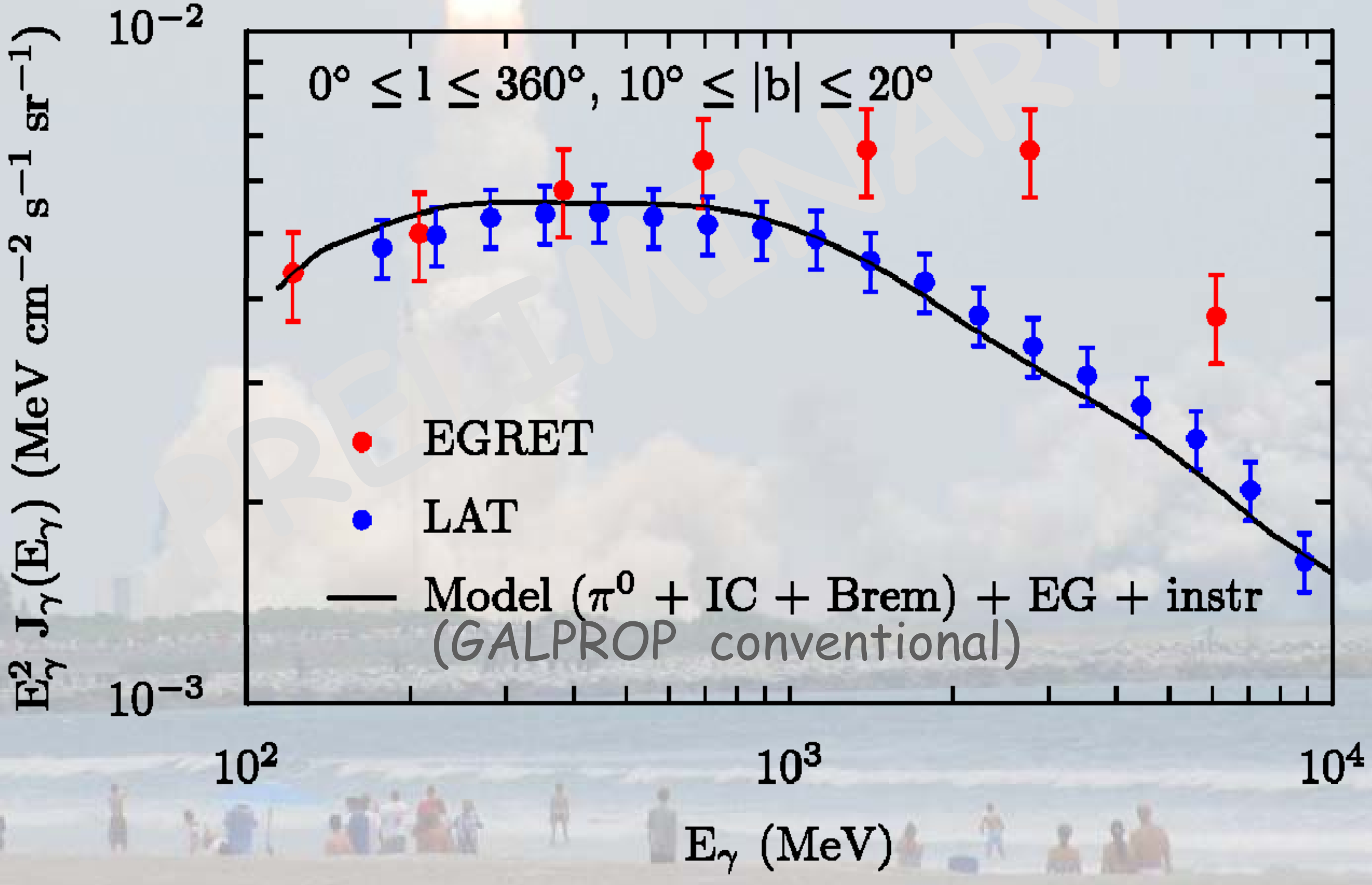
Understanding the backgrounds in indirect dark matter searches

Igor V. Moskalenko (stanford/kipac)

CERN /Feb. 3, 2009

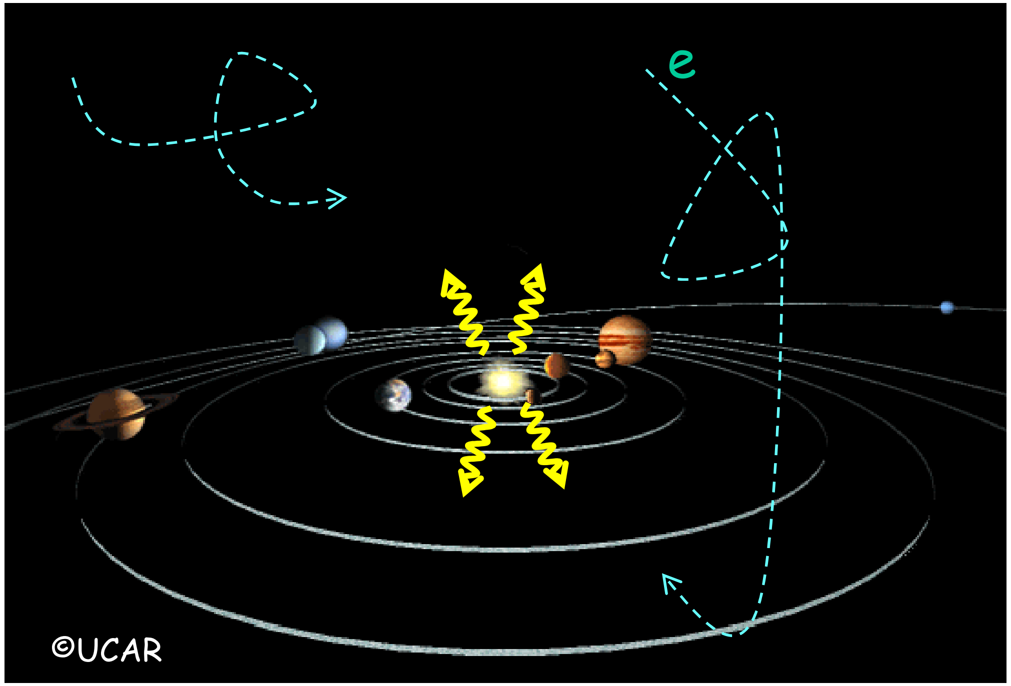
Cosmic Ray are not in a steady state!

- Excesses appear and go away
  - GeV excess in diffuse gammas



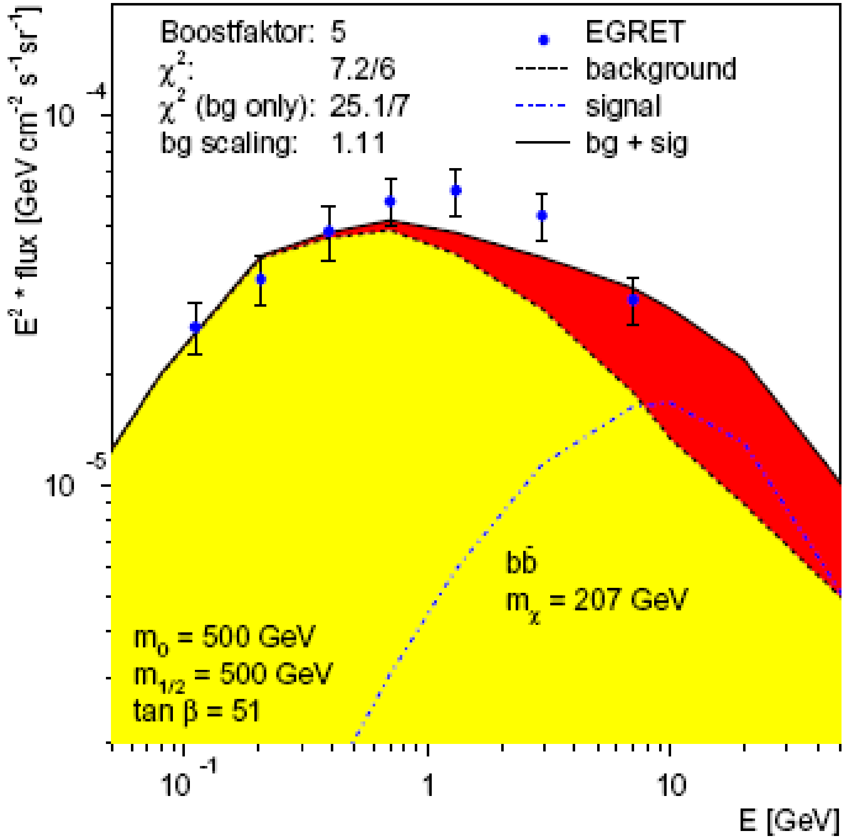
Cosmic Ray are not in a steady state!

- New processes are discovered thus further complicating an already complex picture
  - Inverse Compton scattering of CR electrons off solar photons (new foreground) and the Sun is moving…



Cosmic Ray are not in a steady state!

- *A* lesson learned: *Act* quickly to take advantage of the excesses and features before they go away with a new experiment
  - Interpretation of the GeV excess in terms of the dark matter



de Boer+'03

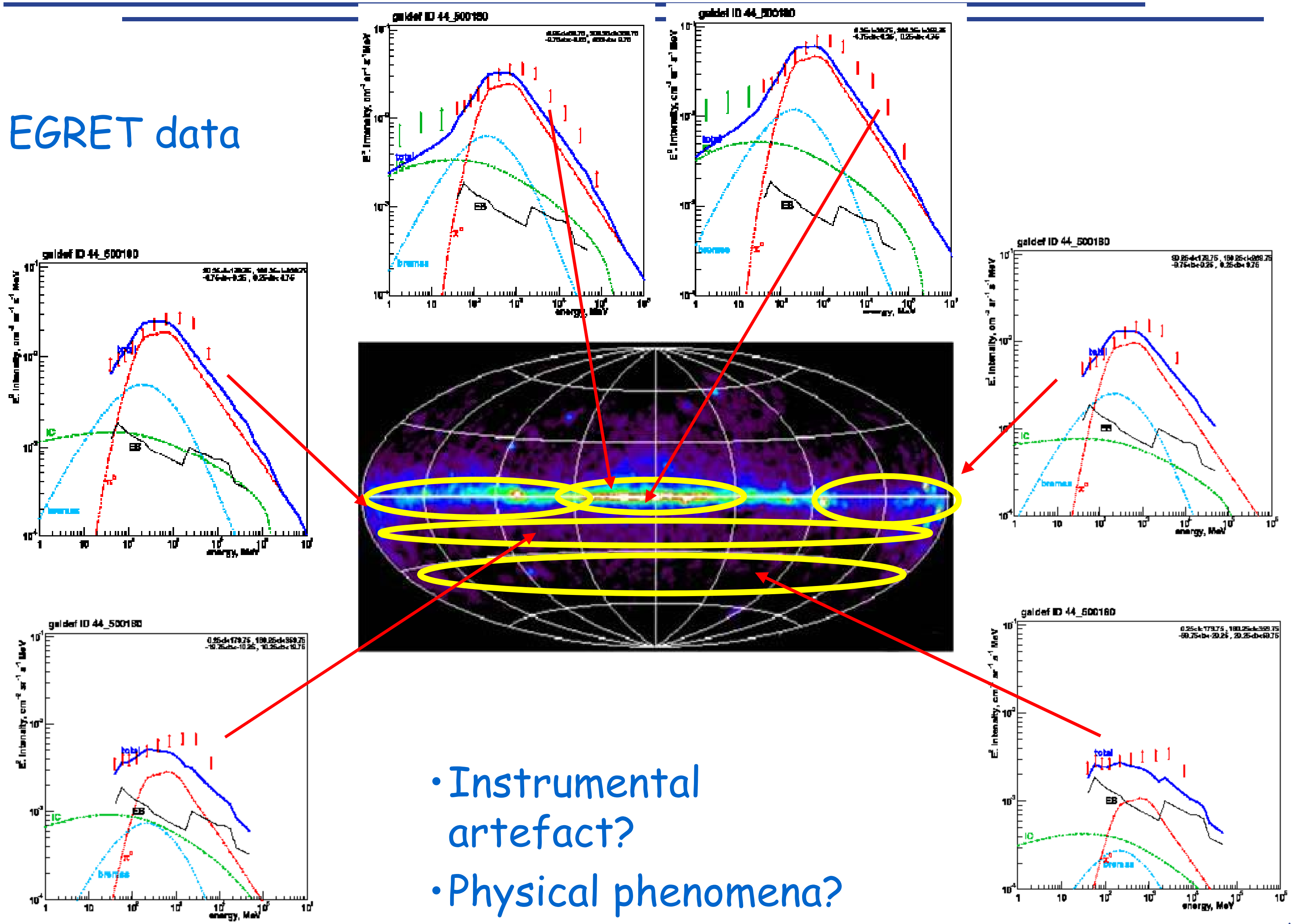
CR vs Accelerators

- First elementary particles were discovered in CR
- Switch to accelerators with controlled energy, beam particles, target material
- Rebirth of Astrophysics of Cosmic Rays
  - Improved technique
  - Indirect searches for supersymmetrical particles
  - Complimentary sensitive X-ray & gamma-ray observations
  - Astrophysical Dark Matter may be not the same as expected to be found on LHC
  - New particles/interactions search – UHECR provide particle energies unreachable on man-made machines
- Very rich Astrophysics!
  - Large scale structure
  - Minihalos
  - Dwarf galaxies
  - Etc.

Status before 2008

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

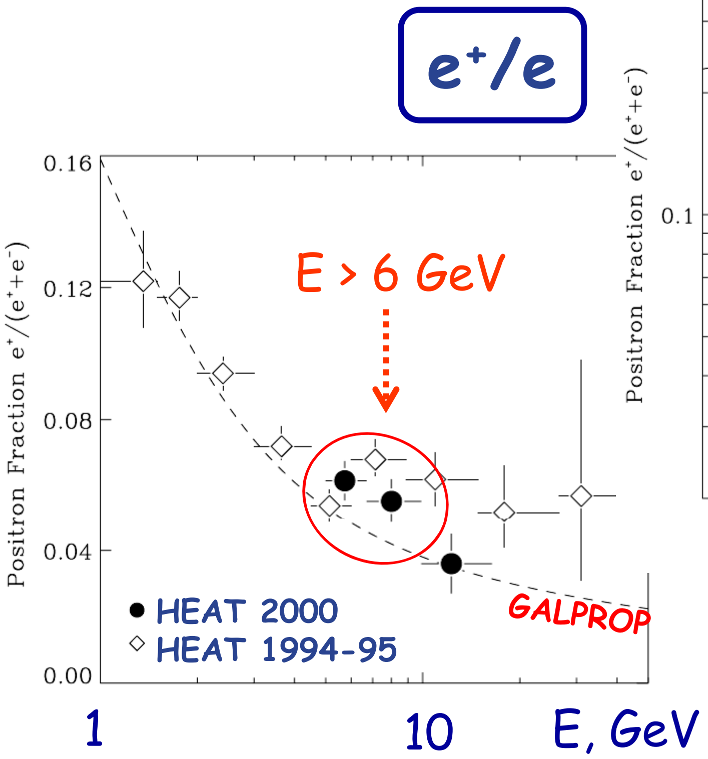
EGRET data

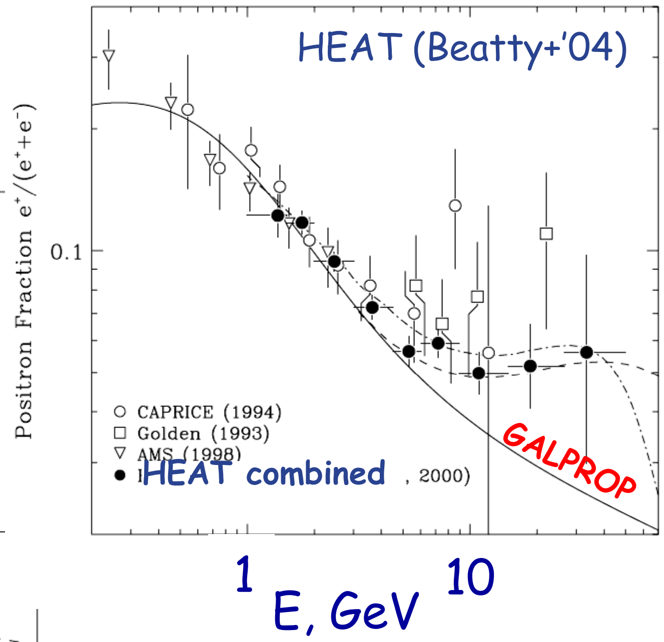


- Instrumental artefact?
- Physical phenomena?

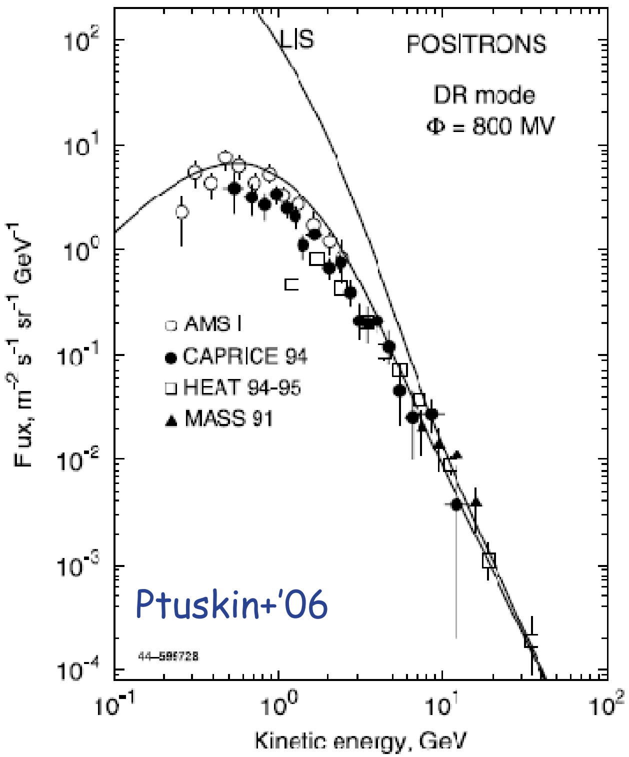
Strong+'00,'04

A hint of the excess in positron fraction





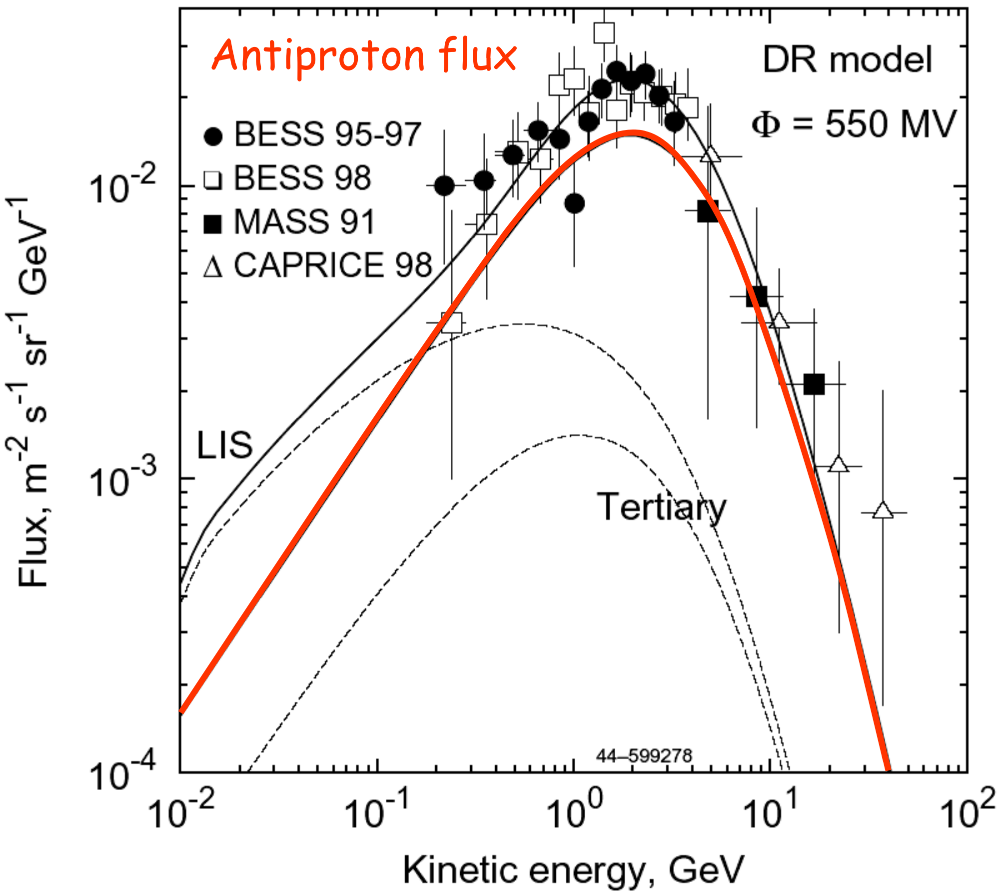
Positron flux



- What is the reason for the excess?
- No definitive answer yet:
  - Systematic errors of different detectors?
  - Dark matter?
  - Pulsar contribution?
  - Absolute flux does not show any excess

Excess in CR antiprotons

Calculations made in diffusive reacceleration model show an excess by a factor of ~2



IM+'02

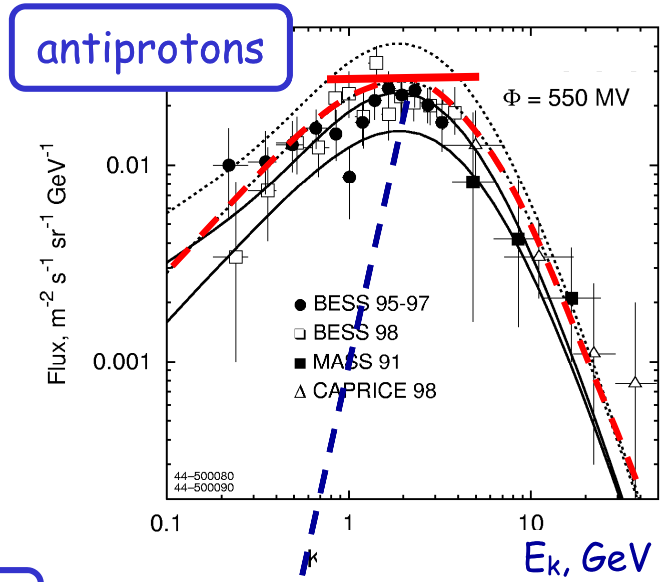
Interpretation (pre-2008)

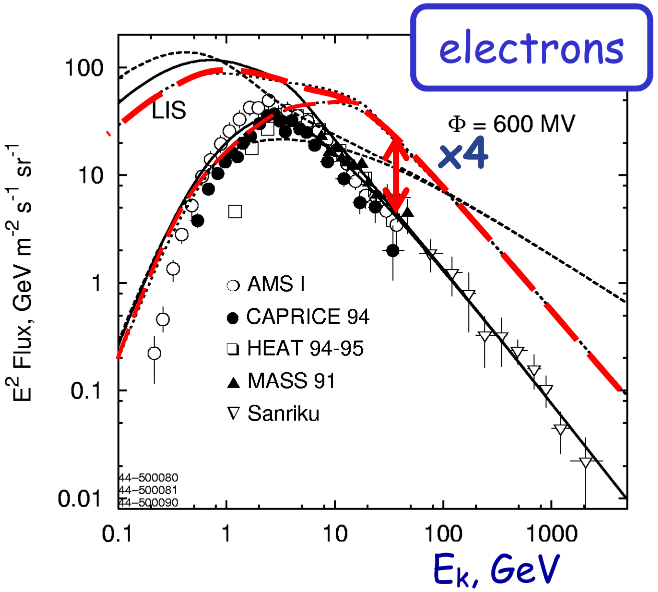
- Variations of cosmic ray intensity
- A discovery of dark matter

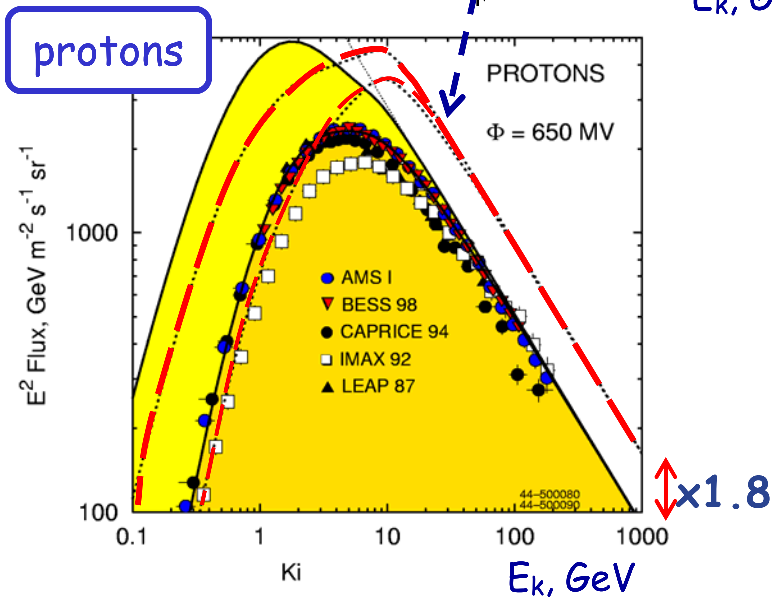
CR variations: Optimized/Reaccleration model

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

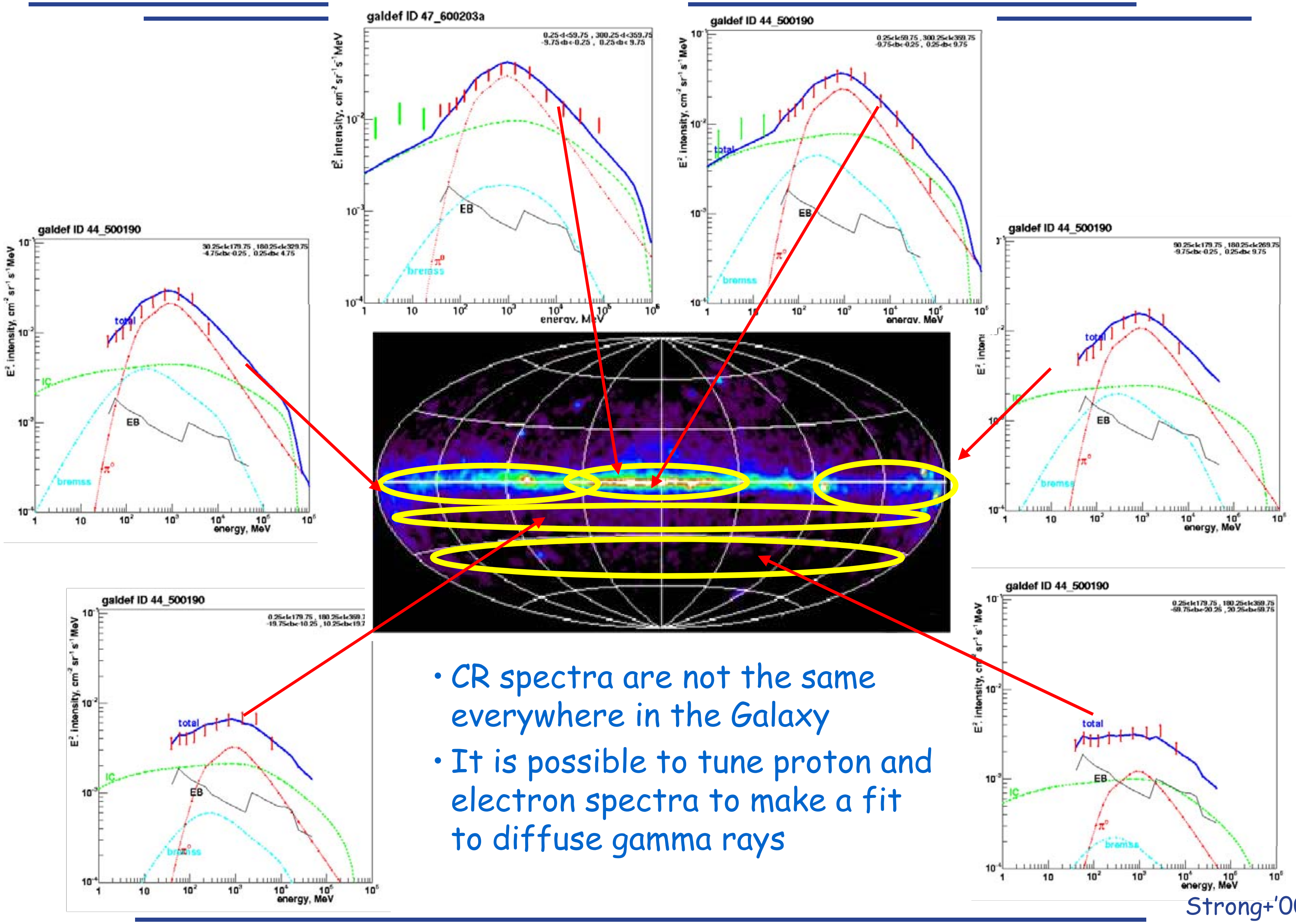
- Uses antiprotons to fix the *intensity* of CR nucleons @ HE
- Uses gammas to adjust
  - the nucleon spectrum at LE
  - the *intensity* of the CR electrons (uses also synchrotron index)
- Uses EGRET data up to 100 GeV







CR variations: Optimized model



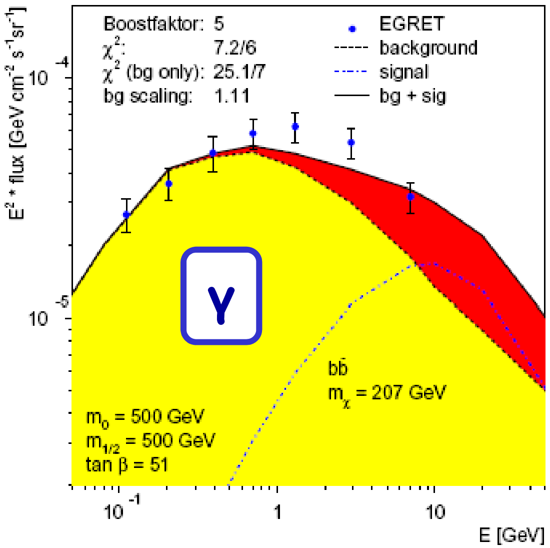
- CR spectra are not the same everywhere in the Galaxy
- It is possible to tune proton and electron spectra to make a fit to diffuse gamma rays

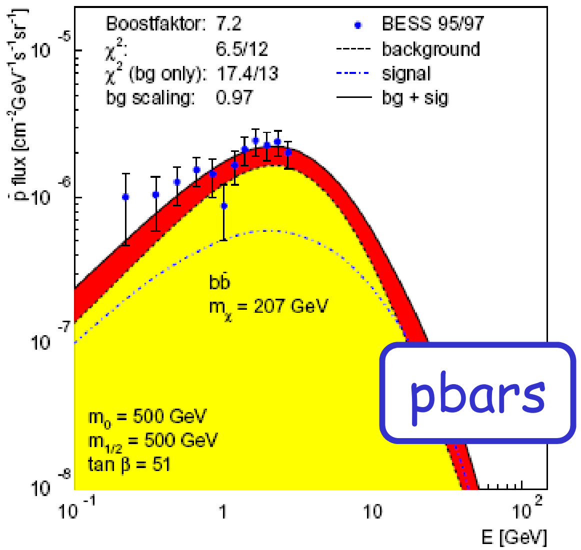
Strong+'00,'04

Discovery of Dark Matter

Supersymmetry:

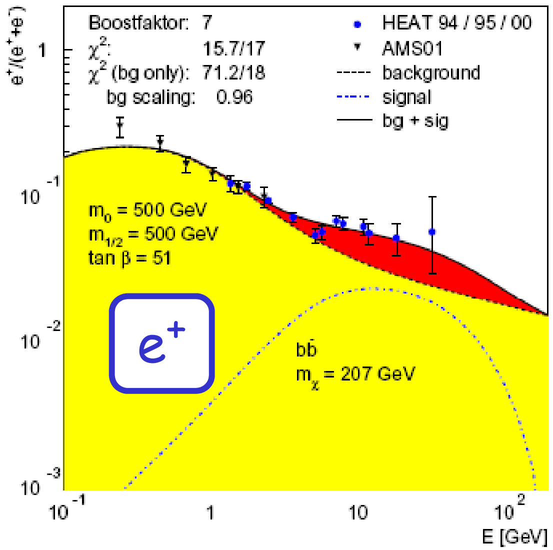
- MSSM
- Lightest neutralino χ^0
- $m_\chi \approx$ 50-500 GeV
- S=½ Majorana particles
- $\chi^0\chi^0$-> p, pbar, e⁺, e⁻, γ





de Boer'03

- Look at the combined (pbar,e⁺,γ) data
- Possibility of a *successful* "global fit" can not be excluded -non-trivial !
- If successful, it may provide a strong evidence for the SUSY DM

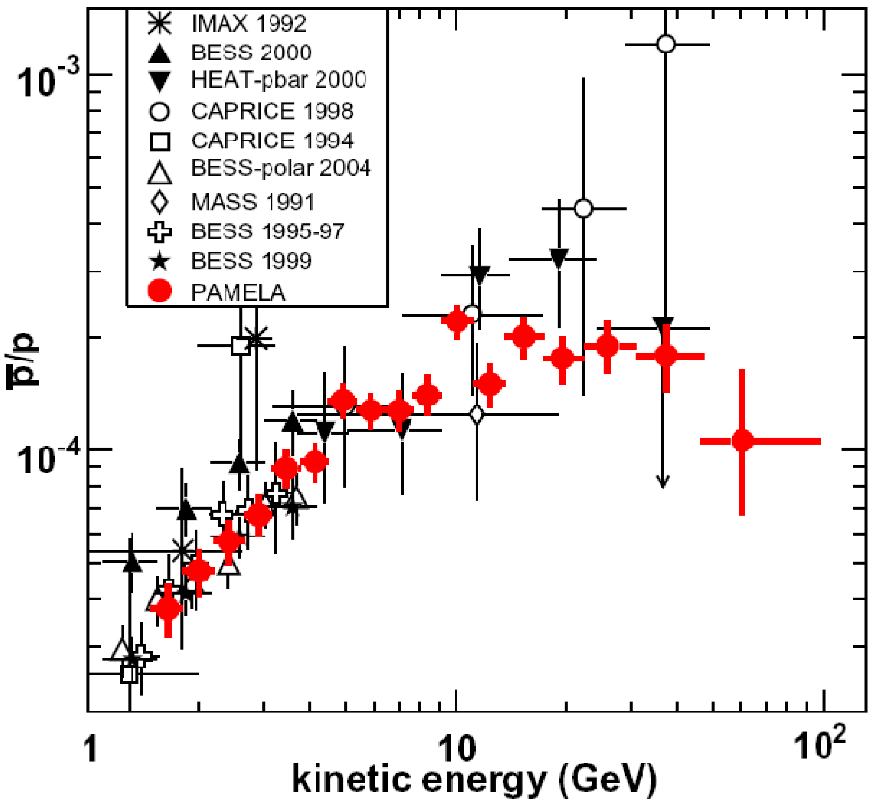


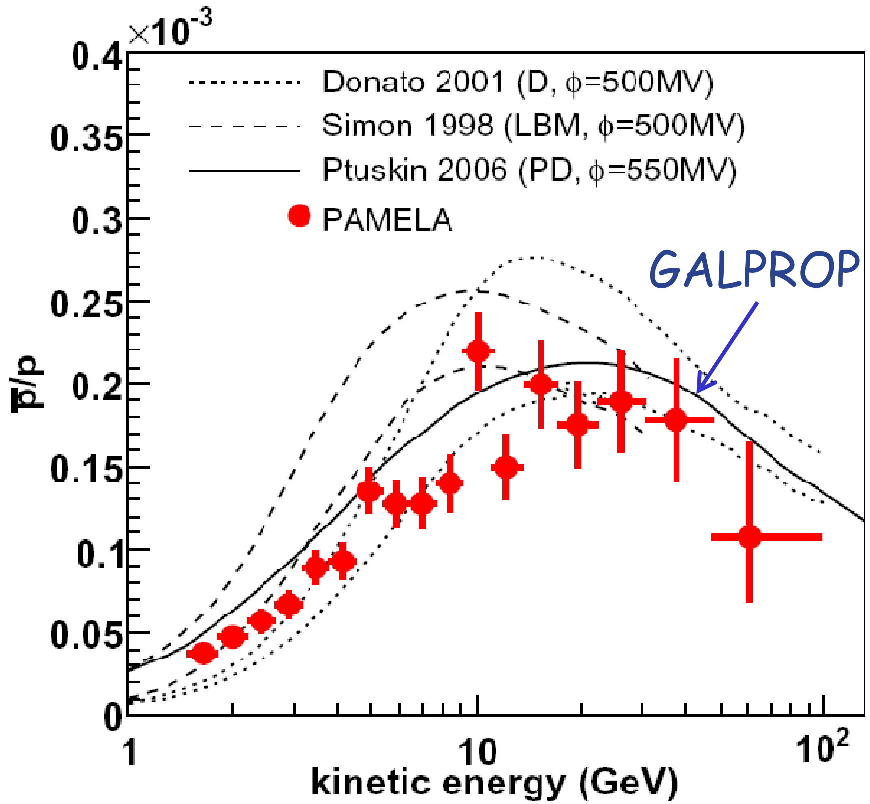
Great October revolution of 2008

Pamela papers on CR positron fraction and pbar/p ratio (arXiv: 0810.4994, 0810.4995) have triggered an avalanche of interpretations followed by ATIC CR electron spectrum and *Fermi*/LAT confirmation of non-GeV excess at mid-latitudes

Pamela: pbar/p ratio

- Pbar/p ratio is consistent with secondary origin

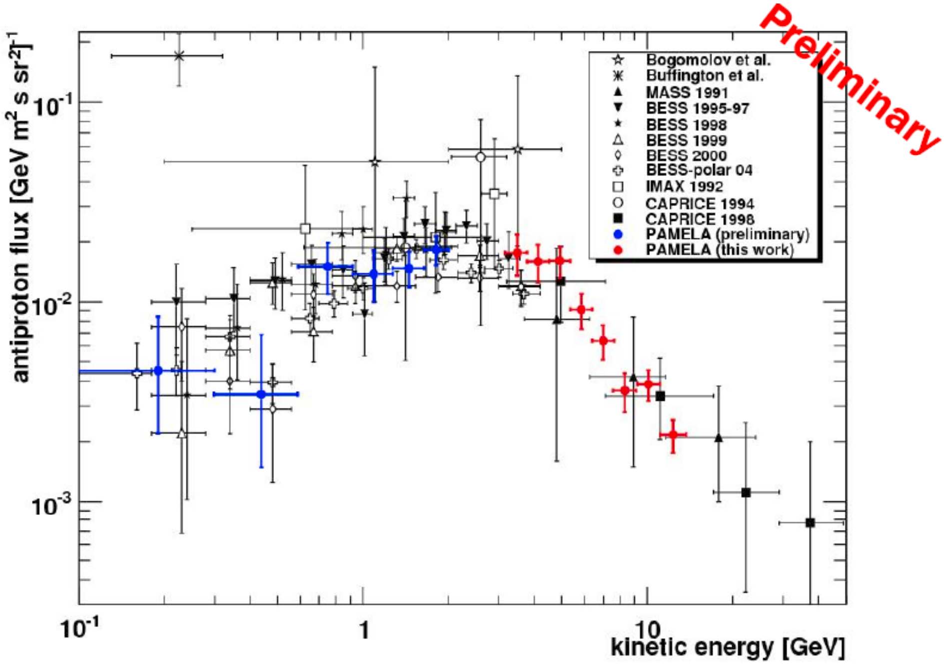


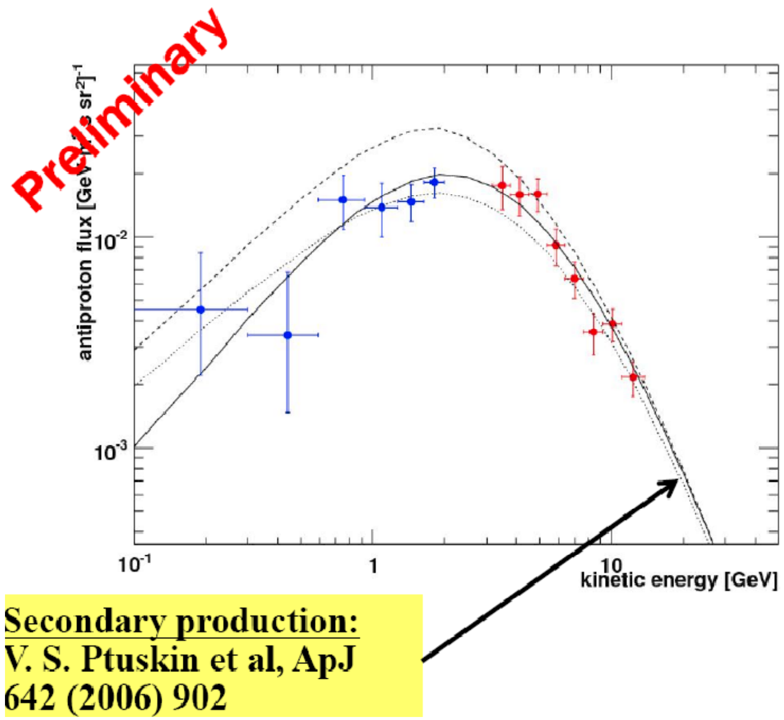


Adriani+'08 (arXiv:0810.4994)

Pamela: pbars

- Absolute pbar flux is consistent with secondary origin

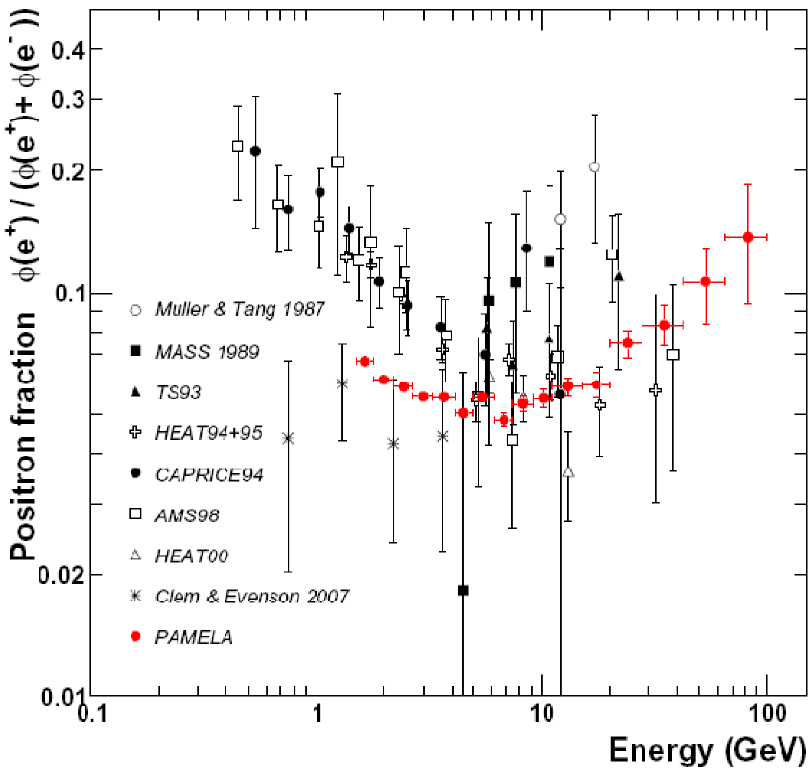


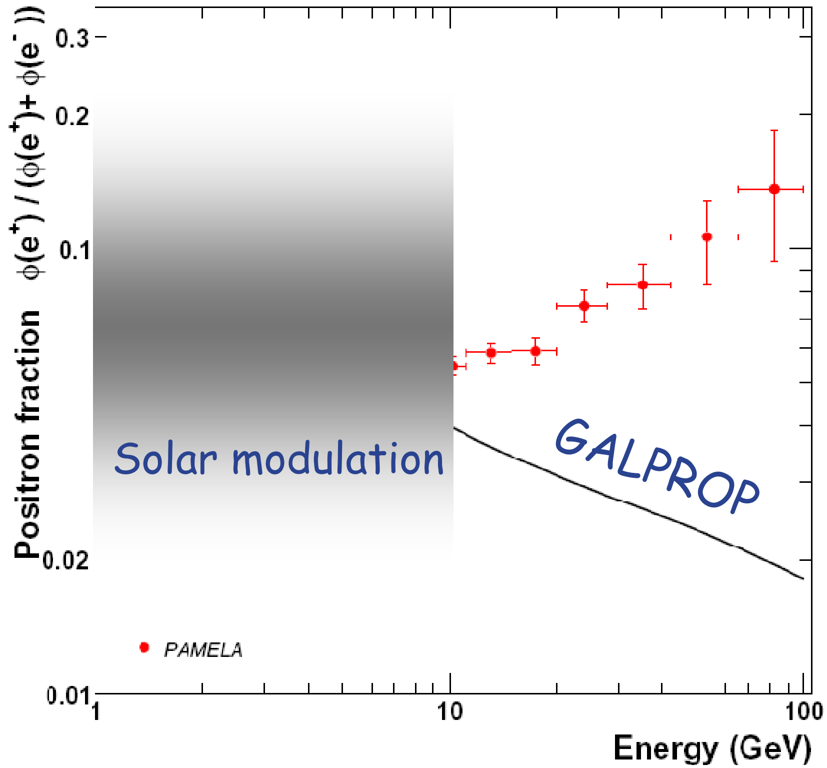


From M.Boezio talk at SLAC

Pamela: positron fraction

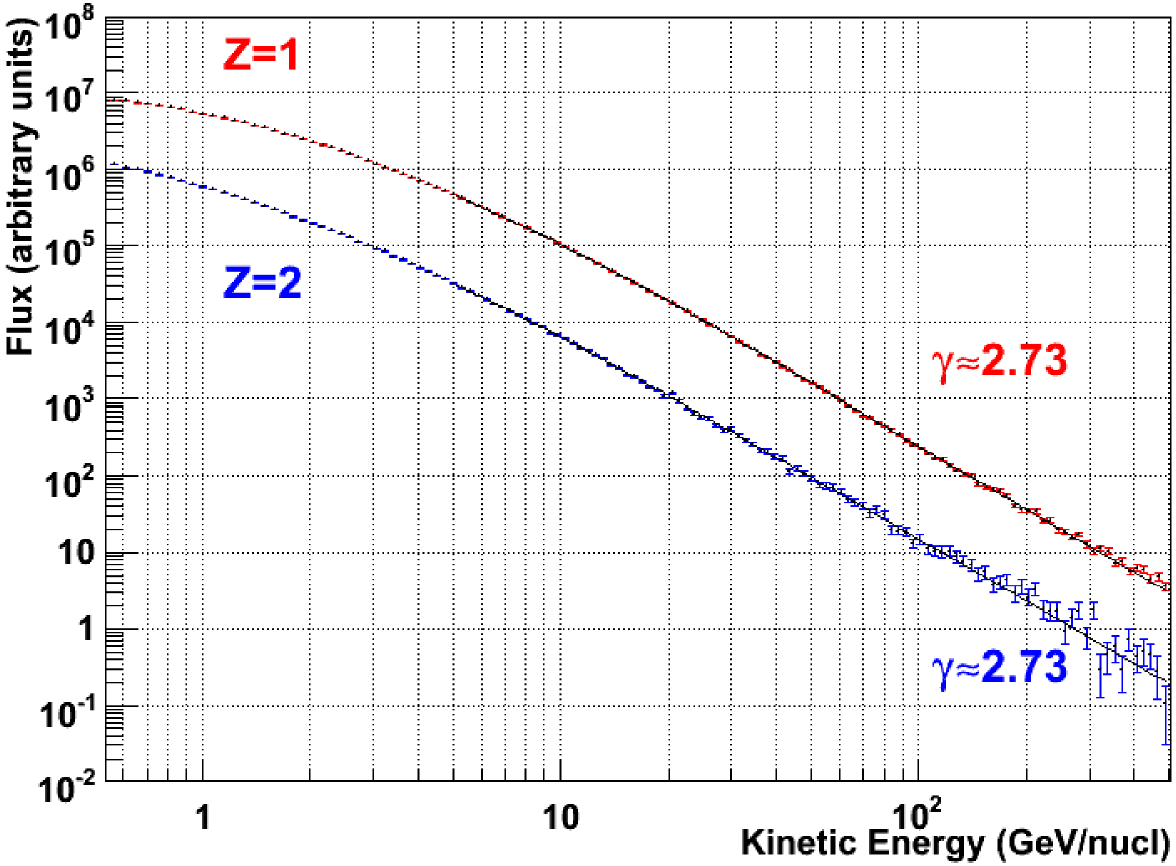
- Excess in positron fraction is confirmed and extended to higher energies





Adriani+'08 (arXiv:0810.4995)

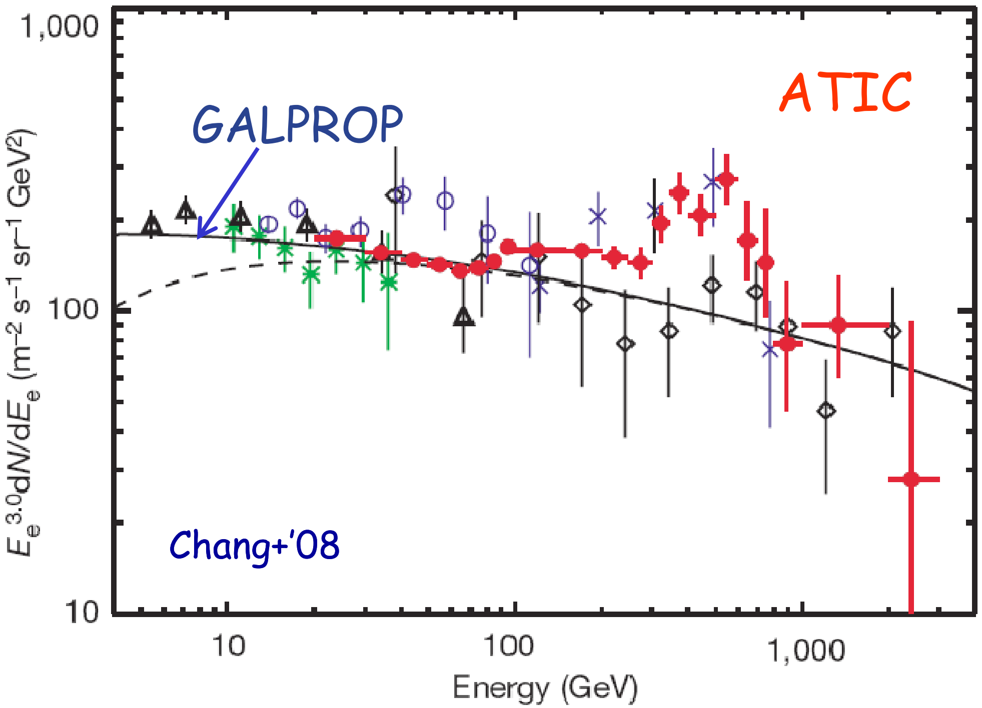
PAMELA: protons and helium

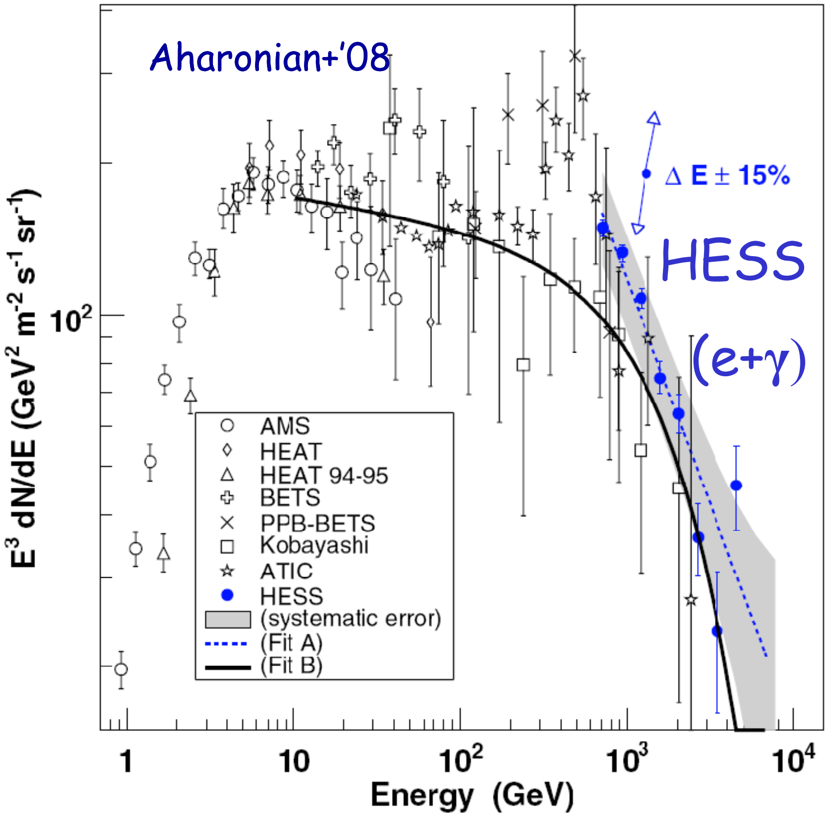


- PAMELA data are tremendously accurate, but currently only the "arb.units"
- Interestingly, the same slope for H and He and very close to C and O from CREAM
- Protons are flatter than BESS and AMS data

ATIC & HESS: electrons

- A feature in the electron spectrum (ATIC) and a sharp cutoff above ~1 TeV



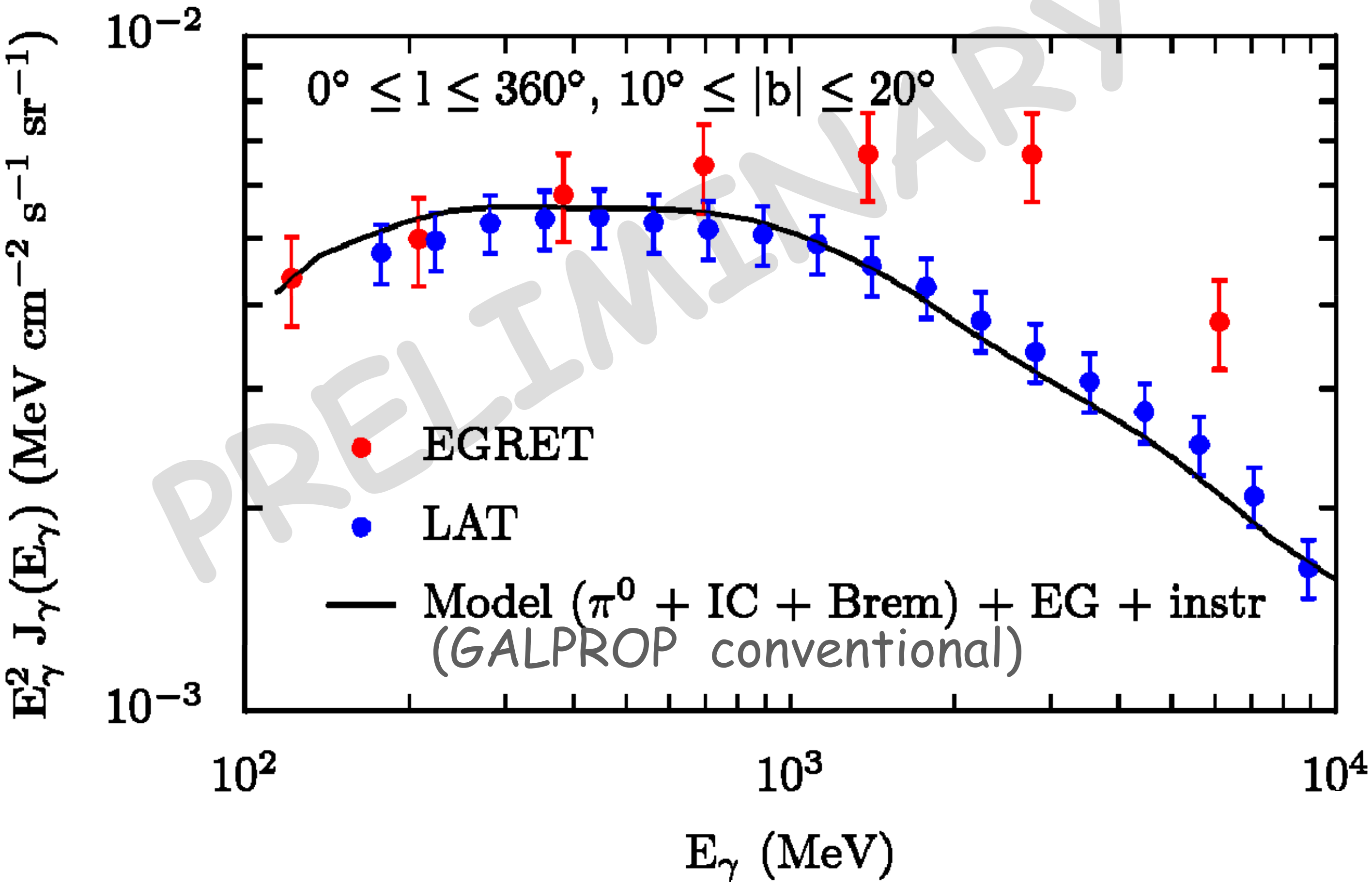



Pitch
In!


June 11, 2008
12:05 pm (EDT)
USAF
ULA
DELTA
GLAST

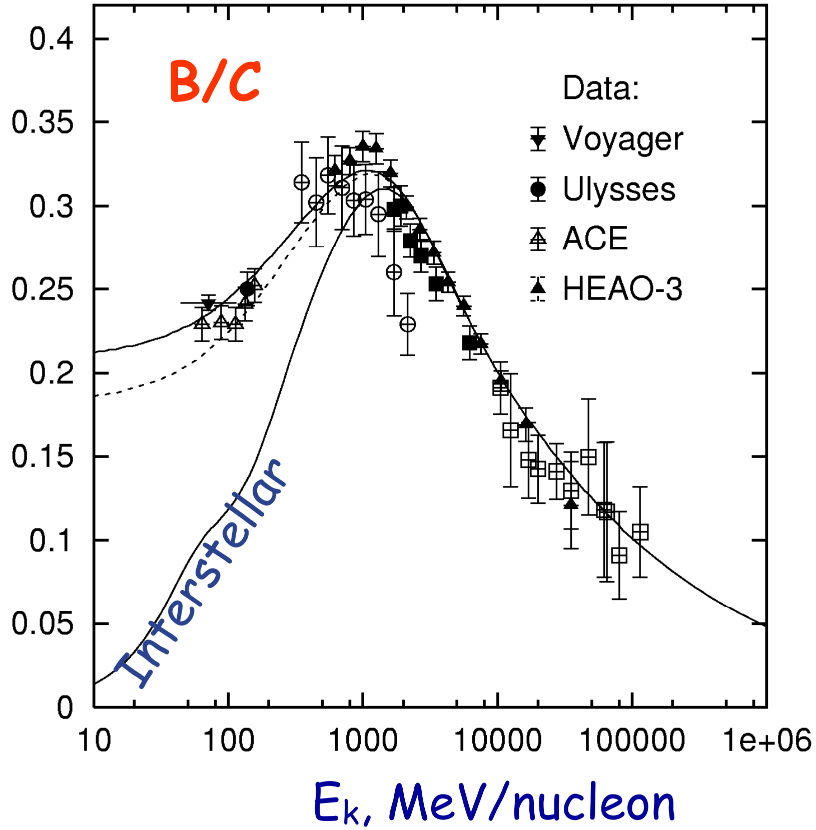
Fermi/LAT: This came in January 2009

- GeV excess has gone (at least at intermediate latitudes) – one excess less!



Pamela: B/C ratio

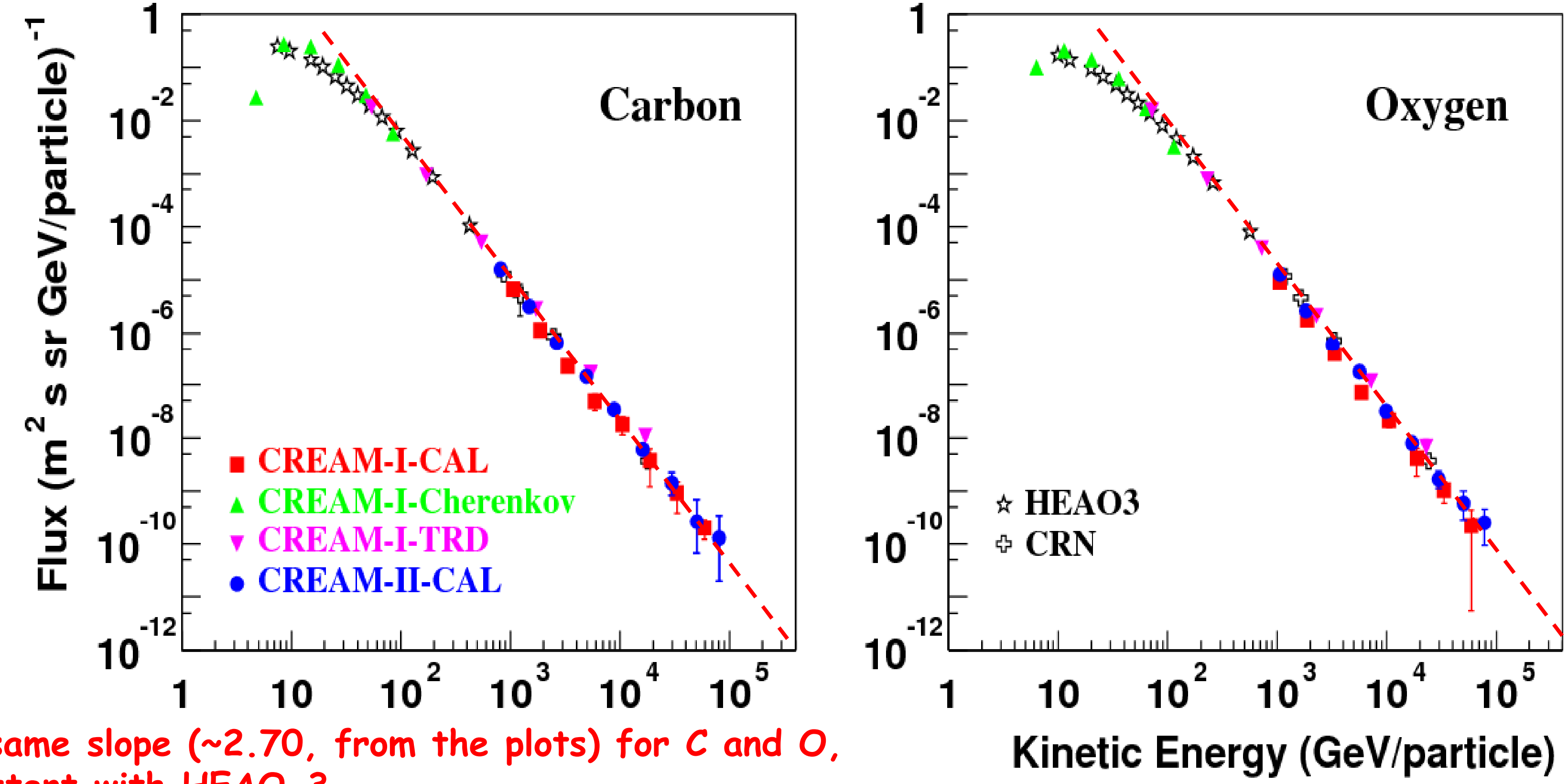
- Pamela B/C ratio (not shown) is consistent with HEAO data



C & O spectra from CREAM

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

Credit P.Blasi/Rapporteur talk

Two options for a scientist

- Hurry and explain new excesses in his/her favorite terms

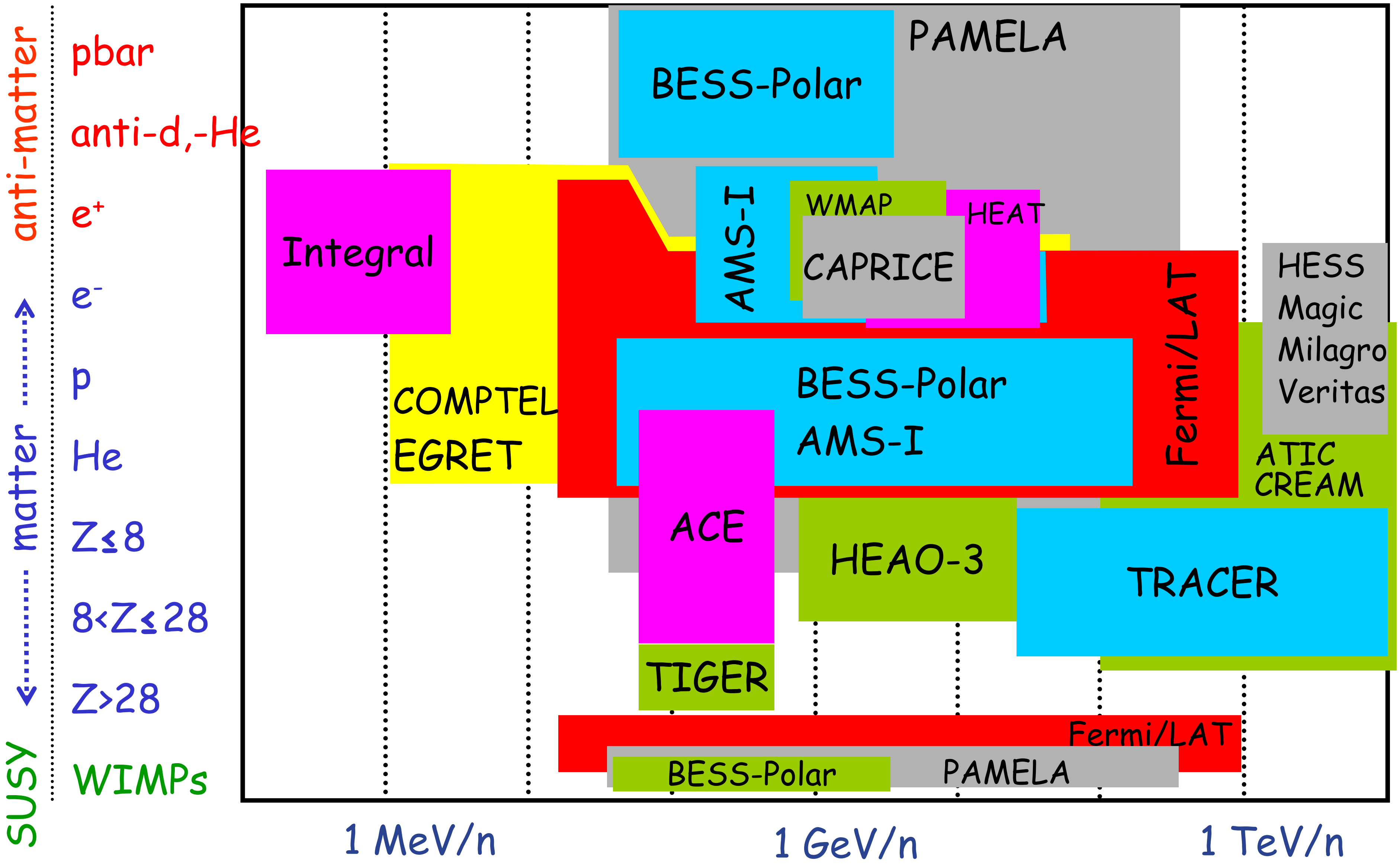
- Do nothing: Wait until the excesses go away by themselves

More data expected!

- ATIC and CREAM
  - Elemental abundances up to ~10^{15} eV
- PAMELA
  - Absolute positron flux
  - More on absolute antiproton flux
  - Electrons
  - Light nuclei
- Fermi Large Area Telescope
  - Electrons up to ~1 TeV
  - Diffuse emission (Galactic and extragalactic)

  Keep tuned:
  - A probe of electron spectrum from the solar surface to Saturn's orbit
  - A probe of CR proton spectrum beyond the heliospheric boundary
- AMS – will it fly?

CR and gamma-ray (CR) instruments



New reality

- The Galactic diffuse emission at intermediate latitudes probes the "local" CR spectrum – it appears to be consistent with local measurements
- Antiprotons in CRs is another probe of the local CR spectrum – consistent with secondary origin
  - Constrains SUSY models
- B/C ratio has not changed
- These measurements assure that we understand the positron background well
  - So what is the origin of the positron excess?

- CR electrons = primary + secondary
  - Secondary electrons can not produce the feature
  - IC emission probes the electron spectrum in the Galaxy but not sensitive to small features
- Any connection between the excesses in primary positrons and electrons?

What are other unknowns (CRs)?

- Propagation in the ISM – will be fixed soon using accurate measurements of B/C ratio in MeV-subTeV range
  - Provides an average diffusion coefficient
- However, the local medium could be quite different - measurements of heavy nuclei and short-lived radio isotopes are needed
- Solar modulation – still open question even though a lot has been learned from Voyagers 1,2 (<~100 MeV/nucleon)
- New approach: using Fermi/LAT observations of the solar system bodies and inverse Compton of CR electrons off solar photons

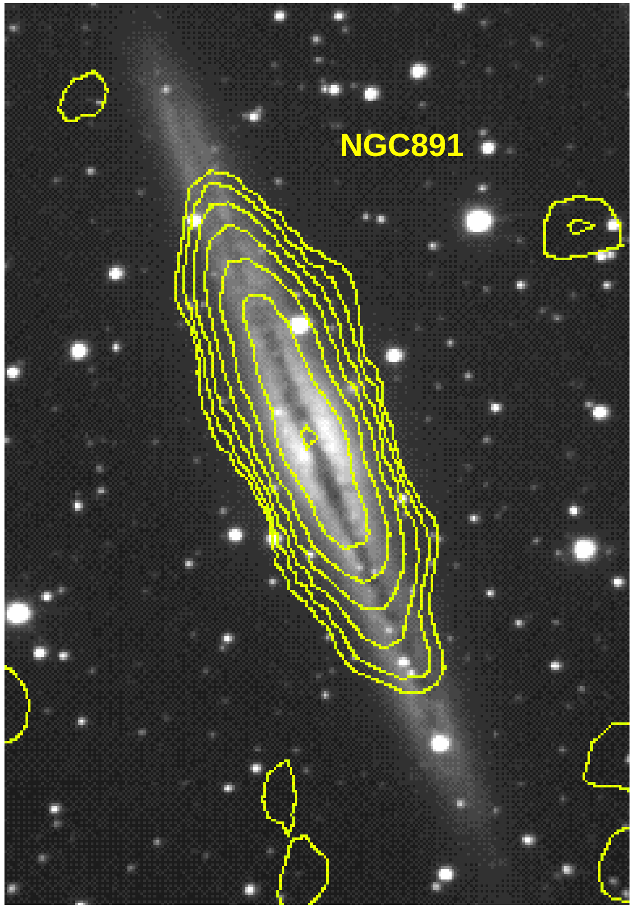
What are other unknowns (gammas)?

- Gas distribution in the Milky Way (π^0-production) is still an issue
- Interstellar radiation field (inverse Compton)
- Galactic center is a very difficult region
  - A crowded region with many sources and many of them are unidentified or unresolved
  - Gas distribution is uncertain (lack of the velocity info)
  - Difficult for background estimates
- Solar modulation – still open question even though a lot has been learned from Voyagers 1,2 (<~100 MeV/nucleon)
- New approach: using Fermi/LAT observations of the solar system bodies and inverse Compton of CR electrons off solar photons

How this is all done

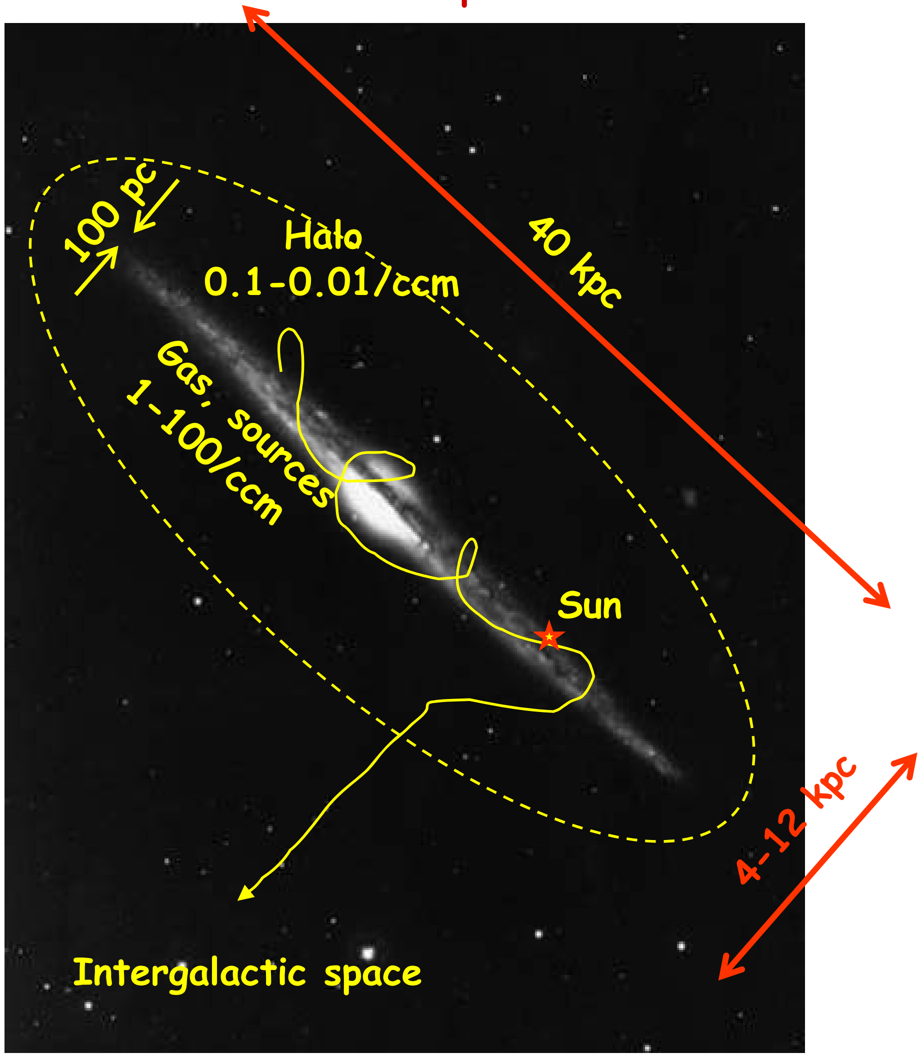
CR Propagation: Milky Way Galaxy

Optical image: Cheng et al. 1992, Brinkman et al. 1993
Radio contours: Condon et al. 1998 AJ **115**, 1693



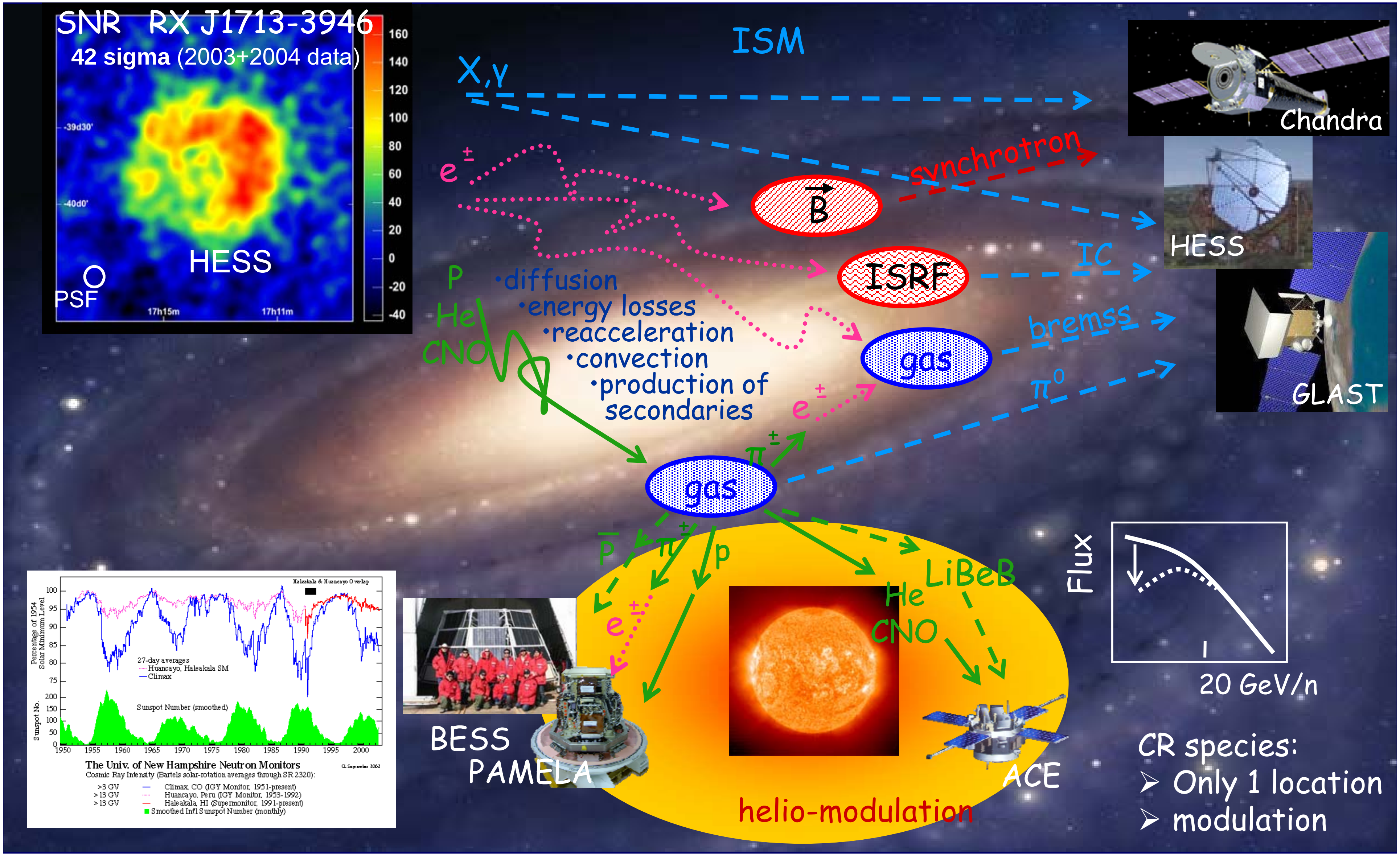
R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam

1 pc ~ 3×10^{18} cm

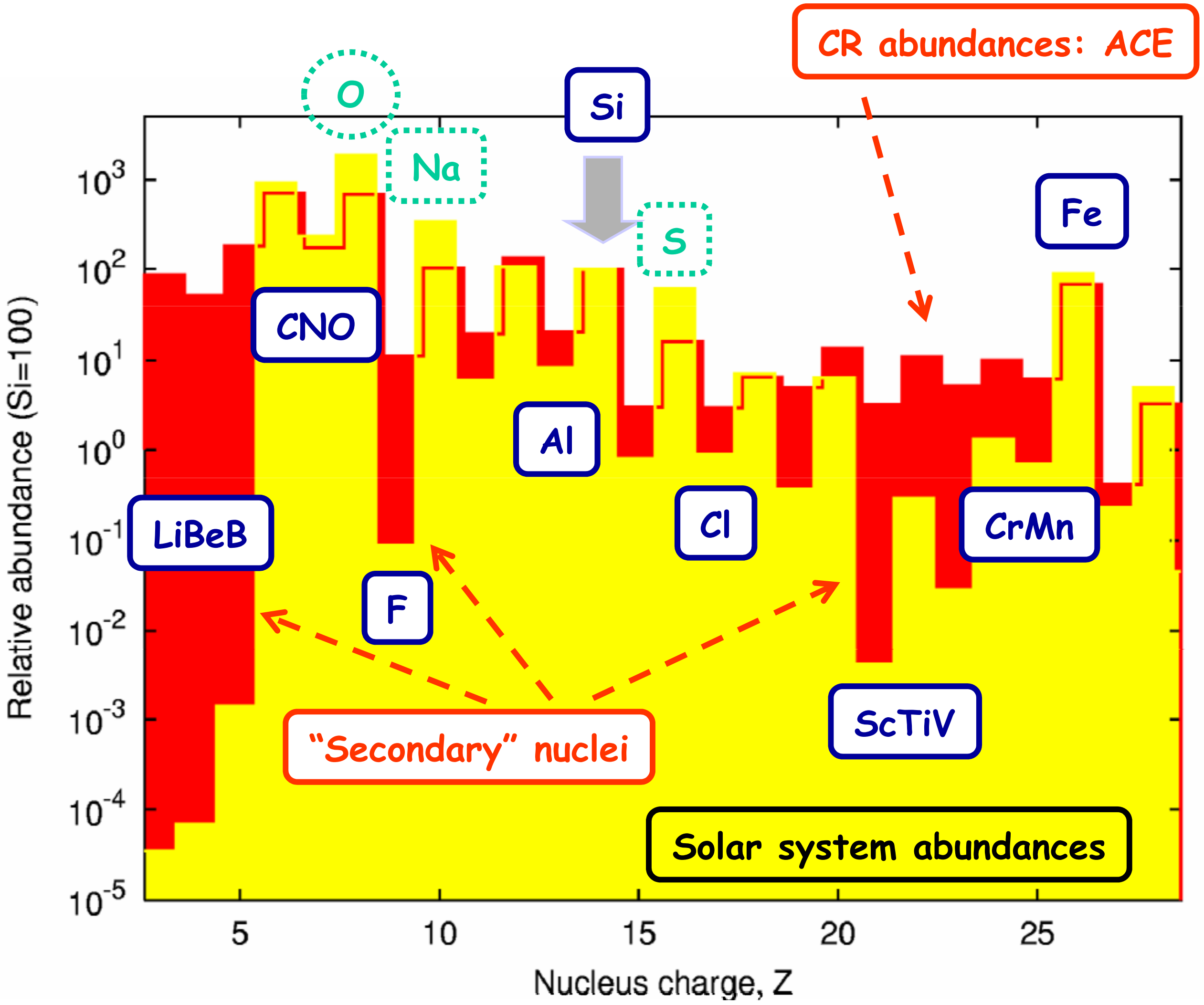


"Flat halo" model (Ginzburg & Ptuskin 1976)

CR Interactions in the Interstellar Medium



Elemental Abundances: CR vs. Solar System



Secondary nuclei is an evidence of the long propagation history of CRs

Why do we know they are secondary?

- A comparison with solar system abundances (interstellar medium ~4 Byr ago)
- Models of nucleosynthesis
- CR propagation models

Transport Equations ~90 (no. of CR species)

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ **sources (SNR, nuclear reactions…)**

diffusion $$+ \vec{\nabla} \cdot [D_{xx} \vec{\nabla} \psi - \vec{V} \psi]$$

convection
(Galactic wind)

diffusive reacceleration
(diffusion in the momentum space)
$$+ \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} \right]$$

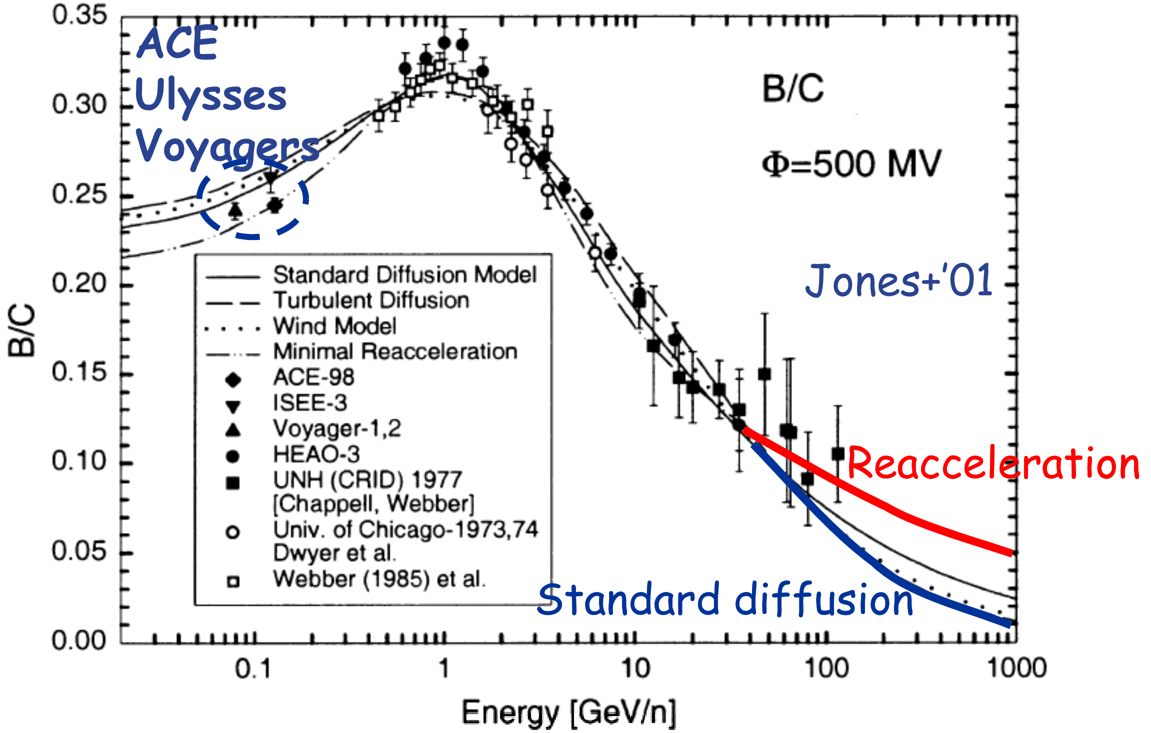
E-loss $$- \frac{\partial}{\partial p} \left[\frac{dp}{dt} \psi - \frac{1}{3} p \vec{\nabla} \cdot \vec{V} \psi \right]$$

fragmentation $$- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ **radioactive decay**

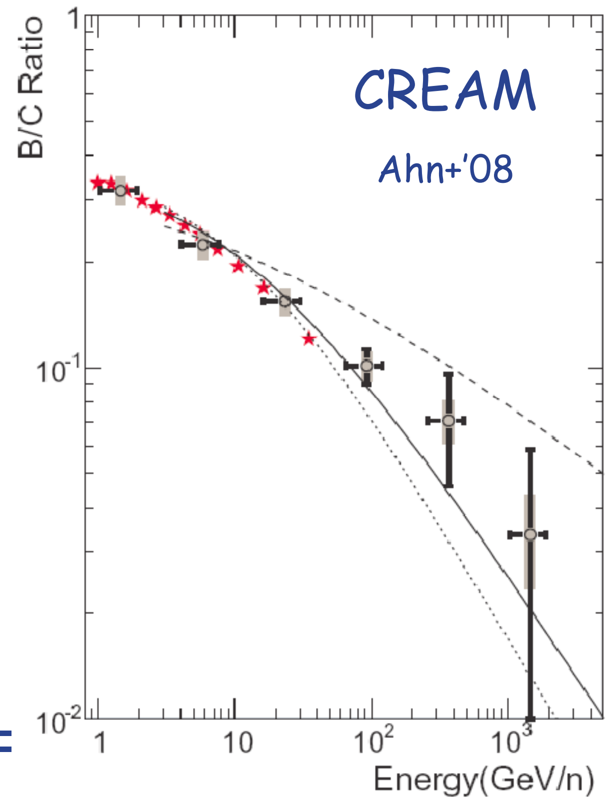
+ boundary conditions

$\psi(\mathbf{r},p,t)$ – *density per total momentum*

B/C ratio



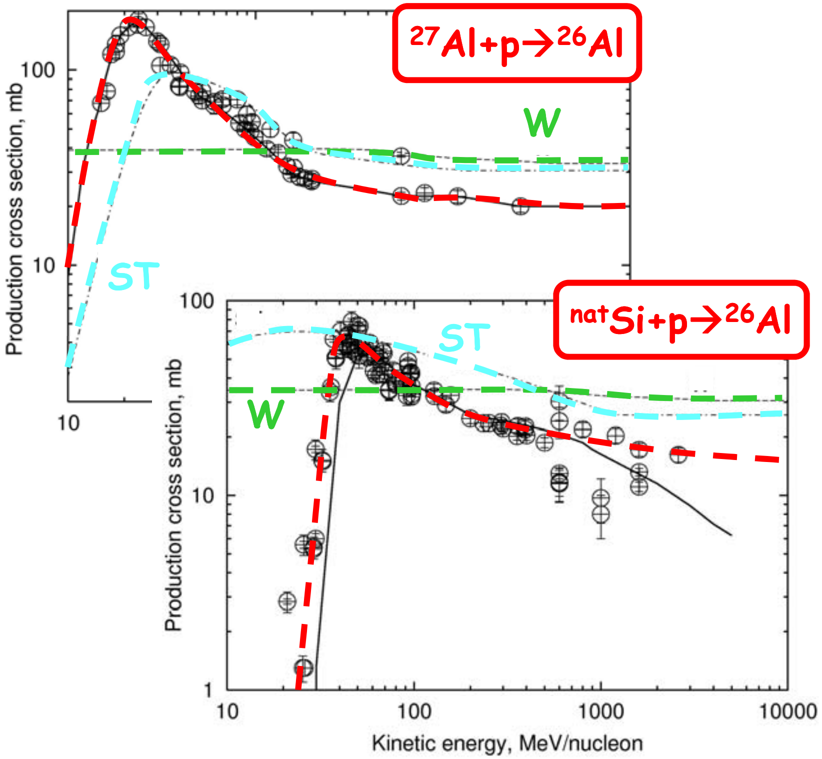
- Different propagation models are tuned to fit the low energy part of sec./prim. ratio where the accurate data exist

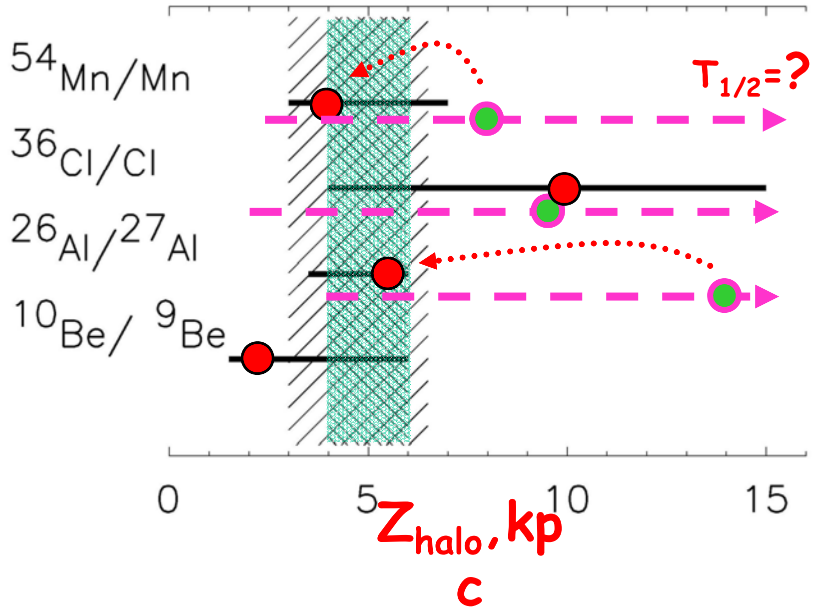


- However, they differ at high energies which will allow to discriminate between them when more accurate data will be available

Effect of Cross Sections: Radioactive Secondaries

Different size from different ratios…



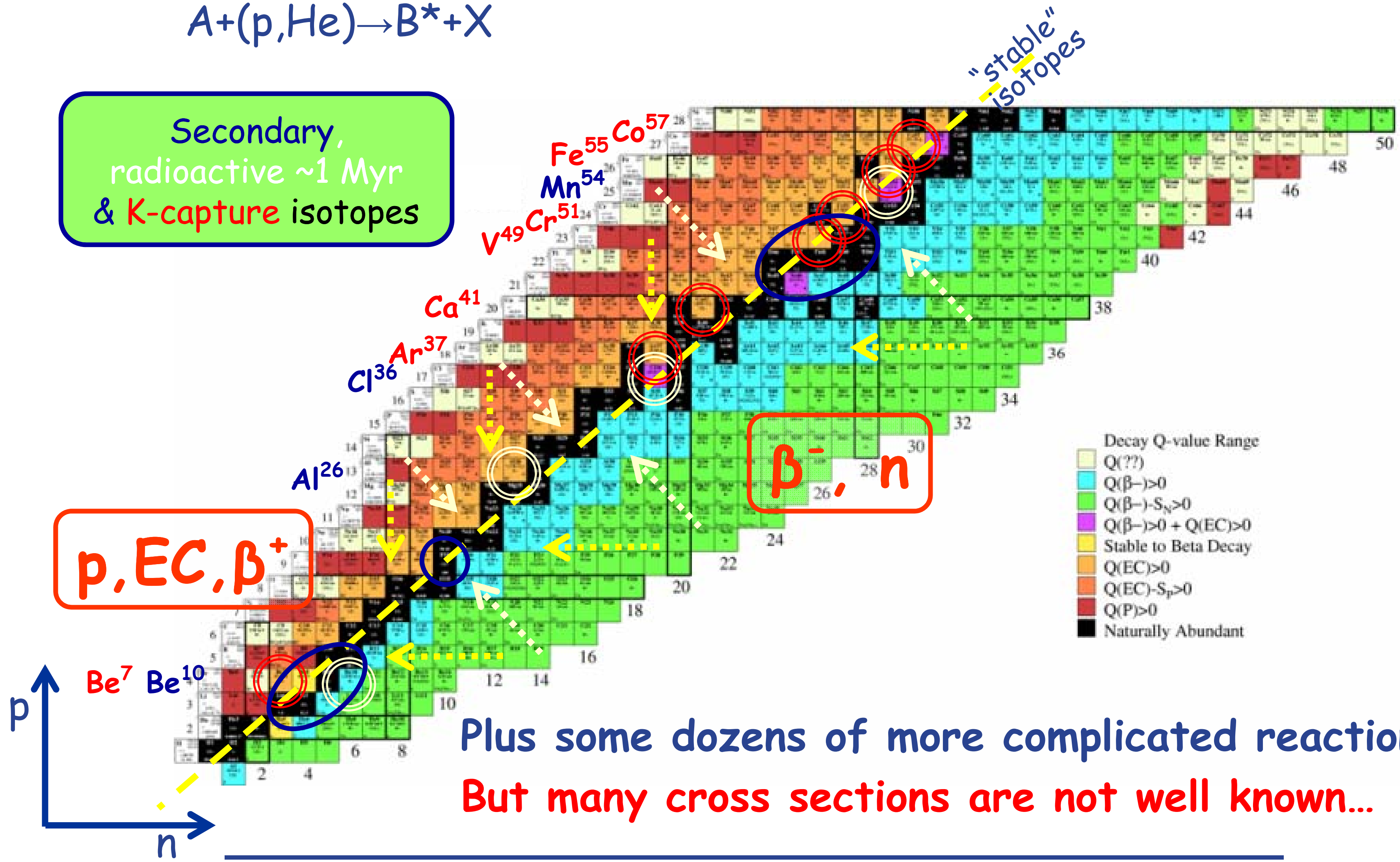


- Errors in CR measurements (HE & LE)
- Errors in production cross sections
- Errors in the lifetime estimates

Nuclear Reaction Network+Cross Sections

Many different isotopes are produced via spallations of CR nuclei:
$A+(p,He)\rightarrow B^{*}+X$

Secondary, radioactive ~1 Myr & K-capture isotopes

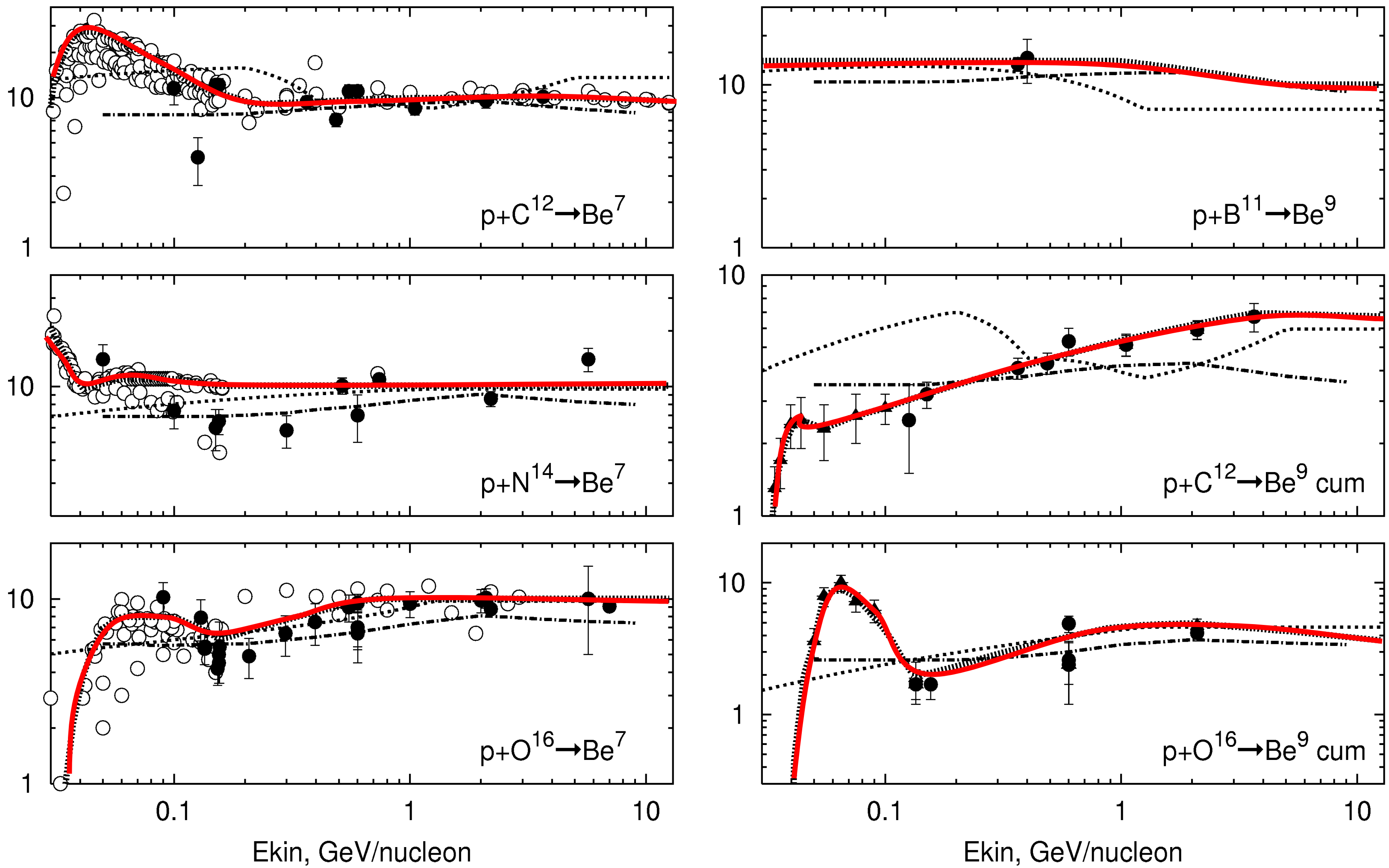


Plus some dozens of more complicated reactions

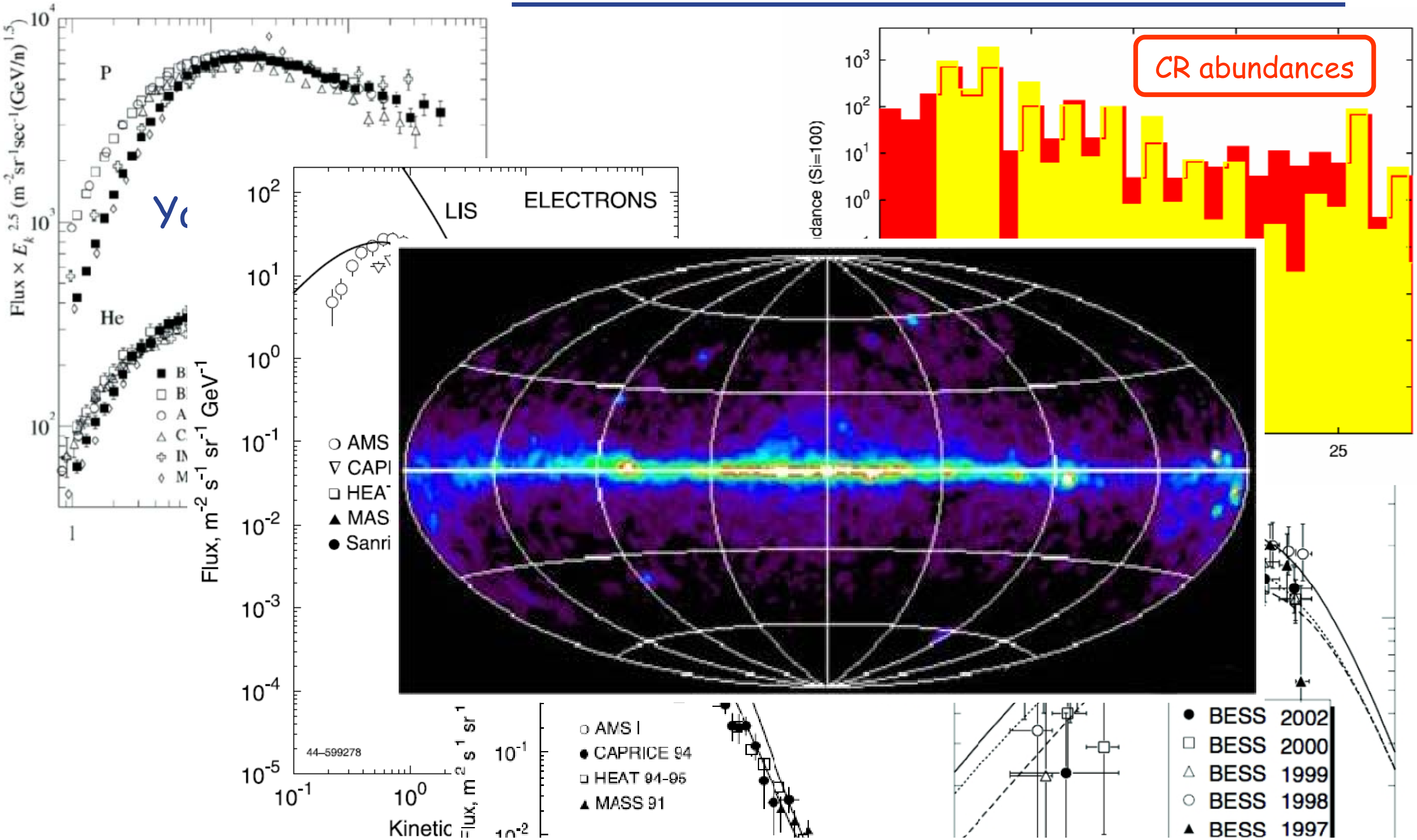
But many cross sections are not well known…

Production Cross Sections of Li,Be,B

Semi-phenomenology: .... Silberberg & Tsao, — · — Webber

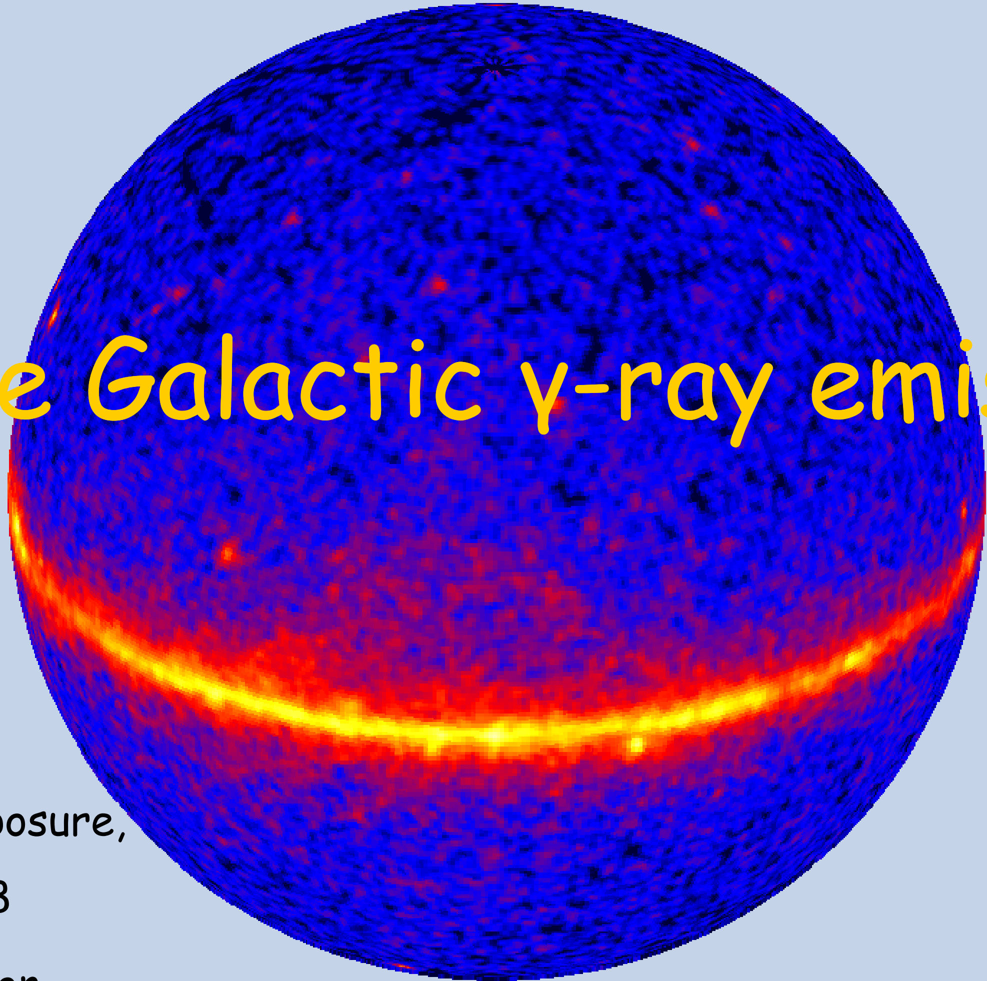


Cosmic Rays vs Diffuse Gamma Rays



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…

Diffuse Galactic γ-ray emission



- ~4-day First Light exposure, June 30 – July 3, 2008
- Orthographic projection

Simplified equation: VHE electrons

The equation describing the dependence of the electron density $N(E, \mathbf{r})$ on energy and position is of the form (Syrovatskii, 1959; Ginzburg and Syrovatskii, 1963)

$$-\nabla D(E)\nabla N + \frac{\partial}{\partial E}(b(E)N) = Q(E, \mathbf{r}).$$

$$\begin{cases} D(E) = D_0 (E/E_0)^{\mu} \\ \frac{dE_{IC}}{dt} \equiv b(E) = -\beta E^2 \\ Q(E, \mathbf{r}) = \frac{KE^{-\gamma_0}}{2\pi a^2 b} \\ N|_{\Sigma} = 0 \end{cases}$$

Cylindrically symmetric solution:

$\mu < 1$

$$N(E, \varrho, z) = \frac{4KE^{-(\gamma_0+1)} (1/2\pi)}{\pi a^2 b(\gamma_0 - 1)\beta} \sum_{n=0}^{\infty} \frac{\sin\left[\pi \frac{b}{d}(n+\frac{1}{2})\right]}{(n+\frac{1}{2})} \times$$

$$\times \cos\left[\pi \frac{z}{d}(n+\tfrac{1}{2})\right] \sum_{m=1}^{\infty} \frac{J_0\left[\nu_m \frac{\varrho}{a}\right]}{\nu_m J_1(\nu_m)} {}_1F_1\left(1, \frac{\gamma_0 - \mu}{1-\mu};\right.$$

$$\left. -\left[\pi^2 (n+\tfrac{1}{2})^2 + \frac{d^2}{a^2}\nu_m^2\right] \frac{D_0 E^{\mu-1}}{d^2(1-\mu)E_0^{\mu}\beta}\right);$$

Bessel fns

hypergeometric fn

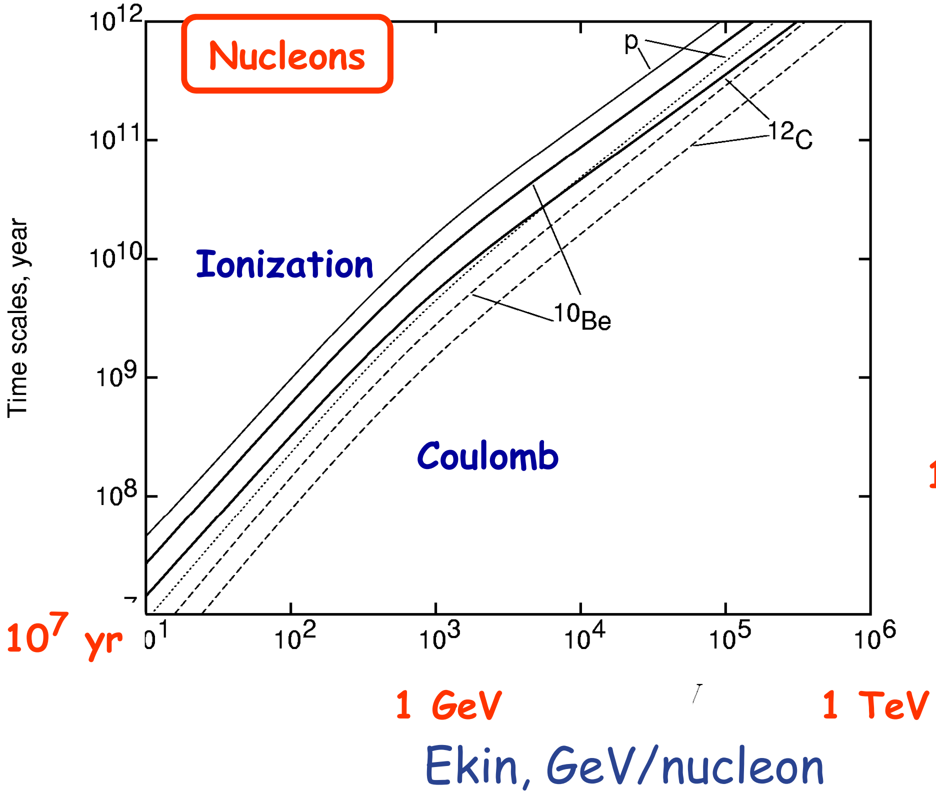
zeros of J_0

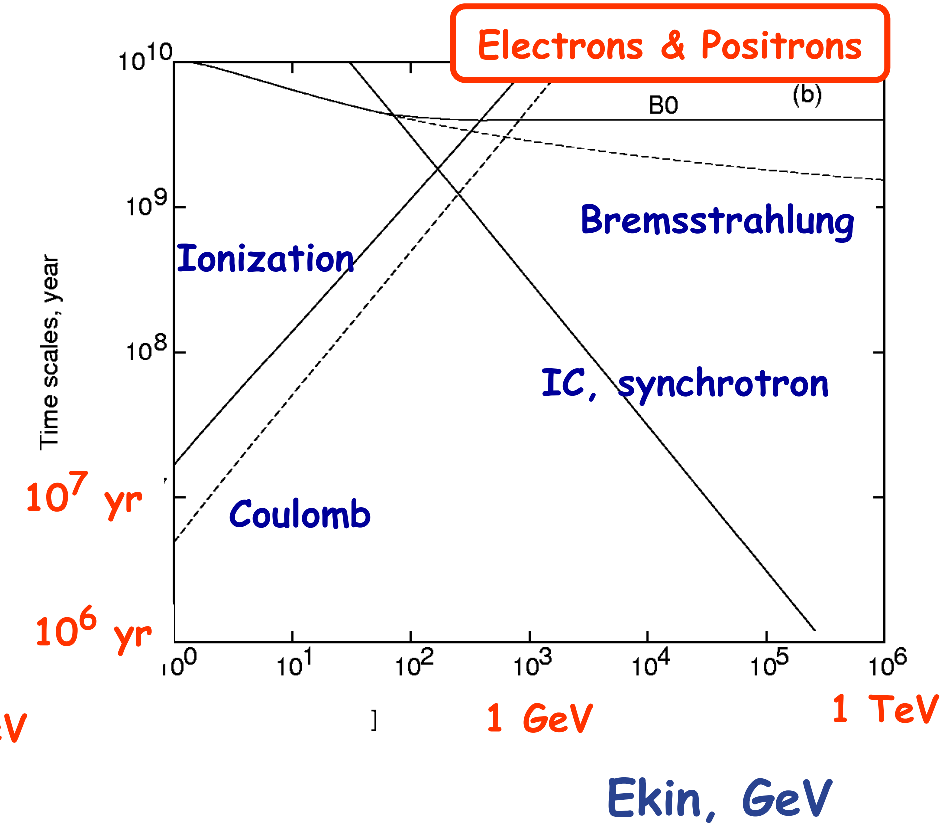
d=halo size

a=radius

Bulanov & Dogiel'74

Energy Losses





Assuming:

H-gas: 0.01 atom/cc

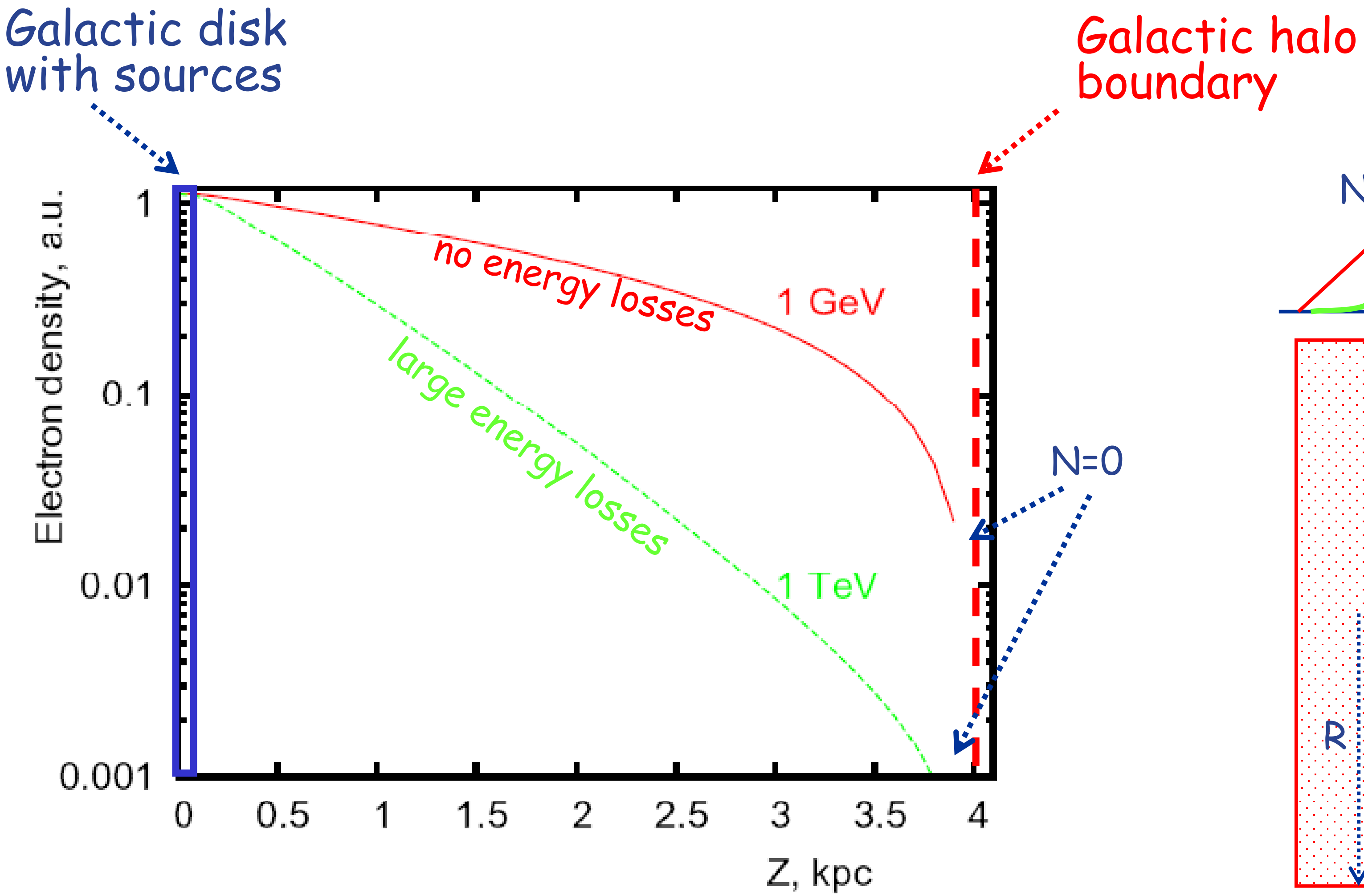
Photon energy density: 1 eV/cc

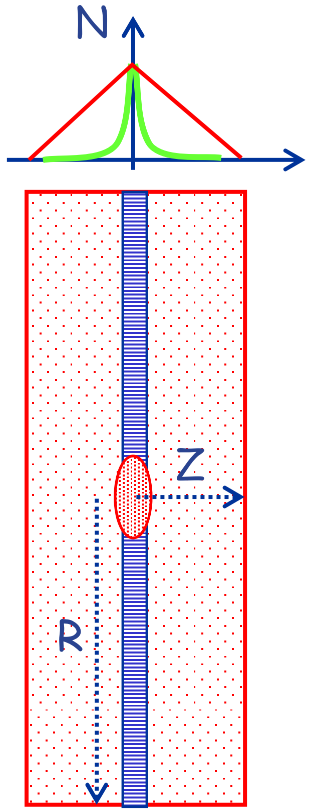
Electron energy loss timescale:

1 TeV: ~300 000 yr

100 TeV: ~3 000 yr

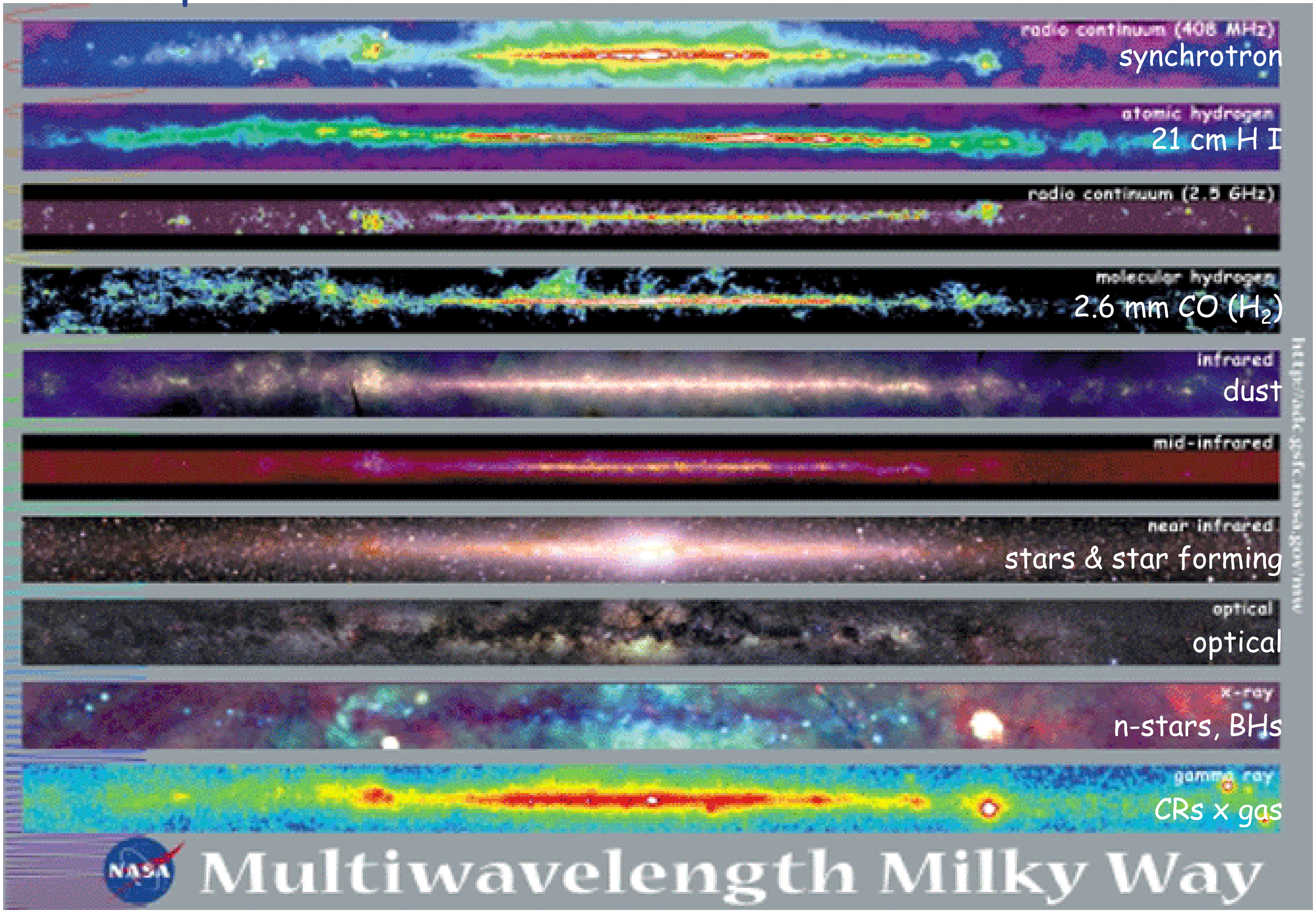
Electron propagation: solutions



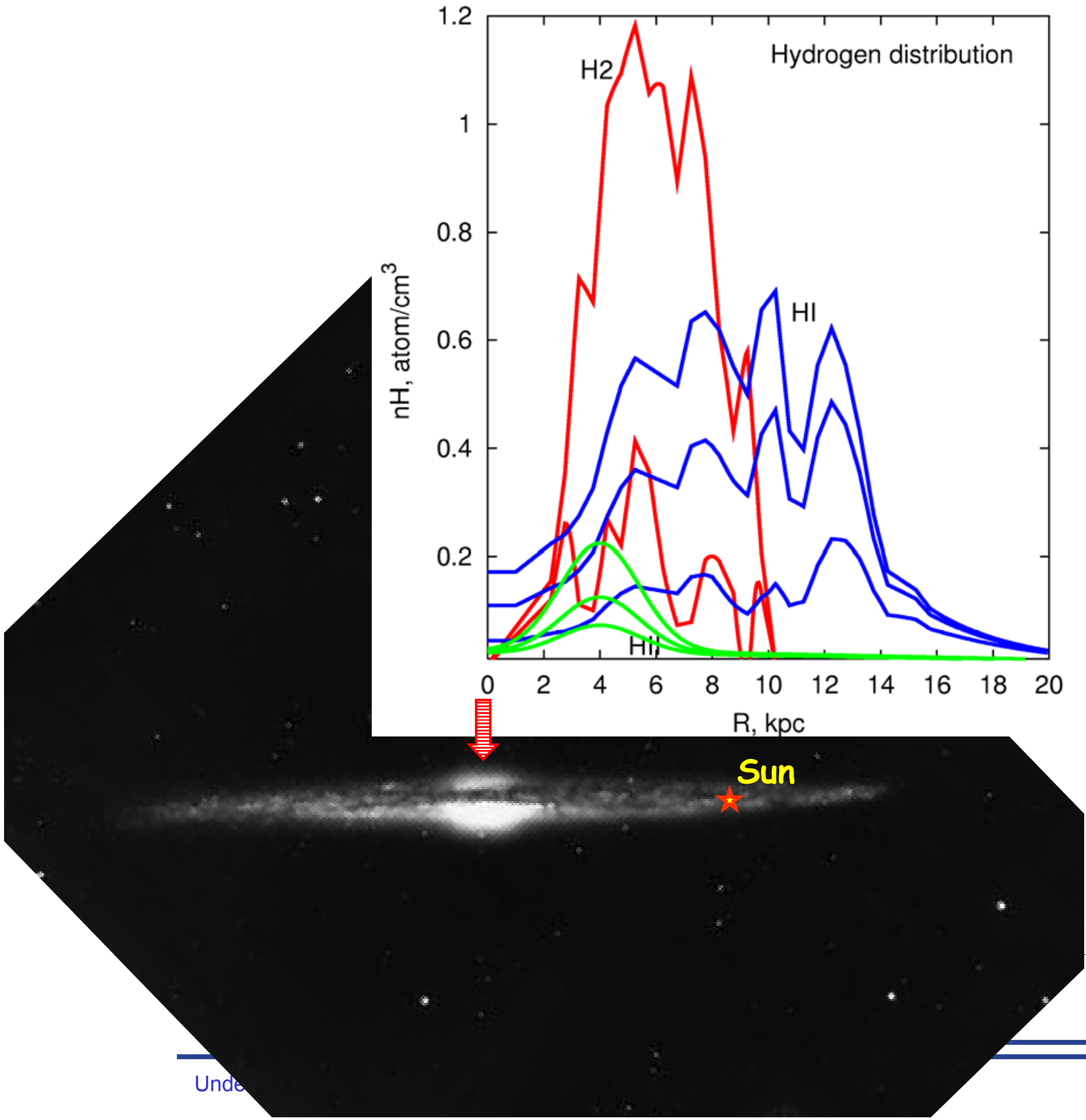


The "Galaxy"

Components of the ISM: Views from the Inside



Gas distribution in the Milky Way



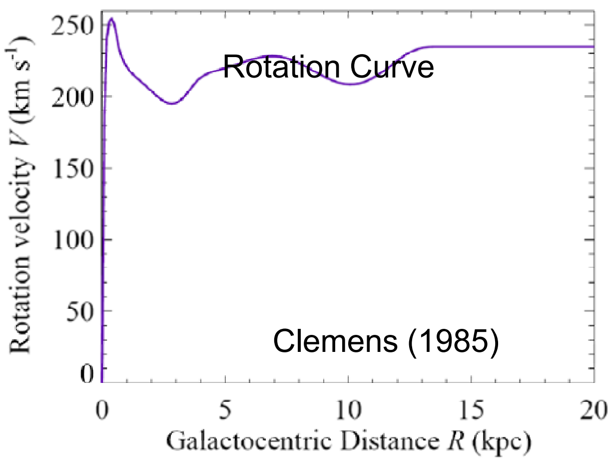
Molecular hydrogen H_2
is traced using J=1-0 transition of ^{12}CO, concentrated mostly in the plane
(z~70 pc, R<10 kpc)

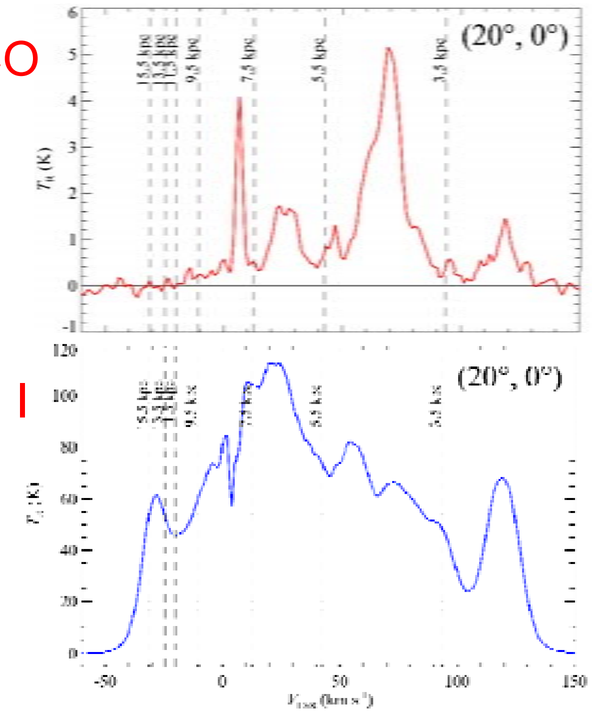
Atomic hydrogen H I
has a wider distribution
(z~1 kpc, R~30 kpc)

Ionized hydrogen H II –
small proportion, but exists even in halo
(z~1 kpc)

Distribution of interstellar gas

- Neutral interstellar medium – most of the interstellar gas mass
  - 21-cm H I & 2.6-mm CO (surrogate for H_2)
  - Differential rotation of the Milky Way – plus random motions, streaming, and internal velocity dispersions – is largely responsible for the spectrum
  - Rotation curve $V(R) \Rightarrow$ unique line-of-sight velocity-Galactocentric distance relationship





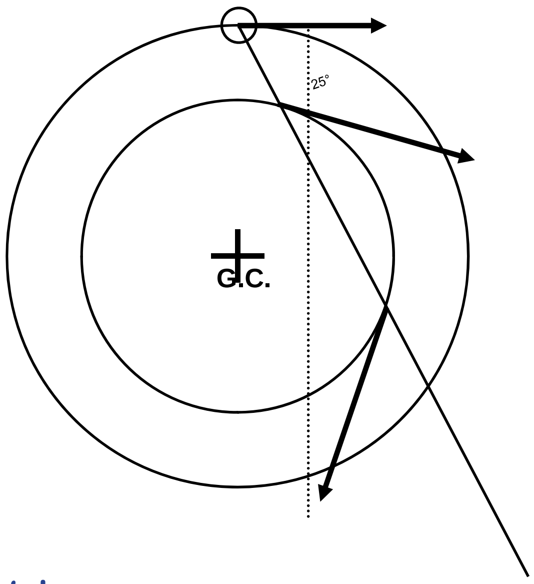
Dame et al. (2001)

Kalberla et al. (2005)

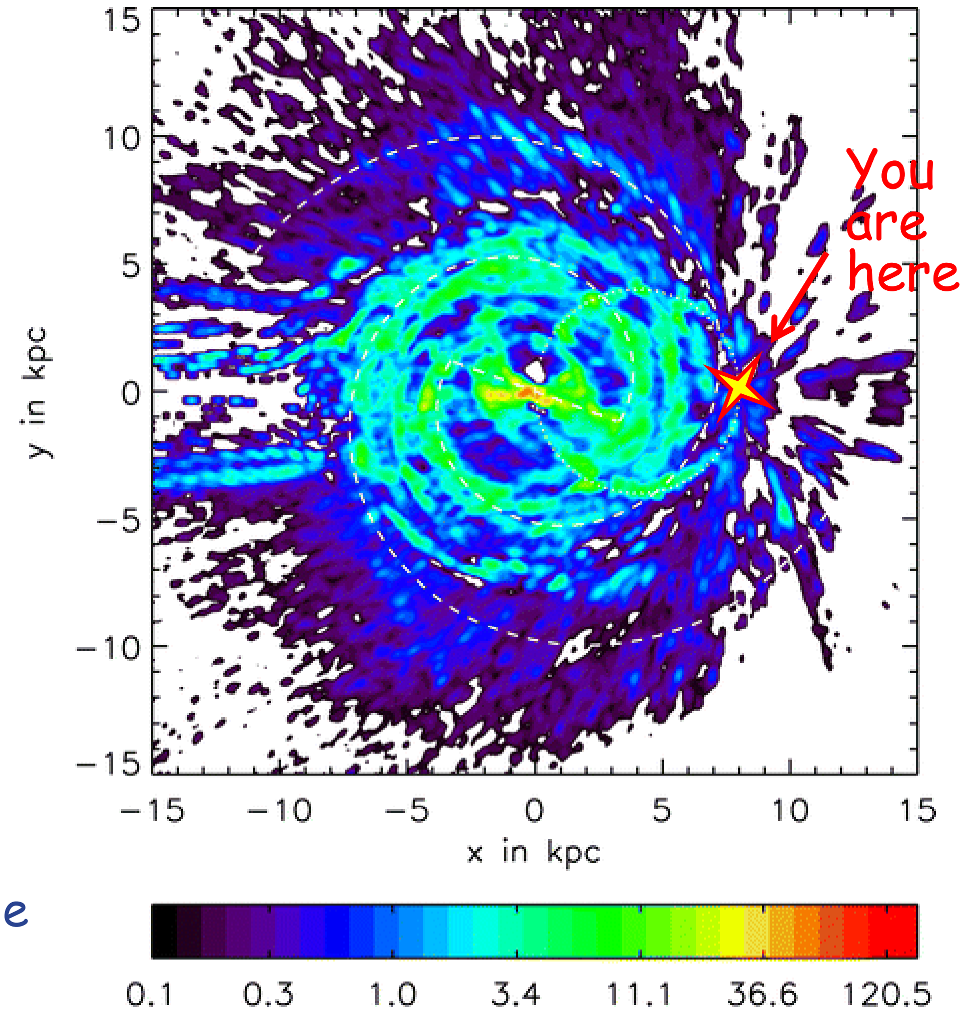
W. Keel

- This is the best – but far from perfect – distance measure available
- Column densities: $N(H_2)/W_{CO}$ ratio assumed; a simple approximate correction for optical depth is made for N(H I); self-absorption of H I remains

More on gas in the Milky Way



Surface mass density of the H_2 in M_{sun} pc^{-2}



Problems:

- Near-far ambiguity
- No velocity information in the Center-Anticenter direction

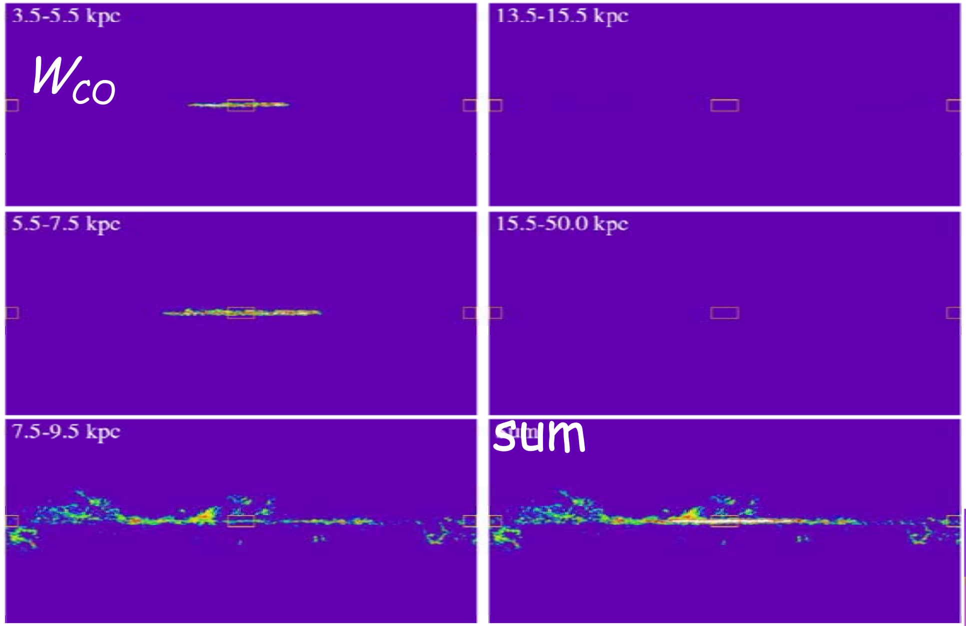
Pohl+'08

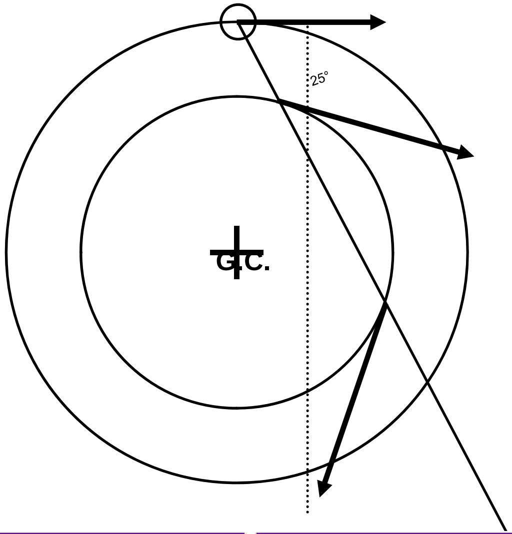
HI gas

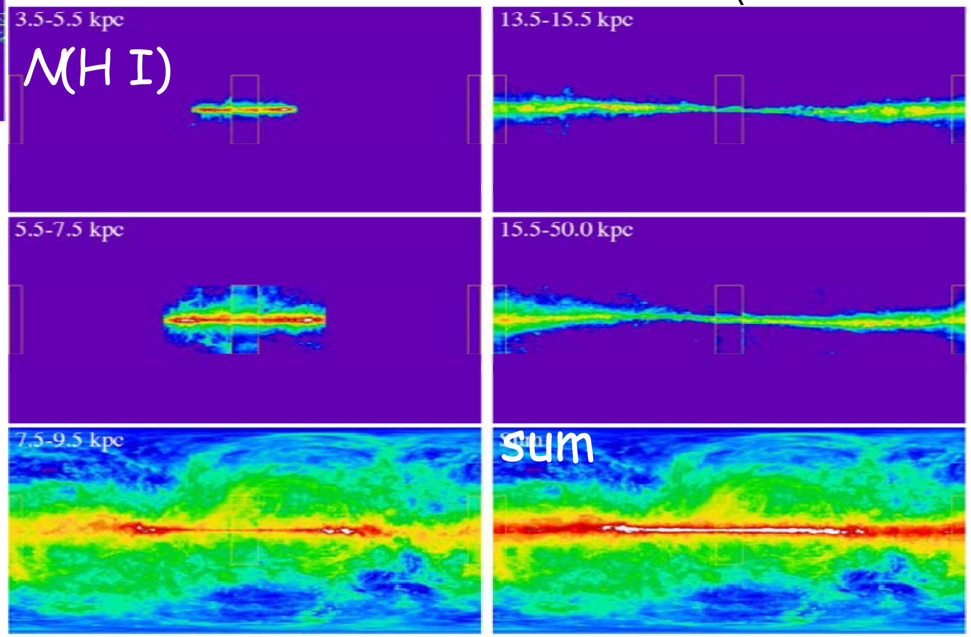
- Spin temperature is unknown, usually used the same temparature ~125K for HI gas in the whole Galaxy

- Self absorption (cold gas cloud in front of the emitting cloud); the optical depth is very large

Milky Way: Column densities of gas







Examples of the
Galactocentric "rings"

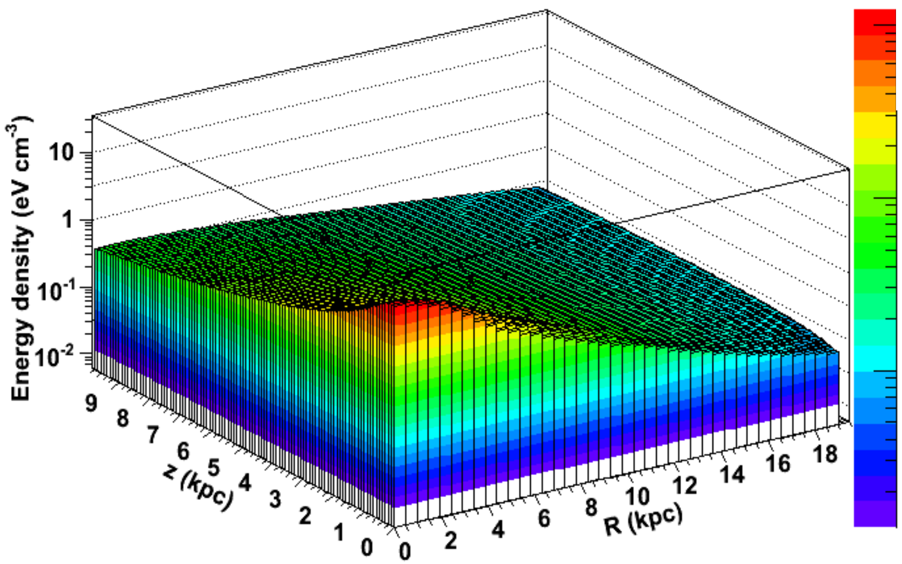
Interstellar radiation field (ISRF)

- CR electrons and positrons lose energy via IC - gamma ray production in ISM (INTEGRAL, GLAST, ACT)
- Gamma rays from SNRs
- Gamma-gamma absorption of TeV photons
- UV Heating of clouds in the Galaxy, etc.
- Extraction of extragalactic background light (EBL)

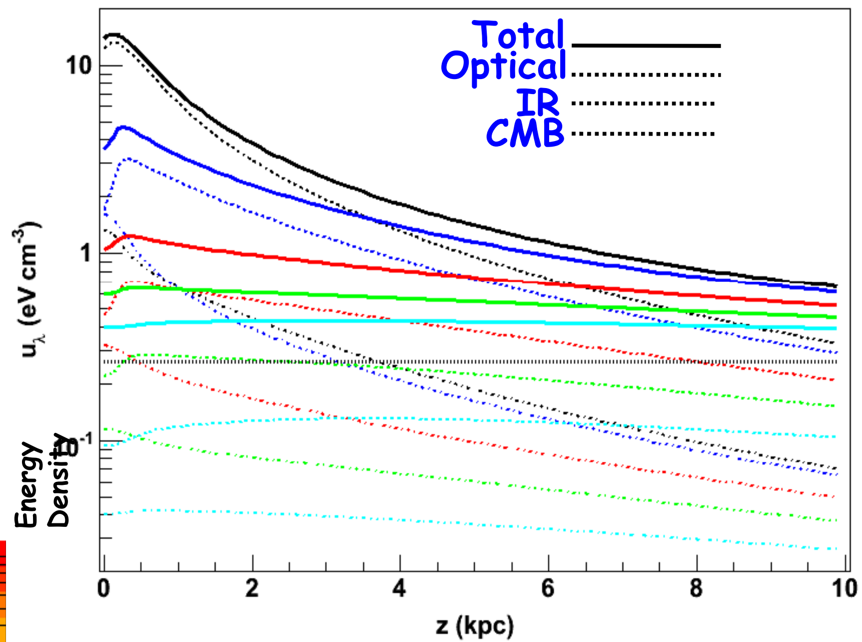
ISRF: Large Scale Distribution

- The z scale height is large, takes 10s of kpc at R = 0 kpc to get to level of CMB
- Mostly due to stellar emission

Optical + IR (no CMB)

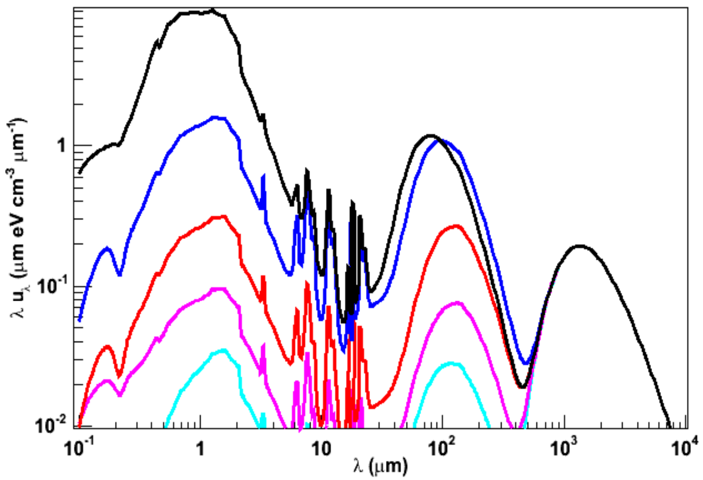


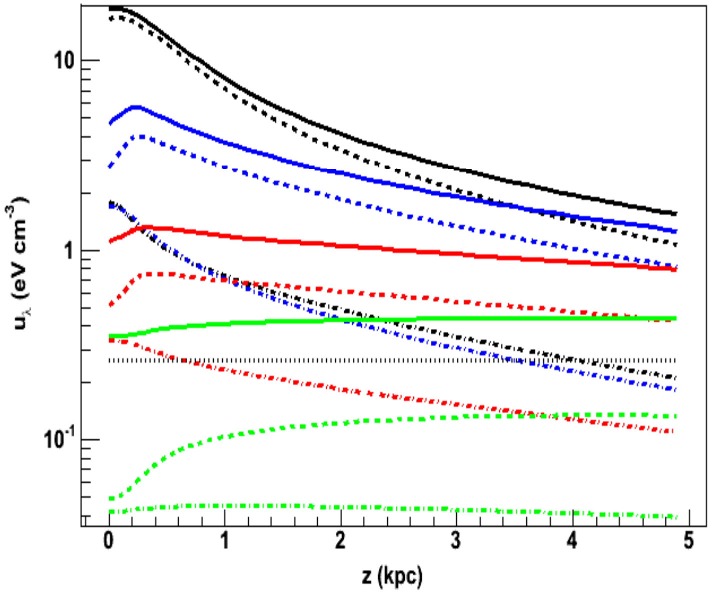
R = 0,4,8,12,16 kpc



New ISRF (Porter & Strong)

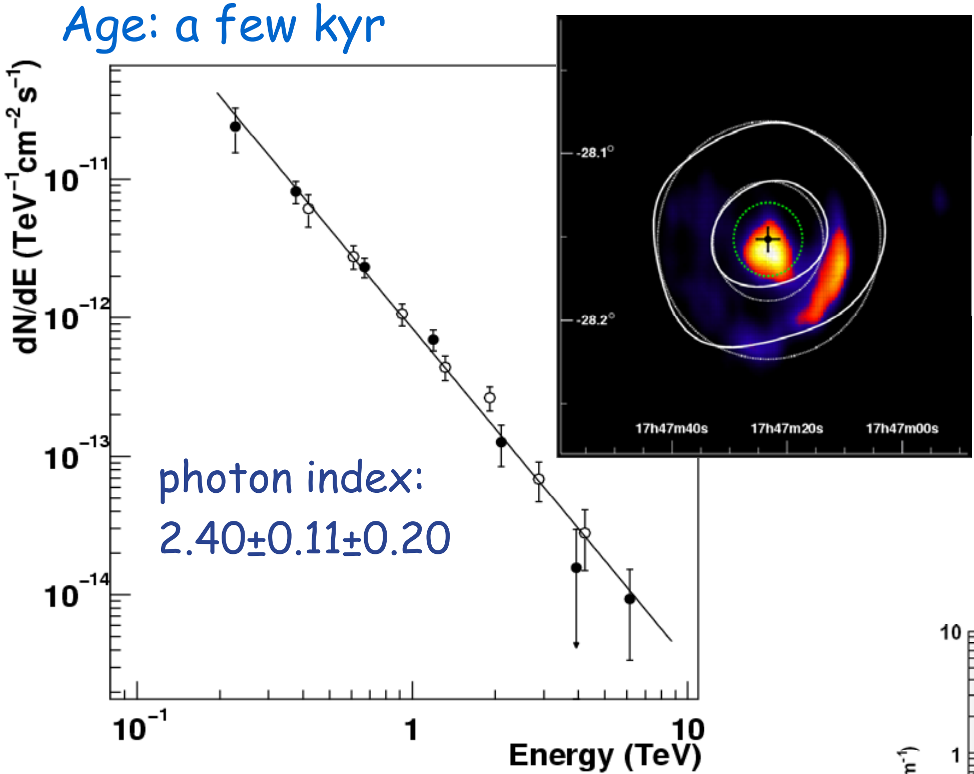
- In-plane energy density
  - Factor ~5 larger than local at 4 kpc
  - Factor ~20 larger around GC
  - Averaged over ΔR ~ 0.5 kpc, dz ~ 50 pc
  - May be larger on sub-scales (cf GC)
- Out-of-plane
  - Even for R~16 kpc ~30% of total
  - Significant energy density even for high-z



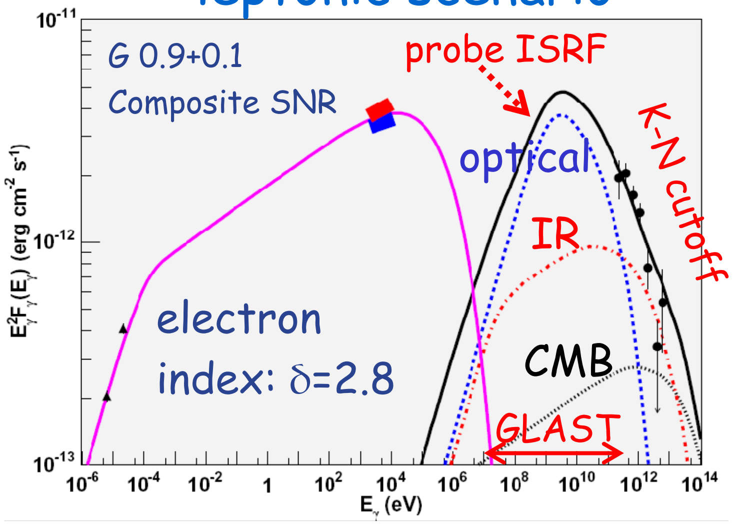


HESS Observations of Composite SNR G0.9+0.1

SNR at the GC
Age: a few kyr

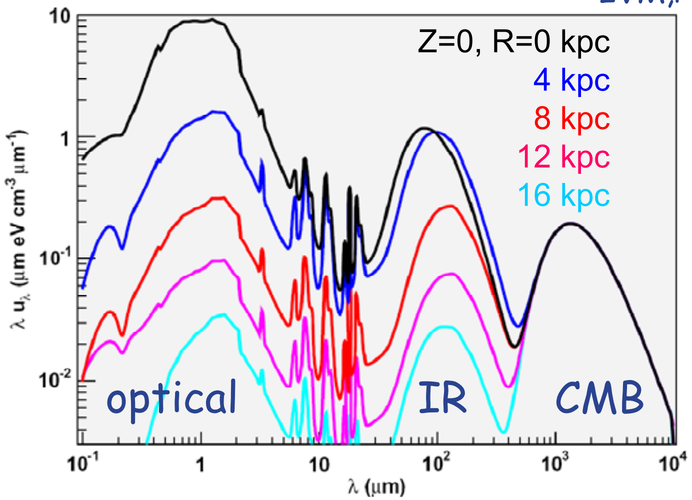


leptonic scenario



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

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



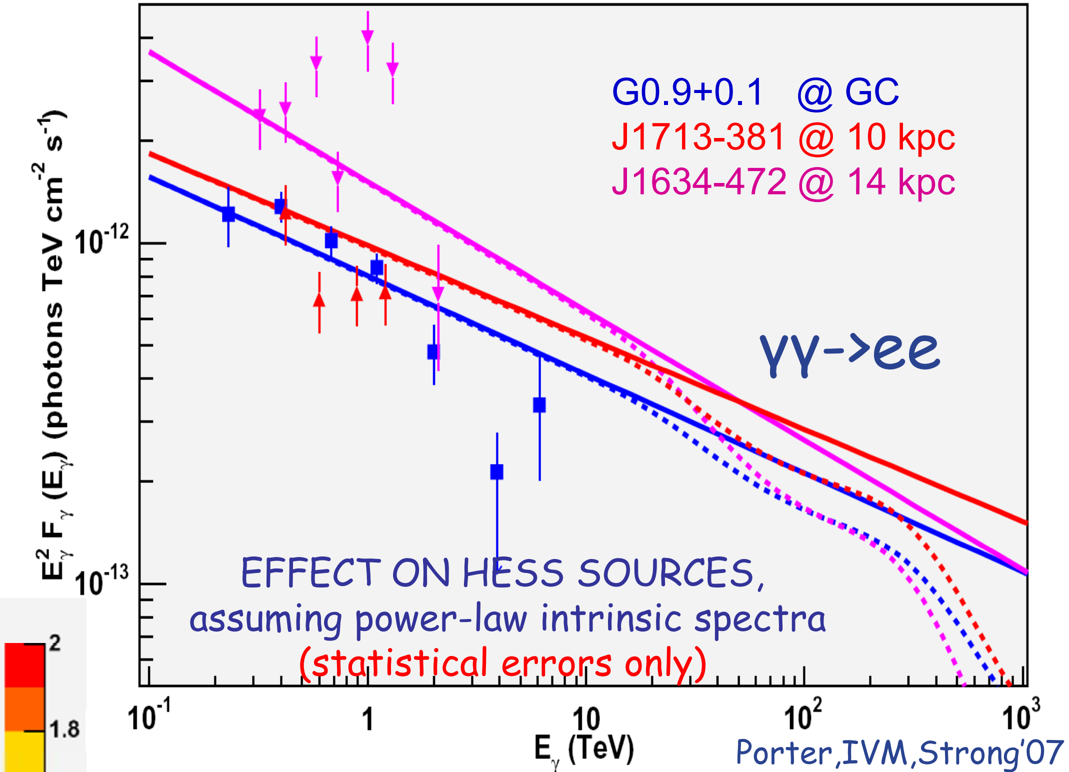
ISRF: gamma-gamma absorption

Threshold of the pair production ($\gamma\gamma$->ee) on thermal (isotropic) photons:

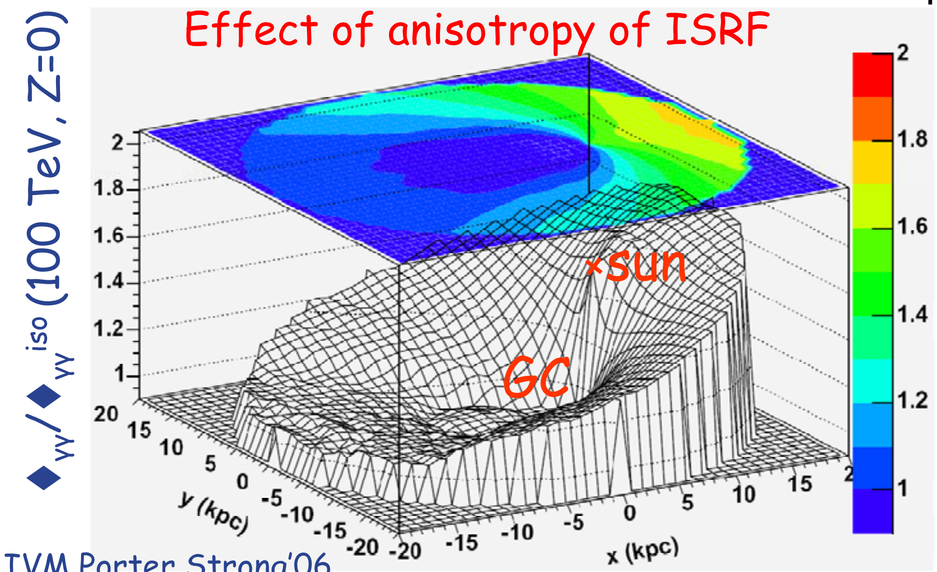
$$E_\gamma \varepsilon \sim m^2c^4$$

ε ~ 1 eV (optical) -> E_γ > 1 TeV

The effect is important above ~30 TeV

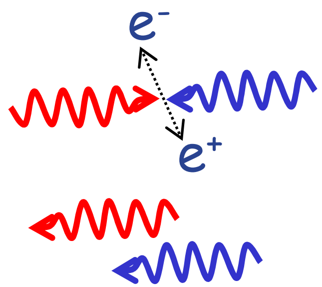


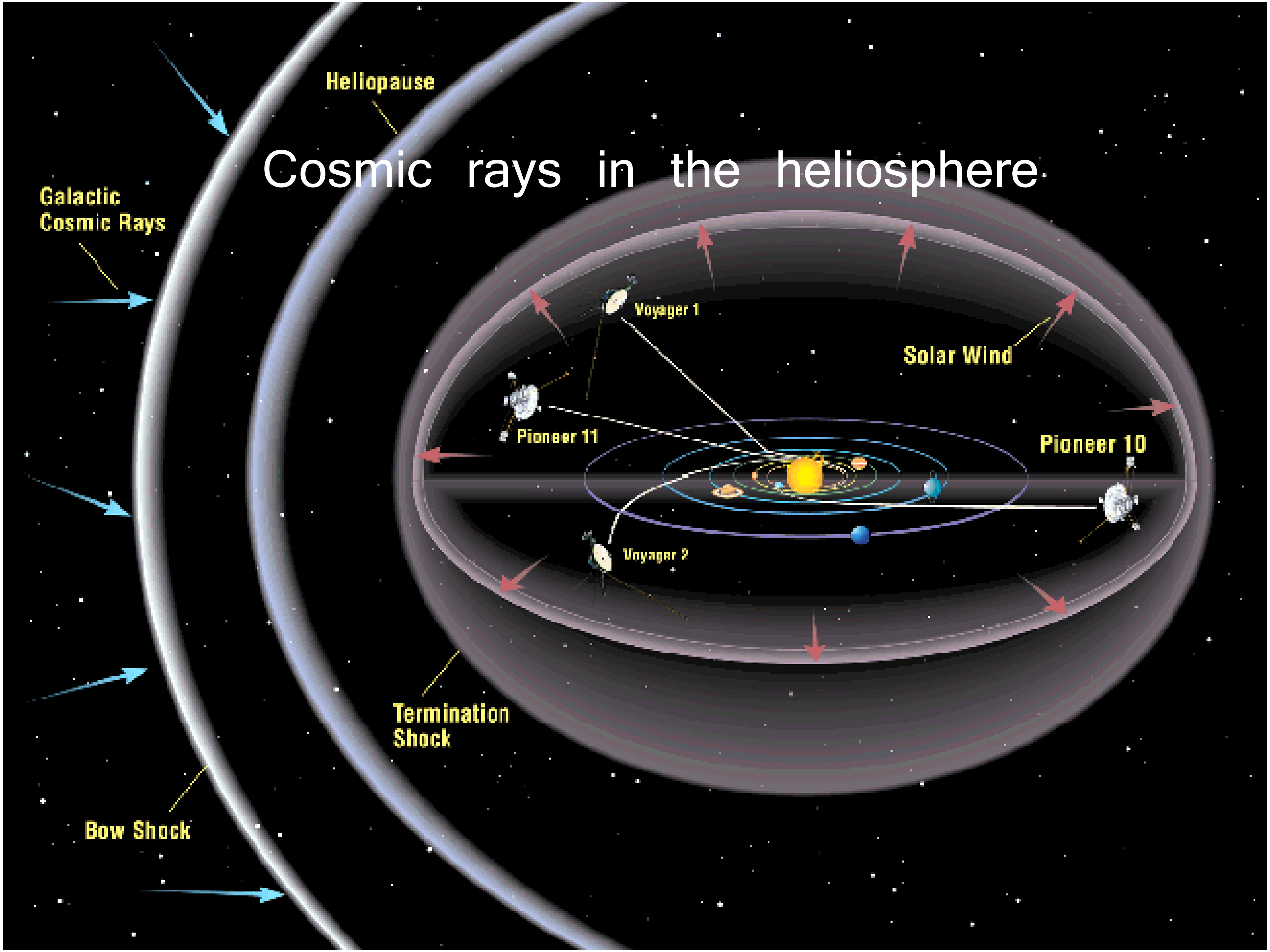
Porter,IVM,Strong'07



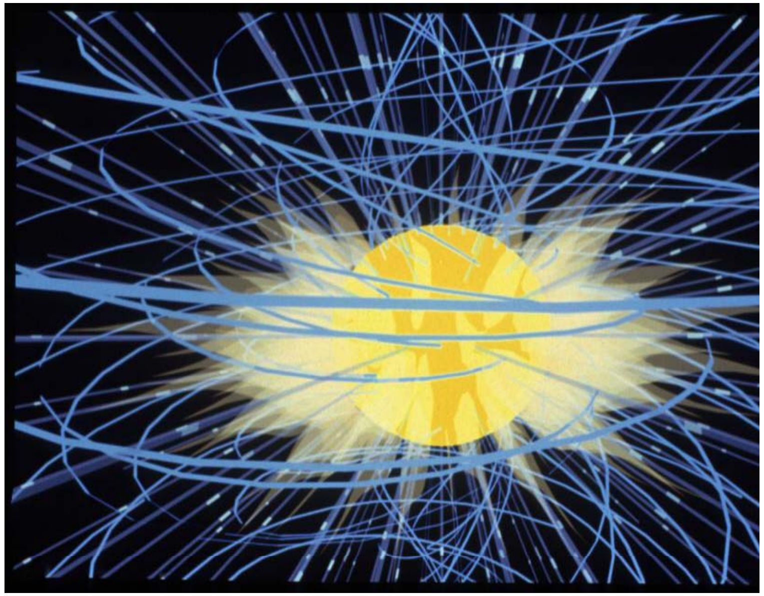
IVM,Porter,Strong'06

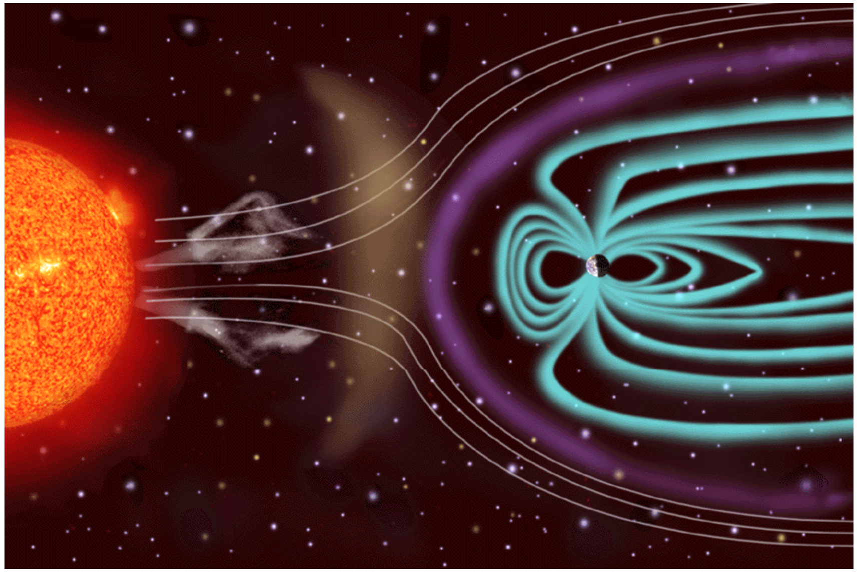
- Head-on
- Following

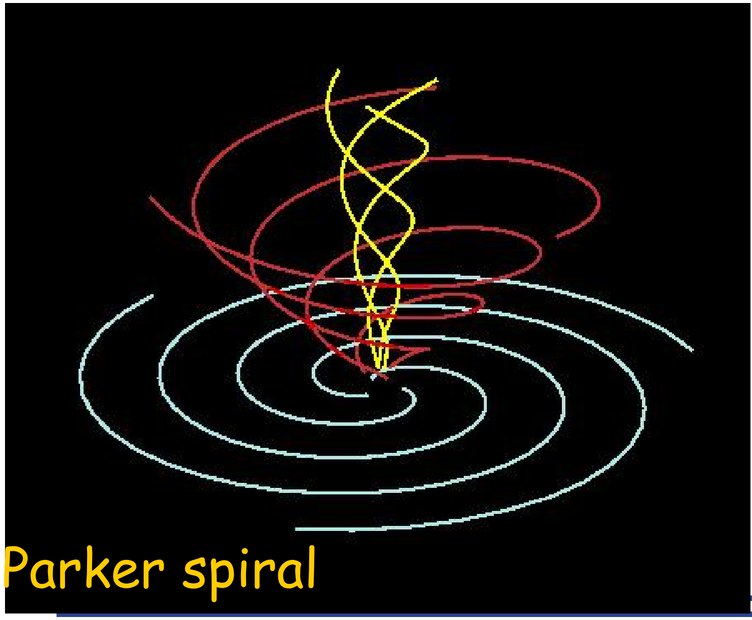


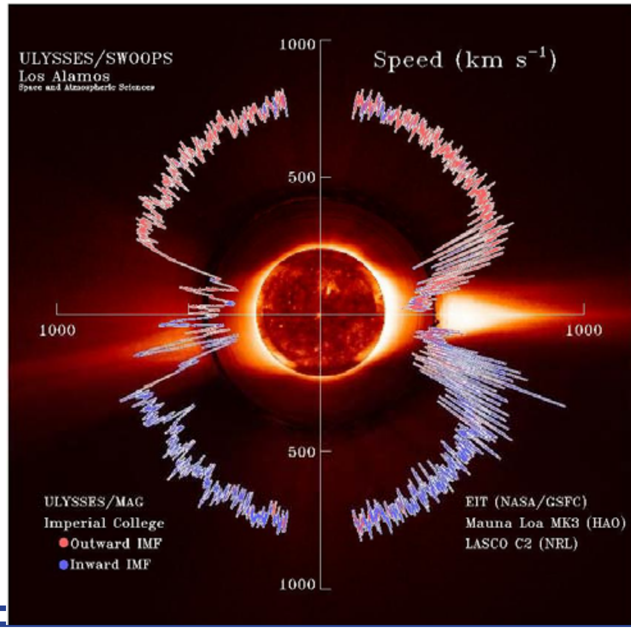

Cosmic rays in the heliosphere
Heliopause
Galactic Cosmic Rays
Voyager 1
Solar Wind
Pioneer 11
Pioneer 10
Voyager 2
Termination Shock
Bow Shock

Interplanetary B-field & solar wind









Transport equation

Modulation models are based on the numerical solution of the CR transport equation (Parker 1965):

$$\frac{\partial f(\boldsymbol{r}, \rho, t)}{\partial t} = -(\boldsymbol{V} + \langle \boldsymbol{v}_D \rangle) \cdot \boldsymbol{\nabla} f + \boldsymbol{\nabla} \cdot (\boldsymbol{K}_S \cdot \boldsymbol{\nabla} f) + \frac{1}{3} (\boldsymbol{\nabla} \cdot \boldsymbol{V}) \frac{\partial f}{\partial \ln \rho}, \quad (5)$$

f – CR distribution function

V - solar wind velocity

$\langle v_D \rangle = \nabla \times K_A \vec{B}/B$

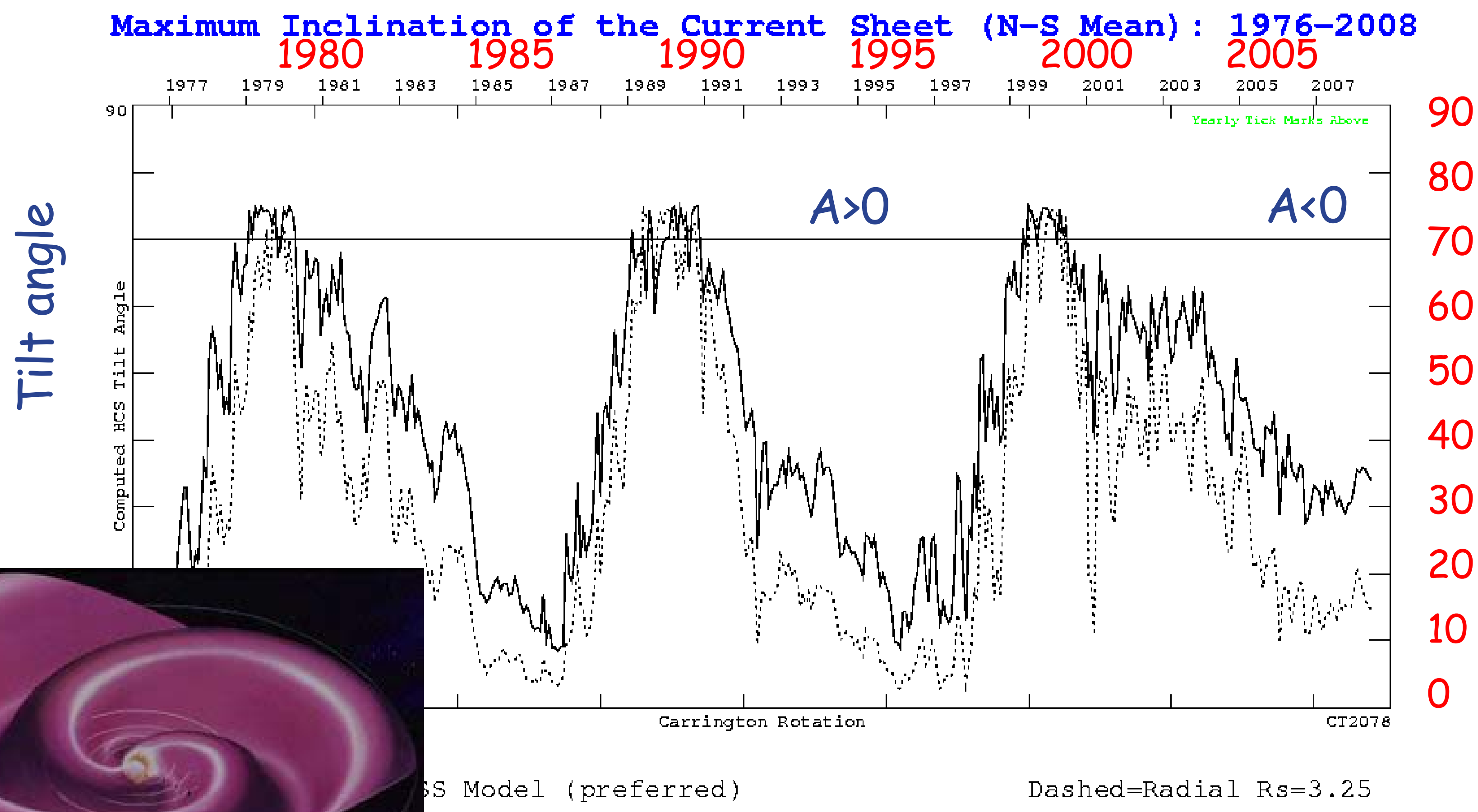
K_A- antisymmetric part of the diffusion tensor

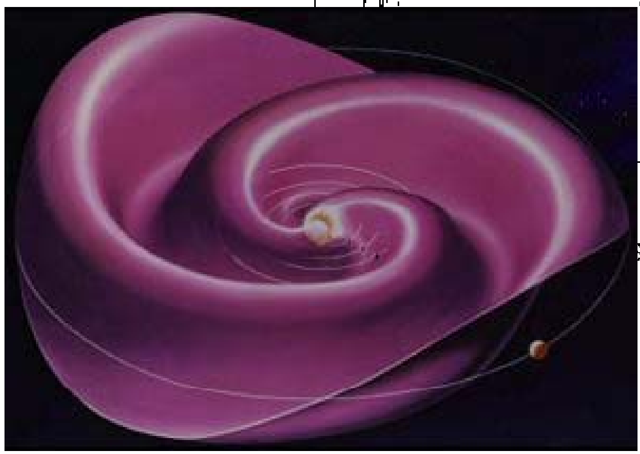
K_S- symmetric part of the diffusion tensor

ρ - rigidity

- Not all factors are known - measurements are done by spacecraft in particular location at different times
- Local interstellar spectrum of CRs is unknown (exception pbars)

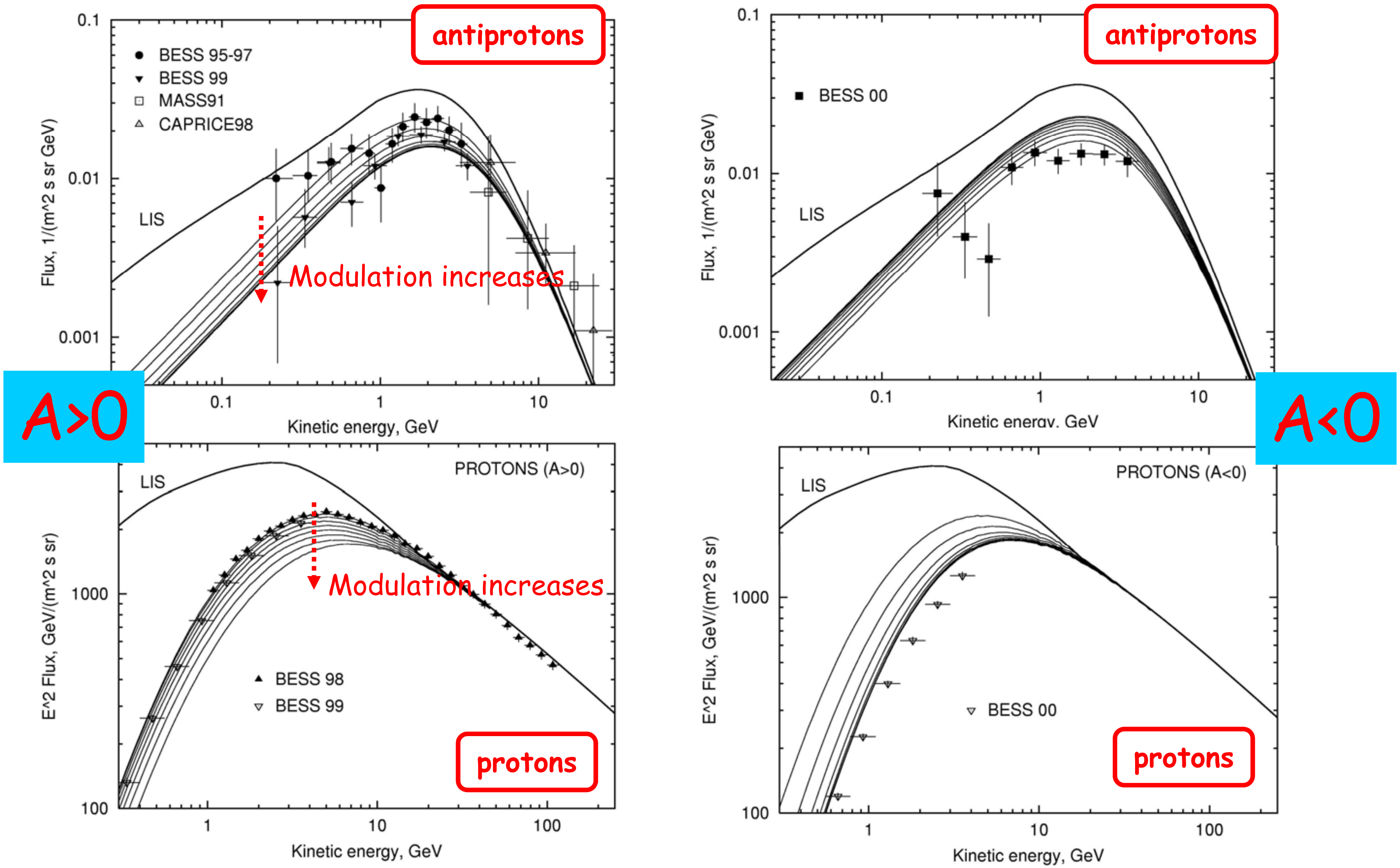
Heliospheric current sheet



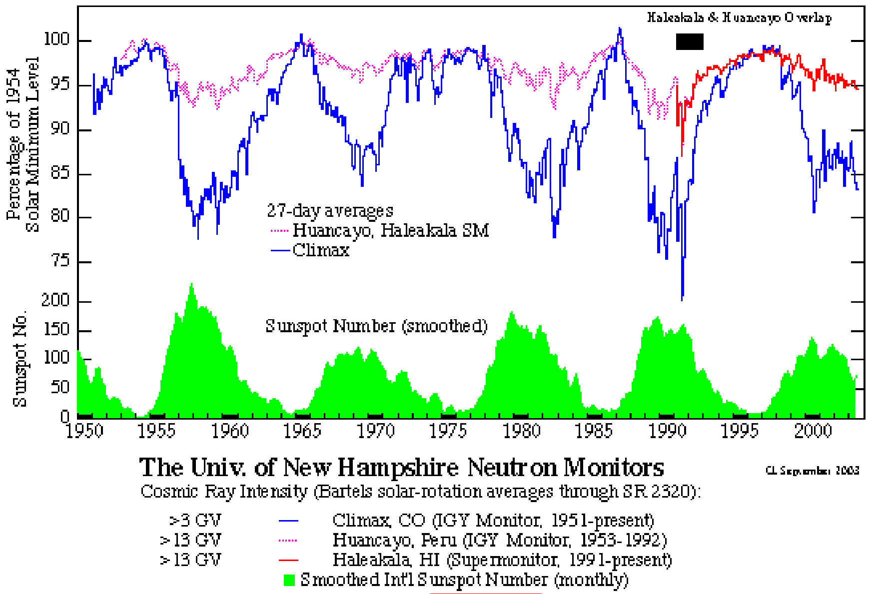


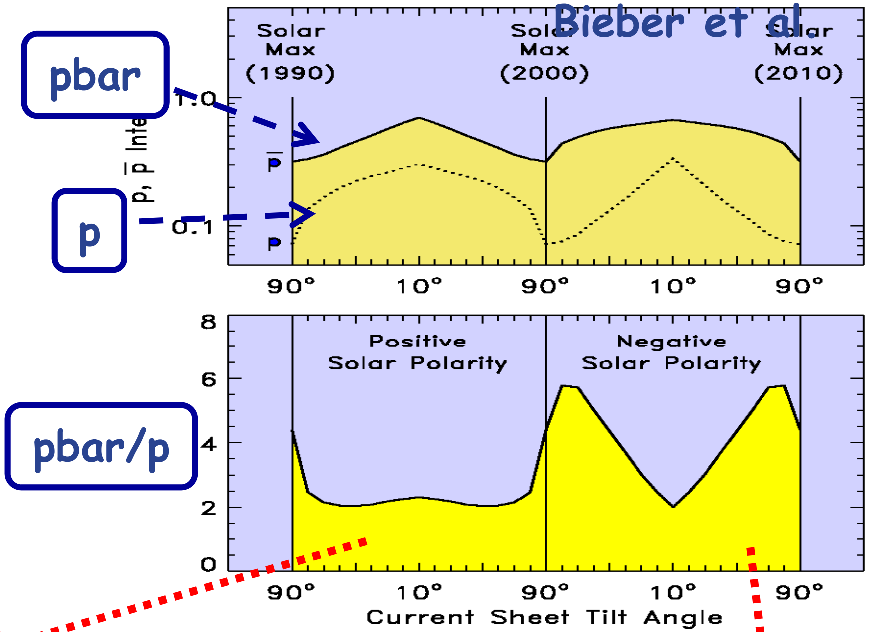
Hoeksema model

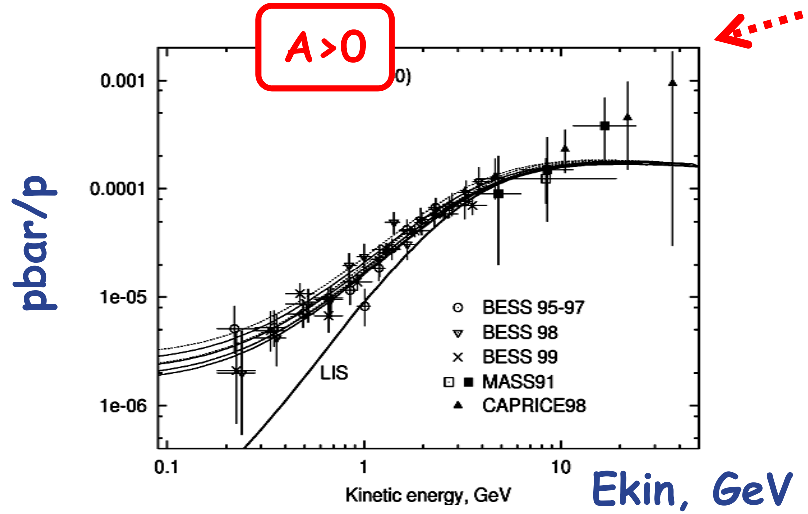
Variations over the solar cycle (pbars, p)

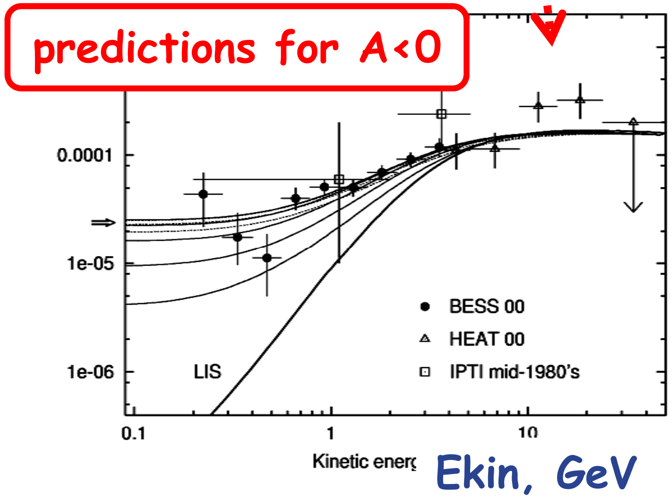


Charge Sign Effect

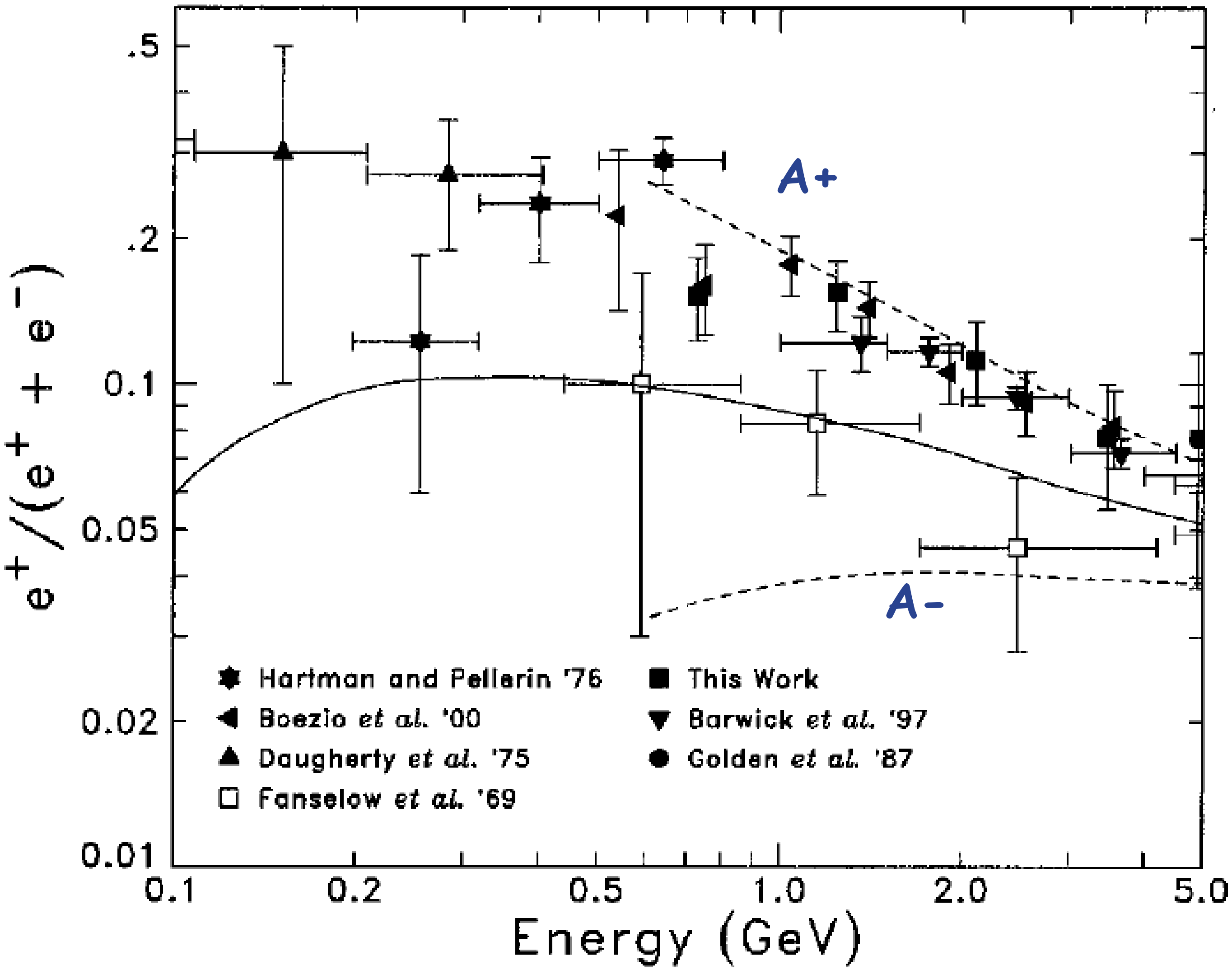








Positron fraction: Charge sign effect



Klem+'00

New foregrounds and new opportunities

A Zoo of Solar System Bodies

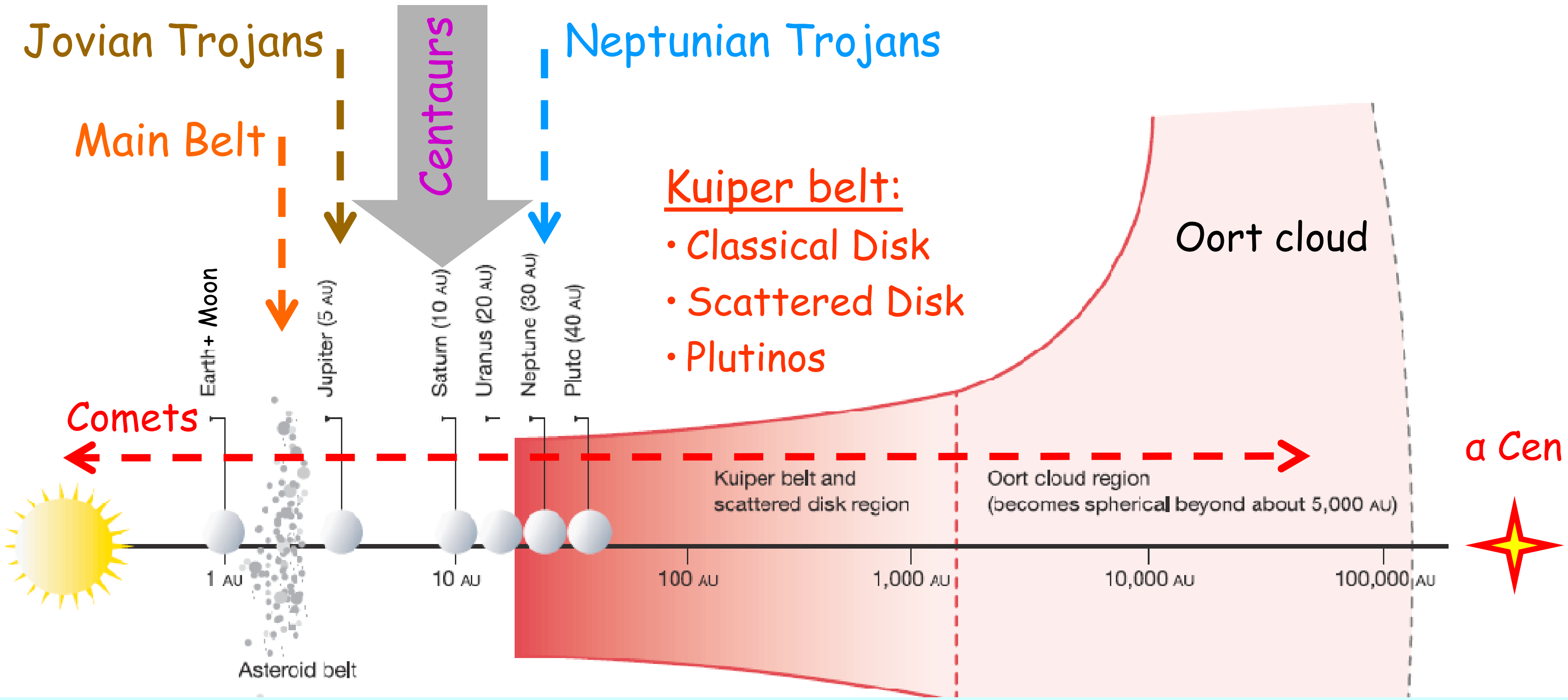
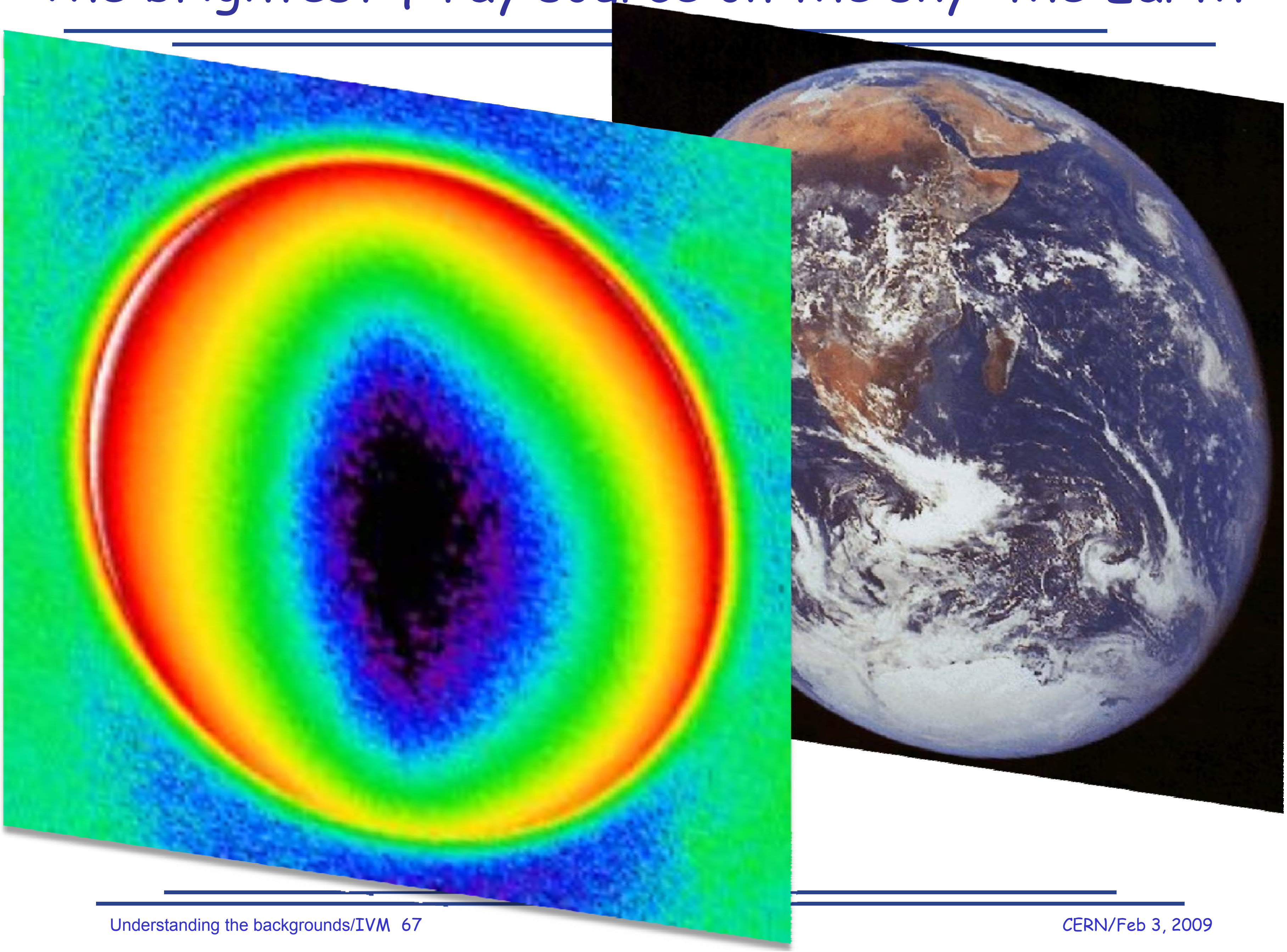


Table 1 **The primary cometary reservoirs of the Solar System**

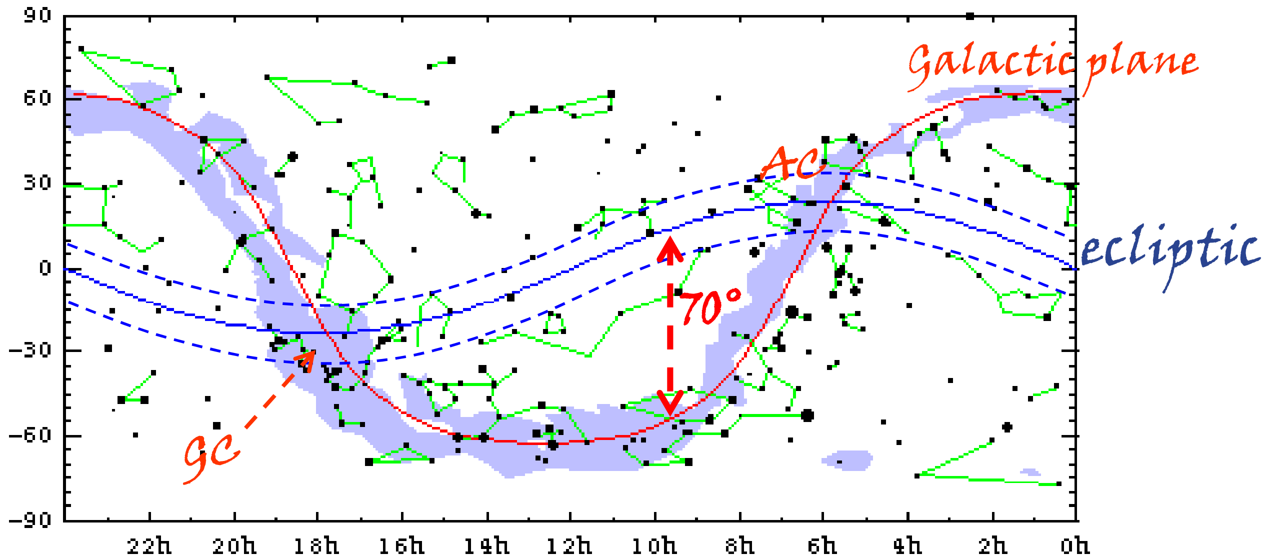
	Kuiper belt	Oort cloud
Shape	Disk-like	Spheroidal
Distance range	30–1,000 AU	1×10^3–1×10^5 AU
Comet population	~5–10 × 10^9	1×10^{11}–5×10^{12}
Estimated mass (including smaller debris)	~0.1 $M_\oplus$	1–50 $M_\oplus$
Ambient surface temperatures	30–60 K	5–6 K
Origin	Largely *in situ*	Ejected material from the Kuiper belt and outer-planets zone
Return mechanism from the reservoir	Dynamical chaos due to planetary perturbations and collisions	Perturbations due to passing stars, galactic tides and molecular clouds

Stern'03

The brightest γ-ray source on the sky: the Earth



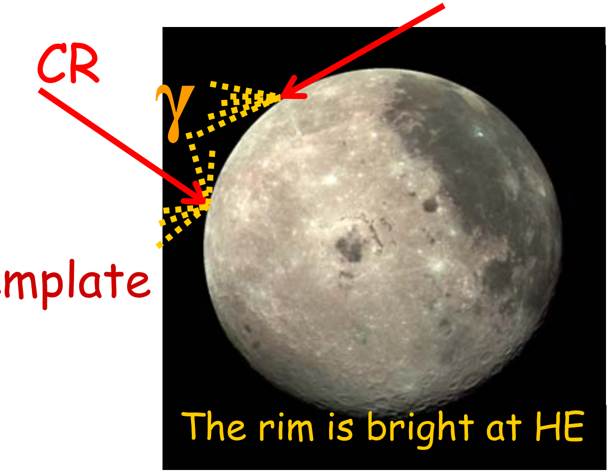
Why do we care?



- The ecliptic crosses the Galactic equator near the Galactic center and anti-center with inclination ~86.5°
- Galactic center is crowded with sources and harbors the enigmatic source of the 511 keV positron annihilation line
- Passes through high Galactic latitudes – extragalactic emission
- The orbits of the Moon and the Sun
- Albedo of the Oort Cloud covers the whole sky

Solar System sources (albedo) - moving sources

- "γ-ray albedo" due to CR interactions with surface material

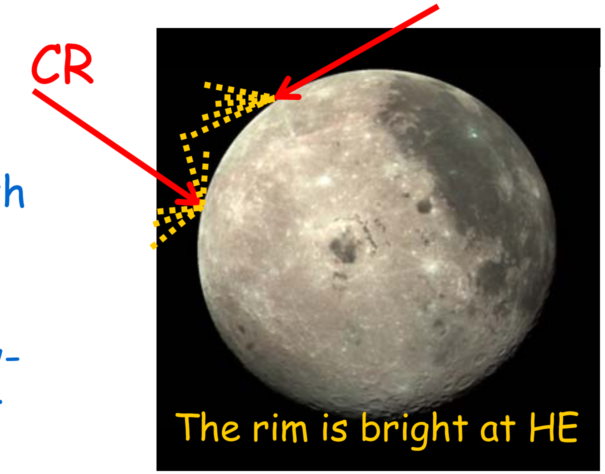


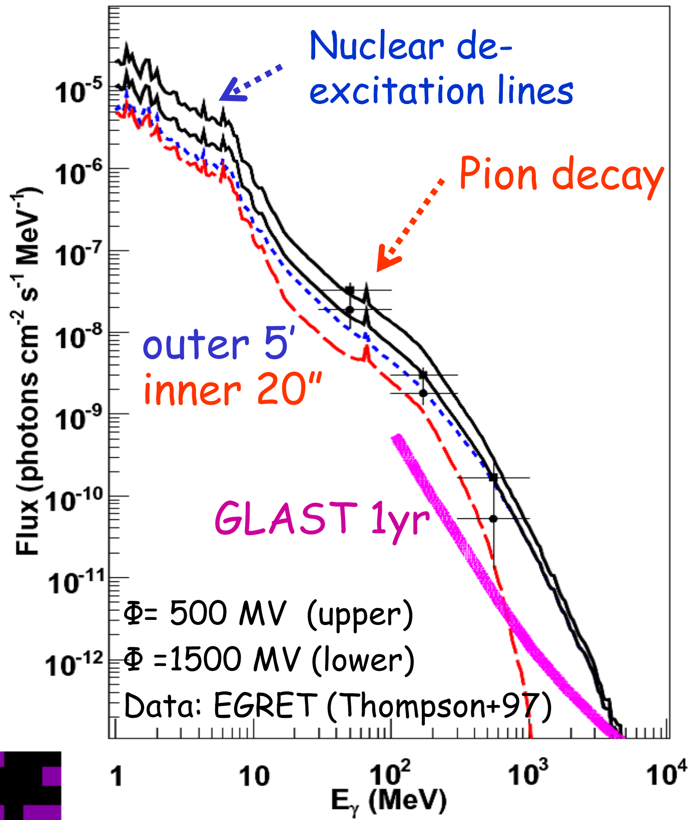
- Guaranteed sources
  - The Moon (brighter than the Sun!) – also a template
  - The Sun (albedo + inverse Compton)
  - The Earth
- Potential Sources (IM+'08, IM & Porter'09)
  - Asteroids (~ few meter size) in different populations:
    - Main Asteroid Belt (MBAs)
    - Jovian and Neptunian Trojans (Trojans)
    - Kuiper Belt Objects (KBOs)
  - Debris (< few meter size, dust, grains)
    - MBAs, Trojans, KBOs
    - Oort Cloud

Dark Face of the Moon: Gamma-ray Albedo Spectrum

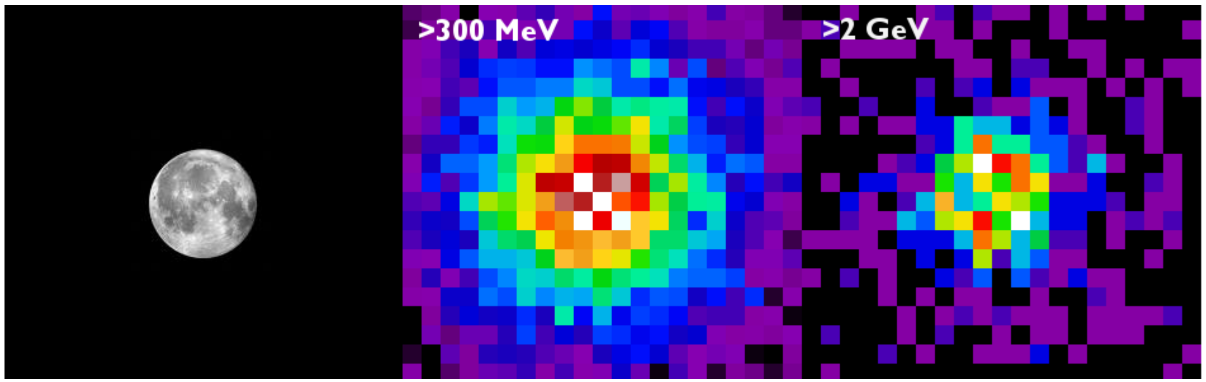
Kinematics of the interaction:

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





Simulation of the GLAST observations



IVM,Porter'07
(earlier work: Morris'84)

Debris albedo

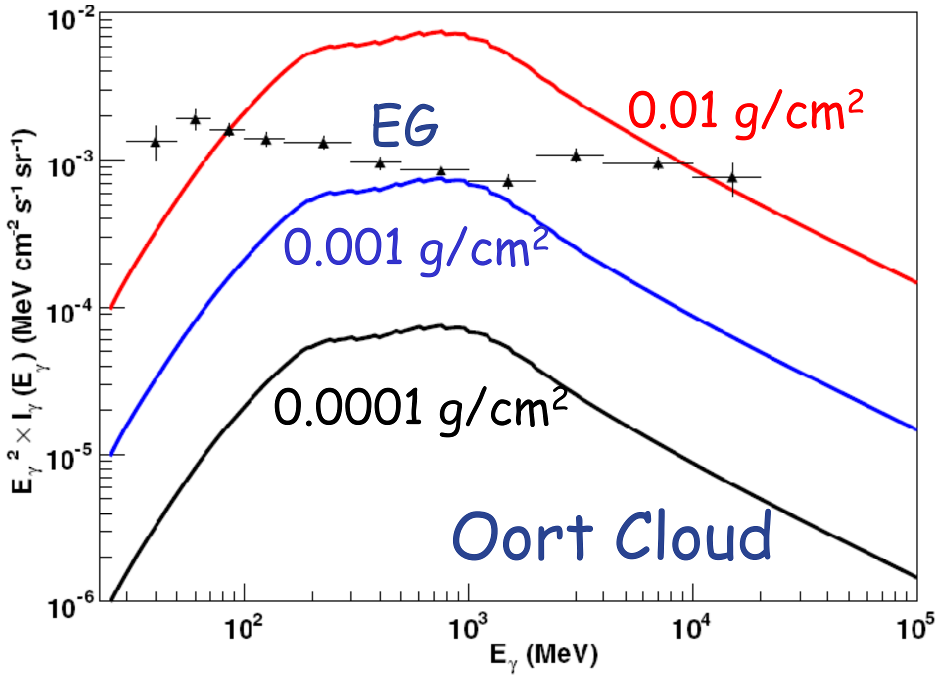


Figure 1. Intensity of the IGRB as derived from the EGRET data (Strong et al. 2004b). Curves are shown for the thin-target case for different column densities (top to bottom): 0.01, 0.001, 0.0001 g cm^{-2}.

- Not much material: One interaction approximation – power-law index is the same as of ambient CRs
- Probe of the interstellar CR spectrum
- Additional foreground

Galactic plane 0.1 g

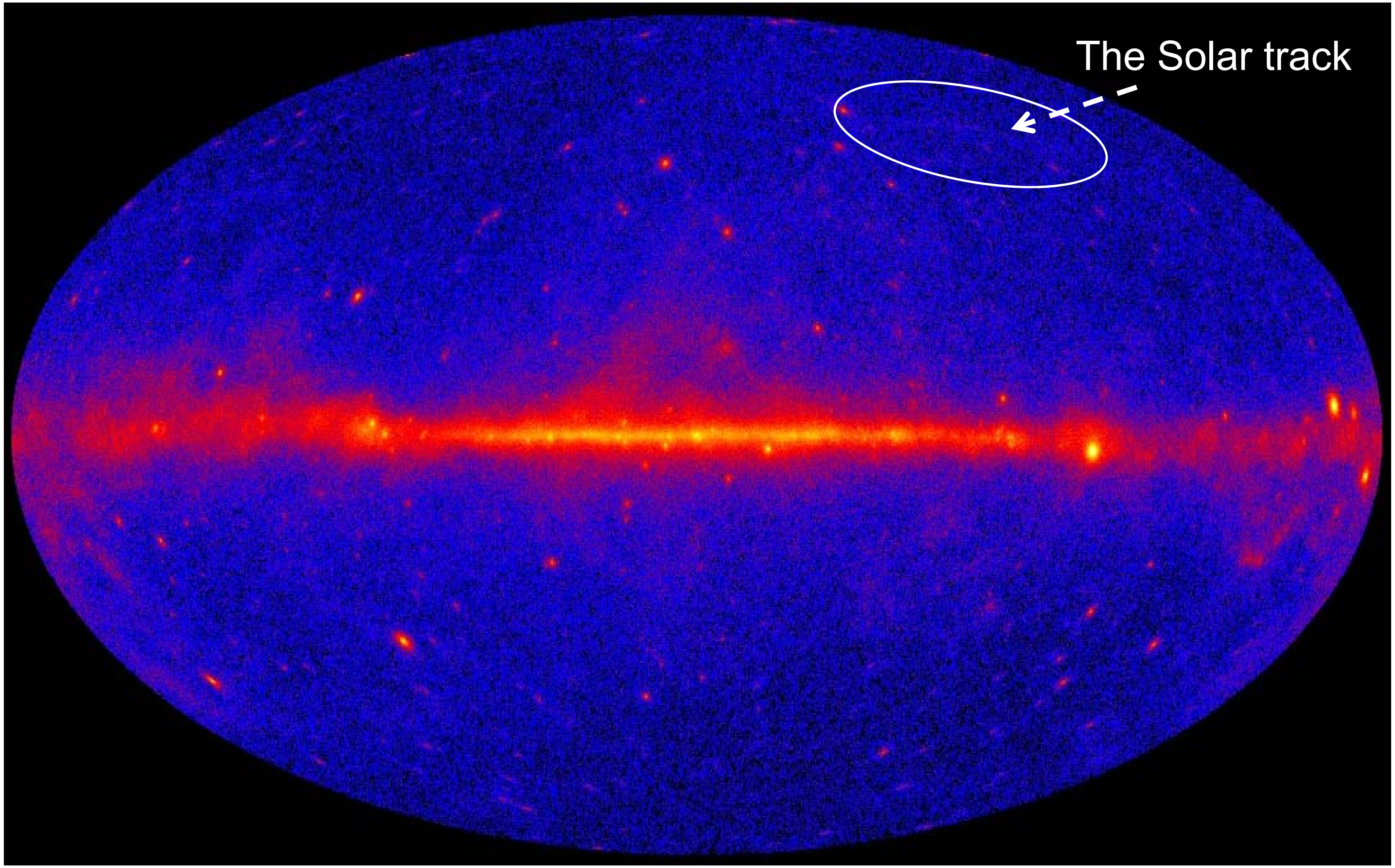
IM & Porter'09

Table 1
Debris Detection Limits in Different Asteroid Populations

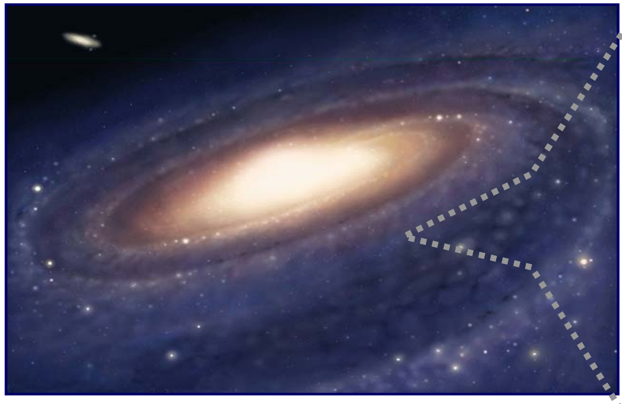
Population	Semimajor Axis, AU	Total Mass, $M_\oplus$	Debris Detection Limit, $M_\oplus$
MBAs[a]	2.1–3.3	$\sim 6 \times 10^{-4}$	$\sim 4 \times 10^{-7}$
Jovian Trojans	5.2	$\sim 1 \times 10^{-4}$	$\sim (1.8\text{–}3.8) \times 10^{-6}$
Neptunian Trojans	30	$\sim 1 \times 10^{-3}$	$\sim 9 \times 10^{-5}$
KBOs[b]	30–50	~ 0.1	$\sim 1.3 \times 10^{-2}$
OC[c]	>100	~ 100	~ 50

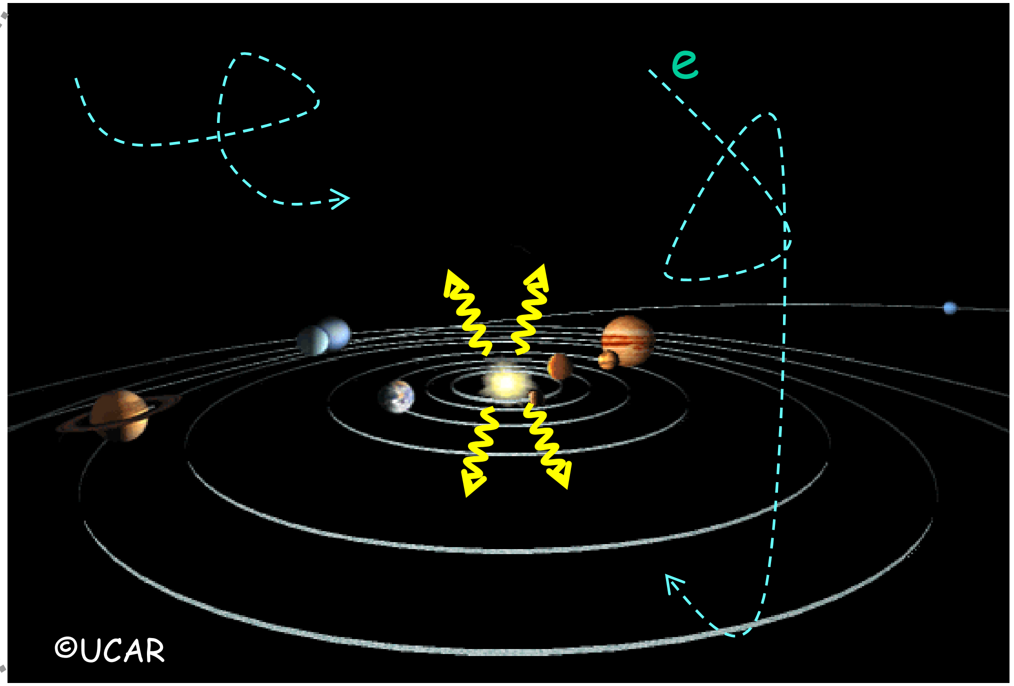
Notes.
[a] Integral over the ecliptic longitude assuming average $d = 2$ AU.
[b] Using $x = 10^{-4}$ g cm^{-2}, $d = 40$ AU.
[c] Using $x = 10^{-4}$ g cm^{-2}, $d = 10^3$ AU.

Fermi/LAT: First 3 months rate skymap

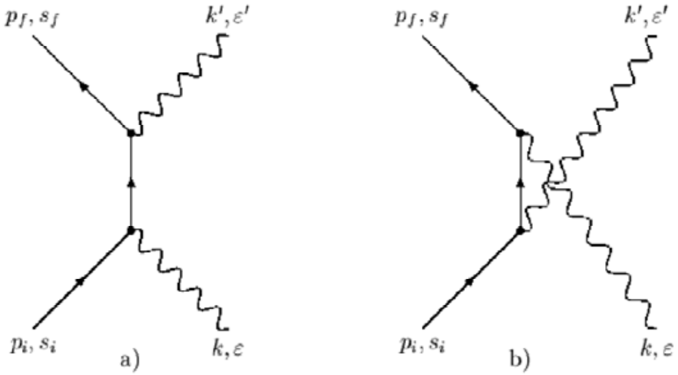


Inverse Compton scattering





QED



The heliosphere is filled with Galactic CR electrons and solar photons

- electrons are isotropic
- photons have a radial angular distribution

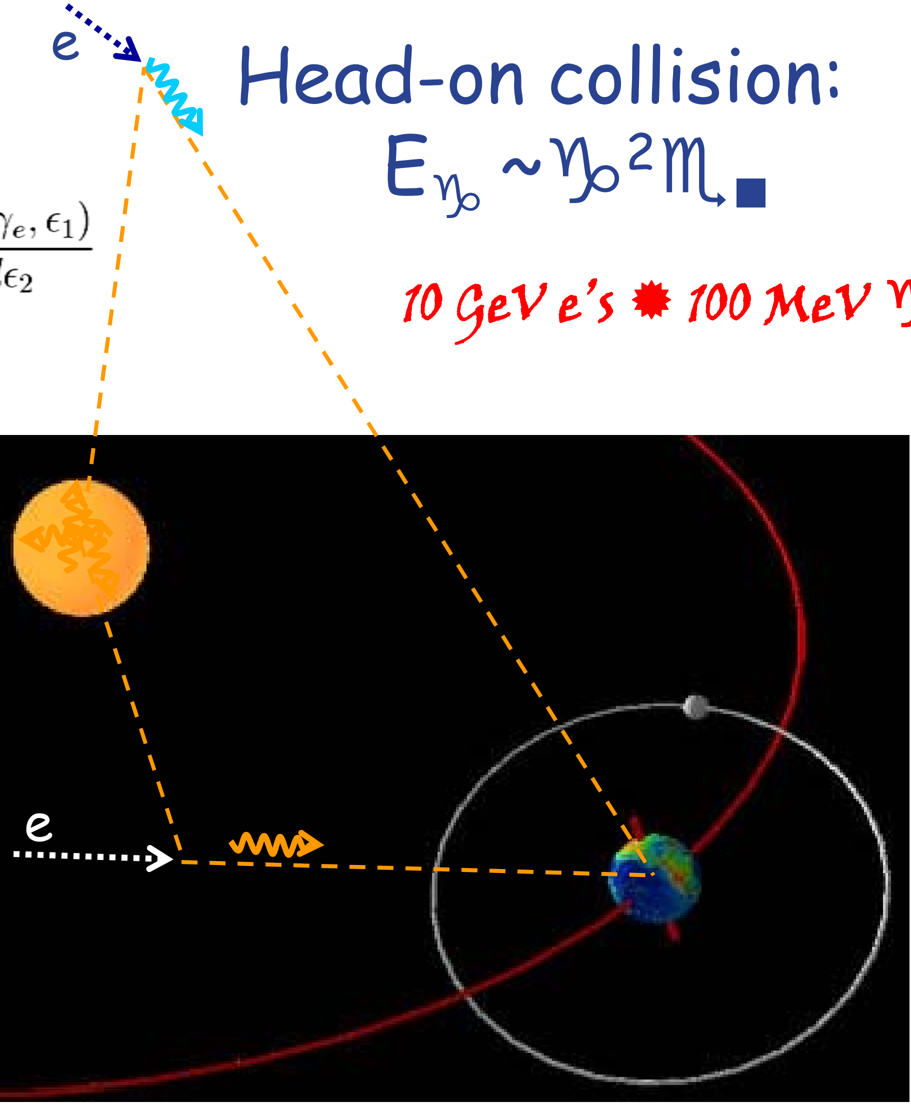
Anisotropic effect on solar photons

$$\frac{dF_\gamma}{d\epsilon_2} = \frac{1}{4}\int_L dx\,\frac{R_\odot^2}{r^2} \int d\gamma_e\,\frac{dJ_e(r,\gamma_e)}{d\gamma_e} \times \int d\epsilon_1 \frac{dn_{bb}(\epsilon_1,T_\odot)}{d\epsilon_1}\,\frac{dR(\gamma_e,\epsilon_1)}{d\epsilon_2}$$

Head-on collision:
$E_\gamma \sim \gamma^2 m_e$

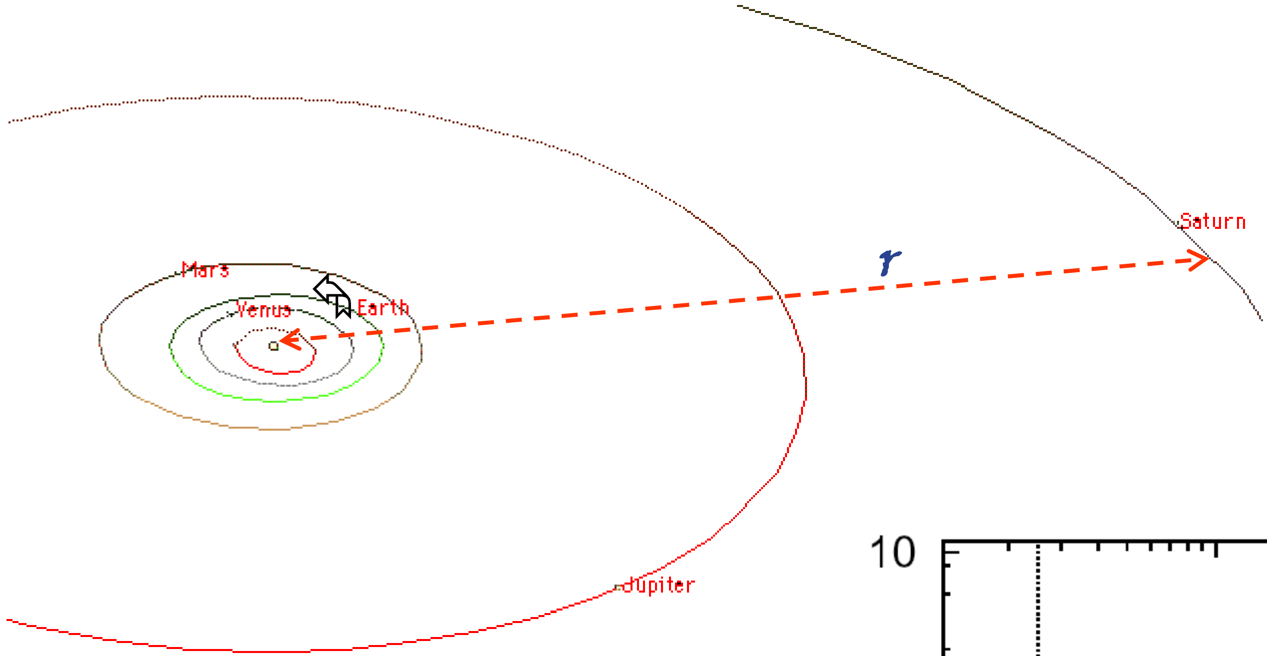
10 GeV e's ✸ 100 MeV γ's

Target photons:
$\rho = 0.25 n_{bb} (R_\odot/r)^2$
$T_\odot = 6000$ K

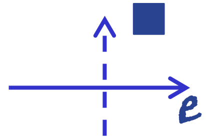


Following collision:
$E_\gamma \sim (1/\gamma)\gamma m_e$
$\sim m_e$

IC in the heliosphere



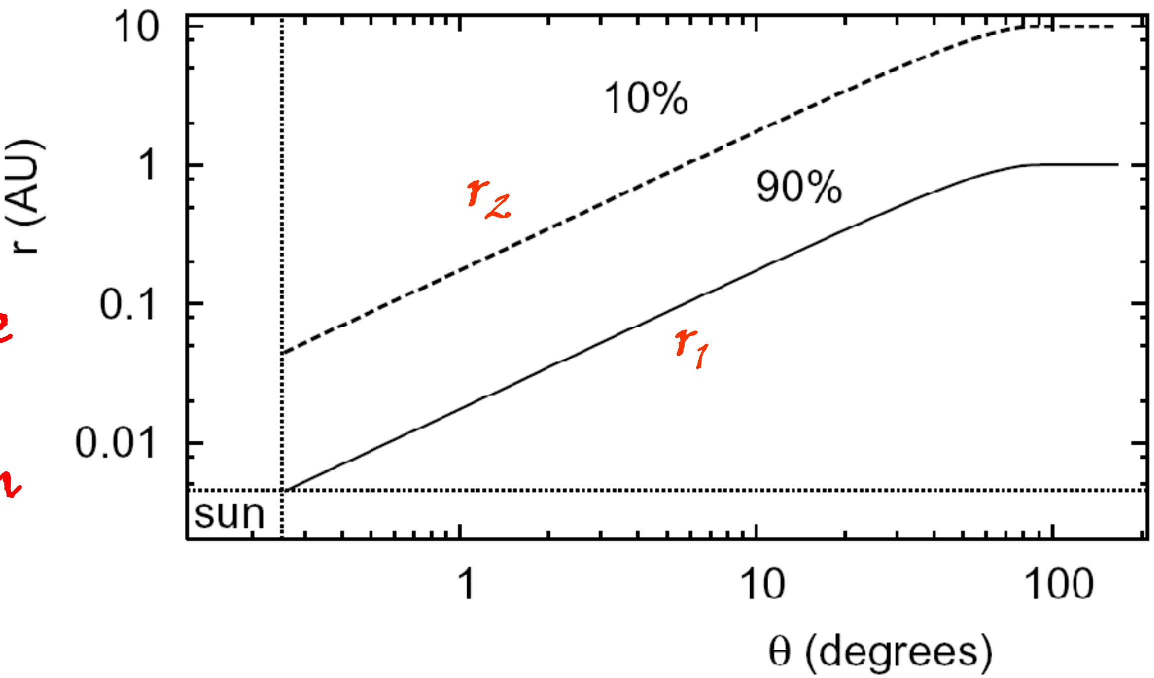
$Flux_{IC} \sim 1/r$



$r_1\,(AU) = \sin\theta, \quad \theta < 90°$

$r_1\,(AU) = 1, \quad \theta > 90°$

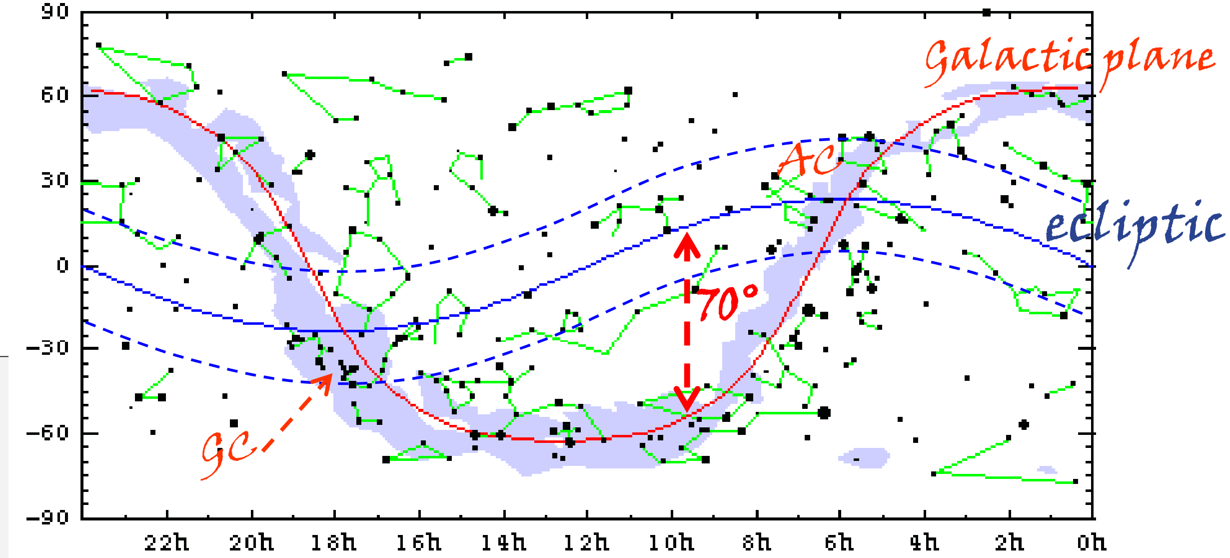
$r_2 = 10 r_1$

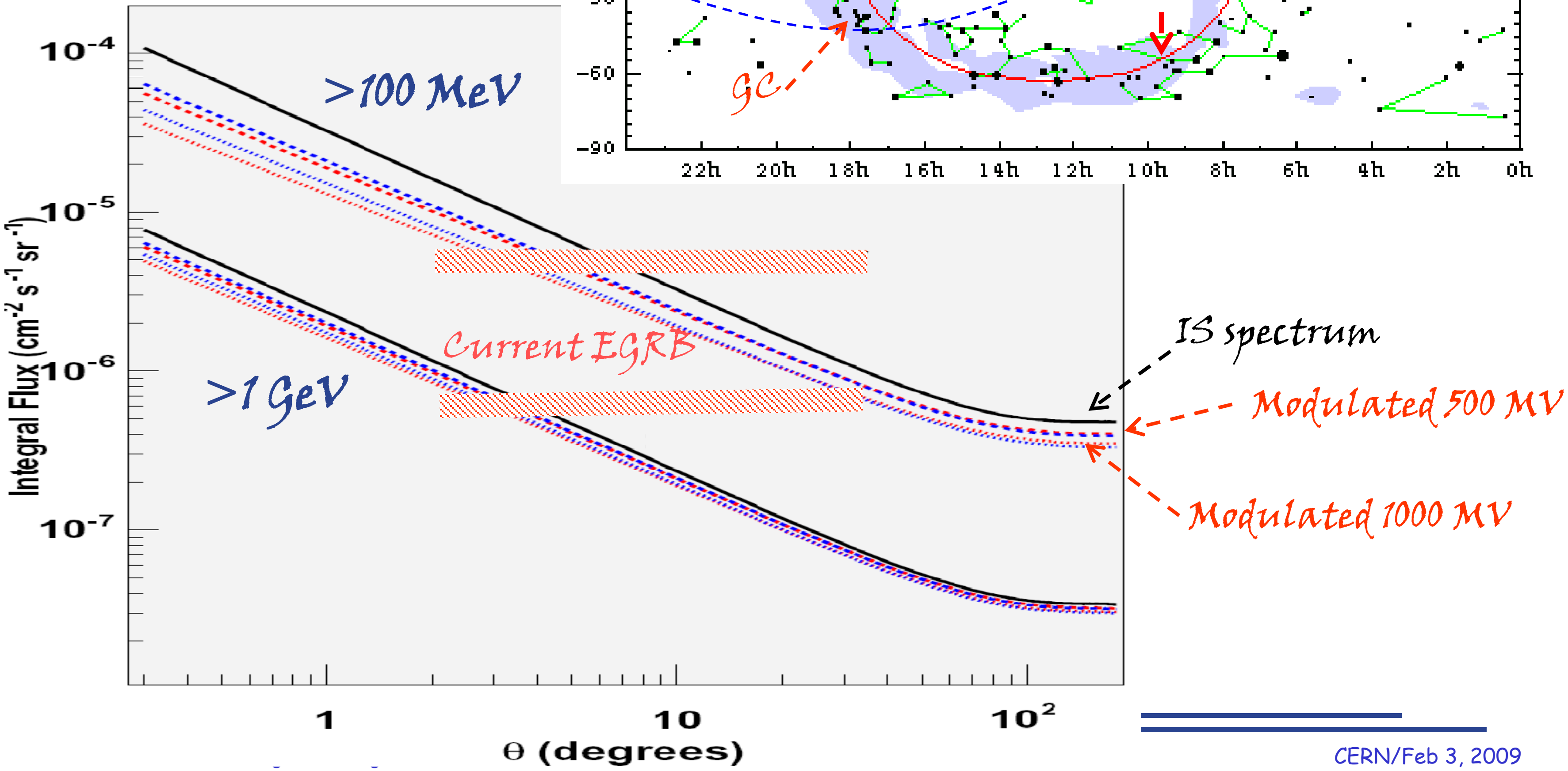


Looking in different directions one can probe the e-spectrum at different distances from the sun!

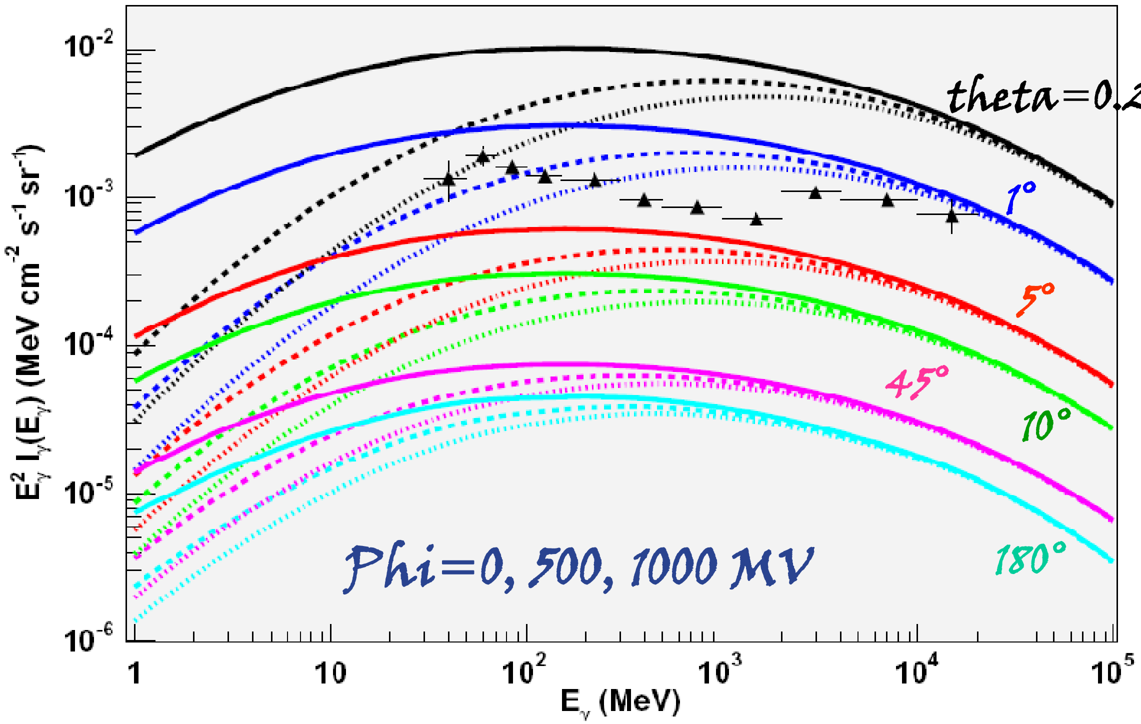
The ecliptic

Averaged over one year, the ecliptic will be seen as a bright stripe on the sky, but the emission comes from all directions





Spectrum



IC spectrum <1 GeV shows strong dependence on the modulation level

> variations of gamma-ray flux over the solar cycle

IC integral flux

F(>100 MeV, <2.5°)~2x10^{-7} cm^{-2} s^{-1}

EGRET upper limit =2x10^{-7} cm^{-2} s^{-1}

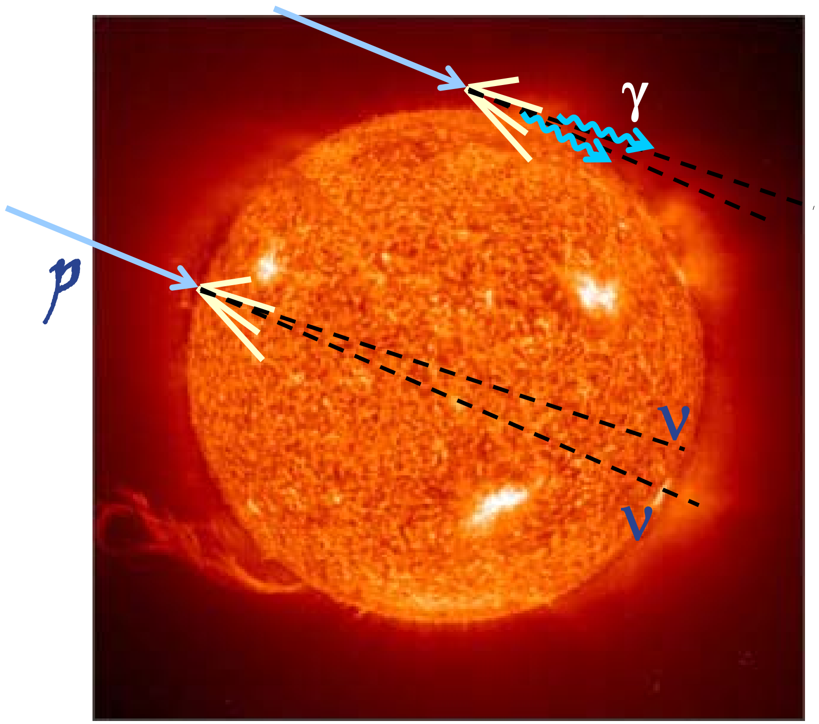
TABLE 1. ALL-SKY AVERAGE INTEGRAL FLUX

E	$\Phi_0 = 0$	500 MV	1000 MV
>10 MeV	5.6	3.4	2.4
>100 MeV	0.69	0.56	0.47
>1 GeV	0.05	0.04	0.04

NOTE. — Flux units 10^{-6} cm^{-2} s^{-1} sr^{-1}.

Gammas & neutrinos from the quiet sun

Missed by the EGRET team!



- Solar "albedo" due to the interactions of CR particles with solar atmosphere: CRs produce cascades in the solar atmosphere
- Gamma rays are be observed by *Fermi*
- Neutrinos propagate through the sun and also can be observed (IceCube)

Can be used to probe the solar atmosphere and the matter distribution in the solar core

IVM+'91, Seckel+'91

Found in EGRET data !

Thompson+ 1997:
Upper limit 2x10^{-7} cm^{-2} s^{-1}

Reanalysis by Orlando+'07:

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

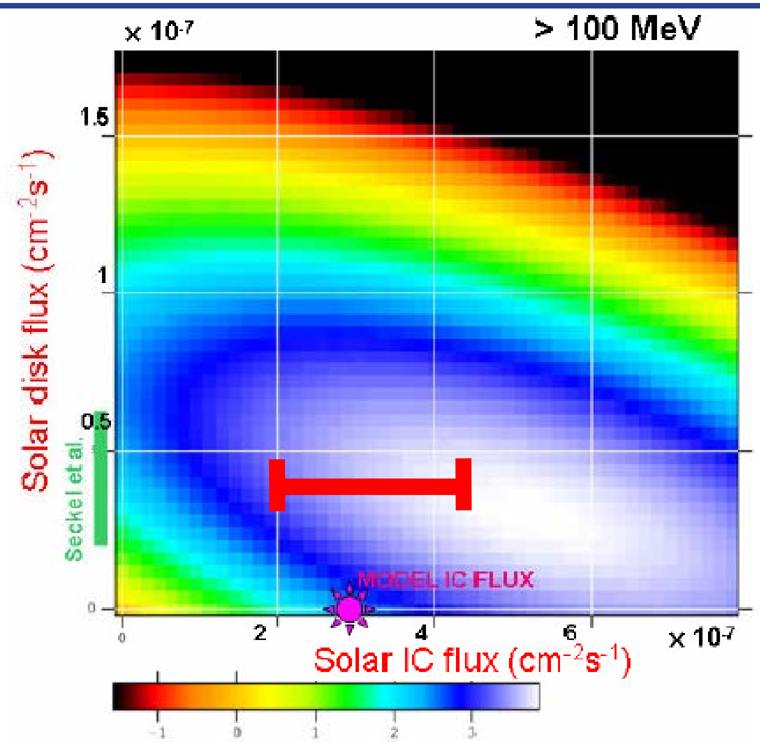


FIGURE 1. Log Likelihood above 100 MeV as function of the solar disk flux and extended solar flux, relative to point at (0,0). The level of our predicted IC model flux and the predicted disk flux [7] are shown.

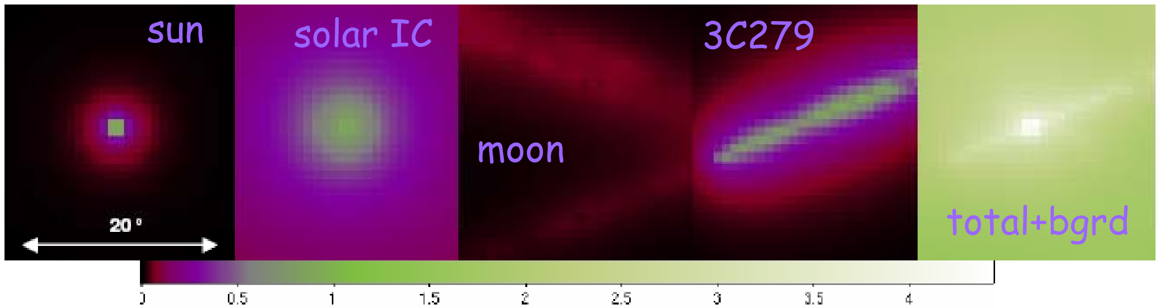
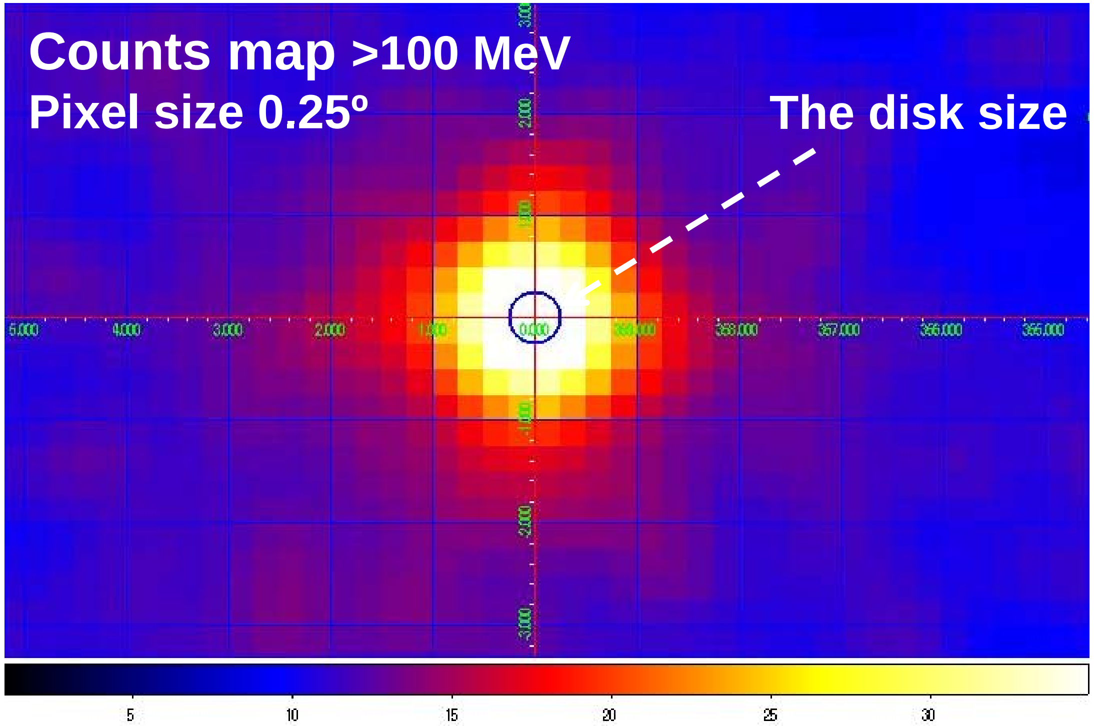


FIGURE 2. Fitted model counts of the main components centered on the Sun. From left to right: Sun disk, Sun IC, moon, 3C 279, and the total predicted counts including uniform background. The colors show the counts/pixel, for 0.5°× 0.5° pixels.

The Sun: 5 months of observations

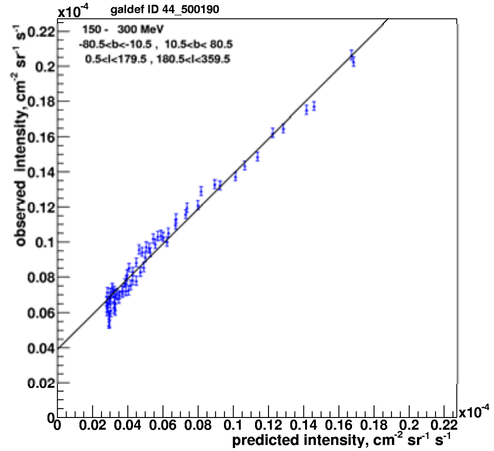


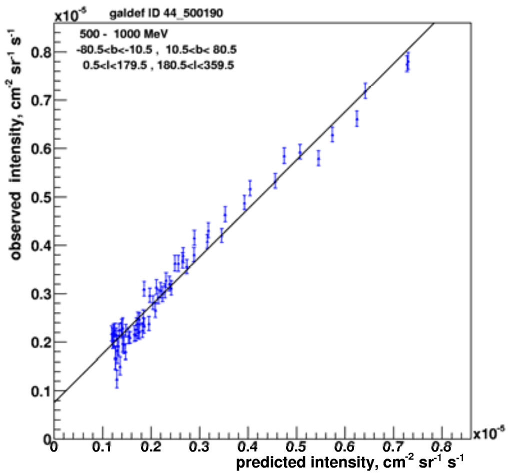
Source Flux (>100 MeV) ~ 4×10^{-7} cm^{-2} s^{-1} (albedo+IC, preliminary)

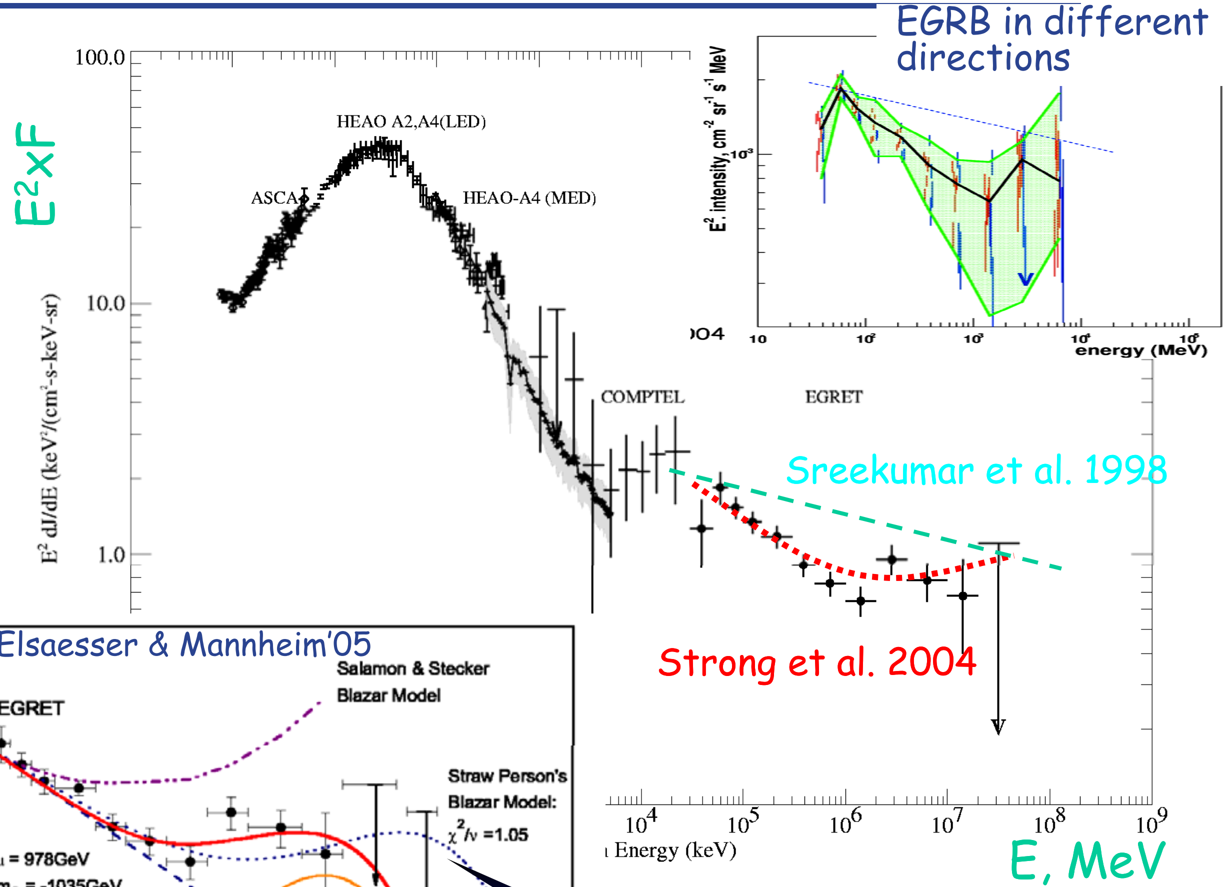
Expected IC Flux (>100 MeV) ~ 4.3×10^{-7} cm^{-2} s^{-1} (near the solar min, IM+'06)
EGRET Flux (>100 MeV) = not found (Thompson+'97)
= $(4.44\pm2.03)\times10^{-7}$ cm^{-2} s^{-1} (albedo+IC, Orlando&Strong'08)

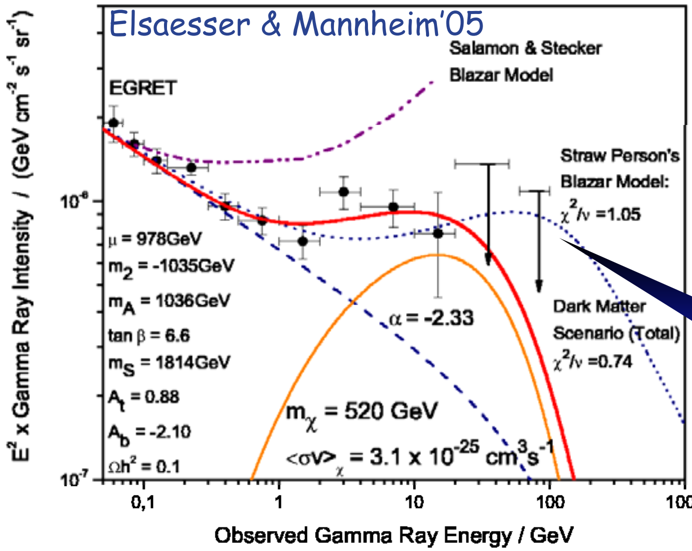
Extragalactic Gamma-Ray Background

Predicted vs. observed



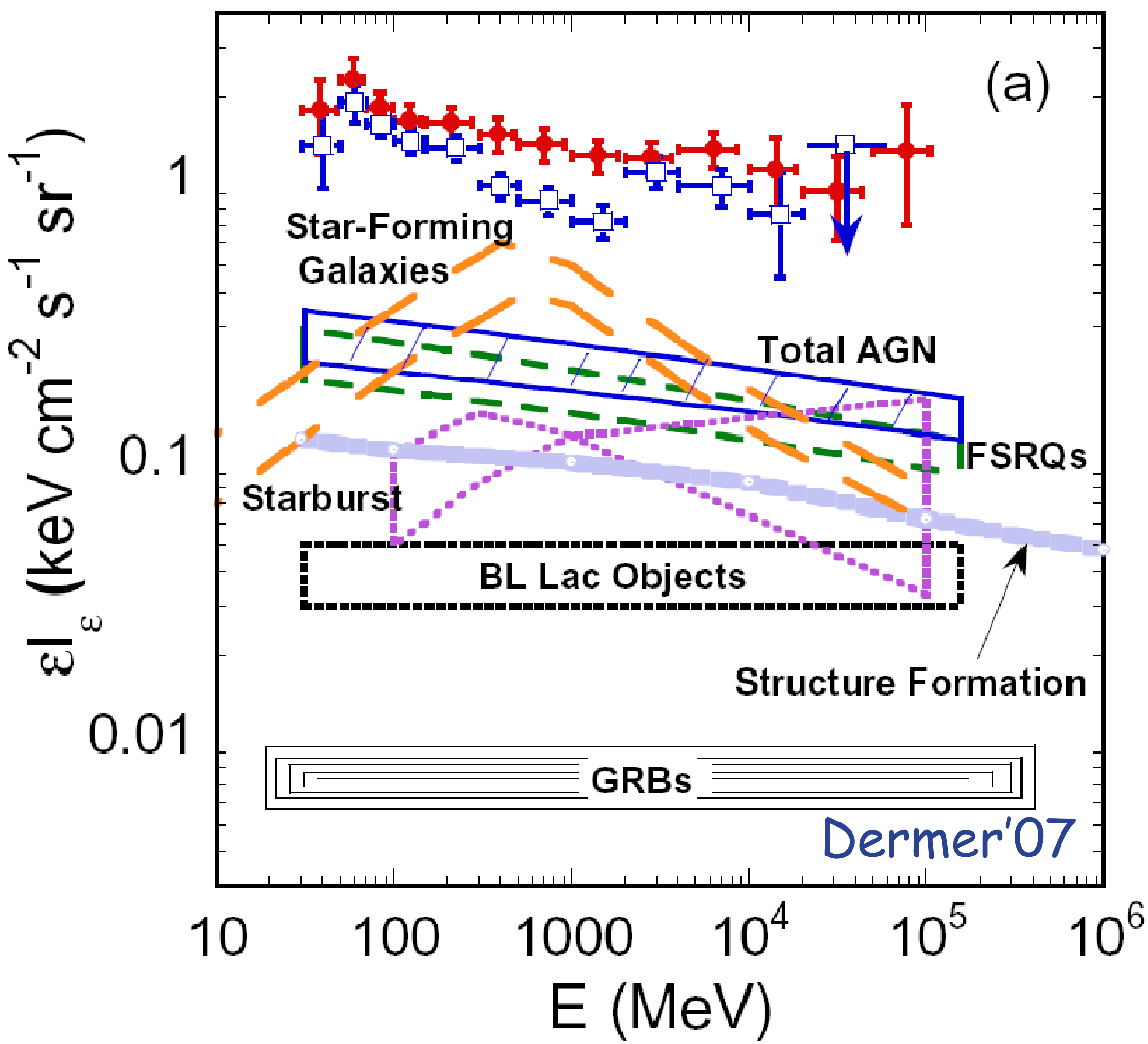






- Blazars
- Cosmological neutralinos

Contributions to the extragalactic background



$\sum$>100%!

- plus albedo of the small solar system bodies and debris
- plus inverse Compton on solar photons

Conclusion

- Many advances in astrophysics of CRs are expected in the near future
- Many long-standing puzzles will be solved
- Much better understanding of the backgrounds
- Better prospects for searches of new physics!