# Prospects for indirect dark matter searches

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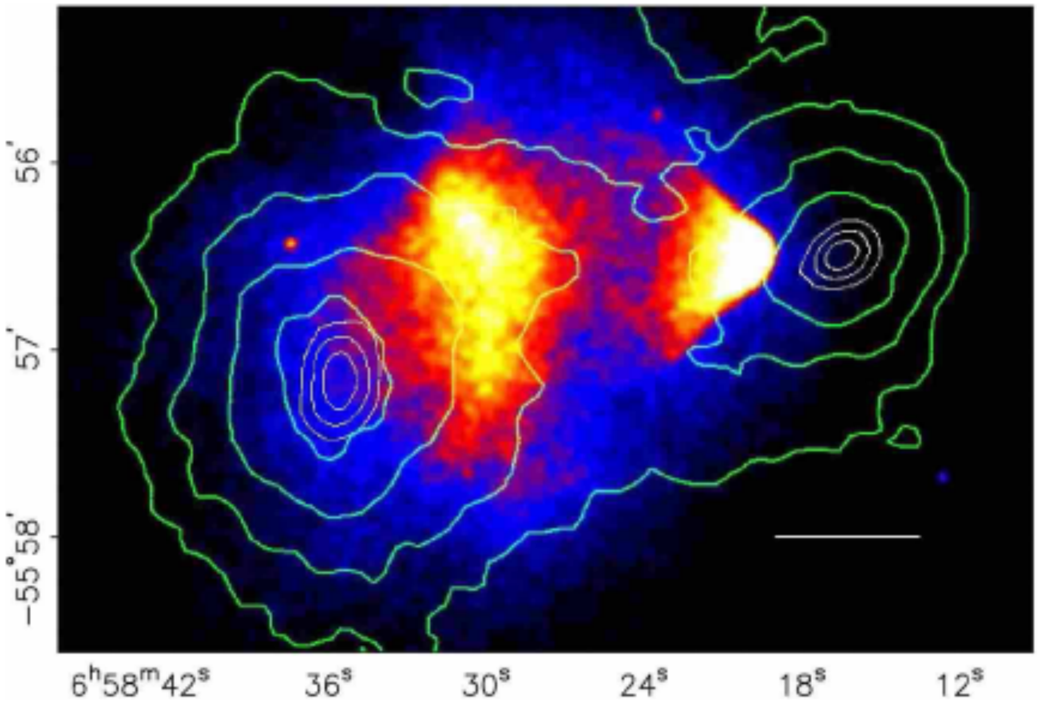
# DM indirectly detected: Classical (local) tests

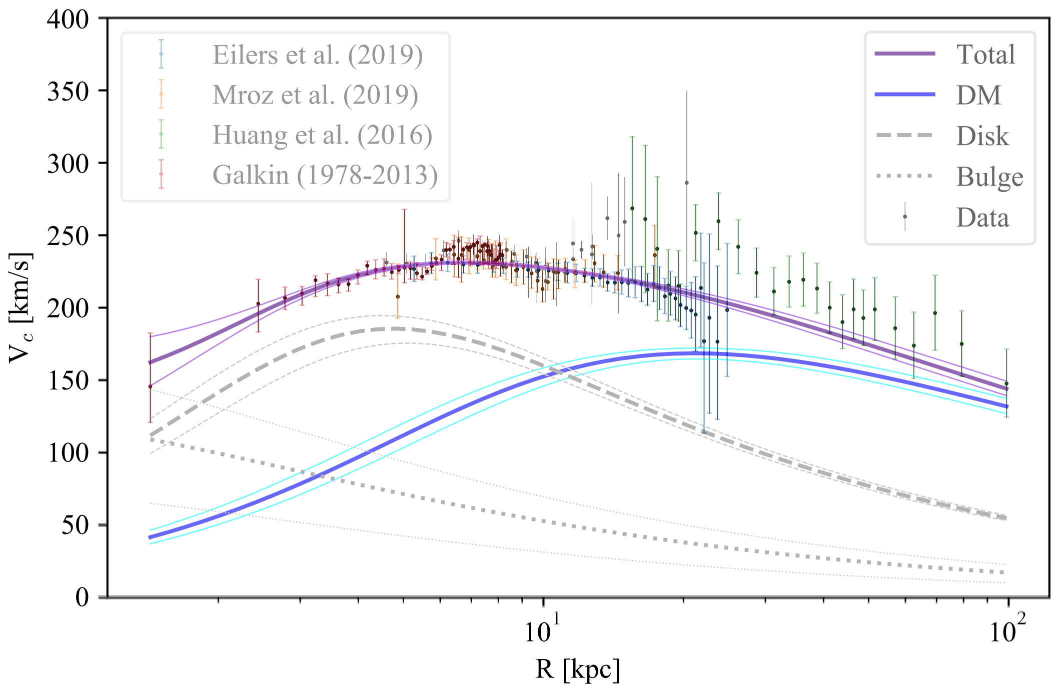
## (merging) galaxy clusters



Component separation

[Clowe et al., 2006]

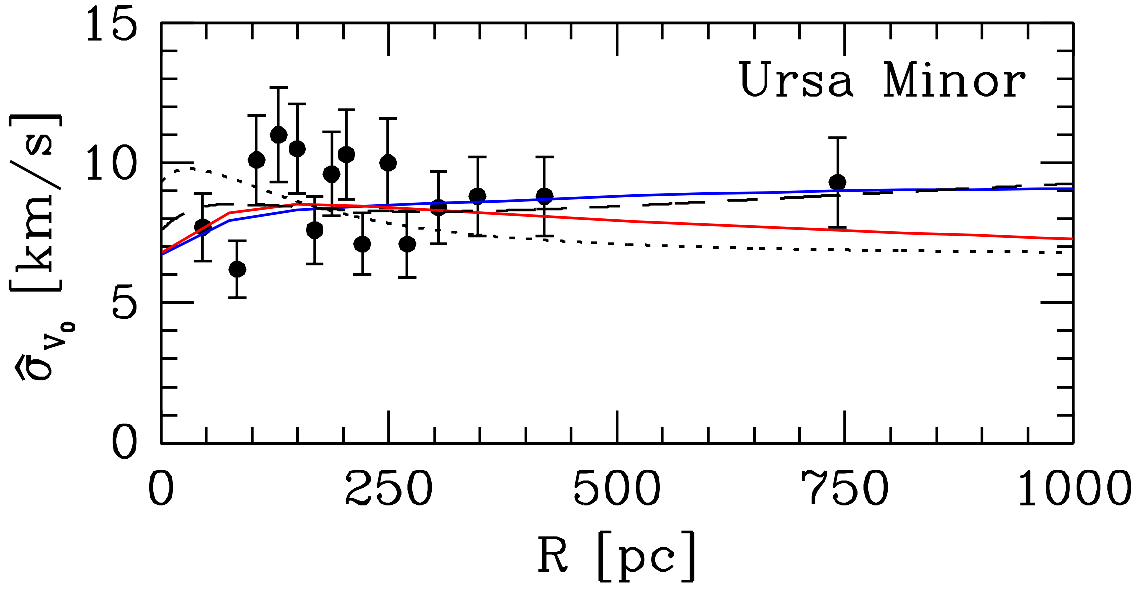
## (rotationally supported) galaxies



Mass decomposition

[Petac & P.U., 2020]

## (pressure supported) systems



DM dominated

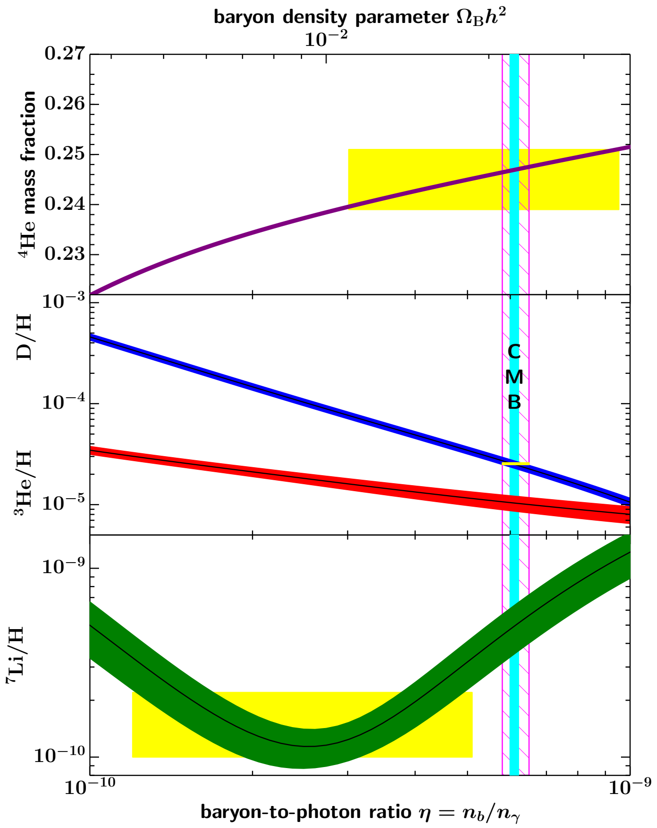
[Walker et al., 2009]

Nowadays not the leading rationale to argue for the ***existence*** of DM.

Direct/indirect particle DM searches are mostly done within these DM labs: these observations provide key ingredients, e.g., DM density and velocity profiles.

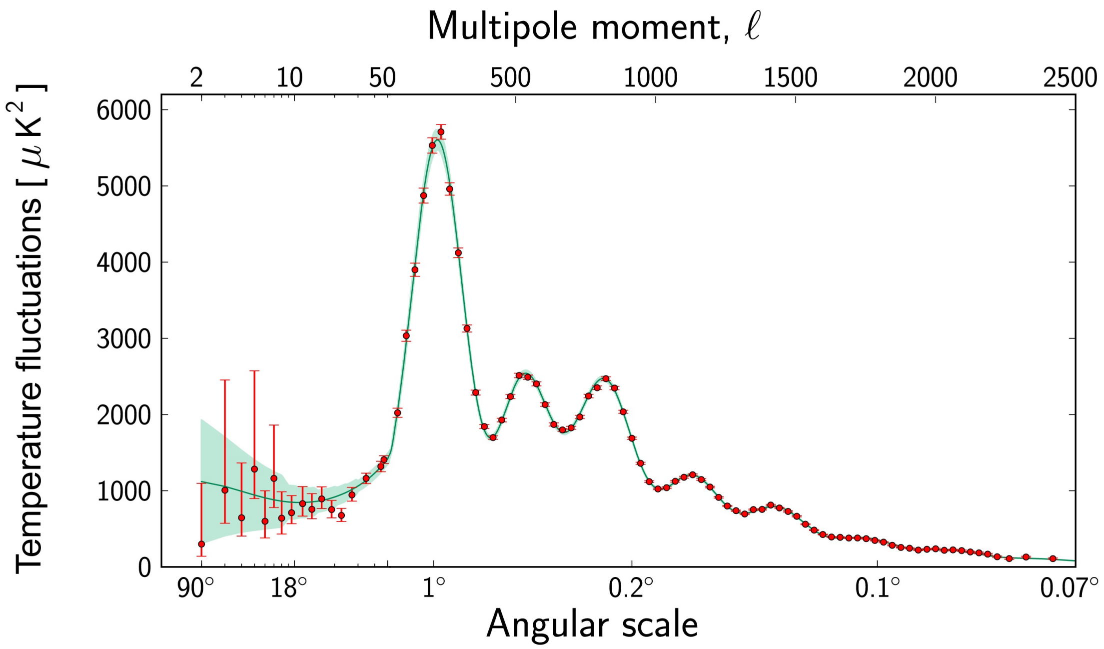
# DM indirectly detected: Cosmological evidence

Dynamics of the Universe, i.e. $\Omega_{\rm M}$, learning about “ordinary matter”, i.e. $\Omega_{\rm b}$, from BBN to deduce $\Omega_{\rm DM}$



*[PDG, 2023]*

Single snapshot of density perturbations, e.g., the CMB:



The SM for cosmology (ΛCDM model) as a minimal recipe to embed the Universe dynamics and a consistent theory for structure formation, tested against a pletora of cosmological probes, in which the DM term is treated as a classical, cold, pressure-less fluid subject to gravitational interactions only.

The leading rationale to argue for the existence of DM and the tool to precisely measure it.

“Concordance” cosmology:

$$\Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012$$

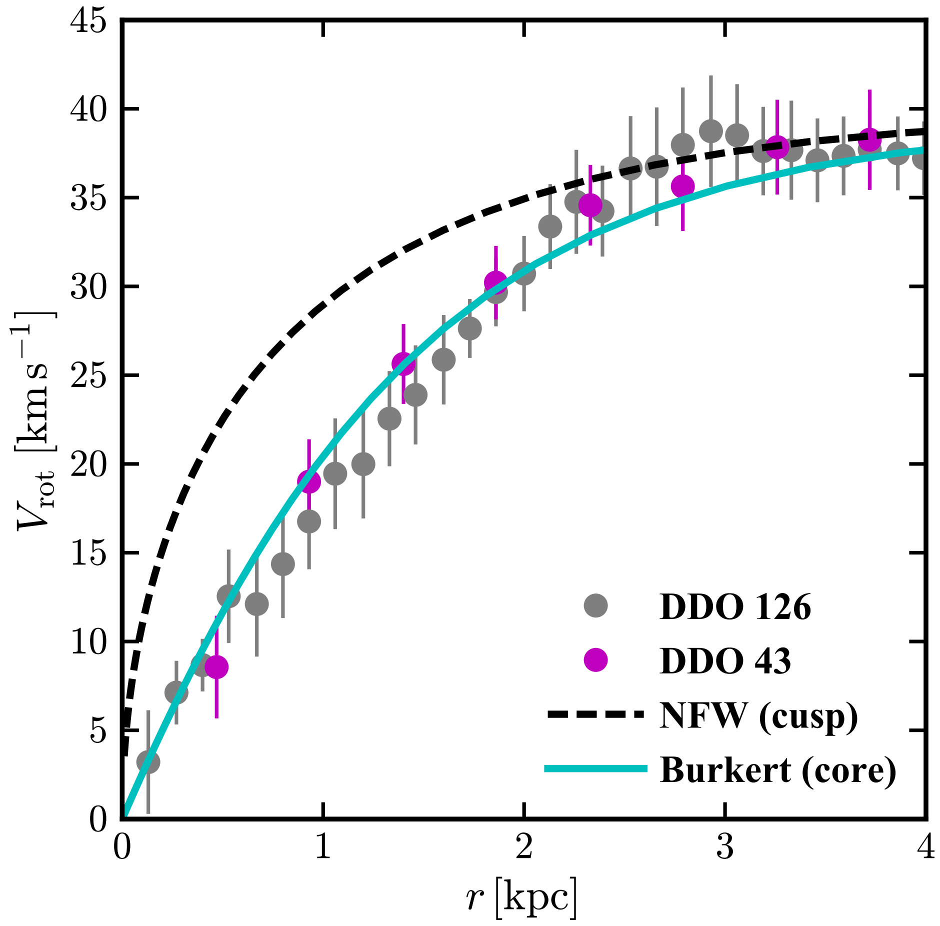
*[Planck Coll., arXiv:1807.06209]*

# “Surprises” versus concordance cosmology

The ΛCDM model under extreme scrutiny may show, on top of the astonishing successes, also few discordances. Most relevantly for dark matter/dark sector:

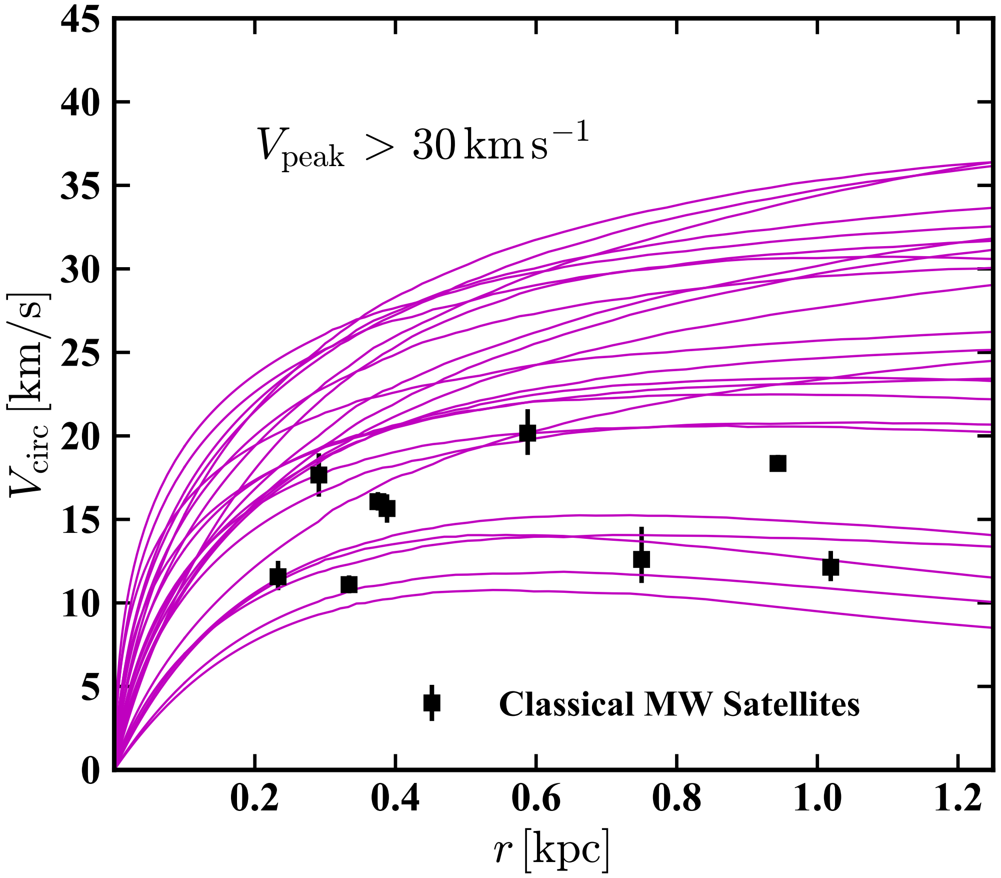
- A small-scale crisis of the CDM paradigm (in the deep non-linear regime, likely where baryonic component modelling do count)?

observational cores versus predicted cusps in the density profile of small dark-matter-dominated galaxies:



[McGaugh, Rubin & de Blok, 2001]

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:



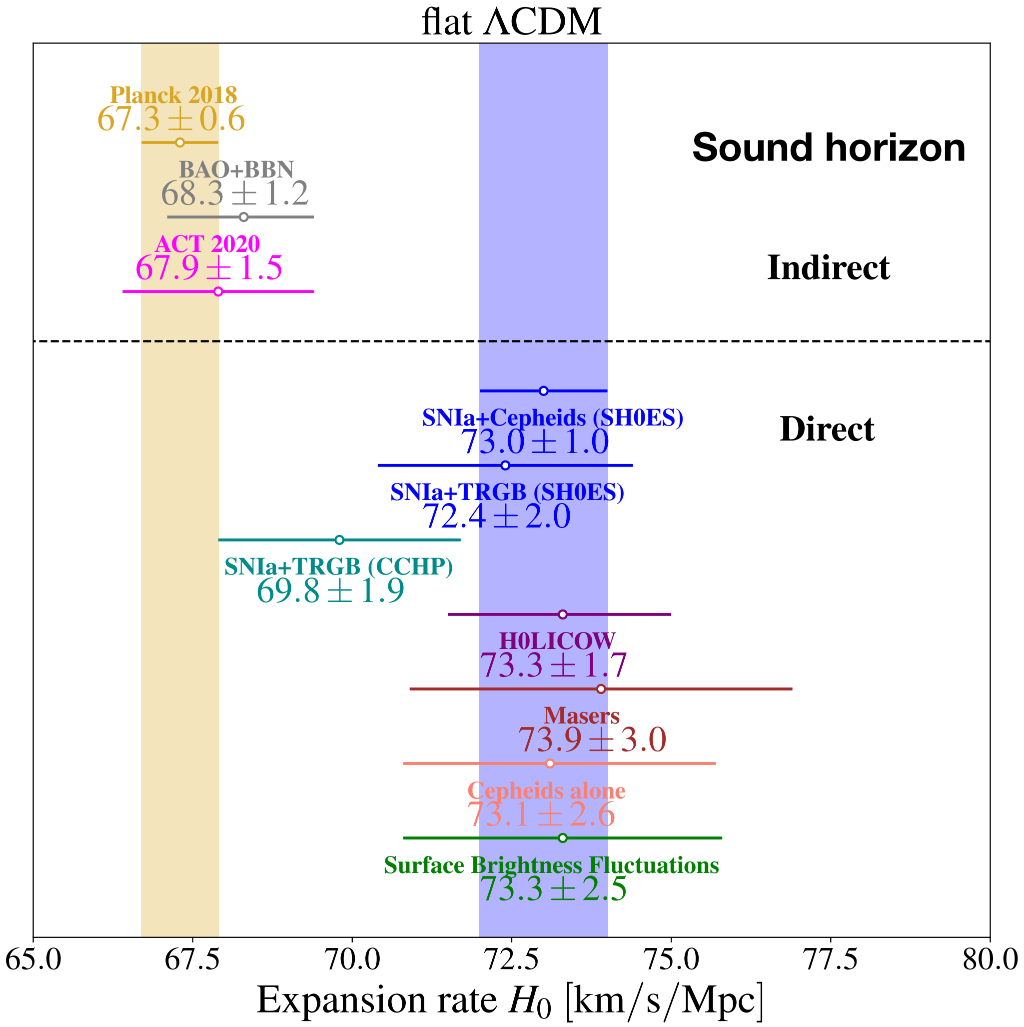
[Boylan-Kolchin, Bullock & Kaplinghat, 2011+2012]

# “Surprises” versus concordance cosmology (2)

The ΛCDM model under extreme scrutiny may show, on top of the astonishing successes, also few discordances. Most relevantly for dark matter/dark sector:

- Tensions in cosmological parameters?

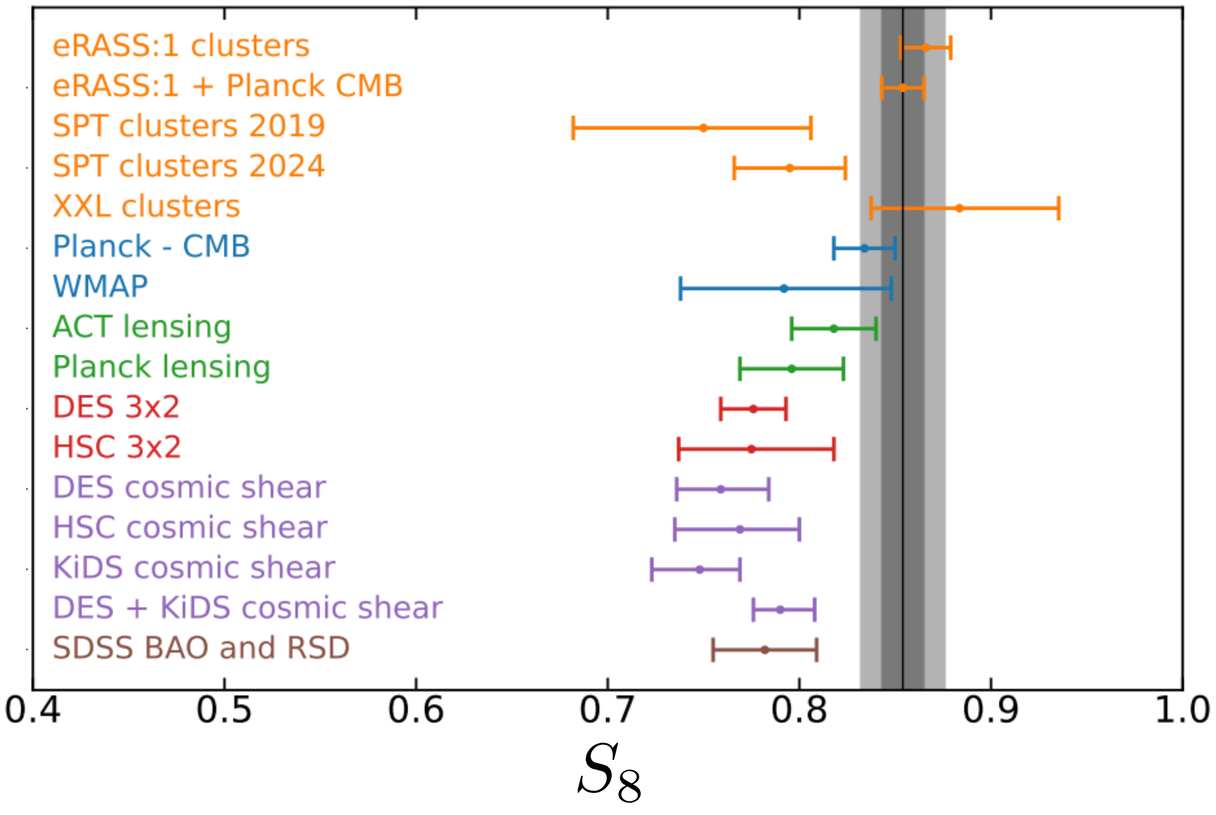
indirect versus direct measurements of $H_0$ - $5\sigma$ discrepancy between Planck CMB and SH0ES SNIa + much more:



*[compilation: Poulin, 2024]*

early Universe versus late Universe determination of the normalisation of the matter power spectrum $S_8$

- latest determination from eRosita actually **not** in tension:

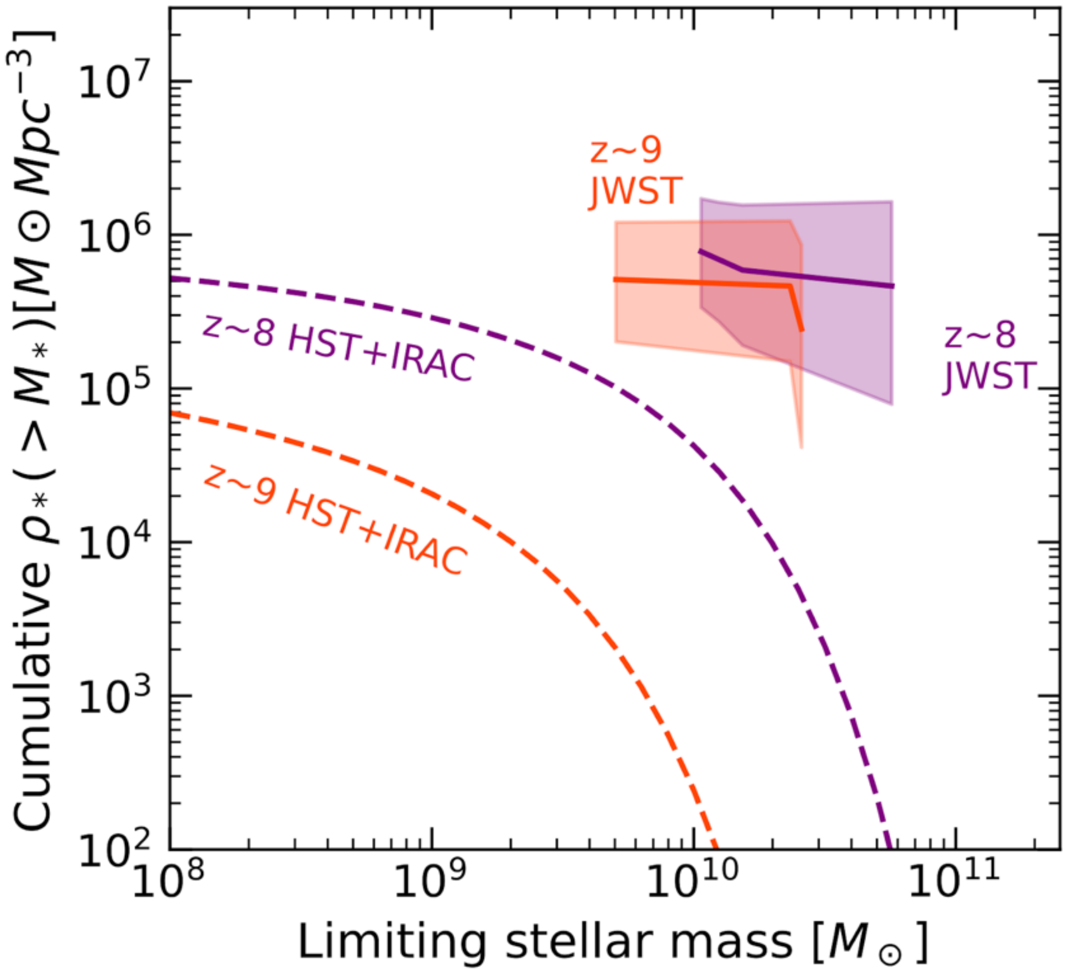


*[Ghirardini et al., 2024]*

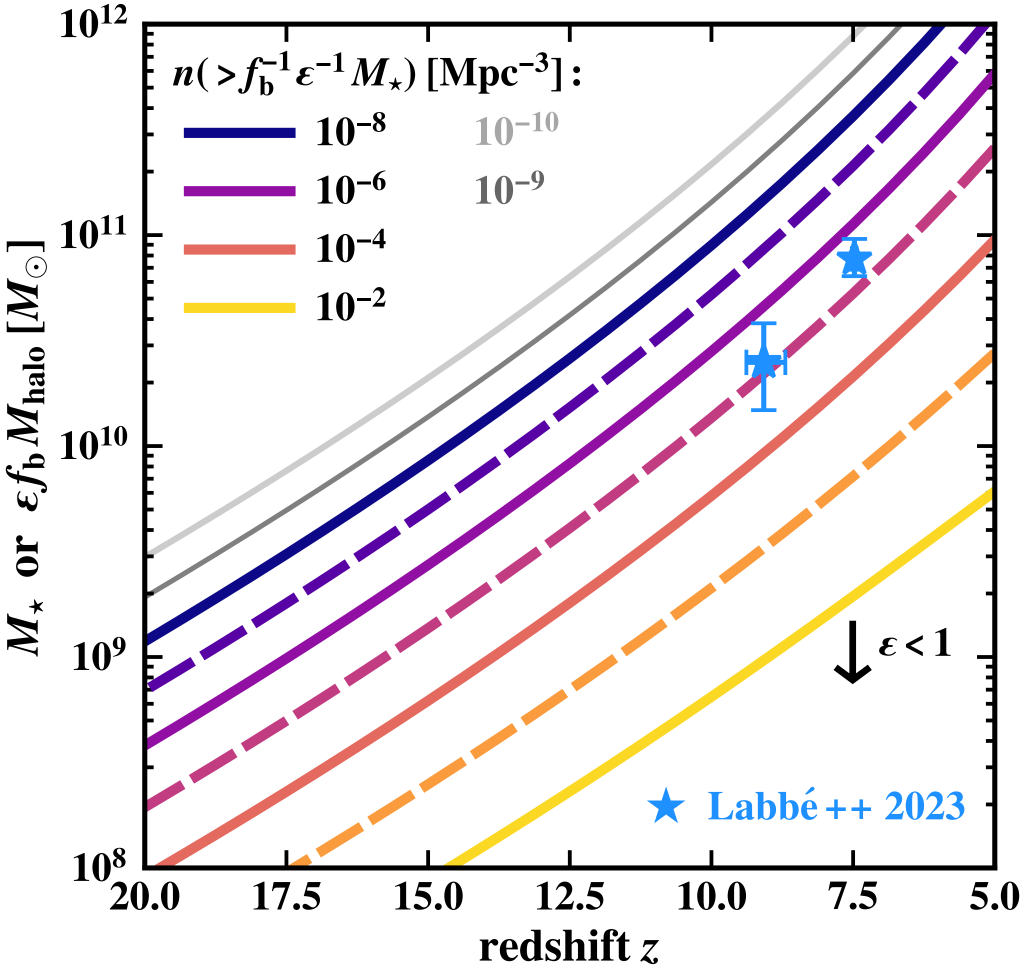
# “Surprises” versus concordance cosmology (3)

The ΛCDM model under extreme scrutiny may show, on top of the astonishing successes, also few discordances. Most relevantly for dark matter/dark sector:

- Surprise from the JWST discovery of the existence of early massive galaxies with stellar masses way larger than what expected within the ΛCDM model;



[Labbe et al., 2023]

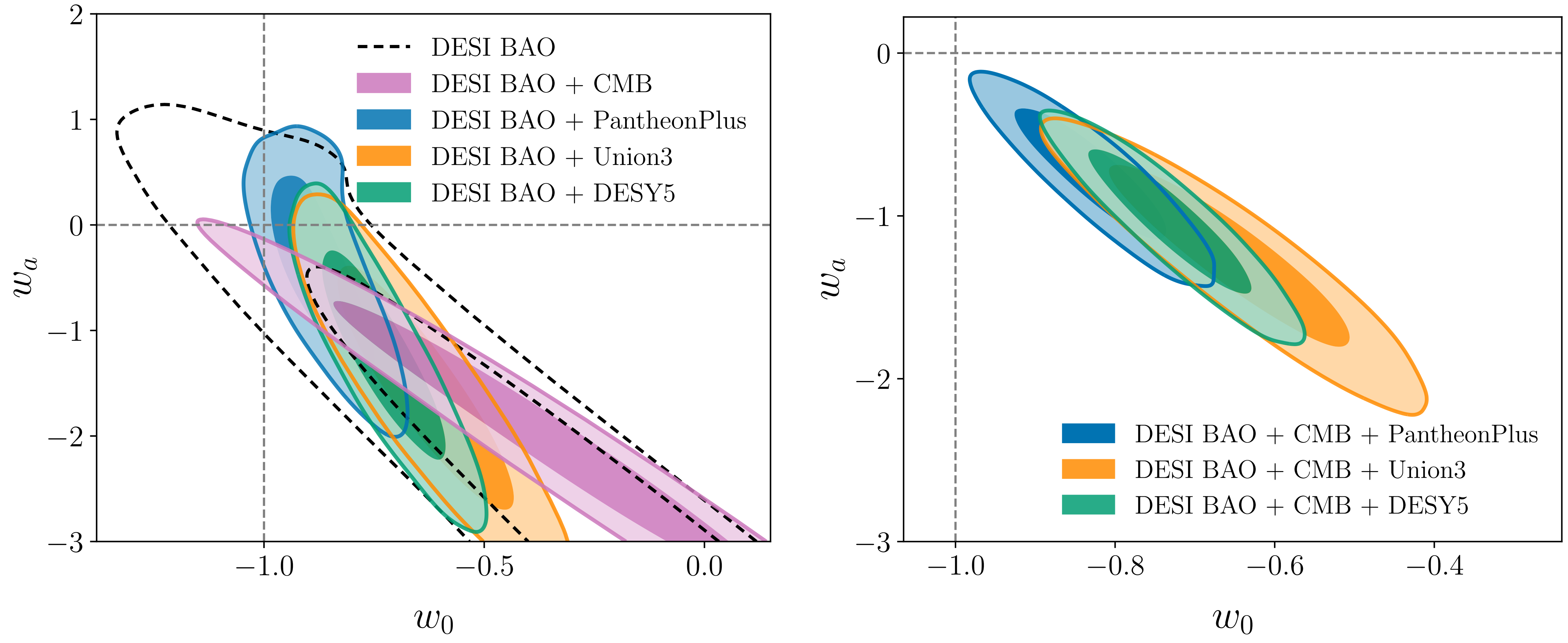


[Boylan-Kolchin, 2023]

# “Surprises” versus concordance cosmology (4)

The ΛCDM model under extreme scrutiny may show, on top of the astonishing successes, also few discordances. Most relevantly for dark matter/dark sector:

- DESI baryon acoustic oscillation measurements favouring dynamical dark energy (assuming a time varying equation of state: $w(a) = w_0 + w_a\,(1 - a)$ at $\sim 3\sigma$ level the quadrant $w_0 > -1,\, w_a < 0$ is preferred).



[Adame et al., 2024]

**Insights on the “true nature” of dark matter and dark energy?**

# Rephrasing DM as a particle physics problem

In the ΛCDM model the DM term is scale free: there is no insight on how to reformulate the DM puzzle in terms of elementary particles (what mass? what interaction strength with ordinary matter or among themselves?)

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???).

# The realm of (moderately motivated) prejudices

As a starting **assumption**, consider a dark sector in terms of elementary particles, to be possibly treated in the dilute limit (two-body interactions dominating over multi-body interactions).

Disclaimer: this is not the only possible extrapolation! In this talk we will not consider, e.g.: scenarios with “macroscopic granularities”, such as primordial black holes - possibly still viable; or scenarios in which gravity is not described by general relativity - no “DM free” variant found so far matching observations on all scales.

Two extra guidelines have been the main model building prejudices:

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.

# SM of cosmology & BSM of particle physics

A common (particle physicist) roadmap some years ago:

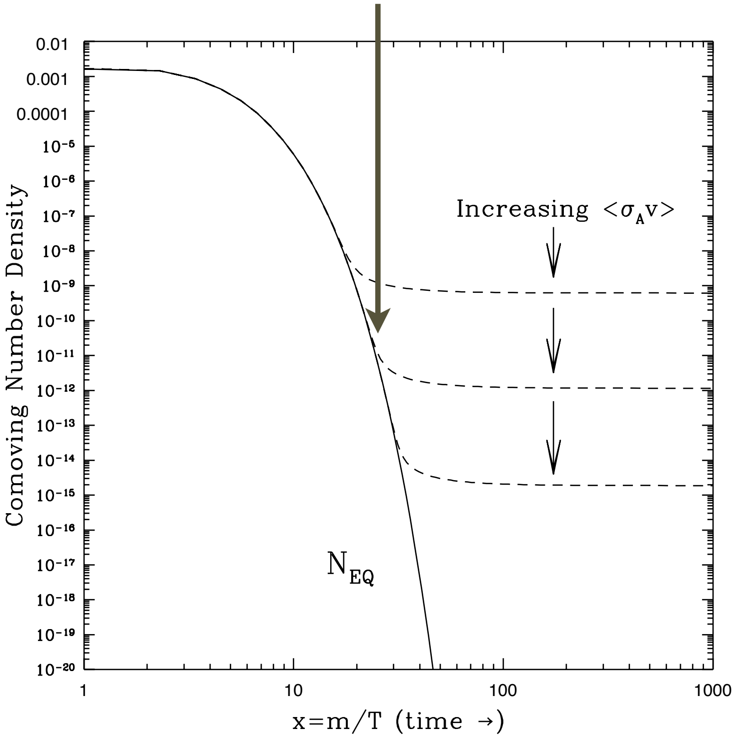
i) A (set of) BSM state(s) to be found at colliders;

ii) Direct detection experiments to demonstrate that the (lightest) state is stable and 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**.

# SM of cosmology & BSM of particle physics

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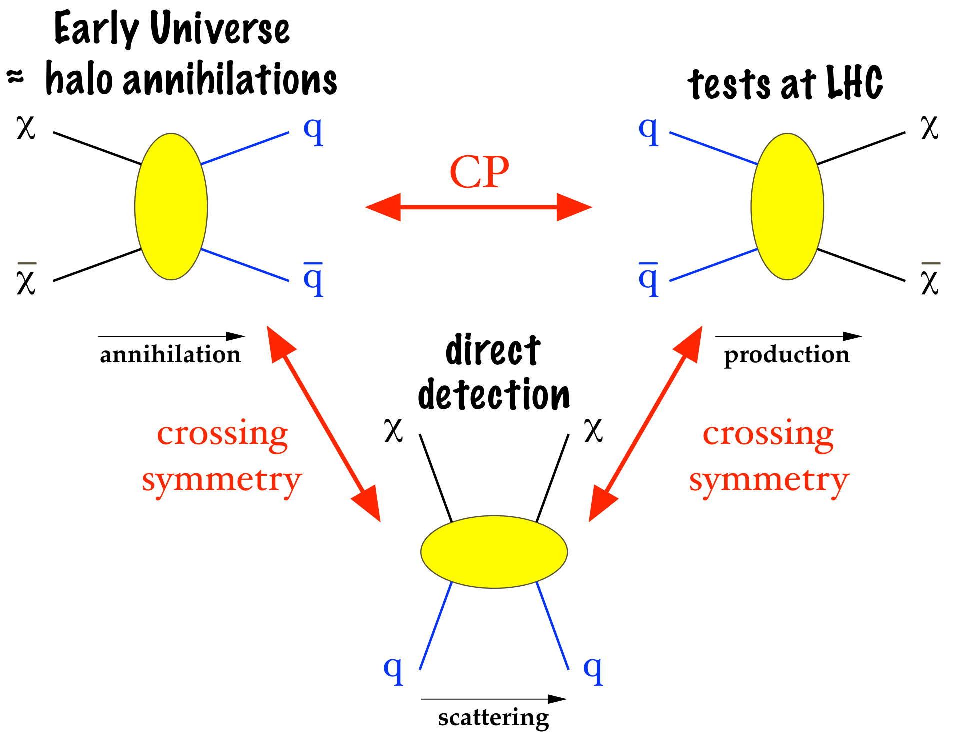
**Thermal relics**: the familiar and beloved scheme



So far, a scheme which has lead only to tentative (and controversial) hints of signals: the WIMP paradigm is well alive (and it will be hard to kill it), however the “naturalness trigger” is fading away, making to some extent the framework less appealing.

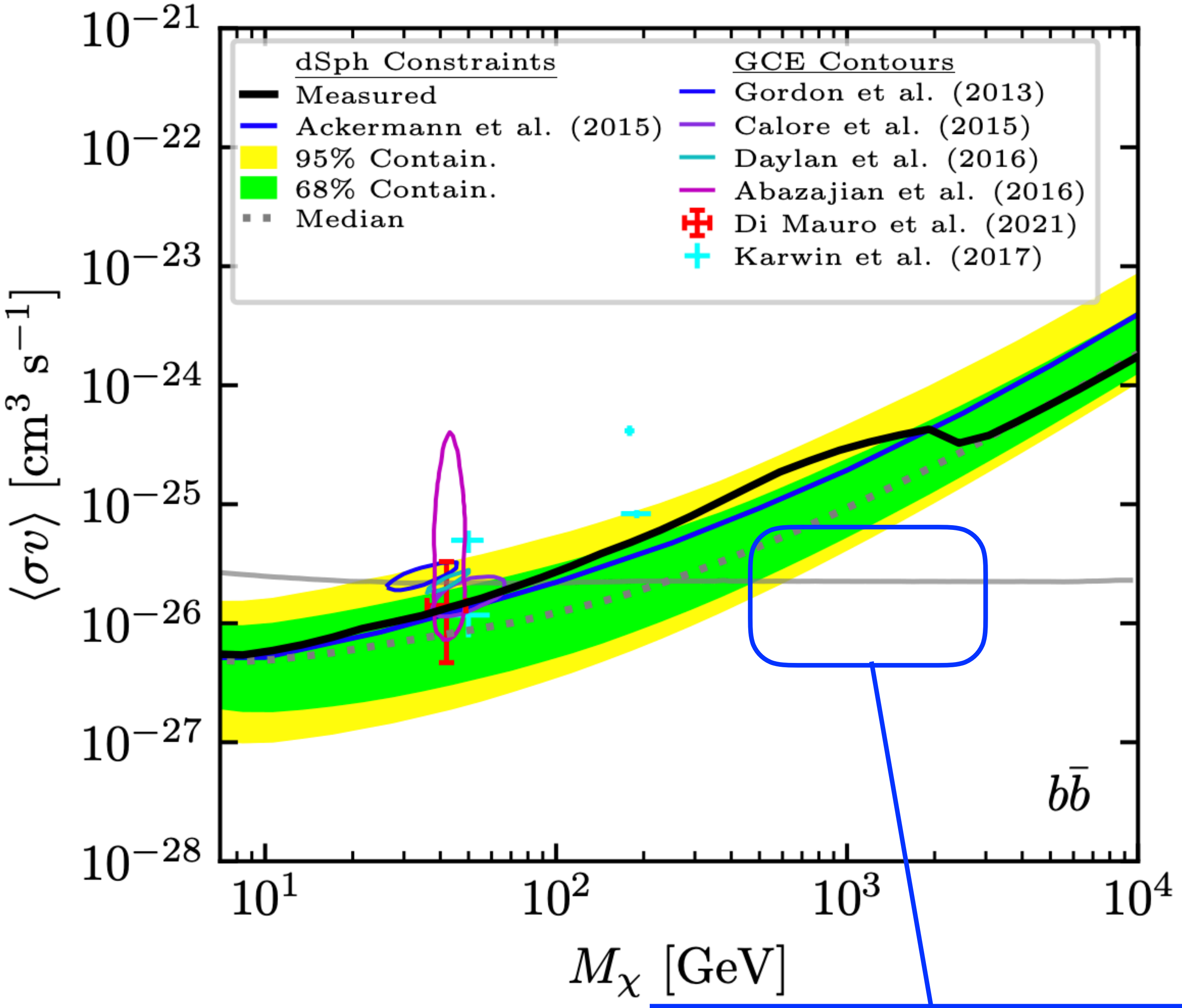
# WIMP indirect detection

In principle a straightforward connection between annihilation in the early Universe and in todays DM halos.

Strong constraints from prompt γ-ray emission (continuum spectrum) from the local population of dwarf spheroidal galaxies, ideal DM labs: very large mass to light ratios, quiet astrophysical environments, relatively close.

In the same plot, models compatible with the excess detected by Fermi from the Galactic Center *[e.g. Fermi collaboration, 2017]*, not an ideal DM lab (is it due to MSPs? *[e.g., latest: Manconi et al., 2024]*).

*[latest update with 14-yr Fermi data, McDaniel et al., 2023]*



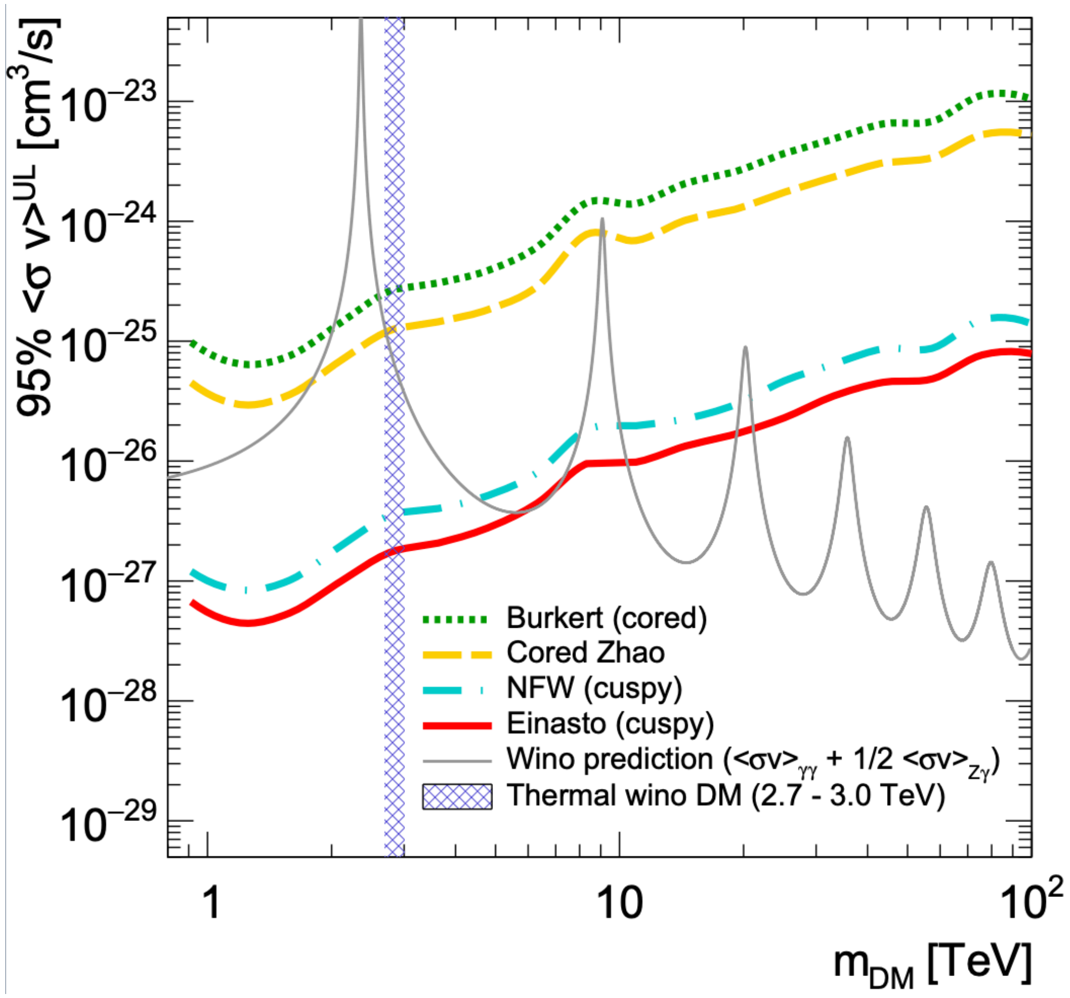
A window of opportunity for CTAO

# Indirect detection, look for signatures

Still a chance to detect smoking gun signals, such as γ-ray lines (arising at loop level): $\chi + \chi \to \gamma + X$

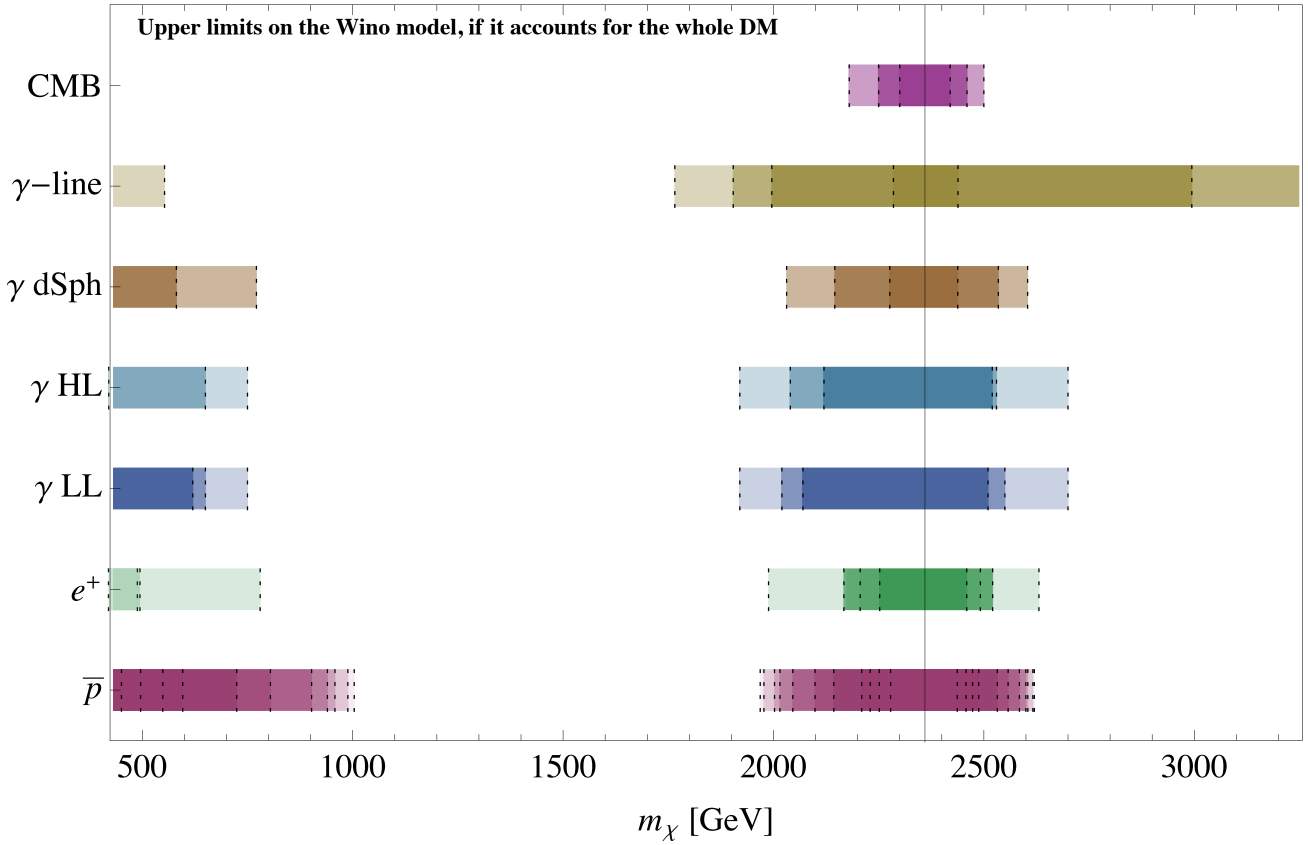
prominent in some specific models, such as pure Wino DM, and a target for CTAO in galactic center observations:

*[Magic Collaboration, 2022]*



still to be cross-checked against other detection channels:

*[Hryczuk, PU et al., 2014]*



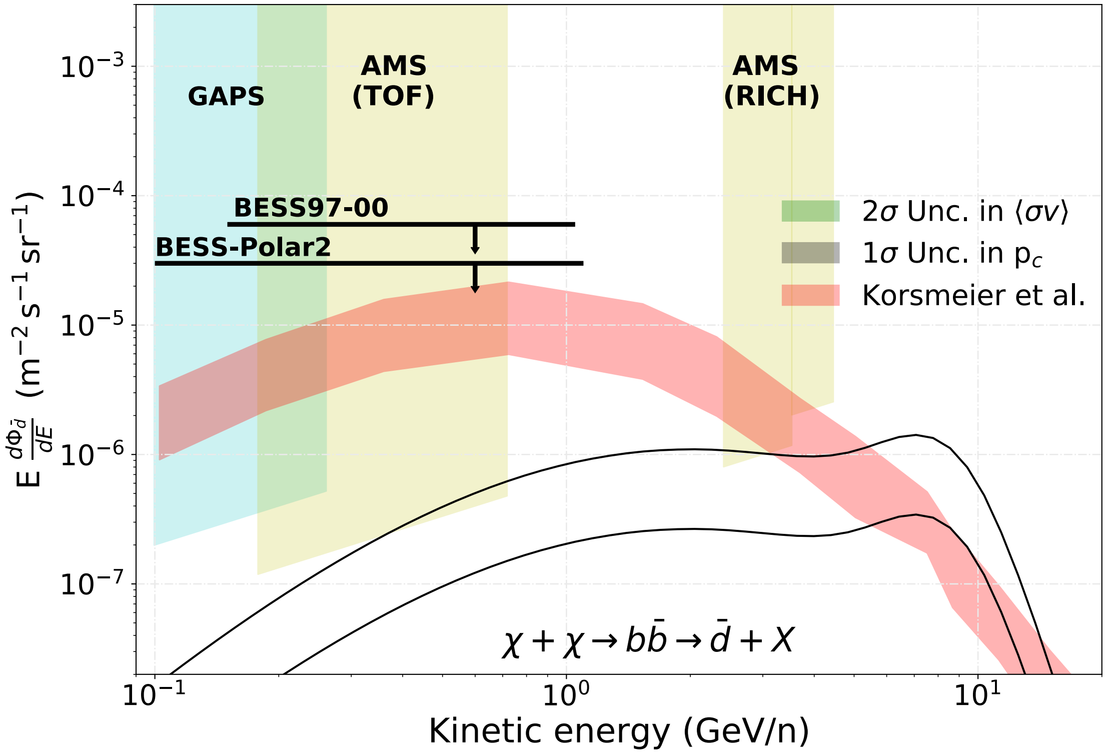
general feature for "minimal DM" models *[Cirelli et al., 2005]* obtained by adding a new SU(2) multiplet to the SM

# Indirect detection, look for signatures (2)

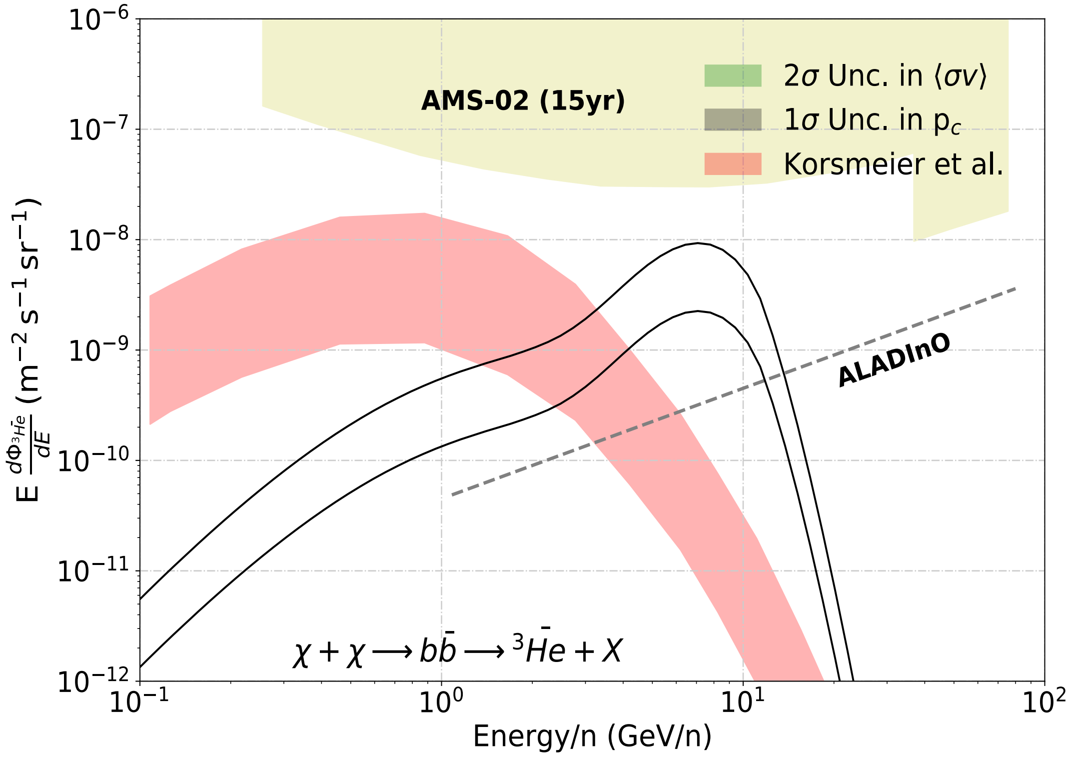
The search for exotic components in cosmic antimatter has long been a prominent channel for WIMP searches: no convincing signature identified in positron and antiproton data, an opportunity with heavier antinuclei?

First data taking on low energy **antideuterons** (and low energy antiprotons) with the **GAPS** antarctic mission later this year. What about the **antihelium** events in **AMS-02** ???

antideuteron flux



antihelium flux



*[De La Torre Luque, Winkler & Linden, 2024]*

1 sample model compatible with antiproton data; the two bands correspond to two different antinuclei coalescence modelling; the peak in the green band comes from including $\bar{\Lambda}_b$- baryons; even including this effect it would be hard to account for an antihelium detection by AMS-02

# Enlarging the parameter space

A dark sector containing multiple states offers the possibility of having multiple variants to the standard WIMP paradigm, such as:

*[very incomplete lists of models and references]*

- there is a dark sector thermal bath (with $T_D$ possibly different from $T_\gamma$), with thermalisation and freeze-out: $\chi + \chi \leftrightarrow \psi + \bar{\psi}$ led by extra interactions (e.g.: extra $U(1)_D$ with $\gamma_D$ mediator)
- there is a different process sustaining (dark) thermal populations, such as, e.g.,:
  - coannihilations: $\chi_i + \chi_j \leftrightarrow \psi + \bar{\psi}$ *[Griest & Seckel, 1991]*
  - semi-annihilations: $\chi + \psi \leftrightarrow \chi + \chi$ *[D'Eramo & Thaler, 2010]*
- dark matter produced out of equilibrium, because, e.g.:
  - there is a particle-antiparticle asymmetry $\eta_\chi$ (analogous or connected to $\eta_B$), asymmetric DM *[e.g., Petraki & Volkas, 2013]*
  - feebly interacting with the heat bath / never in equilibrium:
    - * super-WIMP freeze-in: $\psi + \phi \rightarrow \chi + \phi$ *[Pagel & Primack, 1992]*
    - * exponential production: $\psi + \chi \rightarrow \chi + \chi$ *[Bringmann et al. 2021]*

sub keV ⟵ mass $m_\chi$ ⟶ 10s TeV

gravity ⟵ $\chi - \mathrm{SM}$ inter. ⟶ strong

# Filling in the range of possibilities in the EU

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)

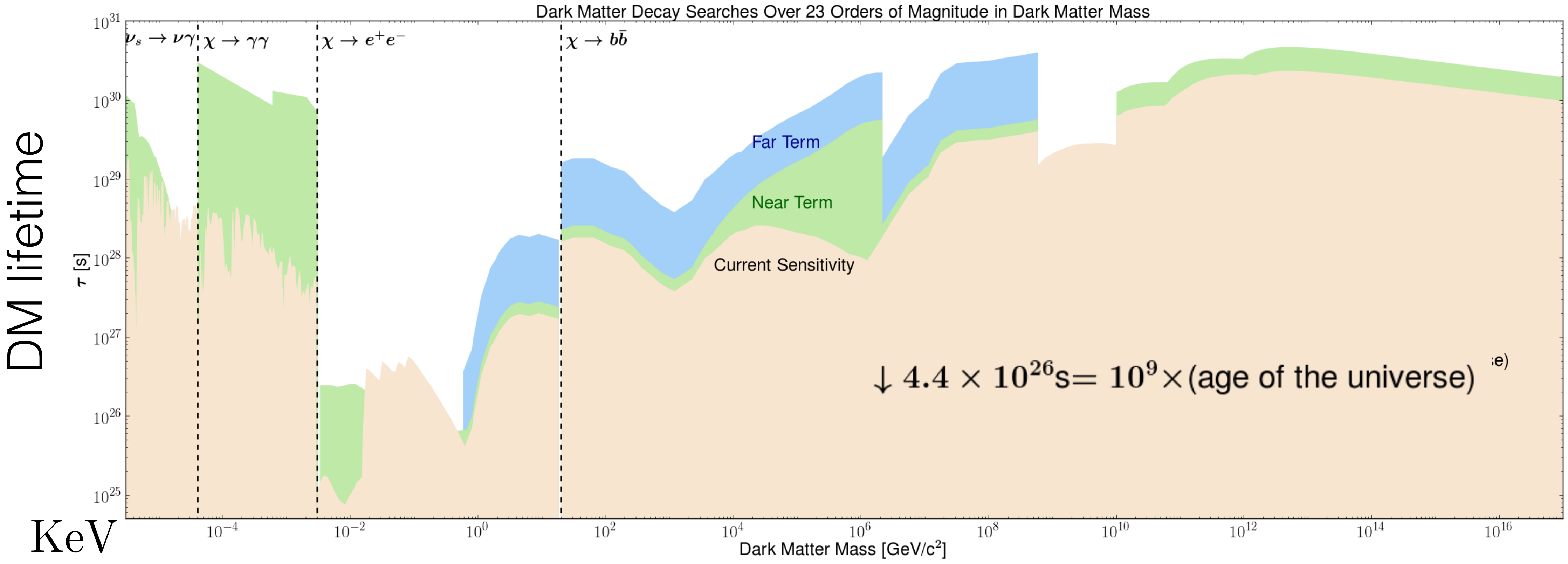
Natural matching $\Omega_\chi \sim \Omega_{\rm CDM}$? Several of the scenarios mentioned above simply do envisage fine-tuning.

# Probing such range with indirect DM detection?

It can still occur (in a fair fraction of models it does occur) that DM particles have interactions producing SM states (and analogously for direct detection).

E.g.: while DM needs to be very long-lived, still it has a non-zero **decay** width into SM particles; DM **pair annihilation** into SM (final) states is still present; **…**

The existing multiwavelength/multimessenger ensemble of observatories, designed to study astrophysics, can be effectively used to tests DM properties over very large mass/energy ranges. E.g., for DM decays into (only) SM:



*[Coley et al., Snowmass 2021]*

However: **what is the physical target in this plot (and in analogous plots)?**

# Opportunity windows or the 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”.

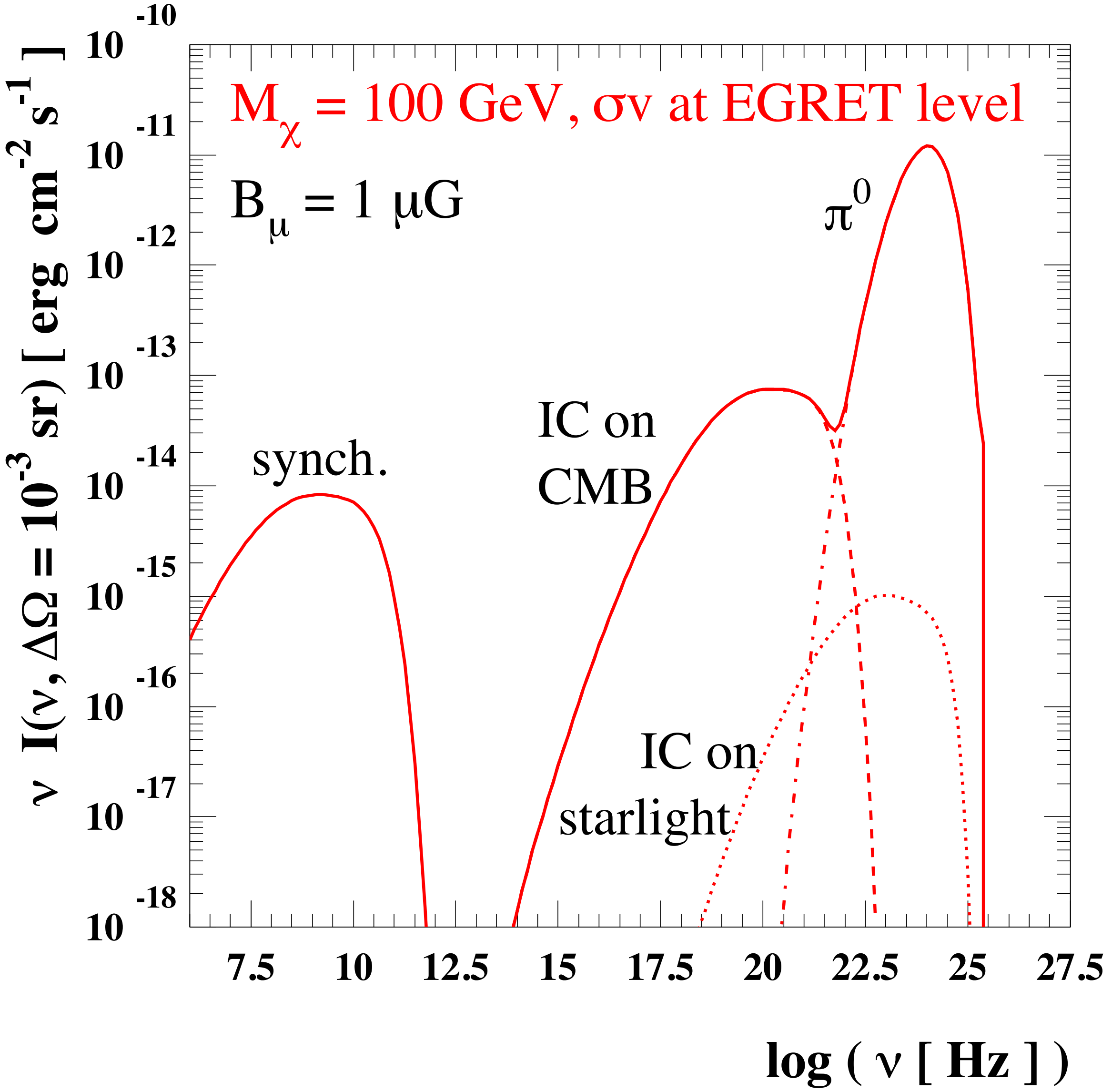
You can call it lamppost searches, still the scientific program is very stimulating; few details on few extra sample cases:

# Multi-wavelength signals from dwarf galaxies?

On top of prompt γ-ray emission, in dwarf galaxies there can be radiative emission connected to leptonic components from DM annihilations/decays:

Early analysis predicting such signal for Draco:

*[Colafrancesco, Profumo & P.U., 2006]*



If you trust these predictions (as done in some later analyses), you would conclude that from radio surveys which did not detect such a signal can put constraints in the (WIMP) parameter space at a level competing with γ-ray telescopes.

These predictions are however model dependent, with especially a serious caveat: what is the level of turbulence (required to confine $e^+/e^-$) in dwarfs?

Comparable to the one in the Milky Way cosmic ray halo? (as assumed in the plot)

# Confining radiating particles in dwarfs

Sizable radiative emission can occur only in case the timescale for energy losses is shorter than the timescale for escape from the source.

For charged particles injected in DM annihilations/decays, this is always true only when considering very extended objects (e.g., galaxy clusters). On galactic and sub galactic scales, in the limit of **ballistic propagation**, this is in general false.

The transport of charged particles in galaxies (galactic CRs with energies up to the knee?) is likely in the **diffusive limit**, as a consequence of the (resonant) “scattering” on magnetic inhomogeneities (the turbulent component on top of the large scale regular galactic magnetic field component) .

Turbulence in structures with sizeable star formation rate is usually assumed as an astrophysical feedback, e.g. from supernovae. Missing detailed generation scenarios, the effect is usually parametrised in terms of a diffusion timescale/diffusion coefficient to be fitted on (CR) data.

Alternative mechanisms for turbulence generation (streaming instabilities from current flows or charge particle gradients) have been recently reconsidered in connection to CR anomalies: the change of diffusive regime for galactic CRs *[e.g. Evoli, Blasi, Morlino & Aloisio, 2018]*, the TeV halos around pulsars *[e.g. Mukhopadhyay & Linden, 2022]*.

# Self-confinement of DM-induced cosmic rays

DM would naturally induced a charged particle density gradient, in turn sourcing turbulence: solve in a dwarf the two coupled equations for the particle density $n_e$ and turbulence power spectrum $W$:

i) $$\frac{\partial n_e}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D\frac{\partial n_e}{\partial r} - r^2 v_A n_e\right] + \frac{2v_A}{r}\frac{\partial}{\partial E}\left[\frac{p}{3}\beta\, c\, n_e\right] - \frac{\partial}{\partial E}\left[\dot{E} n_e\right] + q_{\rm CR}$$

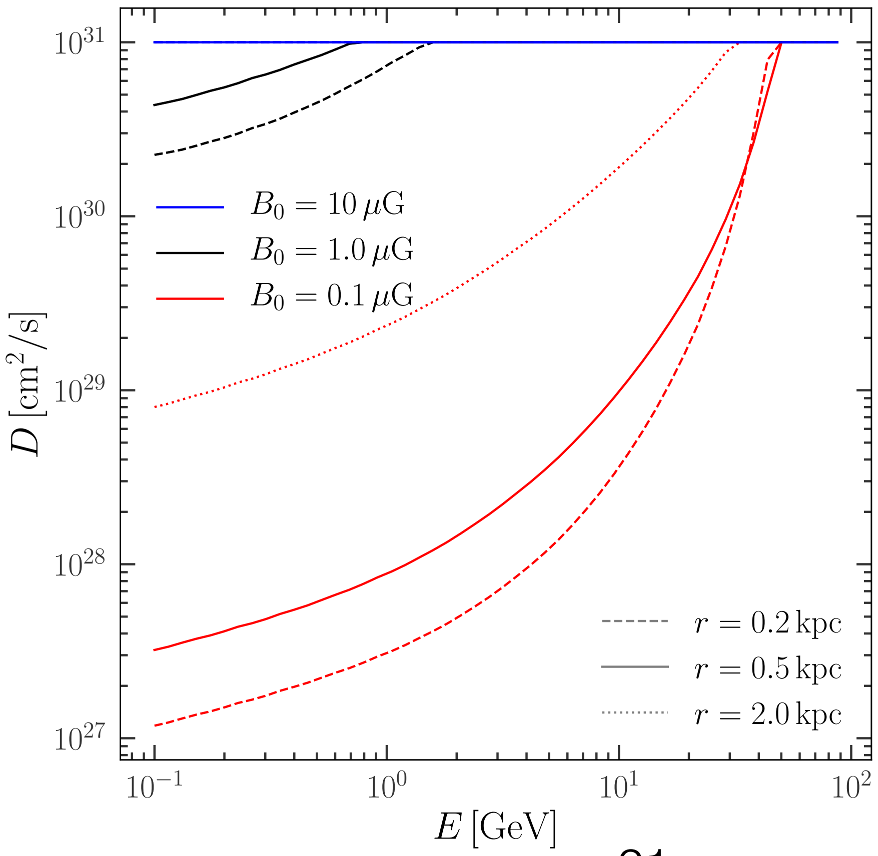
with: $$q_{\rm CR}(r,E) = \langle\sigma v\rangle_f \frac{\rho^2_{\rm DM}(r)}{2\, m^2_{\rm DM}}\frac{dN^f_e}{dE}$$

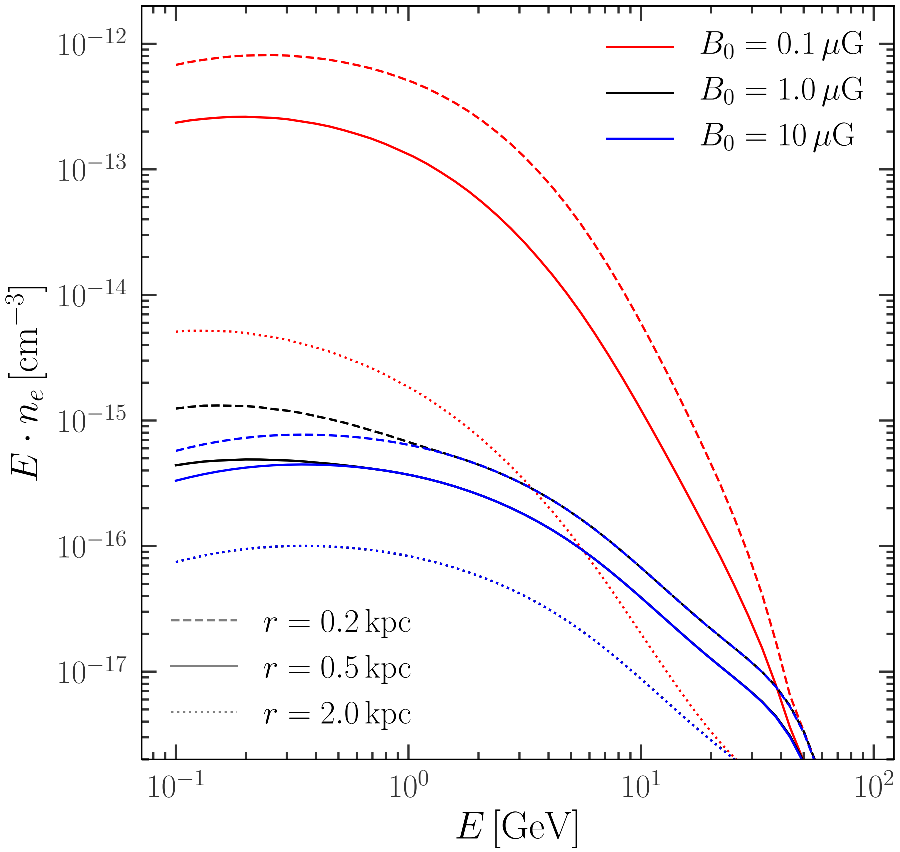
ii) $$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}(W)\frac{\partial W}{\partial k}\right] - \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 v_A W) + \Gamma_{\rm CR}(n_e,k)W$$

with: $D_{kk}(W) = c_k v_{\rm A} k^{7/2}\sqrt{W}$ and $\Gamma_{\rm CR} = \dfrac{4\pi\, c\, v_A}{3\, k\, W(k)\, B_0^2/(8\pi)}\left[\beta(p)\, p^4\left|\dfrac{\partial f_e}{\partial r}\right|\right]_{p=p_{res}}$

Within a simplified geometry and at steady state, a relevant diffusion coefficient may arise:

$$D(r,p,t) = \frac{D_{\rm B}(p)4/\pi}{kW(r,k,t)}$$

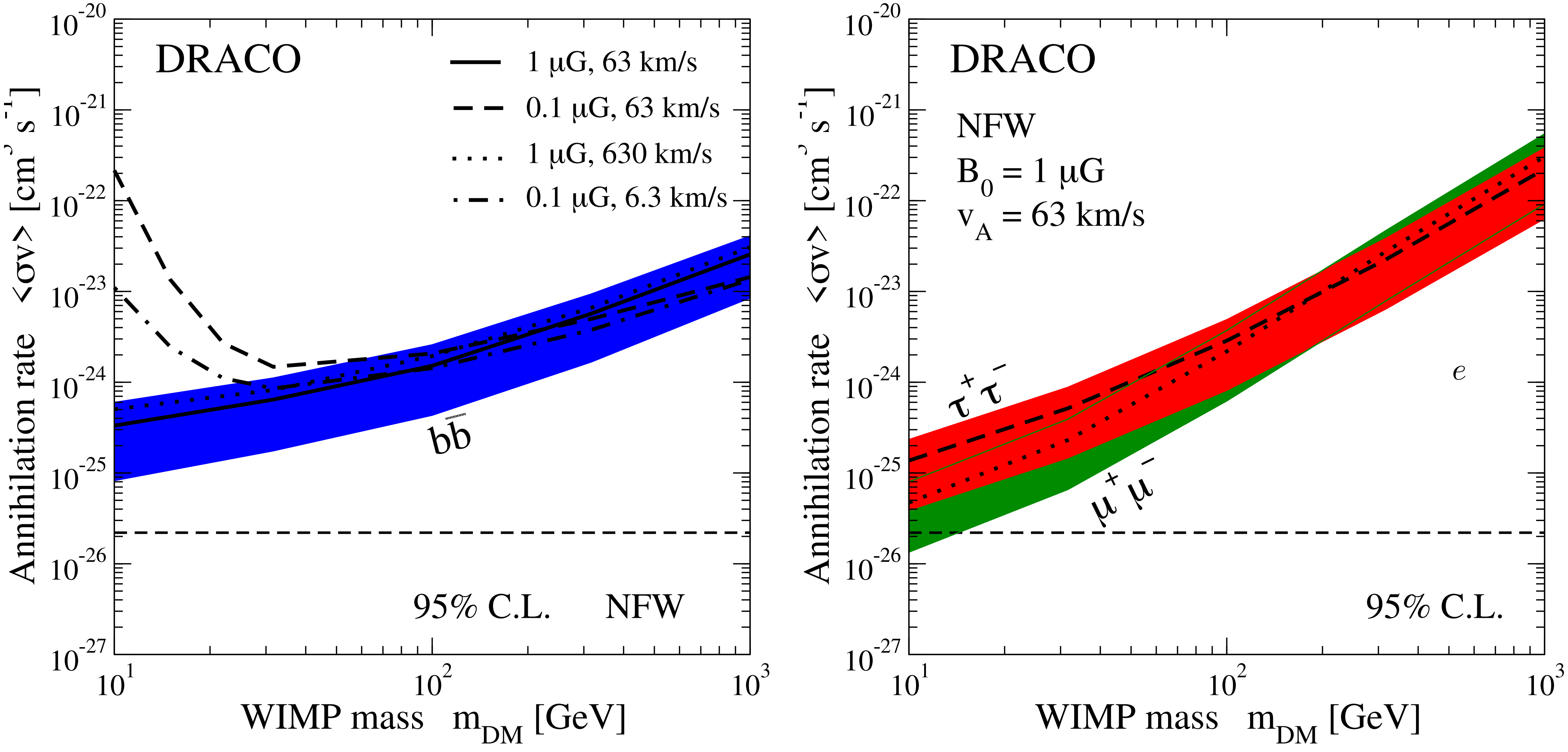




*[Regis, P.U. et al, 2023]*

# Self-confinement of DM-induced cosmic rays

Leading to conservative but competitive limits when applied to dwarfs. E.g.: limits from Draco using uGMRT data at 550-750 MHz:



[Regis, P.U. et al, 2023]

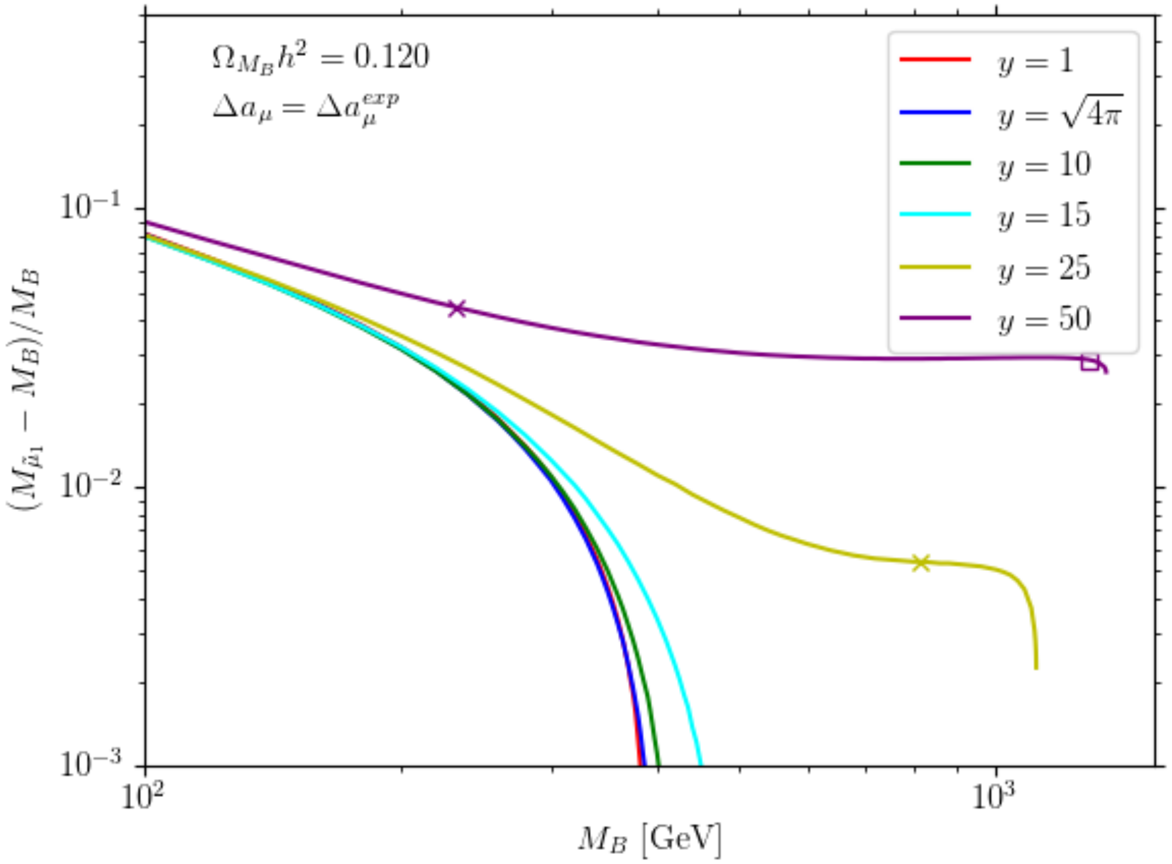
Possibly relevant for other “astrophysically quite” environments: dark matter filaments? dark matter structures in the early (earlier) Universe?

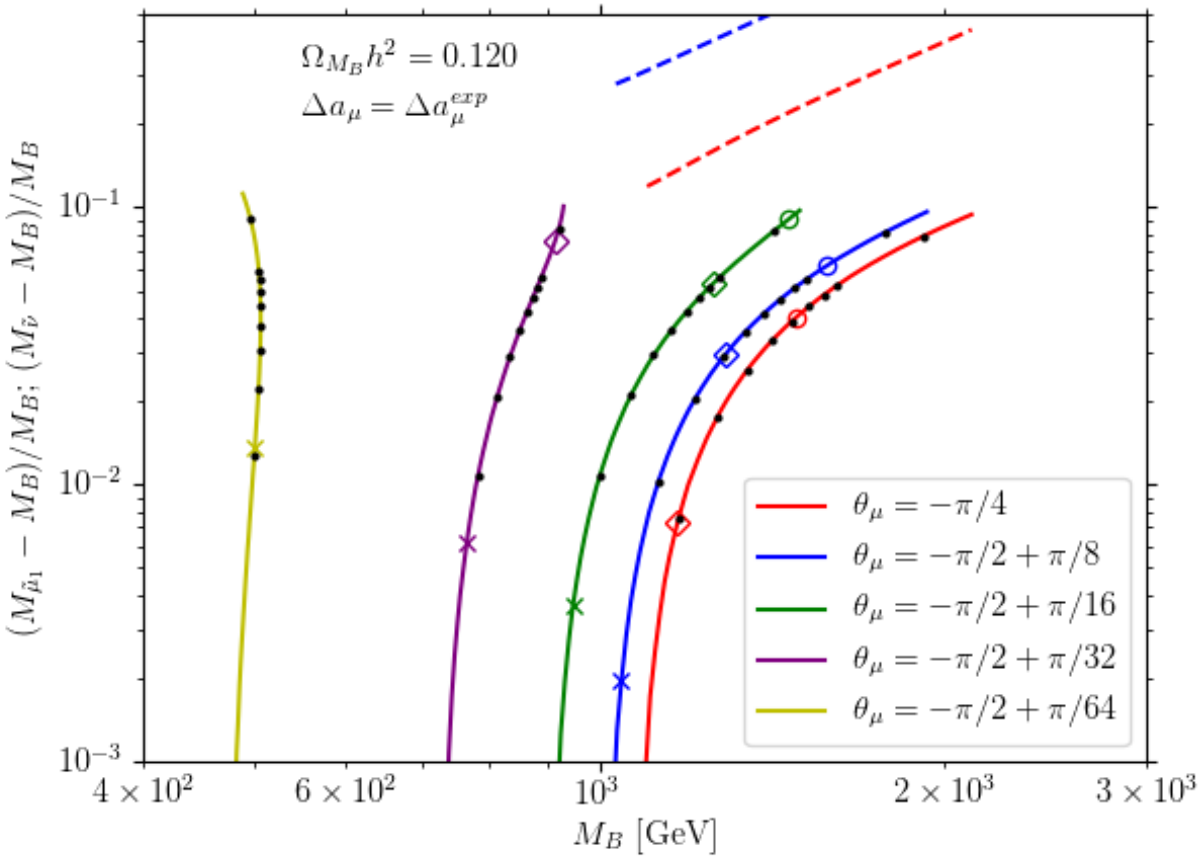
# A minimal DM scheme and (g-2)$_\mu$

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:

*[Acuña, Stengel, P.U., PRD 2022]*



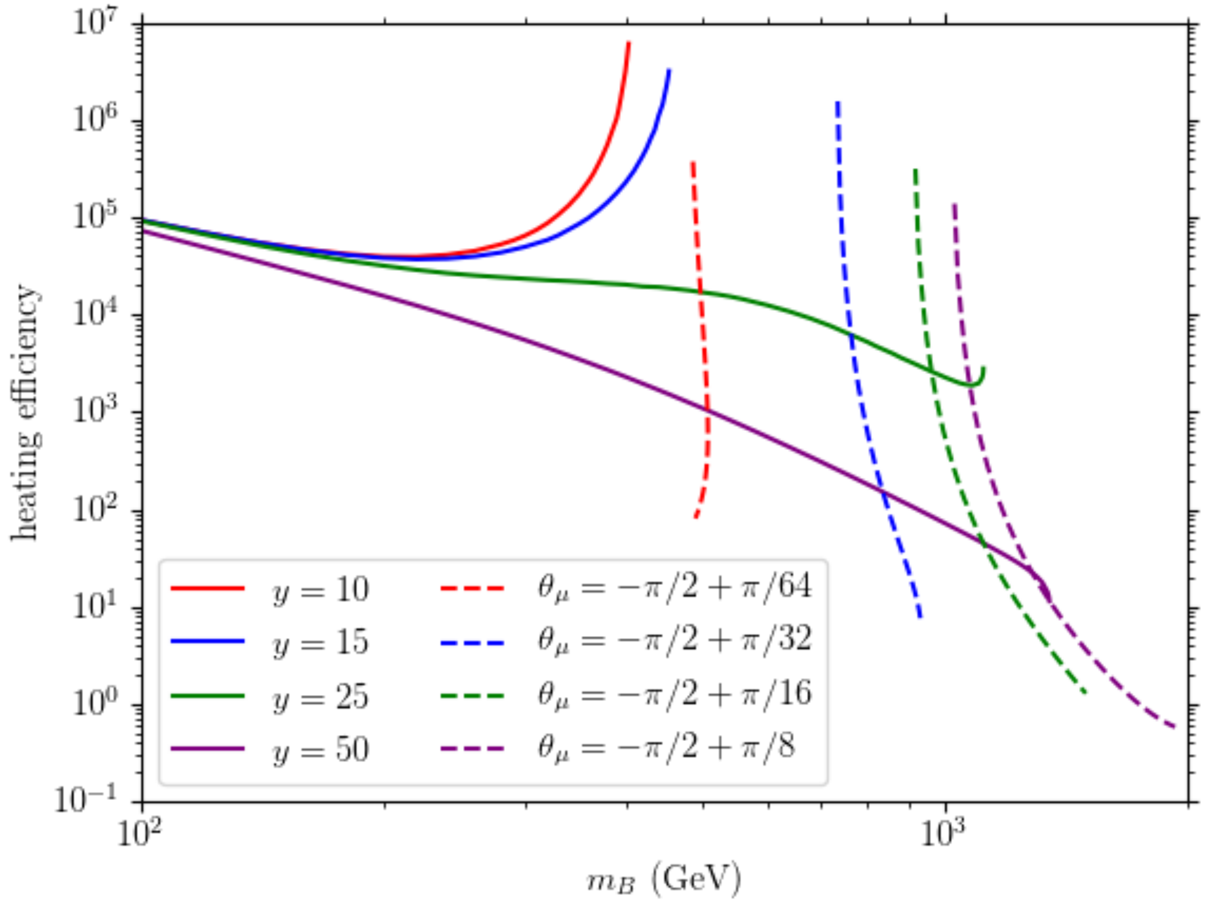


# A minimal DM scheme and (g-2)$_\mu$

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).

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]*



# Readdressing the potential of direct detection

The “standard” picture with direct detection: measuring the recoil energy in elastic (or inelastic?) scattering off nuclei due to the local Milky Way halo population of dark matter particles:

In this picture, there is a “wall” in detector sensitivities at about 1 GeV:

$$E_R = \frac{|\vec{q}\,|^2}{2M_N} > E_{\rm th}$$

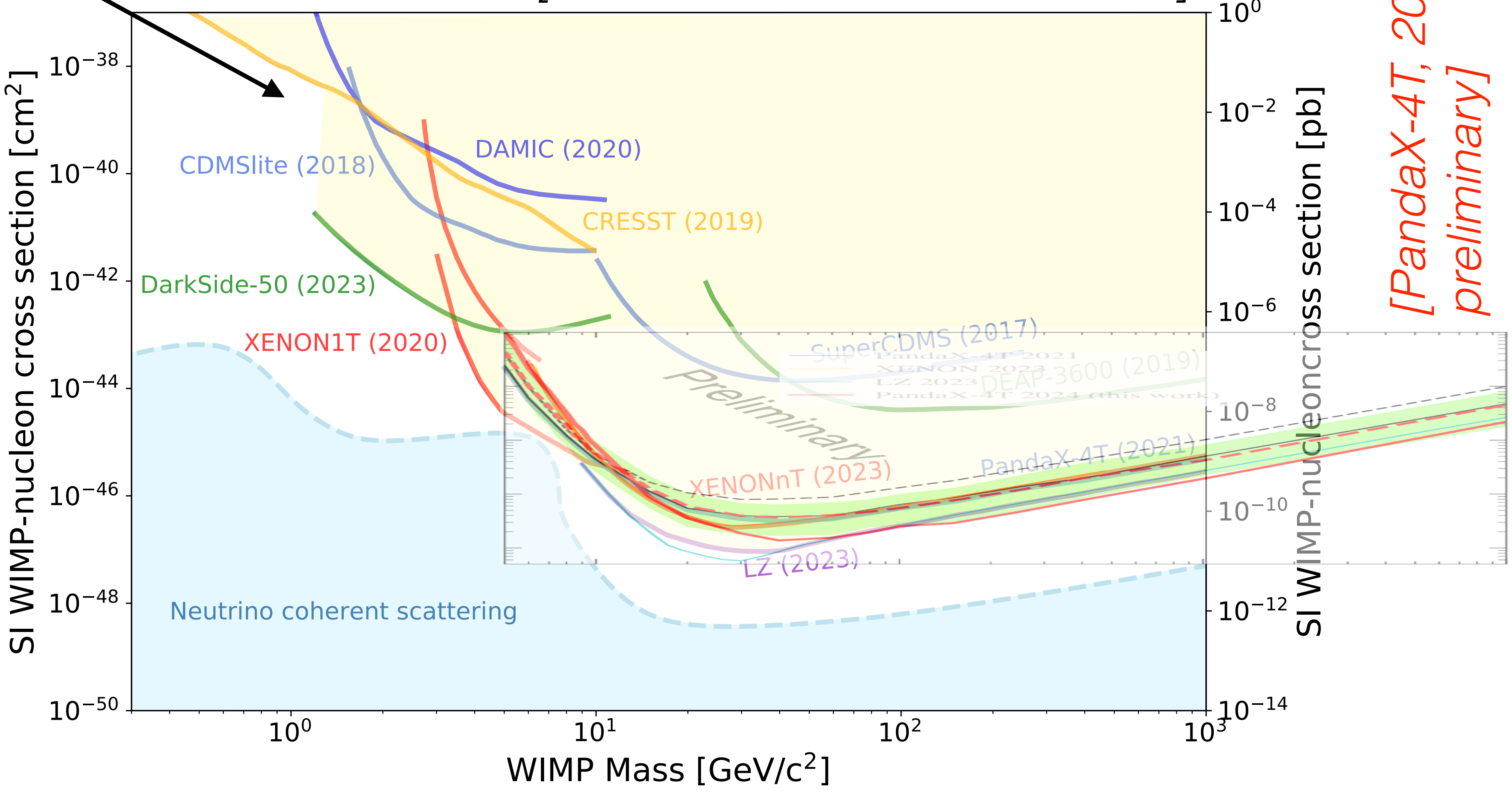
$$\wedge$$

$$E_R^{\rm max} = 2\frac{\mu_{\chi N}^2 v^2}{M_N}$$

$$\sim 2\frac{m_\chi^2 v^2}{M_N}$$

with: $v \sim 10^{-3}c$

[Baudis & Profumo, PDG 2023]



*[PandaX-4T, 2024, preliminary]*

# Dark matter boosted by galactic cosmic rays

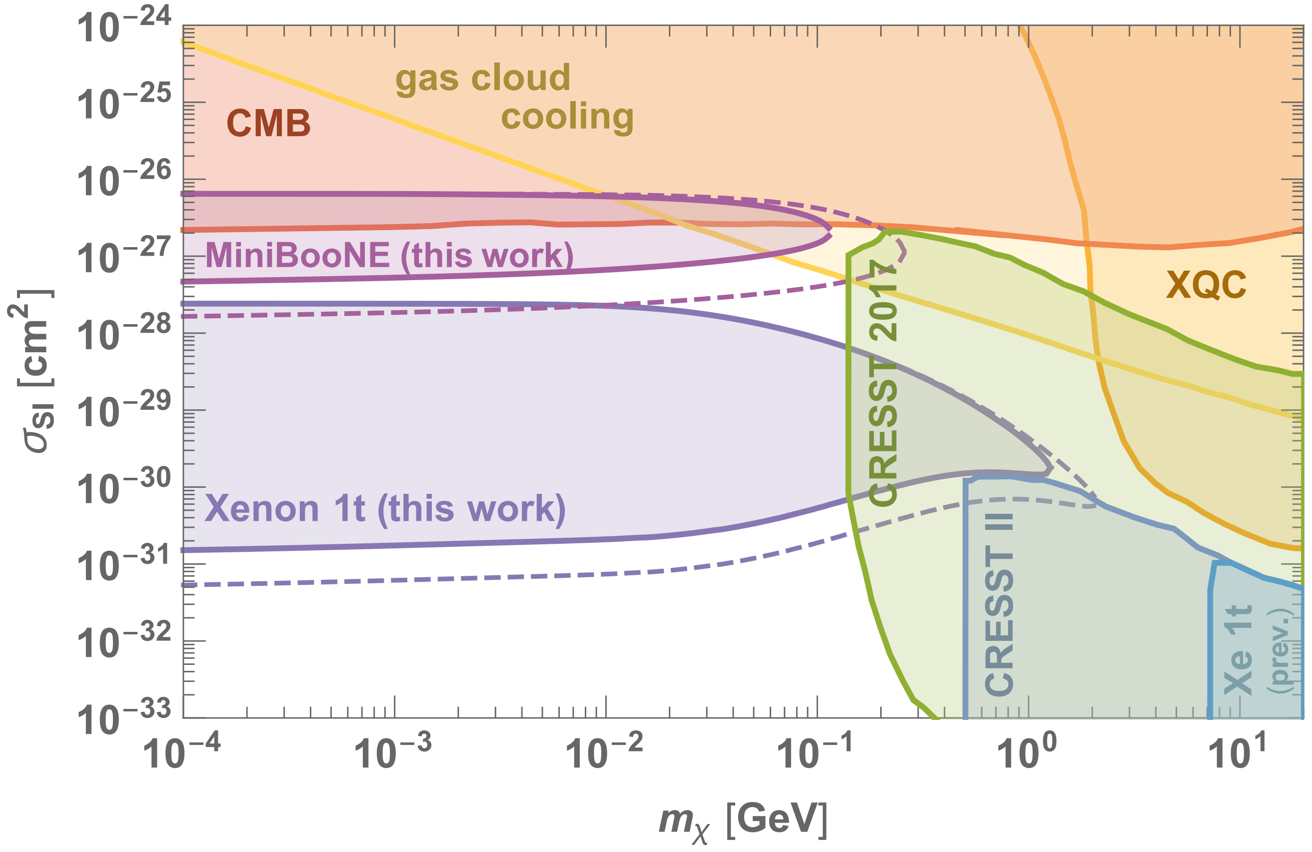
The light mass wall in nuclear recoil at $m_\chi$ lighter than $\sim 1\,\mathrm{GeV}$:

$$E_R^{\max} \sim \frac{m_\chi^2\, v^2}{M_N} > E_{\rm th}$$

disappears if instead targeting non-relativistic galactic DM halo particles ($v \sim 10^{-3}c$), one considers sub-leading populations with more energetic DM particles:

the same coupling DM-ordinary matter being tested in the experiment, may be relevant in the up-scattering by galactic cosmic rays (mainly protons) of a fraction of the DM galactic population to high energies, making sub-GeV dark matter candidates potentially detectable.

*[Bringmann & Pospelov, PRL 2019]:*



# Blazer boosted dark matter

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

**Blazers are the ideal case:**

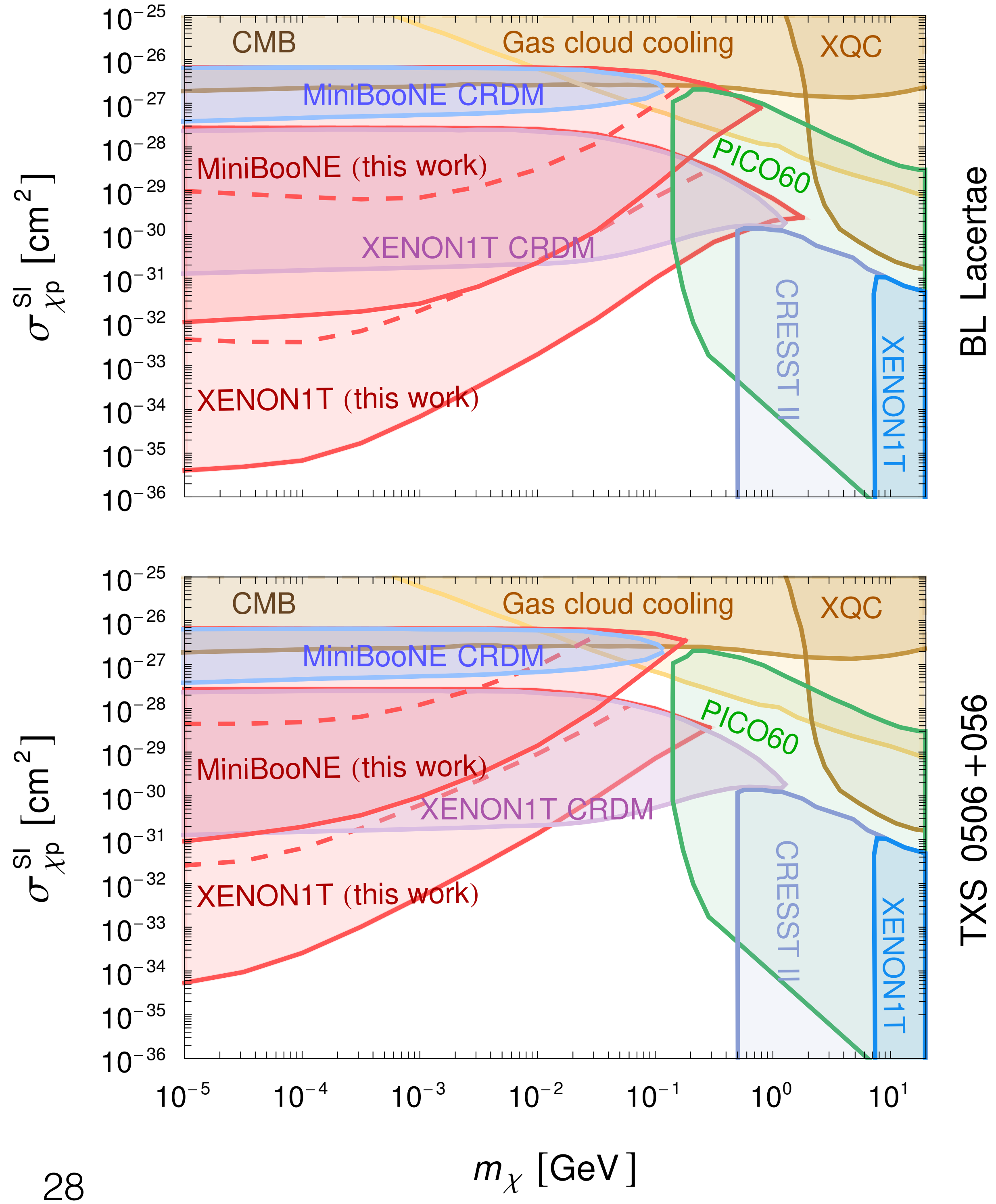
Extremely powerful flux of protons (electrons) through an extremely dense dark matter environment (dark matter spike accreted around the blazer black hole engine), potentially generating a sizable DM flux towards us.

Tightest limits/best discovery potential for light dark matter

See also:

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

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



# Conclusions

Is cosmology shaping a dark sector which will guide us to the solution of the dark matter problem?

New prejudice-free paths to address the dark matter problem from a particle physics perspective; are there efficient ways of walking through them and discriminating among each other?

Several windows of opportunities for dark matter detection still open; will we enter the stage in which models are confirmed or rejected?