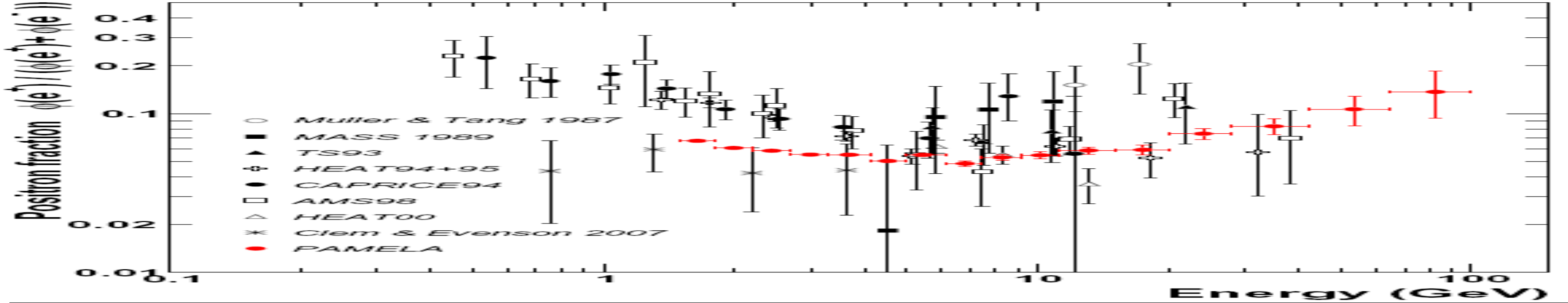
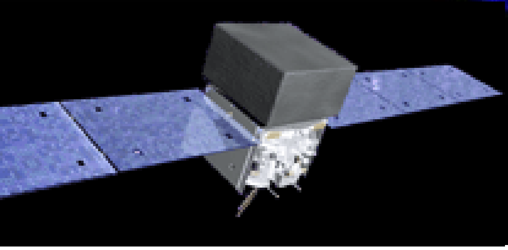


Fermi Large Area Telescope and Propagation of Cosmic Rays

Igor V. Moskalenko (stanford/kipac)

for the LAT collaboration



GLAST - *Fermi*

- Twoinstruments: Large Area Telescope (LAT), 20 MeV - >300 GeV
  - Surveys the whole sky every 2 orbits
- Gamma-ray Burst Monitor (GBM), 10 keV - 25 MeV
  - 4π

DATA BECAME PUBLIC ON AUGUST 11, 2009!

Fermi Gamma-Ray Space Telescope (*Fermi*)

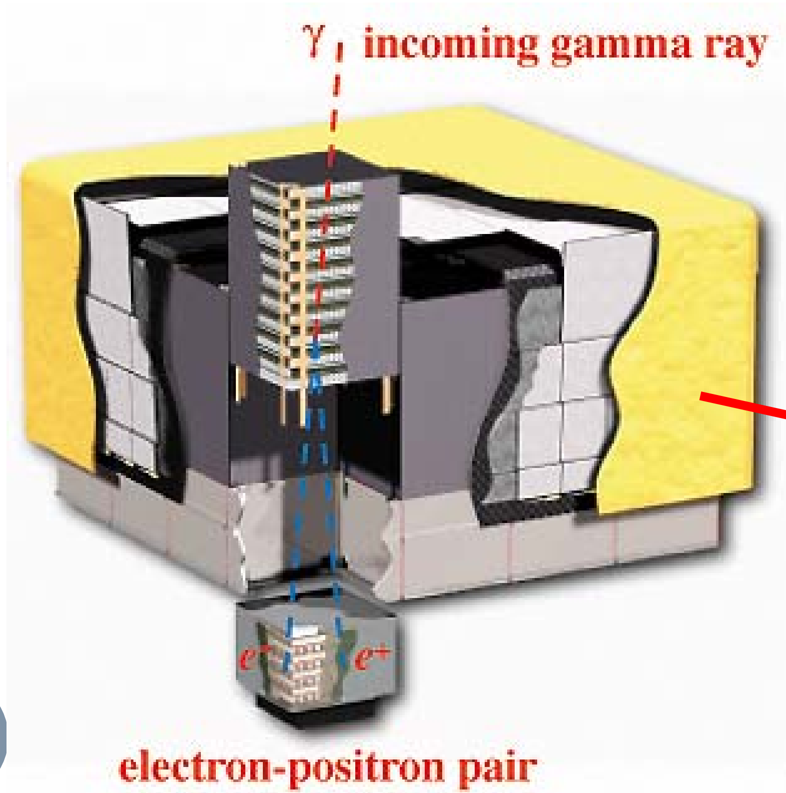
DoE – NASA – international partnership

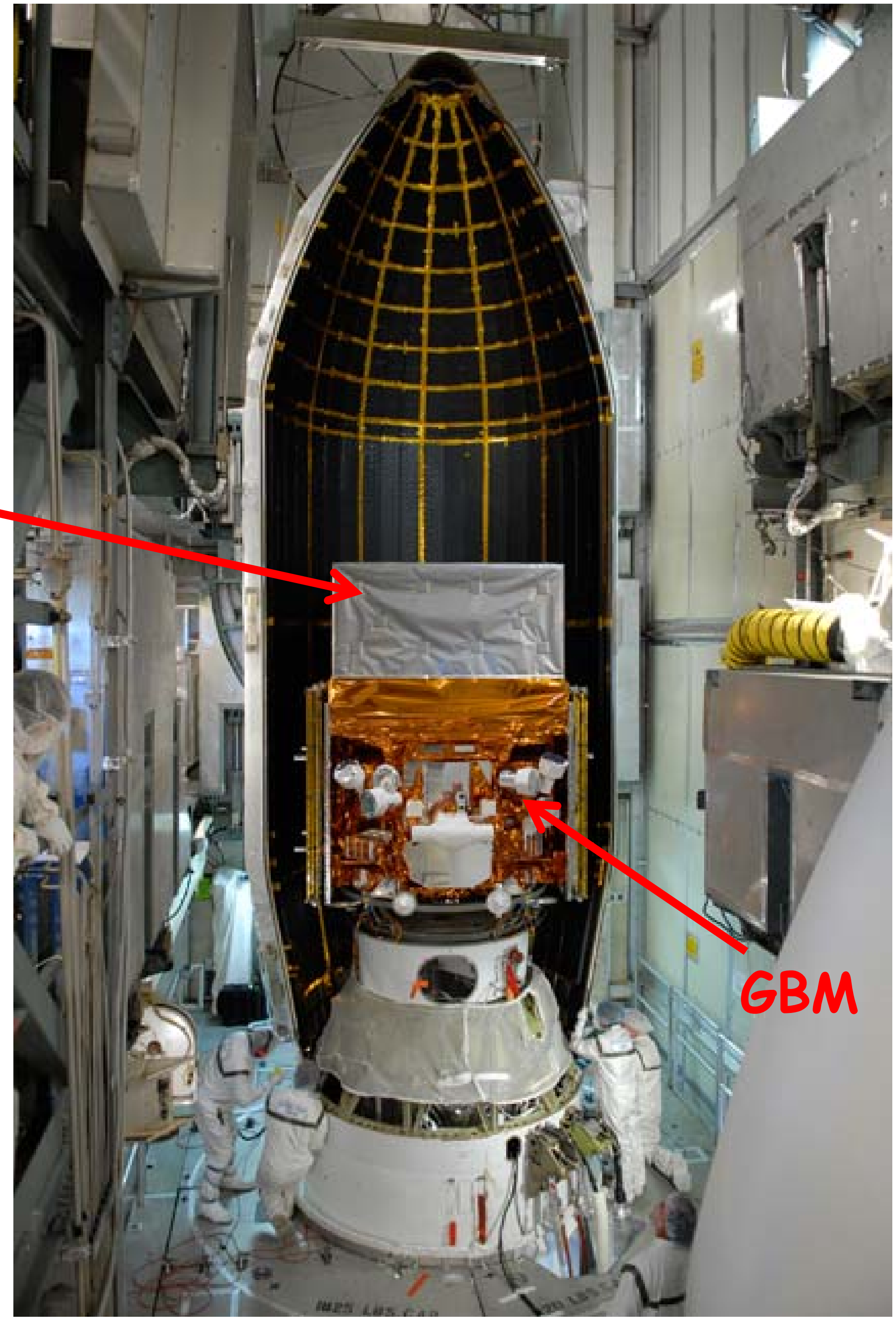
GLAST renamed *Fermi* by NASA on August 26, 2008

http://fermi.gsfc.nasa.gov/

" Enrico Fermi (1901-1954) was an Italian physicist who immigrated to the United States. He was the first to suggest a viable mechanism for astrophysical particle acceleration. This work is the foundation for our understanding of many types of sources to be studied by the Fermi Gamma-ray Space Telescope, formerly known as GLAST. "

The Large Area Telescope (LAT)

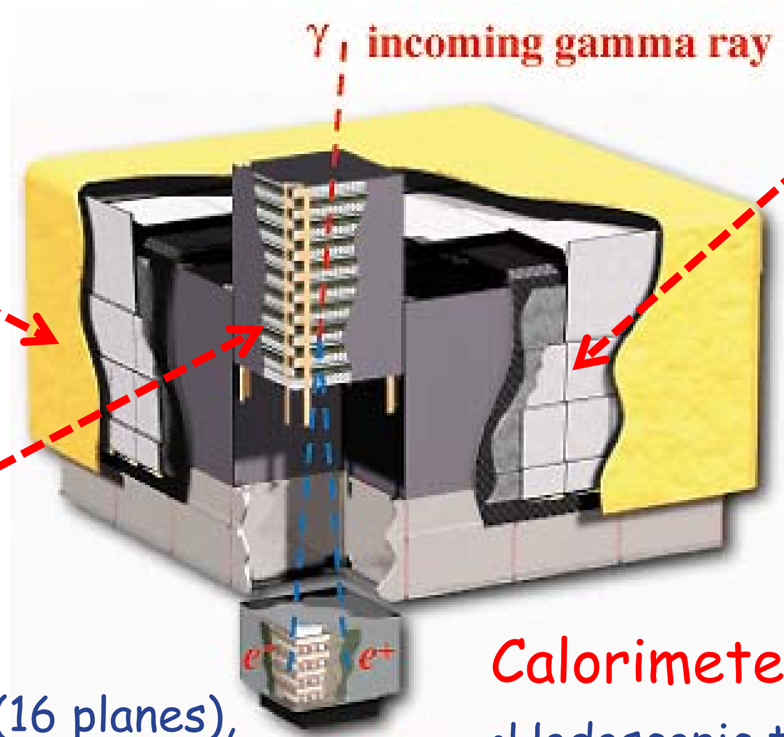




<u>LAT images the sky one photon at a time</u>: γ-ray converts in LAT to an electron and a positron; direction and energy of these particles tell us the direction and energy of the photon

The LAT

- Modular design
- 4x4 array of identical towers
- Anti-coincidence detector (ACD)



Thermal blanket

ACD

- Segmented (89 tiles) to minimize self-veto
- 0.9997 average detection efficiency

Tracker

- Silicon strip detectors (16 planes), 80 m^2 of silicone
- Tungsten conversion foils
- 1M readout channels

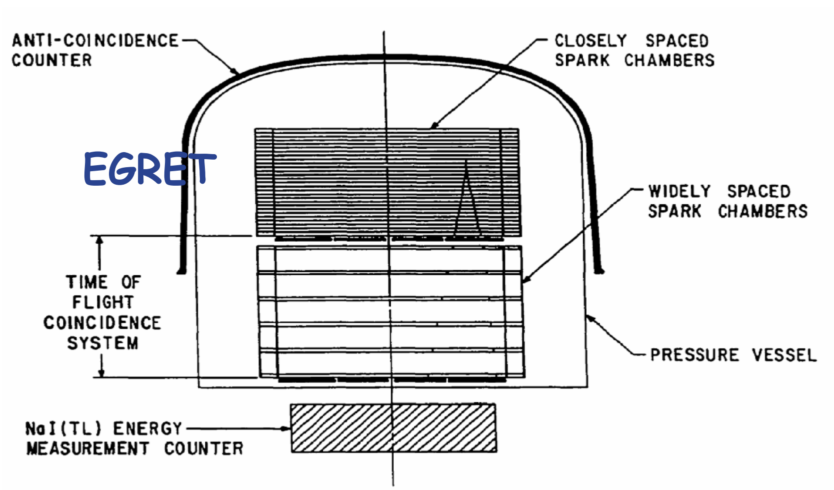
Calorimeter

- Hodoscopic tower of 1536 CsI(Tl) crystals
- 8.6 radiation lengths on-axis
- 3D shower profile reconstruction
- Leakage correction &hadron rejection

LAT as a Gamma-Ray Telescope

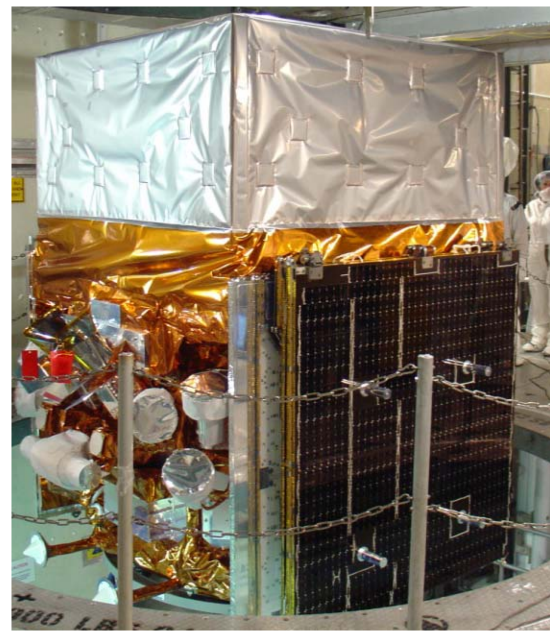
	Years	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Eng. Rng. (GeV)	$A_{eff}\,\Omega$ (cm^2 sr)	# γ-rays
EGRET	**1991–00**	**5.8°**	**0.5°**	**0.03–10**	**750**	**1.4×10^6/yr**
AGILE	**2007–**	**4.7°**	**0.2°**	**0.03–50**	**1,500**	**4×10^6/yr**
***Fermi* LAT**	**2008–**	**3.5°**	**0.1°**	**0.02–300**	**25,000**	**1×10^8/yr**

- LAT has quickly surpassed EGRET and AGILE celestial gamma-ray totals
- Unlike EGRET and AGILE, LAT is an effective All-Sky Monitor whole sky every ~3 hours



CGRO EGRET

AGILE (ASI)



Fermi / LAT

Fermi LAT Science

> 2000 AGNs

blazars and radiogal = $f(\theta,z)$

evolution $z < 5$

Sag A*

10-50GRB/year

GeV afterglow

spectra to high energy

γ-ray binaries

Pulsar winds

μ-quasar jets

Cosmic rays and clouds

acceleration in Supernova remnants

OB associations

propagation (Milky Way, M31, LMC, SMC)

Interstellar mass tracers in galaxies

Possibilities

starburst galaxies

galaxy clusters

measure EBL

unIDs

Dark Matter

neutralino lines

sub-halo clumps

CR electrons

20 GeV – a few TeV

Pulsars

emission from radio and X-ray pulsars

blind searches for new Gemingas

magnetospheric physics

pulsar wind nebulae

Fermi LAT Collaboration

- **France**
  - IN2P3, CEA/Saclay
- **Italy**
  - INFN, ASI, INAF
- **Japan**
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- **Sweden**
  - Royal Institute of Technology (KTH)
  - Stockholm University
- **United States**
  - Stanford University (SLAC and HEPL/Physics)
  - University of California at Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - Ohio State University
  - University of Washington

Principal Investigator:

Peter Michelson (Stanford University)

~270 Members

(~90 Affiliated Scientists, 37 Postdocs,

and 48 Graduate Students)

construction managed by

Stanford Linear Accelerator Center (SLAC), Stanford University

GLAST at the launch pad

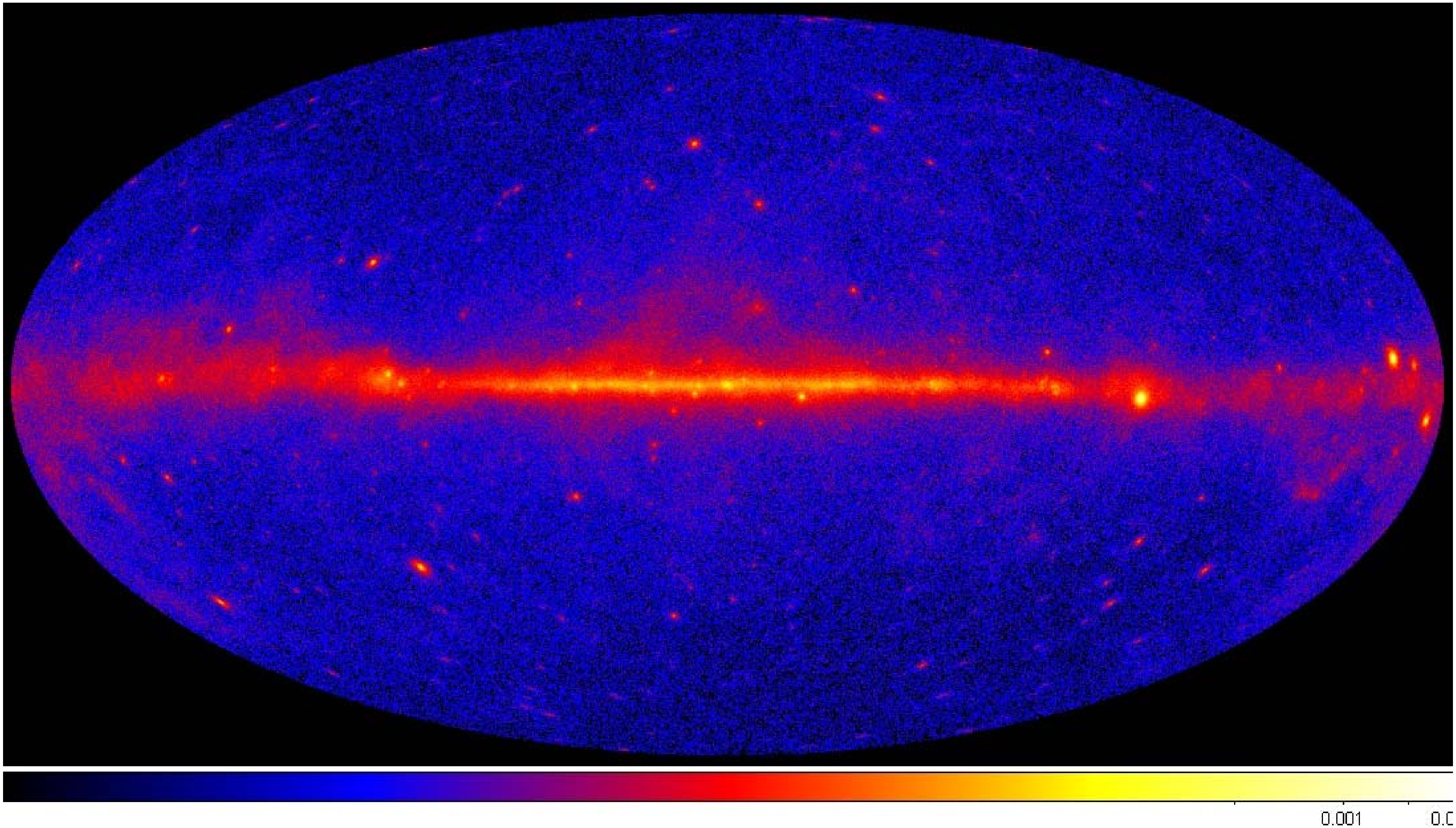
Kennedy Space Flight Center
Delta II heavy
June 11, 2008


Peter Michelson
Bill Atwood
Pitch In!
HELP KEEP THIS PLACE CLEAN
The last final check of ignition…


USAF
ULA
DELTA
GLAST

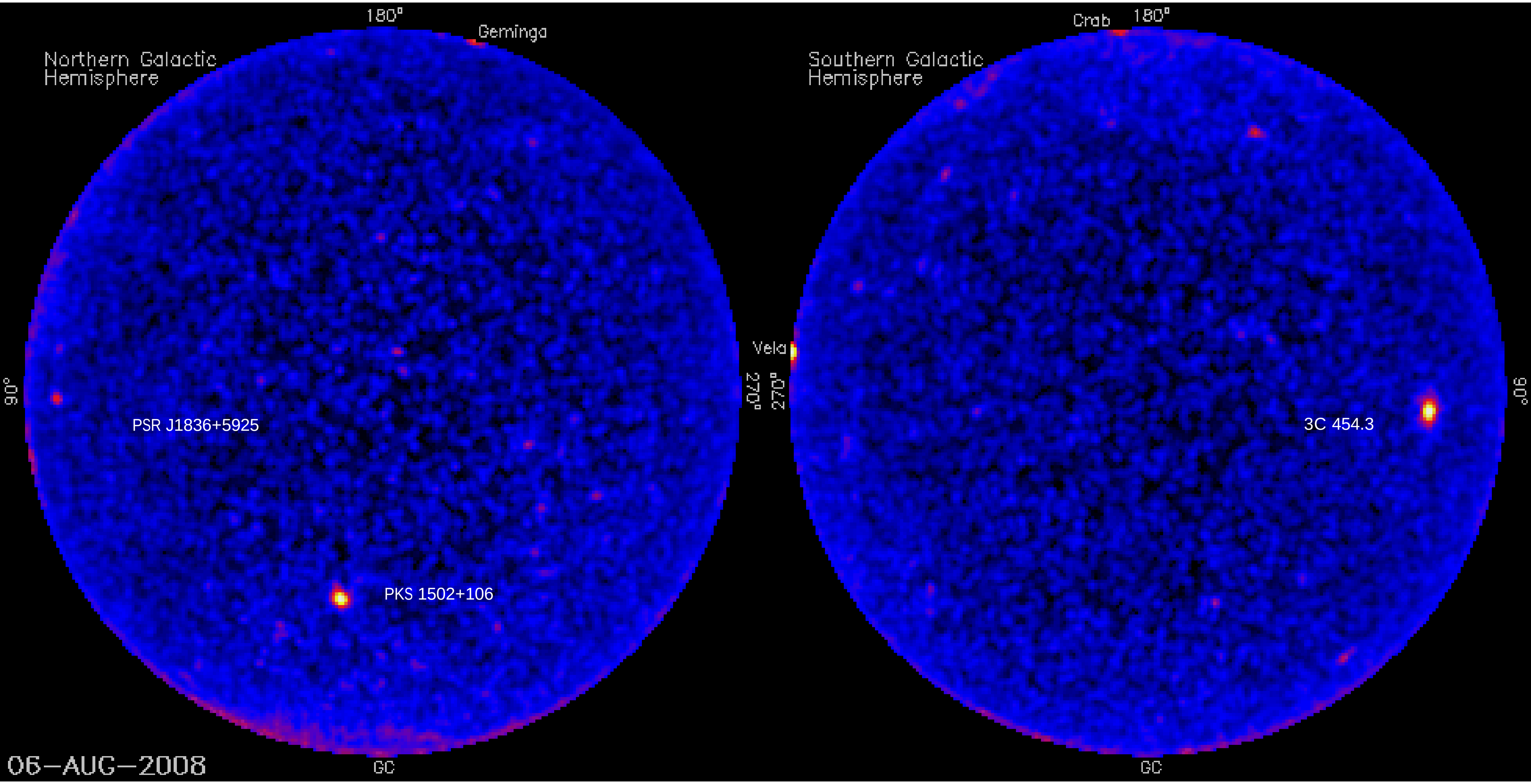

Circular orbit at 565 km
Inclination 25.6°
Lifetime ≥5 years

First 3 Months Skymap (Counts)



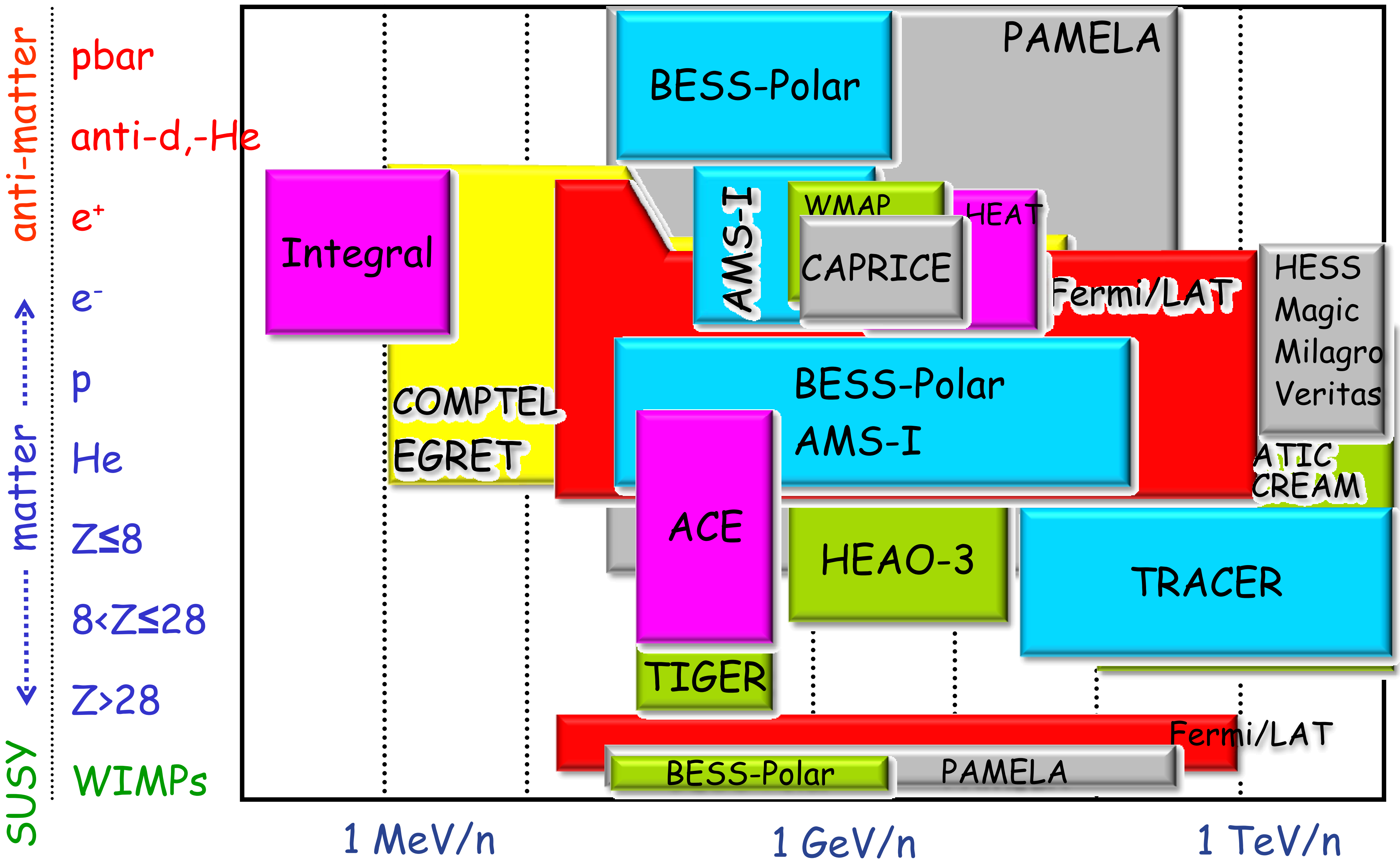
The diffuse emission is the brightest source on the sky: ~80% of all photons

First 3 months of LAT data



First movie in gamma rays ever shot!

A Constellation of CR and gamma-ray (also CR!) instruments



Primary electrons in Cosmic Rays

JOURNAL OF GEOPHYSICAL RESEARCH VOL. 70, NO. 11 JUNE 1, 1965

Letters

Observation of the Cosmic Ray Electron-Positron Ratio from 100 Mev to 3 bev in 1964

R. C. HARTMAN AND PETER MEYER

Enrico Fermi Institute for Nuclear Studies and Department of Physics University of Chicago, Chicago, Illinois

R. H. HILDEBRAND

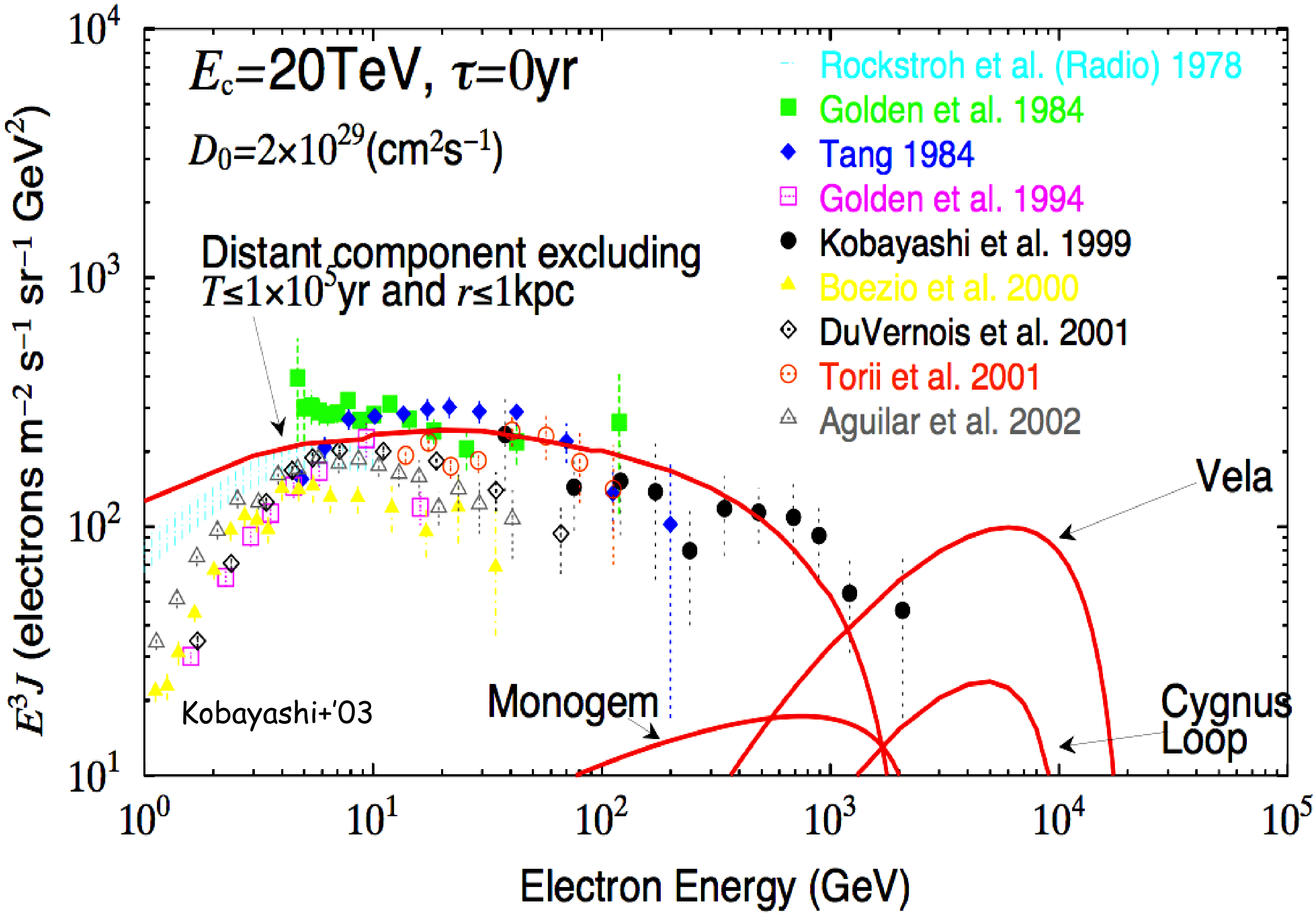
Argonne National Laboratory and University of Chicago Chicago, Illinois

nent. In 1963, *DeShong, Hildebrand, and Meyer* [1964] reported the results of an experiment designed to measure this ratio in the energy interval from 100 to 1000 Mev. They found an excess of negative electrons which led them to conclude that the electron component consists mainly of directly accelerated particles. Their

Now, ~45 years later we are discussing a possibility of primary positrons in CRs

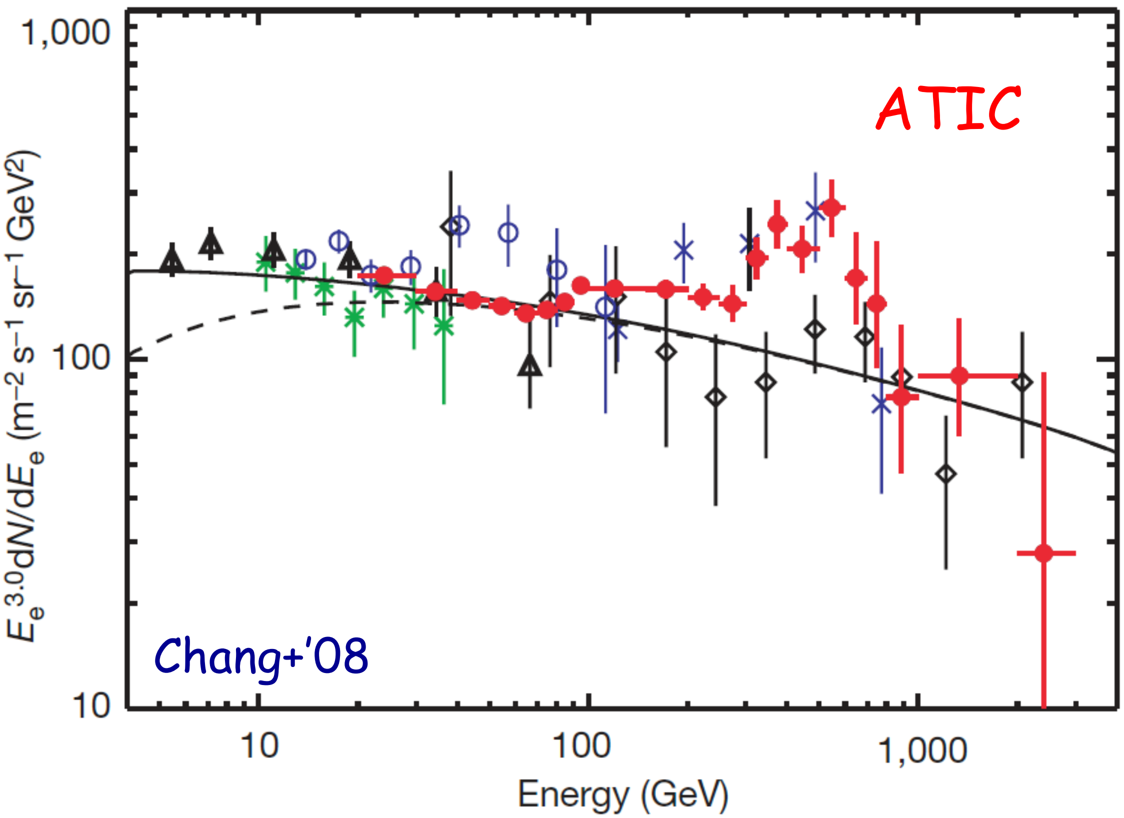
Early Measurements of CR Electrons

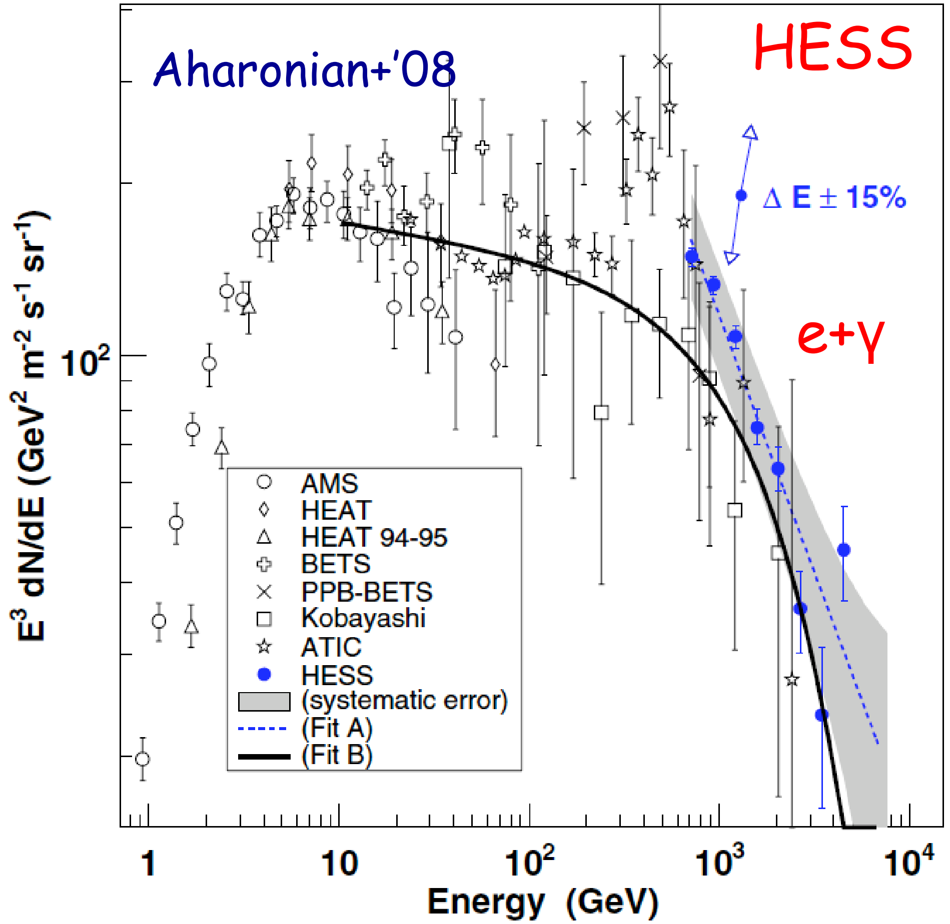
Early measurements of CR electrons and predictions of possible spectral features associated with local SNR



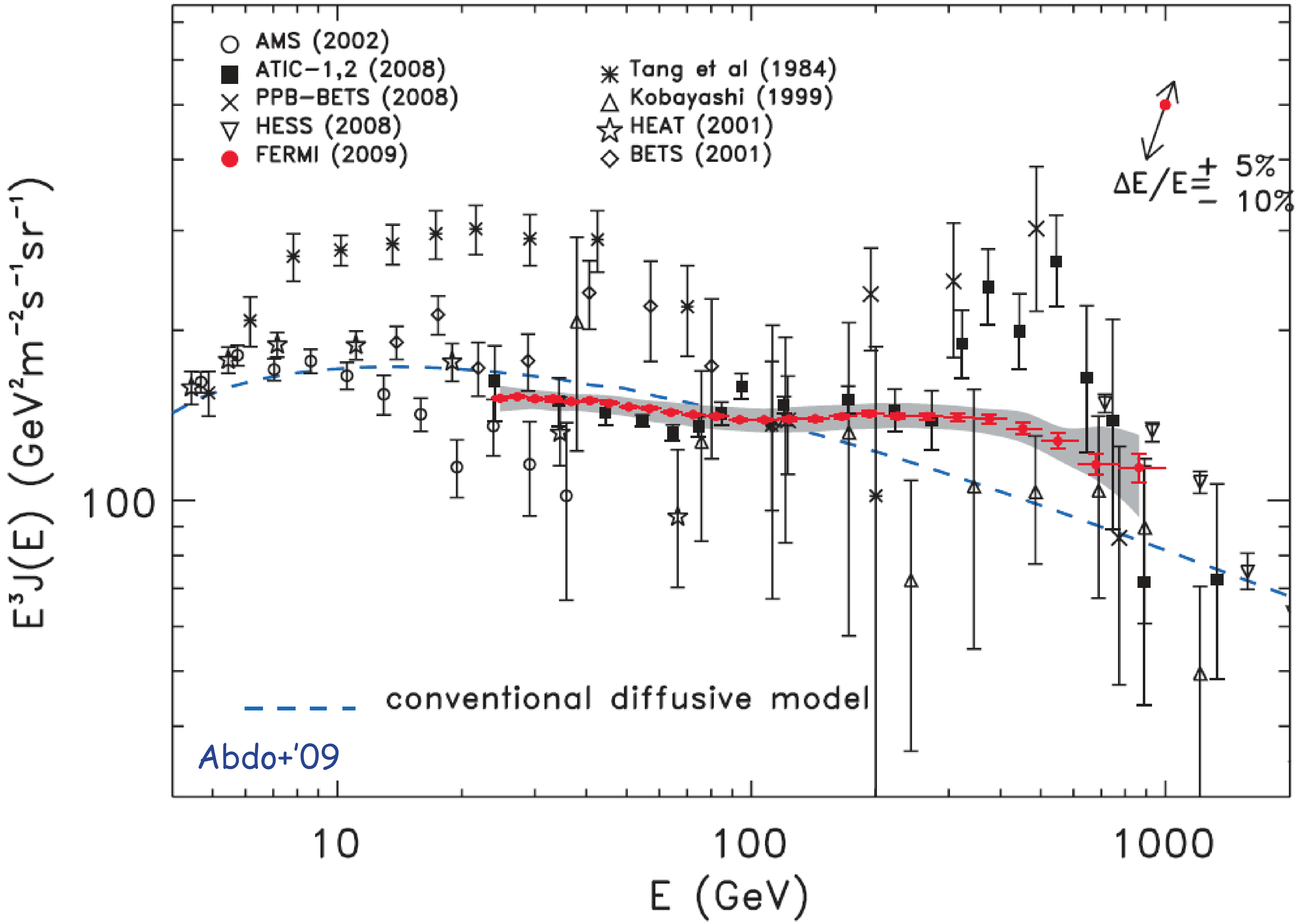
CR Electrons "Pre-LAT"

- Combined measurements from balloons and ground
- Most recent: ATIC (3+ flights) and HESS

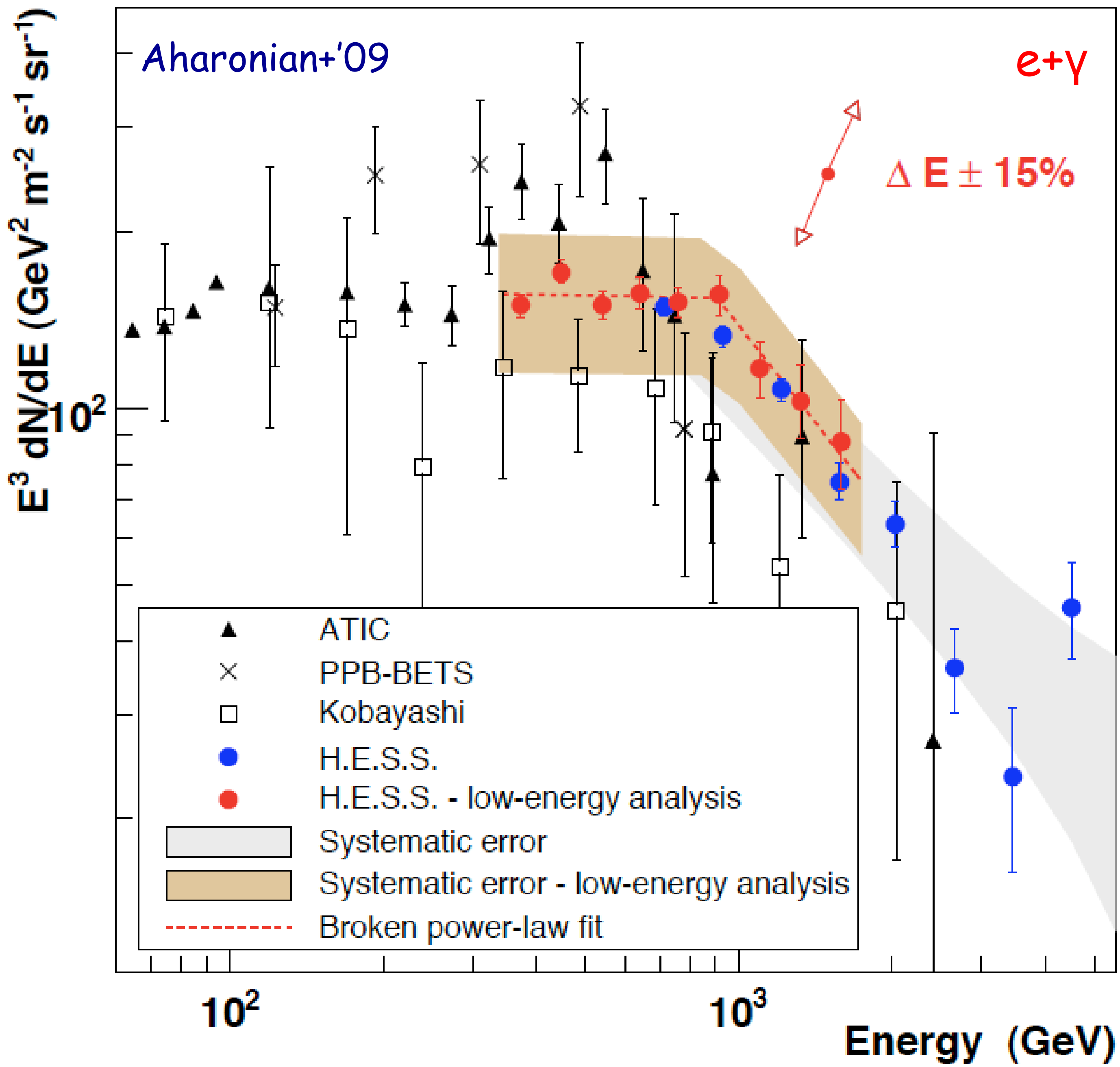




LAT measurements ($e^{-}+e^{+}$)



More HESS electron data



Interpretation

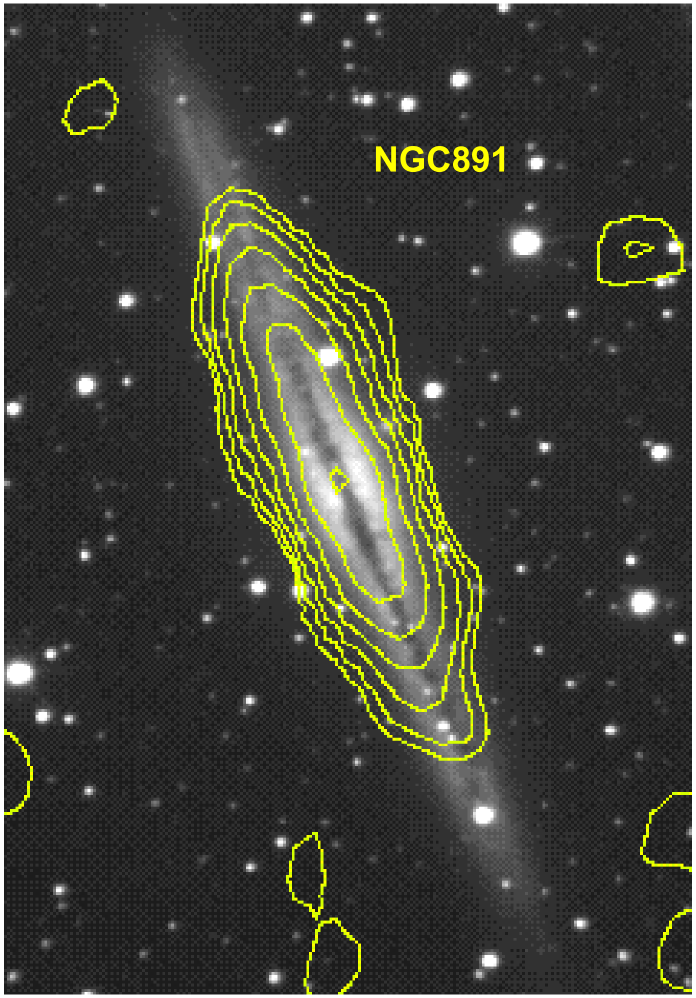
- The CR electron spectrum appears to be flatter (power-law index ~3) than previously thought
- Has a sharp cut off at ~1 TeV (consistent with expectations)

- The origin of the CR lepton (electrons + positrons) spectrum can't be understood based on the lepton data alone
- The key is to look at the lepton spectrum in conjunction with data on other CR species and CR propagation models

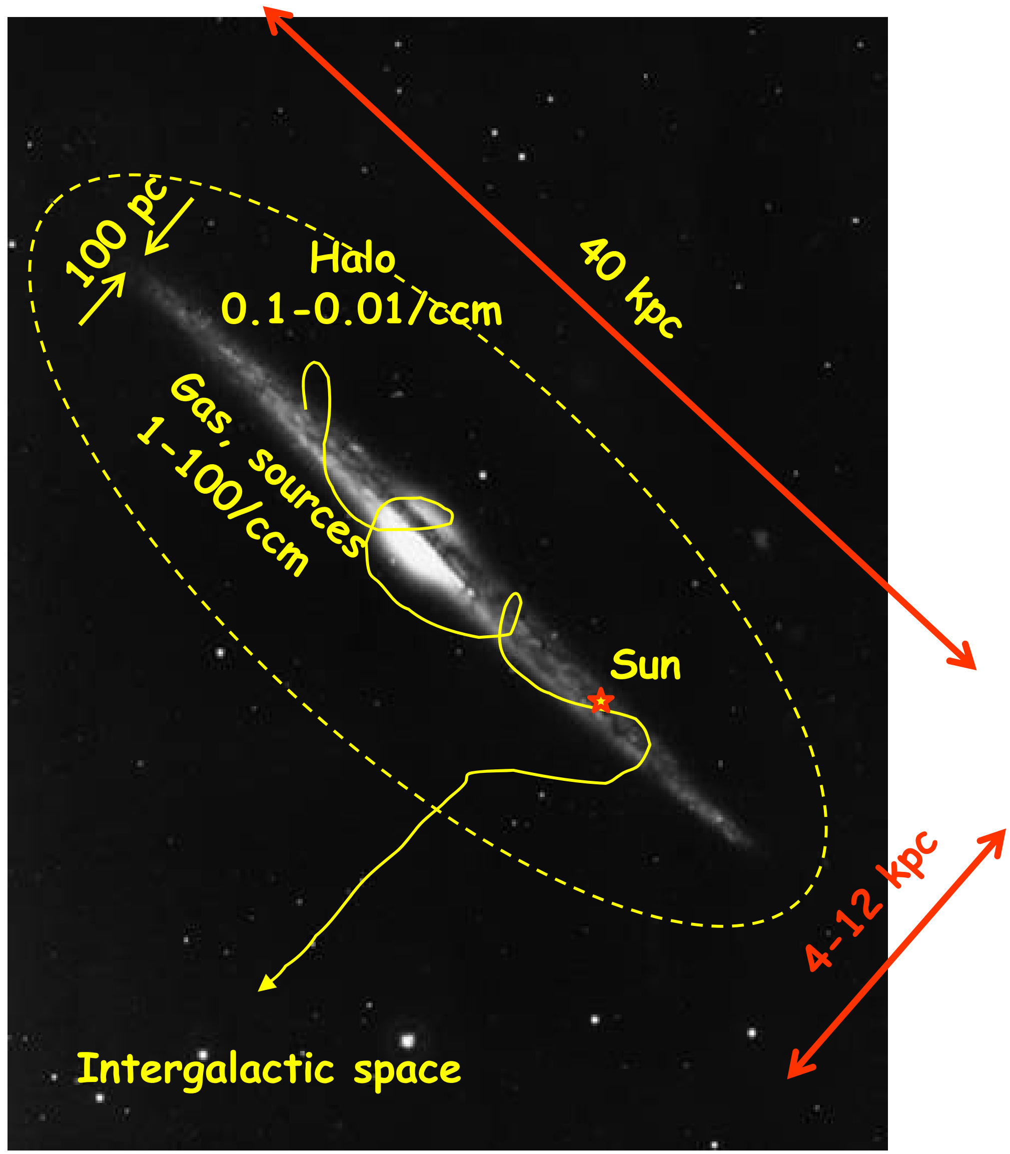
- This is related to both scenario: astrophysical and "exotic"

CR Propagation: the Milky Way Galaxy

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

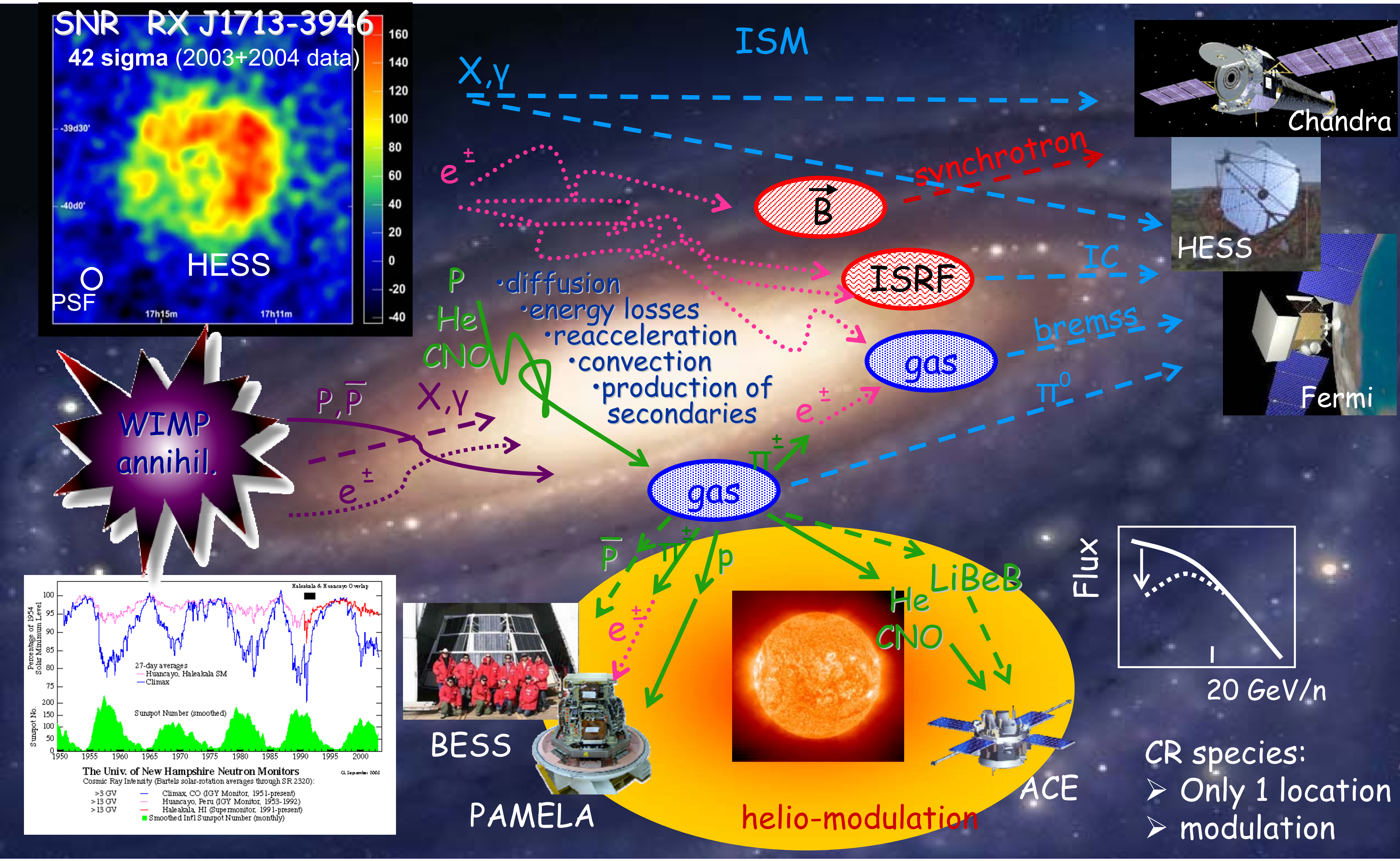


R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam

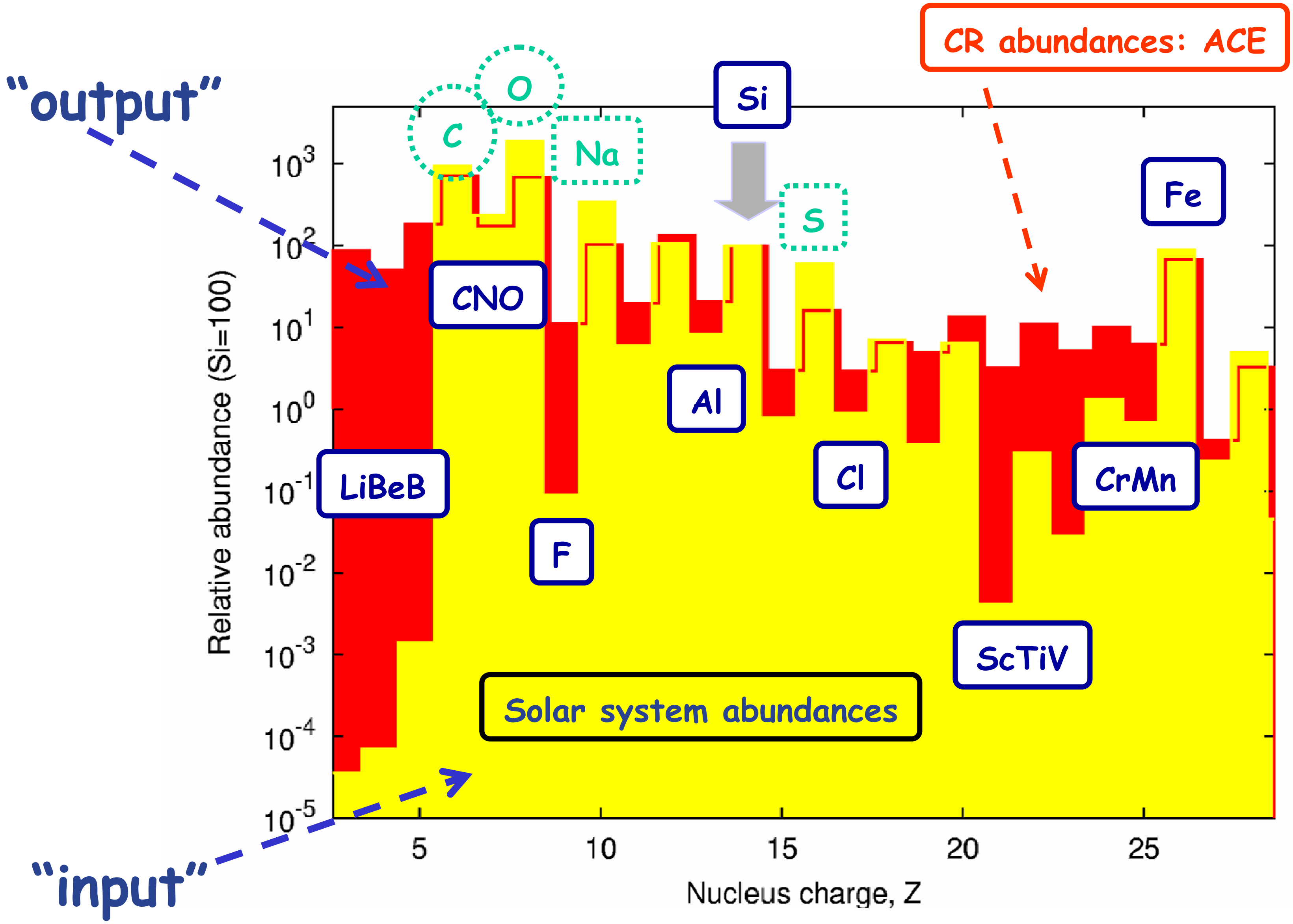


"Flat halo" model (Ginzburg&Ptuskin 1976)

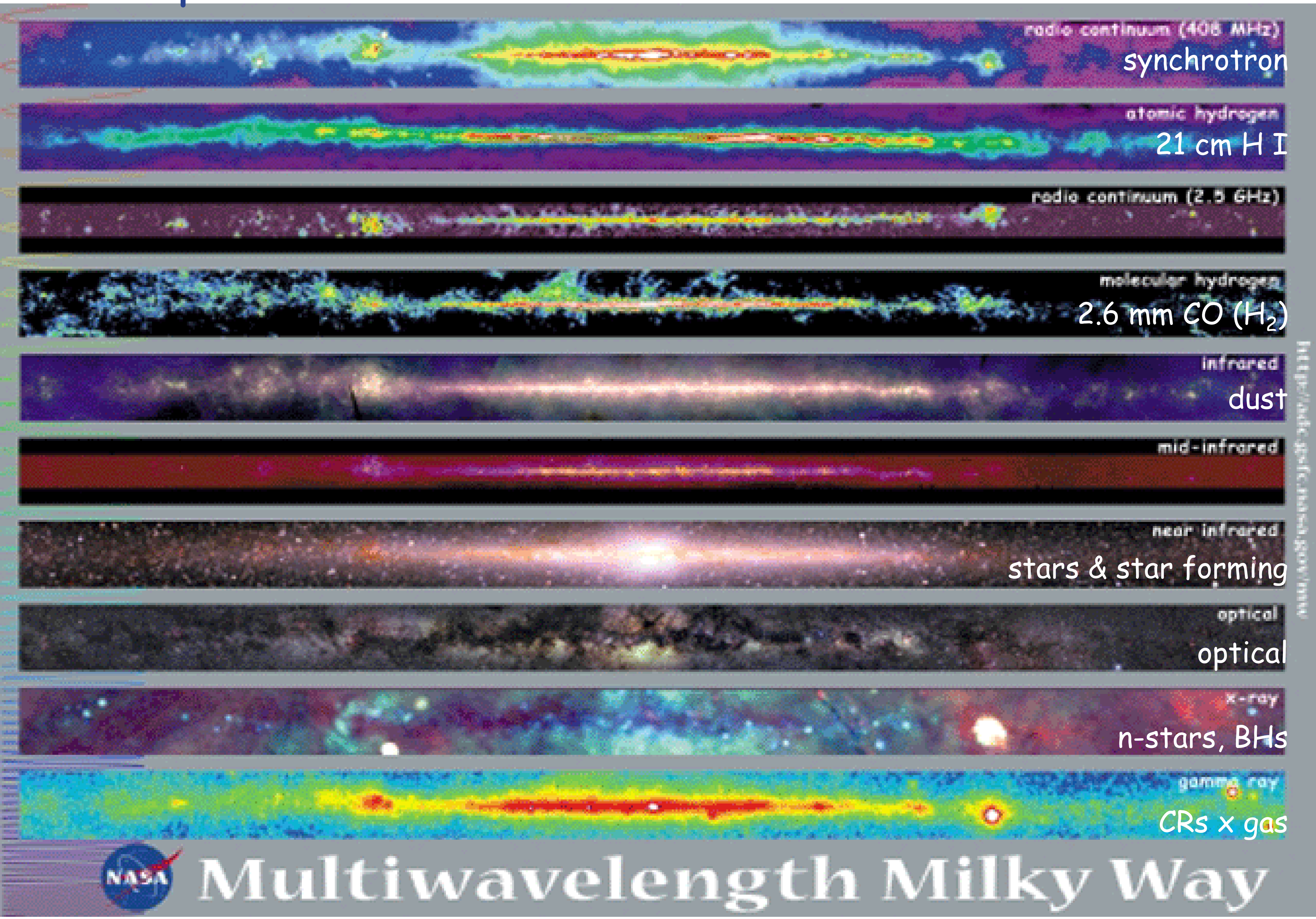
CRs in the Interstellar Medium



Elemental abundances in CRs and in the Solar System

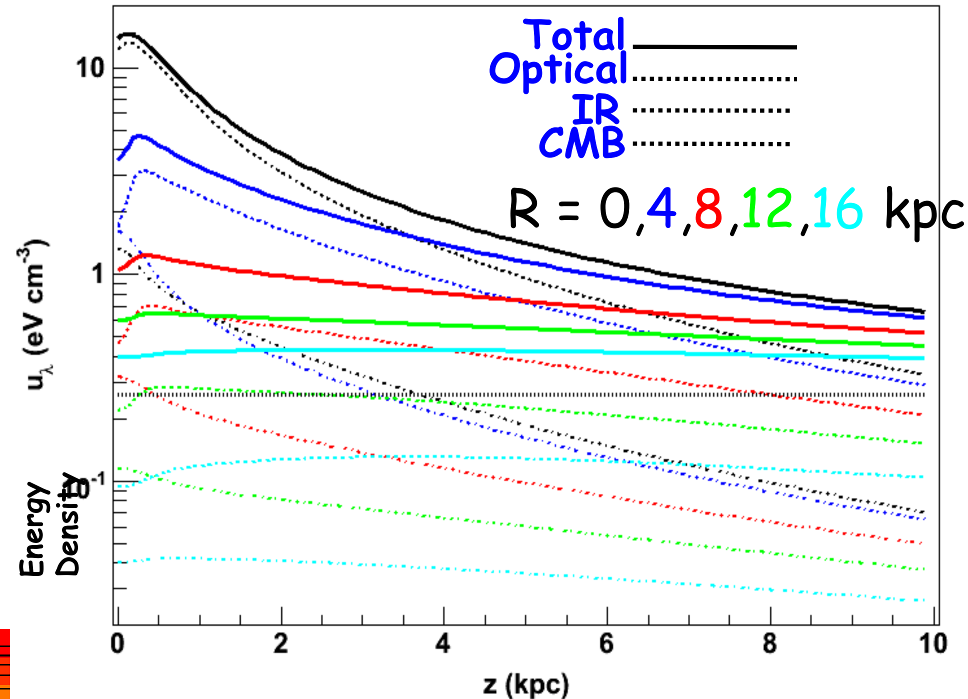


Components of the ISM: Views from the Inside

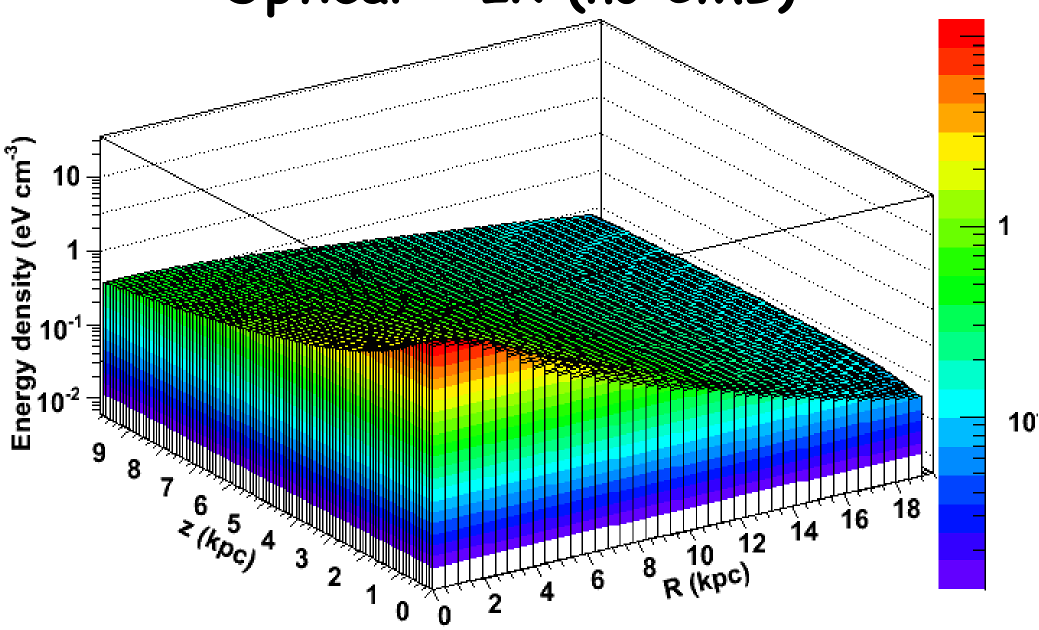


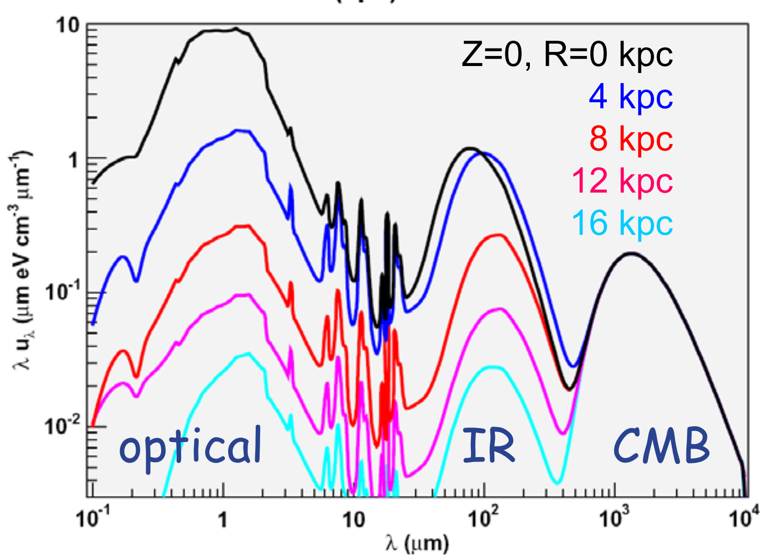
ISRF: Large Scale Distribution

- Requires extensive modeling:
  - Distribution of stars of different stellar classes in the Galaxy
  - Dust emission
  - Radiative transfer
- The z scale height is large, takes 10s of kpc at R = 0 kpc to get to level of CMB



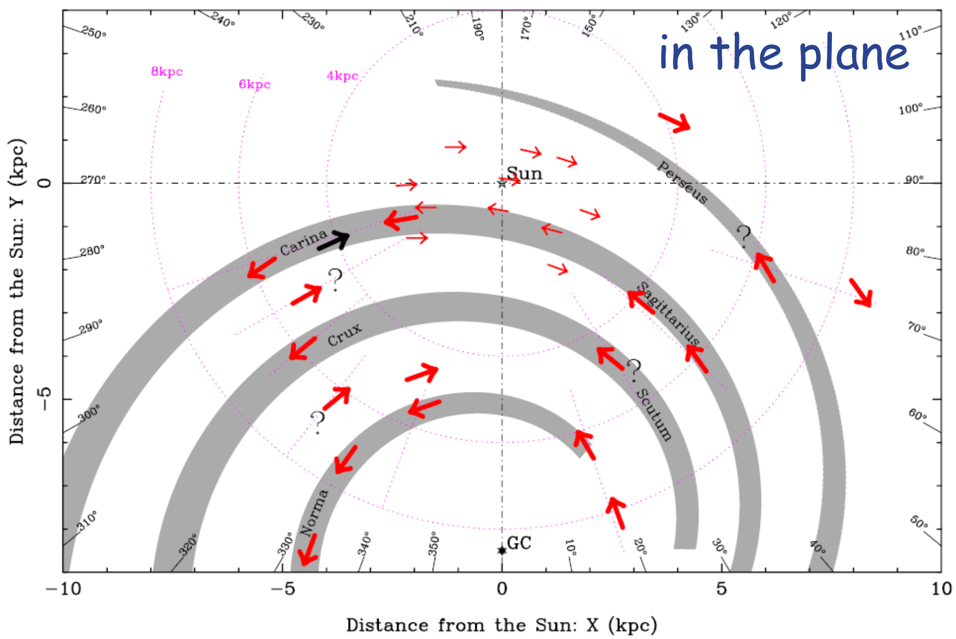
Optical + IR (no CMB)

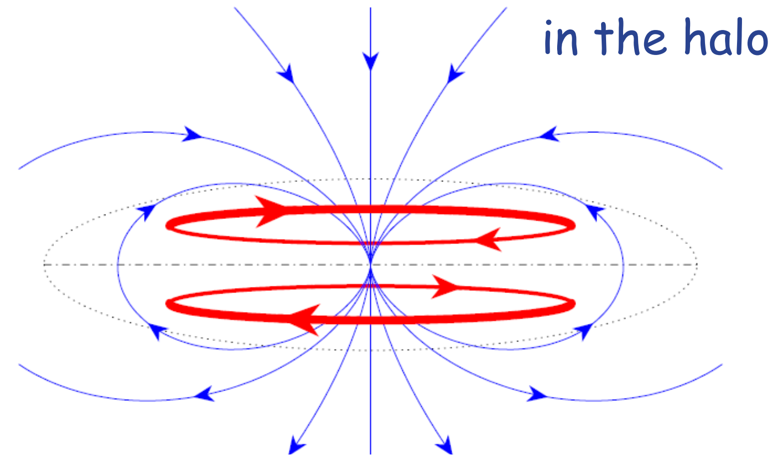




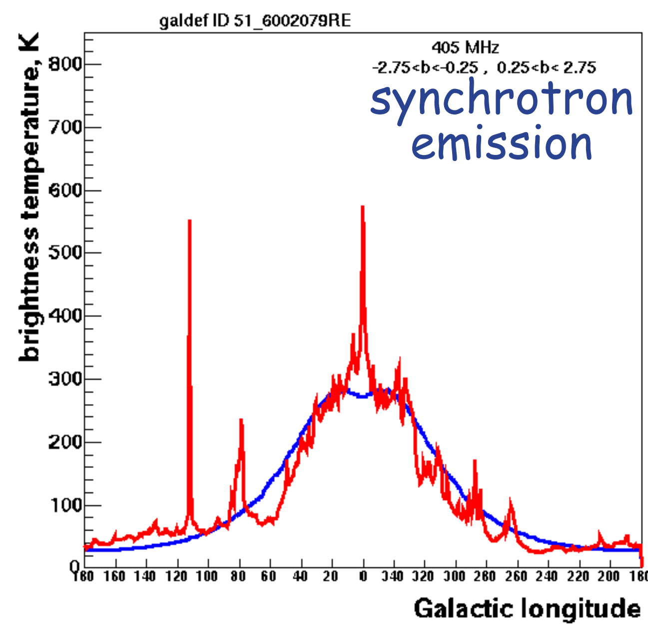
Galactic magnetic field

Regular B-field: large-scale structure





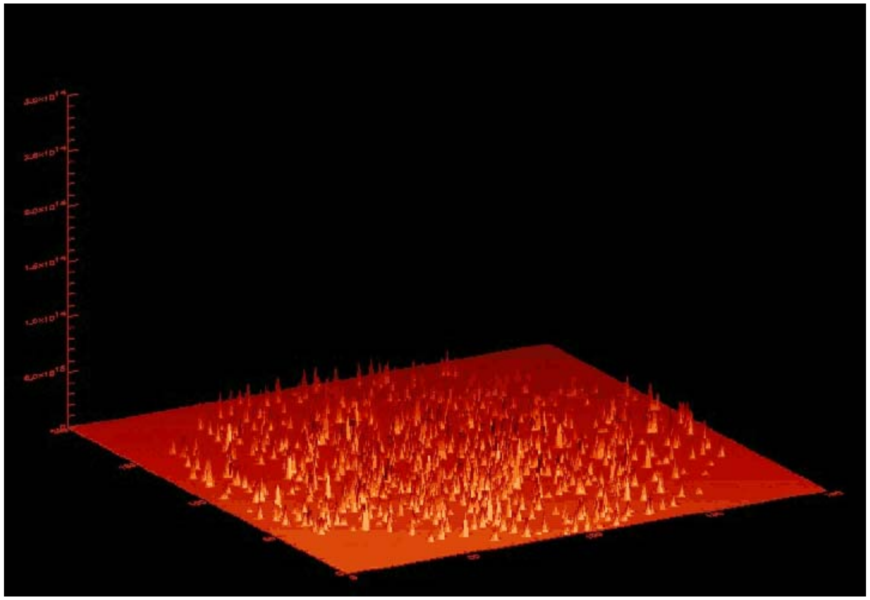
Han’08



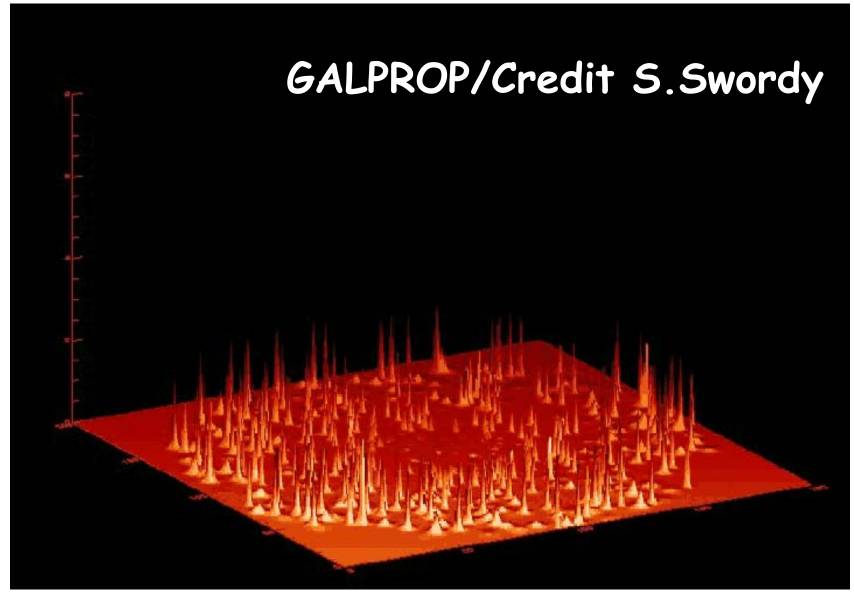
- Plane: bisymmetrical field with reversals on arm-interarm boundaries
- Halo: azimuth B-fields with reversed directions below and above the plane
- Random field ≈ Regular field
- Consistent with observations of the synchrotron emission

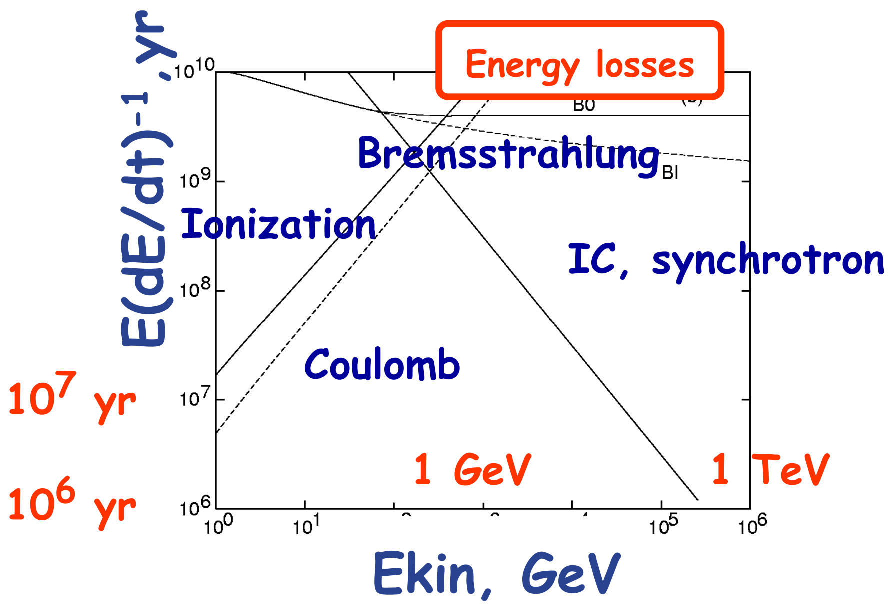
Electron Fluctuations/SNR Stochastic Events

GeV electrons



100 TeV electrons

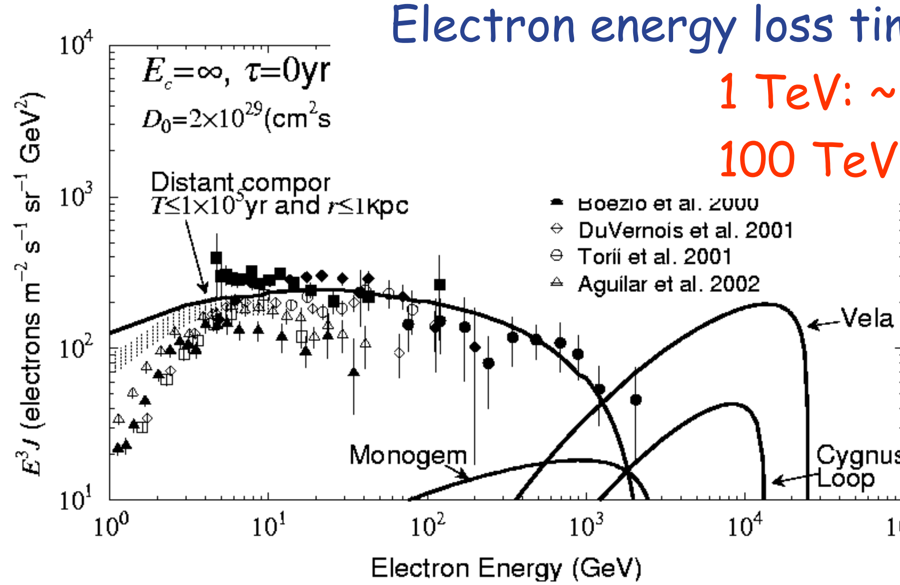




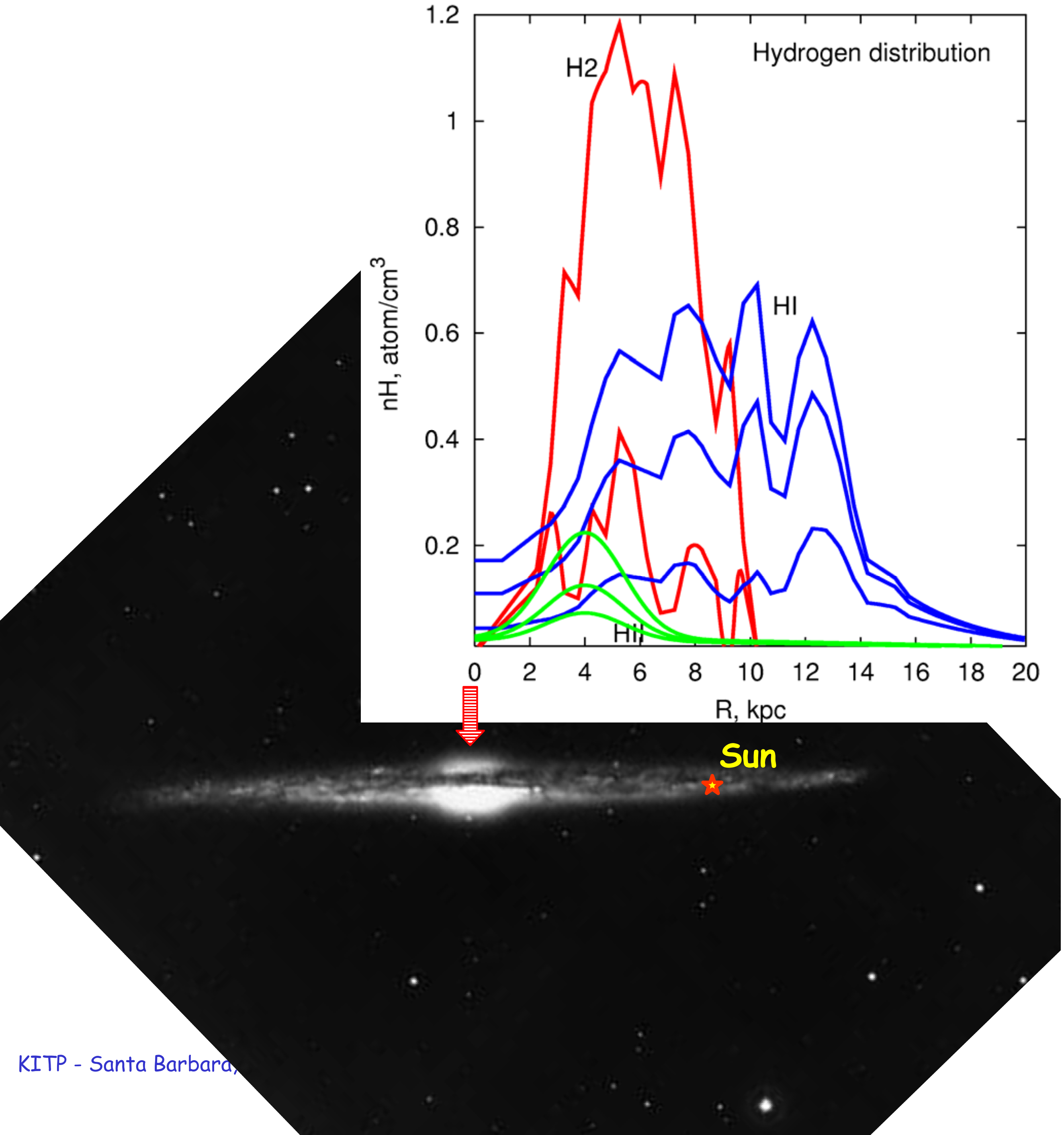
Electron energy loss timescale:

1 TeV: ~300 kyr

100 TeV: ~3 kyr



Gas distribution in the Milky Way



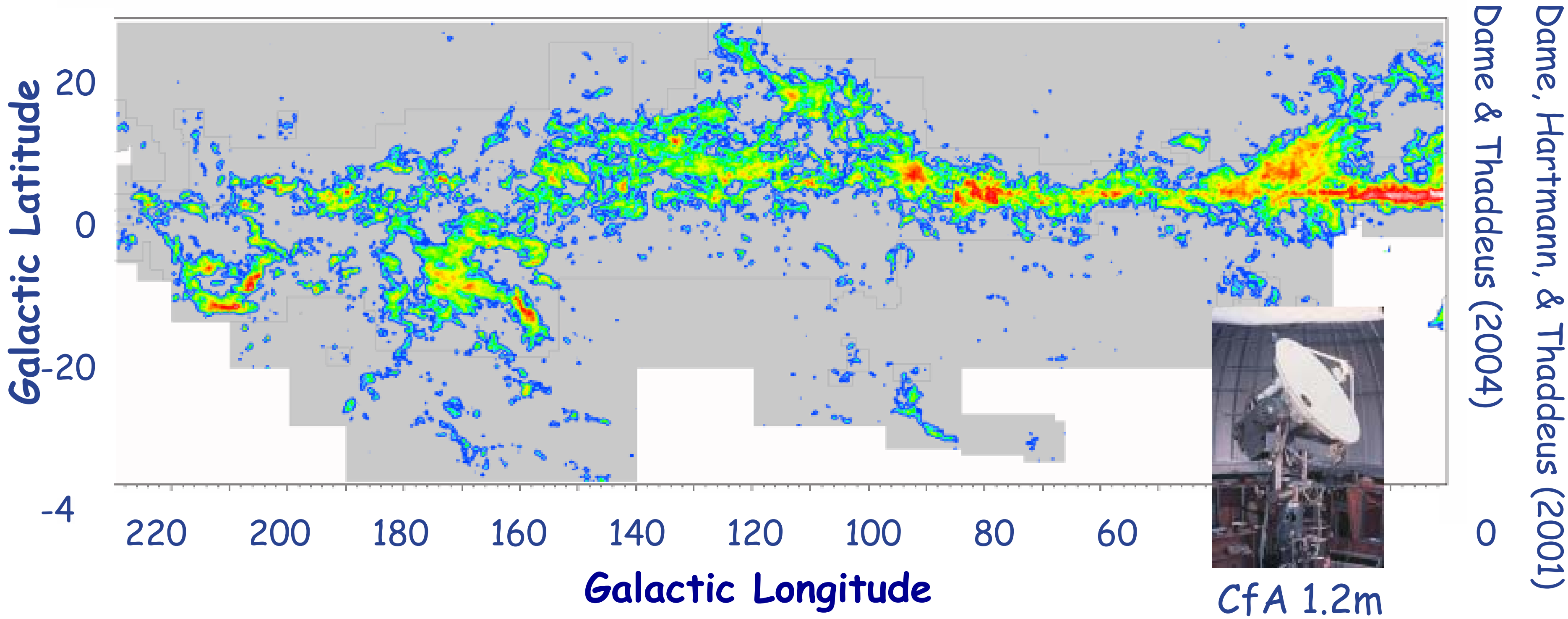
Molecular hydrogen H_2 is traced using J=1-0 transition of ^{12}CO, concentrated mostly in the plane (z~70 pc, R<10 kpc)

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)

CO maps

- **Extend CO surveys to high latitudes**
  - newly-found small molecular clouds will otherwise be interpreted as unidentified sources, and clearly limit dark matter studies

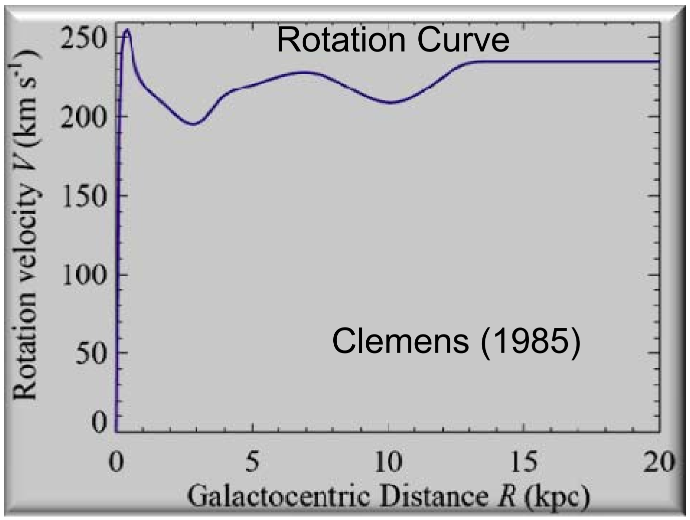


CfA 1.2m

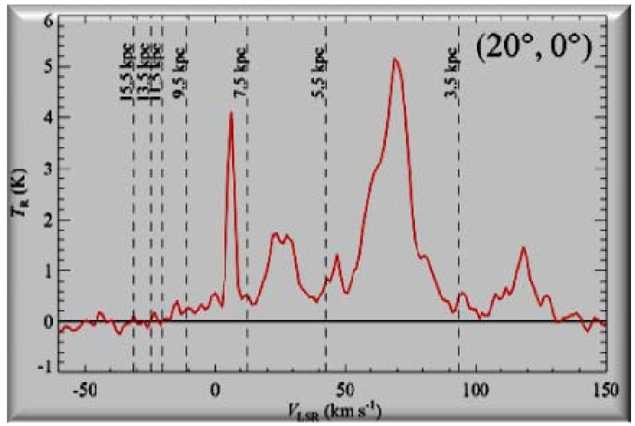
- **$C^{18}O$ observations (optically thin tracer) of special directions (e.g. Galactic center, arm tangents)**
  - assess whether velocity crowding is affecting calculations of molecular column density, and for carefully pinning down the diffuse emission

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

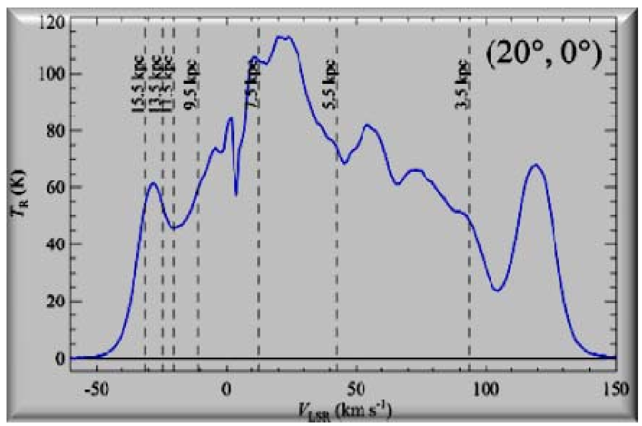


CO



Dame et al. (2001)

H I

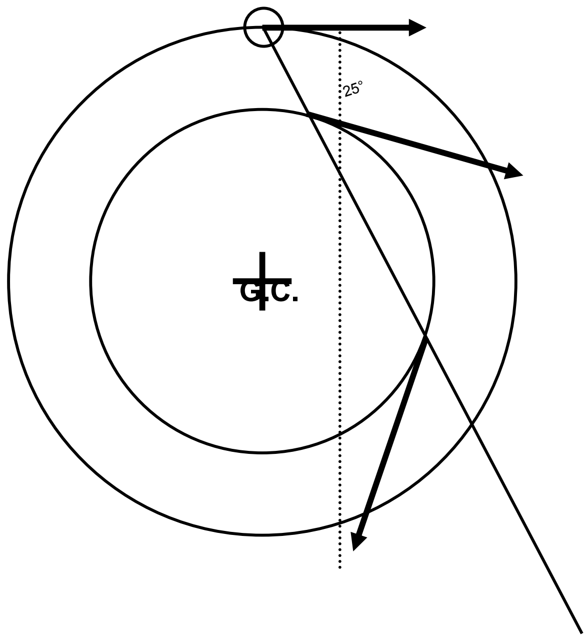


Kalberla et al. (2005)

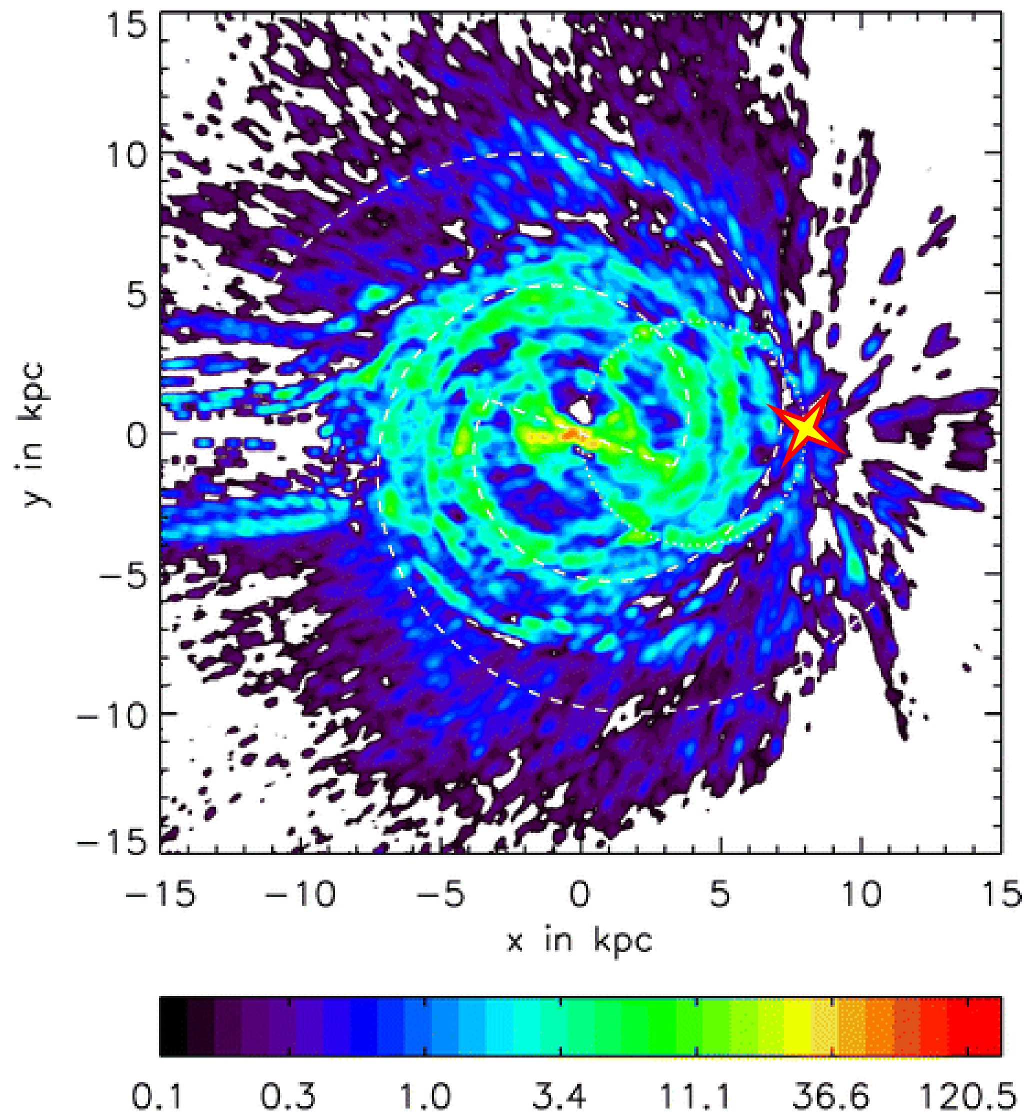
W. Keel

- 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

Problems to deal with…

H_2 gas

- The conversion factor $X = N(H_2)/W_{CO}$ is unknown, most probably variable, and is determined from the diffuse γ-ray emission itself

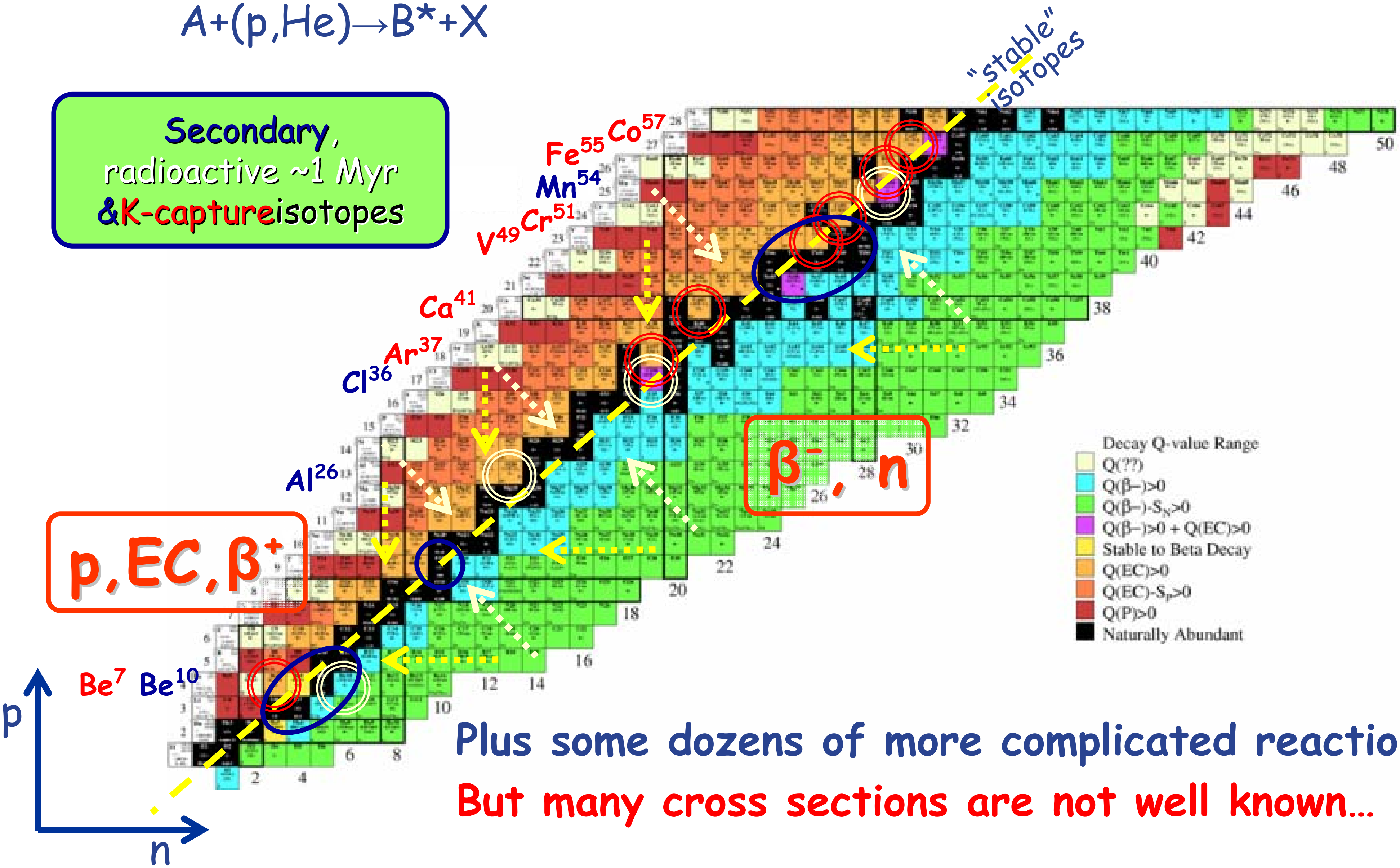
HI gas

- Spin temperature is unknown, it can significantly vary; usually used the same temperature ~125K for HI gas for the whole Galaxy

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

Nuclear Reaction Network+Cross Sections

Many different isotopes are produced via spallations of CR nuclei:
A+(p,He)→B*+X

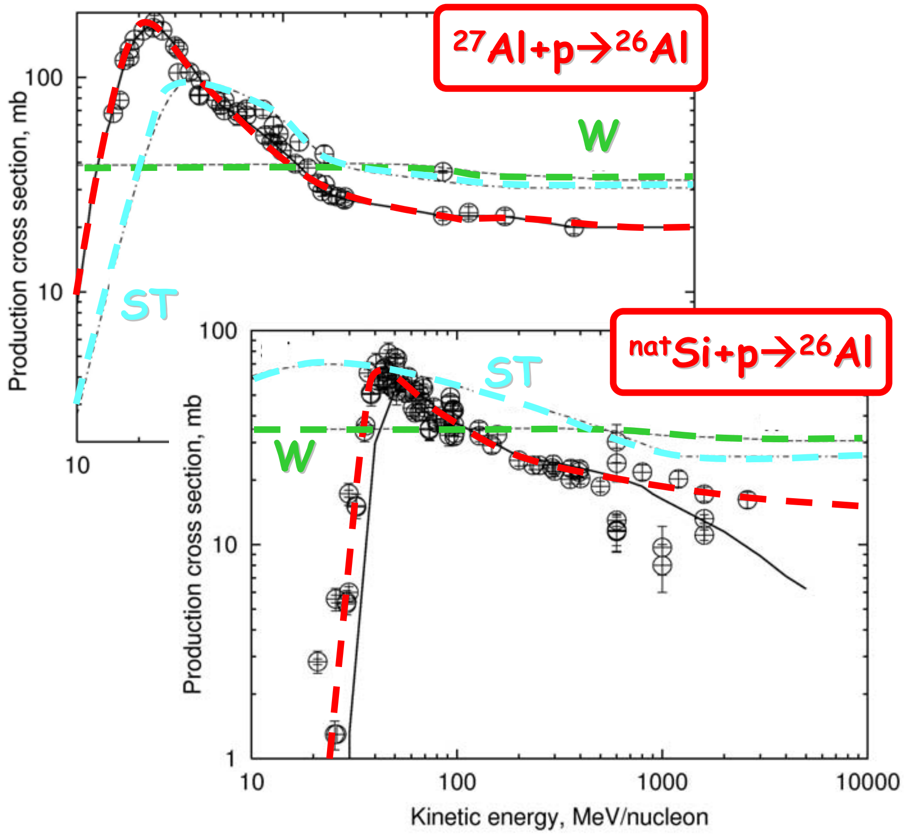


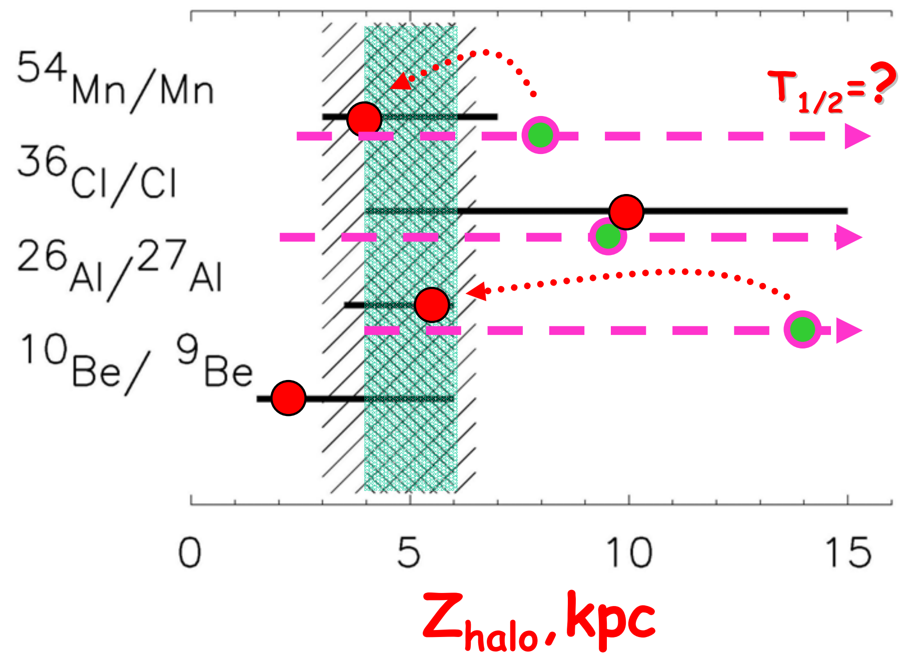
Plus some dozens of more complicated reactions

But many cross sections are not well known…

Effect of Cross Sections: Radioactive Secondaries

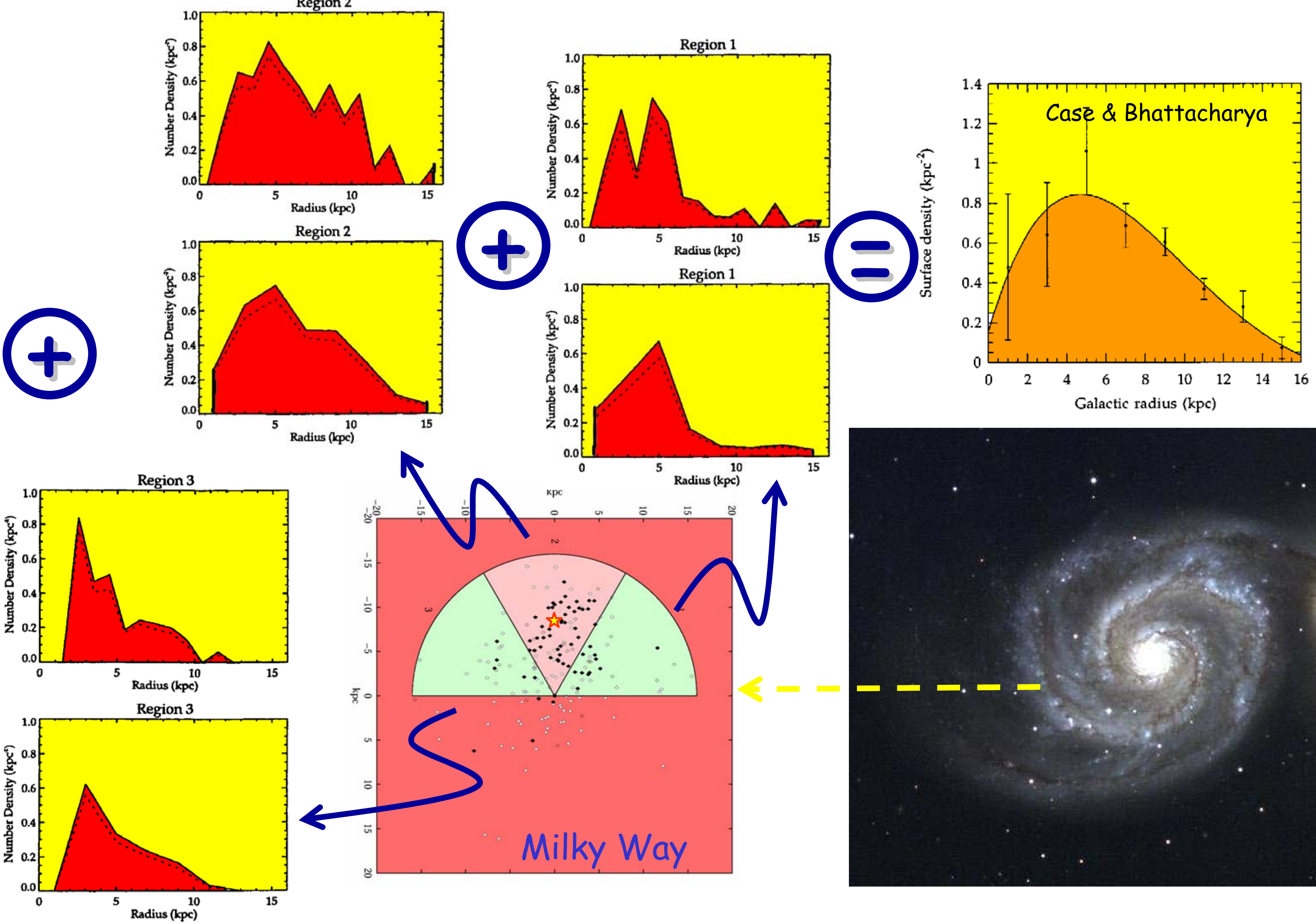
Different size from different ratios…



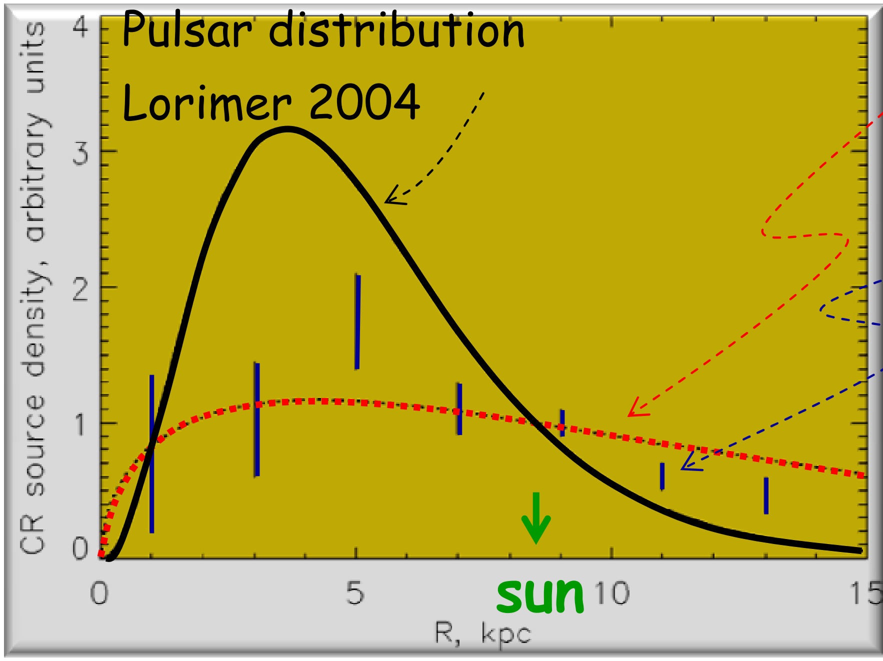


- Errors in CR measurements (HE & LE)
- Errors in production cross sections
- Errors in the lifetime estimates

SNR distribution

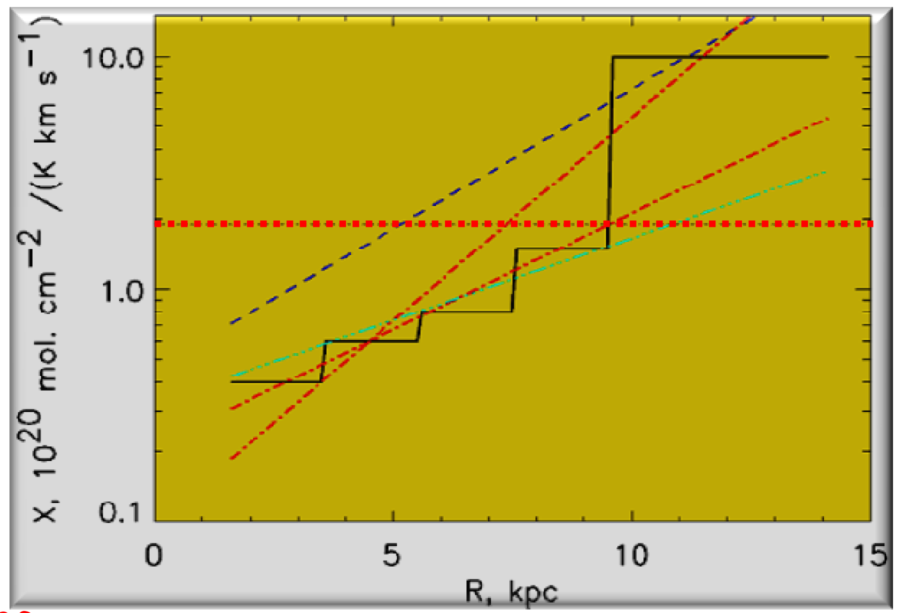


Distribution of CR Sources & Gradient in the CO/H_2



CR distribution from diffuse gammas (Strong & Mattox 1996)

SNR distribution (Case & Bhattacharya 1998)



$X_{CO}=N(H_2)/W_{CO}$:

Histo –This work, Strong et al.'04

----- -Sodroski et al.'95,'97

1.9×10^{20} -Strong & Mattox'96

$\sim Z^{-1}$ -Boselli et al.'02

$\sim Z^{-2.5}$ -Israel'97,'00, [O/H]=0.04,0.07 dex/kpc

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

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

convection (Galactic wind)

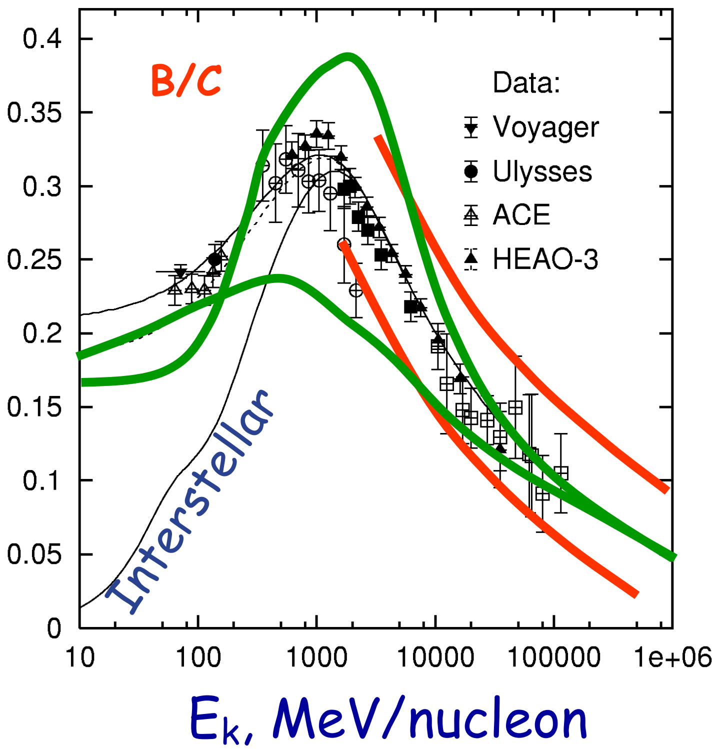
E-loss $$- \frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}\psi\right]$$

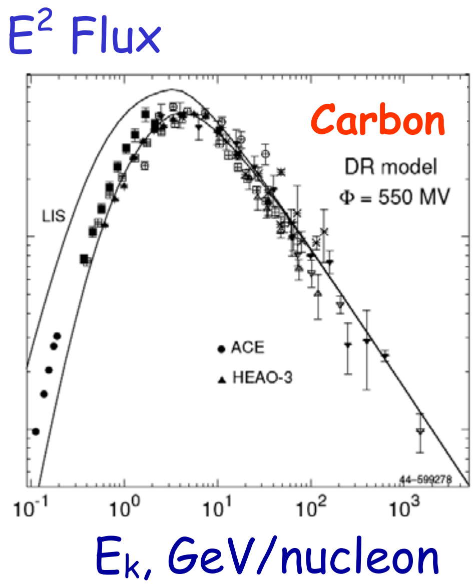
fragmentation $$- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ **radioactive decay**

+ boundary conditions

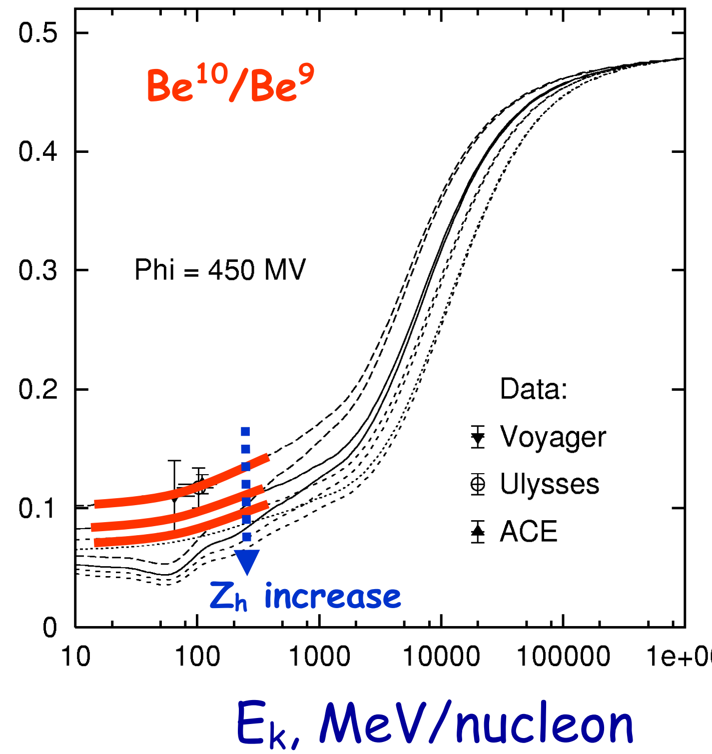
$\psi(\mathbf{r},p,t)$ – density per total momentum

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

Parameters (model dependent):

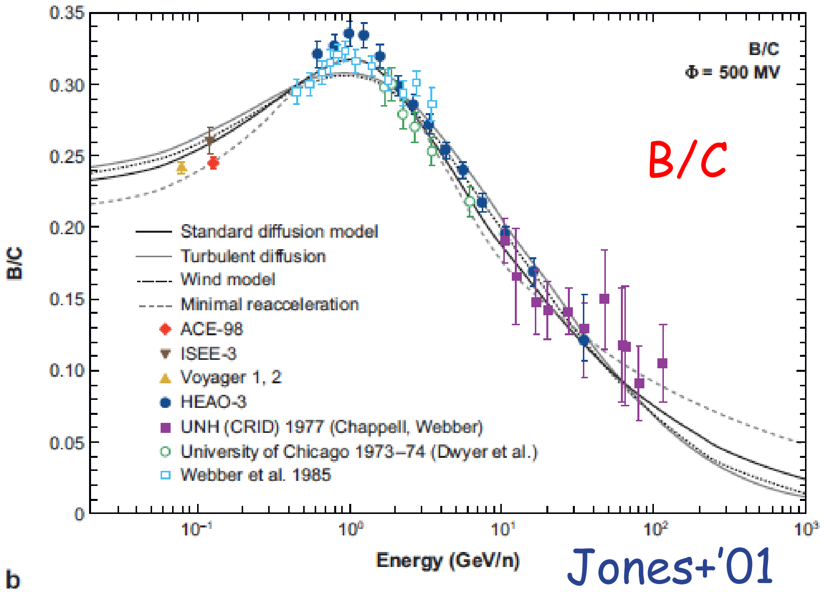
$D \sim 10^{28} (\rho/1\ GV)^{\alpha}\ cm^2/s$

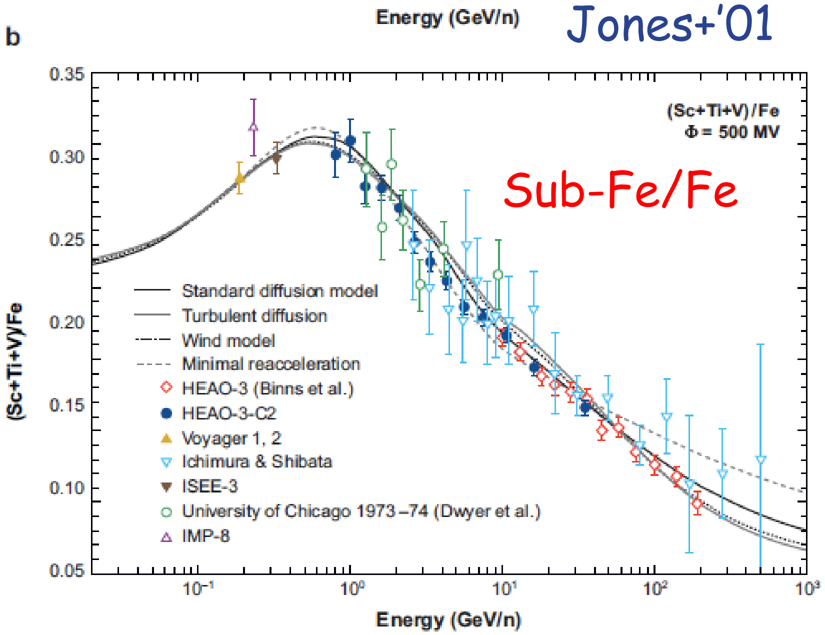
$\alpha \approx 0.3\text{-}0.6$

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

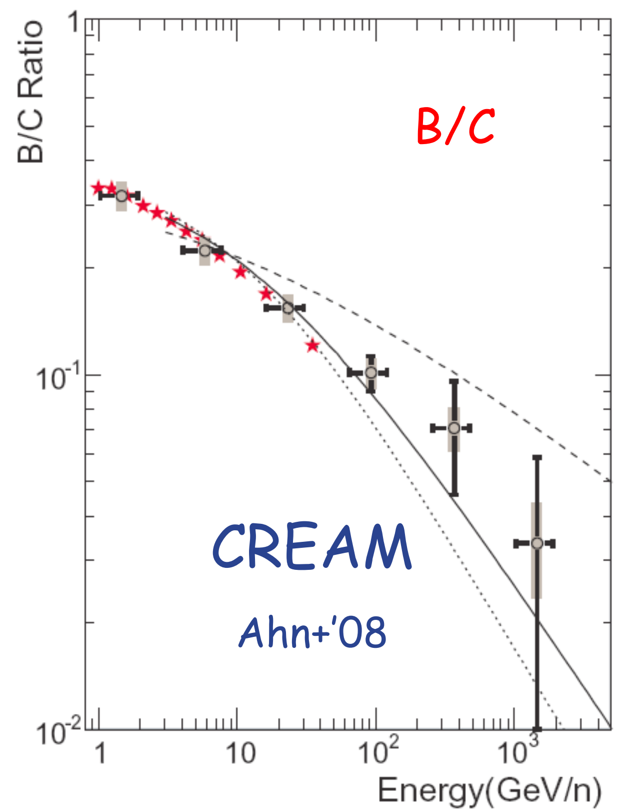
$V_A \sim 30$ km/s

Secondary/Primary Nuclei Ratio





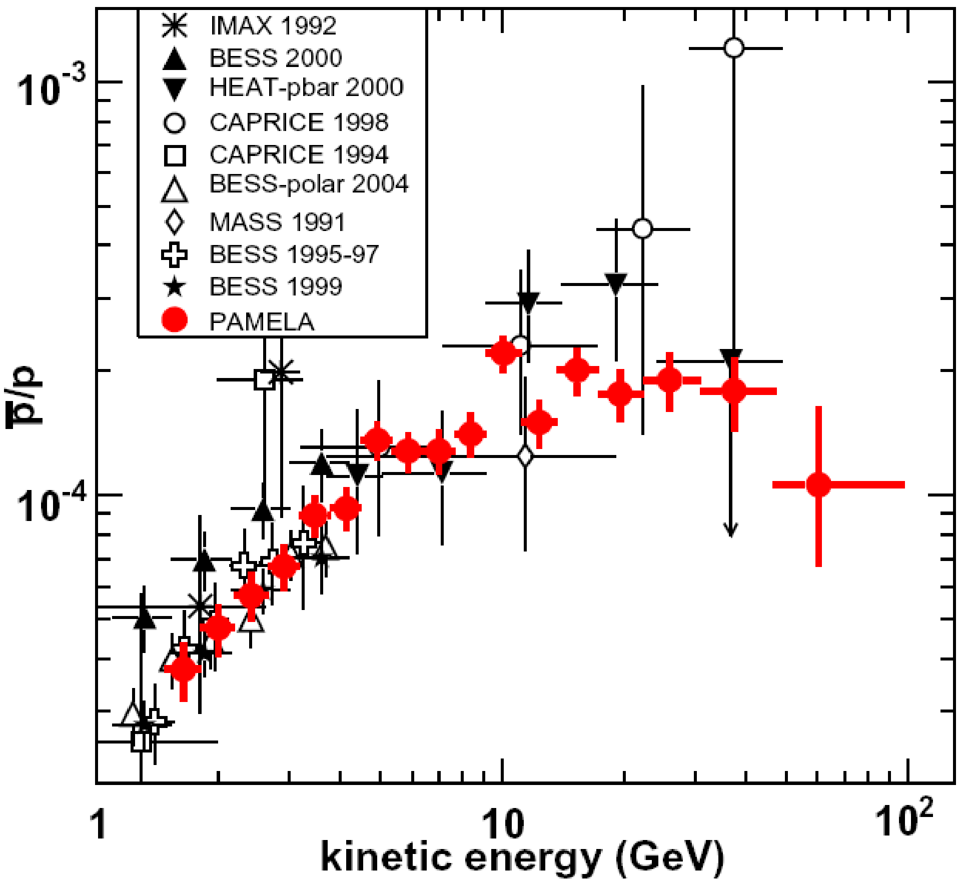
Being tuned to one type of sec/pri ratio (e.g. B/C ratio) the propagation model should be automatically consistent with all sec/pri ratios (sub-Fe/Fe, He^3/He^4, pbar/p…)

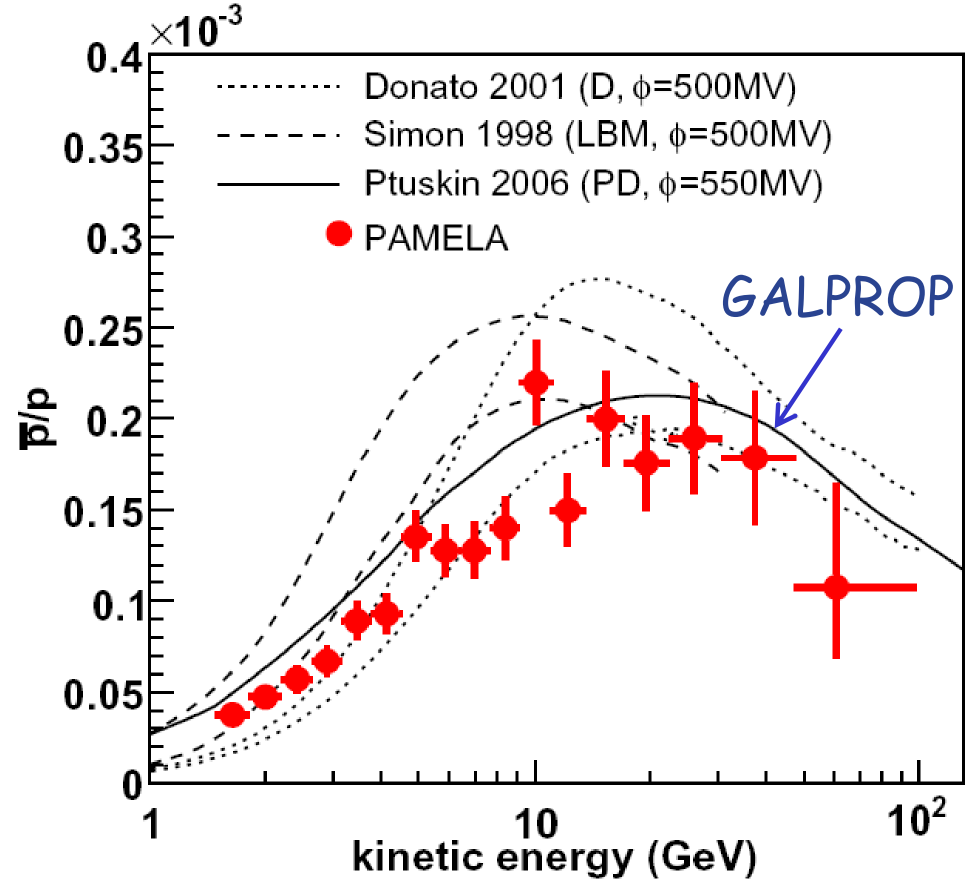


B/C ratio in CR is declining >1 GeV/n, not rising!

Pamela: pbar/p ratio

- Pbar/p ratio is consistent with secondary origin

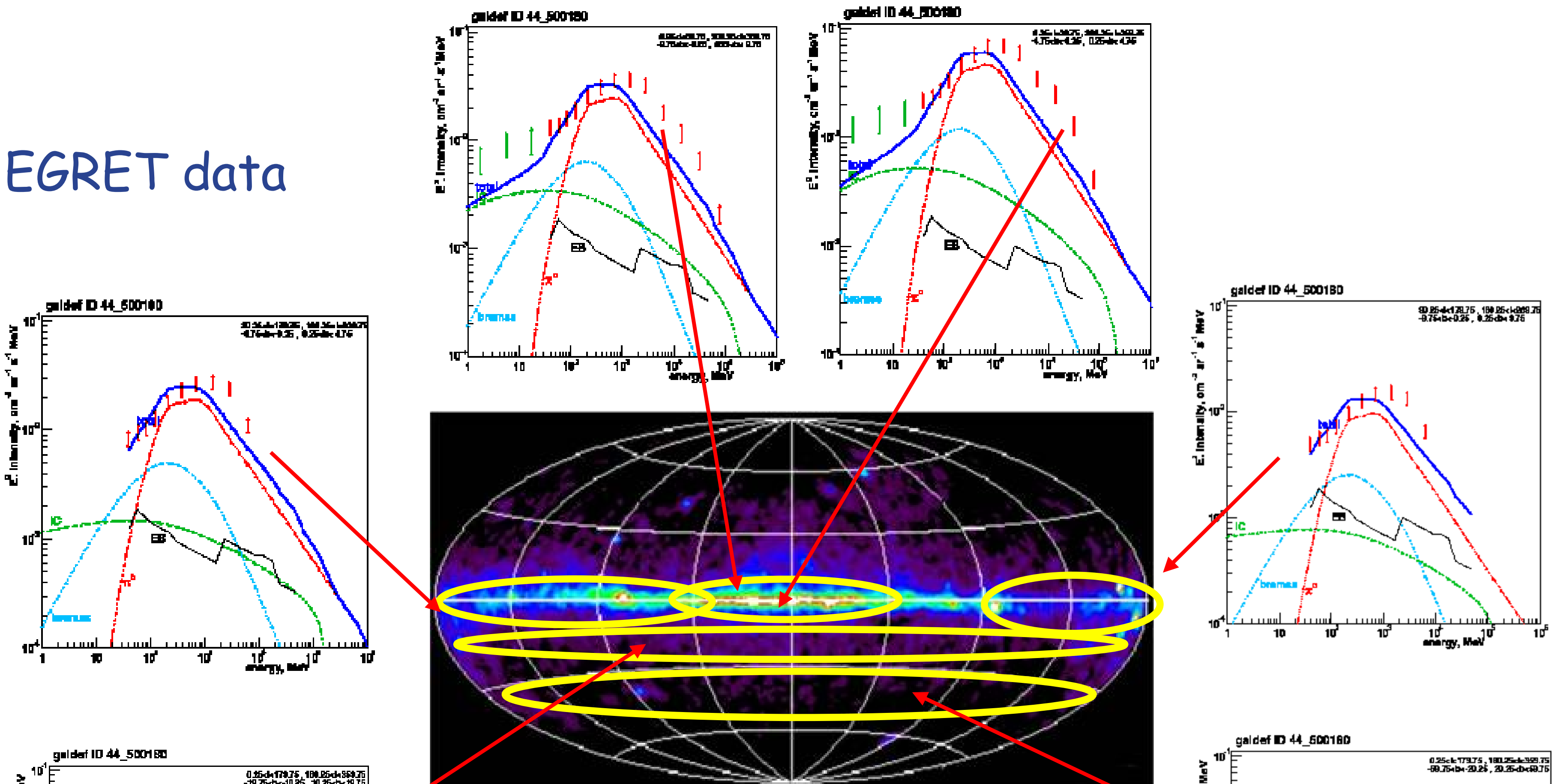


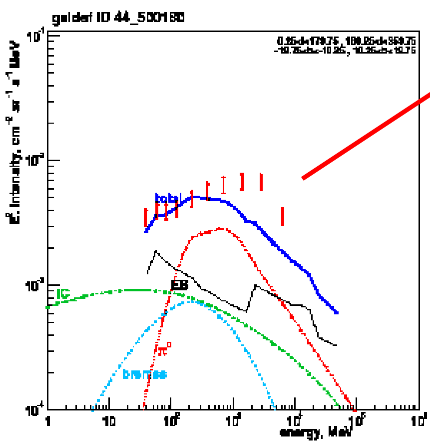


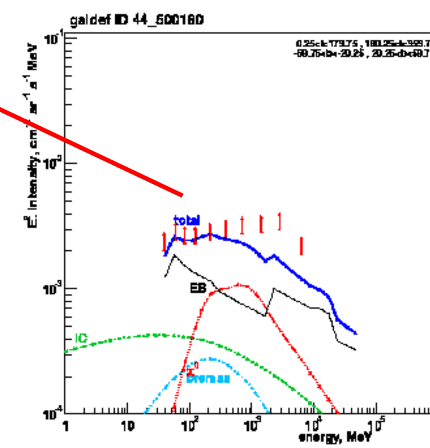
Adriani+'08 (arXiv:0810.4994)

The famous GeV γ-ray excess

EGRET data



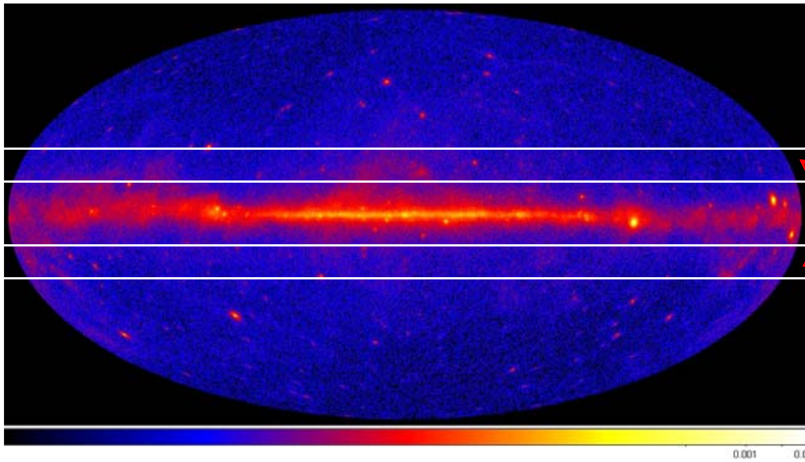




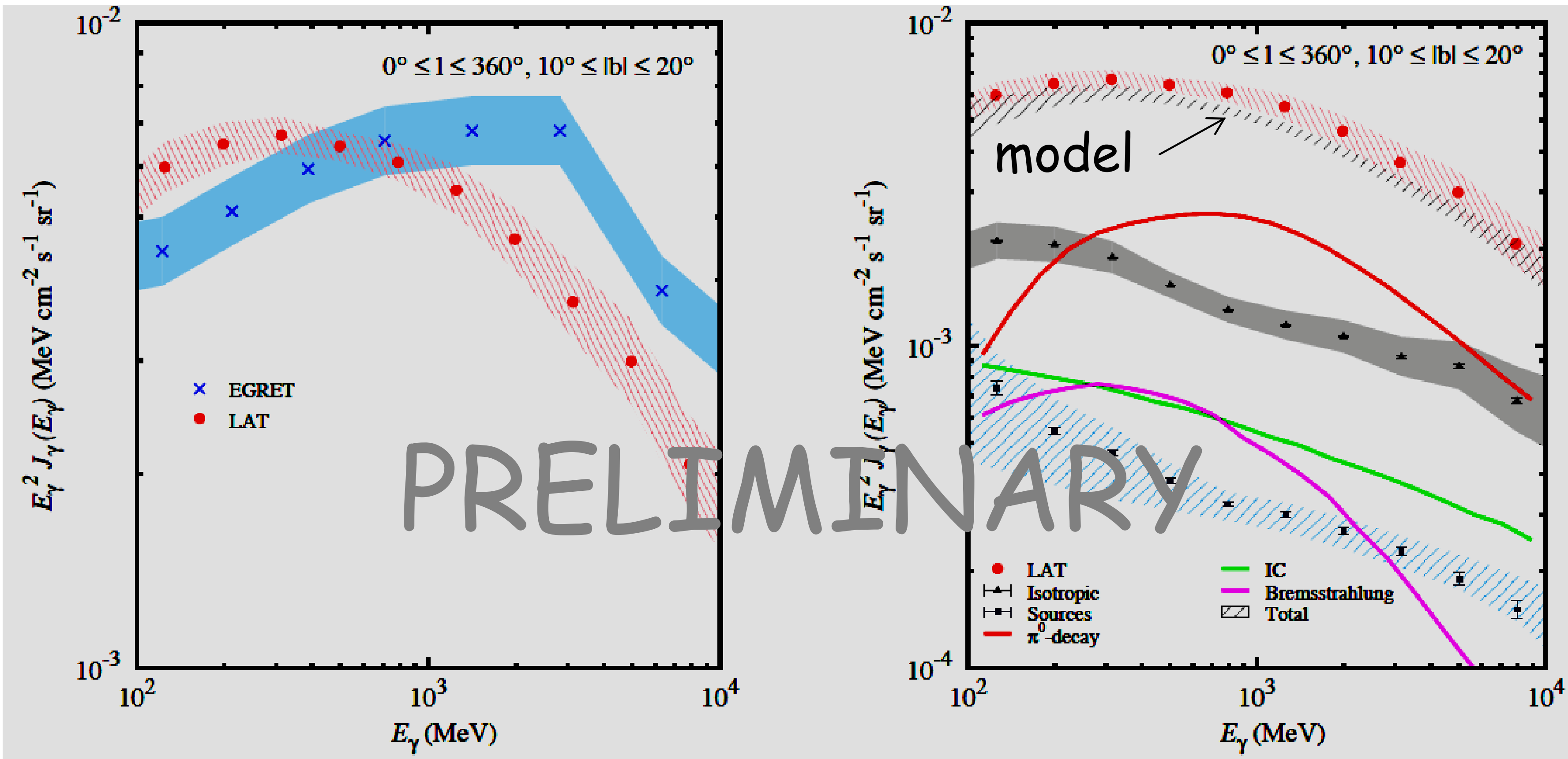
- Instrumental artefact?
- Physical phenomena?
- Dark Matter?

Strong+'00,'04

Fermi/LAT: Diffuse emission at mid-latitudes

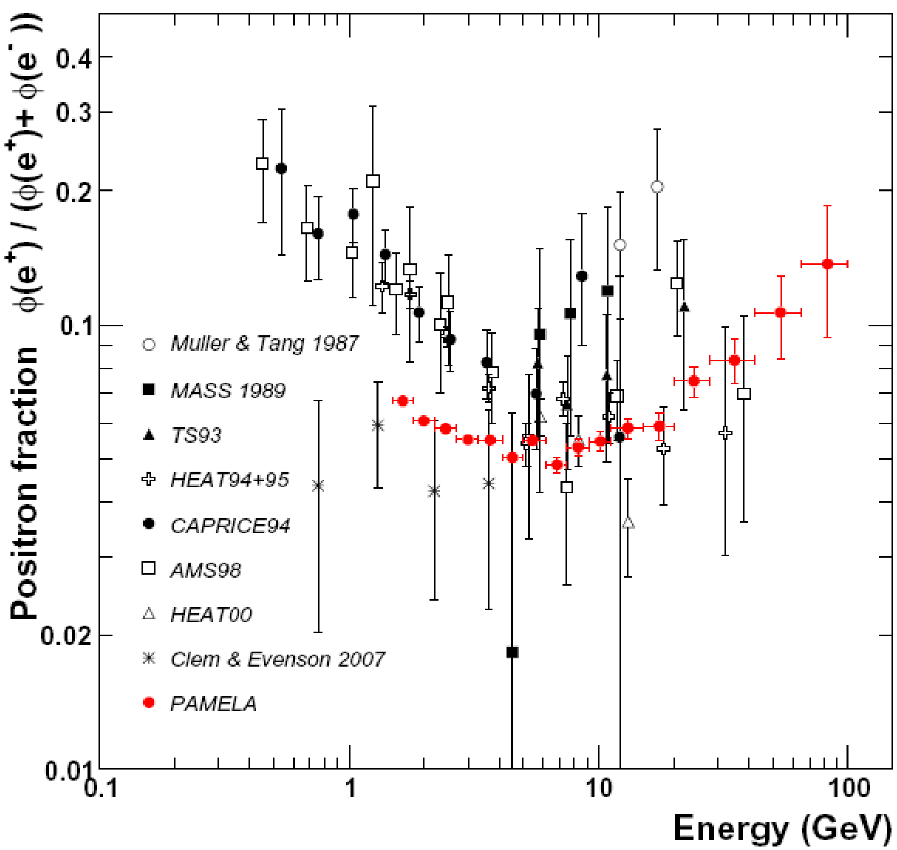


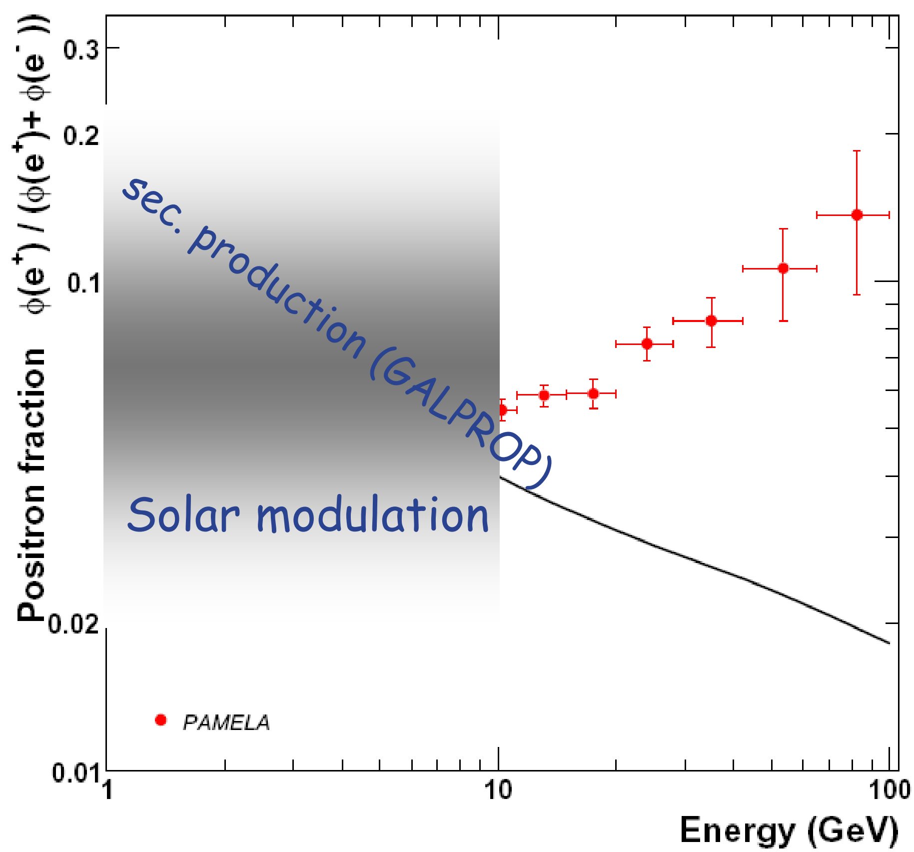
Conventional GALPROP model is in agreement with the LAT data at mid-latitudes (mostly local emission)



Pamela: positron fraction

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





Adriani+'08

Reasons for the positron fraction to rise

- Main reason – primary positrons are perhaps unavoidable
- There is no deficit in papers explaining the PAMELA positron excess (>300 papers since Oct 2008!)
  - Various species of the dark matter (most of papers)
  - Pulsars
  - SNRs
  - Microquasars
  - a GRB nearby
  - …
- Perhaps we have to discuss a deficit of positrons, not their excess!

- Unfortunately, they are >99.7% wrong!
- Reason – we do not know the positron spectrum, just the ratio…

Scientific Impact (using NASA ADS)

- ATIC electrons: >200 citations (in ~1 yr)
- Fermi LAT electrons: >100 citations (in ~1/2 yr)
- HESS electrons: ~100 citations (in <1 yr)
- PAMELA positron fraction: >300 citations (in ~1 yr)
- PAMELA antiprotons: >150 citations (in <1 yr)

The Key Question

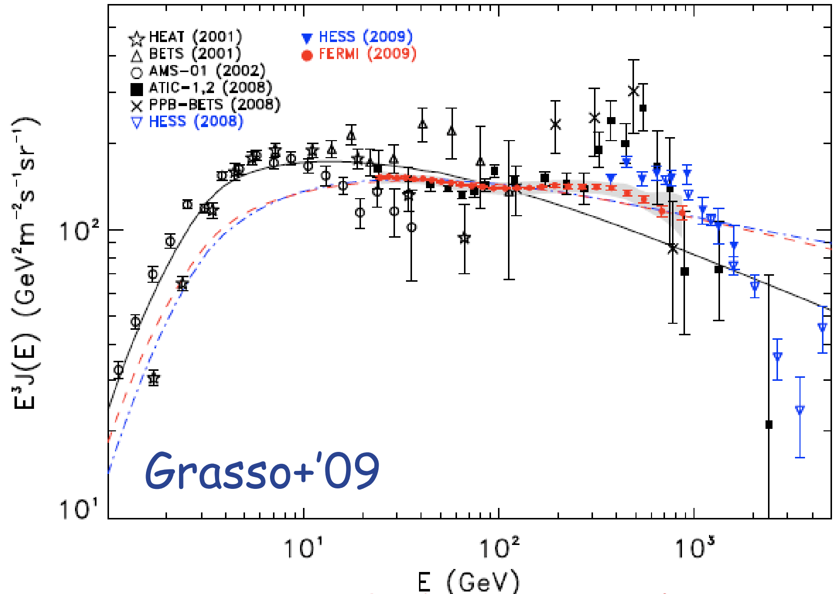
Last couple of years the Cosmic Ray and Astrophysical communities were exposed to the overwhelming amount of new and accurate data and are expecting more to come…

It will probably take a few years to fully appreciate the significance of new information, but it is absolutely clear that we are currently on the verge of dramatic breakthroughs in Astrophysics, Particle Physics, and Cosmology and may soon be able to resolve century-old puzzles such as the origin of cosmic rays and dark matter. Hopefully before 100th anniversary of V.Hess flight in 2012!

The key question to answer is how these new discoveries fit or do not fit into the "standard picture" of the Milky Way galaxy

Hypotheses Currently on the Table: Standard CRs

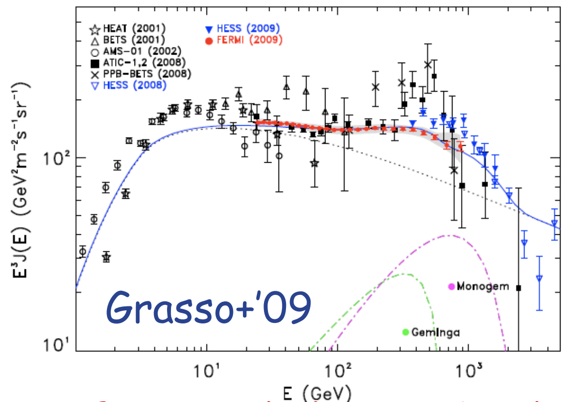
- Currently there is no dominating hypothesis consistent with all sorts of data

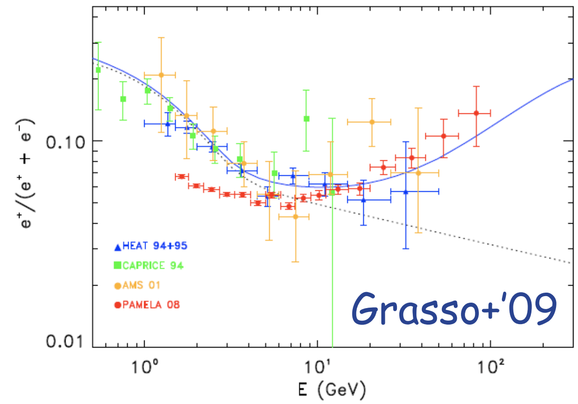


- Pros
  - Agrees with spectra and abundances of the CR nuclear component
  - Consistent with the spectrum of the diffuse emission
  - The CR electron spectrum can be easily matched
- Cons
  - Disagreement with CR electron measurements at low energies
  - It is hard to make the positron fraction to rise given the pbars are consistent with secondary origin (the same progenitor, pp-interactions, for both)

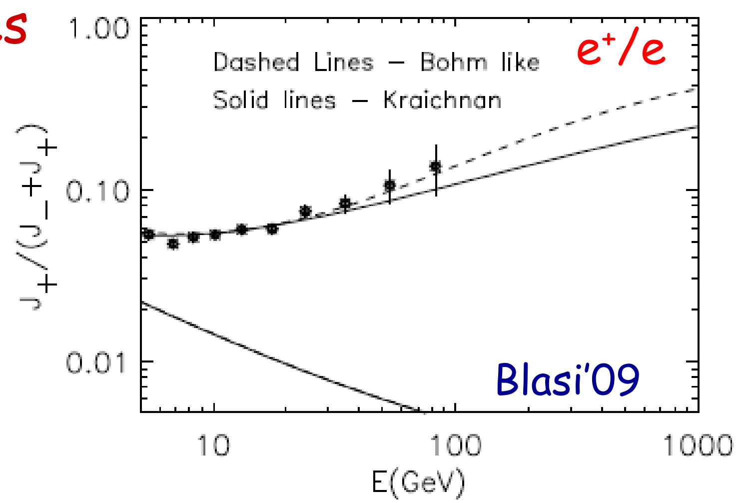
Hypotheses Currently on the Table: Astrophysical Source(s)

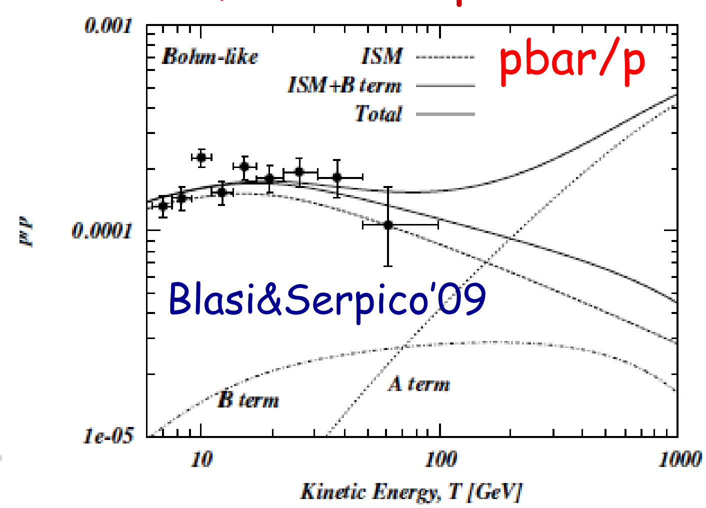
- Pros
  - Pulsars are a viable explanation (Aharonian+'95…), they are the sources of primary electrons and positrons





  - Inhomogeneity of SNR (Shaviv+'09)
- Cons
  - Pulsars: The spectrum of accelerated particles is unknown
  - SNRs accelerate all particles including nucleons, but sec/pri ratio decreases





Hypotheses Currently on the Table: DM

- Pros
  - WIMPs with leptonic final states
  - The WIMP mass and the "boost factor" can be adjusted
- Cons
  - Leptonic final states may lead to a strong gamma-ray signal (not observed)
  - Hard to prove unless a clear spectral feature is discovered

Early Discoveries of New Particles in CRs

1929

Bothe (Nobel Prize 1954) and Kolhorster verified that the cloud chamber tracks were curved. Thus the cosmic radiation was charged particles

1932

a discovery of positron by C. Anderson (Nobel Prize 1936)

1937

a discovery of muon by Neddermeyer& Anderson and simultaneously by Street & Stevenson

1947

pions predicted by Yukawa (1935, Nobel Prize 1949) to explain the force that binds the nucleus together were discovered (Cecil Powell et al.; Nobel Prize 1950)

kaons were discovered by Rochester & Butler

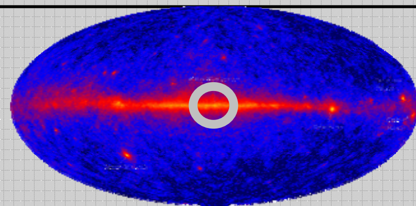
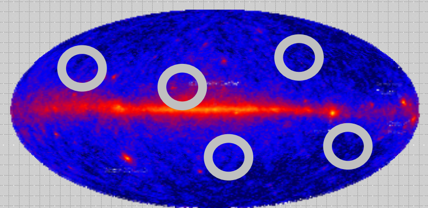
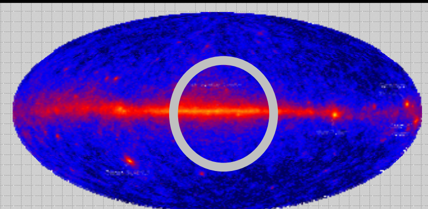
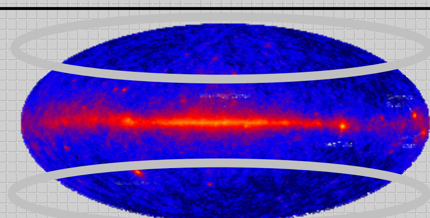
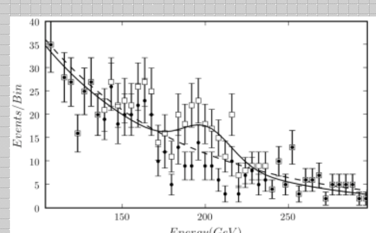
W.Bothe

C. Anderson

H.Yukawa

C.Powell

Searching for Dark Matter

Search Technique		advantages	challenges
Galactic center		Good Statistics	Source confusion / Diffuse background
Satellites, subhalos Point sources		Low background, Good source id	Low statistics
Milky Way halo		Large statistics	Galactic diffuse background
Extra-galactic		Large Statistics	Astrophysics, galactic diffuse background
Spectral lines		No astrophysical uncertainties, good source id	Low statistics

Morphology of the Diffuse Emission @ 150 GeV

Conventional

IC π^0

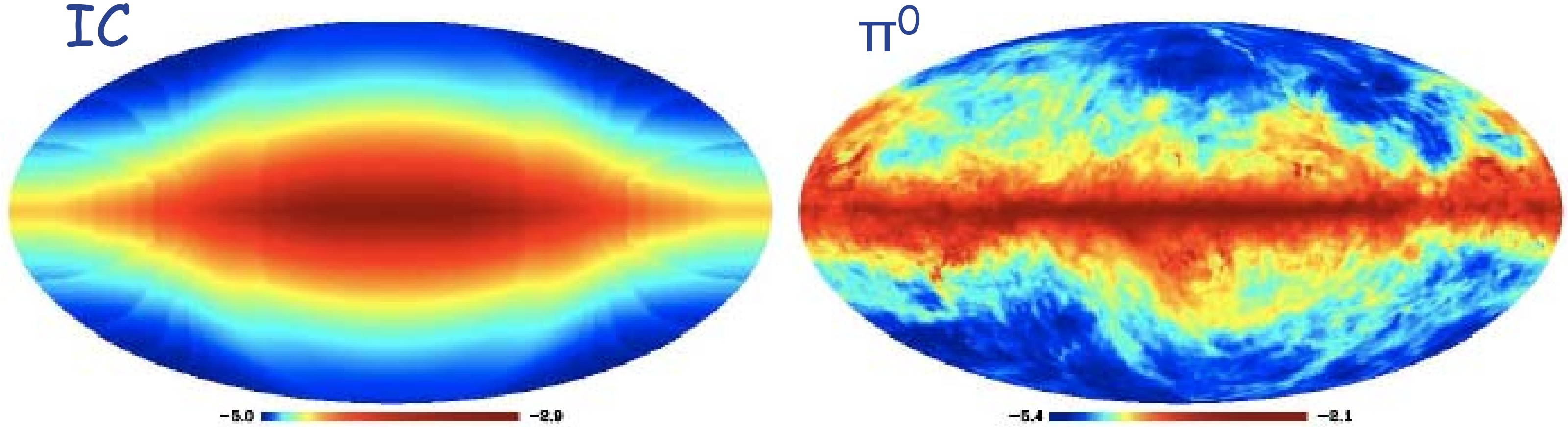


FIG. 9: Sky-map at 150 GeV of the emissions associated to Galactic primary+secondary CRs in the "conventional" model B0. The intensity is shown in logarithmic scale and units [MeV cm^{-2} s^{-1} sr^{-1}]. *Left Panel*: Inverse Compton radiation. *Right Panel*: π^0-decay emission.

Regis&Ullio'09

Dark Matter

IC π^0

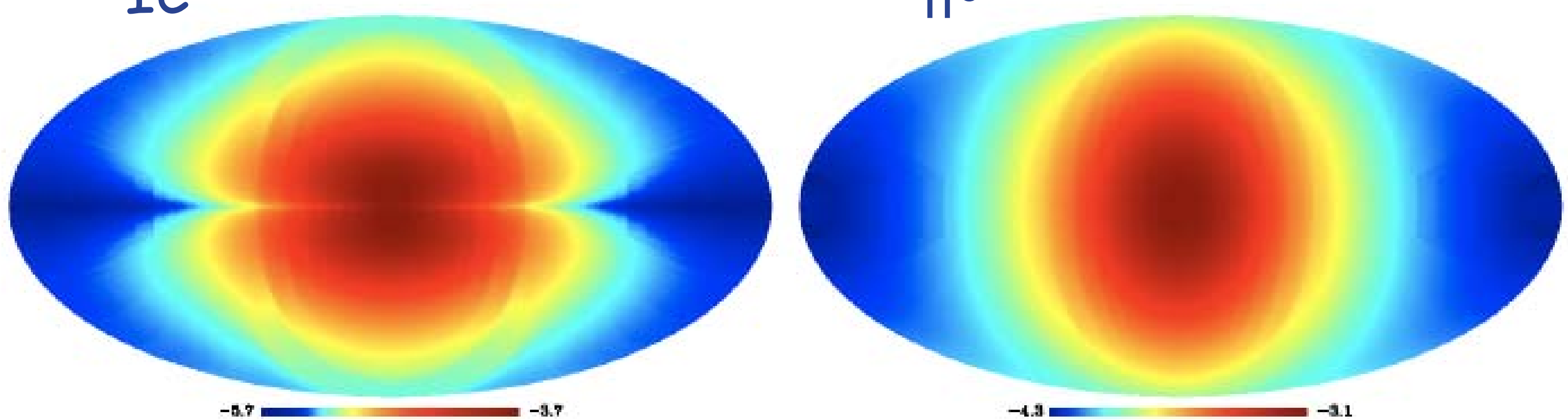


FIG. 10: Sky-map at 150 GeV of the emissions induced by WIMP annihilations in the propagation model B0. The intensity is shown in logarithmic scale and units [MeV cm^{-2} s^{-1} sr^{-1}]. *Left Panel*: Inverse Compton radiation in the DMe scenario. *Right Panel*: π^0-decay emission in the DMτ scenario.

205 Preliminary LAT Bright Sources

Census of Associations (not Identifications)

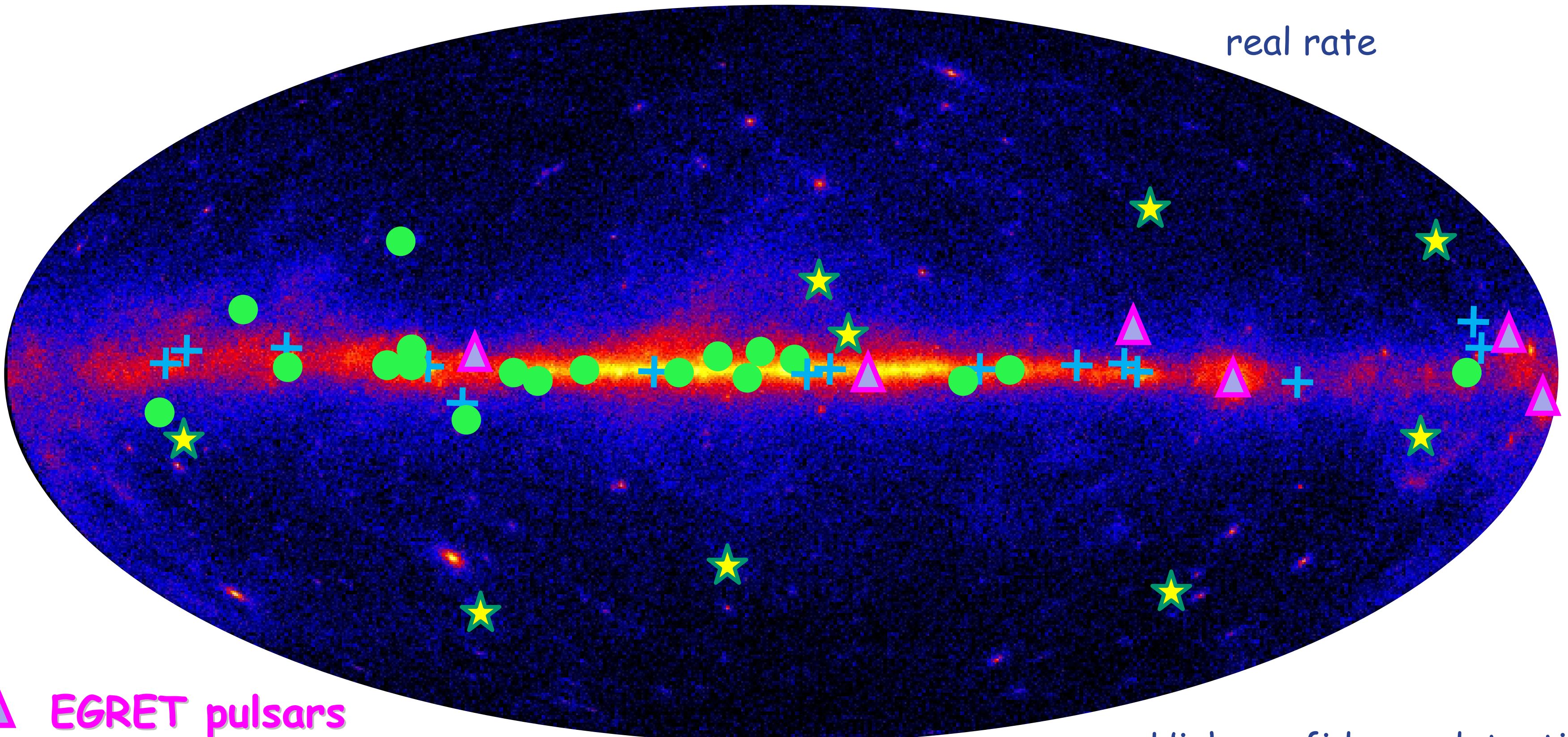
Class	Number
Radio/X-ray pulsar	15
LAT pulsar	14
Globular cluster (pulsars?)	1
HMXB	2
LMC	1
Flat Spectrum Radio Quasars	62
Bl Lac Objects	46
Blazar, uncertain type	11
Radio galaxies	2
Special cases (under study)	14
Unassociated	37

Fermi Pulsars

33 gamma-ray and radio pulsars (including nine ms psrs)

16 gamma-ray only pulsars

Pulses at 1/10th real rate



△ EGRET pulsars

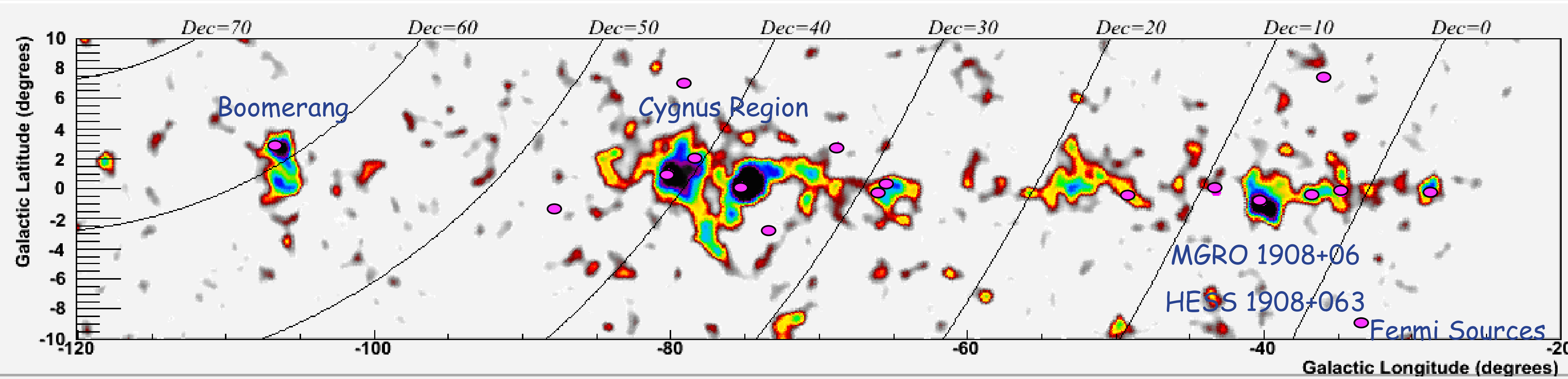
+ young pulsars discovered using radio ephemeris

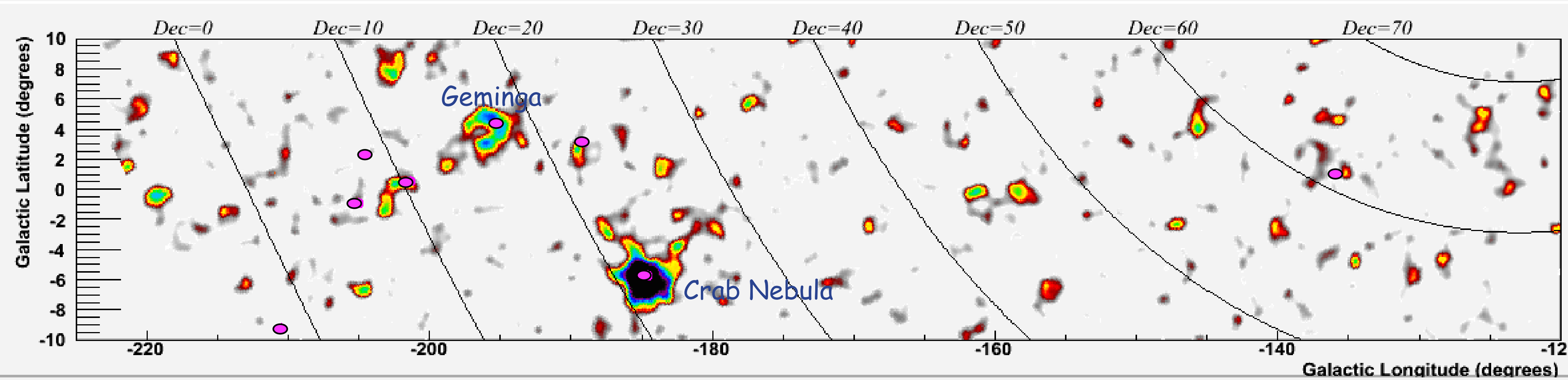
● pulsars discovered in blind search

☆ millisecond pulsars discovered using radio ephemeris

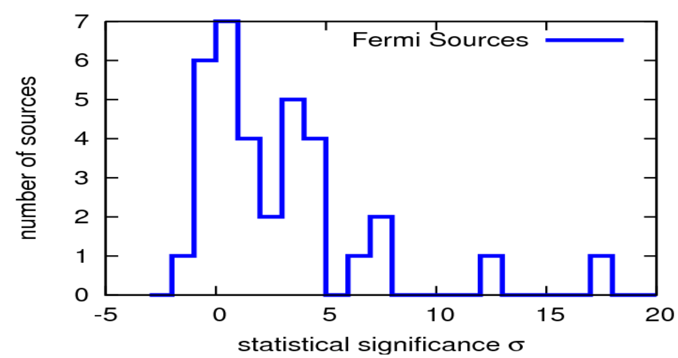
High-confidence detections through 2/28/2009

MilagroSkymap





- 34 Fermi BSL Galactic sources above declination of -5°
- 14 detected by Milagro above 3σ
  - FDR Miller 2001 estimates 1% false positive rate
- 5 new TeV sources
- Geminga 6.3σ as extended source (2.6°fwhm)



Credit G.Sinnis

Milagro: TeV Observations of Fermi Sources

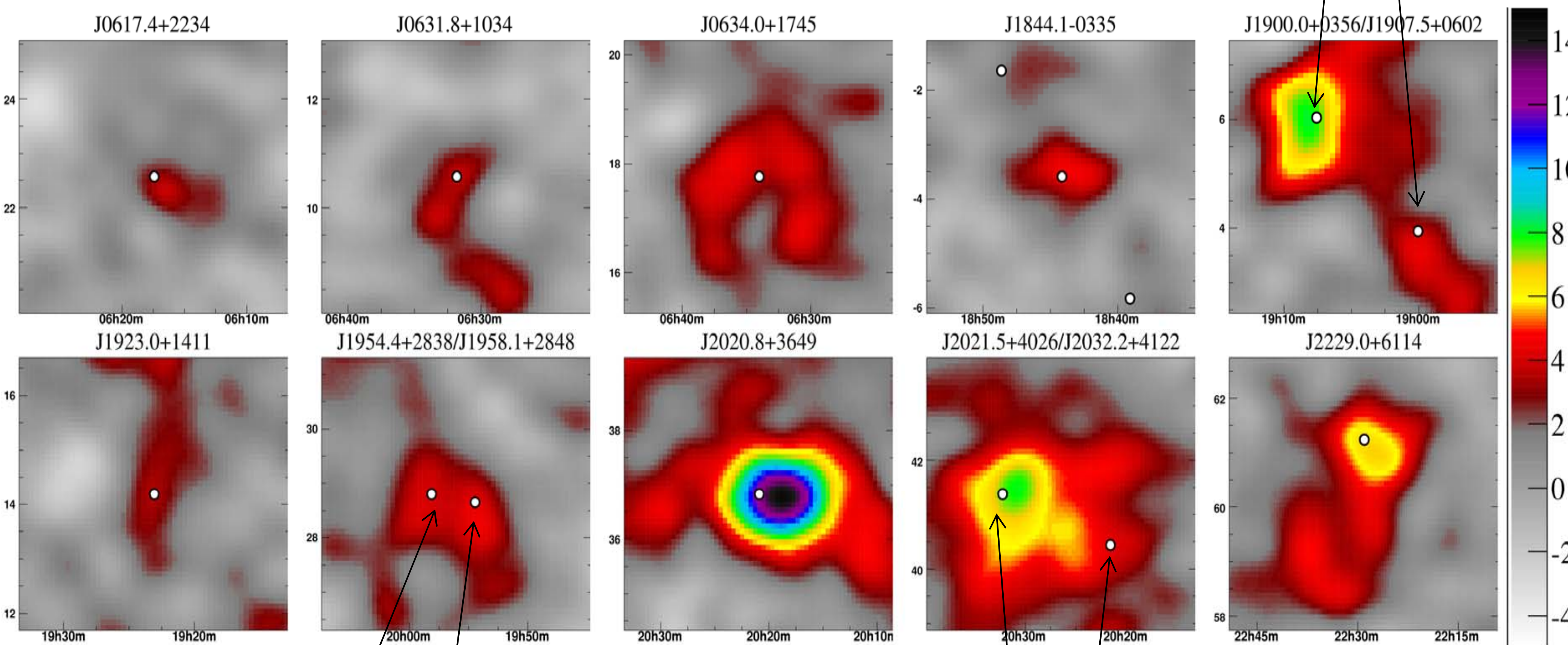
IC433
SNR
MAGIC
VERITAS

Radio pulsar
J0631+10
(new TeV source)

Geminga
Pulsar
Milagro C3

unID
(new TeV source)

unID
(new TeV source)
Fermi Pulsar
MGRO 1908+06
HESS 1908+063



W51
HESS J1923+141
SNR

G65.1+0.6 (SNR)
Fermi Pulsar (J1958)
New TeV sources

Pulsar
(AGILE/Fermi)
MGRO 2019+37

Fermi Pulsar
γCygni SNR
Fermi Pulsar
HESS 2032+41
MGRO 2031+41
MAGIC 2032+4130

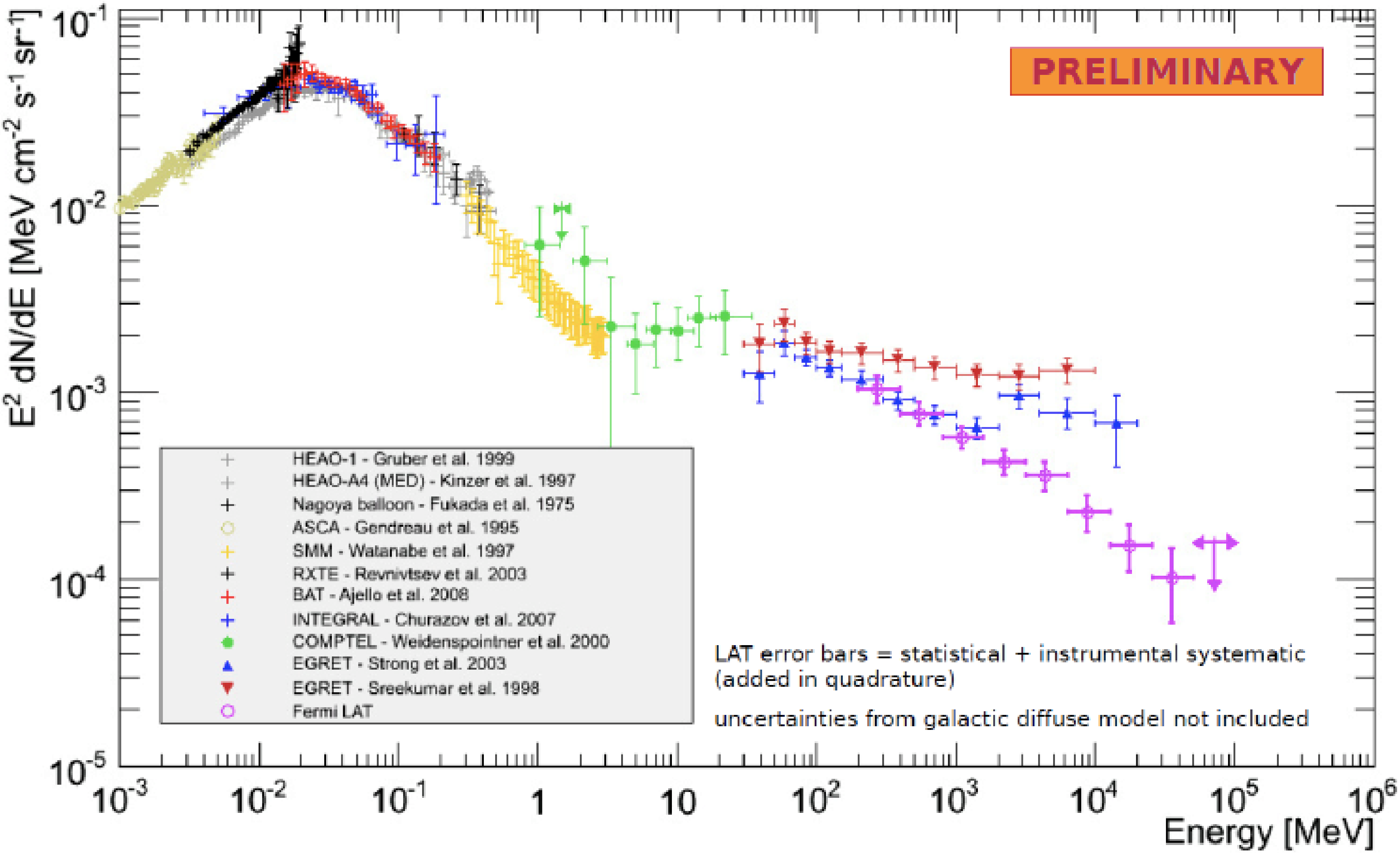
Fermi Pulsar
Milagro (C4)
3EG 2227+6122
Boomerang PWN

Credit G.Sinnis

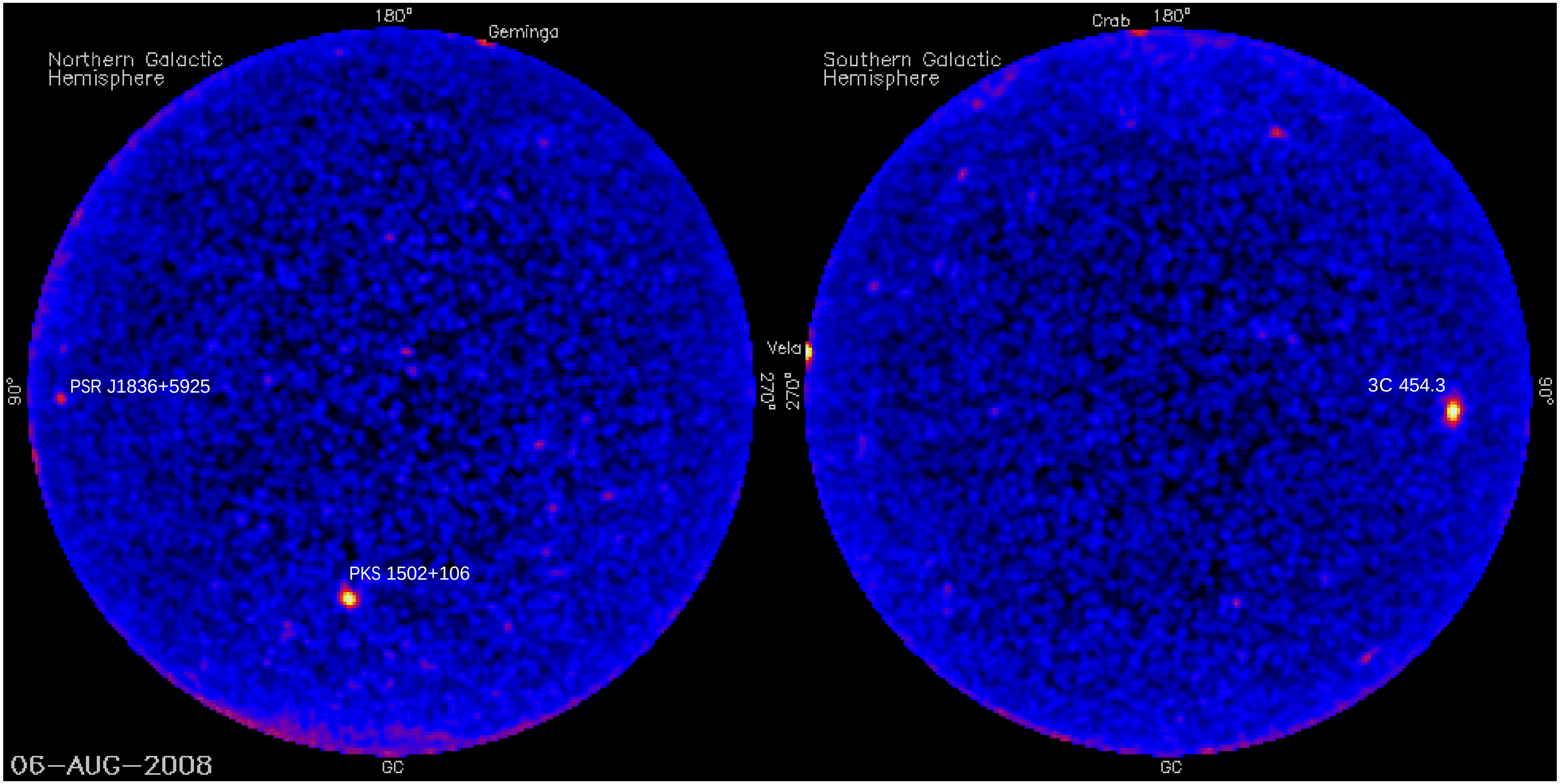
(Some) Important Questions to Answer

- How large is the positron fraction at HE (PAMELA)
  - Identifies the nature of sources of primary positrons
- If SNRs are the sources of primary positrons, this should also affect secondary nuclei…
  - Measure the secondary nuclei (PAMELA, CREAM…)
- How typical for the local Galactic environment is the observed Fermi/LAT spectrum
  - If this is the typical spectrum than the sources of primary positrons are distributed in the Galaxy (could be pulsars, SNRs, or DM)
  - If this spectrum is peculiar than there is a local source or sources of primary positrons
  - The answer is in the diffuse gamma-ray emission (Fermi/LAT)
- Dark matter vs Astrophysical source
  - Distribution of the IC emission at HE (Fermi/LAT)
- **WE HAVE ALL NECESSARY INSTRUMENTS IN PLACE (in the orbit) TO ANSWER THESE QUESTIONS**

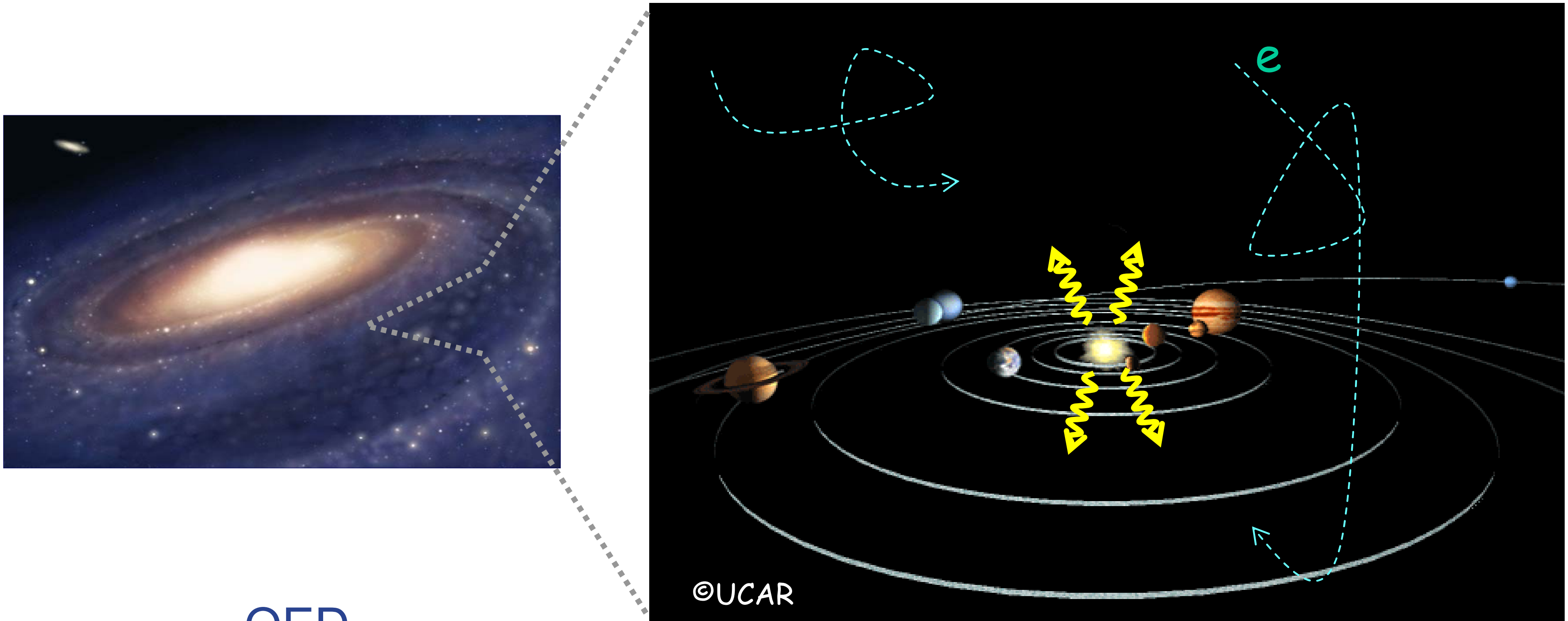
SED of the isotropic diffuse emission (1 keV – 100 GeV)



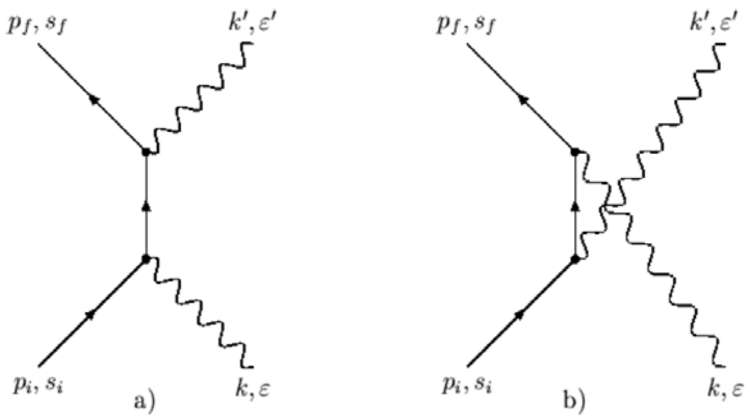
First 3 months of LAT data



Inverse Compton scattering on Solar Photons



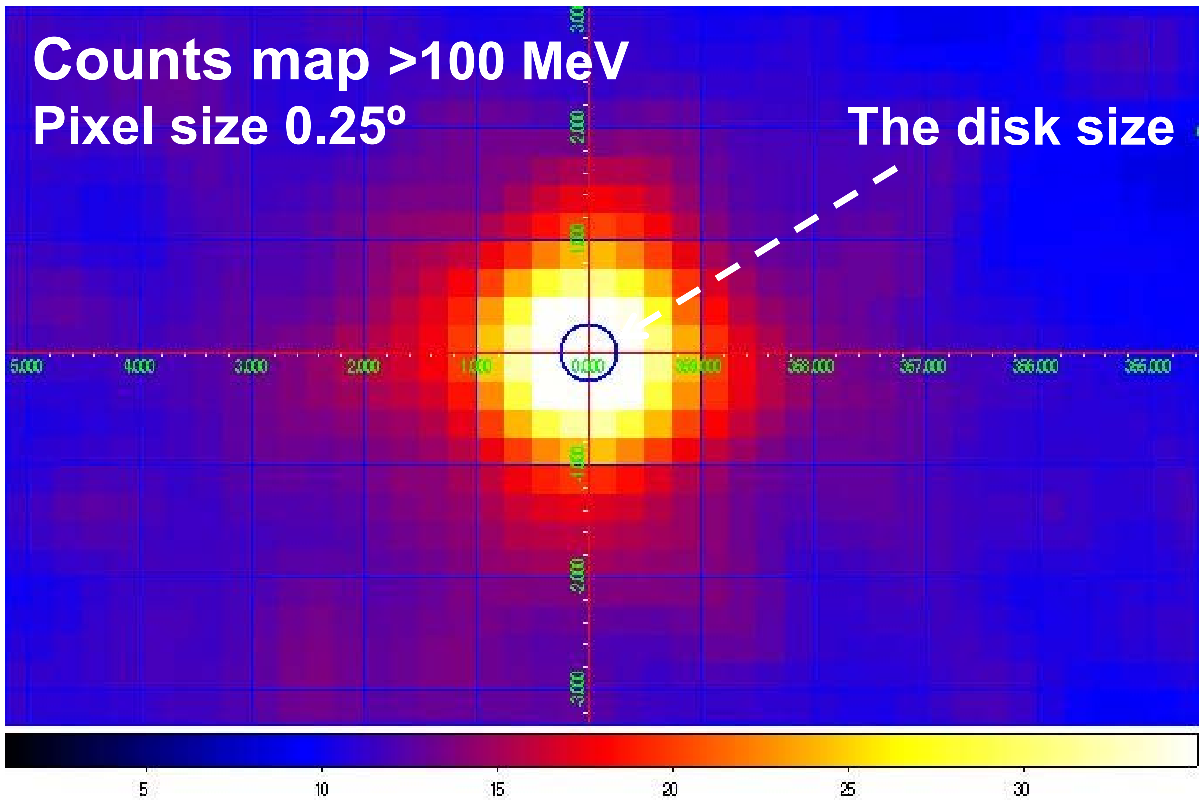
QED



The heliosphere is filled with Galactic CR electrons and solar photons

- •electrons are isotropic
- •photons have a radial angular distribution

The Sun: 5 months of observations

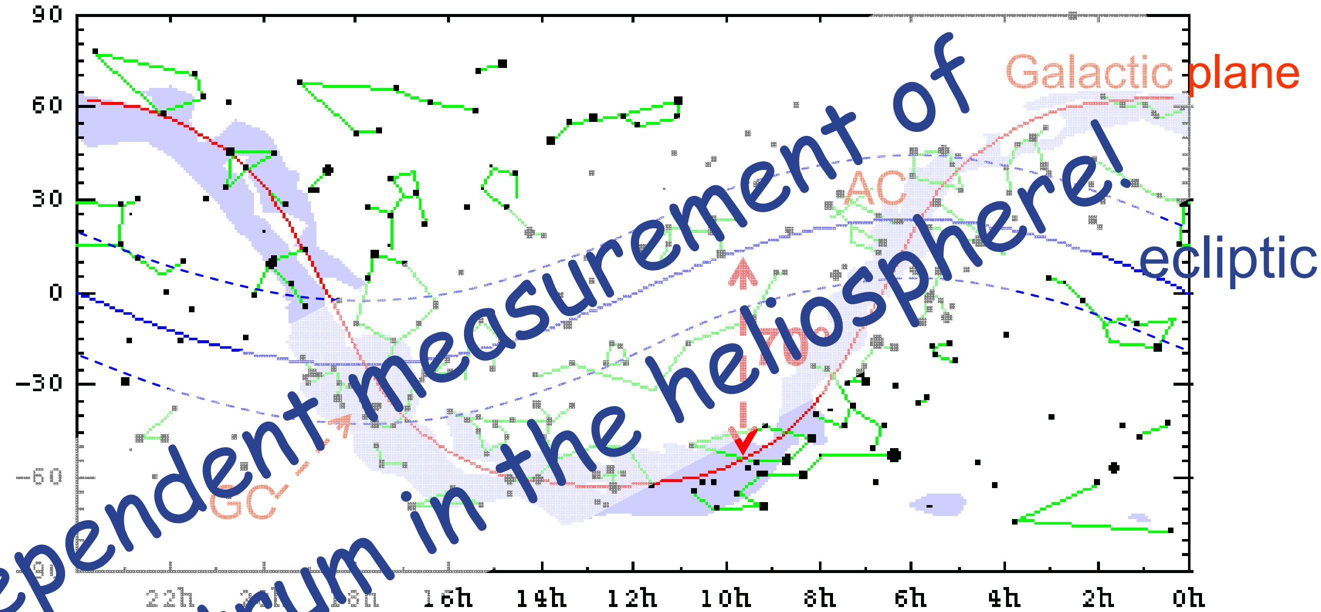


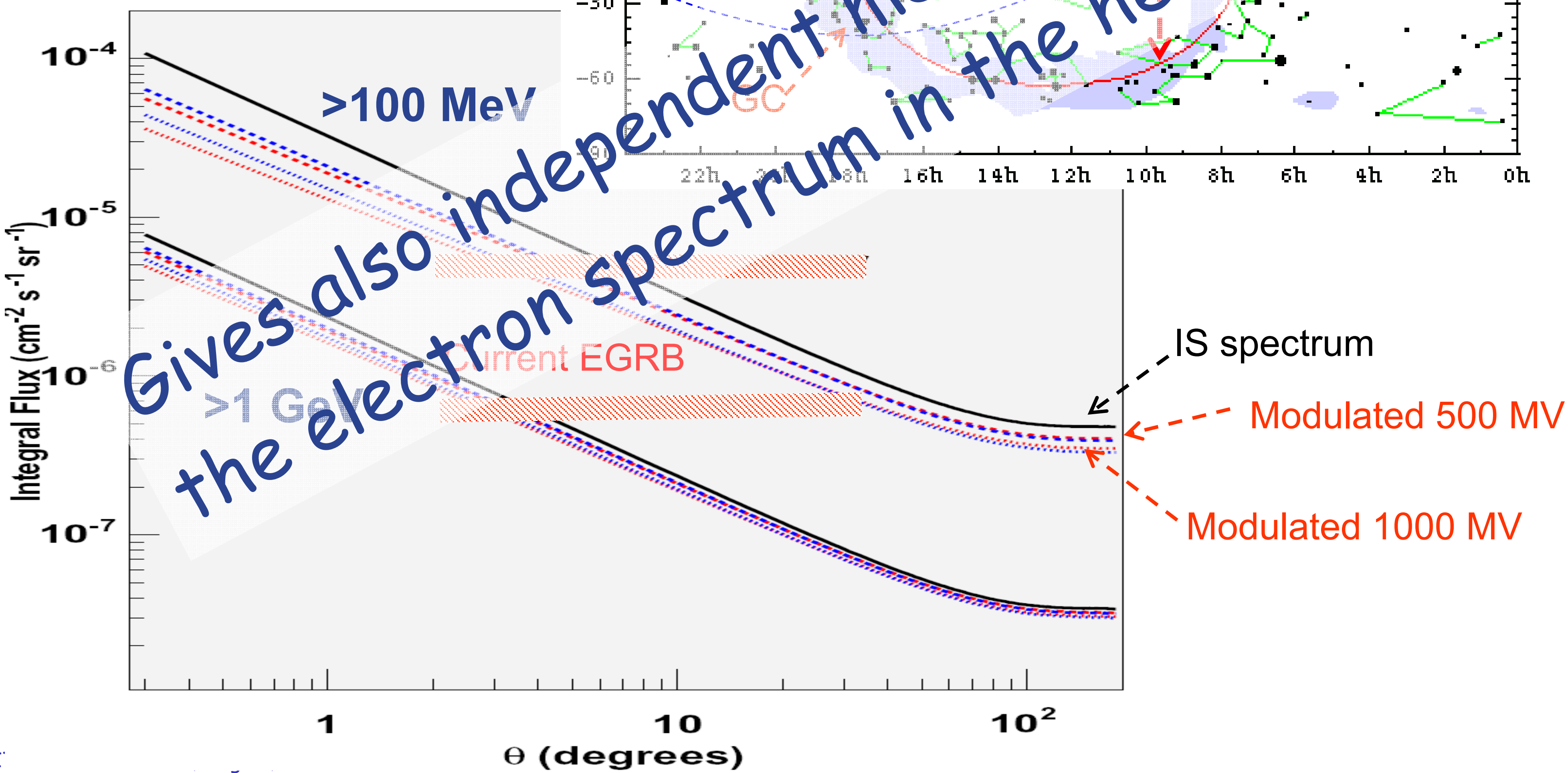
Source Flux (>100 MeV) ~ $4x10^{-7}$ cm^{-2} s^{-1} (albedo+IC,preliminary)

Expected IC Flux (>100 MeV) ~ $4.3x10^{-7}$ cm^{-2} s^{-1} (near the solar min, IM+'06)
EGRET Flux (>100 MeV) = not found(Thompson+'97)
= $(4.44 \pm 2.03)x10^{-7}$ cm^{-2} s^{-1} (albedo+IC, Orlando&Strong'08)

The ecliptic

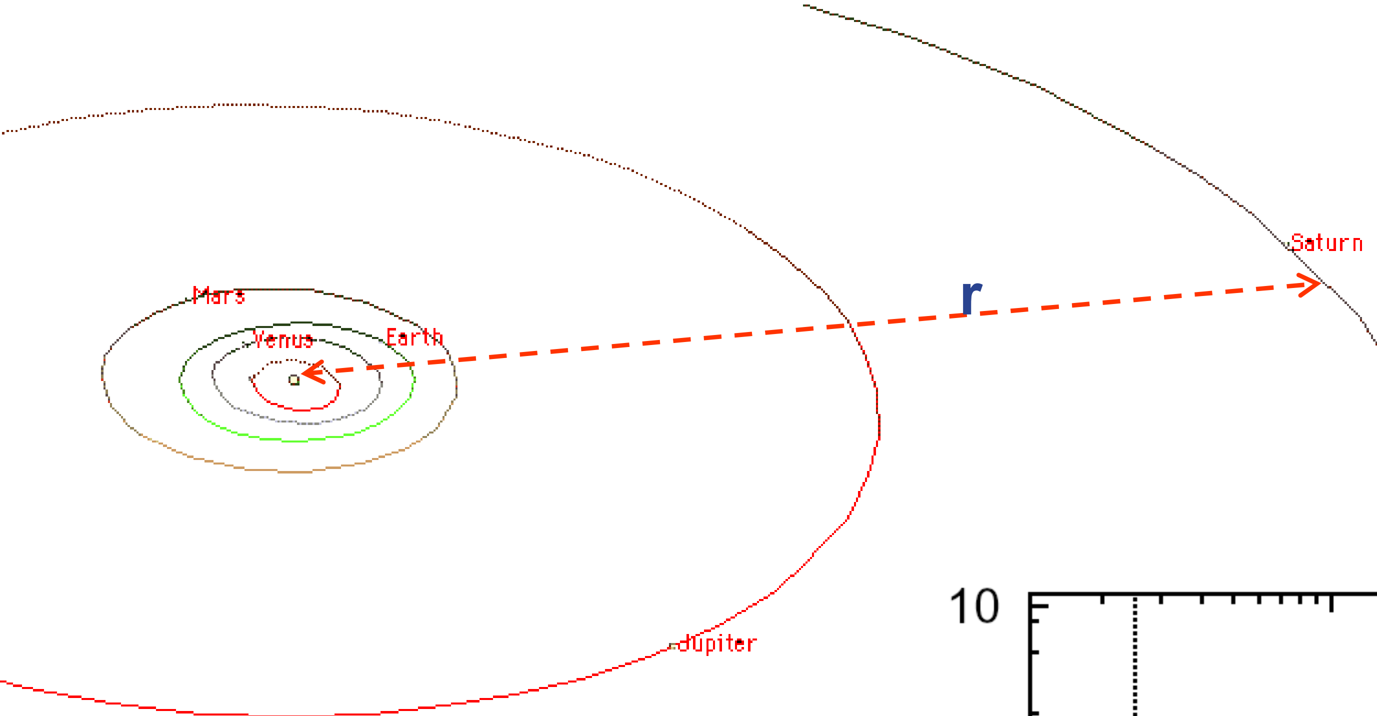
Averaged over one year, the ecliptic will be seen as a bright stripe on the sky, but the emission comes from all directions



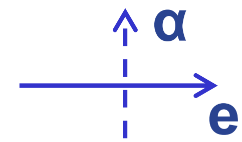


KI

Spectrum of CR electrons in the heliosphere



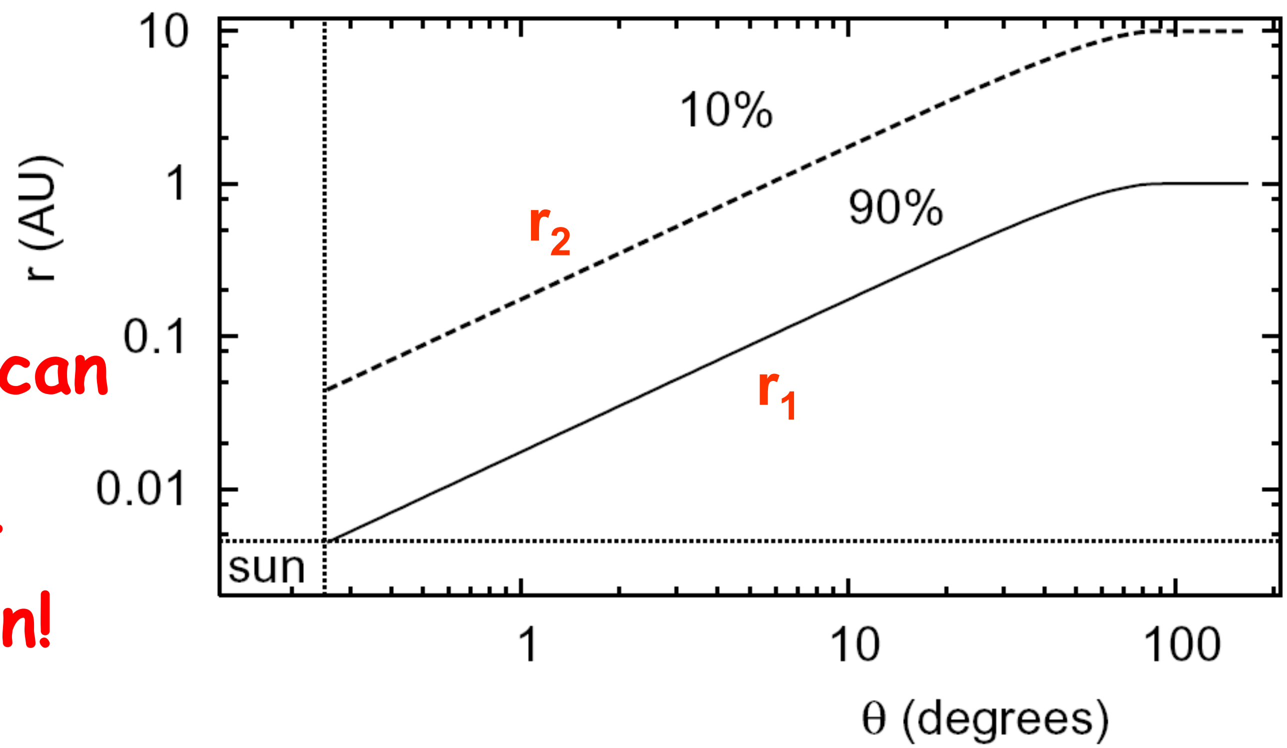
$Flux_{IC} \sim 1/r$



r_1 (AU) = sinα, α<90°

r_1 (AU) = 1, α>90°

$r_2 = 10 r_1$



Looking at different elongation angles one can probe the electron spectrum at different distances from the sun!


Thank you !
You are here
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