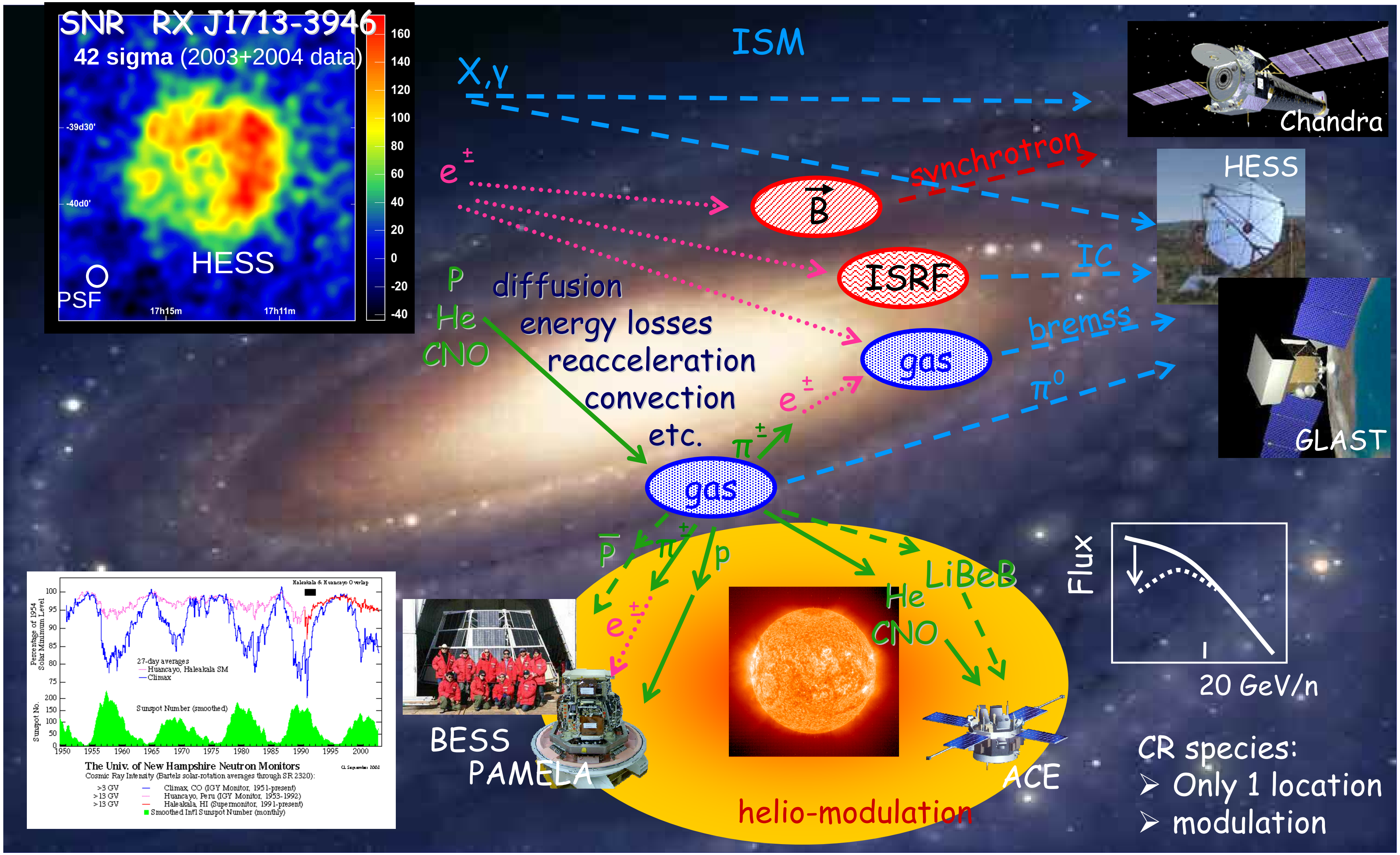
# Matter & Antimatter in Cosmic Rays

Igor V. Moskalenko (Stanford U.)

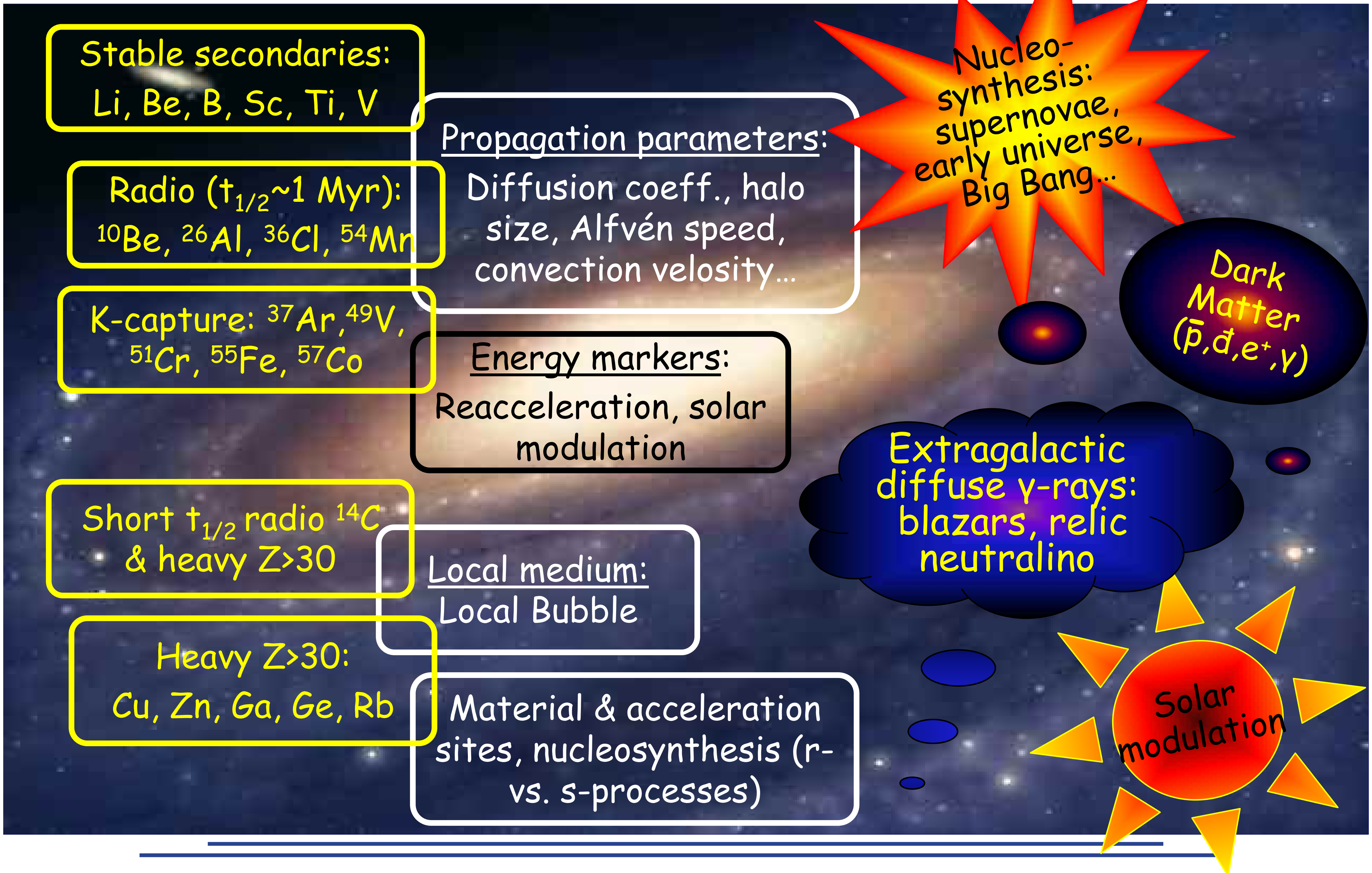
See also talk by J.Wefel

* Some slides are from presentations by P.Blasi (rapporteur, 30th ICRC) and A.Abdo (Milagro)

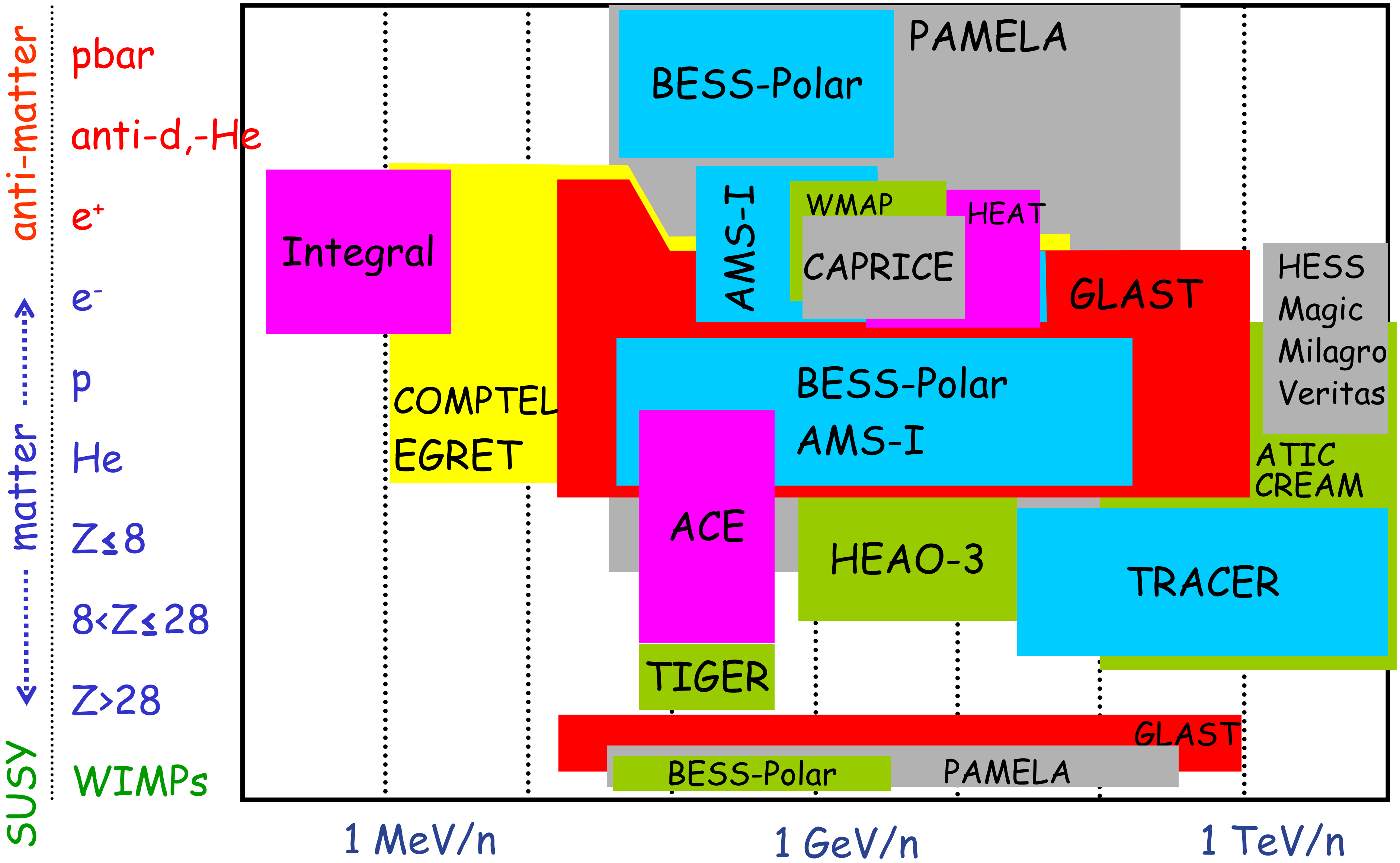
# CR Interactions in the Interstellar Medium



# Nuclear component in CR: What we can learn?



# CR and gamma-ray (CR) instruments



# Direct vs Indirect CR measurements

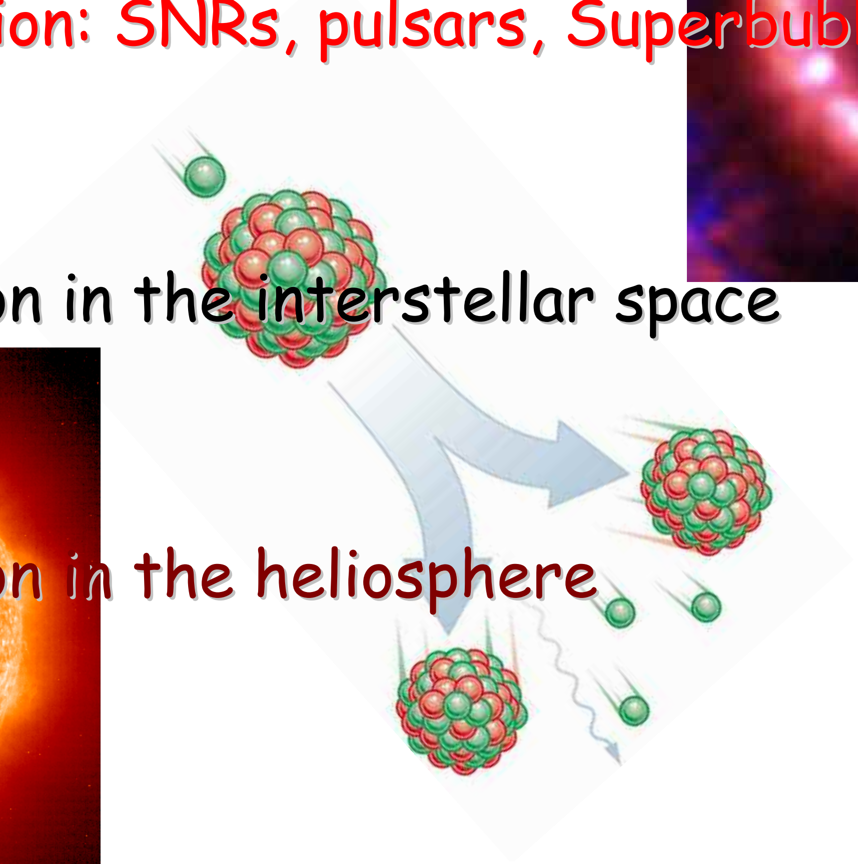
- Direct measurements are done in one particular point in the Galaxy (deep inside the heliosphere)
- Good data exist <200 GeV/n or even less, <30 GeV/n

- The most of indirect measurements are done through the observations of X-, $\gamma$-rays, and synchrotron emission produced by $e^{\pm}$, p, $\alpha$
- Positrons can be observed indirectly via annihilation feature and IC scattering – a unique antimatter observation!
- Gamma-ray telescopes probe the particle spectra $E \gg E_\gamma$, so that direct and indirect measurements are disconnected!
  - ACTs (~300 GeV threshold) probe the CR spectrum above 1 TeV!
  - GLAST will probe particles <1 TeV – a range comparable with direct measurements, e.g. by PAMELA
- Indirect measurements provide a snapshot while direct measurements show the spectrum averaged over time (~10 Myr) and space (~kpc scale)
- The missing link, propagation in the ISM, will be provided by GLAST through the observations of the diffuse emission
- To predict the antimatter fluxes we have to understand the matter!

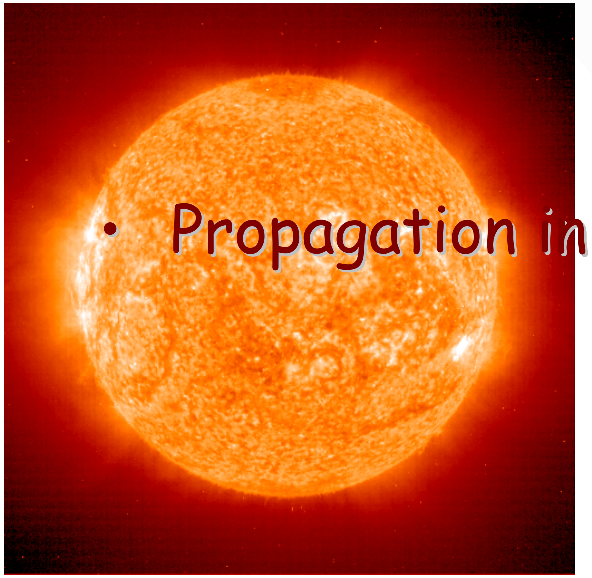
# What's (with) the matter?

## Stages of CR propagation:

- Acceleration: SNRs, pulsars, Superbubbles, whatever

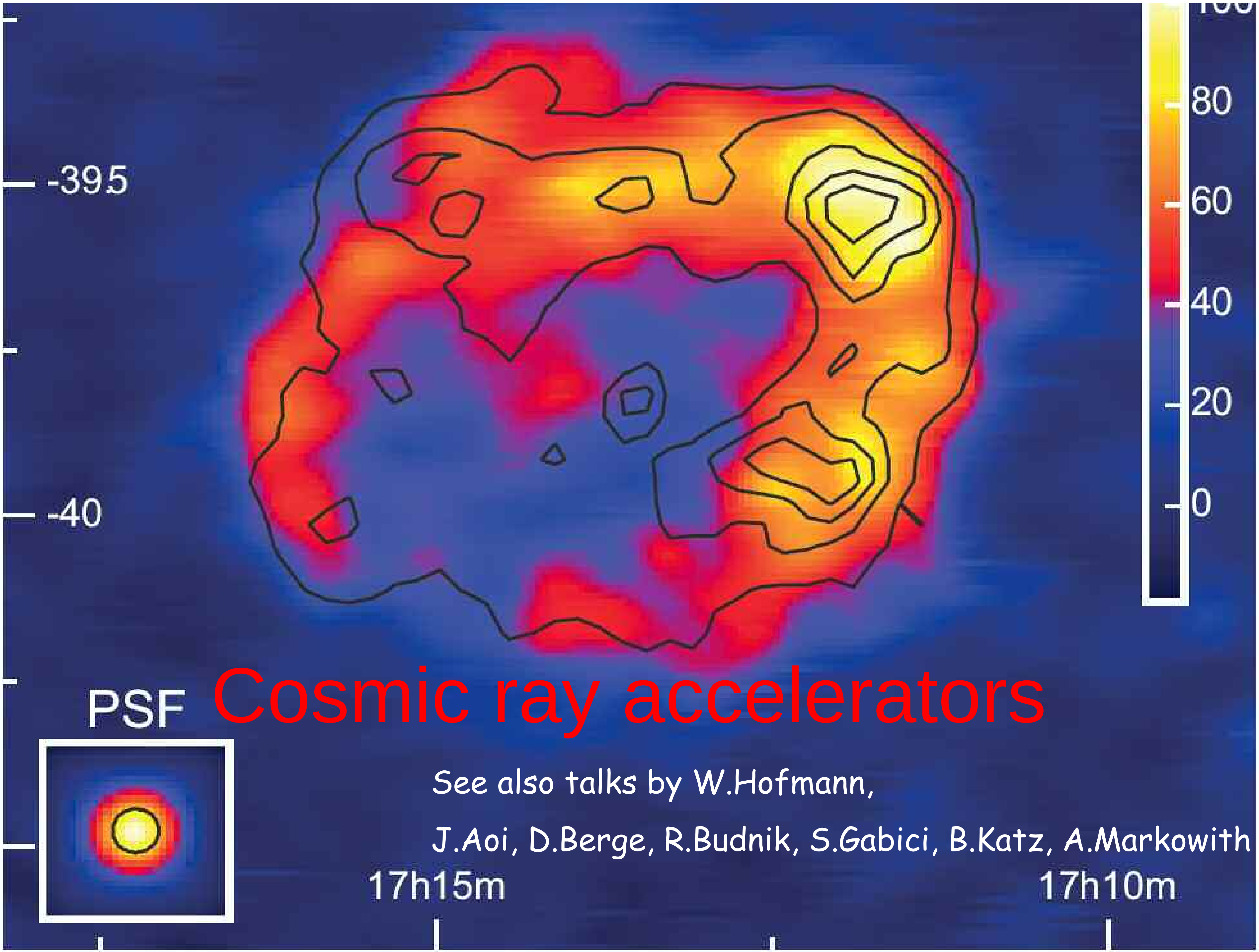


- Propagation in the interstellar space



- Propagation in the heliosphere

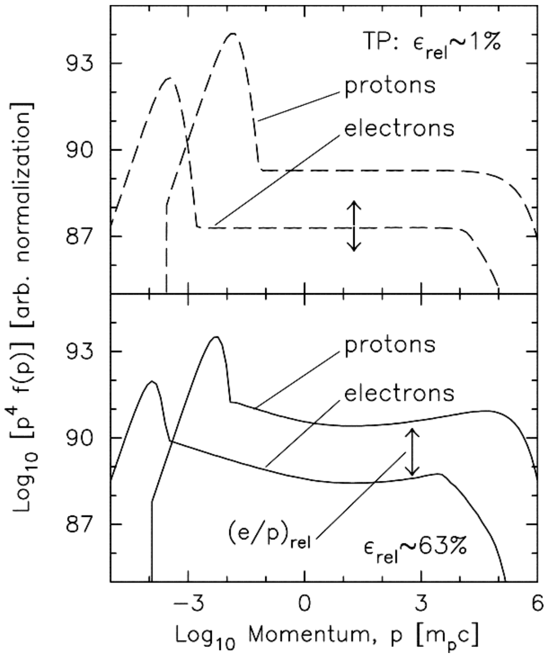
# Cosmic ray accelerators




See also talks by W.Hofmann,

J.Aoi, D.Berge, R.Budnik, S.Gabici, B.Katz, A.Markowith

# CR Sources (SNRs)




Ellison+2007

- Theory of SNR shock acceleration: $\sim p^{-2}$
- To be consistent with local CR measurements, different propagation models require:
  - •Proton spectral index 2.15, 2.25, 2.40
  - •Electron spectral index 2.40,2.50,2.70
- The discrepancy is not easy to overcome

TABLE 1

PROPAGATION PARAMETER SETS

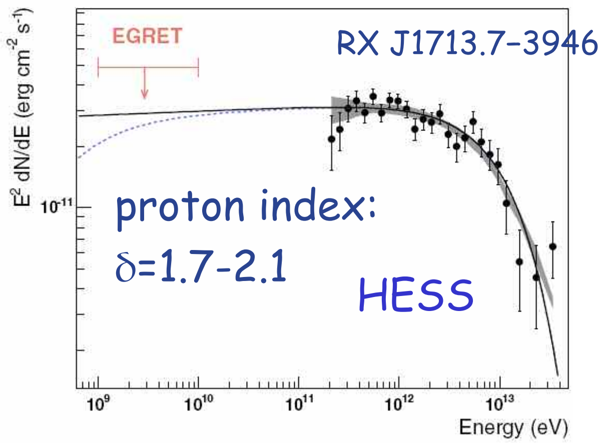
| Model | Injection Index[a] Nucleons ($\gamma_s$) | Injection Index[a] Electrons ($\gamma_e$) | Break Rigidity (GV) | Diffusion Coefficient at 3 GV $\kappa$ ($cm^2\ s^{-1}$) | Diffusion Coefficient at 3 GV Index ($a$) | Alfvén Speed ($V_A$, km $s^{-1}$) | galdef File |
|---|---|---|---|---|---|---|---|
| Plain Diffusion (PD)........................................ | 2.30/2.15 | 2.40 | 40 | $2.2 \times 10^{28}$ | 0.0/0.60[b] | ... | 44_999726 |
| Diffusive Reacceleration (DR)................................ | 1.80/2.40 | 1.60/2.50 | 4 | $5.2 \times 10^{28}$ | 0.34 | 36 | 44_599278 |
| Diffusive Reacceleration with Damping (DRD)............. | 2.40/2.24 | 2.70 | 40 | $2.9 \times 10^{28}$ | 0.50 | 22 | 44_999714kr |

NOTE.—Adopted halo size $H = 4$ kpc.
[a] Index below/above the break rigidity.
[b] Index below/above $R_0 = 3$ GV; $D = \beta^{-2}\kappa(R/R_0)^a$.

Ptuskin+2006

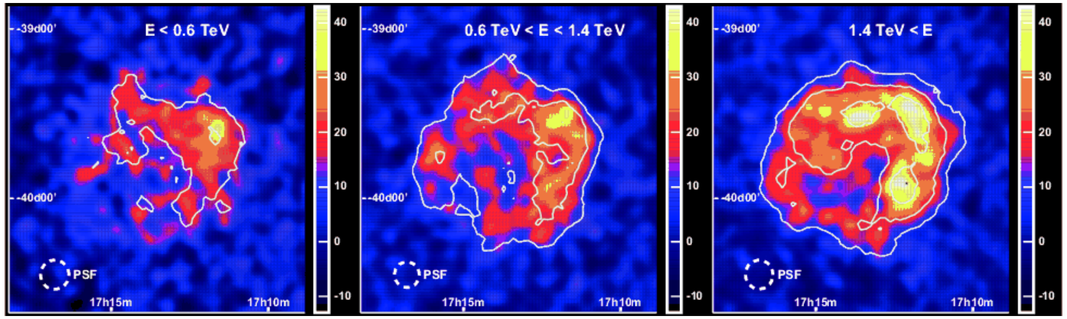
# HESS observations of SNR RX J1713.7-3946

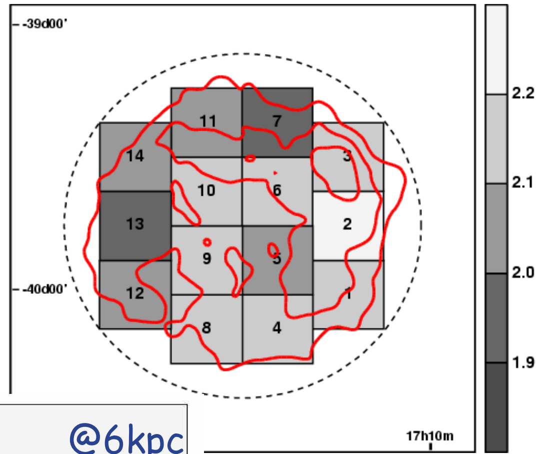
## hadronic scenario

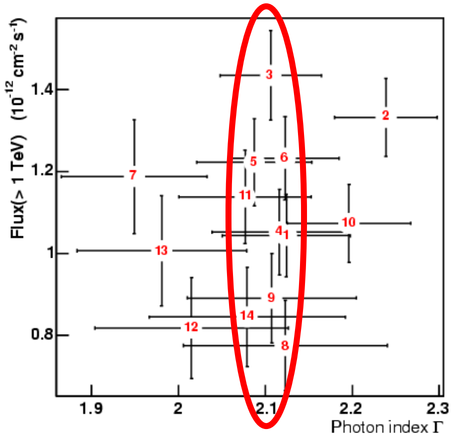



proton index:
$\delta$=1.7-2.1

HESS



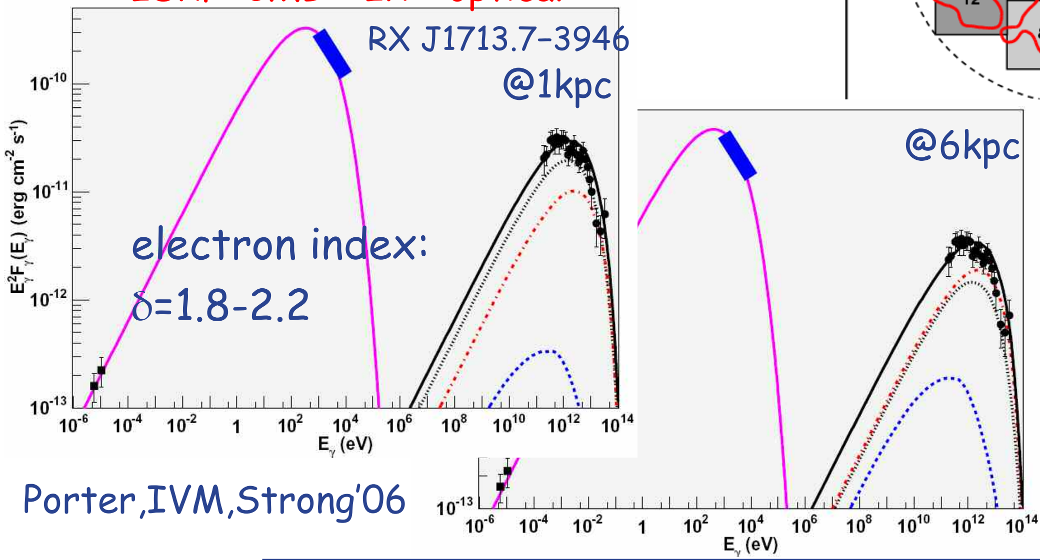




photon index: 2.12±0.03

## leptonic scenario

ISRF: CMB + IR + optical



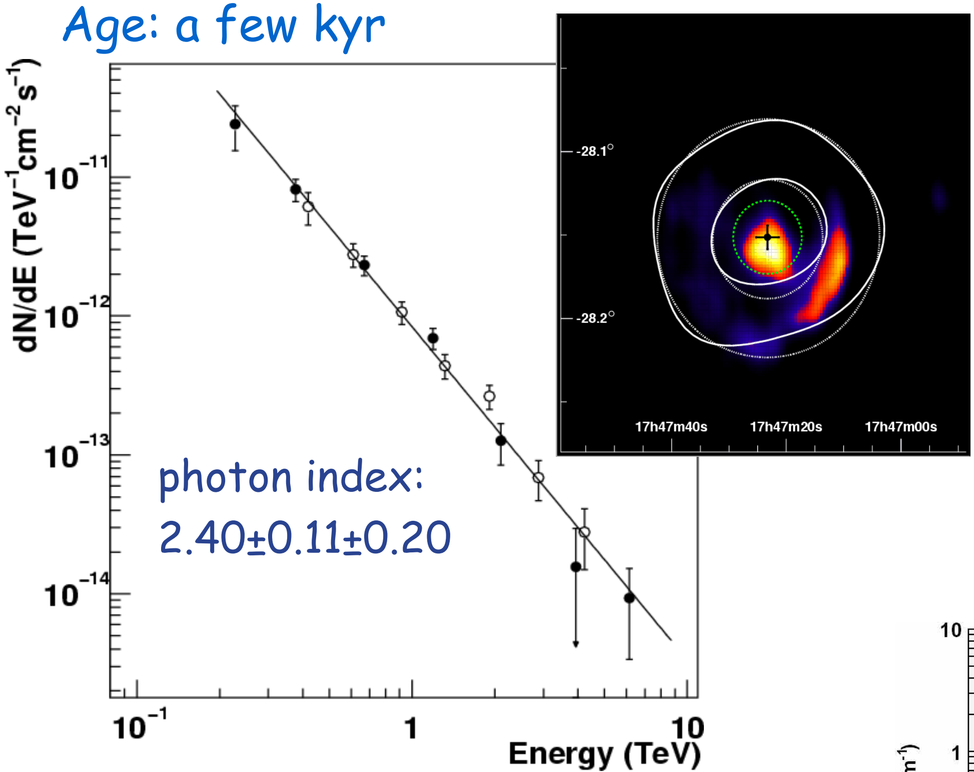

electron index:
$\delta$=1.8-2.2

Porter,IVM,Strong'06

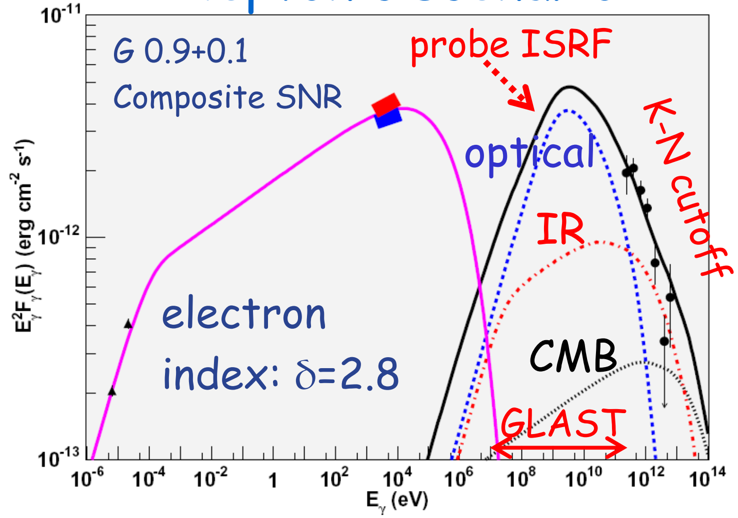
In both cases (hadronic or leptonic), the required particle spectra are hard

# HESS Observations of Composite SNR G0.9+0.1

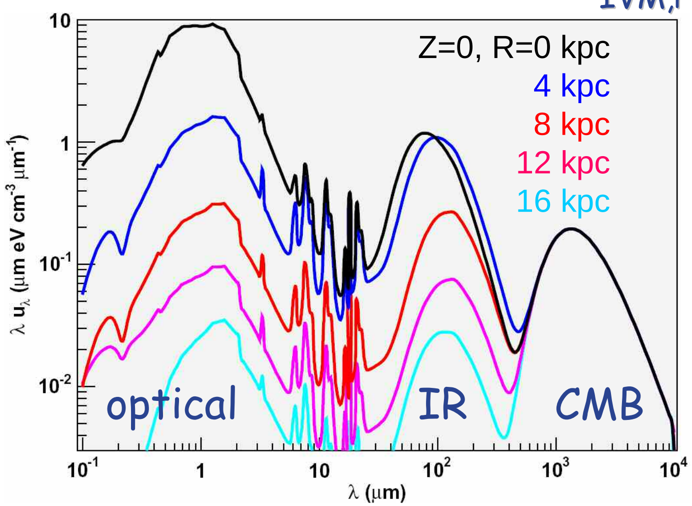
SNR at the GC
Age: a few kyr




## leptonic scenario




Porter,IVM,Strong'06
IVM,Porter,Strong'06




Interstellar radiation field in the inner Galaxy is dominated by the dust (IR) emission and starlight

# Particle Acceleration in the SNRs

- Not all SNRs are created equal…
- It is difficult to distinguish between hadronic and leptonic scenarios based on the spectral shape in 0.5-20 TeV region alone
- Observational bias: TeV instruments see mostly hard spectrum sources
- The observed CR spectrum is cumulative over a large number of sources
- GLAST observation of Galactic sources and the diffuse emission will be critical!

- ISRF is very intense in the inner Galaxy
- GLAST will also probe ISRF

# Close X-ray Binaries @TeV

## Max of the emission

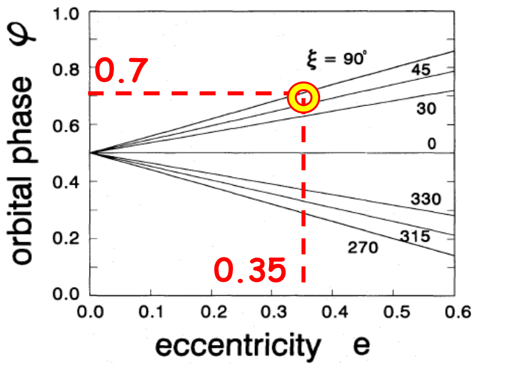
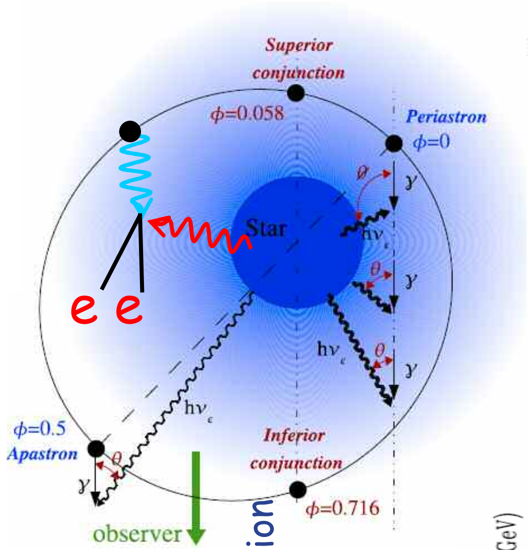
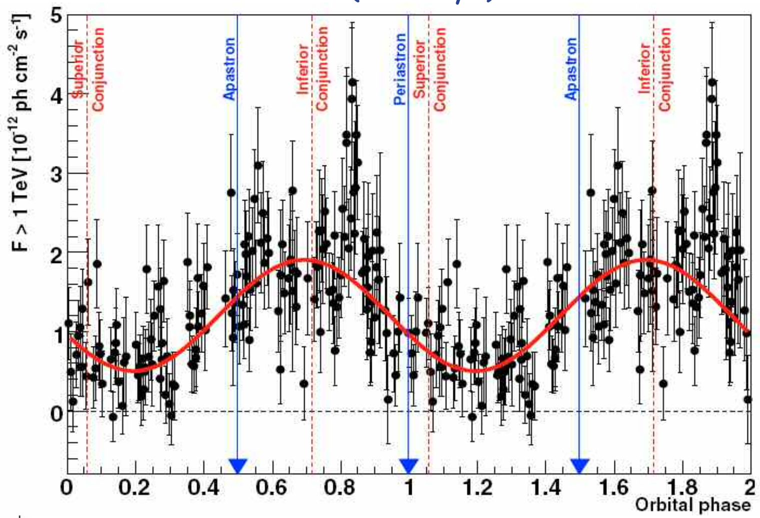


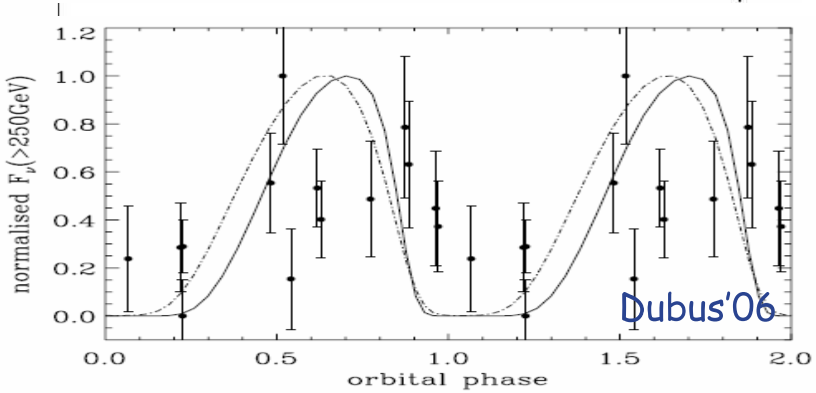

**Figure 2.** The phase of maximum γ-radiation from the binary system against the eccentricity parameter for some values of orbit orientation angle ξ.

## Orbital modulation




HESS: LS 5039 (3.9 days)



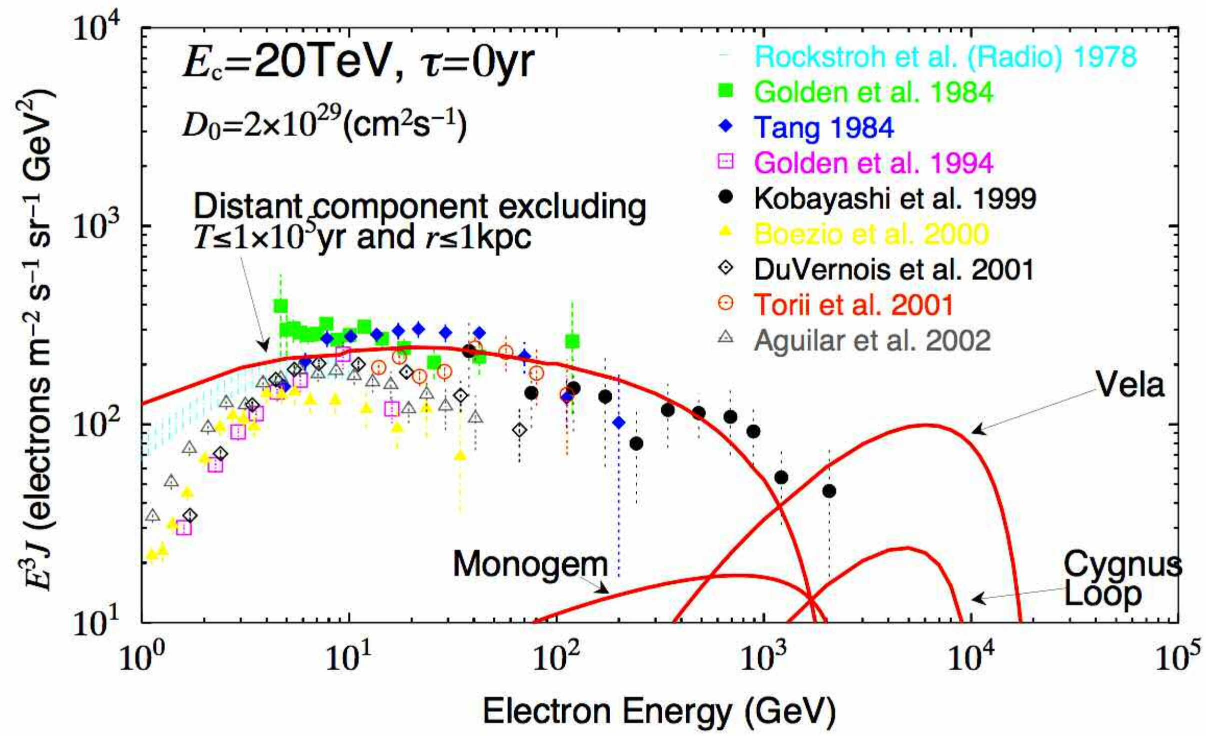




- $\gamma+h\nu \rightarrow ee$
- Predicted ~17 yr ago (IVM+'91,'93,'94,'95)
- Finally discovered in LS 5039 by HESS!
- Recent works: Böttcher,Dermer'05;Dubus'06

- The max emission at the phase corresponding to the direction to the observer indicates that the TeV gammas are produced close to the compact object → efficient particle acceleration!
- GLAST will clarify the mechanism producing gammas

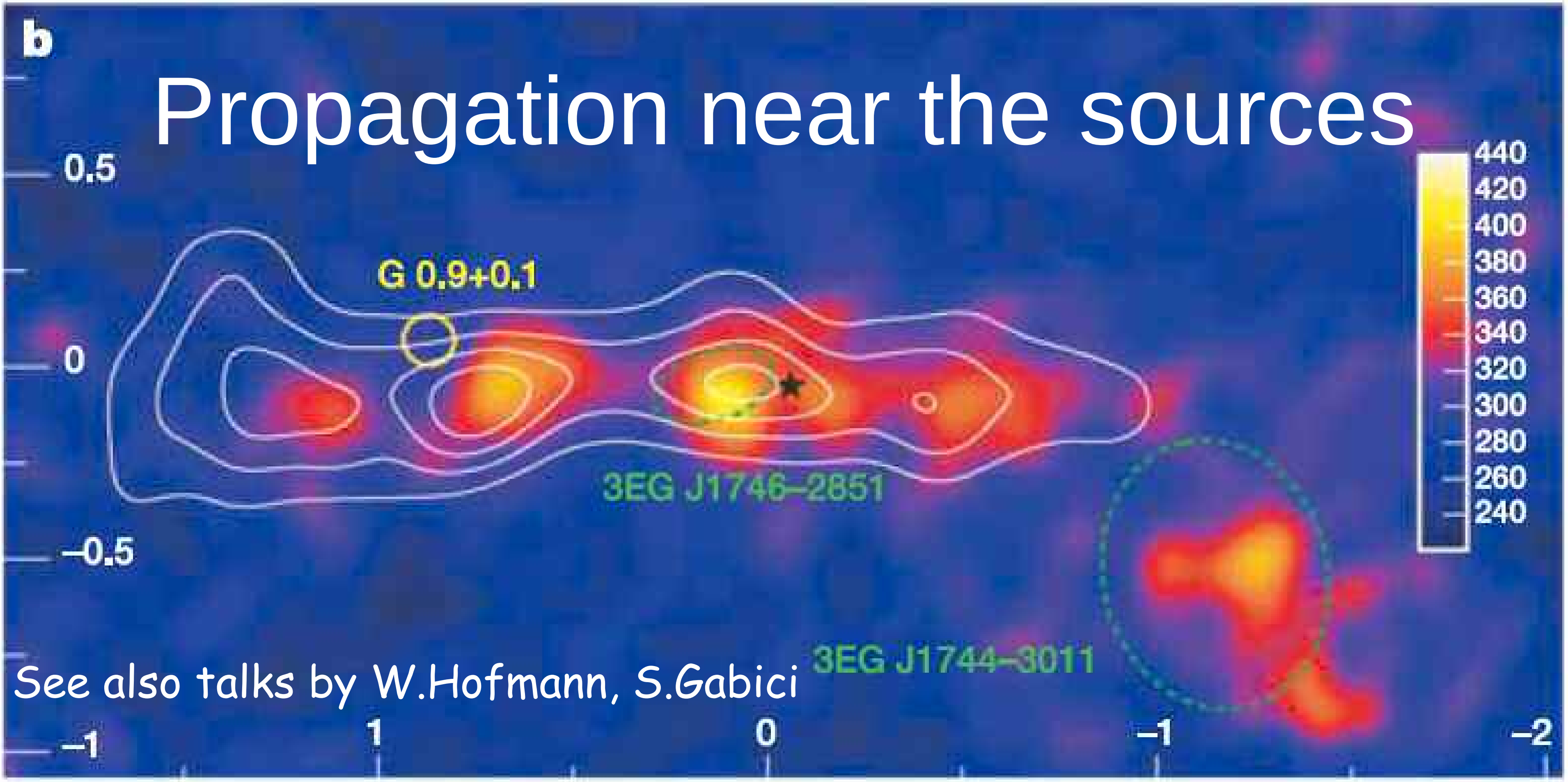
# Pulsars & Plerions

- Produce mostly electrons and positrons
- Can accelerate up to TeV energies, at least
- May produce spectral features in CR electron and positron spectra
- Current measurements are not accurate enough!




Kobayashi+'03

# Propagation near the sources

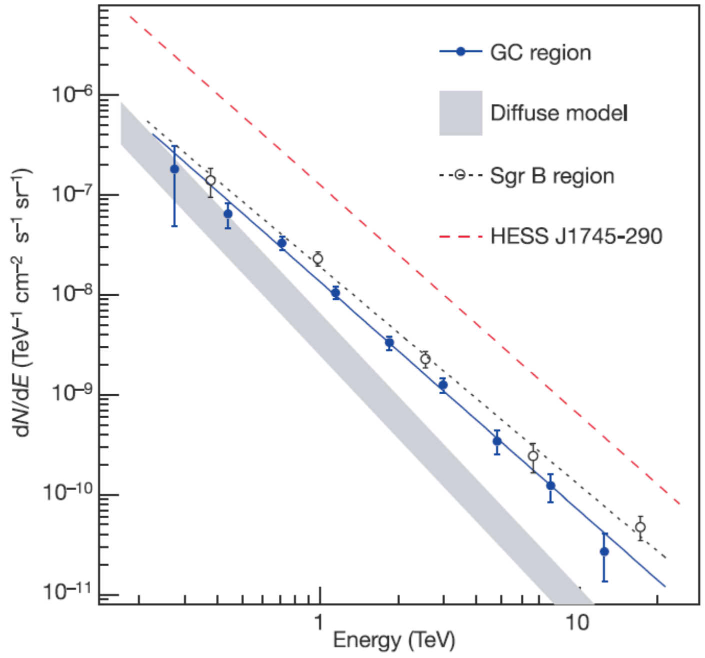


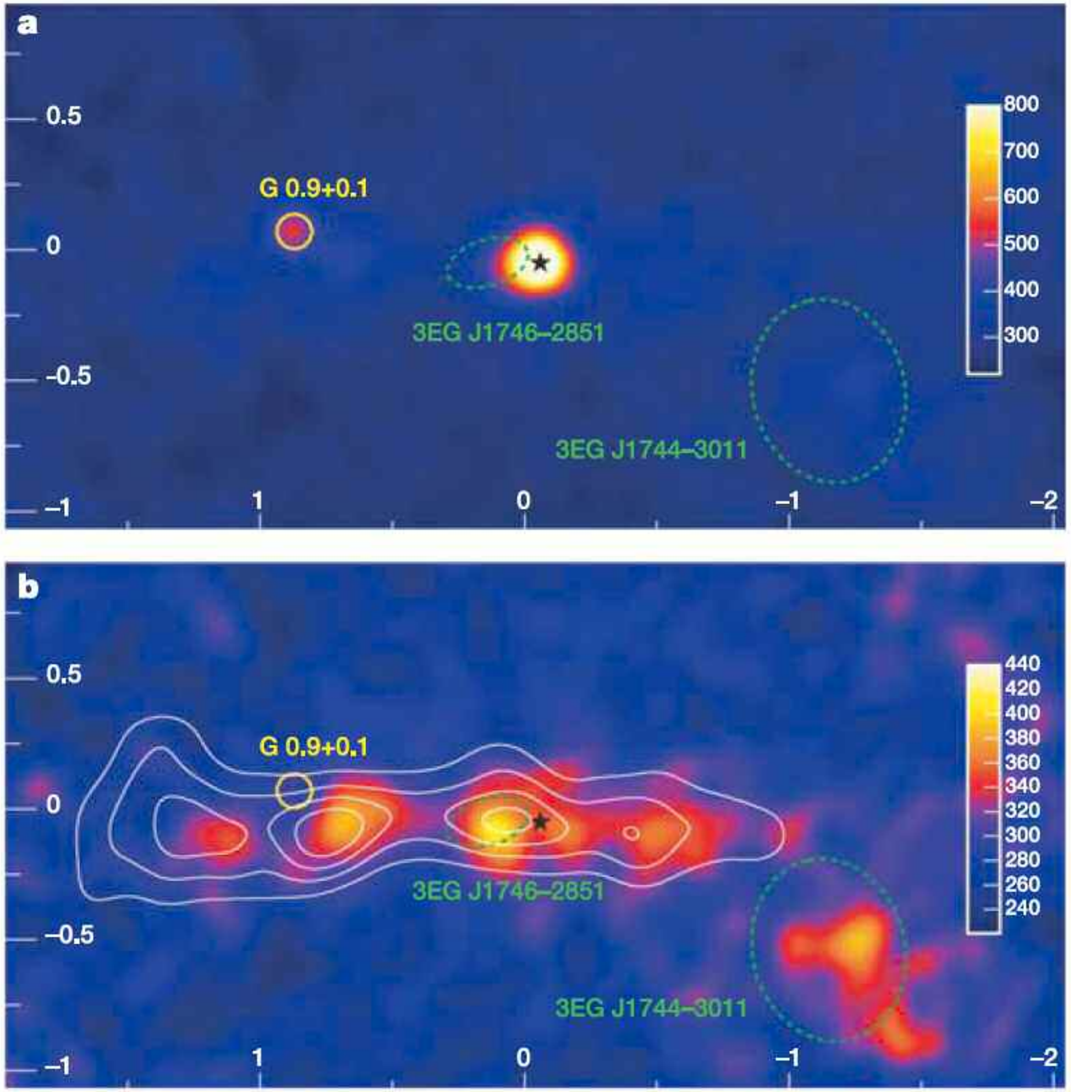

See also talks by W.Hofmann, S.Gabici

# Diffuse VHE γ-ray from the Galactic Center

## Discovery of very-high-energy γ-rays from the Galactic Centre ridge

F. Aharonian[1], A. G. Akhperjanian[2], A. R. Bazer-Bachi[3], M. Beilicke[4], W. Benbow[1], D. Berge[1], K. Bernlöhr[1,5], C. Boisson[6], O. Bolz[1], V. Borrel[3], I. Braun[1], F. Breitling[5], A. M. Brown[7], P. M. Chadwick[7], L.-M. Chounet[8], R. Cornils[4], L. Costamante[1,20], B. Degrange[8], H. J. Dickinson[7], A. Djannati-Ataï[9], L. O'C. Drury[10], G. Dubus[8], D. Emmanoulopoulos[11], P. Espigat[9], F. Feinstein[12], G. Fontaine[8], Y. Fuchs[13], S. Funk[1], Y. A. Gallant[12], B. Giebels[8], S. Gillessen[1], J. F. Glicenstein[14], P. Goret[14], C. Hadjichristidis[7], D. Hauser[1], M. Hauser[11], G. Heinzelmann[4], G. Henri[13], G. Hermann[1], J. A. Hinton[1], W. Hofmann[1], M. Holleran[15], D. Horns[1], A. Jacholkowska[12], O. C. de Jager[15], B. Khélifi[1], S. Klages[1], Nu. Komin[5], A. Konopelko[5], I. J. Latham[7], R. Le Gallou[7], A. Lemière[9], M. Lemoine-Goumard[8], N. Leroy[8], T. Lohse[5], A. Marcowith[3], J. M. Martin[6], O. Martineau-Huynh[16], C. Masterson[1,20], T. J. L. McComb[7], M. de Naurois[16], S. J. Nolan[7], A. Noutsos[7], K. J. Orford[7], J. L. Osborne[7], M. Ouchrif[16,20], M. Panter[1], G. Pelletier[13], S. Pita[9], G. Pühlhofer[11], M. Punch[9], B. C. Raubenheimer[15], M. Raue[4], J. Raux[16], S. M. Rayner[7], A. Reimer[17], O. Reimer[17], J. Ripken[4], L. Rob[18], L. Rolland[16], G. Rowell[1], V. Sahakian[2], L. Saugé[13], S. Schlenker[5], R. Schlickeiser[17], C. Schuster[17], U. Schwanke[5], M. Siewert[17], H. Sol[6], D. Spangler[7], R. Steenkamp[19], C. Stegmann[5], J.-P. Tavernet[16], R. Terrier[9], C. G. Théoret[9], M. Tluczykont[8,20], C. van Eldik[1], G. Vasileiadis[12], C. Venter[15], P. Vincent[16], H. J. Völk[1] & S. J. Wagner[11]

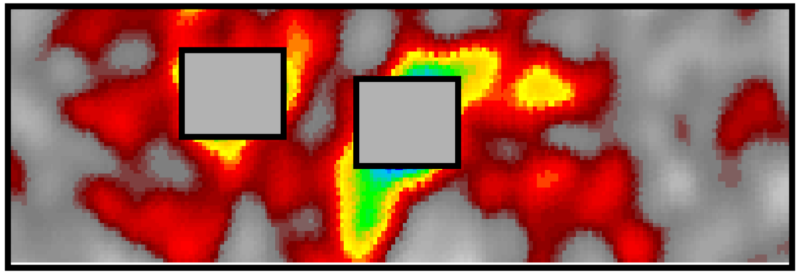


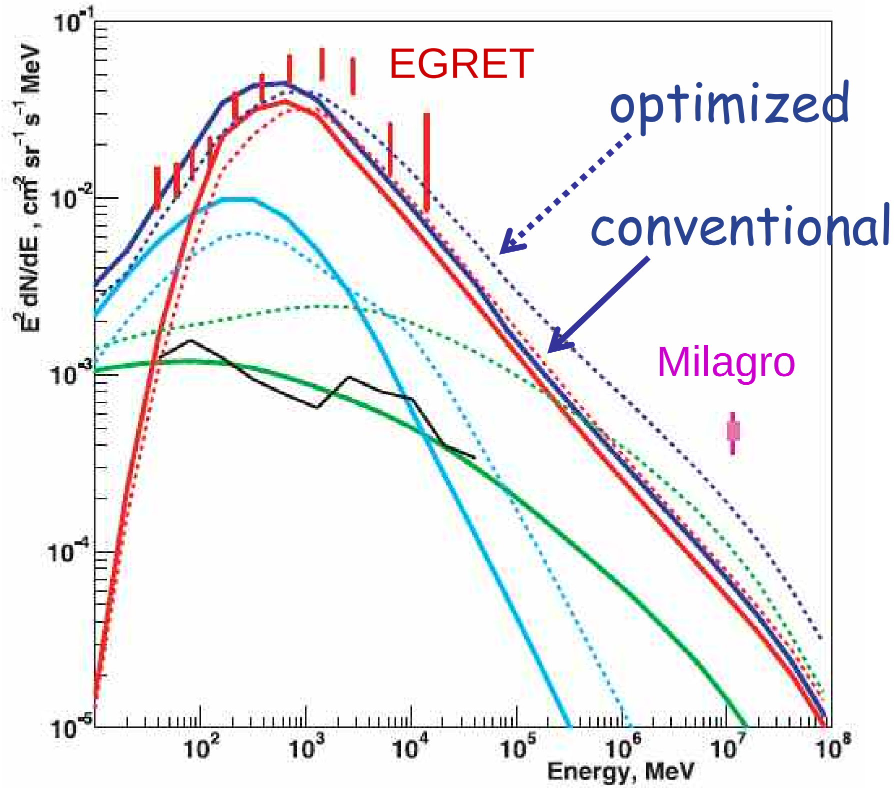




degrees

# Diffuse Emission from Cygnus Region

l(65,85), b (-3,3)



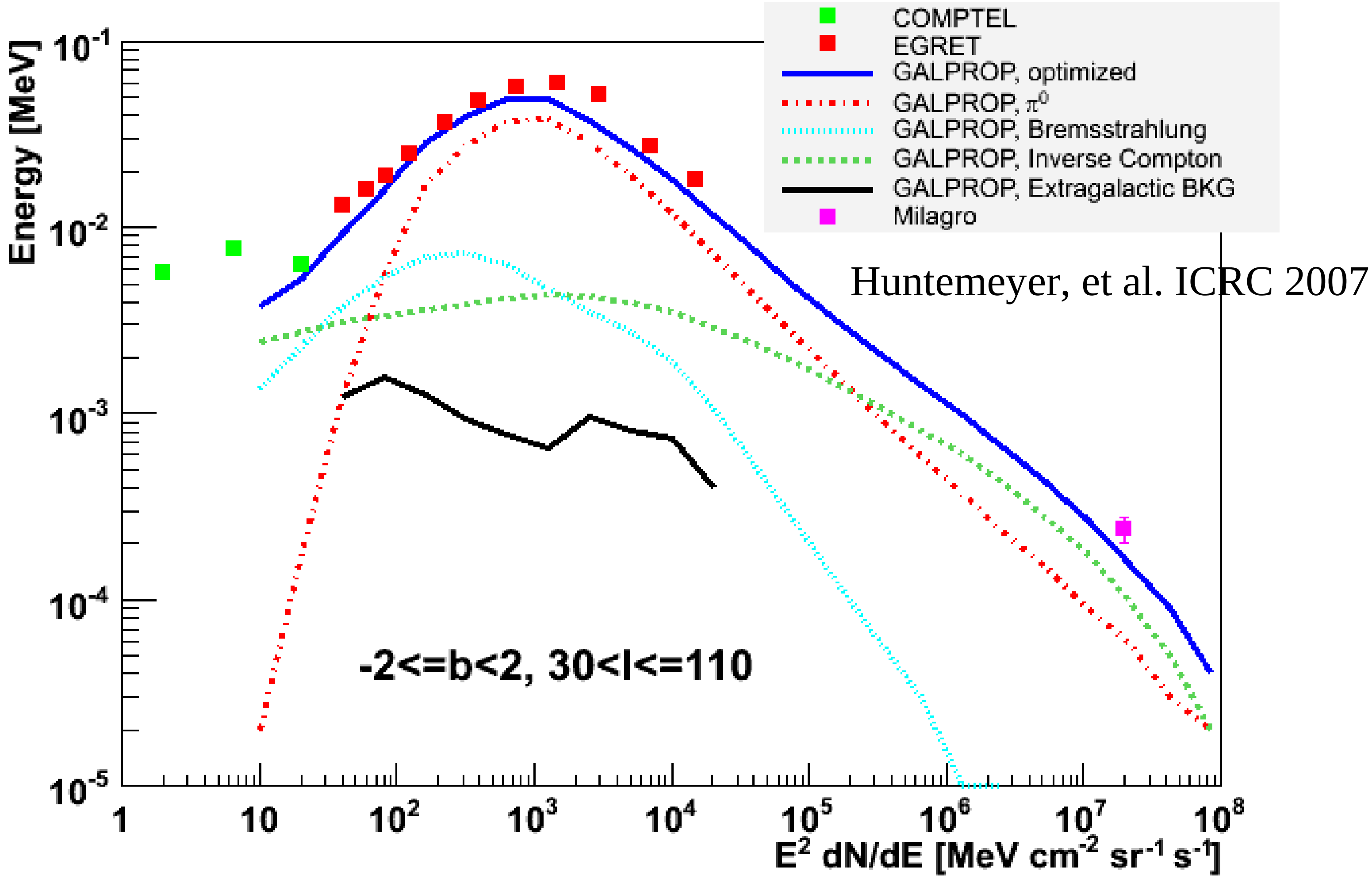



- Exclude a region of 3°×3° around **MGRO J2019+37** and **MGROJ2033+42**
  - Diffuse flux (×$10^{-10}$ TeV $cm^{-2}$ $s^{-1}$ $sr^{-1}$) $= 4.18 \pm 0.52_{stat} \pm 1.26_{sys}$ ~ 2× Crab flux
- Galprop model
  - Milagro flux ~ 7x conventional model of Galprop
  - Milagro flux ~3x optimized model
- "TeV excess"?
- Hard spectrum cosmic ray sources?
- Unresolved point sources?

- GLAST LAT observations are important!

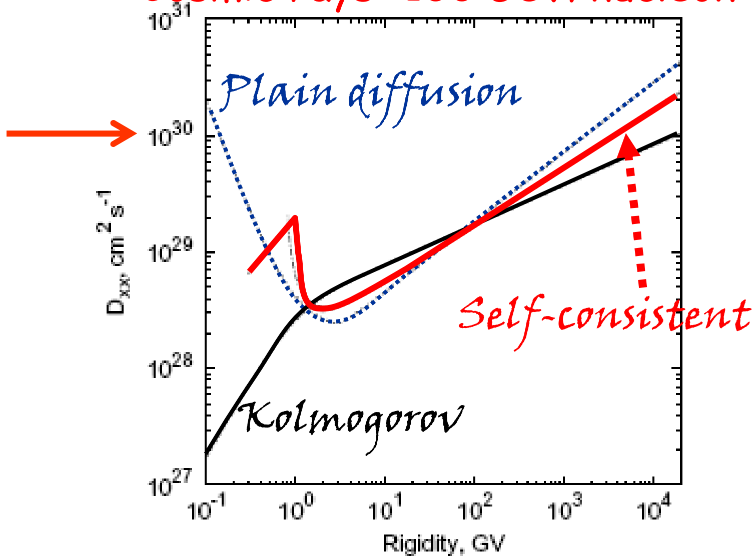
**Abdo A. A. *et al.*, ApJL 658, L33**

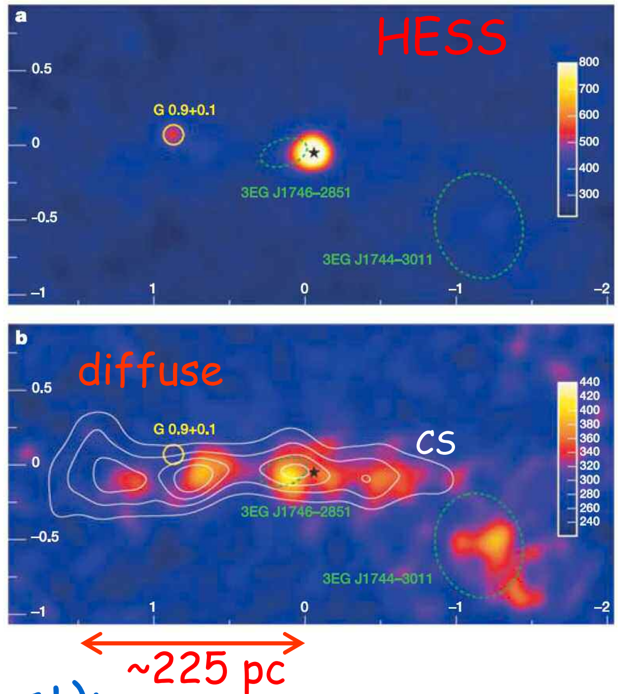
# Gamma-Ray Spectrum of the Diffuse Emission from the Inner Galaxy



# Diffuse emission from the Galactic center

Cosmic rays <100 GeV/nucleon




Back of the envelope estimate (Sgr A East):

$\tau_{SNR}$ <10 kyr; $V_{shock}$ <$10^4$ km/s → $L_{up}$<100 pc

$D_{xx}$ > 1 kpc$^2$/Myr; $\delta\tau$<1.5 kyr

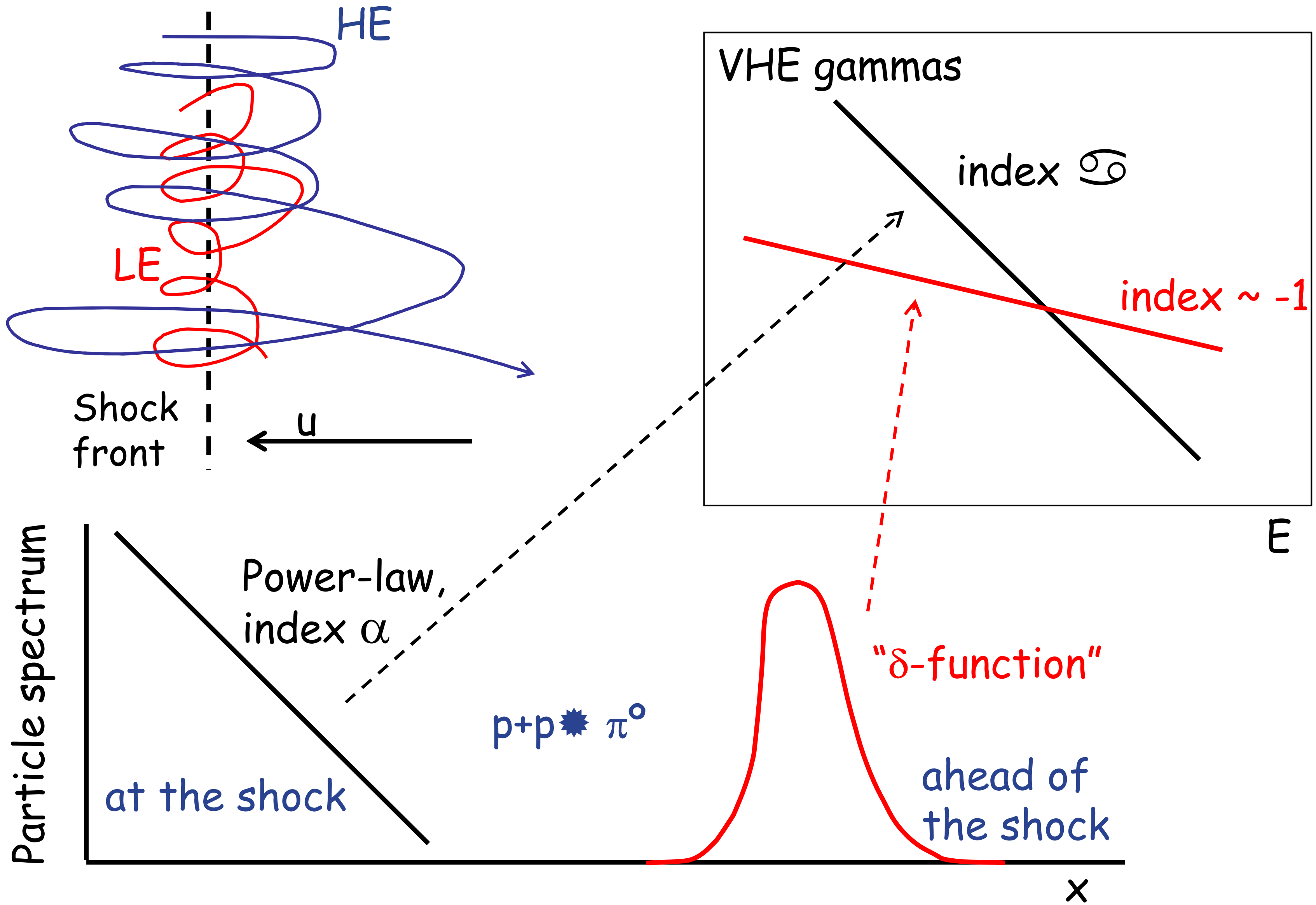
($10^{30}$ cm$^2$/s =3.5 kpc$^2$/Myr)

Buesching+'07: D~1-5 kpc$^2$/Myr

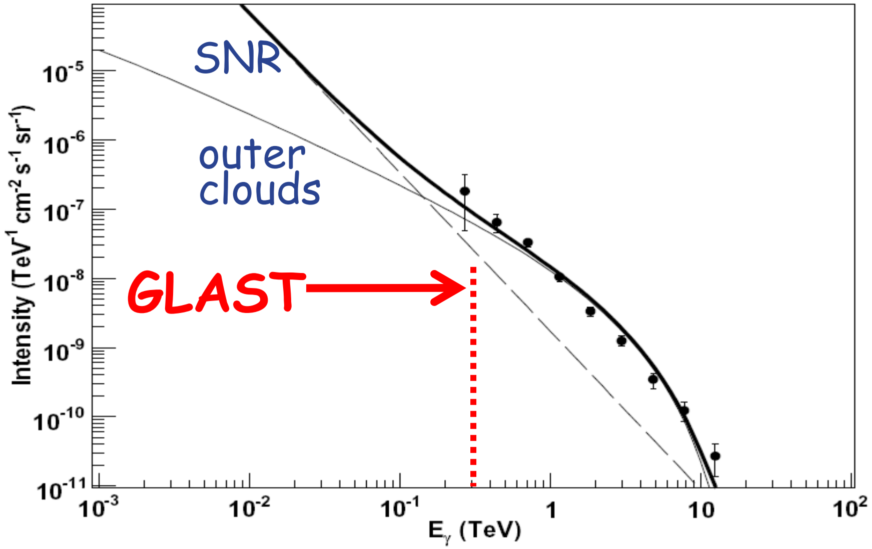
30% of diffuse comes from "sea" CR

- The emission is produced beyond reach of the SNR shell
- Leaking VHE particles?

# Qualitative Picture

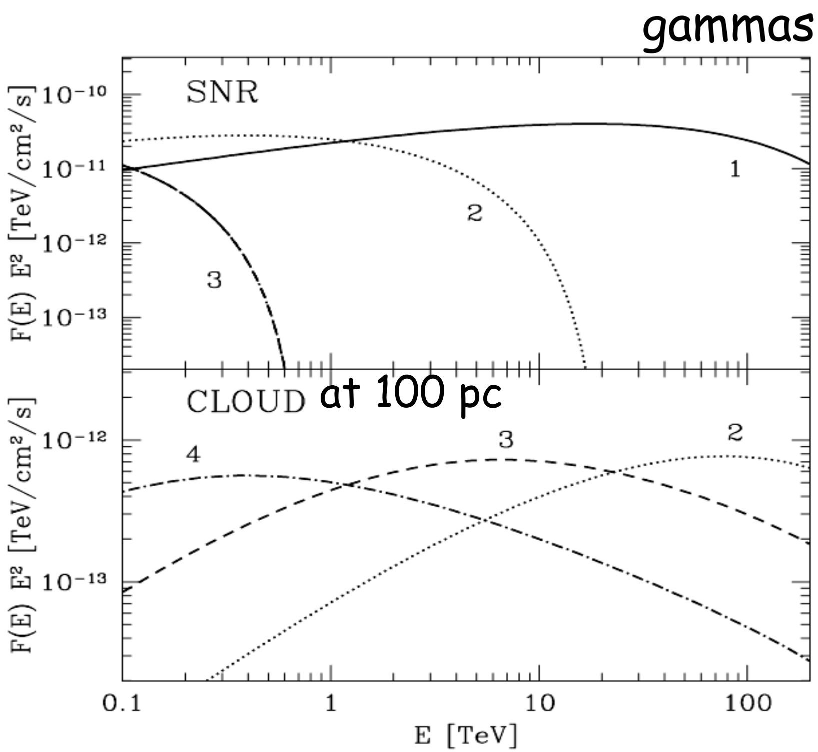


# Diffuse emission from the Galactic center




IVM, Porter, Malkov, Diamond '07

GLAST observations of individual clouds will be important!




Gabici, Aharonian '07: "…the highest energy particles escape the shell first…"

Ptuskin, Zirakashvili '05

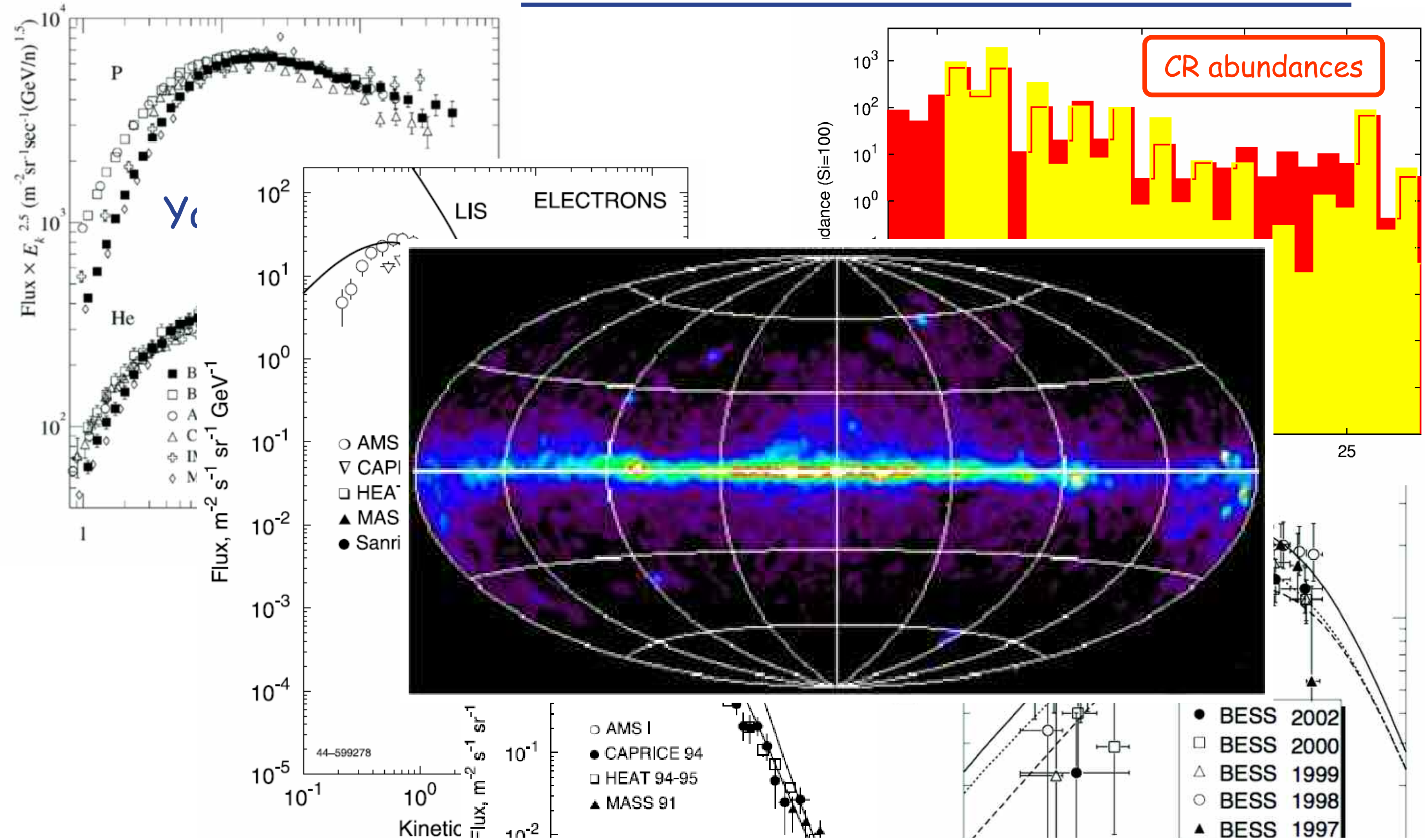
# Summary (relevance to VHE gamma-ray astronomy)

- Diffuse emission at TeV: first direct observation of variations of CR intensity and spectrum in the Galaxy!
- The broad Galactic diffuse component is still significant
- Can probe CR penetration into the molecular clouds
- Possibility of direct determination of the Dxx from observations by measuring gamma-ray spectra from individual clouds at different distances from SNR

- GLAST LAT observations are necessary!

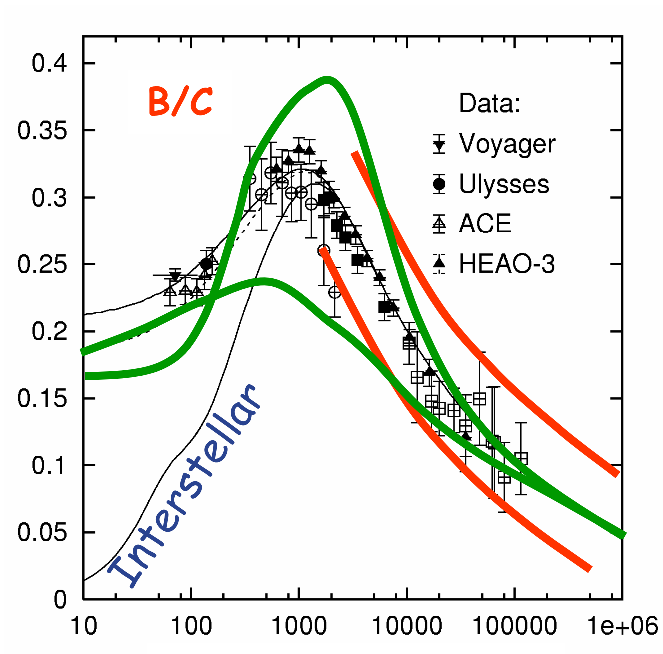
# Propagation in the interstellar medium

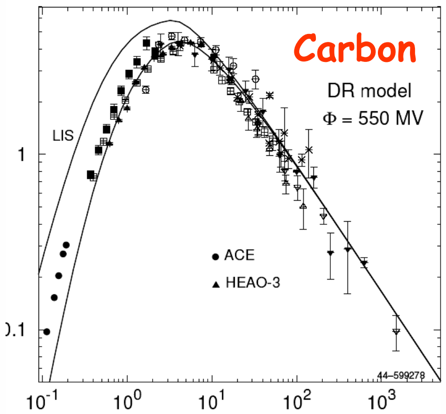
# Cosmic Rays vs Diffuse Gamma Rays



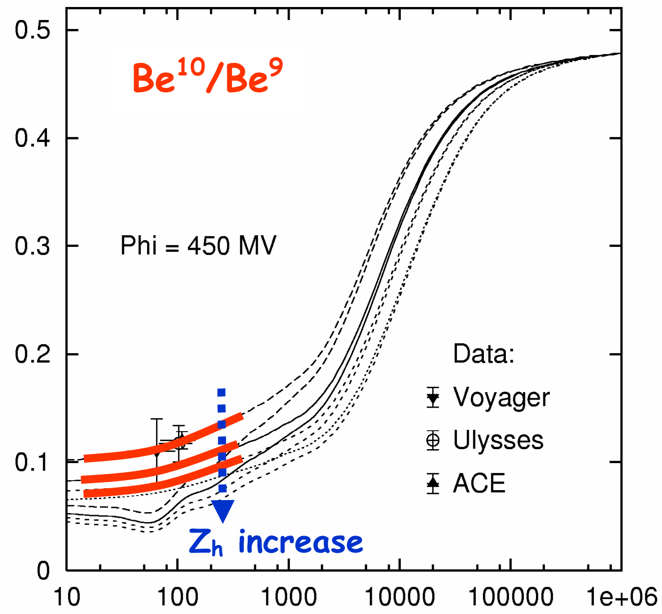

Even an unrealistic model (e.g. Leaky-Box) can be fitted to the CR data, but diffuse emission requires the CR spectra in the whole Galaxy…

# How It Works: Fixing Propagation Parameters




Radioactive isotopes:
Galactic halo size $Z_h$

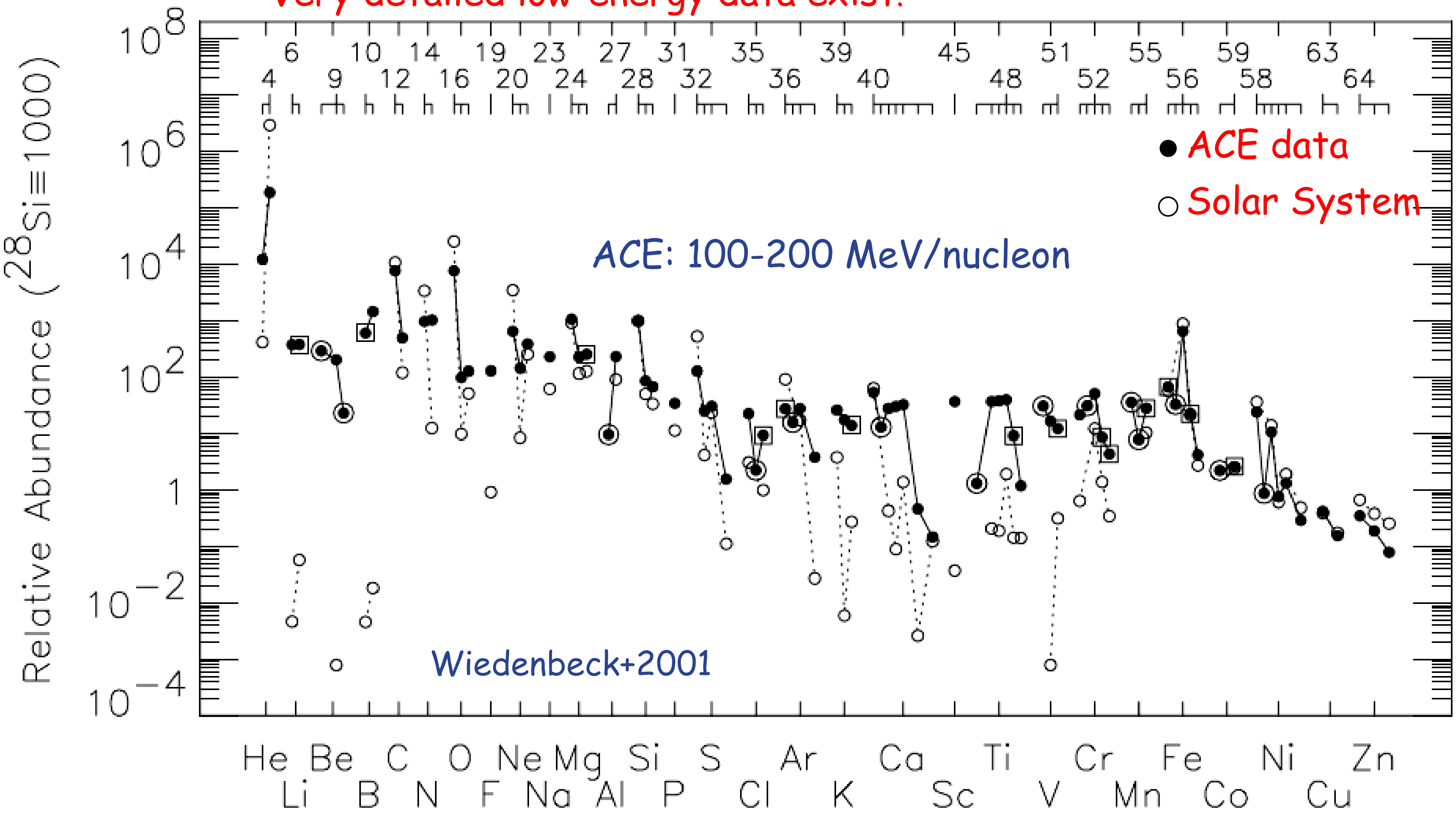



Using secondary/primary nuclei ratio & flux:

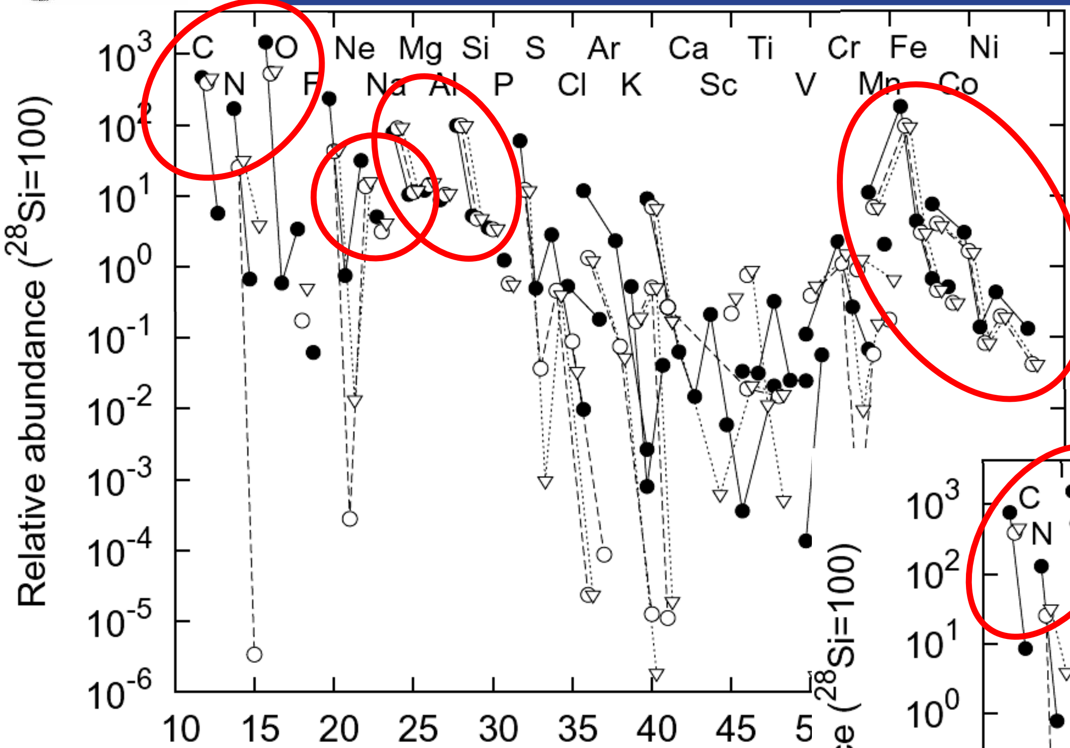
- Diffusion coefficient and its index
- Propagation mode and its parameters (e.g., reacceleration $V_A$, convection $V_z$)
- Propagation params are model-dependent
- Make sure that the spectrum is fitted as well

# CR Isotopic Abundances vs SS Abundances

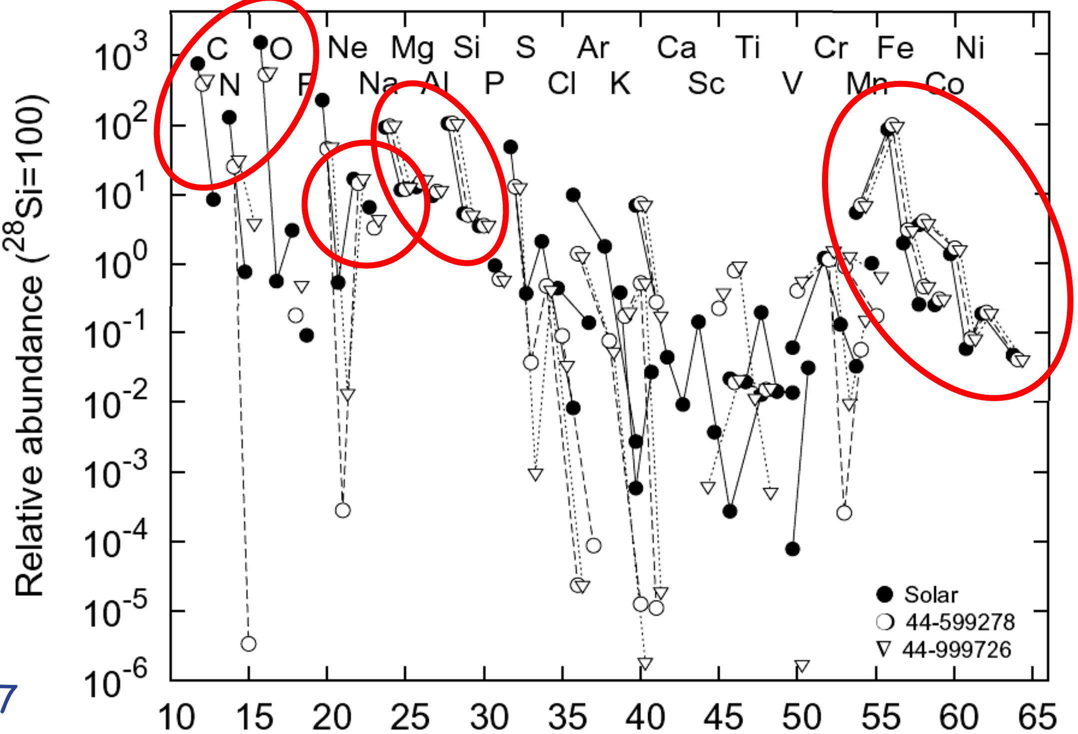
Very detailed low-energy data exist!



# Source Isotopic Abundances (GALPROP) vs SS




Solar system:
Anders & Grevesse'89
Lodders'03

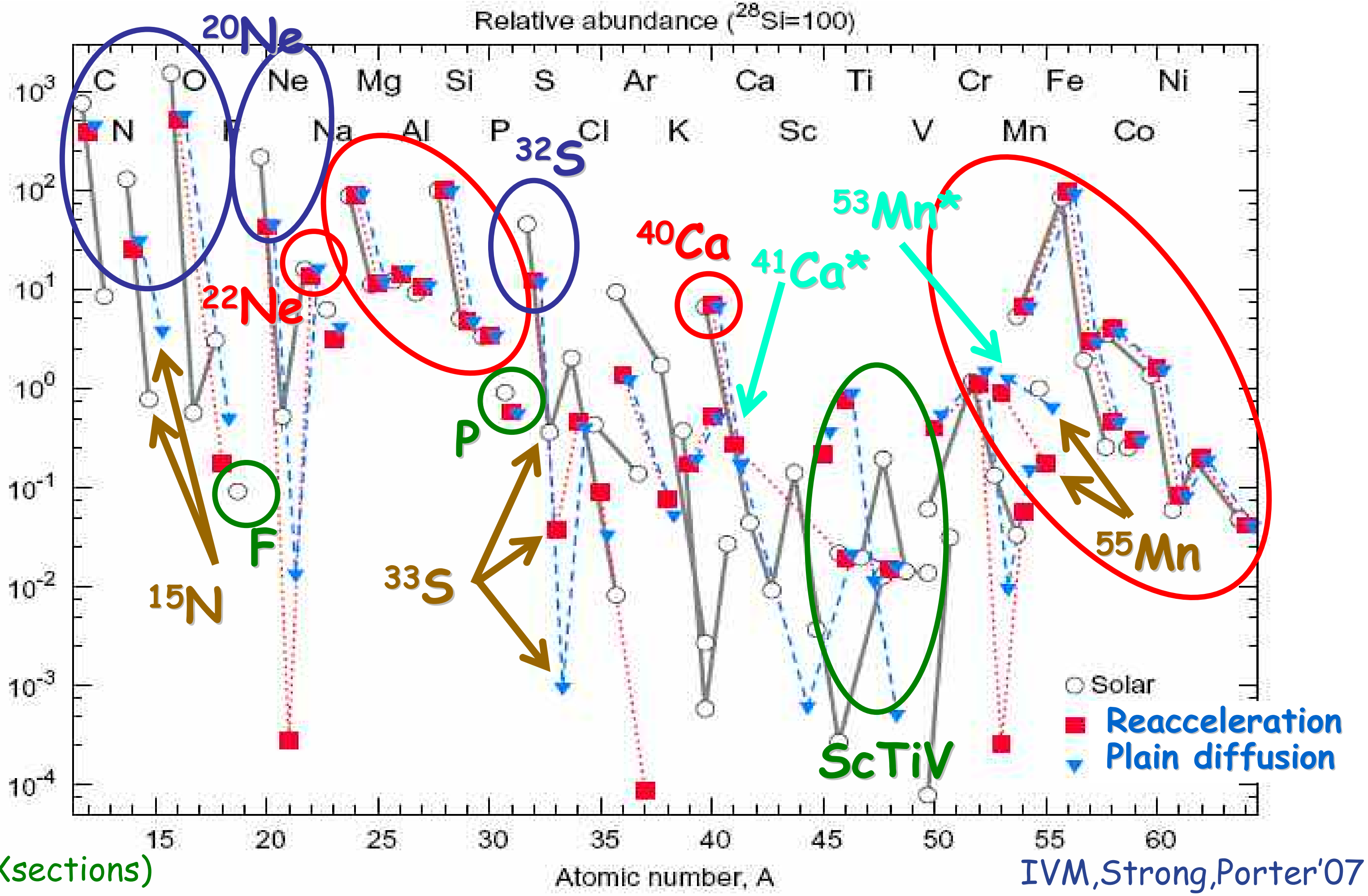



Agrees remarkably well with the latest SS abundances by Lodders for many nuclei!

IVM,Strong,Porter'07

# More Source Isotopic Abundances

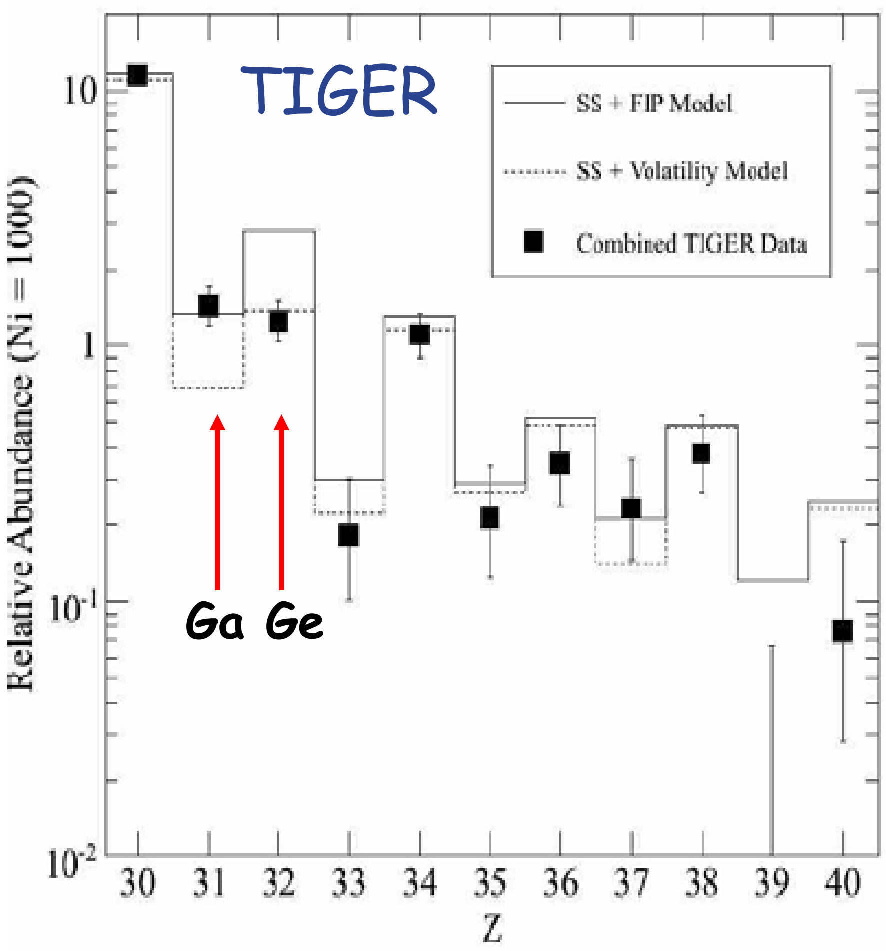
- Two K-capture isotopes are present in the sources! -- $^{41}$Ca*, $^{53}$Mn*
- Could tell us about the origin of CRs -- supports "volatility" hypothesis, but needs more analysis




Good
Not reliable (Xsections)
Well-known
Differences in models

The first time that a realistic propagation model has been used to derive isotopic source abundances !

# RESULTS /P.Blasi Rapporteur talk



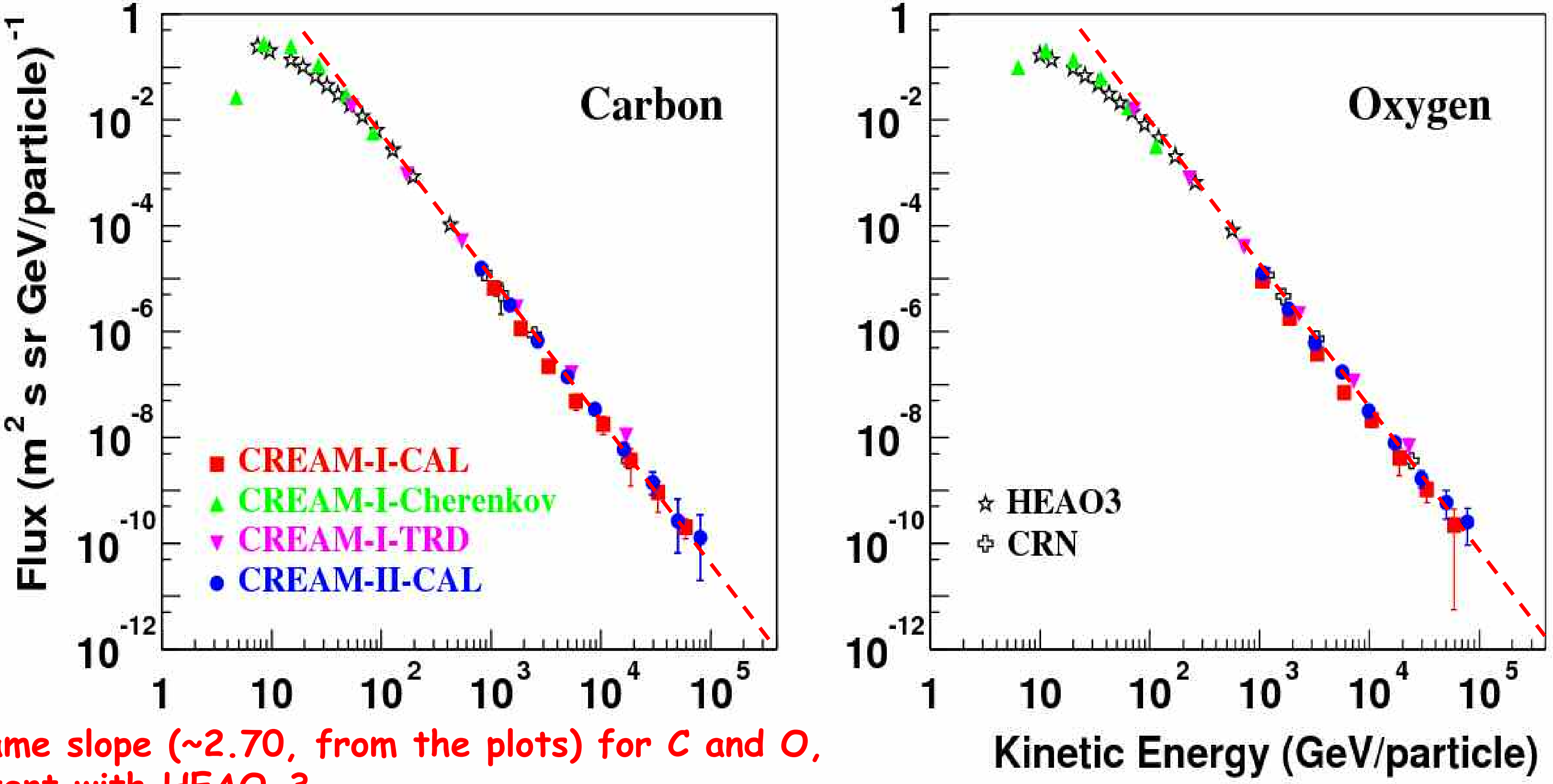

- Starting with Solar System abundances the data are inconsistent with both a FIP and a volatility based model of acceleration
- Or may be the material in the proximity of CR accelerators does not have SS abundances

- It does not have to have the SS abundances. This is a shortcoming of the Leaky-box model; realistic propagation model has to be used instead -IVM

# C & O spectra from CREAM /P.Blasi Rapporteur talk

Wakely et al, OG1.3 oral; Zei et al. OG1.1 oral; Ahn et al. OG1.1 oral

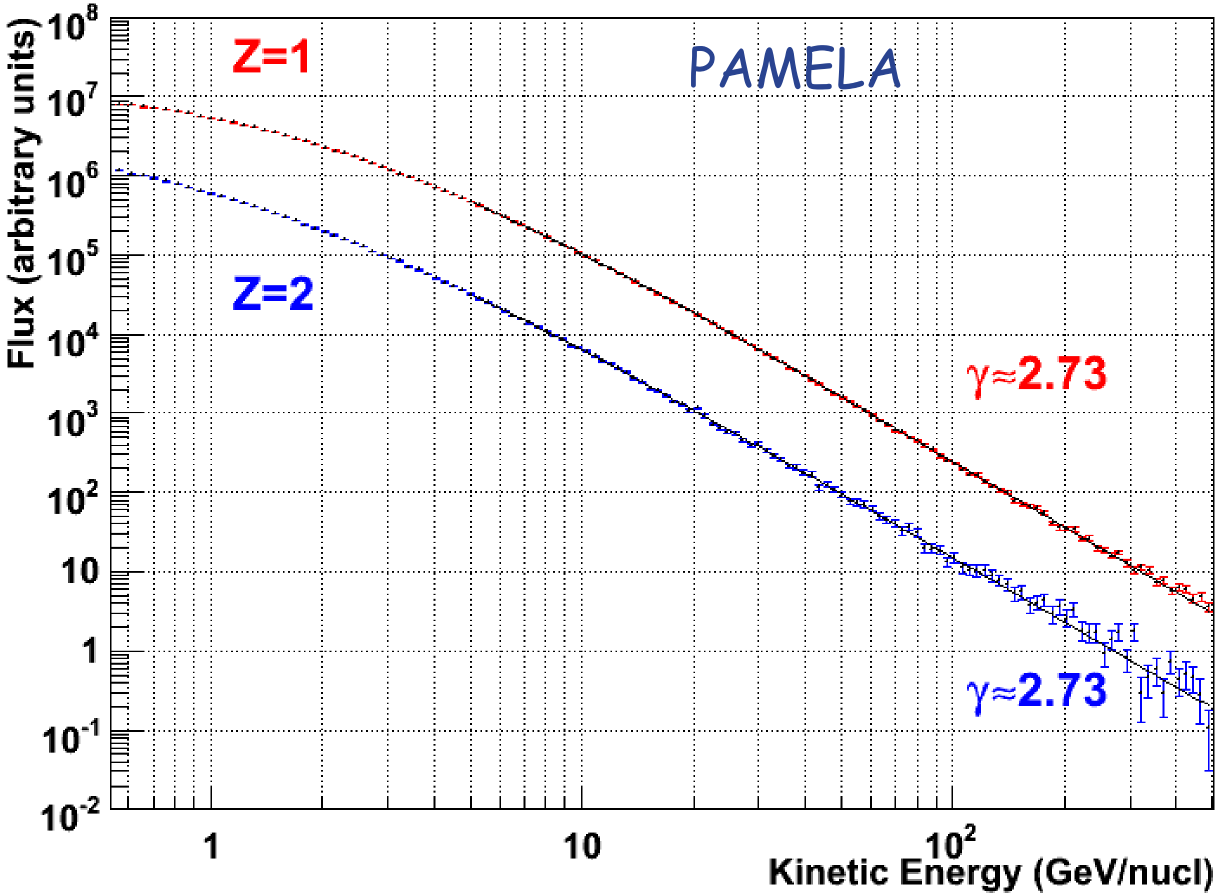
- CREAM results span ~ 4 decades in energy: ~ 10 GeV to ~ 100 TeV
- Different techniques give consistent spectra




- The same slope (~2.70, from the plots) for C and O, consistent with HEAO-3
- The Boron spectrum if measured can tell us about the rigidity dependence of the diffusion coefficient

-IVM

# Already Preliminary Results! /P.Blasi Rapporteur talk




- PAMELA data are tremendously accurate, but currently only the "arb.units"
- Interestingly, the same slope for H and He and very close to C and O from CREAM
- Protons are flatter than BESS and AMS data

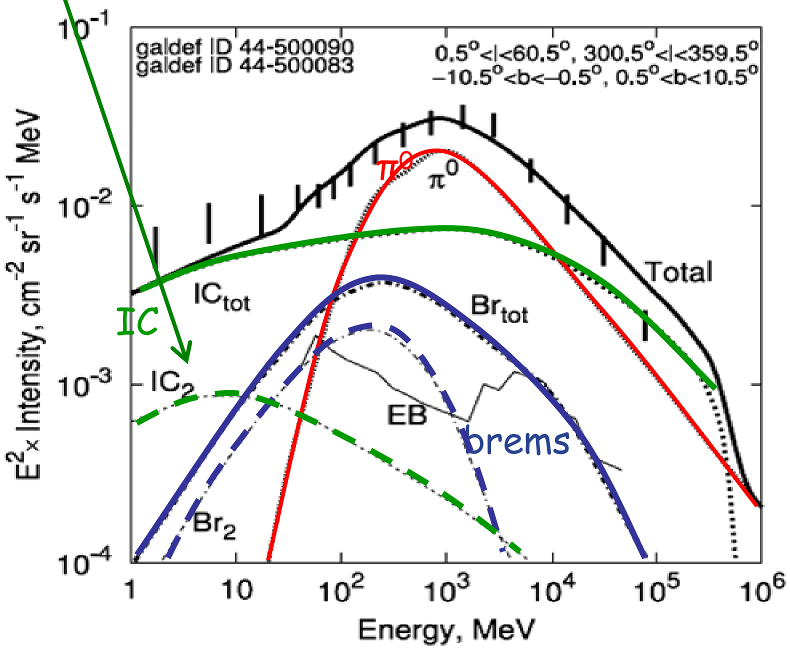
-IVM

# Positrons: Indirect Observations

## 511 keV, INTEGRAL

- Annihilation of ~$10^{43}$ positrons/sec
- The distribution of the 511 keV line is "Galactocentric" and does not match a distribution of any potential positron source (SNRs, pulsars,…)
- Recent data indicate a disk/bulge ratio 1:3

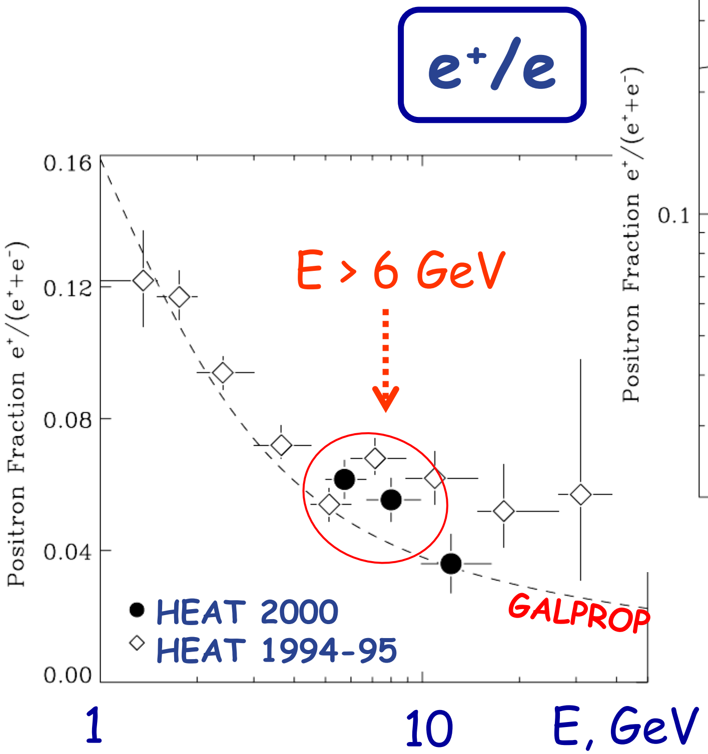
## Secondary positron contribution to IC (COMPTEL range)

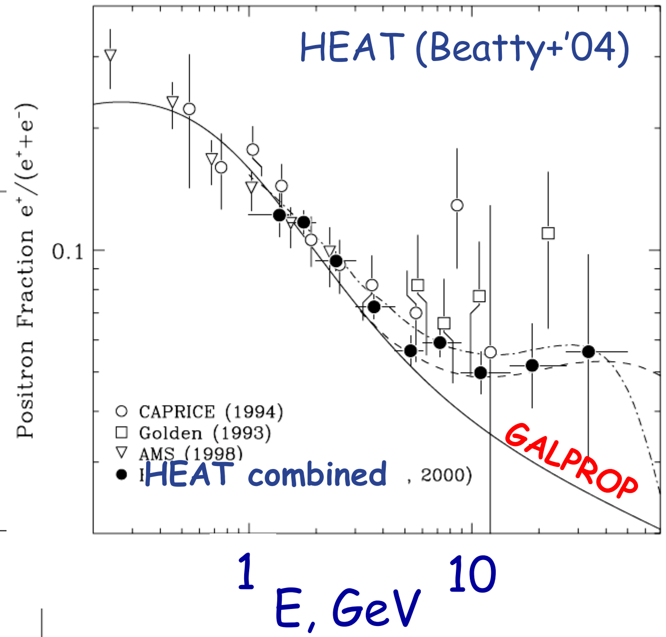


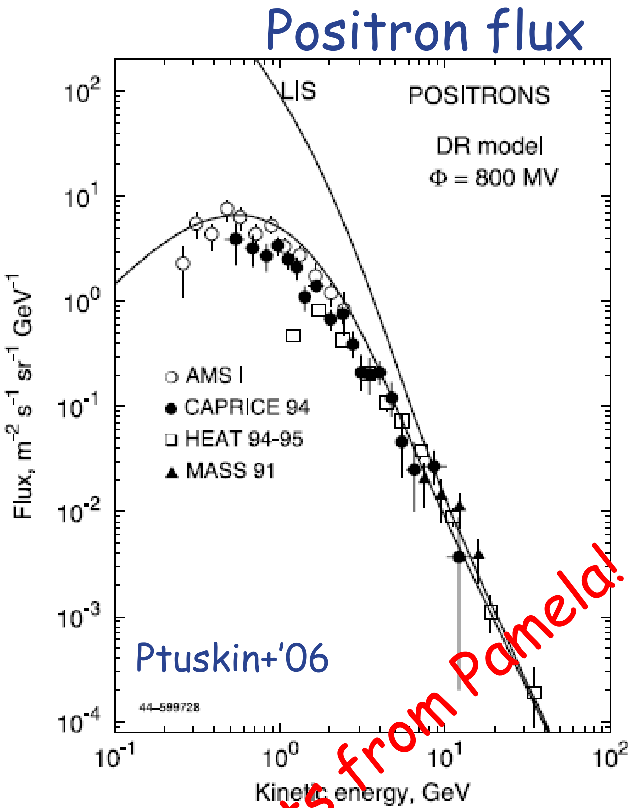

e⁺ flux is comparable to e⁻ flux at 1 GeV and below – contributes to ICS

See also talks by D.Finkbeiner, G.Dobler, T.Totani

# Positron Excess ?



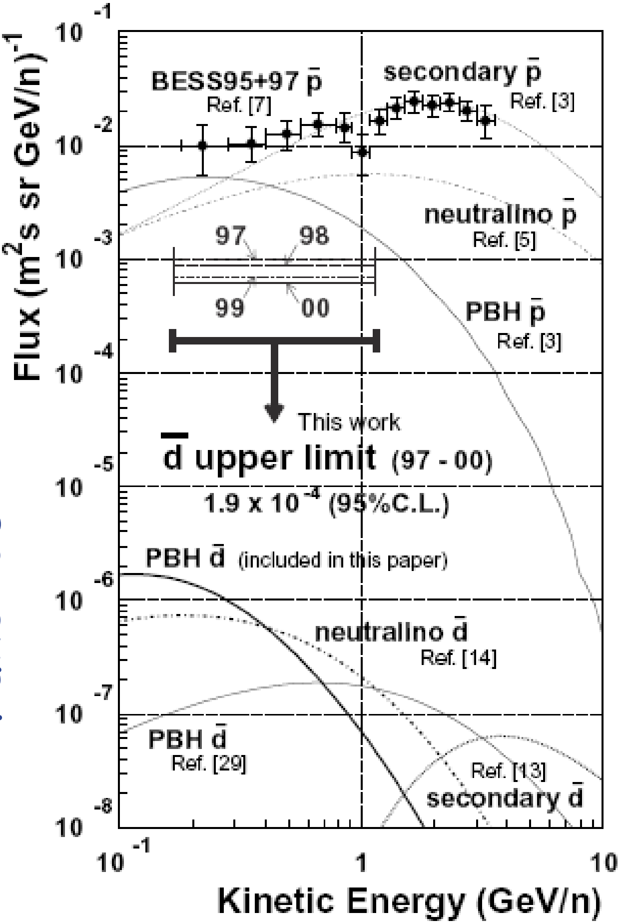

- What is the reason for the excess?
- No definitive answer yet:
  - Systematic errors of different detectors
  - Same progenitor (CR p or DM) for pbars, $e^+$'s, γ's
  - Absolute flux does not show any excess

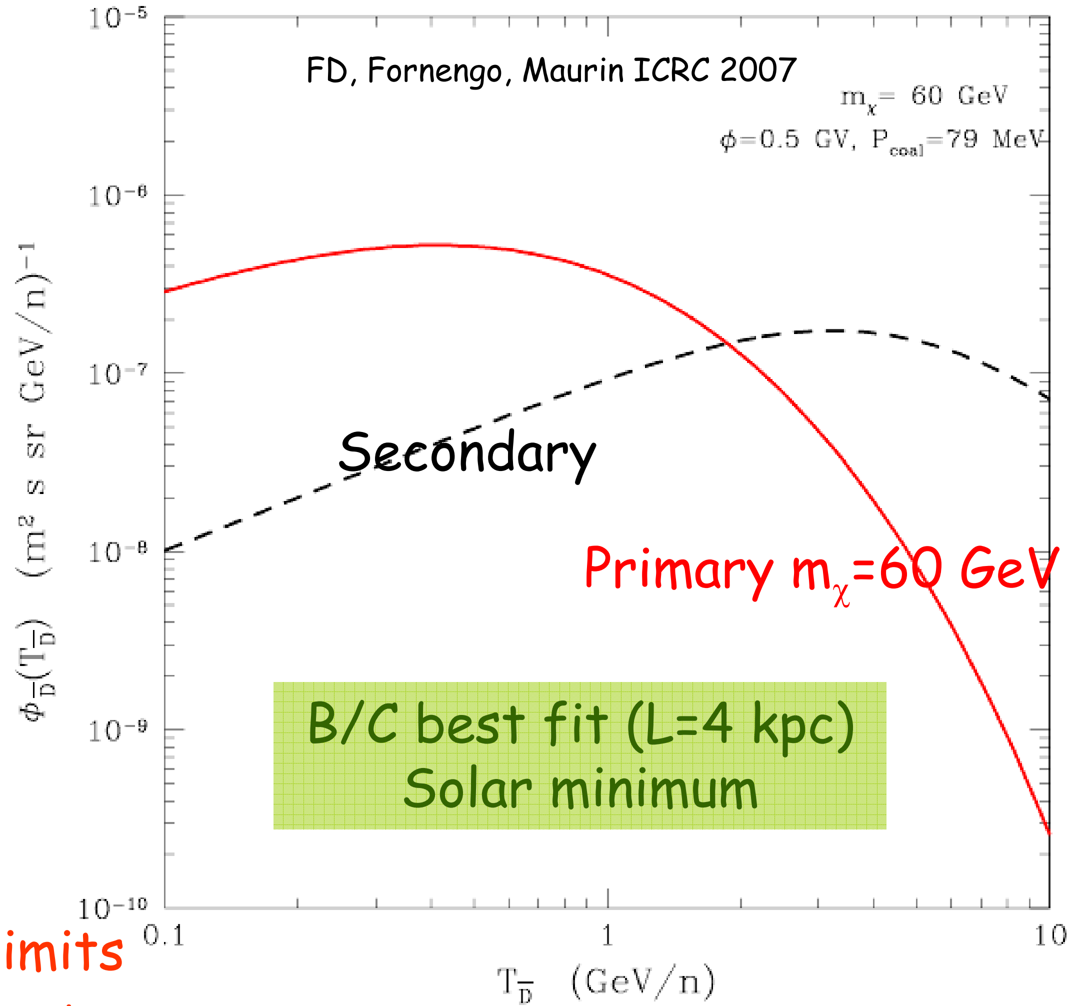
Expect new results from Pamela!

See also a talk by L.Bergstroem

# Anti-deuterons in CR

Fuke+'05

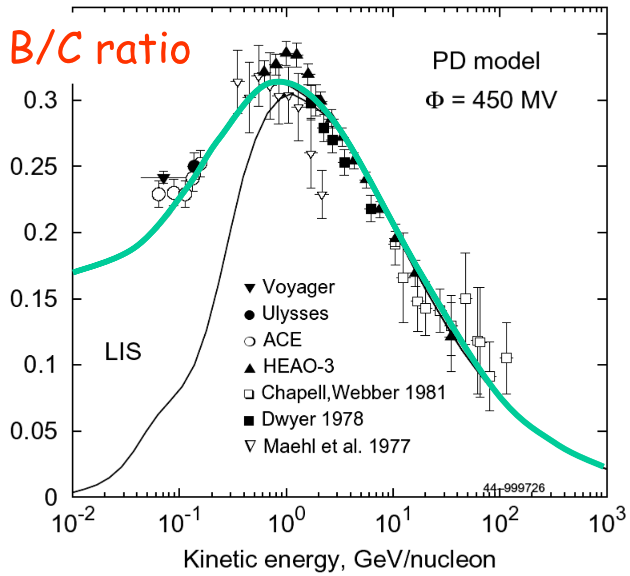



- No detection yet, only upper limits
- Still a long way to detect secondary anti-nuclei

See a talk by F.Donato

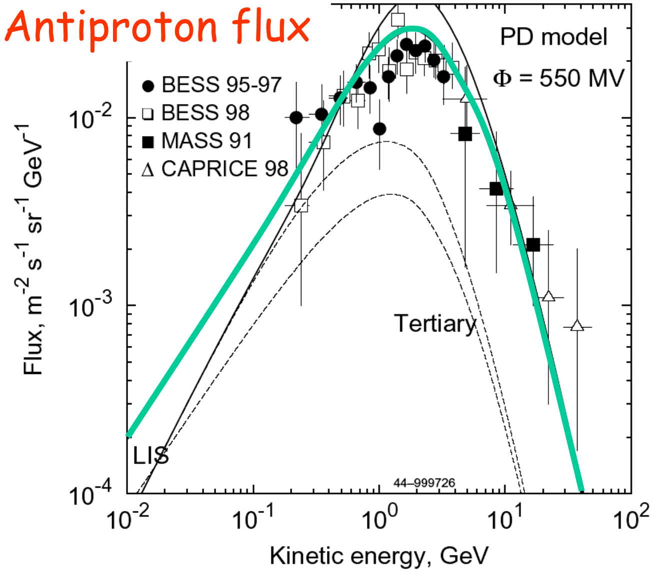
# Reacceleration Model vs. Plain Diffusion

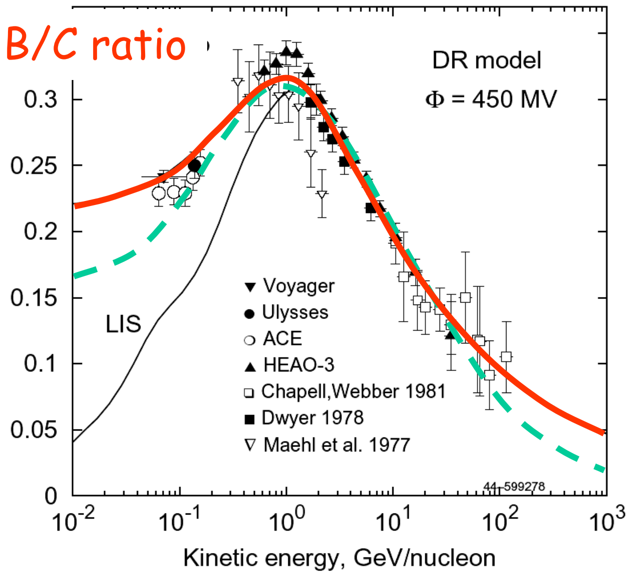



Plain Diffusion

($D_{xx} \sim \beta^{-3} R^{0.6}$)

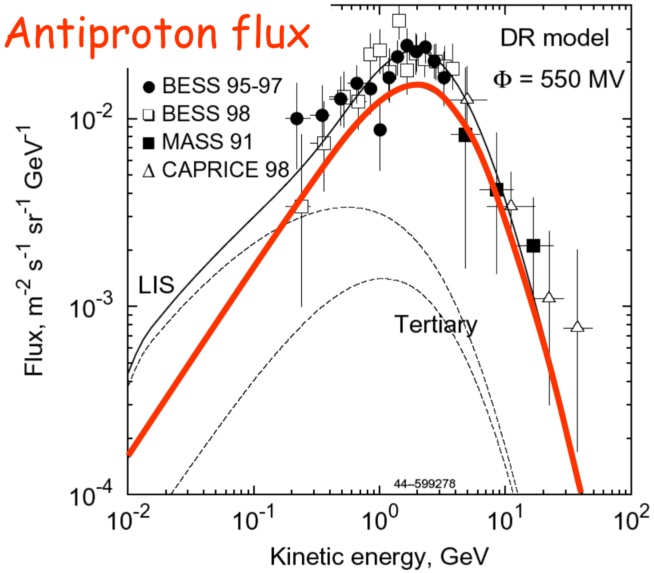
- Require breaks to fit antiprotons and B/C




Diffusive Reacceleration

- Fits B/C, other CR species, but <u>underproduces</u> antiprotons by a factor of ~2

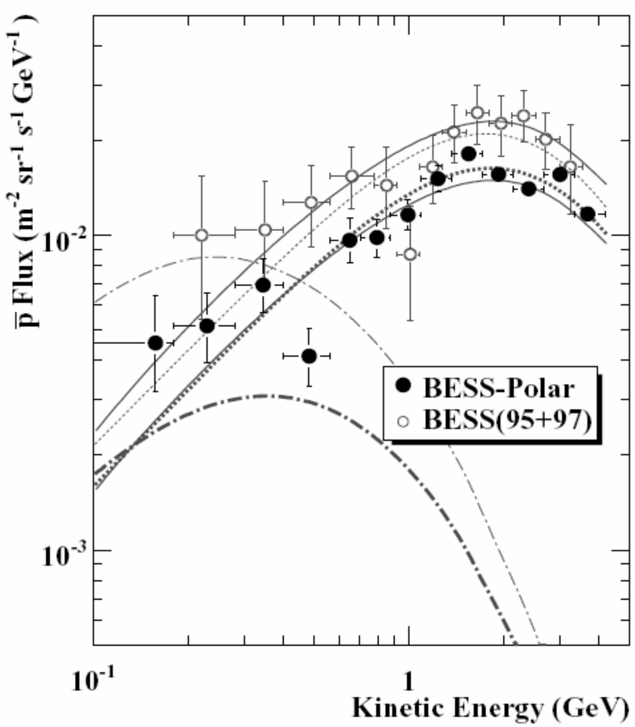


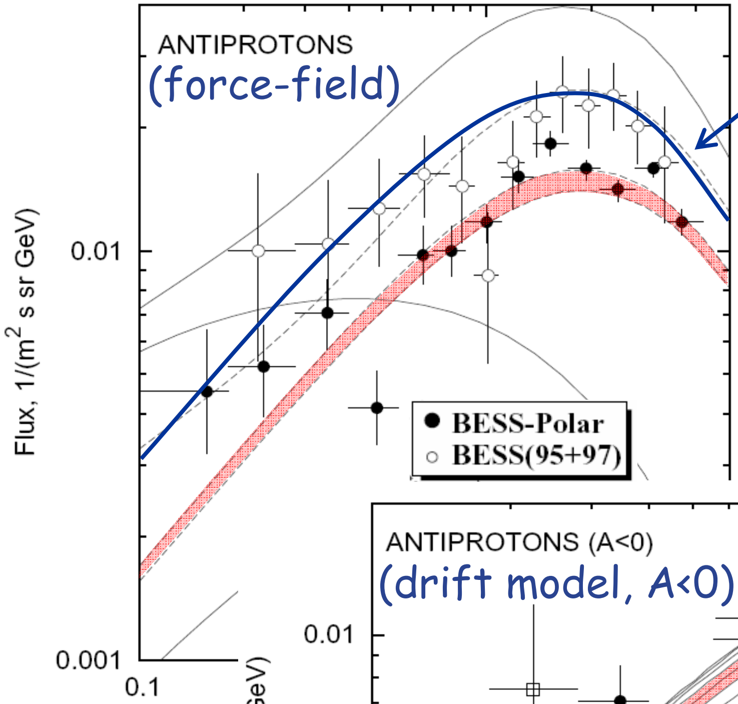

BESS & Pamela will clarify!

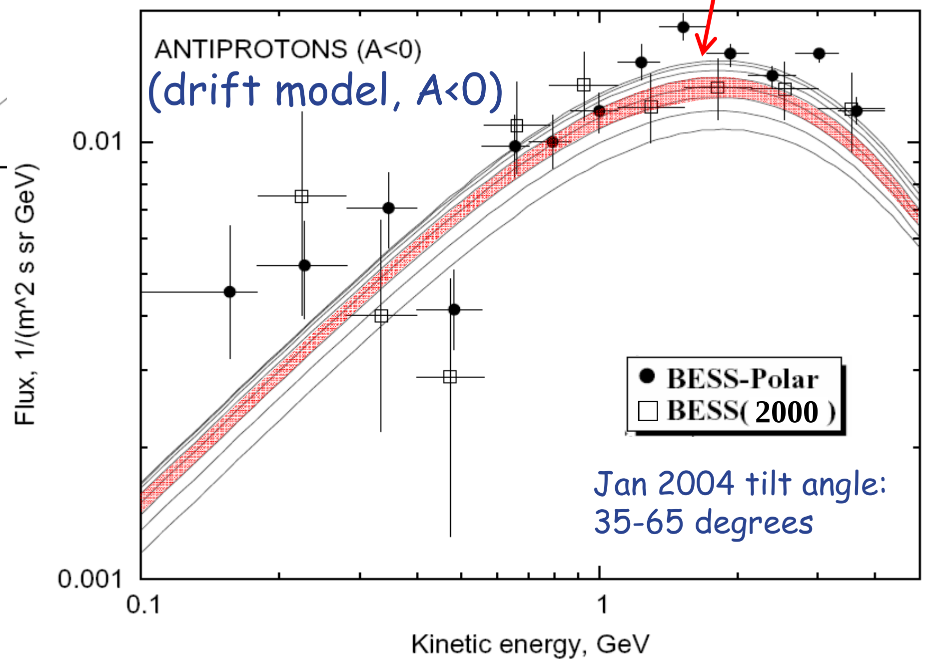
IVM+'02,'03

# Antiprotons: BESS-Polar

## BESS-Polar data are lower!



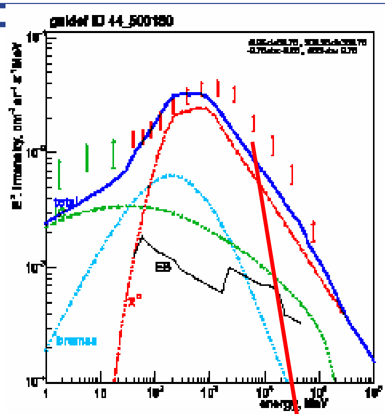



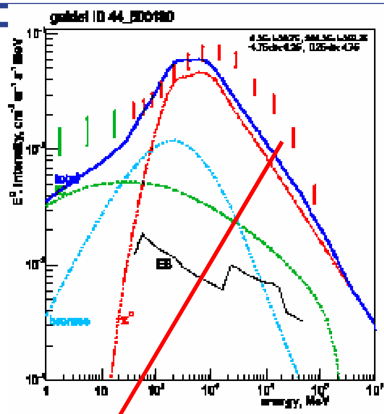



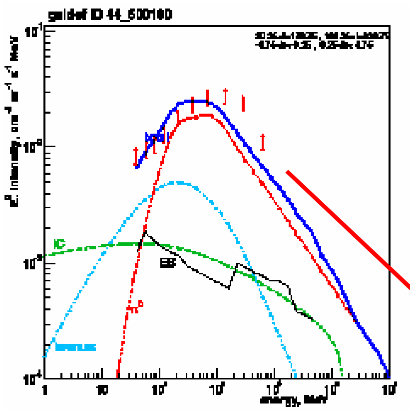

- BESS-Polar data are lower and more consistent with reacceleration model
- In fact, it is inconsistency with older BESS data forced us to look at new propagation models: diffusion + convection , local CR component (IVM+'02,'03)
- Many consequences ! – see next slides

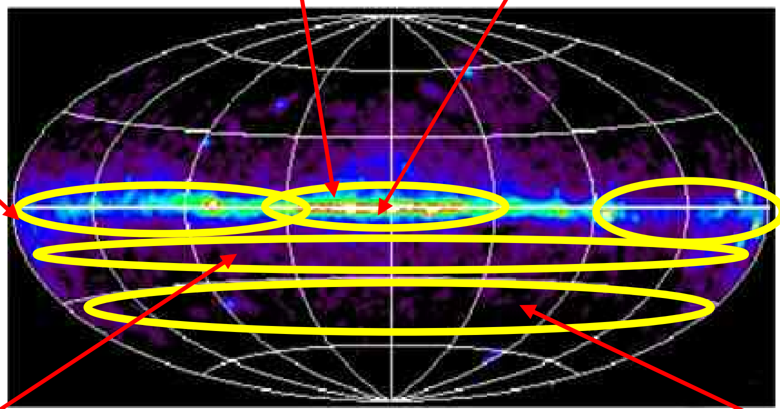
# Wherever you look, the GeV γ-ray excess is there !

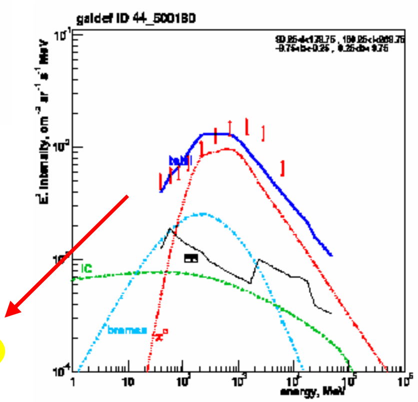
EGRET data

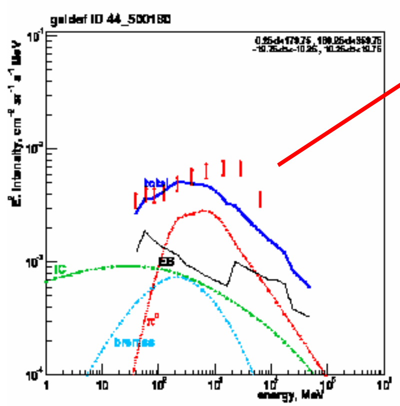


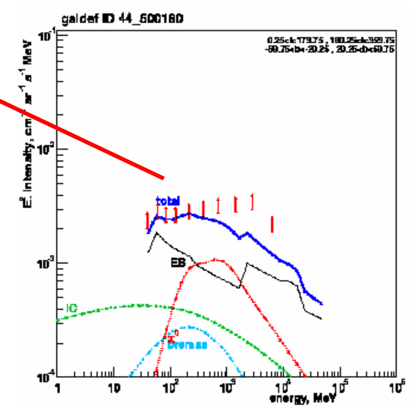






- Instrumental artefact?
- Physical phenomena?

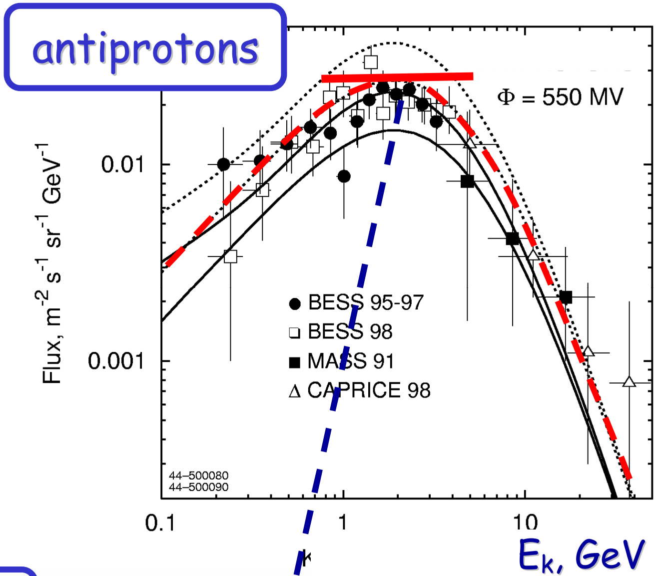
GLAST will answer…

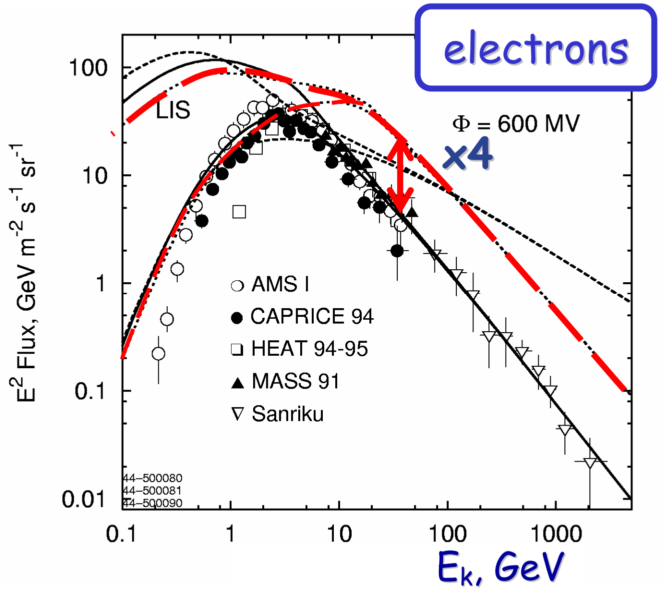
Strong+'00,'04

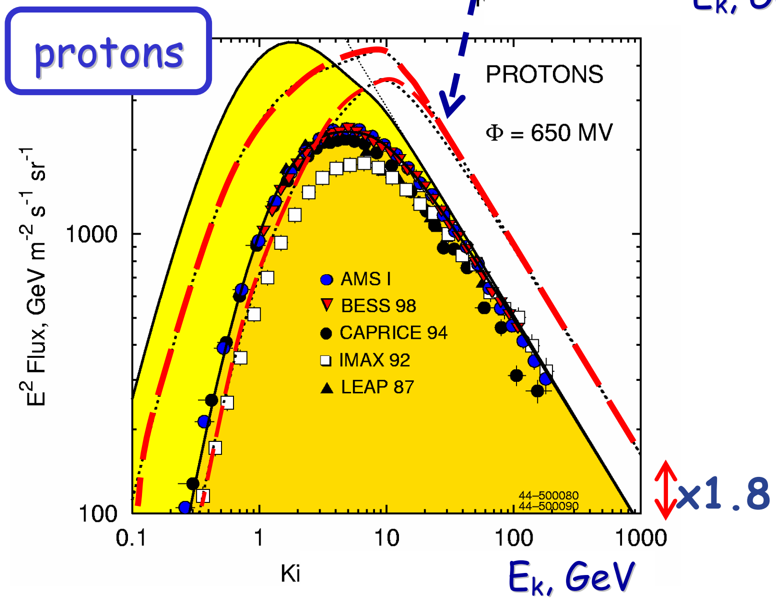
# GeV excess: Optimized/Reaccleration model

**Uses all sky and antiprotons & gammas to fix the nucleon and electron spectra**

- Uses antiprotons to fix the *intensity* of CR nucleons @ HE
- Uses gammas to adjust
  - the nucleon spectrum at LE
  - the *intensity* of the CR electrons (uses also synchrotron index)
- Uses EGRET data up to 100 GeV

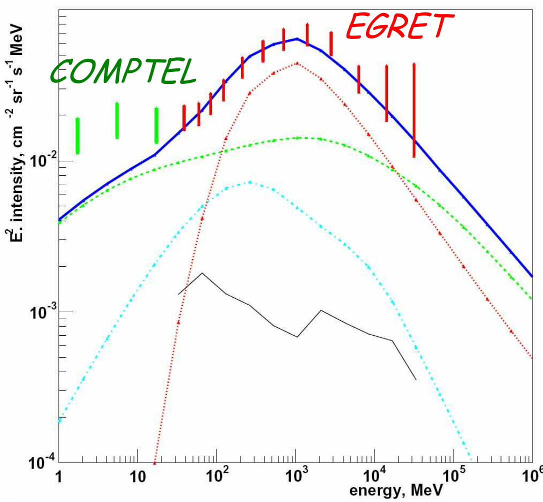


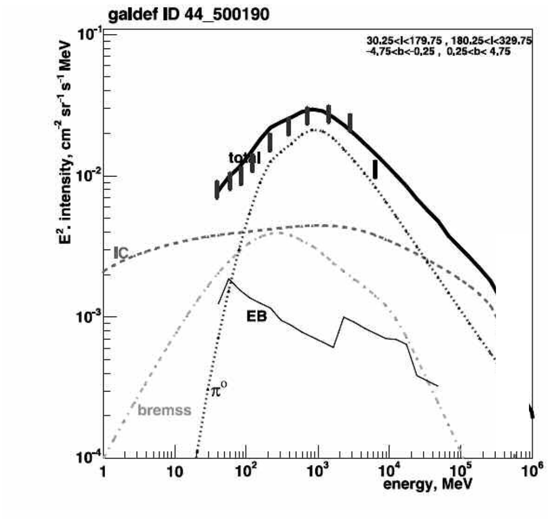



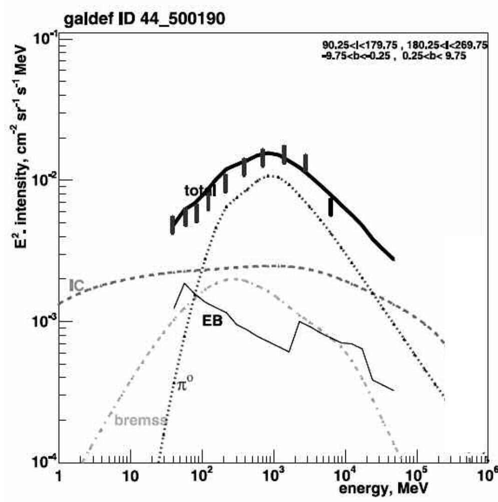



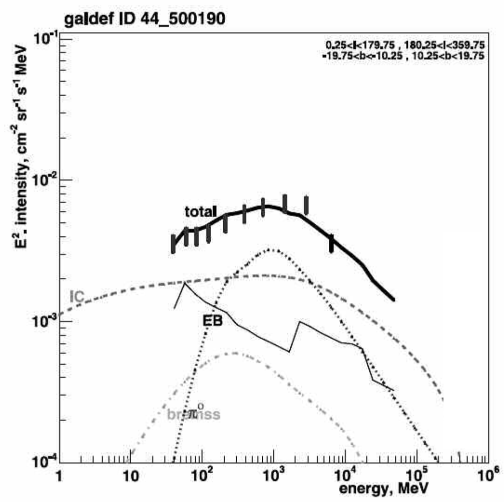

Strong+'04

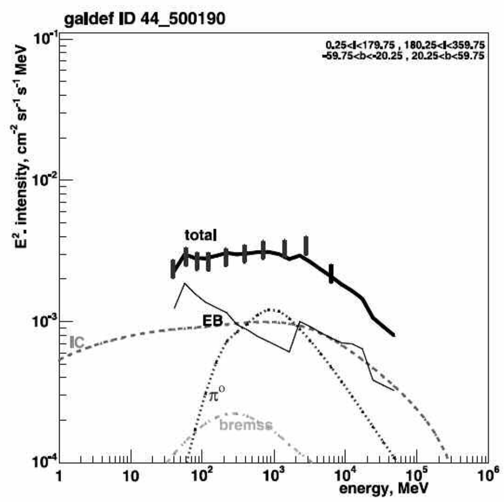
# Optimized model



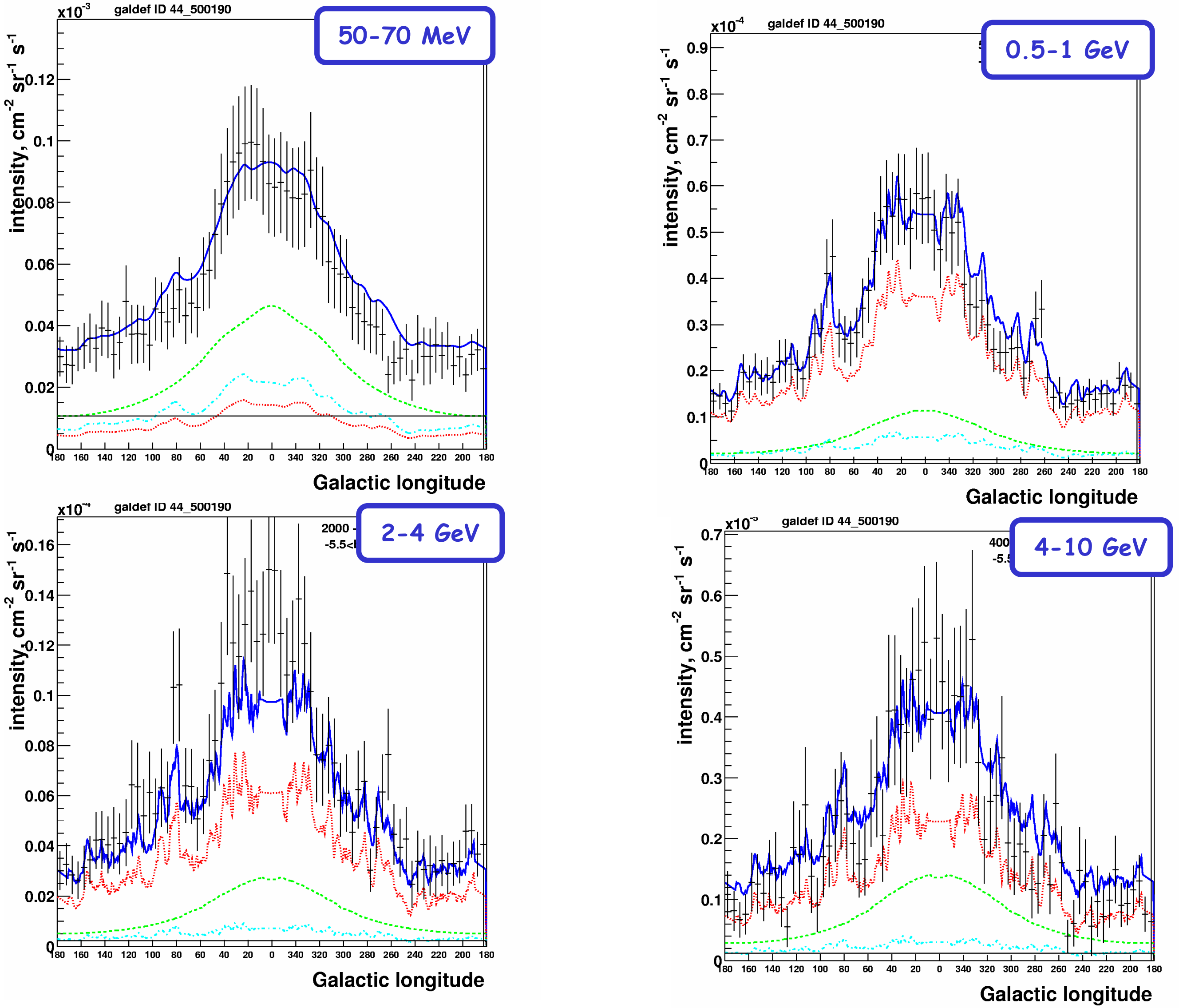




Strong+'04

# Longitude Profiles |b|<5°

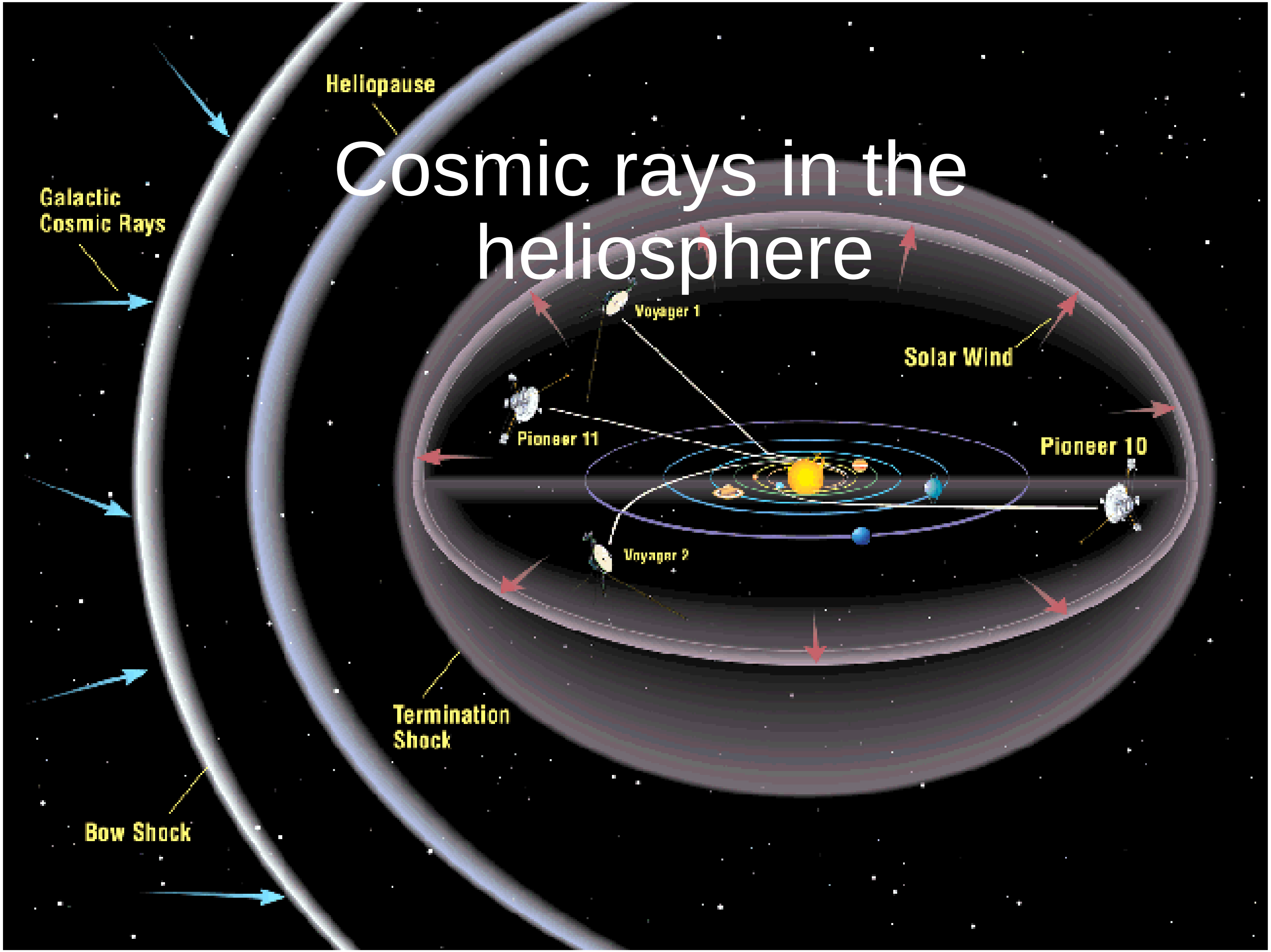



Strong+'04

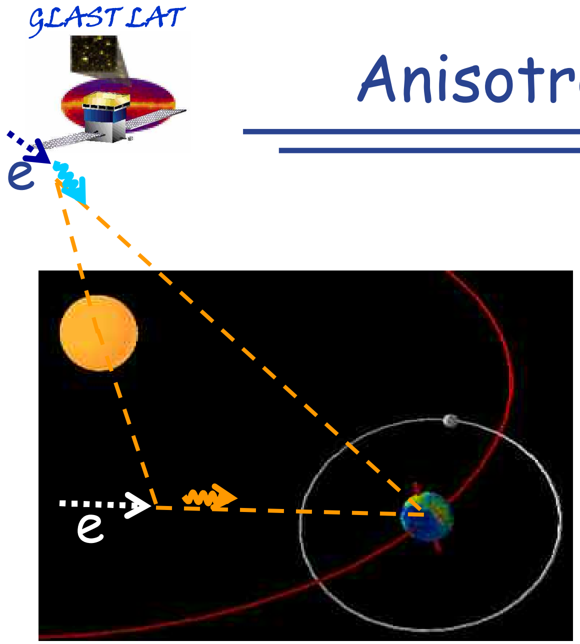
# What makes life more interesting…

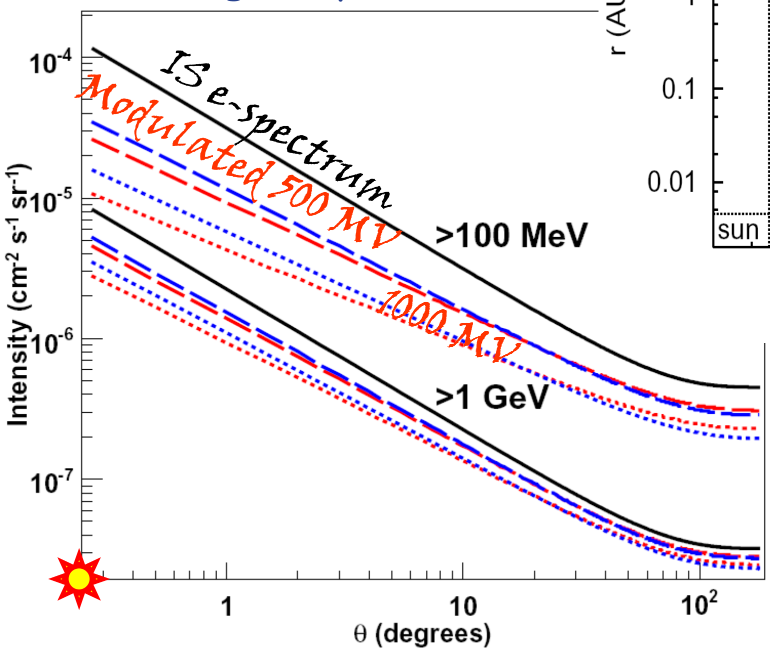
- With these new and more accurate pbar measurements we do not have such a freedom (renormalization of CR proton flux) anymore
- This is more difficult, but makes life more interesting!
- We have to await for confirmation from BESS-Polar and Pamela

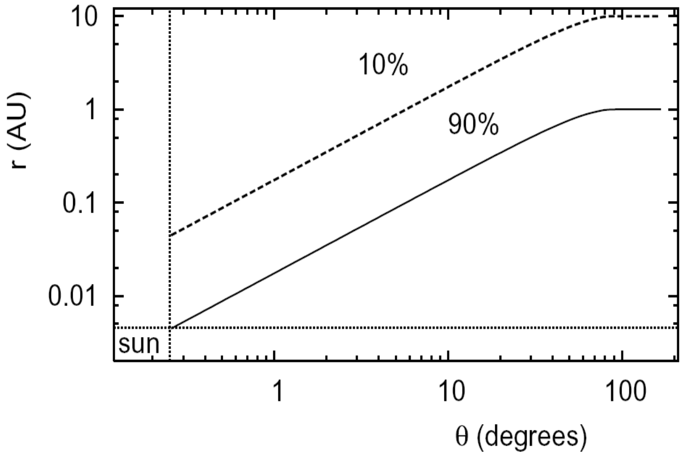
# Cosmic rays in the heliosphere



# Anisotropic IC scattering on solar photons

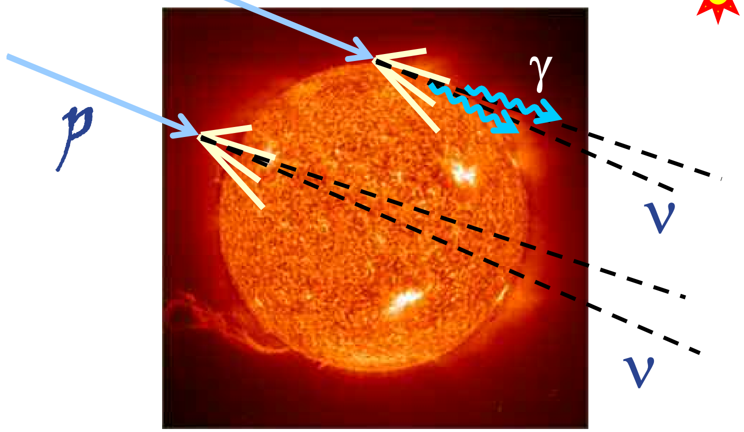



IVM,Porter,Digel'06
Orlando, Strong'06

Gamma-ray and neutrino production by CR interactions in the solar atmosphere




- GLAST will be able to measure the CR electron spectrum from the solar surface up to Saturn's orbit at 10 AU simultaneously
- Averaged over one year, the ecliptic will be seen as a bright stripe on the sky, but the emission comes from all directions
- GLAST will see gamma-ray albedo of the sun (Seckel+'91)

# Found in EGRET data !

Thompson+ 1997:
Upper limit $2\times10^{-7}$ $cm^{-2}$ $s^{-1}$

Reanalysis by Orlando, Petry, Strong 2007:

Discovery of both solar disk pion-decay emission and extended inverse Compton-scattered radiation in combined analysis of EGRET data from June 1991!!

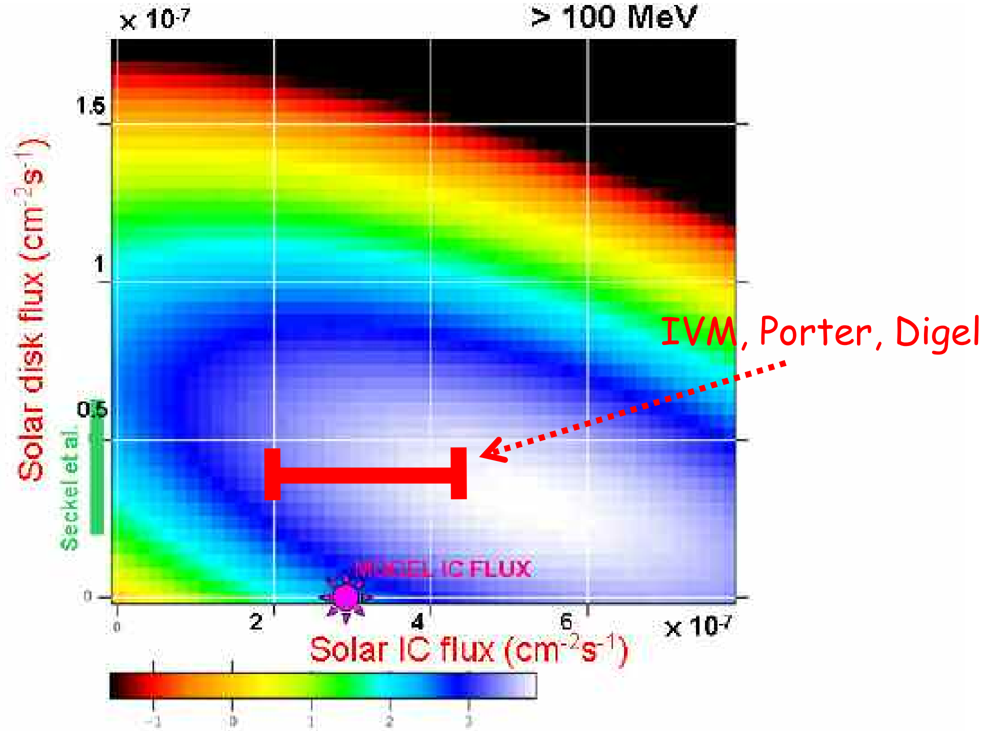



FIGURE 1. Log Likelihood above 100 MeV as function of the solar disk flux and extended solar flux, relative to point at (0,0). The level of our predicted IC model flux and the predicted disk flux [7] are shown.

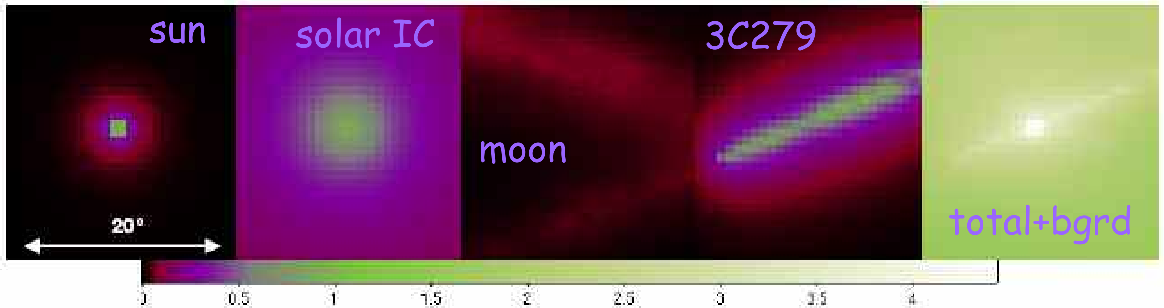
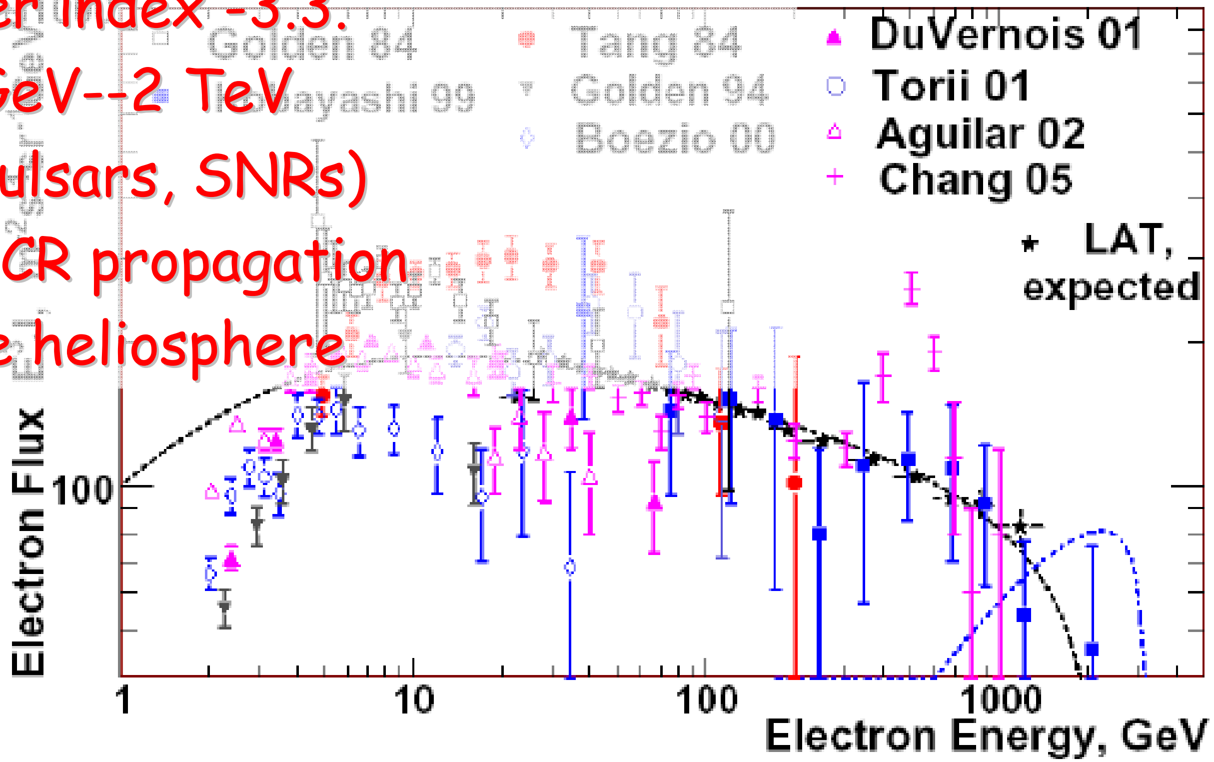



FIGURE 2. Fitted model counts of the main components centered on the Sun. From left to right: Sun disk, Sun IC, moon, 3C 279, and the total predicted counts including uniform background. The colors show the counts/pixel, for 0.5°× 0.5° pixels.

# Electron Spectrum in the Heliosphere

Moiseev+'07:

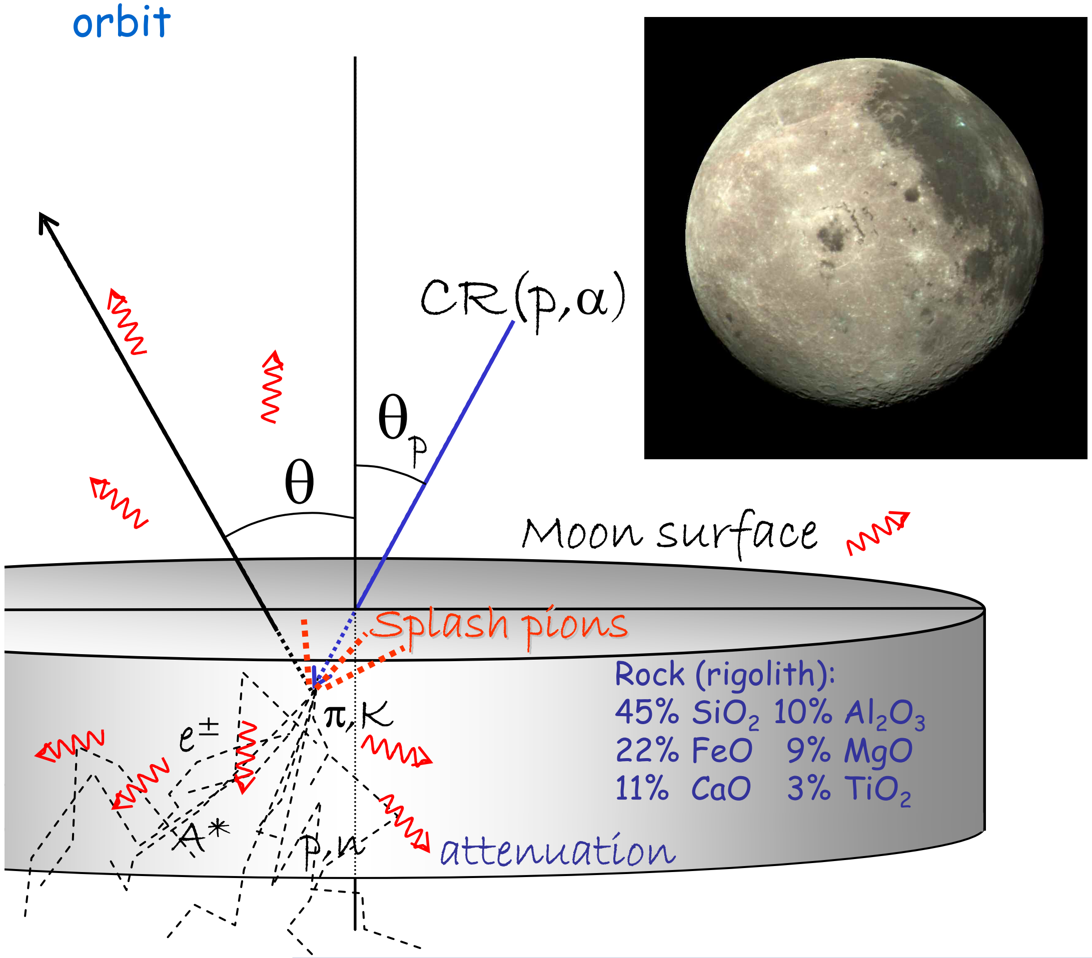
- GLAST LAT is expected to detect ~$10^7$ electrons/yr above 20 GeV, $4\times10^5$ electrons/yr above 100 GeV, and ~2,500 electrons/yr above 500 GeV assuming a steep power law electron spectrum with power index -3.3.
- Energy range ~20 GeV--2 TeV
- Local CR sources (pulsars, SNRs)
- Diffuse emission & CR propagation
- IC scattering in the heliosphere

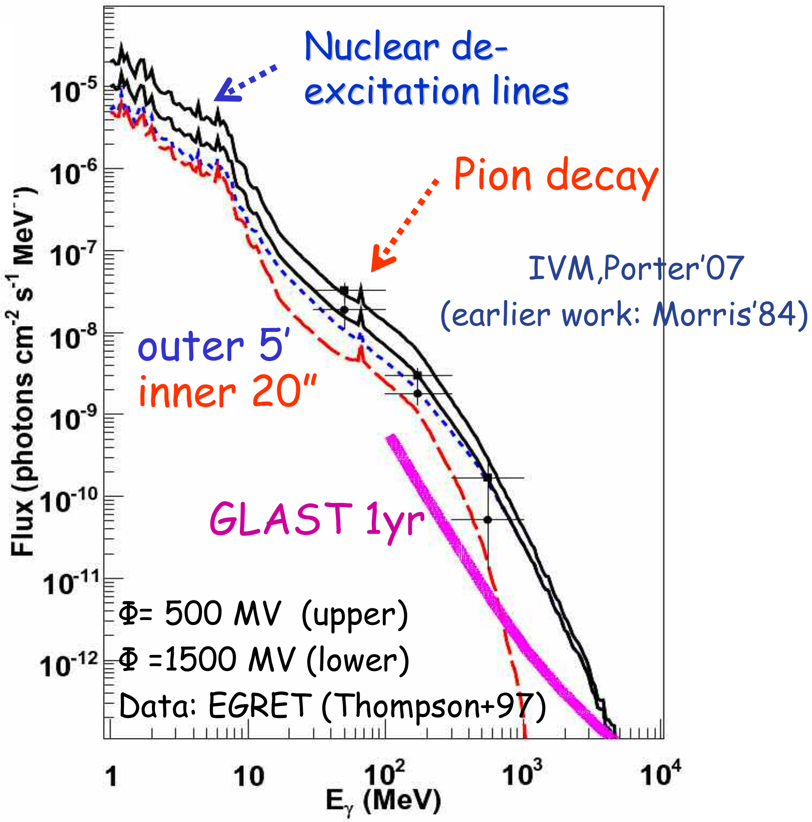



Kobayashi+'03

# Dark Face of the Moon: Gamma-ray Albedo Spectrum

- GLAST calibration (pionic line and steep spectrum)
- Indirect measurement of CR protons at 1 AU
- Cross calibration with Pamela while Pamela is in the orbit



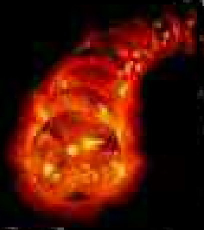



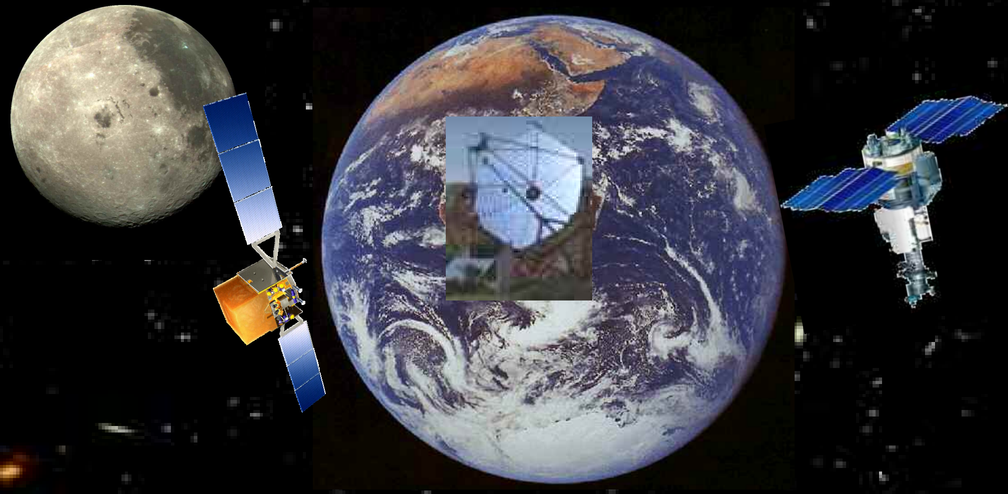

Kinematics of the interaction:

- The cascade goes through to the depth where gamma-rays cannot come out
- Splash pions are low-energy and decay at "rest"

# What We Can Do with the Moon?

- The Moon is the only BLACK SPOT on the sky >4 GeV
- 20% of the time the Moon will be in the FOV
- Moving target: from high Galactic latitudes to the Galactic center
- Useful "standard candle:" the gamma-ray albedo is well understood
- Calibration of the gamma-ray flux using CR proton spectrum from Pamela
- The gamma-ray flux changes with the solar cycle: monitor the CR proton spectrum at 1 AU
- The line feature at 67.5 MeV from pion decay, if detected, can be used for energy calibration
- The steep cutoff of the albedo spectrum at 1 GeV – another possibility for energy calibration





# Conclusions

- A lot of excitement and expectations with all new instrumentation starting to operate (ACTs, VHE CR experiments)
- In GeV -- sub-TeV range GLAST & Pamela will do a very good job (see talks by P.Michelson, F.Longo, D.Paneque, R.Sparvoli)
- The key is the <u>precise</u> measurements
- Exiting discoveries are right around the corner!

- Thank you!