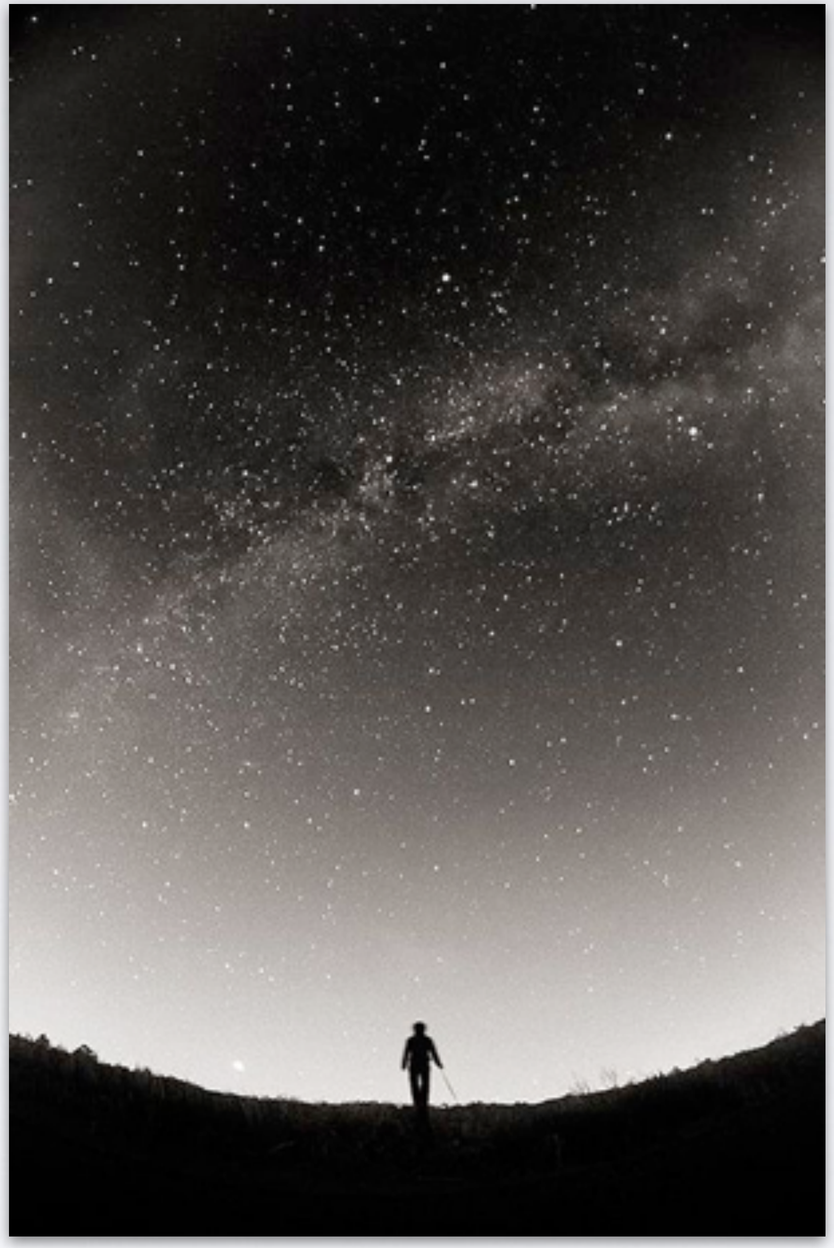
Dark matter: from the Cosmos to colliders

or Indirect Dark Matter searches as a guide to the path BSM



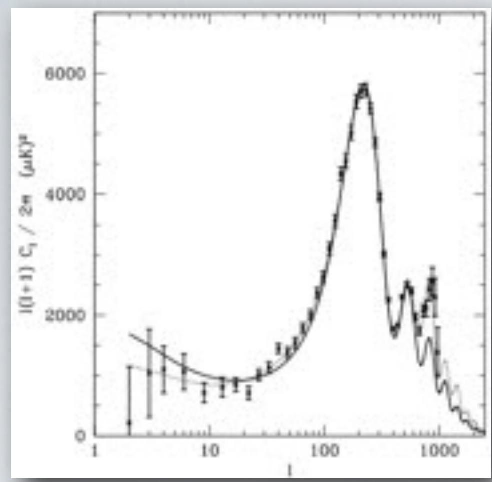
Pasquale Dario Serpico (Annecy, France)

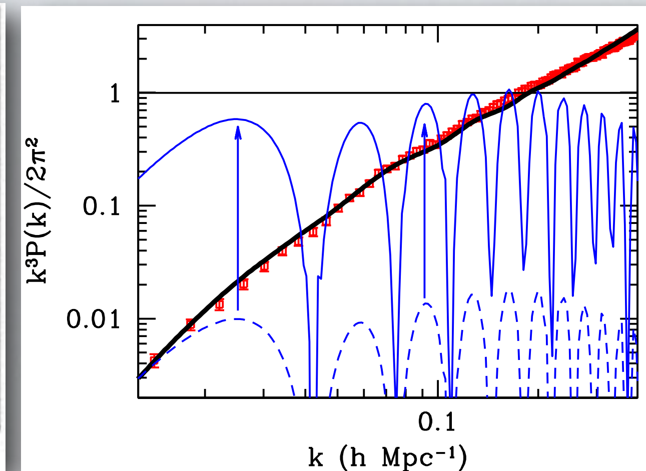
Cosenza (09/02/2016)

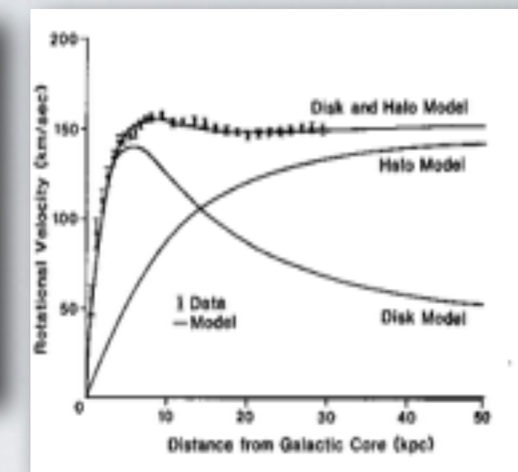
OUTLINE

- Introduction: what we know on DM (in 1 slide) and the search program within the WIMP paradigm
- WIMP search strategy: basic considerations on the collider searches and the interplay with indirect ones
- Phenomenological, bottom-up illustration of this interplay: collider bounds on a IDM hint (from gamma's)
  (Before that, quick intro to WIMP searches in gamma-ray astrophysics)
- Turning the argument around: IDM detection to test "LHC-inspired" particle physics models
- Back to basics: return to the WIMP paradigm… there's life beyond it (but looser links with LHC physics!)
- Dark sector and collider searches: where do we go from here

DM EVIDENCE @ MANY SCALES







CMB anis.

(Growth & Pattern of) Large Scale Structures

Clusters (X-rays, lensing)

Galaxies **Dwarfs (rotation curves, fits...)**

(growing effect of non-linearities, baryonic gas dynamics, feedbacks...)

“Cosmological” → **“Astrophysical”**

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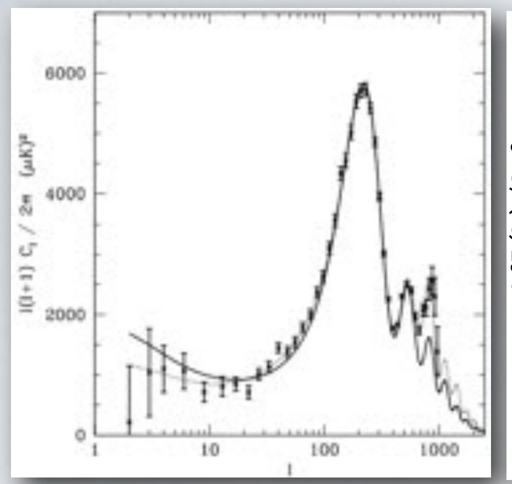

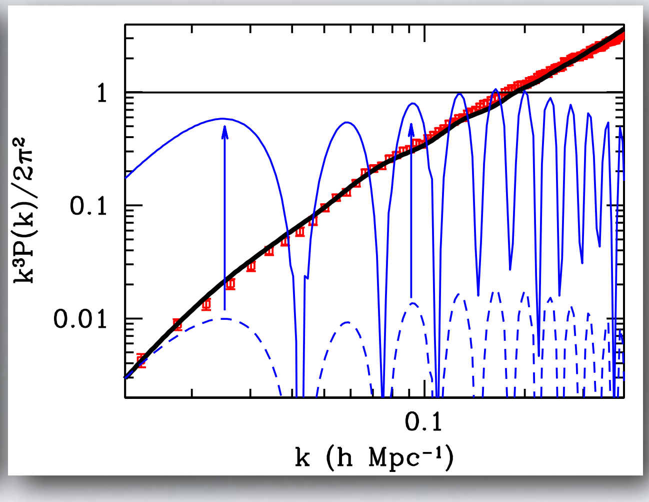

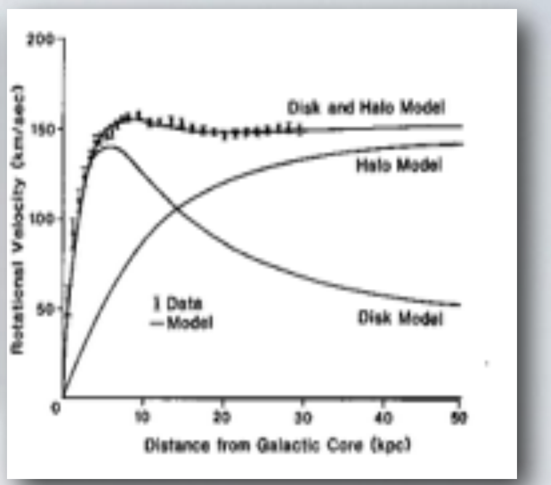

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Especially cosmological evidence of paramount importance for Particle Physics!

- Exact solutions or linear perturbation theory applied to simple physical systems: credible and robust!
- Suggests **"cold" collisionless additional species**, rather than a modification of gravity
- Tells that its majority is **non-baryonic**, rather than e.g. brown dwarf stars, planets...

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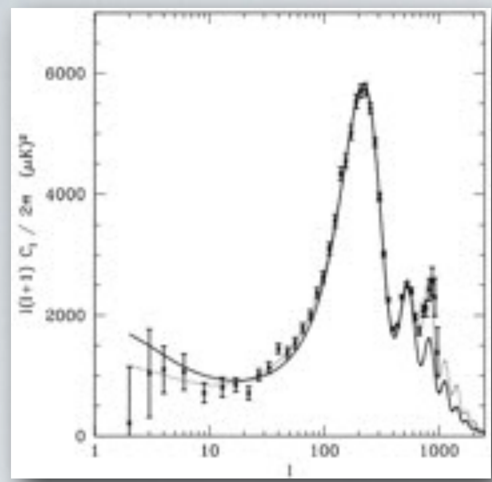

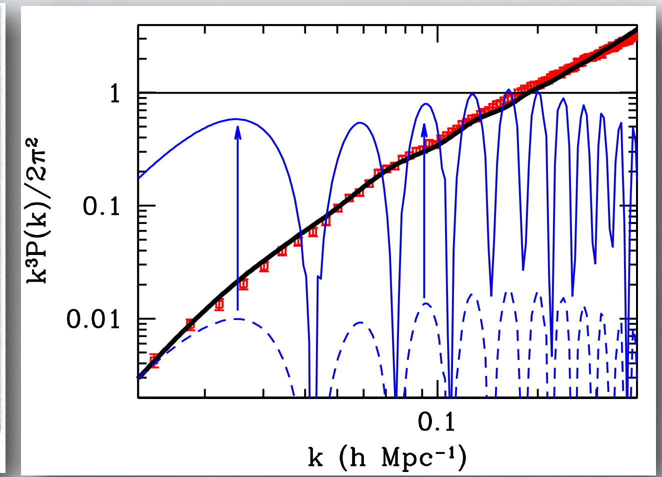

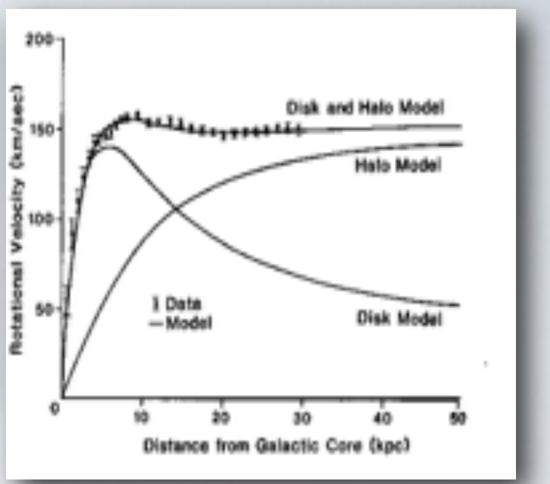

CMB anis. | **(Growth & Pattern of) Large Scale Structures** | **Clusters (X-rays, lensing)** | **Galaxies** | **Dwarfs (rotation curves, fits...)**

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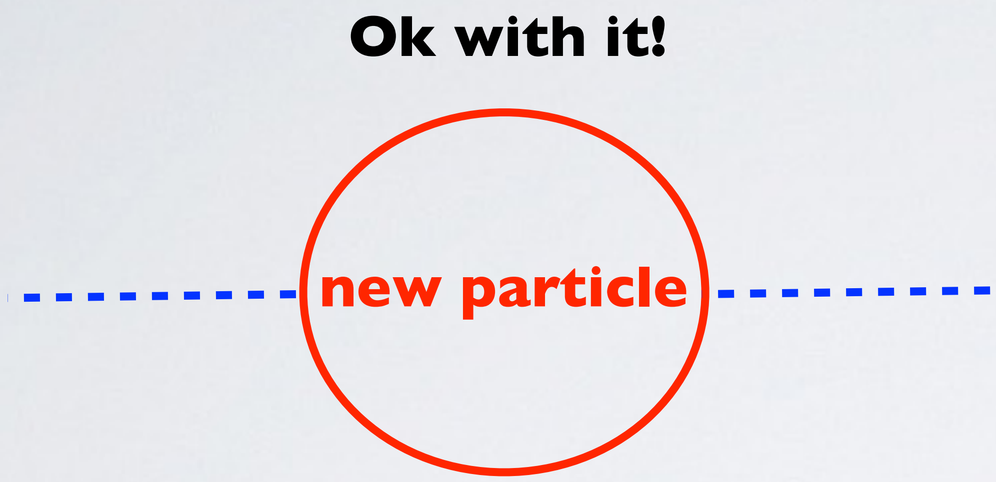
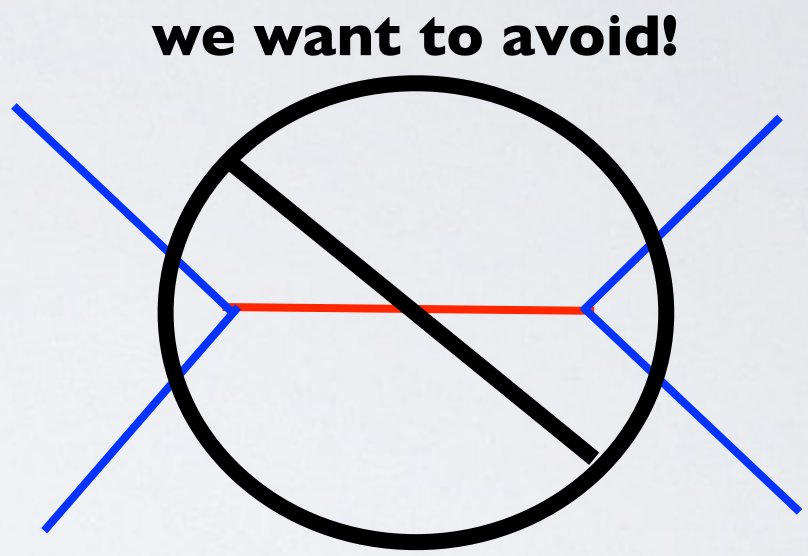
BSM explanation **needed**, but **gravity is universal**: no particle identification! **discovery via other channels** is needed **to clarify** particle physics framework

But **what to look for depends on model-dependent "bias"**

"TRADITIONAL" LINK WITH PARTICLE PHYSICS

- If one has a strong prior for new TeV-scale physics, with coupling $\gtrsim$ ew. strength, due to the hierarchy problem, precision ew data (e.g. from LEP) suggest that tree-level couplings SM-SM-BSM should be avoided!





- *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!

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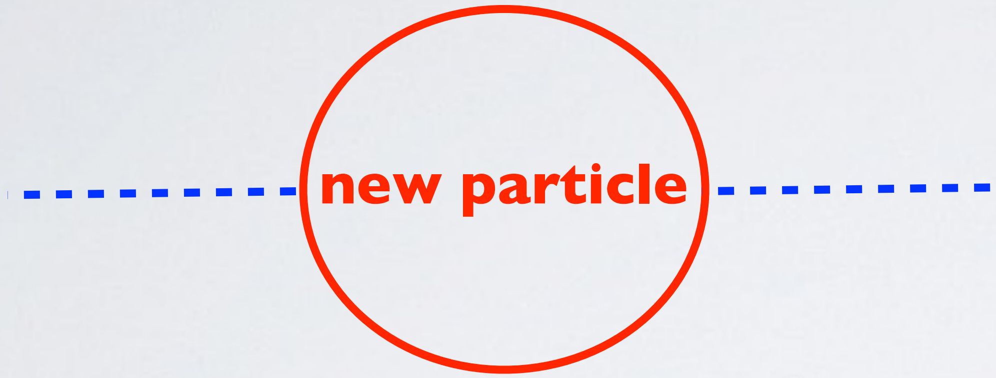
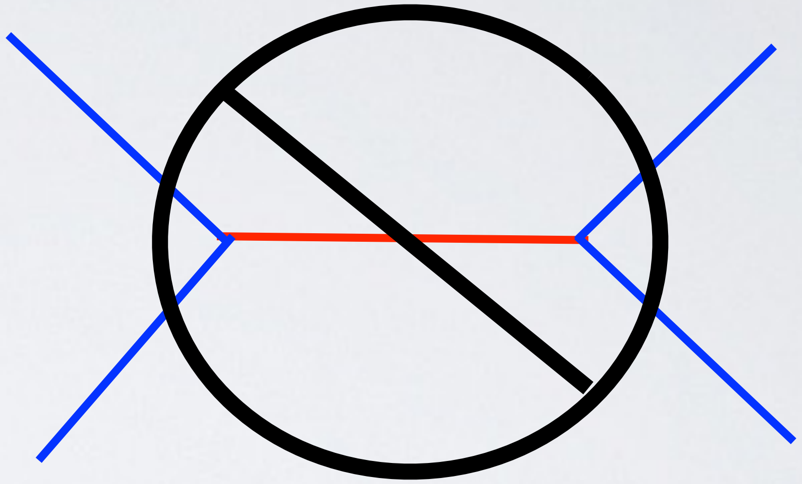
Ok with it!



we want to avoid!



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Cosmology tells us that the early universe was a hot plasma, a soup in which all "thermally allowed" species should be populated.

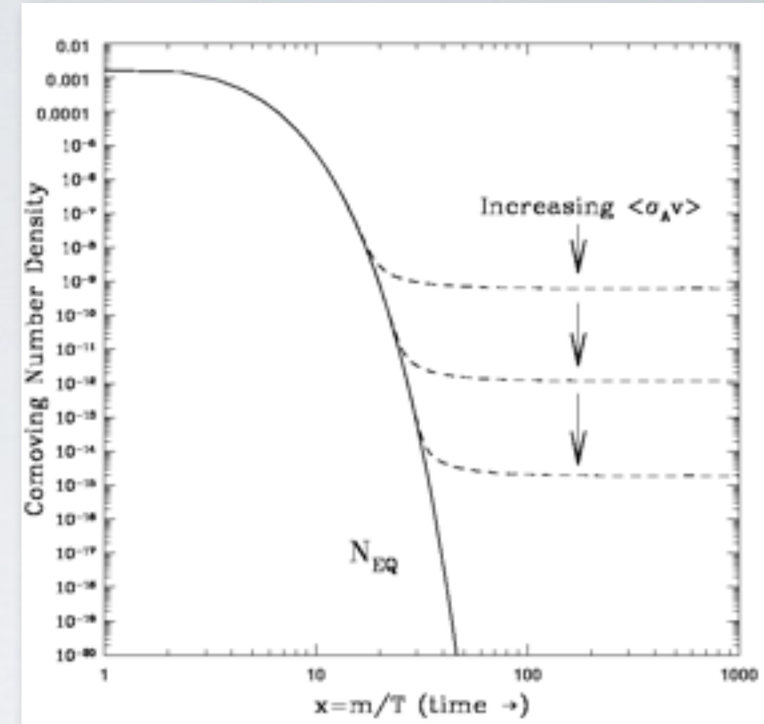
This notion has been tested up to T~ few MeV (BBN, cosmological neutrinos):
What happens if we extrapolate further backwards and account for the hypothetical presence of this new, stable weakly interacting massive particle?

THE WEAKLY INTERACTING MASSIVE PARTICLE PARADIGM

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

Stable, massive particles in chemical equilibrium down to *T*<<*m* (required for **cold** DM, i.e. non-relativistic distribution function!), suffer exponentially suppression of their abundance

So, what is left depends on the decoupling time, or their annihilation cross section: the weaker, the more abundant...



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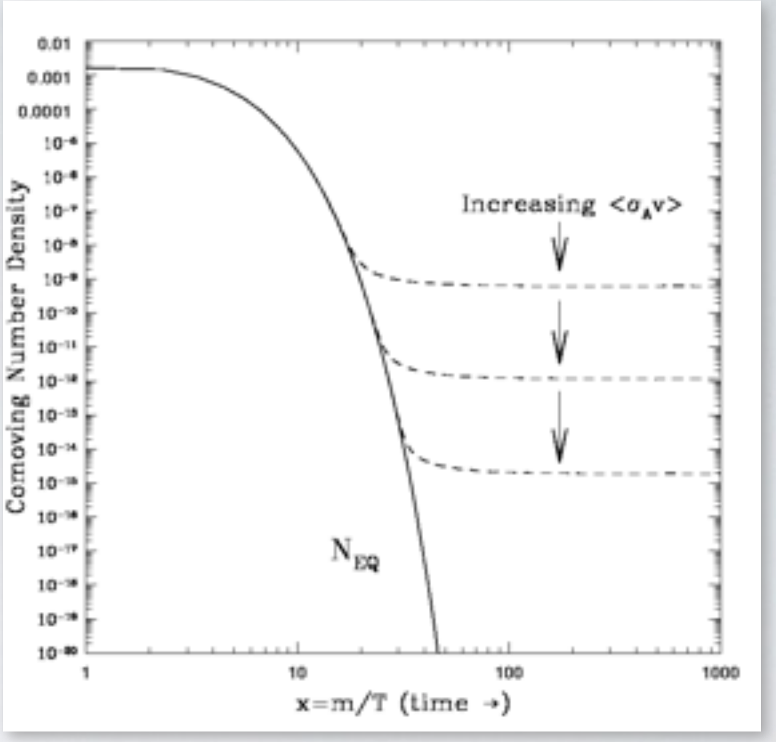


A textbook calculation proves that the current average cosmological energy density writes

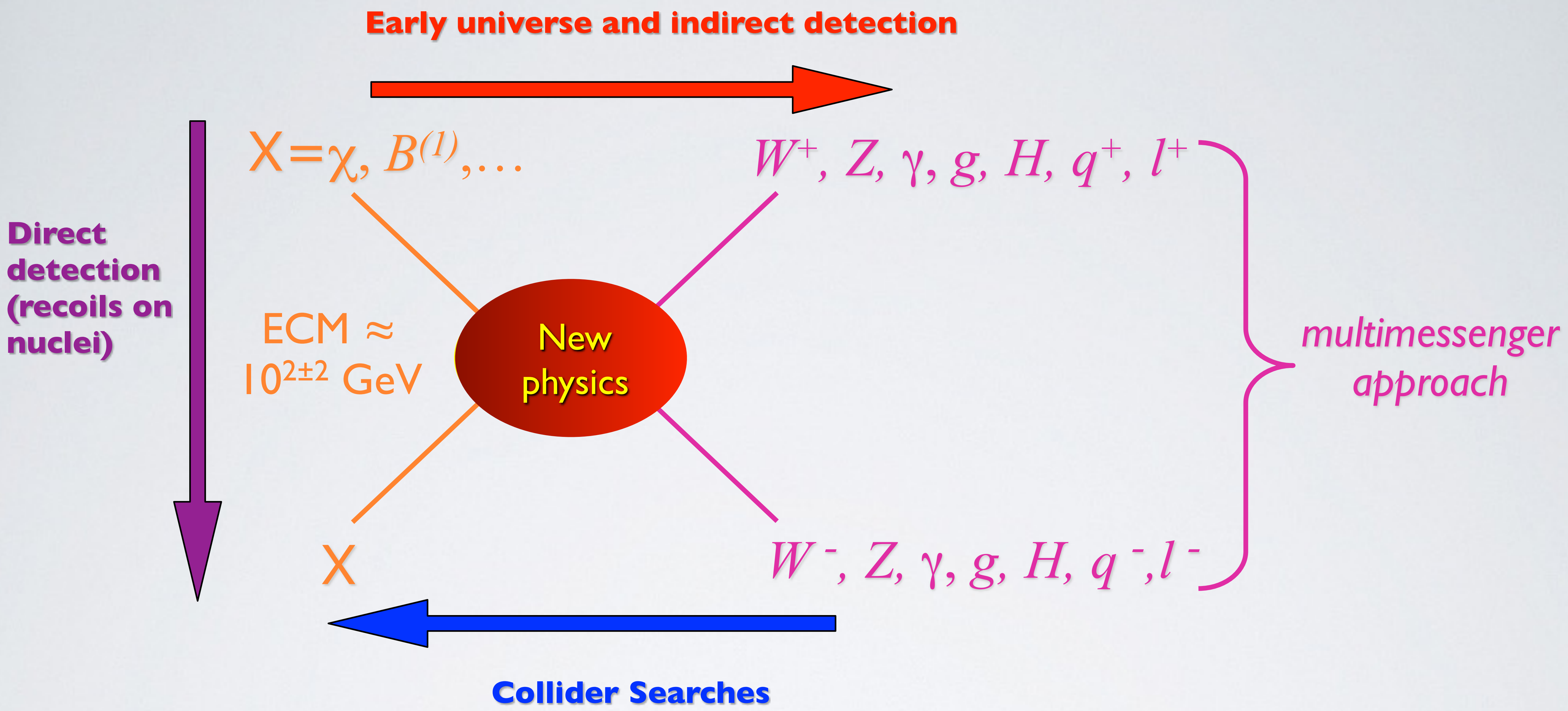
$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}$$

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

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

- Stability results e.g. from the same **discrete "parity" symmetry** previously invoked
- Matches (old?) **theoretical prior for BSM at EW scale**
- Leads to a number of phenomenological consequences

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

BASIC WIMP-RELATED EXPECTATION @ COLLIDERS

SM should be extended by at least a new (neutral, uncolored) massive state, usually the lightest state of a new sector made of unstable particles to which it couples (and coupled to the SM).

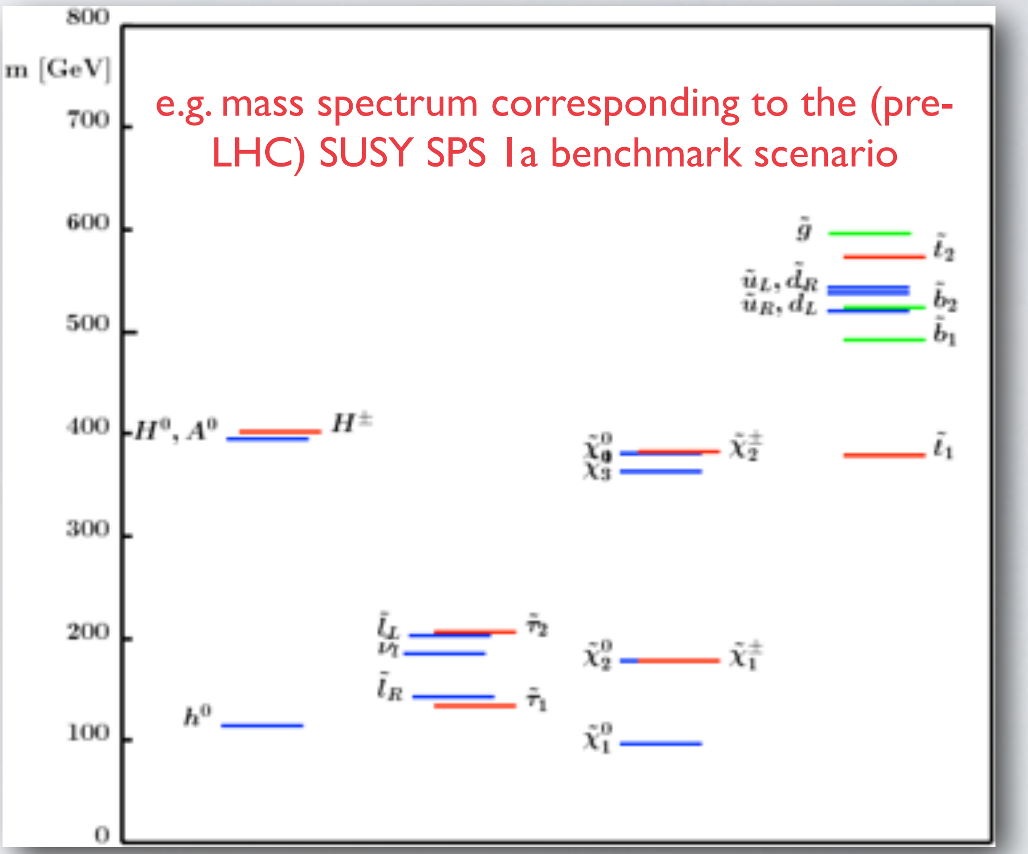
Most effective strategy heavily depends on the spectrum (and couplings) of the new states

<u>Dark Matter studies at LHC are intrinsically model-dependent</u>

Two extreme cases

- **Many/all states kinematically accessible**
  best strategy = benchmark models, i.e. representative points of realistic models where assumptions are made to reduce free parameters. DM typically constrained indirectly, from theoretical relations + experimental constrains on "more easily accessible" states (e.g. colored)
  (Traditional strategy, e.g. within the MSSM…unrealistic by now?)

- **Only DM kinematically accessible**
  EFT approach possible, where all other dof integrated out (contact interactions). Powerful since "model independent", but *regime of validity troublesome* already in LHC-8 (UV breakdown of theory+actual values for the exchanged momenta in LHC sometimes lead to breakdown of perturbativity in the couplings.)

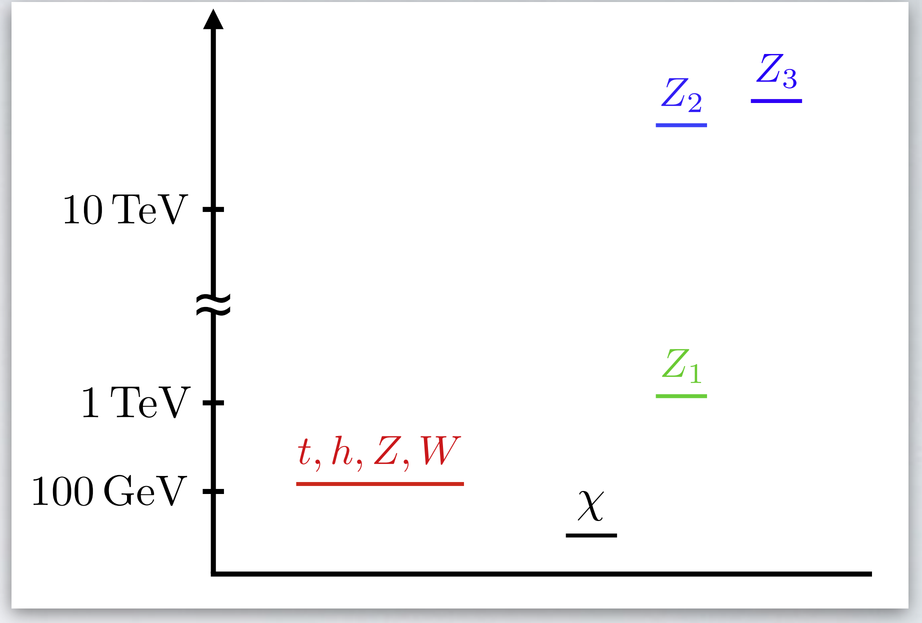


e.g. mass spectrum corresponding to the (pre-LHC) SUSY SPS 1a benchmark scenario

G.Weiglein et al. [LHC/LC Study Group Collaboration], "Physics interplay of the LHC and the ILC" Phys.Rept. 426, 47 (2006) [hep-ph/0410364]

COMPROMISE APPROACH (“SIMPLIFIED MODELS”)

Include not only DM state, but also lightest/most important mediator of DM interaction with the SM and with itself. Construct (in principle) most general renormalizable Lagrangian respecting **DM stability** constraints + **SM exact symmetries** (Lorentz and gauge ones), and make sure the accidental and custodial ones (B,L, flavour…) are not broken too badly.



J. Abdallah et al., “Simplified Models for Dark Matter Searches at the LHC,” Phys. Dark Univ. 9-10, 8 (2015) [1506.03116]

- ➡ Example: Dirac fermion DM, plus pseudoscalar mediator; g_f proportional to Yukawas for MFV

$$\mathcal{L} \supset -i\frac{g_{\rm DM}}{\sqrt{2}} a\bar{\chi}\gamma^5\chi - i\sum_f \frac{g_f}{\sqrt{2}} a\bar{f}\gamma^5 f + \text{h.c.}$$

- Additional a couplings in the Higgs/W,Z boson sector, but more model-dependent (but invisible Higgs decay channels expected if particles light enough, plus electroweak precision bounds)

- Only spin-dependent interactions with nuclei (relatively weak bounds from direct detection!)

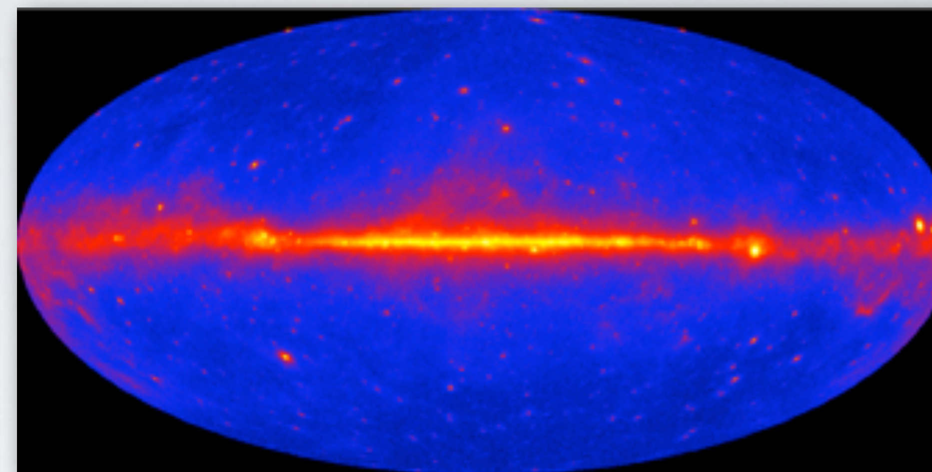
C. Boehm et al., “Extended gamma-ray emission from Coy Dark Matter," arXiv:1401.6458

- Annihilation cross-section into fermions can be sizable (enough for a WIMP-like)

$$\langle\sigma v\rangle_f = \frac{N_C}{8\pi}\frac{y_f^2\, g_{\rm DM}^2 m_{\rm DM}^2}{(m_a^2 - 4m_{\rm DM}^2)^2 + m_a^2\Gamma_a^2}\sqrt{1-\frac{m_f^2}{m_{\rm DM}^2}}$$

INDIRECT DM SEARCHES: MANY CHANNELS

- Gamma rays



- Neutrinos

- Charged cosmic rays

each with advantages and problems, will just provide example of their interplay and their interplay with collider searches

…

GAMMA RAY IDM SEARCHES

☺ Retain directionality (angular info!)

☺ Relatively easy to detect
(potentially high statistics)

☹ A lot of backgrounds (known and unknown)

Flux (from non cosmologically distant sources) often written in a factorized form

particle physics
(we assume its own antip.)

"astrophysics"
(**J-factor**, written *a-dimensional*)

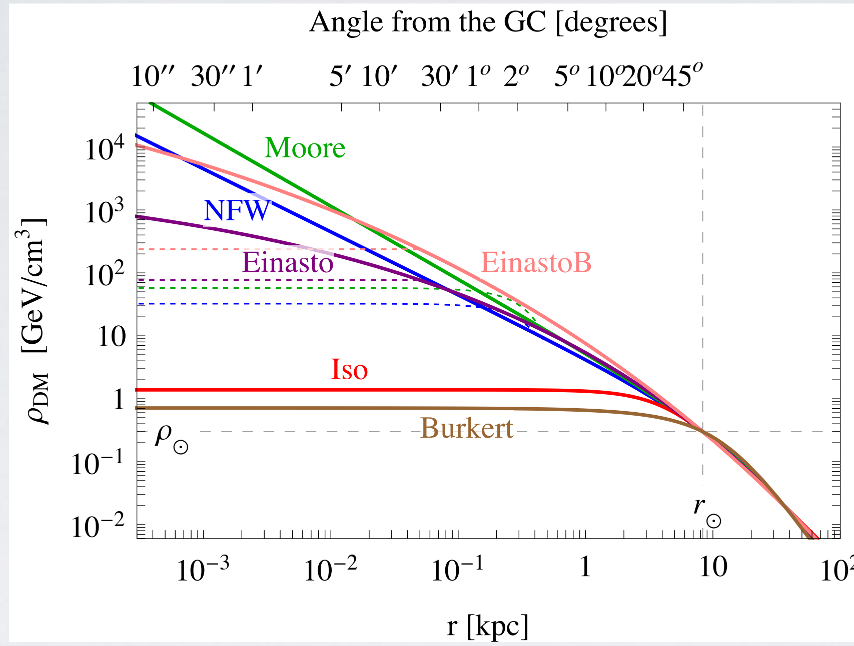
$$\Phi_\gamma(E_\gamma,\Omega) = \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\,\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right] \int_{\mathrm{los}} \rho^2(\ell,\Omega)\,\mathrm{d}\ell$$

[particle] ⊗ (astro) factorization holds if

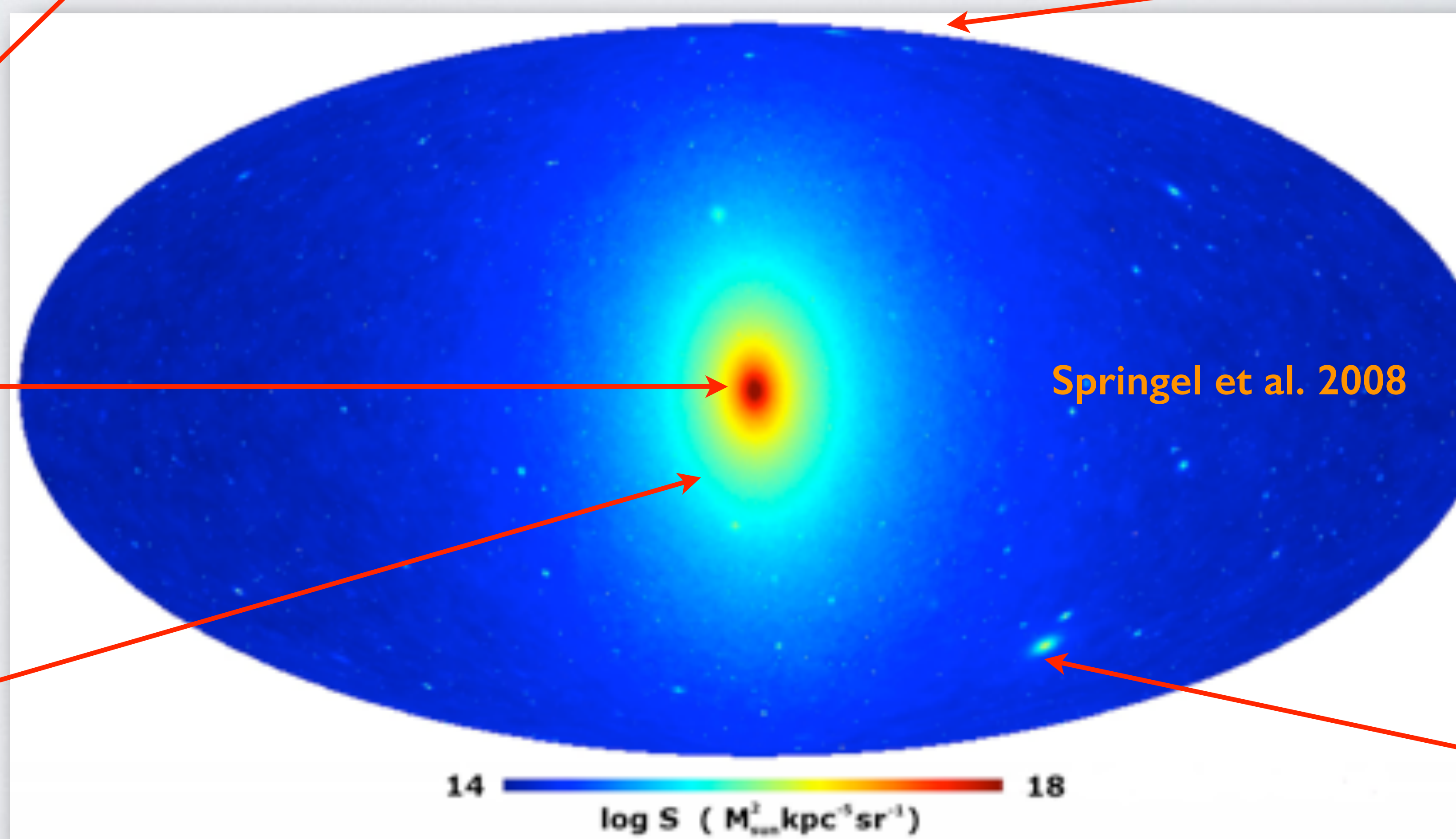
- **σ v is v-independent**
(otherwise goes under integral, over v distribution)
- **if *prompt emission* dominates**
(for secondary emission, need to follow $e^\pm$ propagation…)

WHERE TO LOOK FOR GAMMA'S (ASTRO FACTOR)?

What is the picture of the "DM - gamma sky" suggested by simulations?



Extragalactic
high statistics, lot of diffuse backgrounds



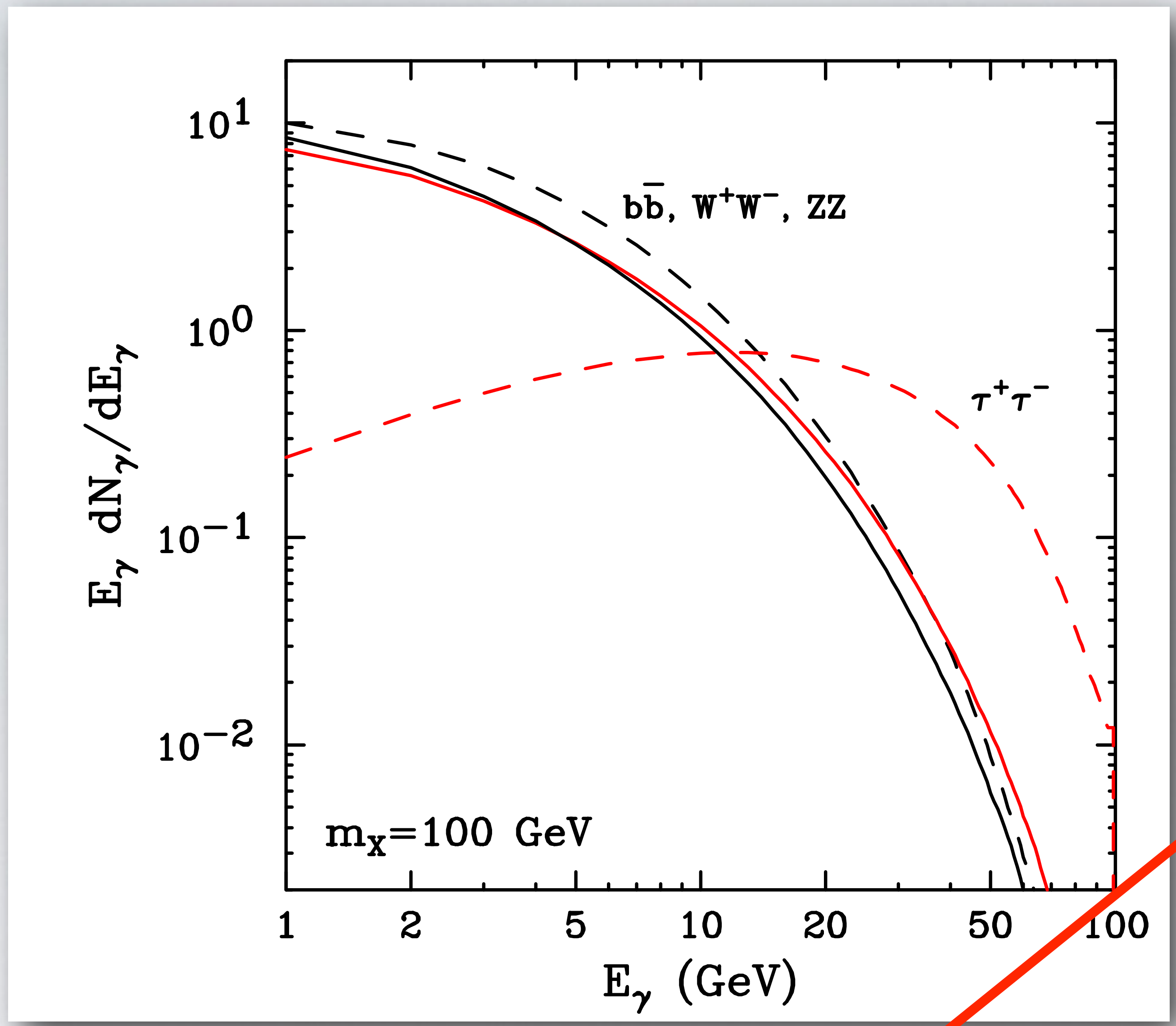
Galactic Center
high statistics, point-like and diffuse backgrounds
halo-model dependence

MW Halo
high statistics,
high diffuse background

Satellites (or Clusters)
low background (?)
low statistics

Lines/Spectral Features (everywhere...)

PREDICTED SPECTRA: CONTINUUM



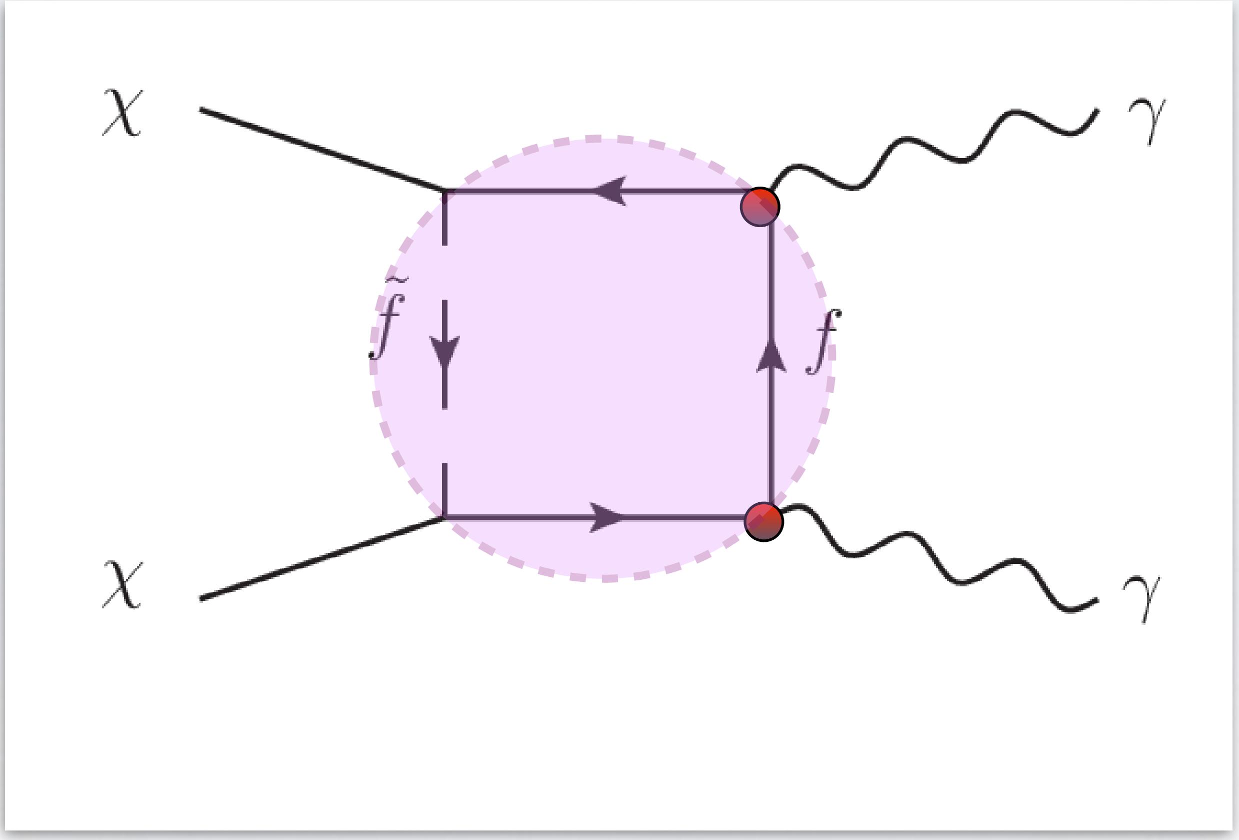
usually handled via e.g. PYTHIA incorporated in dedicated software

- ✓ whenever DM annihilates into quarks or gauge bosons, continuum photon spectrum is quasi-universal, as a result of decays/fragmentations
- ✓ Near the endpoints (~DM mass), 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.

PREDICTED SPECTRA: 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

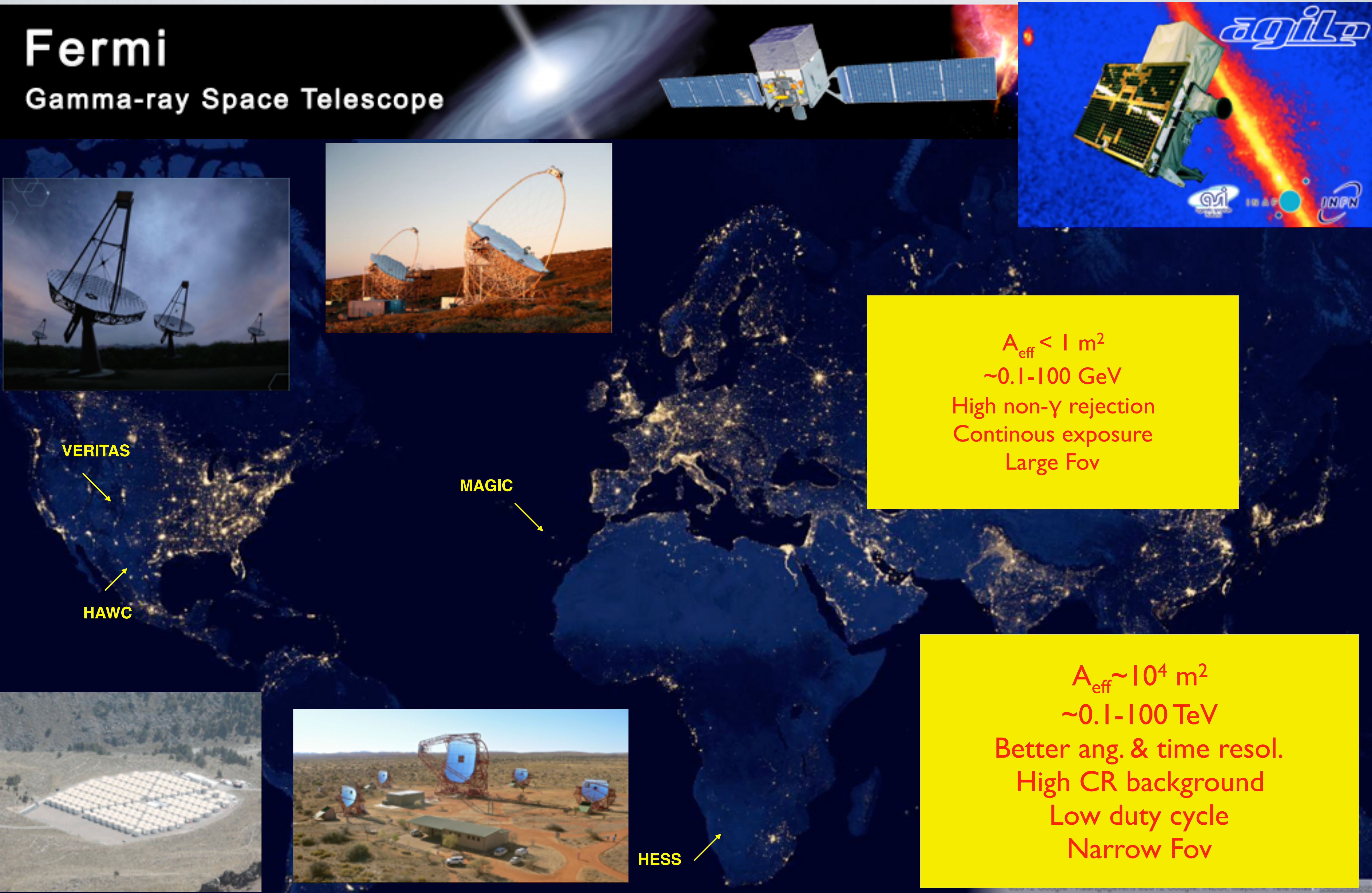
$$\frac{dN}{dE} \propto \delta(E - E_\gamma)\,, \quad E_\gamma \leq m_\chi$$



- 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…)

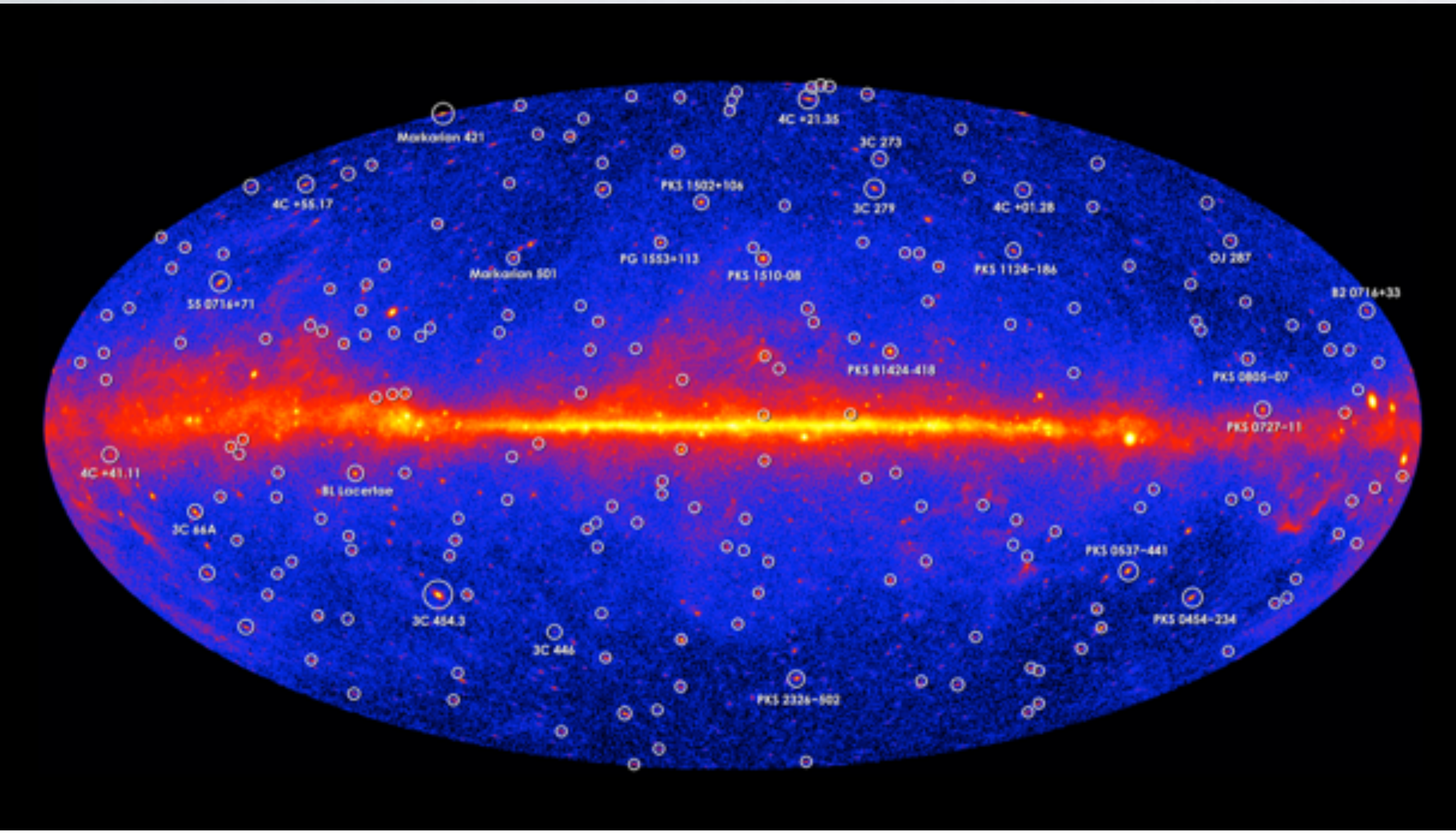
TYPES OF GAMMA TELESCOPES



WHAT DO TELESCOPES SEE? A CROWDED & BRIGHT SKY!

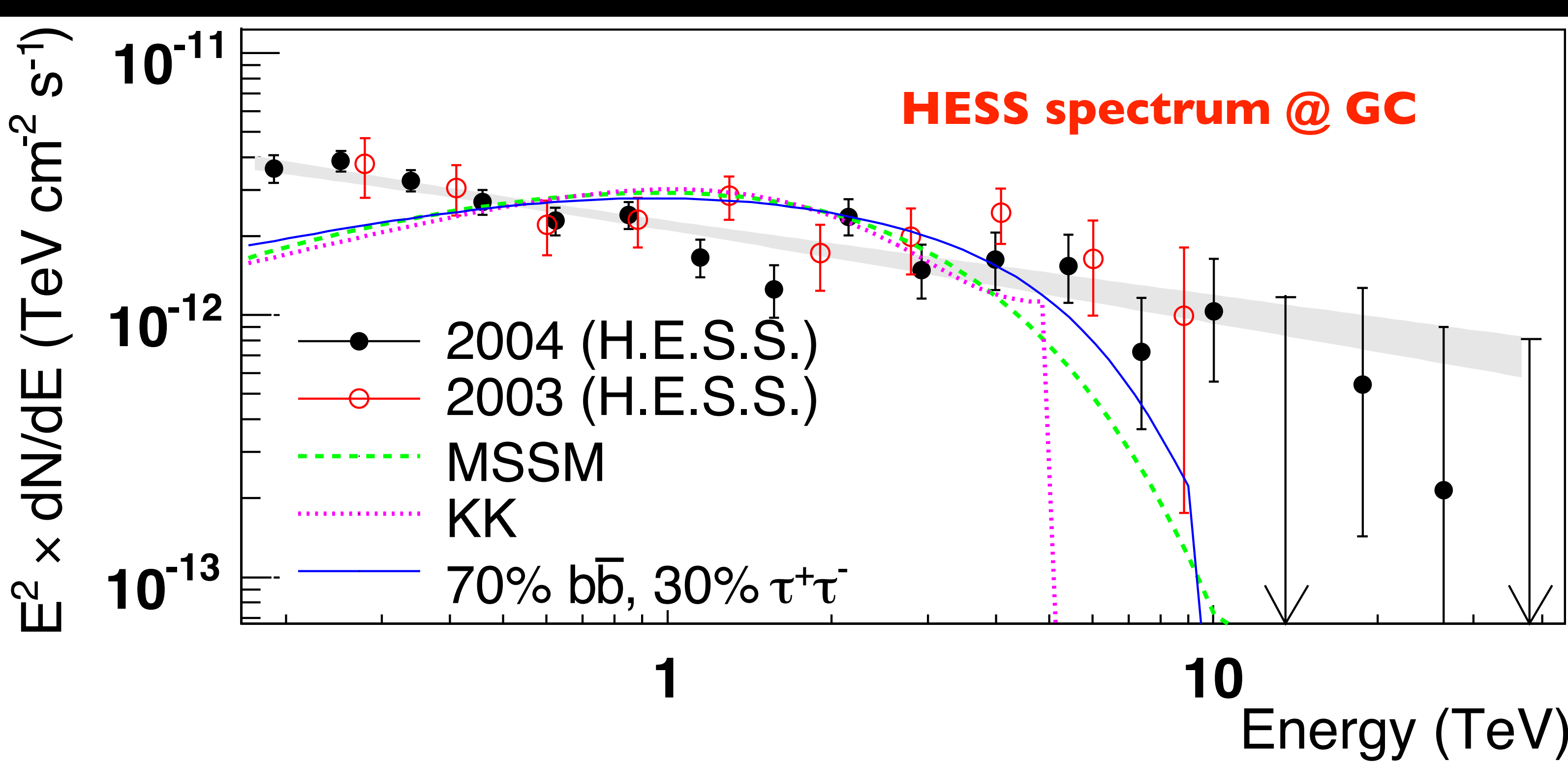
What Fermi or ACTs see looks nothing like DM expectations: **backgrounds are important**!

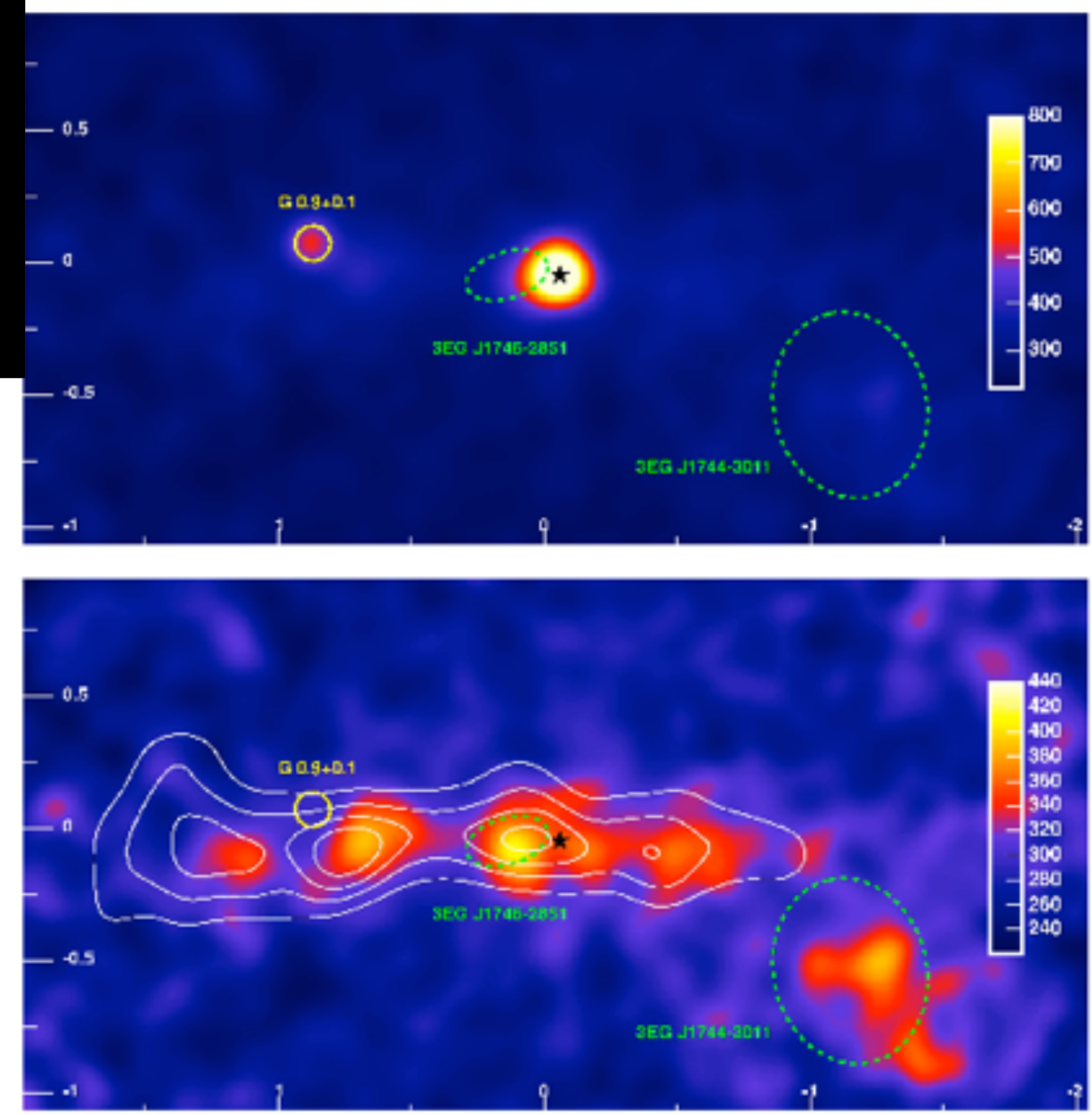
their understanding is the main challenge in tightening IDM bounds (or interpreting some hints)



Fermi sky, GeV range

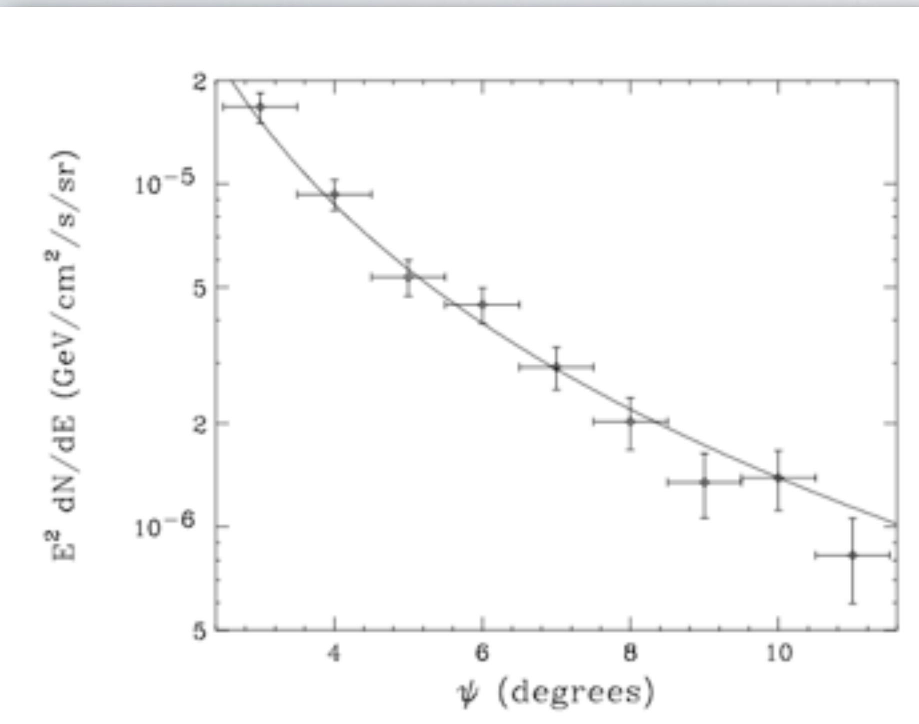
TeV-range: HESS Gal. Center & Galactic Ridge morphology





A GAMMA-RAY EXCESS FROM GAL. CENTER

several groups have claimed a statistically significant gamma-ray excess over diffuse emission *model* + *known* astrophysical sources in Fermi-LAT data



*L. Goodenough and D. Hooper, "**Possible Evidence** For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope," arXiv:**0910**.2998*

D. Hooper and L. Goodenough, PLB 697, 412 (2011) [arXiv:1010.2752]

K. N. Abazajian and M. Kaplinghat, PRD 86, 083511 (2012) [arXiv:1207.6047]

D. Hooper, I. Cholis, T. Linden, J. Siegal-Gaskins and T. Slatyer, PRD 88, 083009 (2013) [arXiv:1305.0830]

C. Gordon and O. Macias, PRD 88, 083521 (2013) [arXiv:1306.5725]

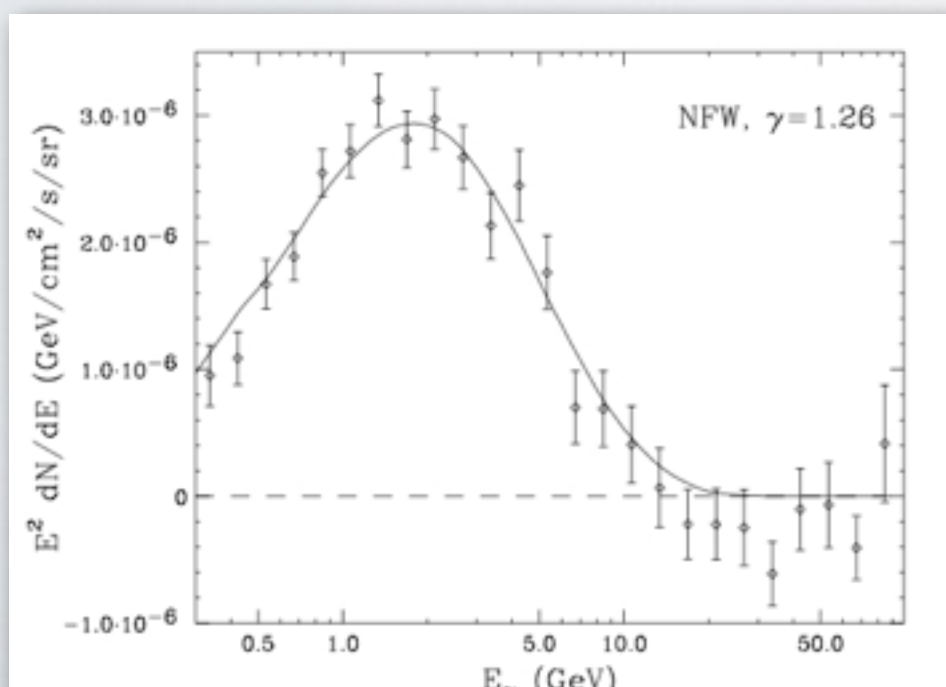
K. N. Abazajian, N. Canac, S. Horiuchi and M. Kaplinghat, arXiv:1402.4090

*T. Daylan et al. "The Characterization of the Gamma-Ray Signal from the Central Milky Way: A **Compelling Case** for Annihilating Dark Matter", arXiv:**1402**.6703*

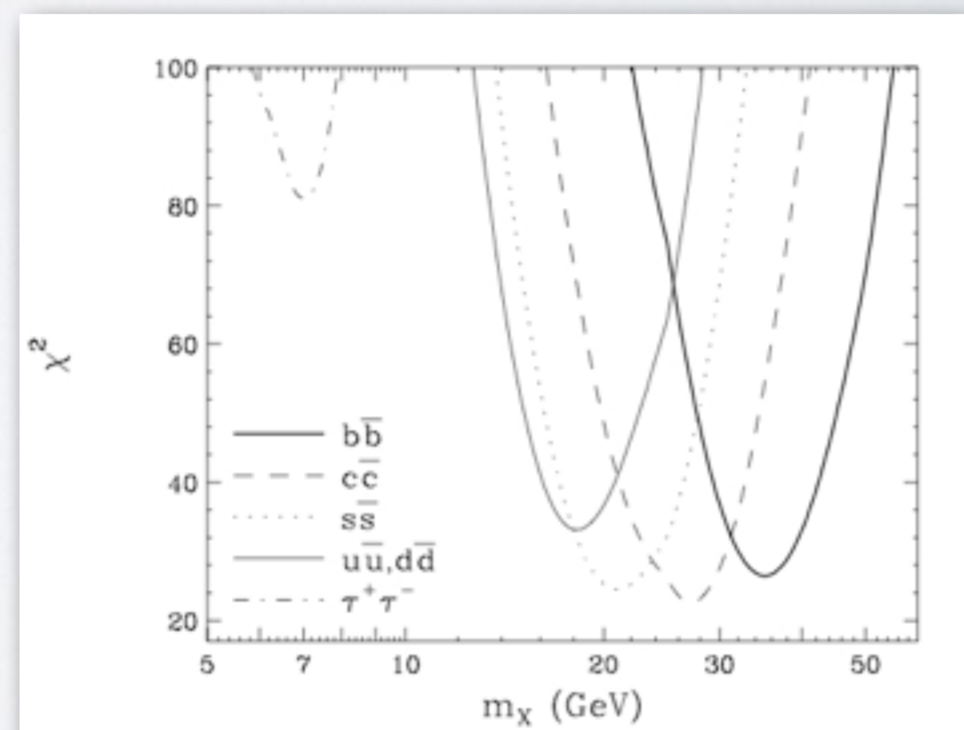
...

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

...



20-80 GeV with "thermal cross section"~few 10^{-26} cm^3/s into quarks, preferentially, with slightly steeper than NFW halo profile



COLLIDER TESTS? E.G. "COY DM"

$$\mathcal{L}_{\rm int} = i g_{\rm DM} A \bar{\chi}\gamma^5\chi + i g_{\rm SM}\sum_q \frac{m_q}{v} A\,\bar{q}\gamma^5 q$$

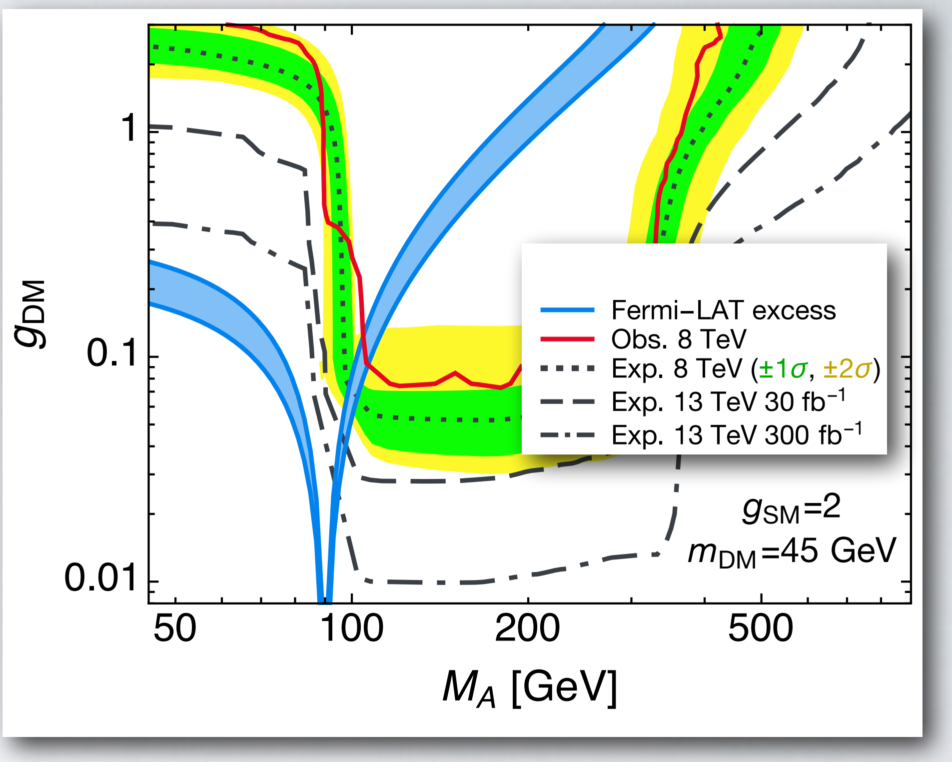
MFV to match flavor constraints

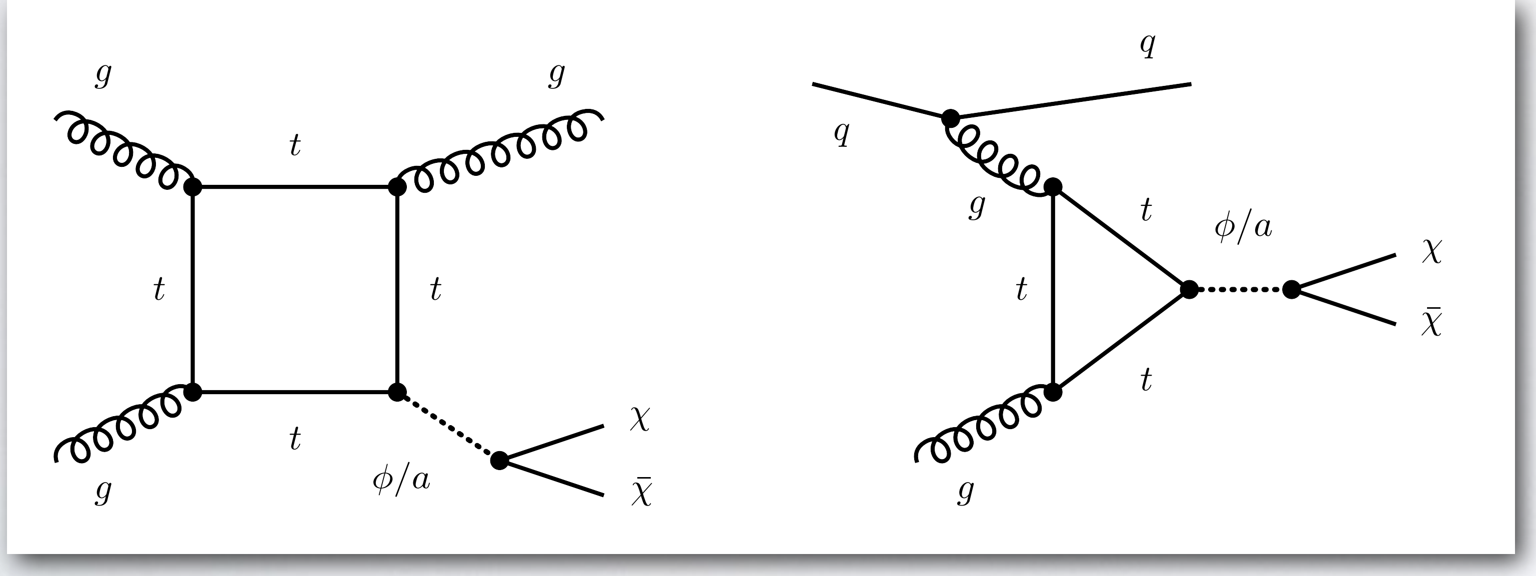
Collider bounds mostly come from jets+MET, usually due to associated t/b-DM mediator production (e.g. via *t t A~tt E_{mis}*)

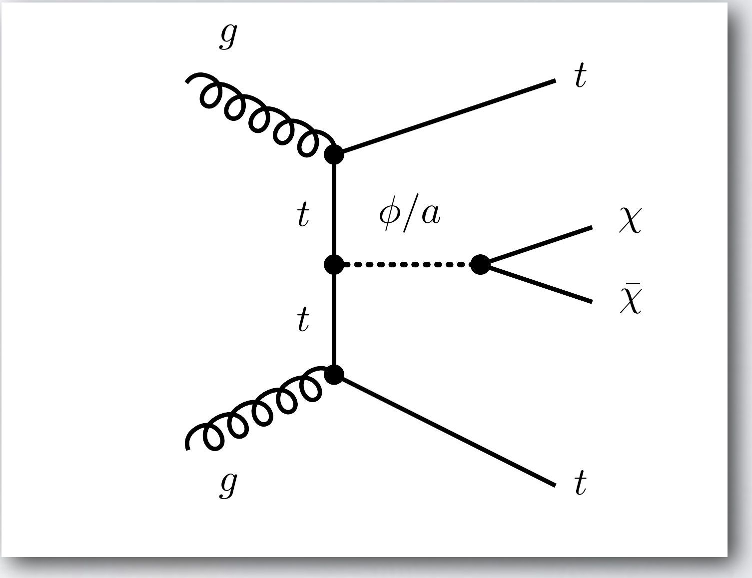
C. Boehm, M. J. Dolan, C. McCabe, M. Spannowsky and C. J. Wallace, "Extended gamma-ray emission from Coy Dark Matter," arXiv:1401.6458

High m_A range already constrained, LHC-13 fully test $m_A > 2\, m_{DM}$

O. Buchmueller, S.A. Malik, C. McCabe and B. Penning, "Constraining the Fermi-LAT excess with multi-jet plus MET collider searches," 1505.07826







1-loop diagrams for monojets + Einv

t-tbar pair production plus Einv

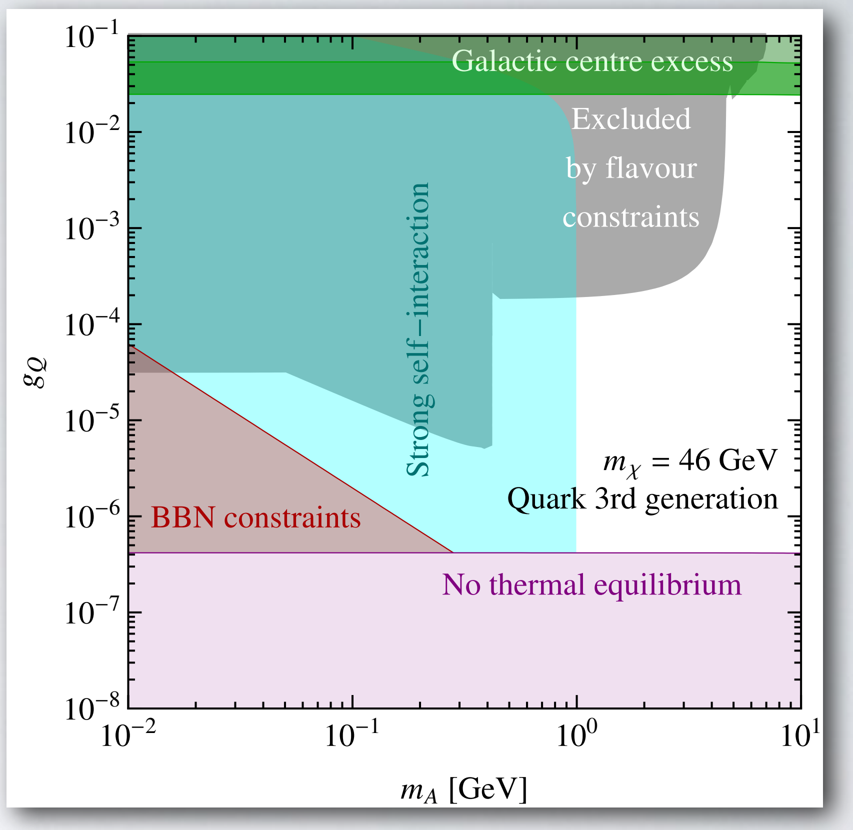
FLAVOUR CONSTRAINTS

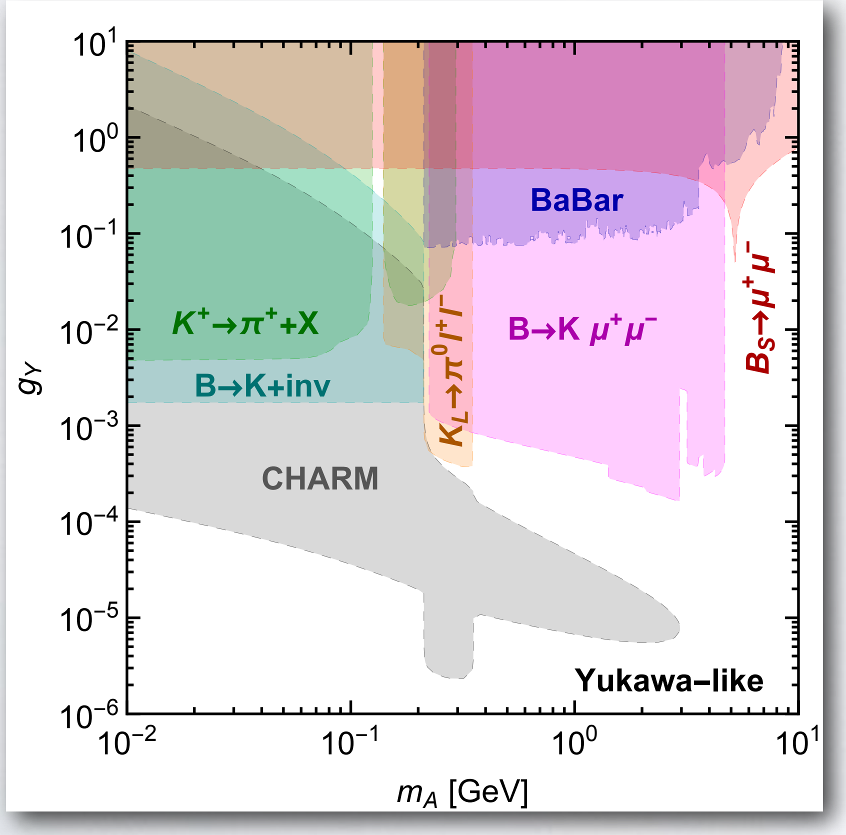
Constrains from Kaon, B, Bs and ϒ decays, including cases where A is off-shell, e.g. $\Upsilon \to \gamma A^* \to \gamma \mu\mu$, or $\to \gamma\tau\tau$

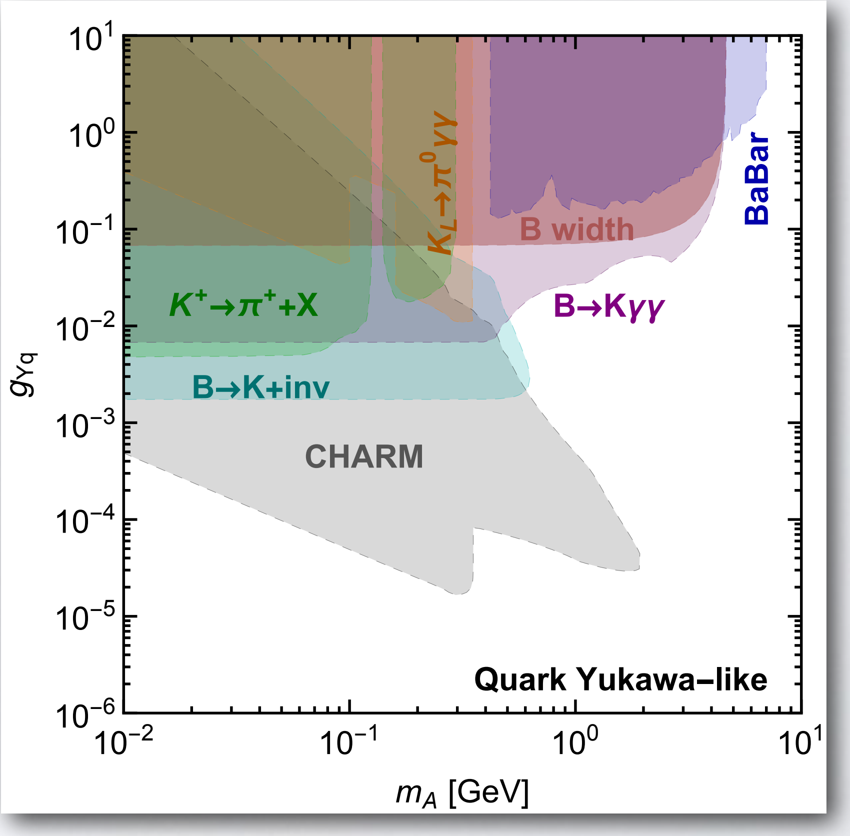
Flavour constraints nicely complementary, excluding light mediators and/or non-MFV case. For instance, in

M. J. Dolan, C. McCabe, F. Kahlhoefer and K. Schmidt-Hoberg, "A taste of dark matter: Flavour constraints on pseudoscalar mediators," arXiv:1412.5174 [hep-ph].

the authors conclude: *it does not seem possible to obtain both large DM self-interactions and at the same time a DM signal from direct or indirect detection experiments given current bounds*







CUTTING A LONG STORY SHORT… DO OTHER DATA FIT THE DM EXPLANATION?

No expected associated **signal** has been **seen** (e.g. gammas from dwarf galaxies, pbar's),
DM explanation excluded or "simply" **disfavoured** depending on the error budget assessment.
Growing **hints of an astrophysical explanation**… but hopefully illustrates you the kind of interplay!

If curious, feel free to ask for more details

STATUS AND ROLE OF IDM

Can indirect methods "detect" dark matter?

✤ In principle, yes. In practice, we are reaching the point where the discovery potential in more and more channels is limited by the knowledge of "astrophysical backgrounds"

✤ Apart for improving our knowledge of astrophysics, currently the main hope relies on *correlated* signals in many channels, each one hard to explain without DM.

✤ Also, it would be important to move beyond "blind" searches. Perhaps the most credible discovery would be a IDM "excess" predicted/suggested by collider or direct detection hints.

Anyway, IDM is a crucial tool!

If a signal is found in other channels (collider/DD) We still *need* ID:

- To confirm that whatever we find in the Lab is the same "dark stuff" responsible for astrophysical and cosmological observations (it's impossible to discover DM at LHC alone...)
- To access particle information not otherwise available in the Lab (annihilation cross section or decay time, b.r.'s)
- to infer cosmological properties of DM (e.g. power spectrum of DM at very small scales) not accessible otherwise.

STATUS AND ROLE OF IDM

Can indirect methods "detect" dark matter?

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EXAMPLE: TAKE 750 GEV RES FOR REAL*

assume it is the mediator between DM (e.g. Majorana fermion) and SM
(not so arbitrary, should a large "invisible" width of the resonance be needed)

(neglecting here possible boson coupling with SM fermions)

option I: **scalar**

$$\mathcal{L}_{0^+} = \frac{c_1}{\Lambda}\phi F_{\mu\nu}F^{\mu\nu} + \frac{c_2}{\Lambda}\phi W^{\mu\nu}W_{\mu\nu} + \frac{c_3}{\Lambda}\phi G^a_{\mu\nu}G^{\mu\nu}_a + g_\phi \phi\bar{\chi}\chi + m_\psi\bar{\chi}\chi.$$

opt. II: **pseudoscalar**

$$\mathcal{L}_{0^-} = \frac{c_1}{\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{c_2}{\Lambda}\phi W^{\mu\nu}\tilde{W}_{\mu\nu} + \frac{c_3}{\Lambda}\phi G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a + ig_\phi \phi\bar{\chi}\gamma^5\chi + m_\psi\bar{\chi}\chi.$$

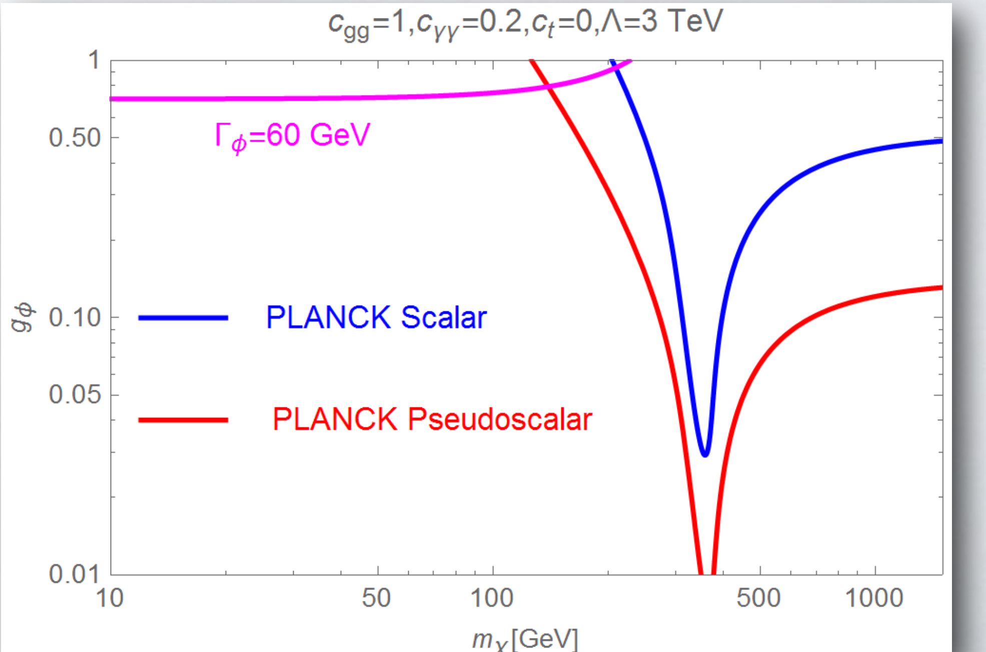
e.g. Y. Mambrini, G. Arcadi and A. Djouadi, "The LHC diphoton resonance and dark matter," arXiv:1512.04913 plus a few tens more, already… 142 citations on 08/02/2016!!!

easier to make sense of perturbative calculations in EFT if DM mostly annihilates into gluons;
"easier" parameter space for pseudoscalar case (which also evades direct bounds more easily)

$$\langle\sigma v\rangle^{0+}_{\gamma\gamma} \simeq \frac{4g_\phi^2 c_{\gamma\gamma}^2 m_\chi^4 v^2}{\pi\Lambda^2(s-M_\phi^2)^2}\,, \quad \langle\sigma v\rangle^{0-}_{\gamma\gamma} = \frac{4g_\phi^2 c_{\gamma\gamma}^2 s^2}{\pi\Lambda^2(s-M_\phi^2)^2}\,, \quad \langle\sigma v\rangle_{gg} = 8\left(\frac{c_{gg}}{c_{\gamma\gamma}}\right)^2\langle\sigma v\rangle_{\gamma\gamma}$$

P-wave **S-wave**

For LHC currently almost no difference between 0^+ or 0^- case:
not so for DM!

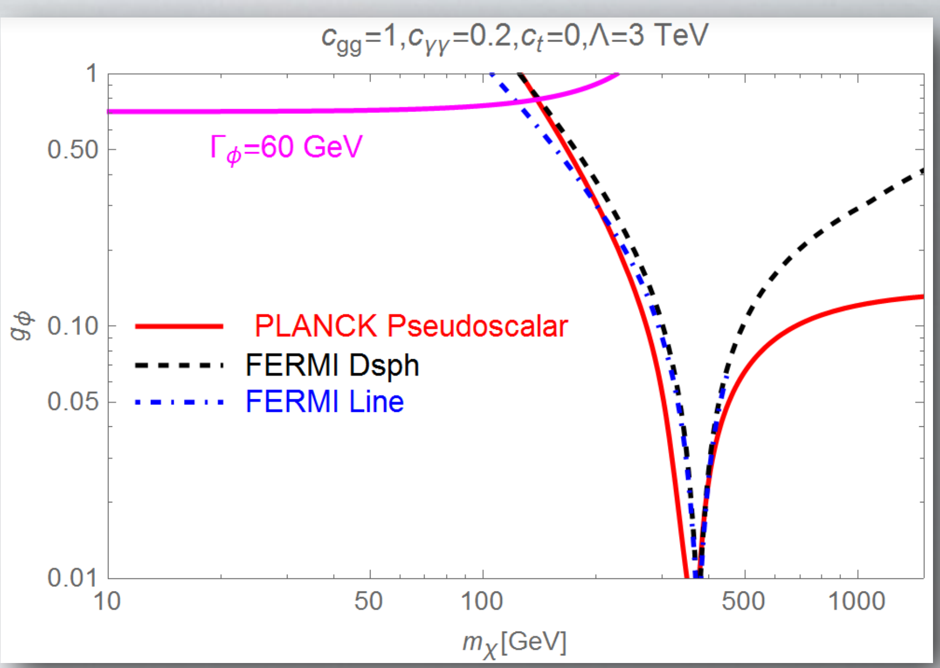


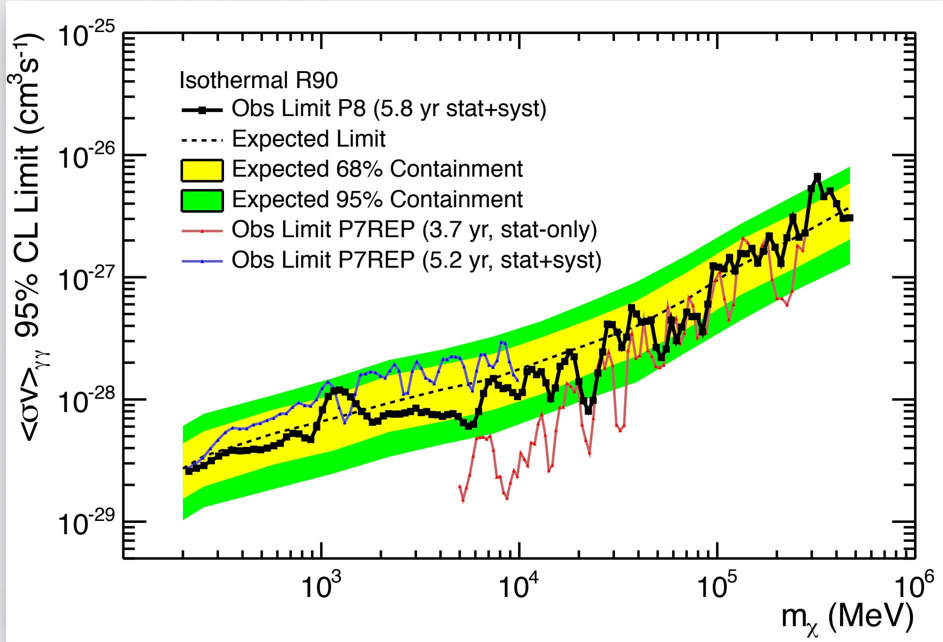
* which… you better don't (yet):
"Plus un fait est extraordinaire, plus il a besoin d'être appuyé de fortes preuves"
Pierre-Simon de Laplace, Théorie analytique des probabilités (1812)

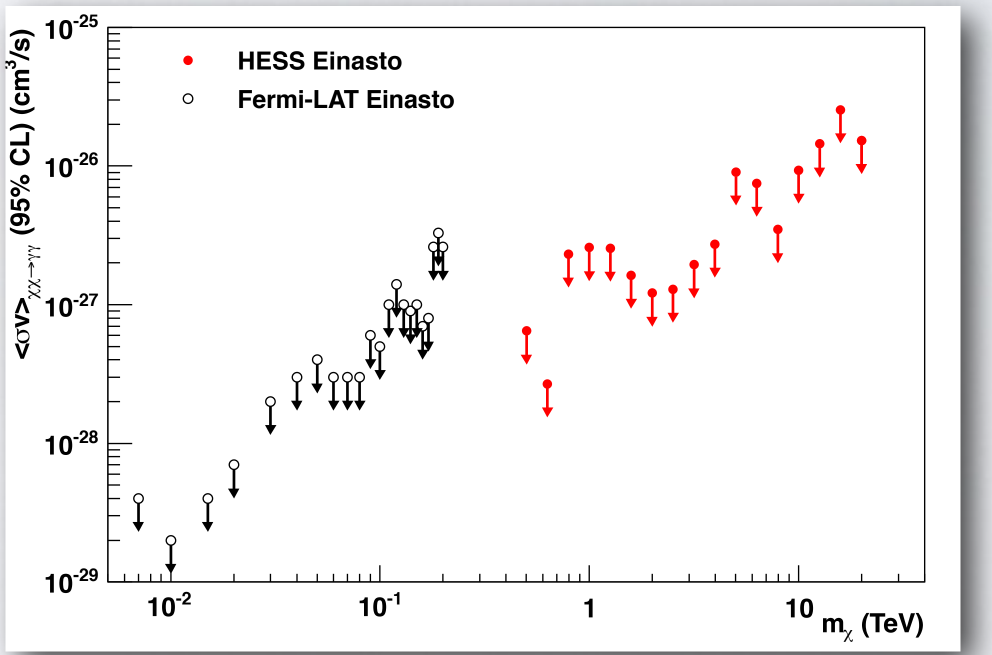
GAMMA-RAY BOUNDS

The model predicts many continuum photons (hadronization of gg channel) + prominent line (γγ) → on the verge of testability (if not ruled out) by Fermi-LAT dwarf spheroidals & especially line searches

(both Fermi & IACTs have interesting line bounds!)







M. Ackermann et al. [Fermi-LAT Collaboration], PRL 115, 231301 (2015) [1503.02641]

A. Abramowski et al. [HESS Collaboration], PRL, 041301 (2013) [1301.1173]

In the future, improved sensitivity via IACTs (HESS II… CTA), some perspectives e.g. in

J. C. Park and S. C. Park, 1512.08117

BE BRAVE, CAN DO BETTER!

scalar DM S, pseudoscalar mediator φ, trying to explain the GC gamma excess as well!

A. Hektor and L. Marzola, arXiv:1602.00004

Free Lag. of new fields

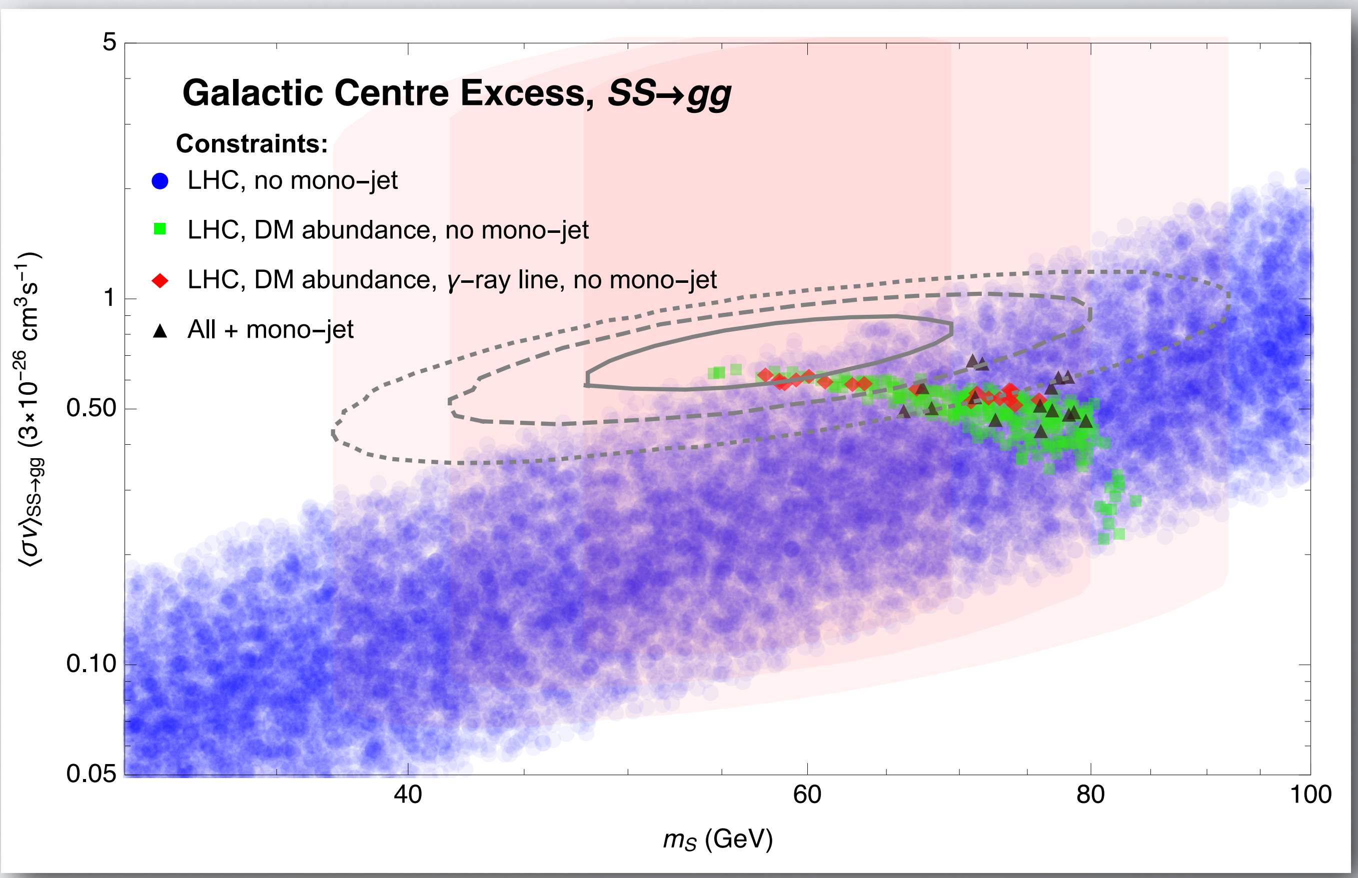
$$\mathcal{L}_0 = \frac{1}{2}\left[(\partial\phi)^2 + m_\phi^2 + (\partial S)^2 + m_S^2\right]$$

Efffective Lag. of mediator-SM

$$\mathcal{L}_\sqcap = \frac{c_1}{v}\,\phi\, B_{\mu\nu}\widetilde{B}^{\mu\nu} + \frac{c_2}{v}\,\phi\, W^a{}_{\mu\nu}\widetilde{W_a}^{\mu\nu} + \frac{c_3}{v}\,\phi\, G^a{}_{\mu\nu}\widetilde{G_a}^{\mu\nu}$$

DM-mediator coupling

$$\mathcal{L}_{S\phi} = \frac{1}{2}\, g_S\,\phi\, S^2$$

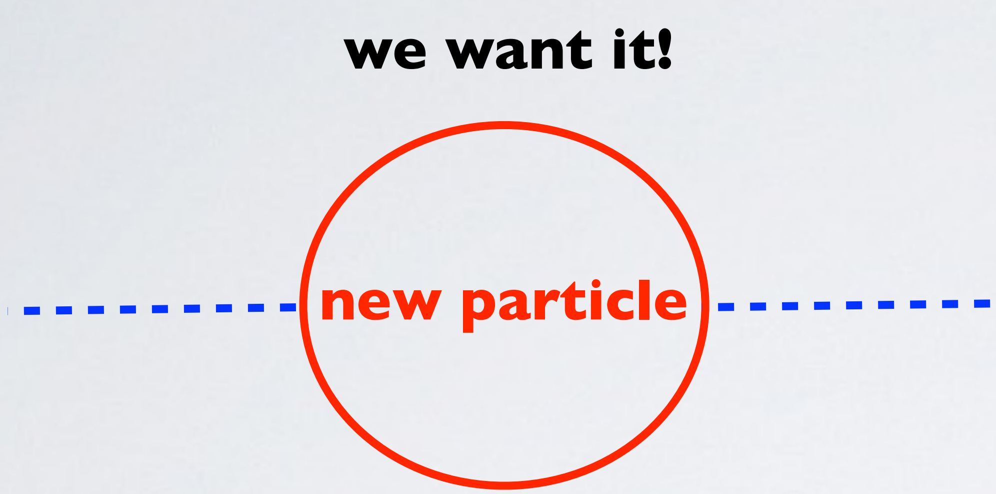


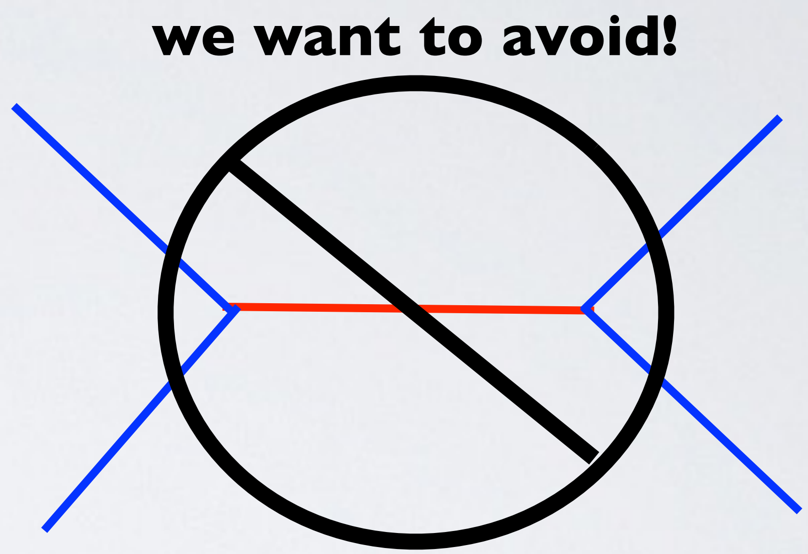
Consistent points claimed to be found, possibly associated with significant antiproton flux (probed by forthcoming AMS-02 data?)

Of course, much more on the market! More generic EFT treatment in F. D'Eramo, J. de Vries and P. Panci, arXiv:1601.01571, spin-2 case in C. Han, H.M. Lee, M. Park and V. Sanz, arXiv:1512.06376 …

TRADITIONAL LINK WITH PARTICLE PHYSICS

- If one has a strong prior for new TeV scale physics (~with ew. strength coupling) due to the hierarchy problem, precision ew data (e.g. from LEP) suggest that tree-level couplings SM-SM-BSM should be avoided!





- *One* straightforward solution is to impose some symmetry (often "parity-like"): 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!

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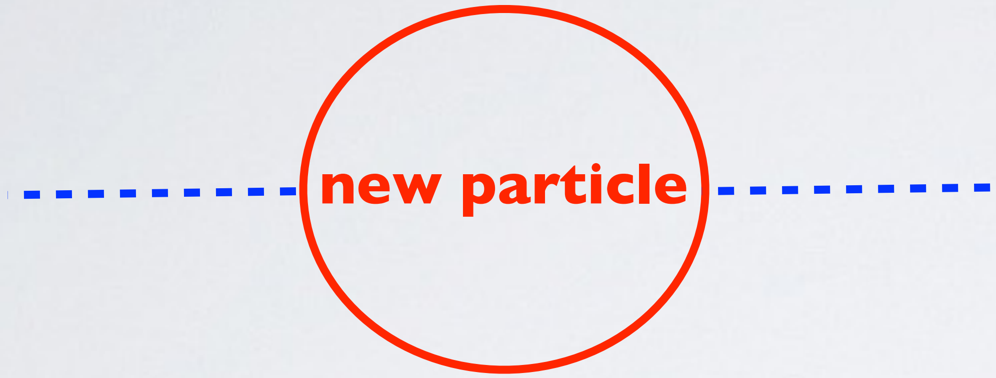

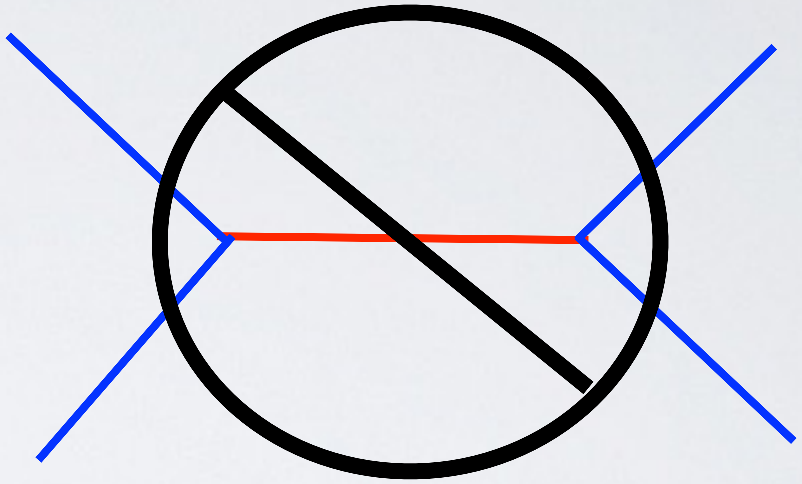

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In a sense, some WIMP DM (too few? too much?) is "naturally" expected for consistency of the currently favored framework for BSM physics at EW scale.

Beware of the reverse induction:

- LHC is current our best tool to test this paradigm, but if no new physics is found at EW scale it is at best the WIMP scenario to be disfavored, not the "existence of DM"
- Conversely, LHC may be probing topics of cosmo relevance beyond the DM problem!

EXAMPLE OF IDM-TESTABLE LHC "MISSES"

What if we give up independent arguments for BSM at the EW scale and just ask for a DM candidate **without invoking extra symmetries**? Some options:

- Extend SM with EW multiplet whose quantum numbers assignments (spin, isospin, hypercharge) fixed by requirement of a good DM candidate: a ~9.4 TeV fermionic hypercharge-less **quintuplet** whose stability of the guaranteed by the SM gauge symmetry and by renormalizability.

M. Cirelli, N. Fornengo and A. Strumia, hep-ph/0512090

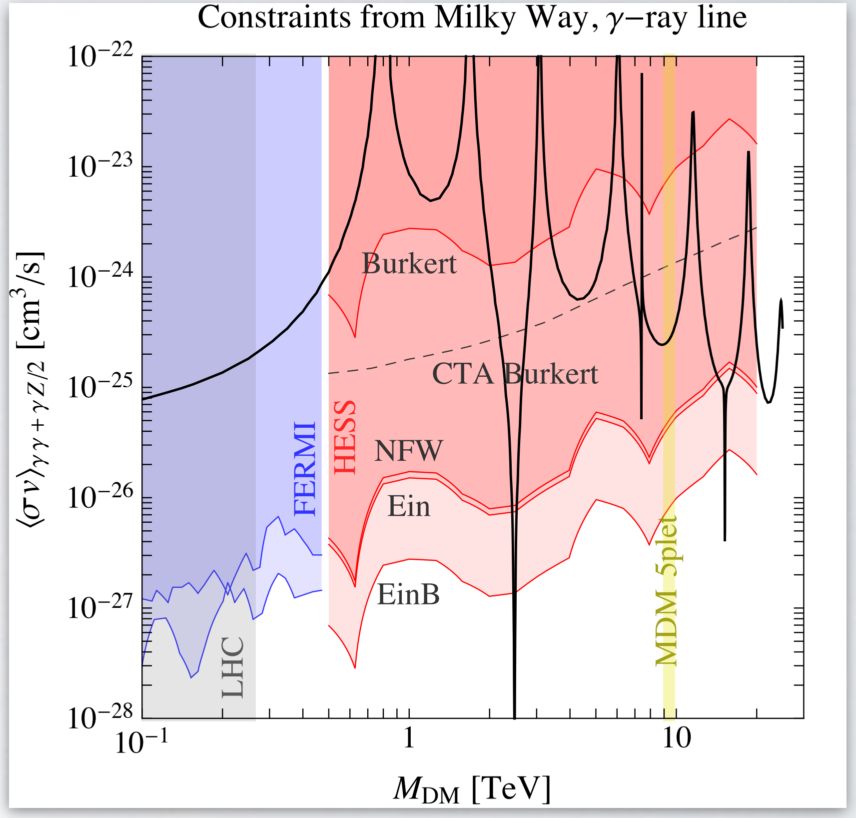
$$\mathscr{L} = \mathscr{L}_{\rm SM} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 \end{cases}$$

- spin 1/2
- spin 0

to prevent decay, no dim≦5 operator with SM allowed

Clearly not accessible to LHC, but currently severely constrained by gamma-ray data with good perspectives for definitive tests with CTA (MW & notably dwarf galaxies…)

M. Cirelli, T. Hambye, P. Panci, F. Sala and M. Taoso, 1507.05519



- For a SM singlet, the absence of additional protective symmetry requires a very light DM candidate with very small couplings, untestable at LHC (paradigmatic case of sterile neutrino)

FOR ASTRO/COSMO, OK! E.G.

- SM Neutrinos do not work as DM, but have some good properties (almost Ok!)

Easy to add one extra neutrino state which works!

- SM singlet, but for mixing with active (one needs ≥2 of these to give mass to ν's...)

$$\delta\mathcal{L} = \bar{N} i \partial_\mu \gamma^\mu N - \lambda_\ell H \bar{N} L^\ell - \frac{M}{2} \bar{N}^c N + h.c.$$

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- Production via oscillations, suppressed by the small mixing ($\sim 10^{-4}$)

(never in equilibrium, non-thermal spectrum, avoid "hot-ness")

$$\theta \sim \lambda v / M$$

- Further adjust mass *M* to obtain right abundance, keV range selected.

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- Interesting astrophysical candidate:
- "cold-to-warm", may suppress structures at sub-kpc scales;
- can be searched for via X-ray line (rare loop-suppressed decay)
- can be embedded in a "minimal extension" of the SM with only 3 right-handed neutrinos

(two GeV-ish ones explaining baryon asymmetry...)

$$N \to \nu + \gamma$$

in principle accessible to colliders,
e.g. high-intensity experiments like SHiP

Physics paper:1504.04855, Technical paper: 1504.04956

***νMSM**, for a review, A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)*

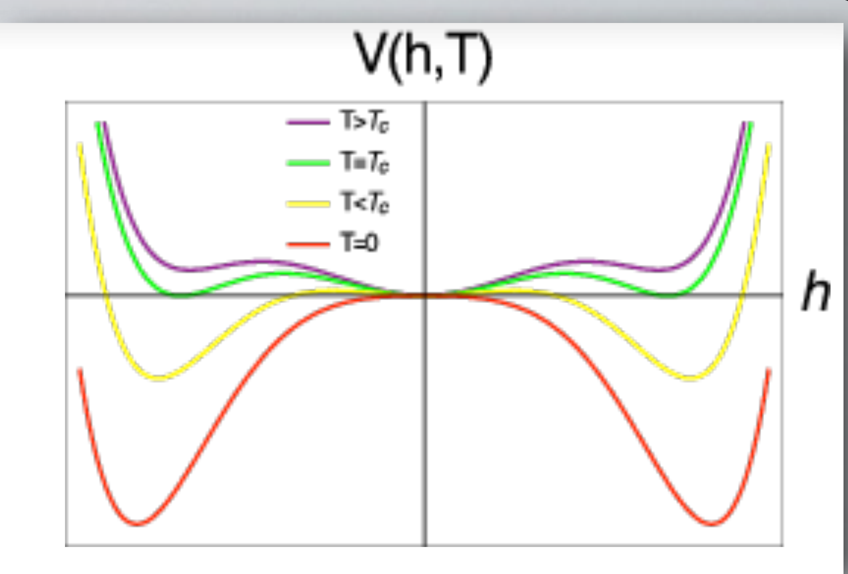
Note: no physics <u>above</u> the electroweak scale is required

LHC AS A PROBE OF EW PHASE TRANSITION?

In the ***SM***, the electroweak phase transition is a ***crossover***.

BSM physics could make it a **1st order PT,** a crucial ingredient (with CP violation) for the origin of the **baryon asymmetry** in the ***electroweak baryogenesis*** class of models

(+Gravity Wave background, cosmological B field seeds…)



Despite what you may have heard, **LHC does not reproduce Big Bang conditions** (thermal corrections to the Higgs potential are for instance not probed directly!)

New dof's altering the potential may or may not be directly accessible. Yet, models that lead to a 1st order through a relevant modification of the ***zero temperature effective potential*** can be **probed** e.g. via O(1) deviation of **triple Higgs coupling** from its SM value, parameterized by the operator

$$\mathcal{O}_6 = \frac{c_6}{\Lambda^2}(H^\dagger H)^3 \Rightarrow \frac{\sigma}{3}h^3$$

which could come e.g. from strong interacting sector at TeV scale, or integrating out heavier scalars…

Challenging, but potentially testable at LHC run 2 high-lum. (and at future colliders)

Incomplete list of refs.: C. Grojean, G. Servant and J. D. Wells, hep-ph/0407019, M. Carena et al. hep-ph/0410352 … C. Delaunay, C. Grojean and J. D. Wells, 0711.2511 … A. Katz and M. Perelstein, 1401.1827; D. Curtin, P. Meade and C. T. Yu, 1409.0005; F. P. Huang et al., 1511.03969; P. Huang, A. Joglekar, B. Li and C. E. M. Wagner, arXiv:1512.00068 …

WHERE WE GO FROM HERE (IDM-ORIENTED)

✤ Good news: at least for WIMPs, many strategies & the efforts are paying off: e.g. gamma-searches, antiproton searches, and CMB constraining for thermal relics up to O(100) GeV

✤ Bad news: "parameter space" of the theoretically unknown is pretty big, so there is no guarantee that we'll find any positive result soon. ***Exploring the reach in testing simplified models-with qualitatively different features-seem a promising way to go.***

✤ Further tests of the "BSM@EW-scale" paradigm are worth, especially given the need for "extra stuff" coming from astro/cosmo. ***LHC is a crucial explorer of the electroweak scale, whose importance for astro/cosmo goes even beyond the realm of DM***

✤ We will never move on by exhausting all the logical possibilities; since astro/cosmo hints at BSM, but does not hint to a scale, it is ***wise to evaluate alternative scenarios and*** multi-faceted ***discovery strategies***. In this task, DM can be taken as robust and interesting case study

This is a high risk/high reward topic of research:
we have some chance of a game-changing discovery but absolutely no guarantee of it
(although likely to learn lots of-sometimes interesting-astrophysics along the way!)

THE ROAD NOT TAKEN

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I —
I took the one less traveled by,
And that has made all the difference.

(Robert Frost, 1916, *Mountain Interval*)

Grazie dell' attenzione!