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NGC 3603: its non-thermal emission through a realistic environment

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Introduction: Star-Forming regions

- **Groups of young massive stars**
- **Supersonic winds**
- **Collective termination shock**

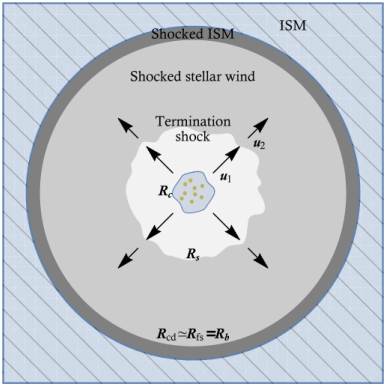


Figure: [Morlino et al, 2021]

Introduction: Star-Forming regions

- **Solve CR composition problem:** ^{22}Ne
- **Many recent detections:** Westerlund 1 & 2, Cygnus Cocoon, NGC 3603, ...

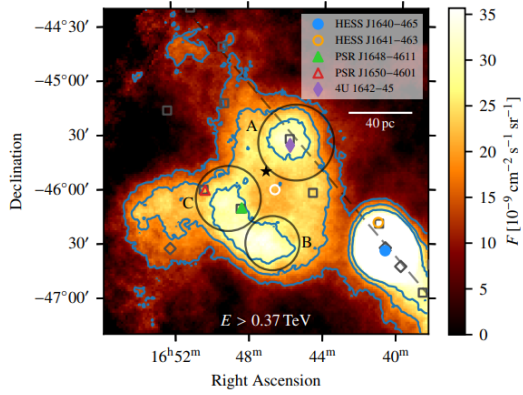


Figure: Westerlund 1 [HESS Collab., 2022]

Introduction: NGC 3603

- **Distance $\sim$ 7 kpc**
- **More than 200 O stars**

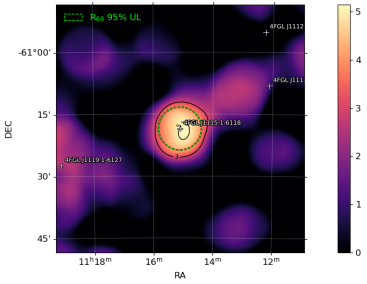


Figure: NGC 3603 above 10 GeV

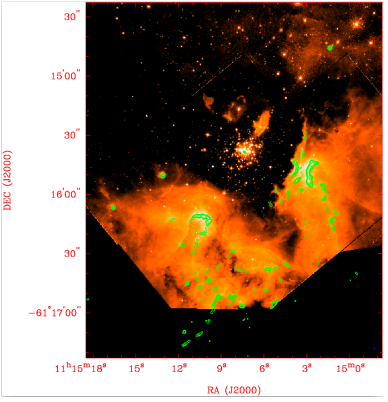


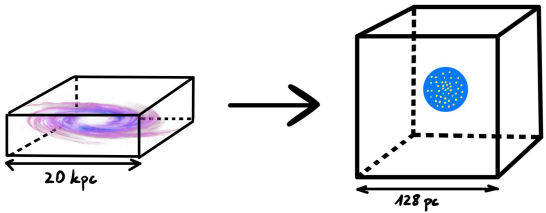
Figure: Hα image & 3 cm contours [Mücke et al, 2002]

Method

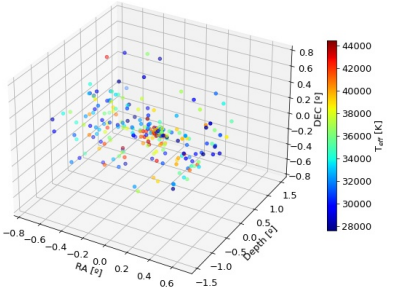
Numerical cosmic-ray propagation solver: PICARD

Necessary ingredients

- Radiation field
- Gas density: H2, HI & HII
- Magnetic field
- Winds
- Diffusion coefficient
- Particle injection



Model: Radiation field

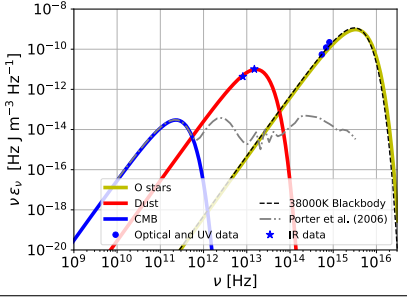


Catalog of O stars [Drew et al, 2019]:

- Gaussian distribution for the depth
- Blackbody radiation $\propto r^{-2}$

Dust [De Buizer, 2024]

CMB



Model: Gas

- **H2:** Graybody fit to Herschel data (λ = 250, 350, 500 μm)
- **HI:** [Retallack et al., 1980] (λ = 21 cm)
- **HII:** [McLeod et al., 2016] (Optical MUSE data)

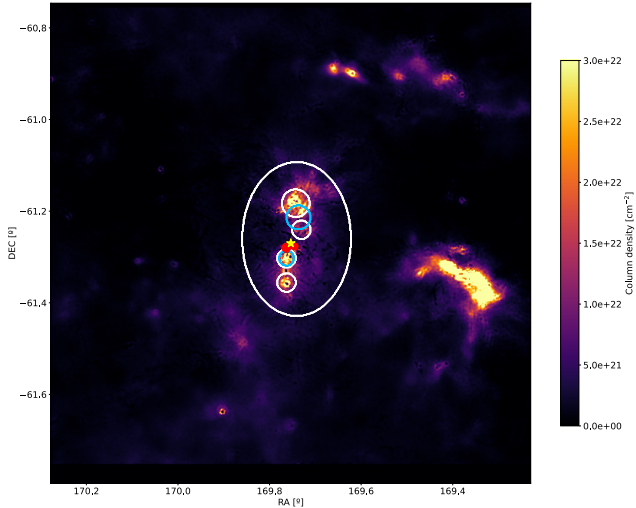


Figure: H2 column density in cm^{-2}

Model: Parameters

- **Magnetic field:** 7 μG inside the shocked region [Badmaev et al, 2023]

- **Diffusion coefficient:** Kolmogorov turbulence [Gallegos-García et al, 2020]:

$$D(E,r) \approx \frac{1}{3} r_L(E) v \left(\frac{r_L(E)}{R_c}\right)^{-2/3} \left(\frac{r}{R_s}\right)^{1/3} = 4{\cdot}10^{26} cm^2 s^{-1} \left(\frac{E}{1\ GeV}\right)^{1/3} \left(\frac{r}{R_s}\right)^{1/3}$$

- **Winds:** 2000 km/s radial winds [Drissen et al, 1995]

- **Kinetic wind luminosity:** $3.2{\cdot}10^{38}$ erg/s [Drissen, 1995]

Model: Injection

Scenarios

- Hadronic
- Leptonic
- Hybrid

Injection at the **termination shock** & modelled as a power-law with a cutoff:

$$s(E) \propto E^{-\alpha} exp(-E/E_c)$$

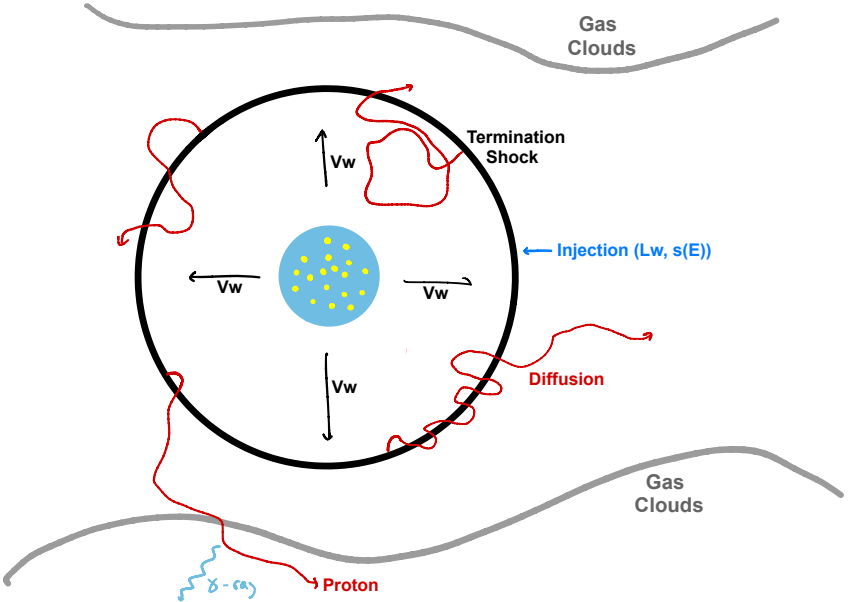
Cutoff energy

- Protons: Determined by the size of the acceleration region

$$E_{c,p} \approx ZeBV_w R_S \approx 50\ TeV$$

- Electrons: Determined by acceleration timescale and energy losses : $E_{c,e} \approx 10 TeV$

Model


Gas
Clouds
Termination
Shock
Vw
Vw
Vw
Vw
Injection (Lw, s(E))
Diffusion
Gas
Clouds
γ - ray
Proton

Data analysis: Fermi-LAT

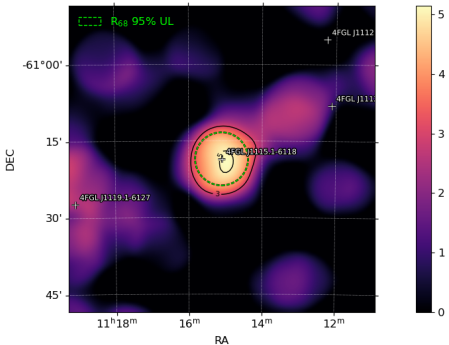


Figure: NGC 3603 $\sqrt{TS}$ map above 10 GeV

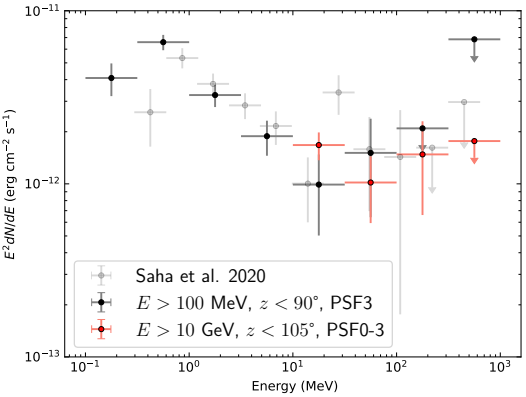
Analysis details

- 15 years of data
- P8R3 SOURCE data
- 100 MeV - 1 TeV

Extension

Analysis optimized above 10 GeV

Data analysis: Fermi-LAT



Analysis details

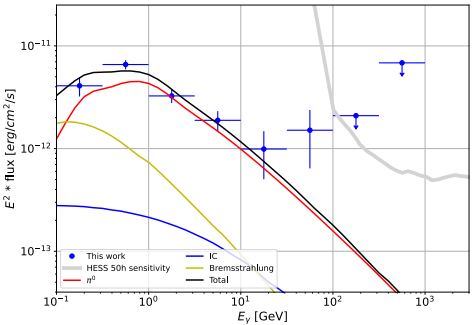
- 15 years of data
- P8R3 SOURCE data
- 100 MeV - 1 TeV

Extension

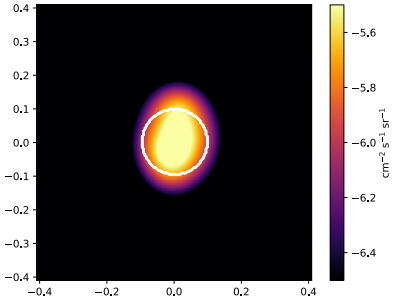
Upper limit of 0.096°

Results: Hadronic scenario

Efficiency η = 30%
Injection index α = 2.6

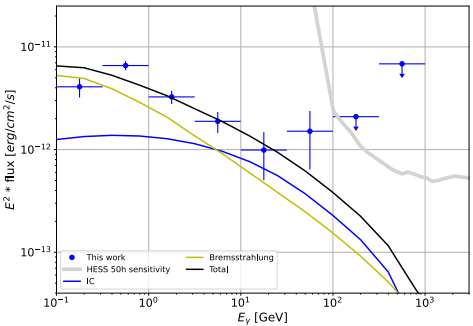


γ-ray data: Upper limit 0.096°
Sim. extension = 0.098° $\pm$ 0.001°



Results: Leptonic scenario

Efficiency η = 0.38%
Injection index α = 2.50

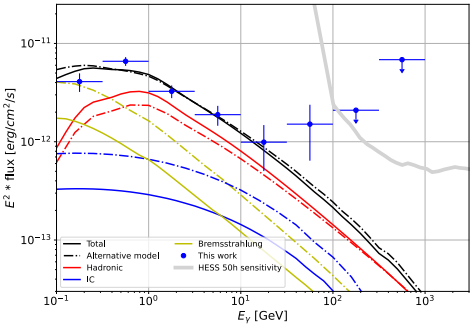


Extension = 0.088° ± 0.001°
Data: Upper limit of 0.096°

Results: Hybrid scenario

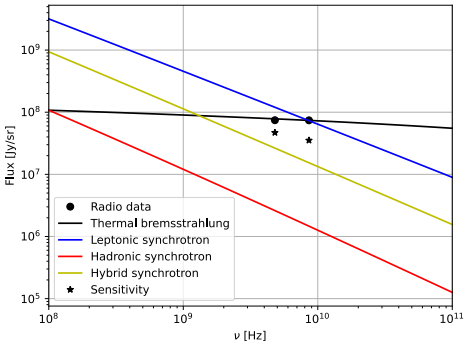
Best-fit model:
η = 20% $\longrightarrow$ p/e = 150
α_p = 2.55, α_e = 2.65

Alternative model:
η = 14% $\longrightarrow$ p/e = 80
α_p = 2.60, α_e = 2.65



Best-fit: 0.096° ± 0.001°
Alt: 0.093° ± 0.001°
Data: Upper limit of 0.096°

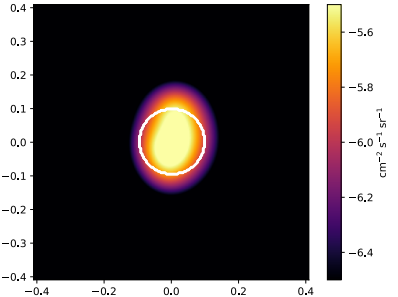
Results: Radio

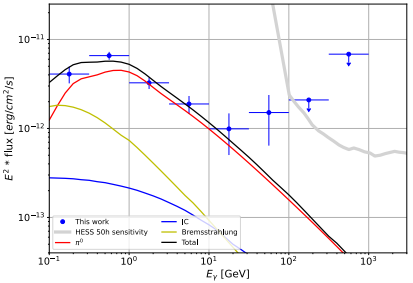


- Emission morphology do not match the observations
- Observed flux explained by thermal bremsstrahlung
- Leptonic-only scenario discarded

Caveats & Alternatives

- $\sim 2\sigma$ preference for point-like source
- Rising trend at high energies: η Car





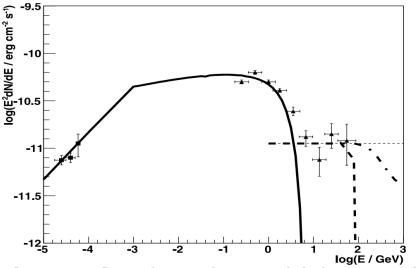


Figure: [Bednarek & Pabich, 2011]

Conclusions

- **Dedicated simulations of CR propagation in the Star-Forming Region NGC 3603**
- **The method allows to study the morphology of the source more in-depth**
- **Primary electrons are necessary to explain the morphology of the γ-ray emission**

Thank you for your attention!

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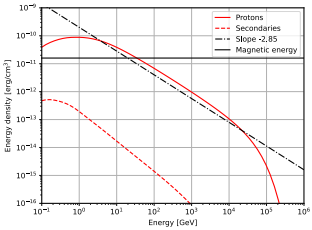
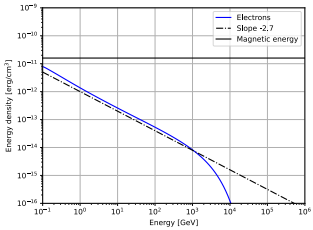
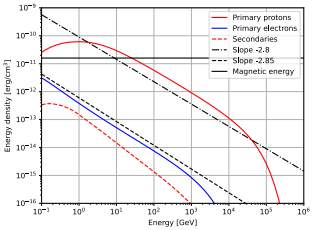
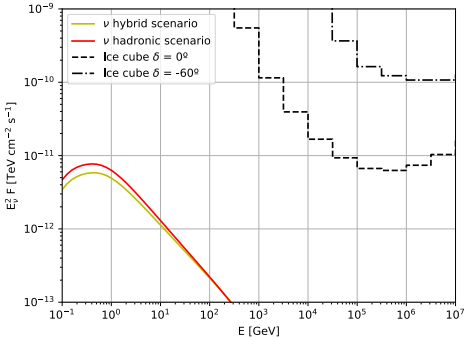
Results: Particle Spectrum







Results: Neutrino



- NGC 3603 located at $\delta \sim -60°$
- Below the current sensitivities of IceCube