Indirect Searches for Dark Matter

Christoph Weniger

22nd June 2015, Zaragoza
Axion WIMP conference – Patras workshop

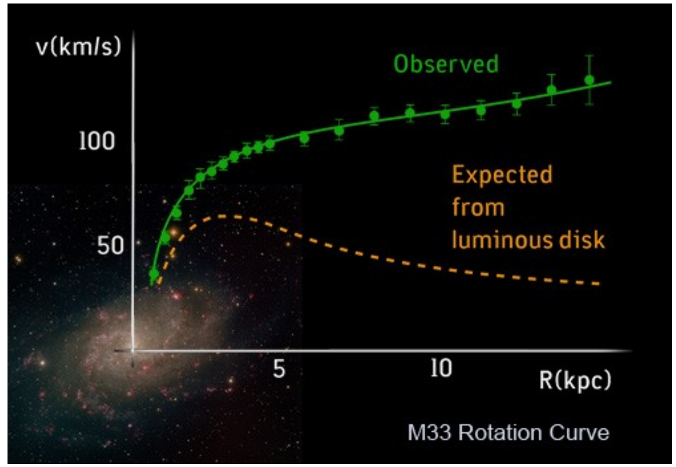
GRAPPA
GRavitation AstroParticle Physics Amsterdam

NWO

Evidence for dark matter is omnipresent

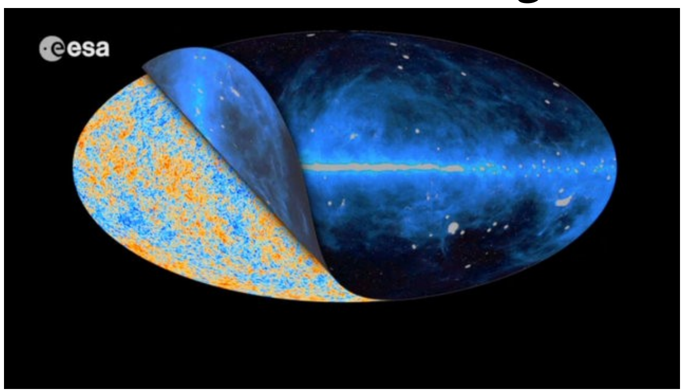
Evidence for the existence of **non-baryonic** dark matter in the Universe comes from gravitational observations at vastly different length scales (galactic to cosmological).

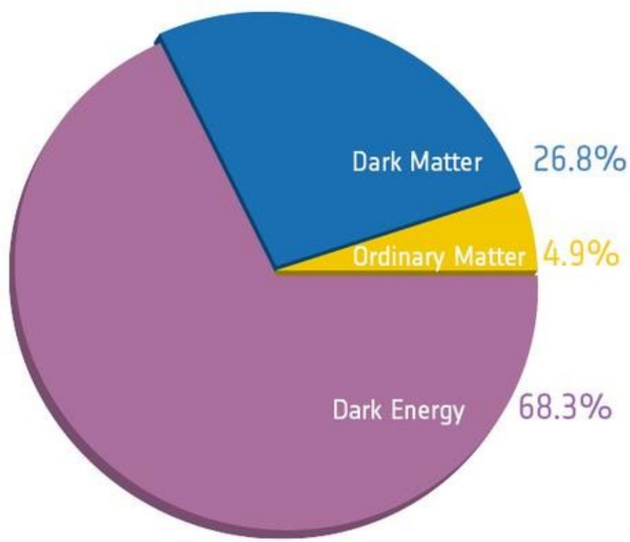
Galaxy rotation curves



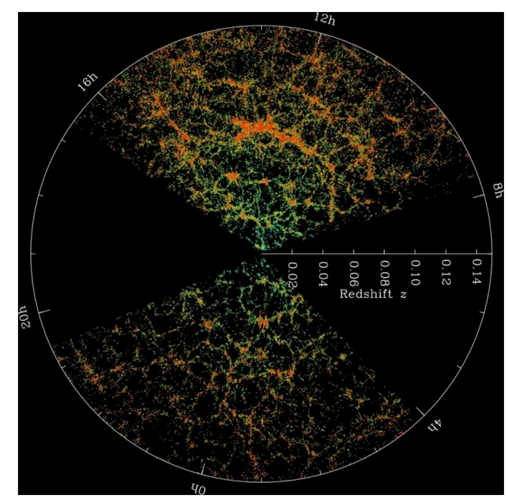
Galaxy clusters

Cosmic microwave background

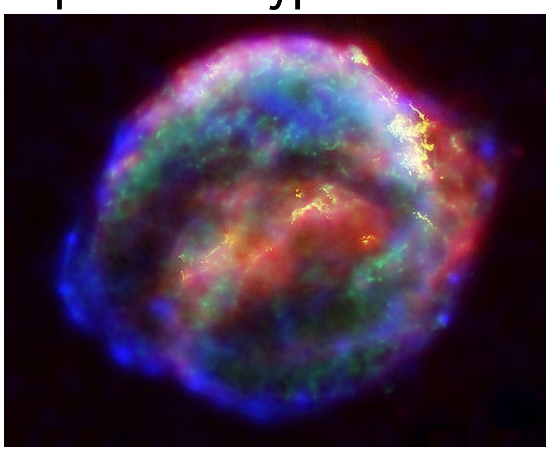




Large scale structures



Supernova Type 1A



85% of all matter in the Universe is **dark** and **non-baryonic**.

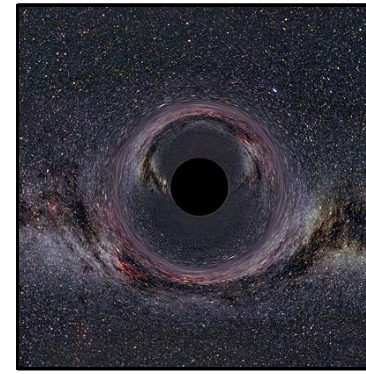
What we know

About 80 years after the first discovery of dark matter by Fritz Zwicky and others, we can now bracket its particle mass to **within 80 orders of magnitude**.

Uncertainty principle
(if DM is bosonic)

Hu+ 2000

MACHO searches
(massive compact
halo objects)

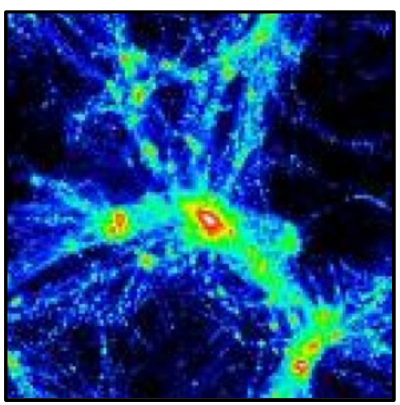


$$10^{-22}\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{50}\mathrm{GeV}$$

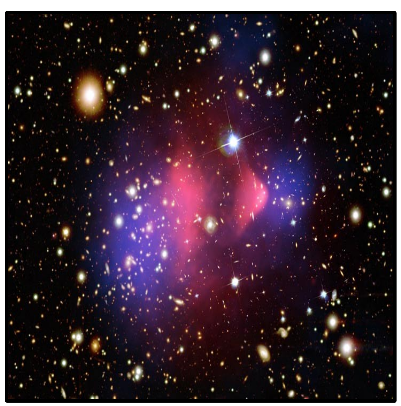
Tisserand+ 2007

Up to now, there are only various upper and lower limits:

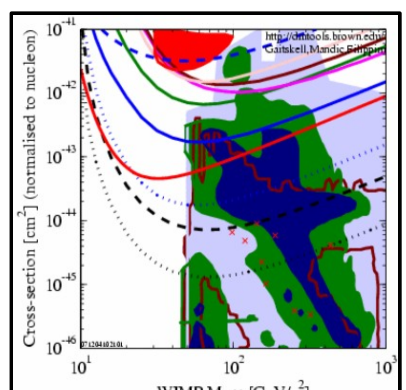
cold:
negligible velocity dispersion

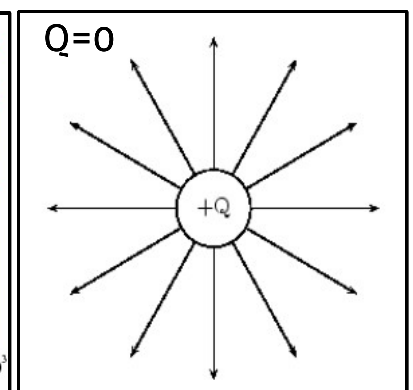


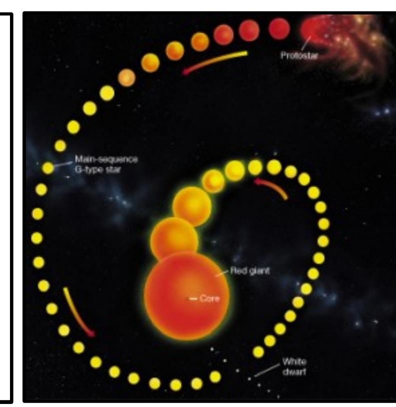
collisionless:
negligible self-interaction



weakly coupled:
negligible interaction with the rest of the world







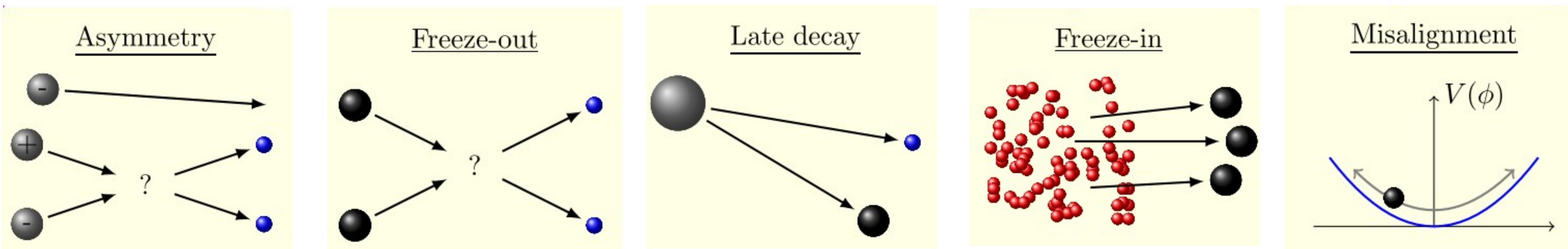
The two corner stones of speculation about DM

DM was produced in the early Universe

Main constraint: observed dark matter density and temperature.

Many ideas for production mechanisms:

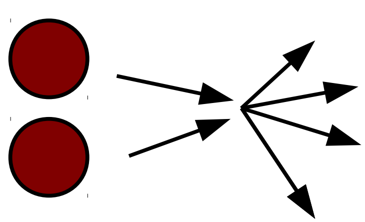
Electro-weakly coupled ⟷ Extremely weakly coupled



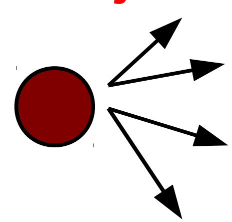
DM is still around today

Protected by symmetry in Lagrangian, which might be slightly broken.

Self-annihilation



Decay on cosmological time-scales

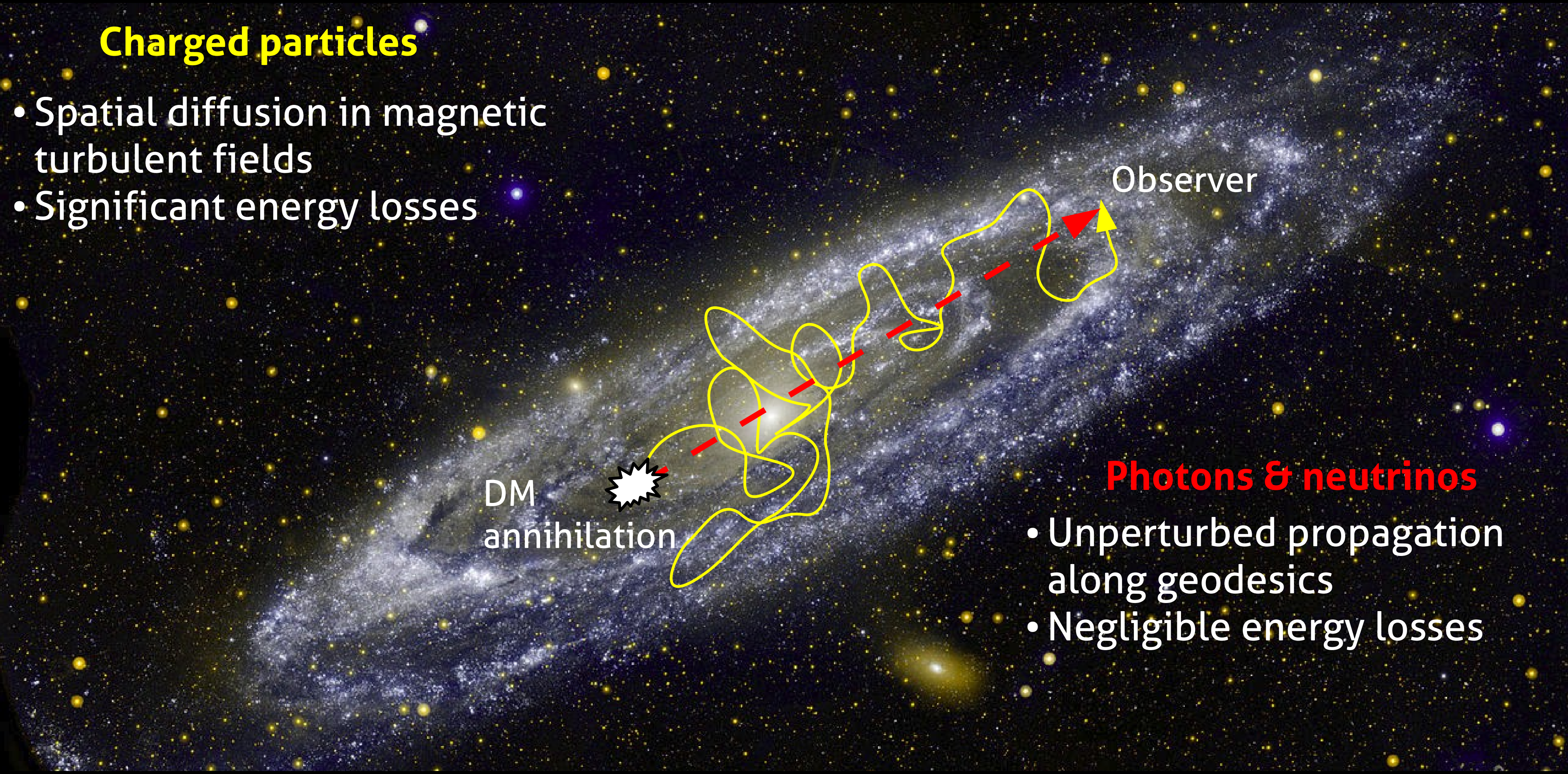


$$\tau_{\mathrm{DM}} \gg \tau_{\mathrm{Universe}}$$

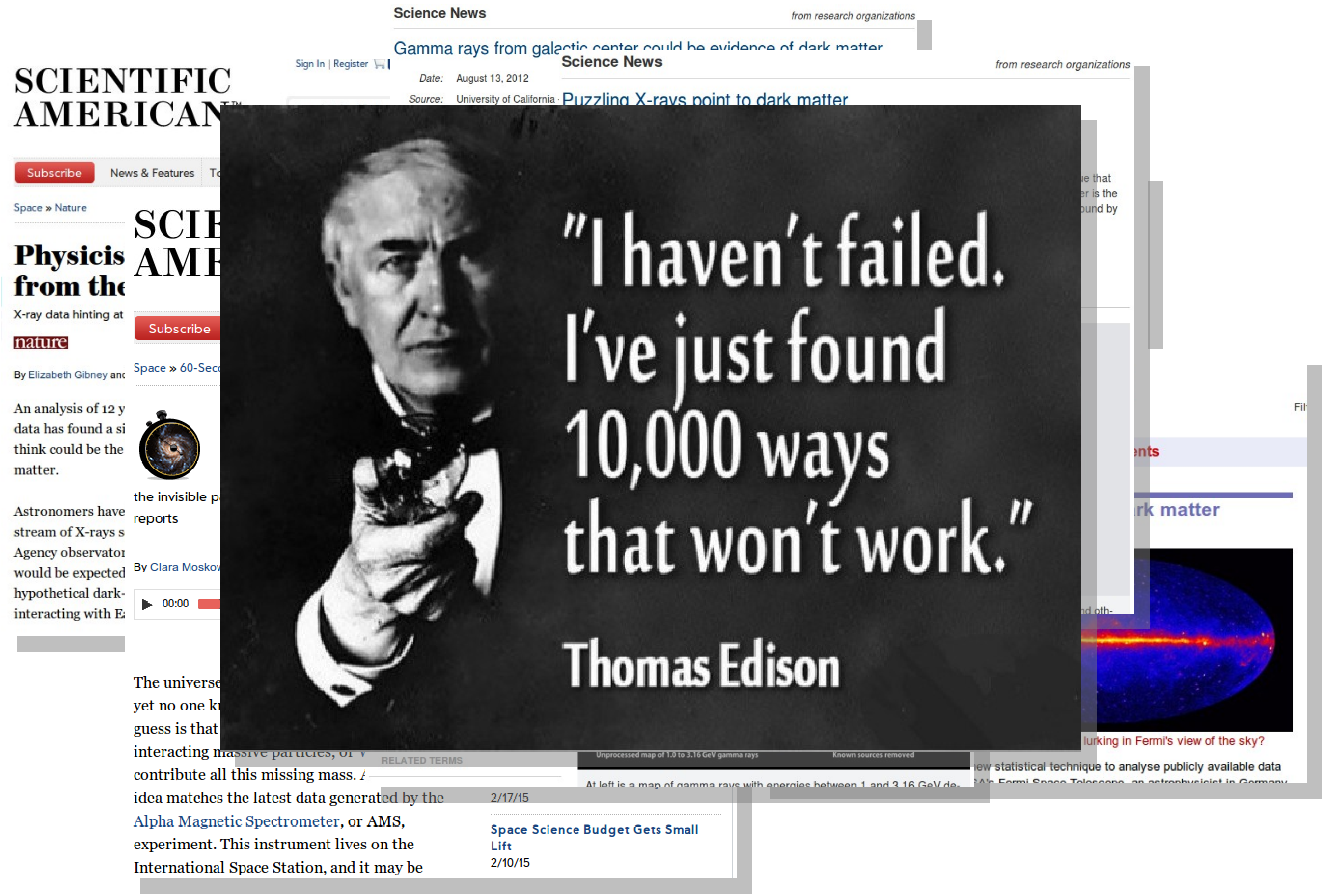
Indirect searches for DM annihilation/decay products

Injection rate of DM annihilation products

$$\frac{d^3 N_X}{dV\,dt\,dE} = \frac{\langle \sigma v \rangle \rho_{\rm DM}^2}{2 m_{\rm DM}^2} \frac{dN_X}{dE}$$



Many false alarms?



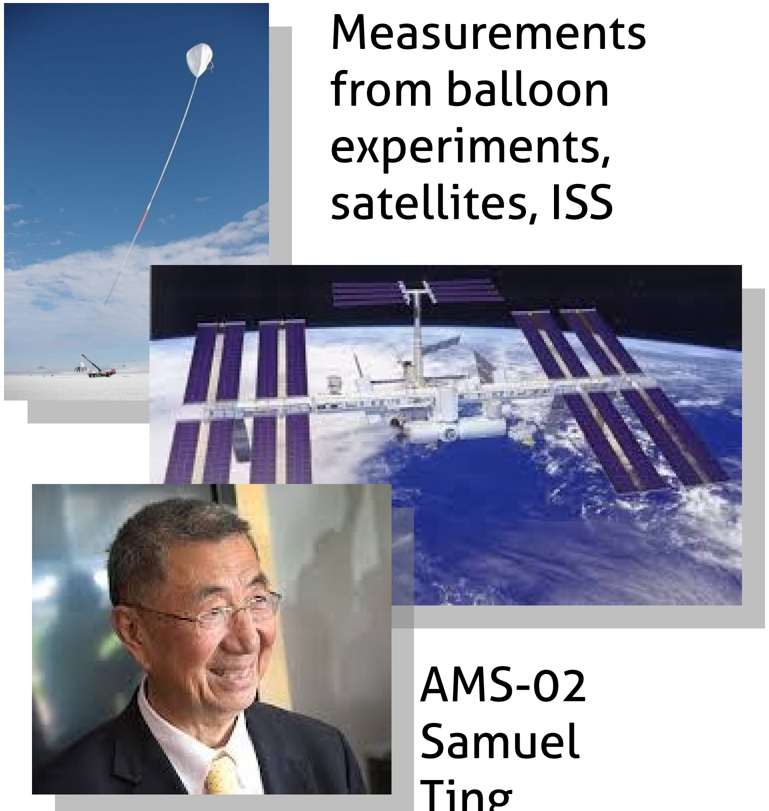
On The Menu

- *AMS-02 anti-protons*
- *AMS-02 positrons*

- *Fermi LAT lines*
- *Fermi LAT <u>Galactic center GeV excess</u>*
- *Fermi LAT dwarf spheroidals*

- *XMM-Newton & Chandra X-ray lines*

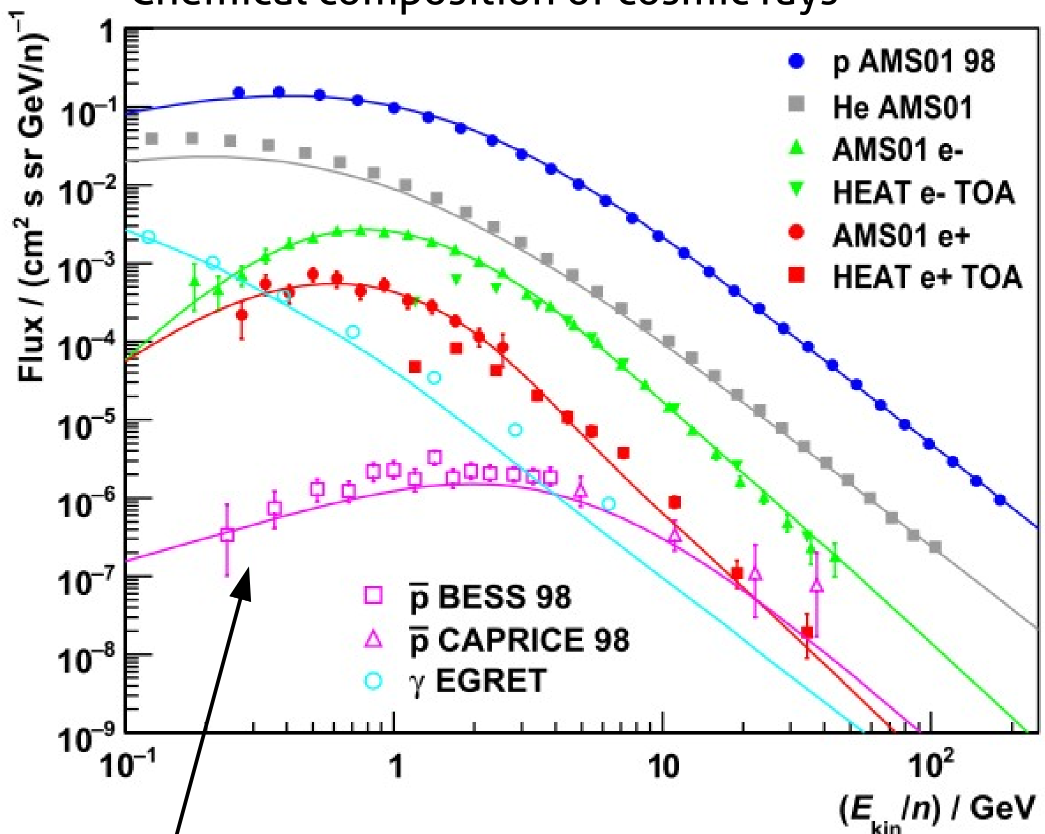
Dark Matter searches with anti-protons



Measurements from balloon experiments, satellites, ISS

AMS-02 Samuel Ting

Chemical composition of cosmic rays



Why anti-protons?

- Very low backgrounds

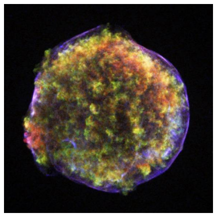
Observed: One **antiproton** per 100-10000 **protons**

- Backgrounds extremely* well understood

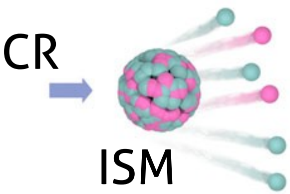
*up to a factor of two

The "grammage" matters

Two sources for cosmic rays

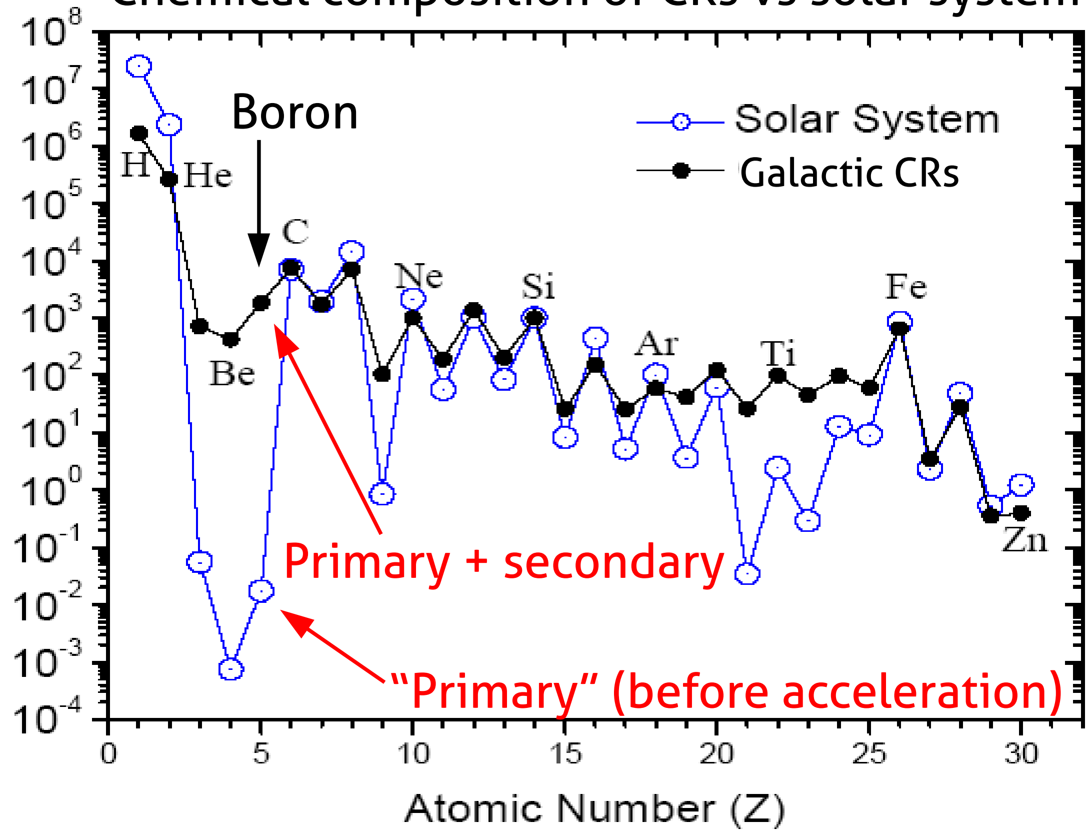


Primary cosmic rays from supernova remnants (likely)

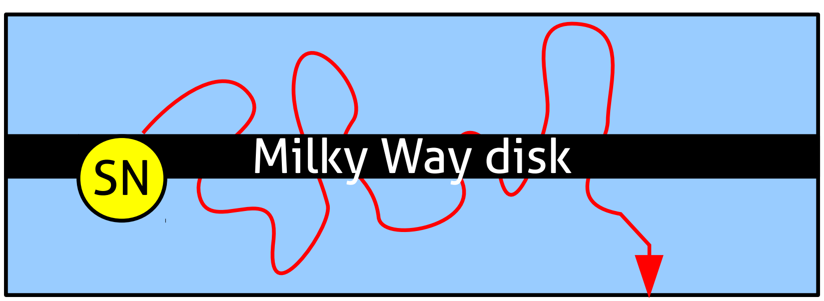


Secondary cosmic rays from spallation etc

Chemical composition of CRs vs solar system



Diffusion in a box



Total grammage (column density along propagation path)

$$G_{\mathrm{total}} = n_{\mathrm{crossings}} G_{\mathrm{disk}} \sim \mathcal{O}(10\ \mathrm{g\ cm}^{-2})$$

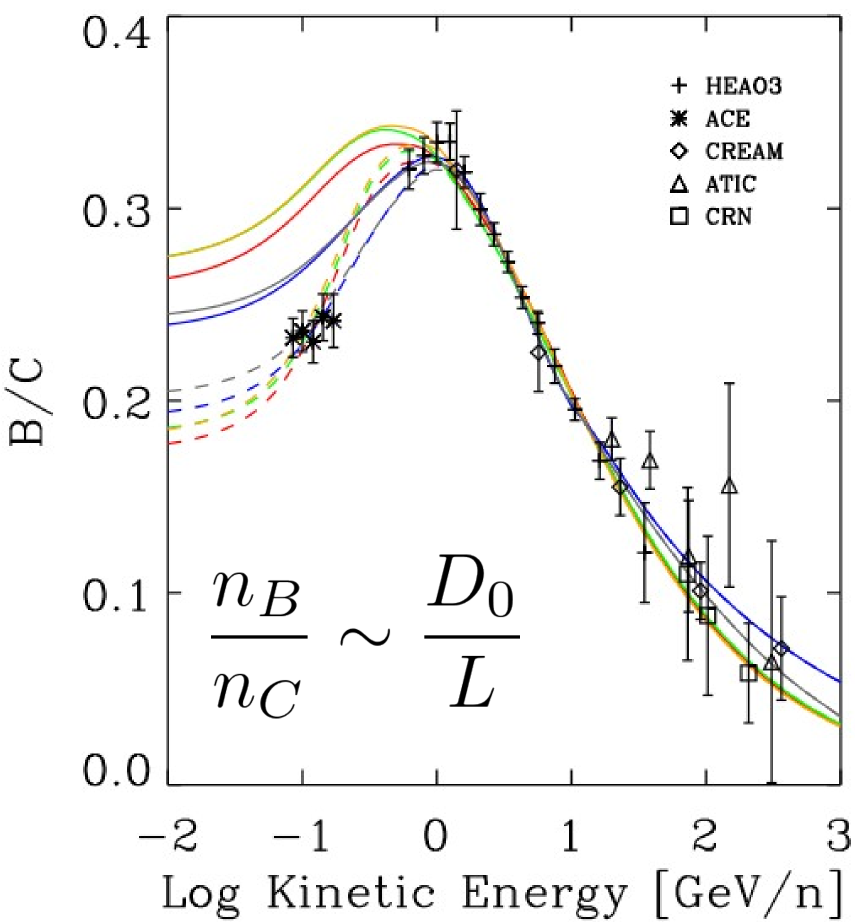
Secondary Boron: $n_B = n_C \sigma(C \to B) \cdot G_{\mathrm{total}} \quad \Rightarrow G_{\mathrm{total}}$

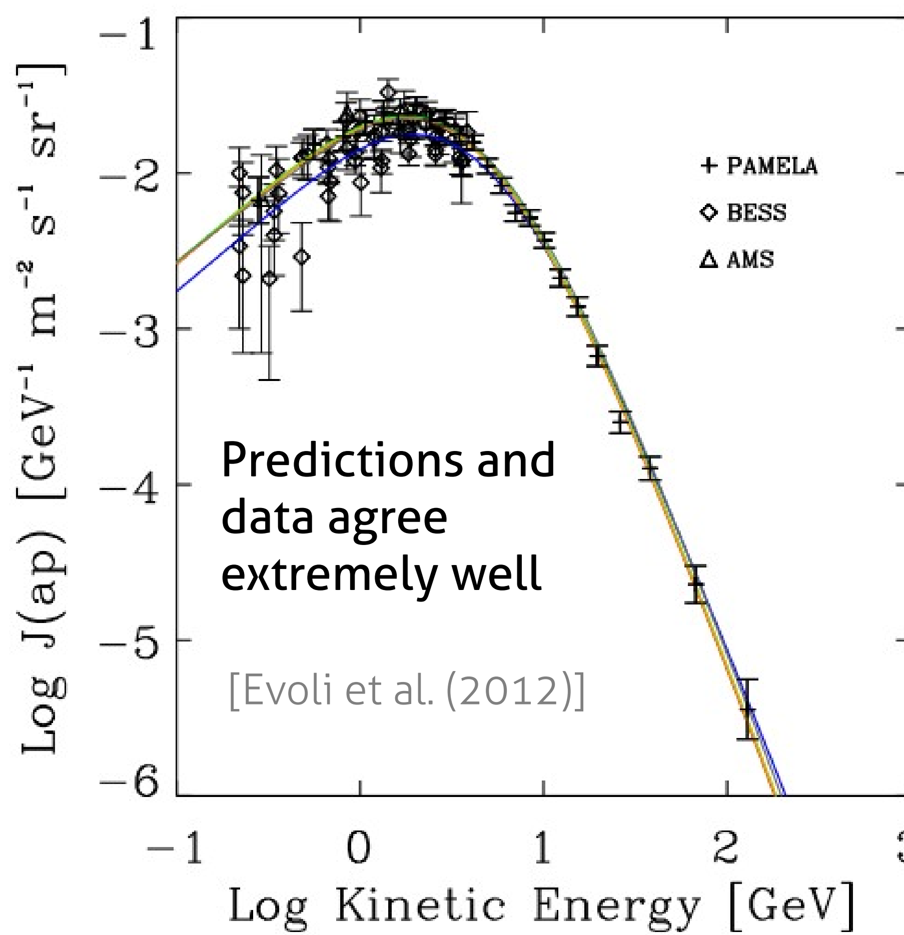
Secondary antiprotons: $n_{\bar{p}} = n_p \sigma(p \to \bar{p}) \cdot G_{\mathrm{total}} \quad \Rightarrow n_{\bar{p}}$

Predictions for secondary anti-protons

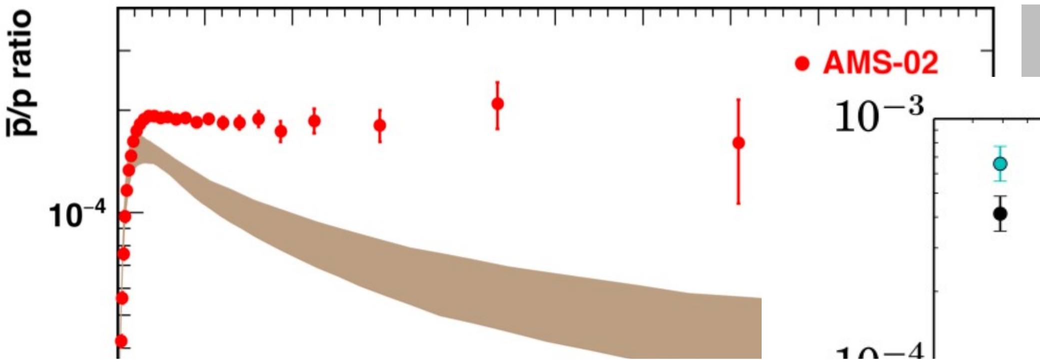
Viable parameters for the propagation model: (fit to B/C and p data)

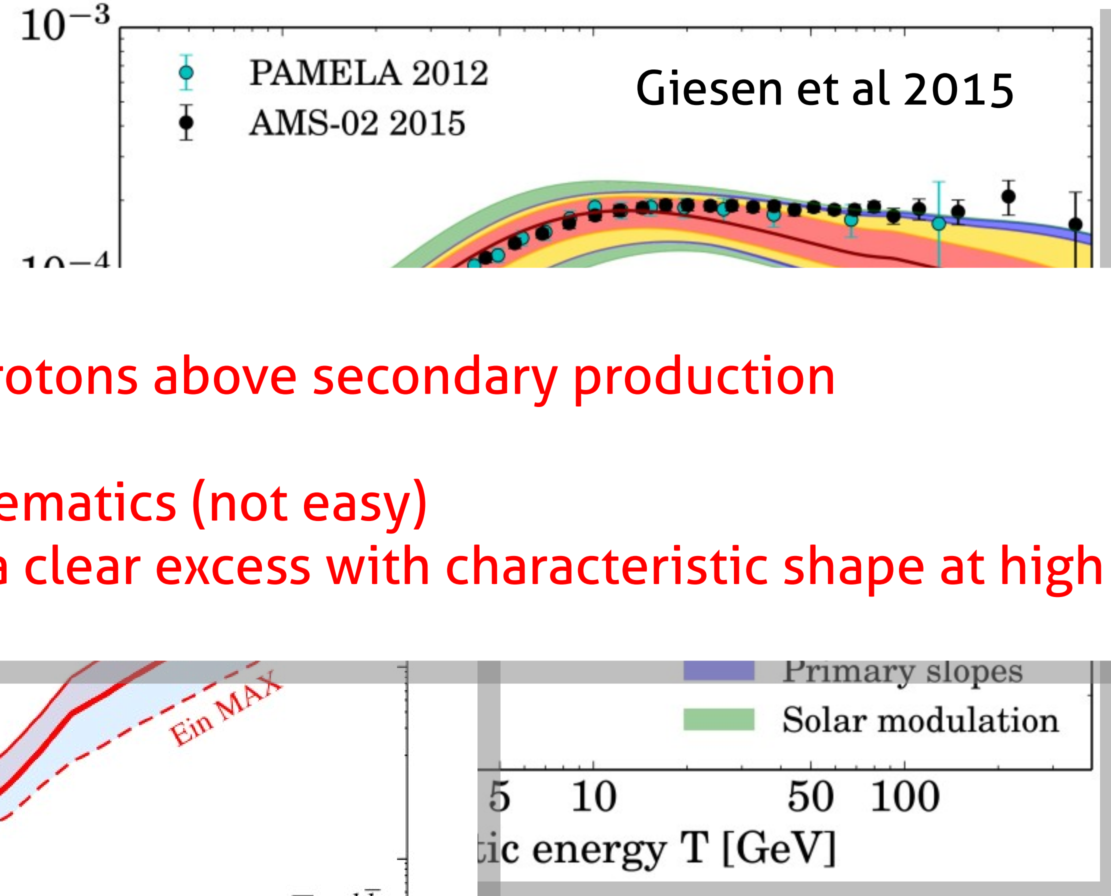
Model	z_t(kpc)	δ	$D_0(10^{28}\mathrm{cm}^2/\mathrm{s})$	η	v_A(km/s)	γ	dv_c/dz(km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (GV)	$\chi^2_{\bar{p}}$	Color in Fig.s
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	0.6	0.47	0.67	0.59	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.4	0.3	0.36	1.84	Blue
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	0.7	0.46	0.70	0.73	Green
THK	10	0.50	4.75	−0.15	14.1	2.35	0	0.7	0.55	0.69	0.62	Orange
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	0.4	0.53	0.21	1.32	Gray





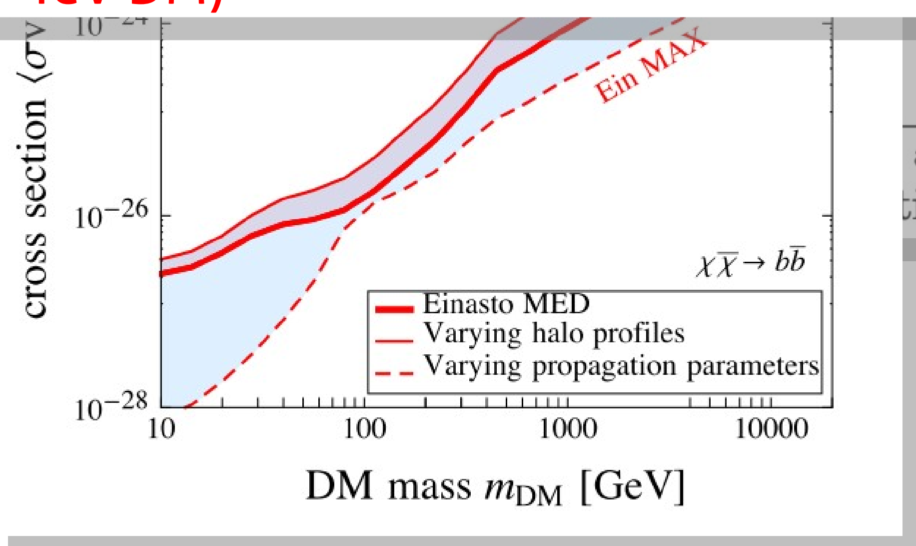
Recent AMS-02 results



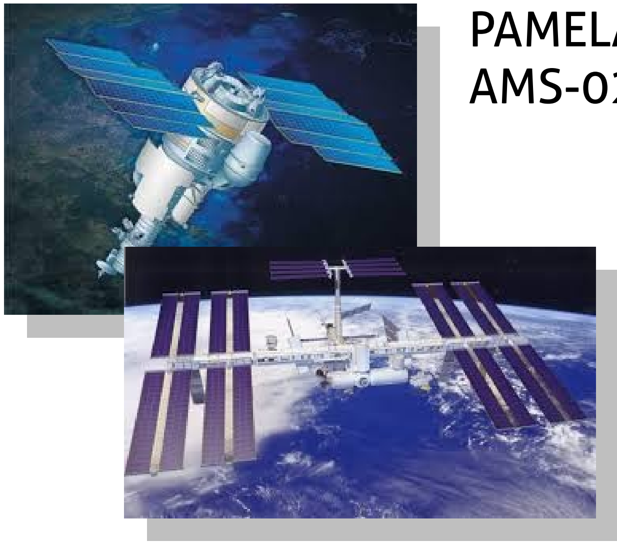


Situation:

- No signficiant excess of anti-protons above secondary production
- Future potential:
  - Better understanding of systematics (not easy)
  - Potential for observation of a clear excess with characteristic shape at high energies (→ TeV DM)

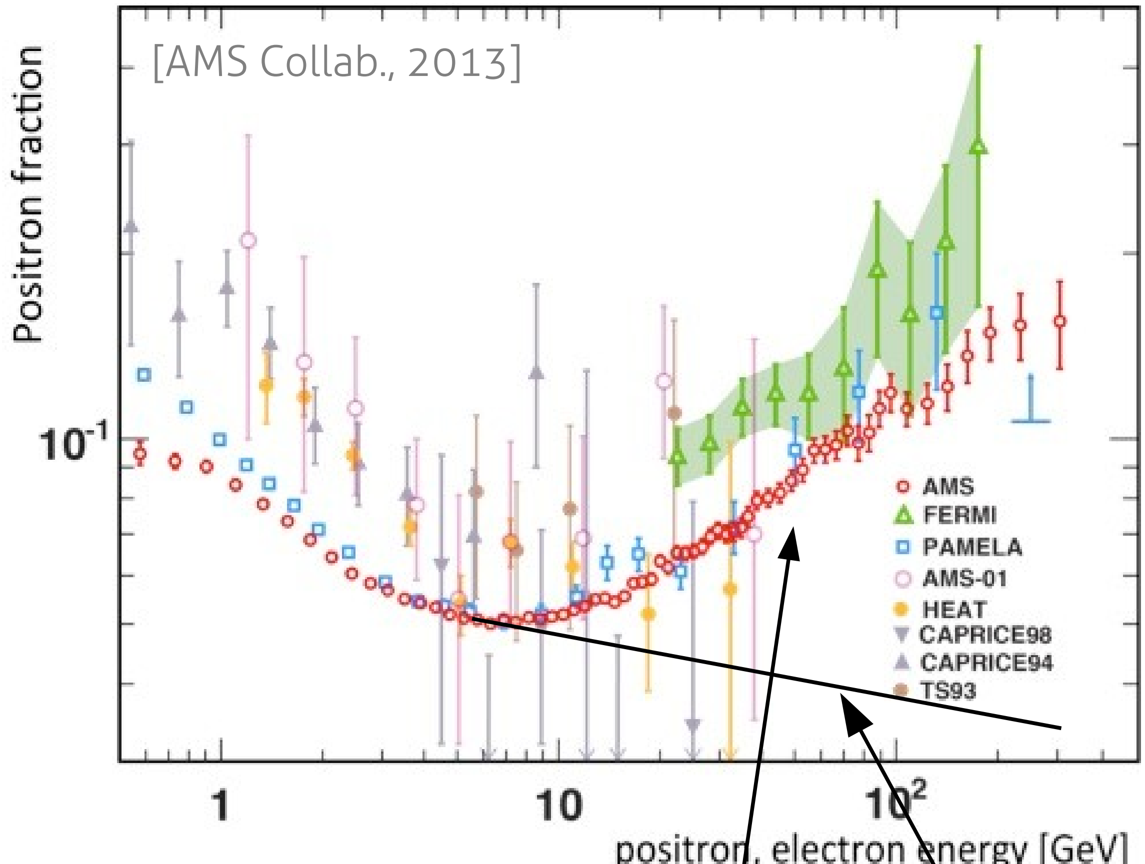


Dark Matter searches with positrons



PAMELA, AMS-02

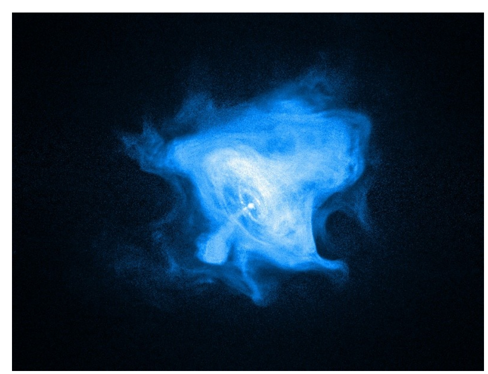
Positron fraction in cosmic rays $\frac{\Phi_{e^+}}{\Phi_{e^\pm}}$



Why cosmic ray positrons?

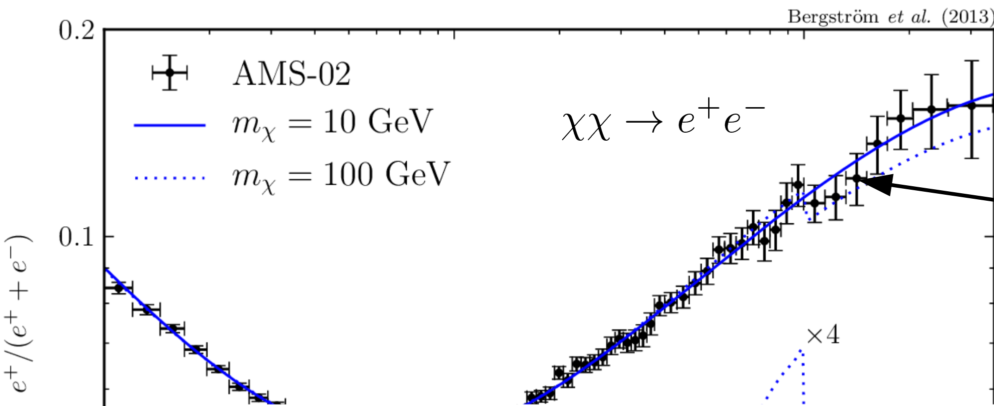
- A clear excess is observed above the expectations from secondary cosmic ray production
- Dark matter could produce spectral signatures that allow a identification

Pulsars or DM?



Secondary production

Extremely sensitive probe for <100 GeV DM

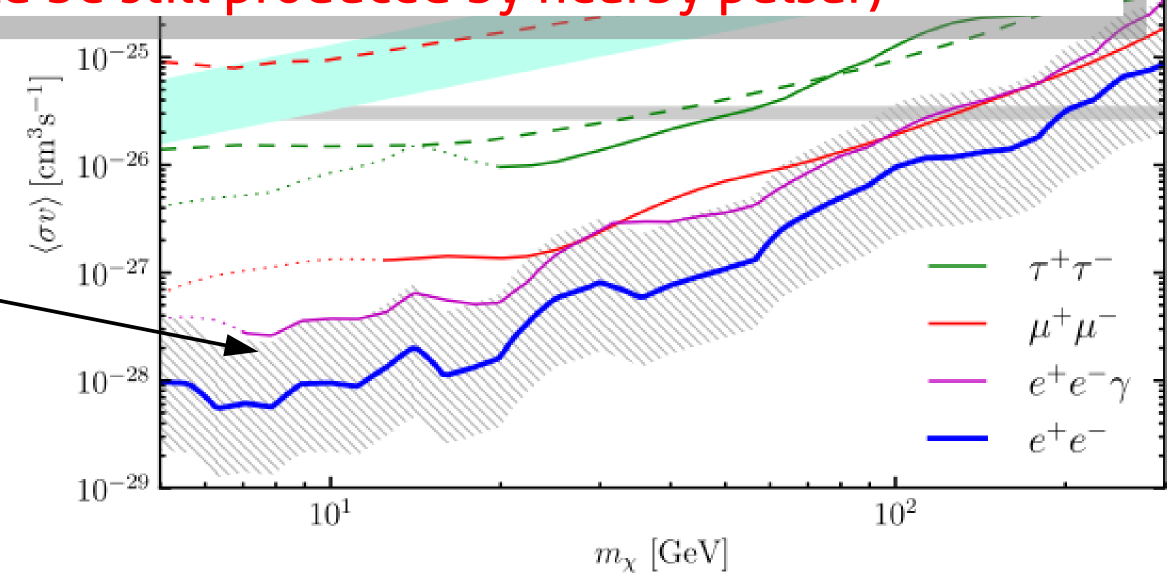


Measured spectrum is smooth

Expected annihilation signal after

Situation:

- A strong excess of positrons above secondary production is observed
- Astrophysical interpretations exist (pulsars, acceleration of primaries)
- Future potential:
  - Detection of sharp cutoff at higher energies, or pronounced peaks at intermediate energies
    (caveat: not unique; could be still produced by nearby pulsar)

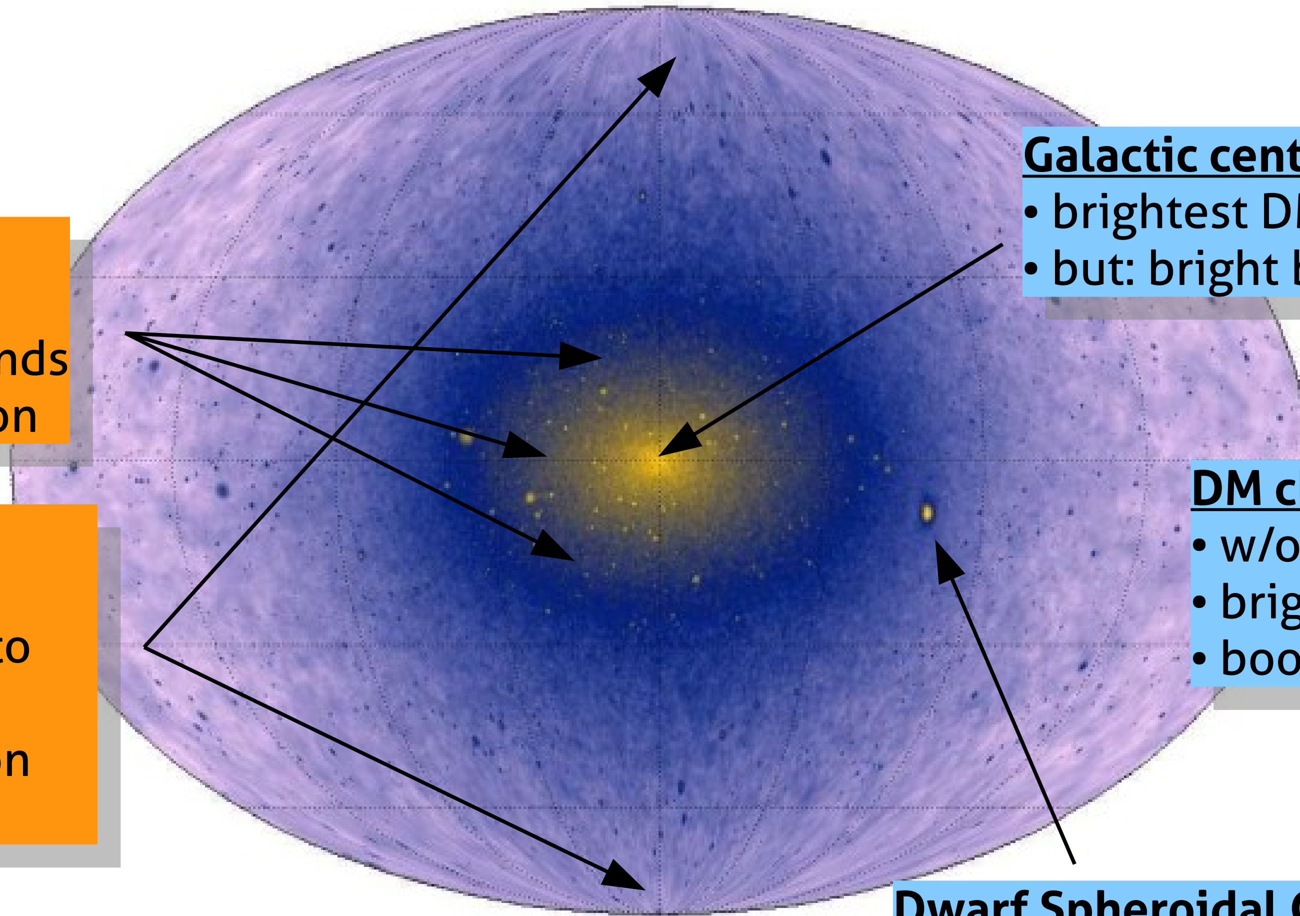


Non-observation of spectral features give extremely stringent constraints on DM annihilation into leptonic final states.

Many potential targets in gamma rays

Signal is approximately proportional to column square density of DM

$$\frac{d^2\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds \;\rho(\vec{r}[s,\Omega])^2$$



Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Extragalactic
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

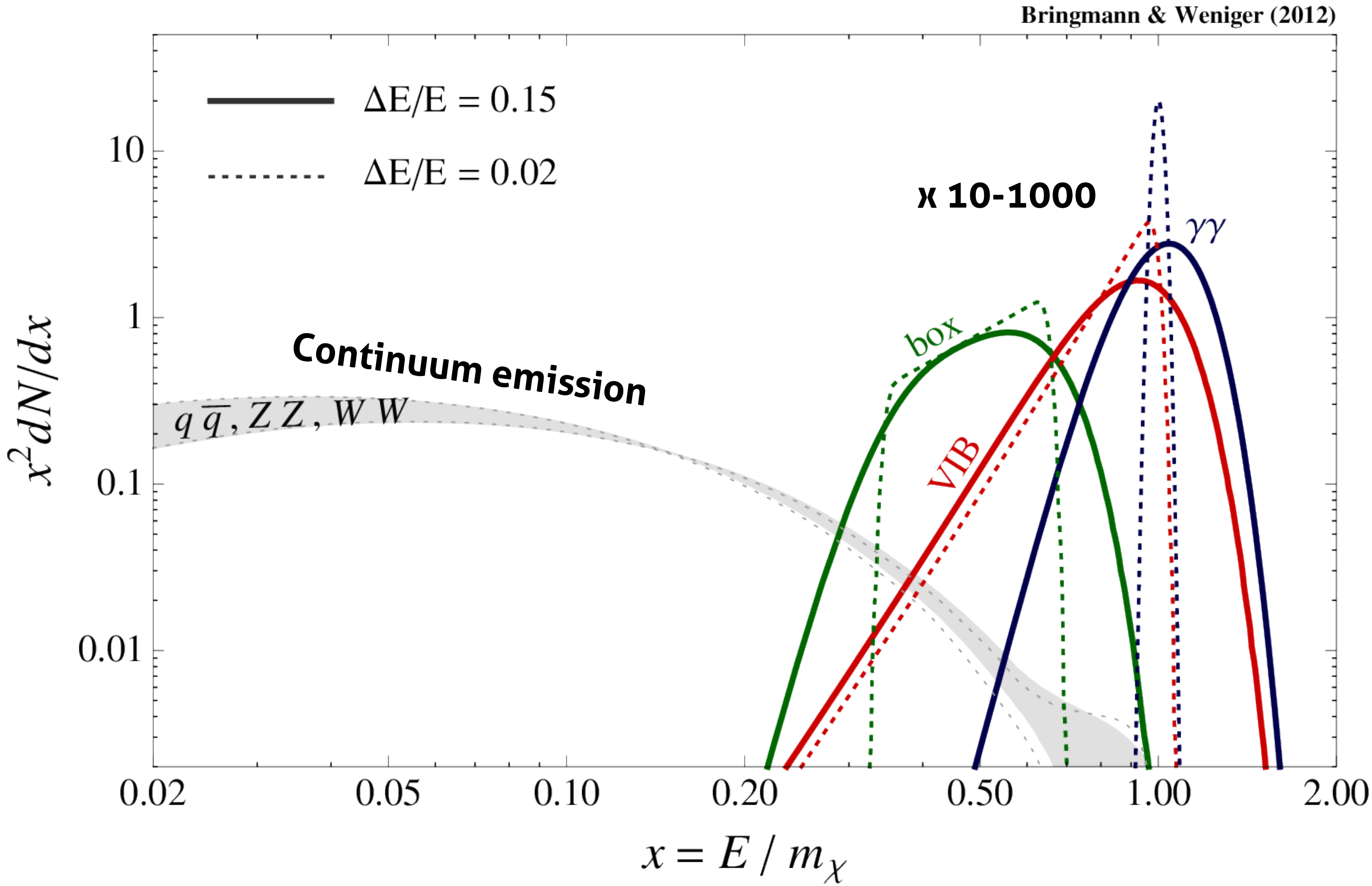
Galactic center (~8.5 kpc)
- brightest DM source in sky
- but: bright backgrounds

DM clumps
- w/o baryons
- bright enough?
- boost overall signal

Dwarf Spheroidal Galaxies
- harbour small number of stars
- otherwise dark (no gamma-ray emission)

[review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)]

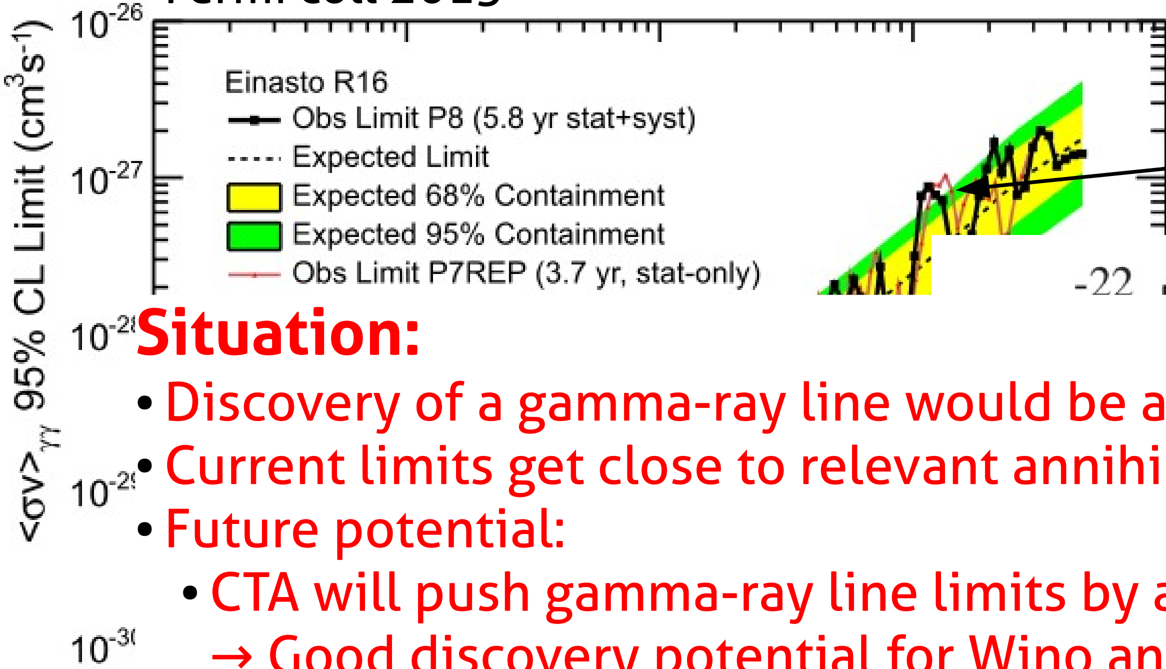
Characteristic photon energy spectrum



End-point features (x10-1000): Gamma-ray lines, bremsstrahlung, box-like spectra

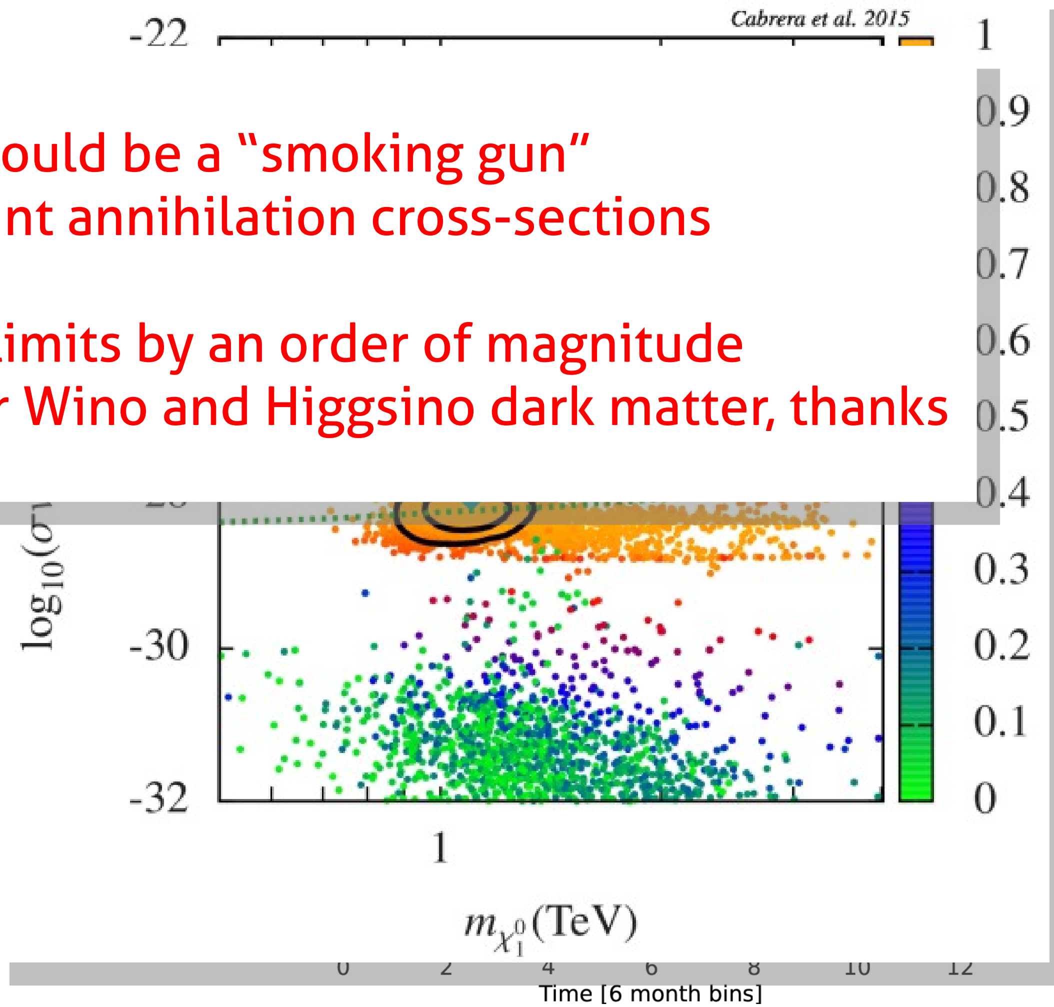
Strong upper limits on annihilation into line photons

Fermi coll 2015



"Thermal cross-section"

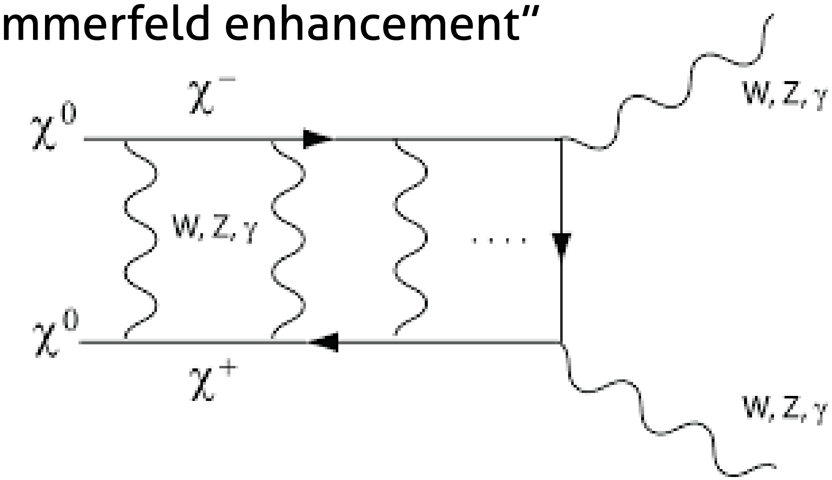
130 GeV feature is gone



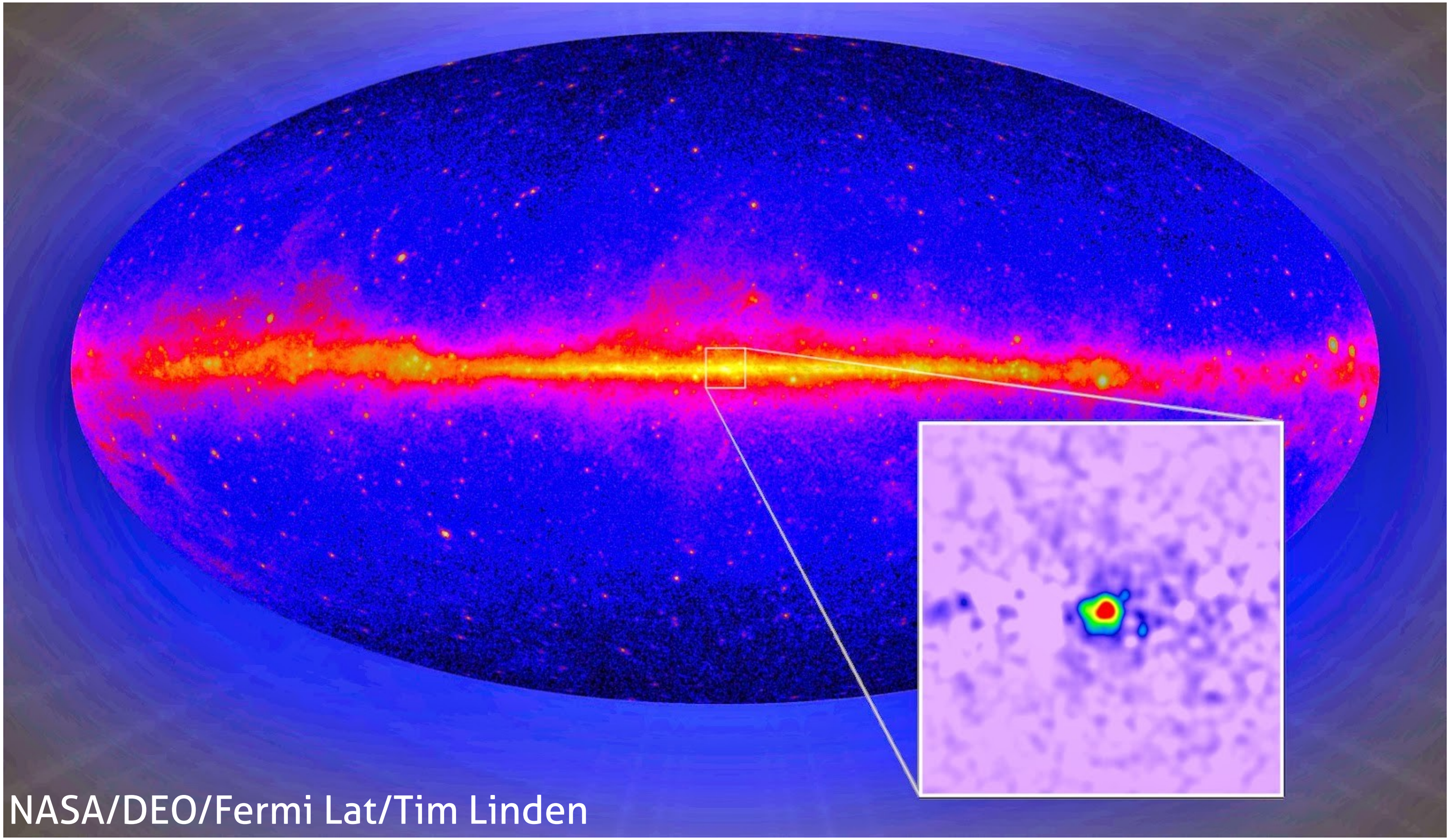
Situation:

- Discovery of a gamma-ray line would be a "smoking gun"
- Current limits get close to relevant annihilation cross-sections
- Future potential:
  - CTA will push gamma-ray line limits by an order of magnitude
    → Good discovery potential for Wino and Higgsino dark matter, thanks to Sommerfeld enhancement

"Sommerfeld enhancement"



The Galactic center GeV excess



Goodenough & Hooper 2009, Vitale+ (Fermi coll.) 2009, Hooper & Goodenough 2011, Hooper & Linden 2011, Boyarsky+ 2011 (no signal), Abazajian & Kaplinghat 2012, Gordon & Macias 2013, Macias & Gordon 2014, Abazajian+ 2014, **Daylan+2014**

First appearance in 2009

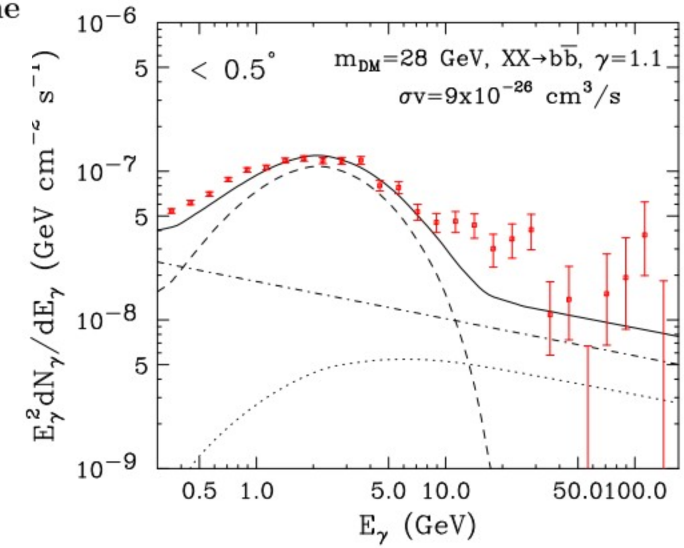
First clear statements about properties of *excess* emission (morphology, spectrum etc, subject to some changes in later analyses):

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[3] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm^3/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astro-



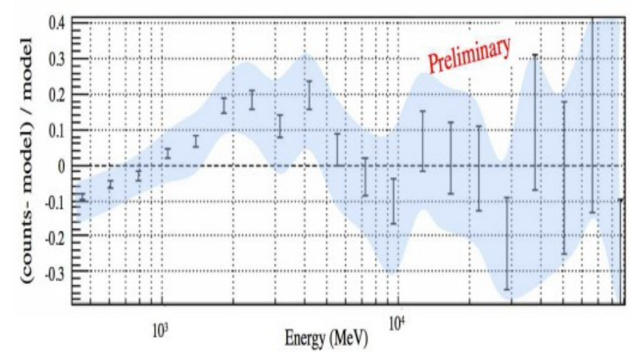
First very cautious comments by the LAT team, without any detailed characterization of the *residual*:

2009 Fermi Symposium, Washington, D.C., Nov. 2-5

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy

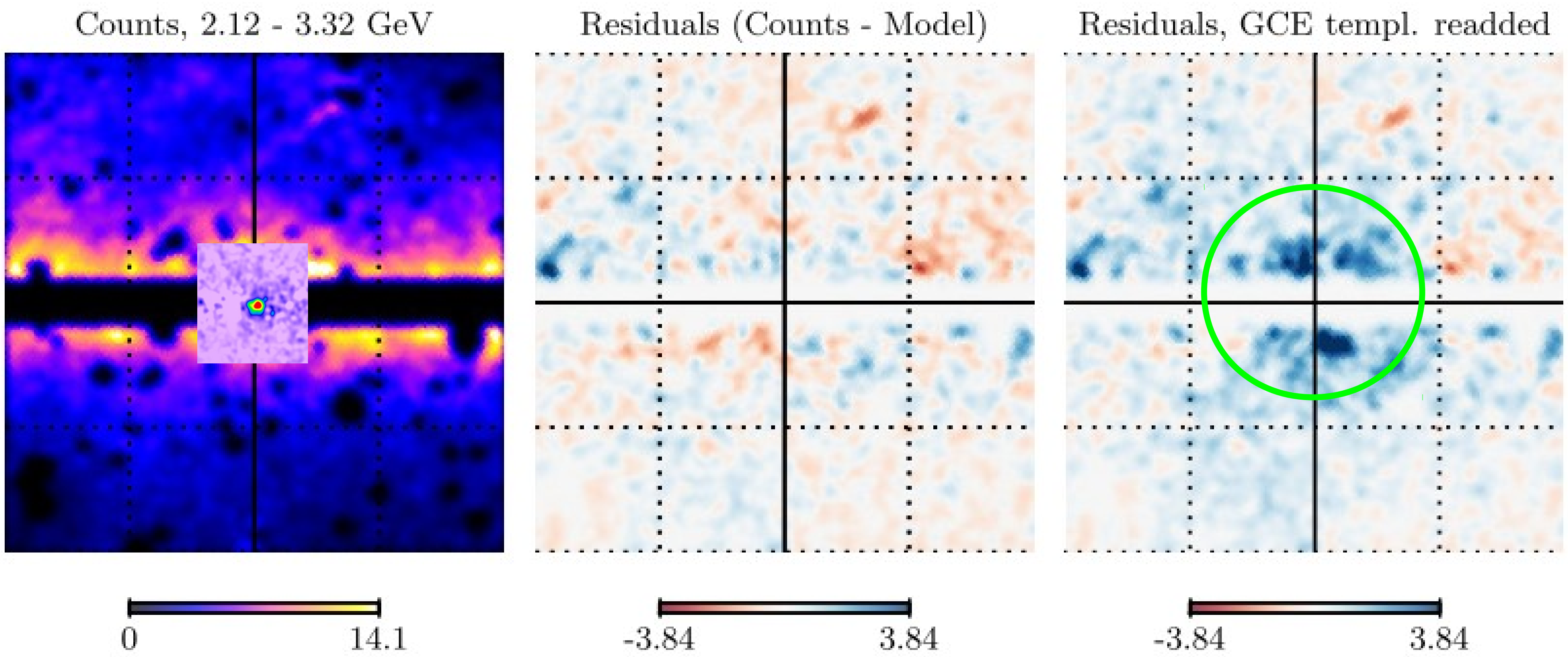
erations, is reported. The diffuse gamma ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models.
An improved model of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.



Typical residuals after foreground subtraction

Calore, Cholis, CW 2014

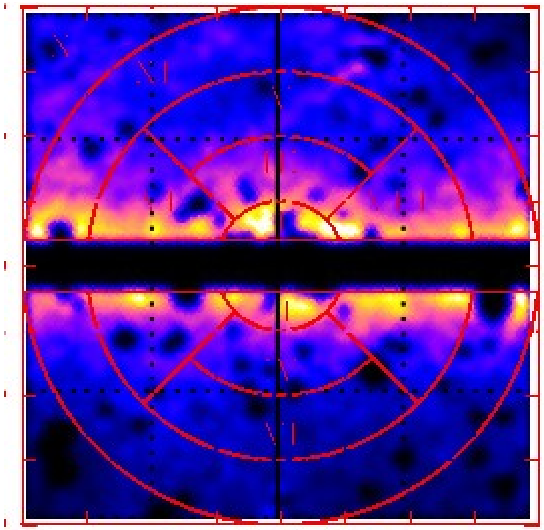
40 deg x 40 deg



- Left: Point source mask clearly visible
- Middle: Residuals at the level of <20% are observed
- Right: Readding the DM template clearly shows an extended excess around the GC

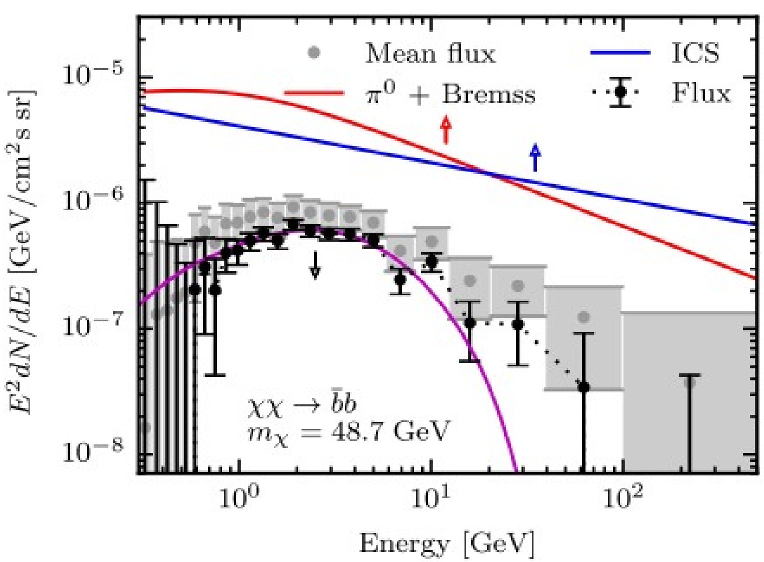
Dark Matter annihilation works just fine

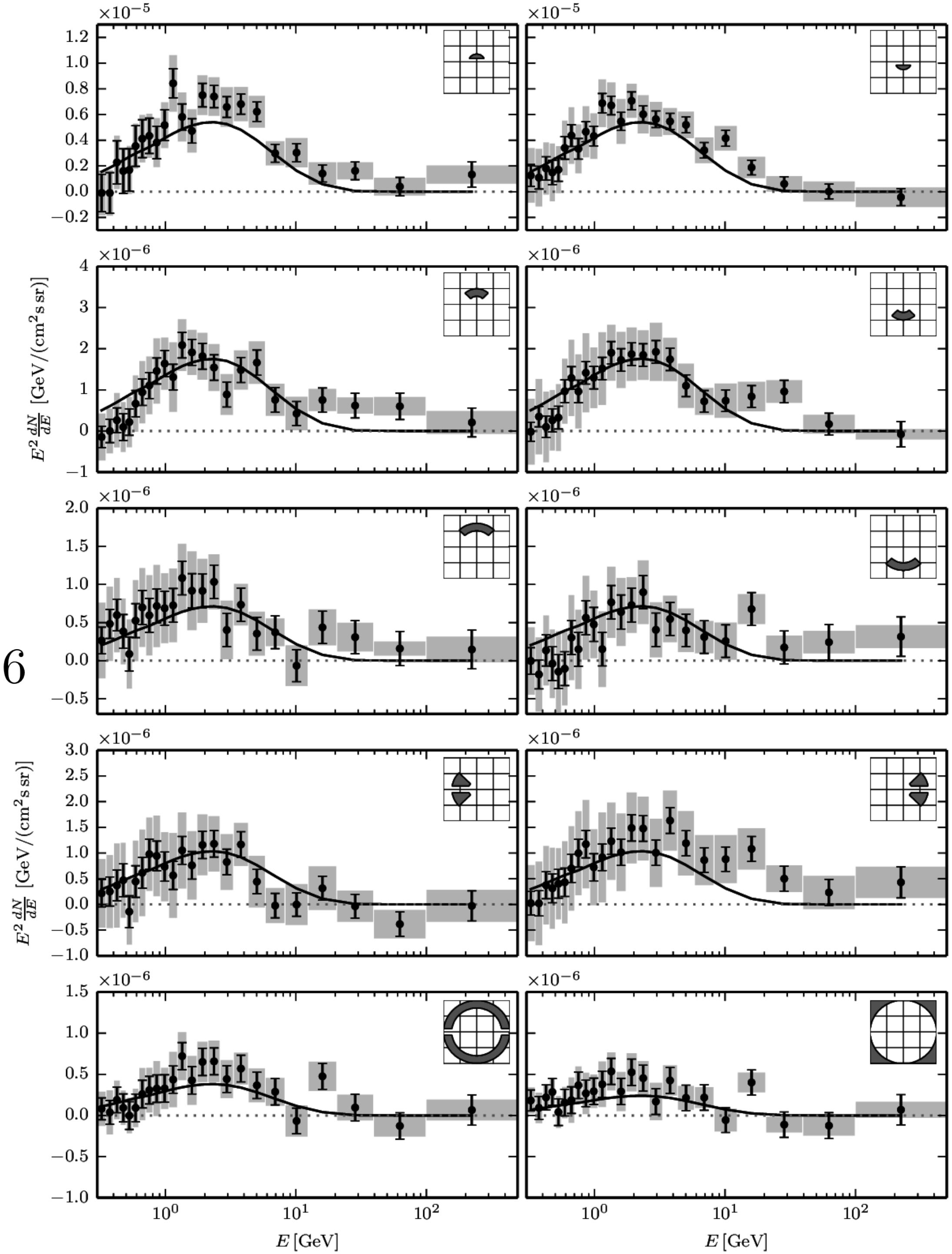
Calore, Cholis, CW 2014



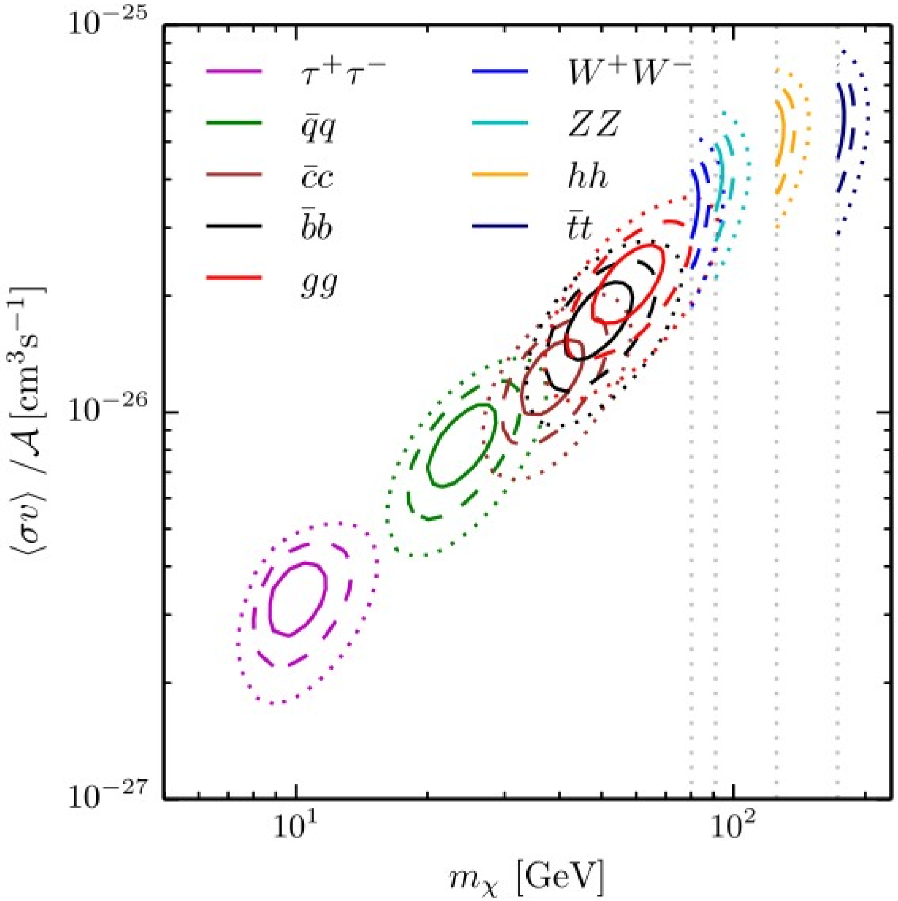
Contracted NFW profile:

$$\rho_{\rm DM} = \frac{1}{r^{\gamma}(r_s + r)^{2-\gamma}} \qquad \gamma \simeq 1.26$$

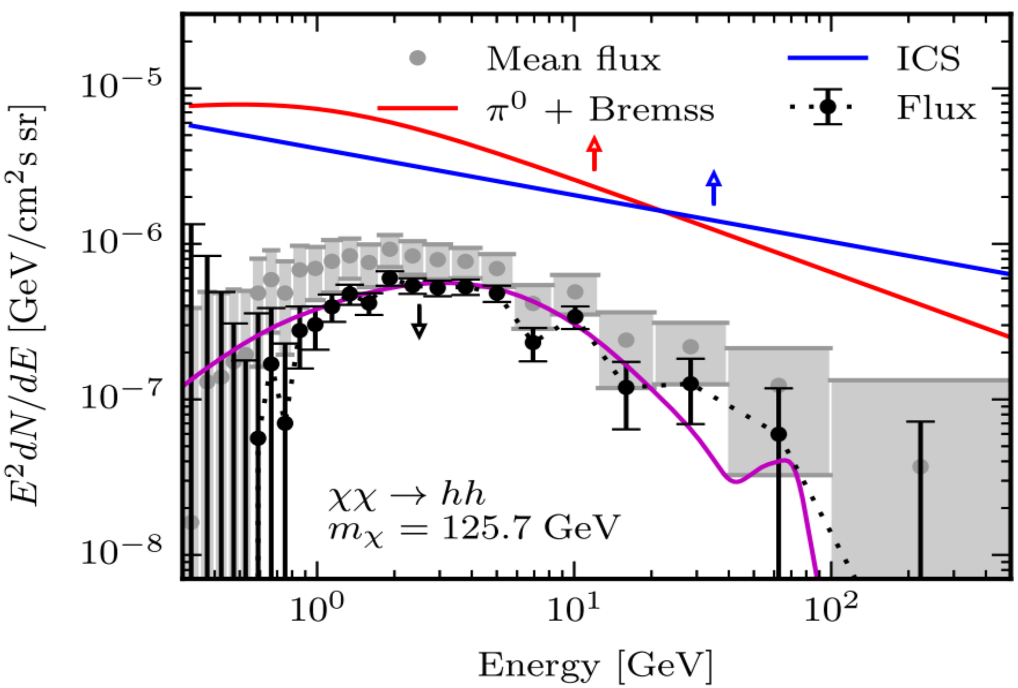




Fits with dark matter annihilation spectra



Channel	$\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm^3\ s^{-1}})$	m_χ (GeV)	χ^2_{min}	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
$[\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	$0.0036]_{\cancel{\mathrm{ICS}}}$

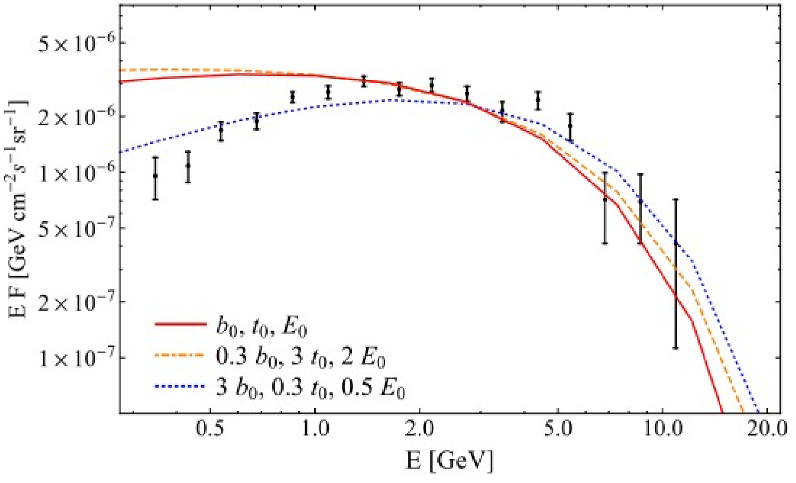


Astrophysical interpretations

Leptonic activity at the Galactic center:

Petrovic+ 2014

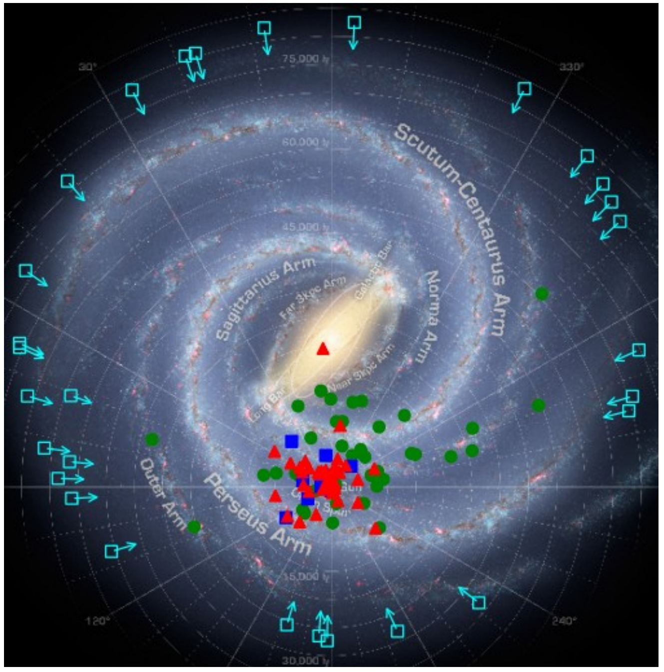
- Recent injection of hard electrons at Galactic center, ~1 Myr ago
- Diffusion → approx. spherical profile & emission
- Can potentially explain peaked spectrum
- The morphology, especially emission above 10 deg (1.5 kpc) is hard to reproduce, since the energy loss time of electrons is < 1 Myr.



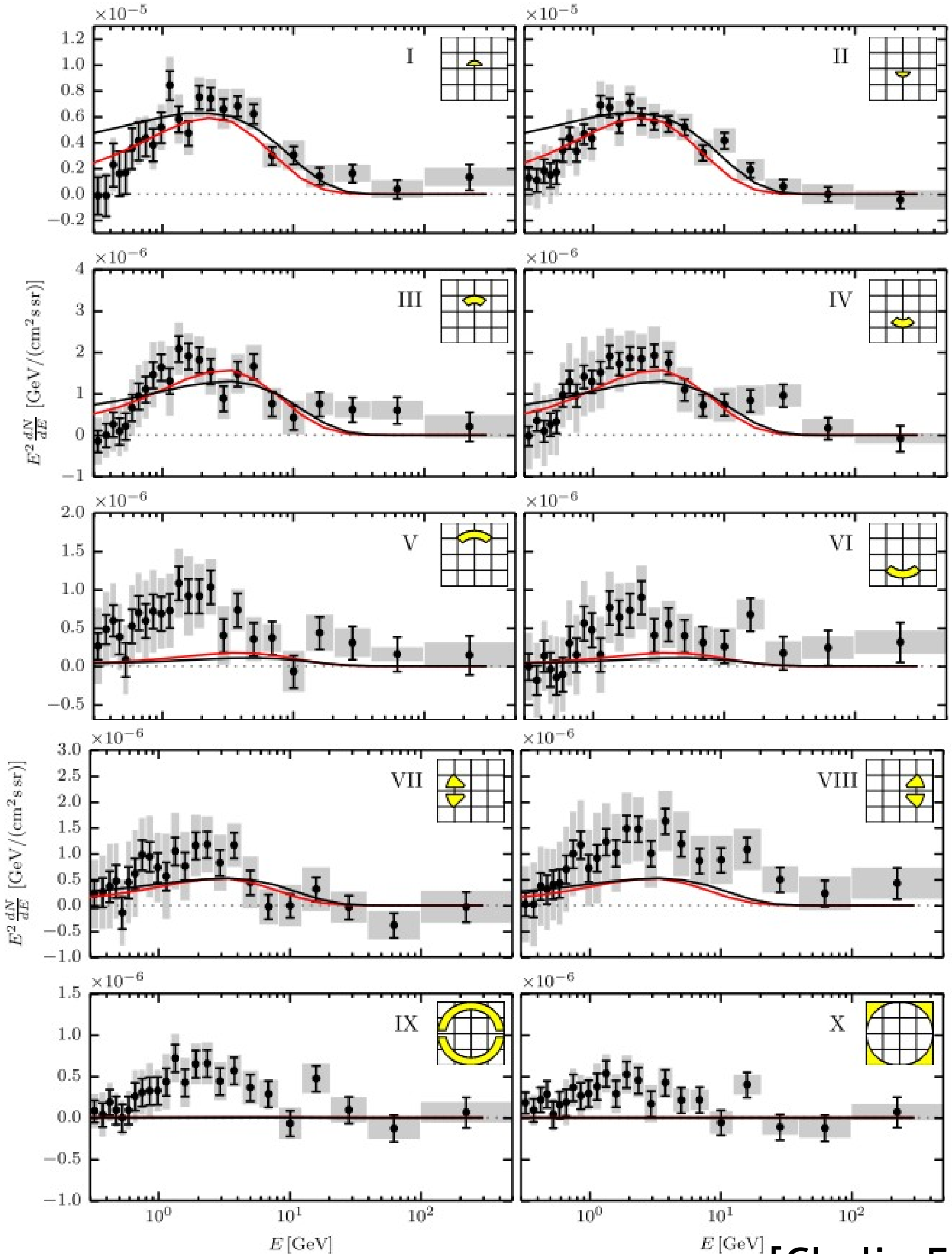
Millisecond pulsars (MSPs):

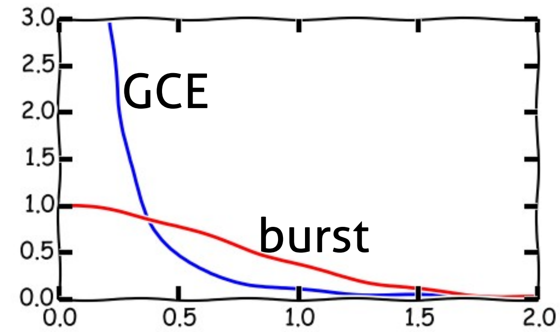
Wang+ 2005; Abazajian 2011; Gordon & Macias 2013; Hooper+ 2013; Yuan & Zhang 2014; Hooper+ 2013; Calore+ 2014; Cholis+ 2014, Petrovic+ 2014

- Spectrum of known MSPs agrees reasonably well with claimed GCE spectrum (except at sub-GeV energies)
- Observed luminosity function is claimed to be incompatible with GCE (we don't see resolved MSPs at GC) Hooper+, Calore+, Cholis+ 2013
- Compatible with distribution of low-mass X-ray binaries (possible MSP progenitors)



One leptonic burst?



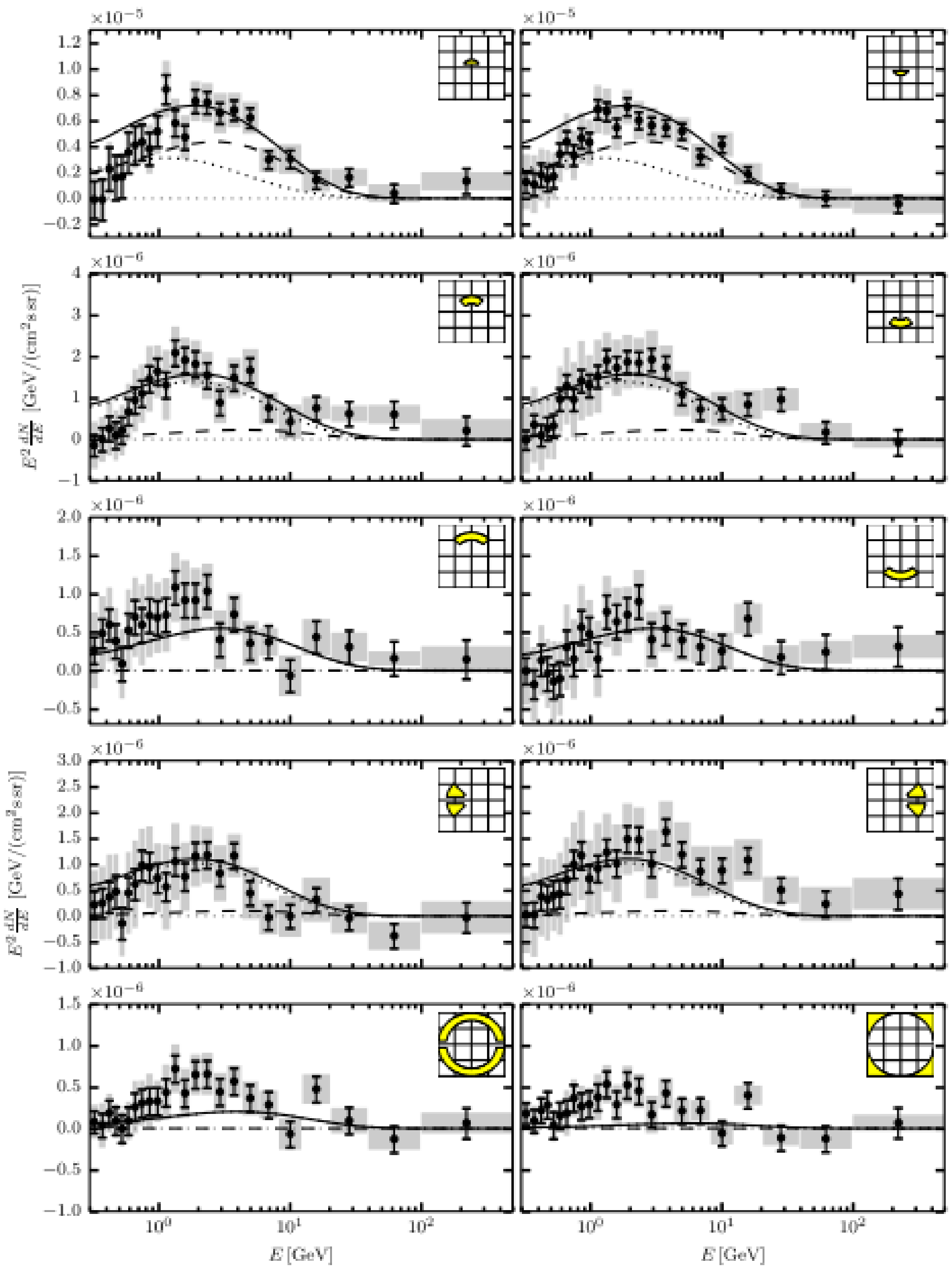


Some tuning is required to make it work reasonably well

- Very hard injection indices (<2)
- One burst around 1 Myr
- O(1) 10^51 erg injected energy
- Still, does not well reproduce the excess at high latitudes

[Cholis, Evoli, Calore, Linden, CW, Hooper 2015]

Two leptonic bursts??



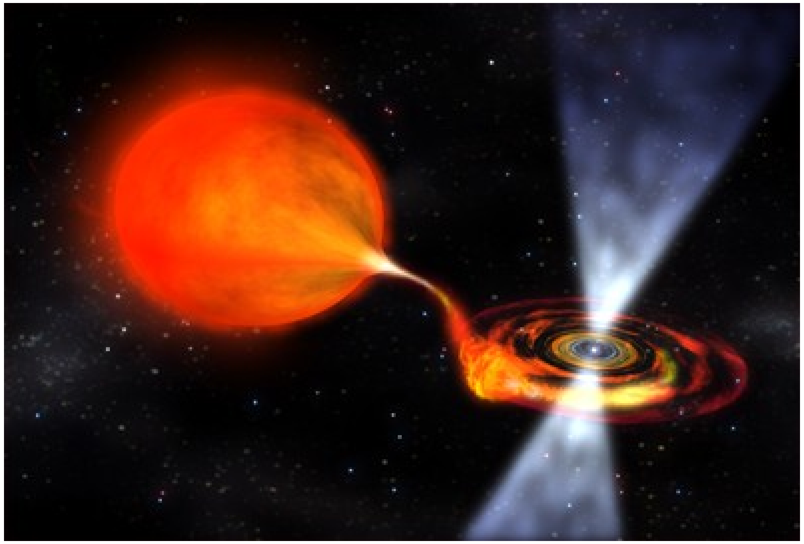
Parameter	Model A	Model B	Model C
α_1	1.2	2.0	1.1
α_2	NA	NA	1.0
$E_{\mathrm{cut},1}$	1 TeV	1 TeV	20 GeV
$E_{\mathrm{cut},2}$	NA	NA	60 GeV
τ_1 (Myr)	0.83	0.46	0.1
τ_2 (Myr)	NA	NA	1.0
N_1 (10^{51} erg)	2.89	9.87	0.1
N_2 (10^{51} erg)	NA	NA	0.88
δ	0.20	0.23	0.3
D_0 (10^{28} cm^2/s)	5.08	9.12	9.0
D_{zz}/D_{xx}	1.12	0.87	NA
v_A (km/s)	176	122	150
B_0 (μG)	11.5	11.5	11.7
r_c (kpc)	10.0	10.0	10.0
z_c (kpc)	2.0	2.0	0.5
dv_c/dz (km/s/kpc)	0.0	0.0	0.0
ISRF	1.0, 1.0	1.0, 1.0	1.8, 0.8
χ^2 ($p-$value)	277 (0.04)	317 (0.0004)	261 (0.14)

Summary

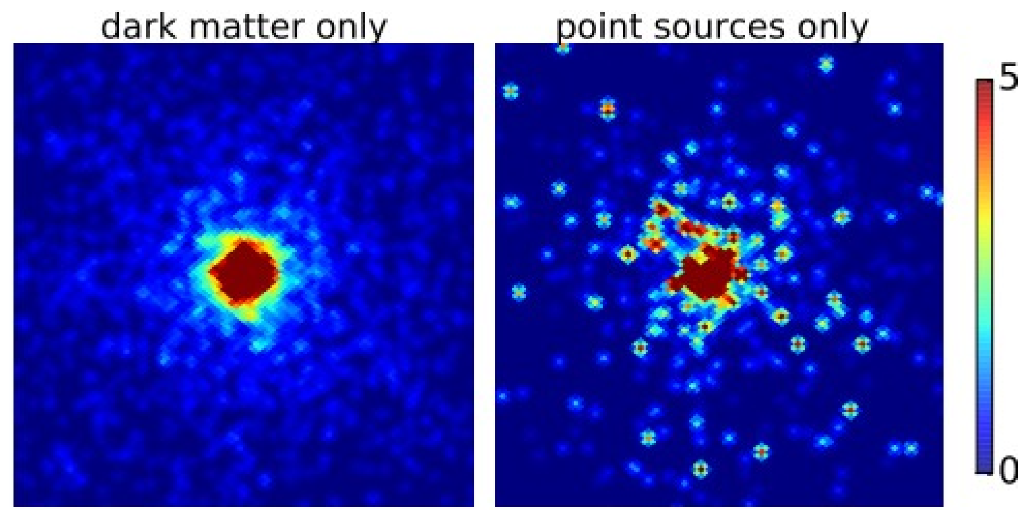
- It *is* possible to achieve a reasonable description of the data by using two bursts and tuning injection and propagation parameters
- However, the rise of the emission towards the inner few 10 pc is not predicted
- A series of leptonic bursts are observationally viable, but not likely to explain all of the excess emission

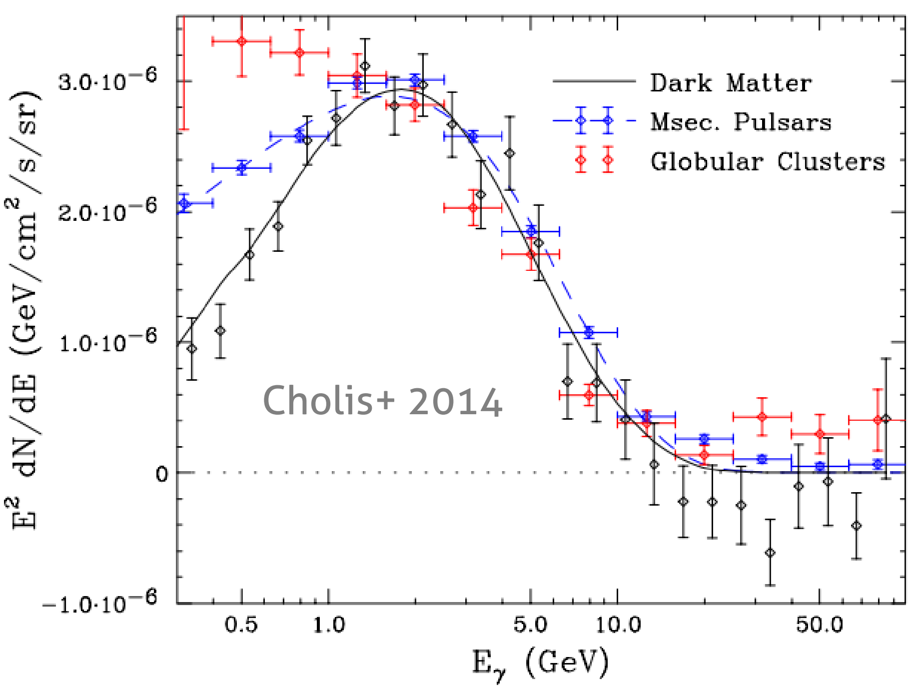
[Cholis, Evoli, Calore, Linden, CW, Hooper 2015]

Discriminating Millisecond pulsars (MSPs) from DM



[Lee, Lisanti, Safdi 2014]



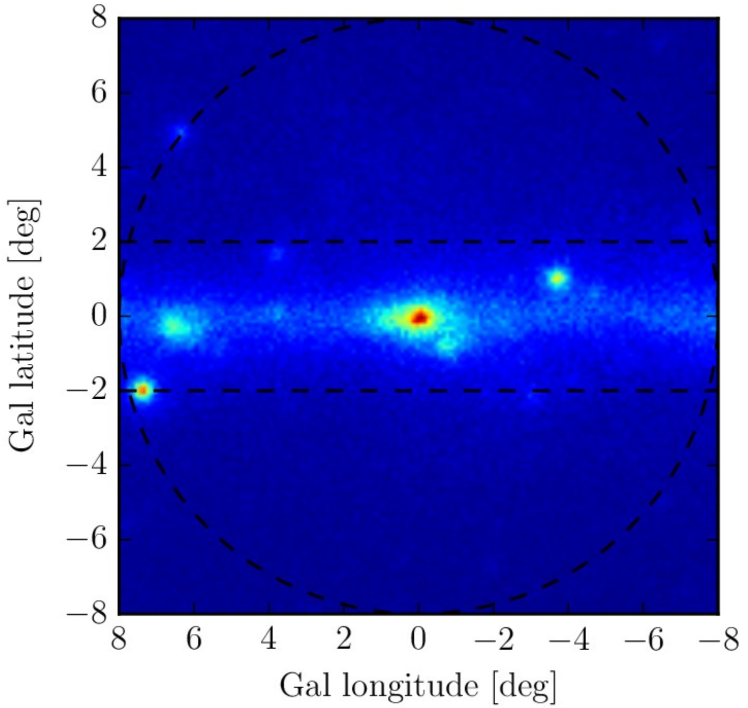


MSPs (or other point sources producing the excess) would produce more "speckled" signal than DM.

→ Can be tested with e.g.

- one-point statistics (Lee et al. 2014, **2015**)
- wavelet analysis (next slides)

Wavelet analysis



[Bartels, Krishnamurthy, CW, 2015]

Wavelet analysis in a nutshell:

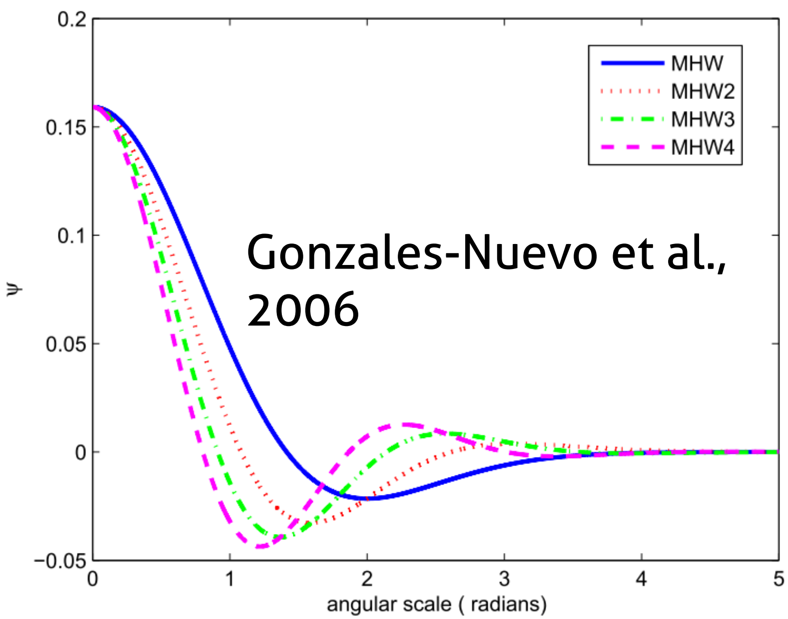
- Remove galactic diffuse emission with wavelet transform

$$\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega) \equiv \int d\Omega\, \mathcal{W}(\Omega - \Omega')\mathcal{C}(\Omega')$$

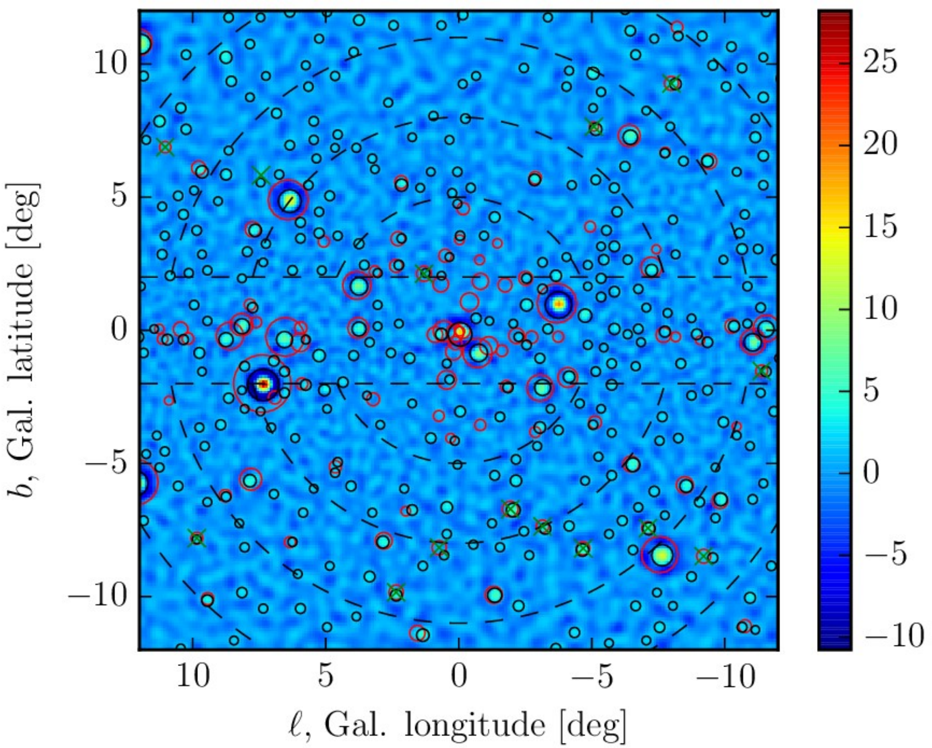
- Extract signal-to-noise ratio of peaks

$$\mathcal{S}(\Omega) = \frac{\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega)}{\sqrt{\mathcal{F}_{\mathcal{W}^2}[\mathcal{C}](\Omega)}}$$

- Analyze statistics of these SNR peaks



Gonzales-Nuevo et al., 2006



Effective modeling of MSPs

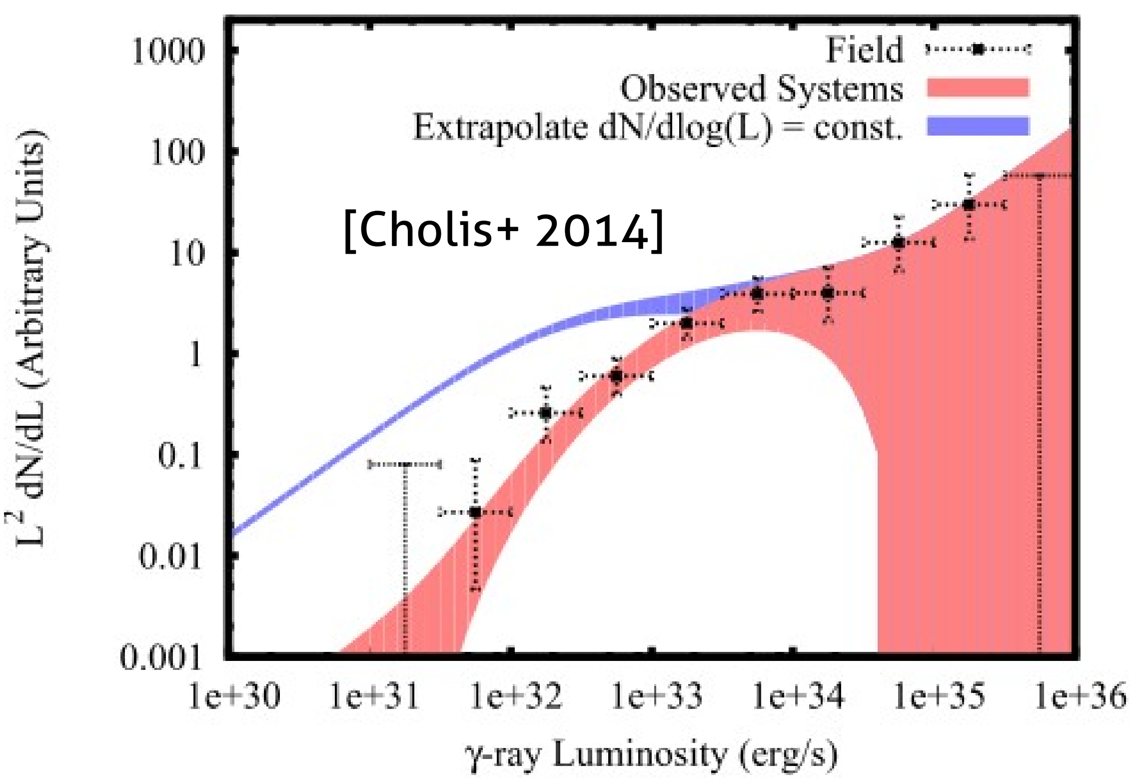
Modeling of unresolved sources

- We assume that they are distributed like required to explain the GCE (with a radial index of -2.5 or so)
- We simulate PSCs that follow a luminosity distribution

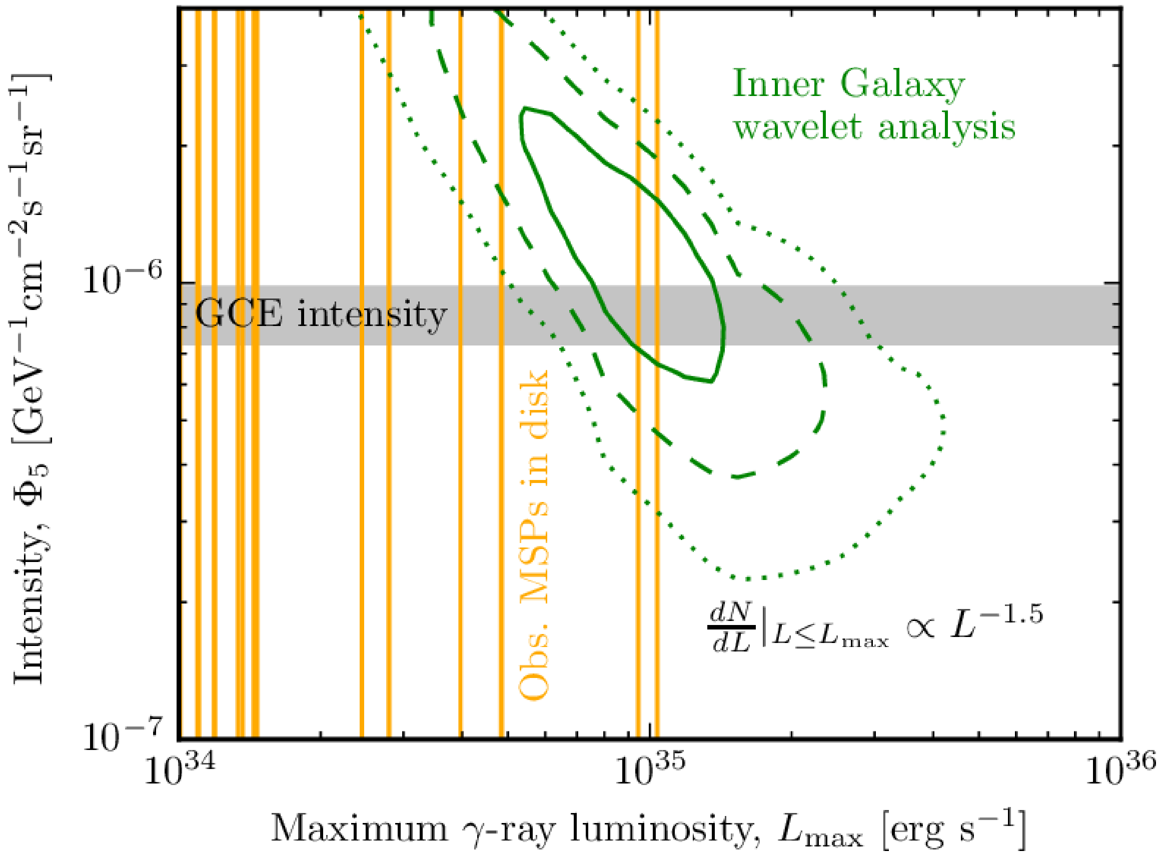
$$\frac{dL}{dN} \sim L^{-1.5}$$

up to some cutoff $L_{\max}$

- Main uncertainties: Slope, normalization and cutoff of the luminosity function. Here: slope fixed to -1.5



Best-fit contours agree with MSP expectations



List of unassociated 3FGL sources with spectrum compatible with MSPs:

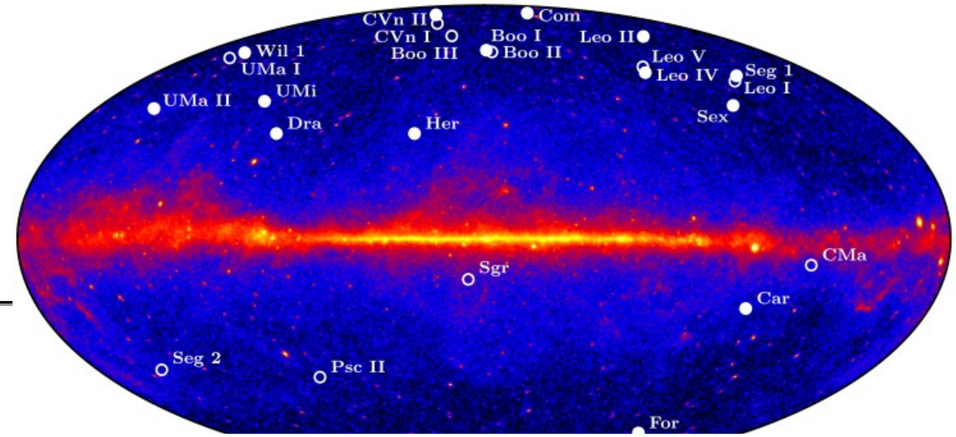
3FGL Name	$\ell\,[°]$	$b\,[°]$	χ^2/dof	$\sqrt{TS}$	$\mathcal{S}$
J1649.6-3007	-7.99	9.27	1.07	5.57	3.68
J1703.6-2850	-5.08	7.65	0.48	2.38	4.24
J1740.5-2642	1.30	2.12	0.37	6.37	2.15
J1740.8-1933	7.43	5.83	0.77	1.89	2.11
J1744.8-1557	11.03	6.88	0.40	3.69	1.96
J1758.8-4108	-9.21	-8.48	0.90	5.56	2.91
J1759.2-3848	-7.11	-7.43	0.35	4.64	4.36
J1808.3-3357	-1.94	-6.71	0.40	6.94	5.46
J1808.4-3519	-3.15	-7.36	0.41	4.55	3.51
J1808.4-3703	-4.68	-8.19	0.22	4.95	4.45
J1820.4-3217	0.74	-8.17	1.04	5.74	2.32
J1830.8-3136	2.35	-9.84	0.54	5.92	3.76
J1837.3-2403	9.85	-7.81	0.28	4.03	2.16

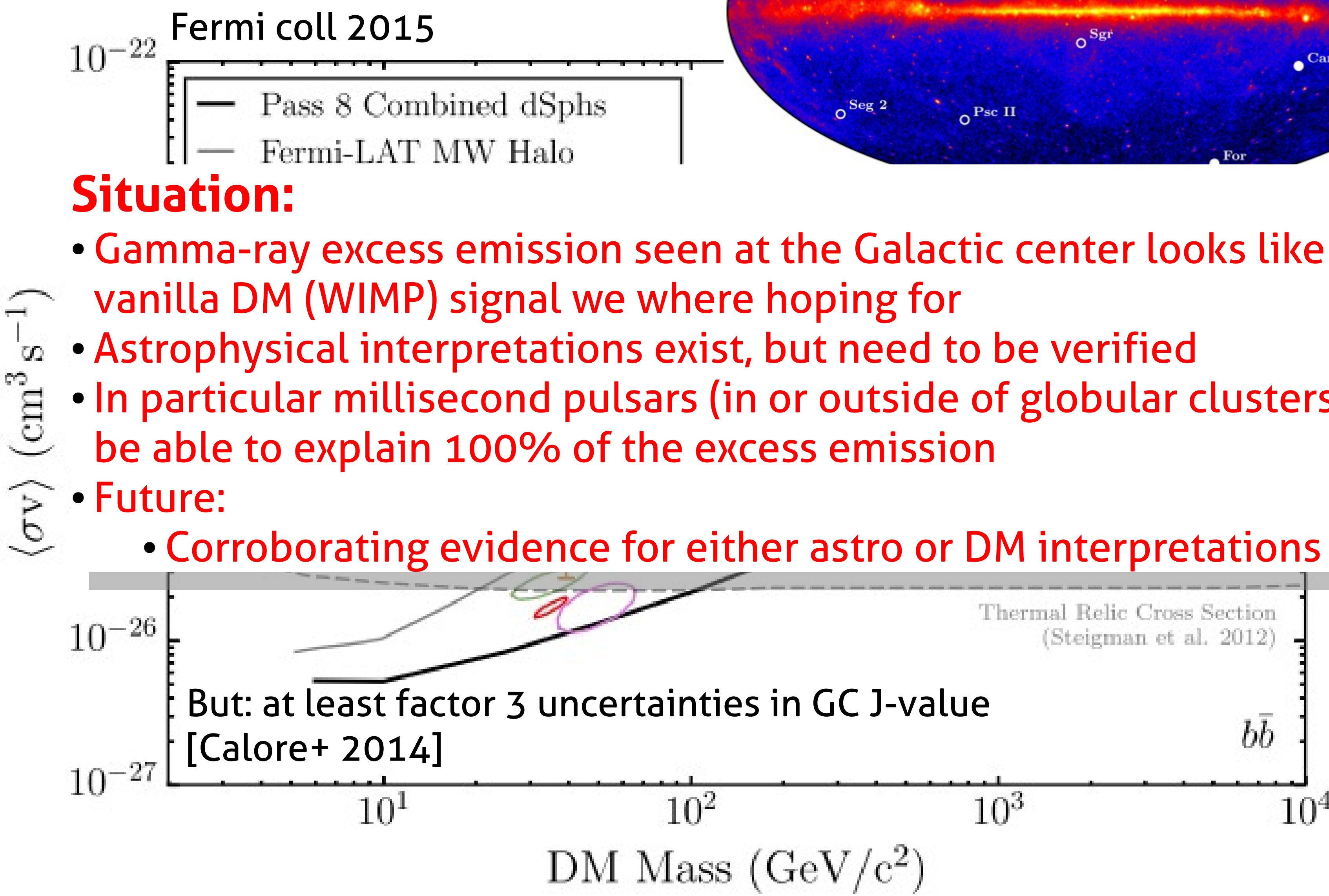
This is not a proof that the GCE is due to millisecond pulsars, but it makes this scenario much more likely. There are a number of MSP-like unassociated sources towards the inner Galaxy that could be the "tip of the iceberg" of the O(1000) MSPs required to explain the excess emission.

→ Confirmation of these unassociated 3FGL sources being MSPs in the bulge region will be likely decisive!

Dwarf limits are in mild tension with GC observations

Fermi coll 2015



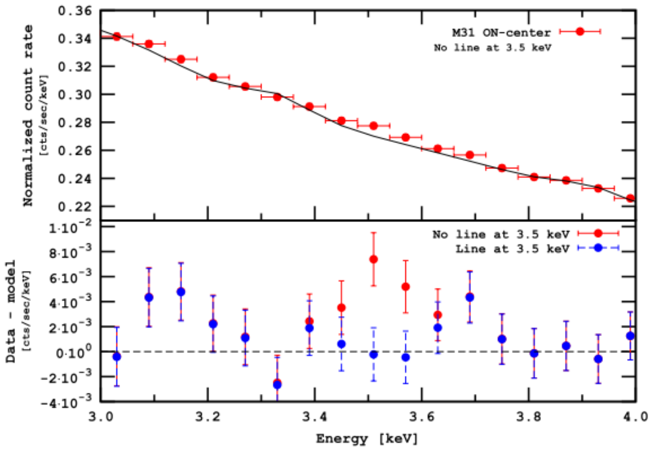


Situation:

- Gamma-ray excess emission seen at the Galactic center looks like the vanilla DM (WIMP) signal we where hoping for
- Astrophysical interpretations exist, but need to be verified
- In particular millisecond pulsars (in or outside of globular clusters) might be able to explain 100% of the excess emission
- Future:
    - Corroborating evidence for either astro or DM interpretations

But: at least factor 3 uncertainties in GC J-value [Calore+ 2014]

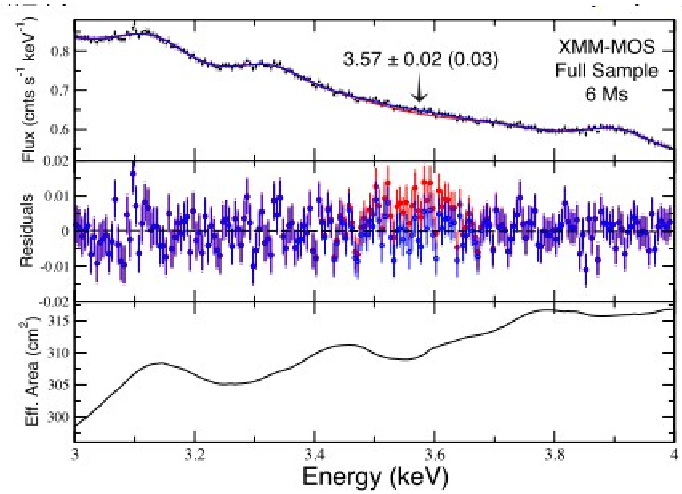
A 3.5 keV line from decaying DM?



Boyarsky et al. 2014

- Unidentified line in M31 and Perseus cluster

$$E = 3.52 \pm 0.02\,\mathrm{keV}$$



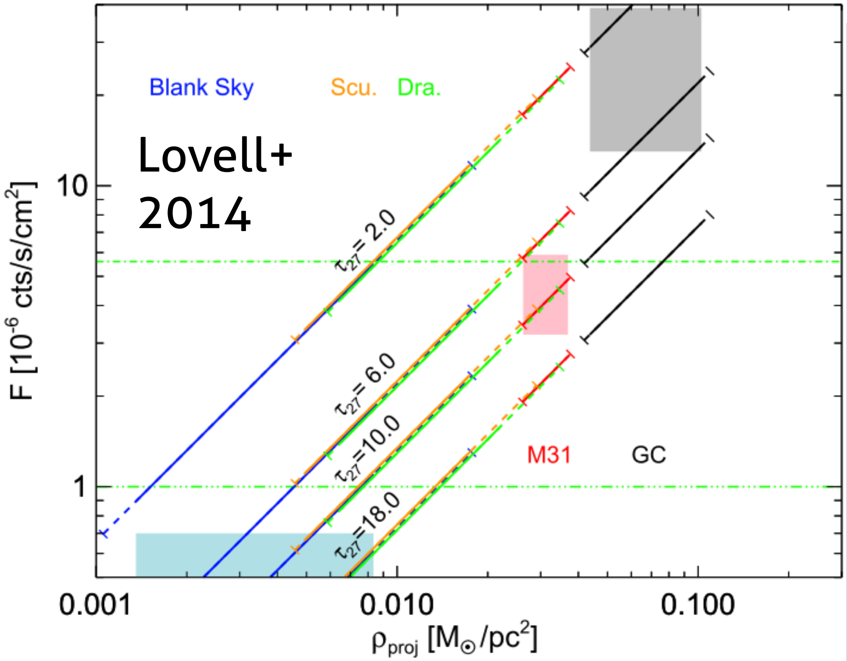
Bulbul et al. 2014

- Unidentified line in stacked XMM spectrum of 73 galaxy clusters
- Too bright in Perseus?

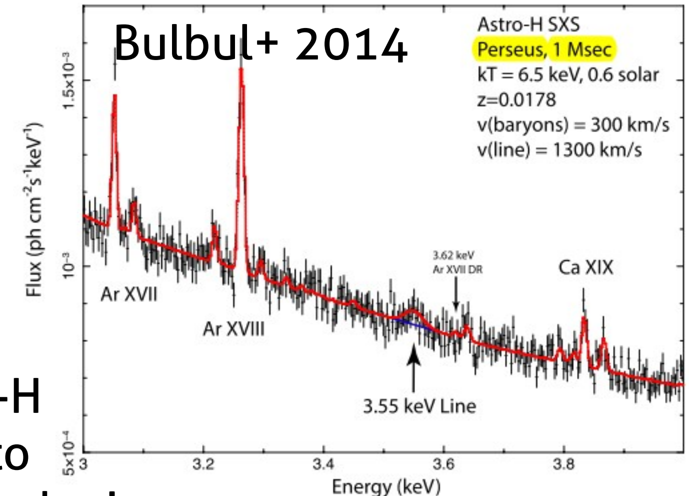
$$E = 3.56 \pm 0.04\,\mathrm{keV}$$

Yes	**No** (no corroborating evidence in other sources)
	Jeltema & Profumo 2014 (Potassium?)
Bulbul+ 2014 & Boyarsky+ 2014	
	Carlson+ 2014 (GC, morphology)
	Anderson+ 2014 (stacked galaxies)
	Malyshev+ 2014 (stacked dwarfs)

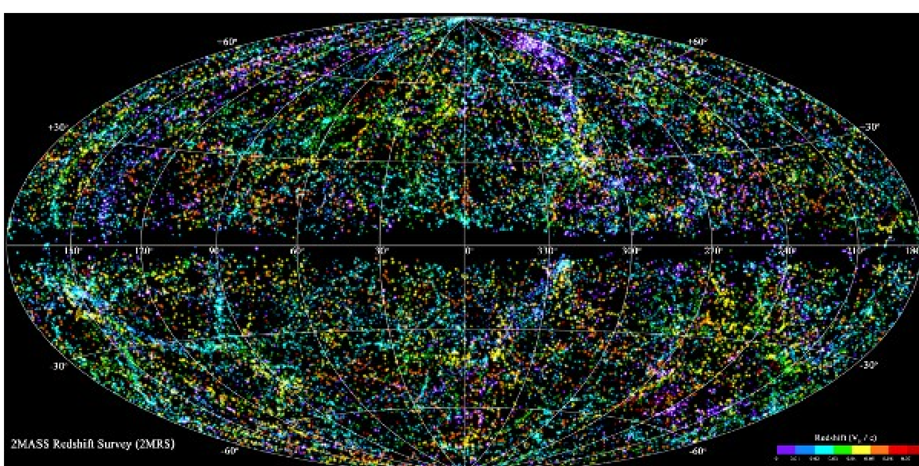
XMM-Newton, Astro-H and eROSITA



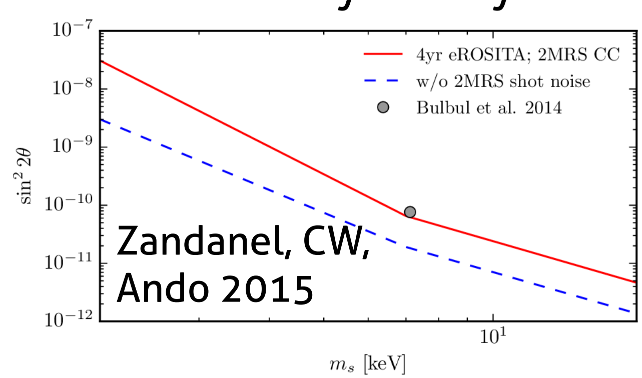
Near future: ~1Msec of XMM-Newton data on the Draco dSph. Good chance that this already settles the issue. Data is taken now.



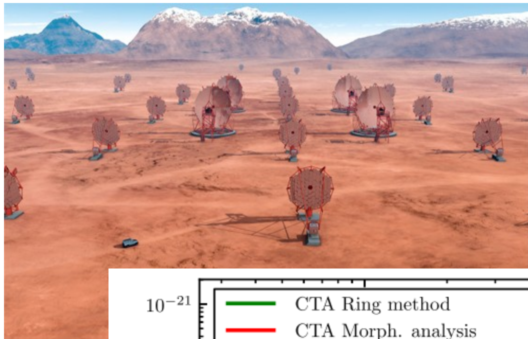
Mid-term: Astro-H should be able to resolve line-broadening

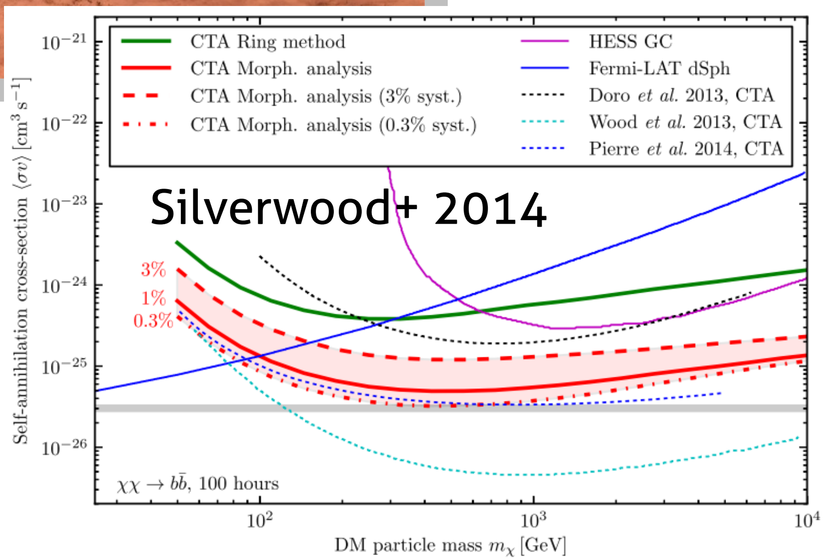


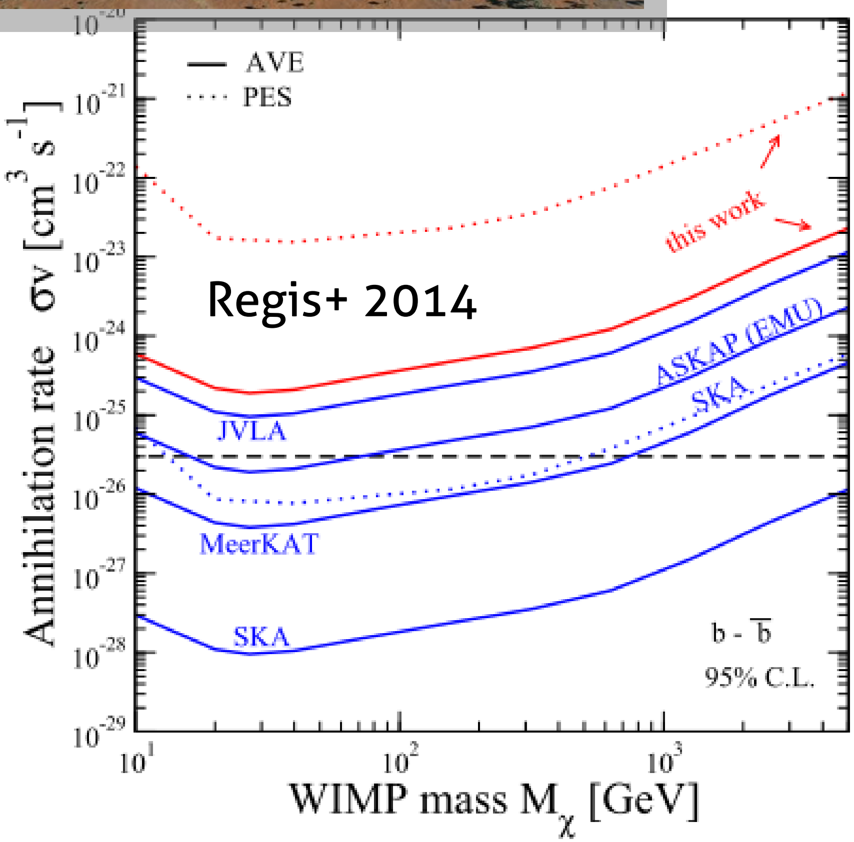
Long-term: Cross-correlations between eROSITA full-sky survey and DM tracers.



Indirect detection prospects for the next years

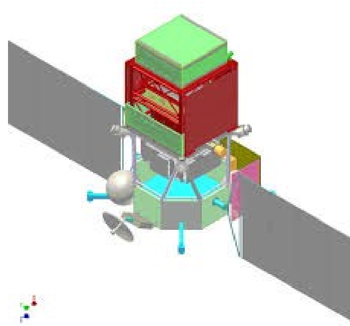






Gamma-ray satellite experiments
- GAMMA-400 (similar to Fermi)
- PANGU (focus on low energies)
- AstroGam

→ Help to clarify GC excess



Conclusions

- Indirect searches benefit from the vast amount of recent cosmic-ray anti-matter, gamma-ray, X-ray, radio etc data

- Anti-protons: No signal, systematics limited
- Positrons: Clear signal, astrophysics unclear
- Gamma-ray lines: Big discovery potential for CTA
- Fermi Galactic center excess: The most “vanilla” signal candidate so far, but unfortunately (spectrally) degenerate with pulsars
- Dwarf spheroidals: No signal right now. Still more dwarfs to come and look at.
- X-ray lines: Several sensitive probes on the way.

- Outlook: multi-wavelength searches, corroborating evidence from colliders and/or direct searches, theoretical studies, ...