Cosmic Rays and Non-Thermal Emission from the (Extended) Galactic Halo

Based on the work in collaboration with:

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Gabici+, *Astropart.Phys.* 30 (2008) 180-185

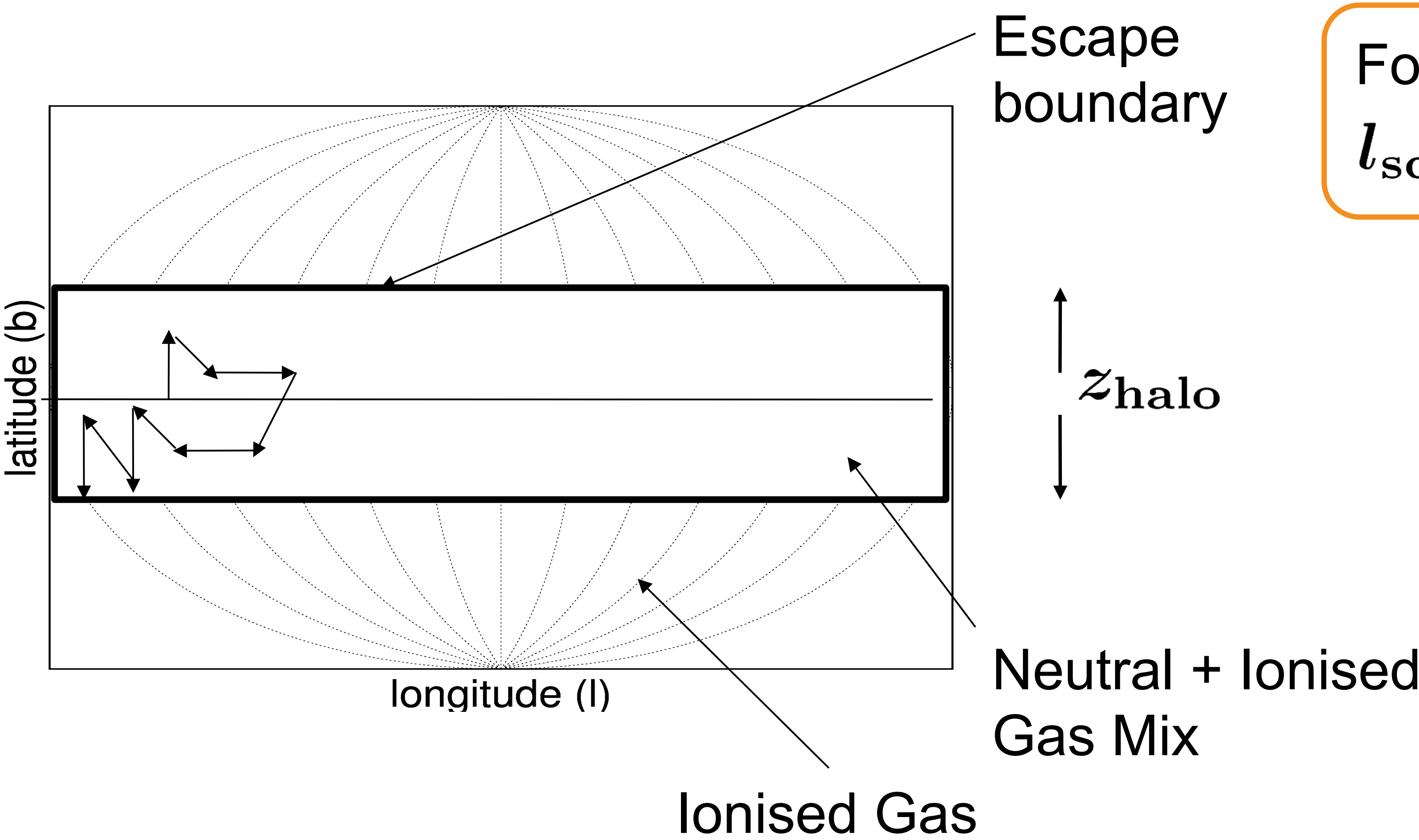
Taylor+, *Phys.Rev.D* 89 (2014) 10, 103003

Crocker+, *Astrophys.J.* 808 (2015) 2, 107

Taylor+, *Phys.Rev.D* 95 (2017) 2, 023001

DESY.

CR Propagation in the Galactic Disk



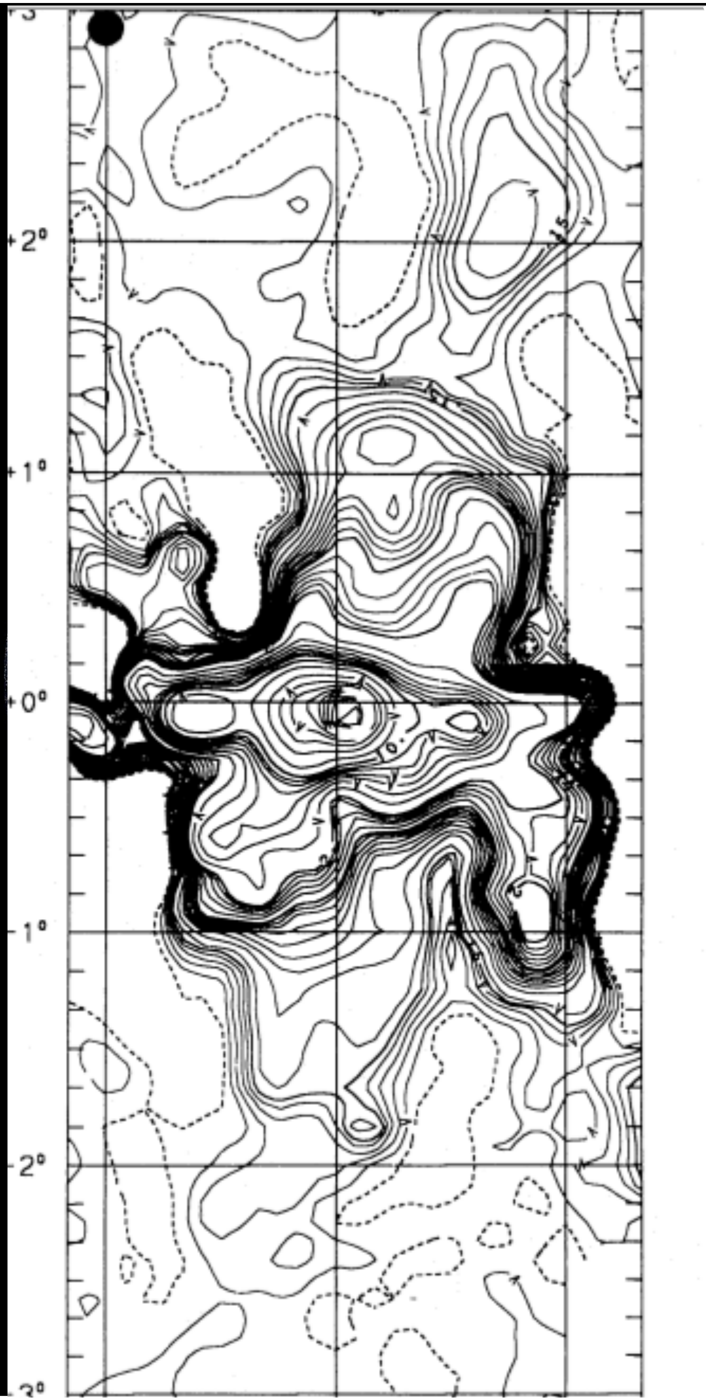
For GeV particles,
$l_{\text{scat.}} \approx 0.1\text{pc}$

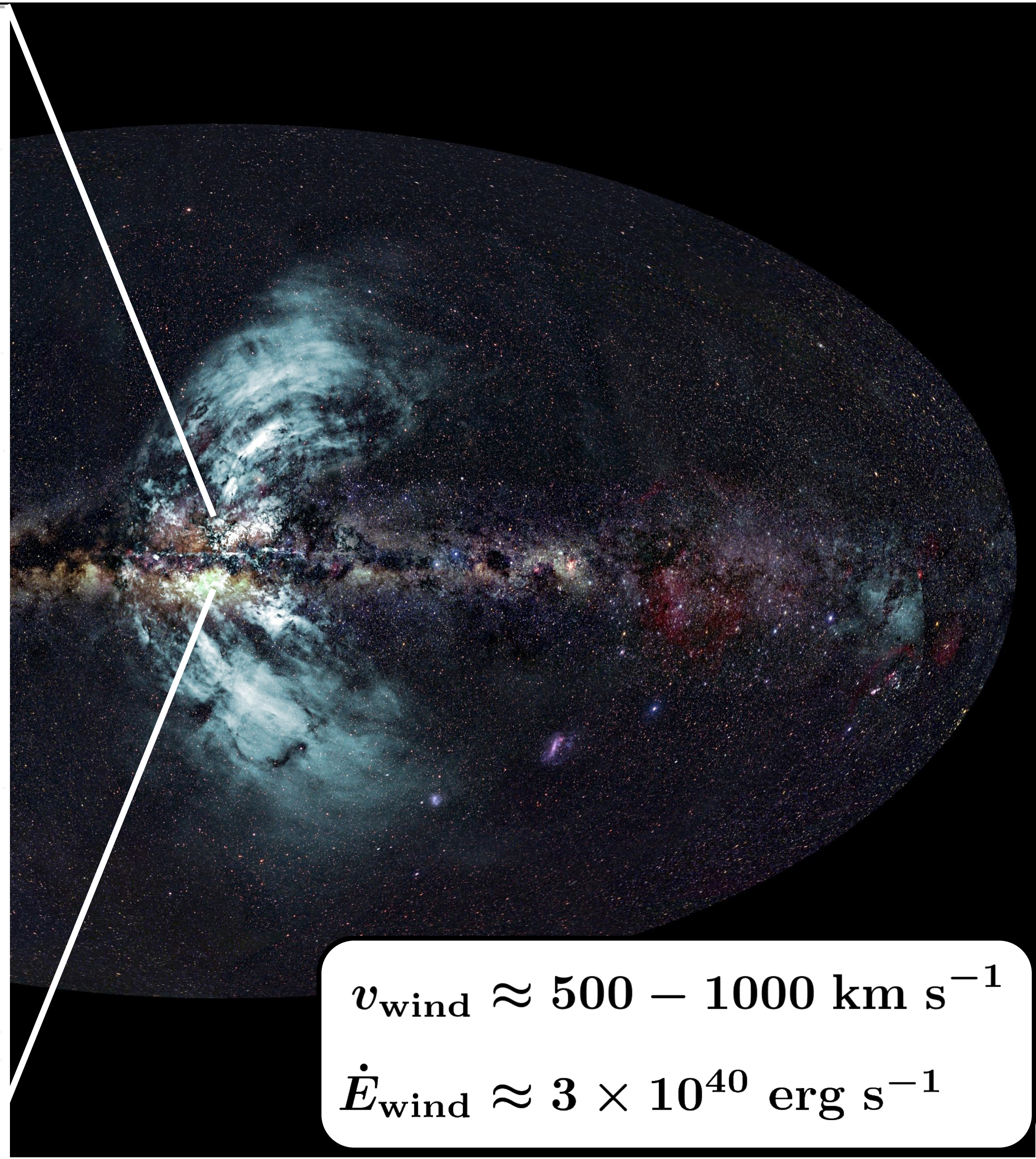
Taylor+, PRD 89, 103003 (2014)
Liu+, ApJ Vol. 871, No. 1 (2019)
Blasi+, PRL122,051101 (2019)

Galactic Diffuse Radio Emission

Pohl+, A&A 262 441 1992

Carretti+, *Nature* **volume 493**, 2013





$$\boldsymbol{v_{\rm wind} \approx 500 - 1000\ \mathrm{km\ s^{-1}}}$$

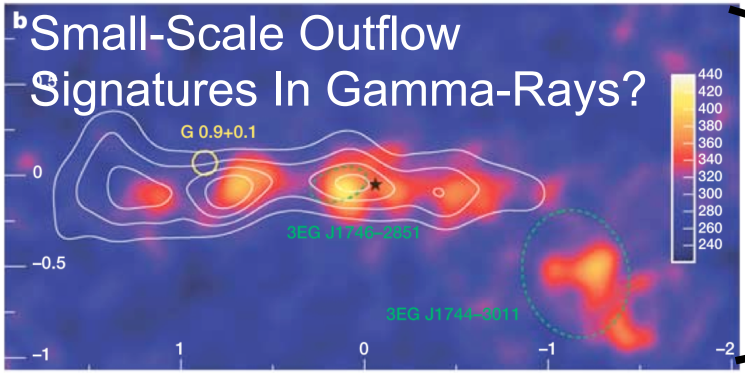
$$\boldsymbol{\dot{E}_{\rm wind} \approx 3 \times 10^{40}\ \mathrm{erg\ s^{-1}}}$$

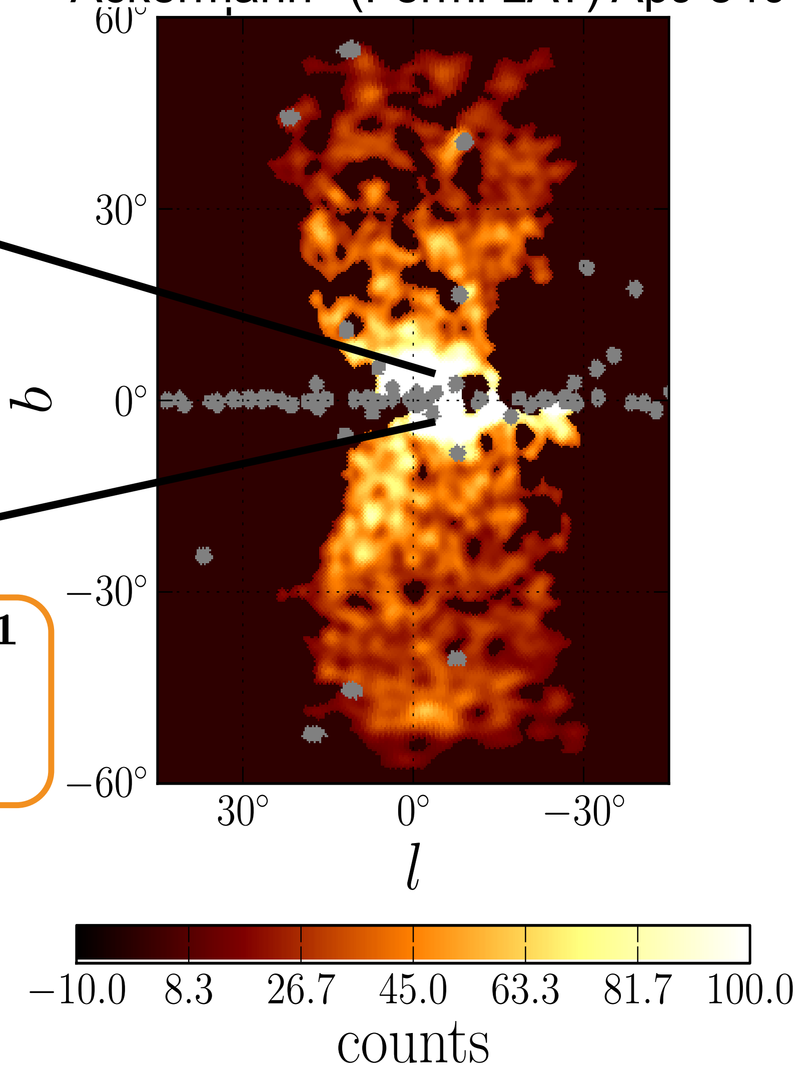
Milky Way- Galactic Center Outflow

Fermi bubbles

Ackermann+ (Fermi LAT) ApJ 840 (2017)

Aharonian+, Nature, 439, 695 (2006)



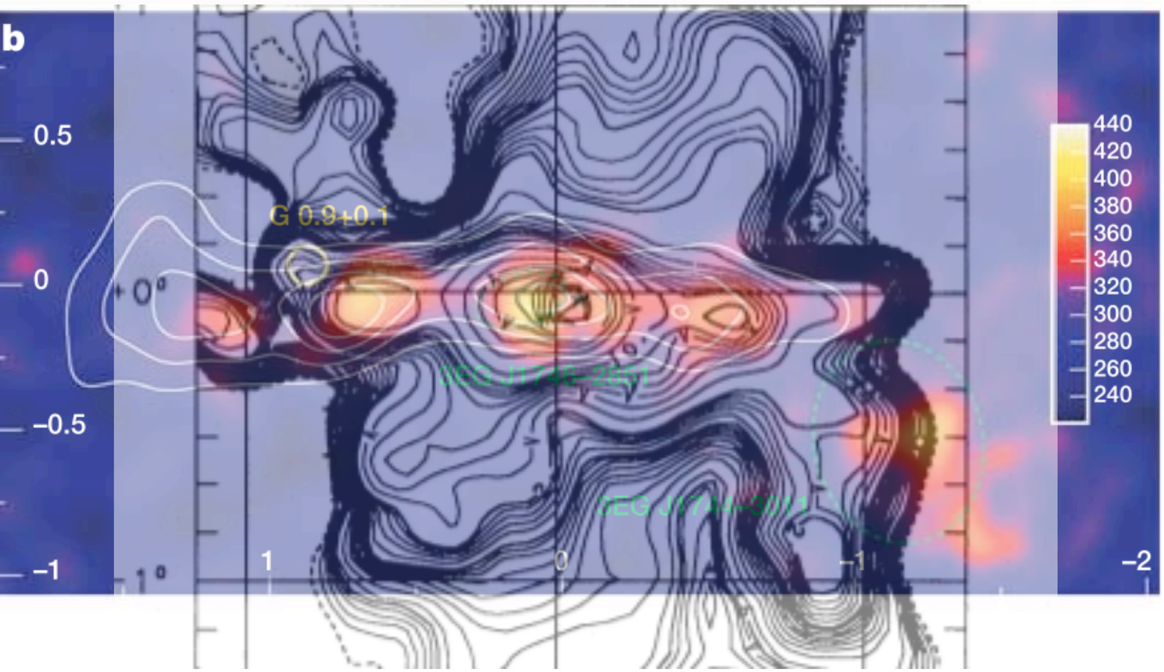


$$\mathbf{L}_\gamma(\mathbf{1\ TeV}) \approx \mathbf{5 \times 10^{34}\ erg\ s^{-1}}$$

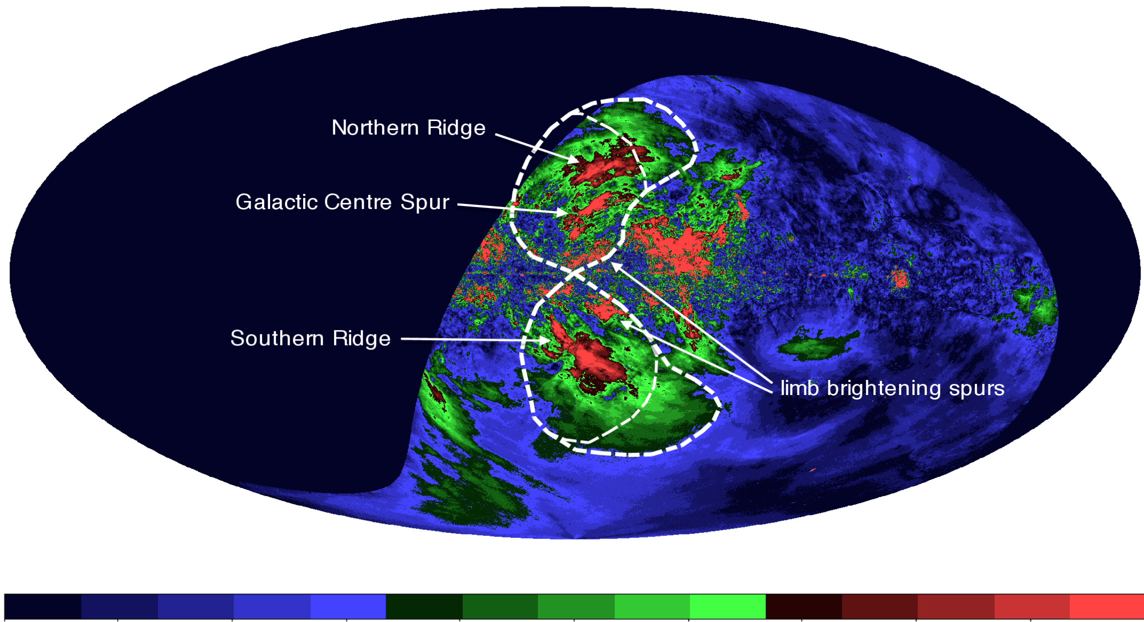
$$\mathbf{L}_\gamma^{\mathbf{IR}} \approx \mathbf{10^{42}\ erg\ s^{-1}}$$

Milky Way- Radio + Gamma-Rays

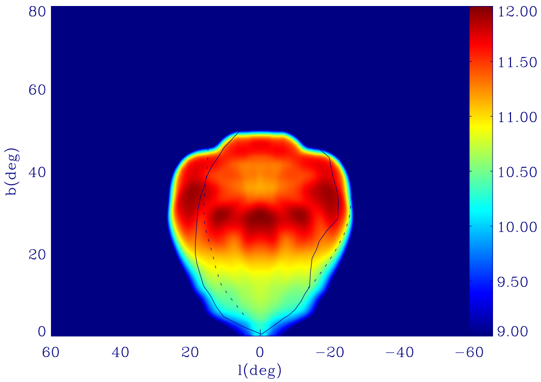
Small scales- morphologies are strikingly similar



Large scales- morphologies are less similar (east-west asymmetry)



Leptonic Bubbles?



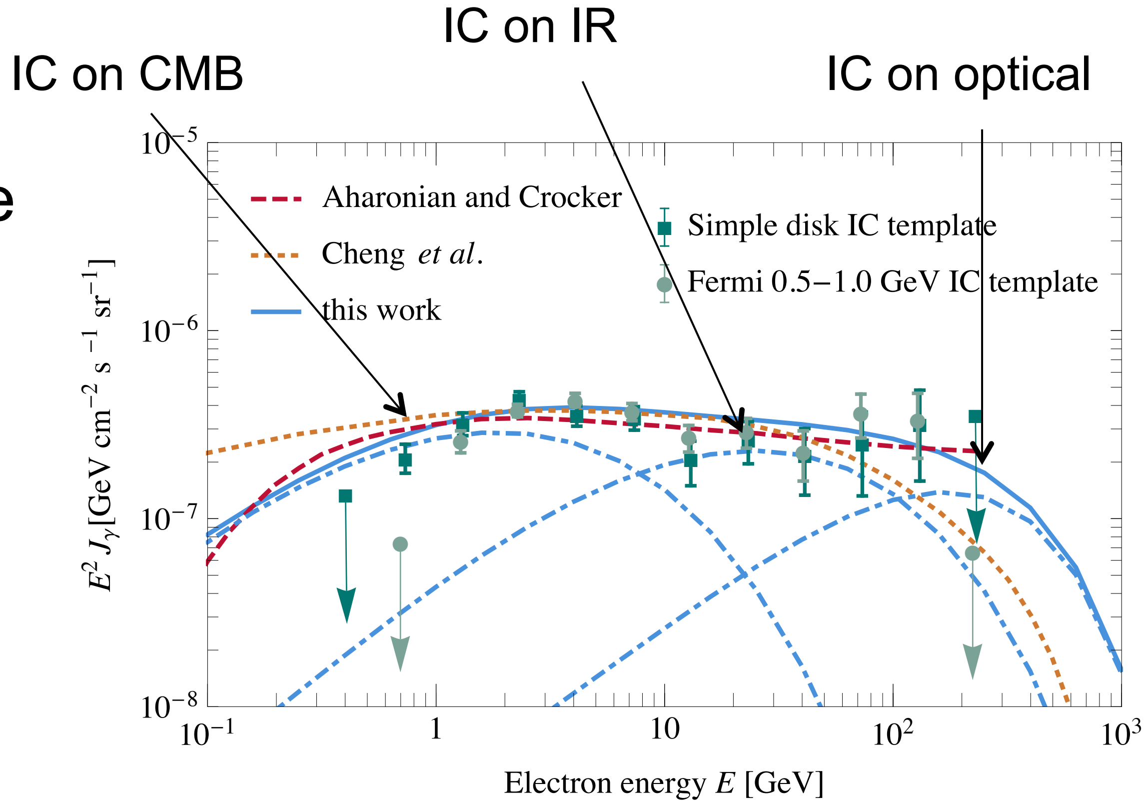
High energy electrons vs expansion velocity

- 1 TeV electrons => age < 1 Myr
- 10 kpc size => expansion velocity ~ 10,000 km/s

(ie. larger than the speed of sound). Is also larger than inferred velocities from observation.

Yang+, ApJ 761 (2012)

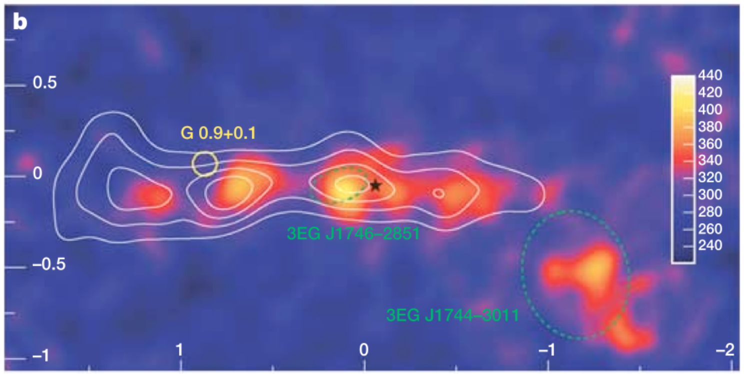
Reacceleration of electrons inside the Fermi bubbles?
Acceleration above TeV energies via reacceleration beyond expectations put forward



Mertsch+, PRL **107** (2011) 091101

DESY.

Hadronic Bubbles?

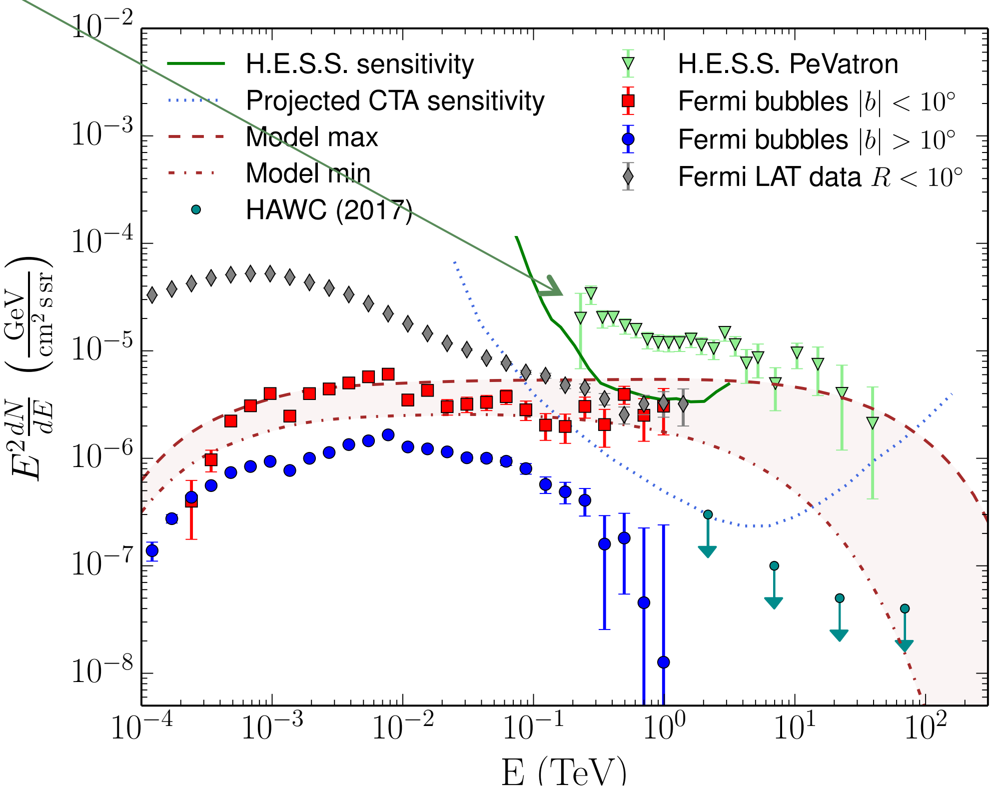


Favours a centrally fed outflow scenario from CMZ, for which gamma-ray emission is expected to be hadronically powered.

Low latitude bubble spectrum sits close to (smaller scale) energy flux level seen by HESS

A hadronic origin demands the presence of extended distribution of target gas

Adapted from Ackermann+ ApJ 840 (2017)



Hot Gas Out in the Halo

Both Suzaku and Chandra X-ray observations of bright AGN (eg. Mkr 501, PKS 2155, NGC 3783) indicate the presence of a hot local absorber with mass:

$$M \approx 10^{11}\ M_{\odot}$$

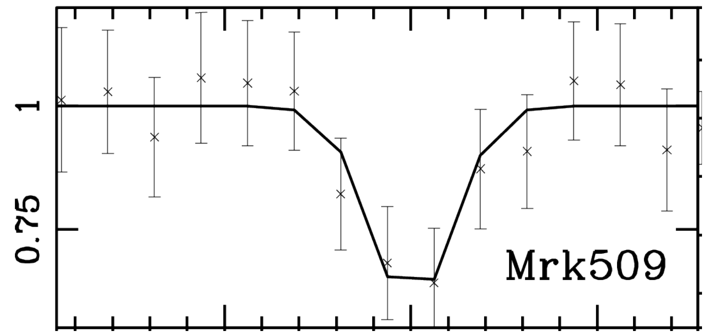
Inside a sphere of size

$$R \approx 100\ \mathrm{kpc}$$

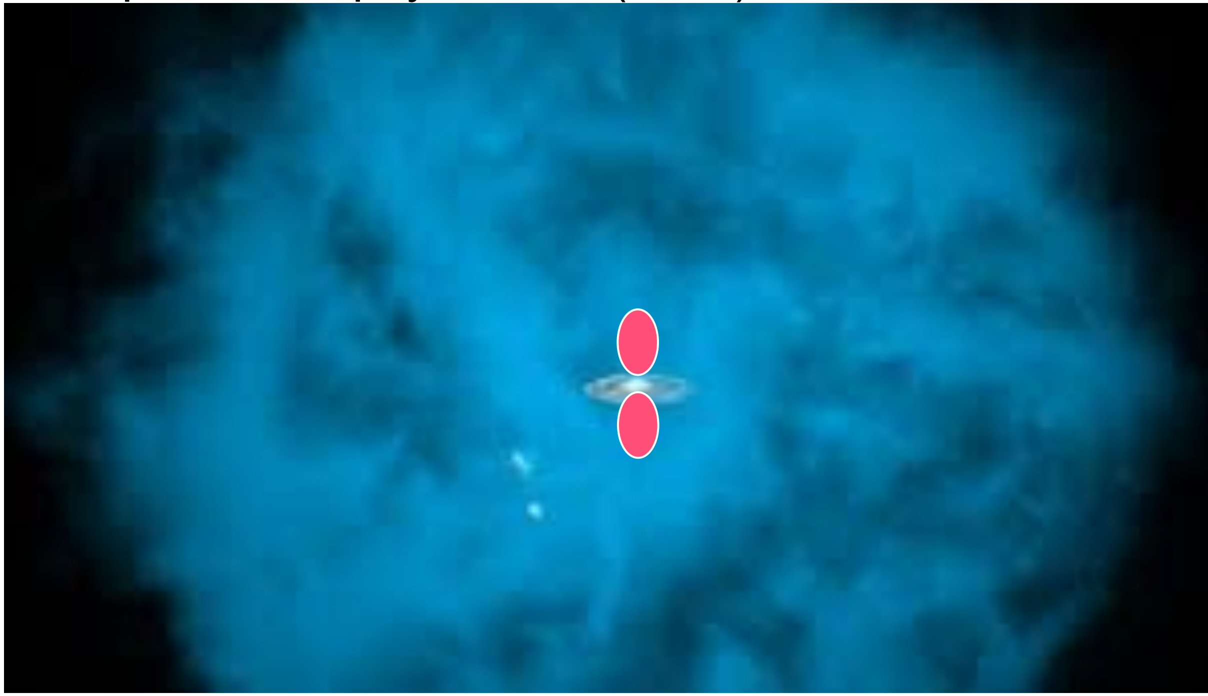
Gives a mean density of this gas of

$$n_p \approx 10^{-3}\ \mathrm{cm}^{-3}$$

$$kT \approx 140\ \mathrm{eV}$$



Gupta+, Astrophys.J. 756 (2012) L8



Nakashima+, Astrophys. J. 862, 1 (2018)

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Lowest Density that Still Allows Hadronic Calorimetry

$$\mathbf{t_{pp} = 10^{10} \left(\frac{3 \times 10^{-3}\ cm^{-3}}{n_p} \right)\ yrs}$$

Diffusive Escape

$$\mathbf{t_{diff} = 3 \times 10^{9} \left(\frac{R}{100\ kpc} \right)^{2} \left(\frac{10^{30}\ cm^{2}\ s^{-1}}{D} \right)\ yrs}$$

Advective Escape

$$\mathbf{t_{adv} = 3 \times 10^{9} \left(\frac{R}{100\ kpc} \right) \left(\frac{30\ km\ s^{-1}}{v_{adv}} \right)\ yrs}$$

CR Propagation into the Halo

Transport Equation

Diffusion

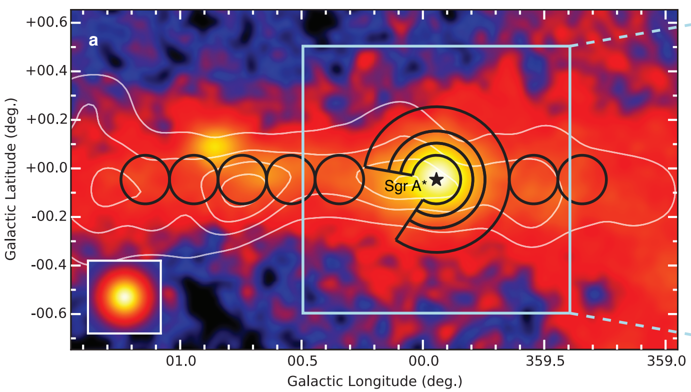
Energy losses

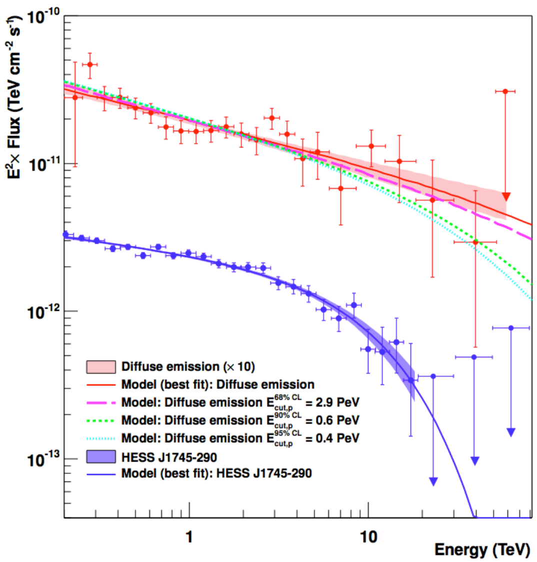
$$\frac{\partial}{\partial t}\mathbf{n(p,x,t)} = \nabla\cdot\mathbf{D}\nabla\mathbf{n(p,x,t)} - \nabla\cdot\mathbf{v_{adv}n(p,x,t)} - \frac{\mathbf{n(p,x,t)}}{\tau_{\mathbf{pp}}} + \mathbf{Q(p,x,t)}$$

Advection

Source term

HESS Coll., Nature 531 (2016) 476





$$\mathbf{p_{max} > PeV}$$

$$\mathbf{Q(p) \propto p^{-2}}$$

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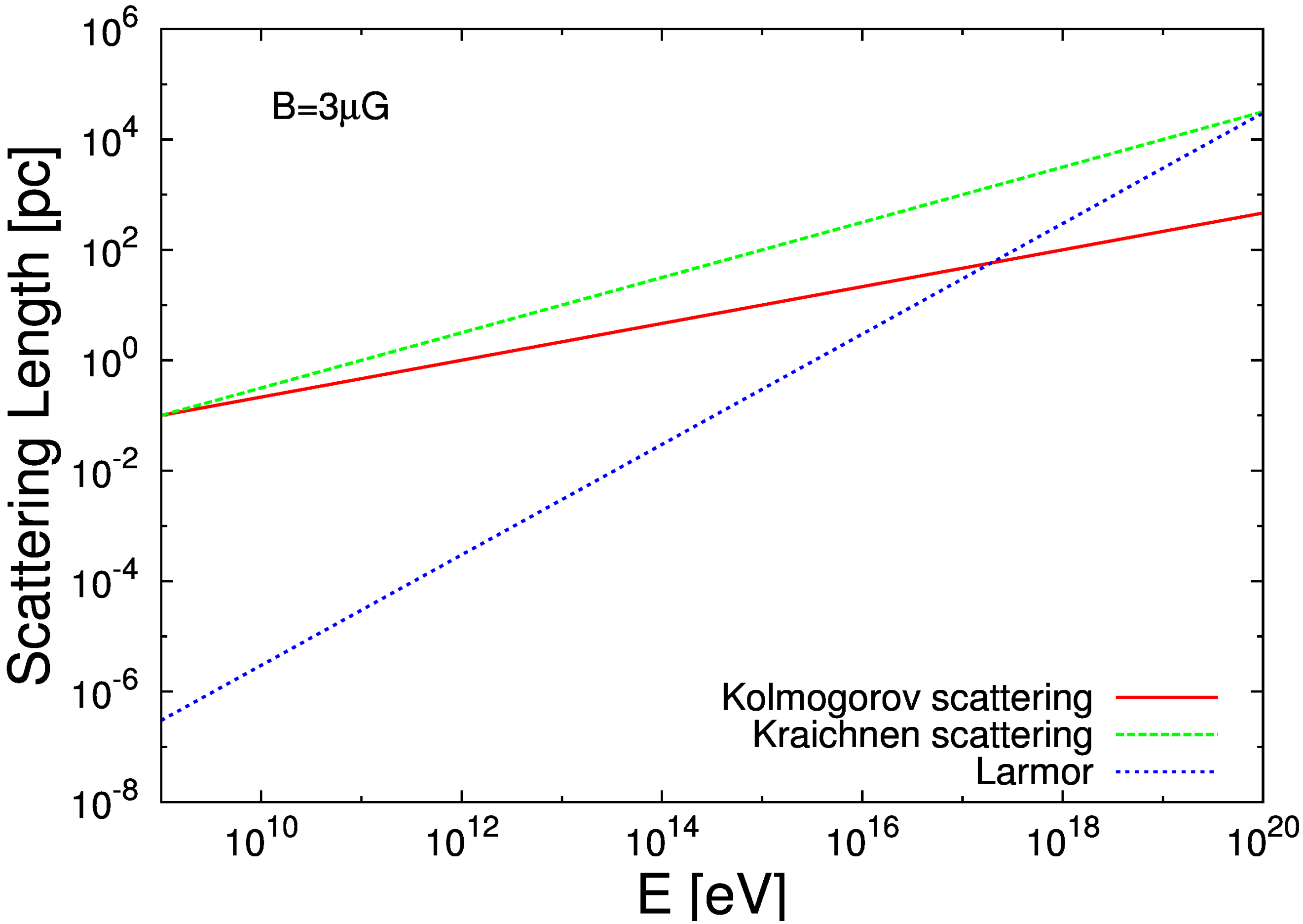
Cosmic Rays Diffusing in Outflow

$$\frac{\partial}{\partial \mathbf{t}}\mathbf{n}(\mathbf{p},\mathbf{x},\mathbf{t}) = \nabla \cdot \mathbf{D}\nabla\mathbf{n}(\mathbf{p},\mathbf{x},\mathbf{t}) - \nabla \cdot \mathbf{v_{adv}}\mathbf{n}(\mathbf{p},\mathbf{x},\mathbf{t}) - \frac{\mathbf{n}(\mathbf{p},\mathbf{x},\mathbf{t})}{\tau_{\mathbf{pp}}} + \mathbf{Q}(\mathbf{p},\mathbf{x},\mathbf{t})$$

$$\mathbf{D} = \mathbf{D_0}\left(\frac{\mathbf{E}}{\mathbf{E_0}}\right)^{\mathbf{2-q}}$$



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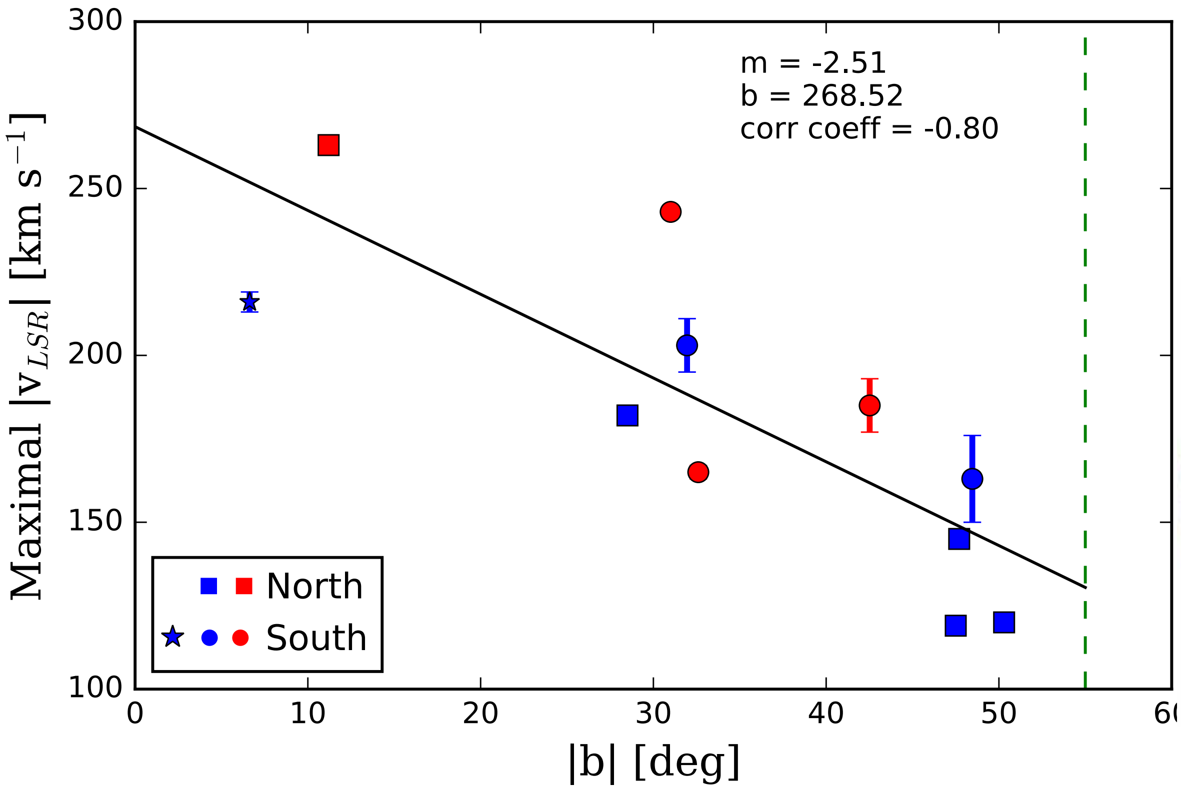
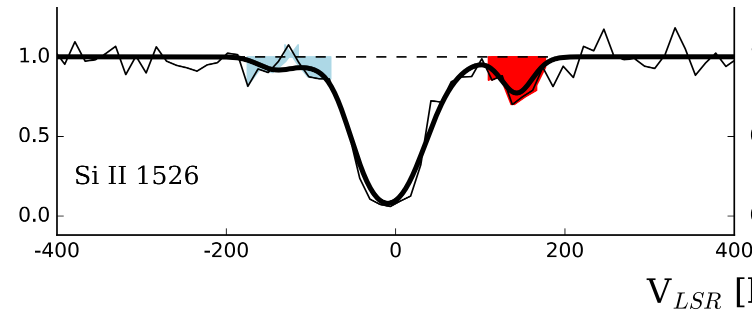
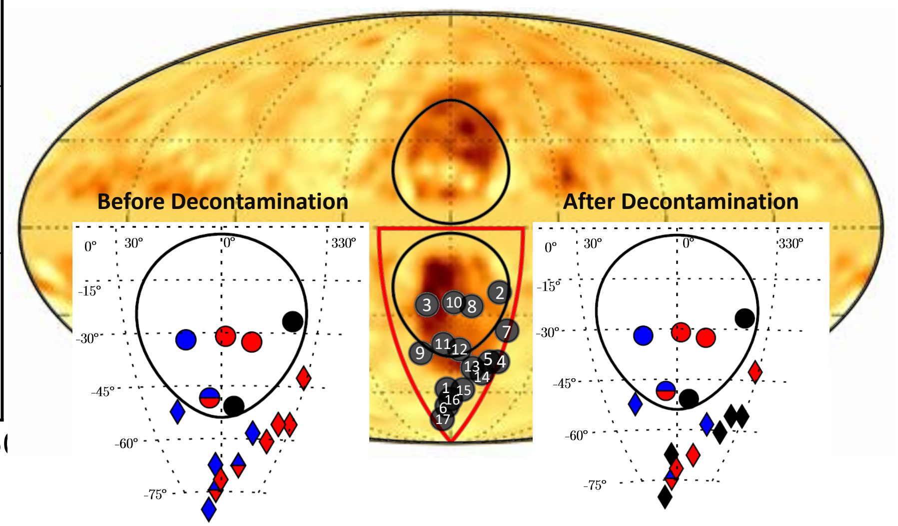
Milky Way- Velocity Profile of Central Chimney



Karim+, Ap.J. 860 (2018)





Nuclear outflow rates:

MW
$> \mathbf{0.2\ M_\odot\ yr^{-1}}$

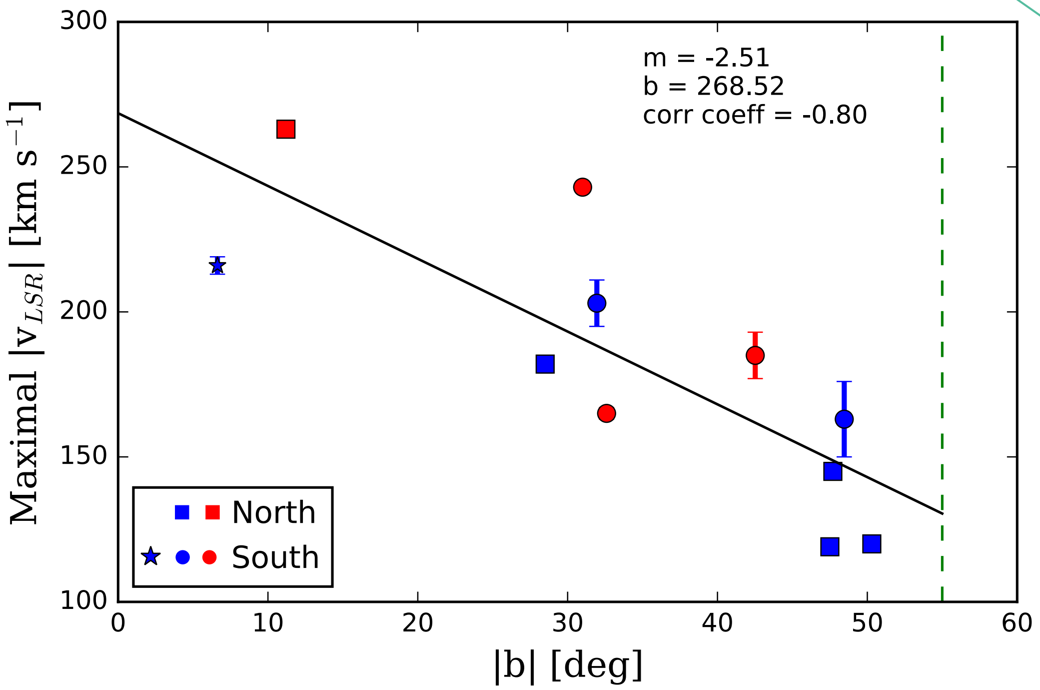
NGC 253:
$> \mathbf{3\ M_\odot\ yr^{-1}}$

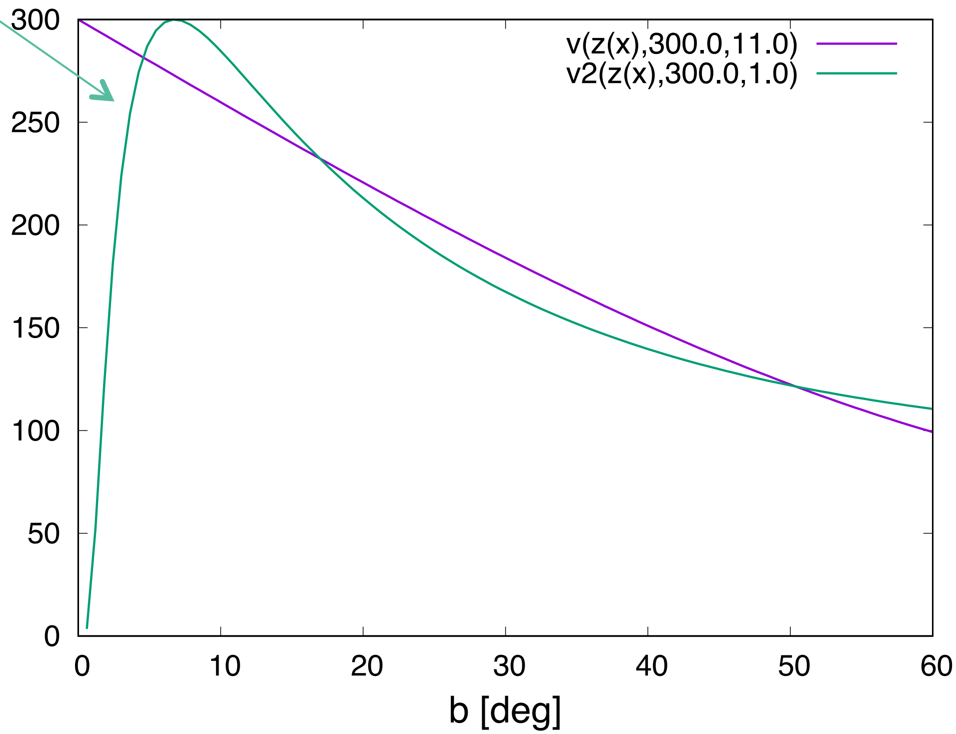
Bordoloi ApJ 834 191 (2017)   Bolatto+, Nature Letter 12351 (2013)

Cosmic Rays Advecting in Outflow

$$\frac{\partial}{\partial \mathbf{t}}\mathbf{n}(\mathbf{p},\mathbf{x},\mathbf{t}) = \nabla\cdot\mathbf{D}\nabla\mathbf{n}(\mathbf{p},\mathbf{x},\mathbf{t}) - \nabla\cdot\mathbf{v_{adv}}\mathbf{n}(\mathbf{p},\mathbf{x},\mathbf{t}) - \frac{\mathbf{n}(\mathbf{p},\mathbf{x},\mathbf{t})}{\tau_{\mathbf{pp}}} + \mathbf{Q}(\mathbf{p},\mathbf{x},\mathbf{t})$$

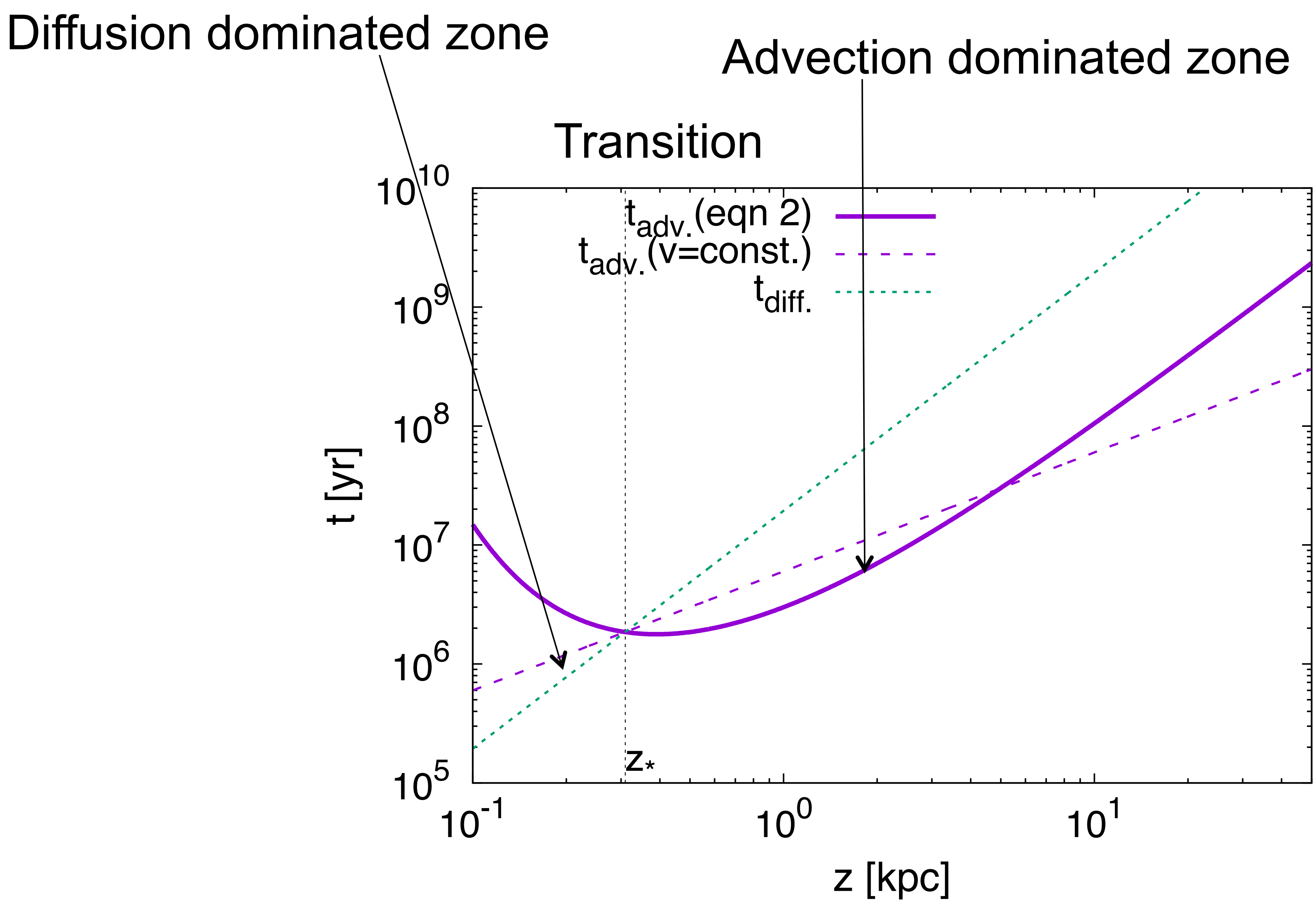
$$\mathbf{v_z} = \mathbf{v}_{\max}\frac{\mathbf{2}}{(\mathbf{1}+\mathbf{z}/\mathbf{d})}\mathbf{e}^{\frac{1}{2}(1-\frac{\mathbf{d}}{\mathbf{z}})}$$





Note- degeneracy exists between v profile and target mass profile in these calculations

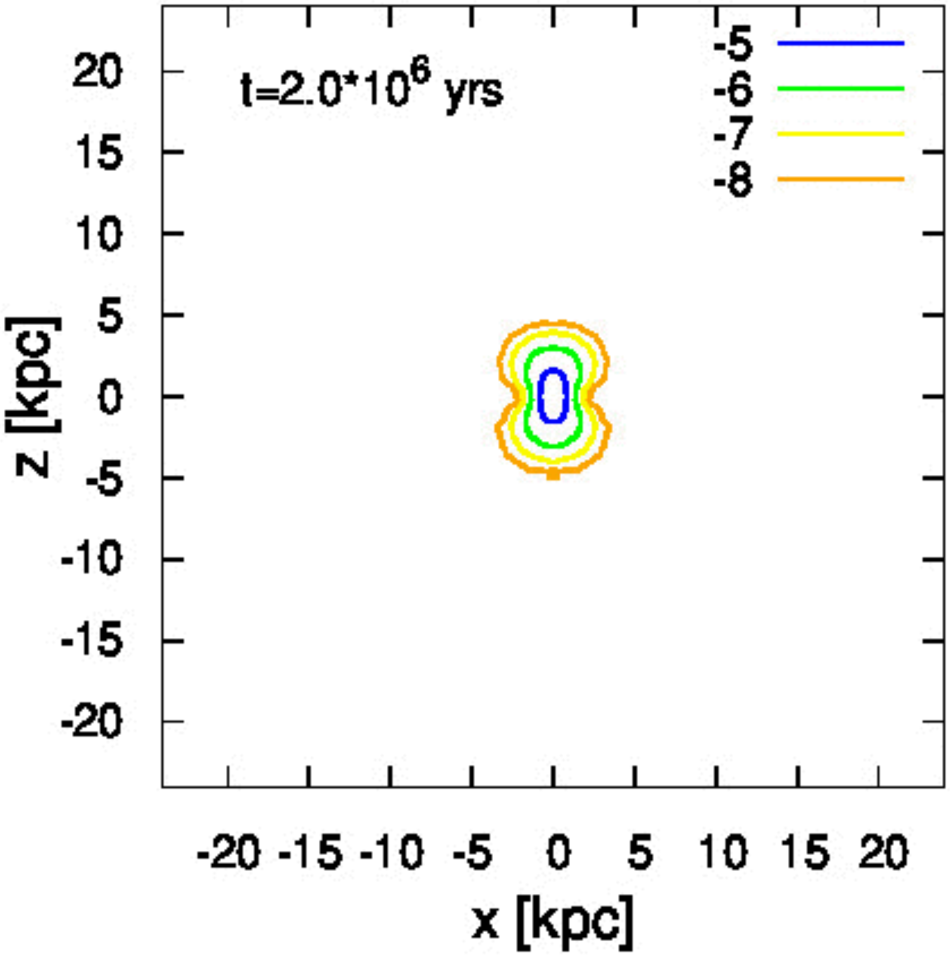
Diffusion-Advection Competition

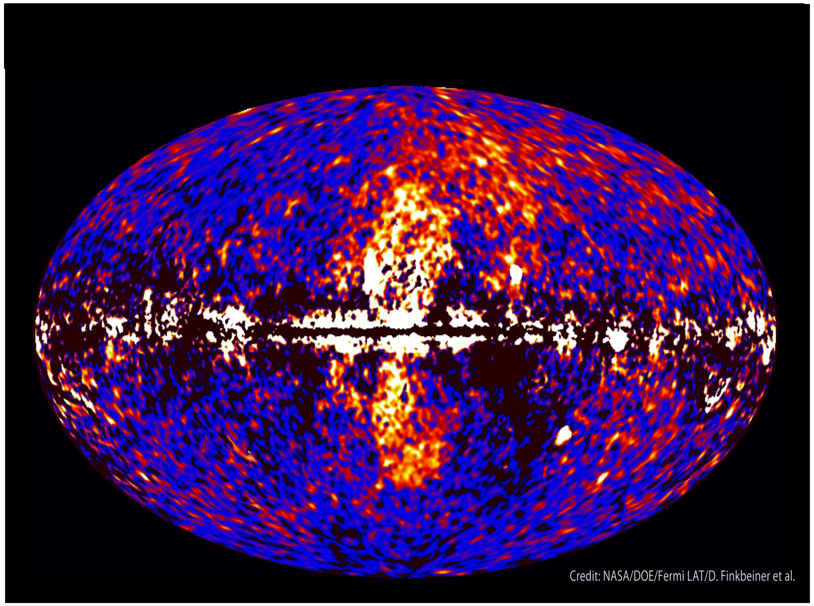


Note, position of z_* is energy dependent, resulting in an energy dependent halo size!

Gamma-Rays from the Bubbles and Beyond!

Evidence for advective cosmic ray transport in the Galaxy?





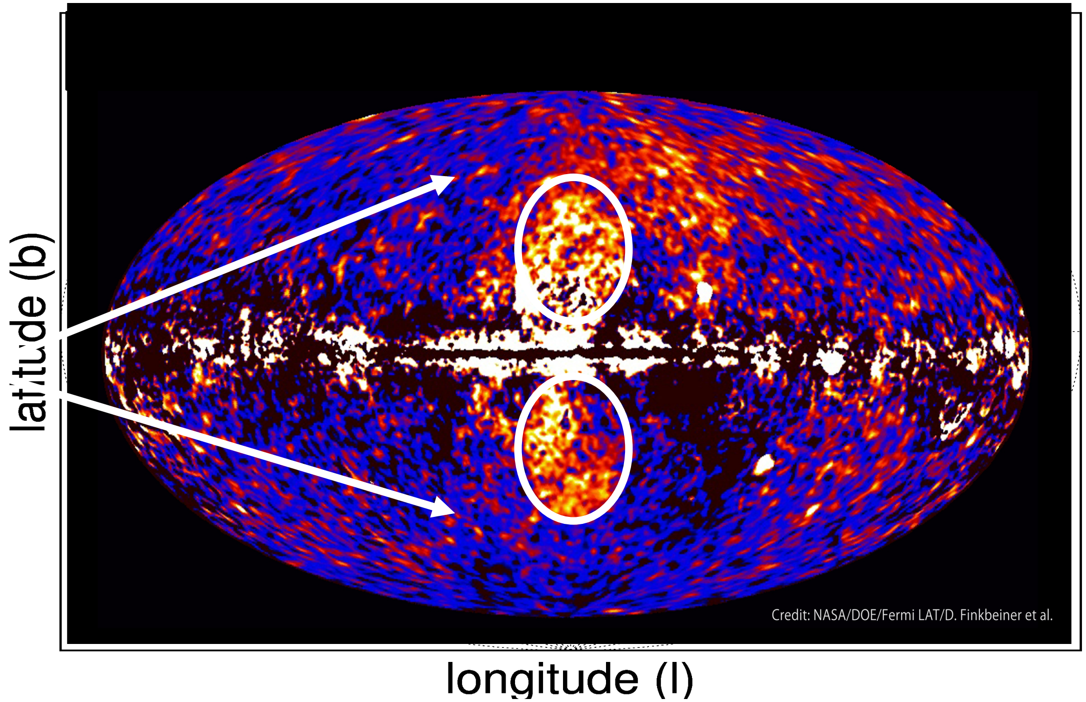
$$\mathbf{n_p \approx 3 \times 10^{-3}\ cm^{-3}}$$

Taylor+, *Phys.Rev.D* 95 (2017) 2, 023001
Liu+, ApJ Vol. 871, No. 1 (2019)

Neutrino from Beyond the Fermi Bubbles?

Total gamma-ray/neutrino emission dominated by regions beyond the bubbles

~9 yr^{-1}



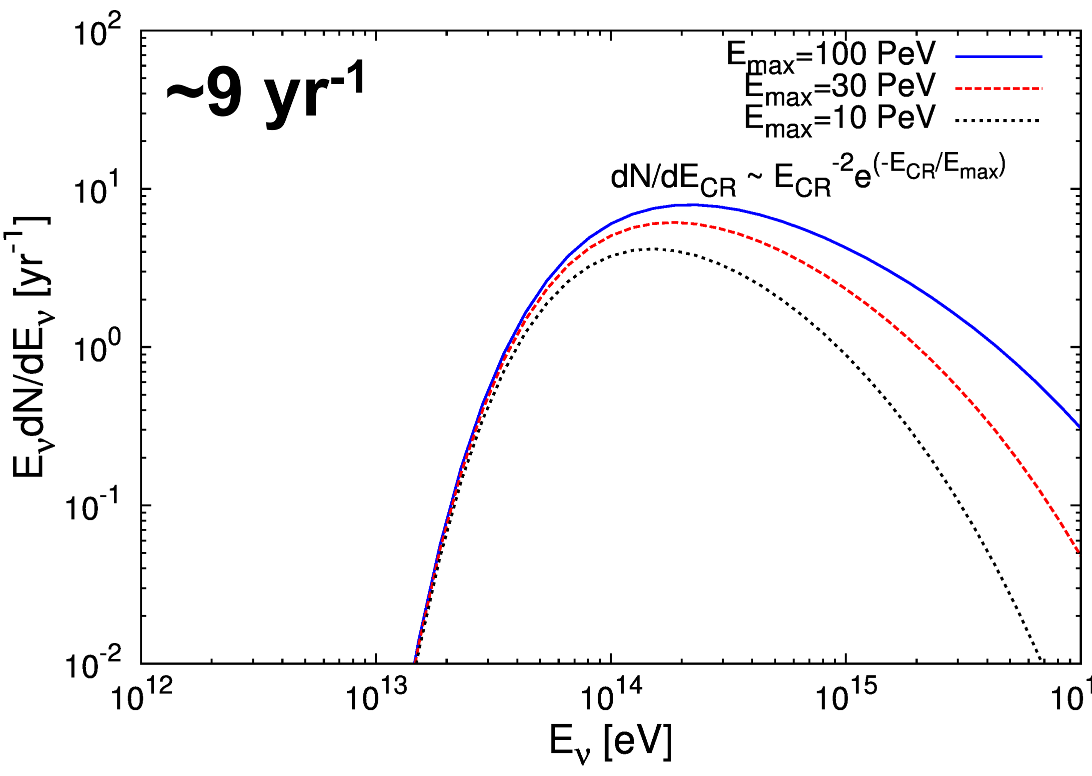
$$\mathbf{L_\nu \approx 8 \times 10^{38}\ erg\ s^{-1}}$$

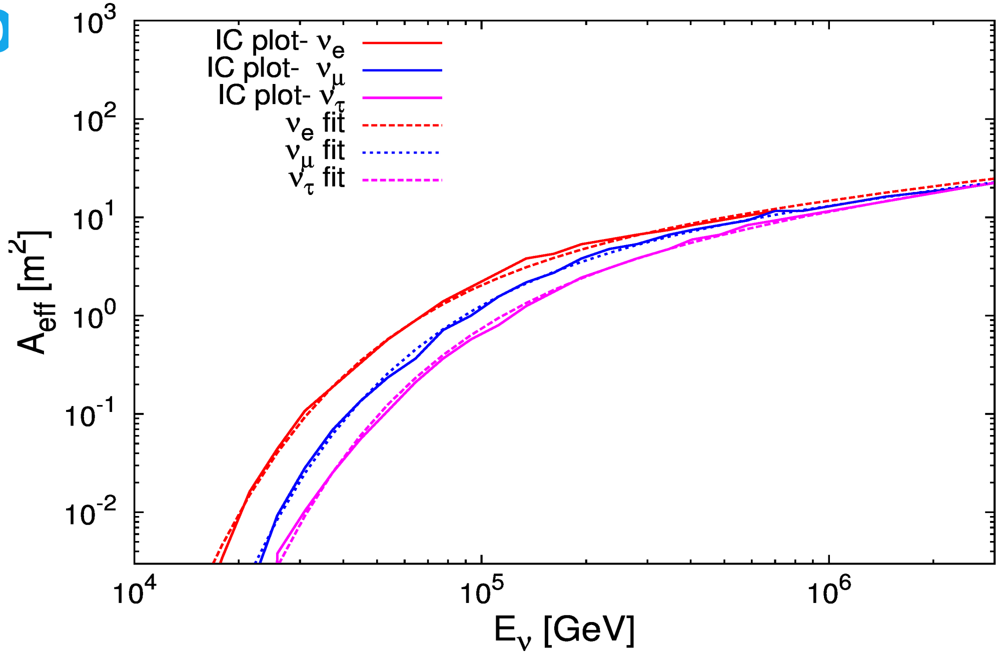
$$\mathbf{L_\nu \approx \left(\frac{t_{adv}}{t_{pp}}\right) L_p}$$

$$E_\gamma F_\gamma = \mathbf{1200\ eV\ cm^{-2}\ s^{-1}}$$

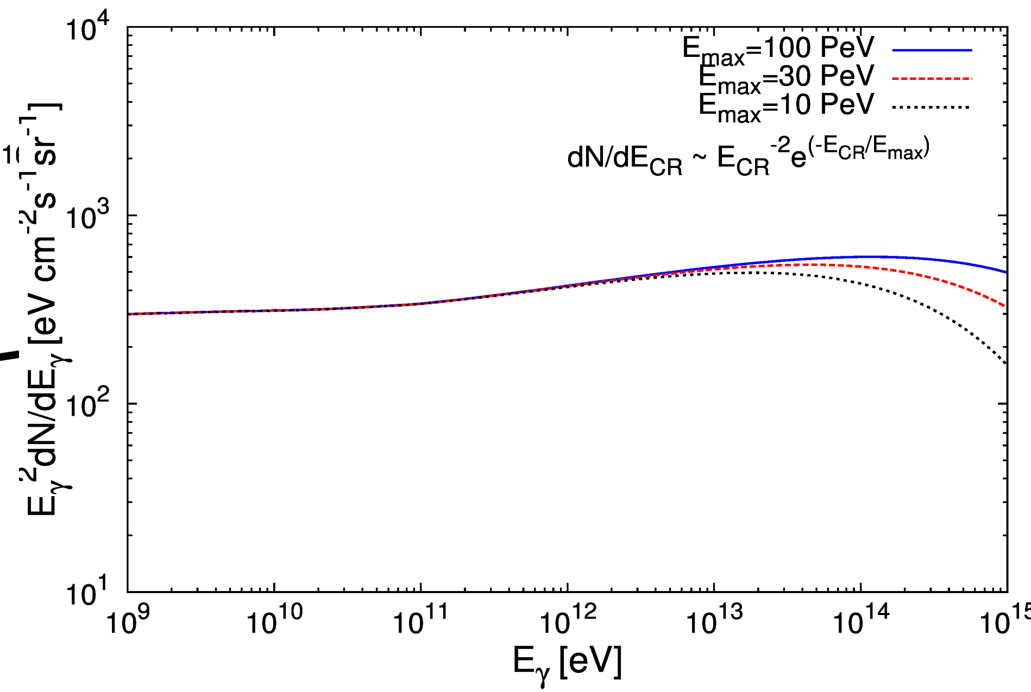
Required PeV luminosity to support this population is ~10^{40} erg s^{-1}

Beyond Fermi Bubble Neutrino Flux Detection with IceCub





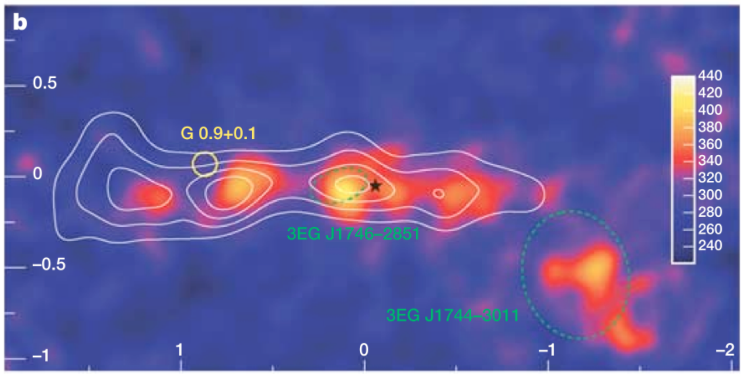
$$E_\gamma F_\gamma = 240 \text{ eV cm}^{-2} \text{ s}^{-1}$$



Potential Future Signatures

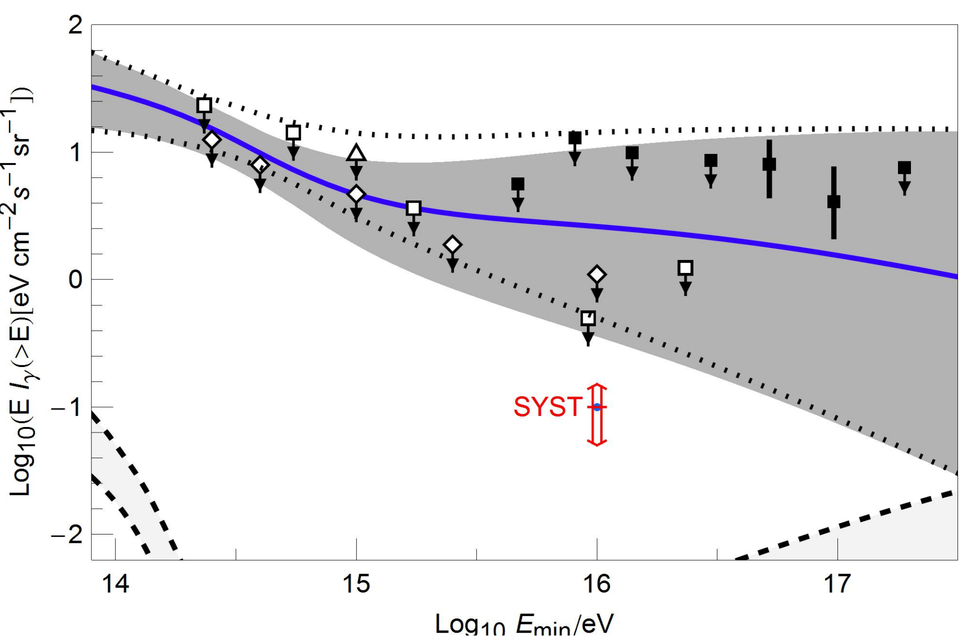
Bubble Chimney Base

Aharonian+, Nature, 439, 695 (2006)



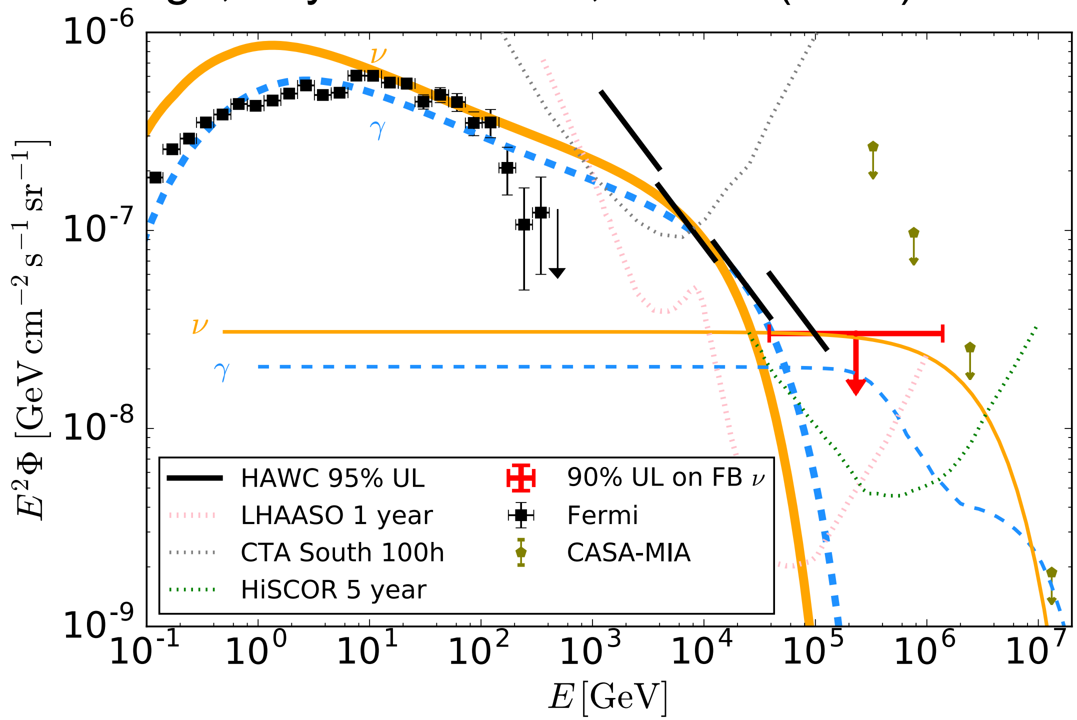
Beyond Bubble Emission

Kalashev+, JETP Letters 100 865-869 (2014)



Bubble Emission

Fang+, Phys. Rev. D 96,123007 (2017)



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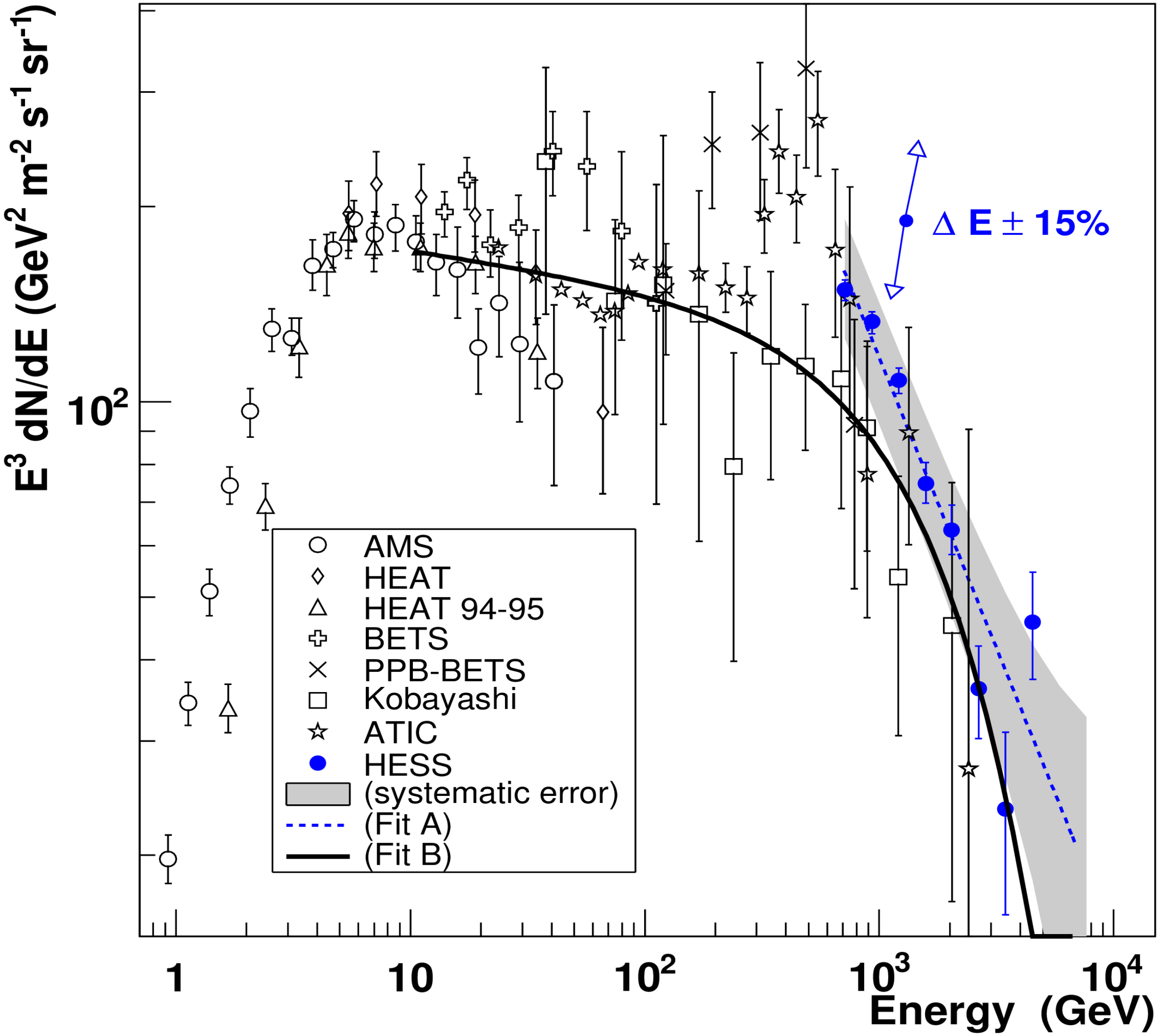
VHE Diffuse Electron Flux

$$E^2 \frac{dN}{dE} \approx 10^4 \left(\frac{E}{\text{TeV}}\right)^{-1.9} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$



If this continues, it falls below Fermi diffuse flux at ~10 TeV and IceCube diffuse flux level at ~20 TeV

HESS Coll., Phys.Rev.Lett. 101 (2008) 261104

Conclusions

- The fate of Galactic cosmic rays (and the nature of the extended Galactic halo out to the virial radius) remains unresolved

- Recent high energy observations have mounted evidence for Galactic outflow activity being relevant for cosmic ray transport

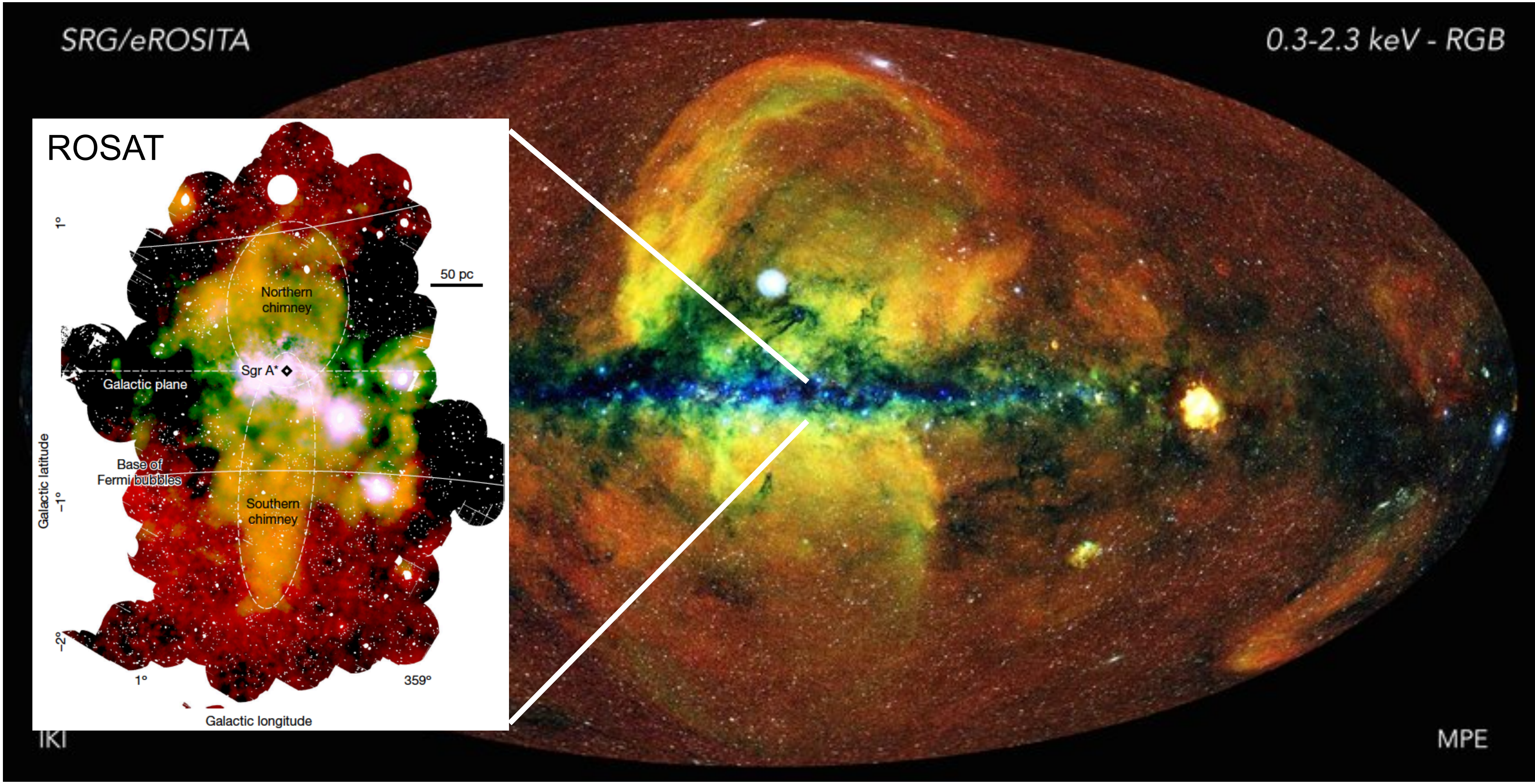
- The Galactic bubbles may originate from the interaction of cosmic rays, produced by the Galactocentric activity

- Additional such interactions beyond the Galactic bubbles are motivated. This emission can account for the >100 TeV IceCube neutrino flux detected

- High energy gamma-ray detectors will probe these signals in the near future, deepening our understanding of the extended Galactic halo

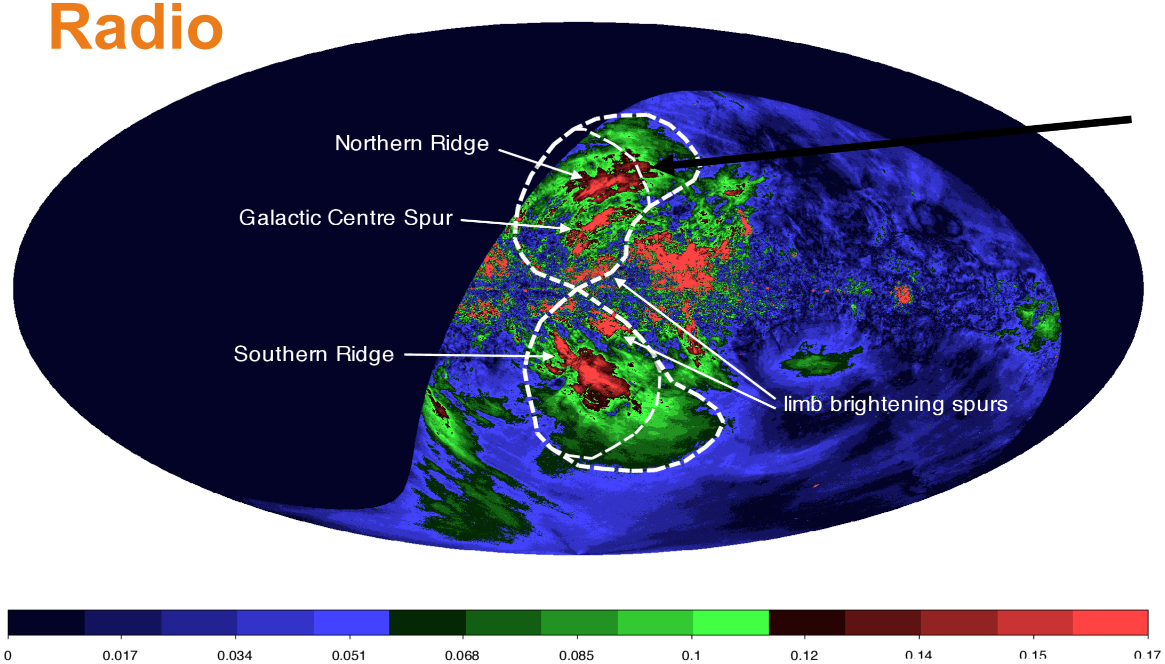
Extra Slides

Recent New (X-ray) Evidence of Outflow



Evidence of a Broader Scale Outflow?

Radio

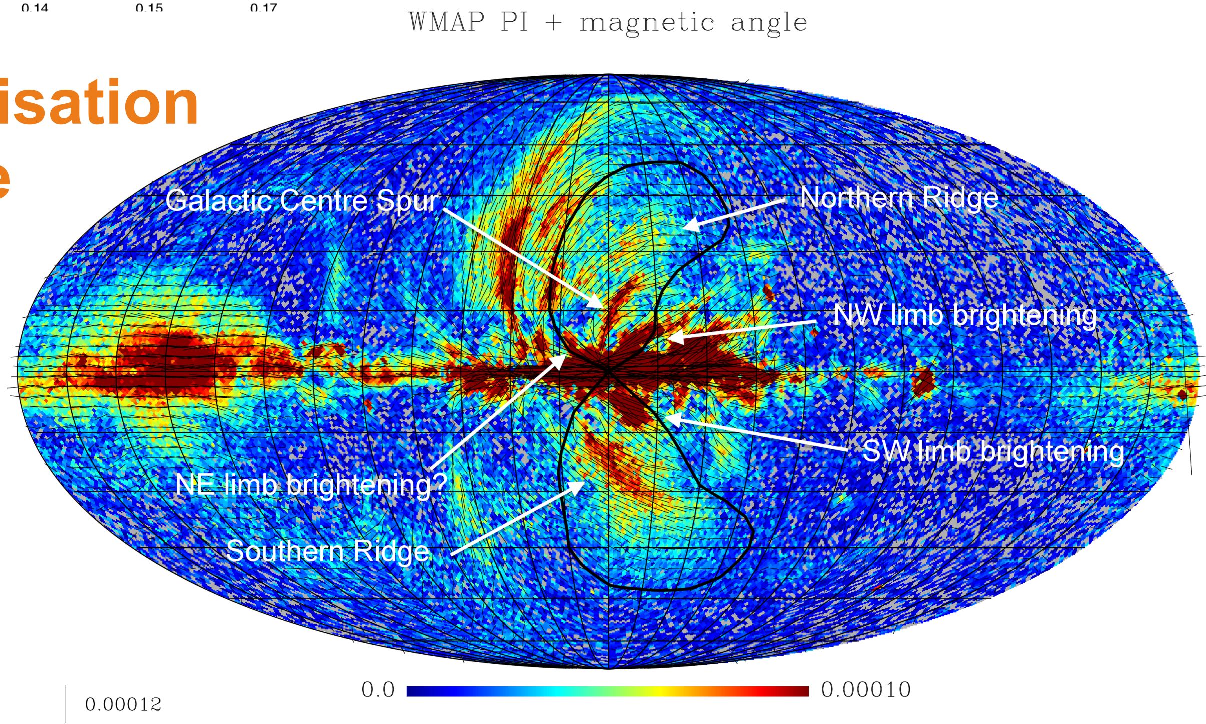


$\mathbf{2.3\ GHz}$

corresponding to

$\approx \mathbf{5\ GeV}$ electrons

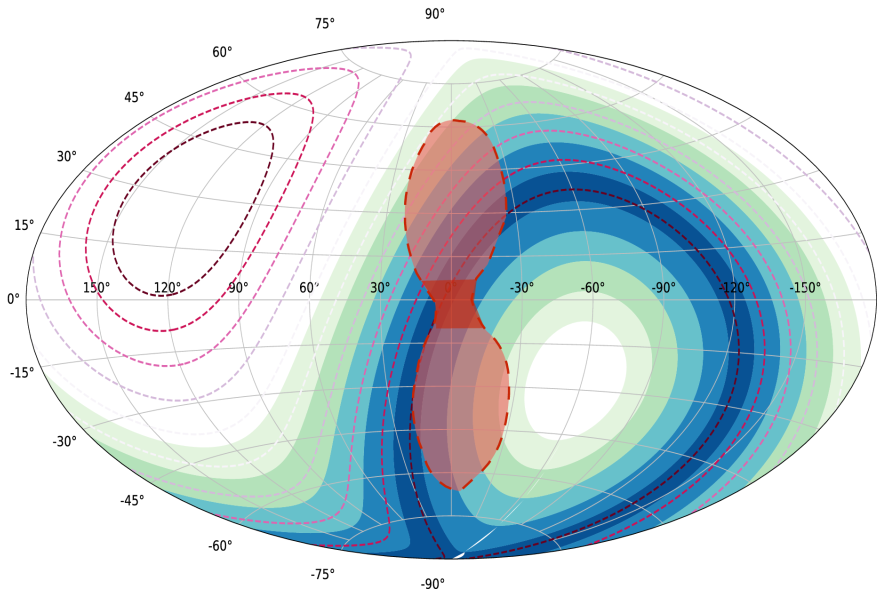
Polarisation Angle



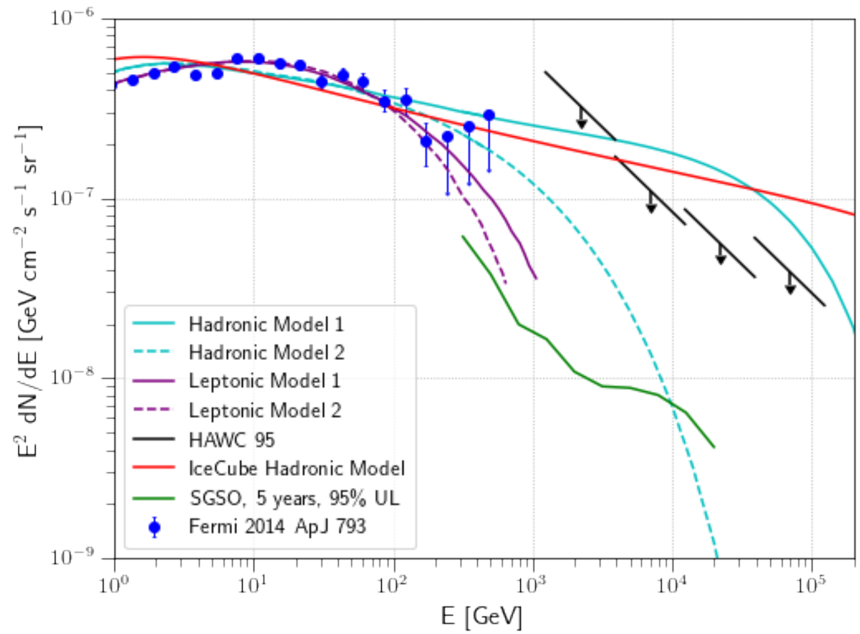
astro-ph/1301.0512

DESY.

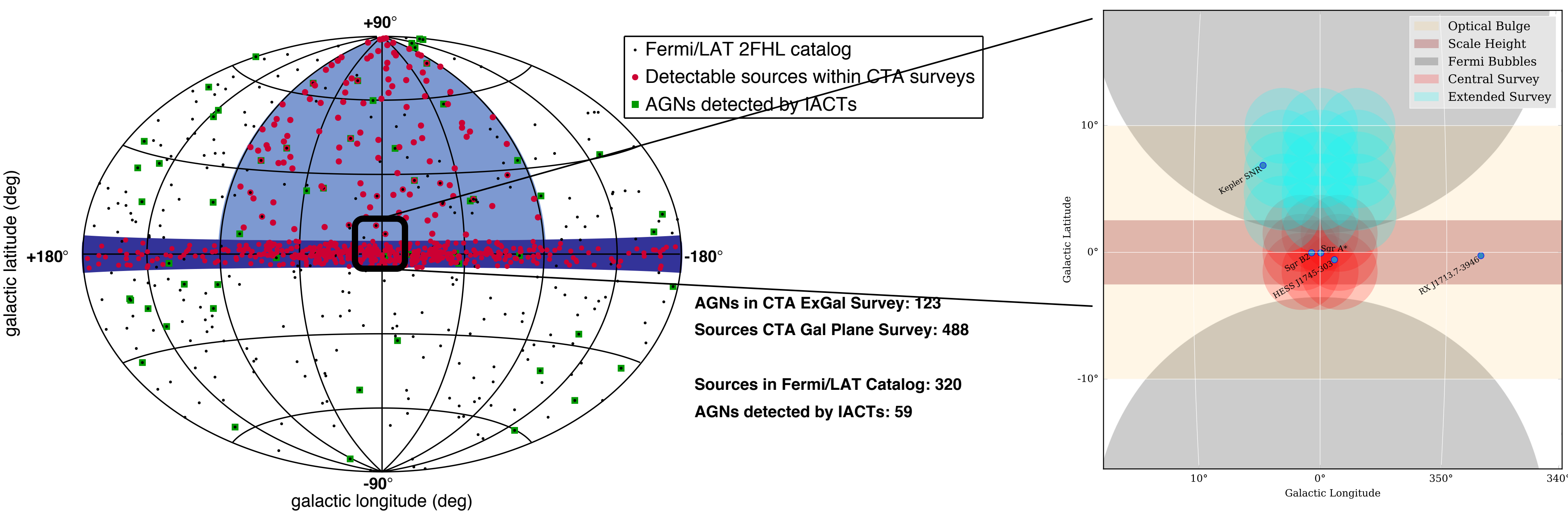
Upcoming Gamma-Ray Signatures



From SGSO white paper just submitted

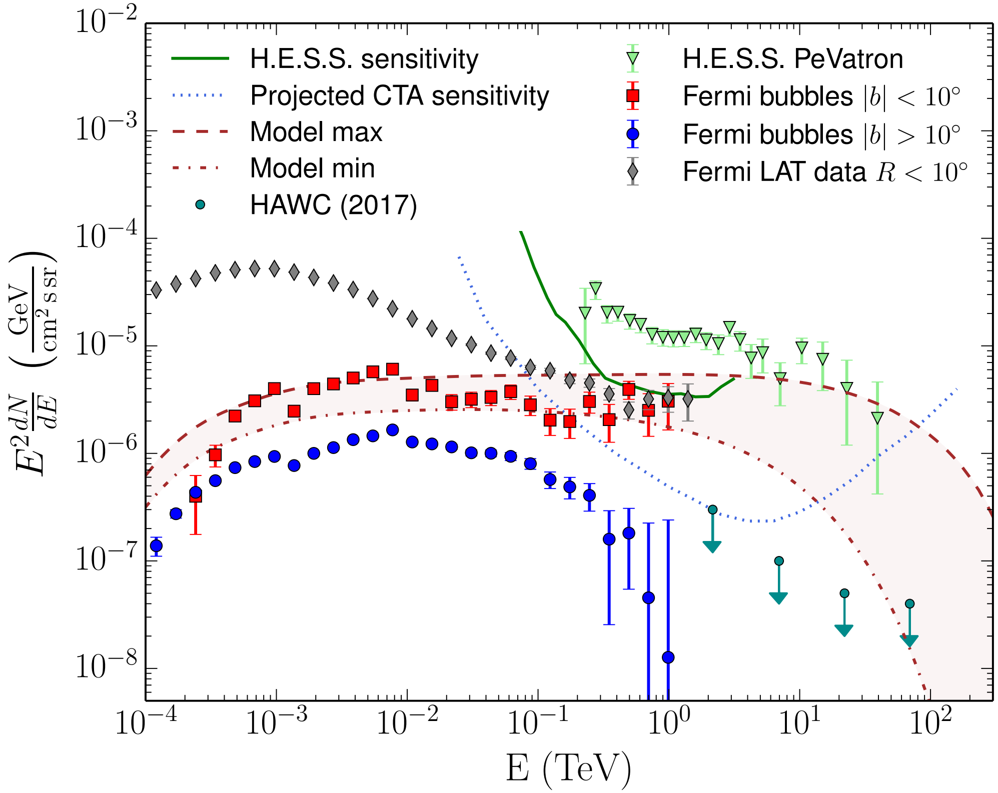


CTA KSP (**astro-ph/1709.07997**)



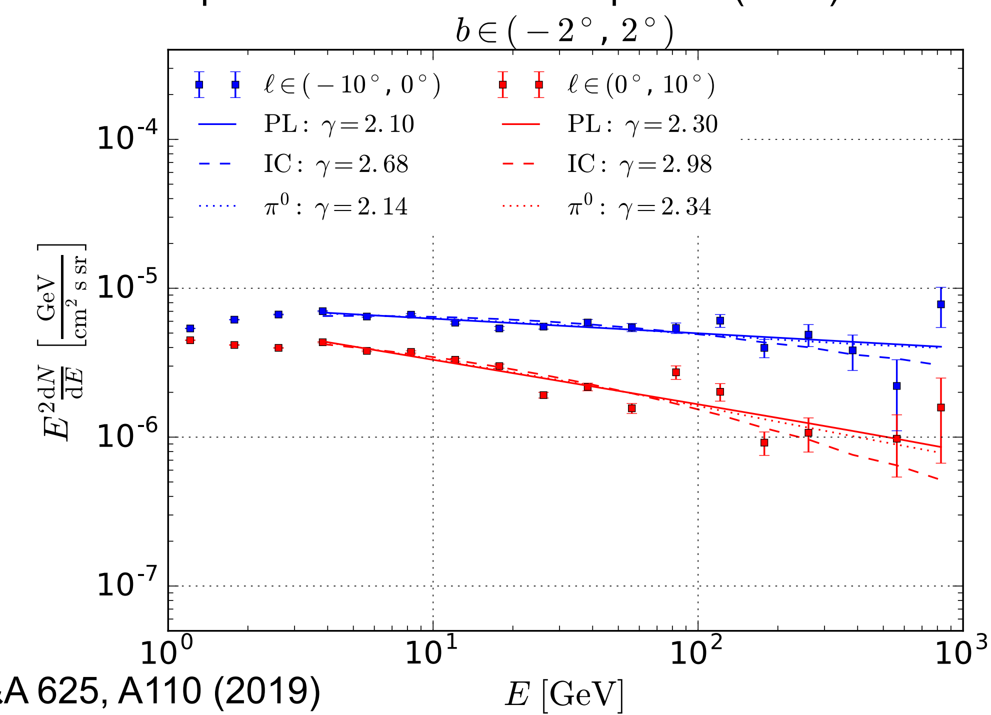
Recent Developments

No cutoff up to ~ 1 TeV for low latitude bubbles emission



Adapted from Ackermann+ ApJ 840 (2017)

An East-West spectral asymmetry in bubble emission appears to be seen



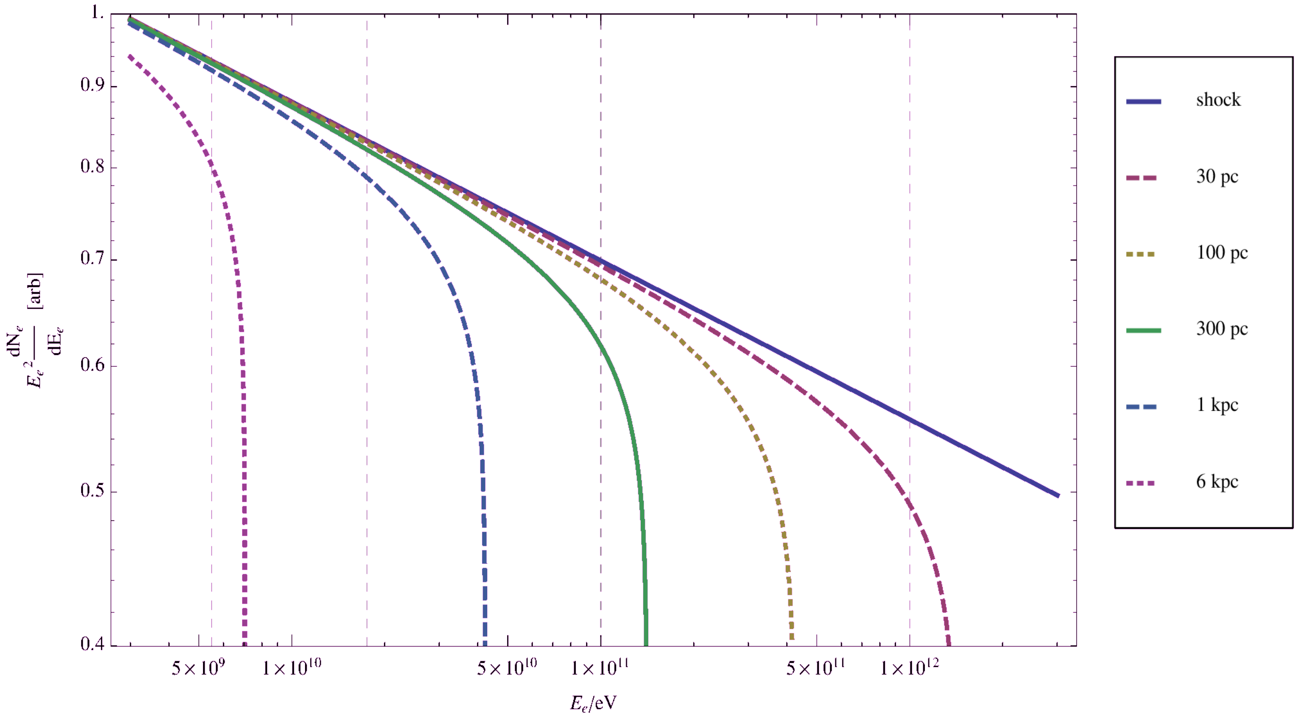
Malyshev+ A&A 625, A110 (2019)

DESY.

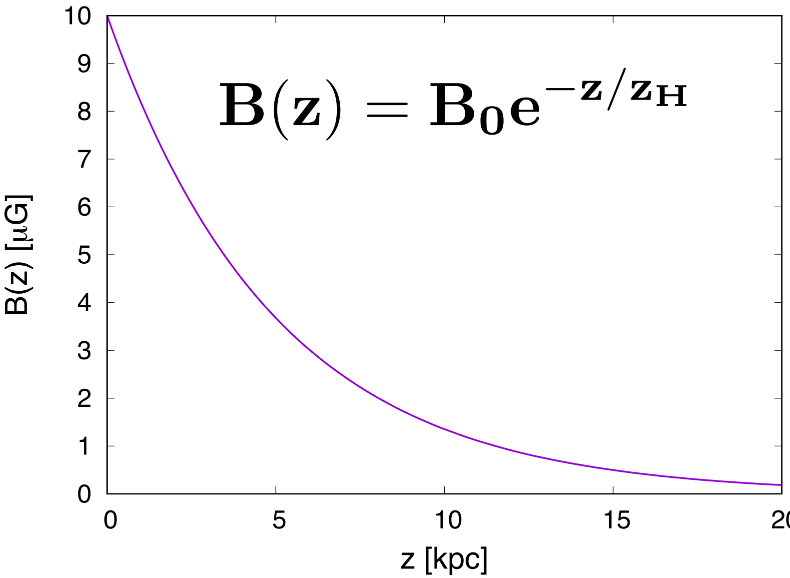
Electron Spectra within an Advective Outflow

$$\tau_e \approx 60 \left(\frac{5\ \mathrm{GeV}}{E_e}\right)\left(\frac{6\mu G}{B}\right)^2 \mathrm{Myr}$$

Electron Spectra at Different Heights Above Disk

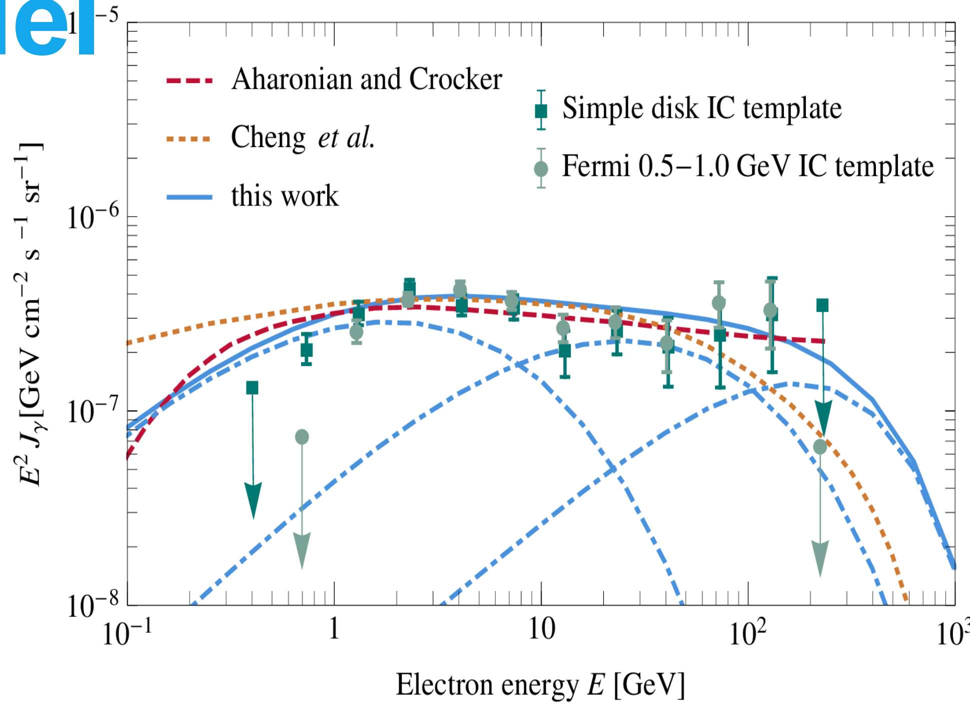


B-field Strength Profile

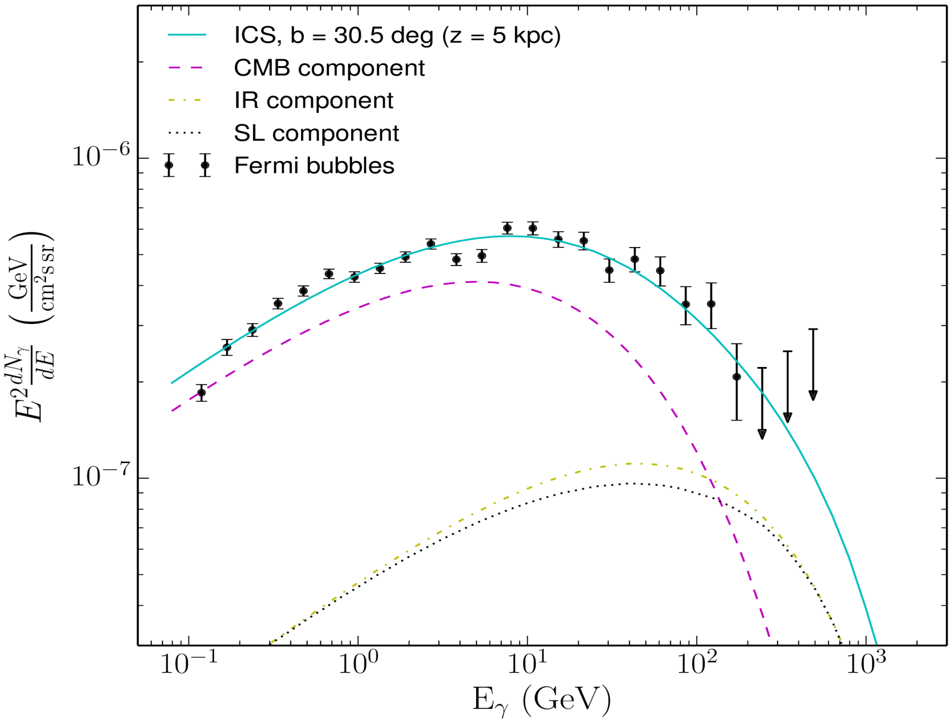


Crocker+, Ap.J. 808 (2015)

Electron Origin IC Model For Gamma-Rays



Mertsch et al.
astro-ph/1104.3585



Fermi Collab.
astro-ph/1407.7905

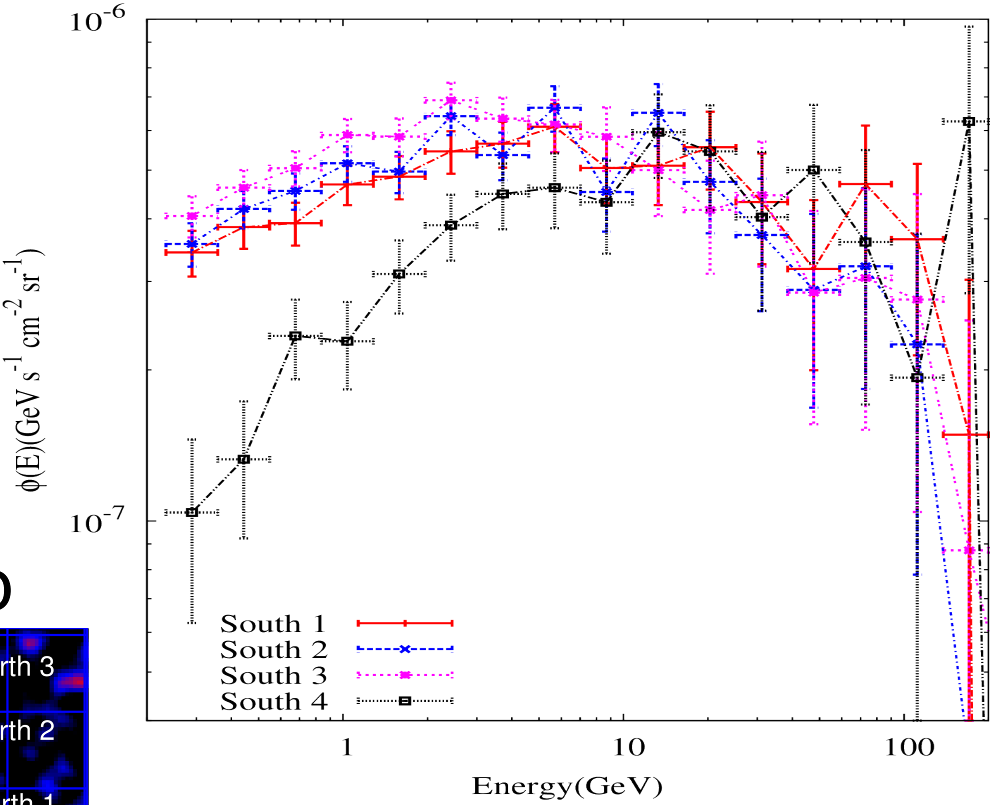
DESY.

Fermi Bubbles- Energy Spectrum

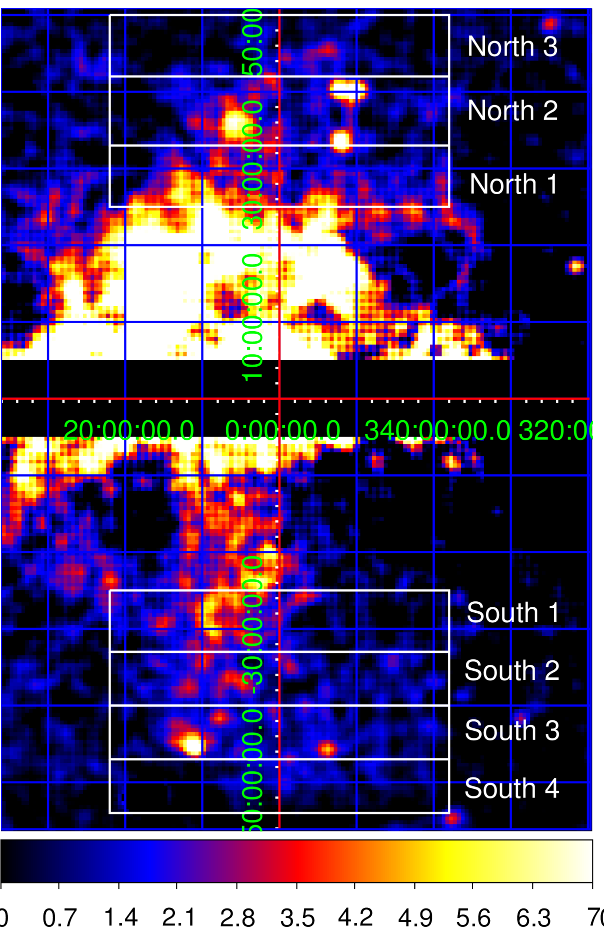
$$E_\gamma F_\gamma = 240\ \mathrm{eV\ cm^{-2}\ s^{-1}}$$

Yang et al. Astro-ph/1402.0403

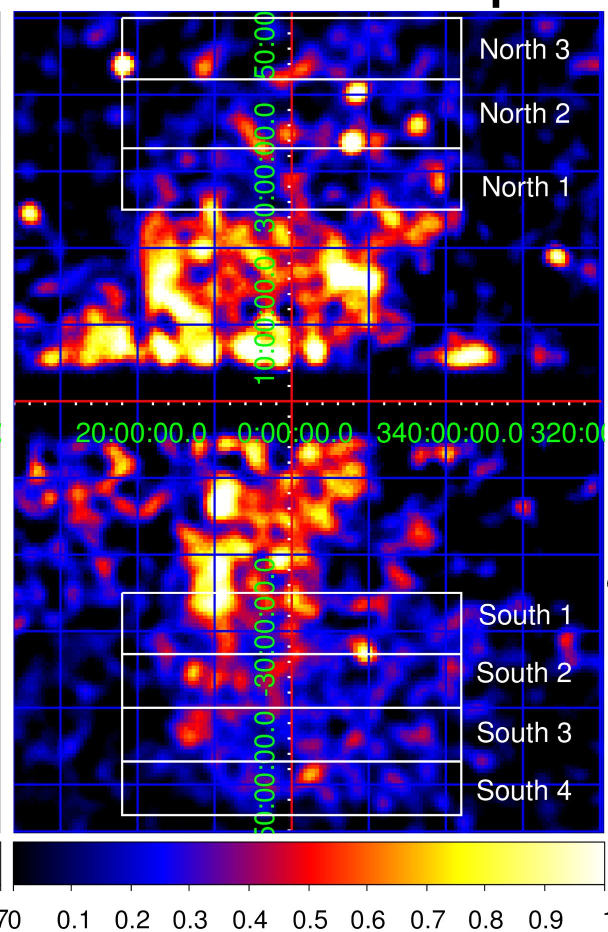
Selig et al. Astro-ph/1410.4562

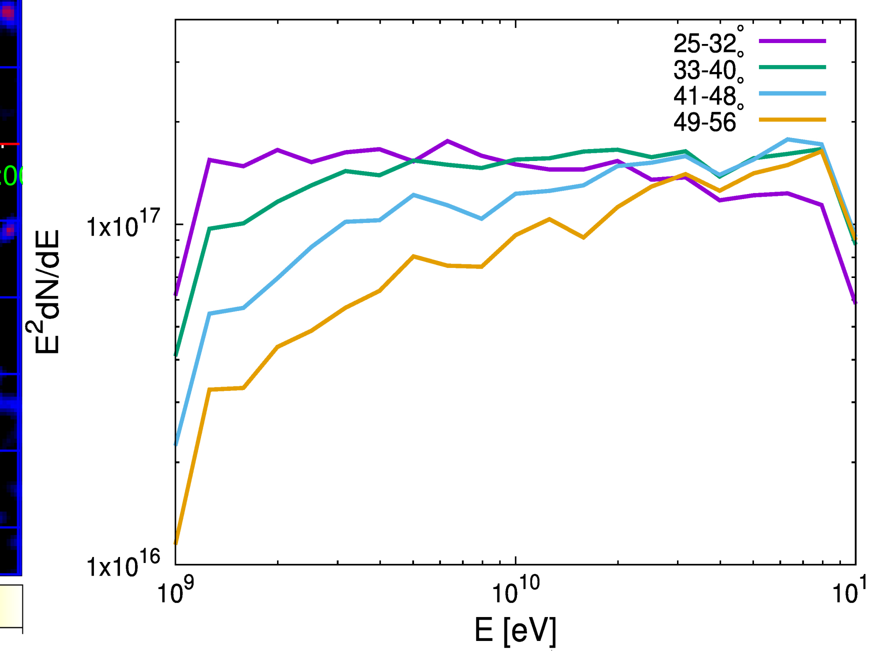


1-2 GeV map



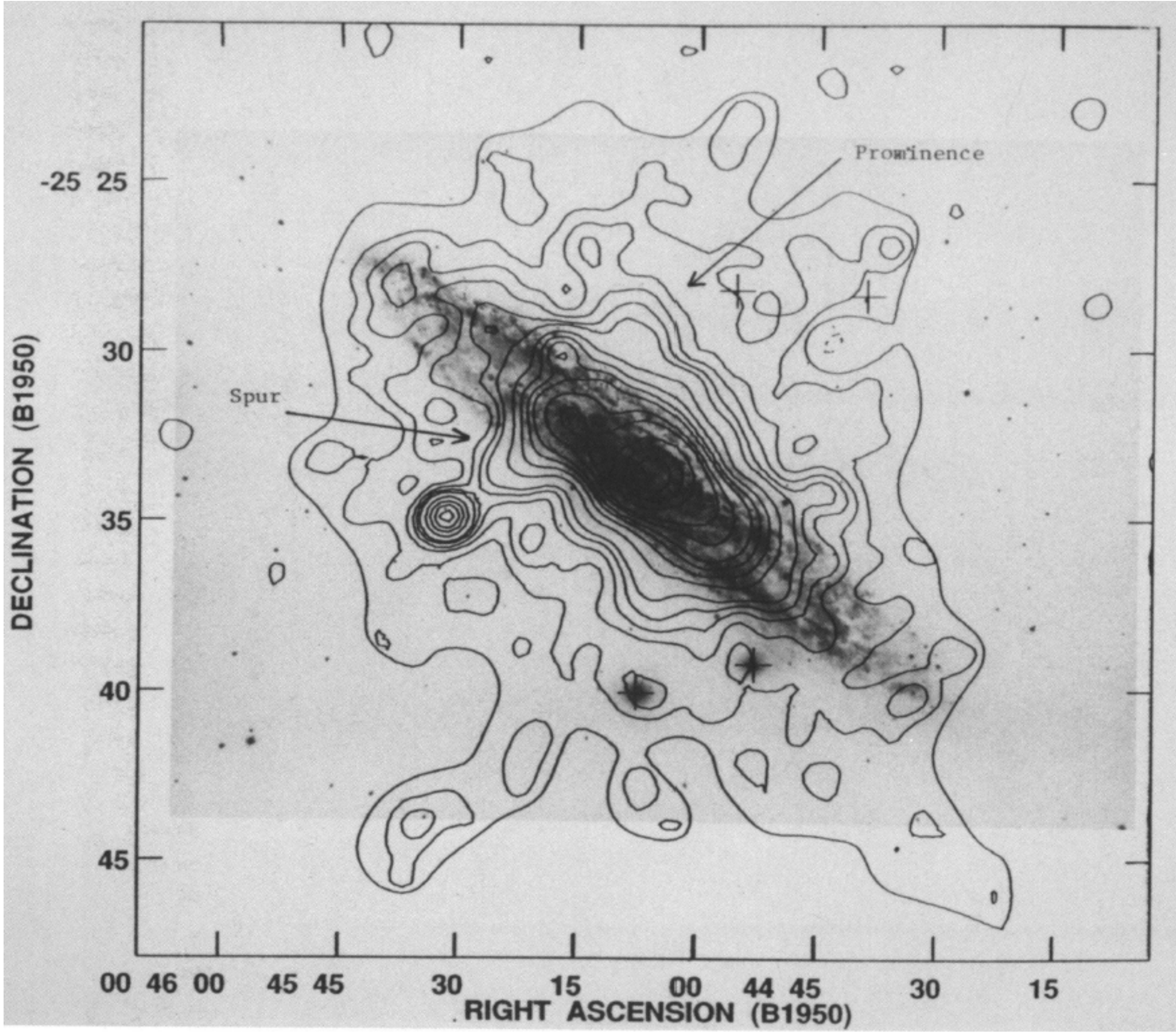
10-30 GeV map





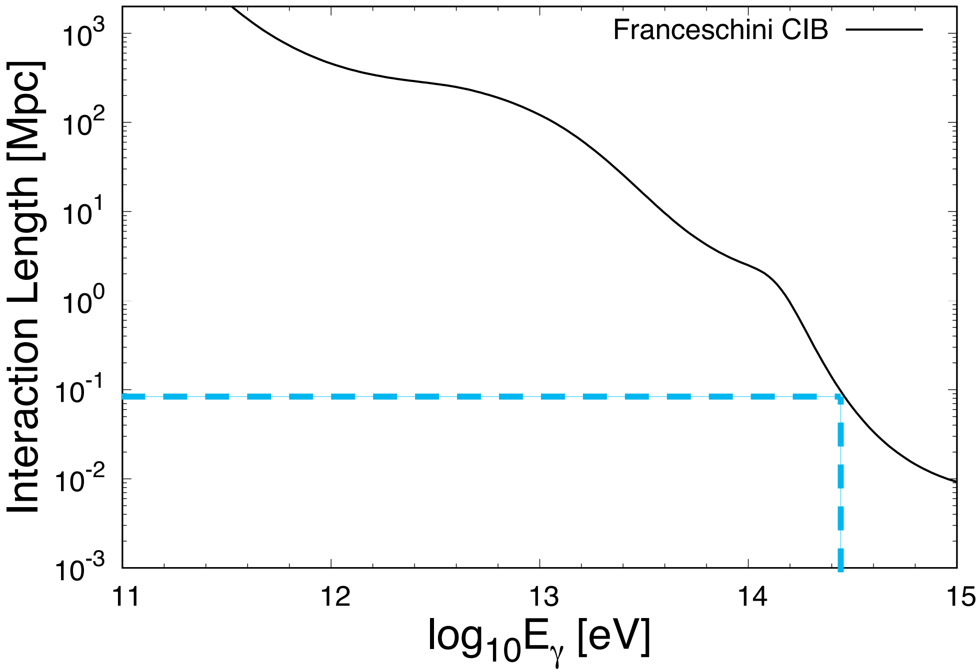
Diffuse Synchrotron Halos Around Nearby Galaxies

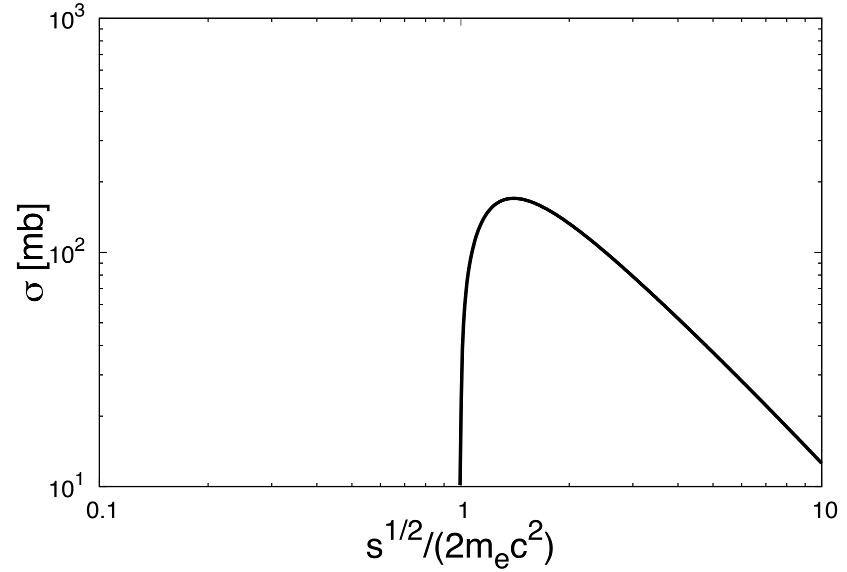
Synchrotron map of **NGC 253**- evidence of at least~10 kpc synchrotron halo

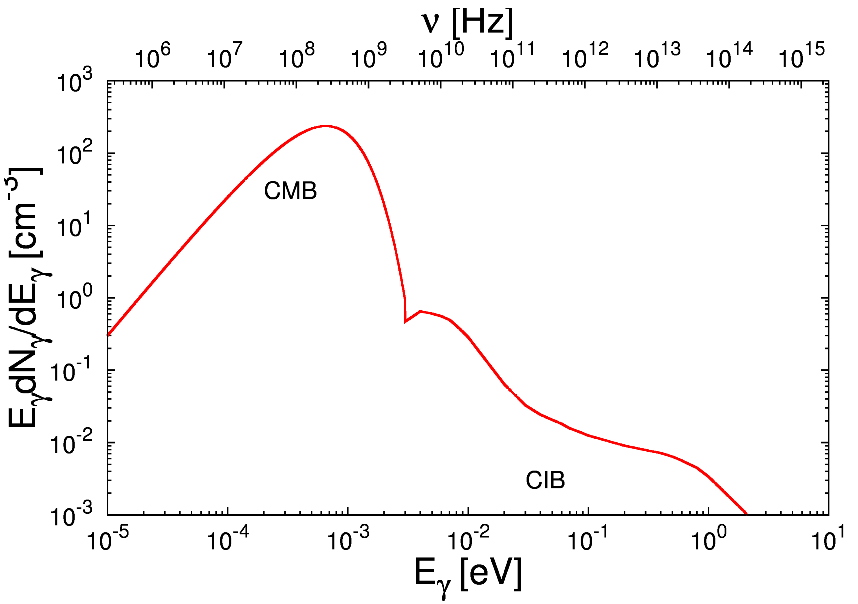


Carilli et al. 1992 (399 L59)

Attenuation of Gamma-Rays from Beyond the Bubbles!







DESY.

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