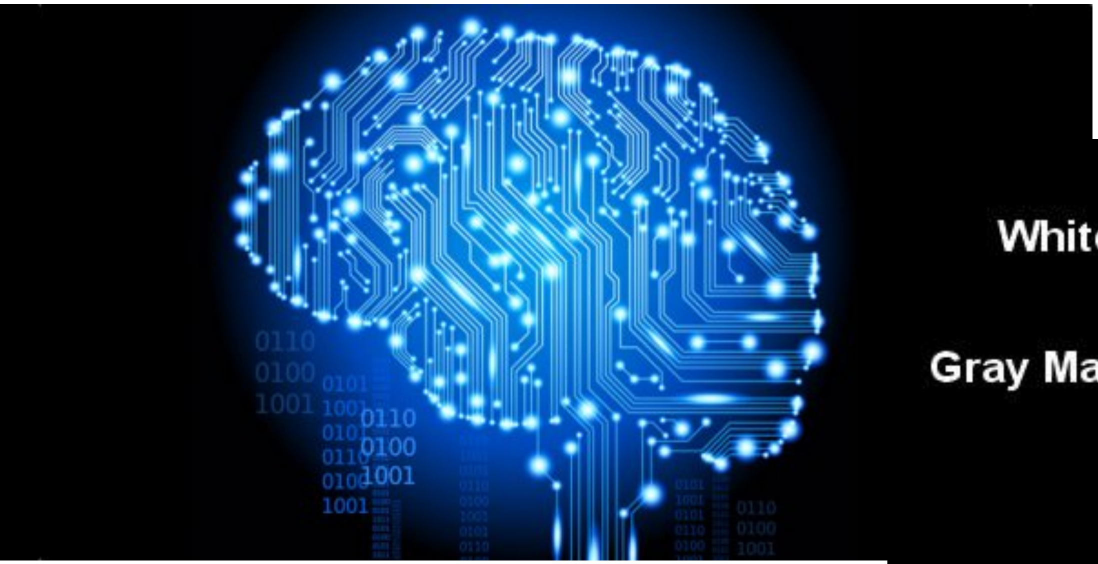
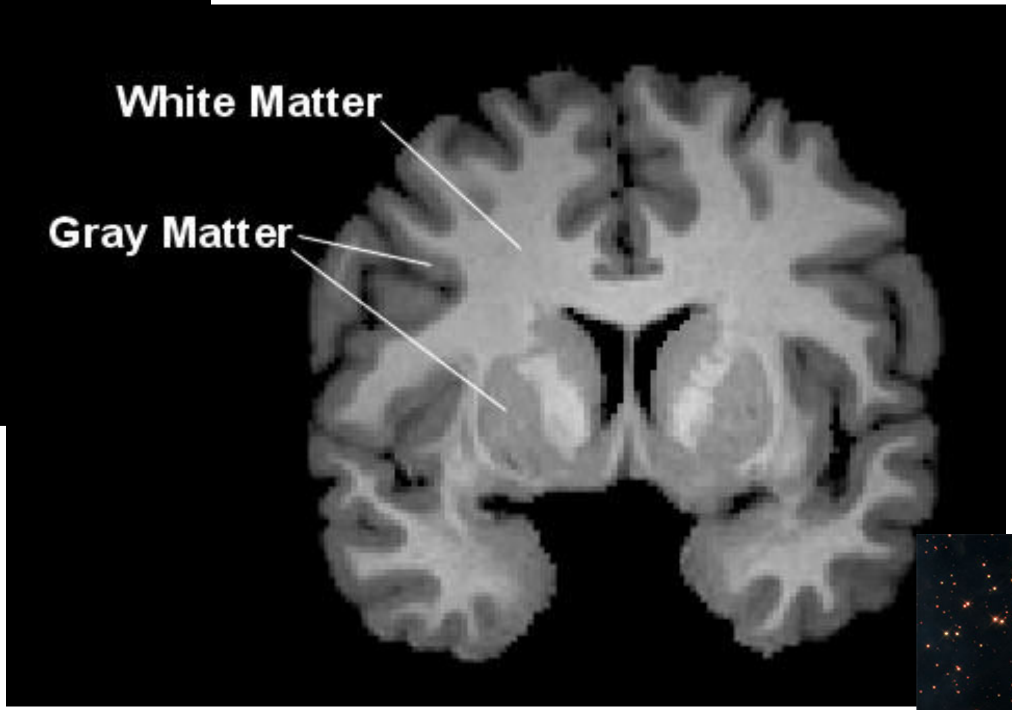
OVERVIEW OF (INDIRECT) DARK MATTER SEARCH CHALLENGES





Pasquale Dario Serpico (Annecy, France)

Accelerating the Search for Dark Matter with Machine Learning

ICTP, Trieste, Apr. 08 2019

Disclaimer

I am not a “machine learning” expert, nor a “data scientist”

I am a curious layman… an interested one, since I hope it might help in my job as well (and already gave it a try)

My talk is intended to set the stage of DM searches, present the subject and raise (what I think are) some critical aspects

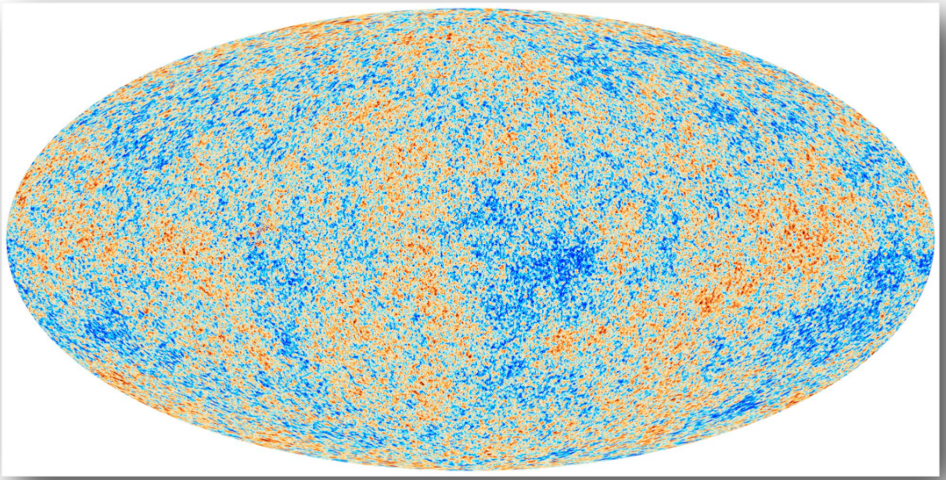
I guess that the organizers felt I’m ideally suited to talk here, since I am supposedly a *dark matter expert*, i.e. I know a lot about my ignorance.

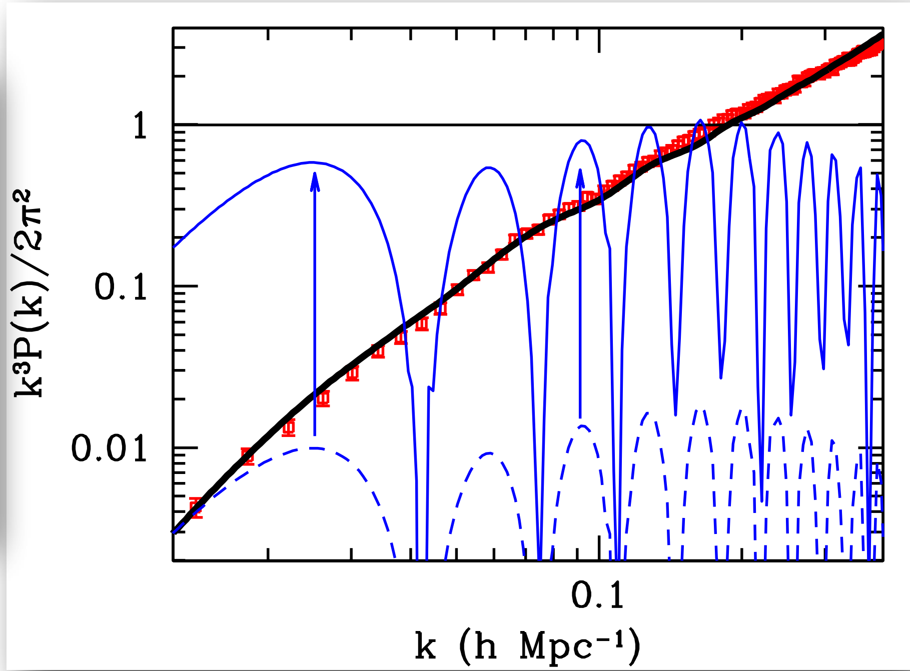
Outline

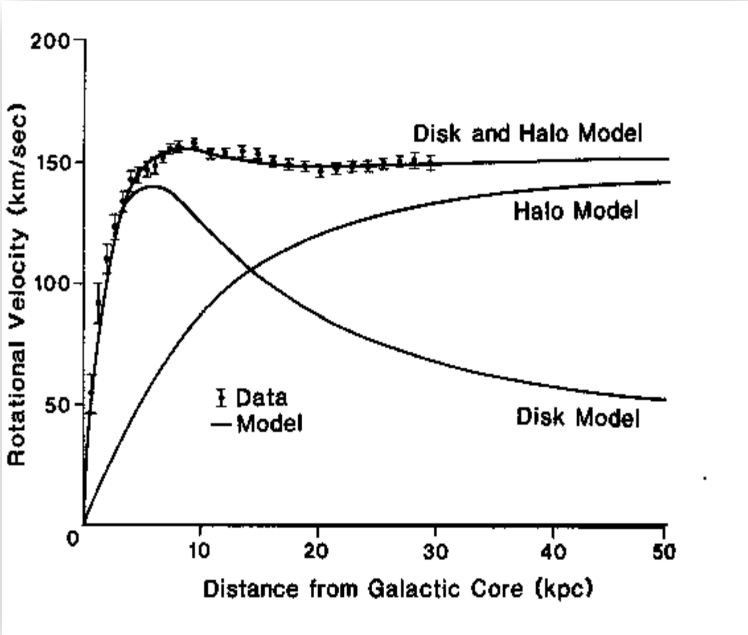
- **Introduction to Dark Matter (DM)**
  What we know, why it’s so interesting and peculiar
- The **quest for (indirect) DM identification**:
  The contours of the bet
- **Opportunities and Problems**
- **An actual example**
- **Conclusions**

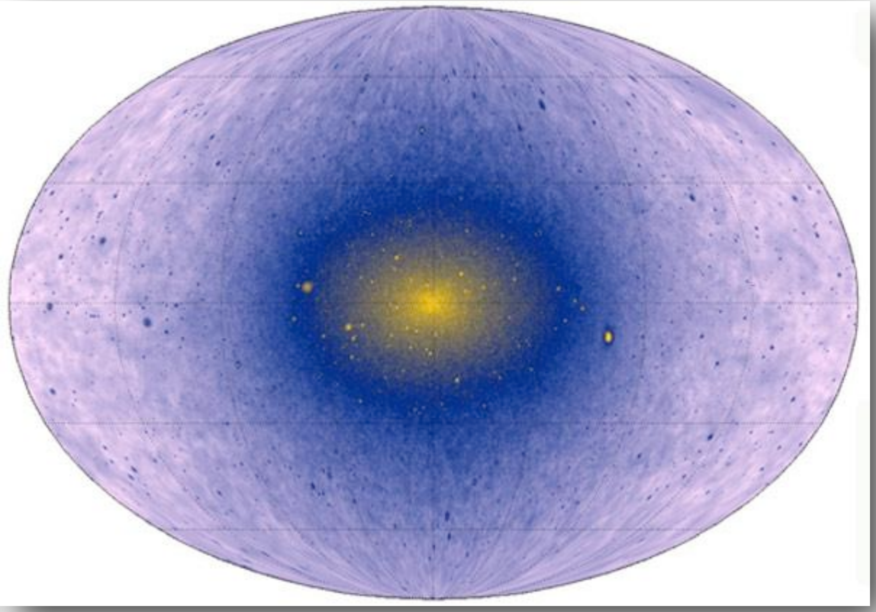
Introduction to /recap on DM

The "Dark Matter" Phenomenon in 1 slide





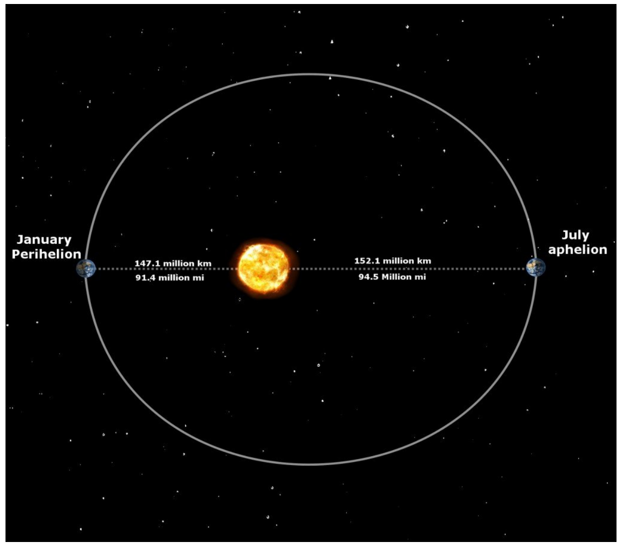




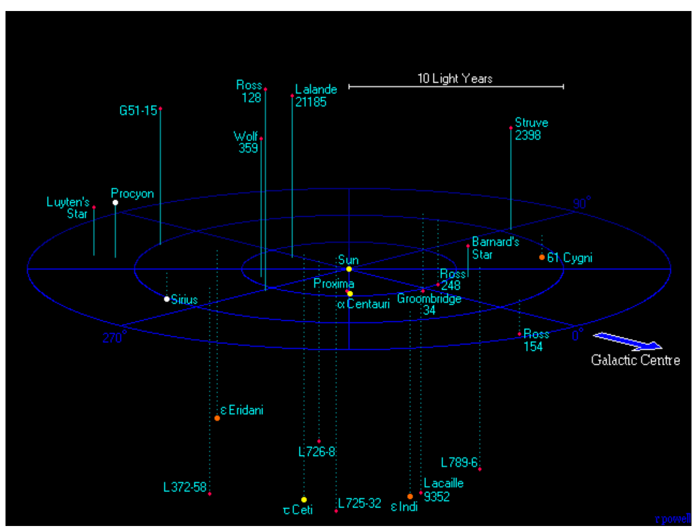
A number of astrophysical & (above all!) cosmological observations only makes sense if adding one (or more?) extra ingredient beyond current model of particle physics + general relativity, which appears to interact only gravitationally

A quick reminder of scales

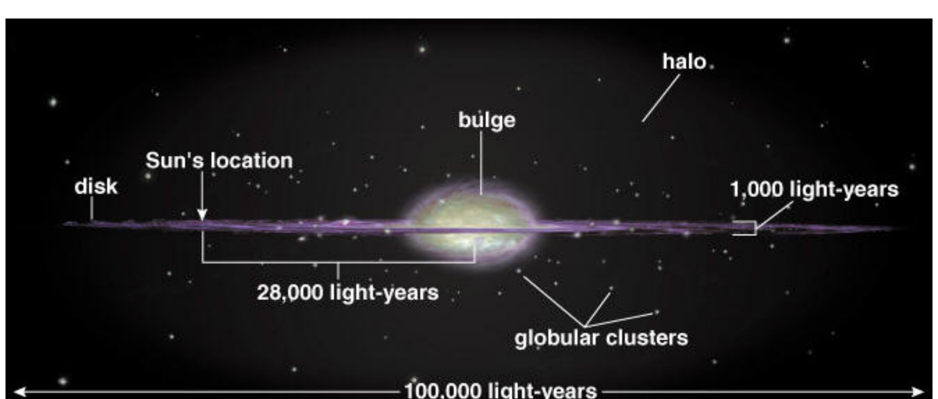
astronomical unit (~1.5 10^{11} m)



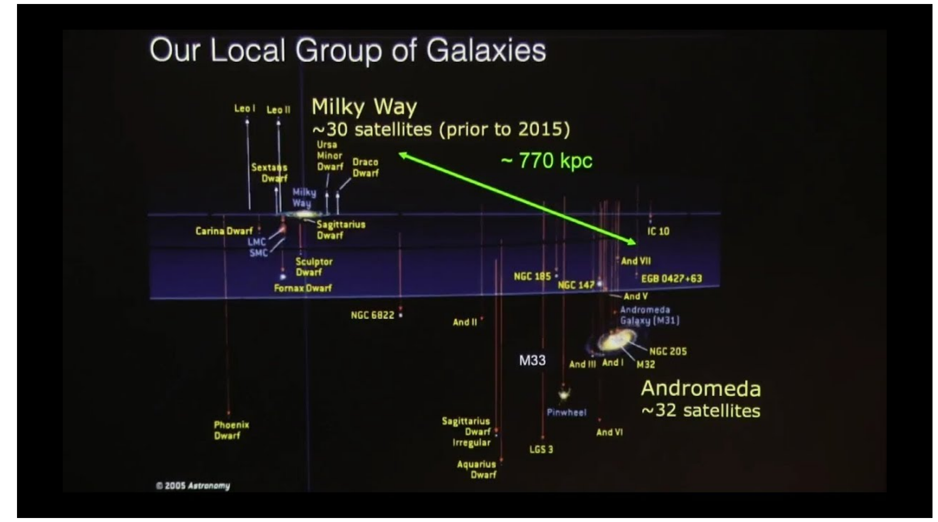
parsec (3 10^{16} m)



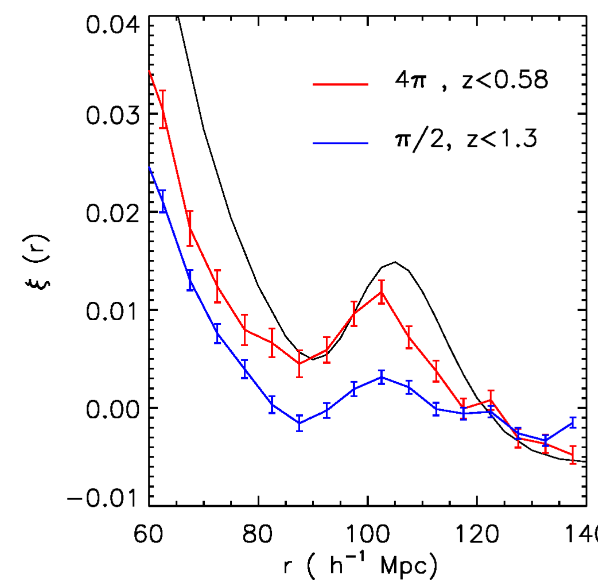
~10 kpc



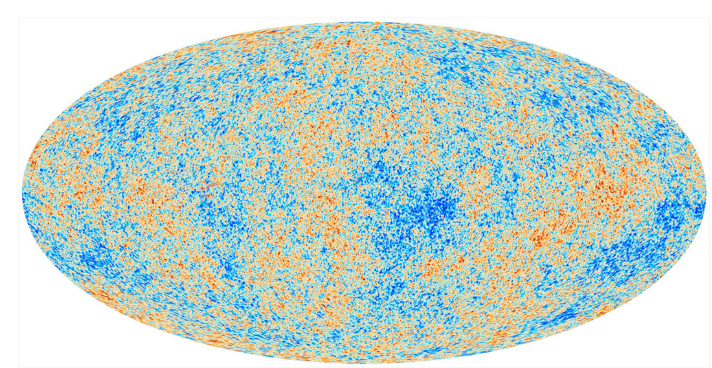
~1 Mpc



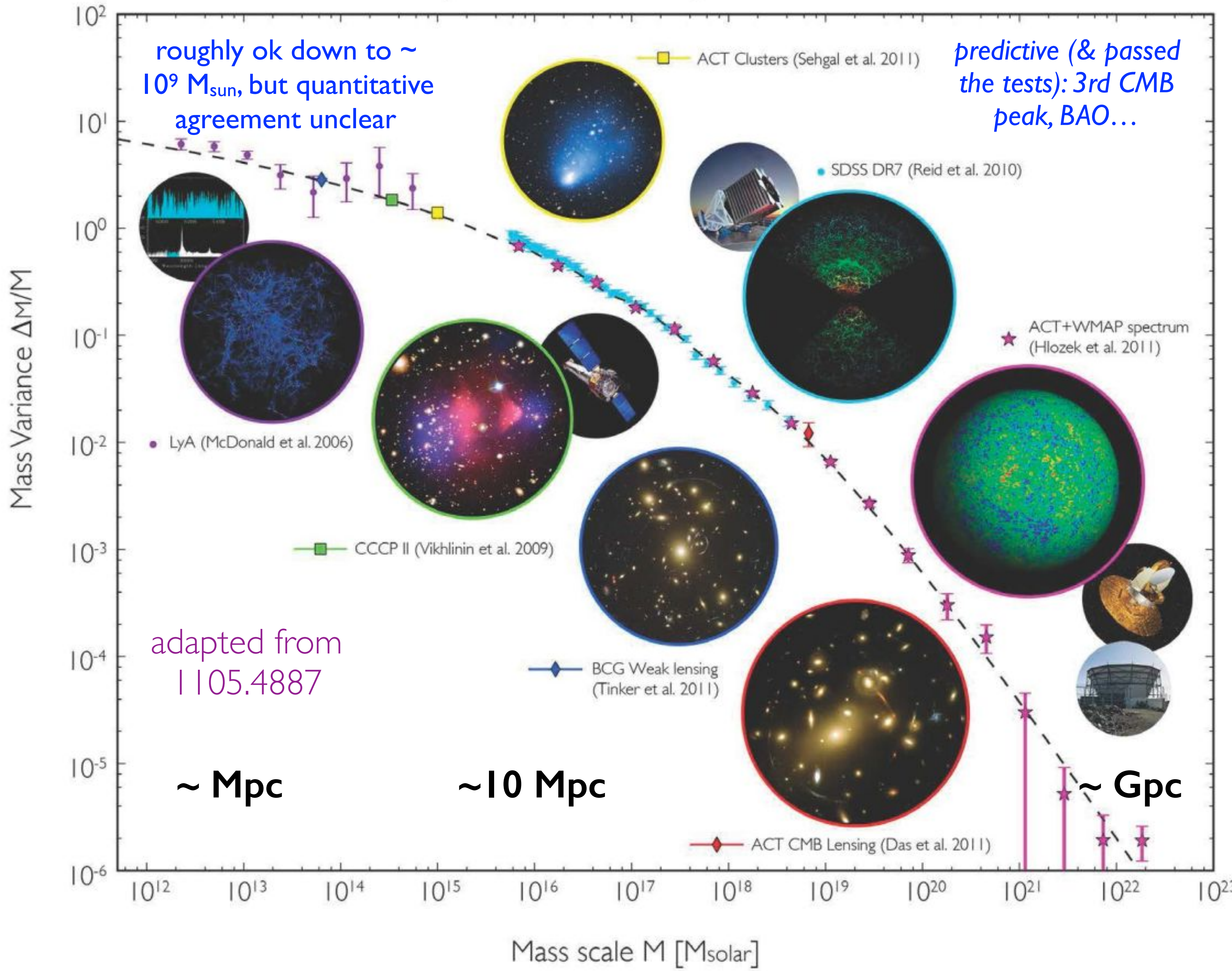
~100 Mpc



~ Gpc



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



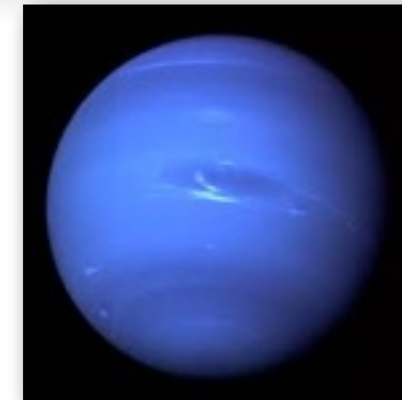
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G \left(T^{\rm known}_{\mu\nu} + T^{\rm DM}_{\mu\nu} \right) \qquad T^{\rm DM}_{\mu\nu} = \rho U_\mu U_\nu$$

“Dark Matters” common in astrophysics

Not shocking to infer presence of “extra stuff” via gravity

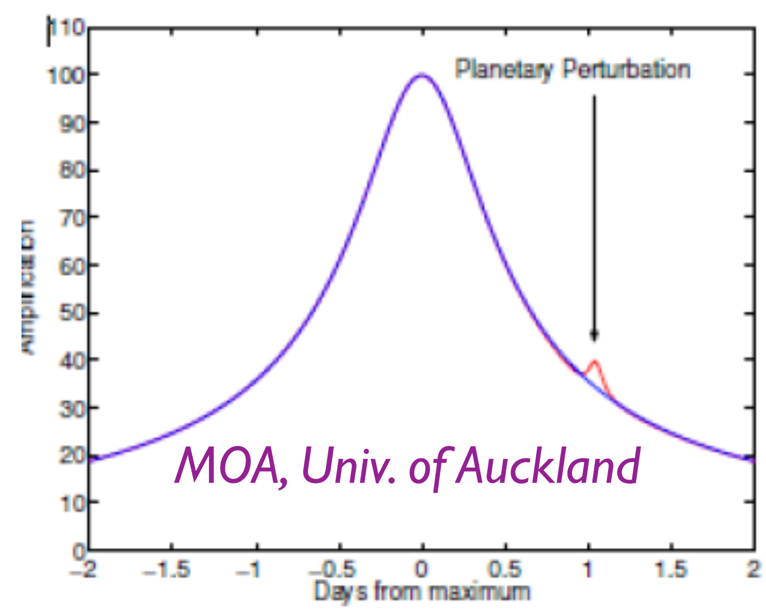
Le Verrier and independently Adams interpreted irregularities in Uranus orbit as due to perturbation by a yet unknown planet, calculating its orbital elements “by inversion”

On September 24, 1846 Galle found that “the planet whose place you [Le Verrier] have [computed] *really exists*” (“indirect DM detection”)



Indirect detection of former Solar System DM by Voyager 2

Microlensing routinely used to discover e.g. brown dwarfs (or exoplanets!)



Inferring the existence of objects from their gravitational effect is familiar in astrophysics!

Crucial role of cosmological evidence!

this is the new element, compared to the other "astro dark stuff"! *(plus its dominance?)*

I. Evidence from exact solutions or linear perturbation theory applied to simple physical systems (gravity, atomic physics...): credible and robust!

II. Can be at least effectively described as an additional <u>matter</u> species.

III. Tells us that the (largest fraction of) required dark matter is non-baryonic, rather than brown dwarf stars, planets, etc.

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III. Tells us that the (largest fraction of) required dark matter is non-baryonic, rather than brown dwarf stars, planets, etc.

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

Problem

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

What we know from cosmo/astro

- **Its mass density** (unless we move too deep into potential wells)
- **Its lifetime** (longer than O(10) times the lifetime of the Universe)
- **It must be "non-relativistic"** (sufficiently 'cold')
- **Not collisional** (compared to 'baryonic gas')
- **Not dissipative** (compared to 'baryonic gas')
- **It has** (very???) **weak interactions with ordinary matter and radiation (dark !)**
- **Its mass between ~10^{-21} eV/c^2 and ~ 10 solar masses** (precision cosmology!)

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

A couple of caveats for IDM

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

important since any algorithm or procedure should allow for "null/inconclusive outcome", i.e. one does not even know, a priori, if there is any signal to dig out

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beware of cognitive biases
→ DM may not be what "you like" or what "you can search for"

e.g.: The success of particle physics make us confident that *everything is made of particles*
Yet, particle DM hypothesis relies on extrapolating the DM phenomenon from Galactic scales to microscopic ones!

I am not criticizing the above as unreasonable. But it is fair that it is not obvious to most people out there who have no training in fundamental physics.

Plus, it is not a logical impossibility that DM is an "effective" or "emergent" phenomenon

…

Just saying: let's try not to transmit by default our biases to "artificial intelligence"

Quest for DM identification: contours of the bet

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

Why IDM??? "Traditional" link DM-particle physics

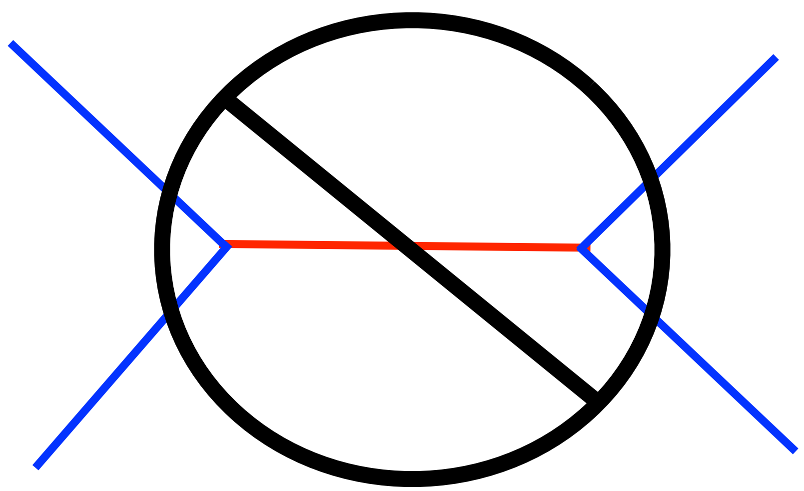
Strong <u>**prior for TeV-scale BSM (with SM-like couplings)**</u> **to cure "the hierarchy problem":**

why is weak scale (notably Higgs mass) insensitive to quantum effects from physics at some much higher energy scale Λ_{UV} (e.g. gravity)?

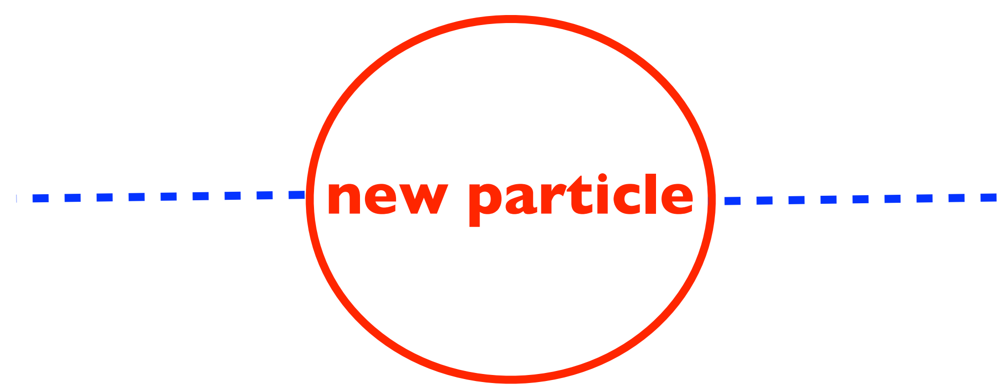
Conjecture: there is some symmetry (e.g. SUSY) @ E~O(TeV), "shielding" low-E pheno from UV.

Precision data suggest that tree-level couplings SM-SM-BSM should be avoided!

we want to avoid!



Ok with it!



One straightforward solution is to impose **some symmetry** (often "parity-like", relic from some UV-sym): SUSY R-parity, K-parity in ED, T-parity in Little Higgs. New particles only appear in pairs!

➡ Automatically makes **lightest new particle stable!**

➡ It has other benefits, e.g. respect **proton stability** bounds!

The WeaklyInteractingMassiveParticle Paradigm

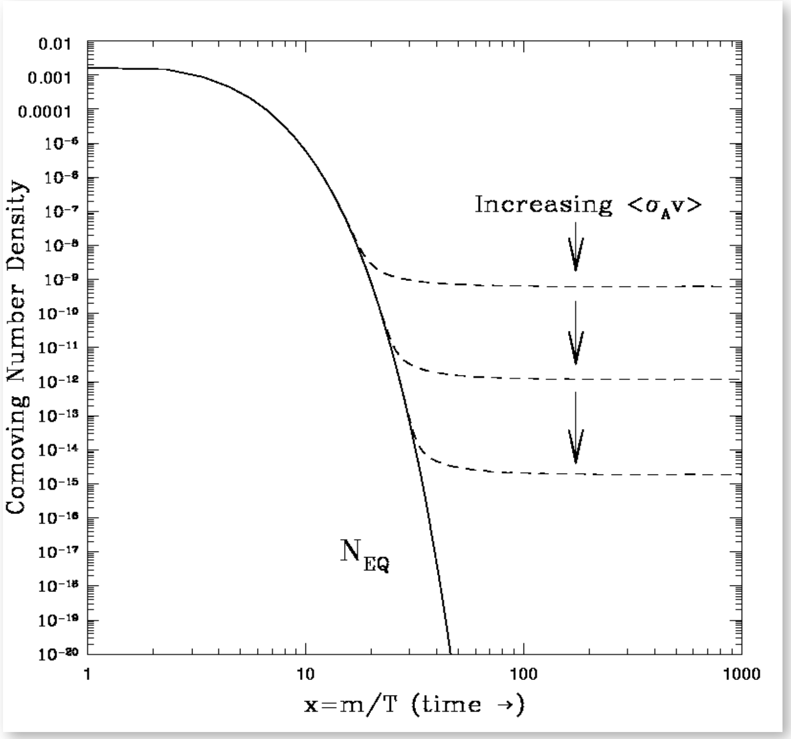
Cosmology tells us that the early universe was a hot plasma, with all "thermally allowed" species populated. Notion tested up to T~ few MeV (BBN, cosmo ν's):

What if we extrapolate further backwards, introducing this new particle?

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

Add to SM *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

What is left of it depends on the decoupling time, or their annihilation cross section: the weaker, the more abundant...



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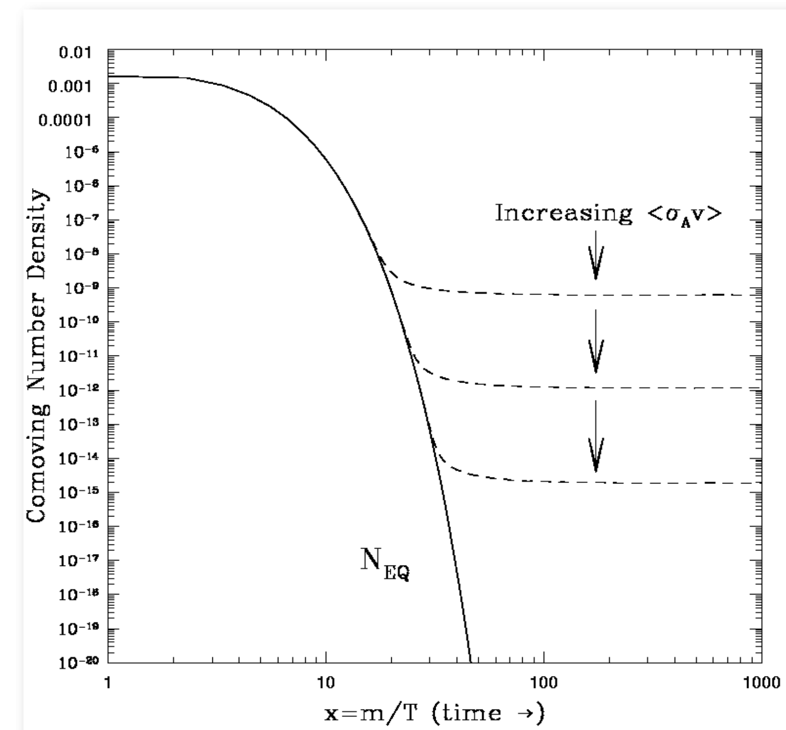


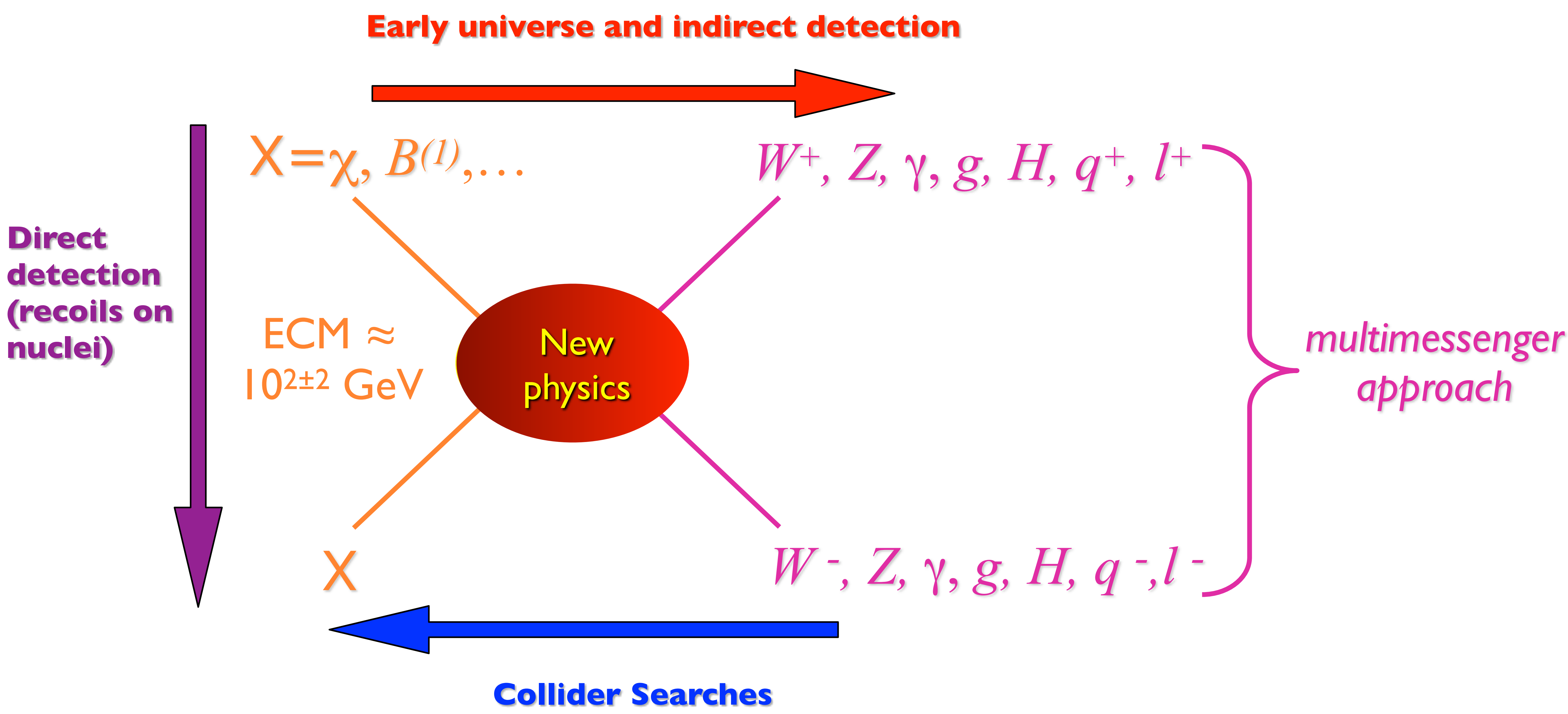
Textbook calculation yields the current average cosmological energy density

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

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

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

WIMP (not generic DM!) search program



✓ demonstrate the "particle physics" nature of astrophysical DM (locally, via DD; remotely, via ID)

✓ Possibly, create DM candidates in the controlled environments of accelerators (but not enough! Neither stability nor relic density "directly tested", for instance…)

✓ Find a consistency between properties of the two classes of particles. Ideally, we would like to calculate abundance and DD/ID signatures → link with cosmology/test of production

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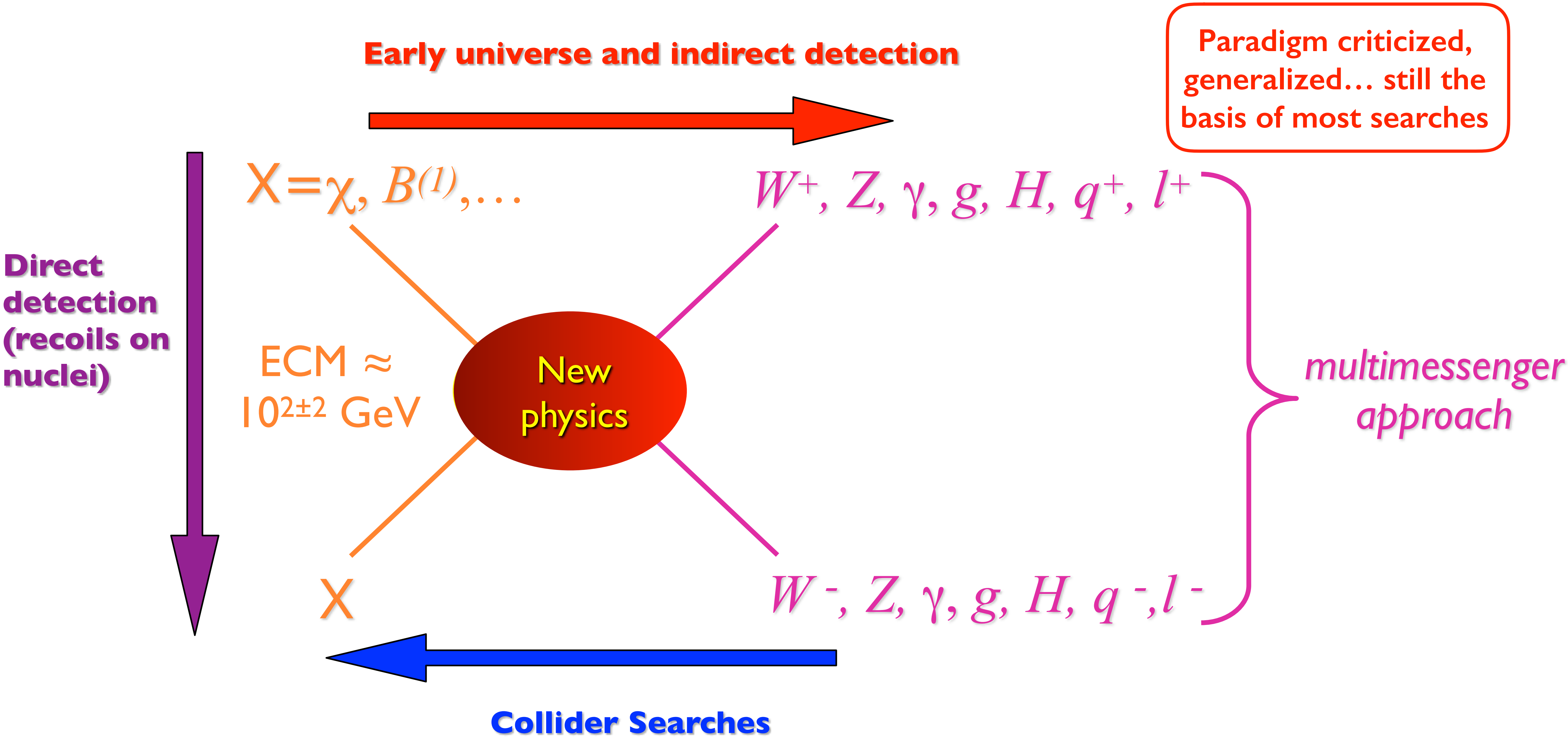

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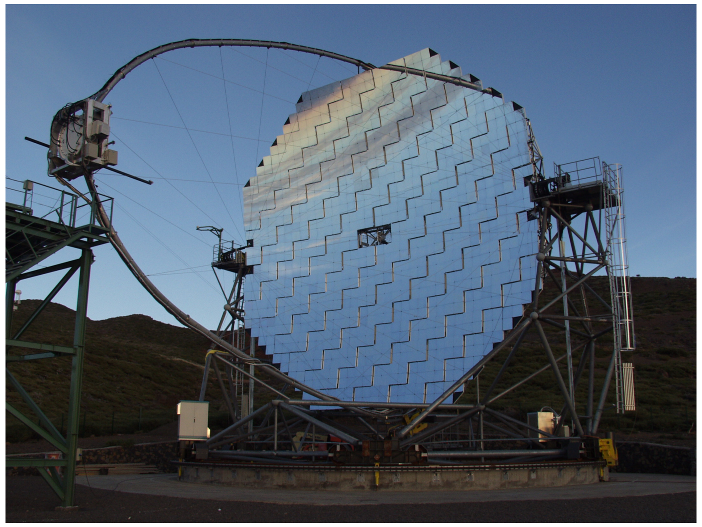
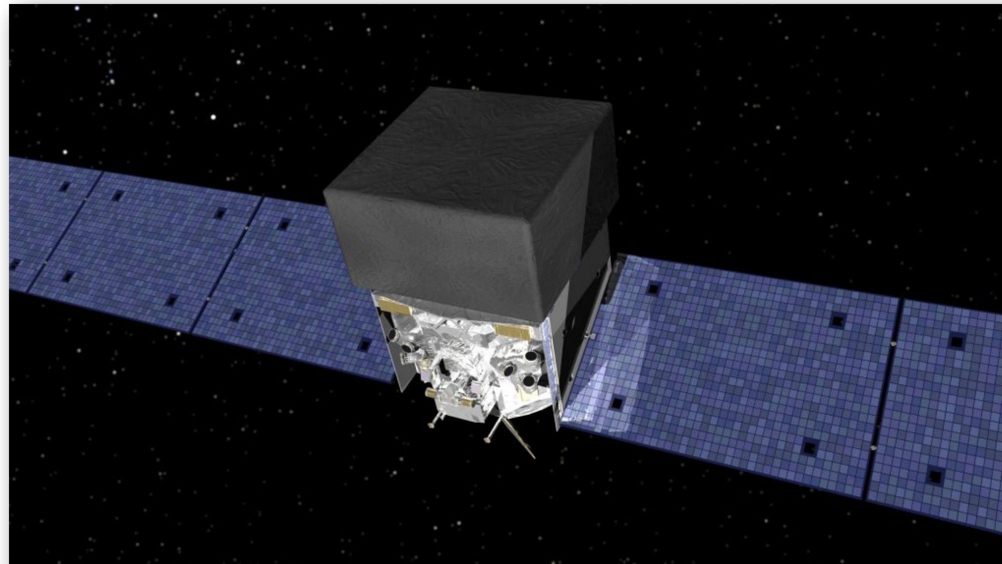
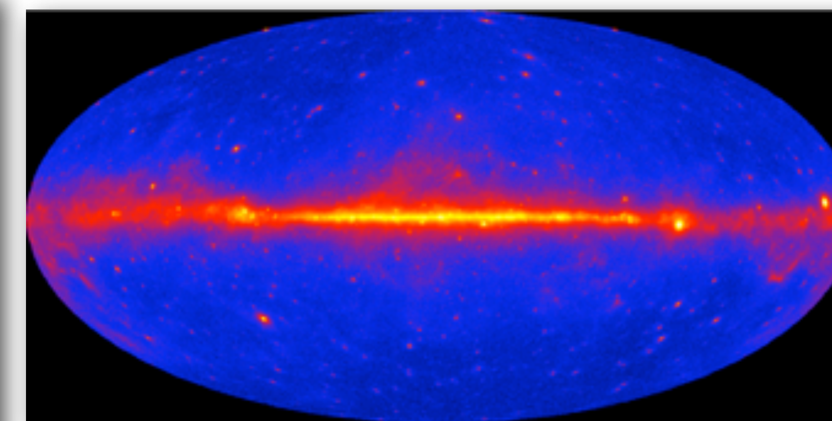
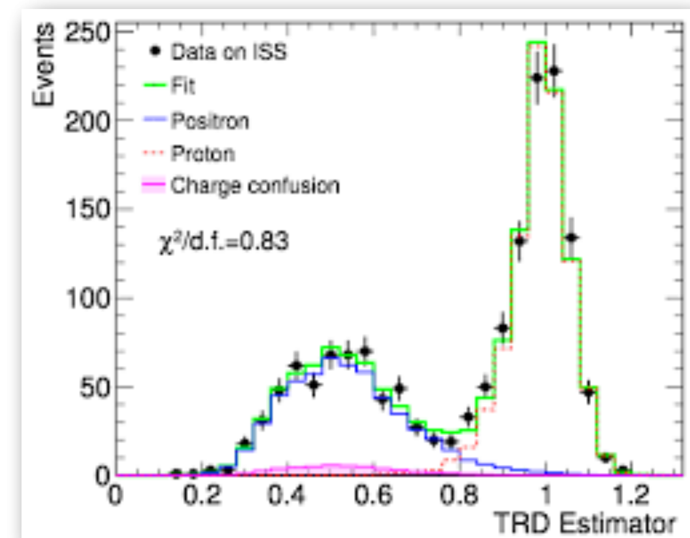
many channels & tools for indirect WIMP searches

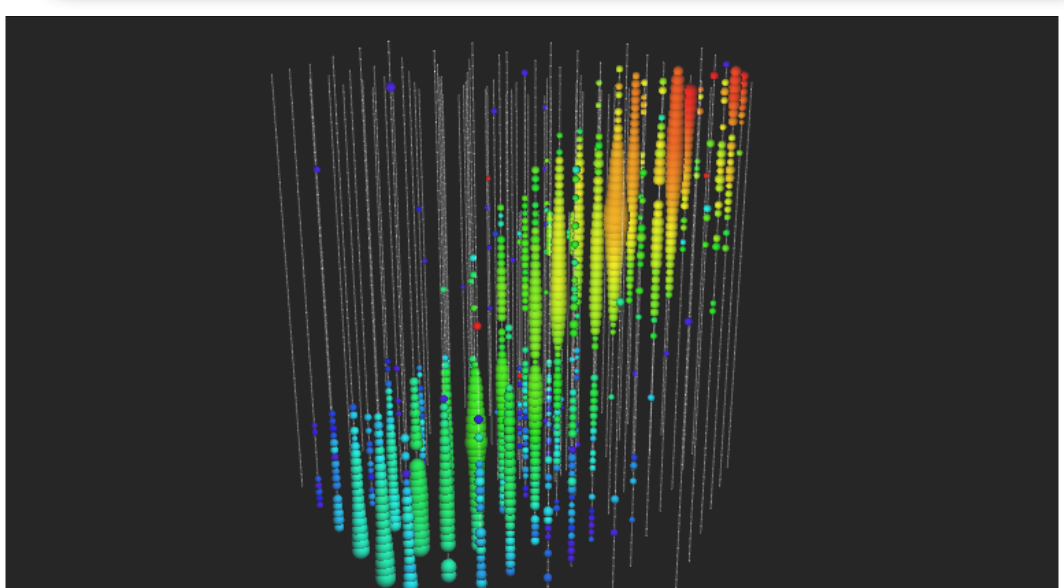
each one with advantages and problems: won't discuss details











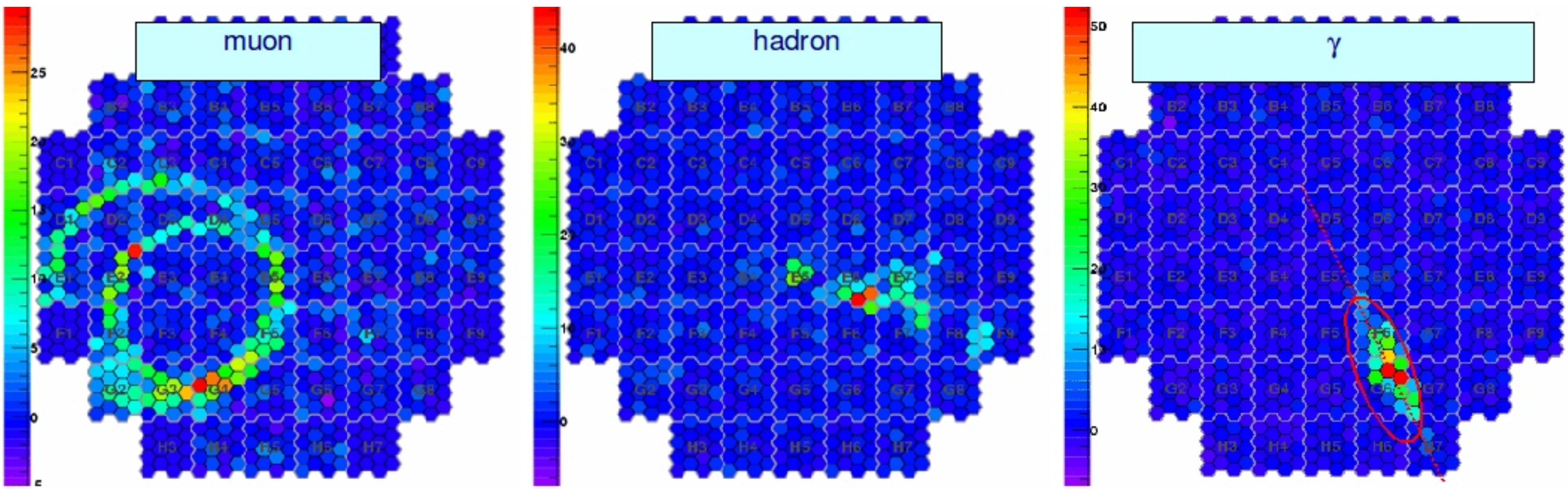
Opportunities and problems

When does machine learning certainly help?

layman point of view

1. **When theory known**, but no *simple (e.g. analytical)* link btw theory parameters & observables

- e.g. event reconstruction and classification (e.g. photon vs. hadron event in a γ-telescope)



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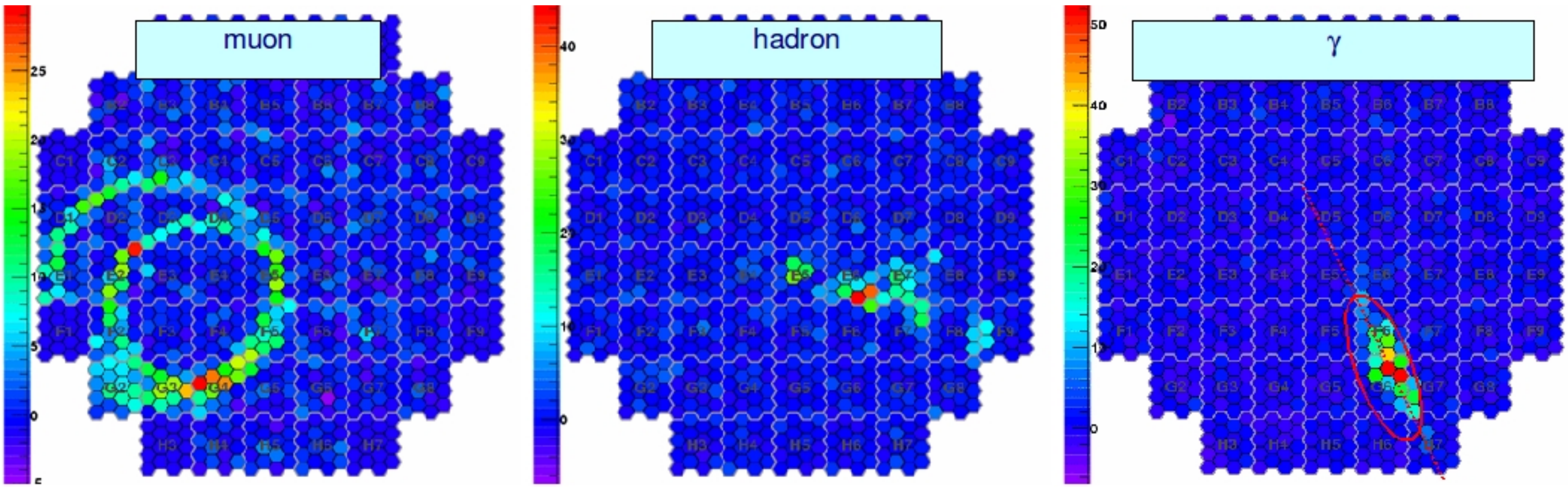

some other examples

- non-parametric reconstructions of DM-related observables, e.g. lensing maps in *J. Caldeira et al., "DeepCMB: Lensing Reconstruction of the CMB with Deep Neural Networks," arXiv:1810.01483*

- To speed up statistical inference in large ***theory*** spaces, e.g *G. Bertone et al., "Identifying WIMP dark matter from particle and astroparticle data," JCAP 1803, 026 (2018) [arXiv:1712.04793]*

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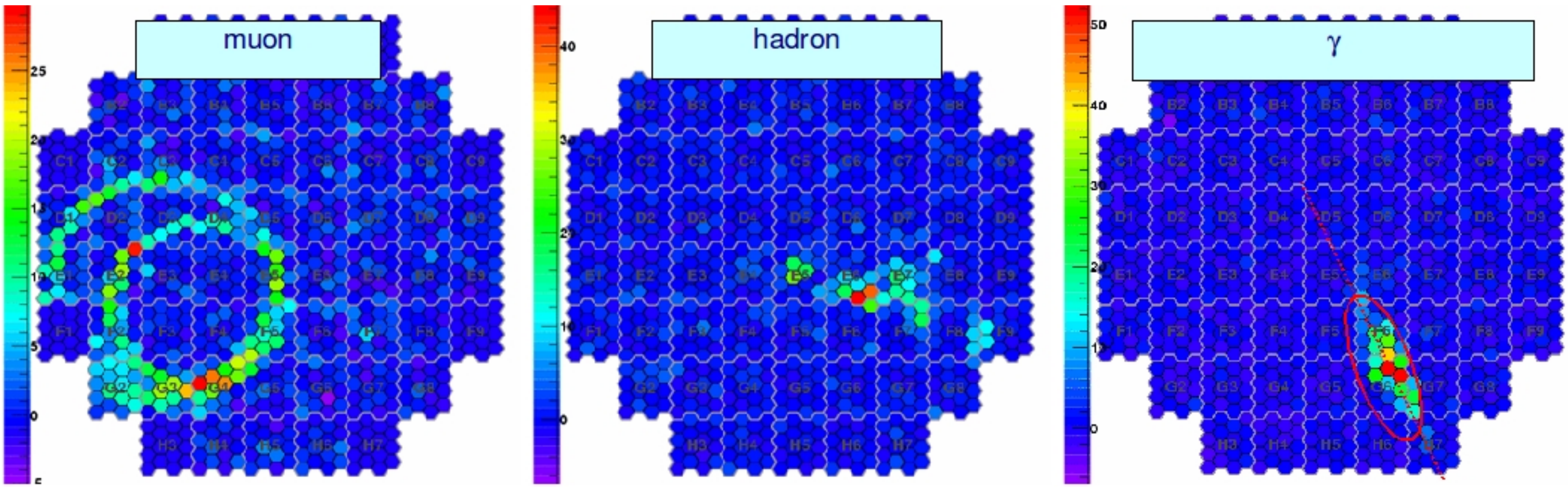

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Only indirectly related to identification problem!

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2. **When 'theory' … empirically known!** *(most common life cases, **not common at all in theoretical physics!** We would say that in this case <u>no theory exists</u>, the antithesis of our job!)*

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layman point of view

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Use lots of data and 'empirical classification' (mostly from unaware "users")

Cat
or
cappuccino?

For details: M.-A. Fardin "On the Rheology of Cats", Rheol. Bull. 83, 16 (2014) [IgNobel prize for physics 2017]

Much easier than to **ask us** to disentangle the two than to "explicitly define what is a cat, what is a cappuccino" and construct a "cat-finder" procedure.

Problems in DM 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

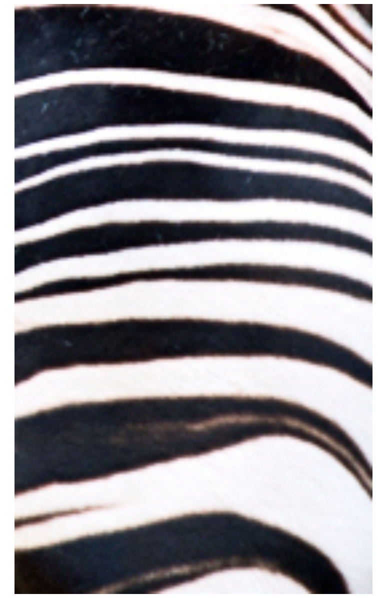
We ***believe*** that the **signal** looks like

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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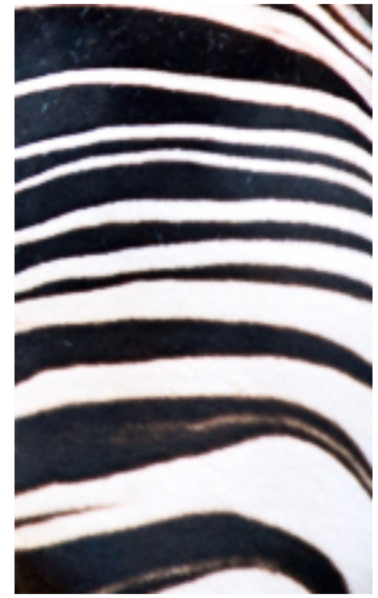


… then many people run writing dozens of papers about the discovery of DM…

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

Okapia johnstoni, fam.: giraffidae

Actual example from the gamma-ray sky

What does "theory" predict?

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

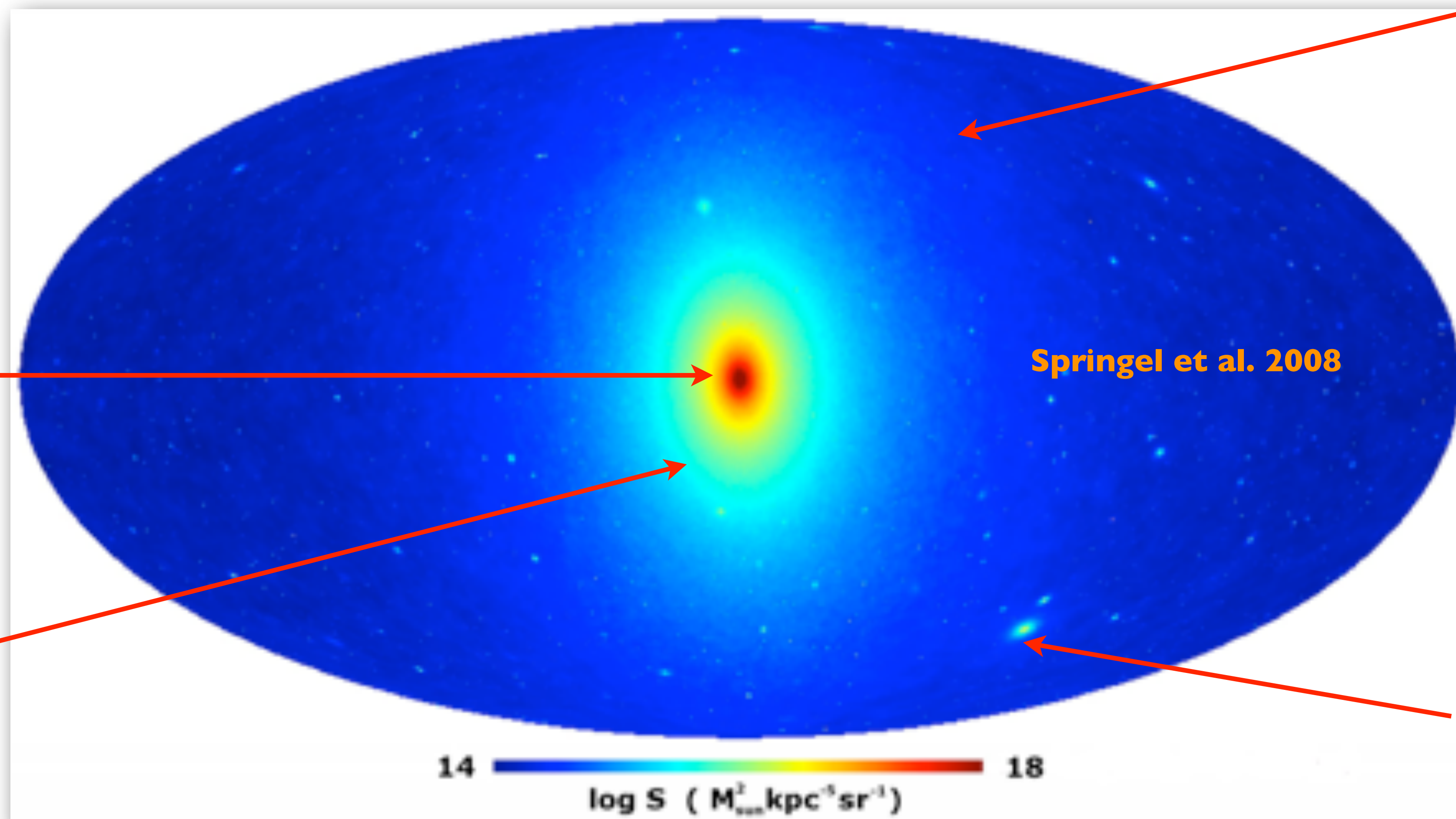
Comment I.
most of the signal depends upon structures deeply in non-linear regime of gravitational interaction. Little "analytical understanding" (very different from the situation in cosmo evidence for DM!)

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)

A prominent signal appears from the inner Galaxy

Extragalactic diffuse

Galactic Center



Inner Halo

Satellites (and Clusters)

What does “theory” predict?

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)

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Extragalactic diffuse

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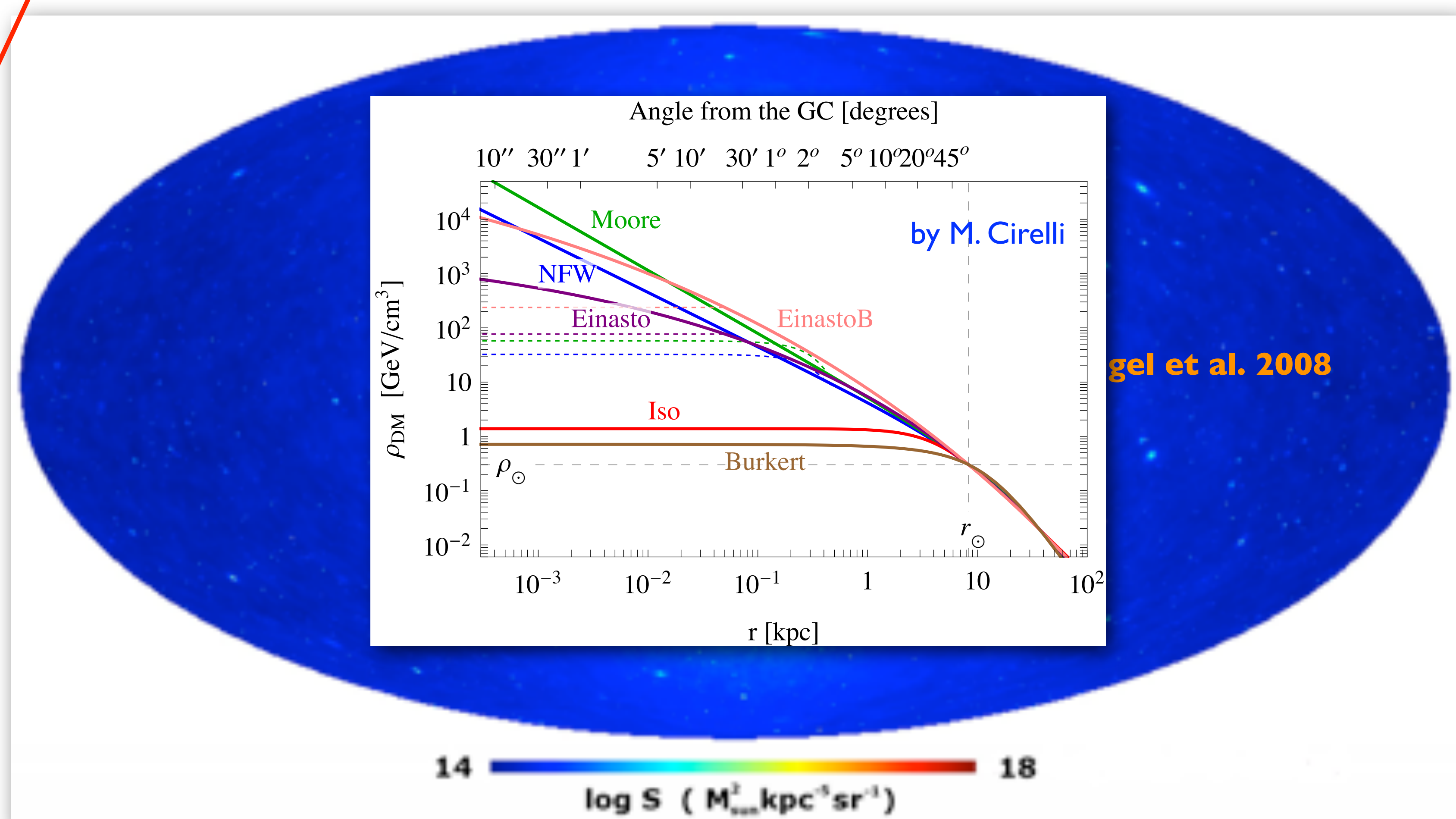


Inner Halo

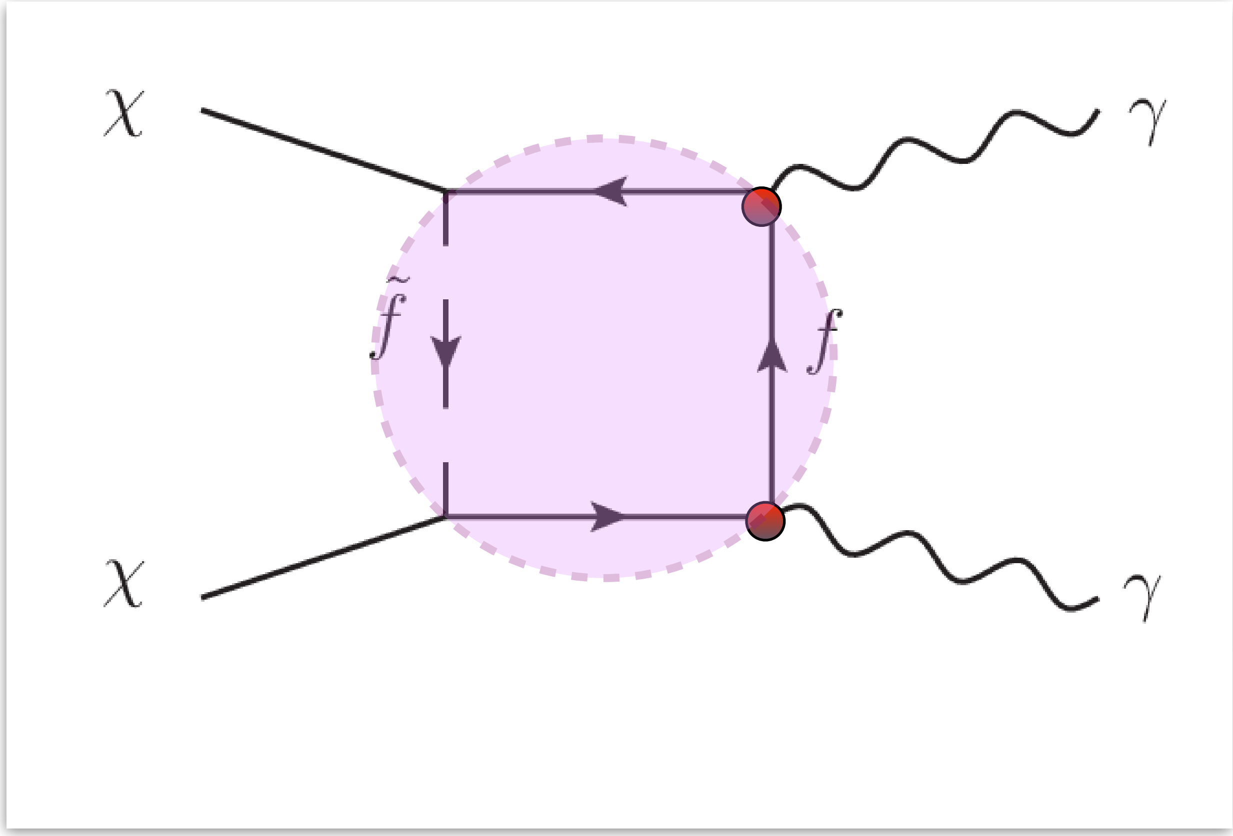
Satellites (and Clusters)

Spectral features: lines

- Line annihilation requires two-body final state channels containing at least one photon (for SM final states, $\gamma\gamma$, γZ, γH) yielding the spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma)\,, \quad E_\gamma \leq m_\chi$$

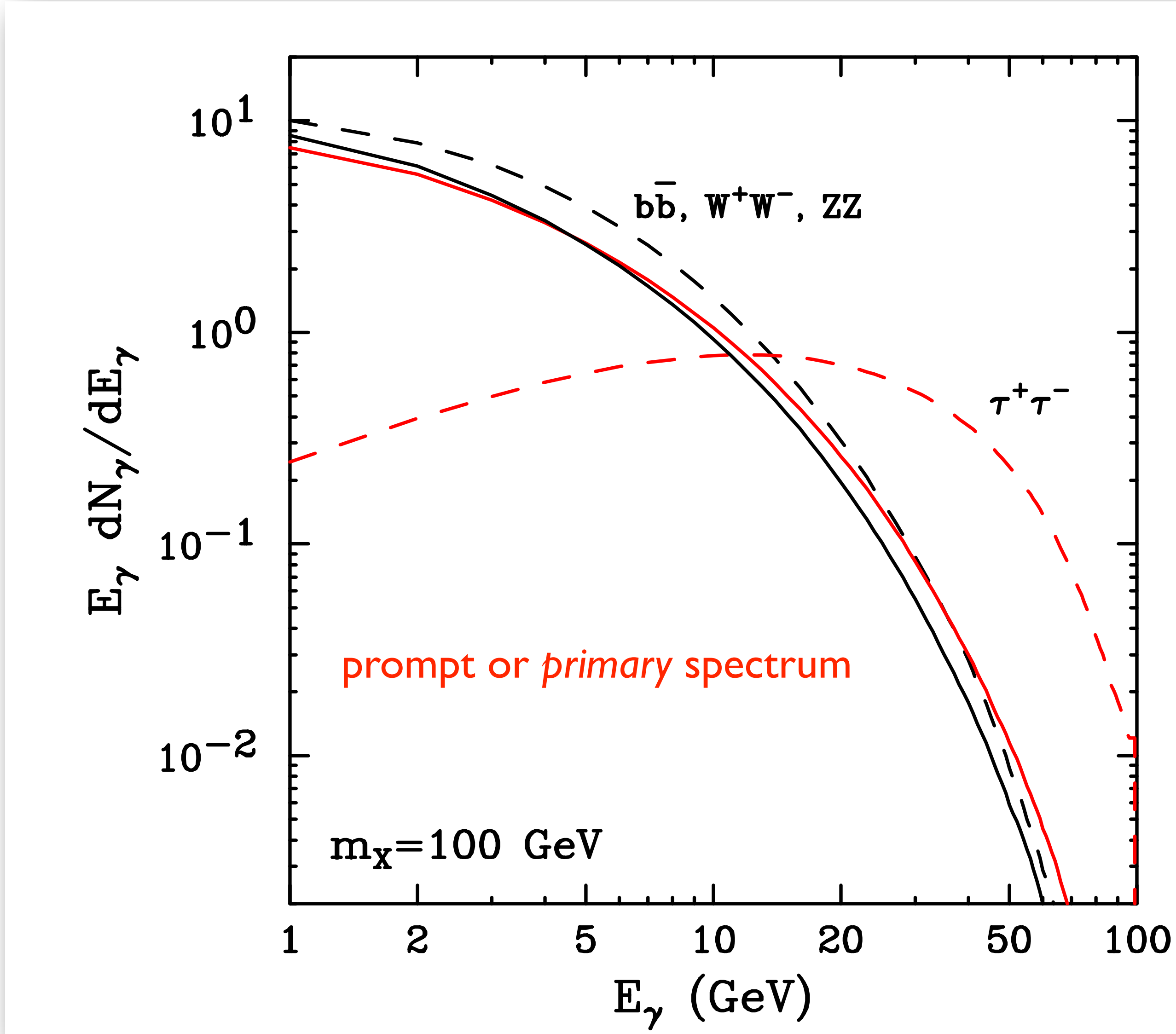
A distinctive feature which is hardly a *discovery* channel



- This must be a loop-level process, suppressed with respect to the tree-level by $\alpha^2 \sim 10^{-4}$

- Usually it's theoretically difficult to produce line flux which is observable, while fulfilling bounds on continuum (easier role if e.g. final state cannot be produced on-shell…)

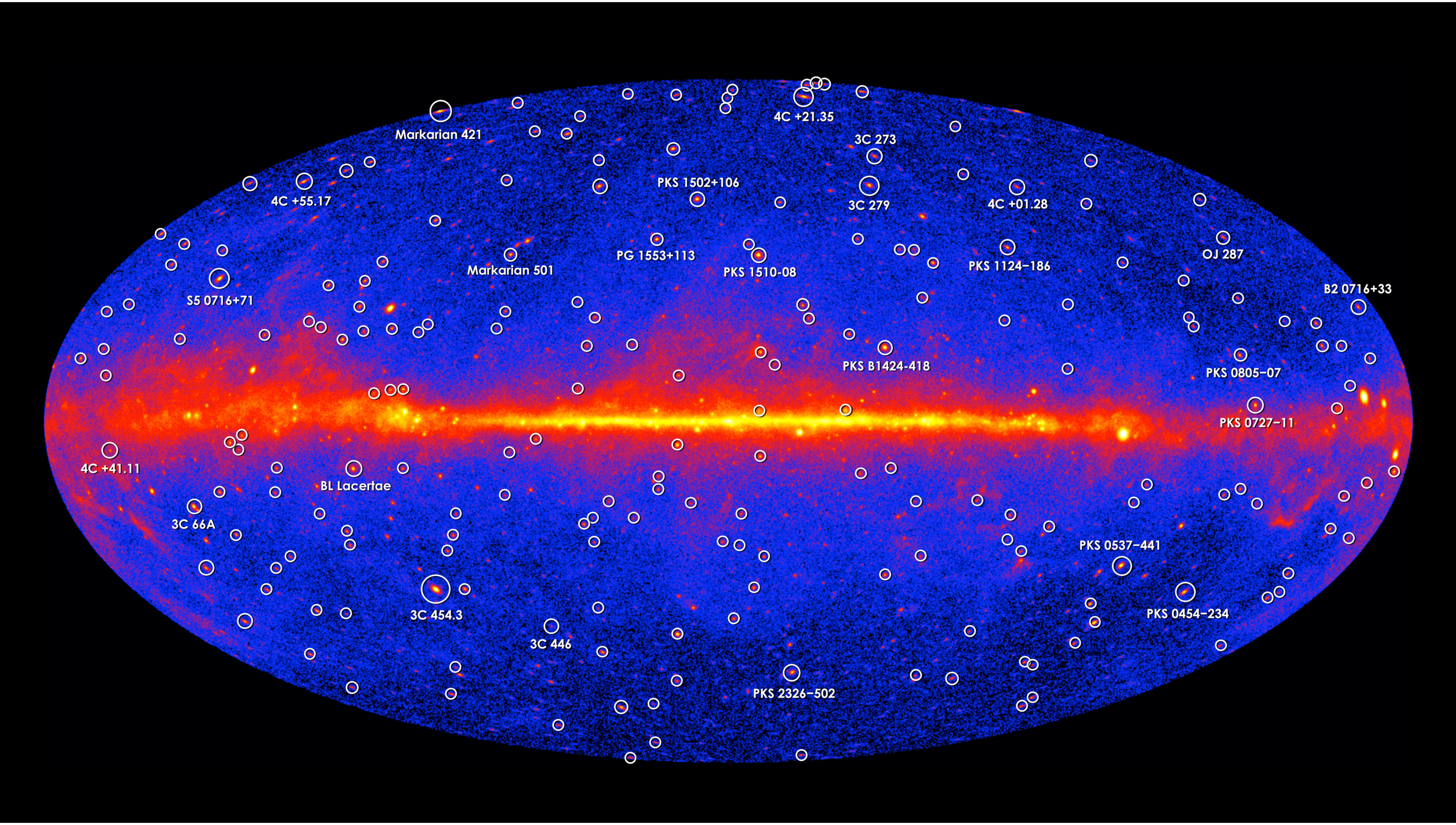
Spectral features: continuum



@ E~m, model dependent
@ E<< m, uncertain

- ✓ whenever DM annihilates into quarks or gauge bosons, continuum photon spectrum is quasi-universal, as a result of decays/fragmentations
- ✓ Near the endpoints, thresholds or for leptonic final states, peculiarities may be present.
- ✓ Significant *secondary* (byproducts of electrons e-losses) gamma radiation may be emitted from electrons. Requires treatment as for charged particles, and astrophysical medium is important.

Actual data: the Fermi sky in the GeV energy range

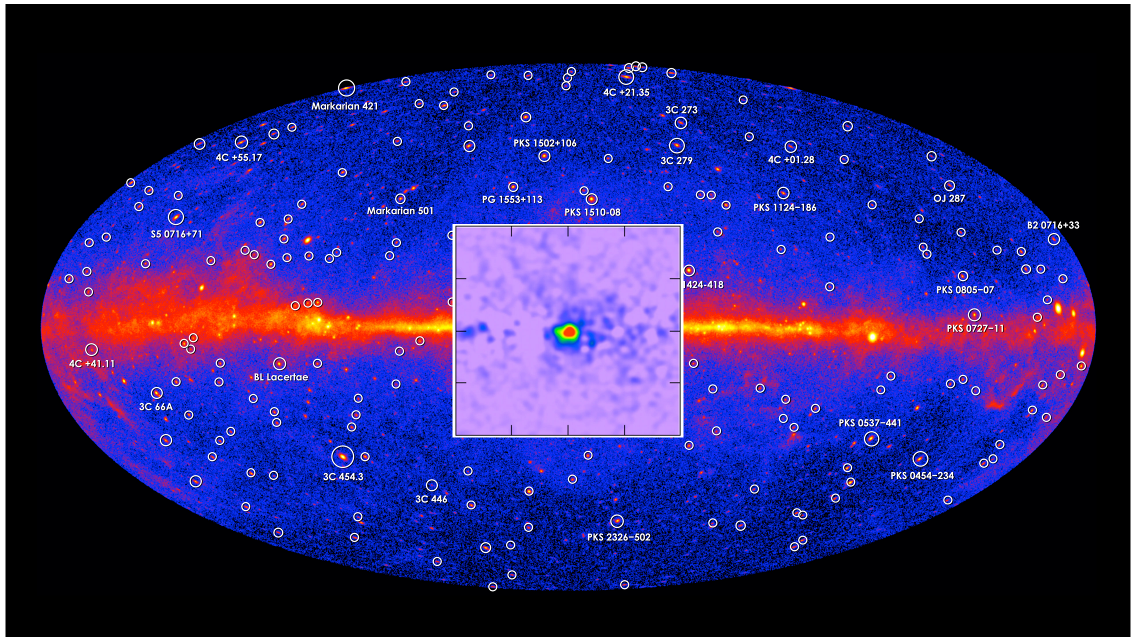


Fermi sees nothing like DM expectations: **backgrounds (aka astrophysical sources) are important!**

Their understanding is the main challenge in indirect DM searches

A Galactic center *excess* found! (*with respect to what?*)

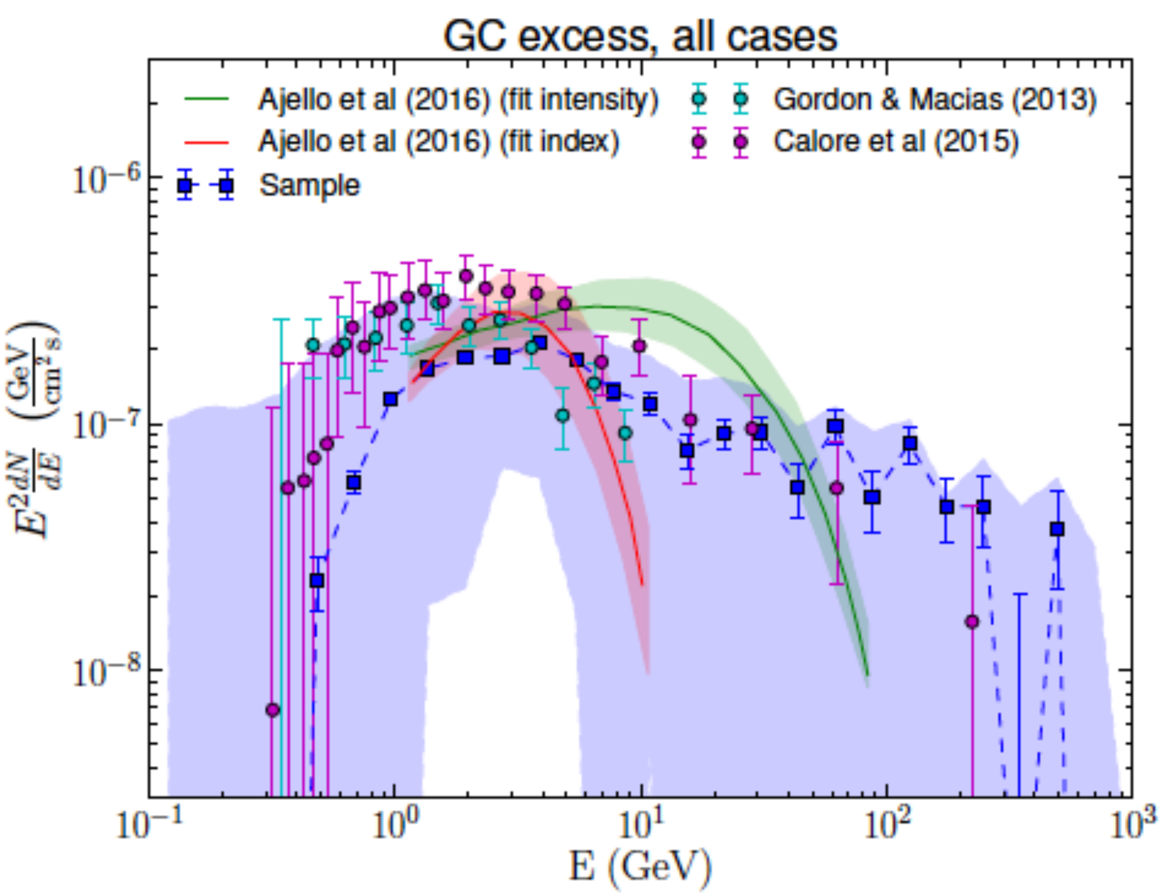
The GCE is 'identified' as the residual of the following subtraction



Ackermann et al [Fermi], ApJ 840, no. 1, 43 (2017) [1704.03910]

Component	Definition
Hadronic interactions and bremsstrahlung	GALPROP, 5 rings
Inverse Compton scattering	GALPROP, 3 components (CMB, starlight, infrared)
Loop I	Geometric template based on radio data (Wolleben 2007)
Fermi bubbles	Flat template from Ackermann et al. (2014)
Point sources	Template derived from 3FGL catalog
Extended sources, Cygnus, LMC	Templates derived from 3FGL catalog
Isotropic emission	Proportional to *Fermi*-LAT exposure
Sun and Moon templates	Derived with *Fermi* LAT Science Tools

(Fermi-LAT data) **-** **("Known" components of the Galactic diffuse emission, isotropic (mostly extragal.) emission, point-like sources, extended sources, Sun and Moon)**



"The **region around the GC** is now well established to be **brighter** at energies of a few GeV **than expected from conventional models** of diffuse γ-ray emission and catalogs of known γ-ray sources"

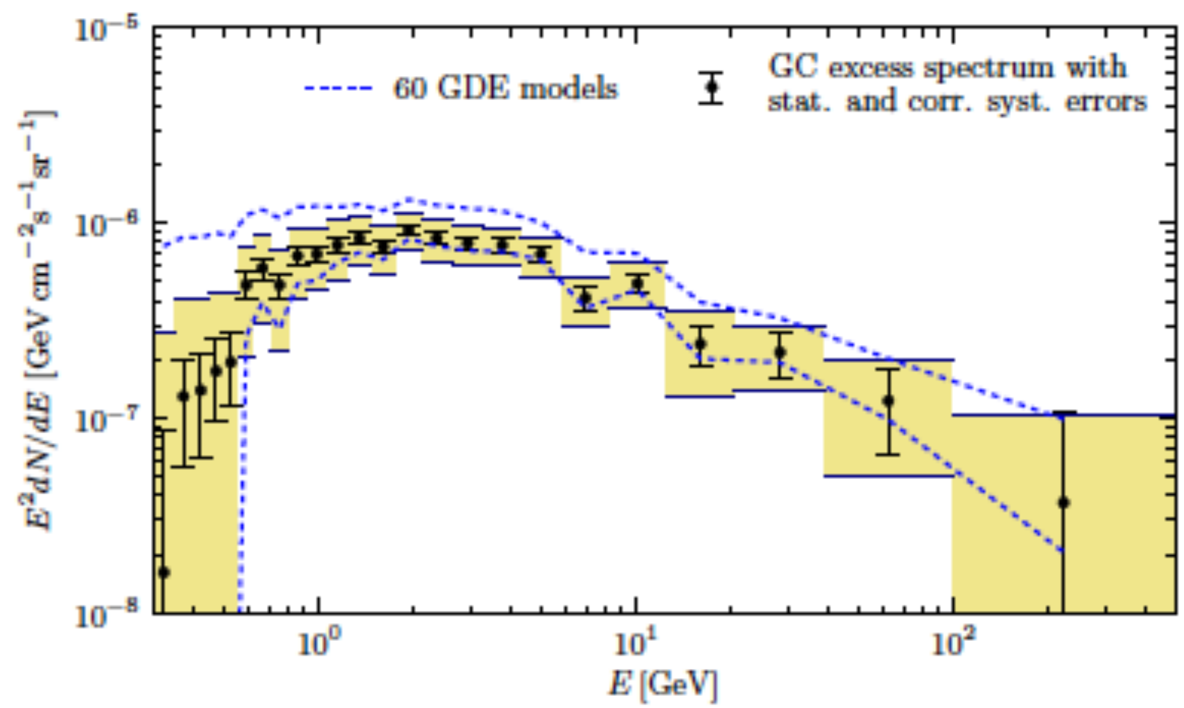
(qualitatively but not quantitatively robust wrt to uncertainties of different components)

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

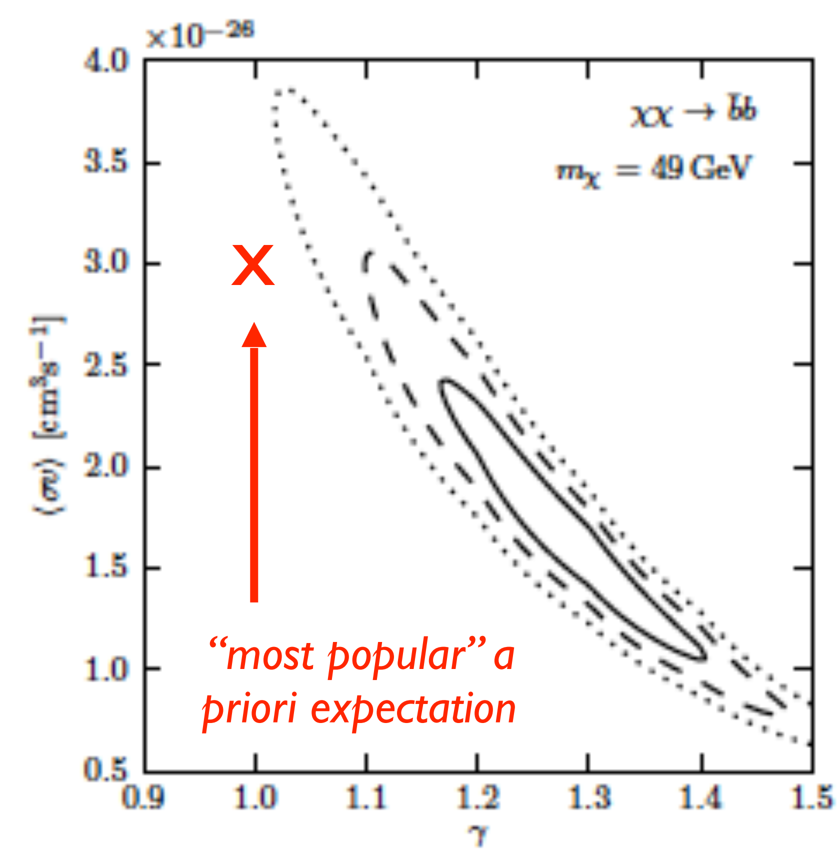
Intensity: Requires an annihilation cross section of $\langle\sigma v\rangle \sim 2\ 10^{-26}\ cm^3/s$, near the value of a thermal relic



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

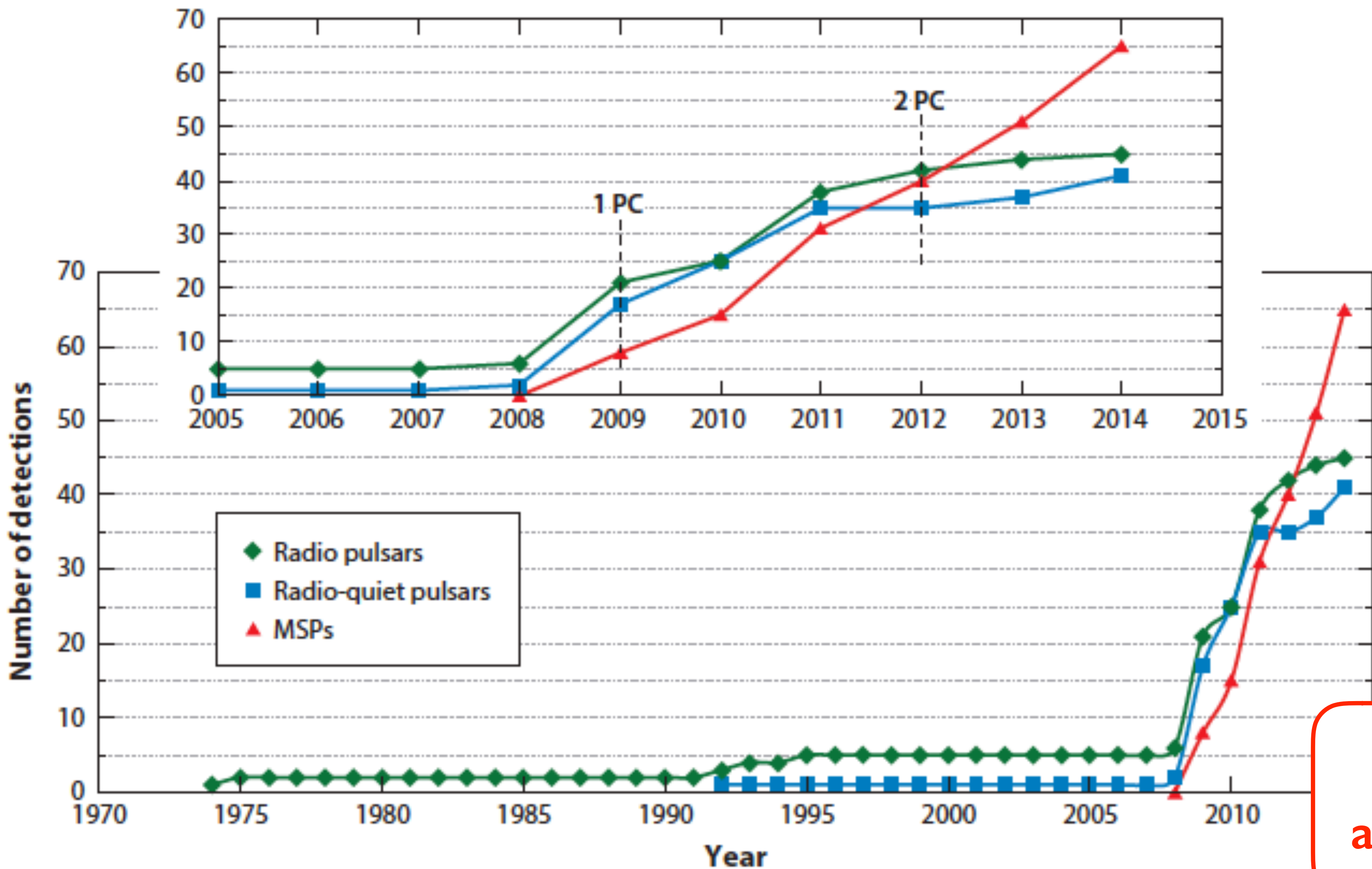
F. Calore, I. Cholis and C. Weniger, "Background model systematics for the Fermi GeV excess," 1409.0042



in parallel: example of surprise with Fermi-LAT mission

➡ **milli-second pulsars (MSPs) have emerged as a numerous new 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?

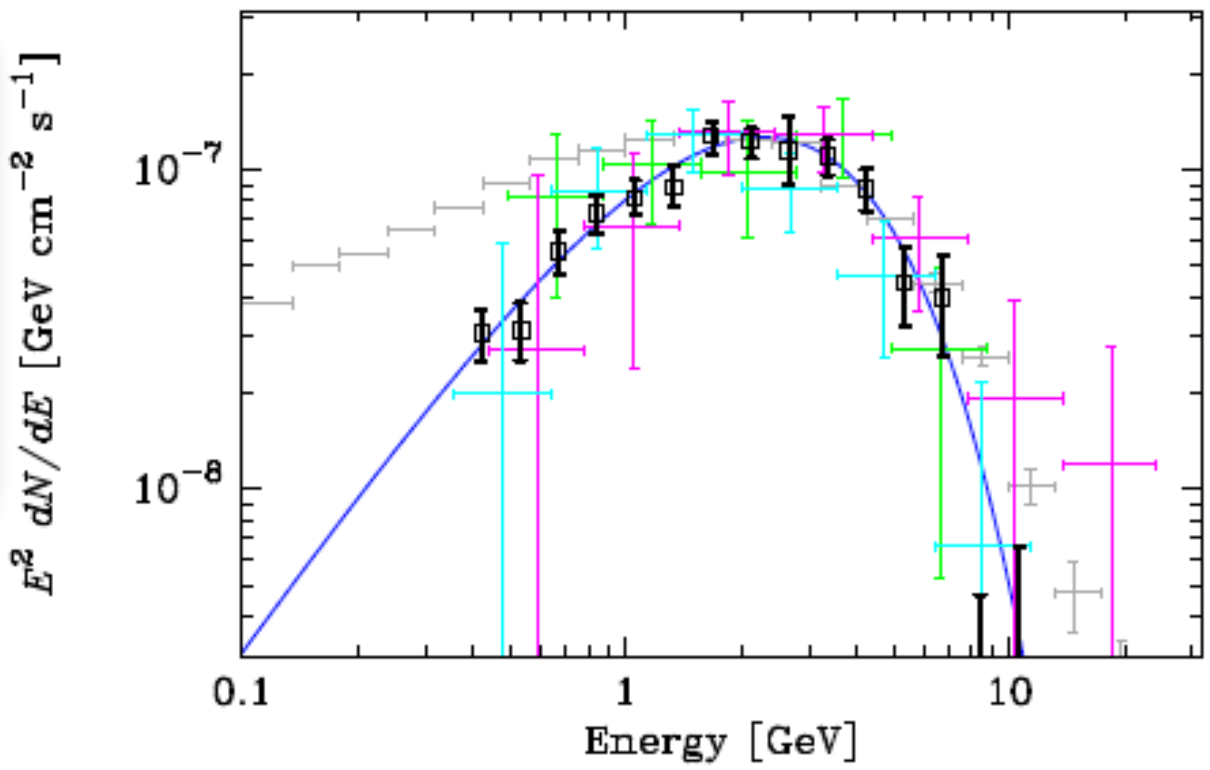
Their discovery notably in the gamma-band has boomed after Fermi launched, now most abundant class in the Galaxy!

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

MSP: spectrum and distribution

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

K.N. Abazajian, JCAP 1103 (2011) 010 [1011.4275]
"The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster,"



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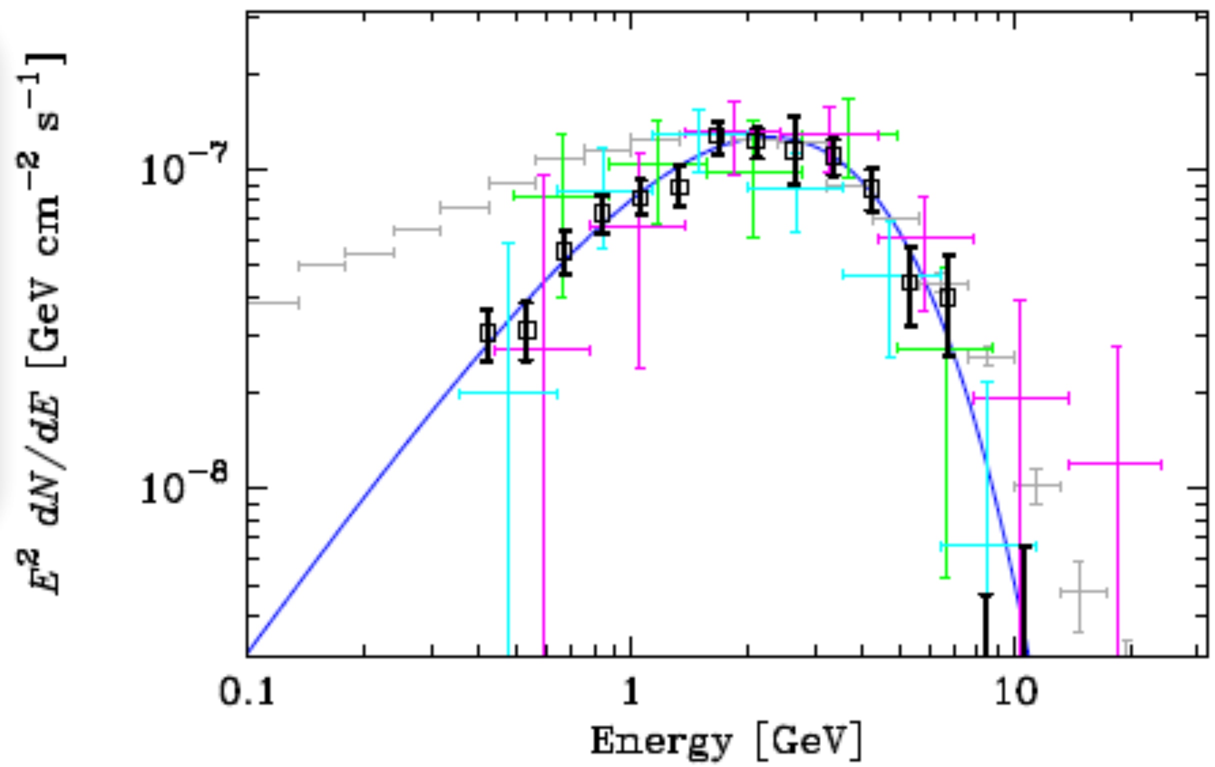

- **A suitable population of MSPs in the inner galaxy?**

Not in the 'pre-existing models'. But based on the MSP in the disk, if just rescaling to the # of stars in the bulge, ~10% to ~200% of the GCE would be accounted for by MSP!!!

C. Eckner et al., Astrophys. J. 862, no. 1, 79 (2018) [1711.05127]

Even stronger, the GCE profile matches the *stellar* one!

O. Macias et al., "Galactic bulge preferred over dark matter for the Galactic centre gamma-ray excess," Nature Astronony (2018) [1611.06644]
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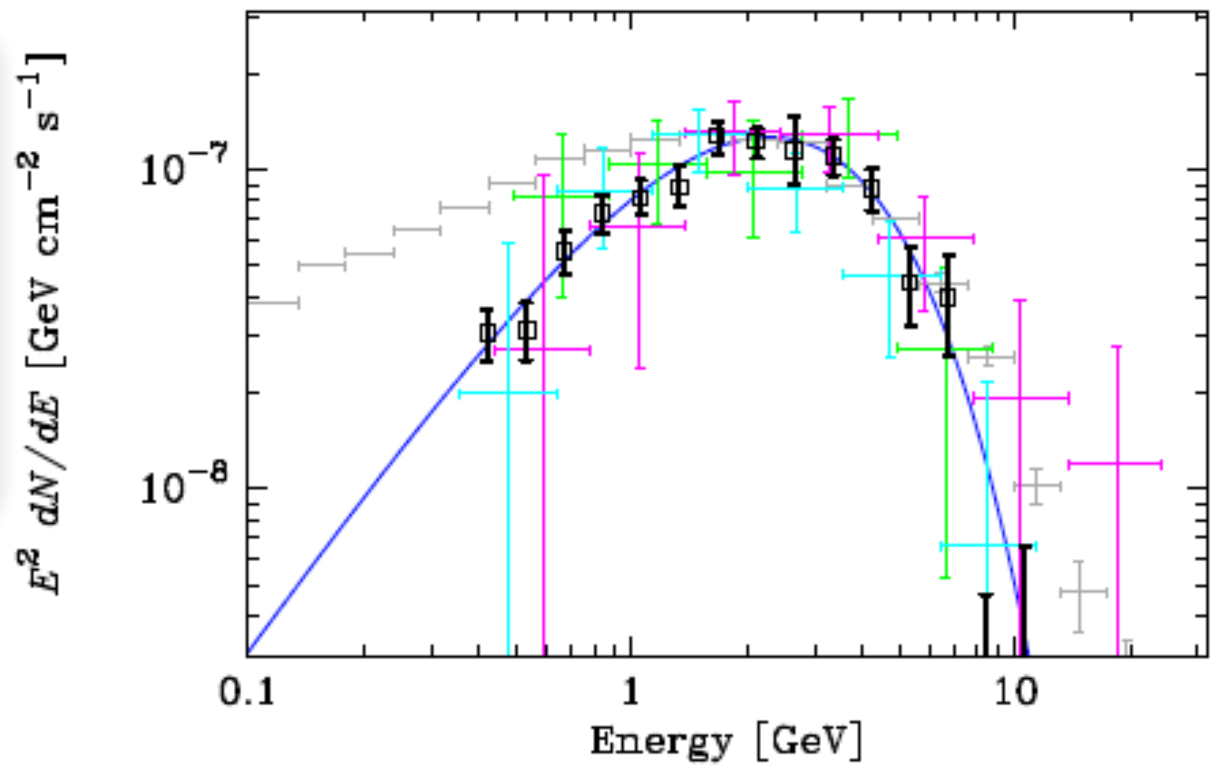

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Short 'distance' in (some) **"data"** (spectrum, space distribution) may **correspond to large distances in theory** space (DM vs MSPs!)

spells troubles even for unsupervised learning?

A turning point: small scale power!

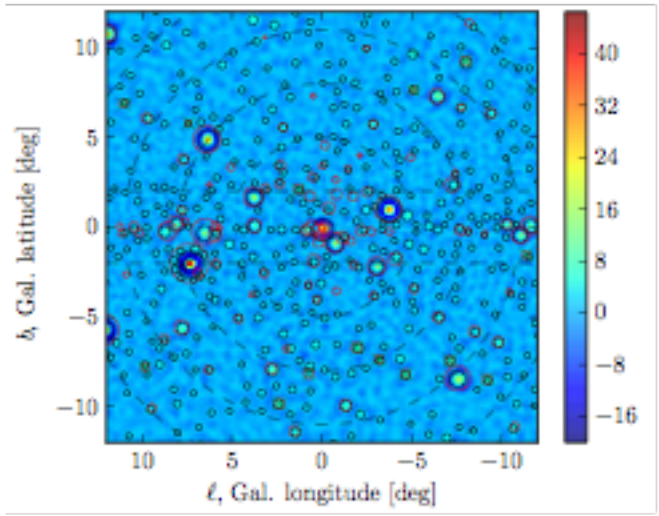
S. K. Lee, M. Lisanti, B. R. Safdi, T. R. Slatyer and W. Xue, "Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy," PRL, 116, 051103 (2016) [1506.05124]

Within 10 deg. of the Galactic Center with |b|<2, we find that 5-10% of the flux can be accounted for by a population of unresolved PSs, distributed consistently with the observed GeV gamma-ray excess in this region. The excess is fully absorbed by such a population, in preference to dark-matter annihilation. The inferred source population is dominated by near-threshold sources, which may be detectable in future searches

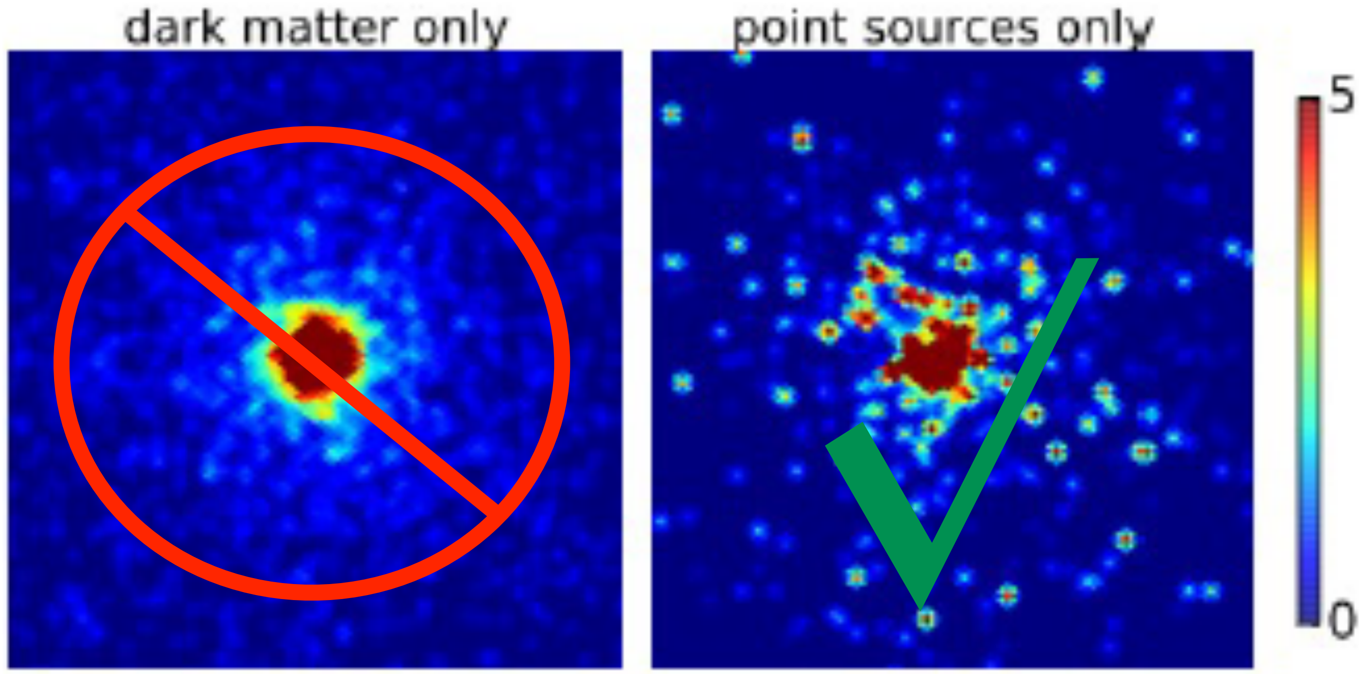
based on 'pixel-statistics'

R. Bartels, S. Krishnamurthy and C. Weniger, "Strong support for the millisecond pulsar origin of the Galactic center GeV excess," PRL 116, 051102 (2016) [1506.05104]

For plausible values of the luminosity function, this population explains 100% of the observed excess emission. We argue that other extragalactic or Galactic sources, a mismodeling of Galactic diffuse emission, or the thick-disk population of pulsars are unlikely to account for this observation.



based on wavelet transform



(Credit: Lee+ 2014)

now being searched for in multiwavelength (e.g. radio) and even multimessenger (GW?!) campaigns

I spare you the latest developments in this story…

You got the message!

Comments & Conclusions

Problems in DM identification quest and Needs

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!)

What would *really* help us in the quest

- Challenge our interpretation frameworks
- Formulate hypotheses relying as much as possible on data
- Devise ways to deduce (yet unthought of) consequences and suggest tests

How to check if small-scale anomalies are DM-related or due to mismodeling of non-linear and baryonic effects?
Is DM related to electroweak physics or not at all?
…

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We look for small (tiny?) ‘anomalies’, need to master tails of distributions, in new windows… algorithms that work ‘for the bulk of cases’ are not necessarily appropriate.

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Google

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{*Anderson, PAMELA*}

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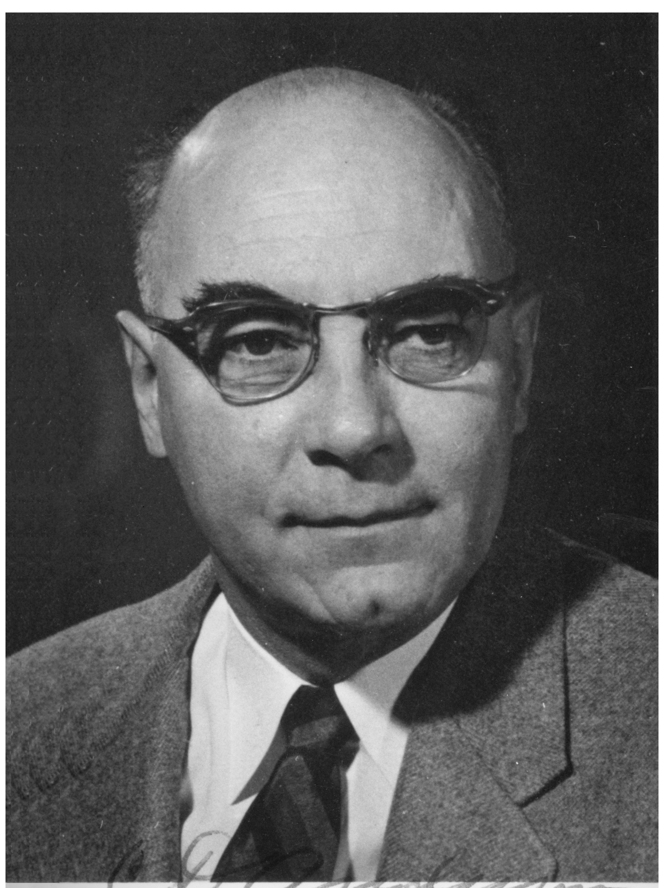
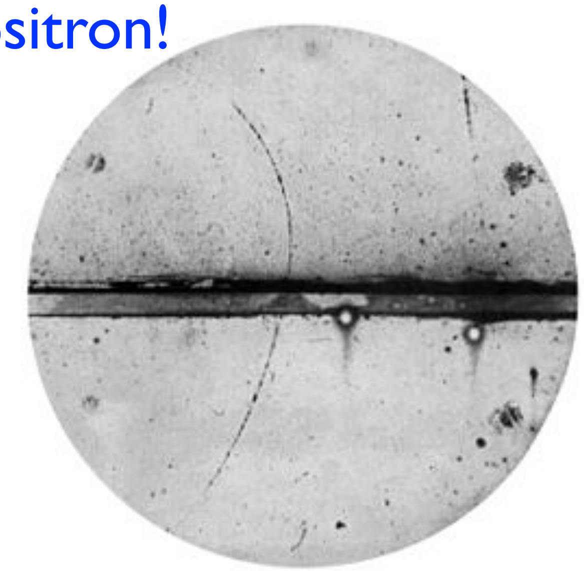
An actress!

Astroparticle physicist

Positron!





Summary and conclusion

Whenever we have a 'model', we can certainly apply machine learning tools to

- DM signals
- "**background**" data

significant improvement expected whenever no simple link between theory parameters and observables exists

Doing that better is ***helpful, but not sufficient*** in tackling the **big issues in the DM quest**

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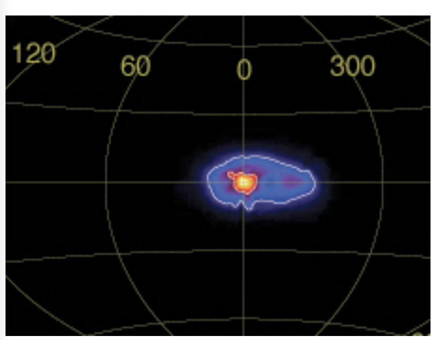
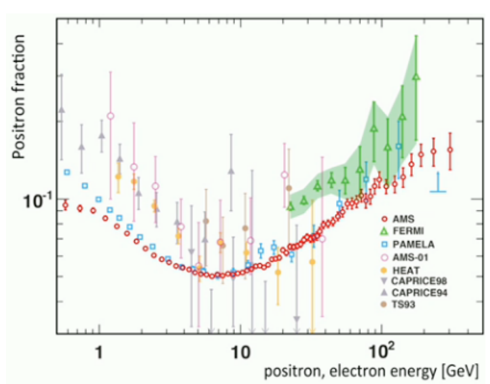
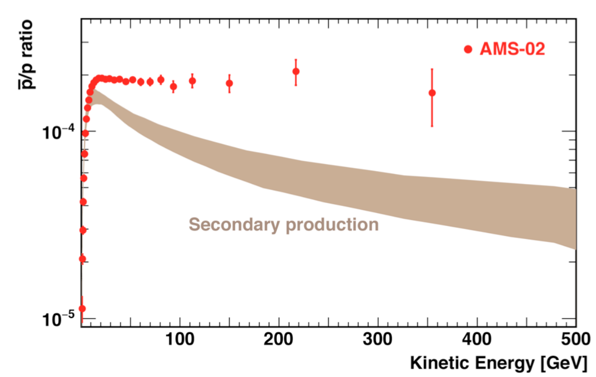
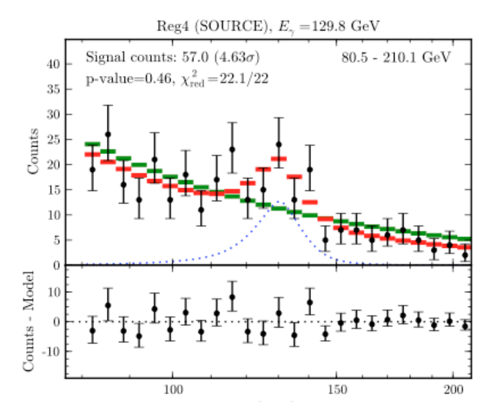
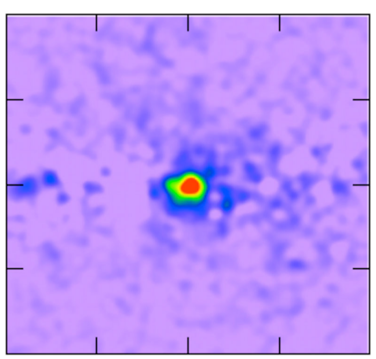
Had that been the case, we would have already discovered DM several times!











I took examples from the indirect search approach, but could apply as well to others (e.g. direct detection)

Summary and conclusion

The tricky part is not "to find" DM (according to necessarily naive, pre-defined criteria) **but to convince yourself that it is what you found.**

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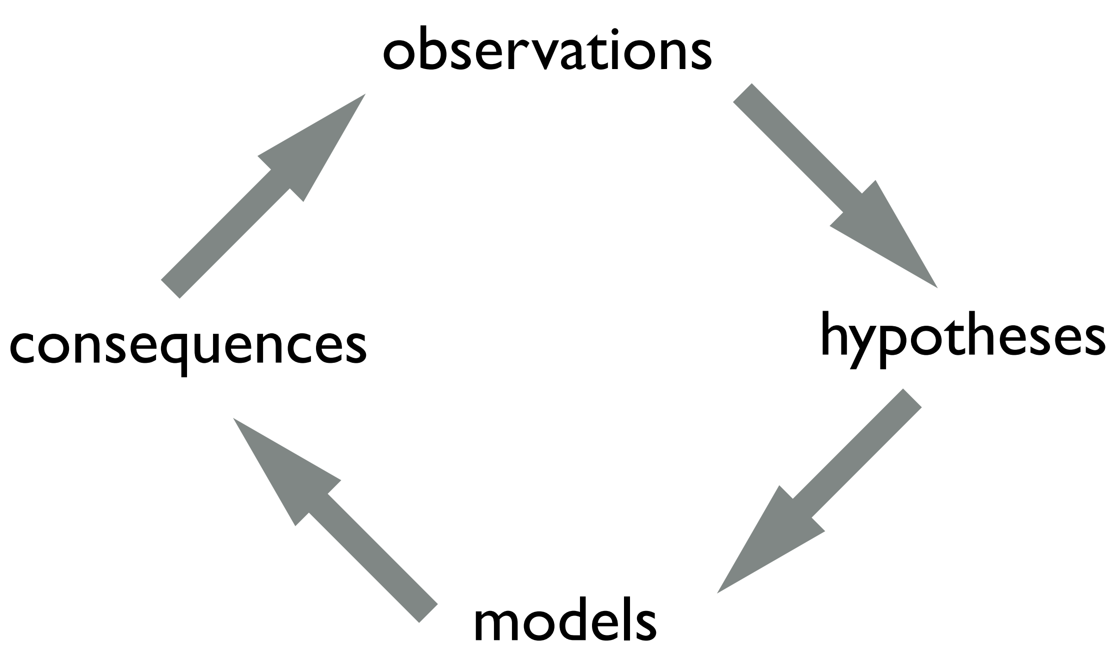

aka "the scientific method" in 'hard' sciences

That's how most of us got eventually convinced that none of the previous ones was due to DM

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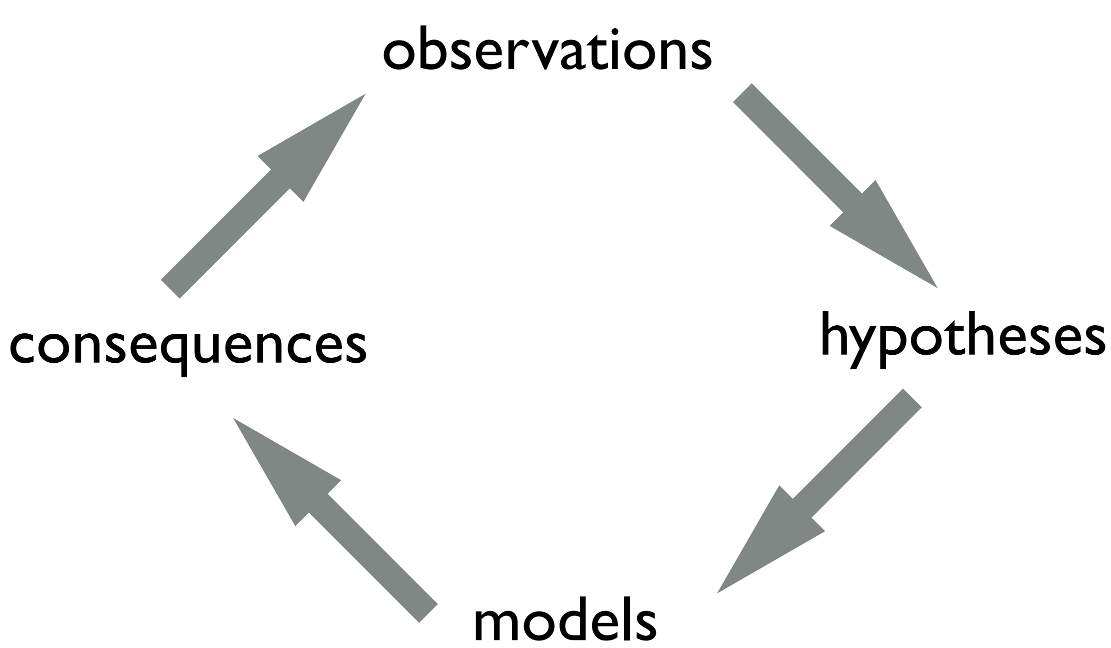

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I personally look forward to advances in AI that will either:

- **emulate and improve upon the above**
- **replace it with some more powerful alternative**