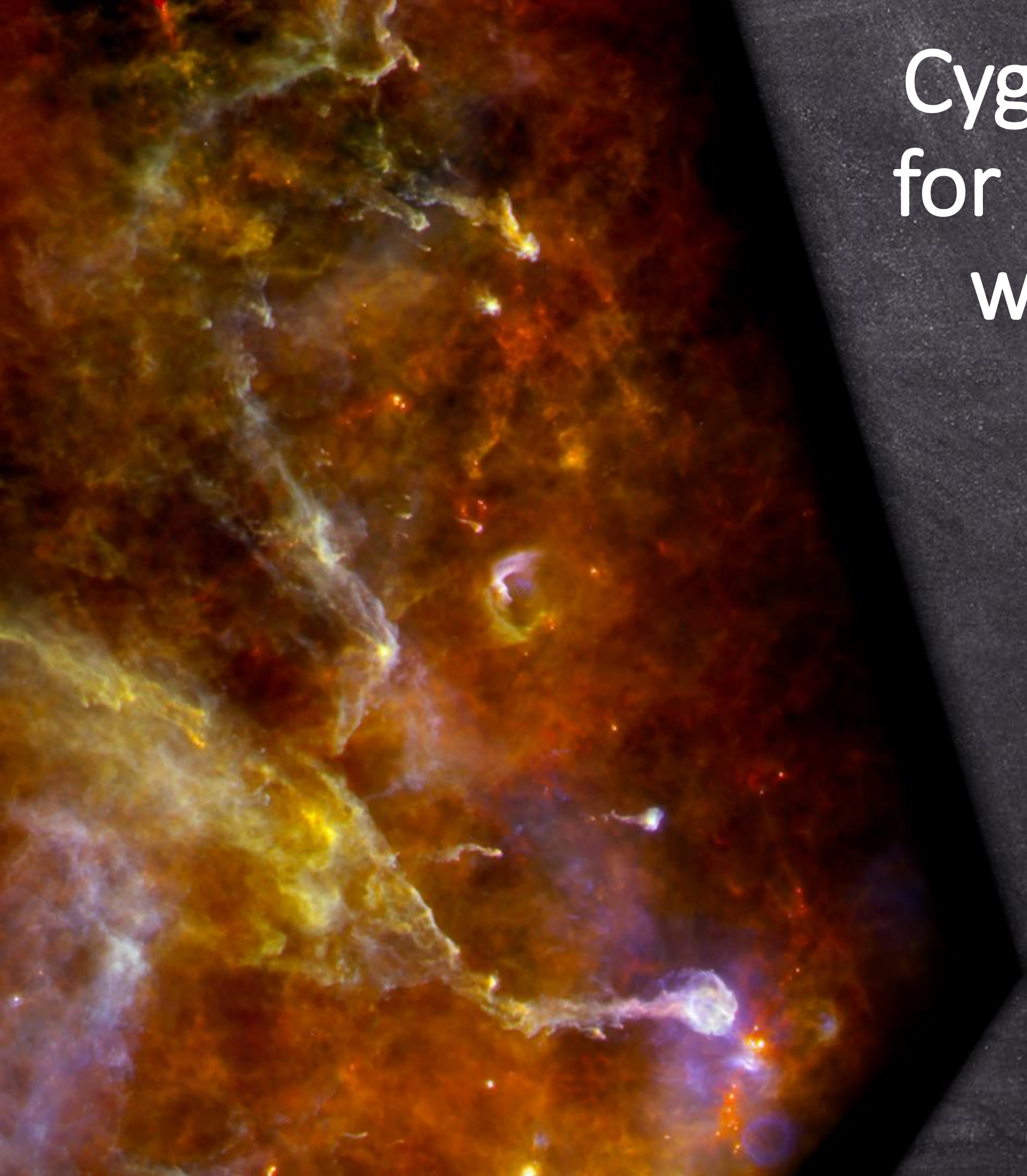

Cygnus OB2 as testing ground for particle acceleration at the wind termination shock of massive star clusters

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Introduction

30 Doradus

Cygnus OB2

Westerlund 1

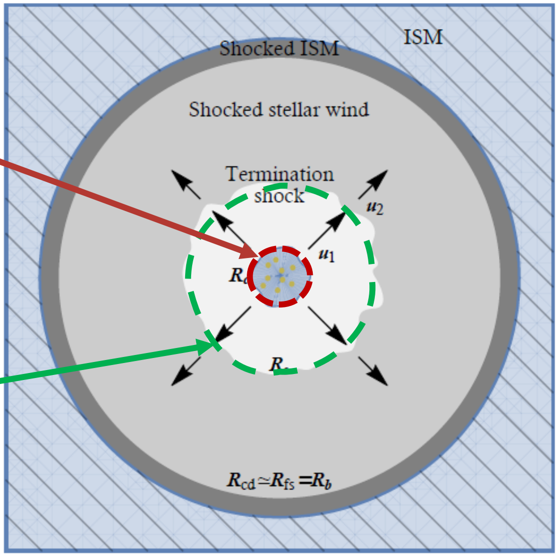
Young massive star clusters (YMSCs) are thought to be a possible class of cosmic ray (CR) accelerators powered by the strong winds blown by the stars inside the cluster.

High energy and very-high energy γ-ray emission has been observed in the direction of several MSCs, such as: Cygnus OB2, Westerlund 1, Westerlund 2, NGC3603, …

The acceleration mechanism is still under debate.
For example, two possible cases are:

Wind-wind acceleration inside the cluster core

Acceleration at the MSC's wind termination shock



Diverse models will produce different distributions of CRs around the cluster. Depending on the propagation properties in the neighborhood of the cluster, the γ-ray morphology and spectrum may vary

General idea of the work:

Consider the case of **Cygnus OB2** and compare with available data the expected γ-ray emission (**spectral energy distribution and spatial morphology**) from a model where CRs are accelerated at the cluster wind's termination shock

Is the model able to reproduce the observed spectrum and morphology?

Cygnus OB2

Cygnus OB2 is one of the most massive MSC in the Milky Way, hosting ≈170 OB stars (Wright et al. 2015).
OB2 is located in the Cygnus X star forming complex, positioned tangent to the local spiral arm
(l=80.22°;b=0.77°)

Cygnus OB2 bubble

d_{OB2}=1.4kpc ; ρ_H=20/cm^3 ; t_{age} =3Myr

$$L_w = \sum_i \frac{1}{2}\dot{M}_i v_{\infty,i}^2 \simeq 1.5 - 5.5 \times 10^{38}\mathrm{erg/s}$$

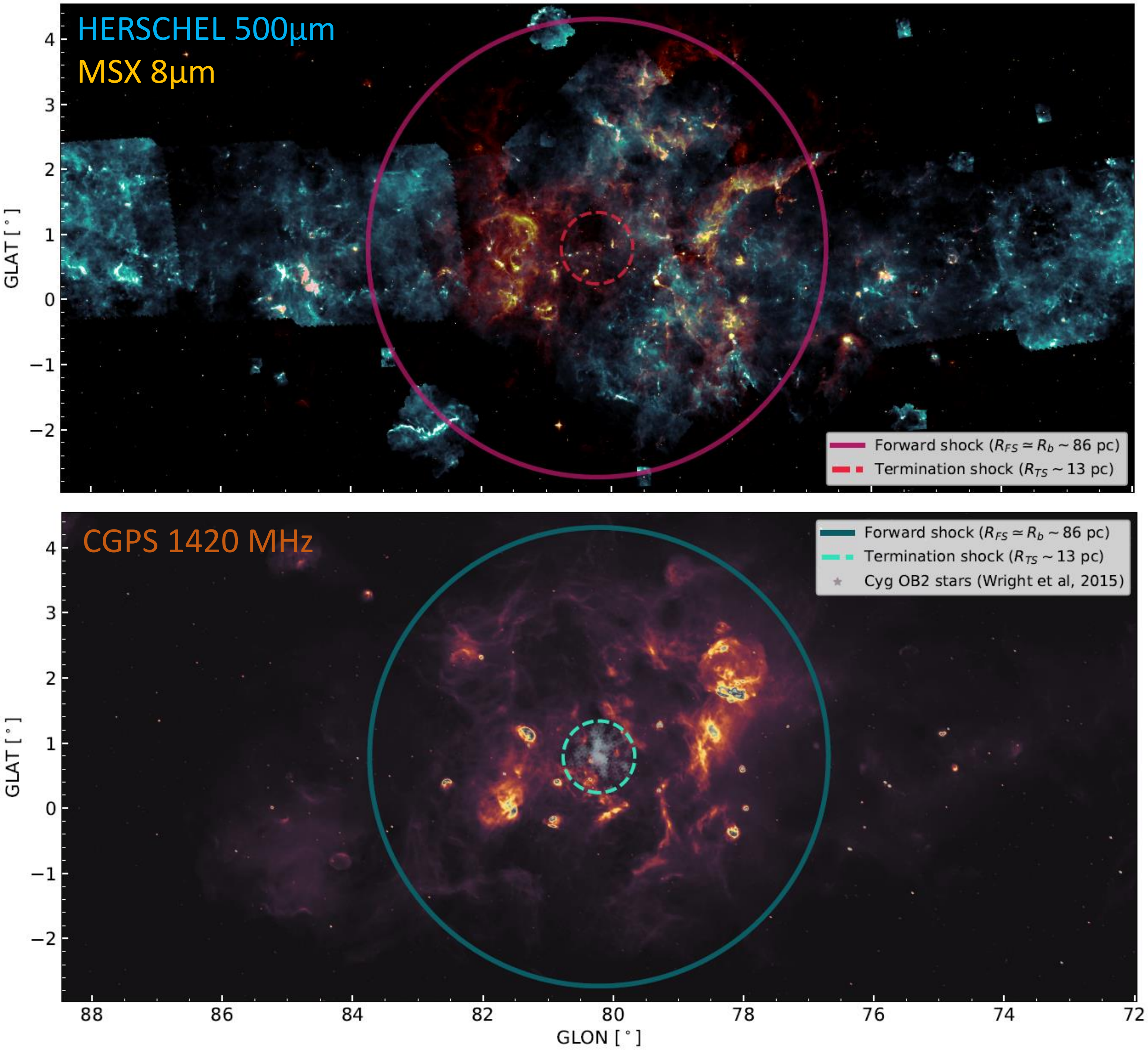
$$\dot{M} = \sum_i \dot{M}_i \simeq 0.3 - 1 \times 10^{-4}\mathrm{M}_\odot/\mathrm{yr} \quad ; \quad v_w = \sqrt{\frac{2L_w}{\dot{M}}}$$

Size of the bubble excavated by the cluster wind (Weaver et al. 1977) assuming L_w=2×10^{38} erg/s and $\dot{M}$=10^{-4} M$_\odot$/yr:

$$R_b \simeq R_{FS} = \left(\frac{250}{308\pi}\right)^{1/5} L_w^{1/5}\rho_0^{-1/5}t_{age}^{3/5} \simeq 86\mathrm{pc}$$

$$R_{TS} = \sqrt{\frac{(3850\pi)^{2/5}}{28\pi}}\dot{M}^{1/2}v_w^{1/2}L_w^{1/5}\rho_0^{3/10}t_{age}^{2/5} \simeq 13\mathrm{pc}$$

Extended γ-ray emission has been detected by several experiments in this region:
Fermi (2011), Argo(2014), HAWC (2021), LHAASO (2021)



CRs distribution function

Steady state solution

We use the model developed by Morlino et al. (2021) of CR accelerated at the winds' termination shock from MSC to obtain the CR distribution function around Cyg OB2.

This model considers a steady state solution for CRs injected at the termination that escape from the system considering both advection and diffusion.

$$f(r < R_{TS}, p) \simeq f_{TS}(p) \cdot exp\left[-\int_{r}^{R_{TS}} \frac{u_1}{D_1(r', p)} dr'\right]$$

$$f(R_{TS} < r < R_b,\ p) = f_{TS}(p)\Gamma_I(D_2) + f_{gal}(p)\Gamma_{II}(D_2)$$

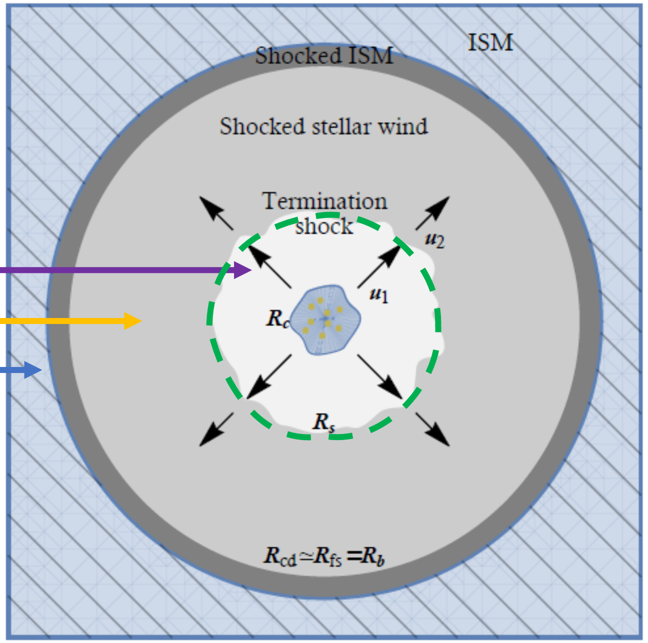
$$f(r > R_b,\ p) = f(R_B, p)\frac{R_b}{r} + f_{gal}(p)\left(1 - \frac{R_{TS}}{r}\right)$$

Where Γ_I and Γ_{II} are function depending on D_2, D_{ism}, u_2, R_{TS} and R_b

The distribution function at the termination shock is the formal solution to transport equation:

$$\boxed{f_{TS}(p) \propto p^{-s} e^{-\xi(p)}}$$

Where ξ (p) is a function accounting for the diffusion coefficient and the geometry of the system



The properties of the accelerated CR (spectrum, radial profile, spectrum of injected protons and maximum achievable energy) greatly depend on the type of diffusion in the system, defined by the nature of plasma turbulence

We consider three types of diffusion: **Kolmogorov, Kraichnan, Bohm**

$$\left.\begin{aligned} D_{K41}(E) &= \frac{1}{3}\beta c r_L^{1/3} L_c^{2/3} \\ D_{Kra}(E) &= \frac{1}{3}\beta c r_L^{1/2} L_c^{1/2} \\ D_{Bohm}(E) &= \frac{1}{3}\beta c r_L \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} E_{max}^{K41} &\propto \eta_B^{1/2} \dot{M}^{-33/20} L_w^{37/20} \rho_0^{-3/5} t_{age}^{4/5} L_c^{-2} \\ E_{max}^{Kra} &\propto \eta_B^{1/2} \dot{M}^{-1/2} L_w^{13/10} \rho_0^{-3/10} t_{age}^{2/5} L_c^{-1} \\ E_{max}^{Bohm} &\propto \eta_B^{1/2} \dot{M}^{-1/4} L_w^{3/4} \end{aligned}\right.$$

We consider that a fraction $\eta_B \approx 0.1$-0.01 of L_w is converted in turbulent magnetic field

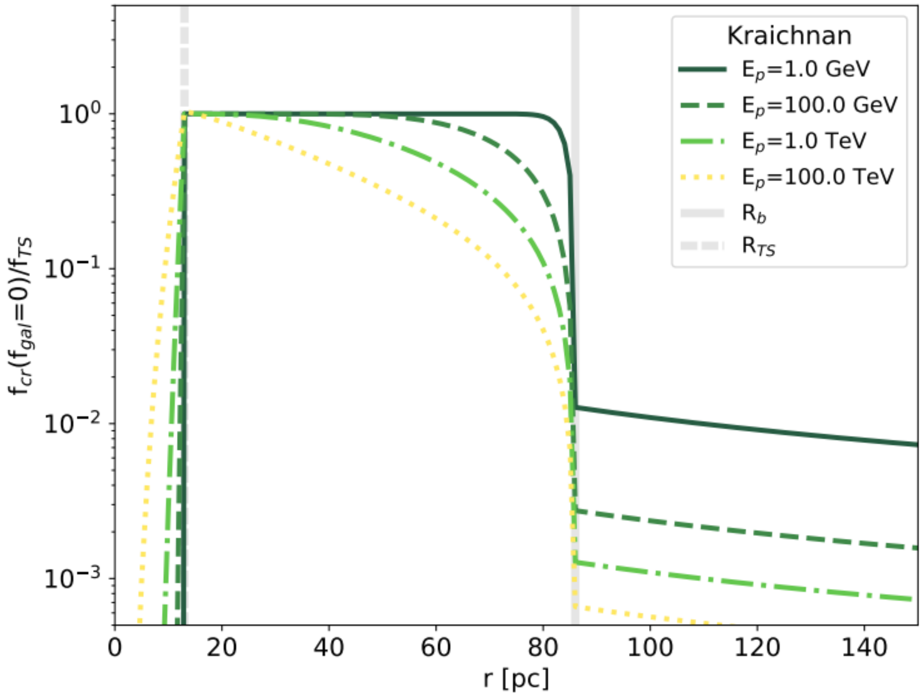
CRs distribution function

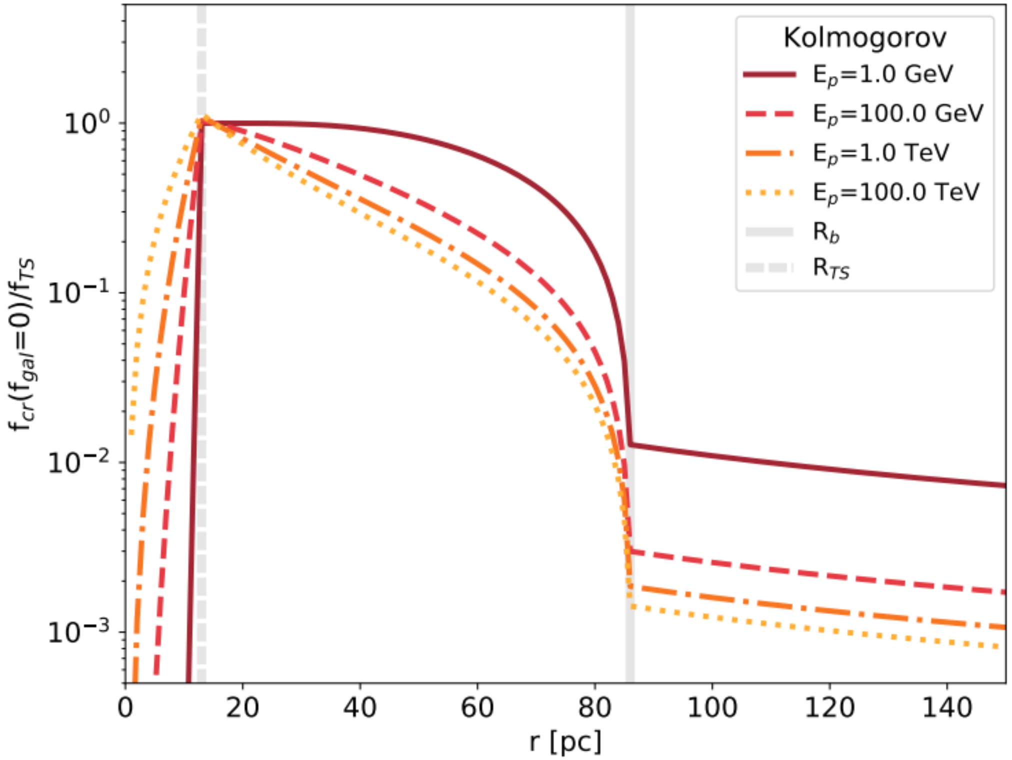
Radial shape

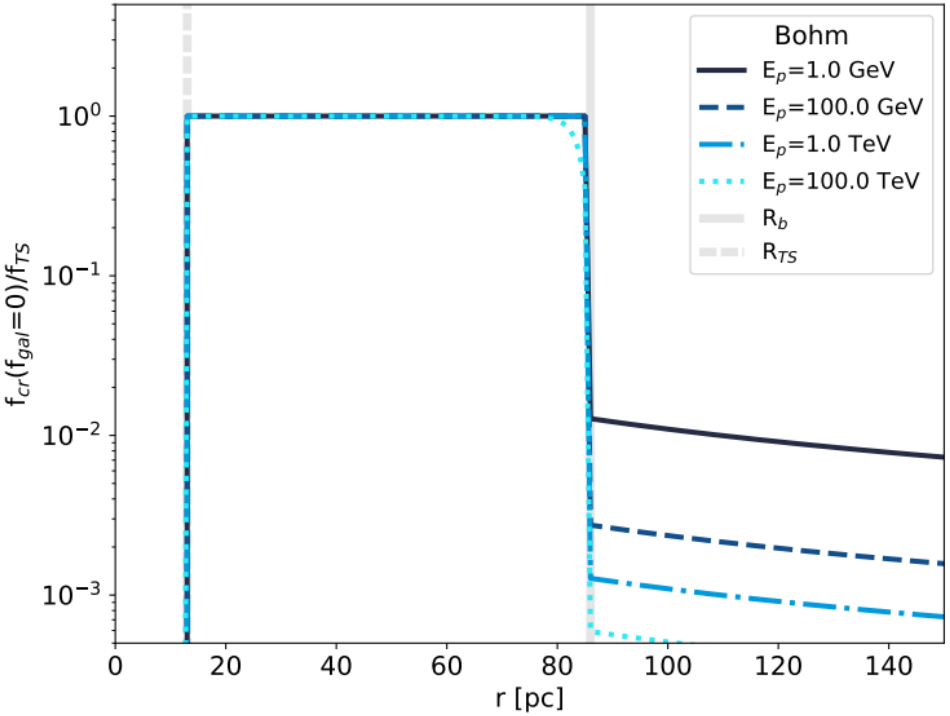
Depending on the diffusion coefficient (and energy), the radial profile of the f_{CR} changes.

Advection dominated → Flat profile ; Diffusion dominated → ≈1/r

Since $u_2 \propto 1/r^2$, the profile will tend to be flat near the termination shock (specially at low energies)







Expected hadronic γ-ray emission and comparison with data

Comparison with published data

The γ-ray flux depends on f_{CR} which in turns is a function of a large number of parameters

($\rho_H=20/\mathrm{cm}^3$, $t_{age}=3\,\mathrm{Myr}$, $\dot{M}=10^{-4}\,M_\odot/\mathrm{yr}$, $\eta_B=0.1$, L_w, s, ε_{CR})

We fix all parameters except L_w, s, ε_{CR} that are varied in order to fit (χ^2 minimization) the observed γ-ray spectrum

A posteriori we check if the best fit parameters are compatible with "reasonable" values

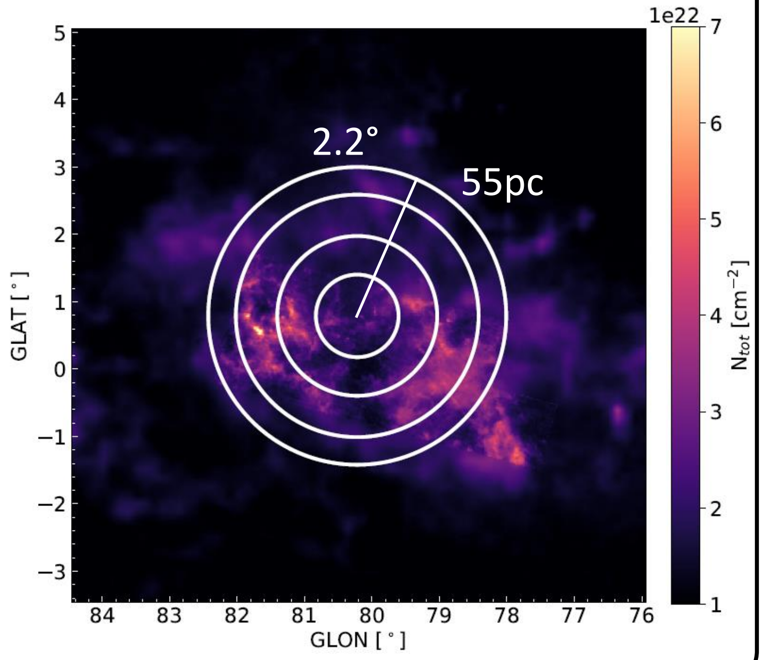
For the spectrum comparison, we extract the γ-ray flux from a **2.2°** region centered on OB2.
Flux data points from experiments are scaled to account only the flux coming from a region of this size.

For the morphology study we compare the expected γ-ray luminosity with the one measured in 4 rings of size [0–0.6°, 0.6–1.2°, 1.2–1.8° and 1.8–2.2°]

We model the ISM around Cyg OB2 as a combination of molecular (H_2) and neutral (HI) hydrogen. Kinematic cuts: -20km/s<v<20km/s
HI and H_2 uniformly distributed along the line of sight in ±400pc

H_2: ^{12}CO(J=1-0) CfA (Dame et al, 2001)
^{12}CO(J=1-0) NRO (Takekoshi et al, 2019)
(using Xco=1.68×10^{20} mol. cm-2 K-1 km-1)

HI: 21cm from CGPS (Taylor et al, 2003)
(using T_{spin}=150°K)



Observation used:

Spectral data points:
- Fermi-LAT (4FGL J2028.6+4110e)
- HAWC (HAWC J2030+409)
- Argo (ARGO J2031+4157)

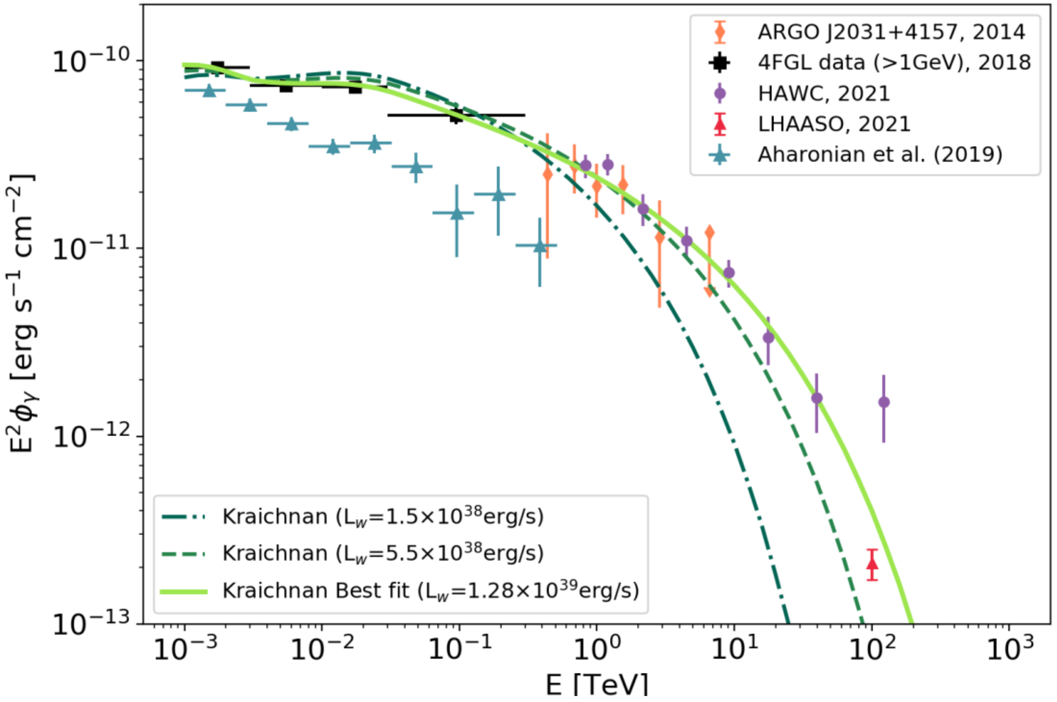
Radial profile:
- Aharonian et al 2019 (Fermi-LAT)
- Abeysekara et al 2021 (HAWC)

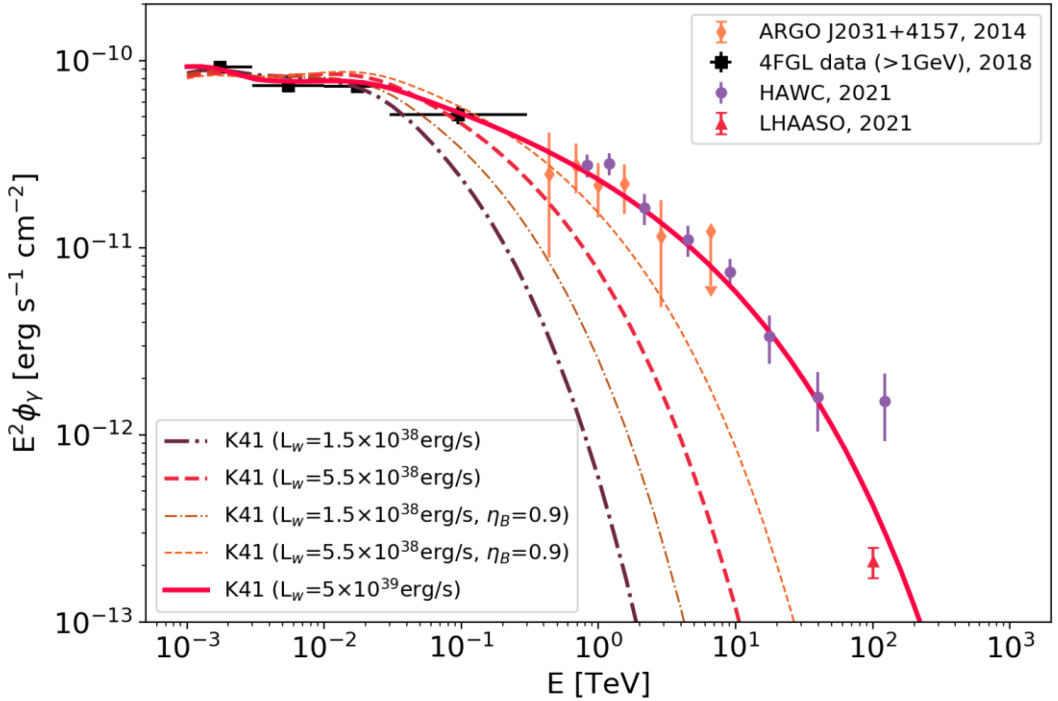
Results
Spectral energy distribution

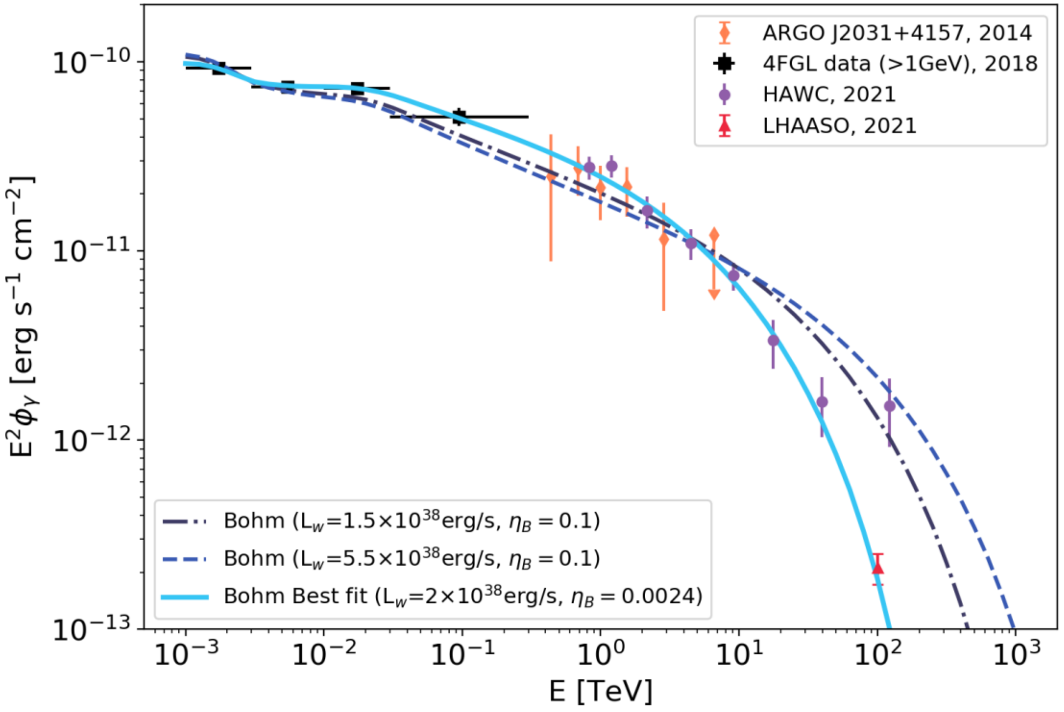
- Kolmogorov requires high values of L_w to reproduce the cut-off region.
  - Kraichnan requires an L_w higher by a factor of 2 than expected.
- Bohm diffusion is very efficient! Best fit obtained fixing L_w and fitting η_B

$$L_w = \sum_i \frac{1}{2}\dot{M}_i v_{\infty,i}^2 \simeq 1.5 - 5.5 \times 10^{38}\mathrm{erg/s}$$

Models	L_w [erg s^{-1}]	s	ϵ_{CR}	η_B	$E_{\rm max}$ [PeV]	R_{TS} [pc]	R_b [pc]	$\bar{\chi}^2_{min}$
Kolmogorov	$5 \cdot 10^{39}$	4.17	$4 \cdot 10^{-3}$	0.1	23	16	163	0.66
Kraichnan	$1.28 \cdot 10^{39}$	4.23	$7 \cdot 10^{-3}$	0.1	3.97	14	124	0.39
Bohm	$2 \cdot 10^{38}$	4.27	$2 \cdot 10^{-2}$	$2.4 \cdot 10^{-3}$	0.47	13	86	0.27





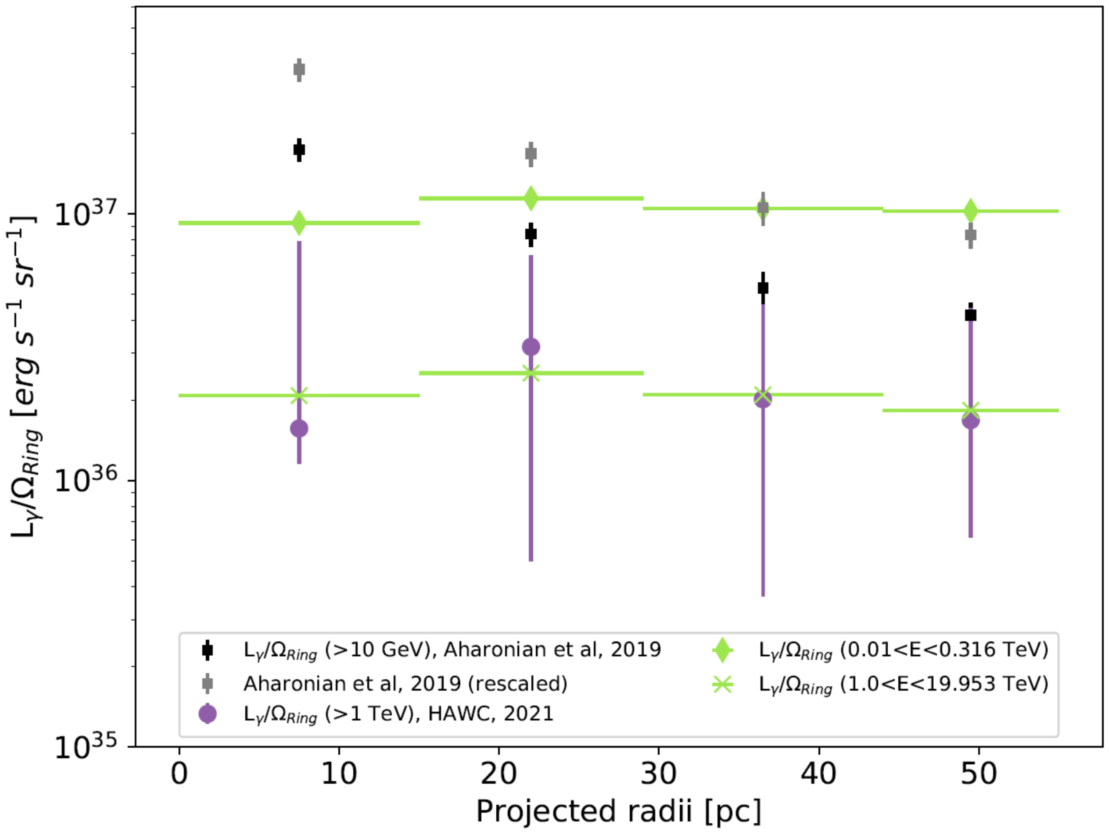


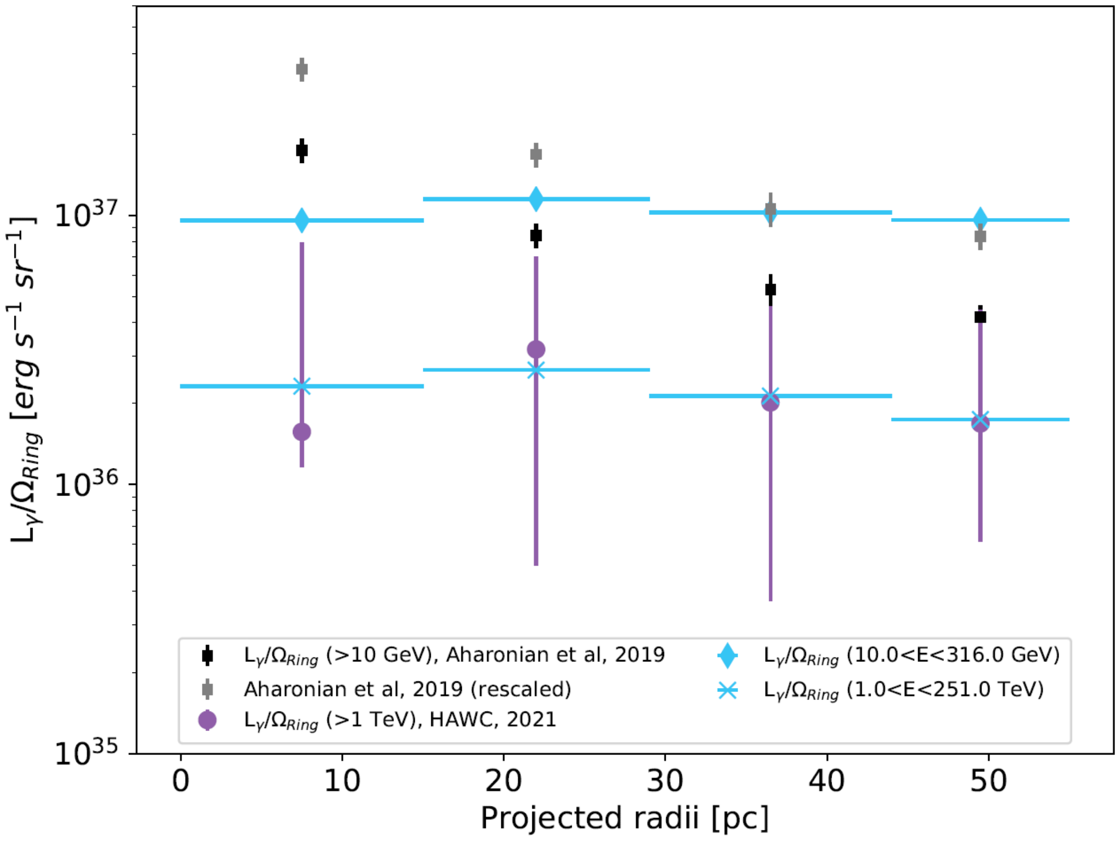
Results
γ-ray radial morphology

Both models realized with Kraichnan and Bohm show a flat profile.

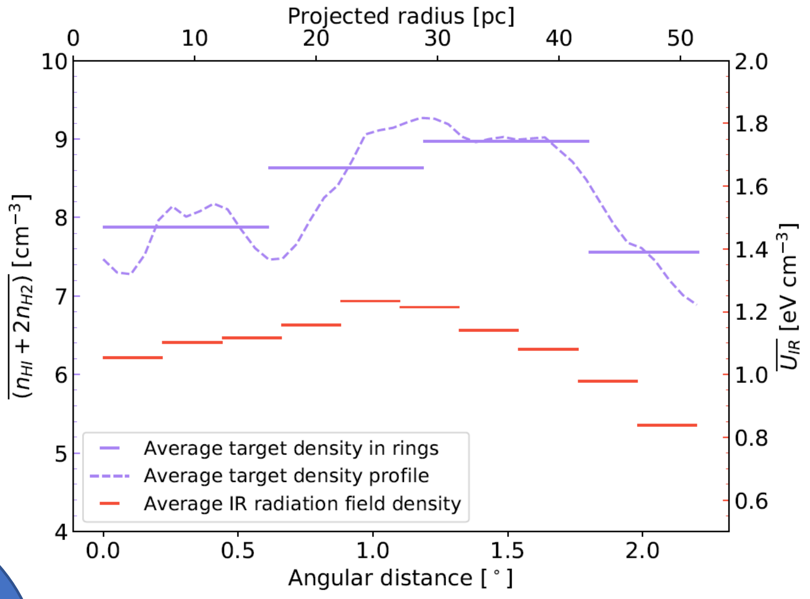
This is fairy well in agreement with HAWC observation but not with Fermi-LAT data.

The probed region is close to the wind termination shock, where the advection velocity is higher → **Flat profile expected**





Leptonic contribution

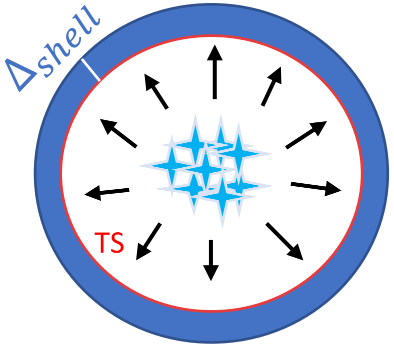


Can we explain central emission with leptonic emission?

A thin shell of electron around the TS emitting by inverse Compton could explain the peaked γ-ray morphology.

The thickness of the shell depends on electrons cooling time and diffusion+advection:

$$\Delta_{\rm shell} = \frac{2D_2(E)/u_{\rm adv}}{\sqrt{1+4D_2(E)/u_{\rm adv}t_{\rm cool}}-1} \quad \begin{cases} \Delta^{\rm Kra}_{\rm shell}(100\ {\rm GeV}) \approx 30\ {\rm pc} \\ \Delta^{\rm Bohm}_{\rm shell}(100\ {\rm GeV}) > 100\ {\rm pc} \end{cases}$$



- ➢ Only for the Kraichnan case electrons could play a role.
- ➢ Assuming electron spectrum as super exponential cut-off power law, with same spectral index equal to that of hadrons and an electron to proton ratio of 10^{-2}

Considering IC scattering on measured IR and CMB

Expected: $L_\gamma^{IC}(10{\rm GeV} < {\rm E}_\gamma < 300{\rm GeV}) \simeq 0.05 \times 10^{34}{\rm erg/s}$

Measured: $L_\gamma(10{\rm GeV} < {\rm E}_\gamma < 300{\rm GeV}) \simeq \underline{1.47 \times 10^{34}}{\rm erg/s}$

Leptonic contribution is likely to be negligible.
In order to explain the central excess, an electron-to-proton ratio of the order of unity is required.
In SNRs the ratio is calculated to be $<10^{-2}$

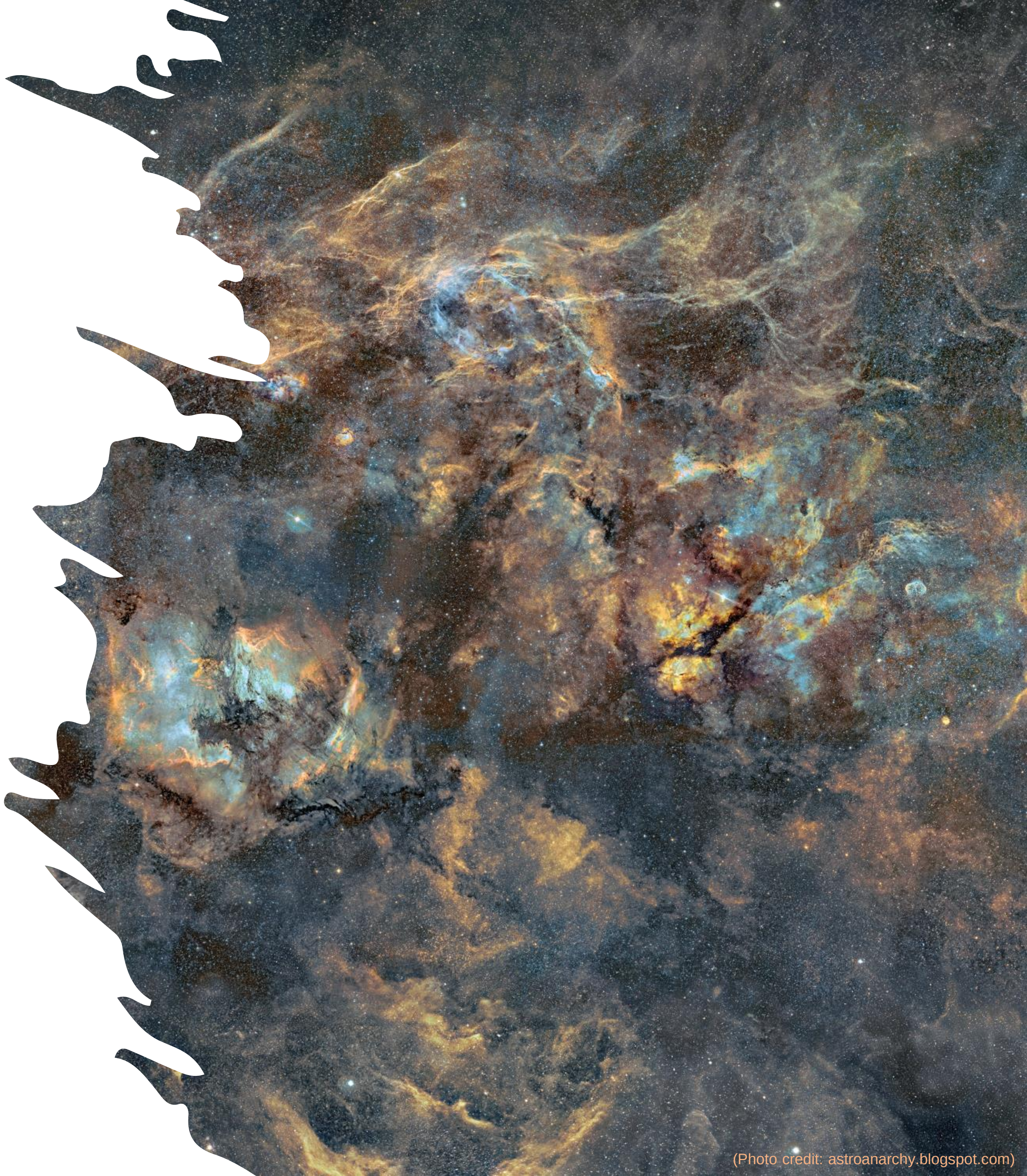
Conclusions

What has been done:

- Particle acceleration at wind termination shock can account for observed γ-ray emission from Cygnus Cocoon
- Comparison with data suggests a diffusion in the bubble between Kraichnan and Bohm like (purely Kolmogorov diffusion is excluded)
- We predict spatially flat γ-ray emission
  - Agreement with HAWC data
  - In tension with Fermi-LAT data
- A relevant leptonic inverse Compton emission is very unlikely

Future steps

- Considering dishomogeneous gas distribution inferred from CO observation
- Considering spatial dependent diffusion (Bohm near shock, Kolmogorov in the bubble)
- Comparison with spectra extracted from different annuli (when available)



(Photo credit: astroanarchy.blogspot.com)

Backup Slides

CRs distribution function

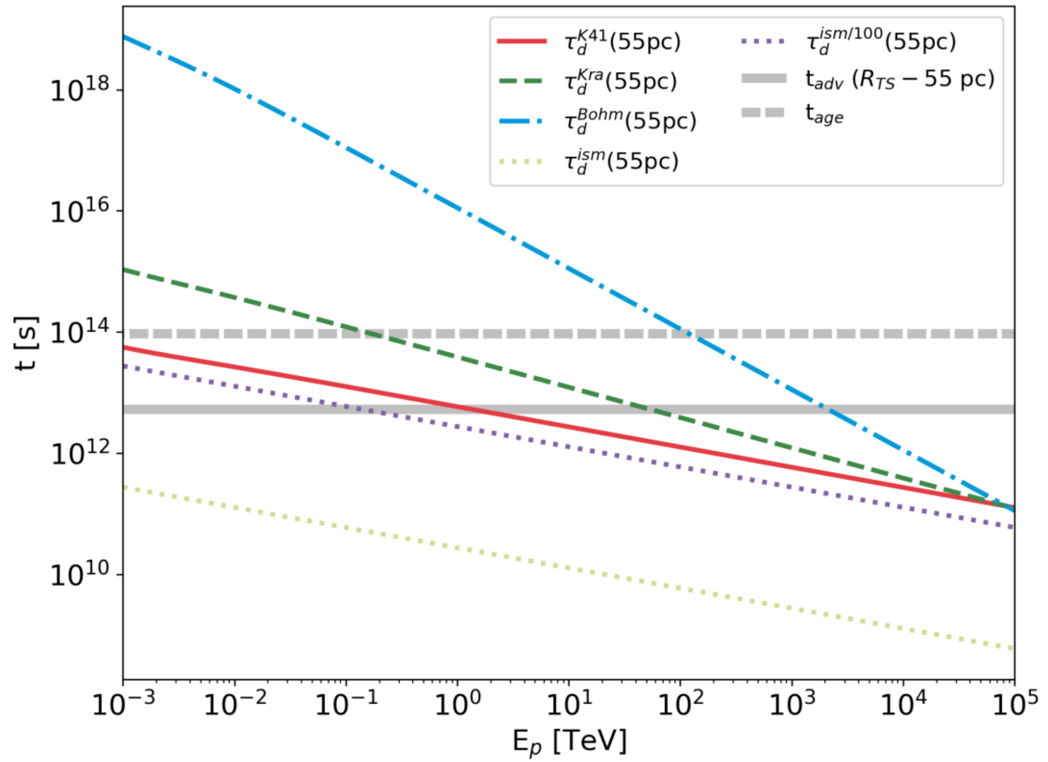
Advection vs Diffusion

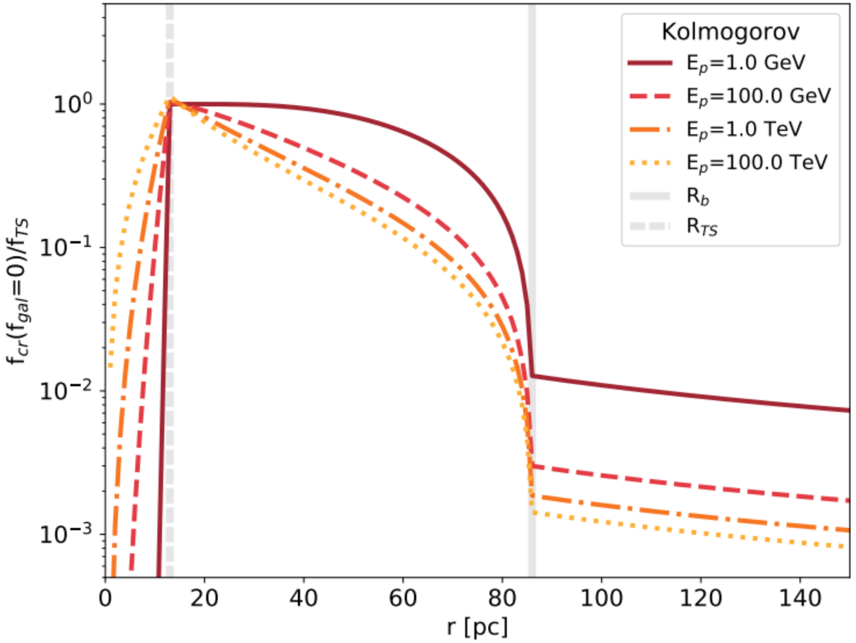
Depending on the diffusion coefficient (and energy), the radial profile of the f_{CR} changes.

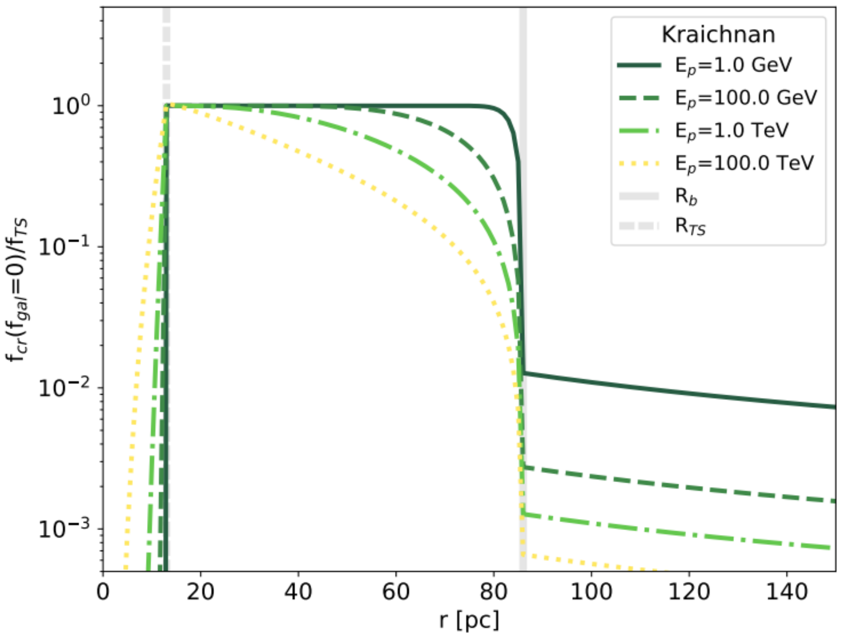
Advection dominated → **Flat profile** ; **Diffusion dominated →** **≈1/r**

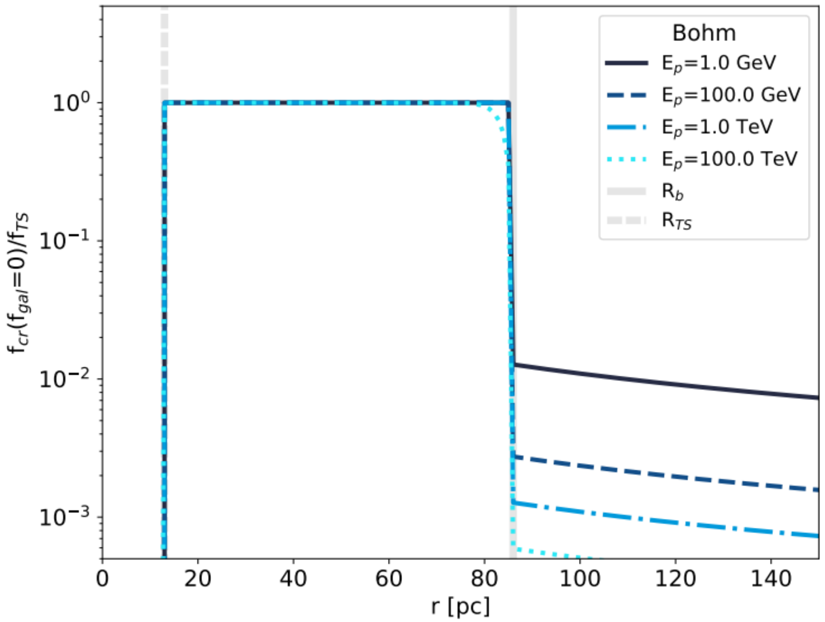
$$t_{adv} = (r - R_{TS})\bar{u}_2(r) \qquad ; \qquad \tau_d = (r - R_{TS})^2/2D_2$$

Since $u_2 \propto 1/r^2$, the profile will tend to be flat near the termination shock (specially at low energies)

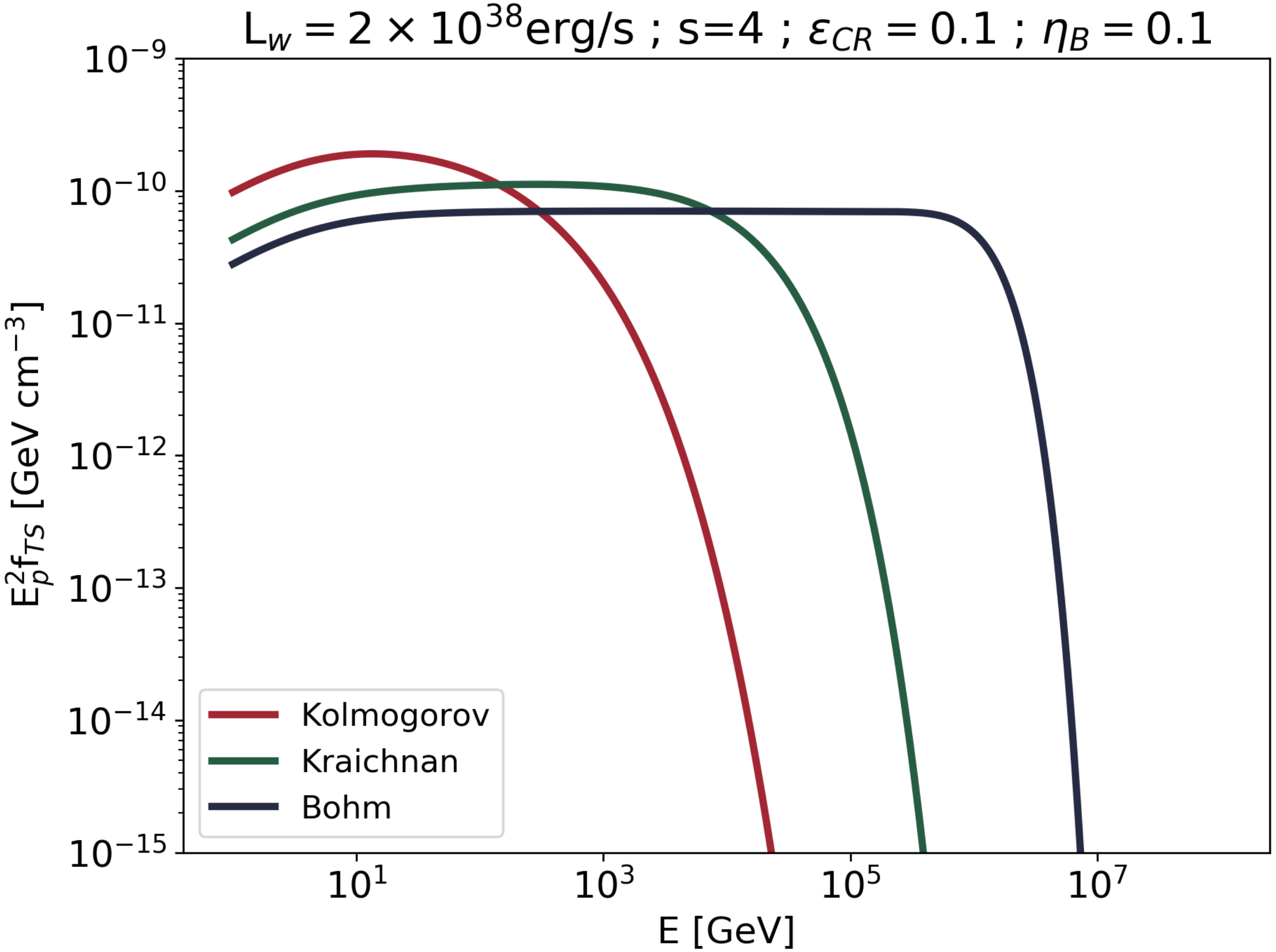




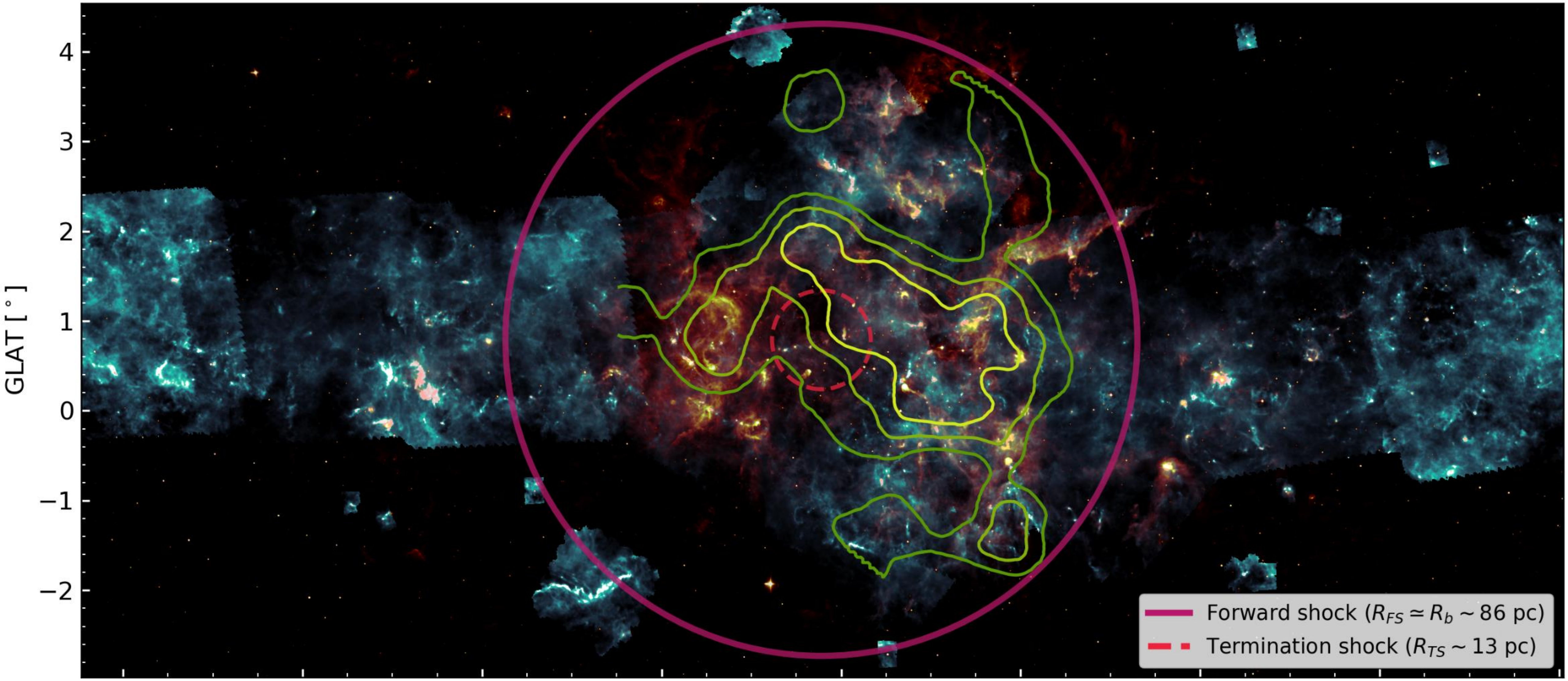




Spectrum of injected particles



HAWC contours



Femi contours (2011)