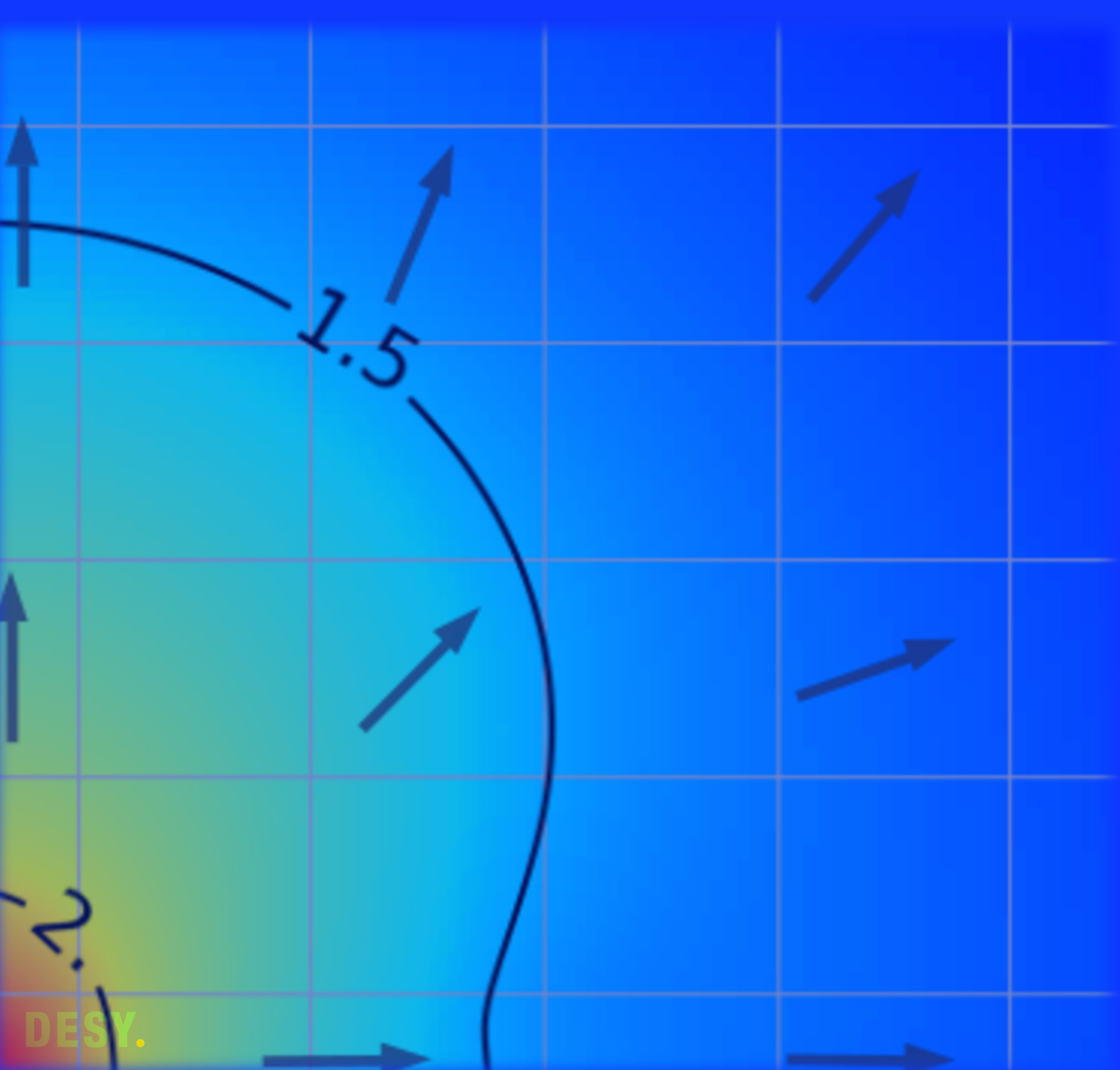


Galactic Pevatron Outflow

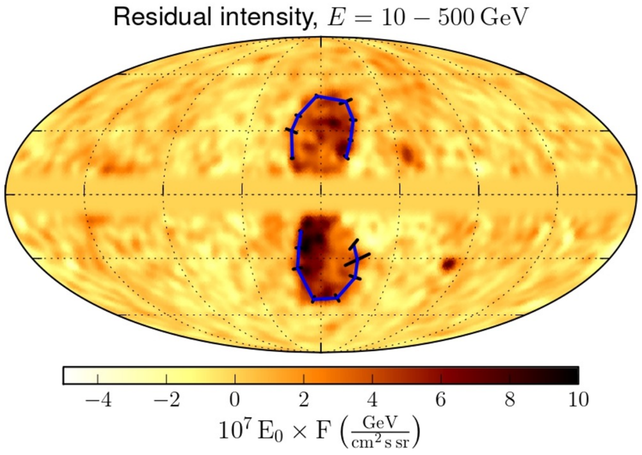
Work done with Olivier Asin and Donna Rodgers-Lee: astro-ph/2207.09189
(accepted for publication in MNRAS)

Motivated by earlier work with Gwenael Giacinti:
Taylor et al. PRD 95 (2017)

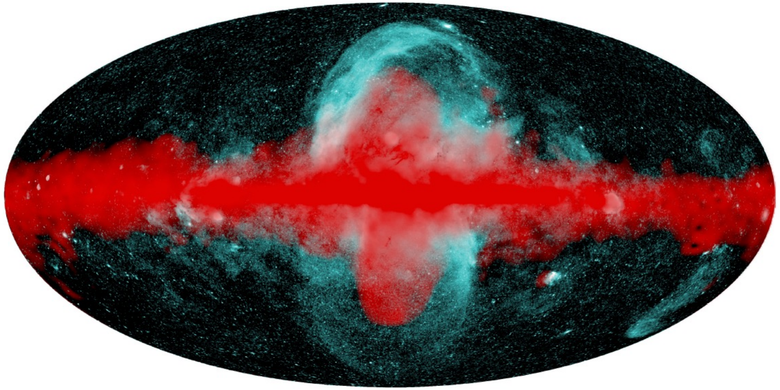
The Fermi Bubbles

- 2 Galactic bubbles emitted from above and below the Galactic plane- relatively uniform in brightness.
- Observed to have a hard photon index (Γ~2.2)
- Suggested to have a luminosity of

L_γ(0.1-500 GeV) ~ 4×10^{37} erg s^{-1}



Ackermann et al. ApJ 793 (2014)



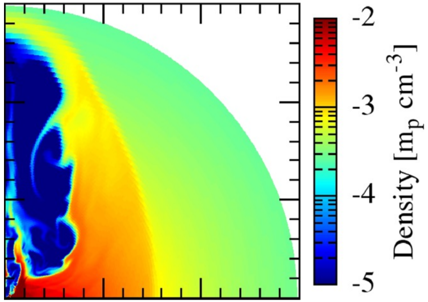
Predehl et al. Nature 588 (2020)

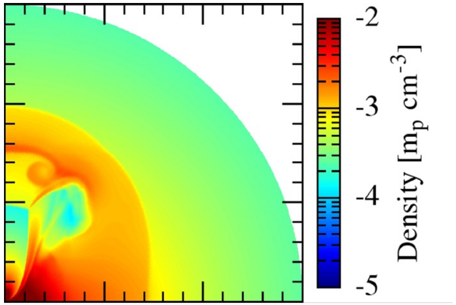
Recent eRosita results suggest that Fermi bubble structures are a subset of even larger (10^{56} erg of hot thermal gas) structure

Previous Considered Options

AGN driven outflow
SF driven outflow

Leptonic origin
Hadronic origin



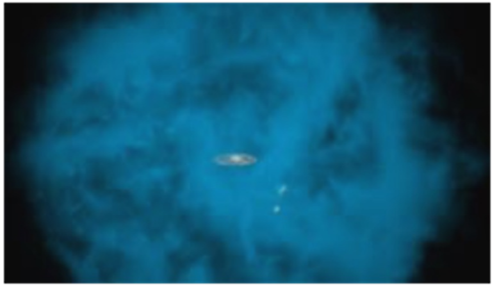


Although fast and slow outflows are generally considered, these are generally adjectives are relative- assumed to all be supersonic outflows (hence the change to the gas density distributions in the plots shown)

Sarkar et al. MNRAS 467 (2017)

Why Consider Slow Outflows?

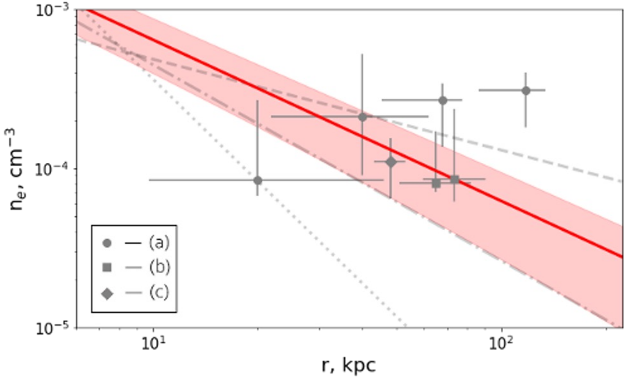
X-ray observations of bright AGN indicate the presence of a hot local absorber (WIM).



Gupta ApJ, 756 (2012)

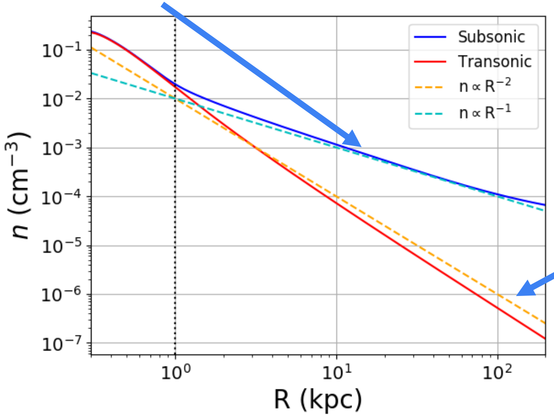
More recently, the ram pressure stripping of satellite galaxies + emission from the hot absorber have been collectively used to probe the halo gas.

Faerman ApJ 835 (2017), Martynenko MNRAS, 511 (2022)



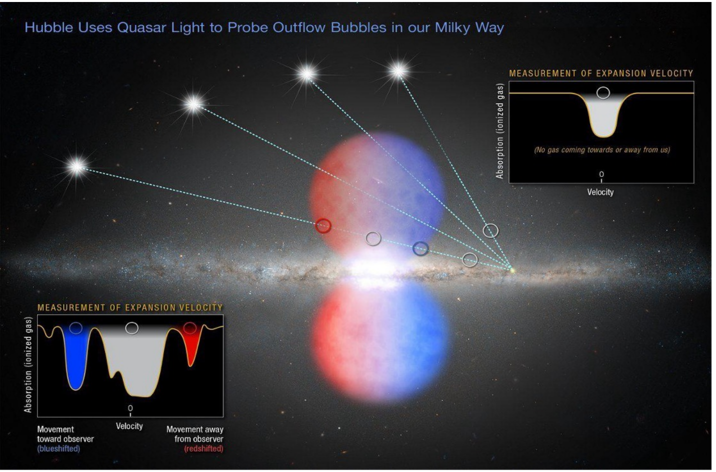
These results are consistent with expectations if the halo gas is in hydrostatic equilibrium

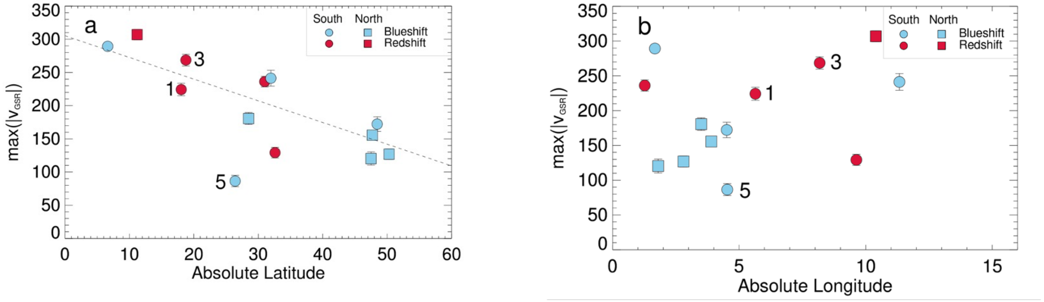
$$\mathbf{n} = \mathbf{n_0} \mathbf{e}^{-\frac{\Phi}{c_s^2}}$$



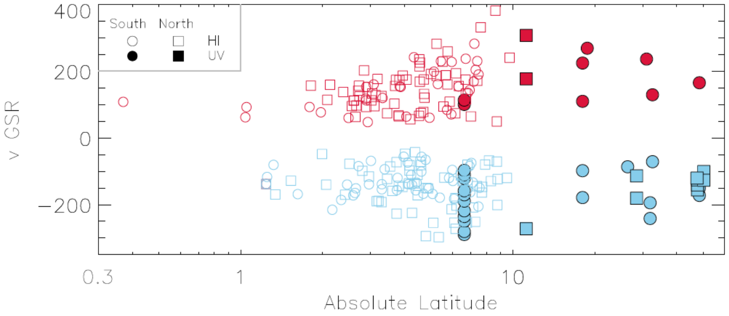
If the Galaxy possessed a supersonic wind, the gas density far out would be much lower than that observationally inferred.

Velocity Flow within the Bubble Structures



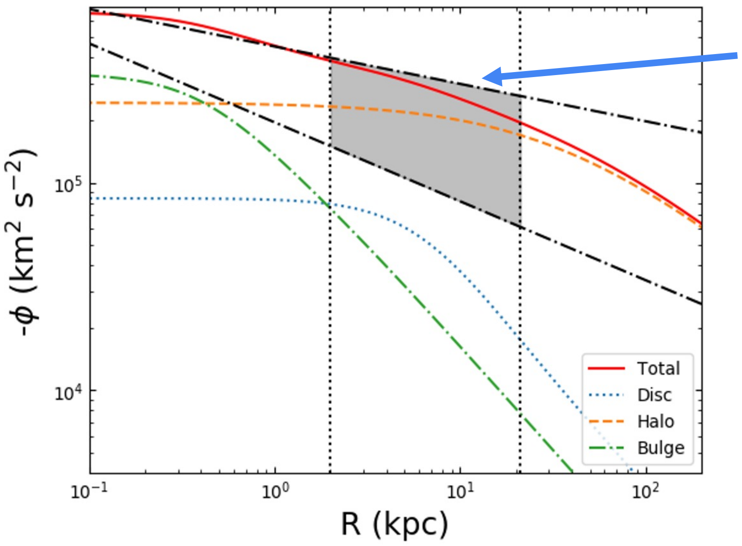


Ashley et al. ApJ 898 (2020)



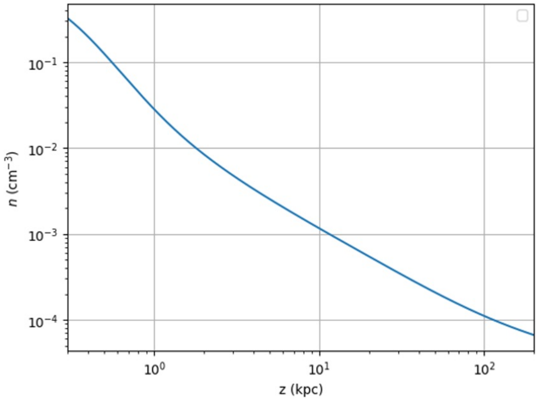
- $v_{max} \approx 300$ km s^{-1}
- $v(z \sim 10$ kpc$) \approx 150$ km s^{-1}
- Exhibits a smooth deceleration profile at large latitudes, -3.3 km s^{-1} deg^{-1}

Inputs for Hydrodynamical Calculation:



Constraint on slope and normalisation of Galactic potential provided by GAIA observations

Watkins et al. ApJ 873 (2019)



Isothermal temperature distribution adopted

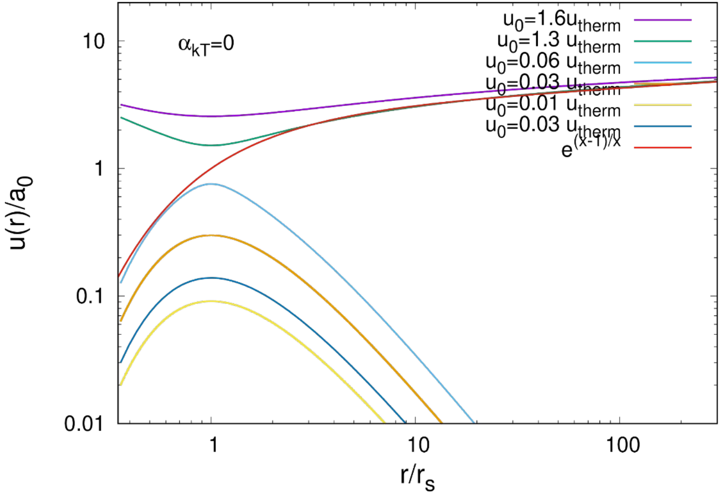
$$\mathbf{kT = 0.4\ keV}$$

- For hydrodynamical simulations, gas density started off in hydrostatic equilibrium distribution
- Assumed a heating process exists throughout the simulation volume that keeps the gas hot (with an isothermal temperature)
- Gas inflow velocity at inner radial boundary, v~100 km s^{-1}

Thermally Driven Outflows

$$\boxed{\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_\rho}$$

$$\boxed{\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\mathbf{I}) = -\rho \nabla \Phi_{\mathrm{eff}}}$$

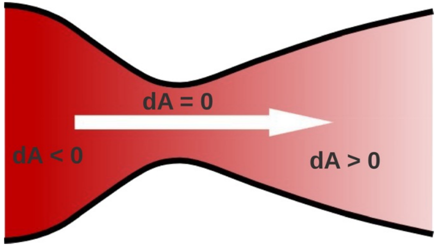


For a spherically symmetric
(isothermal) thermally driven outflow

$$\frac{1}{v}\frac{dv}{dr} = \frac{1}{r}\left(\frac{2c_s^2 - r\frac{d\Phi}{dr}}{v^2 - c_s^2}\right)$$

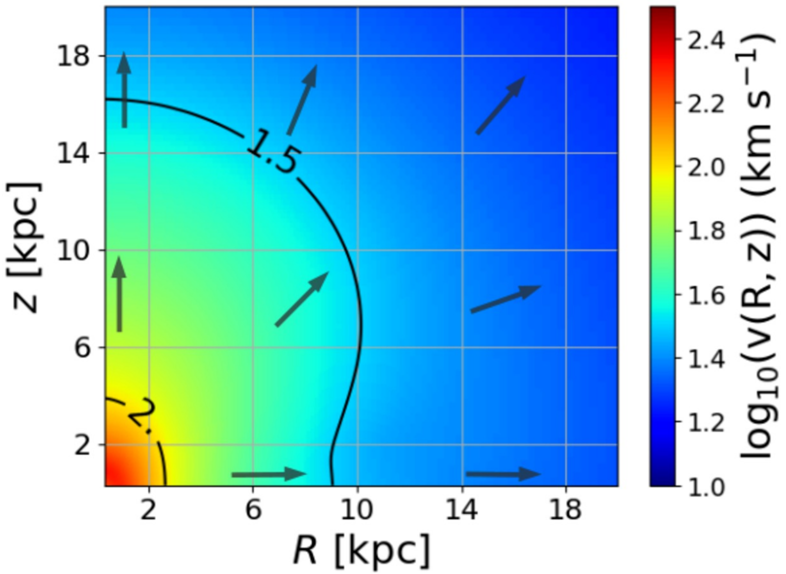
Analogy with Laval nozzle problem

$$\frac{1}{v}\frac{dv}{dr} = \frac{1}{A}\frac{dA}{dr}\left(\frac{1}{M^2 - 1}\right)$$

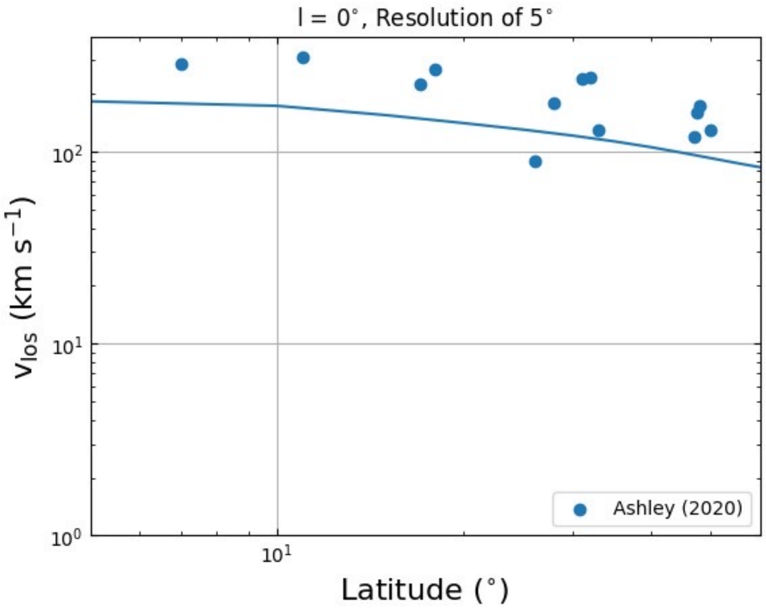


Subsonic Outflow Solution

2D distribution of the steady-state velocity structure produced from isotropic inner boundary conditions

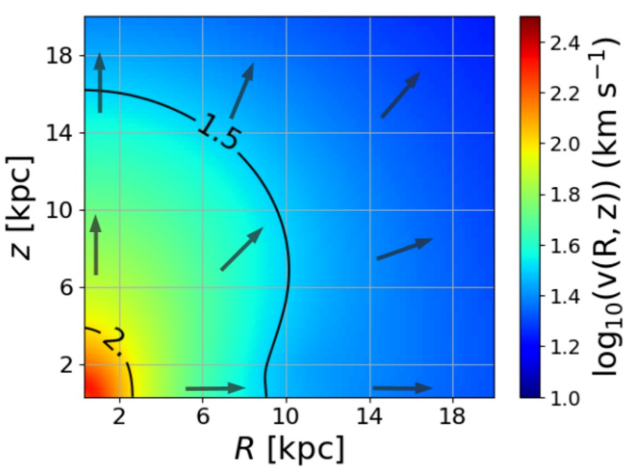


Comparison of the line-of-sight velocities from the subsonic outflow results with observational results

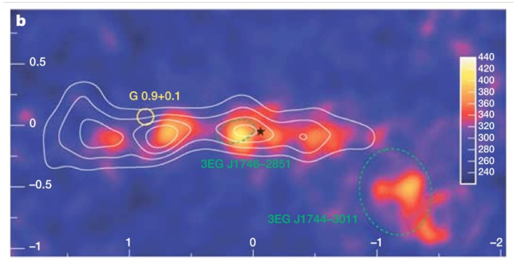


Cosmic Ray Transport Description

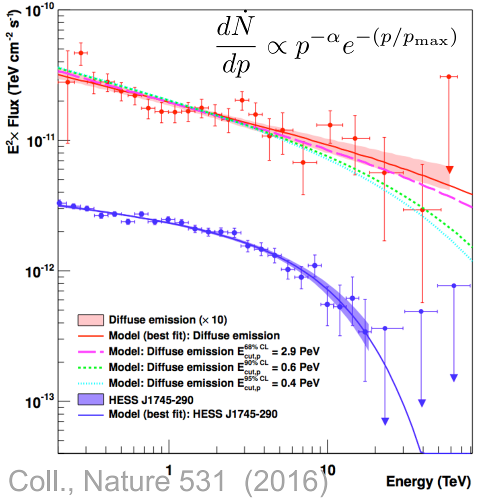
$$\frac{\partial f}{\partial t} = \nabla \cdot (D\nabla f - \mathbf{v} f) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[(\nabla \cdot \mathbf{v})\frac{p^3}{3} f\right] - \frac{f}{\tau_{\mathrm{loss}}} + \frac{Q}{p^2}$$



Very high energy gamma-ray emission map from the Central Molecular Zone



The spectral energy distribution of this gamma-ray emission



HESS Coll., Nature 531 (2016)

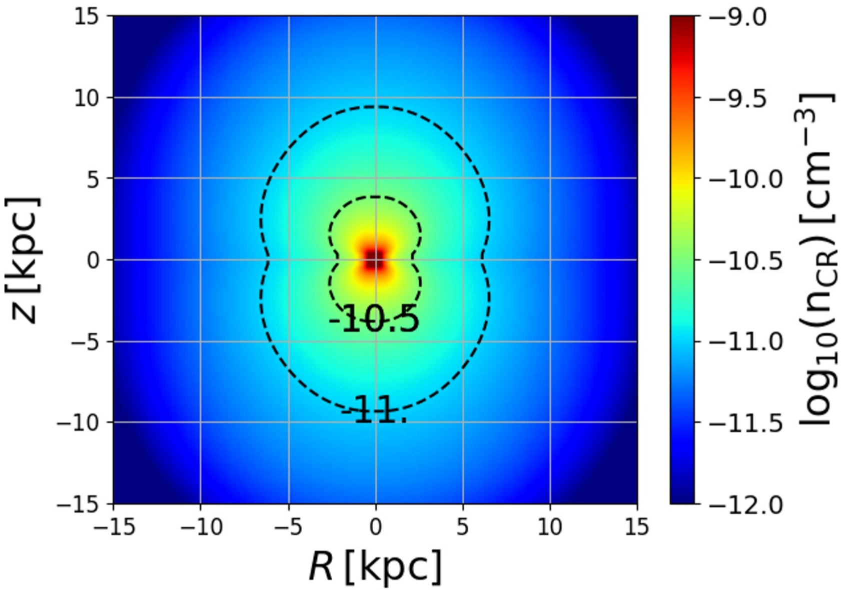
Cosmic Ray Transport Description

$$\boxed{\frac{\partial f}{\partial t} = \nabla \cdot (D \nabla f - \mathbf{v} f) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[(\nabla \cdot \mathbf{v})\frac{p^3}{3} f\right] - \frac{f}{\tau_{\rm loss}} + \frac{Q}{p^2}}$$

$$\frac{D}{c} = 0.1 \left(\frac{p}{10\ \mathrm{GeV}/c}\right)^{2-\gamma}\ \mathrm{pc}$$

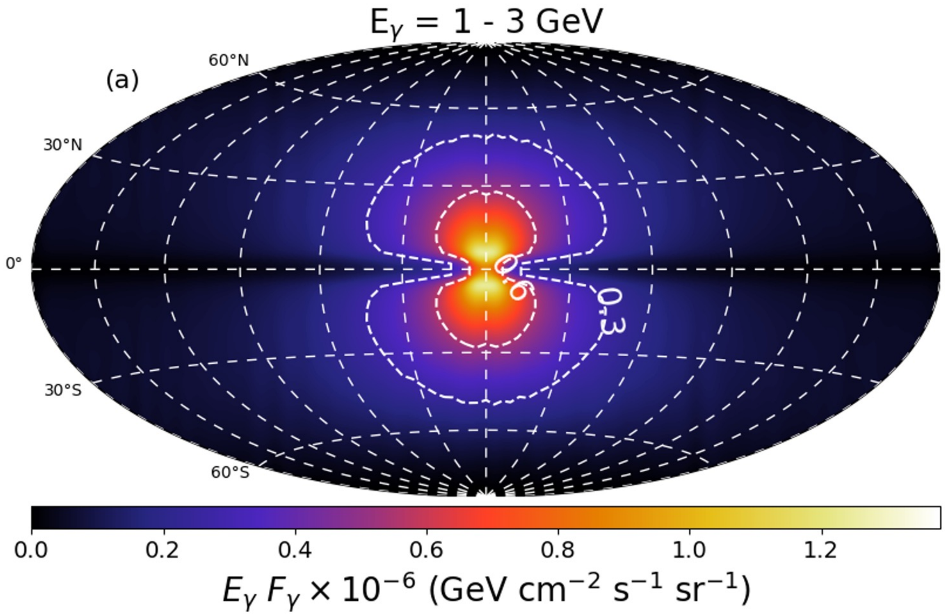
$$\tau_{\rm loss} = 20 \left(\frac{3 \times 10^{-3}\ \mathrm{cm}^{-3}}{n_{\rm halo}}\right)\ \mathrm{Gyr}$$

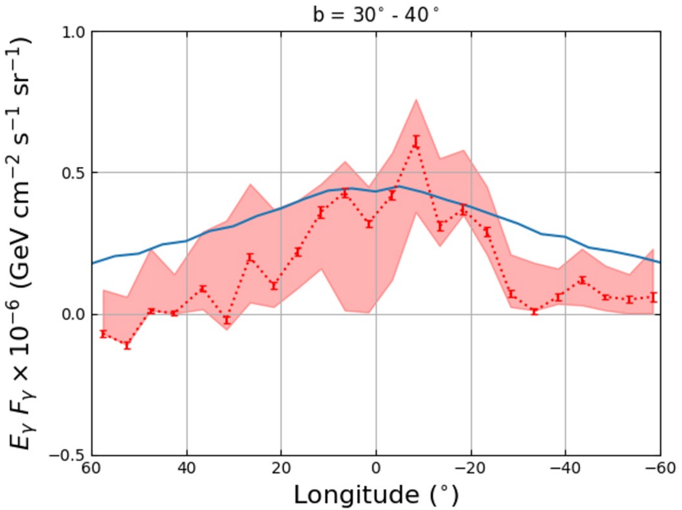
Density map of 10-30 GeV cosmic rays

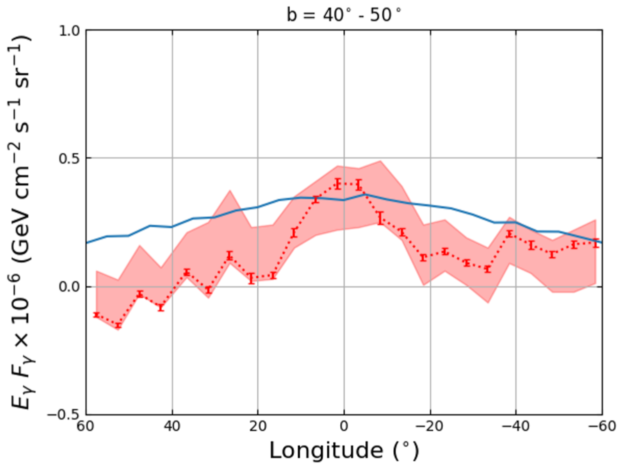


Gamma-Ray Emission (1-3 GeV)

- Cosmic rays are injected at the Galactic center with a luminosity of 6×10^{39} erg s^{-1}
- The gamma-ray emission brightness matches that observed by Fermi-LAT. The morphology is similar, though somewhat broader (in longitudinal distribution)





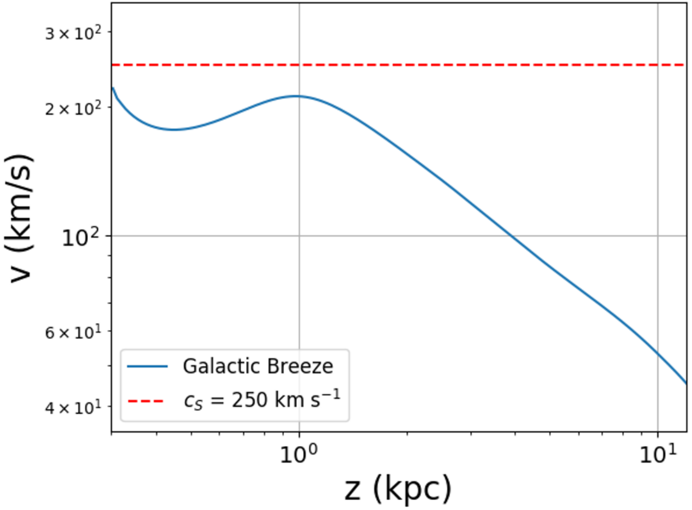


Conclusions

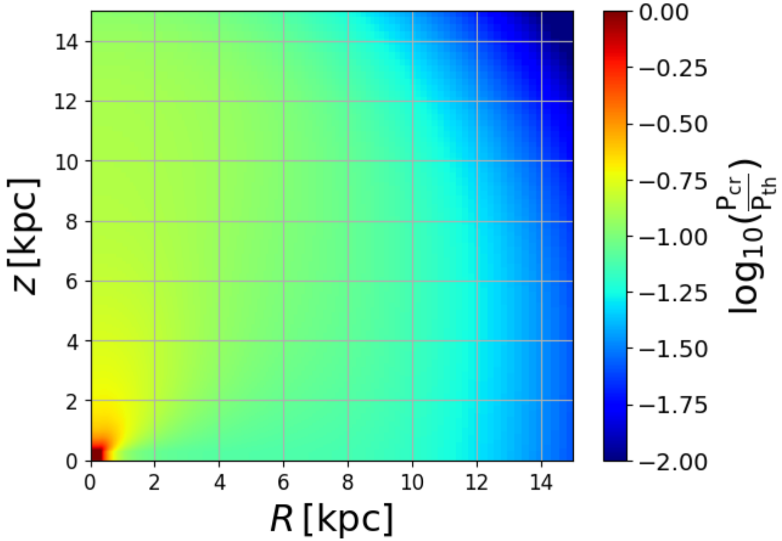
- The Fermi bubble structures appear to be a subset of larger scale outflow structures (eRosita bubbles and WIM material)
- A subsonic outflow would not significantly alter the Galaxy's gas distribution, explaining why the gas distribution in the extended Galactic halo appears to be in hydrostatic requilibrium
- A slow outflow would also be compatible with the velocity profile of the gas within the Fermi bubble structures
- The cosmic rays distribution, resulting from their transportation away from the Galactic center region, within the slow advection flows, leads to lobe-like structures
- Gamma-ray emission from these cosmic rays with the Galactic gas leads to Fermi bubble-like emission maps

Extra Slides

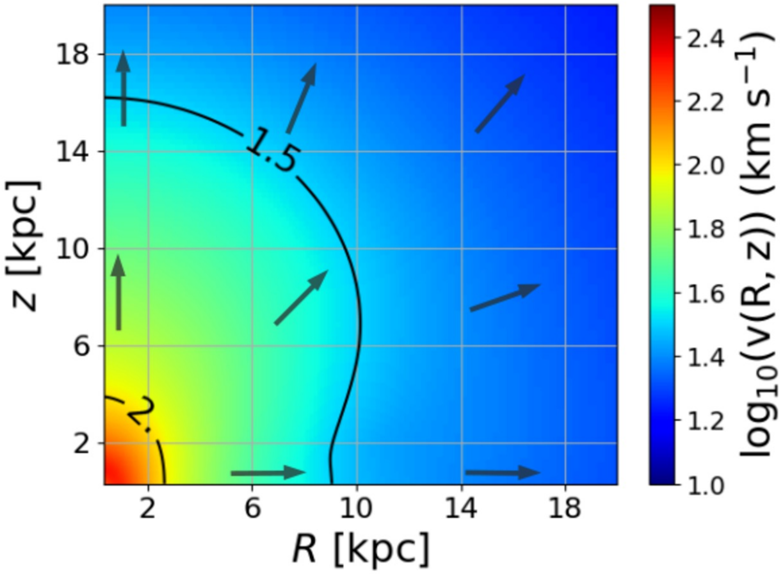
Subsonic Outflow



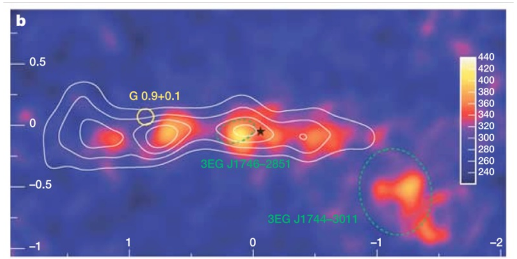
Ratio of Pressures



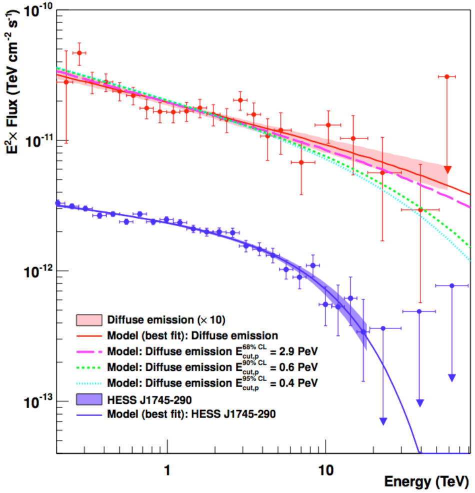
The Galactic Center Connection



Very high energy gamma-ray emission map from the Central Molecular Zone



The spectral energy distribution of this gamma-ray emission



HESS Coll., Nature 531 (2016)