An update on dark matter searches

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Outline of the talk:

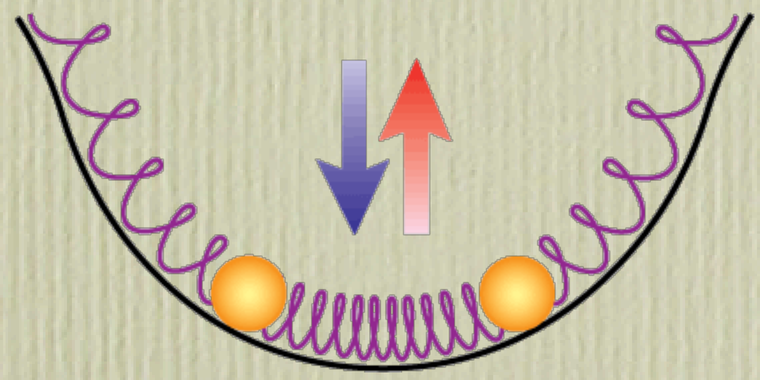
- The dark matter puzzle as one of the deepest and longest-standing problems in Science.
- The evidence for dark matter is very solid, but any particle physics approach has been inconclusive so far: should we challenge the standard lore and search for new guidelines?
- The LHC and it impact on the WIMP paradigm.
- Hints of particle dark matter detection? A sample tentative signal and the broader picture.

Disclaimer: no attempt to be a compact, ultra-fast, all-inclusive review but rather take it as an introduction complementing to some of the topics which will be presented in coming talks.

Dark matter (indirectly) detected!

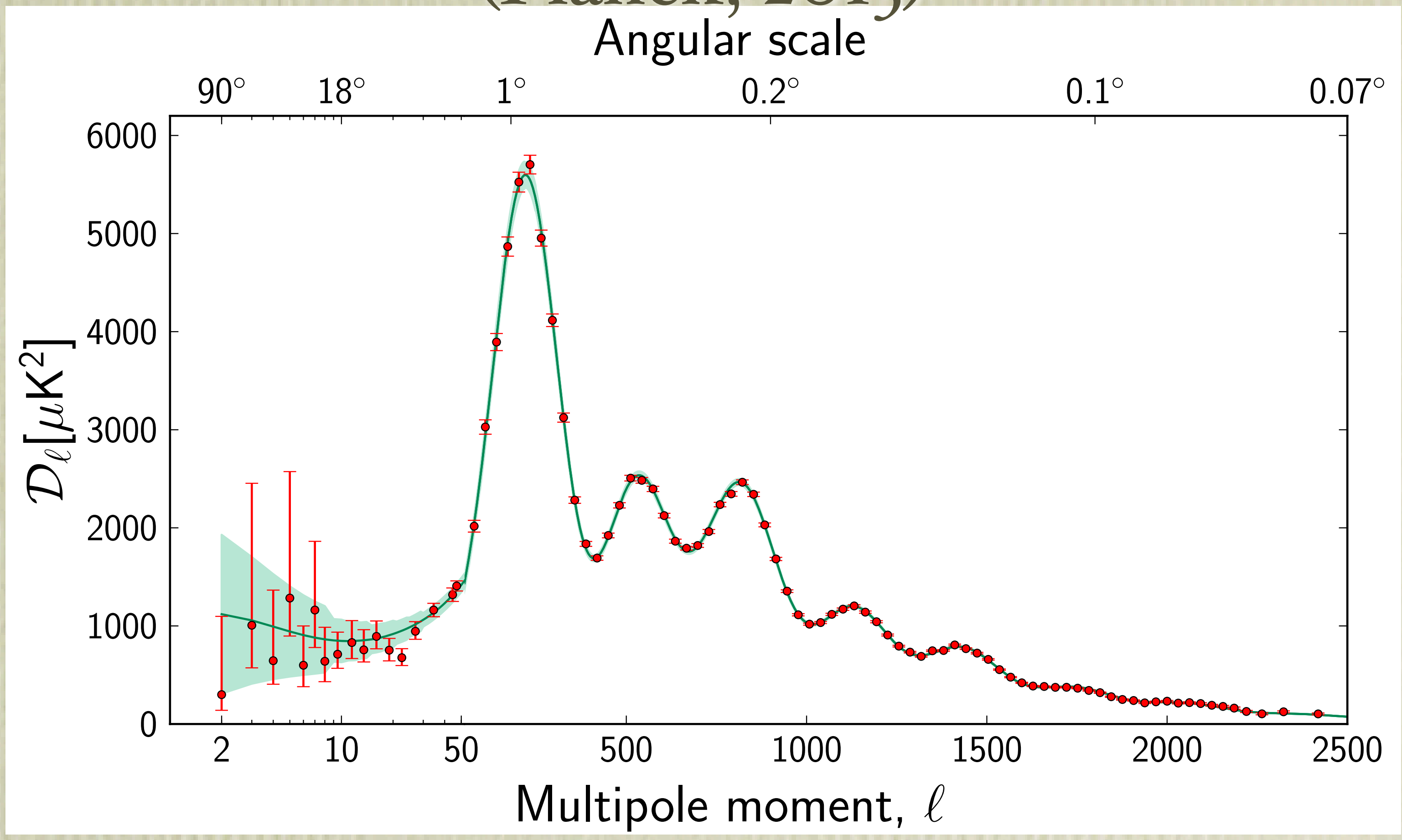
Plenty of (gravitational) evidence for non-baryonic cold (or coldish - as opposed to hot) DM being the building block of all structures in the Universe. E.g.:

it accounts for the gravitational potential wells in which CMB acoustic oscillations take place:



Credit: W. Hu website

(Planck, 2013)



Relying on the assumption that GR is the theory of gravity; still, it is very problematic to explain, e.g., the prominence of the third peak in an alternative theory of gravity and matter consisting of baryons only

Dark matter (indirectly) detected!

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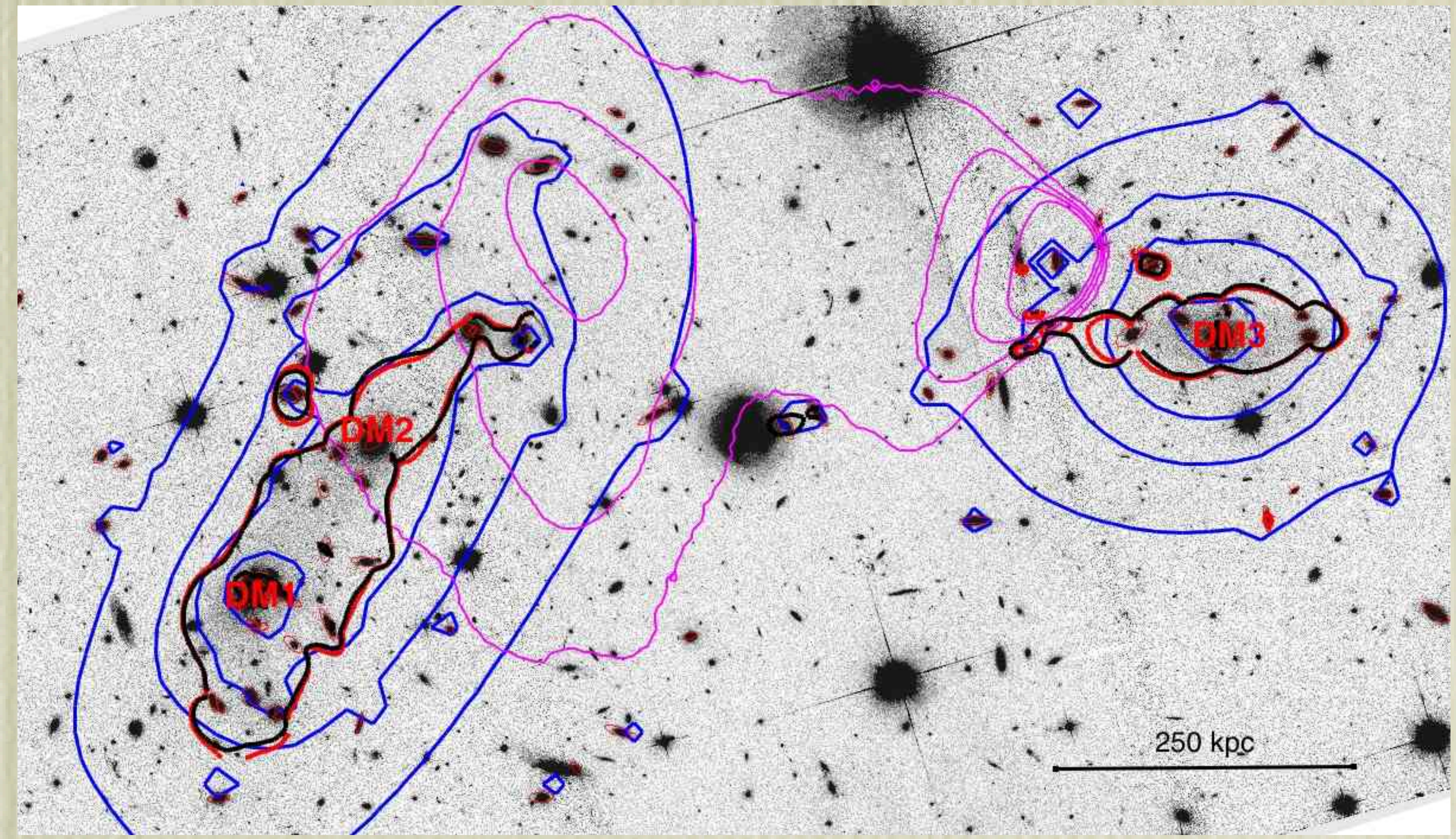
Bullet cluster:

offset between DM, mapped via gravitational lensing, and hot gas - the bulk of the baryonic in the system, traced via its X-ray emissivity, in the 1E0657-558 cluster

magenta contours: Chandra X-ray image; blue contours: strong lensing map

Paraficz et al., arXiv: 1209.0384



Relying again on GR as a theory of gravity; again it is very problematic to introduce an alternative theory and explain the component segregation within a model without DM but having baryons only

Connection to a particle dark matter framework?

The standard model for cosmology, the ΛCDM model, does not aim to address questions regarding the nature of the DM component:

the DM term is treated as 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 with accuracy its mean density:

$$\Omega_{\rm DM} = 0.1199 \pm 0.0027 \qquad \text{(Planck, 2013 + WMAP 7 yr pol.)}$$

and the spectrum of its perturbations (nearly scale invariant, as expected from inflation).

Reformulating the DM problem in terms of elementary particles in the dilute limit (two-body interactions dominating over multi-body interactions) is an assumption, and not the only possible extrapolation, e.g.: the recent attention on primordial black holes as DM; the recent interest on the possibility that DM is the form of (or, in certain regimes behaves like) a condensate. Will it be possible to single out this possibilities?

Observations and particle properties of DM

Assuming a particle formulation, astro/cosmo observables provide mainly informations on the properties that DM does not have, e.g.: it needs to be non-baryonic, non-relativistic at the phase of matter-radiation equality, … This is enough to say that DM is NOT within the SM of particle physics.

At the same time, loose bounds on the properties which are crucial for devising a detection strategy for DM particles - the mass and coupling to ordinary matter.

The mass scale is essentially unconstraint, admitting ultralight bosons (10^{-22} eV with macroscopic de Broglie wavelength), fermions at the level of about $50\,\mathrm{eV}$ (Gunn-Tremaine bound from phase space density limits), and no relevant upper limits (up to the MACHO range tested via lensing searches and even beyond)

The interaction scale has very tight limits with photons (DM millicharge, electric and magnetic dipole moments severely suppressed), significant with baryons, relatively weak for self-interactions (from galaxy clusters morphologies and mergers, such as from the Bullet cluster - early claims of evidence for self interaction from the Musket Ball cluster not confirmed)

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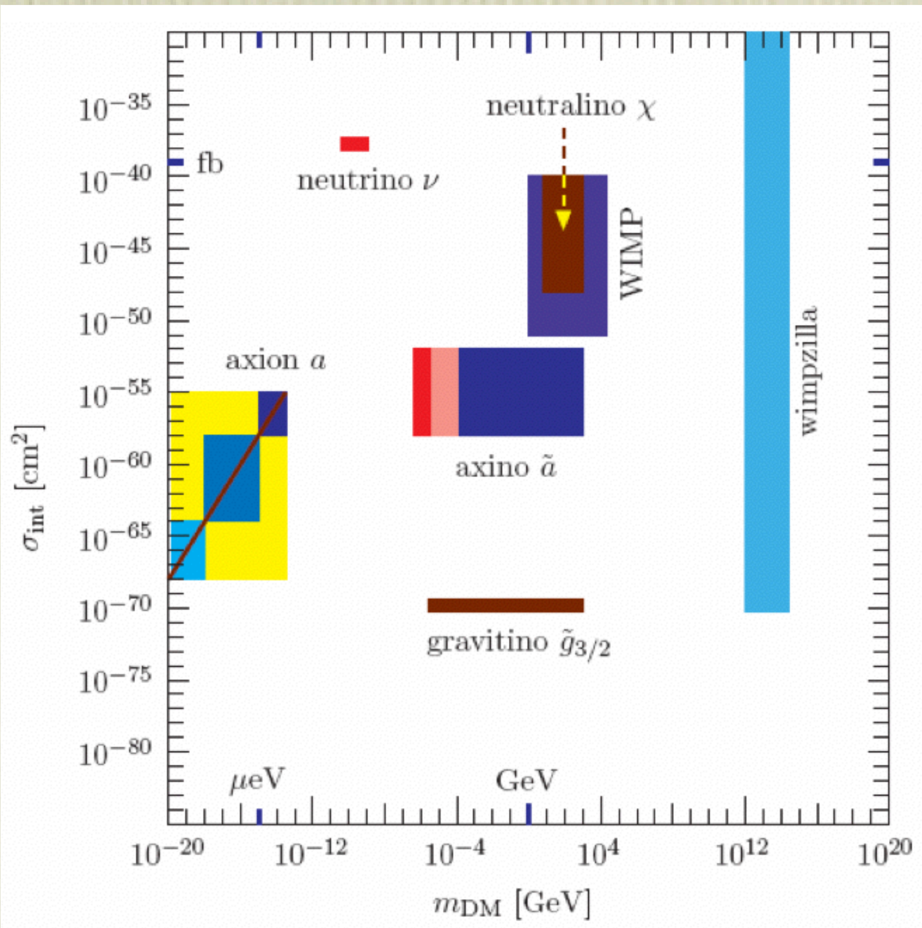
Particle models cover a large part of the available range of masses and interactions: sub-eV axions, keV sterile neutrinos, GeV-TeV WIMPs, supermassive DM close to the Planck scale; gravitinos with gravitational interactions, numerous weakly interacting DM candidates, mirror DM with strong self-interactions, ...



Kim& Carosi, 2010

Guidelines to narrow the DM problem?

Focussing corresponds almost always to ratify a prejudice. Possible criteria to support such option include:

- A clean production mechanism, e.g.: thermal production (symmetric, asymmetric), non-thermal states (e.g. from heavier state decays), production as a condensate, gravitational production, ...

- A motivation from an open problem in the SM of particle physics, e.g.: the naturalness problem, the violation of CP in strong interactions, a mechanism to explain neutrino masses, ...

- An impact on observables in cosmology or astrophysics, in connection, e.g., to the possibly discrepancies of the SM with observations on small scales (non-linear regime; galactic and sub-galactic scales; central over densities and abundance of substructures), e.g.: Warm DM, self-interacting DM, DM carrying macroscopic quantum effects, DM with with non-standard couplings with photons or baryons. Numerical N-body simulations are starting to touch these cases; still to be cleared is the role of baryons in DM numerical simulations.

Guidelines to narrow the DM problem?

- An "aesthetic" motivation in analogy to other counterparts, e.g.: Asymmetric DM relying on a mechanism explaining the reason why the density of baryons and DM are comparable.

- A "pragmatic" motivation: lacking incontrovertible evidence for new physics at accelerators, DM may be the only window for new physics.

- A "contingent" motivation: given some "anomaly" (e.g. an excess in the radiation detected towards the GC) you study the class of compatible candidates (mass, interaction, annihilation or decay mode) without (necessarily) a reference particle framework.

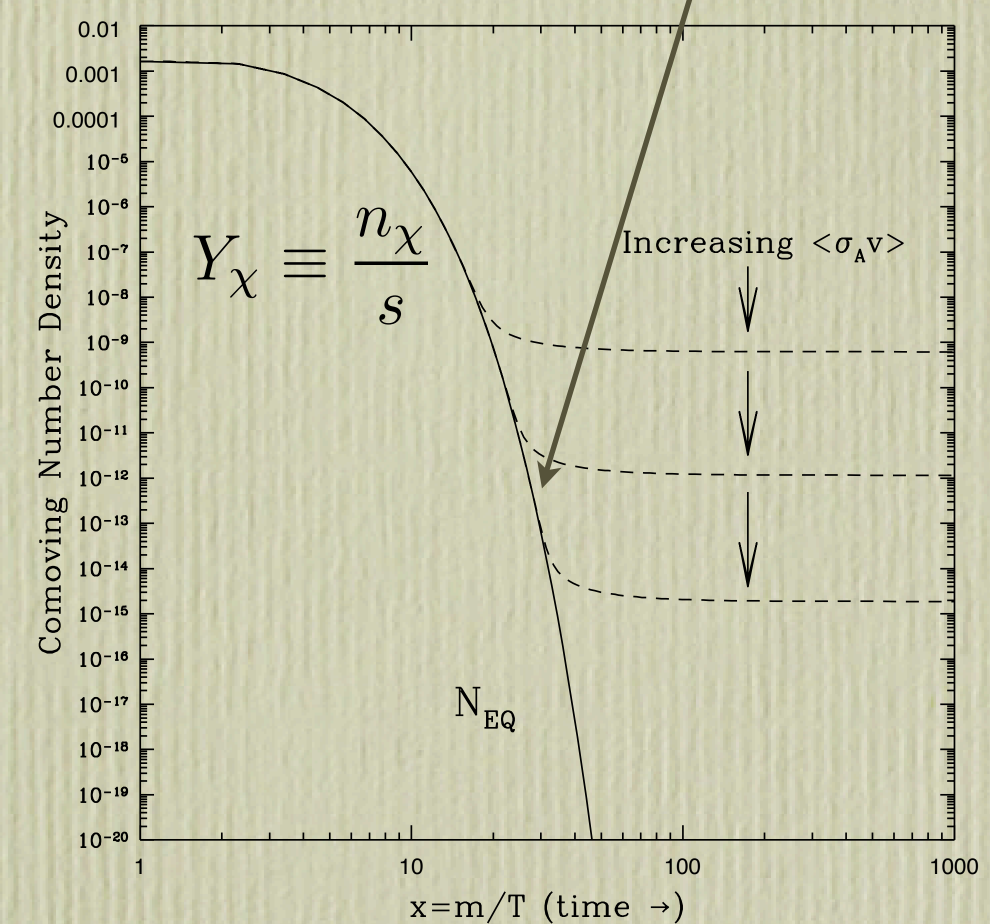
- A systematic evaluation of what is experimentally accessible

"Historical" DM candidates - (SUSY) WIMPs, axions, sterile neutrinos, ... - have mainly been motivated as relying on a natural production mechanism and, at the same time, carrying a particle physics motivation; should one give up on such approach?

CDM particles as thermal relics

Thermal equilibrium of χ enforced via: $\chi\,\bar{\chi} \leftrightarrow \mathrm{SM}\,\overline{\mathrm{SM}}$

$$\Gamma(T_f) = n_\chi^{eq}(T_f)\langle\sigma_A v\rangle_{T=T_f} \simeq H(T_f)$$



$$\Omega_\chi h^2 \simeq \frac{M_\chi\, s_0\, Y_\chi^{eq}(T_f)}{\rho_c/h^2}$$

(freeze-out + entropy conservation)

$$\simeq \frac{M_\chi\, s_0}{\rho_c/h^2}\frac{H(T_f)}{s(T_f)\langle\sigma_A v\rangle_{T_f}}$$

(standard rad. dominated cosmology)

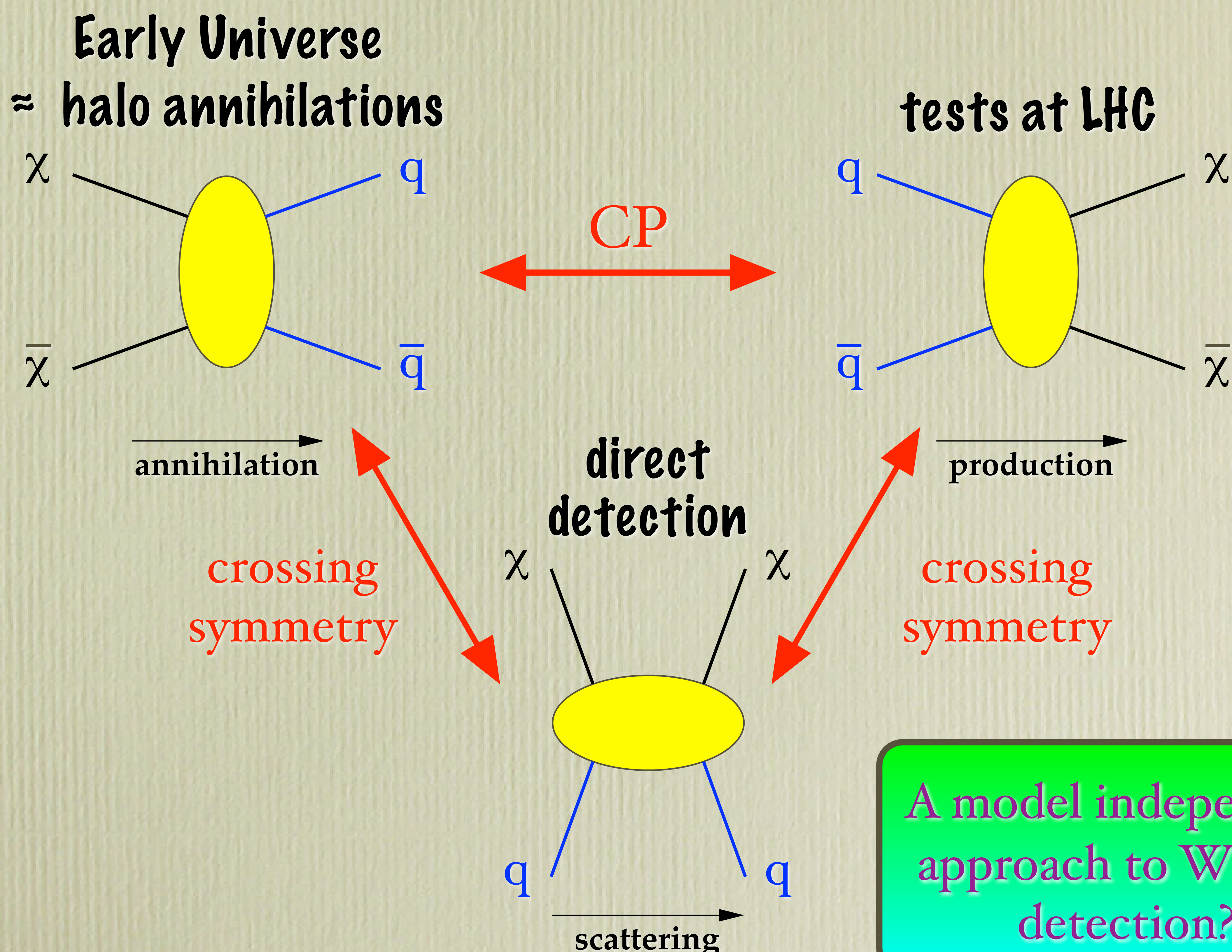
$$\simeq \frac{M_\chi}{T_f}\frac{g_\chi^\star}{g_{\rm eff}}\frac{1\cdot 10^{-27}\mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle\sigma_A v\rangle_{T=T_f}}$$

with: $M_\chi/T_f \sim 20$

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

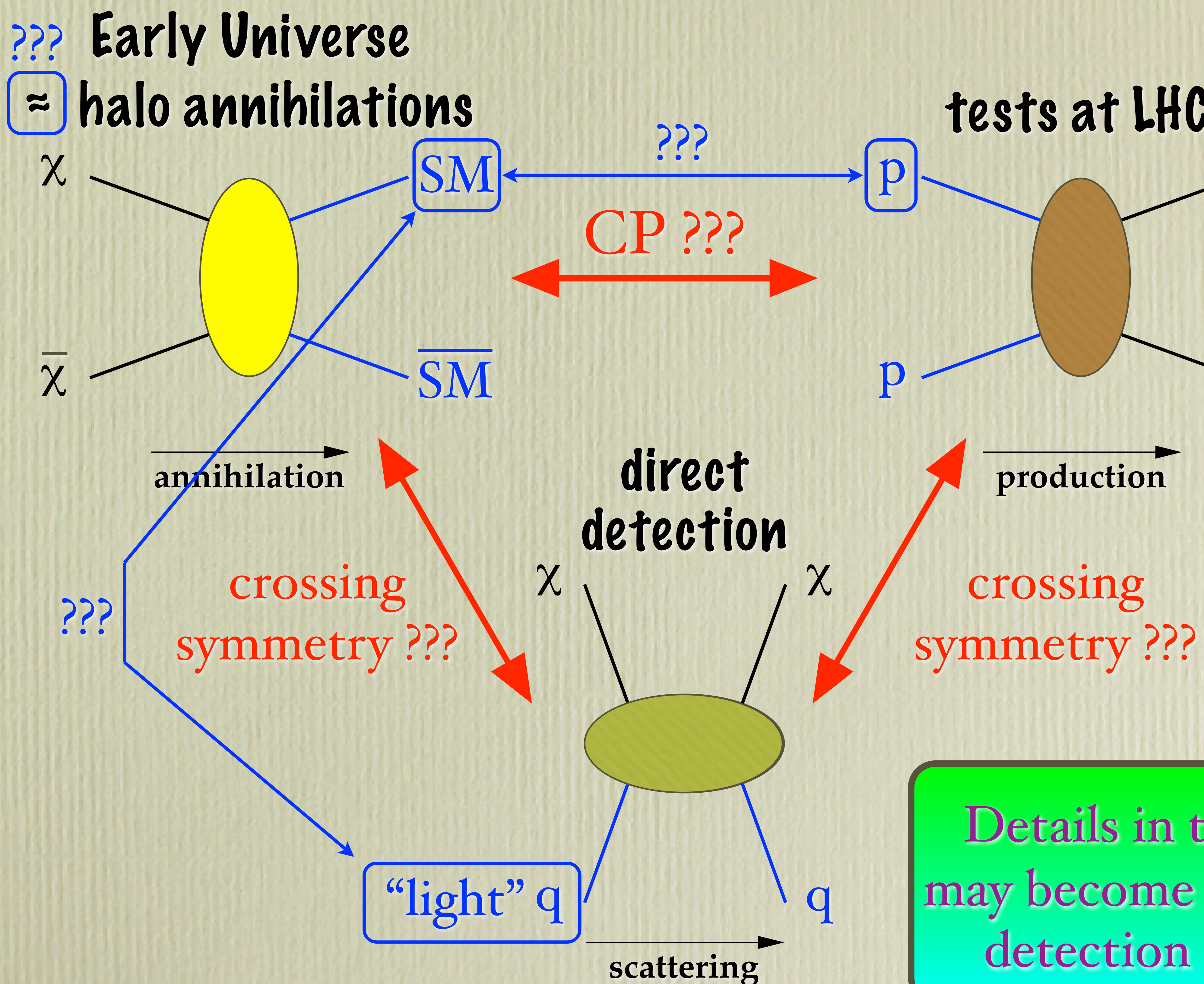
The WIMP recipe to embed a dark matter candidate in a SM extension: foresee an extra particle χ that is stable (or with lifetime exceeding the age of the Universe), massive (non-relativistic at freeze-out) and weakly interacting. Plenty of frameworks in which it is viable to apply this recipe.

WIMP coupling to ordinary matter:



A model independent approach to WIMP detection?

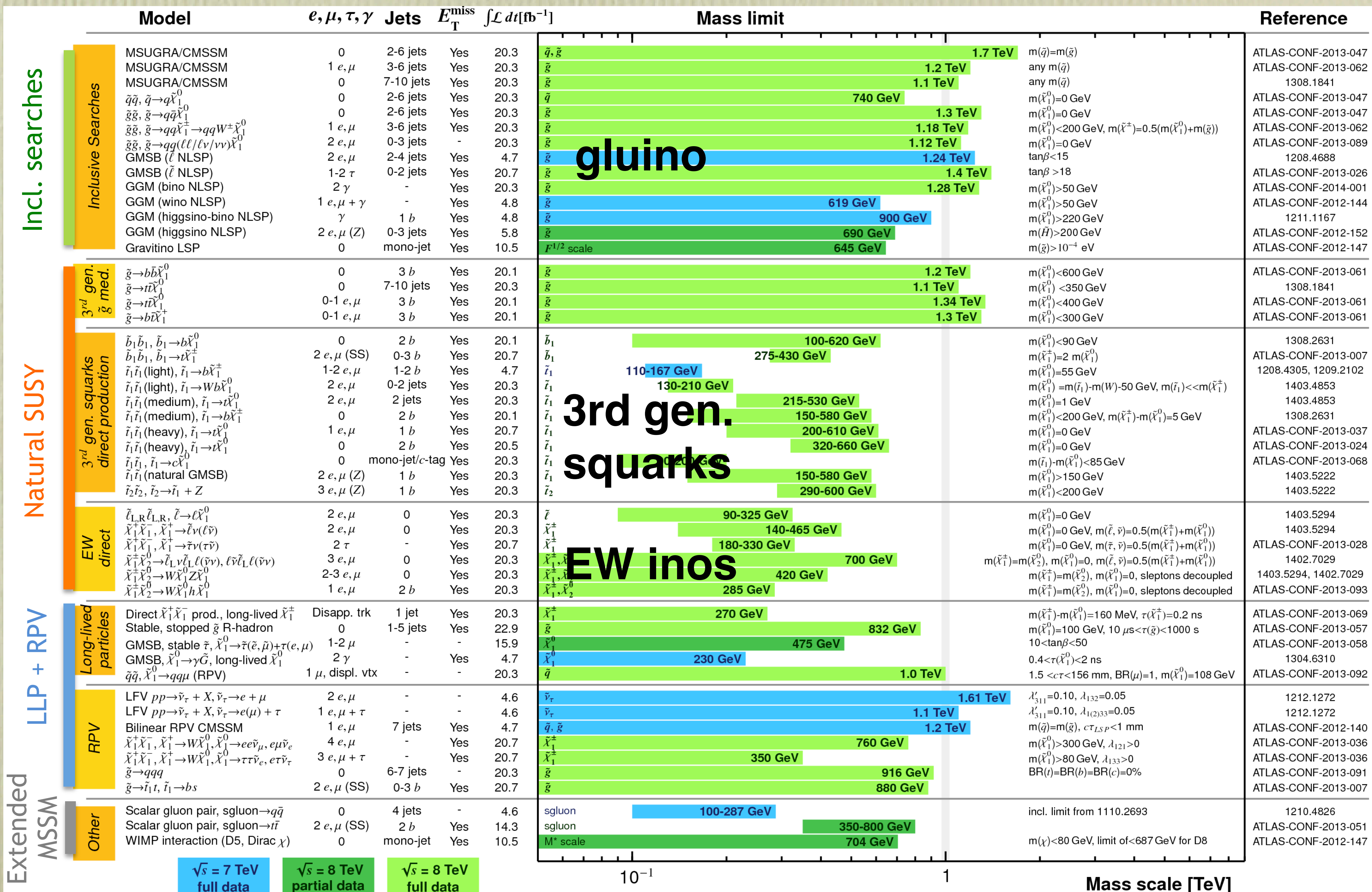
Back to WIMP coupling to ordinary matter:



Details in the model may become critical for detection strategy

LHC impact on the WIMP framework so far

A very large impact on the underlying beyond-SM particle frameworks . E.g. for SUSY searches, ATLAS find 95% CL limits (Moriond 2014):



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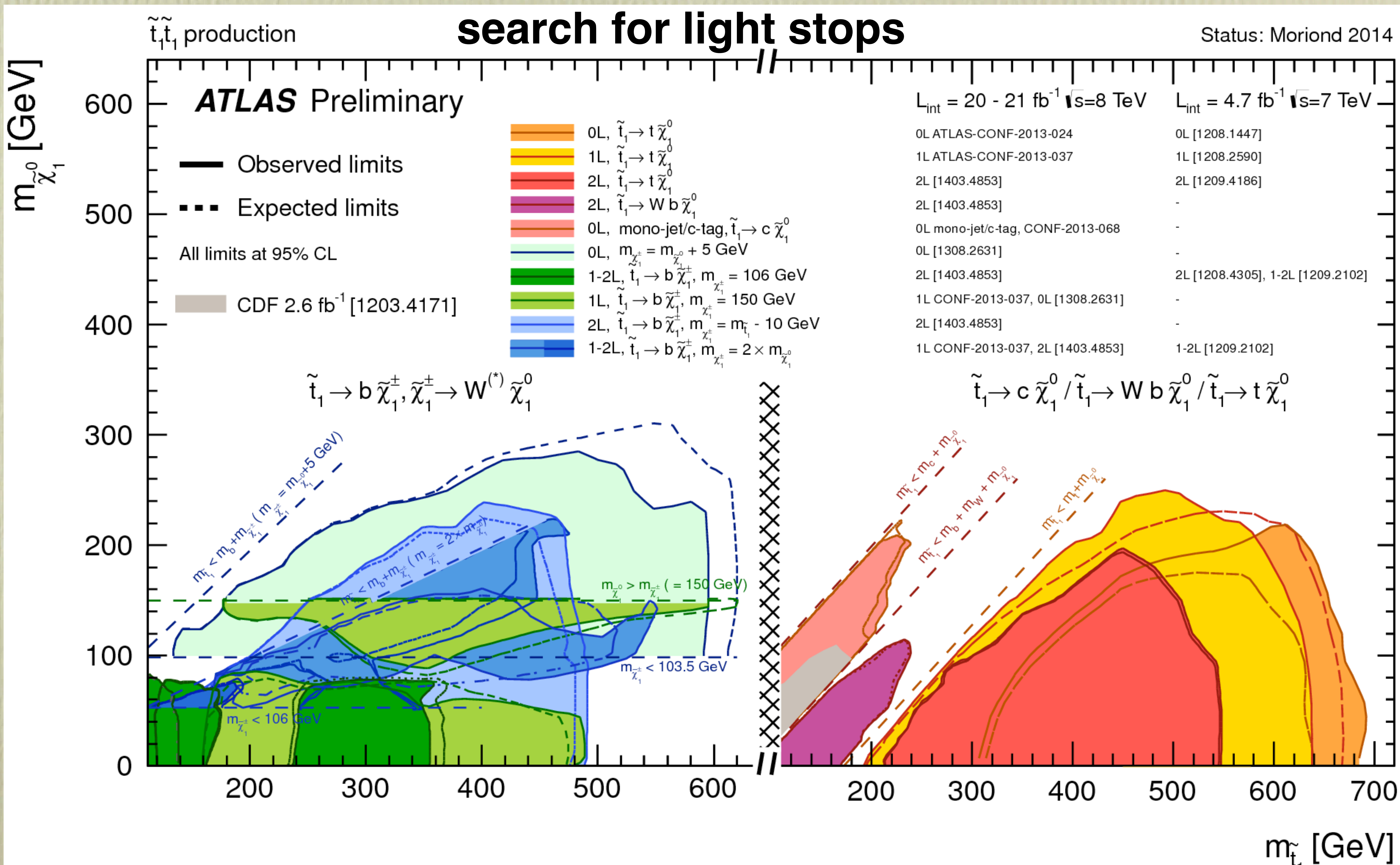


LHC impact on the WIMP framework so far

The viewpoint that new states close to the EW scale are needed to address the hierarchy problem, a pillar of beyond-SM searches, is severely shaking.

The viability of a WIMP DM is significantly reshaped but not ruled out.

E.g.: among the viable option for MSSM neutralino DM prior the LHC:

1. light Bino (SU(2) singlet) annihilating into fermions via t- & u-channel exchange of moderately light sfermion (bulk region of the CMSSM);
2. annihilation on a s-channel Higgs resonance;
3. coannihilation with a sfermion quasi degenerate in mass;
4. well-tempering of Bino-Higgsino fraction; *Direct detection target*
5. pure Higgsino (SU(2) doublet) of 1.1 TeV mass or pure Wino (SU(2) triplet) of 2.5 TeV mass. *Indirect detection target*

only 1. has been wiped out by the LHC (but was already in trouble because of flavour observables and Higgs mass limits); 2. has been reshaped by the (SM) Higgs discovery; 3., 4. & 5. have not (or marginally) addressed.

LHC impact on the WIMP framework so far

The current (pragmatic) tendency is to replace the model building attitude which was applied up to around early 2000 or so:

Construct a natural theory; discover that WIMPs are predicted as part of the spectrum of such natural theory; argue that there is a mechanism enforcing the stability of the lightest of these; compute its thermal relic density and discover that you can solve the DM puzzle! (SUSY, large extra dimensions, Randall-Sundrum model, ...)

with:

Give up on naturalness; construct ab-initio the model assuming the existence of a stable WIMP (sometimes protecting the stability by ah-hoc symmetry) with thermal relic density matching the DM density; match lab constraints, most often making the theory looking SM-like under flavour and EW observables. (split SUSY, minimal DM models, ...)

sometimes preserving extra virtue (e.g.: gauge coupling unification), sometimes as DM as the only target!

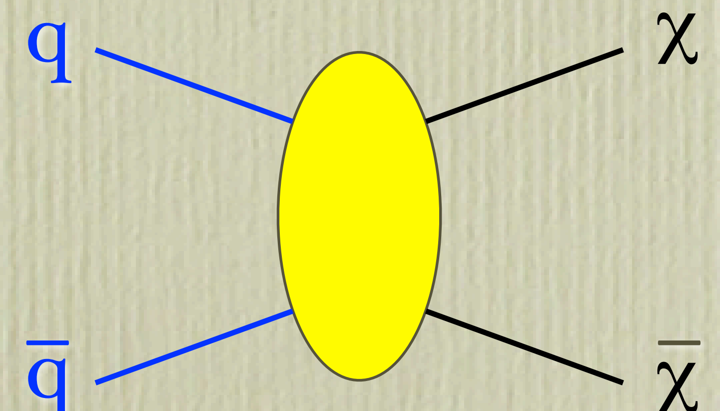
LHC impact on the WIMP framework so far

Models in which the DM sector is the only one relevant for phenomenology may be treated within effective field theory approaches, assuming contact term interactions suppressed over some heavy scale Λ; e.g. for a Dirac fermion χ:

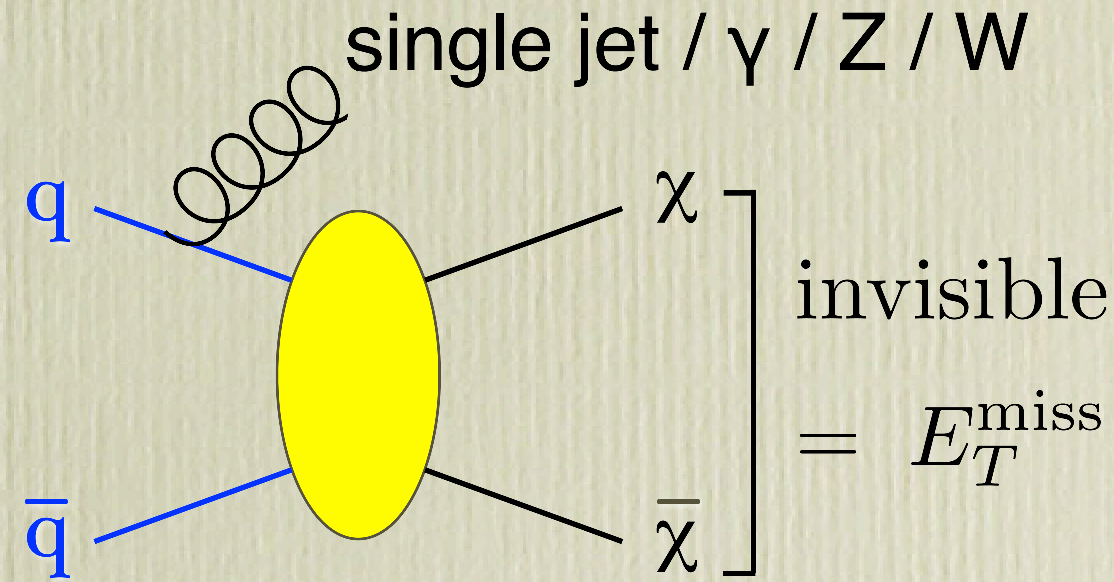
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2} \qquad \text{or:} \qquad \mathcal{O}_G = \alpha_s \frac{(\bar{\chi}\chi)(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3}$$

Focus on generic LHC signatures like the so-called mono-X emission:

tag:



via:



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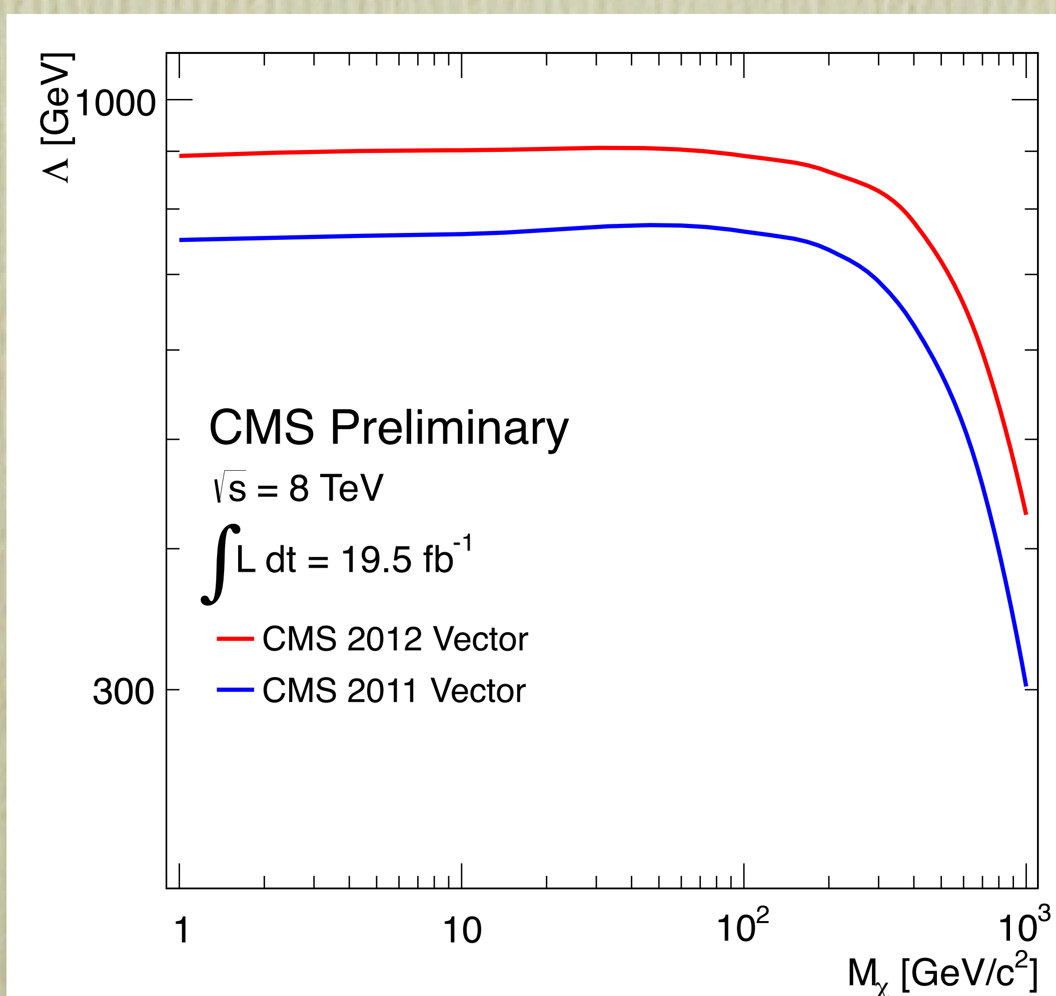
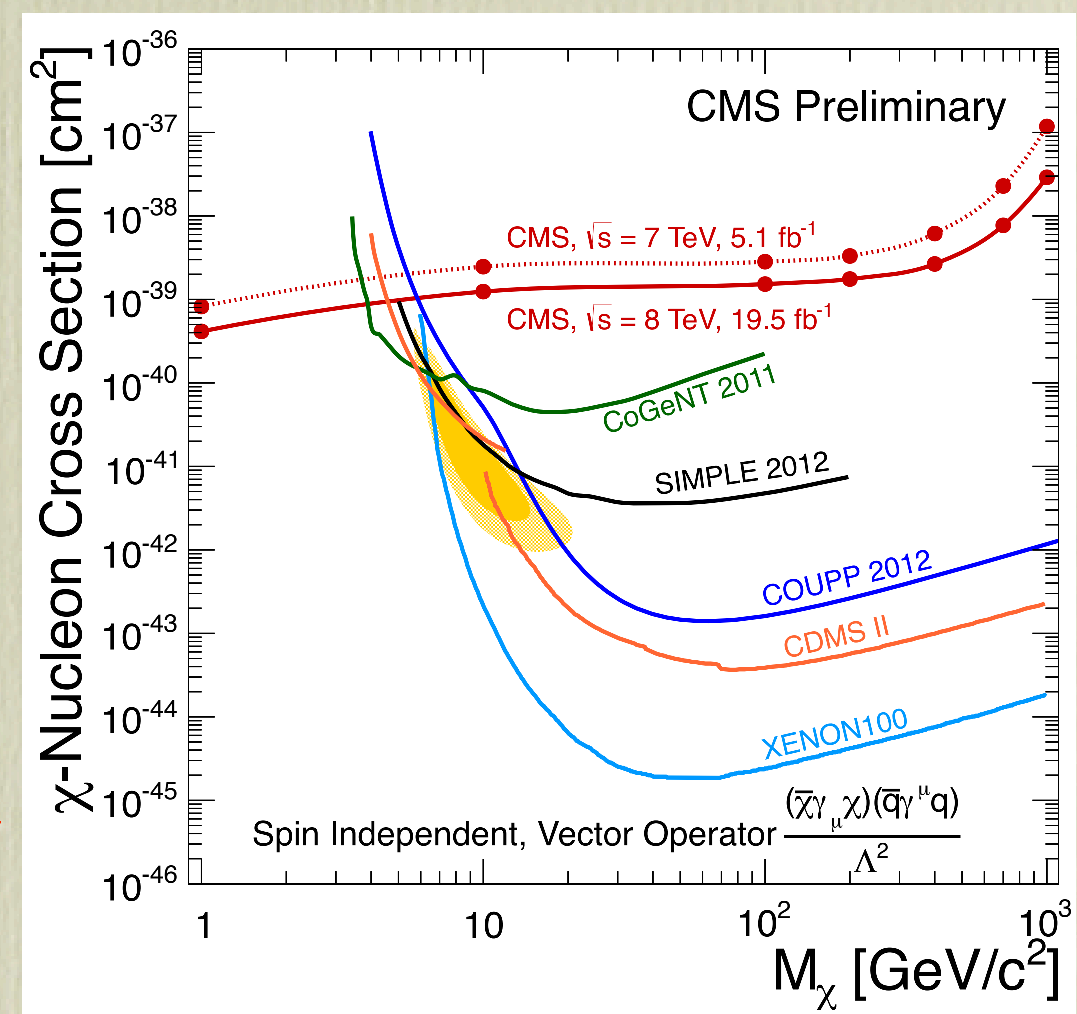
E.g.: CMS mono-jet limit on the scale in $\mathcal{O}_V$:



EXO-12-048-PAS

assuming flavor universality



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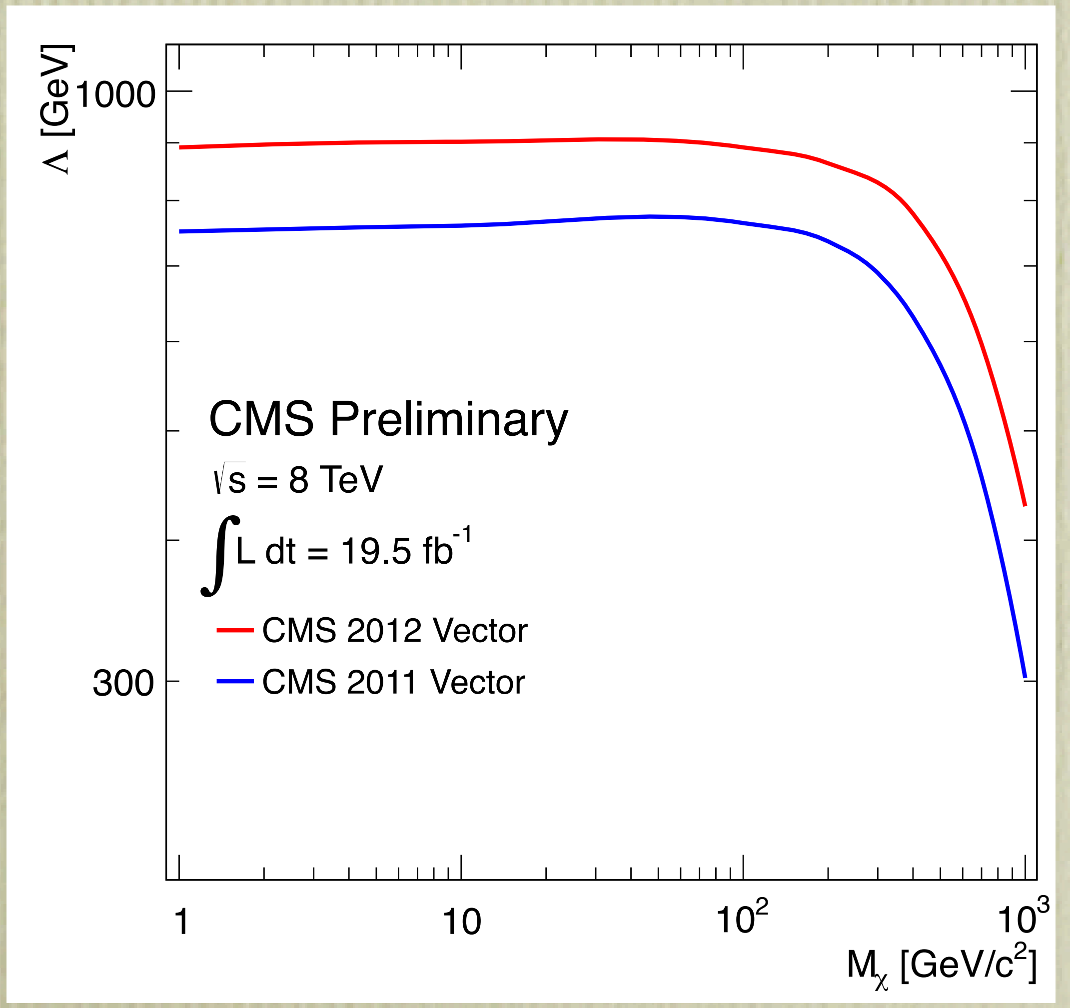

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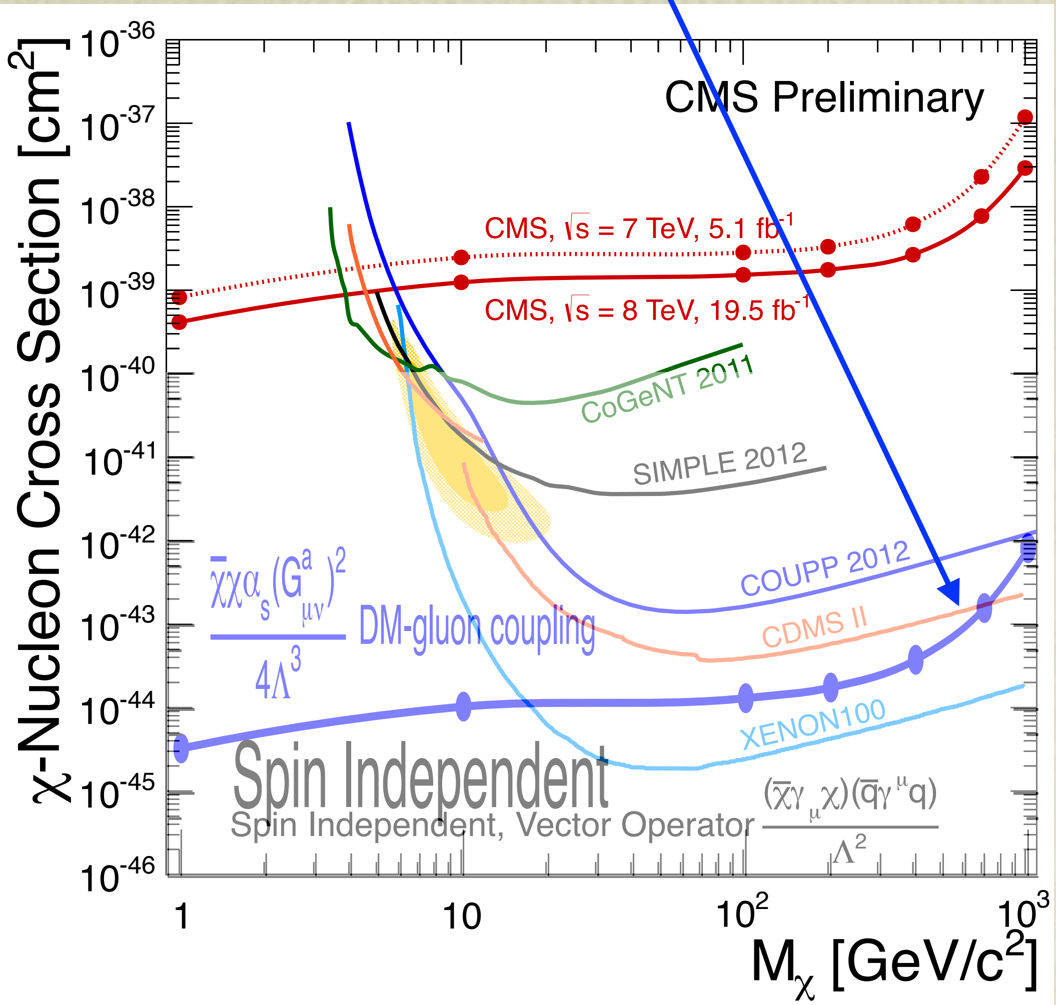
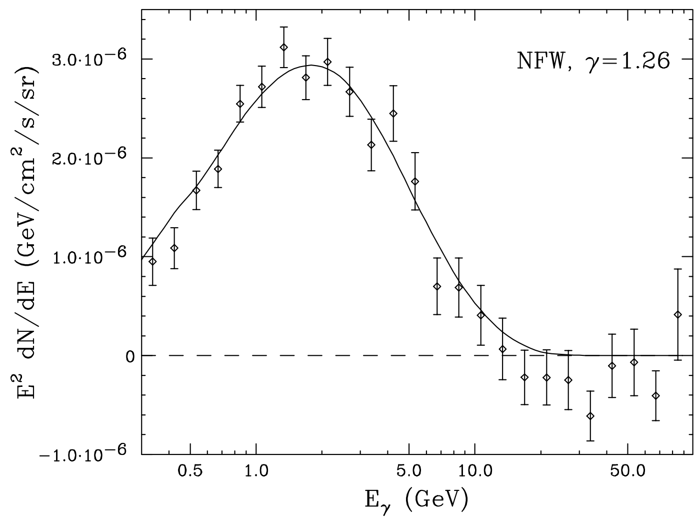
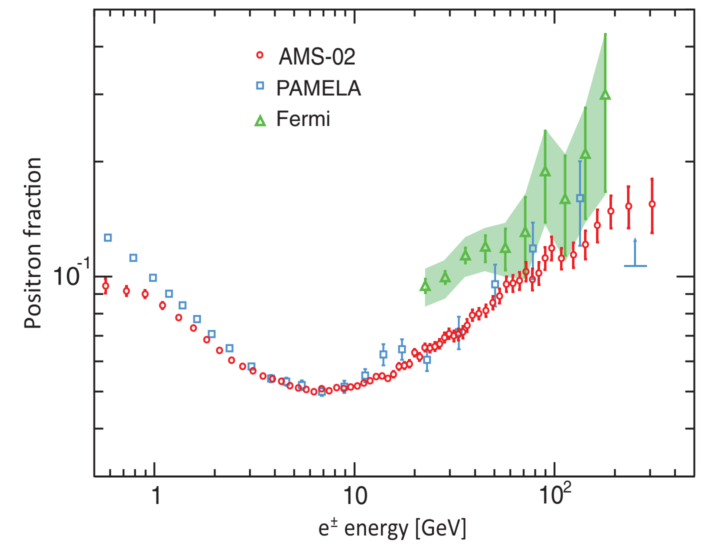


Hints of particle DM detection?



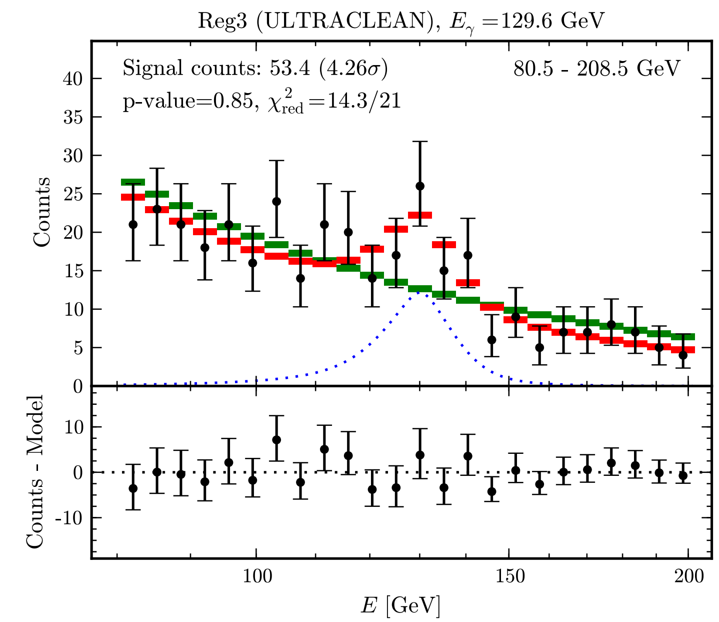
GeV γ-ray excess at the GC?

several authors, 2009-14

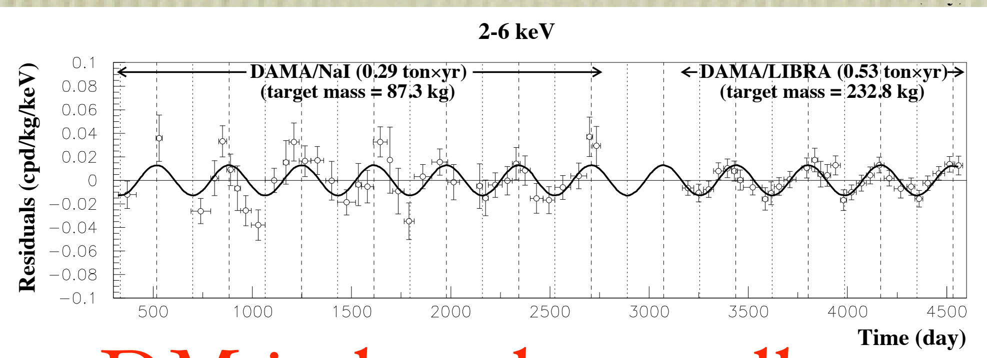


a DM induced positron excess?

Pamela, Fermi, AMS02, 2009-13



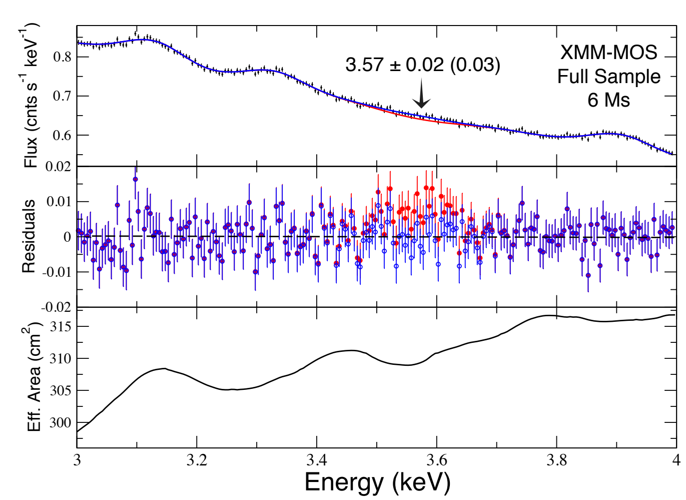
Fermi 130 GeV γ-ray line? Weniger, 2012



a DM induced annually modulation scattering rate?

Bernabei et al., 1997-2013 + other direct detection “hints”

or away from a GeV/TeV DM state to a keV, e.g., sterile neutrino or a axion-like particle:



3.5 keV X-ray line?

Bulbul et al., 2014

The direct detection puzzle:

Inconclusive picture, with some null results and some a potential signal (excess over background or an annual modulation signal); taking all of them at face value and making a (model dependent) projection on the plane WIMP-nucleon SI coupling - WIMP mass, tension among results:

CDMSII Si
(3 WIMP(?) events)
Agnese et al., arXiv: 1304.4279

SuperCDMS
(limit)
Agnese et al., arXiv: 1402.7137

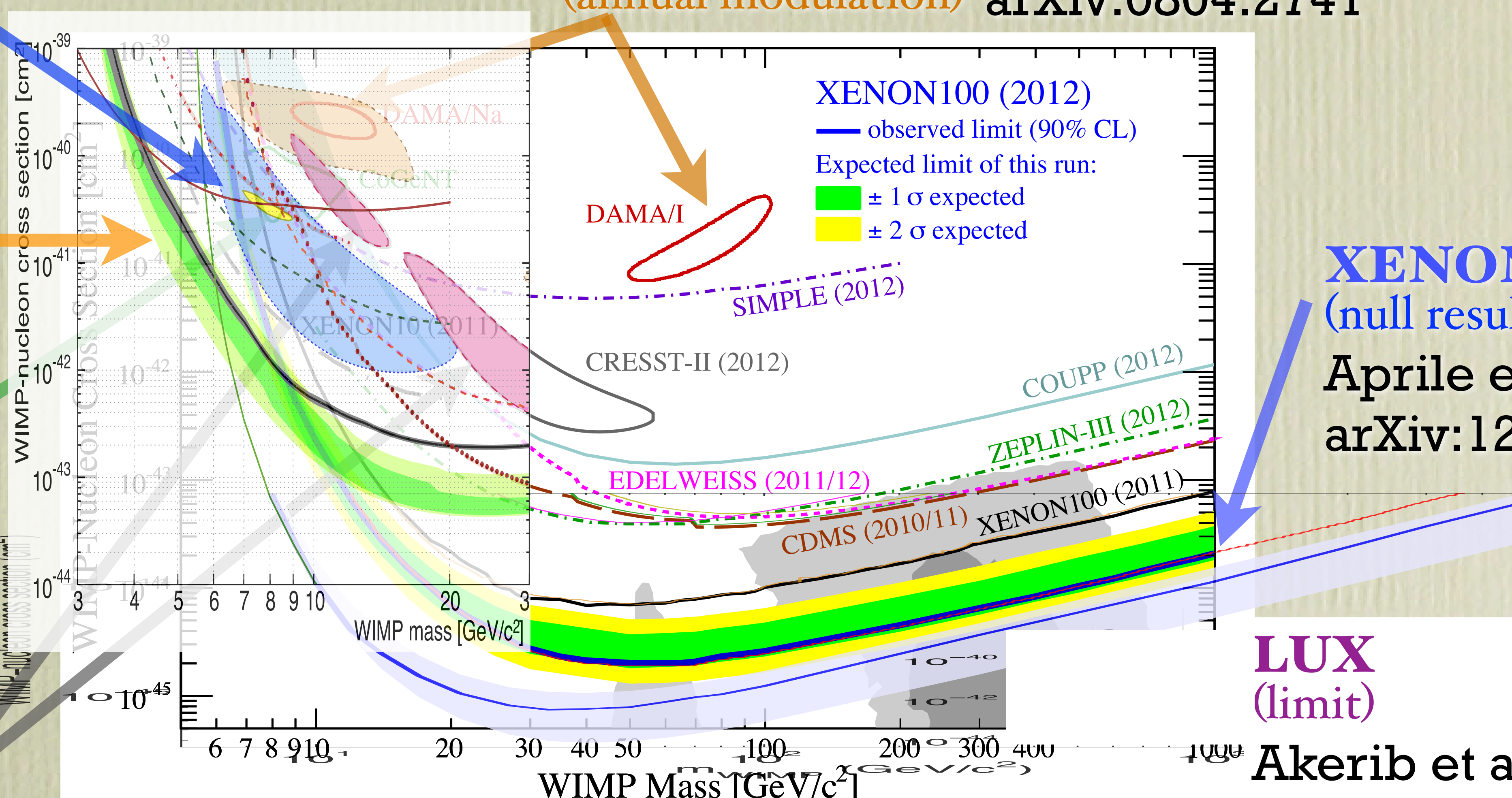
CoGeNT
(excess + ann. mod.)
Aalseth et al., arXiv:1106.0650

CRESST
(excess)
Angloher et al., arXiv:1109.0702

DAMA/LIBRA
(annual modulation)
Bernabei et al., arXiv:0804.2741

XENON100
(null result)
Aprile et al., arXiv:1207.5988

LUX
(limit)
Akerib et al., arXiv:1310.8214



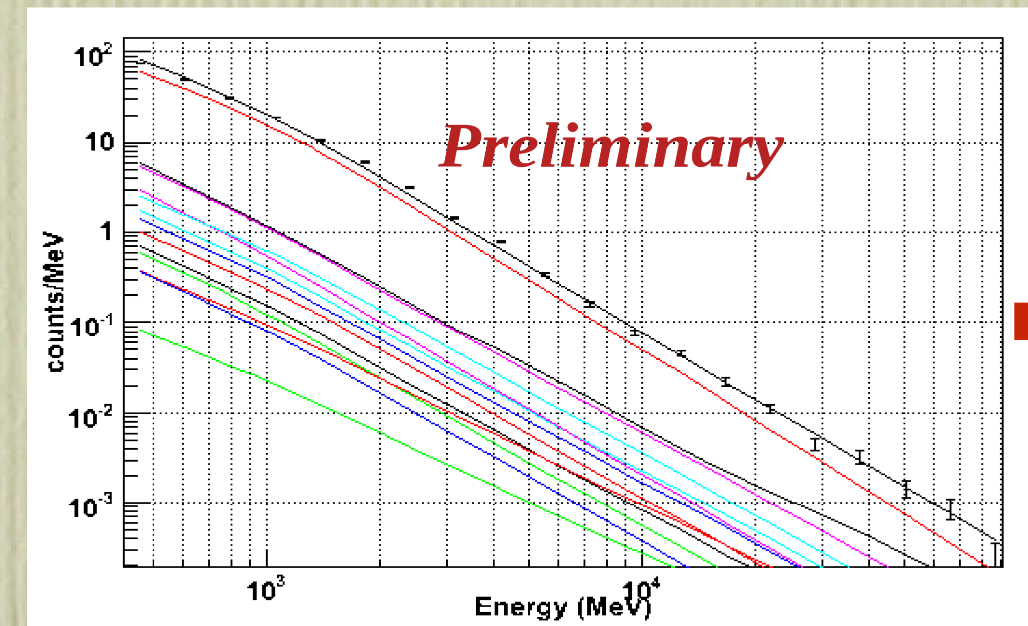
Is the light mass window interesting?

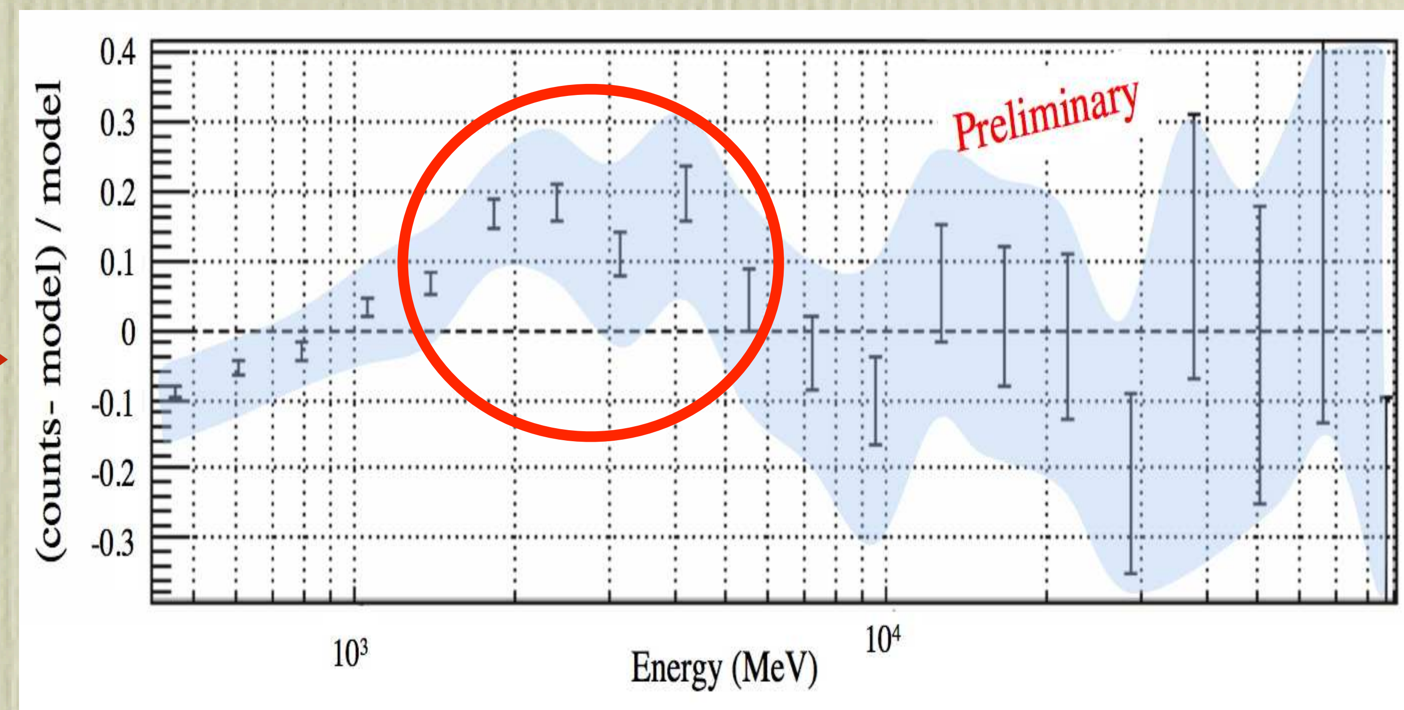
Is this the correct projection plane?

A γ-ray excess at ~ GeV energies towards the GC ?

When comparing the flux measured by Fermi in the Galactic center region against models accounting for diffuse emission and point sources, a residual at the level of 10% of the total intensity emerges, Morselli & Vitale (Fermi Coll.), 0912.3828 (+ Goodenough & Hooper, 0910.2998):

$7^\circ \times 7^\circ$ ROI

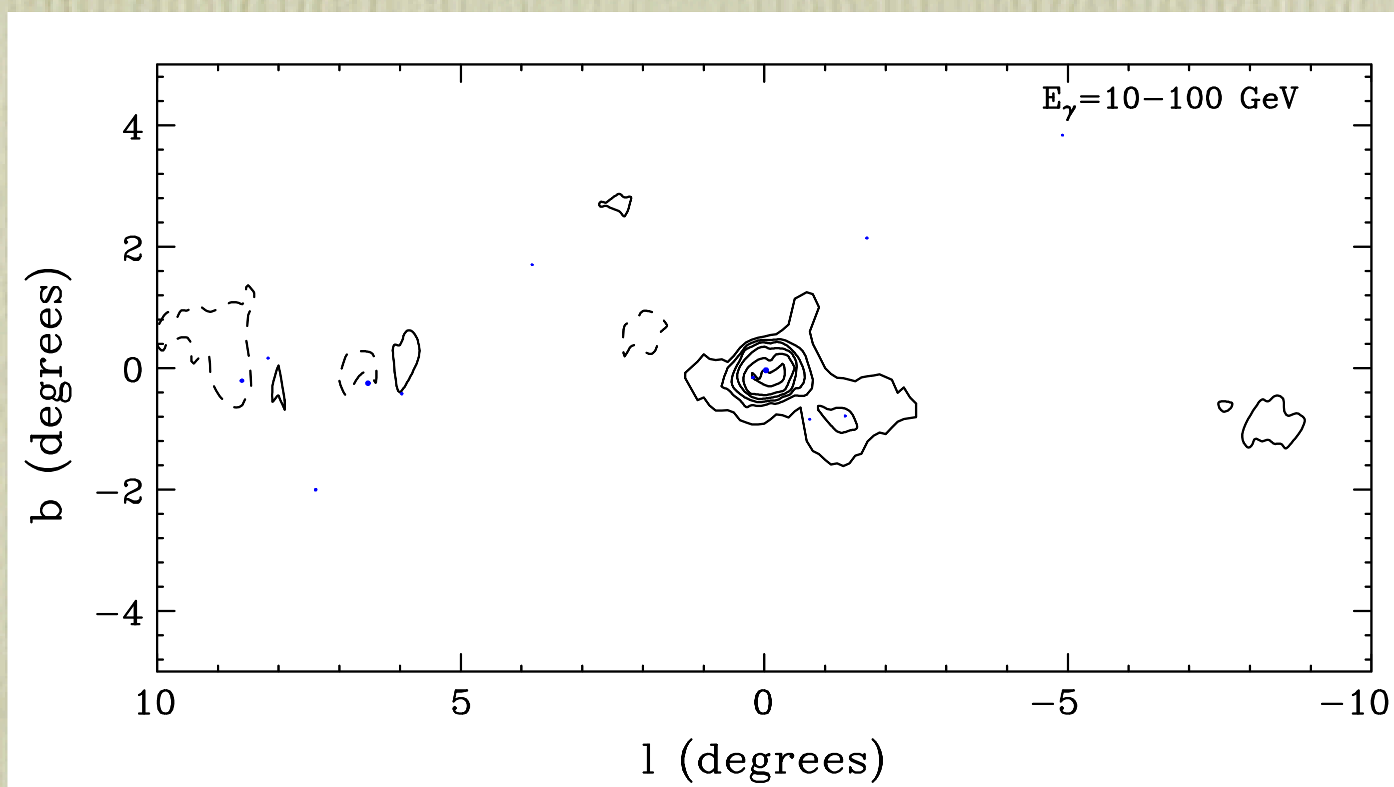


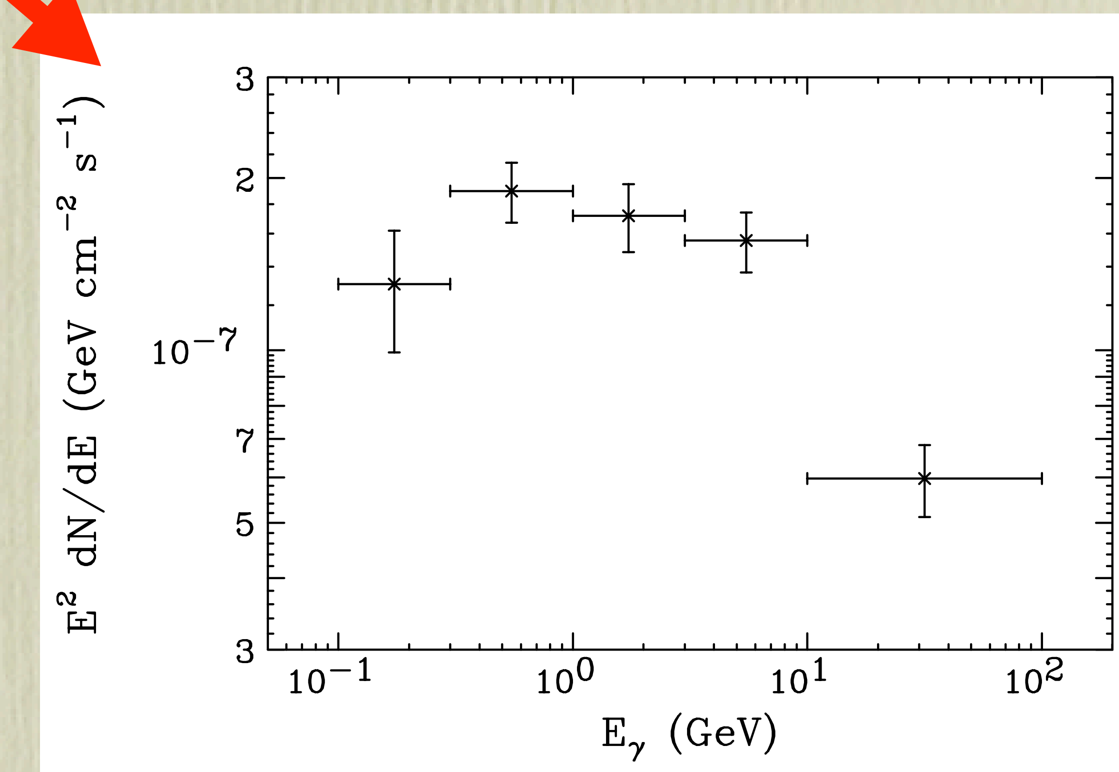


diffuse emission according to a physical propagation model (with Galprop) tuned on data away from GC; isotropic background from all sky data; point sources from the Fermi catalogue. Still: it is tricky to include properly systematic effects and uncertainties in the modelling of each component. An exercise which has been repeated over the years with different assumptions, with the goal of addressing whether this is a DM excess:

A γ-ray excess at ~ GeV energies towards the GC ?

The attractive feature is the morphology signature, as expected from the enhancement in DM density towards the Galactic center: Hooper & Linden, 1110.0006 (building up from 0910.2998 and 1010.2752) use a template fitting procedure to claim a DM signal in the inner few degrees:



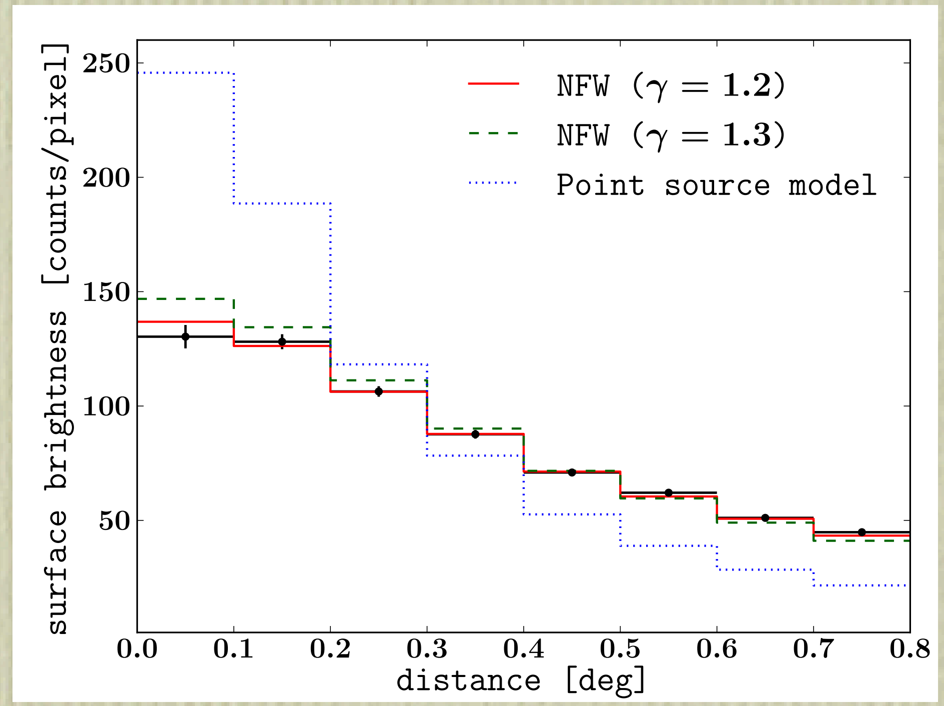


consistent with $\rho_{\rm DM} \propto r^{-1.3}$, e.g. from N-body result $\rho_{\rm NFW} \propto r^{-1}$ + mild adiabatic contraction from baryon infall

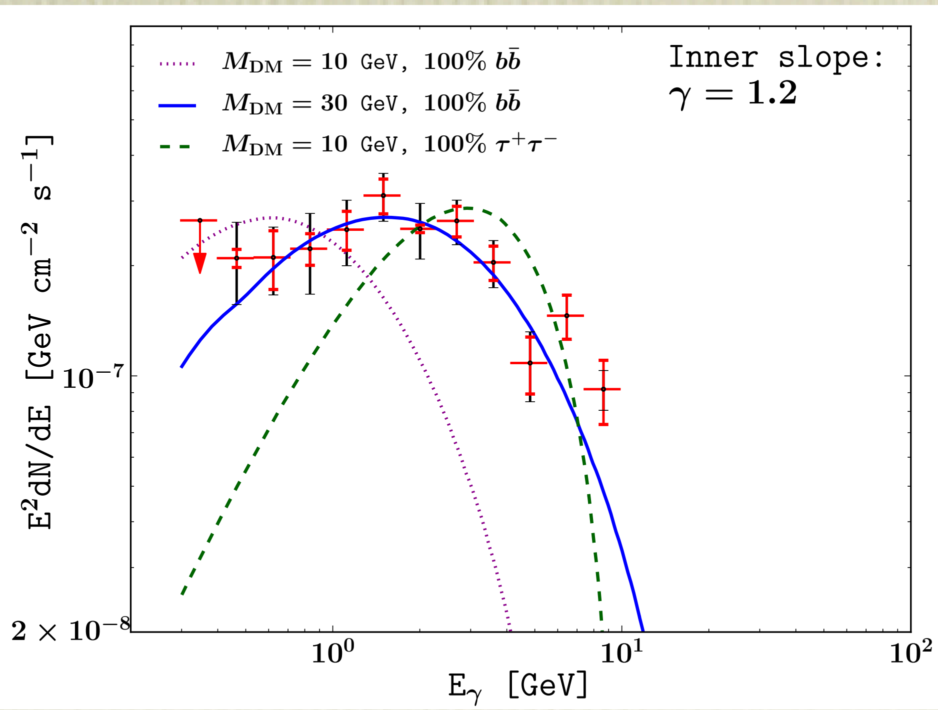
Spectrum with ~ 10 GeV cutoff

A γ-ray excess at ~ GeV energies towards the GC ?

Result confirmed in other independent works, considering slightly different approaches to model the background, see Abazajian & Kaplinghat, 1207.6047 and Gordon & Macias, 1306.5725:

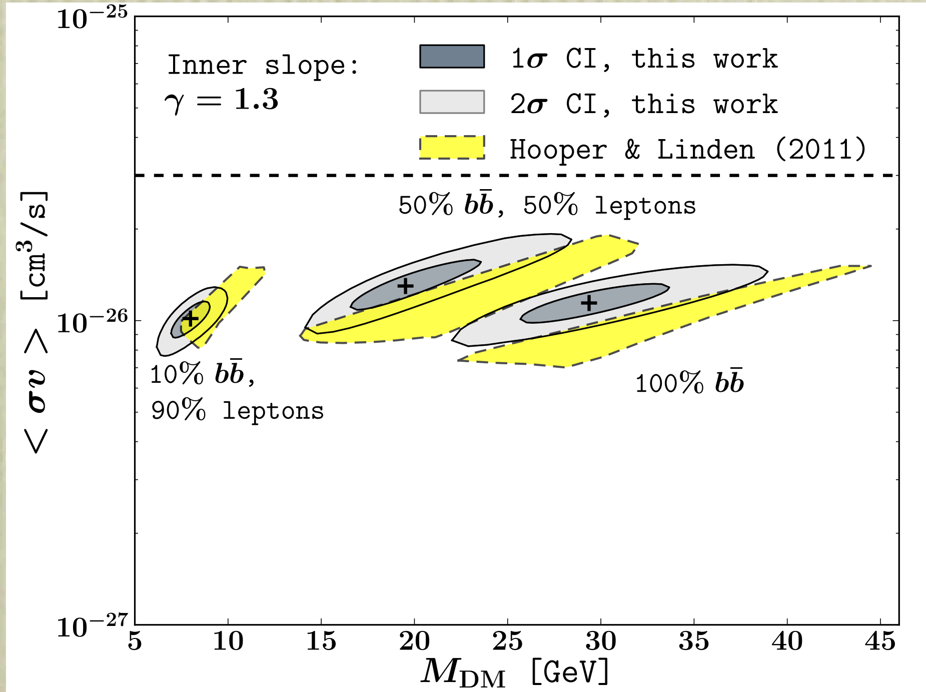


again cuspy profile, not point source



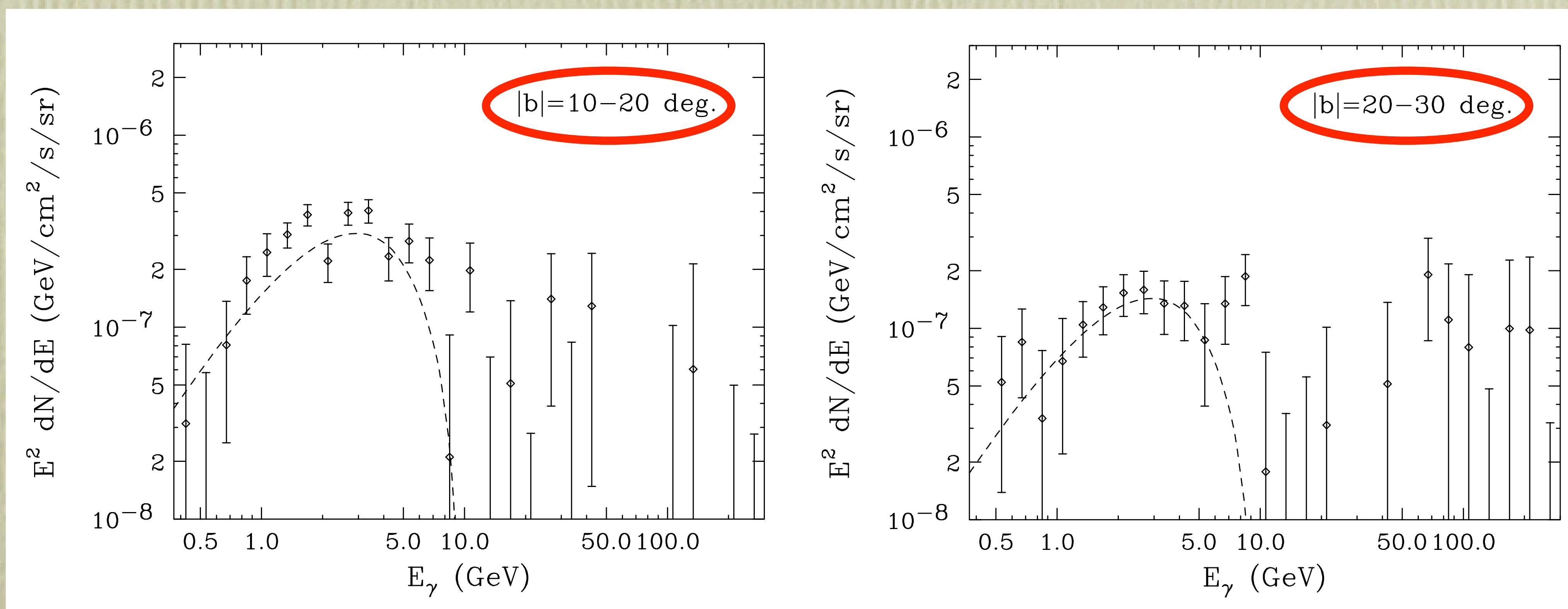
again a sharp cut-off

best fit with WIMP annihilations into b-quarks or leptons or a combination



A γ-ray excess at ~ GeV energies towards the GC ?

Residuals searched for and found also in different parts of the sky; in particular Hooper & Slatyer, 1302.6589 find consistent energy spectrum and morphology at slightly higher latitudes, in the Fermi bubbles region, where assumptions on the background needs to be different, but still very uncertain (see also results from Huang et al., 1307.6862):



$\rho_{\rm DM} \propto r^{-1.2}$

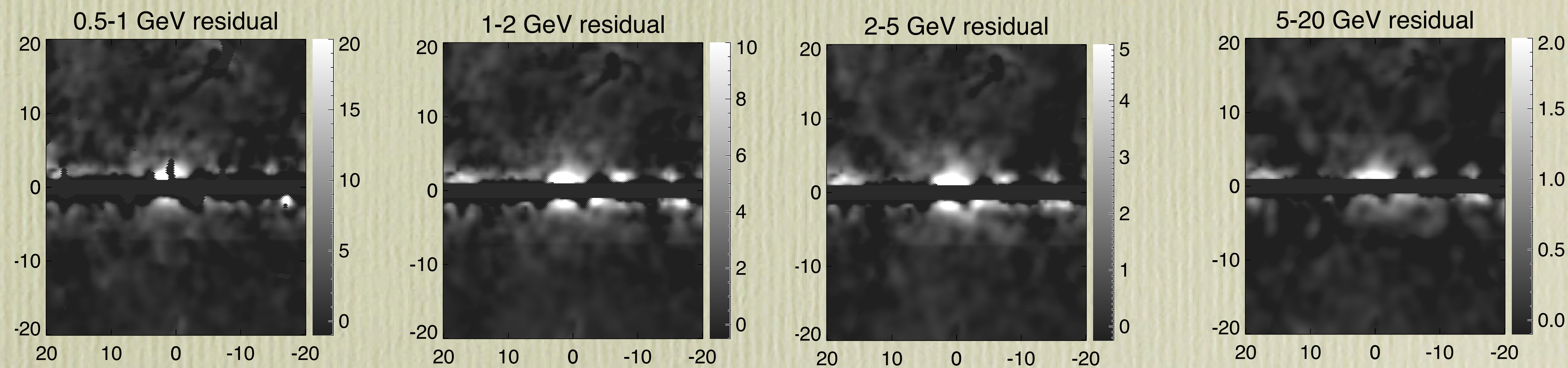
$M_\chi = 10$ GeV

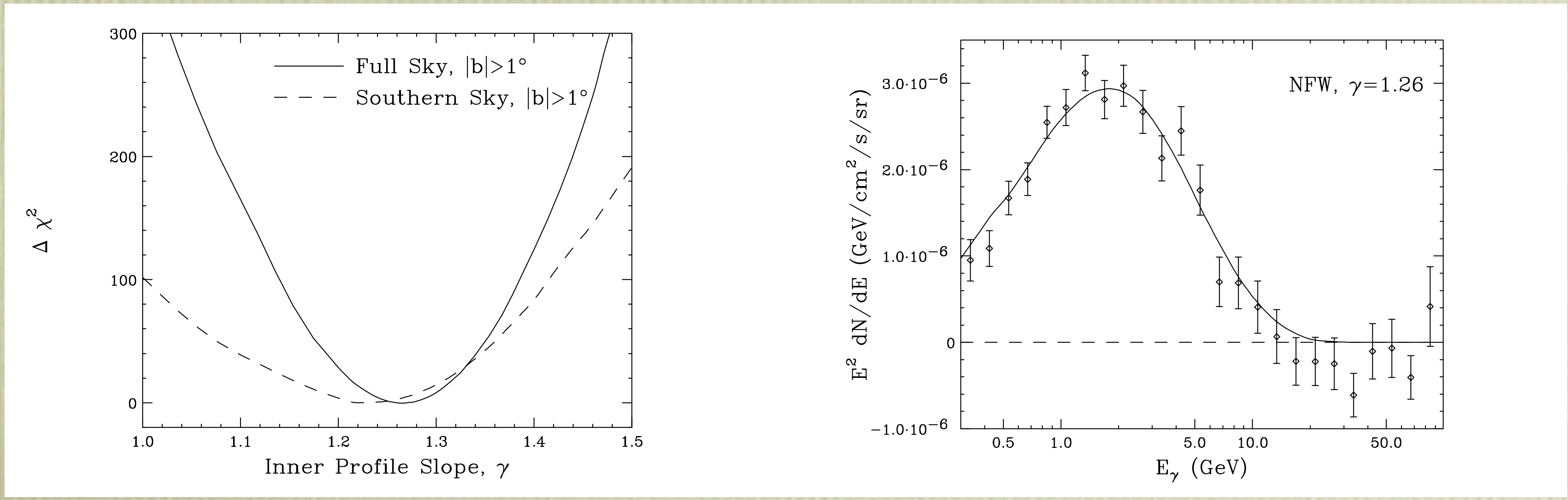
$\tau^+\tau^-$ final state

Hooper et al., 1305.0830 show that this is inconsistent with an unresolved population of millisecond pulsars (MSPs) with the same spectral features as those measured by Fermi for MSPs in the sun neighbourhood. This point has been questioned in other analyses, see Yuan & Zhang,1404.2318.

A γ-ray excess at ~ GeV energies towards the GC ?

Latest update from Daylan et al., 1402.6703: better angular tagging (Fermi CTBCORE parameter discrimination), template fitting on large sky patch all the way from |b|>1° to the Fermi bubble region, higher statistics:





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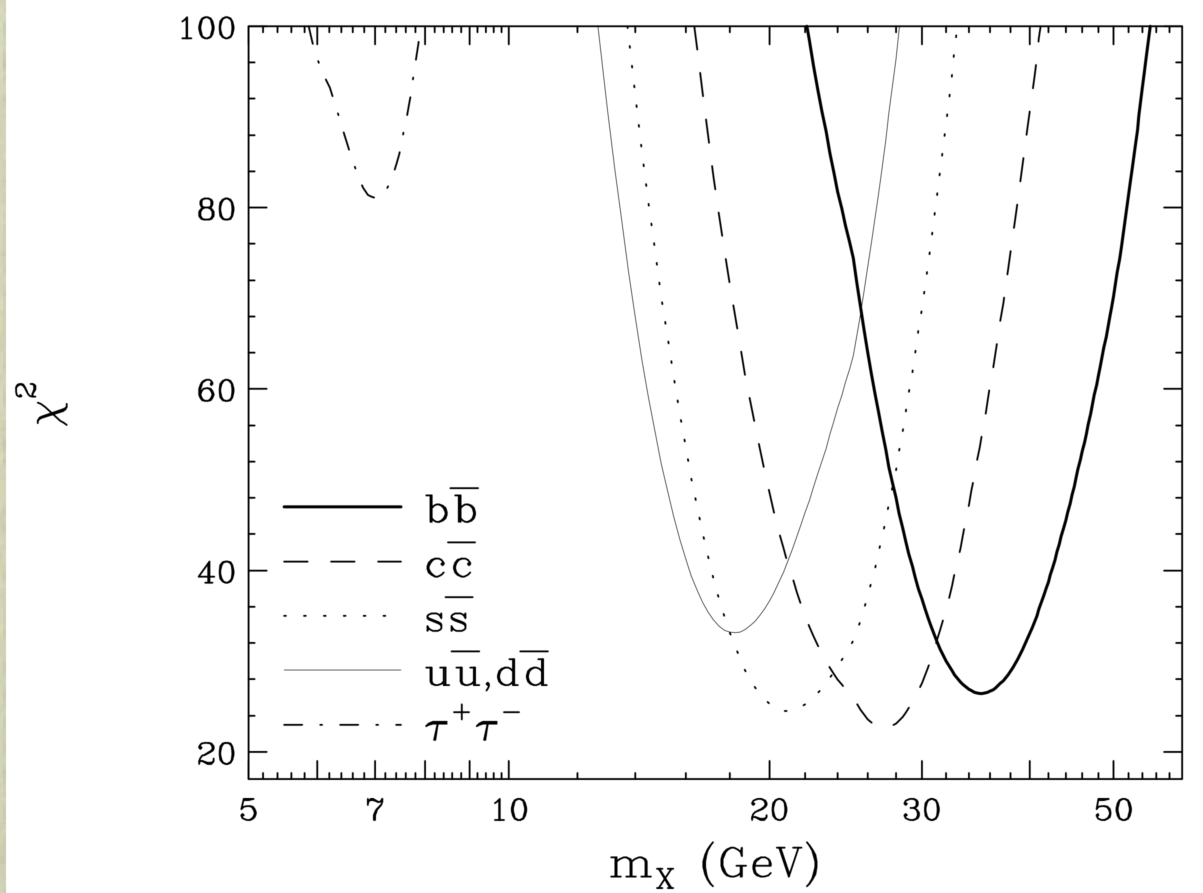
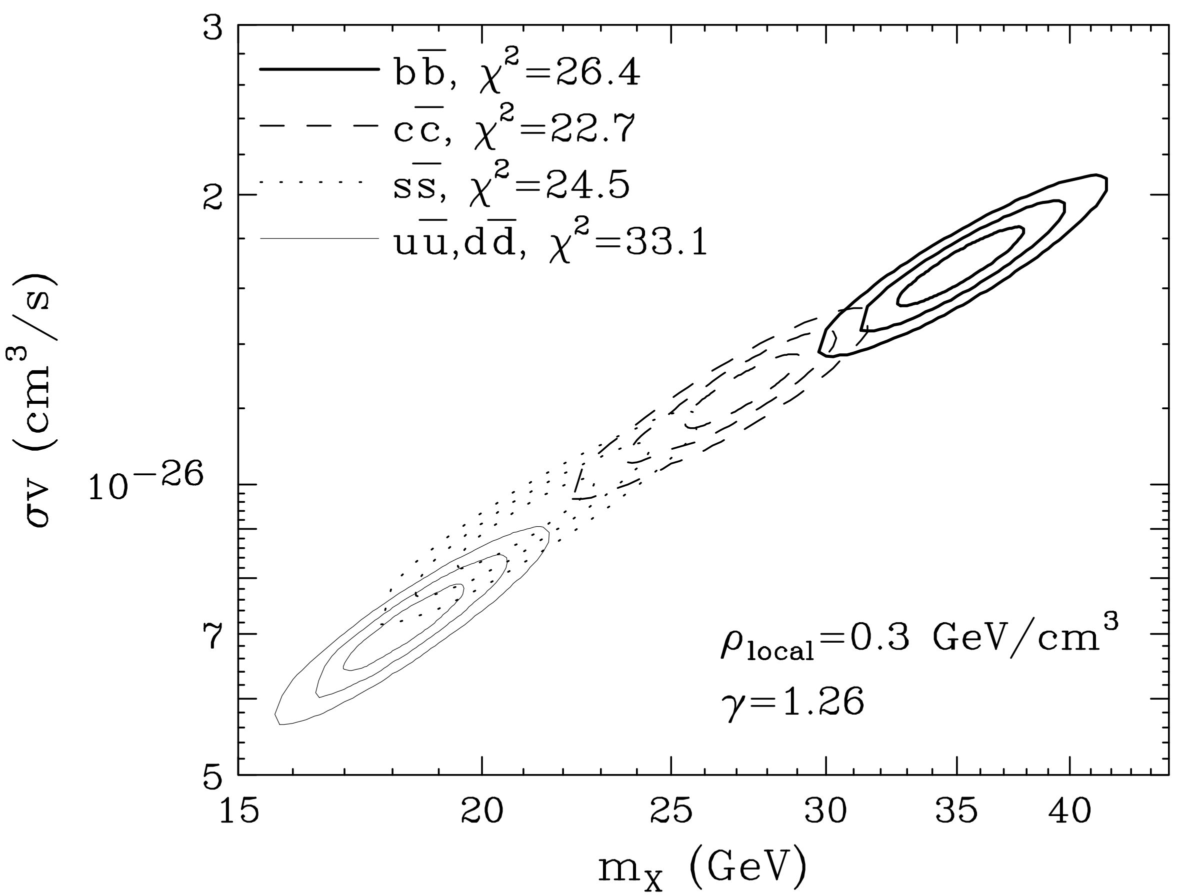
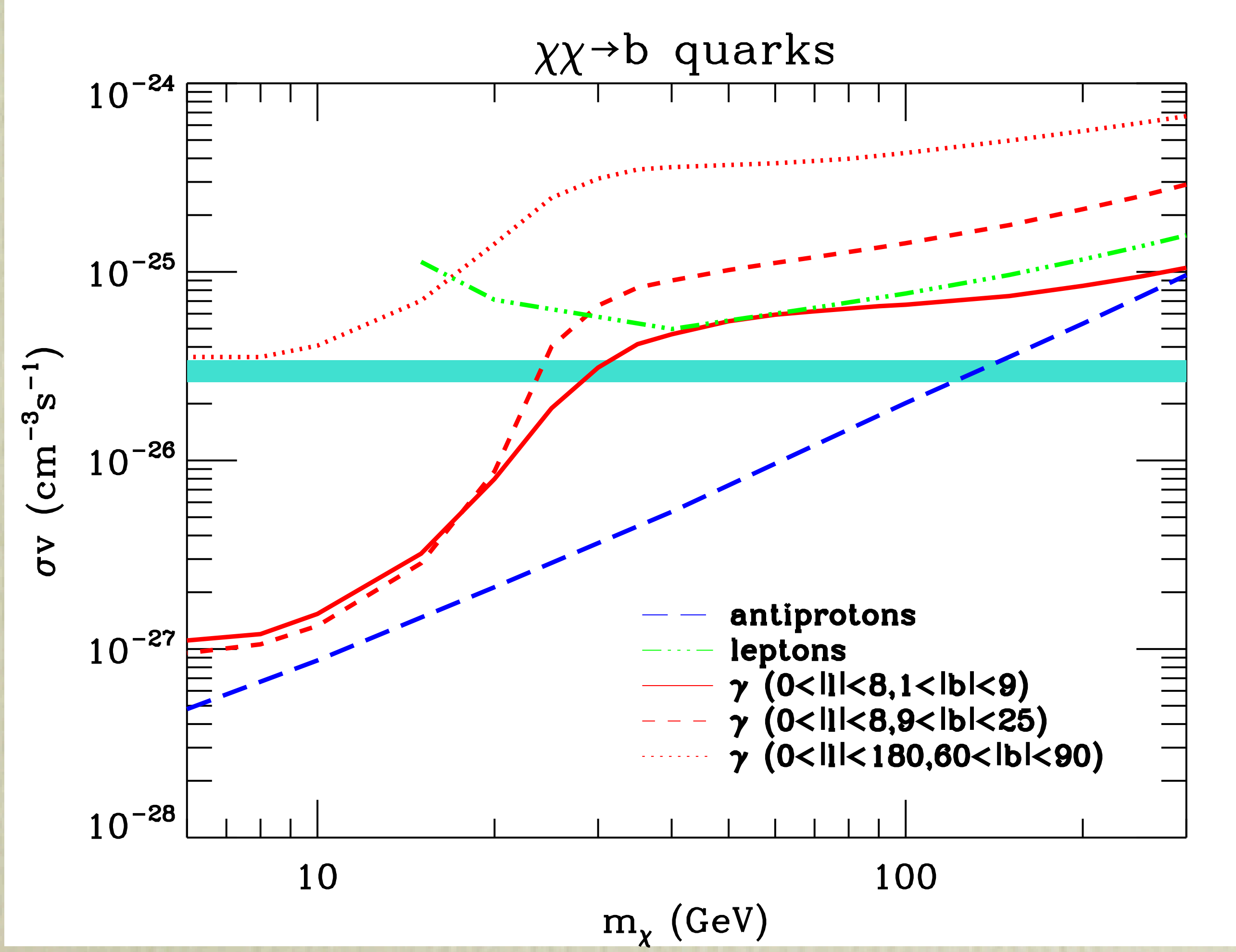




Minor changes for slightly different angular and/or energy cuts; signal robustly associated with an approximately spherical component (not a contaminant from the disc) and extending up at least 10° (hardly compatible with a MSP component).

What about the broader multi-messenger picture?

In most cases a given DM yield impacts several WIMP indirect detection channels at the same time: a multi-messenger and multi-wavelength opportunity to find a signal and cross check limits. A problem requiring a fully self-consistent approach when comparing different observables.
E.g.: within a given WIMP yield, a given model for propagation of CRs in the galaxy, a given model for (radiative) γ-ray emissivities (connected to the gas and ISRF models), you can extract limits from (Tavakoli, PU et al., 1308.4135):



- measurements of the local antiproton flux;
- measurements of the local lepton fluxes;
- γ-rays at low, intermediate and high latitudes.

What about the broader multi-messenger picture?

In most cases a given DM yield impacts several WIMP indirect detection channels at the same time: a multi-messenger and multi-wavelength opportunity to find a signal and cross check limits. A problem requiring a fully self-consistent approach when comparing different observables.

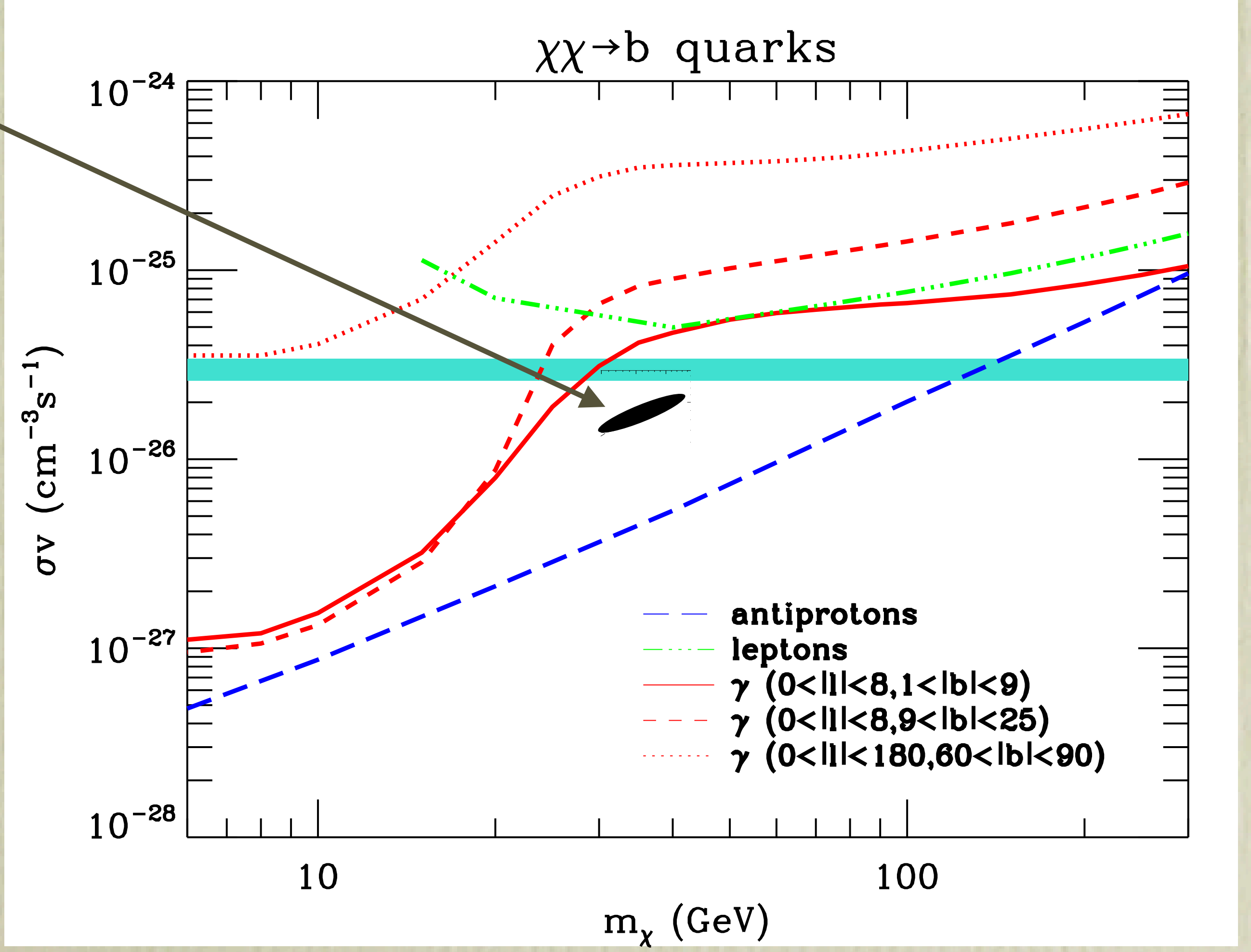
E.g.: within a given WIMP yield, a given model for propagation of CRs in the galaxy, a given model for (radiative) γ-ray emissivities (connected to the gas and ISRF models), you can extract limits from (Tavakoli, PU et al., 1308.4135):

Daylan et al., 1402.6703

3σ GC signal region;

shown to guide the eye only!!

Inconsistent frameworks!

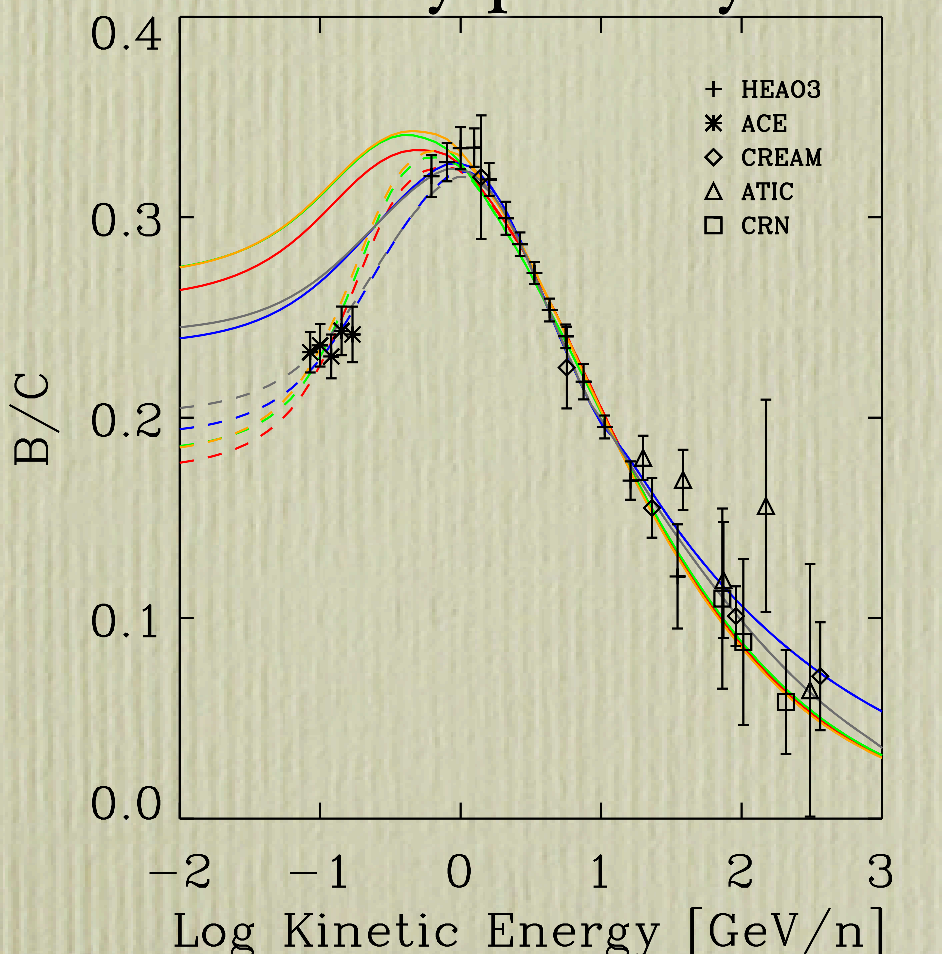


- measurements of the local antiproton flux;
- measurements of the local lepton fluxes;
- γ-rays at low, intermediate and high latitudes.

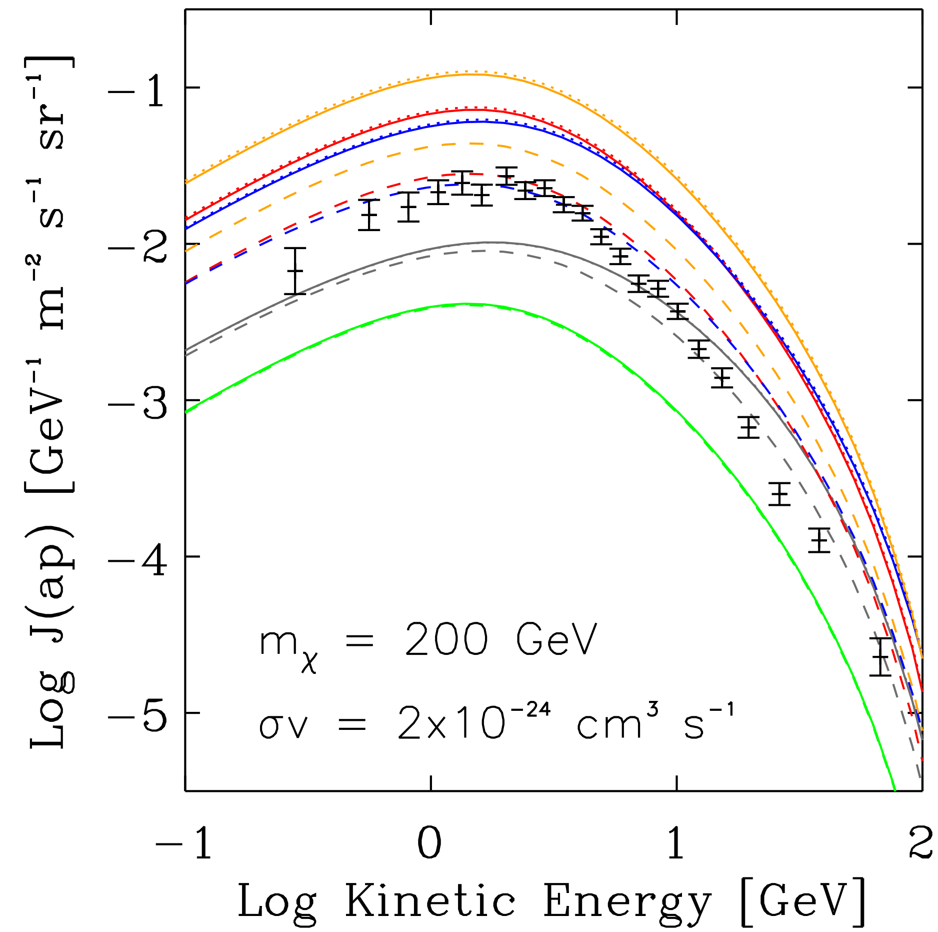
Model dependence of DM antiprotons predictions

Predictions for secondary (background) antiprotons, stemming from CR propagation models calibrated on other secondary/primary CR ratios, are fairly robust; the same is not true primaries from DM annihilations:

secondary/primary B/C



primary $\bar{\mathrm{p}}$ $(M_\chi = 200\,\mathrm{GeV}, W^+W^-)$



Evoli, PU et al., 1108.0664

sample set of CR propagation model:

- "thick"
- Kraichnan
- Kolmogorov
- convective
- "thin"

factor ≈ 50

sample set of DM profiles:

- Einasto (solid)
- Burkert (cored) (dashed)

factor ≲ few

More on DM γ-ray predictions and limits

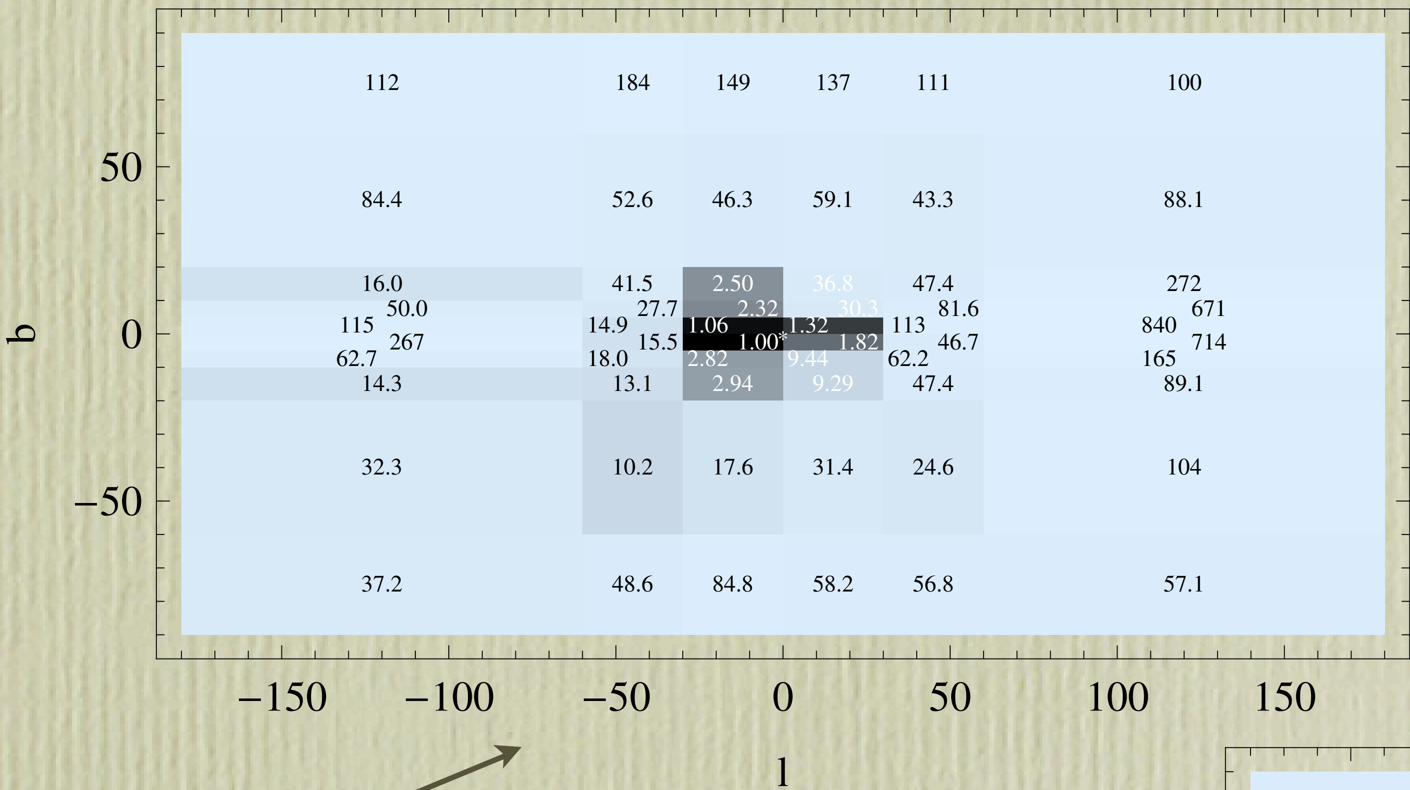
Rather than low, intermediate & high latitude, follow the strength of the limit on the whole sky:

$M_\chi = 10\,\mathrm{GeV},\ b\bar{b}$

plotting: $(\sigma v)^{3\sigma}/(\sigma v)^{3\sigma}_{\min}$

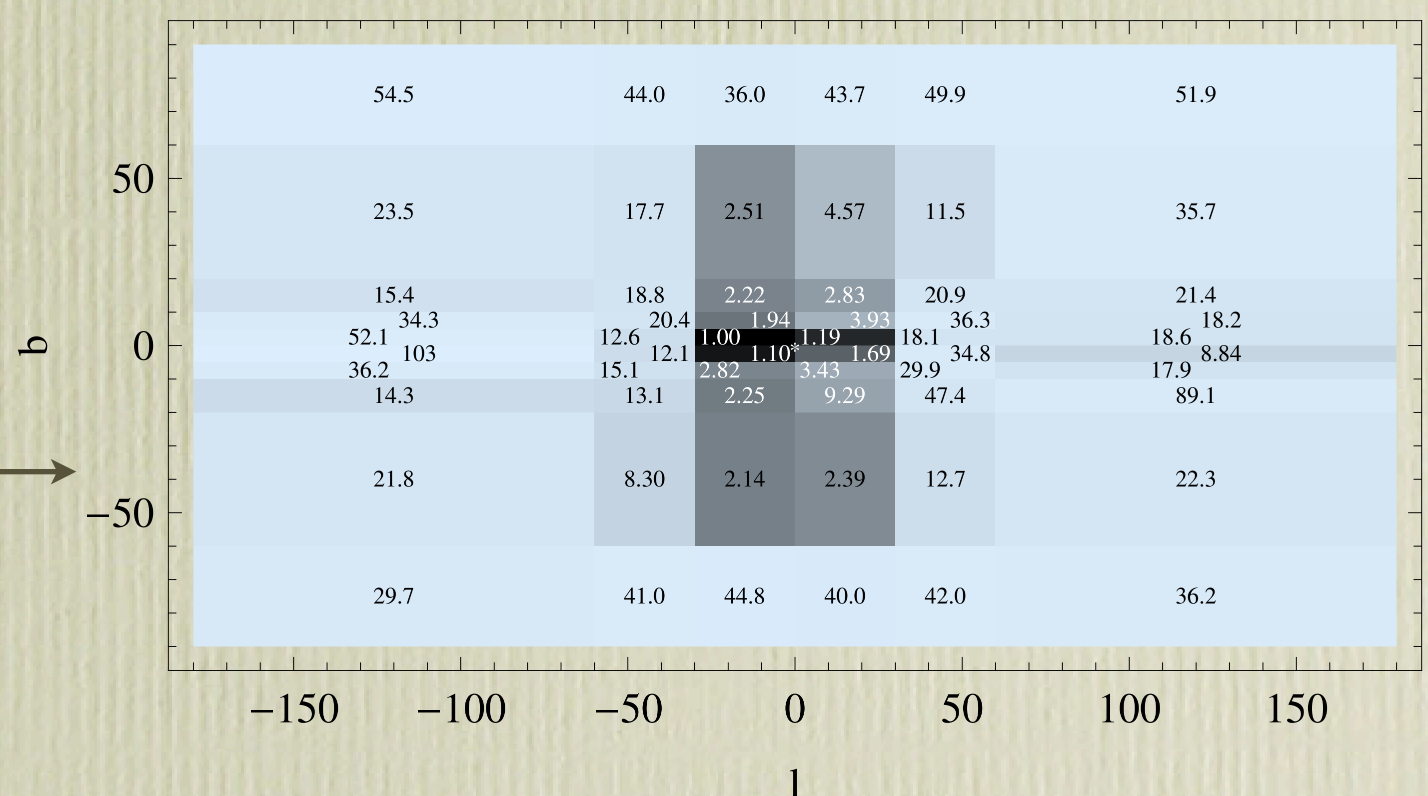
with: $(\sigma v)^{3\sigma}_{\min} = 2.5 \cdot 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$

The darker the region, the tighter the constraint



reference model with "fixed" gas

gas density scaled up to a factor of 2



Tavakoli, PU et al., 1308.4135

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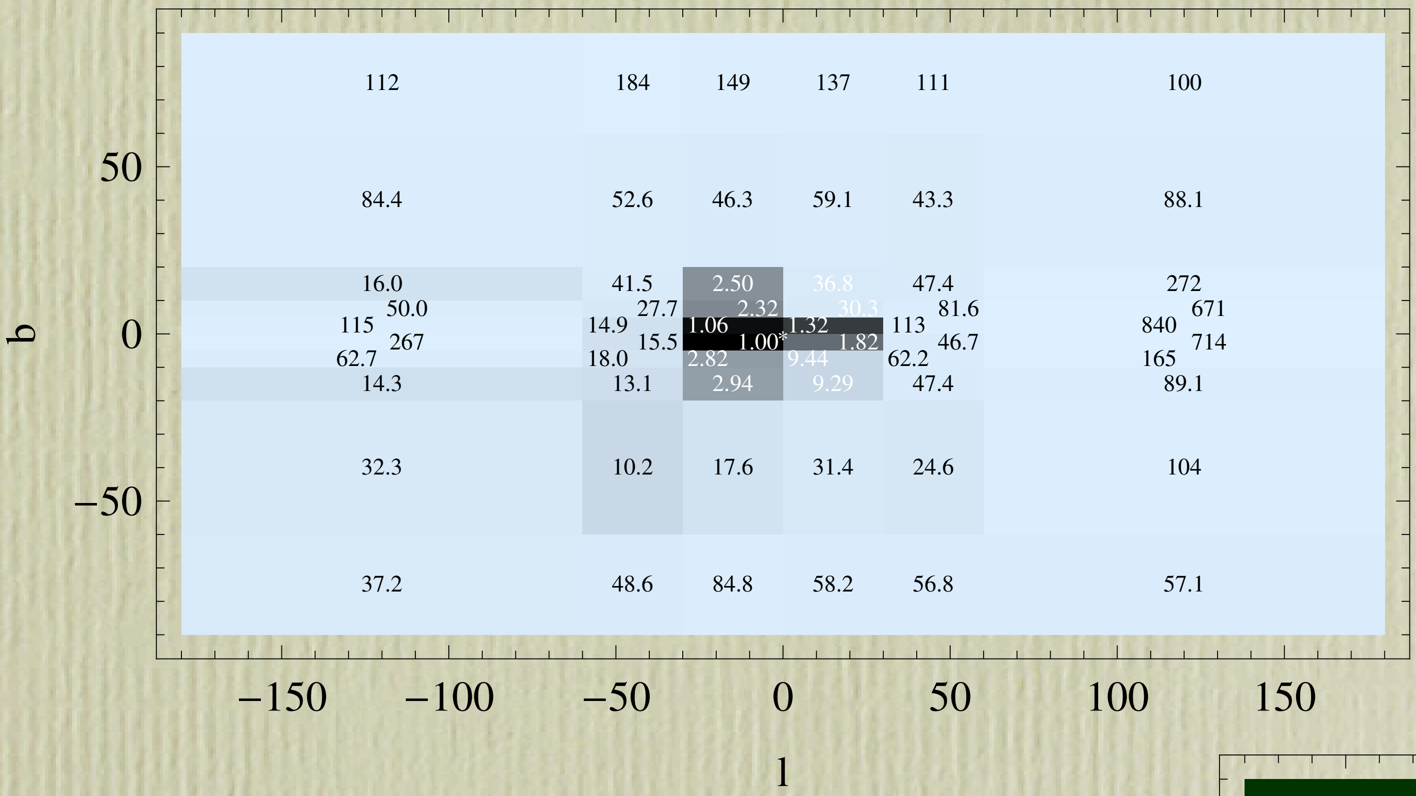


plotting: $(\sigma v)^{3\sigma}/(\sigma v)^{3\sigma}_{\rm min}$

with: $(\sigma v)^{3\sigma}_{\rm min} = 2.5 \cdot 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$

in the "reference" case.

The brightest the color, the less robust the limit:

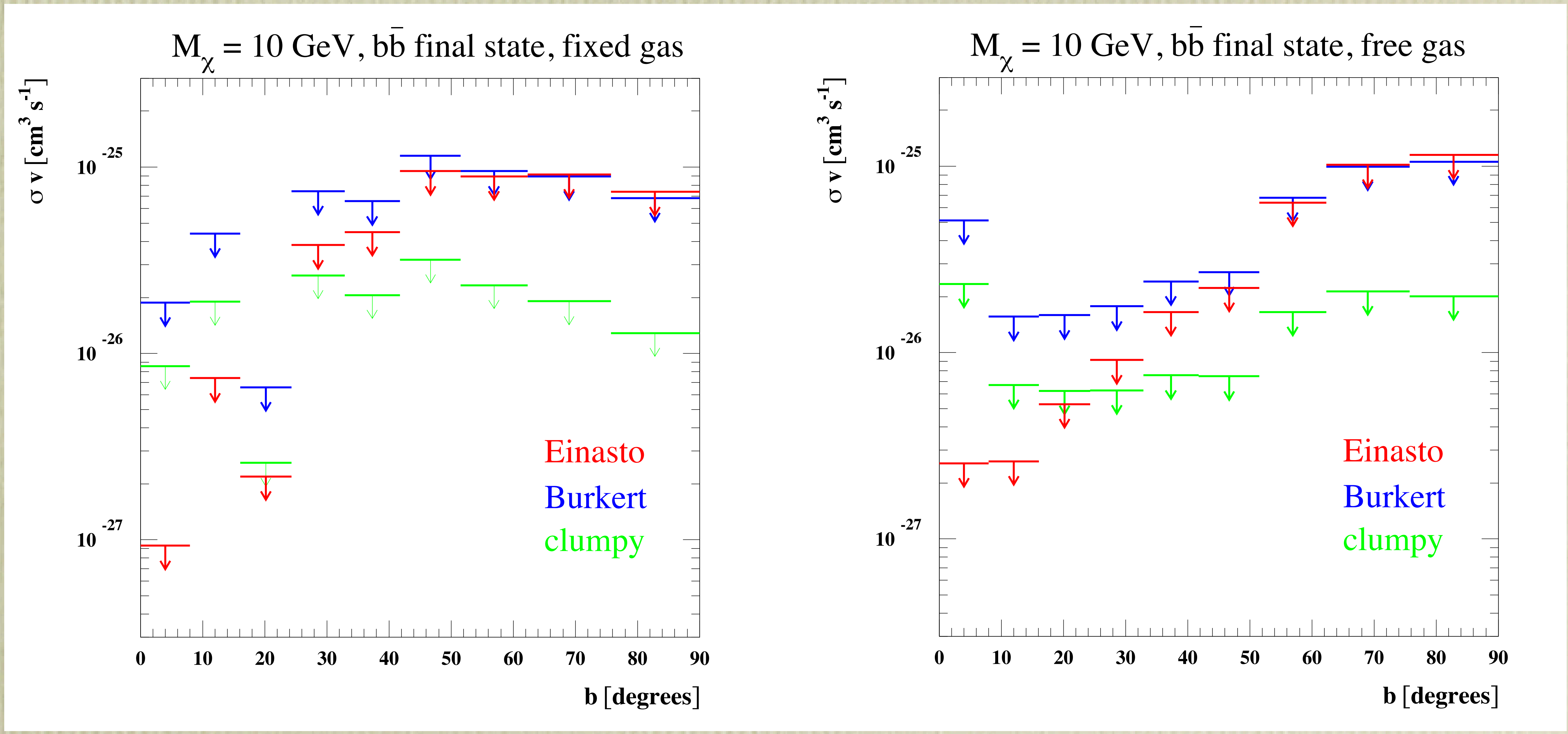
plotting the largest departure from 1 of: $(\sigma v)^{3\sigma}_{\rm i}/(\sigma v)^{3\sigma}_{\rm ref}$

where "i" labels a set of models with different assumptions on the gas (reddish regions) or on the ISRF (greenish regions).

Tavakoli, PU et al., 1308.4135

More on DM γ-ray predictions and limits

Project the limit into latitude bins and translate them from the sample Einasto halo profile into other possibilities:



$\rho_{\rm Ein} \propto \exp\left[-\frac{2}{\alpha}\left(x^\alpha - 1\right)\right]$ $\rho_{\rm Bur} \propto \frac{1}{(1+x)(1+x^2)}$ clumpy: $\mathcal{N}_{\rm pairs} \propto \rho$

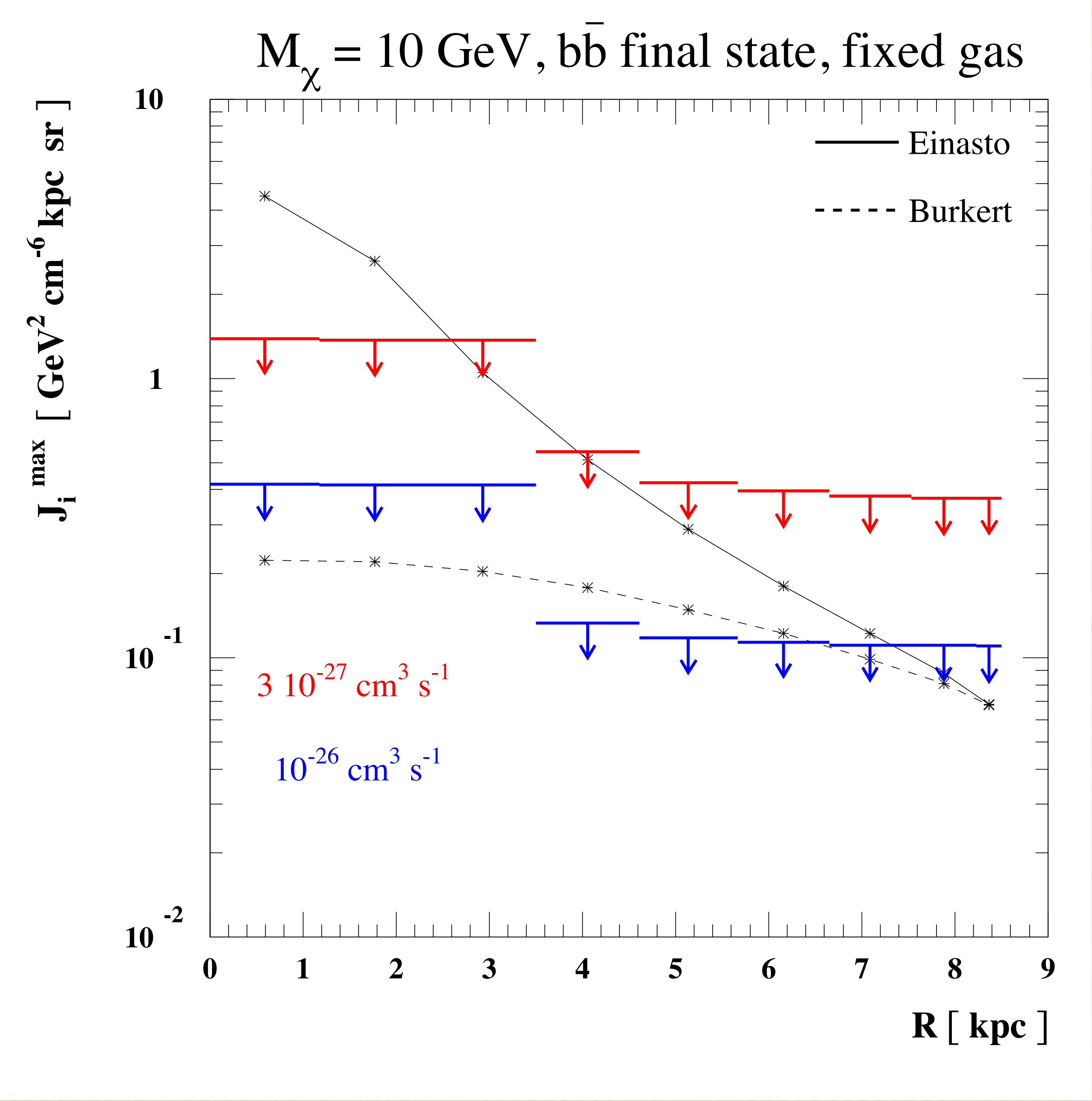
All normalized to a local halo density: $\rho(R_\odot) = 0.4\,{\rm GeV\,cm^{-3}}$

More on DM γ-ray predictions and limits

Play it even harder and define the density profile as log-log interpolation of a set of discrete values ρ_i at the galactocentric distances r_i corresponding to the radii at the tangential points in the latitude bins. Assume also that the profile is monotonic and that:

$$\rho(r) = \rho_{\rm Ein}(r) \quad \text{for} \quad r > R_\odot$$

Fix the annihilation rate, and generate a random sample of ρ_i , testing whether each configuration is excluded by the flux limits in all latitude bins. For all surviving models, consider the bin encompassing the GC and compute the line of sight integration factors J_i obtained by imposing that the density profile is constant below r_i . Plot the maximum of J_i in the sample and compare it to the analogous quantity for the preferred parametric profile:



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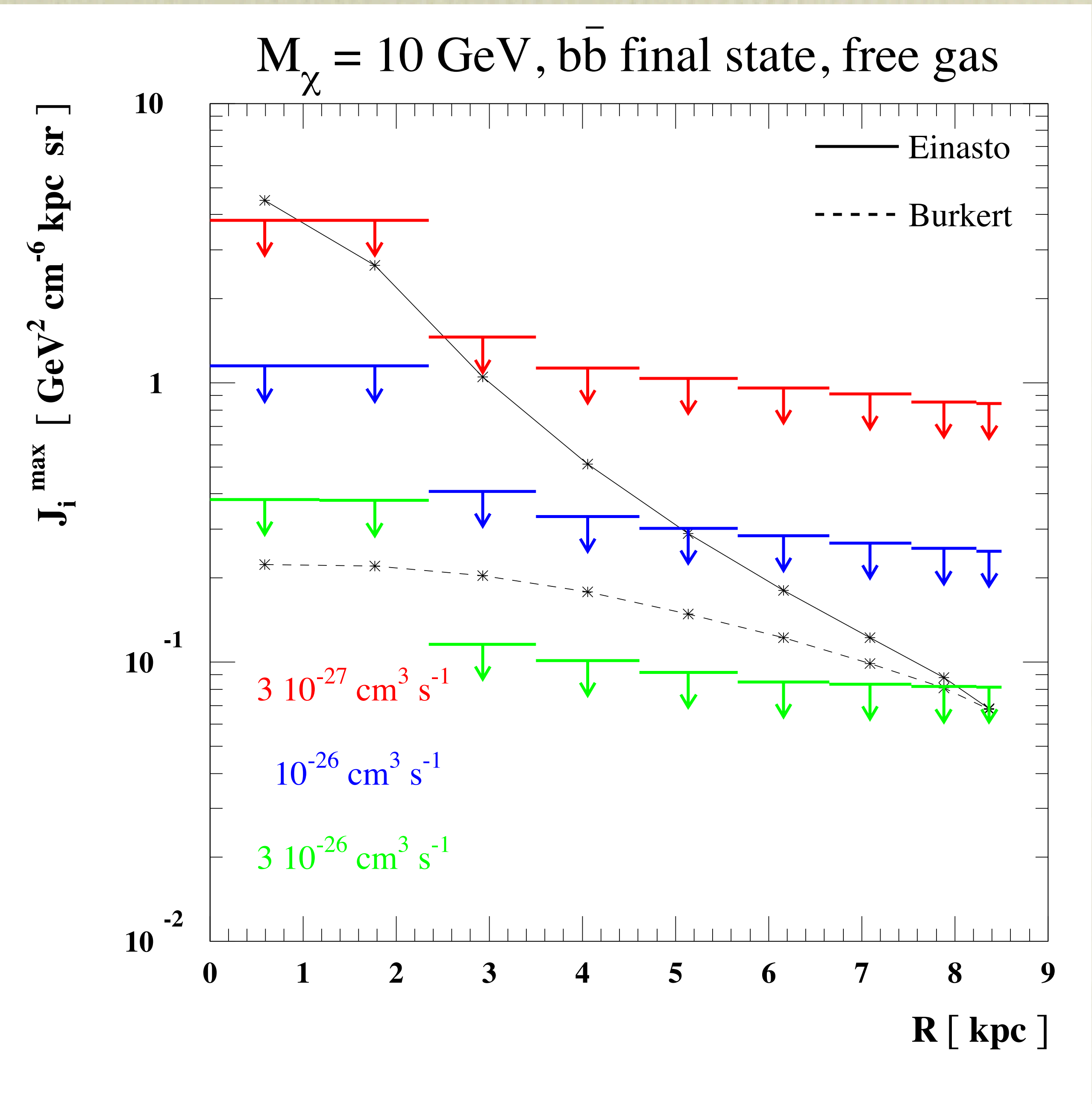

Summary and conclusions

• Plenty of indirect (gravitational) evidence for DM from cosmological and astrophysical observations, but loose connection to specific DM particle physics scenarios. Can we trust any guideline (prejudice) and/or (re)focus the DM problem in directions previously overlooked?

• The LHC is challenging the beyond SM extensions based on naturalness, and is reshaping the WIMP scenario: DM shifting from byproduct to key element for discussing SM extensions.

• DM not detected so far at the LHC; signal and limits from direct detection are in apparent contradiction; a few "hints" of indirect detection have been claimed, but the picture is far from being satisfactory.

• While it is arguable whether a signal in a given detection channel can be trusted (say: the GeV excess in the central region of the Galaxy), the annihilating DM scenario has to be addressed in multi-wavelength and multi-messenger studies; comparing limits however is no back-of-the-envelope task!