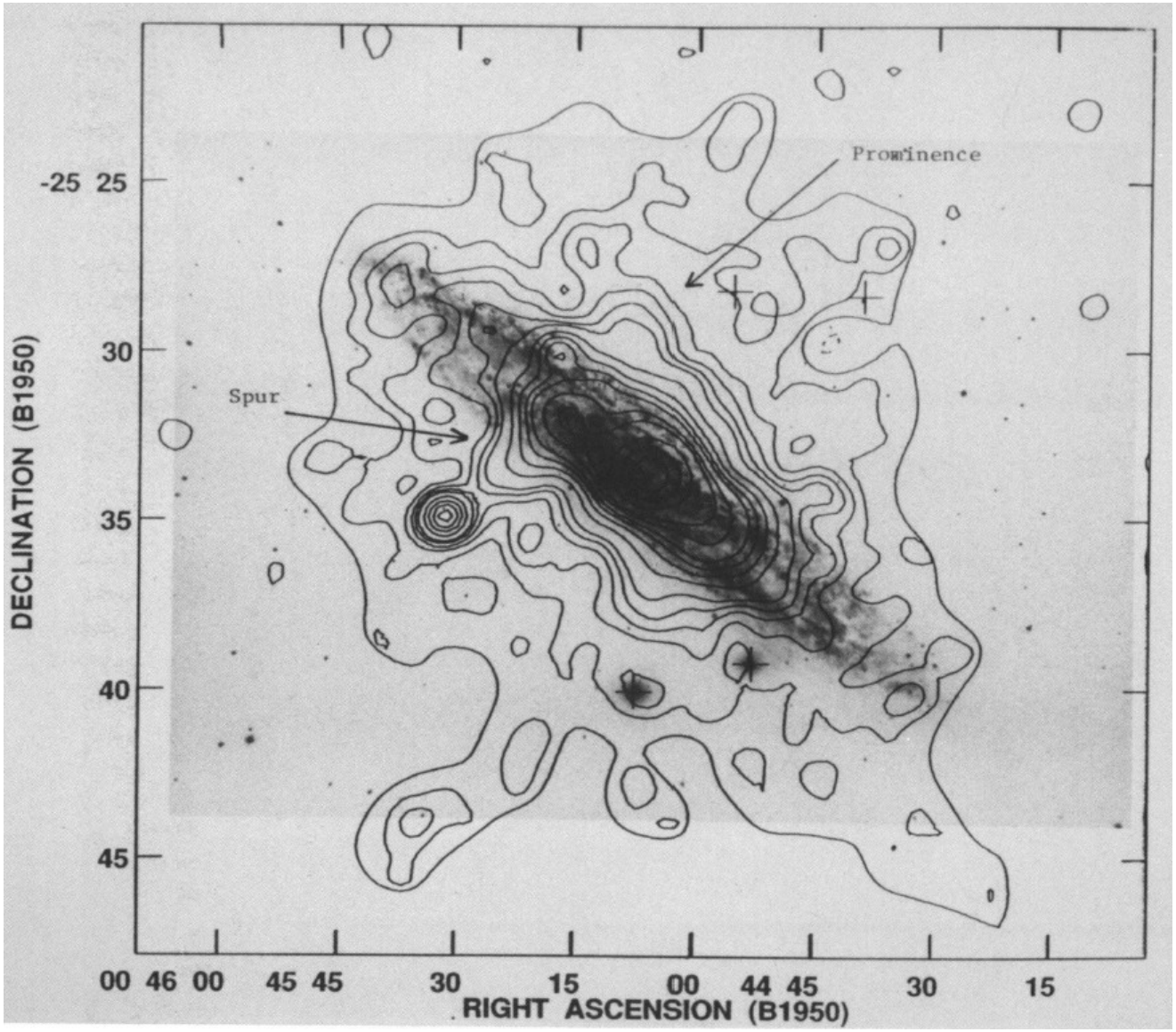
Galactic Outflows, Cosmic Rays, and Non-Thermal Signatures



Andrew Taylor

Outline

- Evidence for Galactic Center Based Outflow
- Description of Outflow
- Fate of Cosmic Rays Embedded in Outflow
- Potential Secondary Signatures of Non-Thermal Emission
- Other Avenues....Not Disconnected!

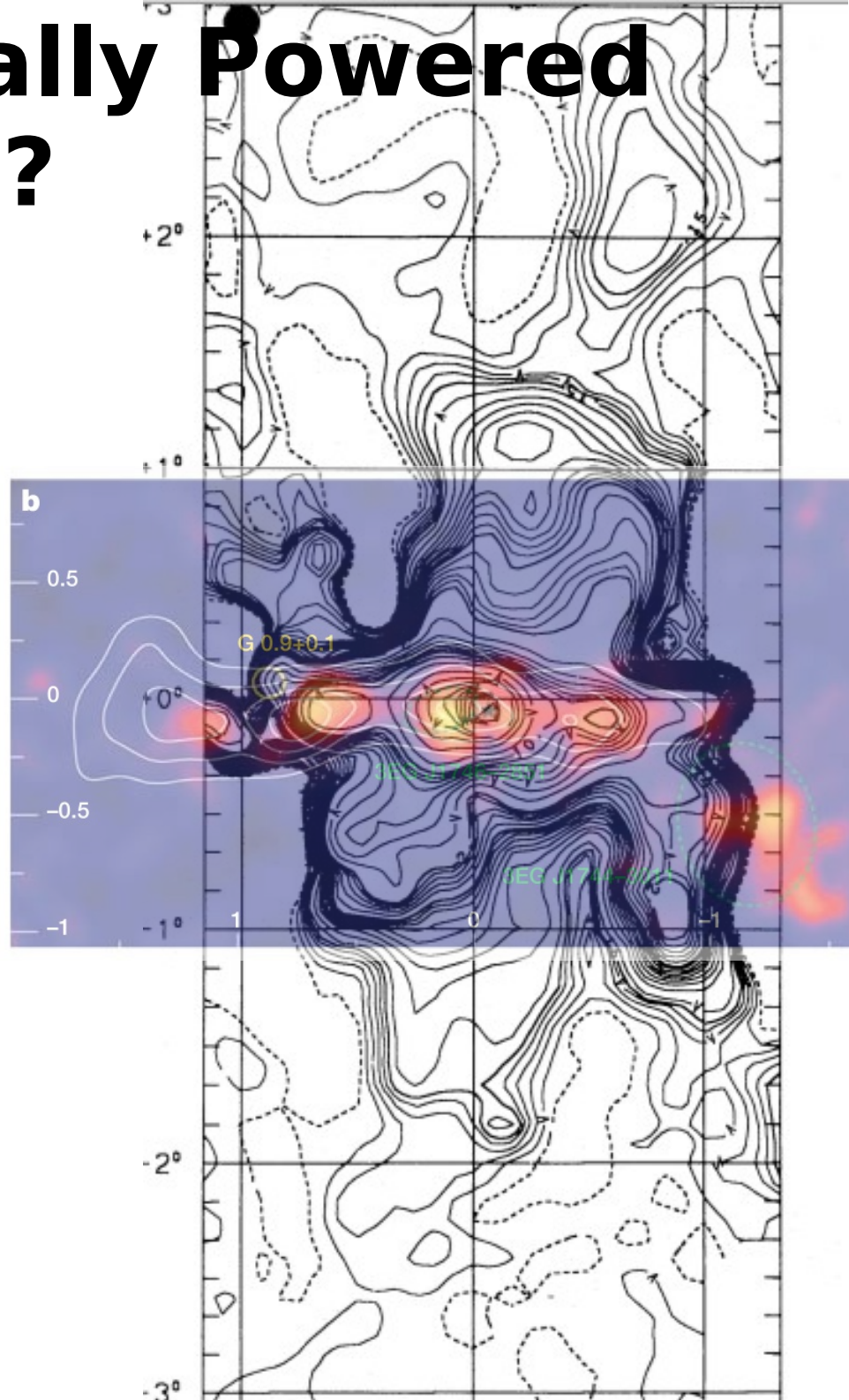
Andrew
Taylor

Evidence of Centrally Powered Escape?

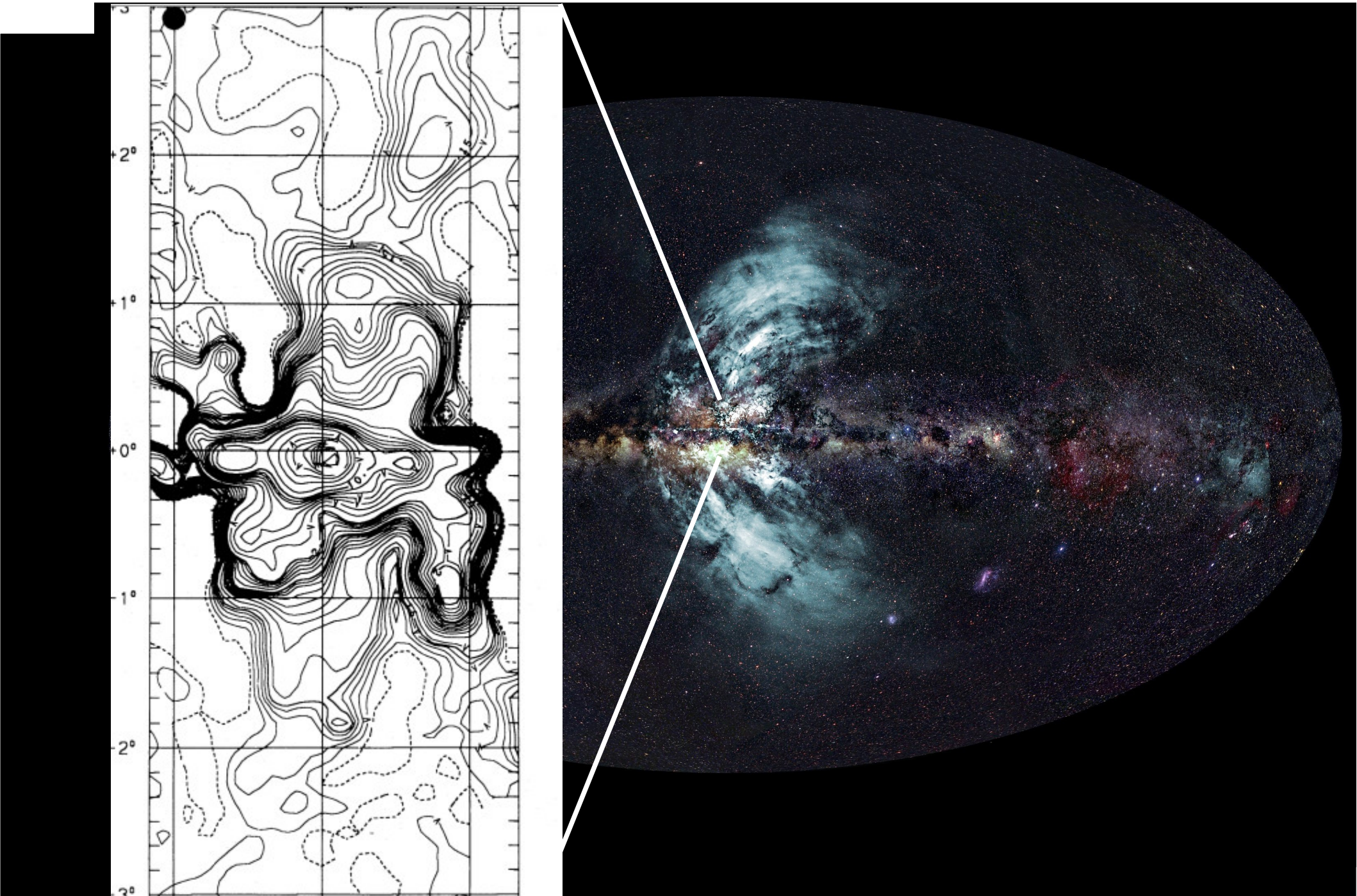
$$v_{\mathrm{wind}} \approx 500 - 1000 \ \mathrm{km\ s^{-1}}$$

$$\dot{M} \approx 0.1 \ M_{\odot} \ \mathrm{yr^{-1}}$$

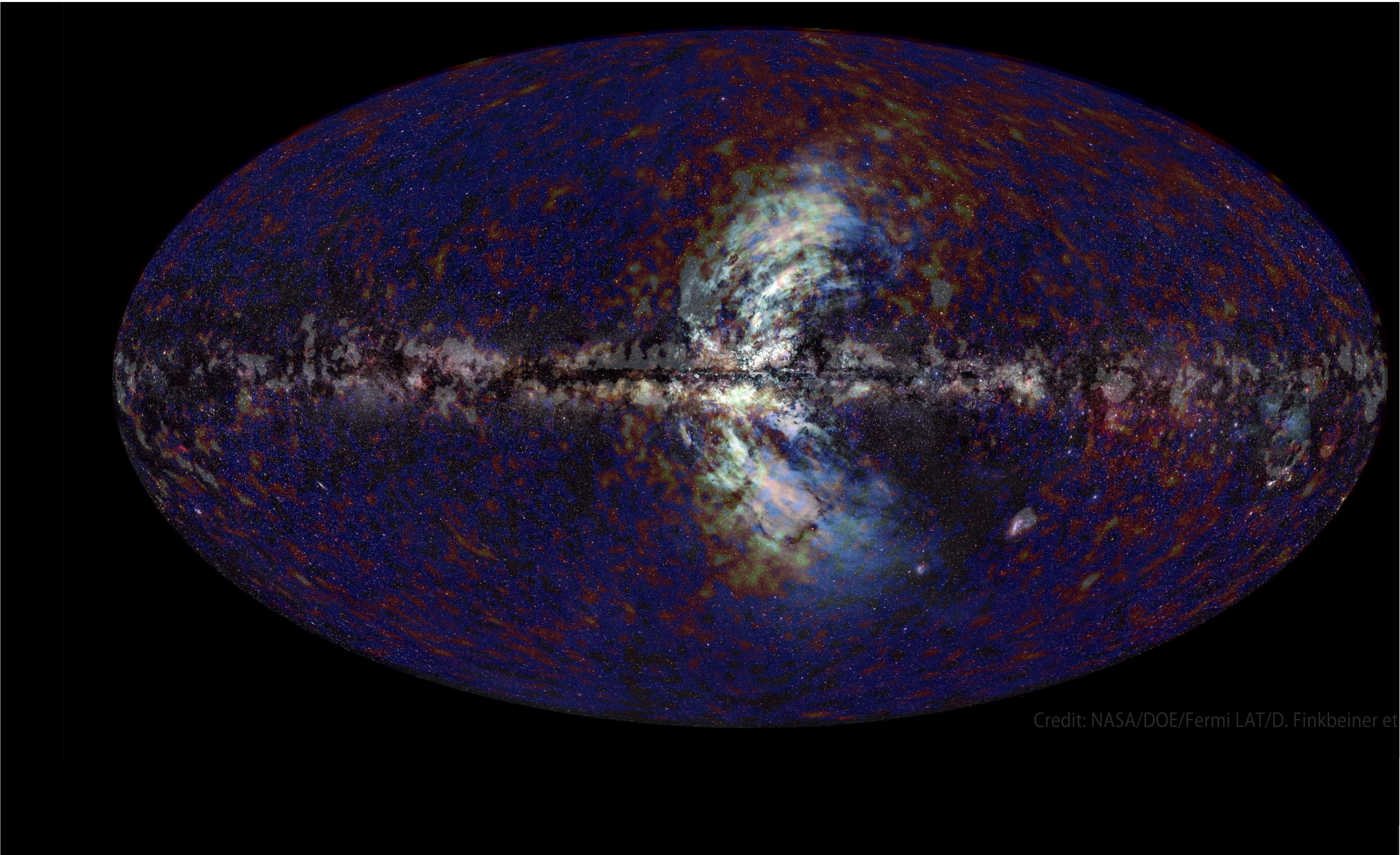
$$\dot{E}_{\mathrm{wind}} \approx 3 \times 10^{40} \ \mathrm{erg\ s^{-1}}$$



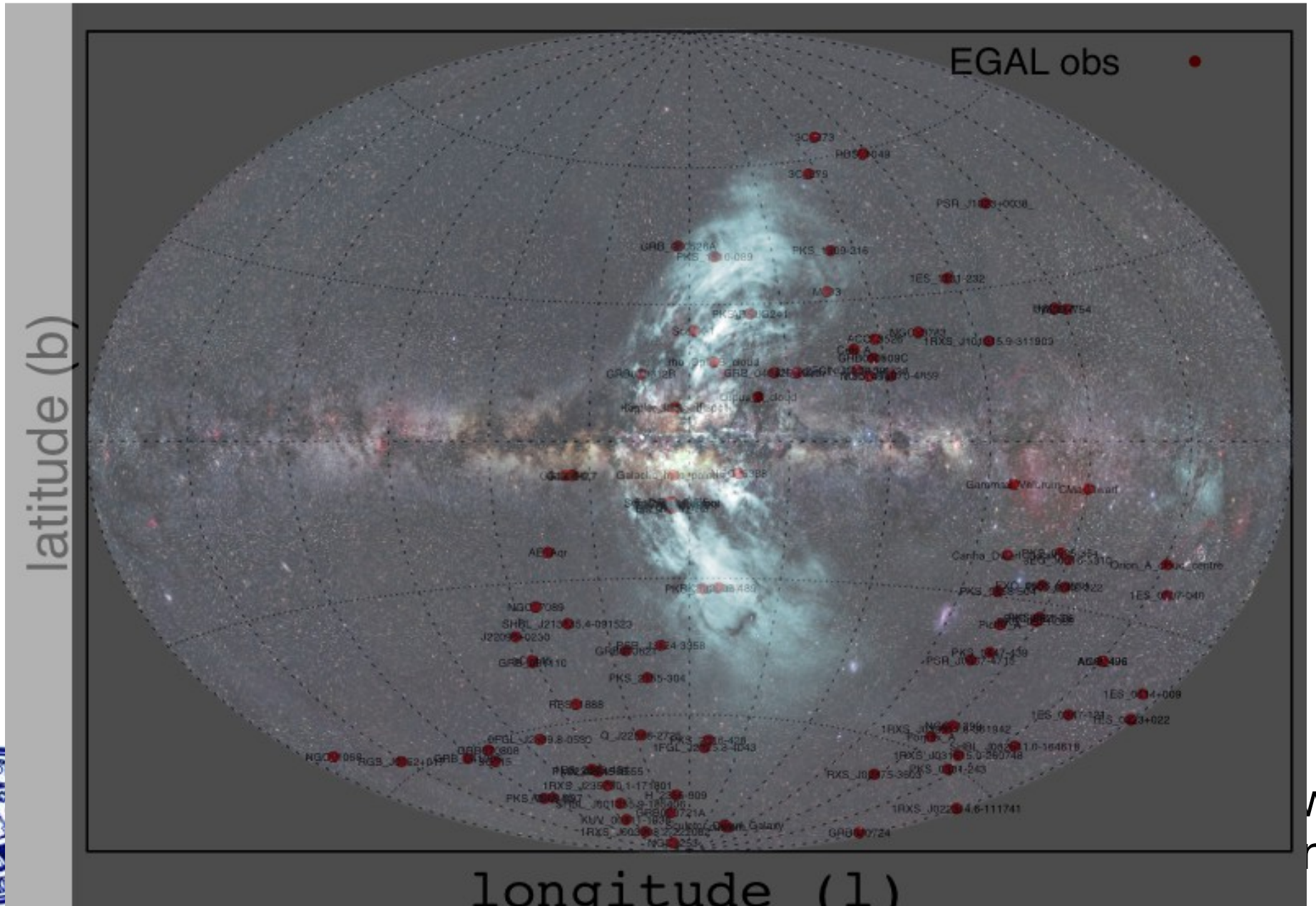
Galactic Diffuse Radio Emission



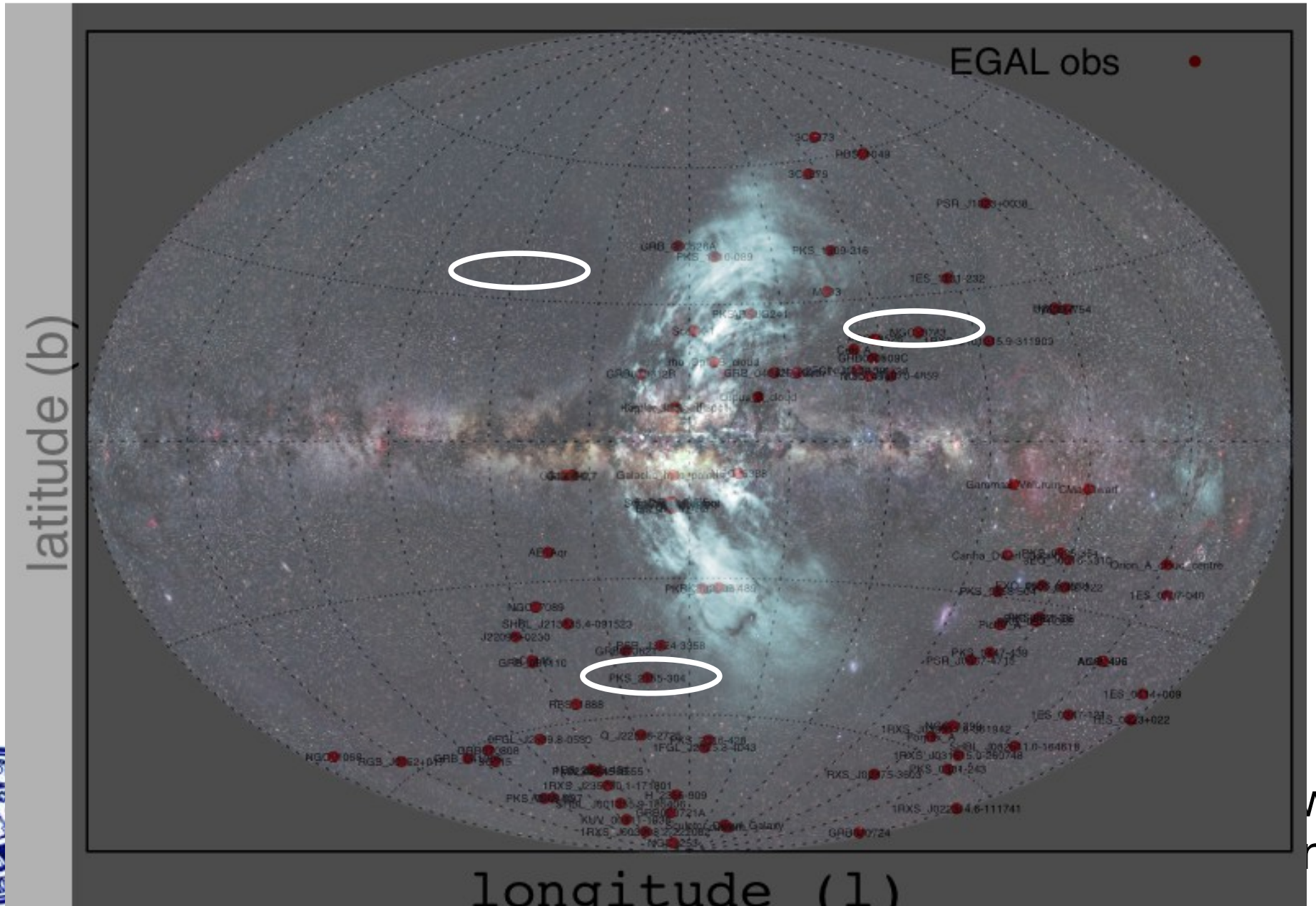
Galactic Diffuse Gamma/Radio



Bright AGN Sitting Close to/Behind the Bubbles

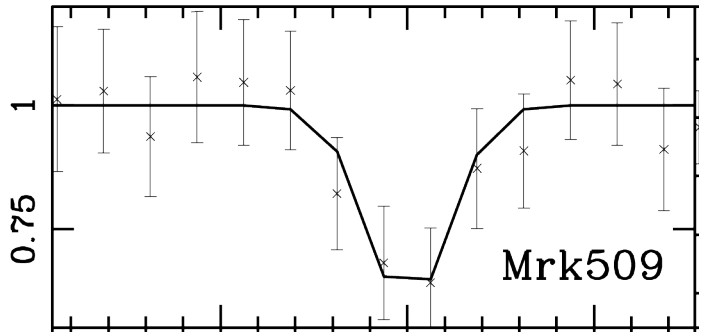


Bright AGN Sitting Close to/Behind the Bubbles



Hot Gas Out in the Halo

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:



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

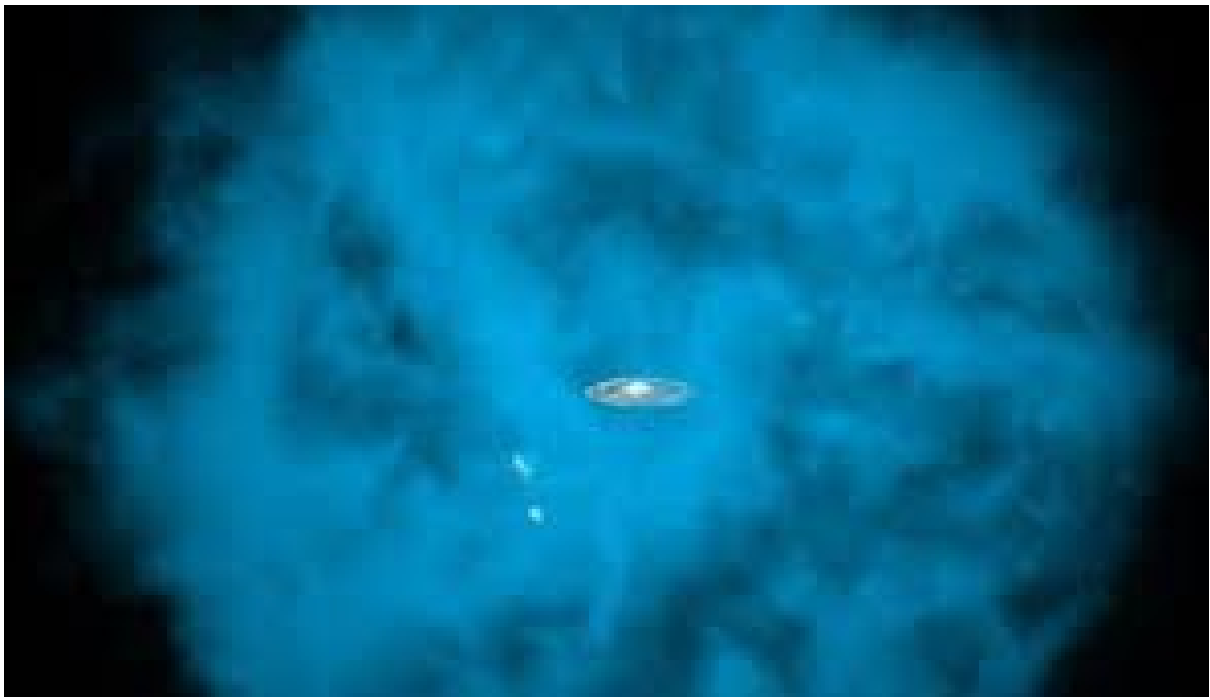
Inside a sphere of size

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

Gives a mean density of this gas of

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

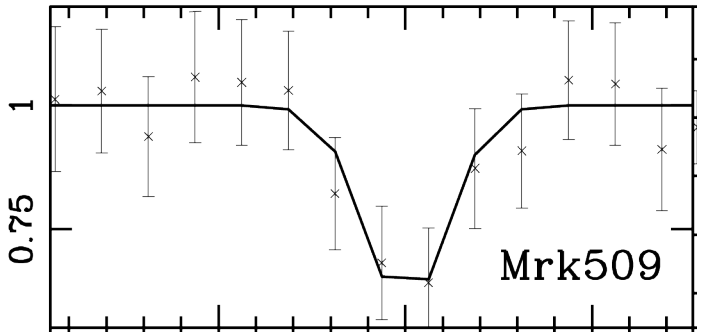
$$kT \approx 140\ \mathrm{eV}$$



Andrew Taylor

Hot Gas Out in the Halo

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:



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

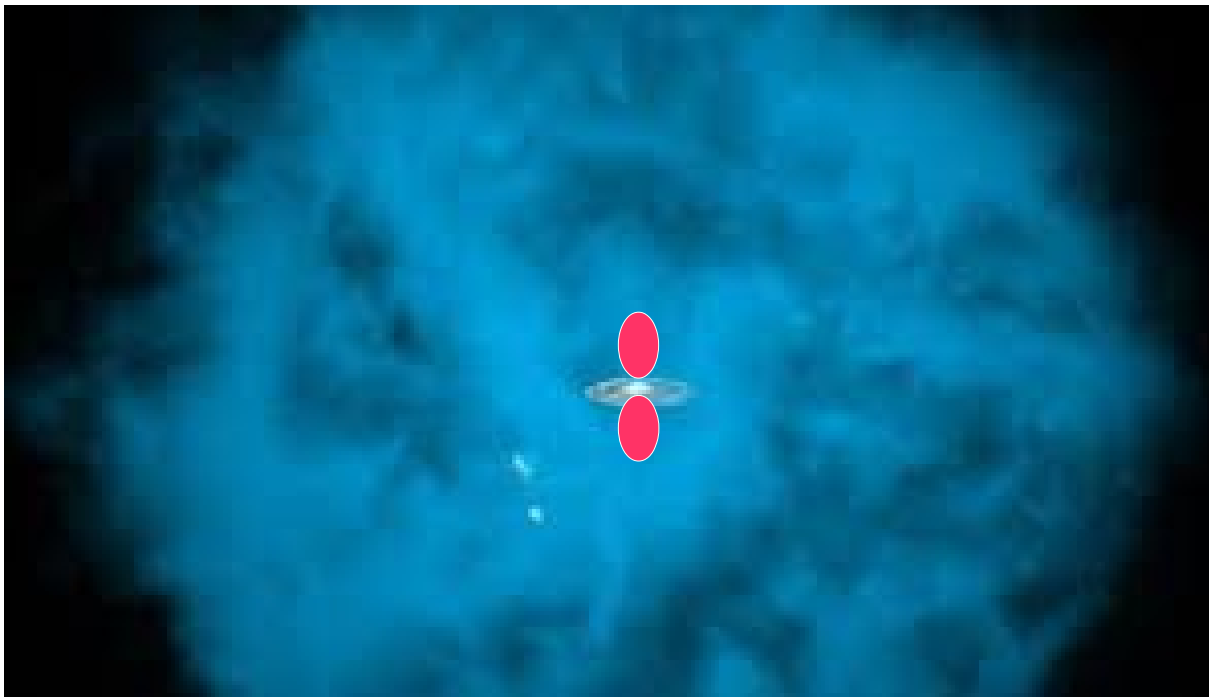
Inside a sphere of size

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

Gives a mean density of this gas of

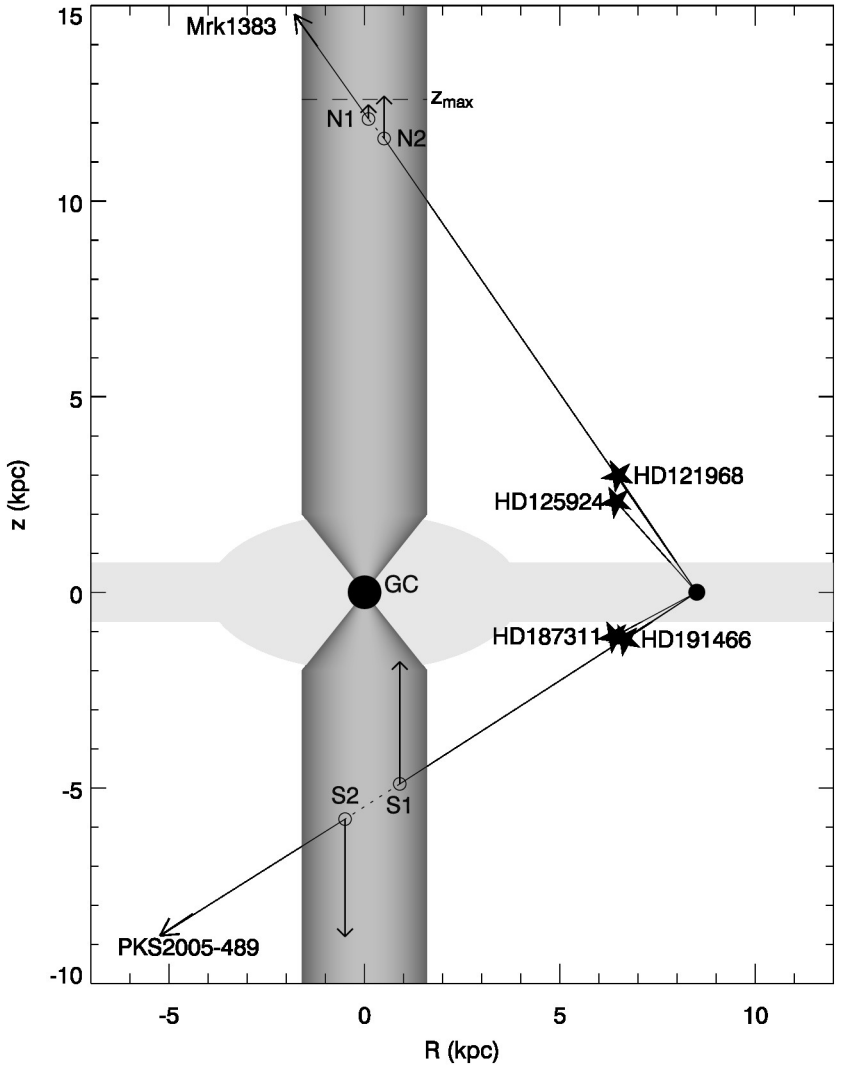
$$n_p \approx 10^{-3}\ \mathrm{cm}^{-3}$$

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



Andrew Taylor

Indicators of Outflow Profile



Absorption lines from partially ionised gas constrain velocity of ejected clumps N1, N2 (~50 km s^{-1}) and S1, S2 (~150 km s^{-1})

Bending of radio bubble structures indicates <50 km s^{-1} velocities in outer region

Such observations are consistent with outflows seen in other nearby systems (eg. NGC 4631, NGC 253)

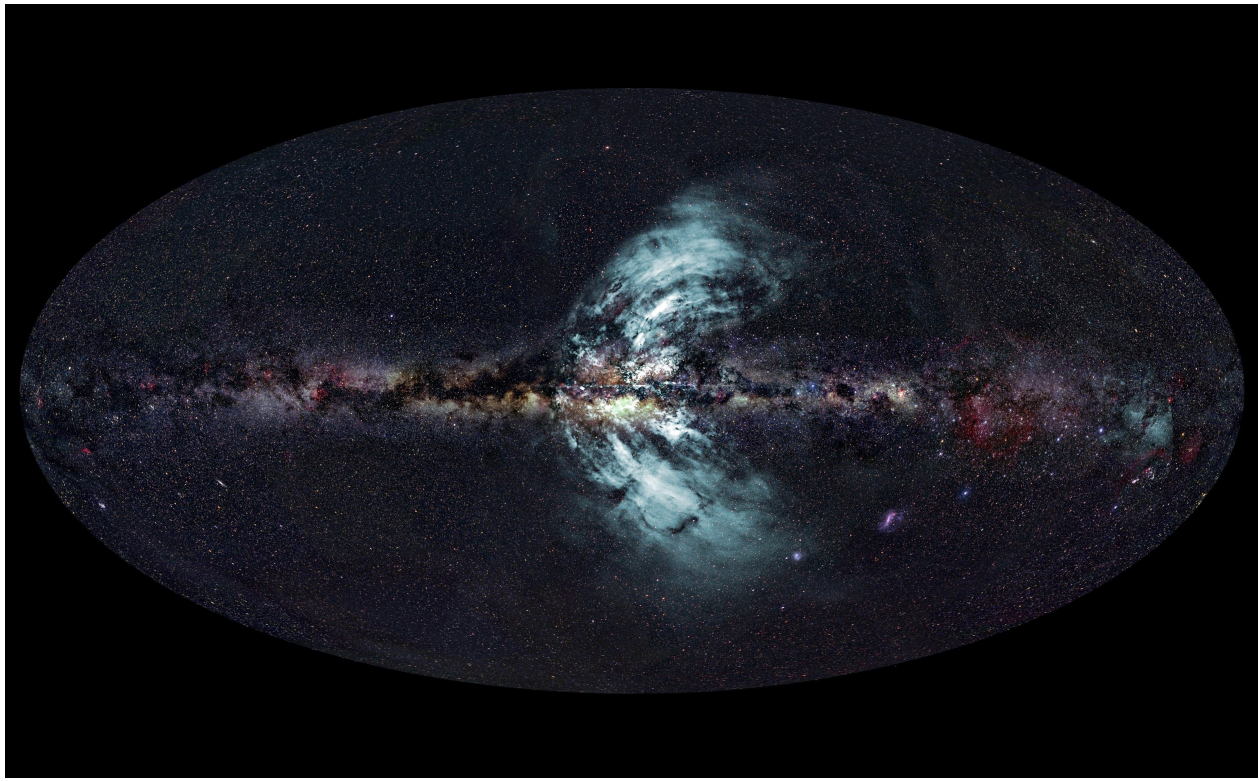
Keeney et al. 2006

Andrew Taylor

Are Magnetic + Cosmic Ray Pressure Important In Outflow?

Minimum energy arguments for synchrotron emission give

$$B_{\mathbf{min}} = 6\ \mu G$$



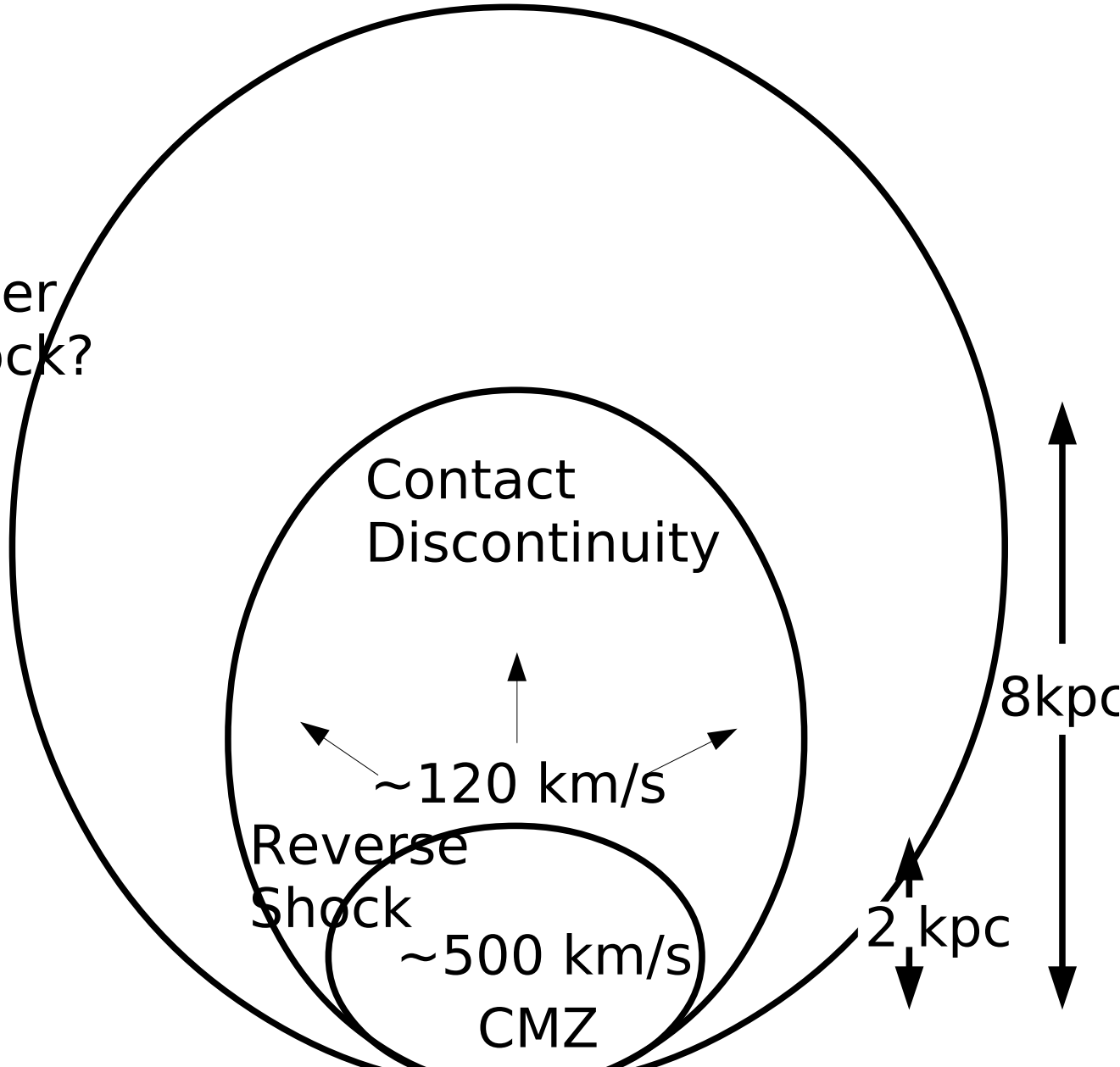
$$U_B^{\mathbf{FB}}(6\mu\ \mathrm{G}) \approx\ \mathbf{eV\ cm^{-3}}$$

$$U_{\mathbf{CR}}^{\mathbf{FB}} \approx\ \mathbf{eV\ cm^{-3}}$$

$$P_{\mathbf{th}}^{\mathbf{FB}} \approx\ \mathbf{eV\ cm^{-3}}$$

Andrew Taylor

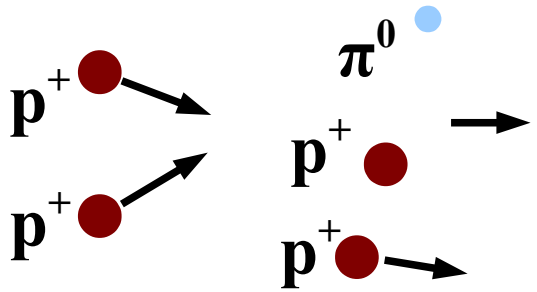
Origin of Galactic Bubble



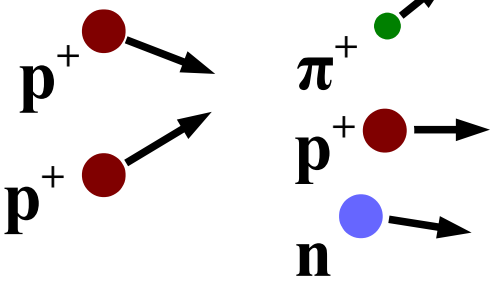
Radiative Signature of Non-Thermal Protons

$$\tau_e \approx 6 \times 10^7 \left(\frac{5\ \mathrm{GeV}}{E_e}\right)\left(\frac{6\ \mu\mathrm{G}}{B}\right)^2\ \mathrm{yrs}$$

$$\tau_p \approx 10^{10} \left(\frac{3\times10^{-3}\ \mathrm{cm}^{-3}}{n_p}\right)\ \mathrm{yrs}$$

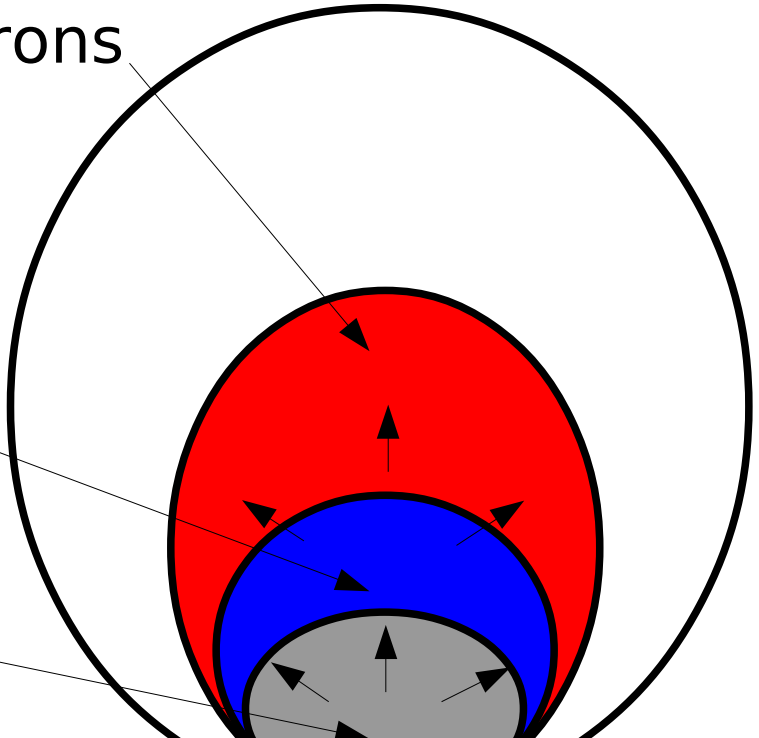


primary protons + secondary electrons present



primary electrons present

primary proton injection



Radiative Signature of Non-Thermal Electrons

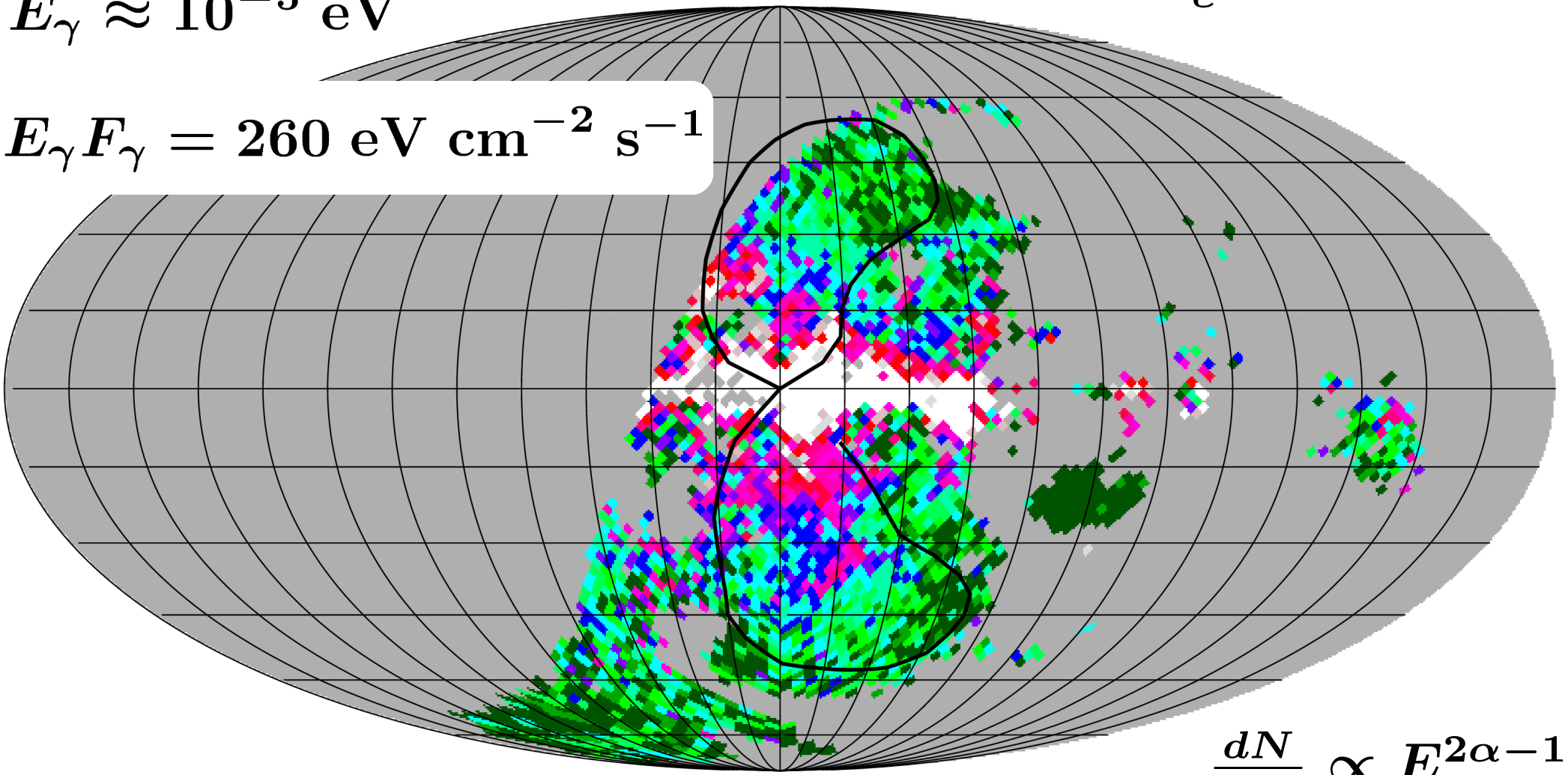
$$E_\gamma \approx \Gamma_e^2 \left(\frac{B}{B_{\mathrm{crit.}}}\right) m_e$$

$$E_\gamma \approx 10^{-5}\ \mathrm{eV}$$

$$\left(\frac{B}{B_{\mathrm{crit}}}\right) m_e \approx 10^{-13}\ \mathrm{eV}$$

$$E_e \approx \mathrm{GeV}$$

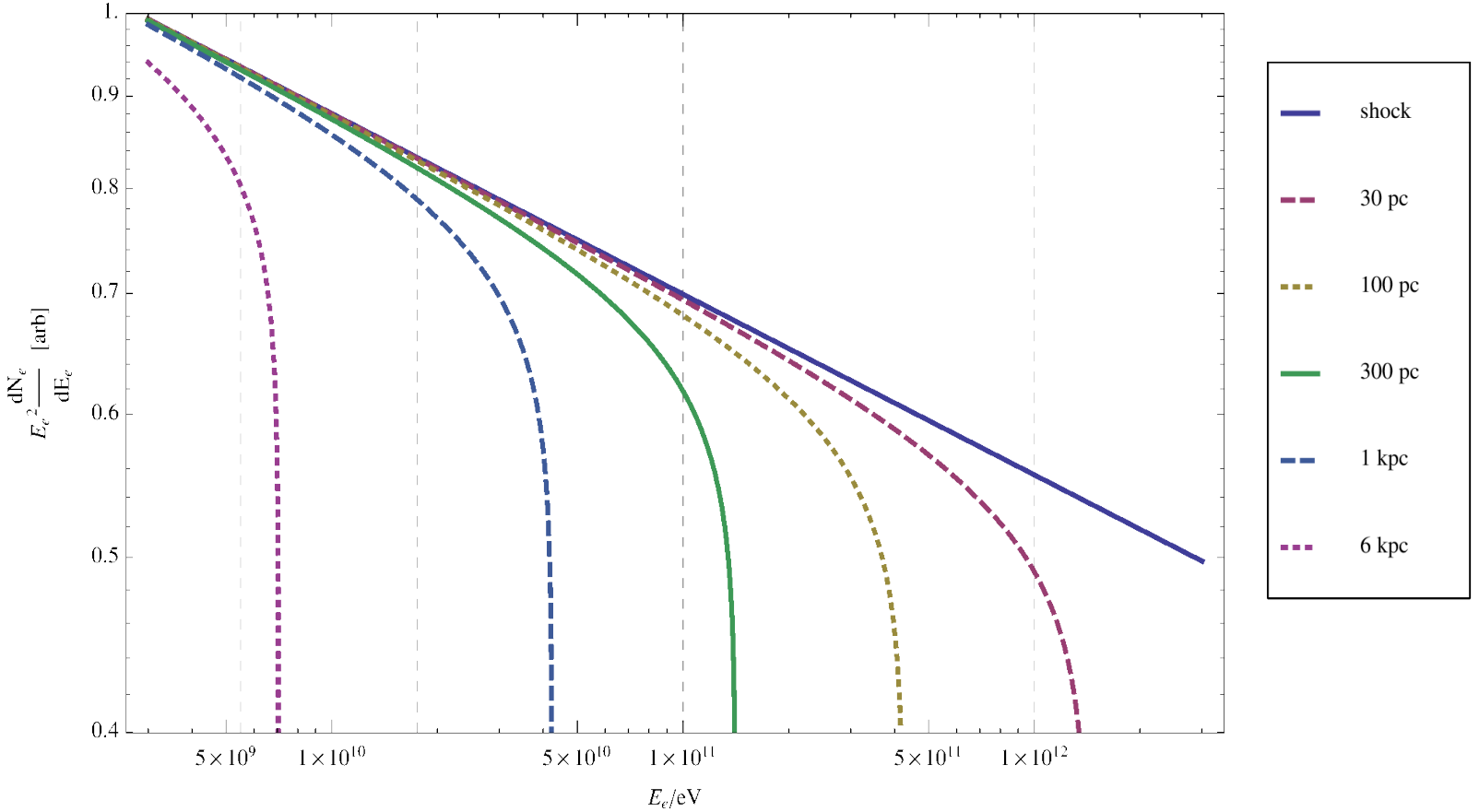
$$E_\gamma F_\gamma = 260\ \mathrm{eV\ cm^{-2}\ s^{-1}}$$



$$\frac{dN}{dEe} \propto E_e^{2\alpha-1}$$

Radiative Signature of Non-Thermal Electrons

$$\tau_e \approx 6 \times 10^7 \left(\frac{5\ \mathrm{GeV}}{E_e}\right)\left(\frac{6\ \mu\mathrm{G}}{B}\right)^2\ \mathrm{yrs}$$

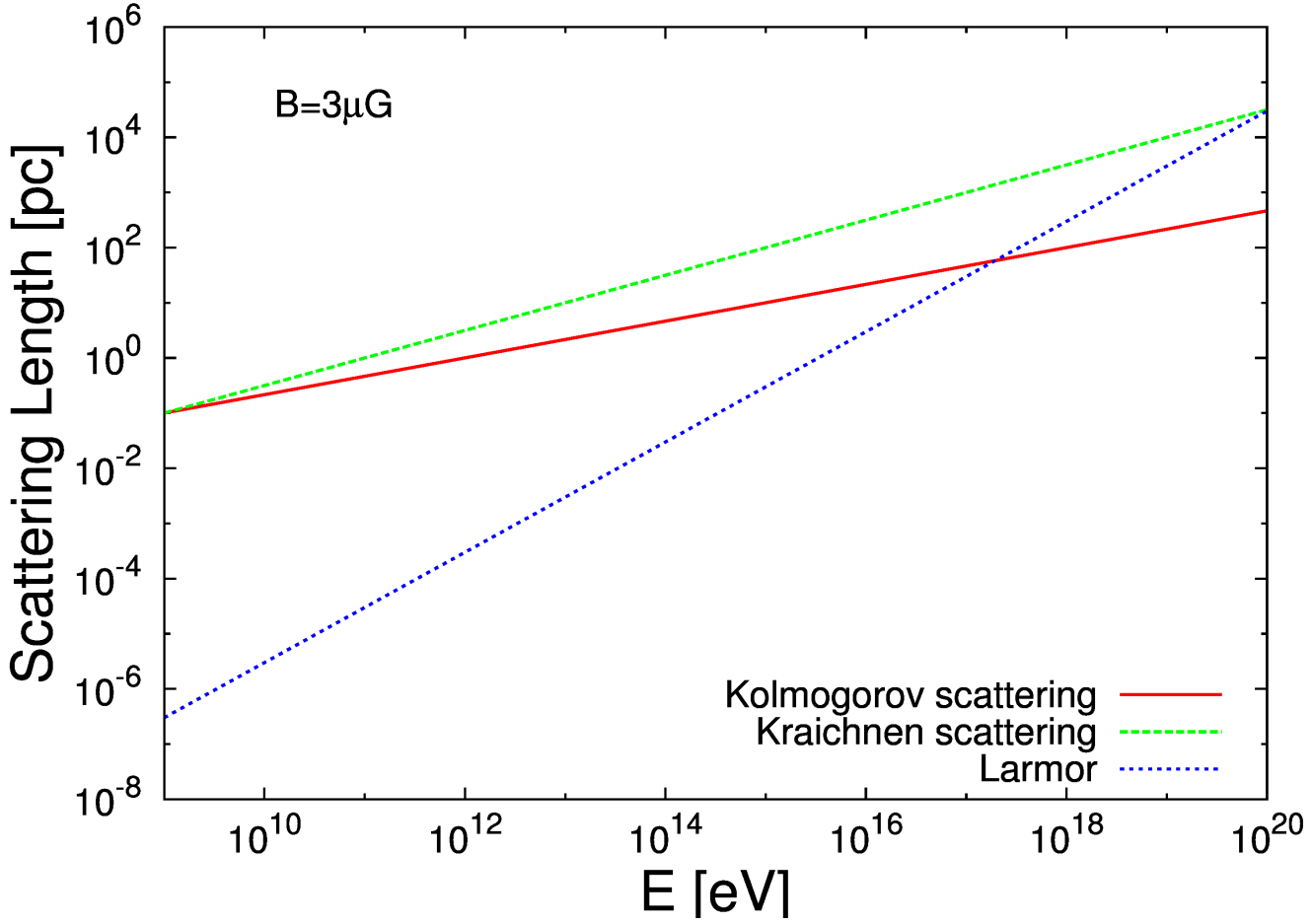


Andrew Taylor

Cosmic Rays Diffusing in Outflow

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

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

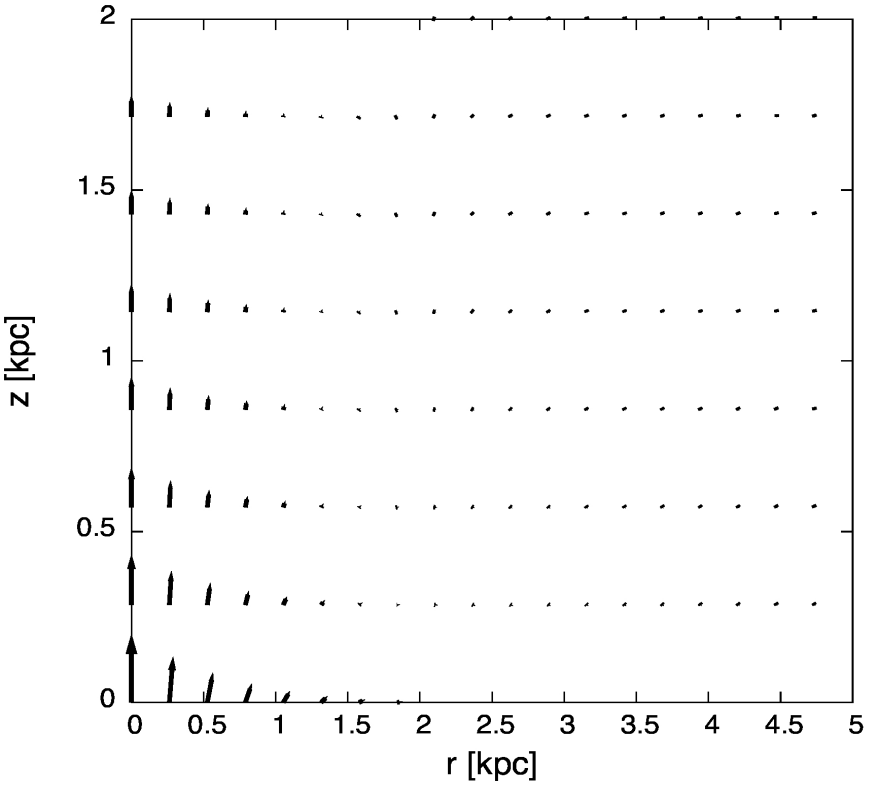


Andrew Taylor

Cosmic Rays Diffusing in Outflow

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

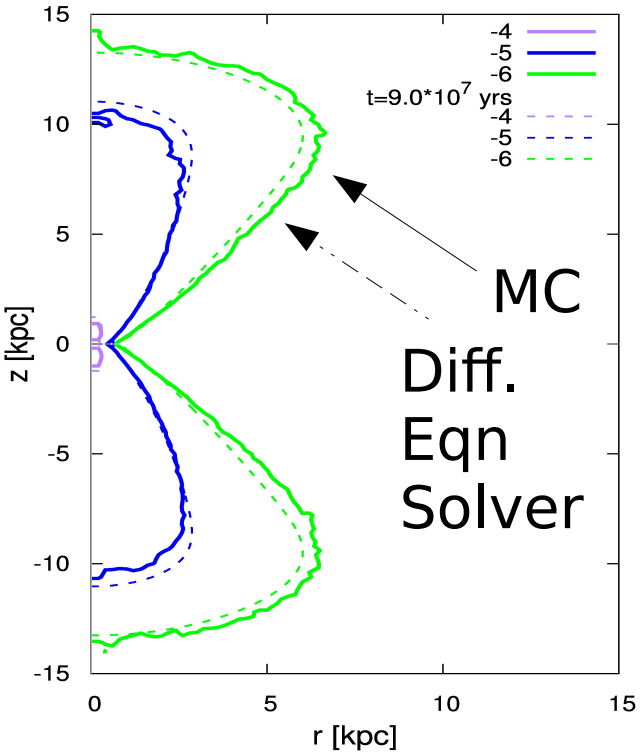
$$v_z = v_0 \frac{(1 - r/2r_{\mathrm{max}}) e^{-r/r_{\mathrm{max}}}}{1 + z/d} \qquad v_r = v_0 \frac{r e^{-r/r_{\mathrm{max}}}/2d}{(1+z/d)^2}$$



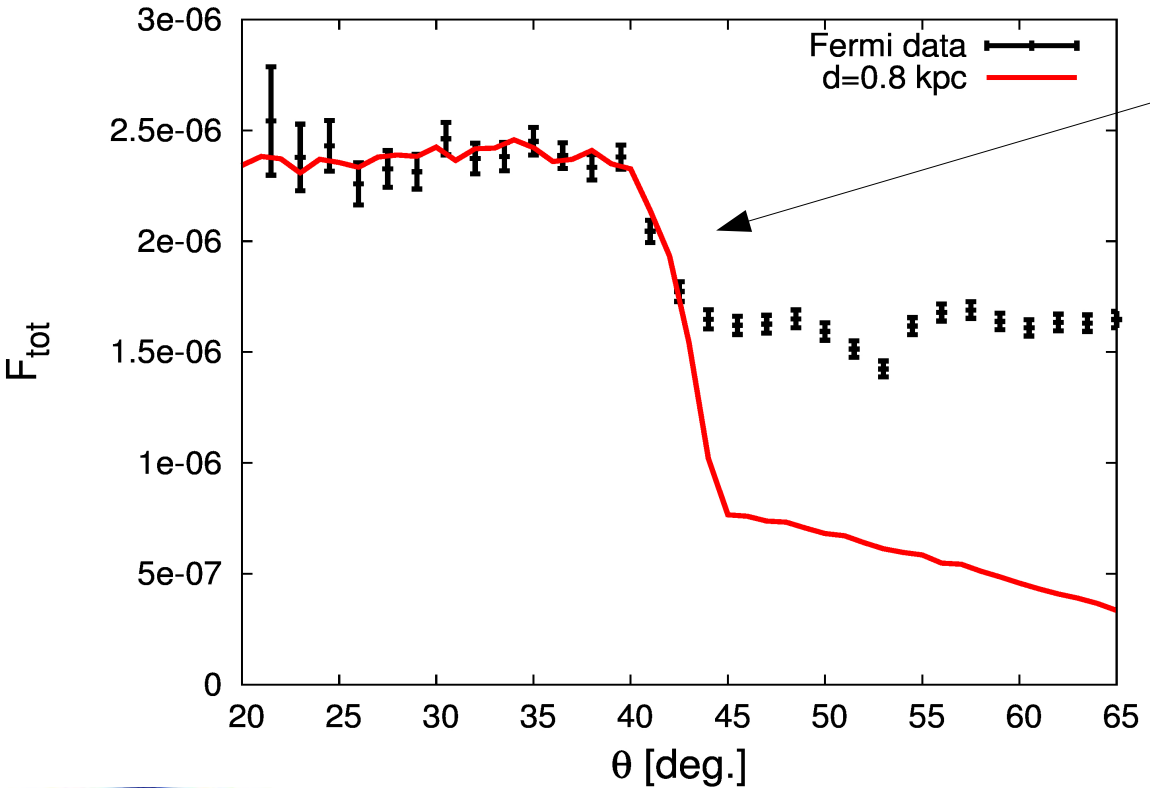
Andrew Taylor

Note- degeneracy exists between v and target mass profile

Radiative Signature of Non-Thermal Protons



Edge of bubble is connected to drop in gas density of contact discontinuity



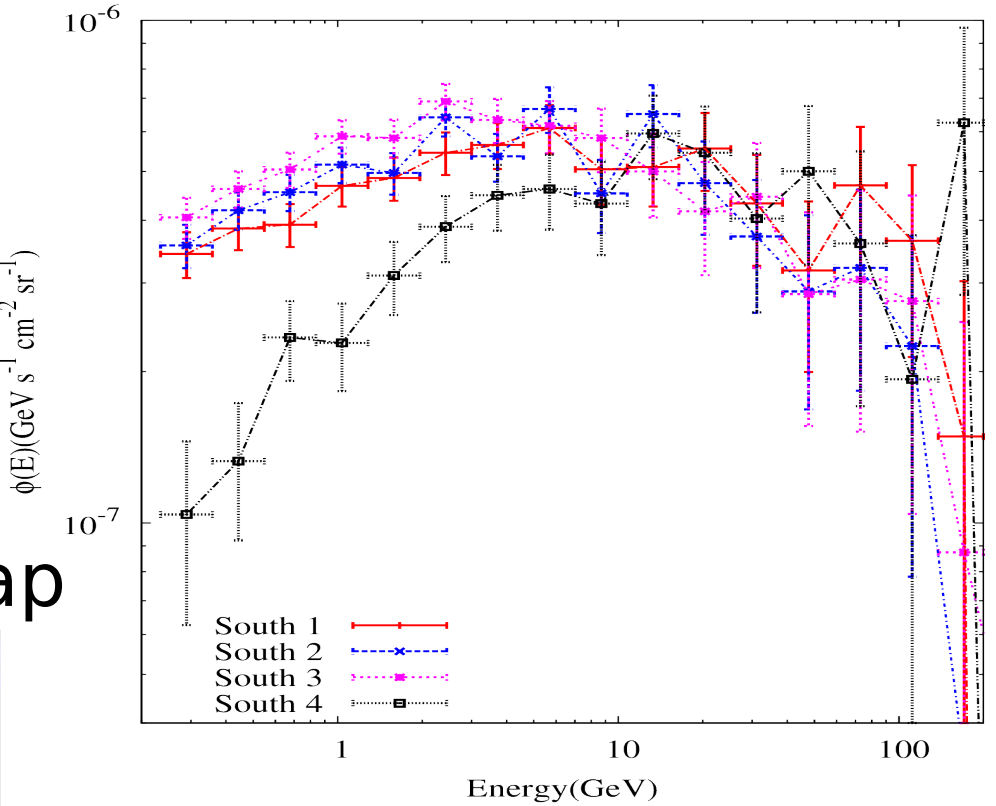
Andrew Taylor

Fermi Bubbles- Energy Spectrum

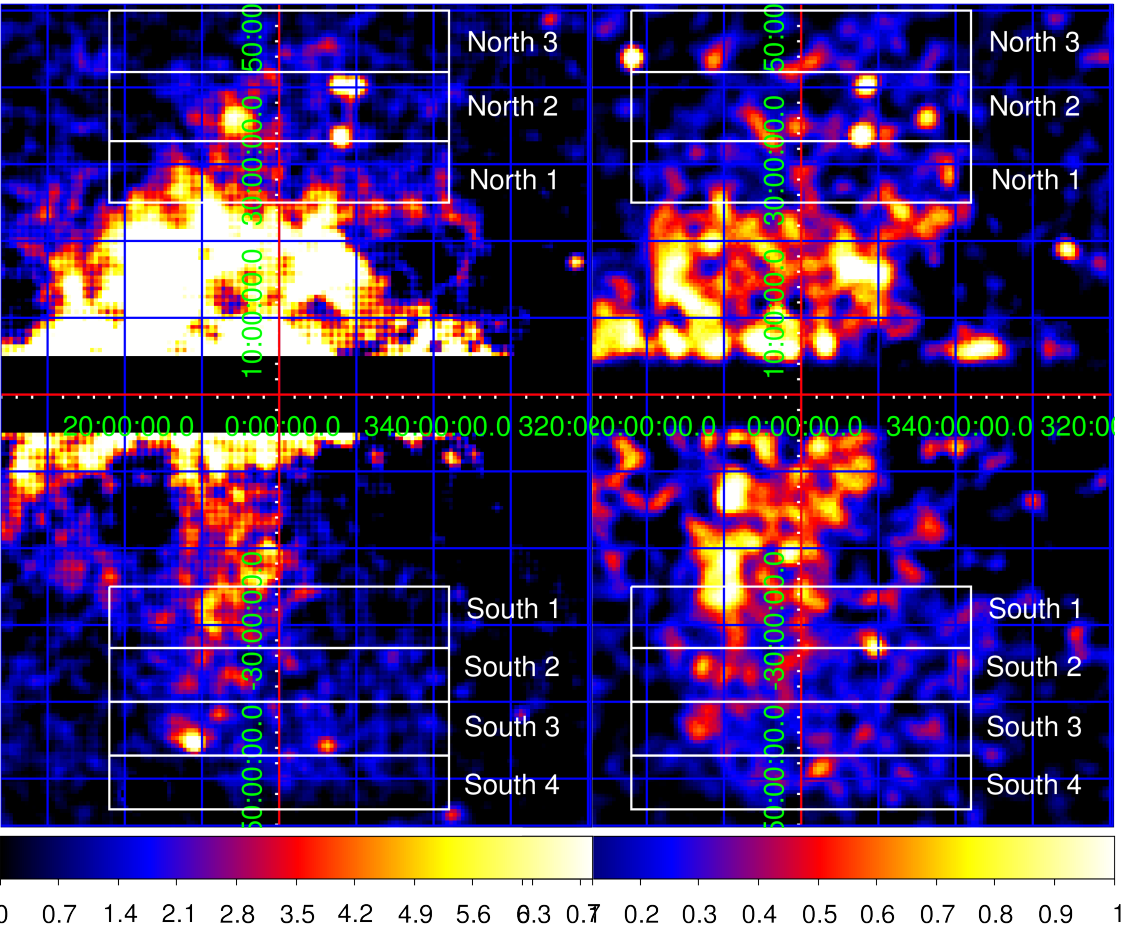
$E_\gamma F_\gamma = 240\ \mathrm{eV\ cm^{-2}\ s^{-1}}$

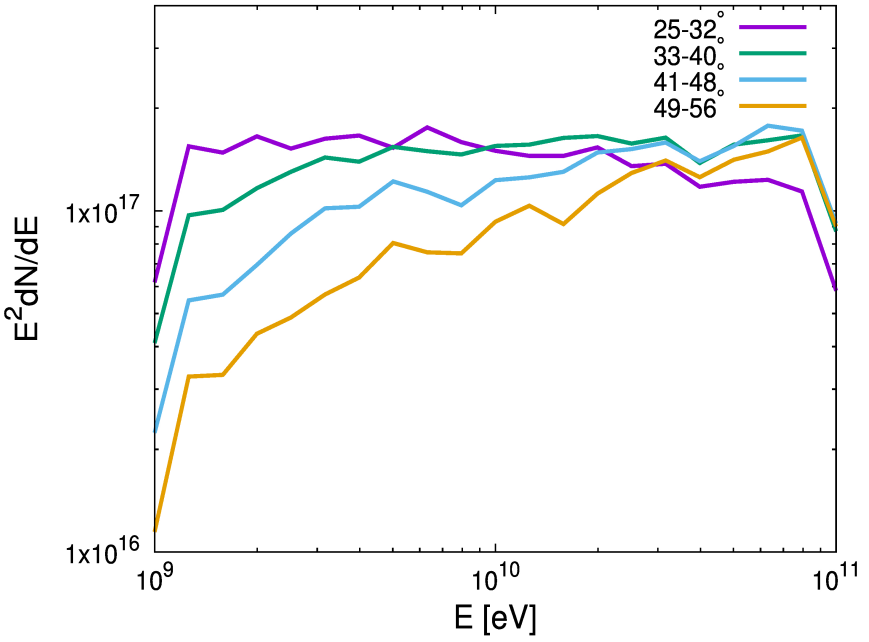
Yang et al. Astro-ph/1402.0403

Selig et al. Astro-ph/1410.4562



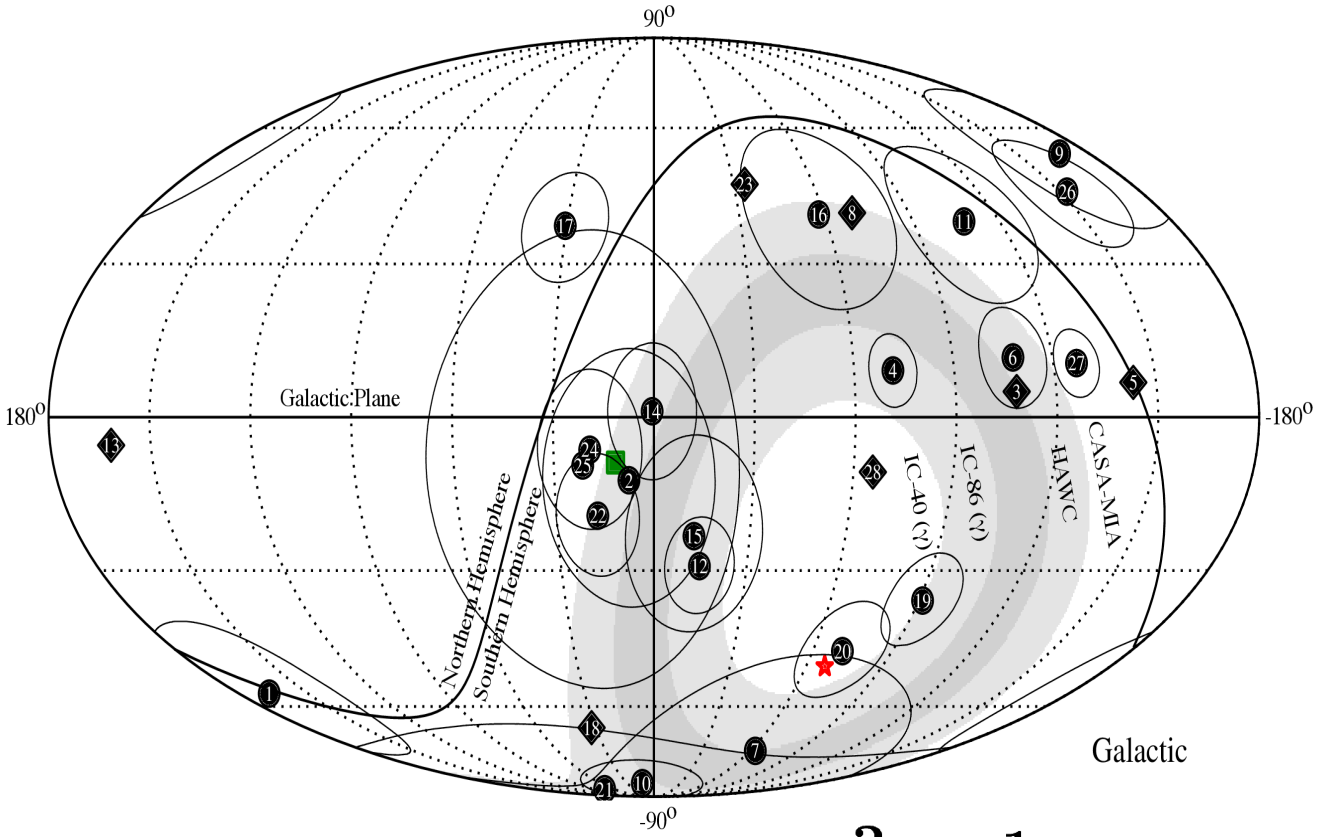
1-2 GeV map 10-30 GeV map





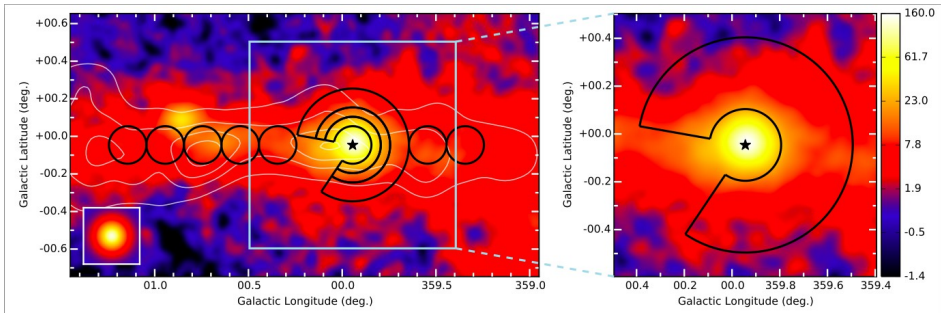
Neutrino Events (multi-TeV - PeV Energies) on the Sky

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

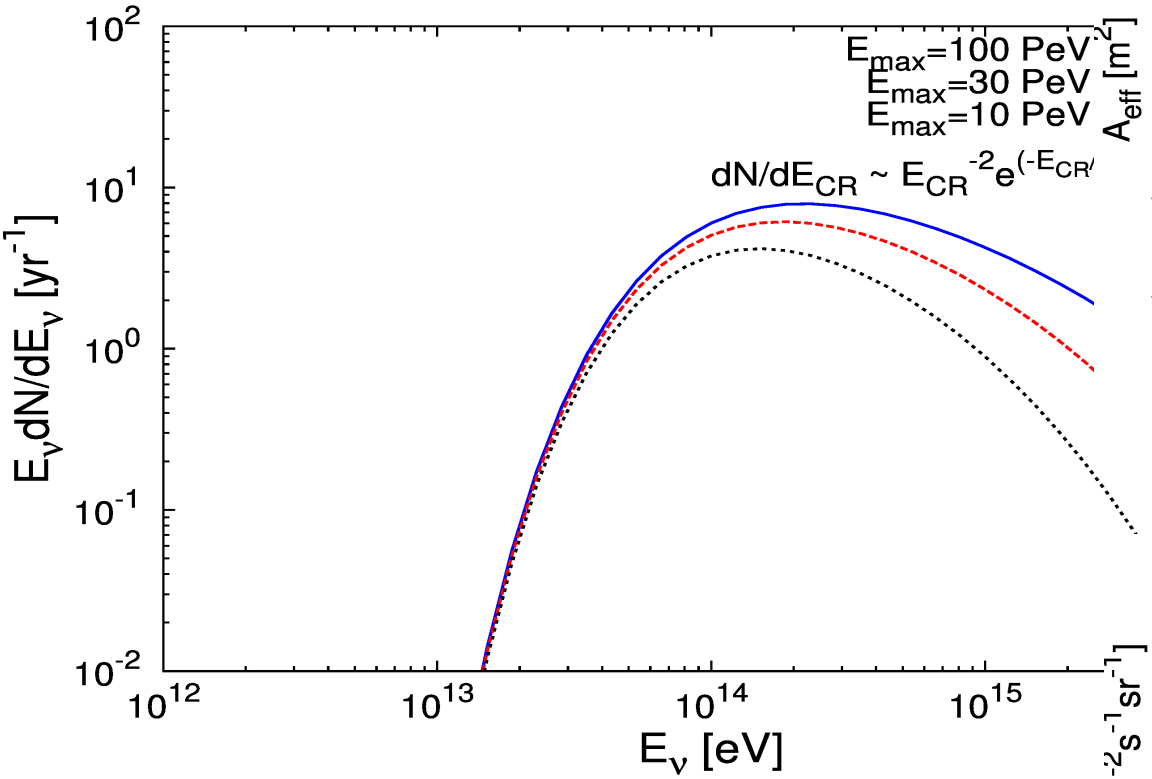


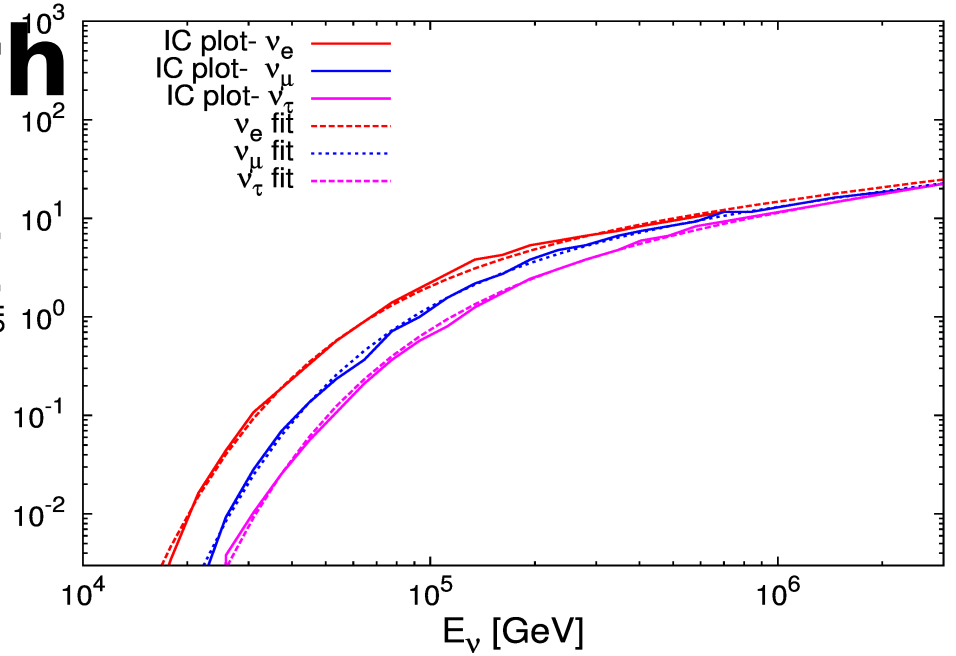
$$E_\nu F_\nu = 370\ \mathrm{eV\ cm^{-2}\ s^{-1}}$$

GC Pevatron
Recently Discovered
(talk by Aion)

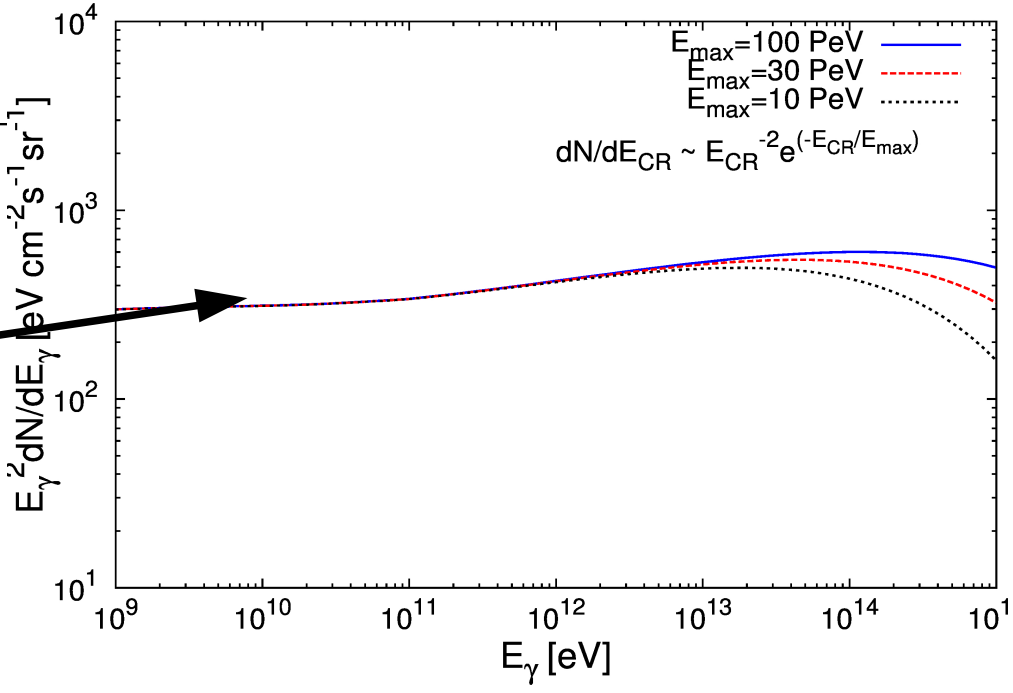


Fermi Bubble Neutrino Flux Detection with IceCube



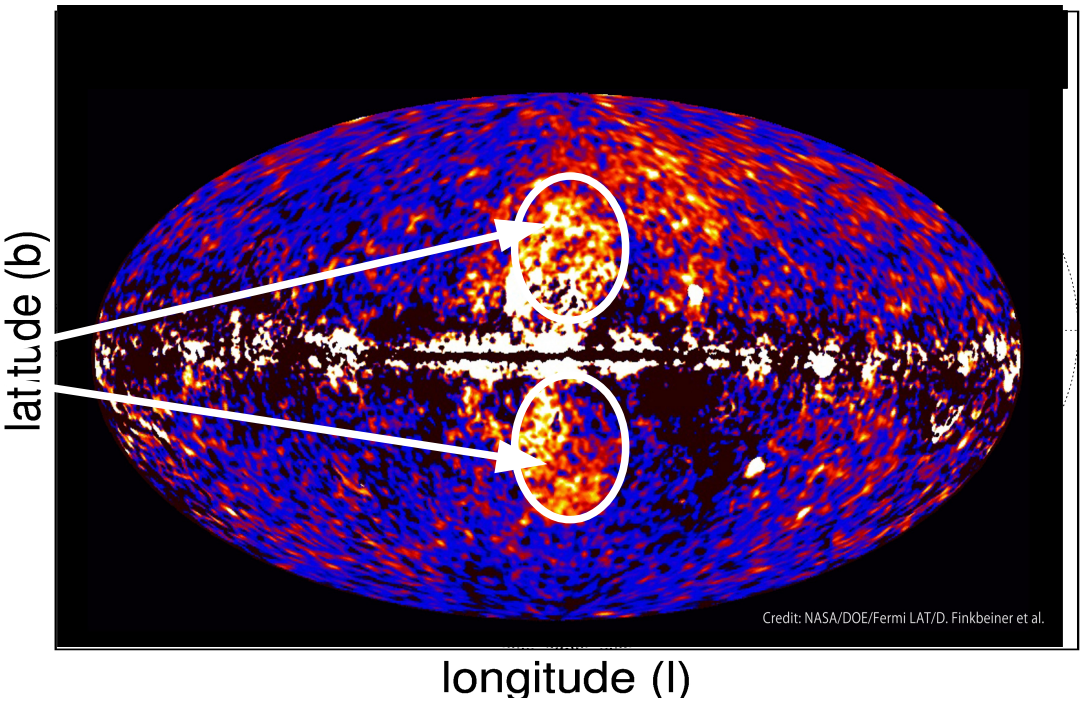


$$E_\gamma F_\gamma = 240 \text{ eV cm}^{-2} \text{ s}^{-1}$$



Fermi Bubbles- Flux Detection with IceCube

~6 yr^{-1}



(ie. follows rule of thumb)

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

$$t_{pp} = \left(\frac{3\times10^{-3}\ \mathrm{cm^{-3}}}{n_p}\right)\ 10^{10}\ \mathrm{yrs}$$

$$t_{\mathrm{esc}} = \left(\frac{R}{10\ \mathrm{kpc}}\right)\left(\frac{100\ \mathrm{km\ s^{-1}}}{v}\right) 10^{8}\ \mathrm{yrs}$$

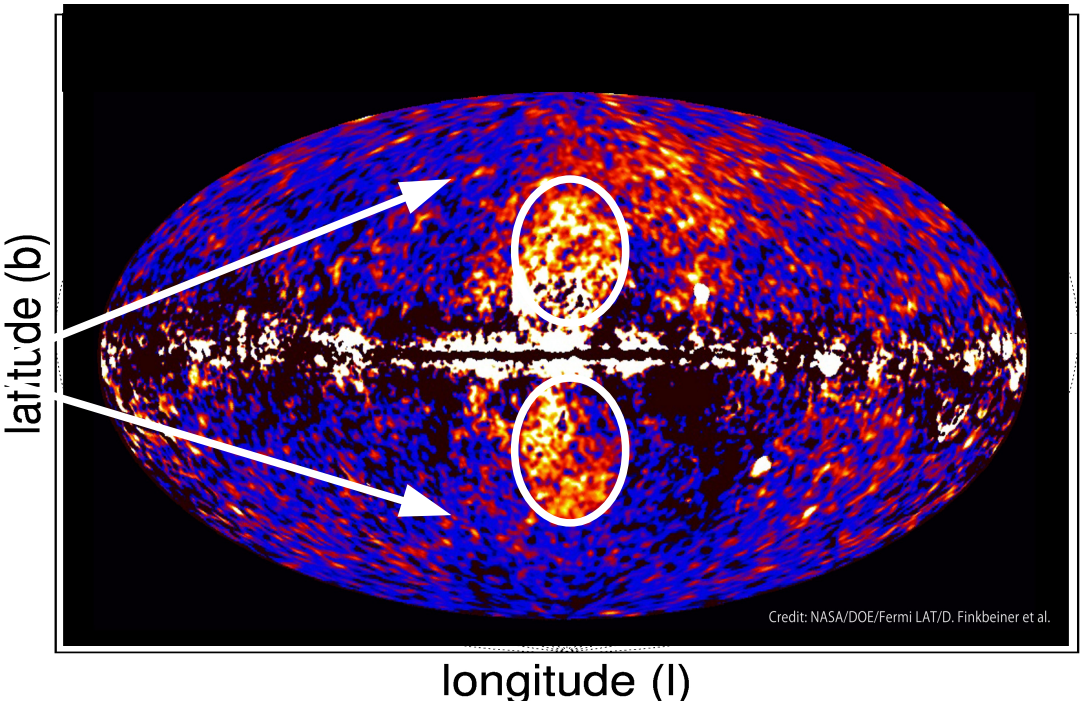
$$L_p \approx \left(\frac{t_{\mathrm{esc}}}{t_{\mathrm{pp}}}\right) L_\nu$$

$$\approx 3 \times 10^{38}\ \mathrm{erg\ s^{-1}}$$

Andrew Taylor

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

Conclusions

- The fate of Galactic cosmic rays 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 cosmic ray protons produced through Galactocentric activity

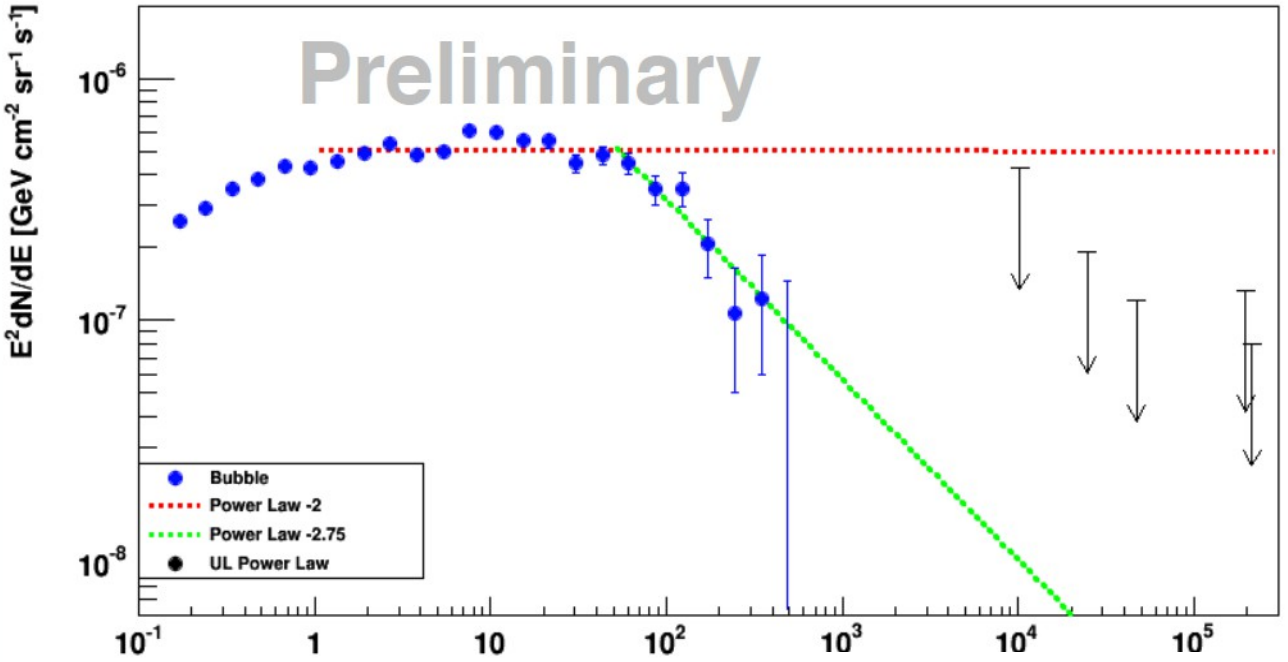
- A significant fraction of the IceCube neutrinos observed may originate from this outflow, from the region beyond the bubble edges

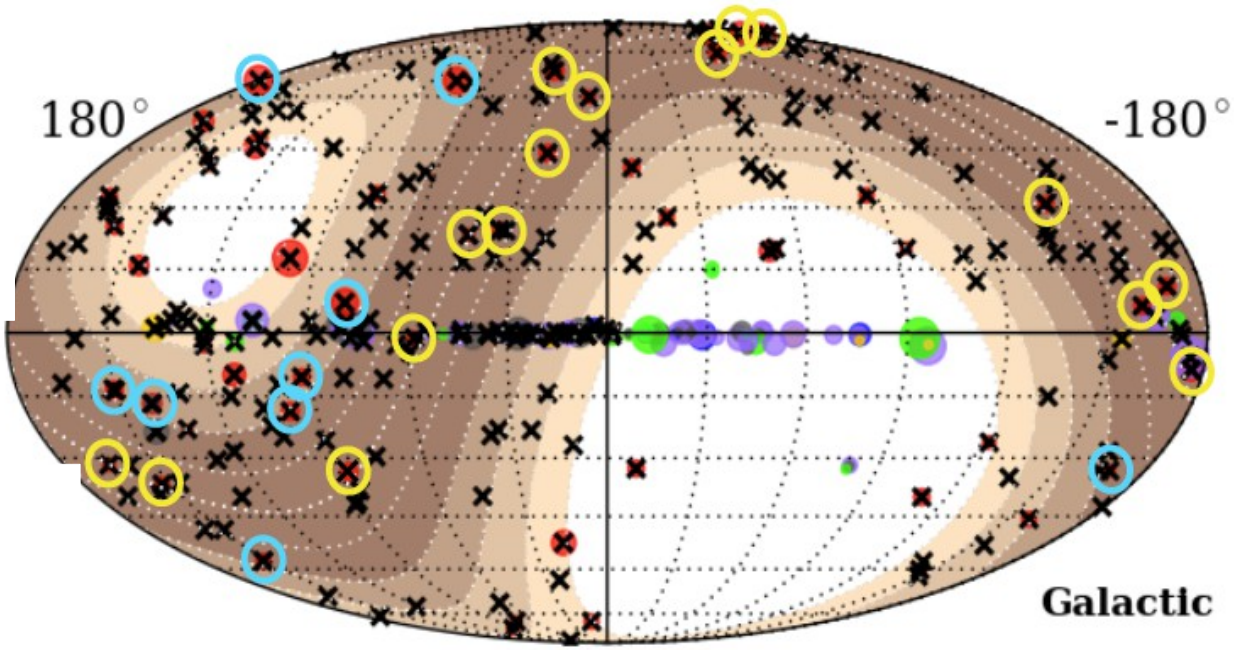
Andrew
Taylor

Extra Slides

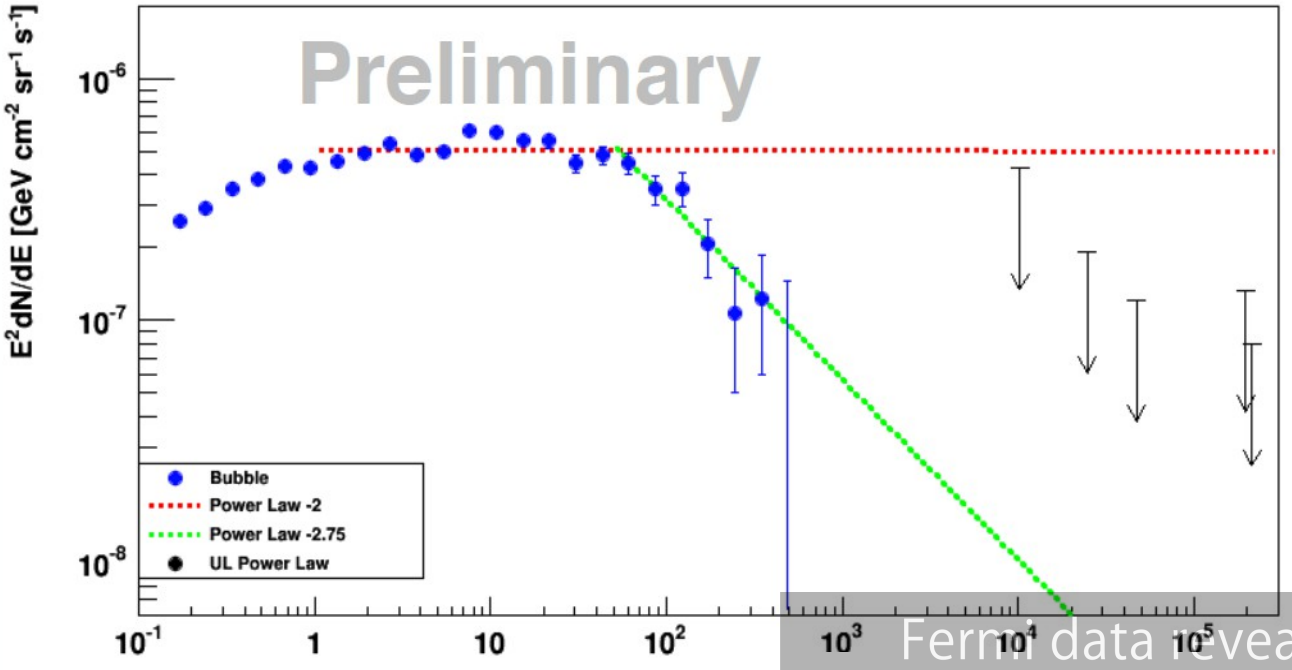
Andrew
Taylor

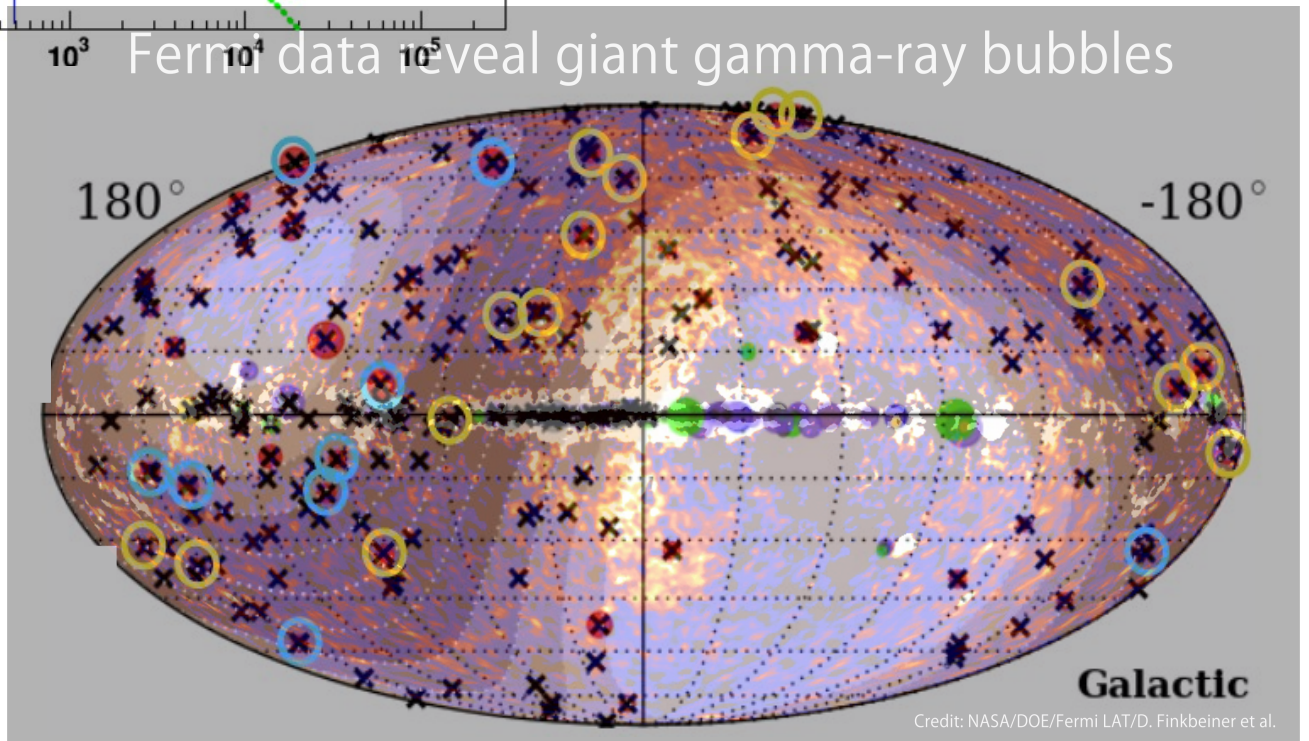
HAWC Constraints on Gamma-Ray Brightness of Bubbles





HAWC Constraints on Gamma-Ray Brightness of Bubbles

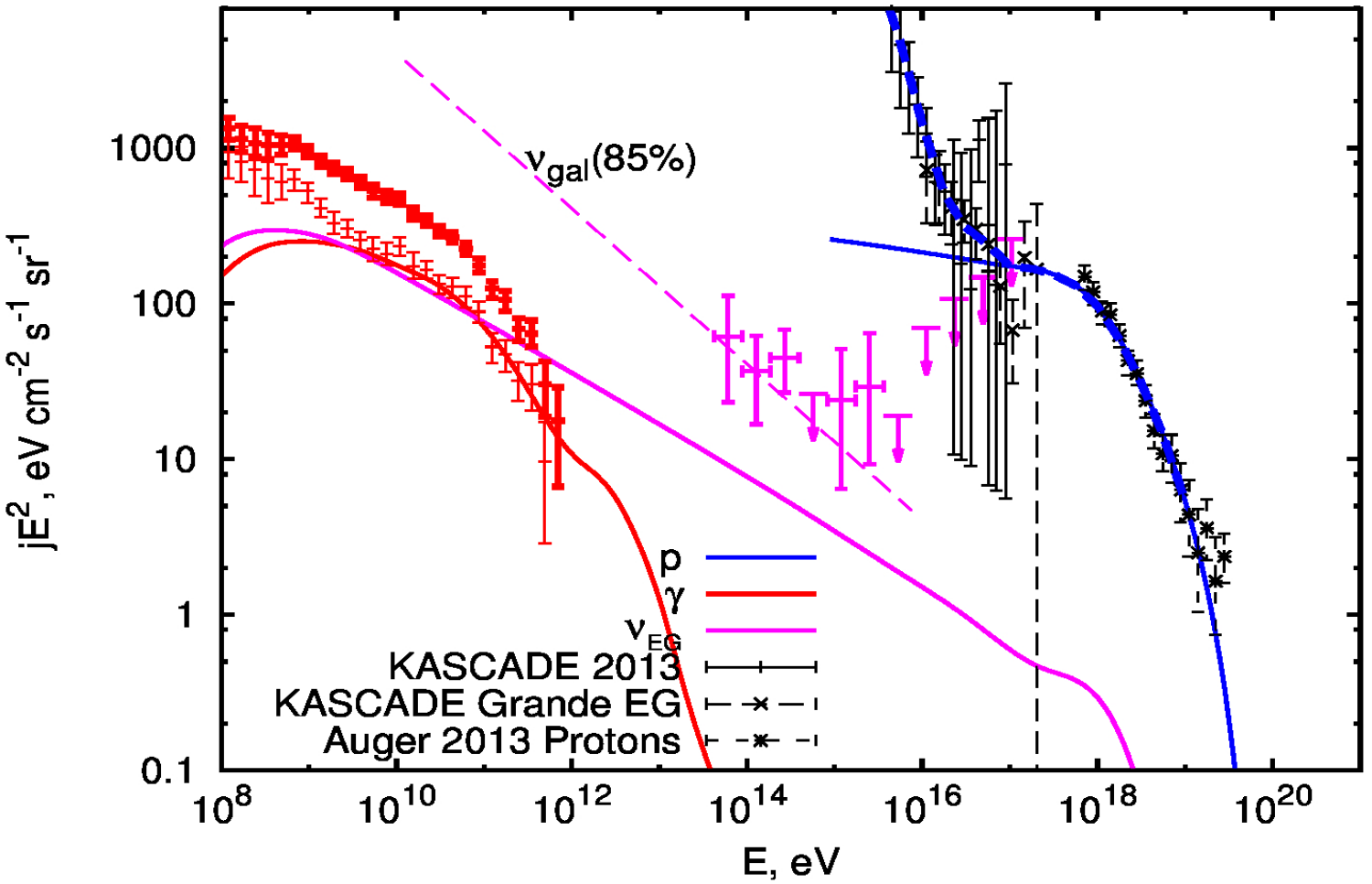




Starforming Galaxies + Blazar (FR1) Scenario Origins for the IceCube Neutrinos

astro-ph/

1507.07534

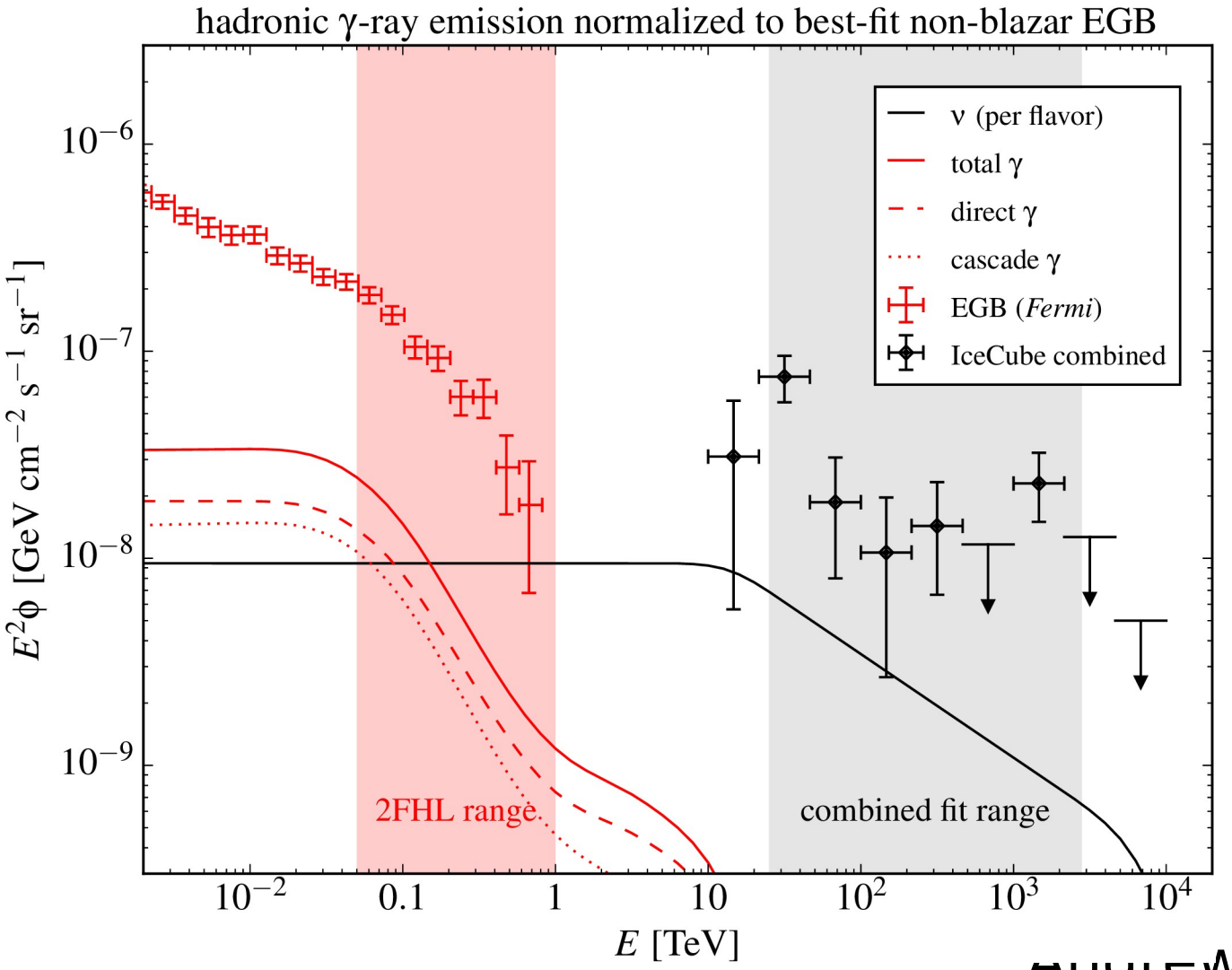


Andrew Taylor

Diffuse Gamma-Ray Background Constraints

astro-ph/

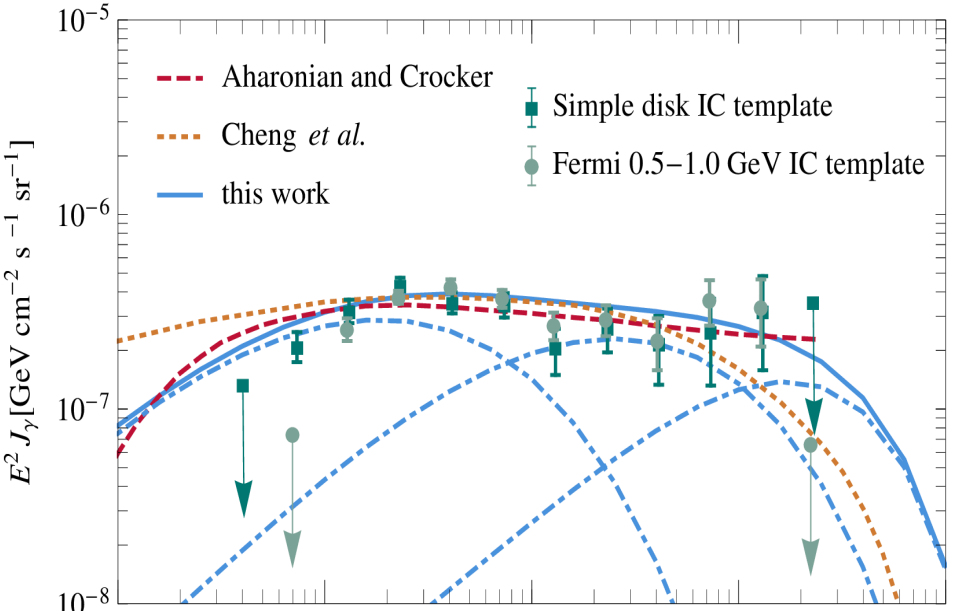
1511.00688



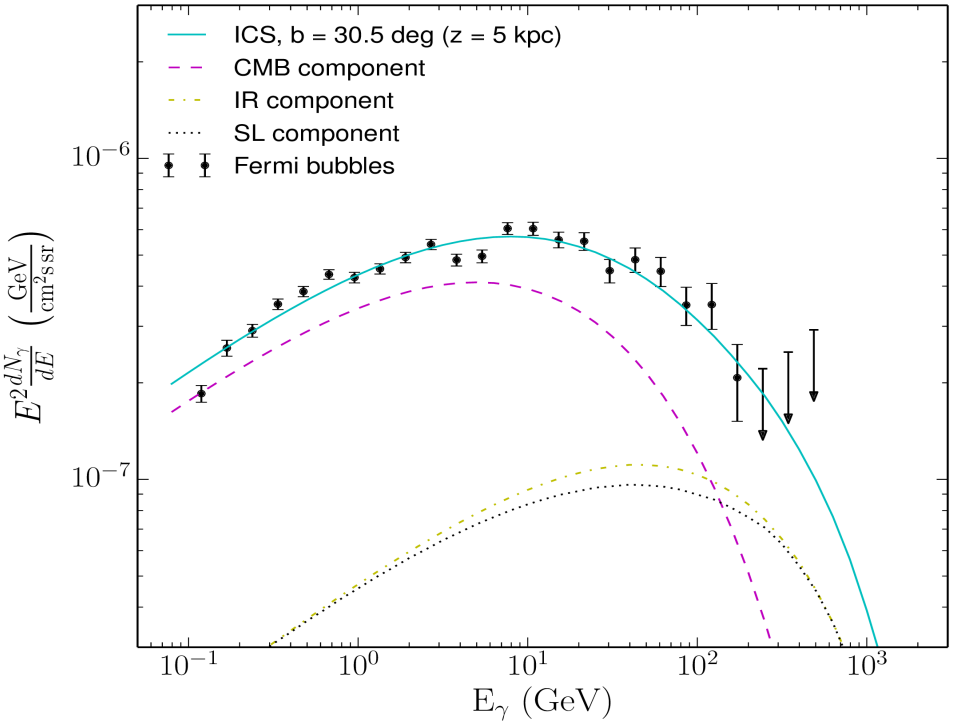
Andrew Taylor

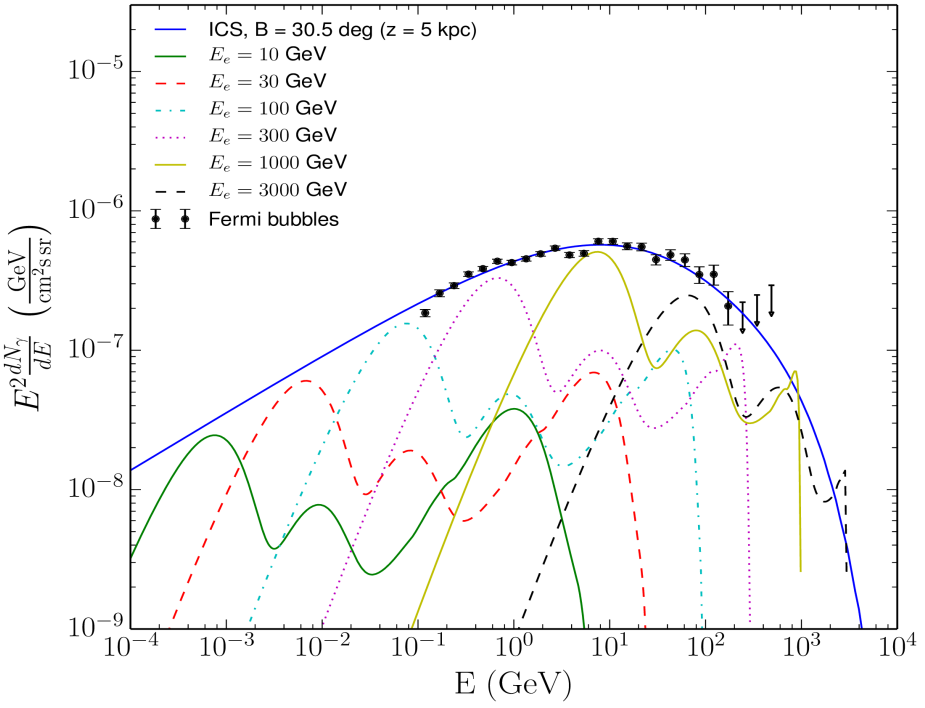
Electron Origin IC Model For Gamma-Rays

Mertsch et al.
astro-ph/1104.3585



Fermi Collab.
astro-ph/1407.7905





Testing the Hadronic Bubble Model

HAWC + LHAASO- search for 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)

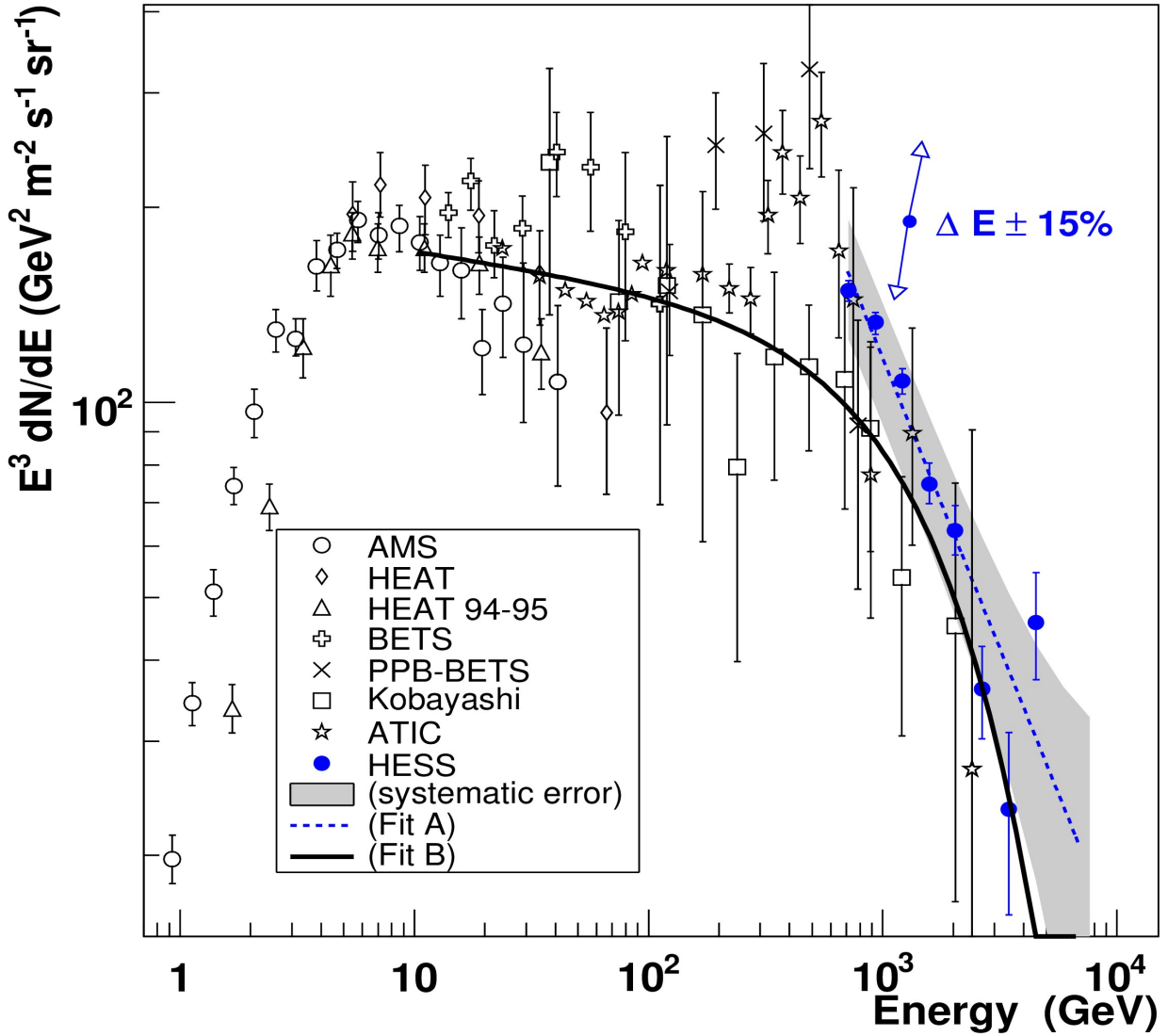
HESS- Evidence for a Galactic Center Pevatron

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

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



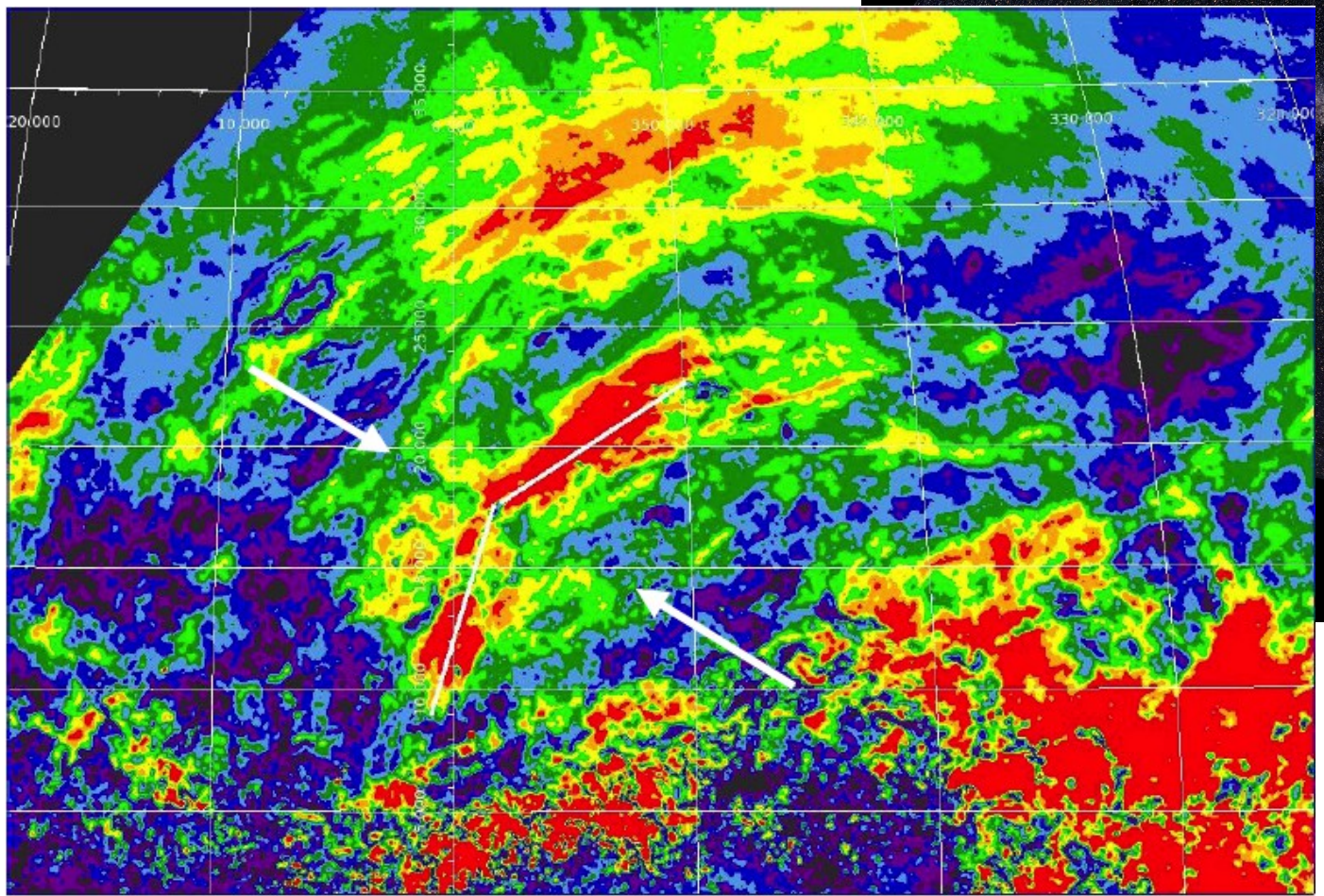
If this continues, it falls below Fermi diffuse flux at ~10 TeV and IceCube diffuse flux level at ~20 TeV

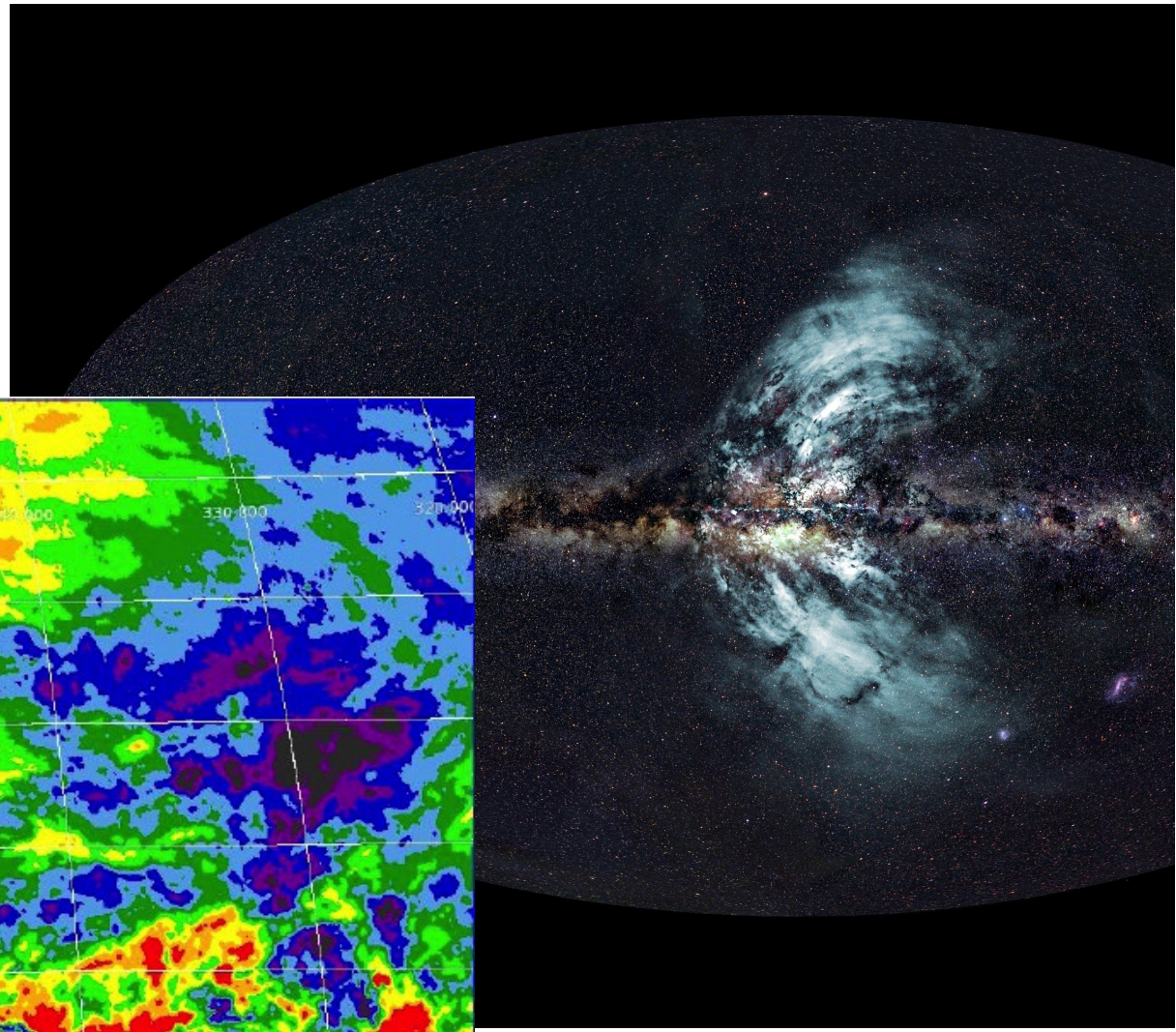
From astro-ph/0811.3894

Andrew Taylor

Evidence of Shock Structure?

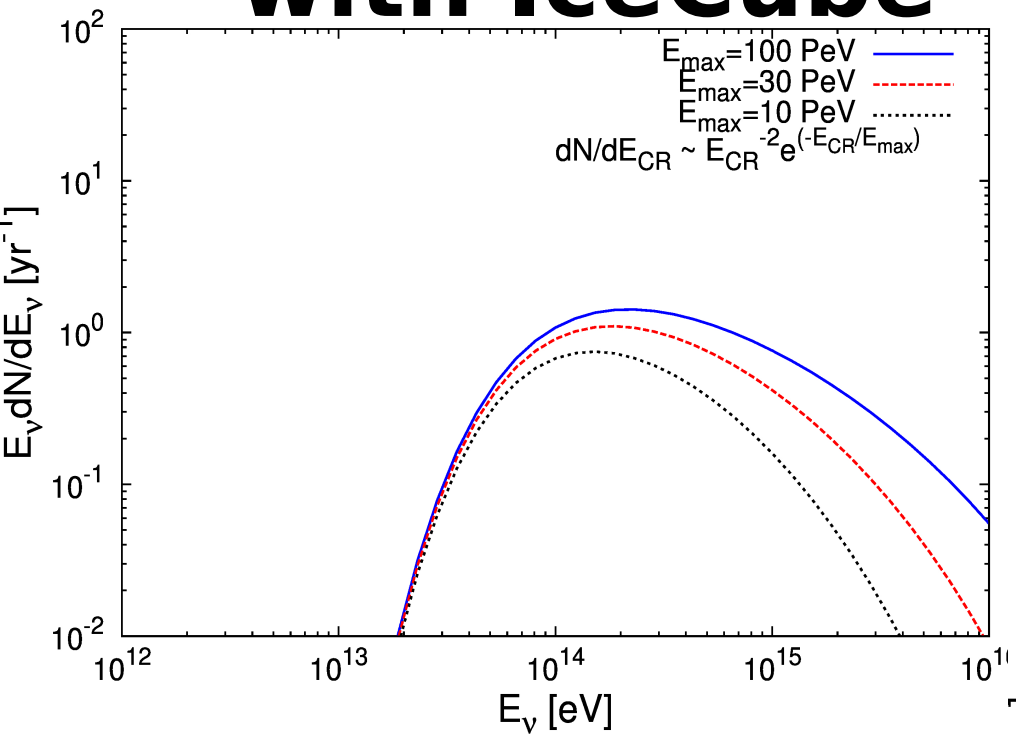
$$\frac{\tan(17^\circ)}{\tan(48^\circ)} \approx 0.27$$



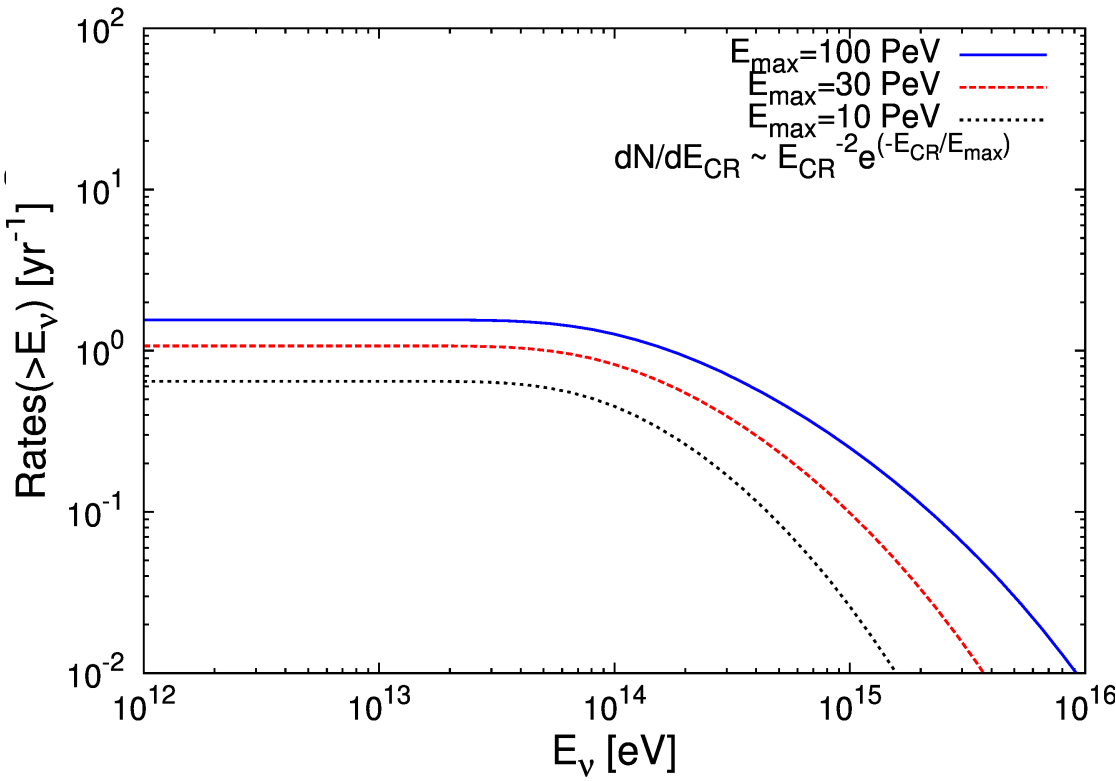


Andrew Taylor

Galactic Plane-Flux Detection with IceCube

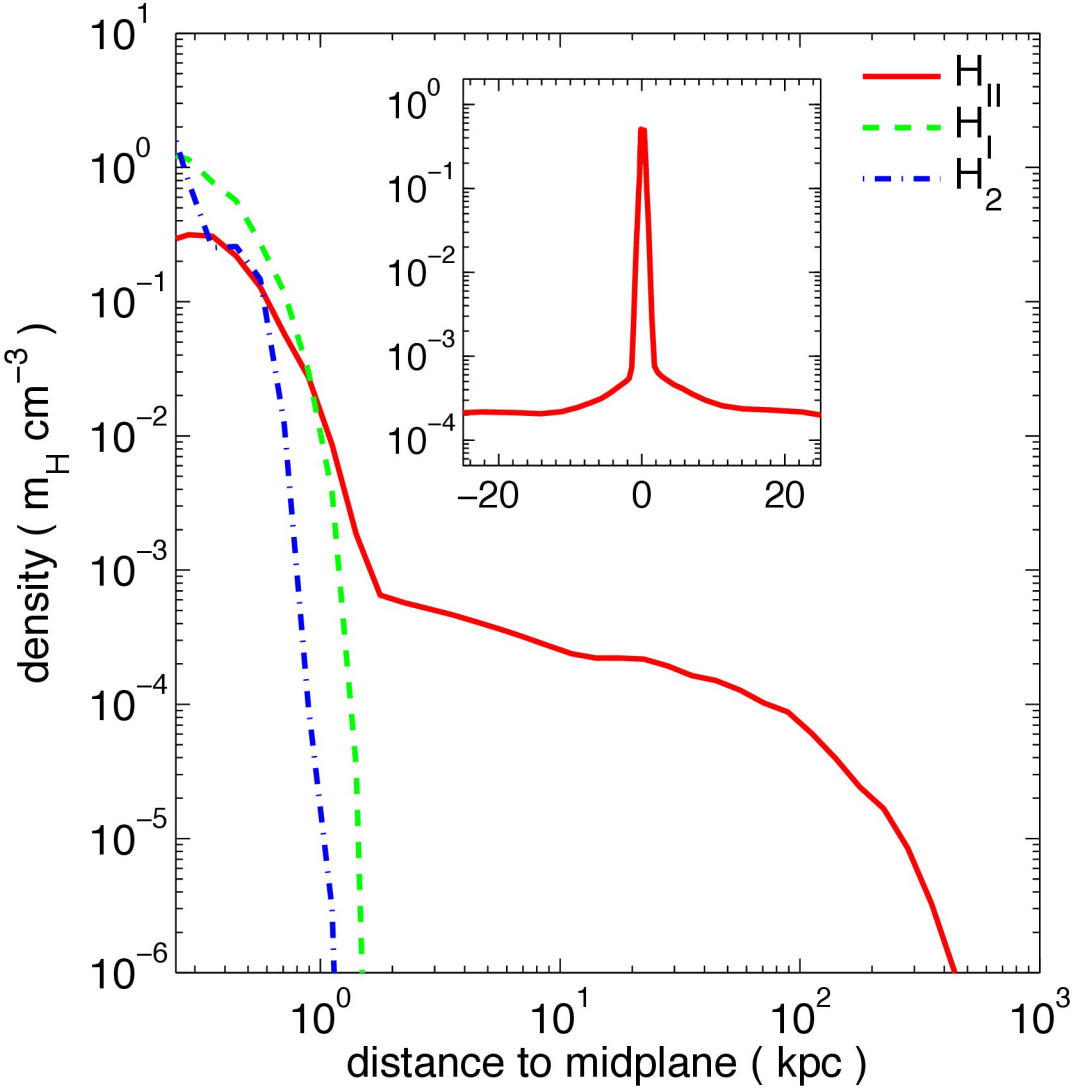


Low rates expected



Galactic Halo Matter Distribution?

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



Andrew Taylor

Cosmic Ray Proton-Proton Pion Production

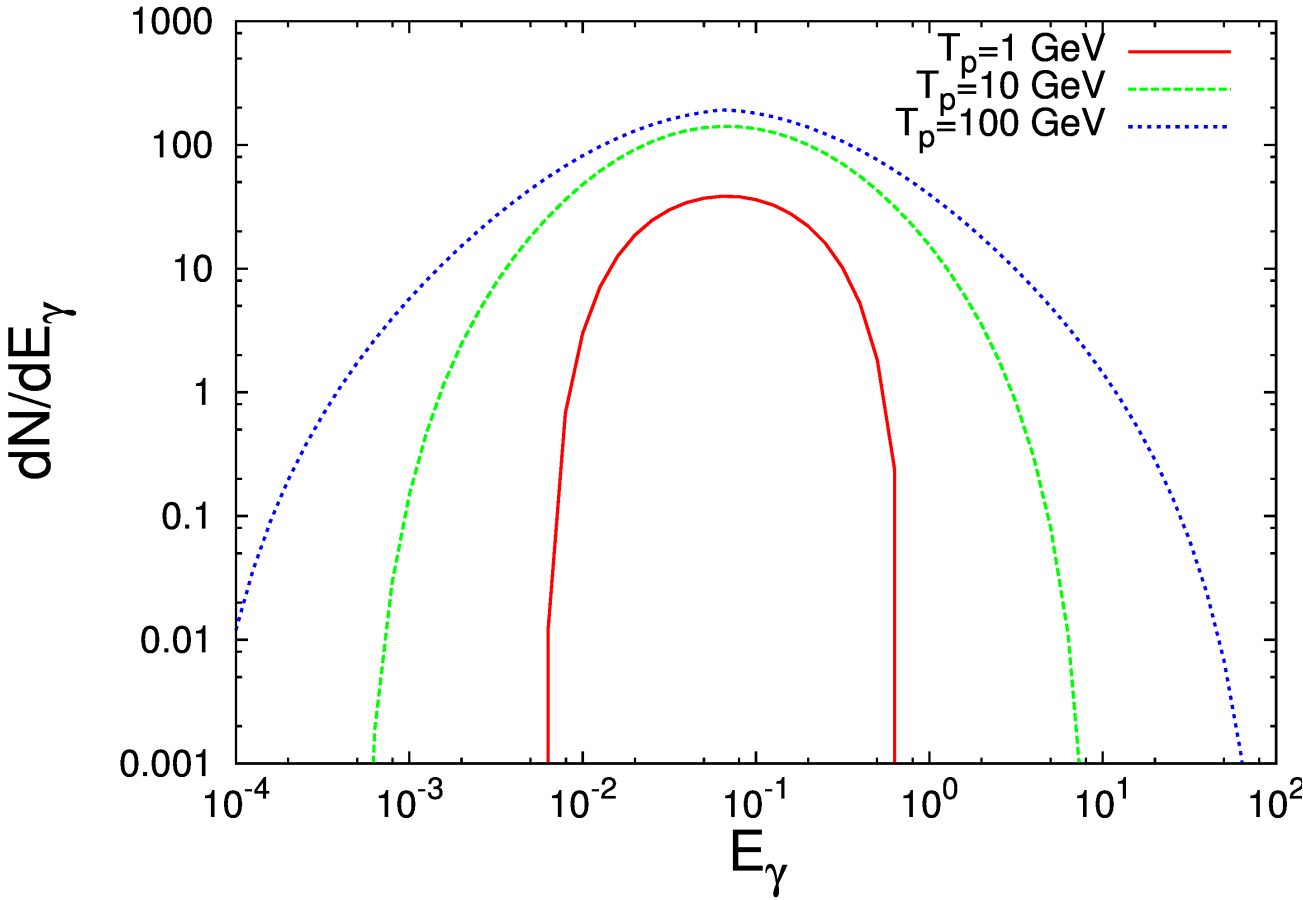
$$Y_\gamma = E_\gamma + \frac{m_\pi^2}{4E_\gamma}$$

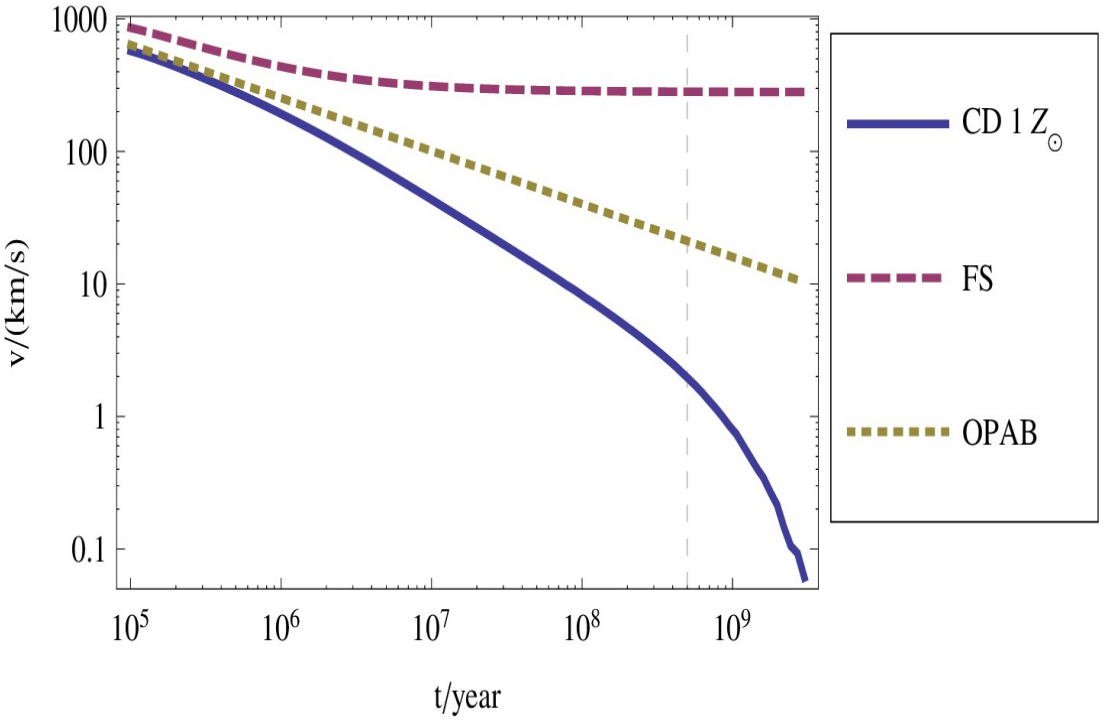
$$Y_\gamma^{\max} = E_\gamma^{\max} + \frac{m_\pi^2}{4E_\gamma^{\max}}$$

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

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

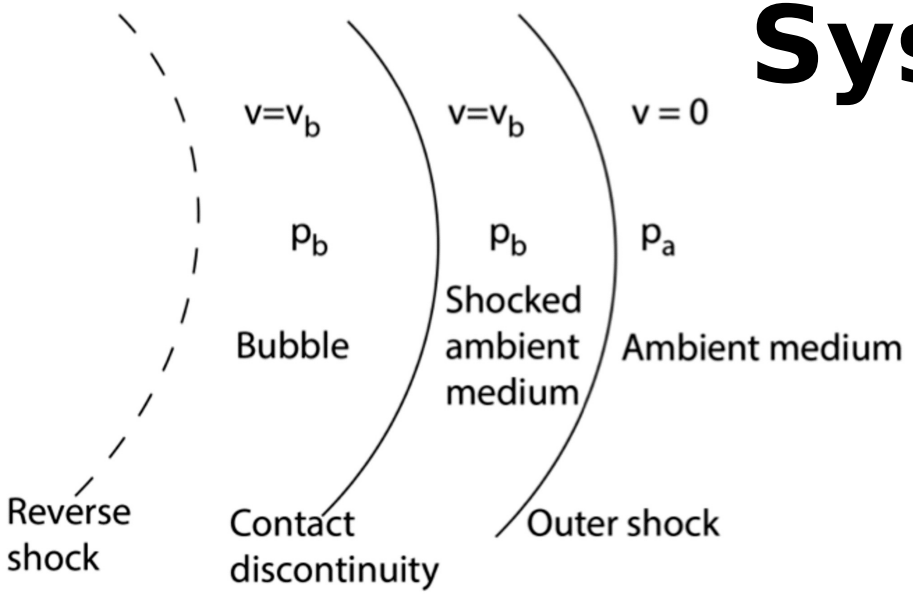
astro-ph/1406.7369





Andrew
Taylor

Galactic (Radiative) Bubble System



Radiative Cooling: line emission + bremstrahlung

$$\frac{dp_b}{dt} = -3\gamma_1 p_b \frac{d\ln R_b}{dt} + \frac{3(\gamma_1-1)}{4\pi}\frac{\dot{E}}{R_b^3} - (\gamma_1-1)\rho^2\Lambda_\rho(T)$$

$$\frac{dM_b}{dt} = \dot{M} - \frac{4\pi}{3}\frac{2}{5}\frac{\mu m}{kT}\rho_b^2\Lambda_\rho(T)R_b^3$$

$$\frac{dR_b}{dt} = \left(\frac{p_a}{\rho_b}\right)^{1/2} \times \frac{(p_b-p_a)/p_a}{\sqrt{\gamma_2+(\gamma_2+1)(p_b-p_a)/2p_a}}$$

$$\frac{dR_s}{dt} = \left(\frac{\gamma_2 p_a}{\rho_a}\right)^{1/2}\left[1+\frac{\gamma_2+1}{2\gamma_2}\left(\frac{p_b-p_a}{p_a}\right)\right]$$

Andrew Taylor

Temperatures & Densities of Outflow

$$kT_{\rm FB} \approx 300\ {\rm eV}$$
$$n_H \approx 3 \times 10^{-3}\ {\rm cm}^{-3}$$

$$kT_{\rm GC} \approx\ ?\ {\rm eV}$$
$$n_H \approx 0.1\ {\rm cm}^{-3}$$

Mass & Energetics of Outflow

$$E_{FB} \approx 7 \times 10^{55} \text{ erg}$$

$$M_{\rm FB} \approx 2 \times 10^{7}\ M_{\odot}$$

$$t_{\rm sys} \approx \frac{PV}{\dot{E}_{\rm GC}}$$

$$\approx 10^{8} \text{ yrs} \left(\frac{7 \times 10^{55} \text{ erg}}{3 \times 10^{40} \text{ erg s}^{-1}} \right)$$

8kpc

Reverse Shcck

2 kpc

CMZ

Origin of Hot Gas

$$\dot{M}_{\rm GC} = n_{\rm GC} m_p v_{\rm wind} \pi r_0^2$$

$$\dot{M}_{\rm cool} = n_{\rm FB} m_p V_{\rm FB} / t_{\rm cool}$$

$$r_0 \approx \sqrt{\frac{V_{\rm FB} n_{\rm FB}}{2\pi n_{\rm GC} v_{\rm wind} t_{\rm cool}}}$$

$$r_0 \approx 100\ {\rm pc} \left(\frac{M_{\rm FB}}{2\times10^7\ M_\odot}\right)^{1/2} \left(\frac{n_{\rm GC}}{0.1\ {\rm cm^{-3}}}\right)^{-1/2} \left(\frac{v_{\rm wind}}{500\ {\rm kms^{-1}}}\right)^{-1/2} \left(\frac{t_{\rm cool}}{5\times10^8\ {\rm yrs}}\right)^{-1/2}$$

$$kT \approx \frac{\dot{E}}{\dot{M}}$$

$$\approx 10^3\ {\rm eV} \left(\frac{3\times10^{40}\ {\rm erg\ s^{-1}}}{0.1\ M_\odot\ {\rm yr^{-1}}}\right)$$

Reverse Shock

CMZ