Dark matter searches: status and prospects

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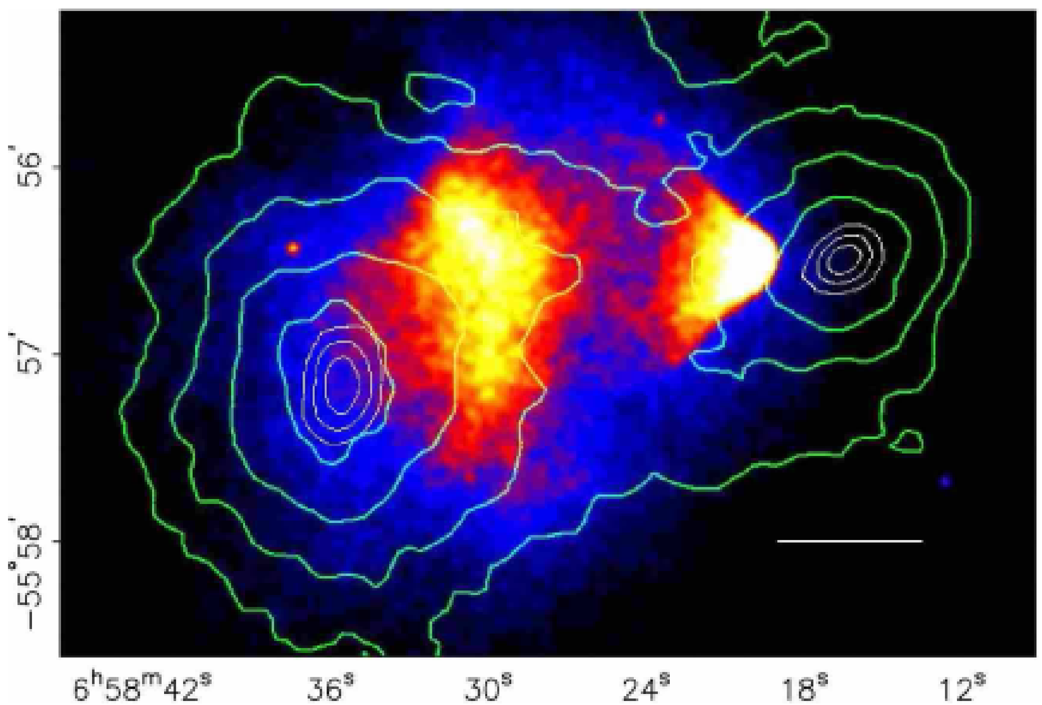
Classical (local) DM tests

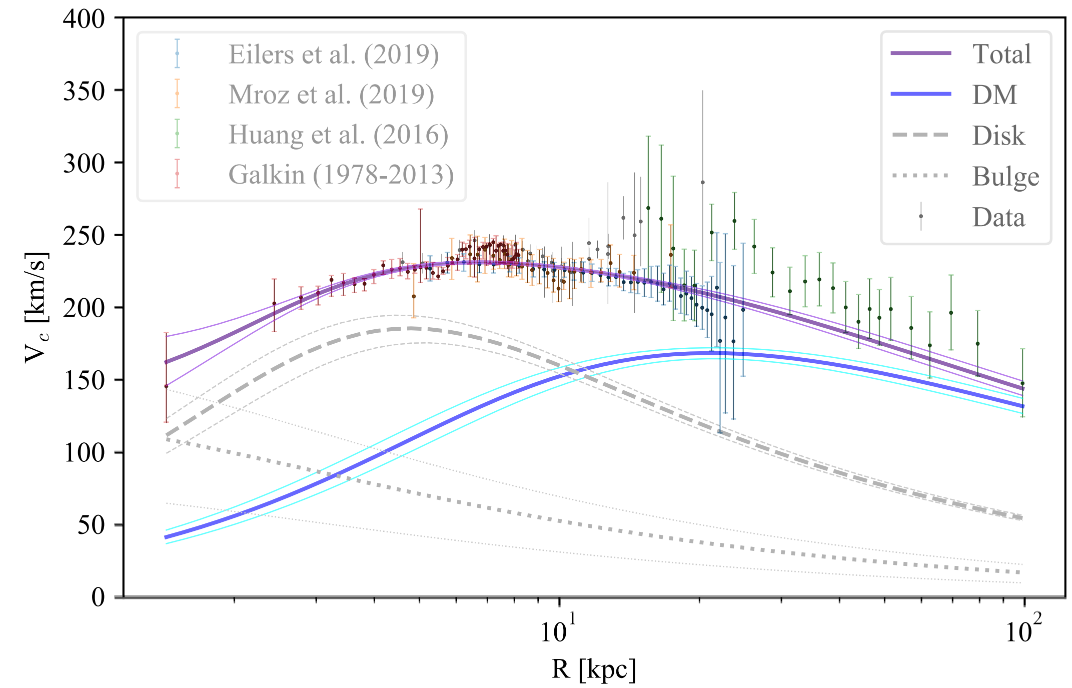
(merging) galaxy clusters



[Clowe et al., 2006]

Component separation

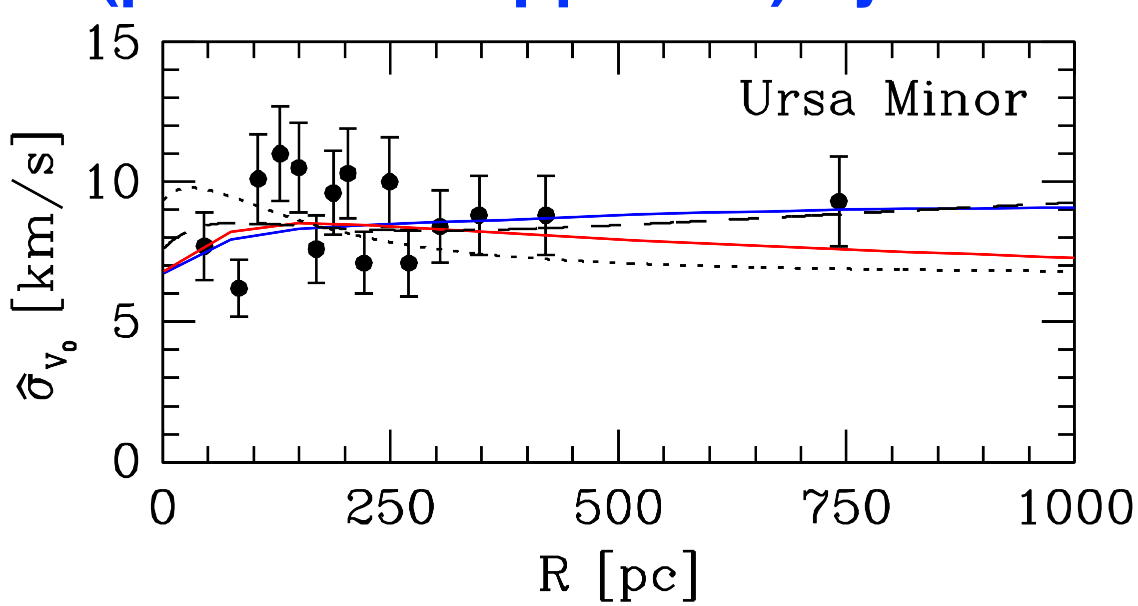
(rotationally supported) galaxies



Petac & P.U., 2020]

Mass decomposition

(pressure supported) systems



[Walker et al., 2009]

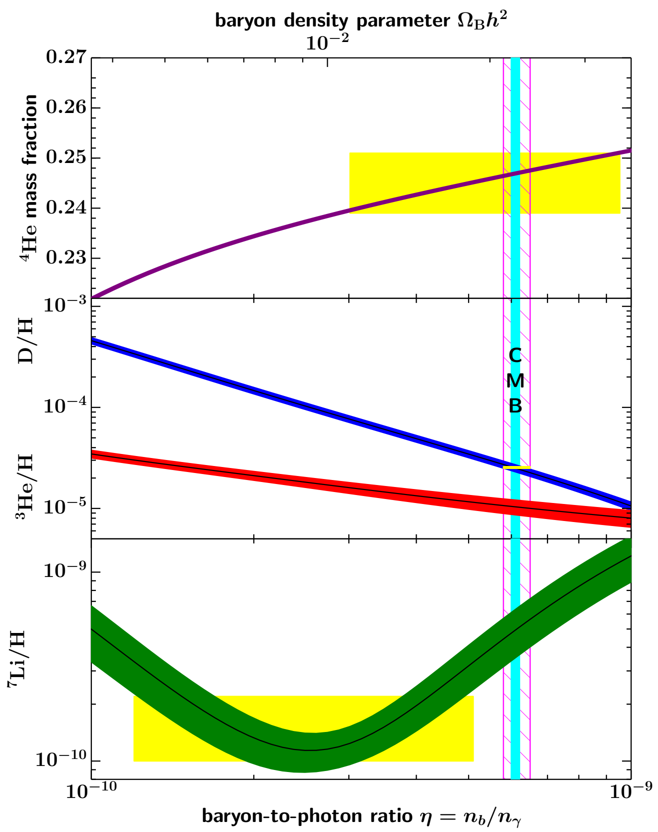
DM dominated

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

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

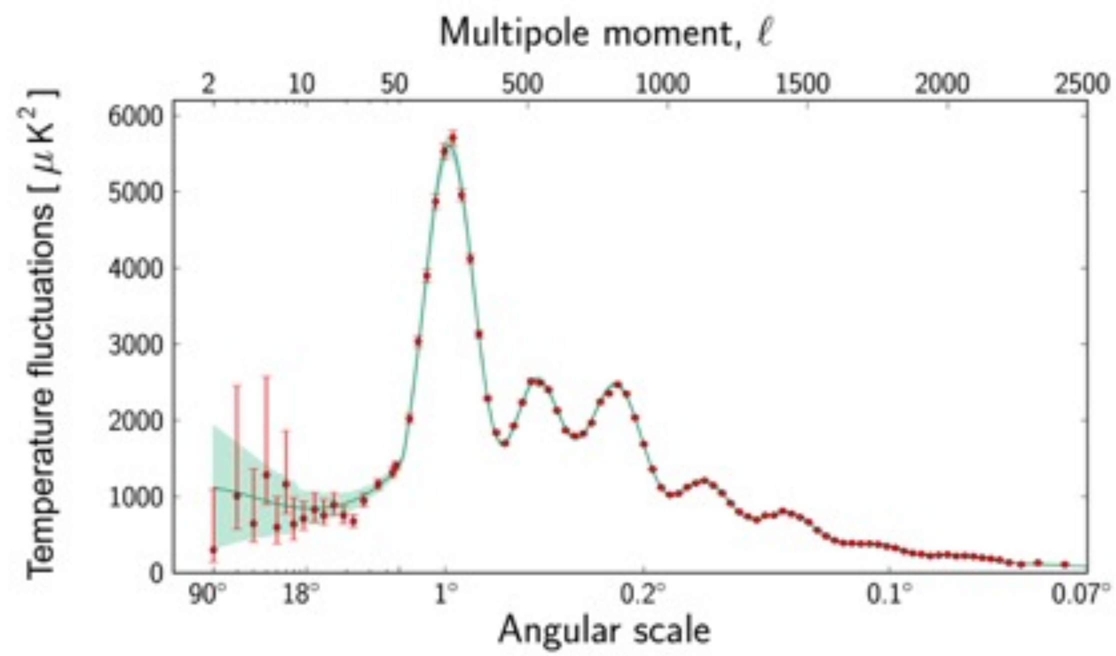
Cosmological evidence for DM

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; 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 - 5σ discrepancy between Planck CMB and SH0ES SNIa + much more; early Universe versus late Universe determination of the normalisation of the matter power spectrum - discrepancy between CMB and weak lensing at $\sim 3\sigma$ level in estimates of S_8;

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

- 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).

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 real 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:

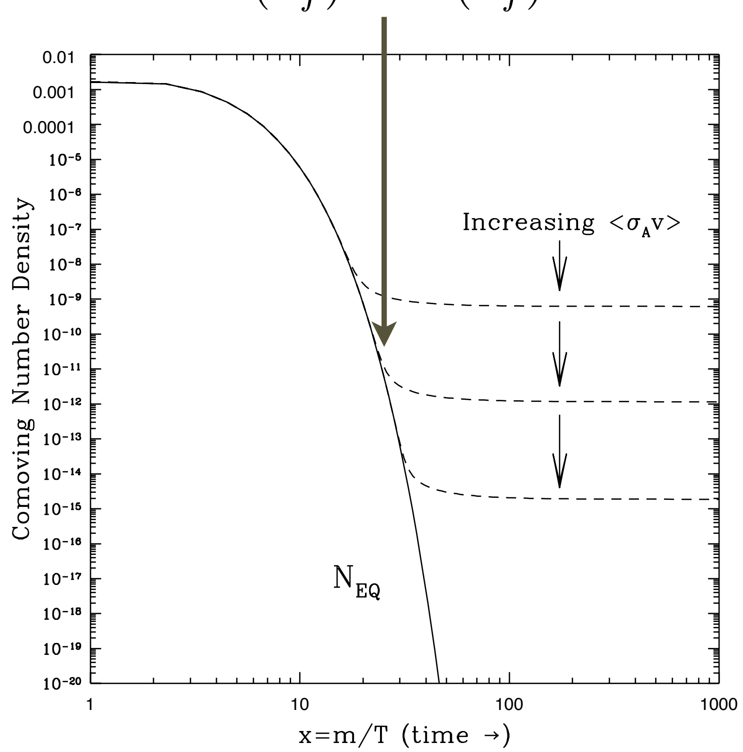
i) A (set of) BSM state(s) to be found at colliders;

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**.

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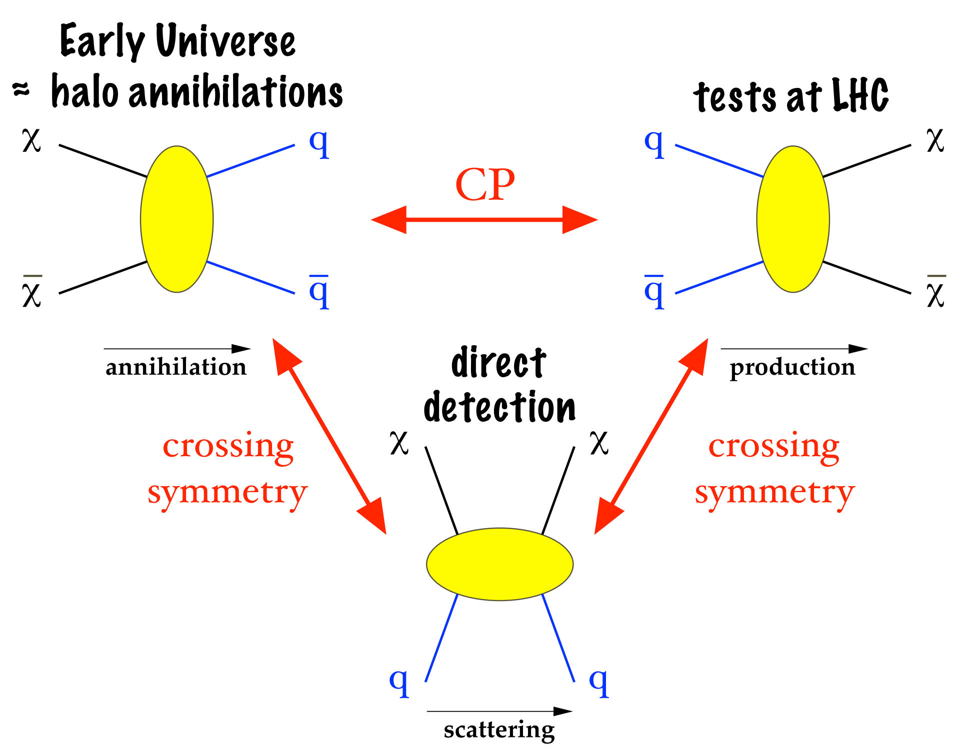
Thermal relics: the familiar and beloved scheme



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.

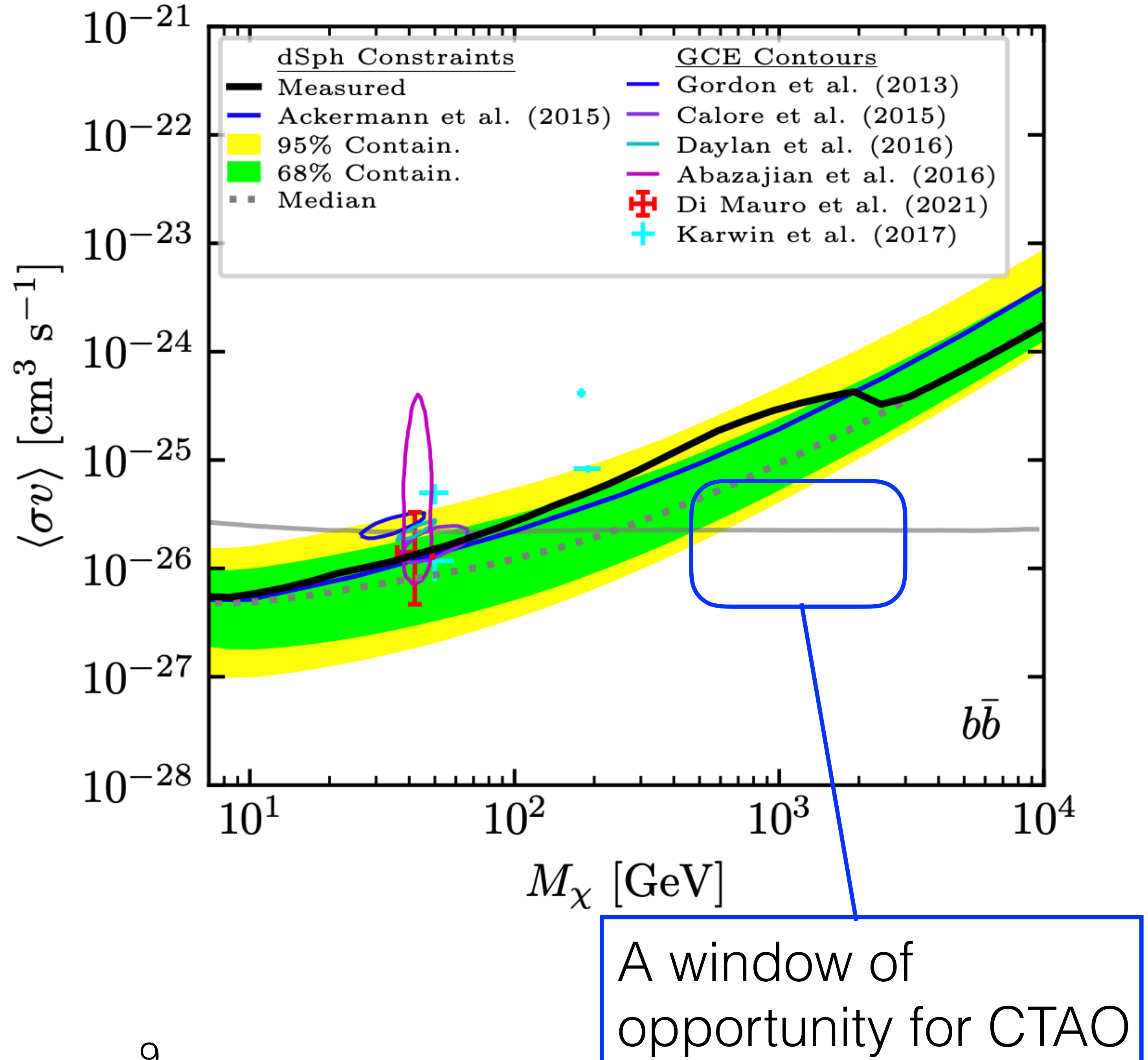
Indirect detection

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]

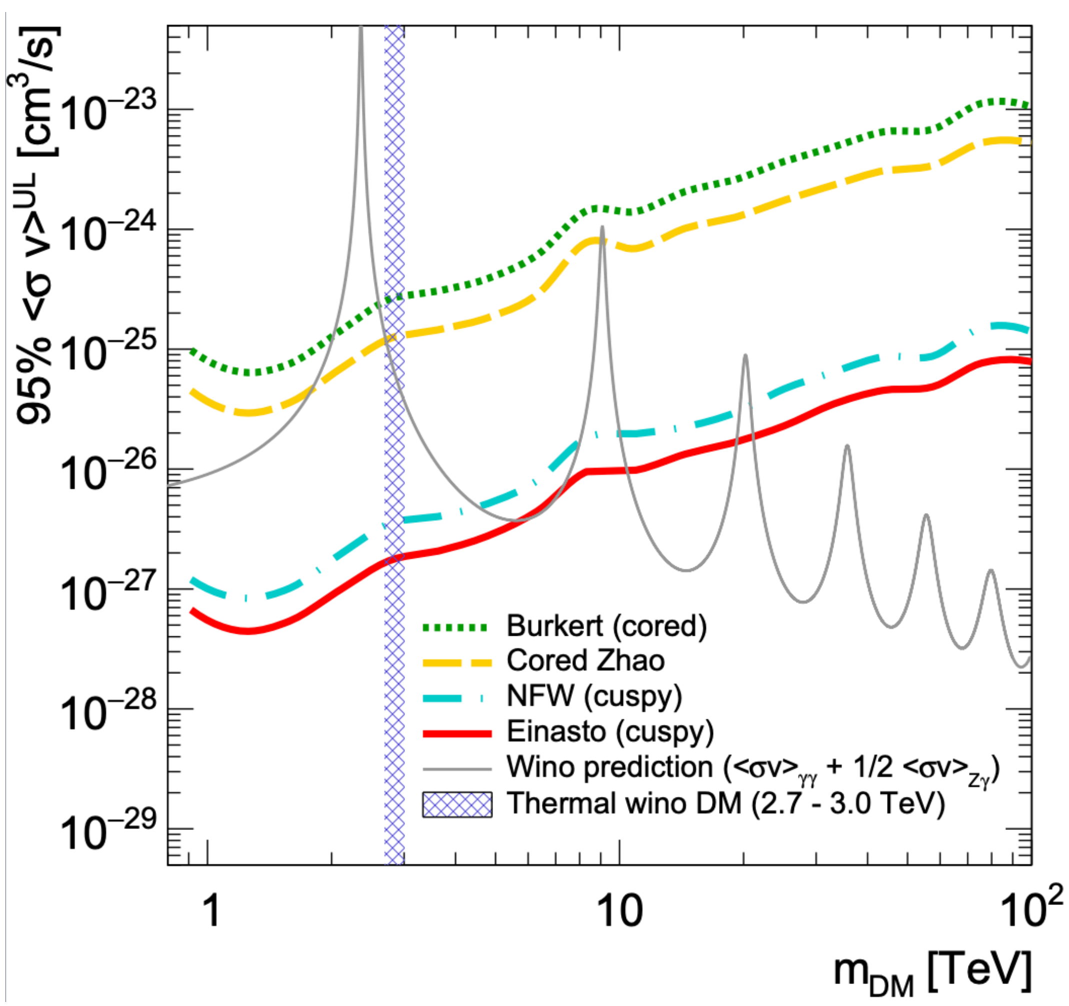


Indirect detection, look for signatures

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

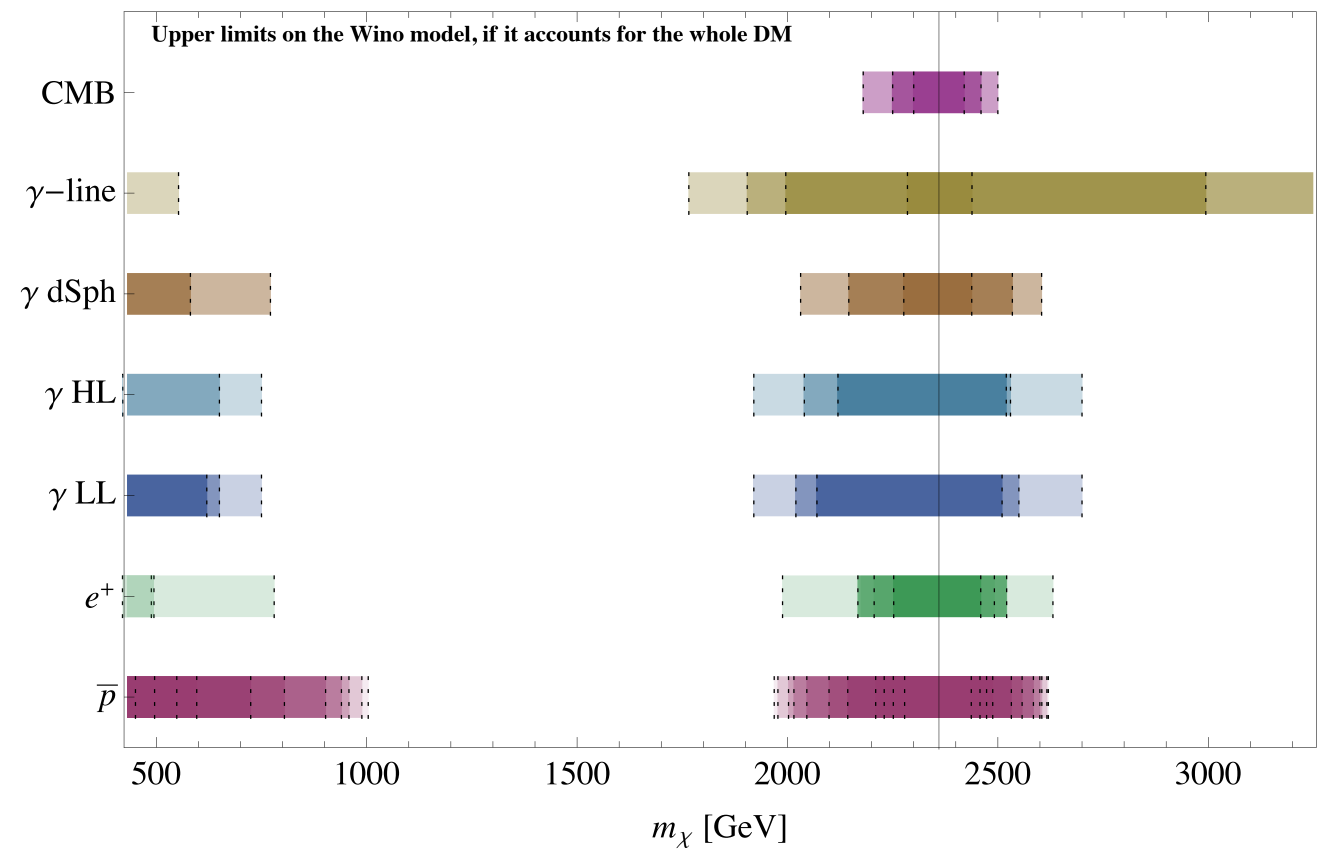
prominent in some specific models, such as pure Wino DM, and a target for CTAO in galactic center observations:

[Magic Collaboration, 2022]



still to be cross-checked against other detection channels:

[Hryczuk, PU et al., 2014]



Antideuterons as a further smoking gun signal? GAPS antarctic mission later this year

Direct detection

Measuring the recoil energy in elastic (or inelastic?) scattering of (local Milky Way halo population) dark matter particles off nuclei:

[Baudis & Profumo, PDG 2023]

Light mass "wall":

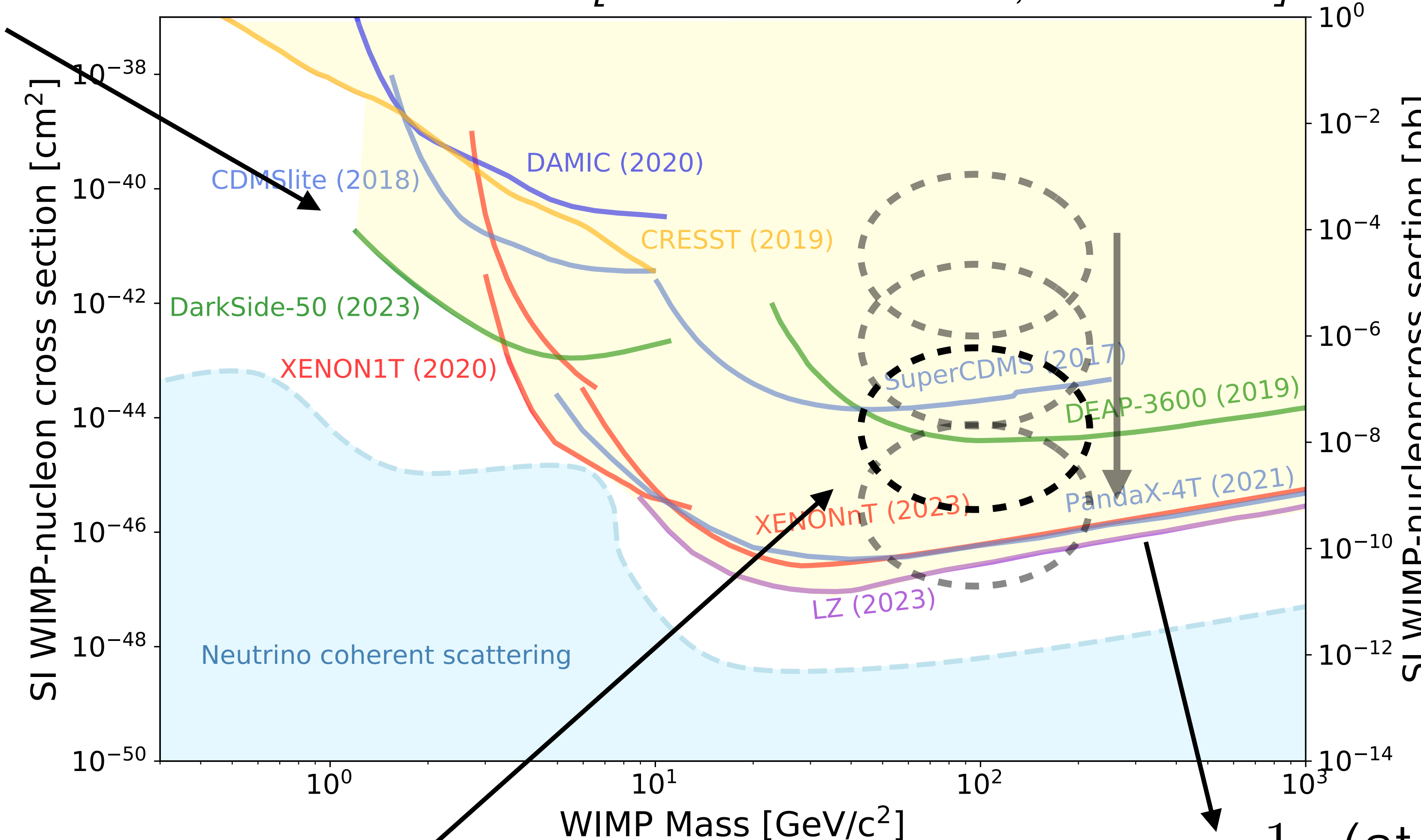
$$E_R = \frac{|\vec{q}\,|^2}{2M_N} > E_{\rm th}$$

$$\wedge$$

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

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

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



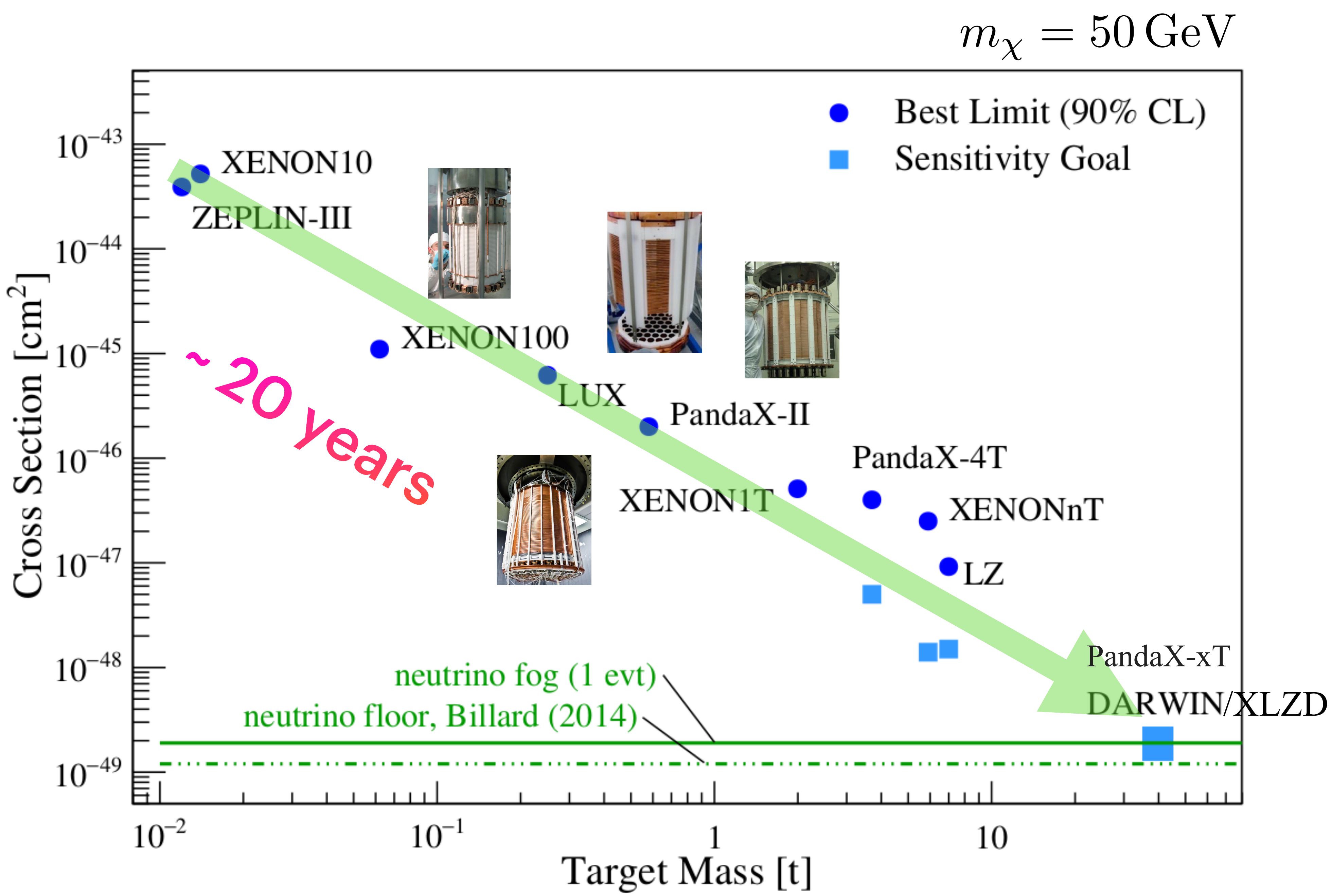
$\propto \frac{1}{m_\chi}$ (at fixed $\rho_\chi(R_\odot)$)

A huge experimental program, originally devised to address "vanilla" (?) WIMPs, with mass close to the weak scale:

Direct detection (2)

Since several years, searches with noble liquid (mainly Xe) detectors have taken the lead in the experimental effort (background rejection + scalability):

- steadily increasing the mass;
- steadily aiming at improving the background rejection;
- to and past the neutrino fog:

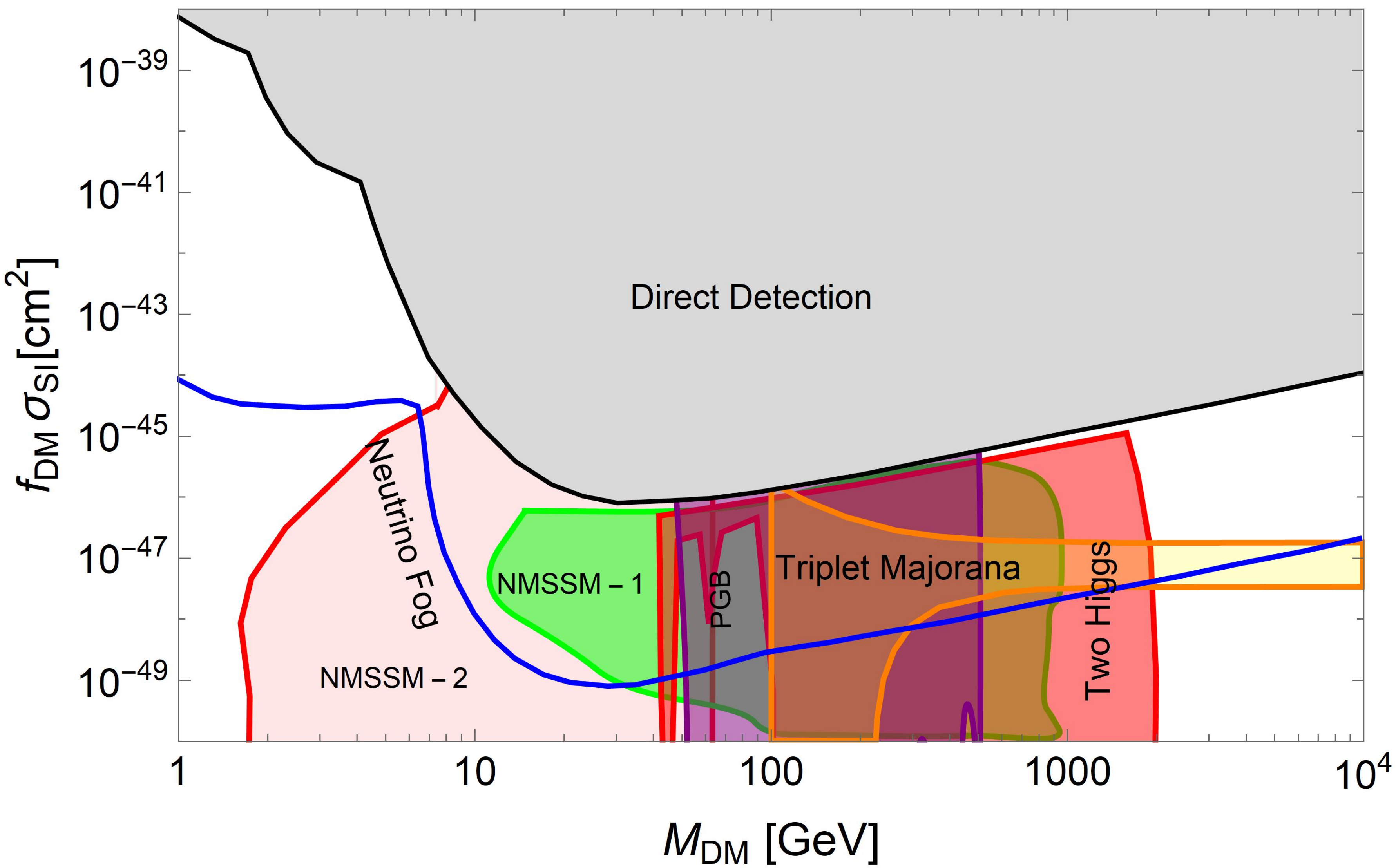


[Snowmass 2021, arXiv:2203.08084, adapted by Baudis 2024]

Direct detection (3)

Current limits versus a representative set of dark matter models within the standard WIMP paradigm, namely states in thermal equilibrium with the SM heat bath, (mostly) because carrying a SM gauge charge (e.g.: SUSY, extended Higgs sectors, …):

- covering the full expected mass range;
- possibly extending to very small cross sections (crossing symmetry not fulfilled);
- mostly not addressing the hierarchy problem:



[Snowmass 2021, arXiv:2203.08084, & refs. therein]

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_γ), with thermalisation and freeze-out: $\chi + \chi \leftrightarrow \psi + \bar{\psi}$ led by extra interactions (e.g.: extra $U(1)_D$ with γ_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 η_χ (analogous or connected to η_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]*

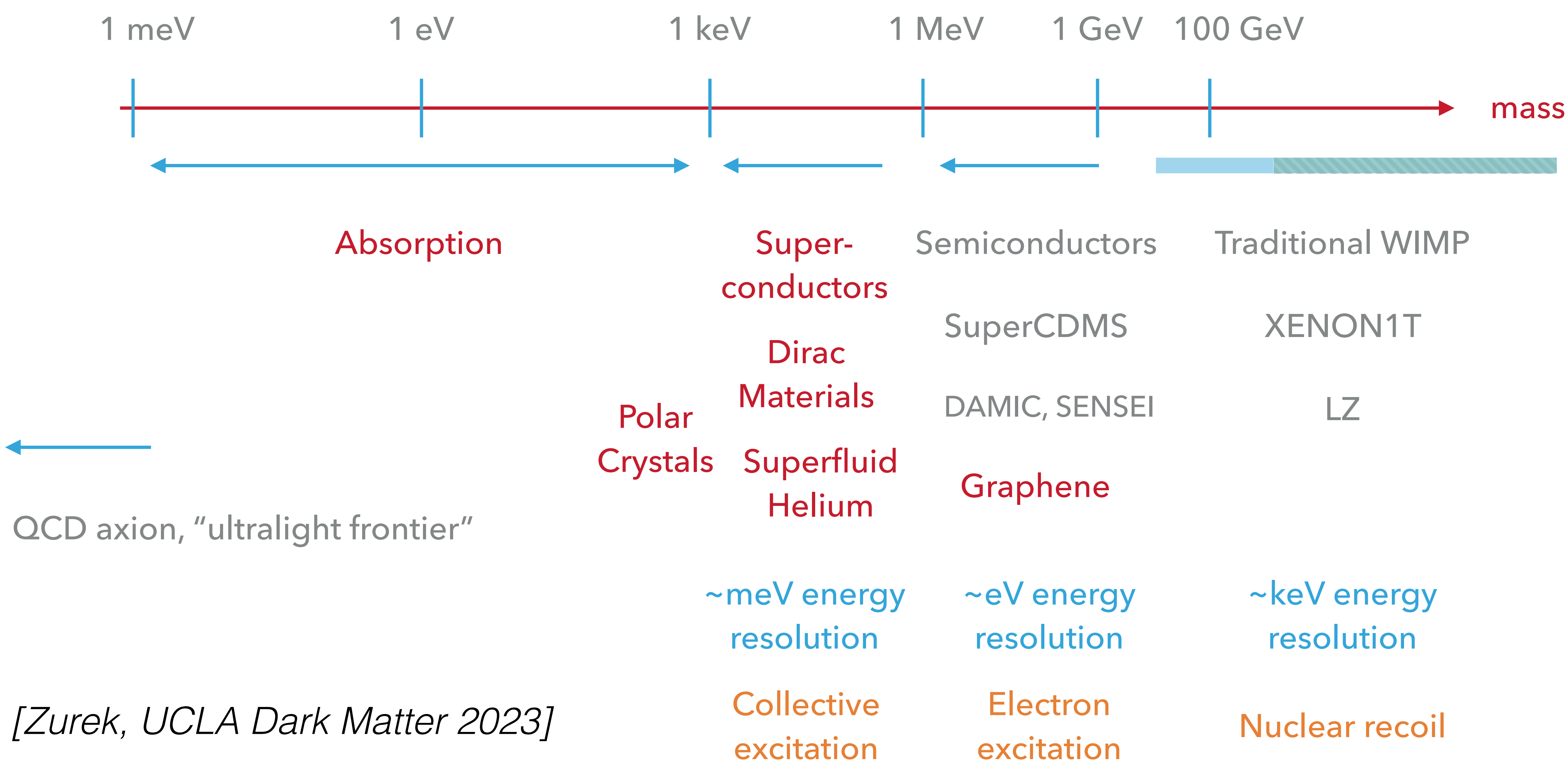
sub keV ← mass m_χ → 10s TeV

gravity ← $\chi - \mathrm{SM}$ inter. → strong

Direct detection away from “vanilla” WIMPs

Below the GeV mass scale alternative techniques and strategies (e.g. electron recoils or small band gaps for electrons excitations):

- Experimental Panorama



[Zurek, UCLA Dark Matter 2023]

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.

Reintroducing a (another) particle physics motivated framework?

The axion solution to the strong CP problem

In the Lagrangian of QCD is not forbidden to have:

$$\mathcal{L}_{\rm QCD} \supset \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$$ (gluon field strength contracted to its dual)

which violates T, P & CP and give rise to dangerous operators such as an electric dipole moment for the neutron:

$$d_n \sim \frac{\theta}{(4\pi)^2} e \frac{m_\pi}{m_N^2} \sim 10^{-16}\theta\, e \cdot {\rm cm}$$

Experimentally $|d_n| \lesssim 10^{-26} e \text{ cm} \implies \theta \lesssim 10^{-10}$ The strong CP problem: why is this parameter so small?

The axion solution: promote it to a dynamical field and "relax" it to 0:

$$\mathcal{L} \supset \left(\theta + \frac{a(x)}{f_a}\right) \frac{g_s^2}{32\pi^2} G\tilde{G}$$

initially with flat potential but at $T \sim \Lambda_{QCD}$ acquiring via instantons:

$$V(a) \simeq \Lambda_{QCD}^4 \left(1 - \cos\frac{a}{f_a}\right) \simeq \frac{1}{2}\Lambda_{QCD}^4 \frac{a^2}{f_a^2} + \ldots \simeq \frac{1}{2} m_a^2 a^2 + \ldots$$

The QCD axion as a dark matter candidate

Misalignment production: very light scalars trapped in modes with coherent oscillations, which behave cosmologically as CDM:

Follow the eq. of motion: $\ddot{a} + 3H\dot{a} + \frac{dV}{da} \simeq \ddot{a} + 3H\dot{a} + m_a^2\, a = 0$

when $3H < m_a$, coherent oscillations with frequency m_a start, i.e.

$\rho_a = \frac{1}{2}\left(\dot{a}^2 + m_a^2 a^2\right)$ evolves as: $\dot{\rho}_a \simeq \left(\frac{\dot{m}_a}{m_a} - 3H\right)\rho_a \;\Rightarrow\; \rho_a \propto \frac{m_a}{(1+z)^{-3}}$

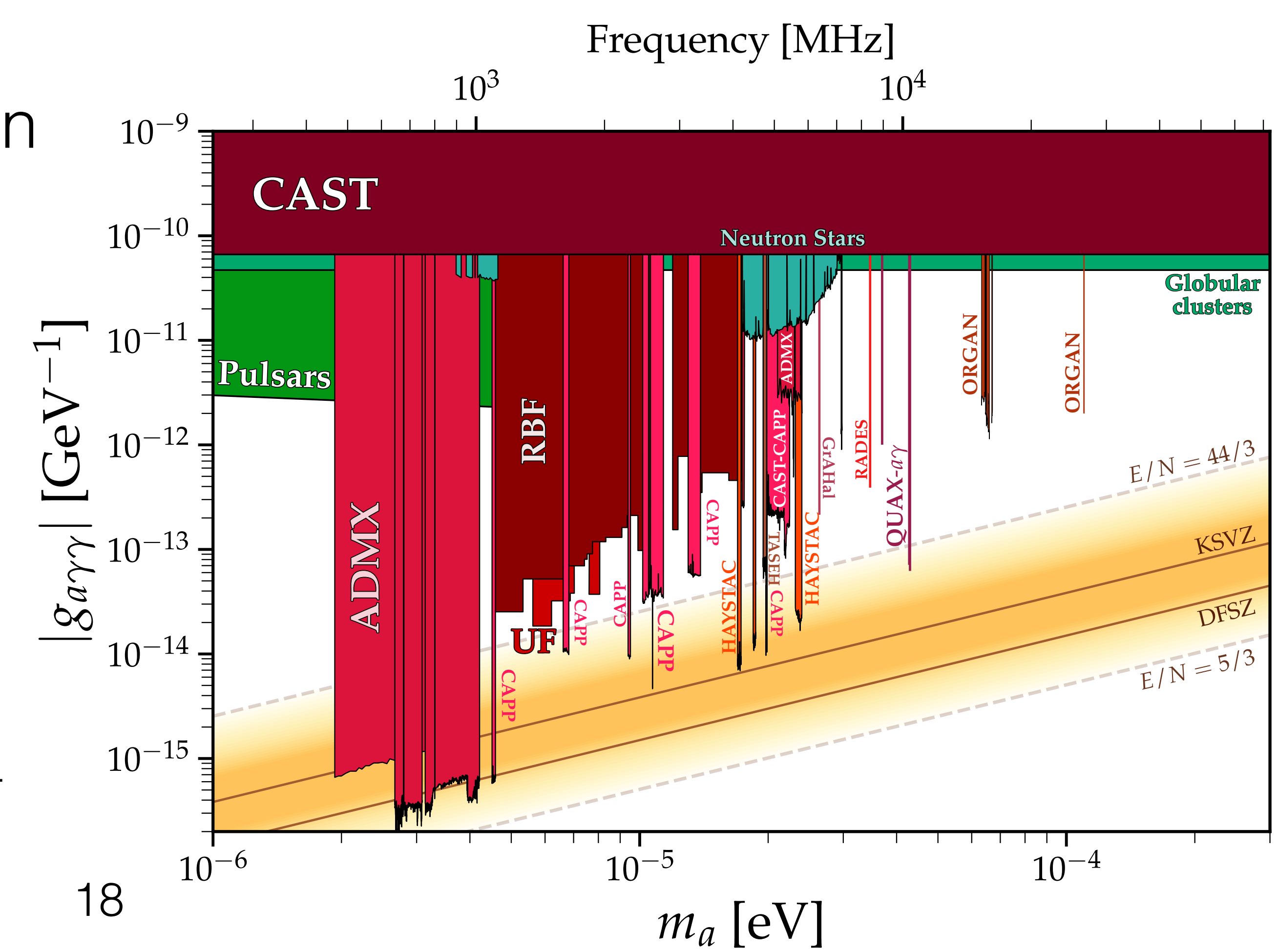
i.e. as matter. $\Omega_a \sim \Omega_{\rm CDM} \;\Rightarrow\; m_a \sim 10^{-6} - 10^{-4}\,{\rm eV}$ (also term from string decay)

The phenomenology mostly based on the axion coupling with photons:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma}}{4} F_{\mu\nu}\tilde{F}_{\mu\nu}\, a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$$

within a specific model:

$$g_{a\gamma} = \frac{\alpha}{2\pi\, f_a}\left(\frac{E}{N} - 1.92(4)\right) = \left(0.203(3)\frac{E}{N} - 0.39(1)\right)\frac{m_a}{\rm GeV^2}$$



[PDG, 2023]

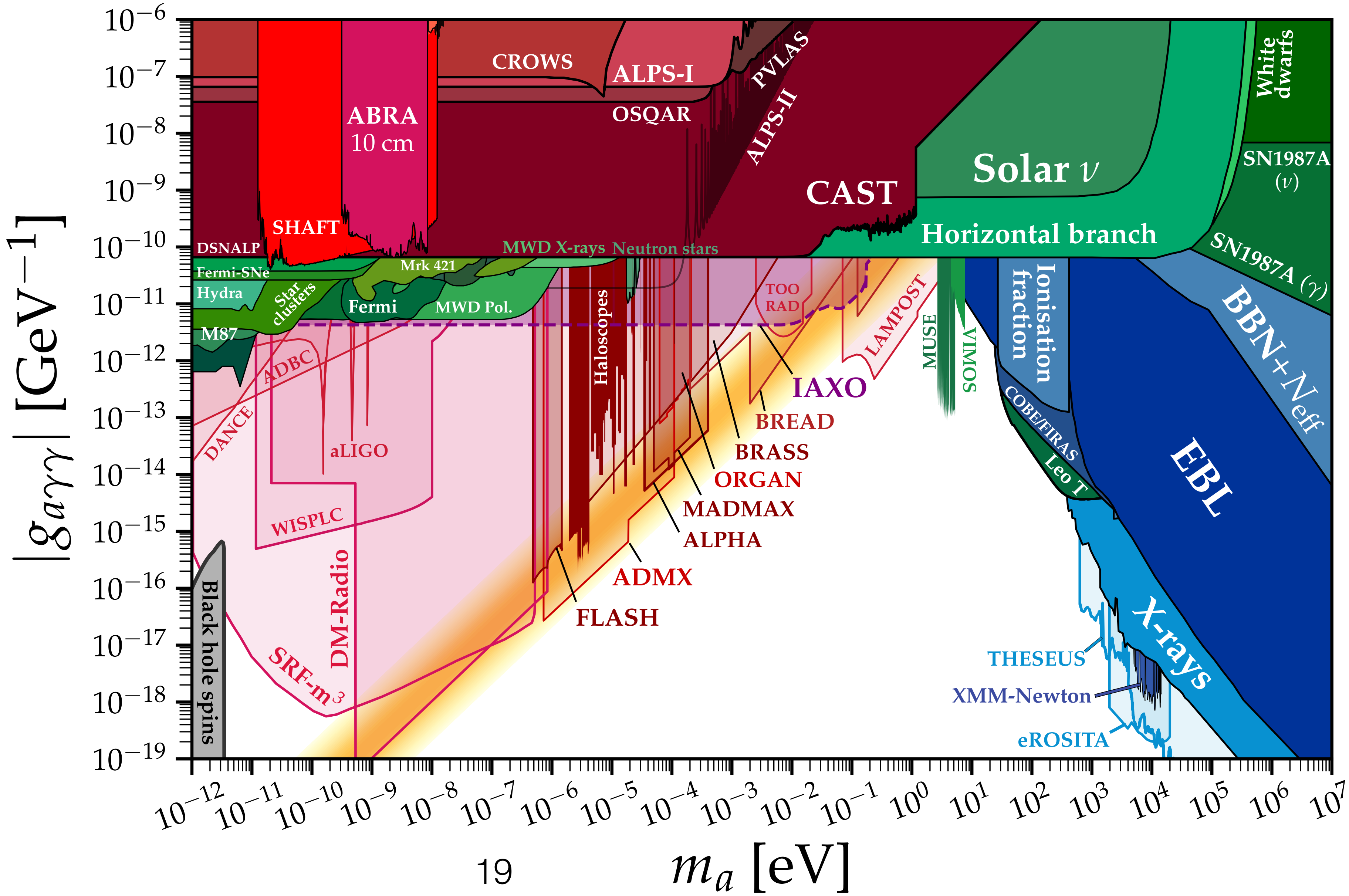
Generalising to axion-like particles (ALPs)

Misalignment production as a generic scheme for light scalar CDM. Remove the link to the strong-CP problem and find much lighter or more strongly coupled cases. Models arising, e.g., in stringy frameworks; possible links with inflation, dark energy, …

A more generic parameter space and a variety of detection techniques: from haloscopes to helioscopes, to cooling of stellar systems, to modifying the γ-ray horizon, …

A set of new ideas and a set of new search techniques being explored and looking promising:

A few windows of opportunity



[Snowmass 2021, arXiv:2203.14923]

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:

Dark matter boosted by galactic cosmic rays

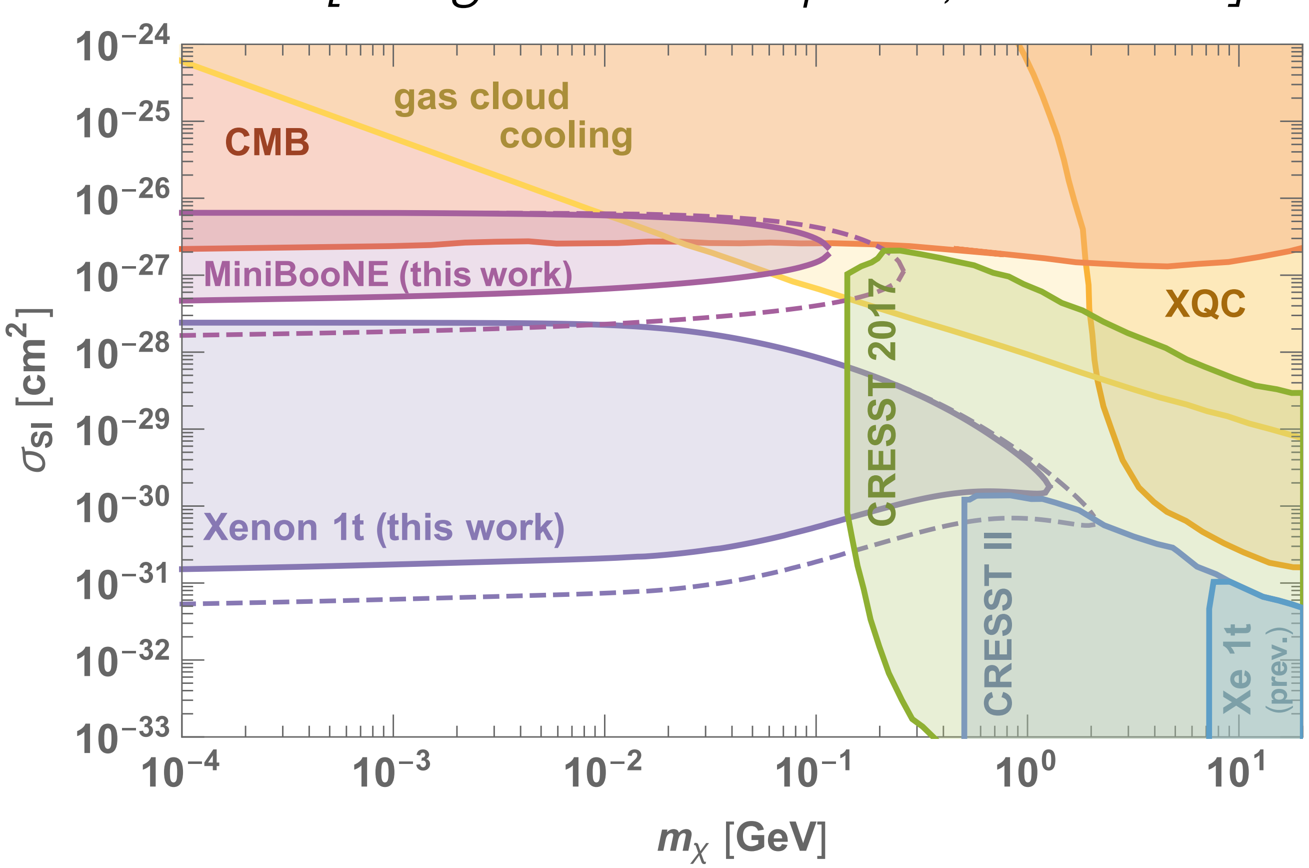
Reconsider the "light mass wall" in nuclear recoil direct detection experiments, namely the maximum recoil energy does **not** fulfil:

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

for non-relativistic galactic DM halo particles ($v \sim 10^{-3}c$), if the DM particle mass m_χ is lighter than $\sim 1\,\mathrm{GeV}$.

However 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:

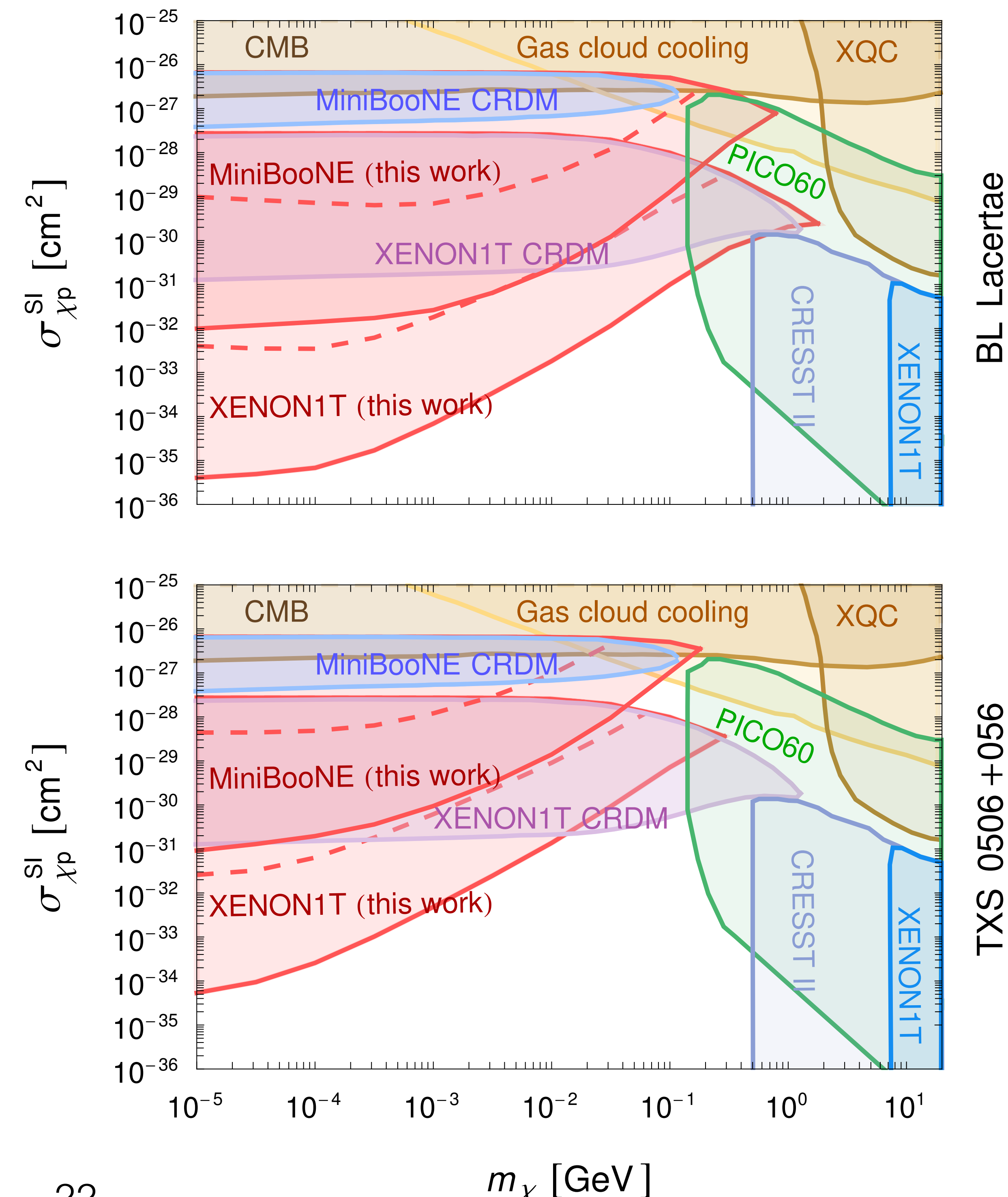
Extremely powerful flux of protons (electrons) through an extremely dense dark matter environment (dark matter spike accreted around the blazer black hole engine), potentially generating a sizable DM flux towards us.

Tightest limits/best discovery potential for light dark matter

See also:

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

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

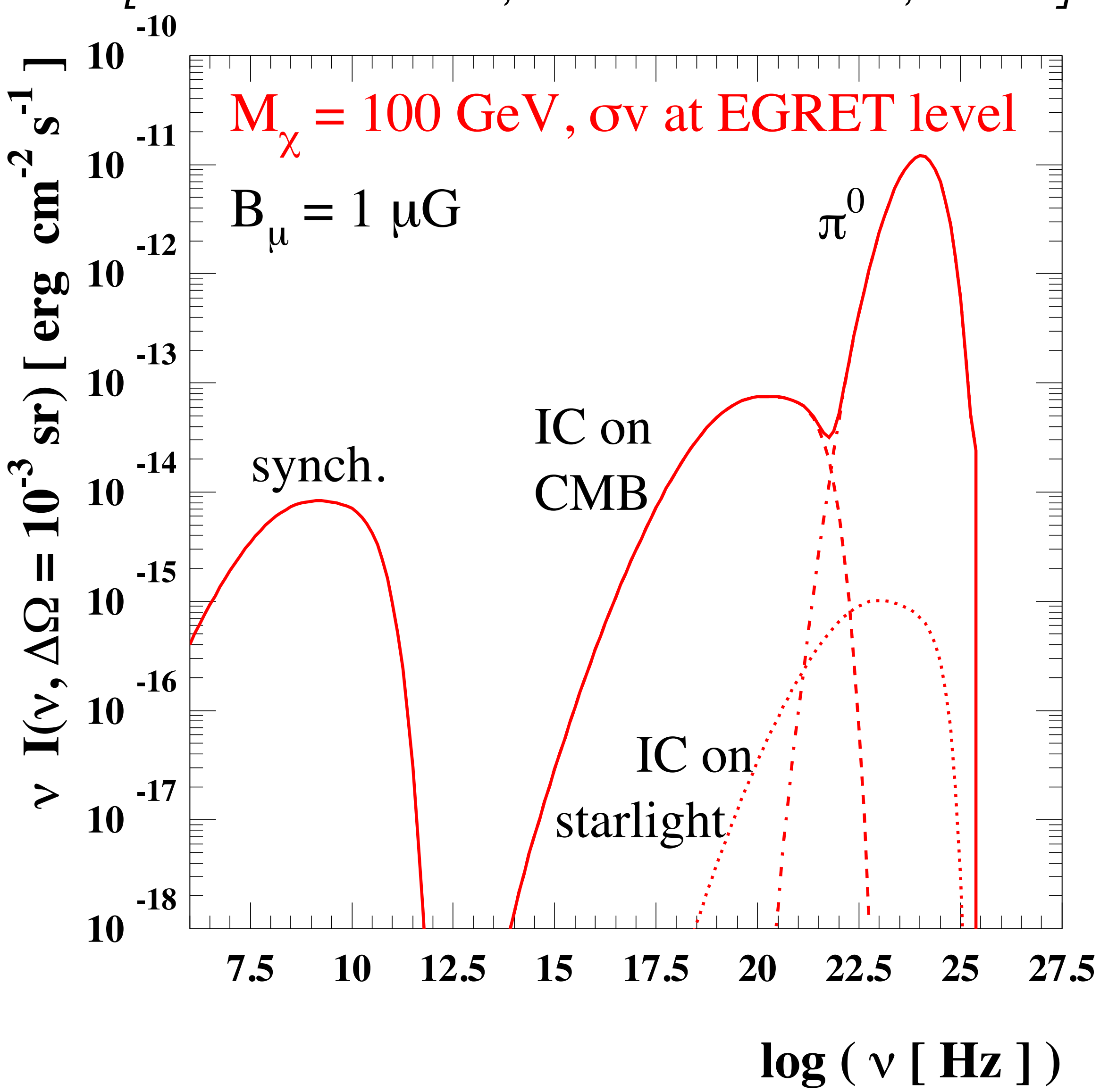


Multi-wavelength signals from dwarf galaxies?

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)

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 eqs.:

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

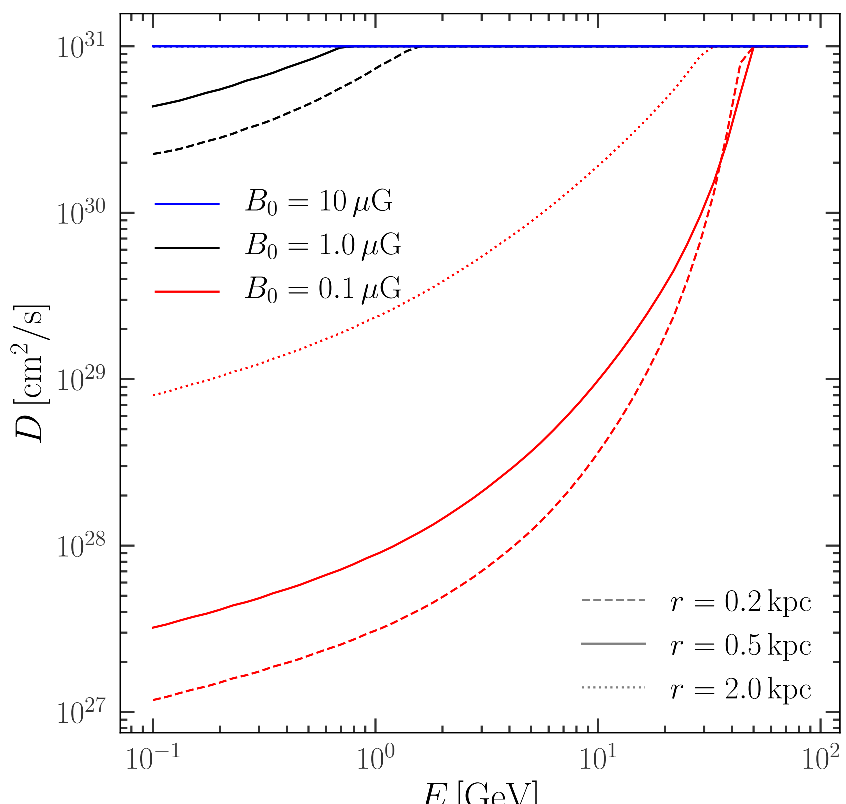
with: $$q_{\rm CR}(r,E) = \langle \sigma v \rangle_f \frac{\rho^2_{\rm DM}(r)}{2\, m^2_{\rm DM}} \frac{dN^f_e}{dE}$$

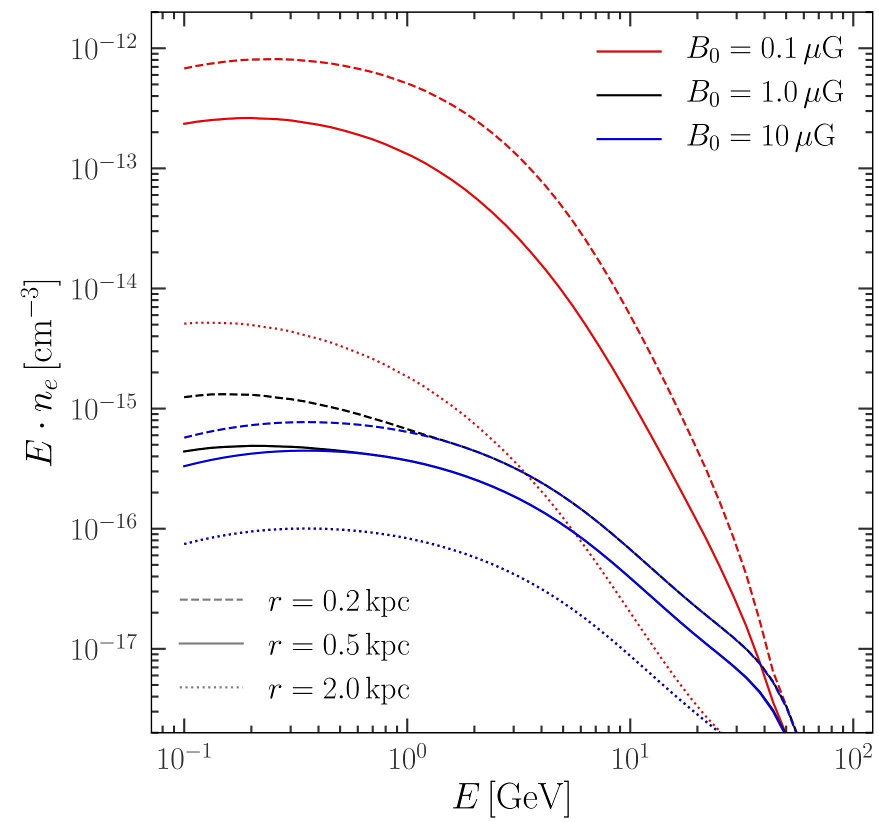
ii) $$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}(W)\frac{\partial W}{\partial k}\right] - \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 v_A W) + \Gamma_{\rm CR}(n_e,k) W$$

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

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]

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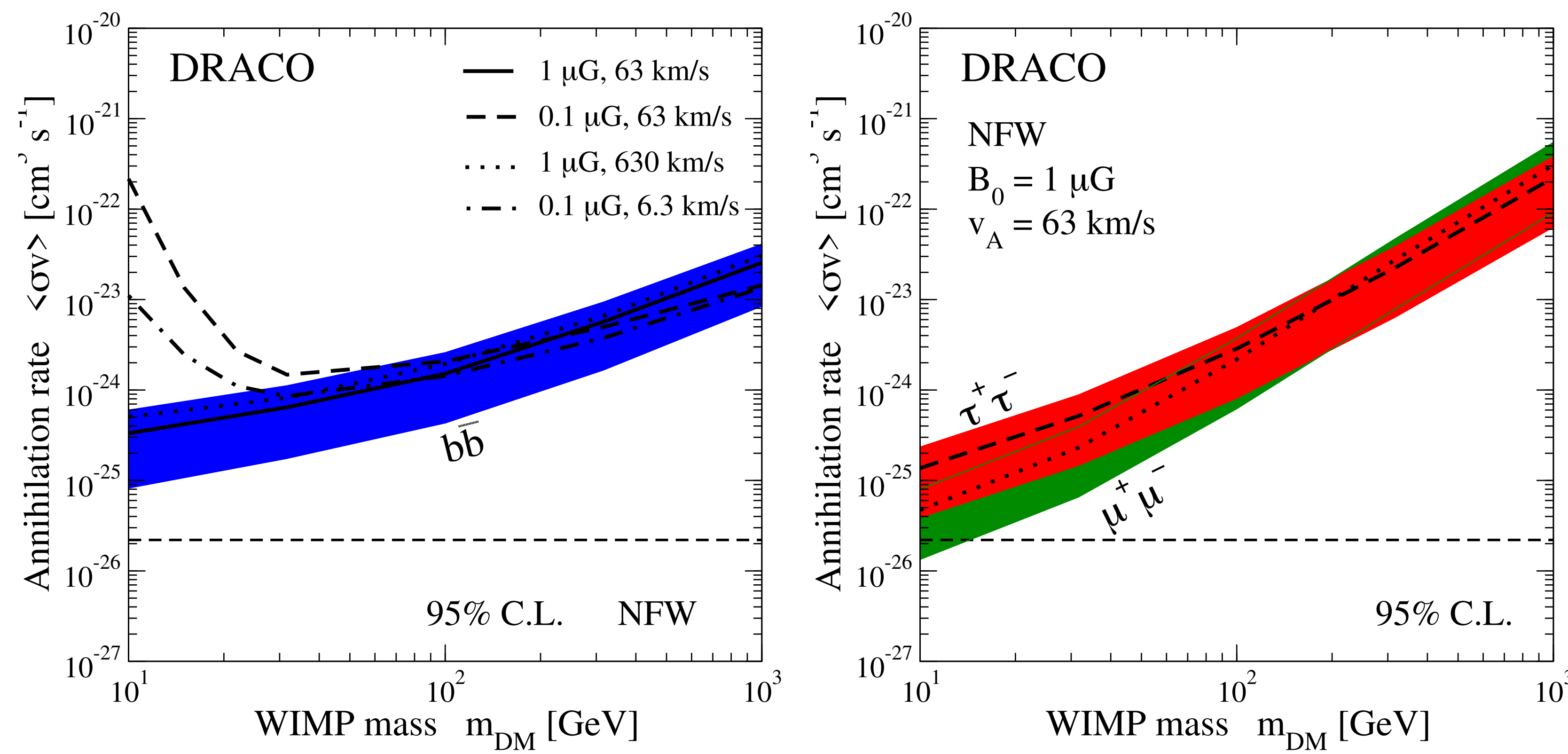
Leading to conservative but competitive limits from uGMRT data at 550-750 MHz:



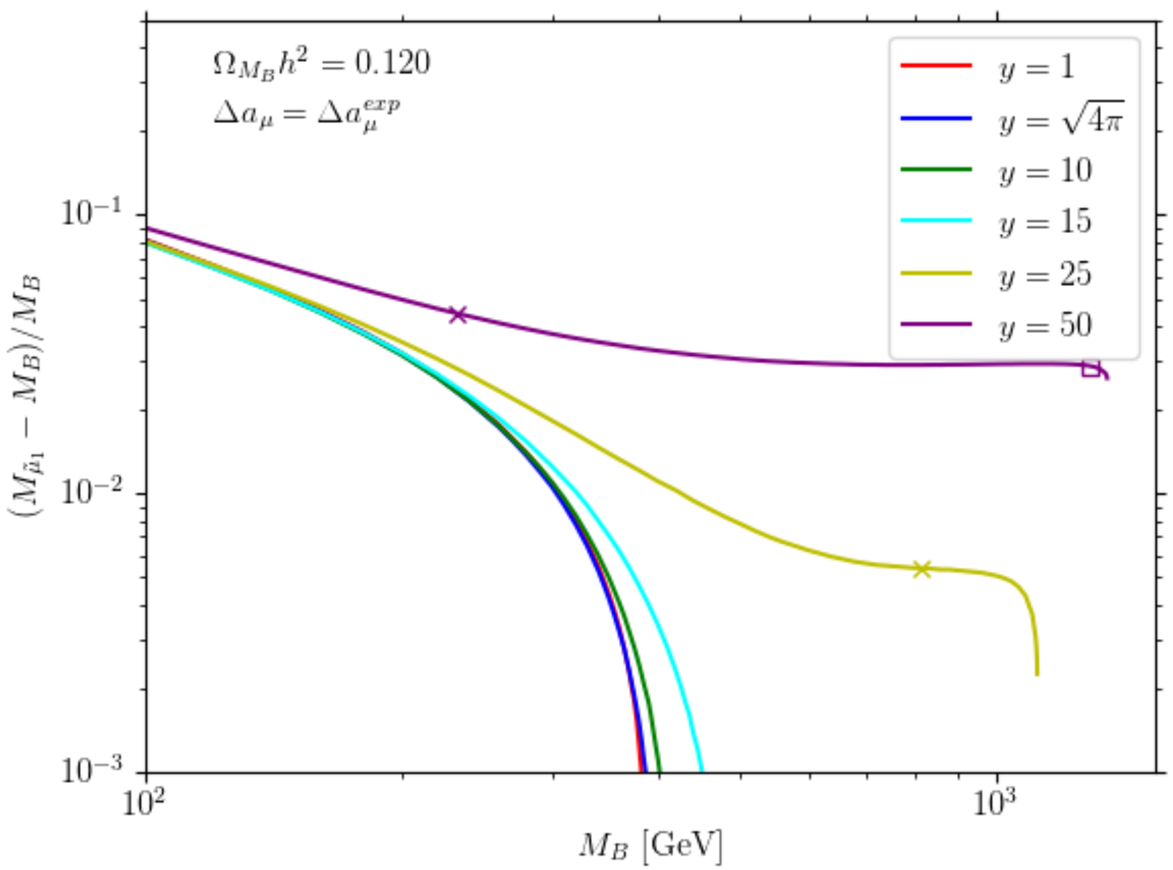
[Regis, P.U. et al, 2023]

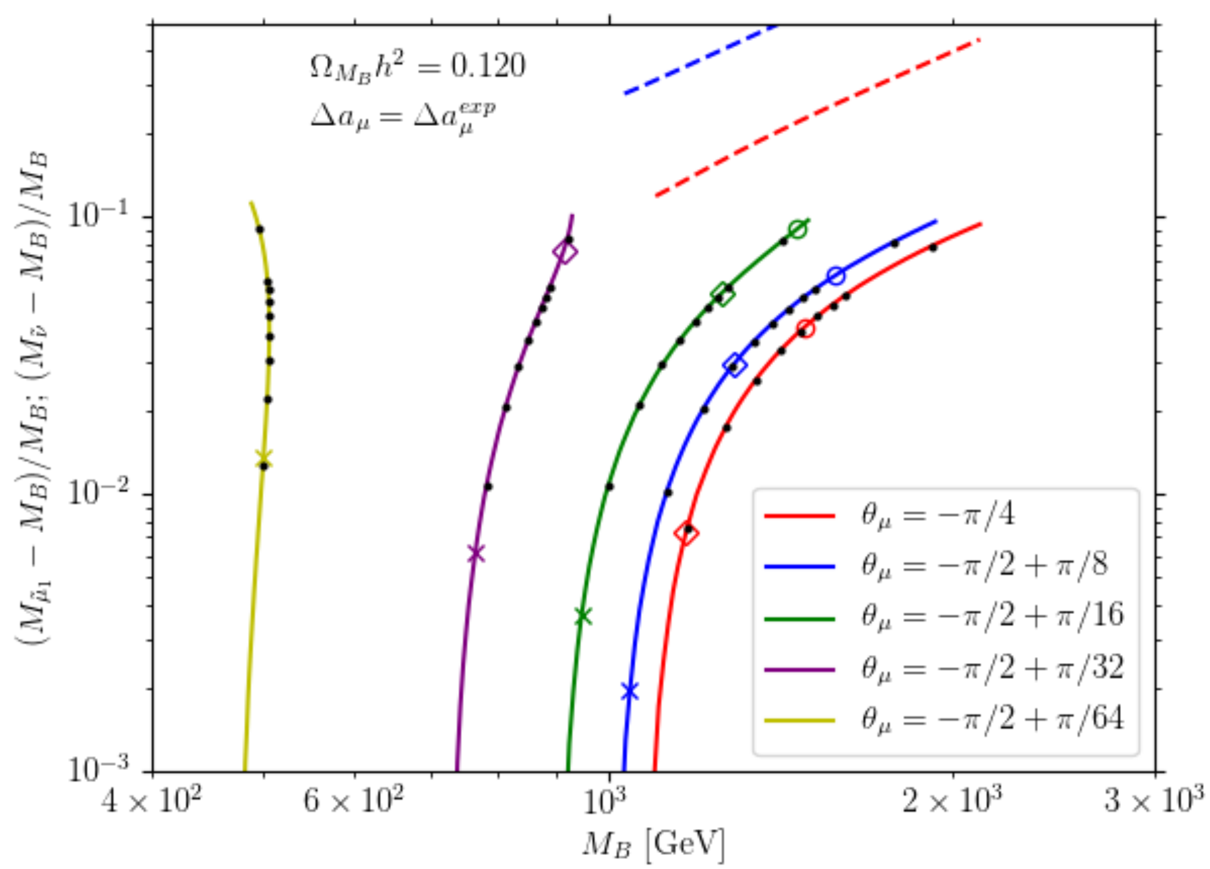
A minimal DM scheme and $(g\text{-}2)_\mu$

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]





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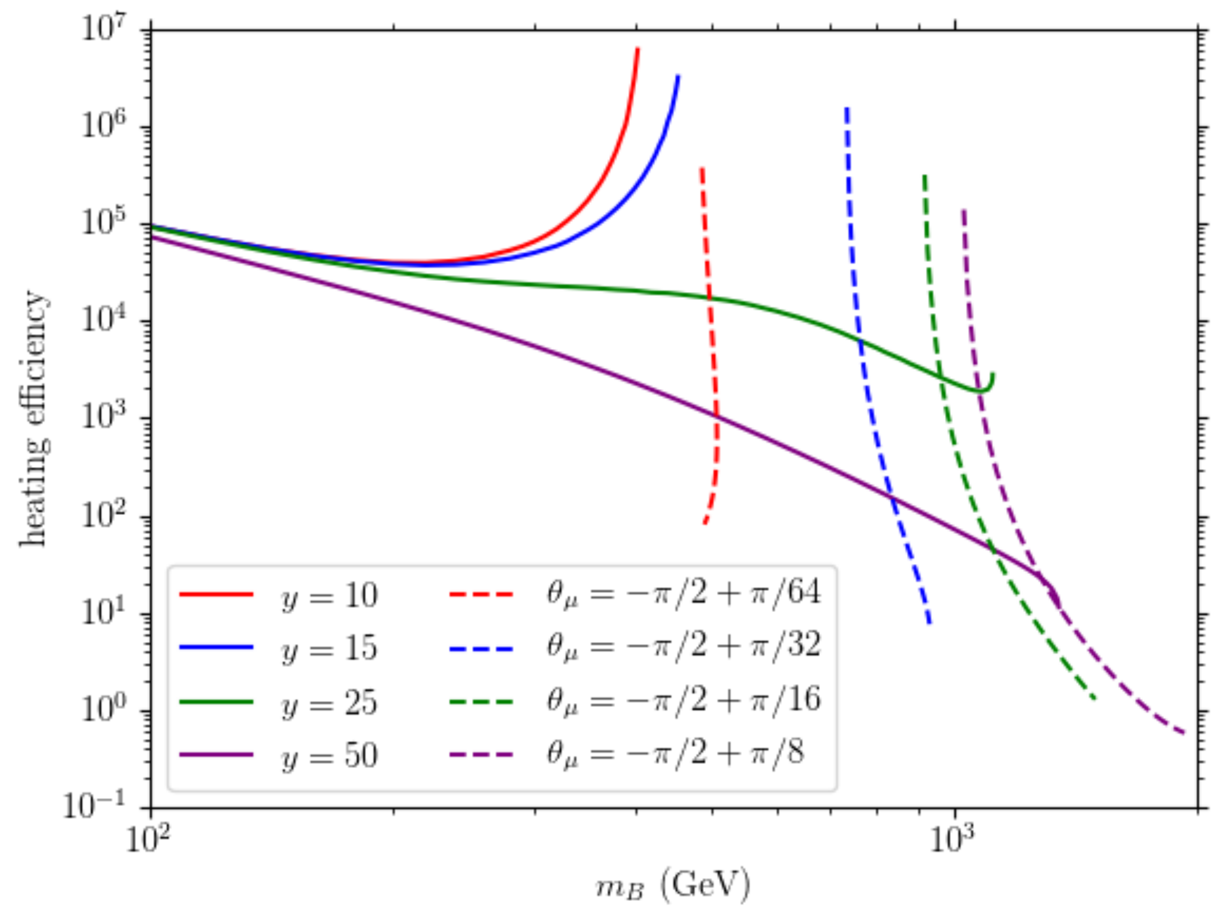
No “traditional” WIMP detection method working in this case; kinetic heating of neutron stars would be instead extremely efficient and future infrared surveys of old neutron star populations should probe the entire parameter space!

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



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?