Propagation of Cosmic Rays. I

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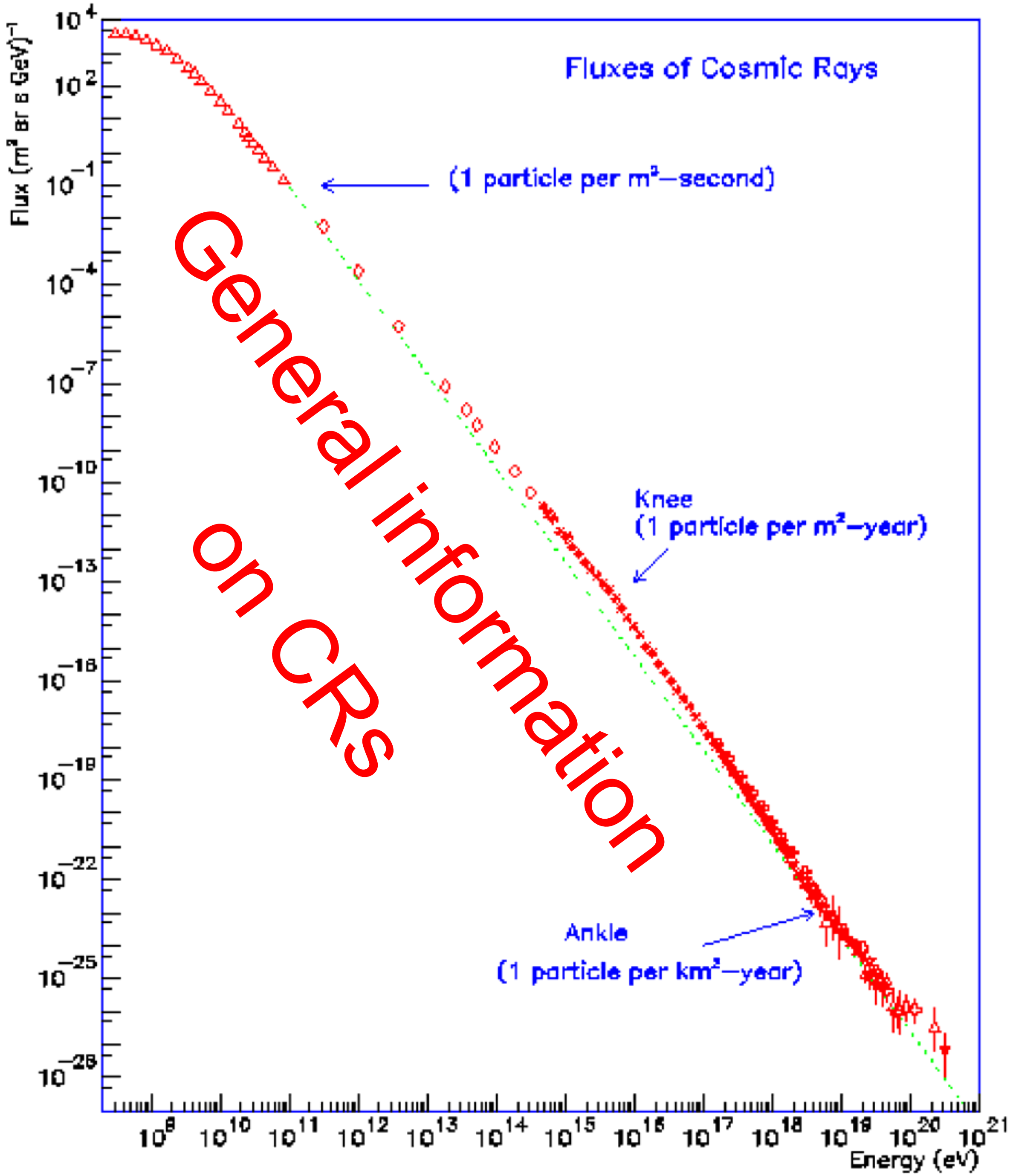
Outline

- General information (covered by Ormes, Petrosian)
  - CR interactions and processes in the IS
  - Nuclear component in CRs
  - Diffuse gamma rays
  - Measurements & Instruments
- Transport equation
  - General equation (diffusion, reacceleration, convection)
  - Simplified equation (VHE electrons)
  - Numerical solution
- Propagation near the CR sources
  - Galactic center (HESS)
  - Cygnus region (Milagro)
  - Pulsars and plerions (VHE electrons)
- Propagation in the ISM. I. Components of the ISM
  - CR source distribution
  - Galactic magnetic field
  - Milky Way in different wavelength
  - Energy losses and propagatin of electrons
  - Interstellar gas
  - Interstellar radiation field

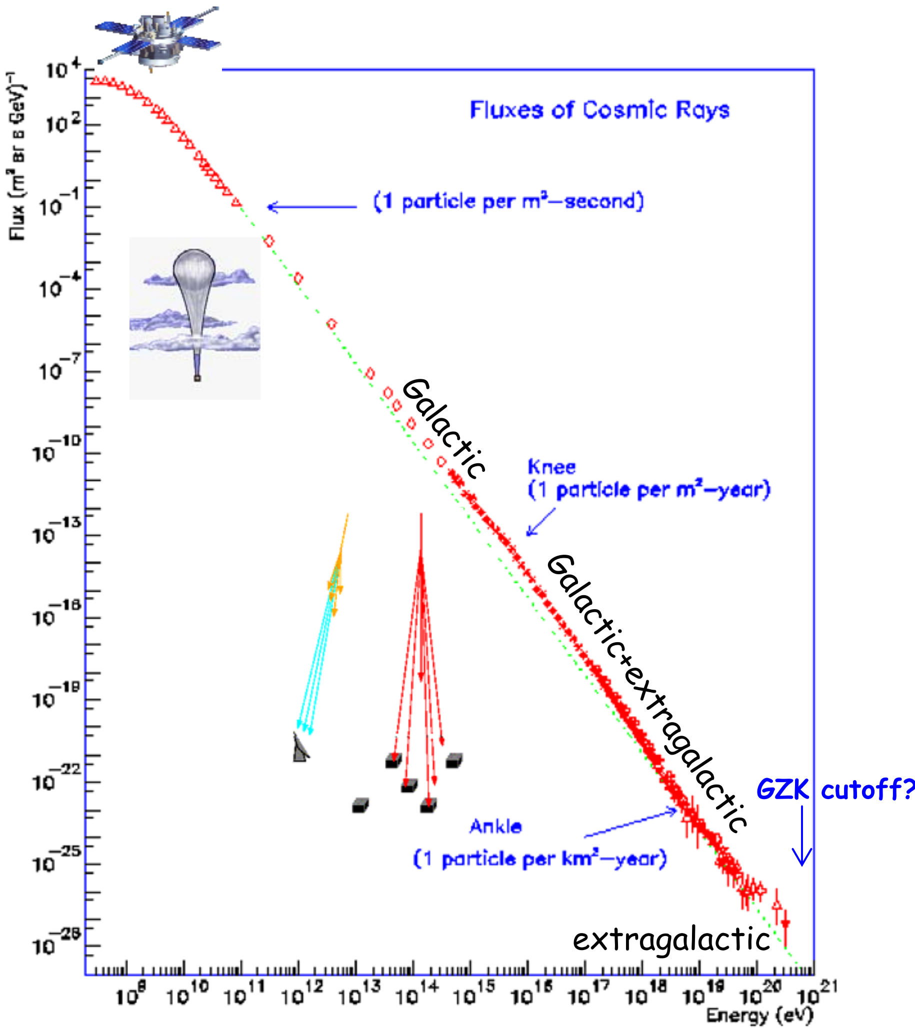
<u>Second lecture</u>

- Propagation in the ISM. II. Cosmic Rays
- CR propagation in the heliosphere
- CRs in the other normal galaxies
- Exotic Physics

General information on CRs



All Particle CR Spectrum



This is an astonishing observation!

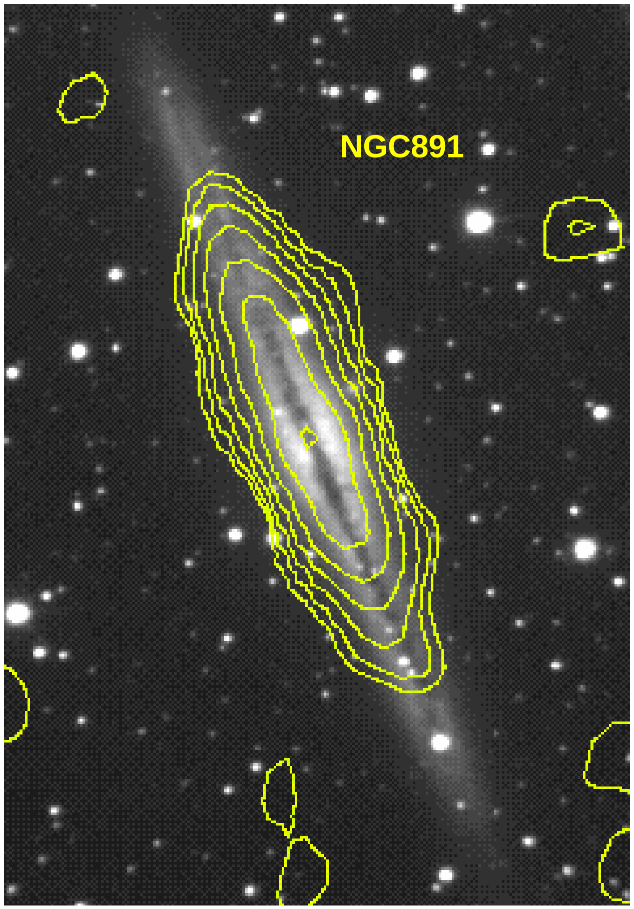
- All particle CR spectrum is almost featureless:
  - the knee
  - the ankle
  - GZK cutoff

  These are the only features in >12 decades in energy and >32 decades in intensity!

  However, there is a lot of information hidden in the spectra and abundances of individual CR species: nuclear isotopes, antiprotons, electrons, positrons (+diffuse gamma rays)
- The whole physics is involved: various branches of Astrophysics, MHD, shock waves, plasma physics, atomic, nuclear, & particle physics, exotic physics – SUSY…
- CRs are the only probes of the interstellar material available to us.

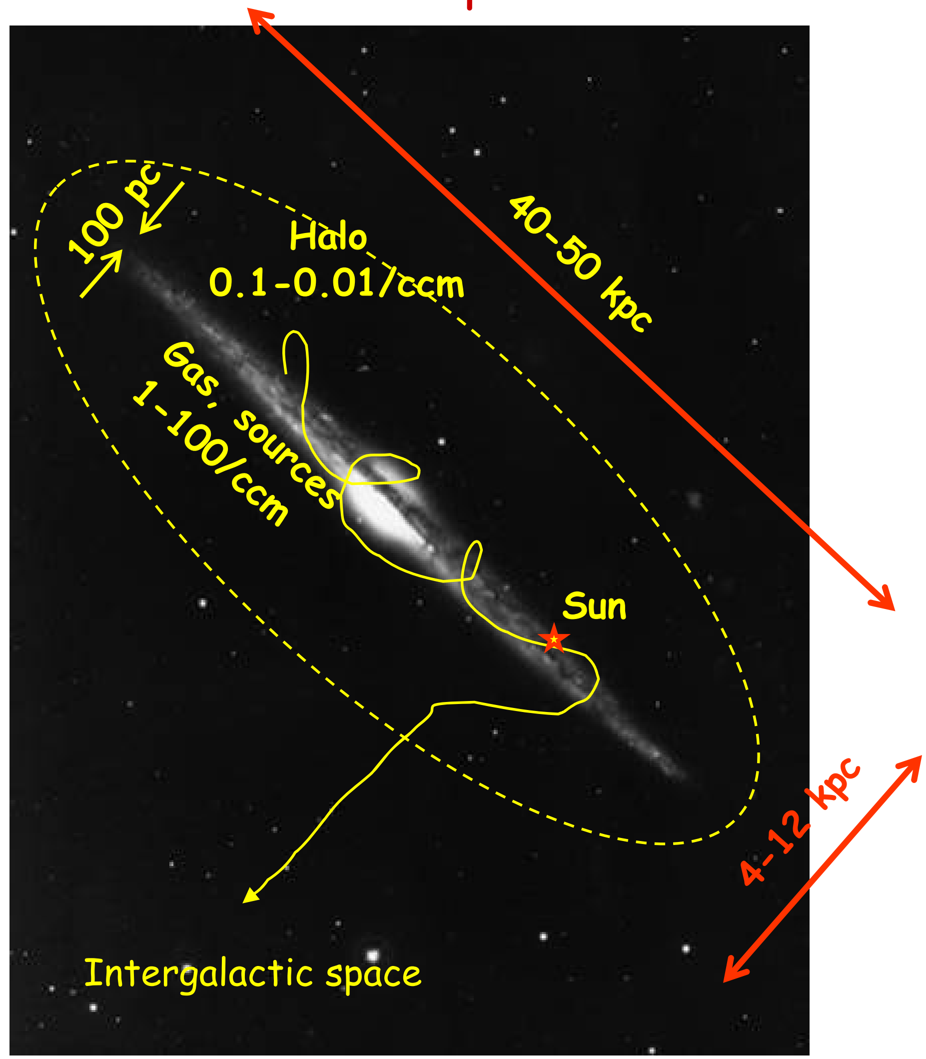
CR propagation: the Milky Way galaxy

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



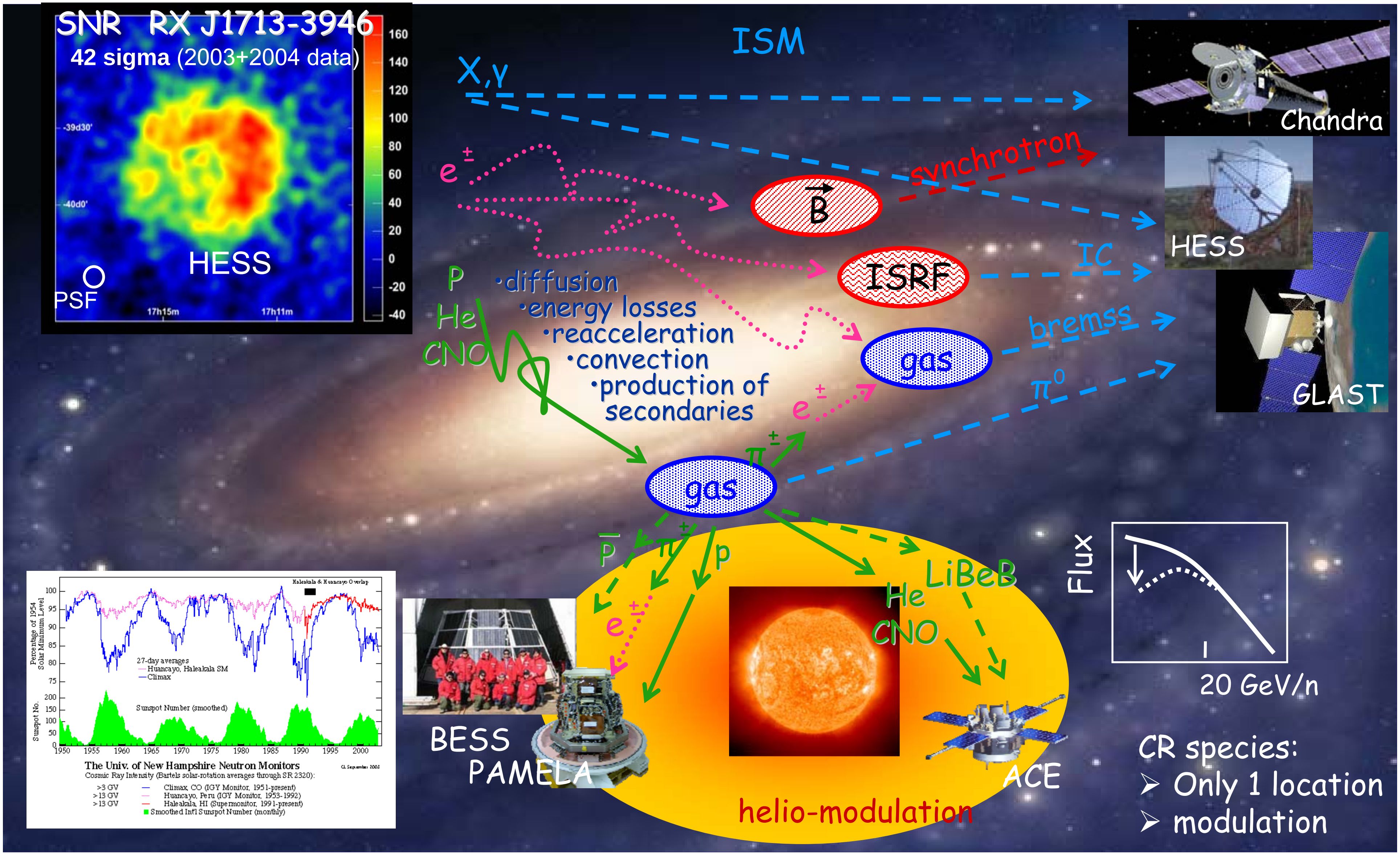
R Band image of NGC891
1.4 GHz continuum (NVSS), 1,2,…64 mJy/ beam

1 pc ~ 3×10^{18} cm



"Flat halo" model (Ginzburg & Ptuskin 1976)

CR Interactions in the Interstellar Medium



PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

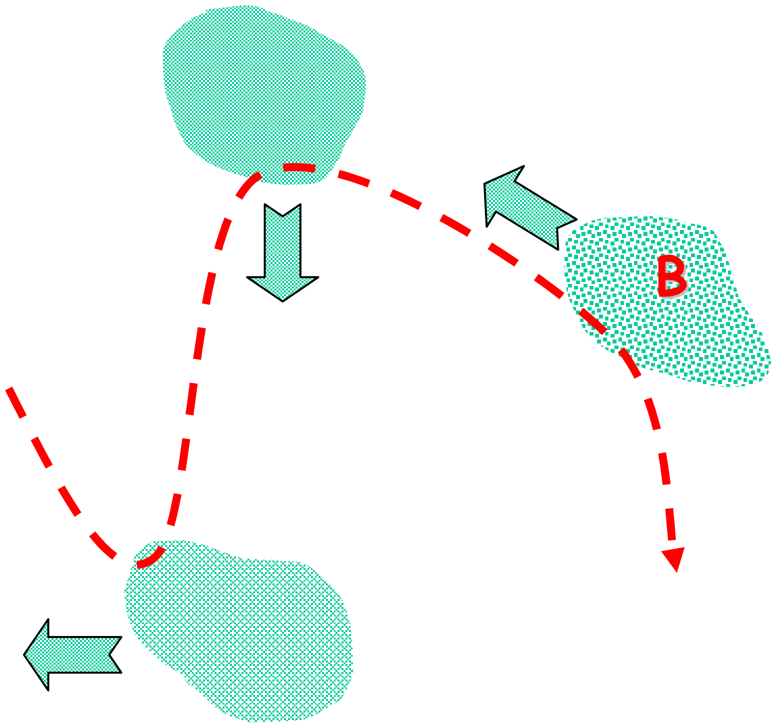
A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

…if the mirror is moving towards the incident particle, the particle gains energy upon reflection, just as does a tennis ball pushed by a racket…

Distributed Stochastic Reacceleration

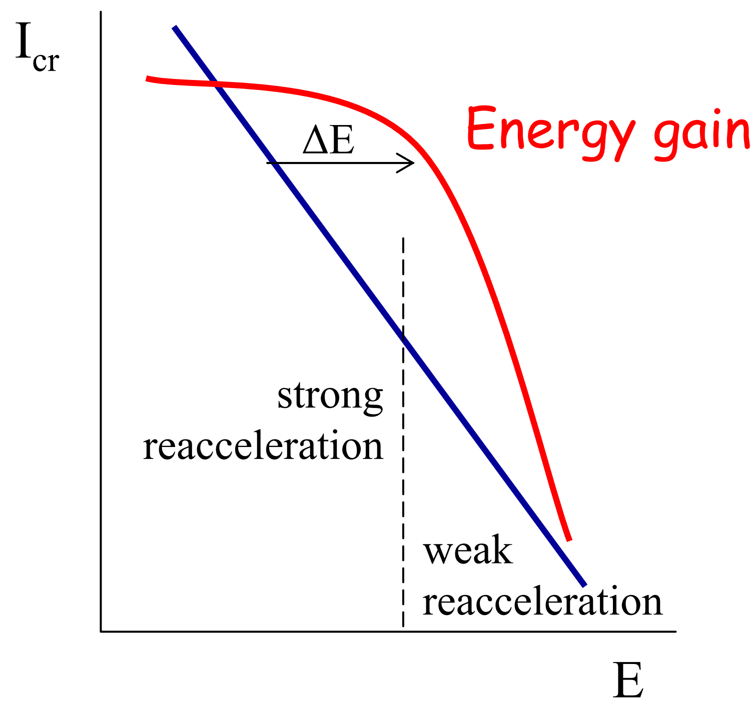
Simon et al. 1986
Seo & Ptuskin 1994

Scattering on magnetic turbulences



$D_{pp} \sim p^2 V_a^2 / D$

$D \sim vR^{1/3}$ – Kolmogorov spectrum

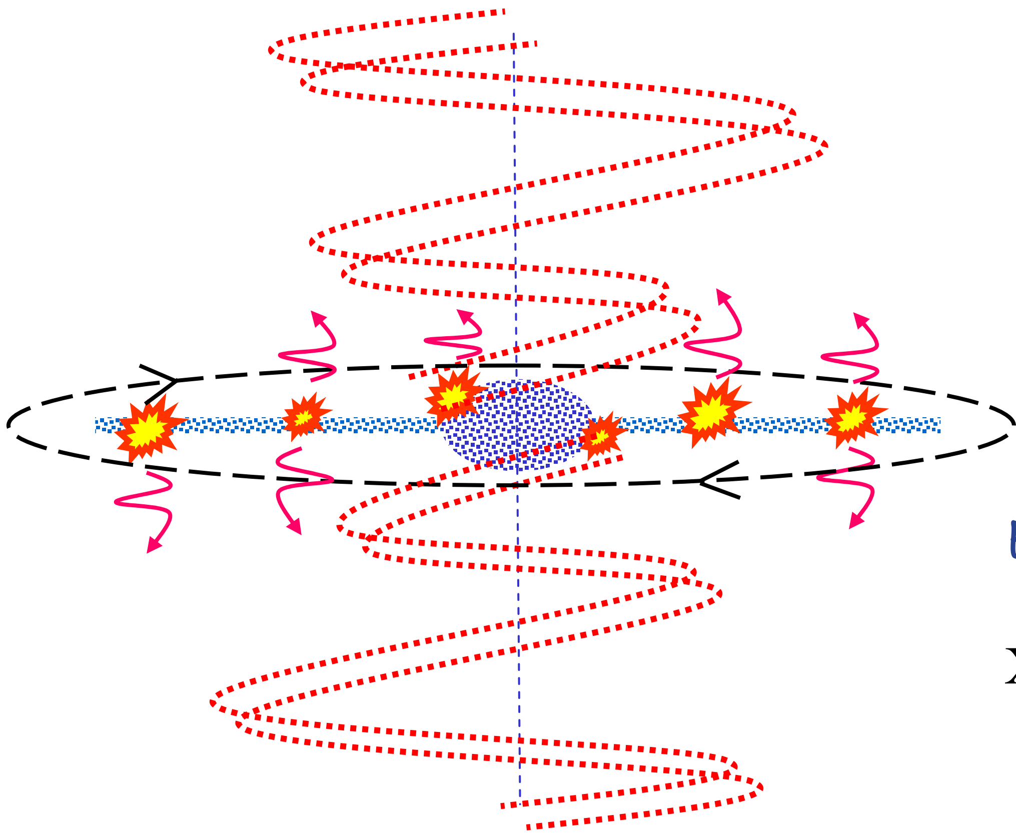


Fermi 2-nd order mechanism:

Head-on collisions are more frequent than following – particle gains energy

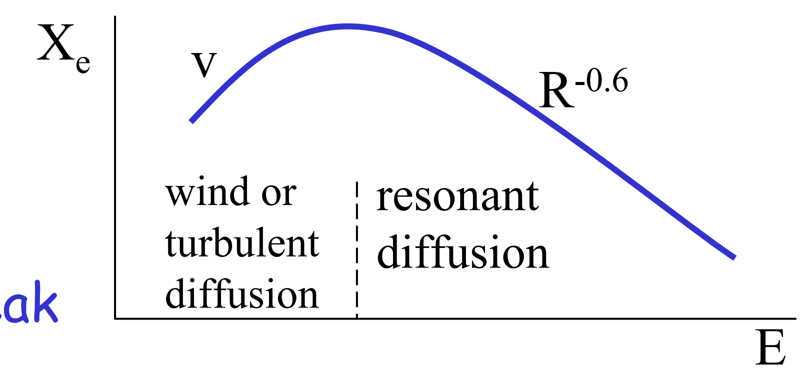
Convection

Galactic wind



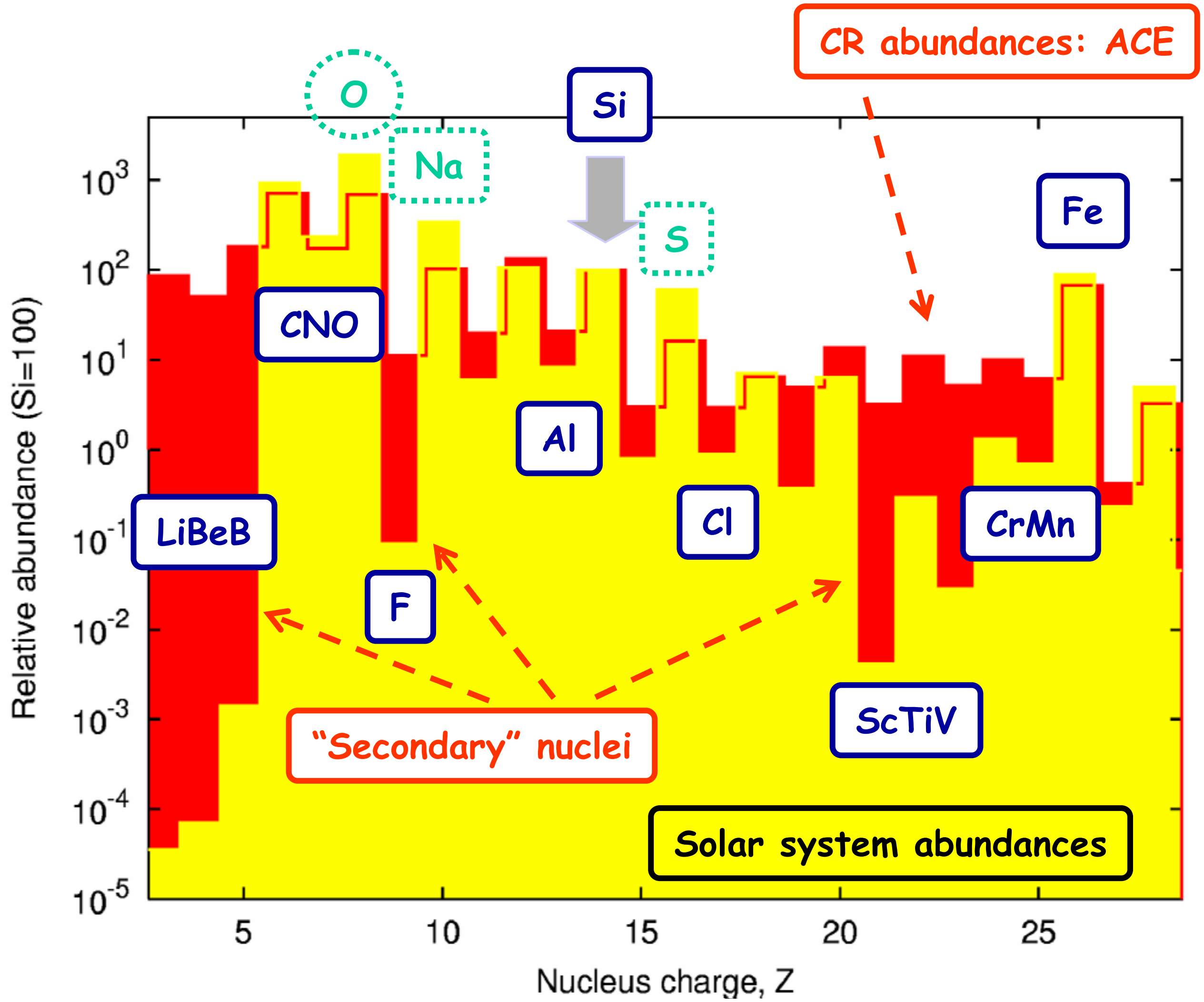
Jones 1979

Escape length



problem: too broad sec/prim peak

Elemental Abundances: CR vs. Solar System

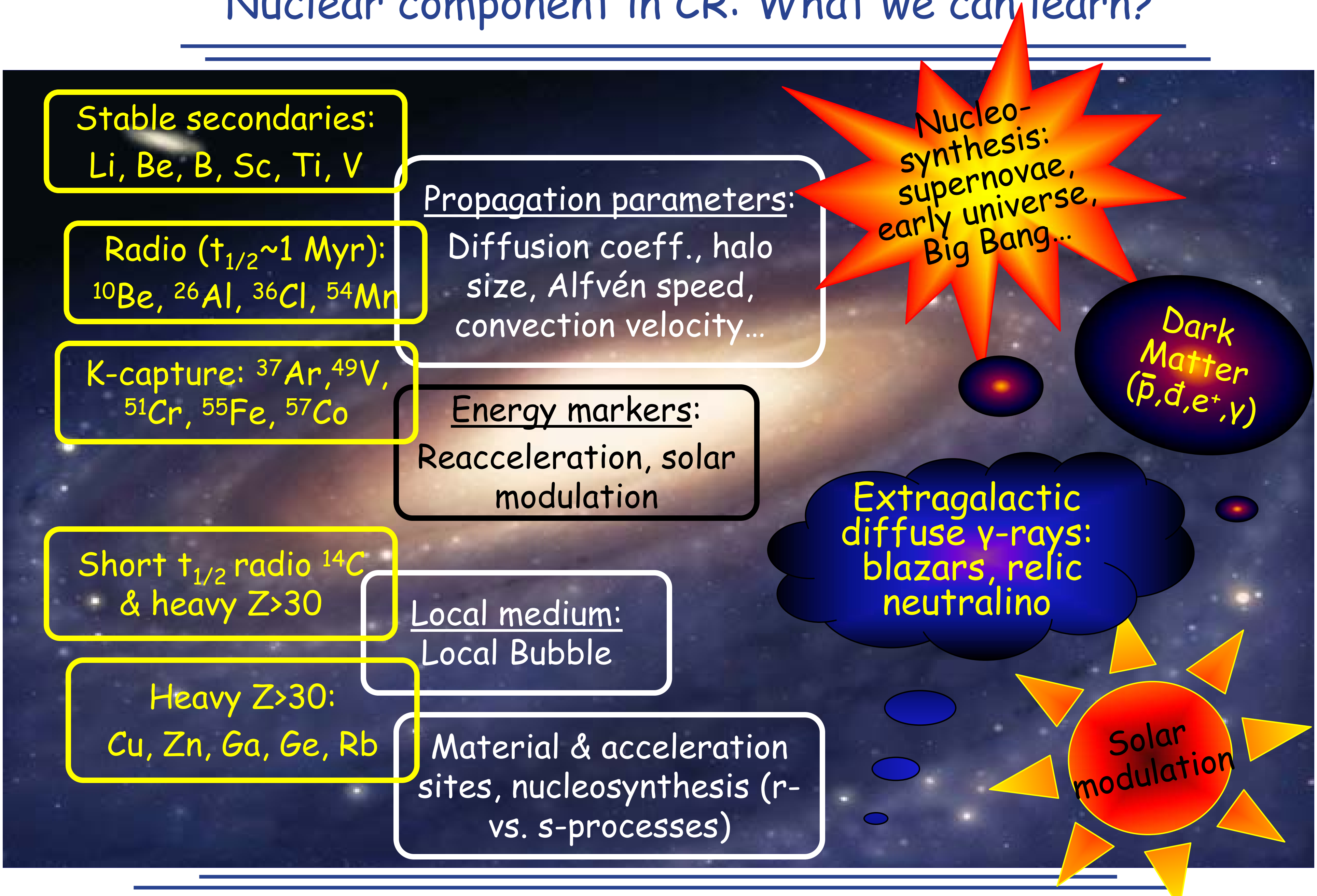


Secondary nuclei is an evidence of the long propagation history of CRs

Why do we know they are secondary?

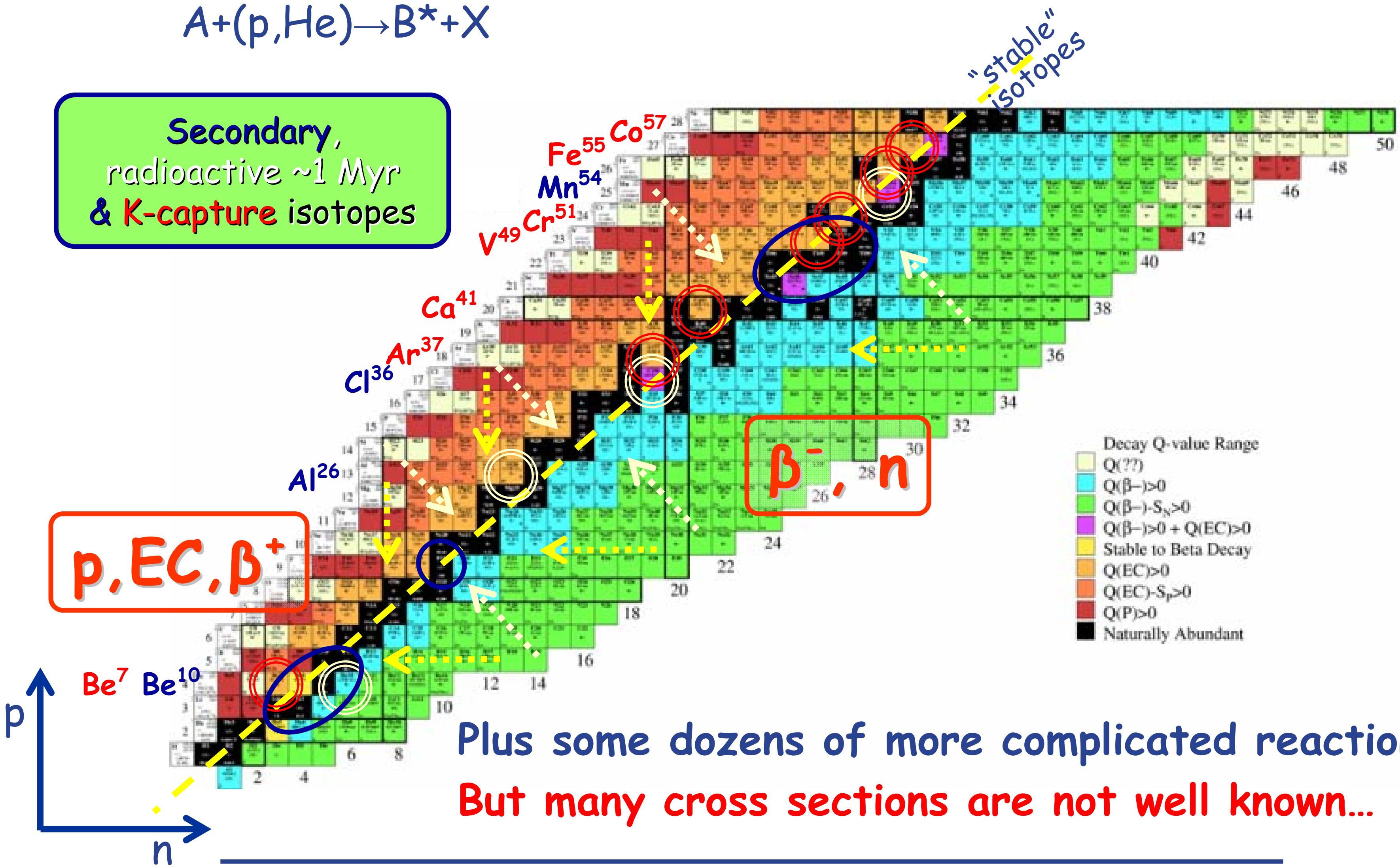
- A comparison with solar system abundances (=interstellar medium ~4 Byr ago)
- Models of nucleosynthesis
- CR propagation models

Nuclear component in CR: What we can learn?



Nuclear Reaction Network+Cross Sections

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

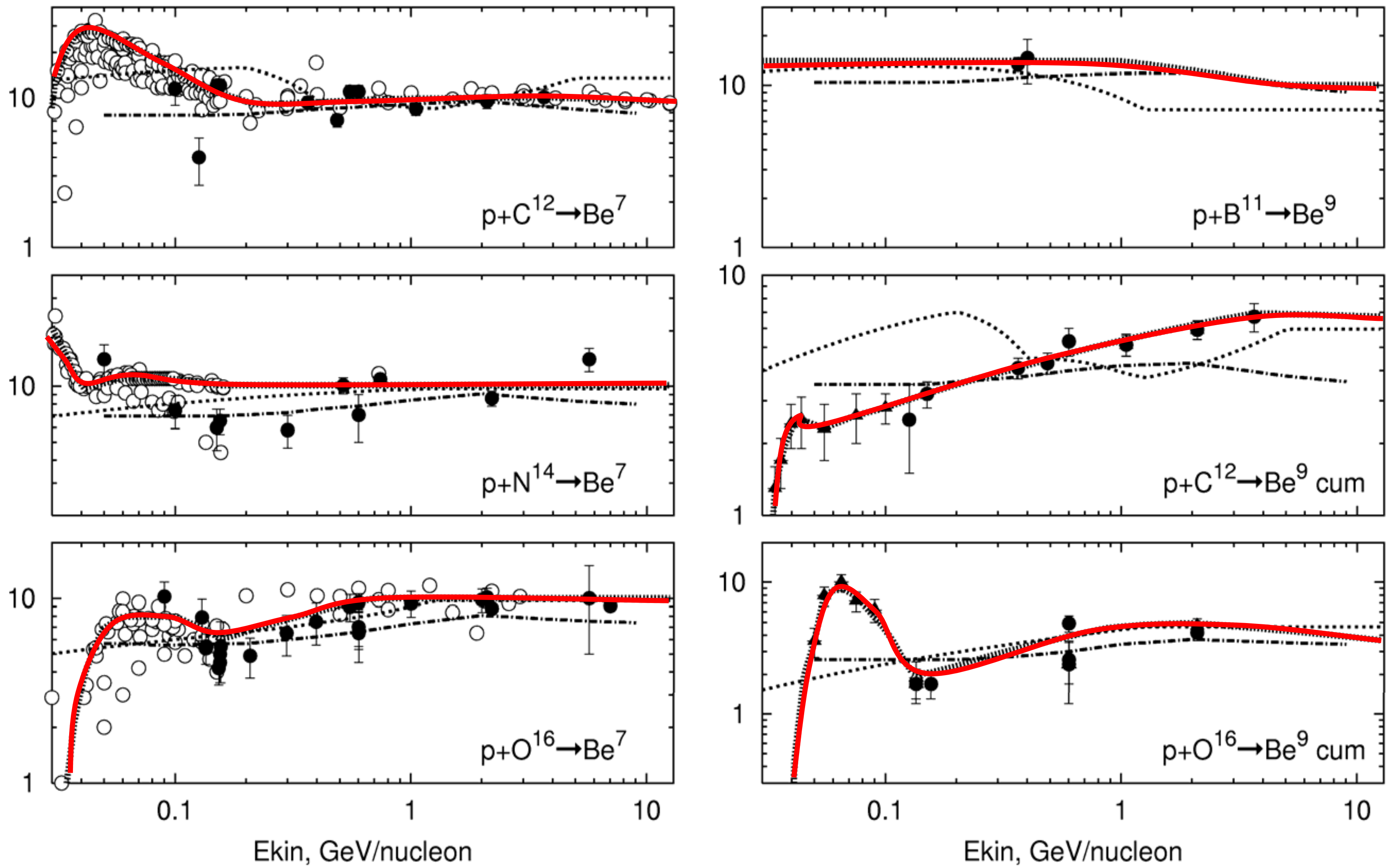


Plus some dozens of more complicated reactions

But many cross sections are not well known…

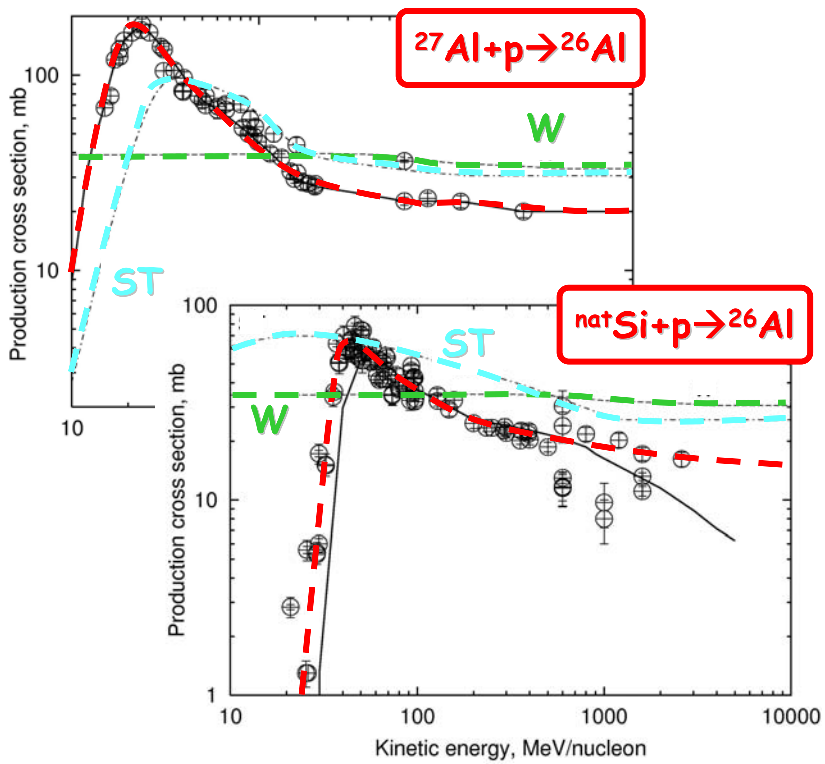
Production Cross Sections of Li,Be,B

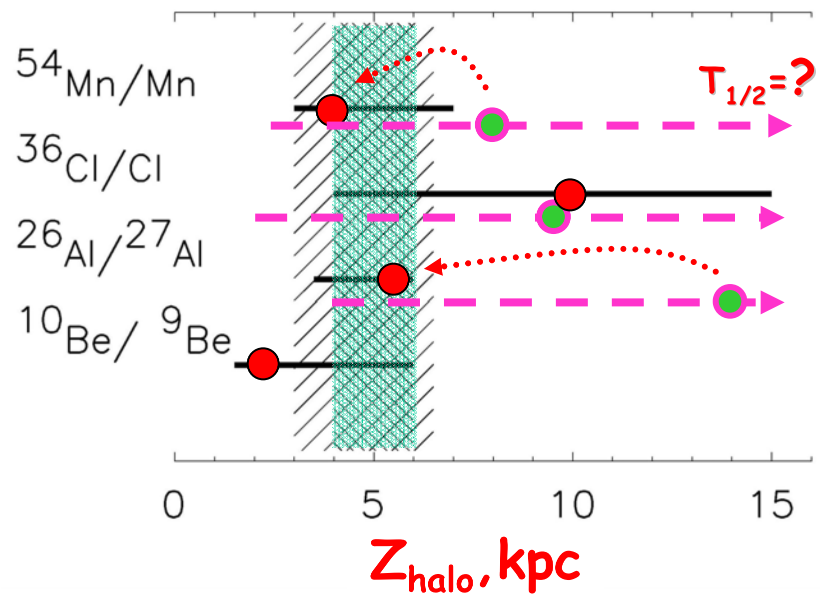
Semi-phenomenology: ········ Silberberg & Tsao, — · — Webber



Effect of Cross Sections: Radioactive Secondaries

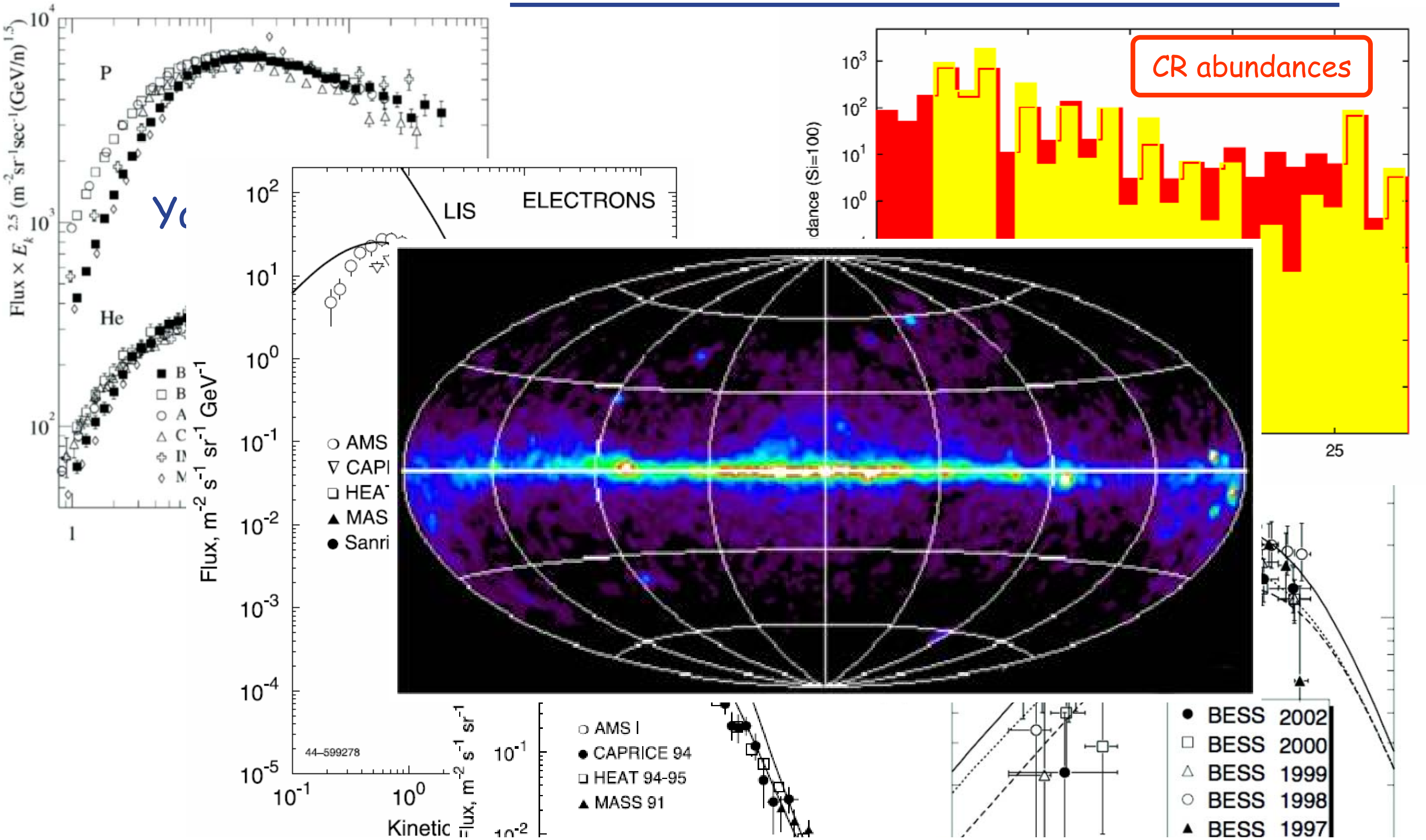
Different size from different ratios…





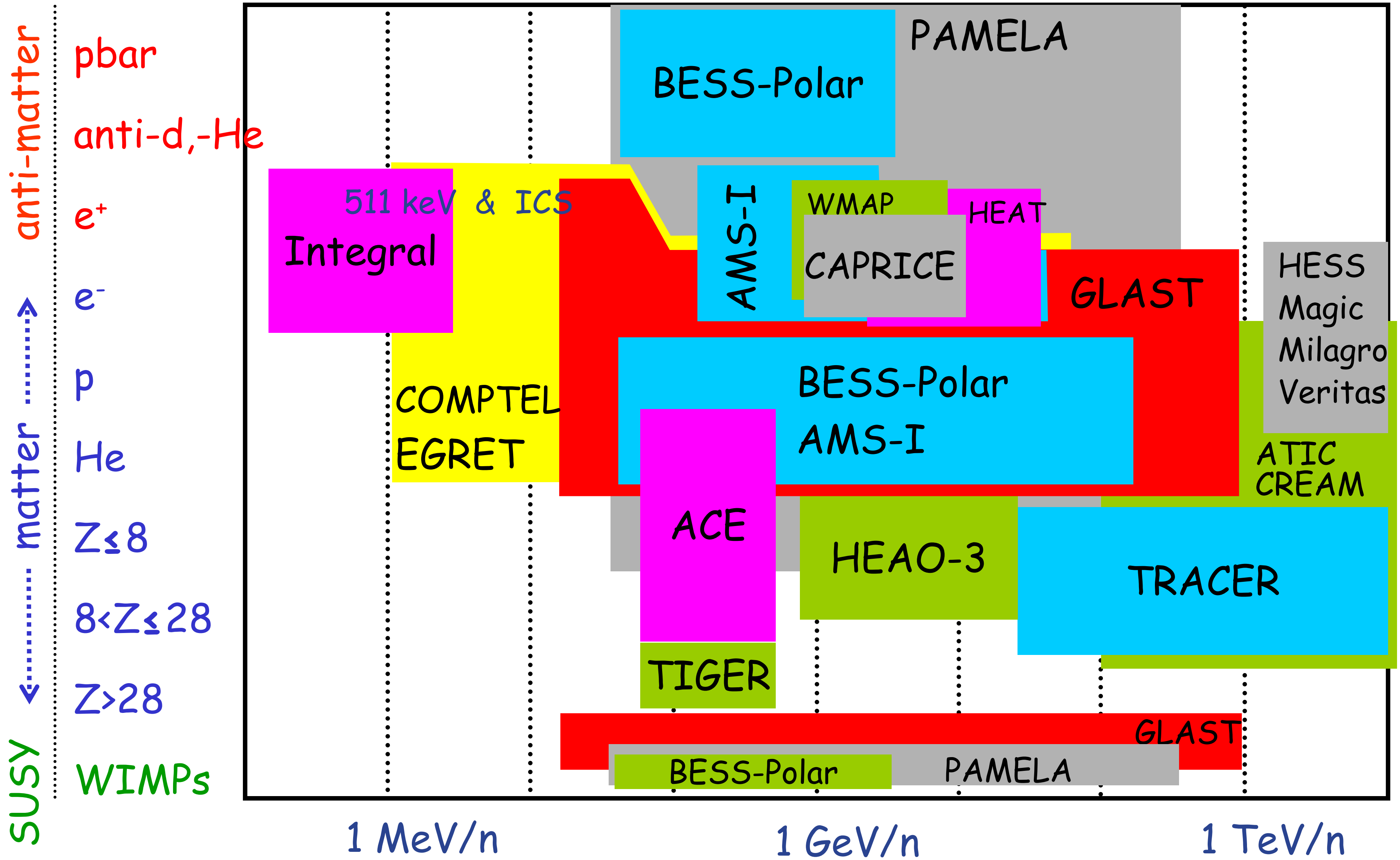
- Errors in CR measurements (HE & LE)
- Errors in production cross sections
- Errors in the lifetime estimates

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…

CR and gamma-ray (CR) instruments



Direct vs Indirect CR measurements

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

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

Transport Equation...

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

Simplified equation: VHE electrons

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

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

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

Cylindrically symmetric solution:

$\mu < 1$

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

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

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

Bessel fns

hypergeometric fn

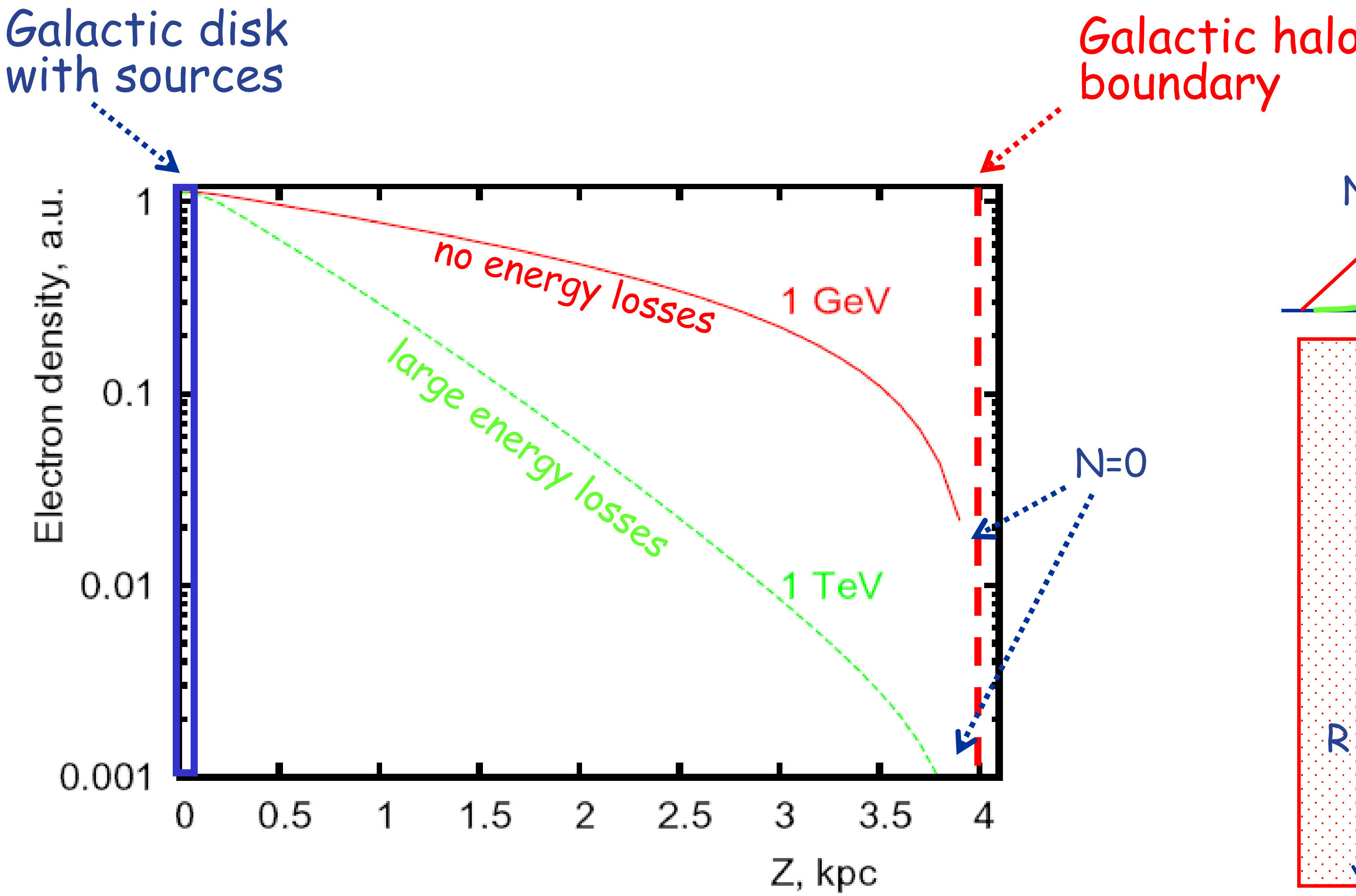
zeros of J_0

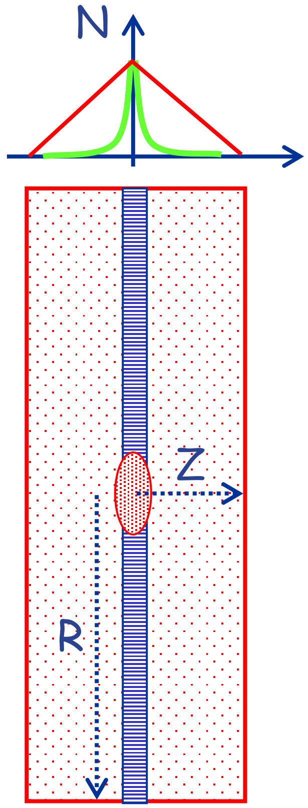
d=halo size

a=radius

Bulanov & Dogiel'1974

Electron propagation: solutions





The "Galaxy"

Analytical vs. Numerical solution

- Analytical solutions for simple cases give insight into the relations between the quantities involved and are useful for rough estimates, but in real cases the analytical formulae may become too complicated so no insight is gained
- Electrons and positrons are beyond the analytical methods because their energy losses are spatially dependent and different processes are important in different energy ranges
- Numerical solutions are fast and more realistic

"It is unclear whether one would wish to go much beyond the generalizations discussed above for an analytically soluble diffusion model. The added insight from any analytic solution over a purely numerical approach is quickly cancelled by the growing complexity of the formulae. With rapidly developing computational capabilities, one could profitably employ numerical solutions…" – J.M.Wallace 1981

Finite Differencing

Each term can be finite-differenced (R, z, p):

$$\frac{\partial \psi_i}{\partial t} = \frac{\psi_i^{t+\Delta t} - \psi_i^t}{\Delta t} = \frac{\alpha_1 \psi_{i-1}^{t+\Delta t} - \alpha_2 \psi_i^{t+\Delta t} + \alpha_3 \psi_{i+1}^{t+\Delta t}}{\Delta t} + q_i$$

The updating scheme (Crank-Nicholson implicit method):

$$\psi_i^{t+\Delta t} = \psi_i^t + \alpha_1 \psi_{i-1}^{t+\Delta t} - \alpha_2 \psi_i^{t+\Delta t} + \alpha_3 \psi_{i+1}^{t+\Delta t} + q_i \Delta t$$

The tridiagonal system of equations:

$$-\alpha_1 \psi_{i-1}^{t+\Delta t} + (1+\alpha_2) \underline{\psi_i^{t+\Delta t}} - \alpha_3 \psi_{i+1}^{t+\Delta t} = \psi_i^t + q_i \Delta t$$

Solving for $\psi_i^{t+\Delta t}$.

Boundary conditions:

$$\psi(R, z_h, p) = \psi(R, -z_h, p) = \psi(R_h, z, p) = 0$$

Tri-Diagonal Matrix

$$
\begin{pmatrix}
(-\alpha_1) & (1+\alpha_2) & (-\alpha_3) & & & & 0 \\
& \ddots & \ddots & \ddots & & & \\
& & (-\alpha_1) & (1+\alpha_2) & (-\alpha_3) & & \\
& & & \ddots & \ddots & \ddots & \\
0 & & & & (-\alpha_1) & (1+\alpha_2) & (-\alpha_3)
\end{pmatrix}
\begin{pmatrix}
\psi_1^{t+\Delta t} \\ \vdots \\ \psi_i^{t+\Delta t} \\ \vdots \\ \psi_n^{t+\Delta t}
\end{pmatrix}
=
\begin{pmatrix}
\psi_1^{t} \\ \vdots \\ \psi_i^{t} \\ \vdots \\ \psi_n^{t}
\end{pmatrix}
+
\begin{pmatrix}
q_1 \\ \vdots \\ q_i \\ \vdots \\ q_n
\end{pmatrix}
\Delta t
$$

$$\alpha_i = \alpha_i(R, z, p)$$

- Can be solved by a standard Crank-Nicholson method
- Looking for a steady-state solution: dψ/dt=0

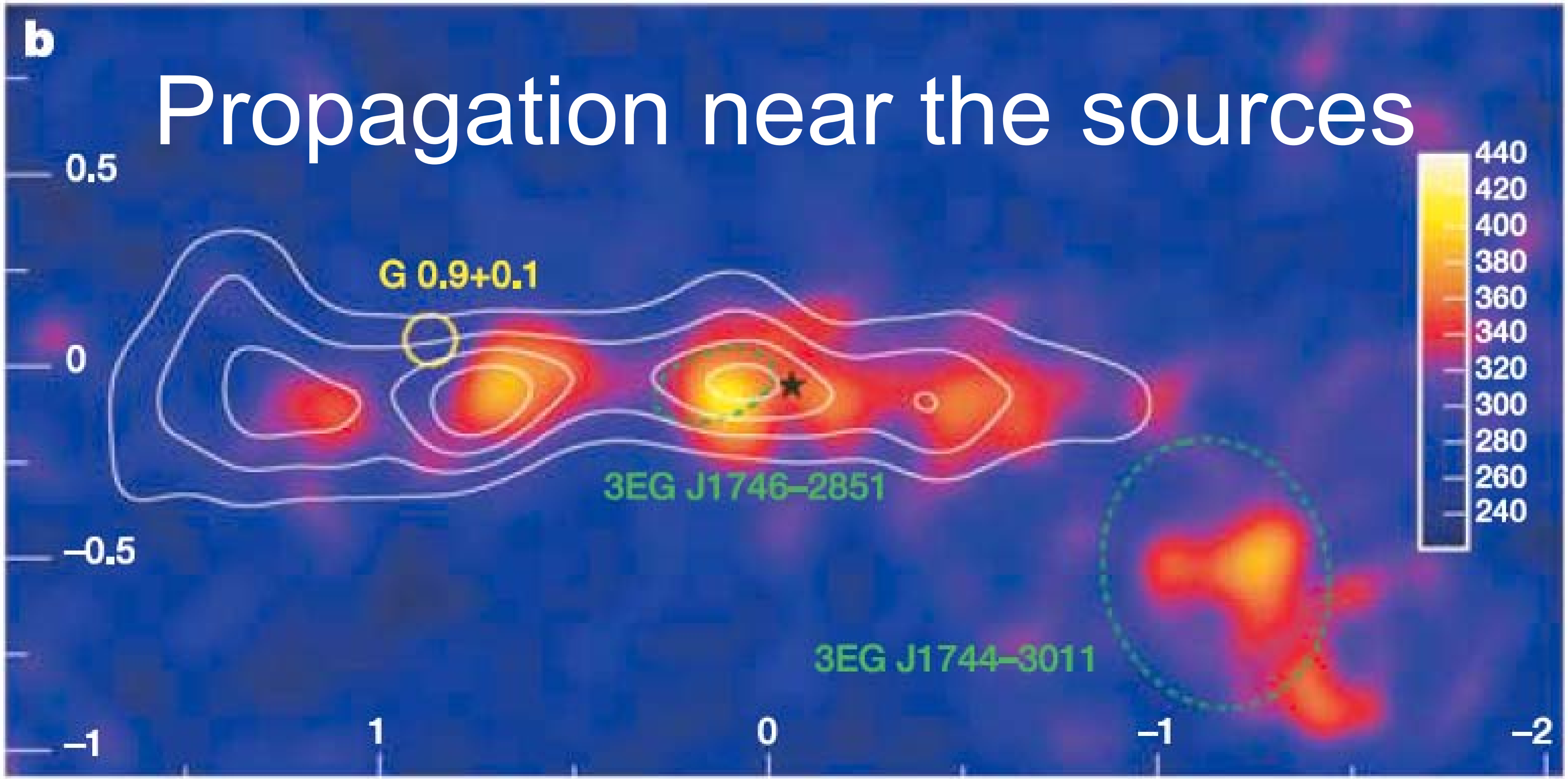
Coefficients for the Crank-Nicholson Method

Process	Coordinate	$\alpha_1/\Delta t$	$\alpha_2/\Delta t$	$\alpha_3/\Delta t$
Diffusion	R	$D_{xx}\frac{2R_i-\Delta R}{2R_i(\Delta R)^2}$	$D_{xx}\frac{2R_i}{R_i(\Delta R)^2}$	$D_{xx}\frac{2R_i+\Delta R}{2R_i(\Delta R)^2}$
	z	$D_{xx}/(\Delta z)^2$	$2D_{xx}/(\Delta z)^2$	$D_{xx}/(\Delta z)^2$
Convection[a]	$z>0\ (V>0)$	$V(z_{i-1})/\Delta z$	$V(z_i)/\Delta z$	0
	$z<0\ (V<0)$	0	$-V(z_i)/\Delta z$	$-V(z_{i+1})/\Delta z$
	$p\ (\frac{dV}{dz}>0)$	0	$\frac{1}{3}\frac{dV}{dz}\frac{p_i}{P_i^{i+1}}$	$\frac{1}{3}\frac{dV}{dz}\frac{p_{i+1}}{P_i^{i+1}}$
Diffusive reacceleration[a]	p	$-\frac{D_{pp,i}-D_{pp,i-1}}{P_{i-1}^{i\,2}} + \frac{2}{P_{i-1}^i}\left(\frac{D_{pp,i}}{P_{i-1}^{i+1}}+\frac{D_{pp,i-1}}{p_{i-1}}\right)$	$-\frac{D_{pp,i}-D_{pp,i-1}}{P_{i-1}^{i\,2}} + \frac{2D_{pp,i}}{P_{i-1}^{i+1}}\left(\frac{1}{P_i^{i+1}}+\frac{1}{P_{i-1}^i}\right) + \frac{2D_{pp,i}}{P_{i-1}^i p_i}$	$\frac{2D_{pp,i+1}}{P_{i-1}^{i+1}P_i^{i+1}}$
Energy loss[a]	p	0	$-\dot{p}_i/P_i^{i+1}$	$-\dot{p}_{i+1}/P_i^{i+1}$
Fragmentation	R,z,p	0	$1/3\tau_f$	0
Radioactive decay	R,z,p	0	$1/3\tau_r$	0

[a] $P_j^i \equiv p_i - p_j$

For more information about numerical model of CR propagation, see: http://galprop.stanford.edu

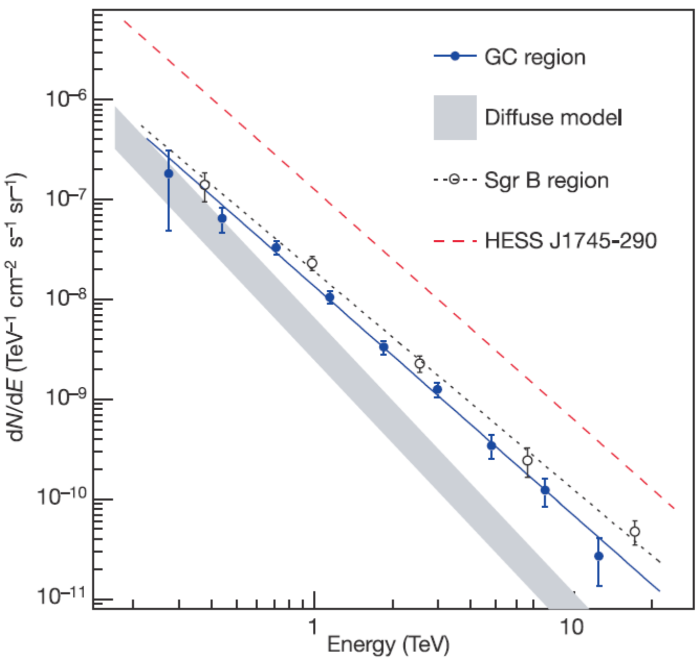
Propagation near the sources

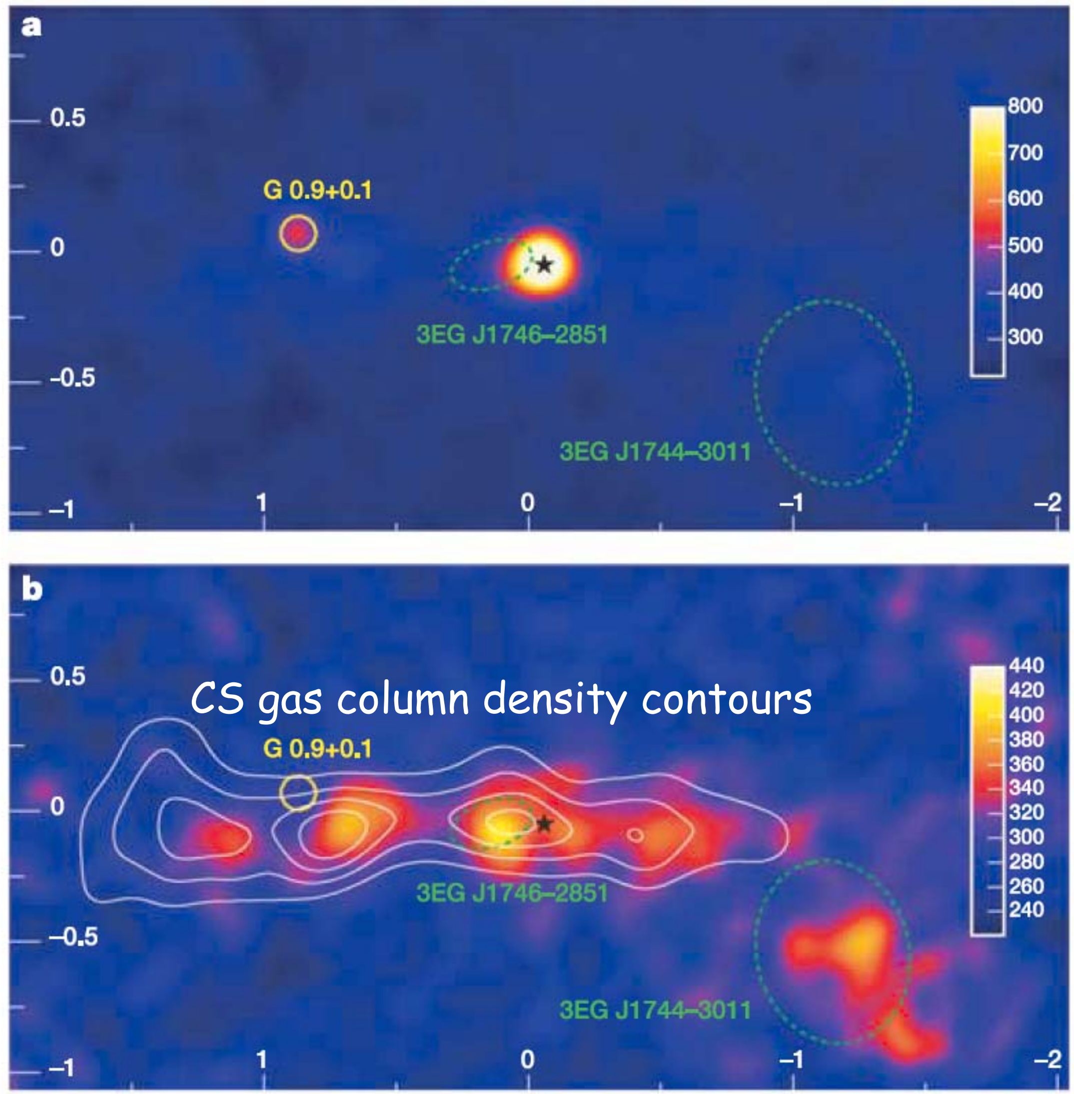


Diffuse VHE γ-ray from the Galactic Center

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

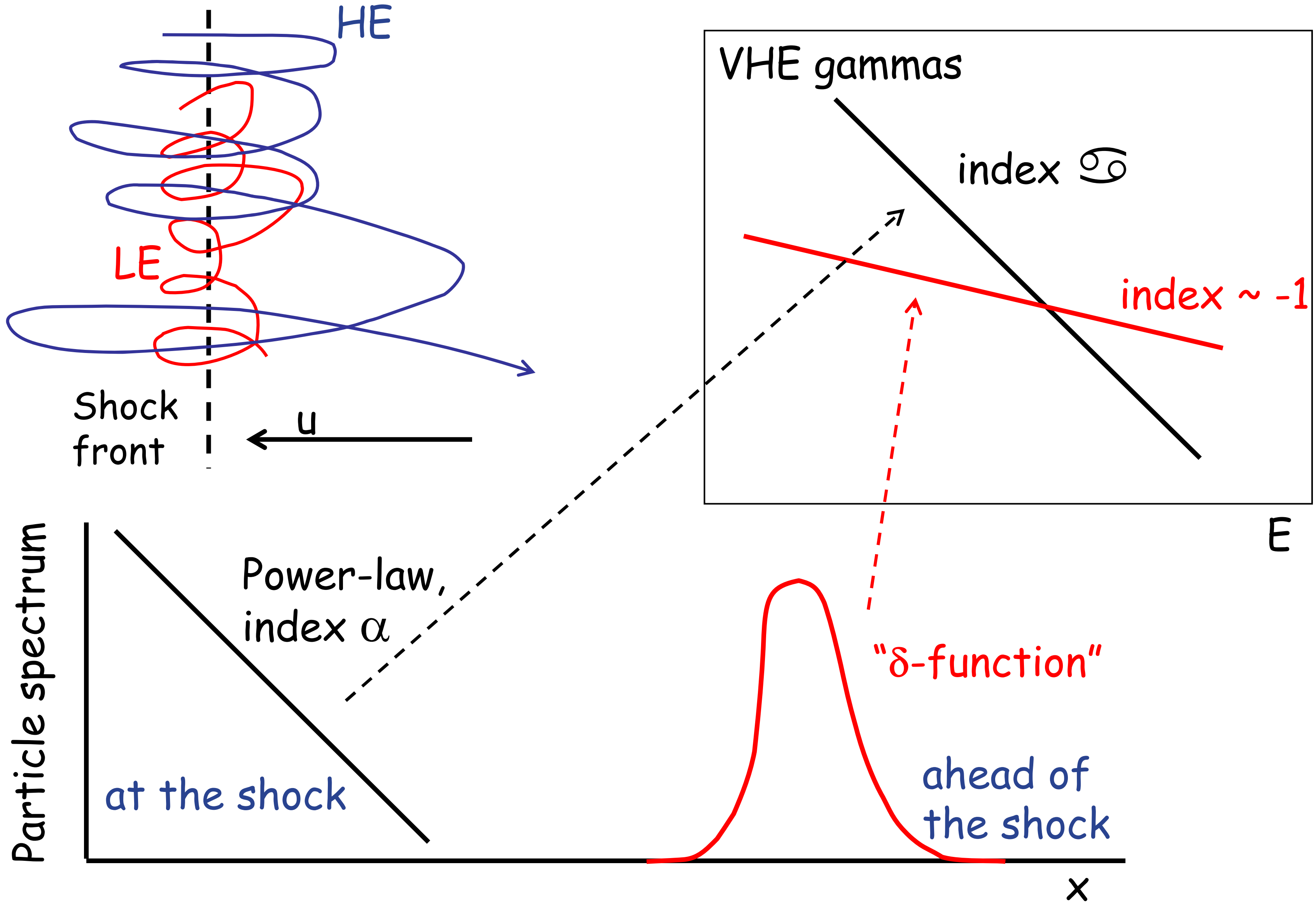
F. Aharonian[1], A. G. Akhperjanian[2], A. R. Bazer-Bachi[3], M. Beilicke[4], W. Benbow[1], D. Berge[1], K. Bernlöhr[1,5], C. Boisson[6], O. Bolz[1], V. Borrel[3], I. Braun[1], F. Breitling[5], A. M. Brown[7], P. M. Chadwick[7], L.-M. Chounet[8], R. Cornils[4], L. Costamante[1,20], B. Degrange[8], H.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





degrees

Qualitative Picture



Diffuse emission from the Galactic center

The spectrum of particles accelerated at the SNR shock is determined by the transport equation:

$$\frac{\partial f}{\partial t} - \nabla D \nabla f + \boldsymbol{u}\nabla f - \frac{\nabla \boldsymbol{u}}{3} p \frac{\partial f}{\partial p} = 0,$$

(See a lecture by L.Drury)

Sedov phase:

$R_{sh} \sim t^{2/5}$ - shock radius

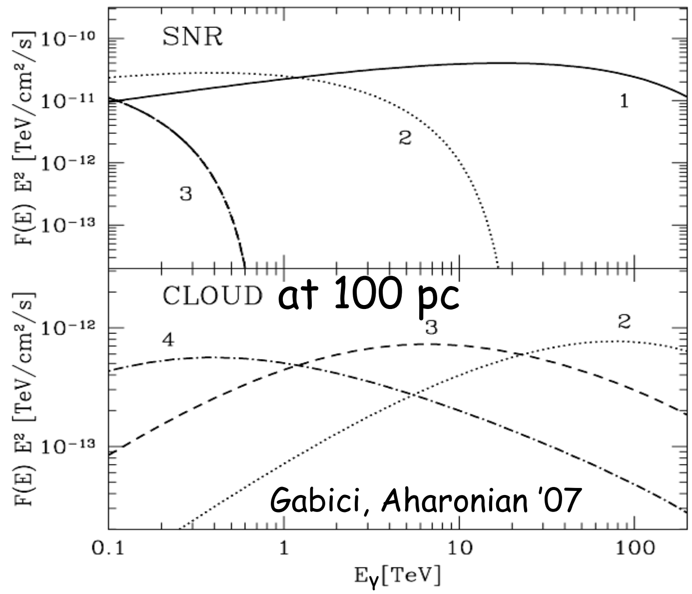
$u_{sh} \sim t^{-3/5}$ – shock velocity

p_{max}: diffusion length $l_d = D(p_{max})/u_{sh} \sim R_{sh}$

D – diff. coeff. (Bohm diffusion)

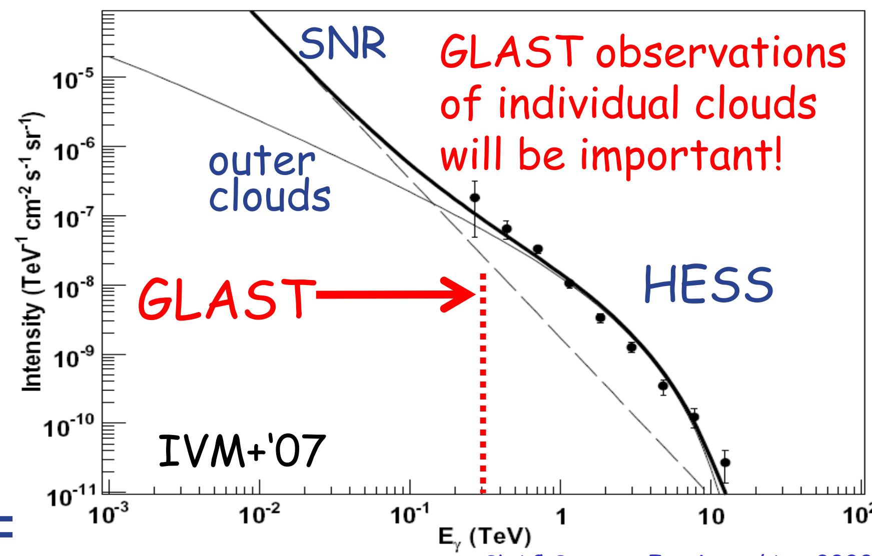
$p_{max}(t) \sim B_{sh}\ t^{-1/5}$

- The highest energy particles escape the shell first
- P_{max} decreases with time

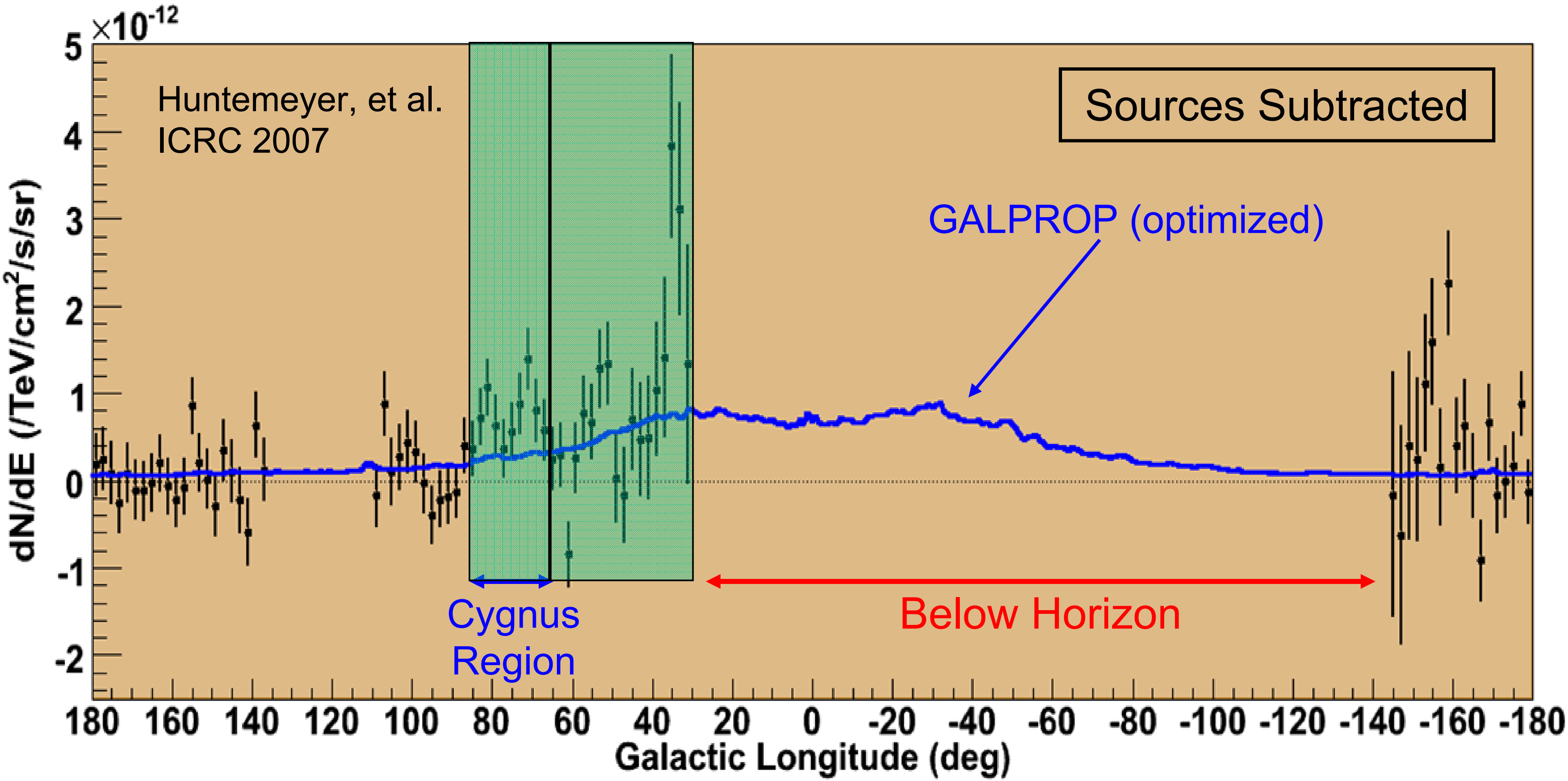


Time since the explosion:

1. t=400 yr
2. t=2 kyr
3. t=8 kyr
4. t=320 kyr



Diffuse Galactic TeV emission (Milagro)



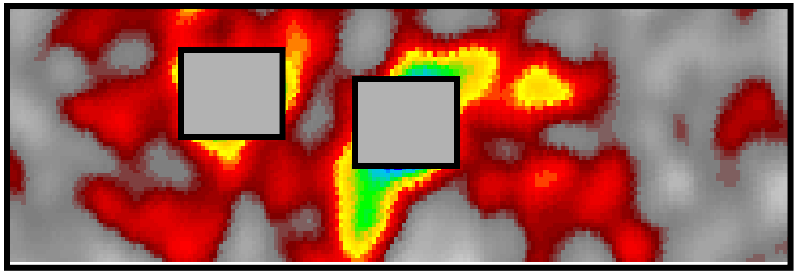
Diffuse Emission from Cygnus Region

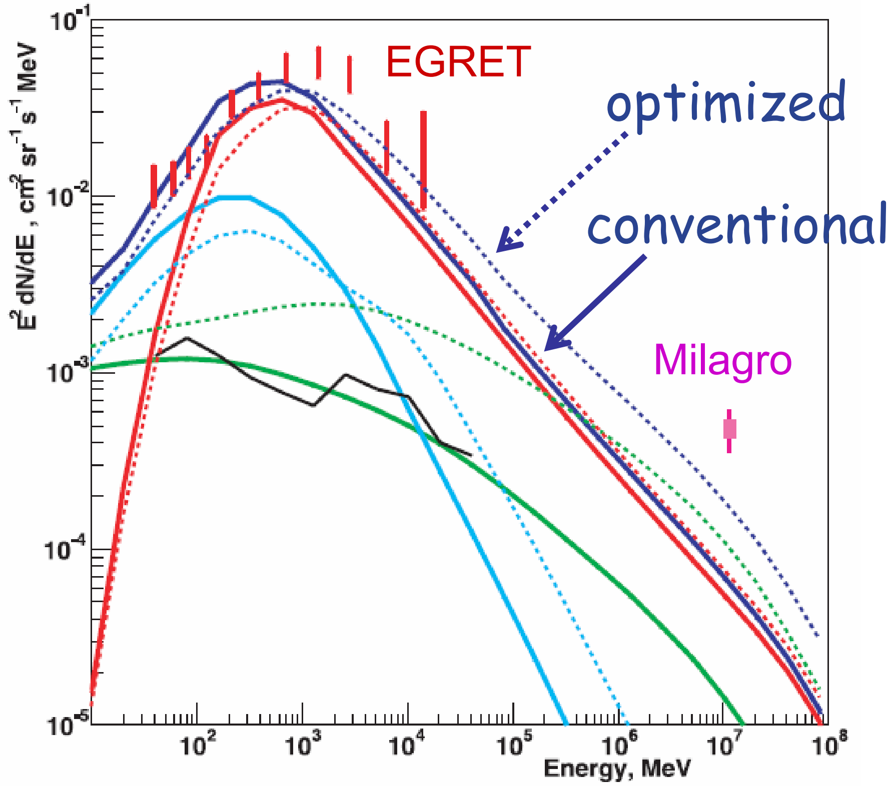
- Exclude a region of 3°×3° around **MGRO J2019+37** and **MGROJ2033+42**
  - Diffuse flux (×10^{-10} TeV cm^{-2} s^{-1} sr^{-1}) $= 4.18 \pm 0.52_{stat} \pm 1.26_{sys}$ ~ 2× Crab flux
- Galprop model:
  - Milagro flux ~ 7x conventional model of Galprop
  - Milagro flux ~3x optimized model
- "TeV excess"?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

- GLAST LAT observations are important!

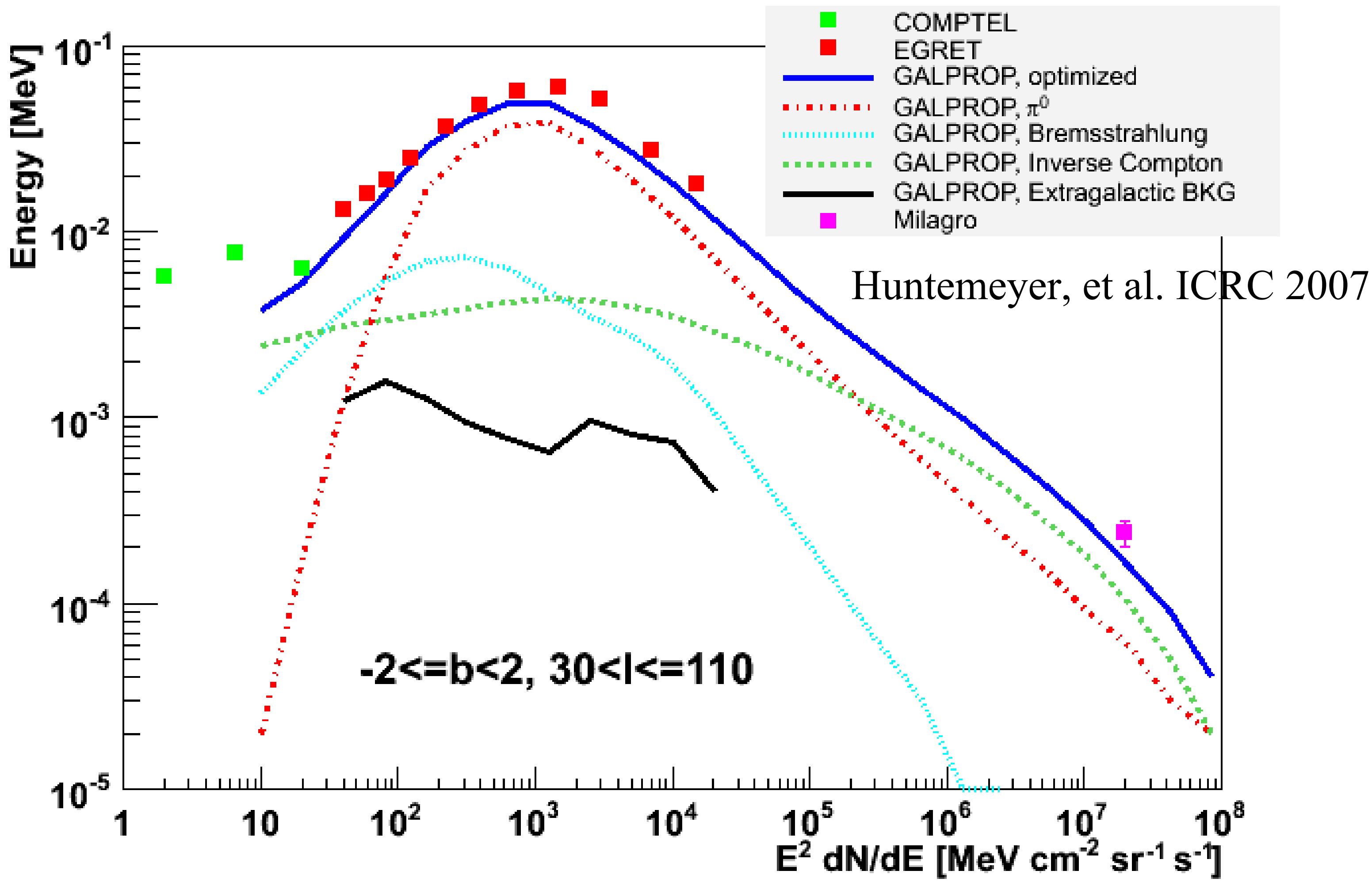
Abdo A. A. *et al.*, ApJL 658, L33

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



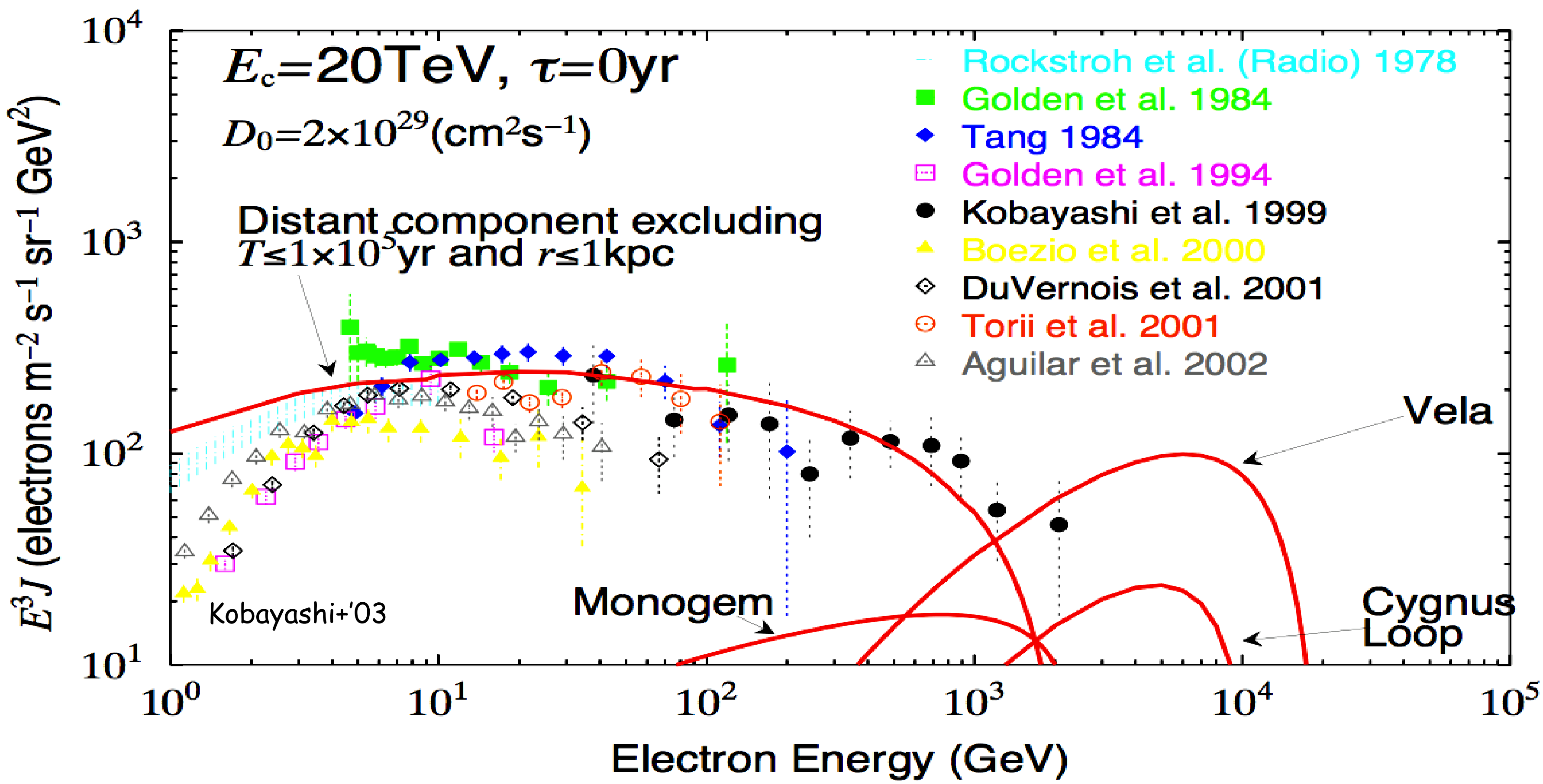


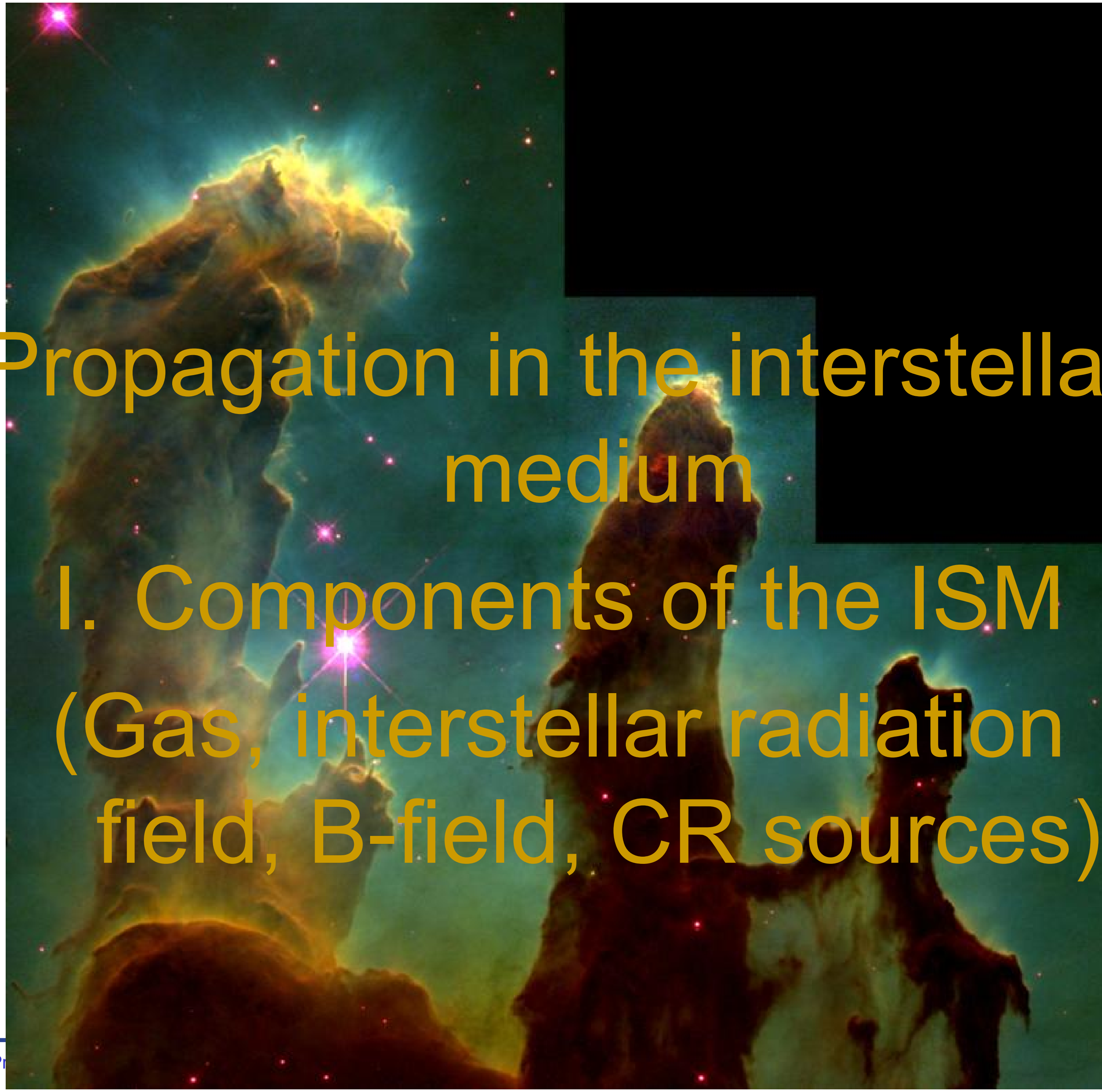
Diffuse Emission from the inner Galaxy



Pulsars, Plerions, & SNRs

- Produce electrons and positrons
- Can accelerate up to TeV energies, at least
- May produce spectral features in CR electron and positron spectra
- Current measurements are not accurate enough!
- GLAST will be able to measure CR electrons up to ~1 TeV



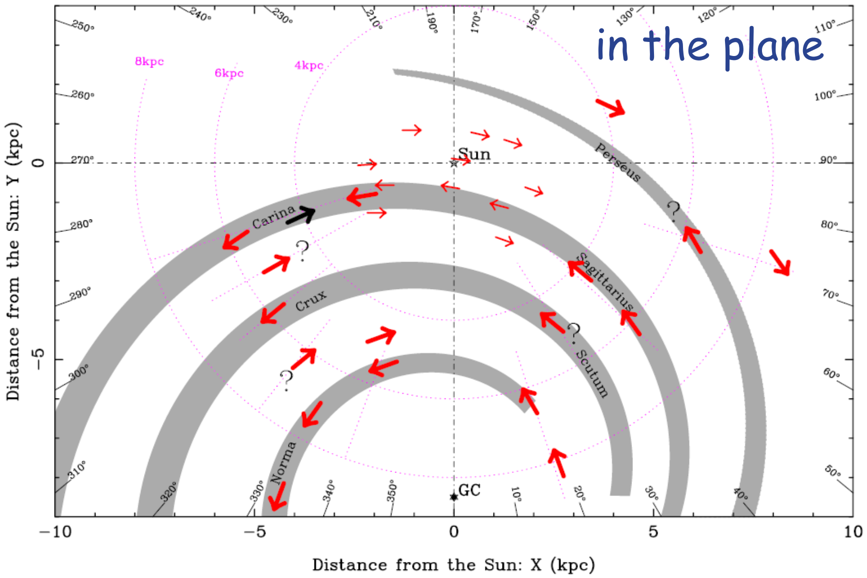


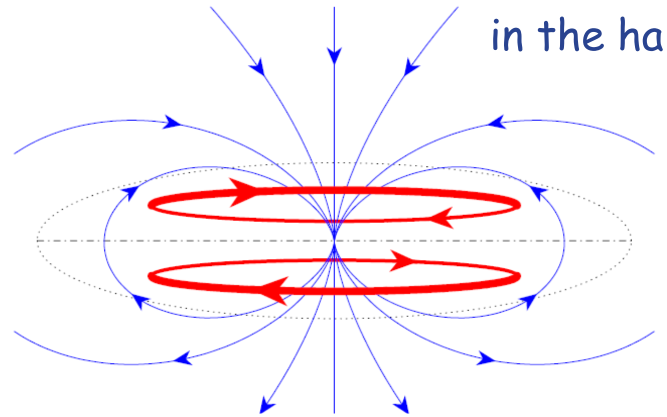
Propagation in the interstellar medium

I. Components of the ISM (Gas, interstellar radiation field, B-field, CR sources)

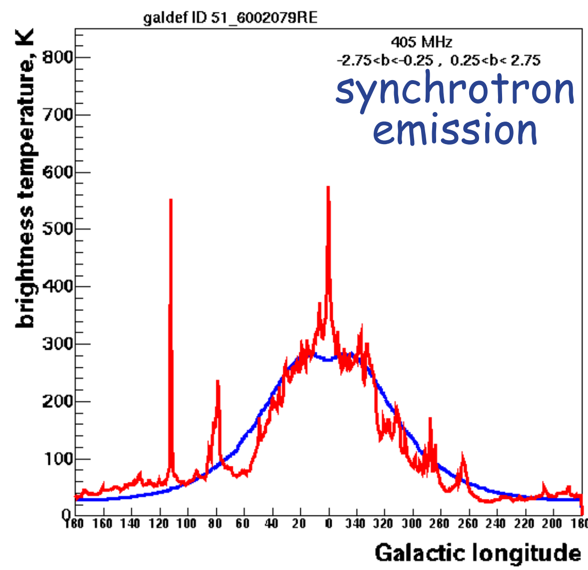
Galactic magnetic field

Regular B-field: large-scale structure (from pulsar RM and DM)





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

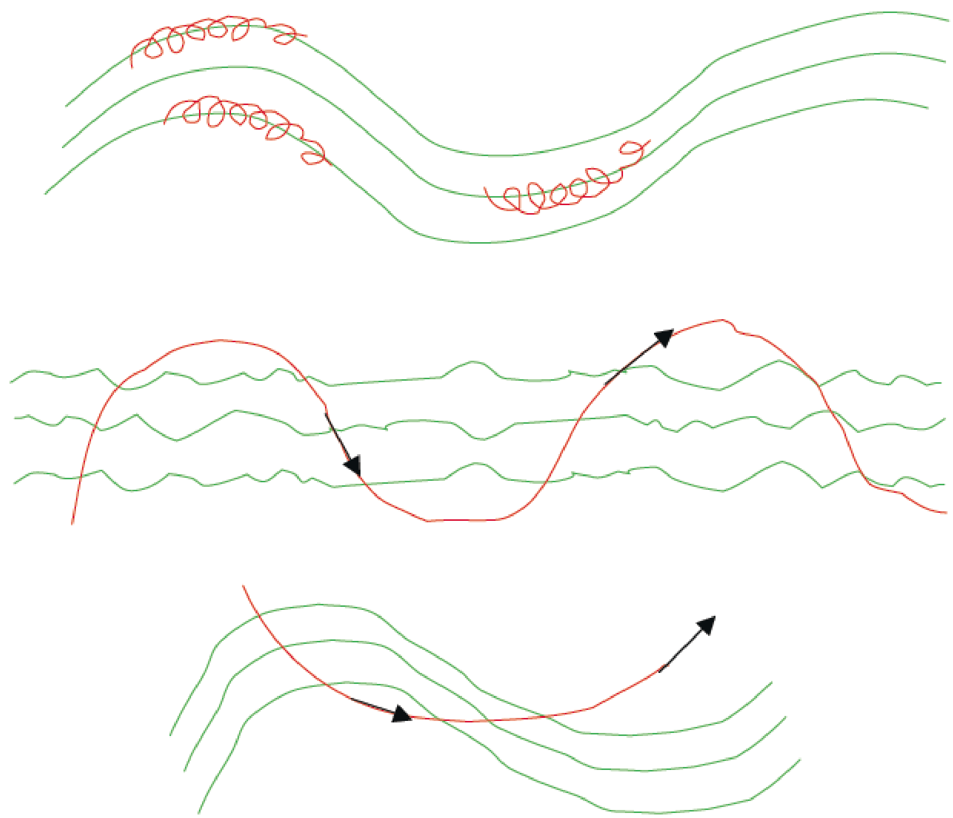
Diffusion in Galactic magnetic fields

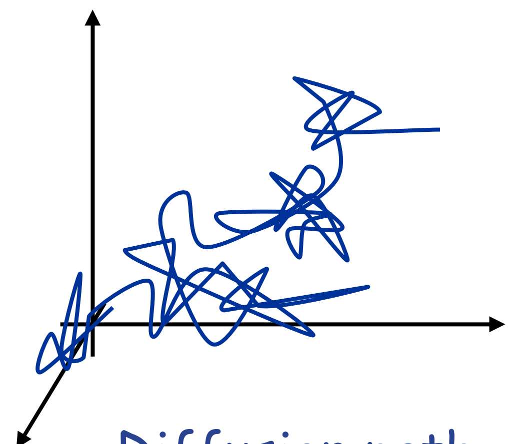
Magnetic turbulences + random field + inhomogeneities = random walk

$r_g \ll \lambda$

$r_g \gg \lambda$

$r_g \sim \lambda$

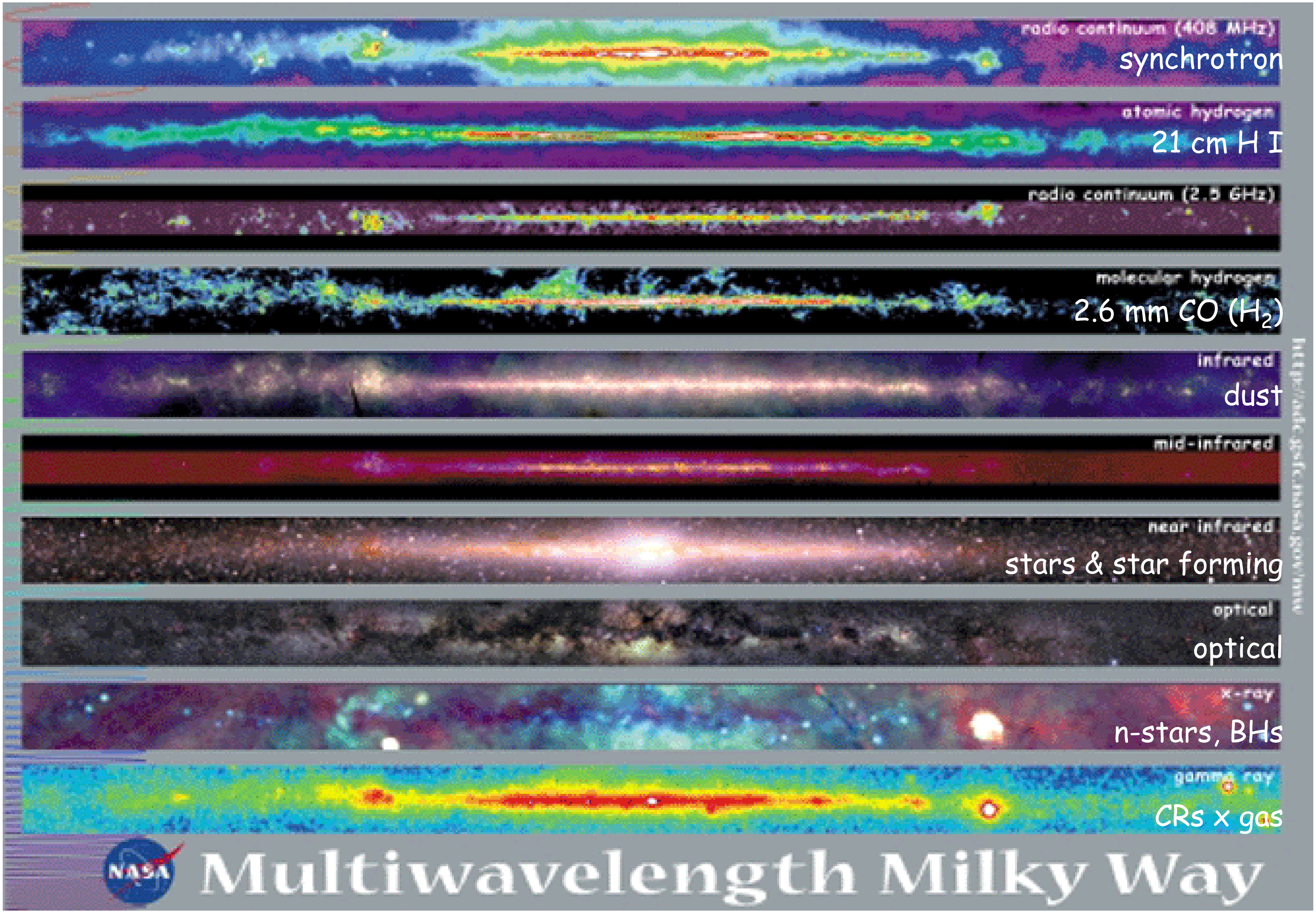




Diffusion path

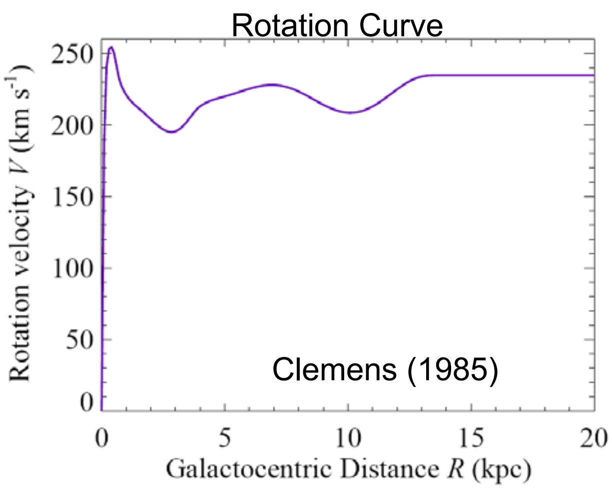
E.Parizot

Different Views from the Inside



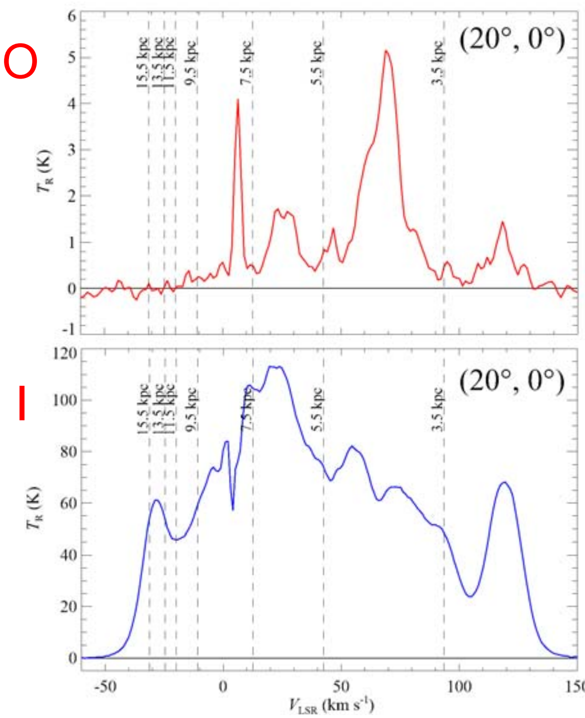
Distribution of interstellar gas

- 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

H I



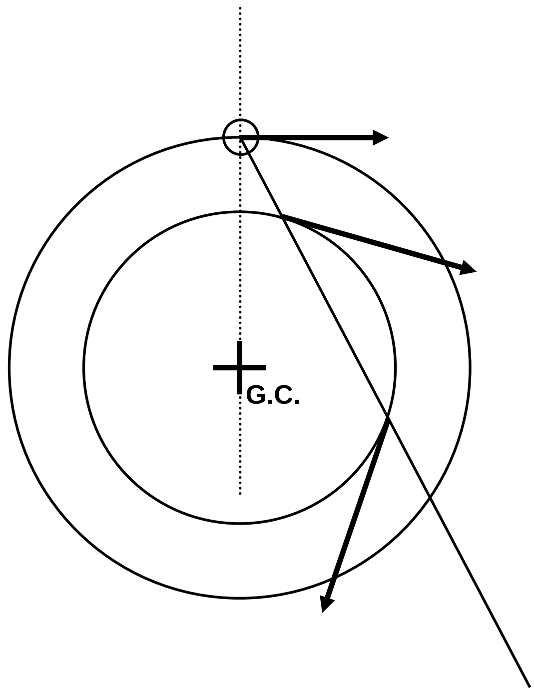
Dame et al. (2001)

Kalberla et al. (2005)

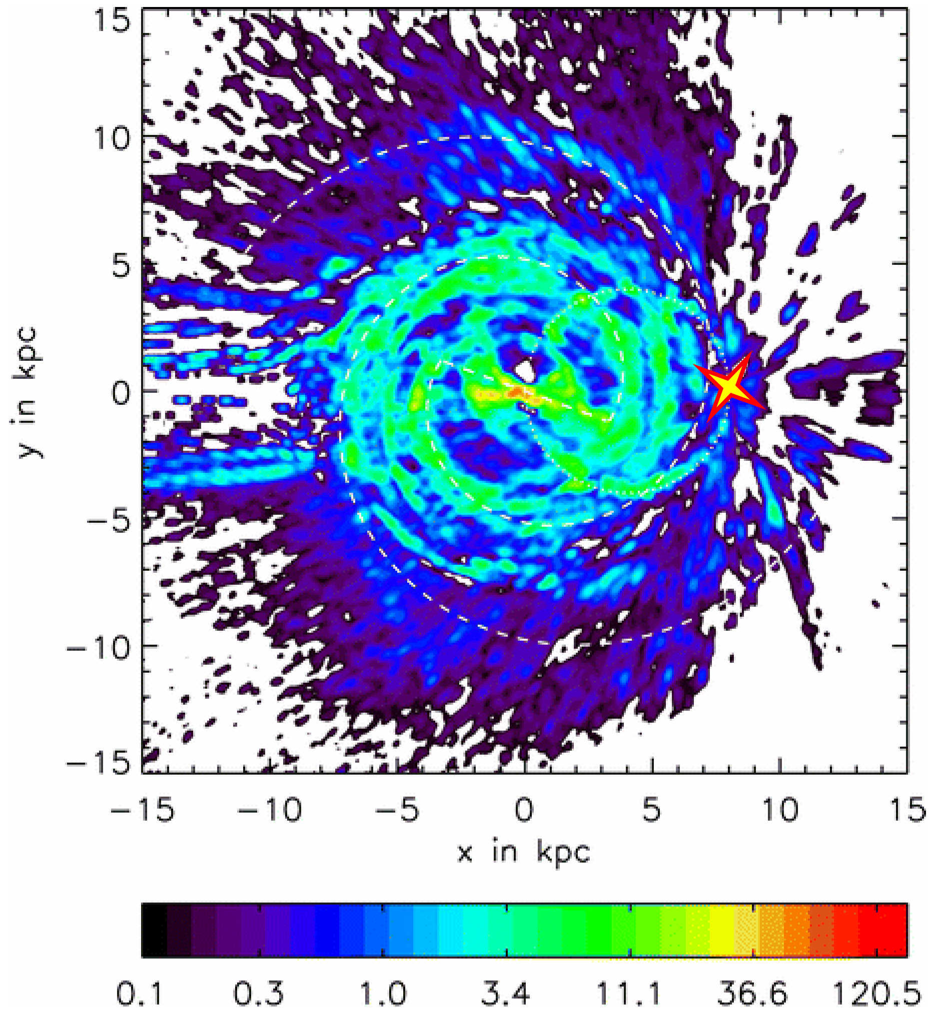
W. Keel

- 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

More on gas in the Milky Way



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

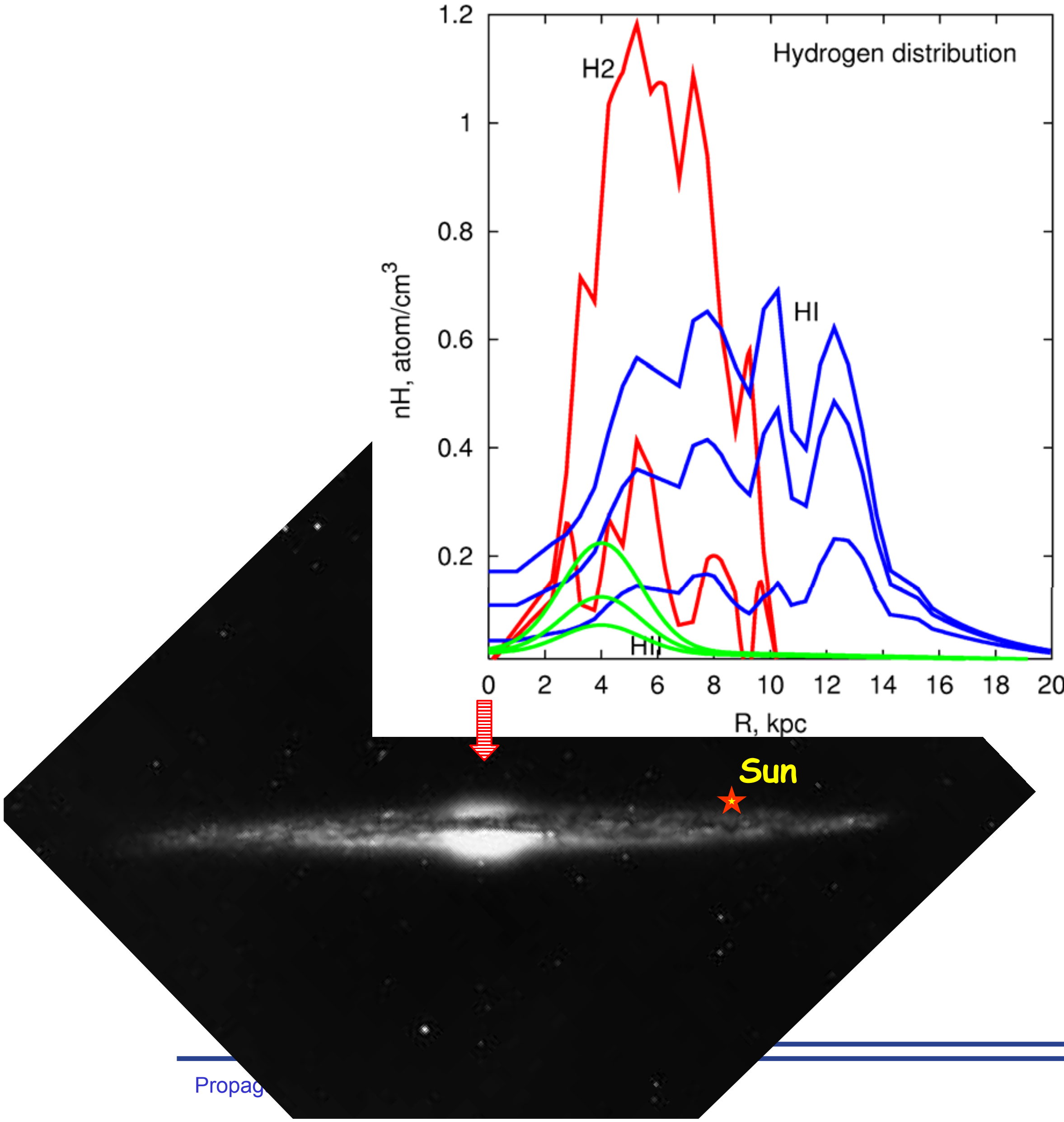


Problems:

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

Pohl+'08

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)

Interstellar radiation field (ISRF)

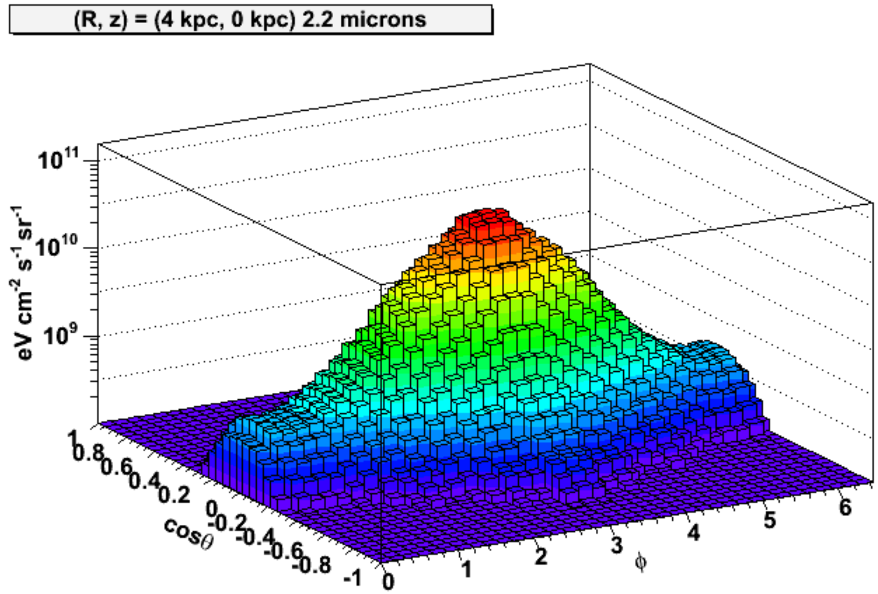
Why should we care?

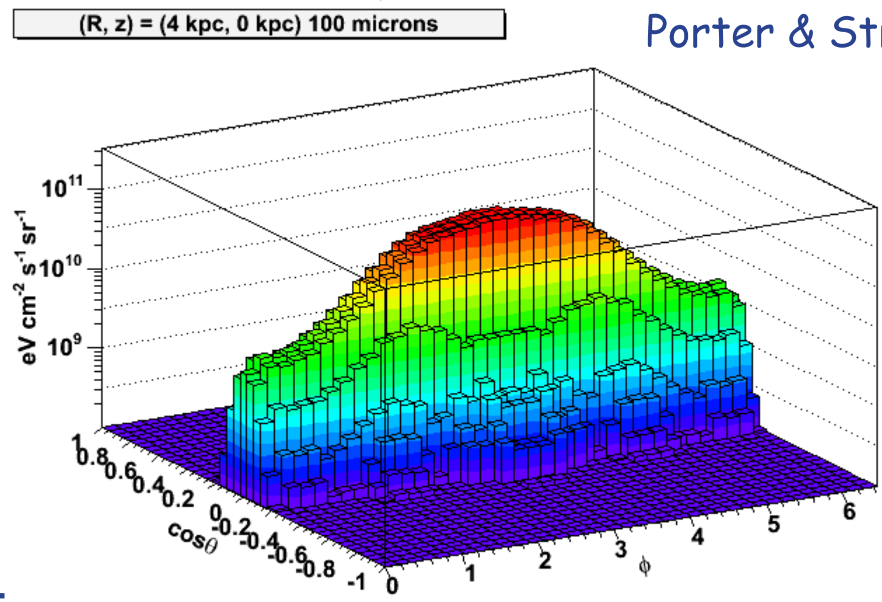
- CR electrons and positrons lose energy via IC - gamma ray production in ISM (INTEGRAL, GLAST, ACTs)
- Electrons in SNRs produce gamma rays (via ICS)
- Gamma-gamma absorption of TeV photons
- UV Heating of clouds in the Galaxy, etc.
- Extraction of extragalactic background light (EBL)

ISRF: Angular distribution

Calculation:

- Calculate intensity maps throughout Galaxy
  - distribution of stars (different spectral classes)
  - distribution of dust
  - radiative transfer
- These vary with position AND wavelength
- Different from local intensity distribution
- Isotropic approximation for anything but CMB is clearly incorrect



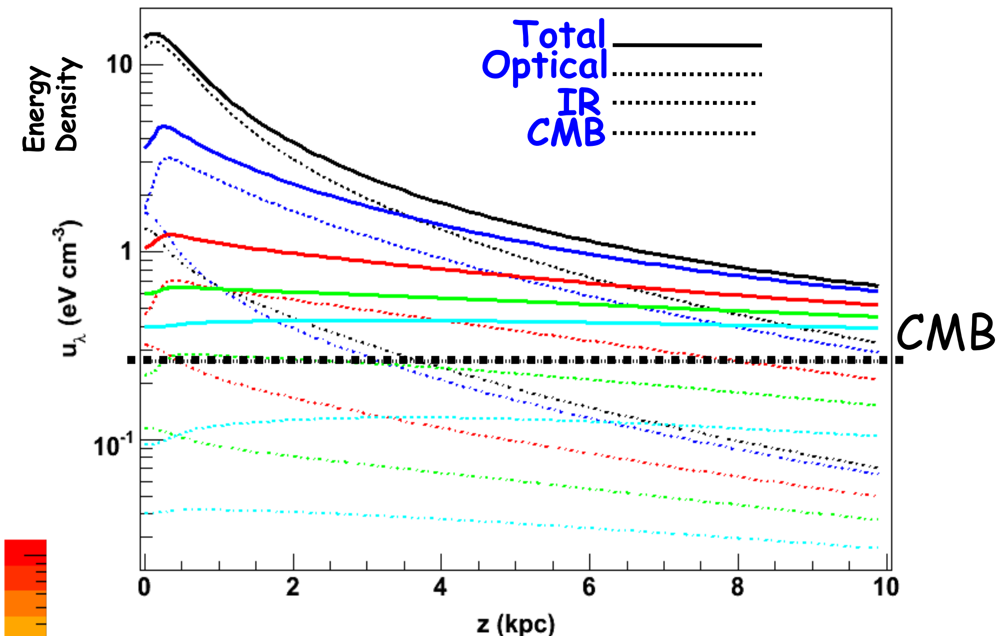


Porter & Strong

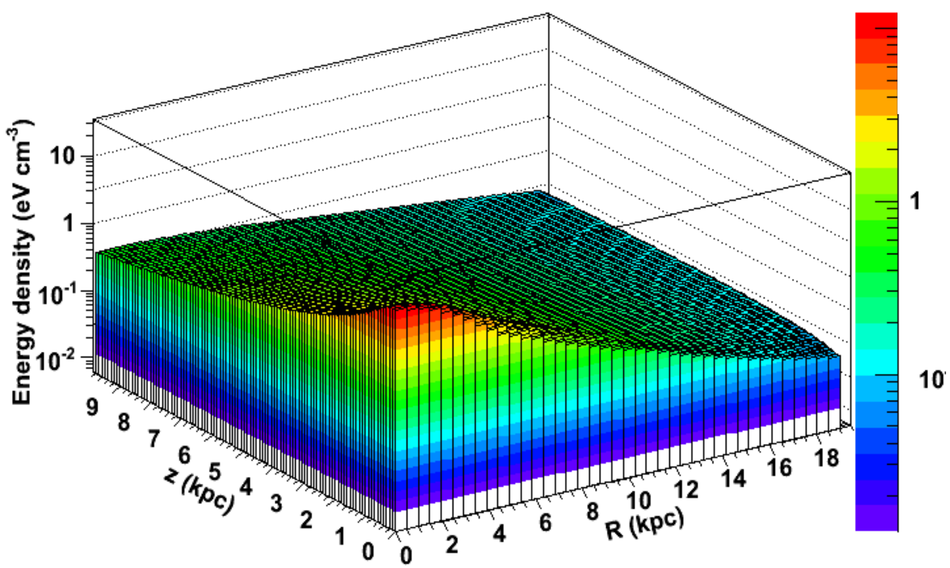
ISRF: Large Scale Distribution

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

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



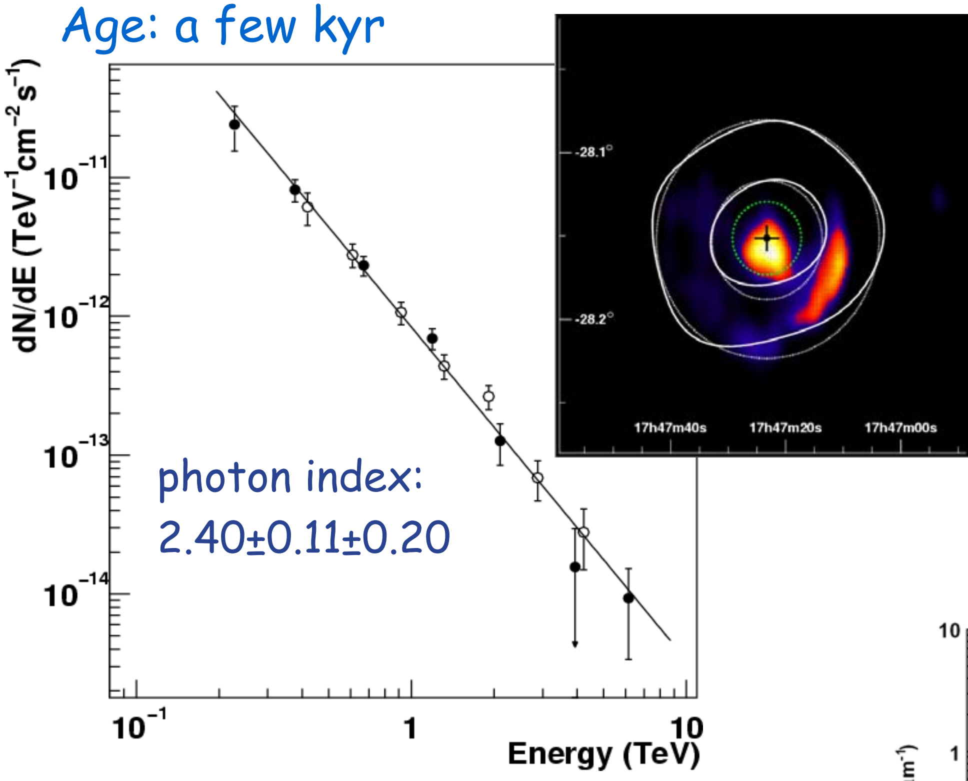
Optical + IR (no CMB)



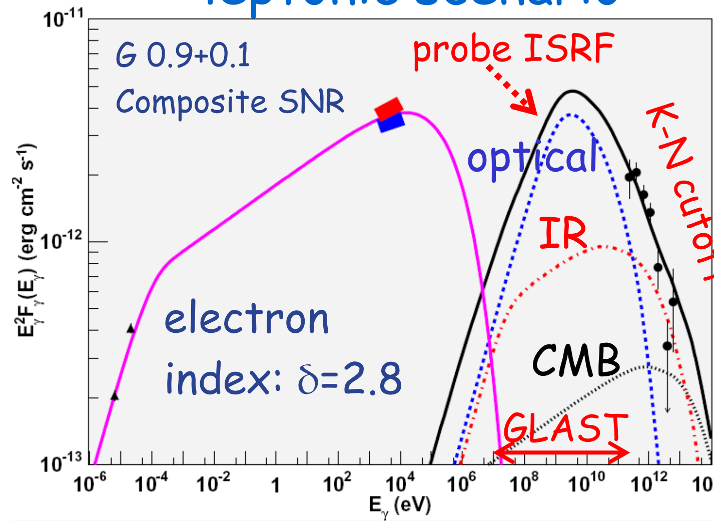
Porter & Strong

HESS Observations of Composite SNR G0.9+0.1

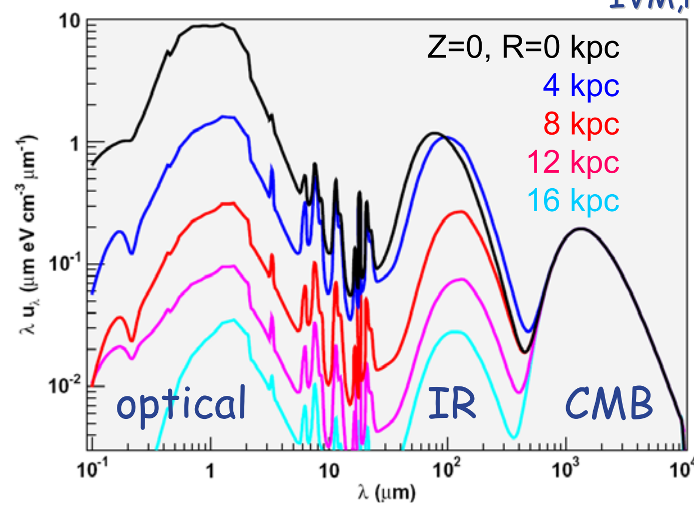
SNR at the GC
Age: a few kyr



leptonic scenario



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



Interstellar radiation field in the inner Galaxy is dominated by the dust (IR) emission and starlight – a possibility to determine ISRF at the GC

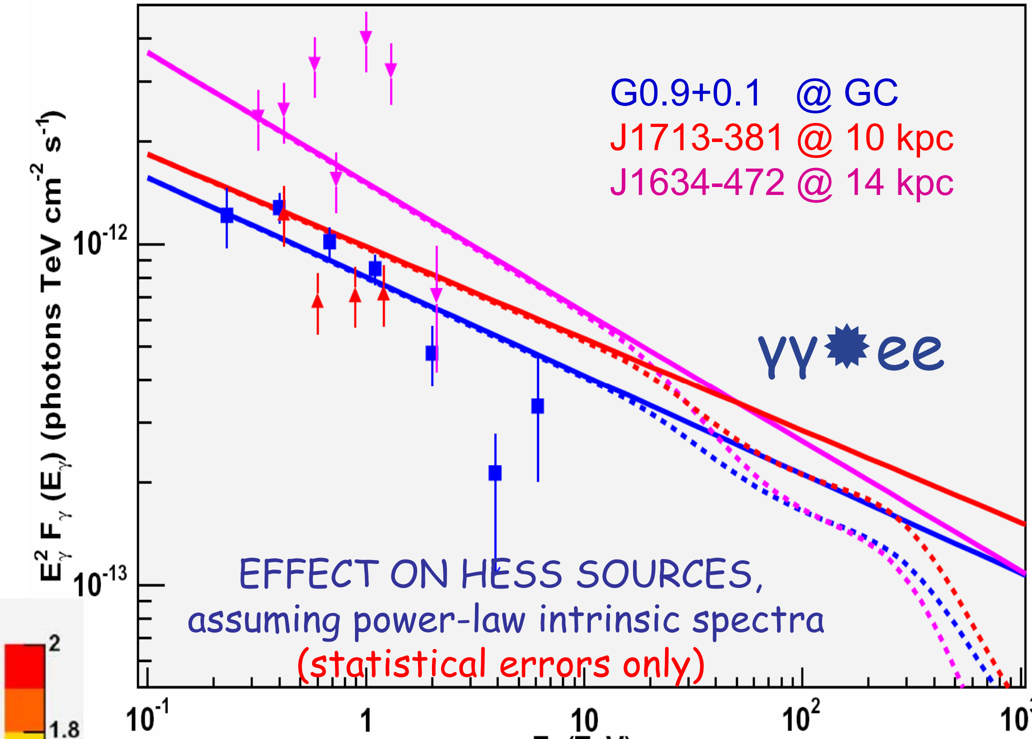
ISRF: gamma-gamma absorption

Threshold of the pair production (γγ✸ee) on thermal (isotropic) photons:

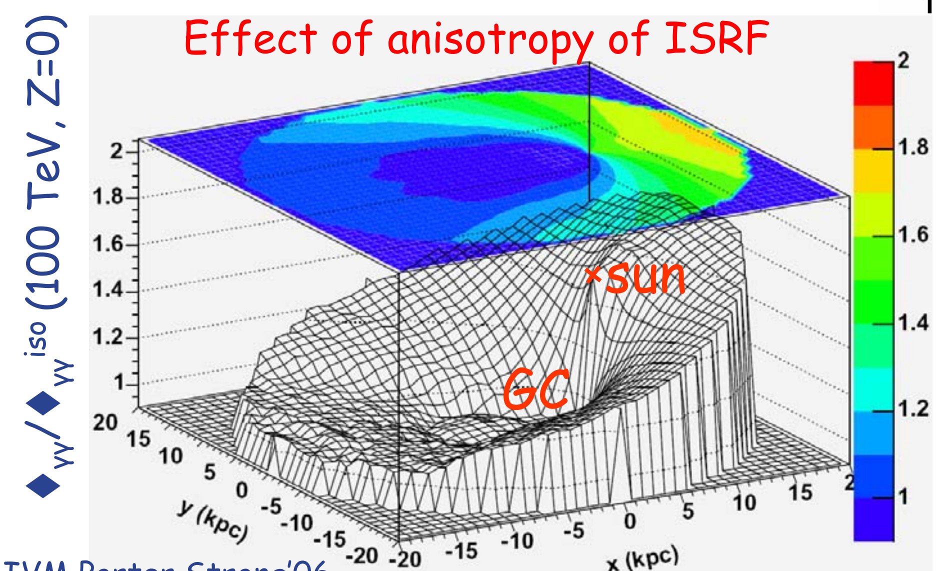
$$E_\gamma \varepsilon \sim m^2 c^4$$

$\varepsilon \sim 1$ eV (optical) -> $E_\gamma > 1$ TeV

The effect is important above ~30 TeV

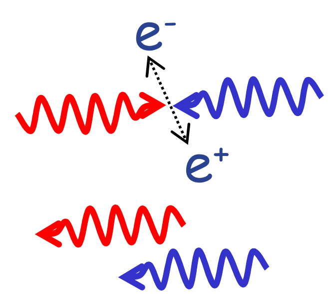


Porter,IVM,Strong'07

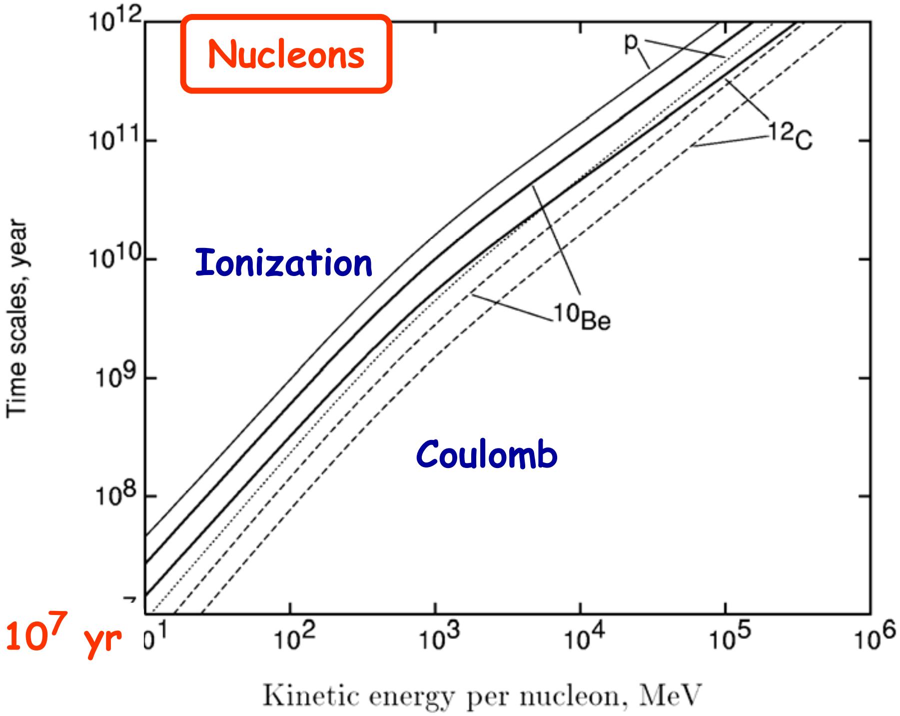


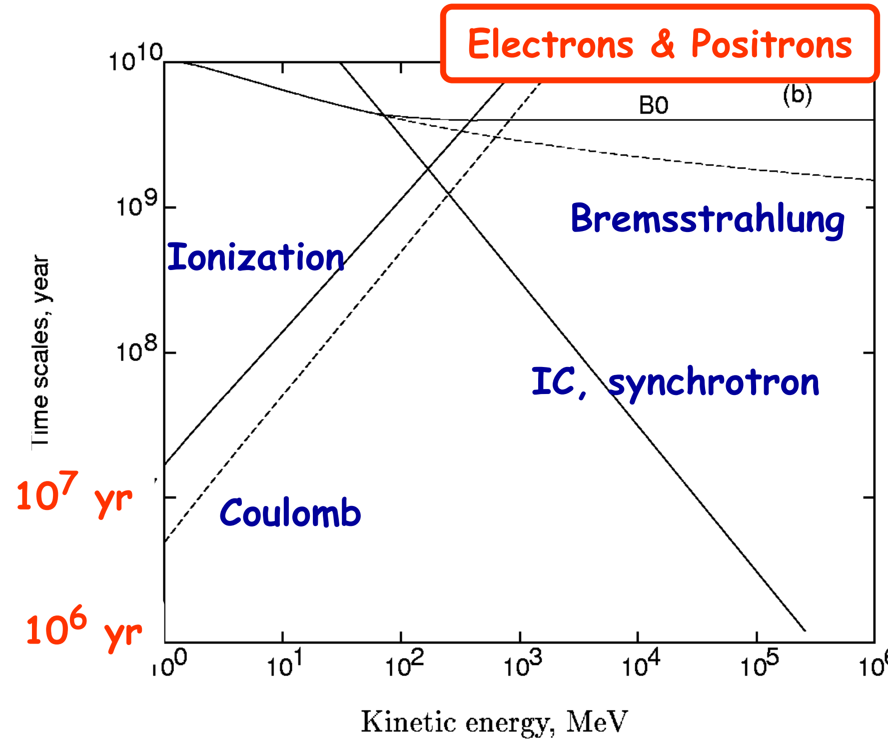
IVM,Porter,Strong'06

- Head-on
- Following



Energy Losses





Assuming:

H-gas: 0.01 atom/cc

Photon energy density: 1 eV/cc

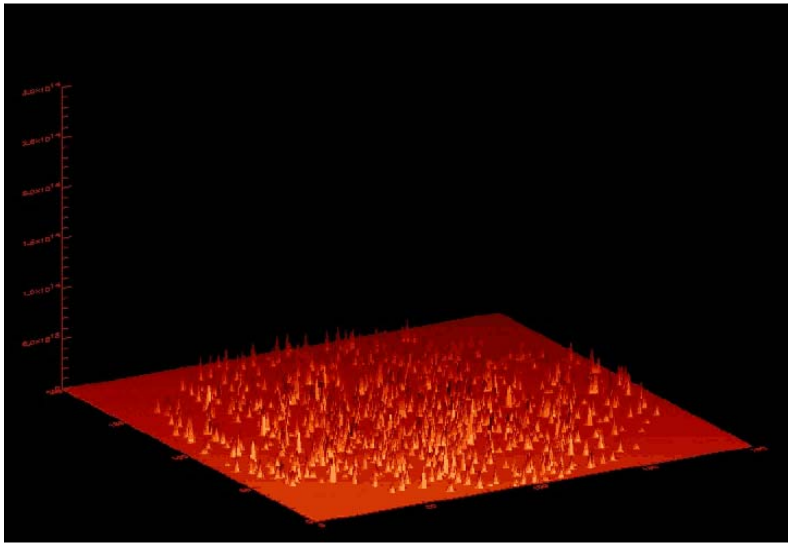
Electron energy loss timescale:

1 TeV: ~300 000 yr

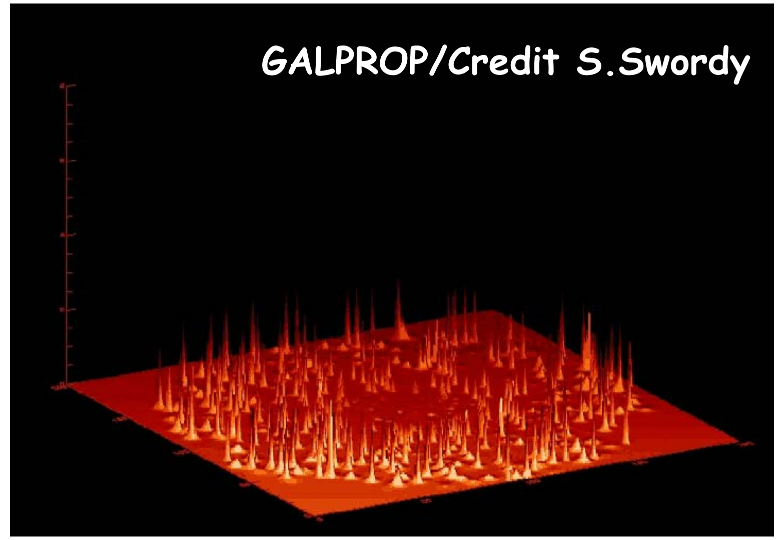
100 TeV: ~3 000 yr

Electron Fluctuations/SNR stochastic events

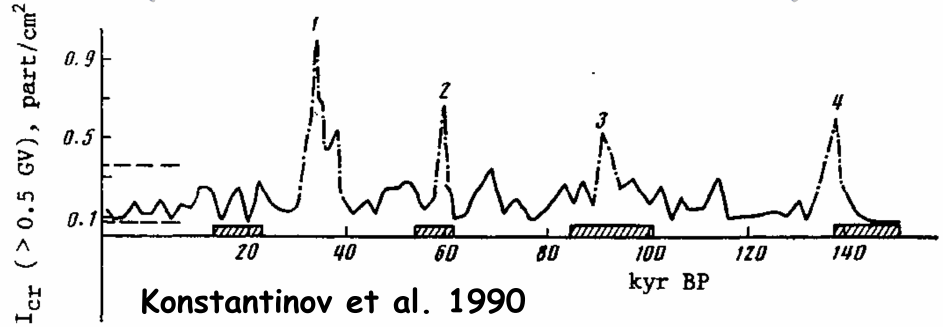
GeV electrons

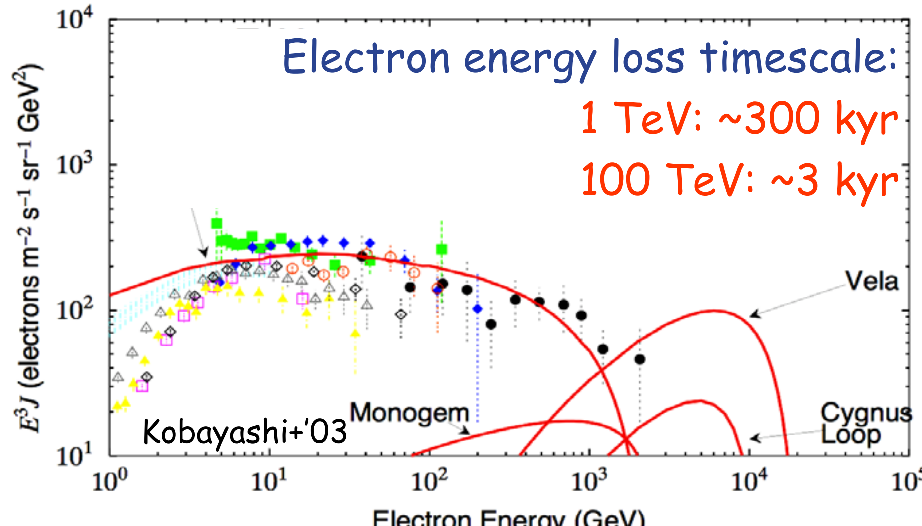


100 TeV electrons

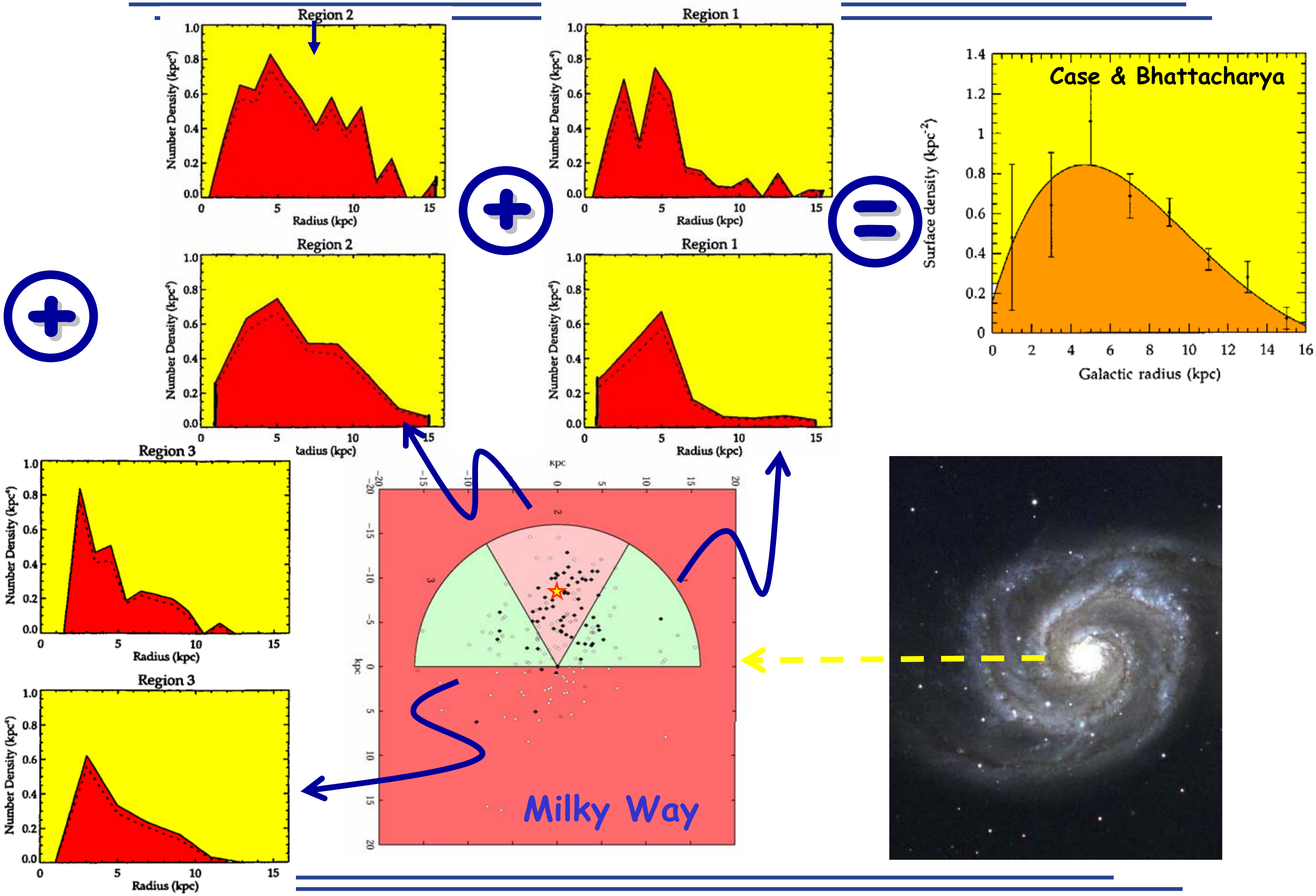


Historical variations of CR intensity over 150 000 yr (Be^{10} in South Polar ice cores)

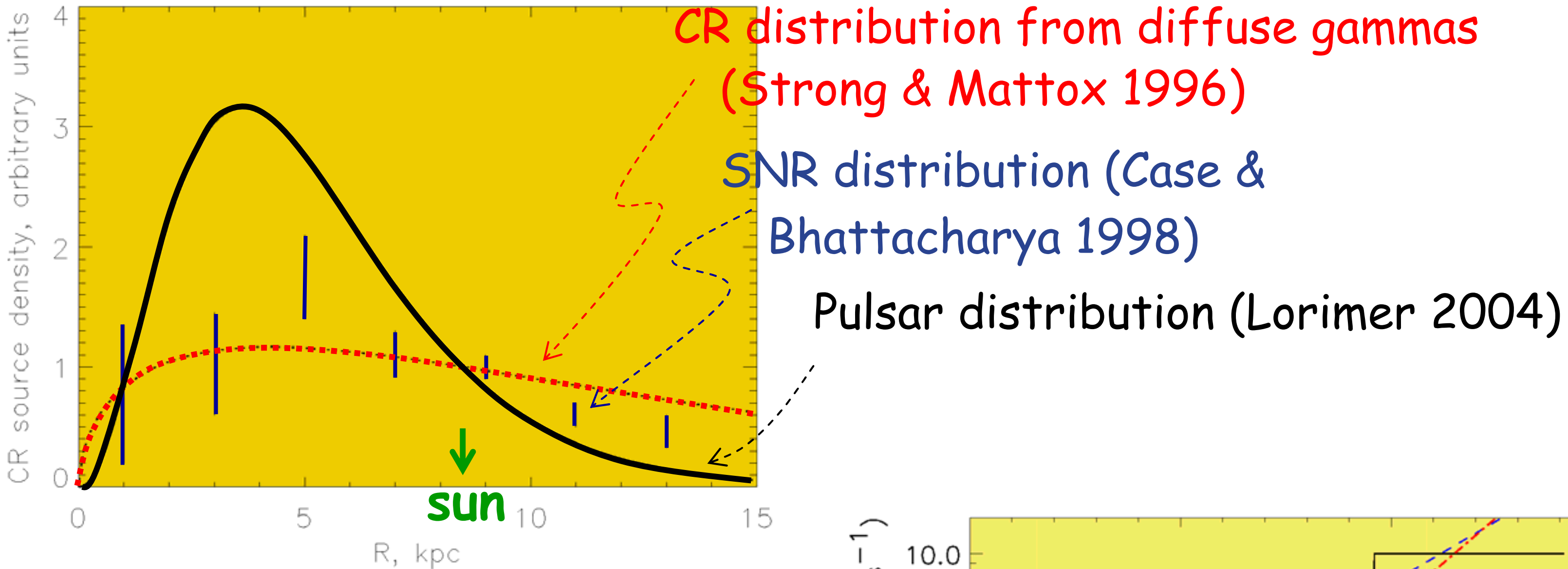




SNR distribution (very biased!)



Distribution of CR Sources & Gradient in the H_2/CO



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

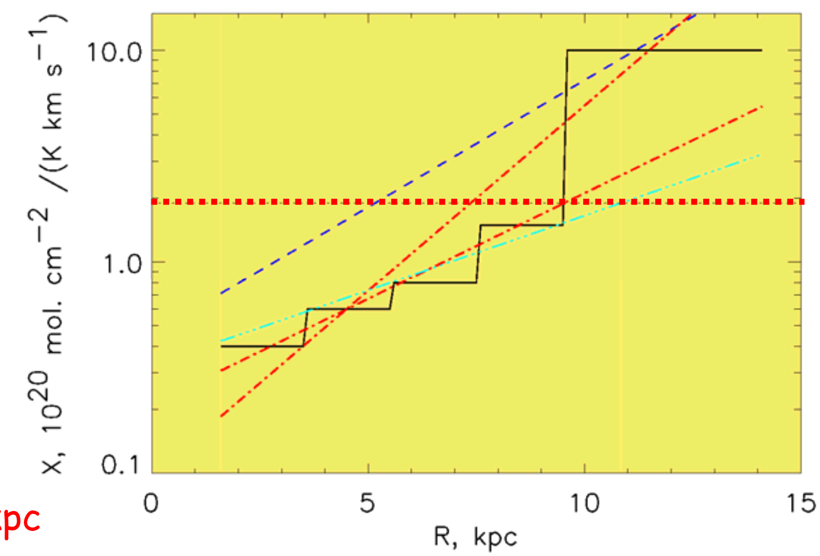
Histo -Strong+'04

----- -Sodroski+95,'97

1.9×10^{20} -Strong & Mattox'96

$\sim Z^{-1}$ -Boselli+'02

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



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