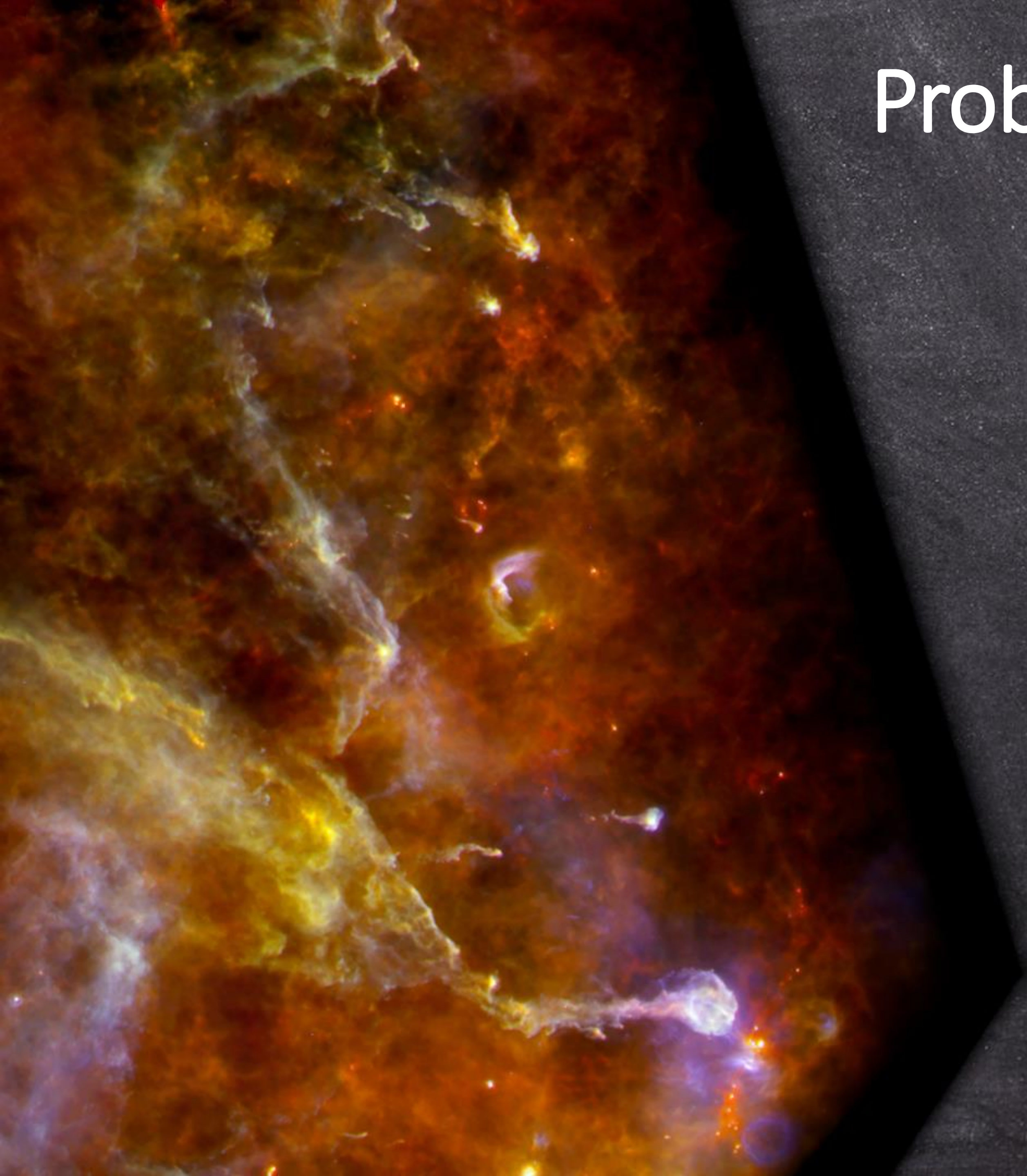

Probing cosmic ray distribution around Cygnus OB2

S. Menchiari (UniSi)
E. Amato (INAF - OAA)
N. Bucciantini (INAF - OAA)
G. Morlino (INAF - OAA)

UNIVERSITÀ DI SIENA 1240

INAF ISTITUTO NAZIONALE DI ASTROFISICA

INFN PISA Istituto Nazionale di Fisica Nucleare Sezione di Pisa

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Introduction

Massive star clusters (MSCs) 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, …

30 Doradus

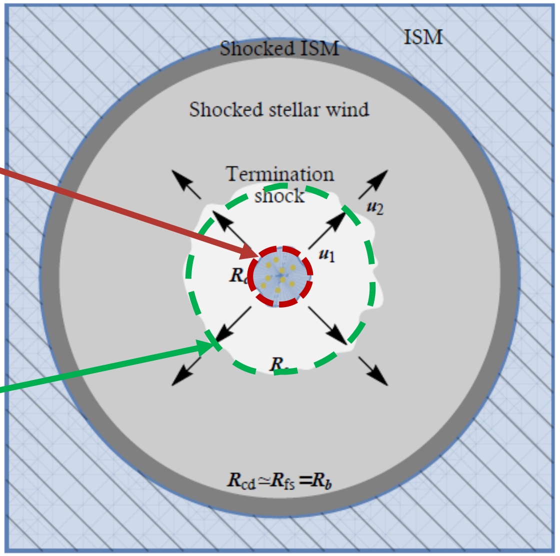
Cygnus OB2

Westerlund 1

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



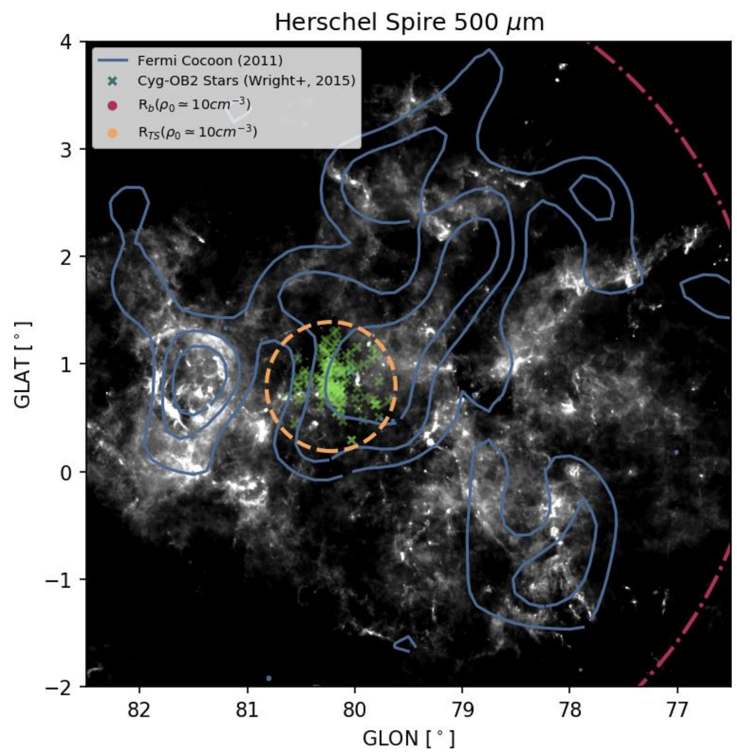
Diverse models will produce different distributions of CRs around the cluster. Depending on the distribution of the interstellar medium (ISM) in the neighborhood of the cluster, the γ-ray morphology and spectrum may vary

Objective:

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

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°)



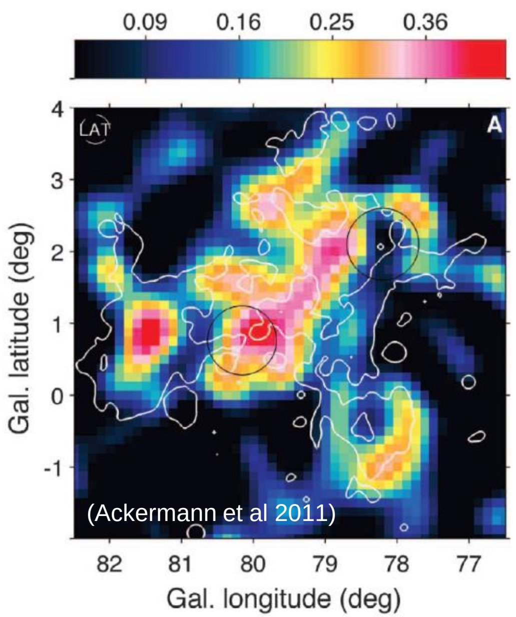
Cygnus OB2 parameters

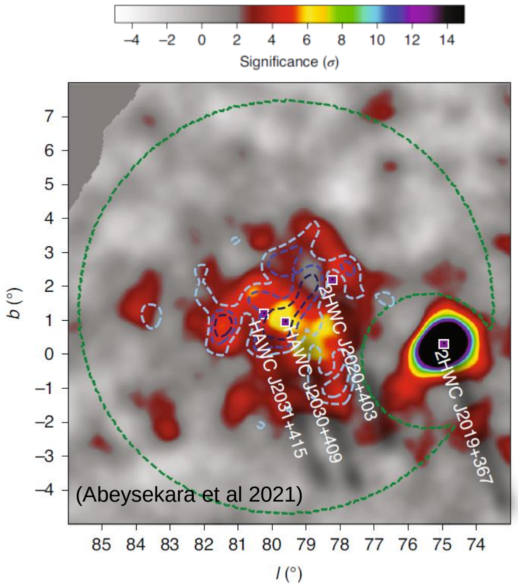
L_{wind}=2x10^{38} erg/s ; dM/dt=10^{-4}M$_{sun}$/yr ; d_{OB2}=1.4kpc

$u_1 \approx$ 2500 km/s ; ρ_H=10/cm^3 ; t_{age} =3Myr

$$R_{TS} = 0.7 \cdot L_w^{-1/5} \dot{M}^{1/2} u_1^{1/2} \rho_H^{-3/10} t_{age}^{2/5} \simeq 16pc$$

$$R_b = 0.76 \cdot \left(\frac{L_w}{\rho_H}\right)^{1/5} t_{age}^{3/5} \simeq 98pc$$





Extended γ-ray emission has been detected by several experiments:
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 OB2.

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

$$f(r < R_{TS}; E) = f_{TS}(E) \cdot exp\left[-\frac{u_1(R_{TS} - r)}{D_1} \right]$$

$$f(R_{TS} < r < R_b; E) = f_{TS}(E)\Gamma_1 + f_{gal}(E)\Gamma_2$$

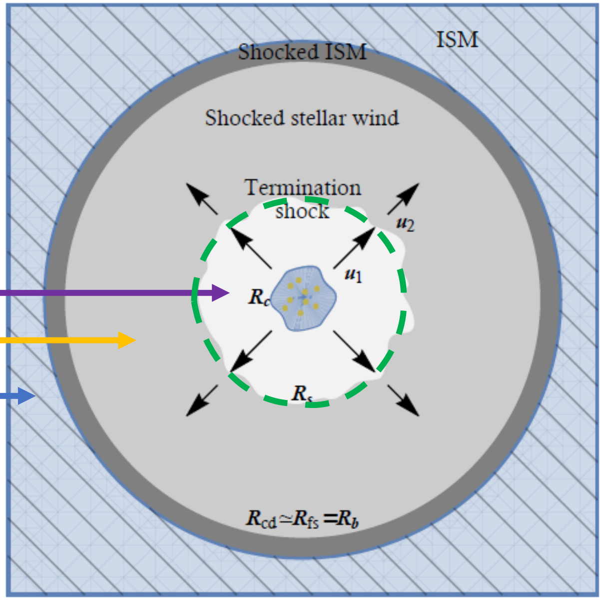
$$f(r > R_b; E) = f(R_b; E)\frac{R_b}{r} + f_{gal}(E)\left(1 - \frac{R_b}{r}\right)$$

Where Γ_1 and Γ_2 are function depending on D_2, D_{ism}, u_2, R_{TS} and R_b

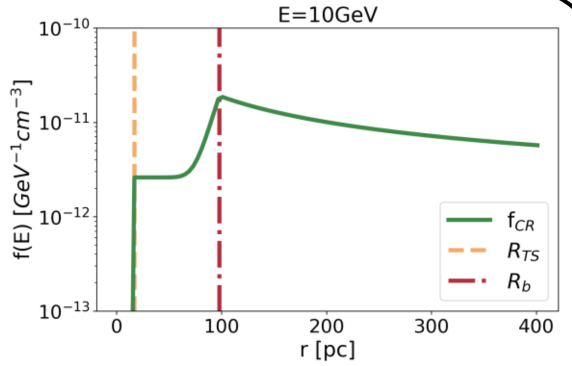
The distribution function at the termination shock is modeled as:

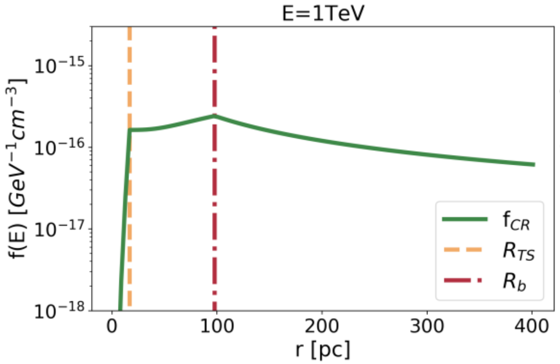
$$f_{\rm TS}(E) = A\left(\frac{E}{1\,\rm TeV}\right)^{-a} \exp\left[-\left(\frac{E}{E_{\rm max}}\right)^{b}\right]$$

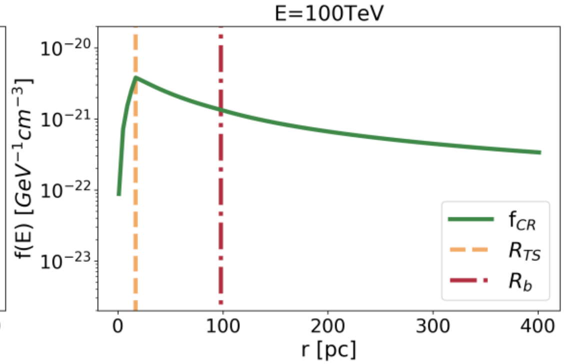
The parameters of f_{TS} are chosen to best reproduce γ-ray observations



Steady state radial distribution of CRs accelerated by Cygnus







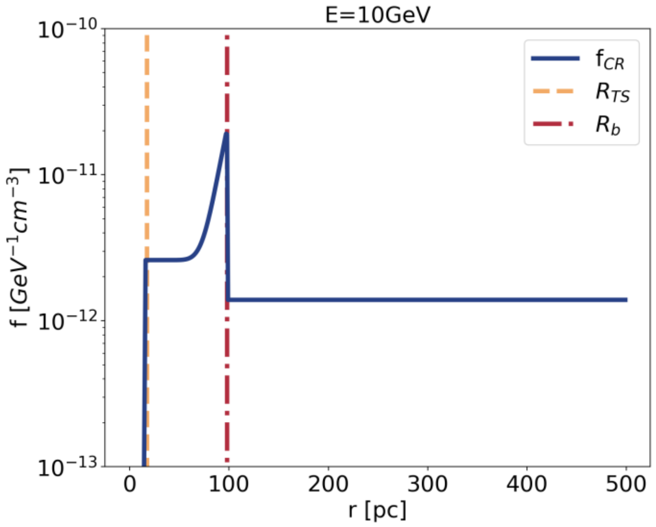
CRs distribution function
Modified solution

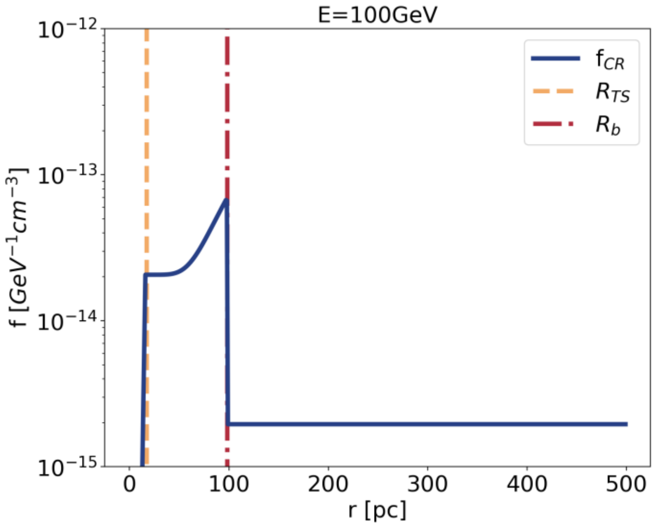
In the steady state model CRs diffuse up to infinity.
f(r,E) must be truncated at a given $R_{cut}(E)$ so that the total injected energy by OB2 is conserved.

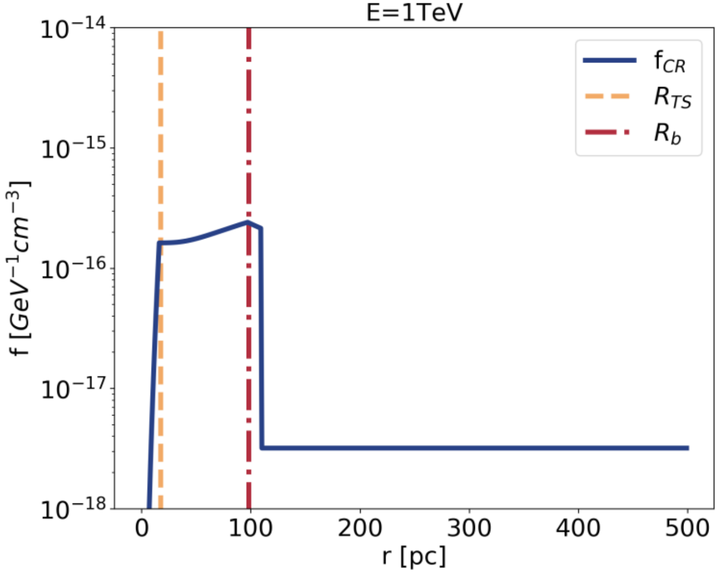
Assuming no energy losses, $R_{cut}(E)$ can be calculated by requiring:

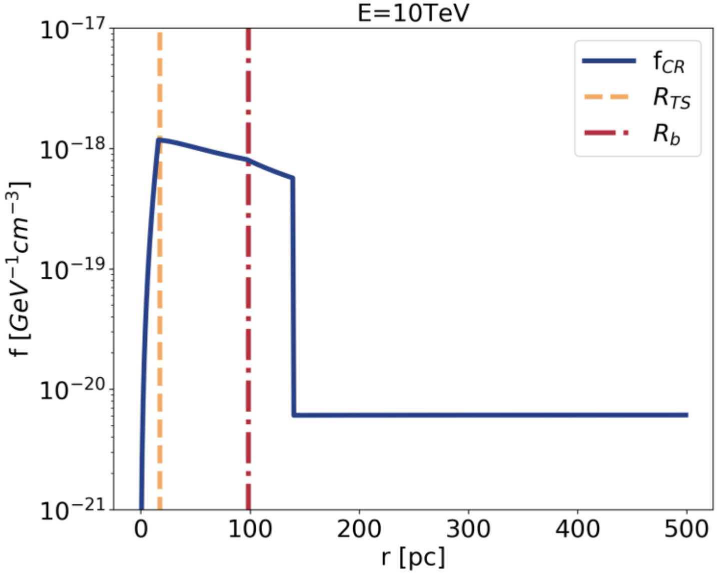
$$\int_0^{R_{\rm cut}(E)} 4\pi r^2 \left[f(r,E) - f_{\rm gal}(E)\,\Theta(r - R_{\rm TS})\right] dr = 4\pi R_{\rm TS}^2\, t_{\rm age}\, u_2 f_{\rm TS}(E)$$

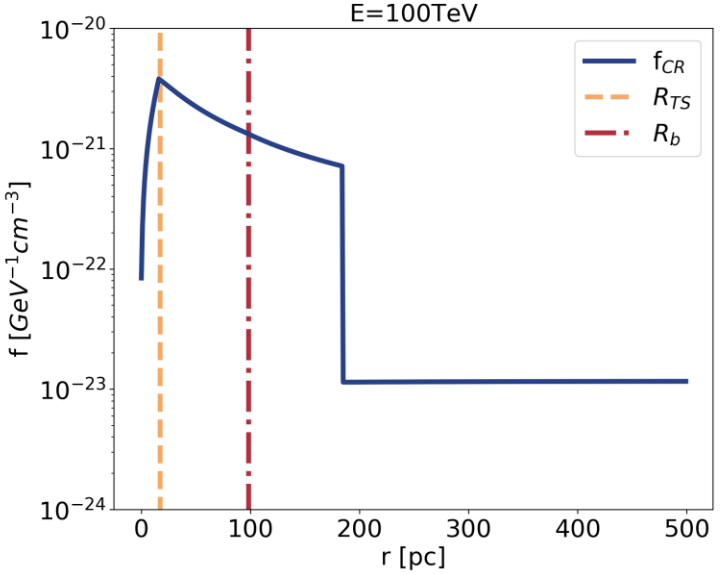
NB: $R_{cut}(E) \approx R_b$ for energies below 1 TeV.
Low energy CRs are dominated by advection and remain trapped inside the expanding bubble











Interstellar medium around OB2

We model the ISM around OB2 as a combination of molecular (H_2) and neutral (HI) hydrogen.
Kinematic cuts: -20km/s<v<20km/s

H_2: ^{12}CO(J=1-0) CfA (Dame et al, 2001) Lowres.
(using Xco=1.68×10^{20} mol. cm-2 K-1 km-1)
^{13}CO(J=1-0) NRO (Takekoshi et al, 2019) Highres.
(assuming LTE + $[H_2]/[^{13}CO] = 69\times10^4$)

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

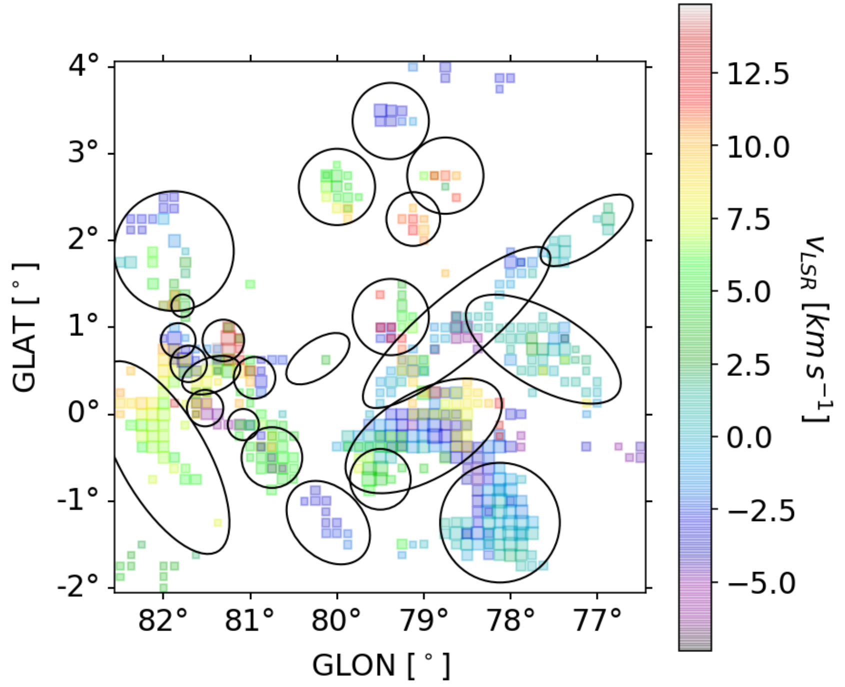
Two different ISM distributions are considered:

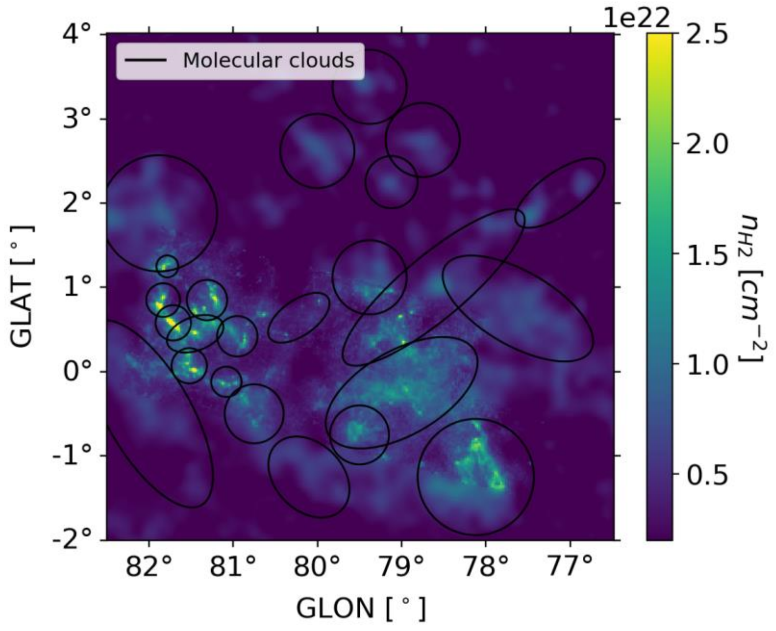
1) HI and H_2 uniformly distributed along the line of sight in ±400pc

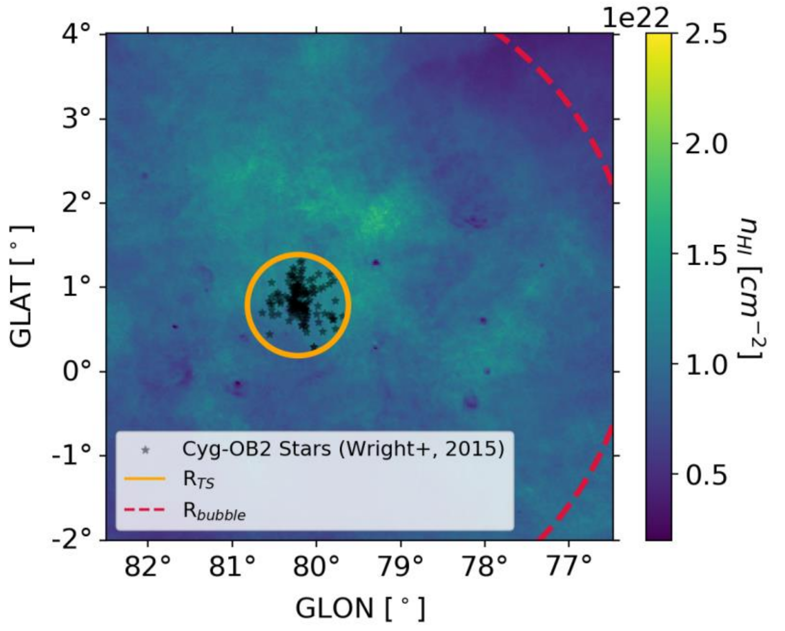
2) Complex ISM distribution with MCs positioned at random distance from OB2 (in ±400pc), and HI uniformly distributed along the line of sight for $r>R_b$ (in ±400pc). Inside R_b we consider a particle density of 10^{-3} cm^{-3}

We consider a total of 24 MCs

MCs in the area are selected considering spatial shape and ^{12}CO line velocity







Results
Spectral energy distribution

When considering the case of complex ISM distribution, we calculate the expected flux using 100 different template realizations, randomly varying MCs' position

The spectral energy distribution (SED) is extracted from a **2.2°** region centered on OB2. Data points from experiments are scaled to account only the flux coming from a region of this size.

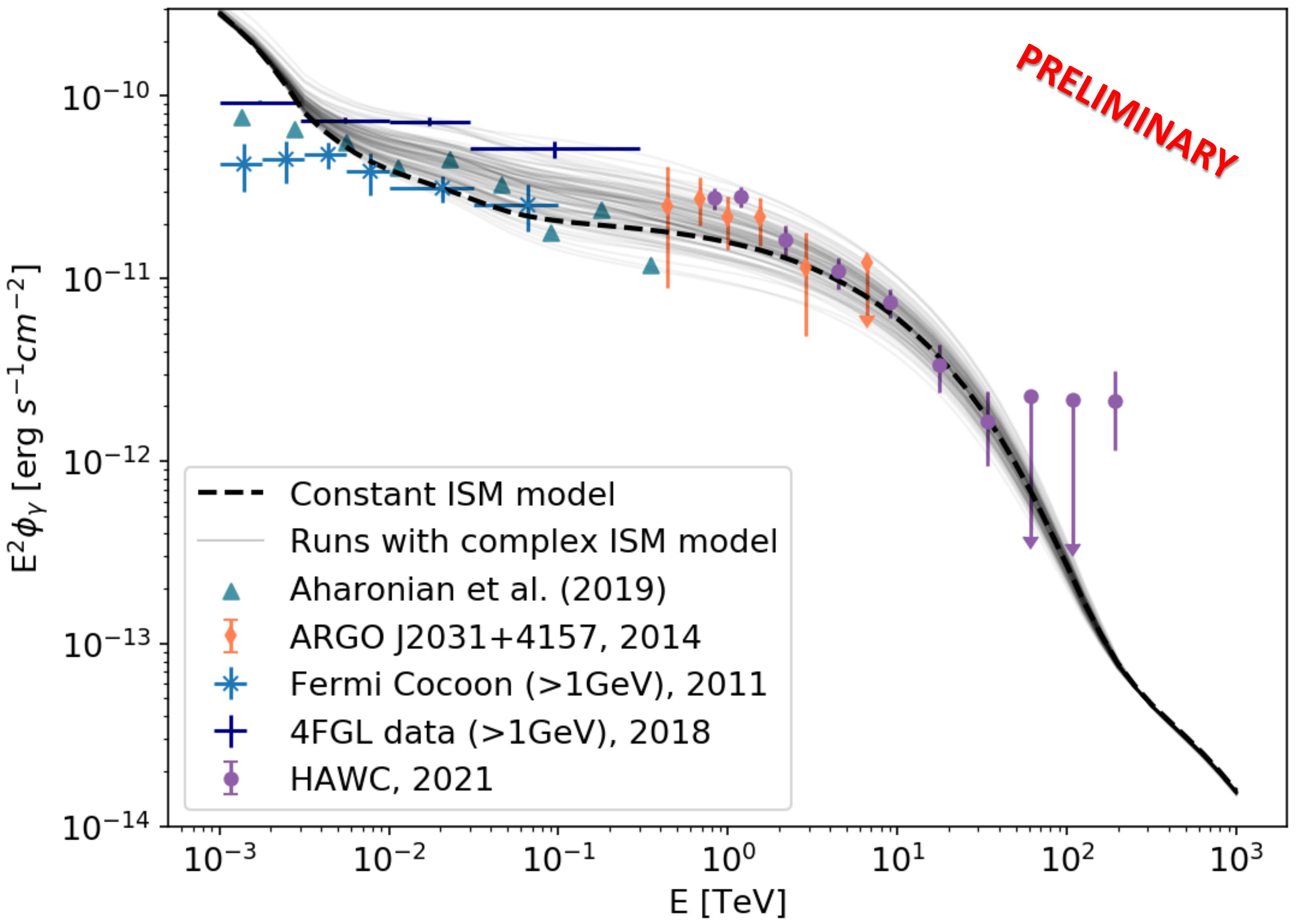
The obtained SED fairly well fit the data point. The distribution of MCs induces a wide variance on the SED at ≈ 100 GeV – 1 TeV.

The following parameters for f_{TS} are used when computing the SEDs:
a=2.1, b=1, E_{max}=100TeV,
A=1.02x10^{-16} cm^{-3} GeV^{-1} (const. ISM case),
A= 0.73x10^{-16} cm^{-3} GeV^{-1} (complex ISM runs)

The γ-ray flux from hadronic interaction is calculated using:

$$\phi_\gamma(l,b;E_\gamma) = \iint \frac{c\,\Omega r^2}{4\pi r^2}\, n_{\rm gas}(l,b,z)\, f_{\rm CR}(l,b,z;E_p)\, \frac{d\sigma(E_p,E_\gamma)}{dE_p} dE_p dz$$

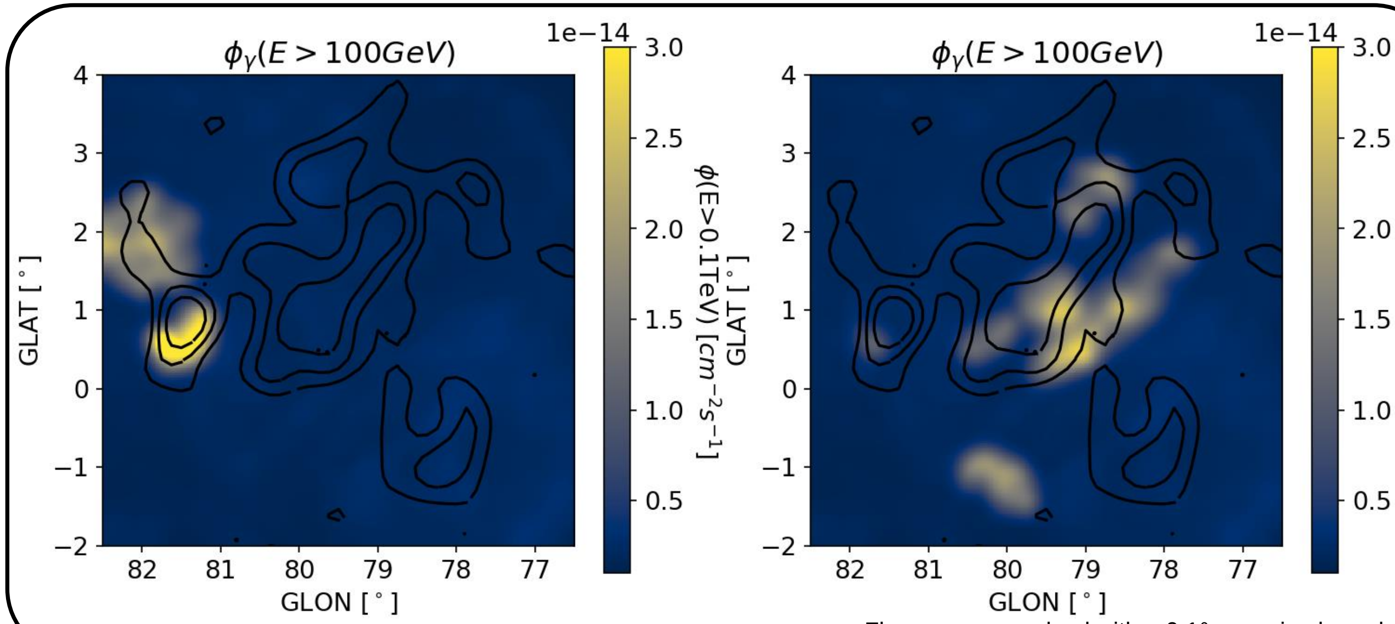
where σ is the cross section for gamma-ray production (Kafexhiu et al 2014), Ω is the pixel size of $(0.02°)^2$ and f_{CR} is the distribution of CRs around OB2.



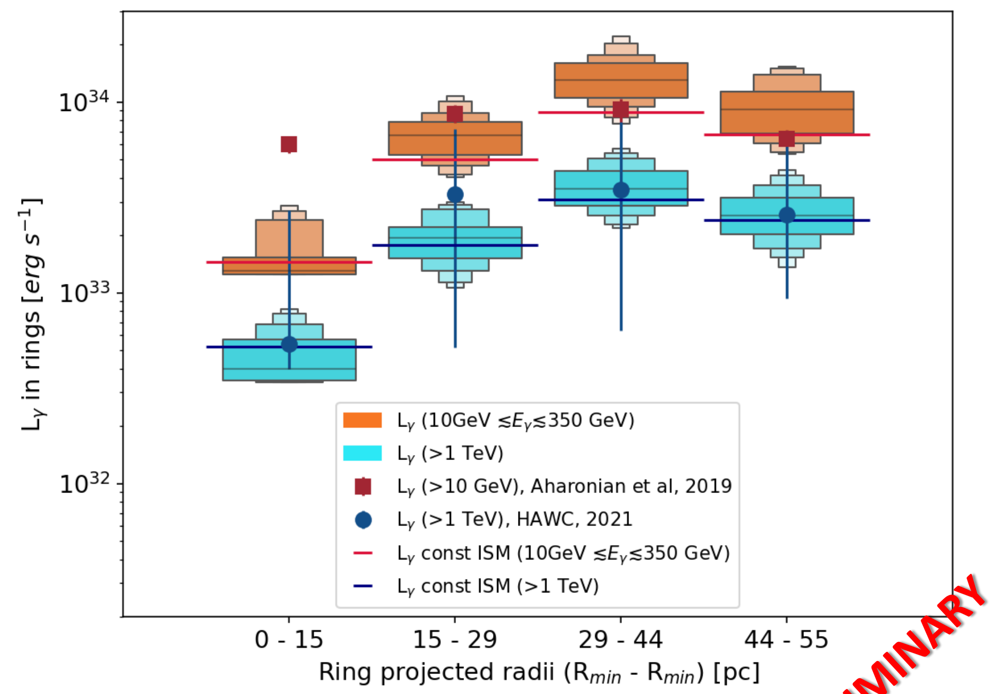
Results
γ-ray spatial morphology

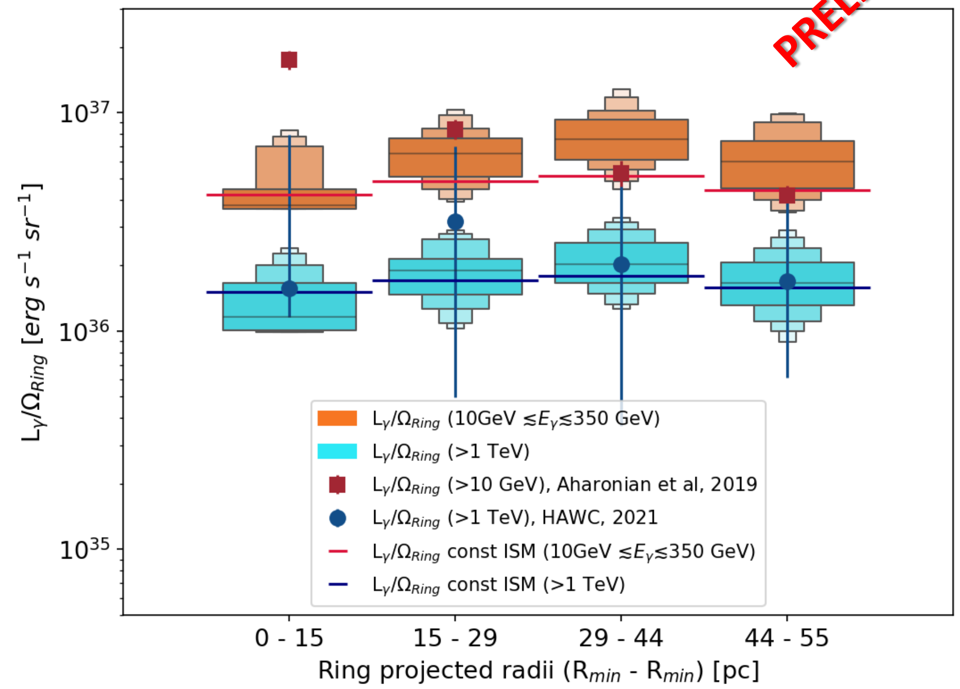
MCs position significantly impact on the observed morphology.

Radial profile extracted from 4 rings [0–0.6°, 0.6–1.2°, 1.2–1.8° and 1.8–2.2°] centered on OB2 is characterized by a **flat trend**.
Radial profile in agreement with all data except for the luminosity in the first ring observed by Fermi (Aharonian et al, 2019)



Flux maps convolved with a 0.1° gaussian kernel





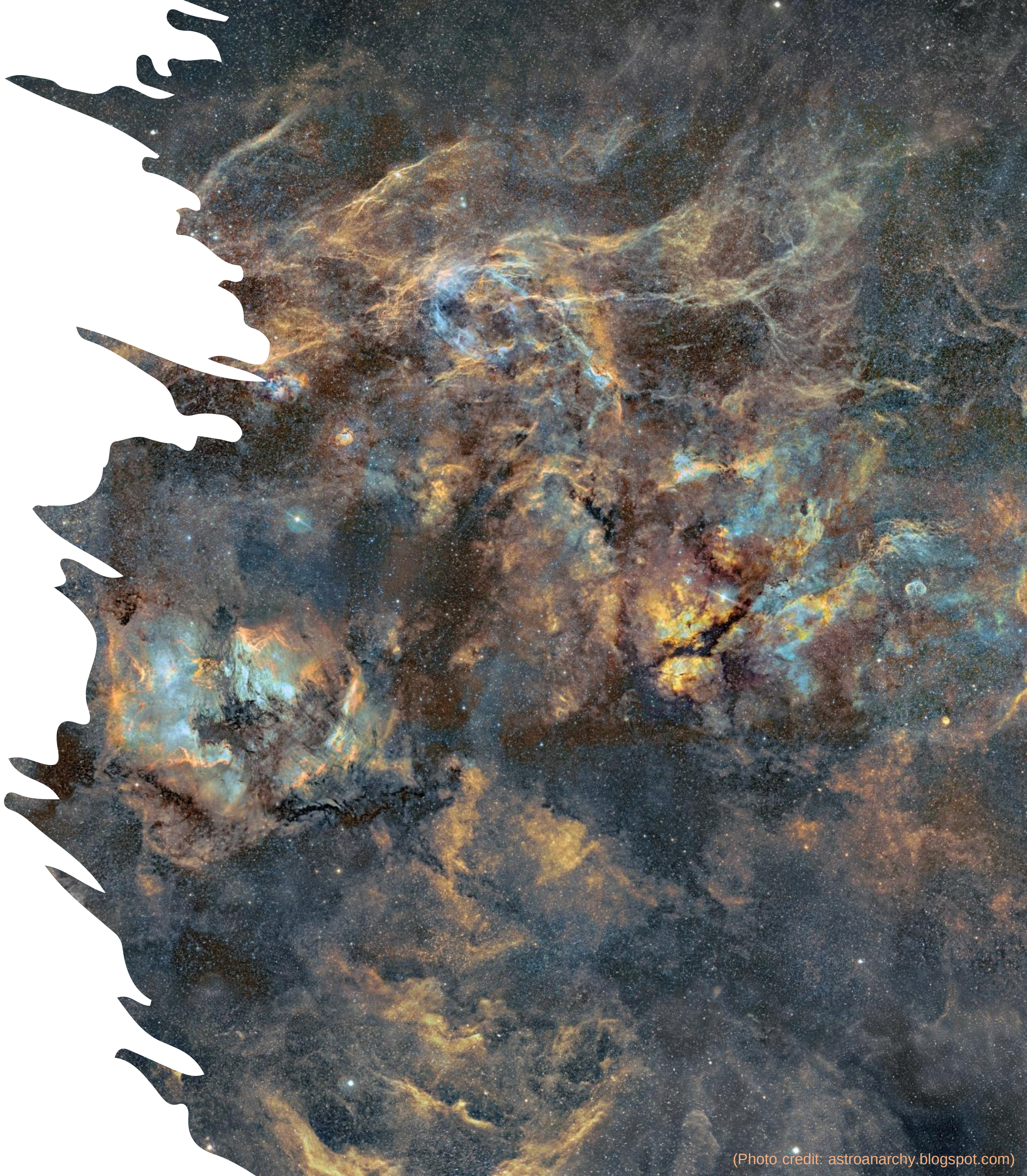
Conclusions

What has been done:

- We simulated hadronic γ-ray emission from Cygnus OB2 assuming a model of CRs accelerated at the cluster wind's termination shock.
- We consider two possible cases of ISM distribution around the cluster, one with uniformly distributed gas, the other with MCs scattered around OB2.
- The SED adequately fit the data from Fermi-LAT to the very-high energy band observed by HAWC
- The γ-ray morphology at $\approx 100\,\mathrm{GeV}$ depends on the relative position between the MCs and OB2.
- The expected radial shape shows a flat trend, in agreement with HAWC data but not completely with Fermi observations.

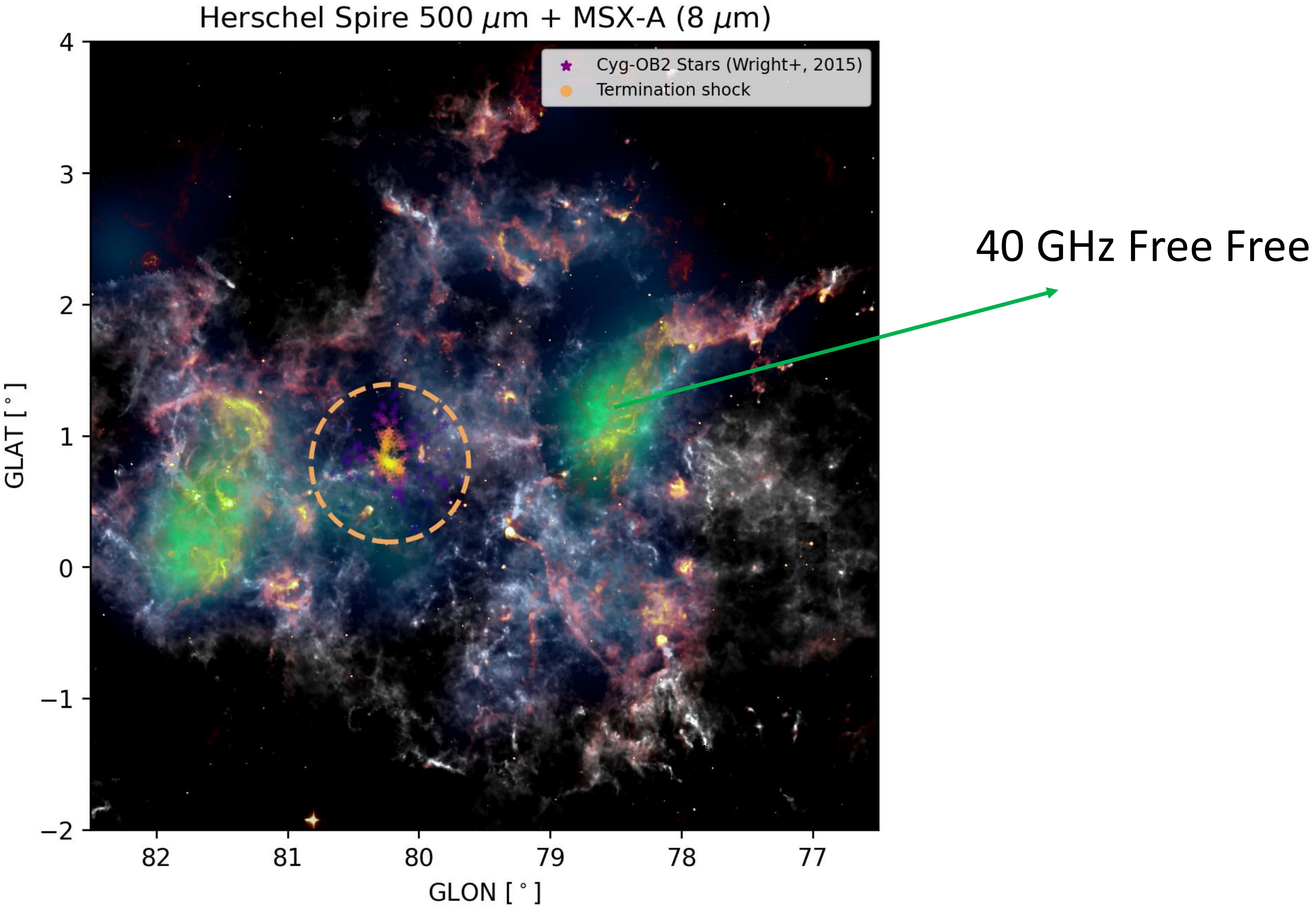
Possible future steps

- Consider the case where acceleration takes place inside the cluster
- Analyze the contribution from leptonic emission
- “Only diffusion” model in the bubble (pure 1/r profile) could be tested



(Photo credit: astroanarchy.blogspot.com)

Backup Slides


Herschel Spire 500 μm + MSX-A (8 μm)
Cyg-OB2 Stars (Wright+, 2015)
Termination shock
GLAT [°]
GLON [°]
4
3
2
1
0
−1
−2
82
81
80
79
78
77
40 GHz Free Free