Dark Matter messages from the sky via Gamma rays

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Partially based on collaboration with:
S. Dodelson, D. Hooper, G. Zaharijas

Planck 2009, Padova - 27 May 2009

Outline

- Introduction
  - → What do we mean by “detecting” Dark Matter?
  - → What kind of Dark Matter candidate are we talking about?
  - → How to “detect” it: directly, indirectly, at colliders.

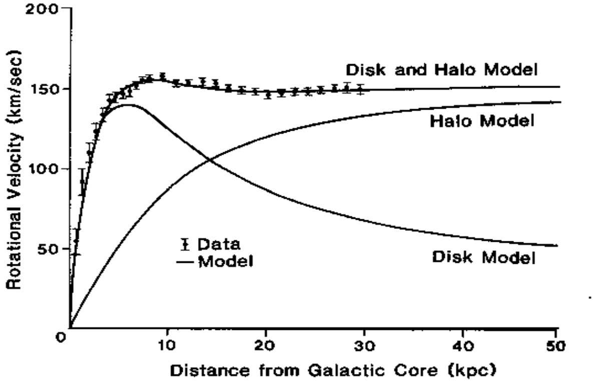
- Generalities on the gamma-ray signatures
  - → the expected energy spectrum of the gamma-ray signal
  - → the expected angular shape of the gamma-ray signal

- Perspectives for Fermi: some targets
  - → Prospects for the Galactic Center
  - → The diffuse Galactic halo signal
  - → Some comments on other signals

- Summary/Conclusions

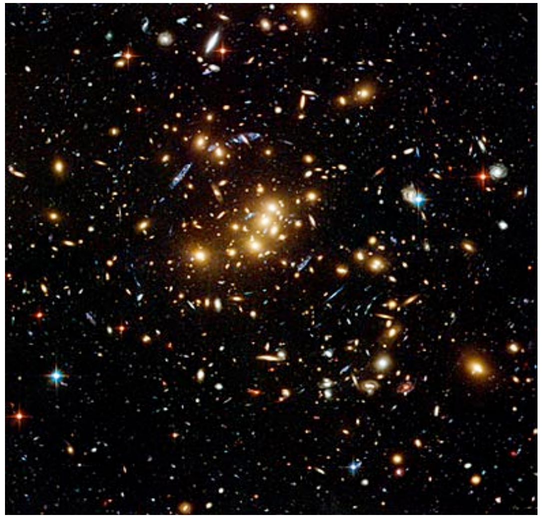
Dark Matter detected… only gravitationally!

Rotation curves of Galaxies

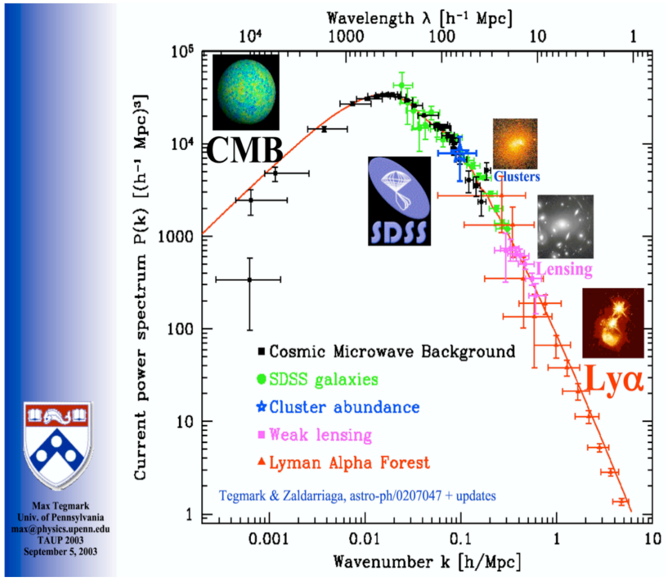


Galaxy Clusters

Lensing



Large scale structures



✓It's cold (maybe a little warm…)

✓It's dark (<u>at most</u> weakly interacting with SM fields)

✓It's non-baryonic (New Physics!)

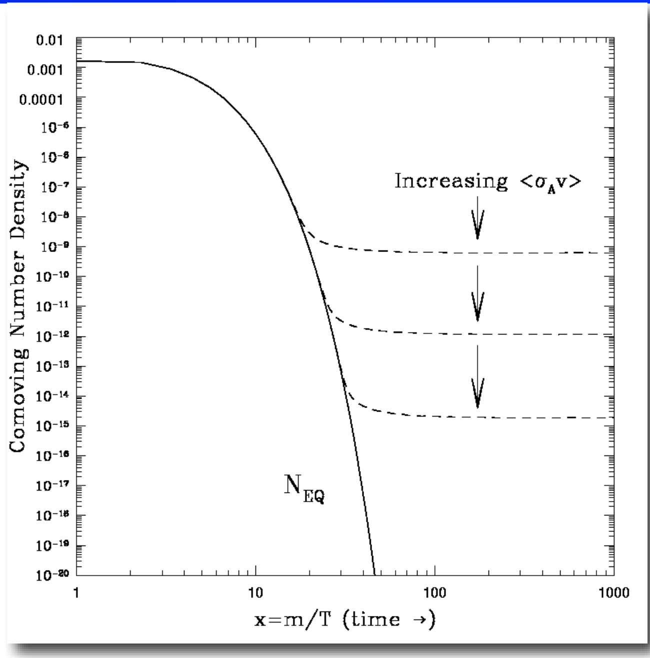
× gravity is "universal", does not permit particle identification: a discovery via electromagnetic, strong or weak probes is needed

What is DM? WIMPs? Reasonable, not guaranteed!

❖ The Weakly Interacting Massive Particle "miracle"
thermal relic with EW gauge couplings & $m_X \approx 0.01 - 1$ TeV matches cosmological requirement, $\Omega_X \approx 0.25$

$$\Omega_{wimp} \sim 0.3 / \langle \sigma v \rangle (pb)$$

❖ EW scale may be related with DM!
Stability ↔ Discrete Symmetry
(SUSY R-parity, K-parity in ED, T-parity in Little Higgs)
Ease agreement with EW observables, Proton stability…



❖ EW-related candidates have a rich phenomenology
Higher chances of detection via collider, direct, and indirect techniques

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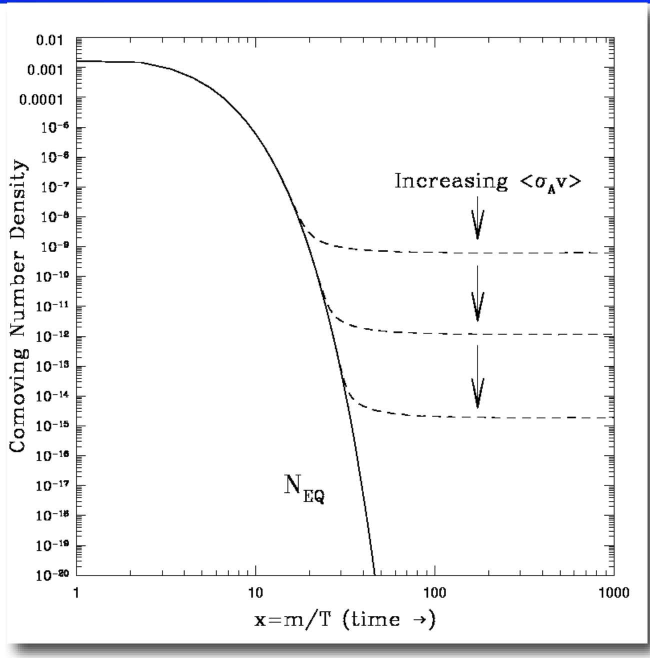

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➢ *Warning: keep in mind other possibilities!*
Candidates from Planck scale to sub-EW scale have been proposed
(Axions, SuperHeavy DM/WIMPZILLAs, MeV DM, sterile neutrinos…)
They have peculiar signatures and require ad hoc searches

Strategies towards detection of WIMP DM

Experiment	*Source*	*Interaction*	*Channel*
Direct	Local (crossing Earth surface)	WIMP-nucleus scattering	Phonons
Indirect	Earth, Sun, Galaxy, Cosmos	WIMP decay/ annihilation	γ,ν, Antimatter
Collider	Controlled production	WIMP pair production	$\cancel{E}$

Indirect Detection offers a way to test the "WIMP miracle"!!!

Rationale behind indirect DM program

As a discovery tool
we search for peculiar signatures, which cannot be (easily) mimicked by astrophysical objects. This is no different from particle physics, where one looks for new particles in the "best channels"!

If no signal is found
One can use indirect constraints (complementary to accelerators) to "motivated particle physics models" (e.g. SUSY in its MSSM incarnation)

If a signal is found in other channels (accelerator/direct detection)
We still *need* indirect detection:

- ✓ To confirm that whatever we find in the Lab is the same "dark stuff" responsible for astrophysical and cosmological observations.
- ✓ 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.

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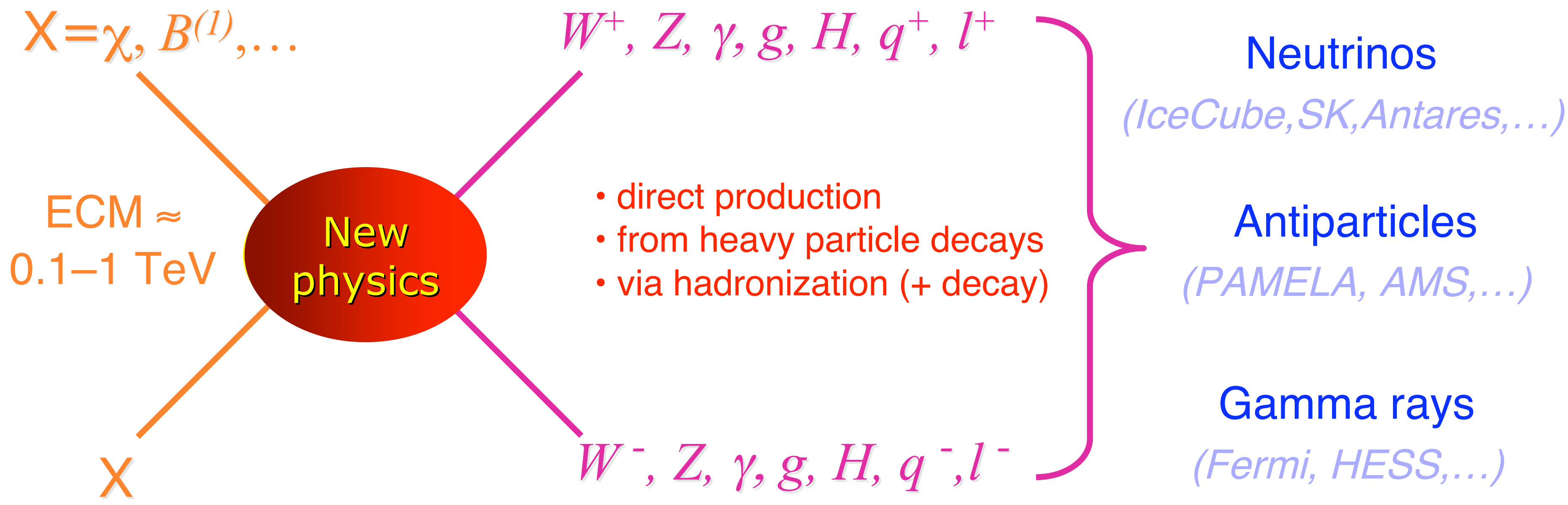
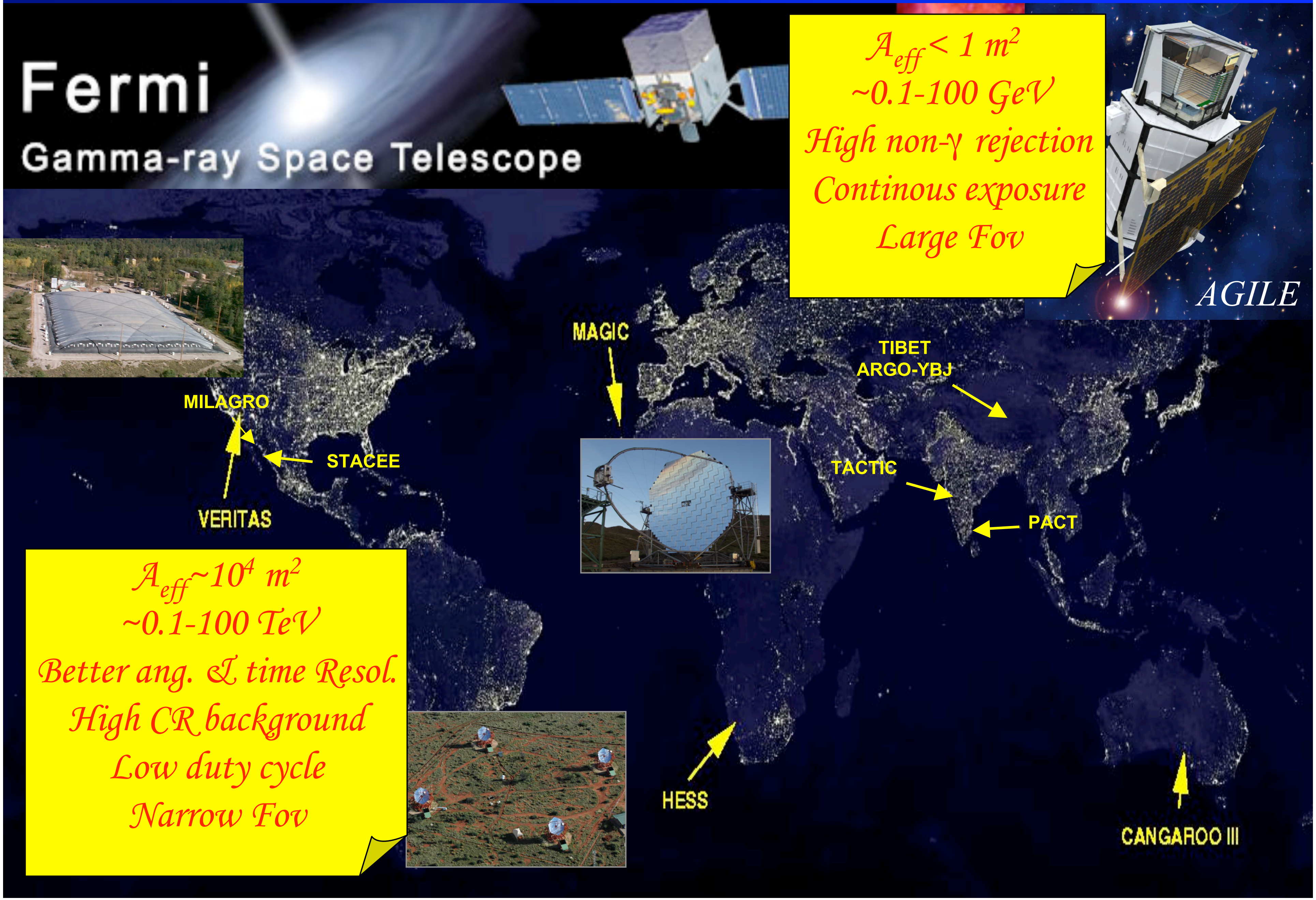
For examples along (or perhaps opposite to!) these lines, see talks tomorrow by A. Strumia, N. Weiner, Y. Nomura, Parallel session A (yesterday talk by A. Ibarra)

Indirect detection of DM: what to look for



Target	*Advantage*	*Challenges*
Spectral line $E \approx m_X$ anywhere	Smoking gun	Loop process, suppressed, Experimental E-resolution
Galactic center	High intensity	DM profile, astrophysical foregrounds
Satellites, μ-halos…	Low background	Low statistics/Model-dep.
Diffuse galactic & extragalactic	High statistics	Cosmological uncertainty, astrophysical foregrounds

High Energy & Very High Energy γ-ray telescopes



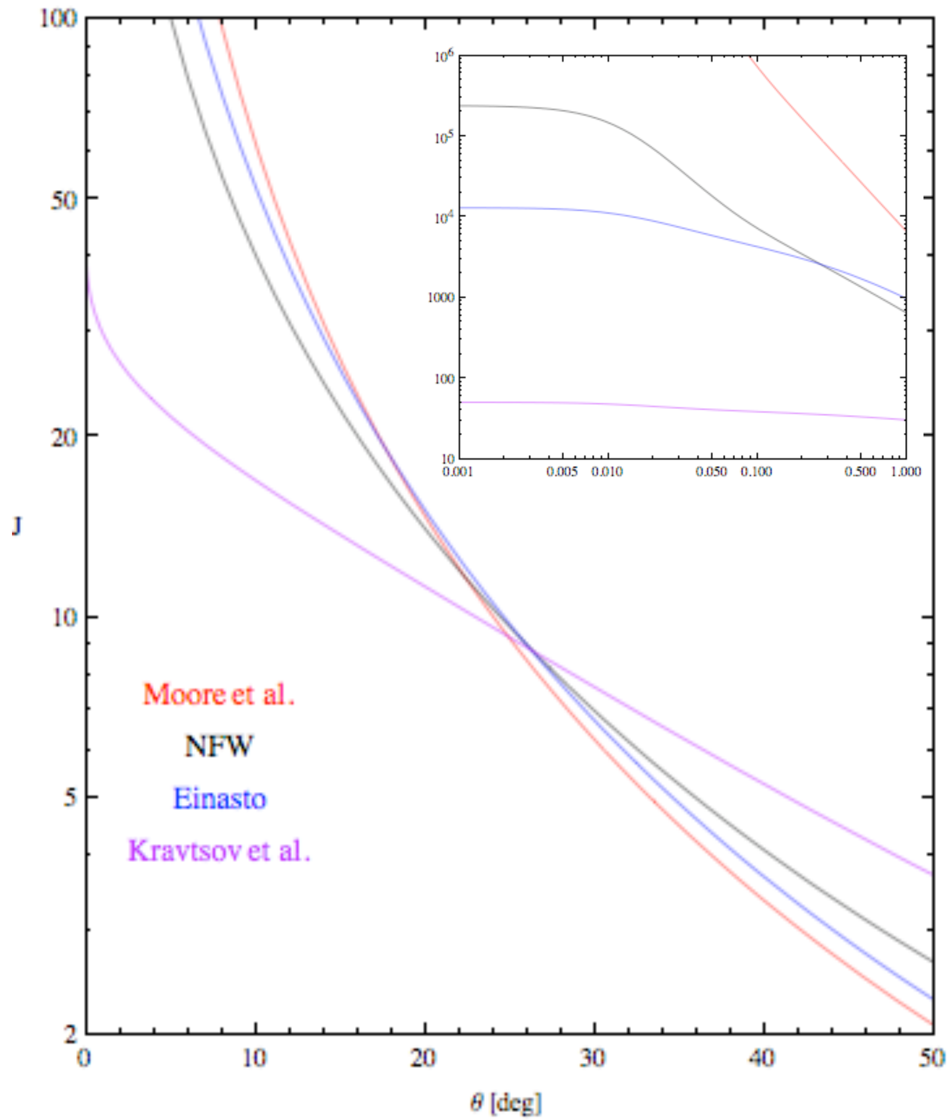
Where to look for gamma rays?

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

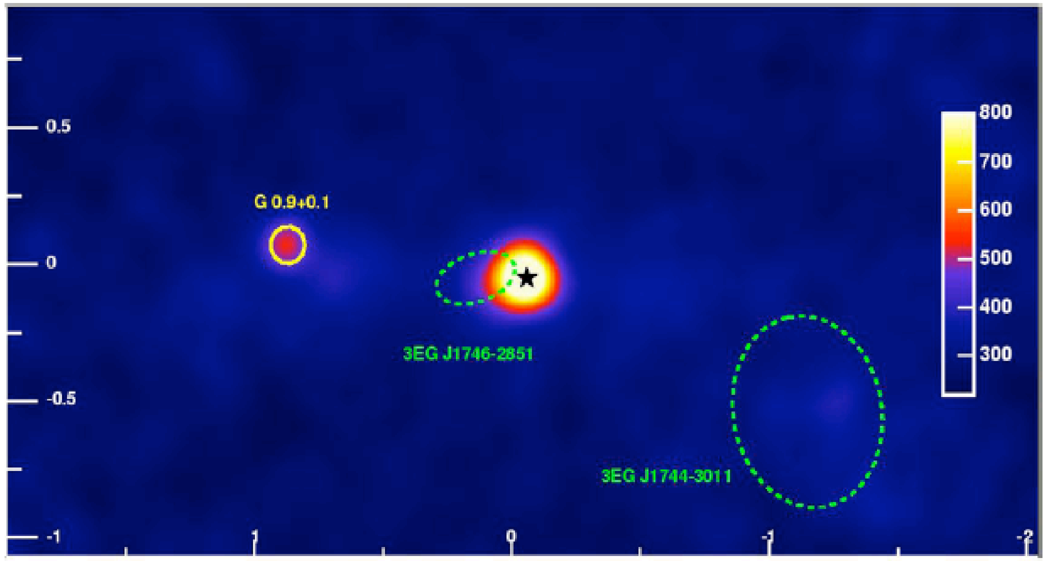
- ✓ The [particle] ⊗ (astro) factorization holds if $<\sigma\, v>$ is v-independent
- ✓ For S-wave thermal relic

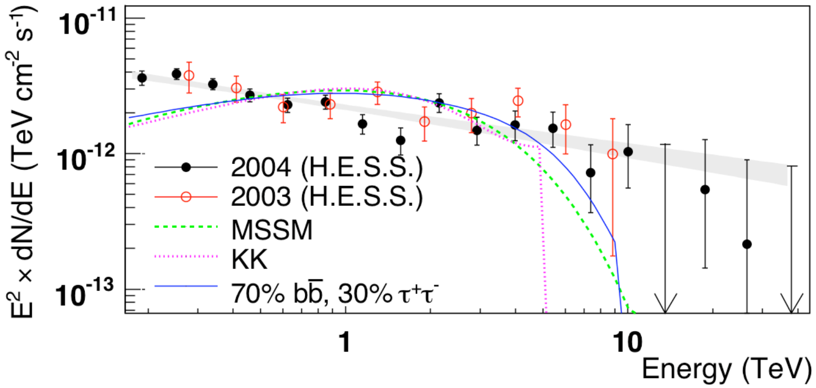
  $<\sigma\, v>$~const~pb
- ✓ The signal is maximal at the Galactic Center → "natural" target!

Problem 1:
Even forgetting substructure,
Halo profile towards GC not known!



EGRET/HESS reveal background from MeV to TeV

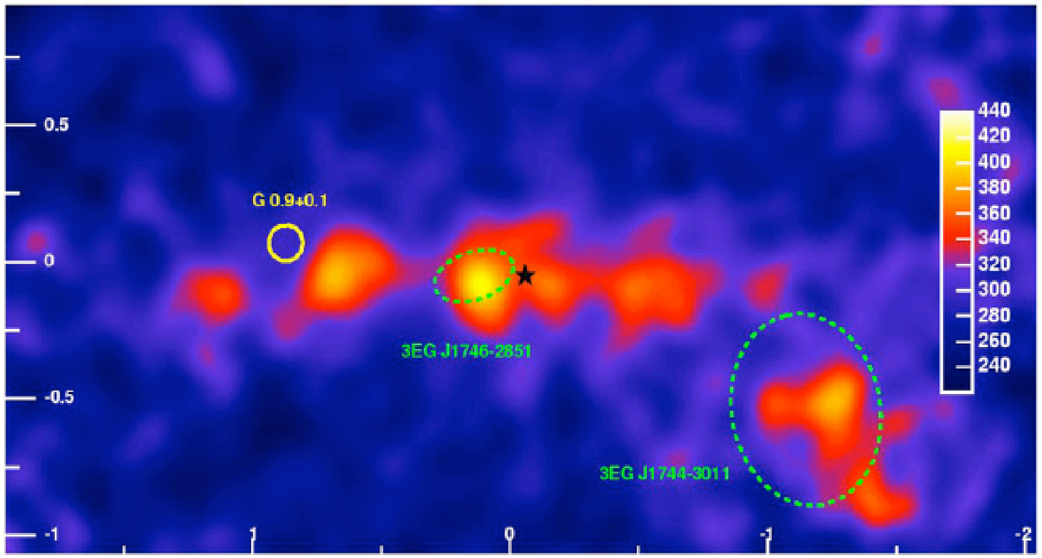




For a Fermi-like instrument, tens of photons from the GC, ≥O(1000) from the whole sky, but…

Problem 2:

Not a background-free detection!

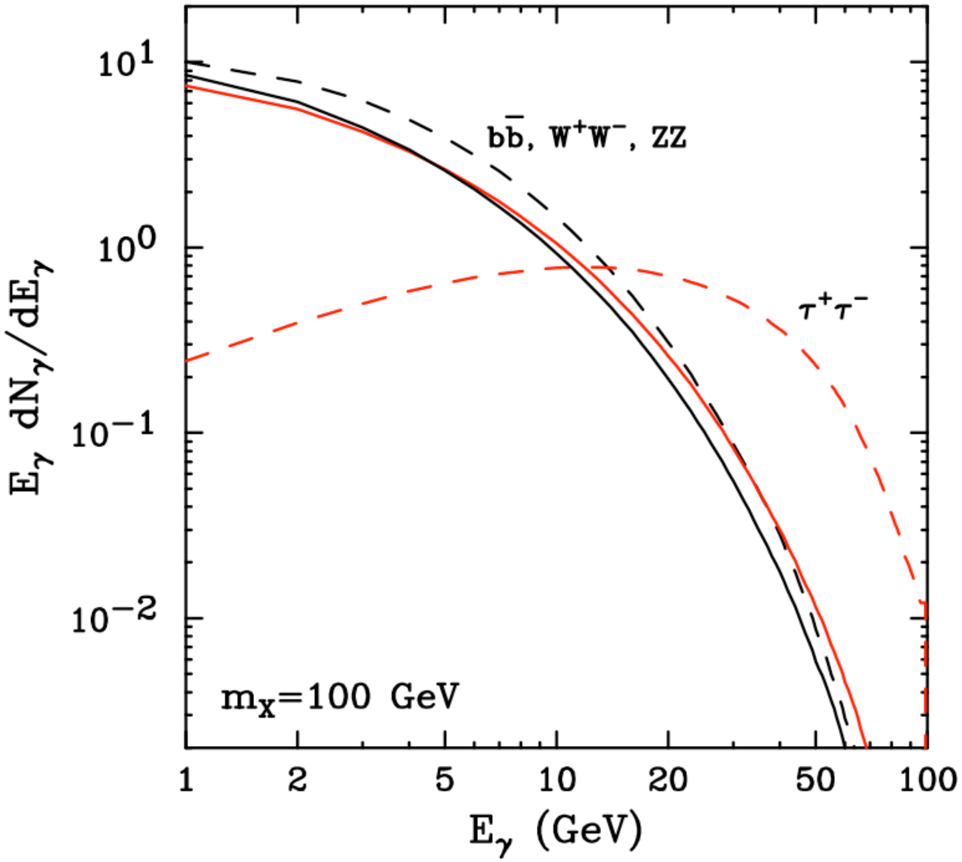


- background-free (?) targets (but low signal, as dwarf galaxies)
- Signal/Background enhancement strategies

Different Spectral Signatures

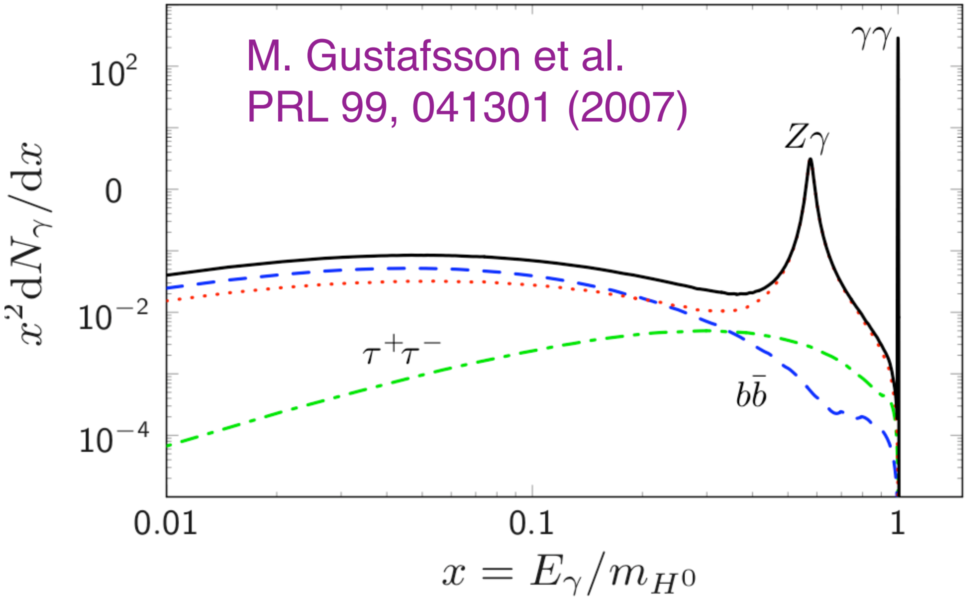
- Astrophysical background mostly from π^0's in pp scattering in the ISM, power-law due to the power-law of parent CR spectra (in turn, due to shock acceleration)

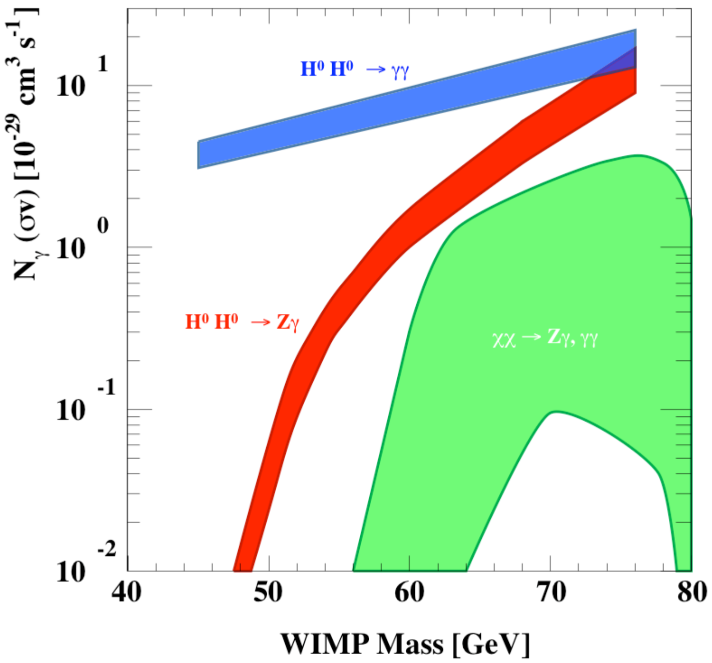
- DM annihilation happens almost at rest, producing a spectrum dominated by γ's from heavy SM particle decays (typically via hadronization), with $E \sim m_\chi/100 - m_\chi/10$



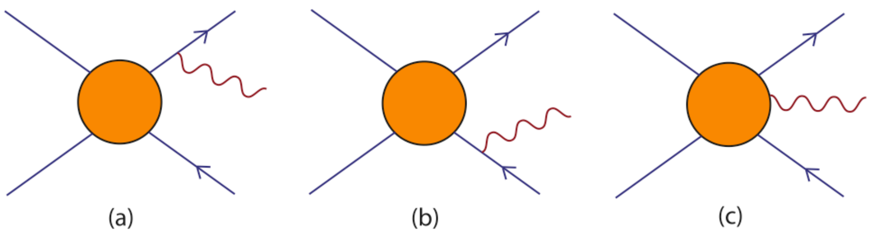
Other spectral features at the endpoint

✓ γγ & Zγ lines: loop suppressed, but in some models relevant (e.g. Inert Higgs Doublet)

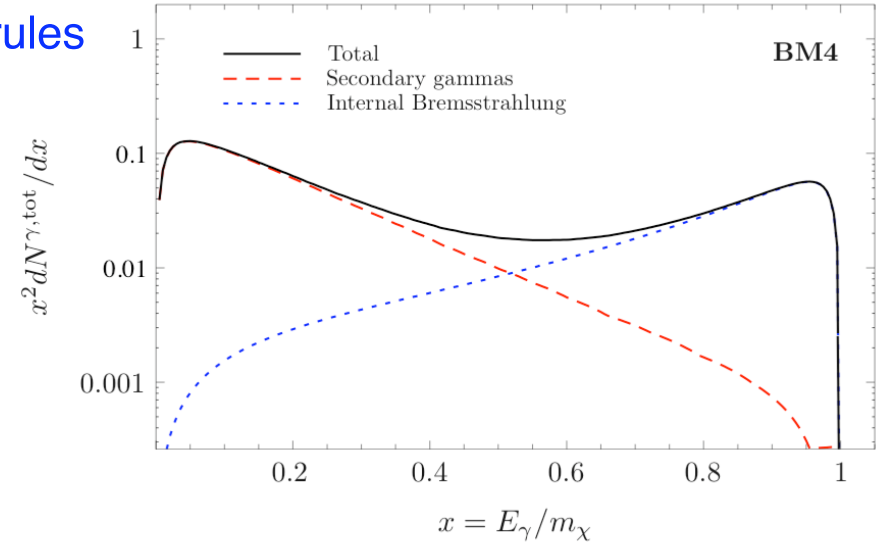




✓ Hard γ's from 3-particle final states, can be relevant if 2-body suppressed e.g. by selection rules



T. Bringmann, L. Bergstrom and J. Edsjo,
JHEP 0801, 049 (2008)



Angular Signatures

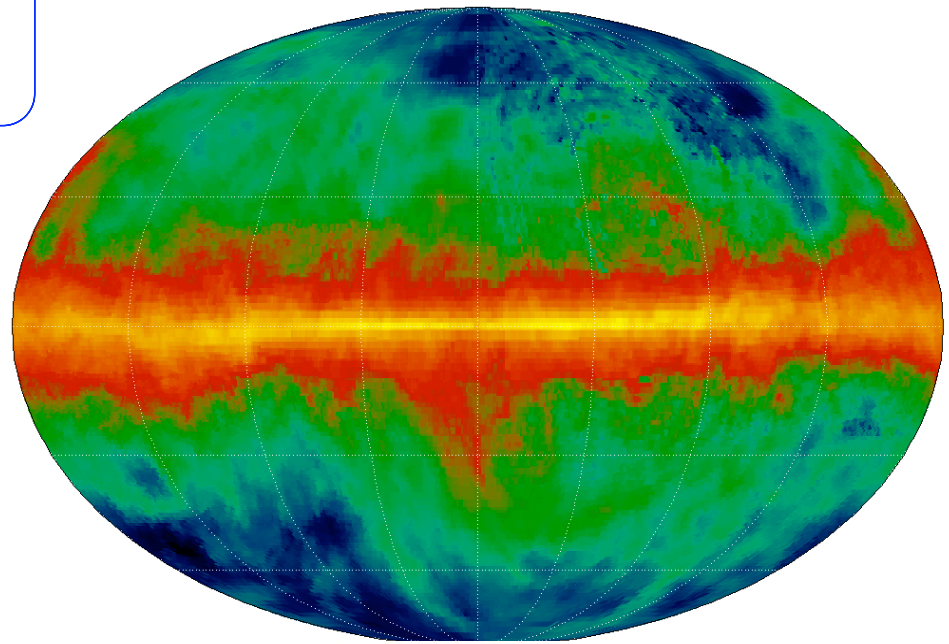
Astrophysical & DM signals have different angular shapes

→ Background is due to:

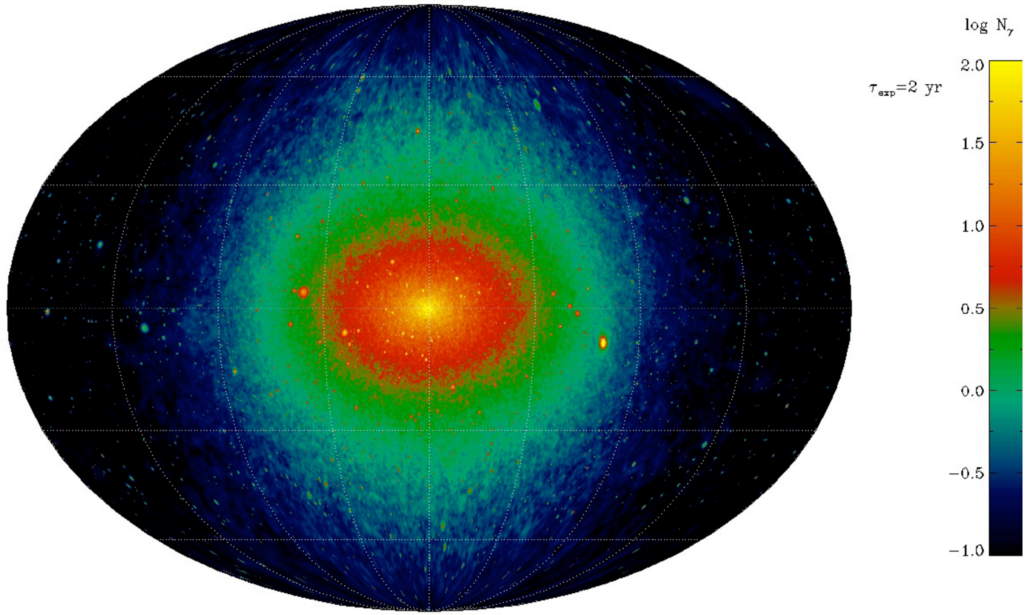
- unresolved point-like sources
- π^0 from CR spallation in the ISM

Both map the gas (max in the Gal. Plane)

→ DM Signal: depends on dark halo shape & substructure ("predicted" from simulations "constrained" by observations)



Kuhlen, Diemand, Madau



Example: 2º×2º around the Galactic Center

- "EGRET" source 0.2º off-set (extrapol. at high Energy)

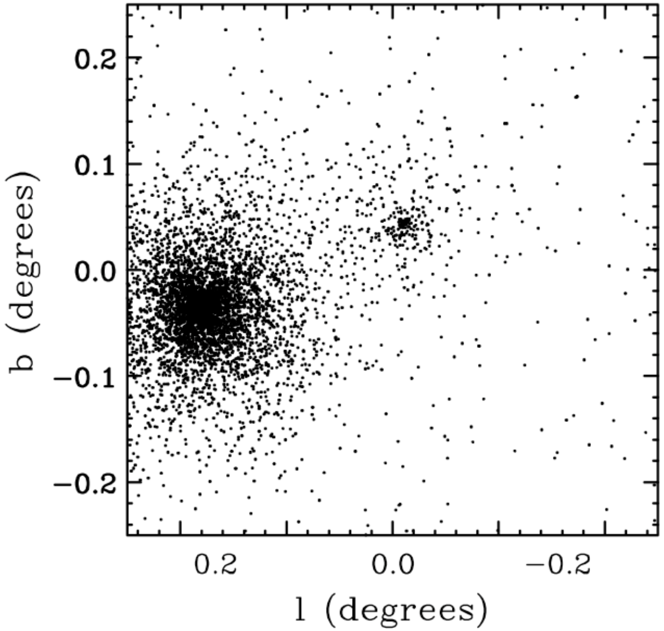
$$\Phi^{EG} = 2.2 \times 10^{-7} \left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-2.2} e^{-\frac{E_\gamma}{30\,\mathrm{GeV}}}\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

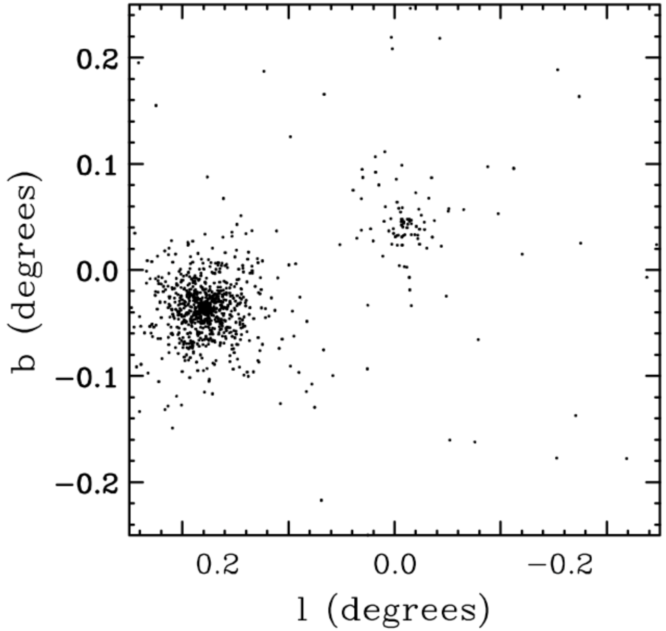
- "HESS" source at the GC (extrapol. at low Energy)

$$\Phi^{ACT} = 1.0 \times 10^{-8} \left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-2.25}\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

- Diffuse flux (constraint: 10^{-4} cm^{-1} s^{-1} sr^{-1})

$$\Phi^{diff}(A,\alpha) = A \left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-\alpha}\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

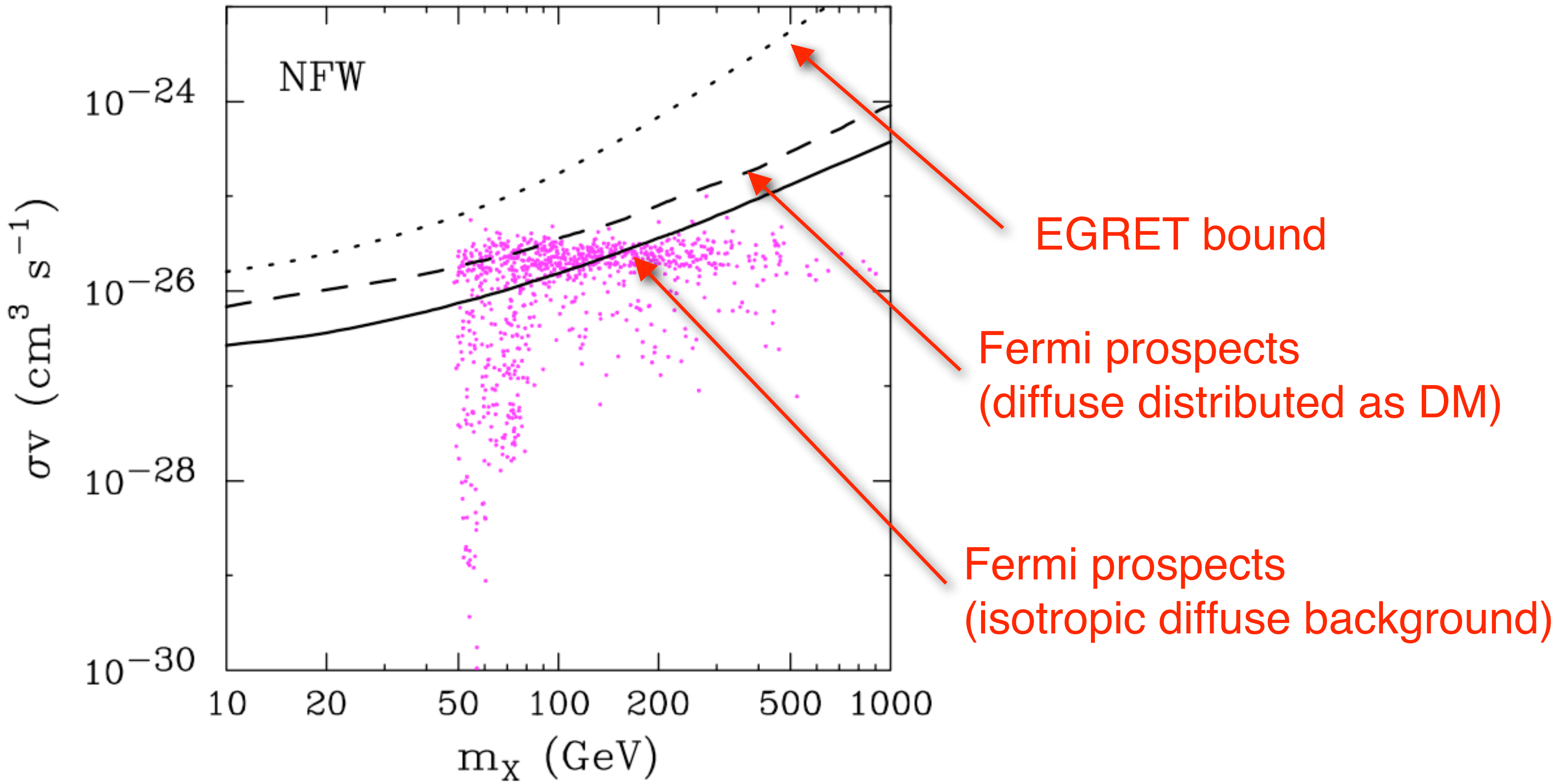




E>3 GeV (Fermi lifetime simulated sky) E>10 GeV

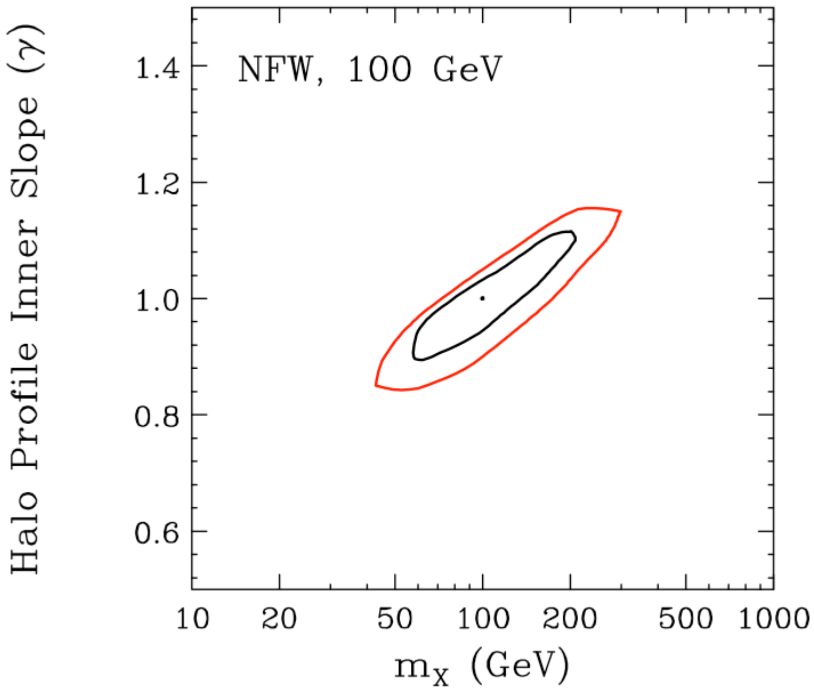
Case of Galactic Center for Fermi

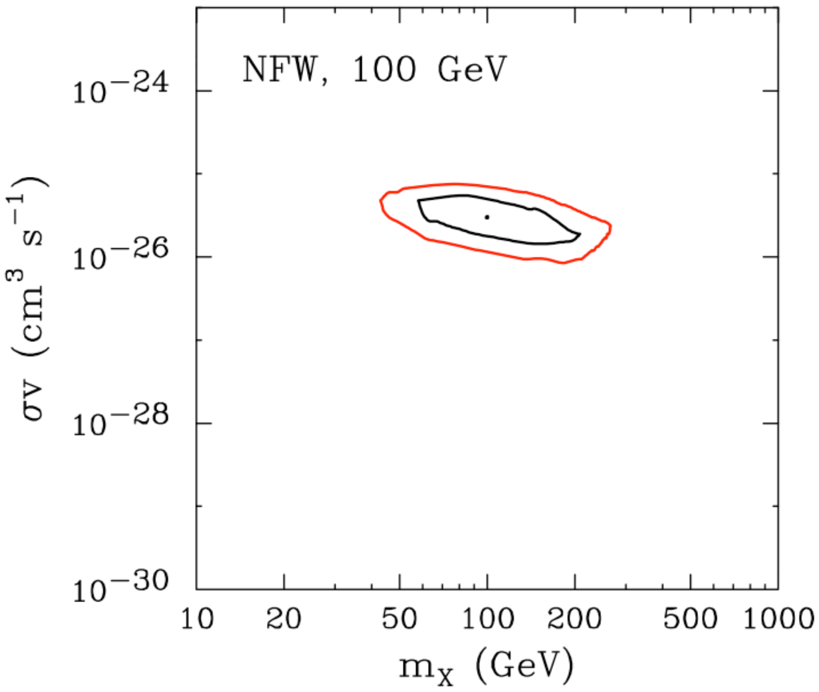
For Fermi 5+5 yrs lifetime, accounting for known point-like and diffuse backgrounds, energy resolution, energy-dependent angular resolution.



S. Dodelson, D. Hooper, PS PRD 77, 063512 (2008)
See also Fermi DM team analysis, JCAP 0807:013,2008

Case of Galactic Center for Fermi (II)

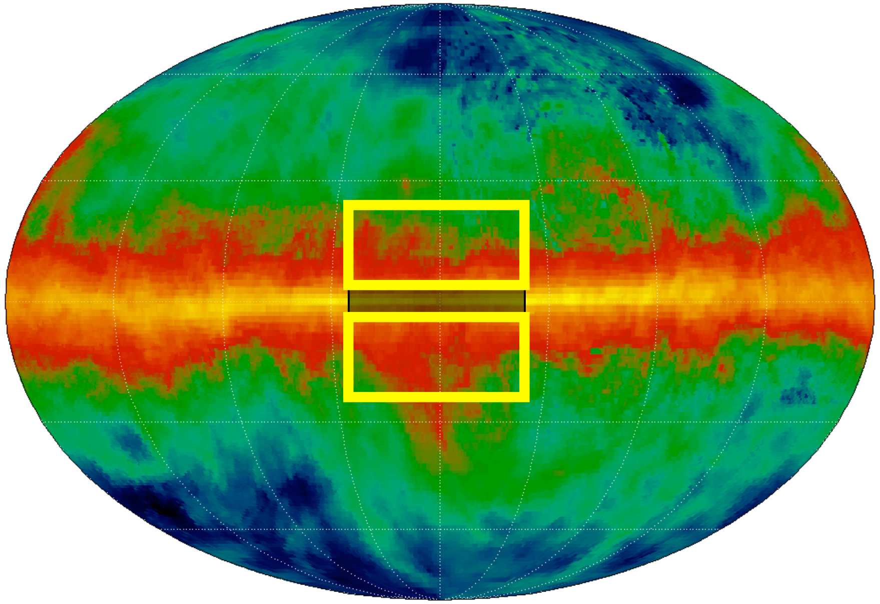


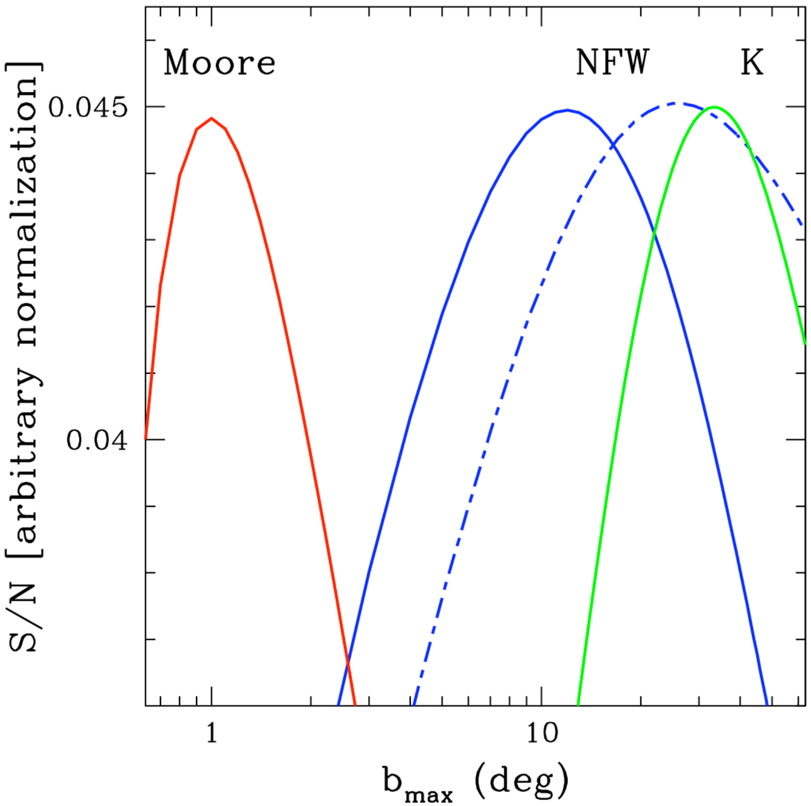


Discovery potential for a fiducial model: 68% & 95% CL, marginalized over diffuse background spectral index & <σ ν> (Left) or halo profile (Right)

Example II: (Inner) Galactic halo

- The GC may reveal more “polluted” than thought, or the DM halo not so cuspy
- An alternative option is to study the diffuse flux from the inner halo



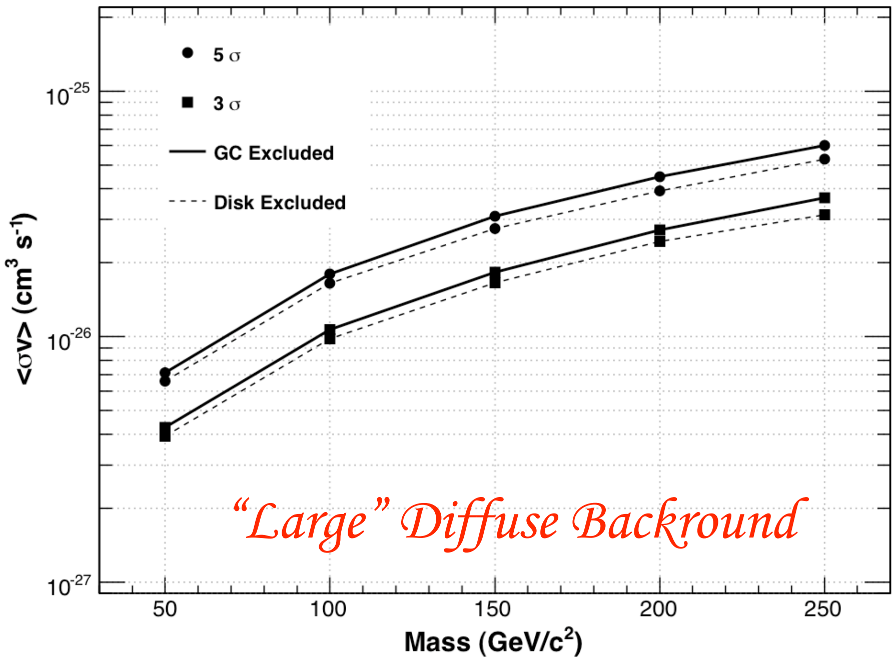


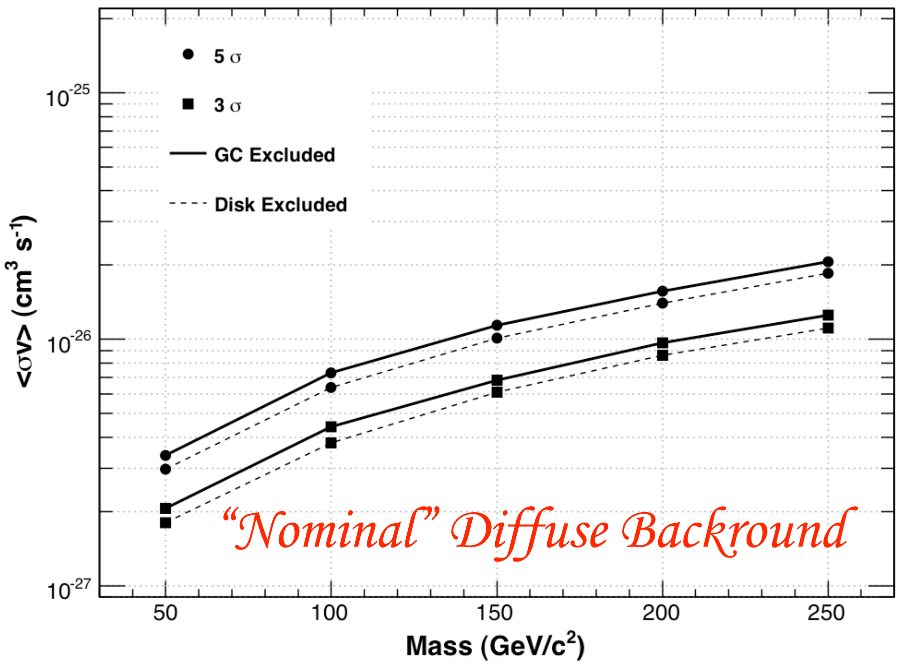
Ex.: for a naïve S/√N ~0.17 in the 2°×2° window considered above, an optimal S/√N~0.4 results for a window of size ~25° around the GC, using simple fits of diffuse γ-backgrounds calibrated on EGRET data

PS & G. Zaharijas,
Astropart. Phys. 29, 380 (2008)

Diffuse Halo signal, forecasts

1 yr Fermi detection regions, NFW, rectangular or circular cut around GC



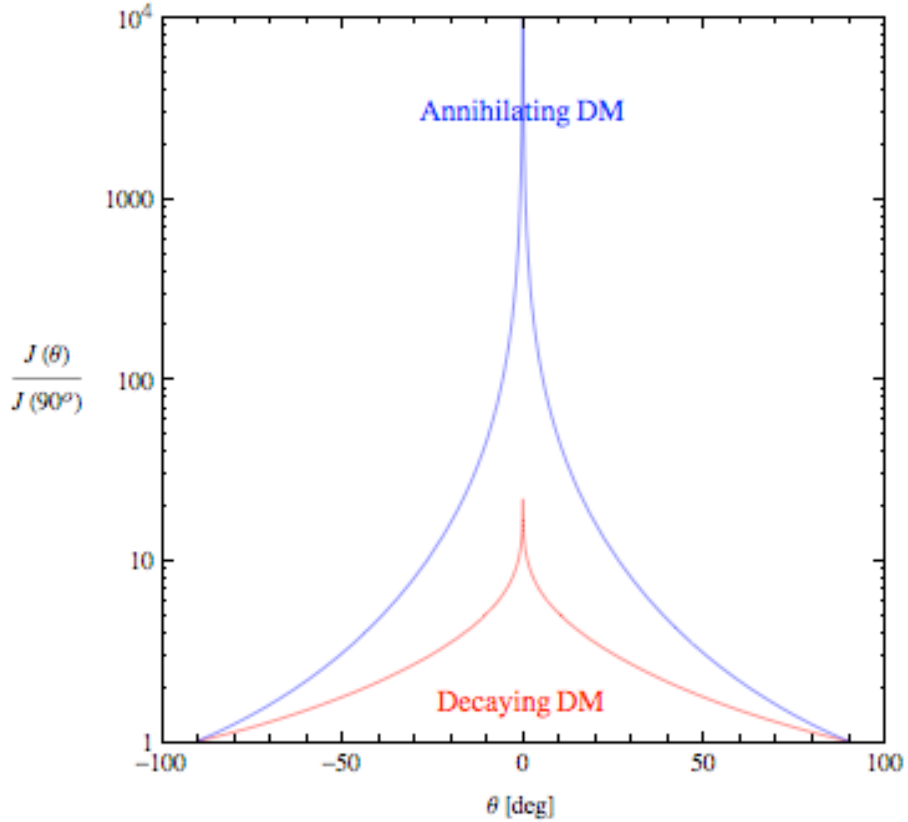


Provided that systematics are kept under control and the diffuse background models are better understood, the diffuse halo signal is very, very promising for detection (also for relatively cored profiles)

Fermi DM team analysis, JCAP 0807:013,2008

Galactic halo: other advantage (if DM detected!)

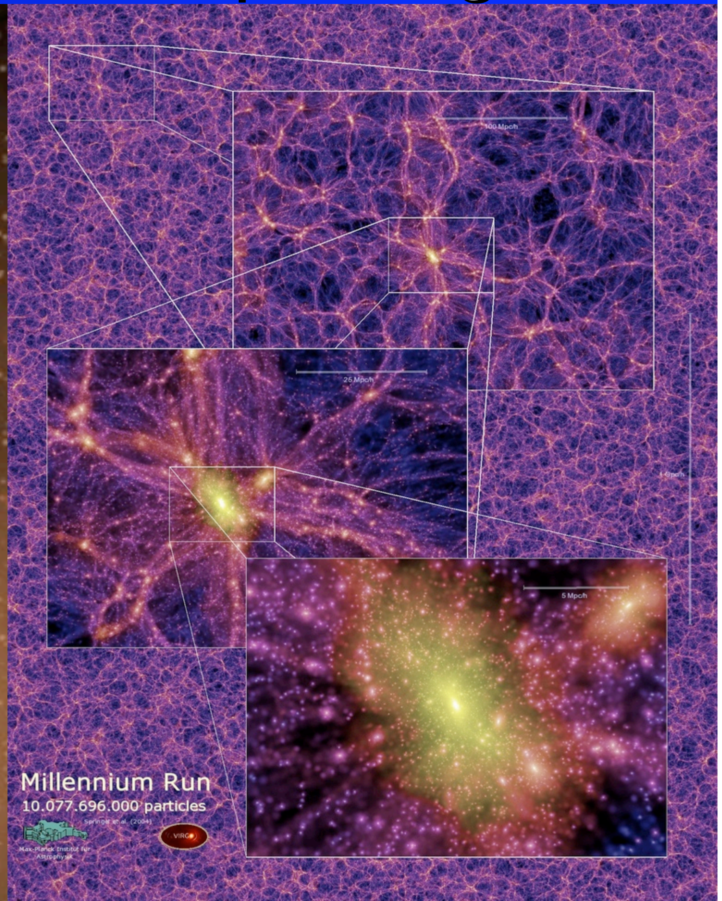
- Independent evidence of DM nature of the excess (e.g., universality of the spectra of the “excess” in different patches of the sky; possibility to look for lines)
- Determination of halo profile outside the very Central region (the latter is influenced by the dynamical role of the Black Hole at the Galactic Center)
- Constraining the amount of DM in substructures
- Distinguish empirically between annihilating and decaying DM



The hierarchical structure formation paradigm

z=0.0

- Primordial fluctuations in DM density led to gravitational collapse. In CDM, structure formed in a hierarchy, from smallest to largest dark matter halos



- When ordinary matter fell into these DM halos, it dissipated heat and collapsed to form stars and galaxies – DM cusps and substructures may persist if not washed out by dynamics

80 kpc

via lactea 234 million particles http://www.ucolick.org/~diemand/vl

Point-like sources due to “substructures"

- More model dependent (cosmological “initial conditions”, merger history of Milky Way)
- Either look for known substructures (dwarf Galaxies) or look for a new populations of “dark sources”: DM sub-halos? IMBH?

Dwarf Galaxies (satellites of the Milky Way)
✓ know where to look… target for IACTs as well.
× expected signal very small (sometimes below 1 event…)

IMBH
× highly speculative (who ordered them, exactly?)
✓ if a population present, they accrete DM and detection is likely

Dark sub-halos
× Their distribution, abundance & survival highly model-depedent
✓ In both cases, follow-up observations with IACTs are possible.

See talk by P. Ullio on Friday

High-latitute/Extragalactic Signal

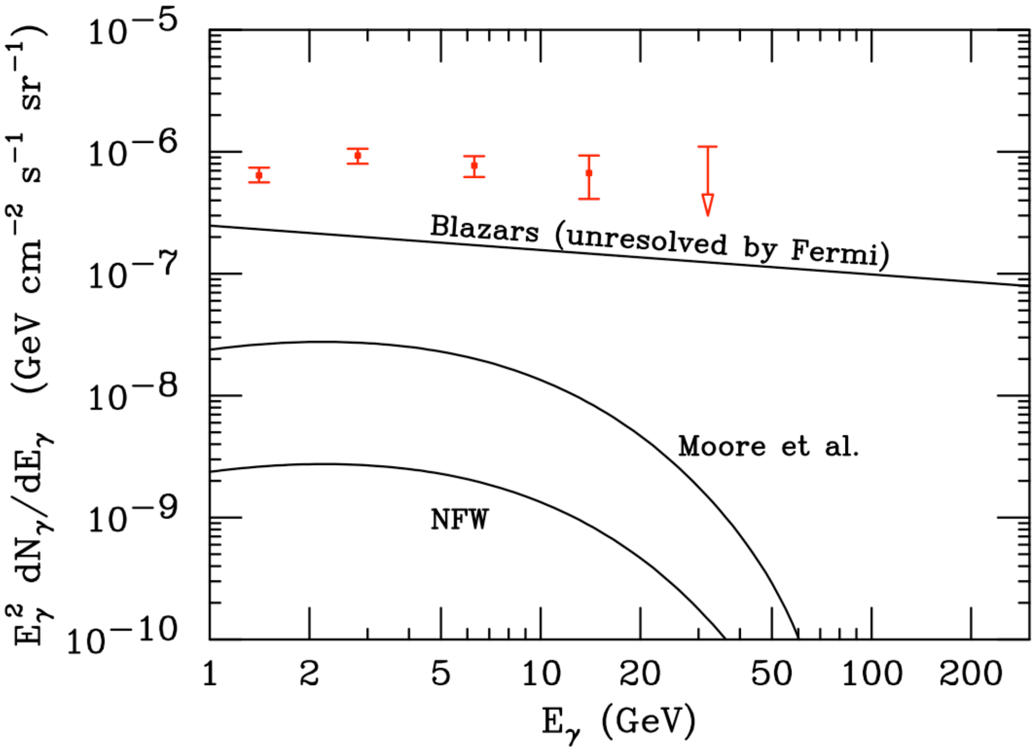
- In general, only detectable when other signatures are "very clear"
- Still, different systematics
(e.g., also works if Milky Way is an exception, in terms of DM distribution)

$$\Phi^{\mathrm{extr.}}(E_\gamma) = \frac{\langle\sigma v\rangle}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_X^2}{m_X^2}\int dz(1+z)^3\frac{\Delta^2(z)}{h(z)} \times \frac{dN_\gamma}{dE_\gamma}(E_\gamma(1+z))e^{-\tau(z,E_\gamma)}$$

- If detected, tells us about integrated properties, not "local" ones!

Statistical separation explored: active research program on high-latitude "contamination" by DM halo signal, multipole analysis techniques (if unresolved halo substr. dominates) 1-point PDF to separate extragal. DM from other components, etc.

Ando, Bertone, Branchini, Cuoco, Hannestad, Kamionkowski, Komatsu, Dodelson, Miele, Pieri, PS, Siegal-Gaskins, Taoso …



Summary

- For the first time, existing astrophysical instruments (especially Fermi) have discovery potential for "benchmark" WIMP Dark Matter candidate: a O(100) GeV thermal relic, distributed in the halo with a profile similar to that obtained in CDM N-body simulations.

- "Detecting the DM photons" does not seem to be the major issue: the crucial aspect is the separation from astrophysical background.

- In that respect, the recent IACTs discovery of an astrophysical accelerator at the GC has worsened the sensitivity to DM; nonetheless, an analysis combining expected angular and spectral information has good potential.

- The Galactic halo signal seems to be as promising (or more, for not-so-cuspy halos). The possibility remains to detect substructures, the lines, or the extragalactic background, which would add important information on DM properties. Synergy with IACTs possible.

- Finally, this is happening in the same time window where other indirect experiments are running/being completed (e.g. IceCube, PAMELA… AMS-02) direct detection is achieving a jump in sensitivity, and LHC will tell us what's really going on at the electroweak scale. Synergy involving several channels is usually very powerful!

We expect quite exciting times!

The power of vision: From Hess Nobel Lecture, 1936

[…] It is likely that further research into "showers" and "bursts" of the cosmic rays may possibly lead to the discovery of still more elementary particles, neutrinos and negative protons, of which the existence has been postulated by some theoretical physicists in recent years.