Shocking uncertainties in Galactic cosmic rays

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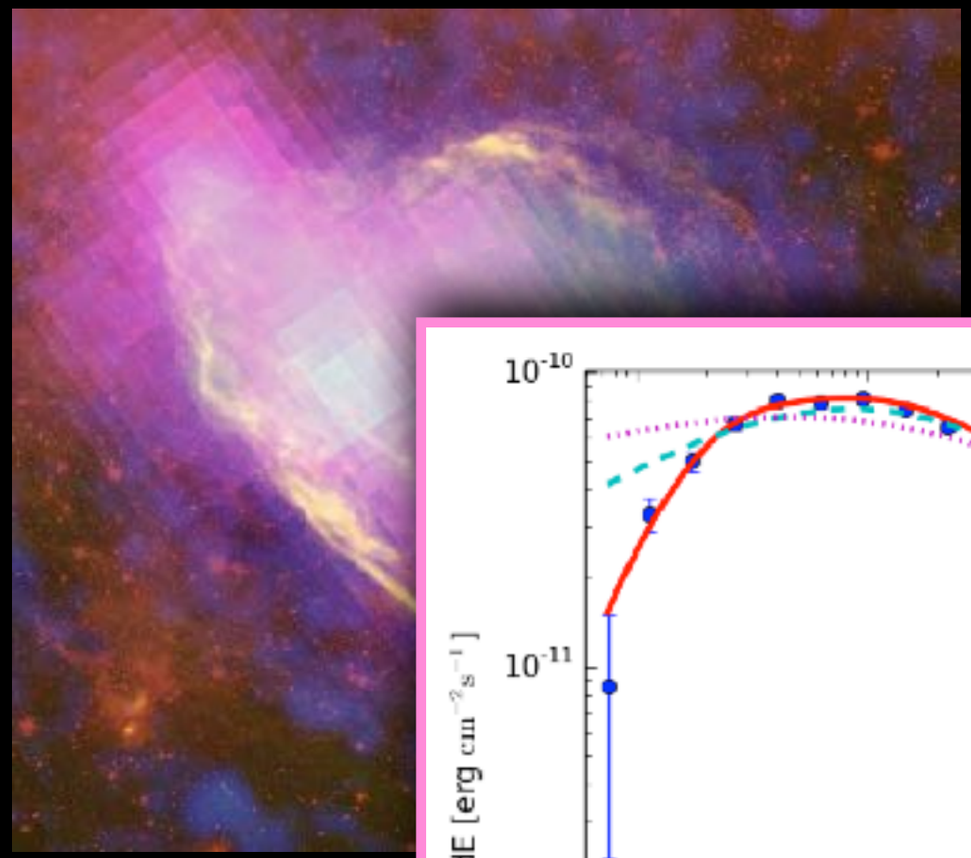
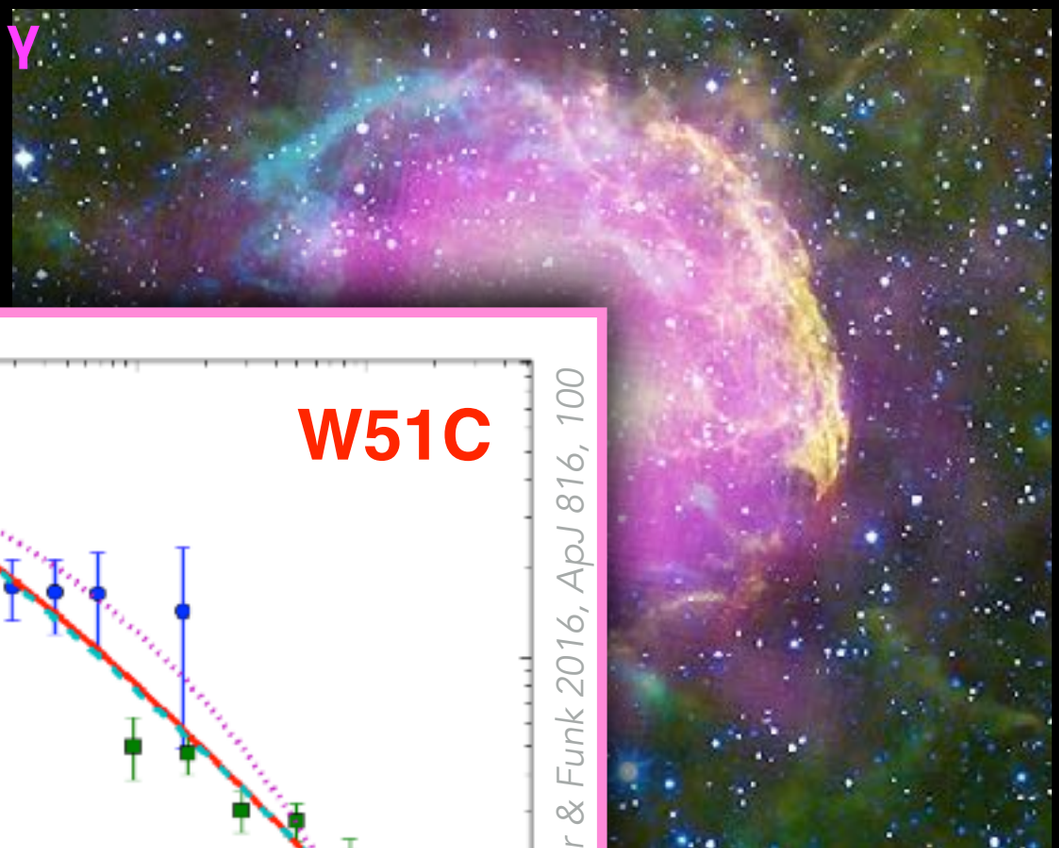
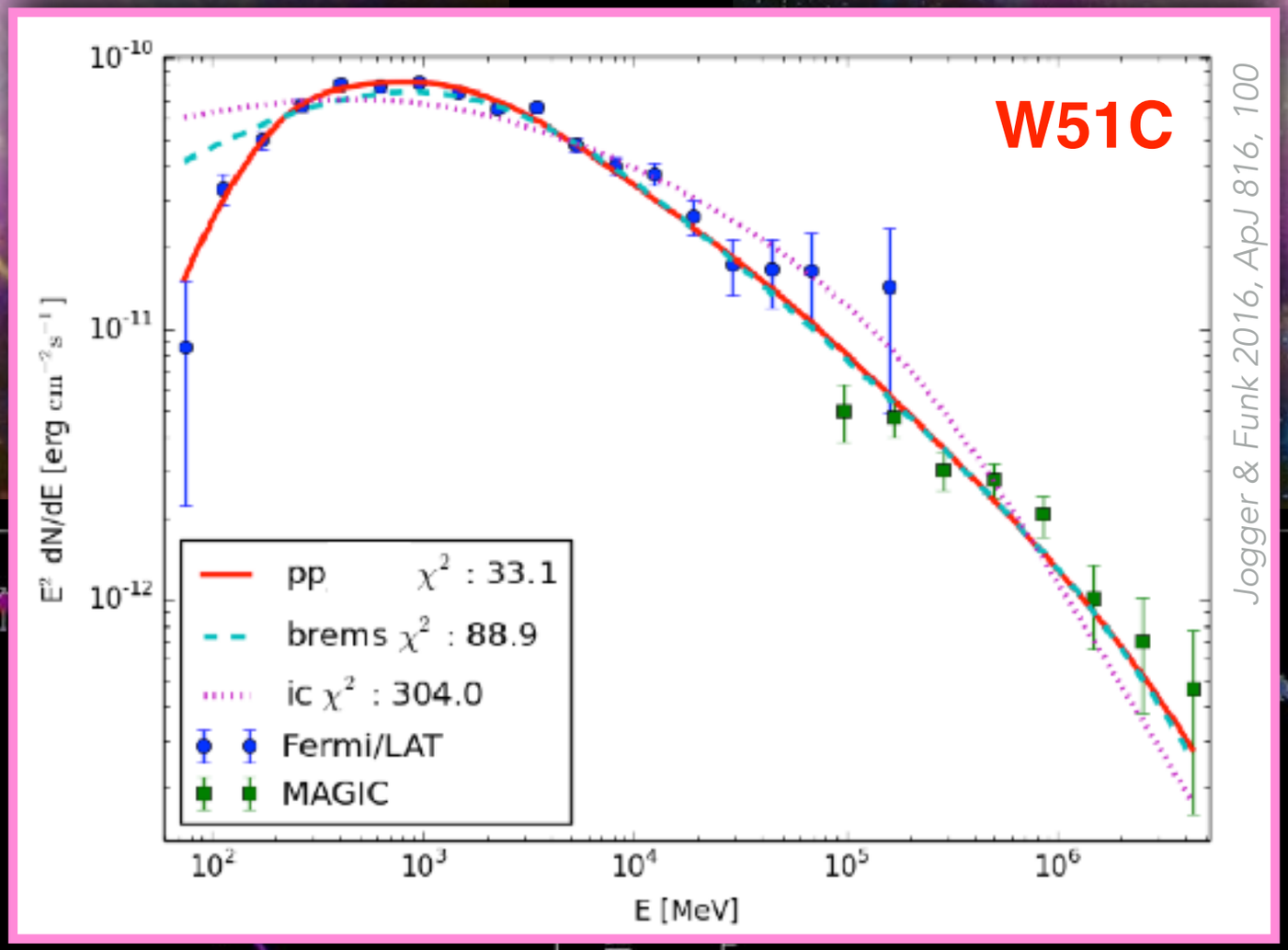
Fermi

signature of freshly accelerated nuclei?

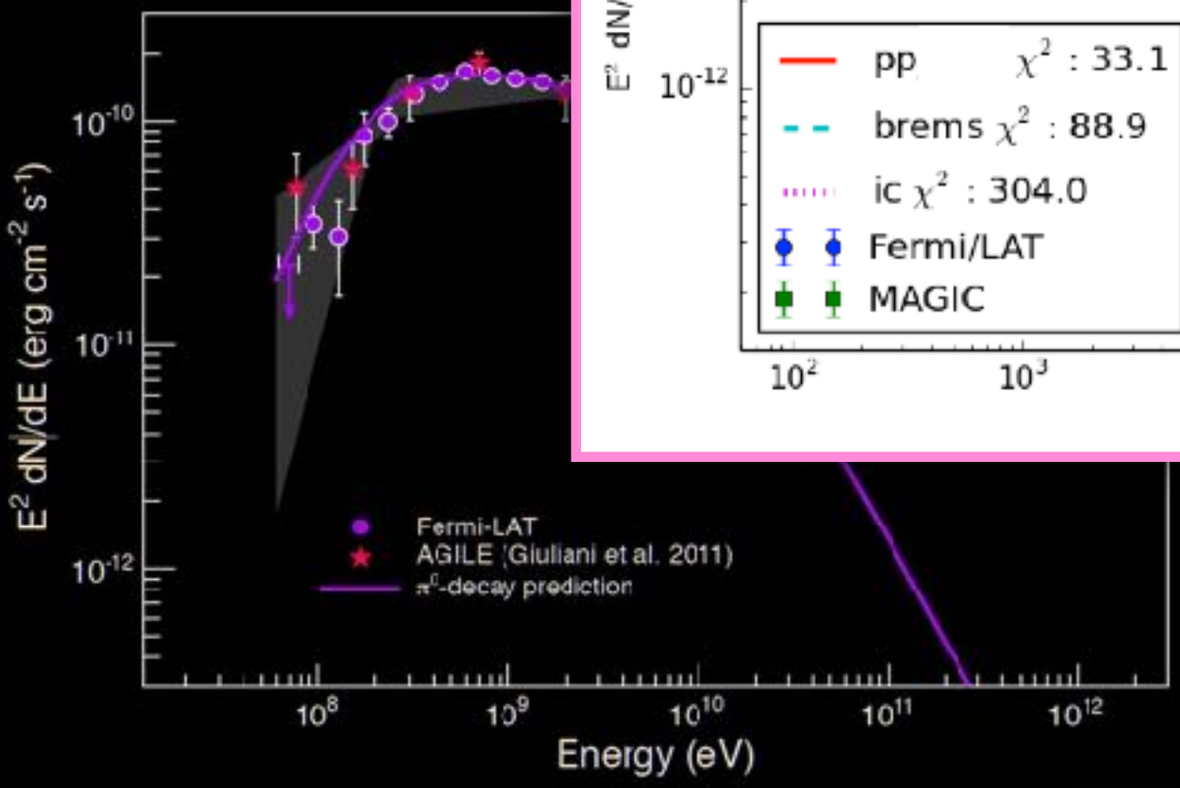
IR opt γ

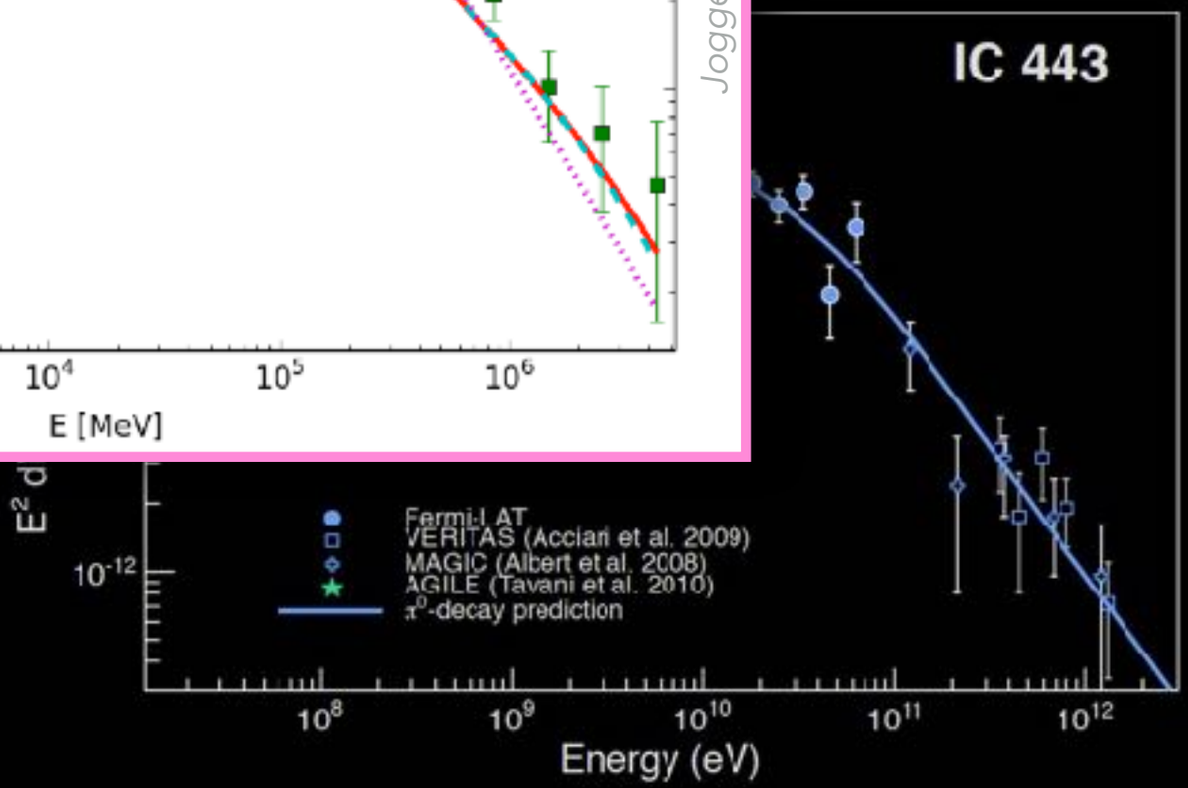






Jogger & Funk 2016, ApJ 816, 100

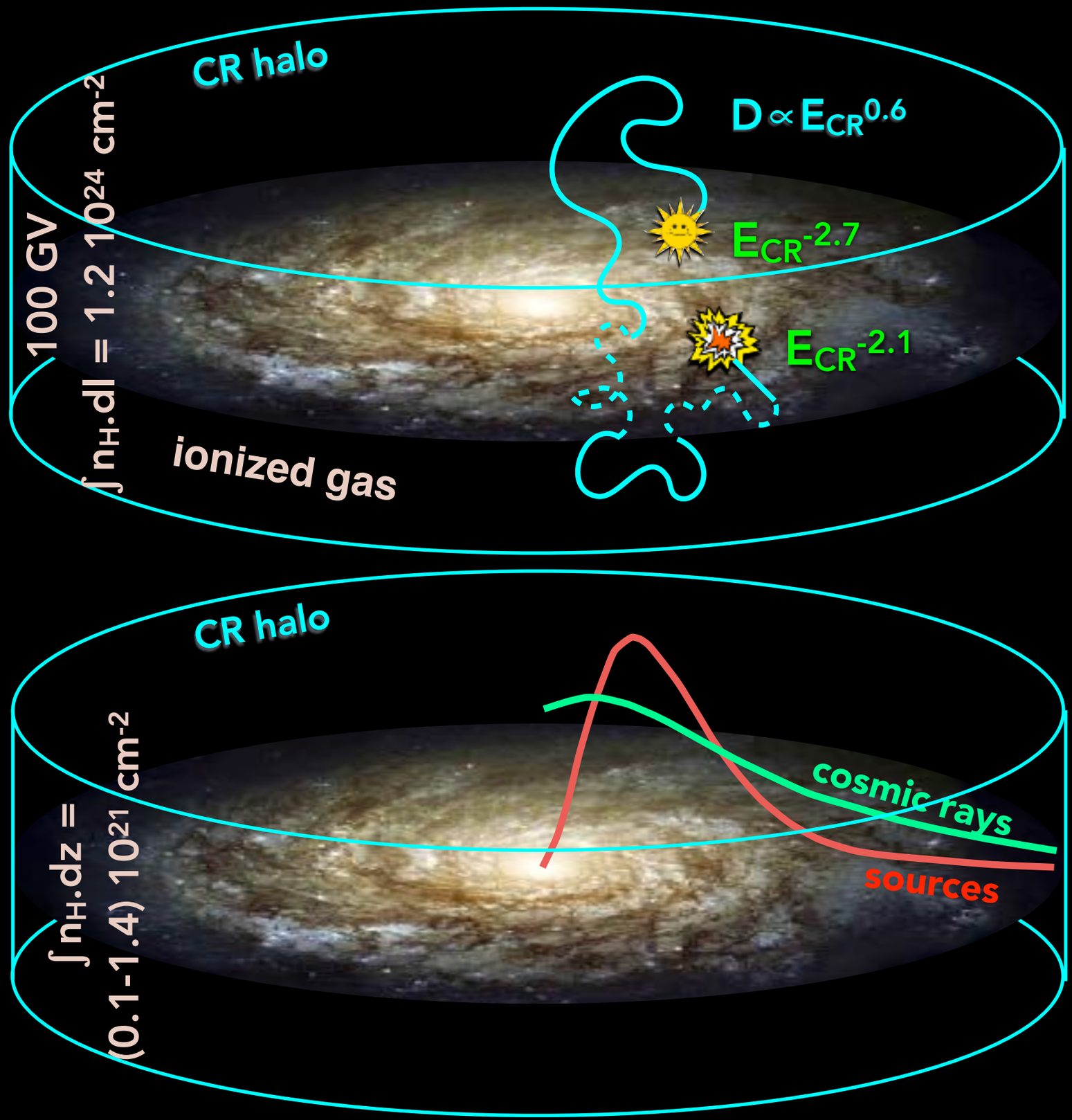


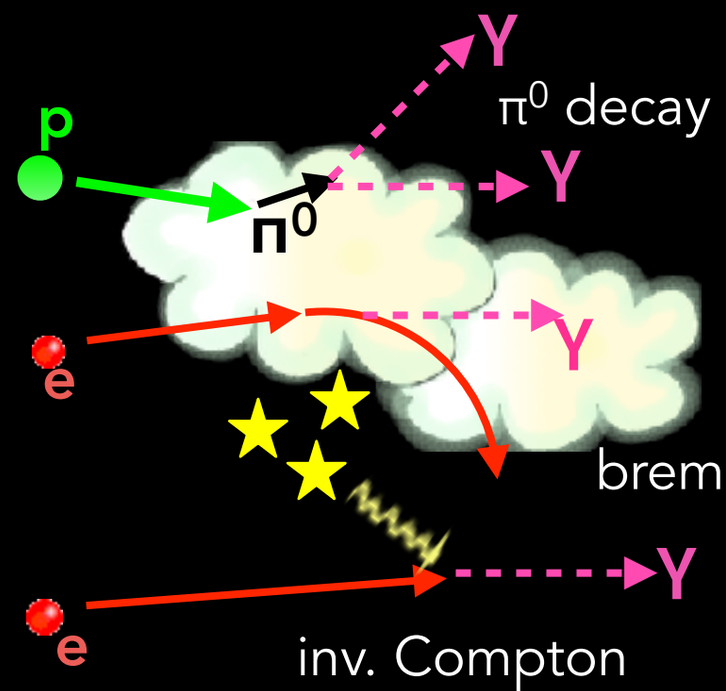


Ackermann+ 2013 Science 339, 807

Galactic cosmic-ray wanderers

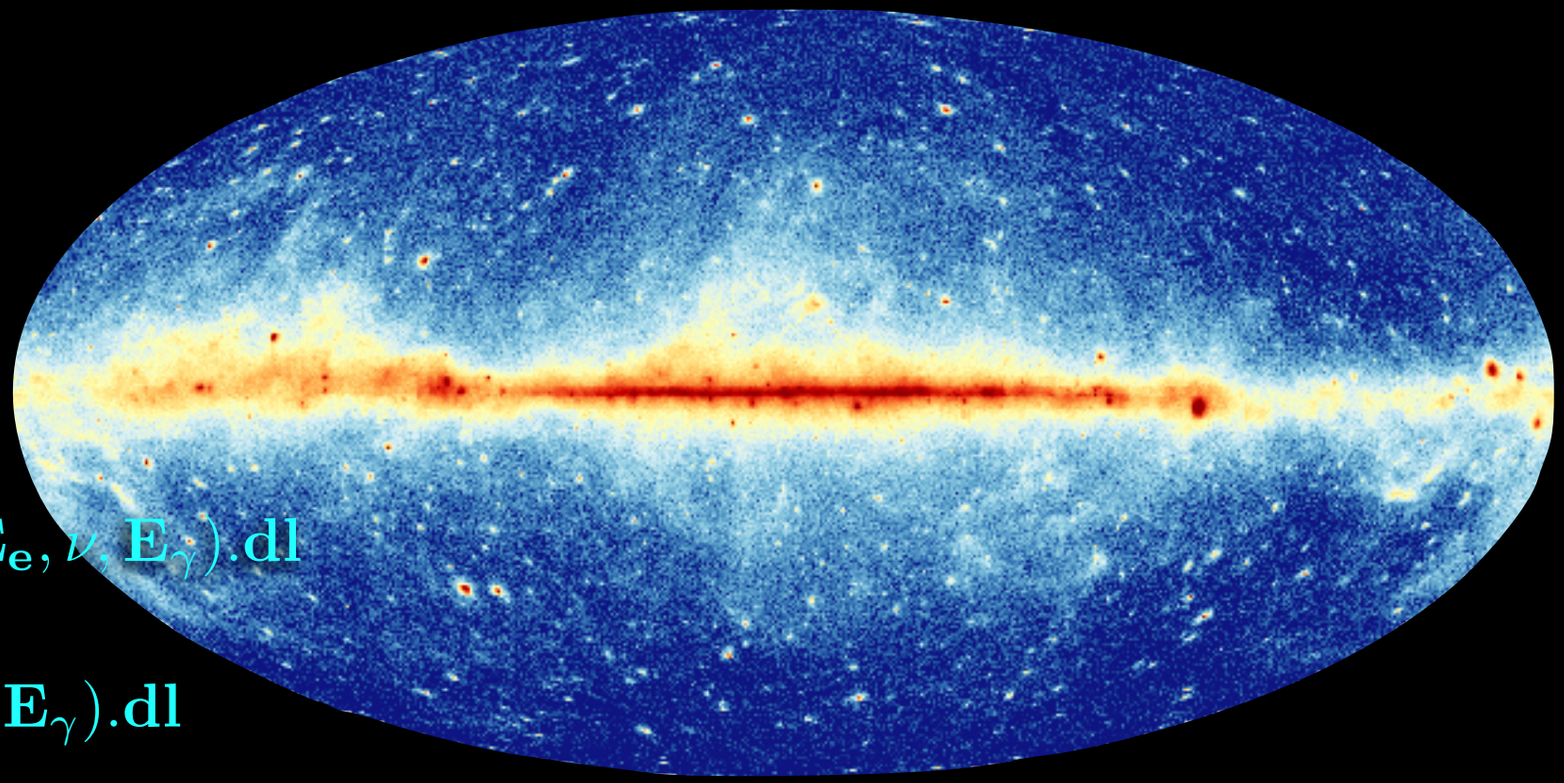
- CRs < few 10^{15} eV: origin in the Milky Way & propagation in a > kpc halo





remote sensing of super-GeV cosmic rays

- (e+p) probed in γ rays
  - Fermi LAT 8 yr > 0.4 GeV



$$\mathbf{I_{\gamma ISM}(x, E_\gamma)} = \int_{\mathbf{los}} \mathbf{n_e(x, E_e)\, n_{ISRF}(x, \nu)\, \sigma_{IC}(E_e, \nu, E_\gamma).dl} + \int_{\mathbf{los}} \mathbf{n_e(x, E_e)\, n_{gas}(x)\, \sigma_{br}(E_e, E_\gamma).dl} + \int_{\mathbf{los}} \mathbf{n_A(x, E_A)\, n_{gas}(x)\, \sigma_\pi(E_A, E_\gamma).dl}$$

- (e) probed by radio synchrotron
  - 35 haloes piled-up by Chan-ges

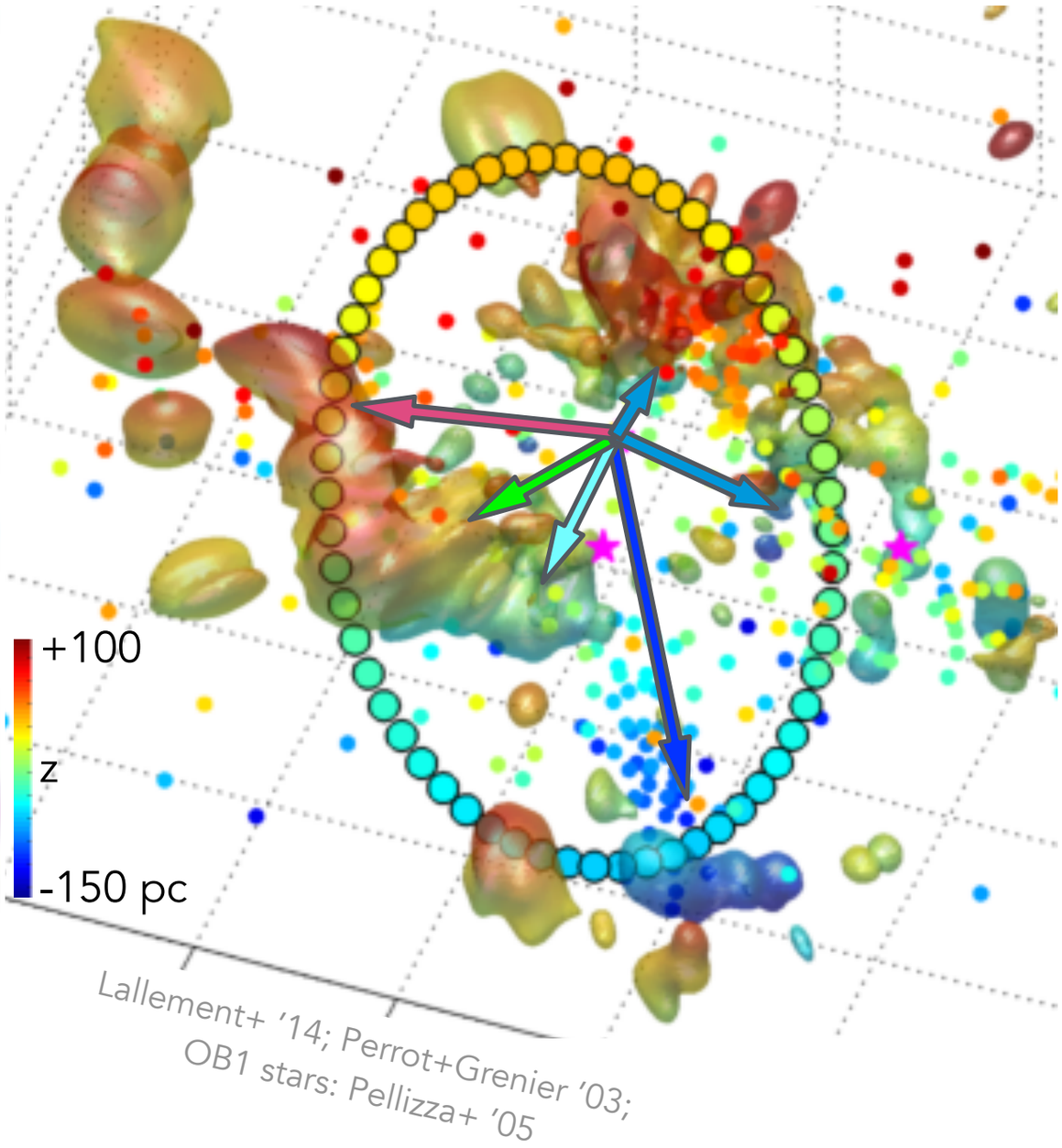
$$\text{if } \mathbf{n(E_e)} = \kappa \left(\frac{\mathbf{E_e}}{\mathbf{E_0}}\right)^{-\mathbf{p}}$$

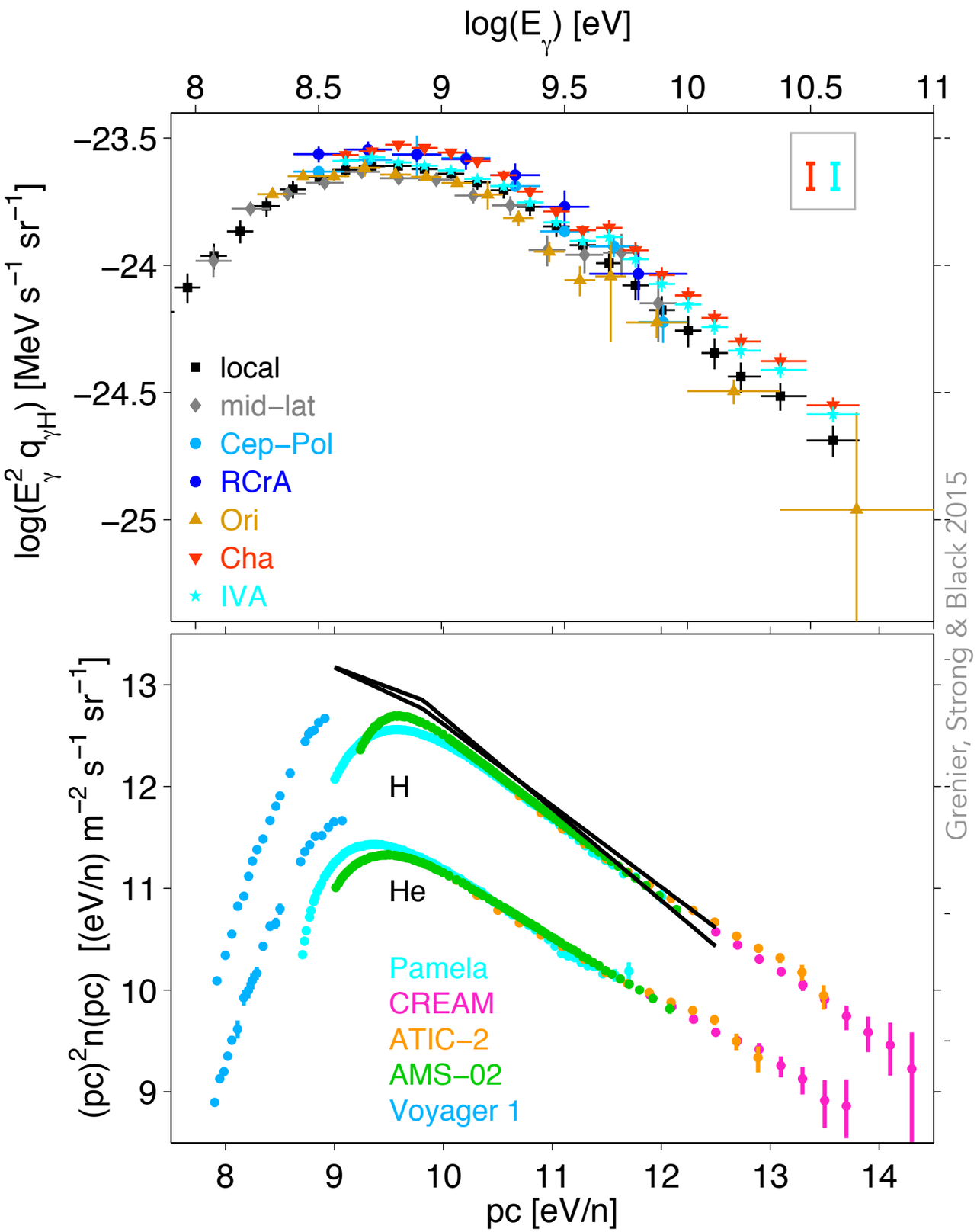
$$\mathbf{S_\nu} \propto \int \kappa\, \mathbf{B}^{\frac{1+p}{2}}\, \nu^{\frac{1-p}{2}}\, \mathbf{dl}$$

Wiegert+ 2015 AJ 150 81

local emissivity spectra in the HI

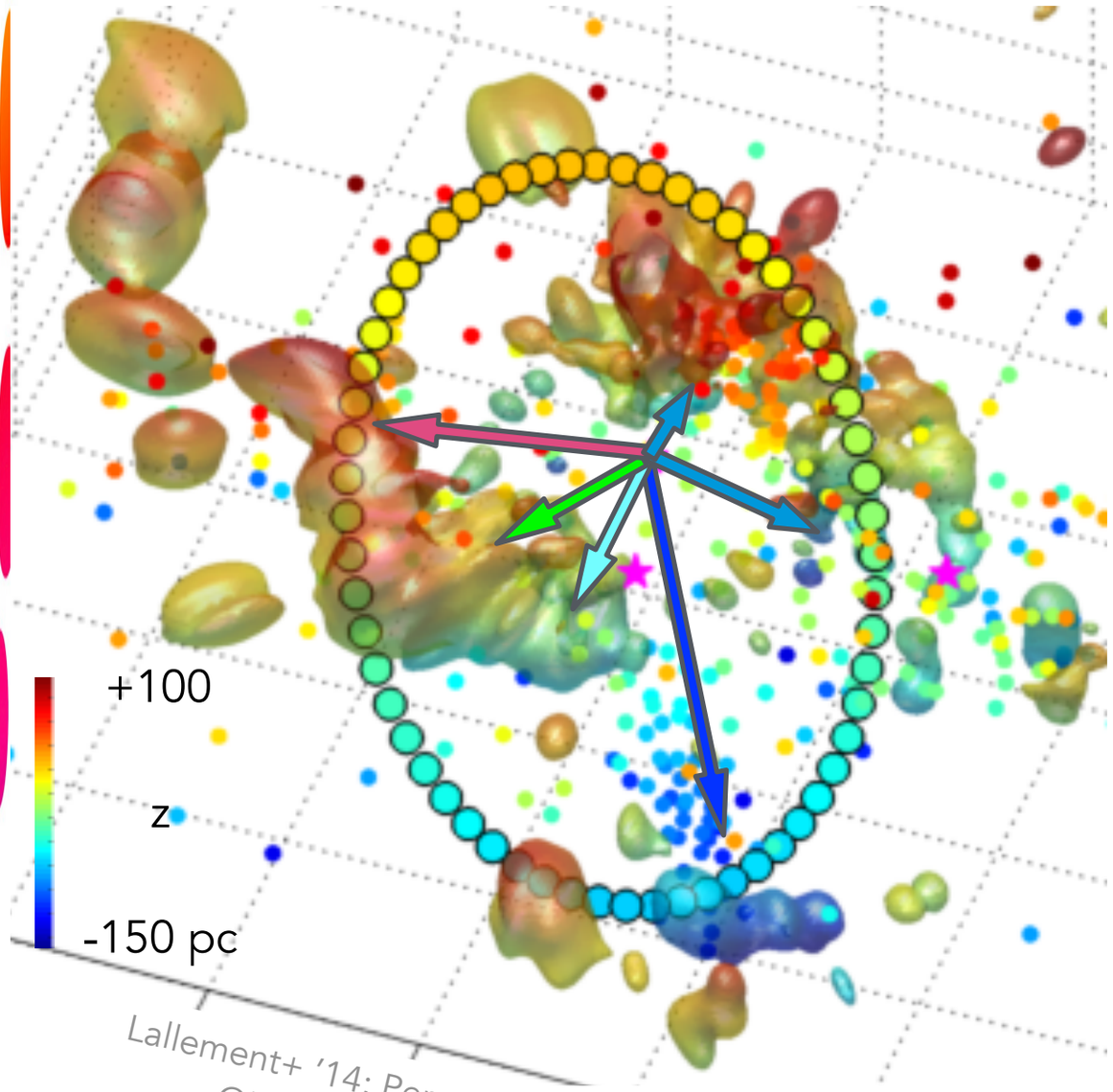
- few GeV to TeV CRs probed in γ rays with Fermi
- LISM spectrum consistent with direct in-situ observations
- upturn > 200 GV in all nuclei



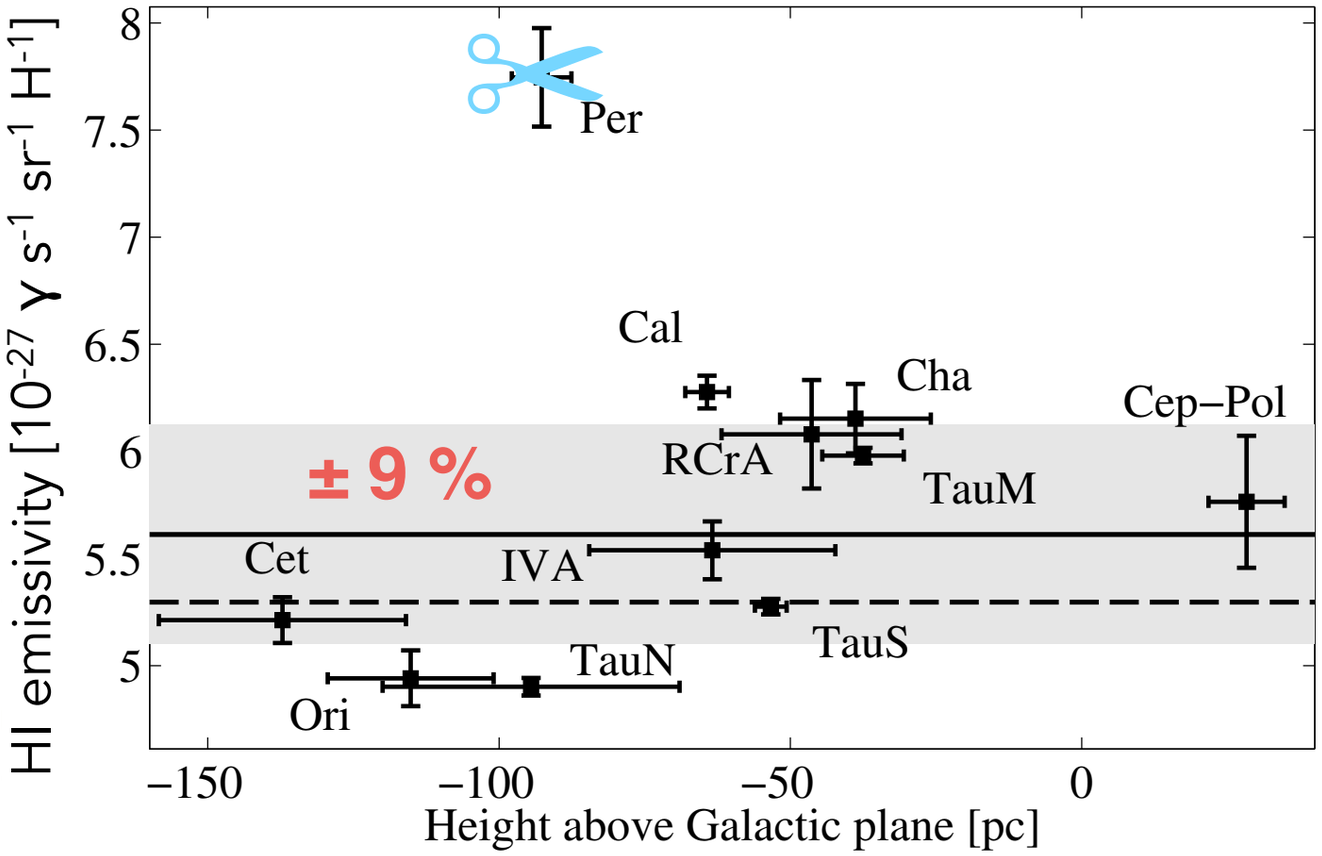


local γ-ray emissivities in the HI

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



Remy+17 A&A 601, 78



- Fermi local ISM + Voyager data
  - $\zeta^{H}_{CR} \approx 1.4\ 10^{-17}\ s^{-1}$ Grenier, Strong & Black 2015
  - from H_3^+

    Per OB2 (300 pc): (5.6±3.2) 10^{-16} s^{-1}

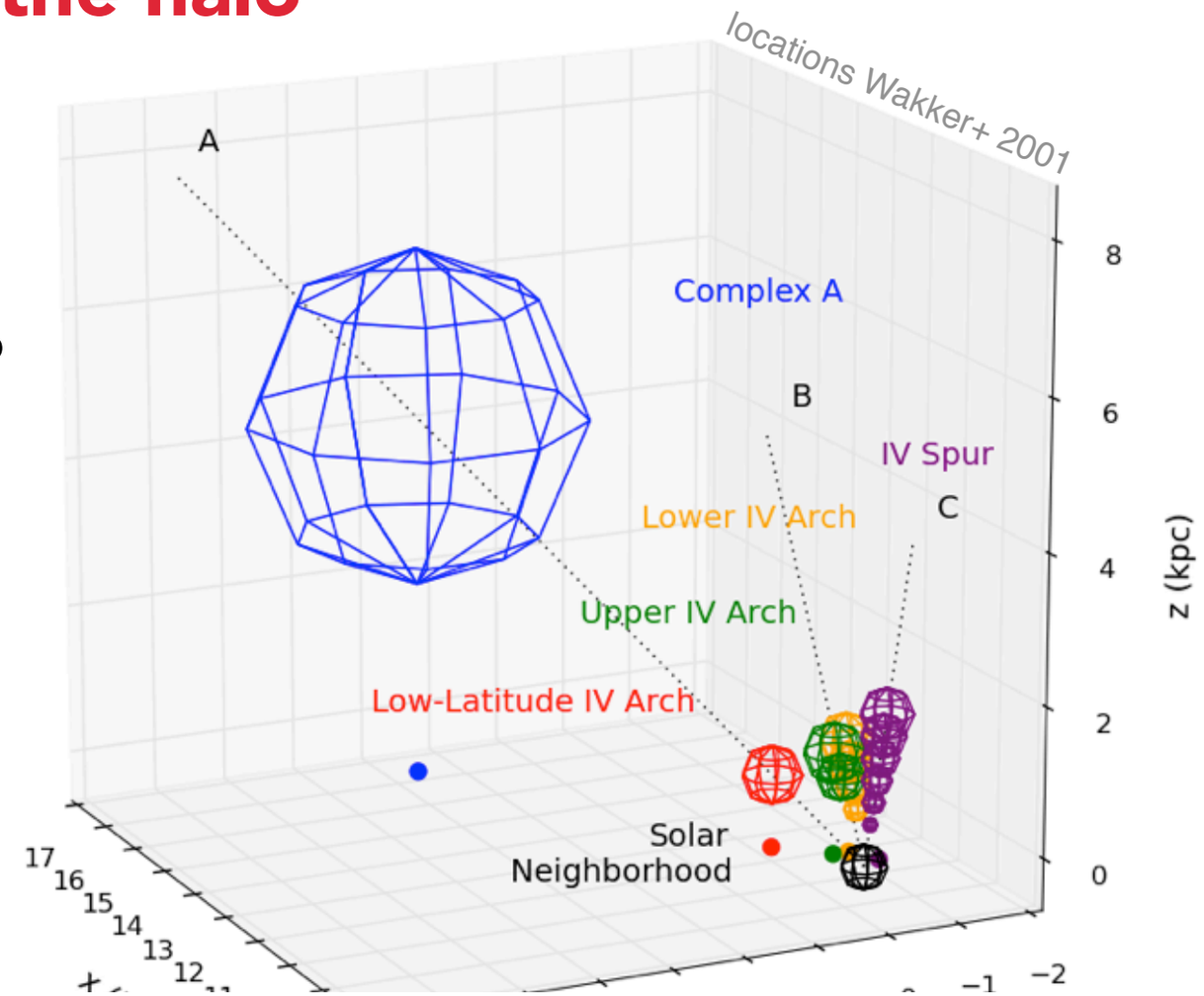
    & (5.9±3.5) 10^{-16} s^{-1}

    despite same GeV CR flux

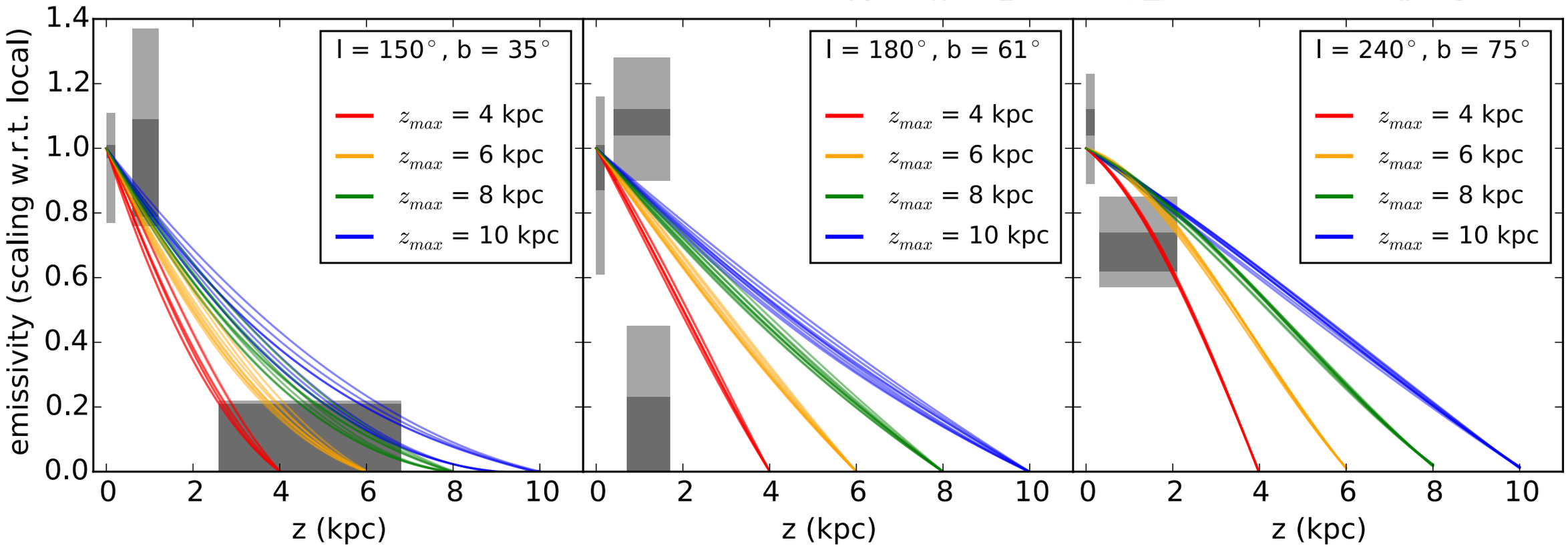
=> low-energy environmental effects ?

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



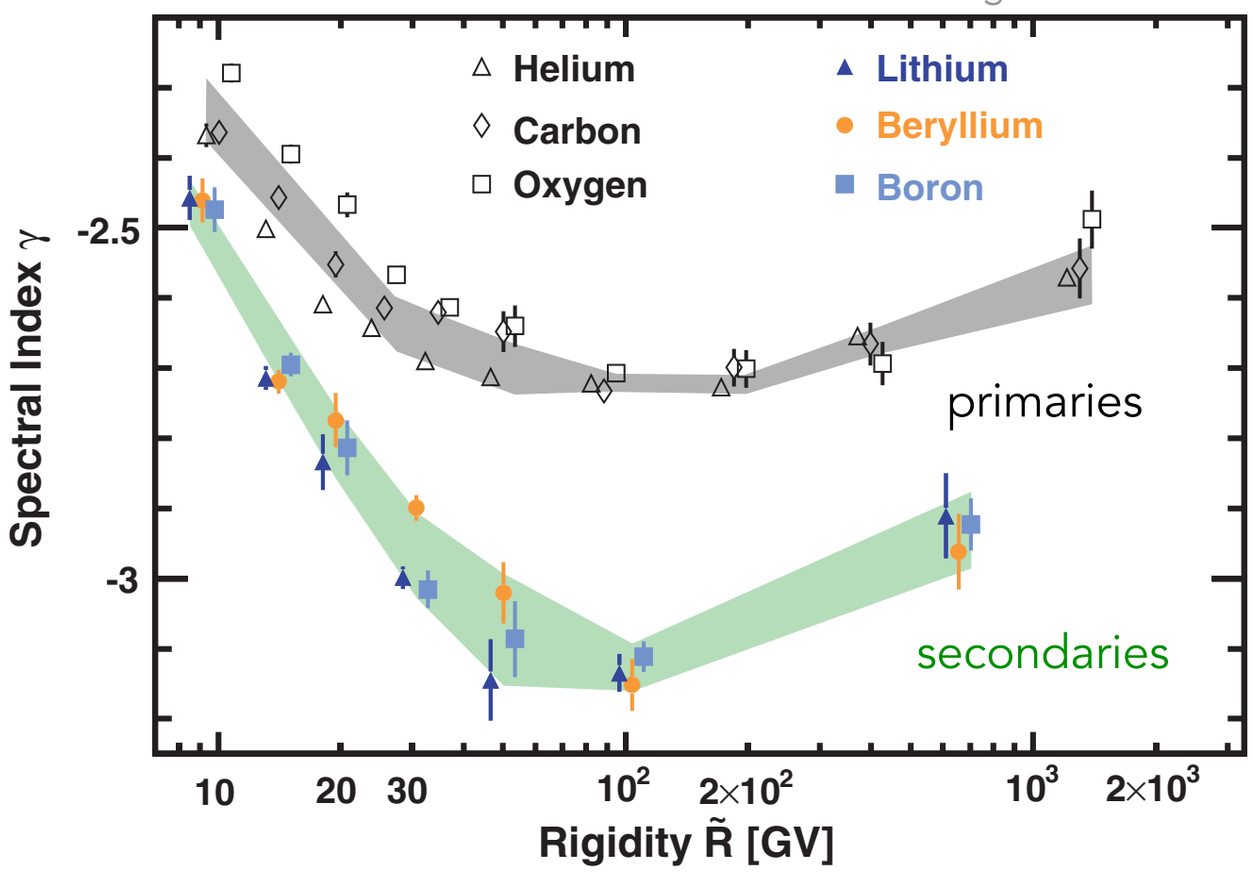
Tibaldo+ 2015 ApJ 807, 161
GALPROP models from Ackermann+ 2012 ApJ 750, 3



local cosmic-ray hardening

- hardening above 200 GV.
  - same rigidity spectrum > 60 GV for He, C, O (primaries), and > 30 GV for Li, Be, B (secondaries)
  - upturn due to non-linear DSA at SNR shocks? diffusion on self-generated waves? spatial variations in D(E)? a nearby source?
- hardening strength
  - same in 1ary and 2ary CRs if related to source injection
  - stronger for 2ary than 1ary CRs if due to Gal. propagation
  - no decisive trend

Aguilar+18 AMS



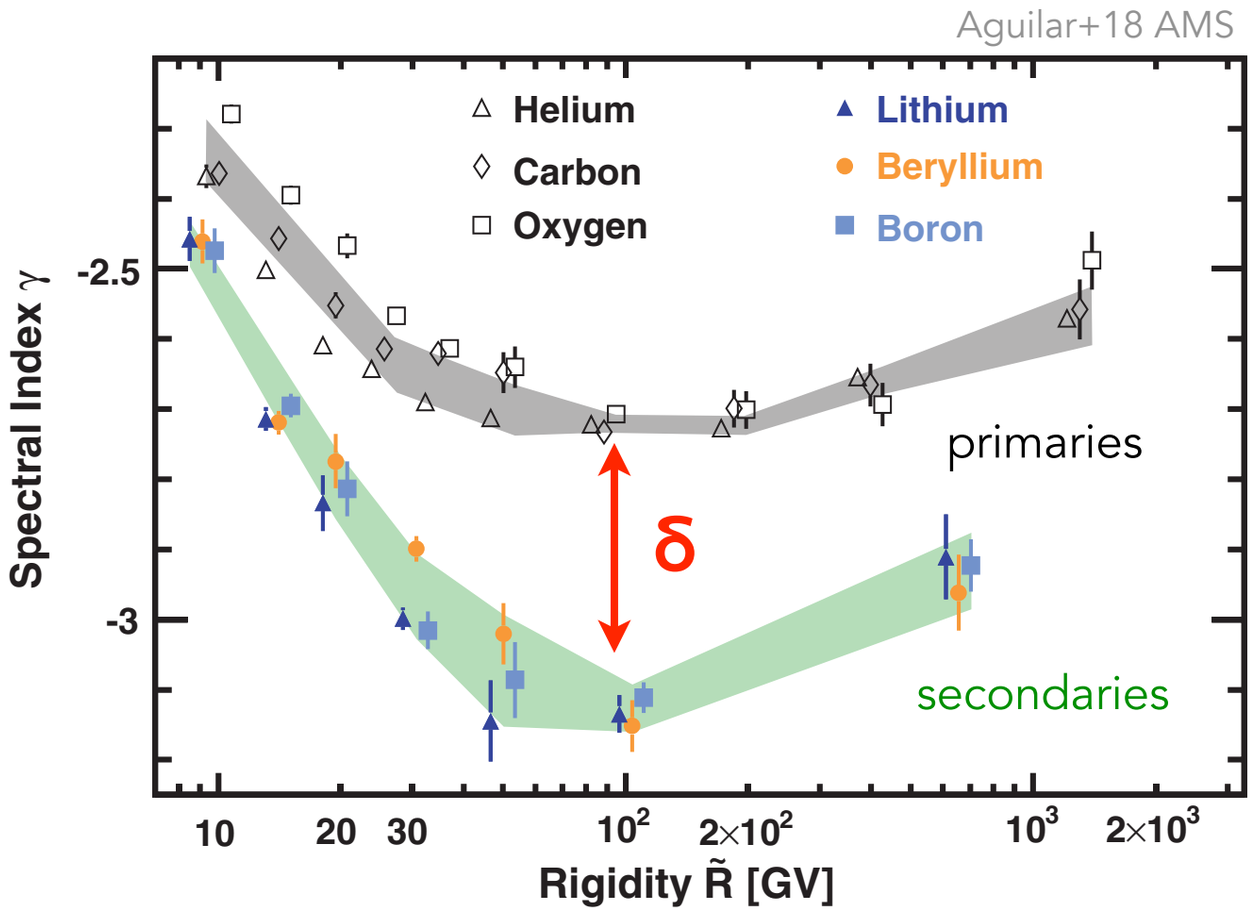
local D(E) dependence?

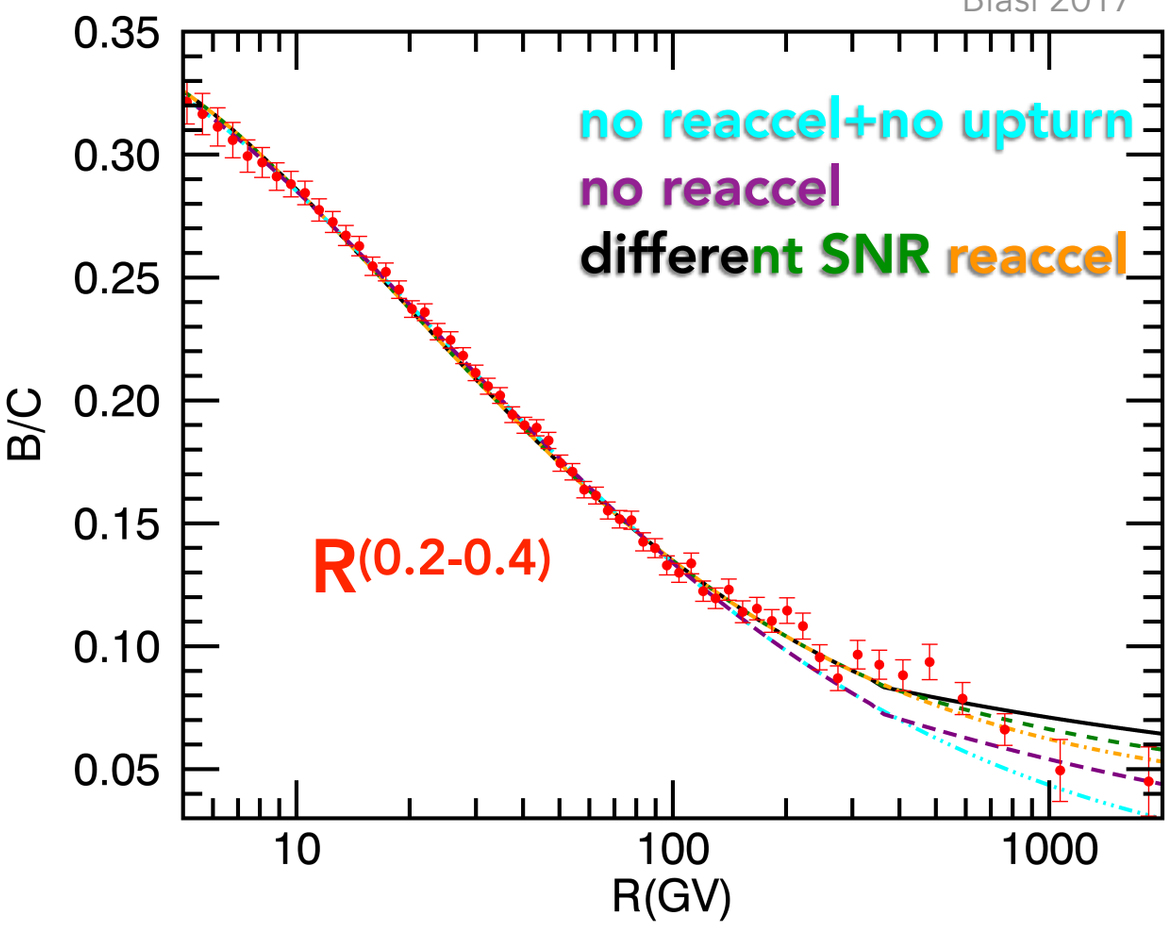
- current paradigm: energy dependence of the local diffusion coefficient directly probed by the 2ary/1ary flux ratio

$$\mathbf{D(E) \propto \left(\frac{E}{E_0}\right)^{\delta}}$$

- measured $\delta < 0.6$ imply
  - need for low-energy reacceleration, such as Fermi-II in the ISM, but 25-50% more energy put into SNR-accelerated CRs, to be provided by the SNe driving the ISM turbulence Drury & Strong 2017
  - reacceleration of secondary CRs by SNRs => $\delta_{2ary/1ary} \neq \delta_{diff}$ Blasi 2017

Blasi 2017

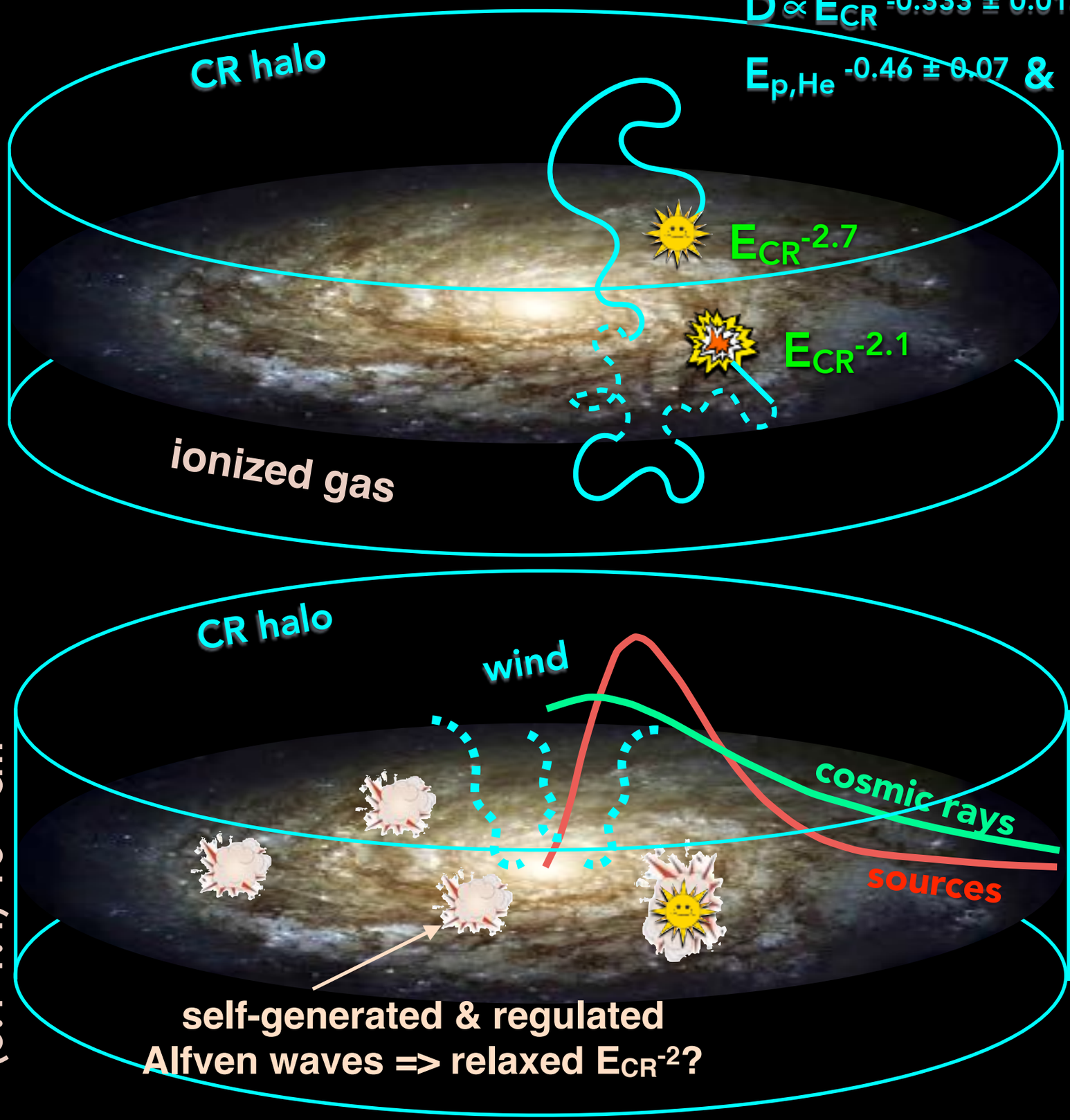




cosmic rays & γ rays in the Milky Way

$D \propto E_{CR}^{-0.333 \pm 0.014}$ (B/C) to

$E_{p,He}^{-0.46 \pm 0.07}$ & $E_A^{-0.38 \pm 0.02}$ (obs+Galprop)



open questions:
SNR shock in ISM vs.
in WR+O wind bubble?

D(E) ?
D(SFR)?

source envt escape?
superbubble escape?

super bubble/SNR
re-acceleration?

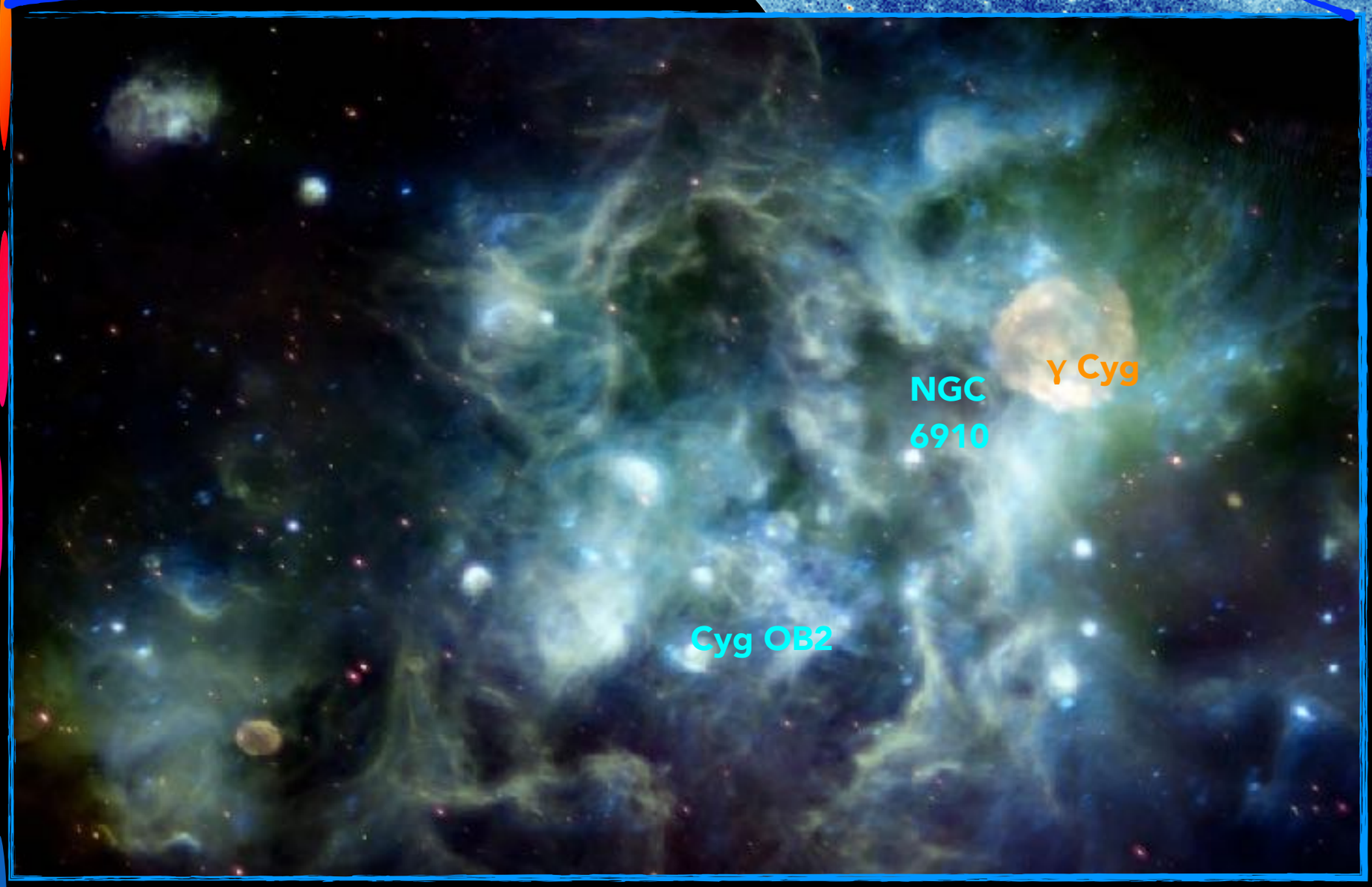
Gal. wind impact?
diffusive ISM re-accel?
Gould Belt impact?

hidden grammage?

starburst CR nurseries

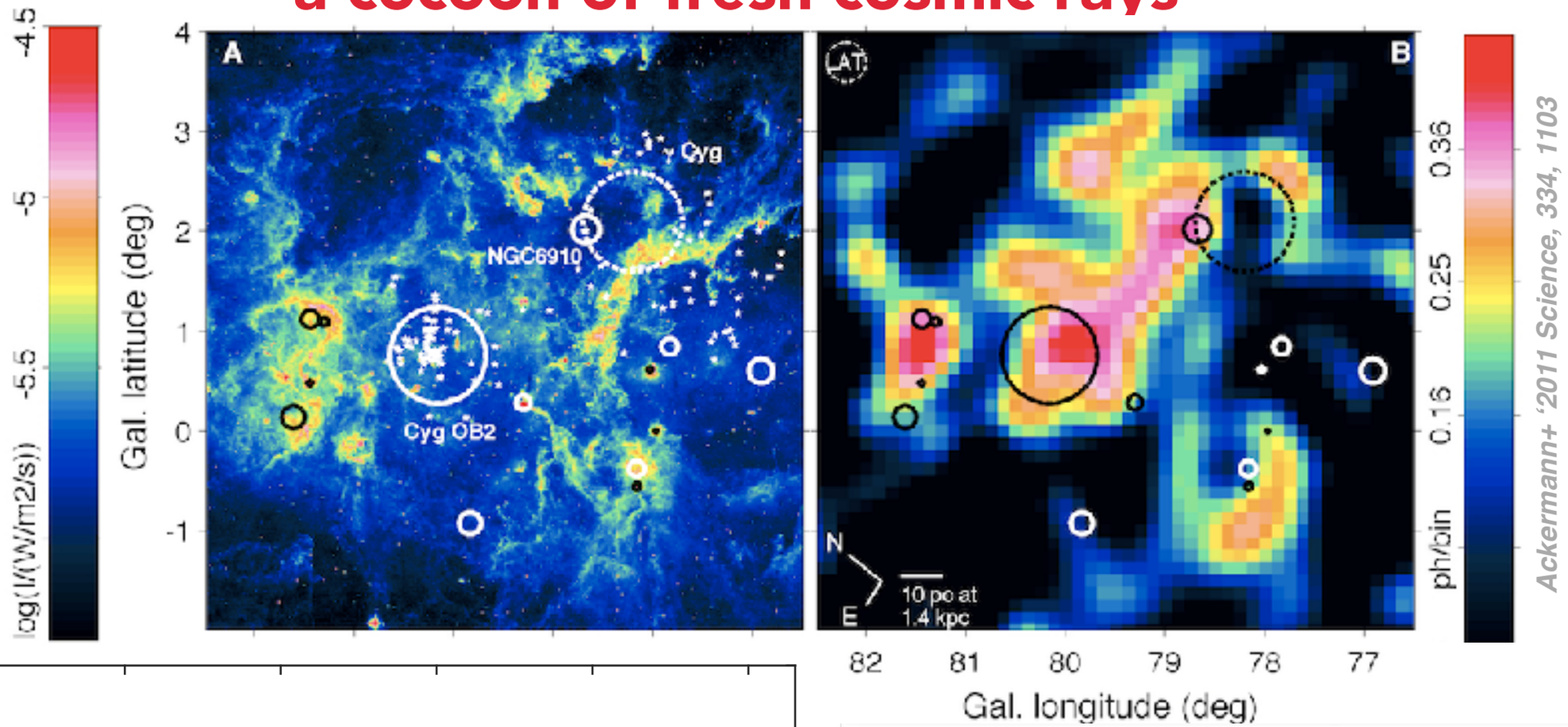
- 8 10^6 M$\odot$ of gas forming stars
  - M(HI)≈M(DNM)≈M(H2)≈M(HII)

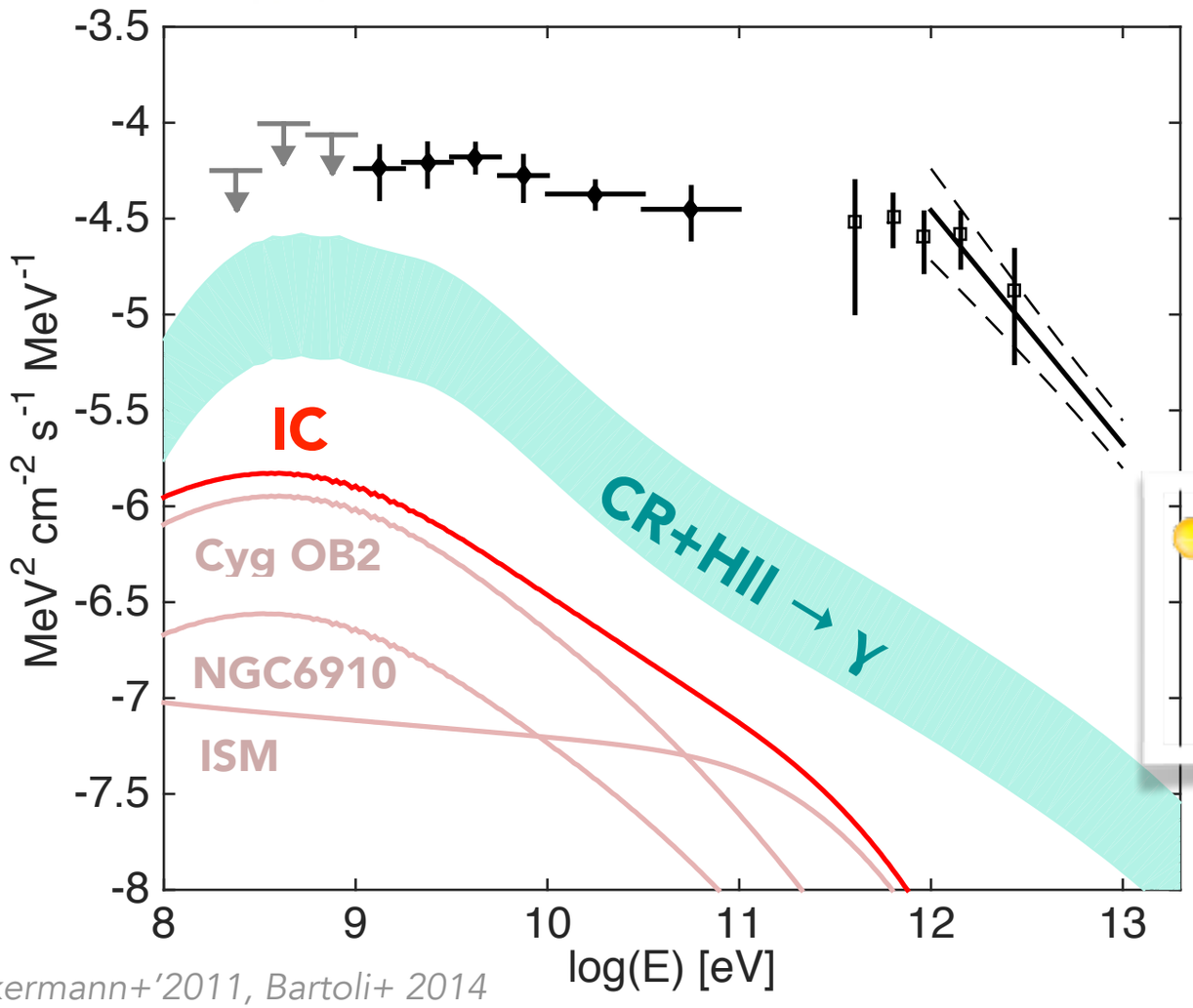
  > 600 stars > 4 M$\odot$, 3.5 - 6 Myr old
- > 10 OB associations at 1.4 kpc



CGPS/IRAS 74 cm
21 cm 60 μ 25 μ

a cocoon of fresh cosmic rays





Ackermann+'2011, Bartoli+ 2014

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

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

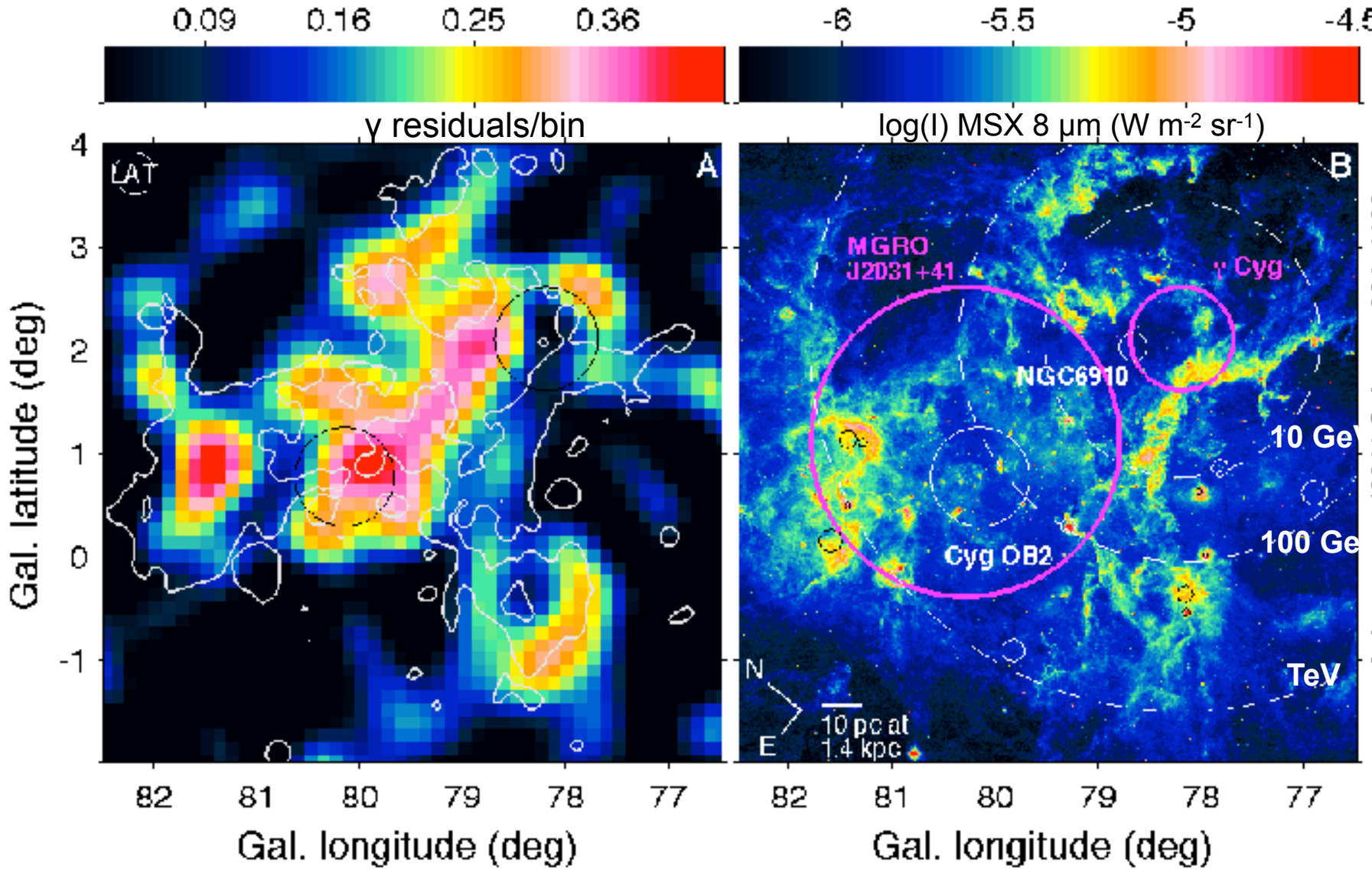
- standard LIS in surrounding & intervening clouds
- if pure pion: $E_{tot} = 1.3\,10^{42}$ J ≈ 1% E_{SN}

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

- in situ (re-)acceleration?
  in situ losses?

particles leaking from γ Cygni ?

- present adiabatic expansion
  - $v = 800^{+50}_{-60}$ km/s, $n_{ext} \sim 0.3$ cm^{-3} ⇒ $B_{ext} \sim 5$ μG
- end of free expansion 5 kyr ago if 10^{44} J, $M_{ejected} = 9\ M\odot$
  - $80 < E_{max}(p) < 200$ TeV
  - $6 < E_{max}(e) < 50$ TeV (syn+IC losses) (not ok for IC emission up to Milagro)
  - diffusion length over 5 kyr with $D_{ISM}(E) \approx$ ok
- but:
  - γ-ray anisotropy ? champagne flow, but no shock break
  - no sign for spectral gradient (TBC)
  - energy-independent apparent size of the cocoon
  - slower diffusion likely



Ackermann+ '2011 Science, 334, 1103

a young super bubble environment

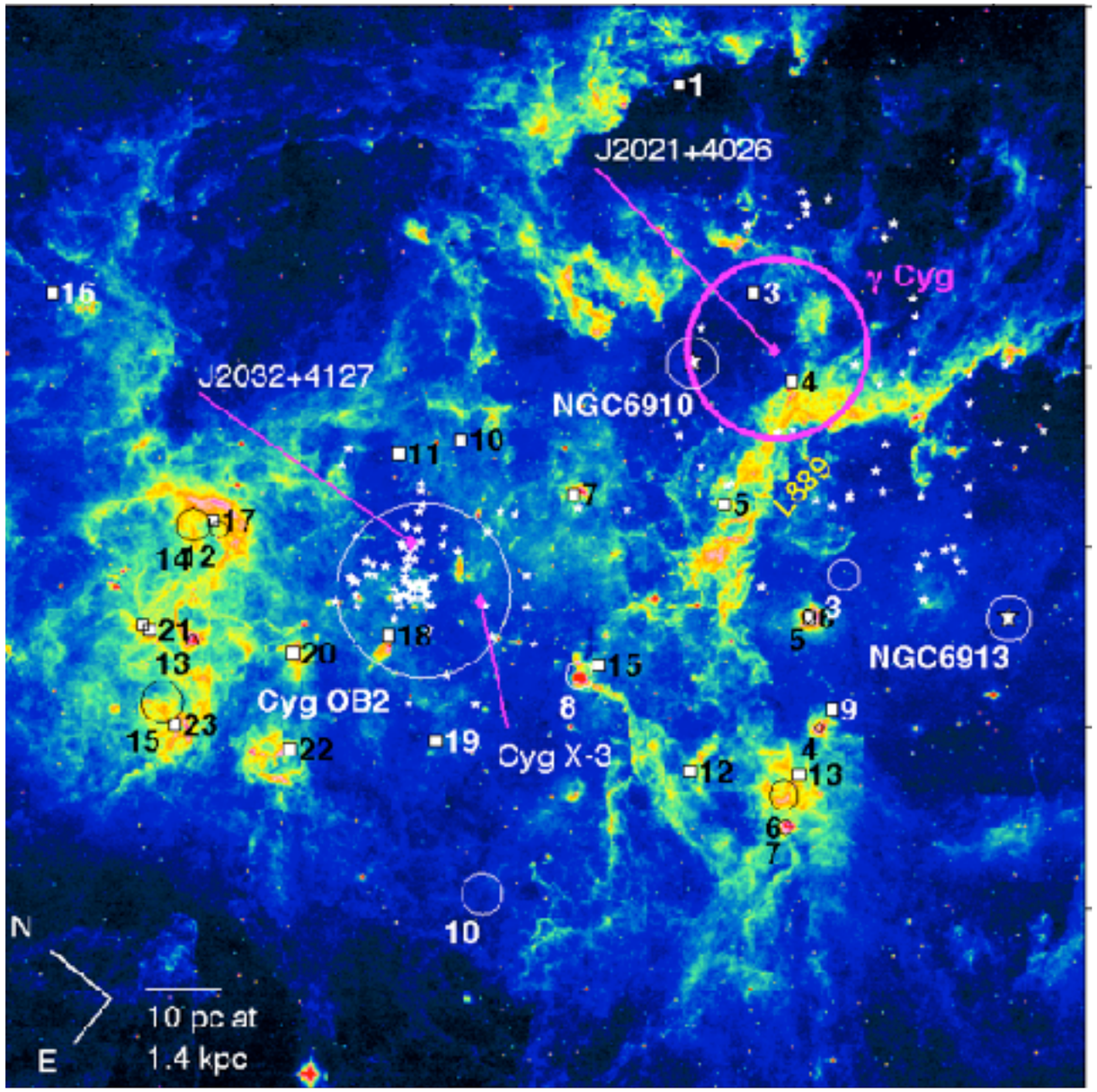
- total of >1500 OB stars
  3-6 Myr old (SNe ≲ 1)
- each WR or O wind
  u_w ~ 10^3 km/s, 10^{30} W, ~100 kyr
  L_{cocoon} < 0.03% and 7% of P_{winds}
- termination shock radius ~ 10 pc
  in p_{gas} ~ 1.4 10^{-12} Pa ≈ 18 μG
  ≈ stellar separation
- turbulent supersonic waves

$$\frac{d(\delta B^2)}{dk} \propto k^{-3/2} \quad k \gg 1/l^*$$

$$\frac{<\delta B^2>}{B^2 + <\delta B^2>} \approx 1$$

$$D = \frac{c}{3} l^* \left(\frac{R_g}{l^*}\right)^{1/2} \approx u_w l^* \Rightarrow E_{max}$$

models by Bykov et al. '01, Parizot et al. '04, Ferrand & Marcowith '10



Ackermann+ '2011 Science, 334, 1103

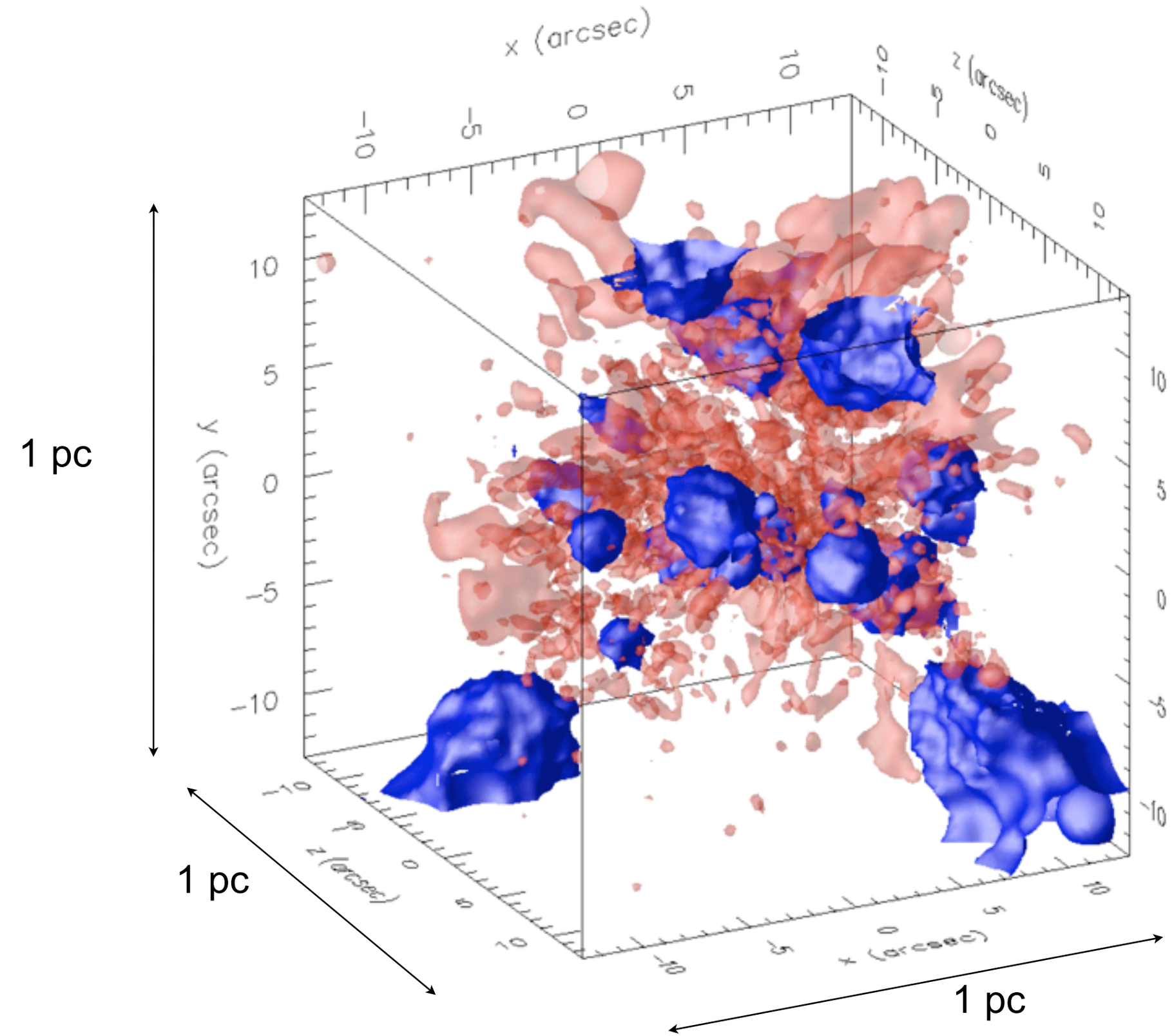
- D(E) = D_{ISM}(E) / 100
  - efficient confinement
    100 kyr at TeV, 300 kyr at 100 GeV
  - flattened 2nd/1ary ratio ≳ 100 GV ?

Berezhko et al. '2003 A&A 410, 189
Blasi 2017

- characteristic acceleration time ⇒
  - max. E(p) = 150 TeV
  - peak E(p) = 10-100 GeV
  - emerging spectrum?

stellar wind turbulence

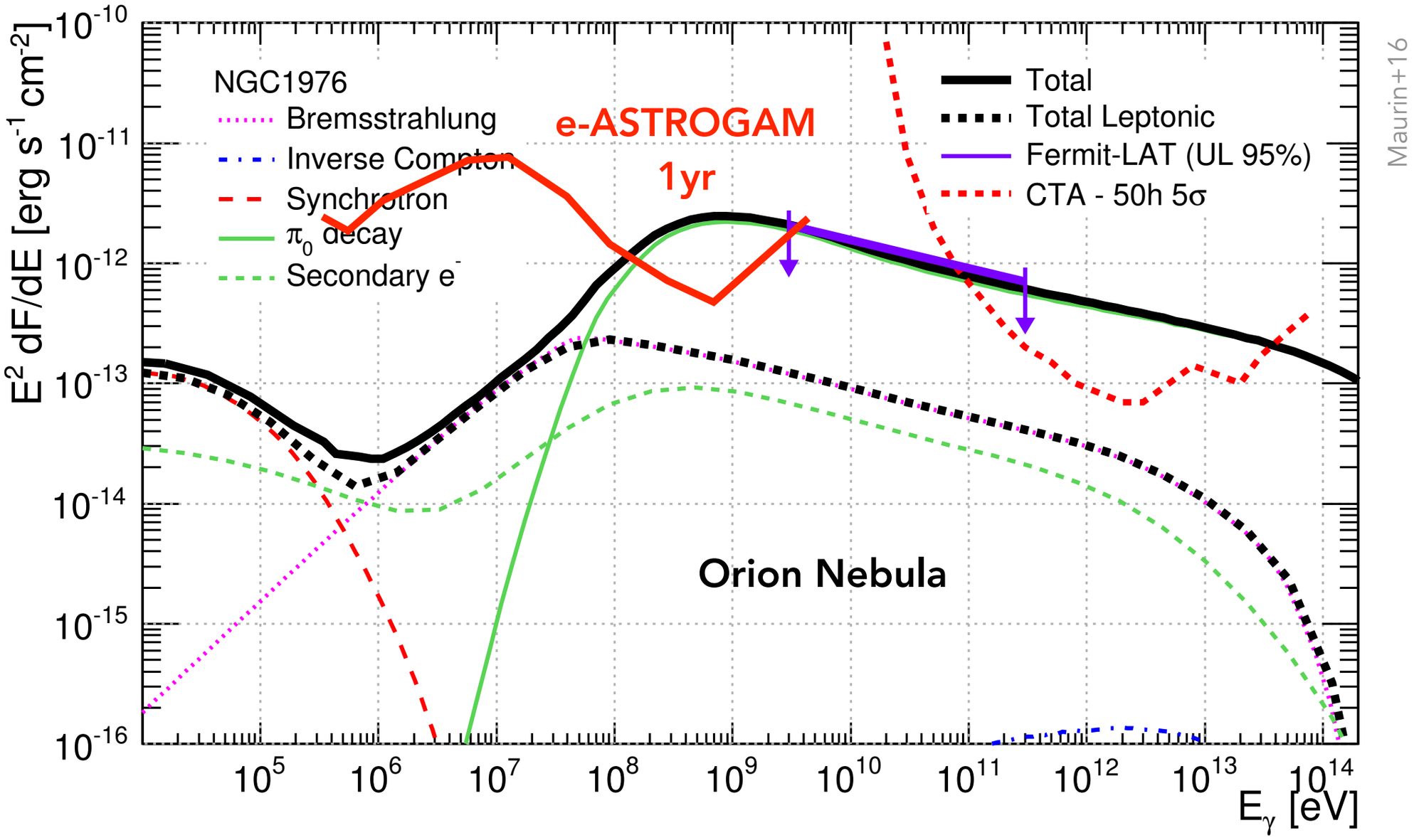
- extreme example: Gal. center: 25 stars blowing (0.7-8) 10^{-4} M⊙ yr^{-1}



Rockefeller+ '2004 ApJ, 604, 662

Orion nebula mini-starburst

- if CR acceleration by supersonic stellar winds (no SNe) in OB associations
  - < 10 % of stellar-wind power into CRs



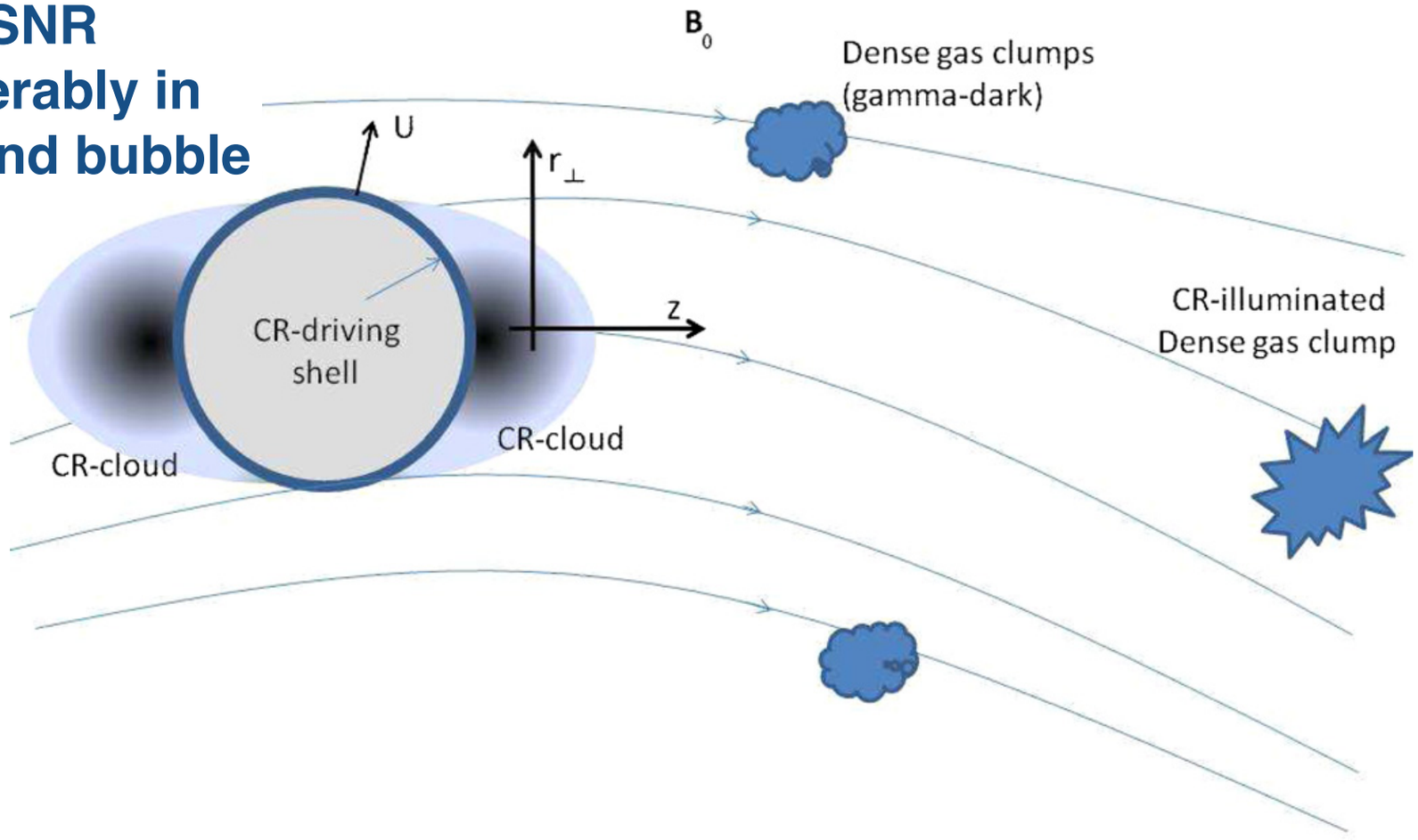
escape

- far from source: test particle solution for simple diffusion
- near the source: zone where CR pressure (Π) is large and anisotropic enough to diffuse on self-generated, regulated, Alfven waves
- => suppressed diffusion coefficient along B wrt ISM value

$$D \approx D_{ISM} e^{-\Pi}$$

Malkov+13

SNR preferably in WR-wind bubble



Gould Belt (chimney) complications

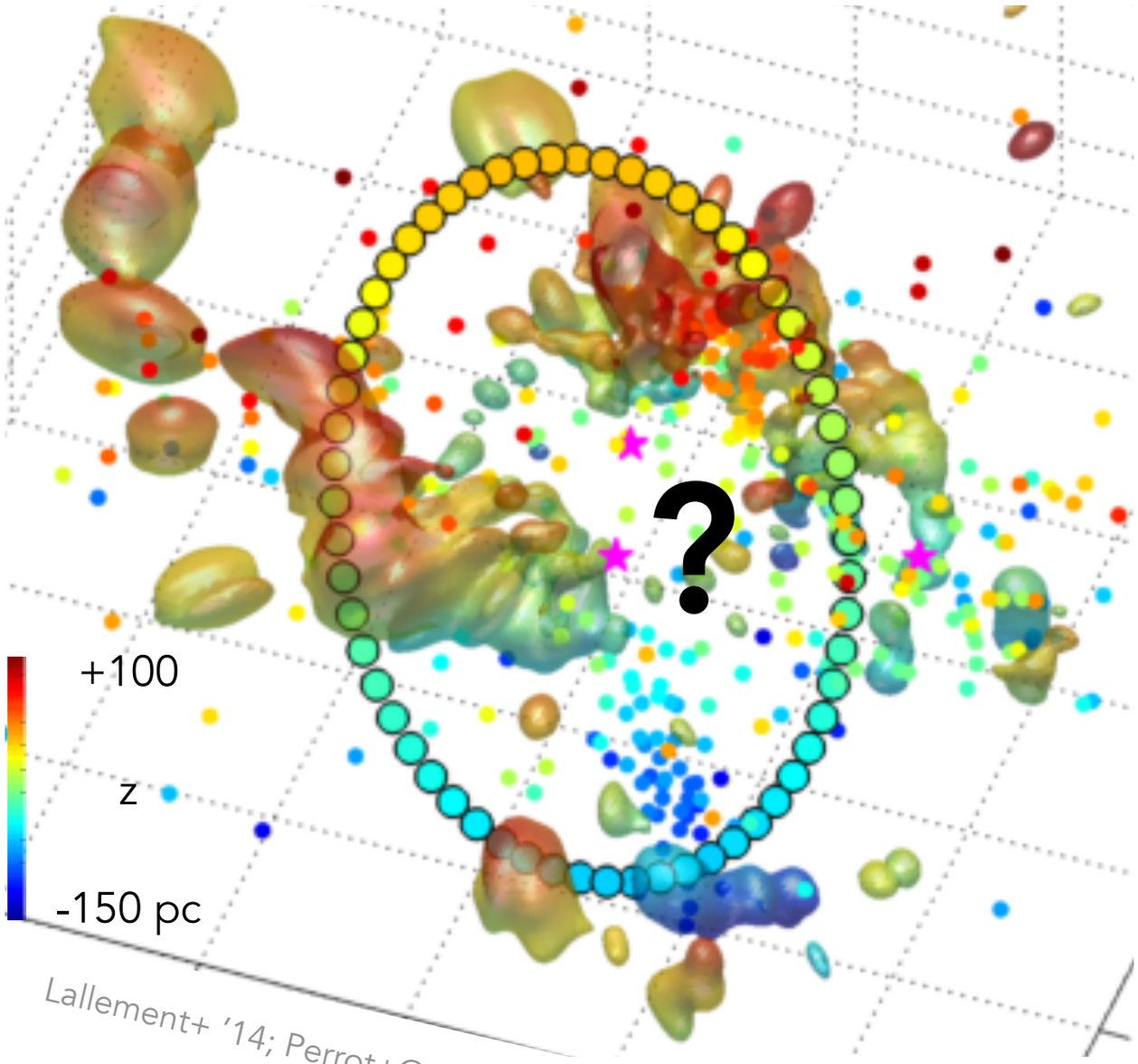
- local supernova nest:
  - 1 SN per 40 kyr (3-4 times the Galactic rate)

    Grenier '00
  - 10-20 SNe from the Pleiades

    Berghöfer & Breitschwerdt'02
  - origin of harder He spectrum?
  - 50% fluctuations in B/C < 0.5 Myr because of passing C waves from successive SNe

    Büsching+2002
- impact of Local Chimney?
  - $D_\perp \neq D_{disc}$ as in Evoli & Yan'14 for the disc
  - need for a local Gal. wind to explain the Voyager p spectrum Schlickeiser+ 2014
  - B/C hardening ?
  - high-Z nuclei: >50% produced locally but lower spallation rate inside Belt, so heavier nuclei less depleted

    Combet+ '05



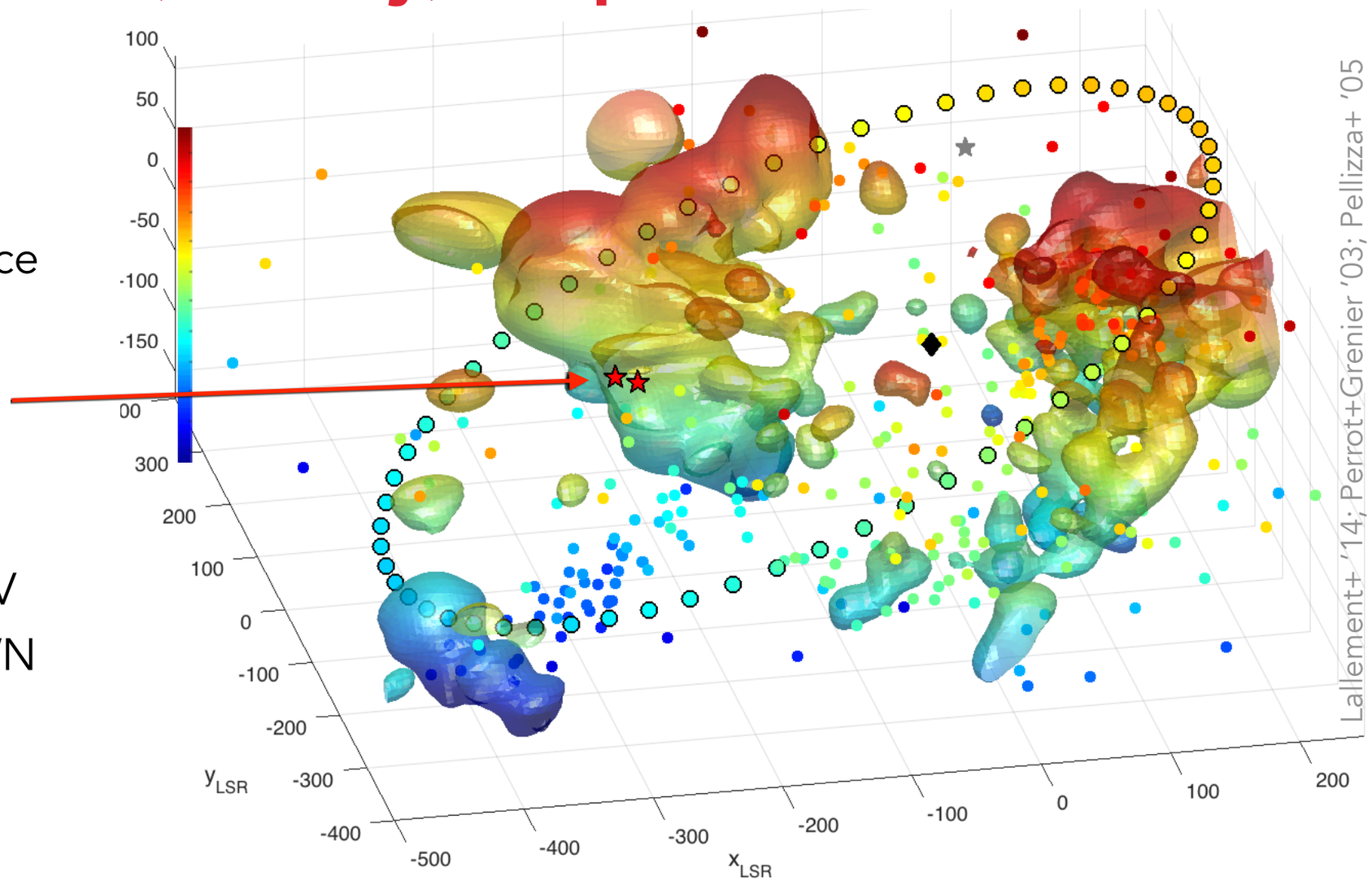
Lallement+ '14; Perrot+Grenier '03; Pellizza+ '05

Gould Belt (chimney) complications

- local supernova nest:
  - 1 SN per 40 kyr Grenier '00
  - 3-4 times the Galactic rate
  - => increased ISM turbulence

- Geminga + PSR B0656+14
  - HAWC extended sources
  - diffusing e^+-e^- wind
    (3-15) 10^{27} cm^2/s at 100 TeV
    => $D \approx D_{ISM}/100$ in the PWN
    or near the pulsars

- Orion blue stream
  in Eridanus superbubble
  - Ori OB1a-d + 48 OB stars
  - 150 to 450 pc,
  - 1 to 12 or up to 20 Myr
  - no CR hardening,
    nor density enhancement
    (stay tuned)



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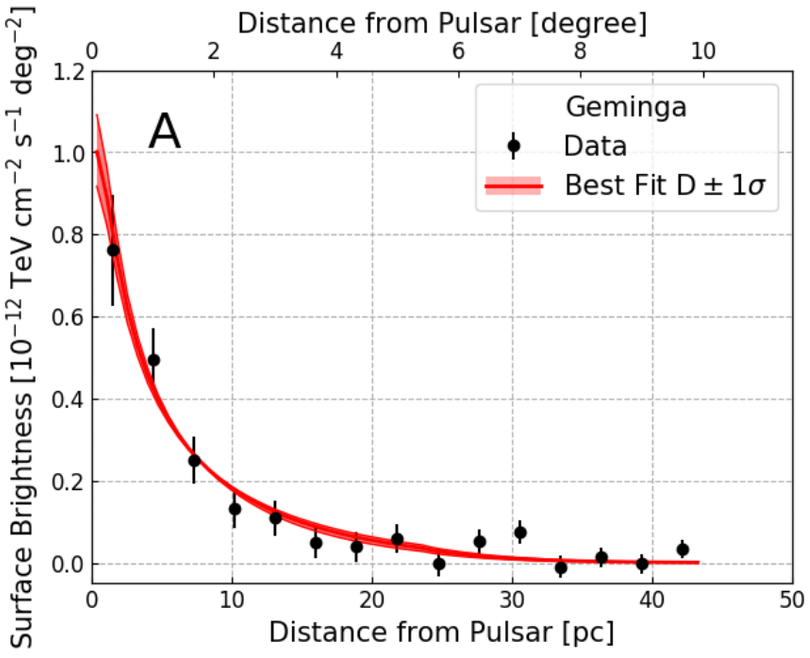
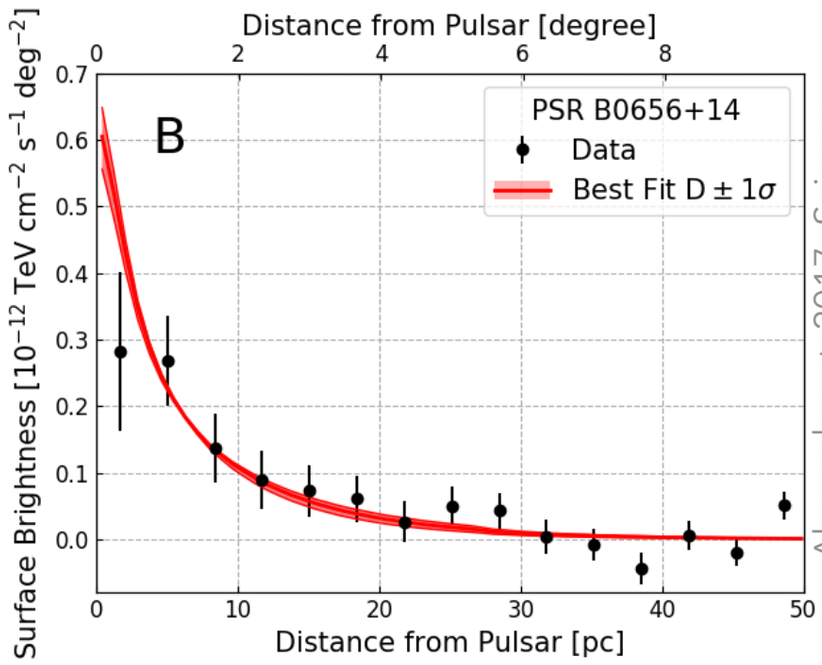
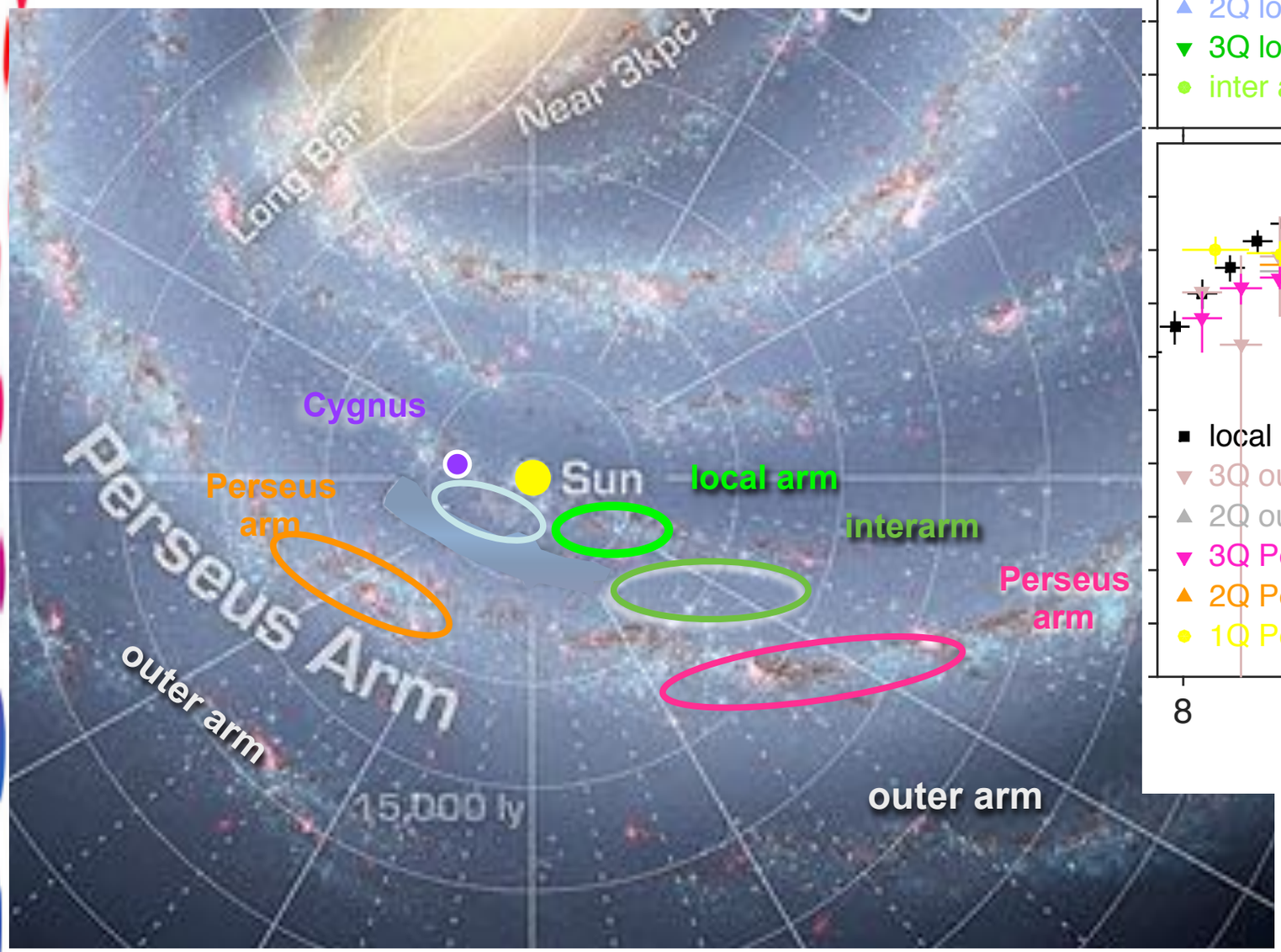


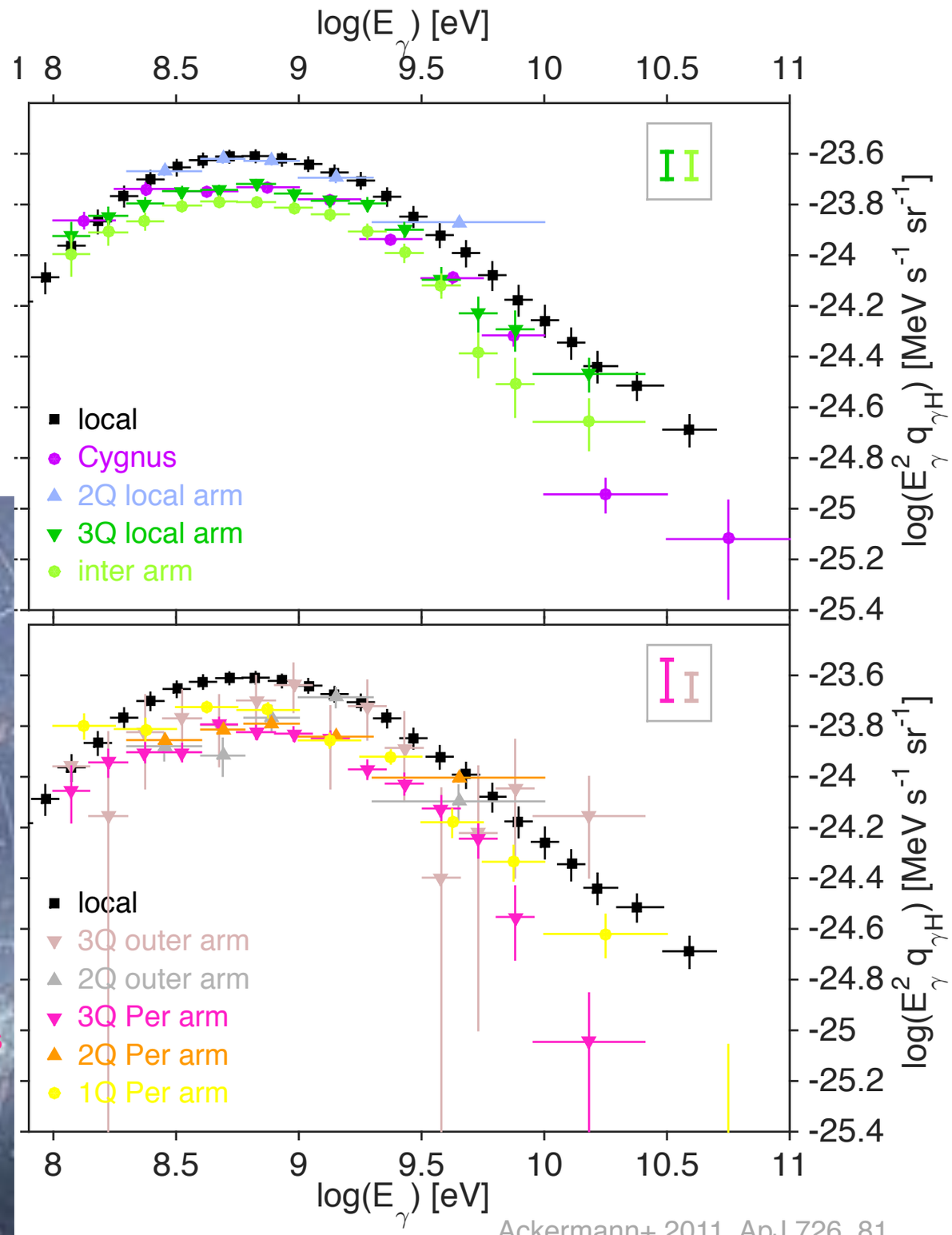


Abeysekara+ 2017, Science

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 ?

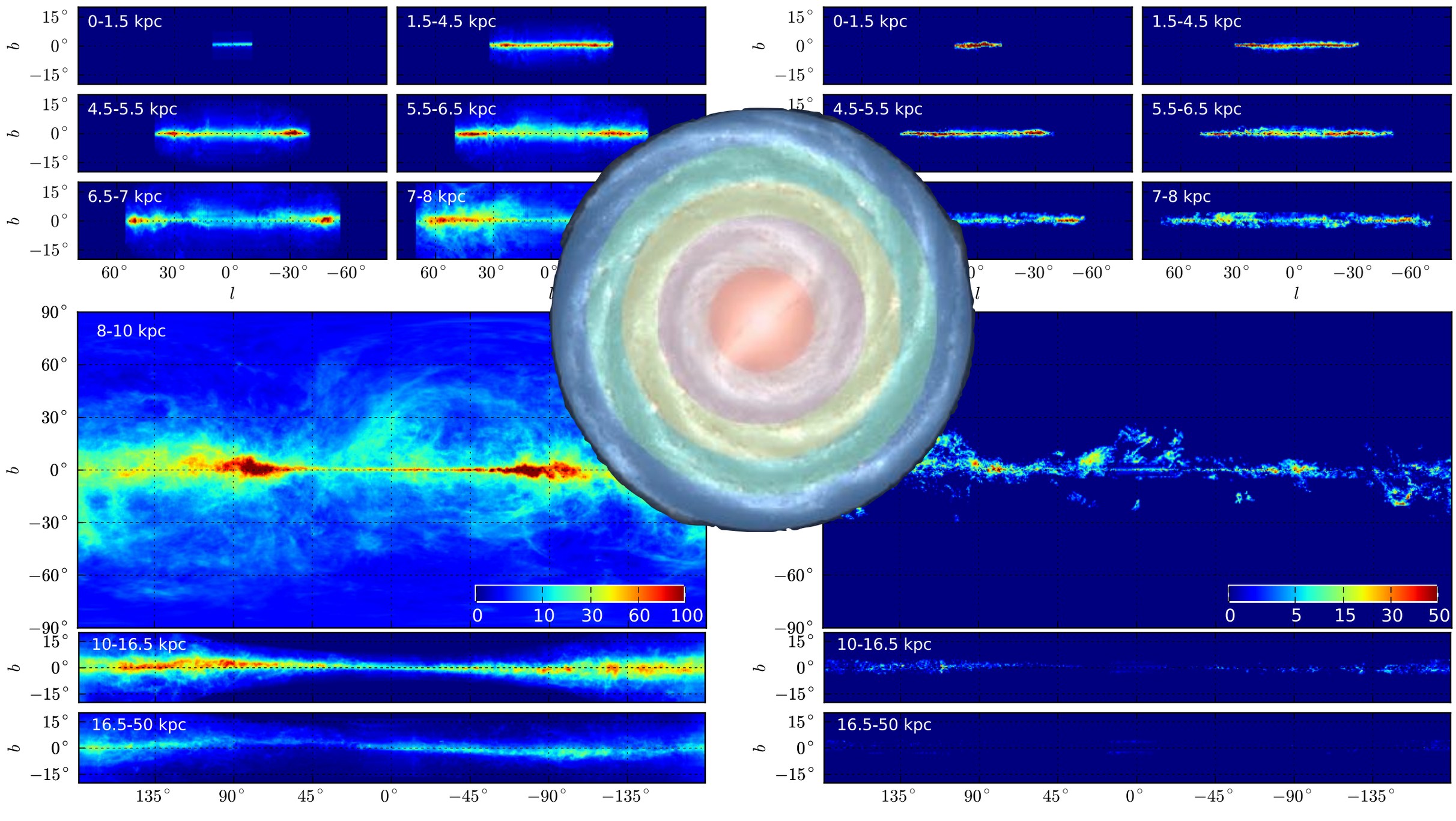




Ackermann+ 2011, ApJ 726, 81
Abdo+ 2011., ApJ 710, 133
Ackermann+ 2012, A&A, 538, A71
Casandjian 2015

Galactocentric rings

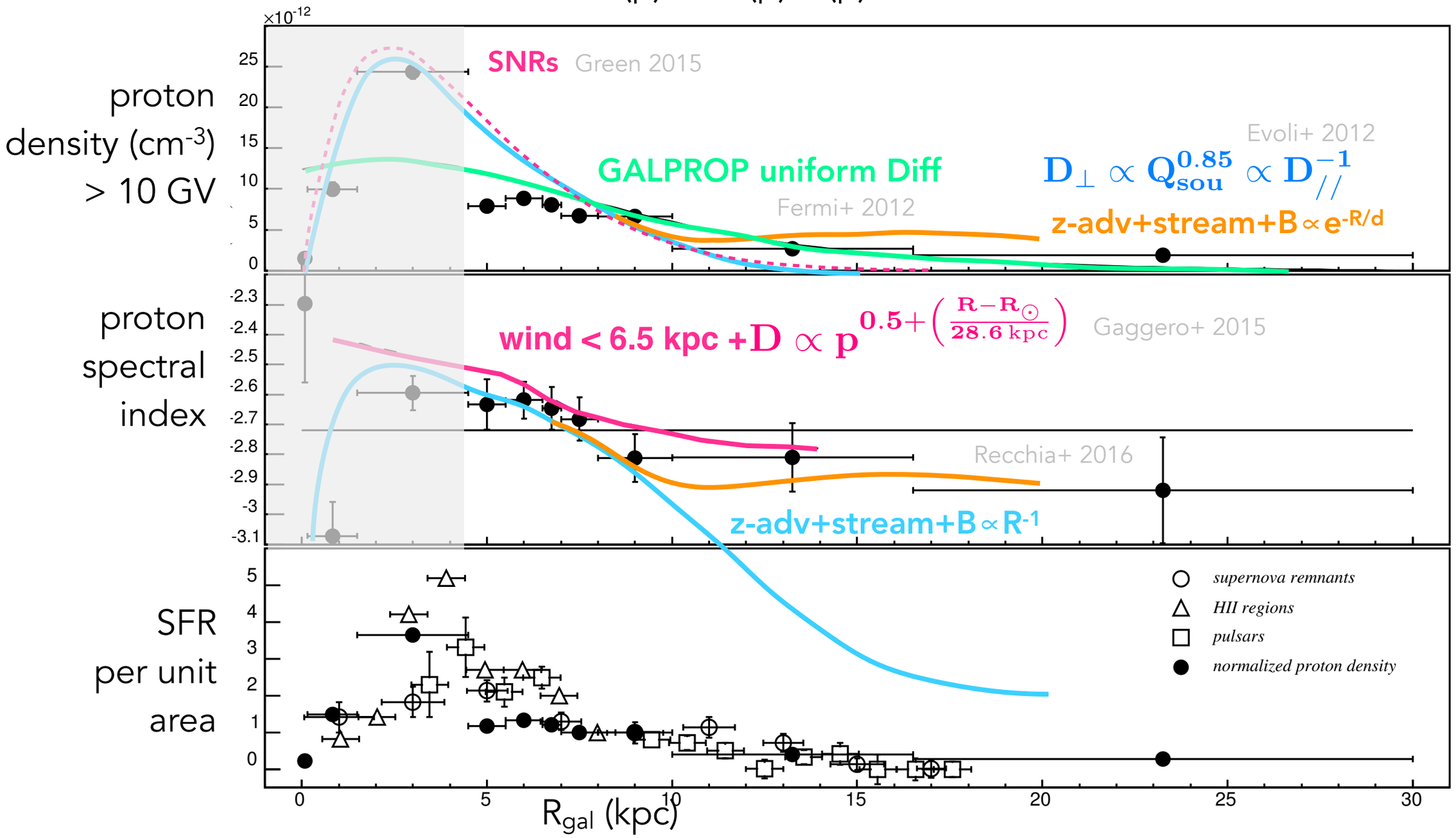
- very uncertain in the inner rings !!!



Acero+ 2016.

Galactic radial gradients

- density gradient flatter than the profile of potential cosmic-ray sources:
  - increased δB/B in spiral arms => smaller $D_{//}$ and larger $D_{\perp}$? large amount of dark gas?
- slight hardening in the inner Galaxy
  - γ-ray source contamination? gas closer to CR sources? diffusion D(R, B(R)) variations?
- inner Gal: importance of advection => f(p) closer to injection spectrum
- outer Gal: diffusion-dominated mode f(p) → Q(p)/D(p)



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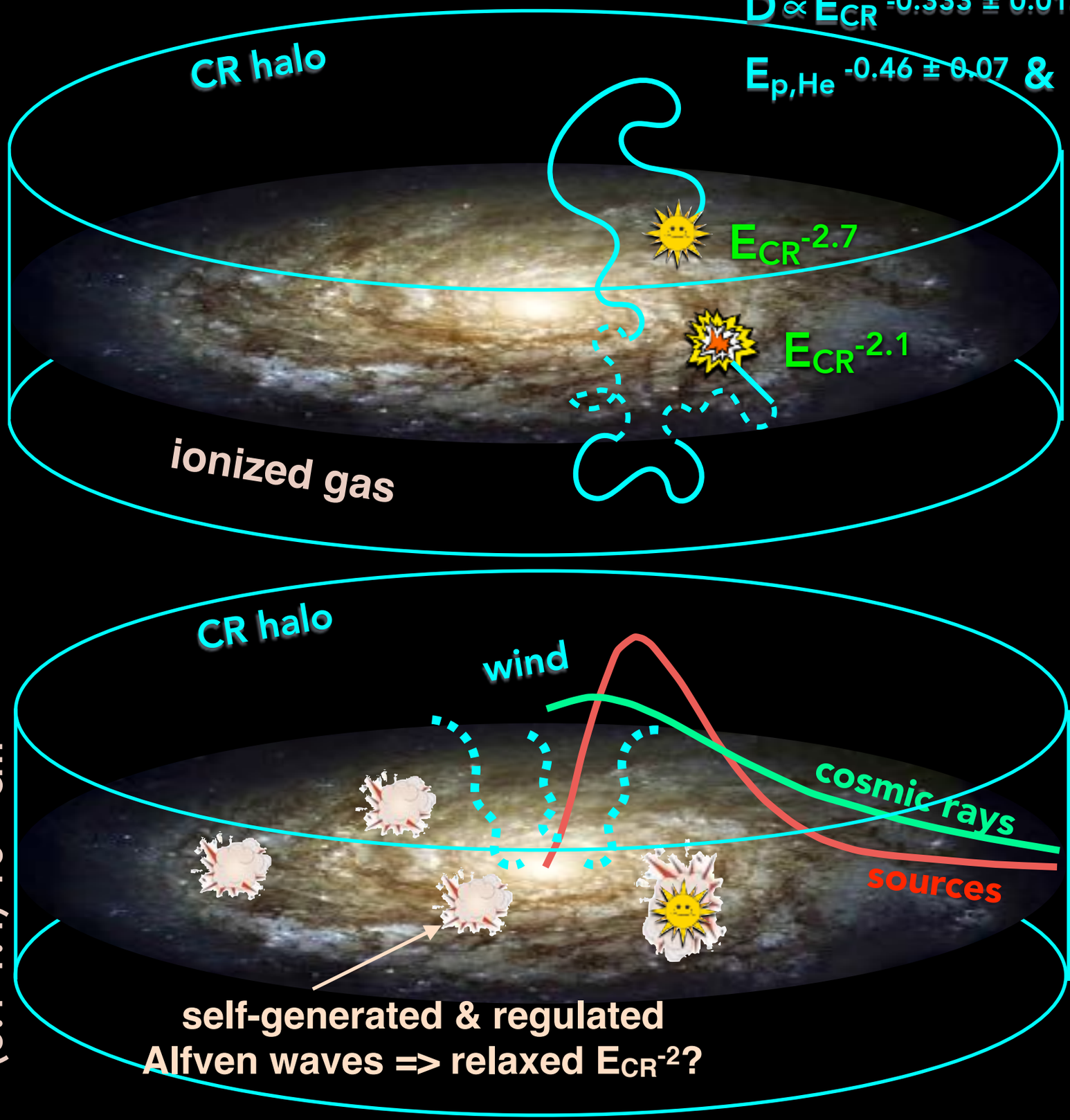

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D(SFR) ?

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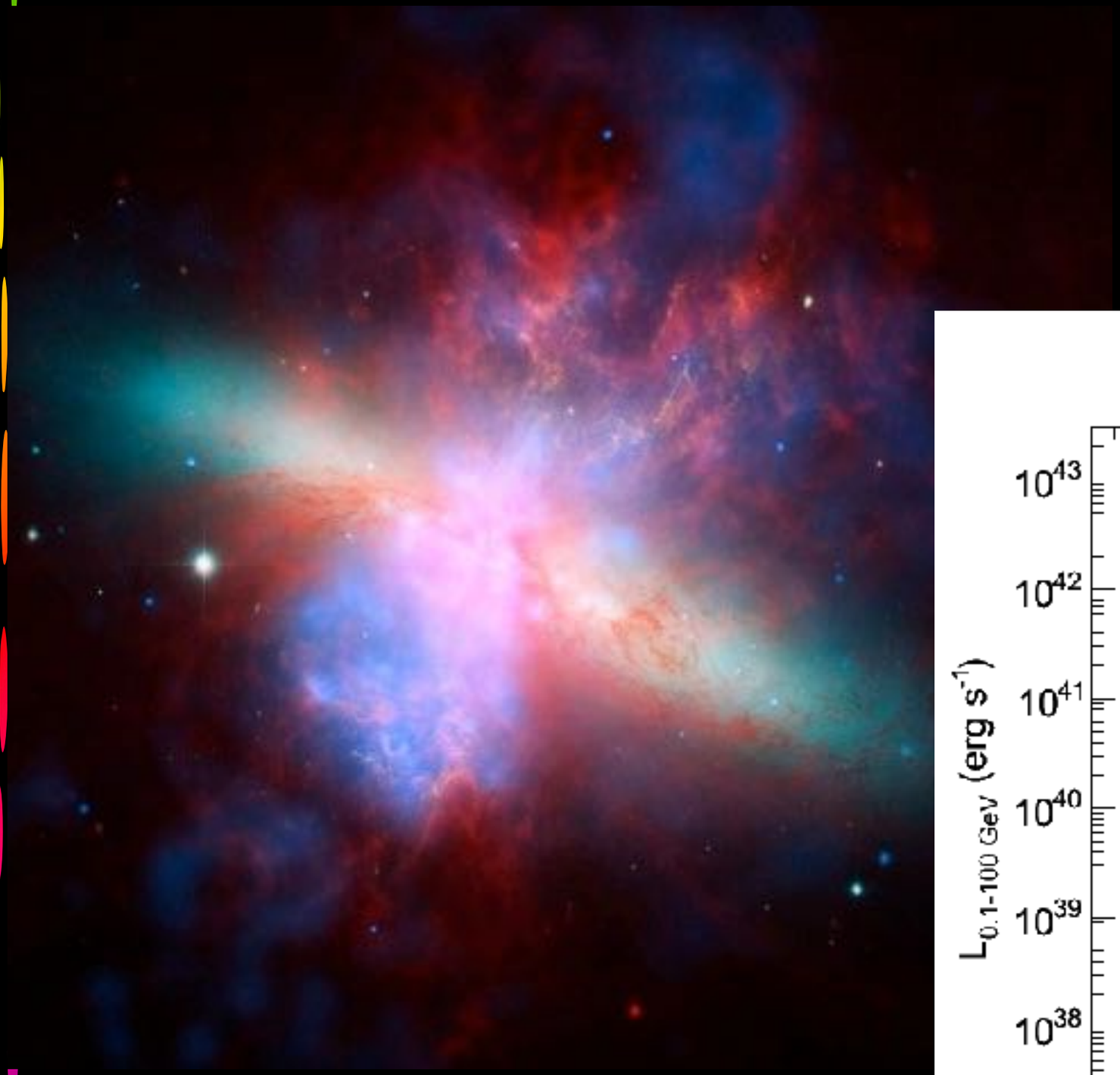
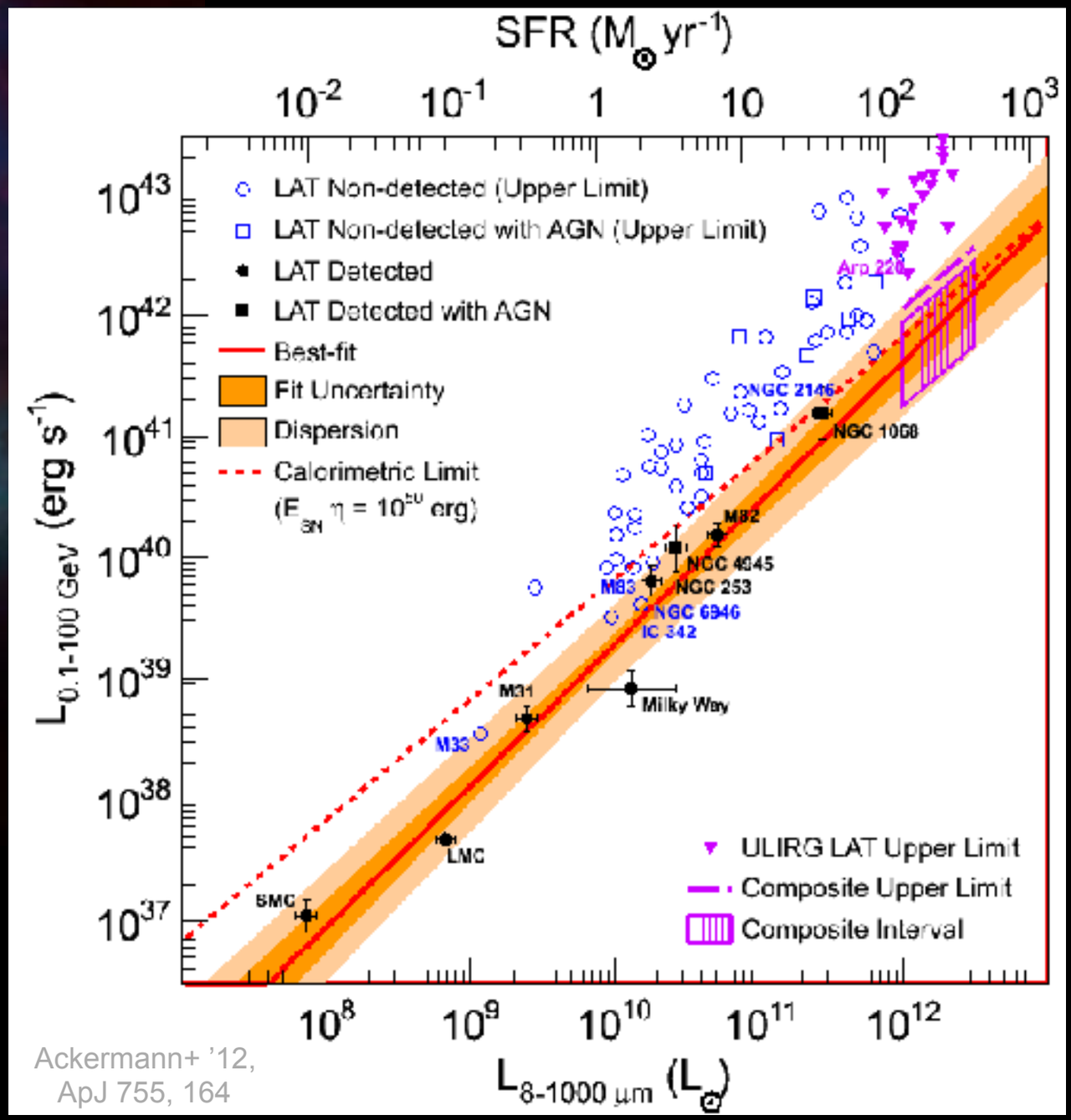
starburst galaxies





Ackermann+ '12, ApJ 755, 164