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University of California, Santa Cruz

Santa Cruz Institute for Particle Physics

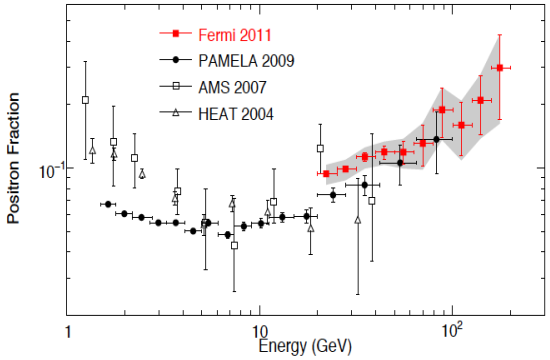
Astrophysical Probes of Dark Matter

TeV Particle Astrophysics 2013

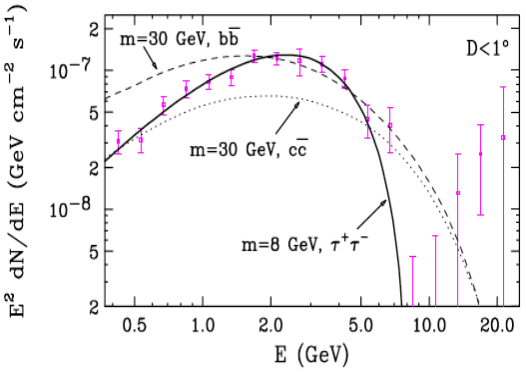
University of California, Irvine, August 29, 2013

3 tantalizing results might start delivering fundamental physics from the sky

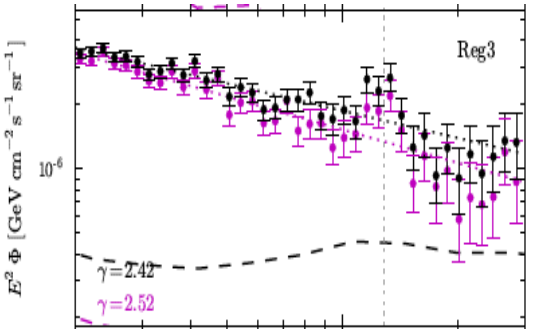
Cosmic-Ray Positron Excess



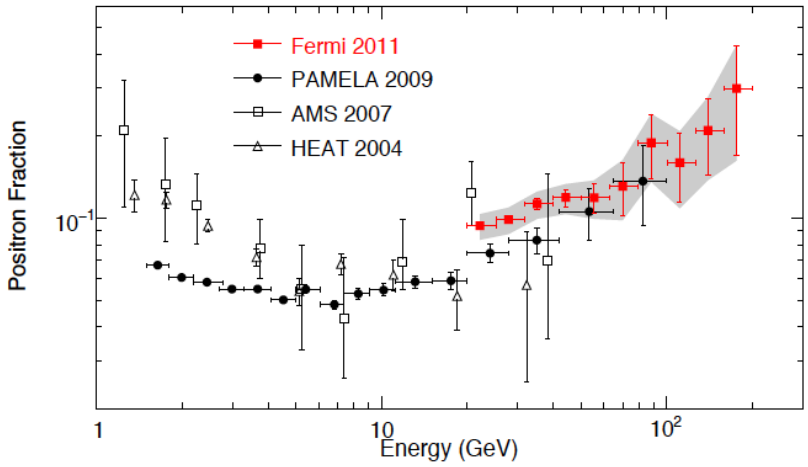
Gamma-ray excess in the Galactic Center?



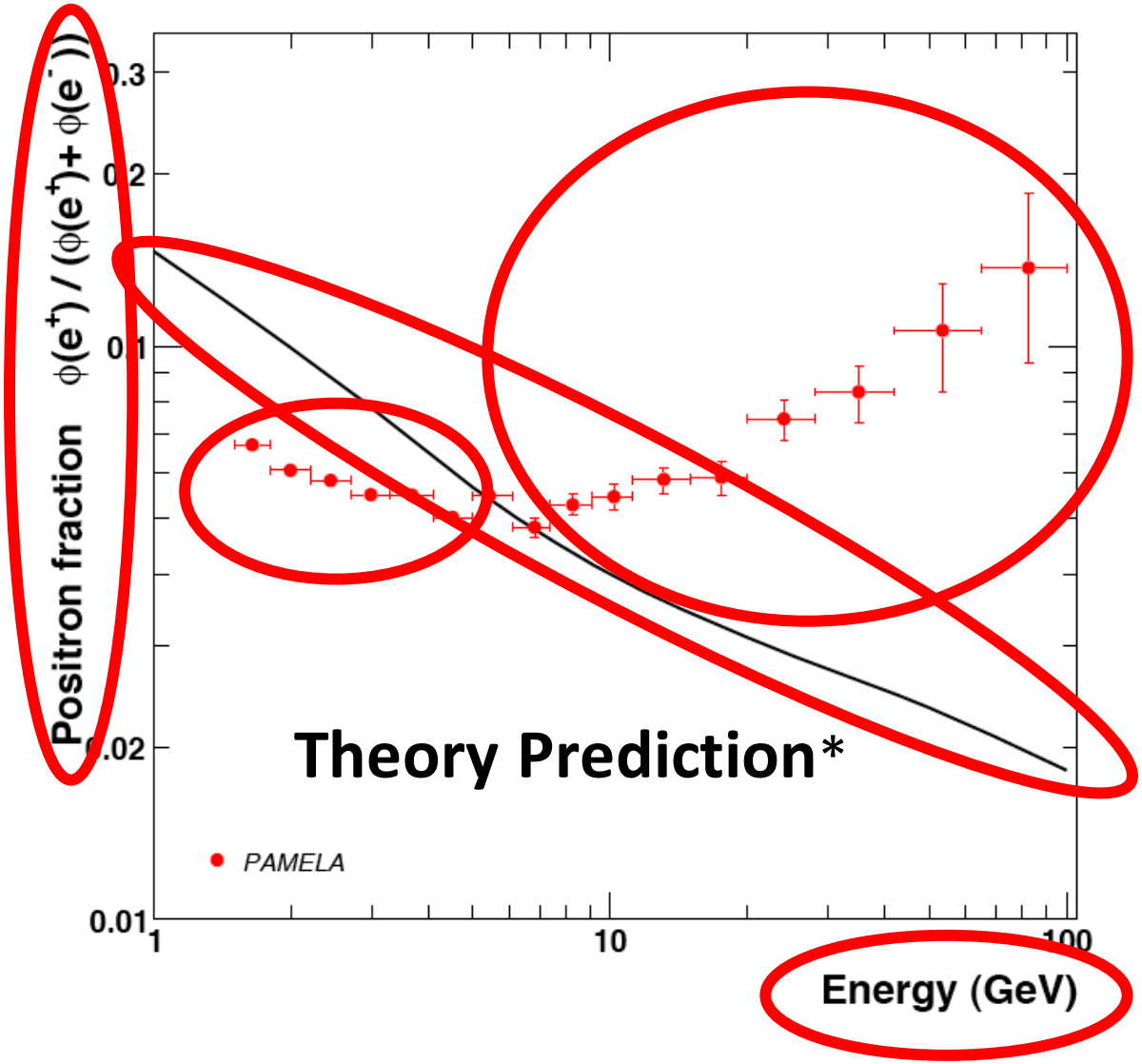
A 130 GeV line



Cosmic-Ray Positron Excess



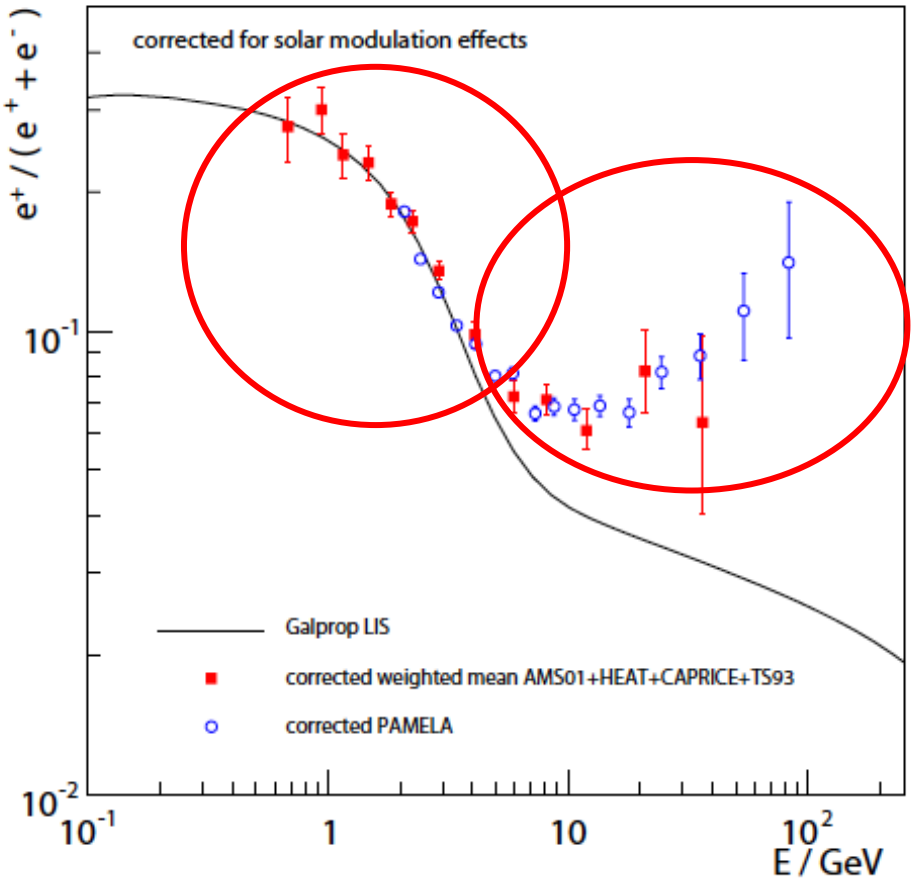
>>1000 CITATIONS!



Adriani et al, Nature 458 (2009) 607, arXiv 0810.4995

*I.V. Moskalenko and A.W. Strong Astrophys. J. 493, 694-707 (1998).

Low-Energy: correct for (charge-dependent) **solar modulation**



22 years full cycle (max every 11 years, with **polarity reversal**)
previous data: solar polarity favored positively charged particles, opposite for PAMELA

Gast & Schael, ICRC Conference, Lodz, 2009

Cosmic Ray **Secondary-to-Primary** ratio

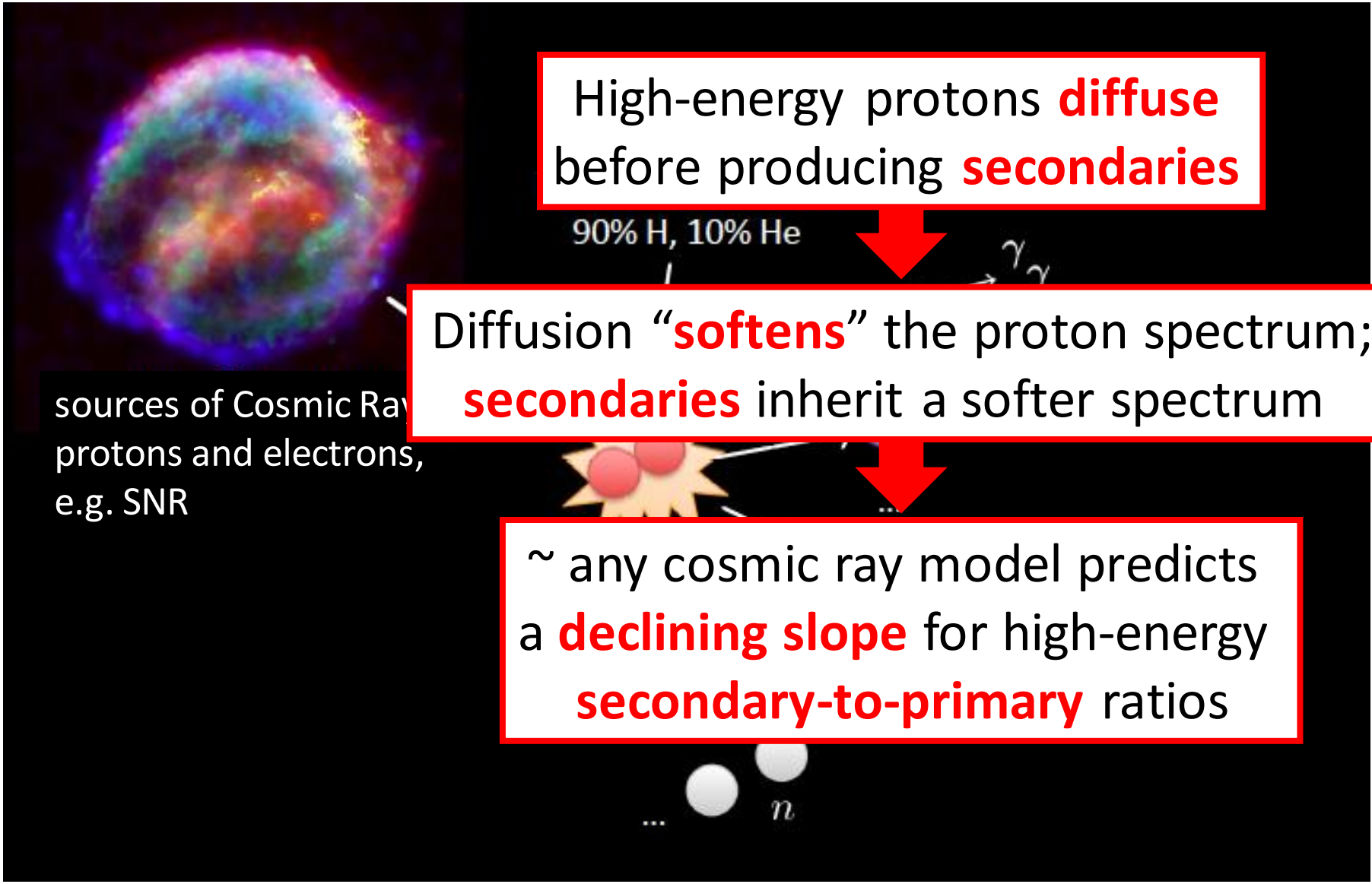


image credit: Philip Mertsch

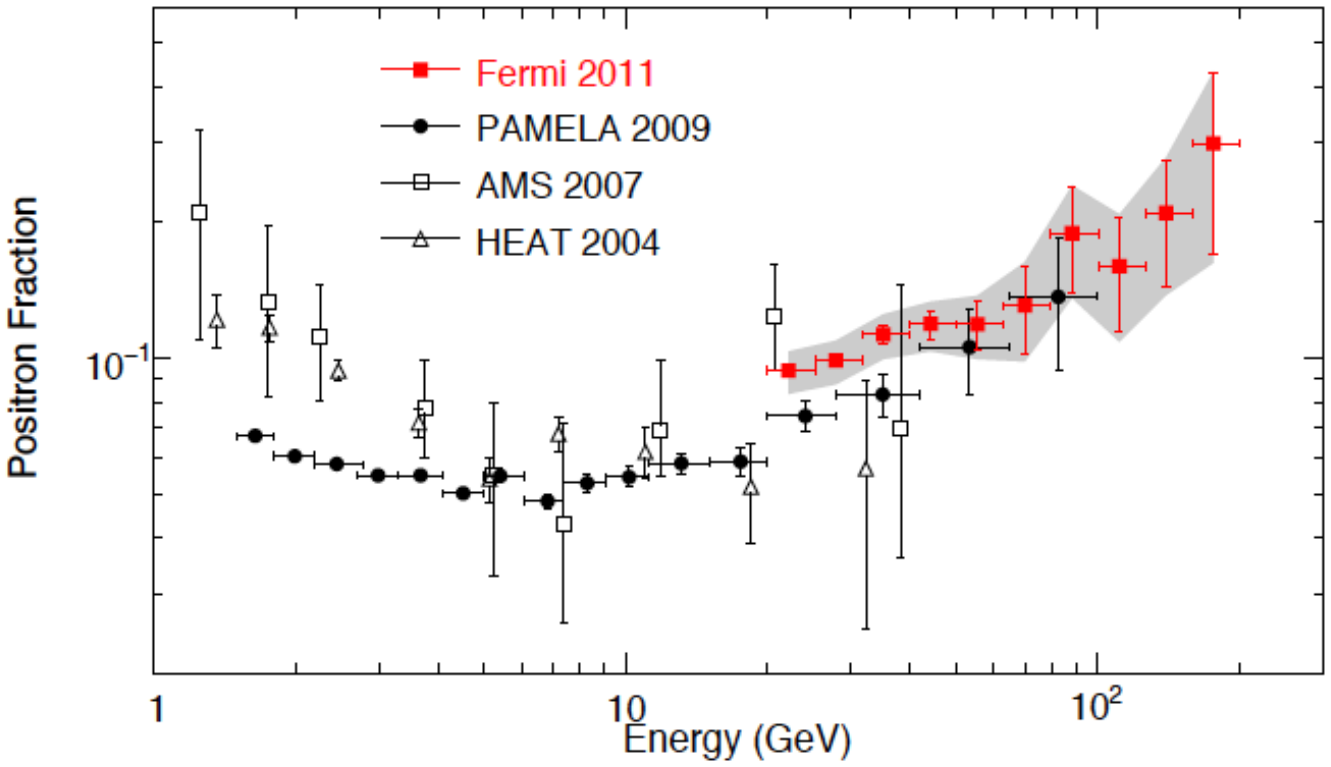
is the **positron** excess **real**?

Experimentalists get ignored if they are right,
and **hugely cited** if they are **wrong**.

Theorists get ignored if they are wrong,
but a **Nobel** Prize if they are **right**.*

Superluminal Neutrinos @ OPERA:
>200 theory papers

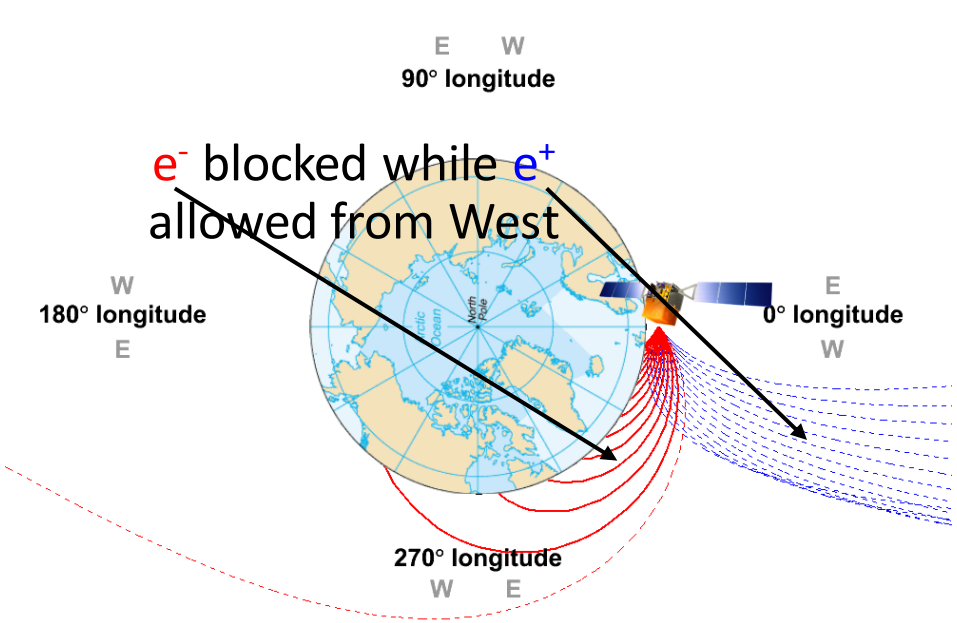
* quoted from the Guardian

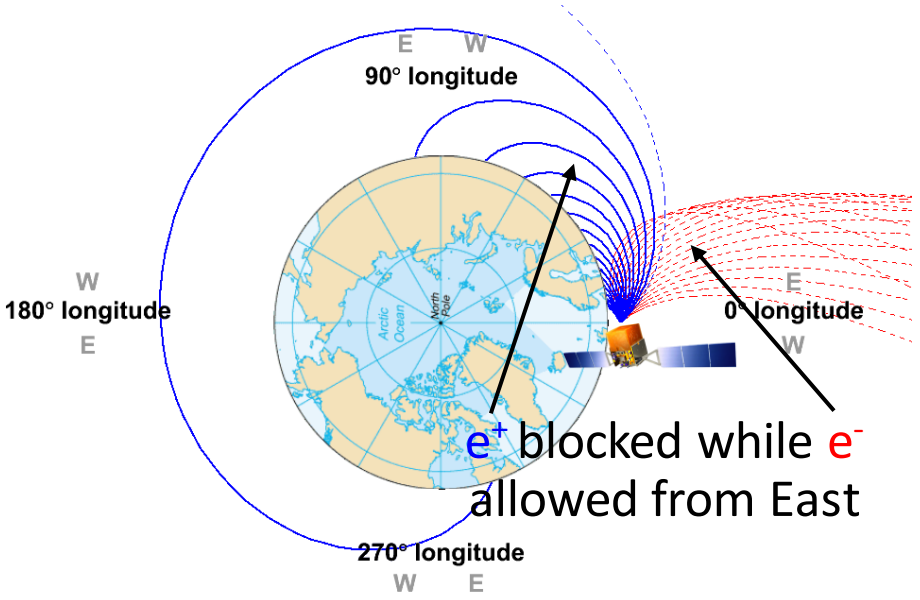


How does **Fermi** tells e^+ apart from e^-?

Fermi-LAT Collaboration, 1109.0521

Geomagnetic field + solid **Earth** shadow = directions from which only electrons or **only positrons** are allowed





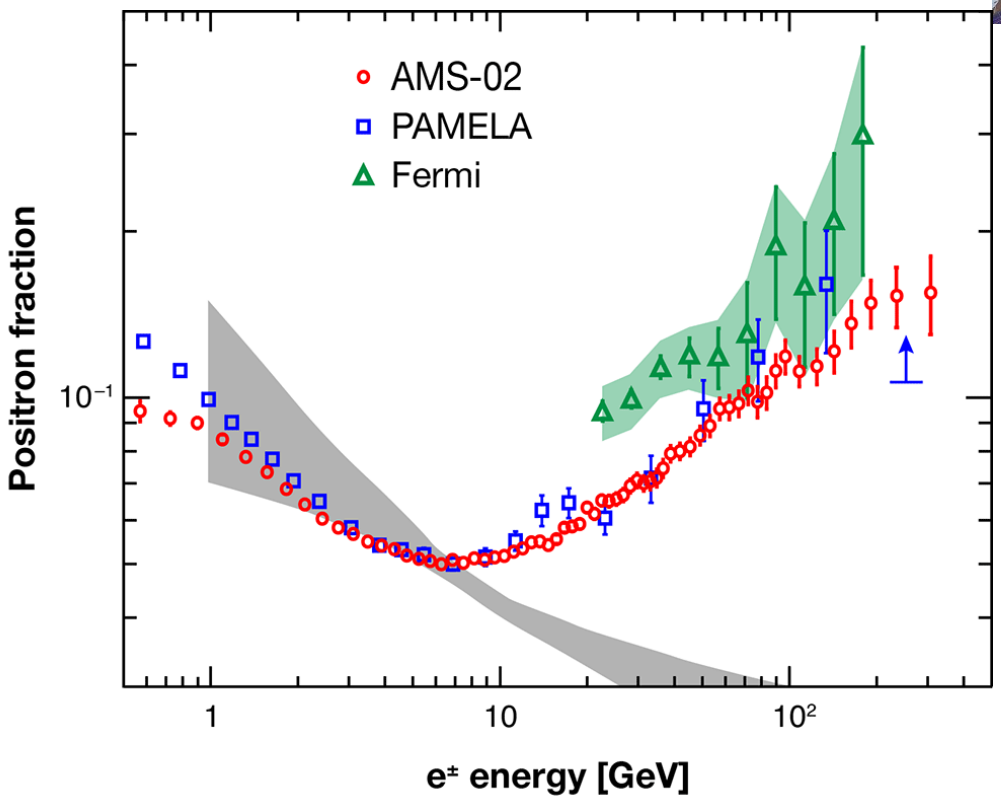
For particular directions, electrons or positrons are completely forbidden

Pure e^+ region looking West and pure e^- region looking East

Regions vary with **particle energy** and **spacecraft position**

Slide concept: Justin Vandenbroucke

April 3, 2013



AMS-02 first results **confirm**

positron excess with very **high statistics** (x100)

PRL, **110** (2013) 14

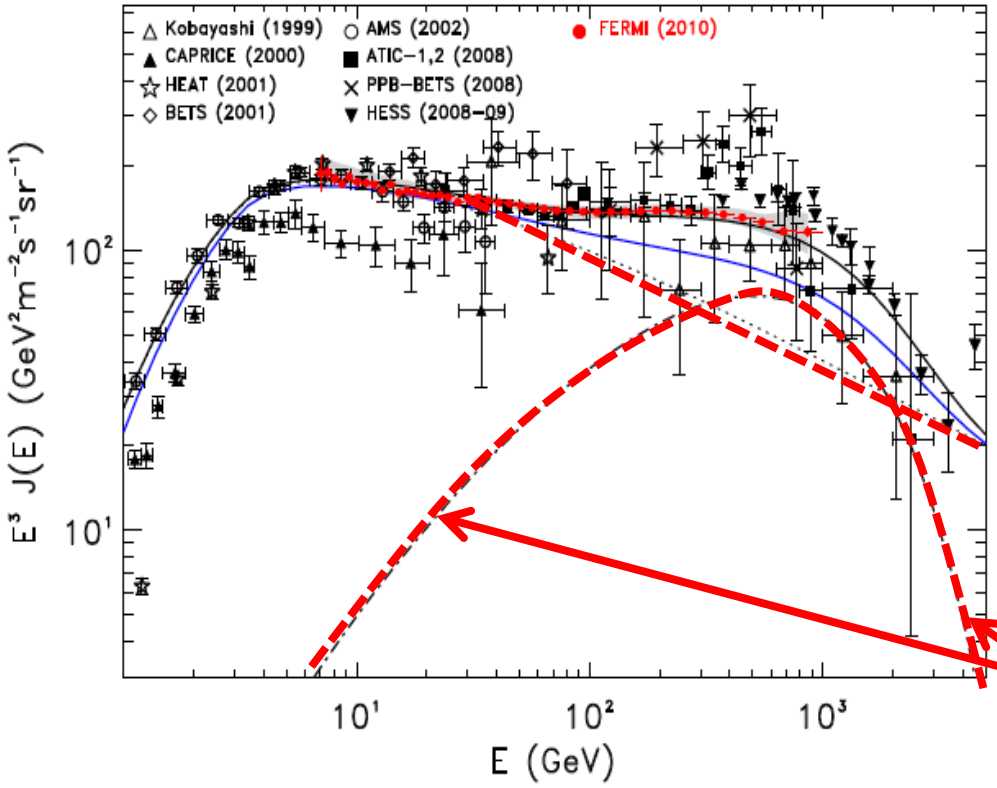
…better **take seriously**
the excess of **HE positrons**

Can we determine the **source/origin?**

Note: this is all **consistent** with Eli's **upper limit** on secondaries

A **marketing problem**:
if data are consistent with a general, model-independent upper limit,
we don't necessarily **understand/predict** the **physical origin** of the HE positrons!

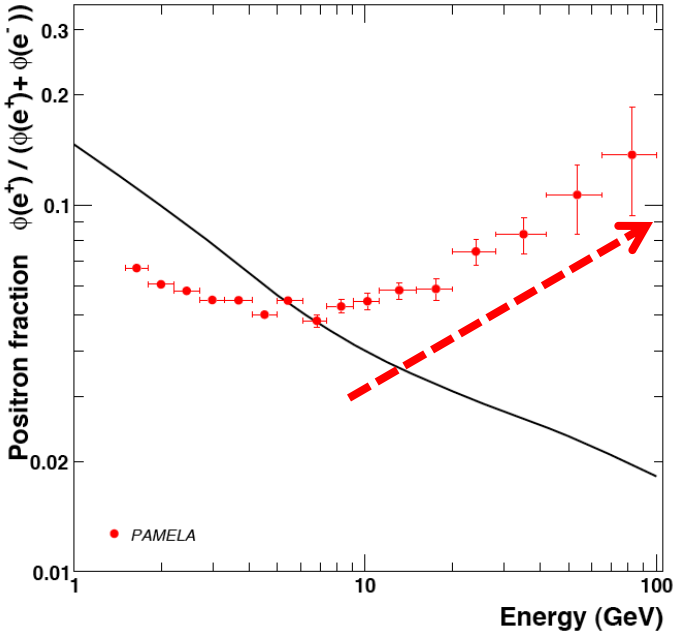
key piece of the **puzzle**: the **Denominator** ($e^+ + e^-$)

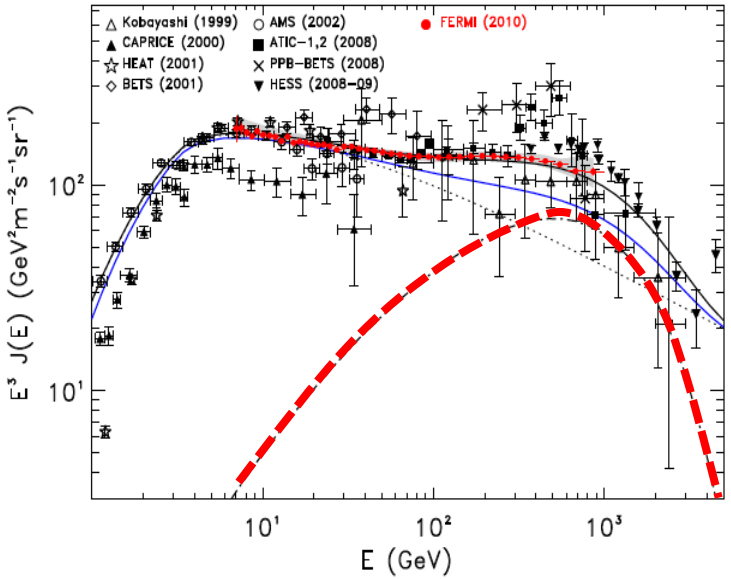


Galactic Cosmic Ray **acceleration** should produce a **power-law** e+e- injection spectrum with a high-energy **cutoff**

Fermi/HESS data **compatible** with an **additional** high-energy source

Solution: postulate **additional source** of (high-energy) electrons **and** positrons:





What is the nature of this **new** powerful electron-positron **source**??

Exciting!

It could be New Physics:

Dark Matter Annihilation!

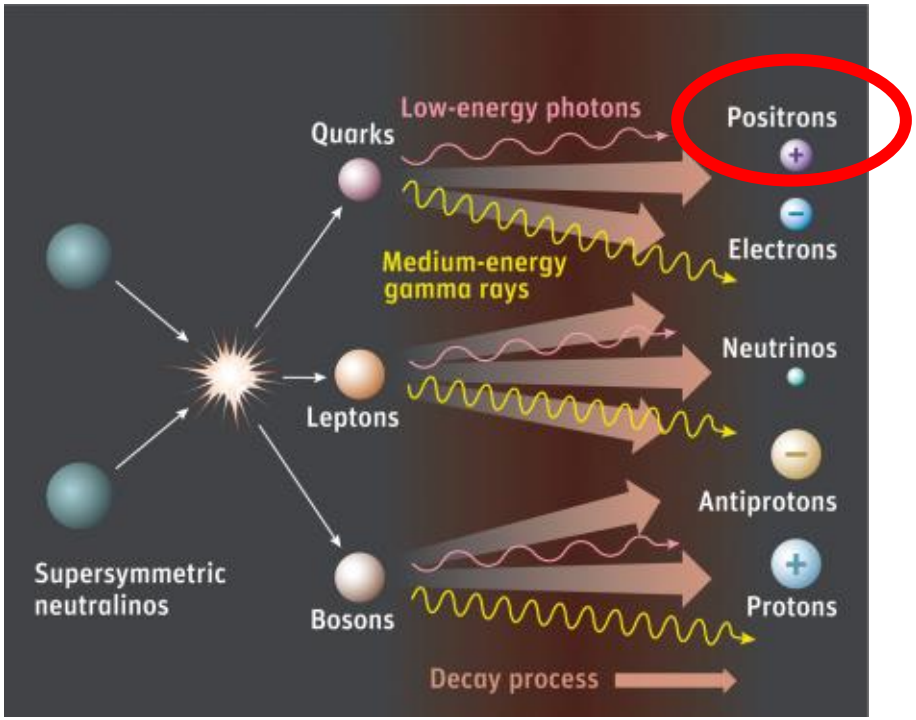


Image Credit: NASA/GLAST collaboration

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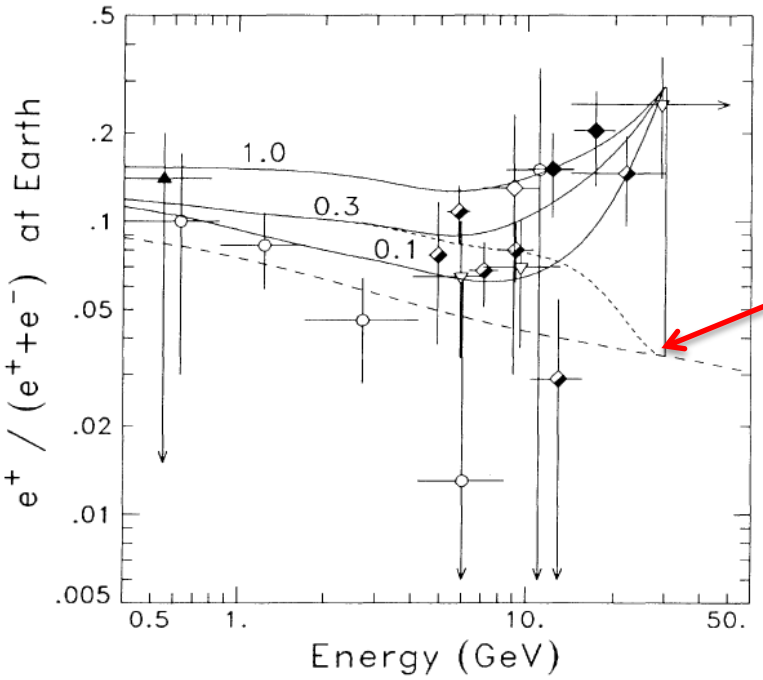
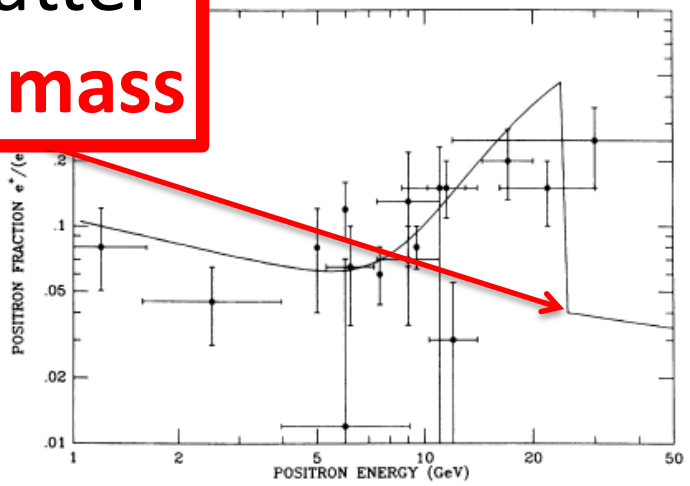


A. Tylka, Phys. Rev. Lett. 63, 840-843 (1989)

Dark Matter particle **mass**



M. Turner and F. Wilczek, Phys Rev. D 42 (1990) 1001.

Exciting!

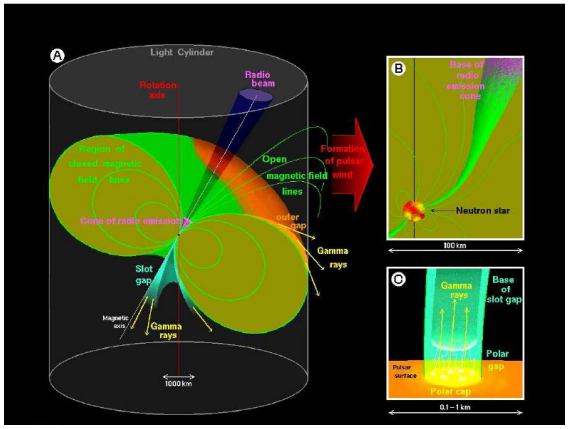
It could be New Physics:

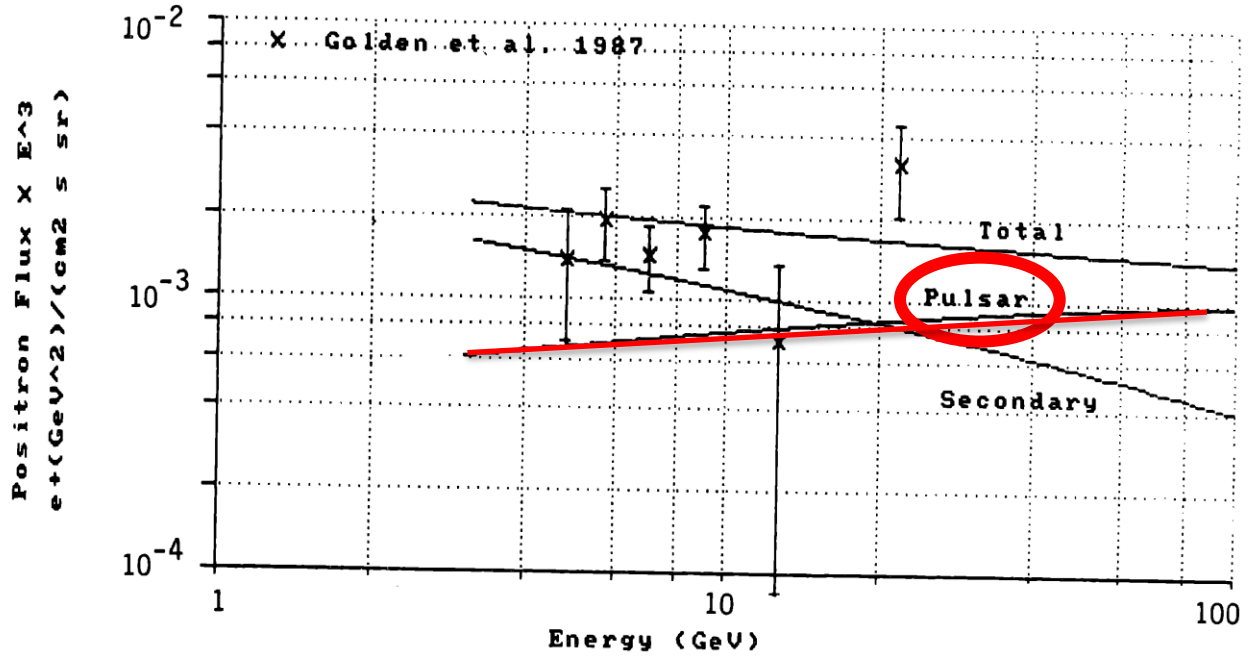
Dark Matter Annihilation!

…or it could **not**…

Pulsar Magnetosphere

Rotation-powered Neutron Stars radiate energy by producing e+e- pairs, injected in ISM when out of Pulsar Wind Nebula





Harding, A. K. & Ramaty, R. The pulsar contribution to galactic cosmic-ray positrons.

Proc. 20th ICRC, Moscow 2, 92-95 (**1987**).

>1000 papers advocate Dark Matter

…**despite** some obvious and significant **issues**:

(i) Need very **large annihilation rates**
($\langle\sigma v\rangle \sim 10^{2}$-$10^{3} \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$)

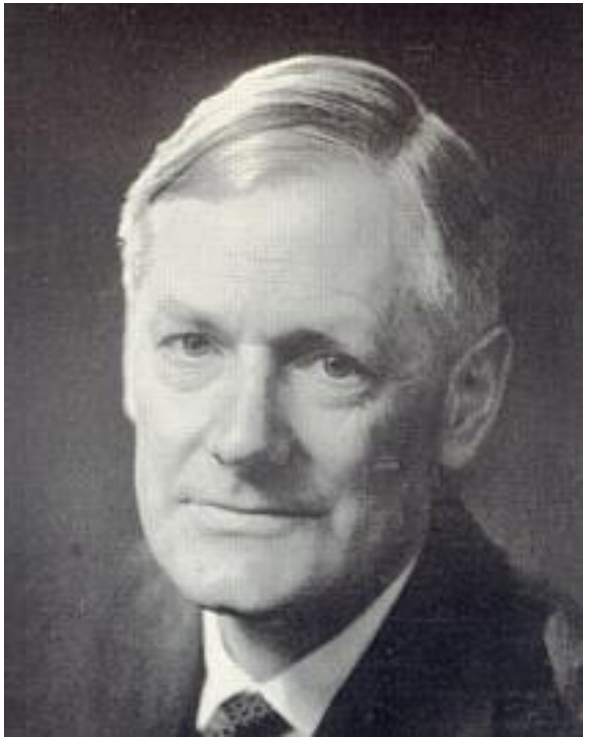
(ii) Need rather **large masses** (~TeV)

(iii) Need special annihilation or decay modes
(suppress **antiprotons** + have a hard spectrum)
e.g.: $\mu^+\mu^-$, or 4μ (even **worse** post-AMS: $\pi\pi$)

…an interesting **riddle** to test a **theorist's creativity**!

Redman's Theorem

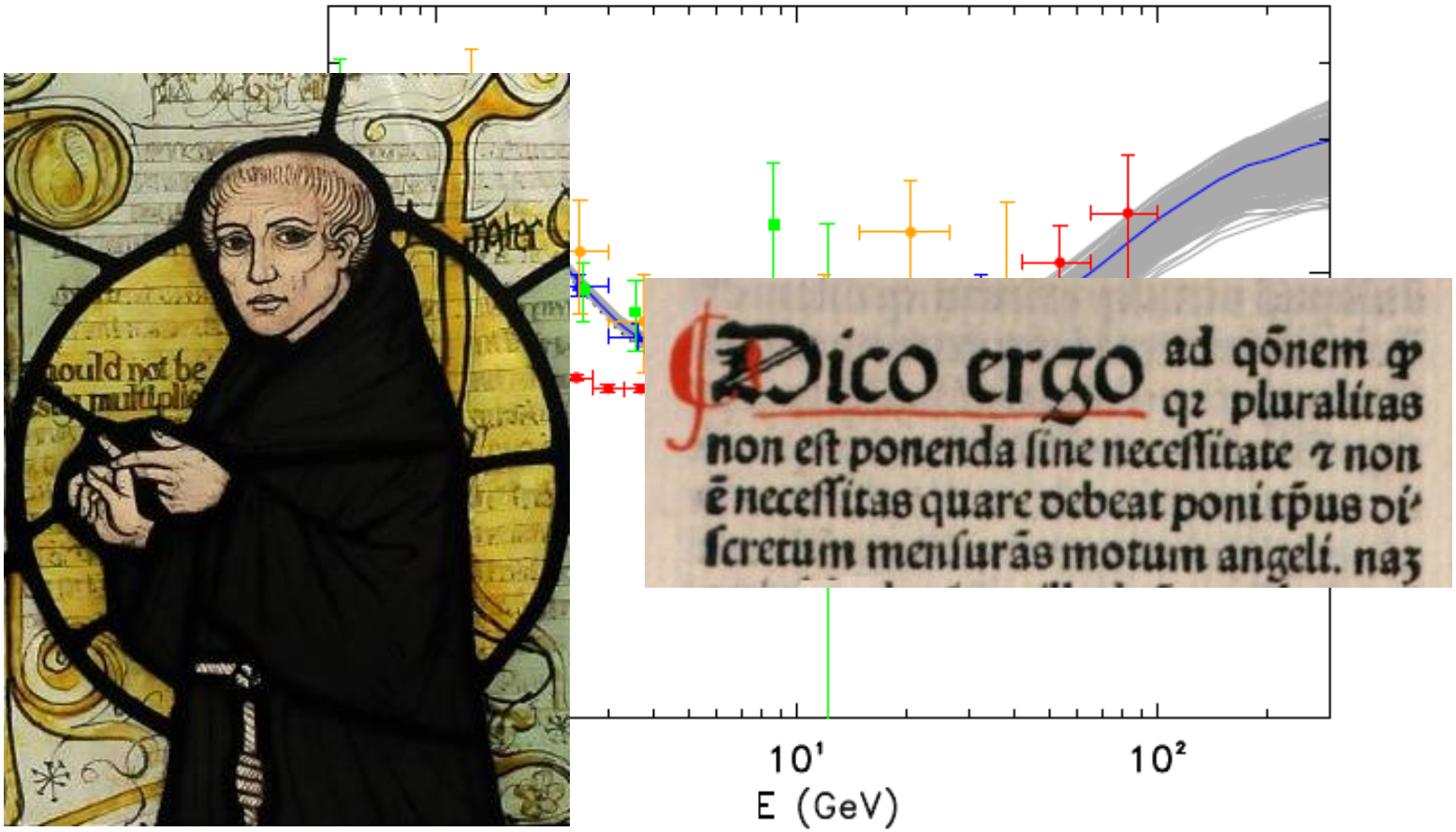
"Any competent theoretician can fit any given theory to any given set of facts" (*)



Roderick O. Redman
(b. 1905, d. 1975)
Professor of Astronomy
at Cambridge University

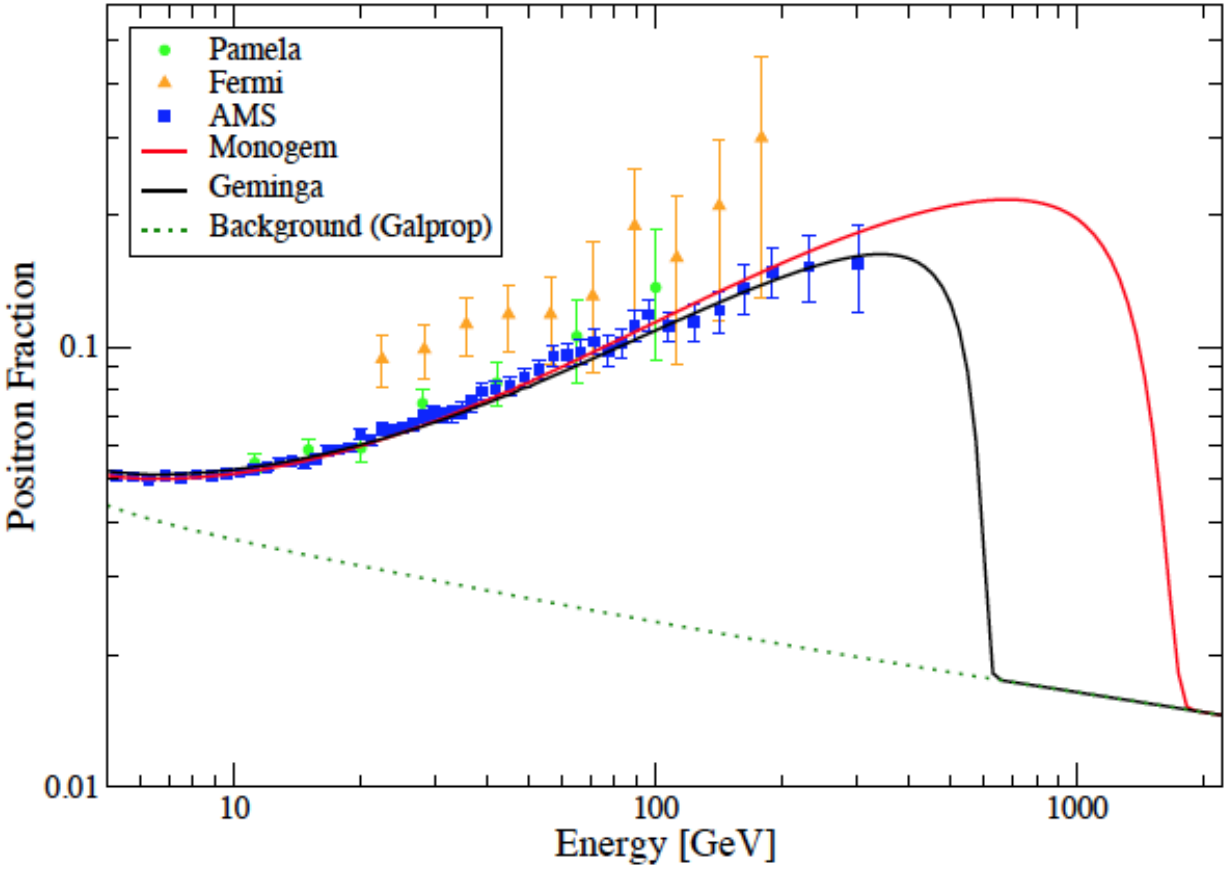
(*) Quoted in M. Longair's "High Energy Astrophysics", sec 2.5.1 "The psychology of astronomers and astrophysicists"

"Dissecting Pamela with **Occam's Razor**: **existing, well-known Pulsars** naturally account for the "anomalous" Cosmic-Ray Electron and Positron Data"*



*Profumo, 0812.4457

…Pulsars Post **AMS**



- **Distance** and **Age** from observation (set the cutoff)
- **Normalization**: 1-10% spin-down luminosity
- Injection **Spectrum**: ~ E^{-2} (Fermi 1st order)

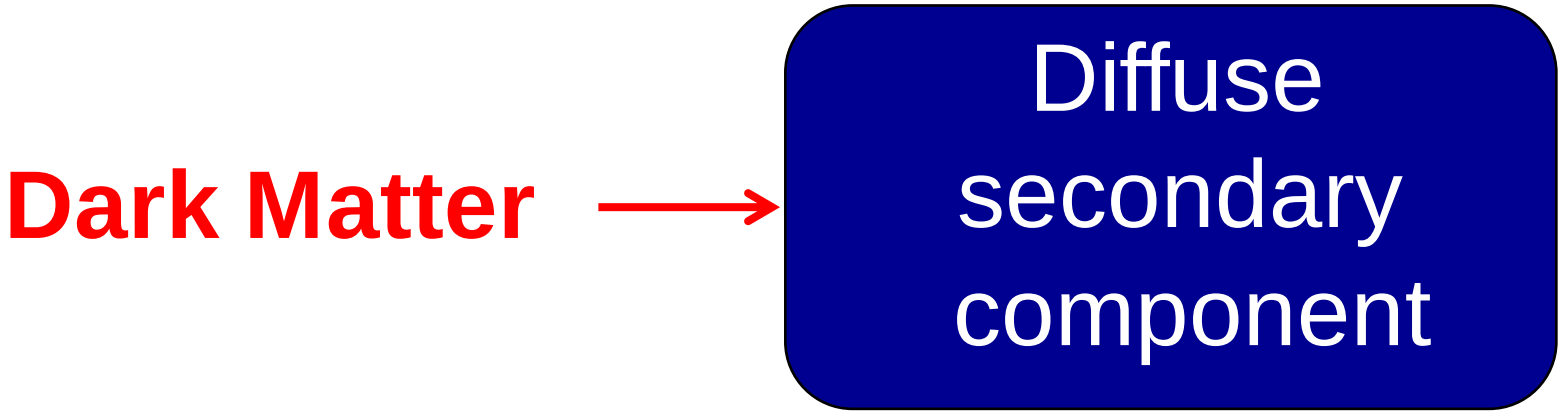
Linden and Profumo, 1304.1791

can we **discriminate** between

dark matter and **pulsars**?

Nearby **Pulsar** → Anisotropy in the arrival direction *(sufficient, not necessary)*

Dark Matter → Diffuse secondary component

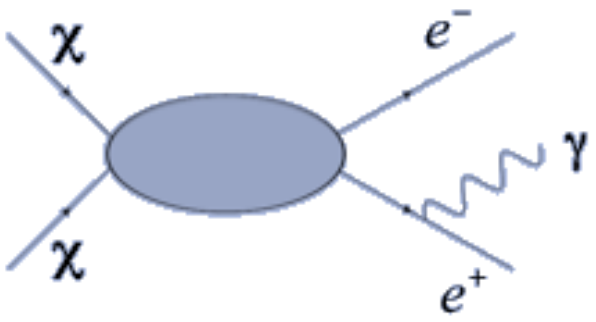

Dark Matter
Diffuse secondary component

Dark Matter: a "**Universal**" Phenomenology

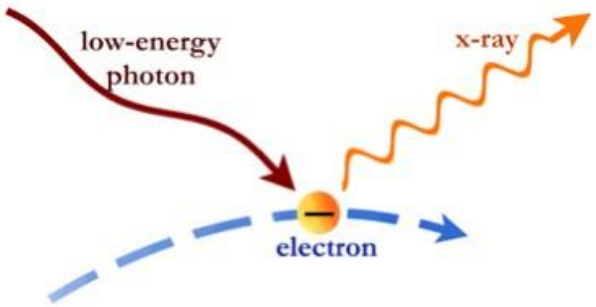
Large **annihilation rates**

Large **masses**

Hard **charged leptons**



Final State Radiation

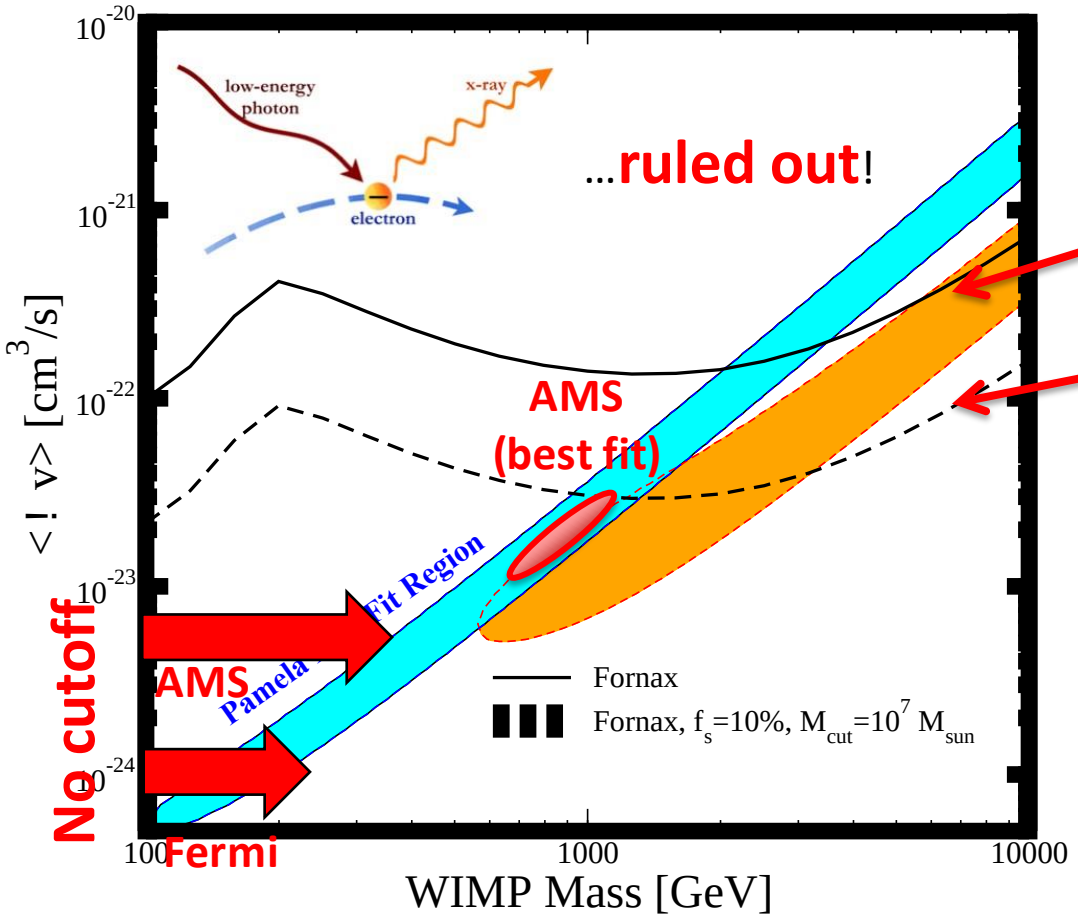


Inverse Compton

Gamma-Ray Searches from **Galaxy Clusters**

Jeltema, Profumo & Fermi-LAT Collaboration, JCAP 2010, arXiv: 1001.4531

Gamma-Ray Searches from **Galaxy Clusters**

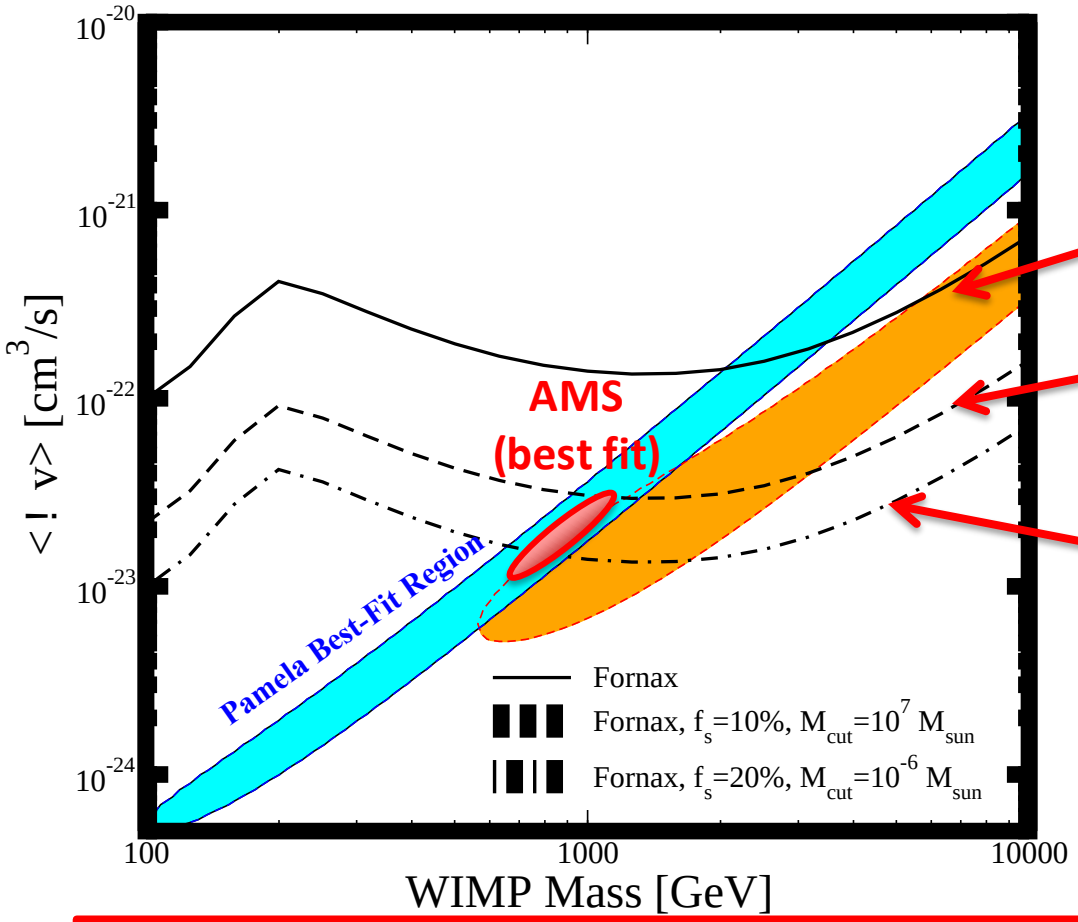


no substructure

galaxies only

Jeltema, Profumo & Fermi-LAT Collaboration, JCAP 2010, arXiv: 1001.4531

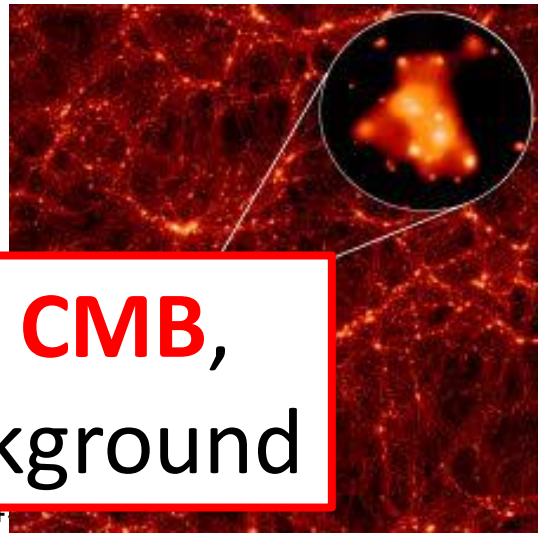
Gamma-Ray Searches from **Galaxy Clusters**



no substructure

galaxies only

substructure
with M > 10^{-6} M_{Sun}

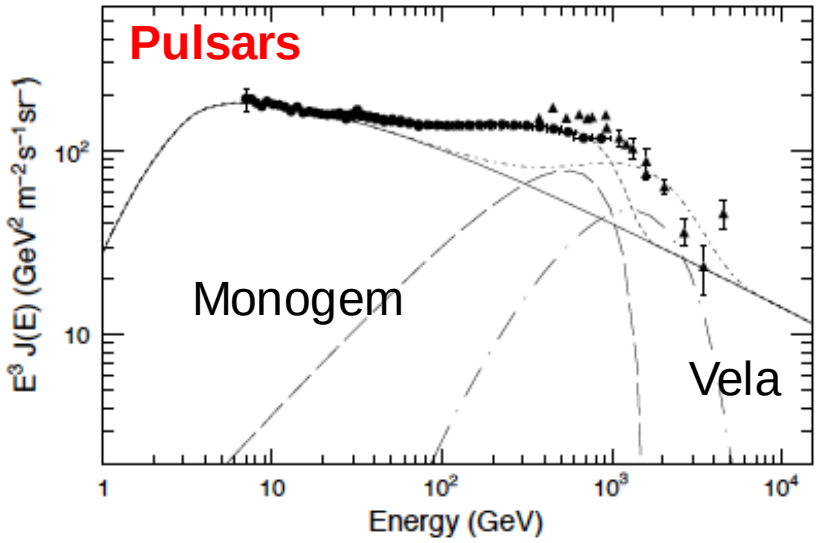


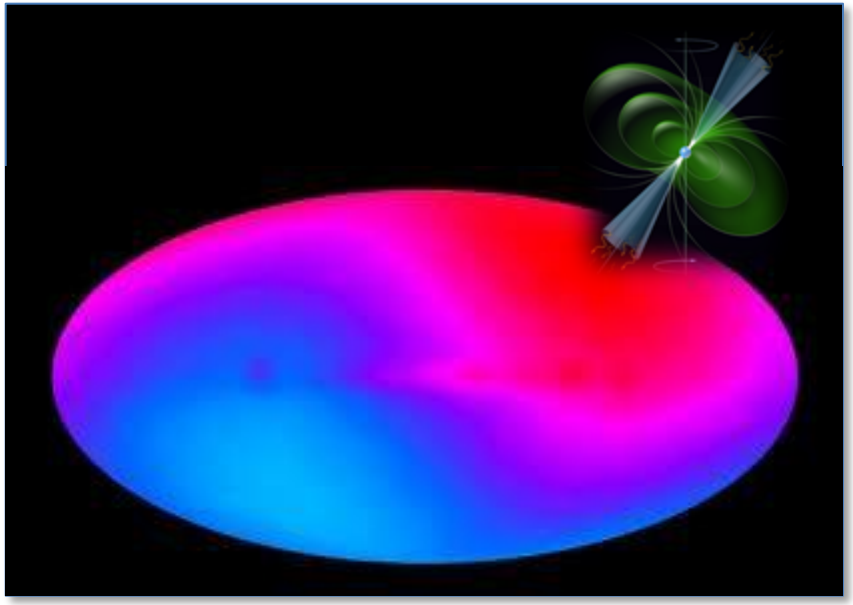
Additional constraints from **CMB**, extragalactic **gamma-ray** background

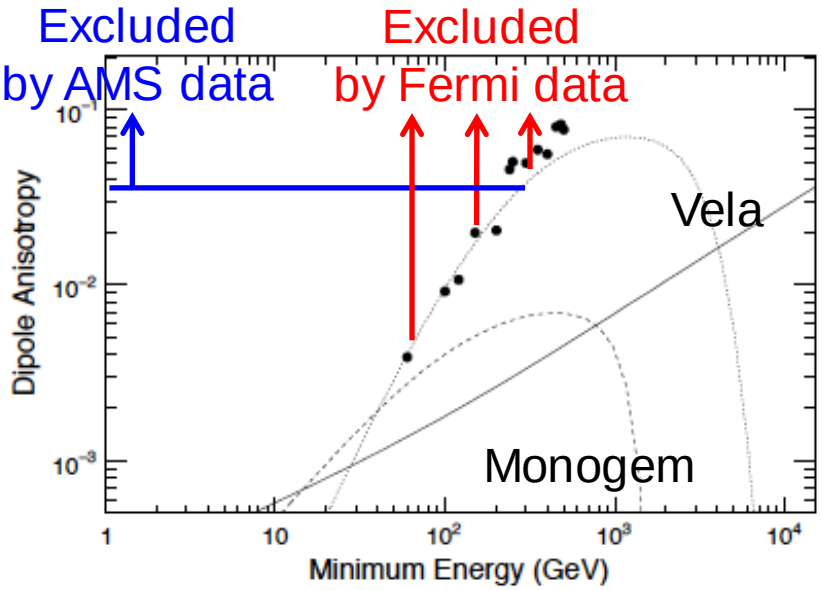
Jeltema, Profumo & Fermi-LAT Collaboration, JCAP 2010, arXiv: 1001.4

Nearby **Pulsar** ⟶ Anisotropy in the arrival direction

(sufficient, not necessary)



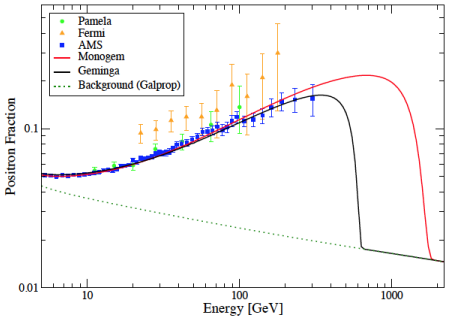


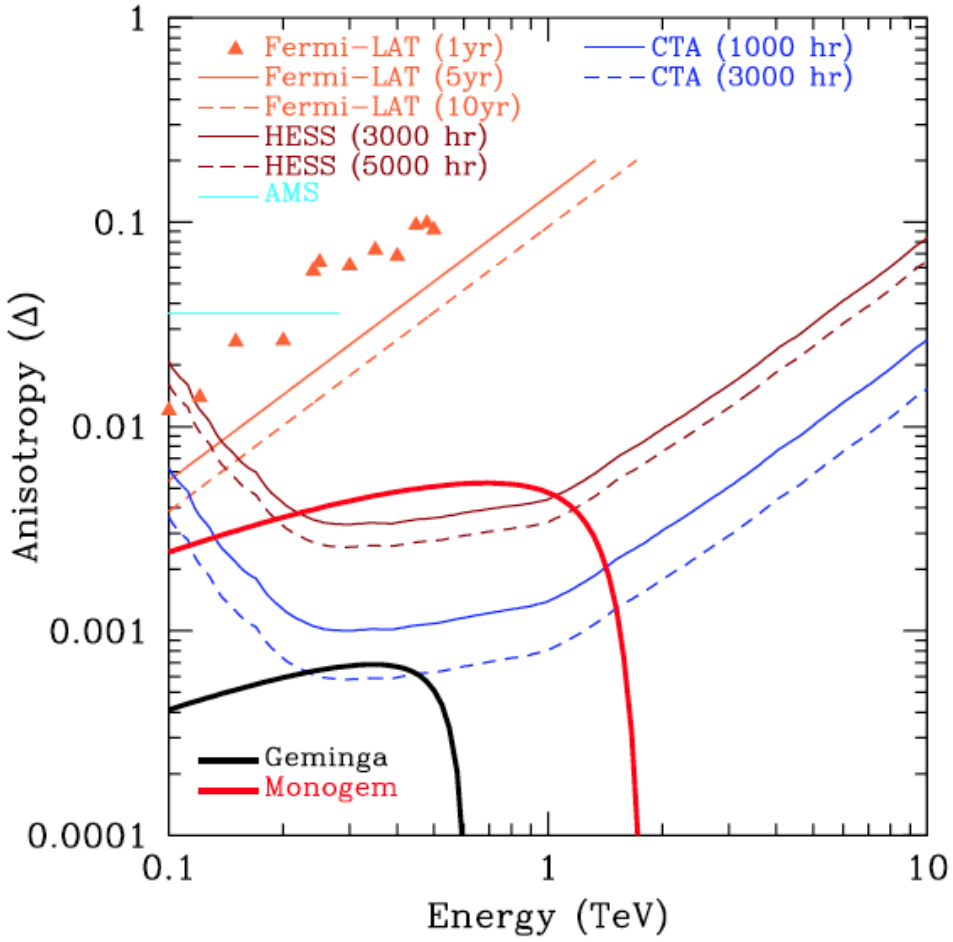


No Anisotropy observed in the **Fermi** e^+e^- data, or in the **AMS** data

Pulsar interpretation entirely **consistent** with **all data**!

Fermi-LAT Collaboration, PRD, 1008.5119
AMS-02 Collaboration, PRL, 110, 141102





Way forward: **Cherenkov Telescopes** sensitive to predicted **anisotropies** at VHE!

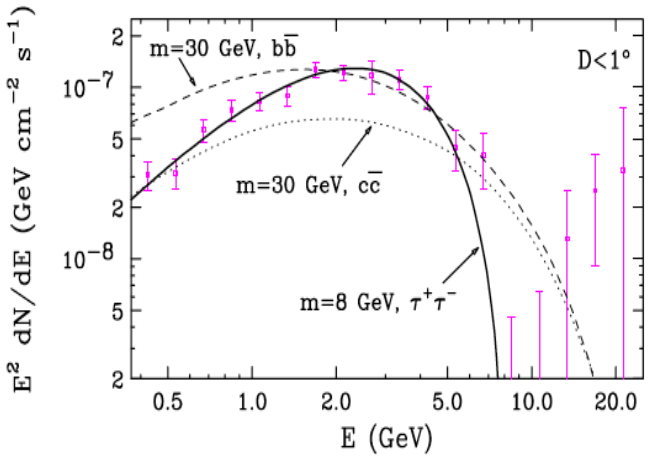
Linden and Profumo, Astroph. J (2013) 1304.1791

- we are **closing in** on the **dark matter** interpretation

- **AMS-02** positron fraction **data "favor" PSR's** over dark matter

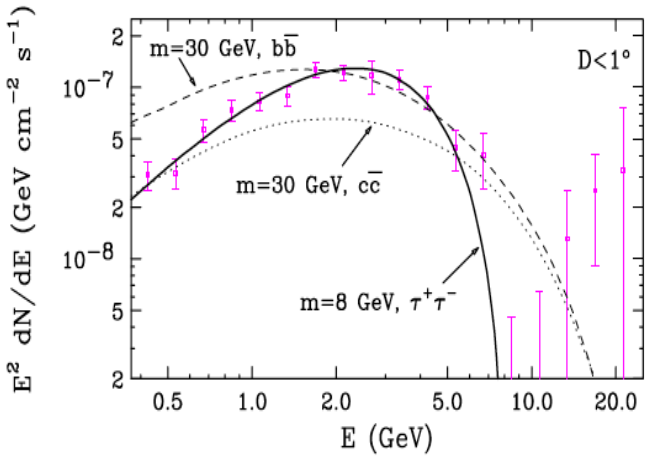
- Conclusive argument against dark matter: **anisotropy** (ACTs!)

Dark Matter annihilation in the Galactic Center?



the problem with the **Galactic Center**: "**under-fitting**" versus "**over-fitting**"

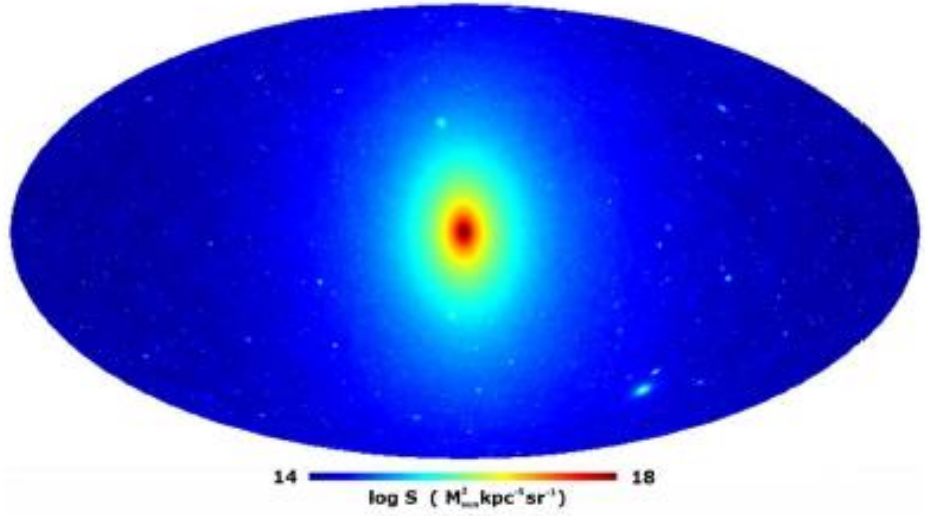
Dark Matter annihilation in the Galactic Center?



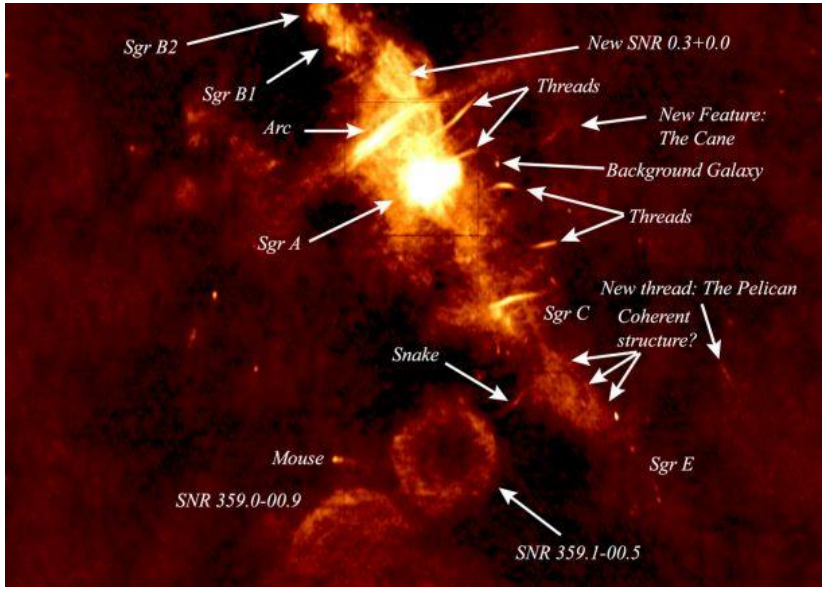
The **Galactic Center** Region: a Holy Grail or a Hornet's Nest?

- Largest (known) Galactic **Dark Matter** Density
- There appears to be an **excess** of soft gamma rays

- Largest **Cosmic Ray** Density
- Largest **Gas** and **Radiation** Densities
- Largest concentration of Galactic **Gamma Ray sources**



Springel et al, 2009



Kassim et al, 1999

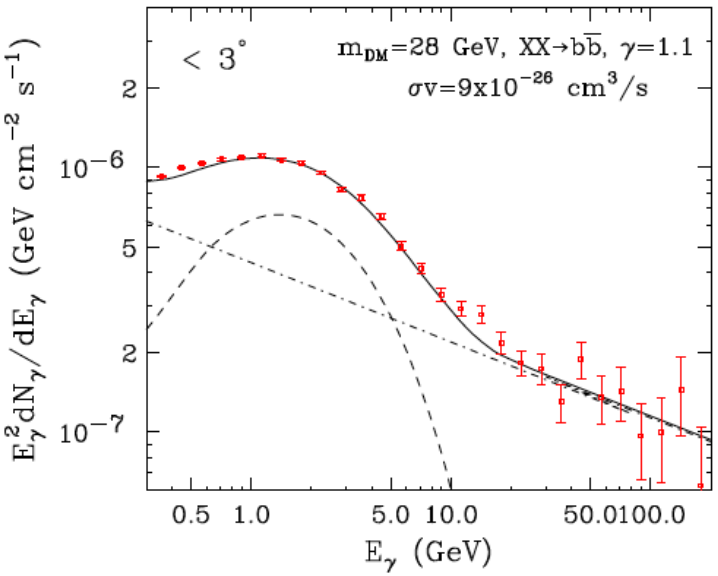
Background **Dark Matter particle**

Oct. 2009

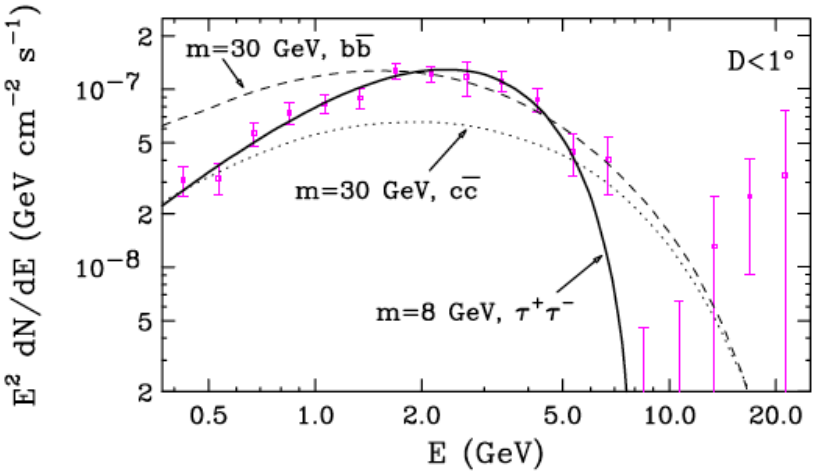
Goodenough, Hooper

Exponential angular fall-off
Power-law spectrum

28 GeV, bb quark



	Background	Dark Matter particle
Oct. 2009 Goodenough, Hooper	*Exponential angular fall-off* *Power-law spectrum*	*28 GeV, bb quark*
Oct. 2010 Hooper, Goodenough	$r^{-1.55}$ *fall-off* Spectrum: extracted from >2deg region	*8 GeV,* $\tau^+\tau^-$

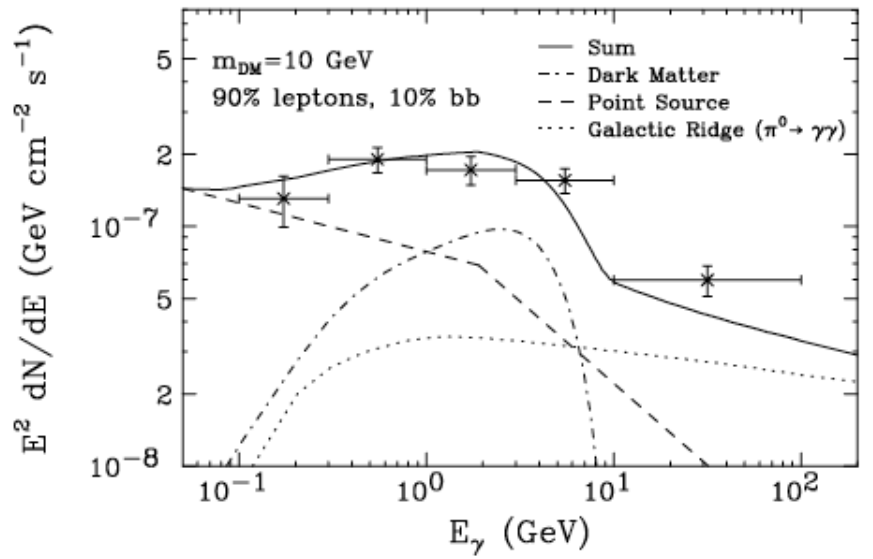


the danger of background “**under-fitting**”:

may end up with a “**Goodenough Hooperon**”

Oct. 2009

Goodenough, Hooper



Matter particle

3 GeV, bb quark

Oct. 2010

Hooper, Goo

8 GeV, $\tau^+\tau^-$

from >2deg region

Several recent studies **confirmed** the 2011 Linden-Hooper **excess** (Abazijian and Kaplinghat, 2012; Hooper and Slatyer 2013)

Oct. 2

GeV,

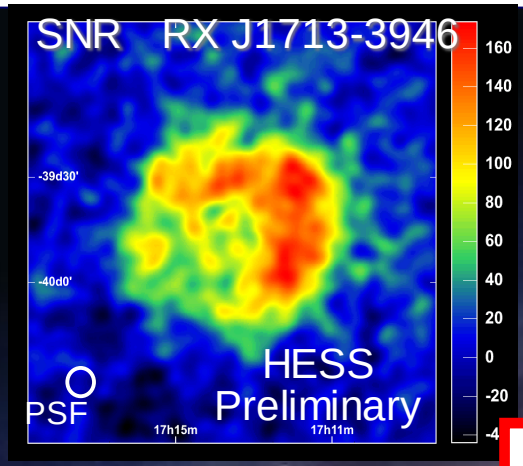
$^-$ or bb,

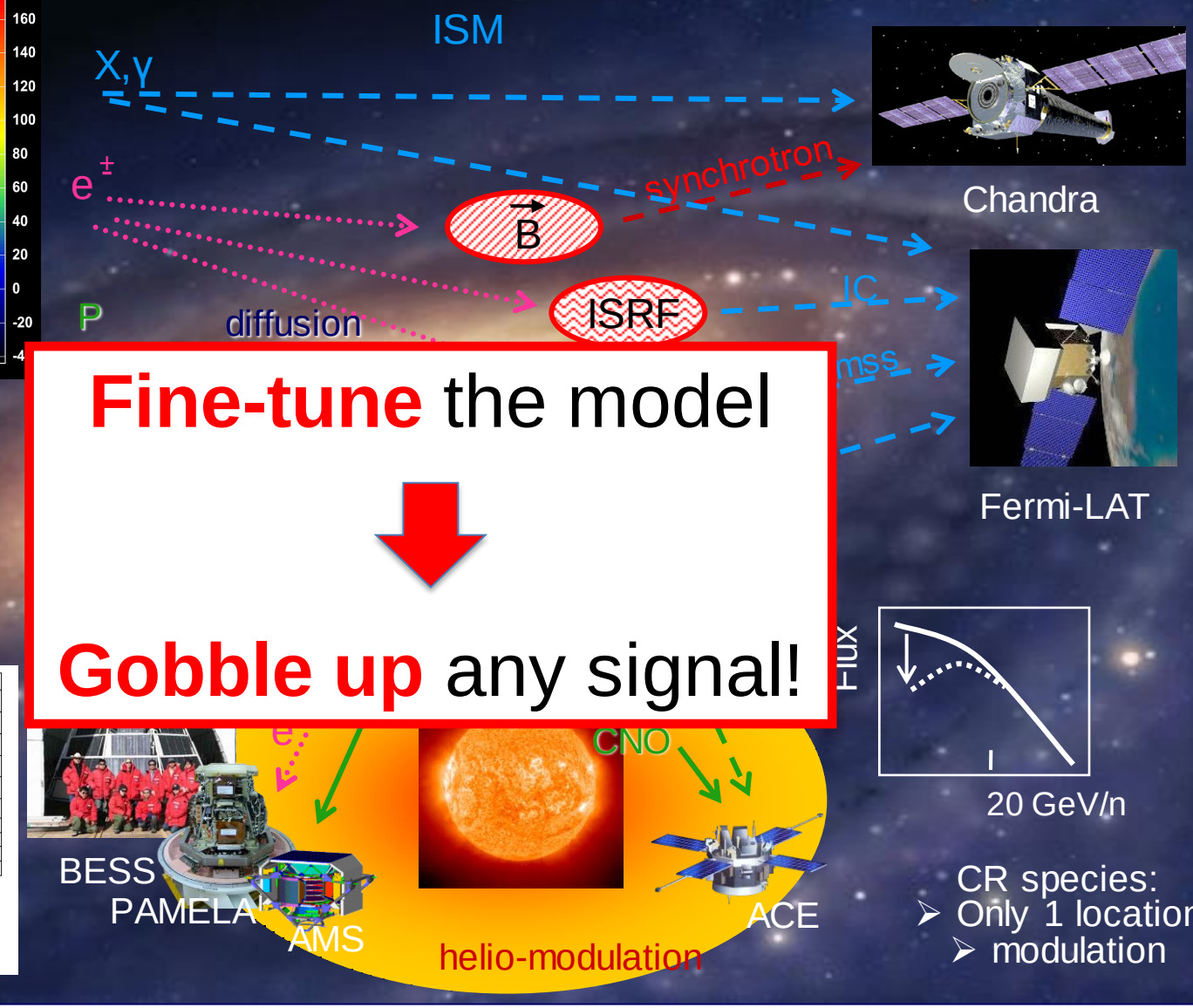
plus point-source

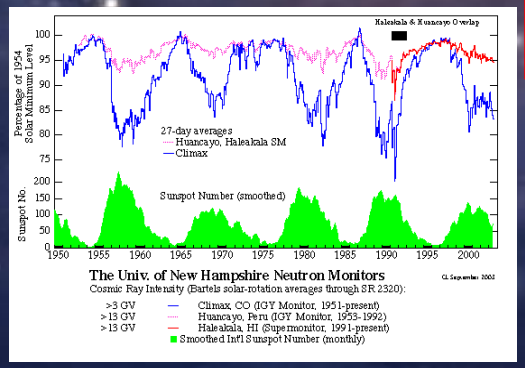
Li

Very **intriguing** mass range (see CDMS+CoGeNT ~ **10 GeV** mass **WIMPs**)

“Over-fitting”

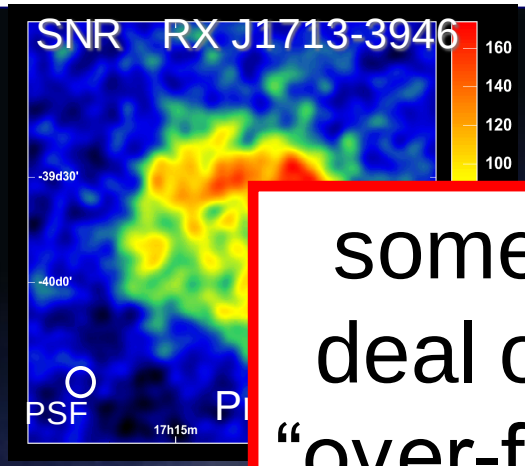






[slide from Igor Moskalenko]

“Over-fitting”



ISM

X,γ

Ira

Fermi-LAT

some diffuse models **designed** to deal optimally with **point sources**: “over-fitting” is welcome in that case!

convection

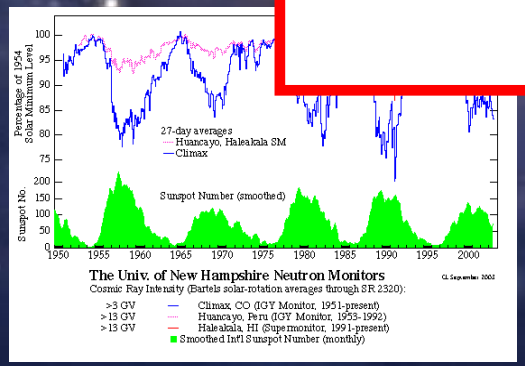
etc.

$e^{\pm}$

$\pi^{\pm}$

π^{0}

beware of how any “**no-residuals**” conclusion is obtained!



BESS

PAMELA

AMS

ACE

helio-modulation

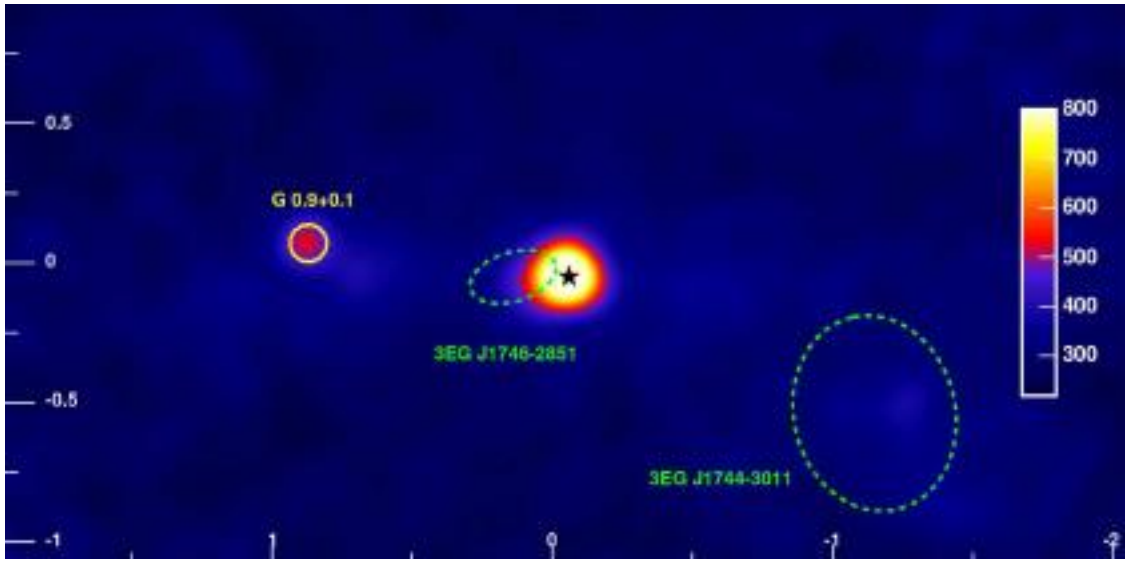
20 GeV/n

CR species:

- Only 1 location
- modulation

[slide from Igor Moskalenko]

One of the elephants in the room: **Sgr A***



We know little about **cosmic rays** in the **GC**

CR power: ~10^{41} **erg/s**; **Sag A*** Eddington lum.: >10^{44} **erg/s**

While very **quiet** now, **Sag A*** likely accelerates and has accelerated protons: study the **gamma-ray** properties

Linden, Lovegrove and SP, 1203.3539 and in prep.

One of the elephants in the room: **Sgr A***

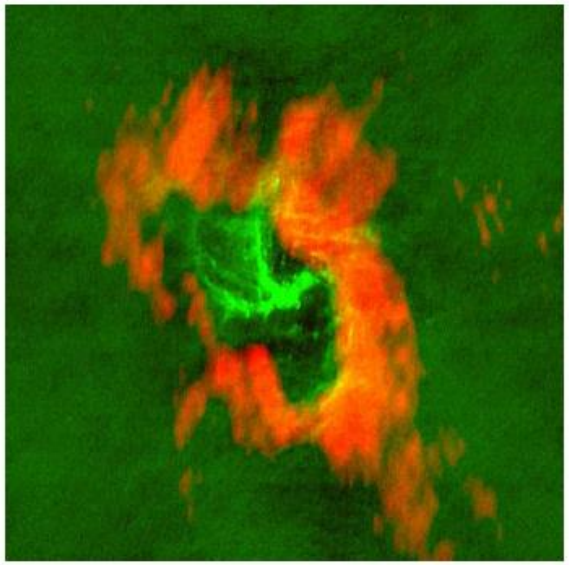
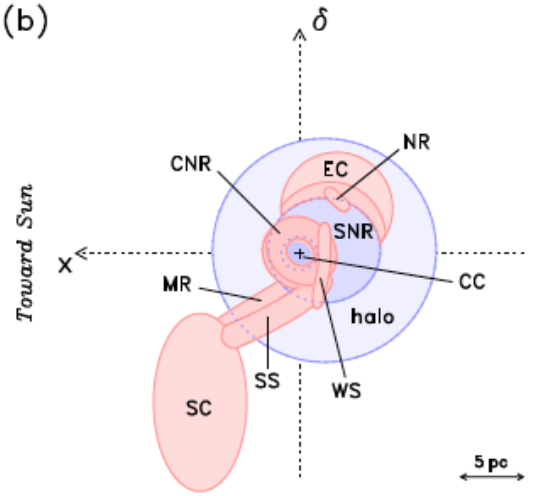


Fig. 2. Composite image showing (in green) the 3.6 cm radio continuum emission from warm ionized gas in the Sgr A West H II region, with the three-arm Minispiral emerging very clearly, and (in red) the 3.4 mm HCN $J = 1 \rightarrow 0$ line emission from the surrounding Circumnuclear Ring (CNR). The radio continuum data are from Yusef-Zadeh et al. (2008) and the HCN data from Wright et al. (2001). Figure credit: Farhad Yusef-Zadeh.

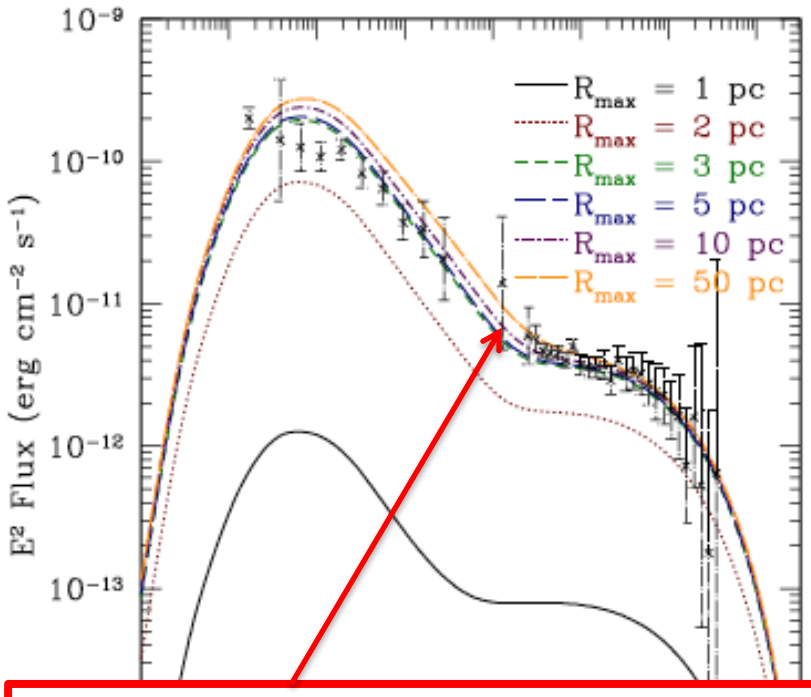
If source is **hadronic**,
GALPROP likely is the **wrong tool**



Need detailed modeling of **gas** distribution
Our approach: **Monte Carlo**

K. Ferrere, 2012; Linden and Profumo, 2012

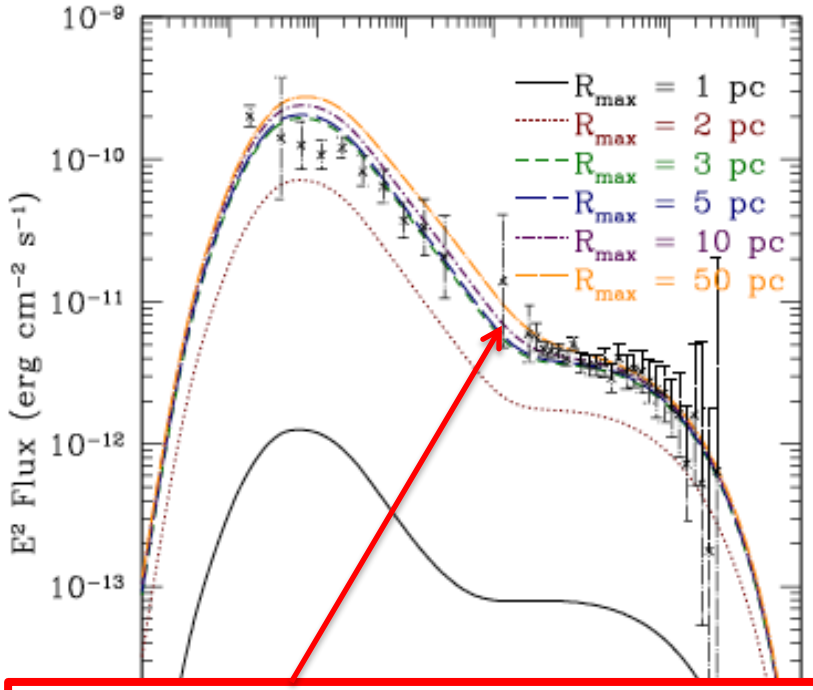
One of the elephants in the room: **Sgr A***



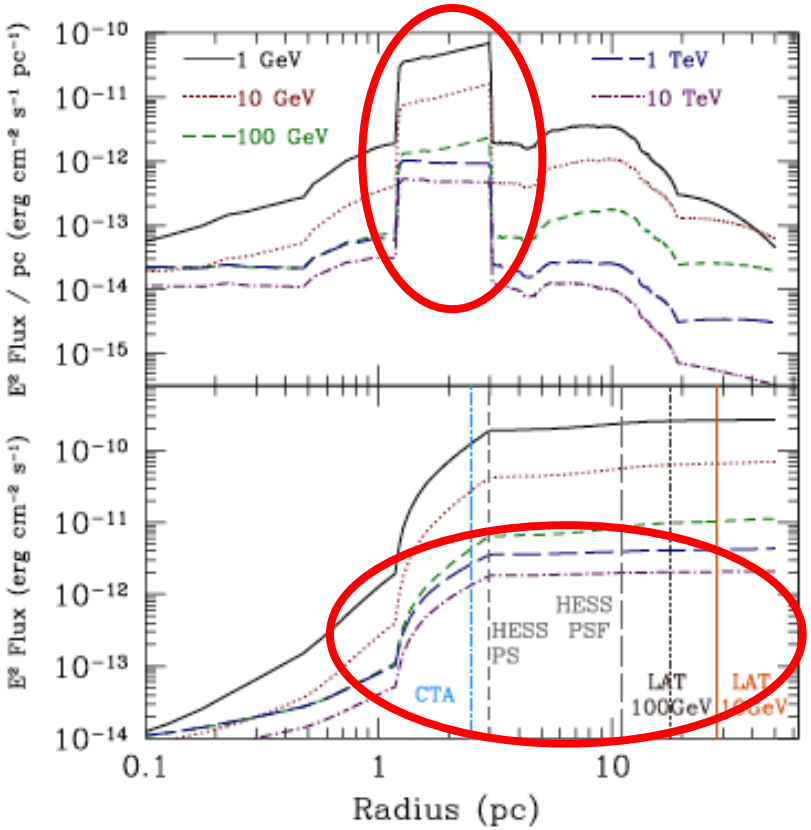
transition between diffusively trapped behavior and rectilinear propagation

Linden, Lovegrove and SP, 1203.3539, ApJ 753 (2012) 41

One of the elephants in the room: **Sgr A***



transition between diffusively trapped behavior and rectilinear propagation



key diagnostics: circum-nuclear ring!

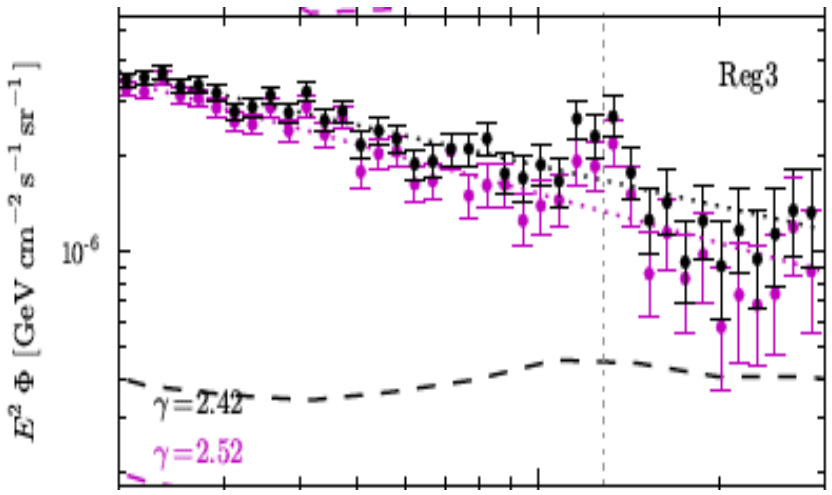
Chernyakova et al, 2011; Linden, Lovegrove and SP, 1203.3539, ApJ 753 (2012) 41

Galactic Center: the way forward??

- seek a "**golden mean**" between over- and under-fitting
- detailed **cosmic ray** and **target density** models
- **data-driven** backgrounds

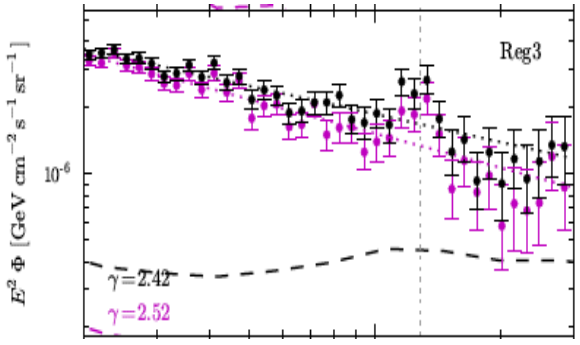
Linden, SP,…, in progress

The Gamma-Ray Line



"Troubling and Inconclusive"

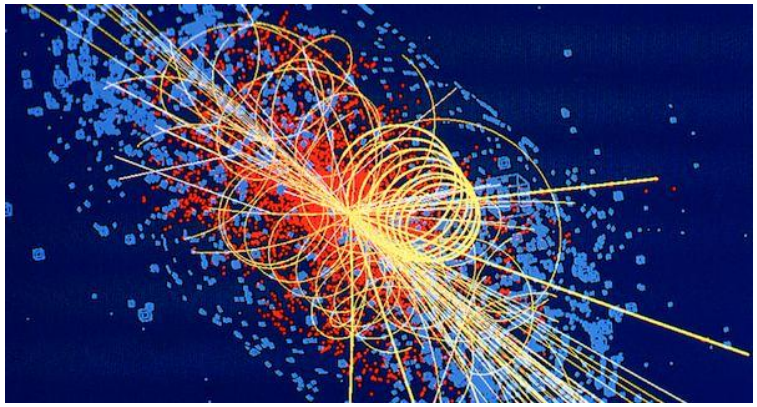
Steve Ritz
Fermi-LAT Deputy PI



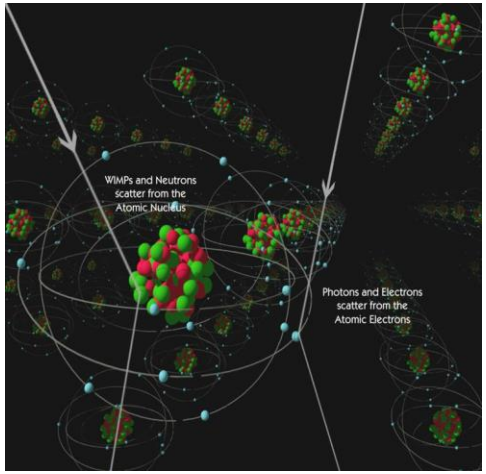
If confirmed, huge **impact** on **particle physics**!

DM particle at rest, so $\chi\chi \rightarrow \gamma\gamma$ implies $\mathbf{E_\gamma = m_\chi}$!

m_χ sets the **missing energy** scale for **collider** studies

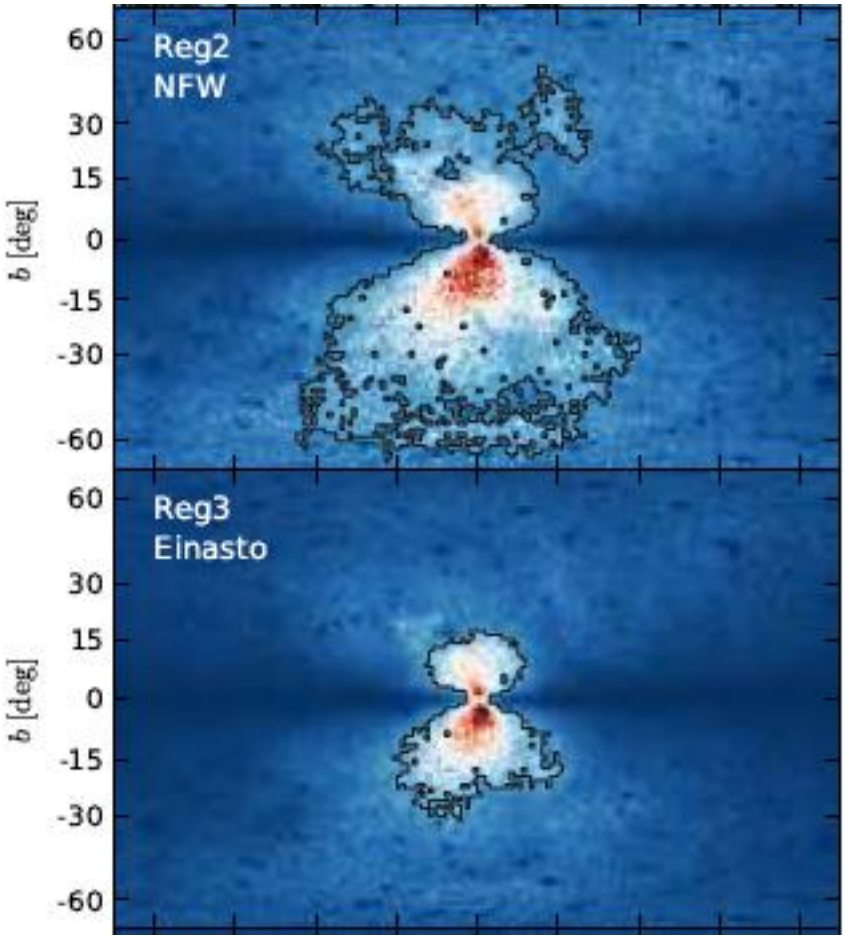


…and the target mass for **direct detection** experiments!



Weniger (1204.2797)

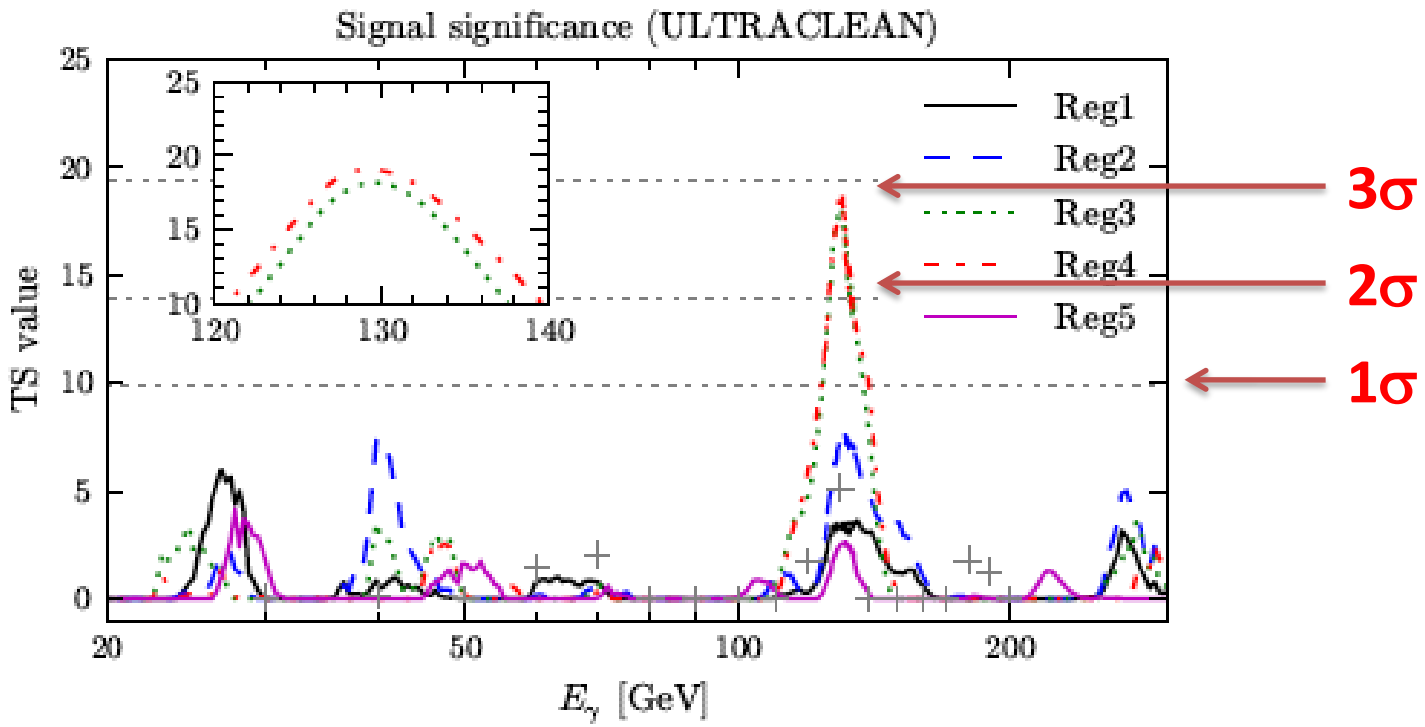
Key novelty: **optimized** Regions of Interest



Signal: $\sim(\rho_{DM})^2$

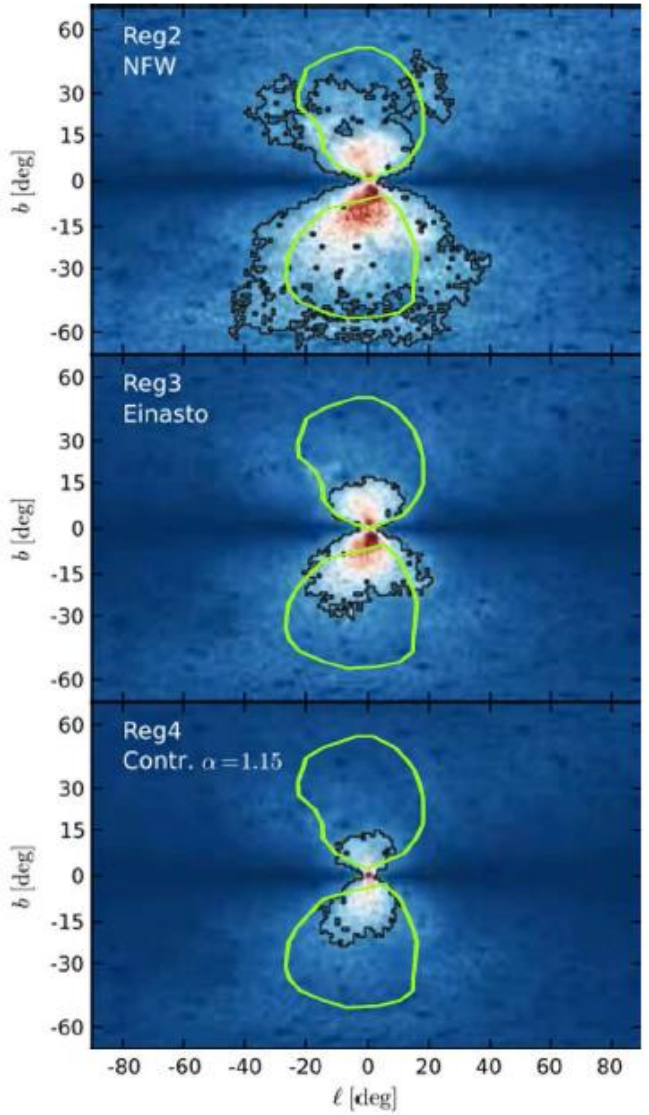
Noise: (1-20 GeV sky)$^{1/2}$

(almost) **3σ effect**, E_γ=**130 GeV** look-elsewhere effect accounted for



Two remarks*

(1) ROI's overlap with **Fermi bubbles**: photons from bubbles are important **background**

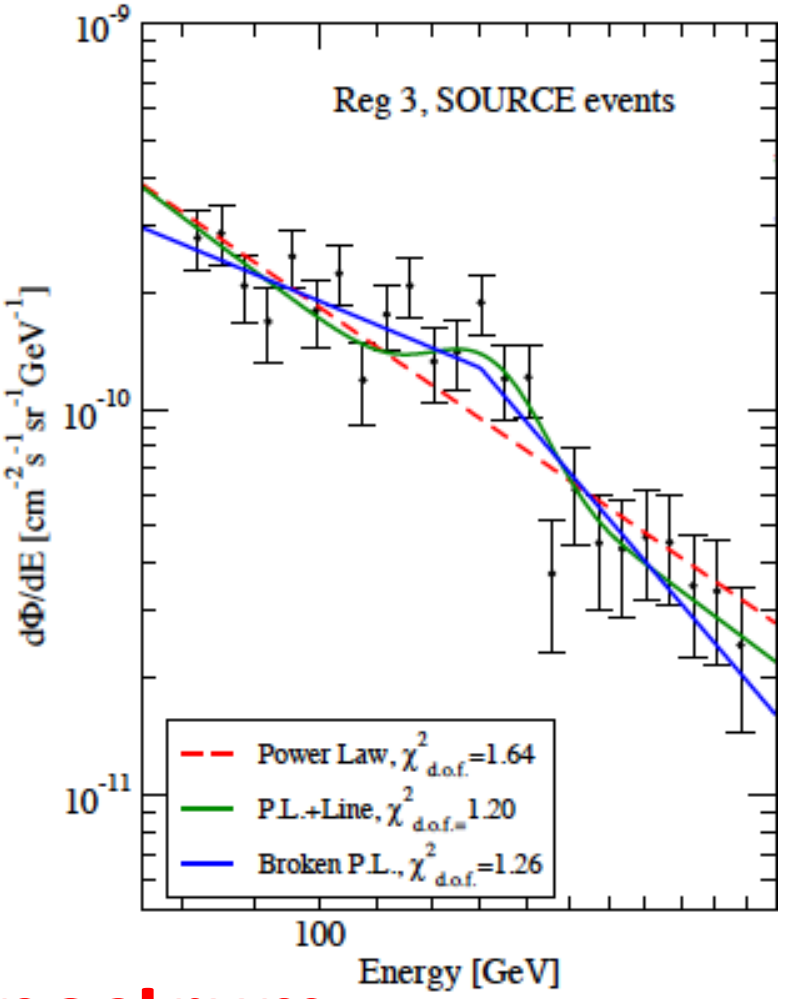


* Profumo and Linden, "Gamma-Ray Line in the Fermi Data: is it a Bubble?", JCAP 2012

Two remarks*

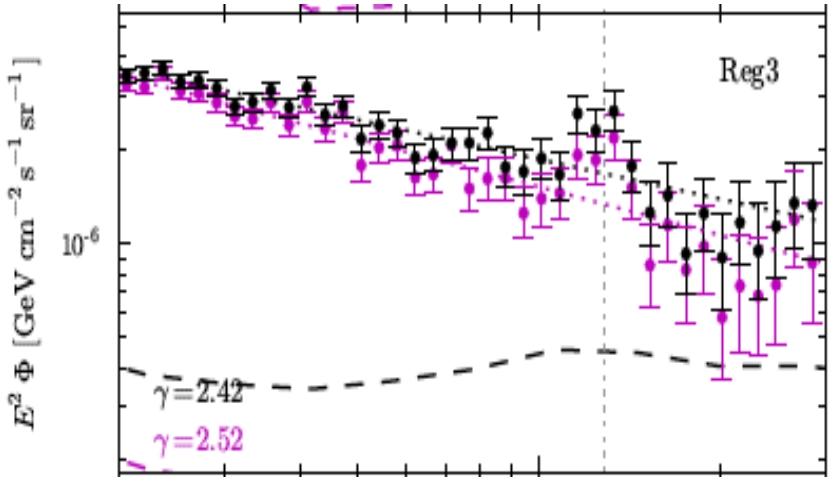
(1) ROI's overlap with **Fermi bubbles**: photons from bubbles are important **background**

(2) broken power-law could be **mistaken** for a **line** - Fermi bubbles have **broken power-law spectrum**



* Profumo and Linden, "Gamma-Ray Line in the Fermi Data: is it a Bubble?", JCAP 2012

could it be an
instrumental effect?



One culprit could be **energy reconstruction**:
E>130 GeV mis-read as E=130 GeV event!

Instr. effects under investigation by Fermi Collaboration,
including troubling **Earth's Limb** feature!
[**Pass 8**: currently being tested internally/public in ~1yr]

If not instrumental, potentially **very interesting**
wait for **more statistics** (so far ~50 photons)!

can we hope for more statistics with **other** existing/near future **telescopes**?

Fermi: $A_{eff} x T_{obs} = (1\ m^2) \times 4\pi \times 10^7 \times (1/6)\ s \sim$ **$2 \times 10^7\ m^2\ s$**

ACT, with 100h: $(10^5\ m^2) \times 100 \times 60 \times 60\ s \sim$ **$3 \times 10^{10}\ m^2\ s$**

e.g., HESS: promising,
but **A_{eff}** rapidly **declining**
in energy region of interest

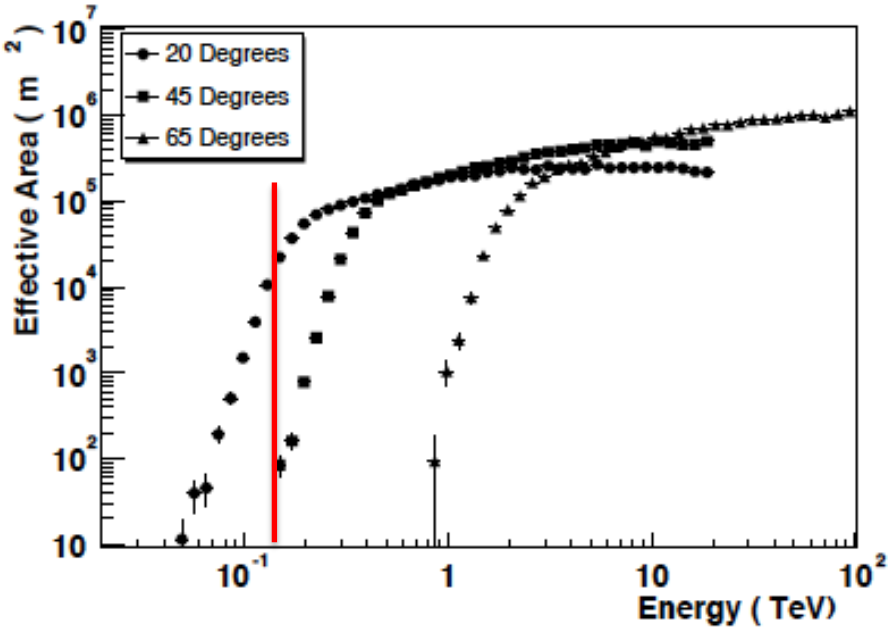
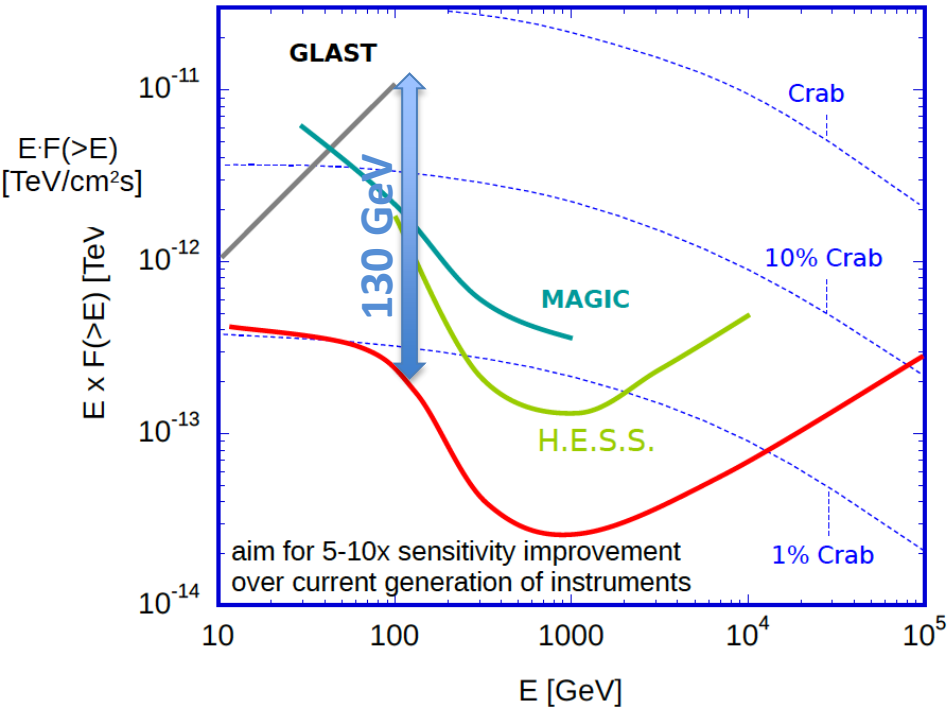
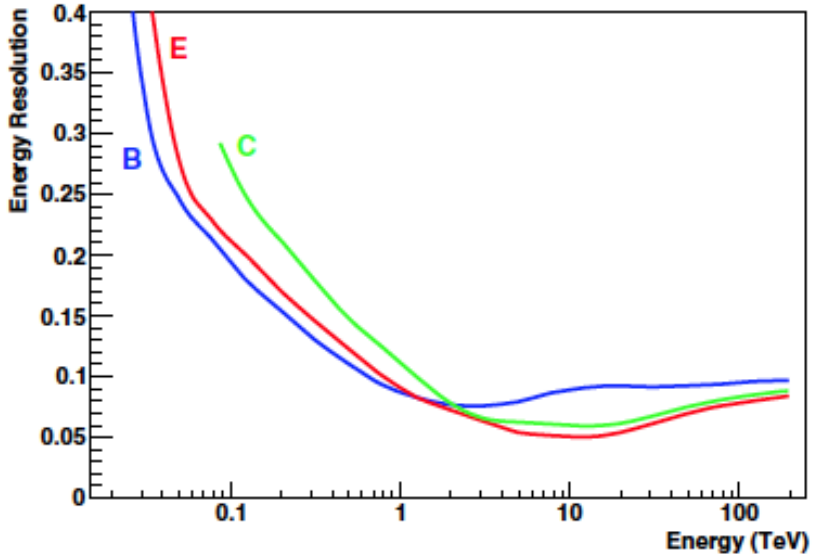


Figure credit: Benow, for HESS collaboration

CTA: superior energy resolution, angular resolution, energy threshold and effective area





Cherenkov Telescopes will be **key** for further studies of the **line**

Astrophysical backgrounds?

Always keep **Occam** in mind!

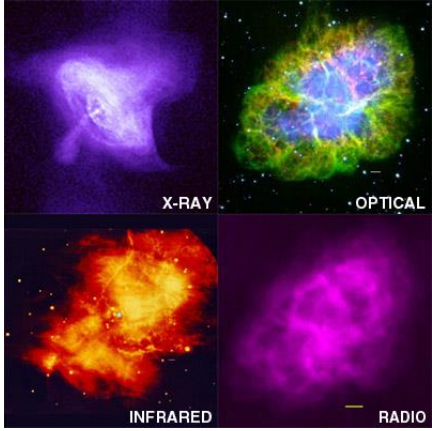
Klein-Nishina regime: almost all energy transferred from e to γ → $\mathbf{E_e \sim 130\ GeV}$

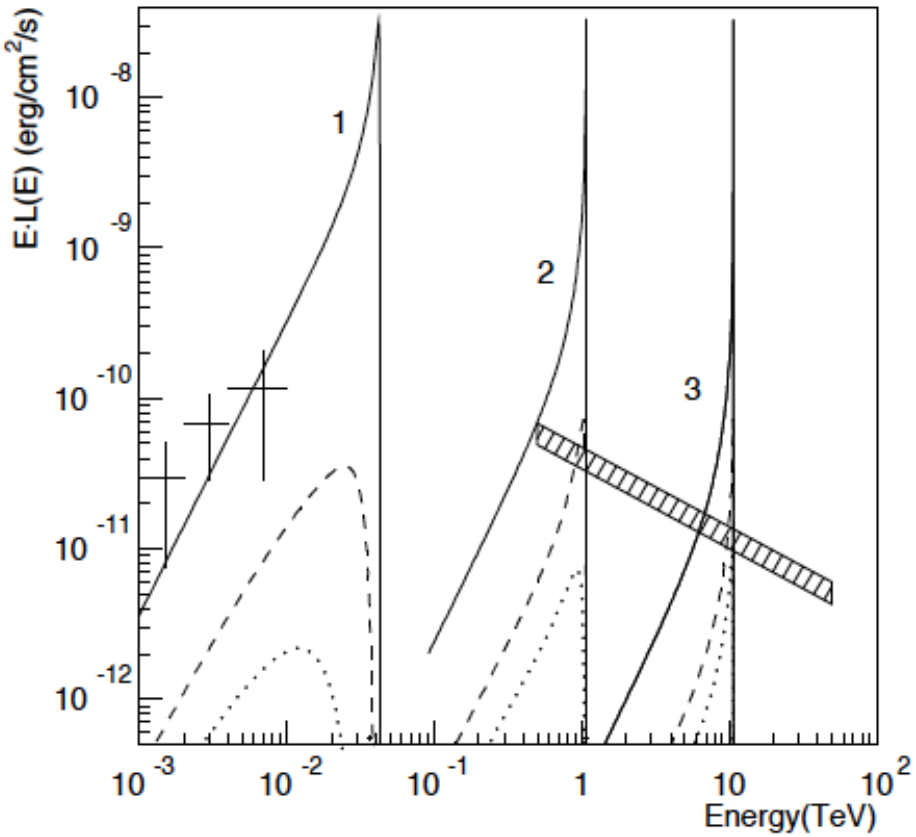
Need~ mono-chromatic electrons and target photons with $\omega_0 >> m_e^2/E_e \sim$ **2 eV**

Both OK with **electron pulsar wind**

Aharonian et al, 2012; image credit: NASA

This is **not** a **POST-diction**!

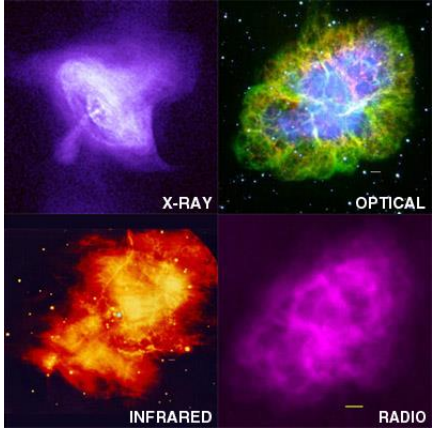




Bogovalov and Aharonian, **2000**

Energetics works out fine!

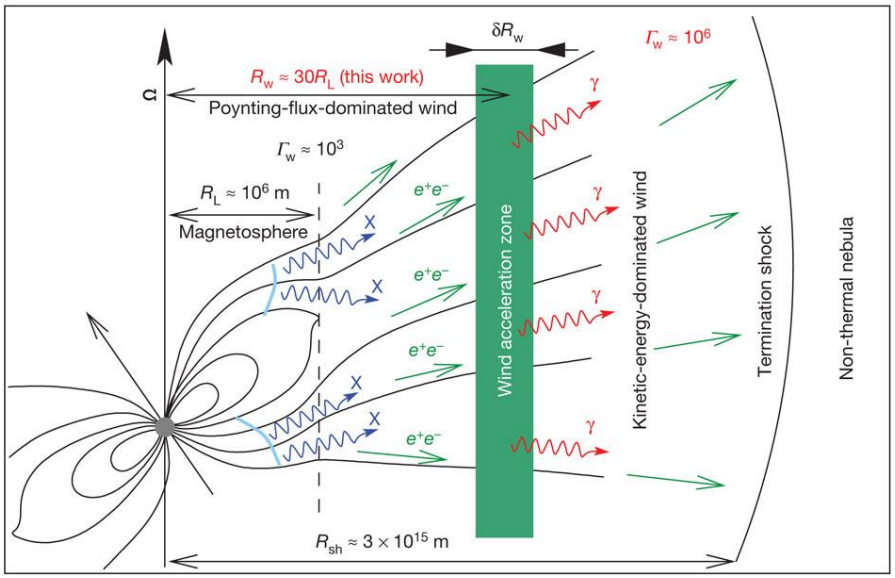
130 GeV line luminosity ~ **3×10^{35} erg/s**



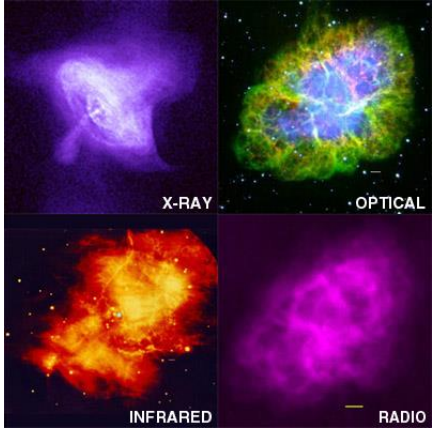
Crab luminosity in shock-acc. e^+e^- ~ **3×10^{38} erg/s**

[spin-down luminosity~ 5×10^{38} erg/s]

efficiency to produce gamma rays??



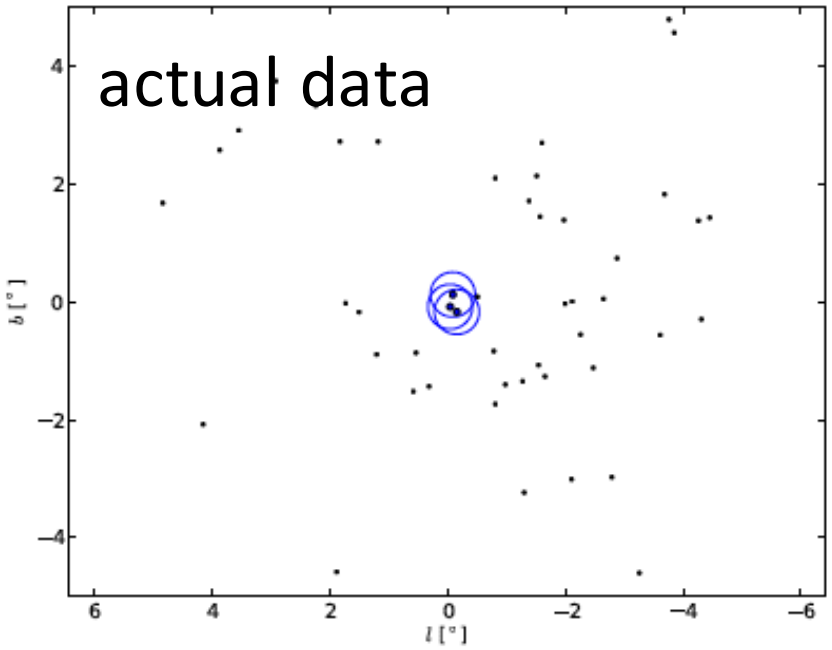
Aharonian et al, Nature 2012

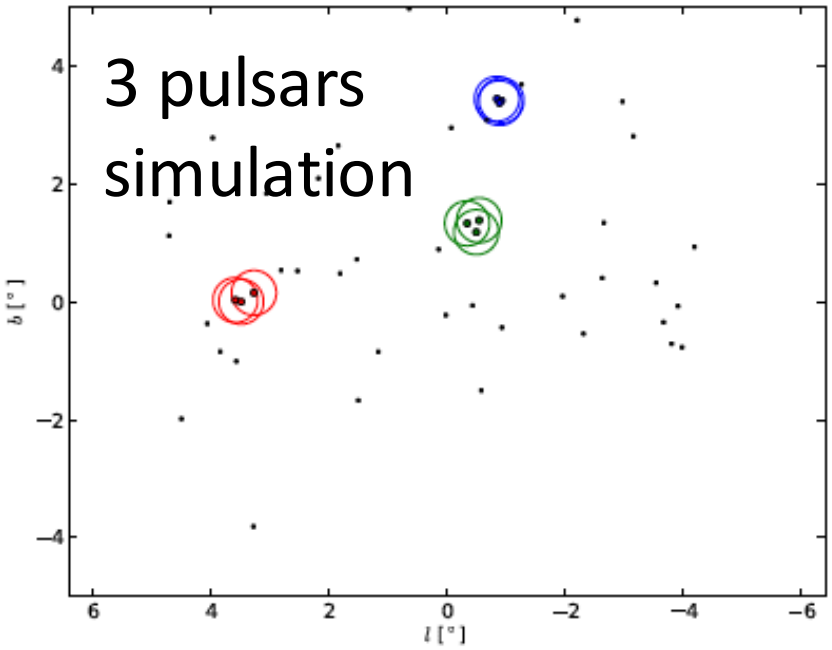


Many open questions…

- **how many** point sources are needed?
- if more than one astrophysical source is needed, do we expect **130 GeV** to be a **special** universal **value**?

Applied a **clustering algorithm** (DBSCAN) and demonstrated one needs at least **5 pulsars** (@90%CL)





Astrophysical backgrounds are **unlikely**, given current data!

Carlson, Linden, Profumo and Weniger, JCAP, 1304.5524 (2013)

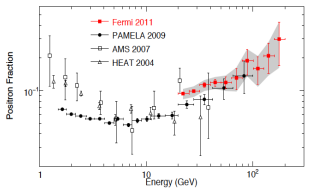
- 130 GeV line “troubling and inconclusive”, yet **exciting**!

- low **statistics**, perhaps **instrumental**, but **unlikely “astrophysical”**

- look forward to: Fermi’s **Pass8** and **ACT**

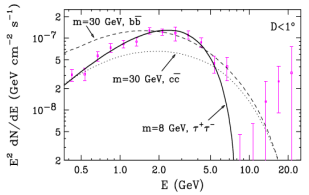
A (dark matter) model that does everything?

Positron Excess



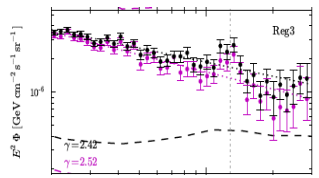
mass ~ 1 TeV,
$\mu^+\mu^-$ (more likely $\pi\pi$)

Galactic Center



mass ~ 10 GeV,
bb or $\tau^+\tau^-$

130 GeV line



mass = 130 GeV,
enhance line, no continuum

Positron excess, **Galactic Center excess**, **“The Line”**

Is this all “chasing ambulances”?

“Ambulance chasing OK,
as long as the **patient is not dead**”