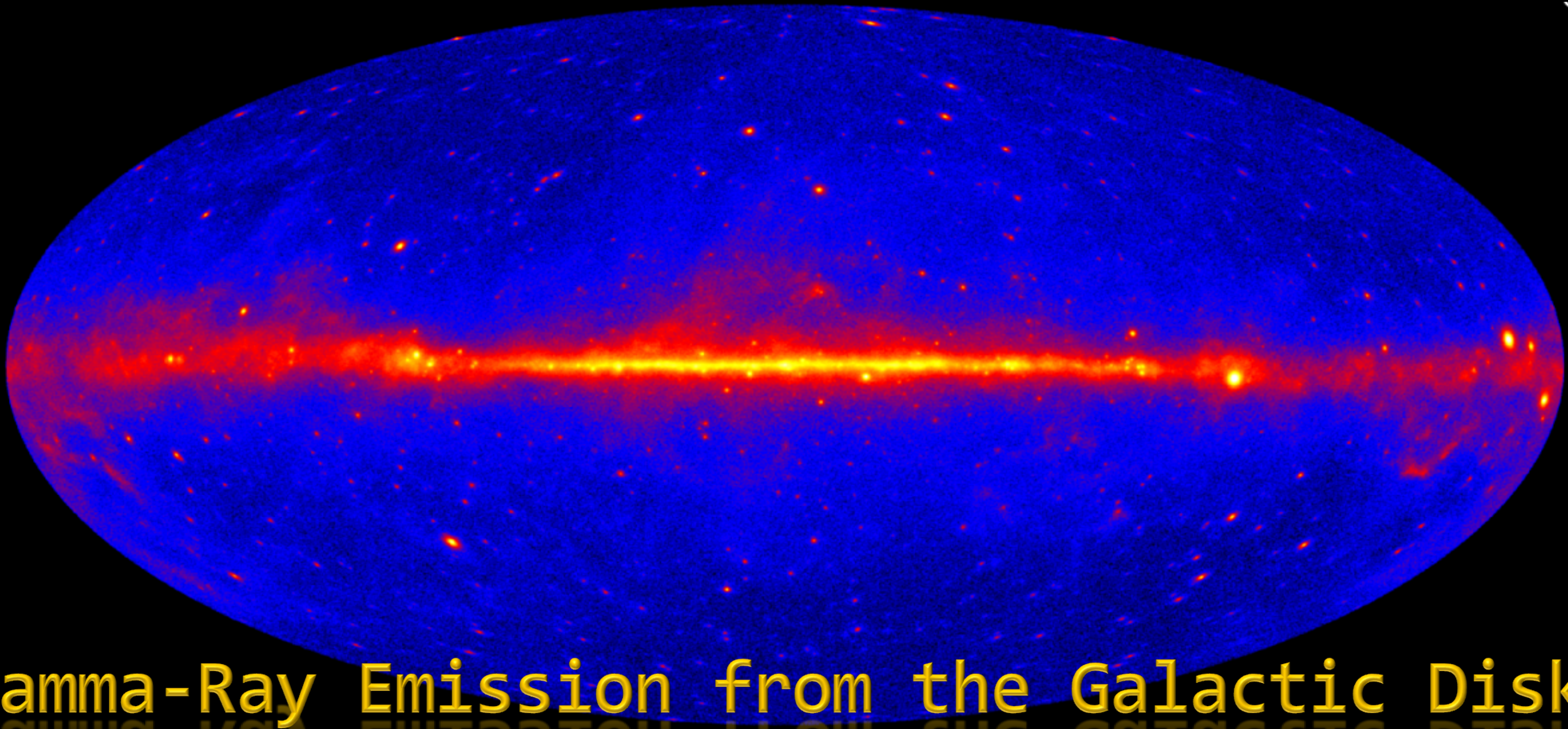


Gamma-Ray Emission from the Galactic Disk

Olaf Reimer Dublin Summer School on High Energy Astrophysics June 12, 2011

Outline

☞ from a historical perspective:

Gamma-ray emission from the Galactic Plane is the *oldest* and *most prominent* phenomenon in high-energy gamma-ray astrophysics

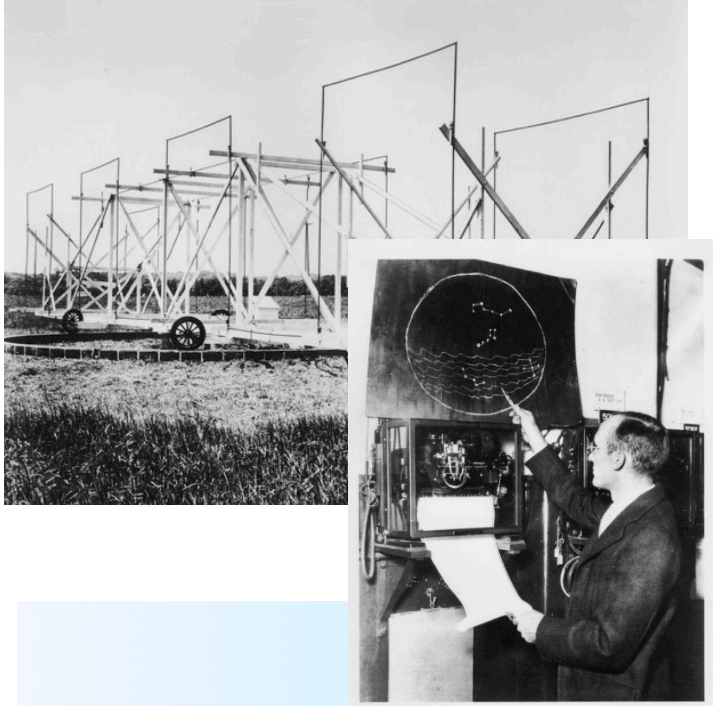
☞ from a Cosmic Ray perspective:

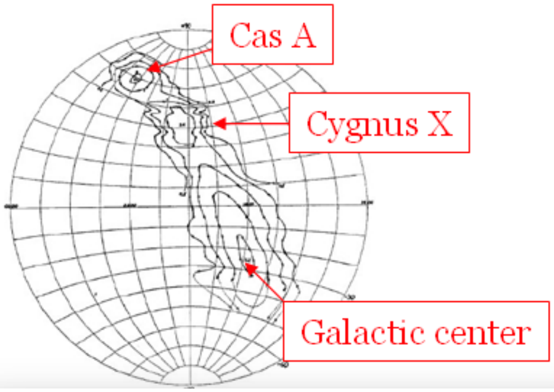
CR sources, CR injection & acceleration, CR transport (diffusion, convenction, energy losses, re-acceleration, aduncances, spallation, decay)

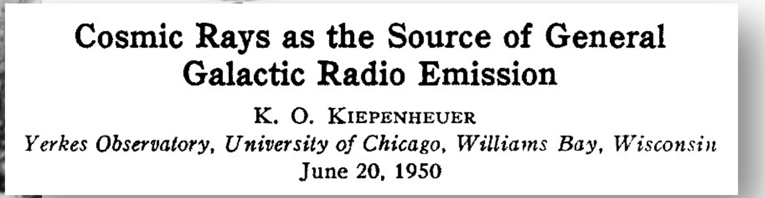
☞ from an observational γ-ray perspective:

global vs. local phenomenology, (tracers of) matter distribution in the Milkyway, sources vs. structured diffuse background

Radio astronomy leads the way







Cosmic Rays as the Source of General Galactic Radio Emission

K. O. Kiepenheuer

Yerkes Observatory, University of Chicago, Williams Bay, Wisconsin

June 20, 1950

1933

Jansky discovers radio emission from our own Galaxy

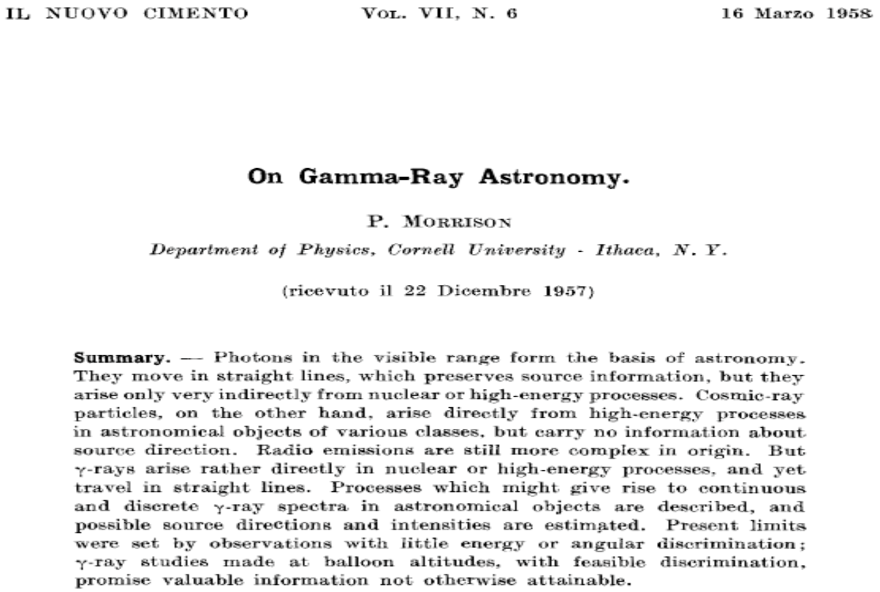
1944

Reber produces first radio sky maps

1950

Kiepenheuer suggests **CR e^-** as common source of radio emission

An astronomical discipline?



IL NUOVO CIMENTO VOL. VII, N. 6 16 Marzo 1958

On Gamma-Ray Astronomy.

P. MORRISON
Department of Physics, Cornell University - Ithaca, N. Y.

(ricevuto il 22 Dicembre 1957)

Summary. — Photons in the visible range form the basis of astronomy. They move in straight lines, which preserves source information, but they arise only very indirectly from nuclear or high-energy processes. Cosmic-ray particles, on the other hand, arise directly from high-energy processes in astronomical objects of various classes, but carry no information about source direction. Radio emissions are still more complex in origin. But γ-rays arise rather directly in nuclear or high-energy processes, and yet travel in straight lines. Processes which might give rise to continuous and discrete γ-ray spectra in astronomical objects are described, and possible source directions and intensities are estimated. Present limits were set by observations with little energy or angular discrimination; γ-ray studies made at balloon altitudes, with feasible discrimination, promise valuable information not otherwise attainable.

*the active Sun, Crab nebula, Cyg A, **continuum***

…predates birth of X-ray astronomy !

1952

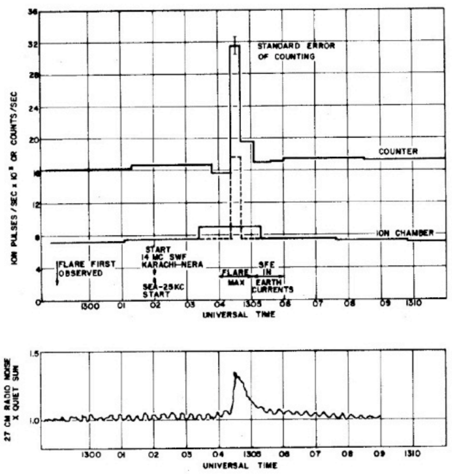
Hutchinson: Prediction of **diffuse γ-ray emission** from CR via bremsstrahlung

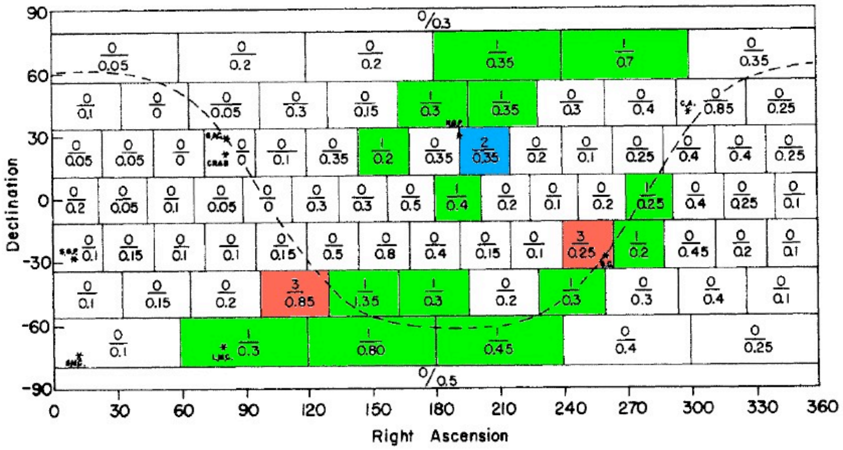
Hayakawa: Prediction **of diffuse γ-ray emission** from π_0 decay in Galaxy

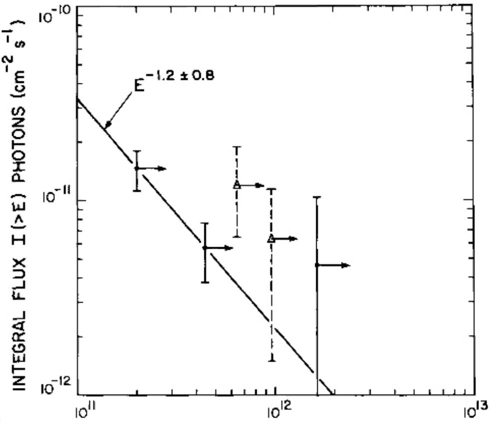
1958

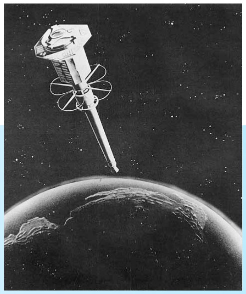
Morrison:
« On Gamma-Ray Astronomy »

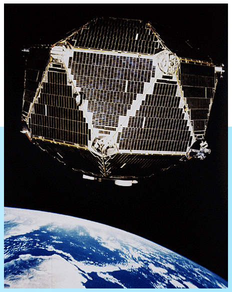
The dawn of experimental gamma-ray astronomy ...



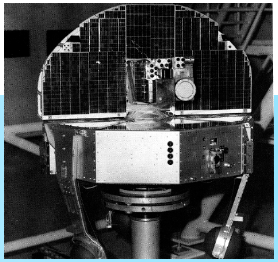








OSO-3



621 photons ...

1958

Peterson & Winckler
Solar flare γ-ray
outburst by balloon
experiment

1962

Kraushaar & Clark
22 high-energy photons
by Explorer 11

1967

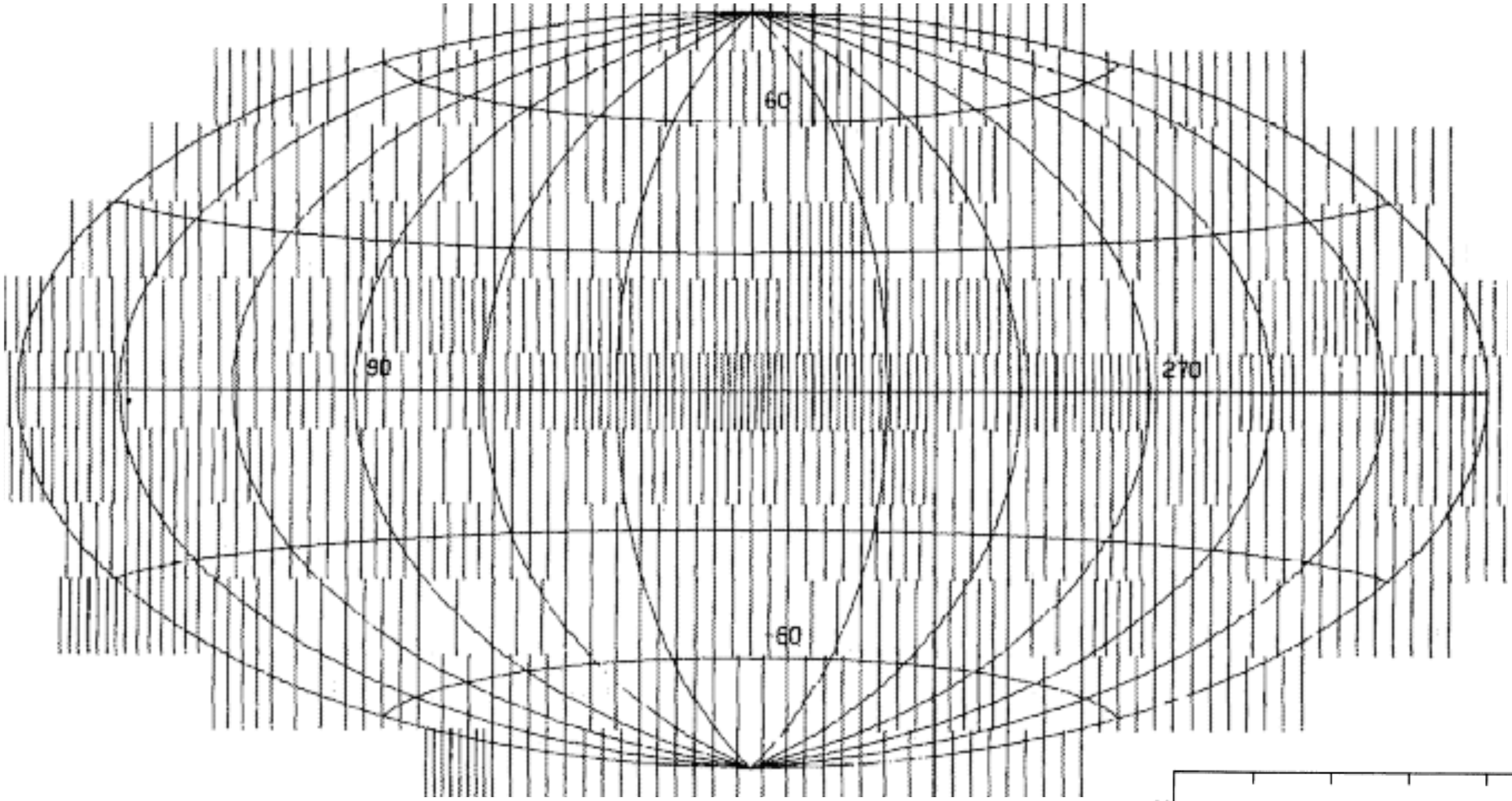
GRBs

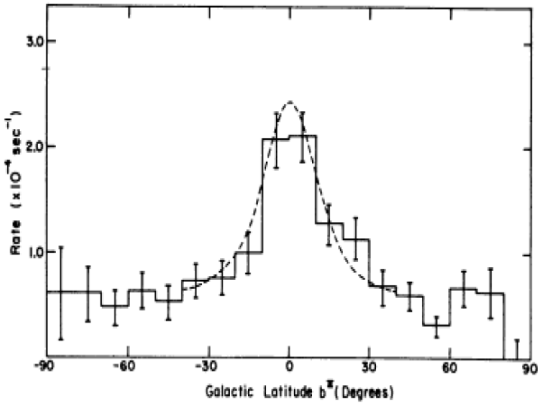
1968

1972

Crab nebula in TeV:
Grindlay (1971, 1972)
Fazio et al. (1972)

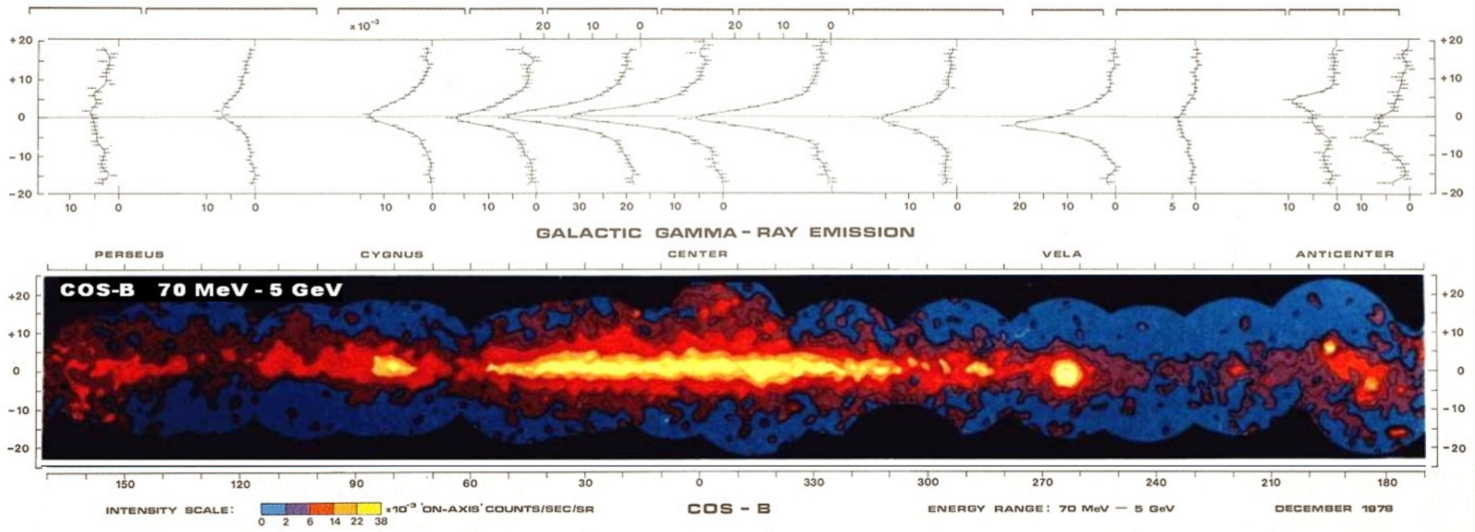
OSO-III 1967-1968

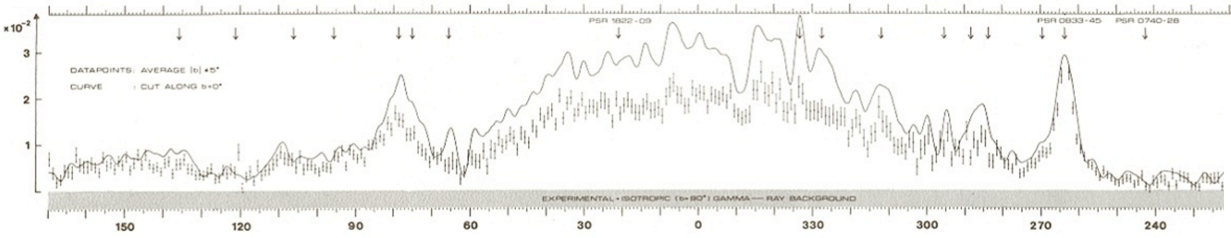


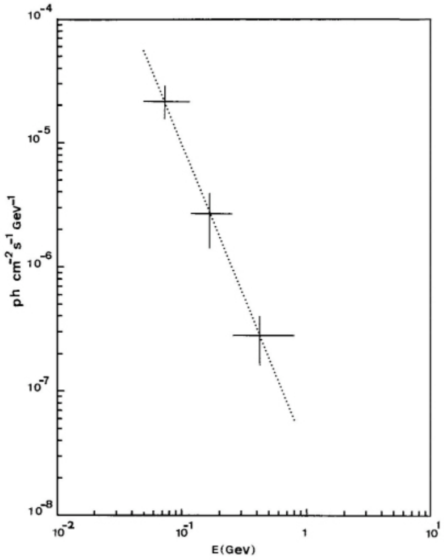


The begin of galactic γ-ray astronomy: Milkyway

COS-B 1975-1982

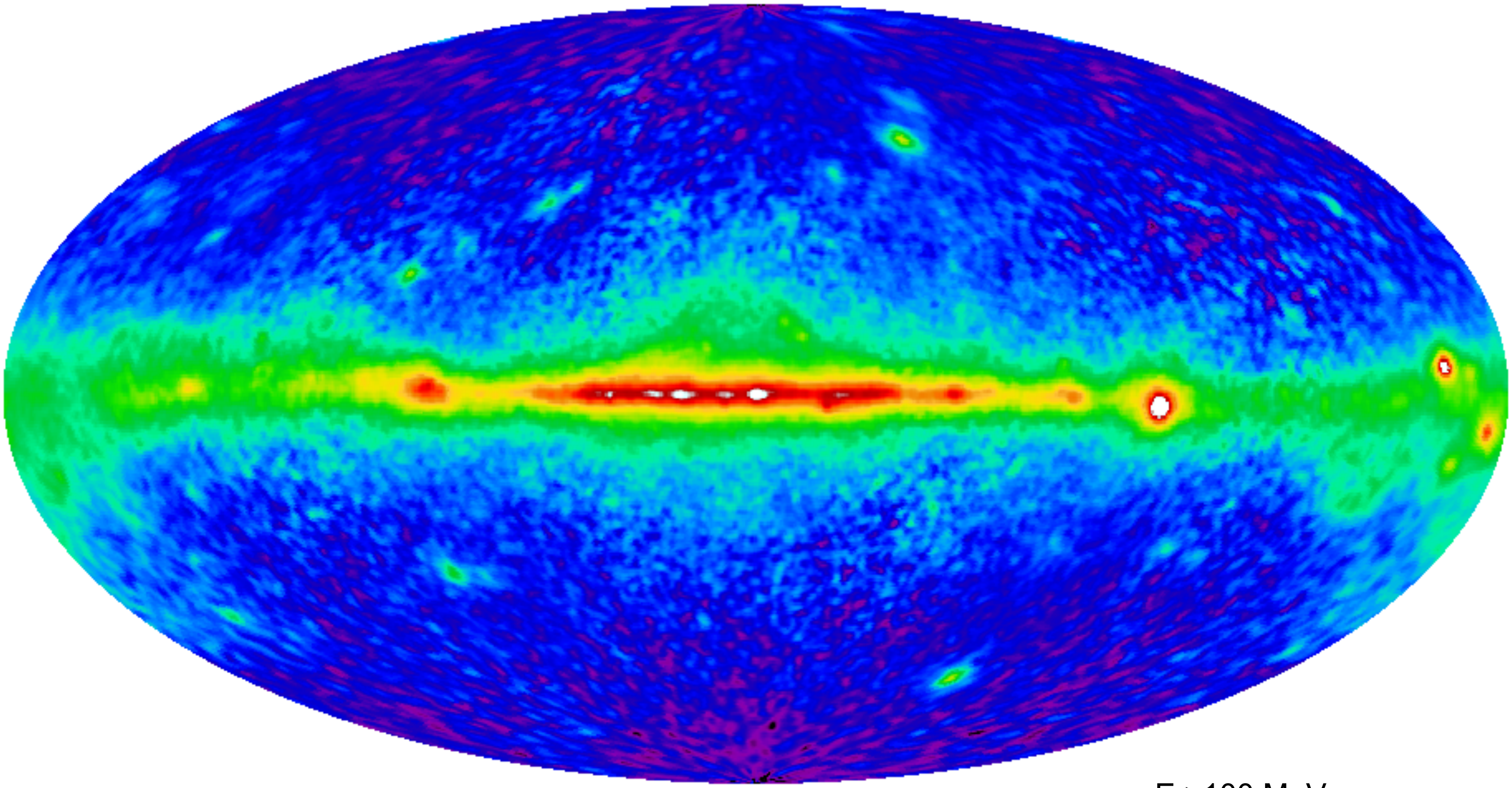






(The begin of extragalactic γ-ray astronomy: 3C273)

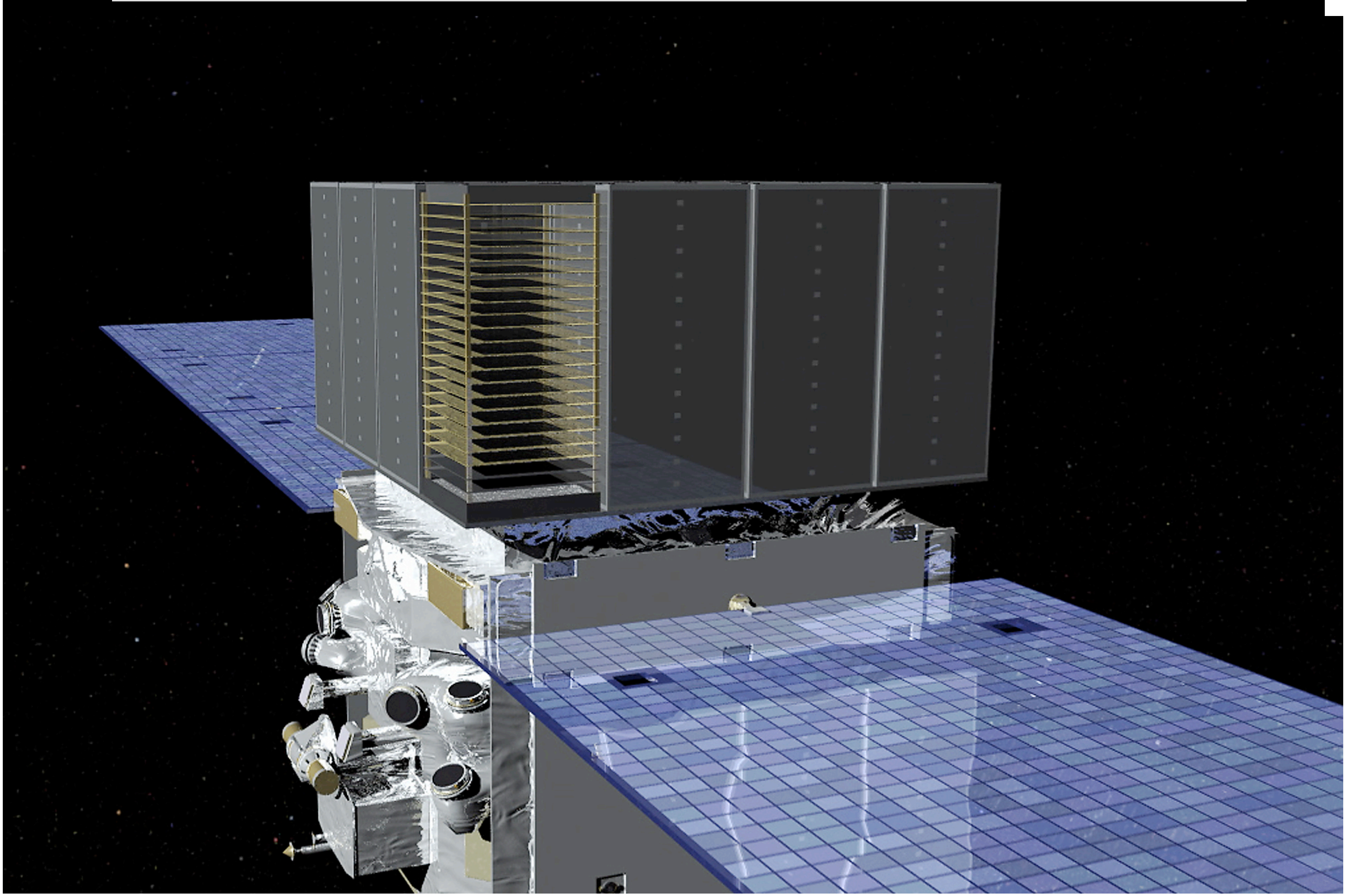
EGRET – 1991-2000



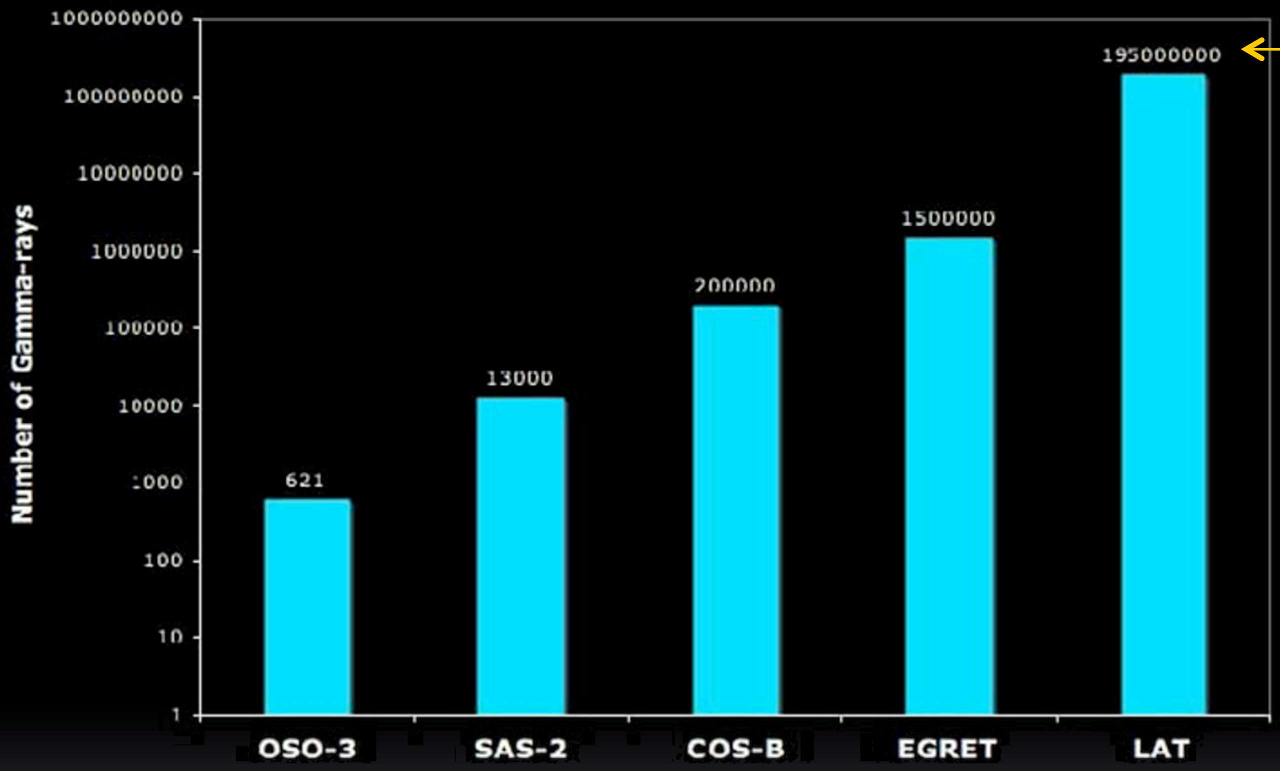
E >100 MeV

- ~$1.4\text{x}10^6\,\gamma$, ~65% interstellar emission from the MW
- ~15% in resolved sources

Fermi Gamma-ray Space Telescope (2008-



…and that concludes the history of satellite-based high-energy γ-ray astronomy



1.95×10^8

(by late 2009)

- As of late 2008, Fermi outperformed any previous (COS-B, EGRET), or operating (AGILE) GeV γ-ray telescope
- This statement relates to simple exposure and number of recorded γ-ray events but independently valid for instrument characteristics like psf, dE/E, A_{eff} , τ_d, Δcalib

Why do we care about the gamma emission from the Milkyway?

- **a background** for those who study Galactic high-energy sources
- a **foreground** for those who study extragalactic high-energy sources
- itself a viable and utterly revealing **laboratory for studying CRs**
- **the major obstacle for all indirect DM-searches**

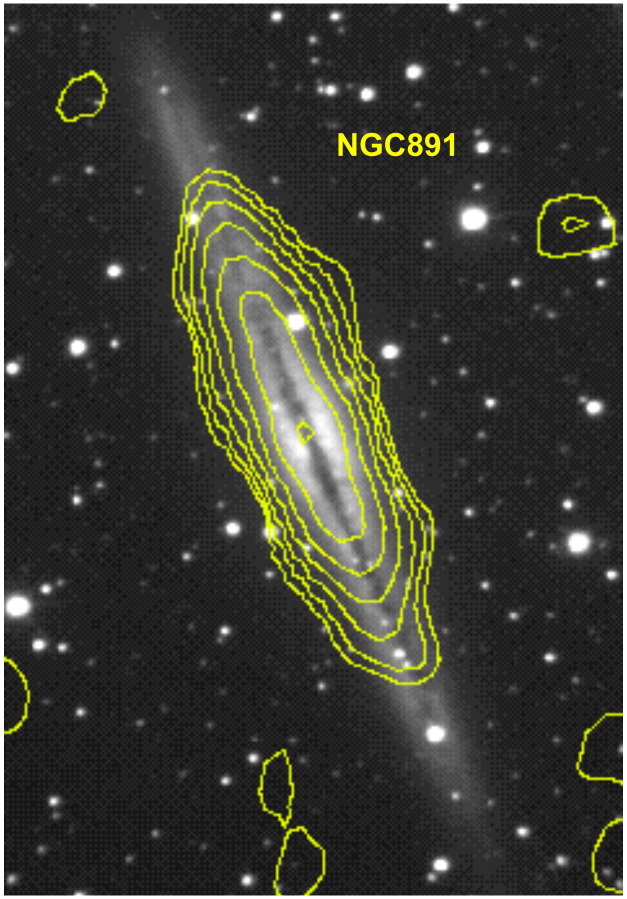
Modeling of CRs and their interactions in our Galaxy requires to combine a variety of different kinds of data, ranging from astronomical observations up to quantities obtained in nuclear and particle physics experiments.

As a reward, an adequate model provides a basis for many studies in Astrophysics, Particle Physics, and Cosmology:

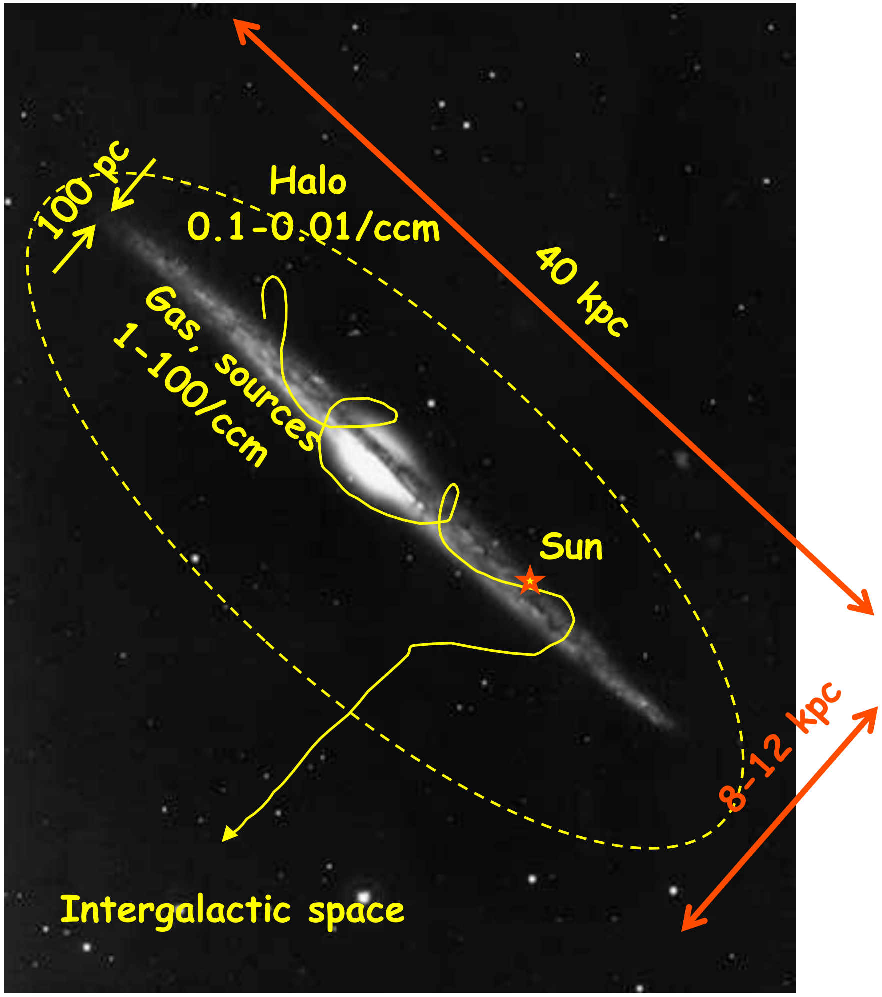
- Spectra & origin of Galactic & extragalactic diffuse gamma rays
- Structure of our Galaxy
- Origin and evolution of elements
- Heliospheric modulation
- credibility of indirect DM searches

CR Propagation: Milky Way Galaxy

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

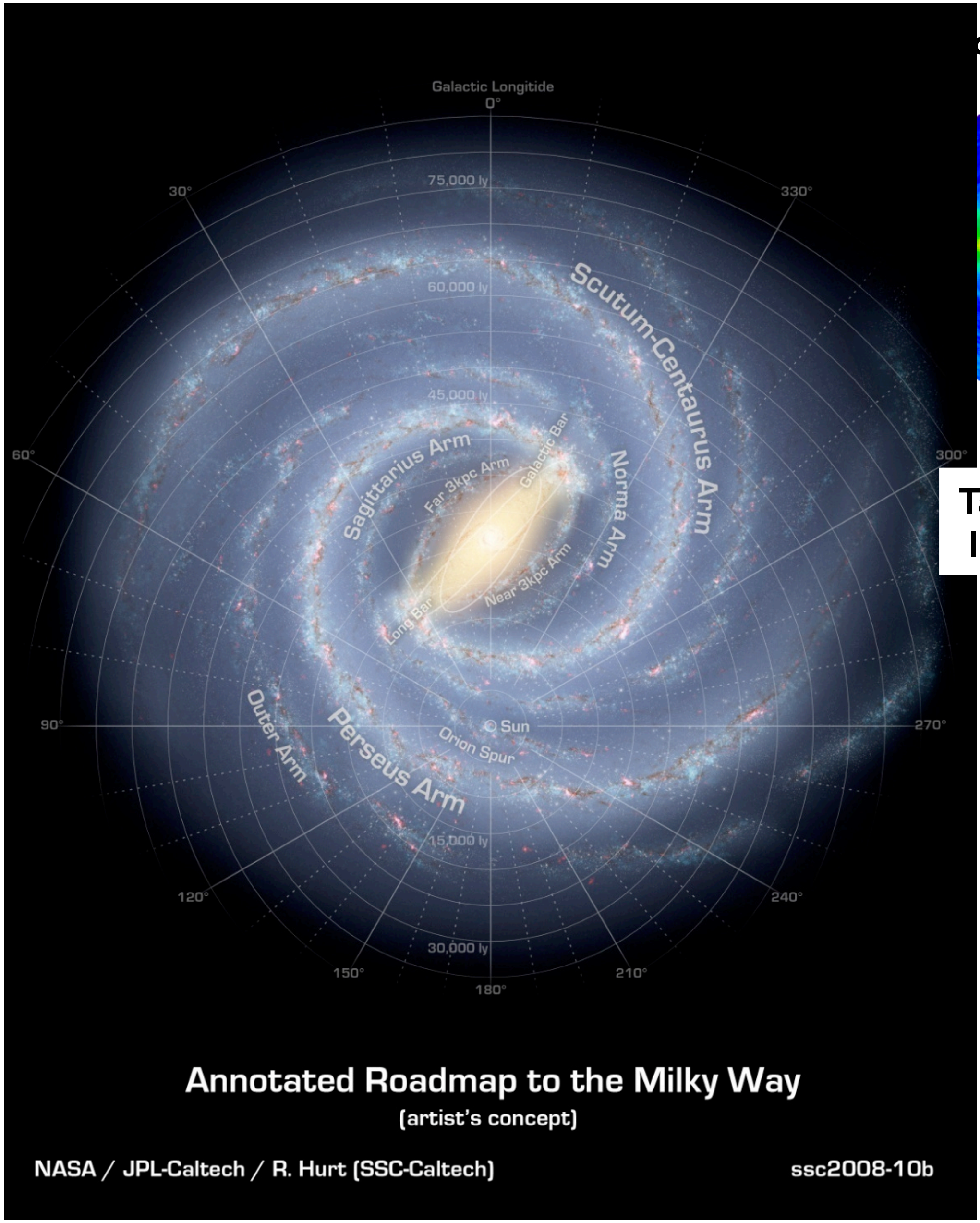


R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam



“Flat halo” model (Ginzburg & Ptuskin 1976)

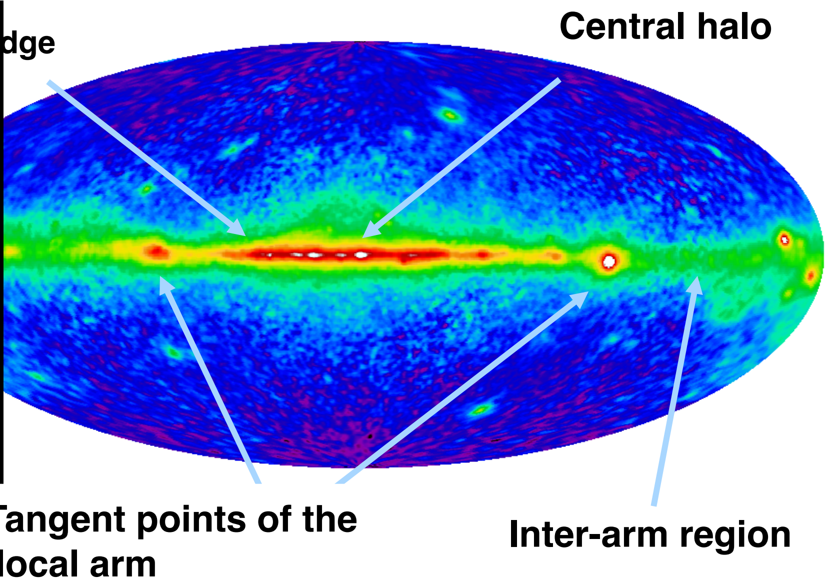
Modeling the Milky Way … in the light of gamma-rays



Annotated Roadmap to the Milky Way
(artist's concept)

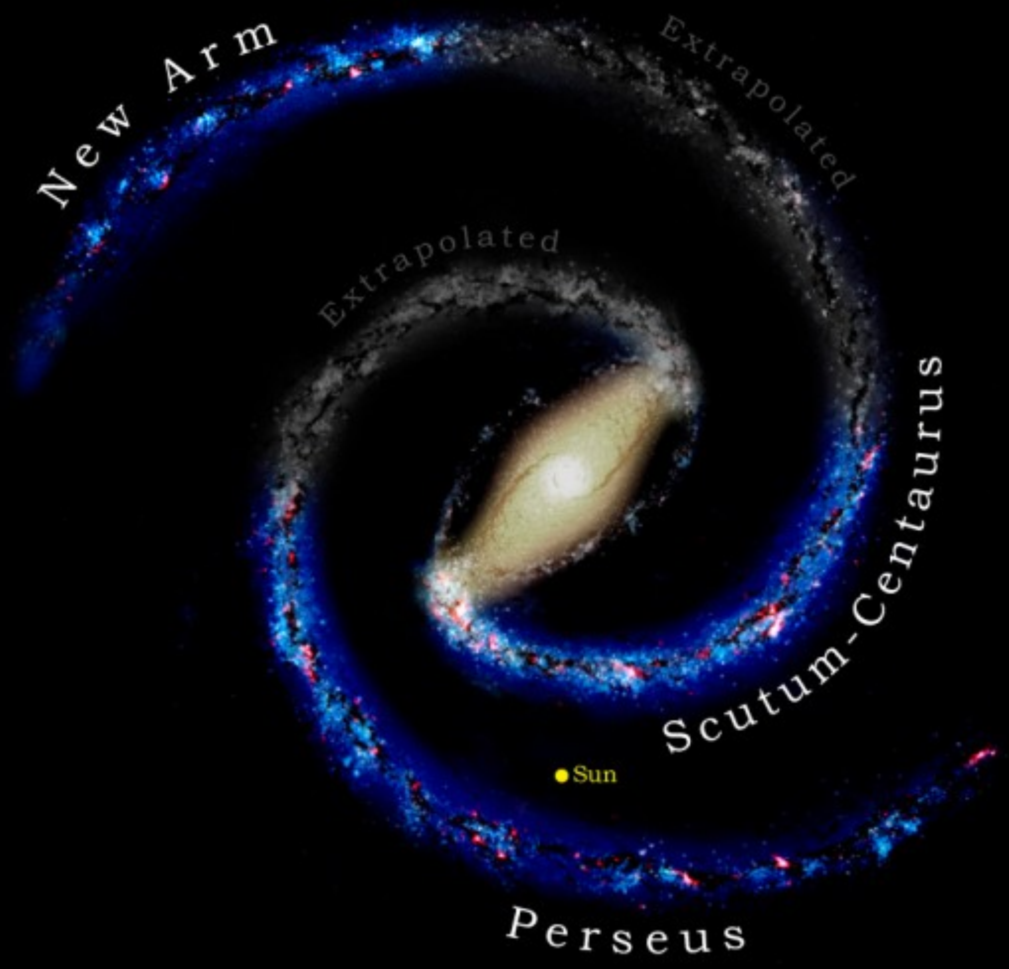
NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

ssc2008-10b

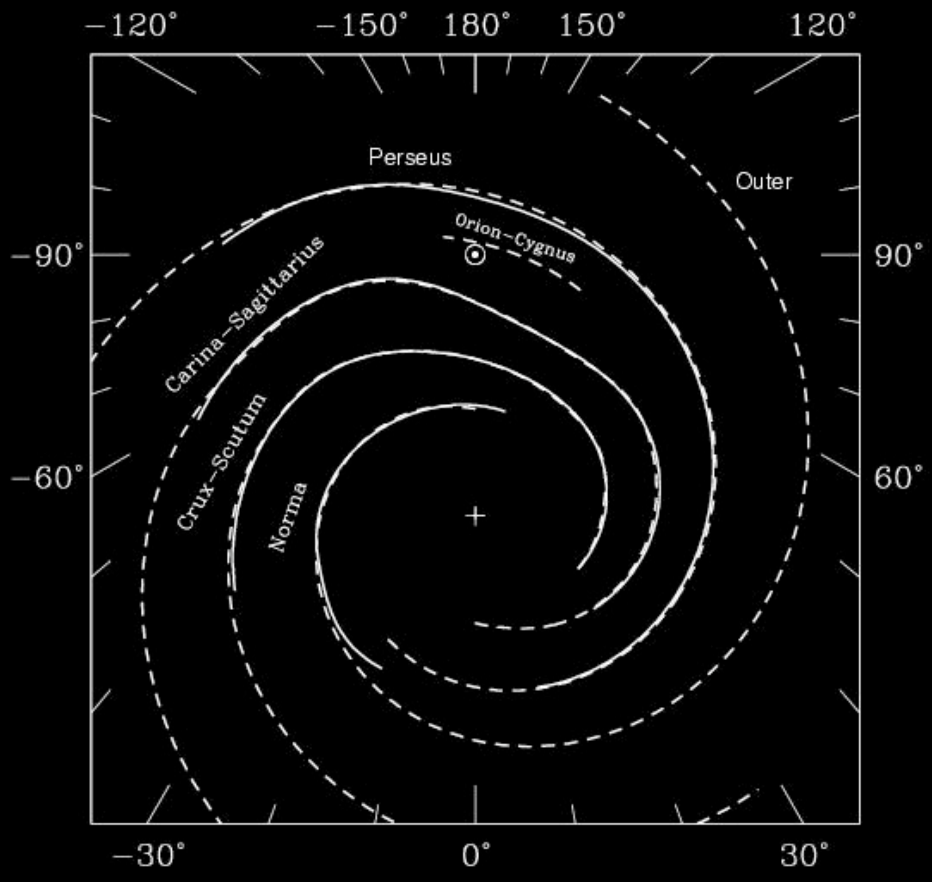


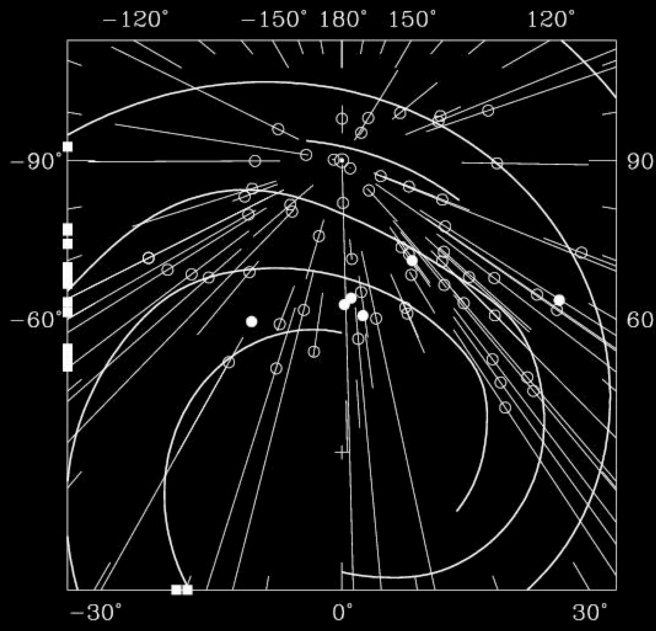
The diffuse γ-ray emission is the dominant feature of the gamma-ray sky – and as such observational evidence of CR interactions in the interstellar medium, and standard gamma-ray production mechanisms at work

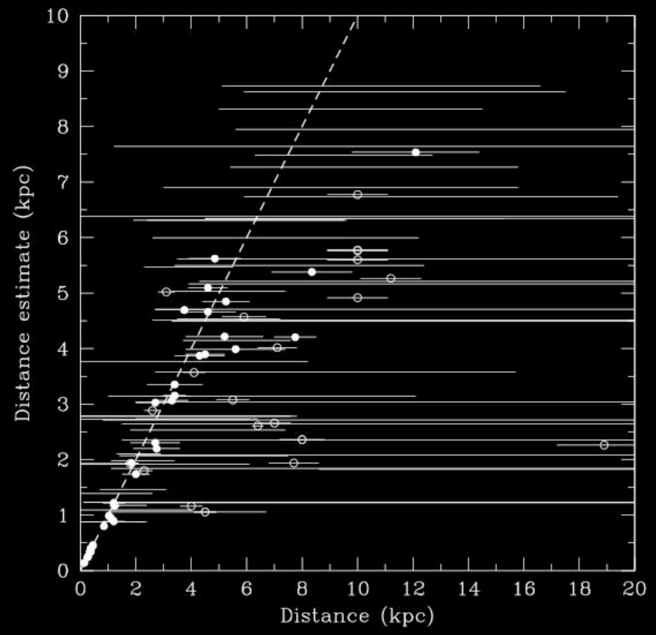
There are alternatives, however …



Dame & Thaddeus 2011



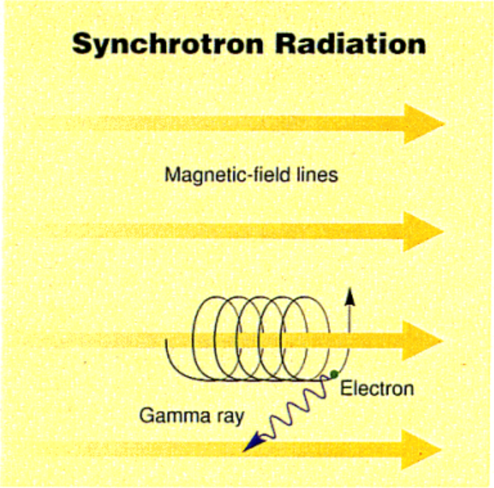


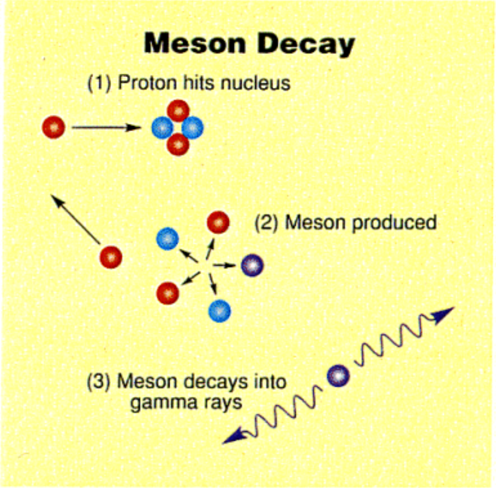


Free-electron density model (NE 2001)

Gamma-ray emission mechanisms

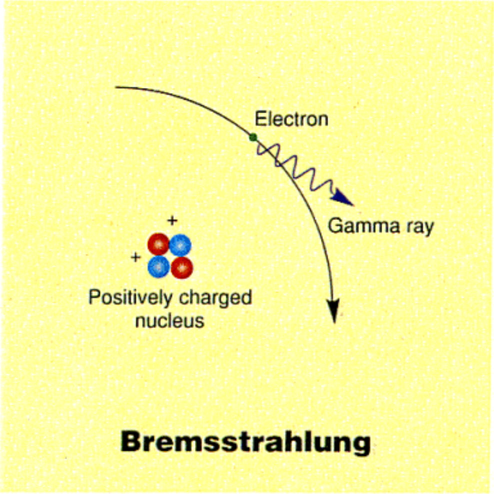
$e^{\pm} + B$

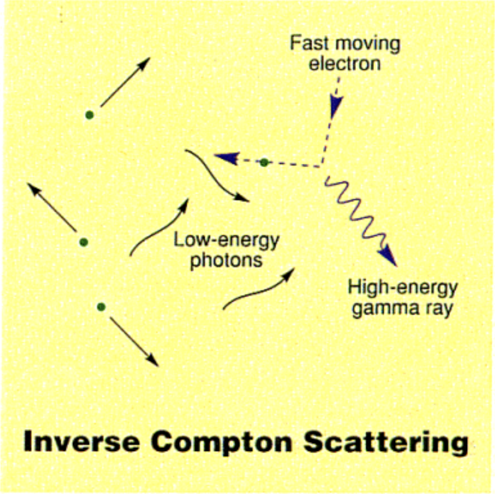




p + matter

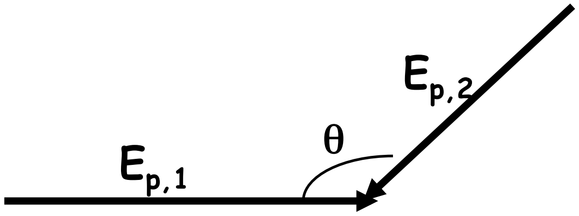
$e^{\pm}$ + matter





$e^{\pm} + h\nu$

The pp-interaction



$\sqrt{s_{threshold}}=2m_pc^2+m_{\pi0}c^2$

$\gamma_{thr} = 1+m_\pi(2/m_p+m_\pi/(2m_p^2)) \approx 1.3$

$$s = (\Sigma E)^2 - (\Sigma p)^2 =$$

$$= 2m_p^2c^4 + 2E_{p,1}E_{p,2}(1-\beta_1\beta_2\cos\Theta)$$

Cooling process in cosmic objects, e.g.

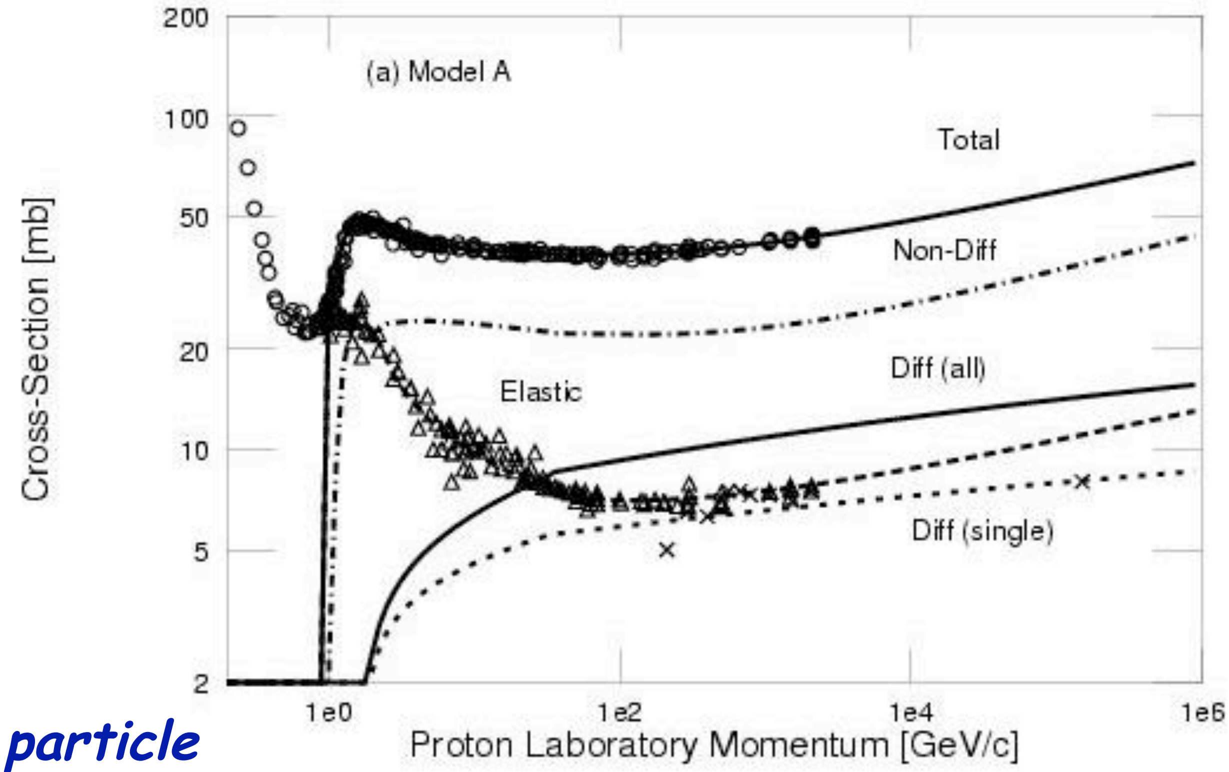
- ISM (n_{ISM}~$1cm^{-3}$) ⟶ galactic diffuse gamma-ray emission

- Supernova remnants (possibly near molecular clouds, n_{cloud}~$100cm^{-3}$)

- Massive stellar winds

- You name it!

The pp-interaction



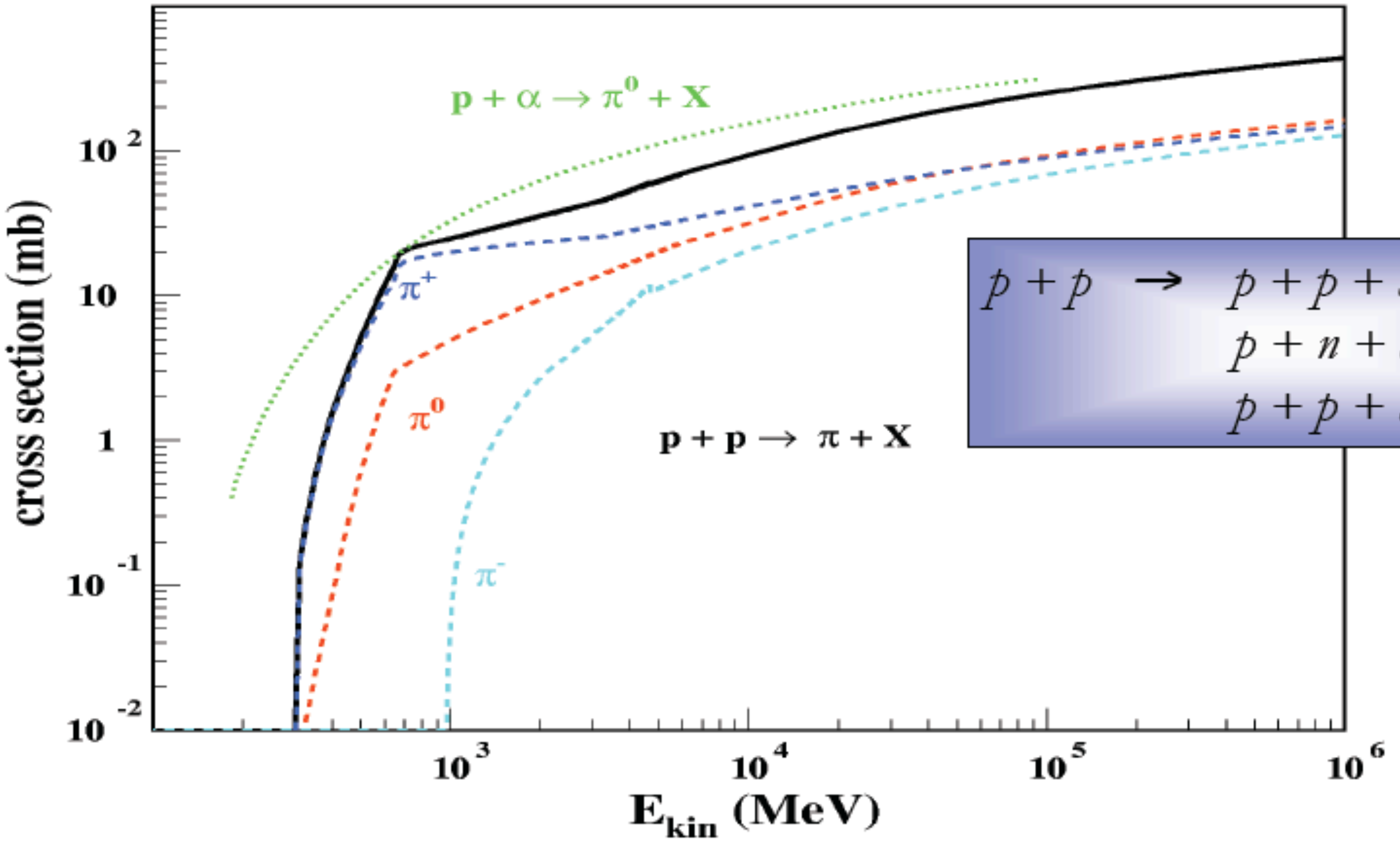
Secondary particle production:

At low energies (<10 GeV) via isobar production

$$(\text{z.B. } pp \rightarrow \Delta 1232 + N \qquad)$$

$$\hookrightarrow N + \pi$$

The pp-interaction

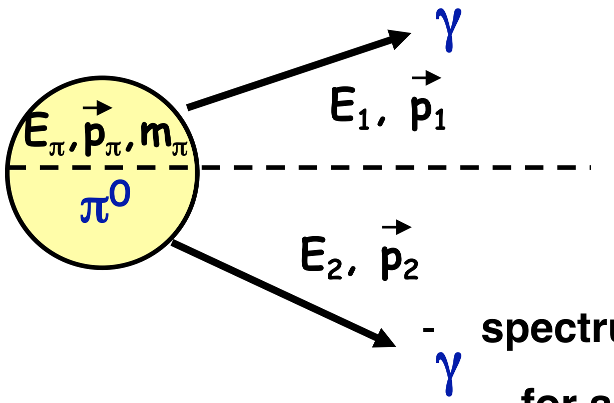


$$
\begin{aligned}
p + p \quad \rightarrow \quad & p + p + \pi^0 \\
& p + n + \pi^+ \\
& p + p + \pi^+ + \pi^-
\end{aligned}
$$

Gamma-ray emission mechanism

Where?

- π^0-decay photons: $\pi^0 \longrightarrow \gamma\gamma$ from CR proton-nucleon collisions
  → CR, gas distribution



$$E_{\gamma,min,max} = \tfrac{1}{2} m_\pi [(1 \pm \beta_\pi)/(1 \mp \beta_\pi)]^{1/2}$$

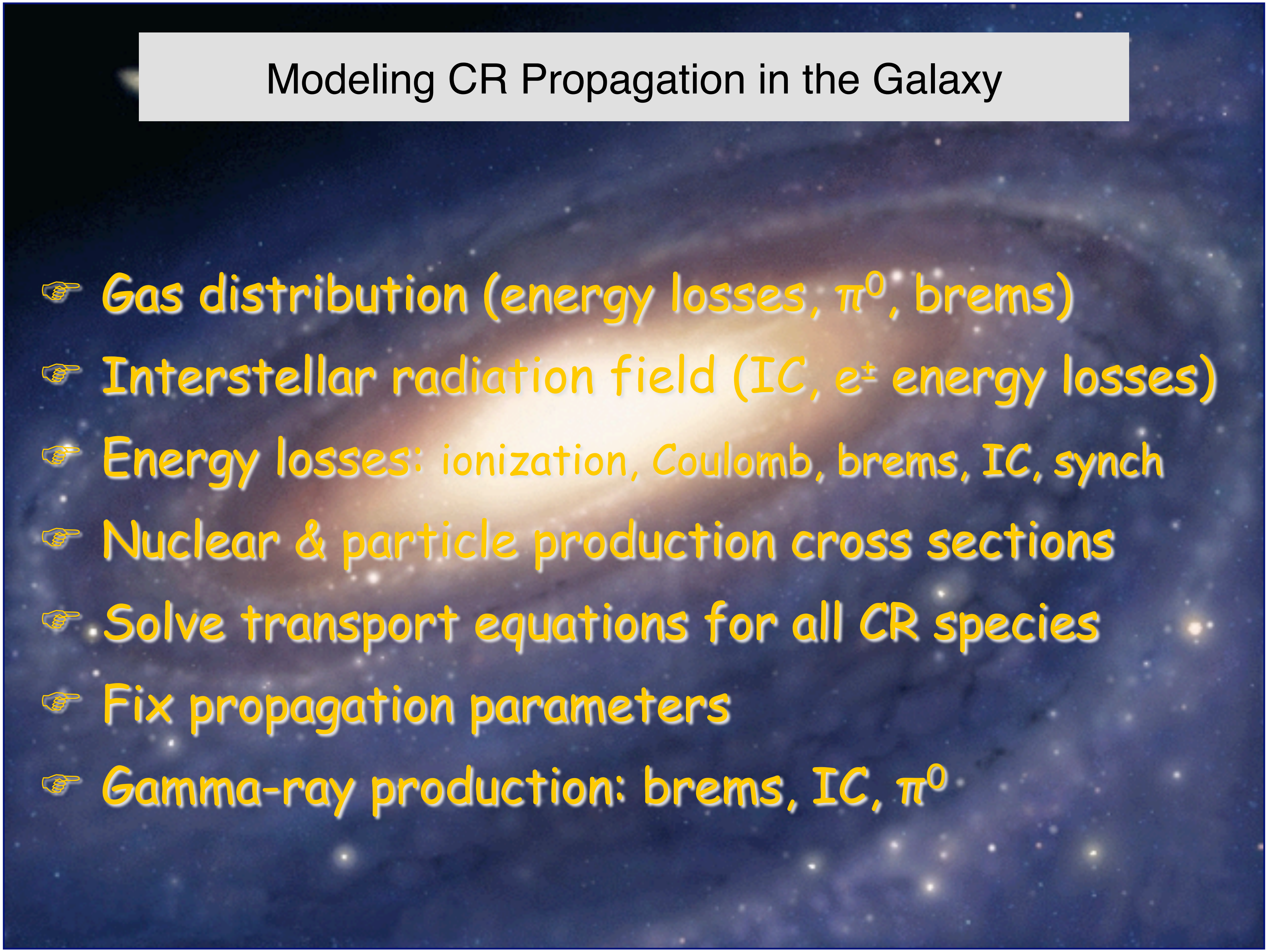
- spectrum of decay photons for each pion energy contains ½ m_p

for a distribution of pion energies the resulting energy spectrum of the decay photons is such, that the resulting g-ray spectrum has a maximum at ½ $m_p \approx$ 67.5MeV:

→ "π^0-bump"

- relativistic bremsstrahlung → CR e^-, gas distribution
- inverse Compton scattering → CR e^-, radiation field

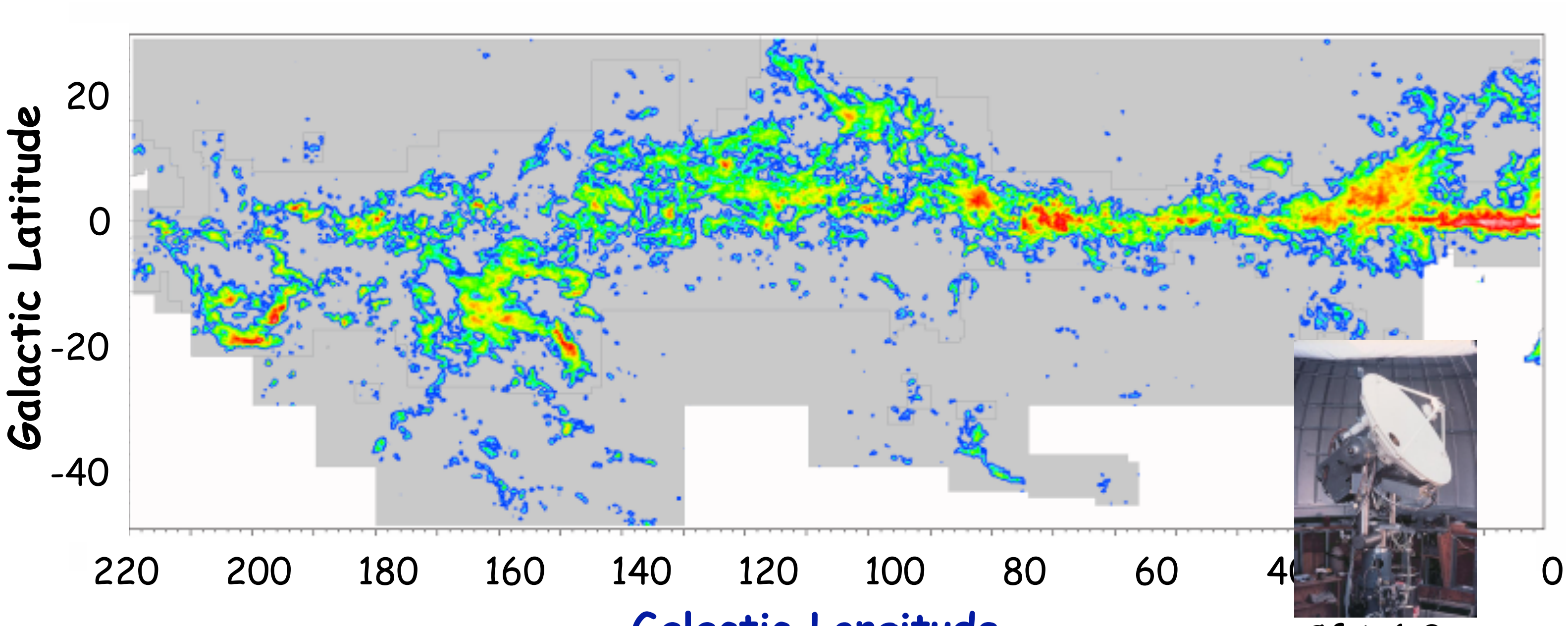
Modeling CR Propagation in the Galaxy



- Gas distribution (energy losses, π^0, brems)
- Interstellar radiation field (IC, $e^\pm$ energy losses)
- Energy losses: ionization, Coulomb, brems, IC, synch
- Nuclear & particle production cross sections
- Solve transport equations for all CR species
- Fix propagation parameters
- Gamma-ray production: brems, IC, π^0

Surveys

- CO (J=1→ 0) line as indicator for molecular hydrogen

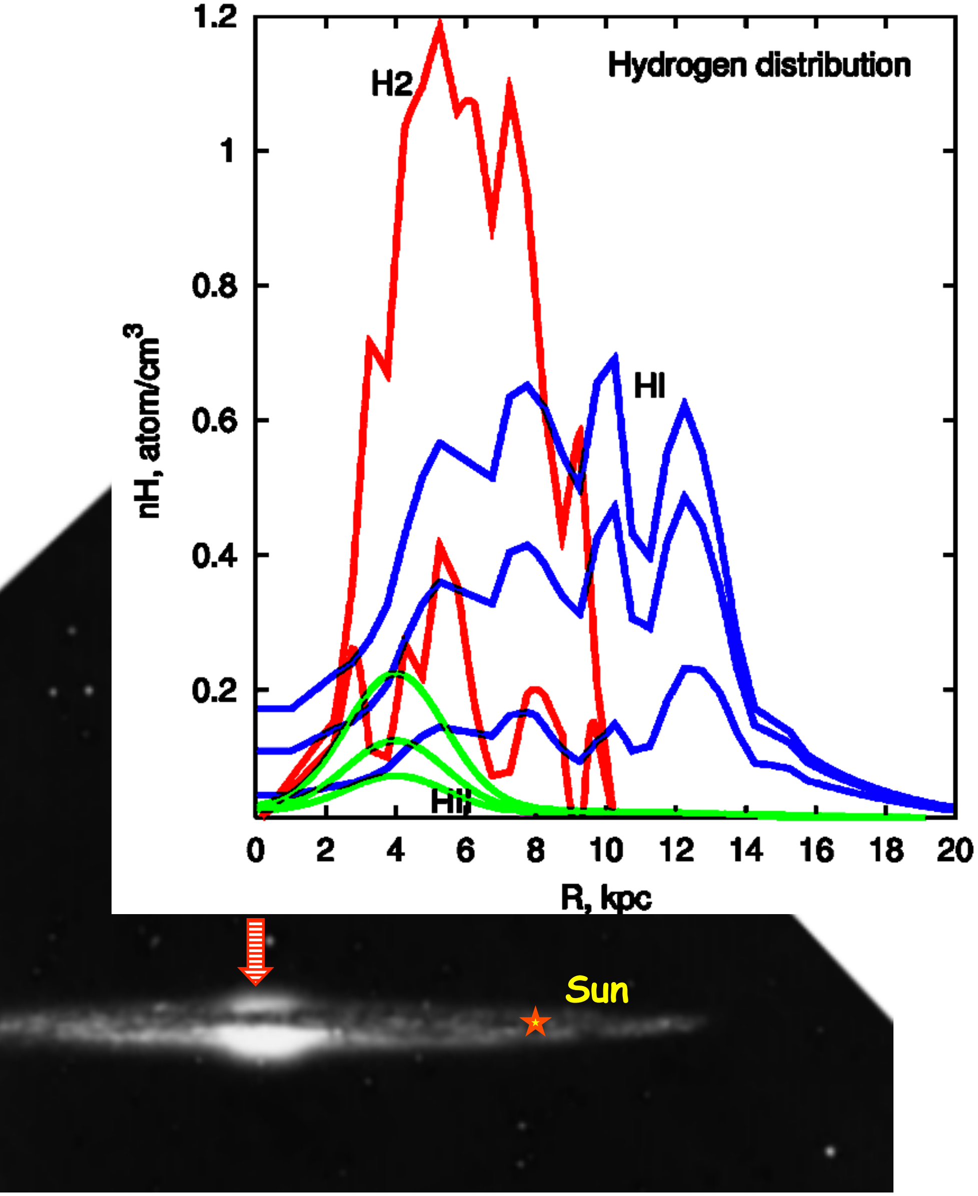


CfA 1.2m

Dame, Hartmann, & Thaddeus (2001)
Dame & Thaddeus (2004)

- $C^{18}O$ 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

Indicators of matter (density)



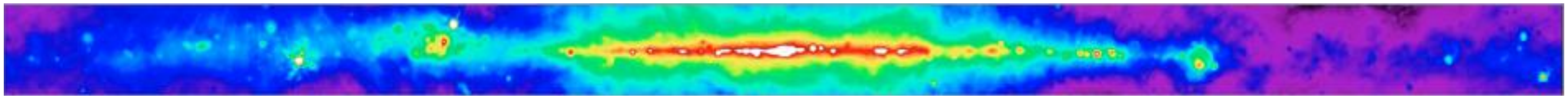
- 21cm-line as indicator for atomic hydrogen HI
- CO-line as indicator for molecular hydrogen H_2
- small contribution from ionisized hydrogen HII

H_2 concentrated at galactic plane,
HI-distribution somewhat broader,
HII is smallest gas contribution

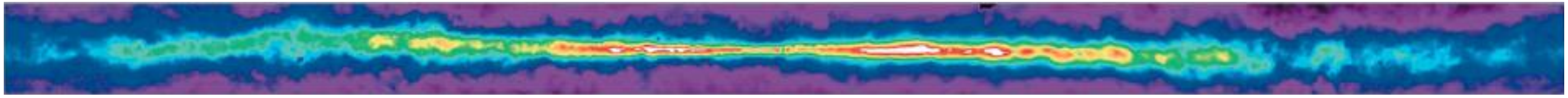
Galactic Tracers of ISM

-> line-of-sight column density

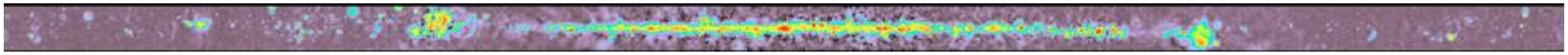
radio continuum (408 MHz)



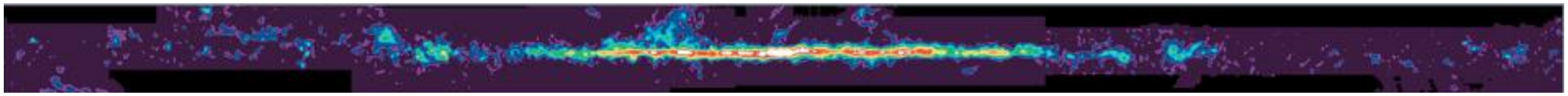
atomic hydrogen



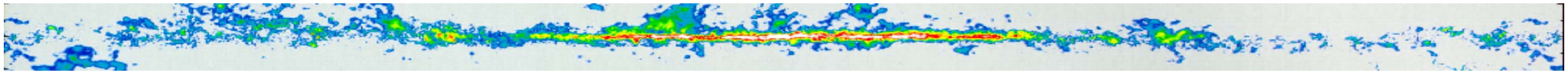
radio continuum (2.5 GHz)



molecular hydrogen



carbon monoxide

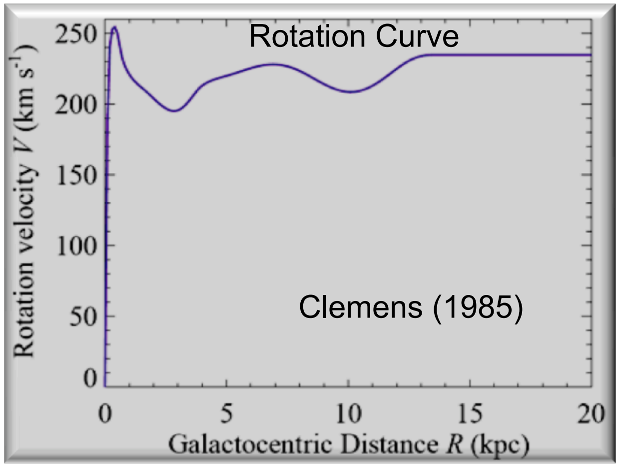


infrared

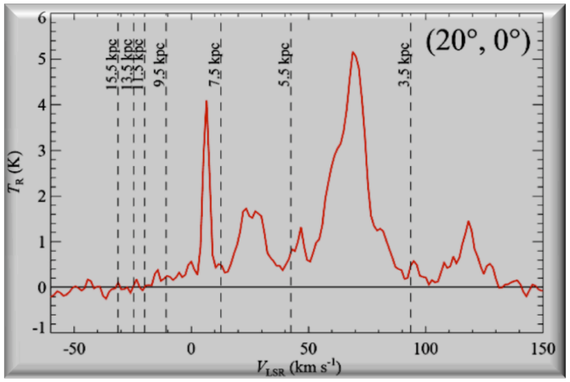
NIR

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

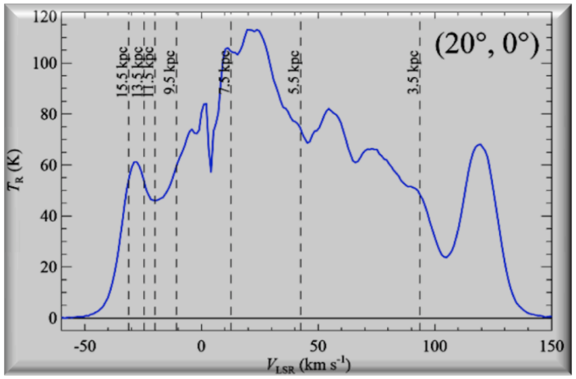


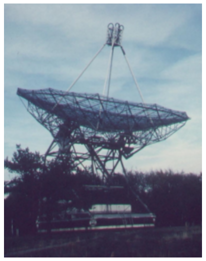
CO



Dame et al. (2001)

H I





Kalberla et al. (2005)

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

Problems to deal with…

H_2 gas

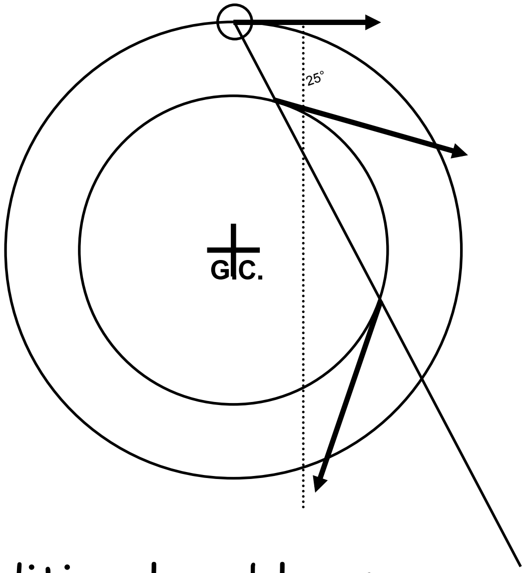
- The conversion factor $X=N(H_2)/W_{CO}$ is unknown, most probably variable, and is determined from the diffuse γ-ray emission itself

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

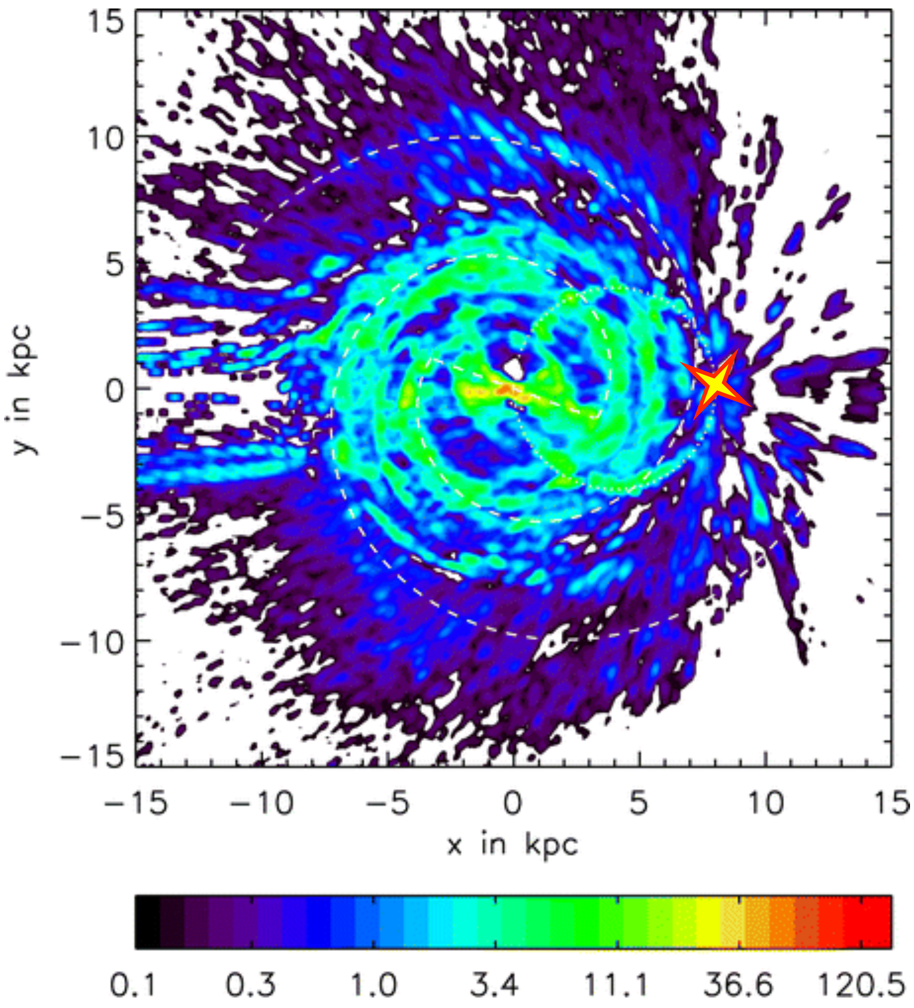
More on gas in the Milky Way



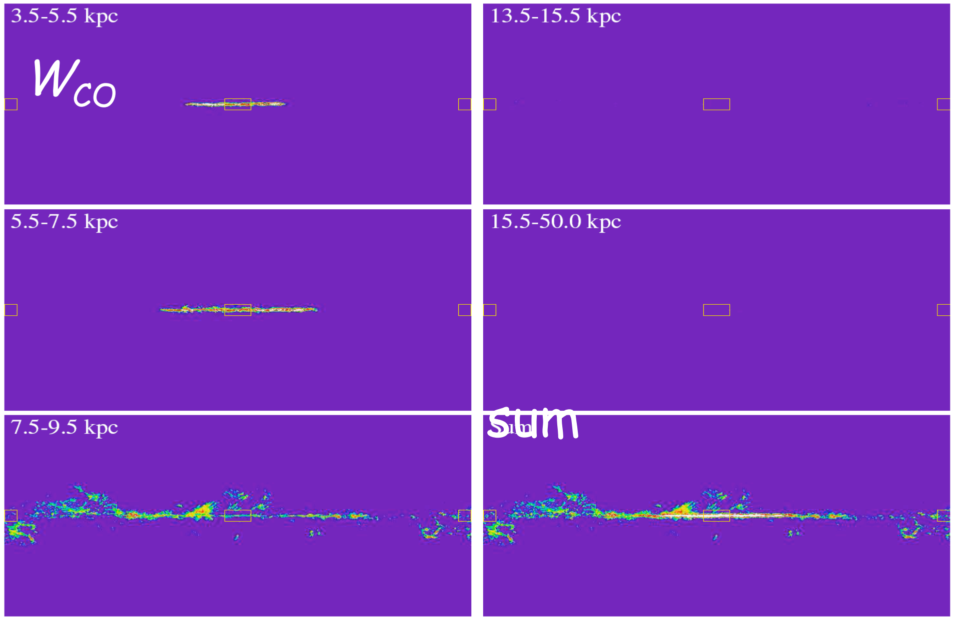
Additional problems:

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

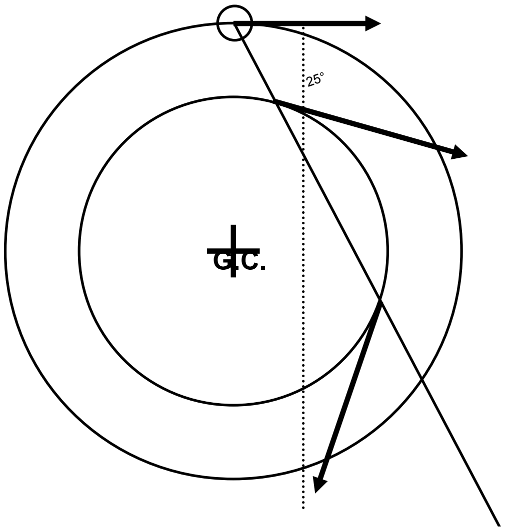
Surface mass density of the H_2 in $M_{sun}\,pc^{-2}$

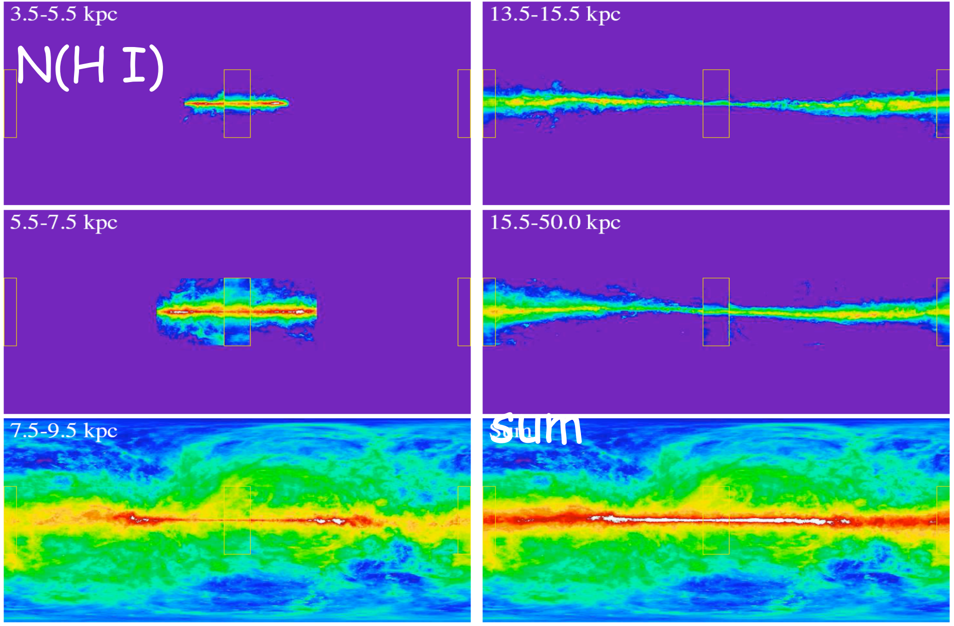


Dealing with neutral gas: galactocentric rings



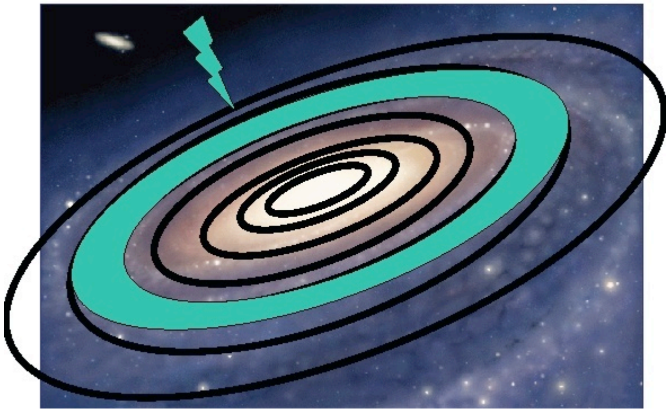
Examples of the Galactocentric “rings”





$N_{\gamma\_i}=\varepsilon(q_{HIi}N_{(HI)_i}+q_{COi}W_{(CO)_i})$

Ring



GALDIF – a emissivity model of the EGRET era

- Relation to the GeV observations:
  - Study the physical structure of the interstellar medium (ISM) in the Milky Way and the distribution of matter and CRs that pervade it
  - One reference model for point source analyses

- Calculation:
  - Two components
    Galactic Diffuse, lbl < 10^{o} + Isotropic Diffuse model, lbl > 10^{o}
    (Hunter et al. 1997, ApJ, 481, 205)   (Sreekumar et al. 1998, ApJ, 494, 523)
  - Common CR distribution, emission discontinuous at lbl = 10^{o}
    - ‘Eliminated’ by PSF convolution

Cosmic Rays and Matter – "Dynamic Balance"

- The cosmic ray and magnetic fields are in a quasi-stationary state, *dynamic balance* (Parker 1969)
  - The CR pressure may not exceed the magnetic field pressure (Parker 1968) and appears to be close to the maximum
- The Galactic magnetic field is confined to the disk by the weight of the interstellar gas ("frozen-in magnetic field")
- CRs (at least < 10^{16-17} eV per nucleon) are bound to the lines of force and the lines of force are normally closed
- CR age, based on isotopic abundance, is slightly more than 10^7 years
  - Consistent with secondary abundance and Galactic matter density
  - Slow diffusion rate in magnetic field and small anisotropy

- Energy density of the cosmic rays is larger where the matter density is larger on some coarse scale: ***Dynamic Balance***

- What's left unanswered?
  - *What is the CR/matter coupling scale? What is the vertical scale height?*

GALDIF – the model of the EGRET era

- Inputs:
  - Gamma-ray production processes in the ISM
    - Pion production, Bremsstrahlung, inverse Compton scattering
  - Tracers of the ISM (matter and radiation) + Galactic rotation curve → 3-D ISM distribution
    - HI (21 cm), H_2 (115 GHz CO), HII (pulsar dispersion), low-energy photon density
  - Physical parameters:
    - $N(HI)/W_{HI}$ conversion factor, CR spectrum, e/p ratio, interaction cross-sections, Galactic rotation curve, etc.
  - Model assumptions:
    - Assume the CRs are in *dynamic balance* with ISM
- *There are only two adjustable parameters in this calculation!*
  - Molecular mass ratio, $X=N(H_2)/W_{CO}$, CR coupling scale
- *Discrepancies between model and observation are directly interpretable in terms of model inputs and parameters.*

GALDIF – a template model

Straight forward integral over the line-of-sight:

Galactic cosmic-ray distribution of
electrons and nucleons (+ He, heavies)

Galactic matter distribution of
atomic, molecular, and ionized hydrogen

$$j(E_\gamma, l, b) = \frac{1}{4\pi}\int (c_e \cdot q_{eb} + c_n \cdot q_{nn}) \times (n_{\mathrm{H\,I}} + n_{H2} + n_{\mathrm{H\,II}})\, \mathrm{d}\rho +$$

$$\frac{1}{4\pi}\sum_i \int c_e \cdot q_{ic,i} \cdot u_{ic,i}\, \mathrm{d}\rho \quad [\mathrm{ph\ cm^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}}]$$

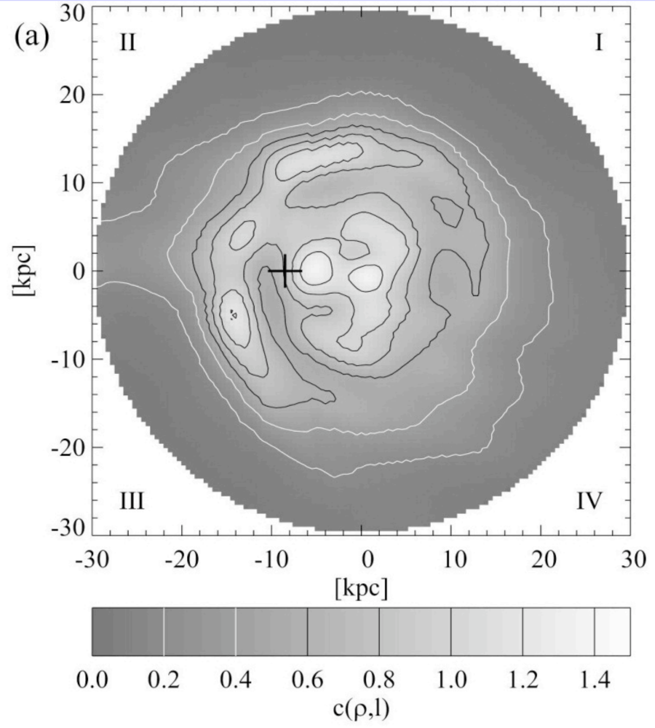
Gamma-ray production functions
electron bremsstrahlung, nucleon
-nucleon (π^o), and inverse Compton
Synchrotron emission is negligible.

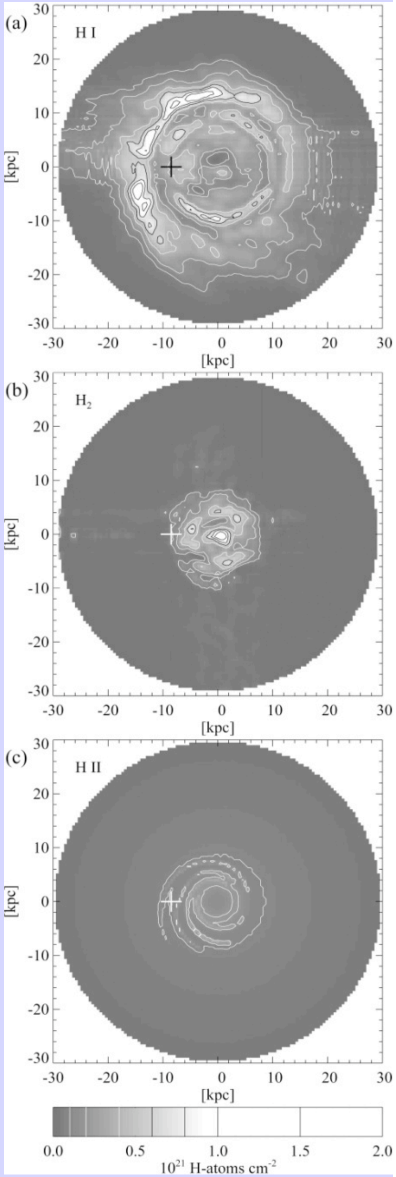
Low-energy photon energy density
cosmic microwave background,
infra-red, visible, and ultraviolet

The hard part: determining the 3-D matter, ISR, and CR distributions.

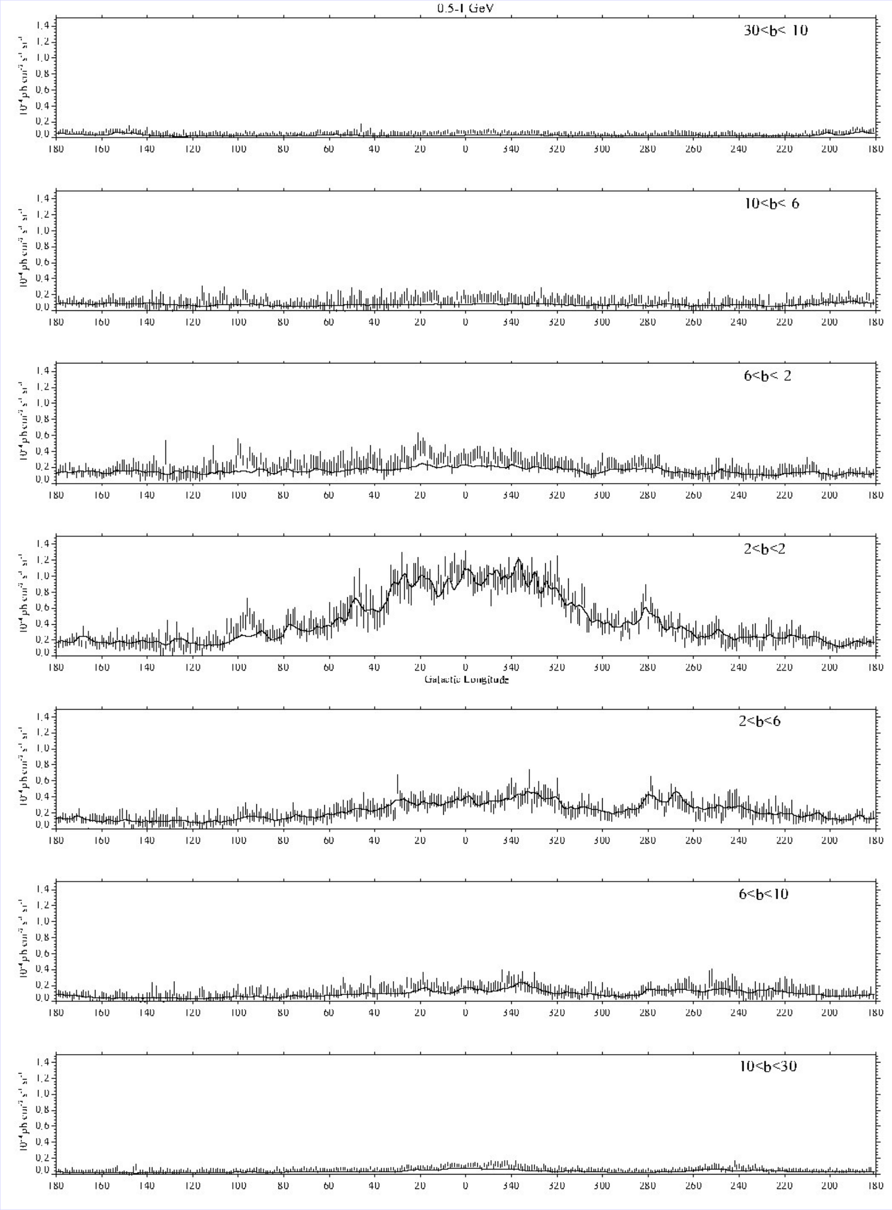
CR Distribution from Dynamic Balance

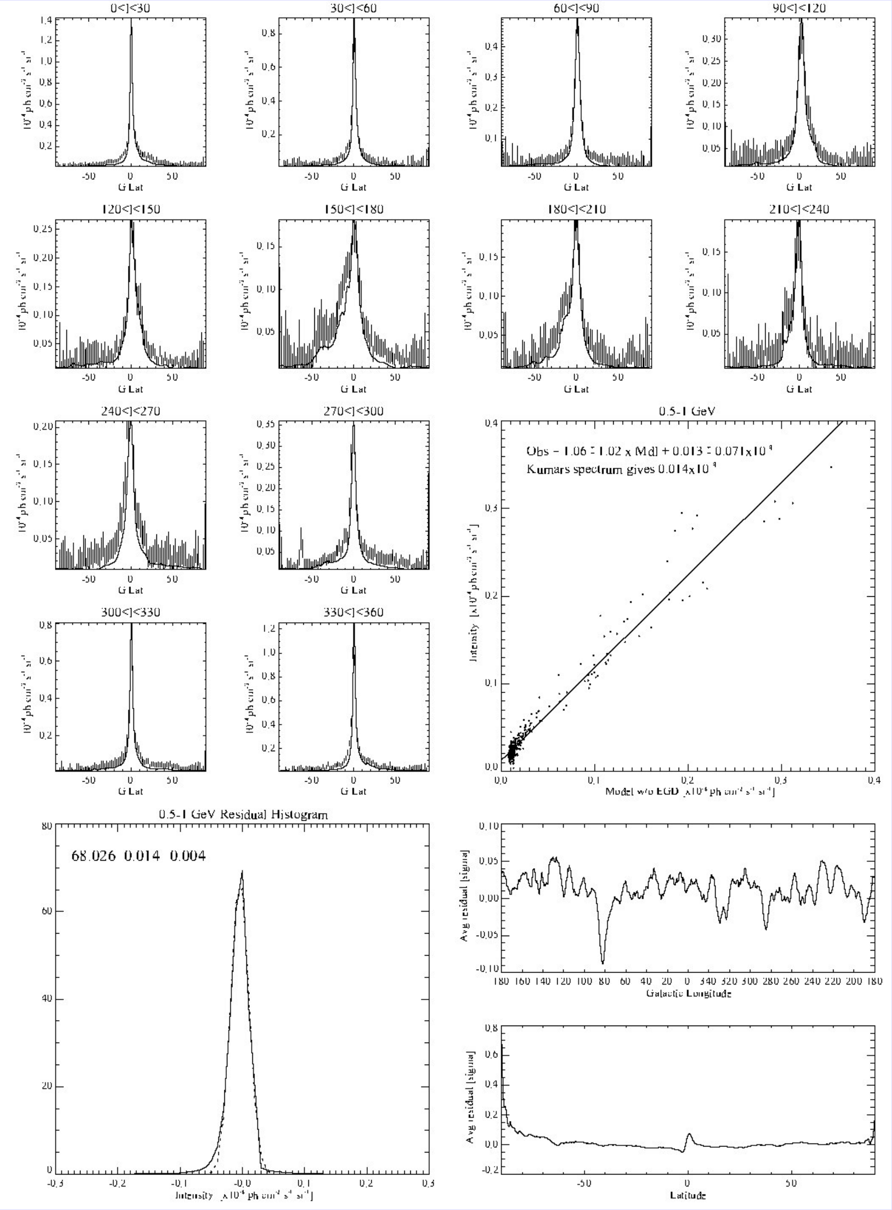
- Derive 3-D distributions of HI, H_2, and HII
- Determine Galactic mater surface density, normalize total Solar density to unity, $c_e = c_n = c(l,\rho)$
- CR density at l,ρ is then Solar CR density × $c(l,\rho)$
- The diffuse emission is ∝ (matter density)^2
- CR scale height assumed to be large compared to matter scale height





Comparison with data



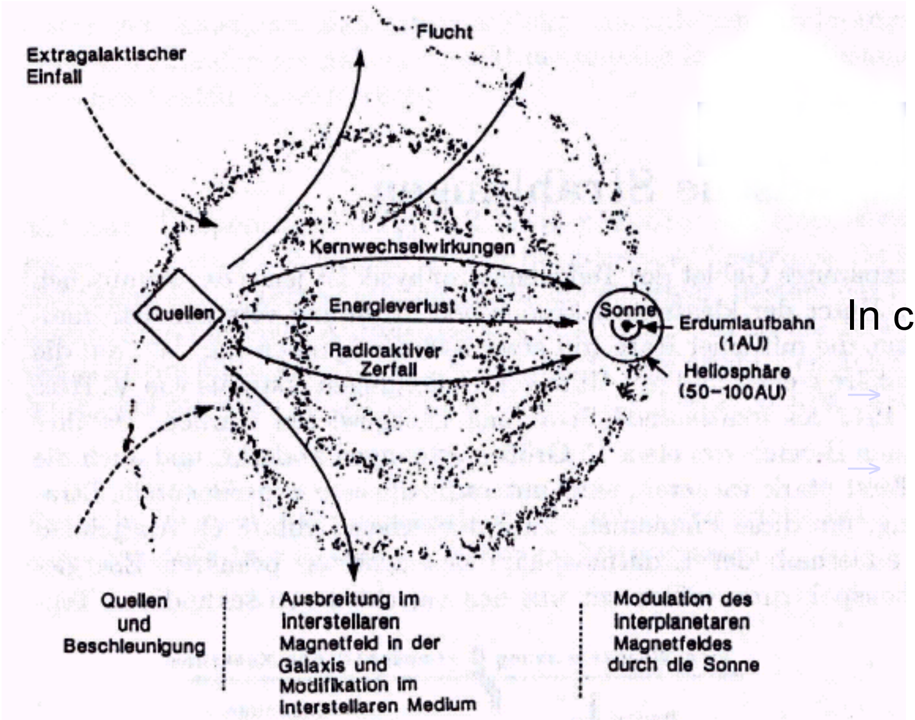


Cosmic Ray Propagation

Propagation of Cosmic Rays

What happens on the way through the ISM?

- deflection by mag. fields
- energy losses and gains
- collisions / fragmentation
- radioactive decay



In cosnequence:

→ **many directional changes;**

→ **CR model as diffusive gas that fills the volume of the milky way**

Quantitative estimates require a model for the particle density $N(E,x,t)$

Towards a transport equation

We'd like $N(E,x,t)$: consider any energy loss that alters $N(E,x,t)$

Particles in volume will experience energy change $\frac{dE}{dt}=b(E)$

with Z being the number of particles per energy interval at time t

$$Z[E,E+\Delta E,t] \sim N(E)\Delta E$$

$$Z[E,E+\Delta E,t+\Delta t] = Z[E',E'+\Delta E',t] \sim N(E')\Delta E'$$

$$\text{with } E'=E-b(E)\Delta t \qquad E'+\Delta E'=(E+\Delta E)-b(E+\Delta E)\Delta t$$

Therefore one transfers the problem to changes of particle numbers over energy

$$\Delta N(E)\Delta E = N(E')\Delta E' - N(E)\Delta E \qquad \Delta E' = ?$$

Towards a transport equation

Diffusive gas: *continuity equation:*

$$\frac{dN}{dt} + div\left(\vec{j}\right) = 0$$

→ 2nd Fick‘s law:

$$\left.\frac{dN}{dt}\right|_{dif\,f} = -\nabla\left(-D\nabla N\right)$$

... too simple, needs corrections to allow at least **production** and **destruction** of radiative particles!

Filling a volume: Source term

$$\left.\frac{dN}{dt}\right|_{quell} = Q$$

Radioactive decay might act constructive or destructive

wins **losses**

$$\left.\frac{dN_i}{dt}\right|_{nuklear} = \sum_{j>i} \underset{\searrow}{\frac{N_j}{\gamma_j \tau_{ij}}} - \underset{\swarrow}{\frac{N_i}{\gamma \tau_i}}$$

$$\tau_i, \tau_{ji}$$

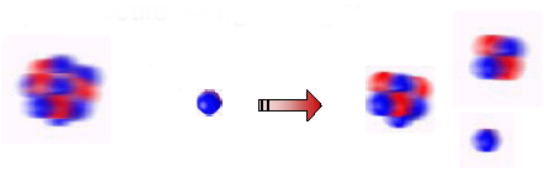
lifetime bzw. decay time j into i

Towards a transport equation

Furthermore: Spallation

Interaction of CR and ISM

Heavy nuclei are split into smaller ones



Li, Be, B & sub-Fe exist roughly in primordial abundance in our Solar System.

Overabundance in CR is due to Spallation.

$$\frac{dN_i}{dt}_{spallation} = \left(\sum_{j>i} n_{ISM} v \, \sigma_{ji} N_j \right) - n_{ISM} v \, \sigma_i N_i$$

wins **losses**

σ_i cross section spallation nucleus i in ISM

σ_{ji} Cross section production of nucleus i from nucleus j in ISM

n_{ISM} particle density ISM

Towards a transport equation

In sum, this costitutes the so-called transport equation for a leaky box model:

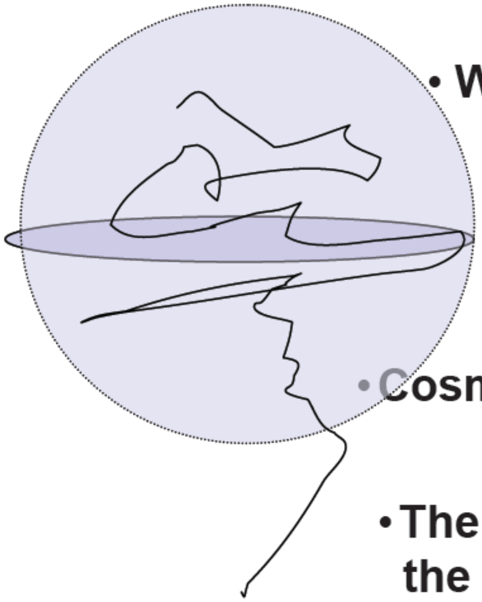
$$\frac{dN_i}{dt} = \frac{dN_i}{dt}_{diff} + \frac{dN_i}{dt}_{ernergie} + \frac{dN_i}{dt}_{quell} + \frac{dN_i}{dt}_{nuklear} + \frac{dN_i}{dt}_{spallatio}$$

$$\frac{dN_i}{dt} = \nabla(D\nabla N_i) - \frac{\partial}{\partial E}(b_i N_i) - nv\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} nv\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

PROBLEM:
- set of differential equation is extremely epensive to solve
- many unknown quantitites, therefore exact solution impossible unless simplifications are made

very common: simpler modelling

The two least complex models



Leaky Box Model

- Cosmic rays confined to a box with leakage at the boundary.
- Within the box, cosmic only interact with interstellar gas

Halo Diffusion Model

- Cosmic rays diffuse through magnetic scattering centers in the Galaxy
- The densities of scattering centers and gas are highest in the Galactic disk but extend into a halo above and below the disk
- Cosmic rays interact with the gas in the Galaxy and escape by diffusion

Leaky Box Model

The level of simplification here:

- instead of proper diffusion we‘re anticipating radiation in a closed volume **(box)**
- radiation remains constant over time but carries an energy-dependend probability to leave the volume **(leaky)**

$$\nabla(D\nabla N_i) \Rightarrow -\frac{N_i}{\tau_{esc}}$$

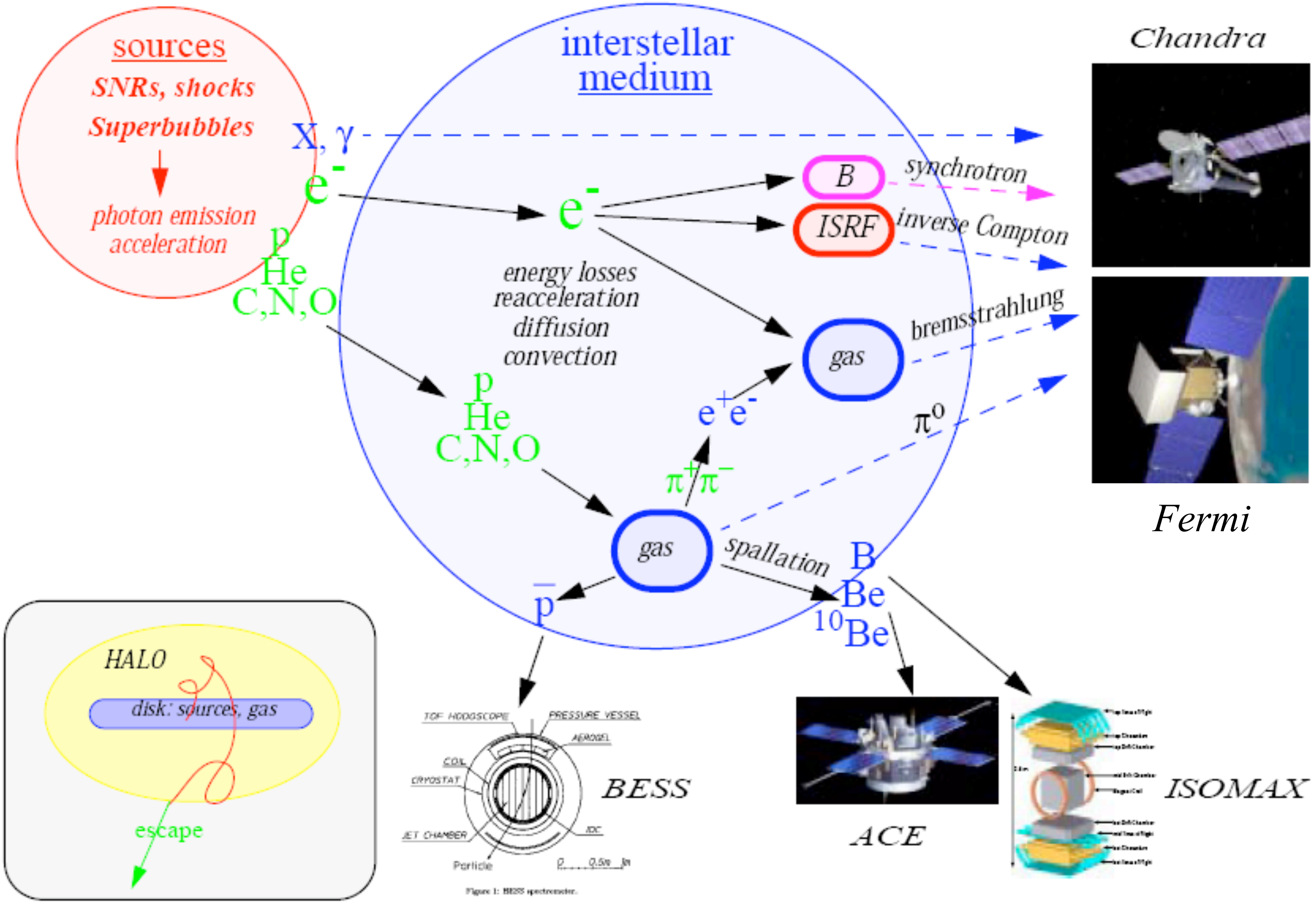
If $\frac{dN_i}{dt} = -\frac{N_i}{\tau_{esc}}$ then $N_i \sim \ e^{-t/\tau_{esc}}$

and τ_{esc} is an average time before leaving the volume.

Consequently, the transport equation for a Leaky Box Model is

$$\frac{dN_i}{dt} = -\frac{N_i}{\tau_{esc}} - \frac{\partial}{\partial E}(b_i N_i) - nv\sigma_i N_i - \frac{N_i}{\gamma\tau_i} + Q_i + \sum_{j>i} nv\sigma_{ij} N_j + \sum_{j>i} \frac{N_j}{\gamma_j \tau_{ij}}$$

More contemporary CR propagation models



sources

SNRs, shocks

Superbubbles

photon emission
acceleration

interstellar
medium

X, γ

e^-

p
He
C,N,O

e^-

B

ISRF

synchrotron

inverse Compton

energy losses
reacceleration
diffusion
convection

gas

bremsstrahlung

p
He
C,N,O

e^+e^-

$\pi^+\pi^-$

π^0

gas

spallation

$\bar{p}$

B
Be
^{10}Be

Chandra

Fermi

HALO

disk: sources, gas

escape

BESS

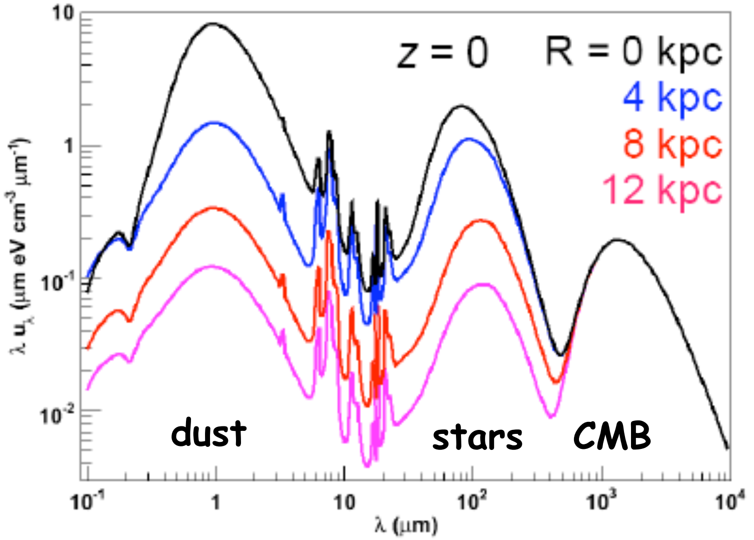
ACE

ISOMAX

Figure 1: BESS spectrometer.

Galactic diffuse γ-ray emission – ISRF

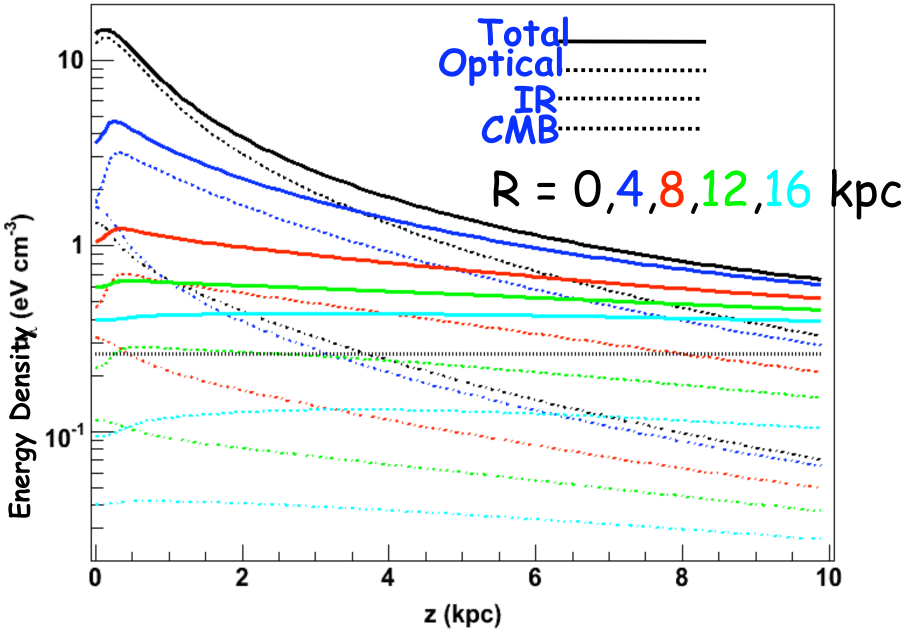
- **Galactic interstellar radiation field:**
  - anisotropic and energy dependent
  - stellar distribution (87 Stellar classes) within the Milky Way: local density, scale hight, spectrum *[synthetic spectra: Girardi et al library]*
  - dust (graphite, PAH, silicates) - extinction: absorption & scattering
- absorption/re-emission of stellar radiation at dust → IR

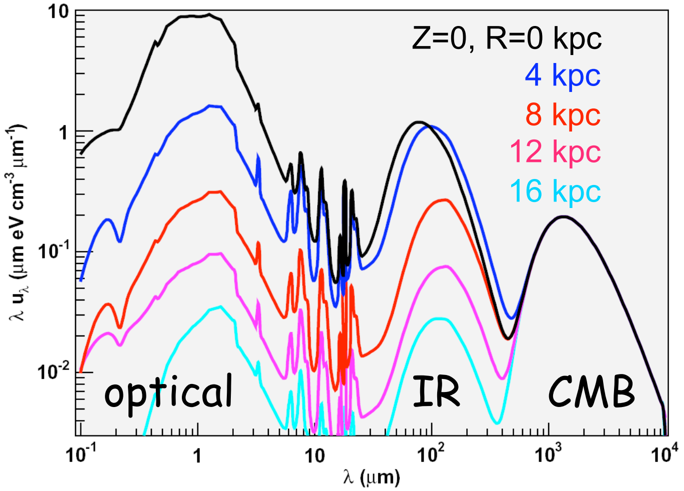


R_{max}=20kpc, z_{max}=5kpc

Galactic diffuse γ-ray emission – ISRF

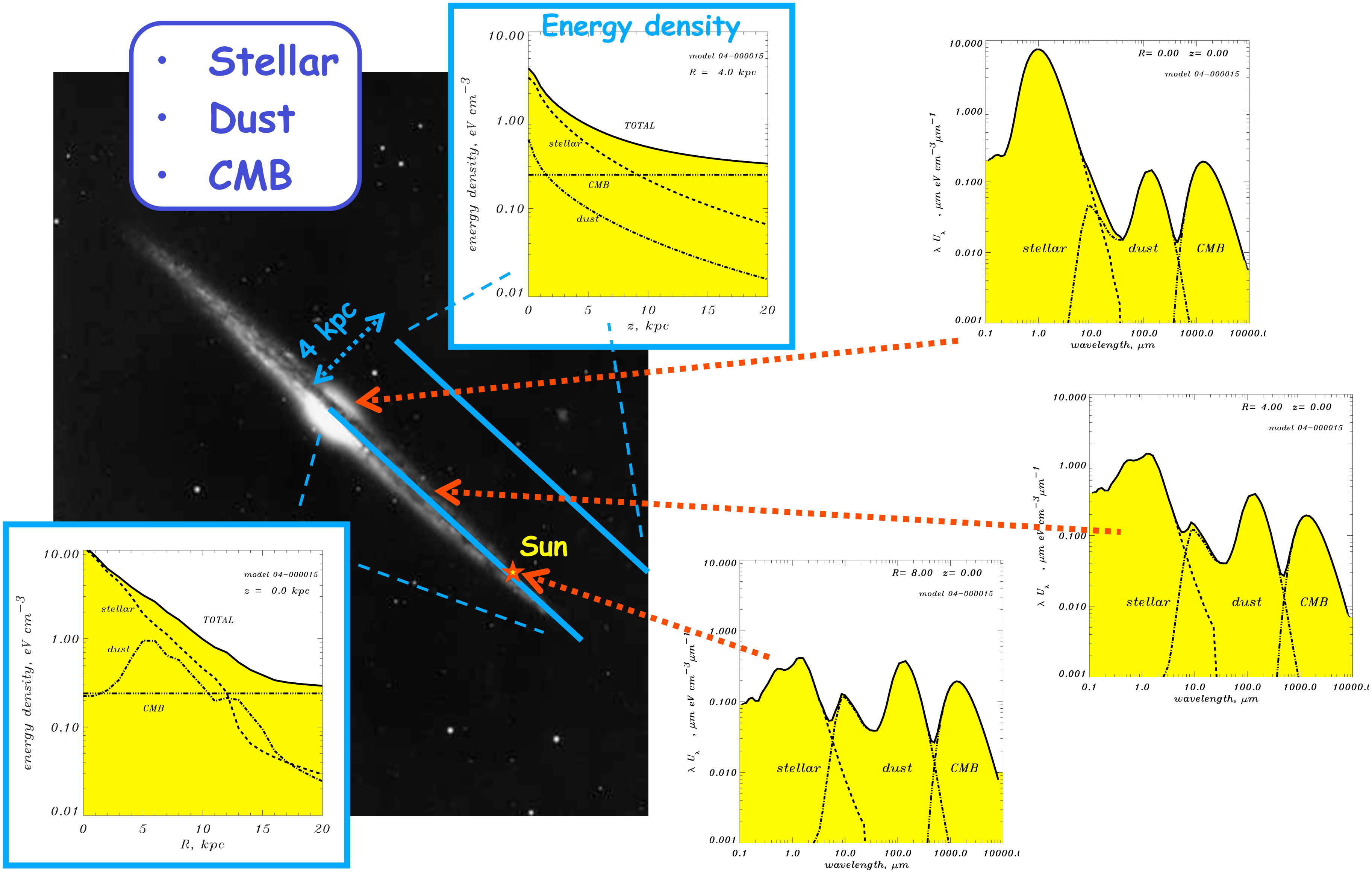
- Requires extensive modeling:
  - Distribution of stars of different stellar classes in the Galaxy
  - Dust emission
  - Radiative transfer
- These vary with position AND wavelength
- Different from local intensity distribution
- Isotropic approximation for anything but the CMB is imprecise



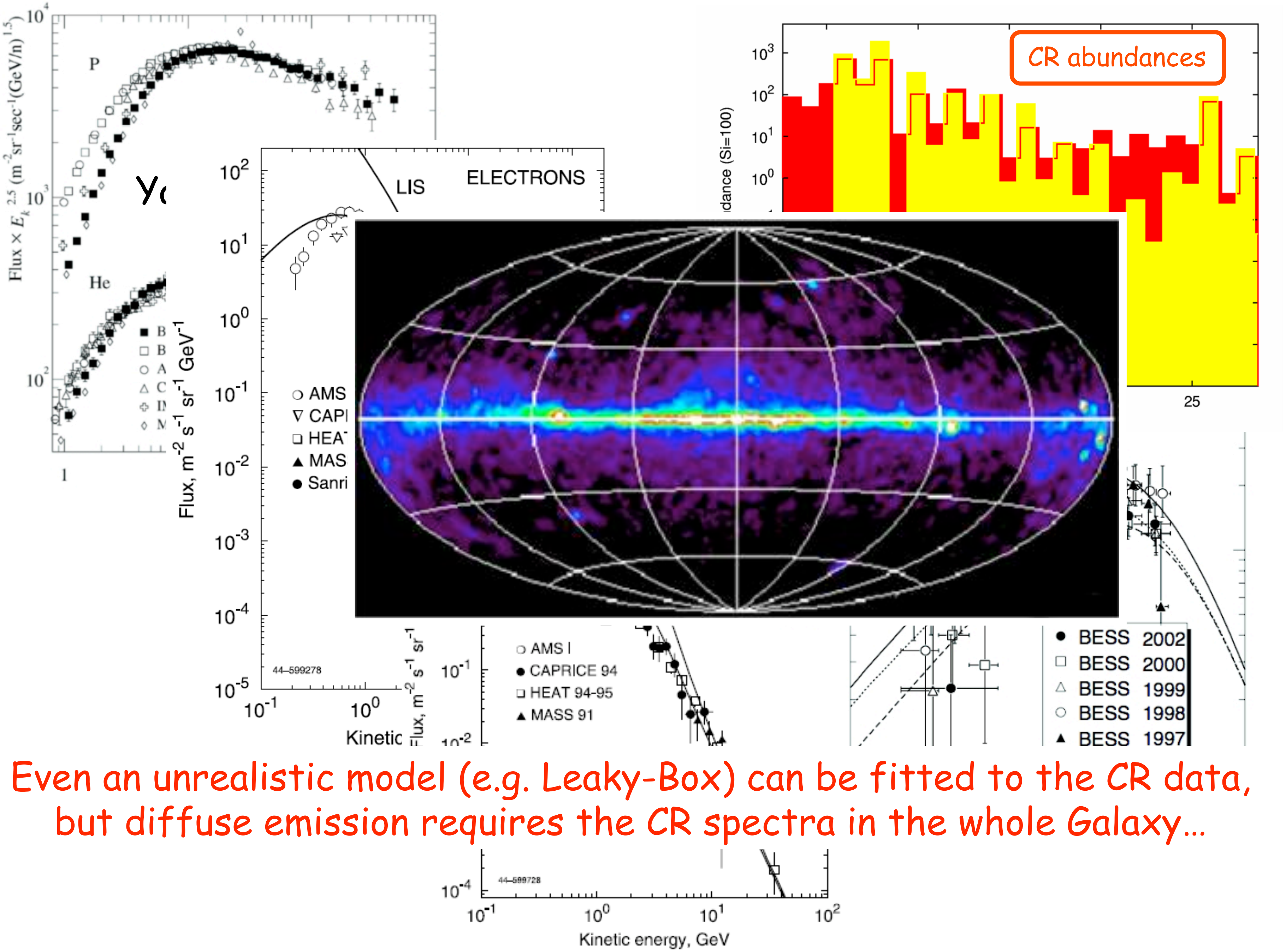


Galactic diffuse γ-ray emission - ISRF

- Stellar
- Dust
- CMB



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…

The transport equation solved by GALPROP

(numerically via Crank-Nicholson implicit 2nd-order scheme, spatial boundary cond.: free particle escape)

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ sources

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

diffusive reacceleration $$+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right]$$

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

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

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

Refinement of the diffuse emission calculations

Contribution of secondary positrons and electrons

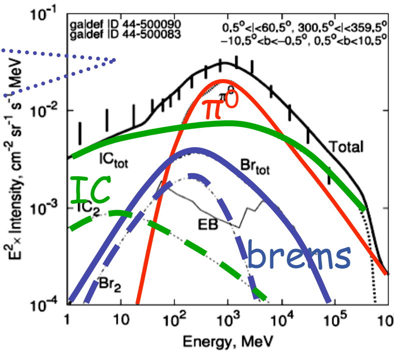
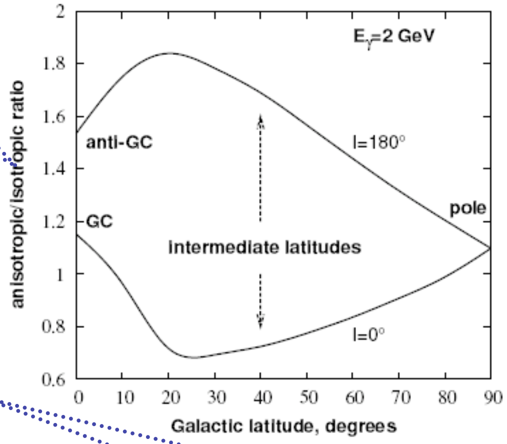
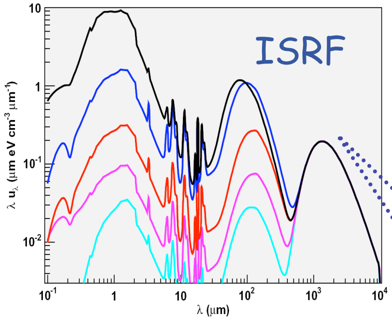


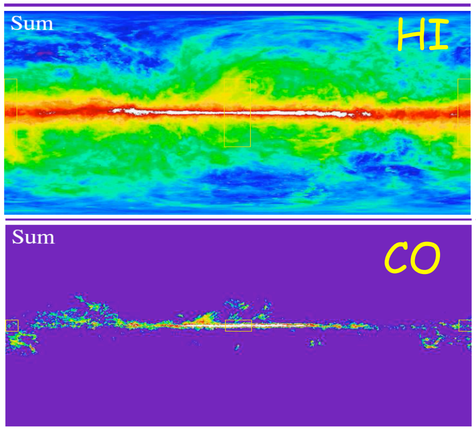
FIG. 13.—Gamma-ray spectrum of optimized model with (*thick lines*) and without (*thin lines*) primary electrons, to show the contribution of secondary electrons and positrons. Br_{tot} and Br_2 labels denote the total bremsstrahlung and the separate contribution from secondary leptons, correspondingly. Similarly, IC_{tot} and IC_2 indicate the total IC and the contribution from secondaries.

Anisotropic IC in the Galaxy

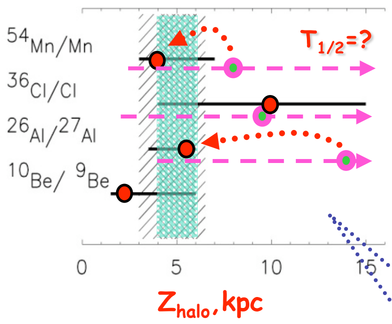




Improvement of the interstellar radiation field model

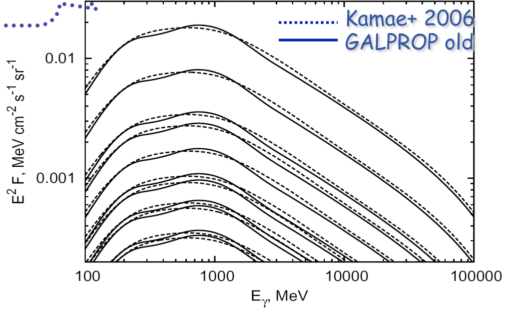


Gas (H_2, HI, HII) distribution and X-factor



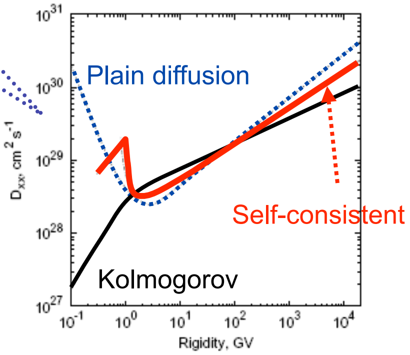
pp- and pA-interactions (hadronic gammas)

Pion decay -ray spectra for different regions on the sky



see also Kelner+'07

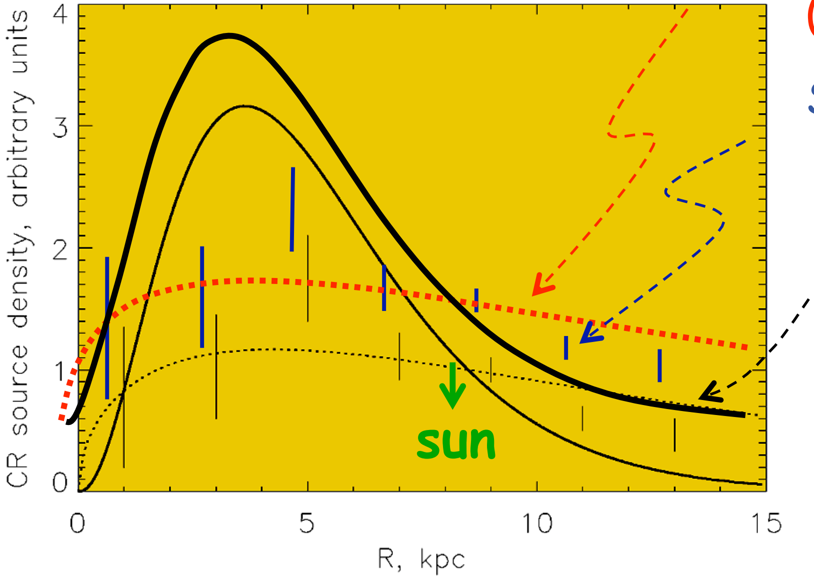
CR propagation models



Nuclear isotopic production cross sections

+source distribution
+source composition…

Distribution of CR Sources & the gradient in CO/H_2



CR distribution from diffuse gammas (Strong & Mattox 1996)

SNR distribution (Case & Bhattacharya 1998)

Pulsar distribution (Lorimer 2004)

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

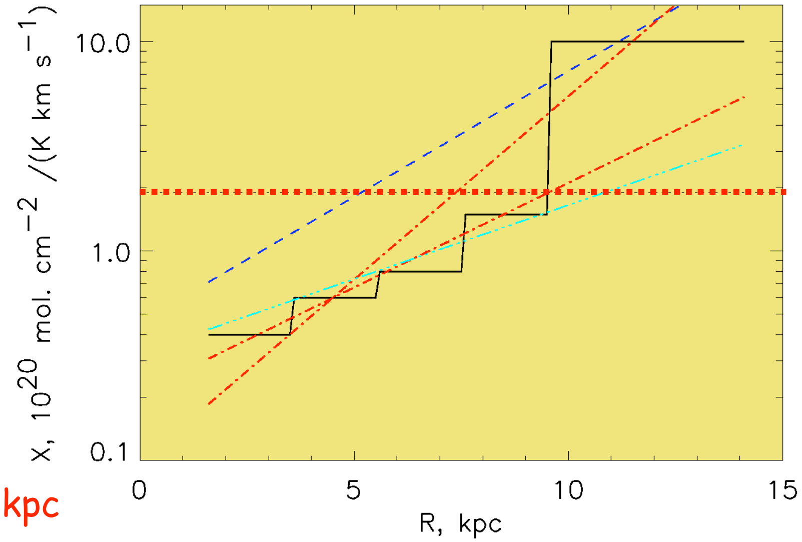
Histo – SMR '04

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

1.9×10^{20} -Strong & Mattox '96

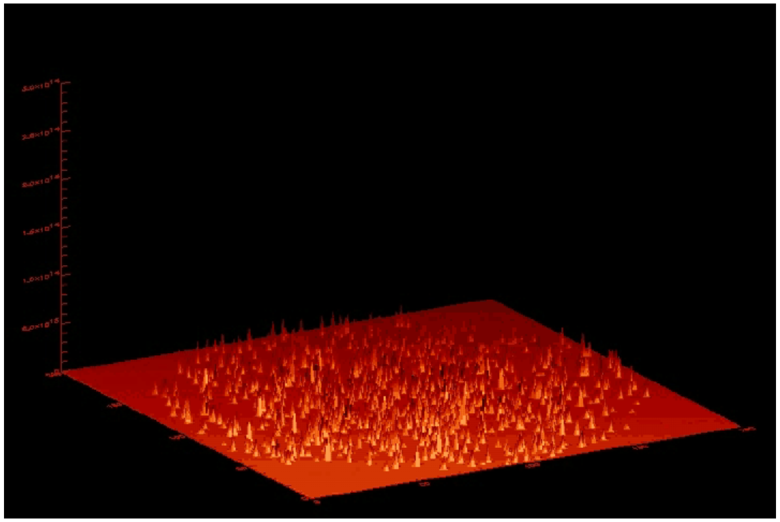
$\sim Z^{-1}$ -Boselli et al. '02

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

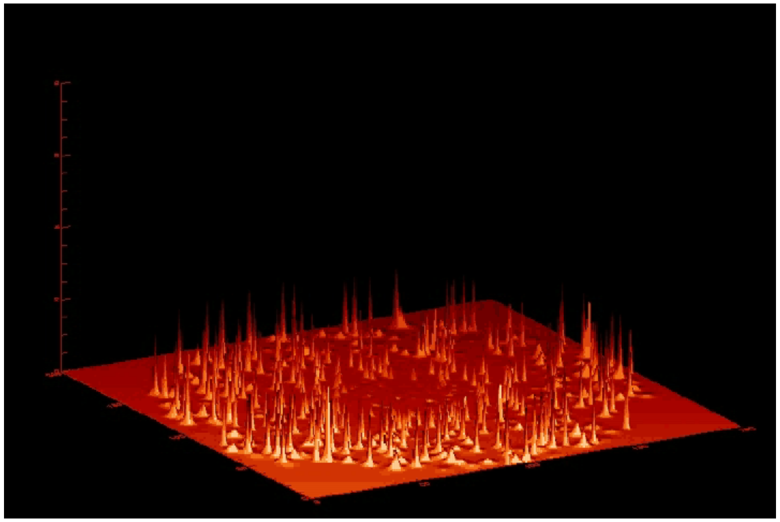


CR sources as stochastic events – energy losses

GeV electrons

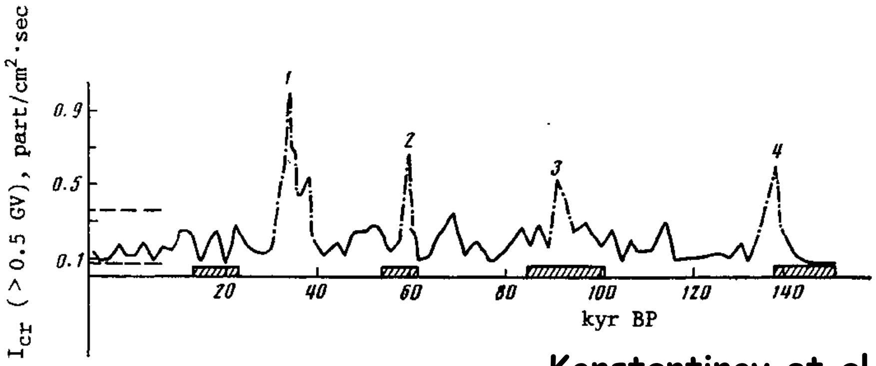


100 TeV electrons



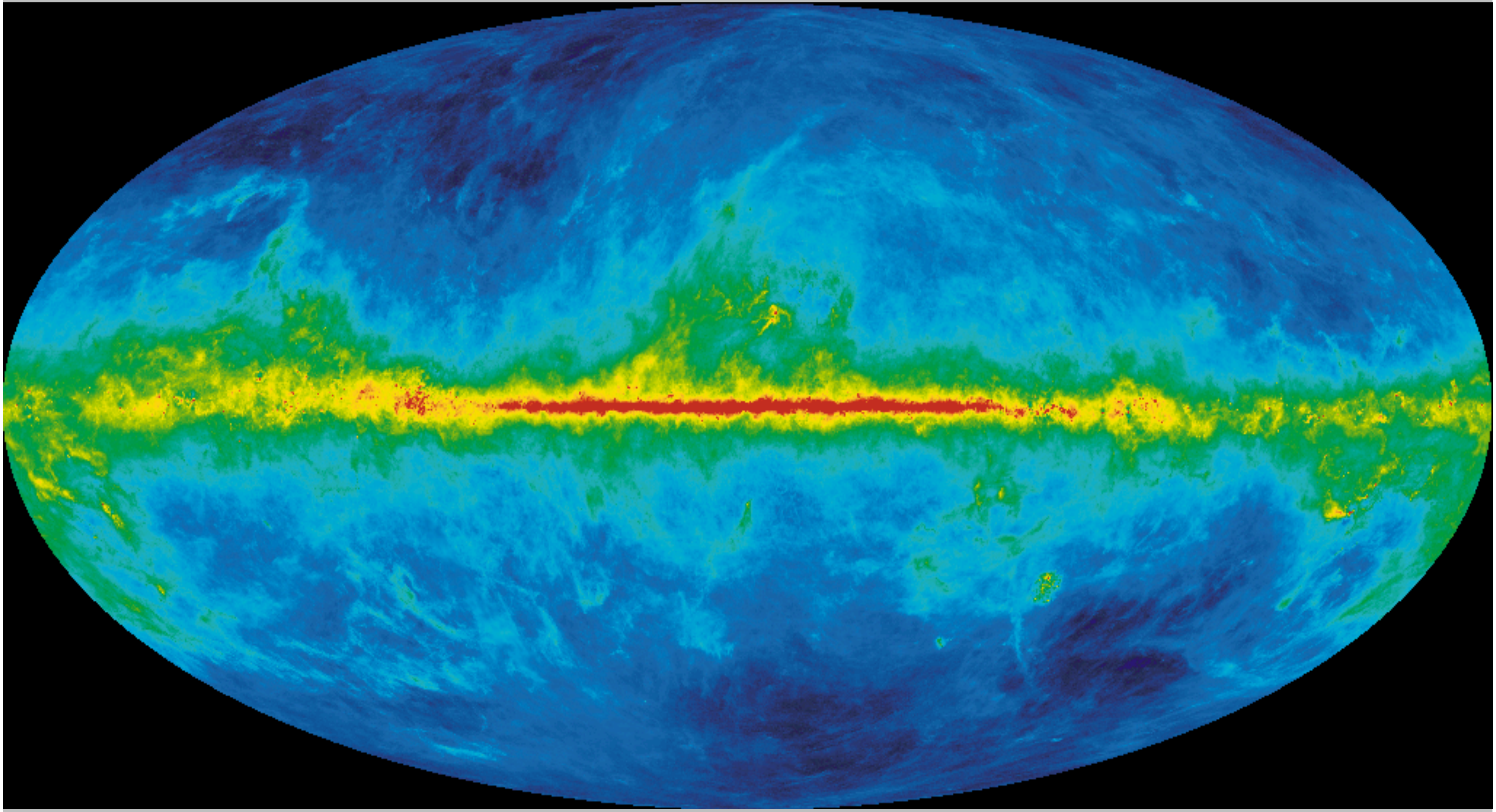
S.Swordy

Historical variations of CR intensity over 150 kyr (Be^{10} in South Polar ice)



Konstantinov et al. 1990

Dust: A forgotten ingredient?



" Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds",

Schlegel, Finkbeiner & Davis (SFD), 1998

π^0

$$I(l,b,E)=\iint \rho_{CR_p}(E',s)\,q_{\pi^0}(E,E')\,\rho_{ISM}(s)\,dE'ds+$$
$$\iint \rho_{CR_e}(E',s)\left[q_B(E,E')\,\rho_{ISM}(s)+q_{IC}(E,E')\,\rho_{ISRF}(s,E')\right]dE'ds$$

Bremsstrahlung

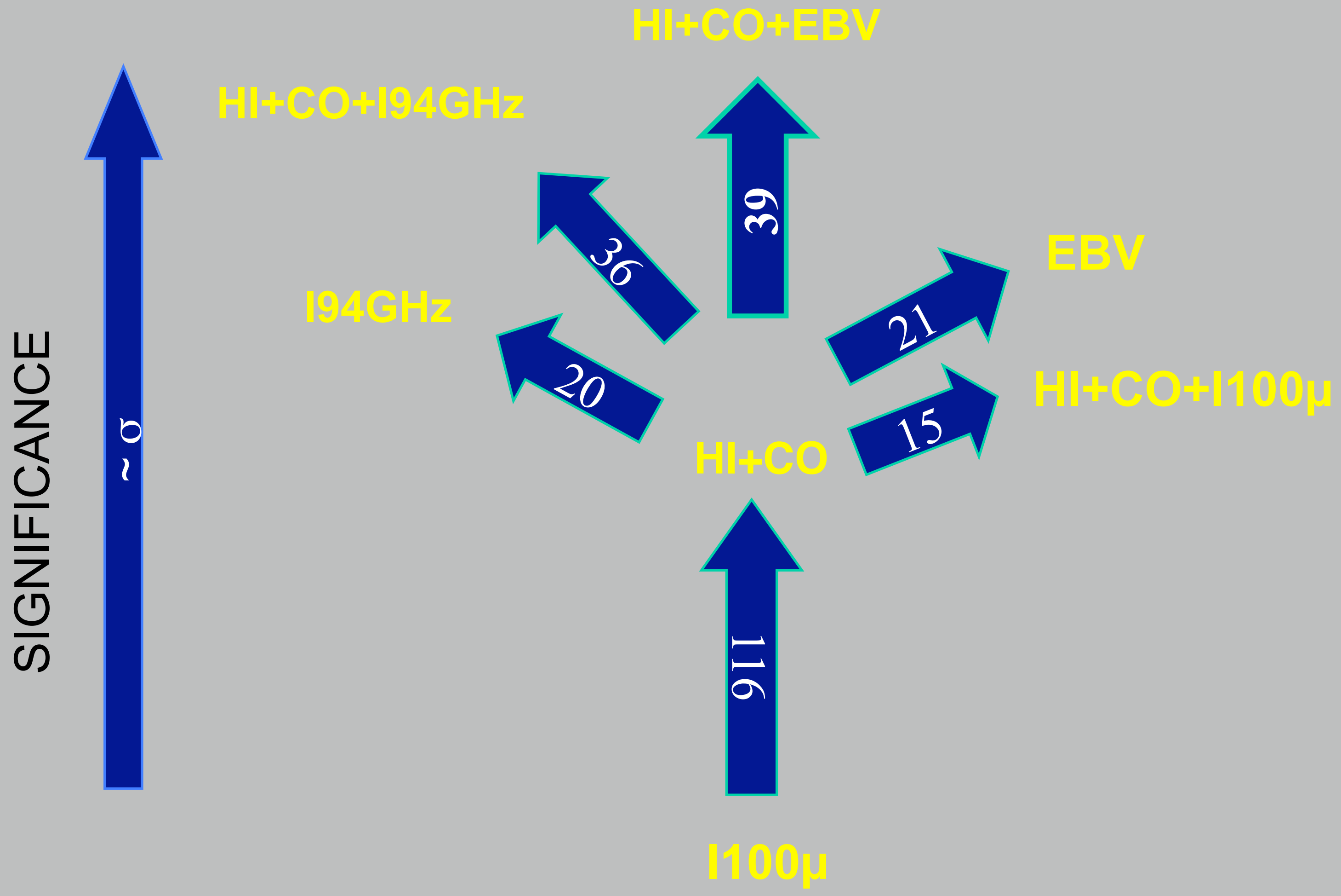
Inverse Compton

$$N_{\gamma\_diff\,us}=\left(q_{HI}N_{(HI)}+q_{H2}W_{(CO)}+q_{IC}I_{IC}+I_{bkg}\right)SA\,\Delta T\,\Delta\Omega$$

convolve with PSF

$$N_{\gamma\_diff\,us}=\left(q_{HI}N_{(HI)}+q_{H2}W_{(CO)}\boxed{+q_{dust}I_{dust}}+q_{IC}I_{IC}+I_{bkg}\right)SA\,\Delta T\,\Delta\Omega$$

Approach: The best tracer or combination of tracers wins!



SIGNIFICANCE

~ σ

HI+CO+EBV

HI+CO+I94GHz

39

36

EBV

I94GHz

21

20

HI+CO+I100μ

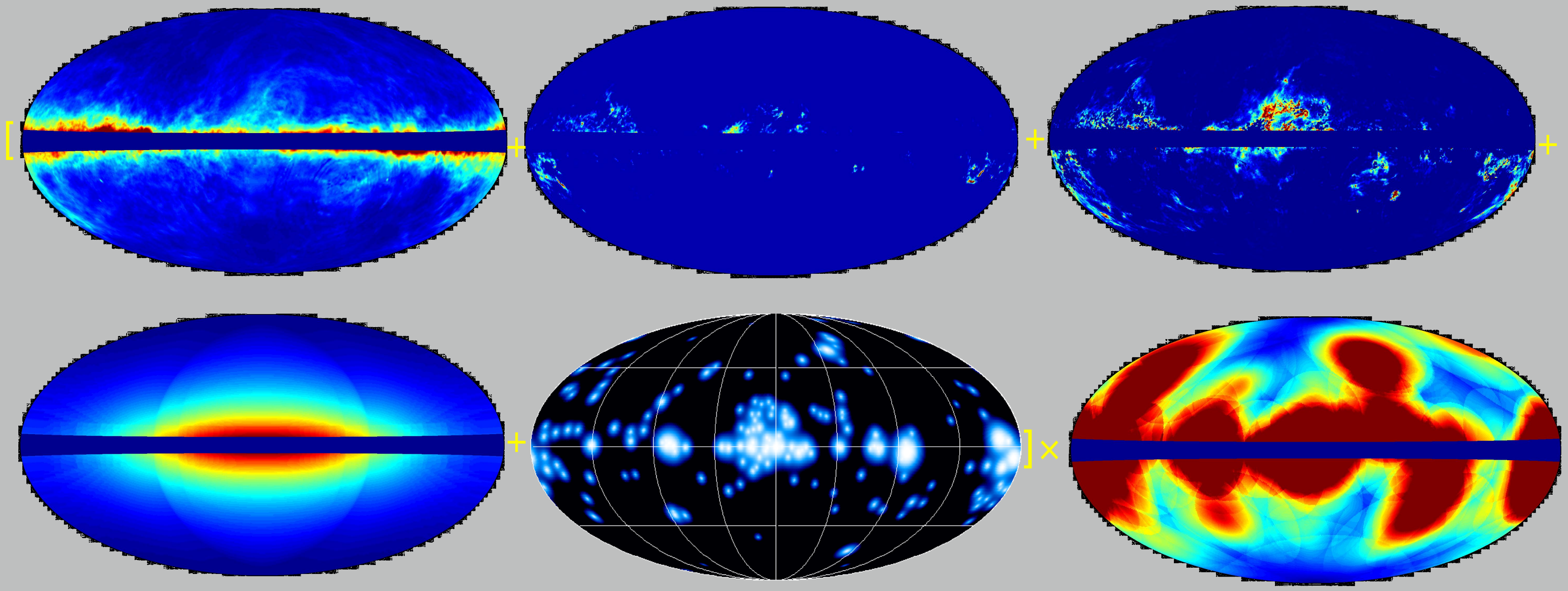
15

HI+CO

116

I100μ

$$N_{\gamma\_dif\,f\,us} = \left(q_{HI}N_{(HI)} + q_{H2}W_{(CO)} + q_{dust}I_{dust} + q_{IC}I_{IC} + I_{bkg}\right)SA\,\Delta T\,\Delta\Omega$$



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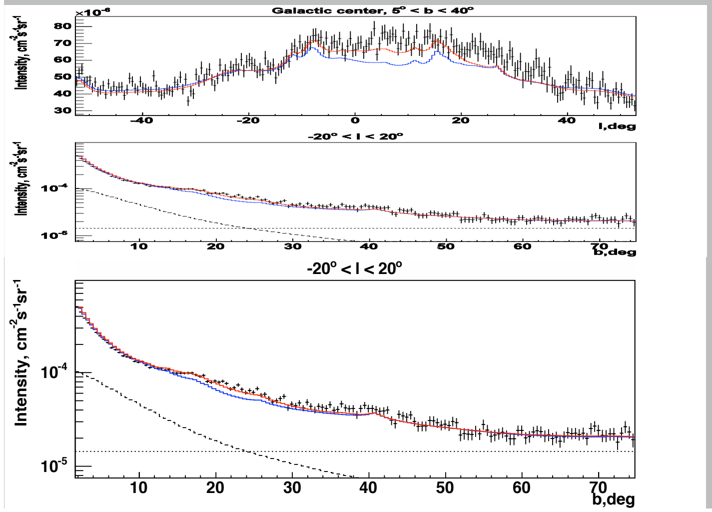
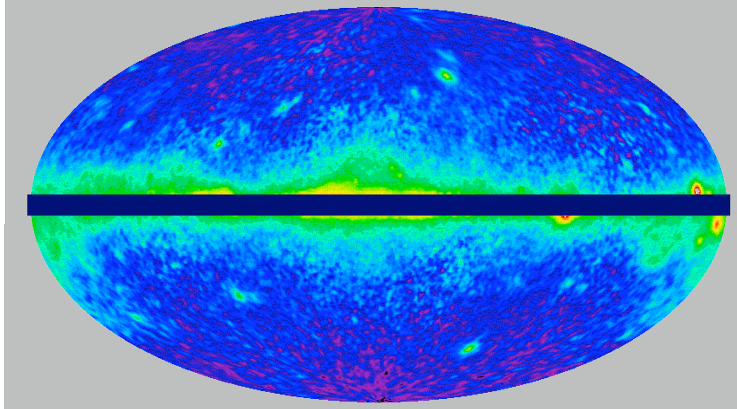
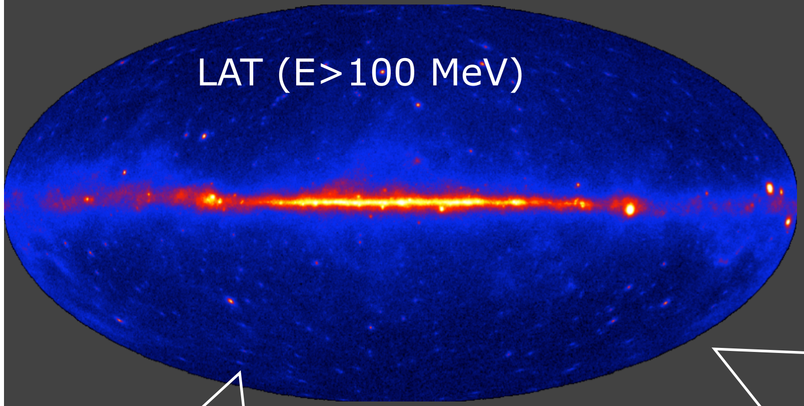




Diffuse emission in the Fermi era

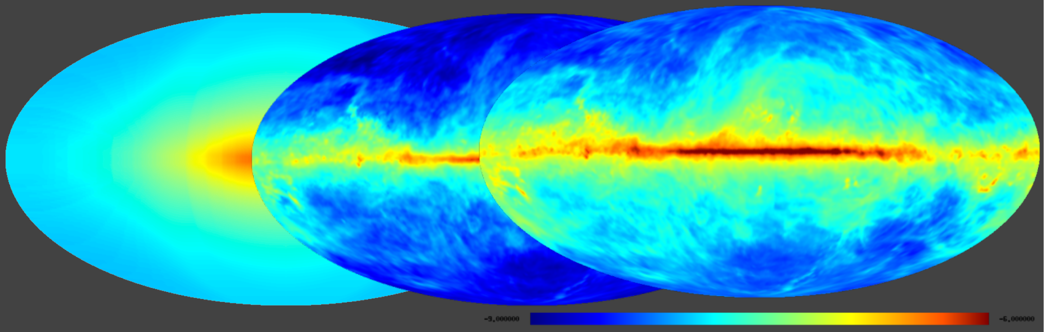


Galactic diffuse emission

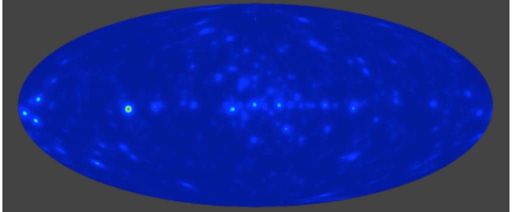
(CR interactions with the interstellar medium)

Inverse Compton

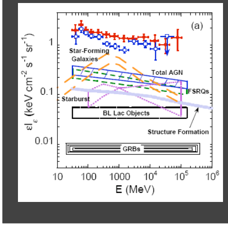
π^0-decay



Bremsstrahlung



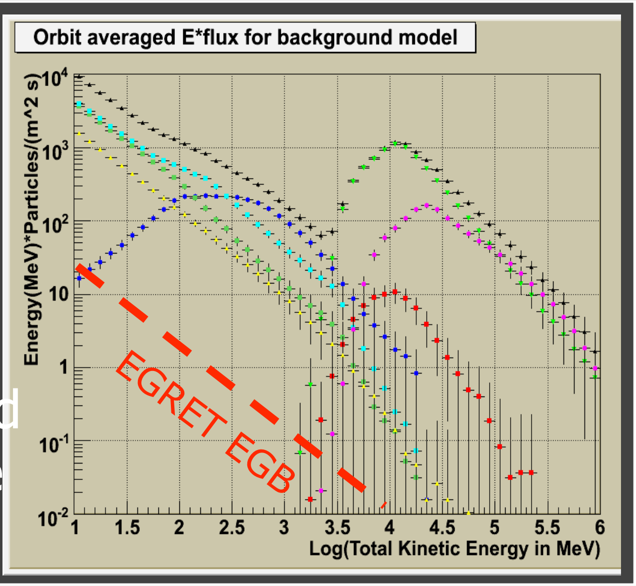
Resolved sources



Isotropic diffuse emission

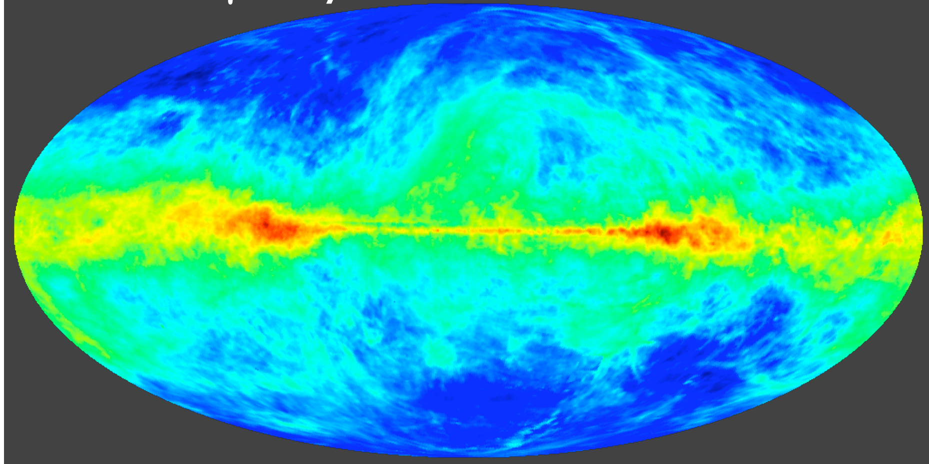
- Residual cosmic rays surviving background rejection filters

- misreconstructed γ-rays from the earth albedo



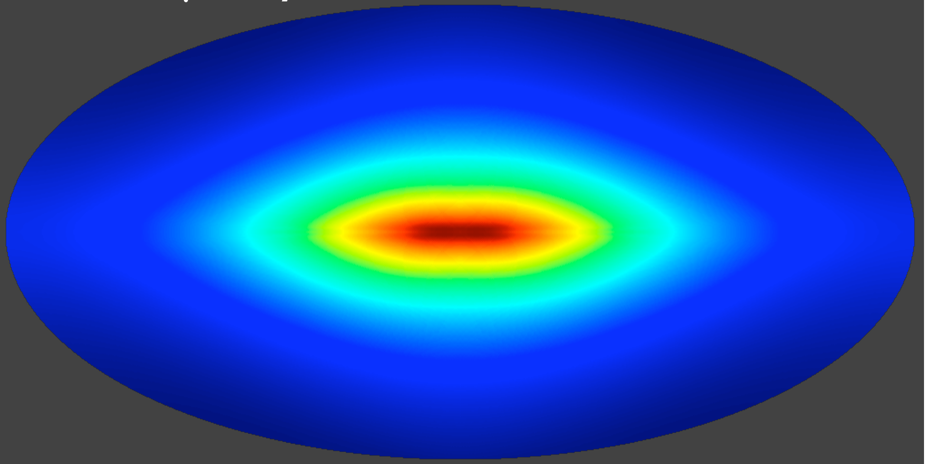
Model of the Galactic foreground

γ-ray emission model



HI (7.5kpc < r < 9.5kpc)

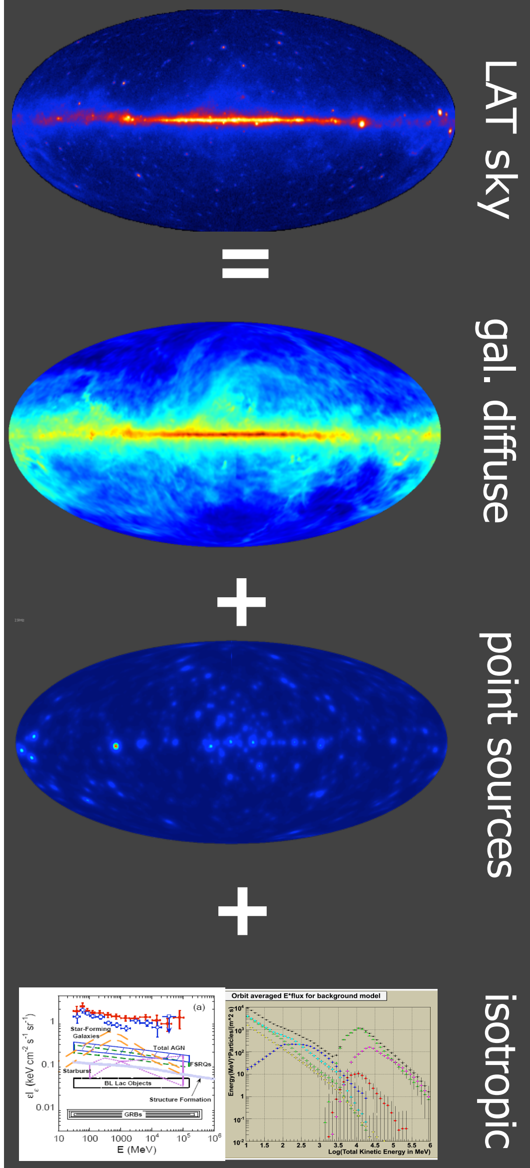
γ-ray emission model



Inverse Compton scattering

- Diffuse gamma-ray emission of Galaxy modeled using GALPROP
- Spectra of dominant high-latitude components fit to LAT data:
  - Inverse Compton emission (isotropic ISRF approximation)
  - Bremsstrahlung and π^0-decay from CR interactions with local (7.5kpc < r < 9.5kpc) atomic hydrogen (HI)
- HI column density estimated from 21-cm observations and E(B-V) magnitudes of reddening
- 4 kpc electron halo size for Inverse Compton component (2kpc - 10kpc tested)

Analysis technique



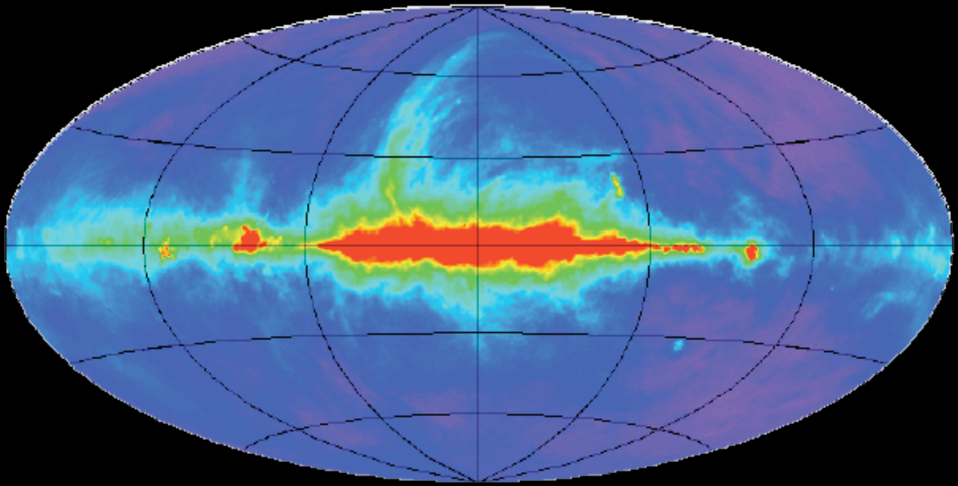
- **Pixel-by-pixel max. likelihood fit** of $|b|>10^{o}$ sky
  - equal-area pixels with ~ 0.8 deg^2 (HEALPIX grid)
  - sky-model compared to LAT data
  - point source /diffuse intensities fitted simultaneously
  - 9 independent energy bins, 200 MeV - 100 GeV
  - 10 month of LAT data, 19 Ms observation time

- **Sky model:**
  - Maps of Galactic foreground γ-rays considering individually contributions from IC and local HI
  - Individual spectra of TS>200 ($\sim>14\sigma$) point sources from LAT catalog
  - Map of weak sources from LAT catalog
  - Solar IC and Disk emission
  - Spectrum of isotropic component

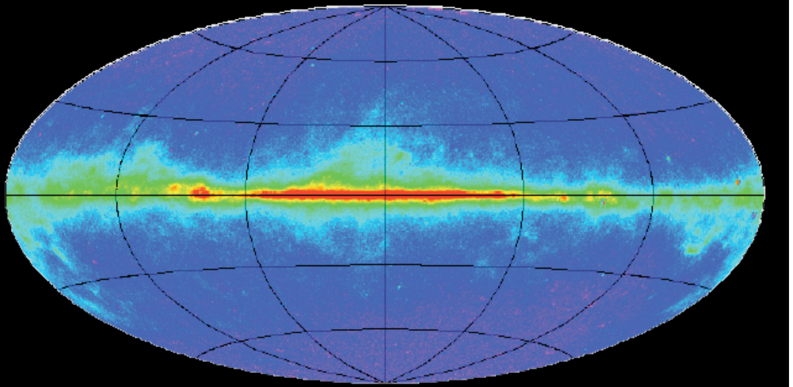
- **Subtraction of residual background** (derived from Monte Carlo simulation) from isotropic component

Results: The Local Bubble and Beyond

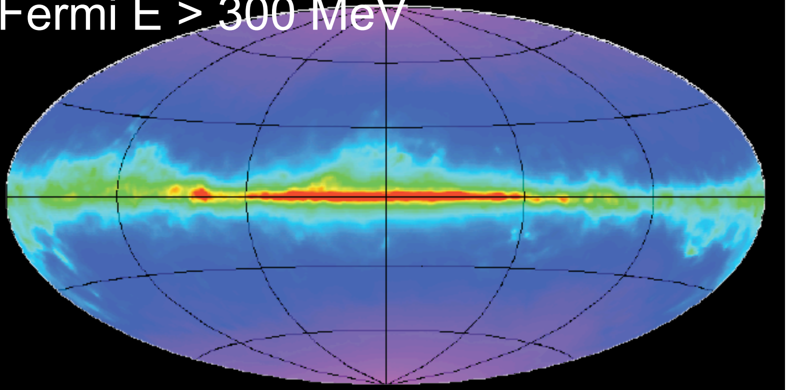
Loop I:



Haslam 408 MHz
(alternatively WMAP 23GHz)



Fermi E > 300 MeV

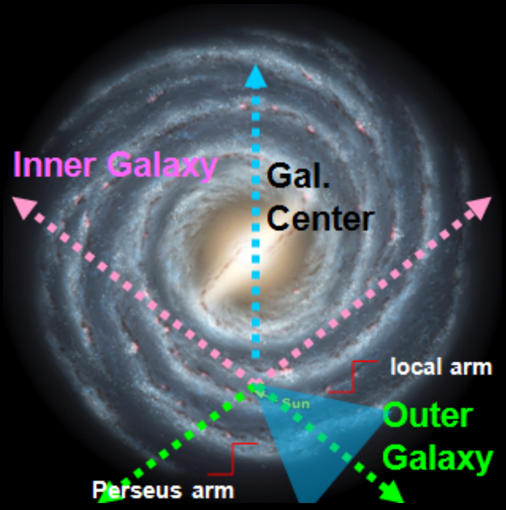


Fermi diffuse model

There appears to exist arc-like excesses against the diffuse model:
Fainter than pion production and bremsstrahlung as calculated from HI tracer, fainter than IC as of GALPROP template. Under investgation.

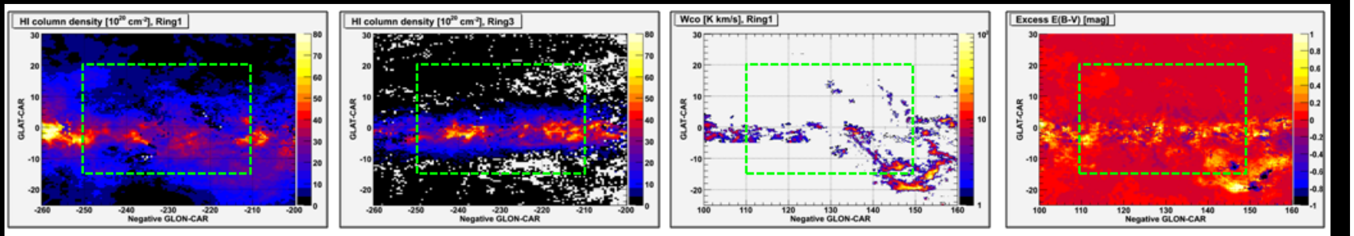
Results: The Local Bubble and Beyond

3nd Quadrant: Perseus



$I(E, l, b) = \Sigma A(E) * HI(l,b) + \Sigma B(E) * W_{co}(l,b) + C(E) * E(B\text{-}V)_{excess}(l,b) + IC(l,b) + Iso(E) + \Sigma$ point_sources

Coefficients give the gamma-ray (CR) spectral distribution and X_{co} evolution in the outer Galaxy

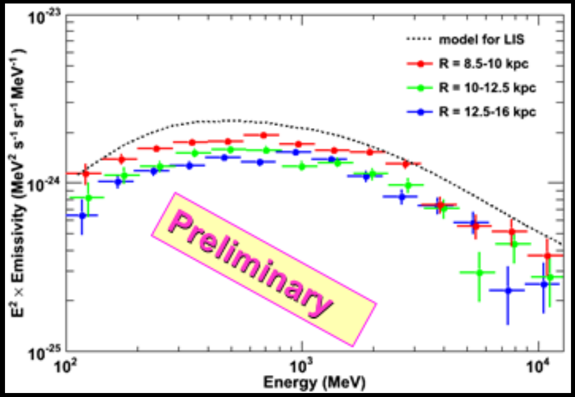


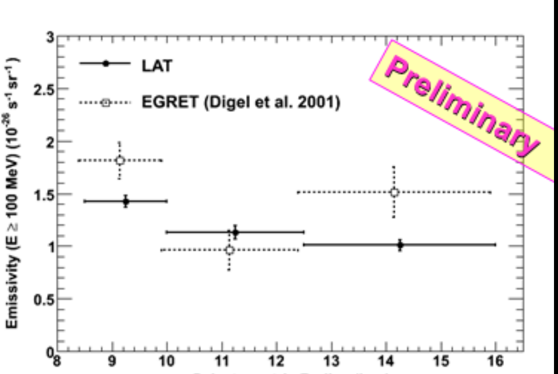
HI, Local arm

HI, Perseus arm

CO, Local arm

Excess E(B-V)

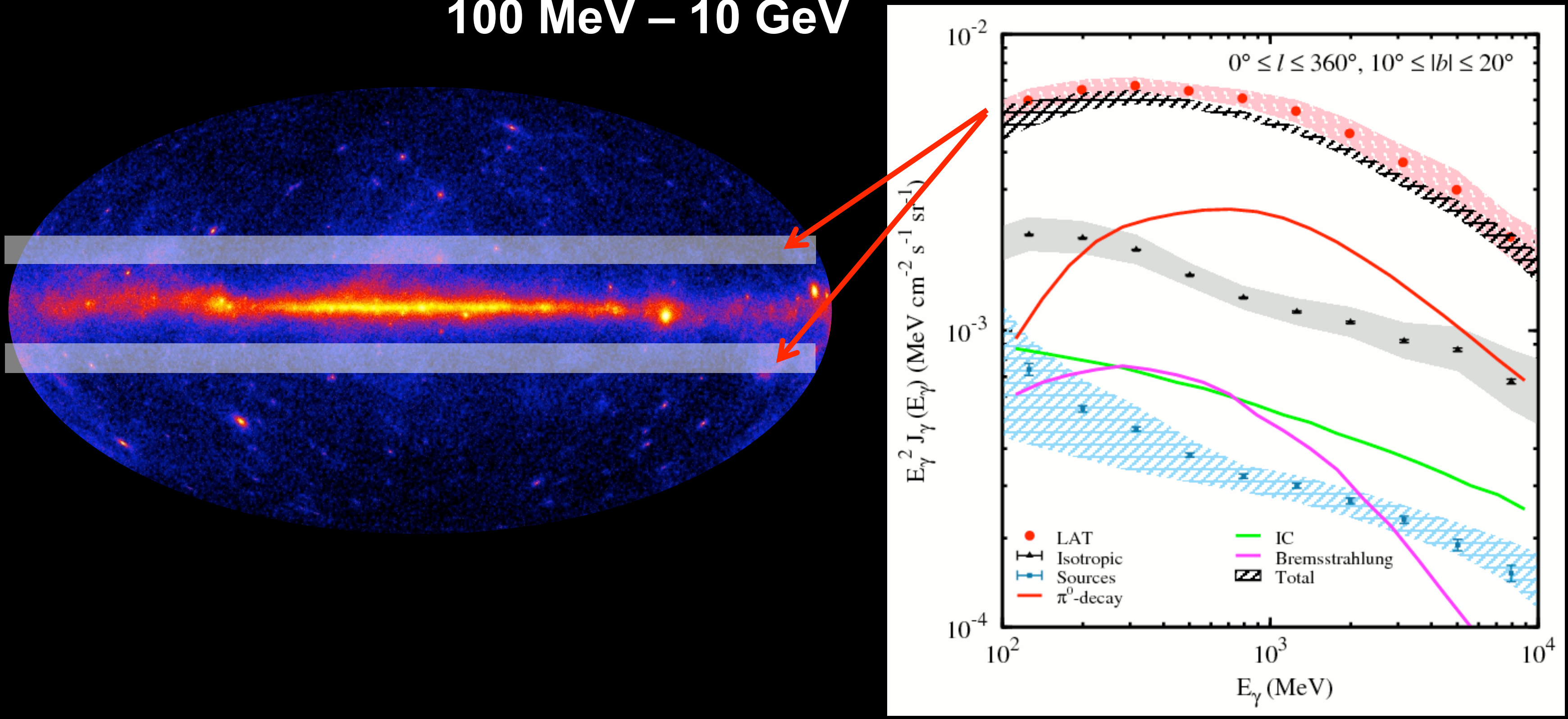




- Obtained spectra from the Outer Galaxy (3rd quadrant) are consistent with locally measured spectral shape.
- No noticable arm-interarm contrast

Results: Mid-galactic latitudes

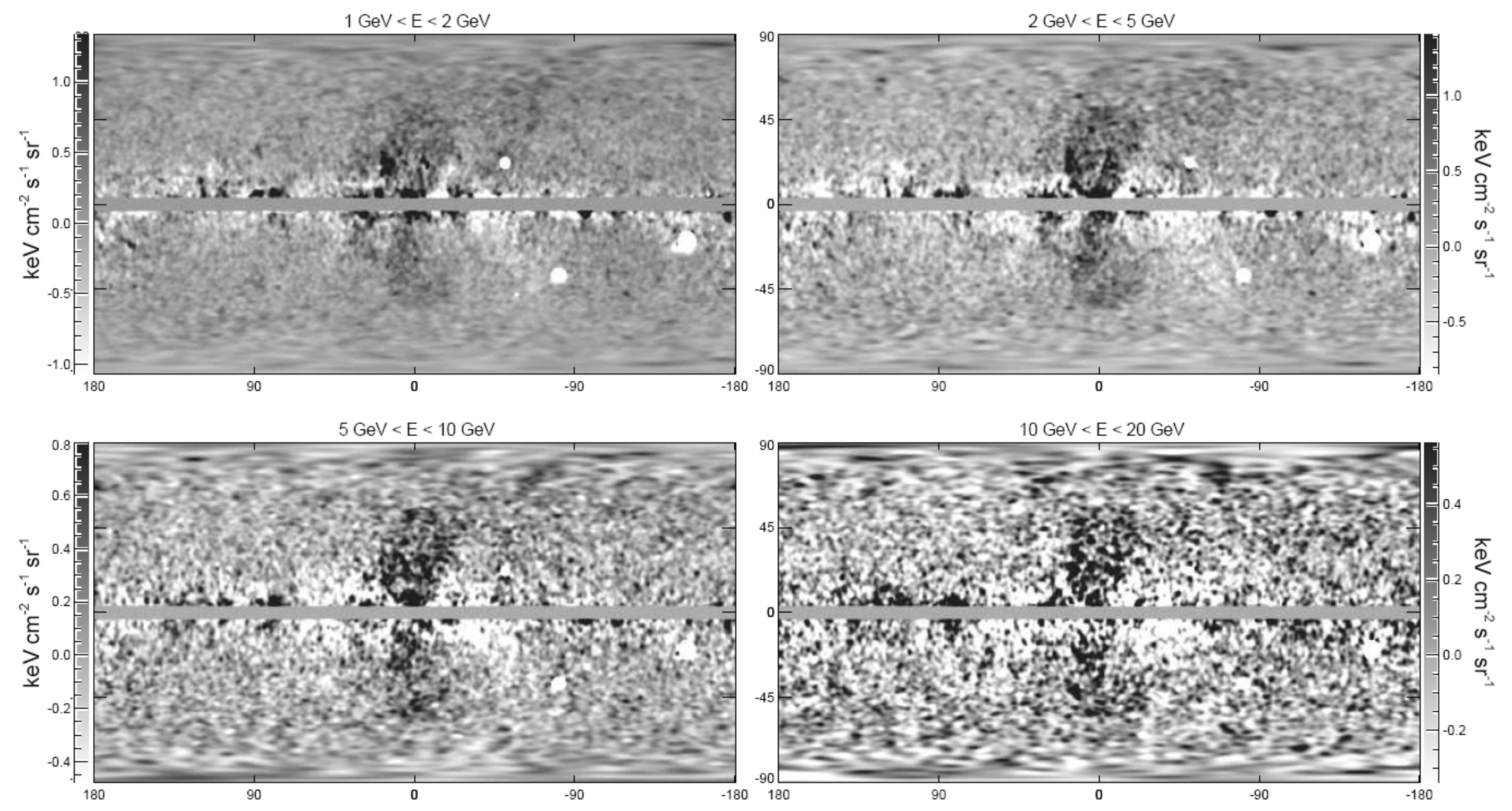
100 MeV – 10 GeV



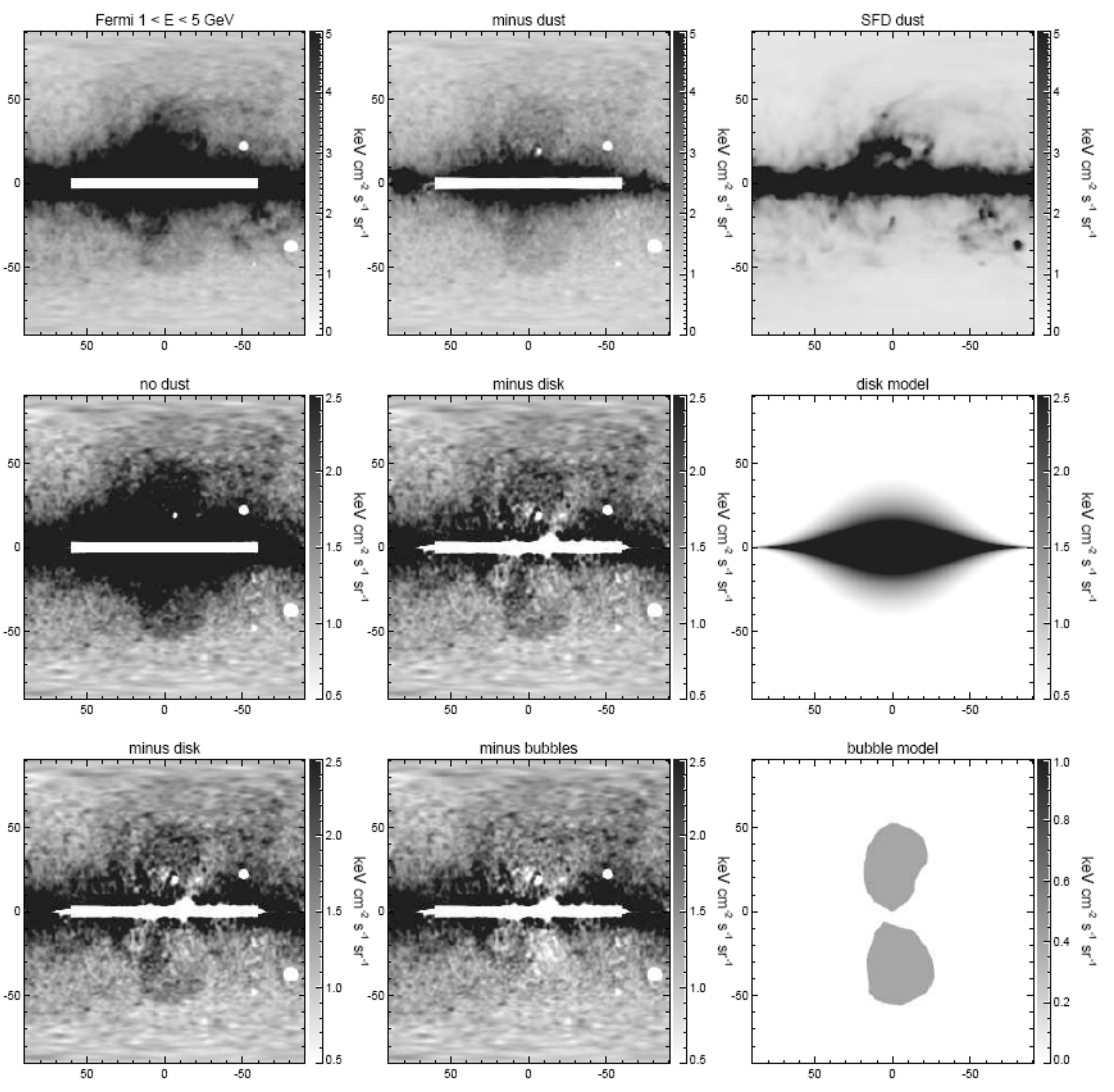
→ **standard CR interaction models adequate (which do justice to locally measured CR abundances, CR sec/prim ratios, long/lat distr.)**

→ **Fermi/LAT errors are systematics dominated, estimated to ~10%**

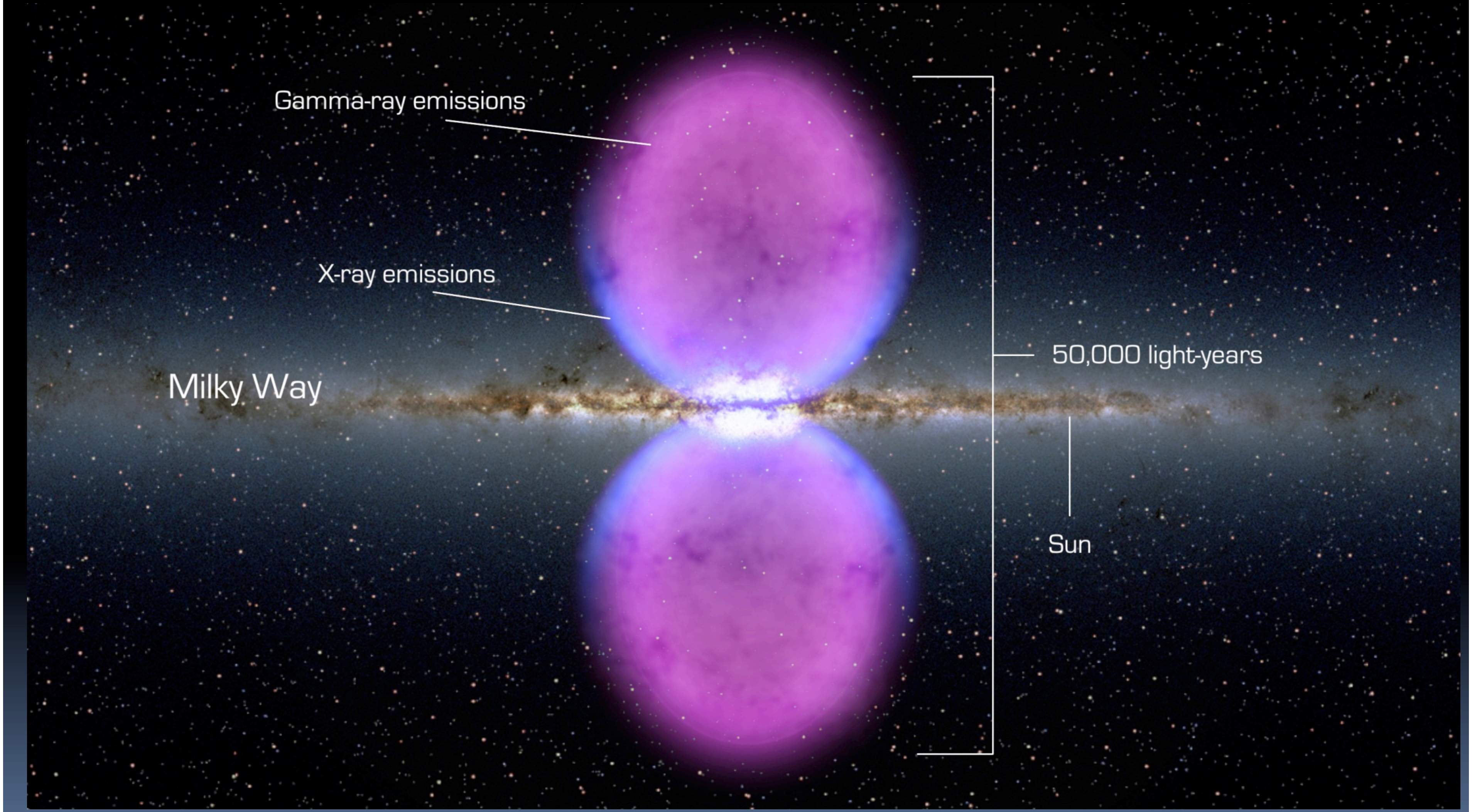
…to me, the single most interesting (unexpected!) finding: The Fermi bubbles

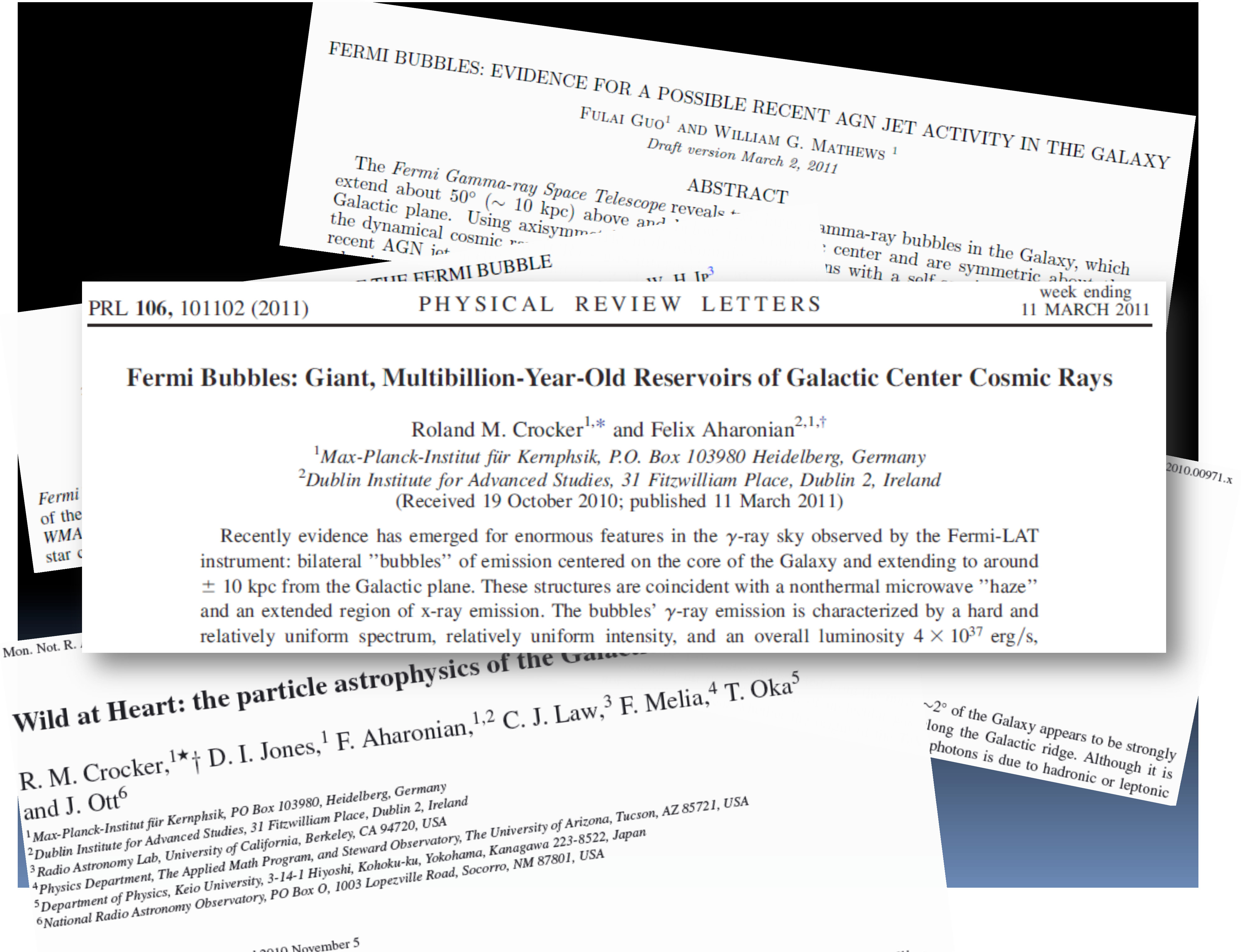


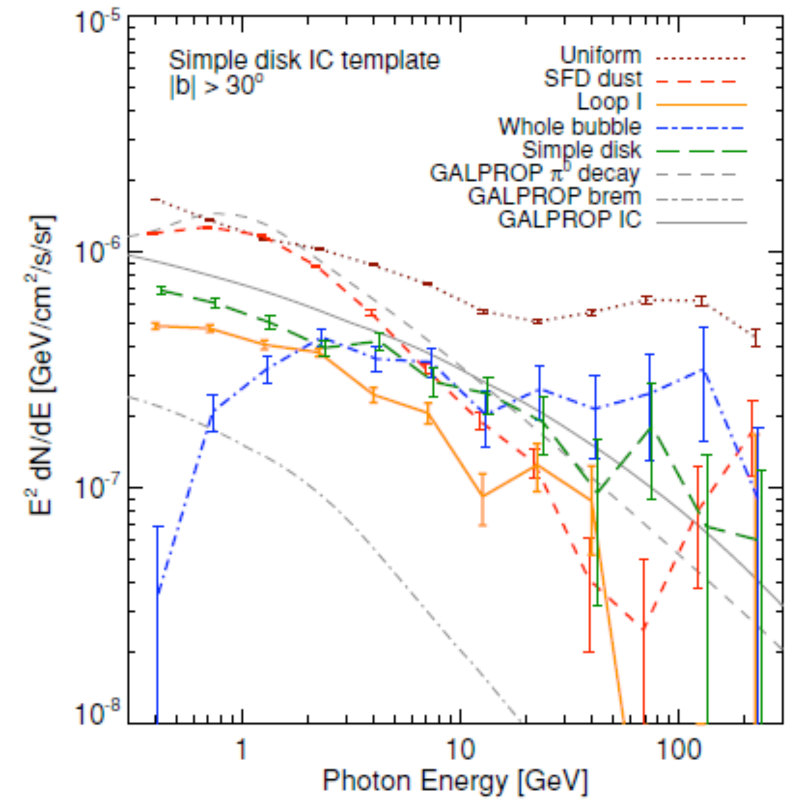
Su, Slatyer & Finkbeiner, December 2010


Fermi 1 < E < 5 GeV
minus dust
SFD dust
no dust
minus disk
disk model
minus disk
minus bubbles
bubble model
keV cm^{-2} s^{-1} sr^{-1}
50
0
-50
5
4
3
2
1
0
2.5
2.0
1.5
1.0
0.5
0.8
0.6
0.4
0.2
0.0

An artistic view:





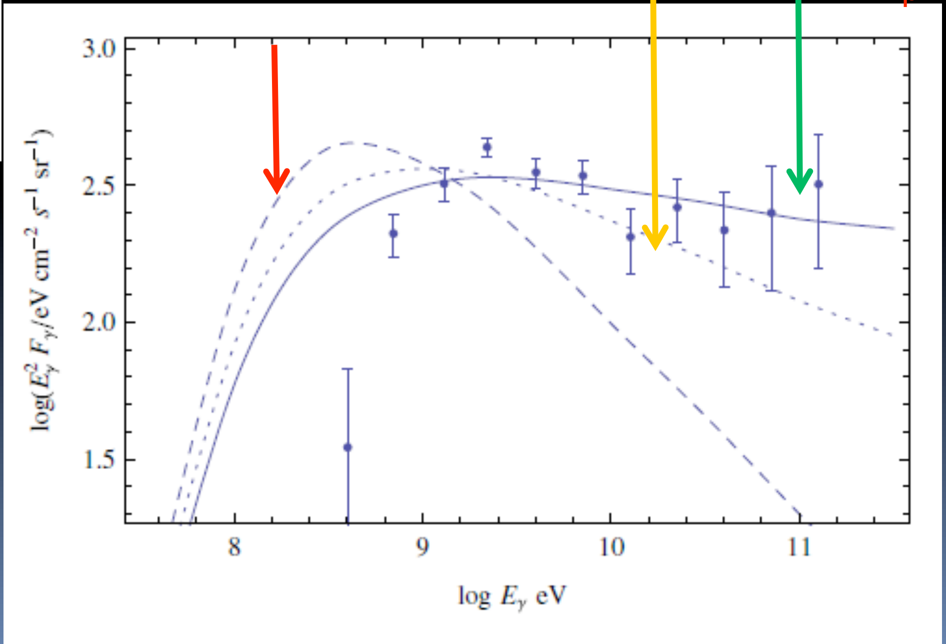


Su et al. 2010

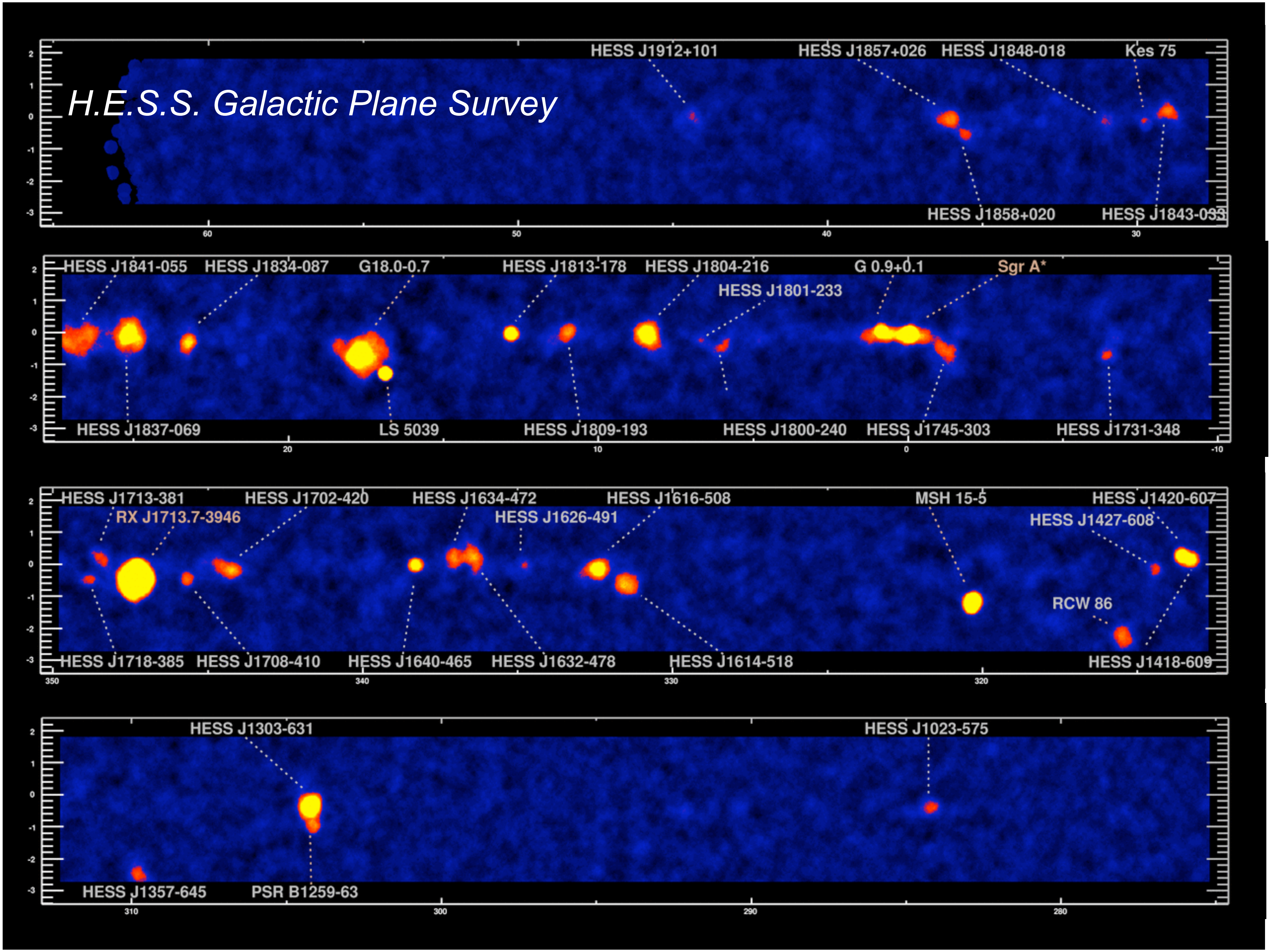
best-fit spectrum Γ_p~ 2.1

steepest reasonable spectrum Γ_p~ 2.3

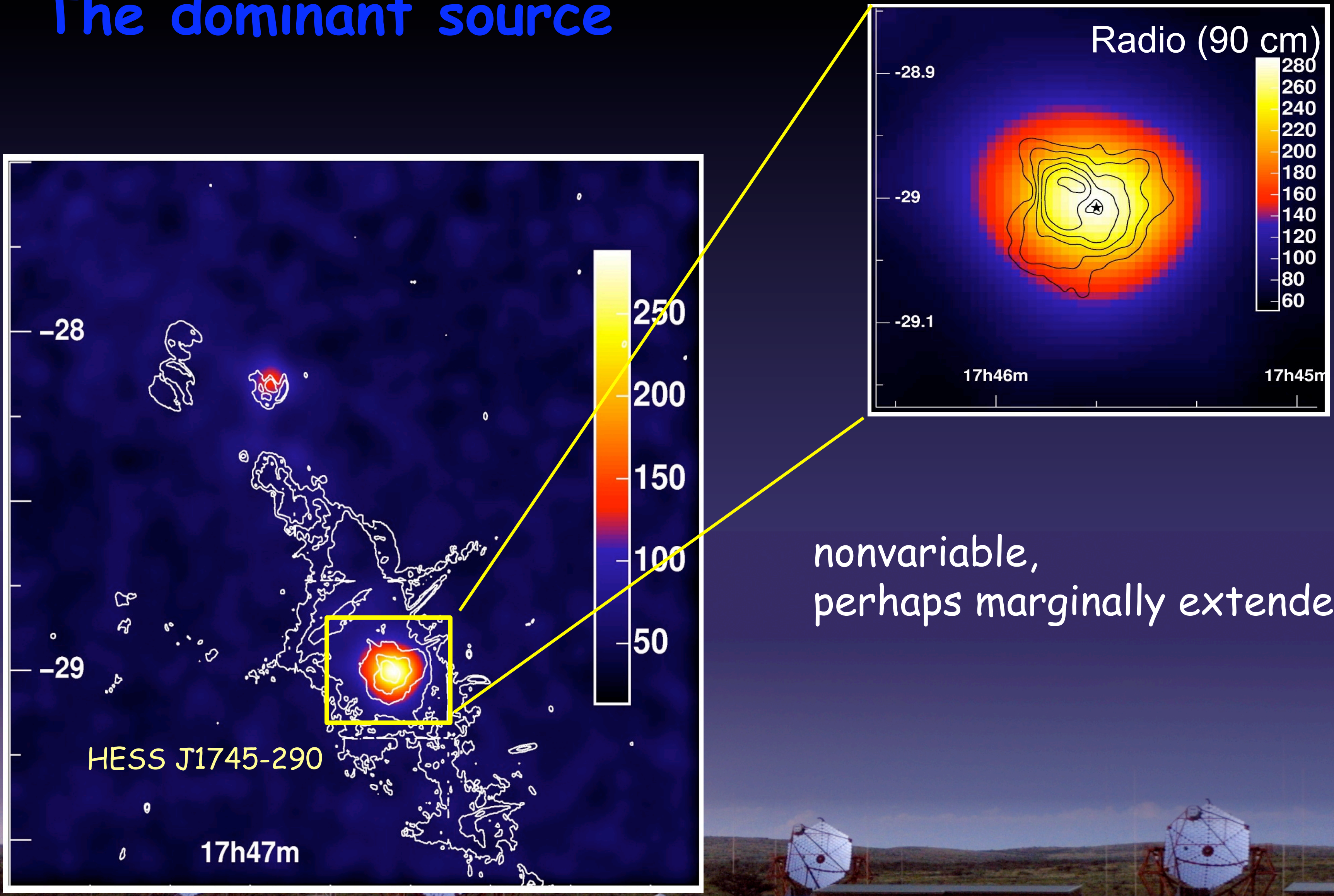
Galactic disk spectral match Γ_p~ 2.7



Crocker et al. 2011

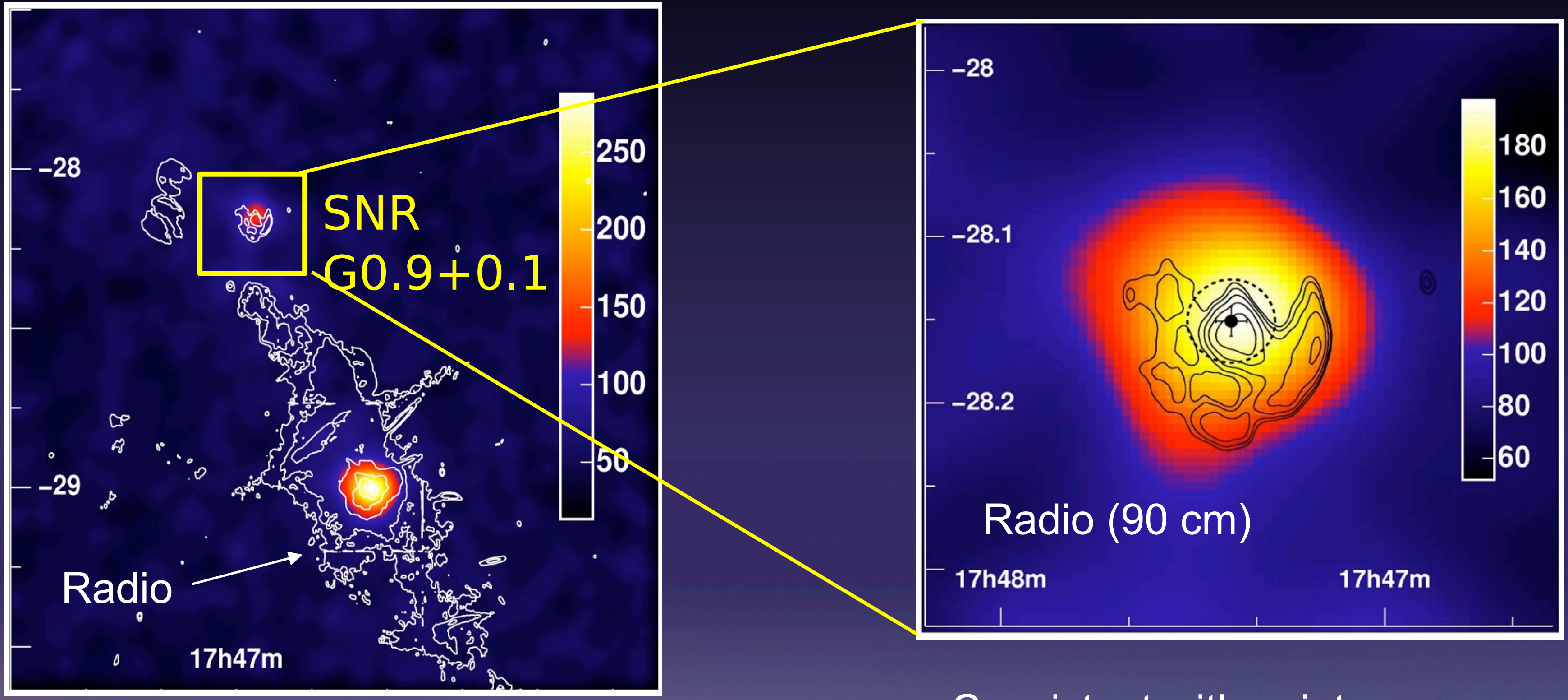

H.E.S.S. Galactic Plane Survey
HESS J1912+101
HESS J1857+026
HESS J1848-018
Kes 75
HESS J1858+020
HESS J1843-033
60
50
40
30
HESS J1841-055
HESS J1834-087
G18.0-0.7
HESS J1813-178
HESS J1804-216
HESS J1801-233
G 0.9+0.1
Sgr A*
HESS J1837-069
LS 5039
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
10
0
-10
HESS J1713-381
RX J1713.7-3946
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
MSH 15-5
HESS J1420-607
HESS J1427-608
RCW 86
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
350
340
330
320
HESS J1303-631
HESS J1023-575
HESS J1357-645
PSR B1259-63
310
300
290
280
2
1
0
-1
-2
-3

The dominant source



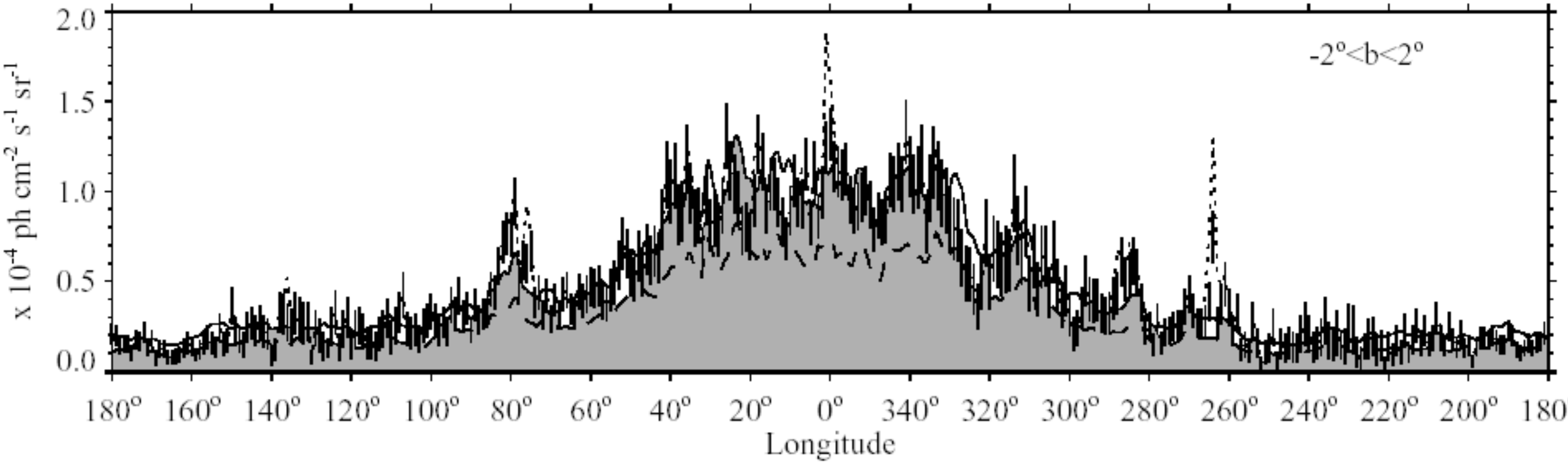
nonvariable,
perhaps marginally extended

The second source in the region:
A SNR/PWN association: G0.9+0.1

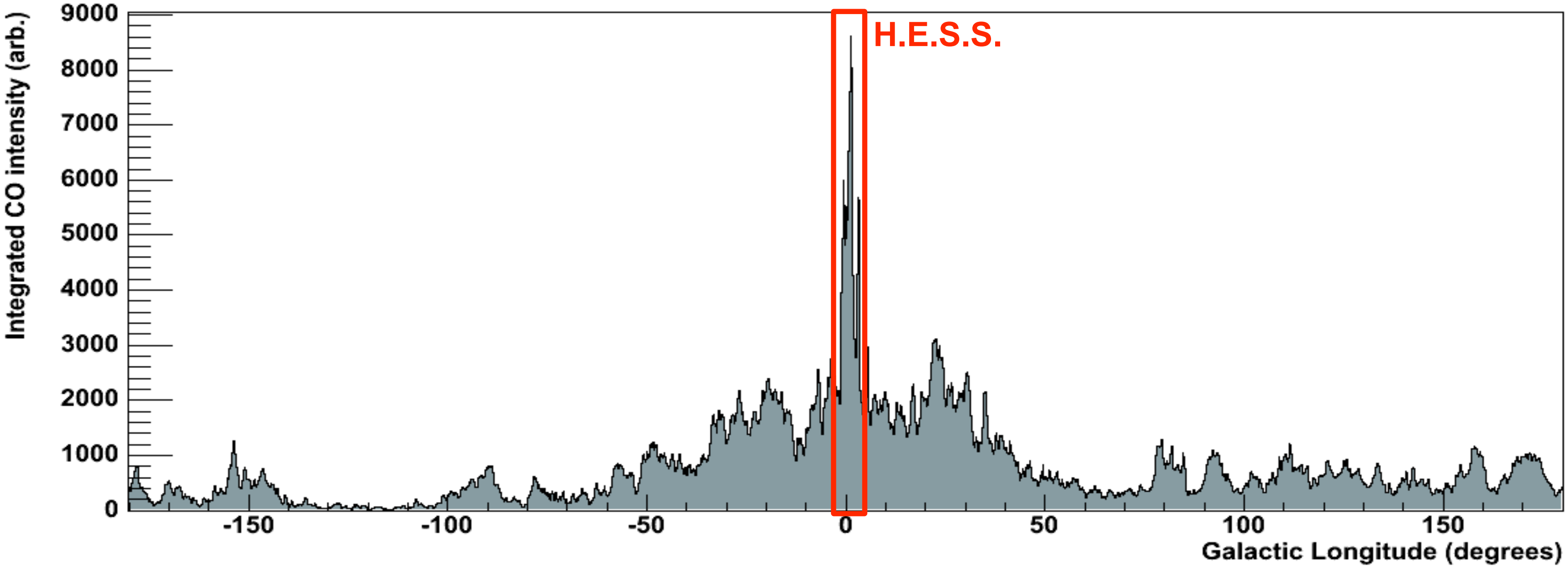


Consistent with point source
at position of PWN
(but not SN shell).
2% Crab flux (50% luminosity).

The diffuse GeV γ-Rays from the inner galaxy

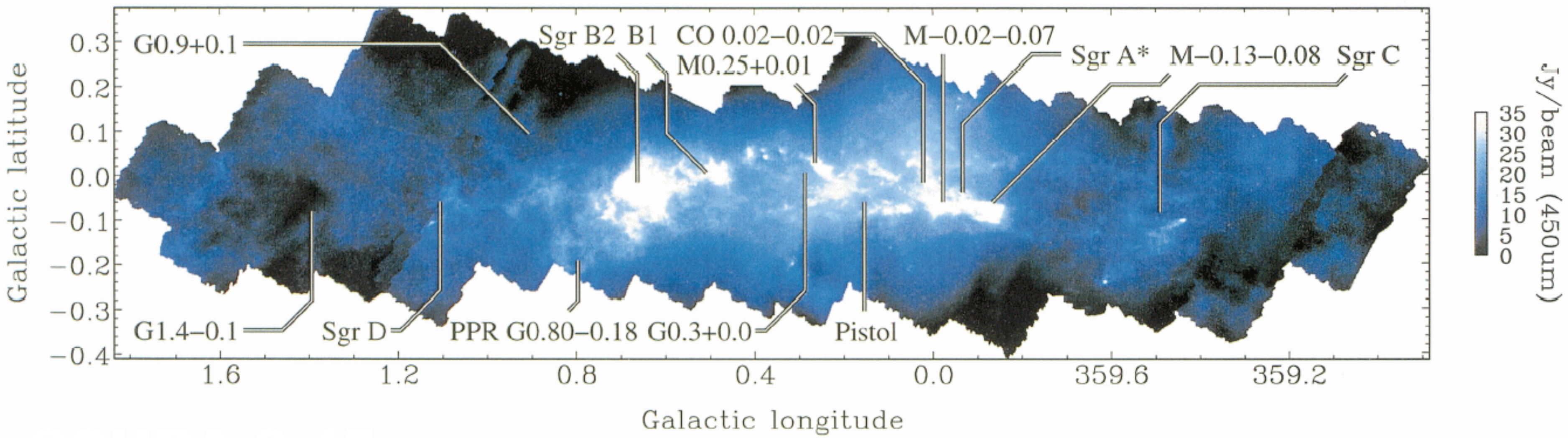


Material in the inner galaxy



- Atomic component is rather uniform
- Molecular part (traced by CO) is strongly peaked along the plane and in the GC region

Dust and Molecules in the GC region

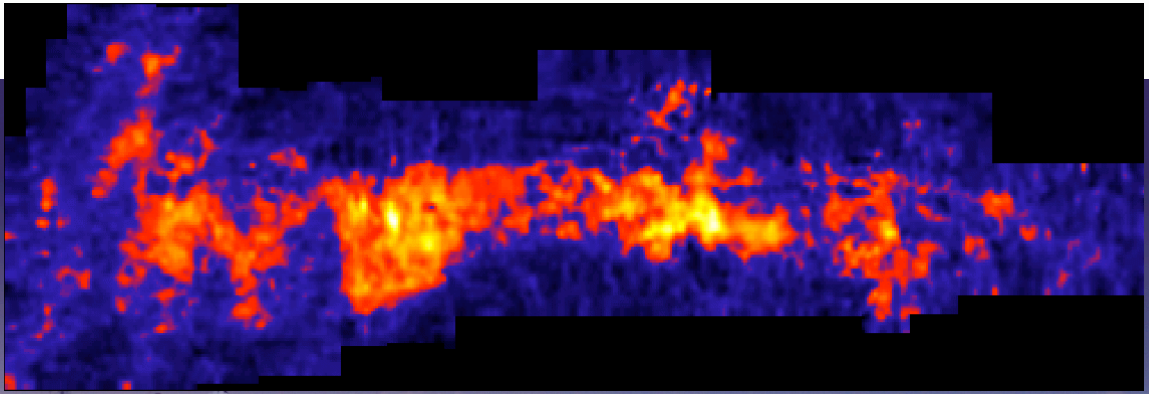


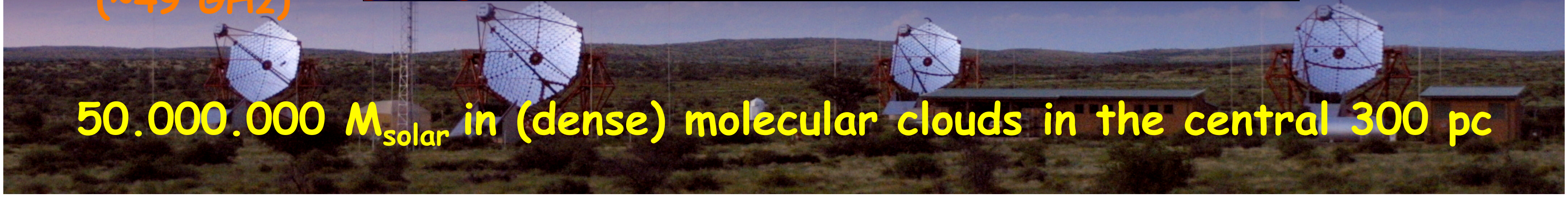
SCUBA 0.45 mm

$C^{32}S$ Line Emission

J = 1 - 0

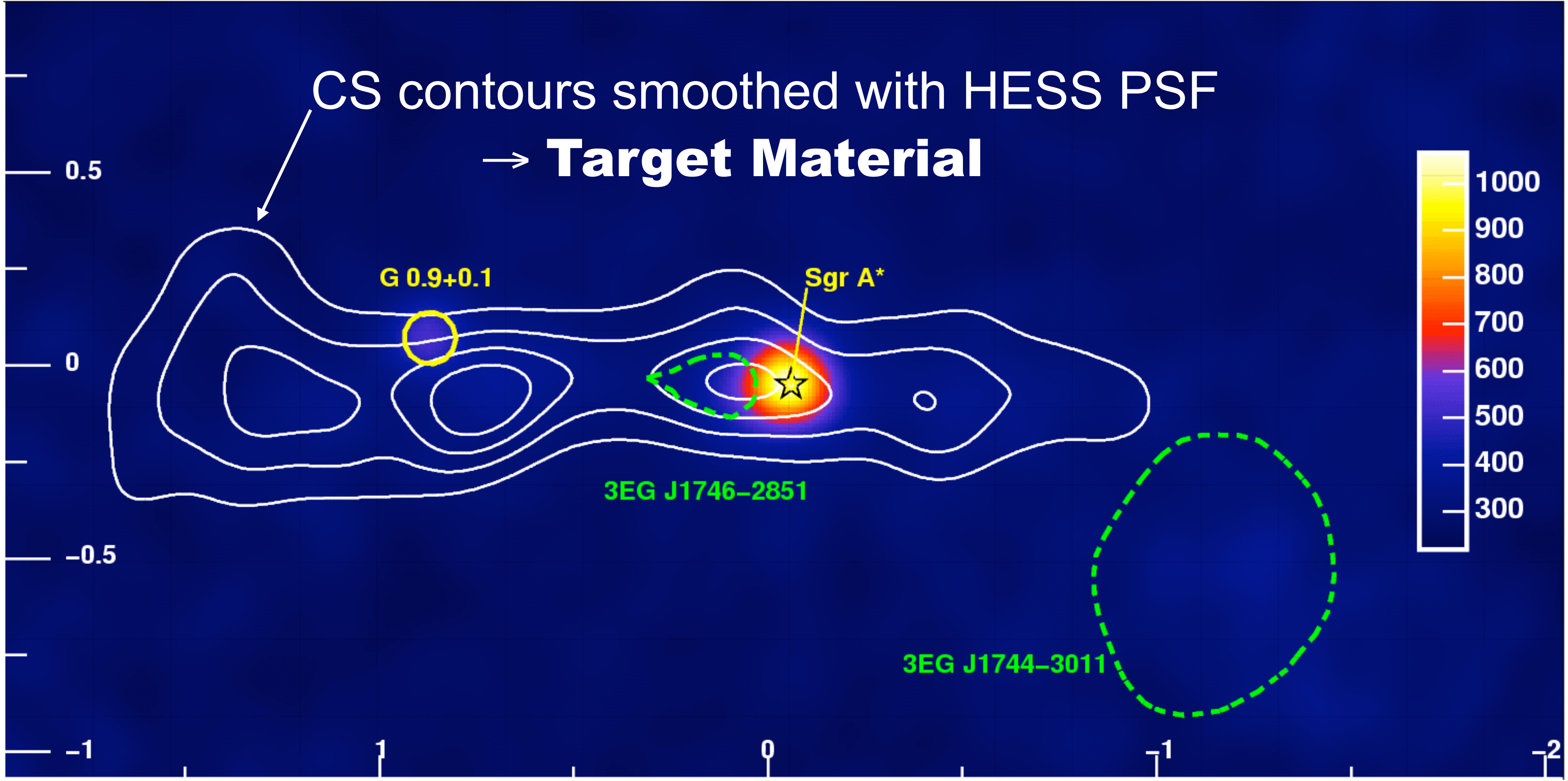
(~49 GHz)





50.000.000 M_{solar} in (dense) molecular clouds in the central 300 pc

? Diffuse γ's in TeV data?

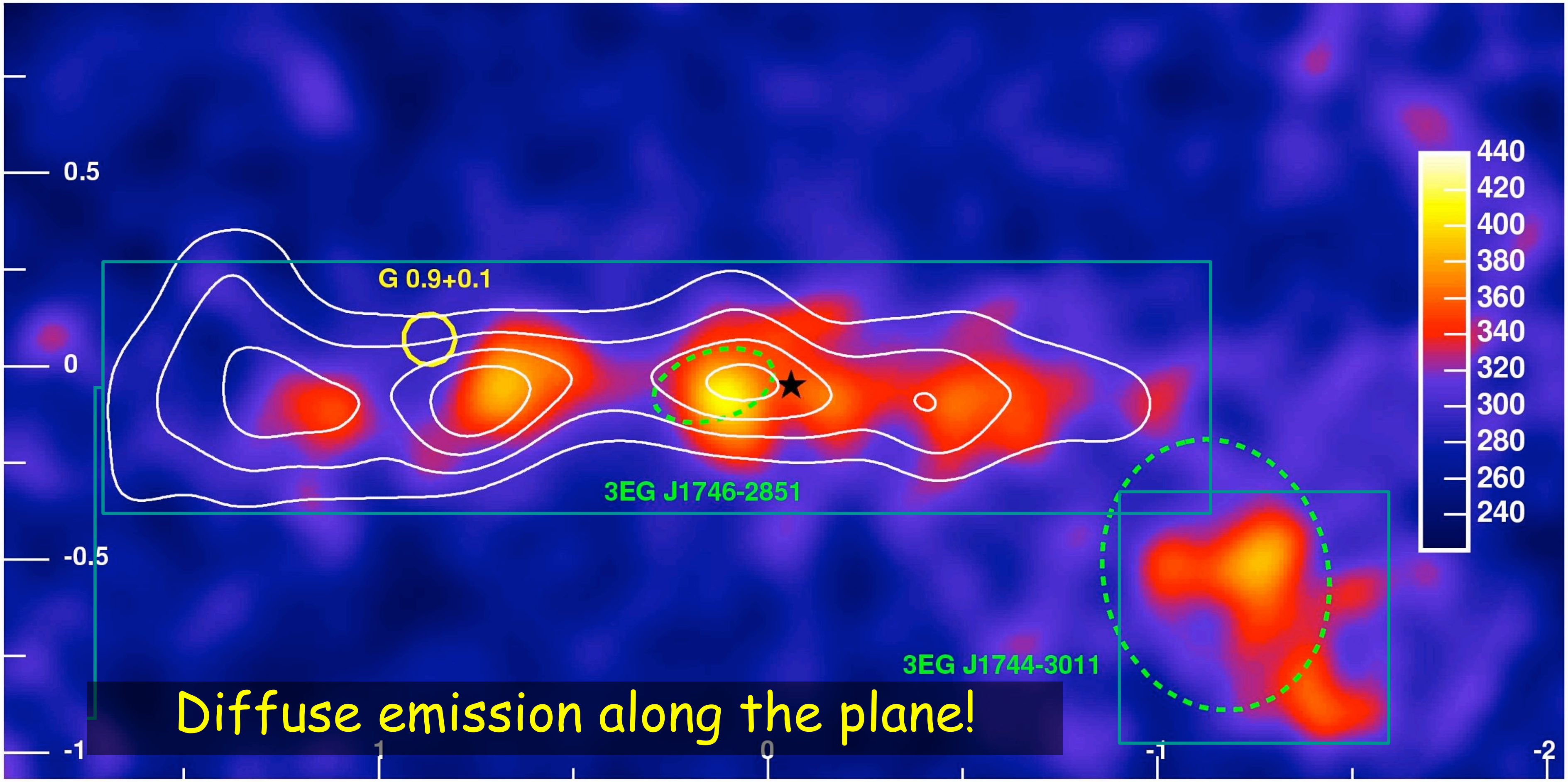


CS contours smoothed with HESS PSF

→ **Target Material**

Need to subtract the two bright sources!

Residuals after source subtraction



Diffuse emission along the plane!

btw: new source HESS J1745-303

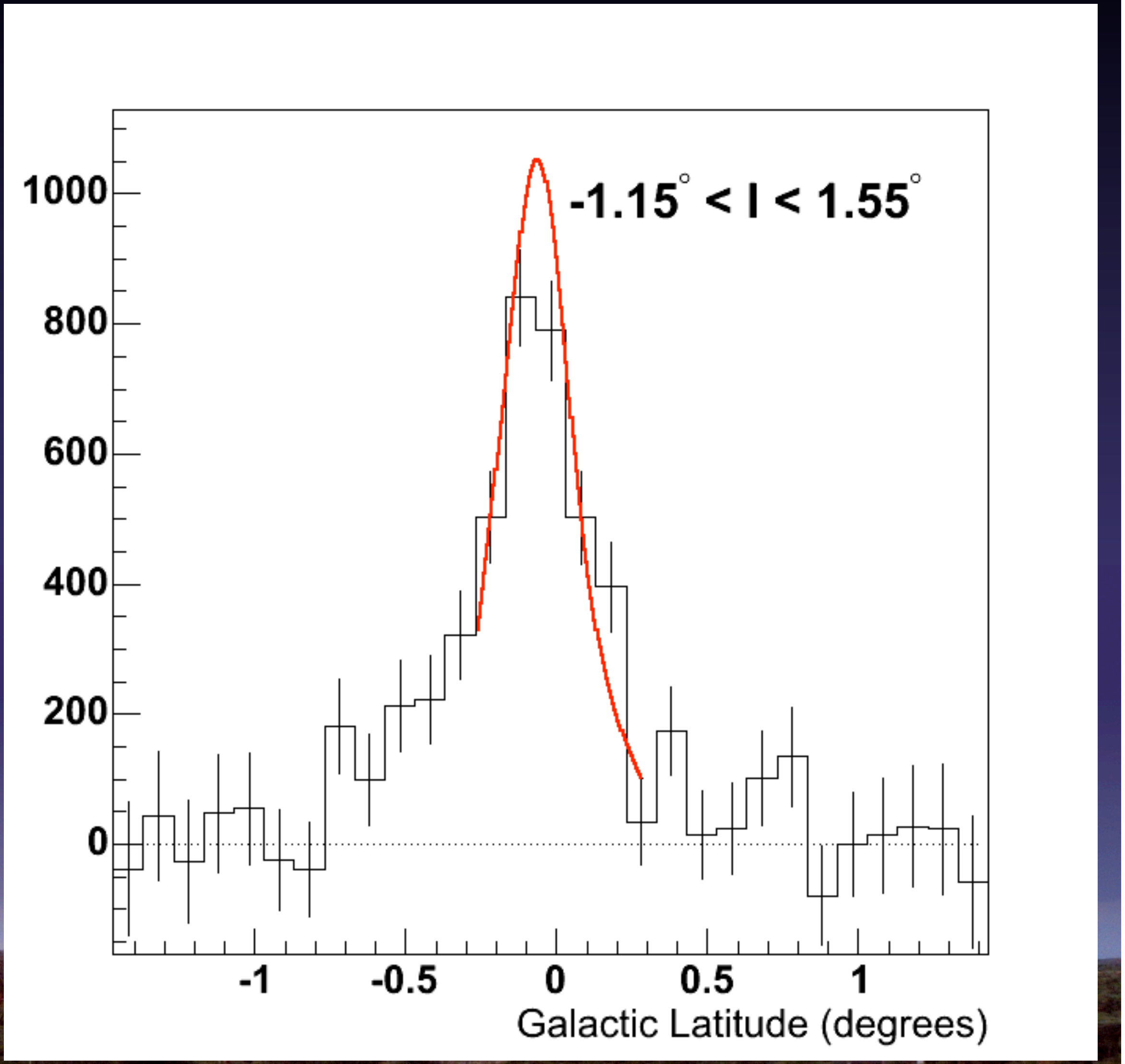
Integrated Latitude Slice

Reasonable agreement in the region covered by CS measurements

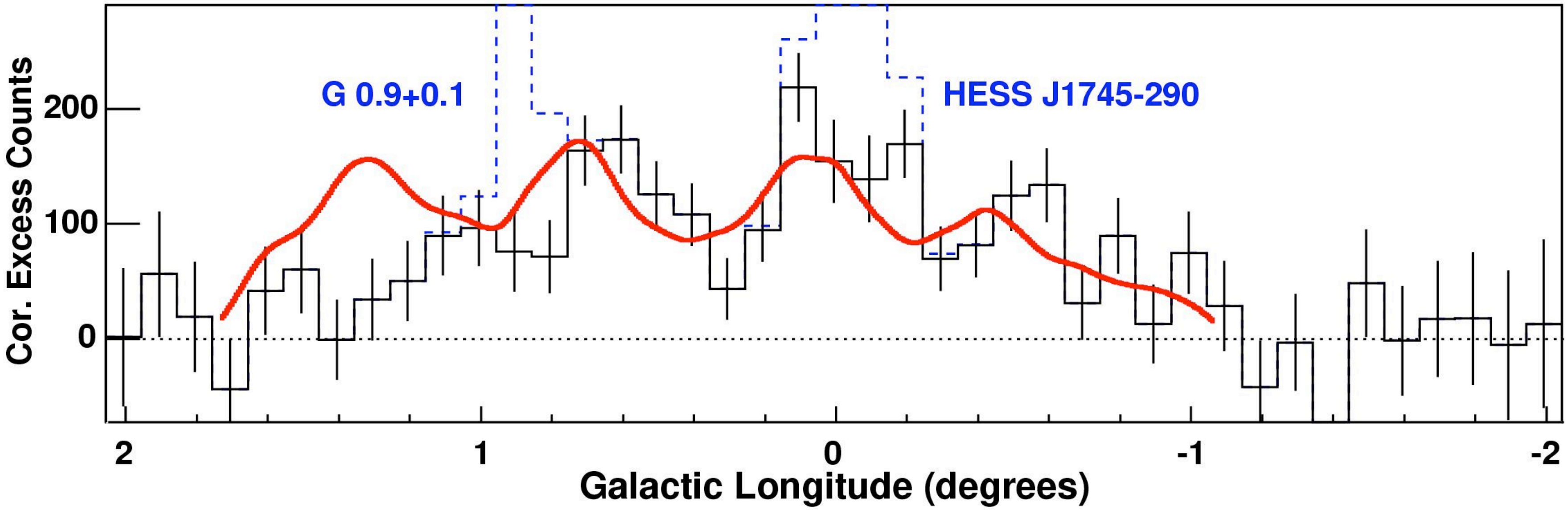
Close to a Gaussian with 0.2° RMS

- CF PSF < 0.1°
- Equivalent to ~30 parsecs

14.6 σ signal



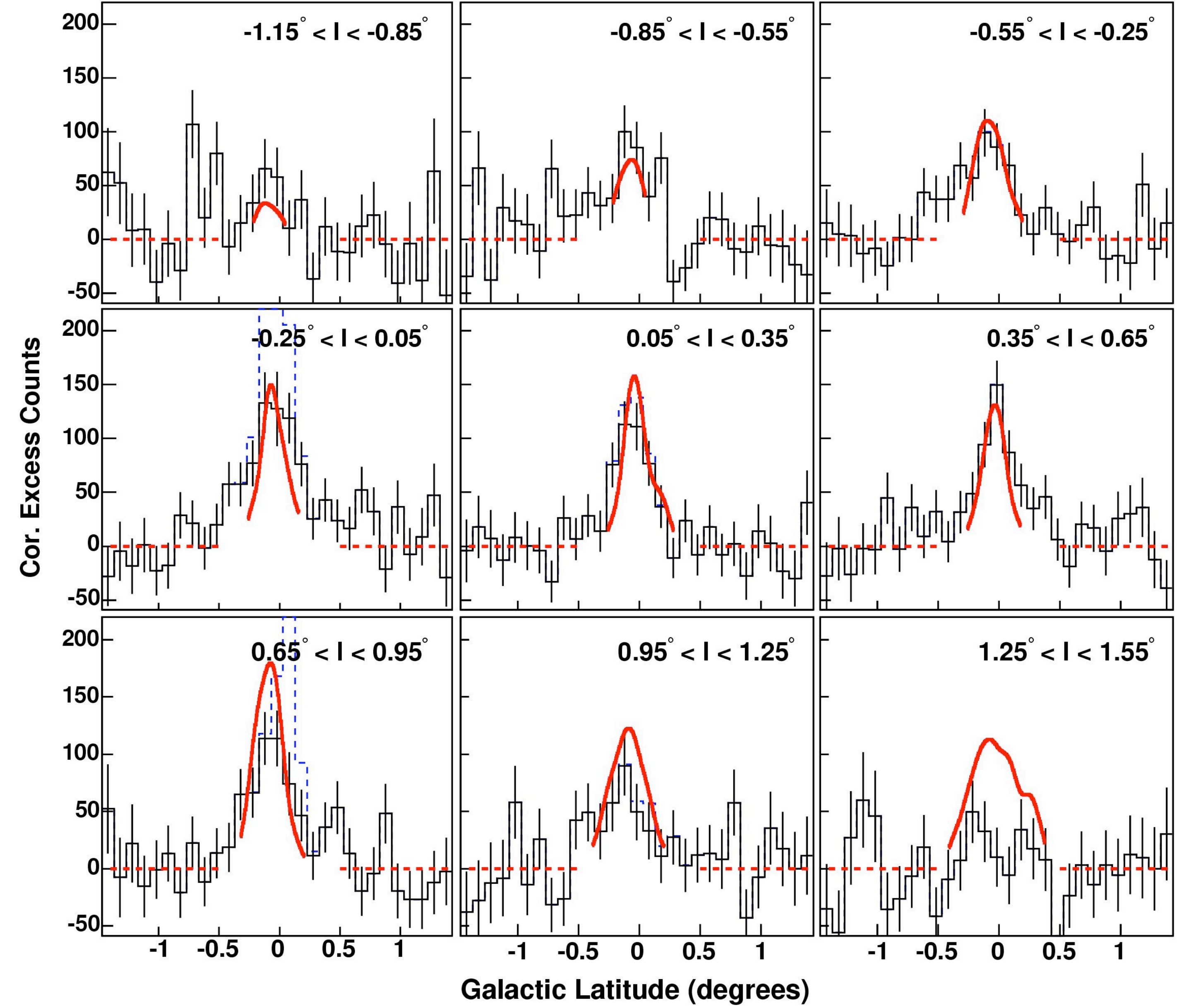
Longitudinal Slice



Reasonable overall agreement

but: deficit around l = 1.3°

...and in the longitude bands



Energy Spectrum

Expectations

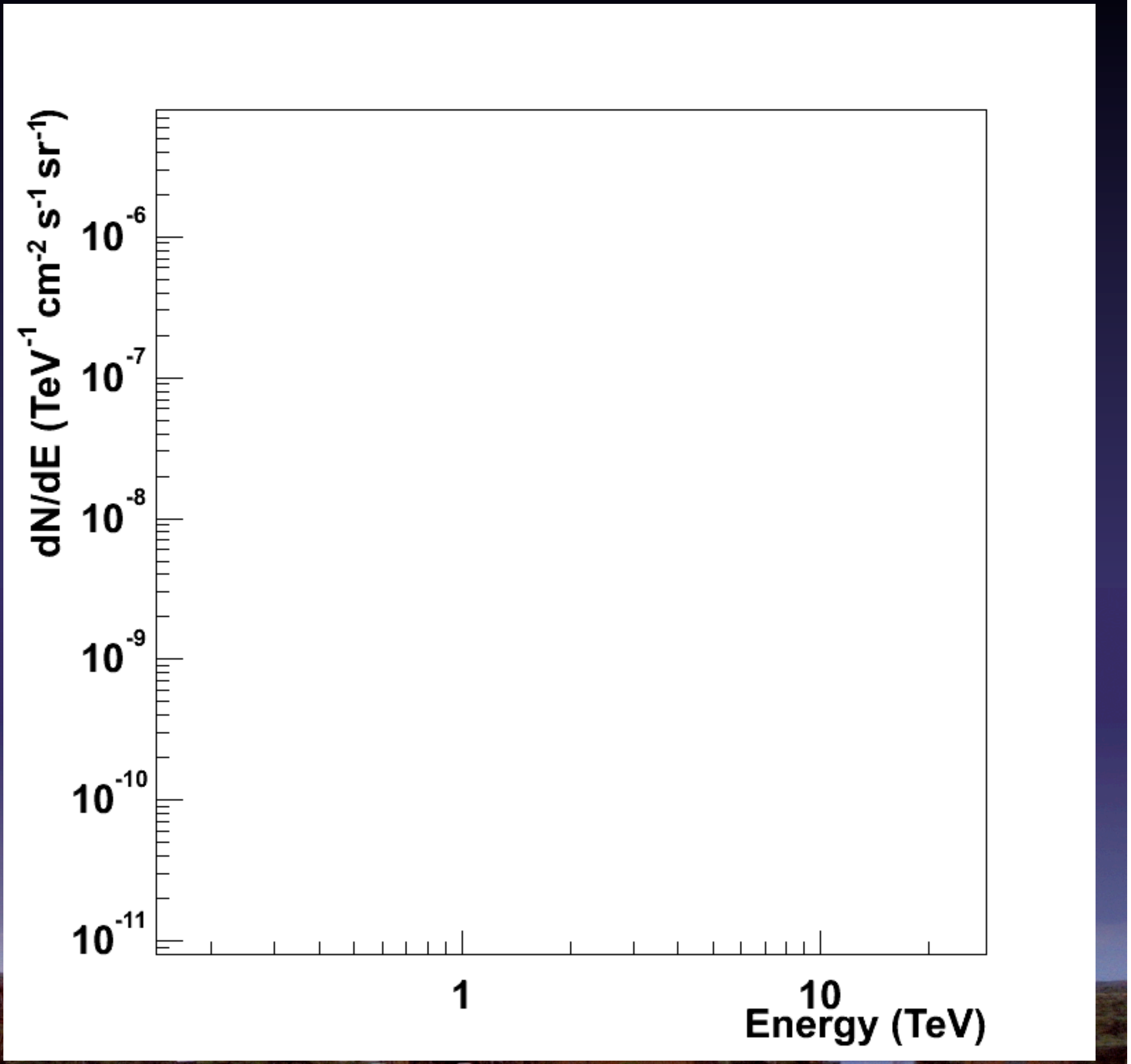
Molecular target material is 3-8 x 10^7 M_{sun} (Tsuboi – CS, SCUBA: 4-6 x 10^6 M_{sun})

Distance ~ 8.5 kpc

Cosmic Ray density?

Assume Local

π^0 decay flux...



Energy Spectrum

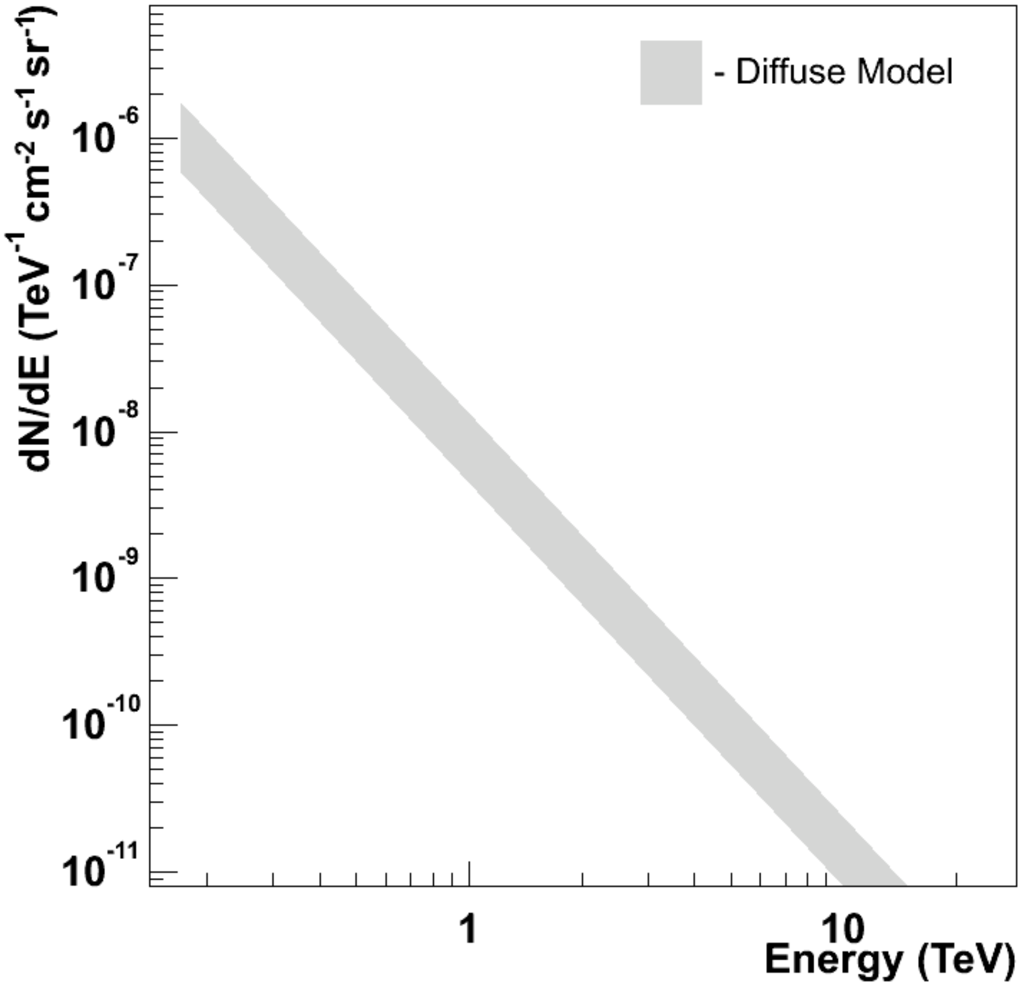
Gamma Flux:

$J(> E) \approx 1.5 \times 10^{-13}$ (E/1TeV) $^{1.75}(M_5/d^2_{kpc})$ photons cm^2 s^{-1}

(a la Aharonian 1991)

Index: $\Gamma_\gamma \sim \Gamma_{XP}$

For M_5 = 300 - 800



Energy Spectrum

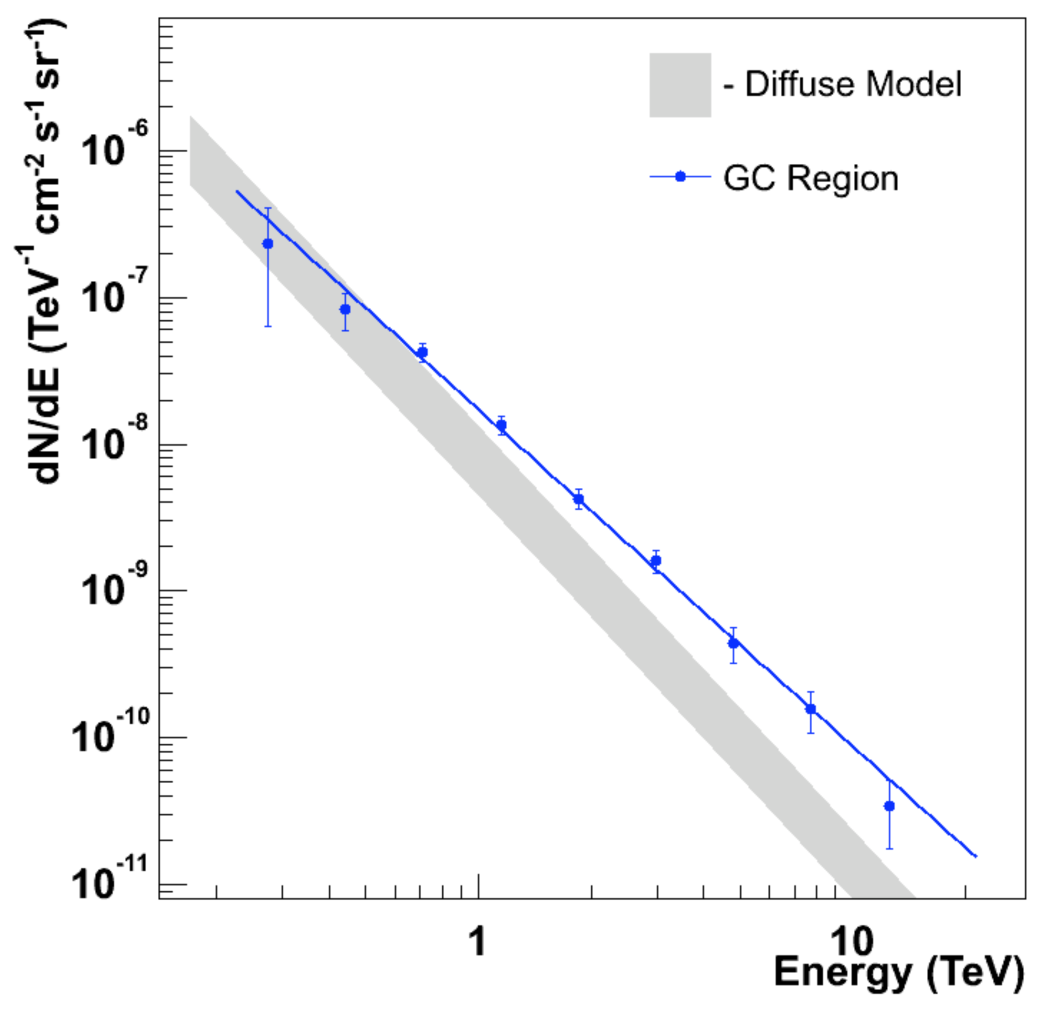
Measured Diffuse Spectrum

Γ_{γ} = 2.29 ± 0.07$_{stat}$ ± 0.20$_{sys}$

Flux > 1 TeV:

3.1 ± 0.3 × 10^{12}

cm^{-2} s^{-1} (13% Crab)



Energy Spectrum

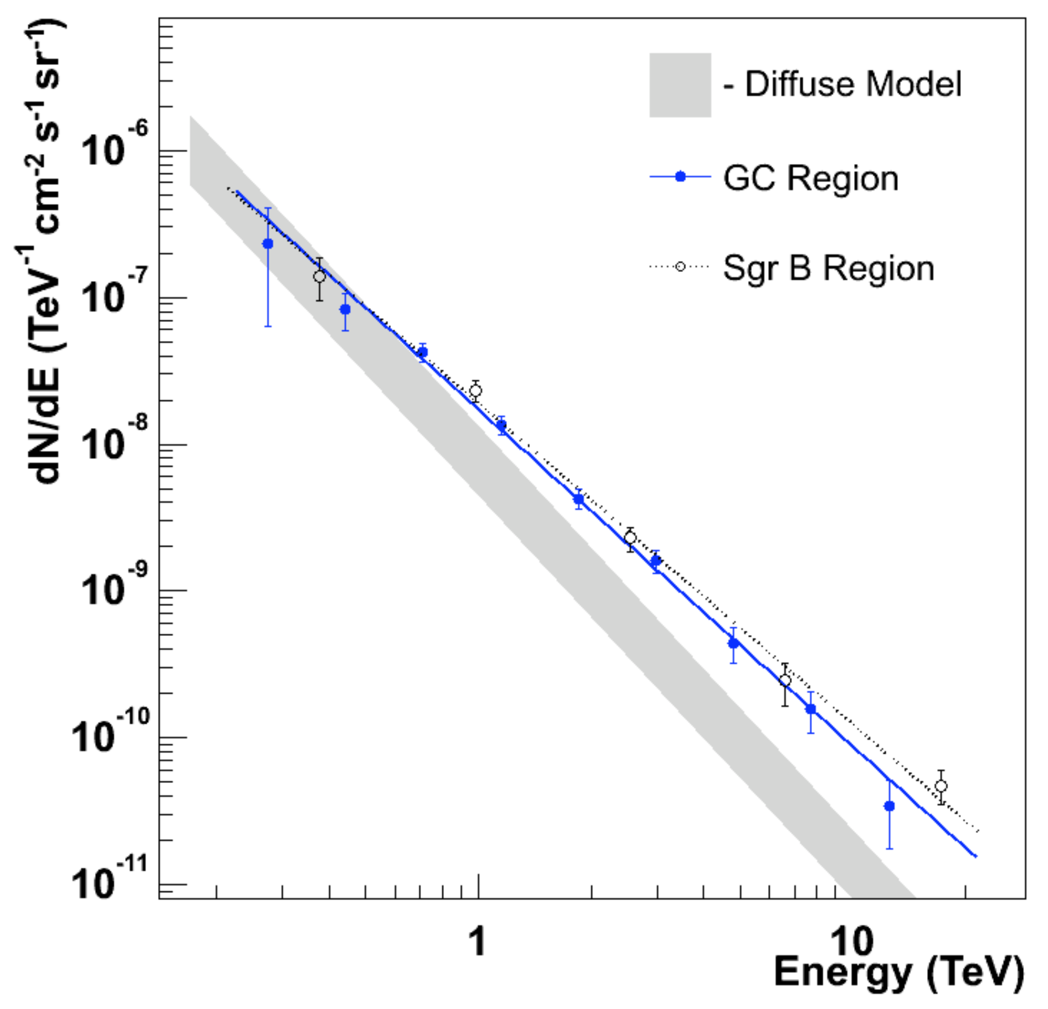
Sgr B region

$\Gamma_\gamma = 2.1 \pm 0.2_{stat} \pm 0.2_{sys}$

Flux > 1 TeV:

$1.2 \pm 0.2 \times 10^{12}$

$cm^{-2}\ s^{-1}$ (5% Crab)



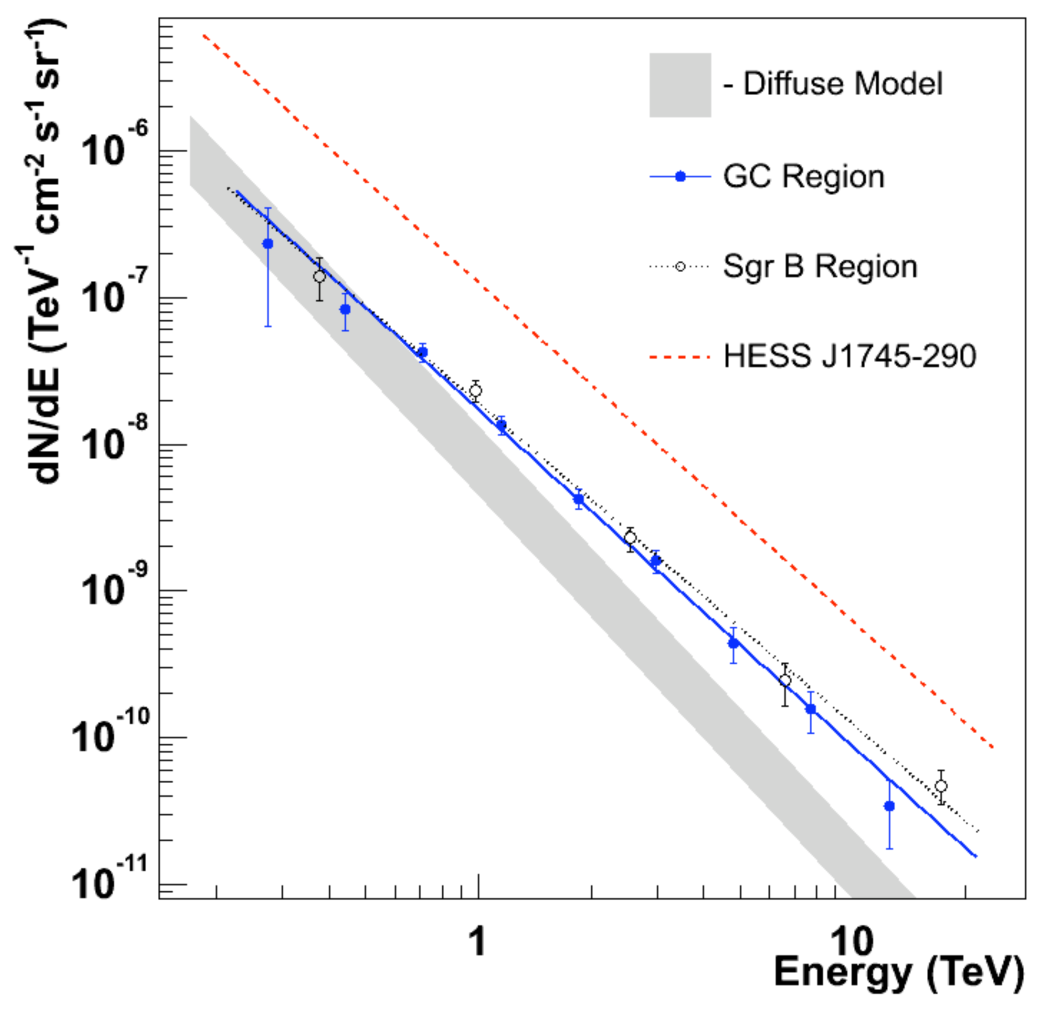
Energy Spectrum

The Galactic Centre Source: HESS J1745-290

(source point-like)

All emission in the GC has

$\Gamma_\gamma \approx 2.2$



Interpretation

Several possibilities exist

- Emission is a superposition of many individual 'active' gamma-ray sources, but
  - ✗ Close correlation with molecular material
  - ✗ Need many unknown sources to do so
- Or diffuse emission, caused by CR interactions
  - High energy CR density enhanced in the GC ?
  - 1) Additional CRs are accelerated by a population of sources in the region
  - 2) A single source (HESS J1745-290) accelerated most high energy (> 10 TeV) CRs in the central 200 parsecs
  - ✓ Same spectral index
  - ✓ Deficit in emission around l = 1.3°

A central accelerator?

Diffusion timescale

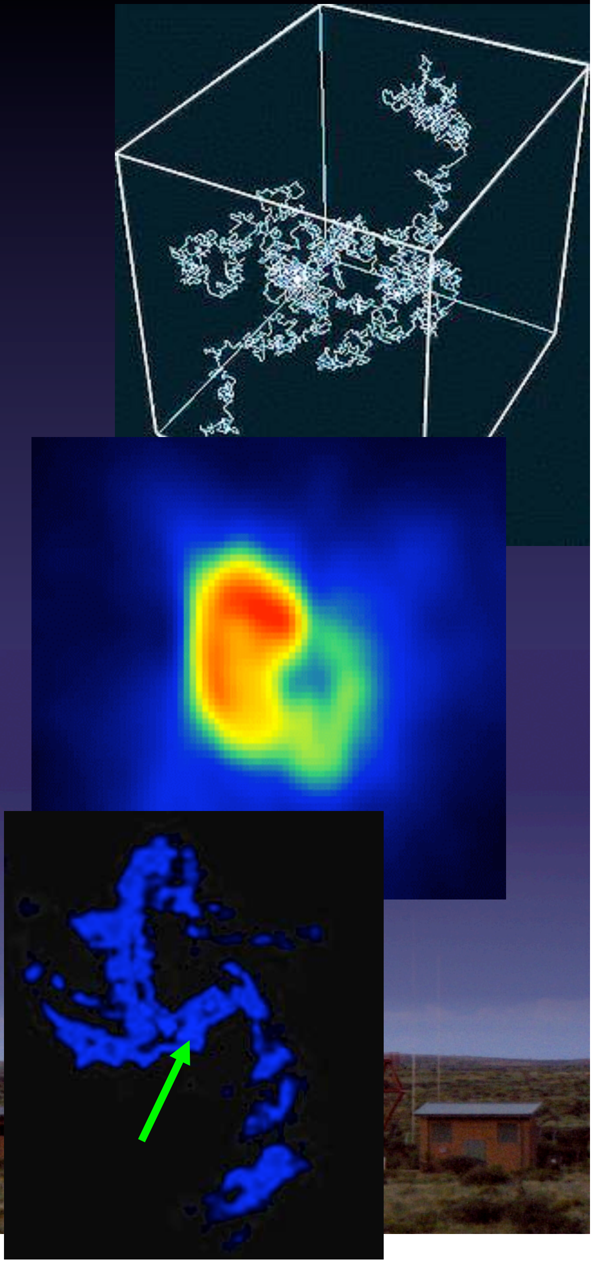
- Say D = $\eta\ 10^{30}$ cm^2 s^{-1} , $\eta < 1$
- $\eta = 1$ typical for TeV CRs in disc
- $t_{kyr} = (\theta\ /\ 0.54°)^2\ /\ \eta$
- e.g. for $\theta = 1°$ and η~0.4, t = 10 kyrs

SNR Sgr A East

- ~10,000 year old supernova explosion
- unusually powerful - 4 x 10^{52} ergs...

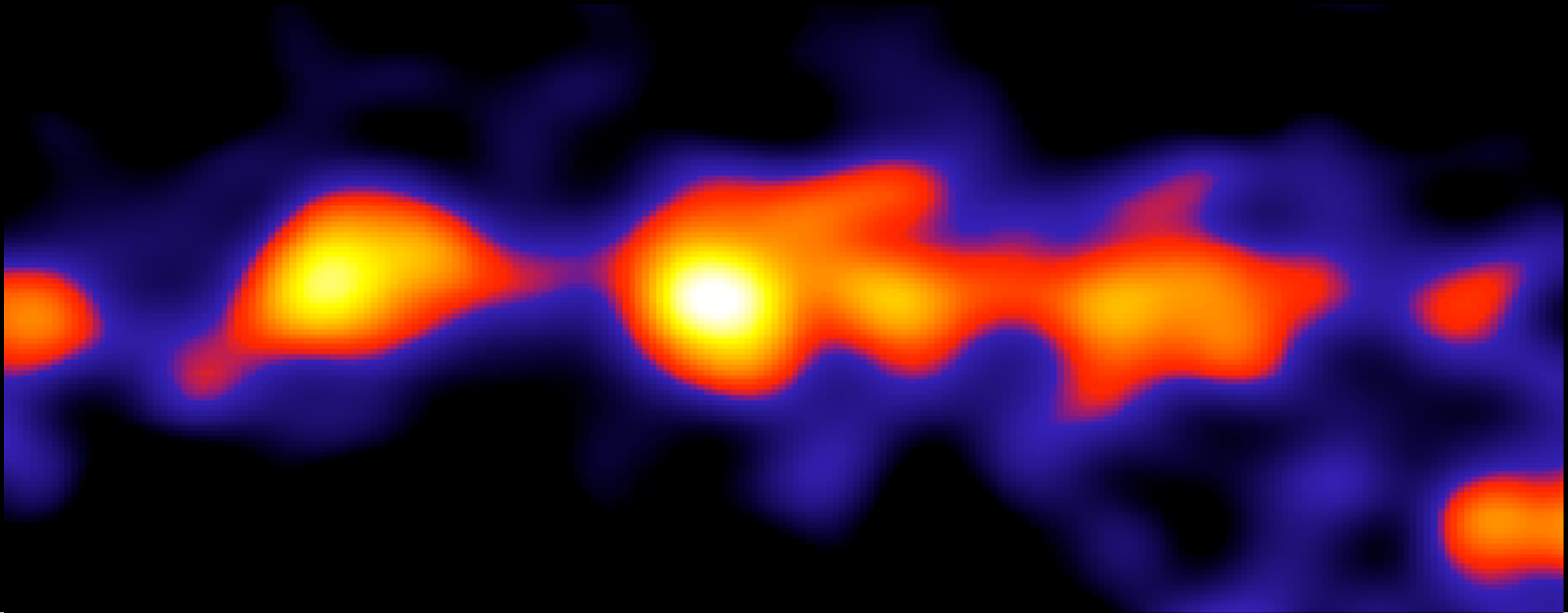
Sgr A*

- Hypothetical historical flare?
- Activity related to the Fermi bubbles?



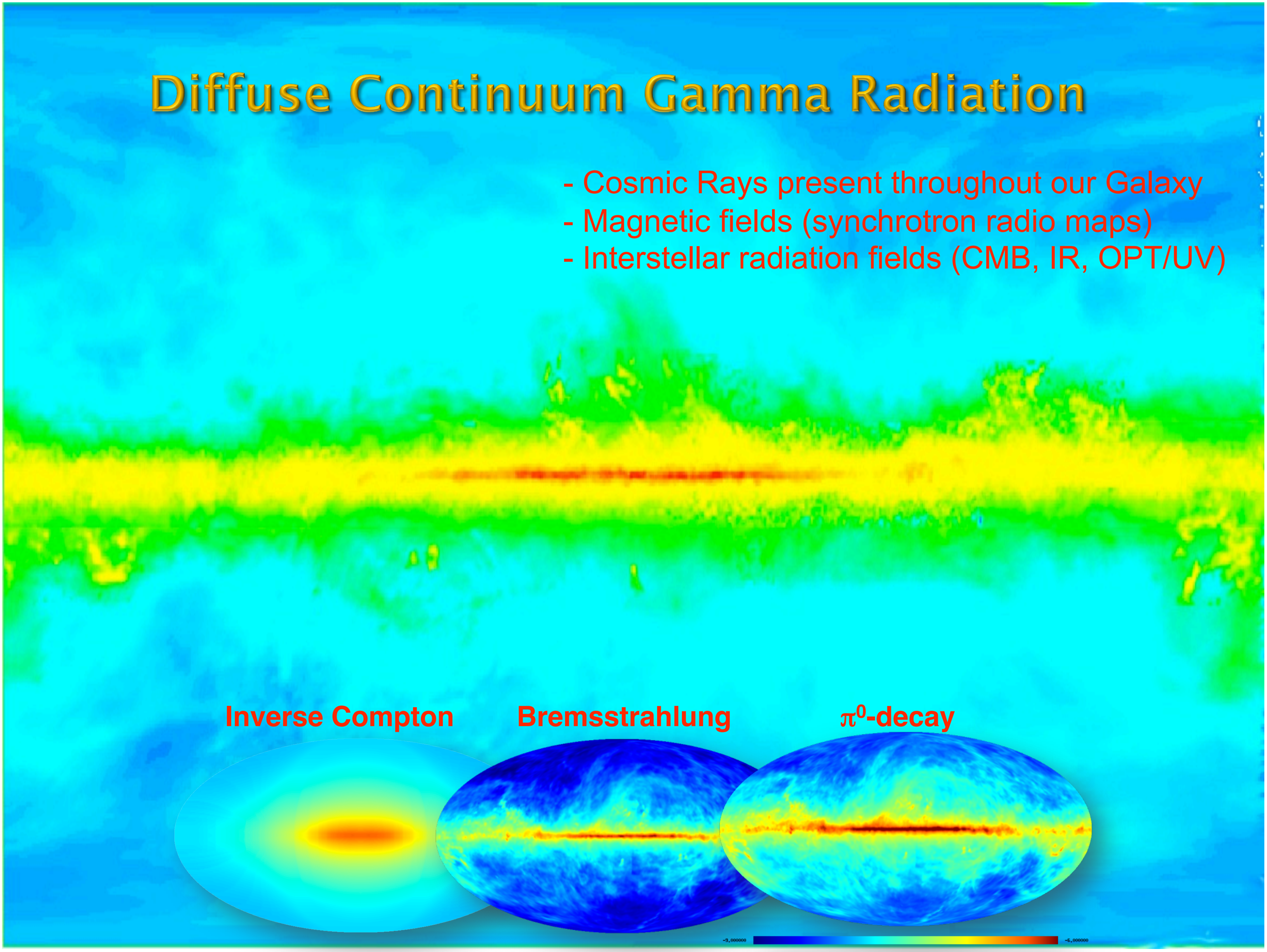
Conclusions

- First measurement of VHE gamma-ray emission from individual molecular clouds
- The Galactic Centre region seems to contain an excess of high energy cosmic rays



Diffuse Continuum Gamma Radiation

- Cosmic Rays present throughout our Galaxy
- Magnetic fields (synchrotron radio maps)
- Interstellar radiation fields (CMB, IR, OPT/UV)



Inverse Compton **Bremsstrahlung** **π^0-decay**