OVERVIEW OF INDIRECT DARK MATTER SEARCH: STATUS AND CHALLENGES

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DarkWin, Natal, September 3rd 2019

Outline

This talk

- What we know on DM, and the **quest for (indirect) DM identification**: The contours of the bet
- **Typical challenges: illustration with the Galactic Center Excess saga.**
- **The road ahead: a couple of strategies**
- **Conclusions**

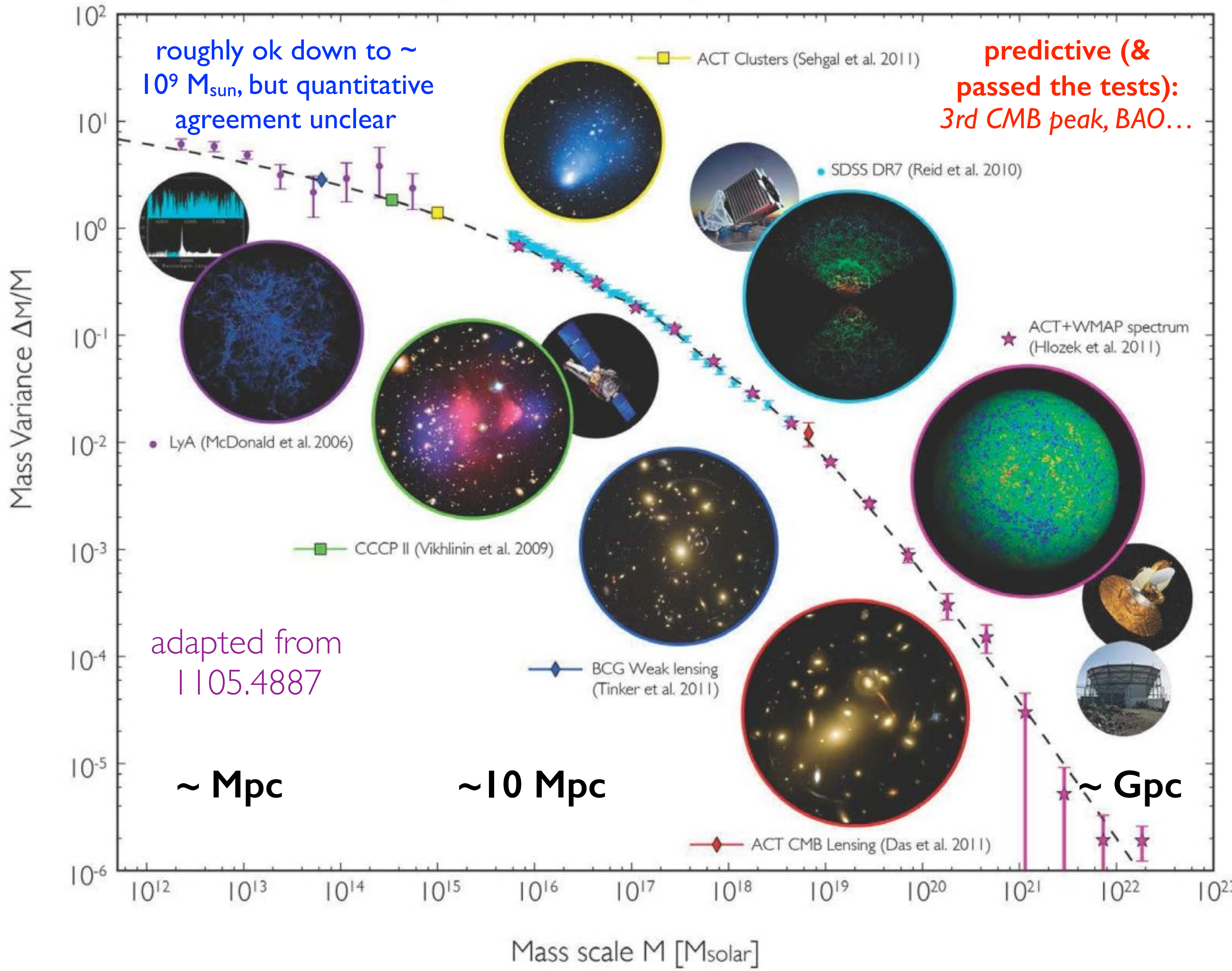
Second talk

more specifically on the (astro)physics involved in the cosmic ray antiproton searches (illustrating some of the nitty gritty you should deal with, if working on these problems…)

What do we know?

(Great review yesterday by Graciela Gelmini, won't spend too much time)

DM is a **simple** description of cosmo/astro data on many scales/at different epochs



$$G_{\mu\nu} + \Lambda\, g_{\mu\nu} = 8\pi G \left(T_{\mu\nu}^{\text{known}} + T_{\mu\nu}^{\text{DM}} \right) \qquad T_{\mu\nu}^{\text{DM}} = \rho U_\mu U_\nu$$

The good, the bad, and the ugly

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The DM problem requires new physics, beyond the "Standard Model" (SM) known today. Only a handful of similar indications exists: explains the **interest of particle physicists**!

Problem

We want to infer the underlying UV theory starting from a very simple cosmological macroscopic description.

Gravity is universal: no particle identification! **discovery via other channels** is needed **to clarify particle physics** framework (*if not merely gravitationally coupled*), or break the fluid limit. But **what to look for is model-dependent!**

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Goal of indirect detection (IDM)
remotely sensing some effects *(such as byproducts of DM decay/annihilation in remote astrophysical sites)* which yield information about **DM nature**

Without forgetting the caveat

there are models fulfilling all the constraints above and that are "undetectable"
→**The DM *identification* quest admits (virtually) untestable solutions**

Quest for DM identification: contours of the bet

Will illustrate with the most popular
(but by no way unique!) line of argument

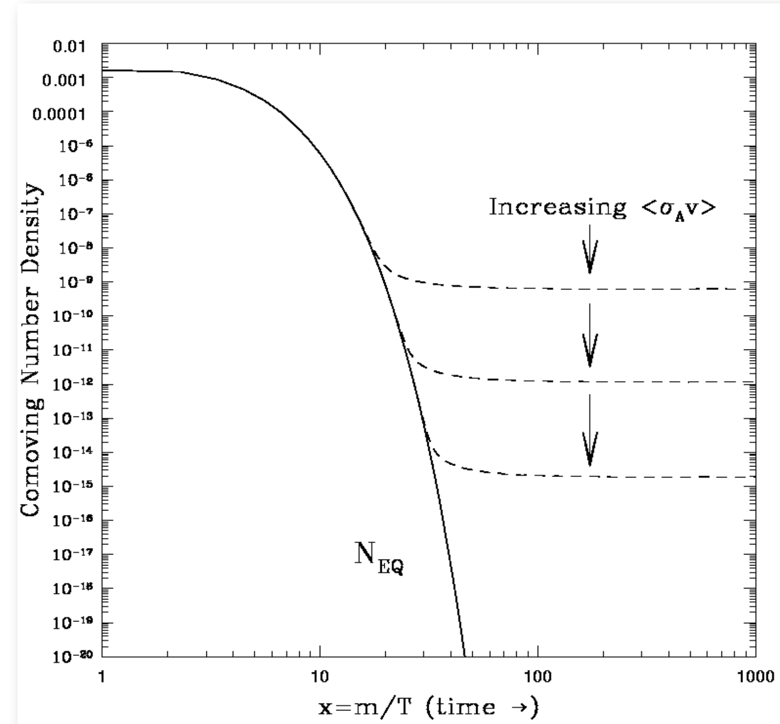
The WeaklyInteractingMassiveParticle Paradigm

Cosmology tells us that the early universe was a hot plasma, with all "thermally allowed" species populated. Notion tested up to T~ few MeV (BBN, cosmo ν's):

What if we extrapolate further backwards, adding to the SM just…

$$X\bar{X} \longleftrightarrow \ell\bar{\ell}$$

…a single ***stable massive particle*** in ***chemical equilibrium with SM*** via ***EW-strength binary interactions*** in early universe down to *T*<<*m* (required for **cold** DM, i.e. non-relativistic distribution function!). It suffers exponential suppression of its abundance



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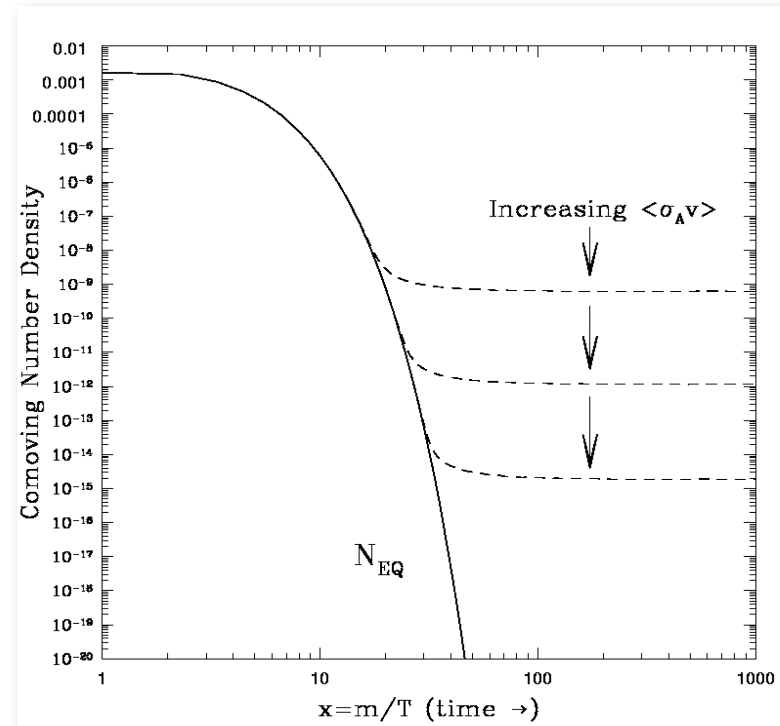


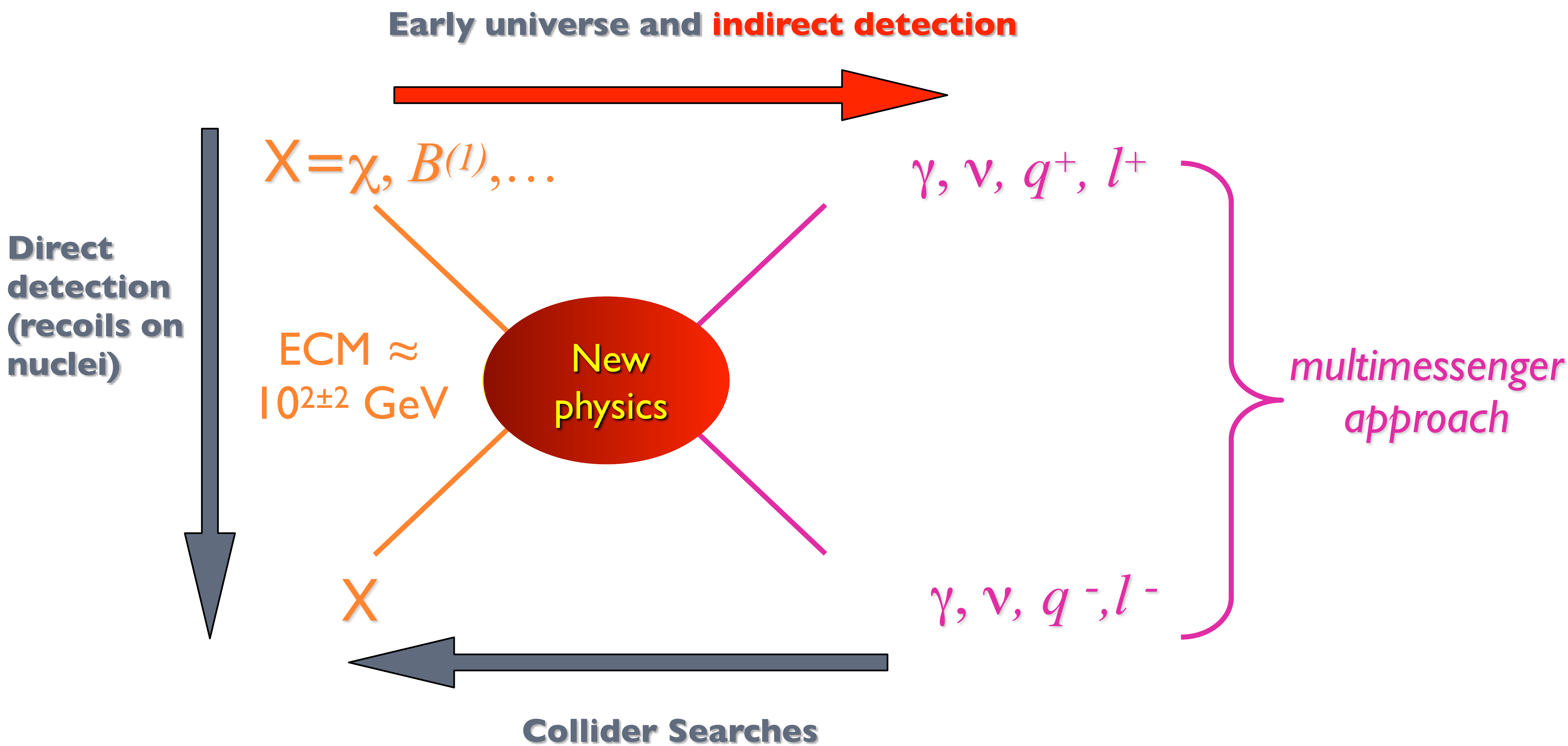
Textbook calculation yields the current average cosmological energy density

$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}$$

Observationally inferred $\Omega_{DM}h^2$~0.1 recovered for EW scale masses & couplings (aka ***WIMP miracle***)!

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m^2} \simeq 1\,\mathrm{pb}\left(\frac{200\,\mathrm{GeV}}{m}\right)^2$$

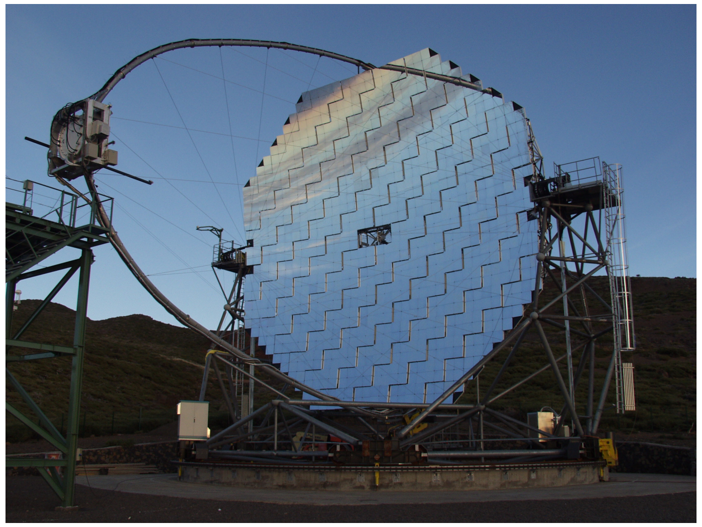
IDM WIMP searches

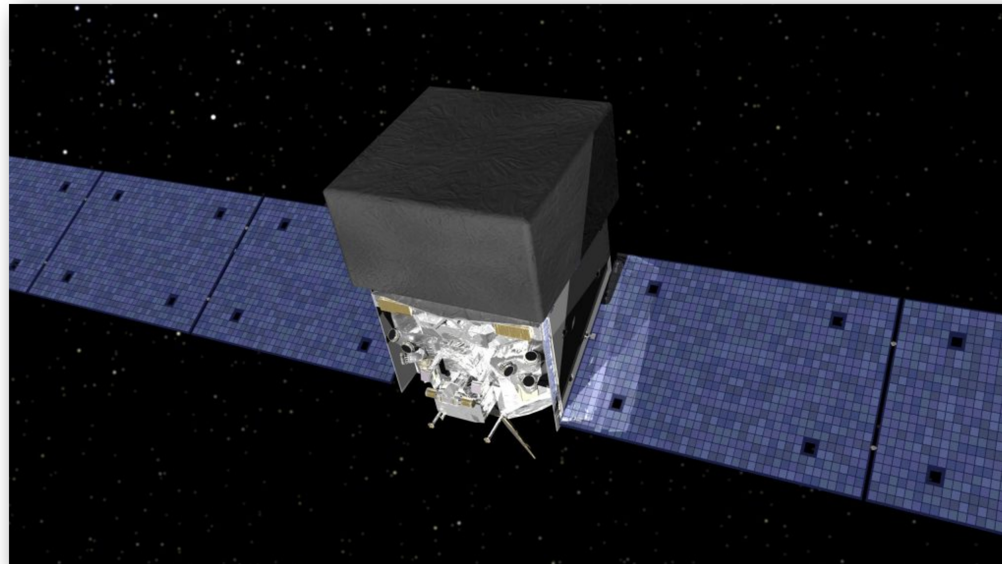


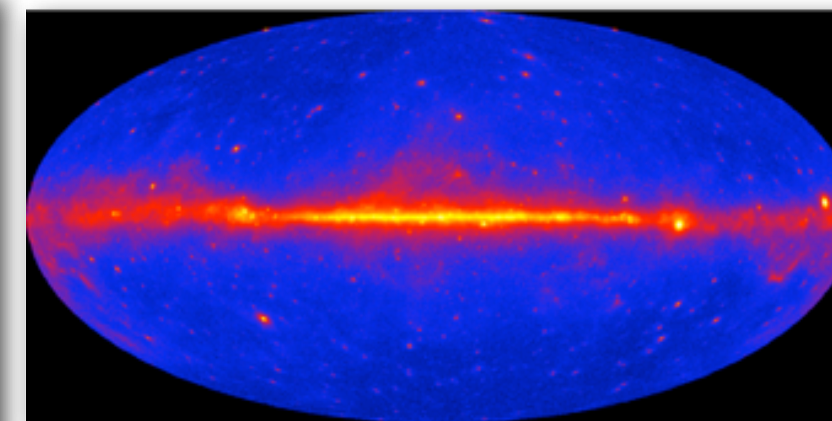
- ✓ Want to detect stable SM particles remotely produced
- ✓ *Injected* SM particles depend on the particle process (above: annihilation) and DM astrophysical distribution
- ✓ Particles at the Earth can be affected by propagation effects (E-losses, diffusion…)

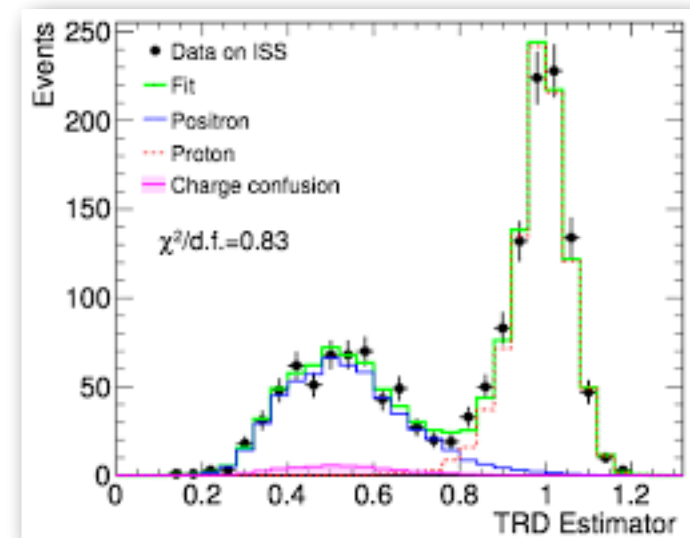
many channels & tools for indirect WIMP searches

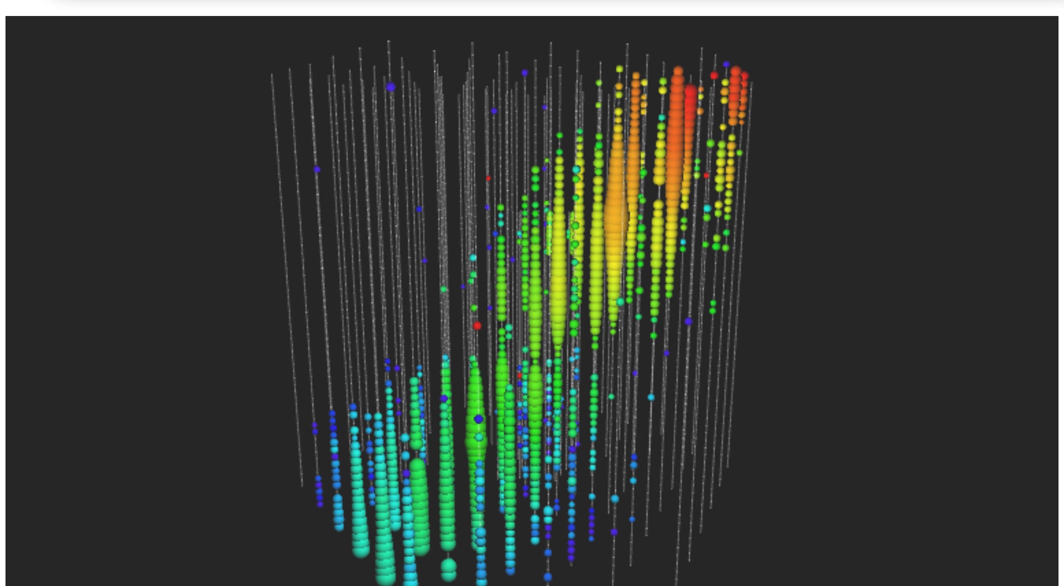
each one with advantages and problems

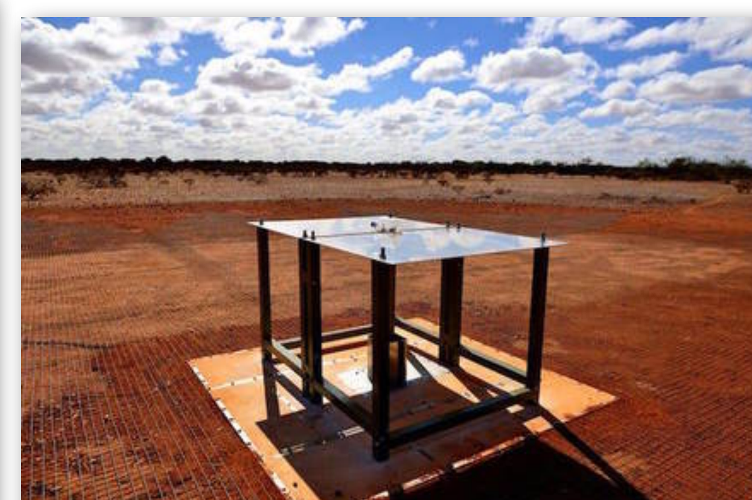












Status of multi-messenger WIMP identification program

Paradigm of the multimessenger program
“The blind men & the elephant”

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Paradigm of the multimessenger program
"The blind men & the elephant"

Mughal painting, ~ 1600 AD

Null results till now *(in none of the channels)*
+
a number of more or less hyped claims
(notably in IDM, none of which confirmed independently, admitting alternative astrophysical or instrumental explanations)

Status of multi-messenger WIMP identification program

Paradigm of the multimessenger program
"The blind men & the elephant"

In our case, it seems that the **men are not blind,** but the **elephant is invisible**

Null results till now *(in none of the channels)*
+
a number of more or less hyped claims
(notably in IDM, none of which confirmed independently, admitting alternative astrophysical or instrumental explanations)

Problems in IDM identification quest

our biggest problems

- **The signal is not known.**
  At best, its vague contours guessed within a multi-parametric model which most likely does not include the "true" solution.

  E.g. even if DM is explained within SUSY (a strong prior!), unclear if it's one of the (simplified) SUSY scenarios already proposed

- The "**background**" is **only approximately known** (sometimes this is an irreducible limitation, since not accessible in the lab!)

Illustration of the frustrating hunt for DM

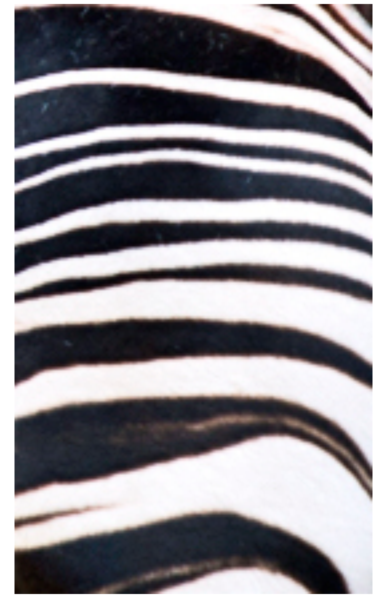
We ***believe*** that the **signal** looks like

Illustration of the frustrating hunt for DM

We ***believe*** that the **background** is rather like

Illustration of the frustrating hunt for DM

When a new experiment provides a new (or deeper) view of the cosmos, often we start to observe



… then many people run writing dozens of papers about the discovery of DM…

Illustration of the frustrating hunt for DM

When a new experiment provides a new (or deeper) view of the cosmos, often we start to observe

… then many people run writing dozens of papers about the discovery of DM…

…eventually realizing that the complete picture is more complex, revealing a **richer background**

Okapia johnstoni, fam.: giraffidae

Actual example from the gamma-ray sky

Gamma signal

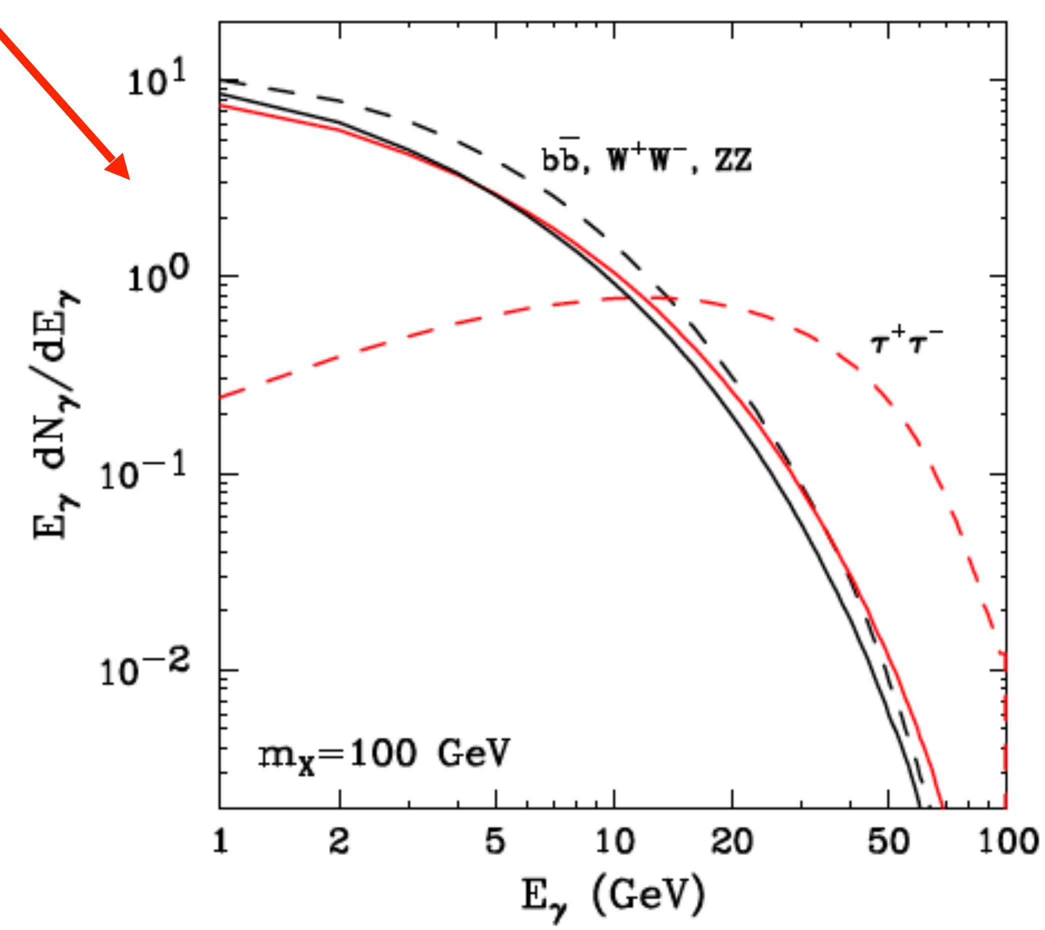
Typically E-loss/absorption negligible for *prompt* emission (one exception will be discussed by A. Esmaili!)

Often factorized:

$$\frac{d^2\Phi_i}{dE d\Omega}(E,\hat{\Omega}) = \frac{\langle \sigma v \rangle}{8(16)\pi m_{\rm DM}^2} \frac{dN_i}{dE}(E) \int_{\rm l.o.s.} \rho_{\rm DM}^2(s,\hat{\Omega}) ds$$

particle physics **astrophysics** *This is known as "J-factor"*

Parametric (depends on the model predictions for the SM final state spectra); computable if model is perturbative…



Note: [particle] ⊗ (astro) factorization only holds if

- **σ v is v-independent**

(otherwise goes under integral, over v distribution)

- **if *prompt* emission dominates**

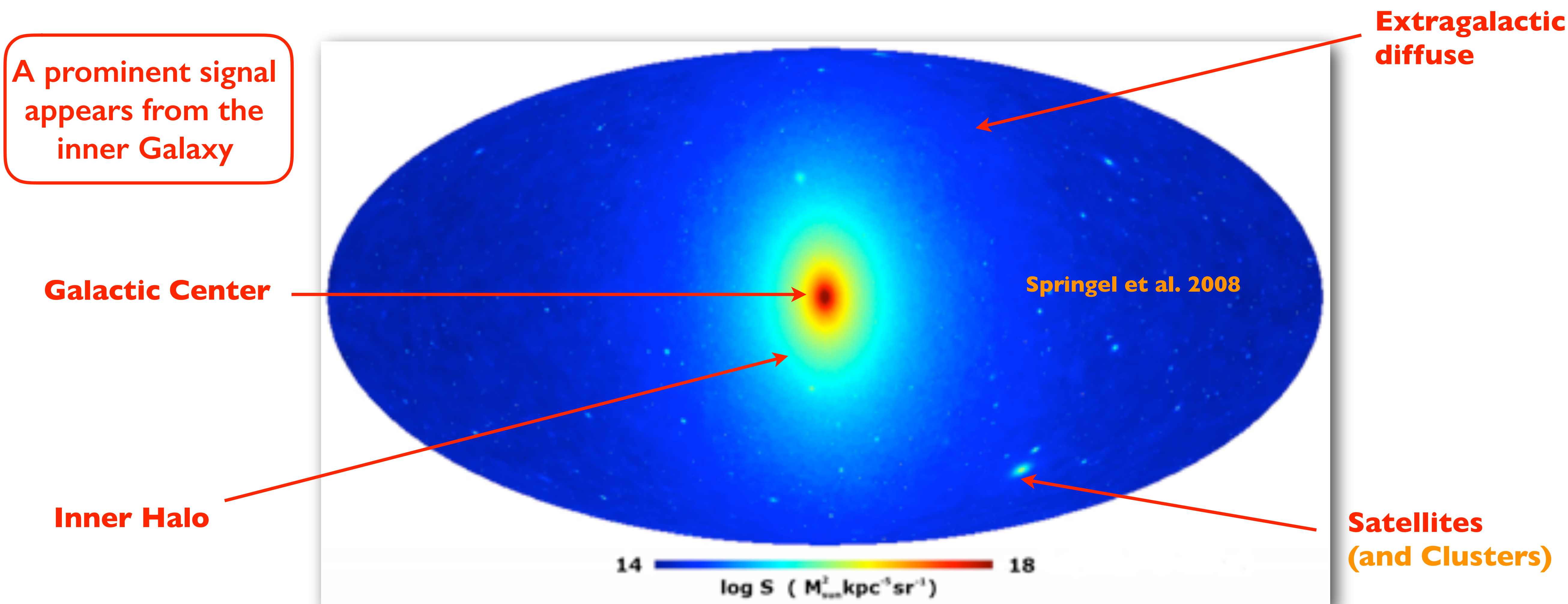
(for secondary emission, need to follow e± propagation…)

What signal morphology does "theory" predict?

γ-ray map from DM annihilation in Galactic coordinates, according to a N-body simulations

Comment I.
most of the signal depends upon structures deeply in non-linear regime of gravitational interaction.
Little "first principle understanding" (very different from the situation in cosmo evidence for DM!)

Comment II.
this simulation includes only DM. But "baryons" do matter (stars form & explode, gas cools, etc.). Modern simulations do include these via some 'parametric recipes' (no way can be dealt with from first principles)



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γ-ray map from DM annihilation in Galactic coordinates, according to a N-body simulations

Actual estimate of uncertainties: Orders of magnitude!

So you can't trust much the morphology when the signal is maximal (worsens the closer one goes to GC)

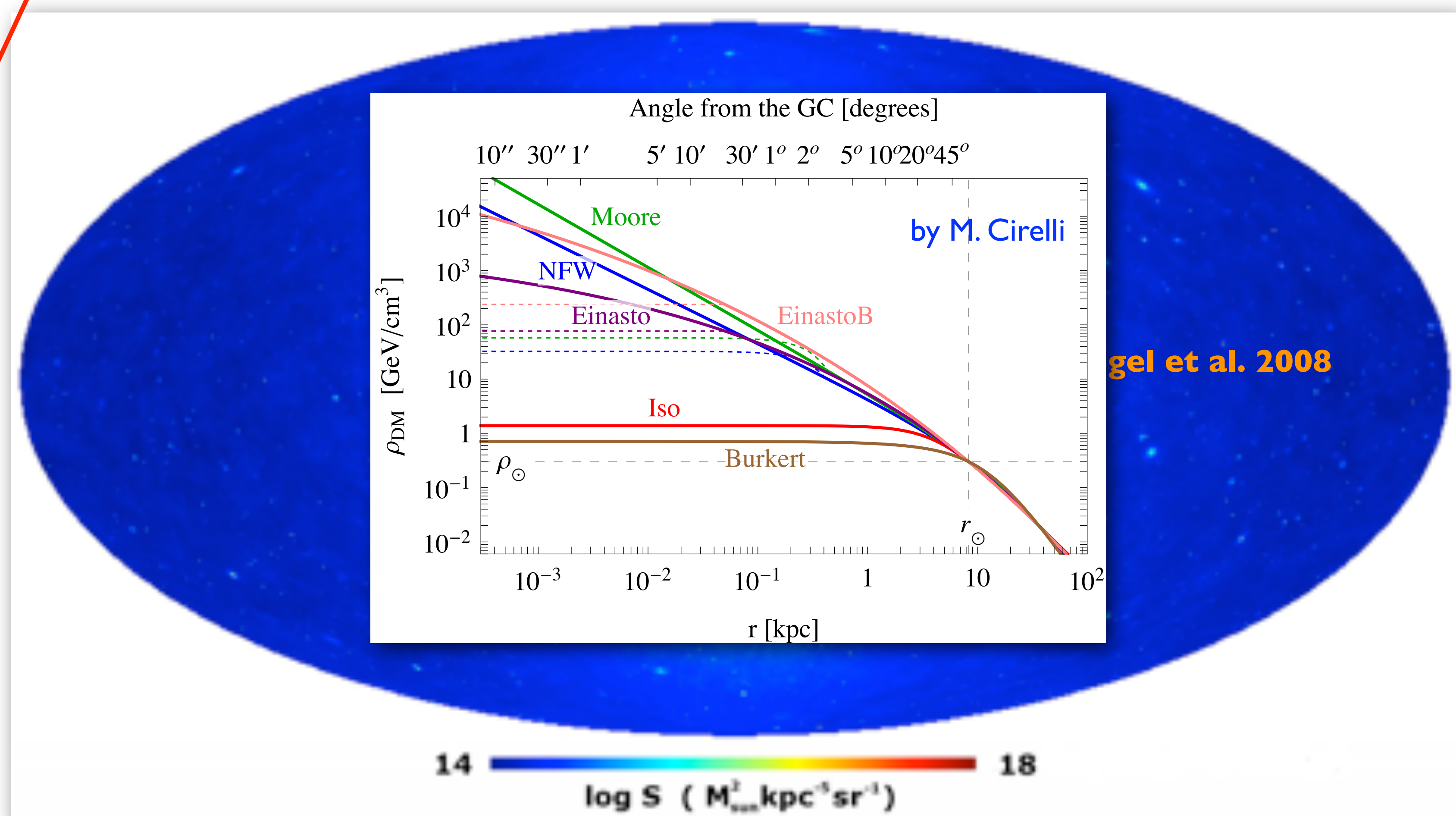
A prominent signal appears from the inner Galaxy

Extragalactic diffuse

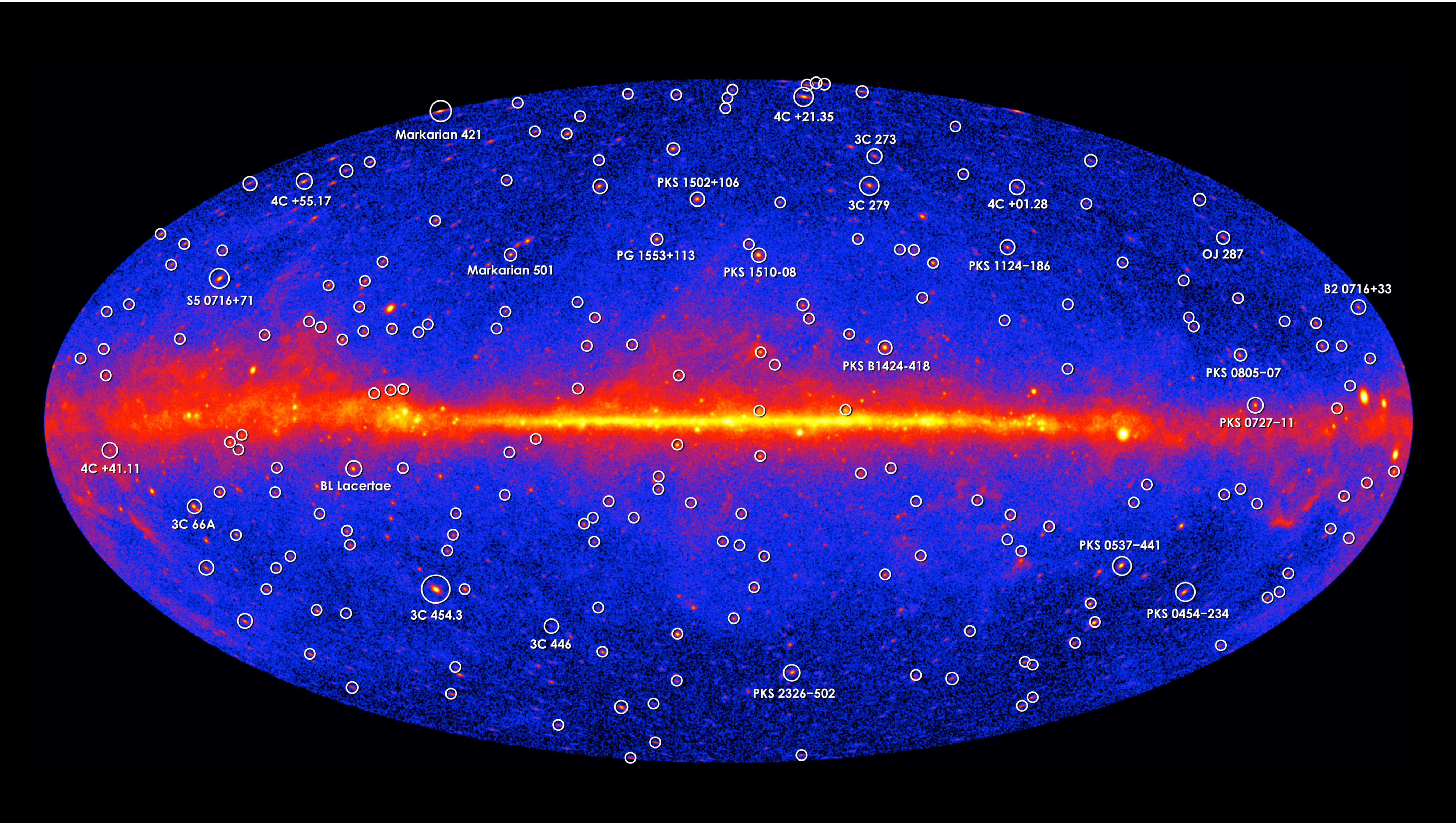
Galactic Center

Inner Halo

Satellites (and Clusters)



The Fermi sky in the GeV energy range



Fermi sees nothing like DM expectations: **backgrounds** (aka astrophysical sources) **important!**
Their understanding is the main challenge in indirect DM searches

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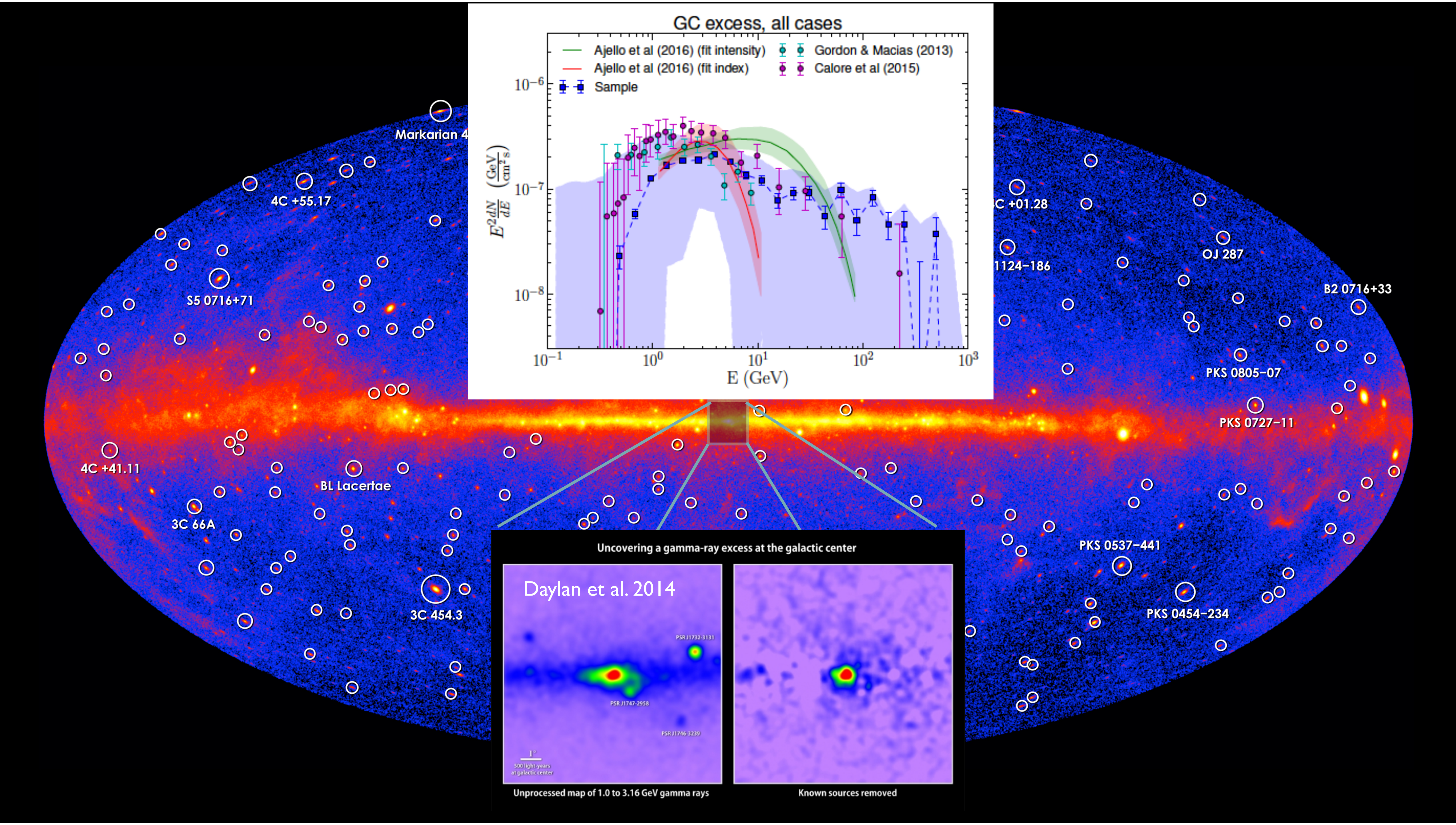


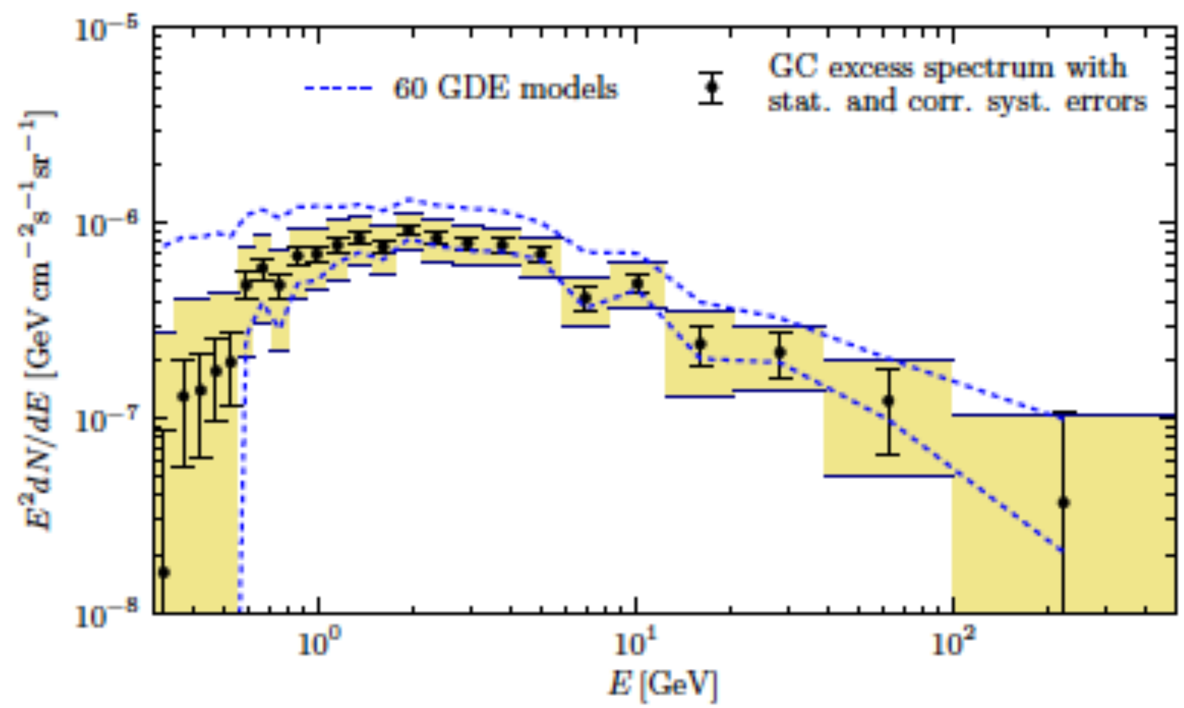
Yet, in the past decade, a statistically significant γ-ray excess over diffuse emission *model* + *known* astrophysical sources has been unveiled

Basic reasons for the DM interpretation

Spectrum: Well fit by a 40-70 GeV particle annihilating to quarks, roughly uniform across the Inner Galaxy

Morphology: Roughly spherically symmetric, with a flux falling as $\sim r^{-2.4}$ out to at least $\sim 10^{o}$, consistent with a DM halo only slightly steeper than the benchmark NFW profile suggested by DM-only simulations

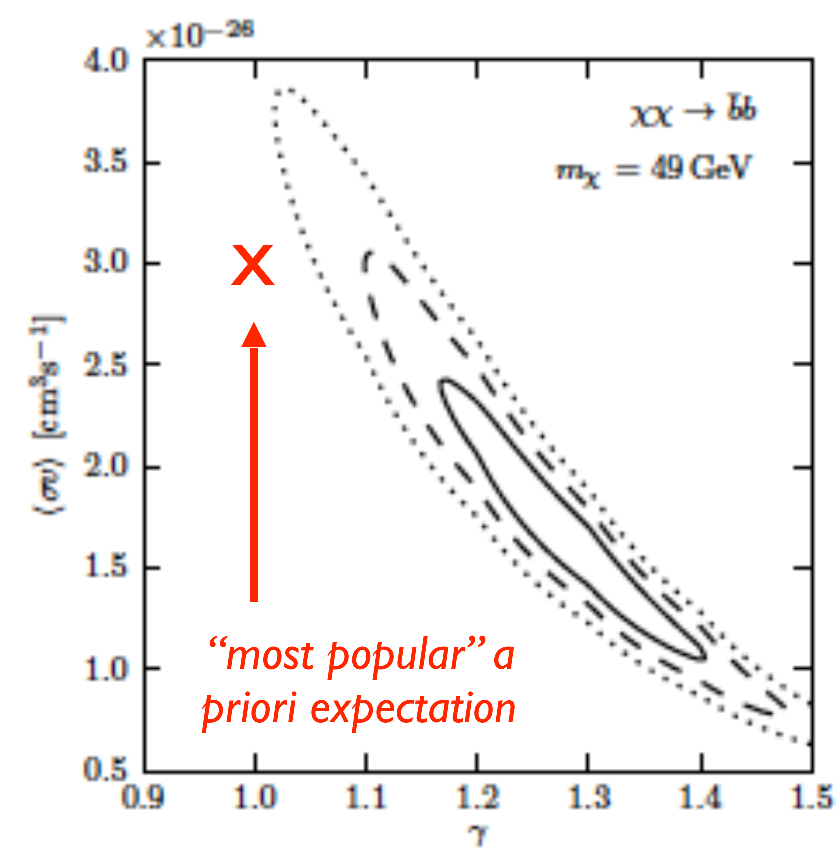
Intensity: Requires an annihilation cross section of $\langle\sigma v\rangle \sim 2\ 10^{-26}$ cm^3/s, near the value of a S-wave thermal relic



some key references

T. Daylan et al. "The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter", 1402.6703

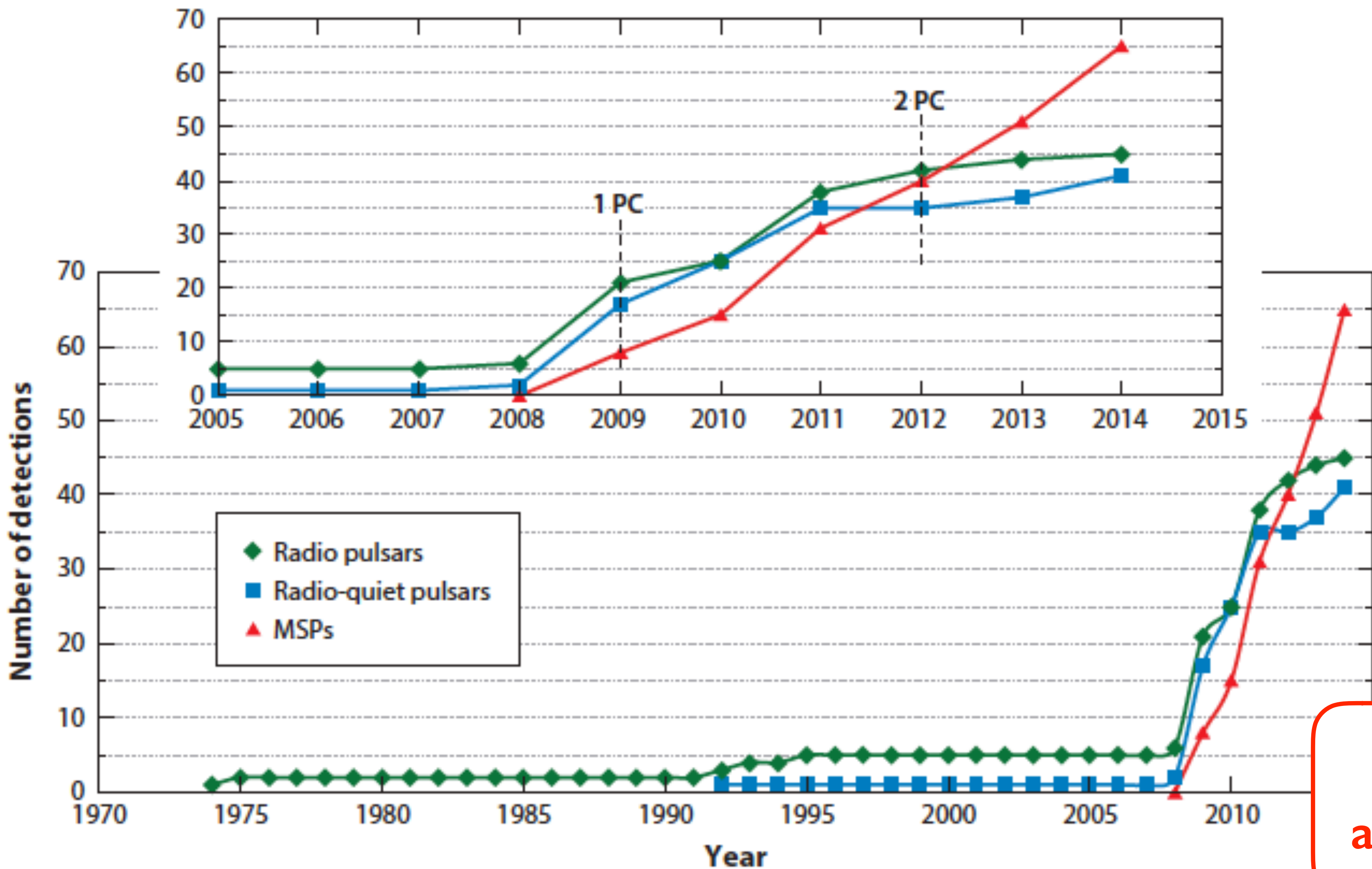
F. Calore, I. Cholis and C. Weniger, "Background model systematics for the Fermi GeV excess," 1409.0042



in parallel: Example of surprise with Fermi-LAT mission

➡ **milli-second pulsars (MSPs) have emerged as a new (& numerous!) class of sources**

usually MSPs interpreted as old, recycled pulsars, spun up due to accretion from companion star.



Could they also account for the GCE?

Their discovery notably in the gamma-band has boomed after Fermi launched, now most abundant class in the Galaxy!

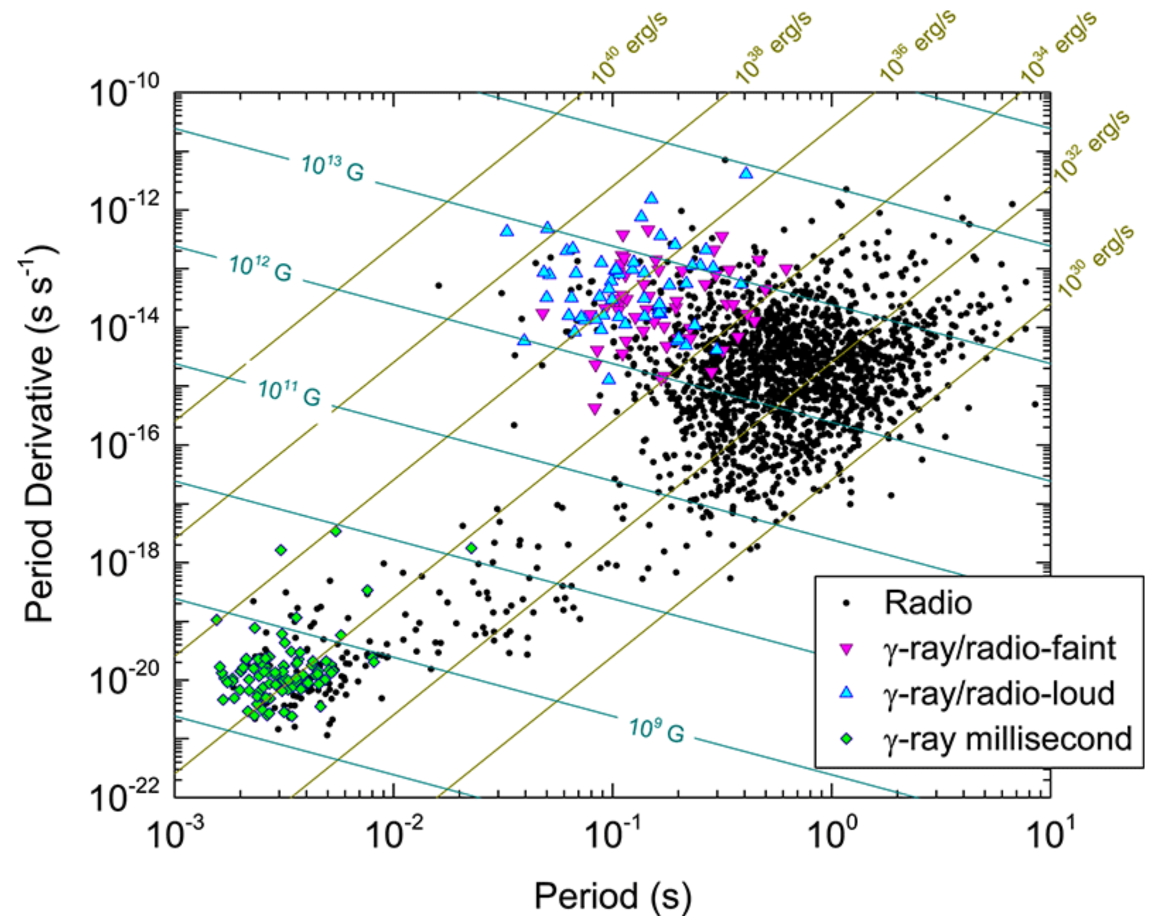
P.A. Caraveo, "Gamma-ray Pulsar Revolution,"
Annual Review of Astronomy and Astrophysics 52 (2014) [1312.2913]

Main reasons for MSP interpretation

✓ **Millisecond pulsars exist (and γ-abundant)**

✓ **Spectrum** of both isolated MSP and of Glob. Clusters similar to the Gal. Center one!

K.N. Abazajian, JCAP 1103 (2011) 010 [1011.4275]



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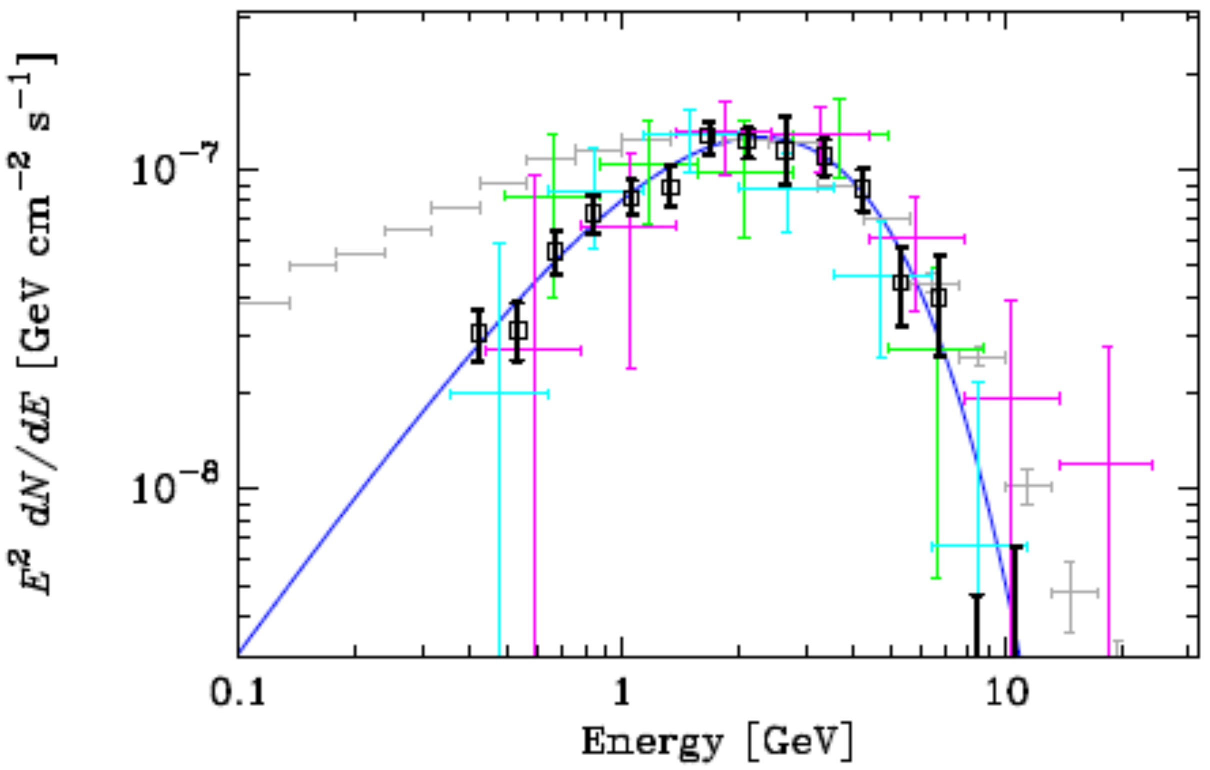

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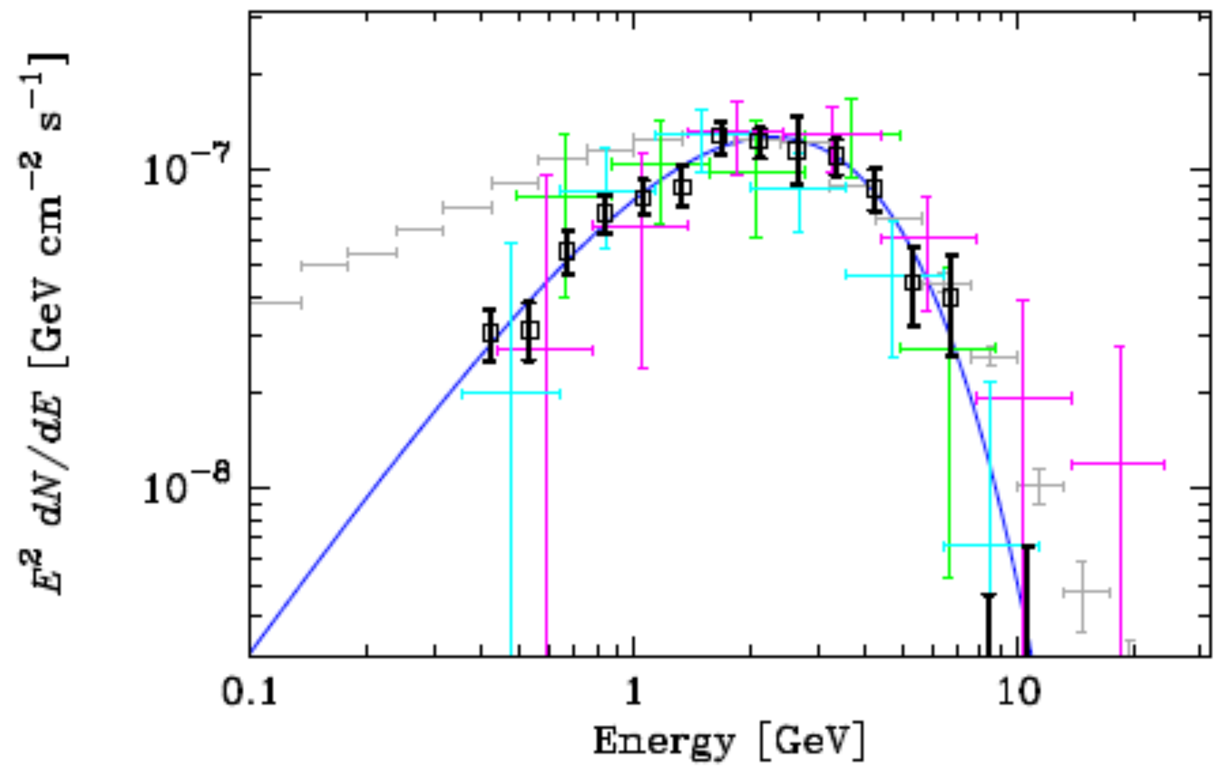
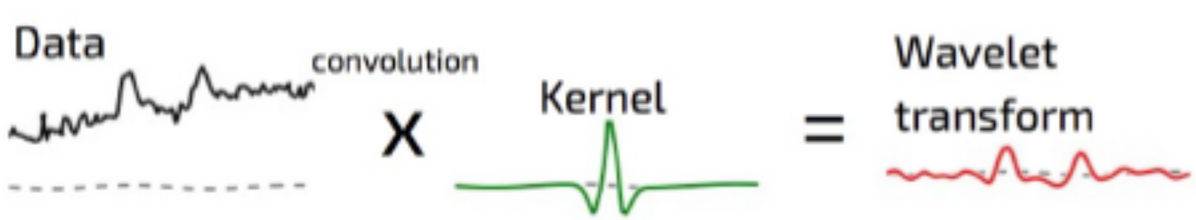
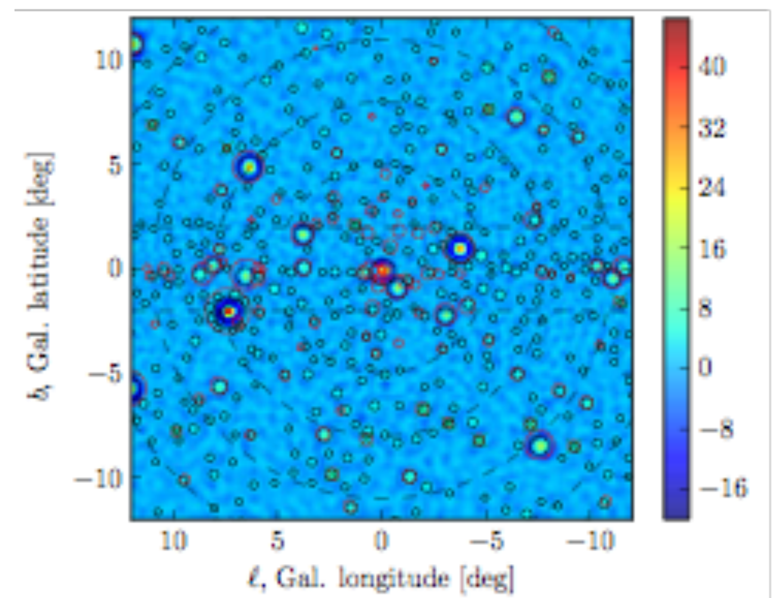


✓ Support for unresolved point sources from Wavelet transform



Excess power at small scales *(no background modeling, constraint on spatial and luminosity distribution)*



R. Bartels, S. Krishnamurthy and C. Weniger, PRL 116, 051102 (2016) [1506.05104]

Similar evidence from pixel statistics reported in *S. K. Lee et al. PRL, 116, 051103 (2016) [1506.05124]*

questionable according to Leane & Slatyer 1904:08430… or not so much, see Chang et al. 1908.10874: open issue the extent to which the method is sensitive (certainly it's not DM that strikes back)

Playing devil's advocate

Hard to tell whether these clustered gamma-rays result from unresolved sources or from backgrounds that are less smooth than being modeled

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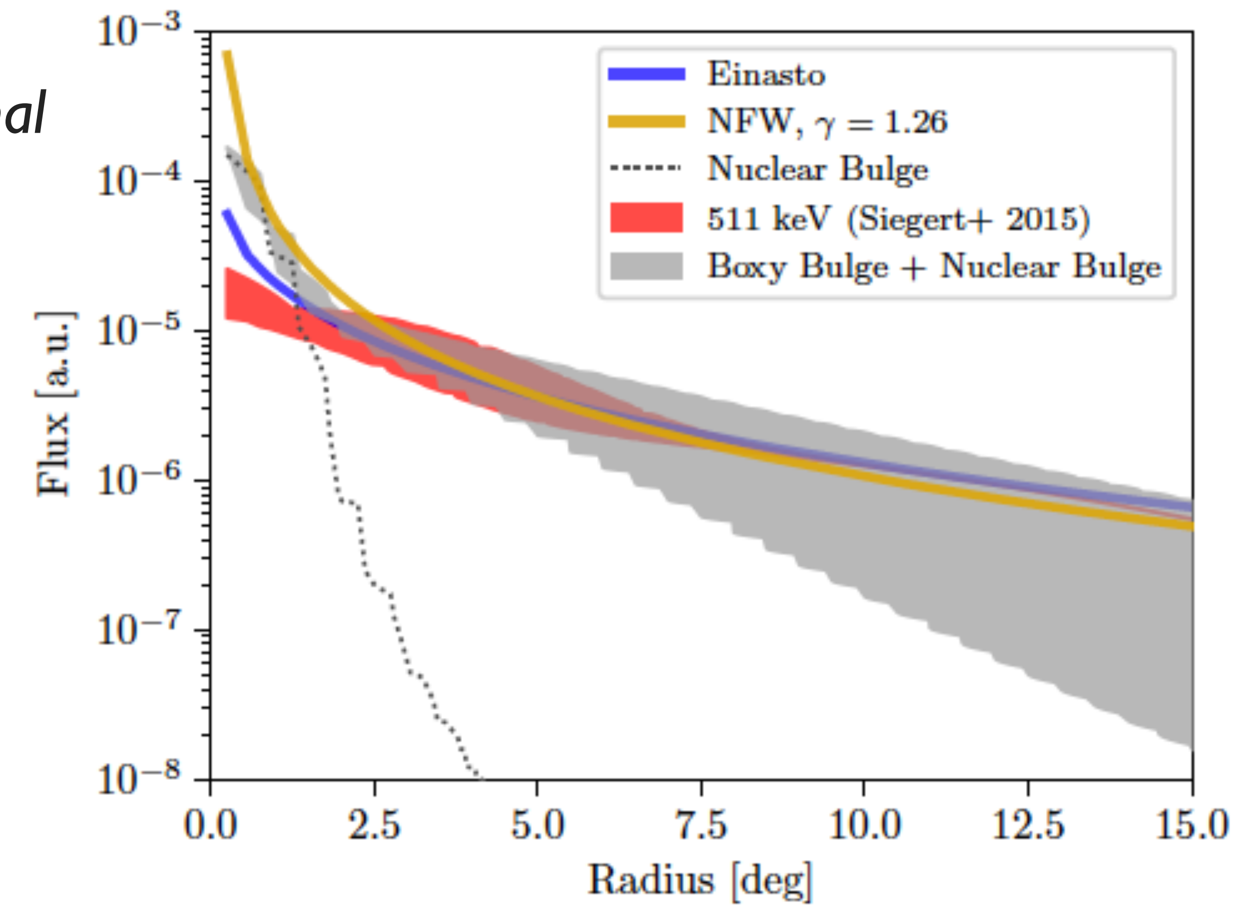
True… however, GCE traces *stellar* density!

O. Macias et al., "Galactic bulge preferred over dark matter for the Galactic centre gamma-ray excess," Nature Astronony (2018)
R. Bartels, E. Storm, C. Weniger and F. Calore, "The Fermi-LAT GeV Excess Traces Stellar Mass in the Galactic Bulge," Nature Astronomy 2018

"Stellar mass templates are preferred over conventional DM profiles with high statistical significance"



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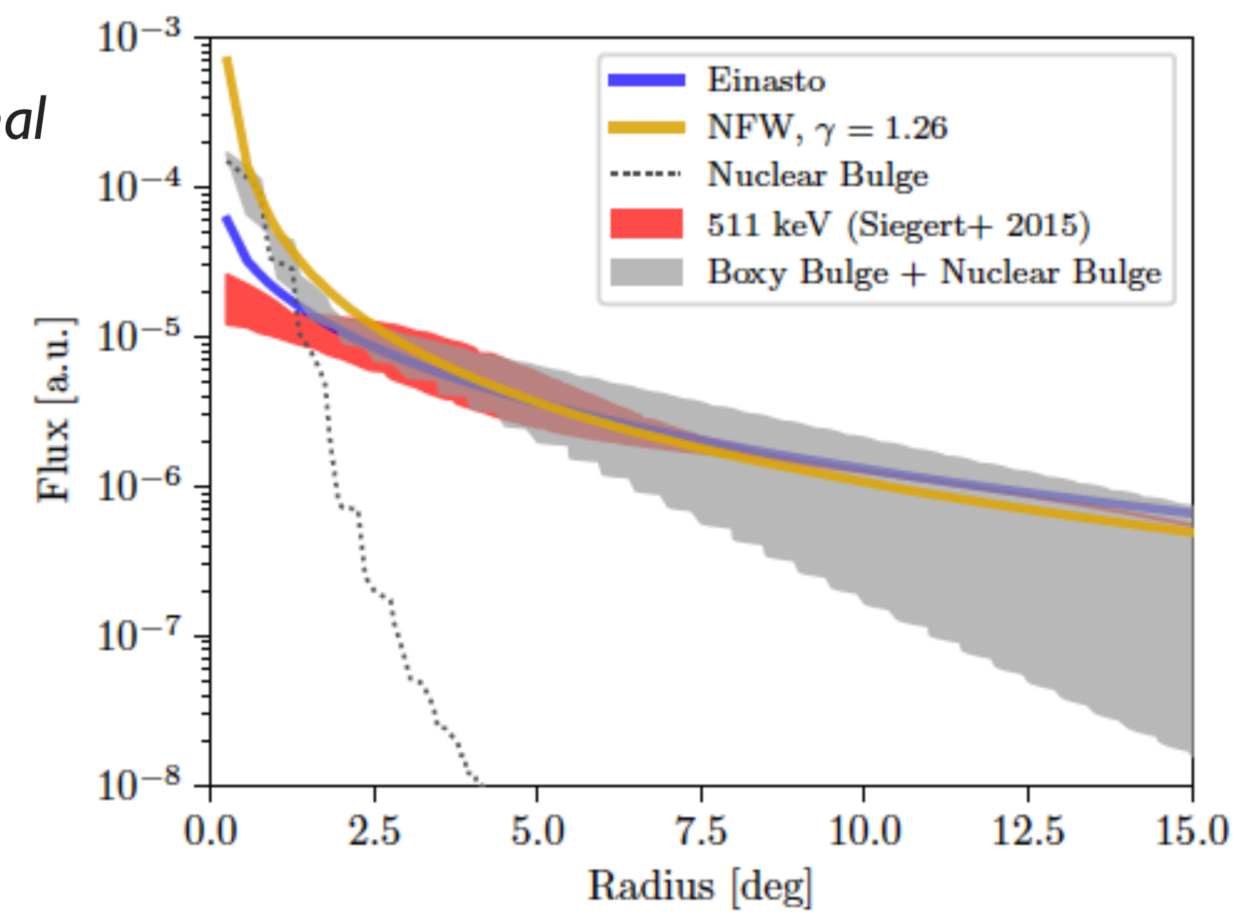
"Stellar mass templates are preferred over conventional DM profiles with high statistical significance"

Also, a not so well-known fact

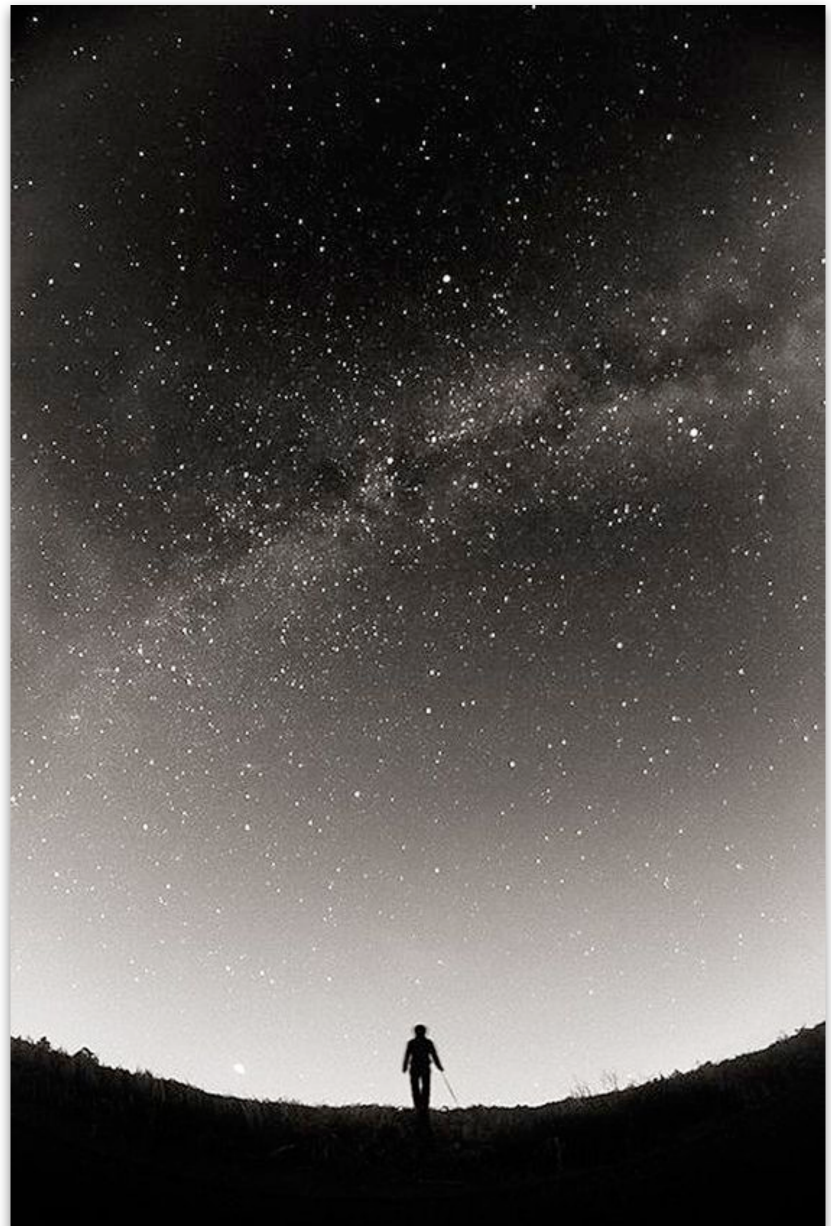
Just rescaling the measured local MSP/star ratio in the disk to the stars in the bulge, ~10% to ~200% of the GCE be accounted for by MSP!!!

C. Eckner et al., Astrophys. J. 862, no. 1, 79 (2018)



In the future, possible multiwavelengths (e.g. radio *F. Calore et al. ApJ 827, 143 (2016)*) or even multimessengers (including GWs, *Calore, Regimbau, PS, Phys. Rev. Lett. 122, 081103 (2019)*) cross-checks of this astro explanation.

The road ahead



What's left? What's going on?

Loosely speaking, I can identify a couple of conceptual directions:

A. "Keep faith": WIMPy ideas ~correct, but we are unlucky, "mild" unexplained fine-tuning is present, e.g.:

1. BSM particles (slightly) too heavy to be produced at LHC, DM may be (multi)TeV, too…
2. … or accidentally light (after all, 1st gen. mass scale<< Higgs vev)
3. Almost mass-degenerate states (long-lived particle signals associated to DM?)

B. "Forget it": at least DM unrelated to hierarchy prob., find inspiration in different theory or pheno

4. BSM too light and/or weakly coupled with the SM. Sufficient to explain lack of direct detection as well Motivations from neutrino physics? Axions from strong-CP and axion-like particles maybe from strings?
5. Problems at "small scales"? (Halo cores, satellite statistics and or variety…): hidden sector & new forces (dark gauge groups), links to the SM via "portal interactions"…

An important comment

Indirect detection is very far from a "critical coverage", even for "vanilla WIMPs"!

many models at few hundreds GeV scale still ok.

The **pessimism on WIMPs is not driven by IDM**.

If interested in pursuing a WIMP search program independently from negative results of EW-scale new physics searches, there is plenty of room in parameter space to justify it!

However, "traditional" WIMP IDM searches are limited by the systematic error with which we know (or can know, even in principle!) the "backgrounds" (*astrophysical signals*)

A commendable effort consists in "trying to squeeze the best we can", with (sometimes computationally painful) theoretical improvements.

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A commendable effort consists in "trying to squeeze the best we can", with (sometimes computationally painful) theoretical improvements.

i.e. WIMP IDM searches are not dead

*but the "**return**" in explored parameter space over the "**investment**" (theory and experiments) is shrinking*

Take advantage of the existing/planned, ex. 1

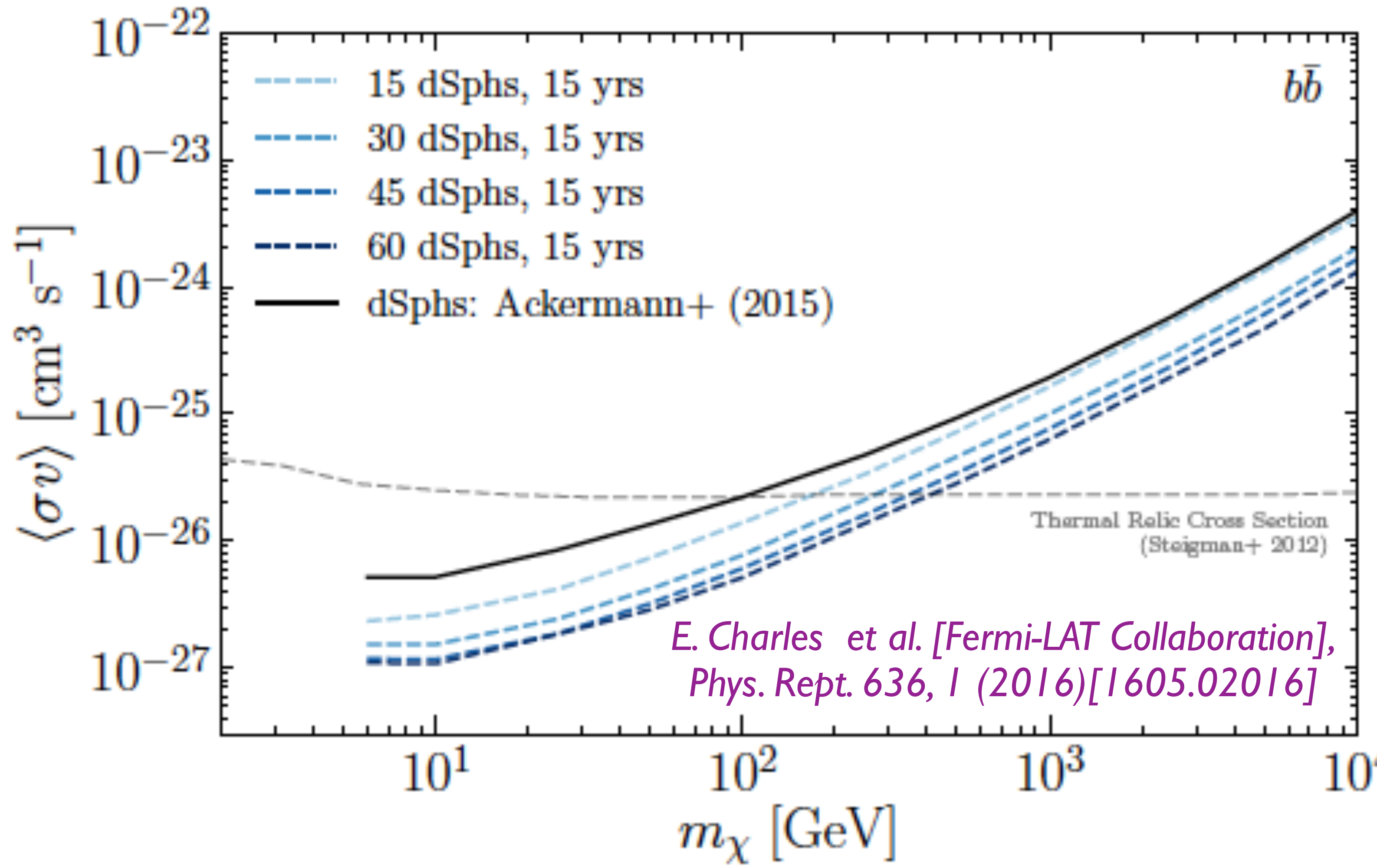
Surveys (e.g. LSST) could discover **hundreds (?) of new Dwarf Spheroidals;** even assuming only ~60 with acceptable determination of DM distribution ("J-factors"), plus few more yrs of Fermi data taking, improvement of a factor of 2-5 expected by the end of Fermi lifetime

- should allow for more credible check of WIMP interpretation of the Gal. Center excess

- eventually (already now?) **background limited**, e.g. uncertainty in diffuse flux & unresolved sources along the l.o.s. Interest in alternative, data-driven techniques, see e.g

F. Calore, P.D. Serpico, B. Zaldivar JCAP 10 (2018) 029 [1803.05508]

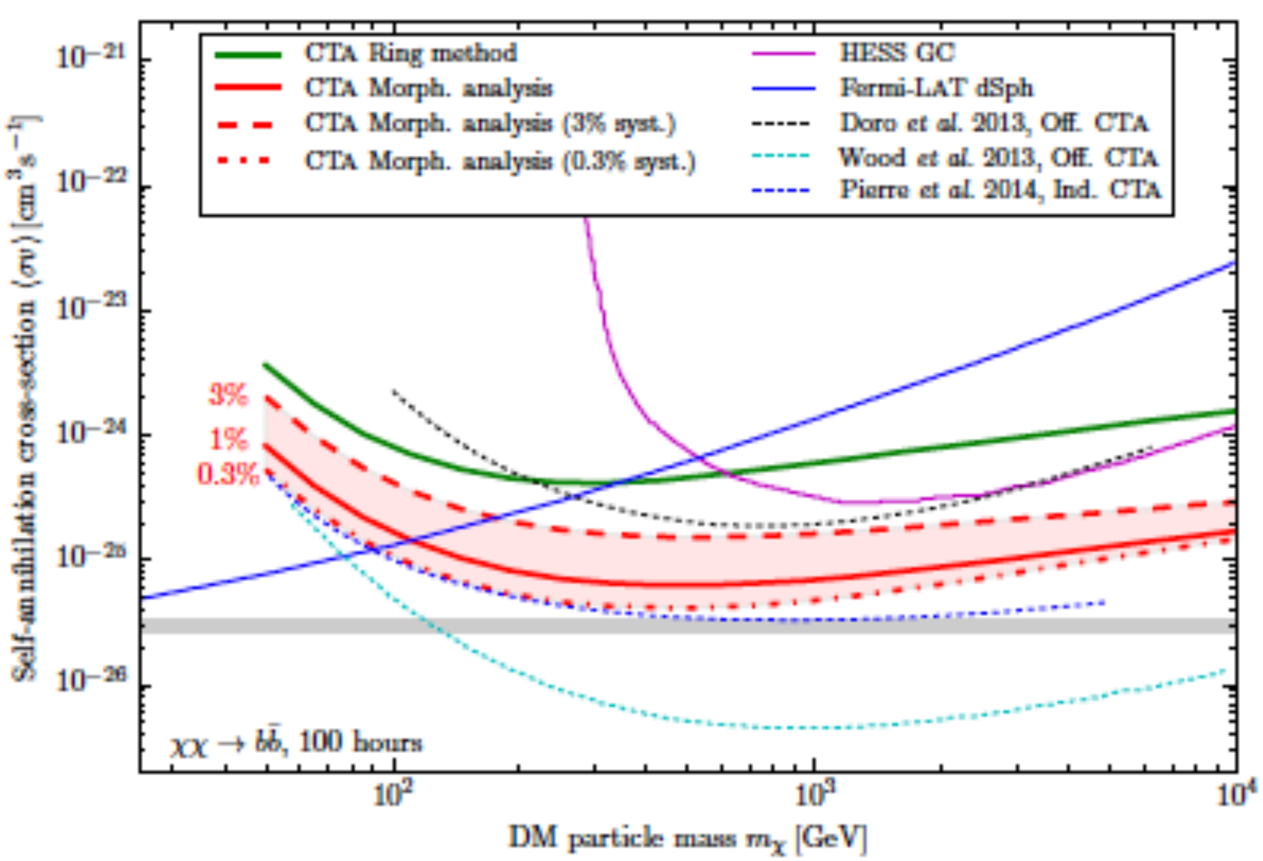
- further **refinements in J-factor** determinations from **surveys** (shrinking errors)



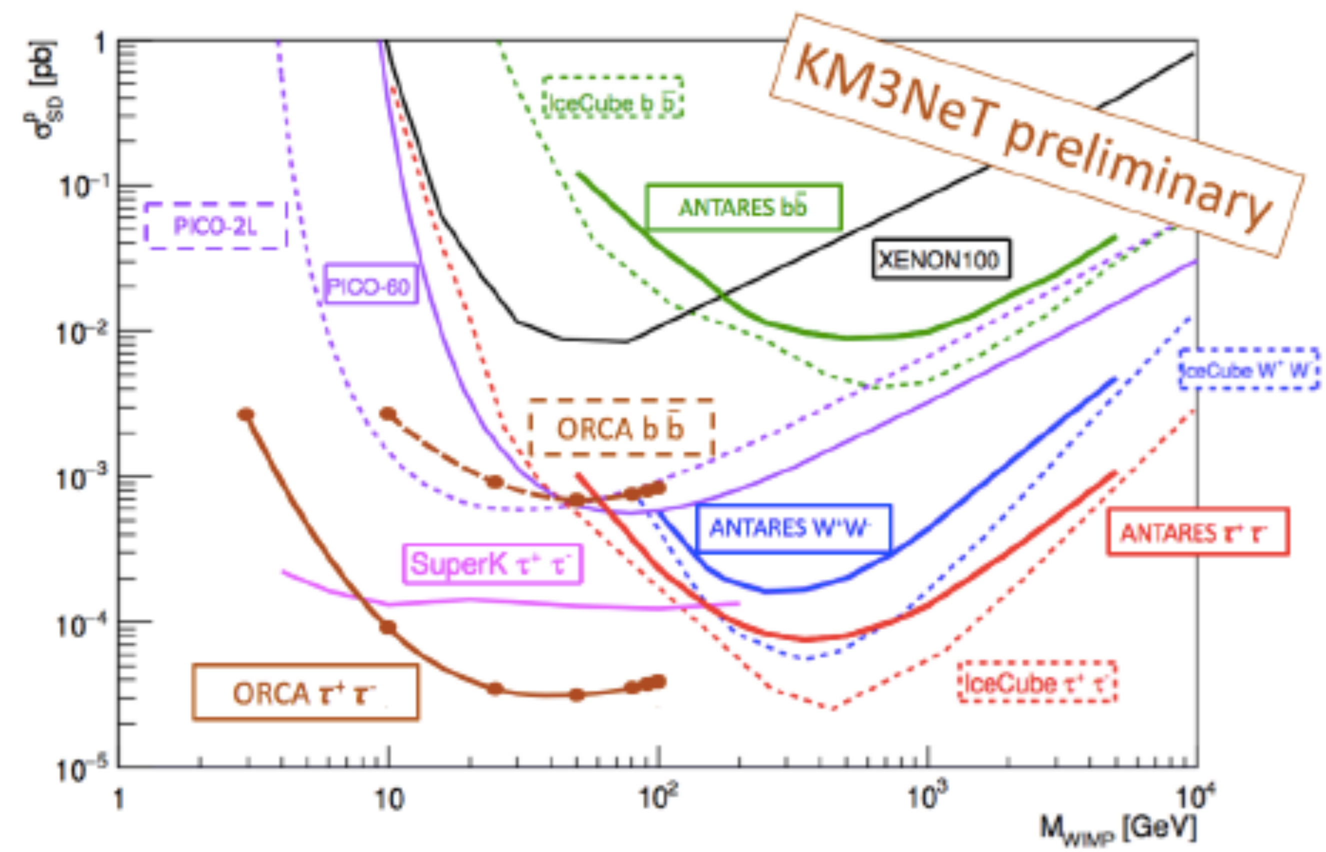
E. Charles et al. [Fermi-LAT Collaboration], Phys. Rept. 636, 1 (2016)[1605.02016]

Take advantage of the existing/planned, ex. II

will be complemented by **CTA**, which will make us access to ~ "vanilla" WIMP x-sections in (multi)TeV mass range; improved sensitivity to WIMP spin-dependent cross section at low masses via ν telescopes low energy extension (ν's from the sun from WIMP capture and annihilation)…



H. Silverwood, C. Weniger, P. Scott and G. Bertone,
"A realistic assessment of the CTA sensitivity to dark matter annihilation,"
JCAP 1503, 055 (2015)



P. Coyle [KM3NeT Collaboration],
"KM3NeT-ORCA: Oscillation Research with Cosmics in the Abyss,"
J. Phys. Conf. Ser. 888, no. 1, 012024 (2017)
[1701.01382]

If not WIMP, what else?

We cannot give up on (meta)stability if we want DM. Relax the condition of relic being in **equilibrium with SM** in the early universe.

Alone, this likely explains negative results at LHC, see for instance:

F. Kahlhoefer, "On the LHC sensitivity for non-thermalised hidden sectors," 1801.07621

"under rather general assumptions, *hidden sectors that never reach thermal equilibrium in the early Universe are also inaccessible for the LHC […]* particles that can be produced at the LHC must **either** have been in **thermal equilibrium** with the Standard Model at some point **or** must be **produced via the decays of another** hidden sector **particle that has been in thermal equilibrium**"

whenever $\Gamma(T) < H(T) = \sqrt{\frac{4\pi^3 g_*}{45}} \frac{T^2}{M_{\rm pl}}$ where $\Gamma \equiv \langle \sigma v \rangle n^{\rm eq} = \int \frac{N_c s^2 K_1(\sqrt{s}/T)}{4\pi^2 T^2} \sigma(\sqrt{s}) \mathrm{d}\sqrt{s}$,

It turns out that $N_{\rm LHC} = \int \mathrm{d}\sqrt{s} \frac{\mathrm{d}x}{x} f_1(x) f_2\left(\frac{s}{s_{\rm tot}\, x}\right) \frac{2\mathcal{L}\sqrt{s}}{s_{\rm tot}} \sigma(\sqrt{s})$ is negligible

While not being a water-proof theorem (e.g. standard cosmology valid up to EW temperatures assumed), it is a valid guide in how to move beyond

Linking to signatures of DM-DM interactions?

It has been realized for instance that:
freeze-in *(with light mediators)*
cannibalization *(in a colder-than-SM dark sector)*
are frameworks allowing one to realize **strongly self-interacting DM**,
while fulfilling constraints.

N. Bernal, X. Chu, C. Garcia-Cely, T. Hambye and B. Zaldivar, "Production Regimes for Self-Interacting Dark Matter," JCAP 1603, 018 (2016) [1510.08063]

Examples of Constraints

for the light mediator case:

- BBN (must not be spoiled by disintegration byproducts of unstable mediator decay)
- CMB anisotropy not disrupted (via alterations to the ionization rate)
- direct bounds from X-ray observations
- direct detection in underground detectors

For the cannibal scenario:

- Ly-alpha (cannot be too hot!)

Additional pheno arguments may require extra ingredients in the dark sector
(e.g. more than 1 dof for v-dependent DM-DM x-sec in clusters, galaxies, etc.)

A generic lesson from non-thermal DM: mass range broadens, pheno too!

- Can have very heavy DM via freeze-in, e.g. ~10 PeV-scale (usually metastable)

What's the best probe of that? Currently, ν telescopes!

A. Esmaili, S. K. Kang and P. D. S., "IceCube events and decaying dark matter: hints and constraints," JCAP 1412, 054 (2014) [1410.5979]

Possibly, in the future, ground-based gamma-ray telescopes for ~100 TeV range, type LHAASO

A. Esmaili and P. D. S., "Gamma-ray bounds from EAS detectors and heavy decaying dark matter constraints," JCAP 1510, 014 (2015) [1505.06486]

- Can have light DM, sub-GeV scale in the problem

also true for small splittings

F. D'Eramo and S. Profumo, "Sub-GeV Dark Matter Shining at Future MeV Gamma-Ray Telescopes," Phys.Rev.Lett. 121, 071101 (2018) [1806.04745].

New, ad hoc technologies being developed in direct detection. In IDM, the soft gamma ray range remains a "juicy" & almost unexplored target of opportunity (e.g. e-ASTROGAM), also for a number of astrophysical questions

When don't know what to do, general rule: go for something unexplored!

Take the opening of the Gravitational Wave window

Although ***almost*** ruled out, revisiting primordial black hole as DM candidates was a healthy exercise!

GW170817 may also remembered as a turning point (blow?) in modified gravity research

Similarly, sizable discovery potential associated to opening new windows, like

21 cm astrophysics see e.g. some exploratory study in *V. Poulin, J. Lesgourgues, PS, JCAP 1703, 043 (2017) [1610.10051]*

(or the literature inspired by the putative EDGES detection)

CMB spectral distortions (e.g. via DM upscattering into states which late decays)

R.T. D'Agnolo, D. Pappadopulo and J.T. Ruderman, "Fourth Exception in the Calculation of Relic Abundances,"' Phys. Rev. Lett. 119, 061102 (2017) [1705.08450]

Overview & Conclusions

- **"Traditional" arguments** relating the DM phenomenon to BSM physics at the EW scale **(WIMPs) have not lead to a discovery**, neither at direct detection nor at colliders.

- The **indirect WIMP detection** techniques have recently reached "meaningful" exploration power, **started digging into interesting parameter space. Improving on this path is possible and will be pursued**, widening the reach in parameter space. Road ahead however uphill to reduce systematics in astro backgrounds & theory (**reduced incremental return over investment)**

- **Alternatives (non-thermal DM candidates) are considered more** & more. Either motivations from *weaker-than-weak scales* (ν mass, axions…) or more modest modeling requirements, sometimes *pheno-inspired,* notably from possible small-scale "problems" ($\rightarrow$*strong self-interacting DM, dark forces, light mediators*…)

- Accrued **interest to significantly explore new windows**:
  - MeV gamma-ray sky
  - Gravitational Waves (e.g."dark sector" phase transitions in the early universe)
  - 21 cm
  - CMB spectral distortions
  - improved X-ray sensitivity
  - $\gtrsim$100 TeV gamma-ray sky (ground based)

  - Light mass frontier in direct DM detection
  - Portal-related pheno at colliders: tracks due to metastable progenitors, displaced vertices, invisible Higgs decay…