Gone with the breeze

A subsonic solution to the Fermi bubbles problem

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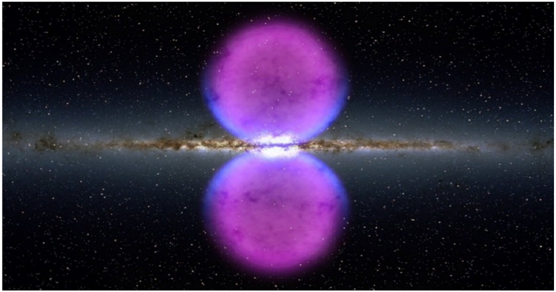
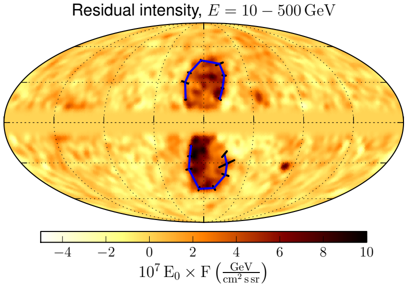


Arxiv: https://arxiv.org/abs/2207.09189

HELMHOLTZ

Fermi bubbles: Features

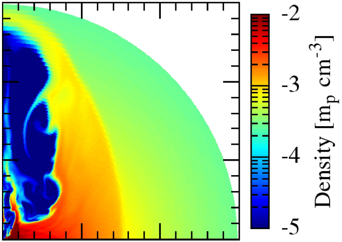
- 2 Galactic bubbles in the gamma ray energy range
- Height: b $\approx 50^\circ$, width: l $\approx 40^\circ$
- Hard spectrum: $\frac{dN}{dE} \propto E^{-\alpha}$, with $\alpha \approx 2$
- Constant brightness intensity and sharp edges
- Where ? When ? How ?



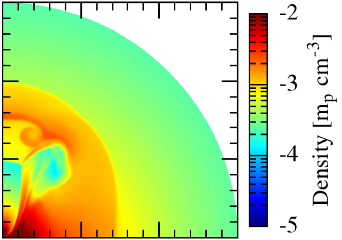
Ackermann et al. (2014)

Fermi bubbles: Emission mechanism model

> Leptonic jet model
  - CR are electrons
  - $\tau_{\rm loss} \sim$ 1-3 Myr
  - Highly supersonic velocity
  - AGN jet



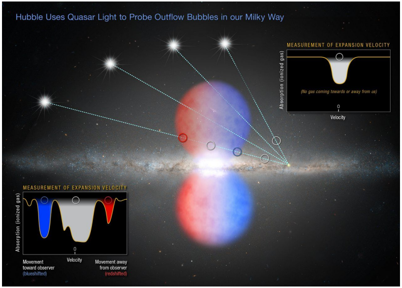
> Hadronic wind model
  - CR are protons
  - $\tau_{\rm loss} \sim$ several Gyr
  - Supersonic velocity
  - Starburst or AGN wind



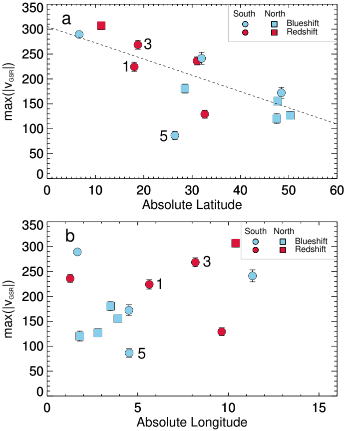
Sarkar et al. (2016)

Fermi bubbles: Decelerating velocity profile

- UV absorption line observations of cold clouds



Source: NASA



Ashley et al. (2020)

- $v_{\rm max} \approx 300$ km s^{-1}
- v(1 kpc) ≈ 180 km s^{-1} (Sofue 2022 PASJ)

Continuous deceleration:
Subsonic profile ?

Thermally-driven outflow solutions

> Mass and momentum conservation,

$$\nabla \cdot (\rho \mathbf{v}) = S_\rho$$

$$\nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\mathbf{I}) = -\rho \nabla \Phi$$

> Thermally-driven spherically symmetric outflow (Parker 1958)

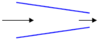
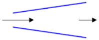
$$\frac{1}{v}\frac{dv}{dr} = \frac{1}{r}\left(\frac{2c_s^2 - \frac{r d\Phi}{dr}}{v^2 - c_s^2}\right)$$

> $r_c \equiv r\frac{d\Phi}{dr} = 2c_s^2$, is the critical radius

- $r < r_c \rightarrow 2c_s^2 < r\frac{d\Phi}{dr}$
- $r > r_c \rightarrow 2c_s^2 > r\frac{d\Phi}{dr}$

Analogy with Laval nozzle:

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

1.	*Subsonic Flow*: $M < 1$ and $dA < 0$, then $dV > 0$: indicating an accelerating flow in a converging channel.	
2.	*Supersonic Flow*: $M > 1$ and $dA < 0$, then $dV < 0$: indicating an decelerating flow in a converging channel.	
3.	*Subsonic Flow*: $M < 1$ and $dA > 0$, then $dV < 0$: indicating an decelerating flow in a diverging channel.	
4.	*Supersonic Flow*: $M > 1$ $dA > 0$, then $dV > 0$: indicating an accelerating flow in a diverging channel.	

E. Pardyjak (U. Utah)

$$\frac{dA}{dr} < 0 \rightarrow 2c_s^2 < r\frac{d\Phi}{dr}$$

$$\frac{dA}{dr} > 0 \rightarrow 2c_s^2 > r\frac{d\Phi}{dr}$$

$$\frac{dA}{dr} = 0 \rightarrow 2c_s^2 = r\frac{d\Phi}{dr}$$

Thermally-driven outflow solutions

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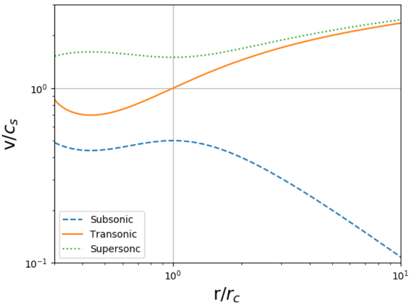


> Transonic solution $\rightarrow$ Wind
> Subsonic solution $\rightarrow$ Breeze

Hydrodynamics simulations

- Isothermal Galactic halo
- Hydrostatic density distribution:

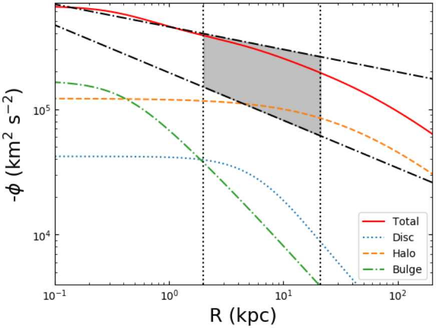
$$\rho = \rho_0 \, \text{exp} \left(-\frac{\Phi}{c_s^2} \right)$$

with $\Phi = \Phi_{\text{bulge}} + \Phi_{\text{disc}} + \Phi_{\text{halo}}$

- Maximise the outflow velocity:

$$r_c = 1 \text{ kpc} \Rightarrow kT \approx 500 \text{ eV}$$

$$\Rightarrow c_s \approx 250 \text{ km s}^{-1}$$

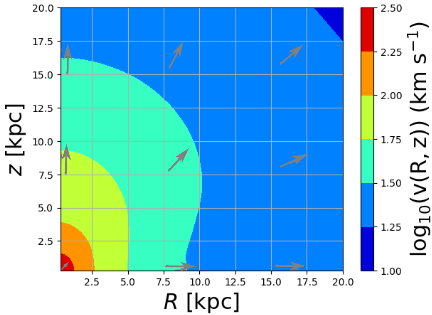


Tourmente et al. (2022)

The fitting range, for R = 2-21 kpc, is provided by Watkins et al. (2019)

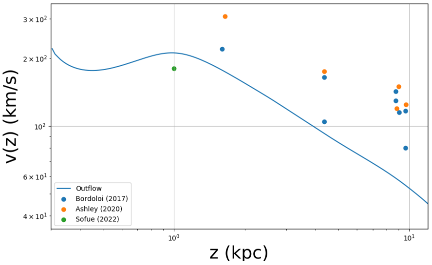
Galactic breeze profile

2D spatial distribution for the subsonic velocity profile



Tourmente et al. (2022)

Comparision of the subsonic outflow (blue line) with data from cold clouds observations



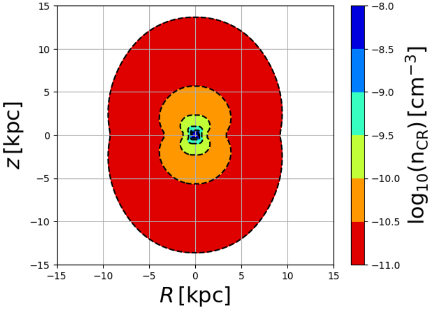
Cosmic rays transport code

- The subsonic velocity profile, simulated with the HD code, is included in a CR transport code.

Advection + Diffusion — Momentun advection — Losses — Injection

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

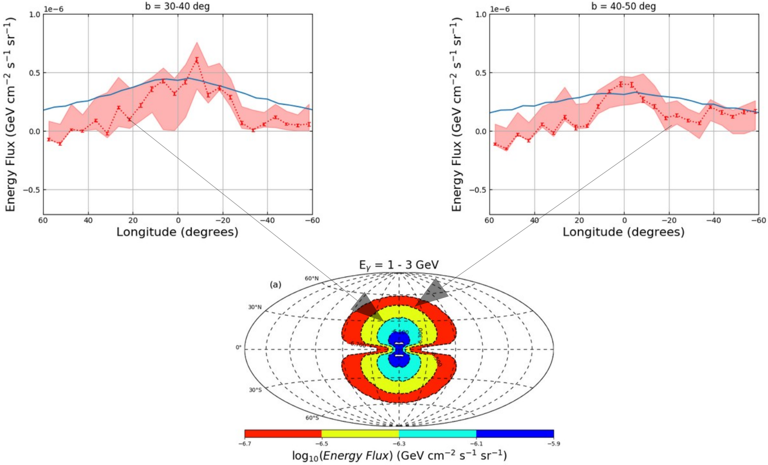
- $\frac{D}{c} = 0.1 \left(\frac{p}{10\ \text{GeV/c}}\right)^{2-\gamma}$ pc
- $\tau_{\text{loss}} = 60$ Gyr
- $\frac{d\dot{N}}{dE} \propto E^{-2}$



Tourmente et al. (2022)

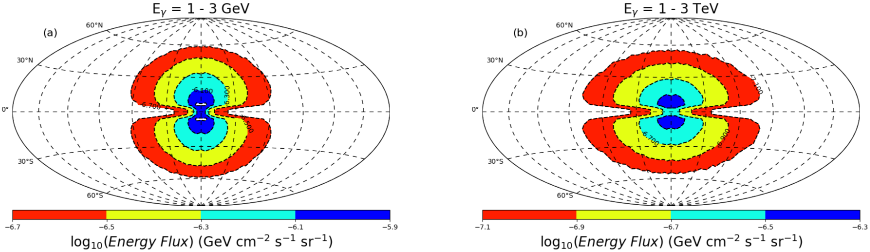
Gamma-rays emission

- CRs are injected with a luminosity of $L_{CR} = 6 \times 10^{41}$ GeV s^{-1}
- The γ rays emissions are compatible with observations provided by Fermi-LAT instruments (Ackerman et al. (2014 APJ)). Howerver the bubbles appear wider.



Prediction for CTA/SWGO measurements

- CTA is the next generation ground-base gamma ray intruments.
  (20 GeV to 300 TeV)
- At $b \sim 50^{\circ}$ the energy flux shoud be between
  $8 \times 10^{-8} - 1.3 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}.



Tourmente et al. (2022)

Conclusions

- A subsonic profile can reproduce the observed gamma ray emission
- Match well with the velocity evolution observed from cold clouds but magnitude is too small
- The simulated bubble is wider than what has been observed
- The outflow profile is strongly dependent on the gravitational potential and the ambient temperature.