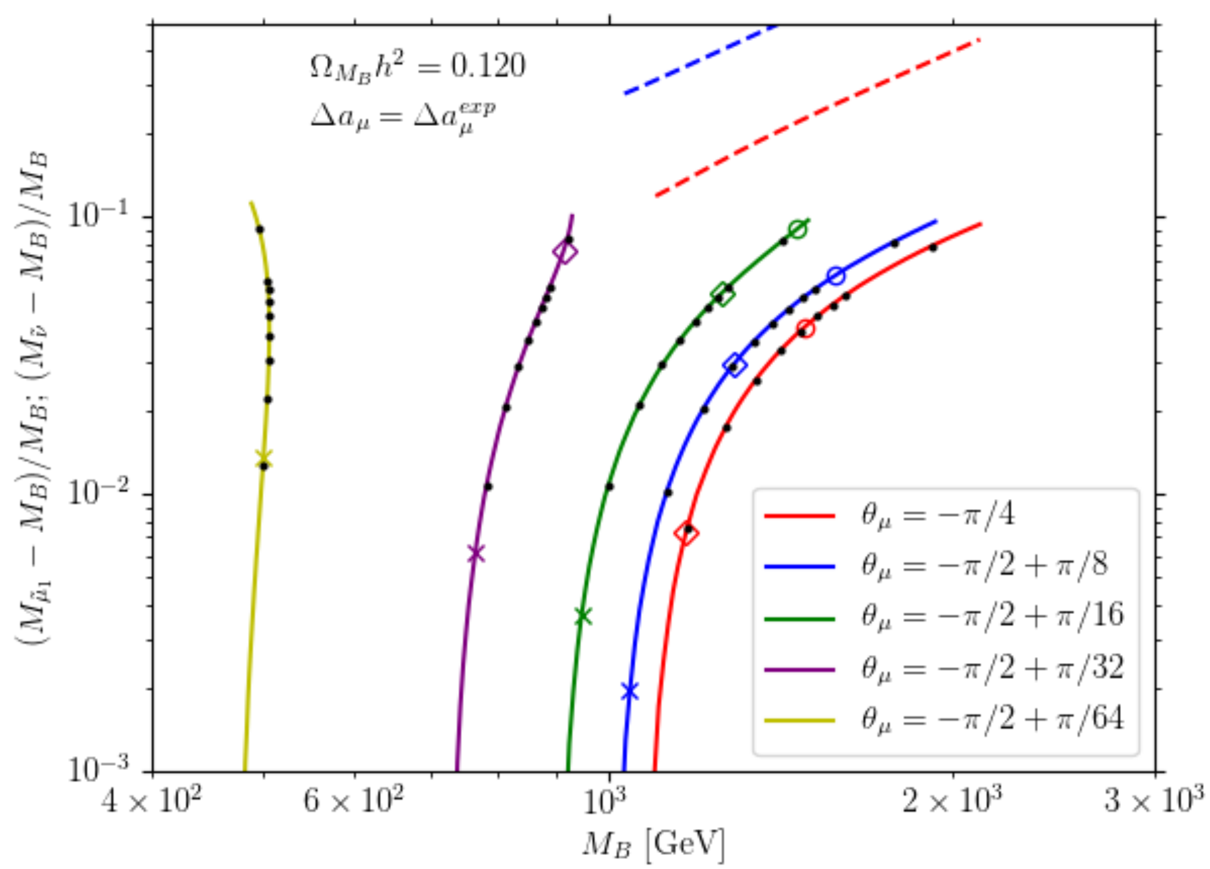
Recent under-lamppost analyses

A minimal DM scheme and $(g\text{-}2)_\mu$ *[Acuña, Stengel, P.U., PRD 2022]*

Account for the muon (g-2) anomaly within the most minimal BSM recipe embedding also a DM candidate: a thermal relic pure Bino + 2 scale muon partners (this is NOT the MSSM).

It works up to the TeV scale and beyond:





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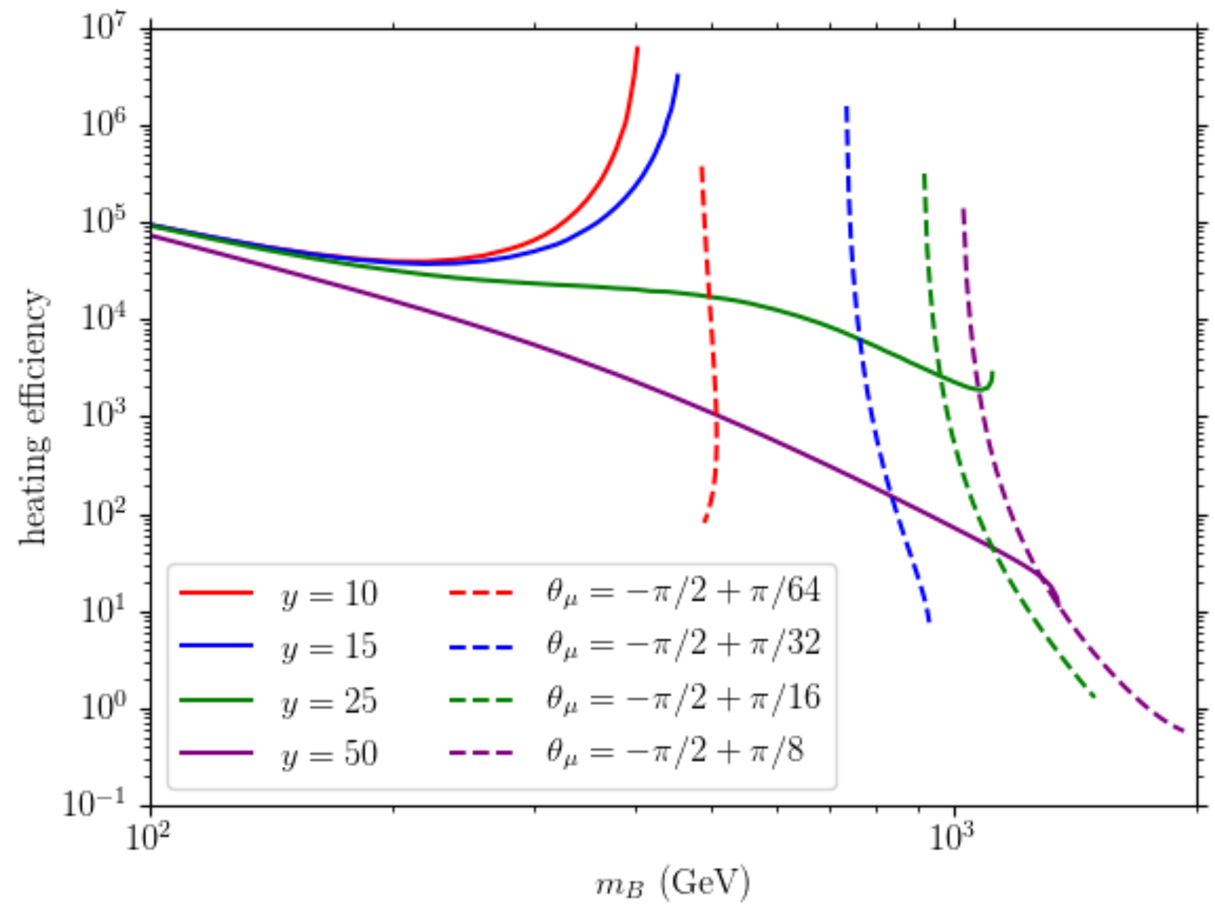
No "traditional" WIMP detection method working in this case; kinetic heating of neutron stars would be instead extremely efficient and future infrared surveys of old neutron star populations should probe the entire parameter space!

[Acuña, Stengel, P.U., arXiv:2209.12552]



… but, come on, SERIOUSLY, what's new with dark matter?

… uhm, … uhm, … uhm, … uhm, … uhm,

… not much Serguey, however I promise that I will try searching for a more appropriate answer, with at least a fraction of the enthusiasm, perseverance and love you devoted to Science and your beloved neutrinos!