Current work on GALPROP

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Topics covered:

- Intro to the physics that we are working with (γ-ray – CR connection)
- GALPROP modeling of diffuse emission
- GALPROP principles
- What needs to be done

Diffuse Galactic Gamma-ray Emission

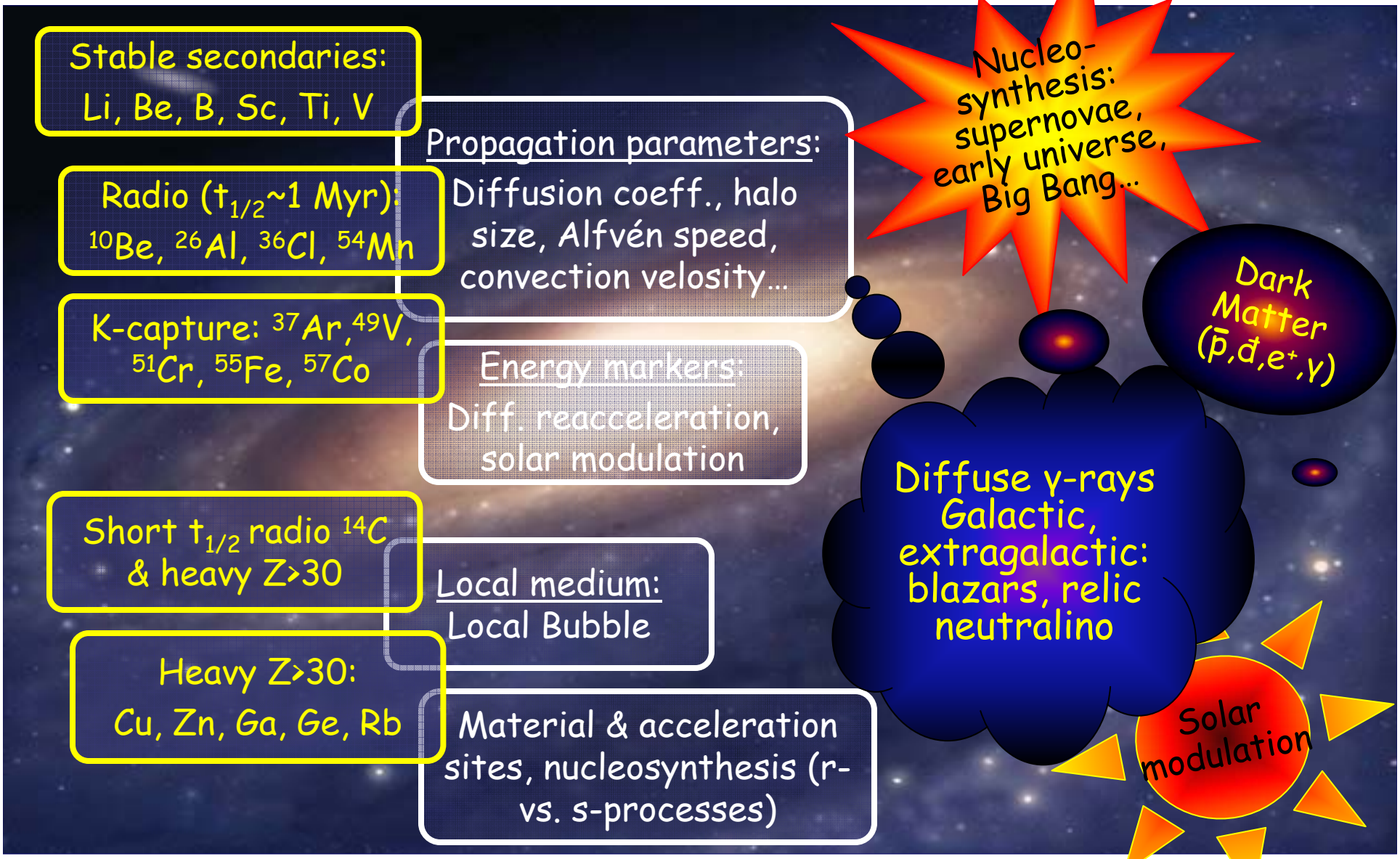
Tracer of CR (protons, electrons) interactions in the ISM:

- Study of CR species in distant locations (spectra & intensities)
  - CR acceleration (SNRs, W-R stars etc.) and propagation
- Emission from local clouds → local CR spectra
  - CR variations, Solar modulation
- May contain signatures of exotic physics (dark matter etc.)
  - Cosmology, SUSY, hints for accelerator experiments
- Background for point sources

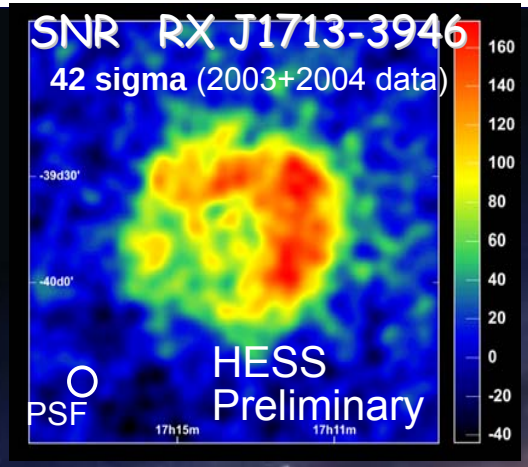
Besides:

- "Diffuse" emission from other regular galaxies
  - Cosmic rays in other galaxies !
- Foreground in studies of the extragalactic diffuse emission
- Extragalactic diffuse emission (blazars ?) may contain signatures of exotic physics (dark matter, BH evaporation etc.)

Nuclear component in CR: What we can learn?



CR Interactions in the Interstellar Medium



ISM

X,γ

$e^{\pm}$

$\vec{B}$

synchrotron

Chandra

ISRF

IC

P
He
CNO

diffusion
energy losses
reacceleration
convection
etc.

gas

bremss

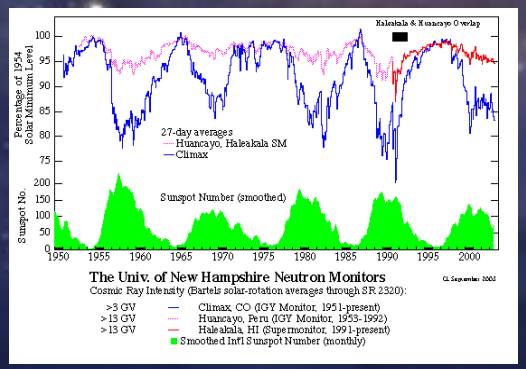
π^0

GLAST

$e^{\pm}$

$\pi^{\pm}$

gas



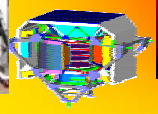
$\bar{p}$

p

He
CNO

LiBeB

BESS

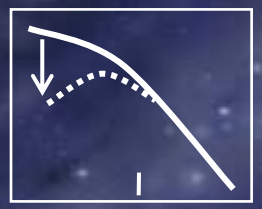


AMS

helio-modulation

ACE

Flux

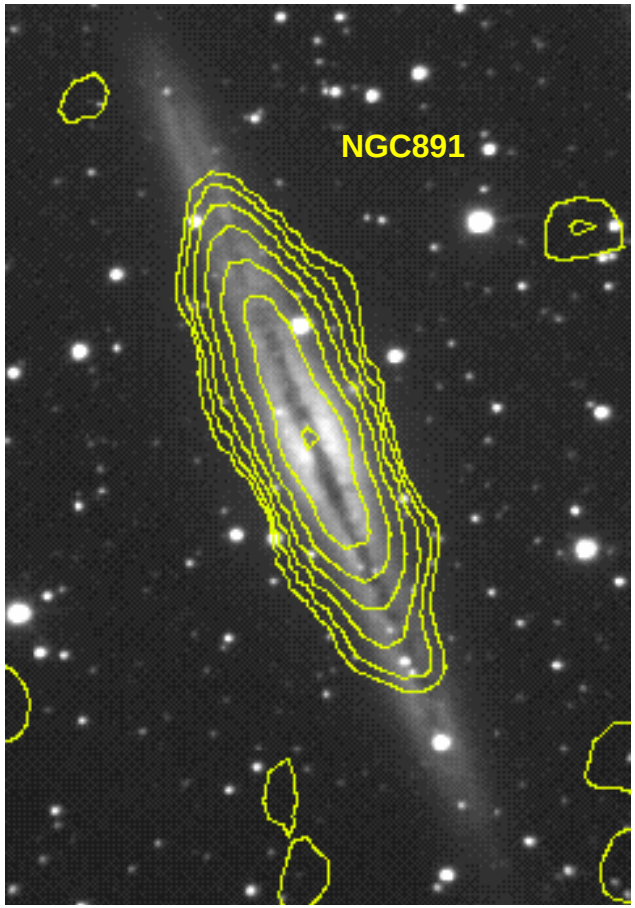


20 GeV/n

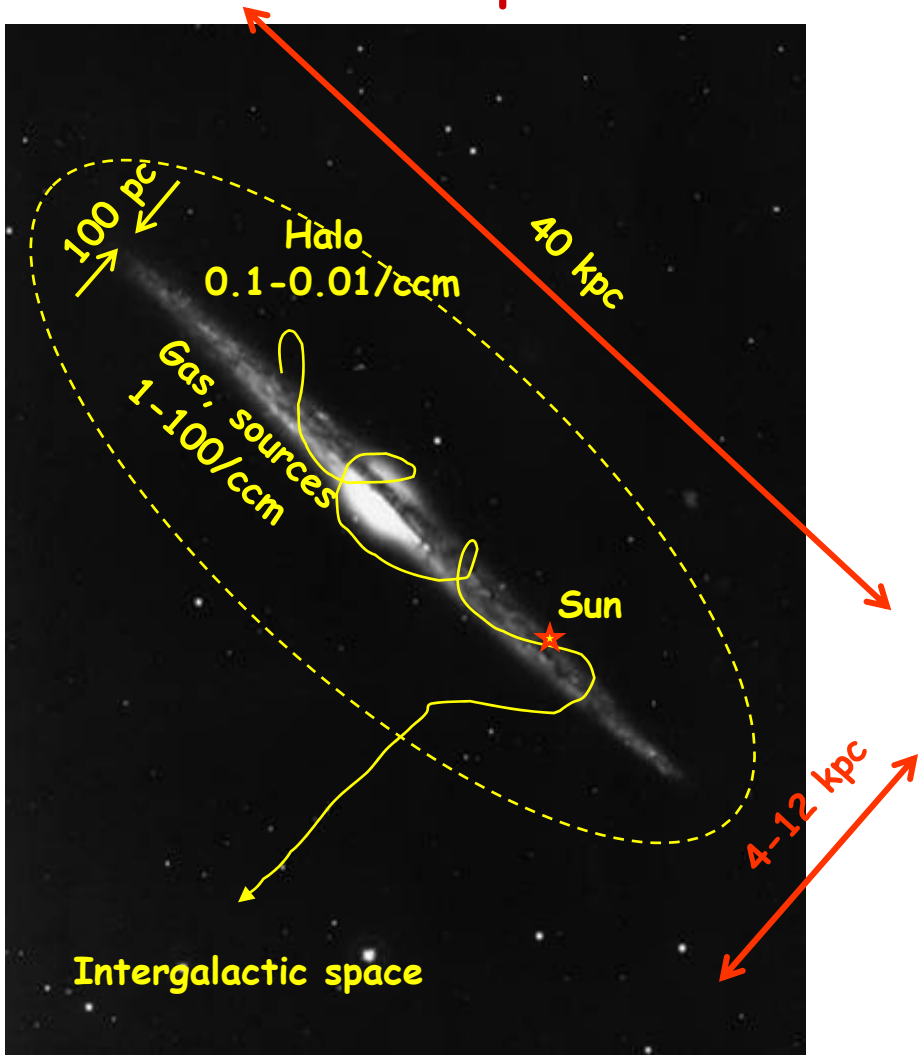
CR species:
- Only 1 location
- modulation

CR Propagation: Milky Way Galaxy

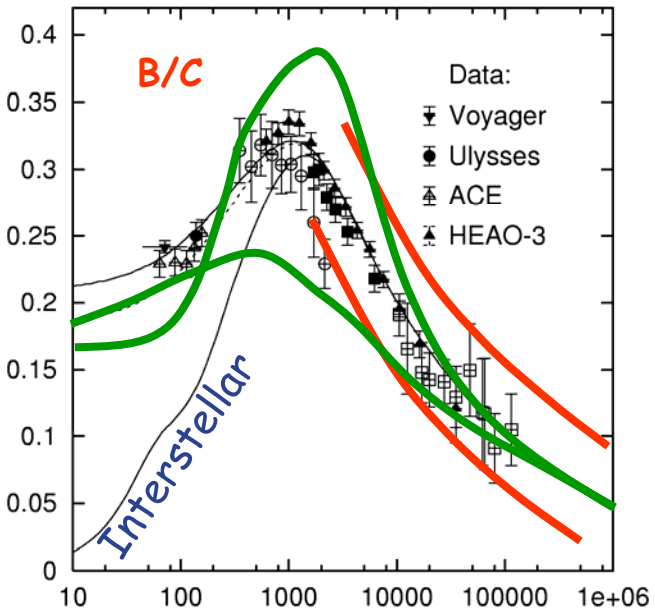
Optical image: Cheng et al. 1992, Brinkman et al. 1993
Radio contours: Condon et al. 1998 AJ **115**, 1693



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



Fixing Propagation Parameters: Standard Way



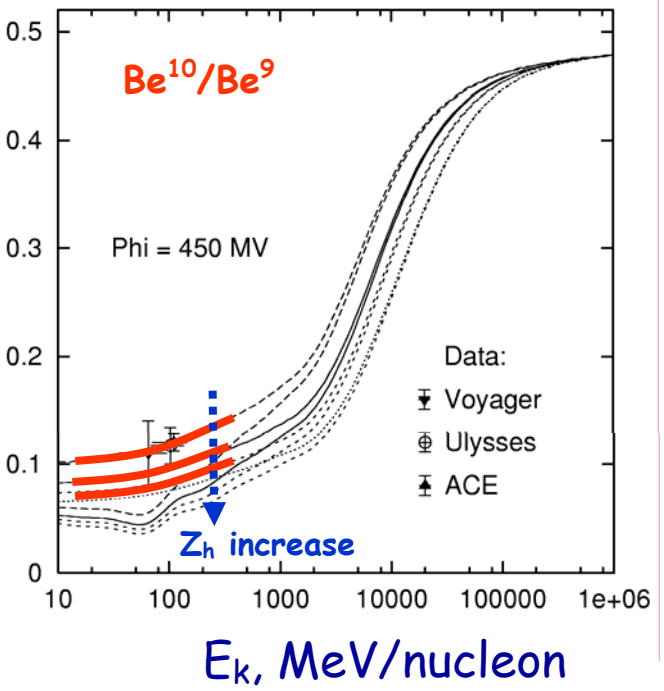
Using secondary/primary nuclei ratio:

- Diffusion coefficient and its index
- Propagation mode and its parameters

(e.g., reacceleration V_A, convection V_z)

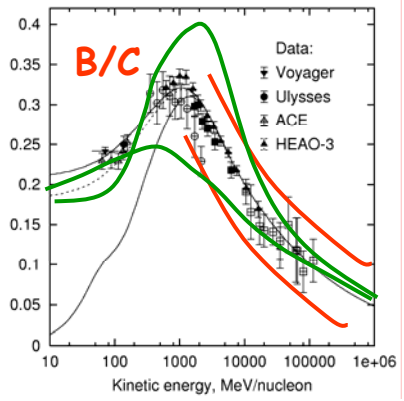
Radioactive isotopes:

Galactic halo size Z_h



Peak in the Secondary/Primary Ratio

- Leaky-box model:
  fitting path-length distribution -> free function

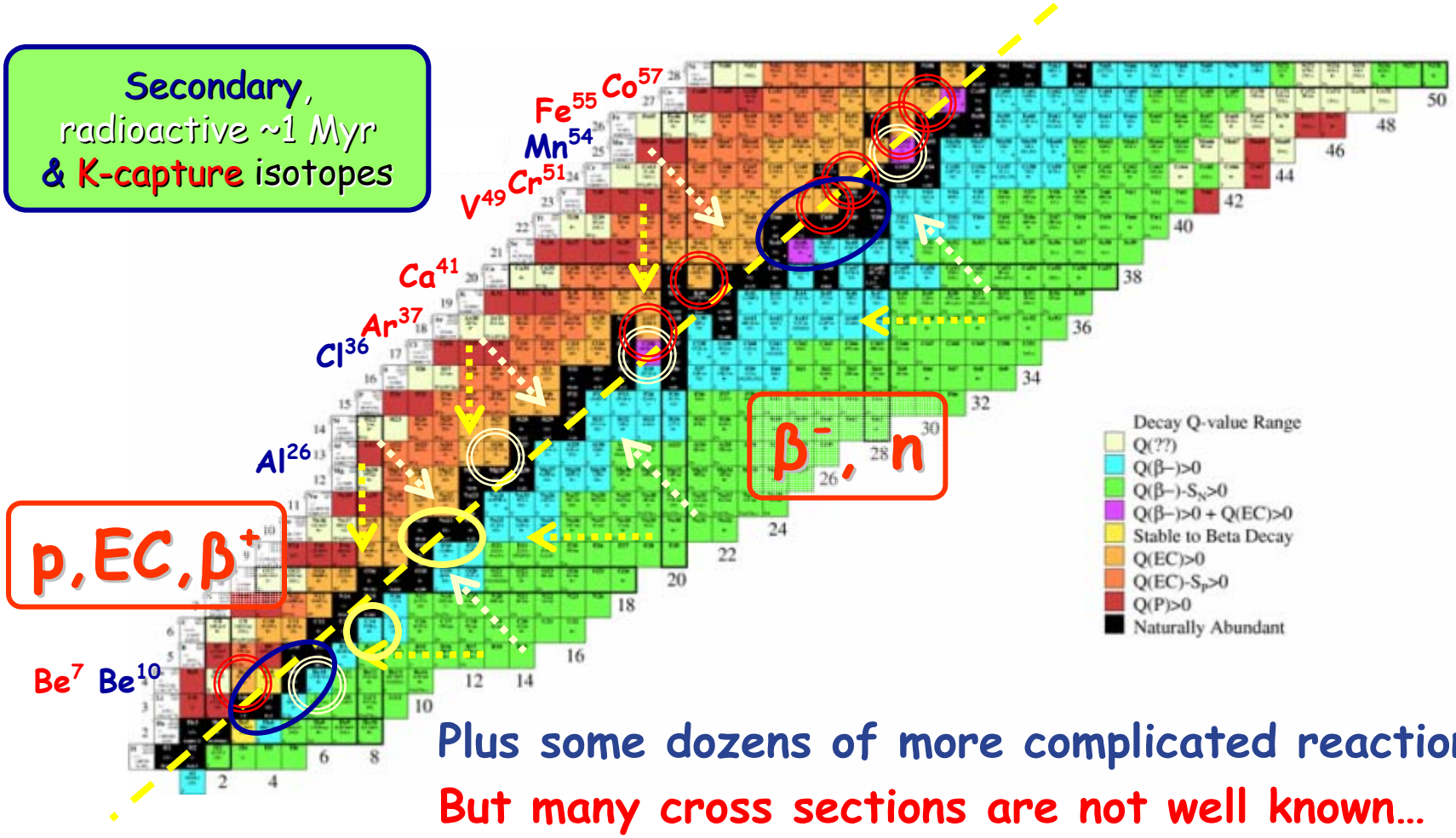


- Diffusion models:
  - Plain diffusion
  - Diffusive reacceleration
  - Convection
  - Damping of interstellar turbulence
  - Etc.

Measuring many isotopes in CR simultaneously may help to distinguish

Nuclear Reaction Network+Cross Sections

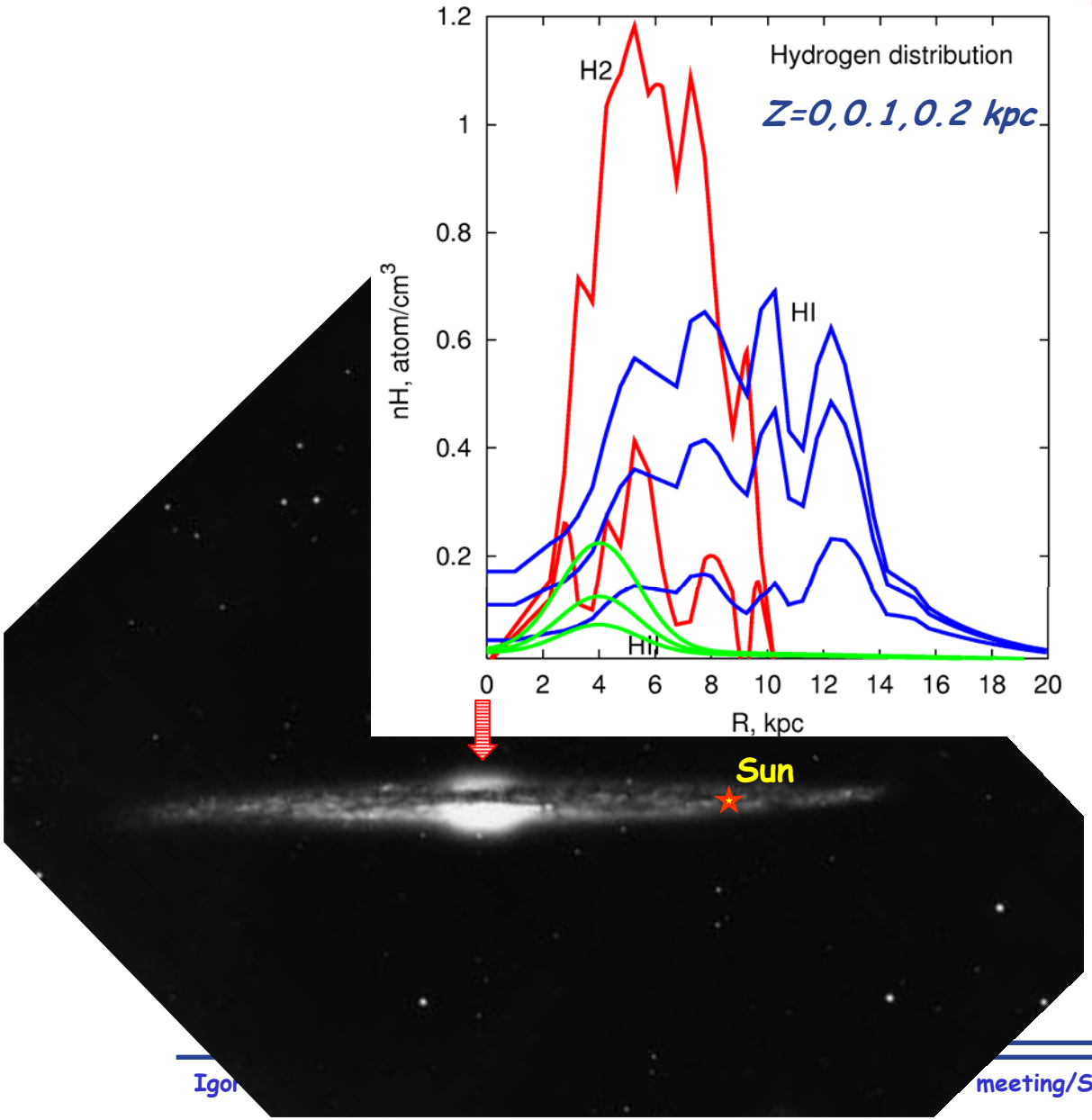
Secondary, radioactive ~1 Myr & **K-capture** isotopes



Plus some dozens of more complicated reactions.

But many cross sections are not well known…

Gas Distribution

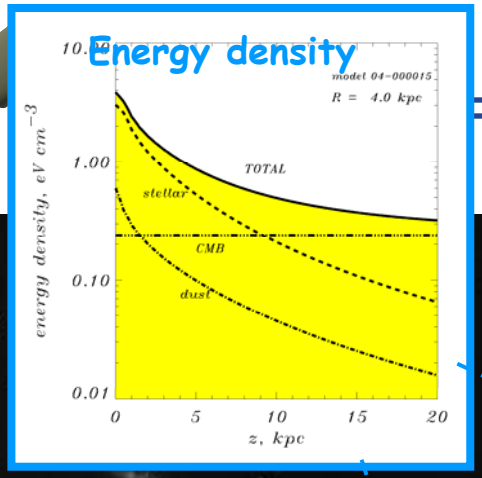


Molecular hydrogen H_2 is traced using J=1-0 transition of ^{12}CO, concentrated mostly in the plane (z~70 pc, R<10 kpc)

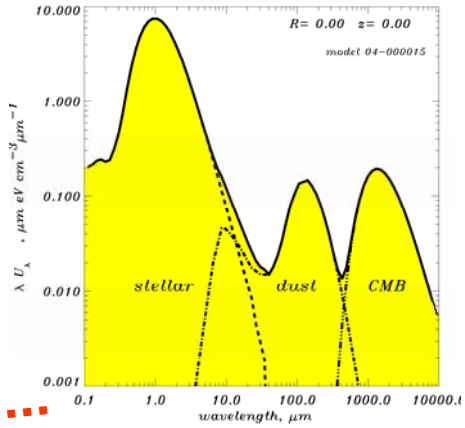
Atomic hydrogen H I (radio 21 cm) has a wider distribution (z~1 kpc, R~30 kpc)

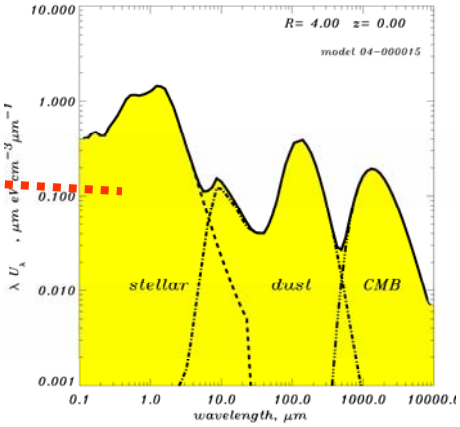
Ionized hydrogen H II (visible, UV, X) small proportion, but exists even in halo (z~1 kpc)

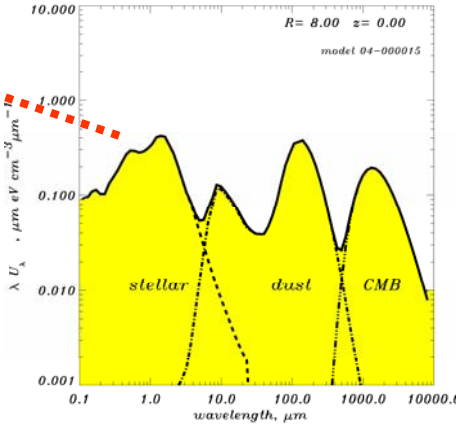
Interstellar Radiation Field



- Stellar
- Dust
- CMB







Transport Equations ~90 (no. of CR species)

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

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

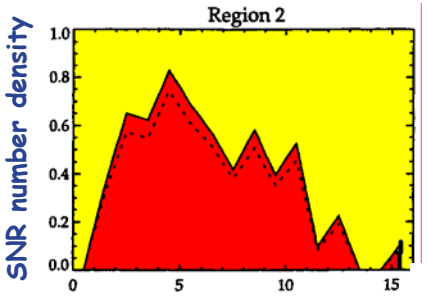
$$+ \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} \right]$$ diffusive reacceleration

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

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

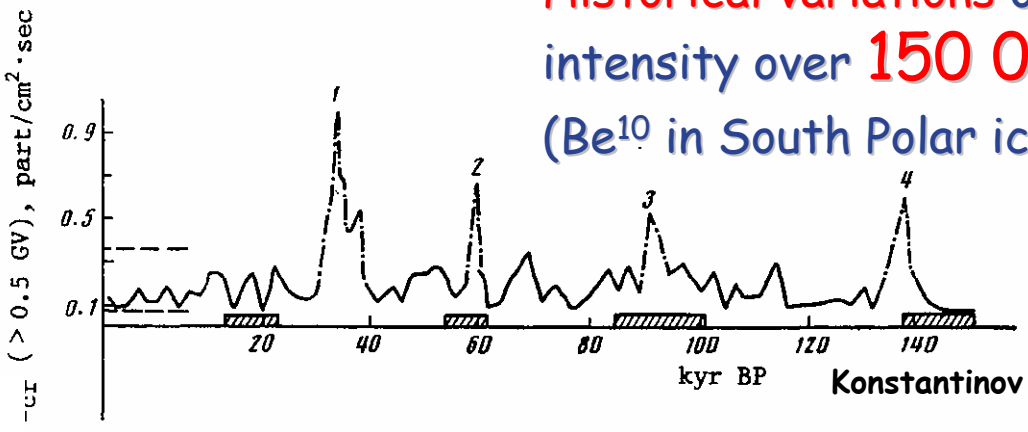
$\psi(\mathbf{r},p,t)$ – *density per total momentum*

CR Variations in Space & Time

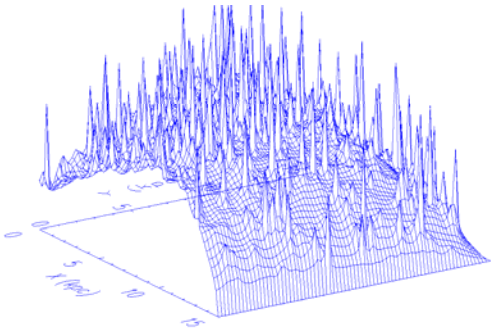


More frequent SN
in the spiral arms

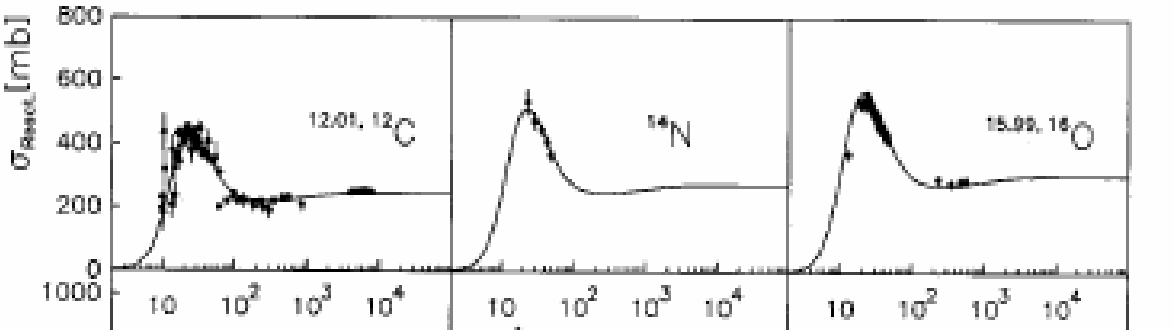
Historical variations of CR intensity over 150 000 yr (Be^{10} in South Polar ice)



Electron/positron energy losses

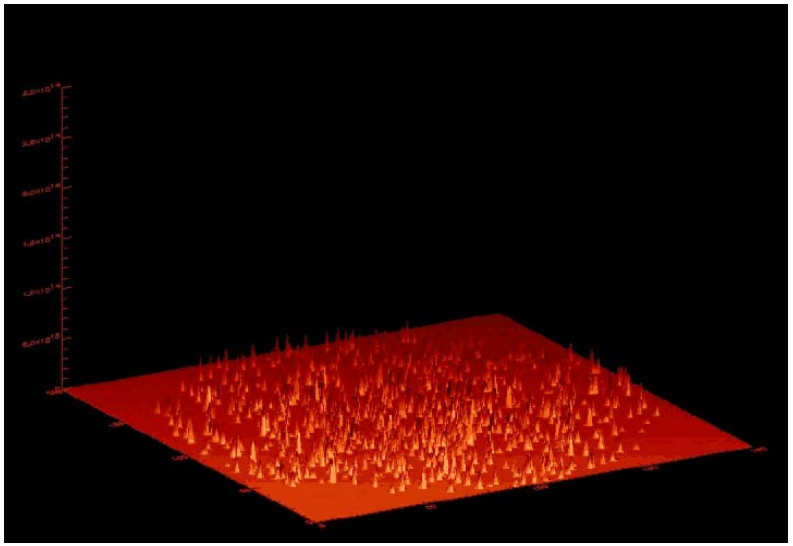


Different "collecting" areas A vs. p

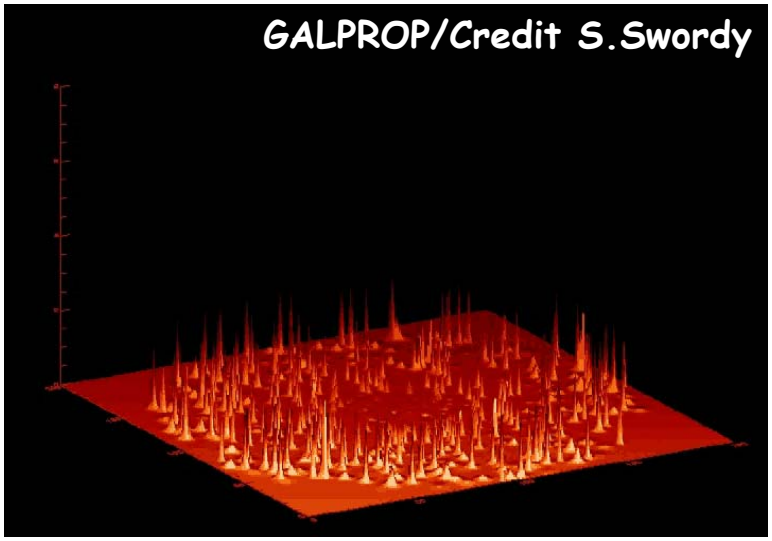


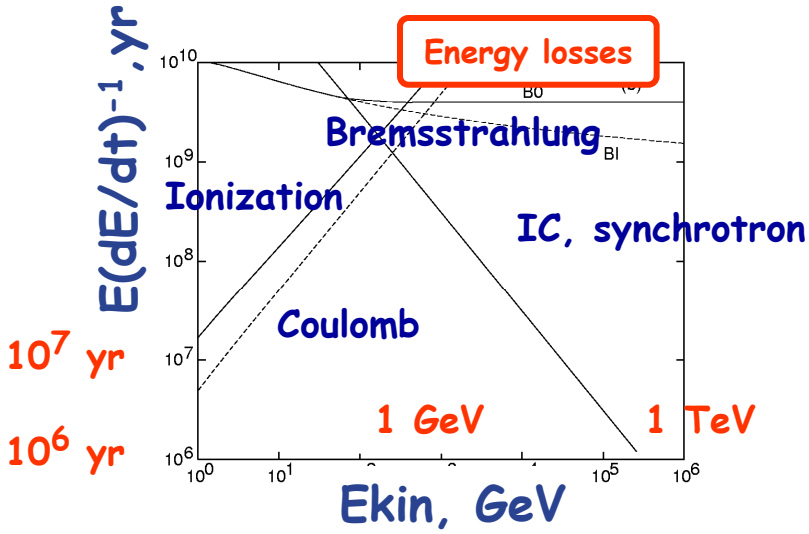
Electron Fluctuations/SNR stochastic events

GeV electrons



100 TeV electrons



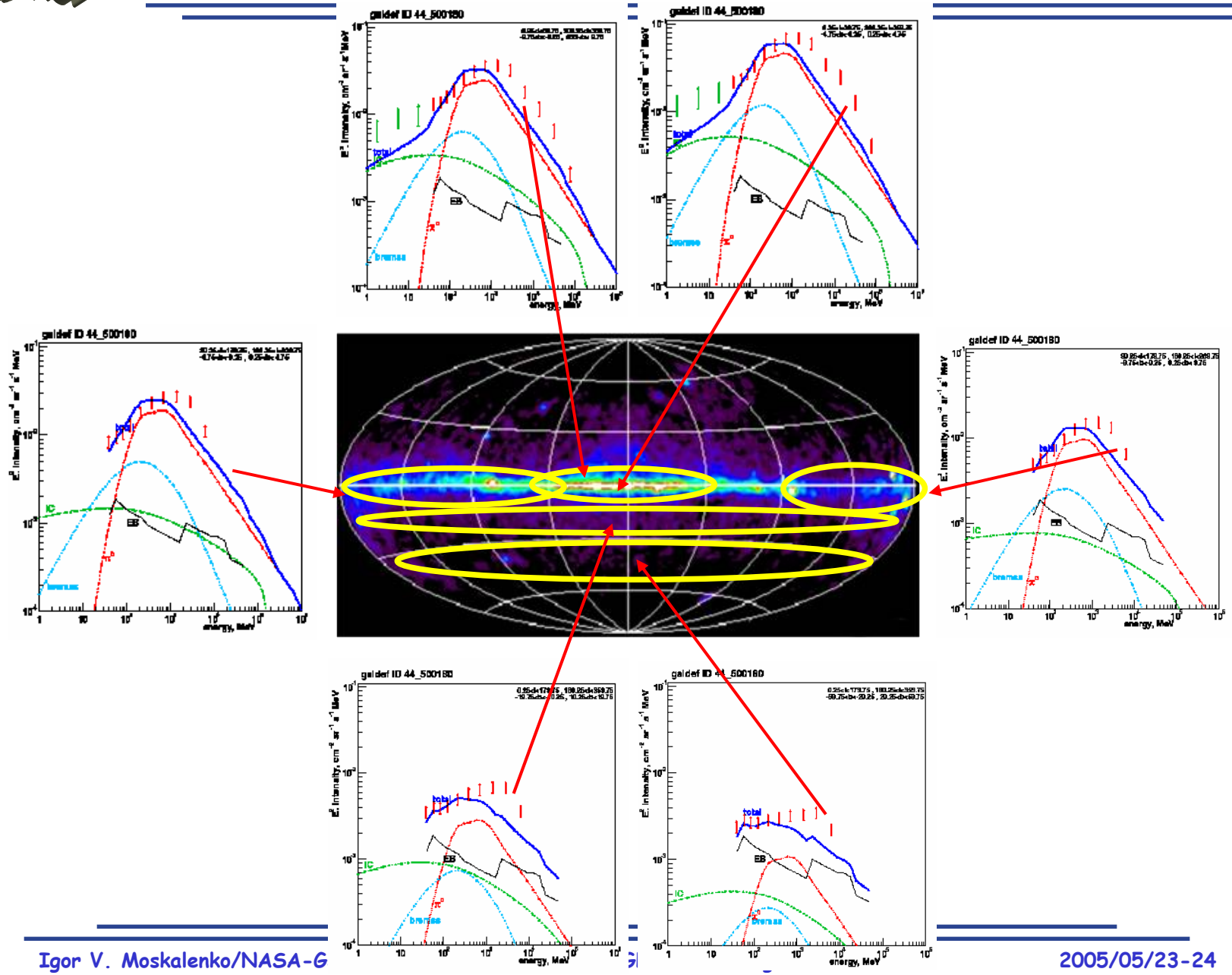


Electron energy loss timescale:

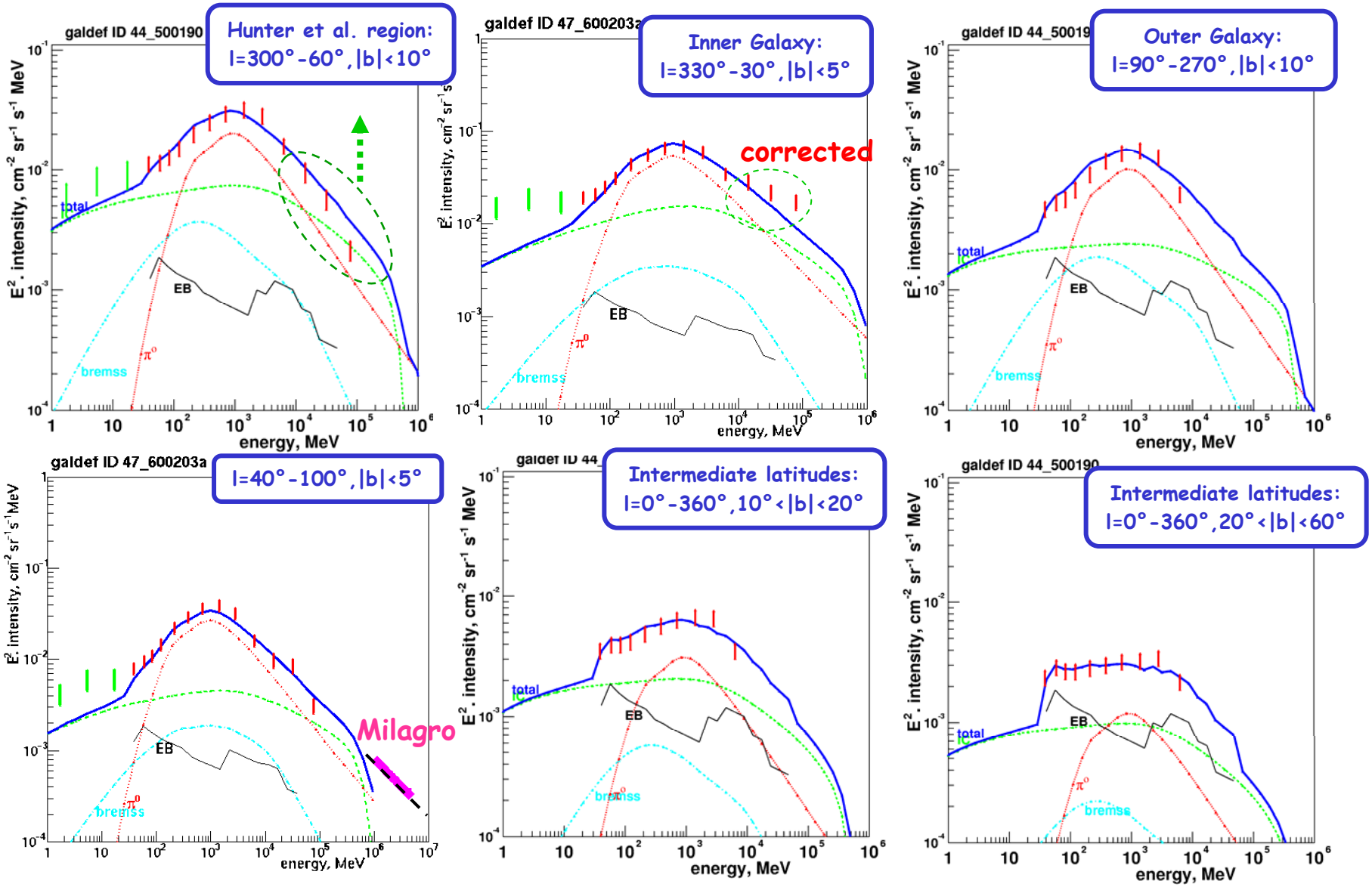
1 TeV: ~300 000 yr

100 TeV: ~3 000 yr

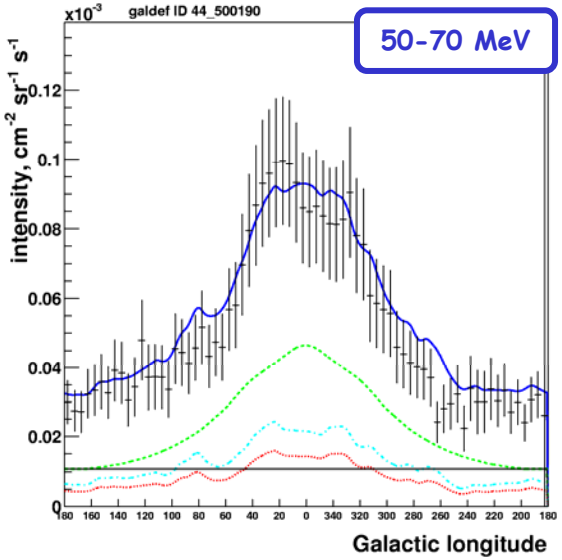
Wherever you look, the GeV γ-ray excess is there !

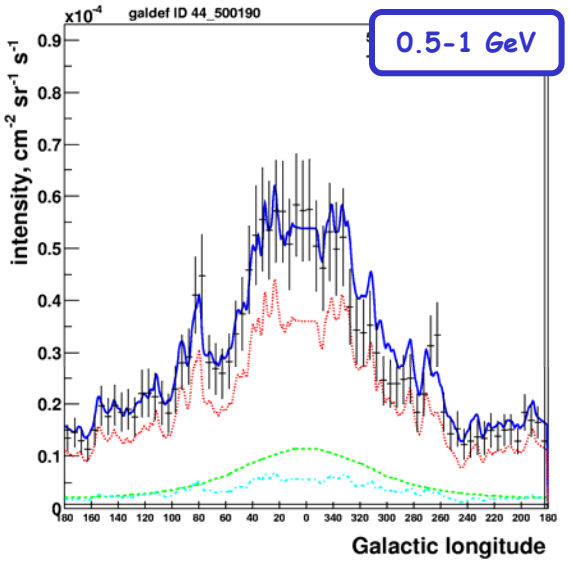


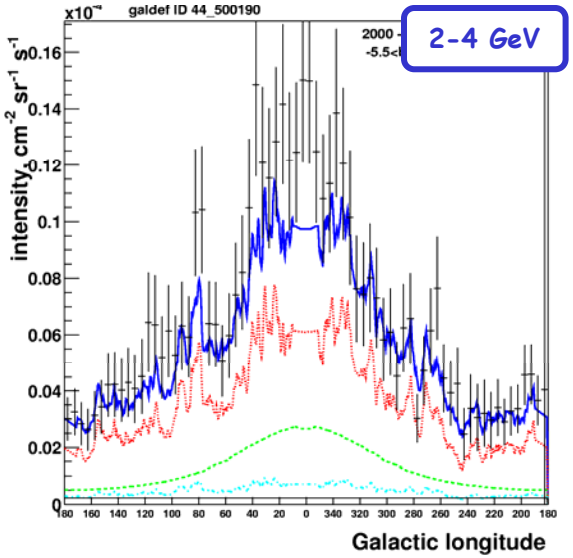
Diffuse Gammas at Different Sky Regions

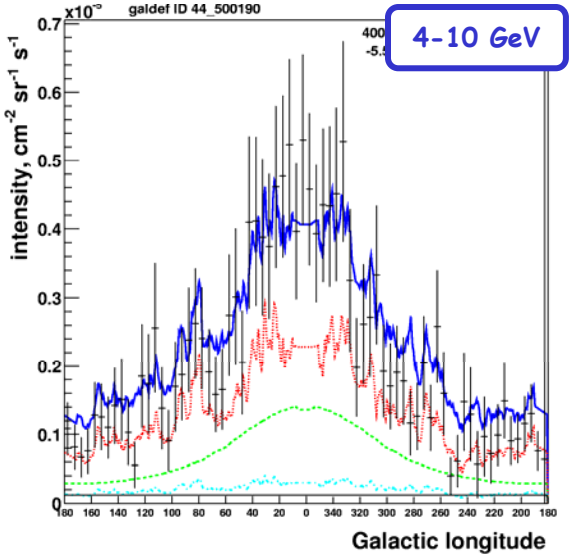


Longitude Profiles |b|<5°

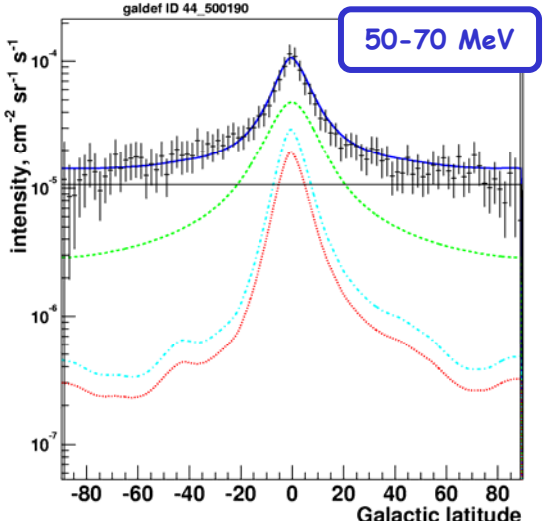


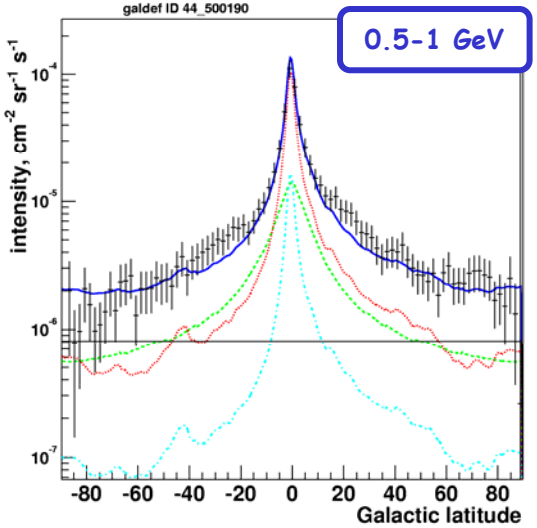


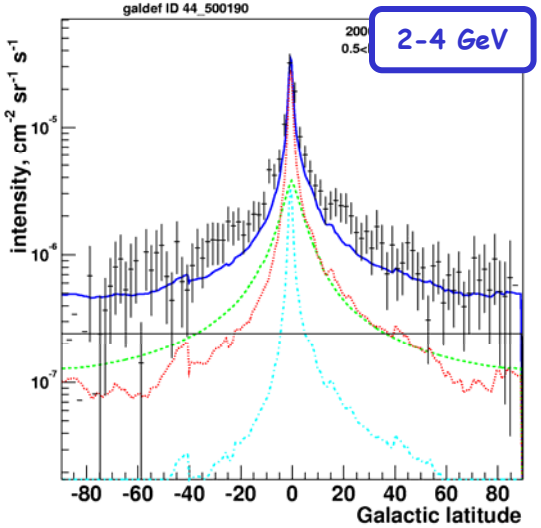


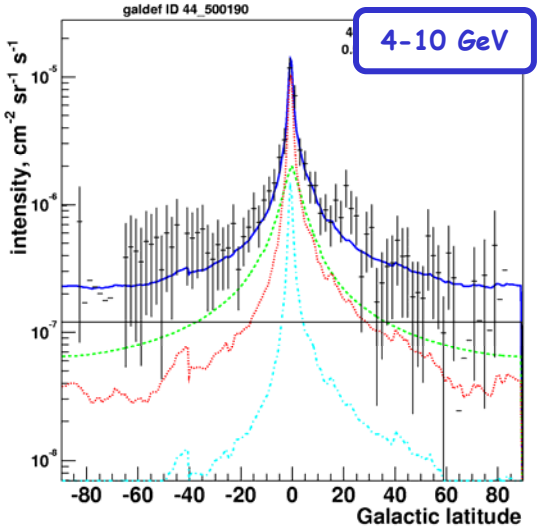


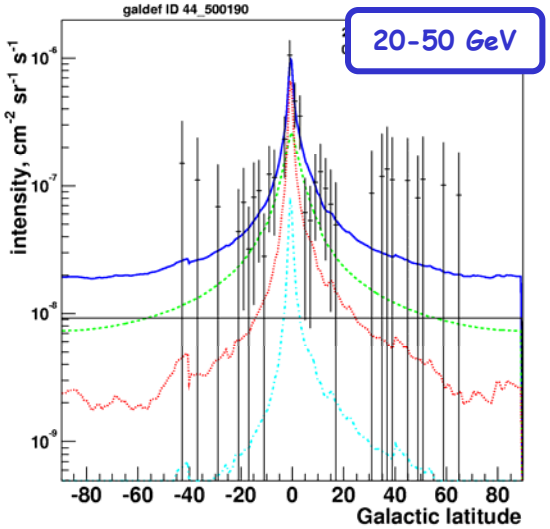
Latitude Profiles: Inner Galaxy



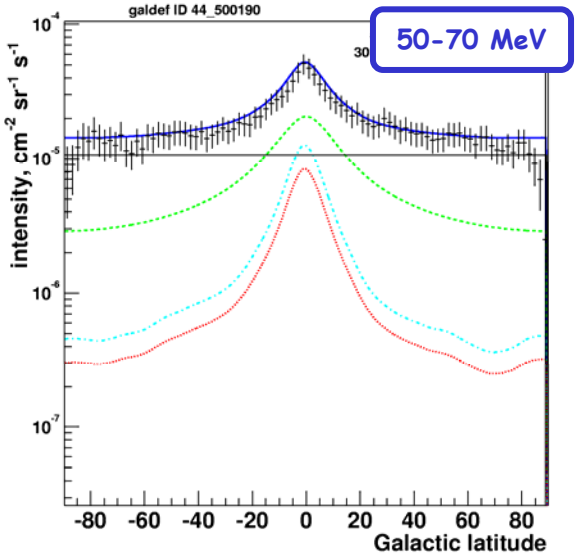


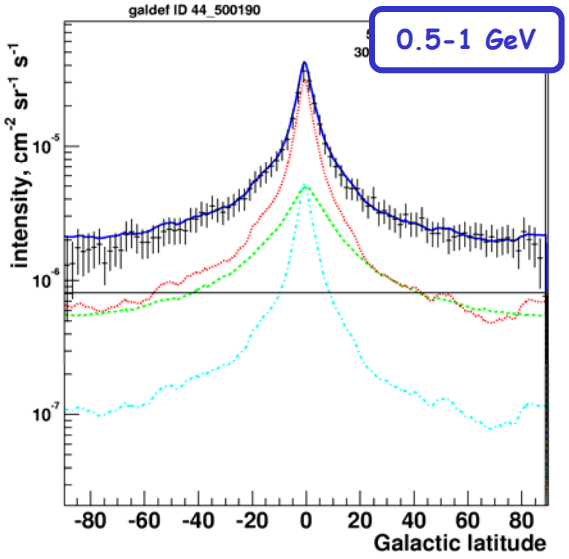


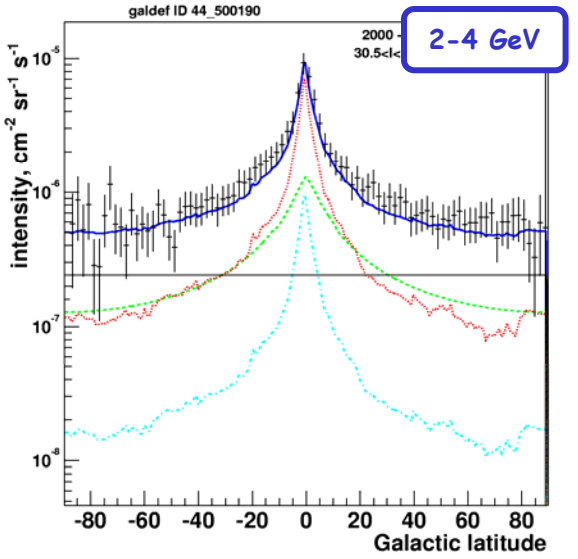


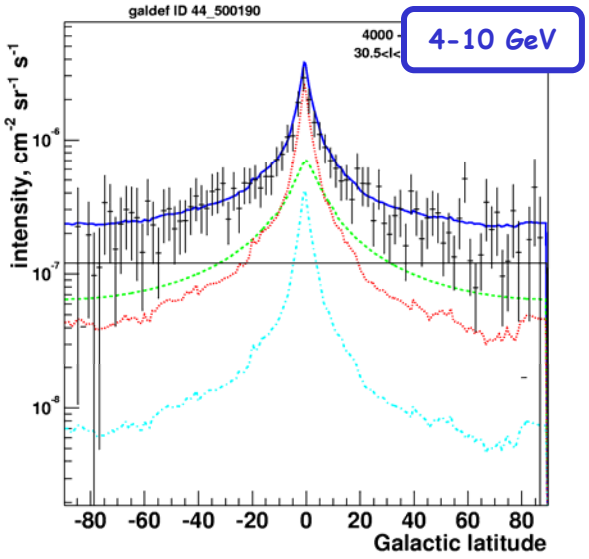


Latitude Profiles: Outer Galaxy



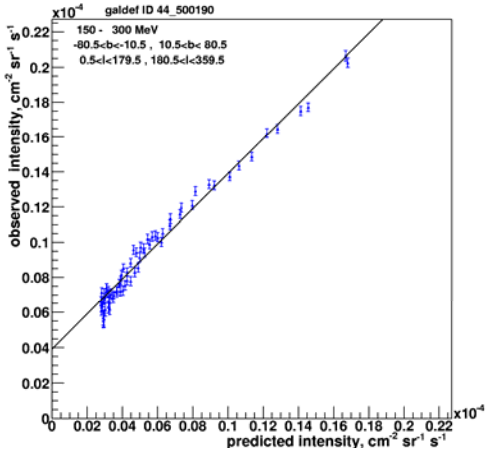


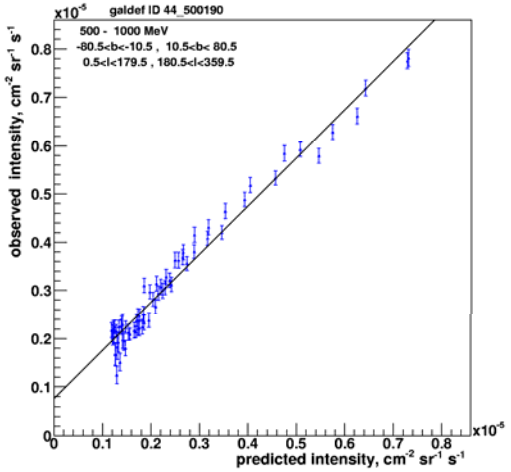


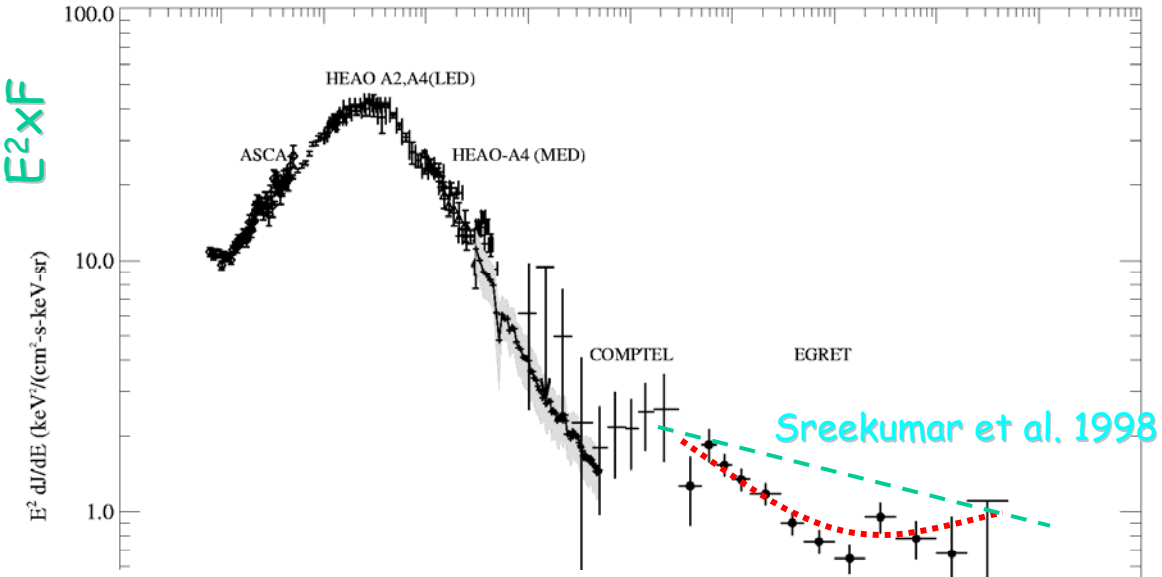


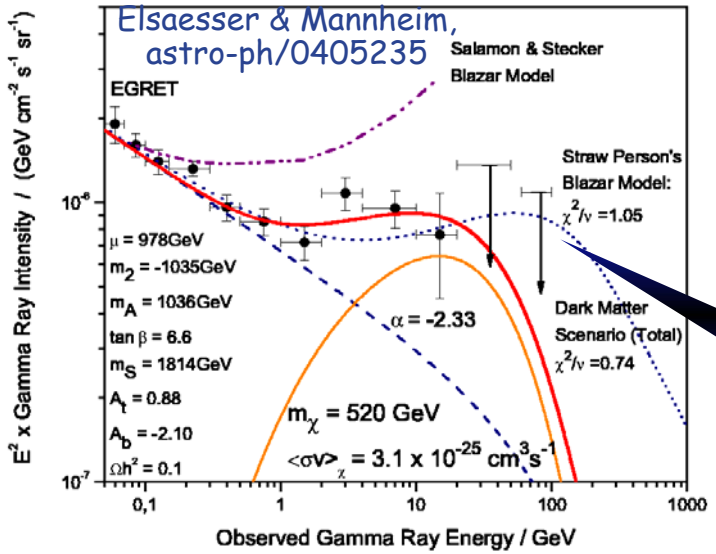
Extragalactic Gamma-Ray Background

Predicted vs. observed



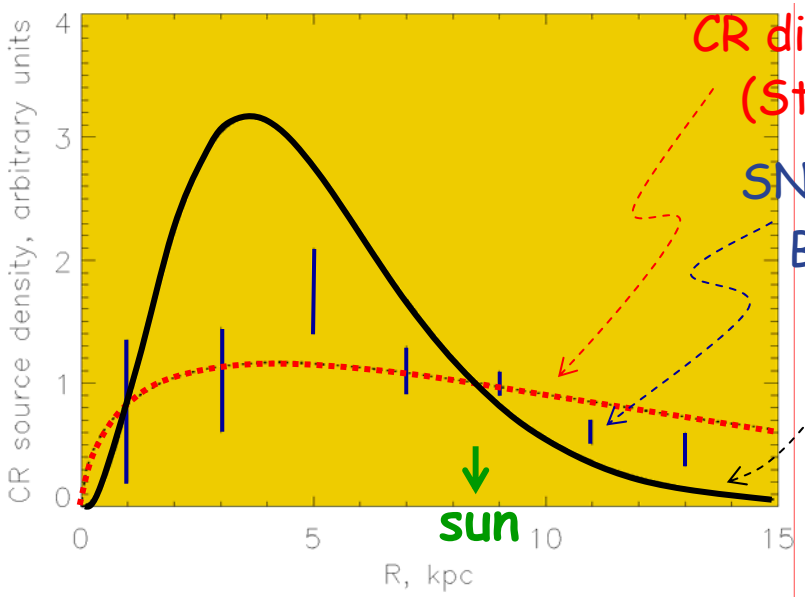






- Blazars
- Cosmological neutralinos

Distribution of CR Sources & Gradient in the CO/H_2



CR distribution from diffuse gammas (Strong & Mattox 1996)

SNR distribution (Case & Bhattacharya 1998)

Pulsar distribution (Lorimer 2004)

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

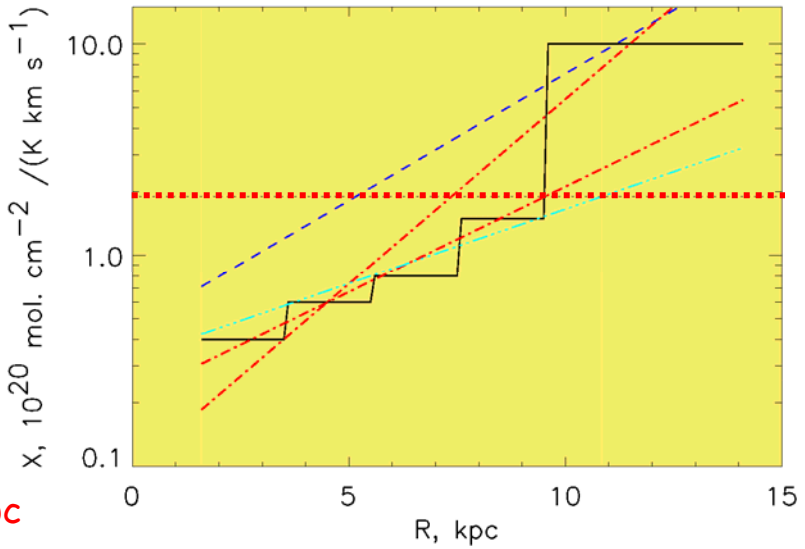
Histo –This work, Strong et al.'04

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

1.9×10^{20} -Strong & Mattox'96

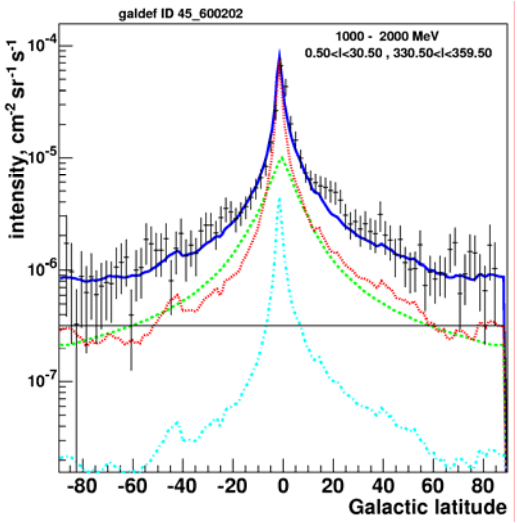
$\sim Z^{-1}$ -Boselli et al.'02

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

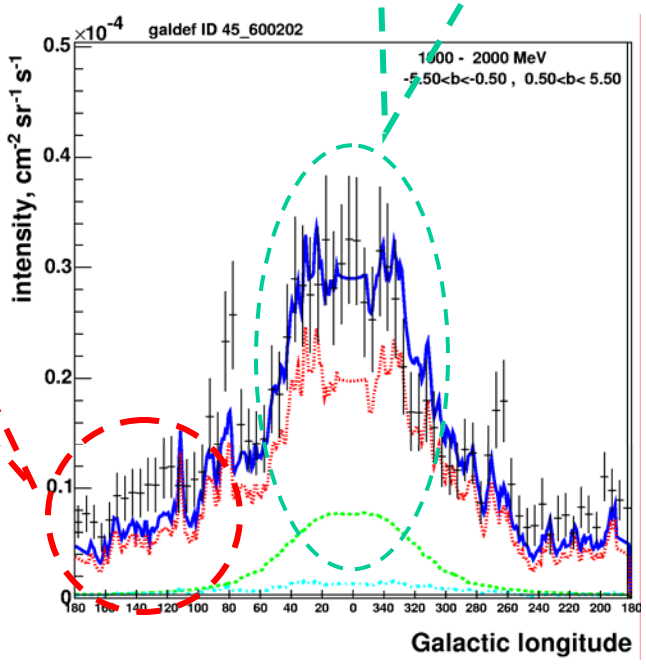


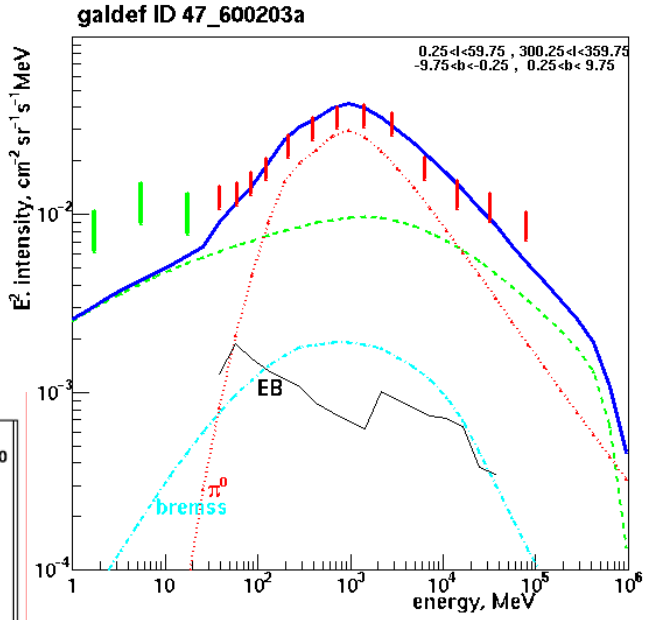
Again Diffuse Galactic Gamma Rays

Very good agreement !



More IC in the GC
-better agreement !





The pulsar distribution vs. R falls too fast **OR** larger H_2/CO gradient

GALPROP Input: galdef-files

GALPROP is parameter-driven (user can specify everything!)

Grids

- 2D/3D –options; symmetry options (full 3D, 1/8 -quadrants)
- Spatial, energy/momentum, latitude & longitude grids
- Ranges: energy, R, x, y, z, latitude & longitude
- Time steps

Propagation parameters

- D_{xx}, V_A, V_C & injection spectra (p,e)
- X-factors (including R-dependence)

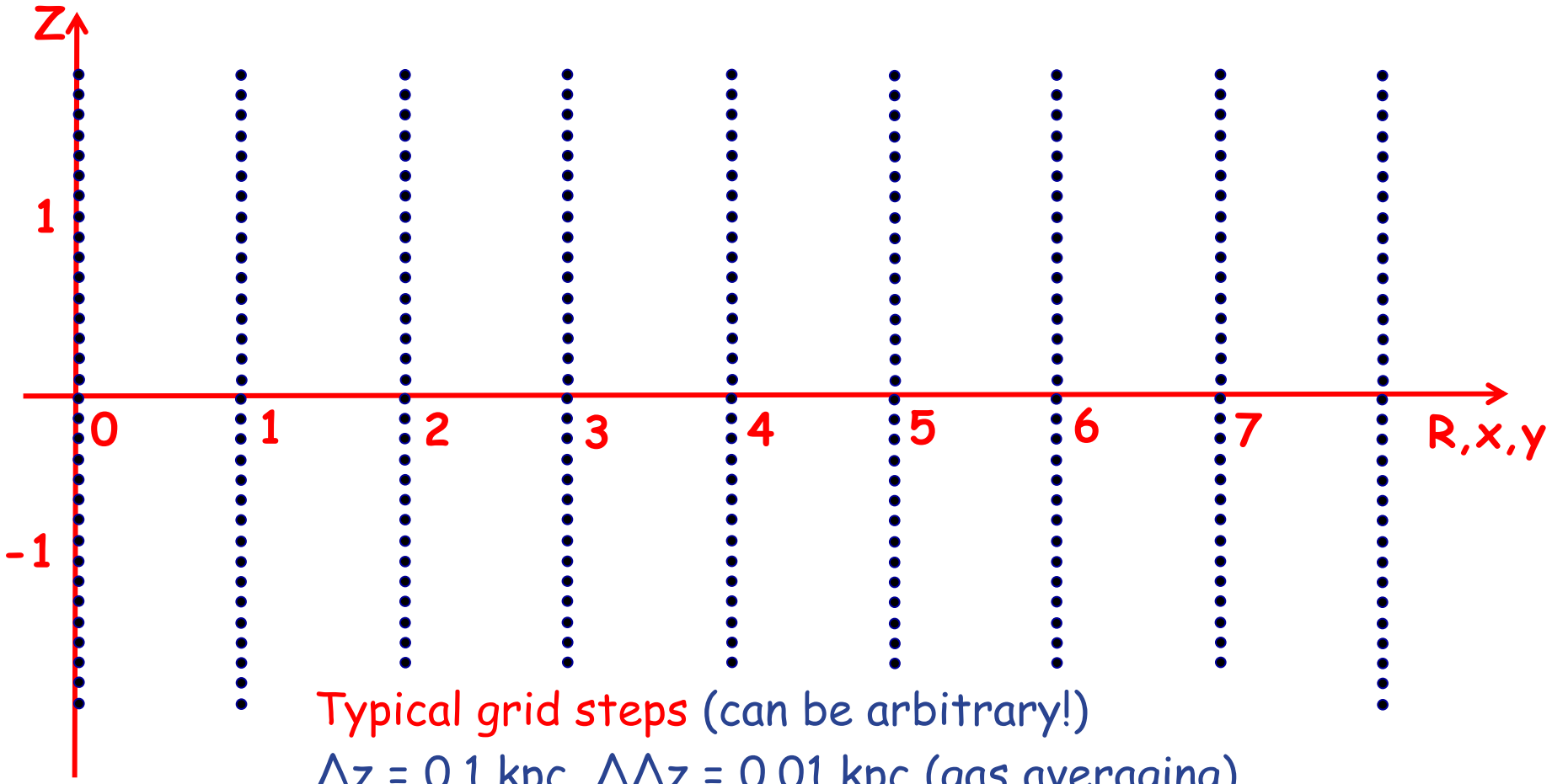
Sources

- Parameterized distributions
- Known SNRs
- Random SNRs (with given/random spectra), time dependent eq.

Other

- Source isotopic abundances, secondary particles (pbar , $e^{\pm}$, γ, synchro), anisotropic IC, energy losses, nuclear production cross sections…

Grids



Typical grid steps (can be arbitrary!)

Δz = 0.1 kpc, $\Delta\Delta z$ = 0.01 kpc (gas averaging)

ΔR = 1 kpc

ΔE = x1.2 (log-grid)

GALPROP Output/FITS files

Provides literally everything:

- All nuclei and particle spectra in every grid point (x,y,R,z,E) -FITS files

Separately for π^0-decay, IC, bremsstrahlung:

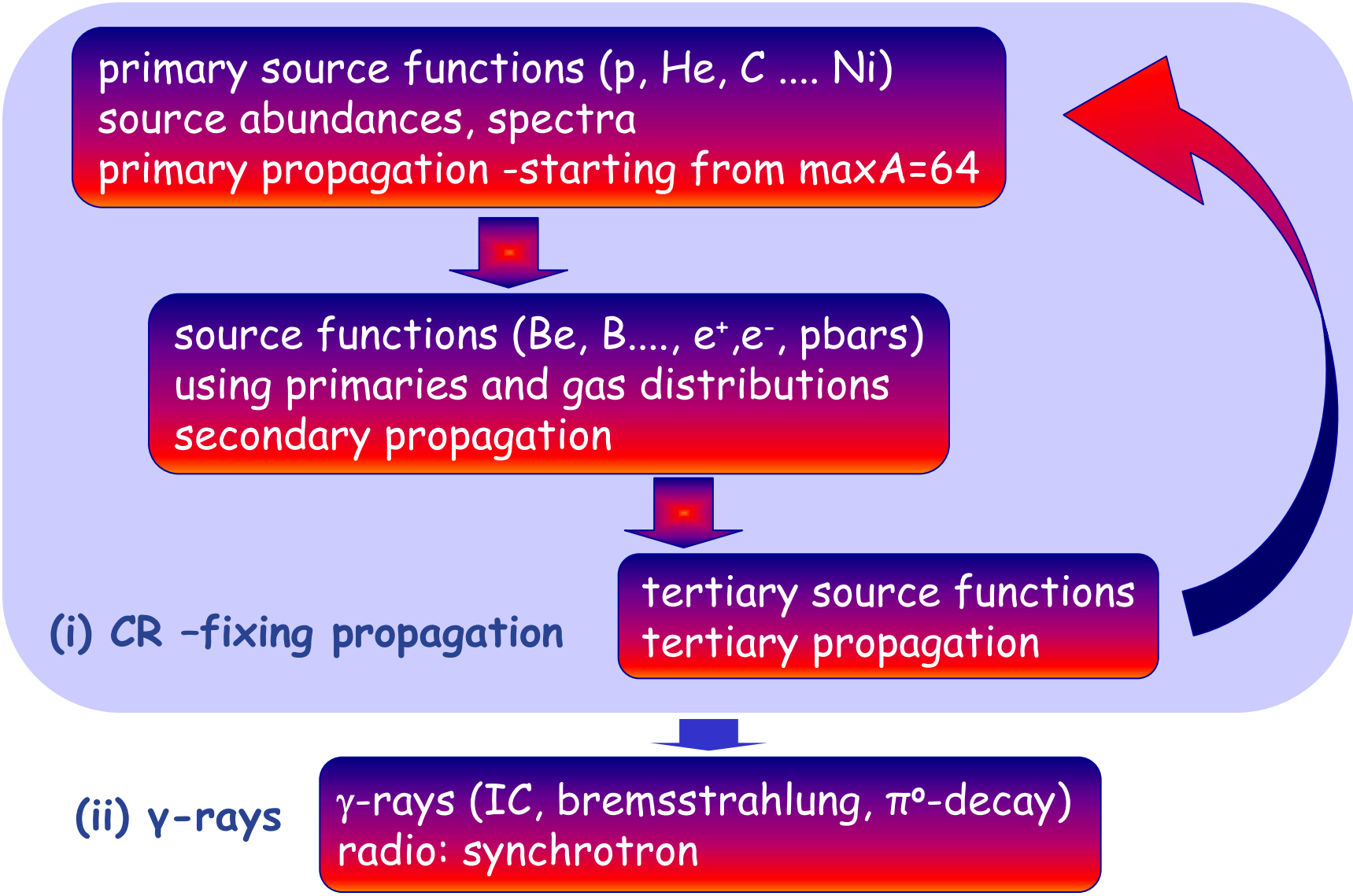
- Emissivities in every grid point (x,y,R,z,E,process)
- Skymaps with a given resolution (l,b,E,process)
- Output of maps separated into HI, H_2, and rings to allow fitting X, metallicity gradient etc.

GALPROP user's community

- GLAST ('07) – spectrum of the diffuse emission (Galactic, extragalactic) & background model
- Pamela ('05!), AMS ('08) – accurate CR measurements (H-C, pbars, $e^{\pm}$), dark matter searches
- ACE, TIGER – interpretation of nuclear isotopic abundances
- HEAT – electrons, positrons
- +many independent researchers world-wide

Each experiment addresses some part of the whole picture "Milky Way galaxy" → results of each experiment are important for others

algorithm


primary source functions (p, He, C .... Ni)
source abundances, spectra
primary propagation -starting from maxA=64
source functions (Be, B...., e+,e-, pbars)
using primaries and gas distributions
secondary propagation
tertiary source functions
tertiary propagation
(i) CR –fixing propagation
(ii) γ-rays
γ-rays (IC, bremsstrahlung, π°-decay)
radio: synchrotron

GALPROP Calculations

Constraints

- Bin size (x,y,z) depends on the computer speed, RAM; final run can be done on a very fine grid !
- No other constraints ! –any required process/formalism can be implemented

Calculations (γ -ray related)

➢ Vectorization options

- ➢ Now 64 bit to allow unlimited arrays
- ➢ Heliospheric modulation: routinely force-field, more sophisticated model ?

1. With propagated CR spectra: calculate the emissivities (π^0-decay, IC, bremss) in every grid point
2. Integrate the emissivities over the line of sight:

- GALPROP has a full 3D grid, but currently only 2D gas maps (H2, H I, H II)
- Using actual annular maps (column density) at the final step
- High latitudes above b=40° -using integrated H I distribution

Near Future Developments

Full 3D Galactic structure:

- 3D gas maps (from S.Digel, S.Hunter and/or smbd else)
- 3D interstellar radiation & magnetic fields (A.Strong & T.Porter)

Cross sections:

- ~~Blattnig et al. formalism for π^0 production~~
- Diffractive dissociation with scaling violation (T.Kamae –param.)
- Isotopic cross sections (with S.Mashnik, LANL; try to motivate BNL, JENDL-Japan, other Nuc. Data Centers)

Modeling the local structure:

- Local SNRs with known positions and ages
- Local Bubble, local clouds –may be done at the final calculation step (grid bin size ??)

Energy range:

- Extend toward sub-MeV range to compare with INTEGRAL diffuse emission (continuum; 511 keV line)

Heliospheric modulation:

- Implementing a modern formalism (Potgieter, Zank etc.)

Visualization tool (started) using the classes of CERN ROOT package: images, profiles, and spectra from GALPROP to be directly compared with data

Improving the GALPROP module structure (for DM studies)

More developments

- Point sources: develop algorithm(s) for modeling the background and interface to the rest of GLAST software
- Instrumental response: how to implement?
- Diffuse emission analysis has to include point source catalog!
- At least, two diffuse models: with/without the "excess"
- Develop test case(s) to test the accuracy of the numerical model (simple gas distribution, no energy losses, uniform ISRF etc.)
- Complete C++ package: rewrite several fortran routines in C++

Develop a dedicated Web-site:

- Controlled changes in GALPROP: tests +documentation +…
- Allow for communication with users
- Post relevant information: best models, gas maps, ISRF, nuclear cross sections…
- Ability to run GALPROP on-line…

- Develop a fitting procedure to make automatic fitting to B/C ratio, CR spectra and abundances


More details at
tomorrow's splinter
section