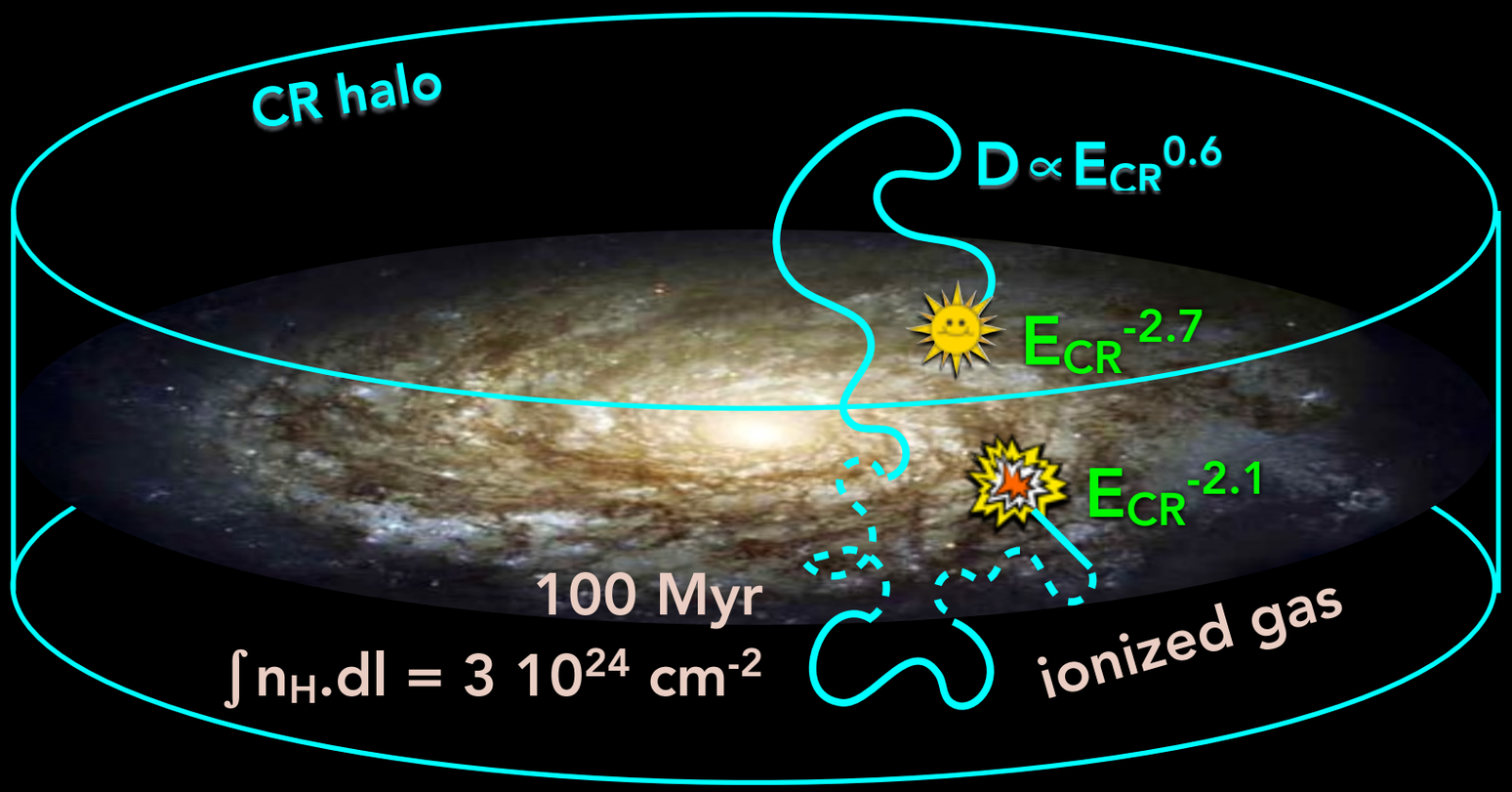
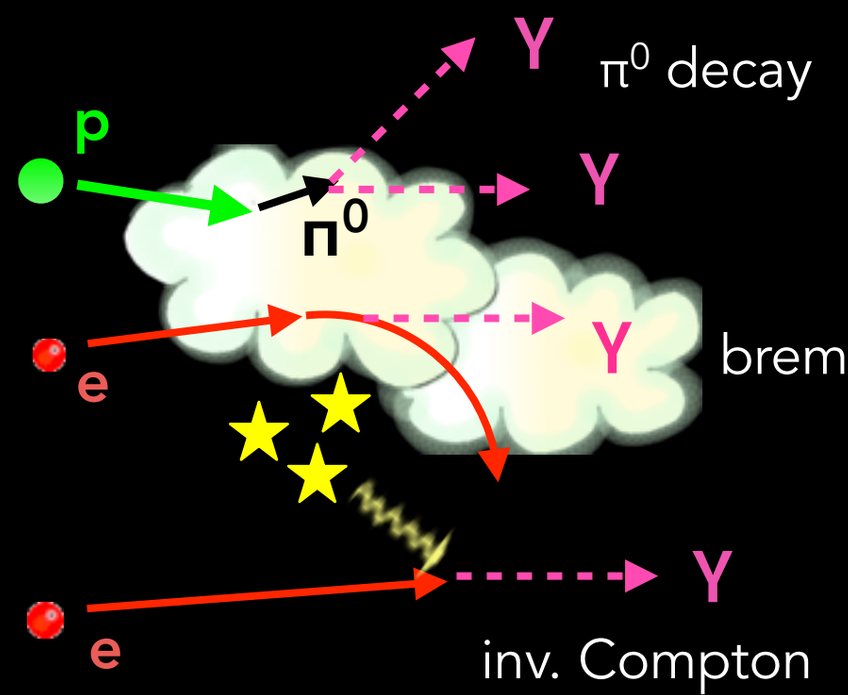
Cosmic-ray & gas investigations with Fermi

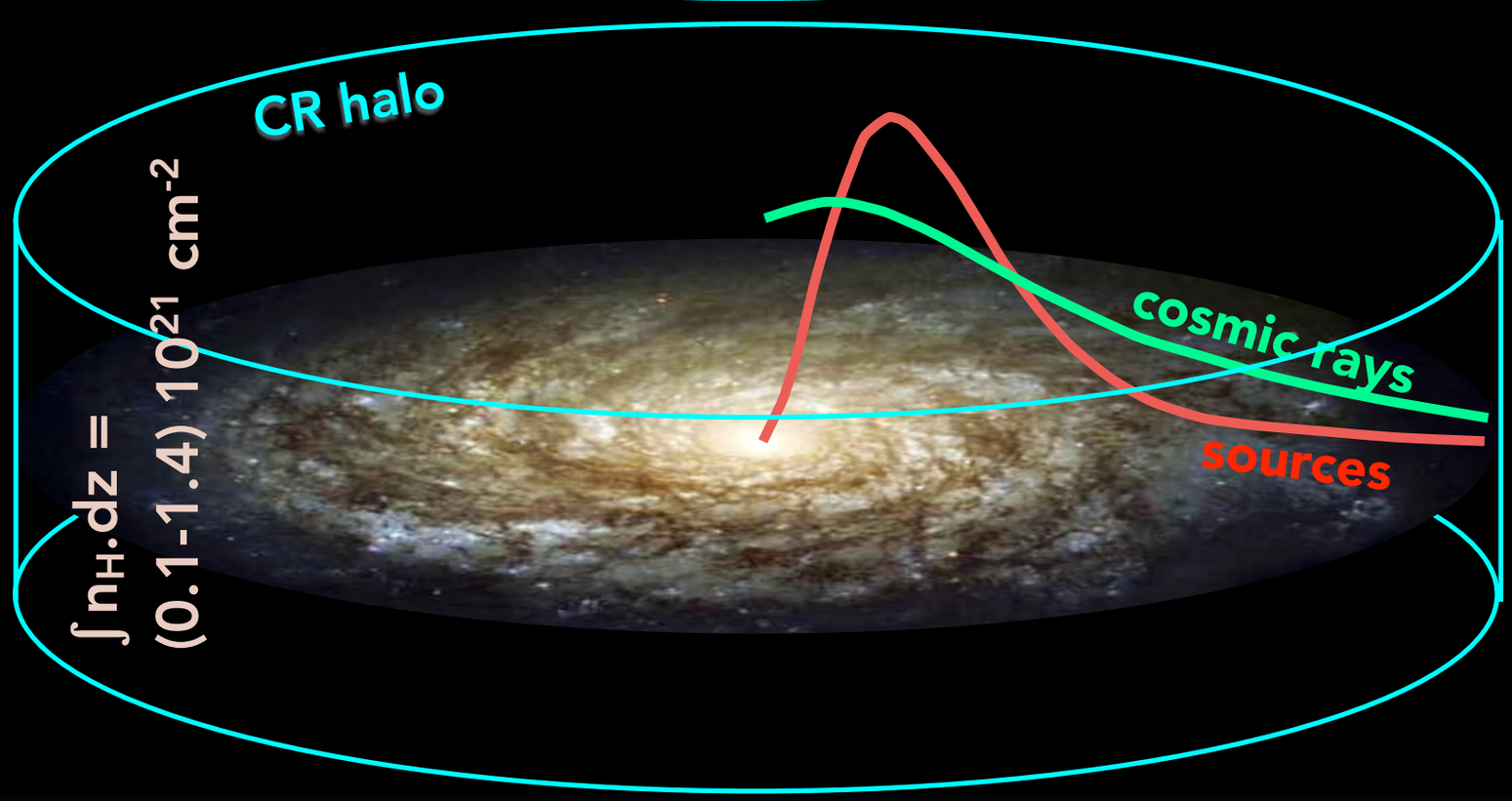
Isabelle Grenier
on behalf of the Fermi LAT Collaboration
AIM, Université Paris Diderot & CEA Saclay

Galactic cosmic-ray wanderers

- CRs < few 10^{15} eV: origin in the Milky Way & propagation in a > kpc halo

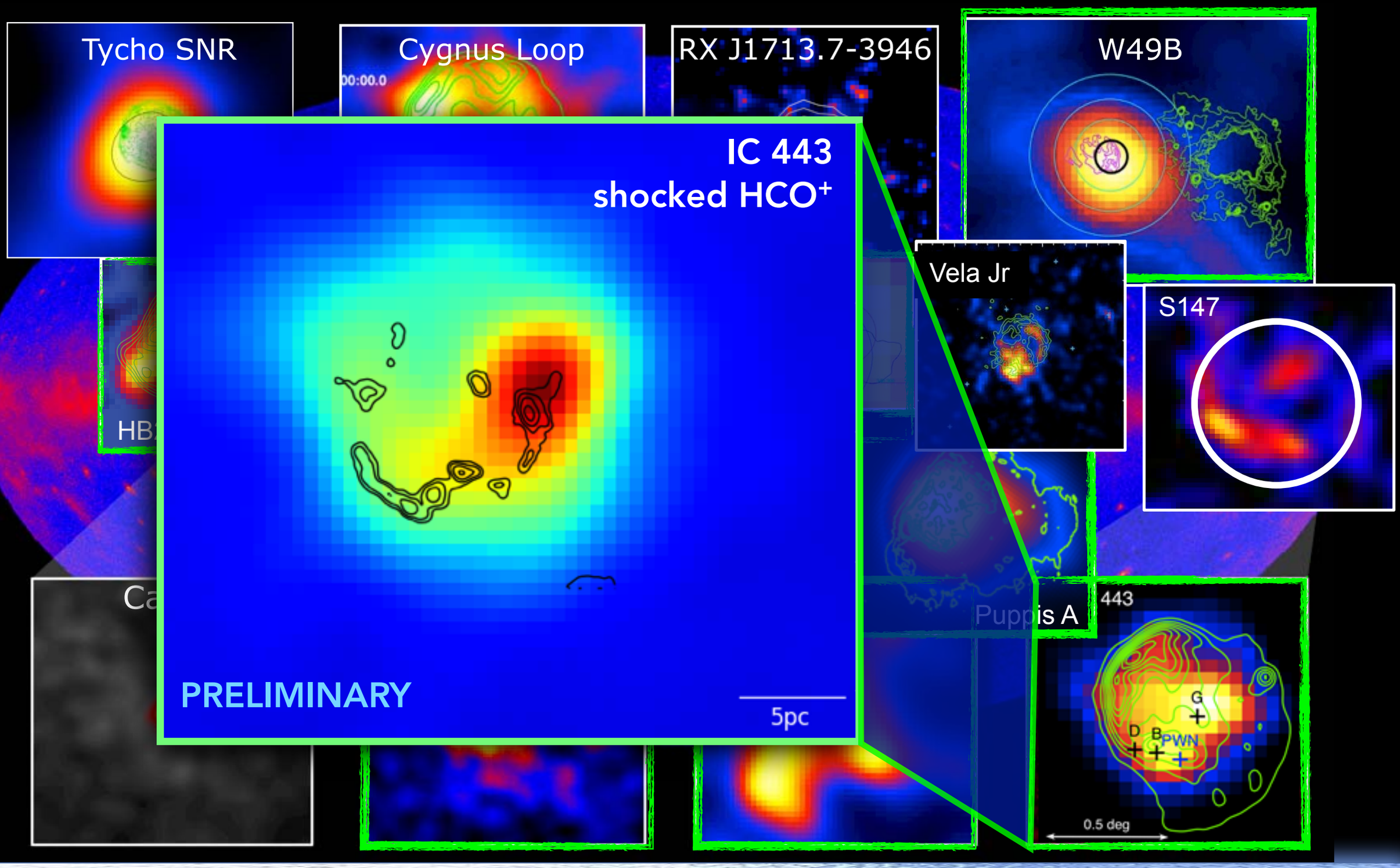






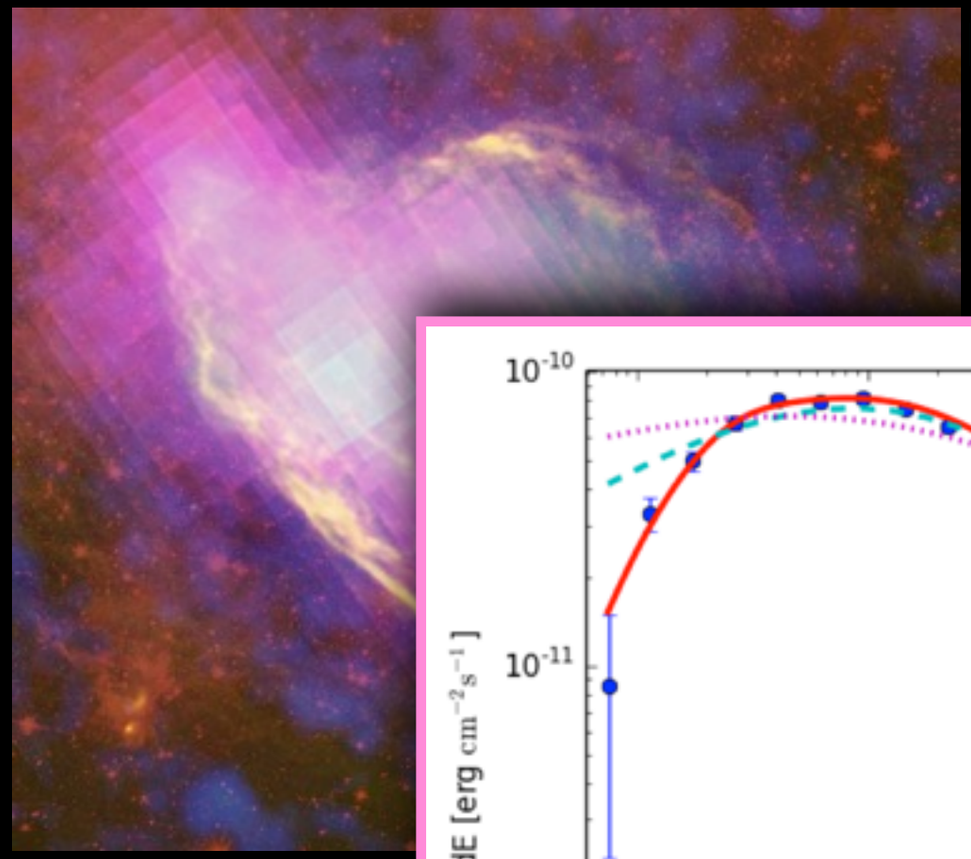
SNR GeV gallery

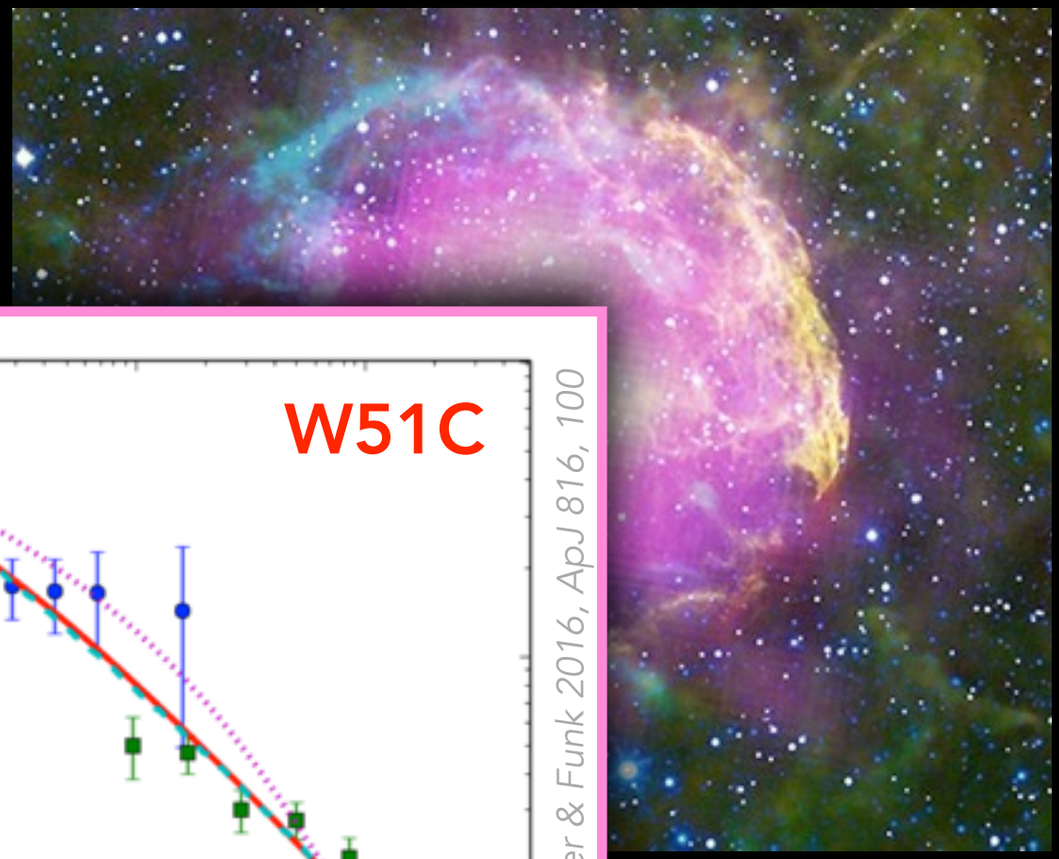
- a catalogue of ≈ 30 extended sources or associations with SNRs including:
  - ★ young historical remnants
  - ★ middle-aged ones often **interacting with surrounding clouds**

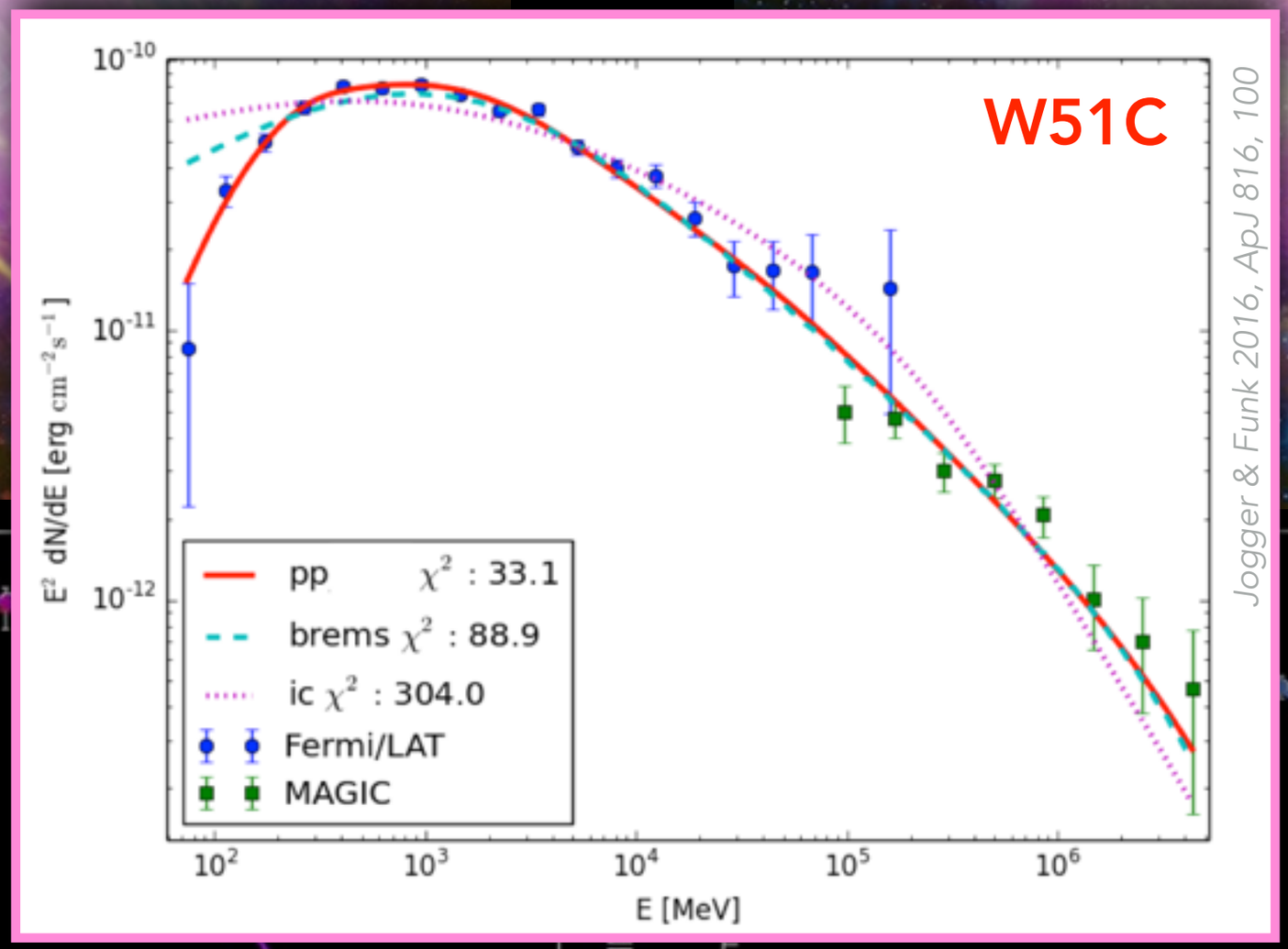


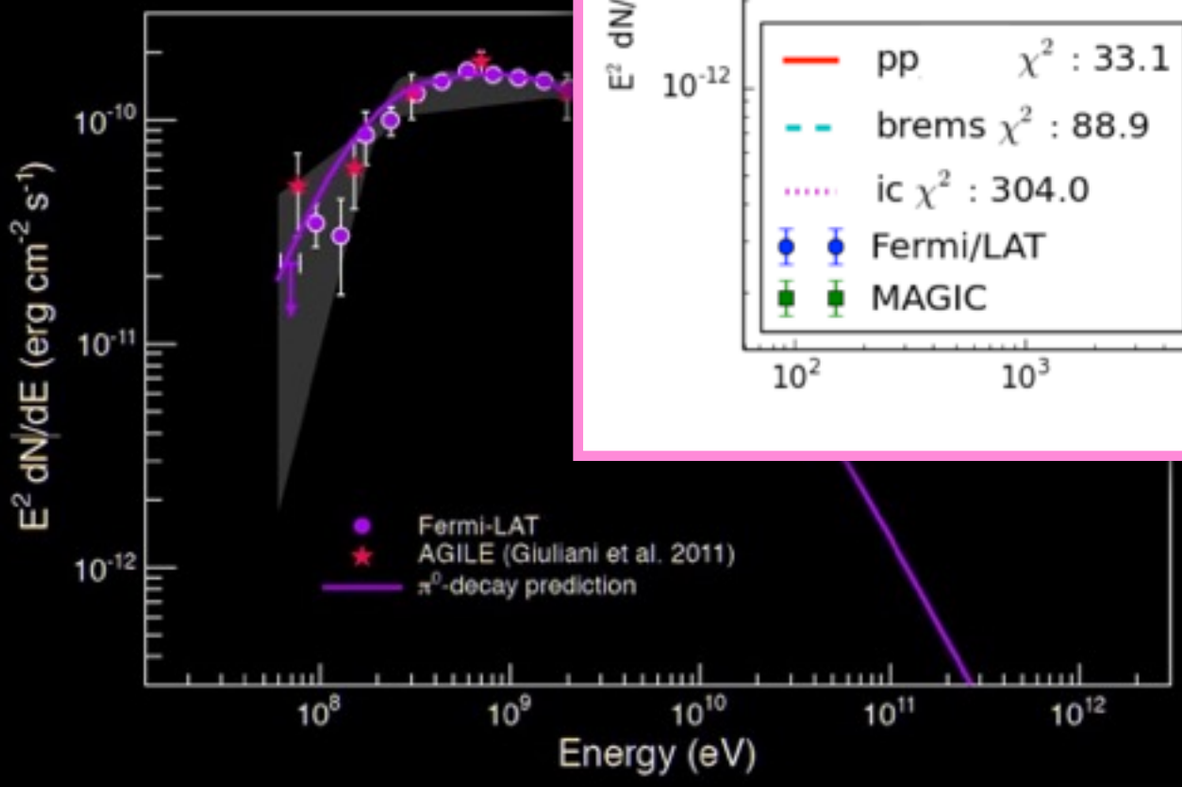
signature of freshly accelerated nuclei?

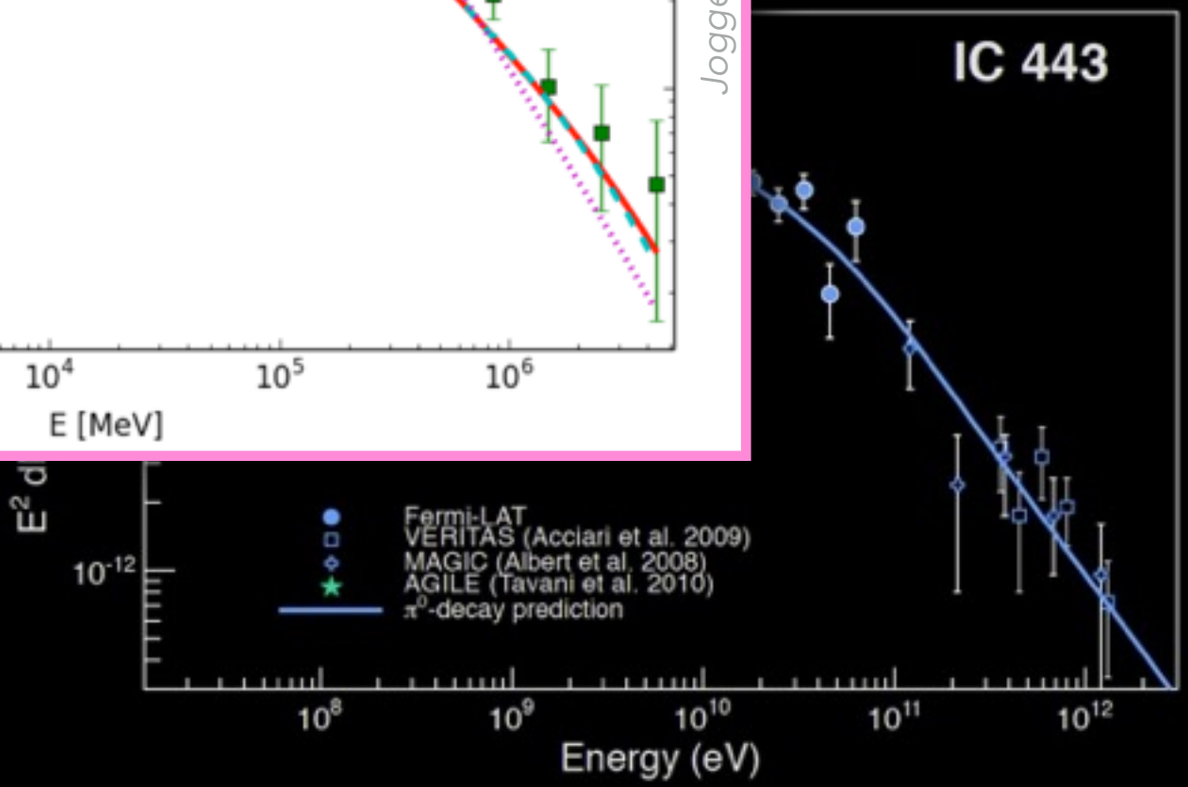
IR opt γ







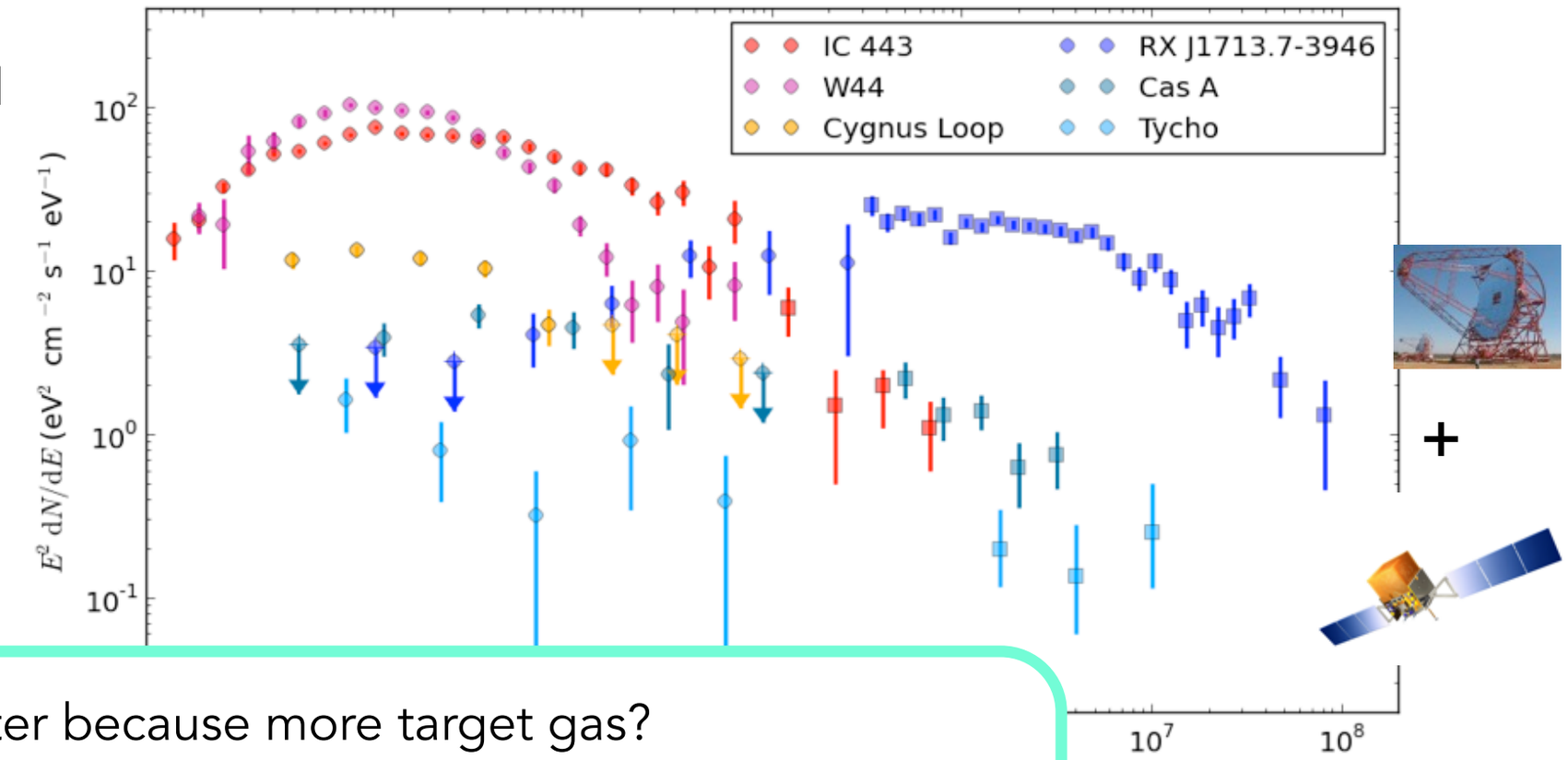




Ackermann+ 2013 Science 339, 807

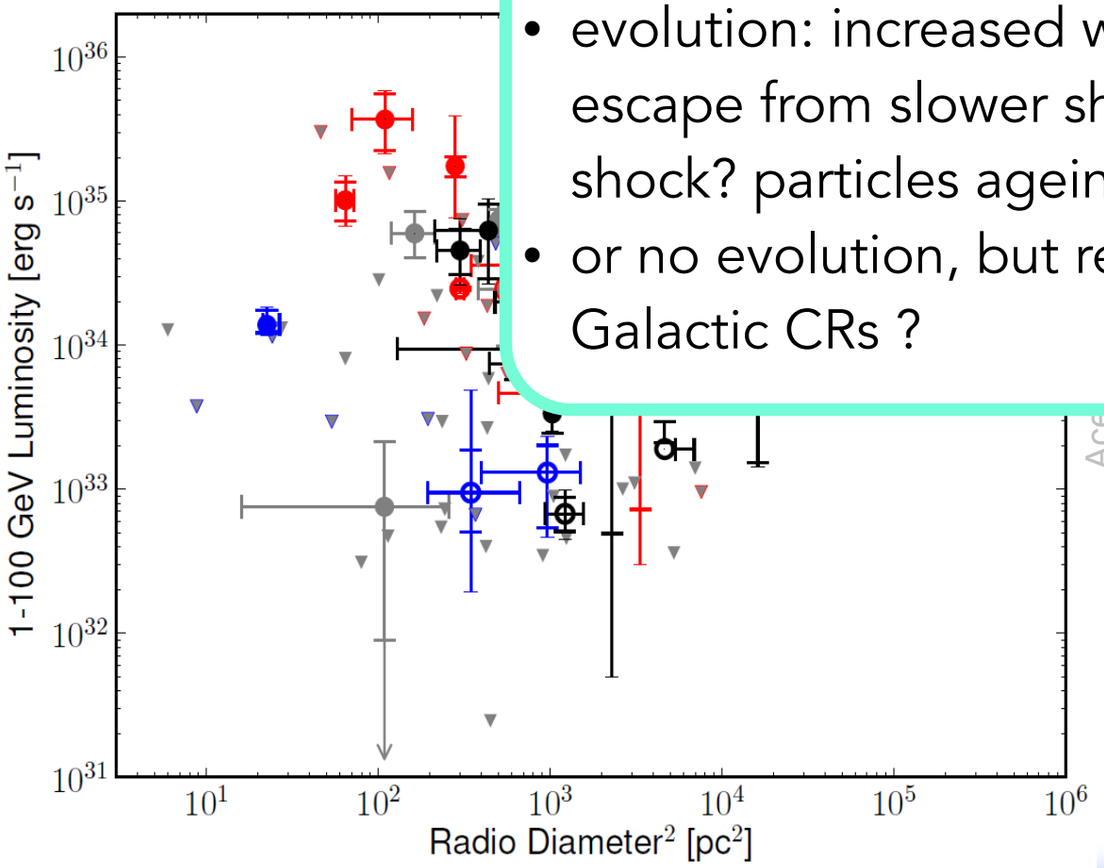
SNR trends in γ rays

- mixed interpretations
  - ✦ some π^0 decay dominated
  - ✦ others IC dominated
- softer spectra (few GeV cut-off energies) than for TeV-bright SNRs
- older SNRs tend to be
  - ✦ brighter
  - ✦ softer



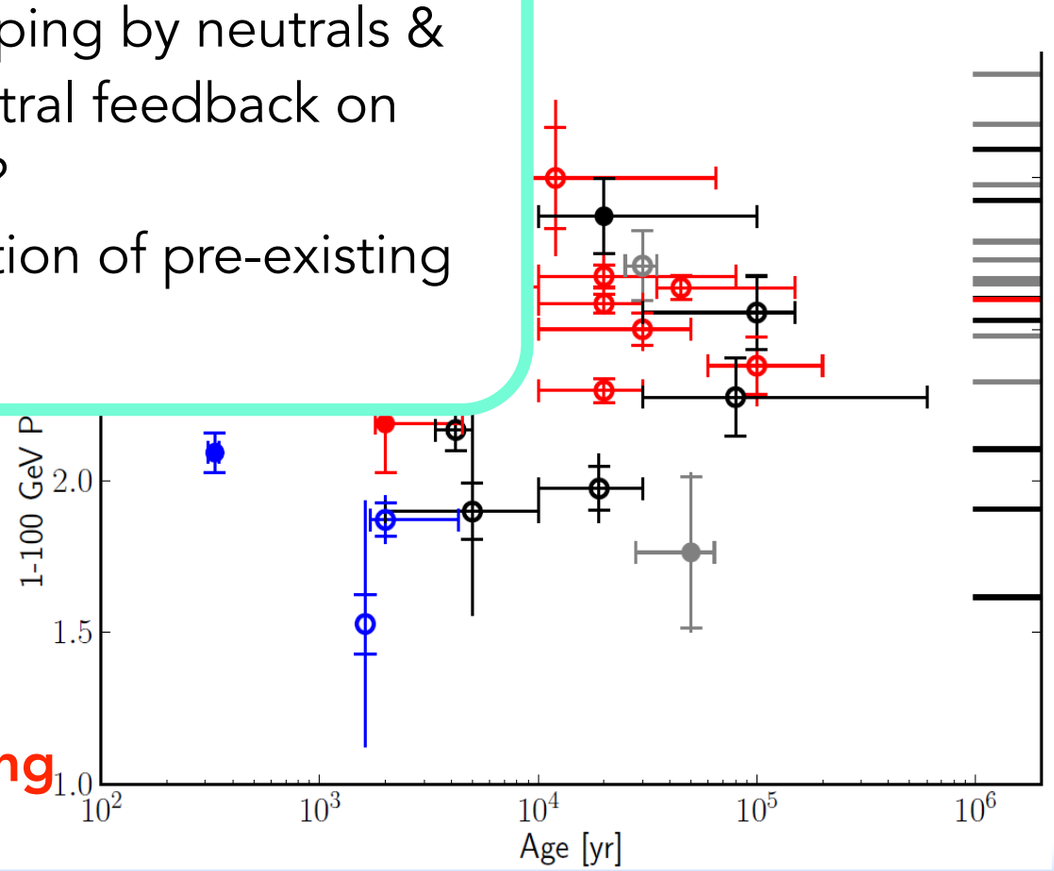
+

- brighter because more target gas?
- evolution: increased wave damping by neutrals & escape from slower shock? neutral feedback on shock? particles ageing inside ?
- or no evolution, but reacceleration of pre-existing Galactic CRs ?



young

interacting

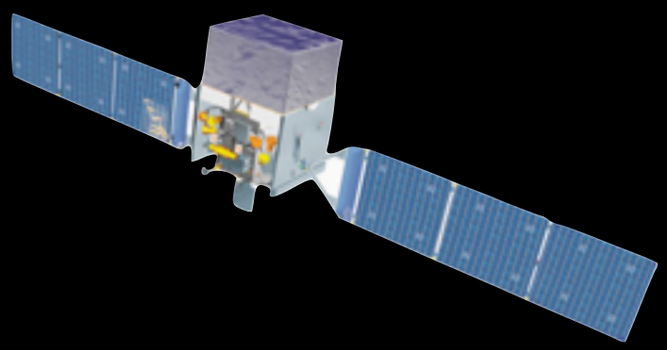


Acero+ 2016, ApJS 224, 8

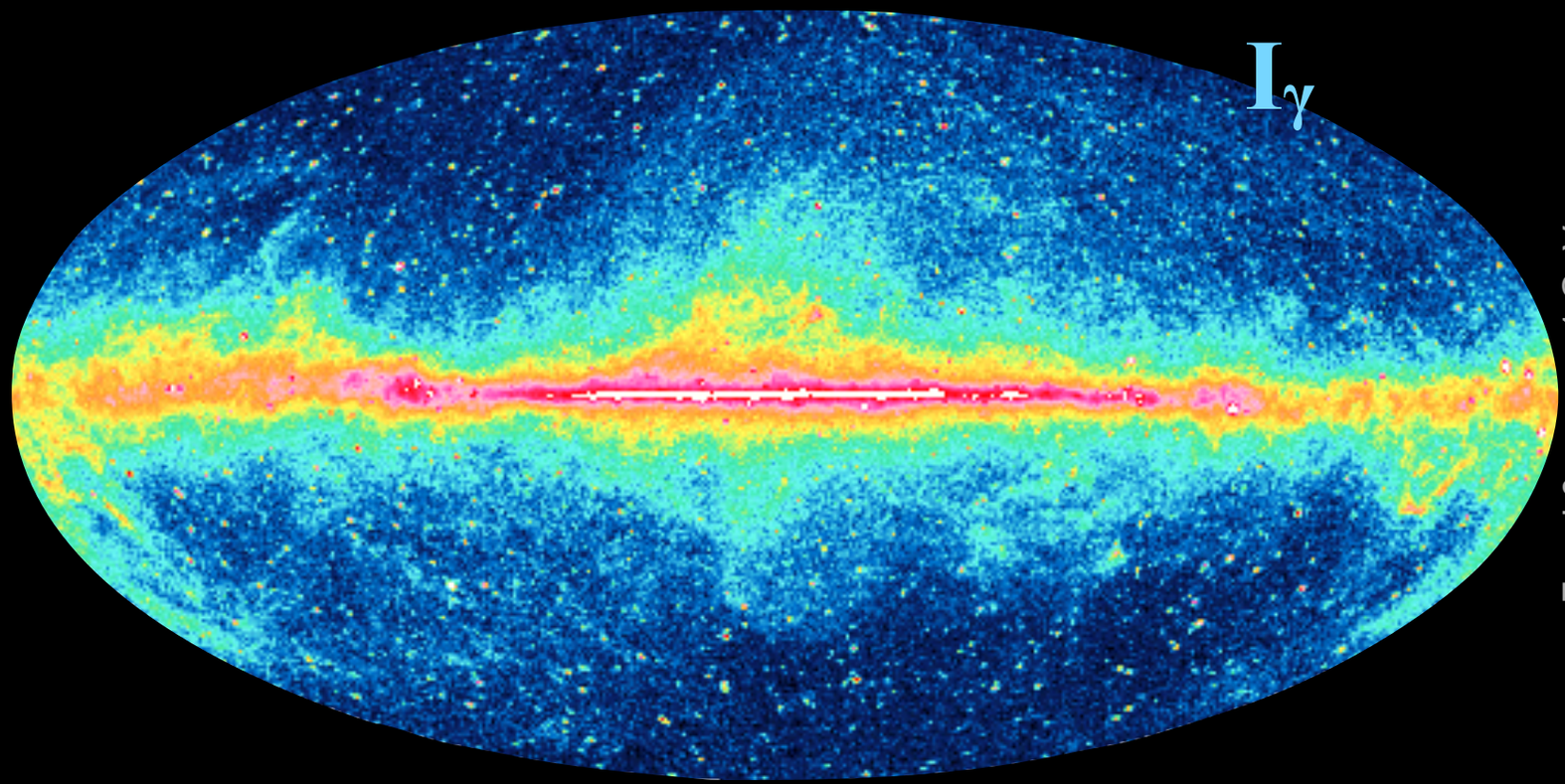
Remote sensing of super-GeV cosmic rays

γ rays & dust tracing of the total gas

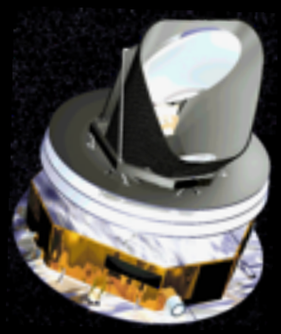
- Fermi-LAT > 1 GeV: diffuse emission + 3033 3FGL sources + Bubbles + ???



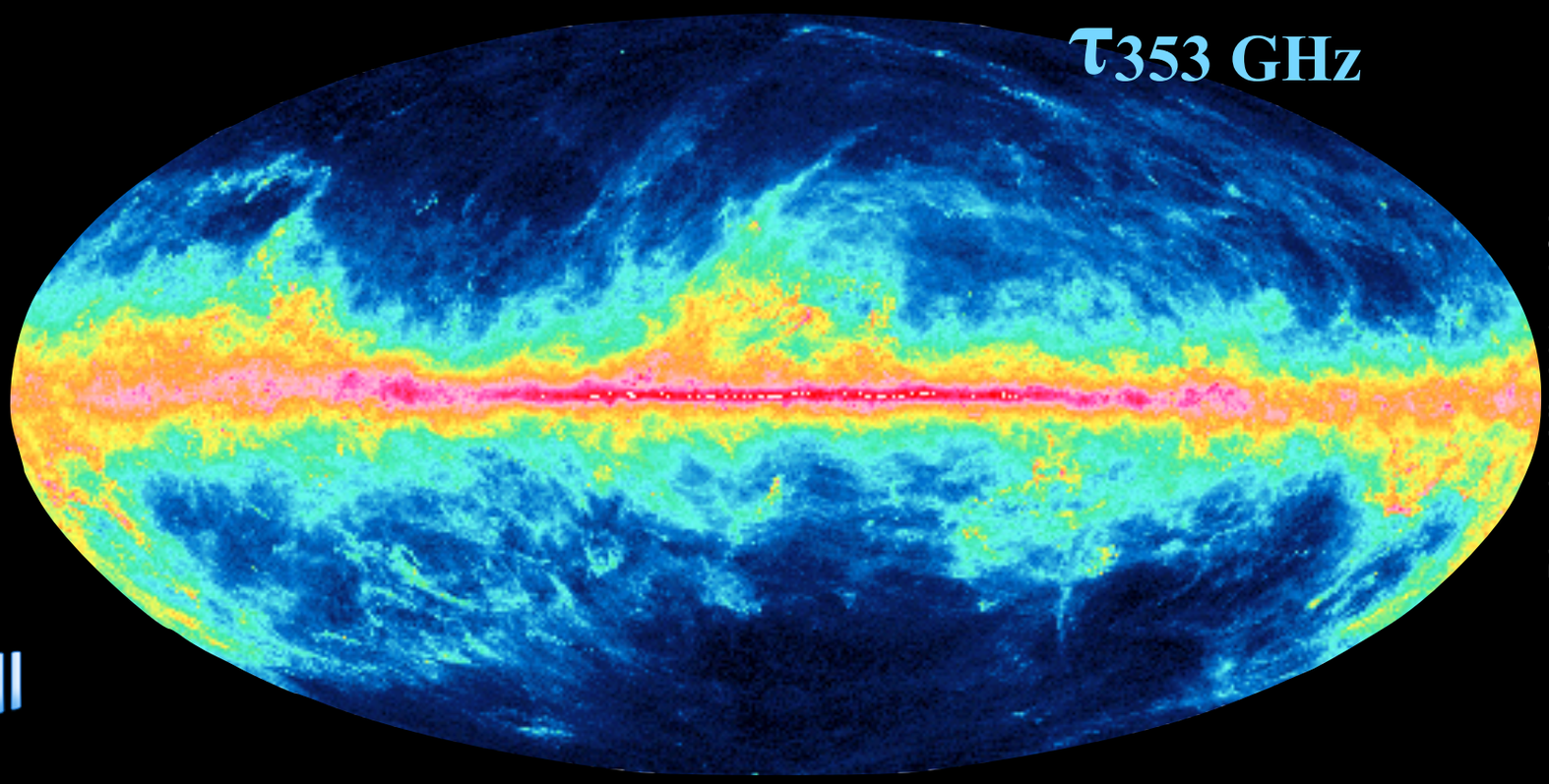
$$\text{diffuse intensity} \propto \int n_{gas}\, n_{CRs}\, dl$$



- Planck + IRAS



$$\text{thermal intensity} \propto \int (M_D/M_{gas})\, \kappa_D\, n_{gas}\, B(T_D)\, dl$$



joint γ-ray and dust modelling

- CRays in HI: N(HI)

$$\frac{dN_{CR}}{dV}$$

- CRays in H_2:

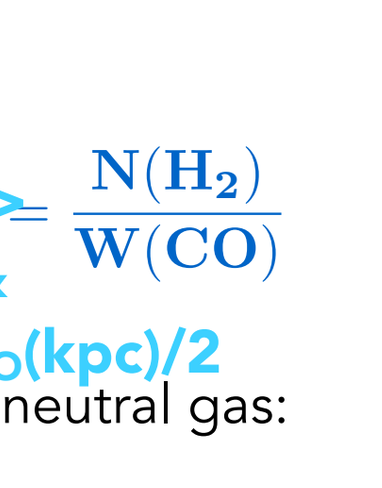
cloud $\langle X_{CO} \rangle = \frac{N(H_2)}{W(CO)}$ dependent &

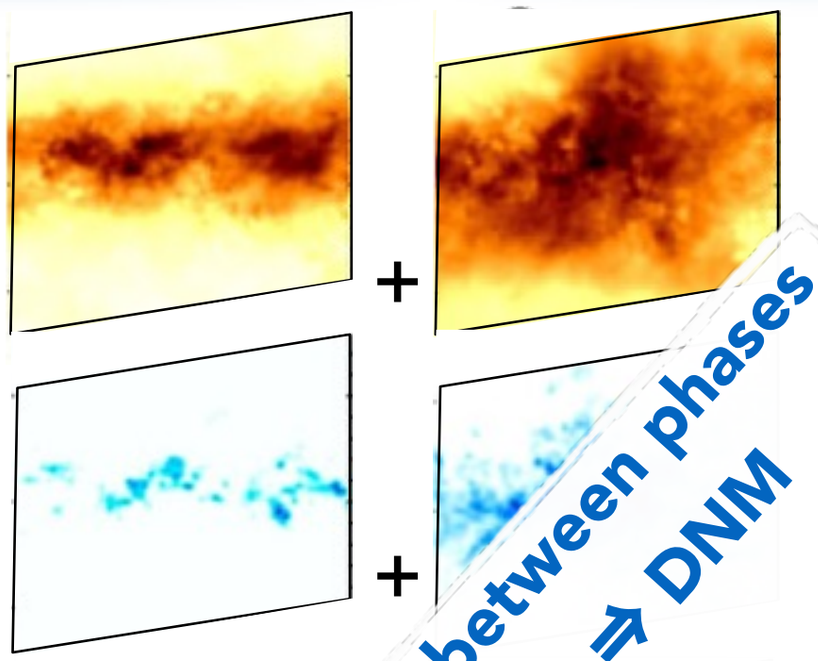
$X_{CO}(pc) \approx X_{CO}(kpc)/2$

- CRays in dark neutral gas:

$$I_\gamma - a\,N(HI) - b\,W(CO)$$

- Galactic inverse Compton
- γ-ray source





dust in HI

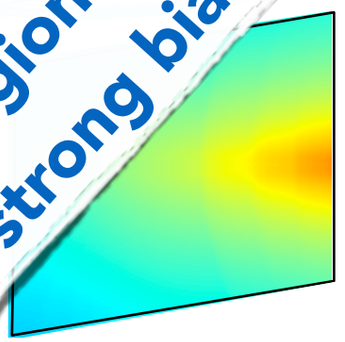
$$\left(\frac{\tau_{dust}}{N_H}\right)_{HI}$$

dust in H_2 — non linear τ/N_H

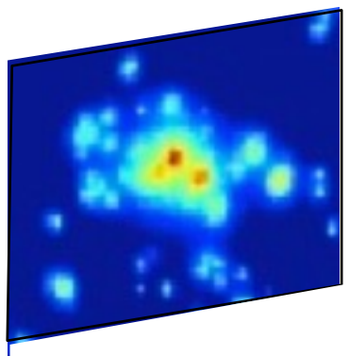
$$X_{CO} = \frac{N(H_2)}{W(CO)}$$

dust in dark neutral gas

$$\tau_{dust} - a'\,N(HI) - b'\,W(CO)$$



CIB + CMB



IR sources

little cross-correlation between phases

multi-tracer coupling ⇒ DNM

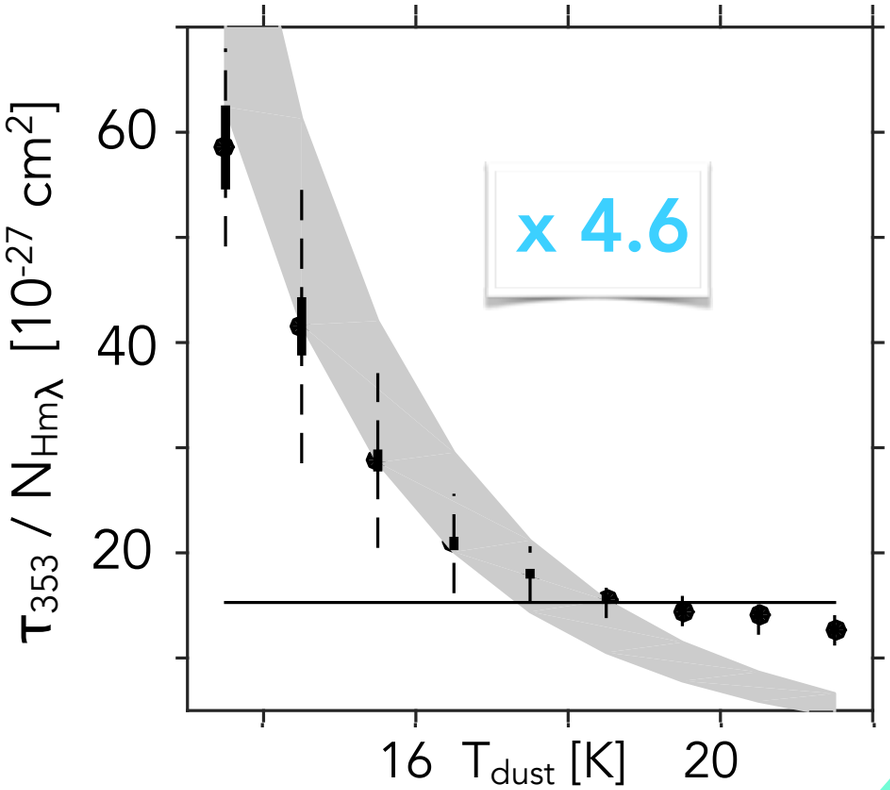
region by region

strong biases in CR spectrum

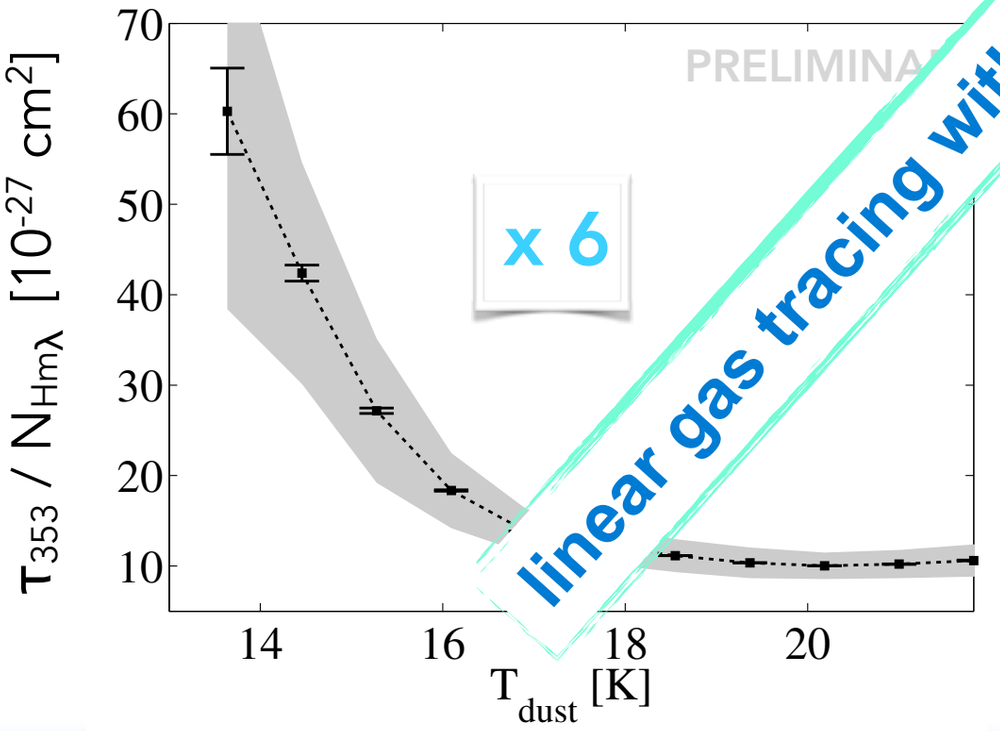
otherwise

gas tracing with dust emission

- significant increase in grain emission cross section
- grain evolution across all phases, more pronounced in CO



Planck+Fermi '15, A&A 582, 31

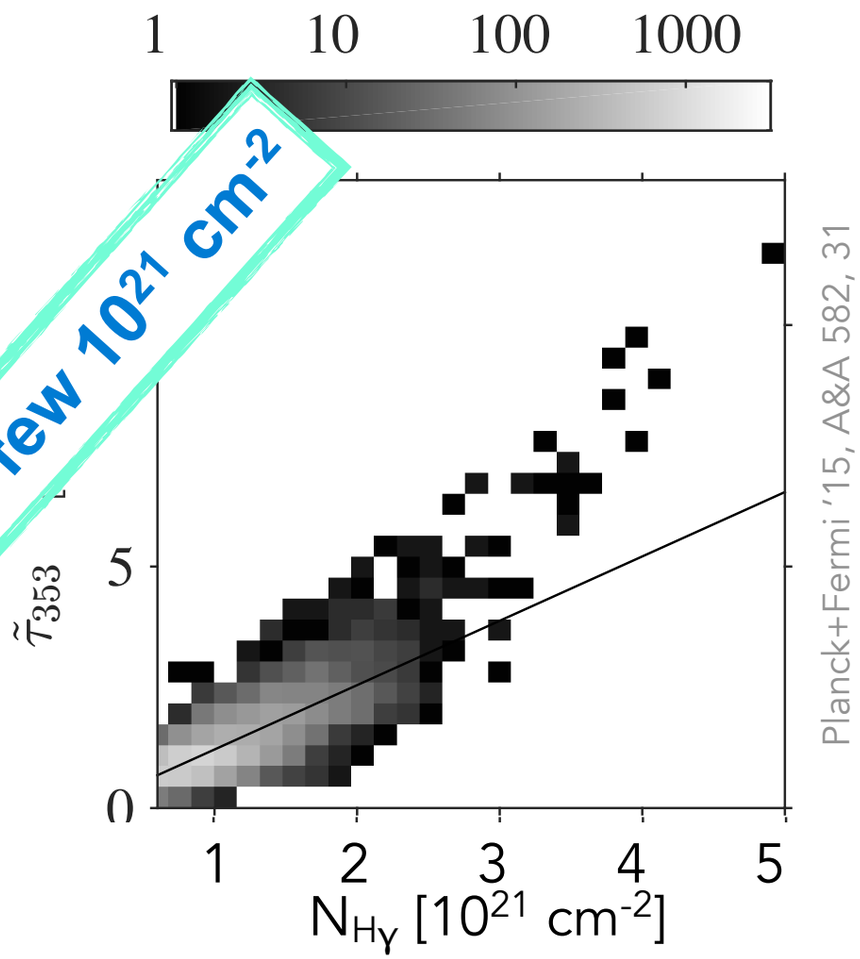


Remy et al., submitted

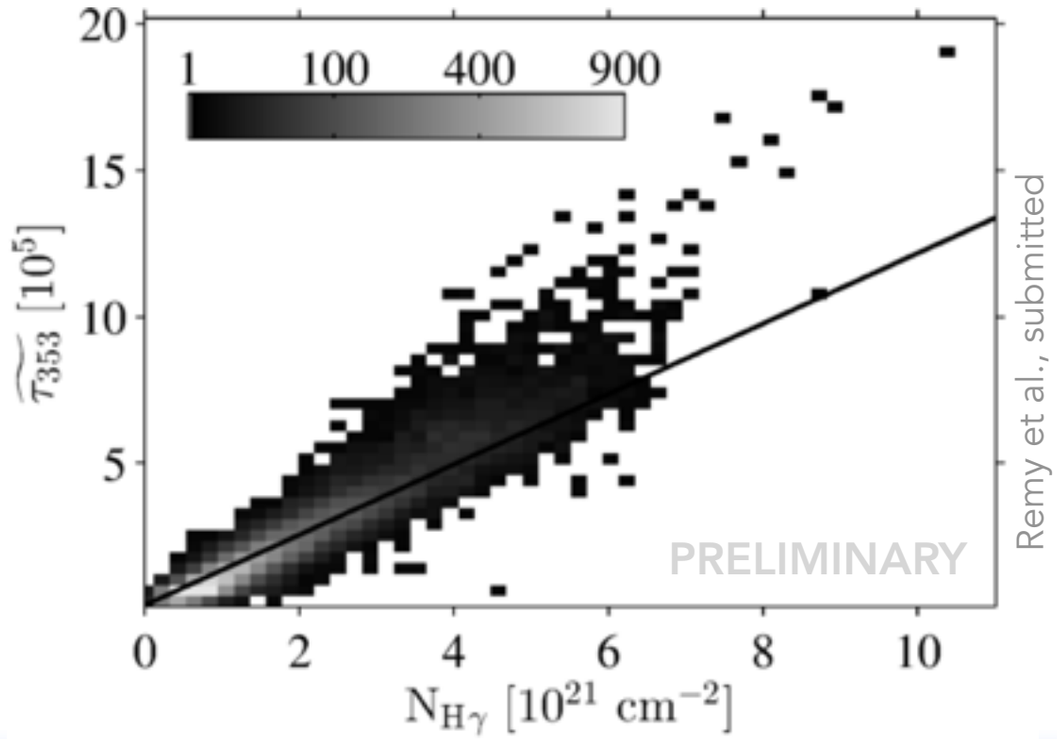
Chamaeleon

Taurus-Perseus-California

linear gas tracing with dust emission if N_H < few 10^{21} cm^{-2}



Planck+Fermi '15, A&A 582, 31

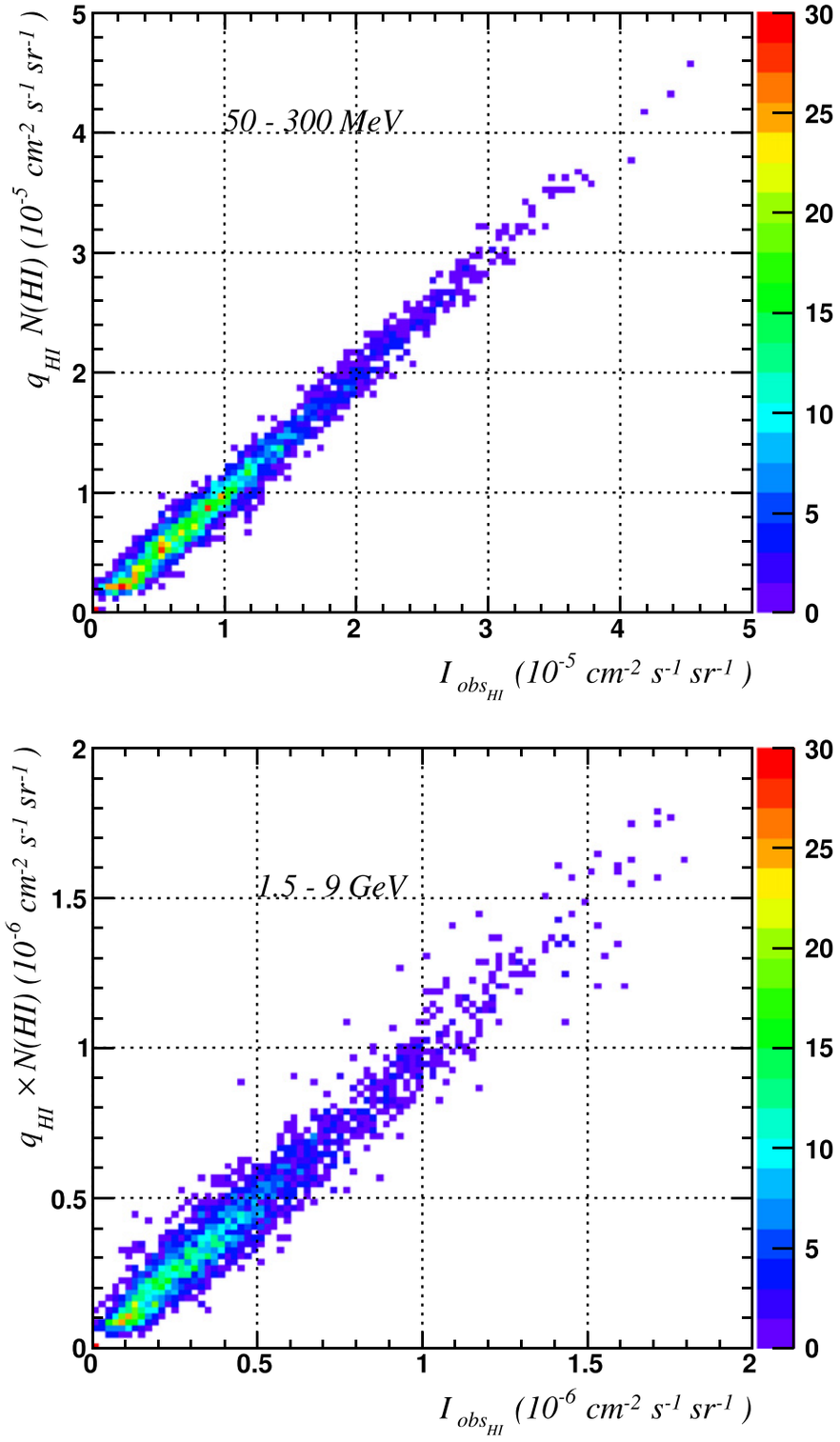


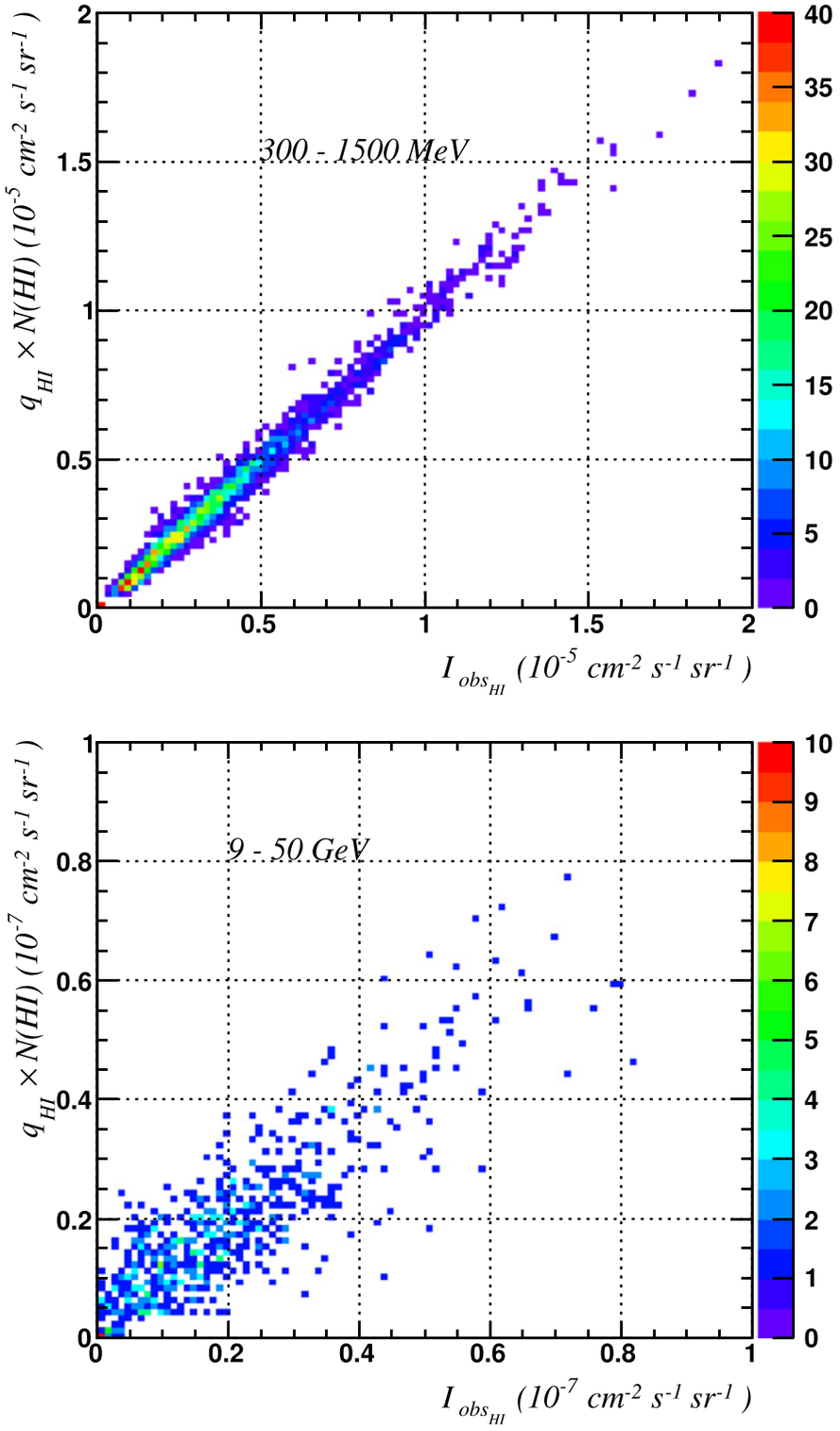
Remy et al., submitted

Multi-GeV cosmic rays in the local interstellar medium

CRs diffusing in the atomic gas

- γ-ray intensity scales well with N(HI) column density => possible measure of $n_{CR}(E)$

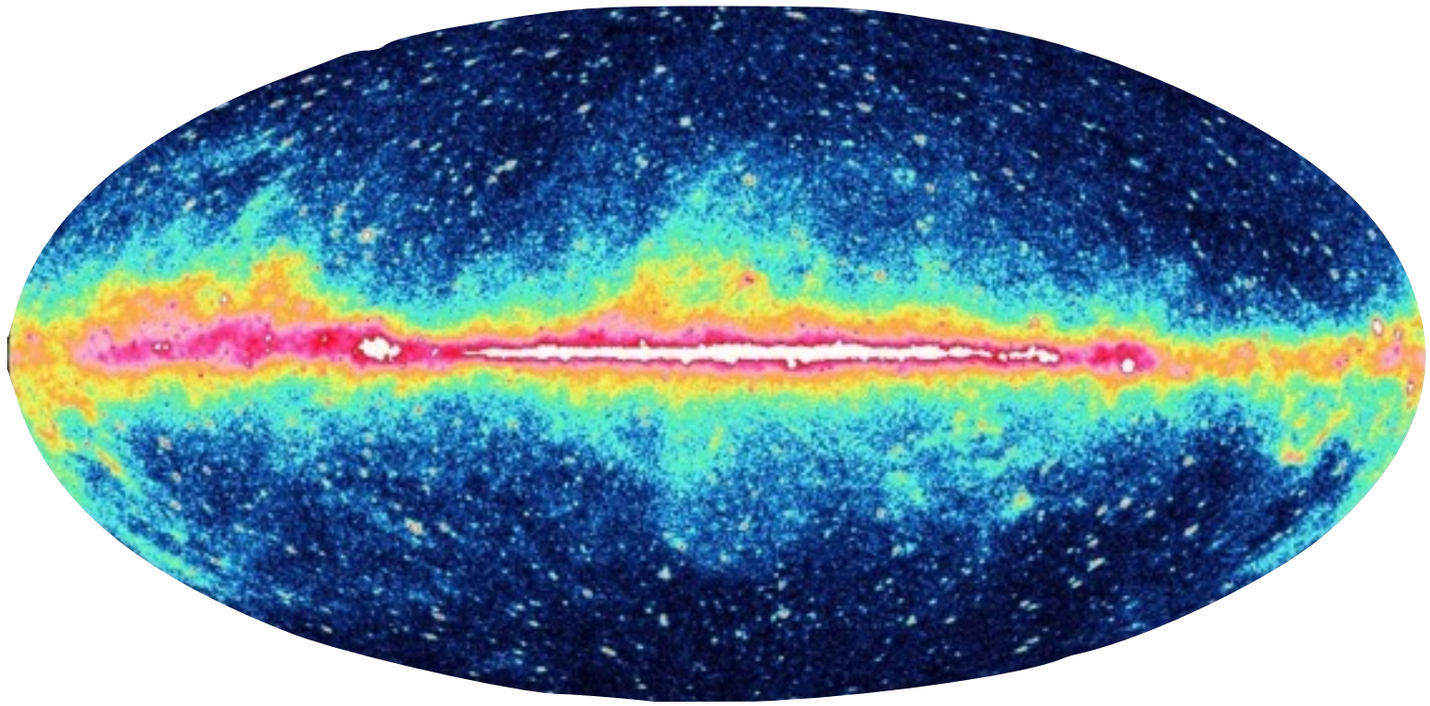


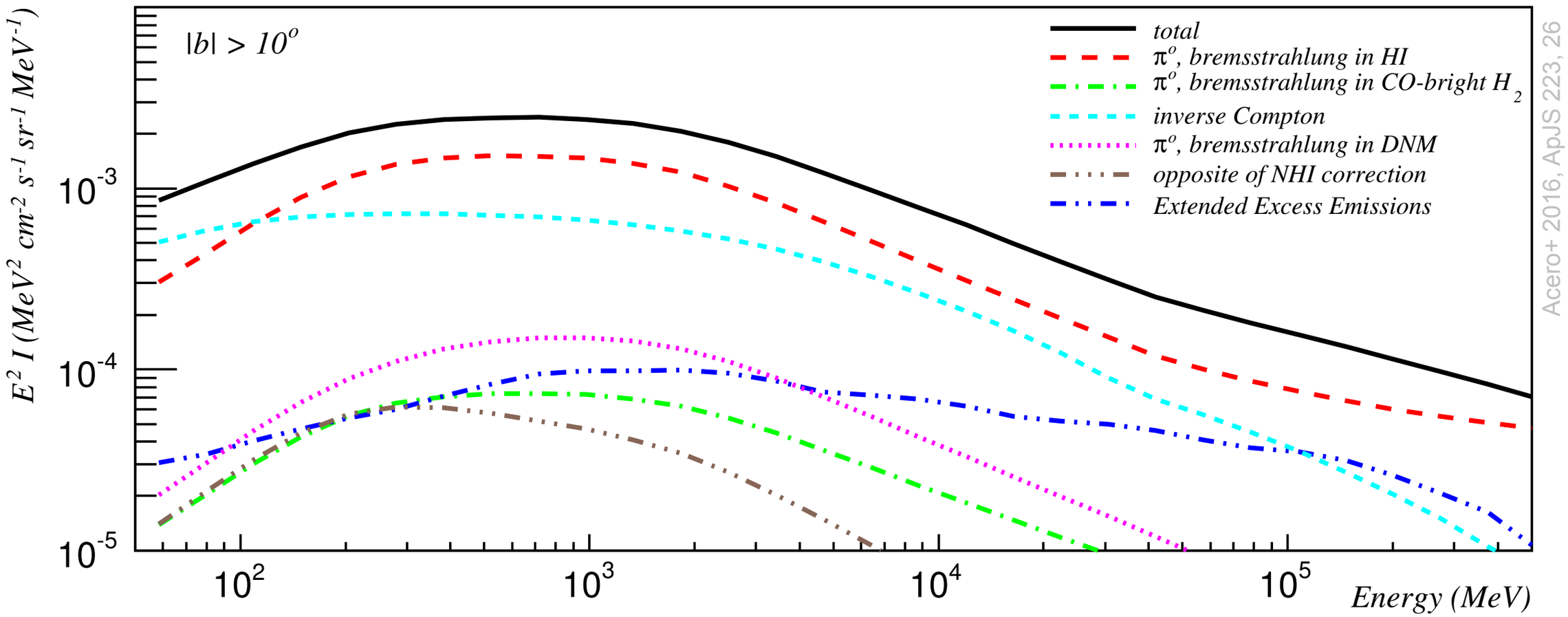


Casandjian 2015, ApJ 806, 240

local ISM off the plane

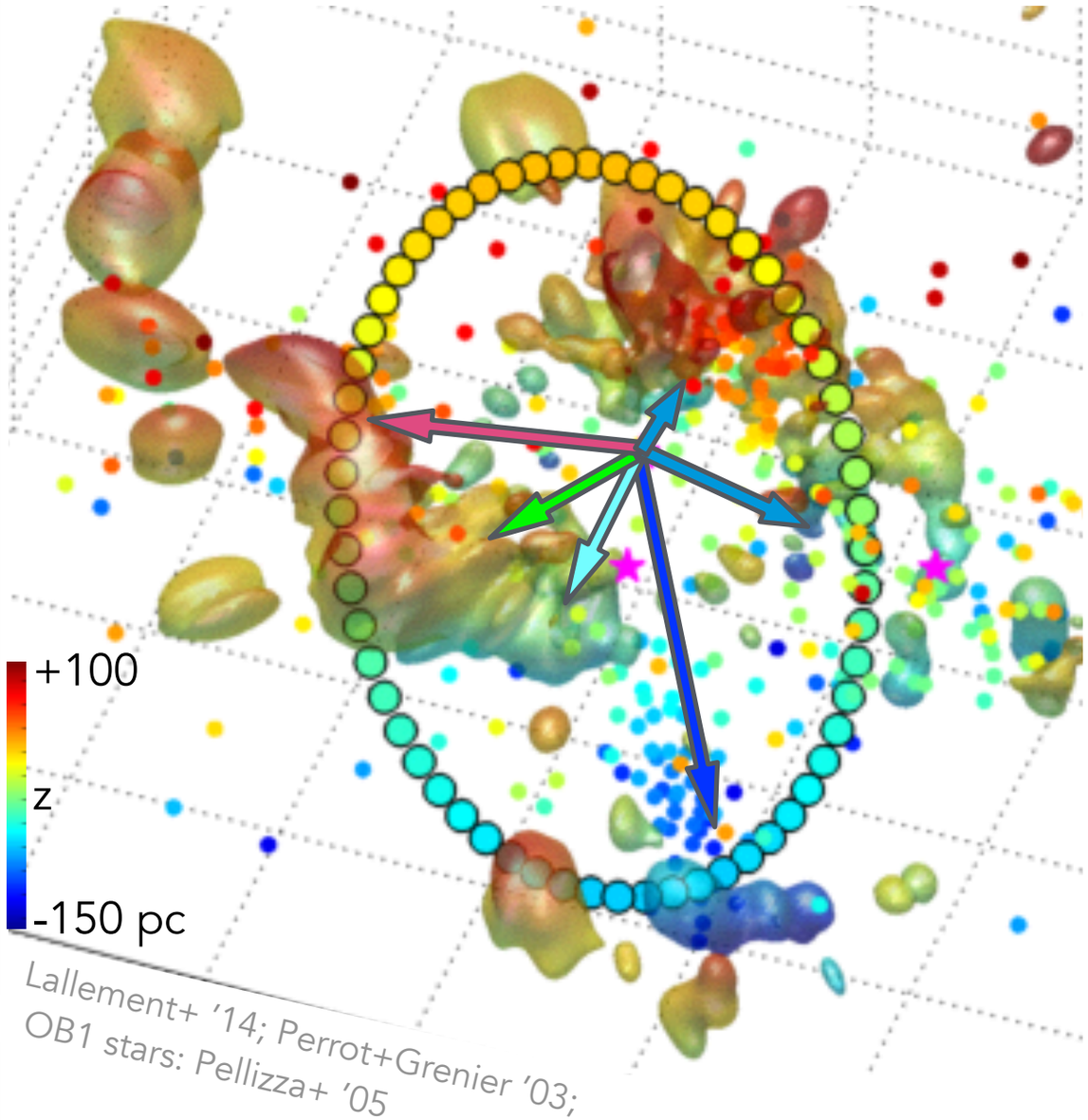
- CR + ISM interactions dominate



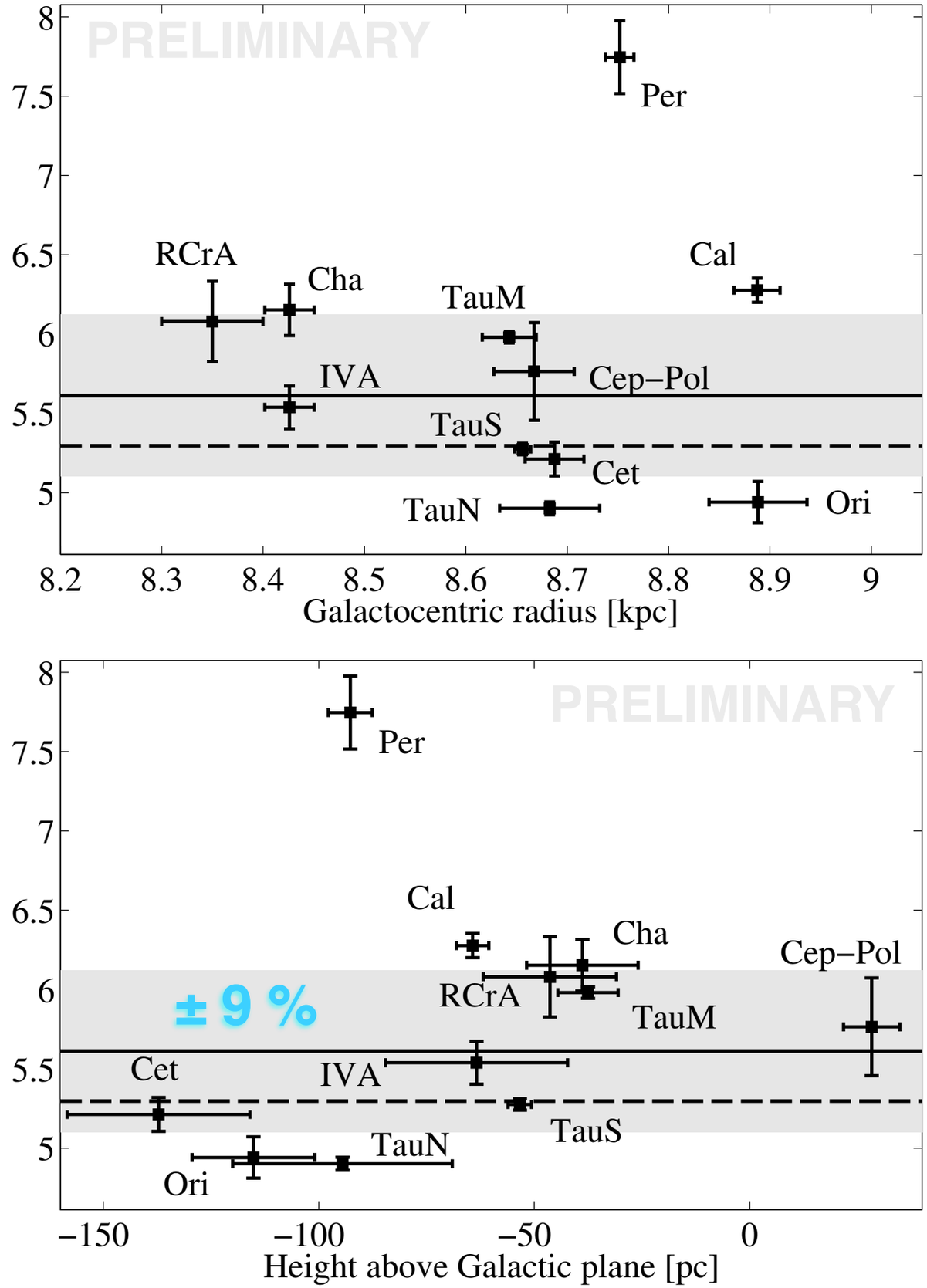


local emissivity spectra in the HI

- within a few 100 pc around the Sun,
- in clouds from 10^3 to 10^5 M⊙
- < 30% variations compatible with uncertainties in N(HI)



Remy+, submitted



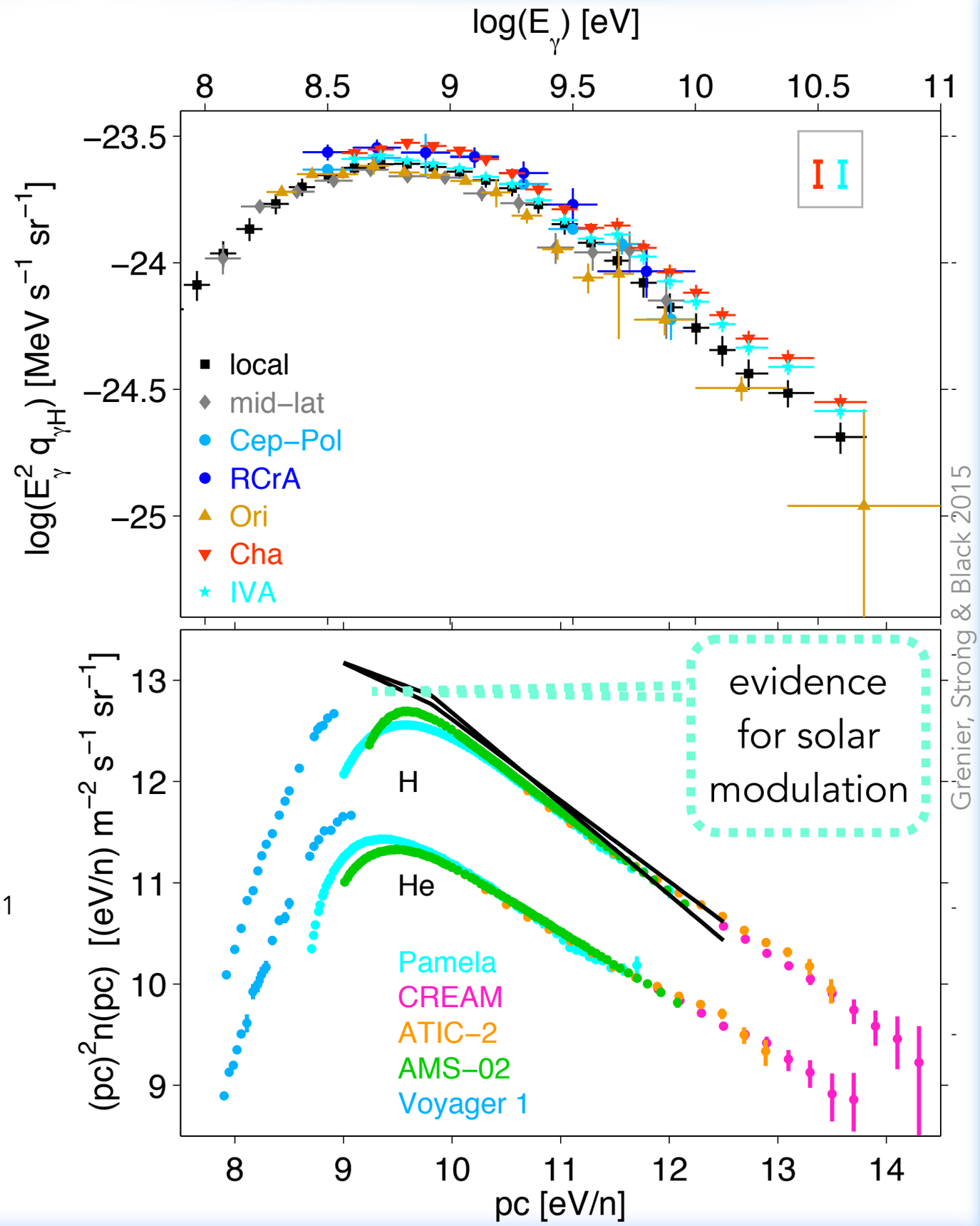
local gas emissivities (0.4-10 GeV)

- uniform CR spectrum
  across the Gould Belt clouds

- Fermi local ISM + Voyager data
  - ✦ $\zeta^{H}_{CR} \approx 1.4\ 10^{-17}\ s^{-1}$
  - ✦ $u_{CR} \approx 1.9\ eV\ cm^{-3}$

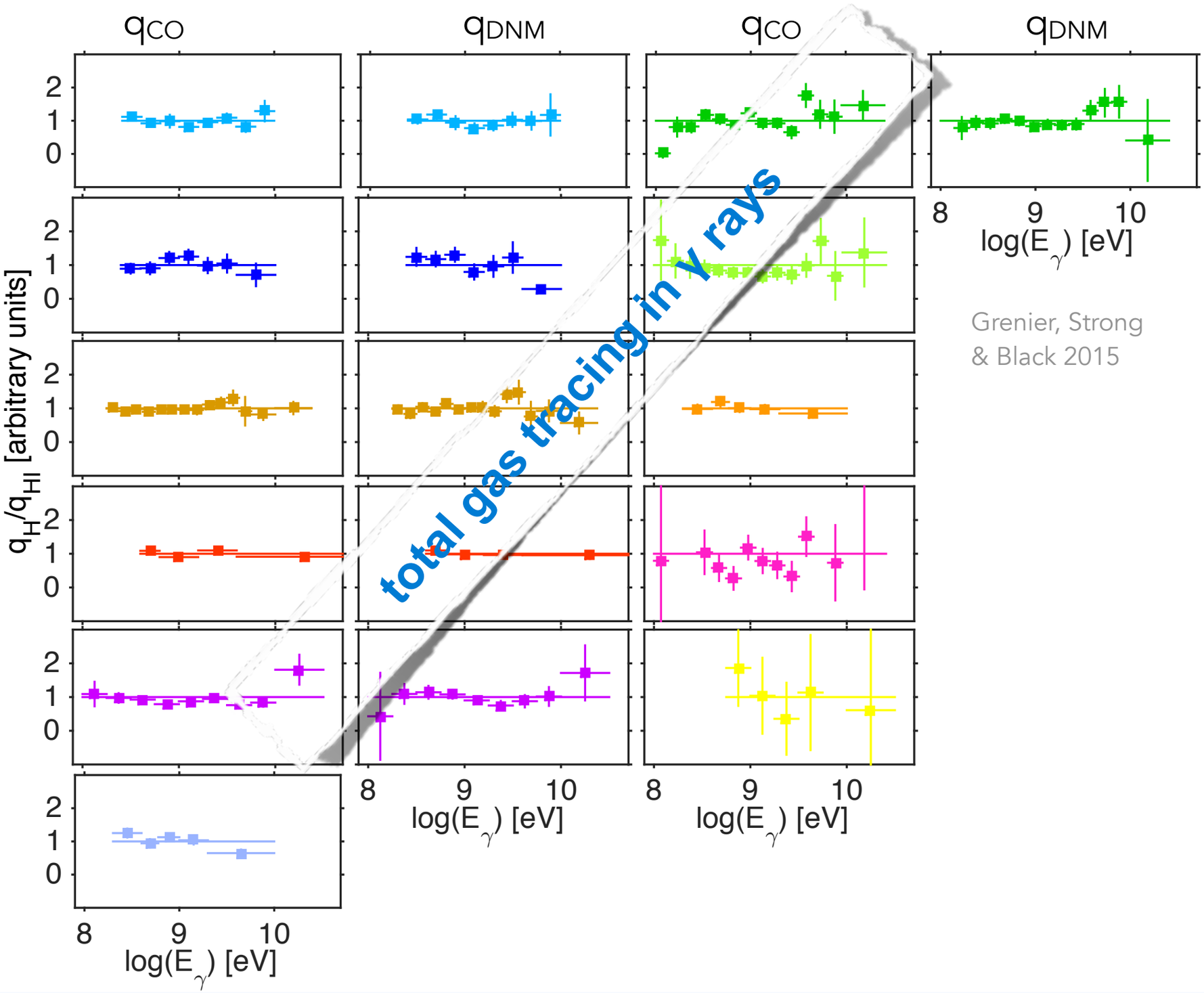
  Grenier, Strong & Black 2015

- from H_3^+ observations:
  - ✦ Sco-Oph (100-200 pc): $\zeta = (2\text{-}12)\ 10^{-17}\ s^{-1}$
  - ✦ Per OB2 (300 pc): $(5.6\pm3.2)\ 10^{-16}\ s^{-1}$
    & $(5.9\pm3.5)\ 10^{-16}\ s^{-1}$
    despite same GeV CR flux
    => low-energy environmental effects ?



uniform penetration inside clouds

- no spectral deviations across the HI, DNM, and H_2 gas phases down to pc scale
- ≈ uniform penetration at the current precision for CRs > GeV
- ok with diffusion scale > kpc and with models by Skilling & Strong '76 or Everett & Zweibel '11

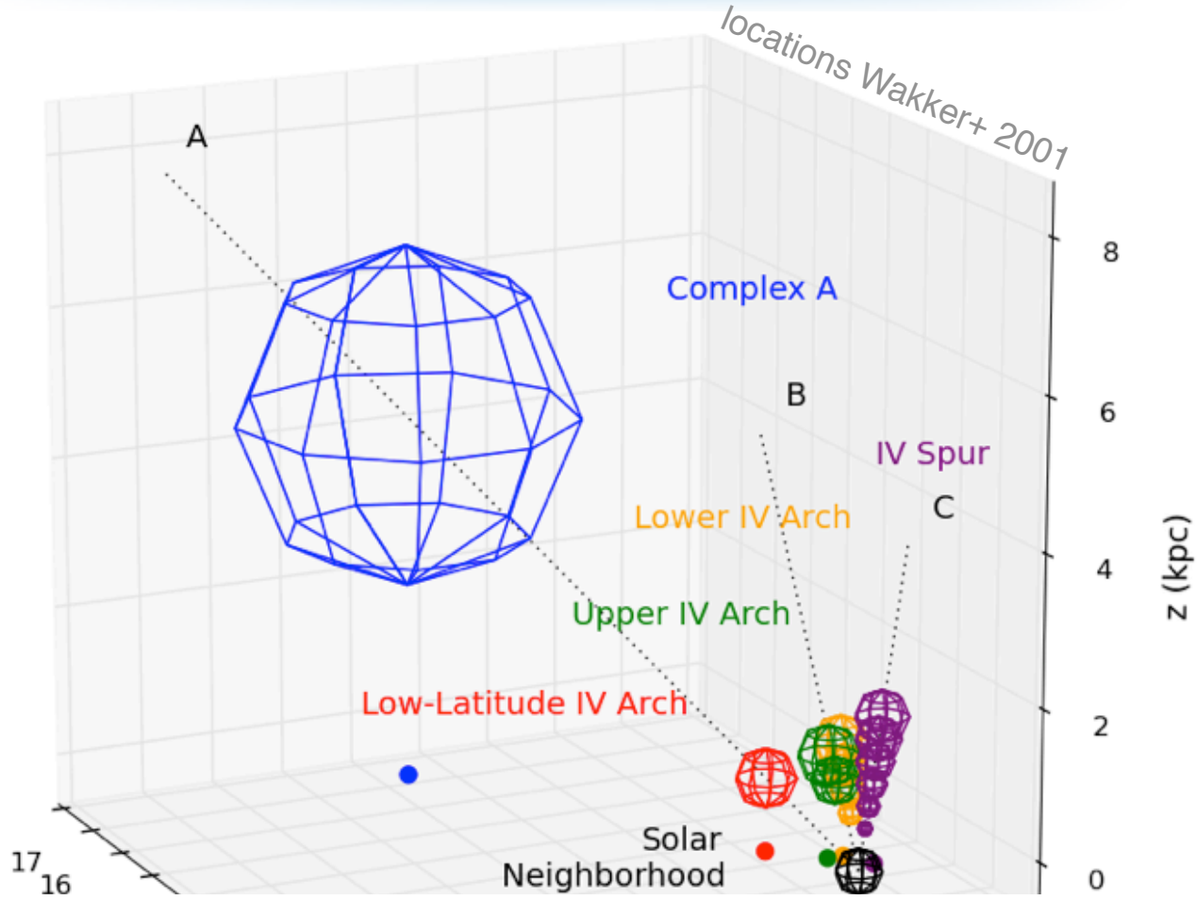


Grenier, Strong & Black 2015

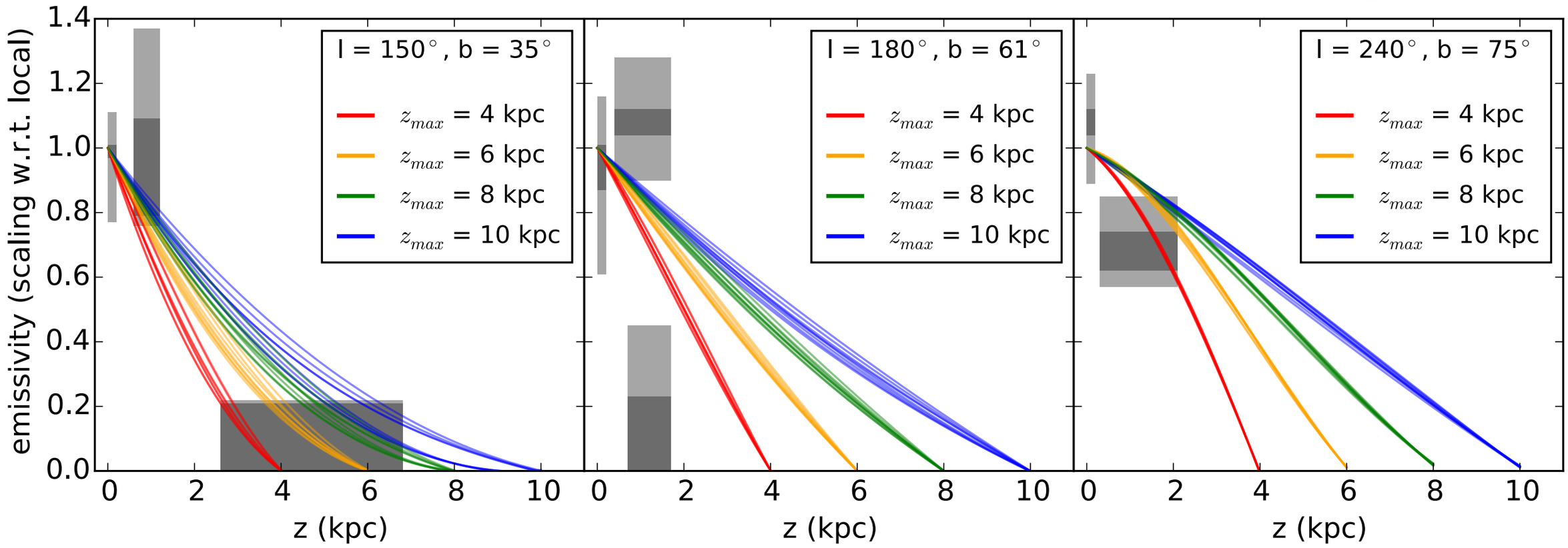
Multi-GeV cosmic rays in the Milky Way

clouds in the halo

- decline in q_{HI} γ-ray emissivity to high altitudes at 97.5% C.L.
  - ✦ unclear trends
  - ✦ may favour diffusion models with a small halo

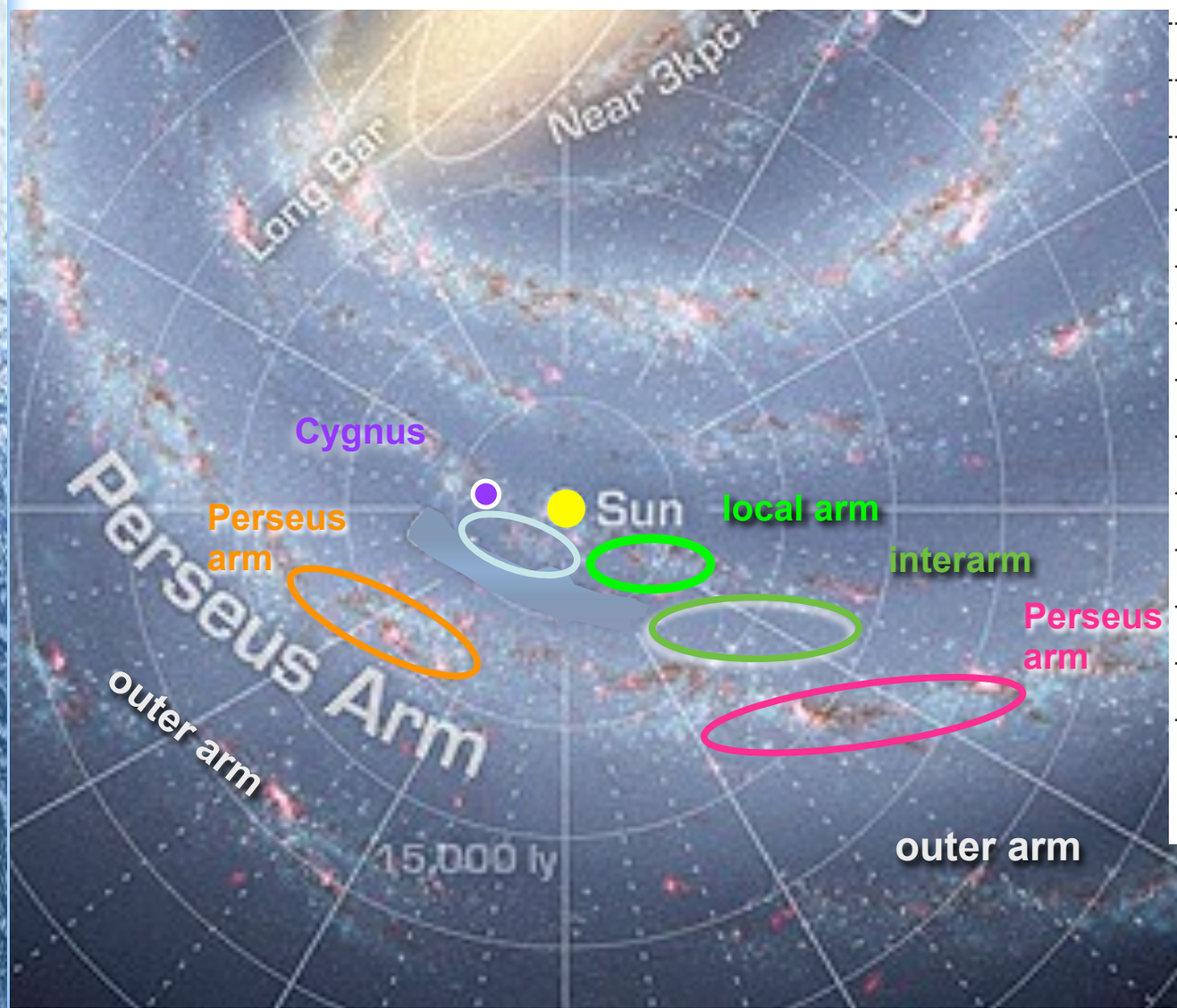


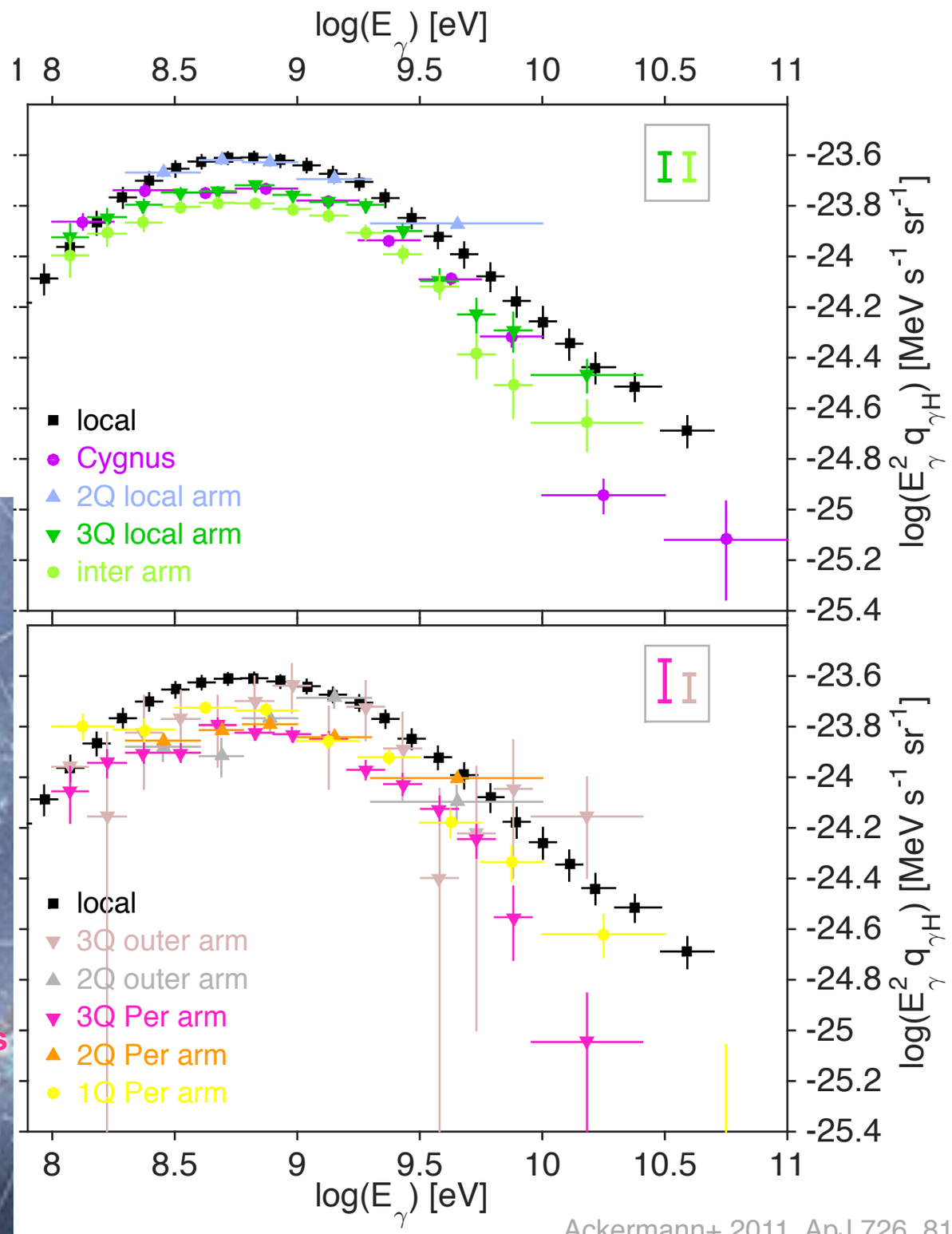
Tibaldo+ 2015 ApJ 807, 161
GALPROP models from Ackermann+ 2012 ApJ 750, 3



cosmic rays across spiral arms

- consistent with LIS spectrum
  => diffusion length > arm scale
- comparable in clouds with $10^3 < M < 8\ 10^6\ M\odot$
- arm/interarm contrast < 10-20%
  & little relation with SFR => loose coupling with the kpc-scale surface density of gas or SFR
  ✦ ok with Dragon-like anisotropic diffusion ?

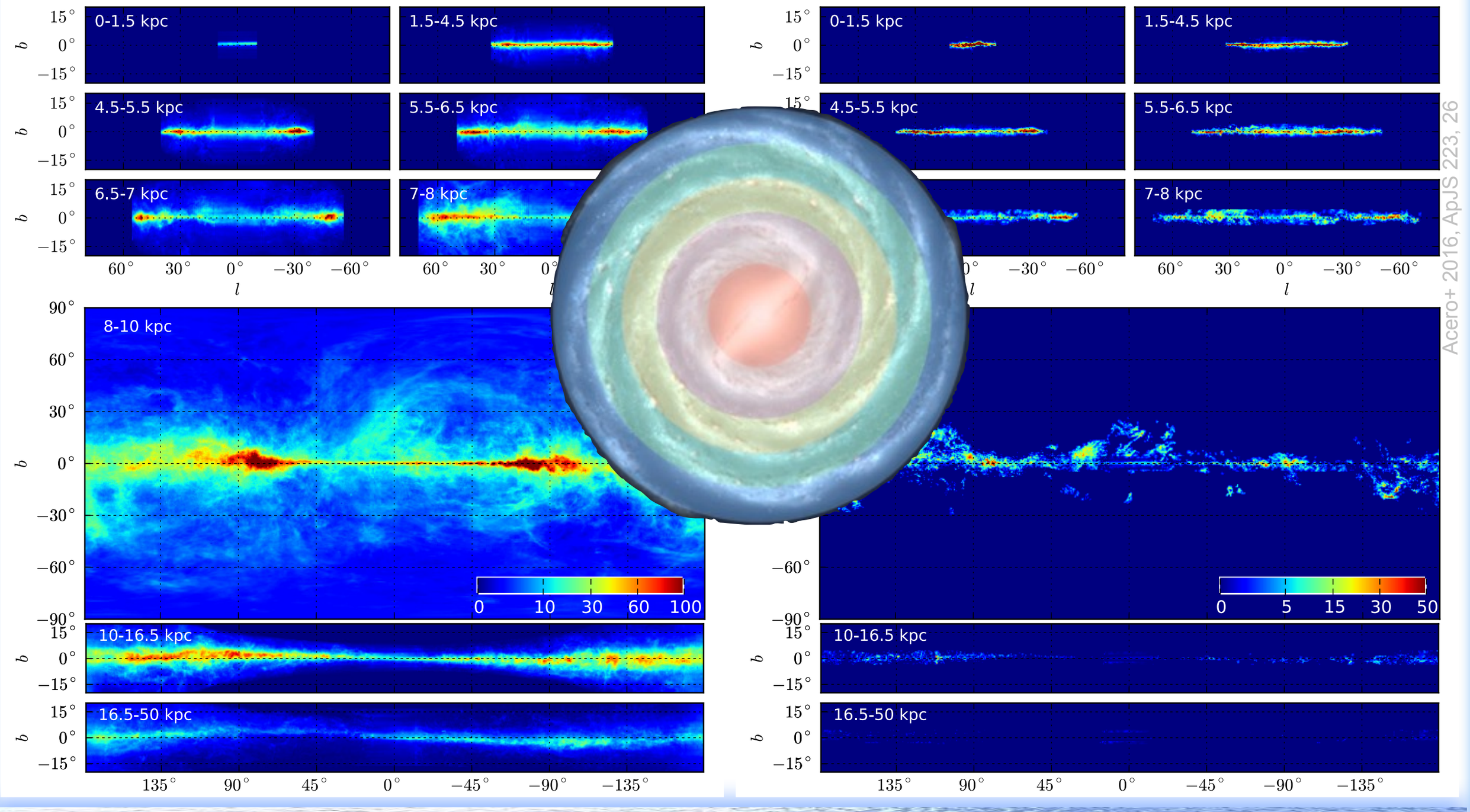




Ackermann+ 2011, ApJ 726, 81
Abdo+ 2011., ApJ 710, 133
Ackermann+ 2012, A&A, 538, A71
Casandjian 2015

Galactocentric rings

- very uncertain in the inner rings !!!



Acero+ 2016, ApJS 223, 26

Galactic radial gradients

$E^2.q_H$ at 2 GeV ($MeV^2\ s^{-1}\ sr^{-1}\ MeV^{-1}$)

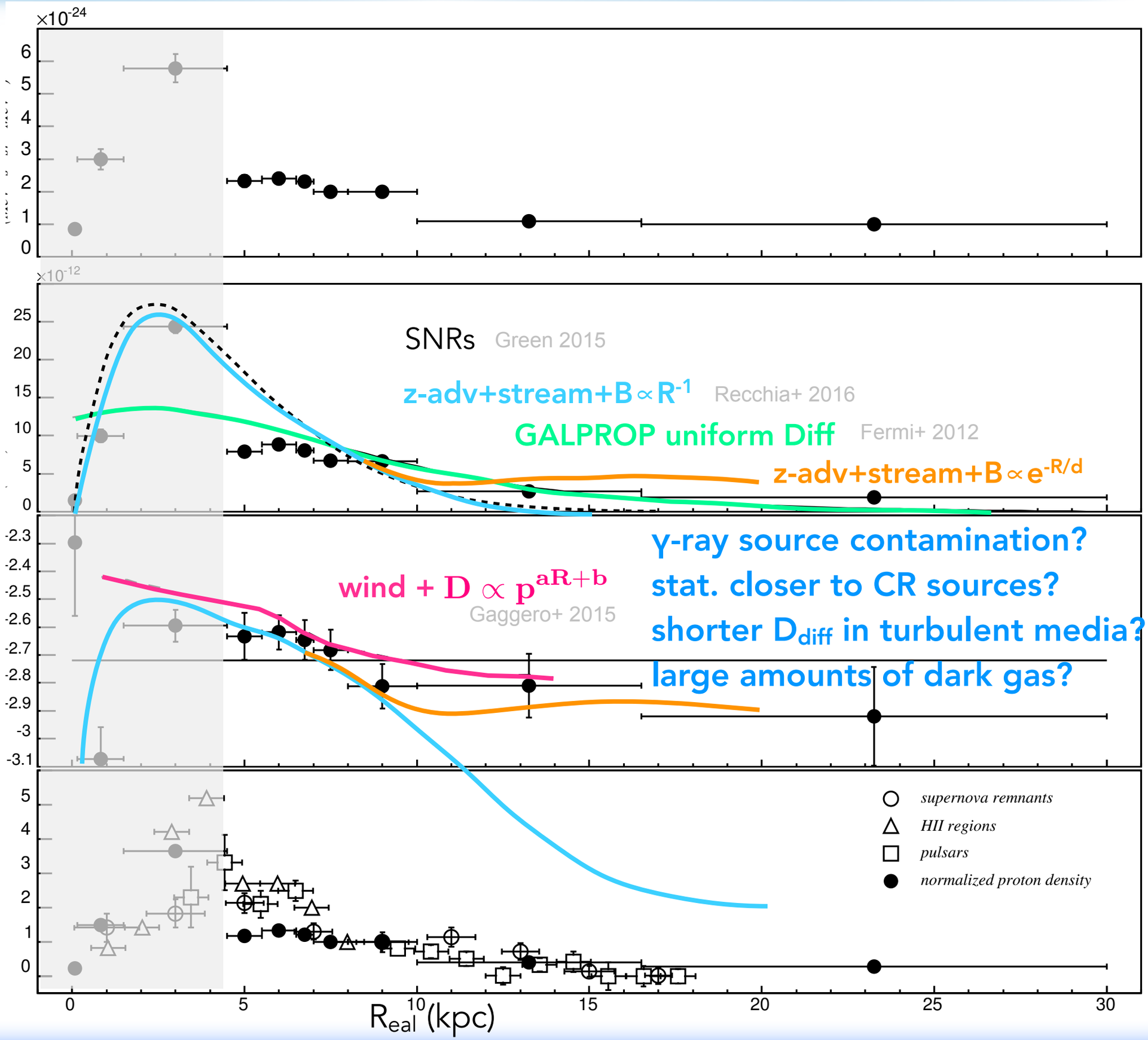
flatter than CR-source profile

proton density (cm^{-3}) > 10 GV

proton spectral index

slight hardening in inner Galaxy

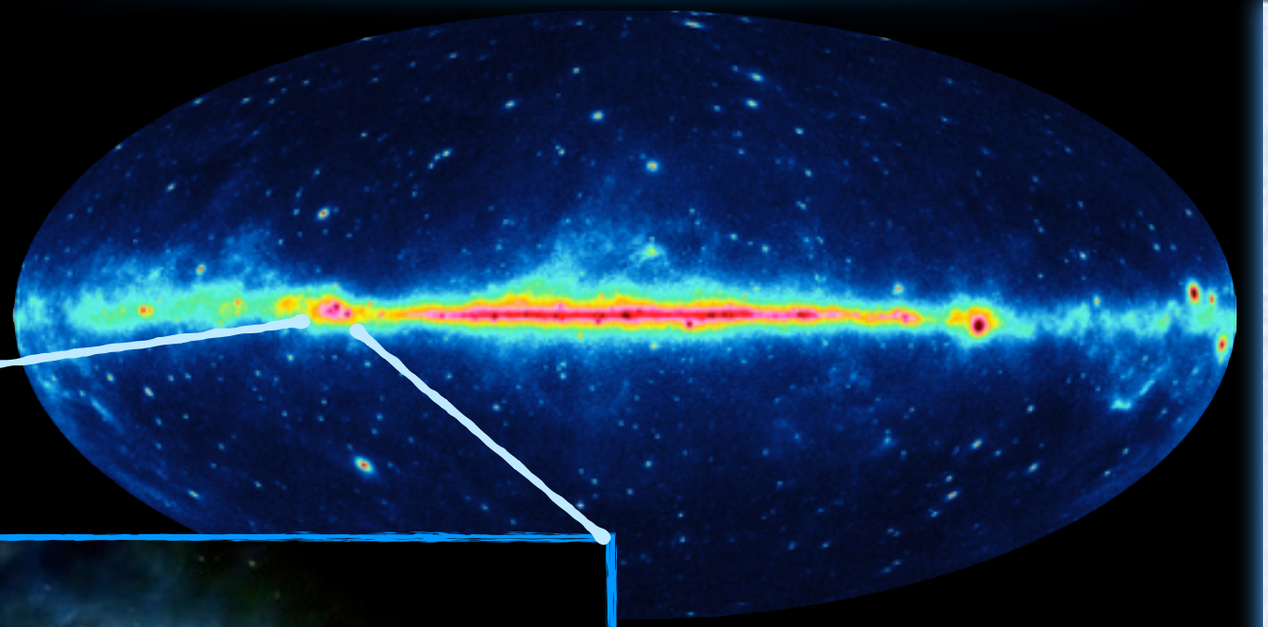
SFR per unit area

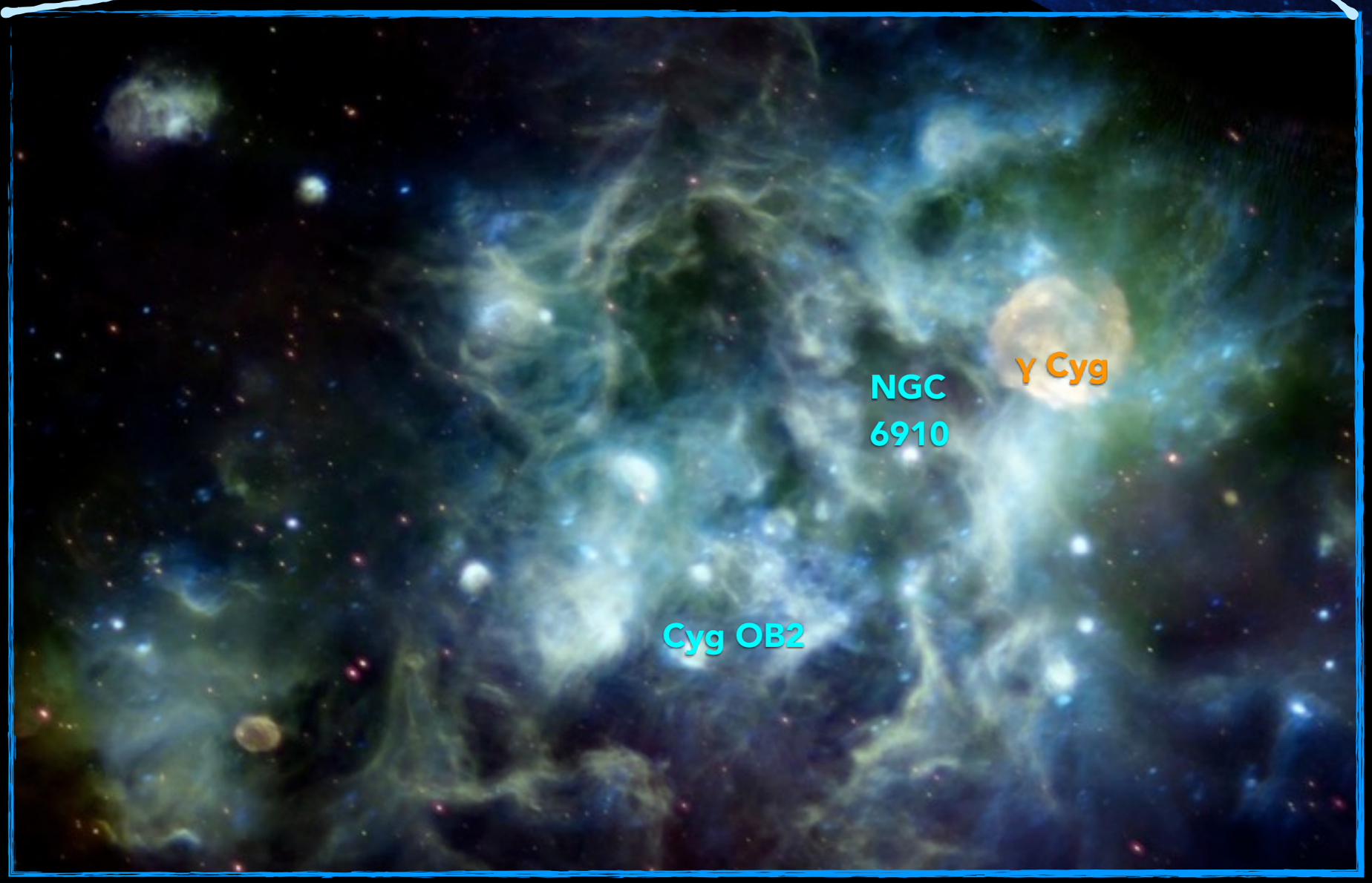


Acero+ 2016, ApJS 223, 26

the Cygnus X nursery

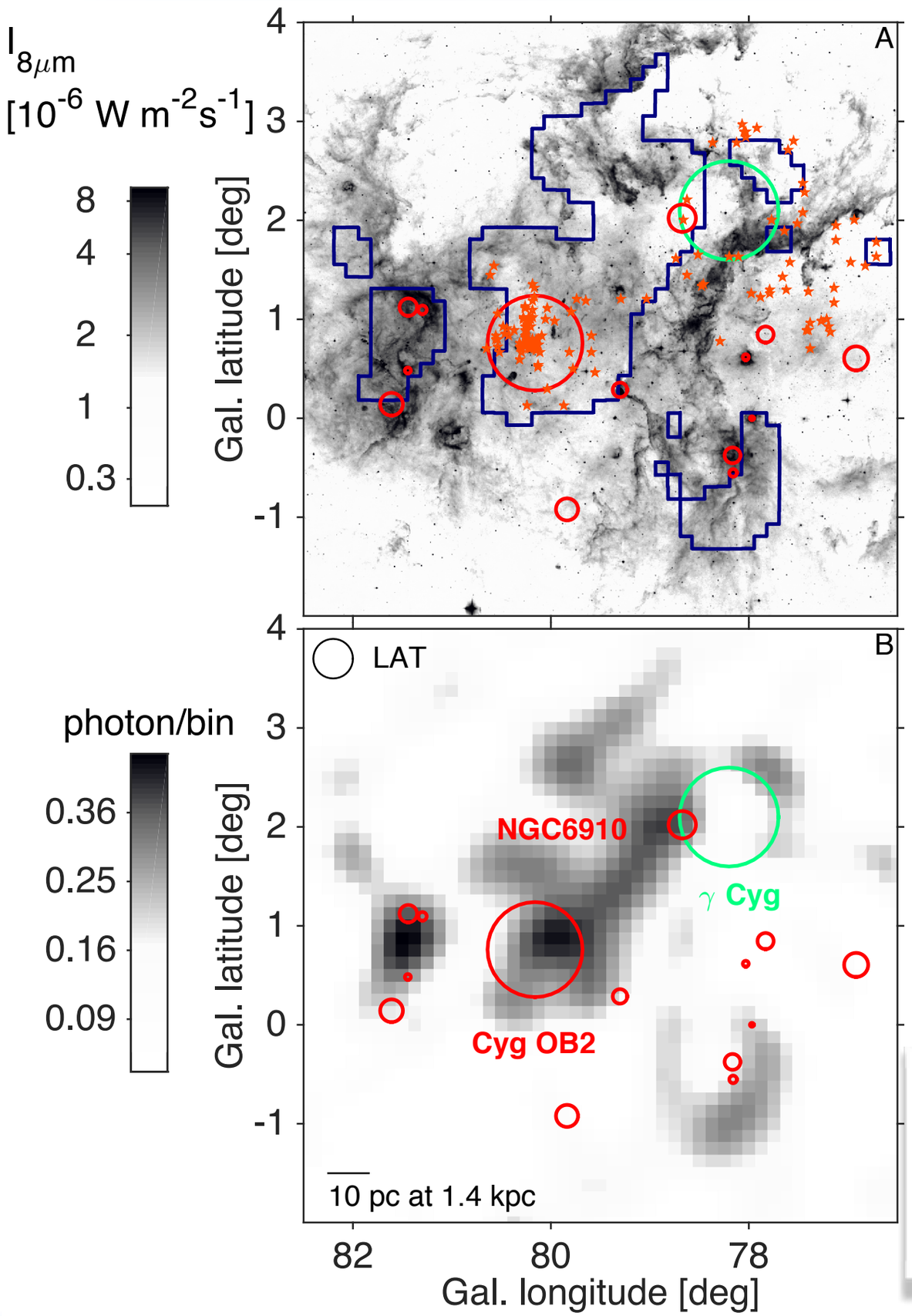
- 8 10^6 M$\odot$ of gas forming stars
  > 600 stars > 4 M$\odot$, 3.5 - 6 Myr old
- > 10 OB associations at 1.4 kpc

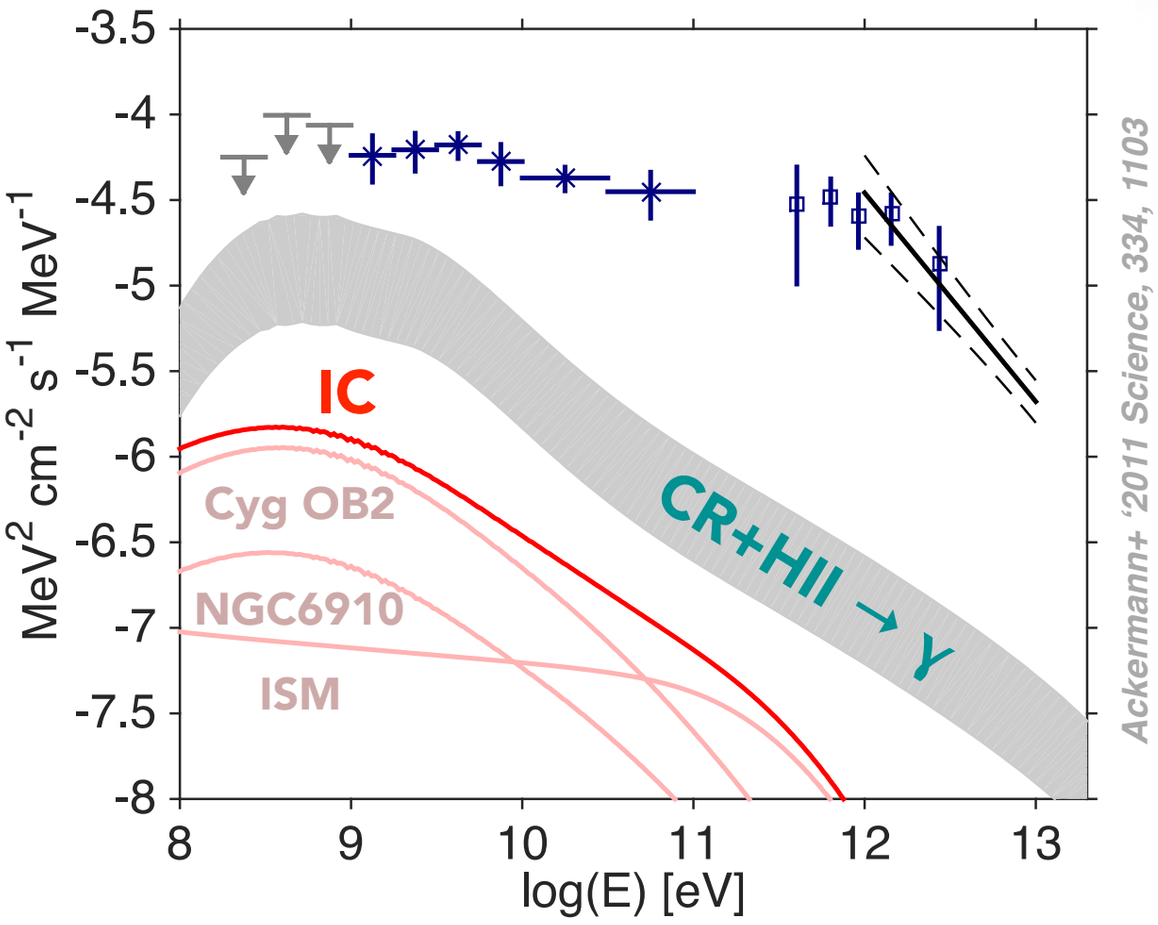




CGPS/IRAS 74 cm
21 cm 60 μ 25 μ

cocoon of fresh cosmic rays





- if pure IC: $E_{tot} = 4\ 10^{41}$ J
- hard γ-ray excess: $E_{CR}^{-2.4}$ above 1 GeV
- bounded by ionization fronts (PDRs)
- extension >> SNR or cluster sizes
- ≈ spectral uniformity

$$\left(\frac{dN_e}{dSdtd\Omega dE_e}\right)_{LIS} \times 60 \left(\frac{E_e}{10GeV}\right)^{0.5}$$

- if pure pion: $E_{tot} = 1.3\ 10^{42}$ J ≈ 1% E_{SN}

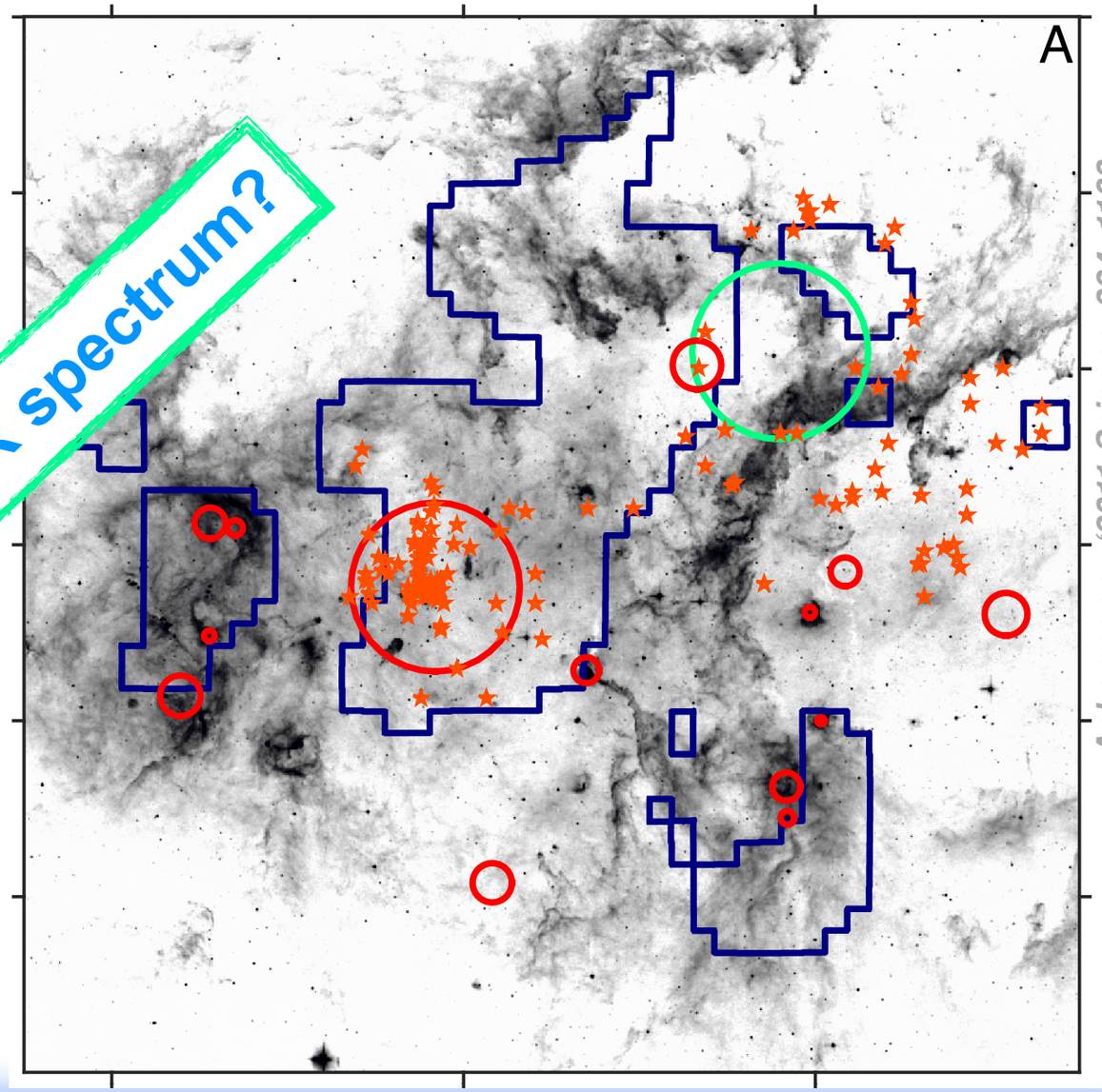
$$\left(\frac{dN_{CR}}{dSdtd\Omega dE_{CR}}\right)_{LIS} \times (1.5-2.0) \left(\frac{E_{CR}}{10\,GeV}\right)^{0.3}$$

cocoon of fresh cosmic rays

- CRs from young γ Cygni SNR ?
  - ✦ barely possible if $D_{ISM}(E)$, spectro-imaging tests soon
- starburst >1500 OB stars, 3-6 Myr old (SNe ≪)
  - ✦ L_{cocoon} < 0.03% and 7% of P_{winds}
  - ✦ saturated MHD turbulence, <B> = 1.8 nT, 10 pc injection scale (wind termination shocks)
- => $D(E) = D_{ISM}(E) / 100$ => efficient confinement (100 kyr at TeV, 300 kyr at 100 GeV)
  - ✦ escape of "exhausted" CRs because of severe hadronic losses ?
    => emerging 2nd/1ary ?
    => CR ionisation rate in surrounding clouds ?
  - ✦ escape of "regenerated" CRs because of repeated wind-shock accelerations
    (re-)acceleration up to E(p) = 150 TeV
    peak 10-100 GeV protons

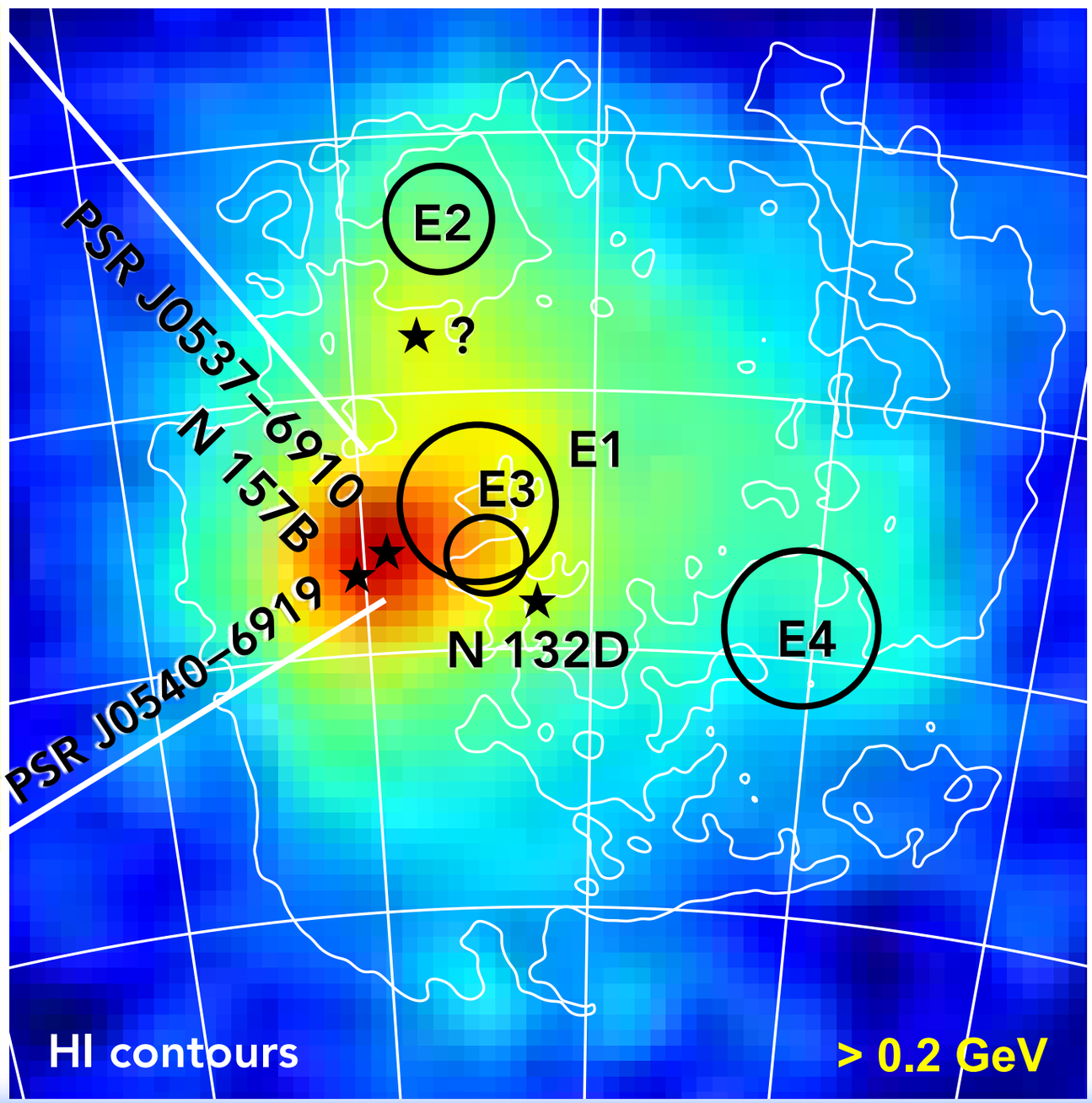
    HE neutrinos ?

- other CR cocoons in Galactic starburst regions?



Cosmic-ray bursts in LMC ?

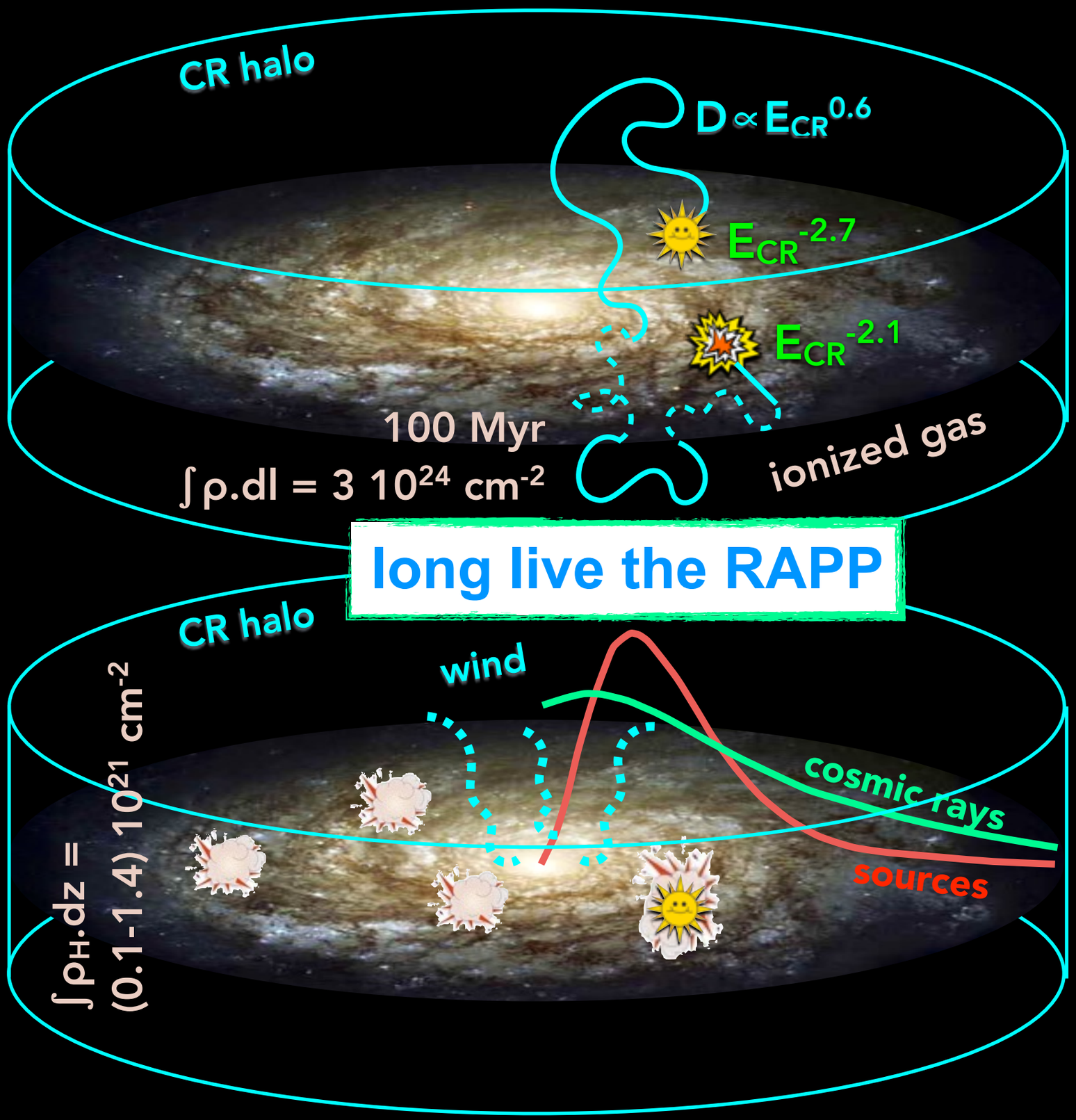
- 30 Doradus starburst: pt-source confusion with 2 bright pulsars, 30 Dor C superbubble not detected
- N11 starburst region not detected
- diffuse emission => central peak CR density of order 1/3 the local Galactic one (LIS)
- extended emission spots: possibly 2 to 6 times more CR density



Ackermann+ 2016 A&A 586, 71

cosmic rays & γ rays in the Milky Way

- CRs < 10^{15} eV: origin in the Milky Way & propagation in a > kpc halo



open questions:
source escape?

superbubble escape?
super bubble
re-acceleration?

non-uniform diffusion?
hidden grammage?