OVERVIEW OF INDIRECT DARK MATTER SEARCH: STATUS AND CHALLENGES

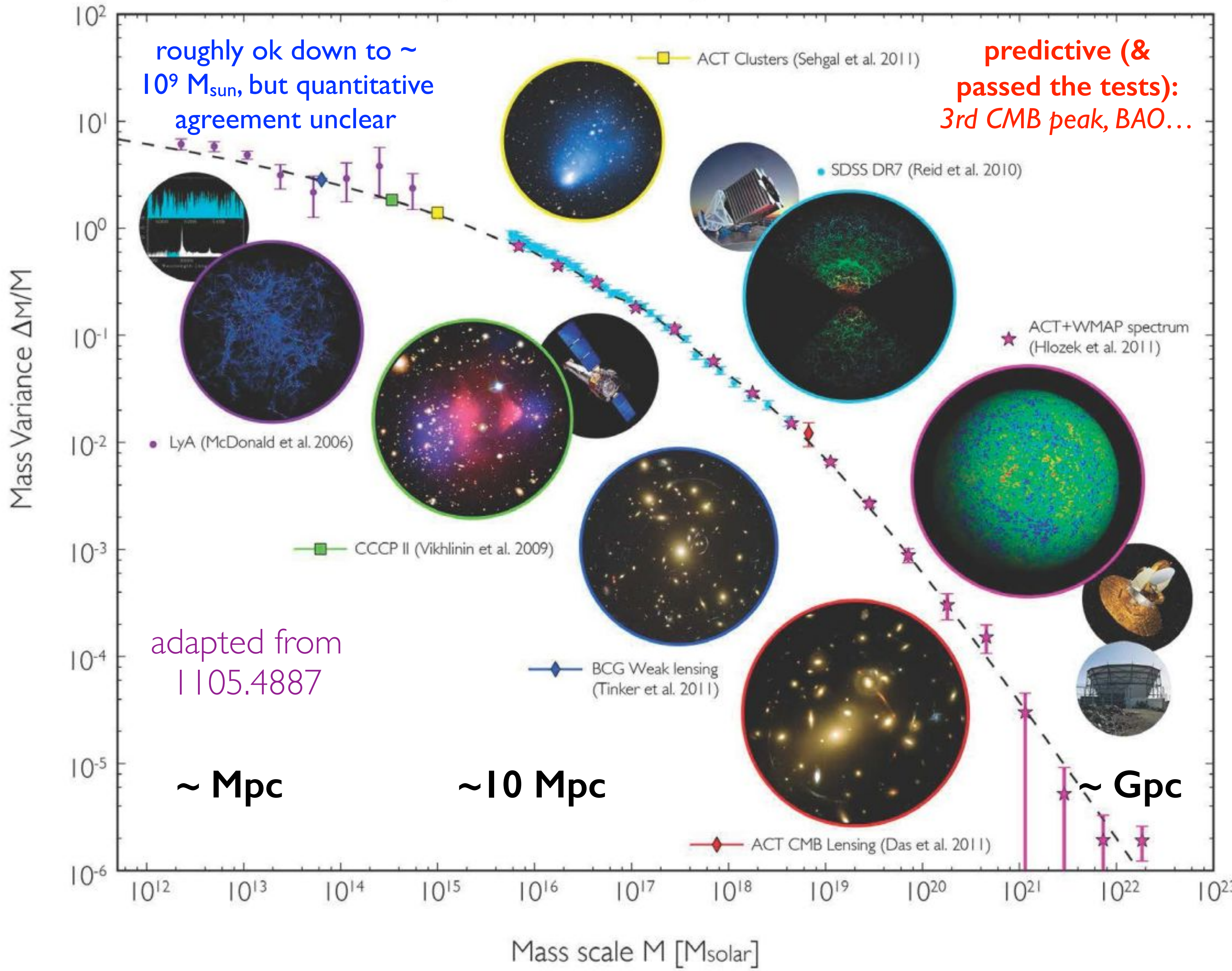
Pasquale Dario Serpico (Annecy, France)

Outline

- Knowns and unknowns on DM
- Typical challenges for Indirect DM detection: Status of searches
- The road ahead: a couple of strategies
- Conclusions

What do we know?

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



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

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 WIMP (rather unrepresented at this conf.)
It's by no way the unique line of argument!

The WeaklyInteractingMassiveParticle Paradigm

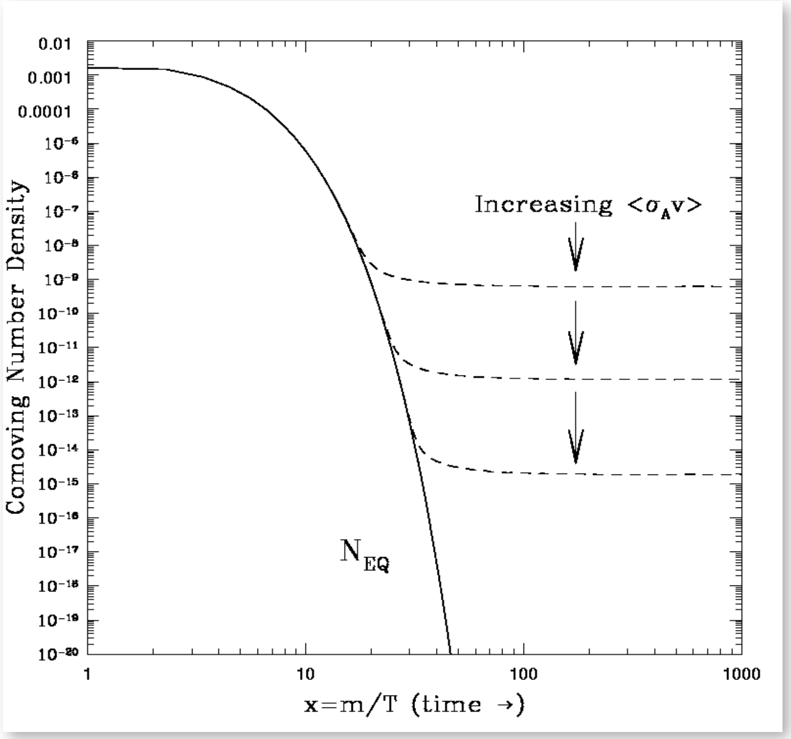
Cosmology tells us that the early universe was a hot plasma, with all "thermally allowed" species populated. Notion tested up to T~ few MeV (BBN, cosmo ν's):

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 $T \ll m$ (required for **cold** DM, i.e. non-relativistic distribution function!). Its abundance suffers exponential suppression

What is left depends on the decoupling time, i.e. annihilation cross section: the weaker, the more abundant...



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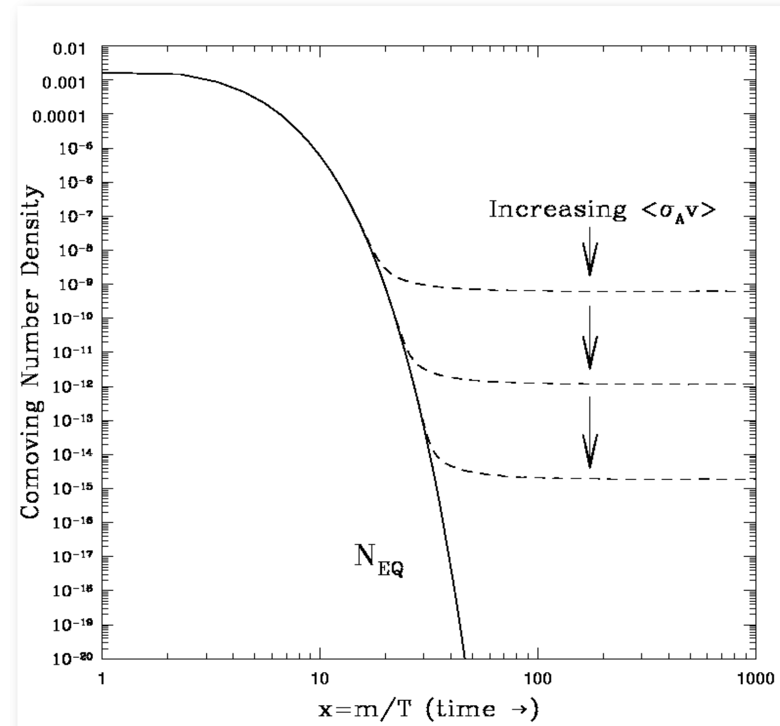


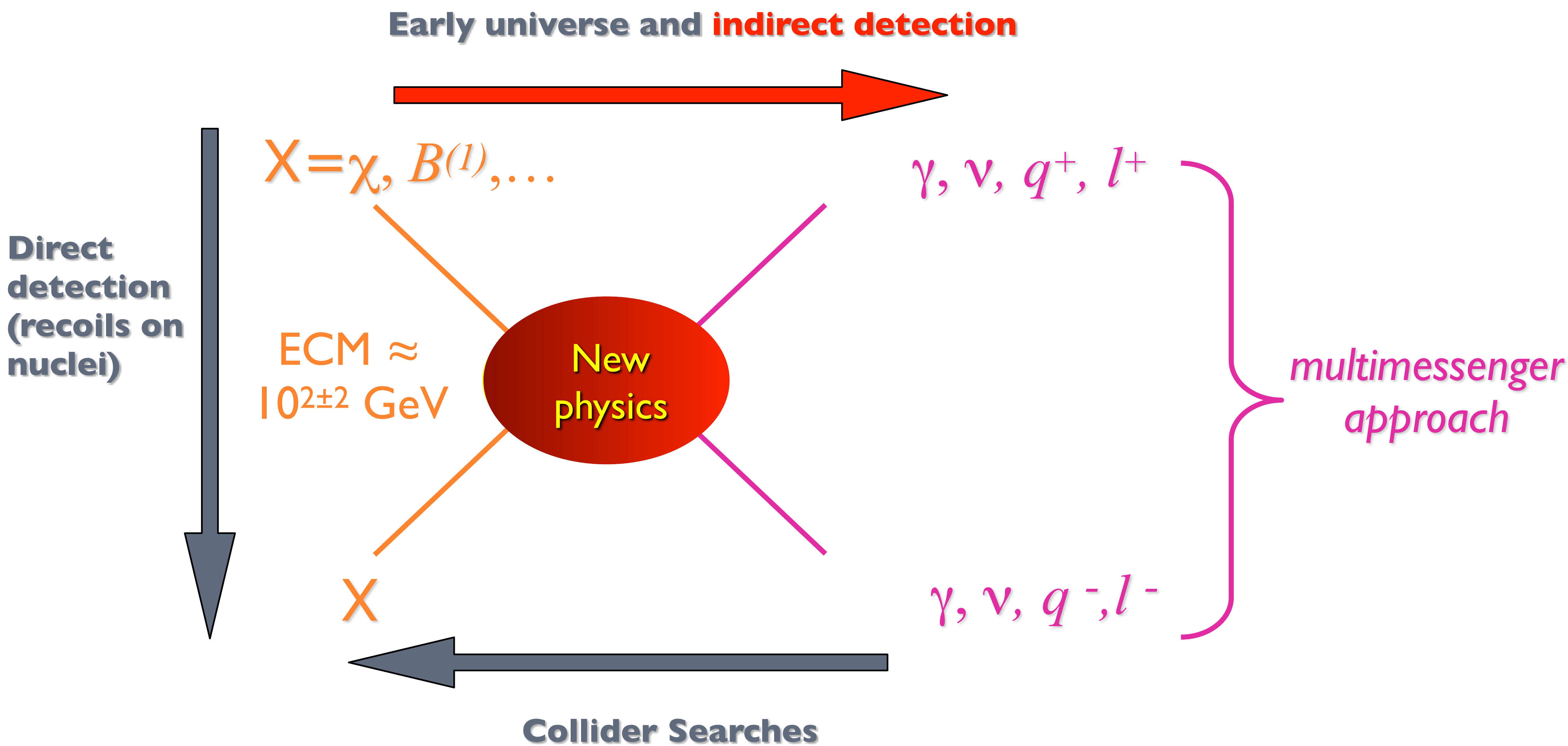
Textbook calculation yields the current average cosmological energy density

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

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

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

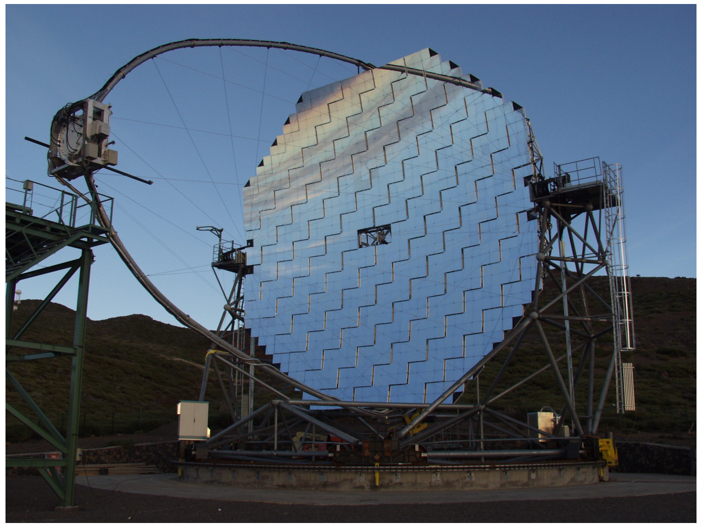
IDM WIMP searches

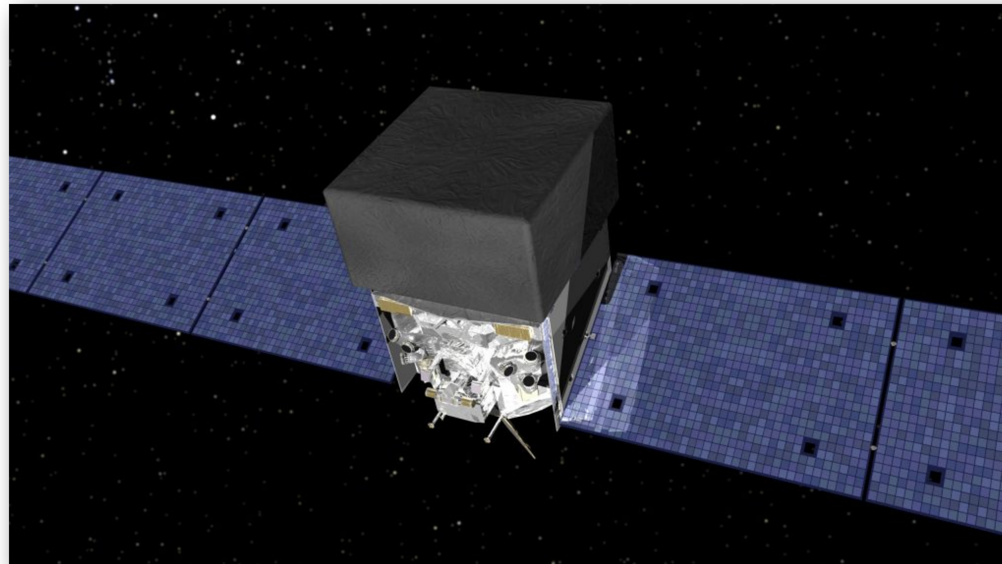


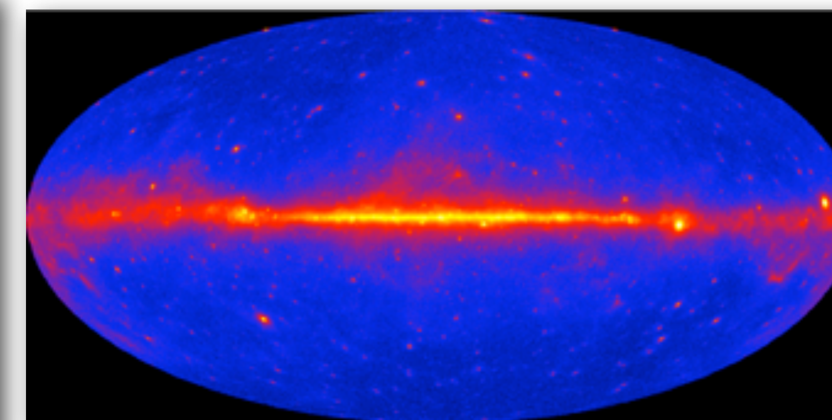
- ✓ Want to detect stable SM particles remotely produced
- ✓ *Injected* SM particles depend on the particle process (above: annihilation) and DM astrophysical distribution
- ✓ Particles at the Earth can be affected by propagation effects (E-losses, diffusion…)

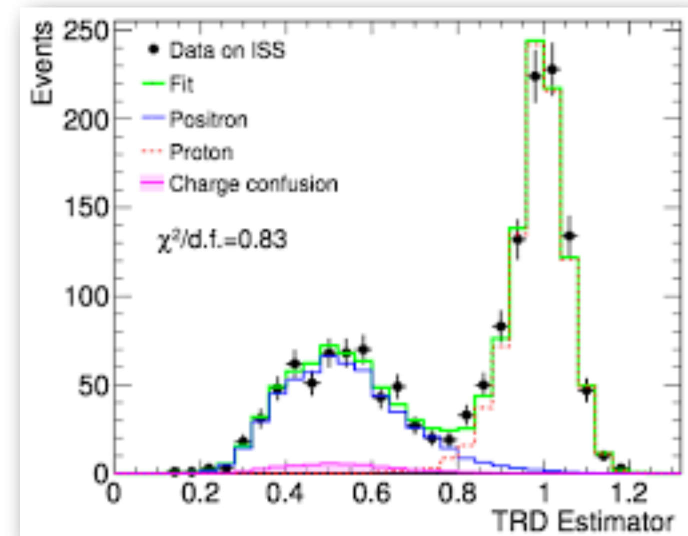
many channels & tools for indirect WIMP searches

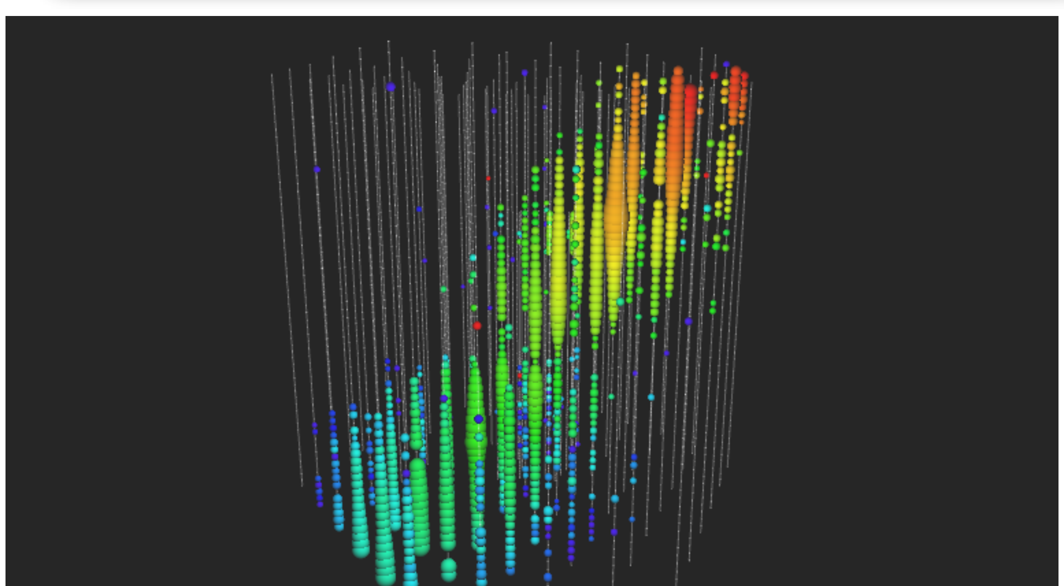
each one with advantages and problems











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

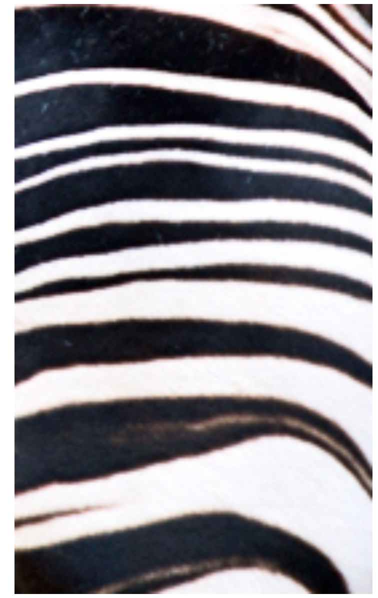
We ***believe*** that the **signal** looks like

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…

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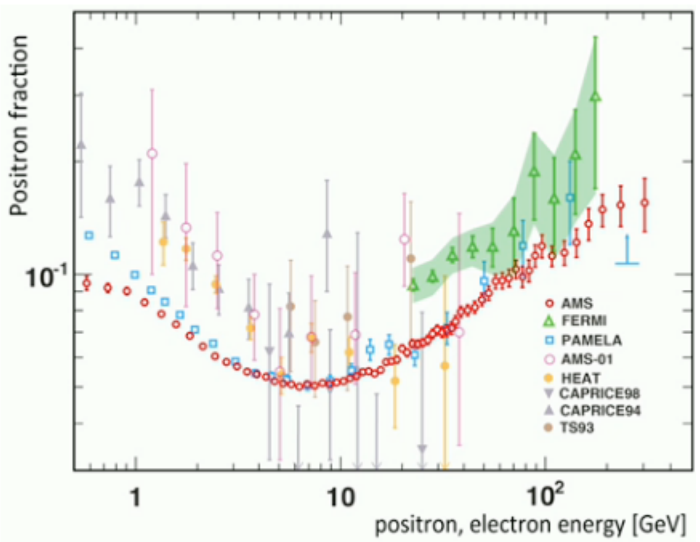
… then many people run writing dozens of papers about the discovery of DM…

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

Okapia johnstoni, fam.: giraffidae

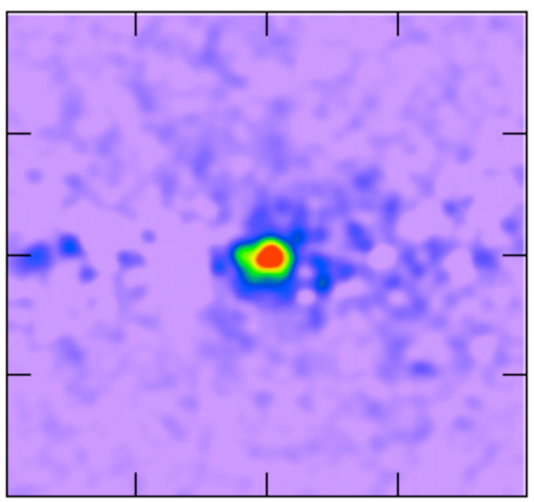
(Some) actual examples of this pattern (last decade)

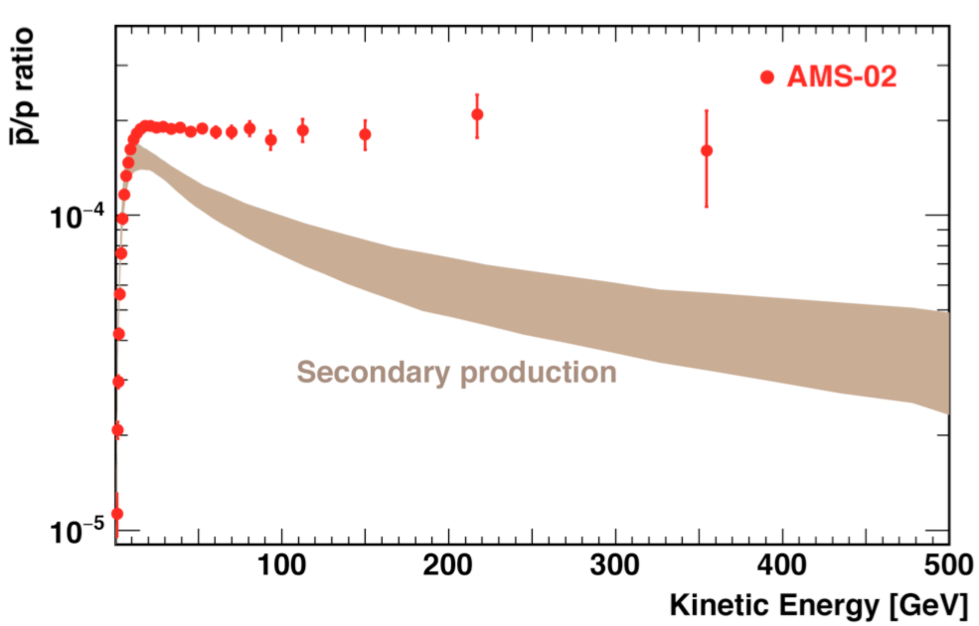


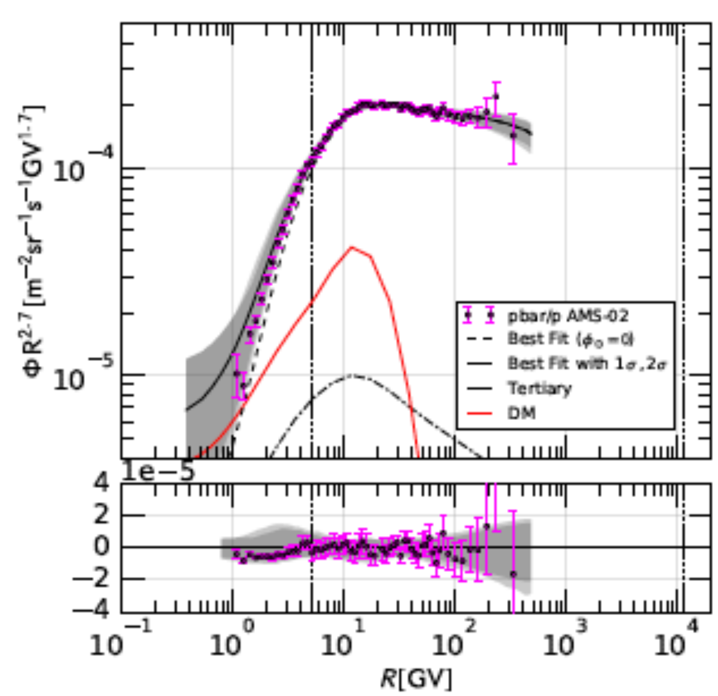
positron excess:
pairs from pulsar wind nebulae

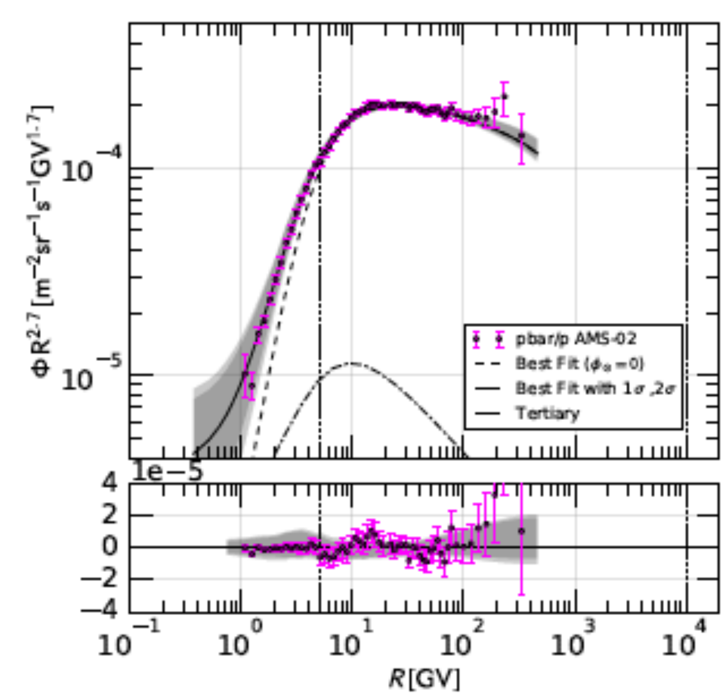
GeV gamma-ray excess @ Gal. Center:
bulge millisecond pulsar population?

antiproton excess(es):
probably ok with secondary yield once accounting for: correlations in observational errors, non-prompt production, isospin-violating effects, non-trivial E-dependence of diffusion coefficient… *M. Boudaud on Wed.*









Status of multi-messenger WIMP identification program

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


Mughal painting, ~ 1600 AD

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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)

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

Mughal painting, ~ 1600 AD

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

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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": possibly DM unrelated to hierarchy prob., find inspiration in different theory or pheno
Often associated to production mechanisms different from thermal freeze-out (*A. Goudelis*)

4. BSM too light and/or weakly coupled with the SM. Sufficient to explain lack of direct detection as well. Motivations from neutrino physics? Baryogenesis? Axions from strong-CP (J. Galan)...
5. Problems at "small scales"? (Halo cores, satellite statistics and or variety…): hidden sector & new forces (J. Cornell), links to the SM via "portal interactions", fuzzy dark matter (S. Sibiryakov)…

An important comment

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

most 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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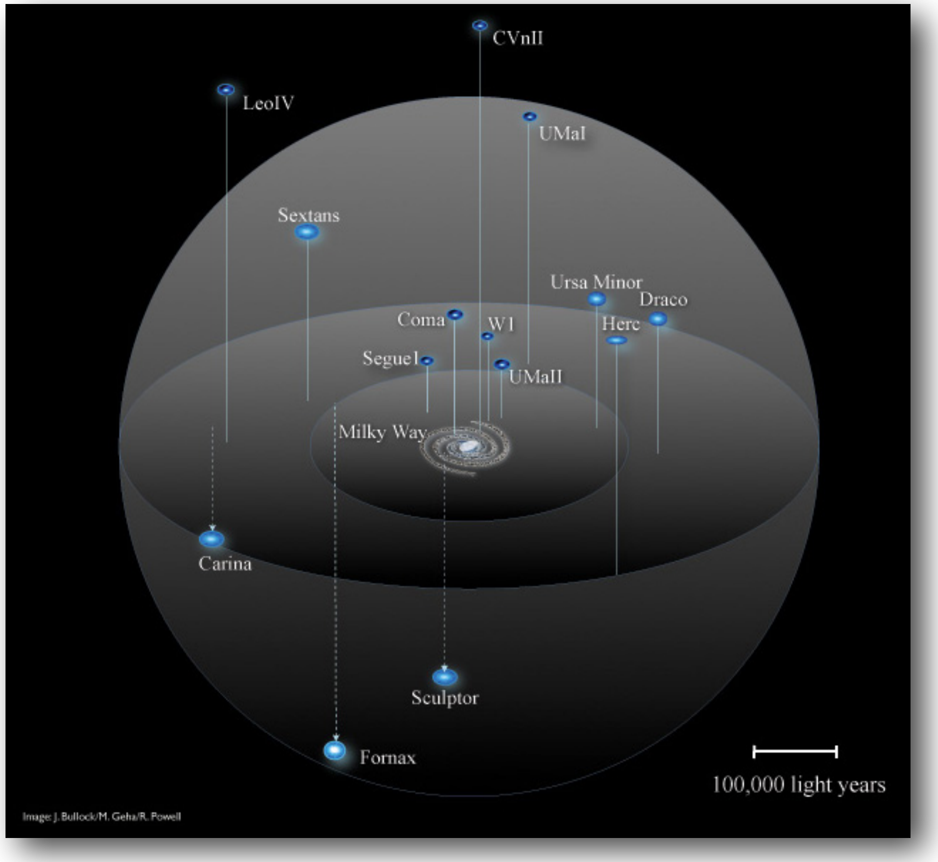
i.e. WIMP IDM searches are not dead

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

Take advantage of the existing/planned, ex. 1

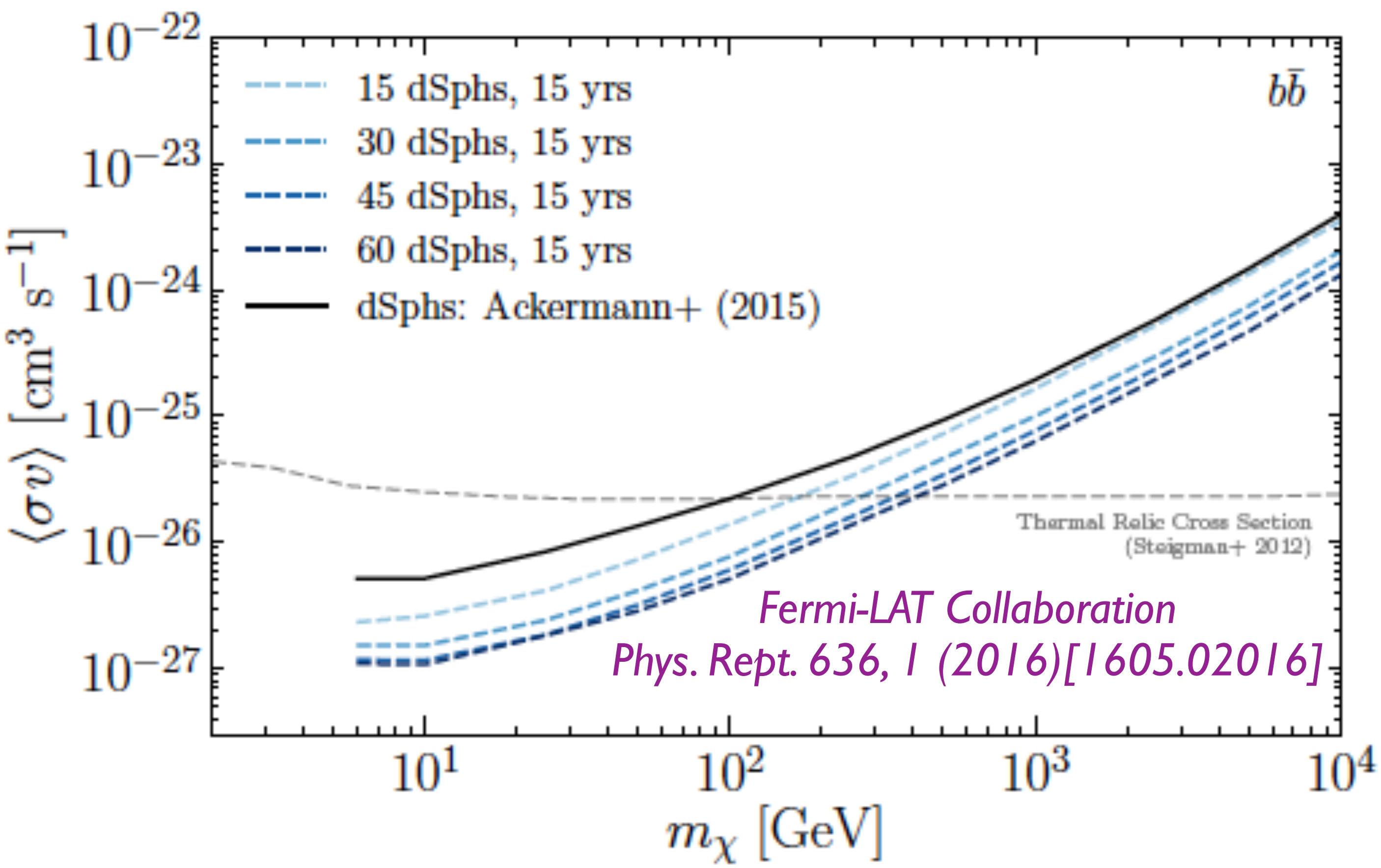
Dwarf Spheroidals: satellites of Milky Way with high DM/ baryon content, 1 to 3 orders of magnitude higher than the MW. Ideal Signal/Noise, even better if stacked! Best current gamma-ray limits



Surveys (e.g. LSST) could discover **hundreds new Dwarf Spheroidals;** even assuming only ~60 with good determination of DM distribution, improvement of a factor of a few expected by the end of Fermi lifetime

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

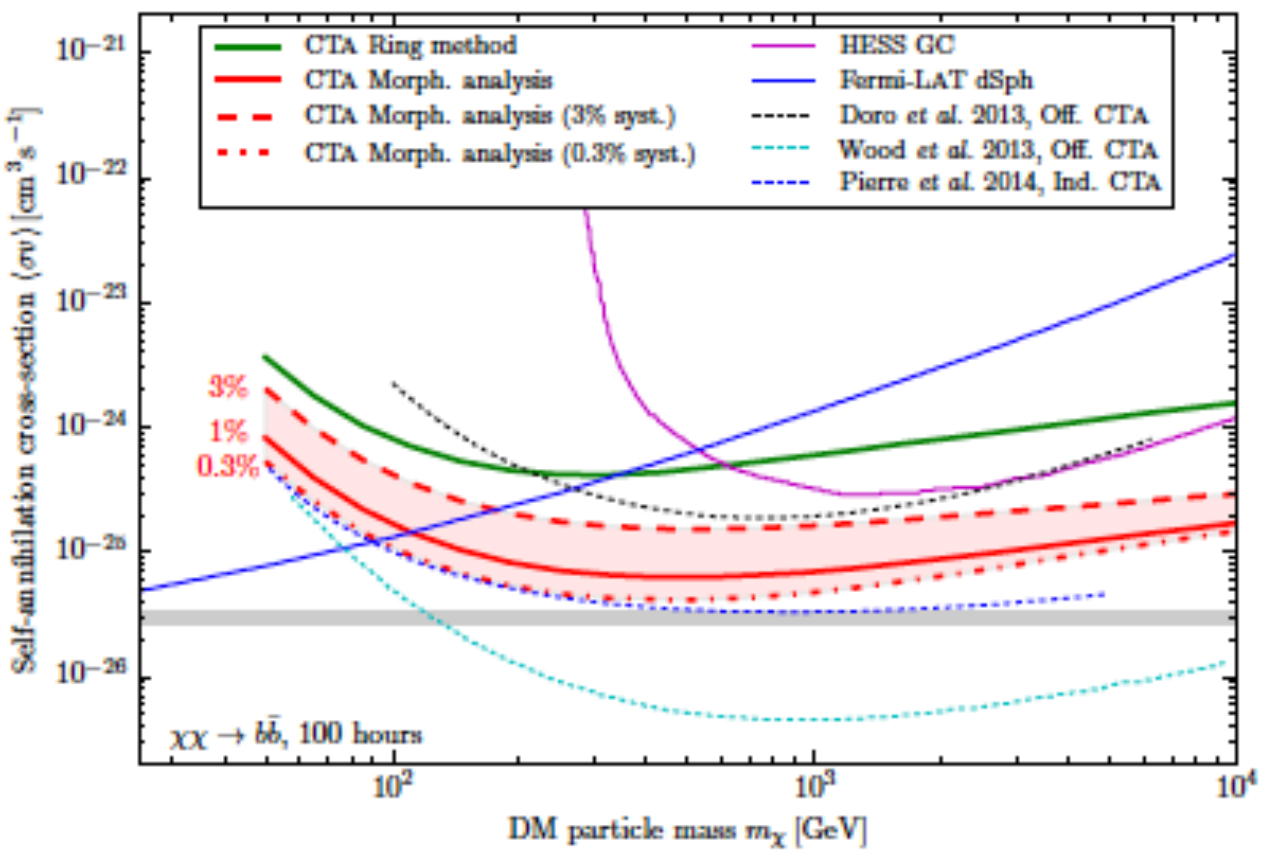
F. Calore, P.D. Serpico, B. Zaldivar
JCAP 10 (2018) 029 [1803.05508]



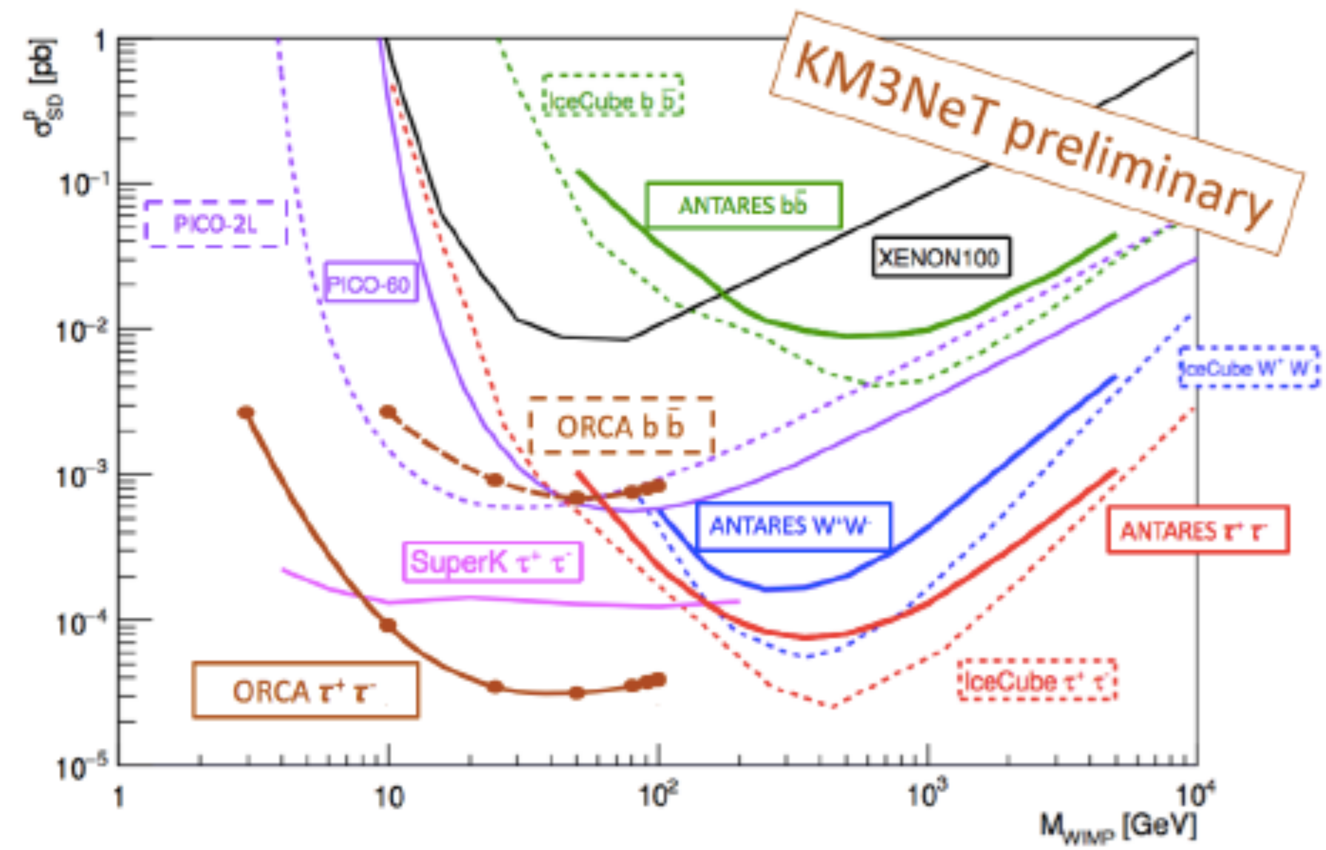
Fermi-LAT Collaboration
Phys. Rept. 636, 1 (2016)[1605.02016]

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. Accounting for effects like Sommerfeld enhancement or bound state formation (*K. Petraki on Mon.*) will be crucial on the theory side.



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]

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)

If not WIMP, what else?

Relax the condition of relic being in **equilibrium with SM** in the early universe.

Alone, this likely reconciles 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, IDM 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

Overview & Conclusions

- **Traditional relation DM $\longleftrightarrow$ BSM** physics @ EW scale **(WIMPs)** has **not lead to discovery**, yet

- The **indirect WIMP detection** techniques have started **digging into interesting parameter space. Improving on this path possible and will be pursued**. Road ahead however uphill due to systematics in astro backgrounds & theory **(reduced incremental return over investment)**

- **Alternatives (non-thermal DM candidates) are considered more** & more. Motivations:
  physics at *weaker-than-weak scales* (ν mass, axions…)
  pheno-inspired, notably from possible small-scale "problems" ($\rightarrow$*strong self-interacting DM, dark forces, light mediators, fuzzy DM…*)

- Accrued **interest to significantly explore new windows** (incomplete list)
  - MeV gamma-ray sky
  - Gravitational waves
  - 21 cm
  - CMB spectral distortions
  - improved X-ray sensitivity
  - precision astrometry, lensing
  - physics of compact astrophysical objects
  - $\gtrsim$100 TeV gamma-ray sky (ground based)

Still links with direct and collider searches, also 'unusual' ones

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

For more DM news… Final opportunity to catch up!

‹ Mon 21/10 | Tue 22/10 | Wed 23/10 | **Thu 24/10** | All days ›

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12:00	**Connections between neutrinos and DM** *Main Auditorium, IFT (Madrid)*	*Bibhushan Shakya* 12:00 - 12:20
	Leptophobic Dark Matter and the Baryon Number Violation Scale *Main Auditorium, IFT (Madrid)*	*Clara Murgui* 12:20 - 12:40
	Leptophilic dark matter *Main Auditorium, IFT (Madrid)*	*Laura Lopez Honorez* 12:40 - 13:00
	Inflation dark matter *Blue Room, IFT*	*Lorenzo Ubaldi* 15:40 - 16:00
16:00	**DAMIC** *Blue Room, IFT*	*Nuria Castello* 16:00 - 16:20
	DM constraints from neutron stars (TBC) *Blue Room, IFT*	*Raghuveer Garani* 16:20 - 16:40