Propagation of Cosmic Rays. II

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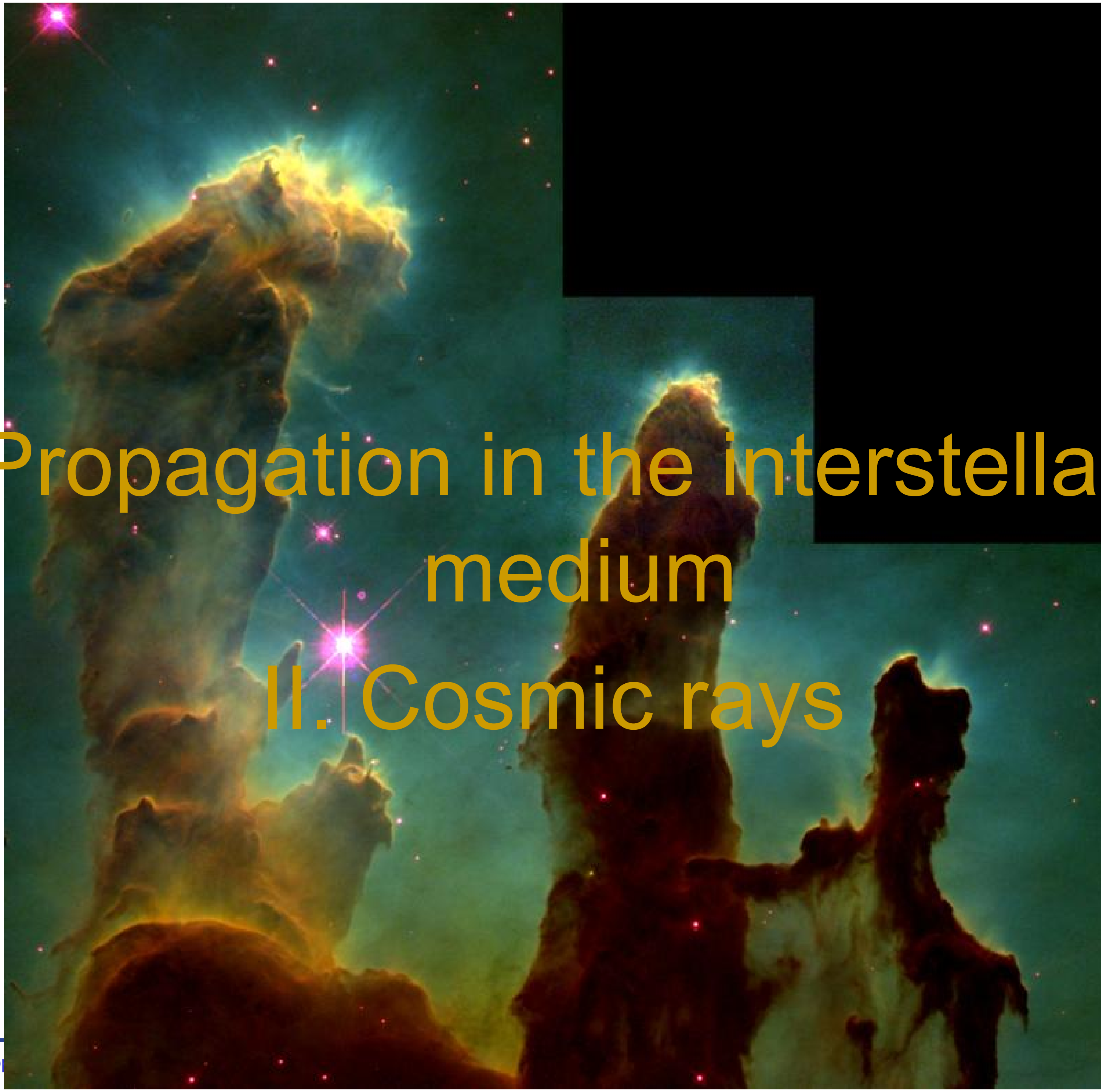
Outline

First lecture

- General information
- Transport equation
- Propagation near the CR sources
- Propagation in the ISM. I. Components of the ISM

Second lecture

- Propagation in the ISM. II. Cosmic Rays
  - Isotopic composition
  - Determination of the Propagation parameters
  - K-capture isotopes
  - Diffuse gamma rays
  - Extragalactic diffuse emission
- CR propagation in the heliosphere
  - Transport equation
  - Heliospheric modulation
  - IC scattering on solar photons
  - gamma-ray albedo of small solar system bodies
- CRs in the other normal galaxies
  - EGRET observations
  - Magellanic clouds and Andromeda galaxy
  - Estimates of gamma-ray fluxes
- Exotic Physics
  - Dark matter
  - Dark matter signatures in CRs and diffuse gamma rays
  - 511 keV line from the Galactic center

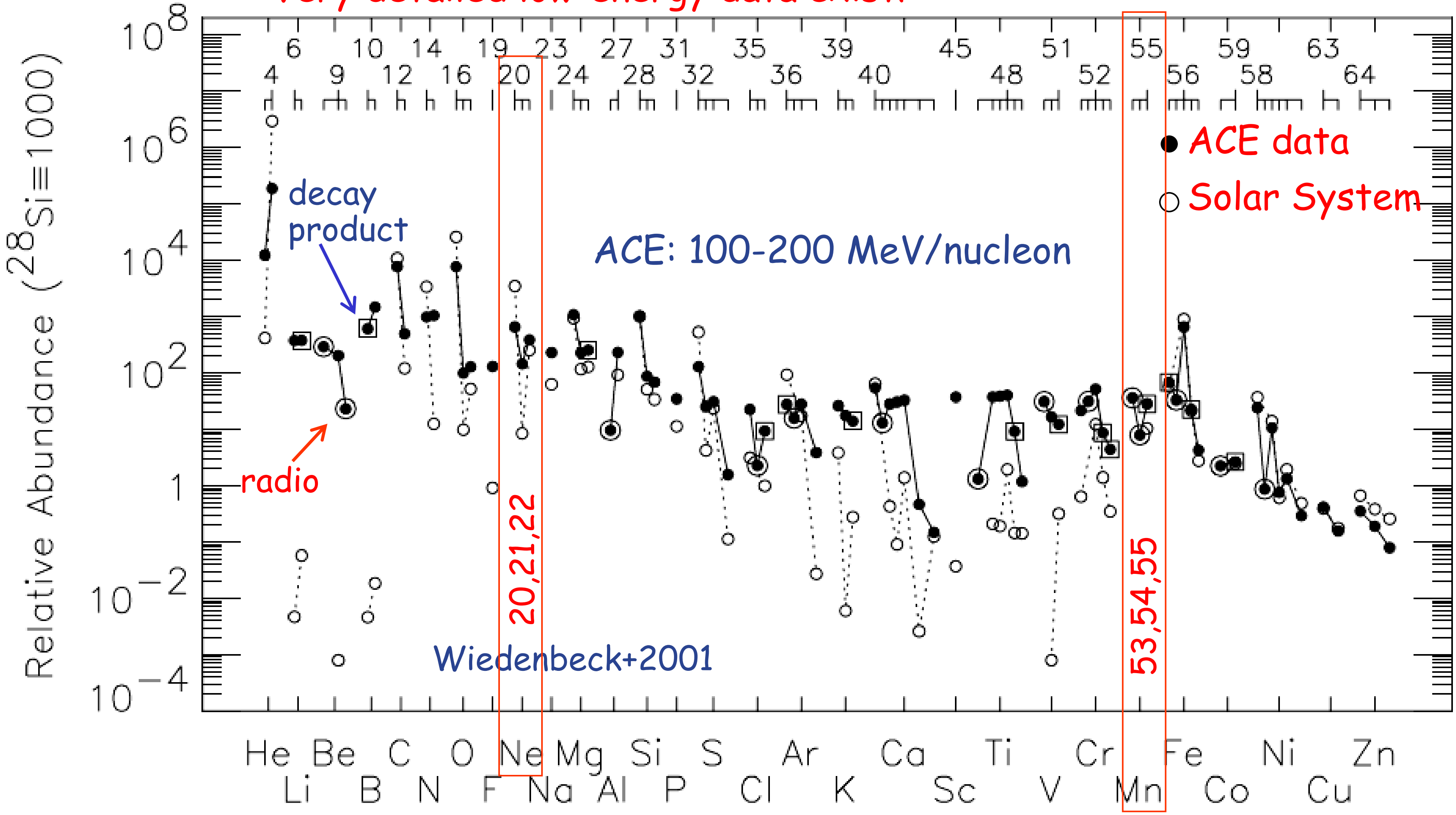


Propagation in the interstellar medium

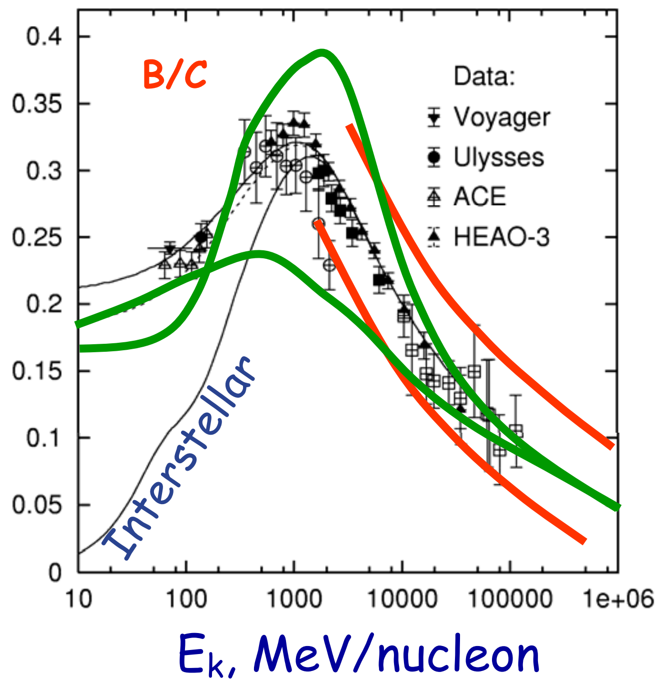
II. Cosmic rays

CR Isotopic Abundances vs SS Abundances

Very detailed low-energy data exist!



How It Works: Fixing Propagation Parameters



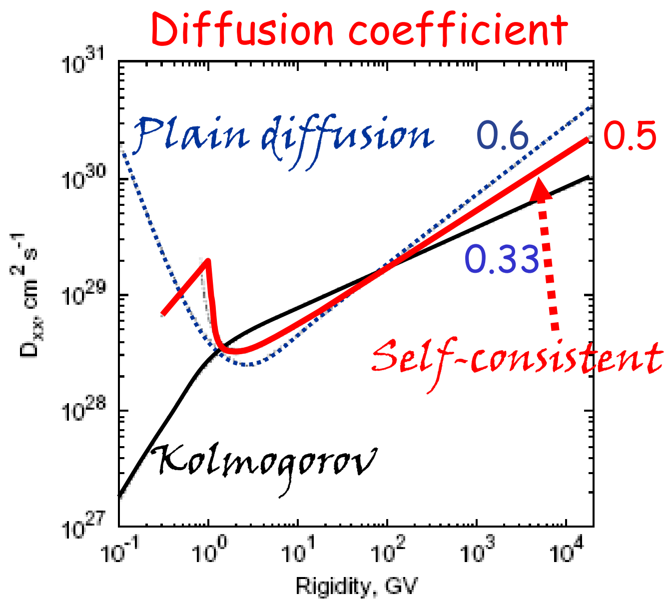
Parameters (model dependent):

$D \sim 10^{28} (\rho/1\ GV)^{a}\ cm^2/s$

$a \approx 0.3\text{-}0.6$

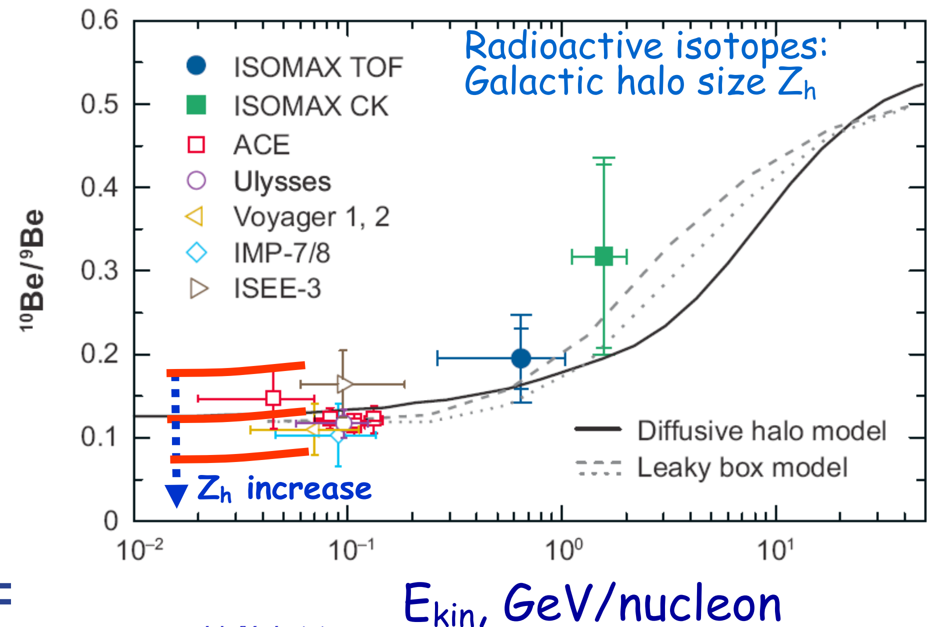
$Z_h \sim 4\text{-}6$ kpc

($V_A \sim 30$ km/s)



Using secondary/primary nuclei ratio & flux:

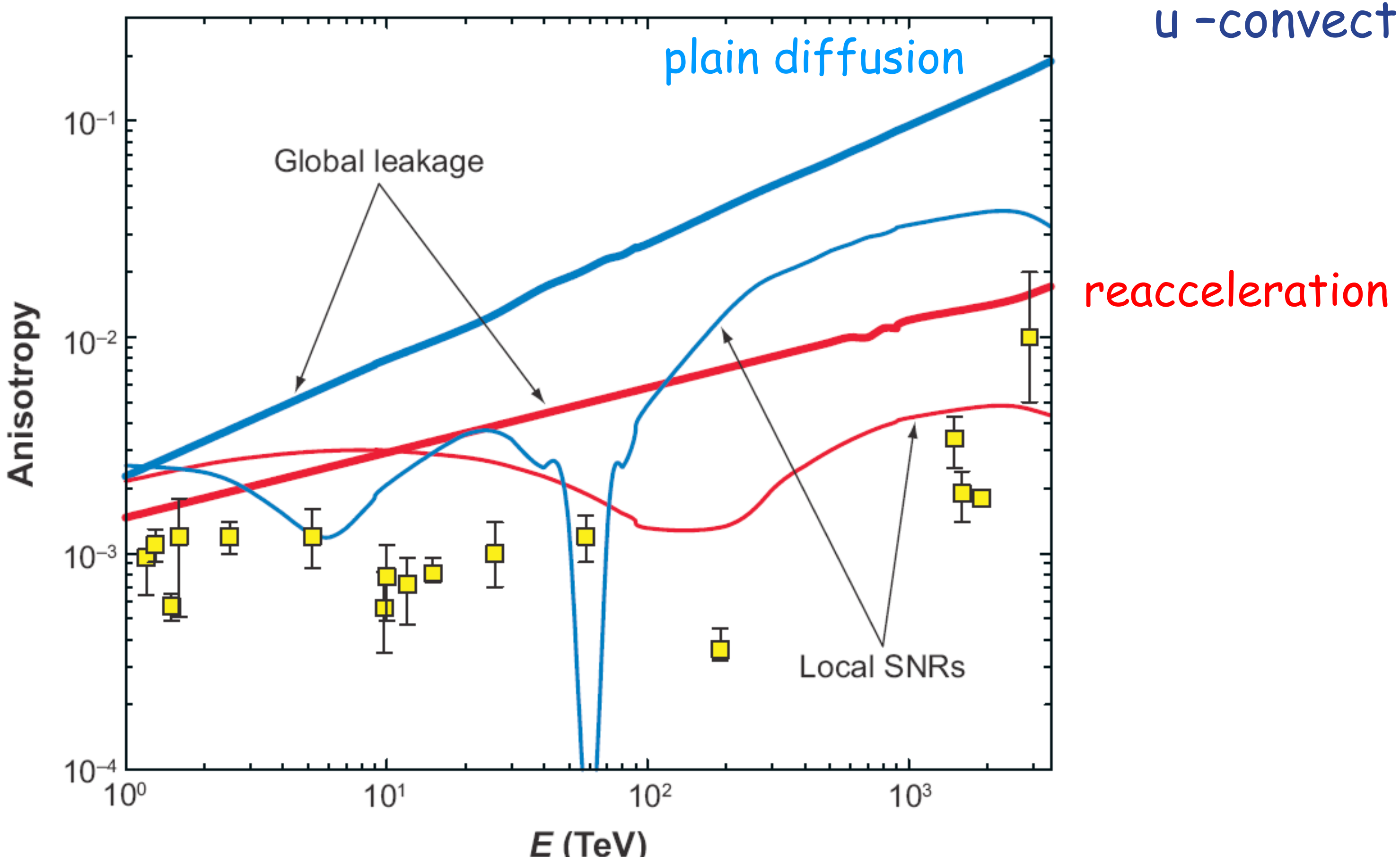
- Diffusion coefficient and its index
- Propagation mode and its parameters (e.g., reacceleration V_A, convection V_z)
- Propagation params are model-dependent
- Make sure that the spectrum is fitted as well



CR anisotropy

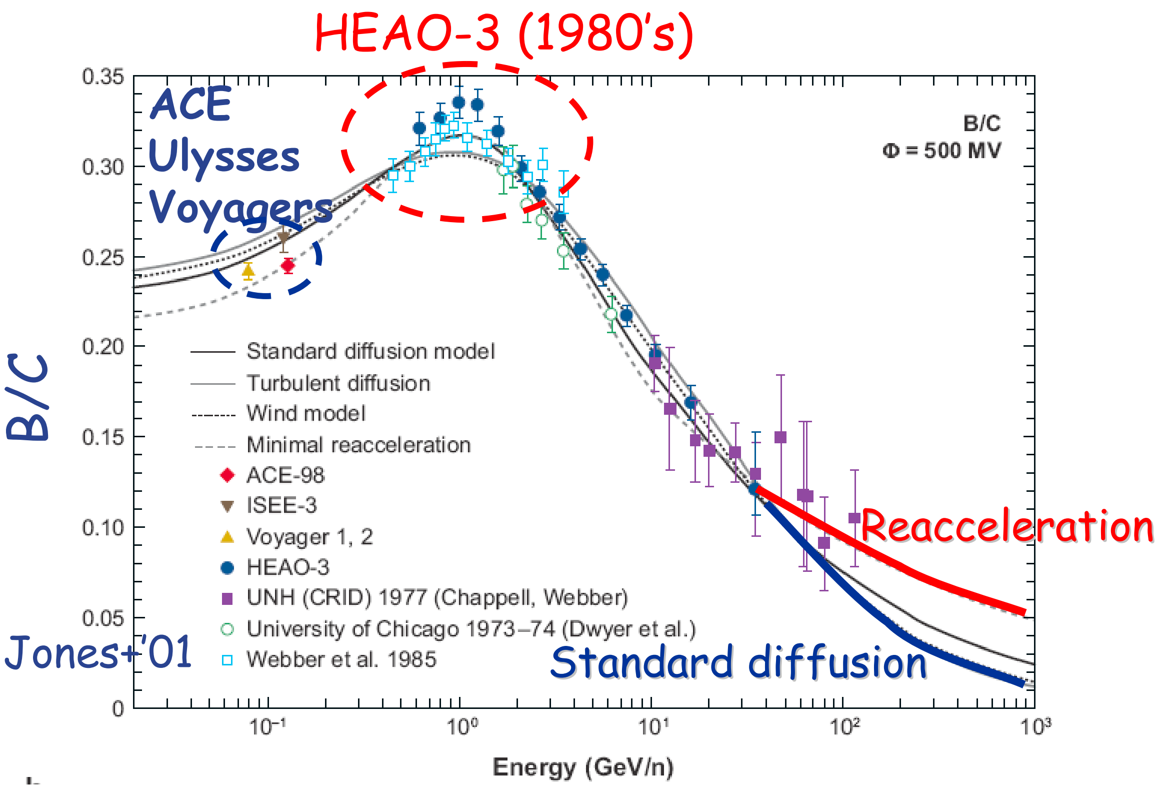
$$\delta = -[3D\nabla f + up(\partial f/\partial p)]/vf$$

f – phase space density
u –convection velosity



Strong+'07

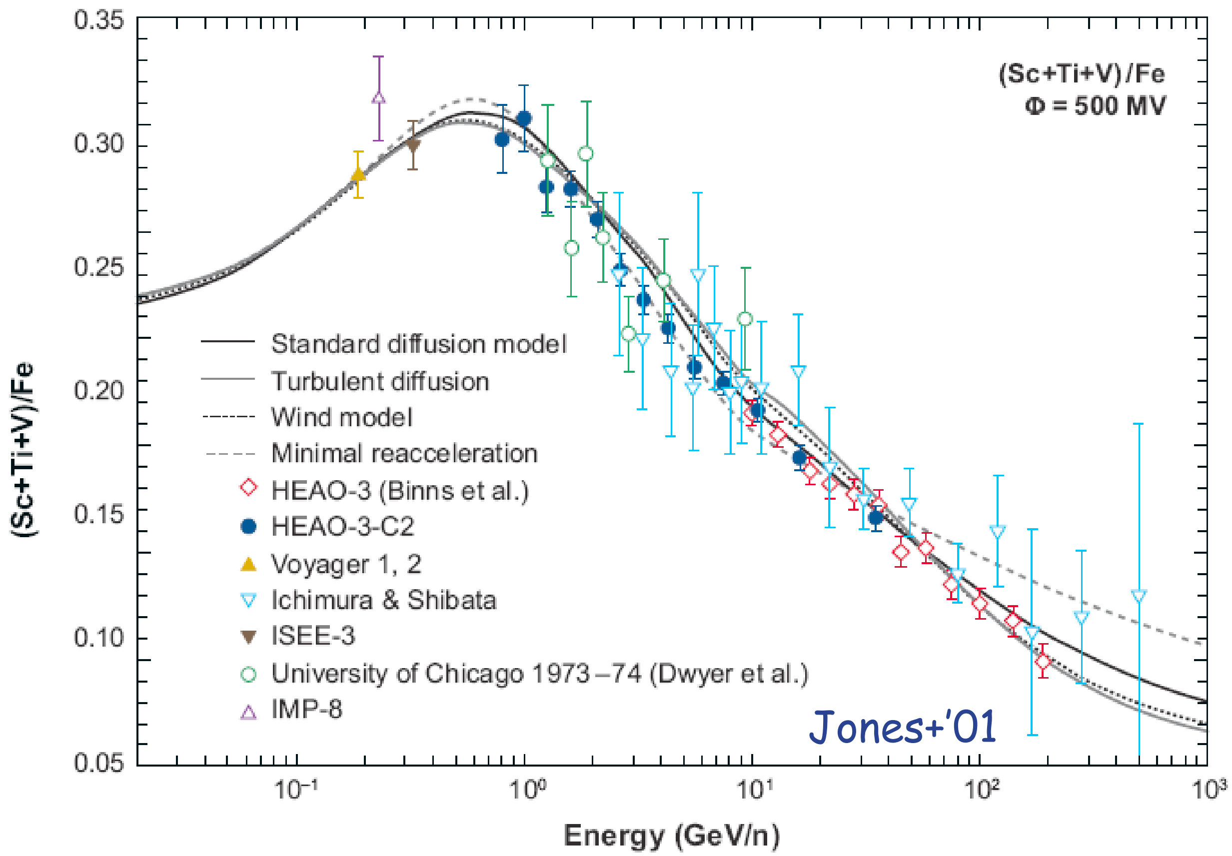
Discrimination of the propagation models



The data were taken at different times (1980-now) in different energy ranges and by different instruments, so the probability of systematic errors is high.

- Different propagation models are tuned to fit the low energy part of sec./prim. ratio where the accurate data exist
- However, the differ at high energies which will allow to discriminate between them when more accurate data will be available
- The sharp peak at ~1 GeV/nucleon seems to be confirmed by Pamela! (Vannuccini talk)

Secondary/primary: (Sc+Ti+V)/Fe



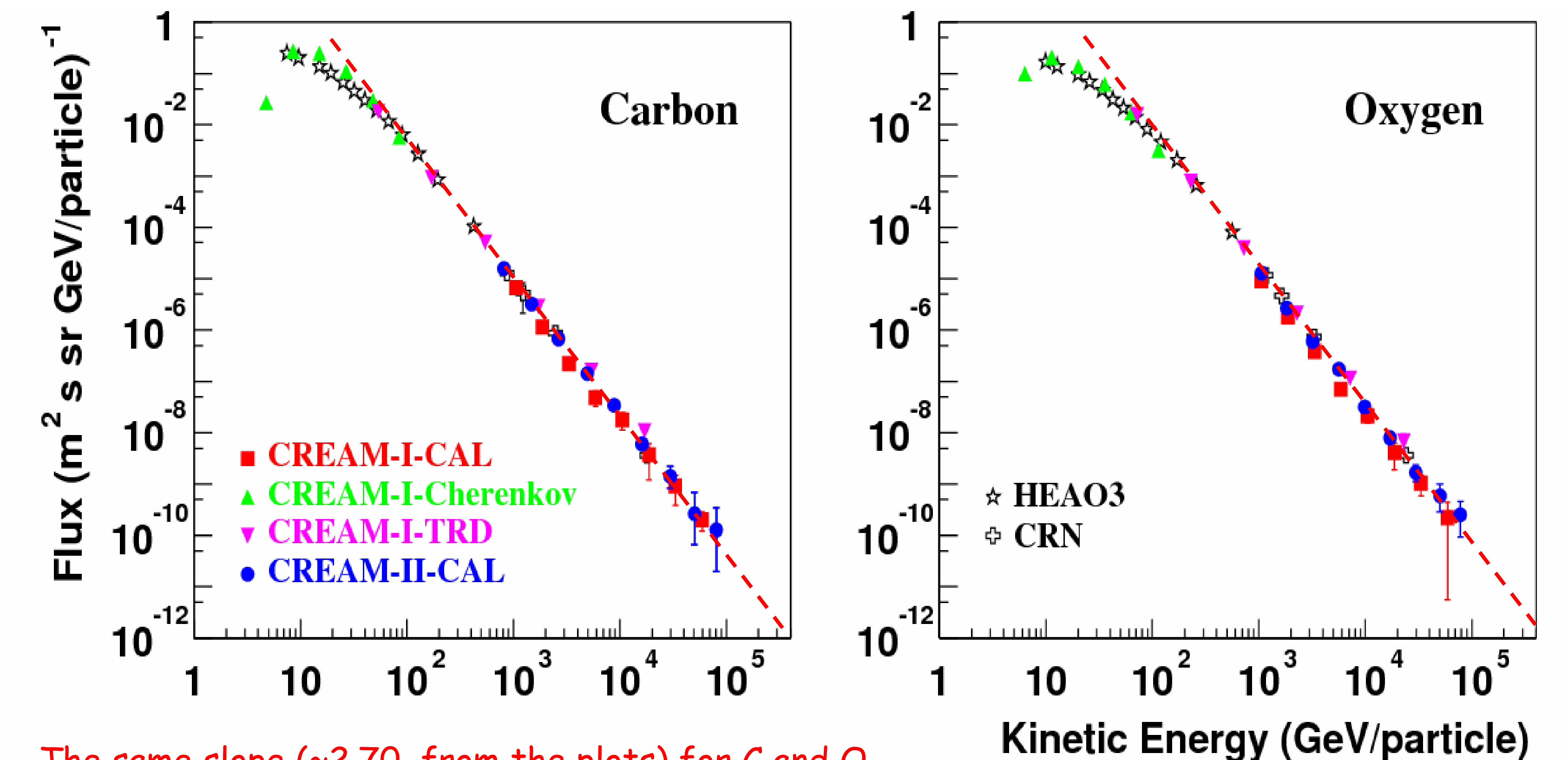
Similar shape, but the data are not that accurate

C & O spectra from CREAM

Wakely et al, OG1.3 oral; Zei et al. OG1.1 oral; Ahn et al. OG1.1 oral (30th ICRC)

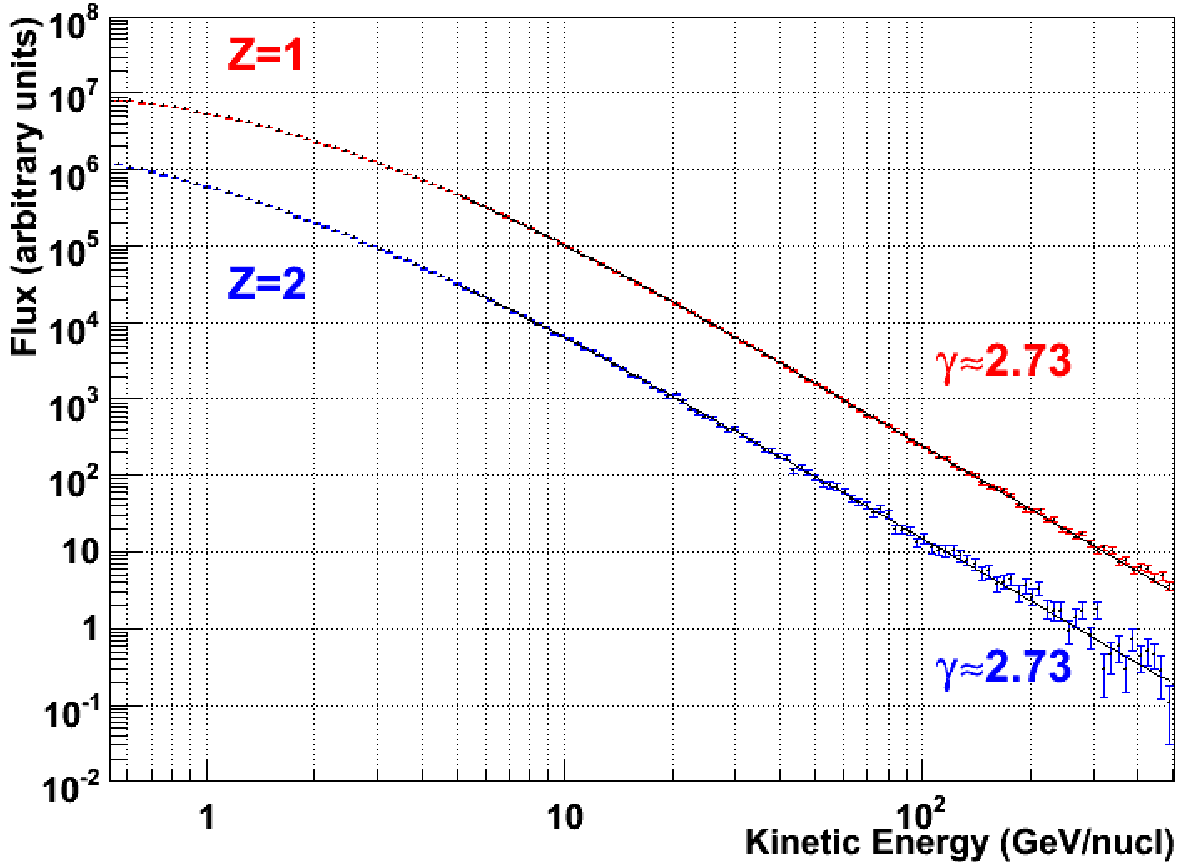
- CREAM results span ~ 4 decades in energy: ~ 10 GeV to ~ 100 TeV
- Different techniques give consistent spectra

Credit P.Blasi/Rapporteur talk



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

Preliminary Results from PAMELA



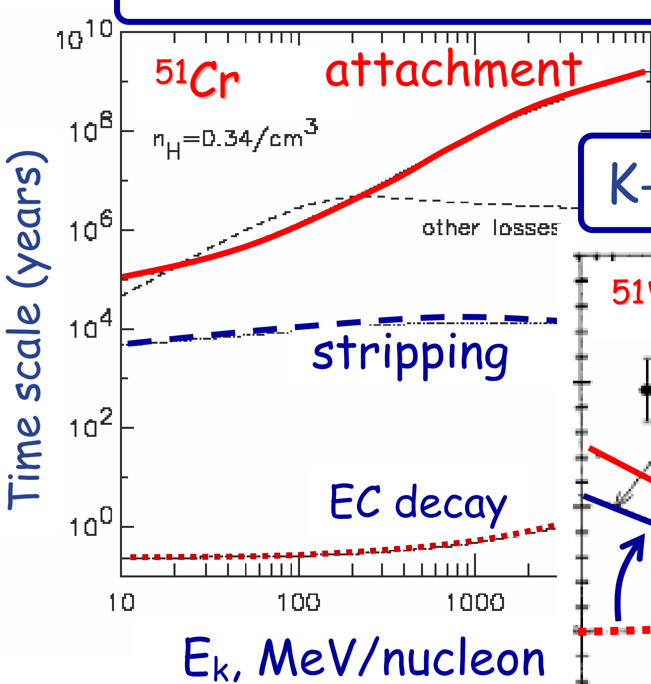
- PAMELA data are tremendously accurate, but currently only the "arb.units"
- Interestingly, the same slope for H and He and very close to C and O from CREAM
- Protons are flatter than BESS and AMS data

K-capture isotopes

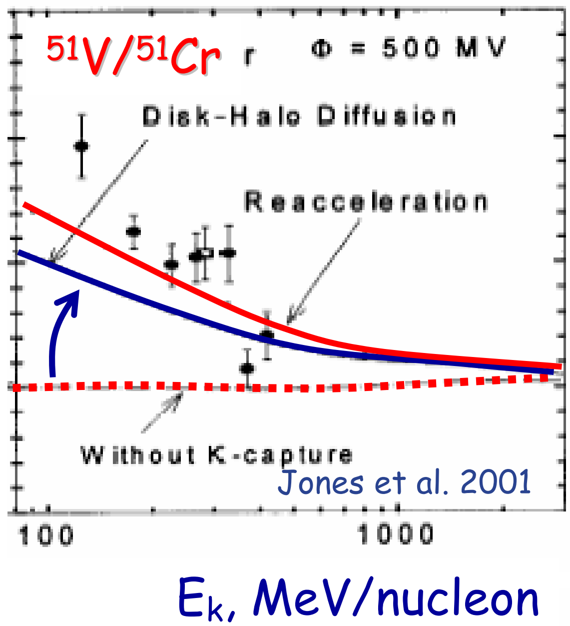
^{51}Cr (τ~28 d)

$^{51}V/^{51}Cr$ ≡ daughter/parent

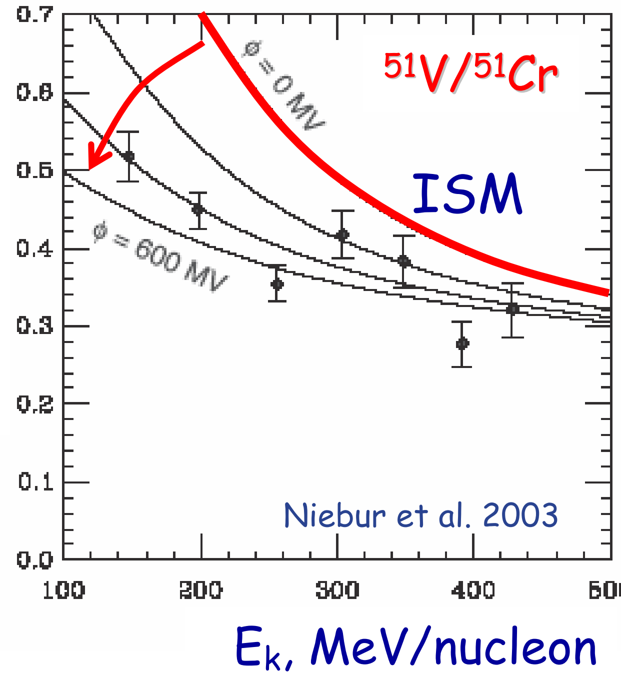
Electron attachment & stripping



K-capture & reacceleration



Solar modulation effect



Stable in CRs (bare nuclei); in the medium decay via electron capture

CR source abundances

Determination of the CR source isotopic abundances is a non-trivial task, but if determined, it can give us a clue of the origin of CRs

Two key measurements (ACE/CRIS):

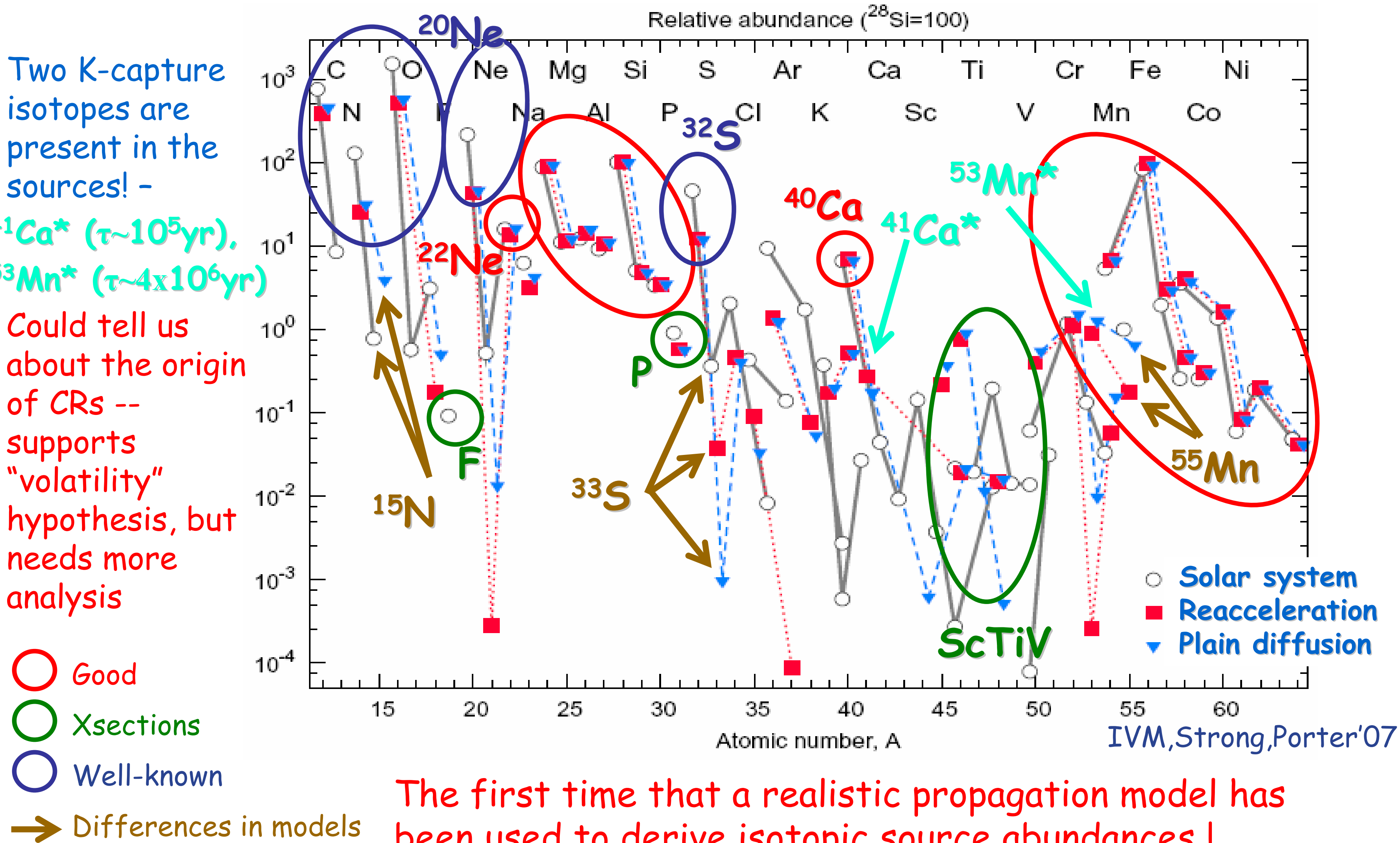
- ^{59}Ni and ^{59}Co abundances in CRs (Wiedenbeck+'99) indicate >10^5 years delay between nucleosynthesis and CR acceleration
- ^{22}Ne/^{20}Ne and ^{58}Fe/^{56}Fe ratios show consistency with a strong Wolf-Rayet star ejecta component in the GCRs (Binns+'05)

CR source material:

80% ISM + 20% ejecta from Wolf-Rayet and massive OB stars

CR source isotopic abundances

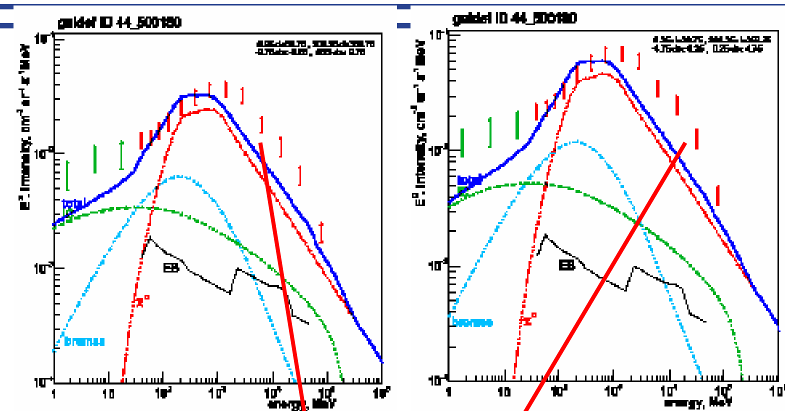
- Two K-capture isotopes are present in the sources! – ^{41}Ca* (τ~10^5yr), ^{53}Mn* (τ~4×10^6yr)
- Could tell us about the origin of CRs -- supports "volatility" hypothesis, but needs more analysis

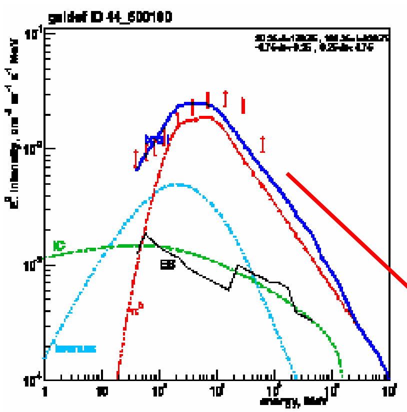


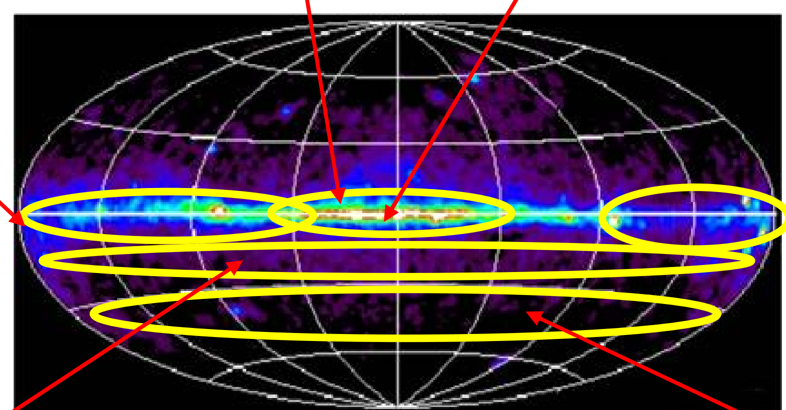
The first time that a realistic propagation model has been used to derive isotopic source abundances !

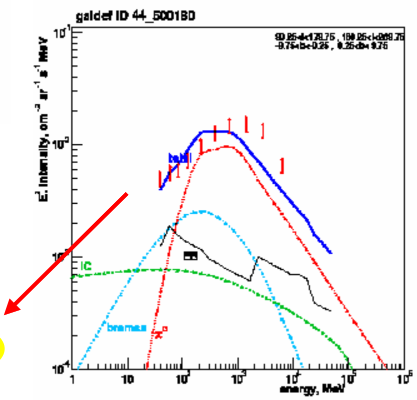
Wherever you look, the GeV γ-ray excess is there !

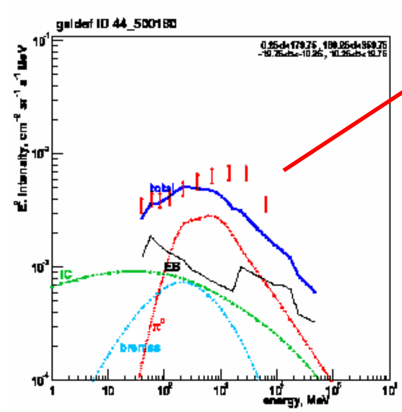
EGRET data





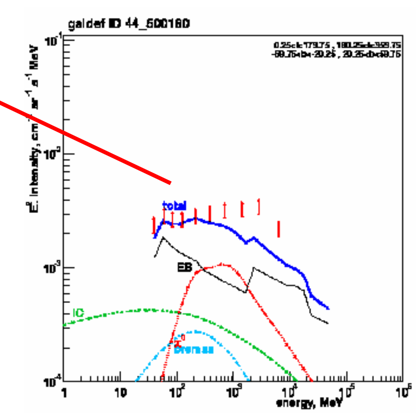






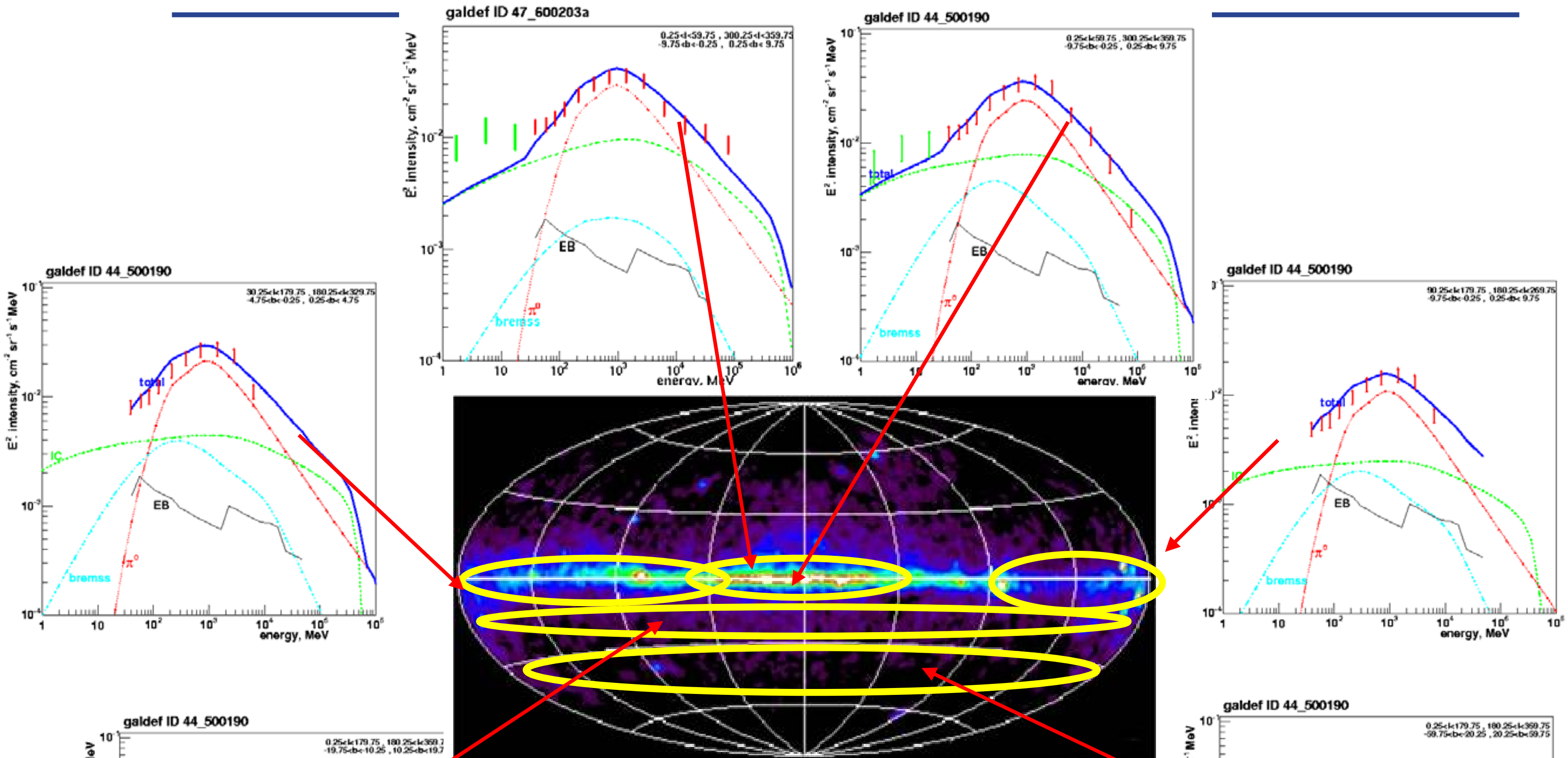
- Instrumental artefact?
- Physical phenomena?

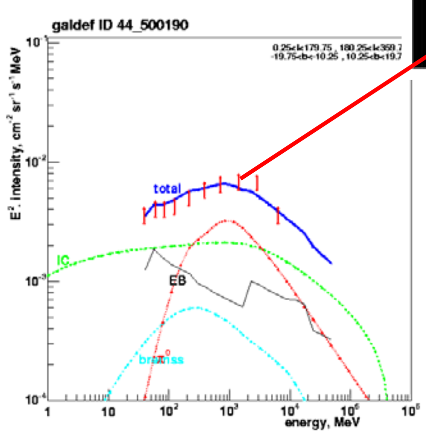
GLAST will answer…



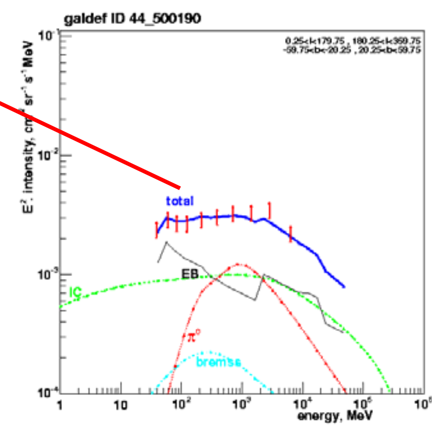
Strong+'00,'04

Optimized model





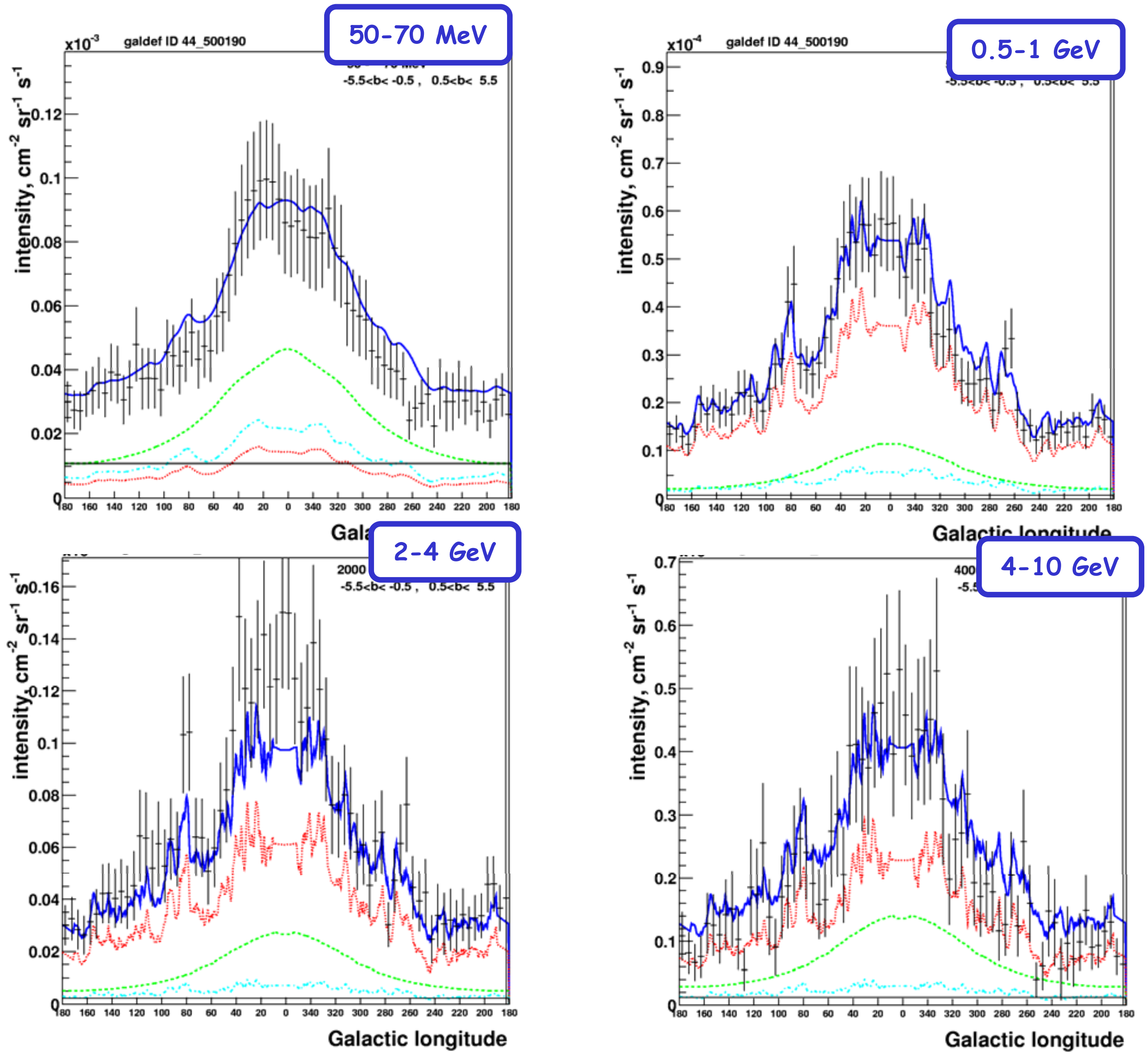
- CR spectra are not the same everywhere in the Galaxy
- It is possible to tune proton and electron spectra to make a fit to diffuse gamma rays



Strong+'00,'04

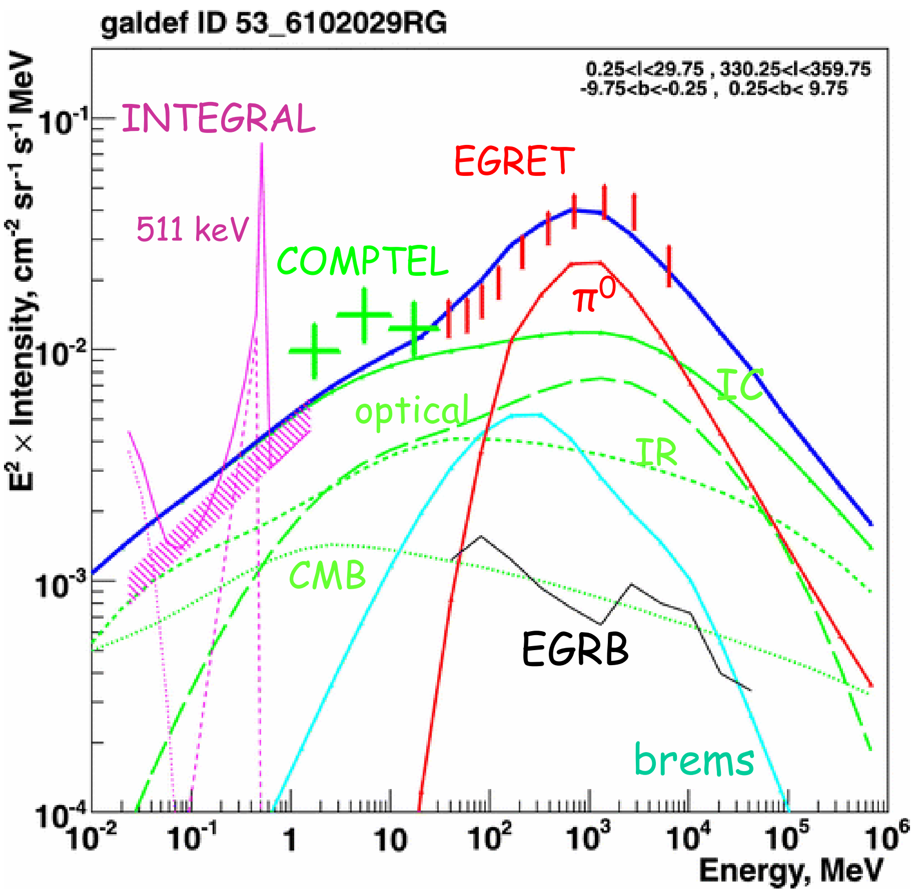
Diffuse emission model vs. EGRET data

Longitude profiles |b|<5°



Strong+'04

Diffuse emission from the Galactic center



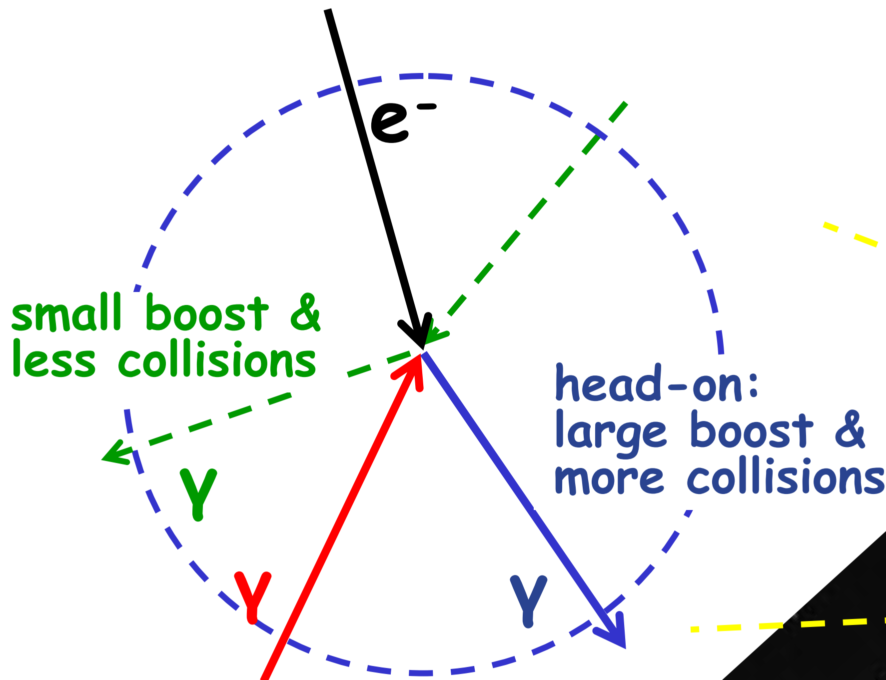
Porter+'08

Intrinsic connection between the diffuse Galactic γ-ray emission in different energy ranges:

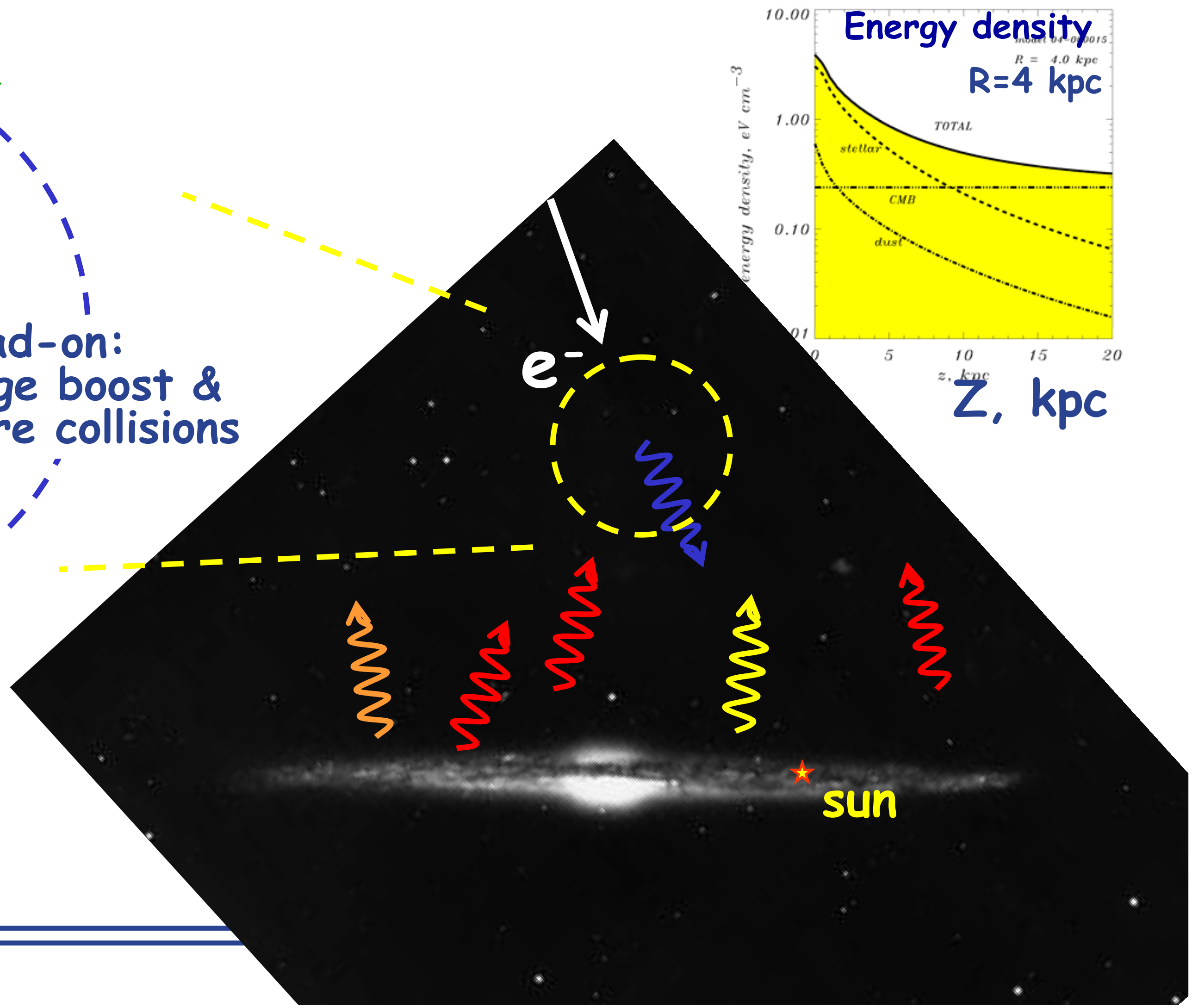
- 100 keV - few MeV: IC emission by CR electrons and positrons on optical & IR radiation (primary + secondary electrons and positrons)
- 100 MeV - 10 GeV: produced by protons via π^0-decay; these protons also produce secondary positrons and electrons
- 10 GeV–10 TeV: Produced via IC scattering of primary electrons on the same optical & IR photons

Anisotropic Inverse Compton Scattering

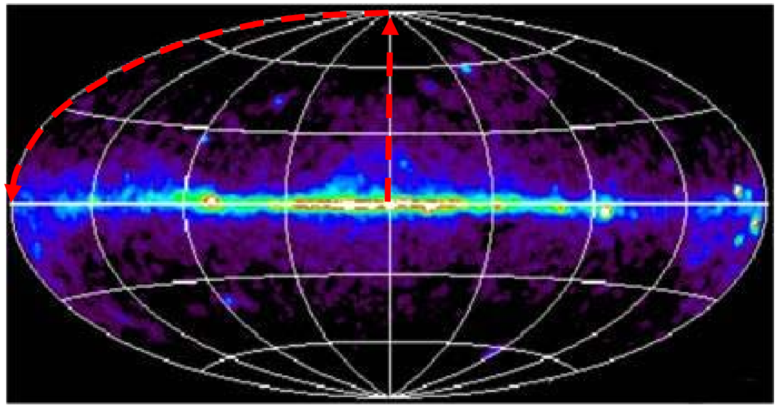
- Electrons in the halo see **anisotropic radiation**
- Observer sees mostly **head-on collisions**

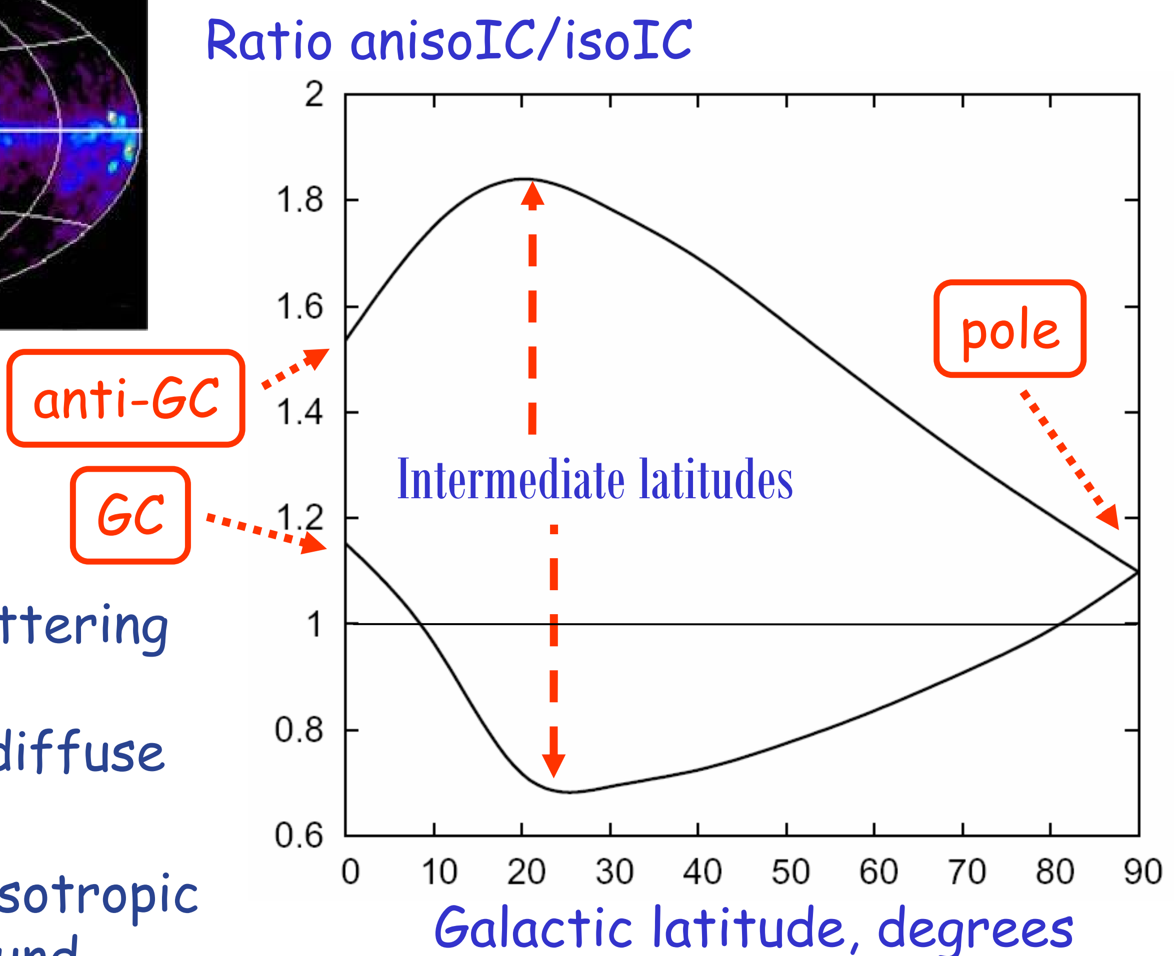


Important @ high latitudes !



Effect of anisotropic ICS

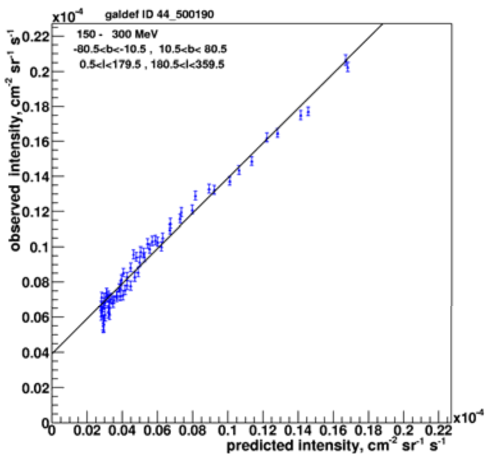


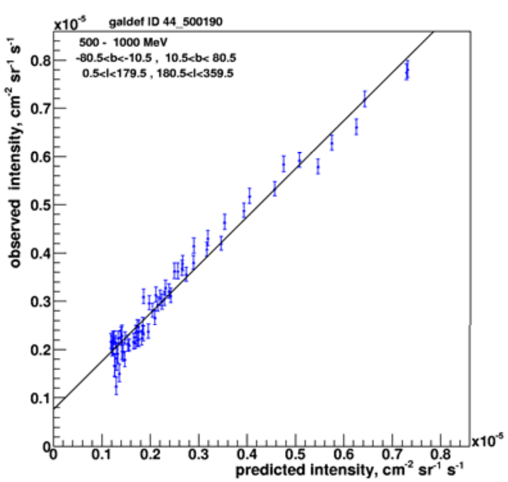


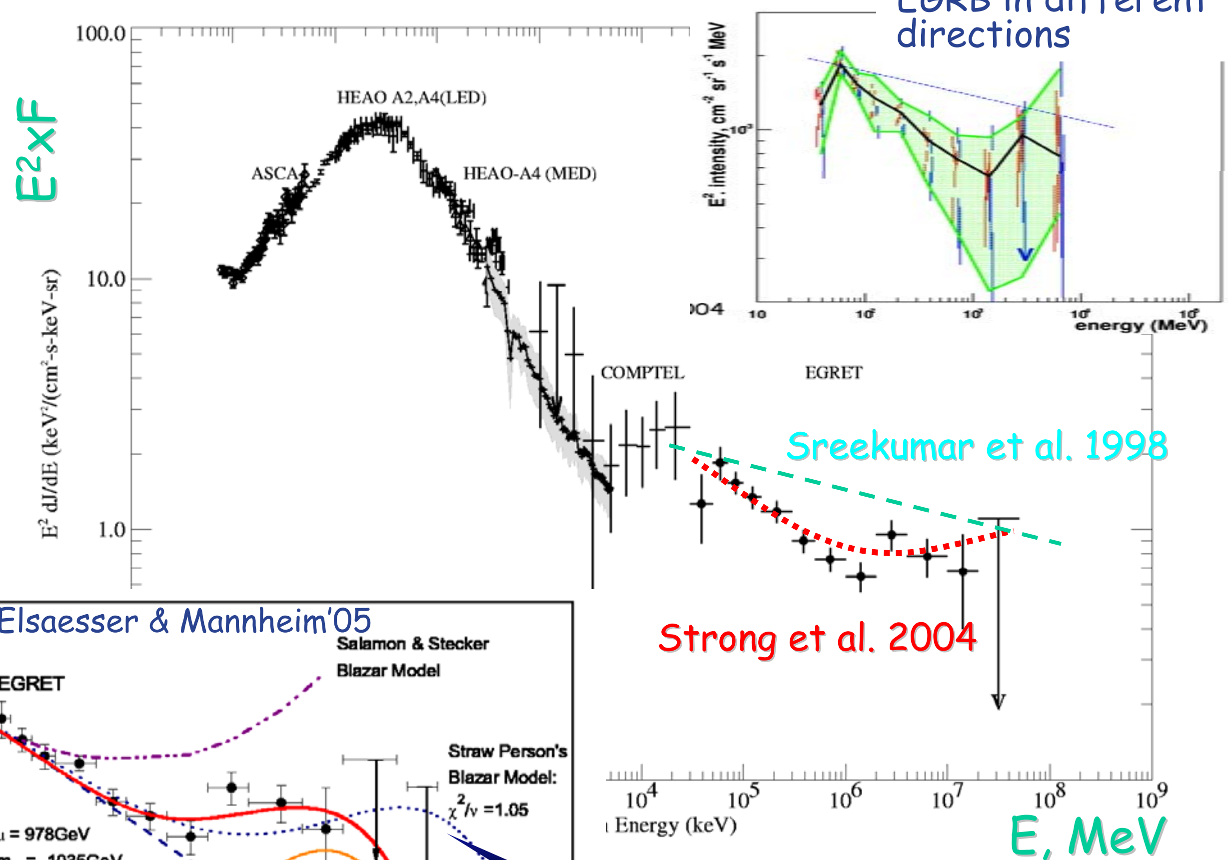
- The anisotropic IC scattering plays important role in modeling the Galactic diffuse emission
- *Affects estimates of isotropic extragalactic background*

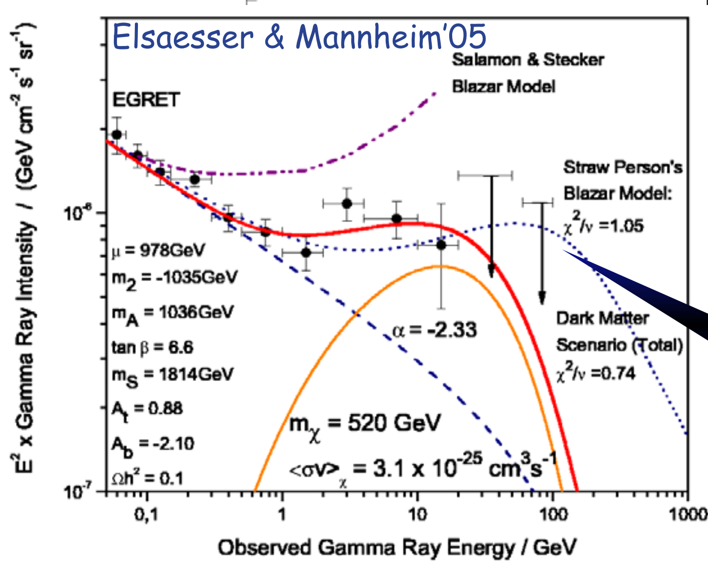
Extragalactic Gamma-Ray Background

Predicted vs. observed



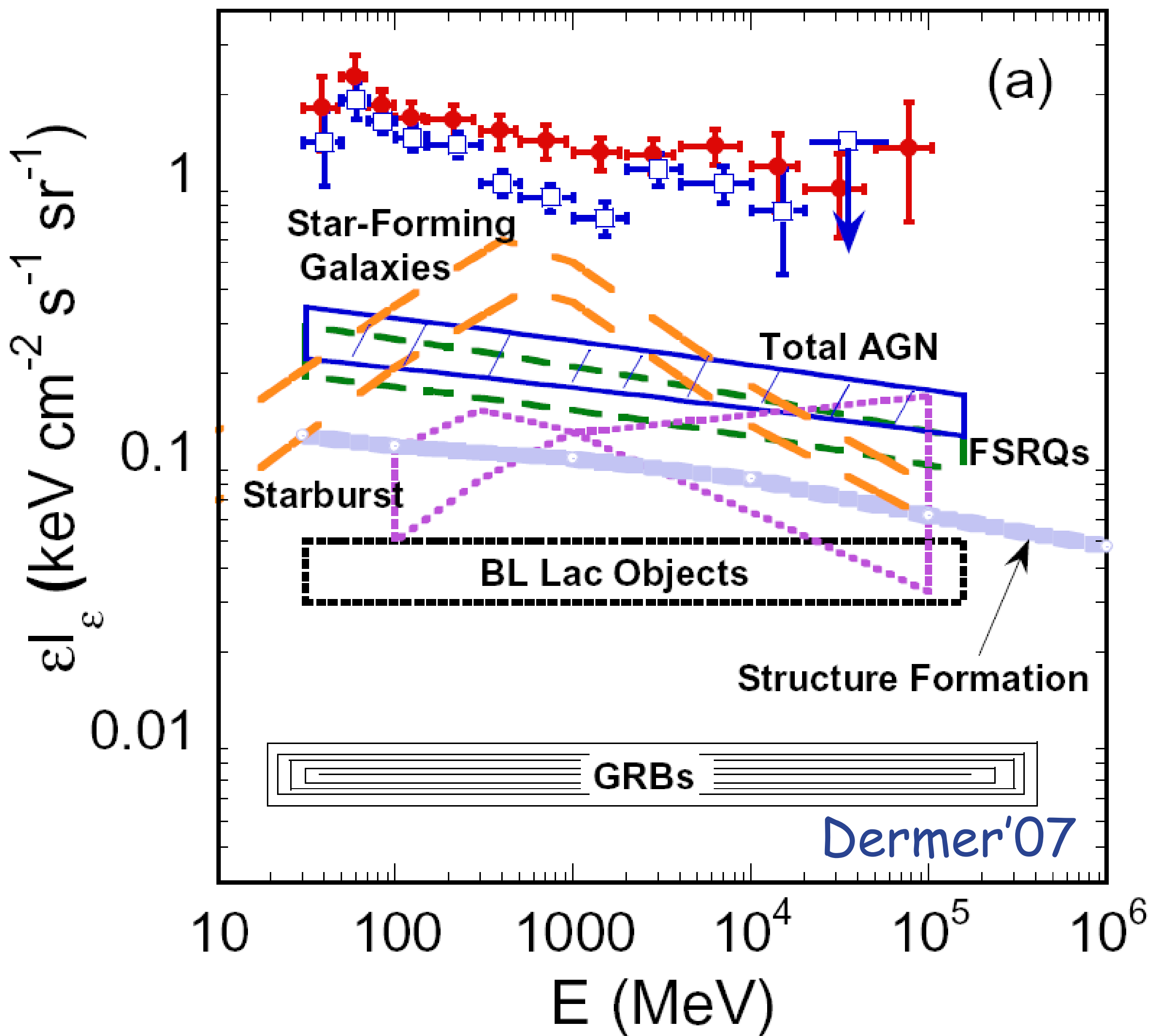






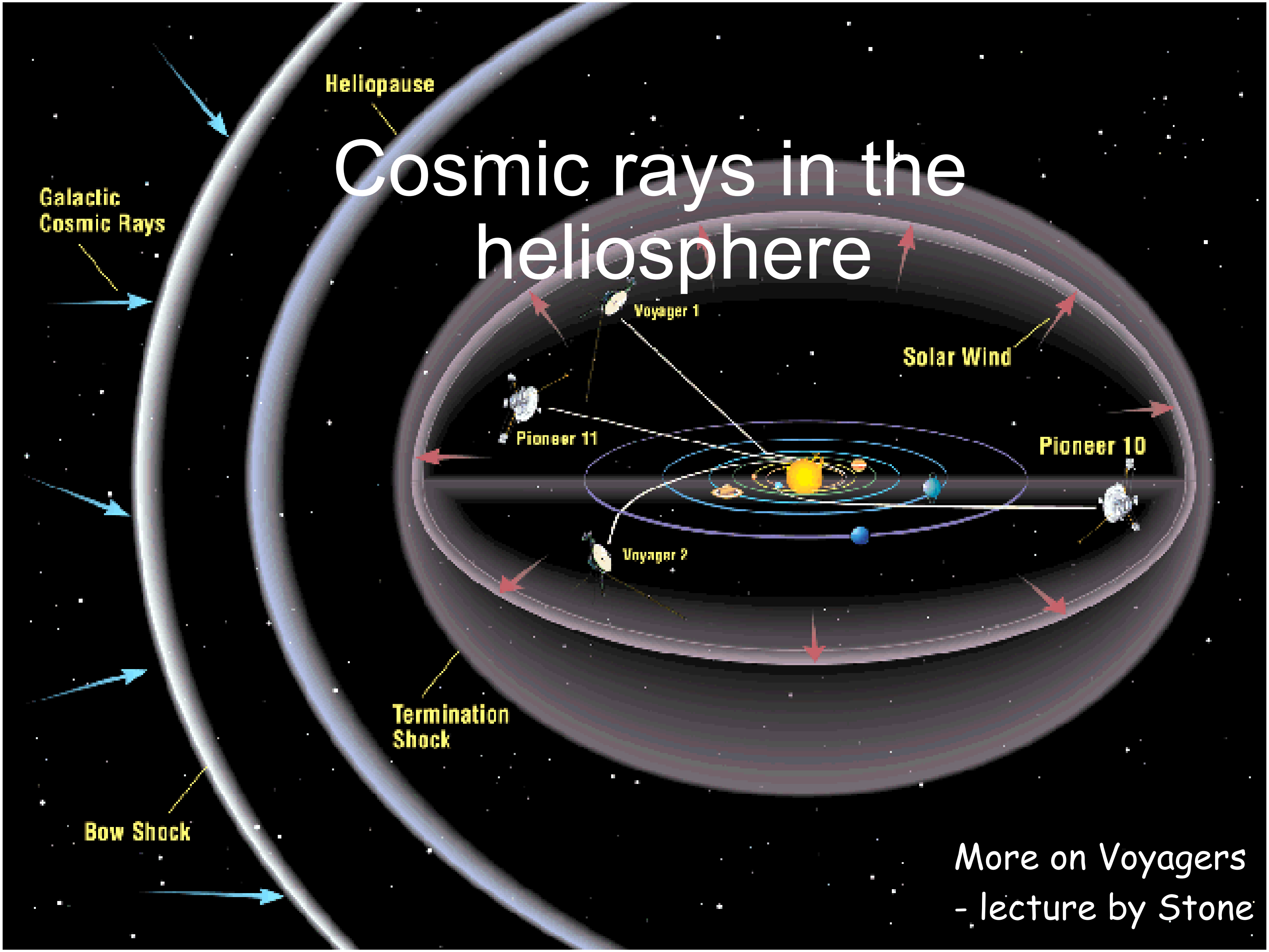
- Blazars
- Cosmological neutralinos

Contributions to the extragalactic background



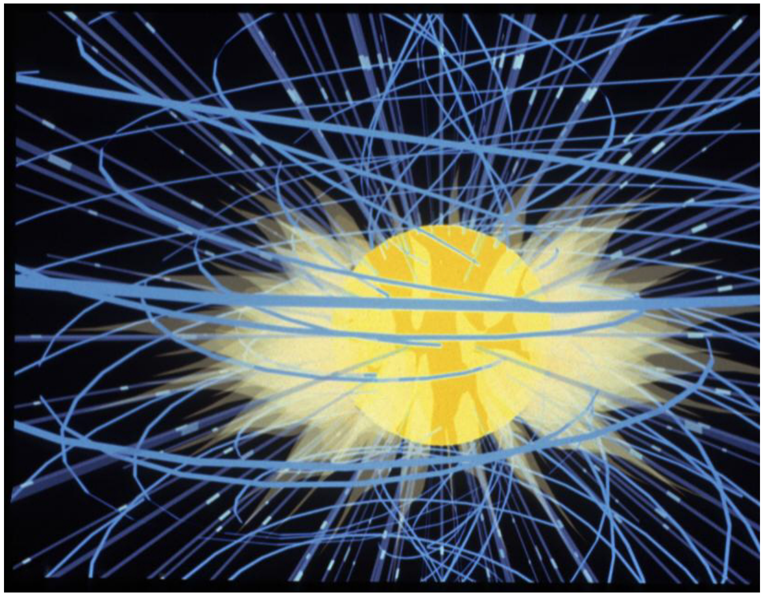
∑ + relic neutralinos >100%!

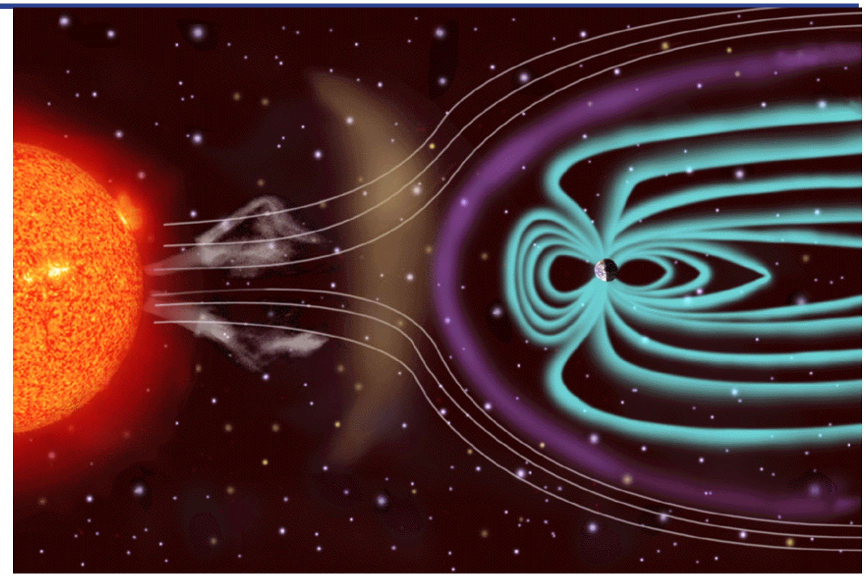
Cosmic rays in the heliosphere

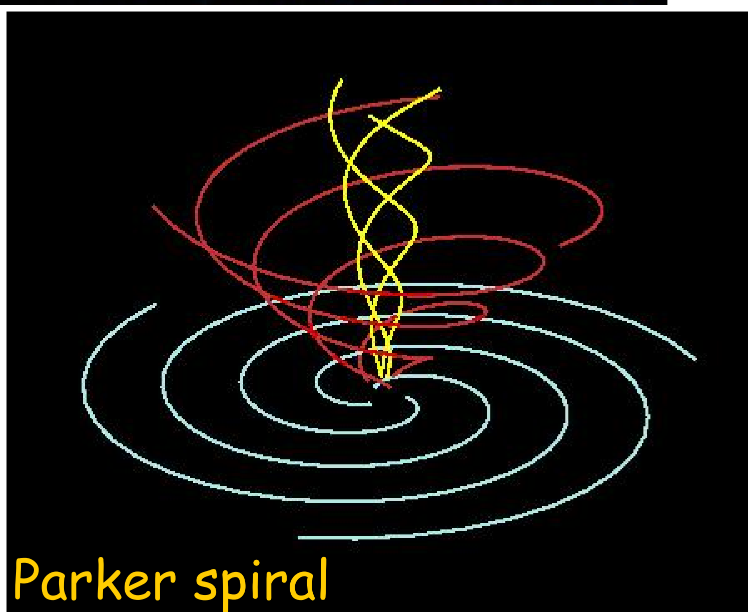


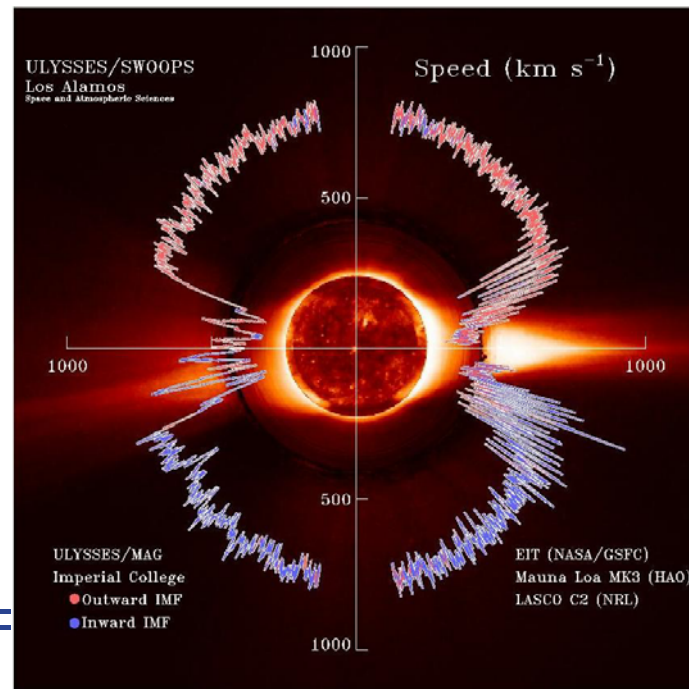
More on Voyagers
- lecture by Stone

Interplanetary B-field & solar wind









Transport equation

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

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

f – CR distribution function

V - solar wind velocity

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

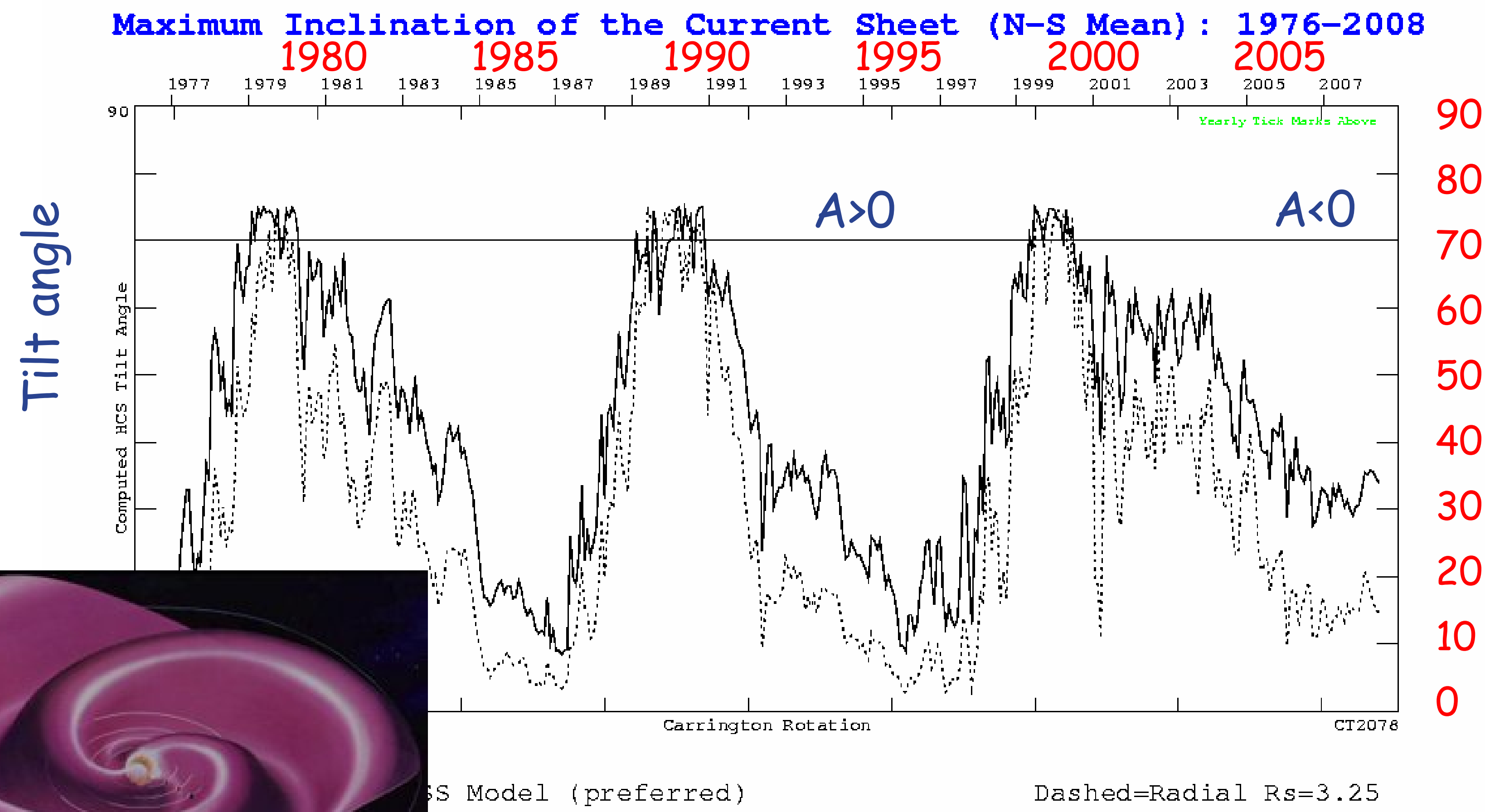
K_A- antisymmetric part of the diffusion tensor

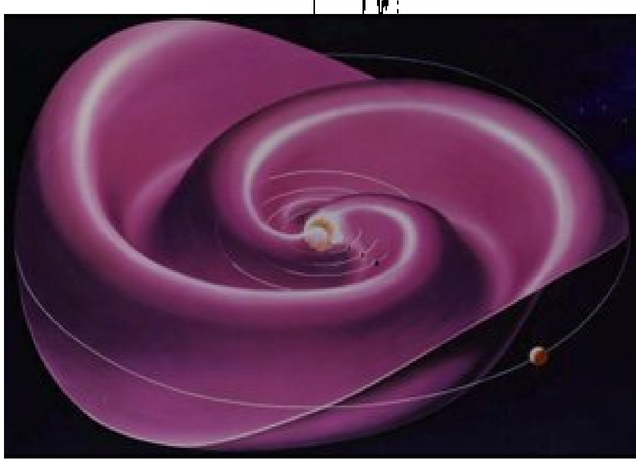
K_S- symmetric part of the diffusion tensor

ρ - rigidity

- Not all factors are well known
- Local interstellar spectrum of CRs is unknown (exception pbars)

Heliospheric current sheet

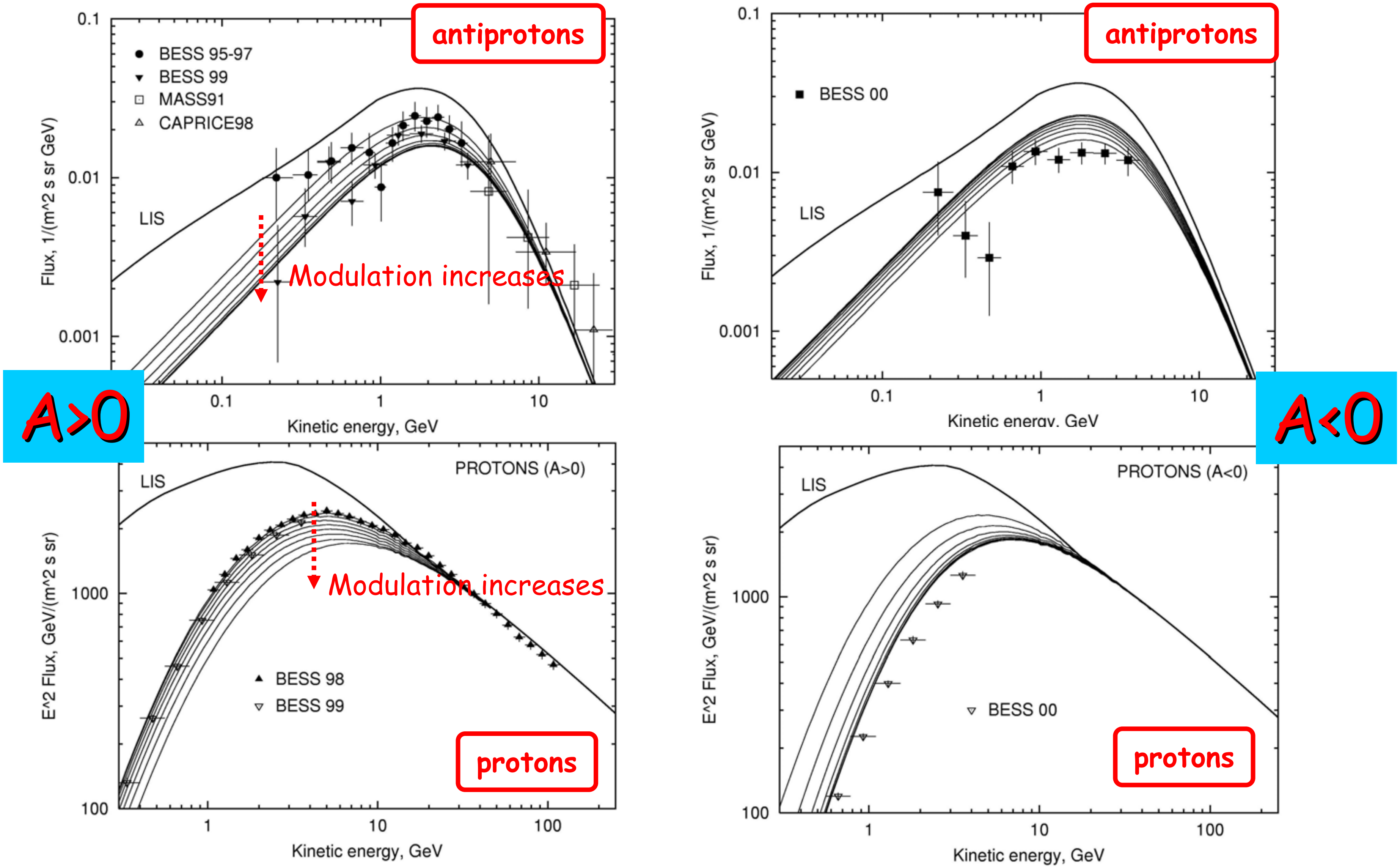




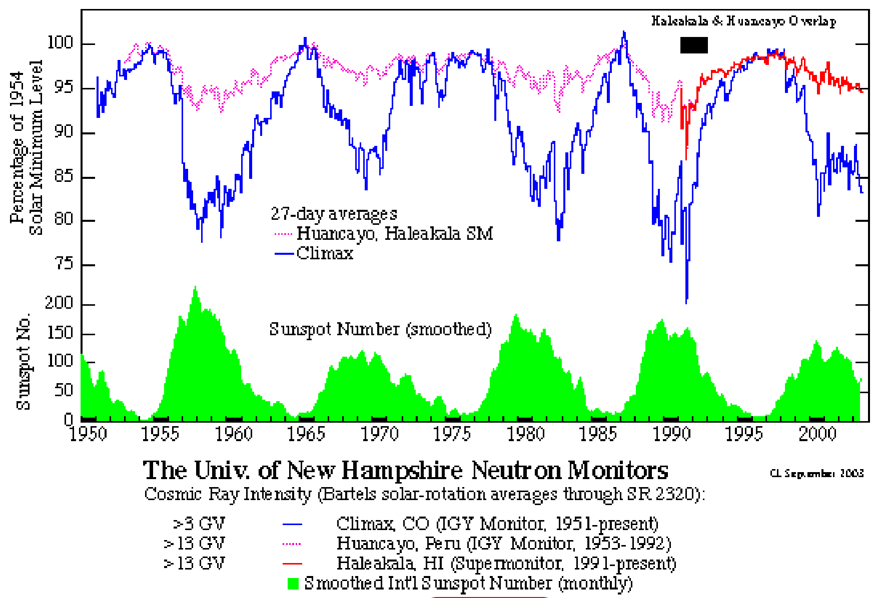
A surface where the polarity of the solar magnetic field changes

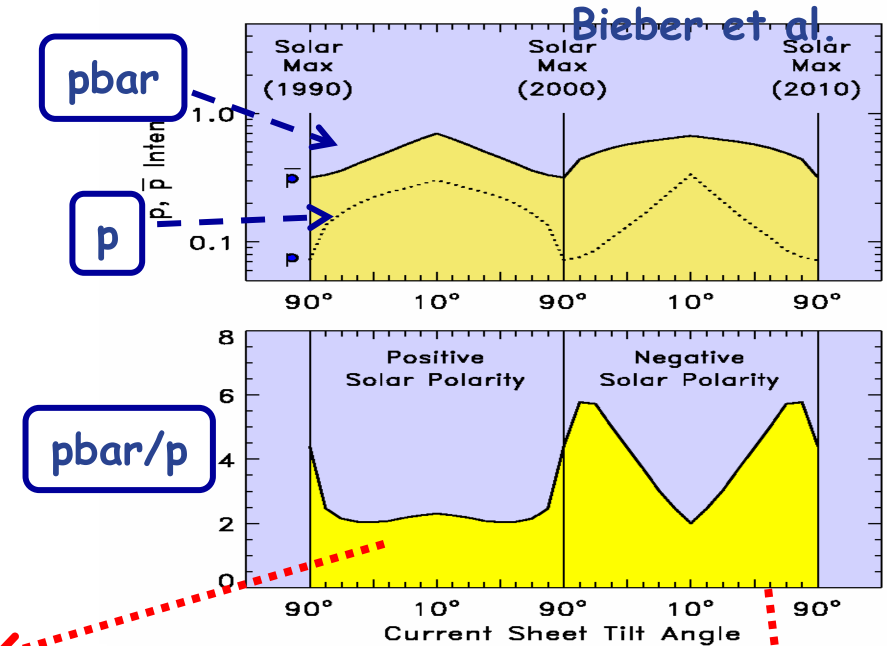
Hoeksema model

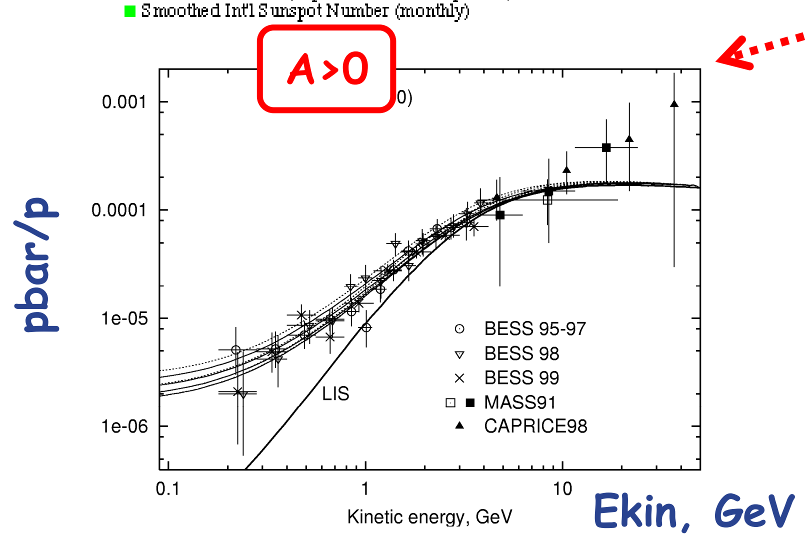
Variations over the solar cycle (pbars, p)

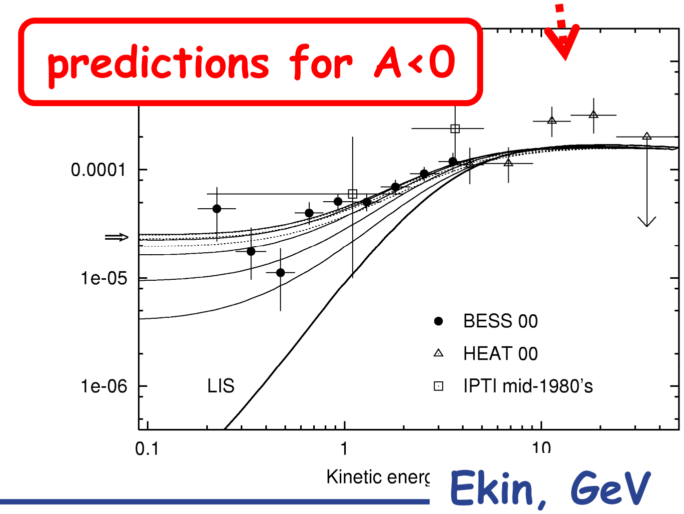


Charge Sign Effect







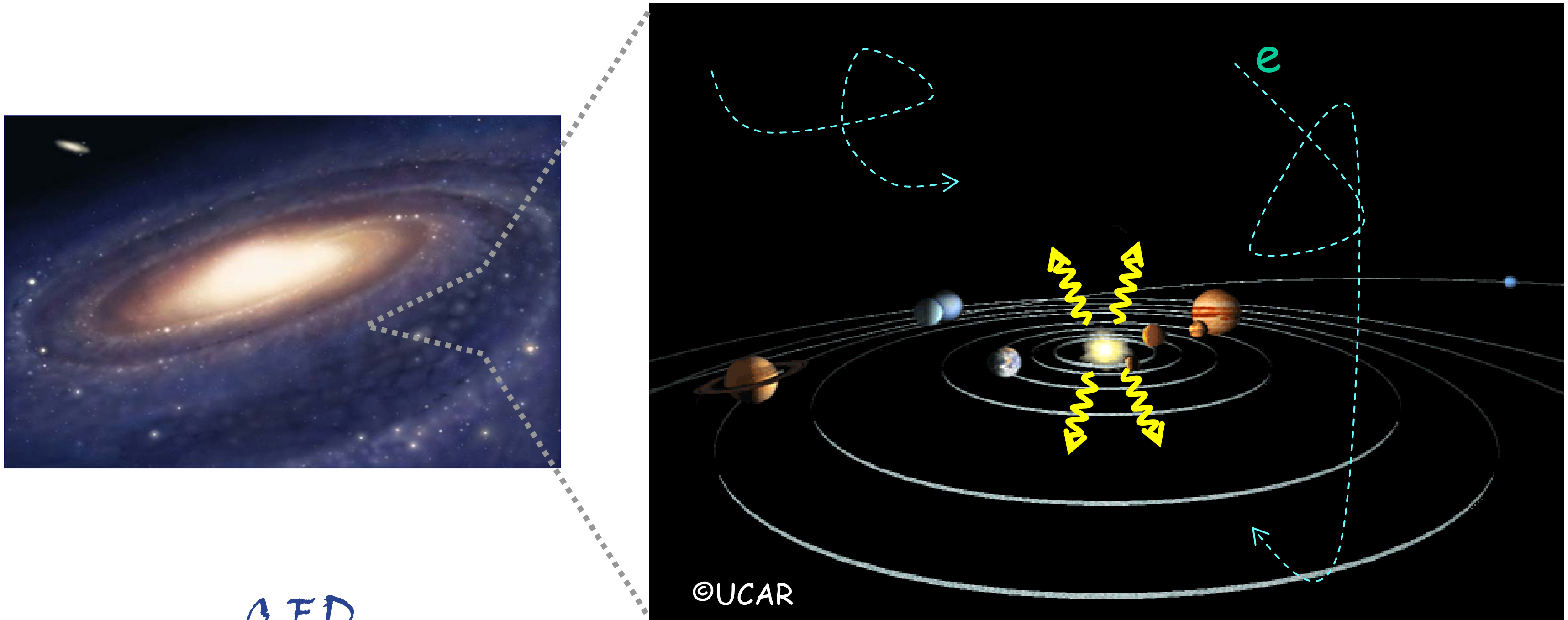


Studies of solar modulation in the GLAST era

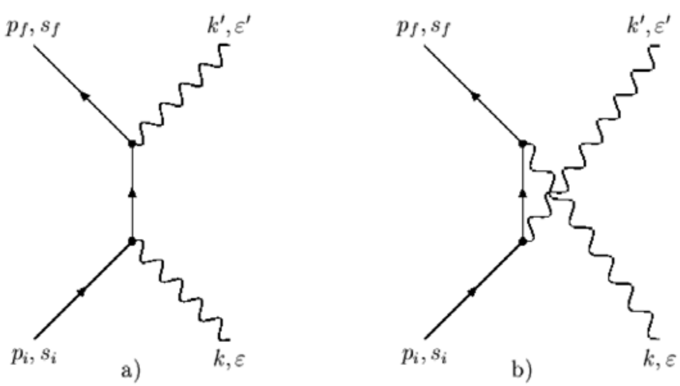
- Direct CR measurements on spacecraft are possible in a few locations at different heliospheric distances
- A sensitive gamma-ray telescope (e.g., GLAST) is able to constantly monitor the CR fluxes in a considerable part of the heliosphere

How?

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

LoS integration — CR flux

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

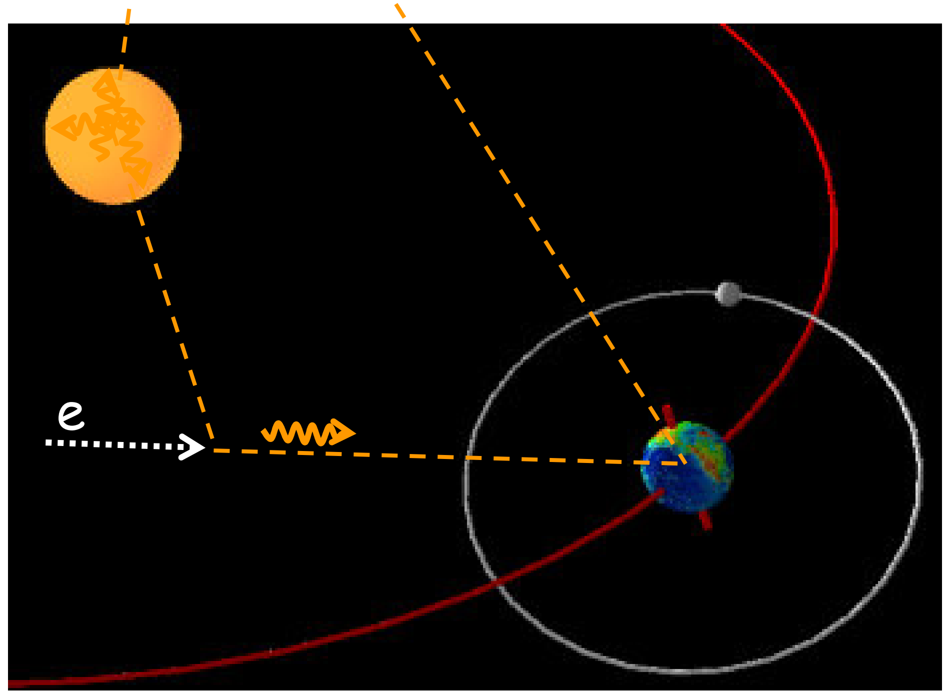
black body — Reaction rate

e

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

10 GeV e's ⇒ 100 MeV γ's

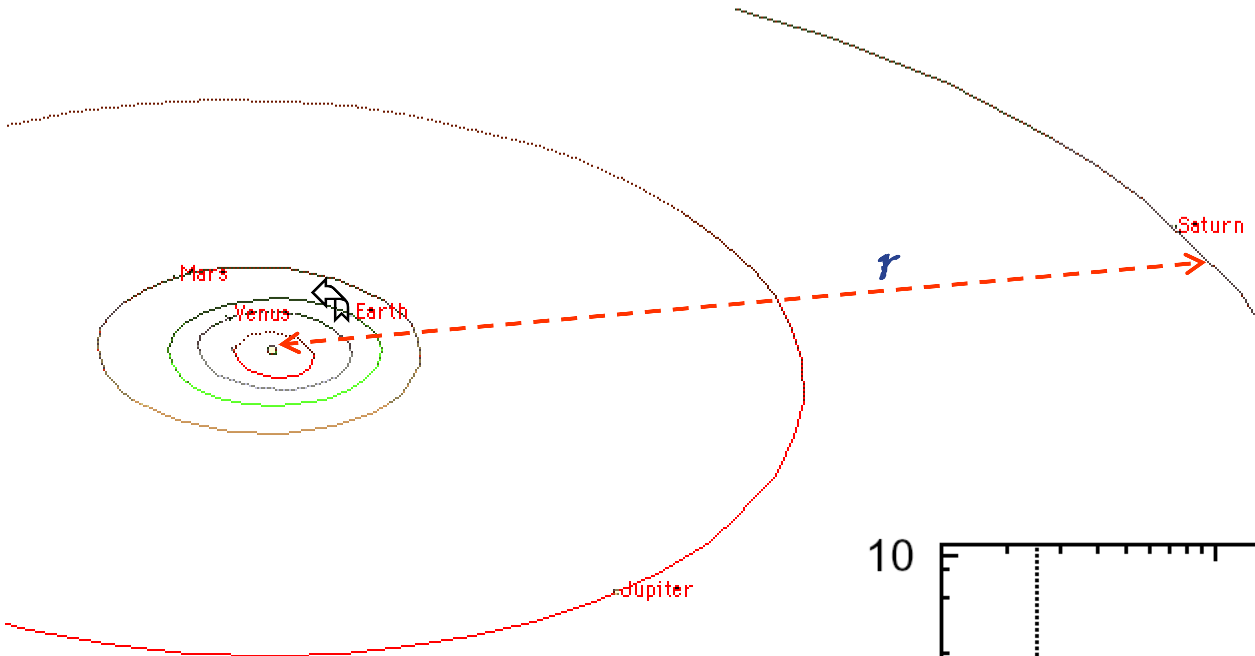
Target photons:
$\rho = 0.25 n_{bb} (R_\odot/r)^2$
$T_\odot = 6000$ K



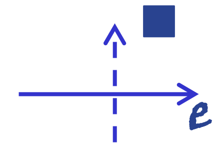
Following collision:
E_γ
$\sim(1/\gamma)\gamma\epsilon_\odot$
$\sim\epsilon_\odot$

IVM,Porter,Digel'06, Orlando & Strong'07

Heliosphere



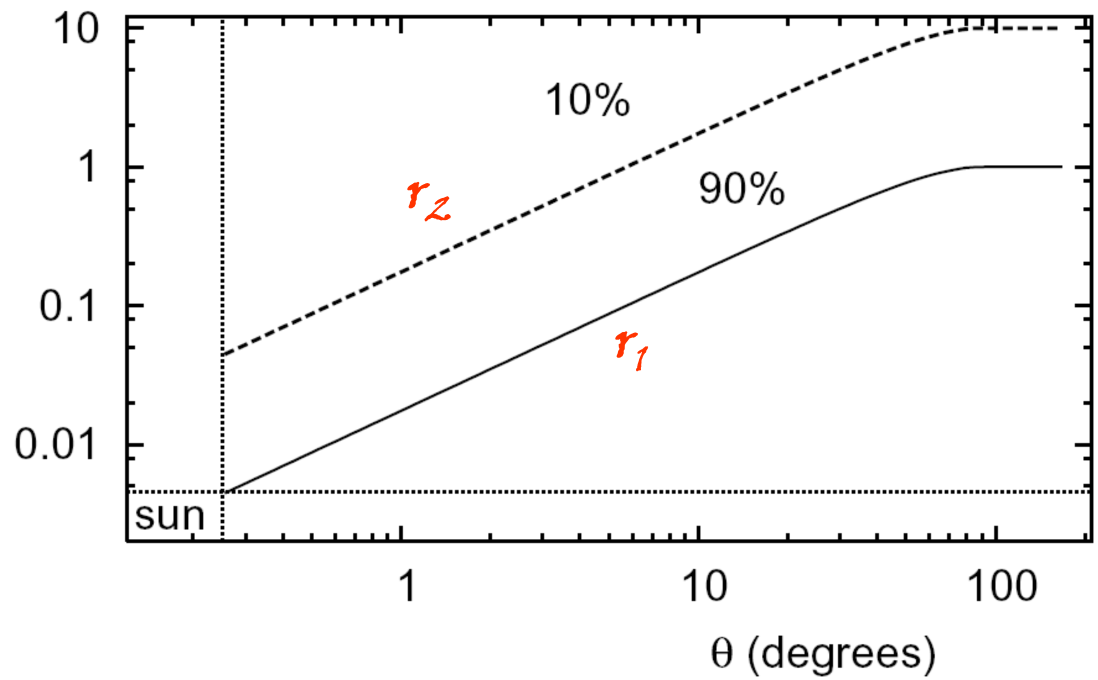
$Flux_{IC} \sim 1/r$



r_1 (AU) = sin❑, ❑<90°
r_1 (AU) = 1, ❑>90°

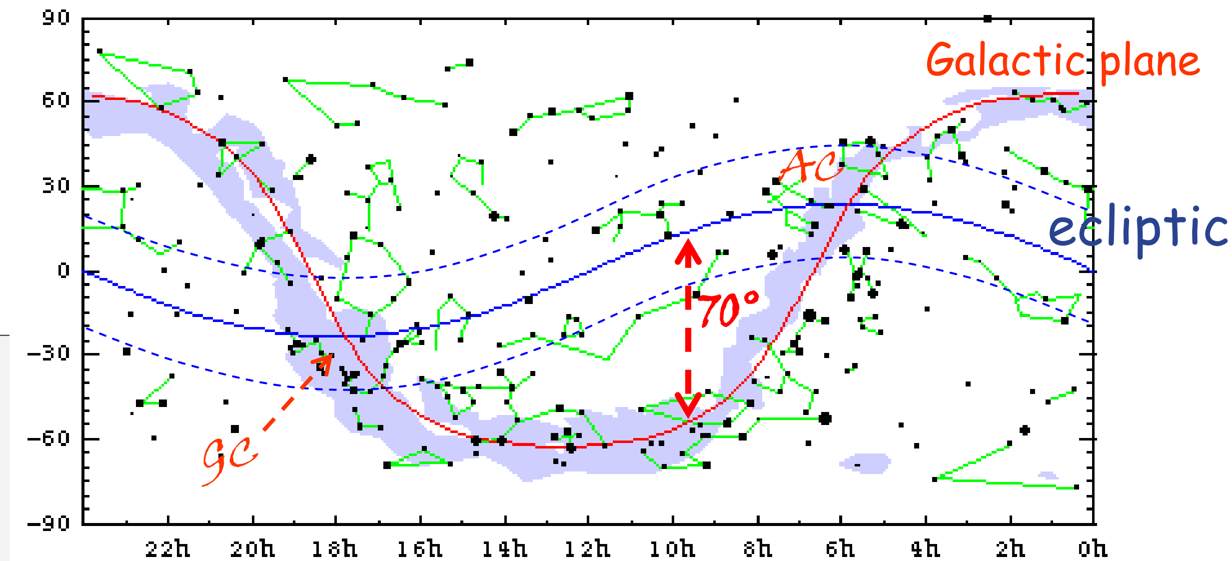
$r_2 = 10 r_1$

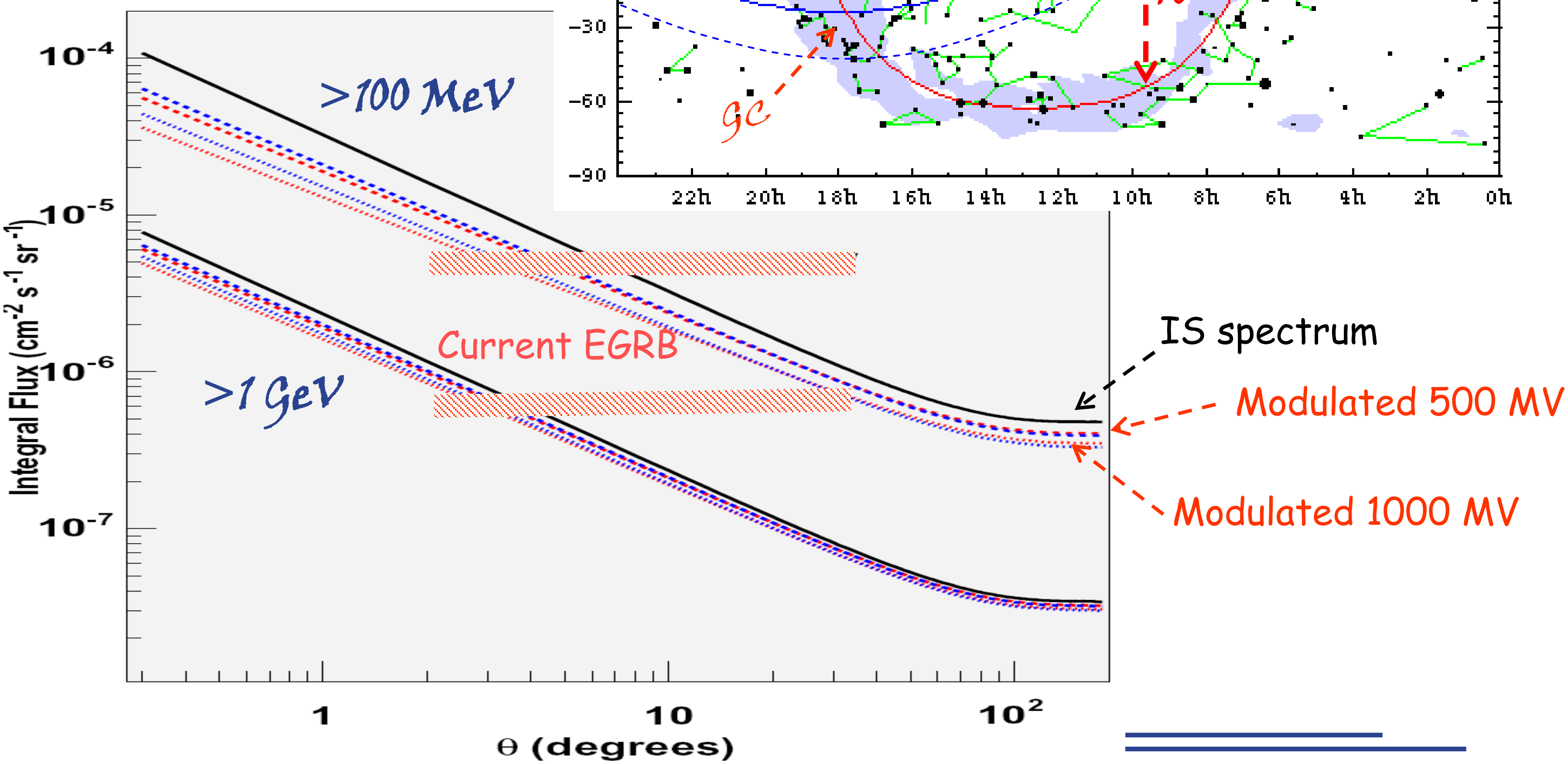
Looking in different directions one can probe the e-spectrum at different distances from the sun!



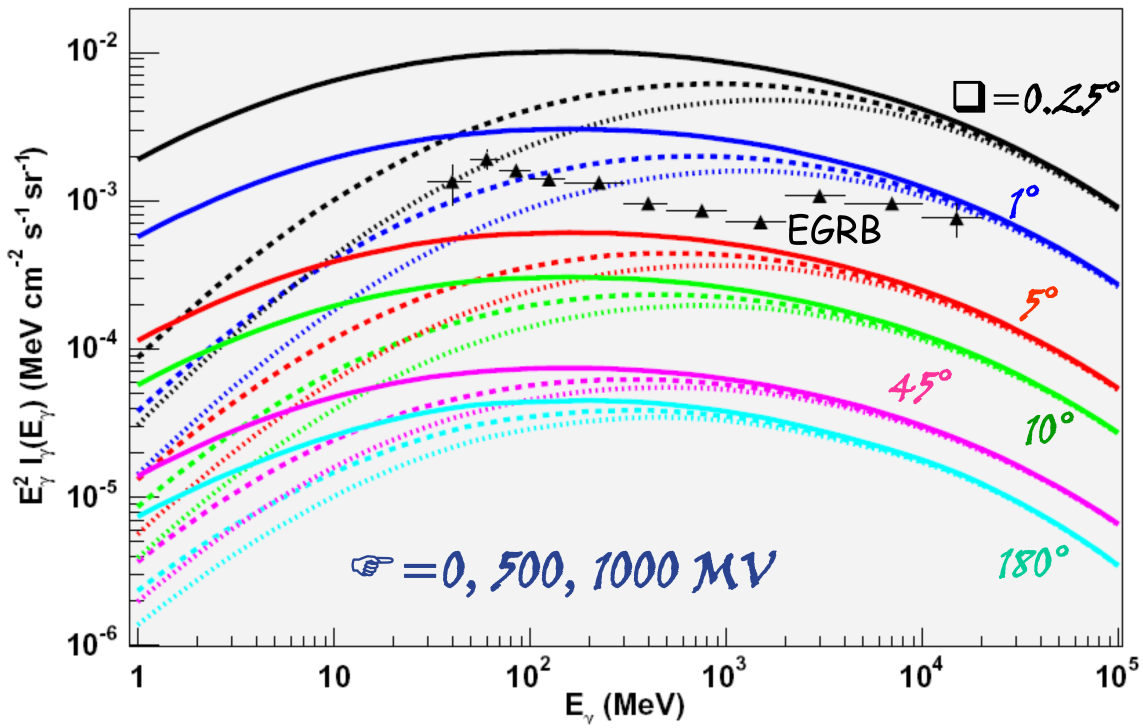
The ecliptic

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 γ-ray flux over the solar cycle

IC integral flux
F(>100 MeV, Θ<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}.

Found in EGRET data !

Thompson+ 1997:
Upper limit (>100 MeV):
2×10^{-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!!

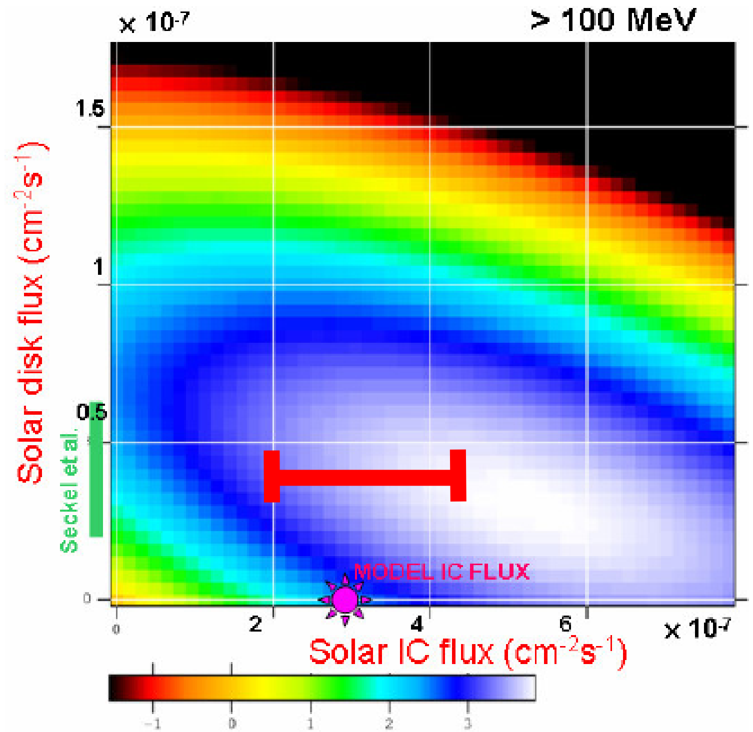


FIGURE 1. Log Likelihood above 100 MeV as function of the solar disk flux and extended solar flux, relative to point at (0,0). The level of our predicted IC model flux and the predicted disk flux [7] are shown.

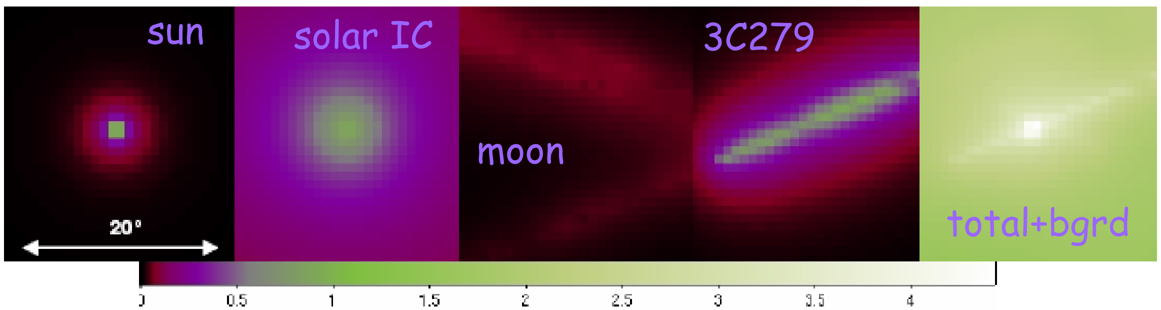
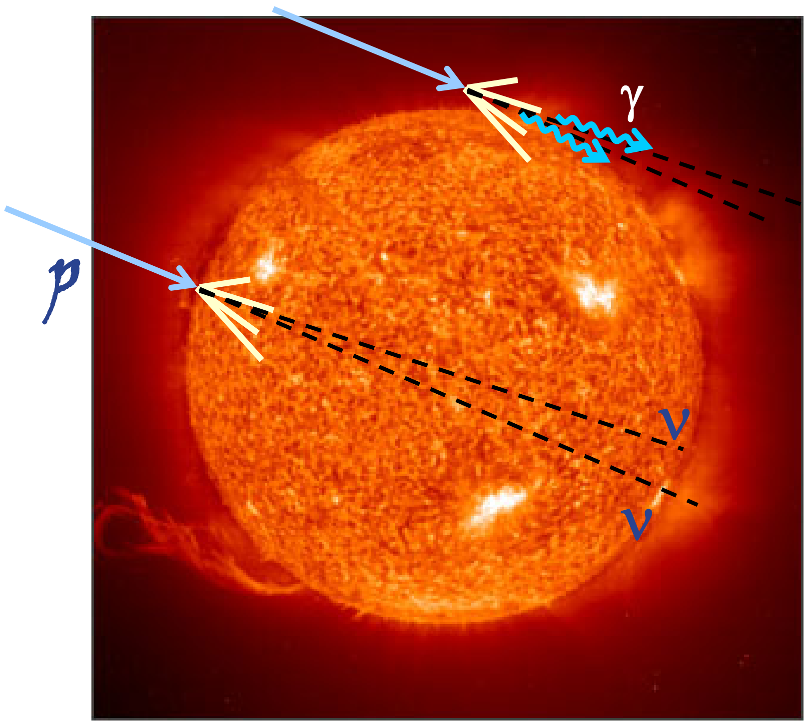


FIGURE 2. Fitted model counts of the main components centered on the Sun. From left to right: Sun disk, Sun IC, moon, 3C 279, and the total predicted counts including uniform background. The colors show the counts/pixel, for 0.5°× 0.5° pixels.

Gammas & neutrinos from the quiet sun



Solar "albedo" due to the interactions of CR particles with solar atmosphere: CRs produce cascades in the solar atmosphere

- Gamma rays can be observed (GLAST)
- 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

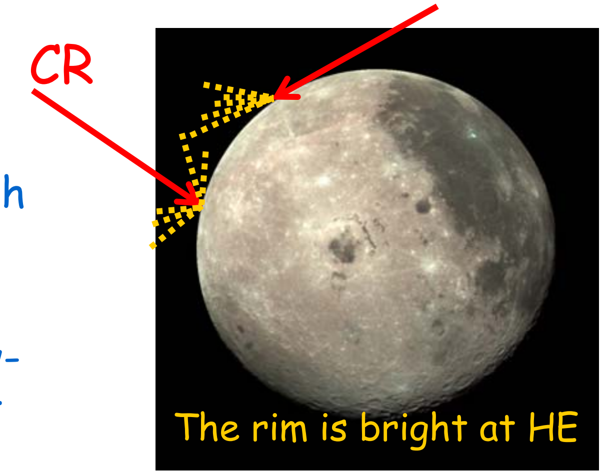
IVM+'91, Seckel+'91

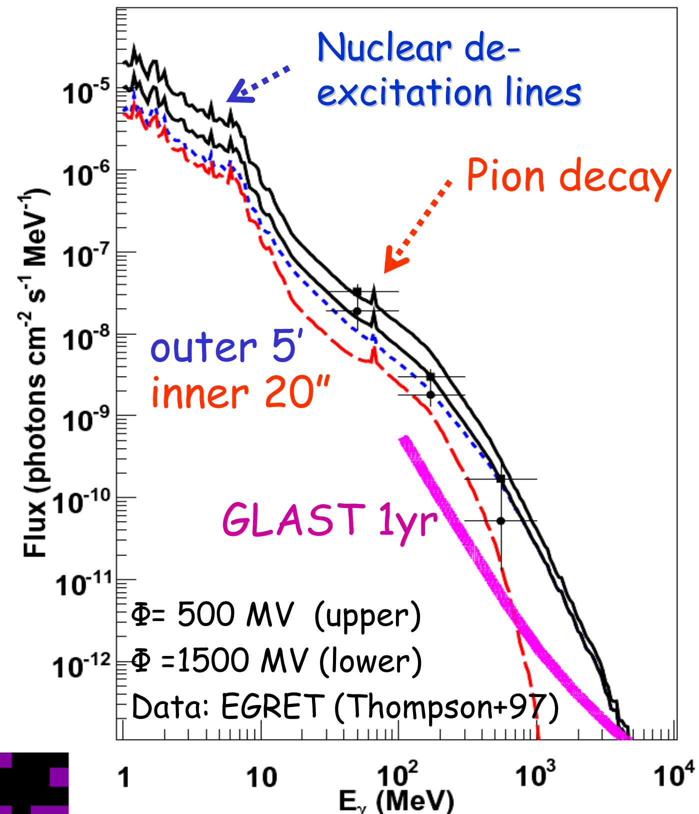
Dark Face of the Moon: Gamma-ray Albedo Spectrum

The moon is brighter in gamma rays than the sun!

Kinematics of the interaction:

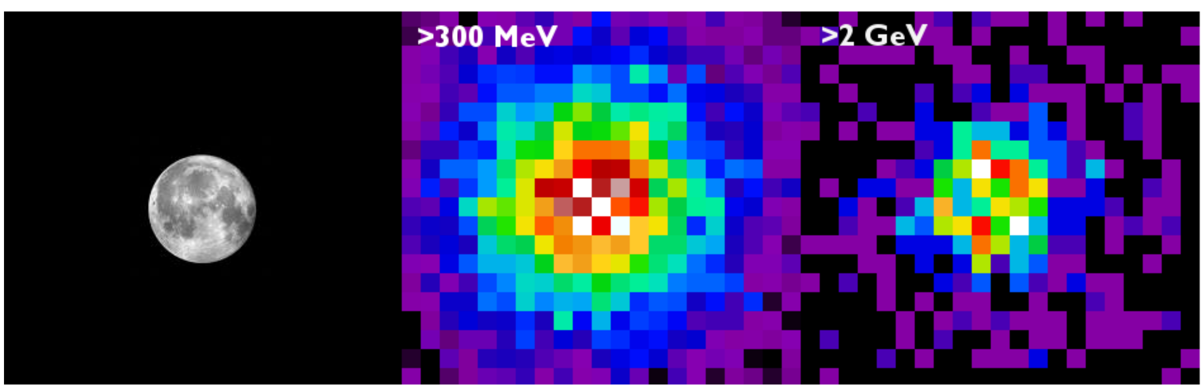
- The cascade goes through to the depth where gamma-rays cannot come out
- Splash pions are low-energy and decay at "rest"





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

Simulation of the GLAST observations



A Zoo of Small Solar System Bodies

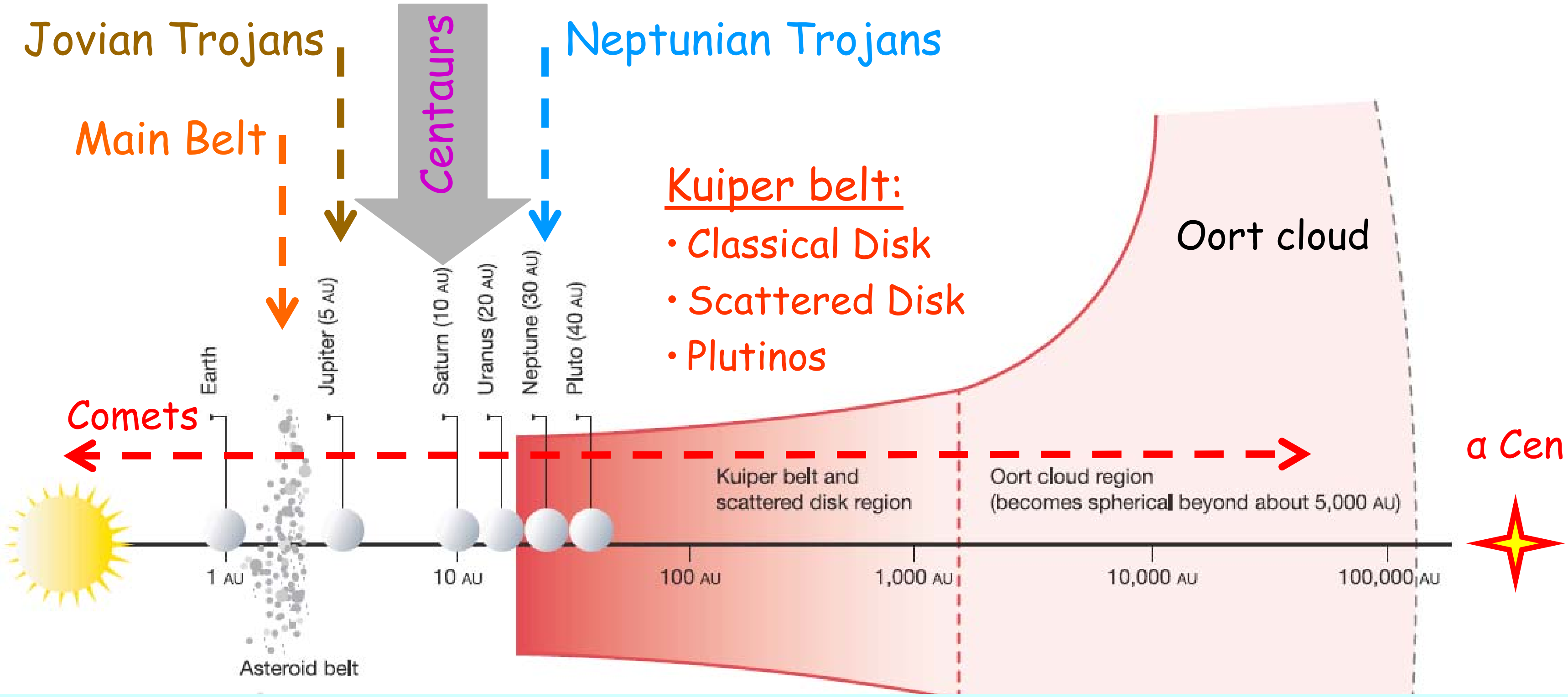


Table 1 **The primary cometary reservoirs of the Solar System**

	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

Hot Topics

- Formation and evolution of the planetary system and exo-solar planetary systems
  - 1992 (Jewitt & Luu) – first object beyond Neptune since Pluto
  - 2004, 2005 (Sheppard& Trujillo) – discovery of Neptunian Trojans (L4); L5 is currently in the direction of the GC
  - Ejection of material into distant eccentric orbits (Oort cloud)
  - Orbital precession (expansion/contraction) of the giant planets and SSSB families (Neptune: 20 AU -> 30 AU; Kuiper belt)
- The number of small solar system bodies in different dynamic families and their size distributionTest particles
  - Formation of planetesimals
  - Pristine material
  - "Freeze-in" capture (Trojans)

- Probe of interstellar spectrum of CR protons + He

SSSB Size Distributions

2. SMALL SOLAR SYSTEM BODIES

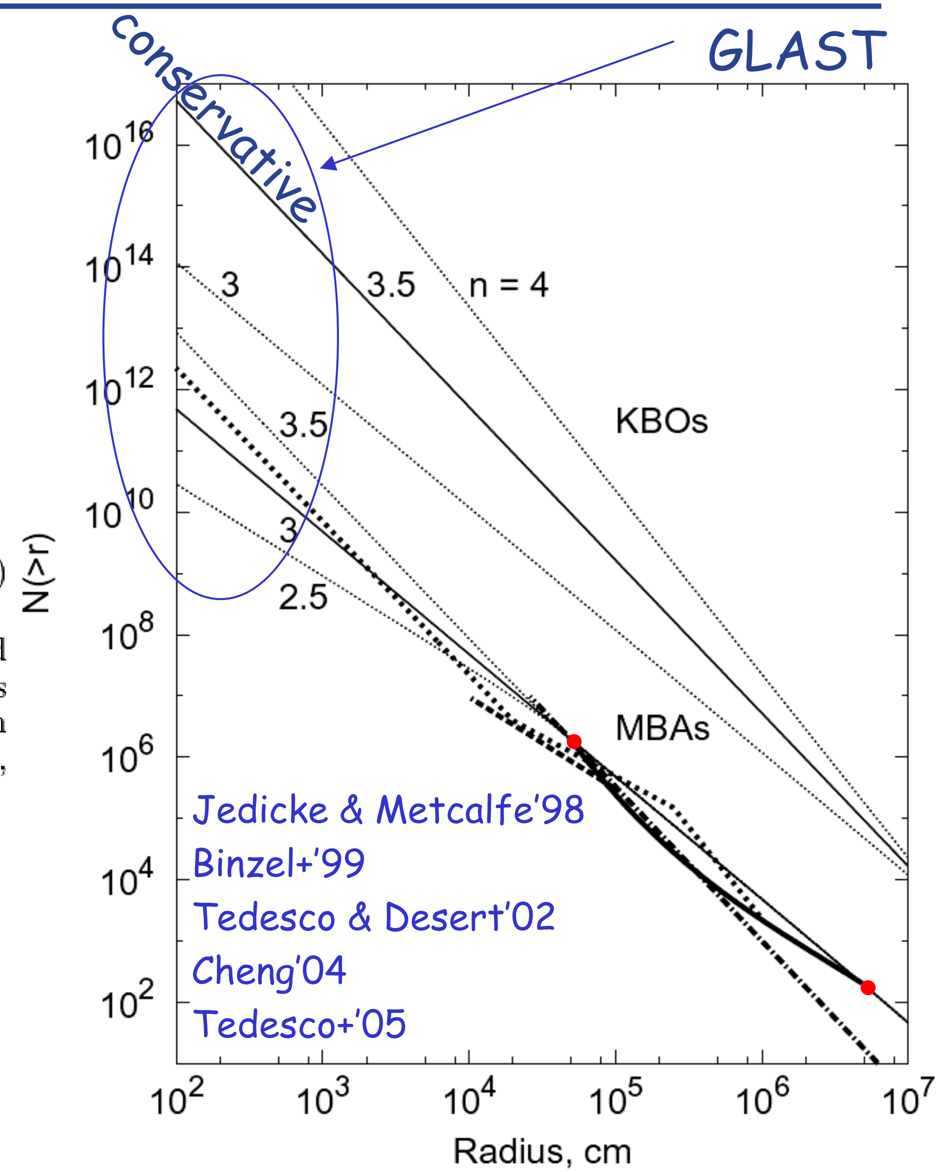
The asteroid mass and size distributions are thought to be governed by collisional evolution and accretion. Collisions between asteroids give rise to a cascade of fragments, shifting mass toward smaller sizes, while a small body impact with a much larger asteroid leads to the growth of the latter. The first comprehensive analytical description of such a collisional cascade is given by Dohnanyi (1969). Under the assumptions of scaling of the collisional response parameters and an upper cutoff in mass, the relaxed size and mass distributions approach power-laws:

$$dN = am^{-k}dm \quad (1)$$

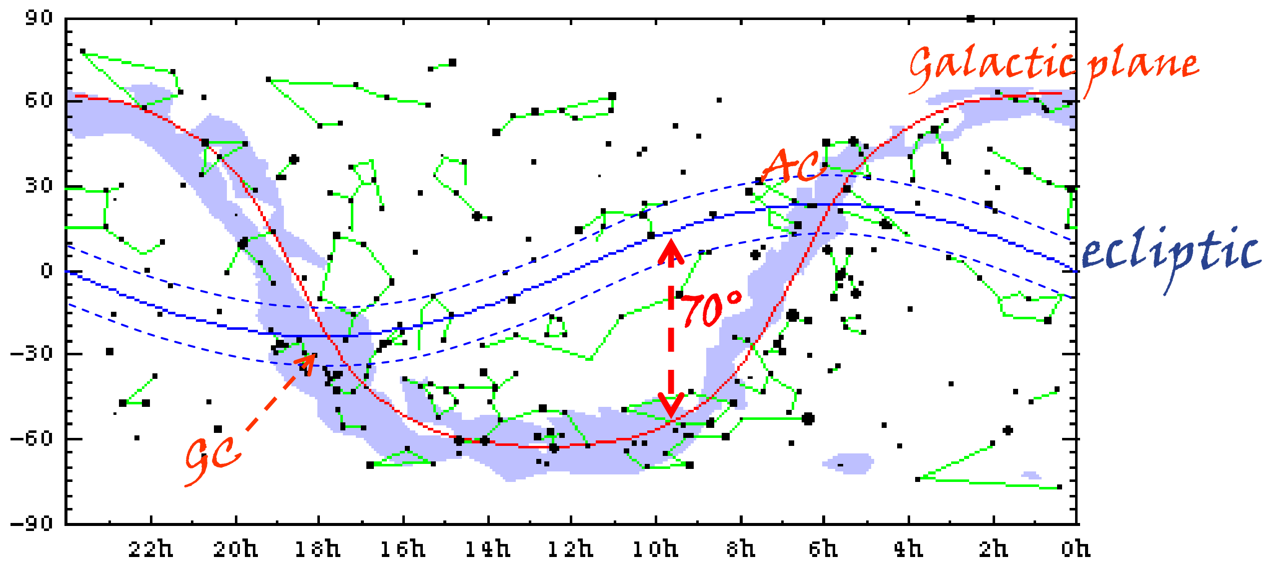
$$dN = br^{-n}dr, \quad (2)$$

where m is the asteroid mass, r is the asteroid radius, and a, b, k, n are constants. These equilibrium distributions extend over all size and mass ranges of the population except near its high-mass end. The constants in eqs. (1),

- Collisional evolution & accretion
- Relaxed size distribution n=3.5 (assuming scaling of collisional response parameters)
- Scaling breaks…



SSSB Albedo and the Ecliptic



- 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

Gamma-Ray Albedo Flux Estimates (Moon flux units)

- MBAs (sum over ecliptic latitude and longitude)
  $F_{tot}/F_{moon} \sim 0.06, 0.67, 10$ (n = 2.5, 3.0, 3.5)
  Changes by x5 with solar elongation angle (from 1.7 AU to 3.7 AU)

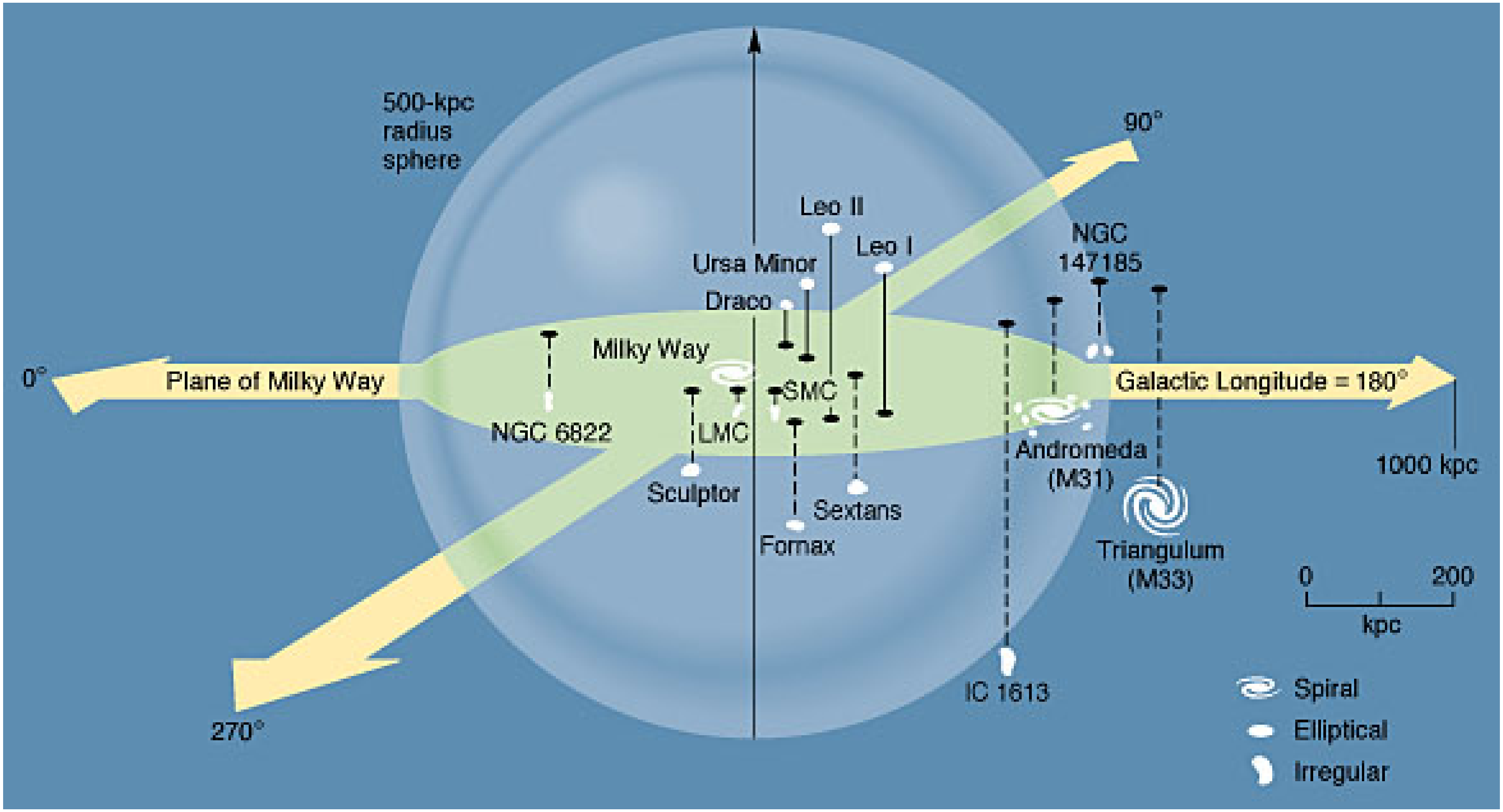
- Jovian Trojans (assuming the same size distr. as MBAs)
  $F_{tot}/F_{moon} \sim 0.009, 0.07, 0.77$ (n = 2.5, 3.0, 3.5) –average
  $F_{tot}/F_{moon} \sim 0.01, 0.1, 1.1$ (n = 2.5, 3.0, 3.5) -max
  $F_{tot}/F_{moon} \sim 0.006, 0.05, 0.5$ (n = 2.5, 3.0, 3.5) –min
  Concentrated in small bunches, positions are well known – relative to Jupiter

- KBOs (probe of the local interstellar CR spectrum!)
  $F_{tot}/F_{moon} \sim 0.2, 34, 1168$ (n = 3.0, 3.5, 3.9)
  Does not vary with solar elongation angle

cf. EGRET upper limit ~12 F_{Moon}

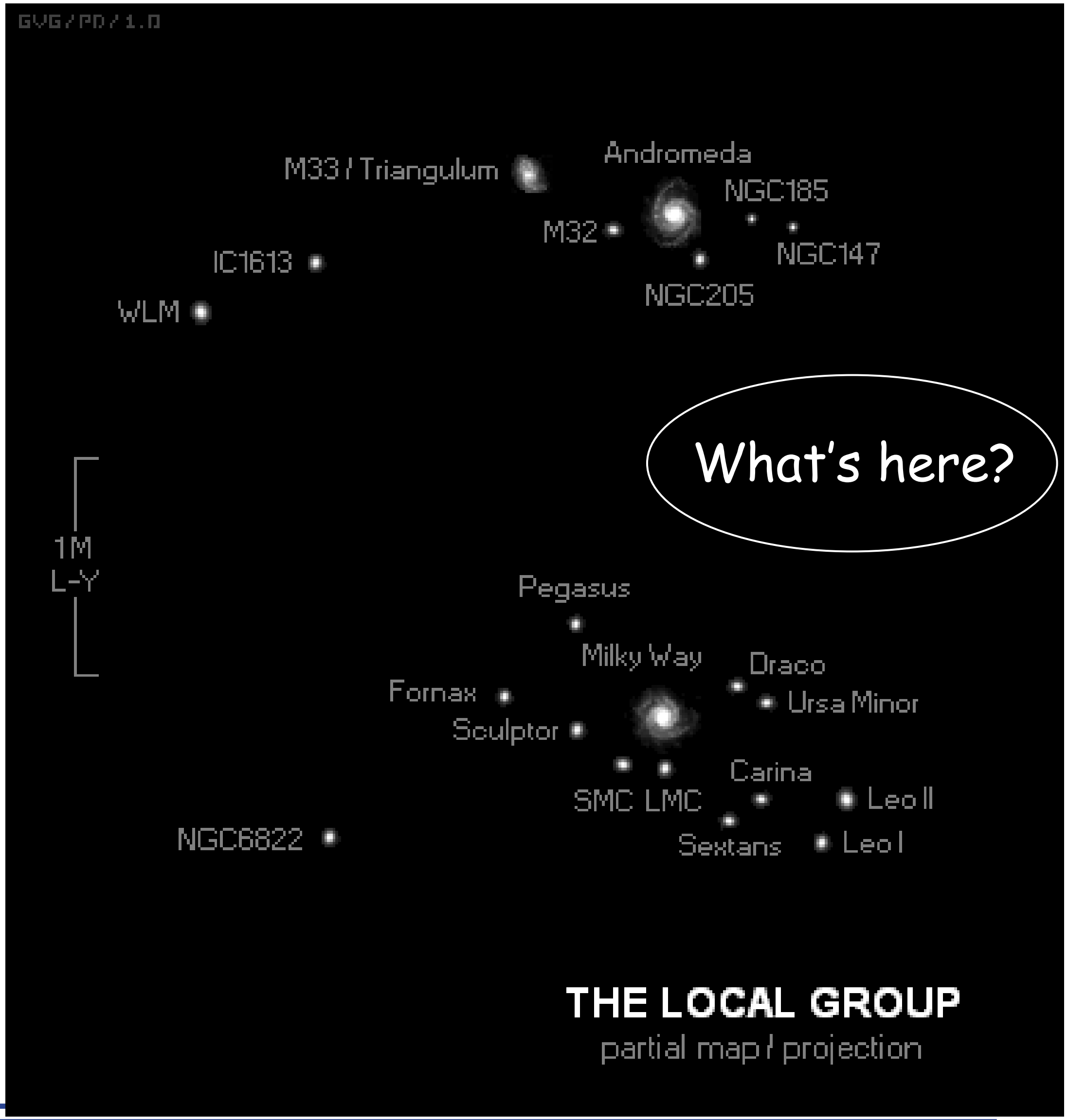
CRs in Other Normal Galaxies

Local Group Galaxies



Cosmic Rays – galactic or universal?

- Milky Way and M31 are the dominant galaxies in the group
- Many others are irregular or dwarf spheroidal
- Additional members are still being discovered



Summary: EGRET Observations

- LMC detection: CR density is similar to MW
- SMC non-detection: CR density is smaller than in the MW (otherwise it would be $\sim 2.4\times10^{-7}$ cm^{-2} s^{-1})
- First direct evidence:

  CRs are galactic and not universal !

- M31 non-detection: has to have smaller CR density than the MW (size M31>MW!)

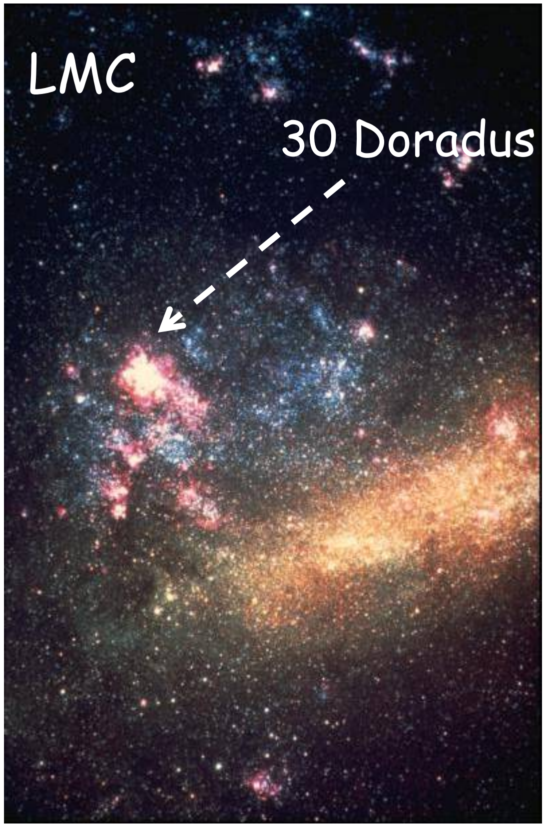
Source	F(>100 MeV), cm^{-2} s^{-1}
LMC	$(1.9\pm0.4)\times10^{-7}$
SMC	$<0.5\times10^{-7}$
M31	$<0.8\times10^{-7}$

Sreekumar et al.(1992-94)

L_{MW}(>100 MeV)$\sim 5.4\times10^{39}$ erg/s (SMR00)
$\sim 3\times10^{43}$ phot/s

F_{MW}(@M31 distance) $\sim 4.4\times10^{-7}$cm^{-2} s^{-1}

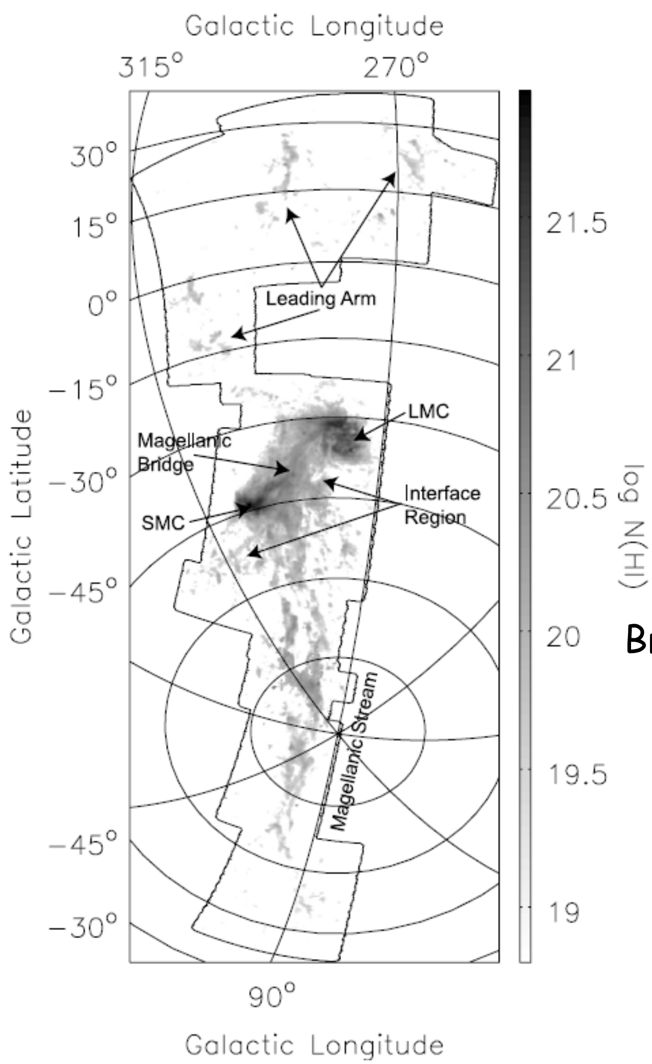
Magellanic Clouds

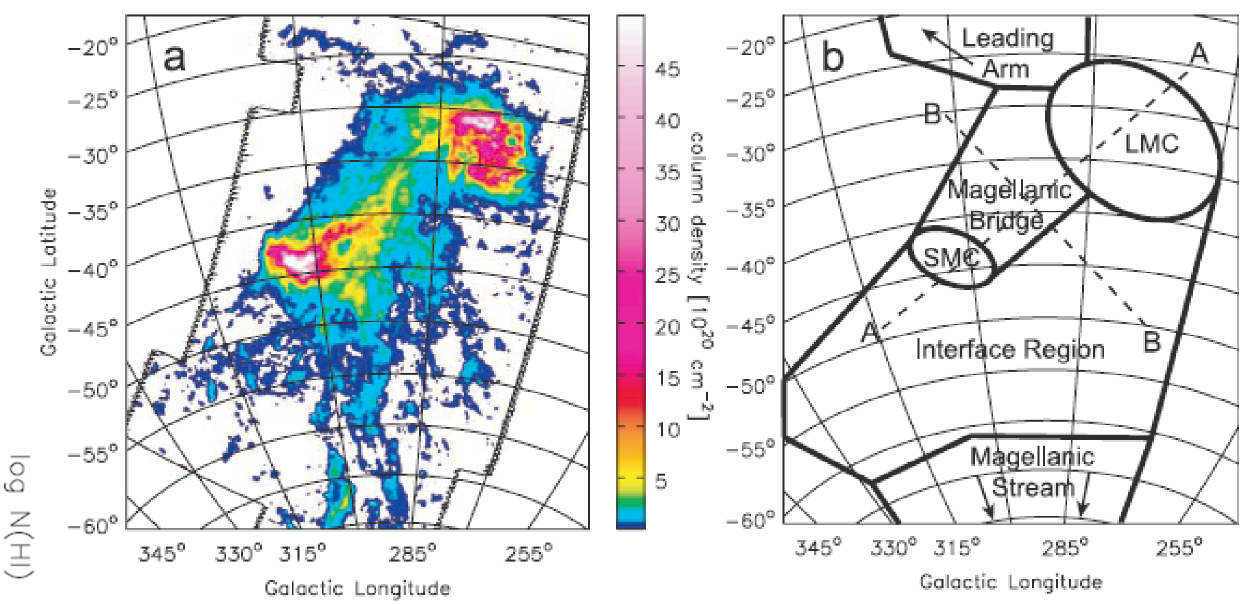


Type: Im IV-V
Magnitude: 2.3
Size: 280 x 160 arcmin <kpc
Distance: ~60 kpc

Type: Irr/SB(s)m
Magnitude: 0.9
Size: ~10°x10° ~few kpc
Distance: ~50 kpc

Parkes HI survey: LMC & SMC





Brüns et al. (2005)

	HI ($\times 10^8\ M_\odot$)
LMC	$(4.41\pm0.09)\times[d/50\mathrm{kpc}]^2$
SMC	$(4.02\pm0.08)\times[d/60\mathrm{kpc}]^2$
Bridge	$1.84\times[d/55\mathrm{kpc}]^2$
Interface	$1.49\times[d/55\mathrm{kpc}]^2$

Andromeda Galaxy: M31

Type: SA(s)b I-II

(Hubble: ordinary spiral s-shaped with well defined arms)

Magnitude: 3.4

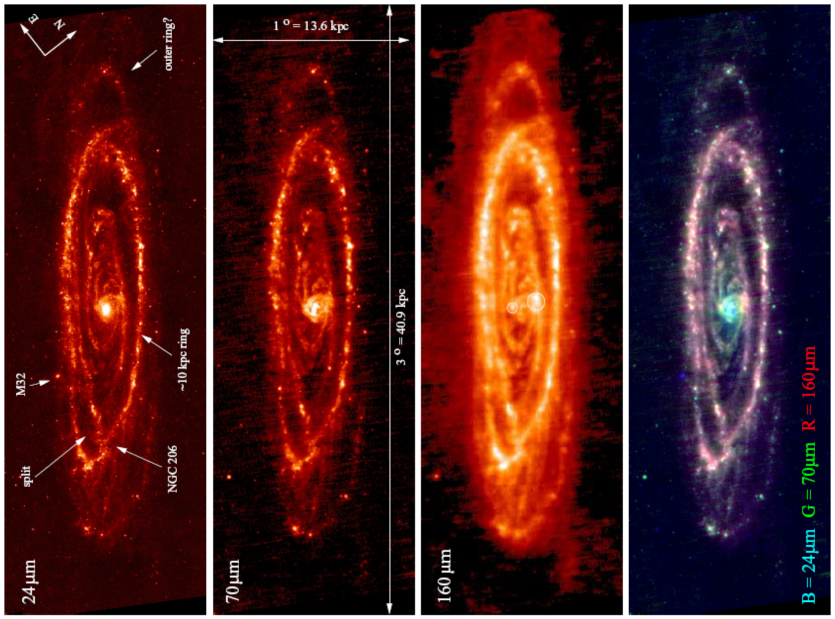
Size: 185.0 x 75.0 arcmin

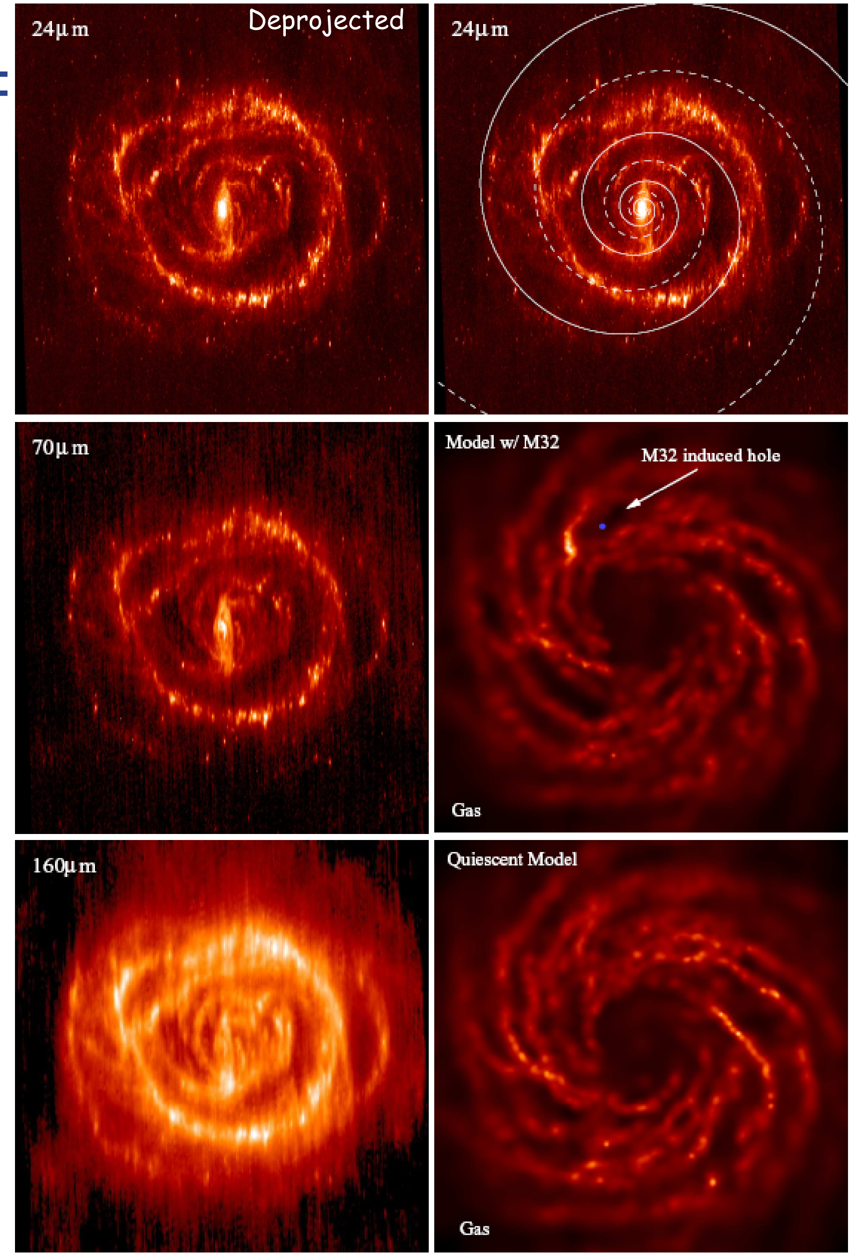
>50 kpc

Distance: 725 kpc

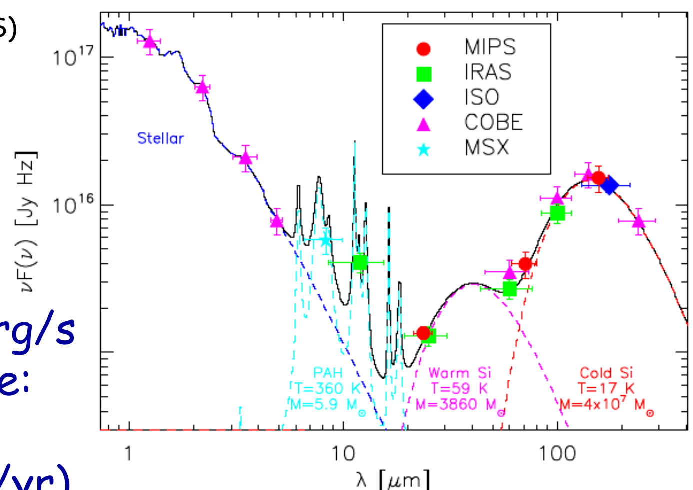
Larger than the Milky Way!

Radiation Field in M31





Gordon et al. 2006 (MIPS)



L_{IR}~1.7x10^{43} erg/s
Star form. rate:
~0.75 M_*/yr
(cf. MW ~3M_*/yr)

Some Math (Pavlidou & Fields 2001)

Transport equation for CR number density (steady-state leaky-box):

$$\frac{\partial N_i(T,t)}{\partial t} = Q_i(T,t) + \frac{\partial}{\partial T}[b_i(T)N_i(T,t)] - \frac{1}{\tau_{\rm esc}} N_i(T,t)$$

Trivial solution:

$$0 = Q_p(T) - \frac{1}{\tau_{\rm esc}} N_p(T)$$

In terms of CR flux:

$$\phi_p(T) = l_{\rm esc}\, Q_p(T)$$

$$l_{\rm esc} = \tau_{\rm esc}\, v$$

$$l_{esc}(G) \sim l_{esc}(MW)$$

Assuming CR injection rate proportional to SN rate: $Q_p^G \propto \mathcal{R}_G$

CR flux in a galaxy G:

$$\frac{\phi_p^G}{\phi_p^{\rm MW}} = \frac{\mathcal{R}_G}{\mathcal{R}_{\rm MW}} = f_G$$

Some Math (cont'd)

γ-ray flux from a galaxy:

$$F_\gamma^G = \frac{1}{4\pi d^2}\frac{M_{\text{gas}}}{m_p} q_\gamma^G$$

$$q_\gamma^G(>100\ \text{MeV}) = 2.36 \times 10^{-25} f_G\ \text{photons s}^{-1}\ (\text{H atom})^{-1}$$

Emissivity calcs q(>100 MeV): pp→ π^0 x1.55 (bremss) x1.5 (A>1 nuclei)

Combined:

$$F_\gamma^G(>100\ \text{MeV}) = 2.34 \times 10^{-8} f_G \frac{M_{\text{gas}}}{10^8\ M_\odot} \times \left(\frac{d}{100\ \text{kpc}}\right)^{-2} \text{photons cm}^{-2}\ \text{s}^{-1}$$

Properties of the LG galaxies & γ-ray flux

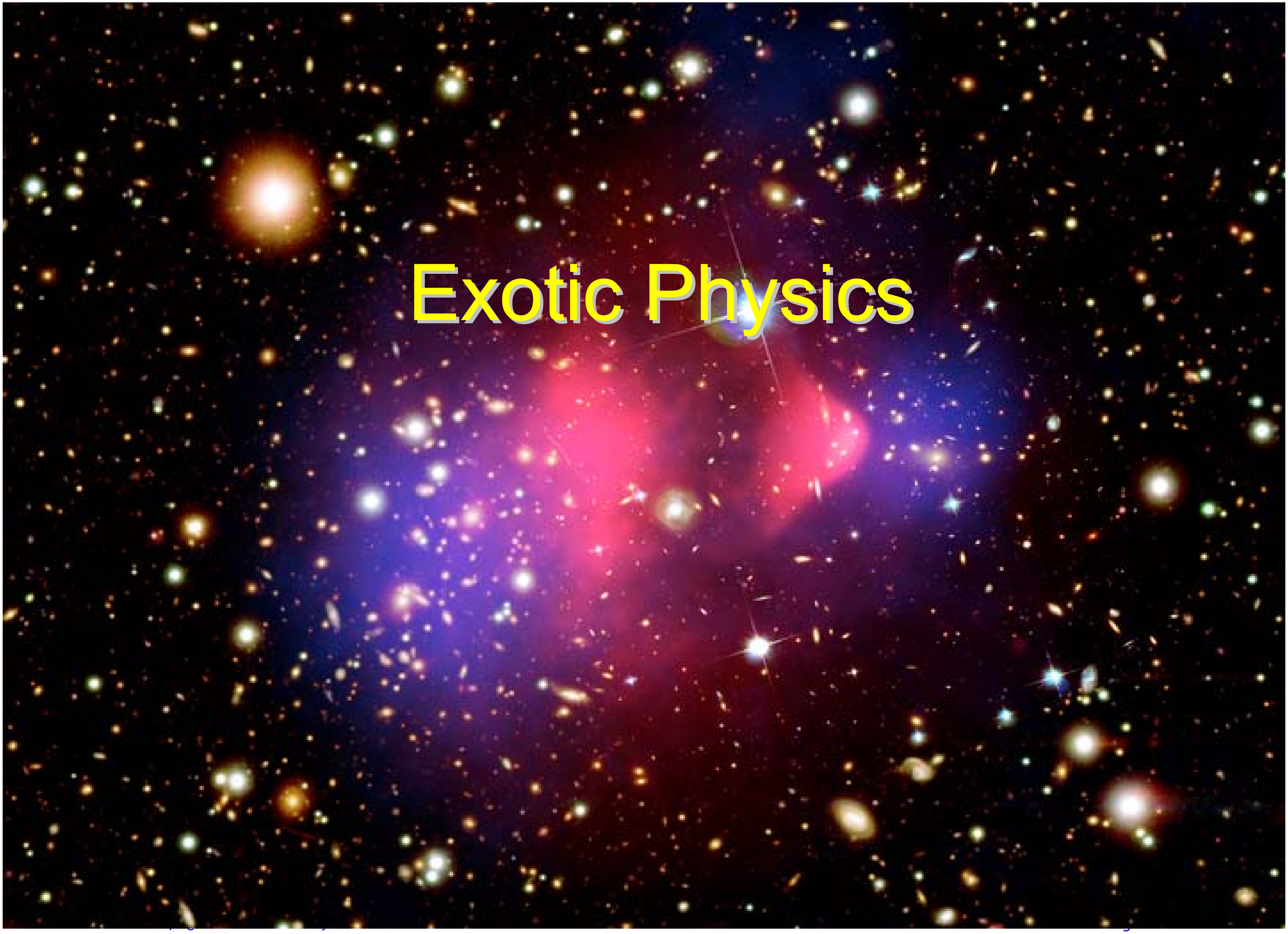
Observed Properties of Selected Local Group Galaxies

$$\Sigma = \frac{M_{gas}}{d^2}$$

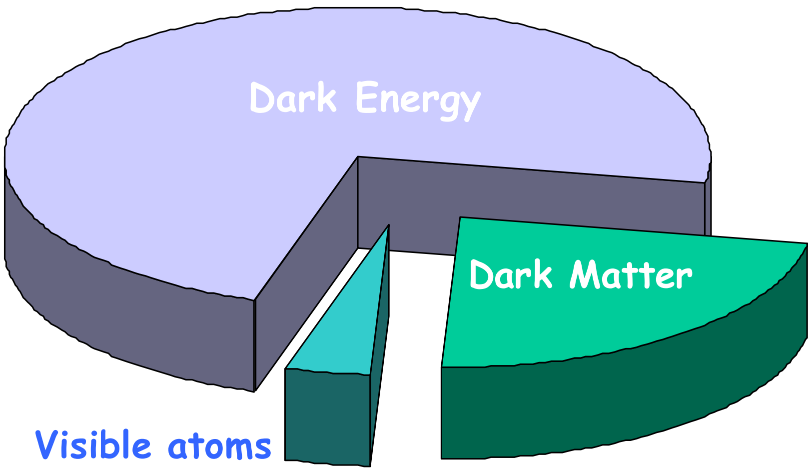
Galaxy		SN Rate (century^{-1})	Adopted f	Σ HI ($\times 10^4\ M_\odot$ kpc^{-2})	$M_\bullet$	Σ H_2 ($\times 10^4\ M_\odot$ kpc^{-2})	$M_\bullet$	Σ total ($\times 10^4\ M_\odot$ kpc^{-2})	$M_\bullet$
LMC	50 kpc	0.1,[a] 0.23,[b] 0.49[c]	0.14	22 ± 6[d,e,f,g]	5.5×10^8	4.63[g]	1.2×10^8	26.6	6.7×10^8
SMC	60 kpc	0.065,[b] 0.12[c]	0.04	17 ± 4[d,h]	6.1×10^8	0.76[g]	0.3×10^8	17.8	6.4×10^8
M31	725kpc	0.9,[i] 1.21,[c] 1.25[j]	0.45	0.9 ± 0.2[d,k]	4.7×10^9	0.06[l]	0.3×10^9	0.92	5.0×10^9
M33	795kpc	0.28,[m] 0.35,[i] 0.68[c]	0.17	0.26 ± 0.05[d]	1.6×10^9	0.004[n]	0.3×10^8	0.264	1.6×10^9
NGC 6822		0.04[o]	0.02	0.05 ± 0.02[d]		0.006[p]		0.056	
IC 10		0.082–0.11[q]	0.04	0.016 ± 0.003[r]		$\gtrsim 10^{-5}$[s]		0.016	
MW		~2.5		HI ~ H_2					(2-6)x10^9

Predicted Gamma-Ray Flux and *GLAST* Requirements for Selected Local Group Galaxies

Galaxy	Flux > 100 MeV: Prediction (photons cm^{-2} s^{-1})	Flux > 100 MeV: EGRET Value/Limit (photons cm^{-2} s^{-1})	*GLAST* Significance: 2 yr (σ)	*GLAST* Significance: 10 yr (σ)	*GLAST* On-Target 5 σ Exposure Time (yr)
LMC	11×10^{-8}	$(14.4 \pm 4.7) \times 10^{-8}$	42	93	4.6×10^{-3}
SMC	1.7×10^{-8}	$<4 \times 10^{-8}$	19	43	2.1×10^{-2}
M31	1.0×10^{-8}	$<1.6 \times 10^{-8}$	13	31	4.1×10^{-2}
M33	0.11×10^{-8}	...	1.9	4.1	2.31
NGC 6822	2.6×10^{-11}	...	0.04	0.09	$\gg 10$
IC 10	2.1×10^{-11}	...	0.02	0.05	$\gg 10$


Exotic Physics

Matter, Dark Matter, Dark Energy…



$\Omega \equiv \rho/\rho_{crit}$

Ω_{tot}	=1.02	+/-0.02
Ω_{Matter}	=4.4%	+/-0.4%
Ω_{DM}	=23%	+/-4%
Ω_{Vacuum}	=73%	+/-4%

SUSY DM candidate has also other reasons to exist -particle physics…

Supersymmetry is a mathematically beautiful theory, and would give rise to a very predictive scenario, if it is not broken in an unknown way which unfortunately introduces a large number of unknown parameters…

Lars Bergström (2000)

Where is the DM ?!

took from
E.Bloom presentation

Flavors:

- Neutrinos ~ visible matter
- Super-heavy relics: "wimpzillas"
- Axions
- Topological objects "Q-balls"
- ✓ Neutralino-like, KK-like

Places:

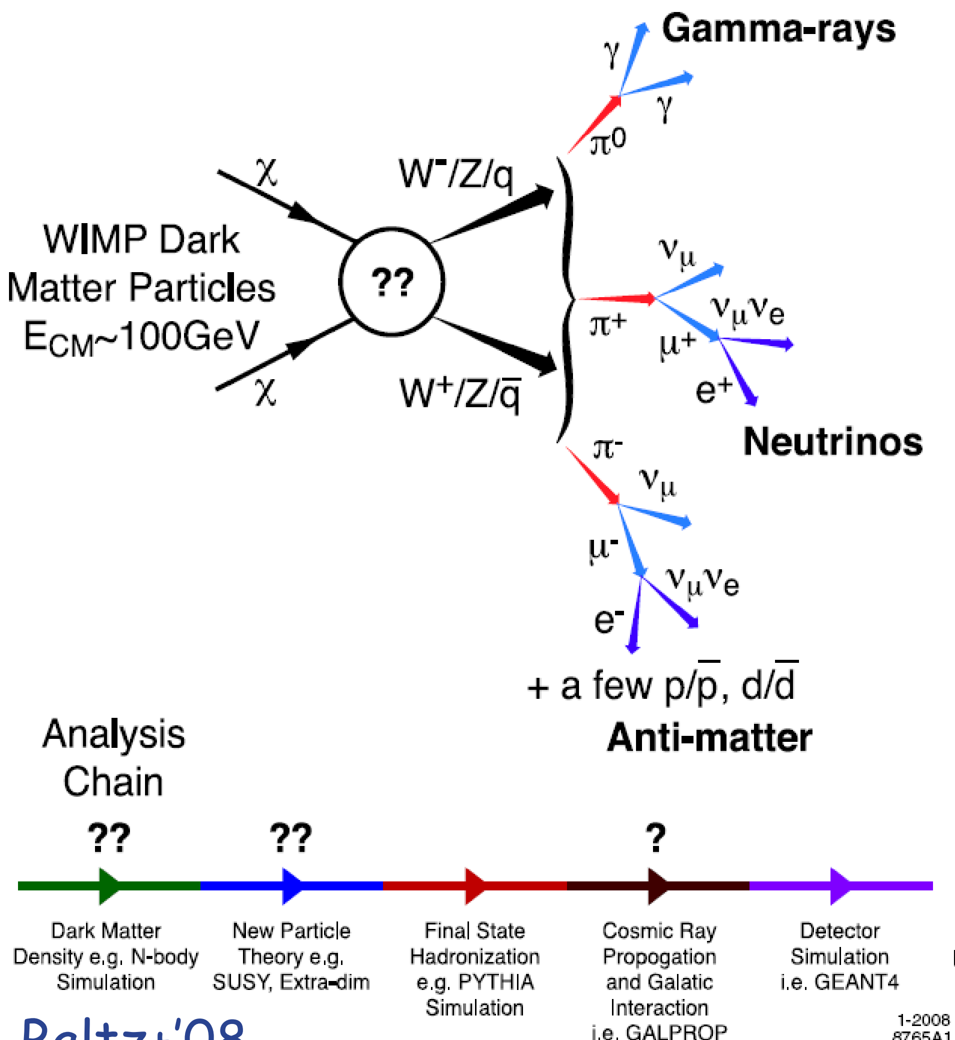
- ✓ Galactic halo, Galactic center
- ❖ The sun and the Earth

Tools:

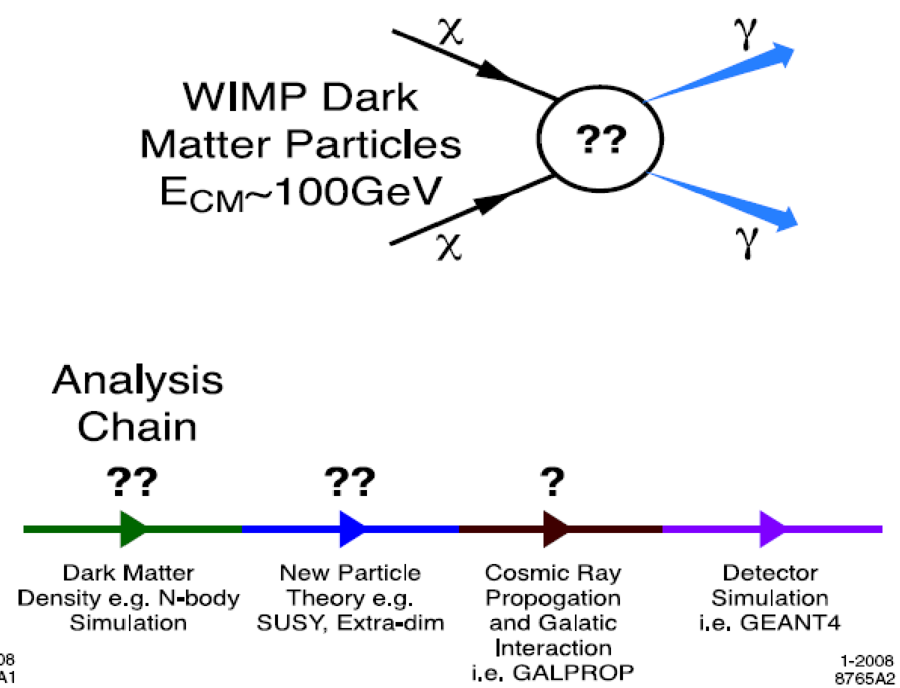
- ❑ Direct searches
  - low-background experiments (DAMA, EDELWEISS)
  - Accelerators (LHC)
- ✓ Indirect searches
  - neutrino detectors (AMANDA/IceCUBE)
  - CR, γ's (*PAMELA,GLAST,BESS*)

DM signal analysis chain

Annihilation into secondary particles



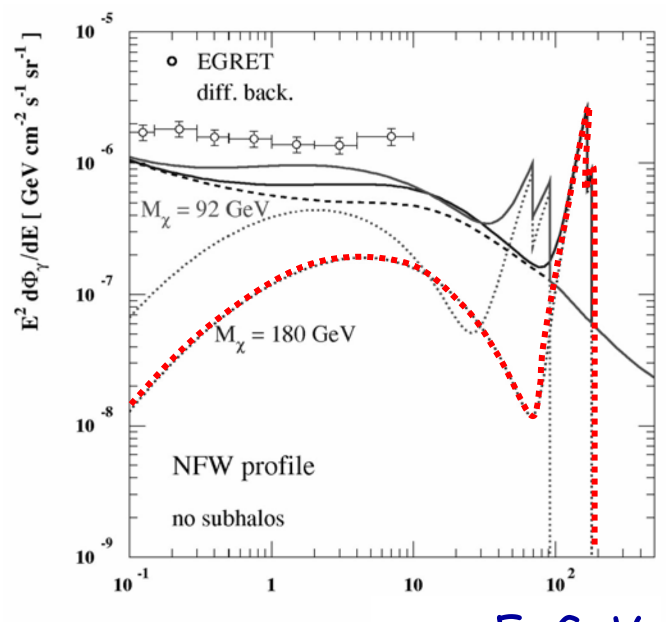
Direct annihilation into 2γ



Baltz+'08

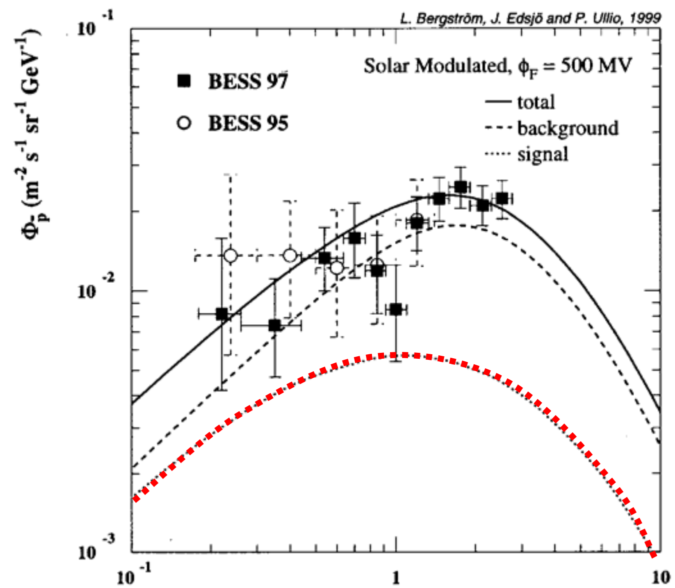
Examples of Dark Matter Signatures in CR

Diffuse gammas



E, GeV

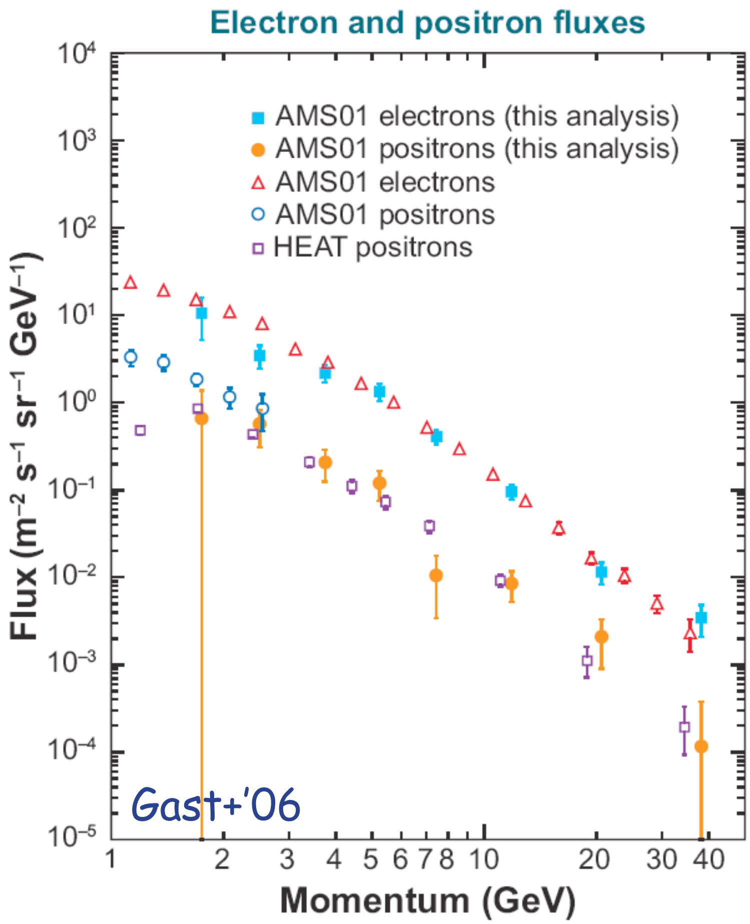
Antiprotons



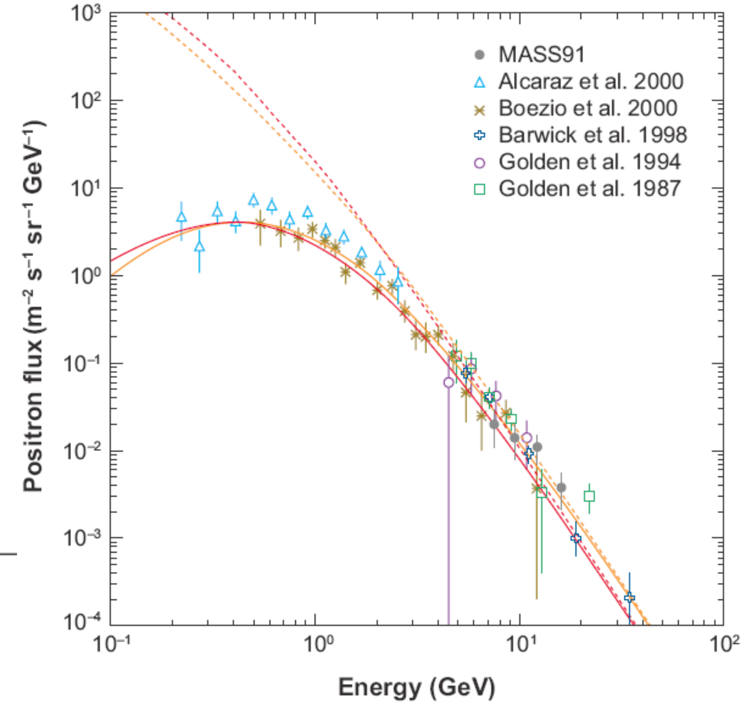
E_k, GeV

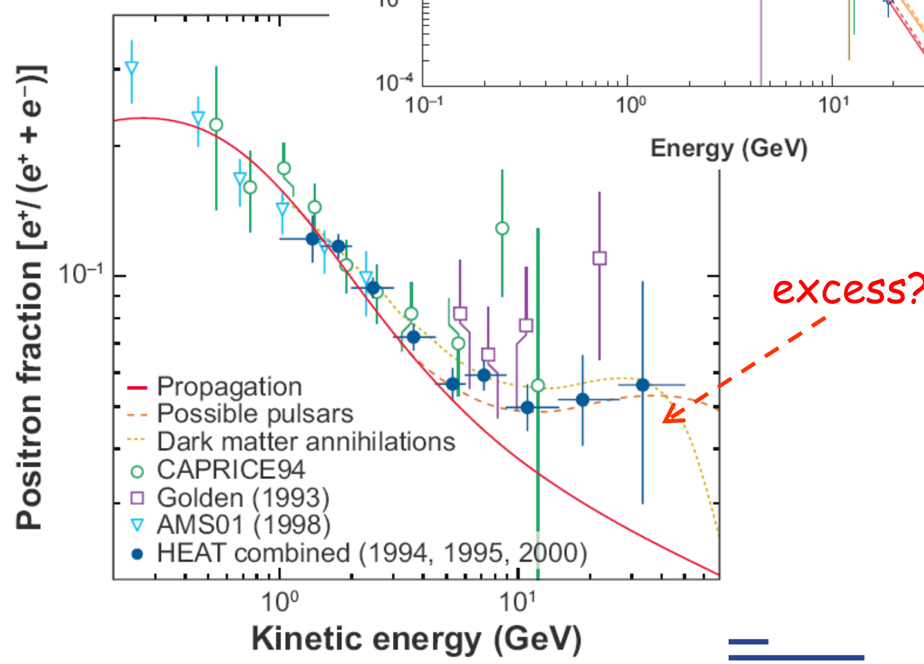
Look for a consistent signal in diffuse gamma rays, and CRs (antiprotons, antideuterons, positrons)

Positrons

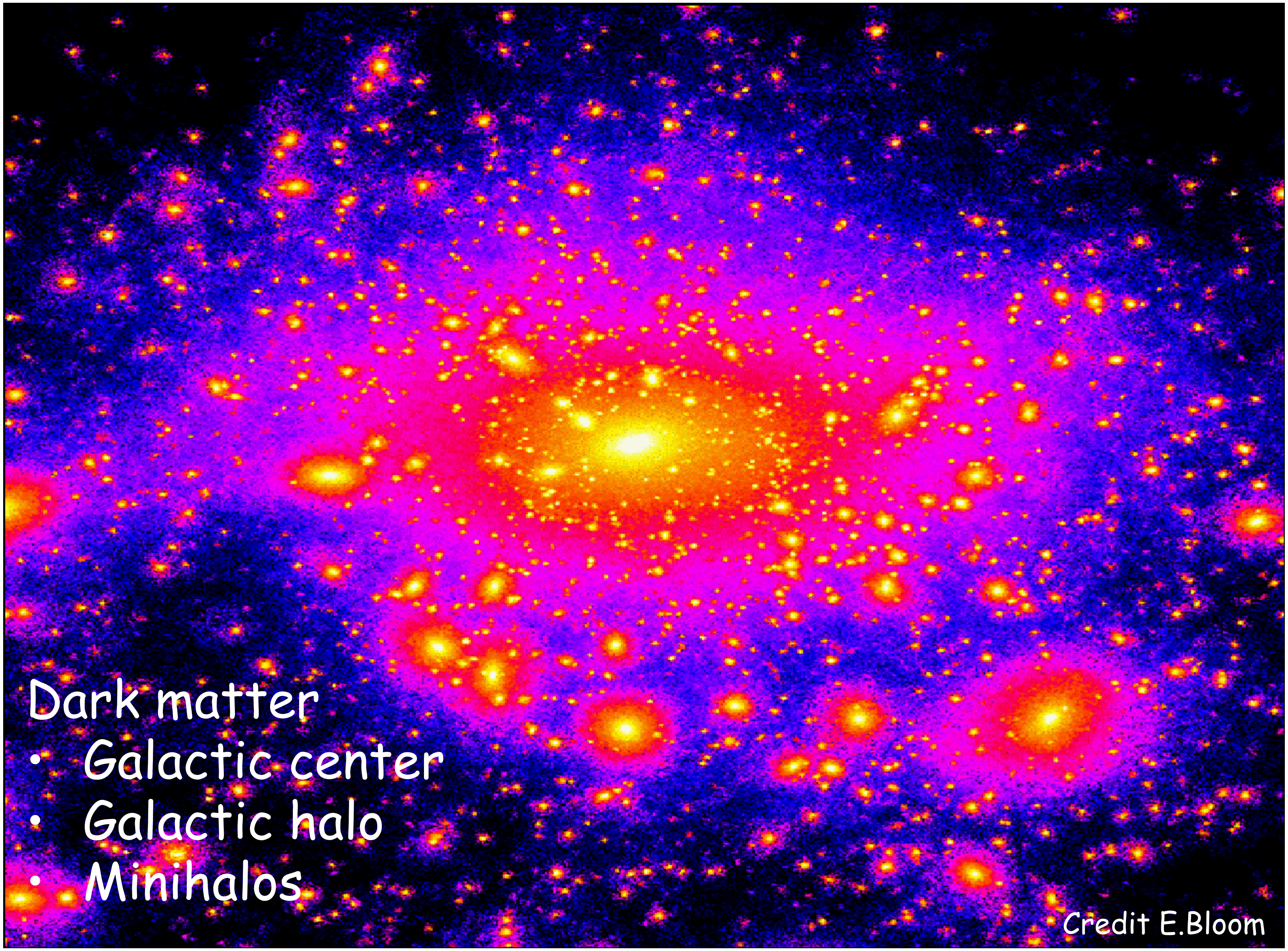


Positron flux is consistent with predictions, but the error bars are large



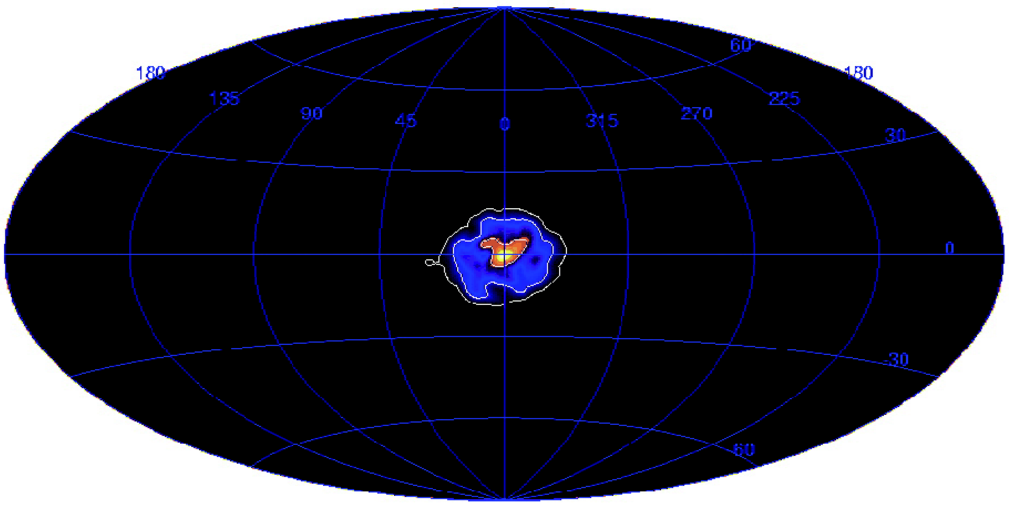


Simulated DM skymap

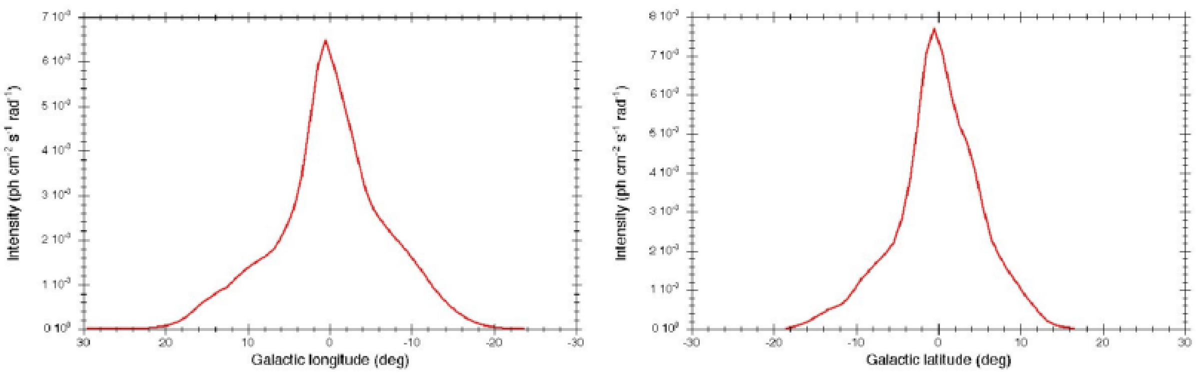


INTEGRAL/SPI observations of 511 keV line

511 keV skymap



Longitude and latitude profiles

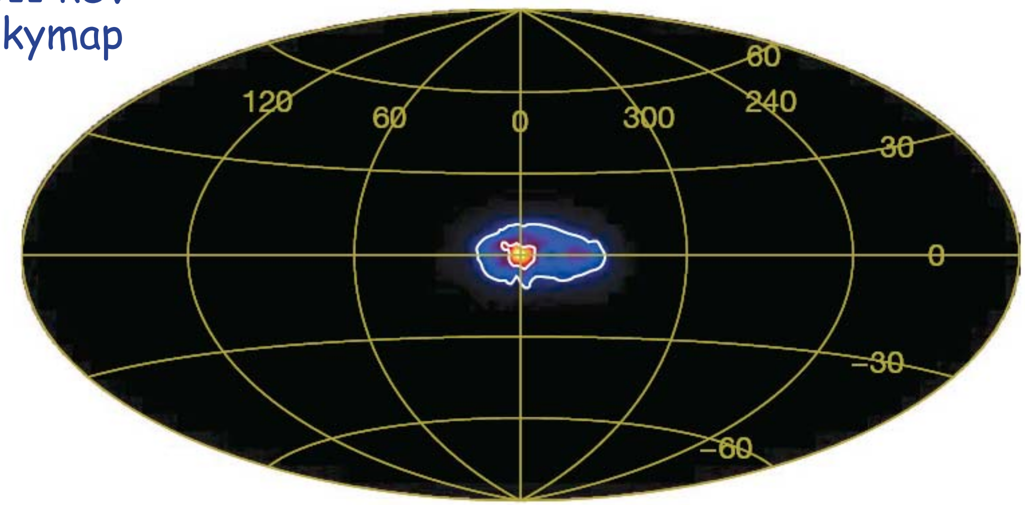


Clueless:

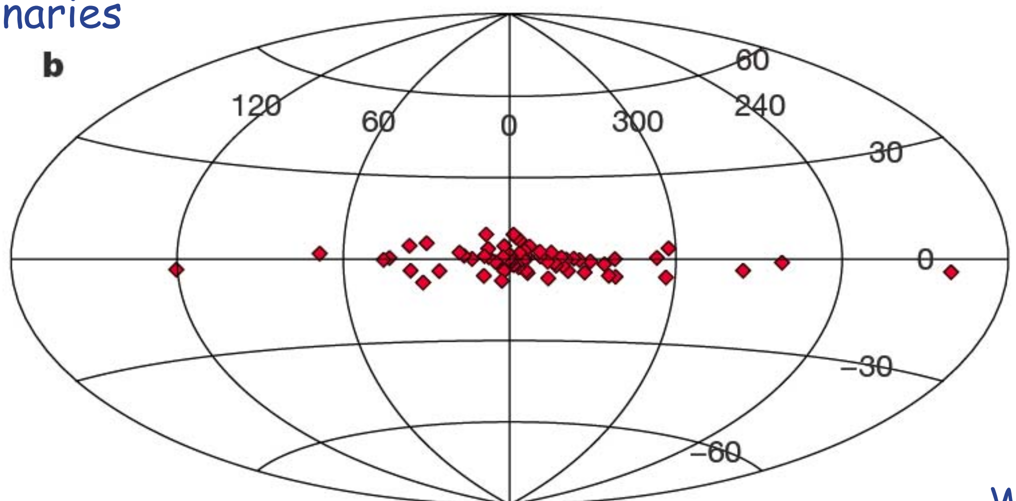
- Annihilation rate ~10^{43} positrons/s
- The distribution of the 511 keV line is "Galactocentric" and does not much a distribution of any potential positron source (SNRs, pulsars,…)
- Dark Matter?
- Recent data indicate a disk/bulge ratio 1:3

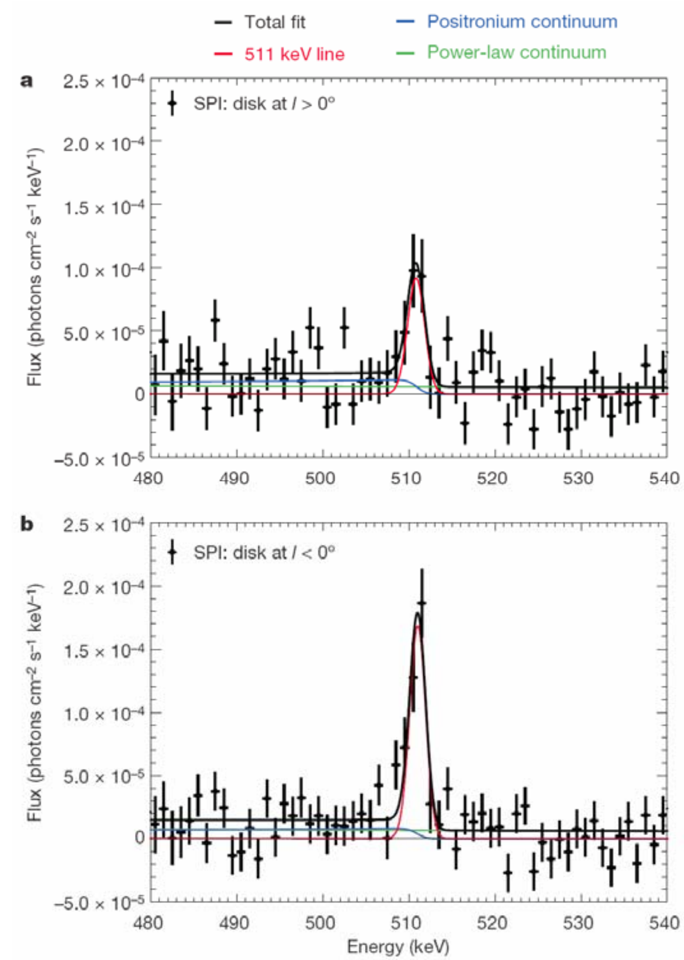
Galactic positron factory: low mass X-ray binaries?

511 keV skymap



Low mass X-ray binaries





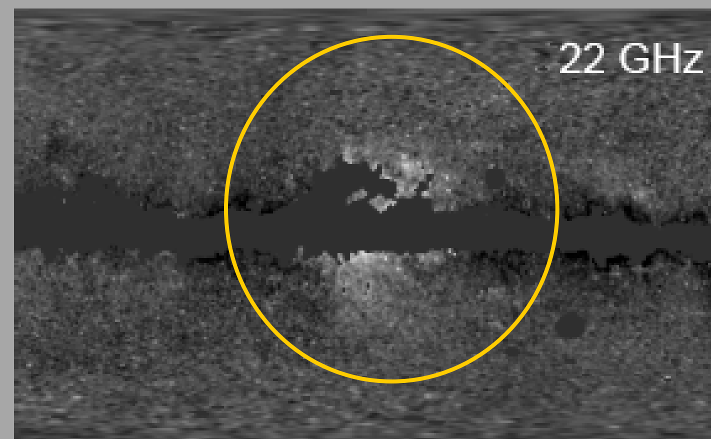
Weidenspointner+'08

The "haze" at the Galactic Center (WMAP)

Synchrotron emission from leptons produced in WIMP annihilations?

Dark Matter in the WMAP Sky

•In 2004, Doug Finkbeiner suggested that the WMAP Haze could be synchrotron from electrons/positrons produced in dark matter annihilations in the inner galaxy (astro-ph/0409027)



•In particular, he noted that:

1) Assuming an NFW profile, a WIMP mass of 100 GeV and an annihilation cross section of 3×10^{-26} cm^3/s, the total power in dark matter annihilations in the inner 3 kpc of the Milky Way is

$\sim1.2\times10^{39}$ GeV/sec

Coincidence?

2) The total power of the WMAP Haze is between

0.7×10^{39} and 3×10^{39} GeV/sec

Dan Hooper - *Dark Matter Annihilations in the WMAP Sky*

Conclusion

Astrophysics of cosmic rays and related topics is a very dynamic field:

expect many breakthroughs and discoveries soon!