A **Galactic Halo Origin** for the Diffuse Neutrino Flux Detected by IceCube

Based on the work by:

S. Gabici

A. M. Taylor

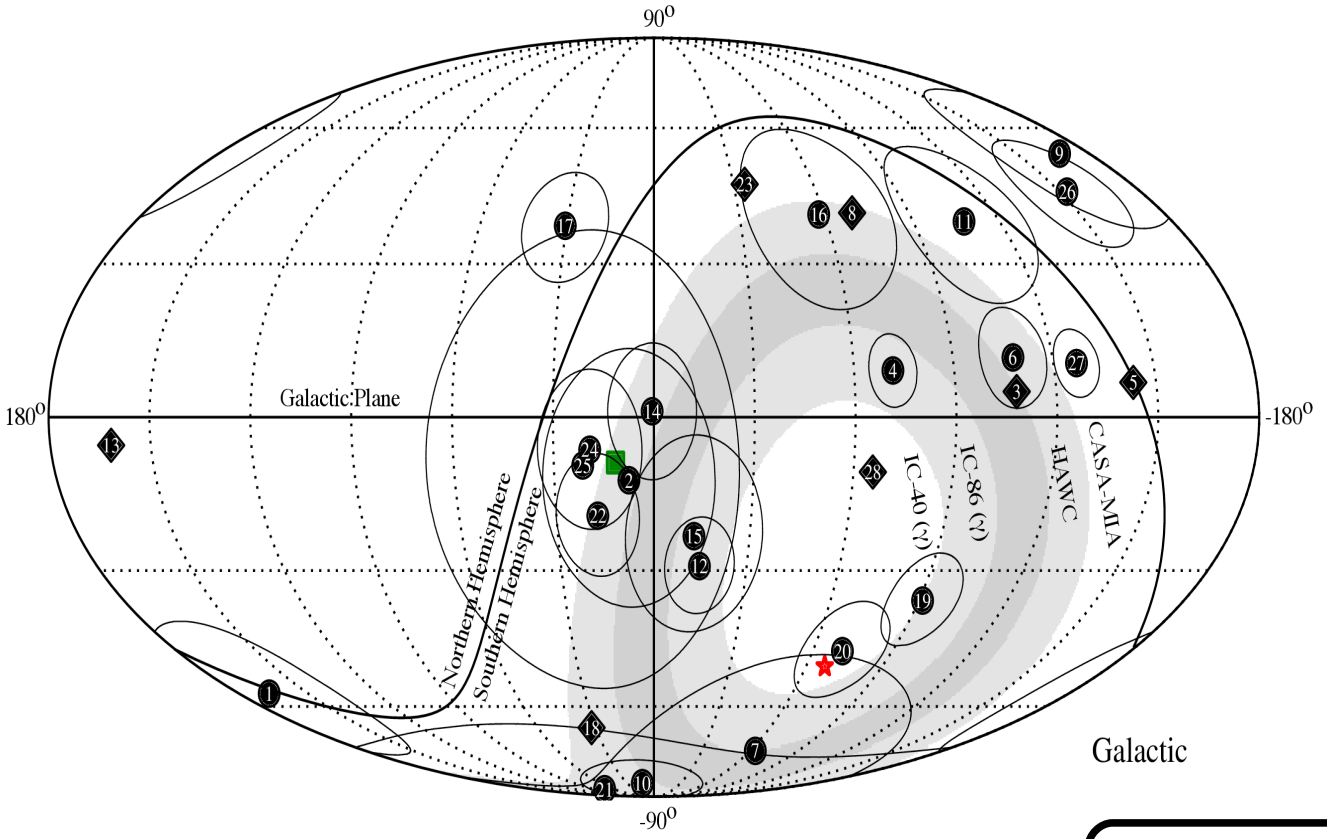
F. Aharonian

astro-ph/0806.2459

astro-ph/1403.3206

Neutrino Events on the Sky

From Ahlers et al. 2014- astro-ph/1309.4077



$$E_\nu F_\nu = 370\ \mathrm{eV\ cm^{-2}\ s^{-1}}$$

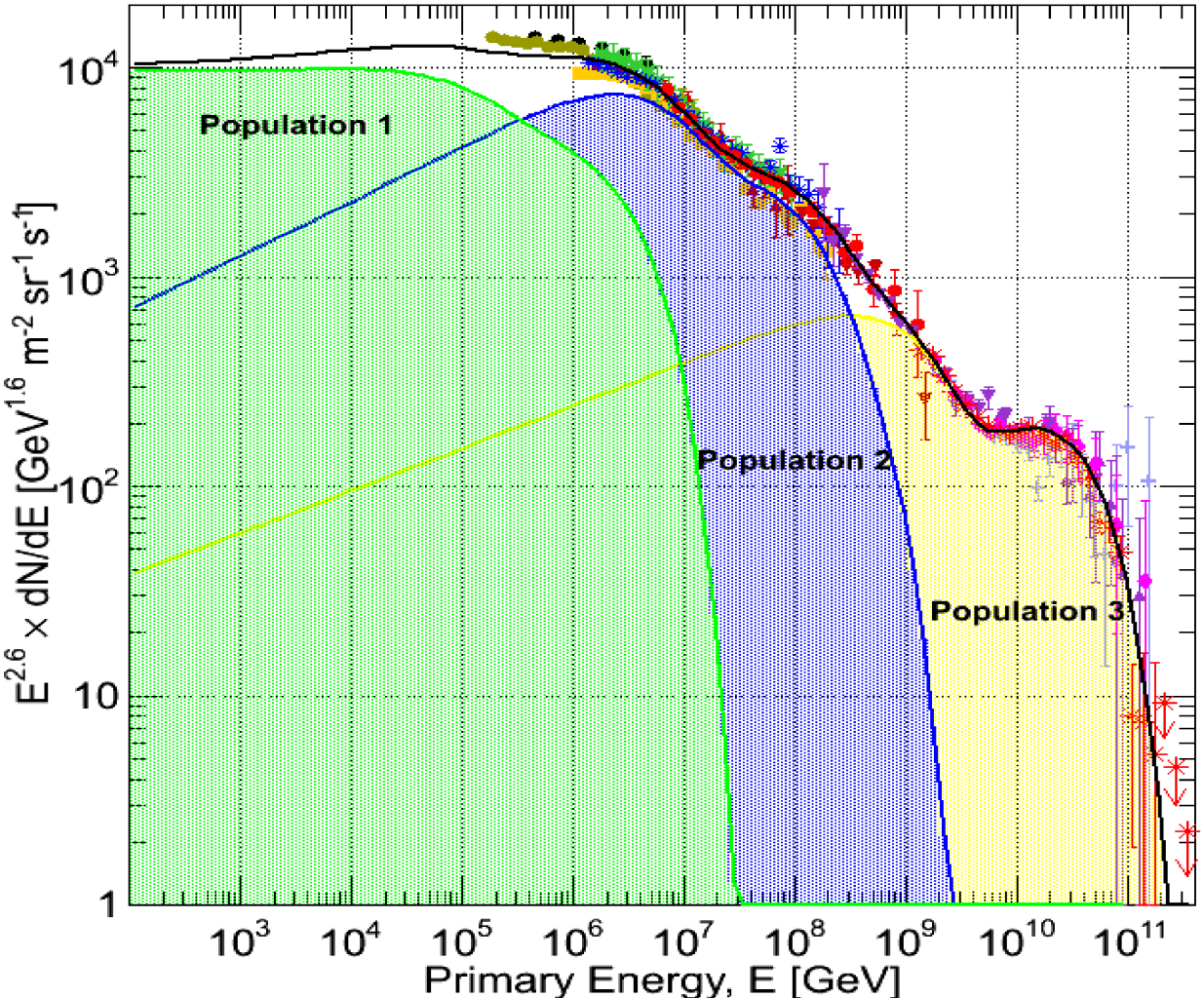
Andrew Taylor

Bridging the PeV-EeV Gap

For SNR (Bell 2013 ICRC Review)

$$E_{\max} = 230 \left(\frac{n_e}{1\ \mathrm{cm}^{-3}}\right)^{1/2} \left(\frac{v_{\mathrm{sh}}}{10^7\ \mathrm{m\ s}^{-1}}\right)^2 \left(\frac{R}{\mathrm{pc}}\right)\ \mathrm{TeV}$$

From Gaisser et al. 2013- astro-ph/1303.3565



Still awaiting first observational evidence of where Galactic Pevatrons reside

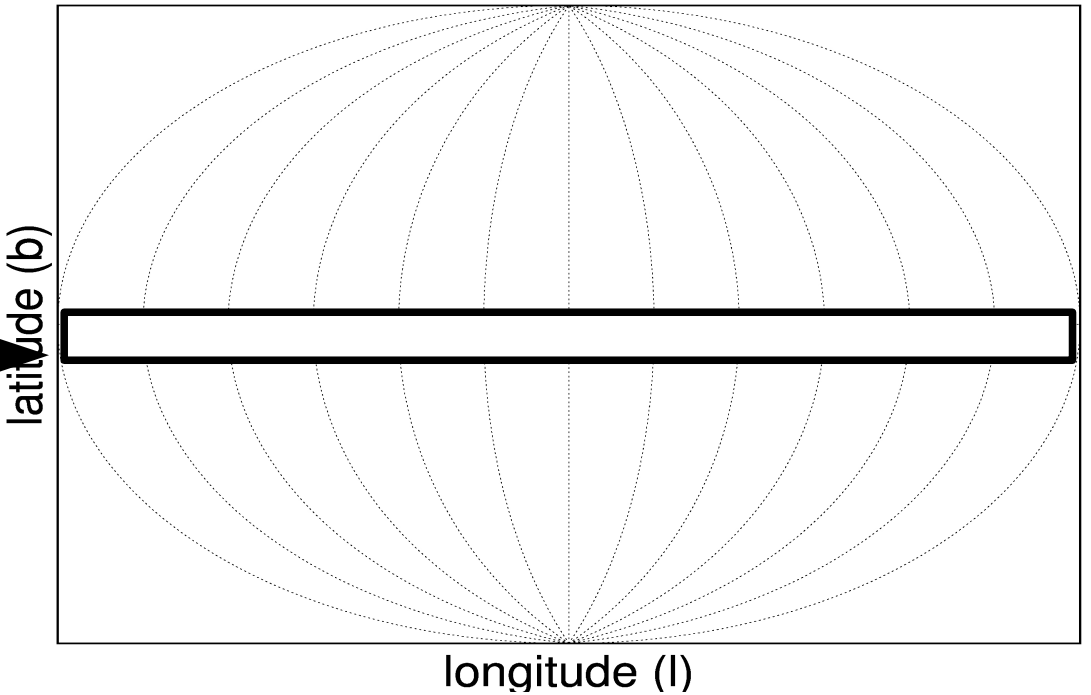
Galactic GeV cosmic rays require a source power output of $\sim 10^{41}$ erg s^{-1}

Naively, source "B" requires a CR proton luminosity of $\sim 10^{39}$ erg s^{-1}

Andrew Taylor

Galactic Plane-Flux Detection with IceCube

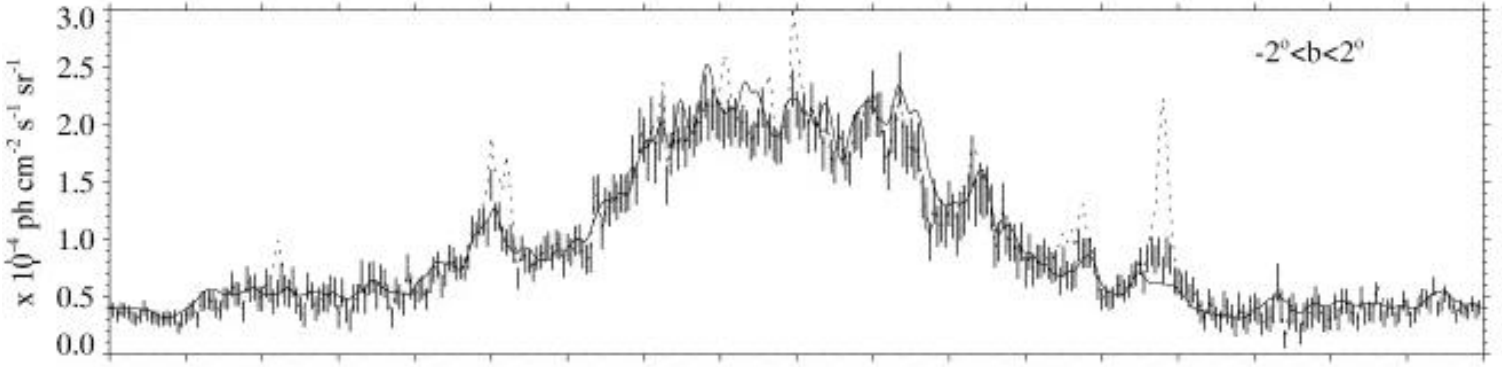
? yr^{-1}



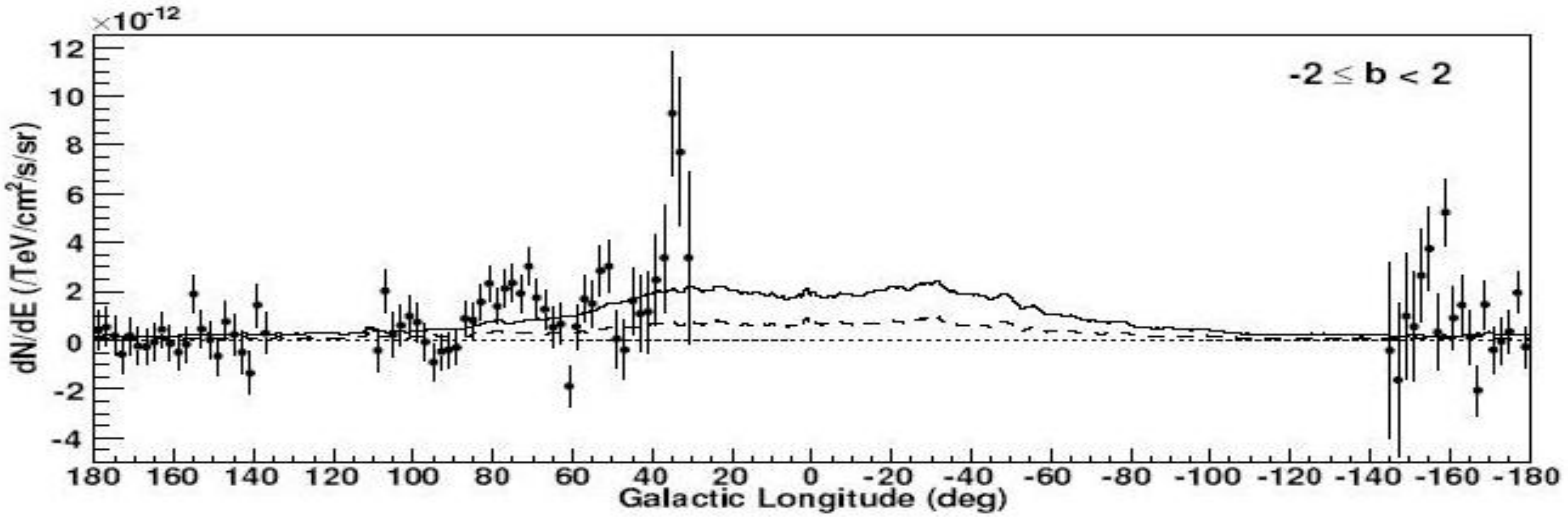
Andrew Taylor

The Milagro (~TeV) Observations

Spatial Distribution of EGRET Signal (300-1000 MeV)-

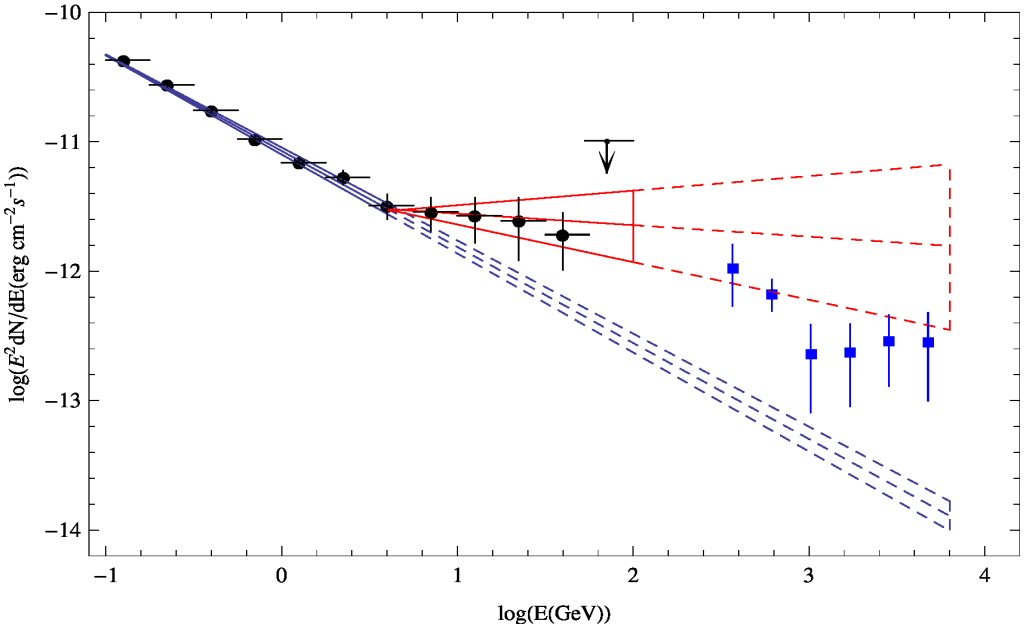


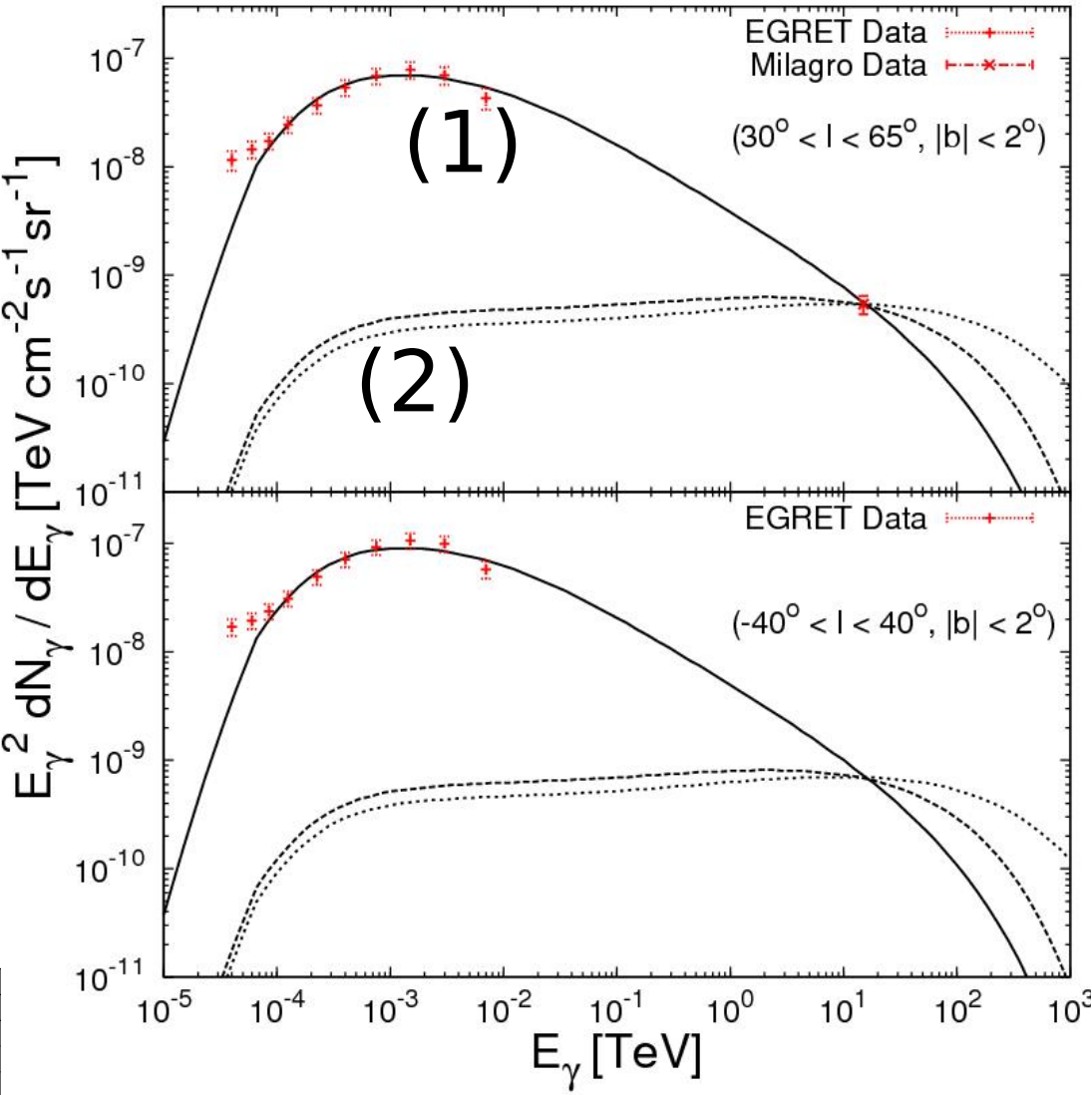
Spatial Distribution of Milagro Signal (~15 TeV ???)-



Fits to the Data

Sahakyan et al. 2013

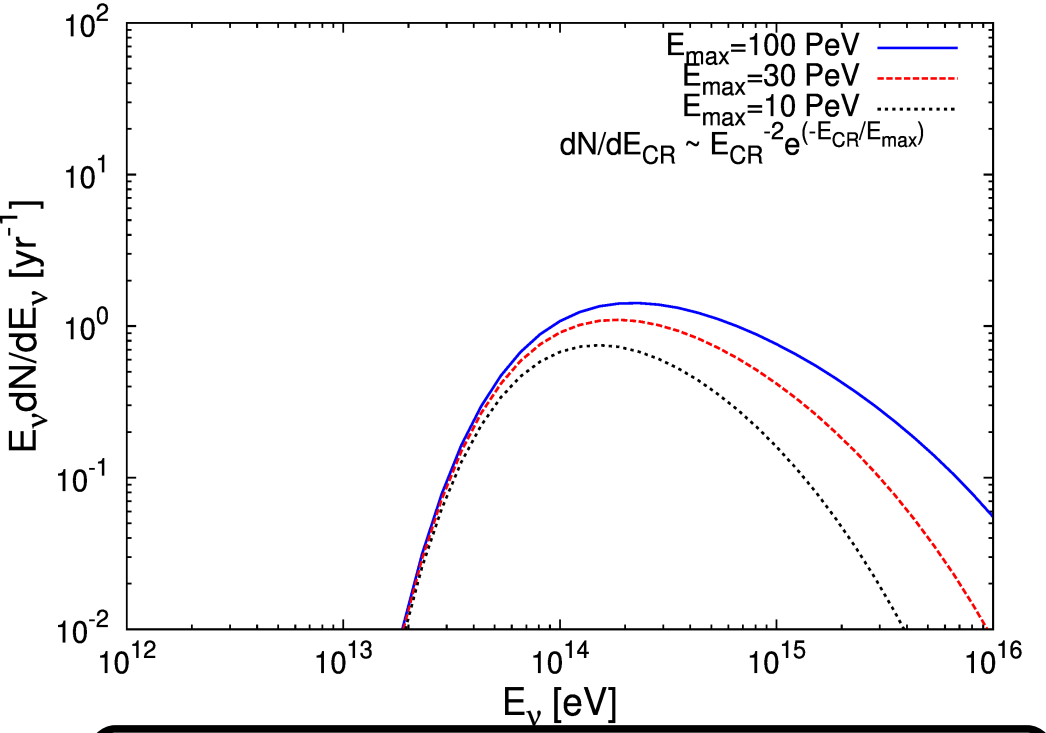


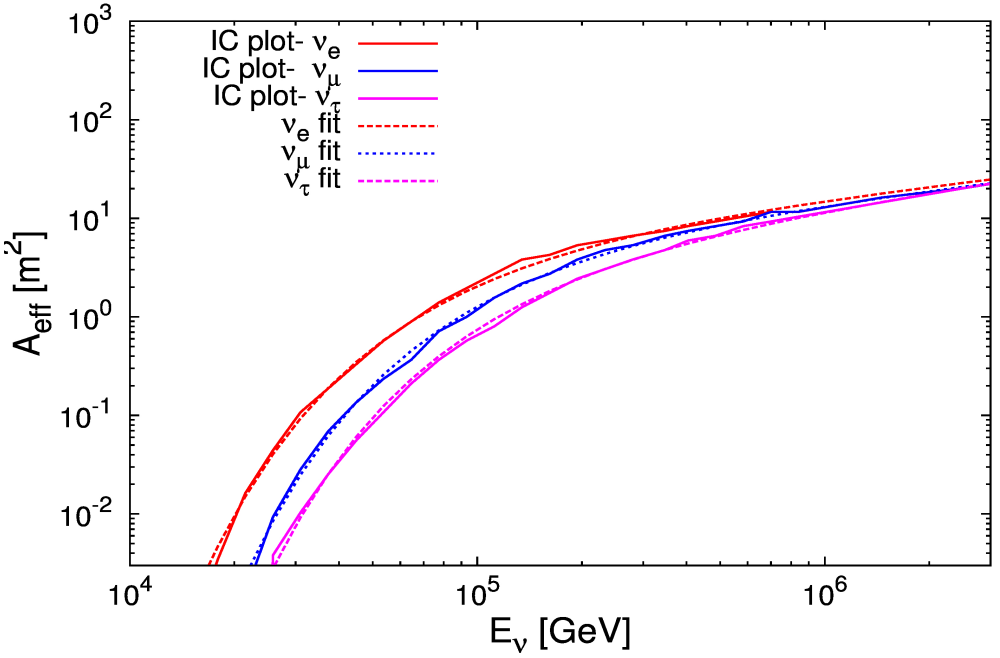


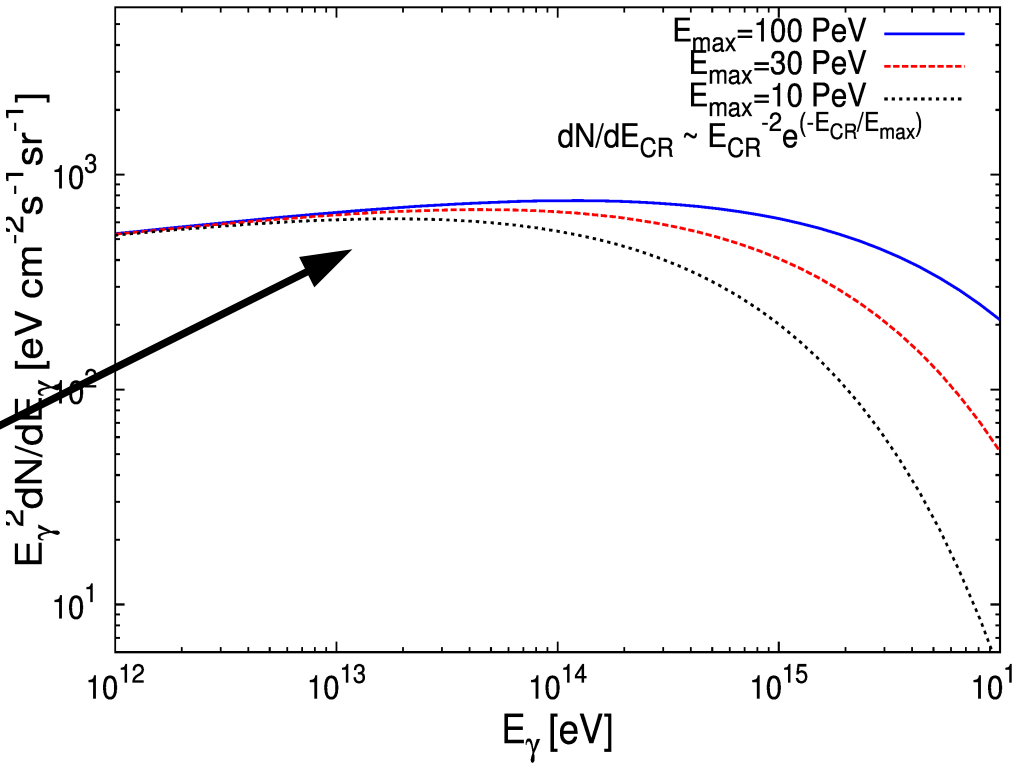
astro-ph/0806.2459

Andrew Taylor

Galactic Plane-Flux Detection with IceCube





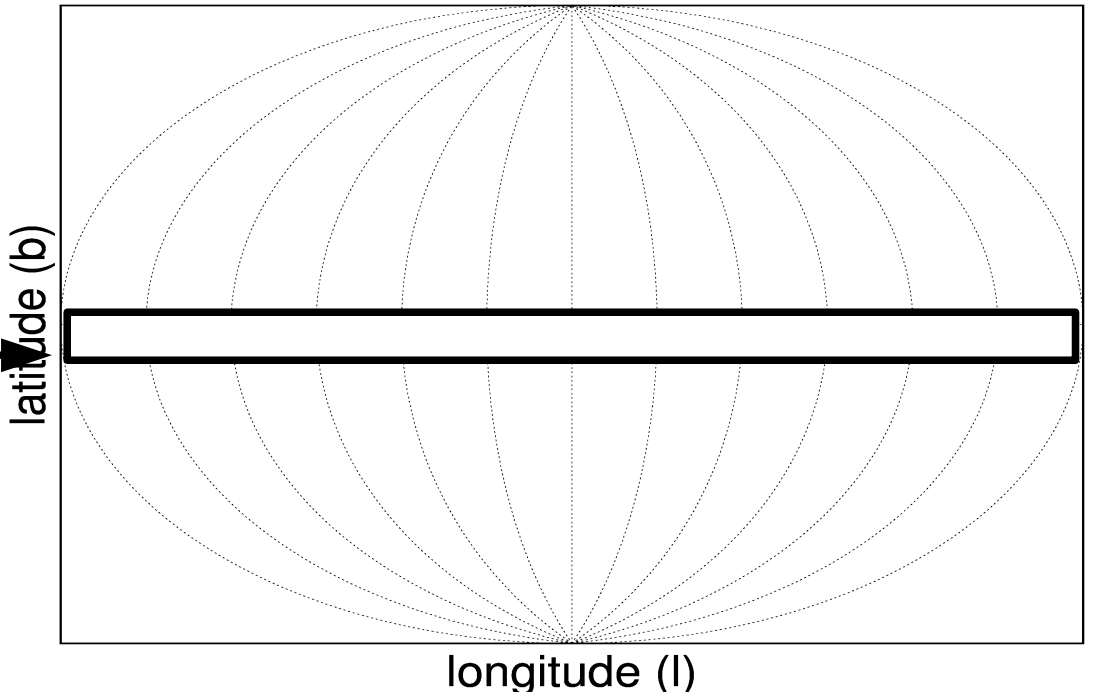


$$E_\gamma F_\gamma = 70 \text{ eV cm}^{-2} \text{ s}^{-1}$$

(~2 Crab in brightness)

Galactic Plane-Flux Detection with IceCube

~1 yr^{-1}



Rule of Thumb Detection Rate with km^3 Instrument

$$F_\nu(> \mathrm{TeV}) \sim 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \textbf{(ie. Crab level flux)}$$

~1 ν yr^{-1}

Andrew Taylor

Galactic Plane/Halo Emission Rates?

Assuming the CR fluxes in the two regions are **the same**, the relative emission rates go as

$$\frac{N_\nu^{\rm halo}}{N_\nu^{\rm disk}} = \left(\frac{n_p^{\rm halo}}{n_p^{\rm disk}}\right)\left(\frac{L^{\rm halo}}{L^{\rm disk}}\right)\left(\frac{\Delta\Omega^{\rm halo}}{\Delta\Omega^{\rm disk}}\right)$$

$$\frac{N_\nu^{\rm halo}}{N_\nu^{\rm disk}} = 0.05\left(\frac{n_{p,-3}^{\rm halo}}{n_{p,0}^{\rm disk}}\right)\left(\frac{L_{10}^{\rm halo}}{L_{10}^{\rm disk}}\right)\left(\frac{\Delta\Omega_{2\pi}^{\rm halo}}{\Delta\Omega_{0.1}^{\rm disk}}\right)$$

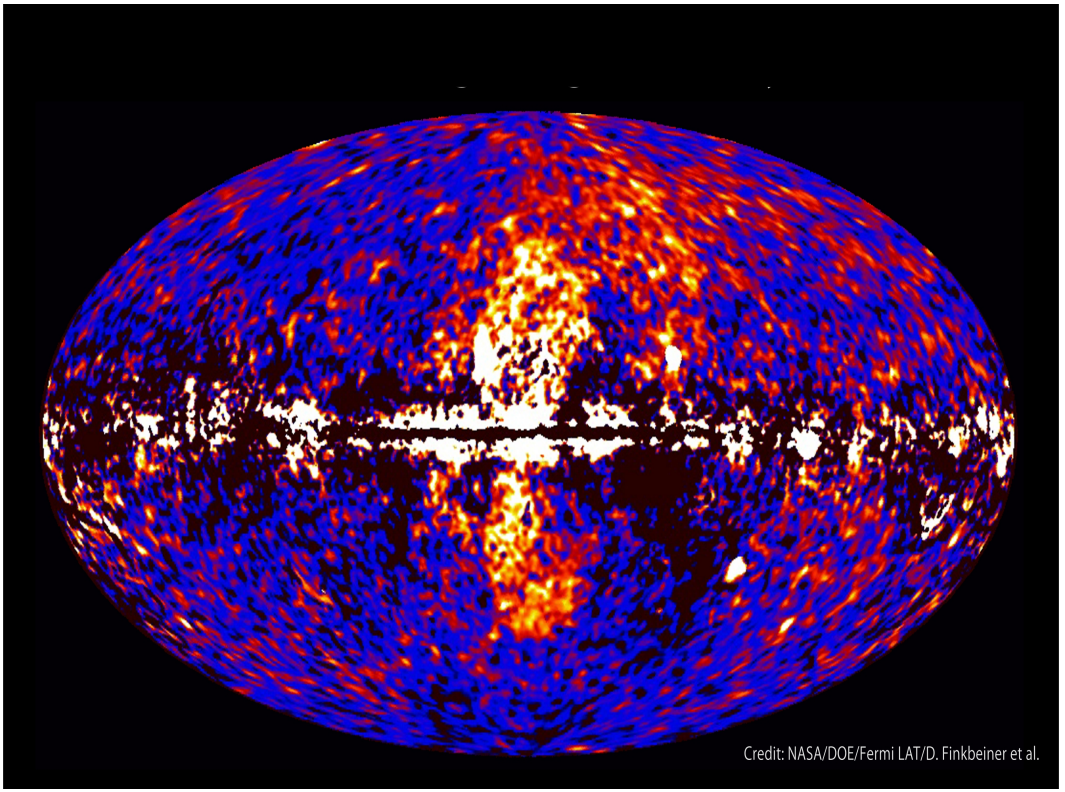
So can become comparable if

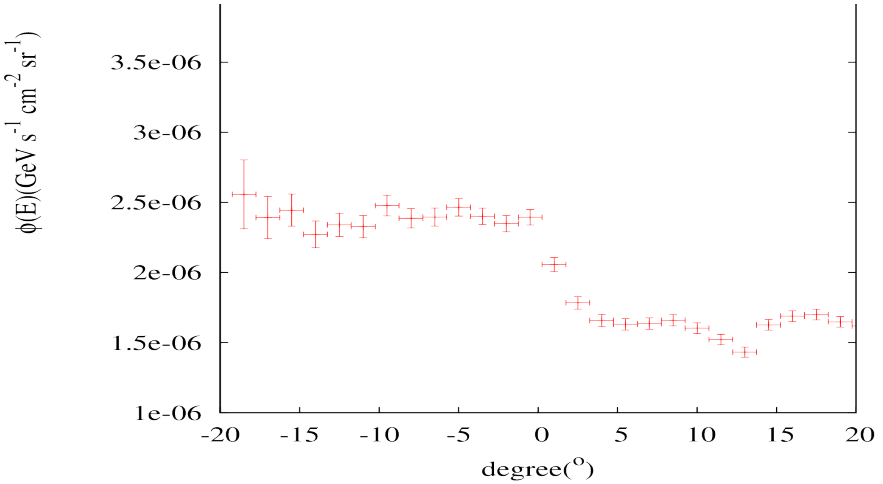
$$L^{\rm halo} \gg L^{\rm disk}$$

Thus, to motivate dominant Halo emission, we **relax** the uniform CR flux/diffusion only assumption

Fermi Bubbles

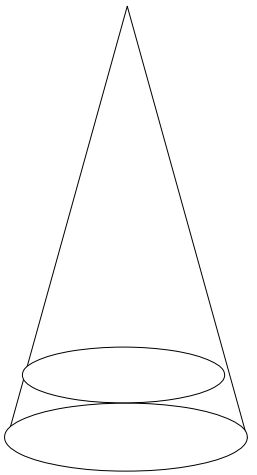
Evidence for advective cosmic ray transport in the Galaxy?



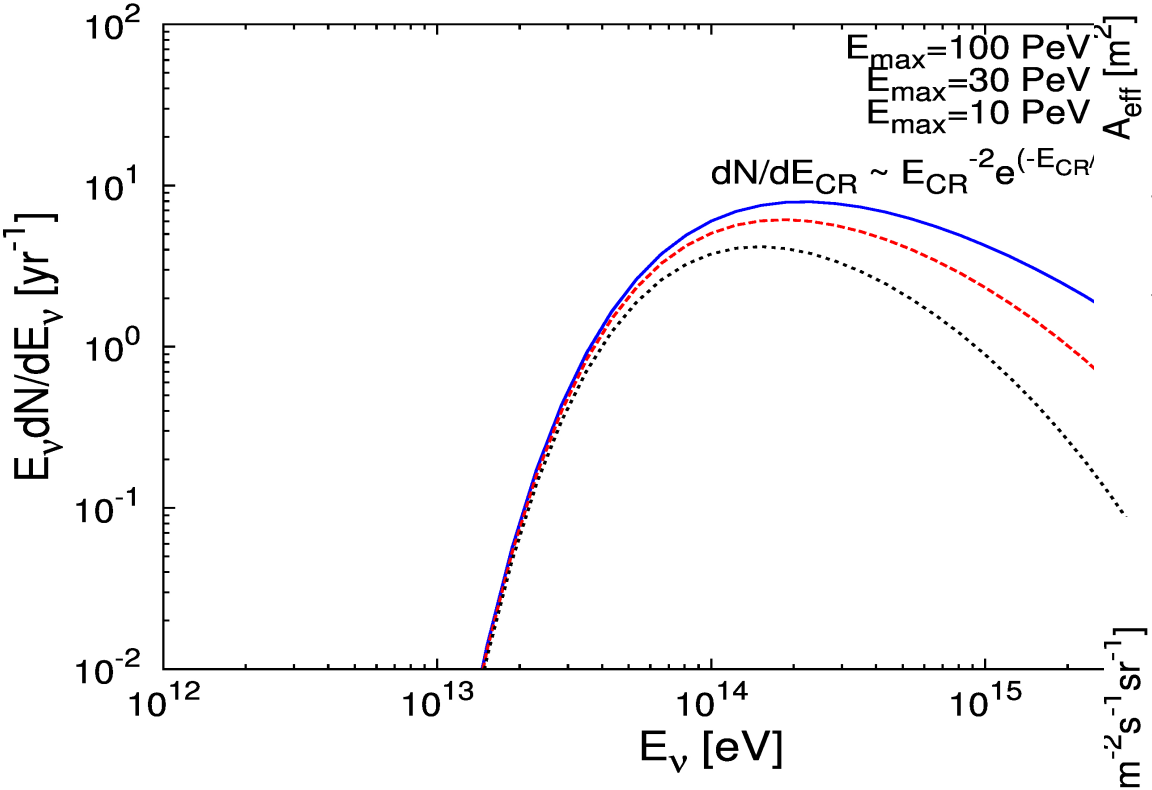


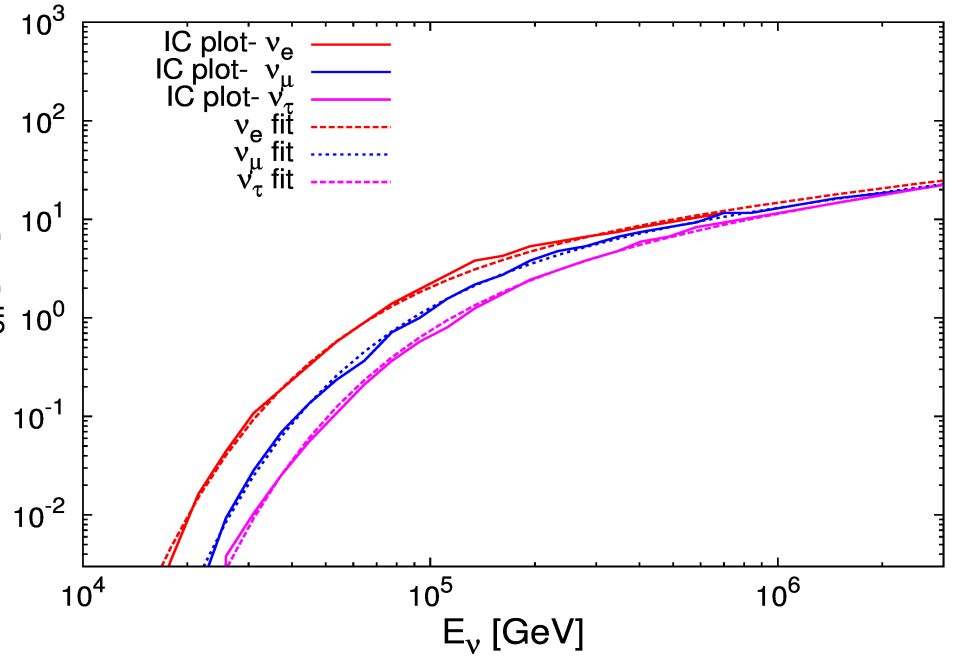
$$n_p \approx 10^{-2}\ \mathrm{cm}^{-3}$$

$$\frac{dN_{\mathrm{CR}}}{dr} \propto r^{-1}$$

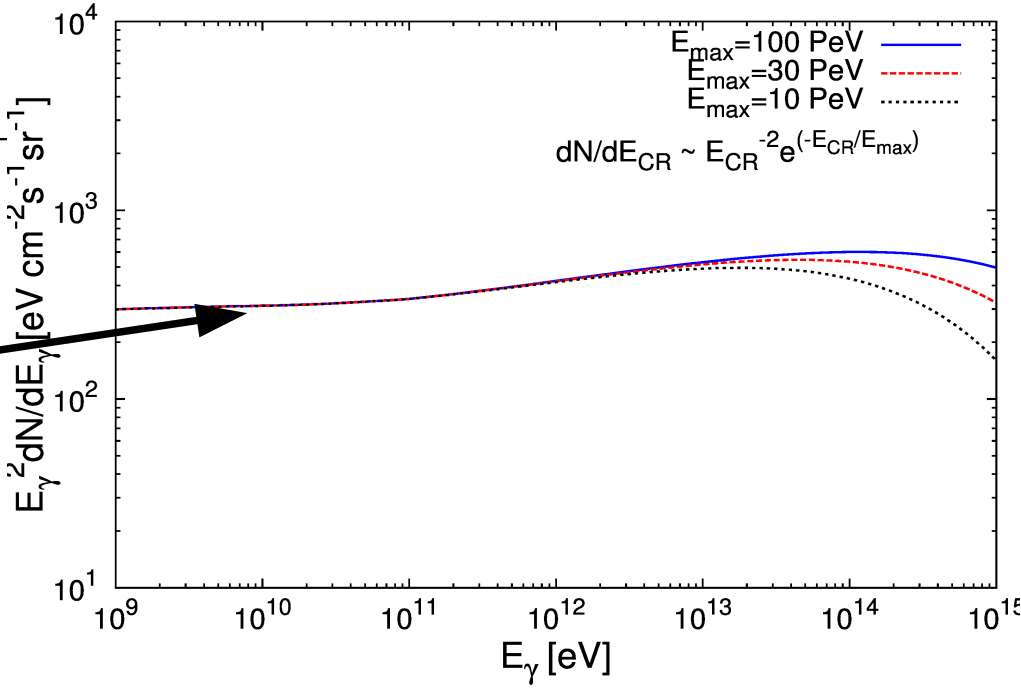


Fermi Bubbles- Flux Detection with IceCube



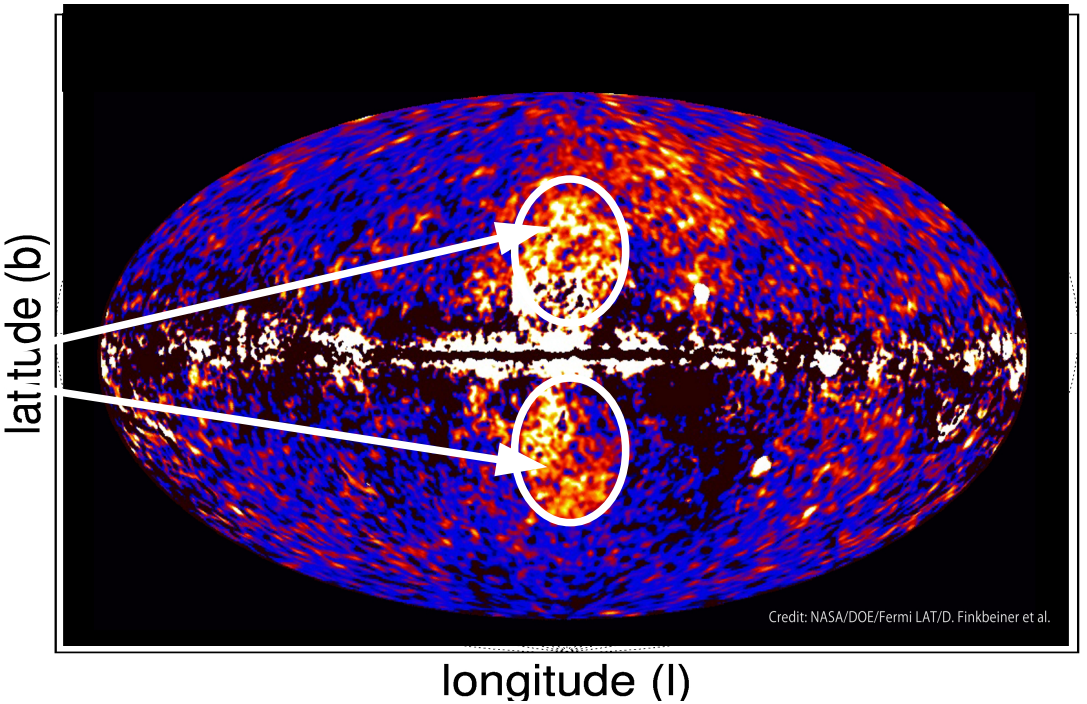


$$E_\gamma F_\gamma = 240 \text{ eV cm}^{-2} \text{ s}^{-1}$$



Fermi Bubbles- Flux Detection with IceCube

~6 yr^{-1}



(ie. follows rule of thumb)

$$L_\nu = 3 \times 10^{36}\ \mathrm{erg\ s^{-1}}$$

$$t_{pp} = \left(\frac{10^{-2}\ \mathrm{cm^{-3}}}{n_p}\right)\ 3 \times 10^{9}\ \mathrm{yrs}$$

$$t_{\mathrm{esc}} = \left(\frac{R}{10\ \mathrm{kpc}}\right)\left(\frac{300\ \mathrm{km\ s^{-1}}}{v}\right) 3 \times 10^{7}\ \mathrm{yrs}$$

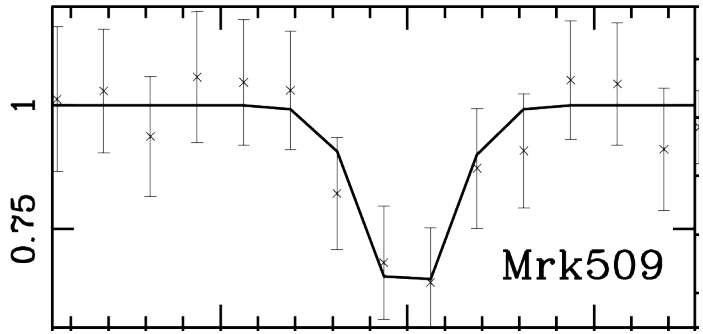
$$L_p \approx \left(\frac{t_{\mathrm{esc}}}{t_{\mathrm{pp}}}\right) L_\nu$$

$$\approx 10^{39}\ \mathrm{erg\ s^{-1}}$$

Andrew Taylor

Possible Connection to the Missing Baryon Problem?

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



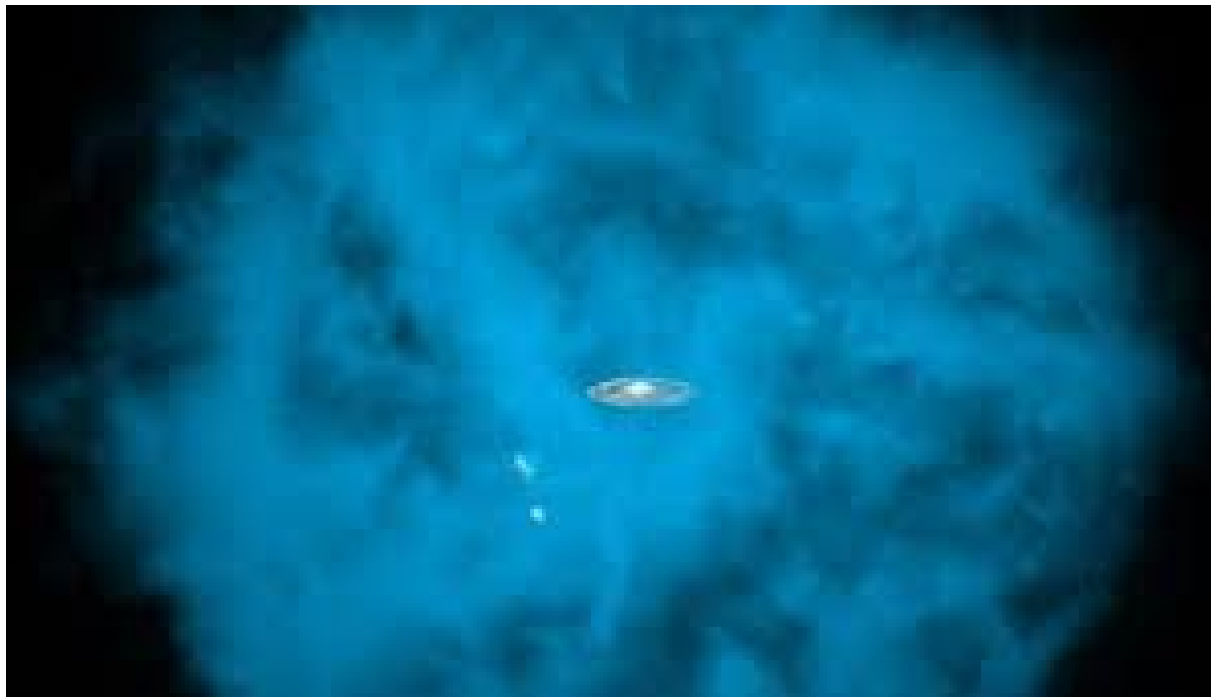
$$M \approx 10^{11}\ M_{\odot}$$

Inside a sphere of size

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

Gives a mean density of this gas of

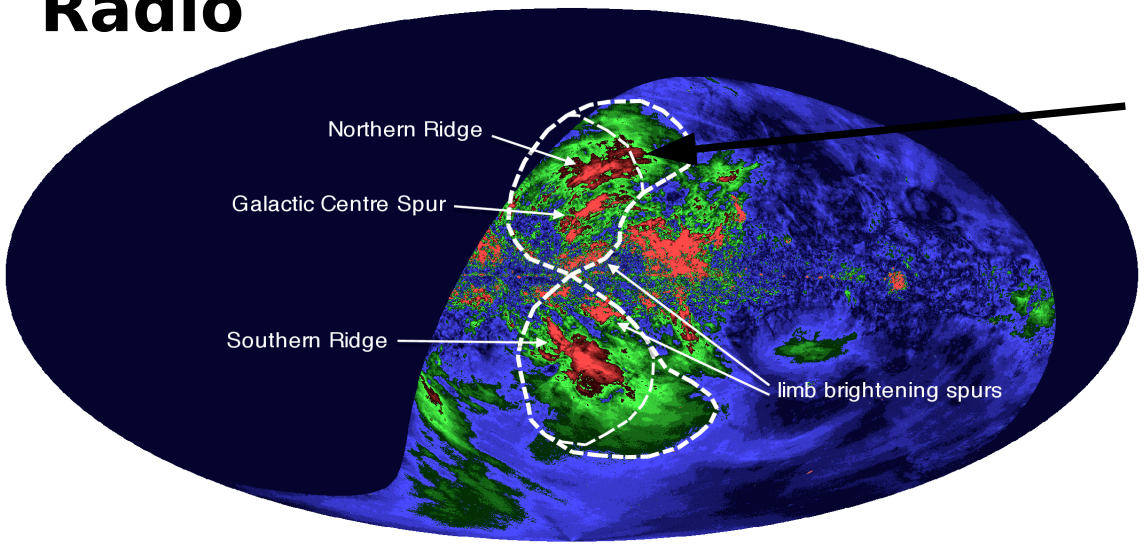
$$n_p \approx 10^{-3}\ \mathrm{cm}^{-3}$$

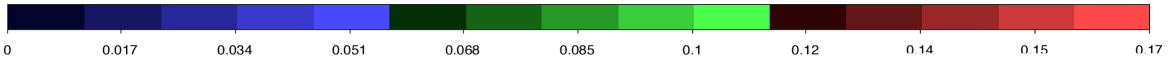


(see Stocke et al.- ApJ 763 148 for recent review)

Evidence of a Broader Scale Outflow?

Radio



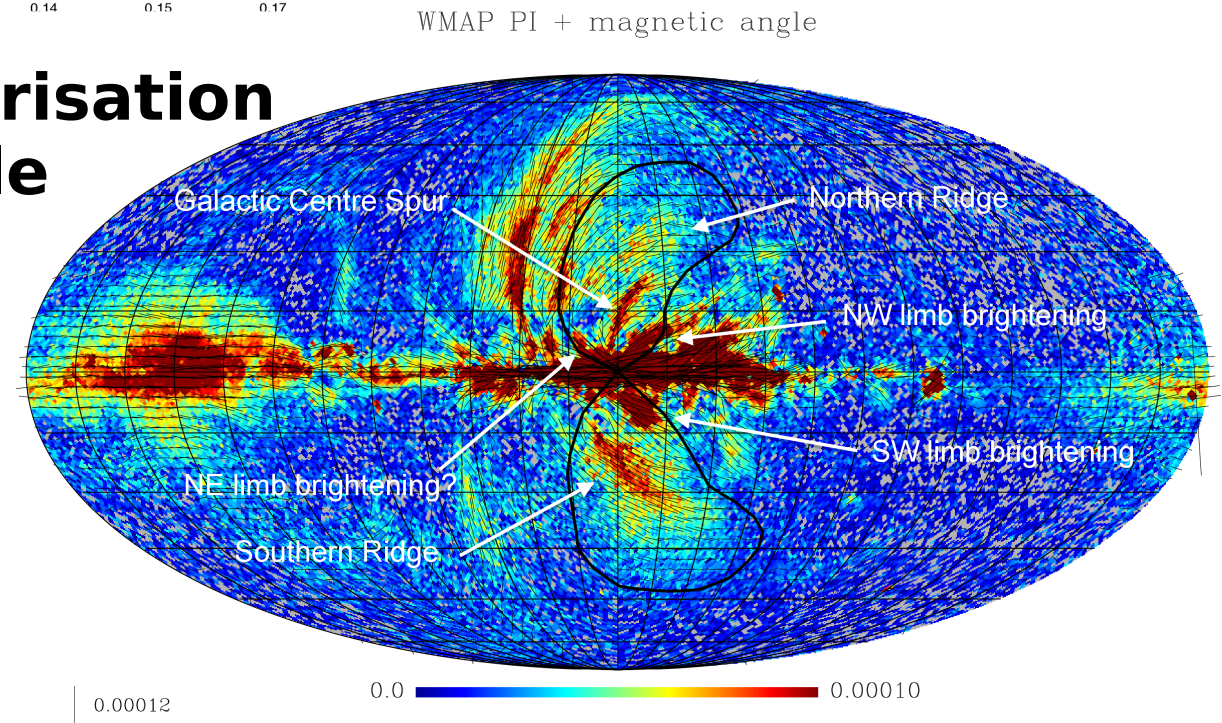


$2.3\ \mathrm{GHz}$

corresponding to

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

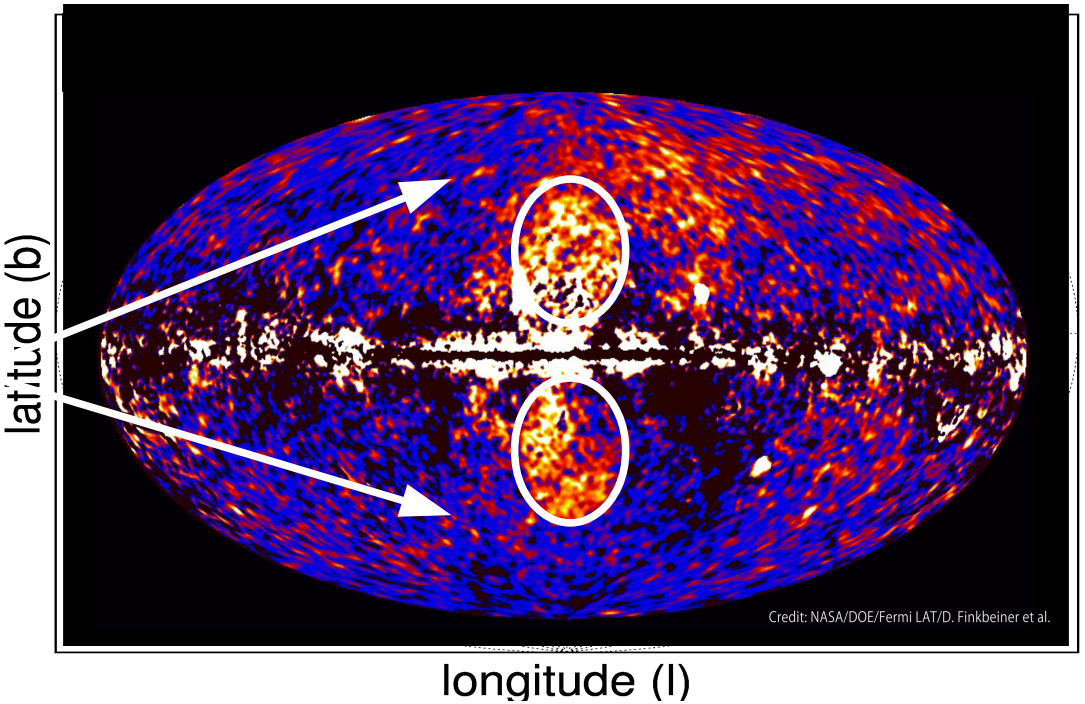
Polarisation Angle



astro-ph/1301.0512

Beyond the Fermi Bubbles?

~9 yr^{-1}



$$L_\nu = 8 \times 10^{38}\ \mathrm{erg\ s^{-1}}$$

$$L_p \approx \left(\frac{t_{\mathrm{esc}}}{t_{\mathrm{pp}}}\right) L_\nu$$

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

Required PeV luminosity to support this population is ~10^{39}-10^{40} erg s^{-1}

Andrew Taylor

Detectability?

HAWC + LHAASO- verification of Milagro level flux and multi-TeV diffuse photon detection

IceCube/IceTop map collectively search for a γ-ray component of the signal

HESS/Veritas/MAGIC- electromagnetic cascade studies (electrons at multi TeV energies can't propagate far at all)

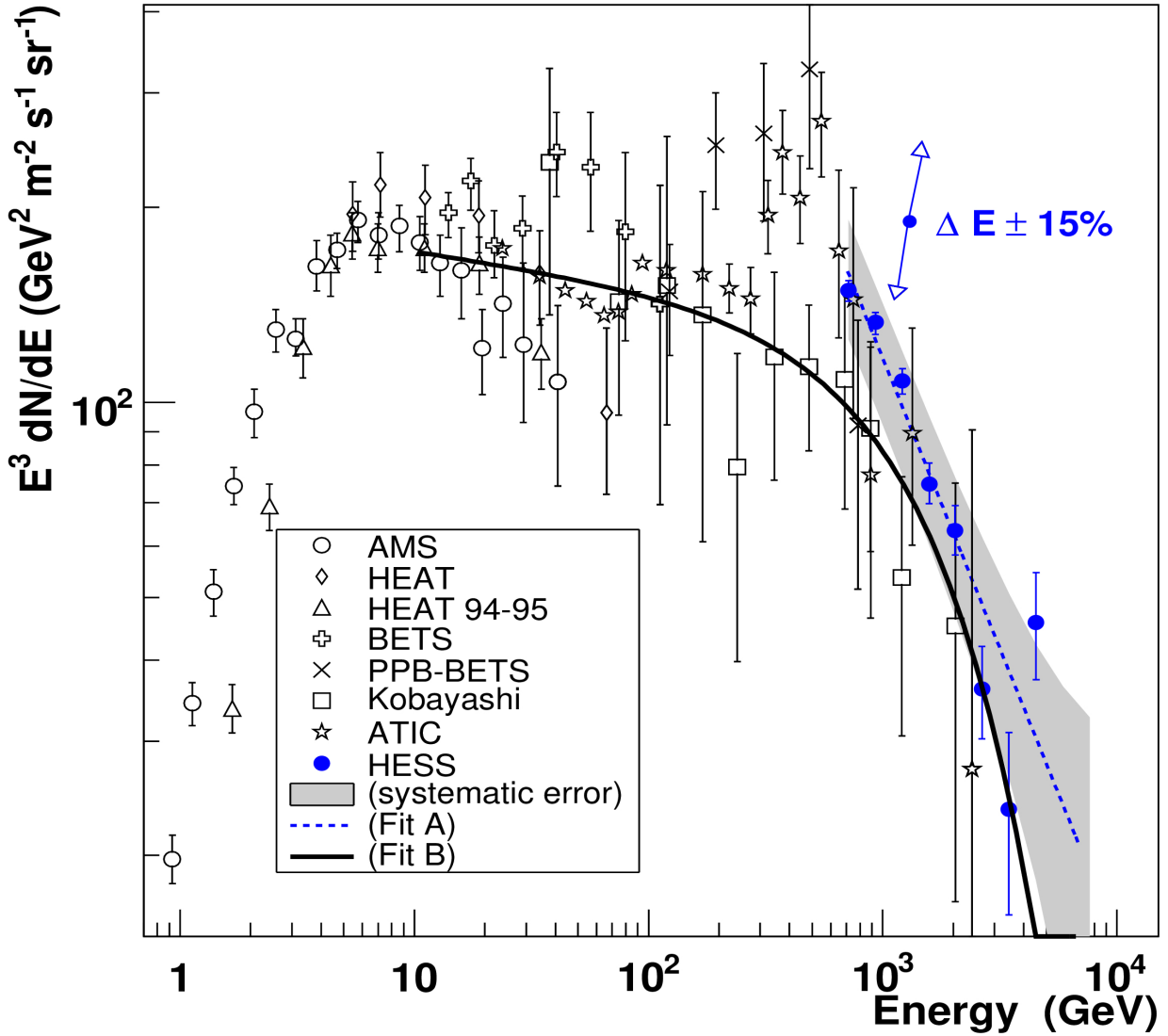
HESS- Evidence for a Galactic Center Pevatron

NuStar- X-ray observations from other systems with similar “synchrotron halos”

LoFar- Able to probe, with improved sensitivity, the presence of synchrotron halos in nearby systems

HESS Diffuse Electron Flux

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



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

From astro-ph/0811.3894

Andrew Taylor

Conclusions

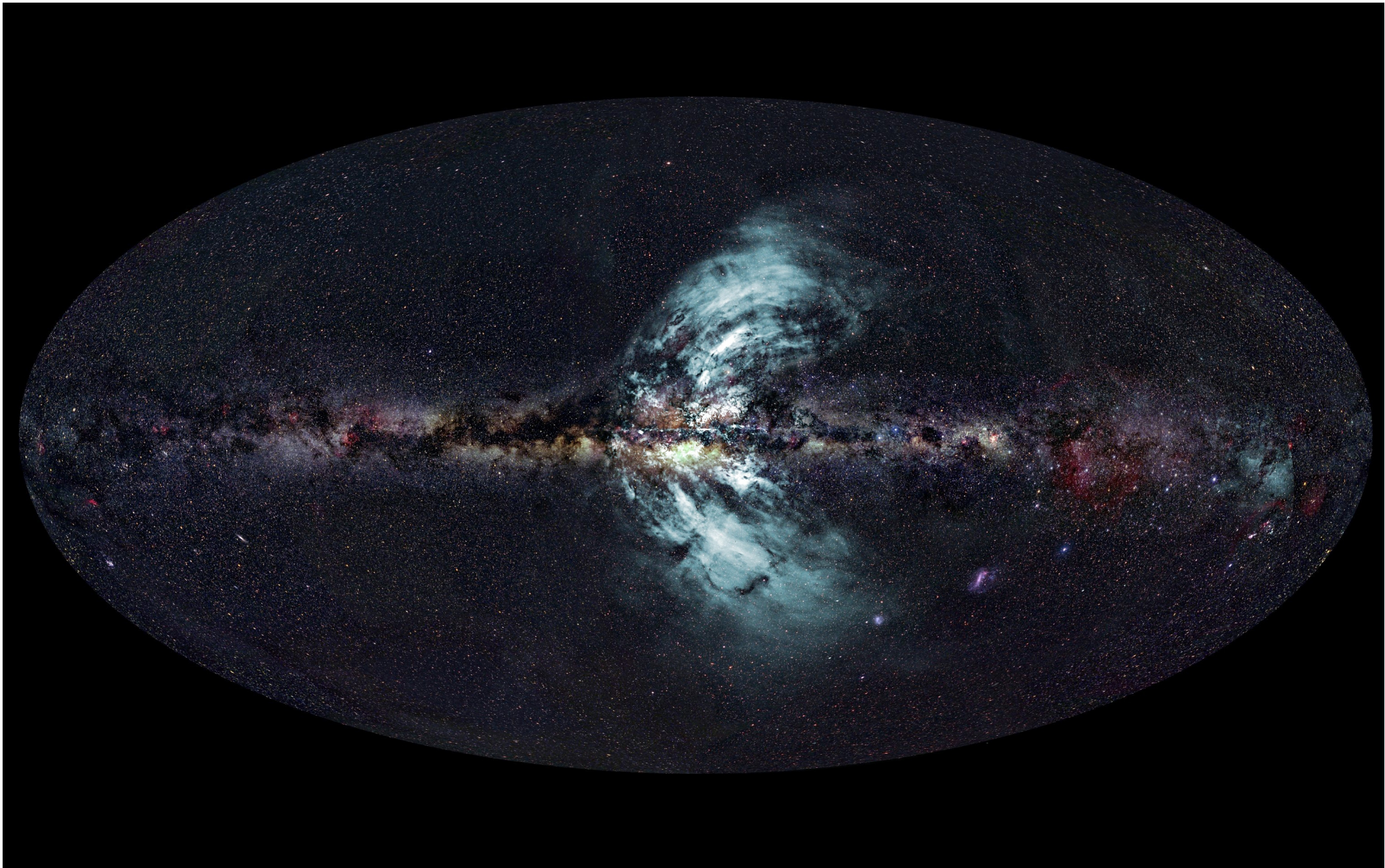
- A Galactic origin of the neutrinos observed by IceCube cannot be ruled out

- The expected Galactic plane emission can be outshone by the Galactic halo, provided the halo is sufficiently big and contains sufficient target material

- The Fermi bubbles may be an indicator of cosmic ray outflow following Galactocentric activity

- The detection of a Pevatron in gamma-rays is crucial for helping understand this signal

Andrew
Taylor

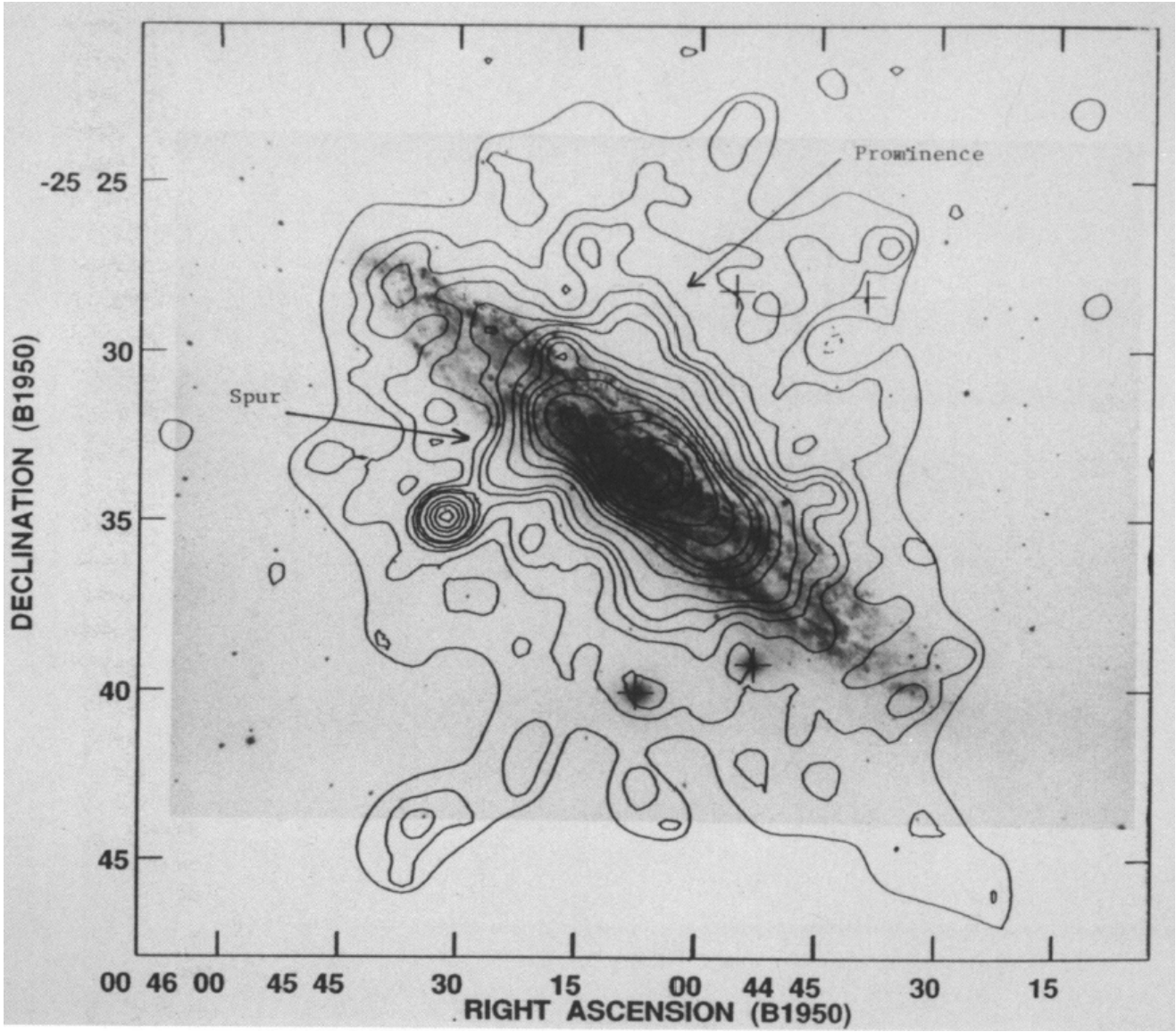


Extra Slides

Andrew
Taylor

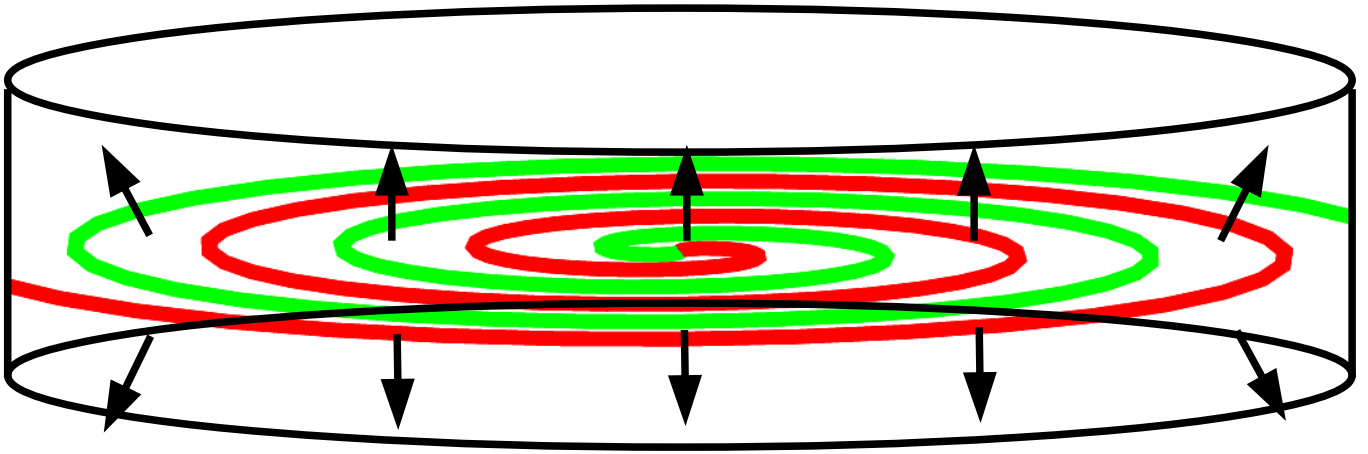
Diffuse Synchrotron Halos Around Nearby Systems

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



Carilli et al. 1992 (399 L59)

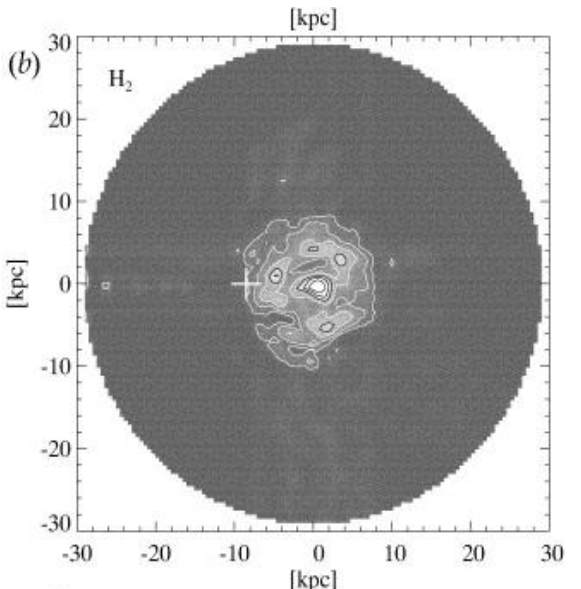
Galactic Plane Emission



plot:(Hunter *et al.* 1997)
data: (Dame et al.)

Molecular Gas Target

molecular gas →

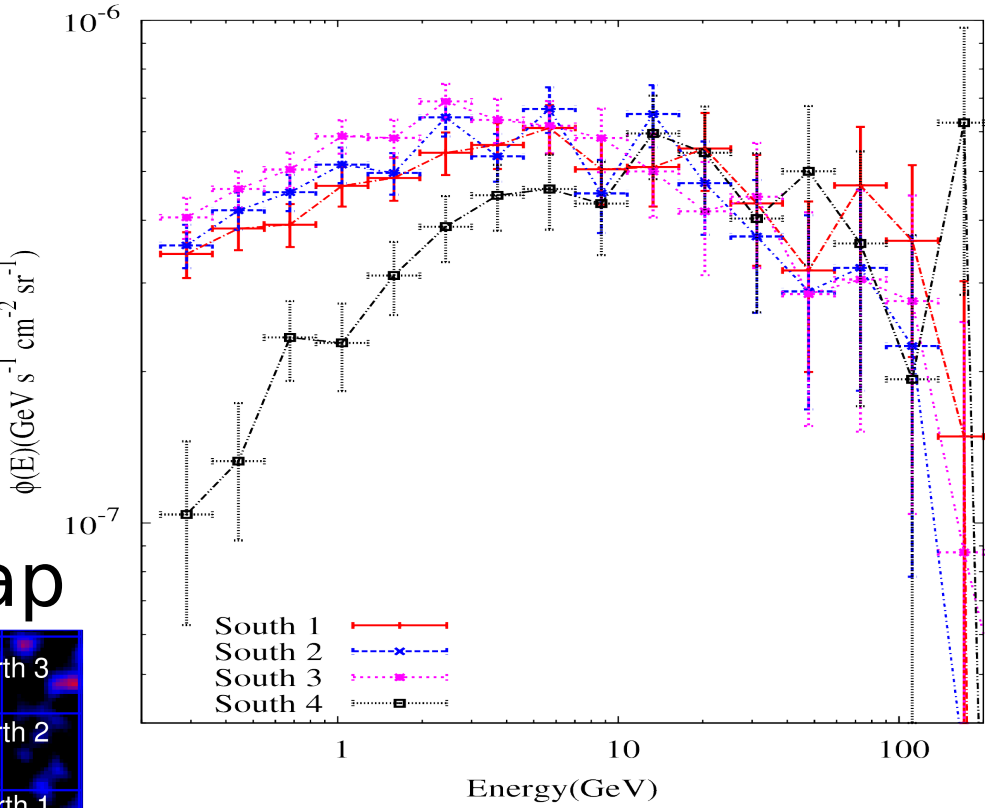


$n = n_0 e^{-\left(\frac{R}{R_{H_2}}\right)}$ where $n_0 = 4\ \mathrm{cm}^{-3}$, $R_{H2} = 2.6\ \mathrm{kpc}$

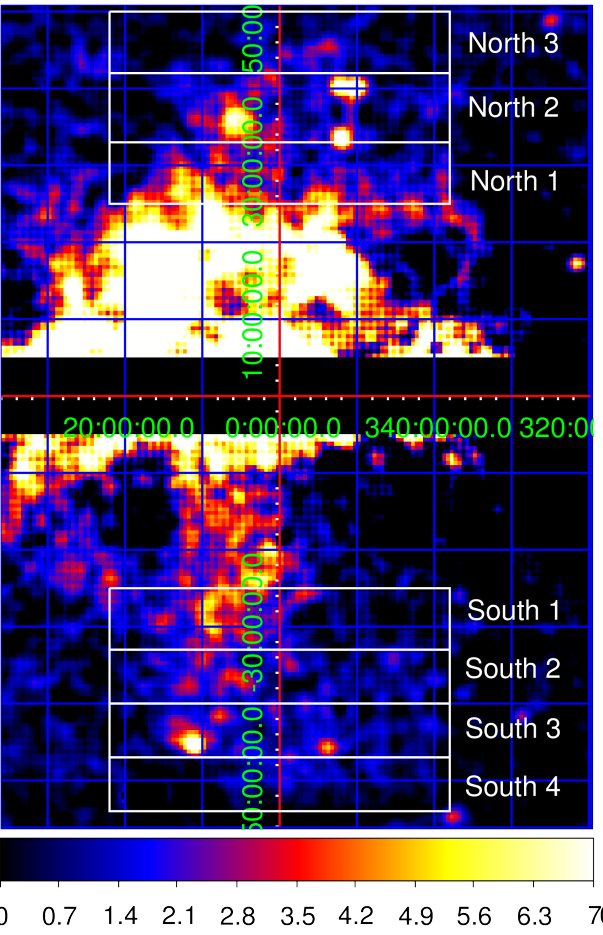
(Misiriotis *et al.* 2006)- inferred using CO measurements and the $\mathbf{X_{factor}}$ relation

Fermi Bubbles- Energy Dependent Morphology

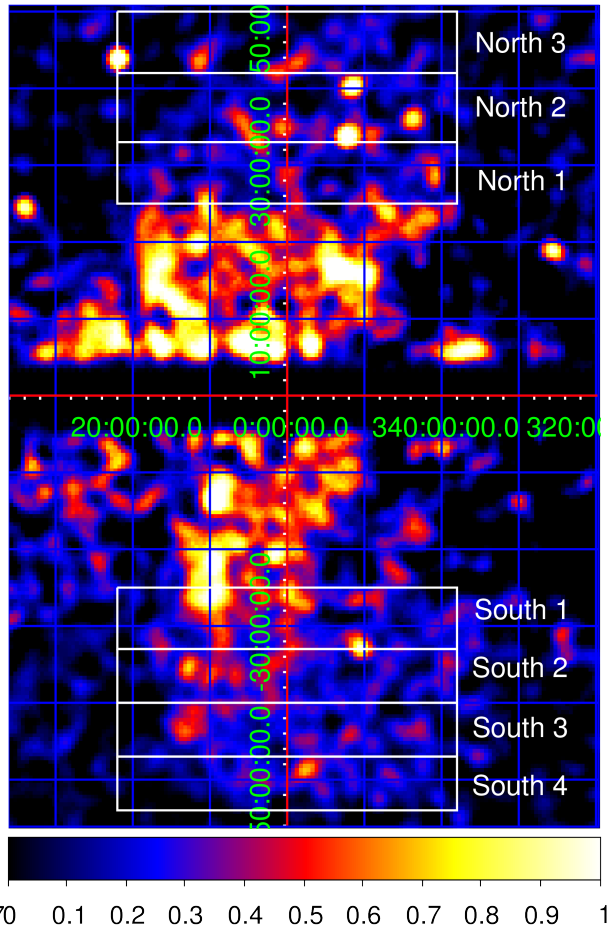
From astro-ph/1402.0403



1-2 GeV map

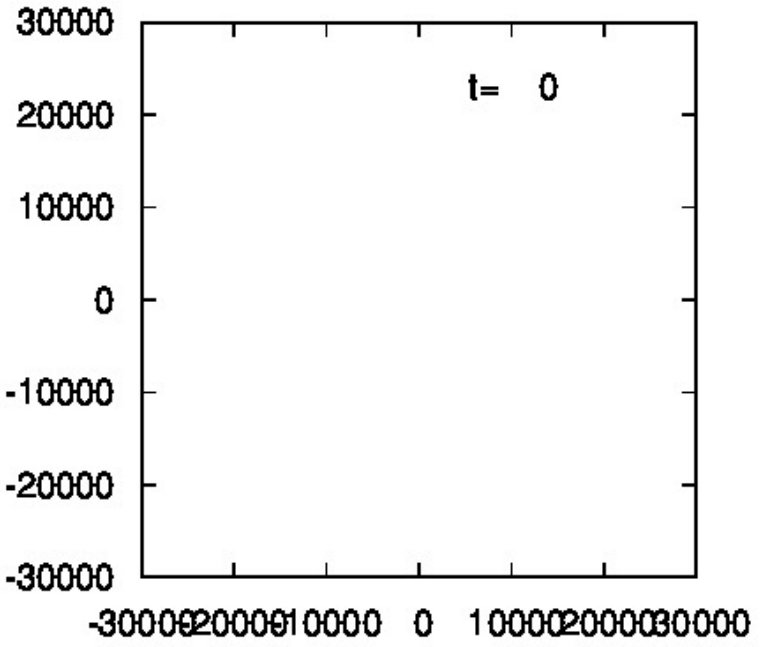


10-30 GeV map



Fermi Bubbles- Galactic Outflow

$$\frac{\partial}{\partial t} n(E) = \nabla \cdot D \nabla n(E) + \nabla \cdot v_{\rm adv} n(E) + Q(E, x, t)$$

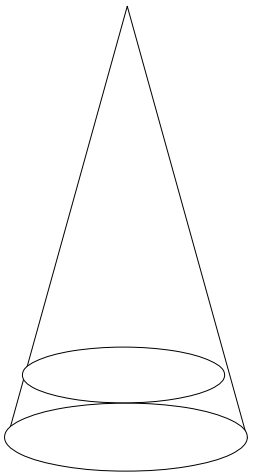


$$D(\mathrm{PeV}) = 10^{29}\ \mathrm{cm^2\ s^{-1}}$$

$$v_{\rm adv} = 30 - 300\ \mathrm{km\ s^{-1}}$$

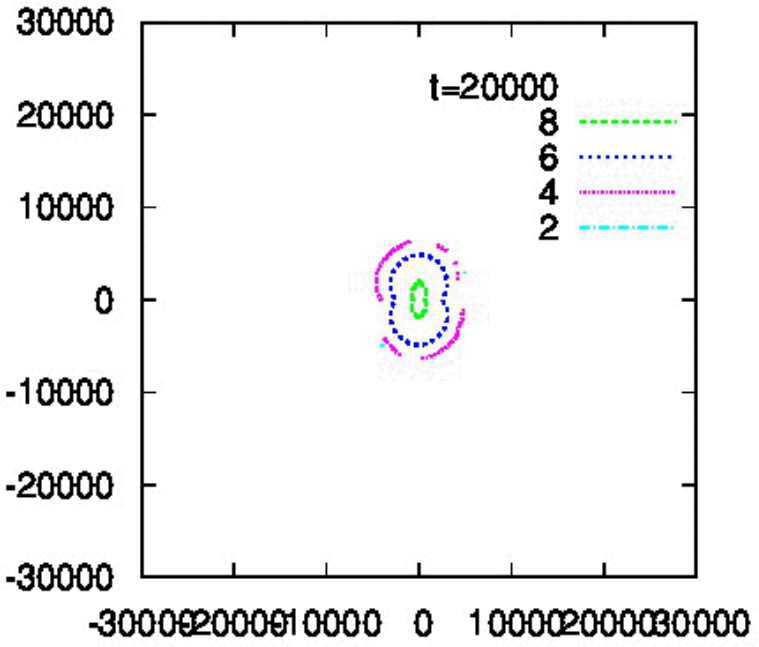
$$n_p \propto \left(\frac{1}{1+r/r_0}\right)^{\beta}$$

$$\frac{dN_{\rm CR}}{dr} \propto r^{-1}$$



Fermi Bubbles- Galactic Outflow

$$\frac{\partial}{\partial t} n(E) = \nabla \cdot D \nabla n(E) + \nabla \cdot v_{\rm adv} n(E) + Q(E, x, t)$$

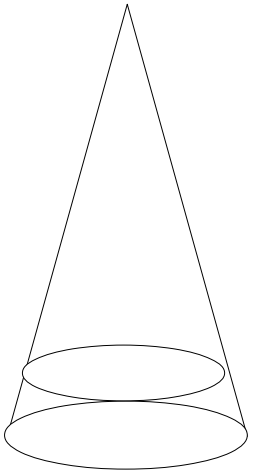


$$D(\mathrm{PeV}) = 10^{29}\ \mathrm{cm^2\ s^{-1}}$$

$$v_{\rm adv} = 30 - 300\ \mathrm{km\ s^{-1}}$$

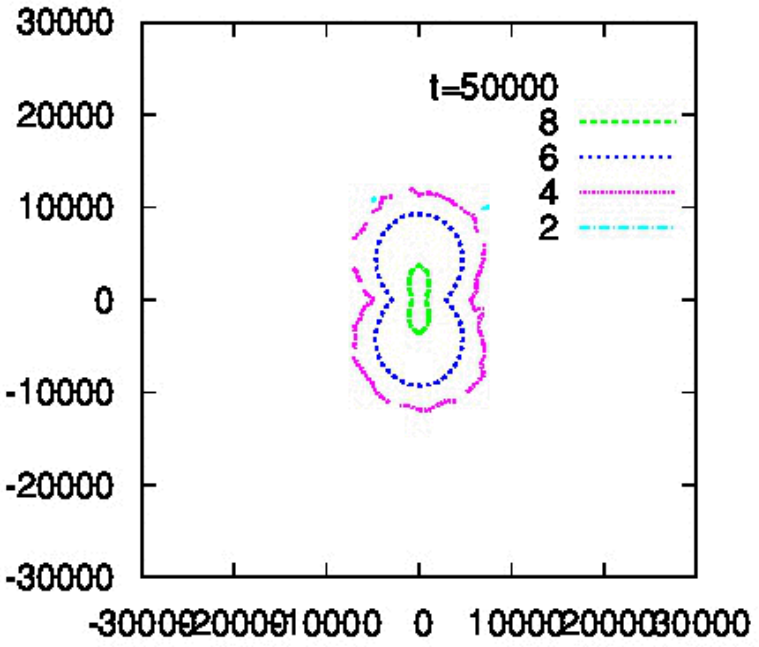
$$n_p \propto \left(\frac{1}{1+r/r_0}\right)^{\beta}$$

$$\frac{dN_{\rm CR}}{dr} \propto r^{-1}$$



Fermi Bubbles- Galactic Outflow

$$\frac{\partial}{\partial t} n(E) = \nabla \cdot D \nabla n(E) + \nabla \cdot v_{\rm adv} n(E) + Q(E, x, t)$$

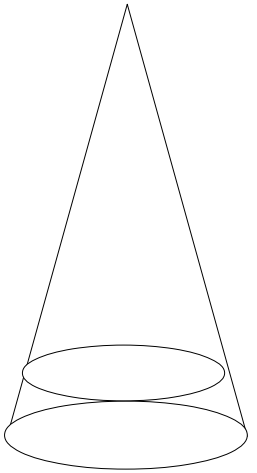


$$D(\mathrm{PeV}) = 10^{29}\ \mathrm{cm^2\ s^{-1}}$$

$$v_{\rm adv} = 30 - 300\ \mathrm{km\ s^{-1}}$$

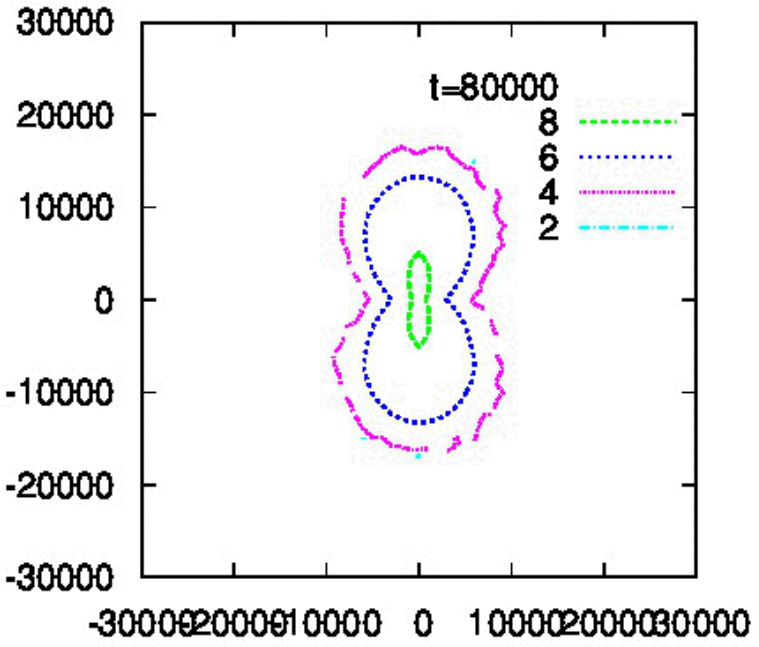
$$n_p \propto \left(\frac{1}{1+r/r_0}\right)^{\beta}$$

$$\frac{dN_{\rm CR}}{dr} \propto r^{-1}$$



Fermi Bubbles- Galactic Outflow

$$\frac{\partial}{\partial t} n(E) = \nabla \cdot D \nabla n(E) + \nabla \cdot v_{\rm adv} n(E) + Q(E, x, t)$$

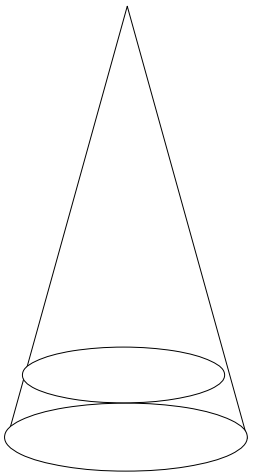


$$D(\mathrm{PeV}) = 10^{29}\ \mathrm{cm^2\ s^{-1}}$$

$$v_{\rm adv} = 30 - 300\ \mathrm{km\ s^{-1}}$$

$$n_p \propto \left(\frac{1}{1+r/r_0}\right)^{\beta}$$

$$\frac{dN_{\rm CR}}{dr} \propto r^{-1}$$



Aims

The IceCube neutrino flux

The cosmic rays connected to their production

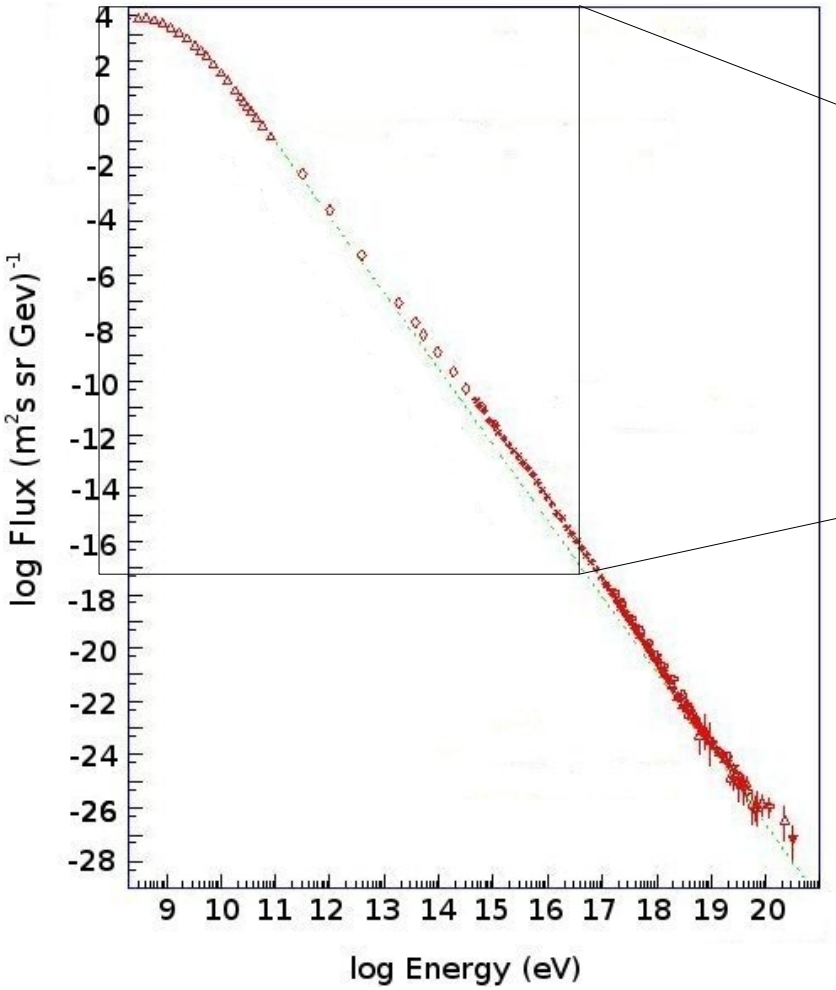
Bright Galactic γ-ray fluxes observed

New ν flux observations in a Galactic context

How to hide a > 10 x Crab sized flux!

Andrew
Taylor

The Cosmic Ray Flux



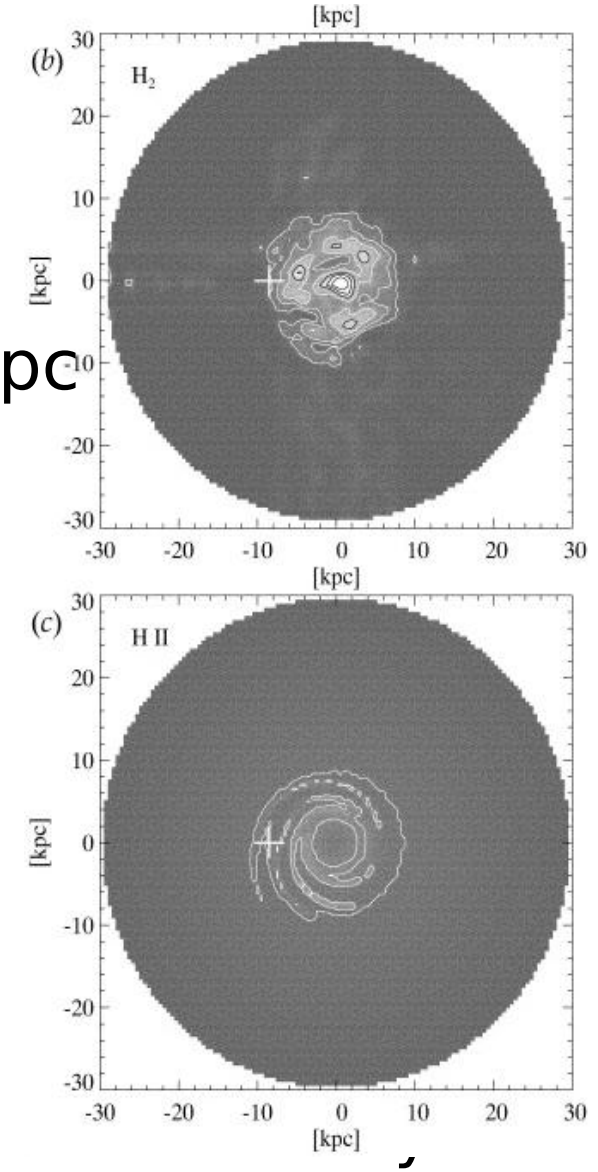
cosmic rays which may be Galactic in origin (diffuse on sub-Galactic scales in μG fields)

Galactic cosmic rays require a source power output of ~10^{41} erg s^{-1}

Andrew Taylor

Galactic Disk Matter Distribution

plot:(Hunter *et al.* 1997)
data: (Dame et al.)



Molecular Gas Target

molecular gas →

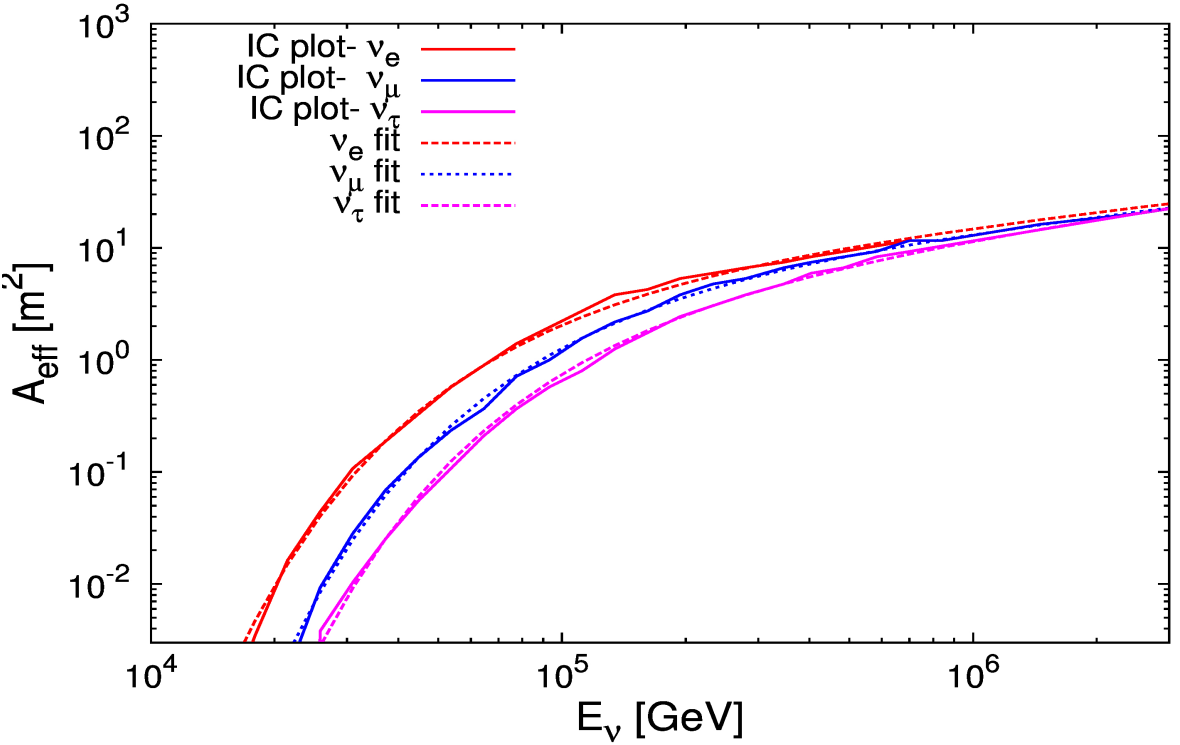
$n = n_0 e^{-\left(\frac{R}{R_{H_2}}\right)}$ where $n_0 = 4\ \mathrm{cm}^{-3}$, $R_{H2} = 2.6$ kpc

(Misiriotis *et al.* 2006)- inferred using CO measurements and the $\mathbf{X_{factor}}$ relation

(possible enhancement)

existence of a density enhancement of $n_p \sim 10^4\ \mathrm{cm}^{-3}$ in central 200 pc (containing 10% of all H_2) should be noted

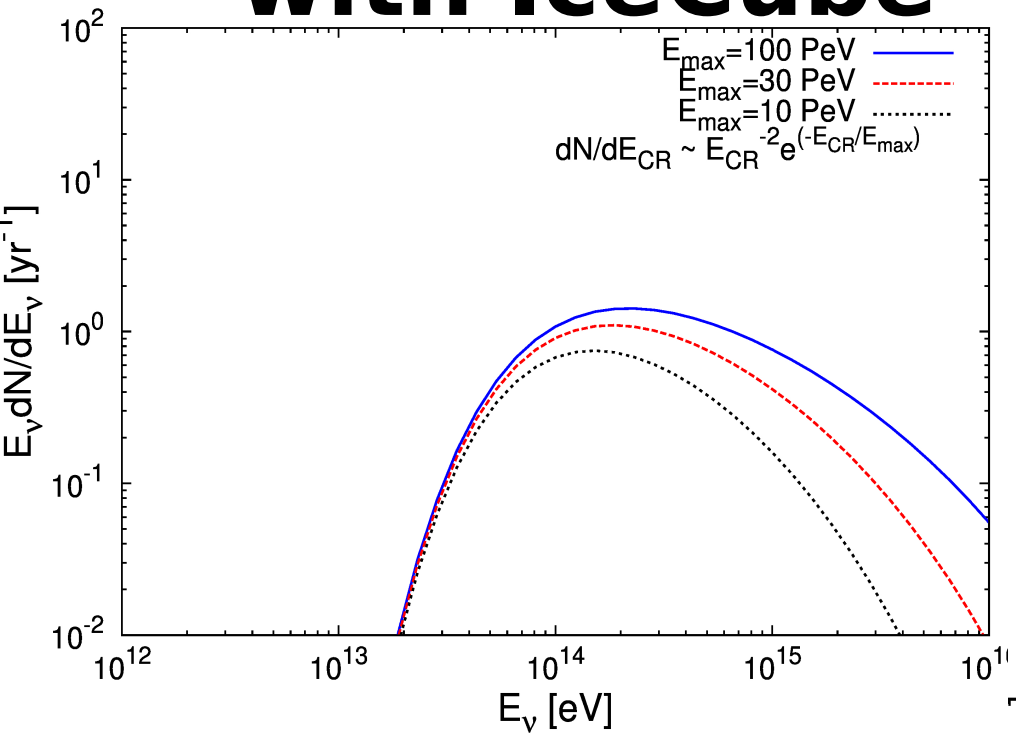
Effective Area of IceCube



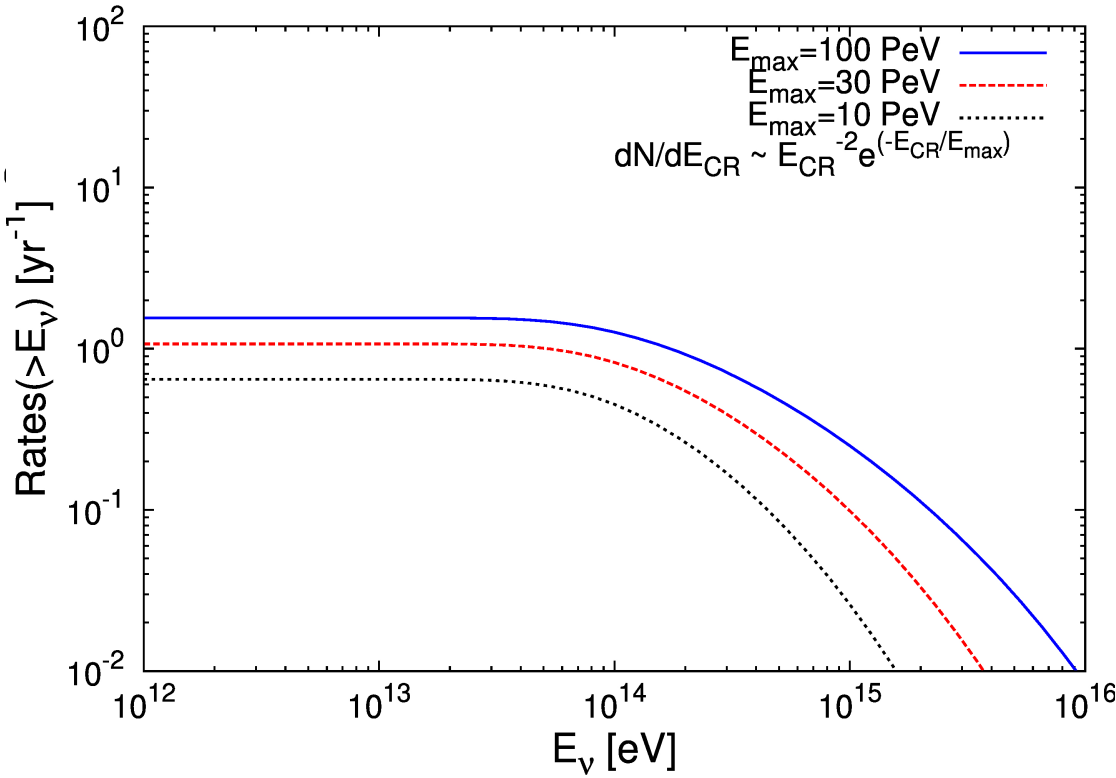
$$A^{\nu}_{\mathbf{eff}} = A_0 \left(\frac{E_\nu}{\mathrm{TeV}}\right)^{\gamma} e^{-E_b/E_\nu}$$

Andrew Taylor

Galactic Plane-Flux Detection with IceCube



Low rates expected →



A Galactic Pevatron?

$$L = \frac{V \rho_{\mathrm{CR}}}{\tau}$$

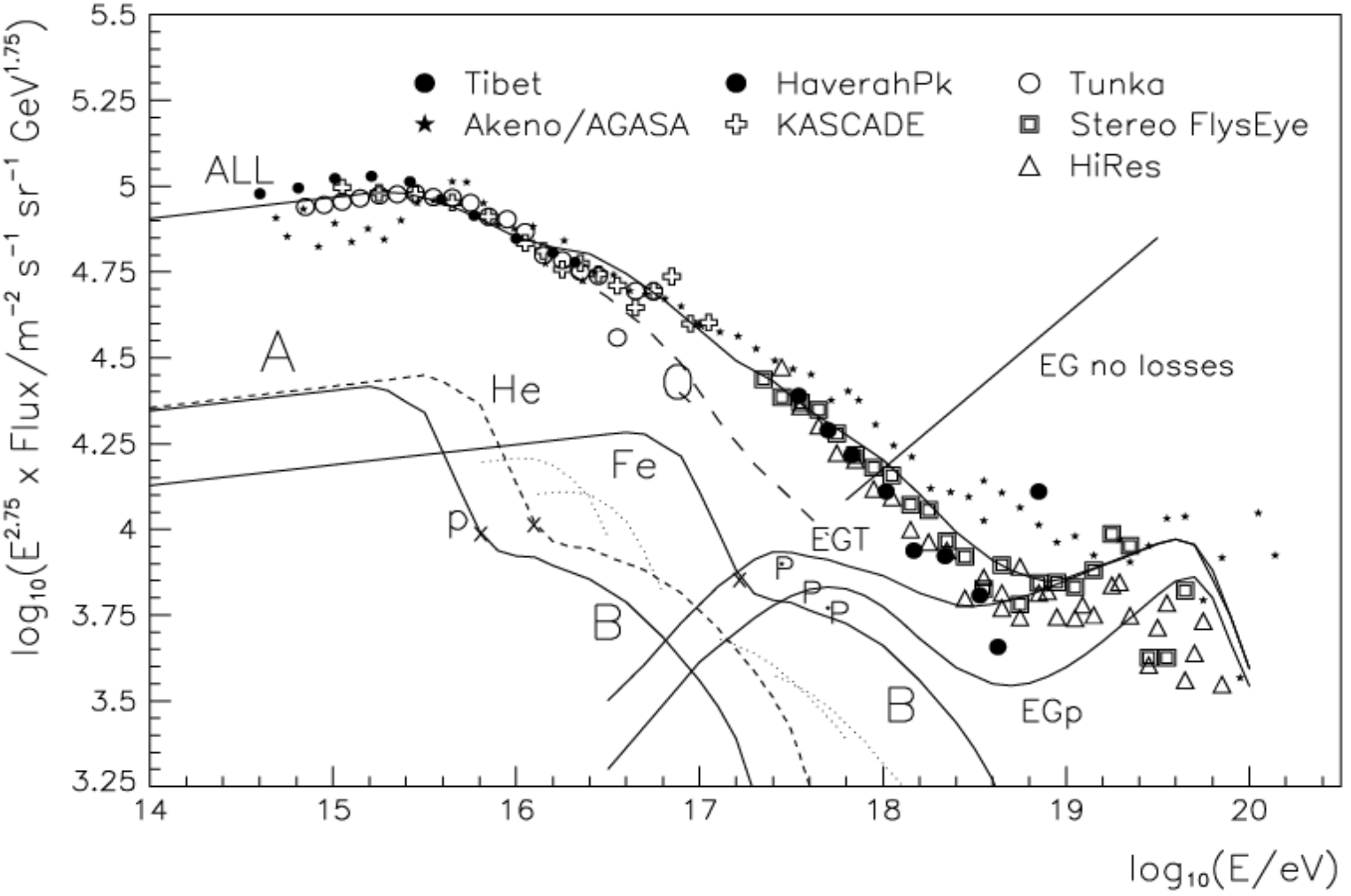
$$V = \pi R^2 h \approx 10^{66}\ \mathrm{cm}^3$$

$$\rho \approx\ \mathrm{eV\ cm}^{-3}$$

$$\tau \approx 10^7\ \mathrm{yrs}$$

Andrew
Taylor

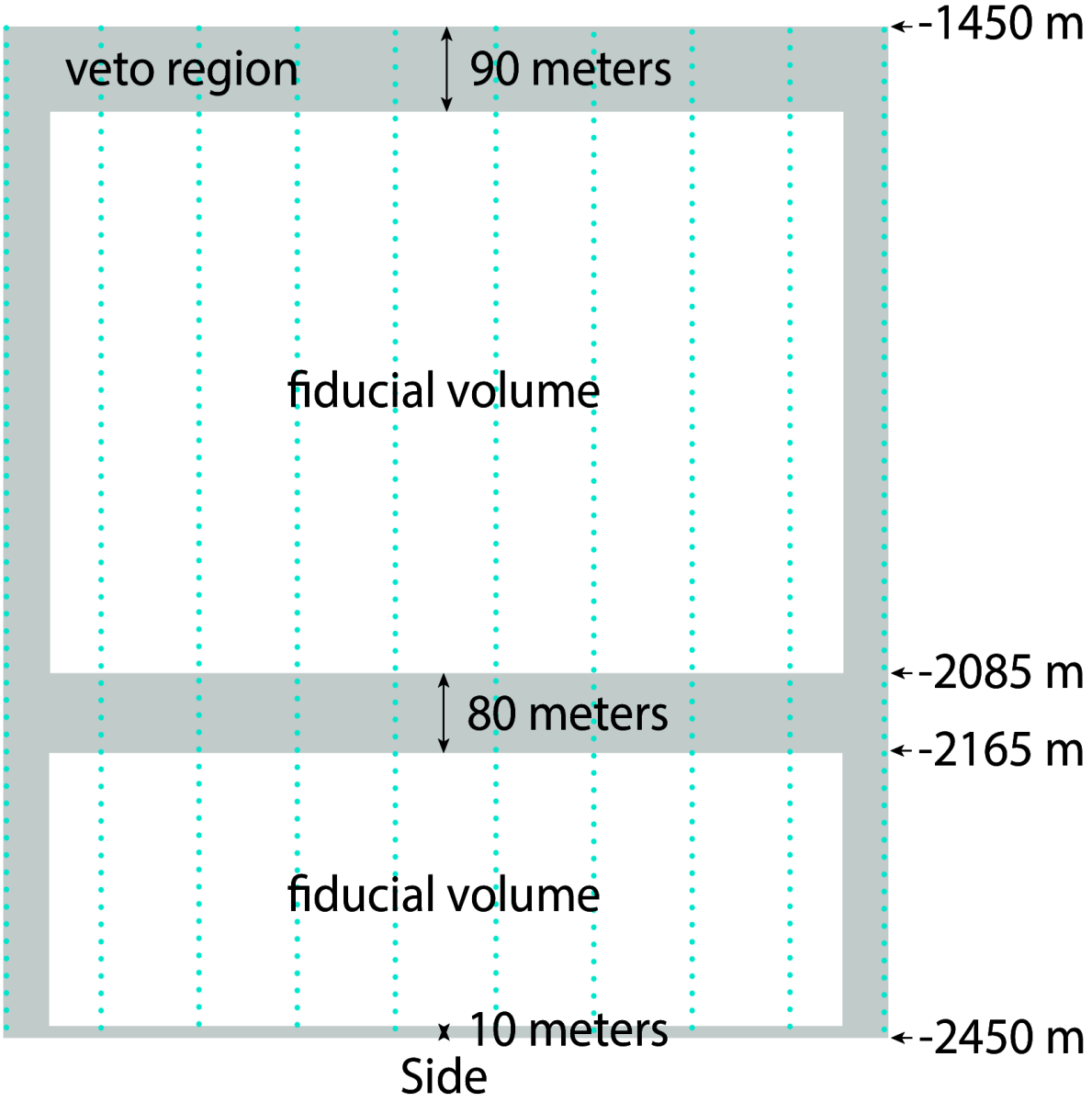
Bridging the PeV-EeV Gap



Naively, source “B” requires a CR proton luminosity of $\sim 10^{39}$ erg s^{-1}

Andrew Taylor

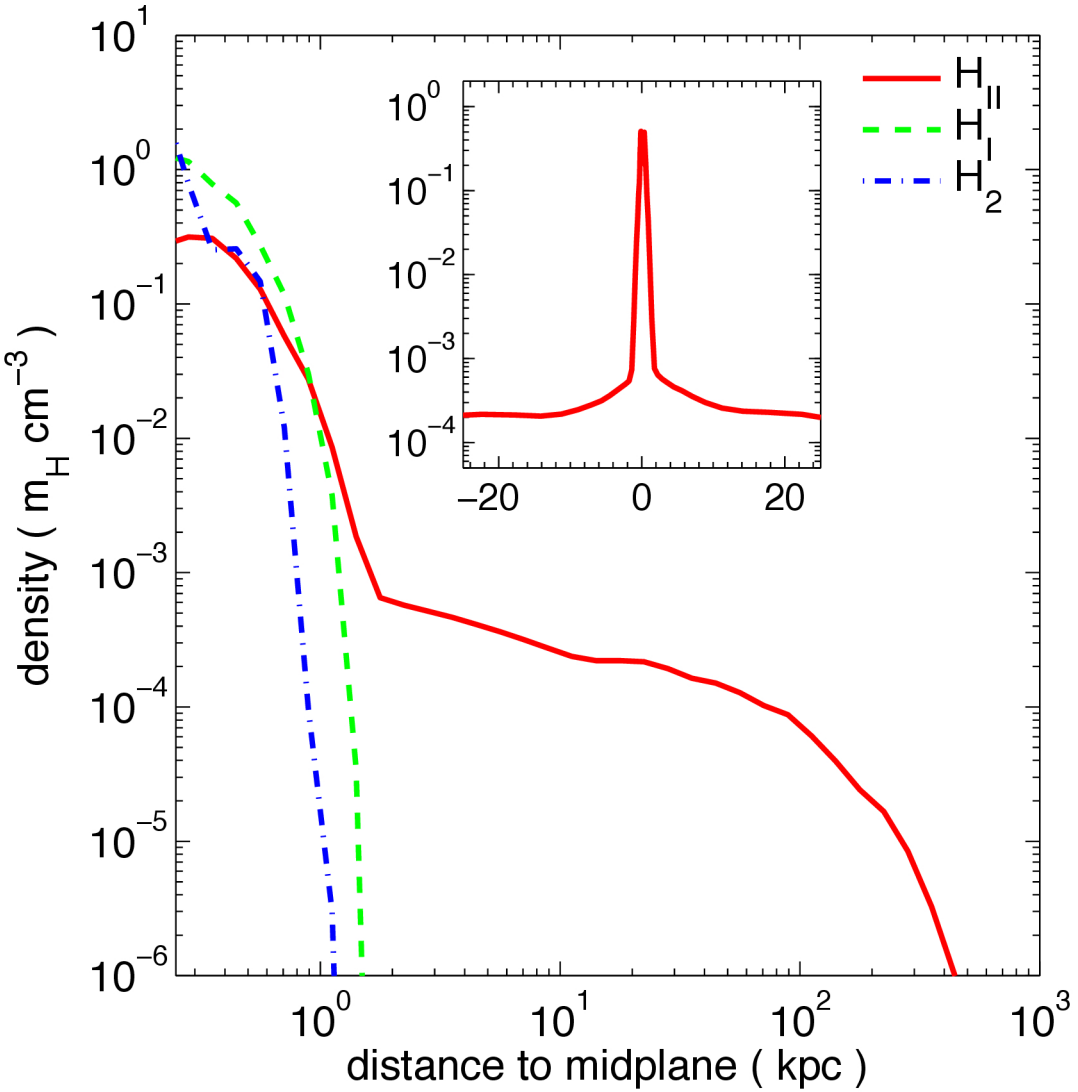
IceCube Can Look Up?



Andrew
Taylor

Galactic Halo Matter Distribution?

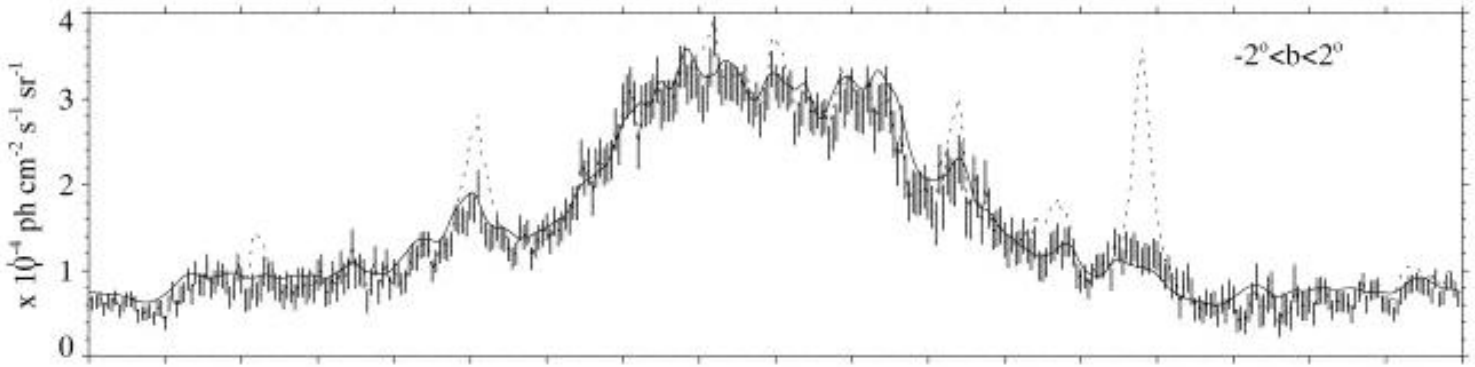
From Feldmann et al. 2012- astro-ph/1205.0249



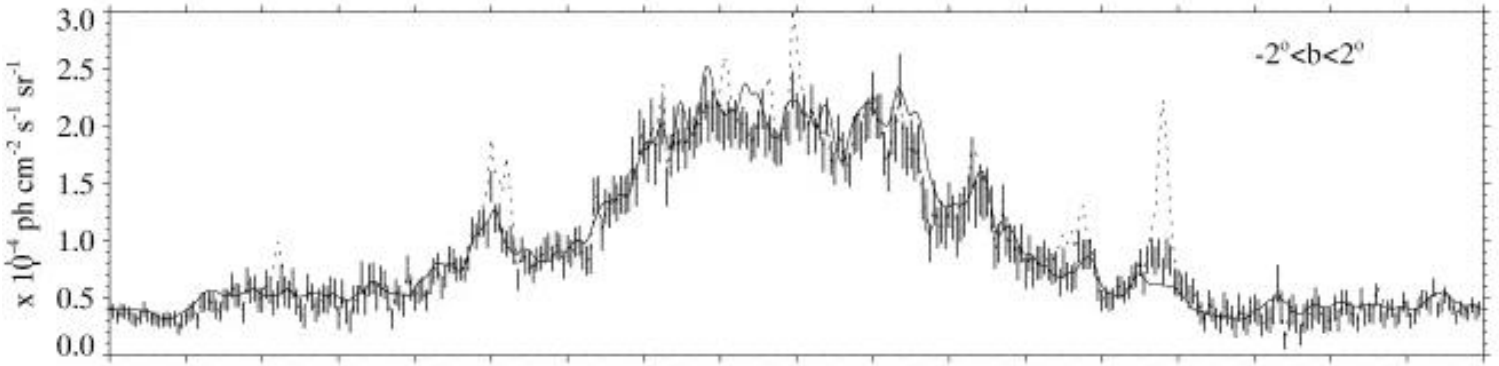
Andrew Taylor

The EGRET (~GeV) Observations

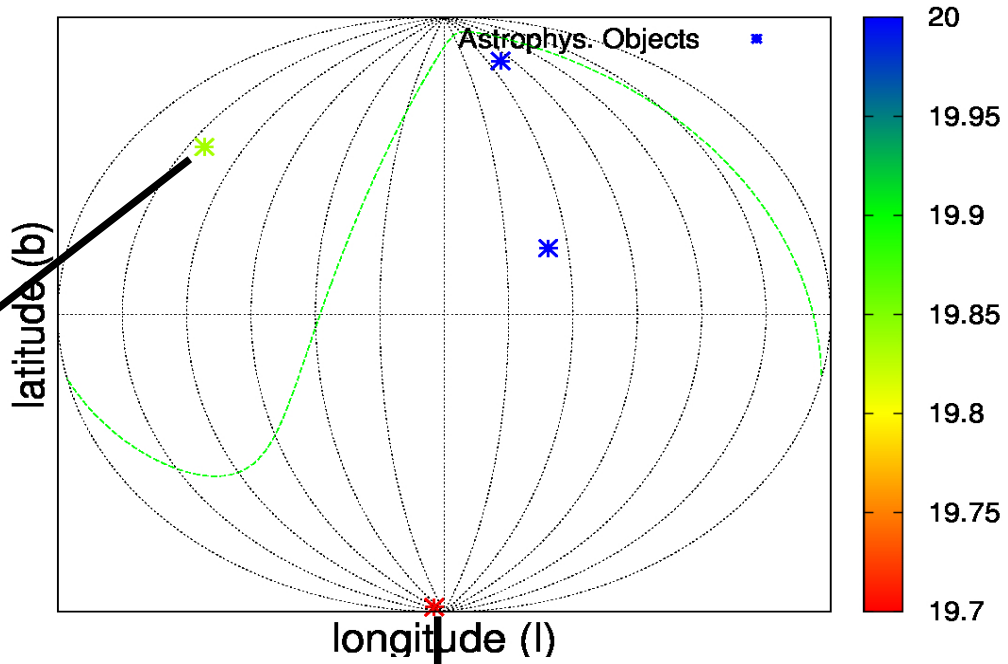
Spatial Distribution of EGRET Signal (100-300 MeV)-

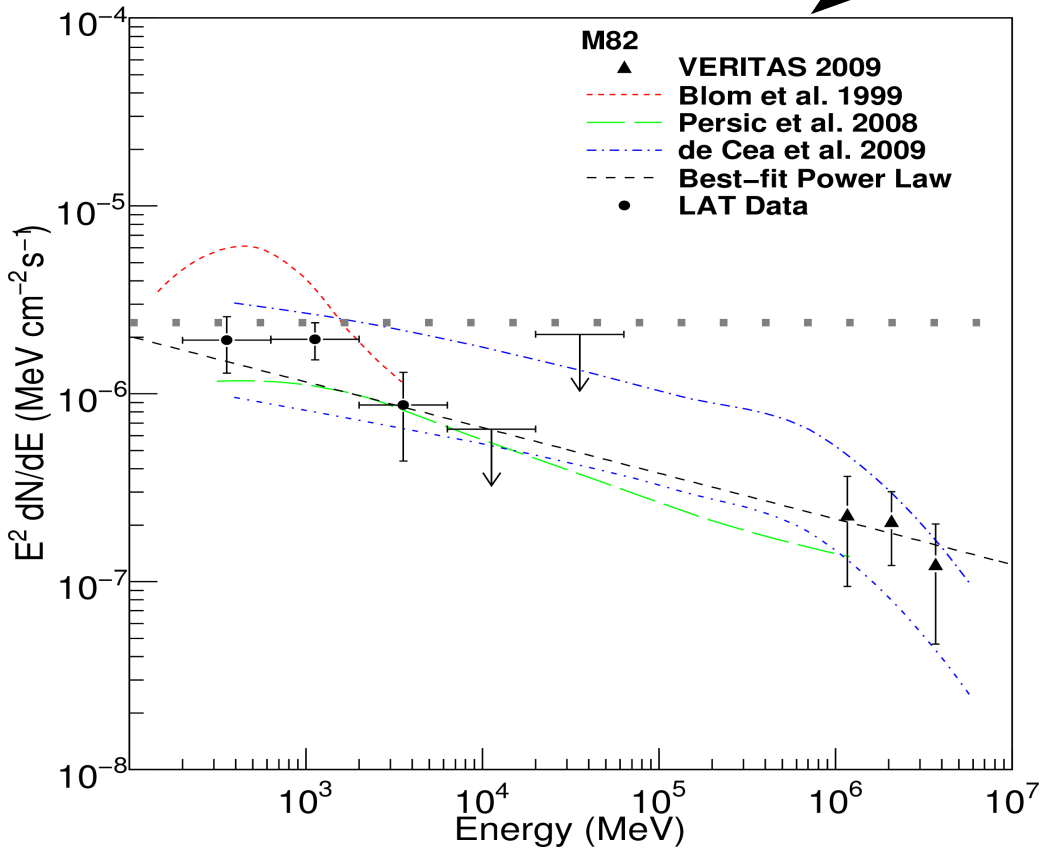


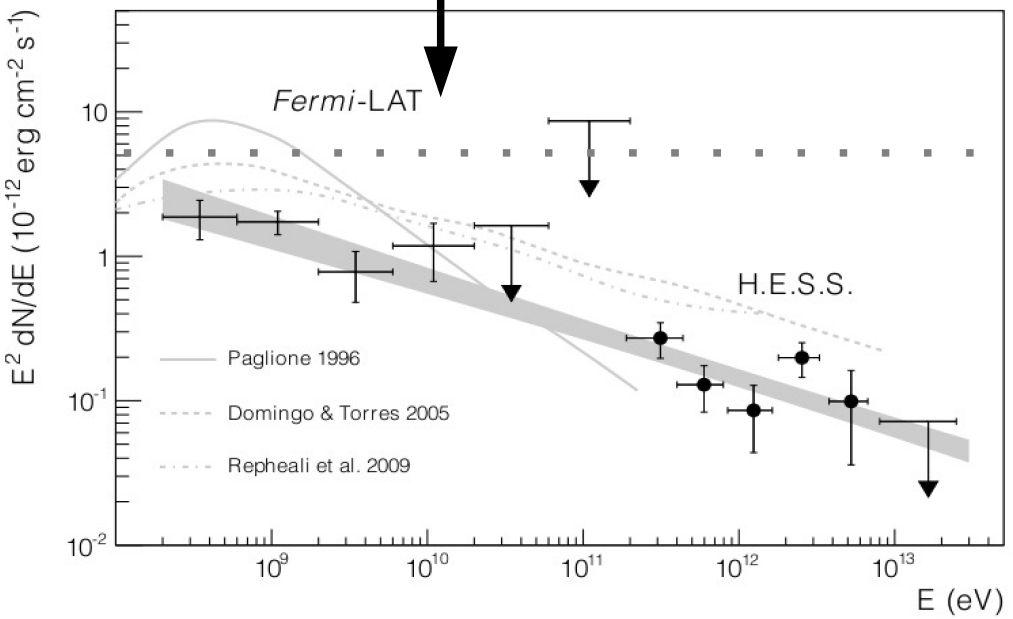
Spatial Distribution of EGRET Signal (300-1000 MeV)-



Local AGN/Starburst Galaxies Detected at TeV







A **Galactic Halo Origin** for the Diffuse Neutrino Flux Detected by IceCube

Based on the work by:

A. Taylor

S. Gabici

F. Aharonian

E. Kafexhiu

G. Vila

astro-ph/0806.2459

astro-ph/1403.3206

astro-ph/1406.7369

Cosmic Ray Proton-Proton Pion Production

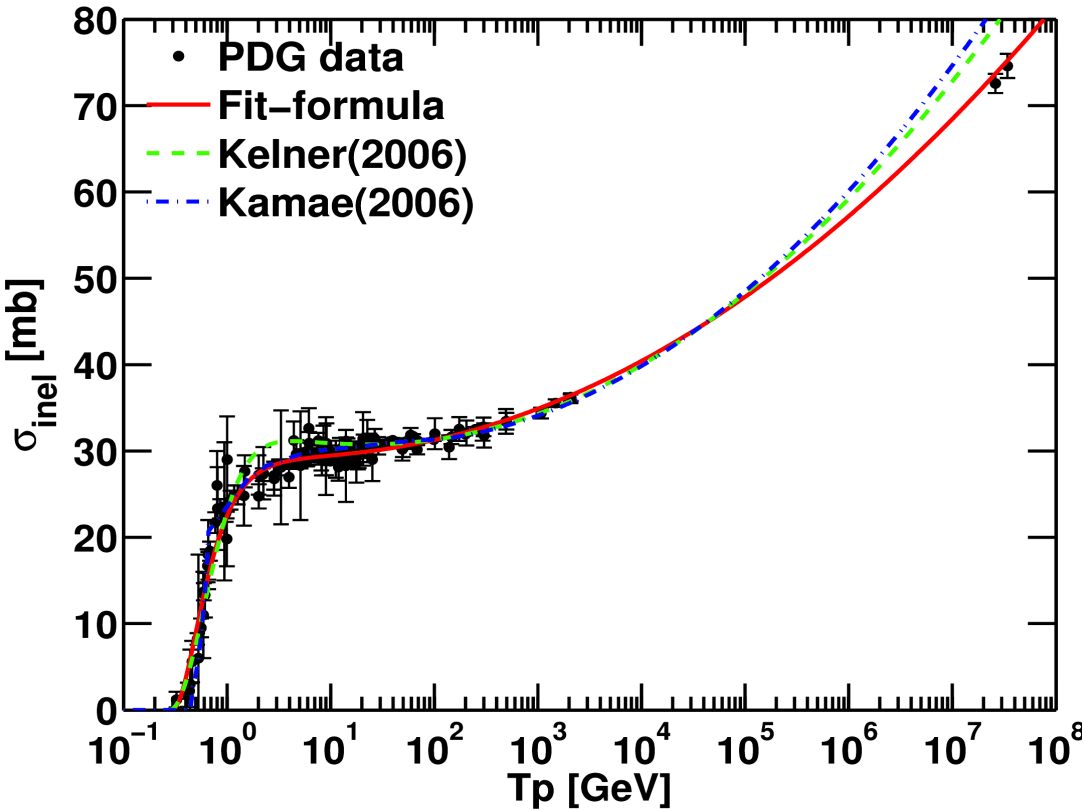
Proton-Proton Pion Production (threshold)-

$$p + p \rightarrow p + p + \pi^0$$

$$E_p^{th} = \frac{\left[(2m_p + m_\pi)^2 - 2m_p^2\right]}{2m_p} \sim 1.23 \text{ GeV}$$

note- threshold value is in lab frame

astro-ph/1406.7369



Cosmic Ray Proton-Proton Pion Production

$$Y_\gamma = E_\gamma + \frac{m_\pi^2}{4E_\gamma}$$

$$Y_\gamma^{\max} = E_\gamma^{\max} + \frac{m_\pi^2}{4E_\gamma^{\max}}$$

$$X_\gamma = \frac{Y_\gamma - m_\pi}{Y_\gamma^{\max} - m_\pi}$$

$$\frac{dN}{dE_\gamma} = \frac{\left(1 - X_\gamma^{\alpha(T_p)}\right)^{\beta(T_p)}}{\left(1 + \frac{X_\gamma}{C}\right)^{\gamma(T_p)}}$$

astro-ph/1406.7369