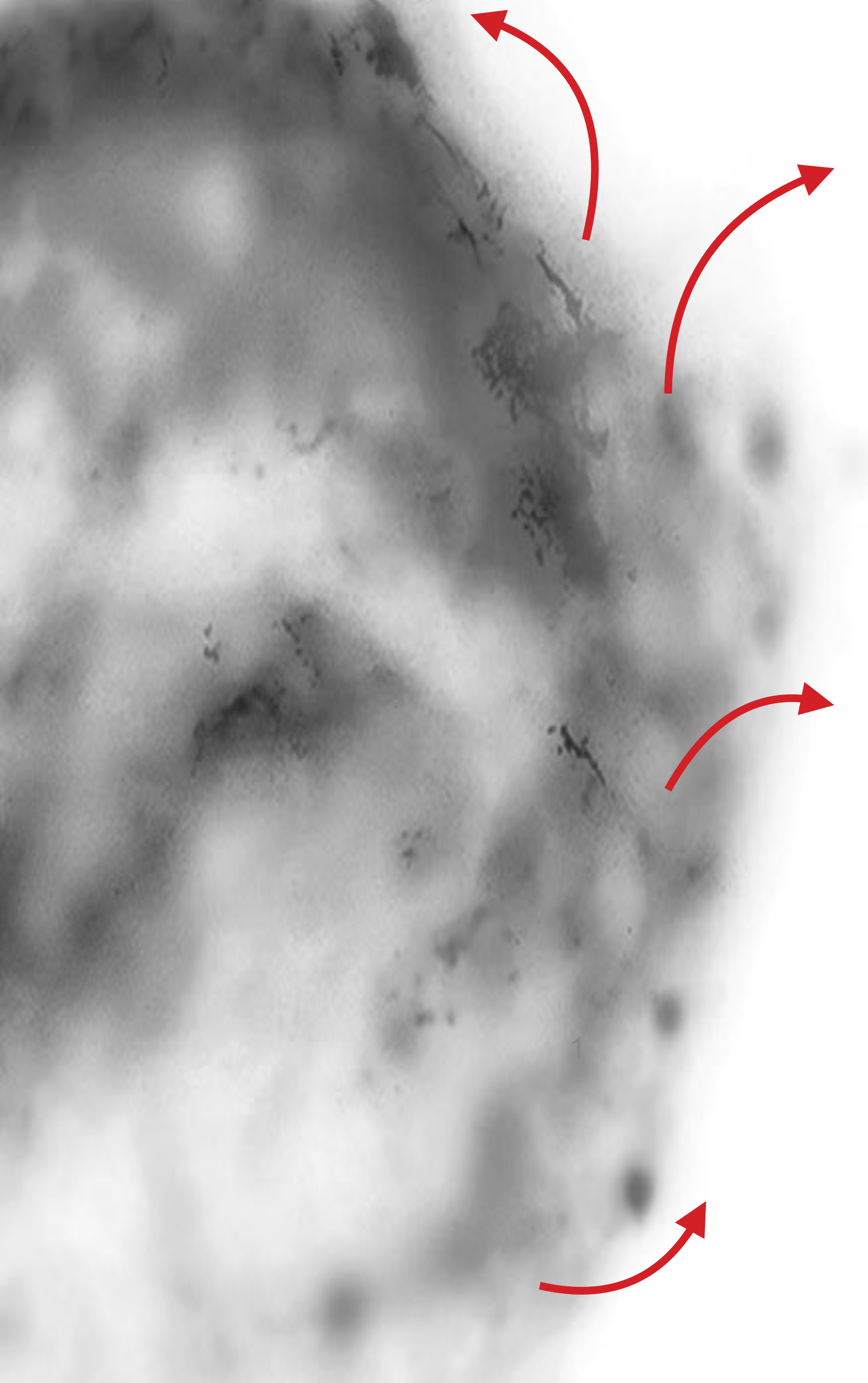

Modelling the Gamma-ray Morphology of the Supernova Remnant W28

A 3D Approach

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THE UNIVERSITY of ADELAIDE

AIP 2022, Adelaide
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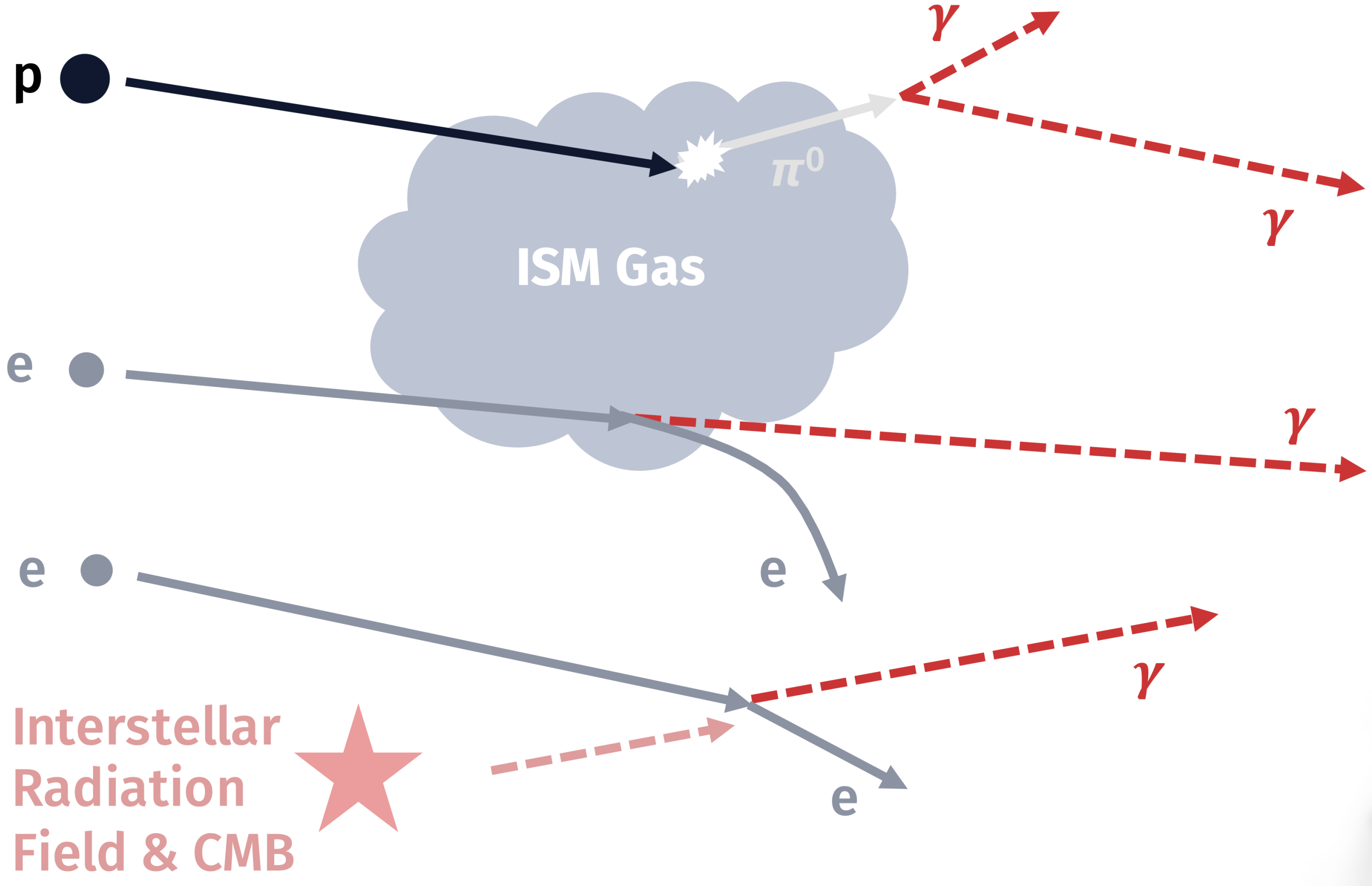
GROUP FOR ASTROPARTICLE PHYSICS

The Supernova Remnant W28

- Mixed-morphology SNR
- Well-studied
- Prime candidate to study cosmic-ray acceleration and diffusion
  - Adjacent molecular clouds provide target material for gamma-ray production
  - Most particles already escaped (due to its age)
- Successful modelling of spectra
- BUT: Morphology missing!

Gamma-Ray Production

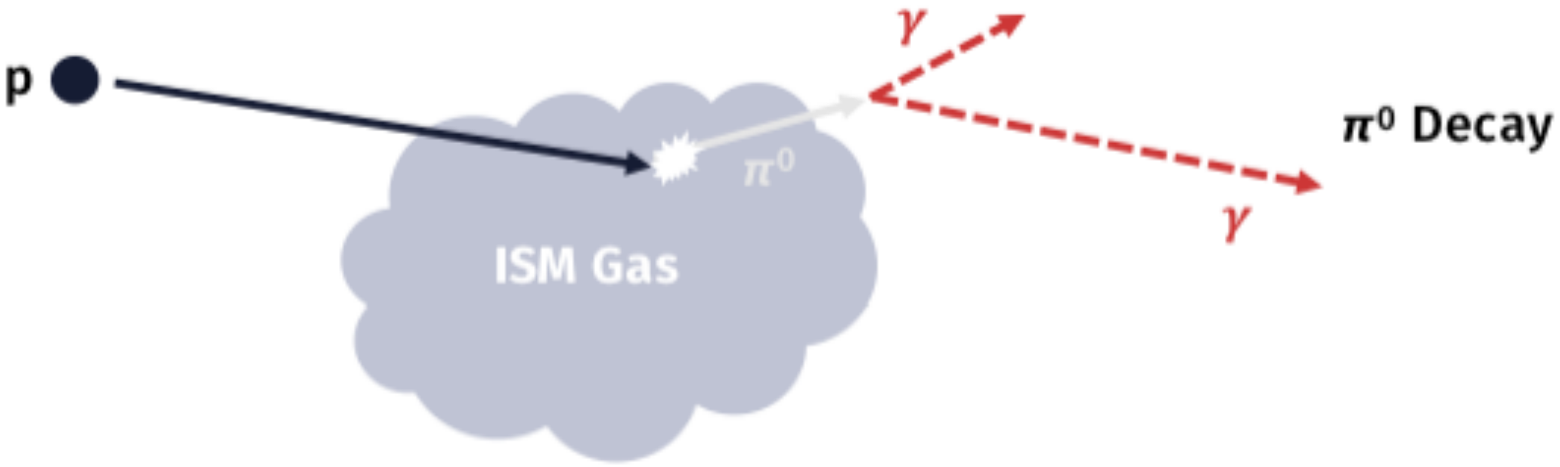


π^0 Decay

Bremsstrahlung

Inverse Compton

Modelling: Gamma-Ray Distribution



$$\Phi_\gamma = \frac{c\, n_{\mathrm{H}}\, V}{4\pi D^2} \int_{E_\gamma}^{\infty} \sigma_{\mathrm{pp}}(E_{\mathrm{p}})\, J_{\mathrm{p}}(E_{\mathrm{p}}, R, t)\, F_\gamma\left(E_{\mathrm{p}}, E_\gamma\right) \frac{dE_{\mathrm{p}}}{E_{\mathrm{p}}}$$

Total Number Density (ISM): n_{H}

Volume of ISM: V

Distance: Earth - Accelerator: D

Cosmic-Ray Proton Volume Distribution: $J_{\mathrm{p}}(E_{\mathrm{p}}, R, t)$

Photons per collision: F_γ

Kelner et al. (2006)

Modelling: Cosmic-Ray Proton Distribution

Escaped Cosmic Rays ($E_p > E_{p,esc}$)

Steady-state solution to transport equation

$$J_\mathrm{p} = N_0\, E_\mathrm{p}^{-\alpha} \frac{f_0}{\pi^{3/2} R_\mathrm{dif}^3} \exp\left(-\frac{(R - R_\mathrm{esc})^2}{R_\mathrm{dif}^2} \right)$$

adapted from *Aharonian & Atoyan (1996)* to include escape at time

$$t_\mathrm{esc} = t_\mathrm{Sedov} \left(\frac{E_\mathrm{p}}{E_\mathrm{p,max}} \right)^{-1/\delta_p}$$

Gabici et al. (2009)

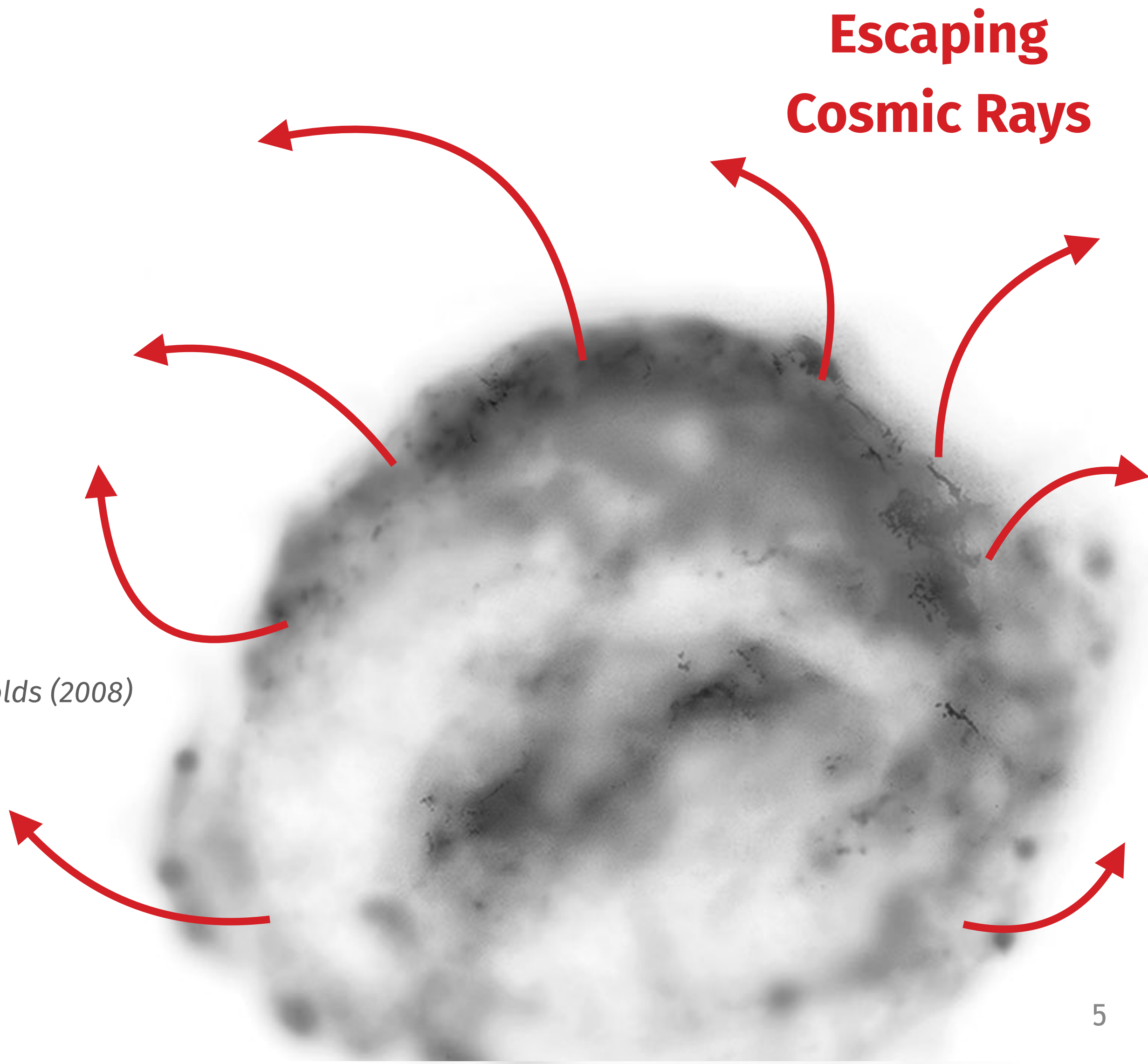
and at distance

$$R_\mathrm{esc} = 0.31 \left(\frac{E_\mathrm{SN}}{10^{51}\,\mathrm{erg}} \right)^{1/5} \left(\frac{n_0}{\mathrm{cm}^{-3}} \right)^{-1/5} \left(\frac{t_\mathrm{esc}}{\mathrm{yr}} \right)^{2/5} \mathrm{pc}$$

Reynolds (2008)

with diffusion length

$$R_\mathrm{dif} = \sqrt{4D(t - t_\mathrm{esc})}$$



Modelling: Cosmic-Ray Proton Distribution

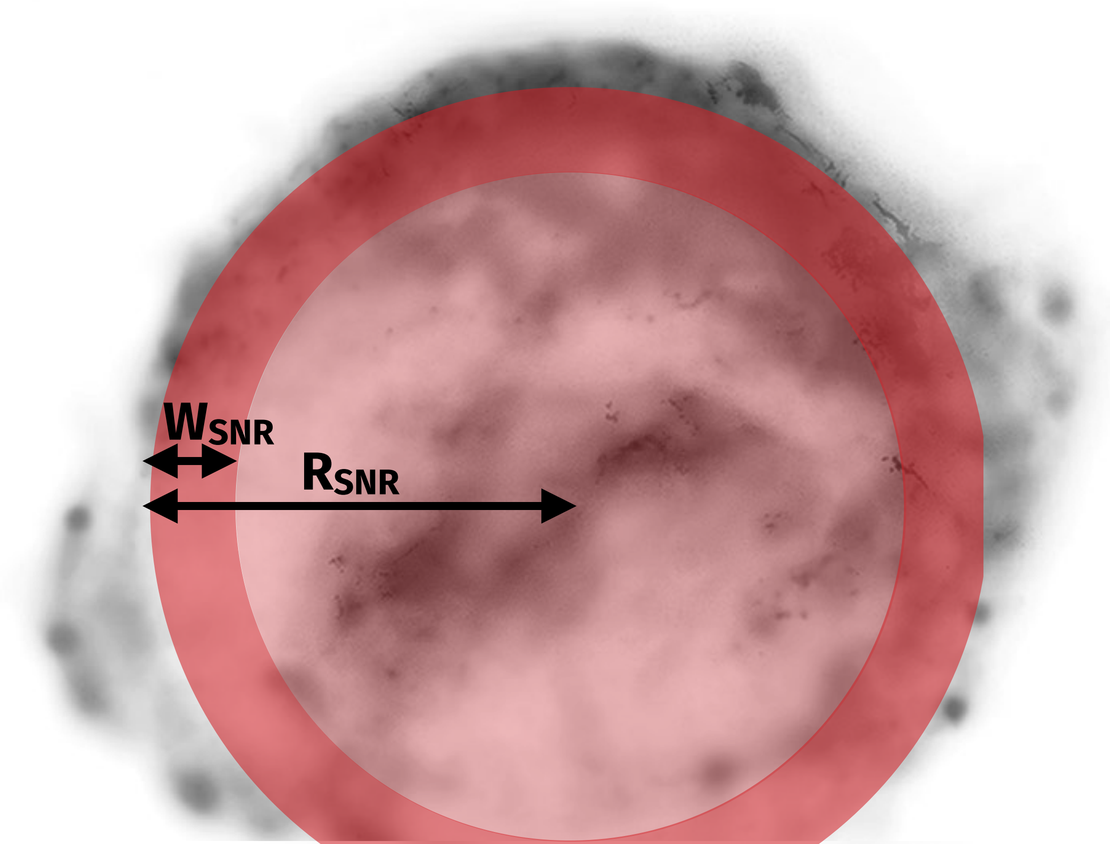
Confined Cosmic Rays ($E_p < E_{p,esc}$)

Fraction *f* of confined particles uniformly distributed in shell of width W_{SNR}

$$J_{\mathrm{p}} = f \cdot N_0\, E_{\mathrm{p}}^{-\alpha} \left(4/3\, \pi\, R_{\mathrm{SNR}}^3 - (R_{\mathrm{SNR}} - W_{\mathrm{SNR}})^3\right)^{-1}$$

Remaining particles uniformly distributed in inner sphere

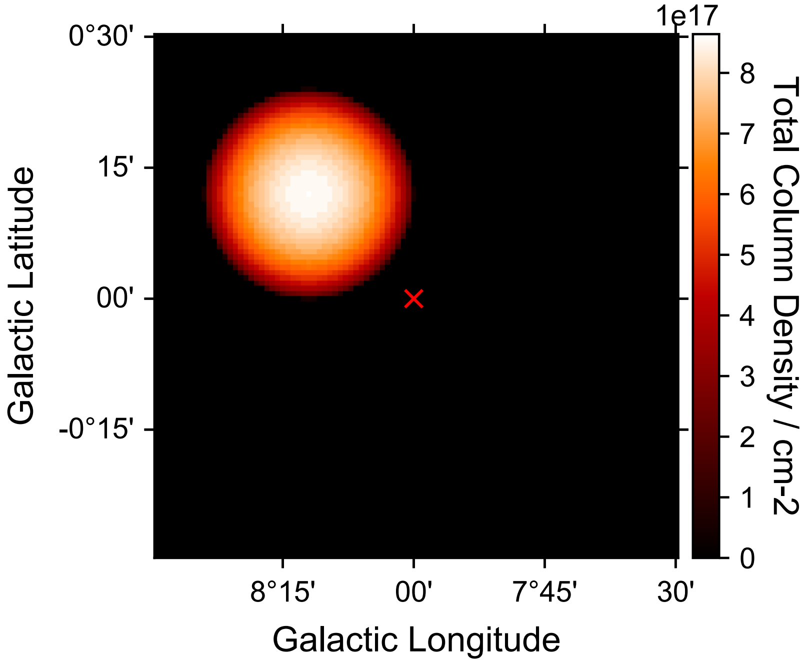
$$J_{\mathrm{p}} = (1 - f) \cdot N_0\, E_{\mathrm{p}}^{-\alpha} \left(4/3\, \pi\, (R_{\mathrm{SNR}} - W_{\mathrm{SNR}})^3\right)^{-1}$$



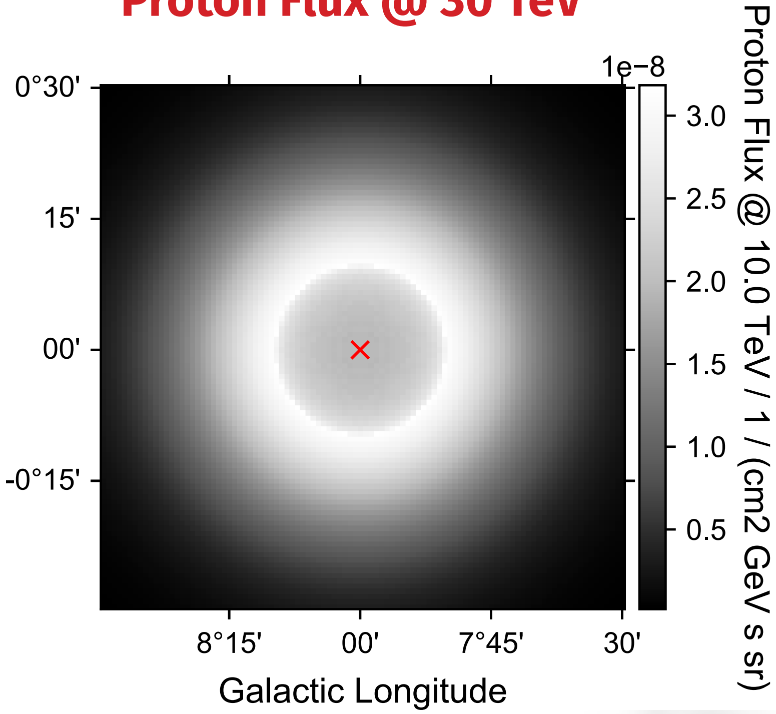
Modelling: Morphology

Modelling of cosmic-ray protons and gamma rays for a **3D** spatial grid, determined by resolution of interstellar gas measurements

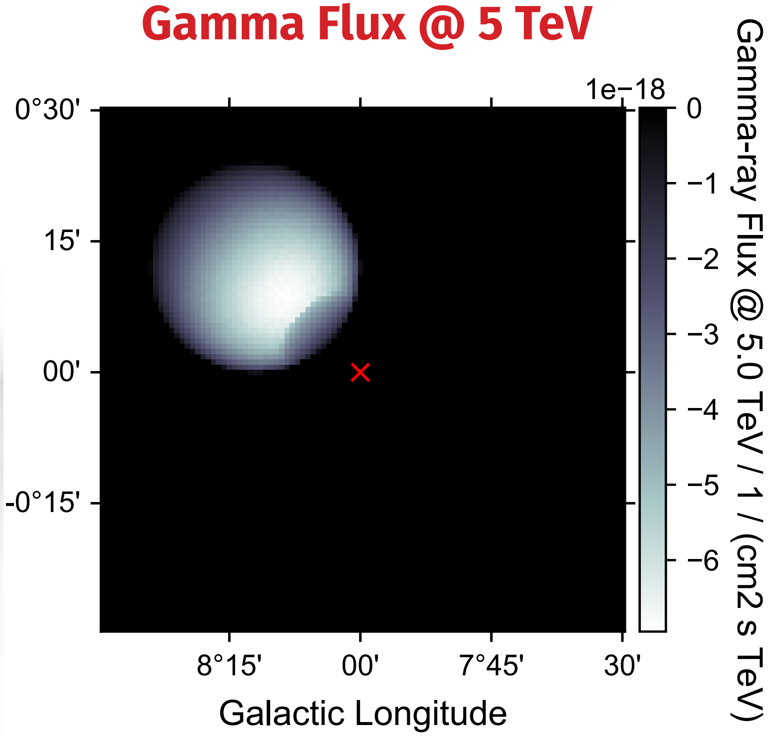
Interstellar Gas



Proton Flux @ 30 TeV

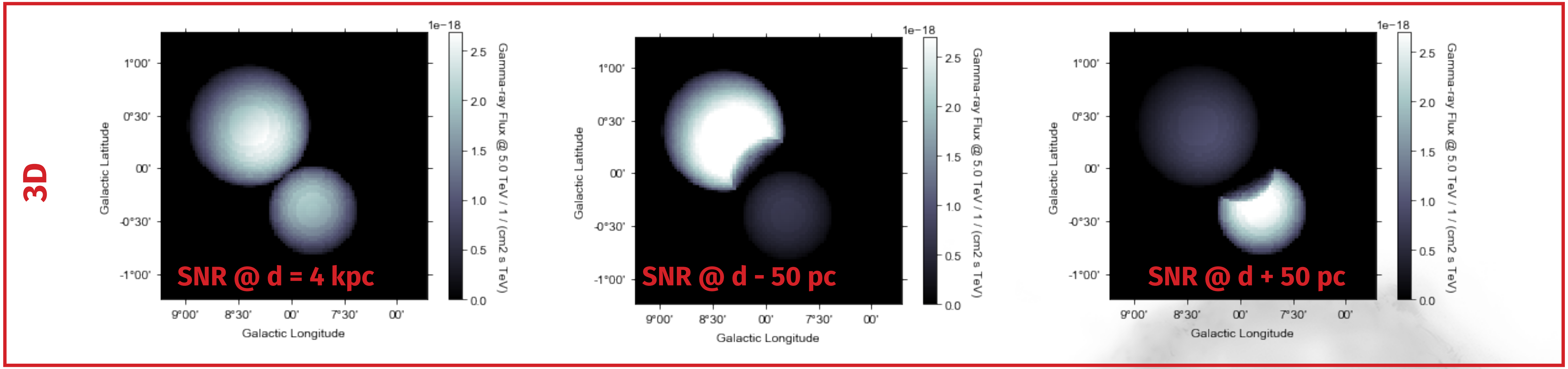


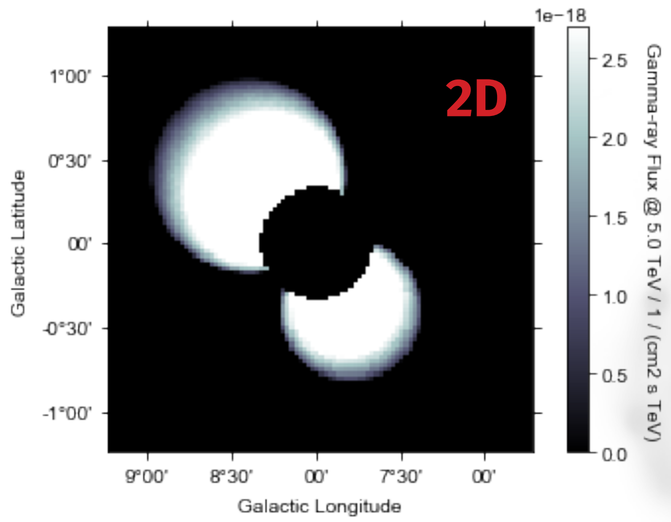
Gamma Flux @ 5 TeV



(Note: All distributions here integrated over z-axis for illustration.)

Gamma-Ray Morphology: Importance of 3D





Example:
Gas clouds with different distances to Earth

partISM

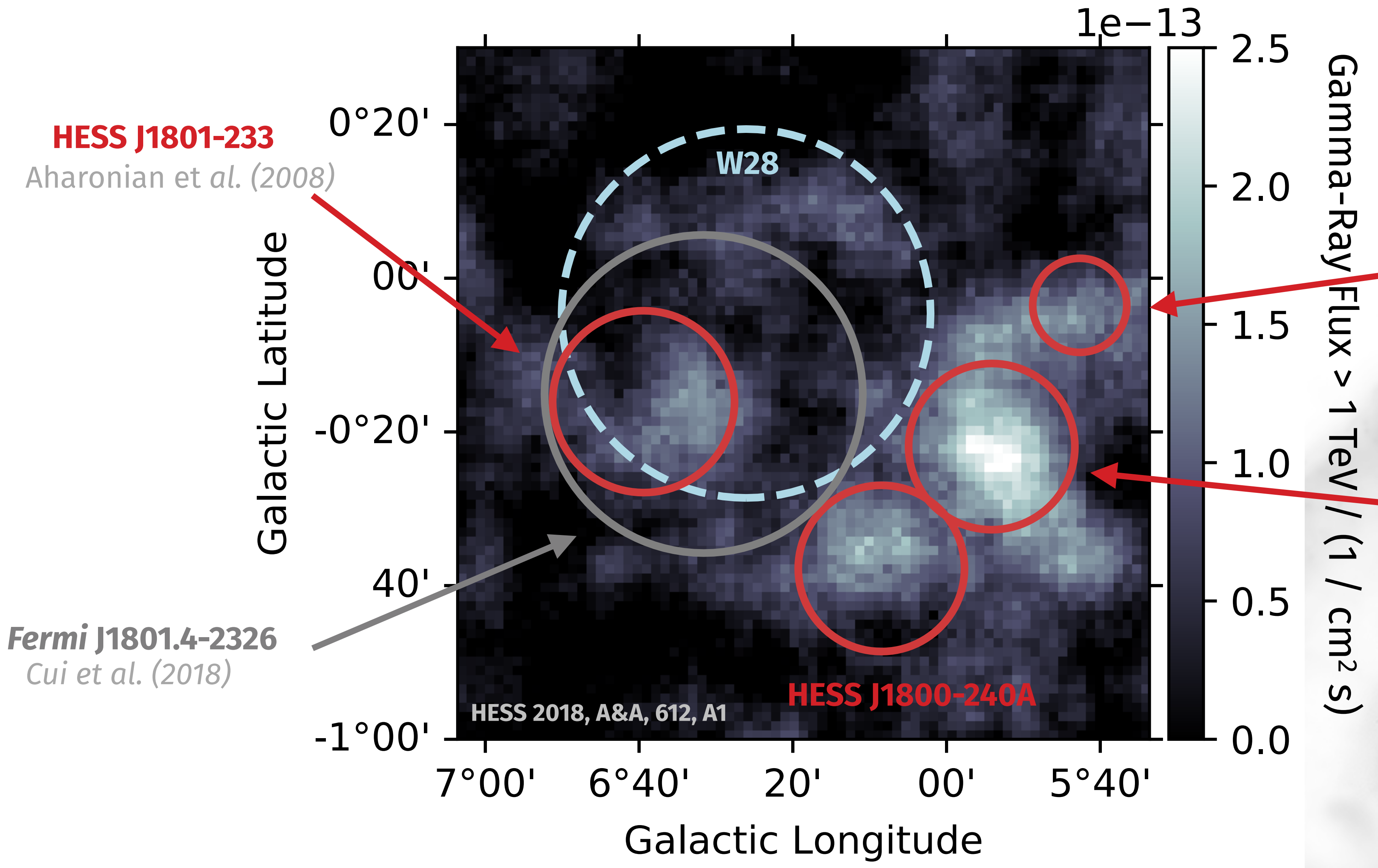
- Python framework for modelling **part**icles (protons, gamma rays and neutrinos) in the **ISM**
- Modular and user-friendly structure
- Hosted on GitHub
  (to be released together with publication)

- Novel modelling of morphology
- Novel modelling in 3D

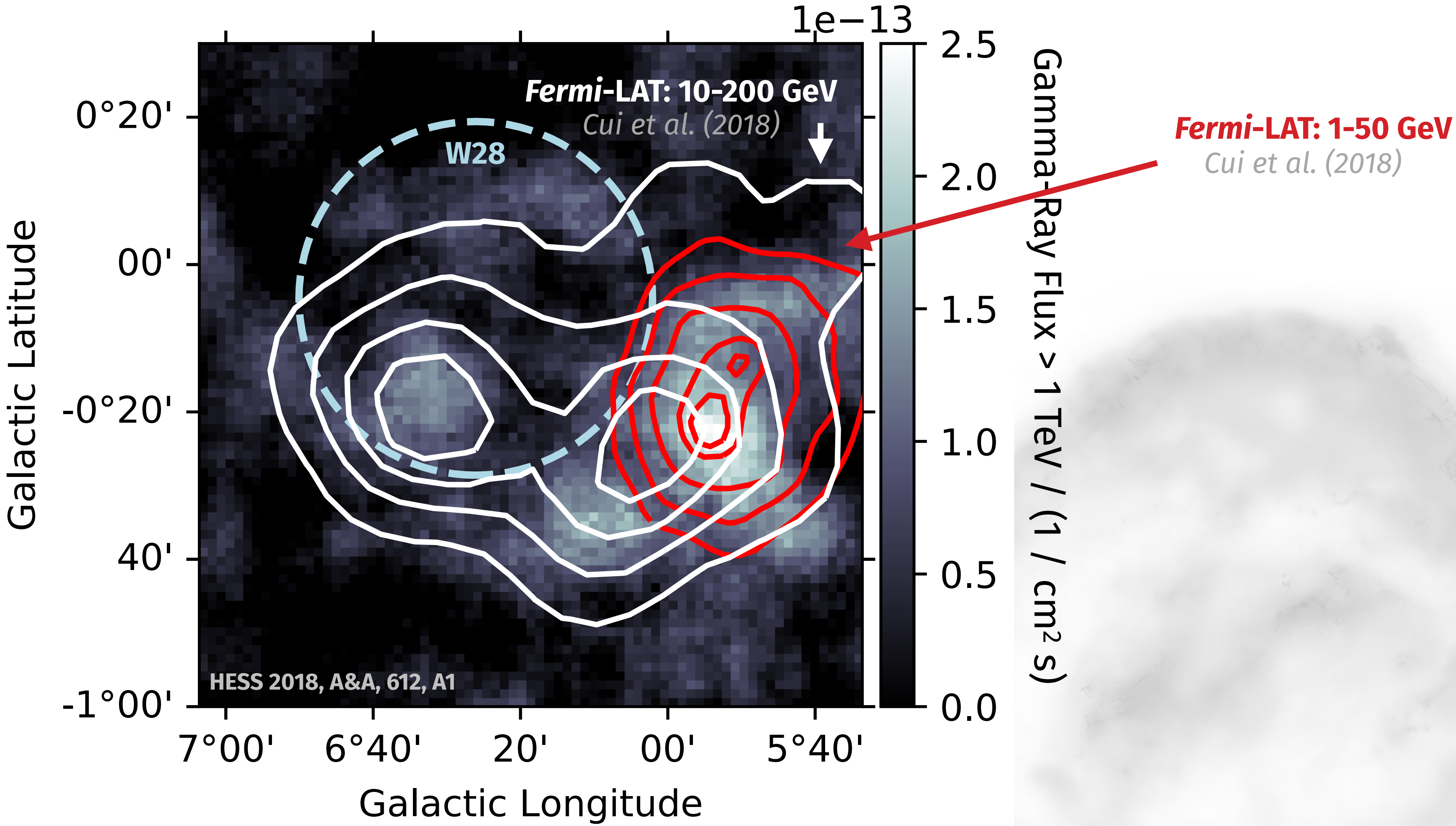
- Notebooks available with examples and reproduction of plots from
  - *Aharonian and Atoyan (1996) A&A 309*
  - *Kelner et al. (2006) Phys Rev D 79*
  - *Mitchell, Einecke et al. (2021) MNRAS 503*
  - *Feijen, Einecke et al. (2022) MNRAS 511*

Thursday 3pm: Ryan Burley, *Gamma-ray and Neutrino Emission from SNRs and Molecular Clouds*

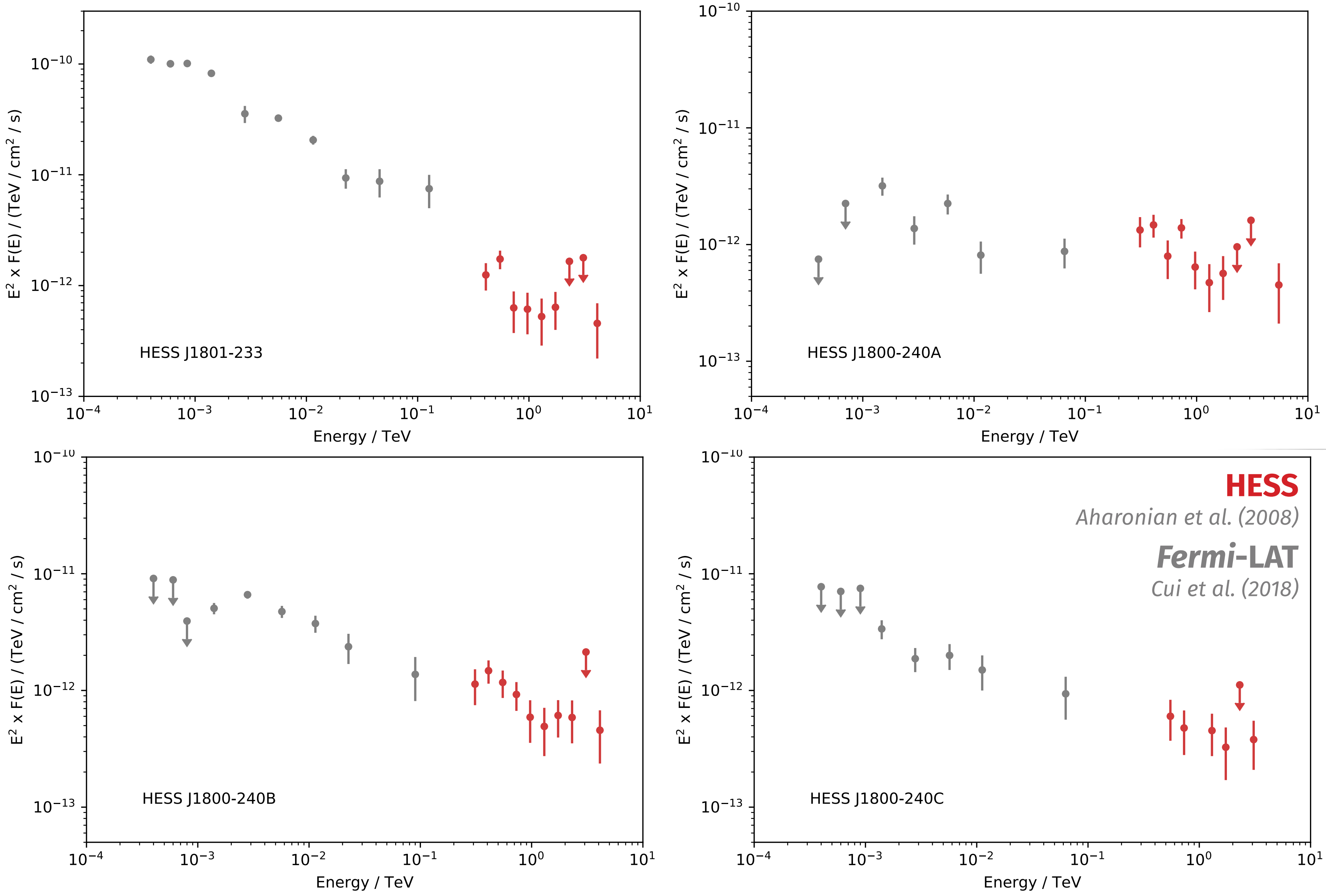
Measurement: Gamma-ray Distribution towards W28



Measurement: Gamma-ray Distribution towards W28



Measurement: Gamma-ray Distribution towards W28

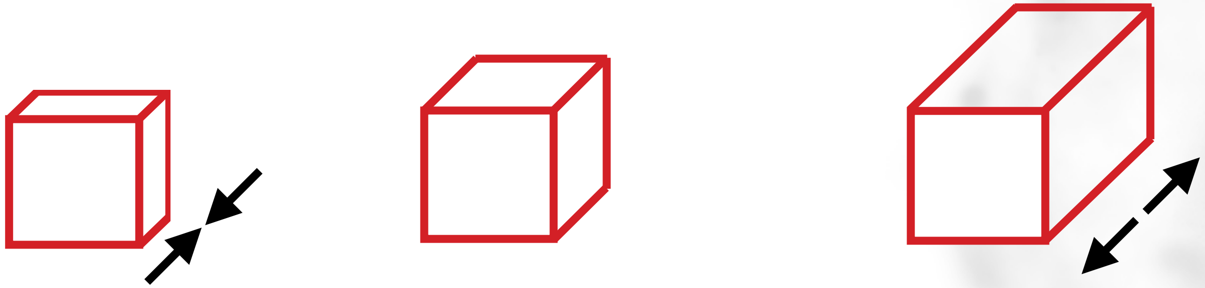


Measurement: Gas Distribution

Challenges

- Measurement of line-of-sight Doppler velocities instead of physical distance
- Model of Galaxy’s rotation translates these velocities to distances, but …
  - … often it has two solutions (‘near’ and ‘far’ distance)
  - … it does not consider local velocities of the gas
  - … it has rather large uncertainties (for our application)

- Iterative approach:
  - Location of centre of 3D gas distribution
  - Compress / stretch distance dimension of 3D gas distribution



Measurement: Gas Distribution towards W28

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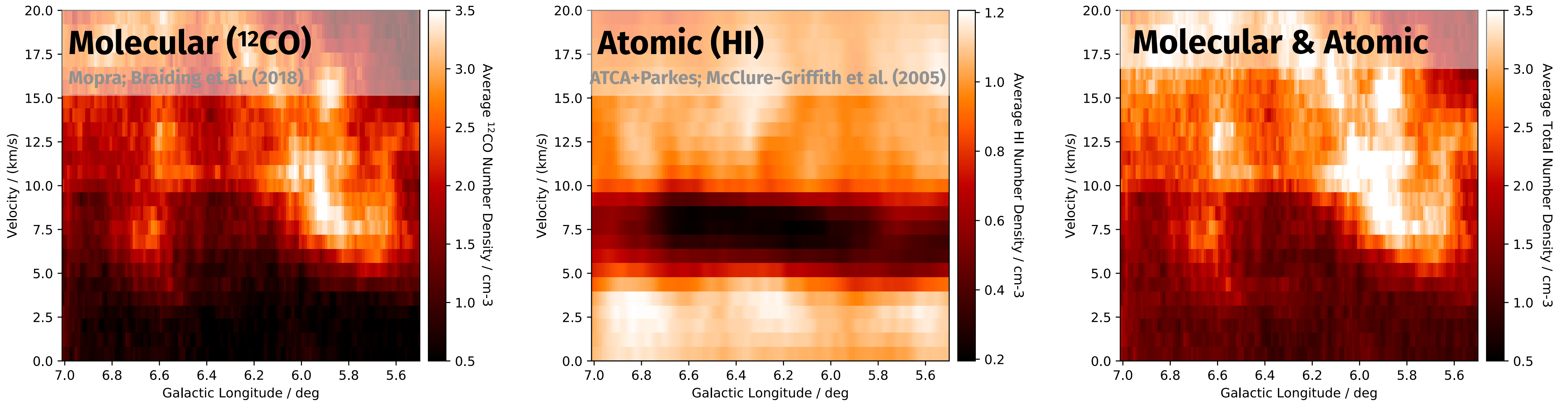
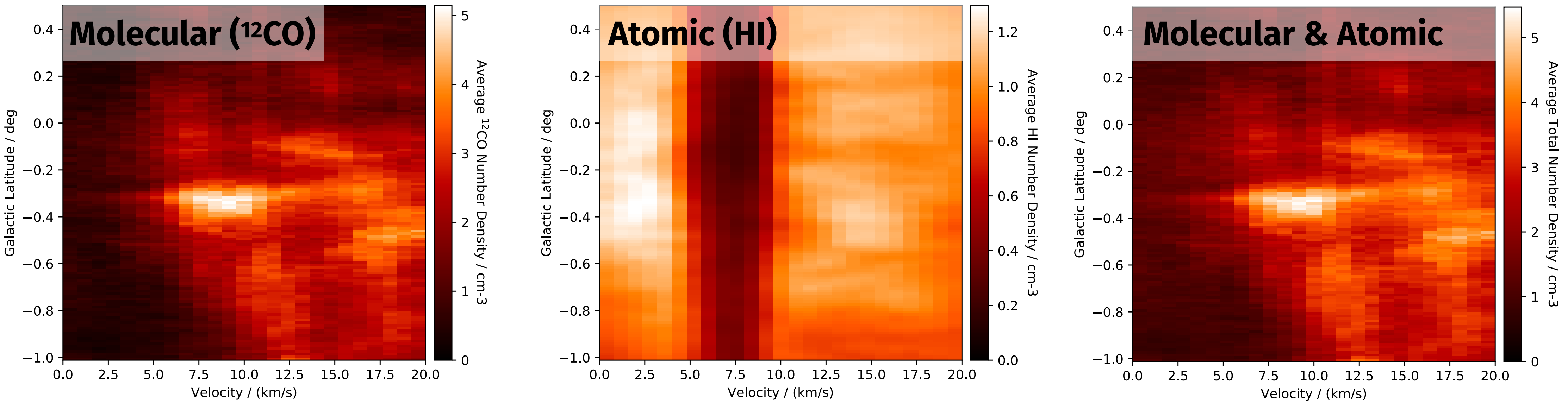
Averaged over Latitudes -1.0° to 0.5°

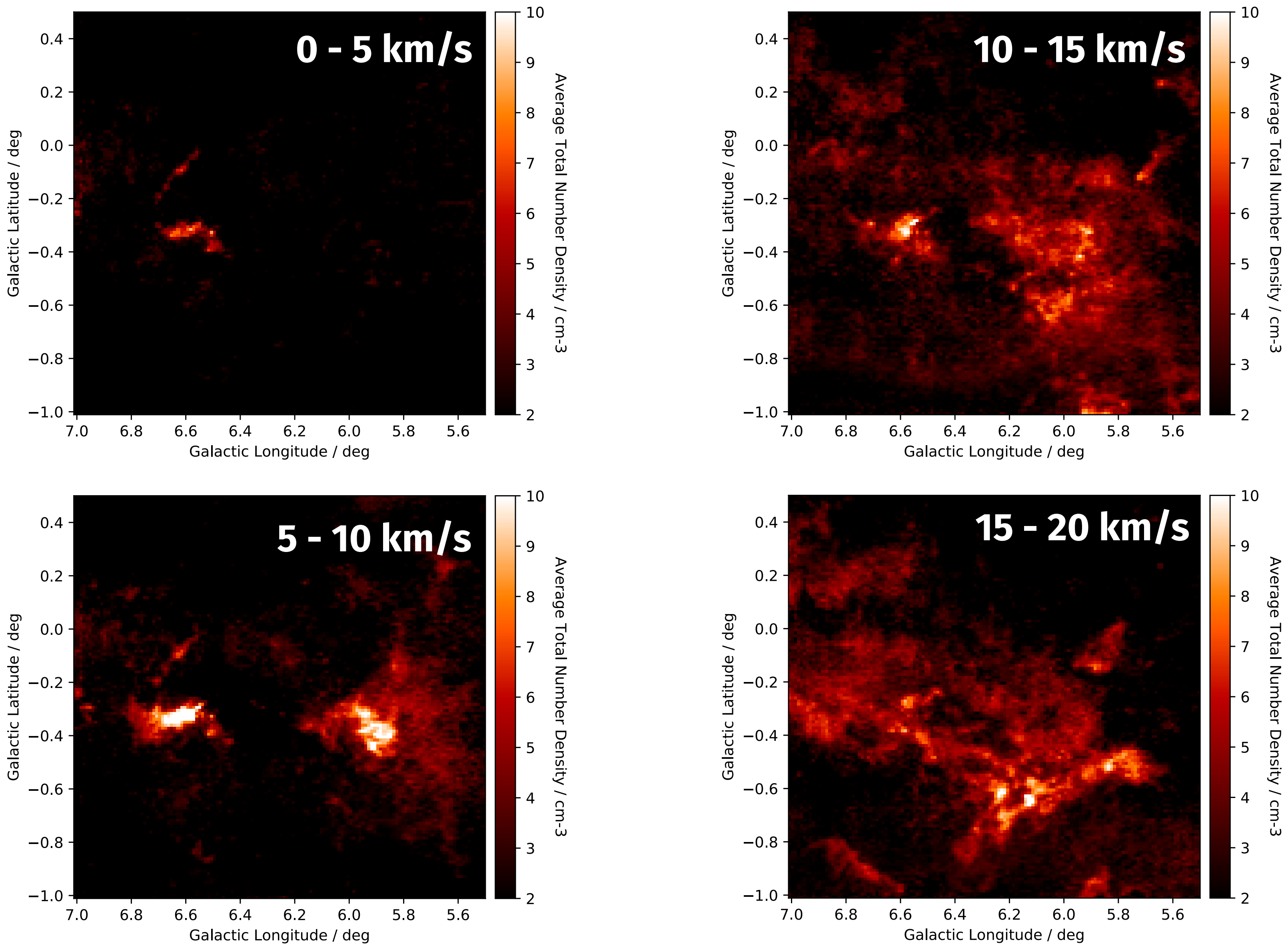


Averaged over Longitudes 5.5° to 7.0°



Measurement: Gas Distribution towards W28

ATOMIC & MOLECULAR
Averaged over Velocities



Model Parameters

Grid search

- Spectral index α: 2.0, 2.2
- Diffusion suppression factor $\chi_{diffusion}$: 0.01, 0.1, 1
- Index of diffusion coefficient $\delta_{diffusion}$: 0.3, 0.5, 0.7
- Ambient magnetic field B: 10, 50, 100 μG
- Energy dependence of escape δ_p: 1.4, 2.5
- $E_{p,max}$: 1 PeV

- Total ejected kin. energy of SN E_{SN}: 1e51, 2.5e51, 5e51 erg
- η ($W_p=\eta E_{SN}$): 0.3, 0.35, 0.4, 0.45, 0.5
- Ambient hydrogen number density n_0: 10, 20, 30 cm^{-3} (n_0 of 10 cm^{-3} belongs to E_{SN} of $1e^{51}$ erg etc.)
- Mass of SN ejecta M_{ej}: 1, 5, 10 M_{sol}

- Velocity centre: 11, 13, 15 km/s
- Velocity range (around centre): ±5, ±10 km/s

Fixed parameters:

- SNR age: 37 kyr
- SNR distance: 1.9 kpc
- n_0 = 10 * E_{SN} [$1e^{51}$erg]
- Shell width of confined particles: 3.7 pc
- Fraction of confined particles in shell: 68%

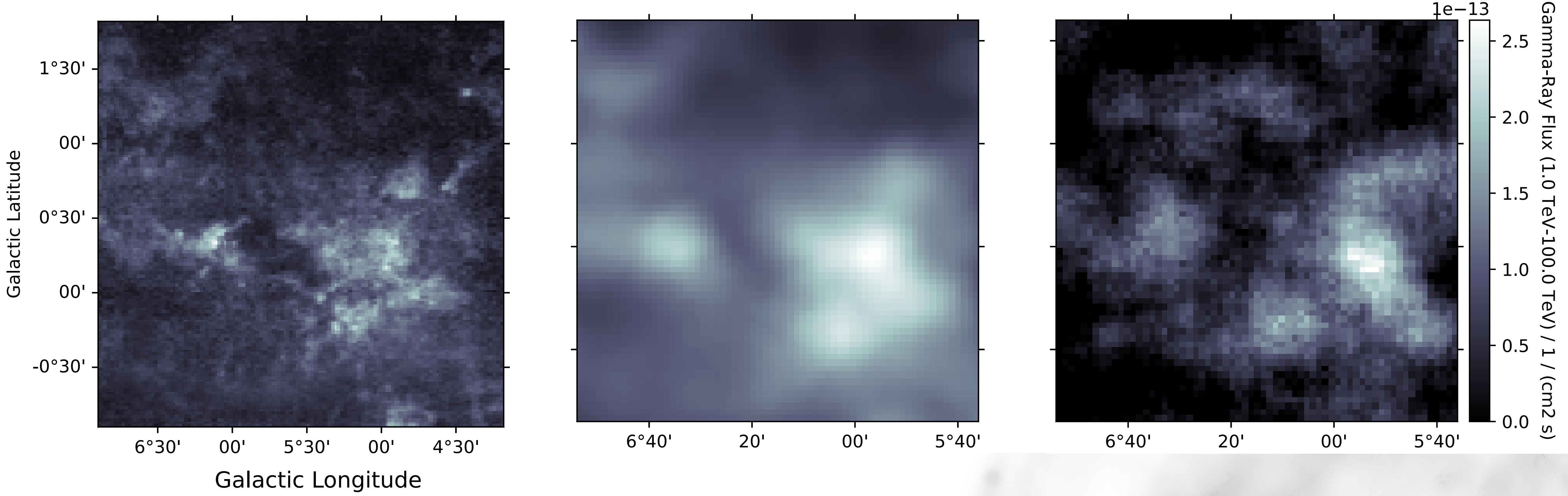
Additional constraint:

E_{esc} < 1 TeV

(based on *Fermi*-LAT measurements, low-energy particles must have escaped already)

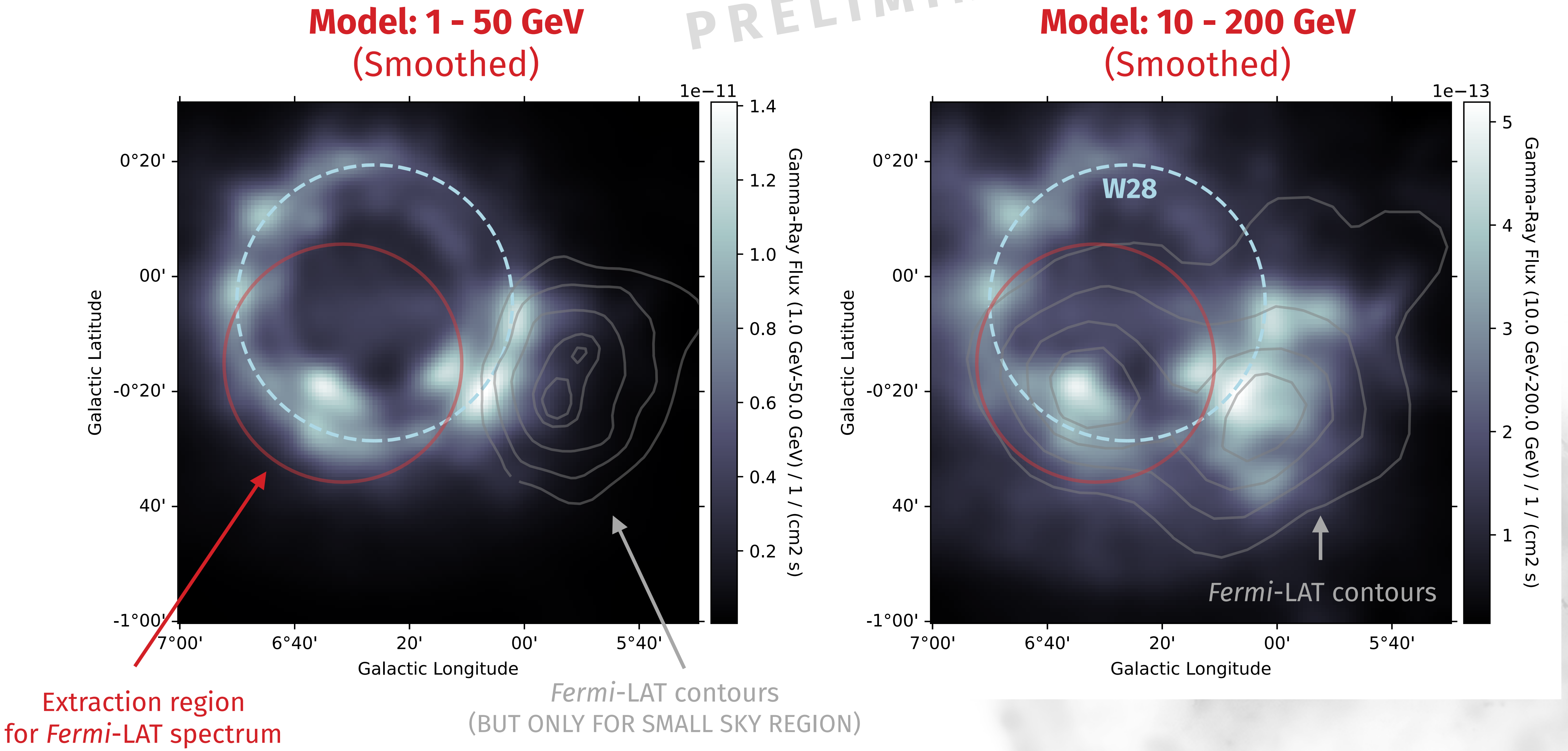
Results

Model: > 1 TeV | **Model: > 1 TeV (Oversampled)** | **HESS: > 1 TeV (Oversampled)**



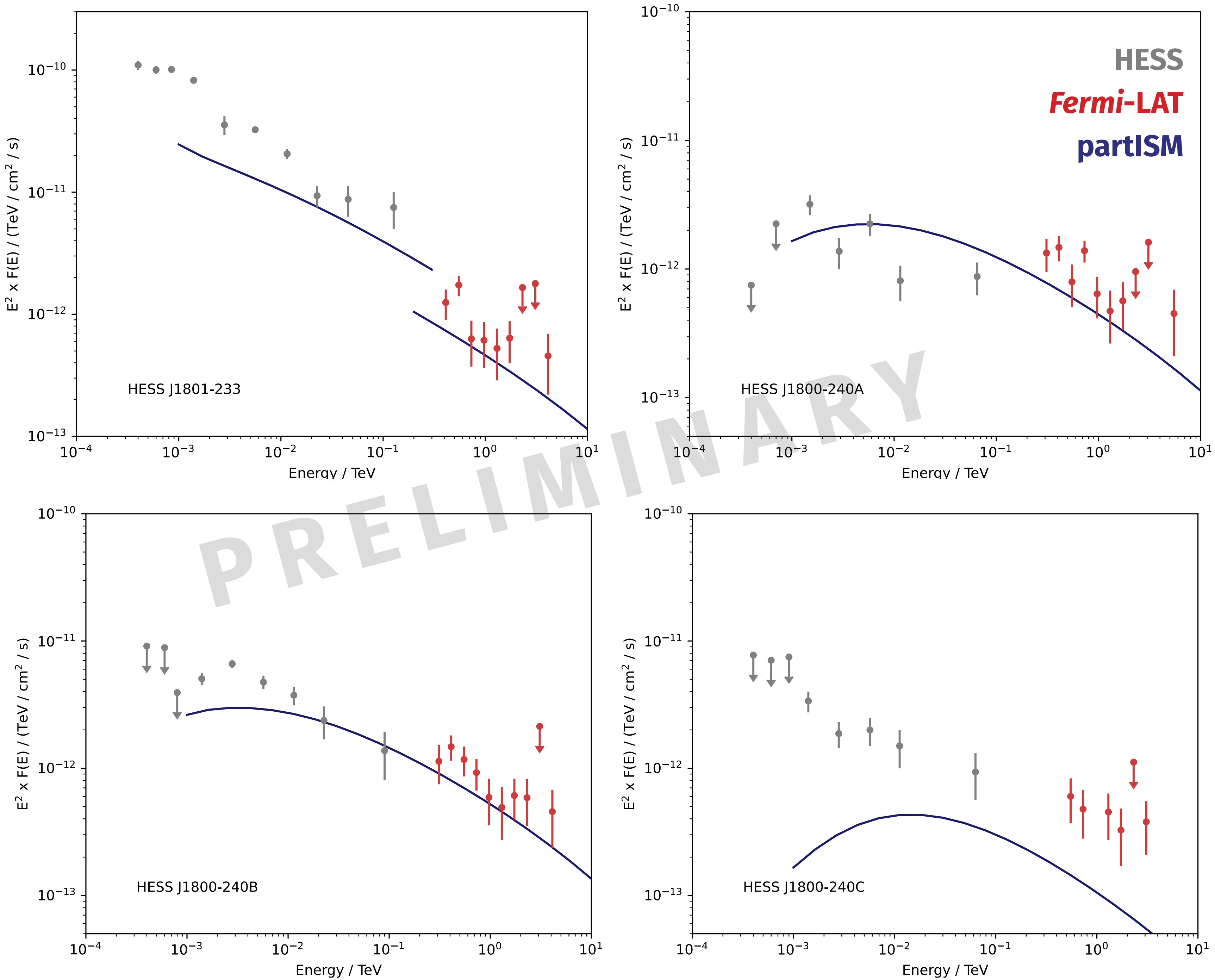
- α: 2.2, $\chi_{\mathrm{diffusion}}$: 0.1, $\delta_{\mathrm{diffusion}}$: 0.5, B: 100 μG, δ_p: 2.5, E_{SN}: 5e51 erg, n_0: 50 cm^{-3}, M_{ej}: 10 M_{sol}
- Velocity: 8 - 18 km/s

Results



PRELIMINARY
Model: 1 - 50 GeV
(Smoothed)
1e−11
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Gamma-Ray Flux (1.0 GeV-50.0 GeV) / 1 / (cm2 s)
0°20'
00'
-0°20'
40'
-1°00'
7°00'
6°40'
20'
00'
5°40'
Galactic Latitude
Galactic Longitude
Model: 10 - 200 GeV
(Smoothed)
1e−13
5
4
3
2
1
Gamma-Ray Flux (10.0 GeV-200.0 GeV) / 1 / (cm2 s)
W28
Fermi-LAT contours
Extraction region
for *Fermi*-LAT spectrum
Fermi-LAT contours
(BUT ONLY FOR SMALL SKY REGION)

Results



HESS
Fermi-LAT
partISM
PRELIMINARY
HESS J1801-233
HESS J1800-240A
HESS J1800-240B
HESS J1800-240C
E2 x F(E) / (TeV / cm2 / s)
Energy / TeV

Conclusion

- To understand particle accelerators and their environments,
  we need to be able to reproduce their gamma-ray spectra **and** their morphologies
- New software framework to model **part**icles (protons, gamma rays, neutrinos) in the **ISM**
  - 3D models: Morphologies & spectra
  - Computation time allows constraining model parameters for more computationally expensive models
- First model of morphology of SNR W28
  - Very promising results
  - New insights into SNR and its environment
- Demonstrated importance of modelling in 3D
- Modelling gamma-ray distribution and matching observations can constrain gas distribution