Cosmic-ray investigations with e-ASTROGAM

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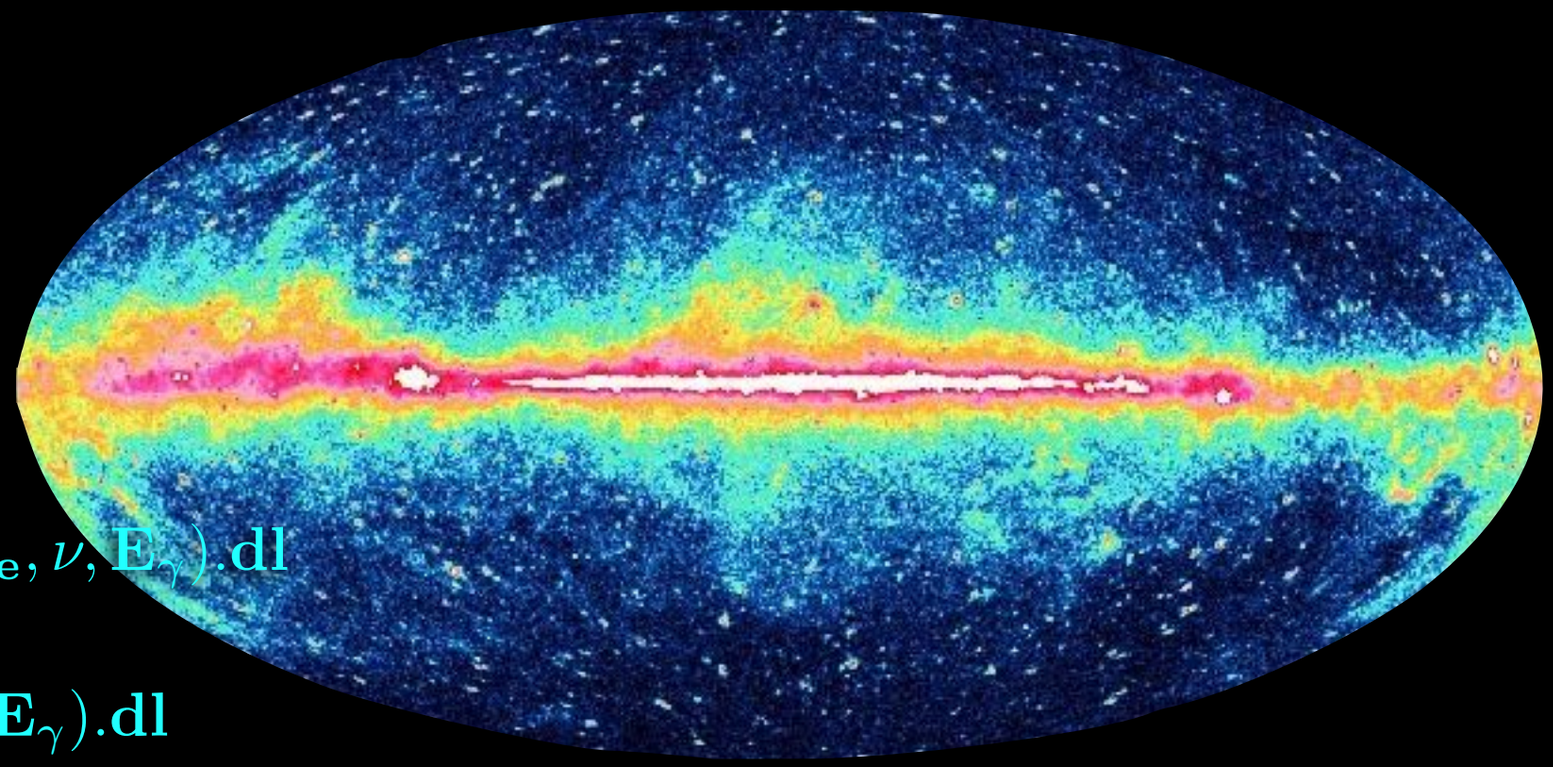
with the help of the Fermi LAT Collaboration

remote sensing of super-GeV cosmic rays

- (e+p) probed in γ rays
  Fermi LAT



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

- (e) probed by radio synchrotron ha
  35 piled-up here: Chan-ges

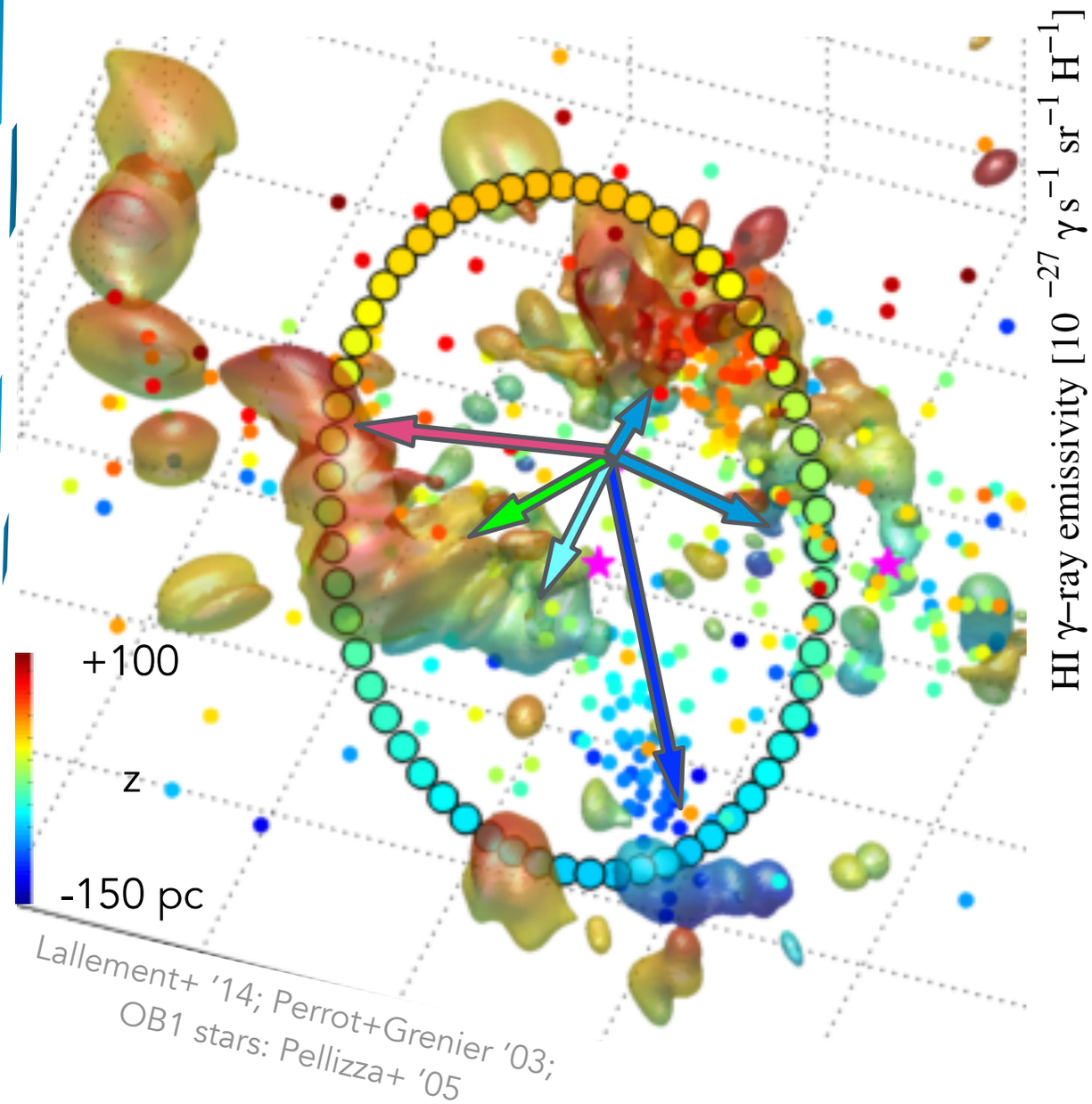
$$\mathbf{if\ n(E_e) = \kappa \left(\frac{E_e}{E_0}\right)^{-p}}$$
$$\mathbf{S_\nu \propto \int \kappa\, B^{\frac{1+p}{2}} \nu^{\frac{1-p}{2}}\, dl}$$

Wiegert+ 2015 AJ 150 81

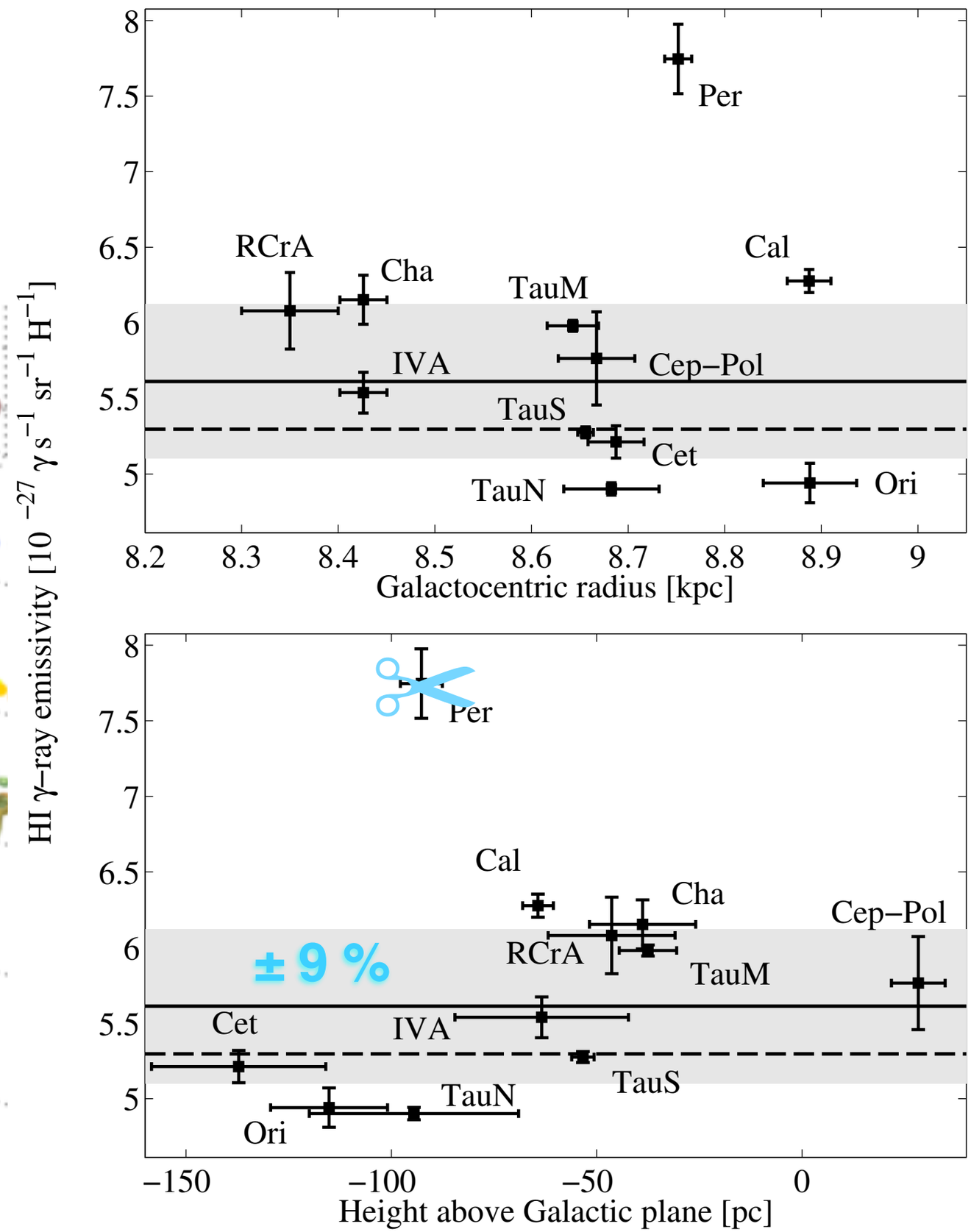
Multi-GeV cosmic rays in the local interstellar medium

local gas 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

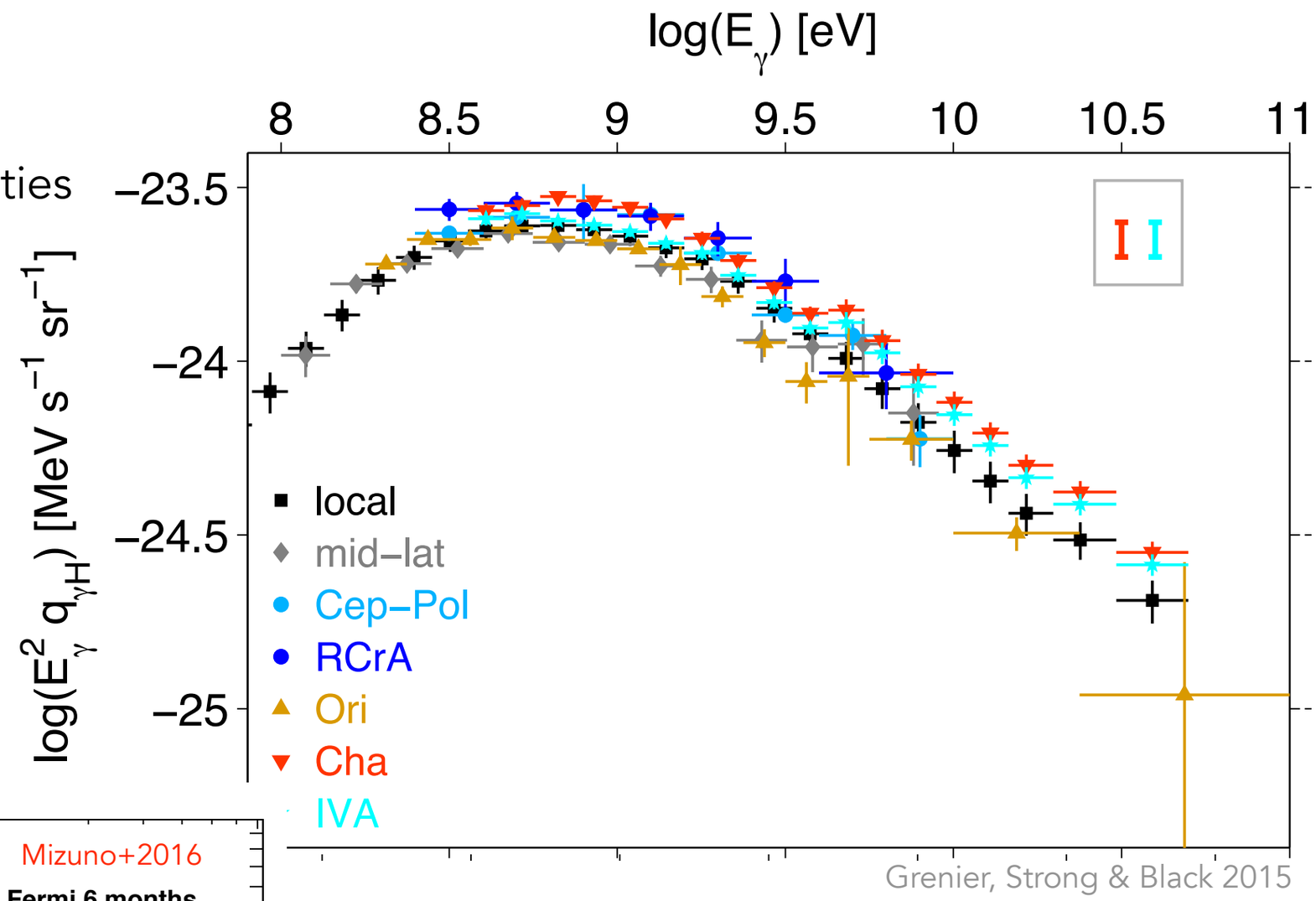


Remy+17, in press



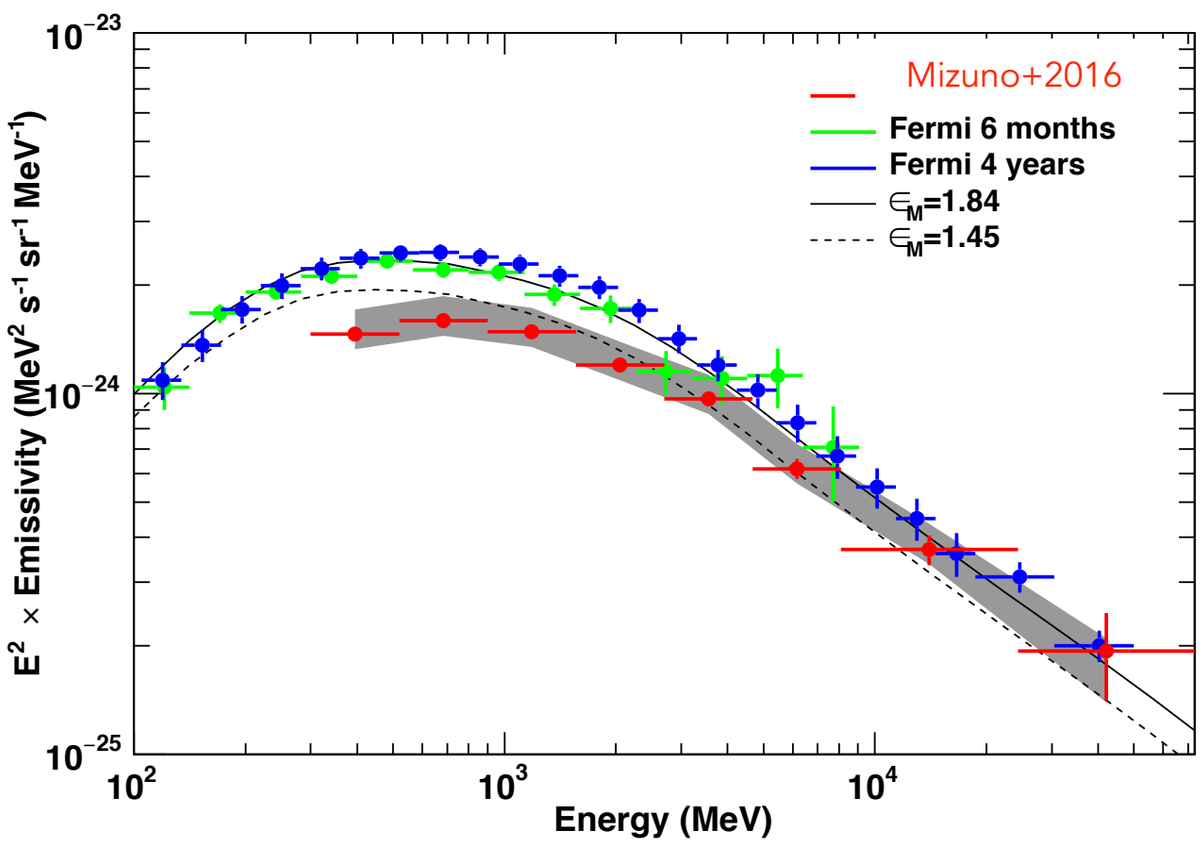
local emissivity spectra (0.4-10 GeV)

- uniform CR spectrum across the Gould Belt clouds
- < 20% differences due to uncertainties in HI column densities or use of different NH tracers



Grenier, Strong & Black 2015

e.g. dust:



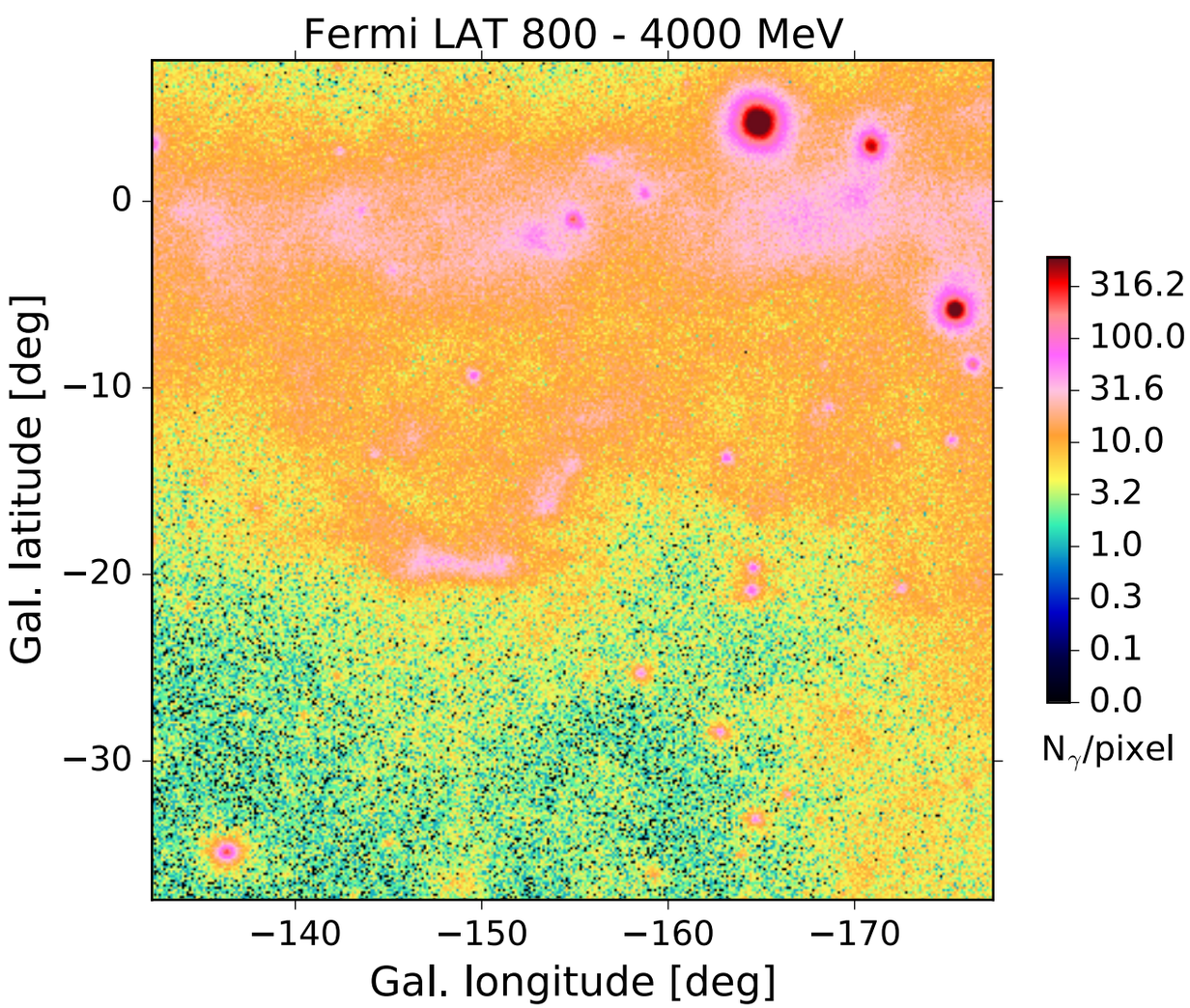
local prospects for e-ASTROGAM

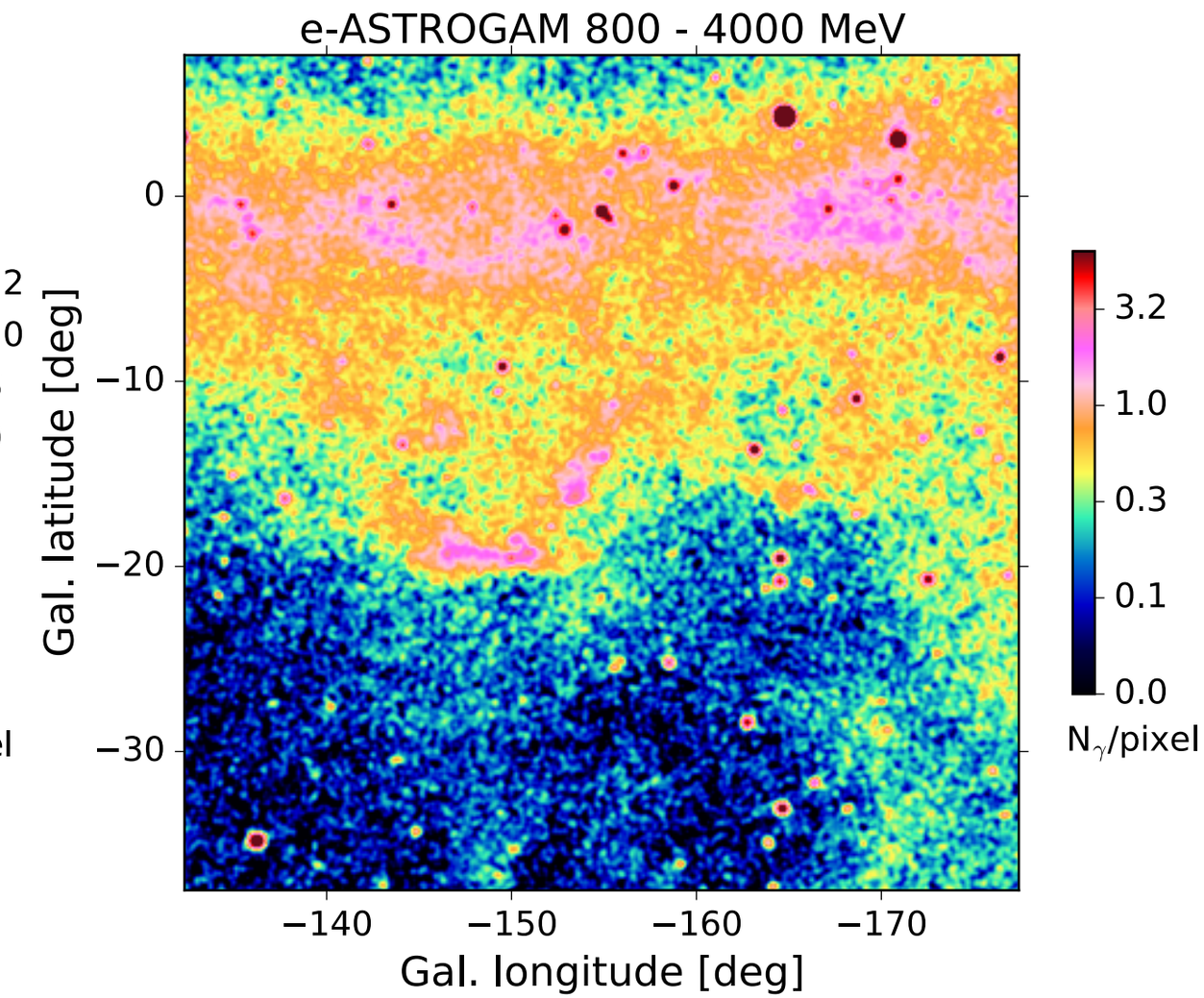
- improved separation of HI and H_2 clouds ⇒ CR density in the atomic gas
  - throughout the local ISM (cf Perseus problem)
  - in cirrus vs. massive clouds (B configuration)
- e-ASTROGAM (low-E) + Fermi (high-E) ⇒ firm local CR spectrum from ∼1 GeV to TeV energies
  - impact of the Local Chimney on CR advection (local wind), damping of MHD waves thus D(E)…
  - in WIM versus WNM

Schlickeiser+14

Evoli & Yan 2014

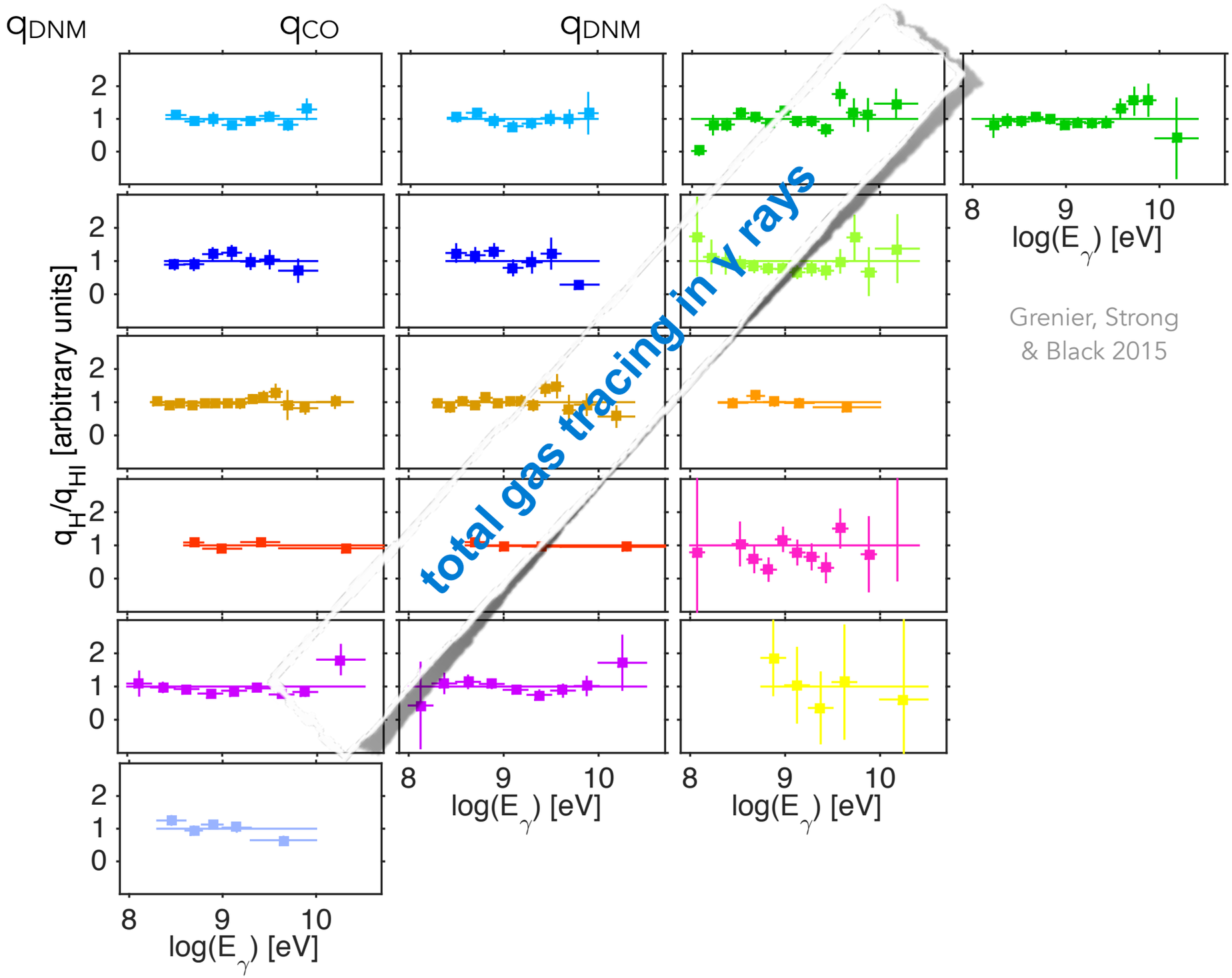
- e-ASTROGAM sensitive enough to study high-z and high-velocity clouds???





uniform penetration inside clouds

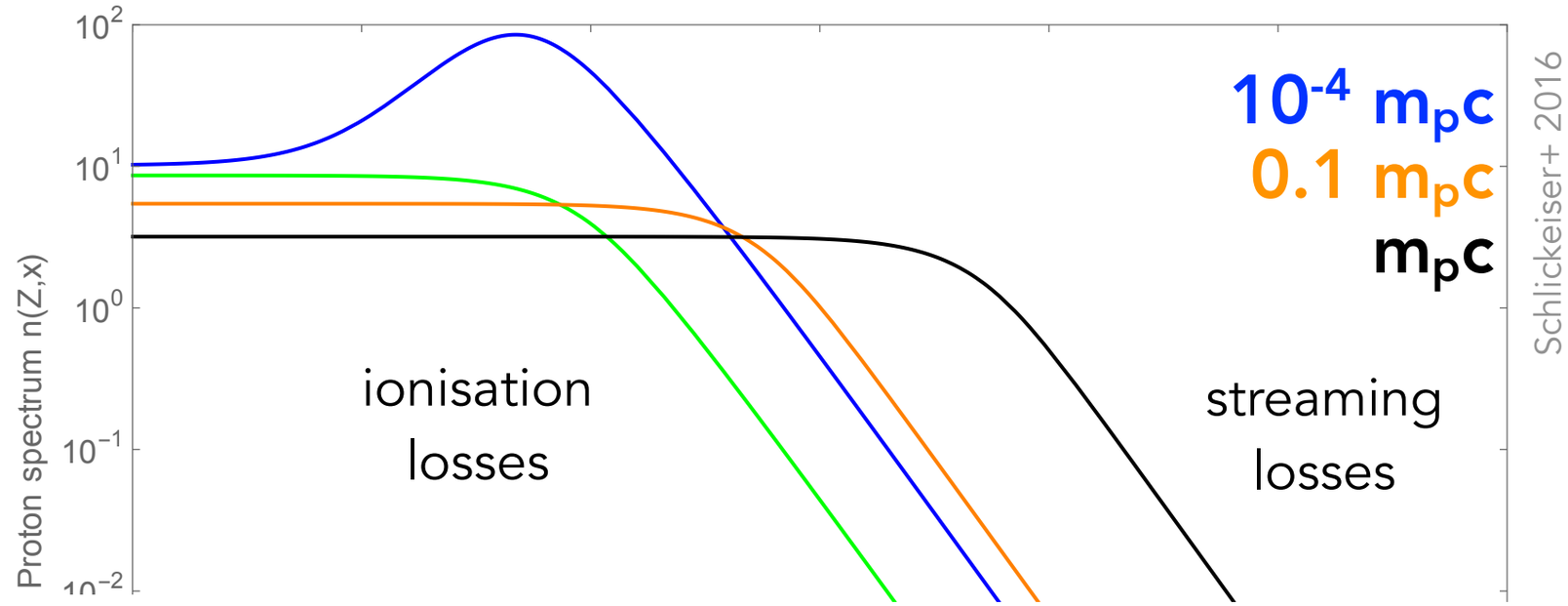
- no spectral deviations across the HI, DNM, and H_2 gas phases down to pc scale
- ≈ uniform penetration at the current precision for CRs > GeV
- ok with diffusion scale > kpc and with models by Skilling & Strong '76 or Everett & Zweibel '11



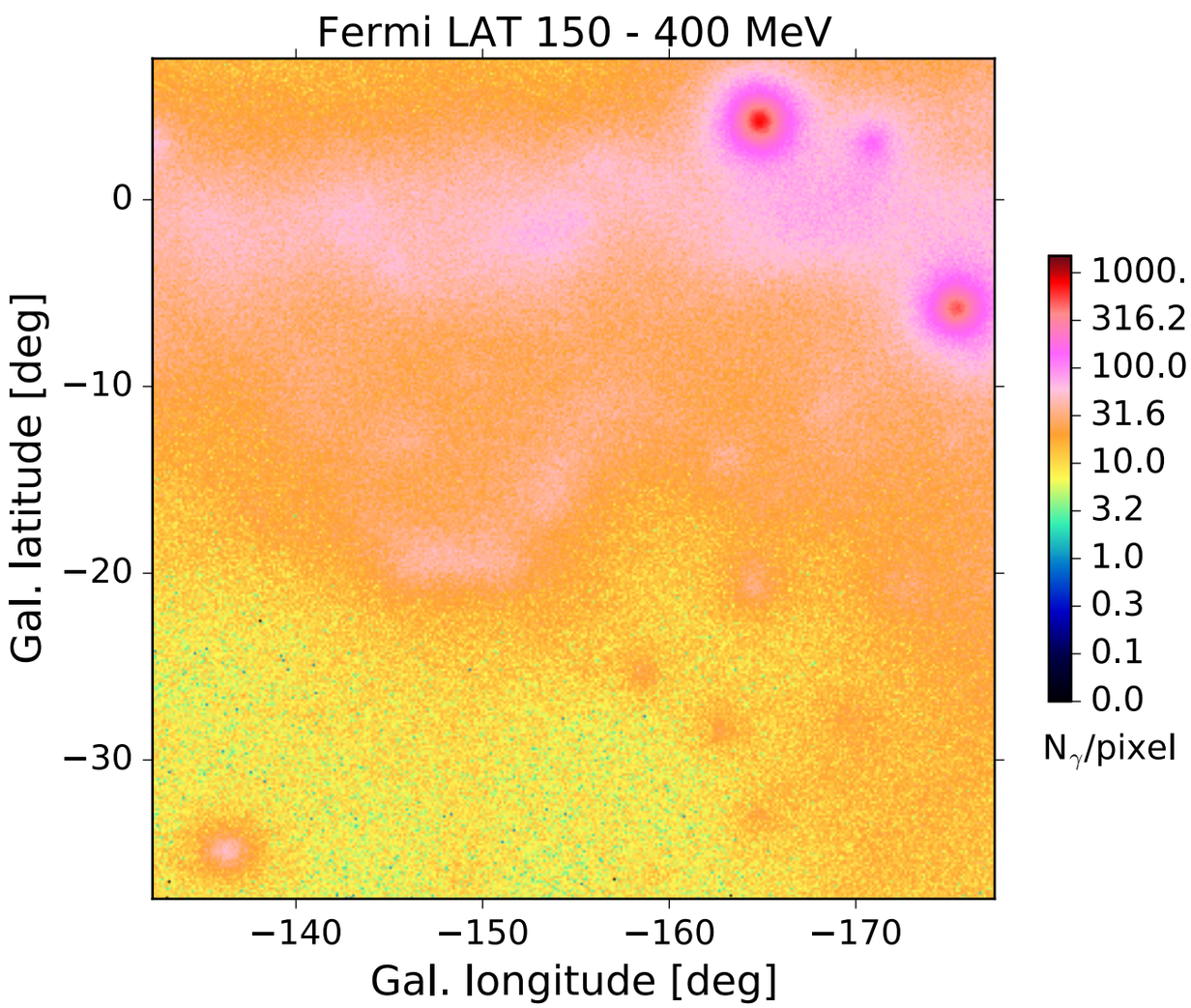
Grenier, Strong & Black 2015

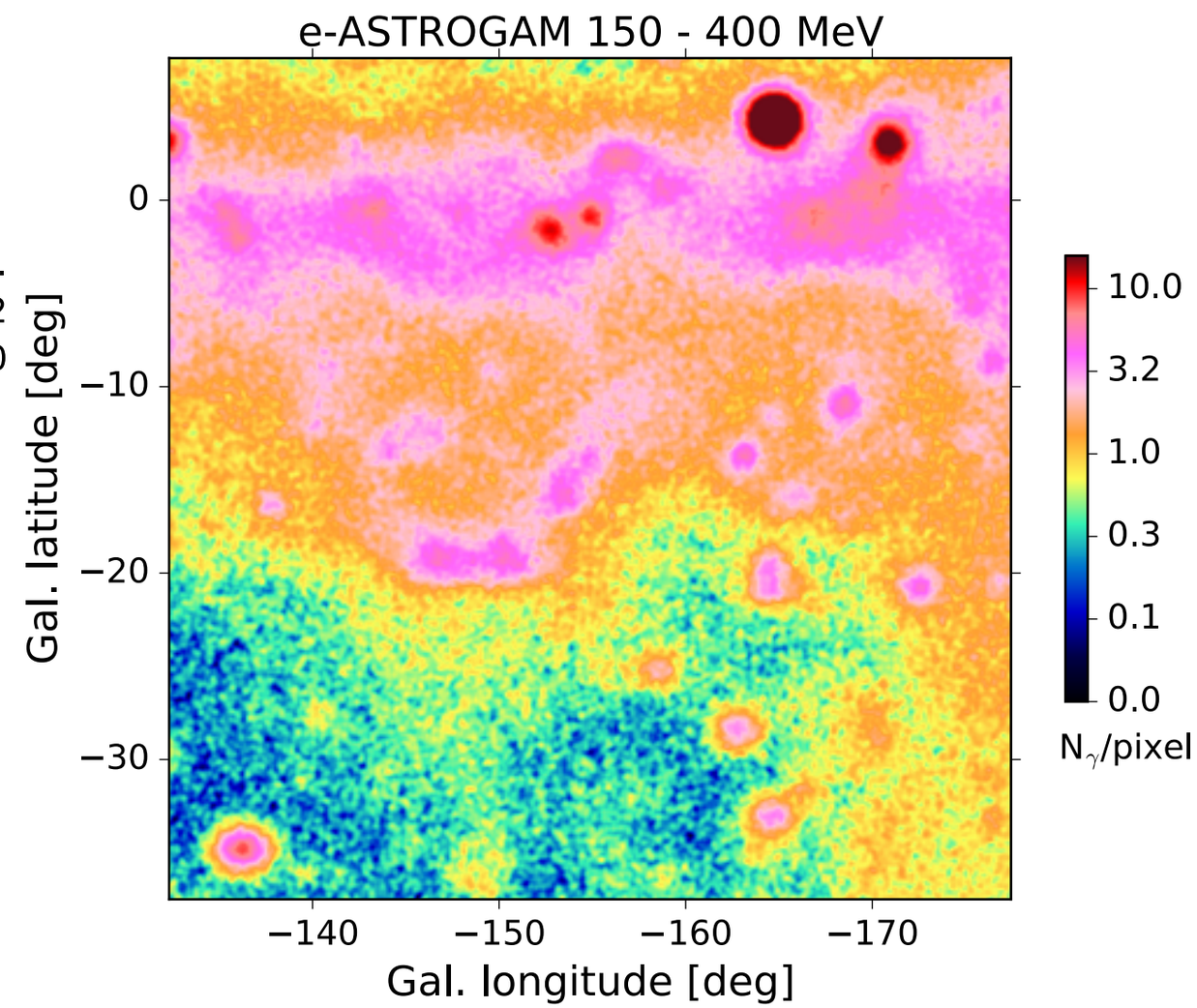
prospects for e-ASTROGAM

- separate the HI, DNM, and CO-bright H_2 phases down to a few 100 MeV



in real fractal inhomogeneous ISM





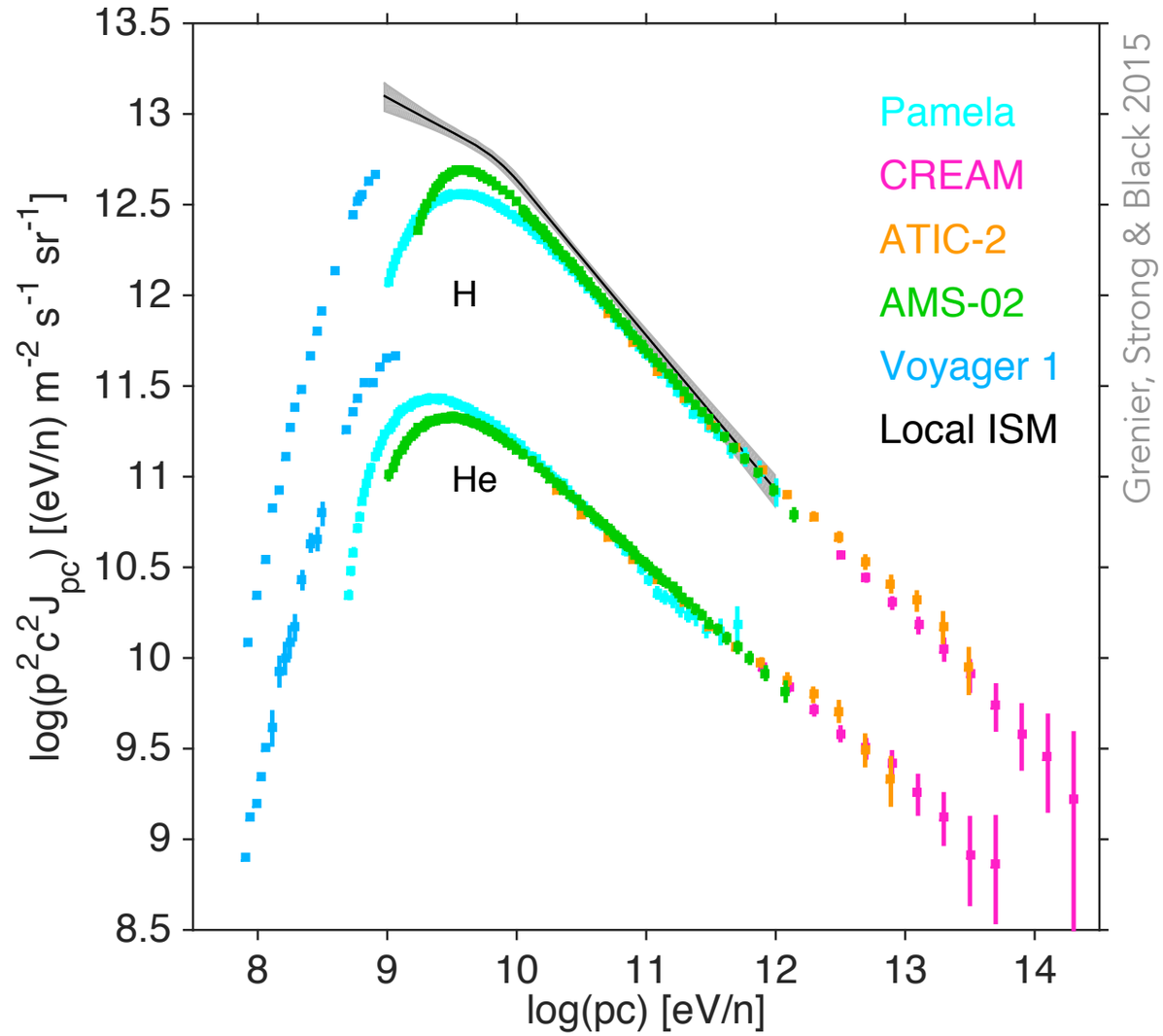
CR ionisation rate

- 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

- Voyager + GALPROP or leaky box
  - $\zeta^{H}_{CR} \approx (1.51\text{-}1.64)\ 10^{-17}\ s^{-1}$
  - $u_{CR} \approx (0.83\text{-}1.02)$ eV cm^{-3}

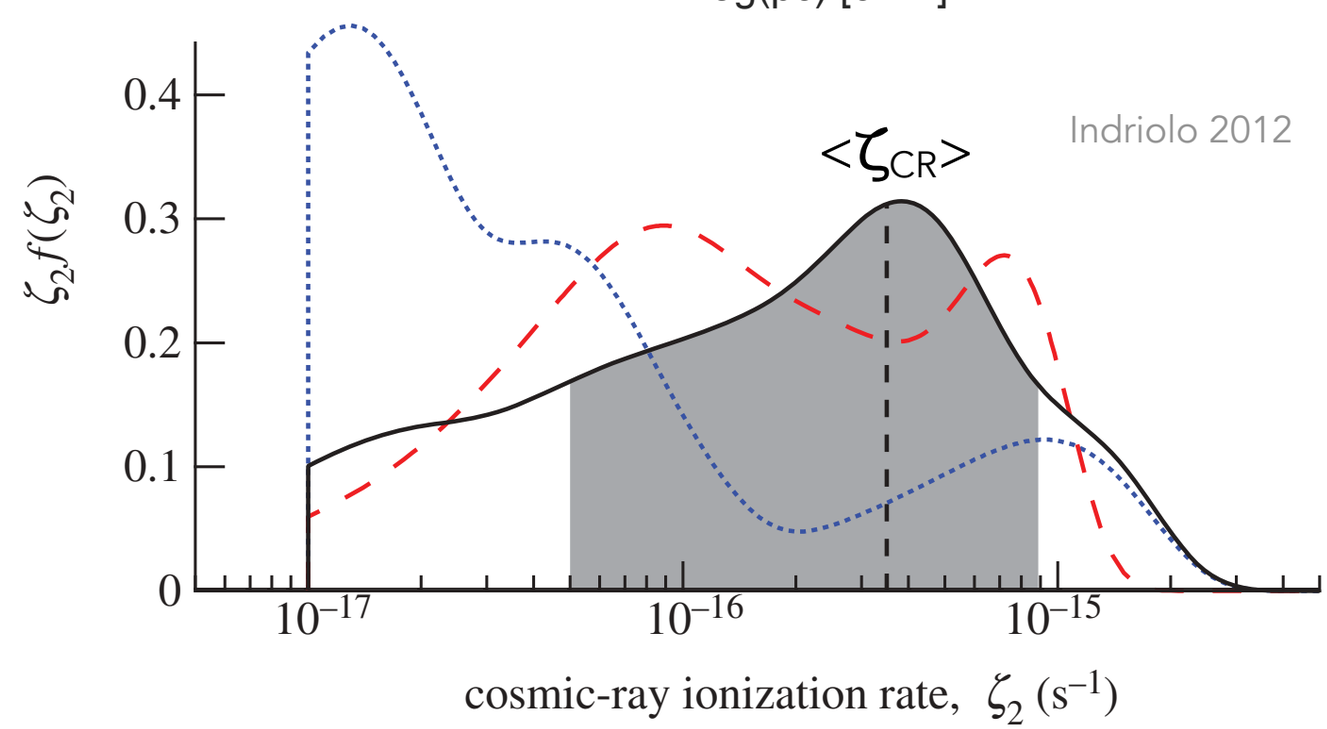
Cummings+ 2015



- from H_3^+ observations
  - Galactic disc average: $\langle\zeta_{CR}\rangle \approx 3.5\ 10^{-16}\ s^{-1}$
  - 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

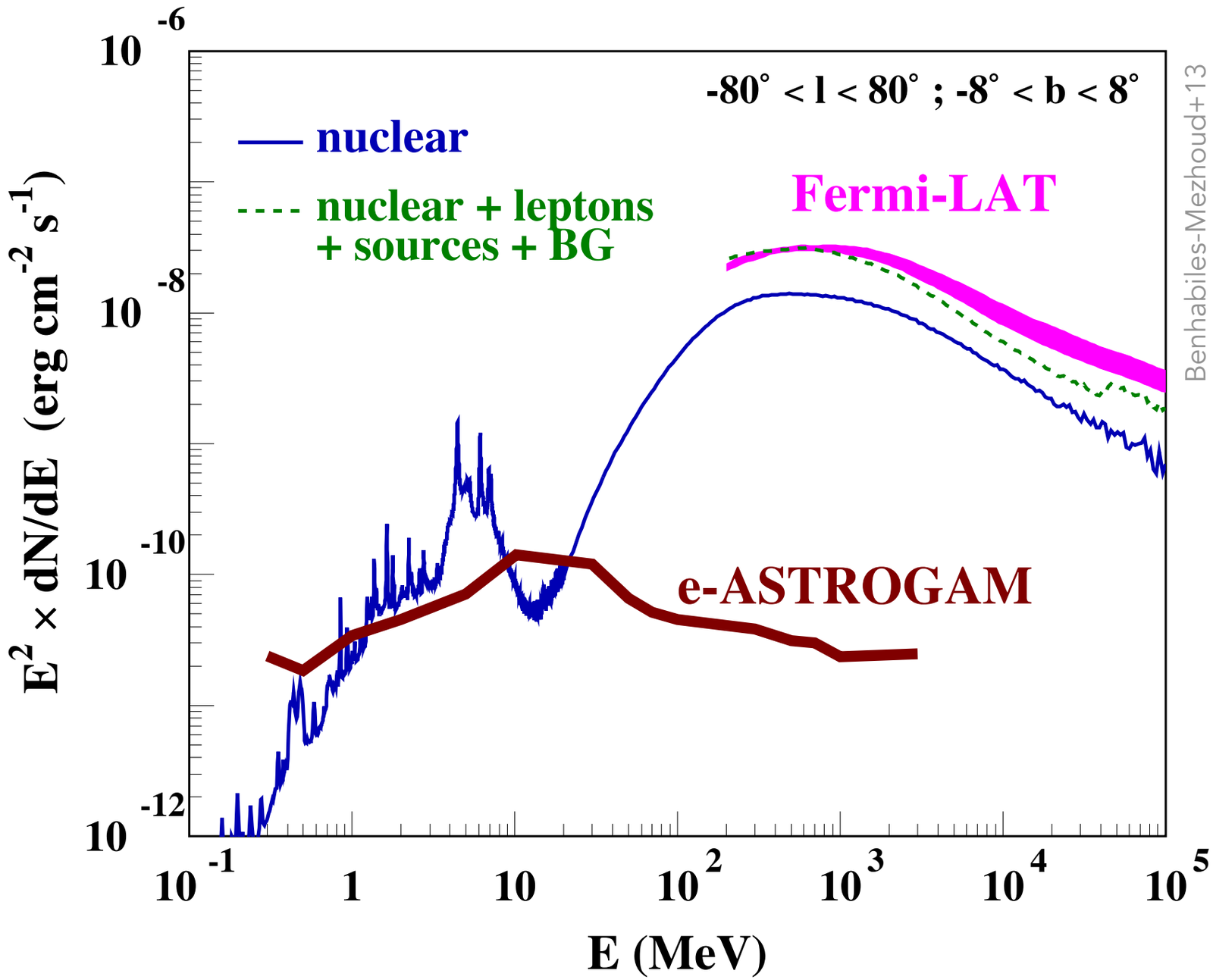
=> low-energy environmental effects ?

  - Horse Head: edge-to-inside decline
    from $5\ 10^{-15}$ to $7.5\ 10^{-16}\ s^{-1}$
    (using chemical probes)



prospects for e-ASTROGAM

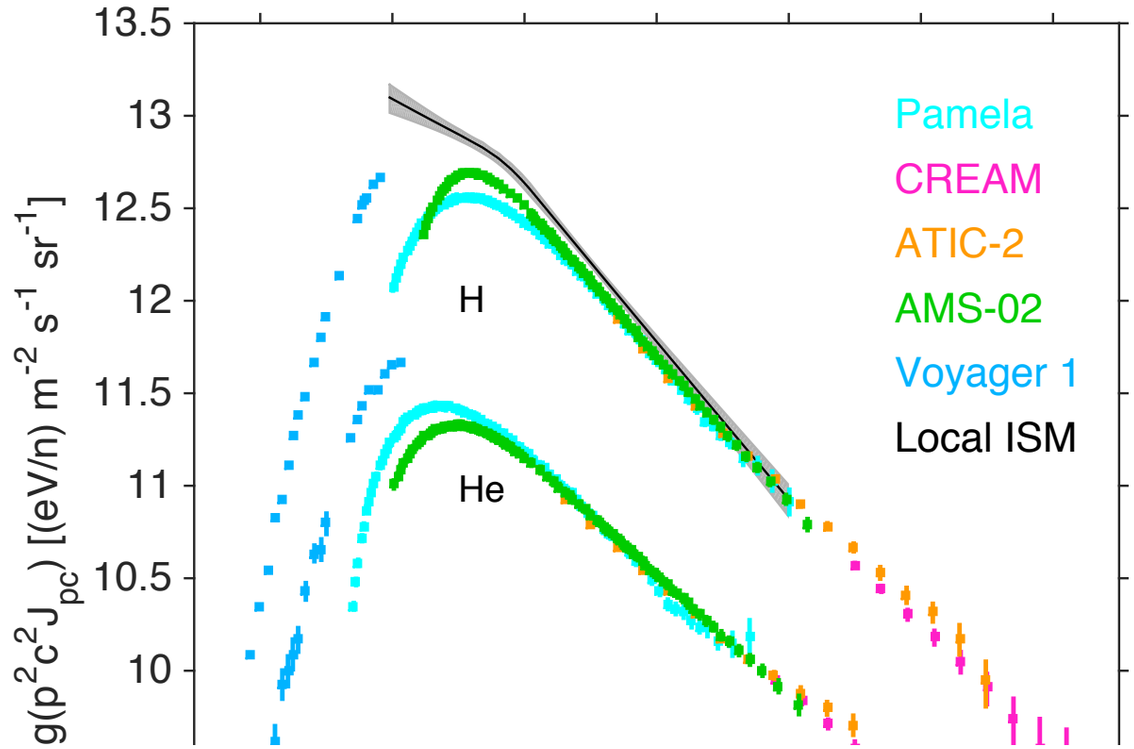
- direct measurements of low-energy CRs
- only an integral across the whole inner Galaxy

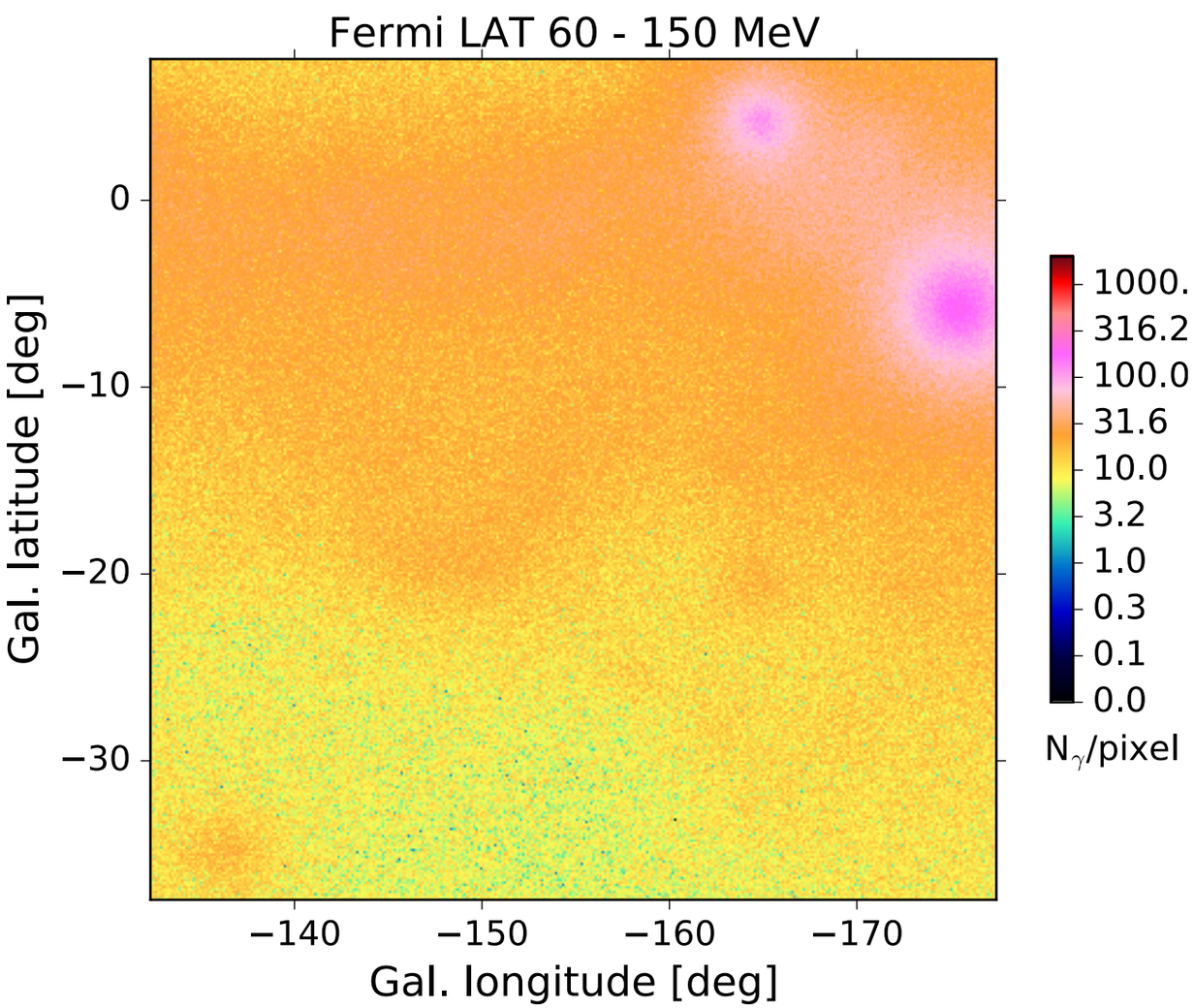


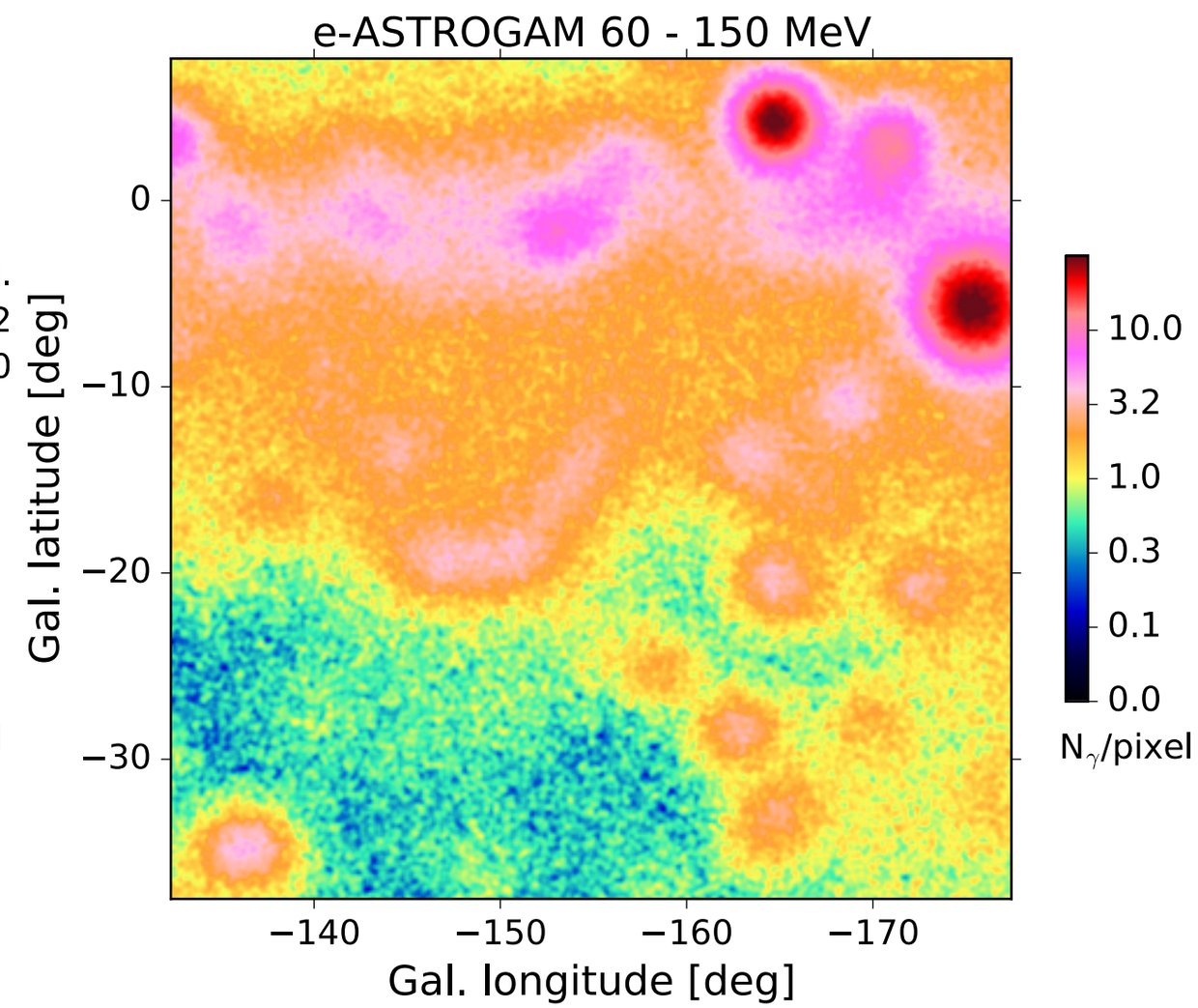
Benhabiles-Mezhoud+13

prospects for e-ASTROGAM

- resolve local clouds to < 100 MeV
- remove pt-source contamination
- ⇒ search for
  - inflexions in the nuclei spectrum at low energies
  - electron bremsstrahlung





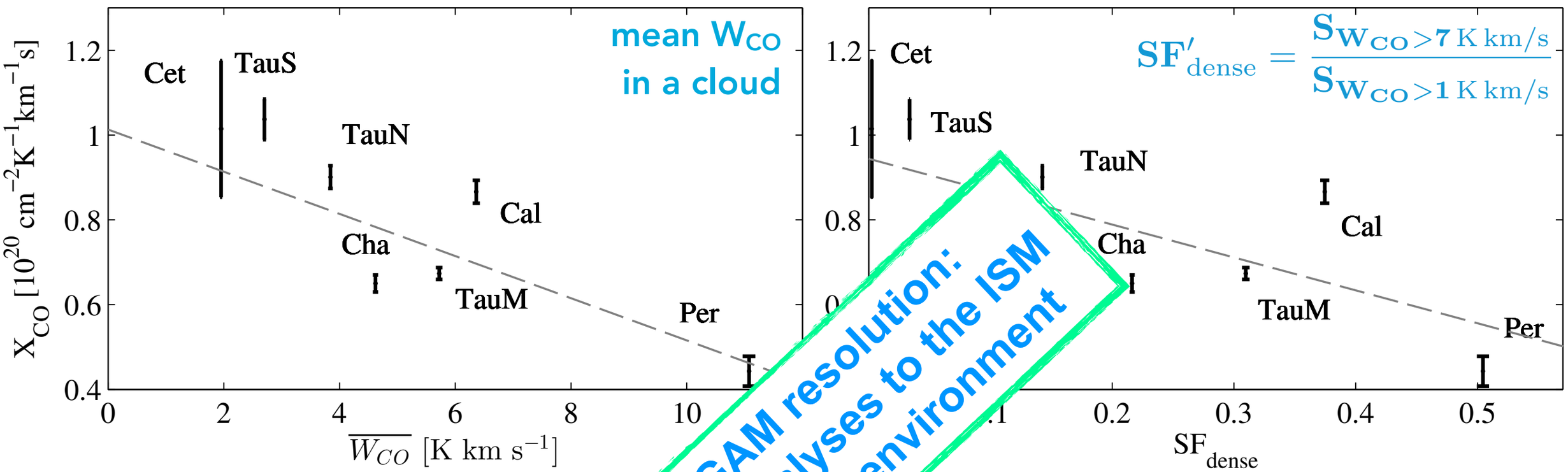


ISM properties

validating gas tracers

- gradients across molecular clouds of the CO-to-H_2 conversion factor (X_{CO})

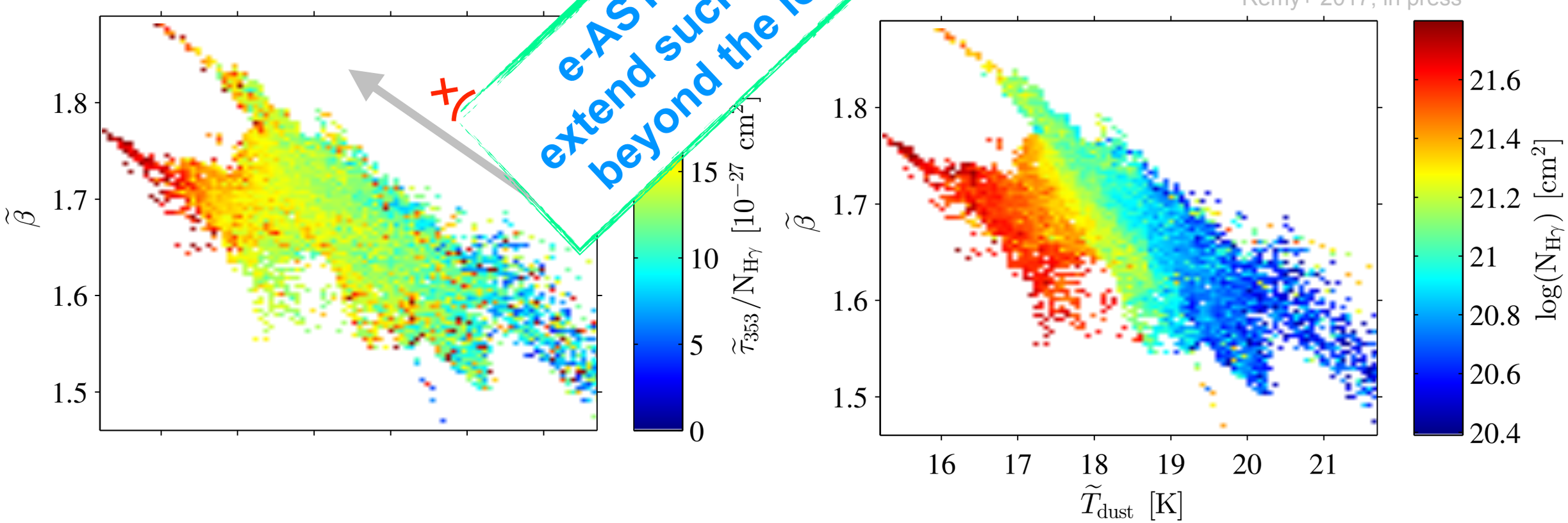
Remy+ 2017, in press



- gradients of the dust opacities with ga

e-ASTROGAM resolution: extend such analyses to the ISM beyond the local environment

Remy+ 2017, in press

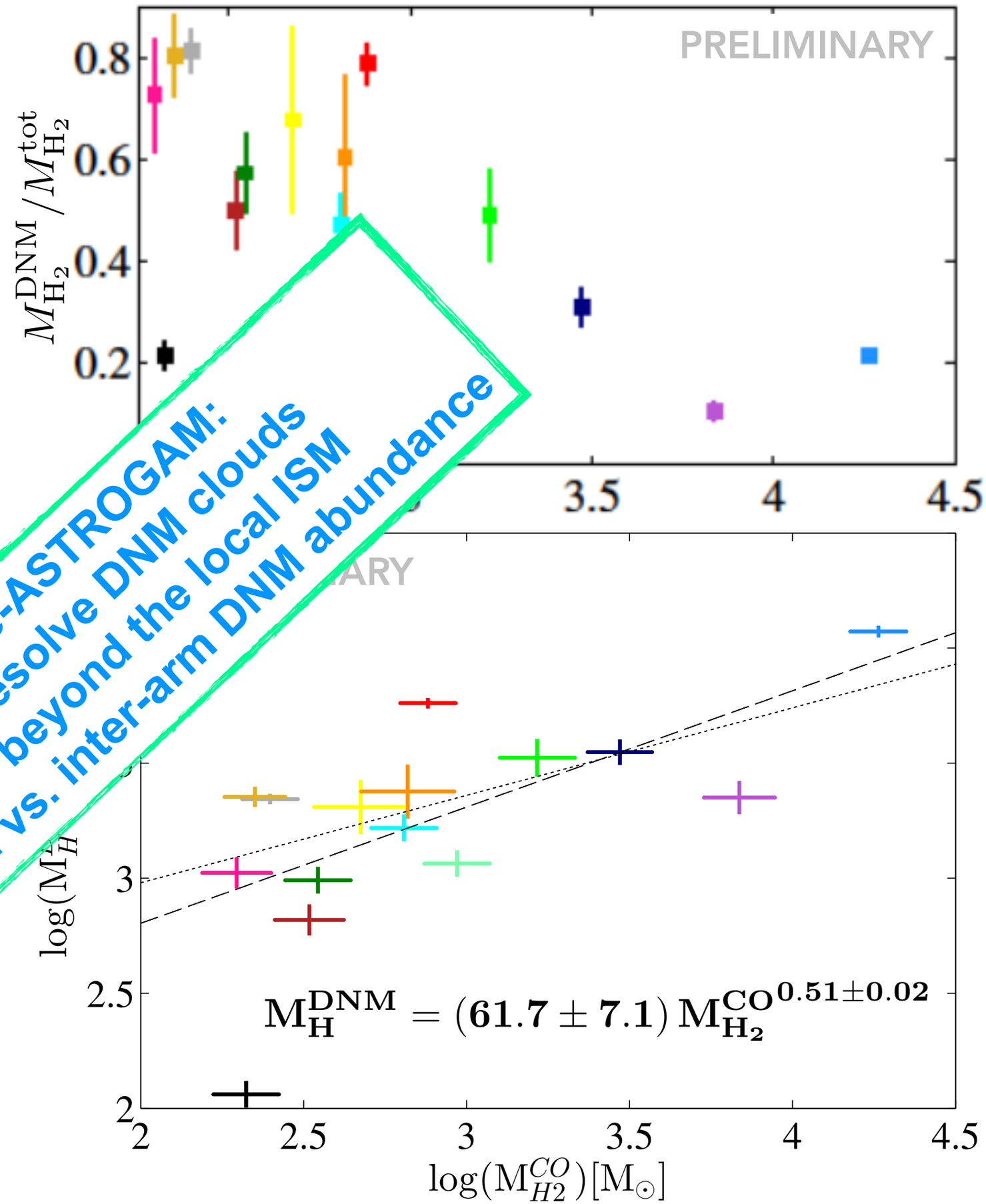


gas census

- the DNM mass abundance decreases with the H_2 mass revealed by CO observations

- the DNM mass in a cloud scales approximately with the square root of the CO-bright H_2 mass

(as in Grenier+ 2005, Science, 307, 1292)



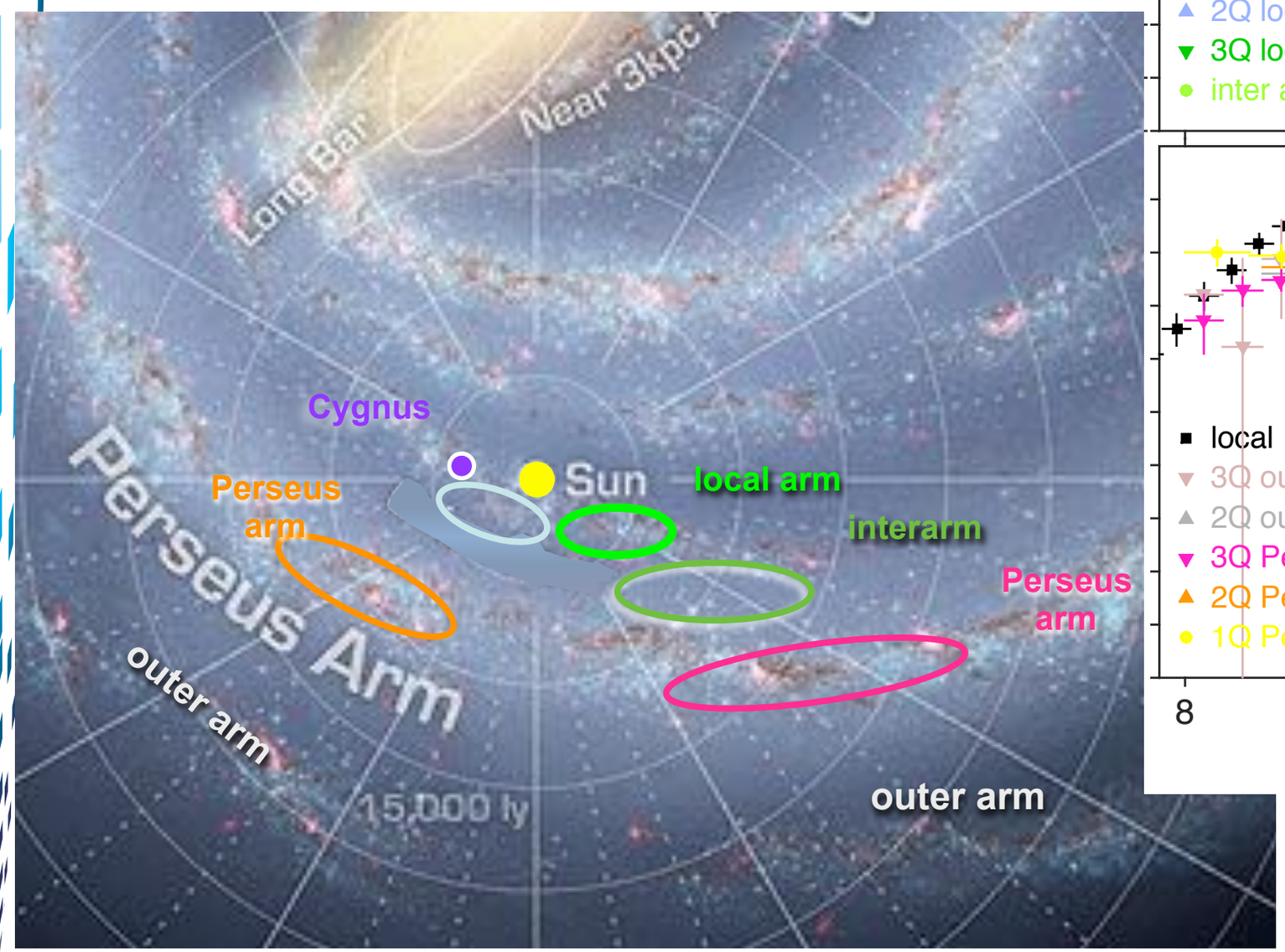
e-ASTROGAM: resolve DNM clouds beyond the local ISM arm vs. inter-arm DNM abundance

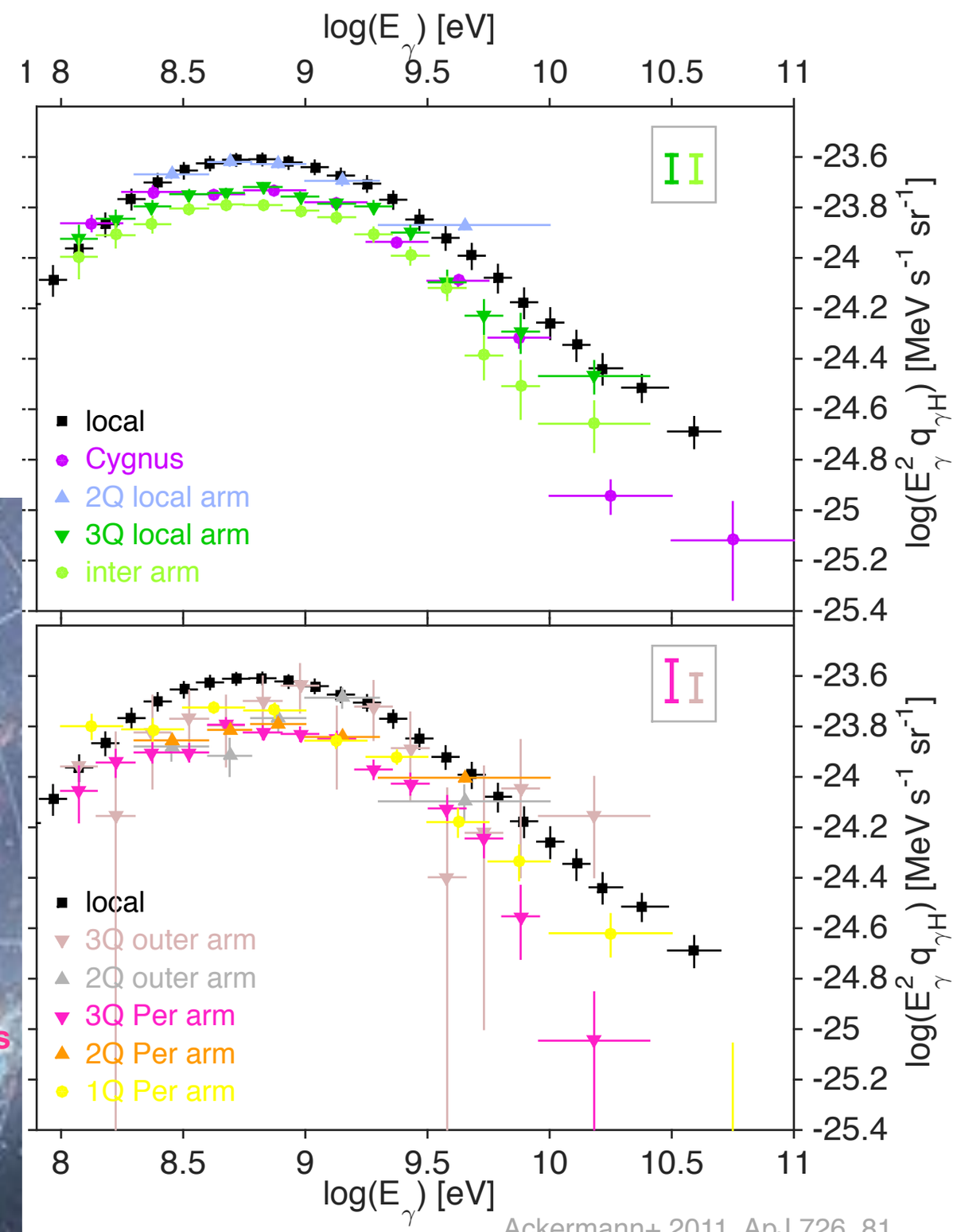
✦ the outlier black cloud has a peculiar, filamentary structure

Multi-GeV cosmic rays in the Milky Way

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 ?

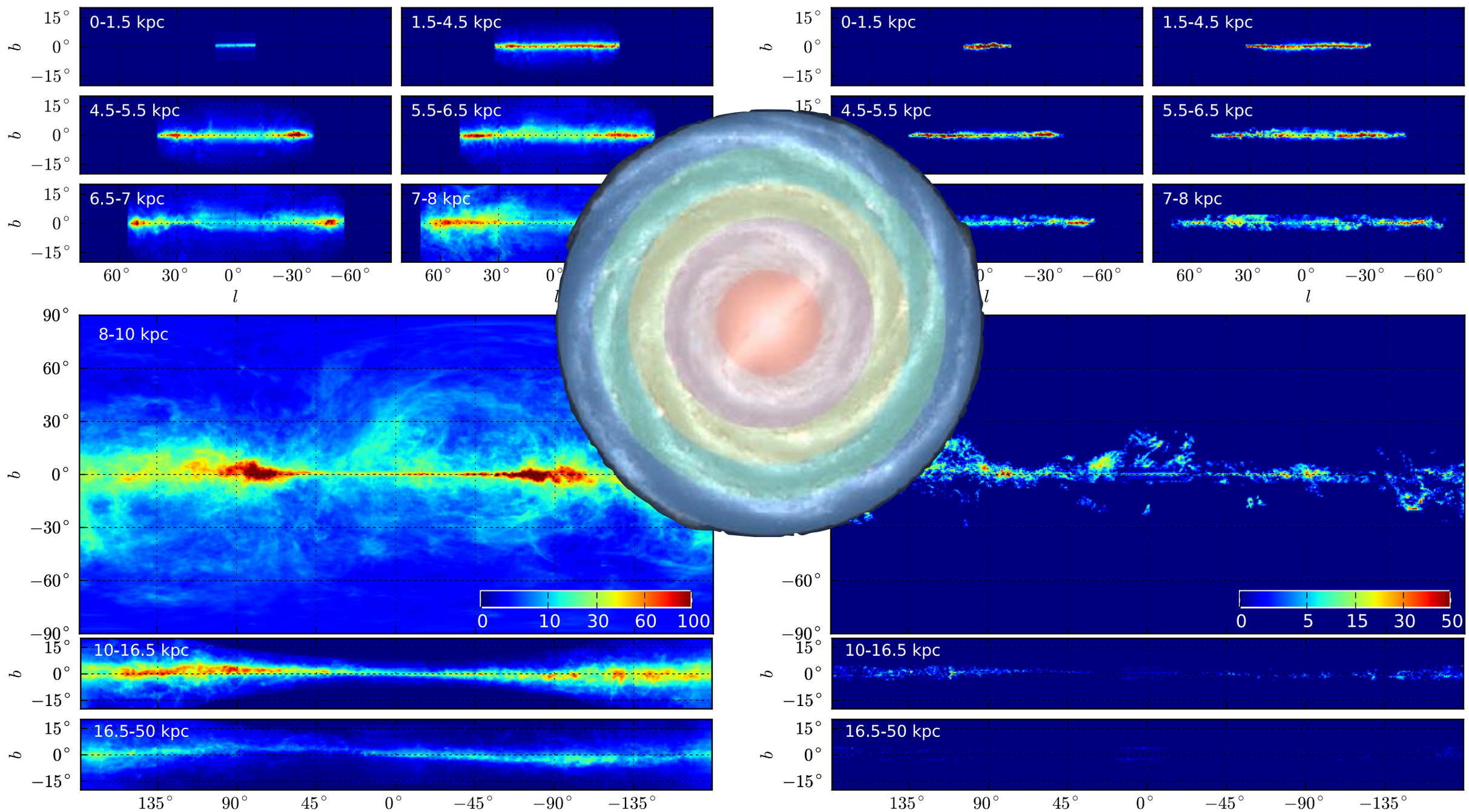




Ackermann+ 2011, ApJ 726, 81
Abdo+ 2011., ApJ 710, 133
Ackermann+ 2012, A&A, 538, A71
Casandjian 2015

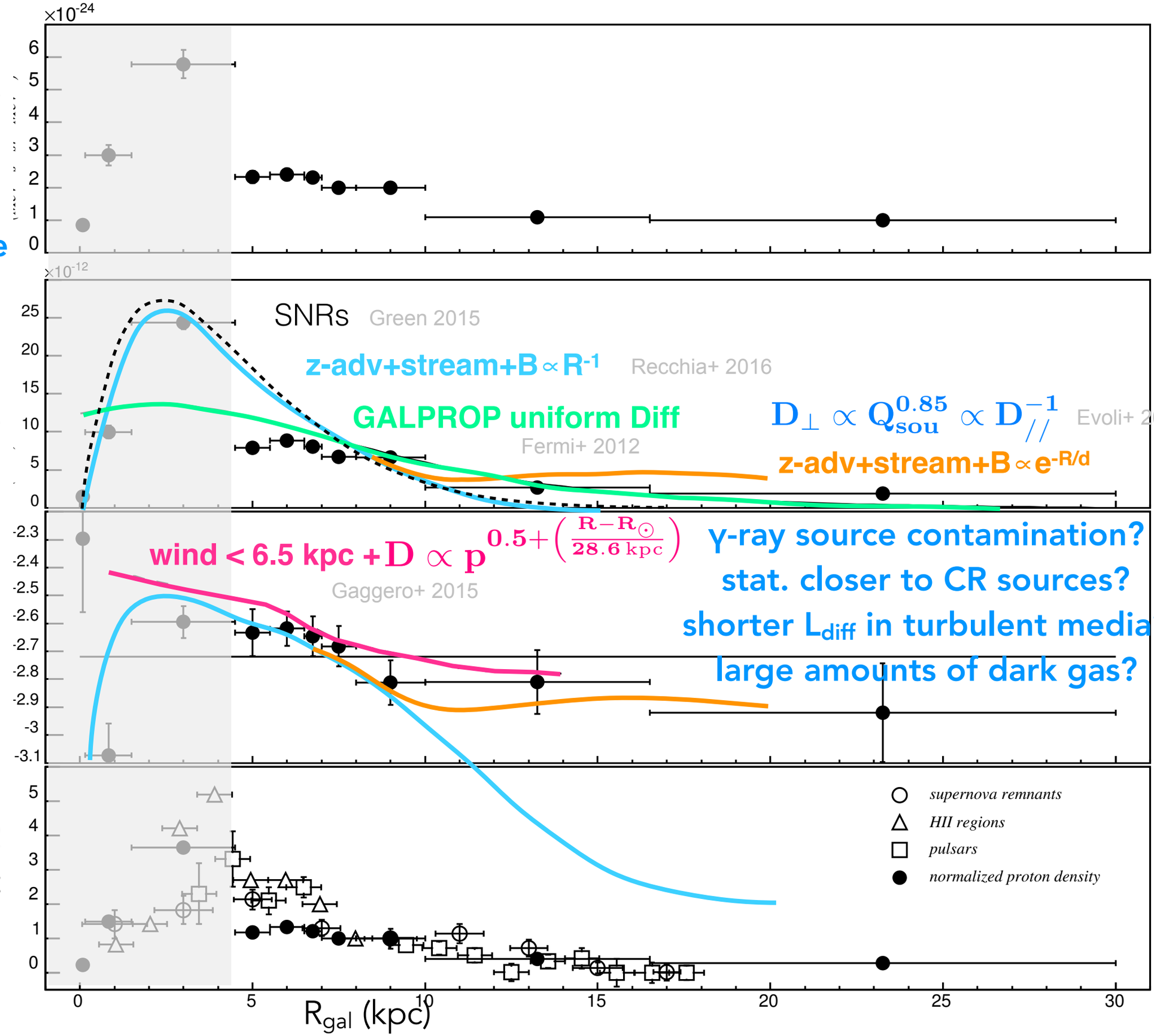
Galactocentric rings

- very uncertain in the inner rings !!!



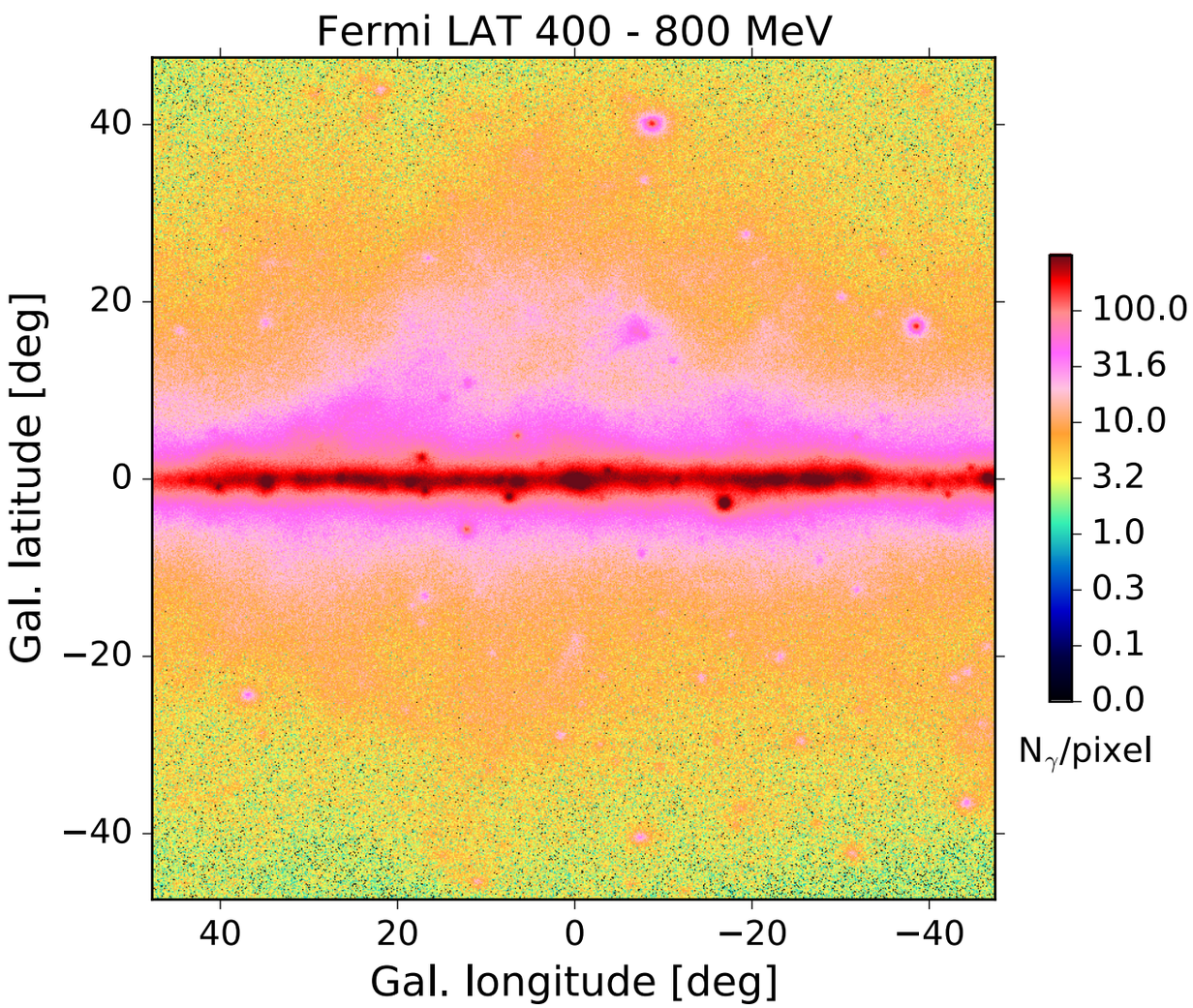
Acero+ 2016, ApJS 223, 26

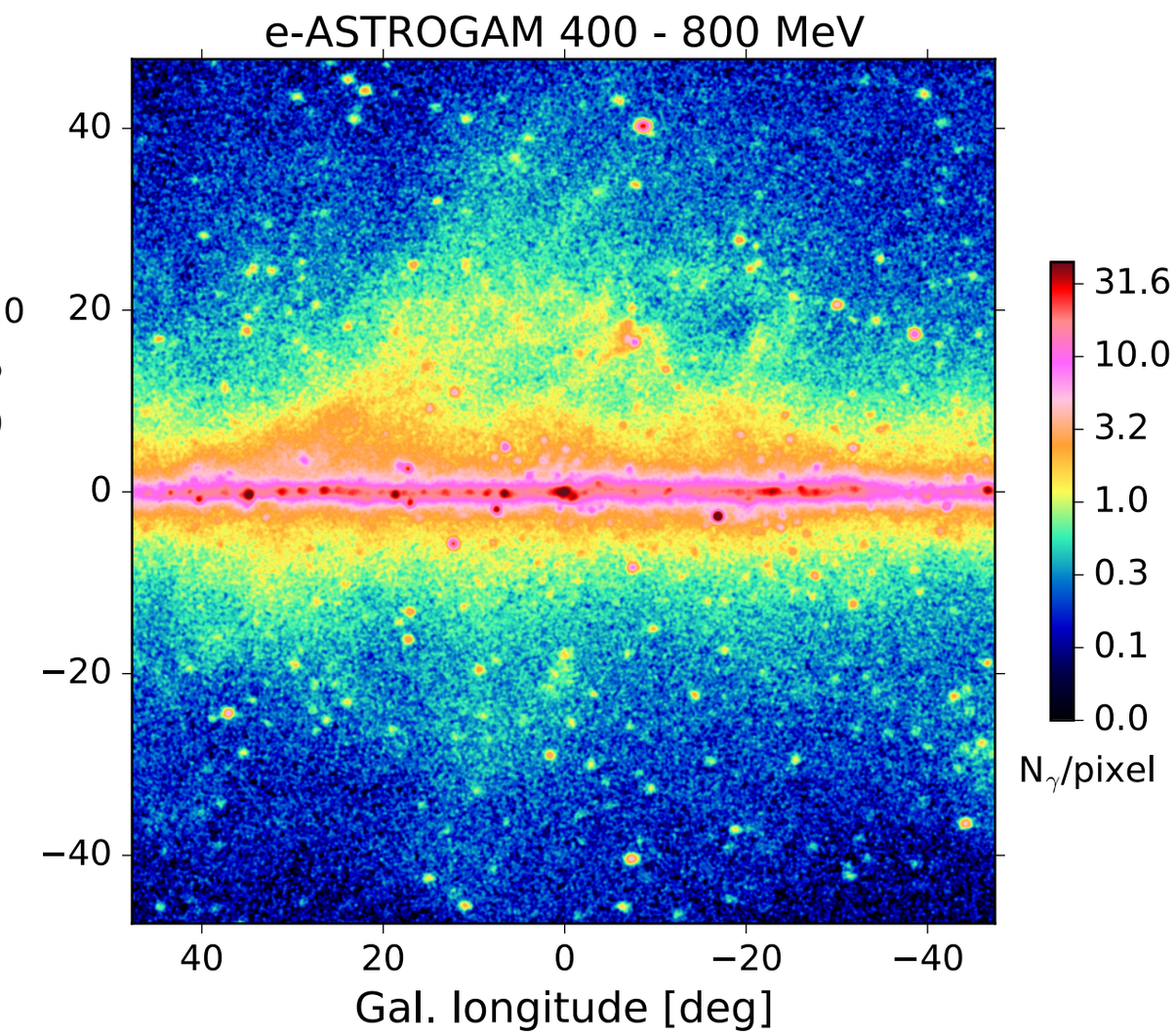
Galactic radial gradients



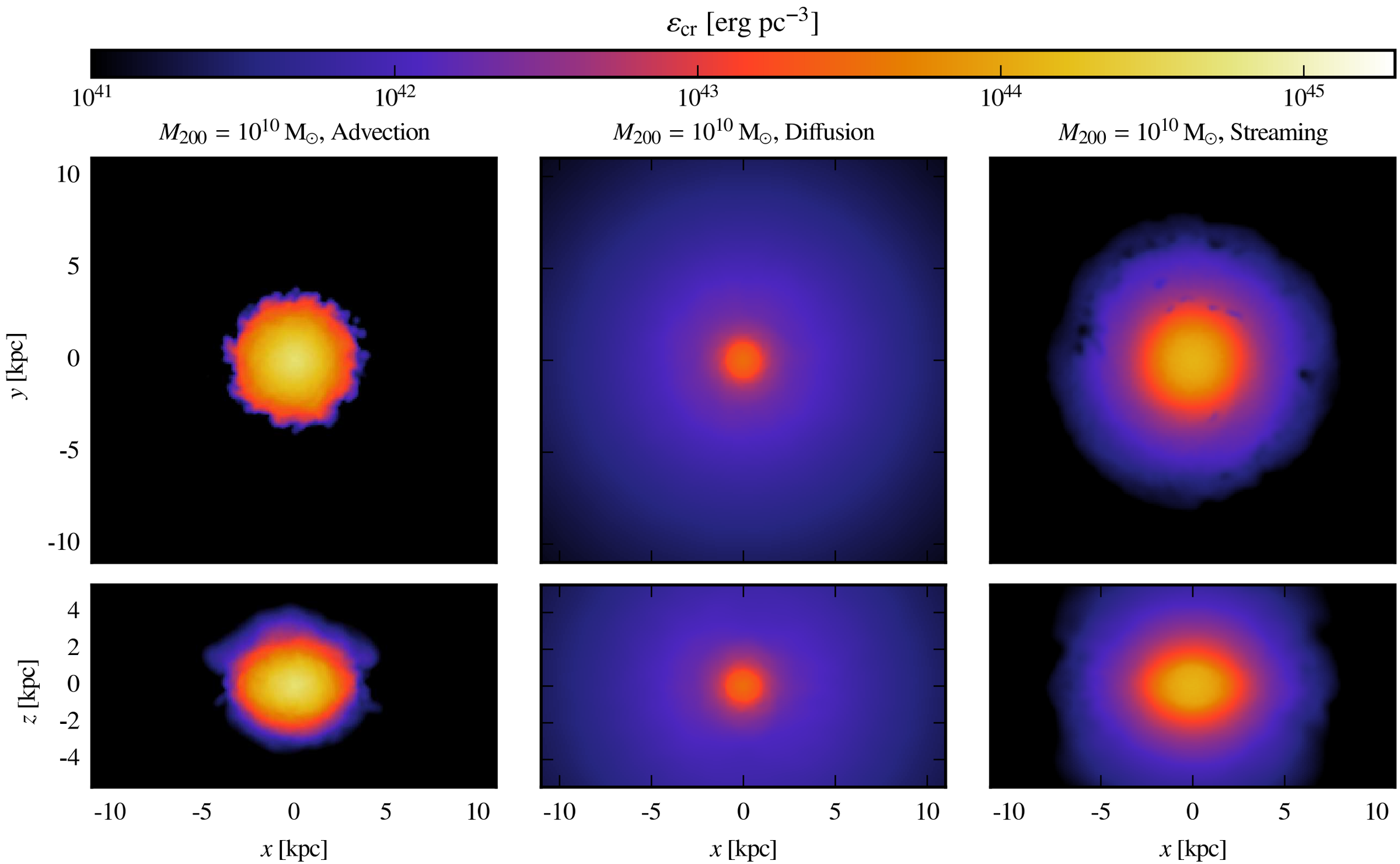
prospects for e-ASTROGAM

- reduced pt-source contamination
- inner Galaxy: less confusion with distance =>
  - from axisymmetric to spiral-arm Galaxy => $D_{\perp}$ & $D_{//}$ (PICARD, DRAGON, Benyamin et al….)
  - CR spectrum as a function of ambient SFR
  - importance of advection in the inner regions => f(p) closer to injection spectrum
- outer Galaxy: e-ASTROGAM + Fermi + CTA? + HAWC?
  - diffusion-dominated mode f(p) → Q(p)/D(p)





CR feedback



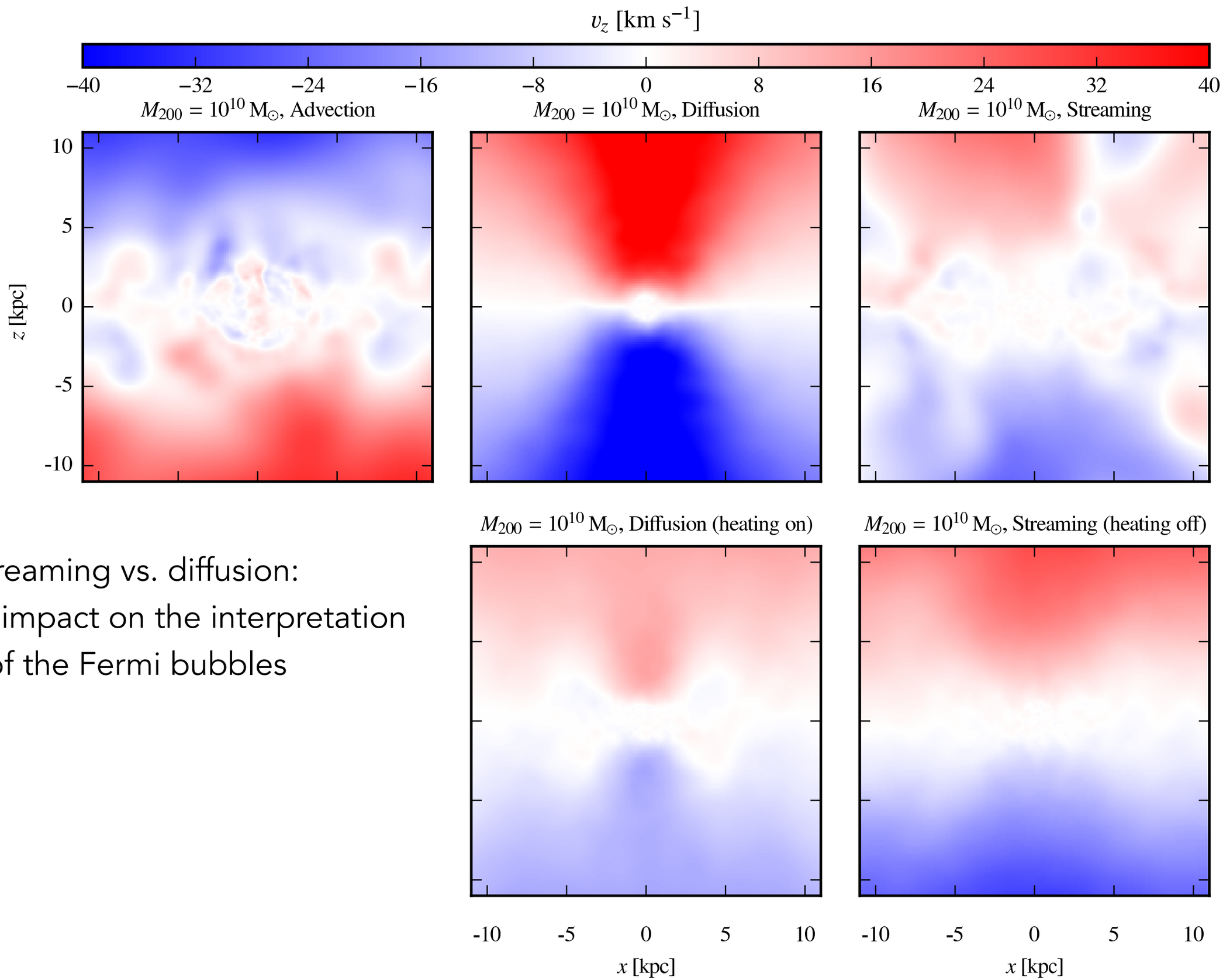
Wiener+ 2017

CR advection with gas

advection with gas
+ isotropic diffusion

advection with gas
+ streaming (no diff)

CR feedback



Wiener+ 2017

- streaming vs. diffusion:
  - impact on the interpretation of the Fermi bubbles

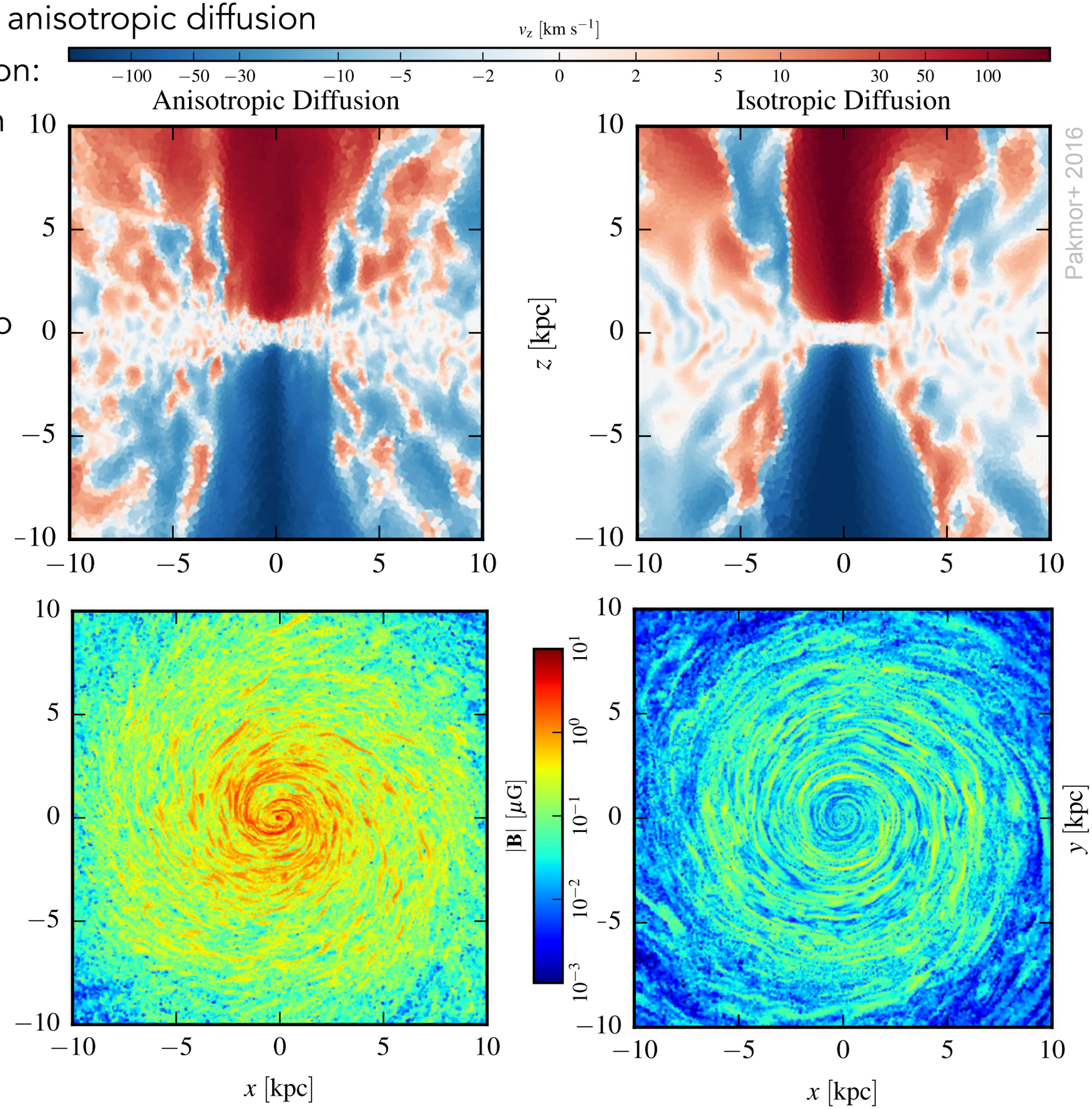
CR advection with gas

advection with gas + isotropic diffusion

advection with gas + streaming (no diff)

CR feedback

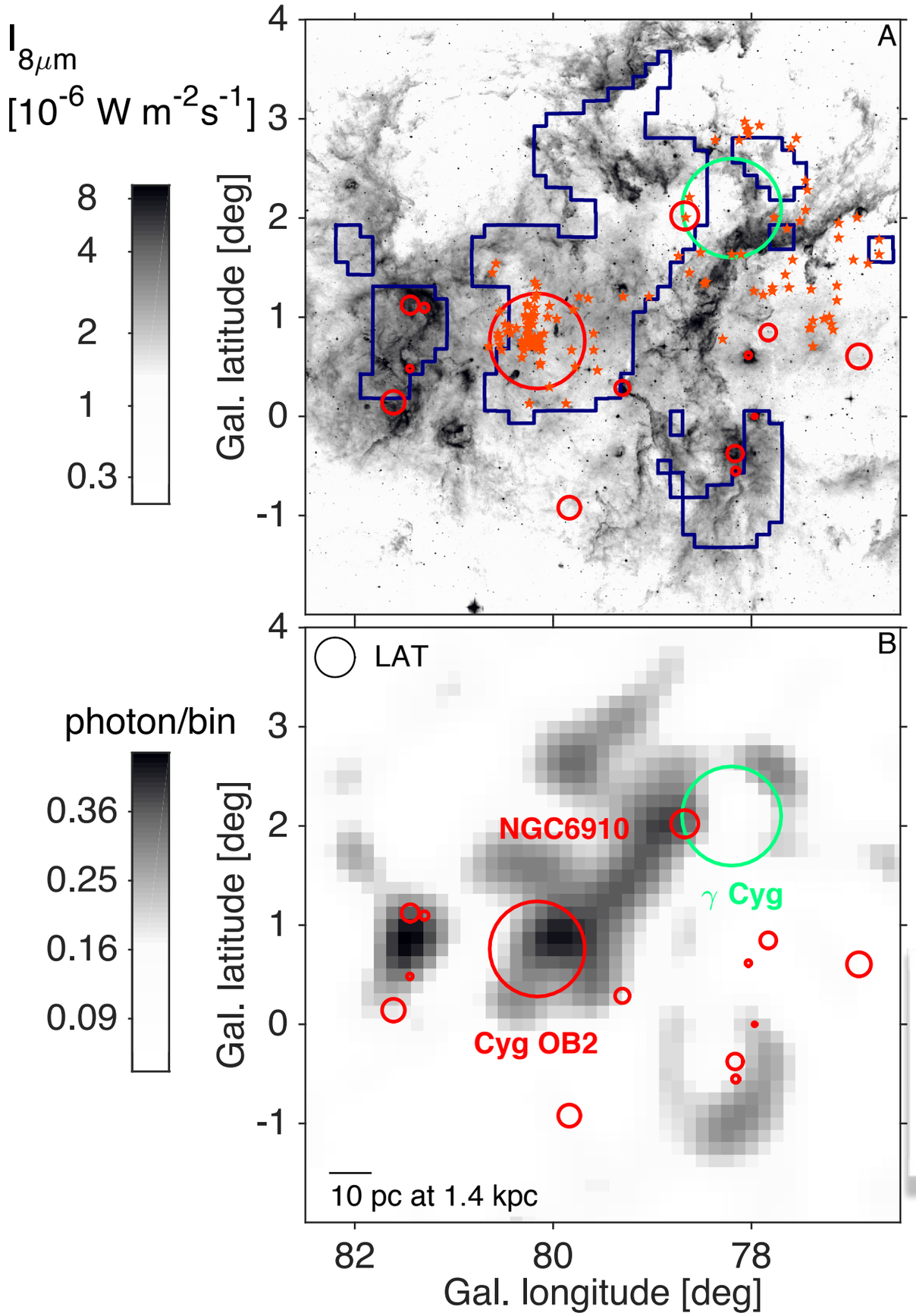
- contraints on streaming and anisotropic diffusion important for galaxy evolution:
  - feedback outflow strength weaker if anisotropic CR diffusion cf Pakmor+16, Ruszkowski+16
  - B amplification by dynamo faster if anisotropic CR diffusion cf Pakmor+16

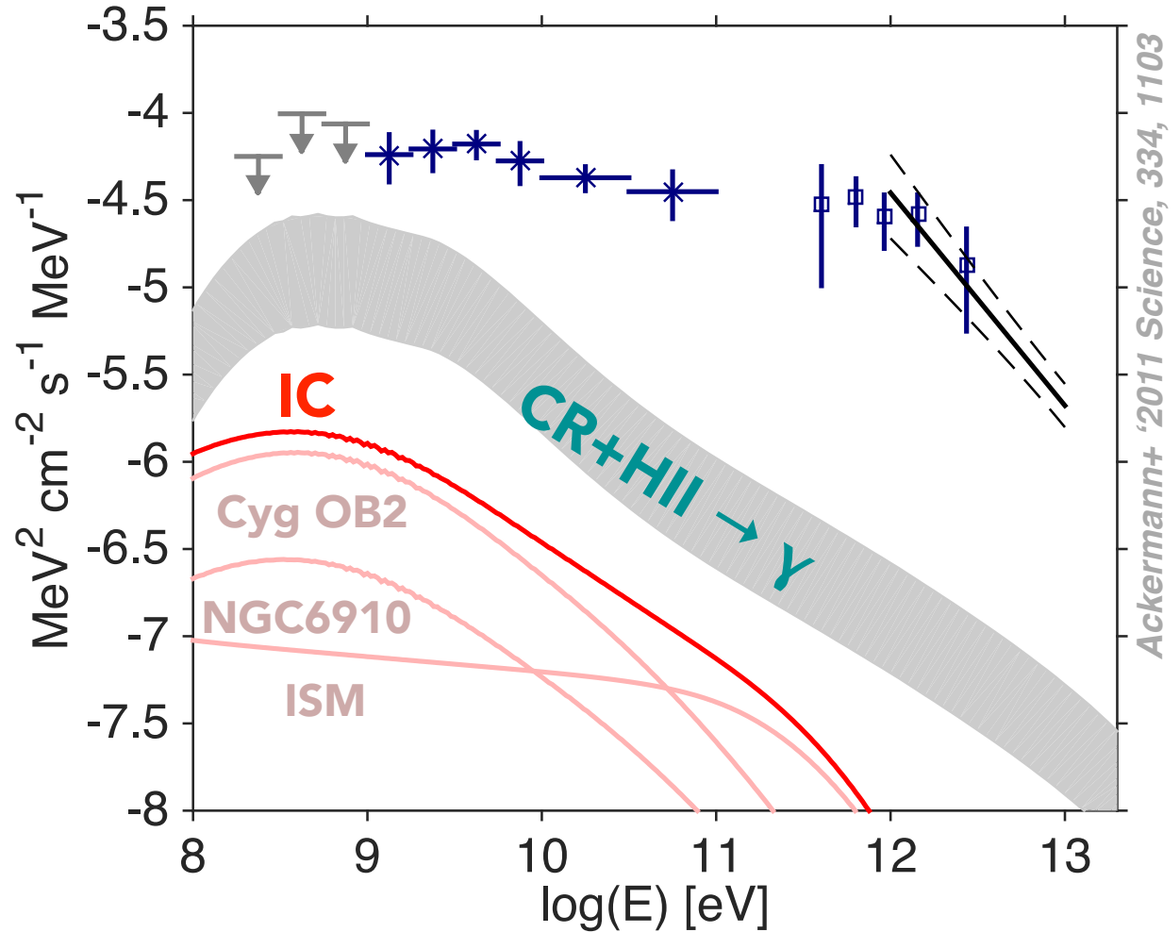


Pakmor+ 2016

- diffusion-dominated in the outer Galaxy
  - constraint on B(R) at far distance

cocoon of fresh cosmic rays





- hard γ-ray excess: $E_{CR}^{-2.4}$ above 1 GeV
- bounded by ionization fronts (PDRs)
- extension >> SNR or cluster sizes
- ≈ spectral uniformity

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

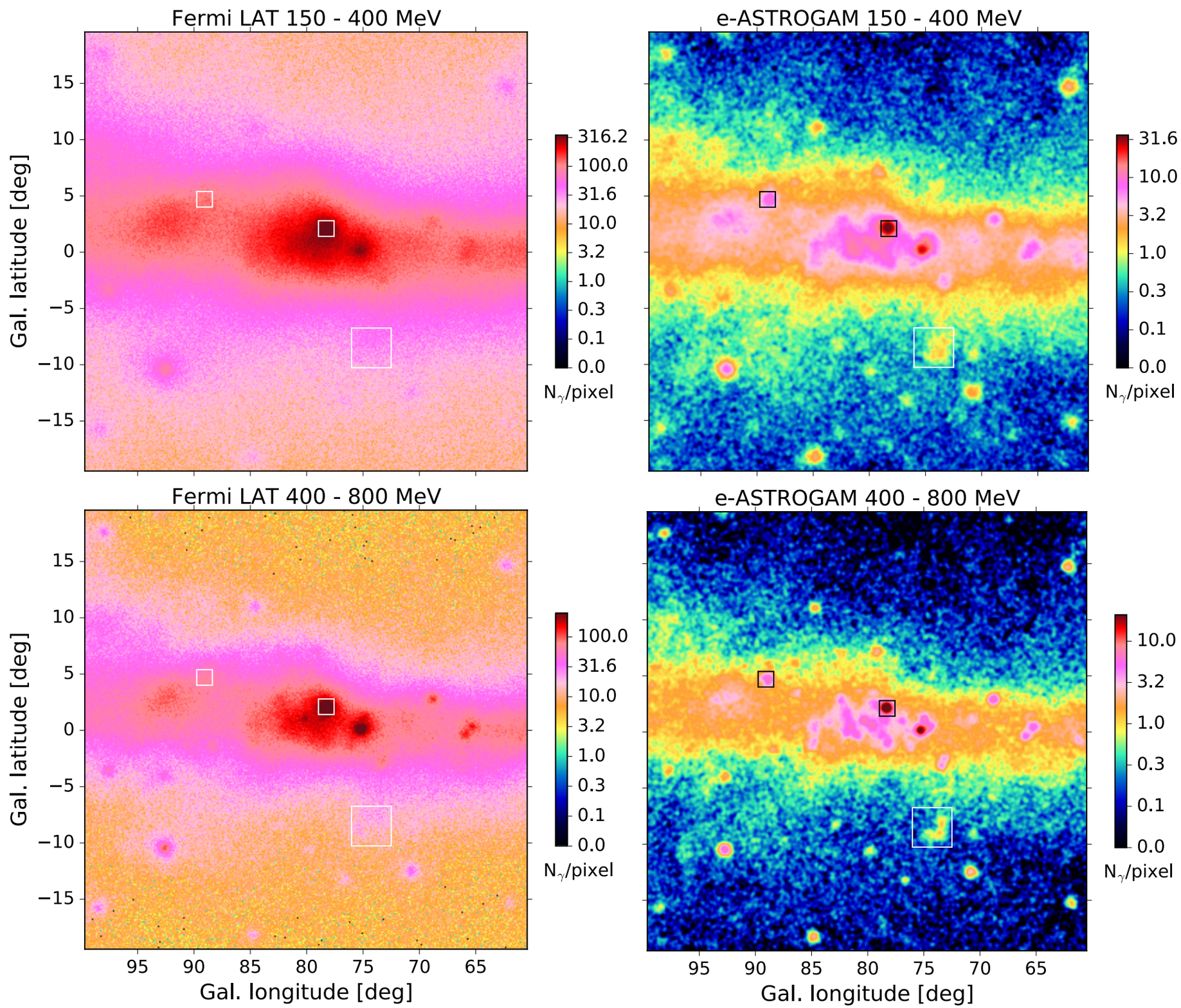
- if pure IC: $E_{CR} = 4\,10^{41}$ J
- if pure pion: $E_{tot} = 1.3\,10^{42}$ J ≈ 1% E_{SN}

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

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

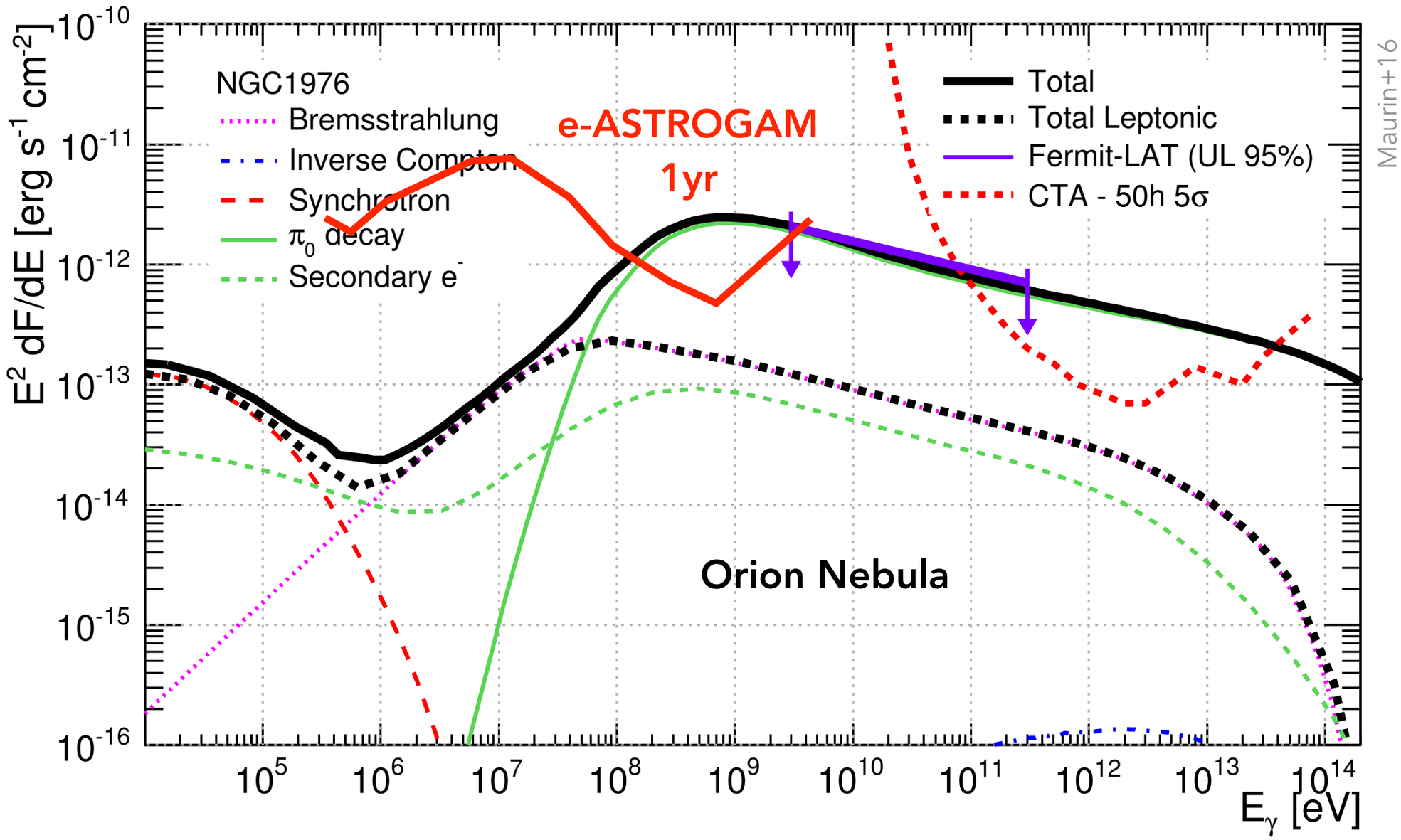
prospects for e-ASTROGAM

- extend the cocoon spectrum < 1 GeV (IC contribution to the total signal)
- search for spectral variations across the cocoon (with Fermi + CTA + HAWC)
- search for other starburst regions
- resolve SNRs down to a few 100 MeV (IC/π^0 constraints)



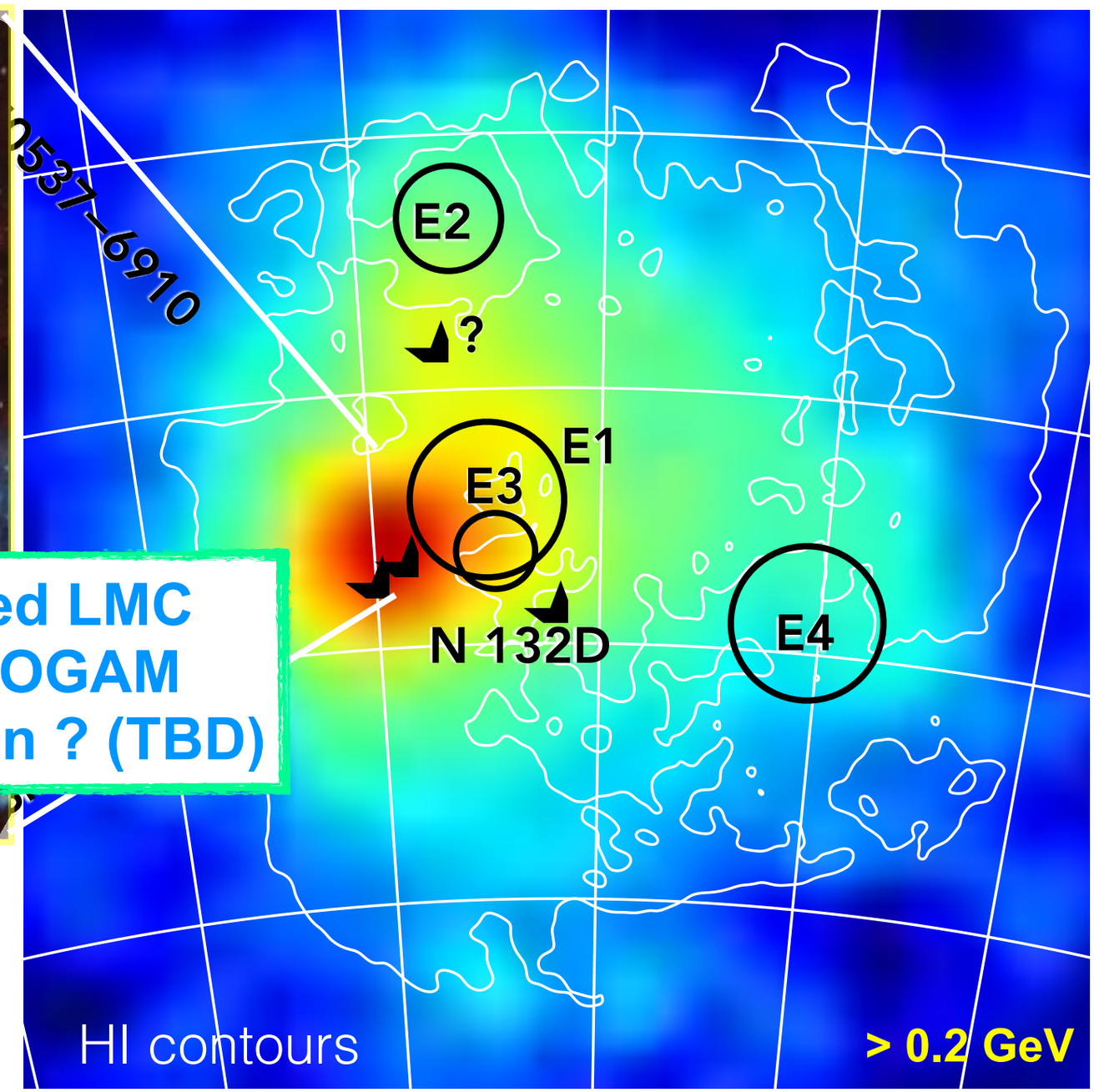
prospects for e-ASTROGAM

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



cosmic-ray bursts in LMC ?

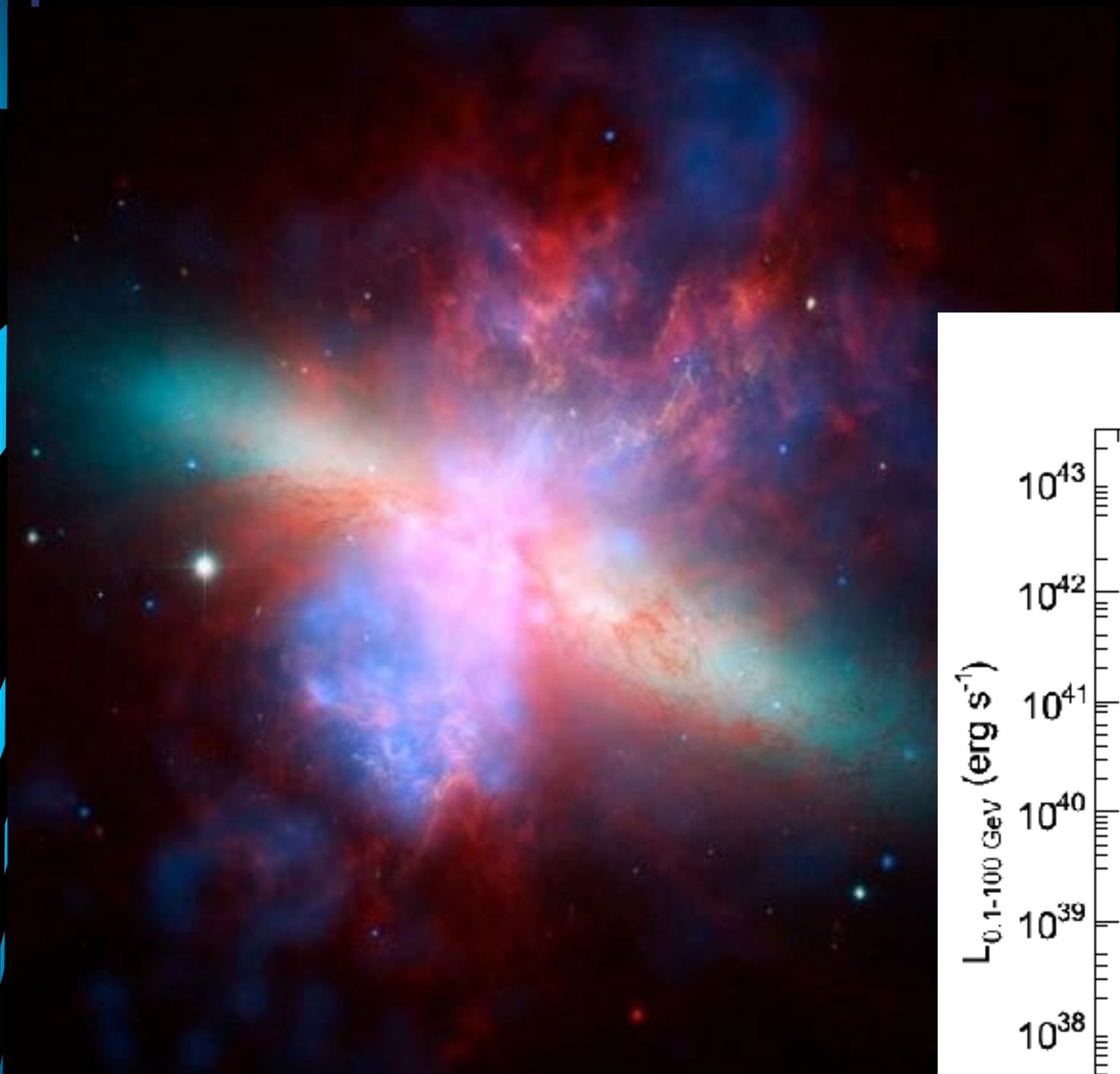
- 30 Doradus starburst: pt-source confusion with 2 bright pulsars, 30 Dor C superbubble not detected
- N11 starburst region not detected
- diffuse emission => central peak CR density of order 1/3 the local Galactic one (LIS)
- extended emission spots: possibly 2 to 6 times more CR density

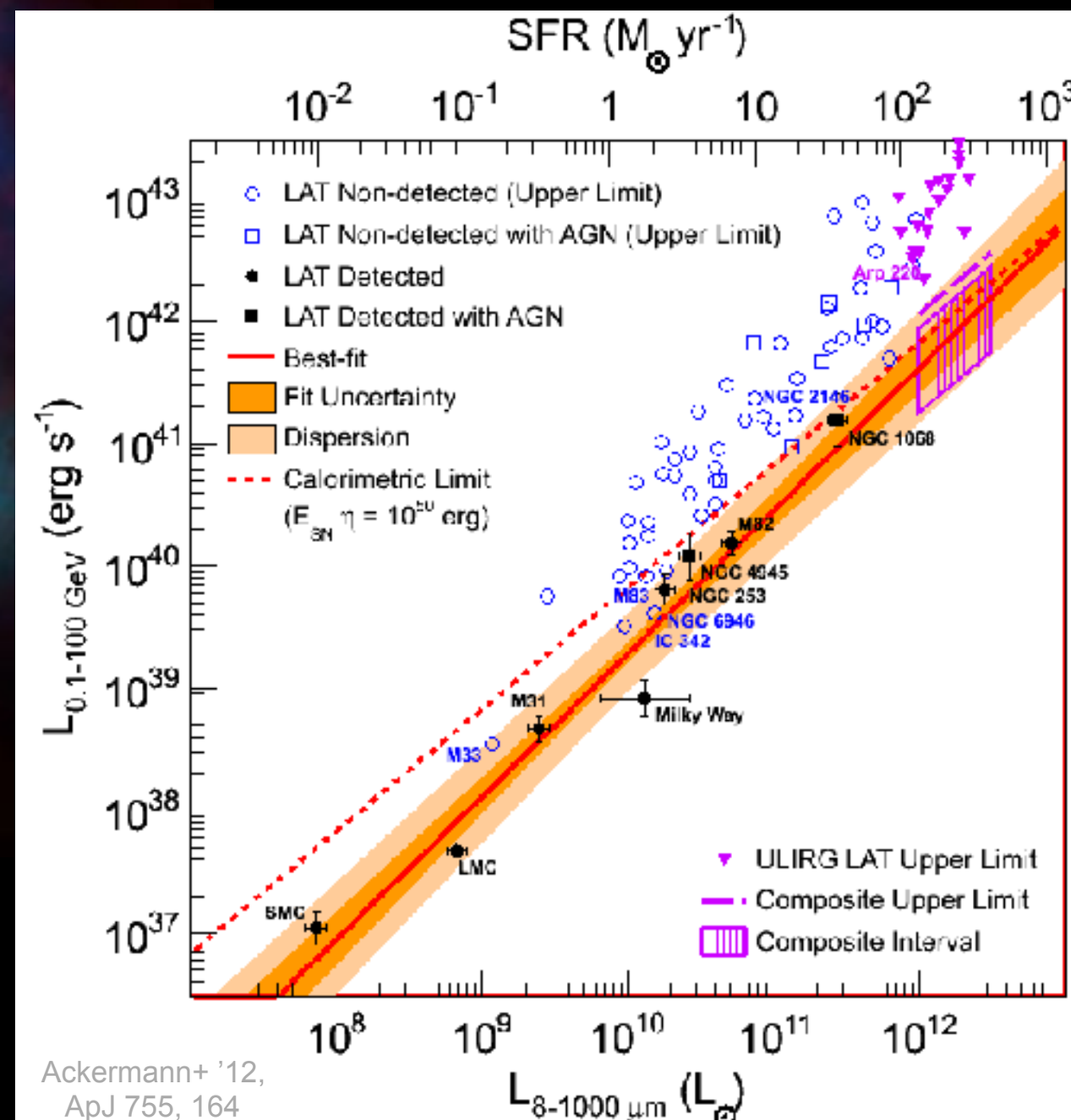


dedicated LMC e-ASTROGAM observation ? (TBD)

Ackermann+ 2016 A&A 586, 71

starburst galaxies





Ackermann+ '12, ApJ 755, 164

within e-ASTROGAM's reach: important breakthroughs in interstellar & cosmic-ray physics