A HADRONIC MODEL OF THE FERMI BUBBLES : GALACTIC COSMIC-RAYS IN A BREEZE

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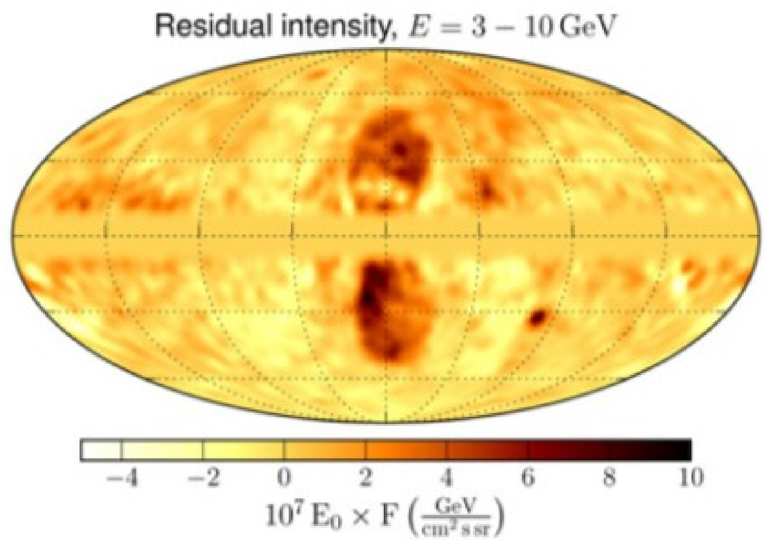
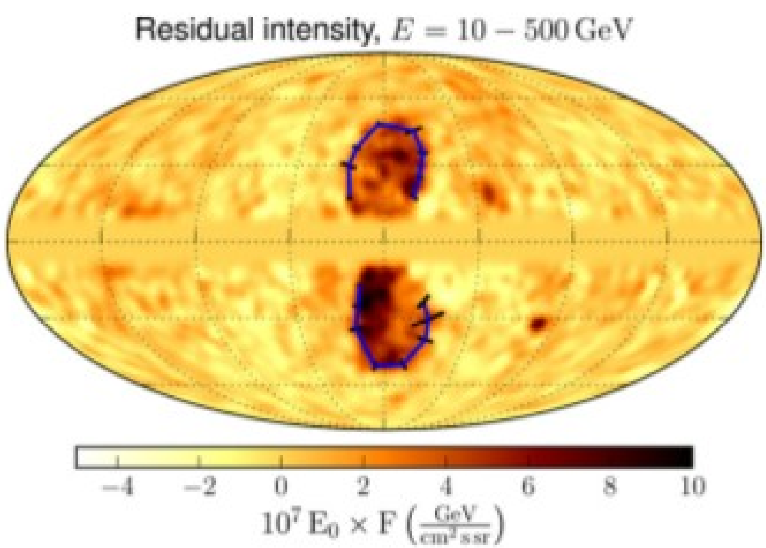
Fermi Bubbles: Observations

Ackermann et al., ApJ (2014) : Fermi-LAT data (100 MeV – 500 GeV).





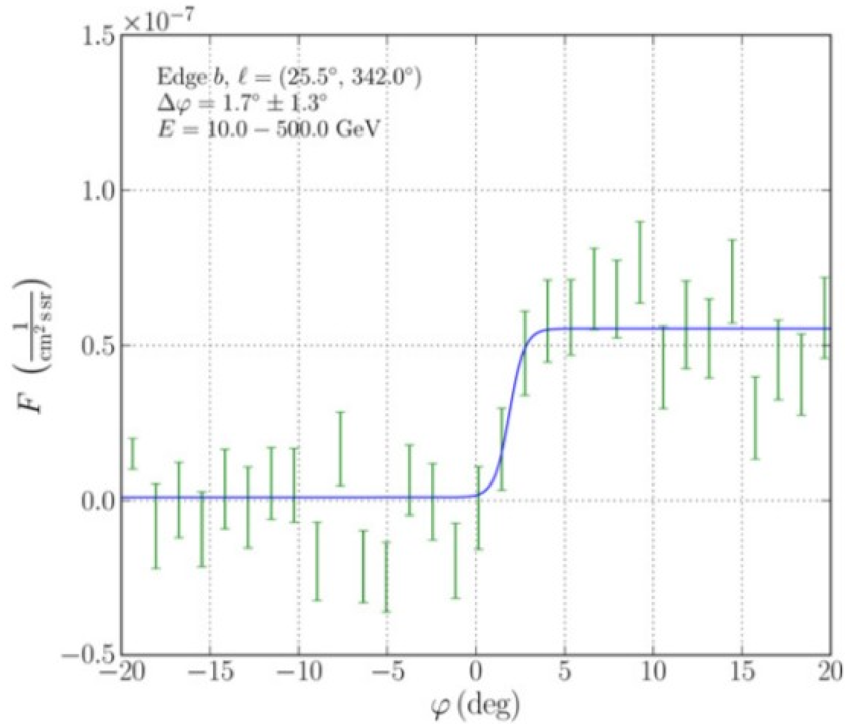
→ **γ-ray luminosity : ~ 4 x 10^{37} erg/s**

→ **Hard spectrum with a cutoff**

(Index : 1.9 ± 0.2 ; Cutoff : 110 ± 50 GeV)

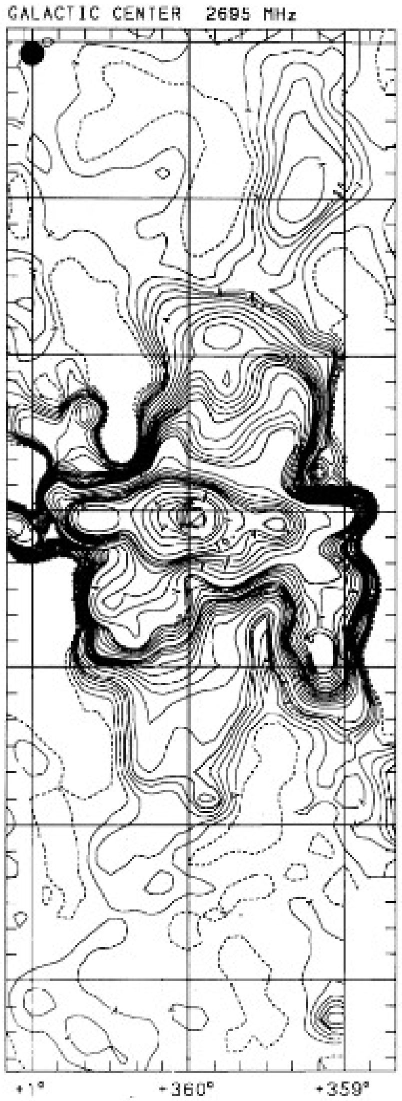
→ **Sharp edges**

→ **Approx. constant surface brightness.**

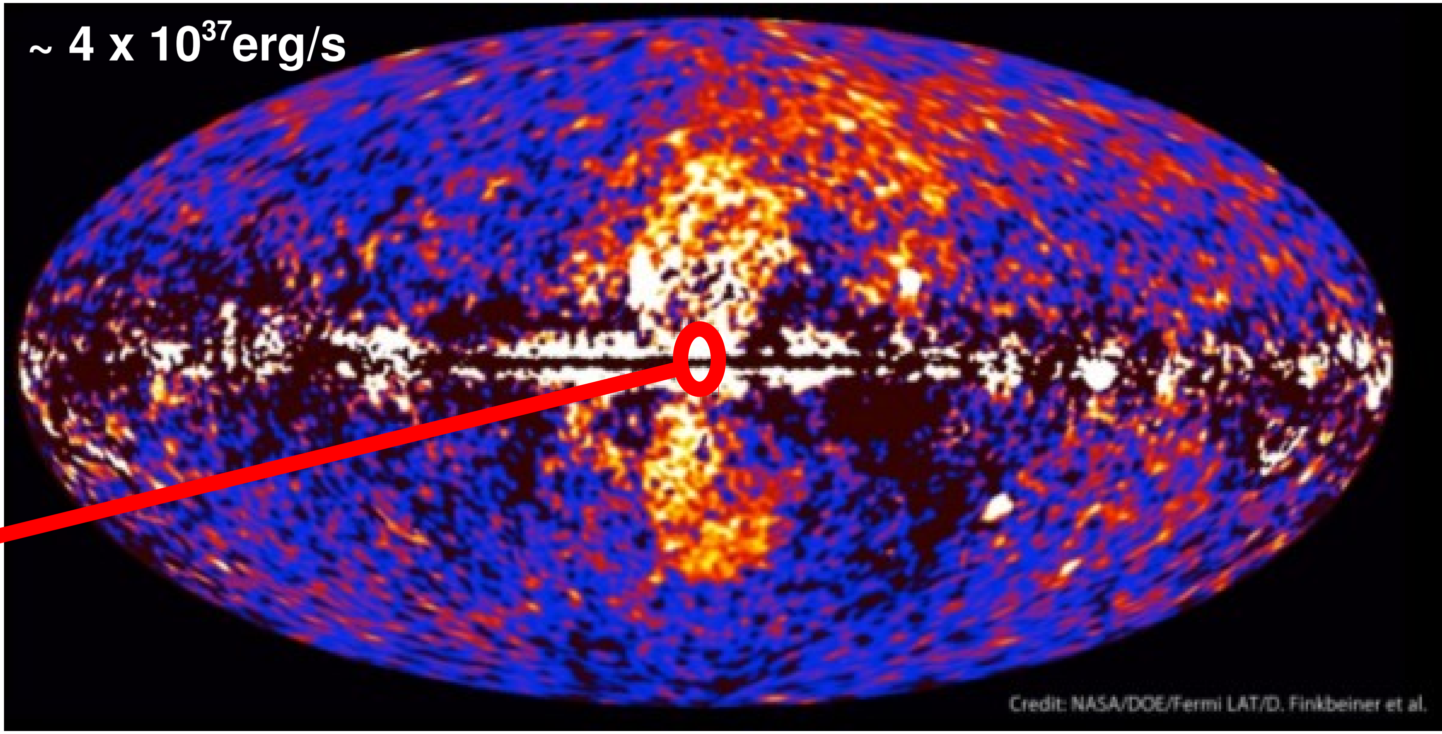


Evidence for an outflow from the GC?

2.7 GHz radio data



Pohl, Reich, Schlickeiser (1992)



Su, Slatyer & Finkbeiner (2010)

U_{outf} ~ 100's – 1000 km/s, P_{outf} ~ 3 x 10^{40} erg/s

→ SMBH ? *Transient episode, <u>~ several Myr time-scale</u>*

→ SFR in Central Molecular Zone : 5 – 10 % of MW's massive SF, SFR density ~ 1000 x avg in MW disk ⇒ compatible with P_{outf} , too.

<u>~ 100 Myr time-scale</u>

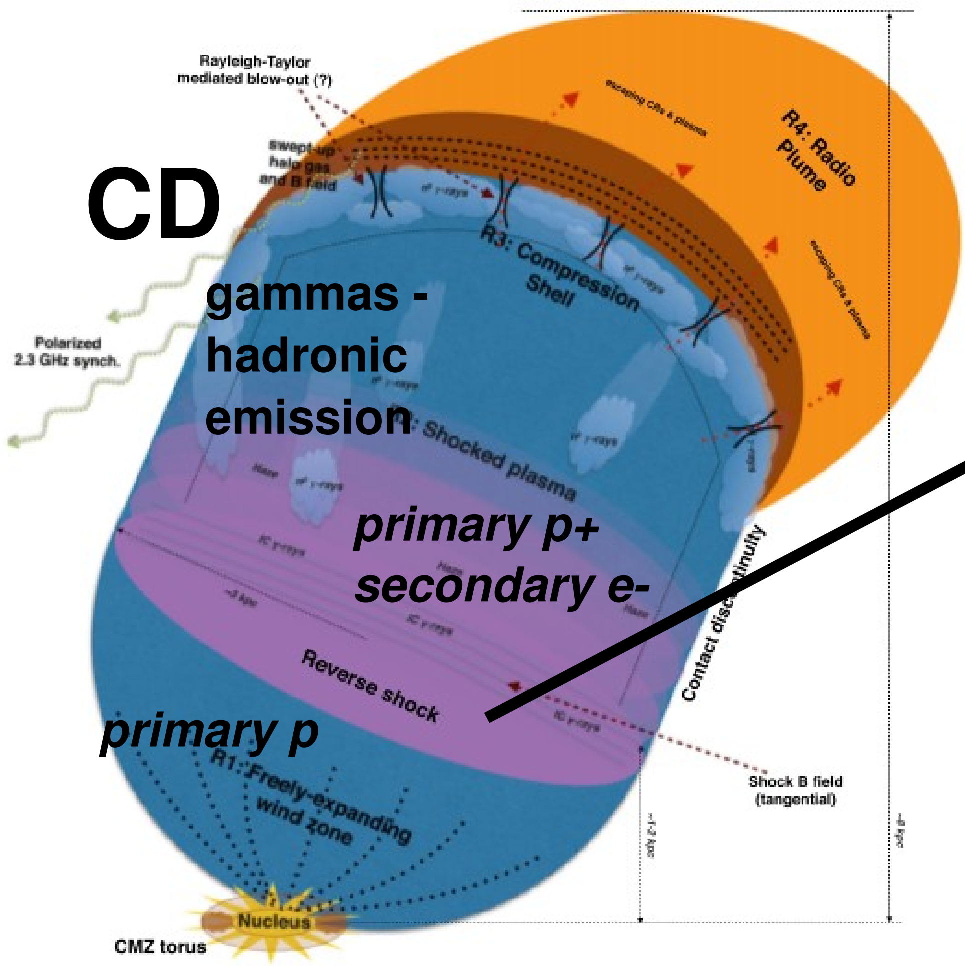
→ **Which velocity profile ?**

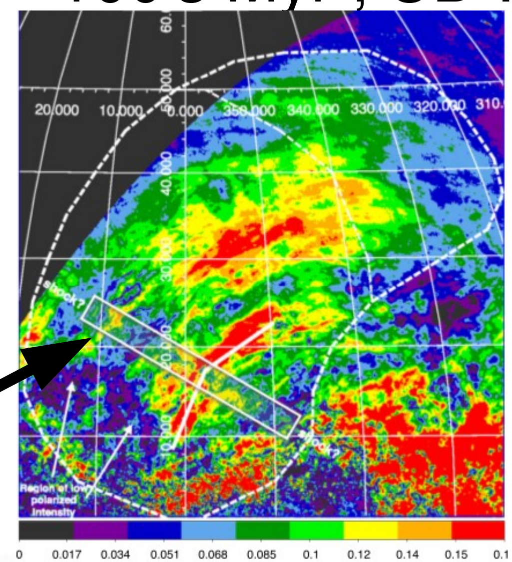
→ **CRs blown out of GC in this outflow: What happens to them ?**

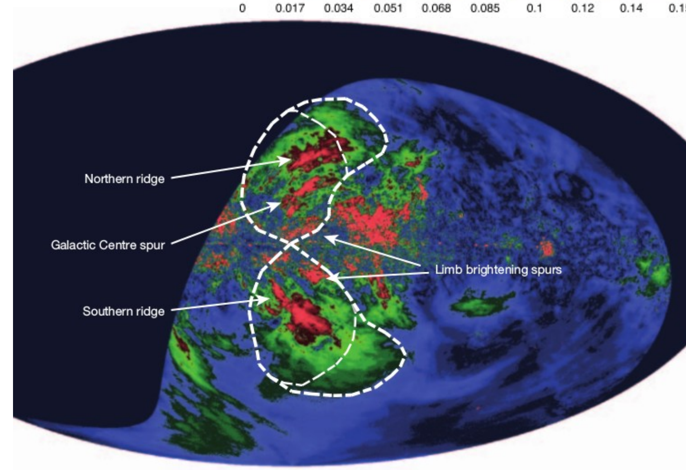
Two different models (examples)

Mertsch & Sarkar, PRL (2011): Leptonic model : 2[nd] order Fermi of e^- through entire volume of the bubbles ; Outflow timescale : ~ Myr.
+ : Cutoff at a few 100 GeV (e^- energy-losses) ; - : U ~ 1000 km/s

Crocker et al., ApJ (2015): slow nuclear outflow inflate bubbles into the halo (FB edge = contact discontinuity). ~ 100's Myr ; CD : ~ static.







Carretti 2013

2.3 GHz From S-PASS

Outflow velocity profile ?

Keeney et al., ApJ (2006)

ABSTRACT

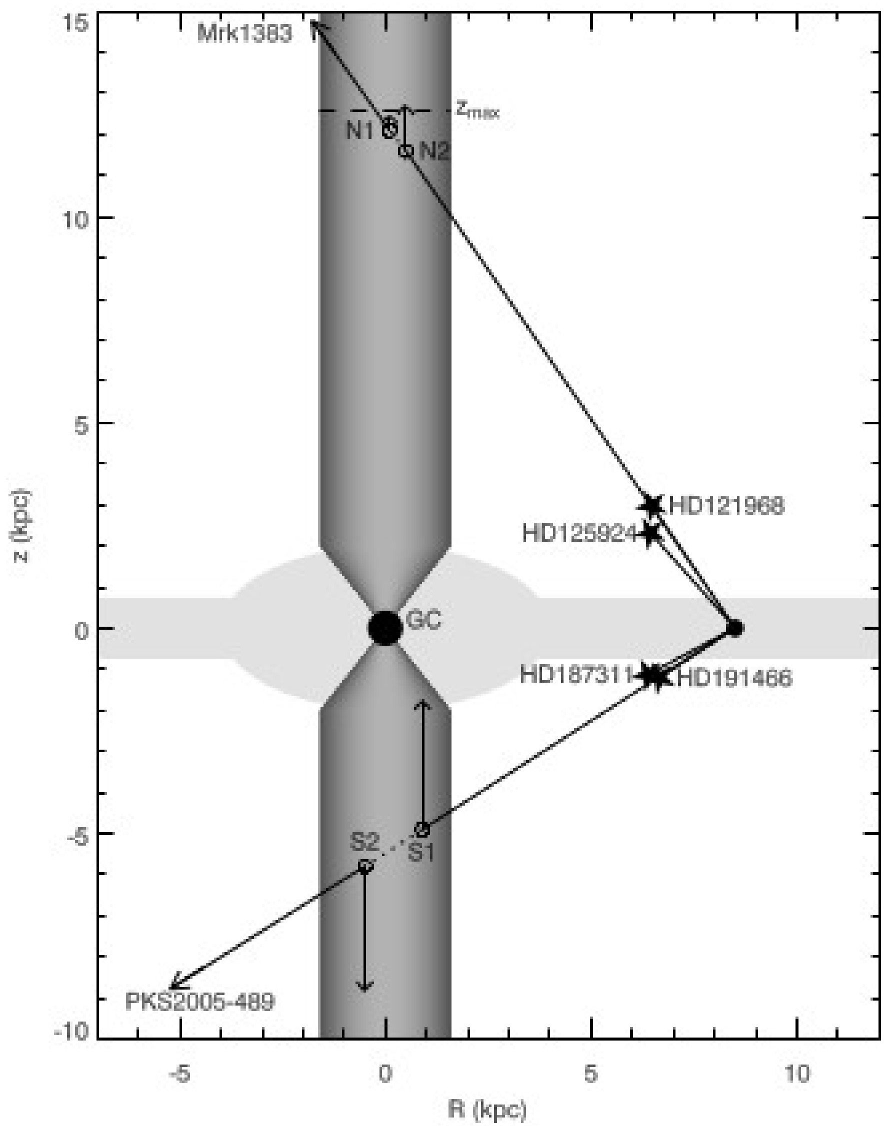
We detect high-velocity absorbing gas using *Hubble Space Telescope* and *Far Ultraviolet Spectroscopic Explorer* medium-resolution spectroscopy along two high-latitude active galactic nucleus (AGN) sight lines (Mrk 1383 and PKS 2005−489) above and below the Galactic center (GC). These absorptions are most straightforwardly interpreted as a wind emanating from the GC that does *not escape* from the Galaxy's gravitational potential. Spectra of four comparison B stars are used to identify and remove foreground velocity components from the absorption-line profiles of O VI, N V, C II, C III, C IV, Si II, Si III, and Si IV. Two high-velocity (HV) absorption components are detected along each AGN sight line, three redshifted and one blueshifted. Assuming that the four HV features trace a large-scale Galactic wind emanating from the GC, the blueshifted absorber is falling toward the GC at a velocity of 250 ± 20 km s^{-1}, which can be explained by "Galactic fountain" material that originated in a bound Galactic wind. The other three absorbers represent outflowing material; the largest derived outflow velocity is +250 ± 20 km s^{-1}, which is only 45% of the velocity necessary for the absorber to escape from its current position in the Galactic gravitational potential. All four HV absorbers are found to reach the same maximum height above the Galactic plane ($|z_{max}|$ = 12 ± 1 kpc), implying that they were all ejected from the GC with the same initial velocity. The derived metallicity limits of ≳10%–20% solar are lower than expected for material recently ejected from the GC unless these absorbers also contain significant amounts of hotter gas in unseen ionization stages.

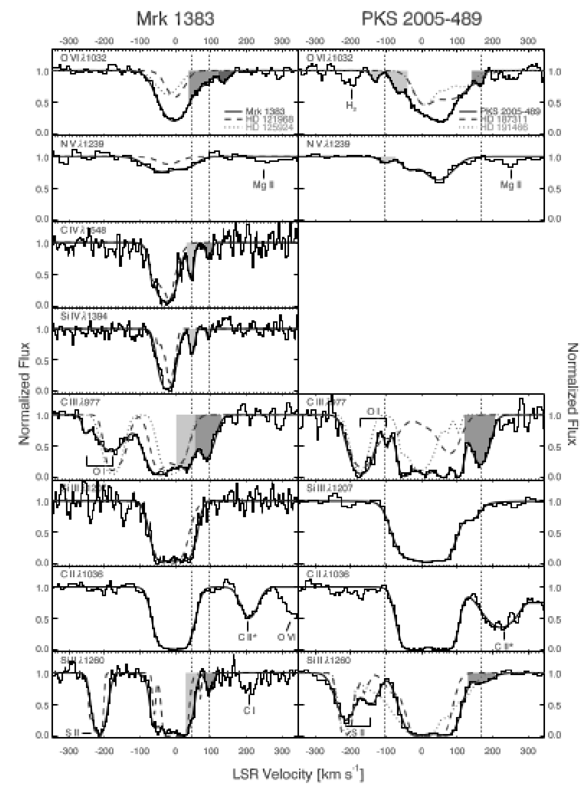
Constraints on outflow velocity profile

Keeney et al., ApJ (2006)

Absorption lines (from partially ionised gas)
⇒ Velocity of clumps N1, N2 is ~50 km/s,
And velocity of S1, S2 is ~150 - 250 km/s.

Also, the bending at the top of the "radio bubbles"
⇒ < 50 km/s velocities higher up…
⇒ Outflow decelerating with height z





Consistent with other outfows such as in NGC 4631, NGC 253

Diff.-advection in a Galactocentric breeze

Taylor & Giacinti, PRD (2017)

Diffusion – advection of pre-acc. CRs originating from the GC region :

$$\frac{\partial \psi_{\rm CR}}{\partial t} = \nabla \cdot (D \nabla \psi_{\rm CR} - V \psi_{\rm CR}) + \frac{\partial}{\partial p}\left[\frac{p}{3}(\nabla \cdot V)\psi_{\rm CR}\right] - \frac{\psi_{\rm CR}}{\tau_{\rm CR}} + Q_{\rm CR}$$

*CR density per unit of momentum p at **r*** *pp loss* *source term*

with a CR mean free path : $\lambda_{10\,\rm GV} = 3D_{10\,\rm GV}/c = 0.3\,{\rm pc}$ ↔ B/C

and a CR luminosity (source term) of ~ 10^{40} erg s^{-1} .

Outflow velocity profile : (decelerating at high z ; divergence free)

$$V \cdot \hat{\mathbf{z}} = v_{\rm max} e^{\frac{1}{2}(1-\frac{d}{z})} \times \frac{2}{1+z/d}$$, with $v_{\rm max} = 300\,{\rm km\,s^{-1}}$ and $d = 1\,{\rm kpc}$.

→ Timescale of **O(100 Myr)** to fill a region beyond the bubbles.

→ Broadly encapsulates the velocity profile of a **"breeze" solution** for the isothermal outflow problem. The gas density plateaus within the decelerating flow phase. ⇒ motivates ~ **cst gas density in the bubbles** ~ **3 x 10^{-3} cc**.

Diff.-advection in a Galactocentric breeze

Taylor & Giacinti, 1607.08862

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, with $v_{\rm max} = 300\,\rm km\,s^{-1}$ and $d = 1\,\rm kpc$.

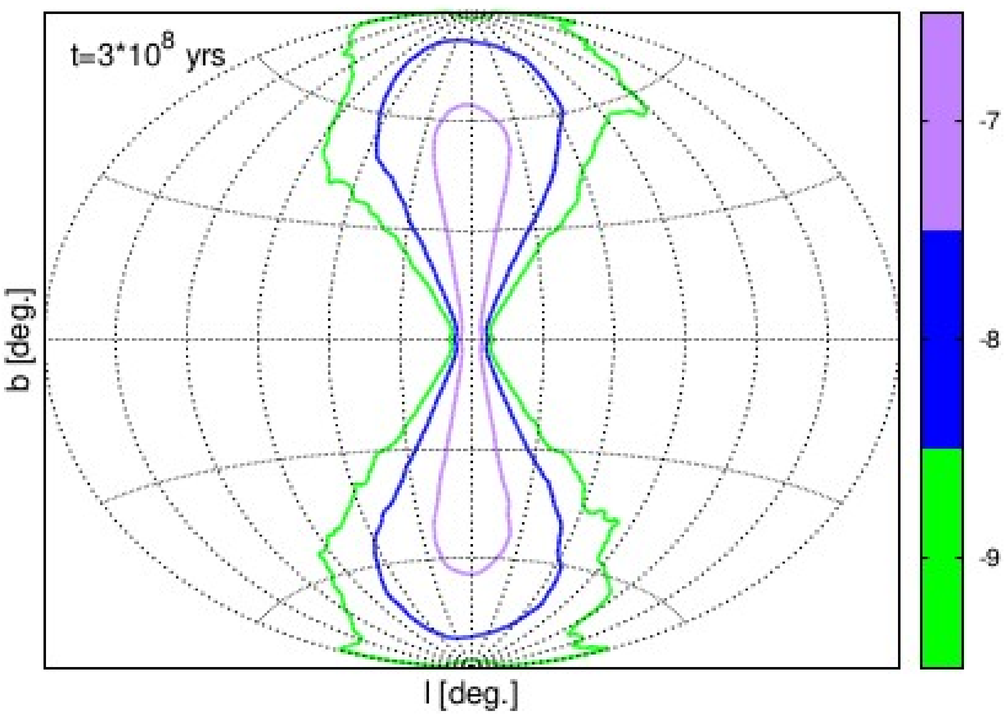
Indeed, the Bondi radius is :

$$d = 2GM/v_{\rm th}^2 \approx 2\left(\frac{M}{10^{10}\ M_\odot}\right)\left(\frac{300\,\rm eV}{kT}\right)\ \rm kpc$$

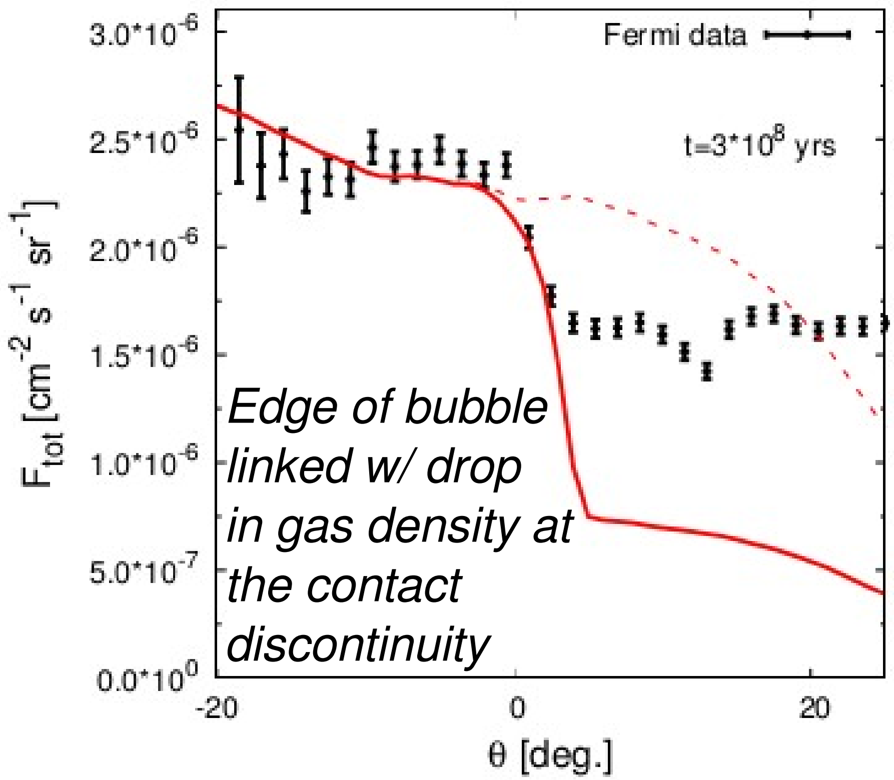
mass within the bulge around 1 kpc — *isothermal T at the base of the wind*

Our results

Contour plots for $\log_{10}$ of the γ-ray flux surface brightness ($cm^{-2}\, s^{-1}\, sr^{-1}$) :



Edge of the 1 – 2 GeV bubble from our model with that from the Fermi data analysis :



→ **Morphology + Cst surface brightness well reproduced**.

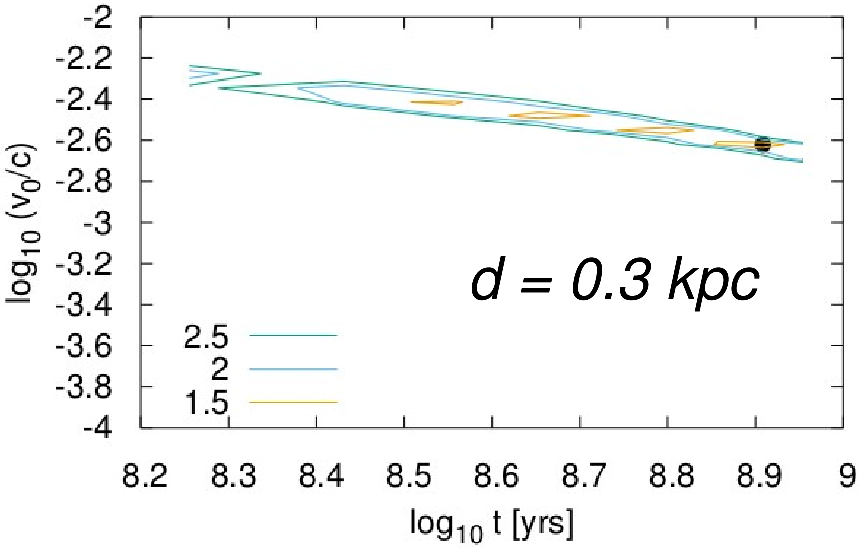
→ In general, for cst gas density, **γ-ray data prefers decelerating profiles**.

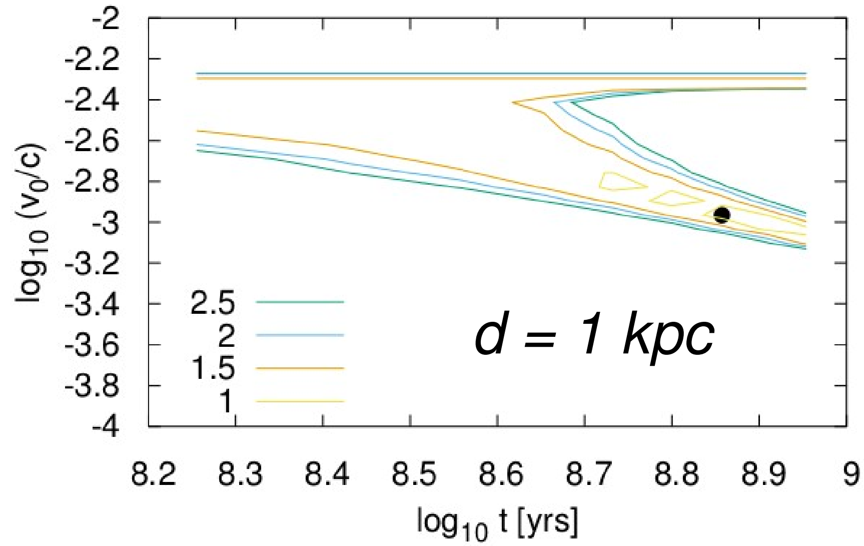
→ Sharp edge ↔ Change in gas density at the CD … or CR mfp smaller.

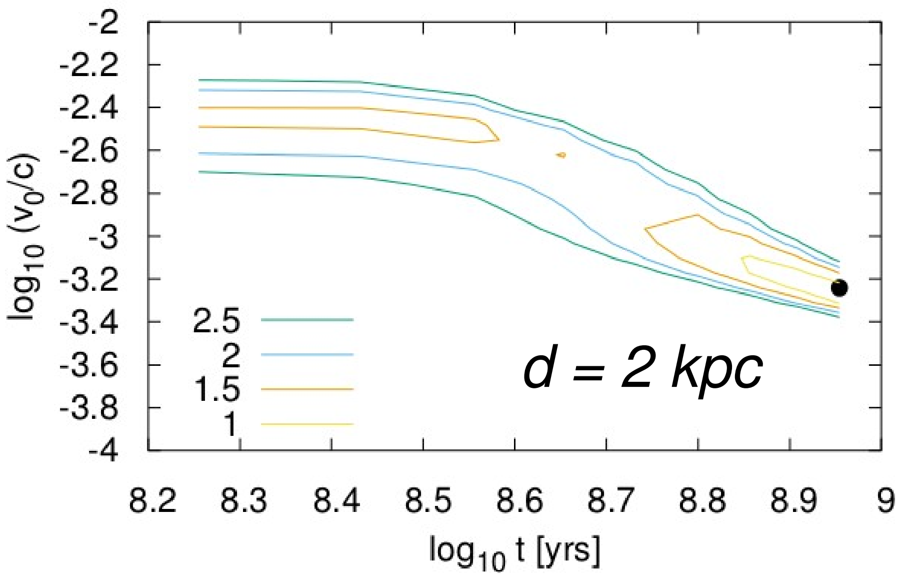
→ Explains discrepancy between γ-ray data and 2.3 GHz data. Both p and e- possess extended distributions. Difference in morphology of emission due to differing distributions of target gas and magnetic fields.

Our results

<u>Value of *d* :</u> For the majority of the parameter space, small values of *d* are problematic. Intermediate and "large" values of *d* both show non-negligible regions of parameter space able to provide sufficiently flat profiles in agreement with that measured :



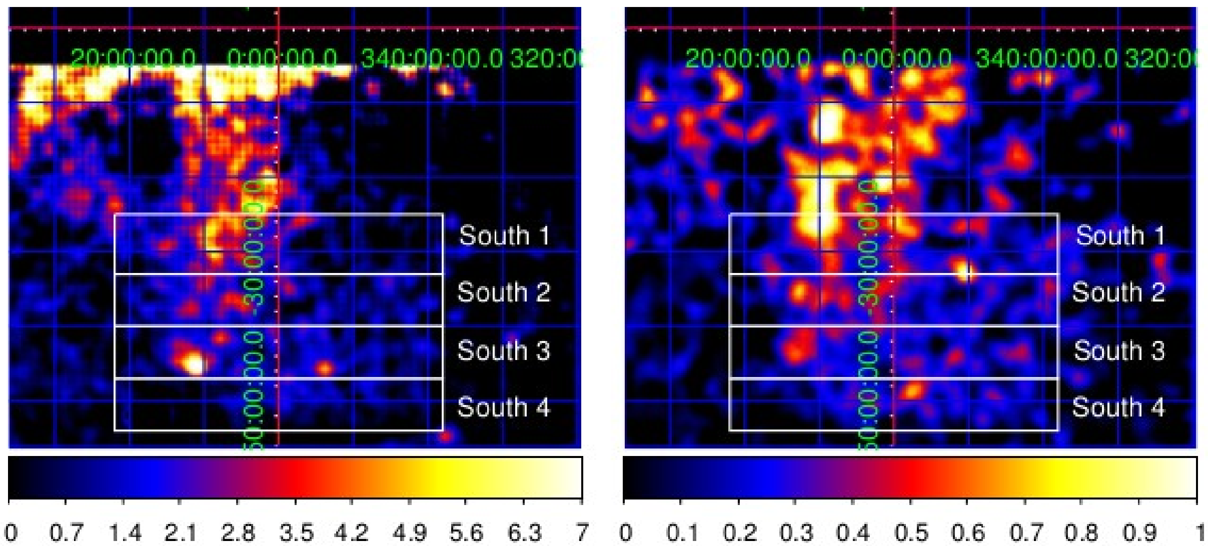




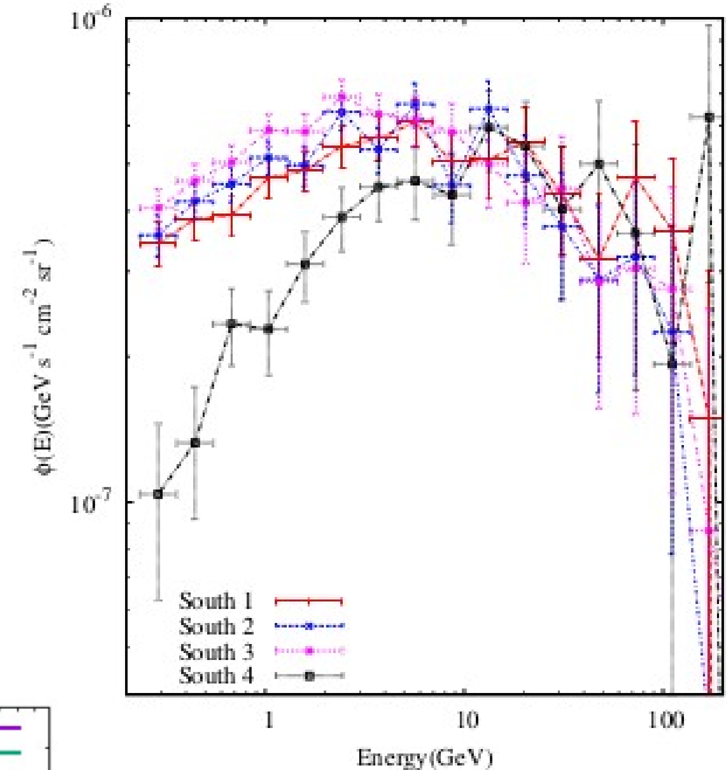
$\chi^2_{\rm d.o.f.}$ contours for fits to the γ-ray flux surface brightness profile of the FBs using Fermi measurements in the range $\theta < 2^o$.
Black circles : Best-fit parameters.

Energy spectra Southern Bubble

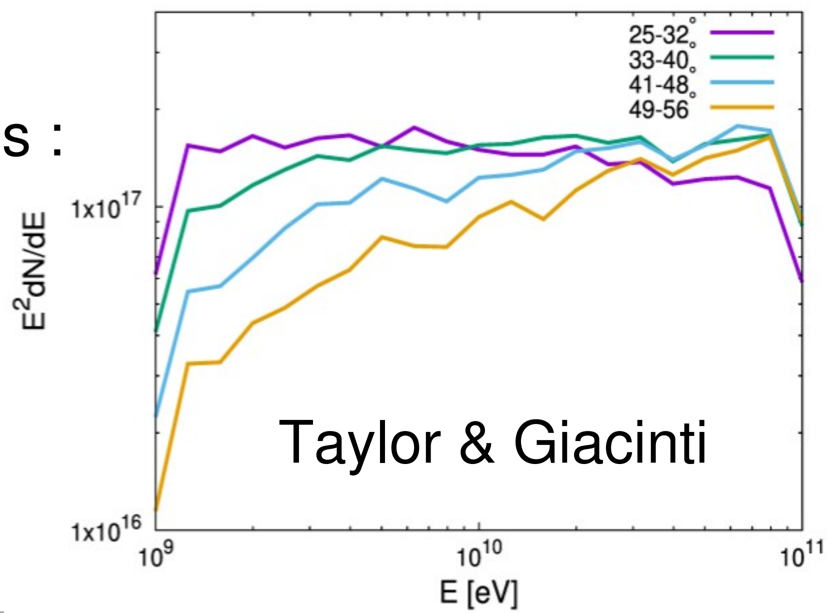
→ Measurements of Yang et al., 1402.0403 :



1 – 2 GeV   10 – 30 GeV

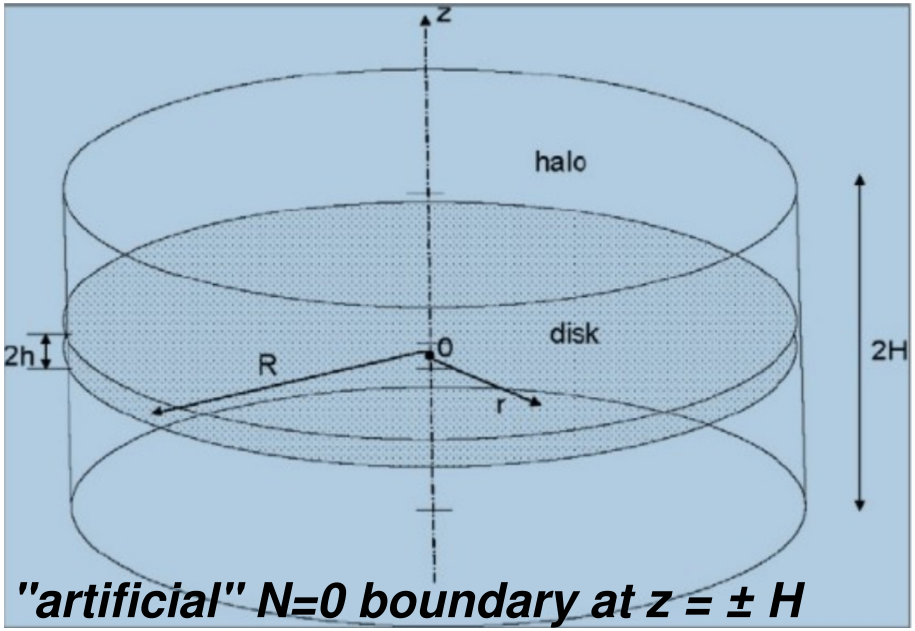


→ vs our predictions :



Galactic winds (or breezes) at larger Galactocentric radii ?

" ↔ "



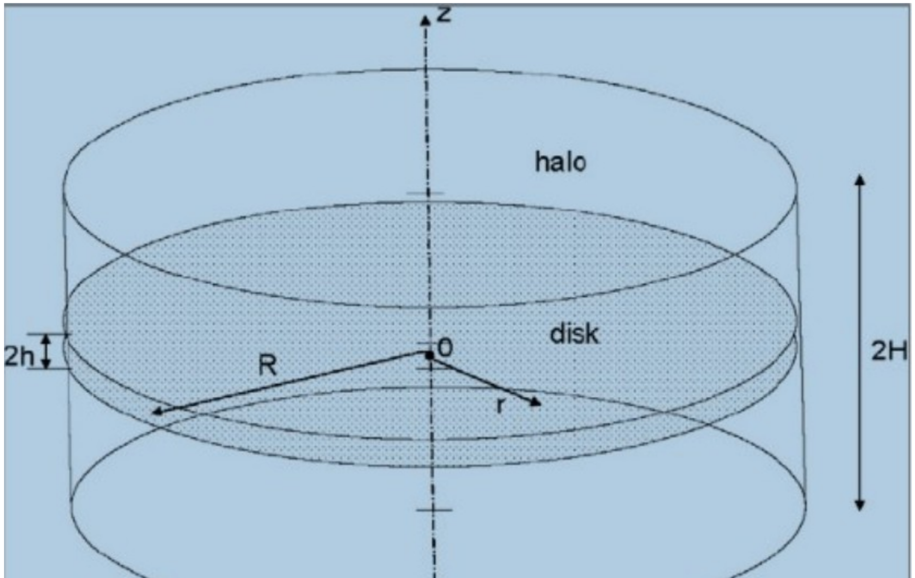
Galactic winds (or breezes) at larger Galactocentric radii ?

"NO WIND" CASE:

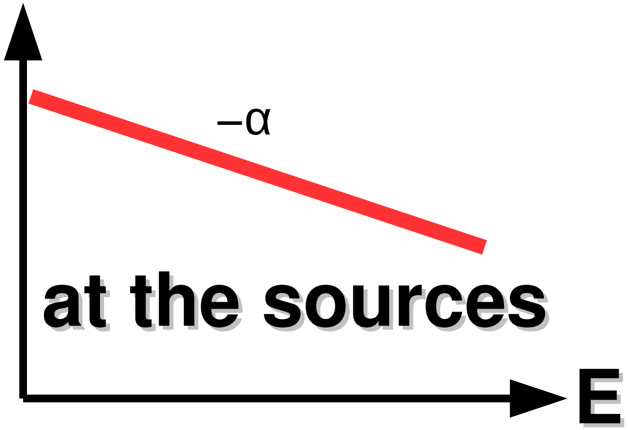
CR spectrum at sources: $\sim E^{-\alpha}$

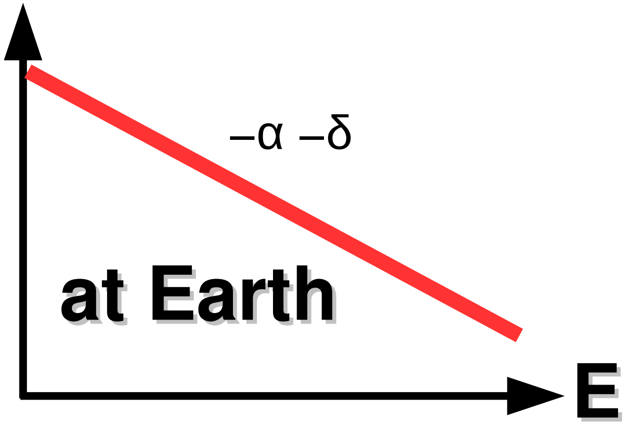
D: $\sim E^{\delta}$;   B/C: $\sim E^{-\delta}$

CR spectrum at Earth: $\sim E^{-\alpha-\delta}$



"artificial" N=0 boundary at z = ± H





Galactic winds (or breezes) at larger Galactocentric radii ?

"WIND V(z) ~ z" CASE:

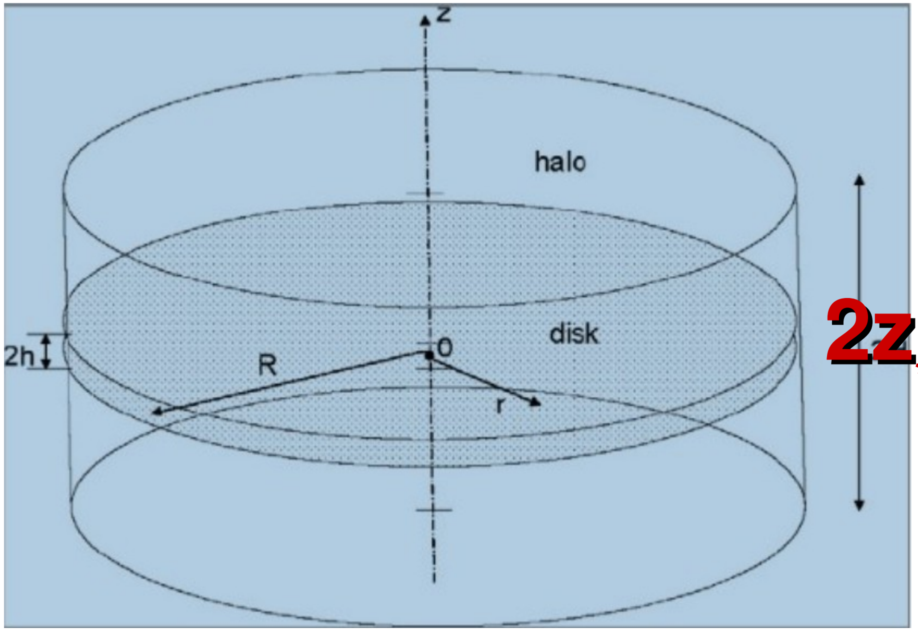
CR spectrum at sources: $\sim E^{-\alpha}$

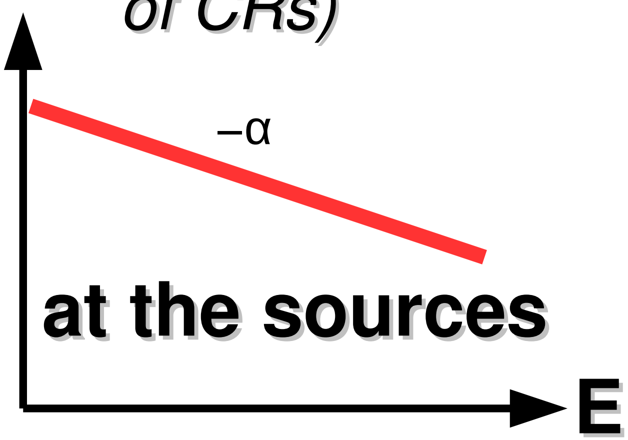
D: $\sim E^{\delta}$; B/C: $\sim E^{-\delta/2}$

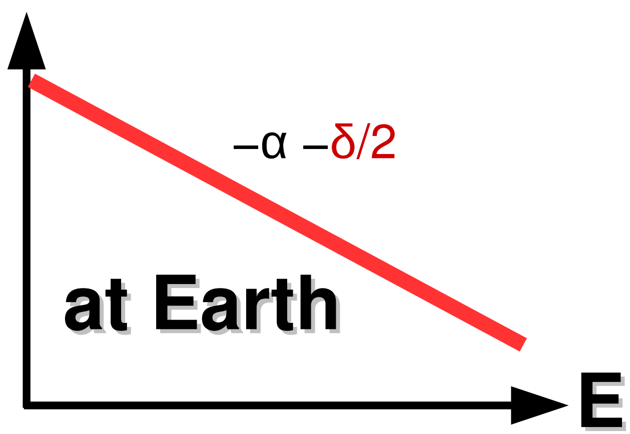
CR spectrum at Earth: $\sim E^{-\alpha-\delta/2}$

e.g. Bloemen + '93, Ptuskin + '97

(see S. Recchia's talk for dyn. impact of CRs)







Diffusion time : $t_{diff} \sim z^2/D$

Advection time : $t_{adv} \sim z/V$

(*independent of z*)

$$\Rightarrow z_* \sim D/V \propto D^{1/2}$$

Conclusions & Perspectives

- Modelled the Fermi Bubbles as a **Galactocentric outflow of gas and pre-accelerated CRs.**

- **Flat surface brightness** (as observed by Fermi) can be **reproduced with outflows decelerating with distance to the Galactic disk (e.g. breeze profiles)**,

- Future observations will be able to test the presence or absence of **winds or breezes** at larger Galactocentric radii, thanks to **local CR observables**.