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SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

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Searching for Dark Matter from the Sky

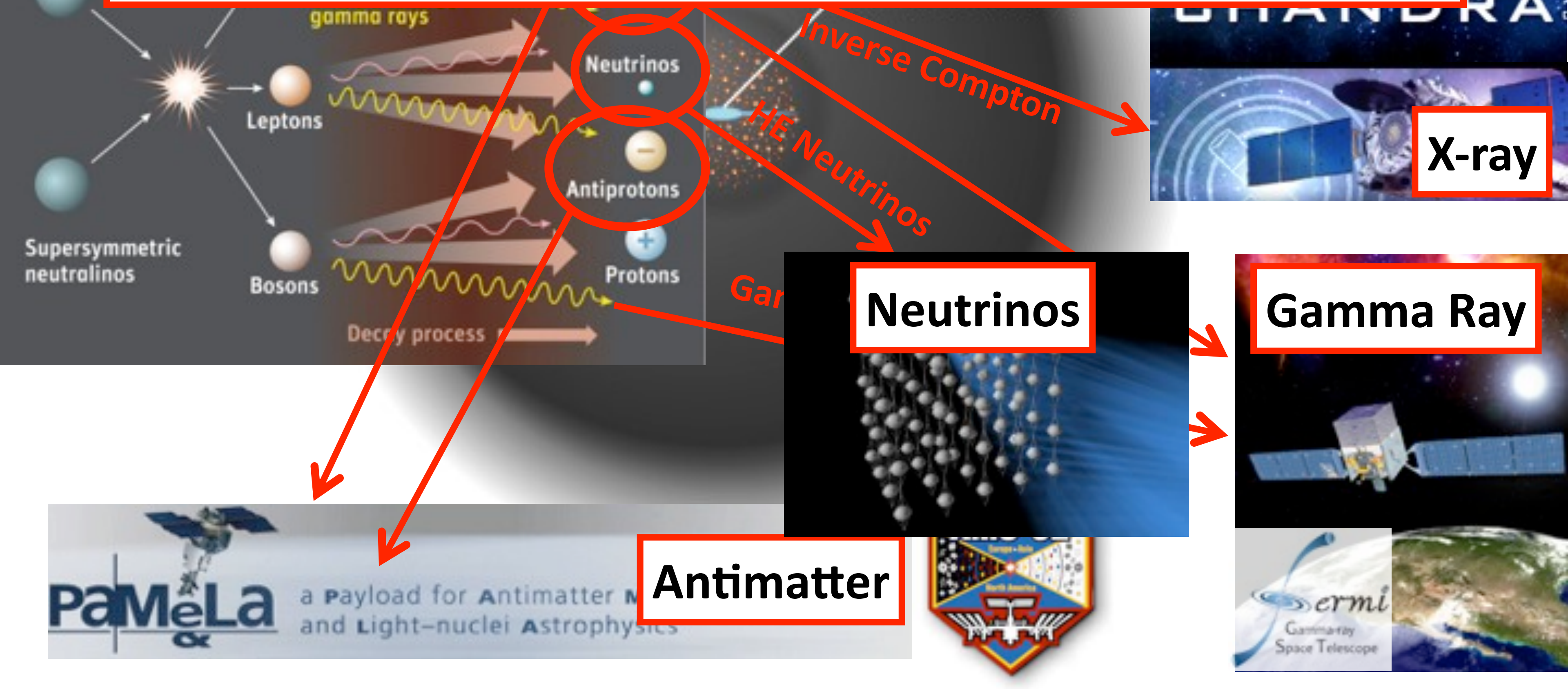
Cosmic Rays, Gamma Rays, and the Hunt for Dark Matter

21st International Conference on Supersymmetry and Unification of Fundamental Interactions

ICTP, Trieste, August 26, 2013

“Indirect” Dark Matter Detection

Can we do fundamental physics with indirect DM detection?

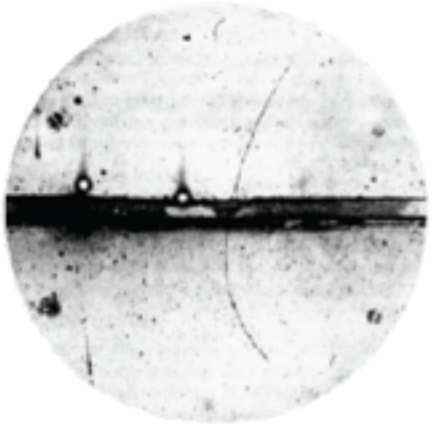


“Indirect” Dark Matter Detection

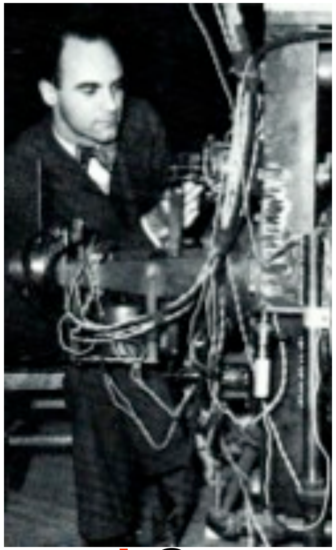
Can we do fundamental physics with indirect DM detection?

“Indirect” Dark Matter Detection

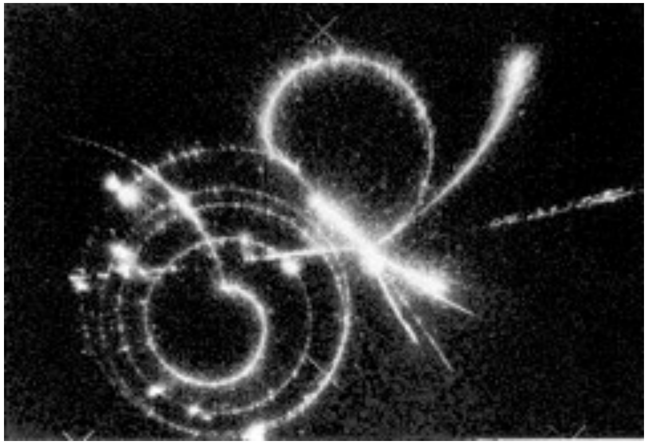
Can we do fundamental physics with cosmic-ray/gamma-ray data?



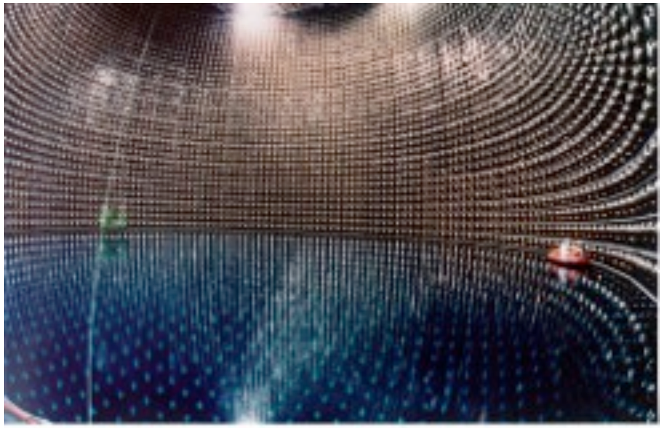
Antimatter
(positron, Anderson, 1932)



Second Generation
(muon, Anderson, 1936)



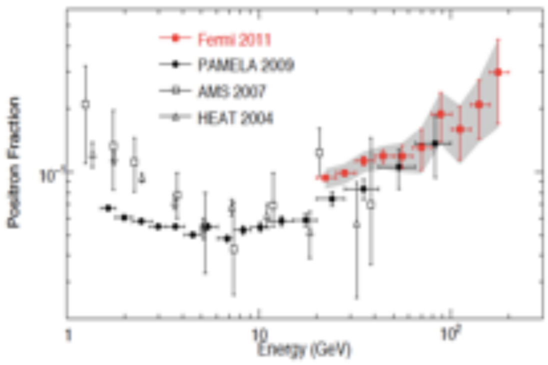
Pions ("Yukawa" particles)
(Lattes, Powell and
"Beppo" Occhialini)



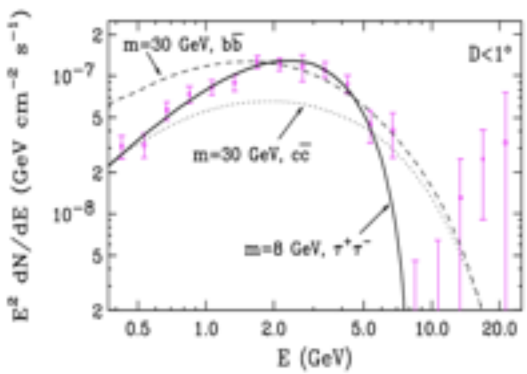
Neutrino Masses

3 tantalizing results might start delivering fundamental physics from the sky

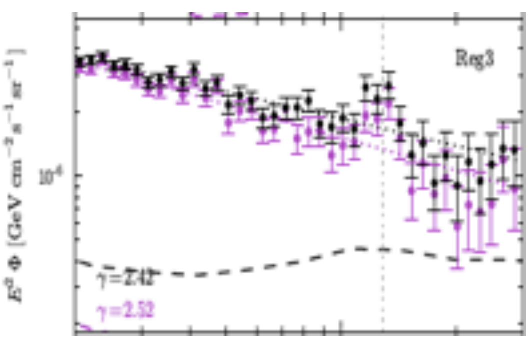
Cosmic-Ray Positron Excess



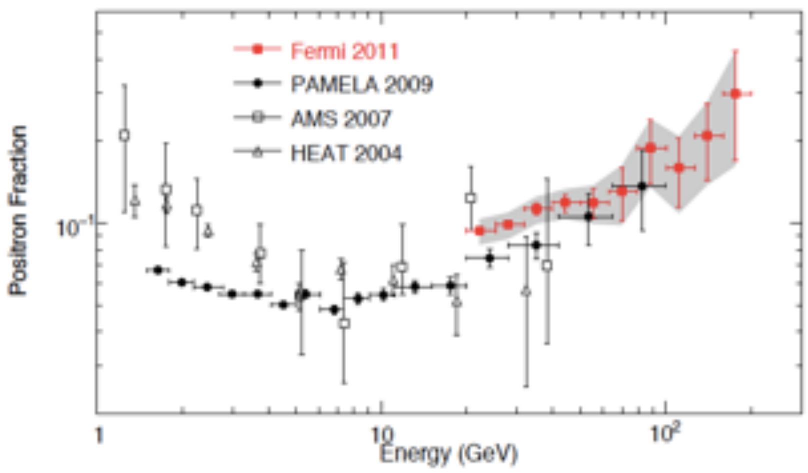
Gamma-ray excess in the Galactic Center?

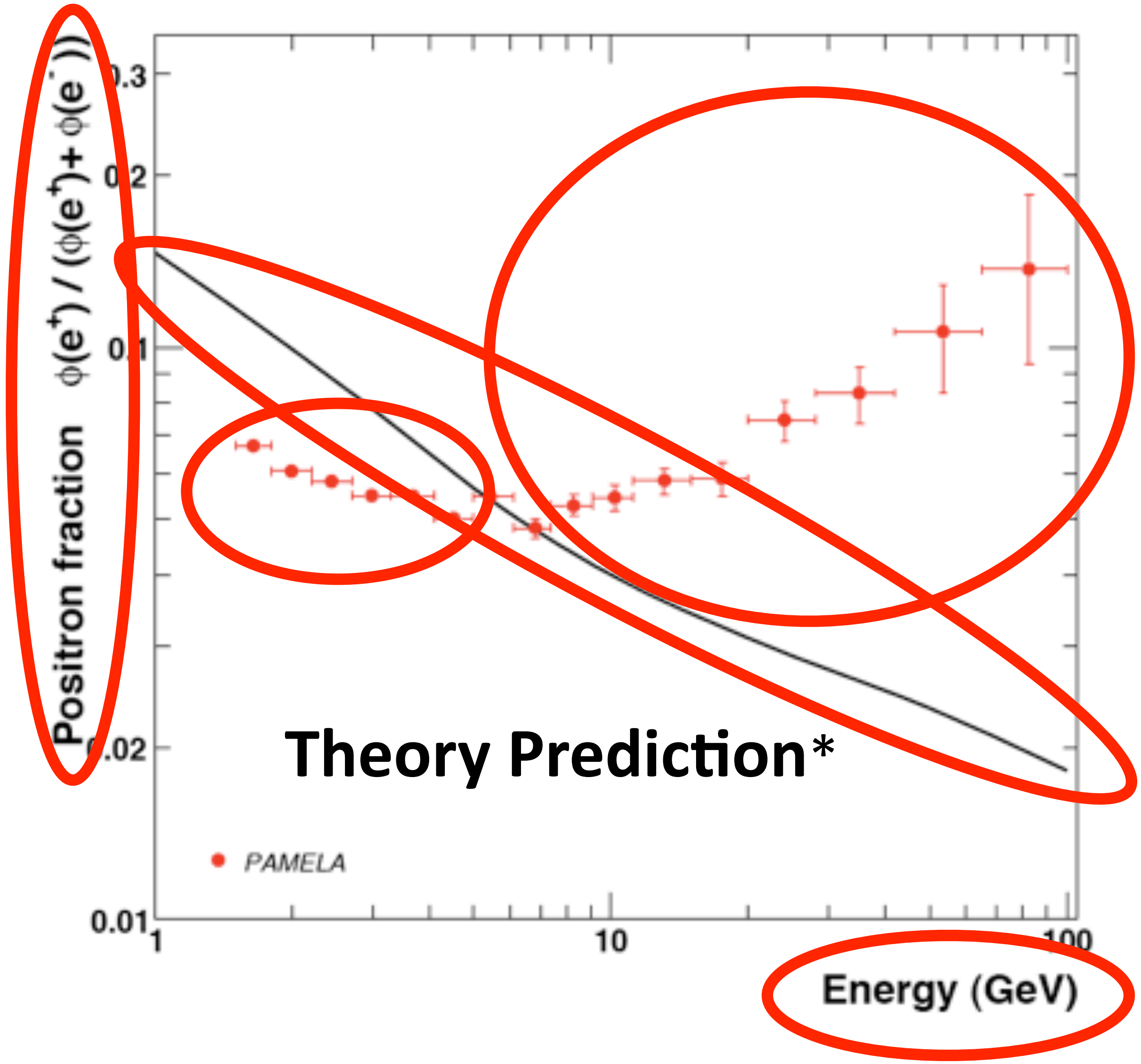


A 130 GeV line



Cosmic-Ray Positron Excess

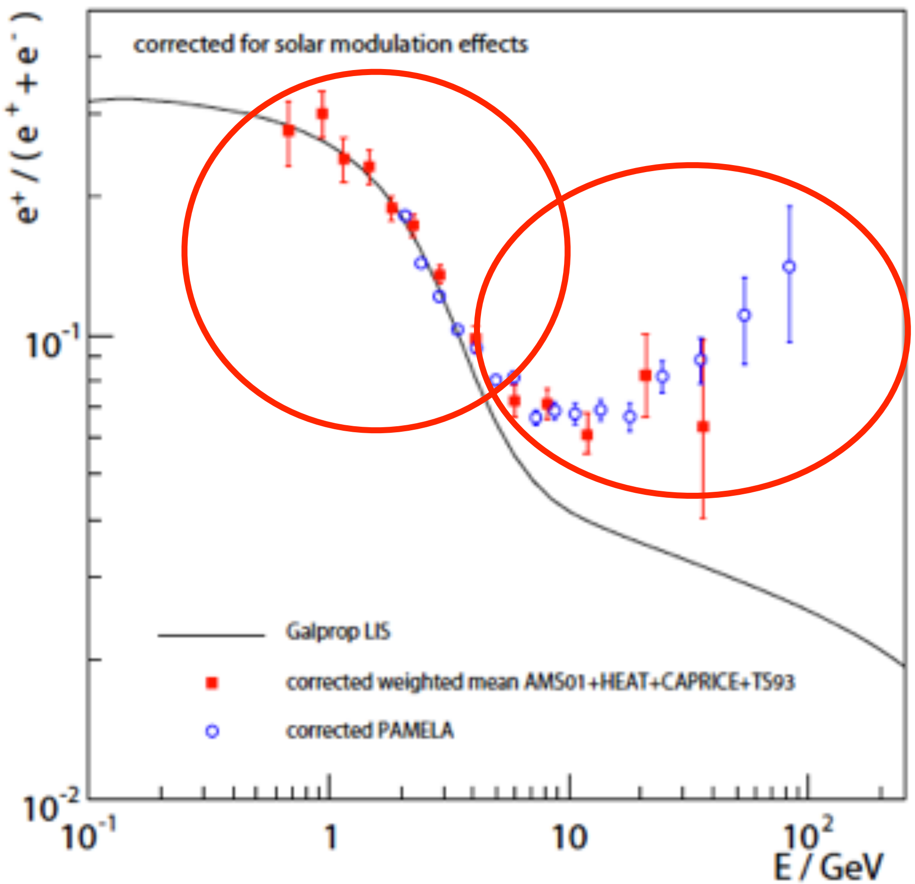




Adriani et al, Nature 458 (2009) 607, arXiv 0810.4995

*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

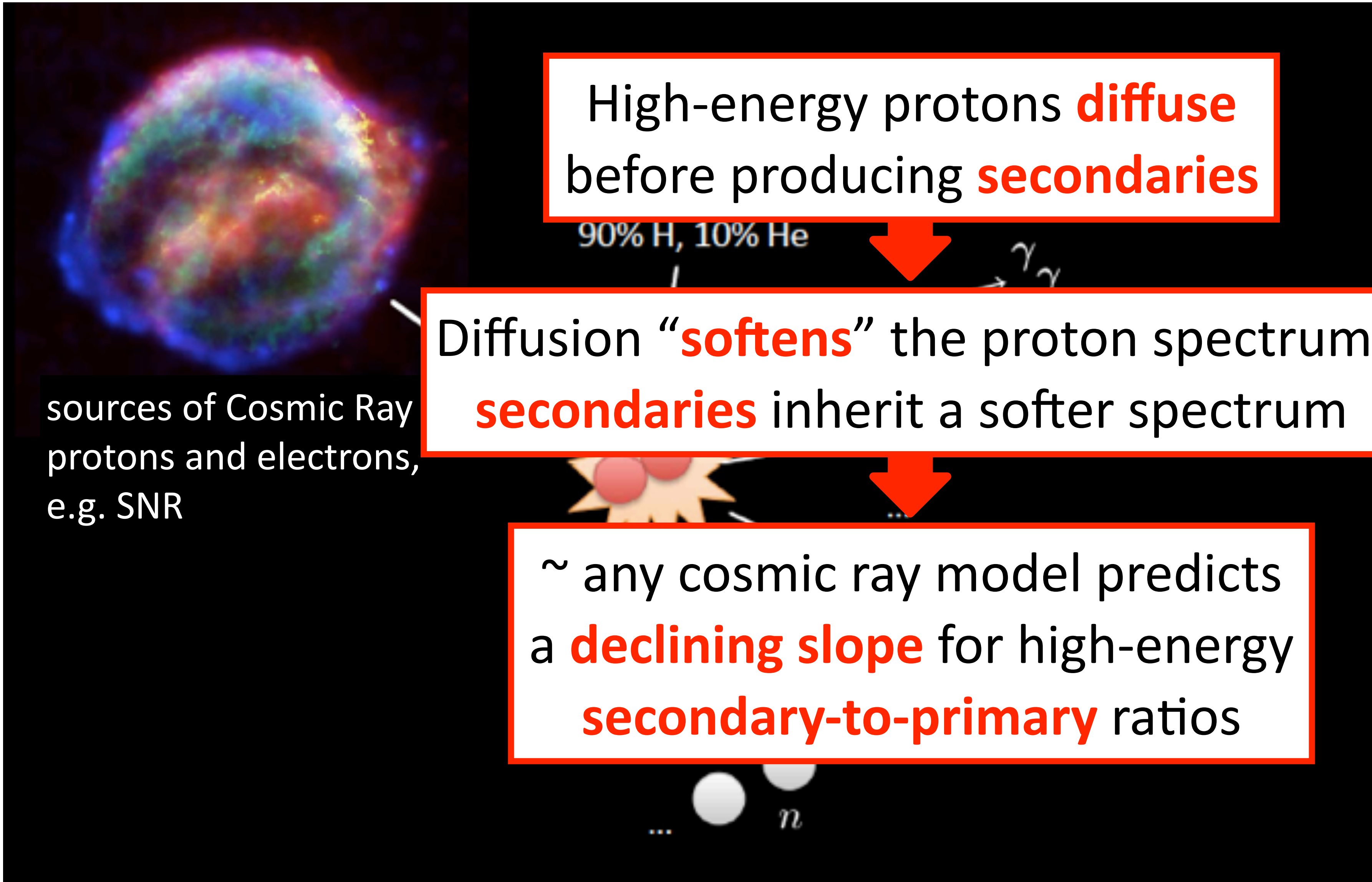


image credit: Philip Mertsch

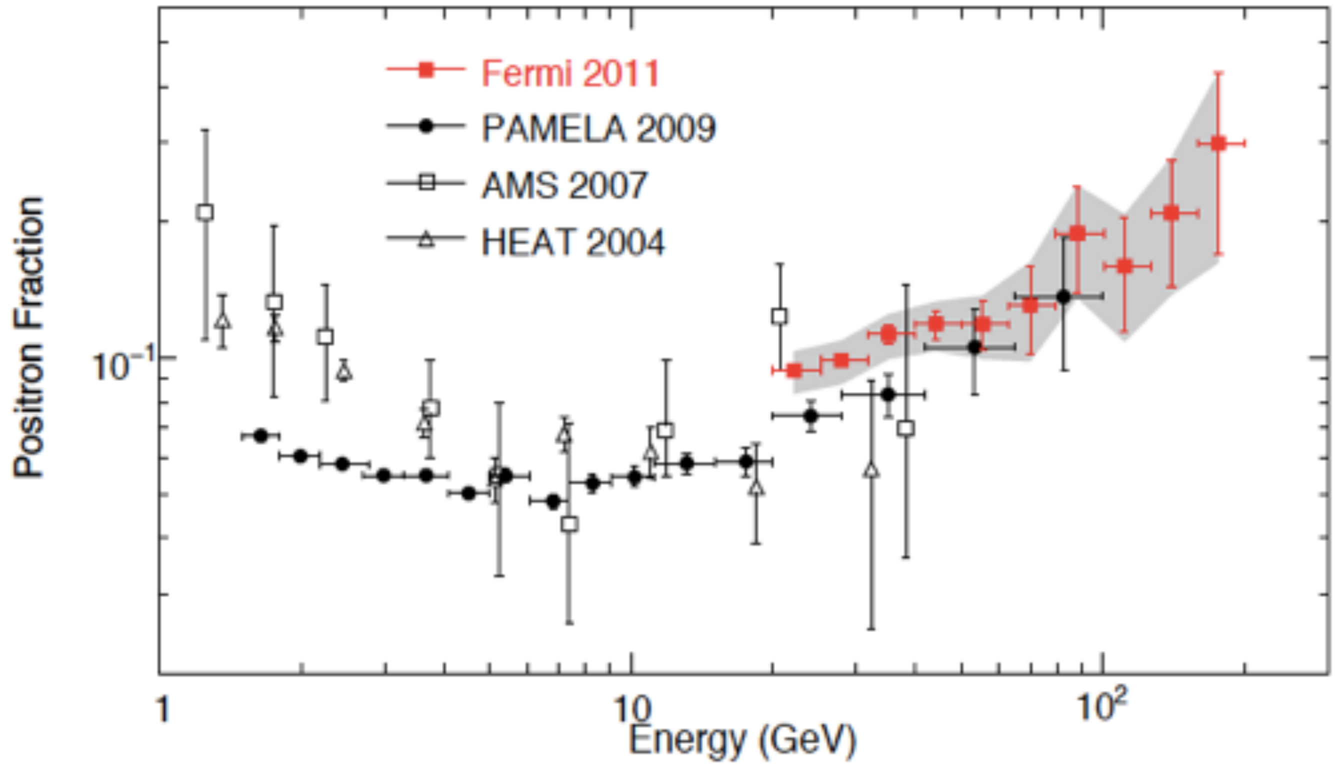
is the **positron** excess **real**?

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

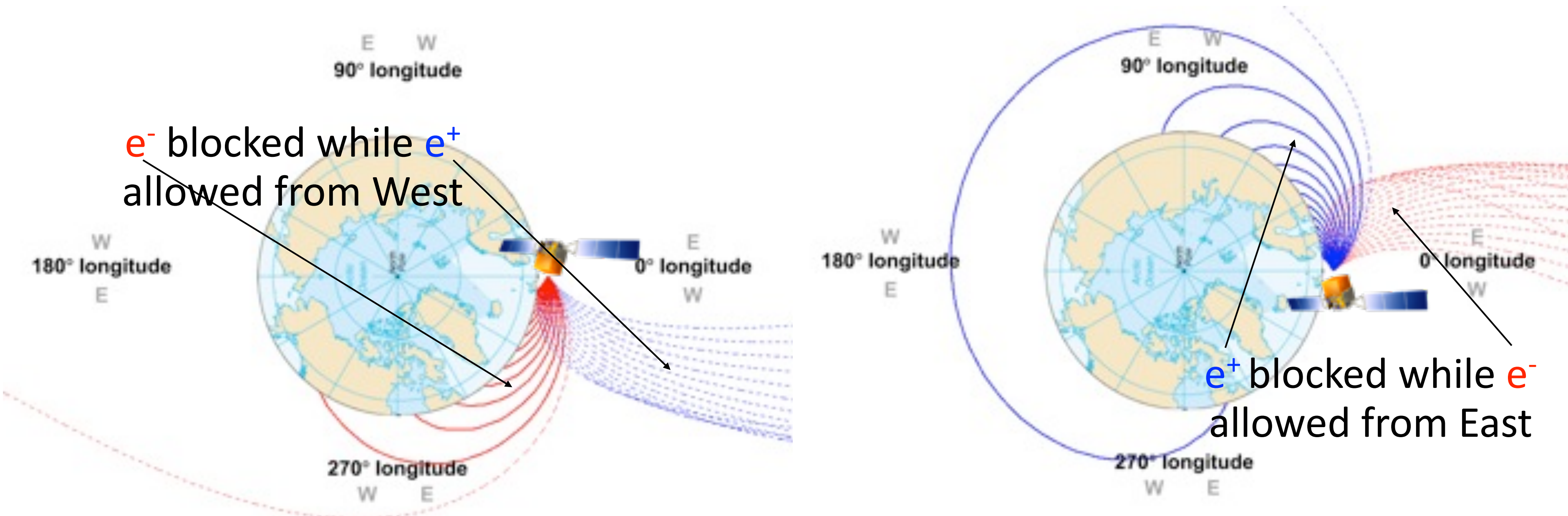
* quoted from the Guardian



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

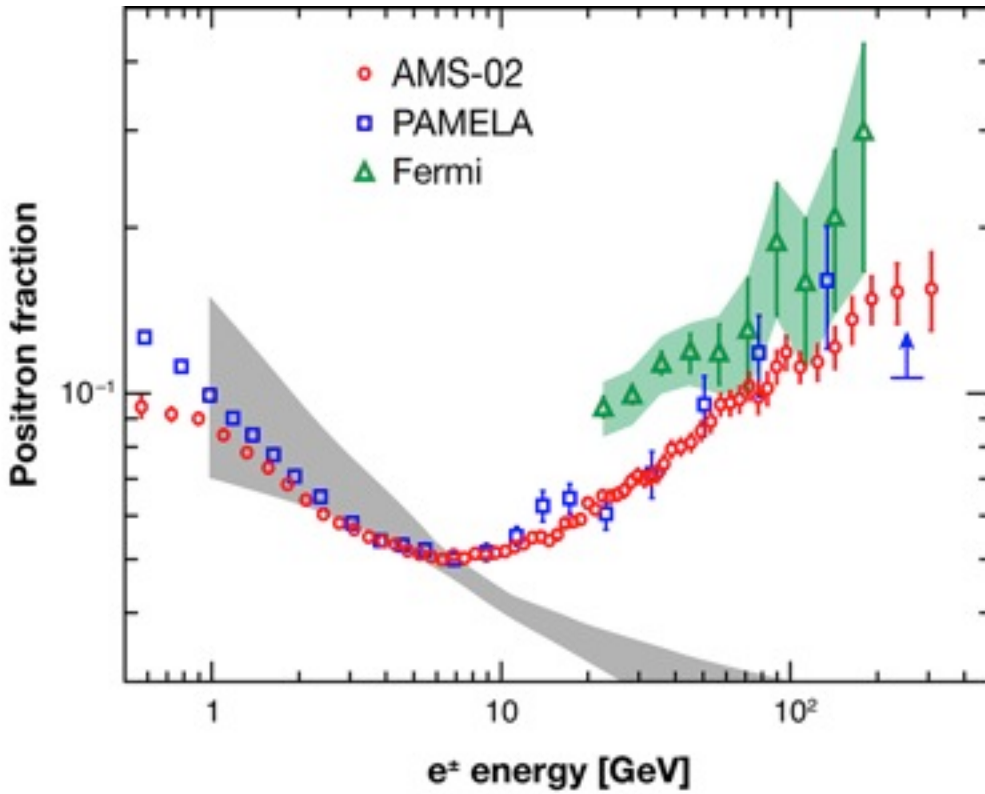


For particular directions, electrons or positrons are completely forbidden

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

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

April 3, 2013



AMS-02 first results **confirm**

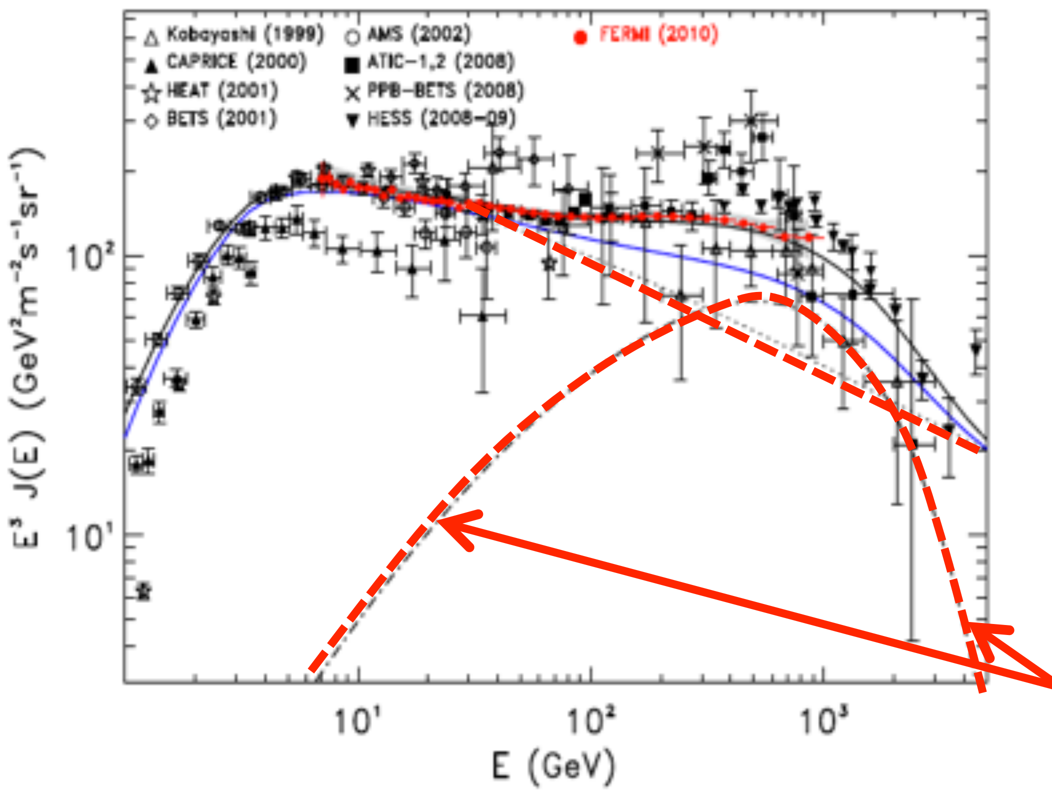
positron excess with very **high statistics** (x100)

PRL, **110** (2013) 14

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

Can we determine the **source?**

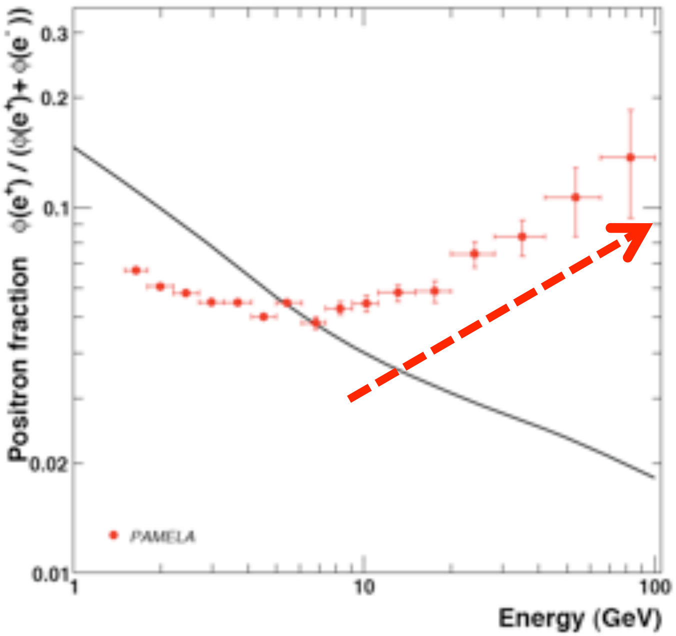
key piece of the **puzzle**:
the **Denominator** ($e^+ + e^-$)

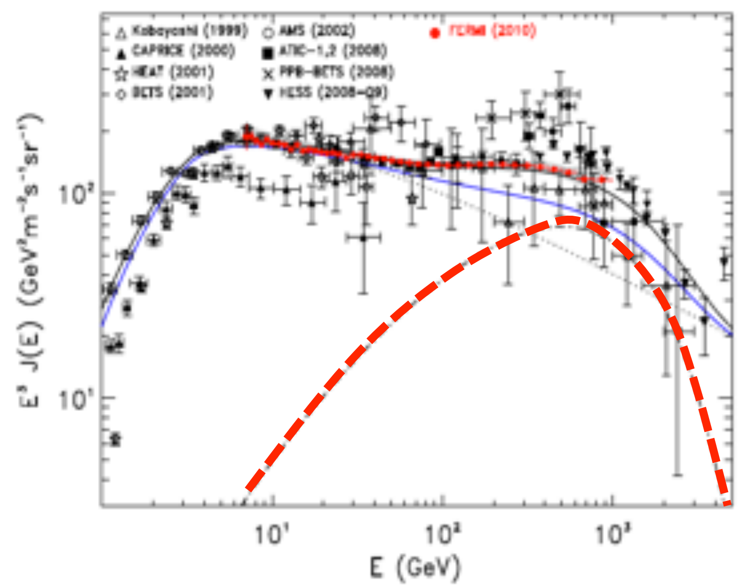


Galactic Cosmic Ray **acceleration** should produce a **power-law** e+e- injection spectrum with a high-energy **cutoff**

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!

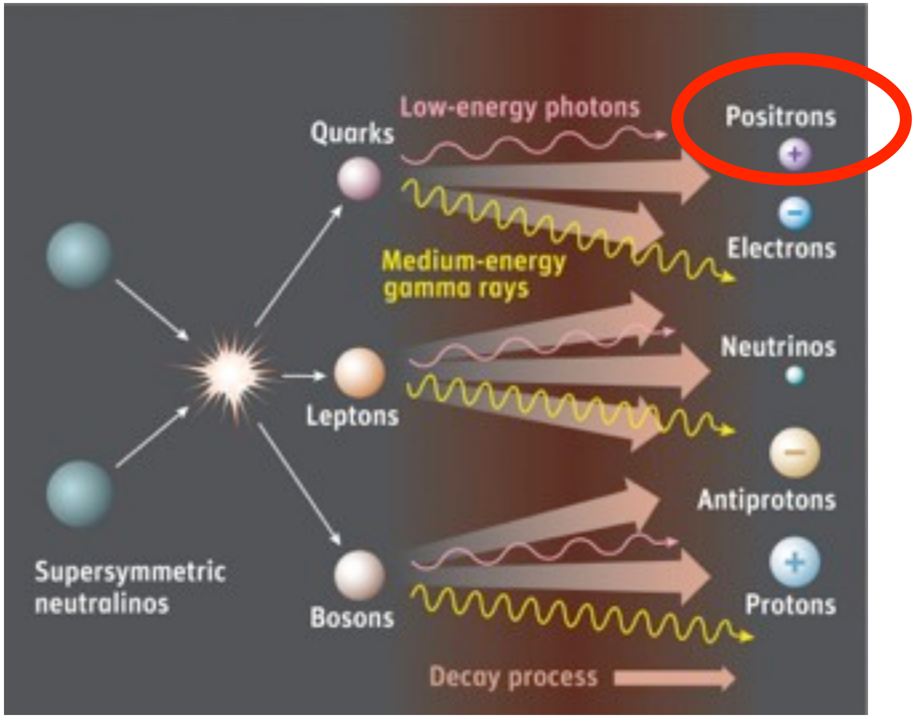


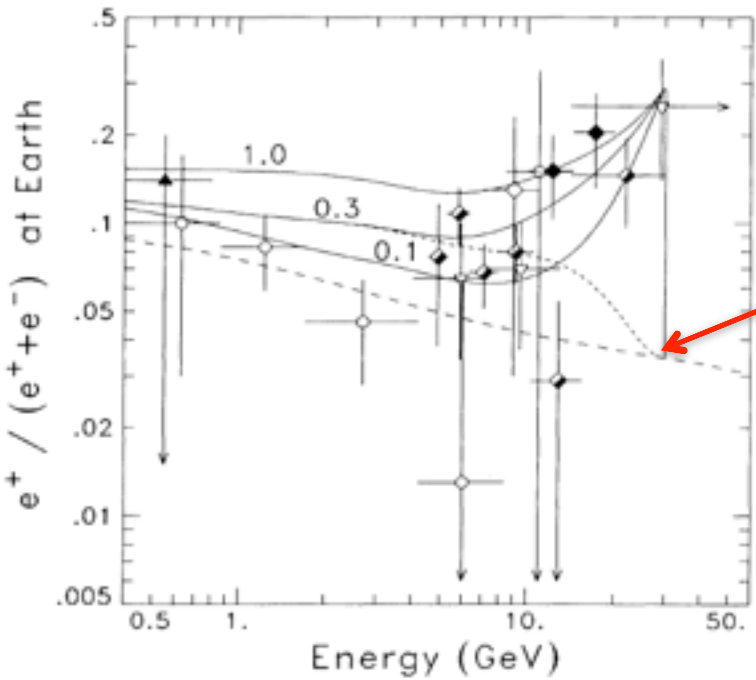
Image Credit: NASA/GLAST collaboration

Exciting!

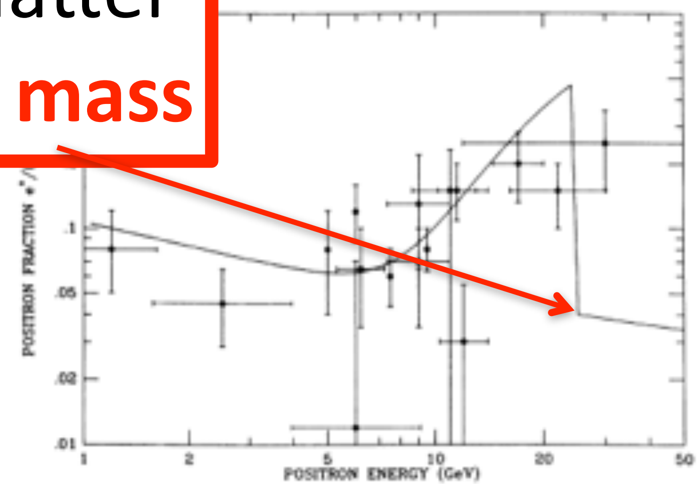
It could be New Physics:

Dark Matter Annihilation!

Dark Matter particle **mass**



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



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

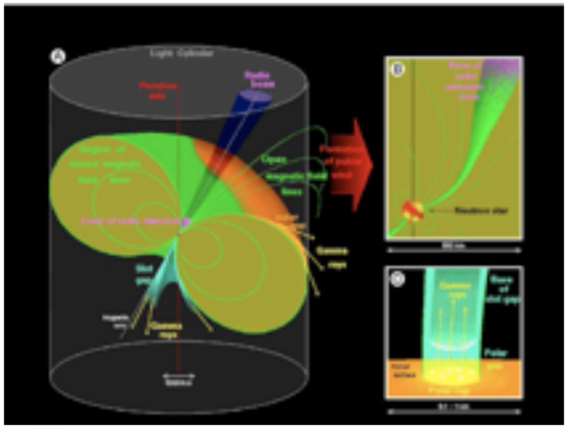
Exciting!

It could be New Physics:

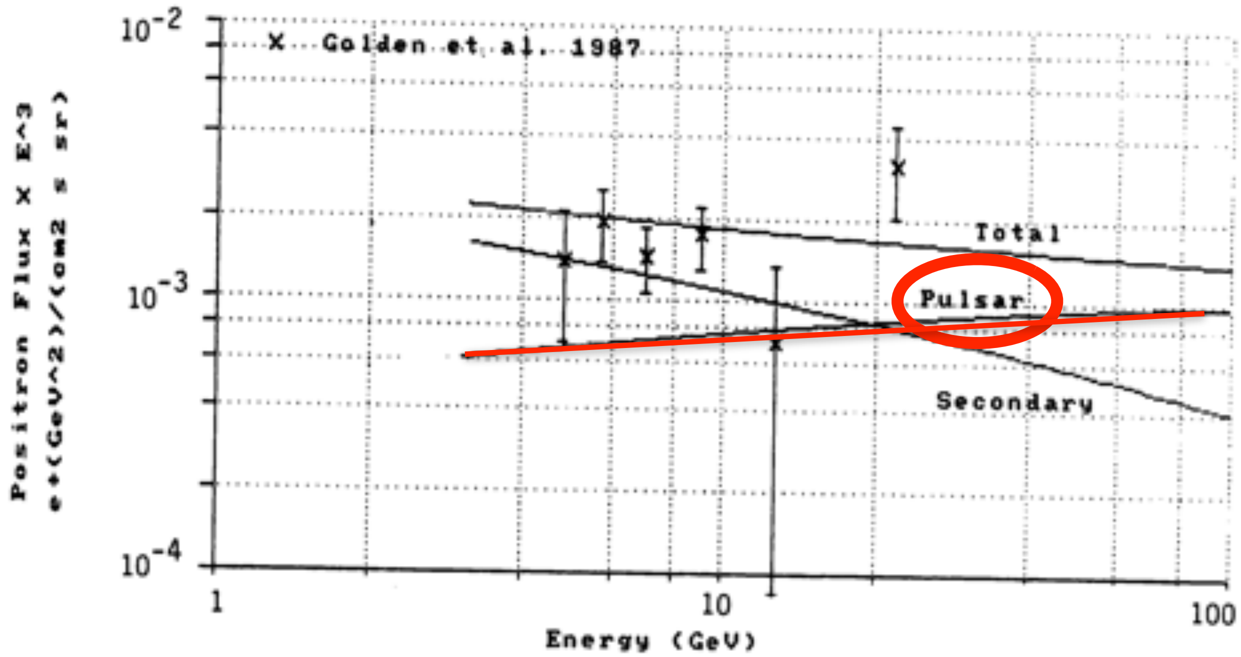
Dark Matter Annihilation!

...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**).

~ 900/1000 papers advocate Dark Matter

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

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

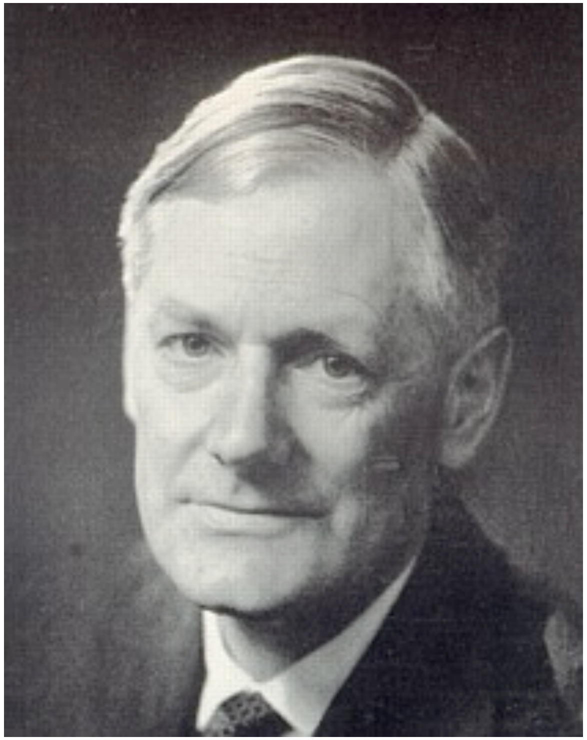
(ii) Need rather **large masses** (~TeV)

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

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

Redman's Theorem

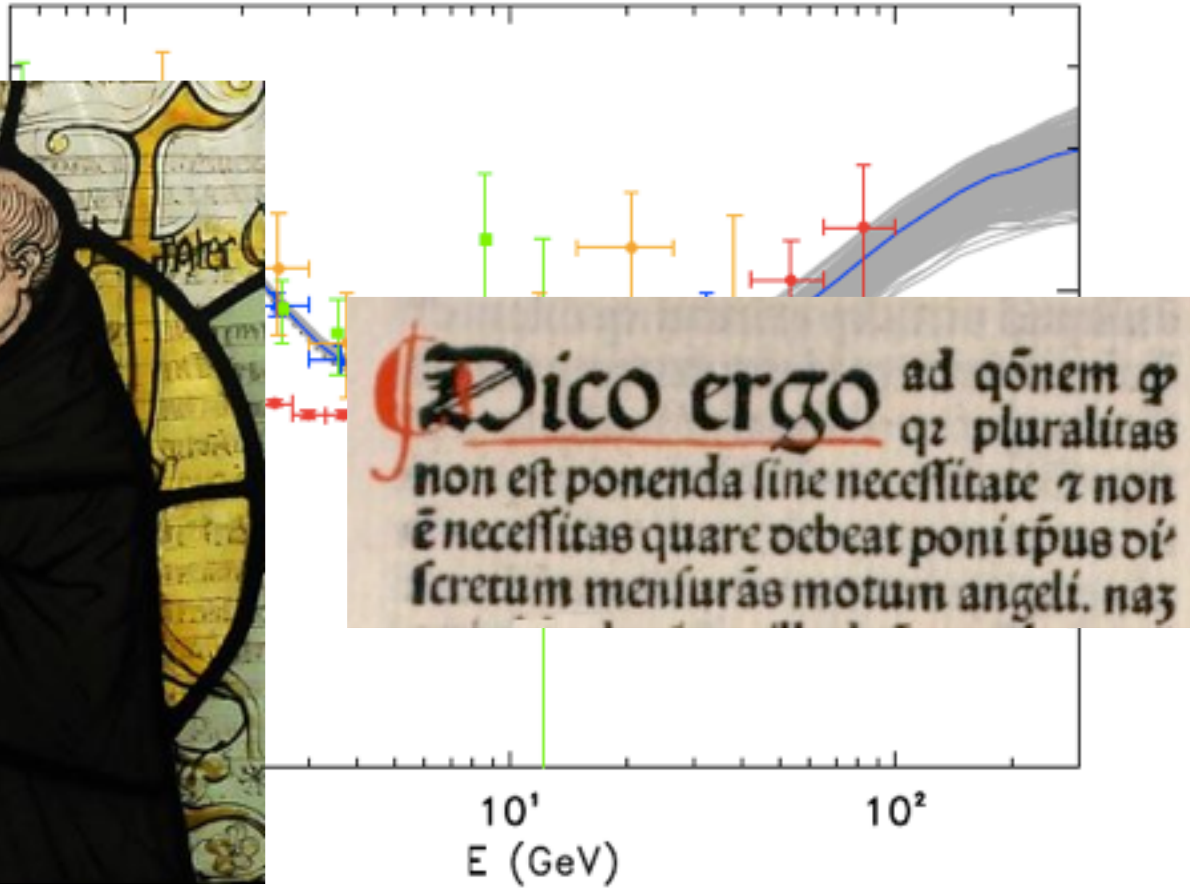
"Any competent theoretician can fit any given theory to any given set of facts" (*)



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"*

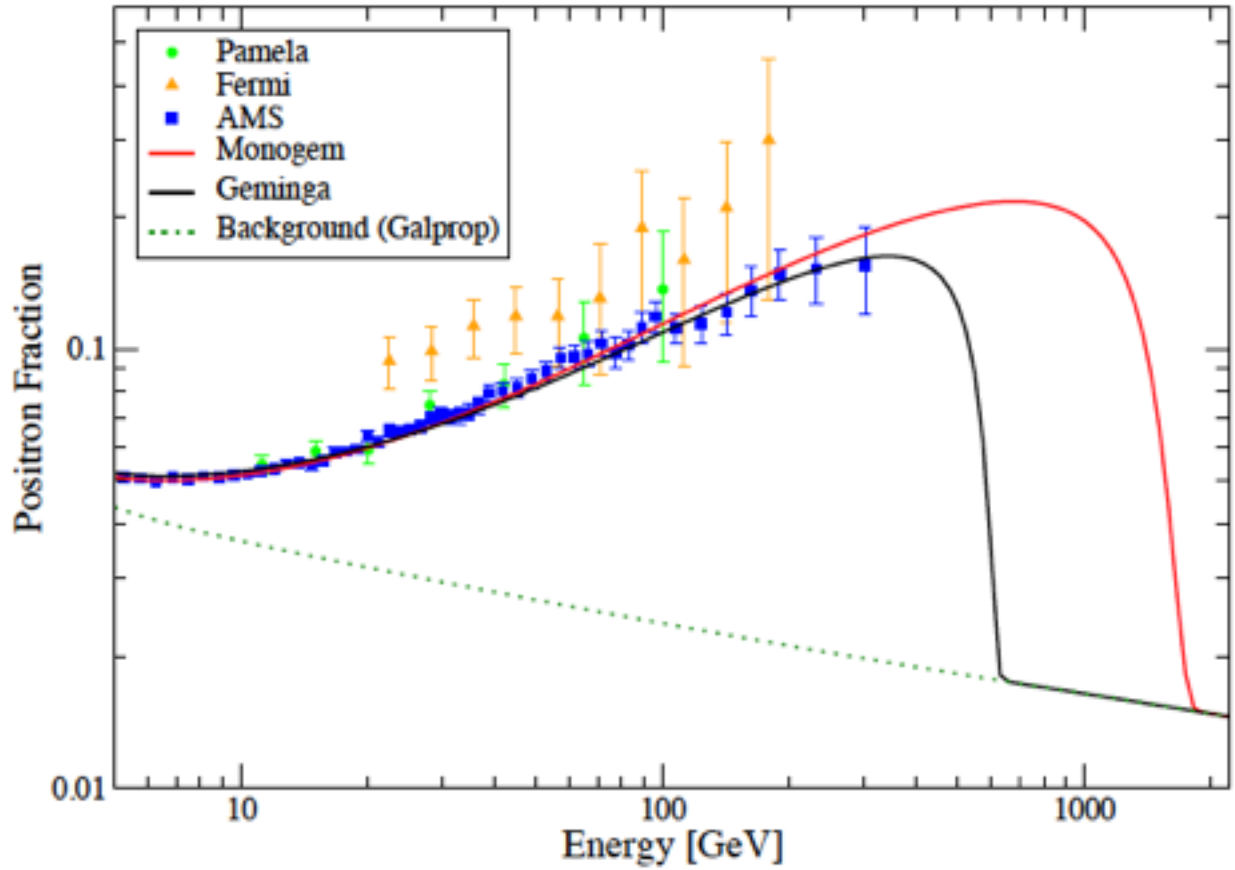


Dico ergo ad qōnem q̄ qꝛ pluralitas non est ponenda sine necessitate & non ē necessitas quare debeat poni tpus di-scretum mensurās motum angeli. naȝ

*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 1^{st} 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

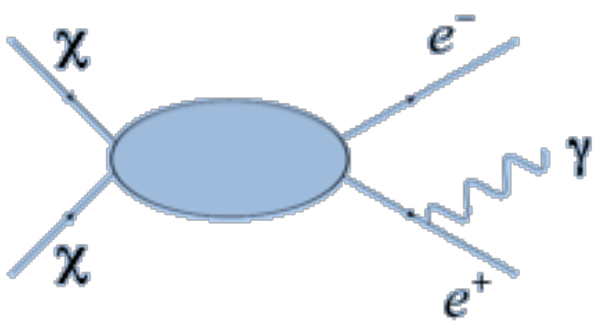
Dark Matter → Diffuse secondary component

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

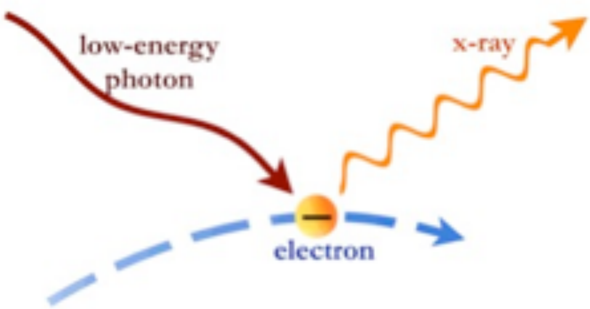
Large **annihilation rates**

Large **masses**

Hard **charged leptons**

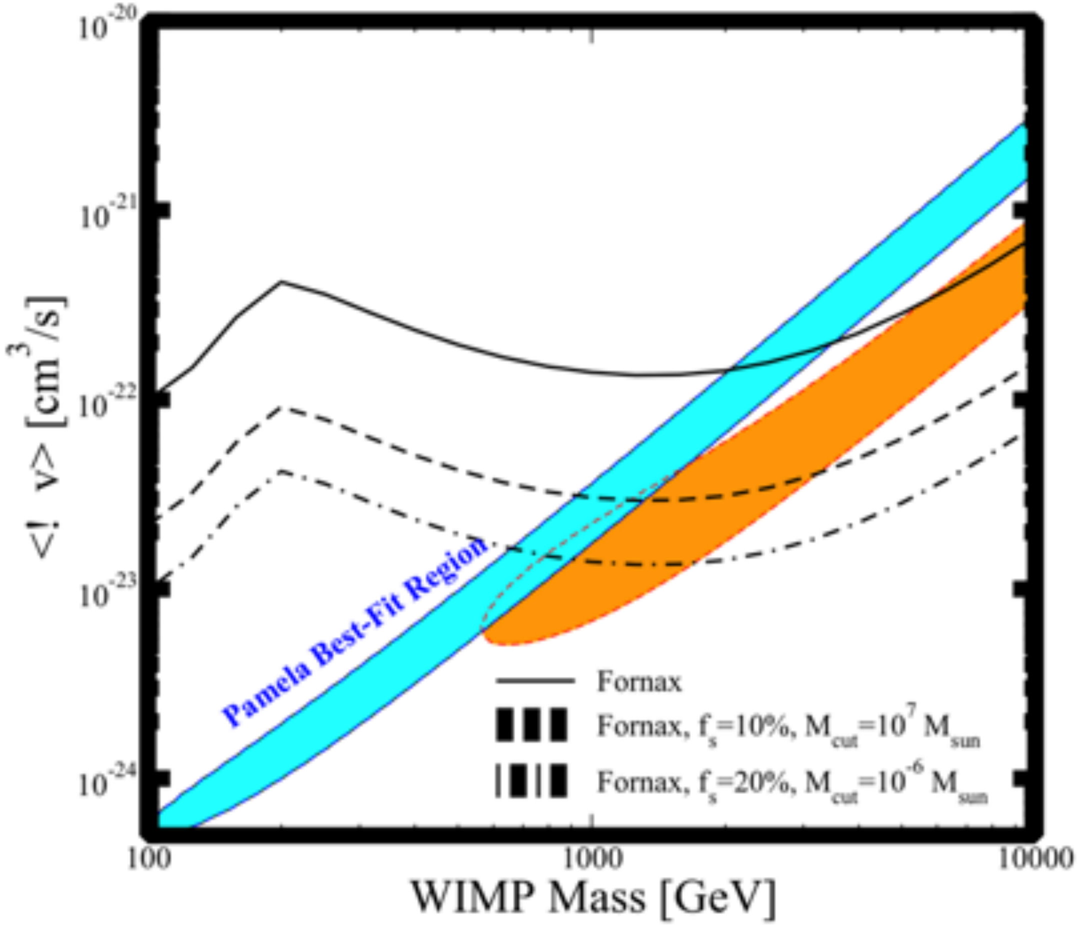


Final State Radiation



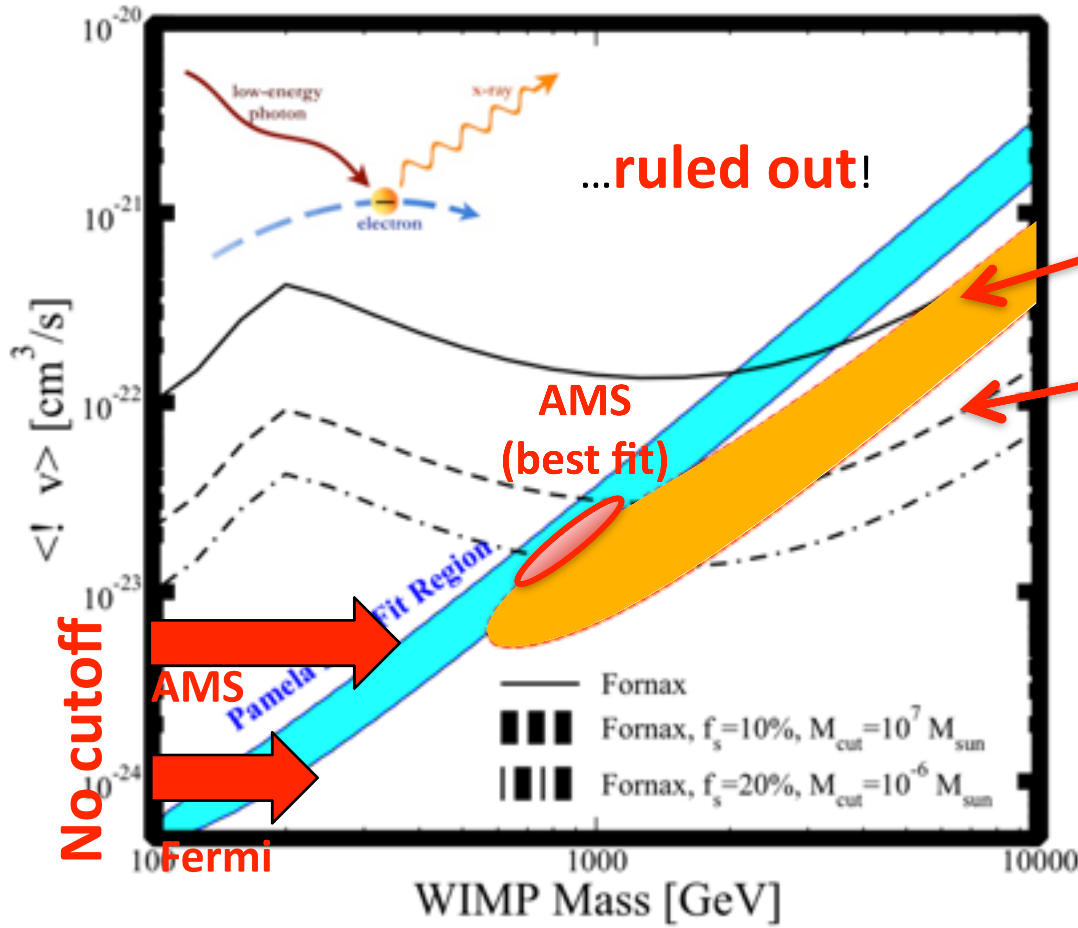
Inverse Compton

Gamma-Ray Searches from **Galaxy Clusters**



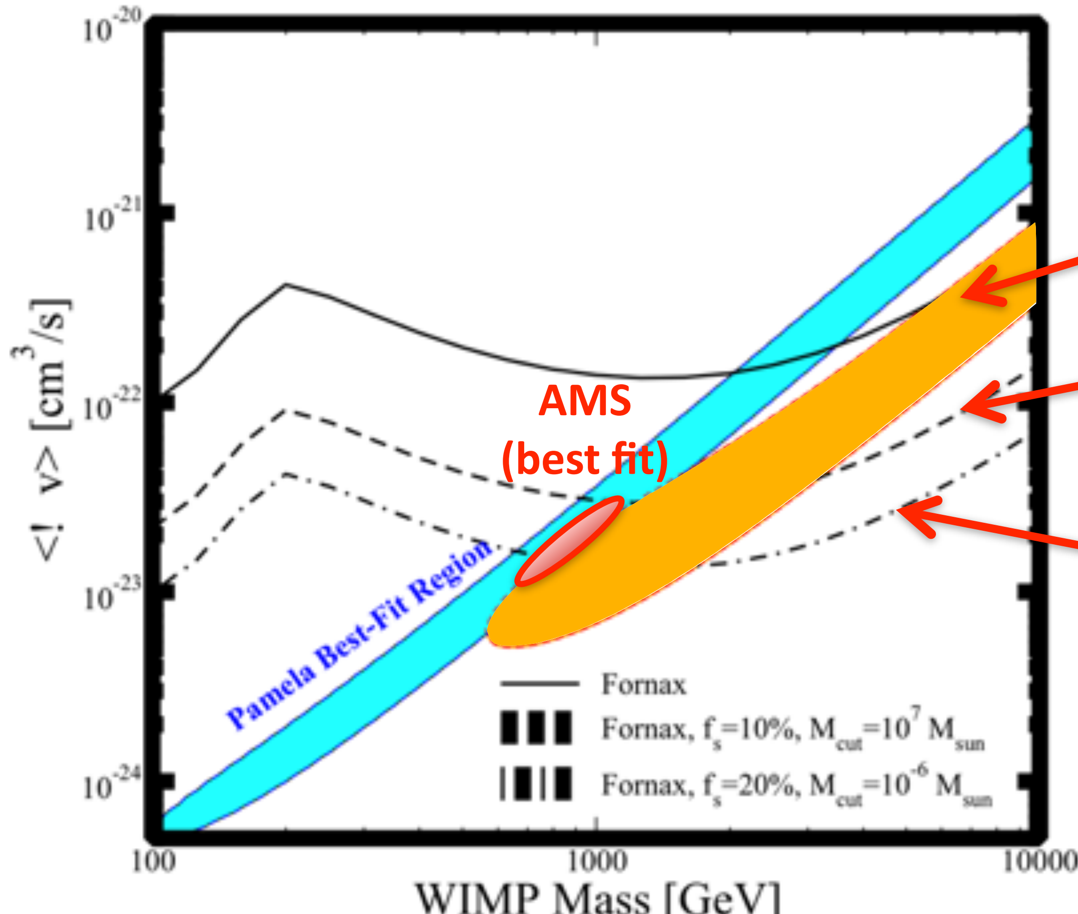
Jeltema, Profumo & Fermi-LAT Collaboration, JCAP 2010, arXiv: 1001.4531

Gamma-Ray Searches from **Galaxy Clusters**



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

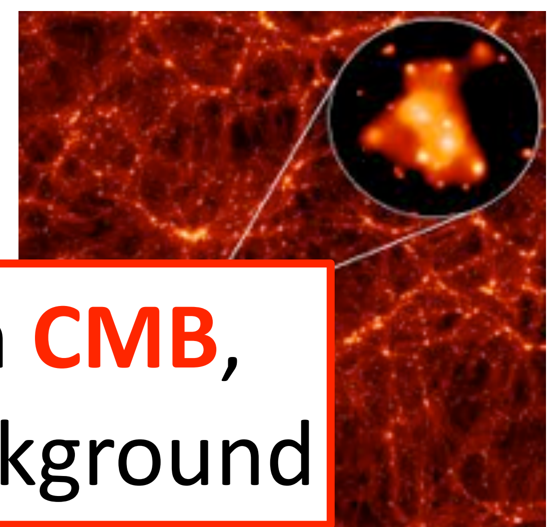
Gamma-Ray Searches from **Galaxy Clusters**



no substructure

galaxies only

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

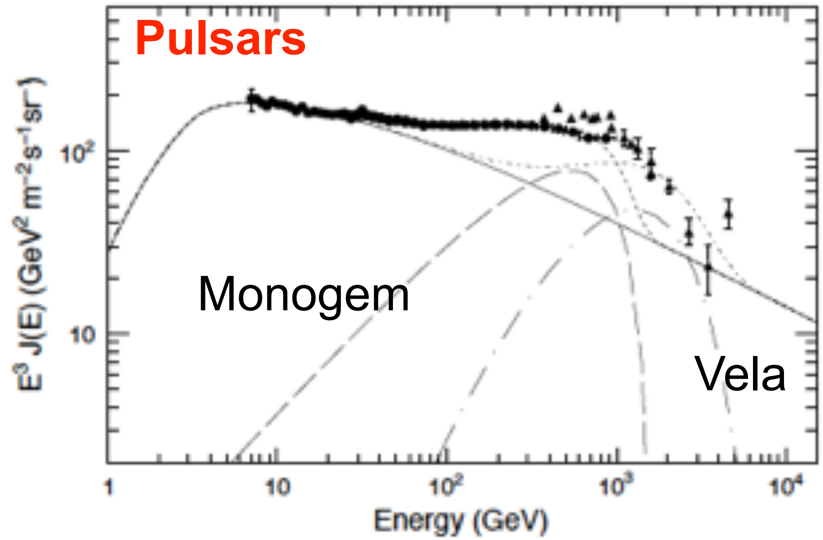


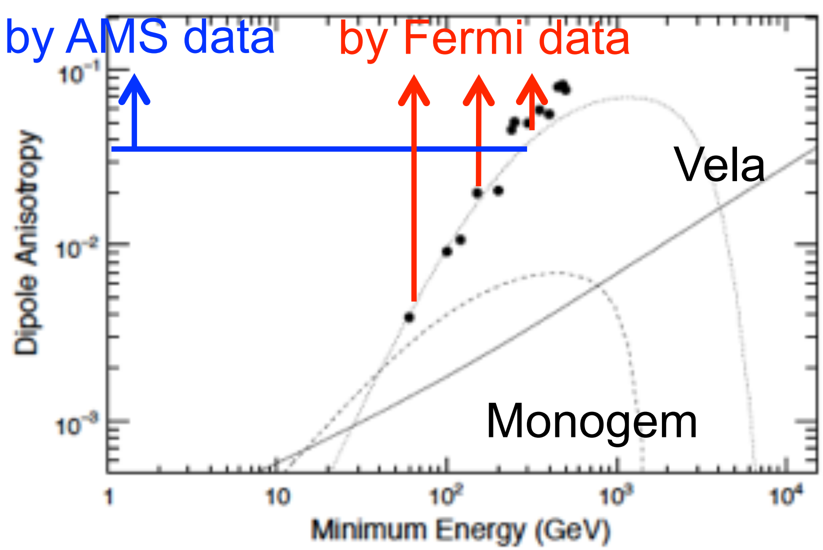
Additional constraints from **CMB**, extragalactic **gamma-ray** background

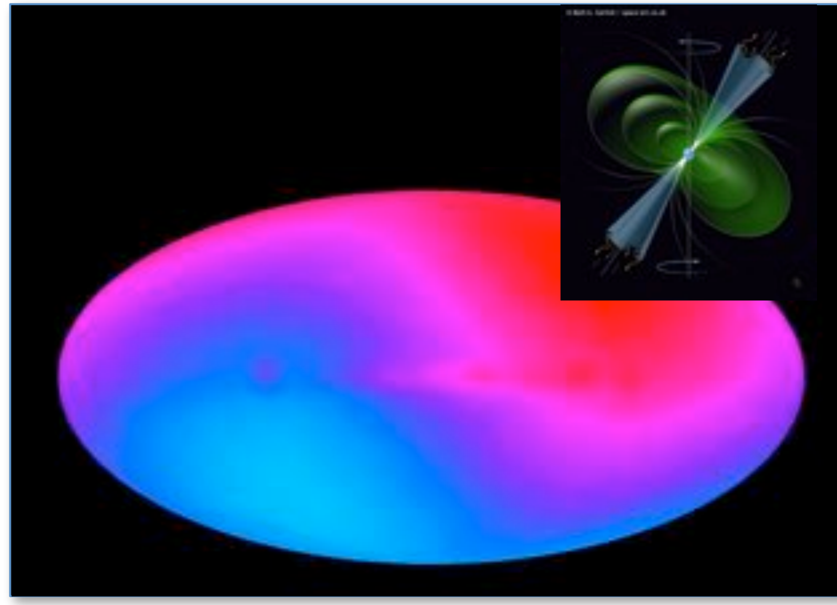
Jeltema, Pr

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

(sufficient, not necessary)



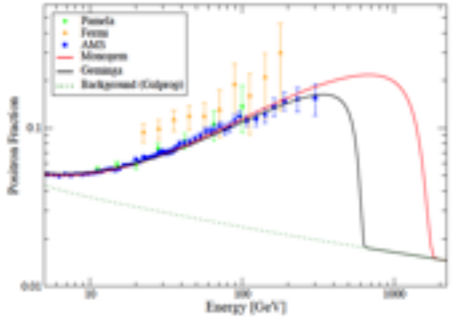


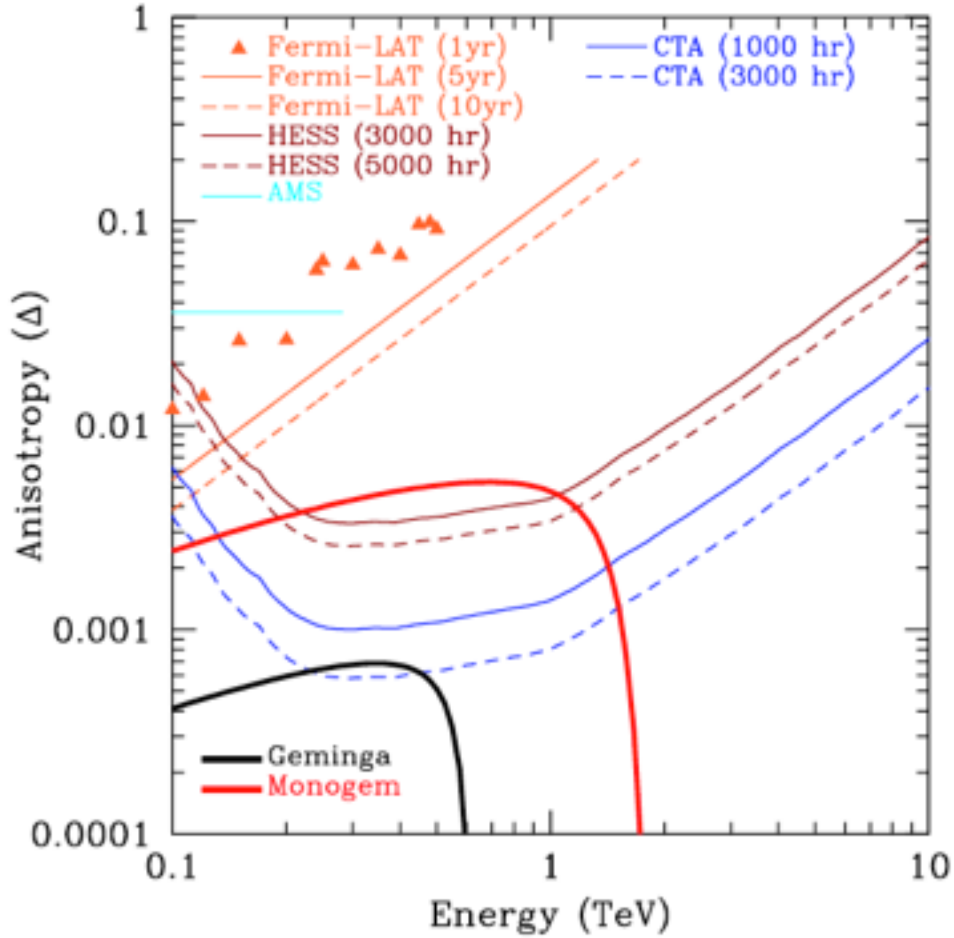


No Anisotropy observed in the **Fermi** e^+e^- data, or in the **AMS** data

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

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





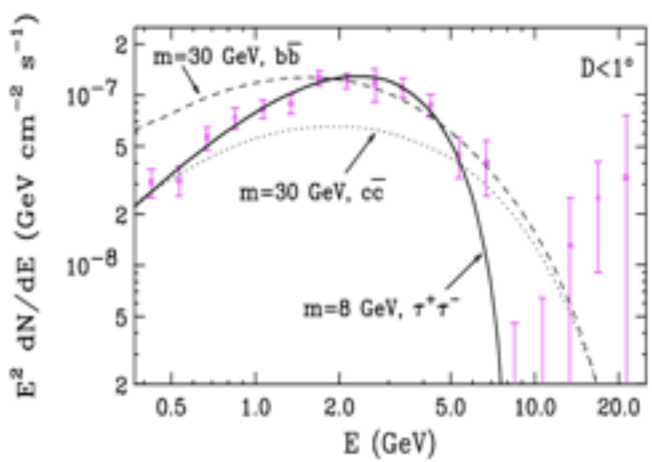
Way forward: **Cherenkov Telescopes**

sensitive to predicted **anisotropies** at VHE!

Linden and Profumo, Astroph. J (2013) 1304.1791

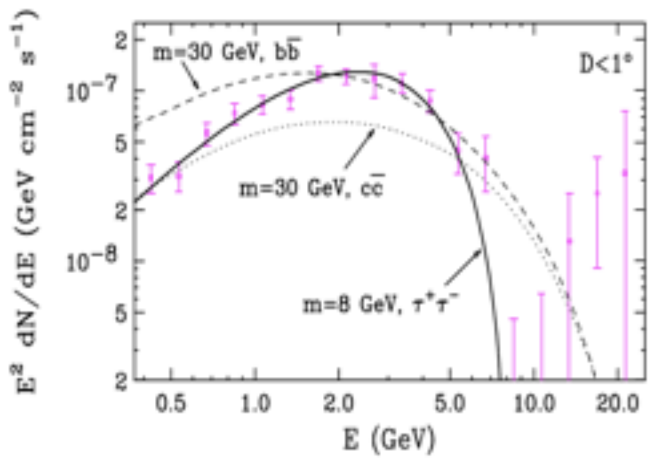
- we are **closing in** on the **dark matter** interpretation
- **AMS-02** positron fraction **data "favor" PSR's** over dark matter
- Conclusive argument against dark matter: **anisotropy** (ACTs!)

Dark Matter annihilation in the Galactic Center?



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

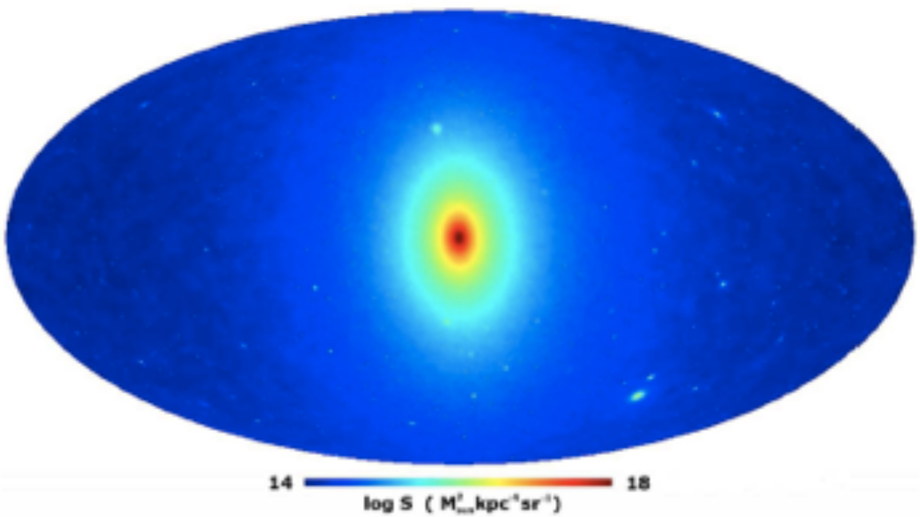
Dark Matter annihilation in the Galactic Center?



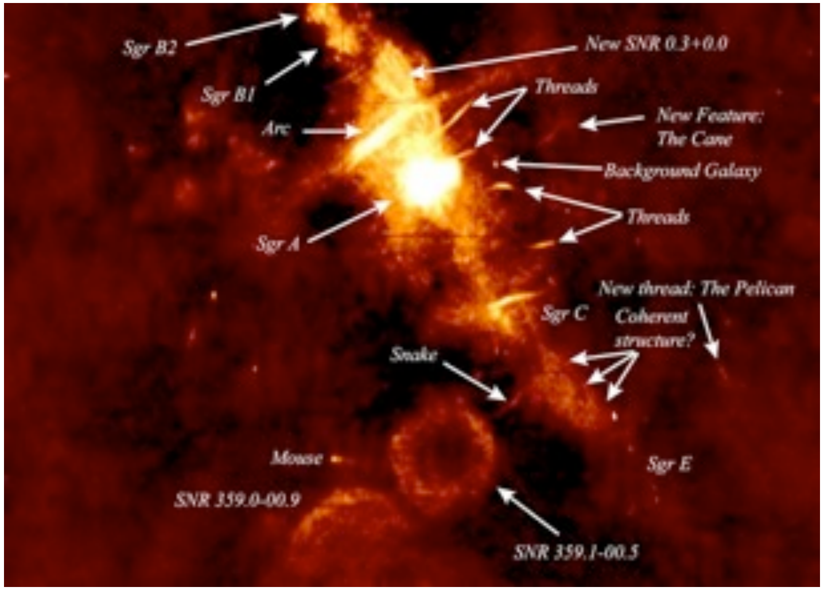
The **Galactic Center** Region:
a Holy Grail or a Hornet's Nest?

- 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

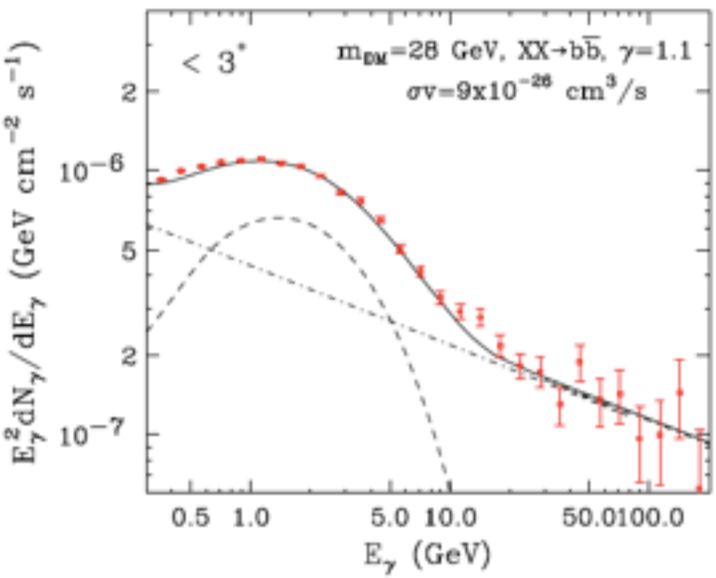
Background | **Dark Matter particle**

Oct. 2009

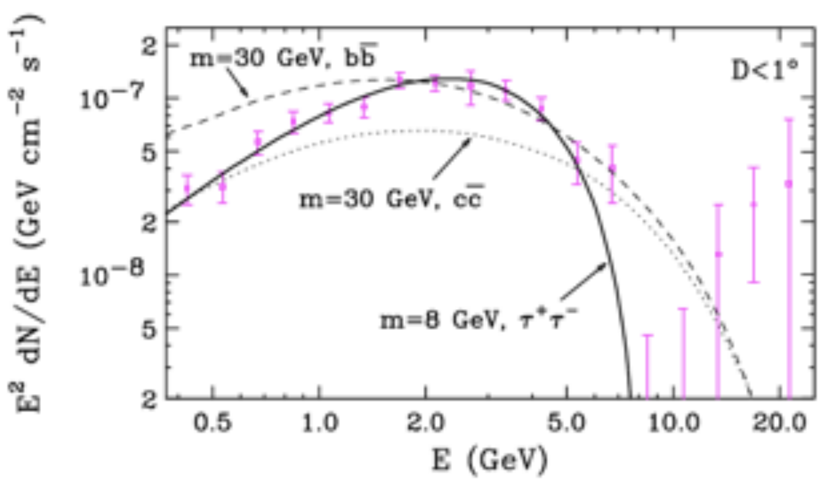
Exponential angular fall-off
Power-law spectrum

28 GeV, bb quark

Goodenough, Hooper



	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**”:

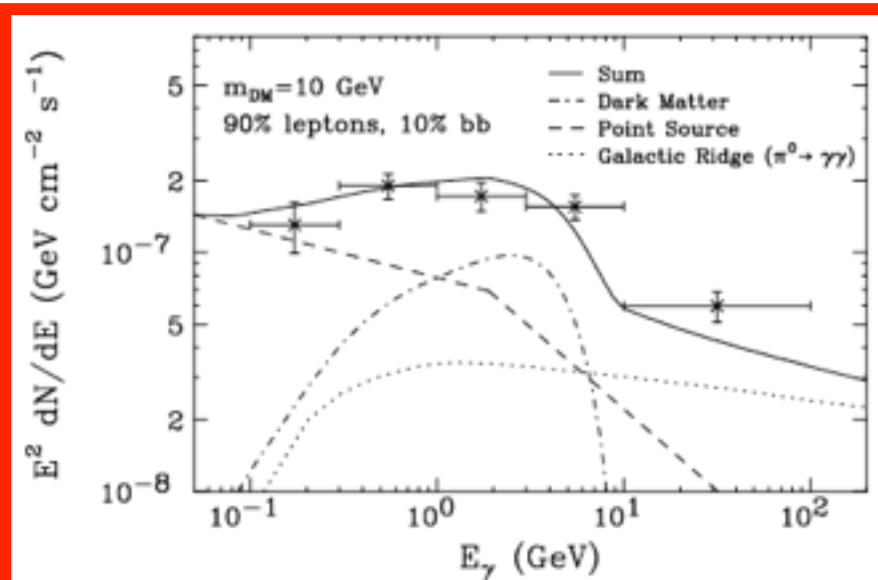
may end up with a “**Goodenough Hooperon**”

Matter particle

Oct. 2009

Goodenough, Hooper

GeV, bb quark



Oct. 2010

spectrum: extracted

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

Hooper, Good

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

Oct. 2

***GeV**,*

or bb,

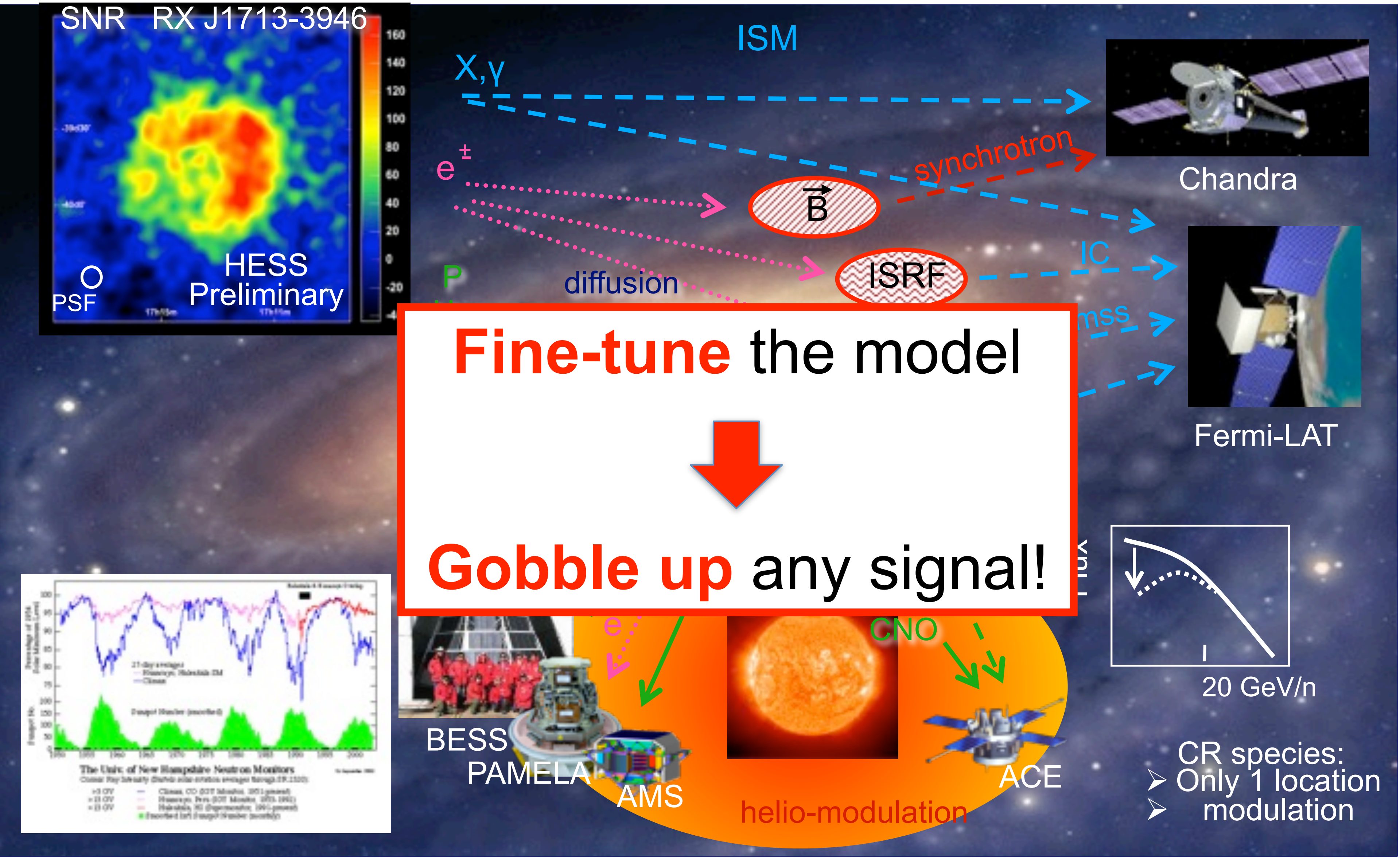
plus point-source

or generic

Li

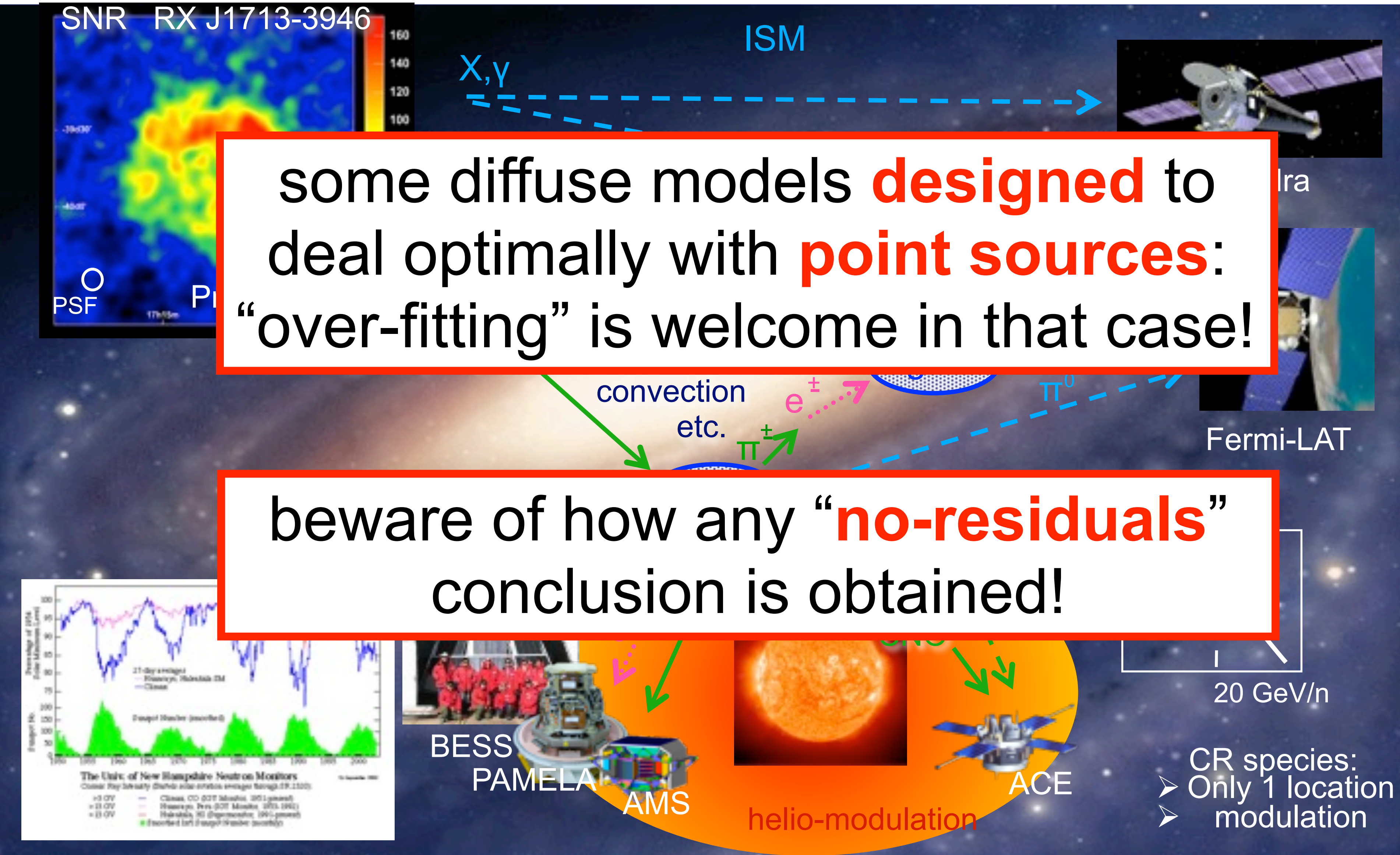
Very **intriguing** mass range
(see CDMS+CoGeNT ~ **10 GeV** mass **WIMPs**)

"Over-fitting"



[slide from Igor Moskalenko]

“Over-fitting”

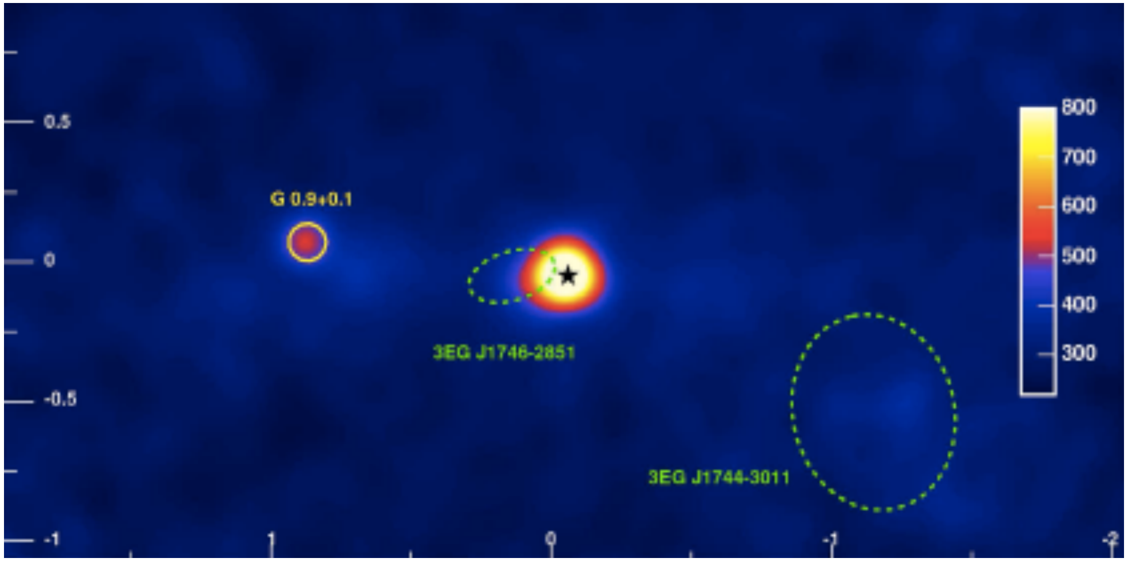


some diffuse models **designed** to deal optimally with **point sources**: “over-fitting” is welcome in that case!

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

[slide from Igor Moskalenko]

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



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

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

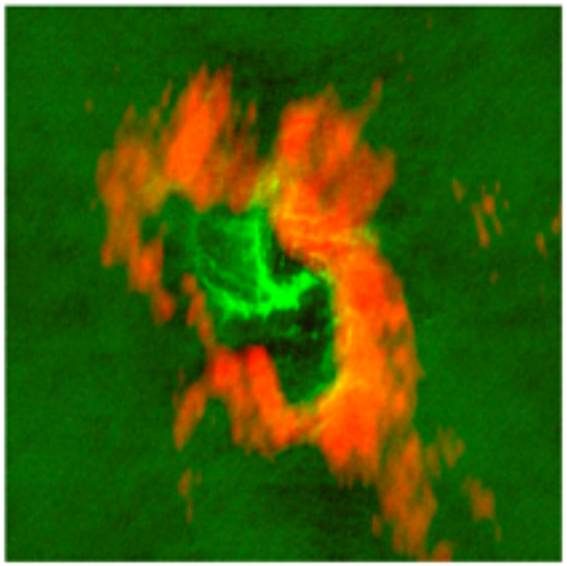
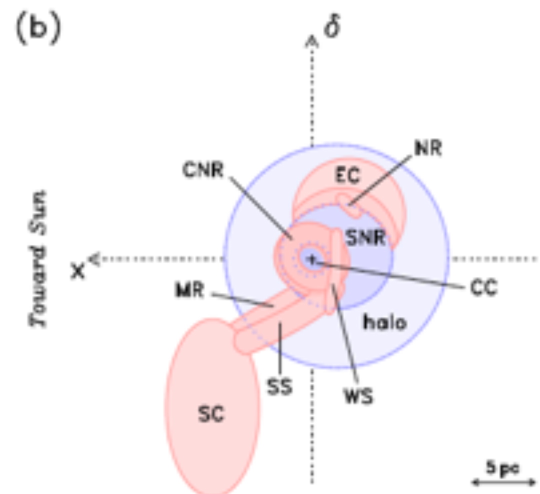


Fig. 2. Composite image showing (in green) the 3.6 cm radio continuum emission from warm ionized gas in the Sgr A West H II region, with the three-arm Minispiral emerging very clearly, and (in red) the 3.4 mm HCN $J = 1 \rightarrow 0$ line emission from the surrounding Circumnuclear Ring (CNR). The radio 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**

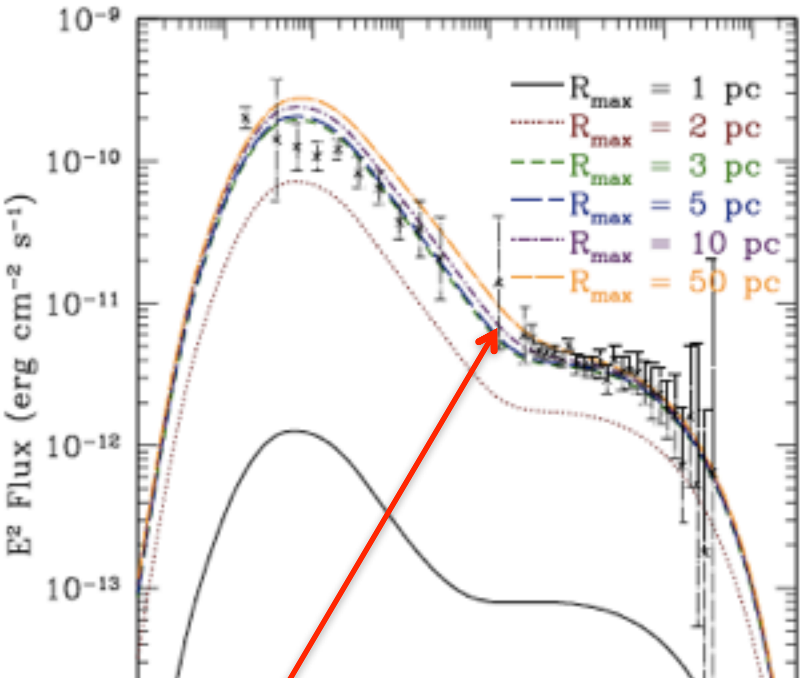


Need detailed modeling of **gas** distribution

Our approach: **Monte Carlo**

K. Ferrere, 2012; Linden and Profumo, 2012

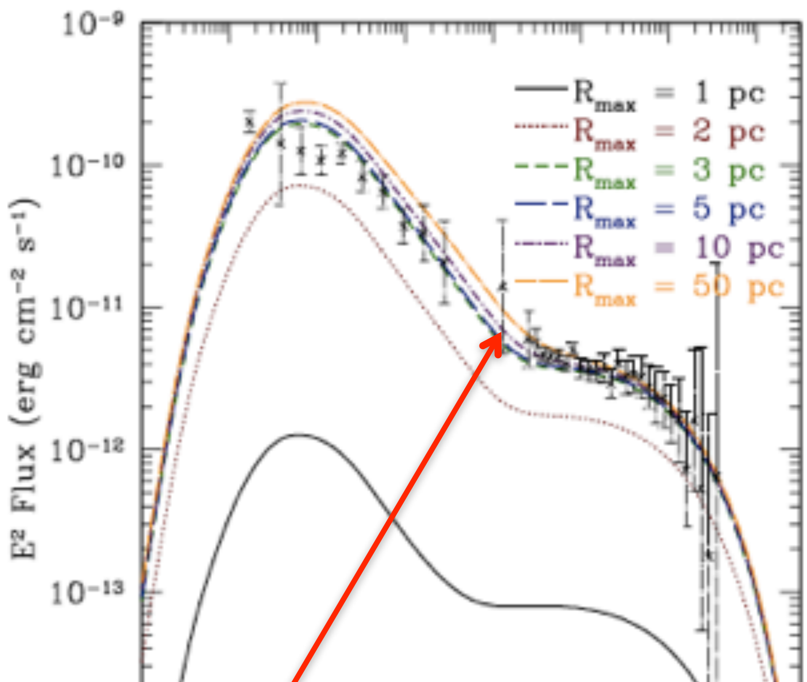
One of the elephants in the room: Sgr A*



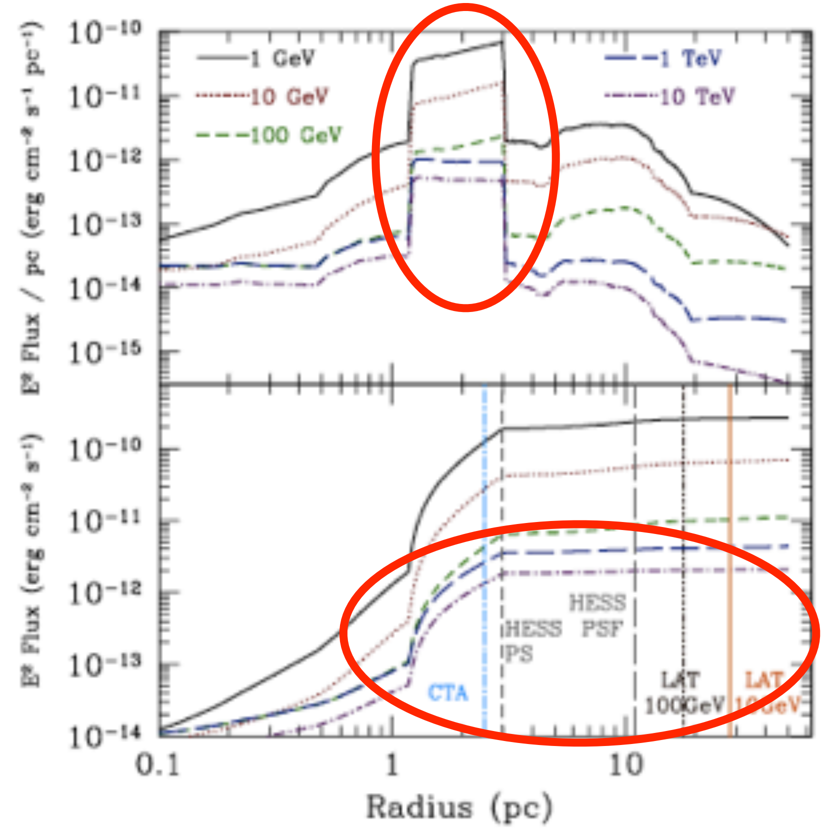
transition between diffusively trapped behavior and rectilinear propagation

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!

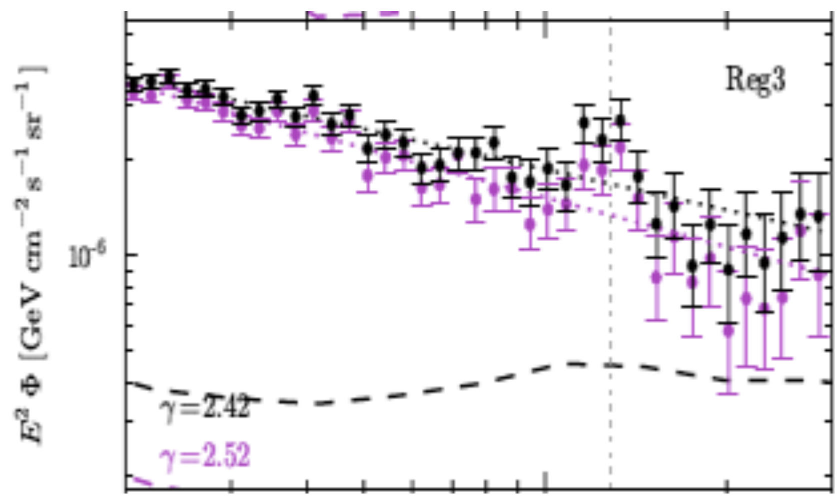
Chernyakova et al, 2011; Linden, Lovegrove and SP, 1203.3539, ApJ 753 (2012) 41

Galactic Center: the way forward??

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

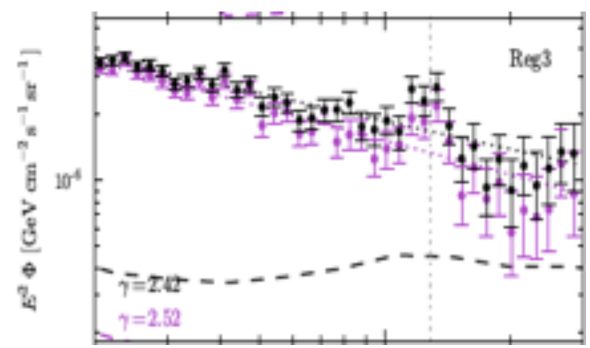
Linden, SP,..., in progress

The Gamma-Ray Line



“Troubling and Inconclusive”

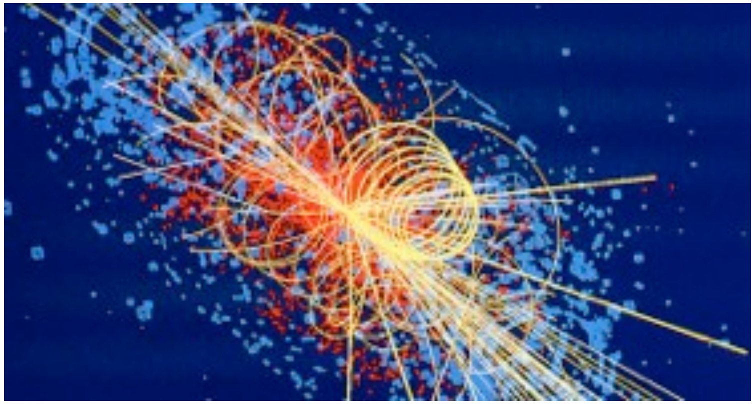
Steve Ritz
Fermi-LAT Deputy PI



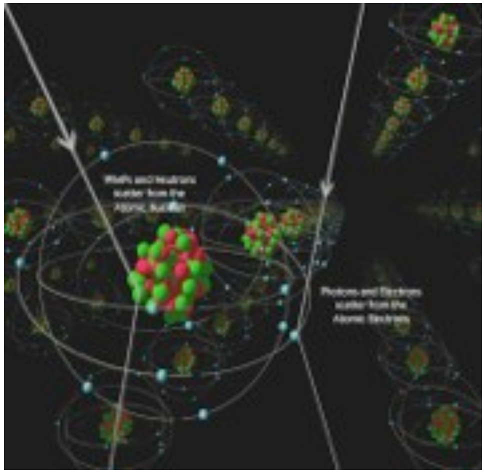
If confirmed, huge **impact** on **particle physics**!

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

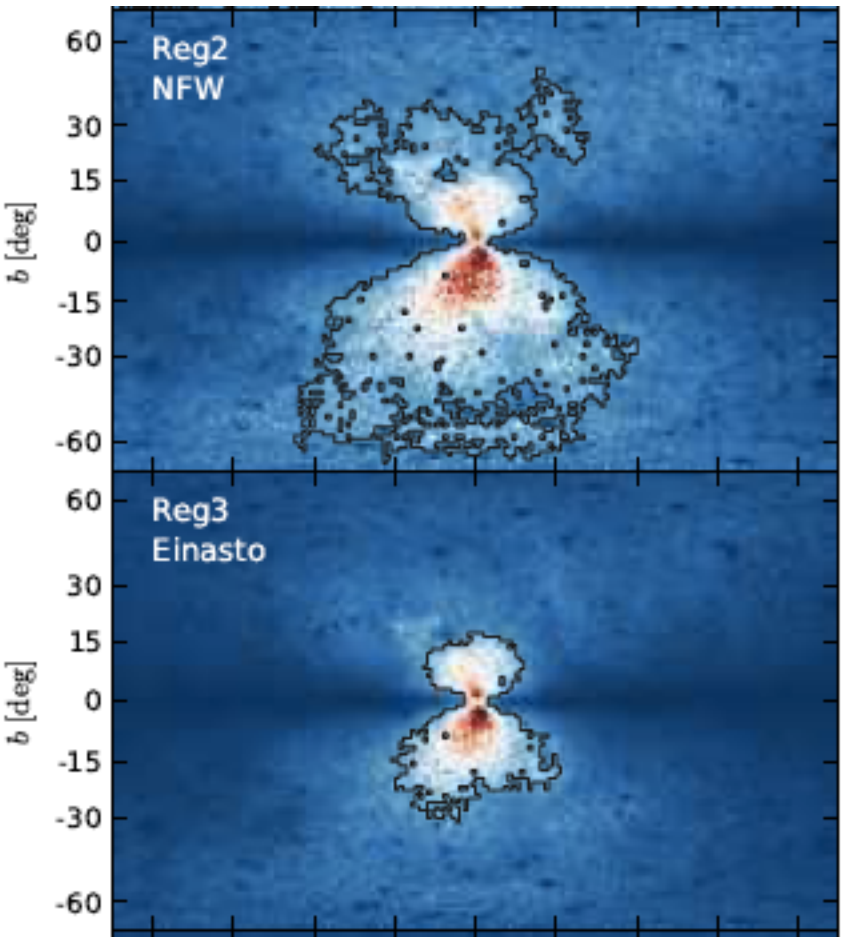


...and the target mass for **direct detection** experiments!



Weniger (1204.2797)

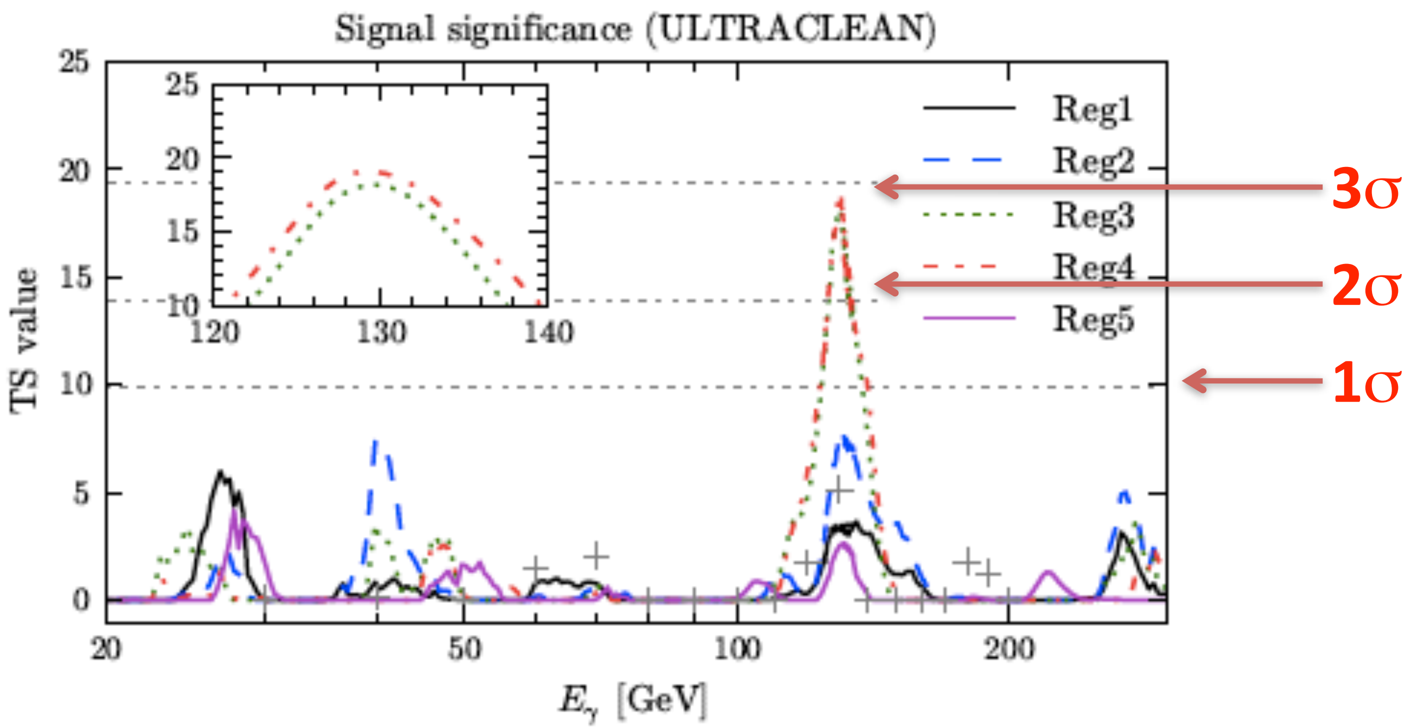
Key novelty: **optimized** Regions of Interest



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

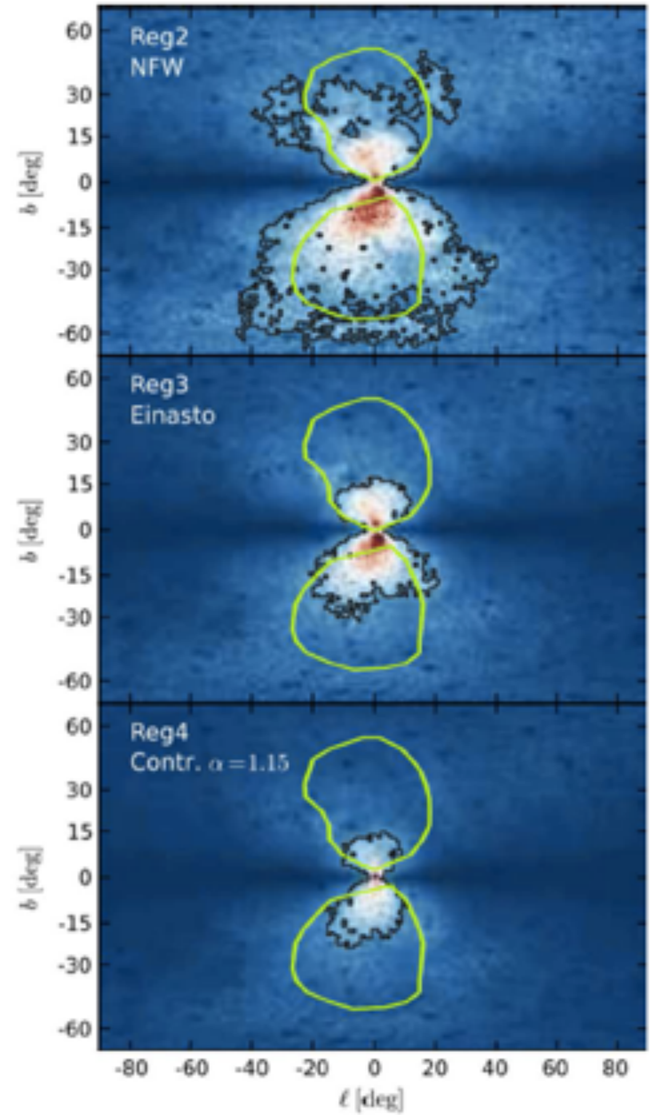
Noise: (1-20 GeV sky)$^{1/2}$

(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**

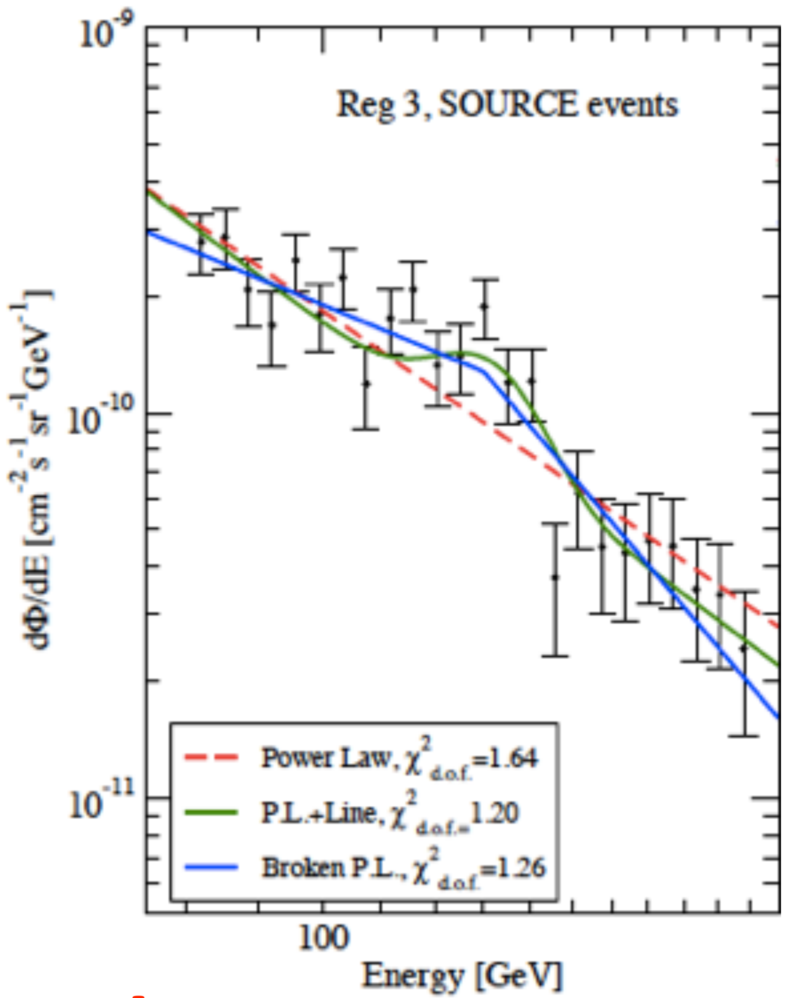


* Profumo and Linden, "Gamma-Ray Line in the Fermi Data: is it a Bubble?", JCAP 2012

Two remarks*

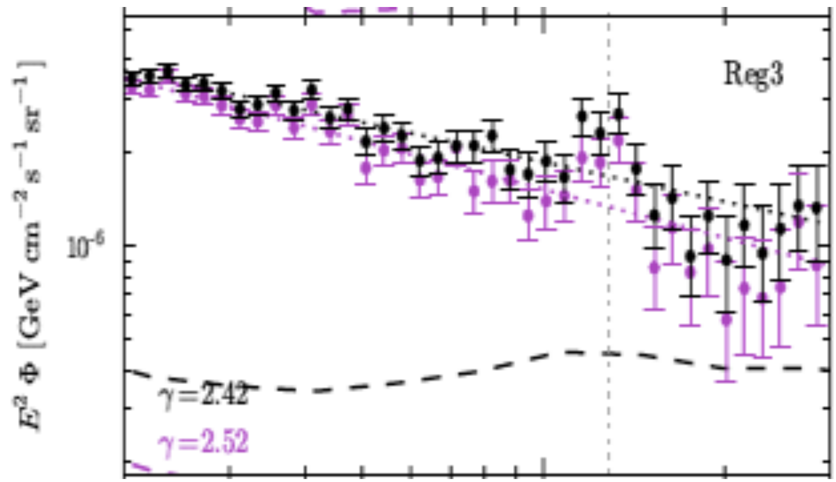
(1) ROI's overlap with **Fermi bubbles**: photons from bubbles are important **background**

(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) x 4πx10^7 x (1/6) s ~ **2x10^7 m^2 s**

ACT, with 100h: (10^5 m^2) x 100x60x60 s ~ **3x10^{10} m^2 s**

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

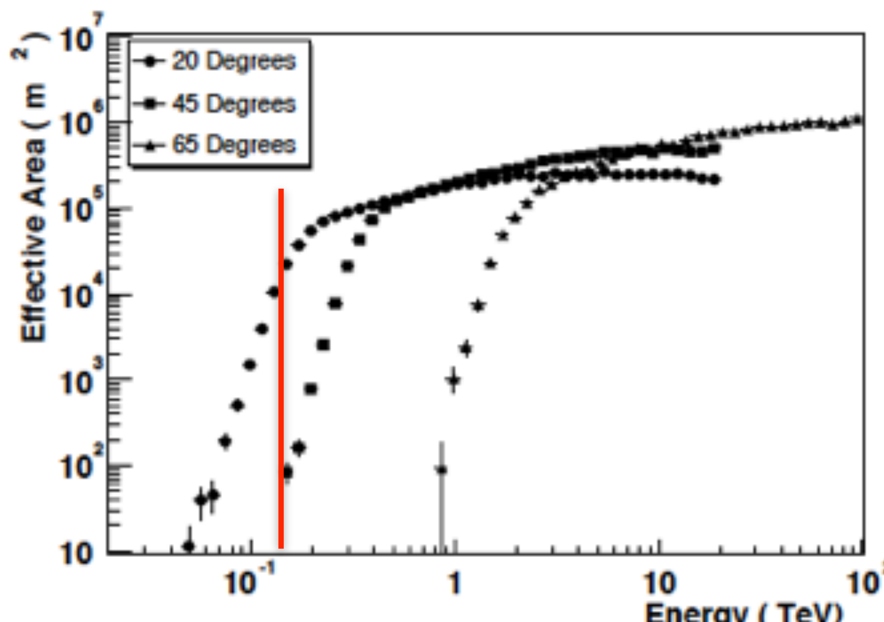
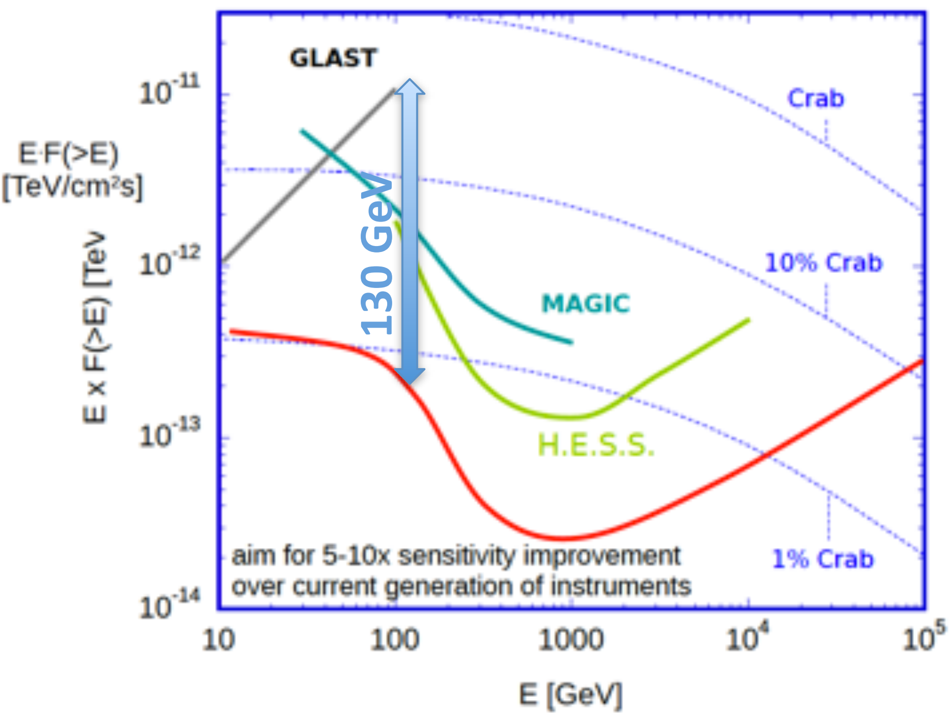
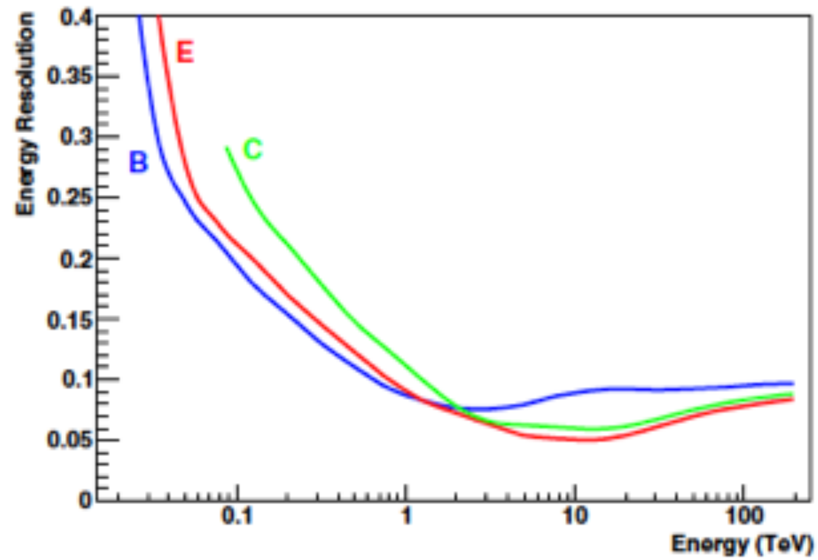


Figure credit: Benow, for HESS collaboration

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





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

Astrophysical backgrounds?

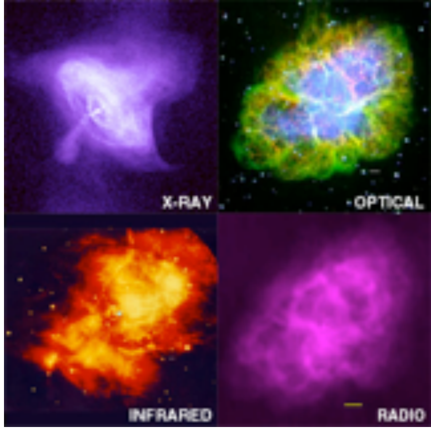
Always keep **Occam** in mind!

Klein-Nishina regime: almost all energy transferred from e to γ → **E_e~ 130 GeV**

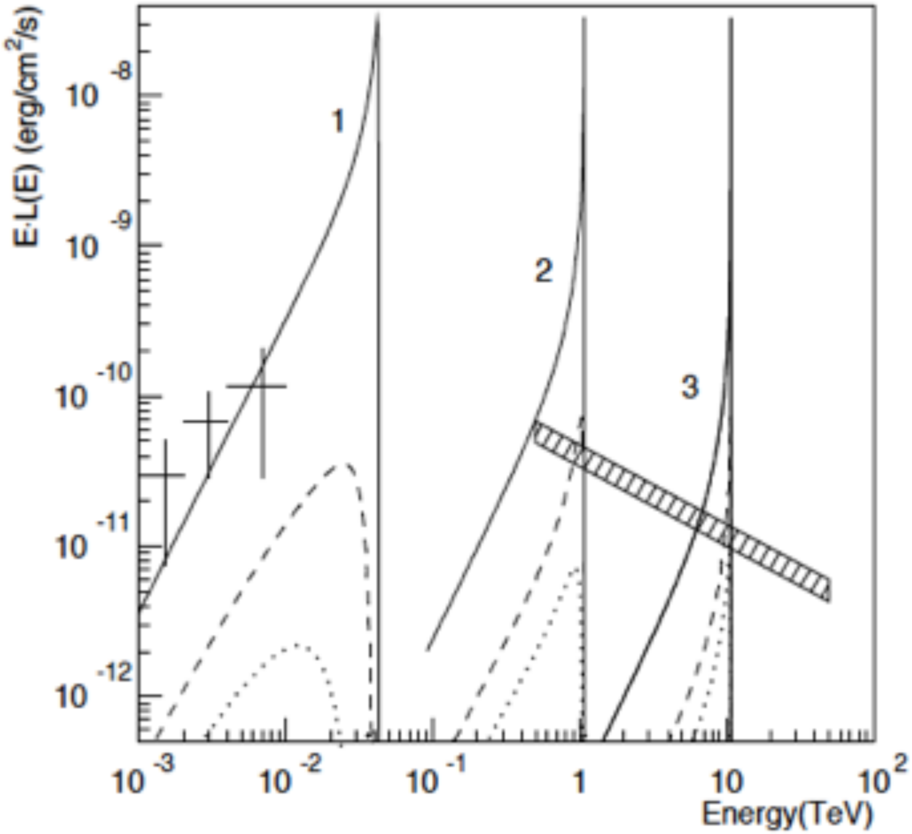
Need~ mono-chromatic electrons and target photons with $\omega_0 >> m_e^2/E_e$ ~ **2 eV**

Both OK with **electron pulsar wind**

Aharonian et al, 2012; image credit: NASA



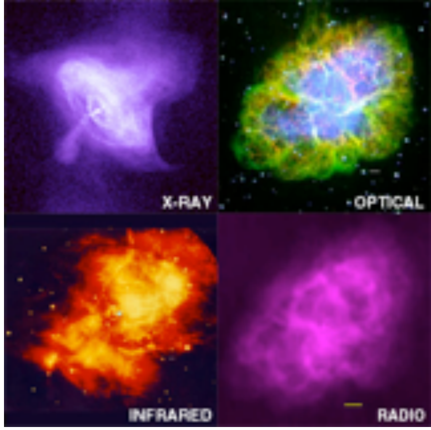
This is **not** a **POST-diction**!



Bogovalov and Aharonian, **2000**

Energetics works out fine!

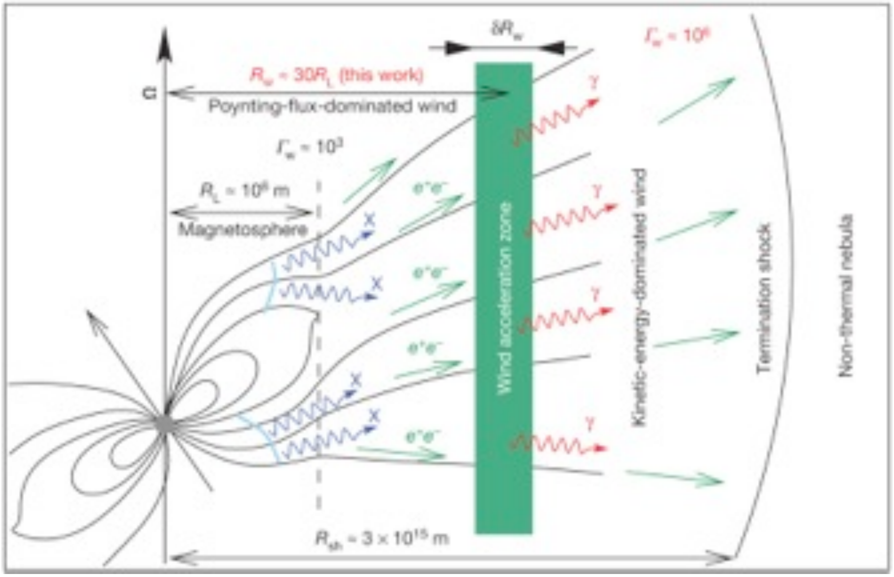
130 GeV line luminosity ~ **$3x10^{35}$ erg/s**



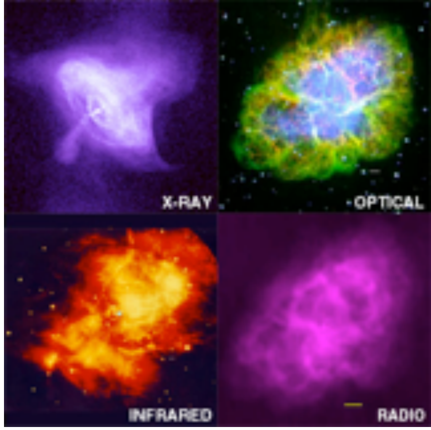
Crab luminosity in shock-acc. e^+e^- ~ **$3x10^{38}$ erg/s**

[spin-down luminosity~ $5x10^{38}$ erg/s]

efficiency to produce gamma rays??



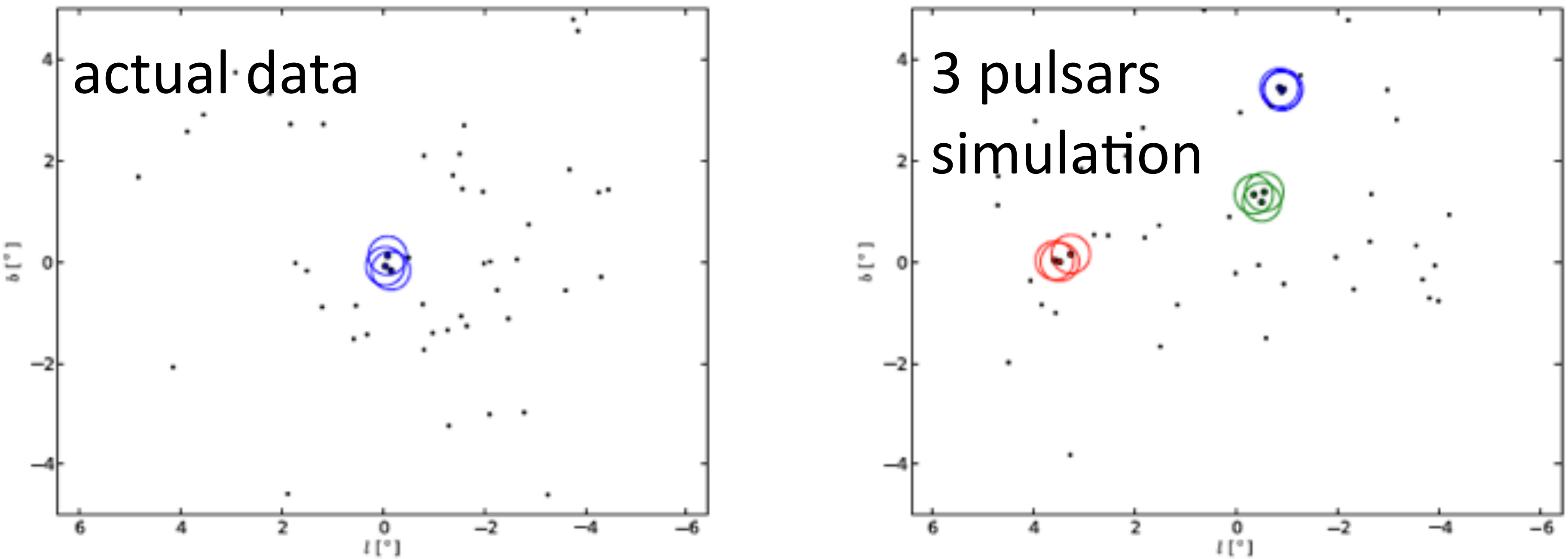
Aharonian et al, Nature 2012



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)



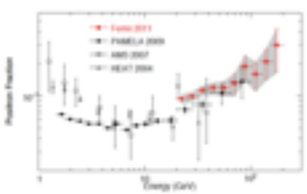
Astrophysical backgrounds are unlikely, given current data!

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**

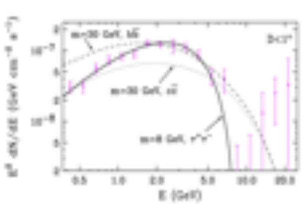
A (dark matter) model that does everything?

Positron Excess



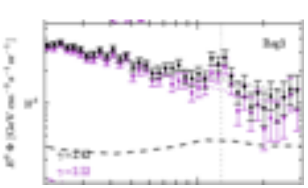
mass ~ 1 TeV,
$\mu^+\mu^-$ (more likely $\pi\pi$)

Galactic Center



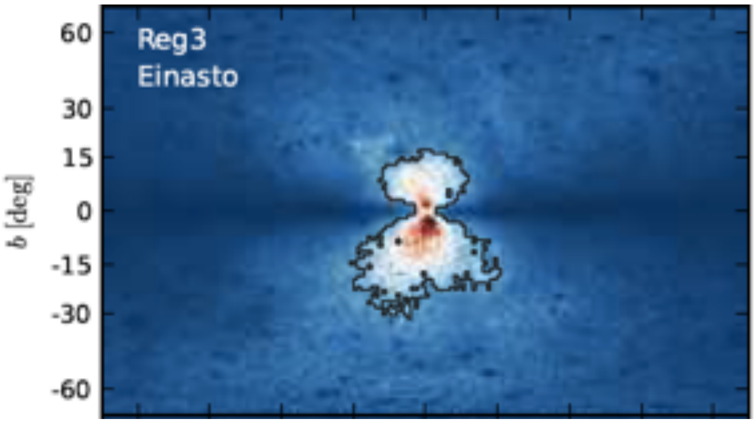
mass ~ 10 GeV,
bb or $\tau^+\tau^-$

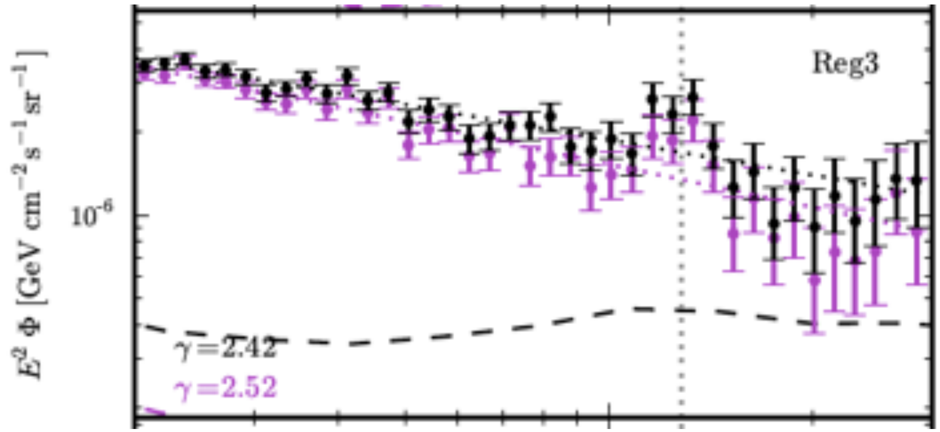
130 GeV line



mass = 130 GeV,
enhance line, no continuum

A model that “does everything”





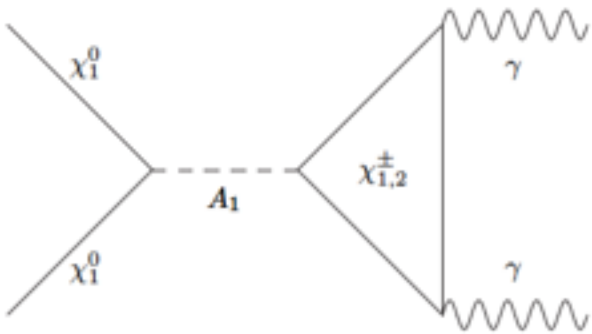
- **Line** with right cross section
- Suppressed GR **continuum**
- Right **Higgs** mass
- Right Thermal **Relic Density**
- Successful **EW Baryogenesis**
- Strongly first order **EWPT**
- OK with direct detection
- OK with SUSY searches
- OK with EDM searches

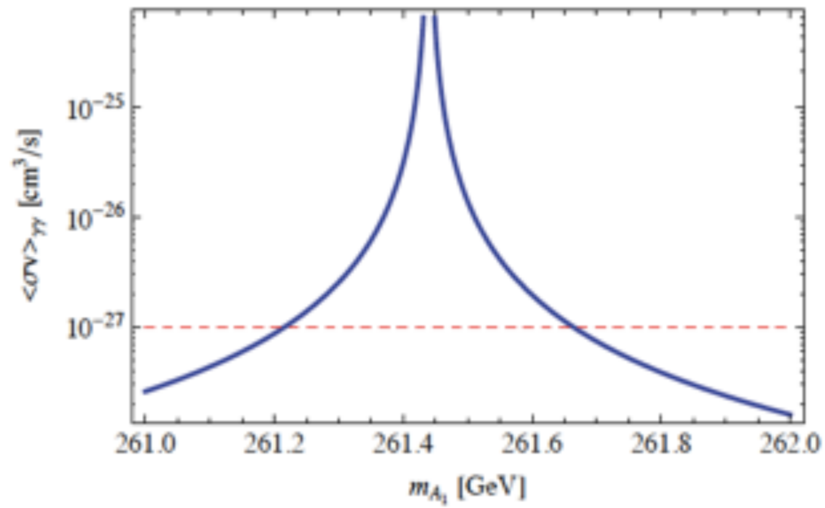
Weniger, 2012; Kozaczuk, Profumo and Wainwright 2013

A model that "does everything"

$$W = W_{\rm MSSM}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3,$$

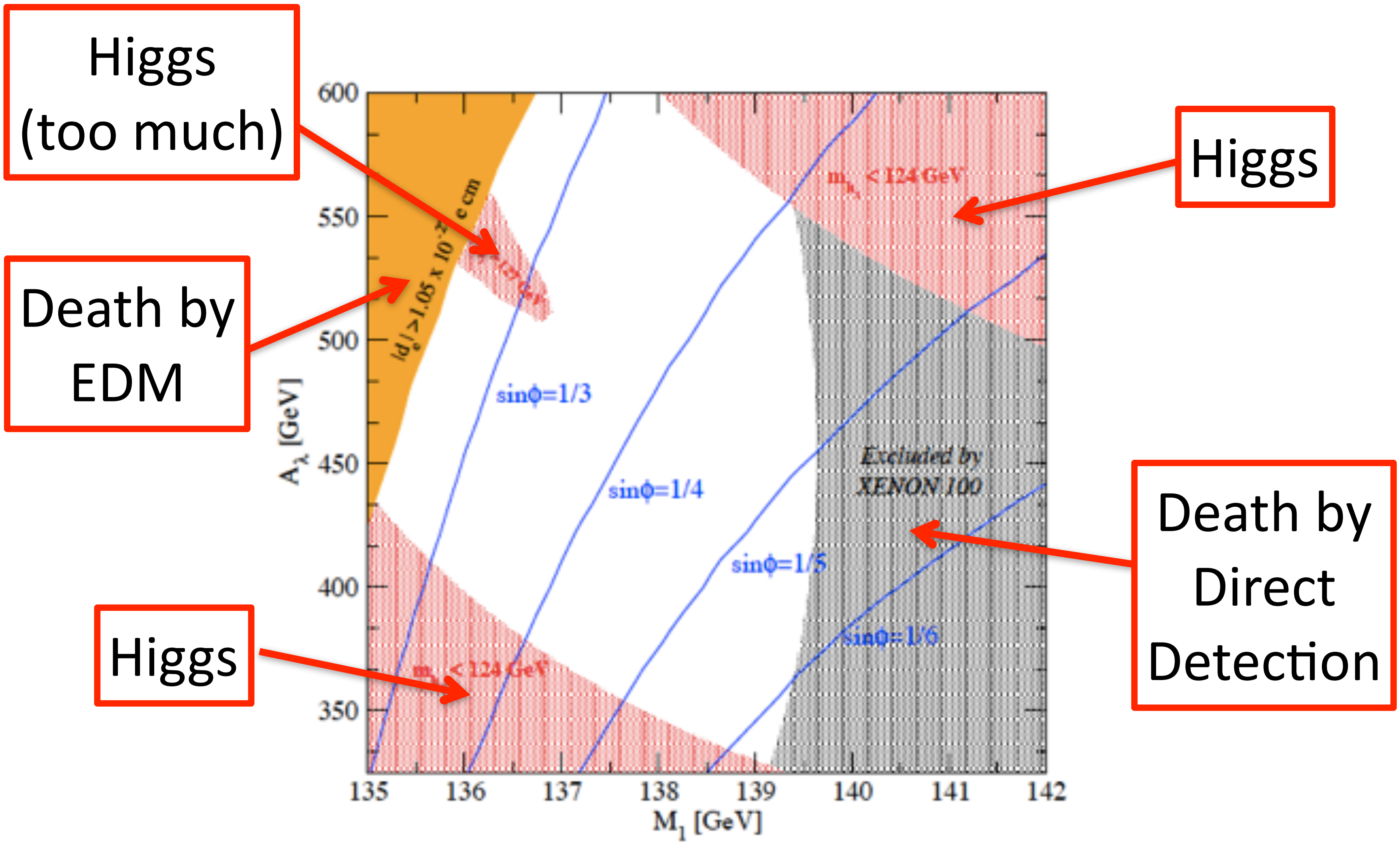
$$-\mathcal{L}^{soft} = -\mathcal{L}^{soft}_{\rm MSSM} + m_S^2\,|S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3\right) + \text{h.c.}$$





Kozaczuk, Profumo and Wainwright, 2013

A model that "does everything"



Kozaczuk, Profumo and Wainwright, 2013

Positron excess, **Galactic Center excess**, **"The Line"**

Is this all "chasing ambulances"?

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

The promenades of Euclid

an appropriate adage for
indirect dark matter detection :

**“Everything we see
hides another thing,**

**we always want to see
what is hidden
by what we see”**

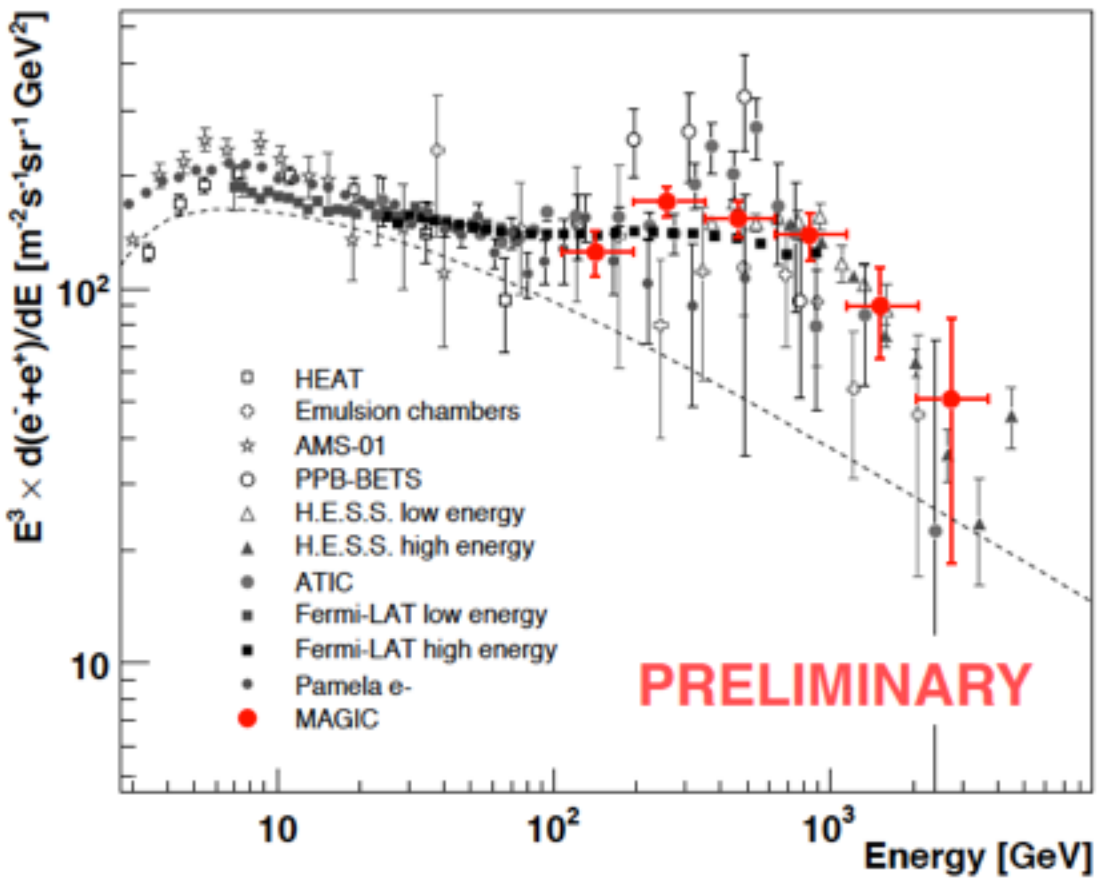
R. Magritte

[slide concept: Pasquale Serpico]

…plus, radio-quiet **gamma-ray** pulsars!

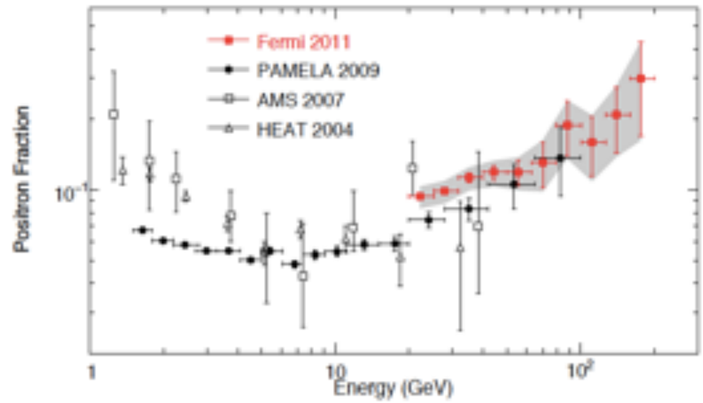
Gendelev, SP and **Dormody**
JCAP 1002 (2010) 016

Spectral information key, but not sufficient…



Borla-Tridon (MAGIC Coll.) 1110.4008 (ICRC)

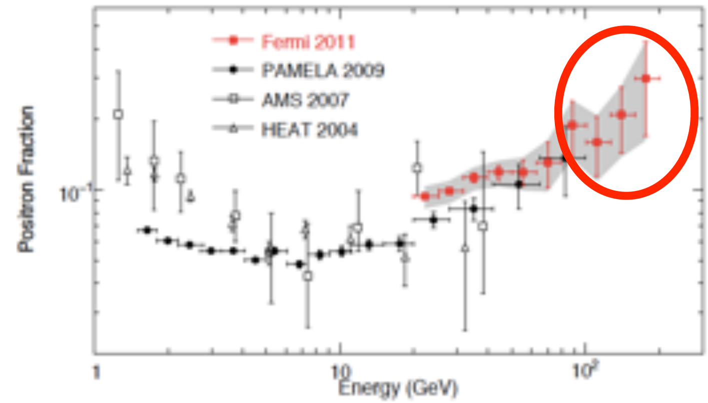
Why is this measurement **important**?



(i) For **every** (50 GeV) **cosmic-ray positron**, 10 electrons and **10,000 protons**!

*important confirmation that the extra positrons measured by Pamela are **not mis-ID protons**!*

Why is this measurement **important**?

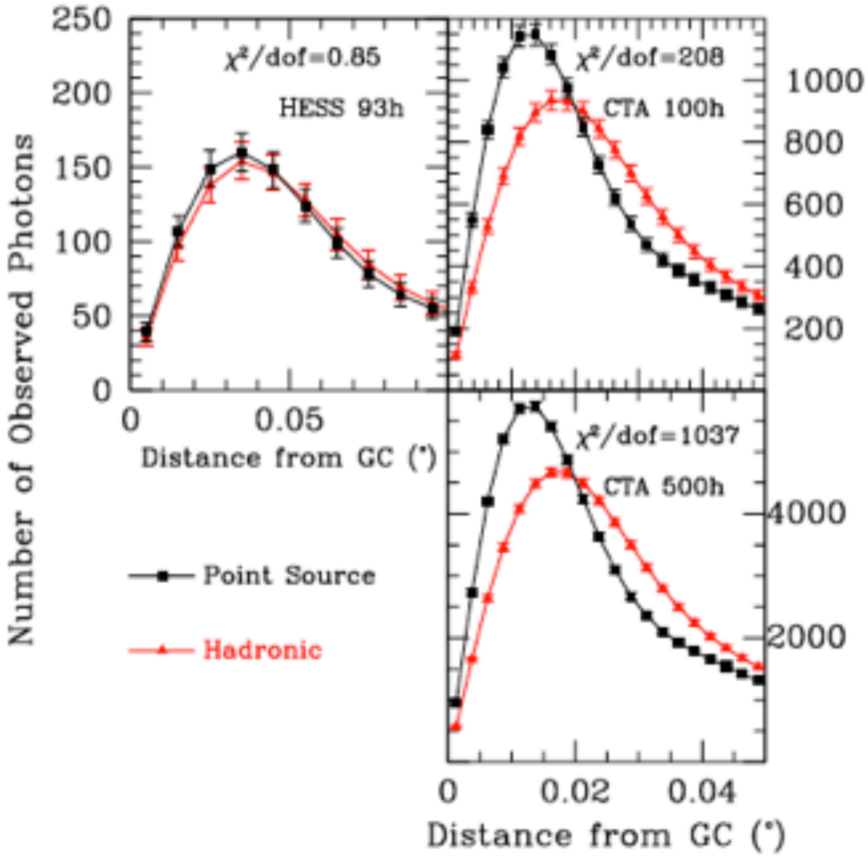


(ii) Extends Pamela results to **higher energy**, E=200 GeV

consistent spectrum, no turnover

More to come **soon** from **AMS-02**!

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

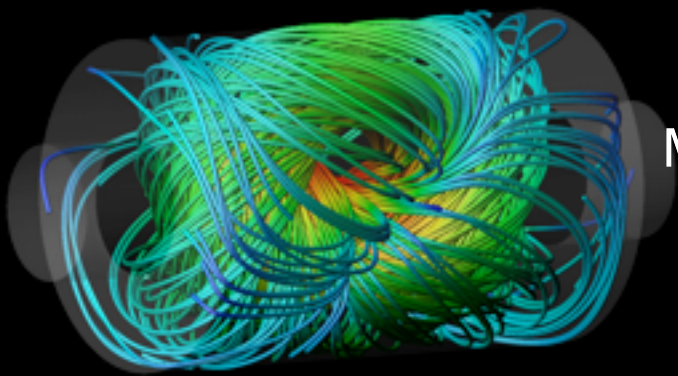


CTA: ability to **discriminate** point source versus diffuse hadronic emission

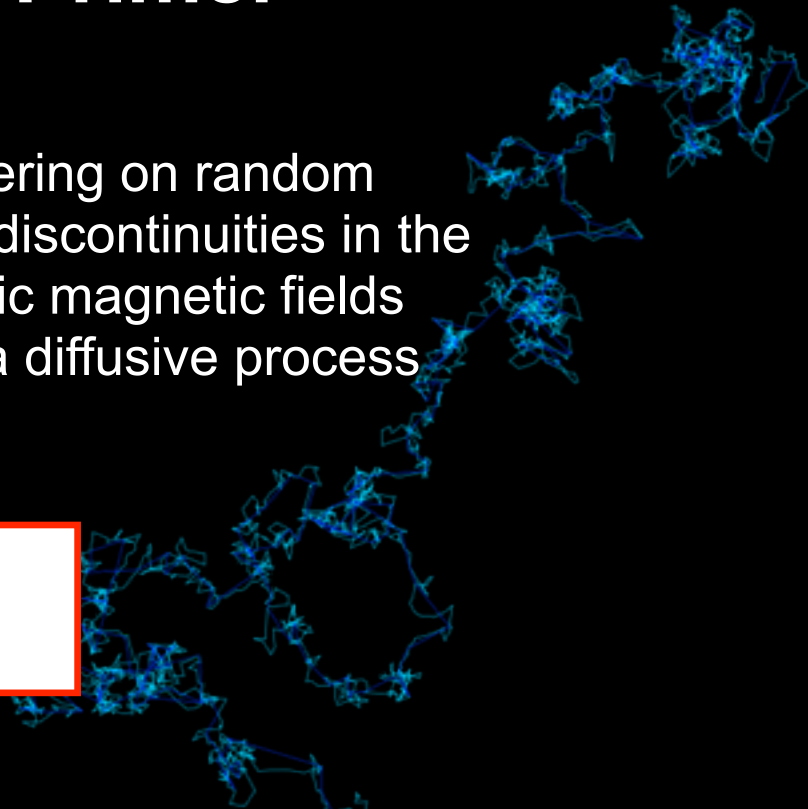
CTA key to understand physics of Galactic Center at high energies!!

Linden and SP, 1206.4308

A "Cosmic Ray Primer"



Particle scattering on random MHD waves and discontinuities in the tangled Galactic magnetic fields is modeled as a diffusive process



$$\frac{dn_{e^\pm}(E,\vec{r},t)}{dt}$$

$$D(E,\vec{r}) = D_0 E^\delta$$

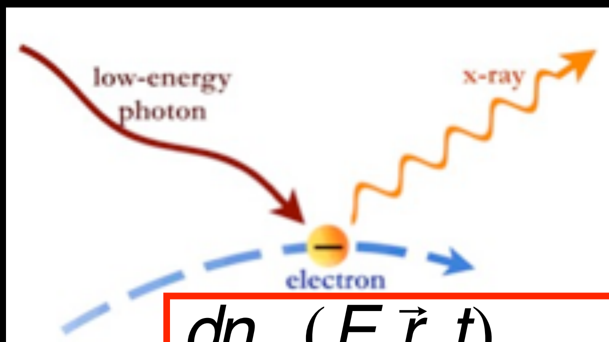
$$D_0(E = 1\ \mathrm{GeV}) \sim 10^{28}\ \mathrm{cm}^2/\mathrm{s}$$

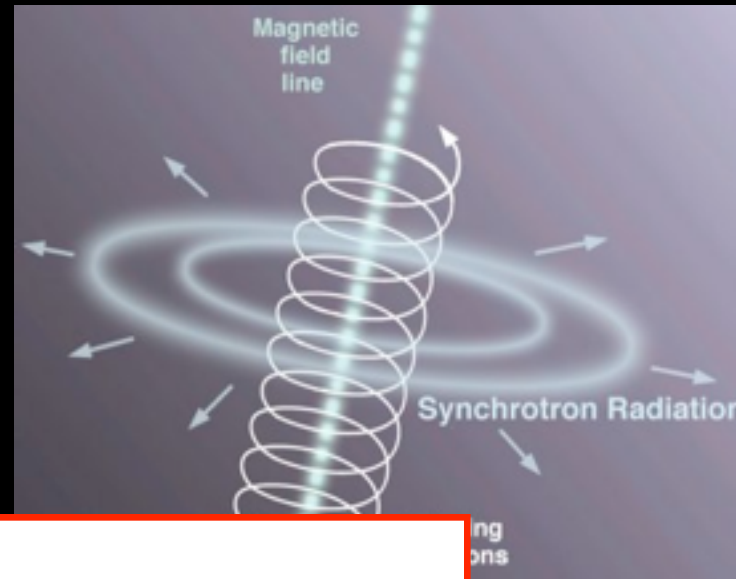
$$\delta \sim 0.3 \ldots 0.7$$

Associated Diffusion Time Scale: $\tau_{\mathrm{diff}} \sim \frac{R^2}{D(E)}$

A "Cosmic Ray Primer"

For electrons and positrons, main energy losses:
Inverse Compton + Synchrotron





$$\frac{dn_{e^\pm}(E,\vec{r},t)}{dt}$$

$$b(E) \sim 10^{-16}\ \mathrm{GeV/s}\ \ (\mathrm{E/GeV})^2$$

Associated Energy-Loss Time Scale:

$$\tau_{\mathrm{loss}} \sim \frac{E}{b(E)}$$

A “Cosmic Ray Primer”

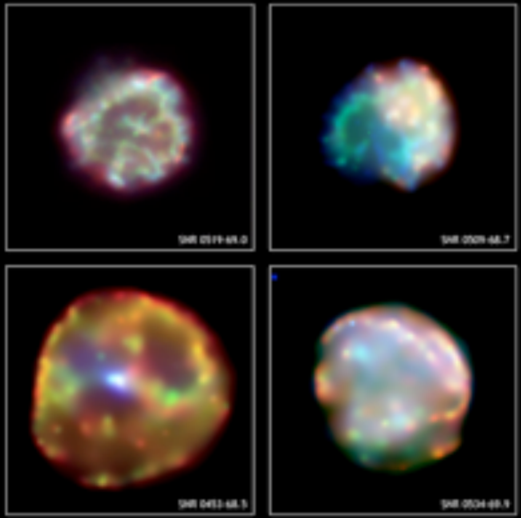
Diffusion-loss equation then reads (neglecting reacceleration, convection…)

$$\frac{dn_{e^\pm}(E,\vec{r},t)}{dt}$$

Averaging over diffusive halo – steady-state solution

$$0 = -\frac{n_{e^\pm}}{\tau_{diff}}$$

$$n_{e^\pm} = Q \times \min[\tau_{diff}, \tau_{loss}]$$



Sources of Cosmic Rays?
SNR – Fermi acceleration

$$Q \sim E^{-2\ldots-2.5}$$

Energy Spectra

primary electrons

- - - - - *production: $E^{-2.2}$*

propagation: min $[\tau_{esc}, \tau_{loss}] \sim E^{-0.6}, E^{-1}$

——— *ambient: $E^{-2.8}, E^{-3.2}$*

(energy-loss-dominated !!!)

primary protons/nuclei

——— *ambient: $E^{-2.8}$*

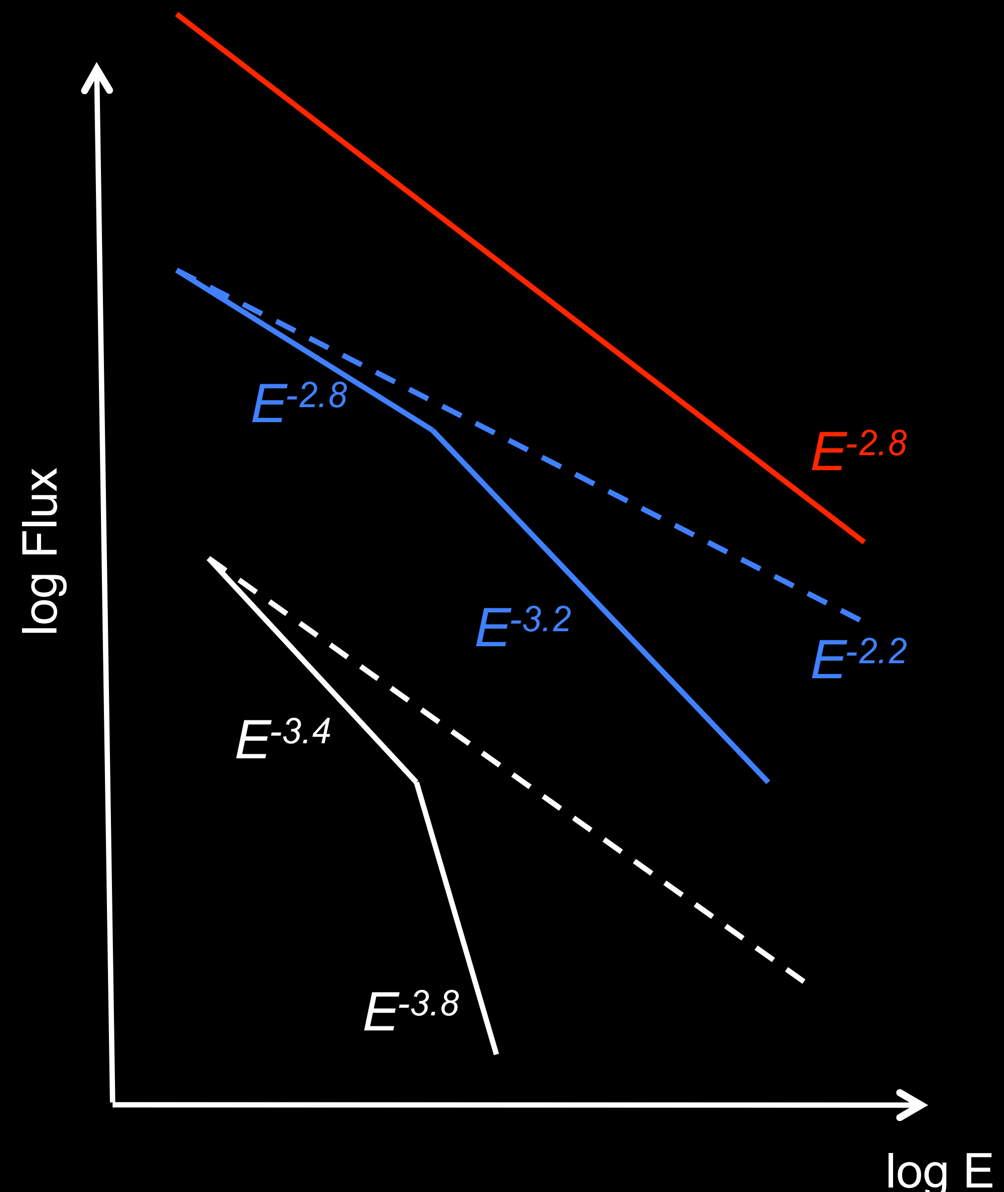
(diffusion-dominated !!!)

secondary e+e-

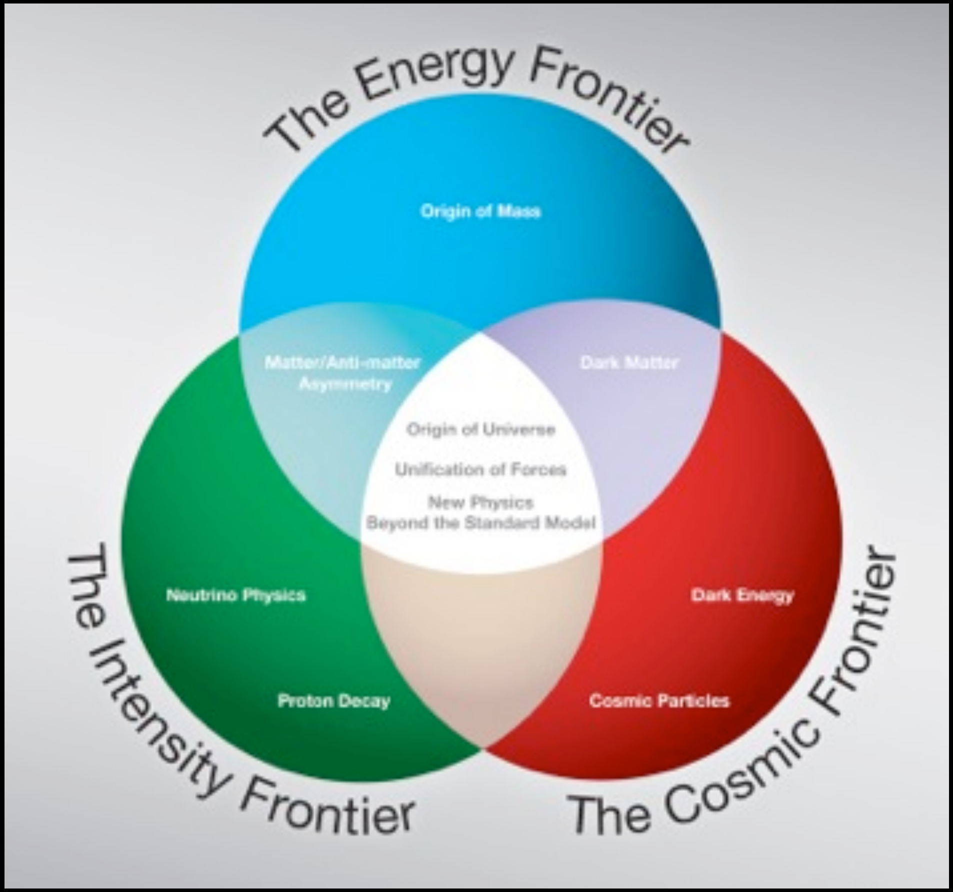
- - - - - *production: $E^{-2.8}$*

propagation: min $[\tau_{loss}, \tau_{esc}] \sim E^{-0.6}, E^{-1}$

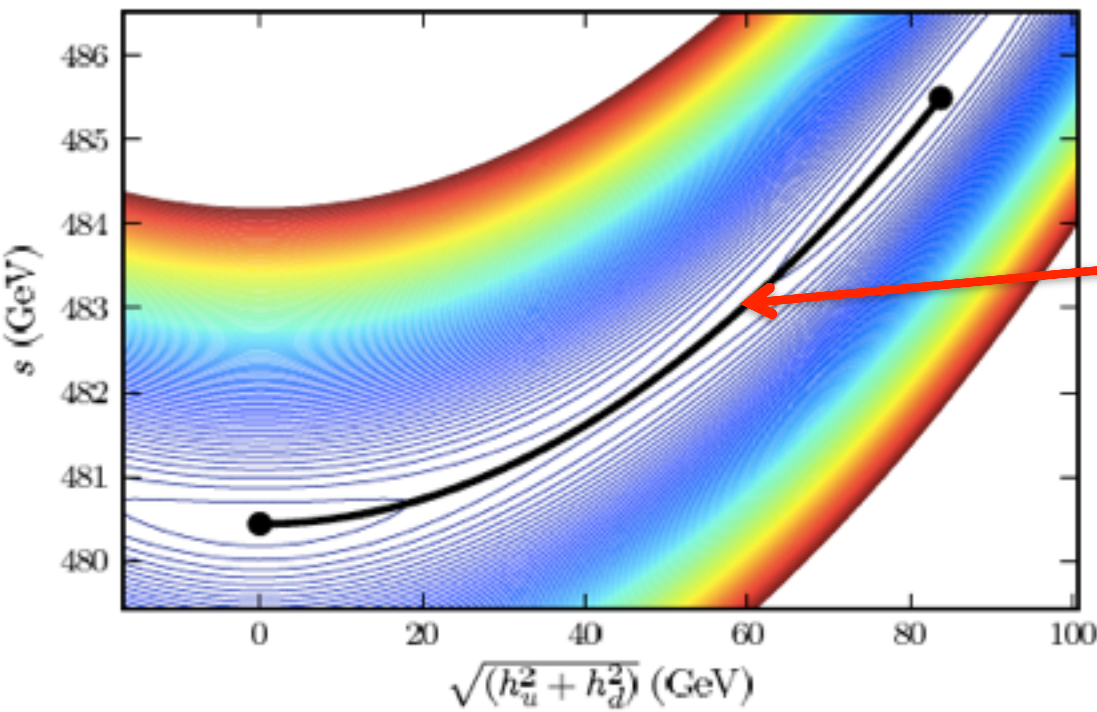
——— *ambient: $E^{-3.4}, E^{-3.8}$*



slide concept: Philip Mertsch


The Energy Frontier
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

A model that does everything…
…across all three frontiers!



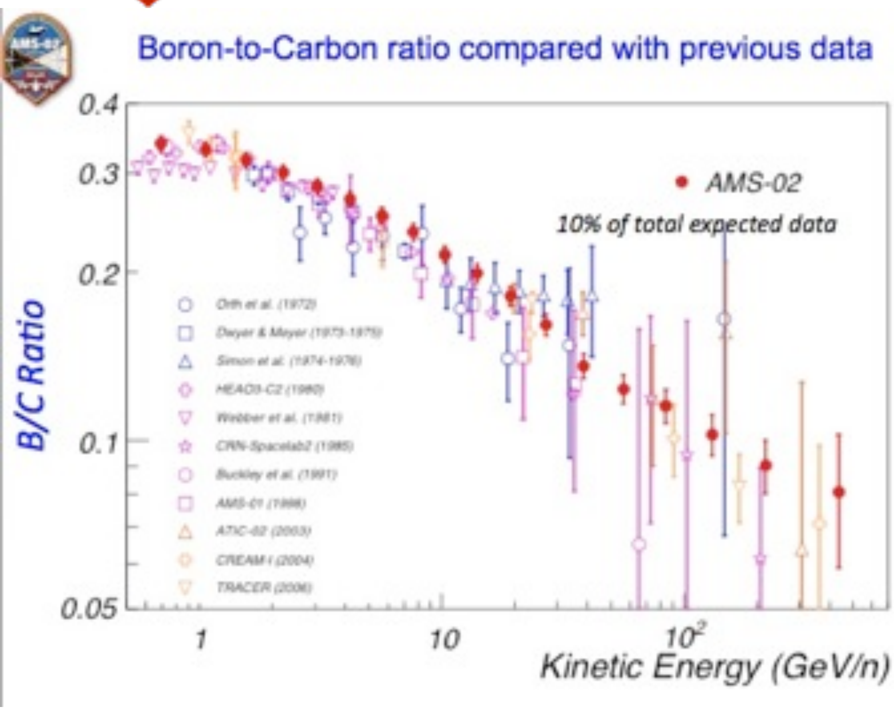
Tunneling
Direction
in field space

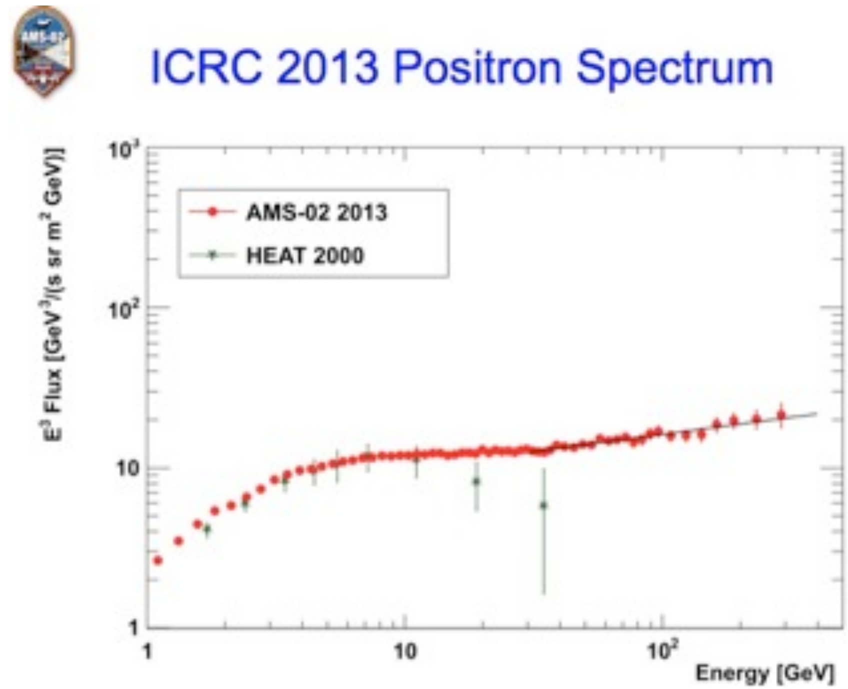
Effective potential at critical temperature
(all NMSSM degrees of freedom included!)

CosmoTransitions

Kozaczuk, Profumo and ***Wainwright****, 2013*

July 8, 2013





Very recently: results on **other cosmic-ray species** and detailed, separate **positron and electron spectra**

PRL, **110** (2013) 14