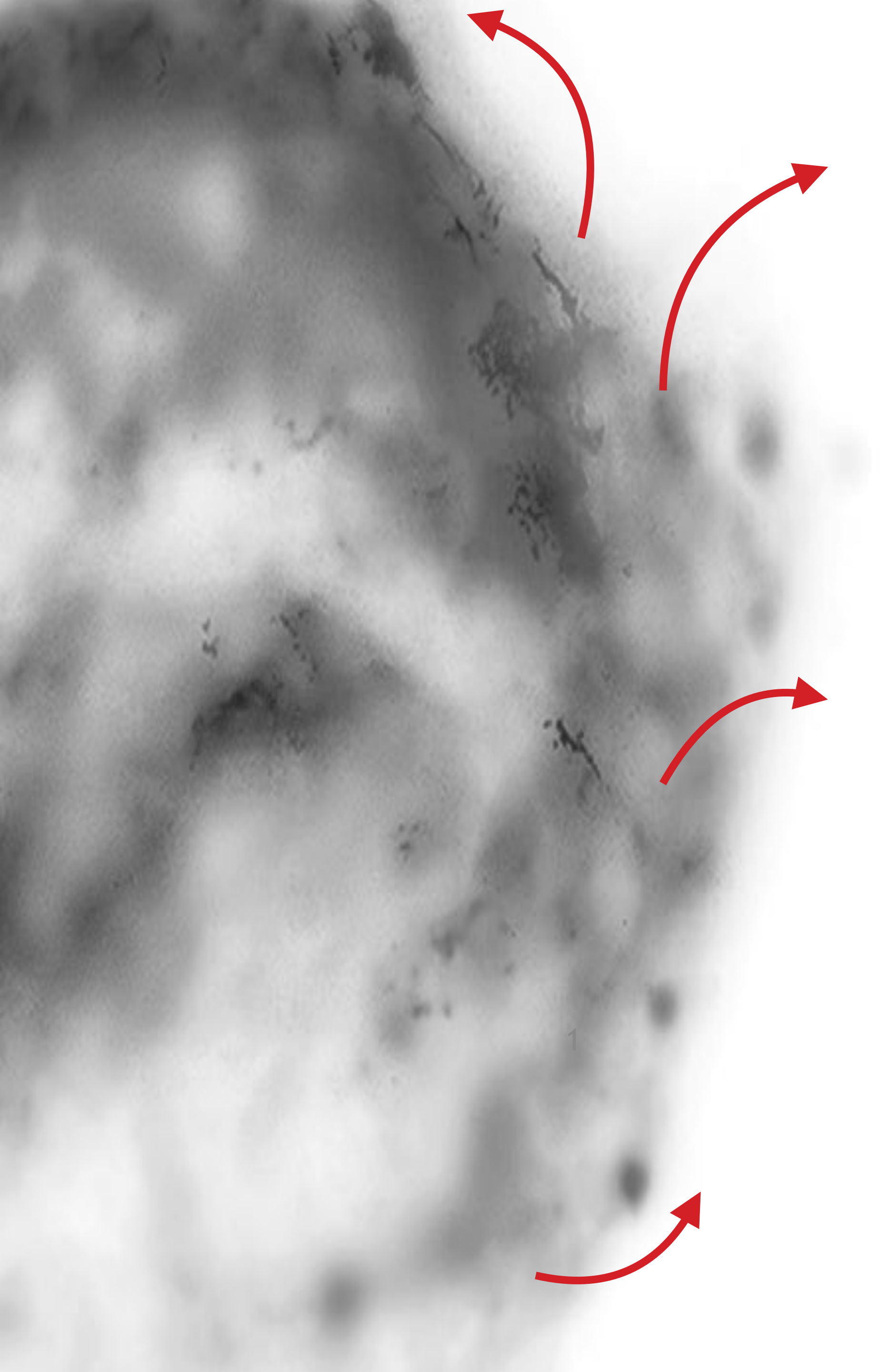


3D Modelling of Galactic Sources

Overview, Status & Future

Sabrina Einecke, Gavin Rowell ++

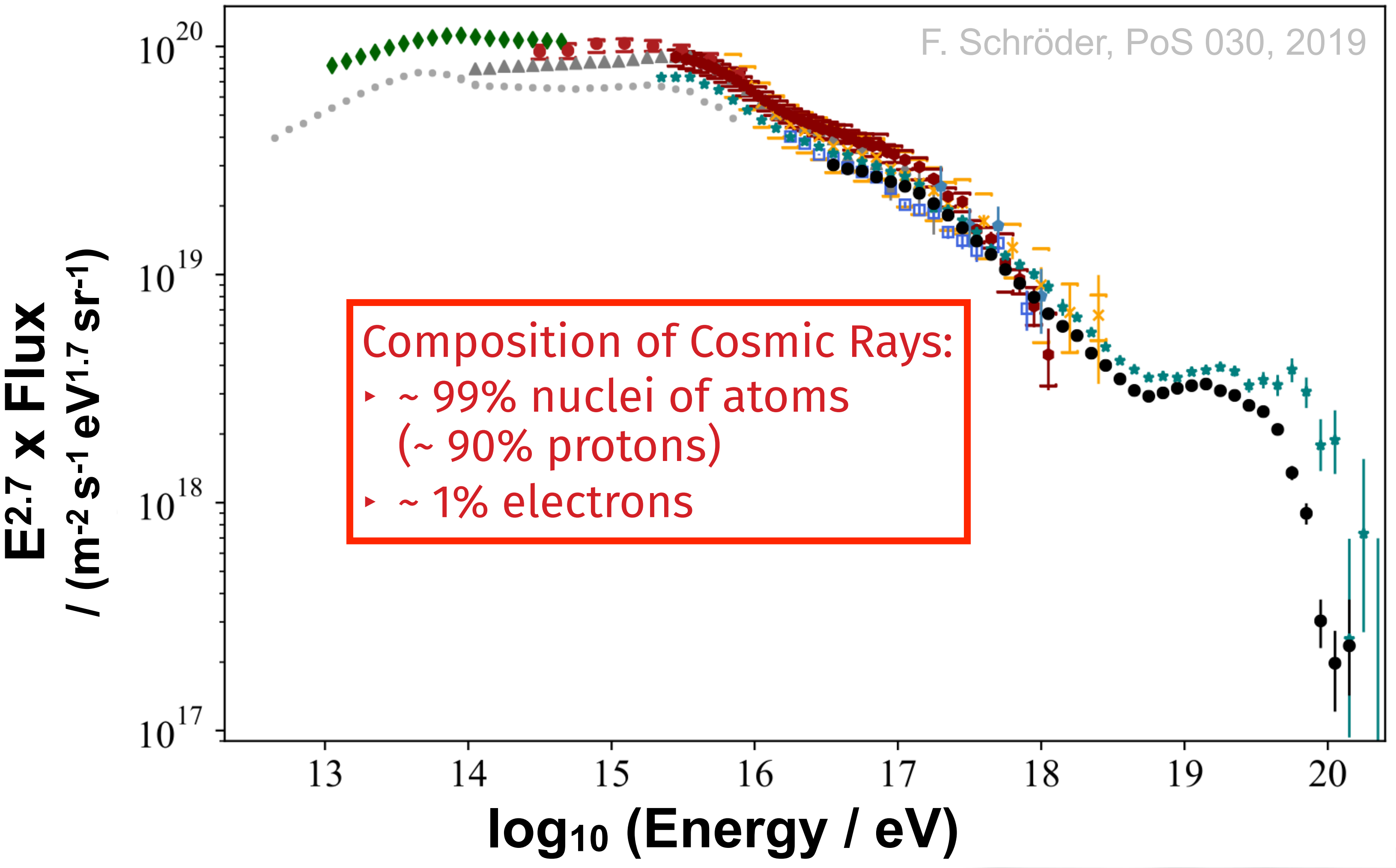
THE UNIVERSITY of ADELAIDE

CTAO-Oz Meeting
Sydney, Australia
November 13th, 2024

GROUP FOR ASTROPARTICLE PHYSICS

Motivation

Origin of Cosmic Rays



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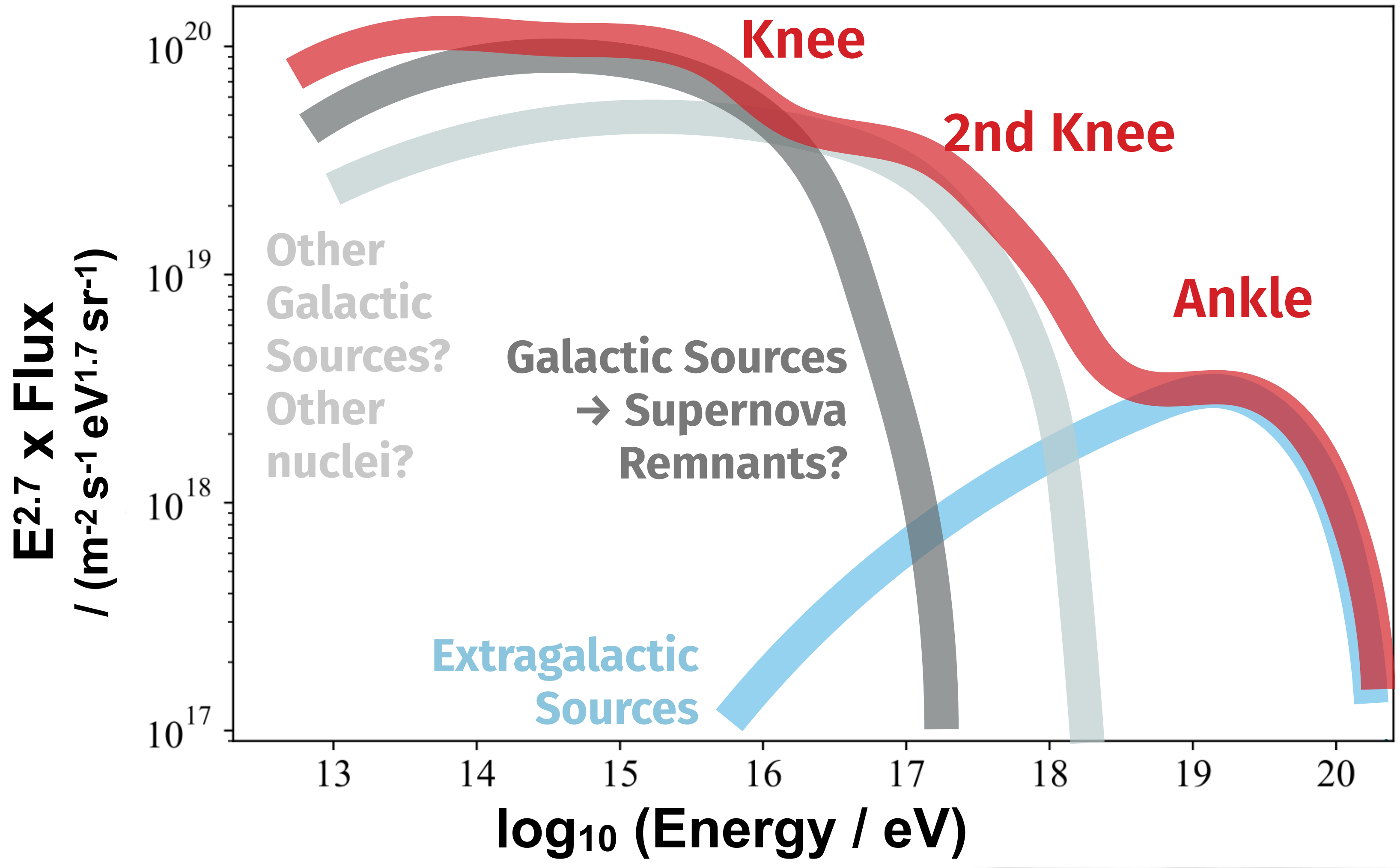
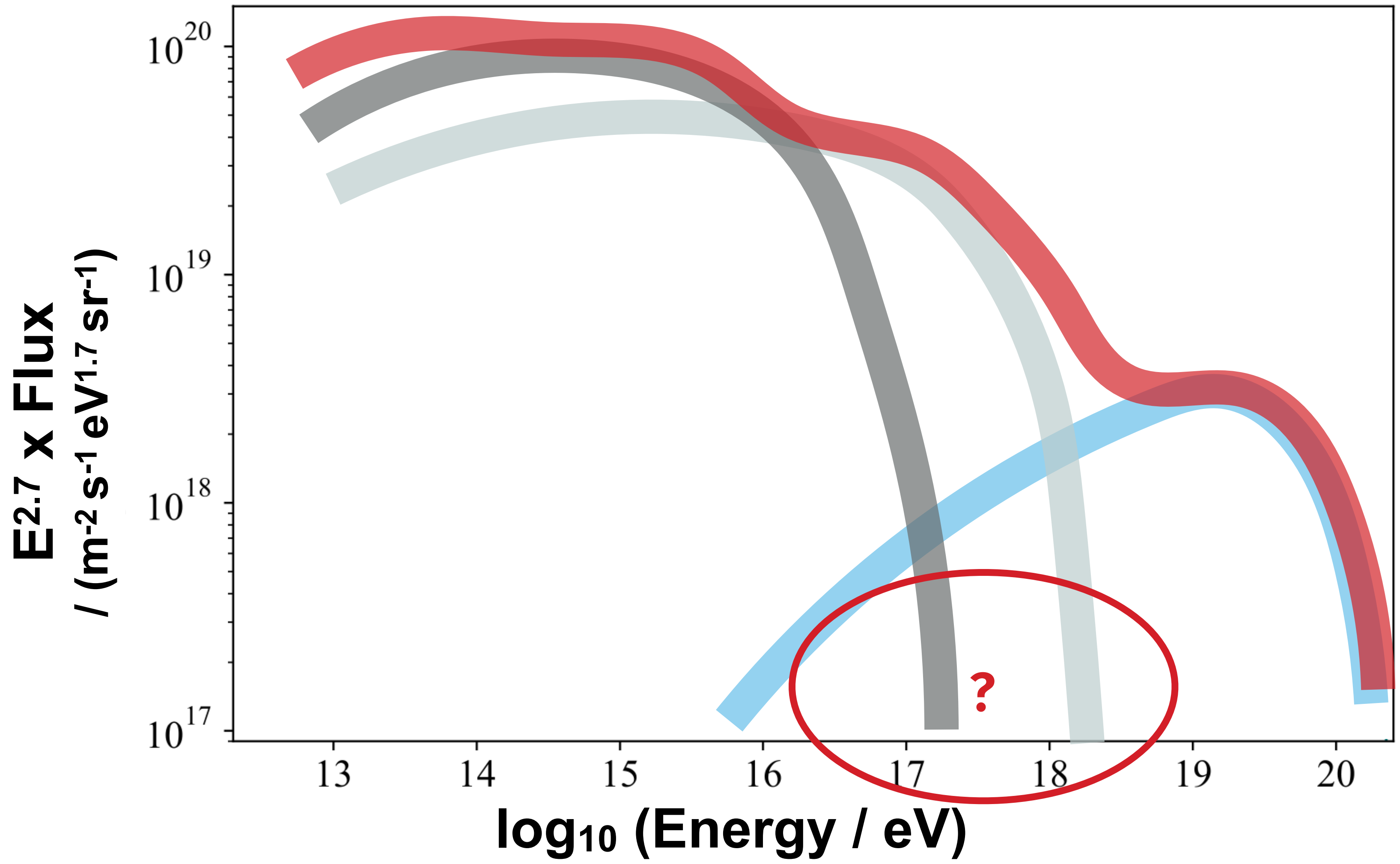
Origin of Cosmic Rays



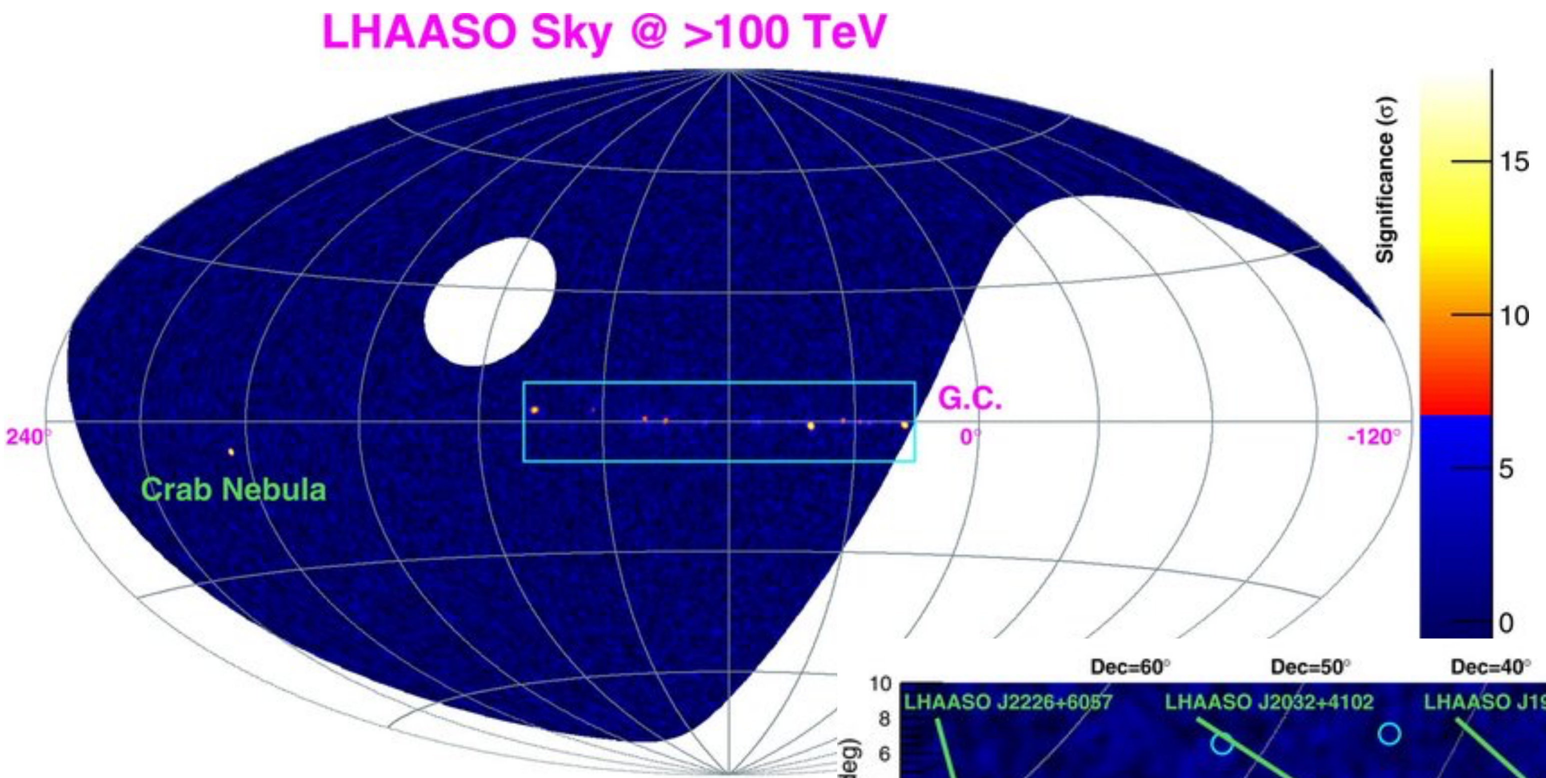
Motivation

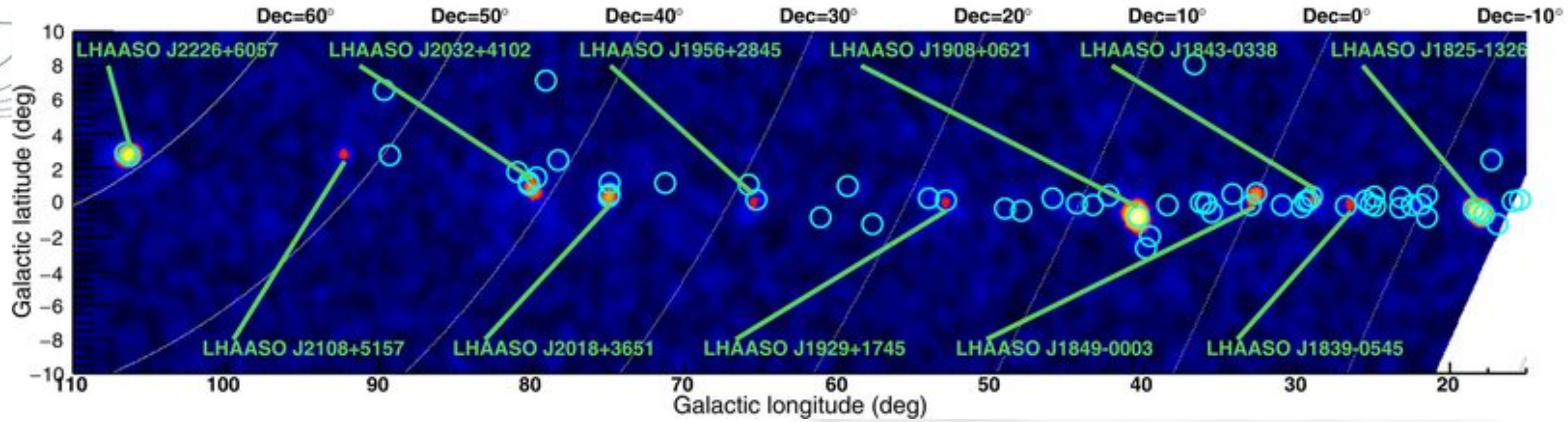
PeVatrons: What objects are behind the most energetic cosmic rays in our Galaxy?



Motivation

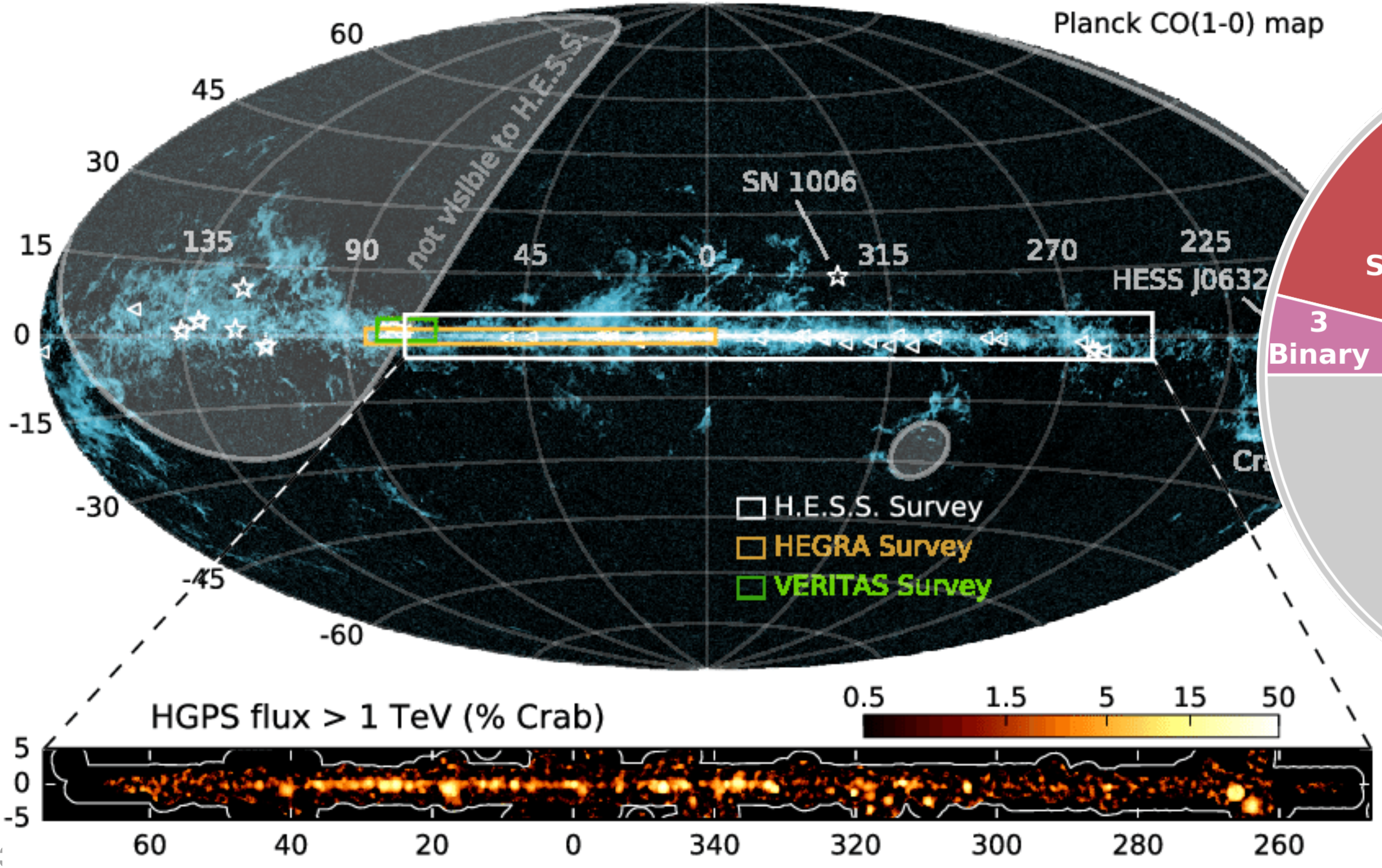
LHAASO Observations: What objects are behind the UHE gamma-ray sources?

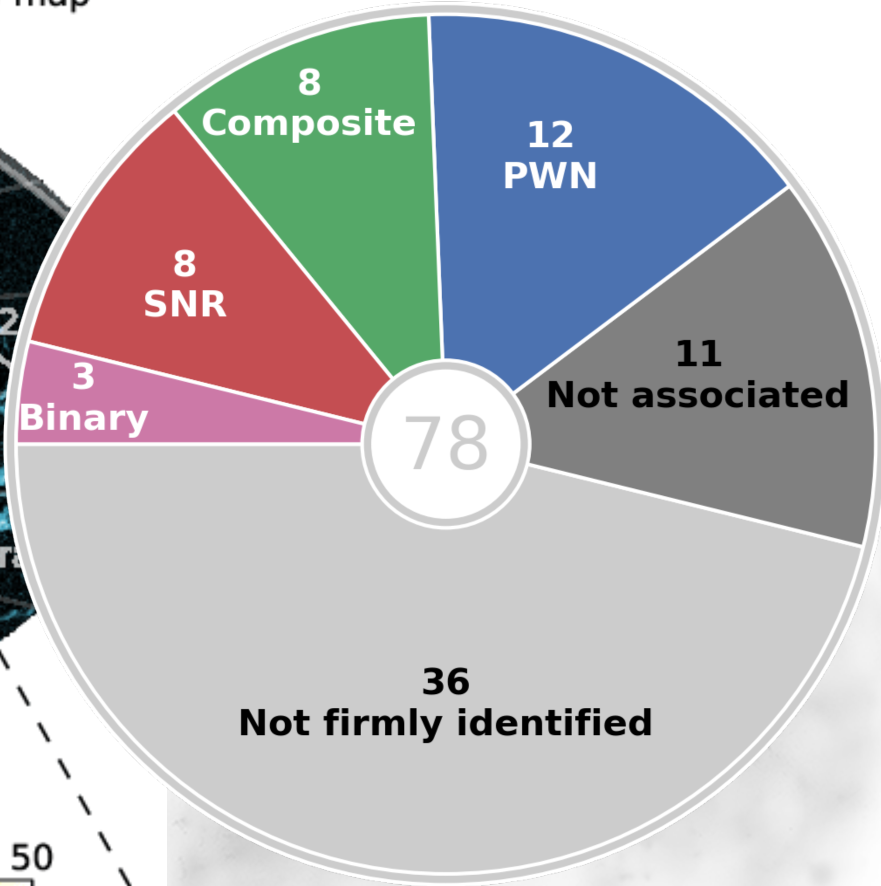




Motivation

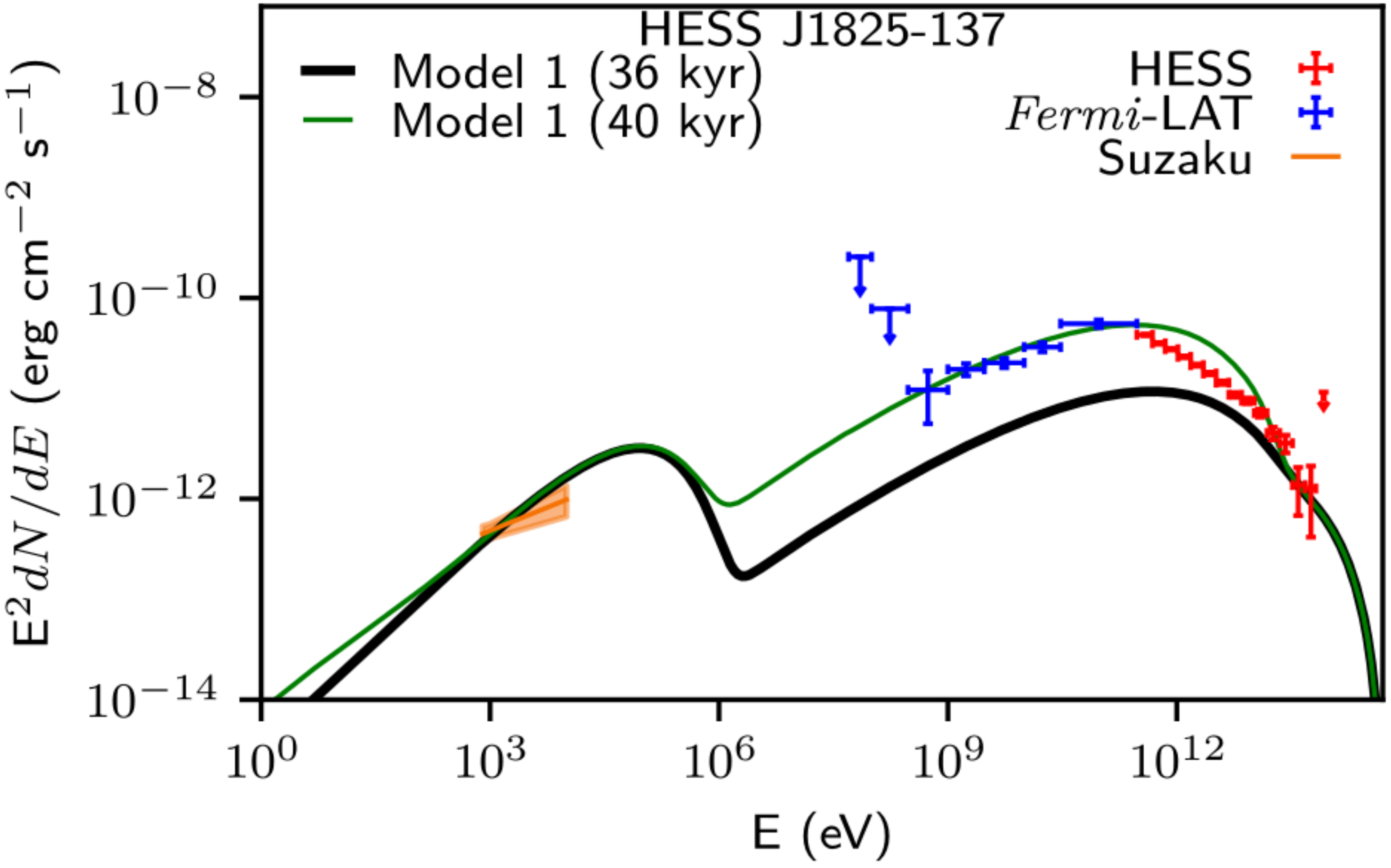
HESS Galactic Plane Survey: What objects are behind the unassociated gamma-ray sources?





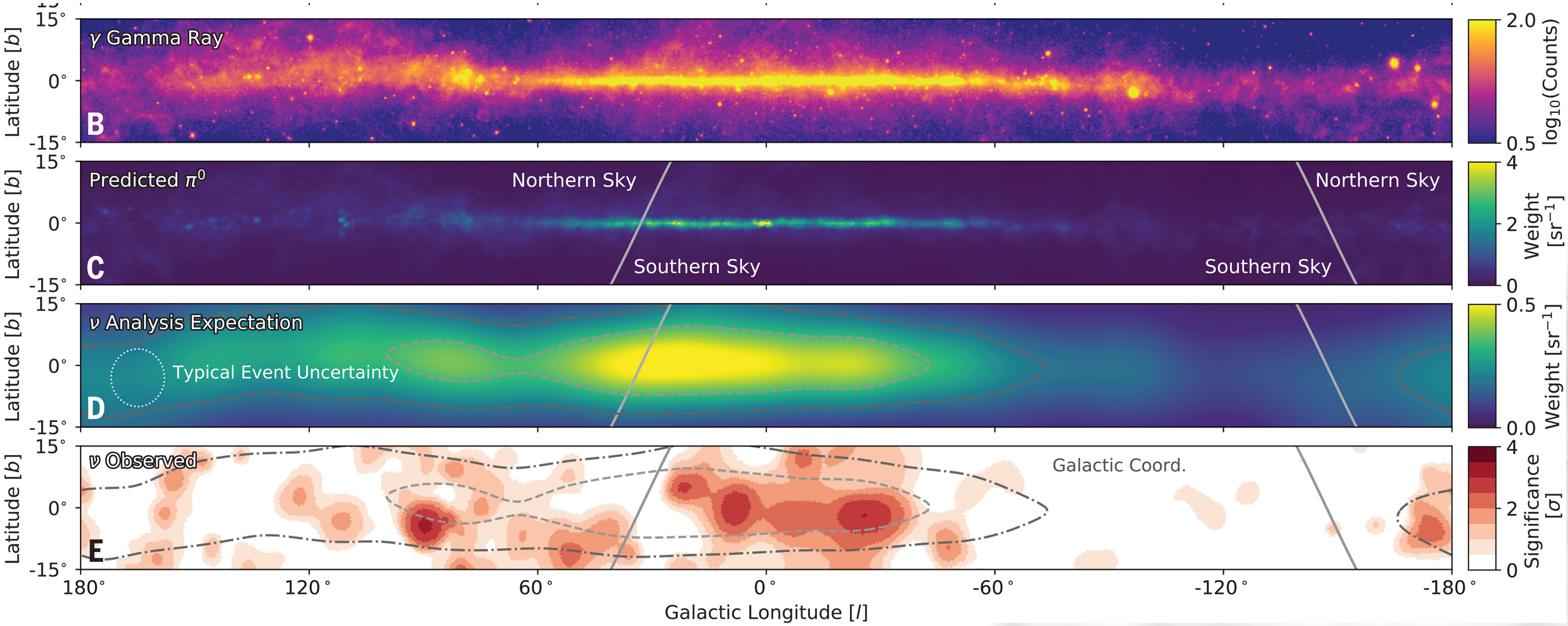
Motivation

Individual Galactic sources:
What are the acceleration and emission processes? What are the characteristics of the source?



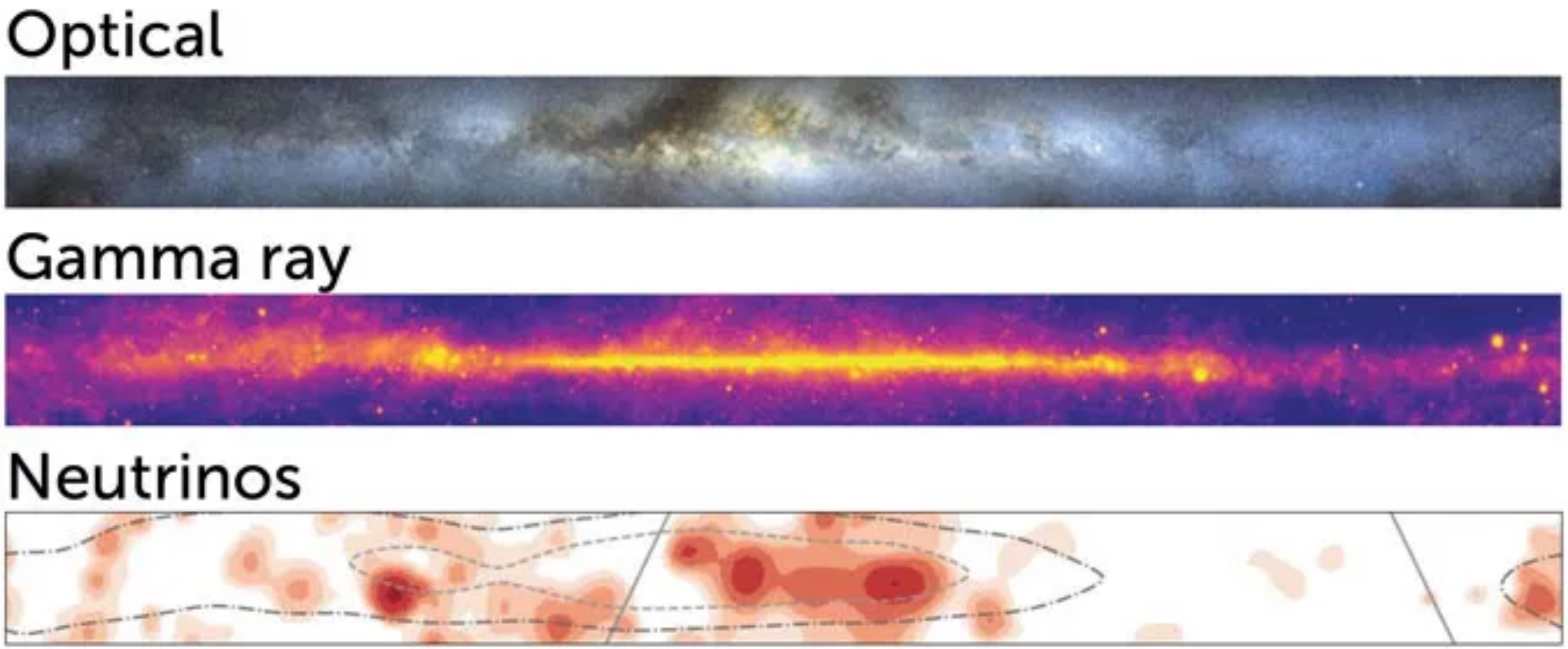
Motivation

How many gamma rays are produced in hadronic interactions, and how many in leptonic ones?

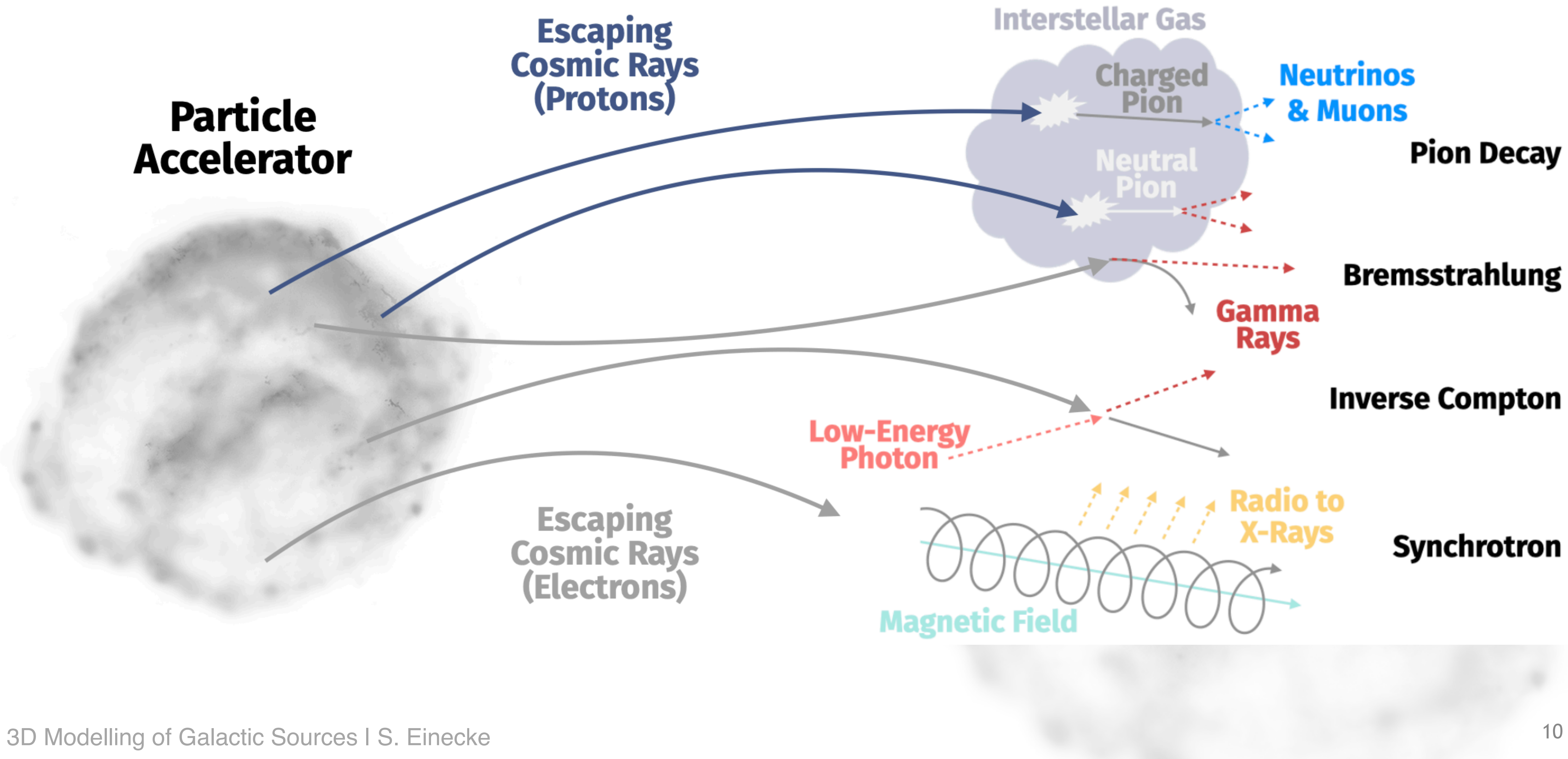


Motivation

What objects are responsible for the Galactic neutrino emission?



Cosmic Rays, Gamma Rays and Neutrinos



Cosmic-Ray Transport

$$\frac{\partial f}{\partial t} = Q + \nabla\left(D_{rr}\nabla f\right) - \frac{\partial}{\partial p}\left(\dot{p} f\right)$$

Injection | Spatial Diffusion | Momentum Gain / Loss

$$-\nabla(\mathbf{v}f) + \frac{1}{3}\frac{\partial}{\partial p}\left(p\,(\nabla\mathbf{v})f\right) + \frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{1}{p^2 f}\right)\right) - \frac{1}{\tau_f}f - \frac{1}{\tau_r}f$$

Convection | Adiabatic Momentum Gain / Loss | Diffusive Re-acceleration | Losses by radioactive decay and fragmentation

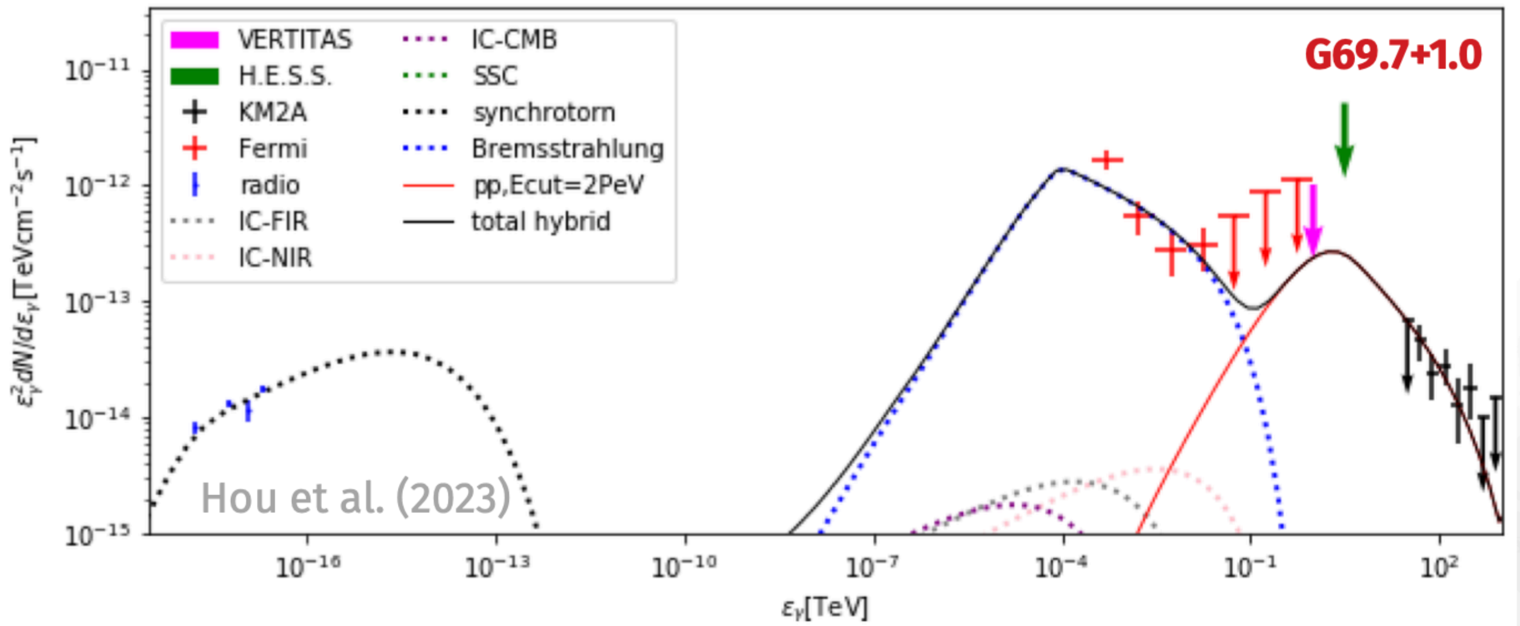
p: particle momentum

$f \equiv f(\vec{r}, p, t)$

$Q \equiv Q(\vec{r}, p, t)$

Typical Approaches

- Power law, broken power law or similar distribution of CRs at adjacent ISM gas cloud
  - Good for comparing different SNRs and ISM gas clouds at different distances from SNR
  - Resulting parameters not directly related to mechanisms and environment
  - Physical motivation: Simplified assumptions about time evolution and particle diffusion can lead to power law Gabici (2009) or broken power law Ohira (2011)

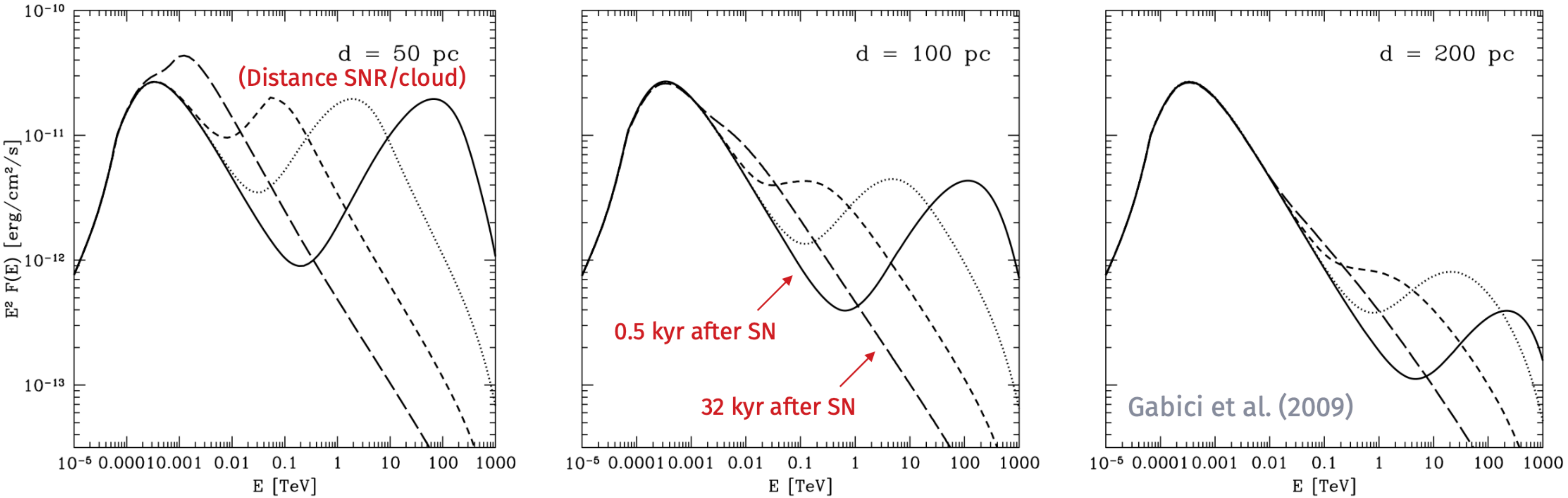


$$\frac{dN_p}{d\varepsilon_p} \propto \varepsilon_p^{-2.6} \exp[-(\varepsilon_p/2\mathrm{PeV})]$$

$$\frac{dN_e}{d\varepsilon_e} \propto \varepsilon_e^{-2.4} \exp[-(\varepsilon_e/0.1\mathrm{TeV})]$$

Typical Approaches

- CR distribution at fixed distance by analytically solving transport equation
  - Immediate conclusions about SNR and environment
  - Requires simple assumptions
    (only spatial diffusion and radiative losses, spherical symmetry, isotropic and homogeneous external fields, ...)
  - Extension of ISM gas cloud (and anisotropic CR distribution over cloud) not taken into account

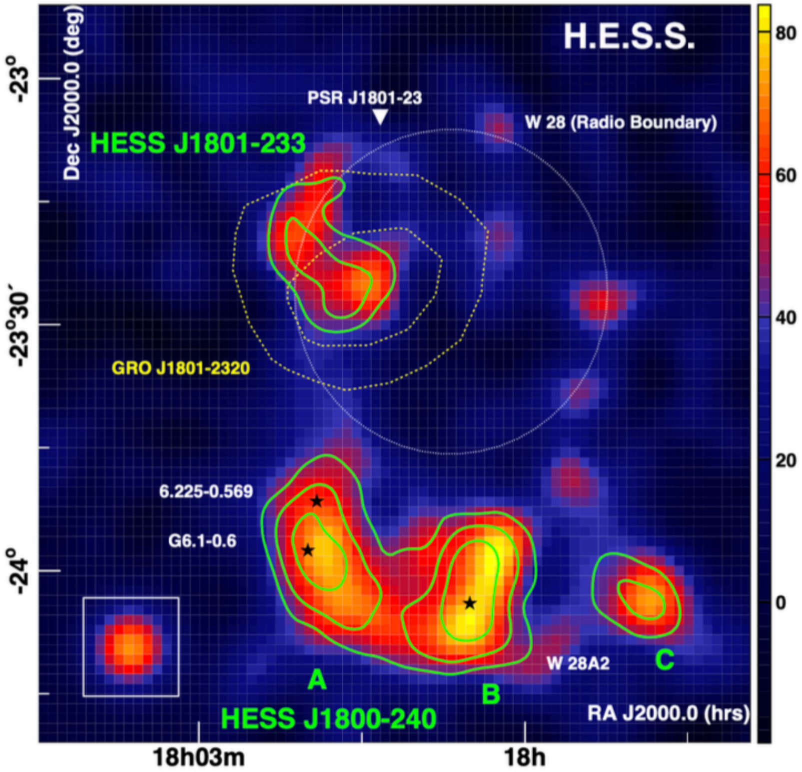


Typical Approaches

- Search for spatial correlation between ISM and gamma-ray observations
  - Good indicator for interaction of CRs and ISM gas
  - Conclusions about mechanisms and environment limited

W28

Aharonian et al. (2008)



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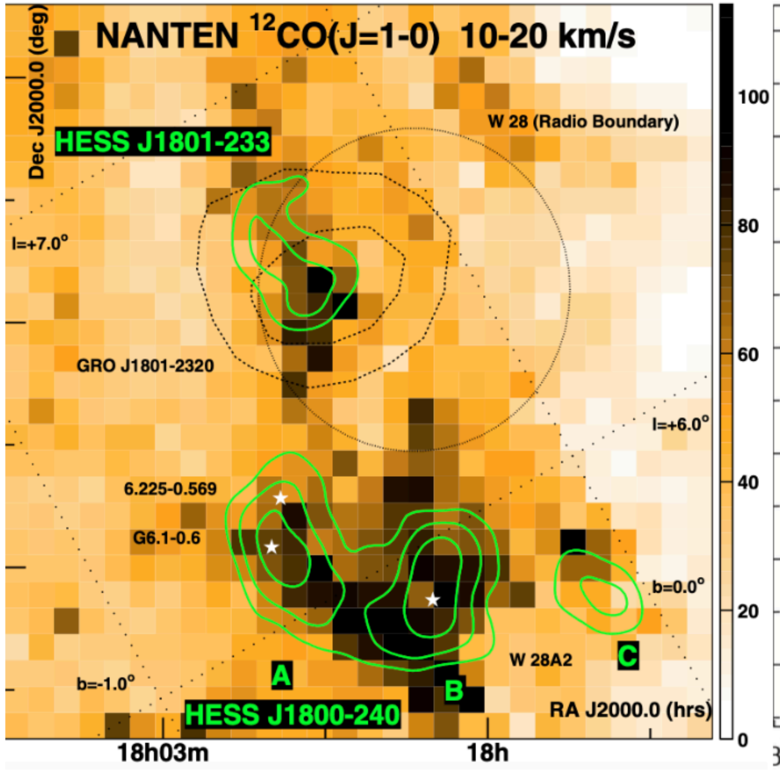
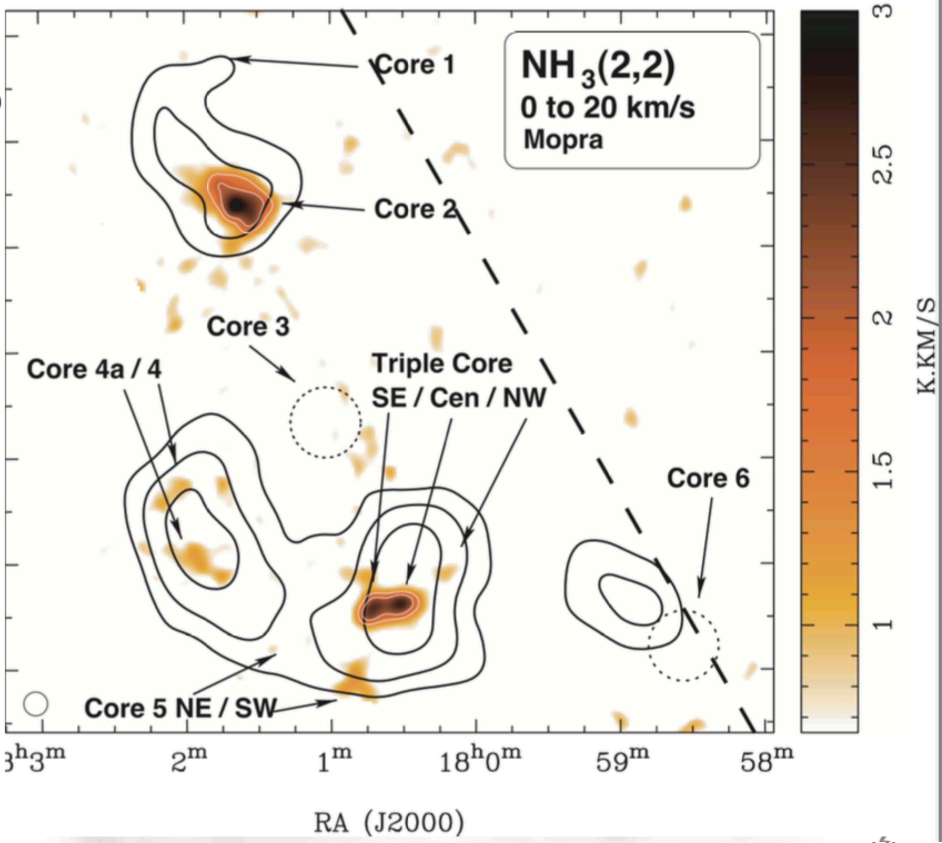


Nicholas et al. (2011)



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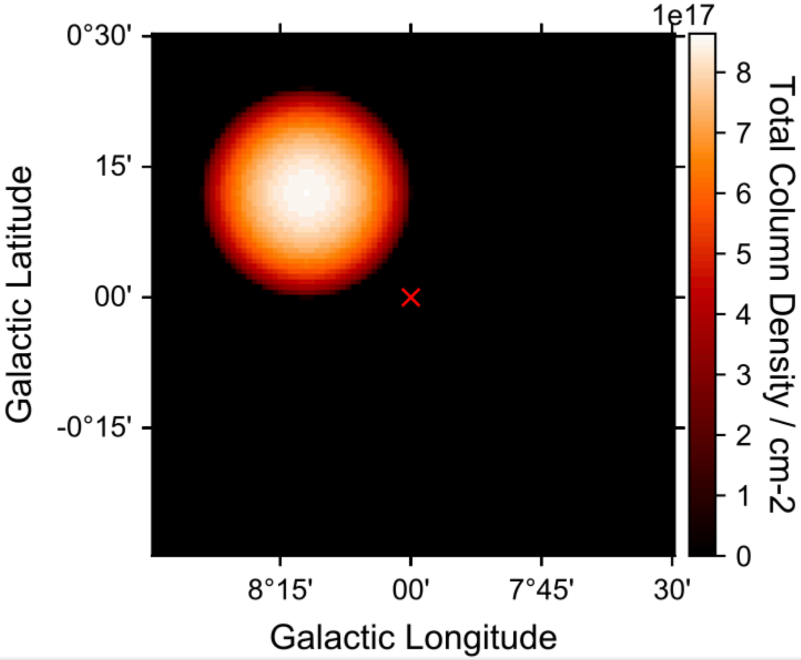
➡ **How can we do better?**

Modelling Energy-Dependent Morphology in 3D

- **Aim:** Reproduce both spectra and maps from observations
- **Approach:** Modelling of cosmic-ray protons and gamma rays for a **3D** spatial grid, determined by resolution of interstellar gas measurements

→ Important, but challenging!

Interstellar Gas
(based on observations)



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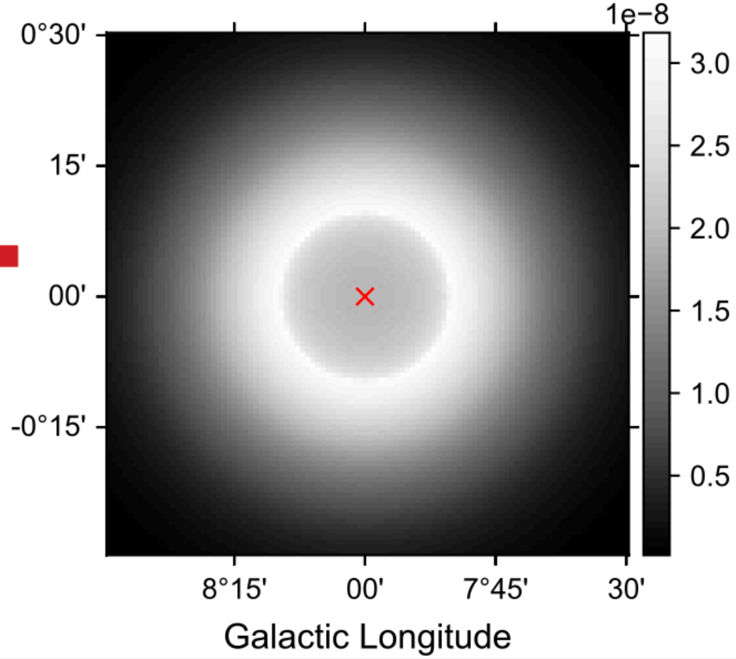
Cosmic Ray Flux
(based on model)



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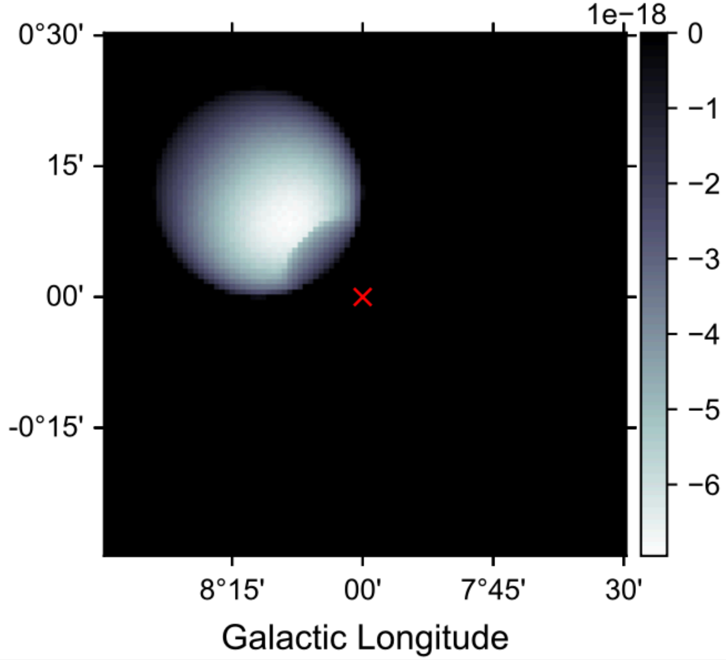
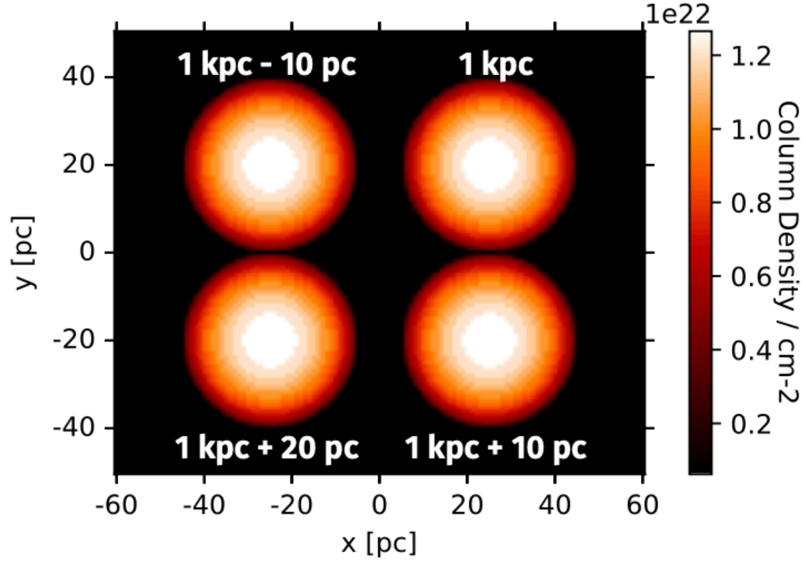
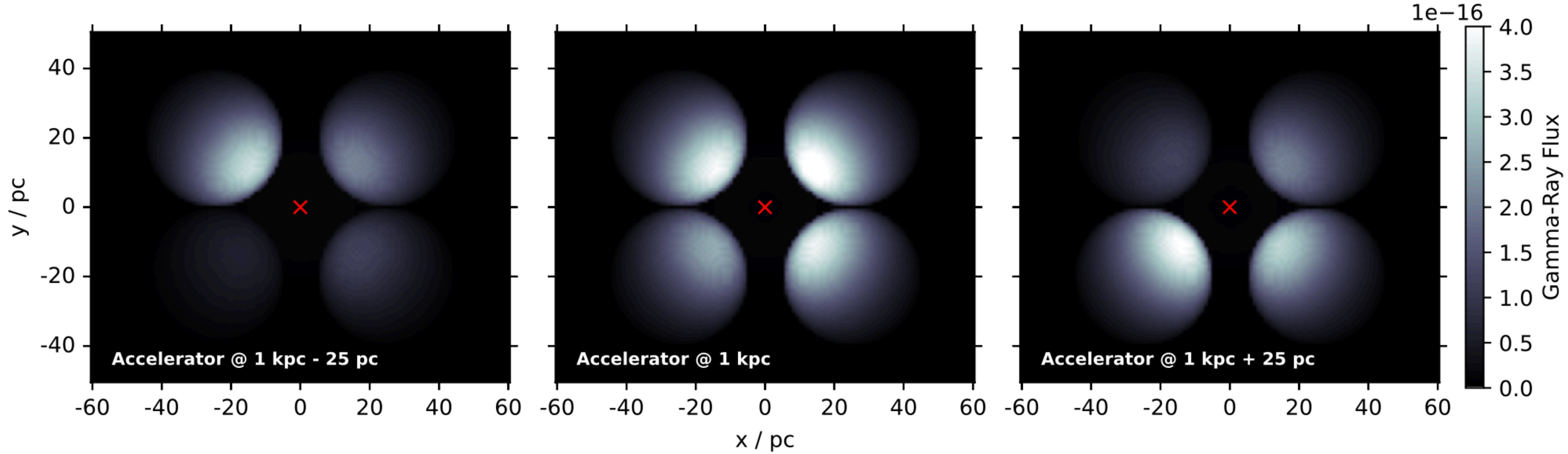
Gamma Flux



Importance of 3D Modelling



Example:
Gas clouds with different distances to Earth



Measurement: Interstellar Medium Gas Distribution

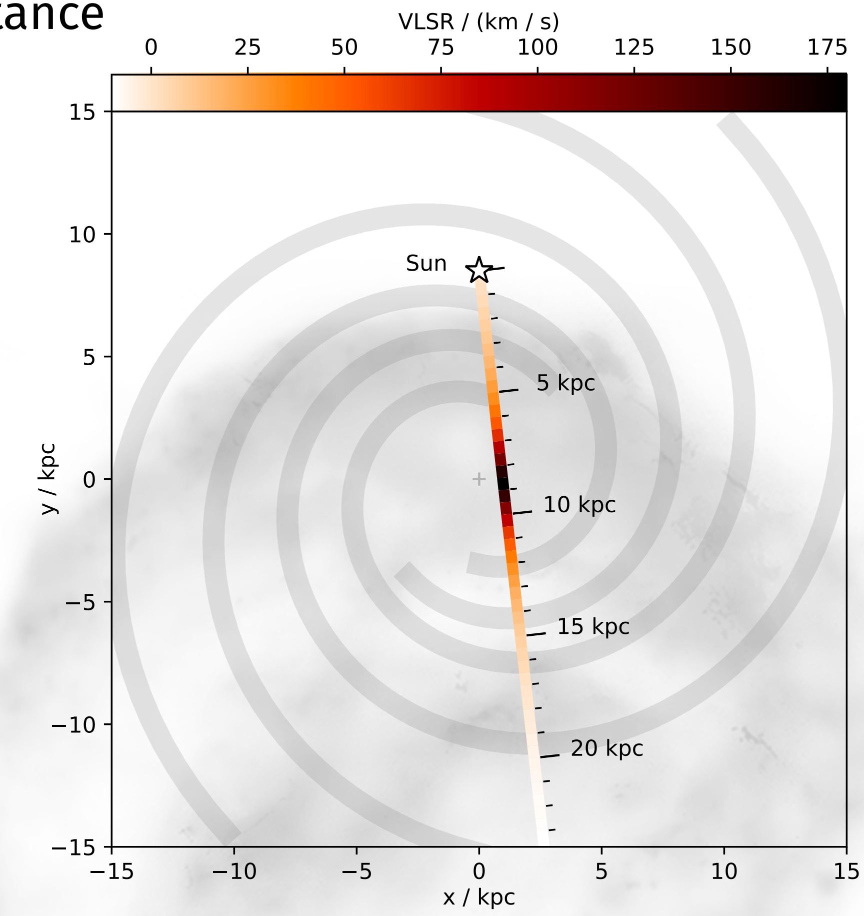
Challenges

- 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 motions of the gas

  … it produces rather large uncertainties (for our application)



Optimisation Approach

- Location of individual clouds
- Selection of individual clouds

➡ Need to know which voxel (=3D pixel) belongs to which cloud

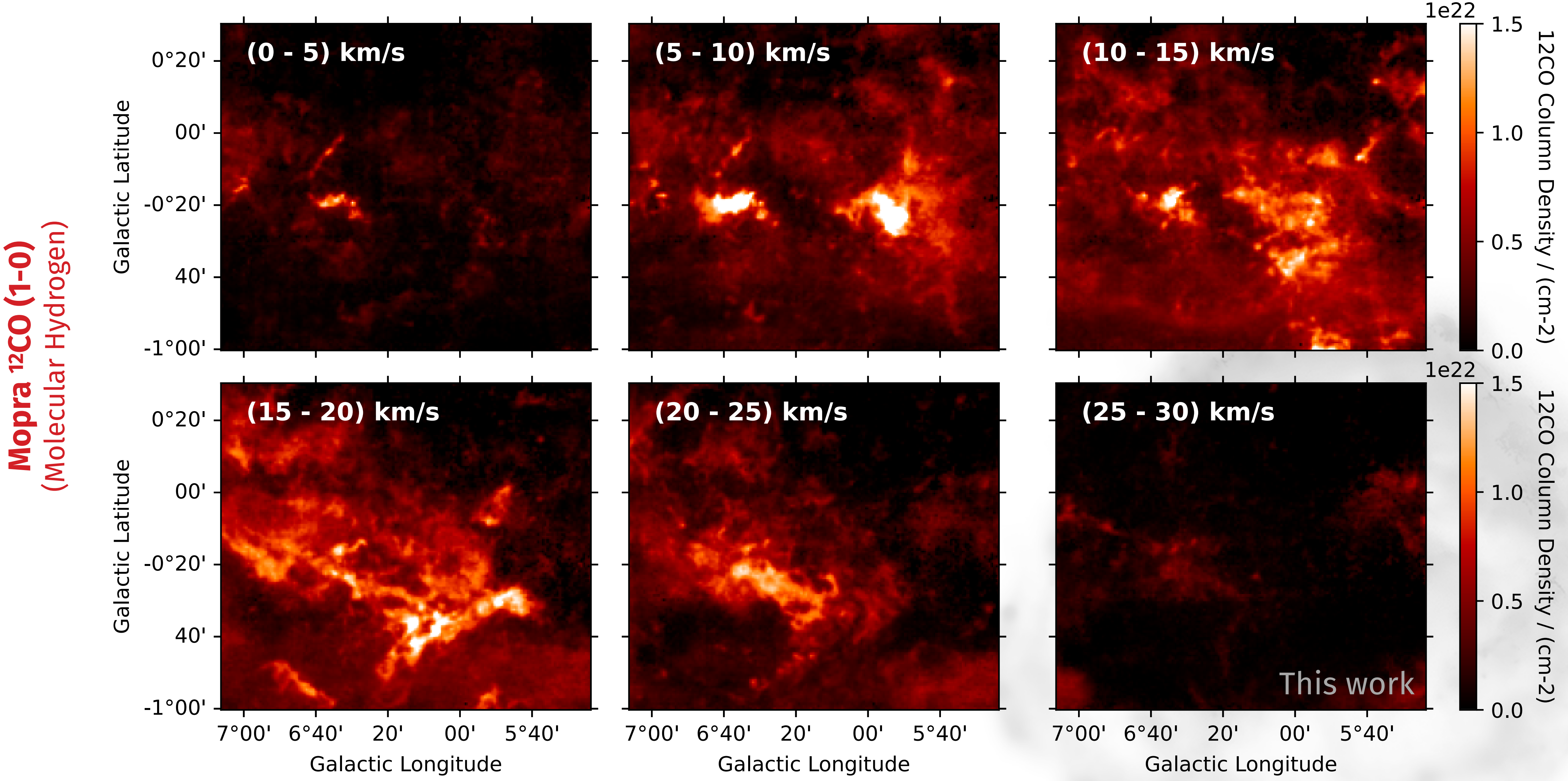
Modelling: Interstellar Medium Gas Distribution

Identification of Individual Clouds

- Gaussian decomposition with GaussPy+ (Riener et al., A&A 628 (2019) A78), including spatial re-fitting procedure
- Creation of new PPV cube:
  Place integrated Gaussian component at its derived velocity
- Hierarchical clustering with astrodendro:
  Determines label for each component, specifying which molecular cloud it belongs to
- Selection of clouds to be included in final cube
- Selection of each cloud's location in final cube

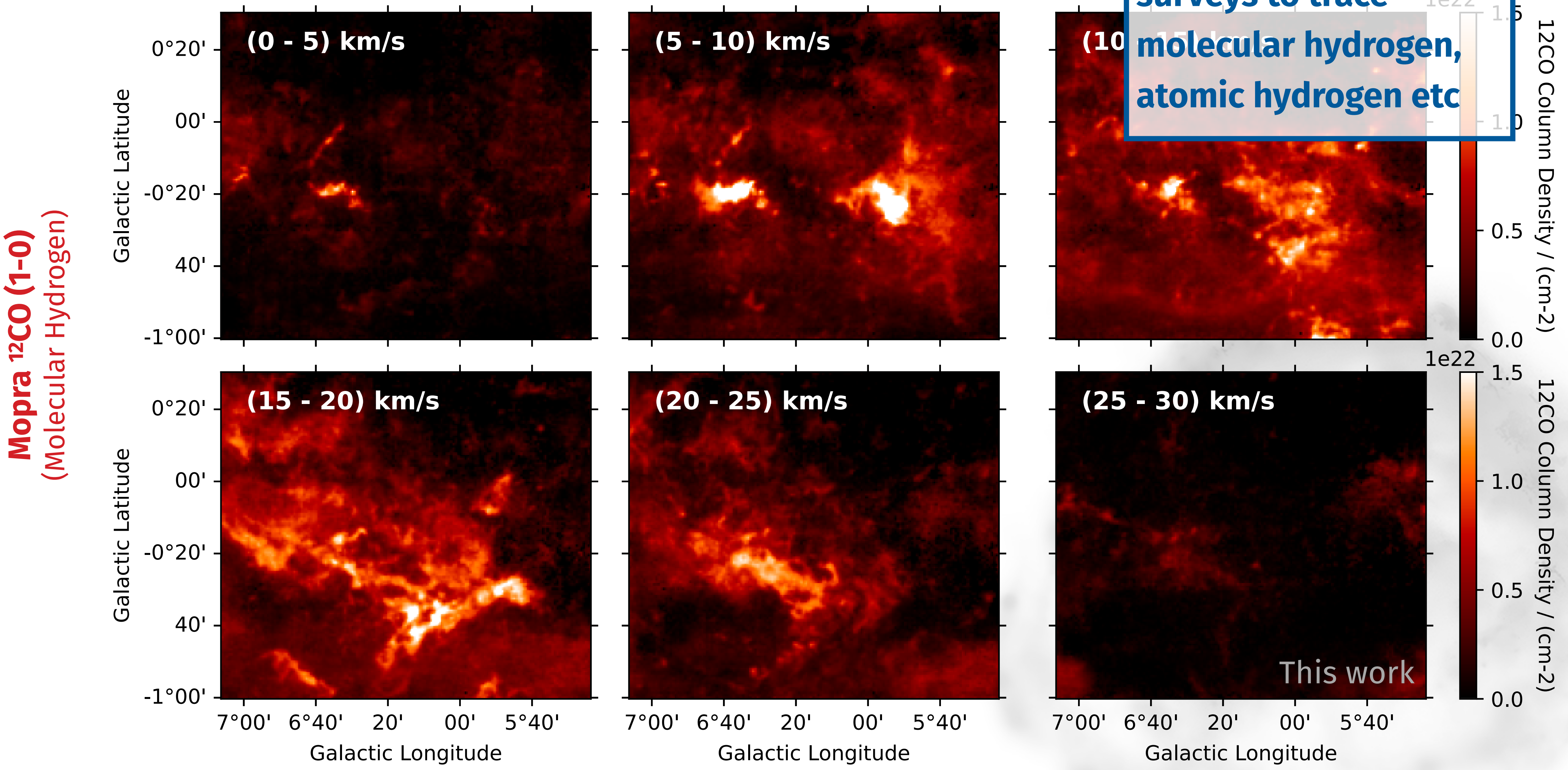
➠ PPP cube with any user-specified distance axis
➠ Capable of separating overlapping clouds
➠ Capable of moving clouds along distance axis separately

Measurement: Interstellar Medium Gas Distribution

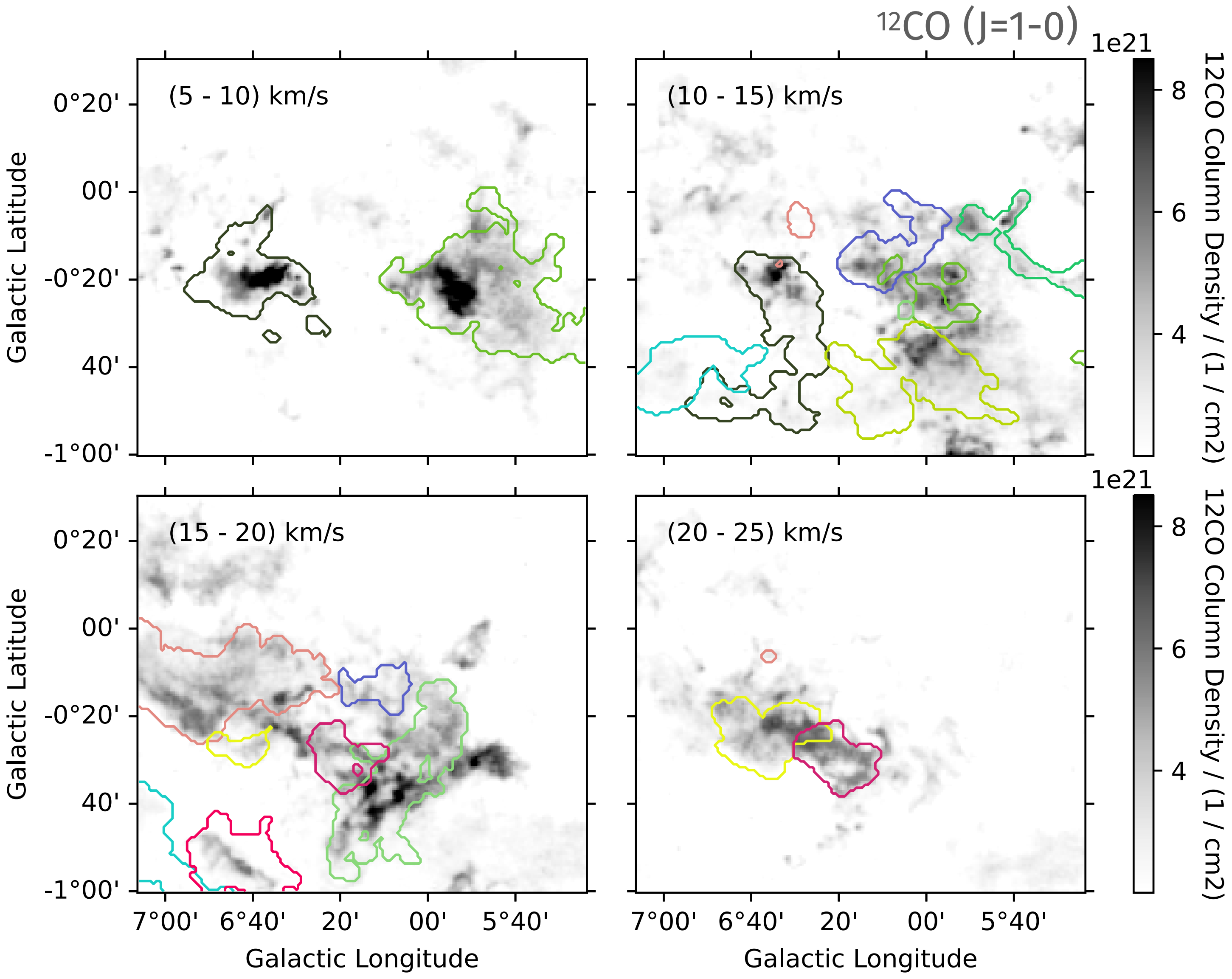


Measurement: Interstellar Medium Gas Distribution

Synergies with radio surveys to trace molecular hydrogen, atomic hydrogen etc



Modelling: Interstellar Medium Gas Distribution



GLON / deg	GLAT / deg	Velocity / (km/s)	Components	Mass / (1e^3 $M_\odot$)	Y/N
5.8 ± 0.4	−0.4 ± 0.3	8.7 ± 2.0	1510	19.9	Y
6.6 ± 0.3	−0.4 ± 0.5	10.2 ± 5.3	1239	16.3	Y
6.0 ± 0.3	−0.7 ± 0.2	11.4 ± 1.4	794	8.7	Y
5.7 ± 0.3	−0.2 ± 0.2	12.6 ± 1.0	234	2.8	Y
6.1 ± 0.2	−0.2 ± 0.2	14.3 ± 2.3	434	6.7	Y
7.0 ± 0.2	−0.7 ± 0.3	14.4 ± 4.1	641	7.3	N
6.1 ± 0.3	−0.6 ± 0.4	17.9 ± 2.0	946	13.1	Y
6.8 ± 0.4	−0.2 ± 0.2	18.1 ± 1.9	1297	20.1	N
6.7 ± 0.2	−0.9 ± 0.1	18.6 ± 0.8	537	3.5	N
6.3 ± 0.2	−0.5 ± 0.1	20.5 ± 1.1	319	5.6	Y
6.6 ± 0.2	−0.4 ± 0.1	21.8 ± 3.0	577	6.4	Y

Fig.: Outermost extension of each cluster in corresponding velocity range (Distr. and clusters are 3D)

Modelling: Interstellar Medium Gas Distribution

PhD student @ UofA: Imogen Barnsley, *Clustering the ISM*

THE UNIVERSITY of ADELAIDE

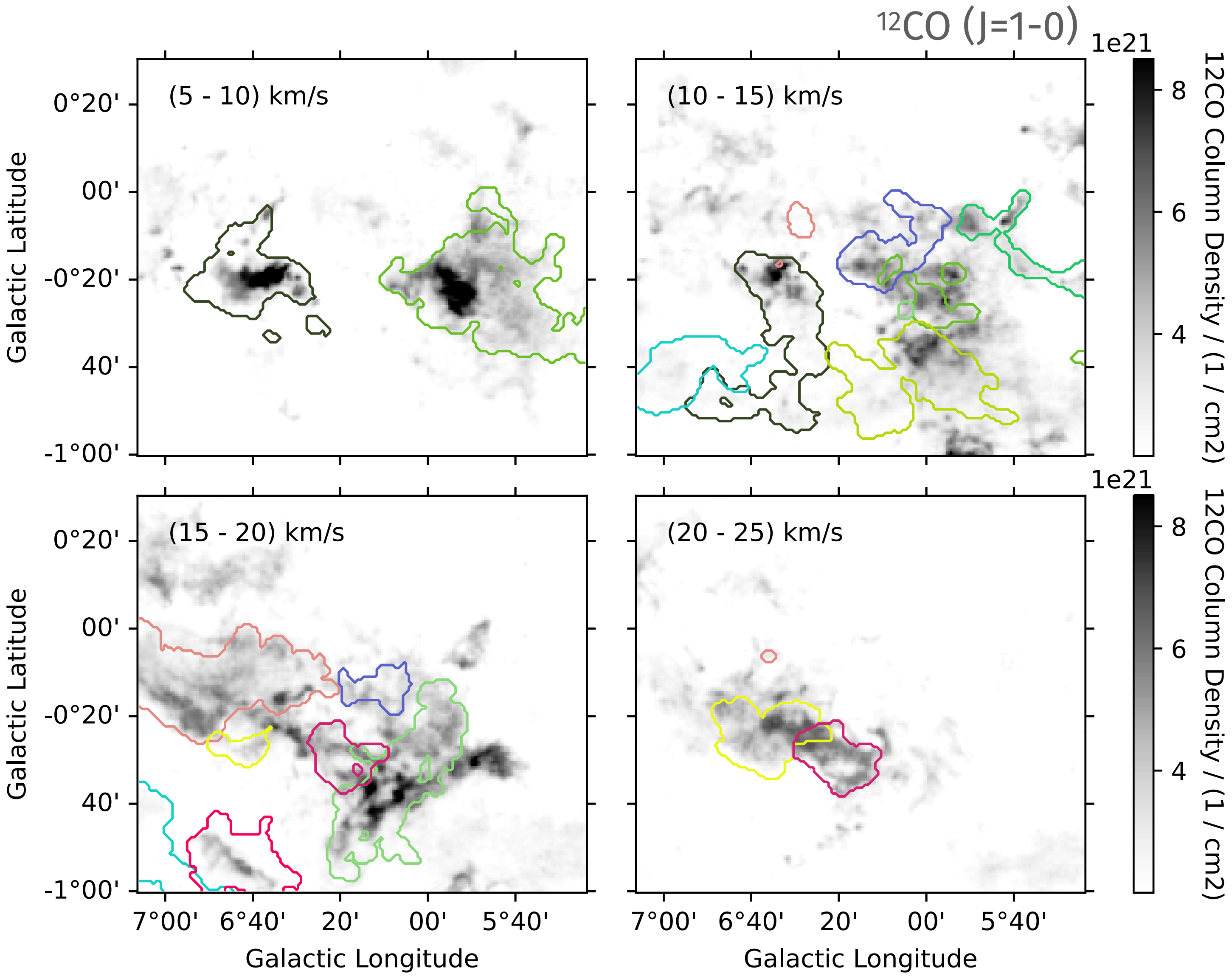


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Fig.: Outermost extension of each cluster in corresponding velocity range (Distr. and clusters are 3D)

multiverse

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

Overview: Modelling Software

DONE
ONGOING
PLANNED

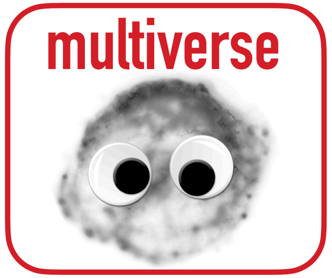
Solution to transport eq.
- Analytical
- Numerical

CR species
- Protons
- Electrons

Gal. source types
- SNRs
- PWNe

Production of messengers
- Gamma rays
- Neutrinos

Transport
- Diffusion
- Energy loss/gain
- Advection



Environment & interactions
- Homogeneous
- Isotropic
- Inhomogeneous
- Anisotropic

Background models
- Diffuse emission

Effects on messengers
- Absorption of gamma rays due to IGMF & CMB
- Neutrino oscillation

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PhD student @ UofA: Robert König, *RX J1713*

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multiverse

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PhD student @ UofA: Teddy McKennall

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Postdoc @ Stanford / former UofA PhD: Peter Marinos, *GALPROP* *(see talk later)*

multiverse

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PhD student @ UofA: Ryan Burley
Gamma rays and neutrinos from SNR and molecular cloud interactions

Production of messengers
- Gamma rays
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multiverse

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Synergies with radio surveys to trace ISM, polarisation etc

Background models
- Diffuse emission

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Overview: Modelling Software

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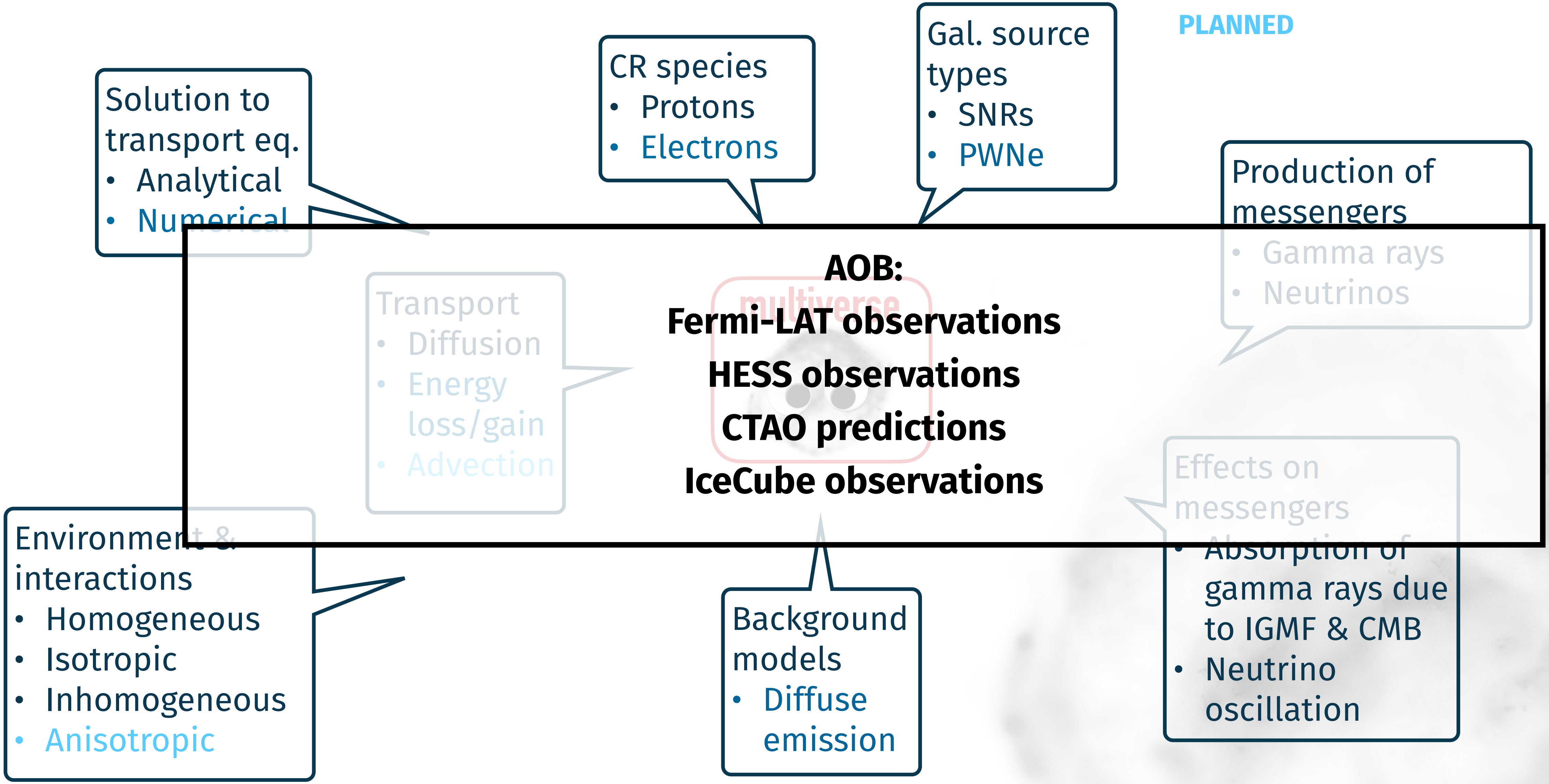


AOB:
Fermi-LAT observations
HESS observations
CTAO predictions
IceCube observations

Specifics for Different Types of Objects

Above certain energy, cosmic-ray protons escape at time

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

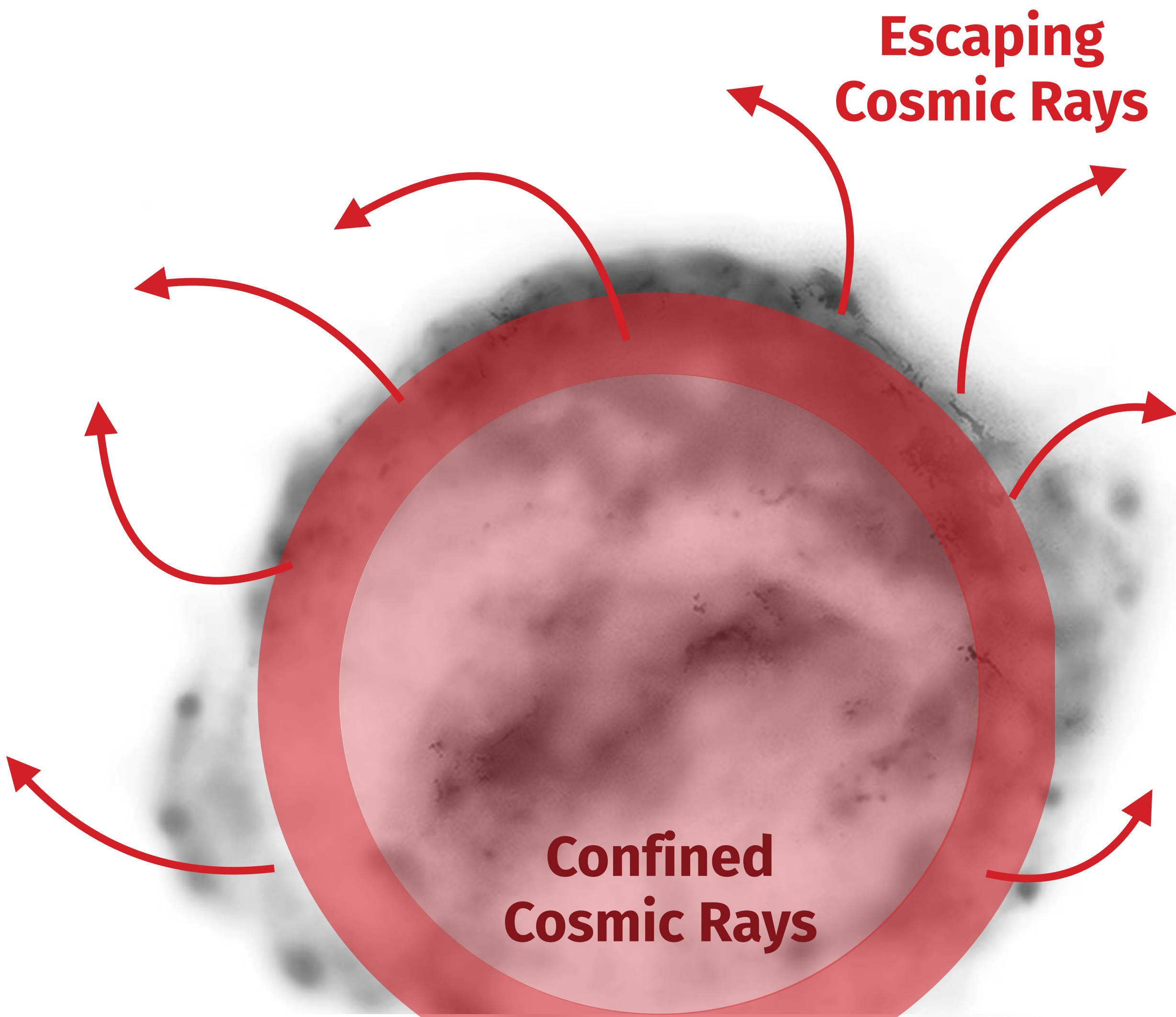
from radius

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

and diffuse a length of

$$l_{\rm dif} = \sqrt{4\,D\,(t - t_{\rm esc})}\ .$$

Remaining protons are confined inside SNR.



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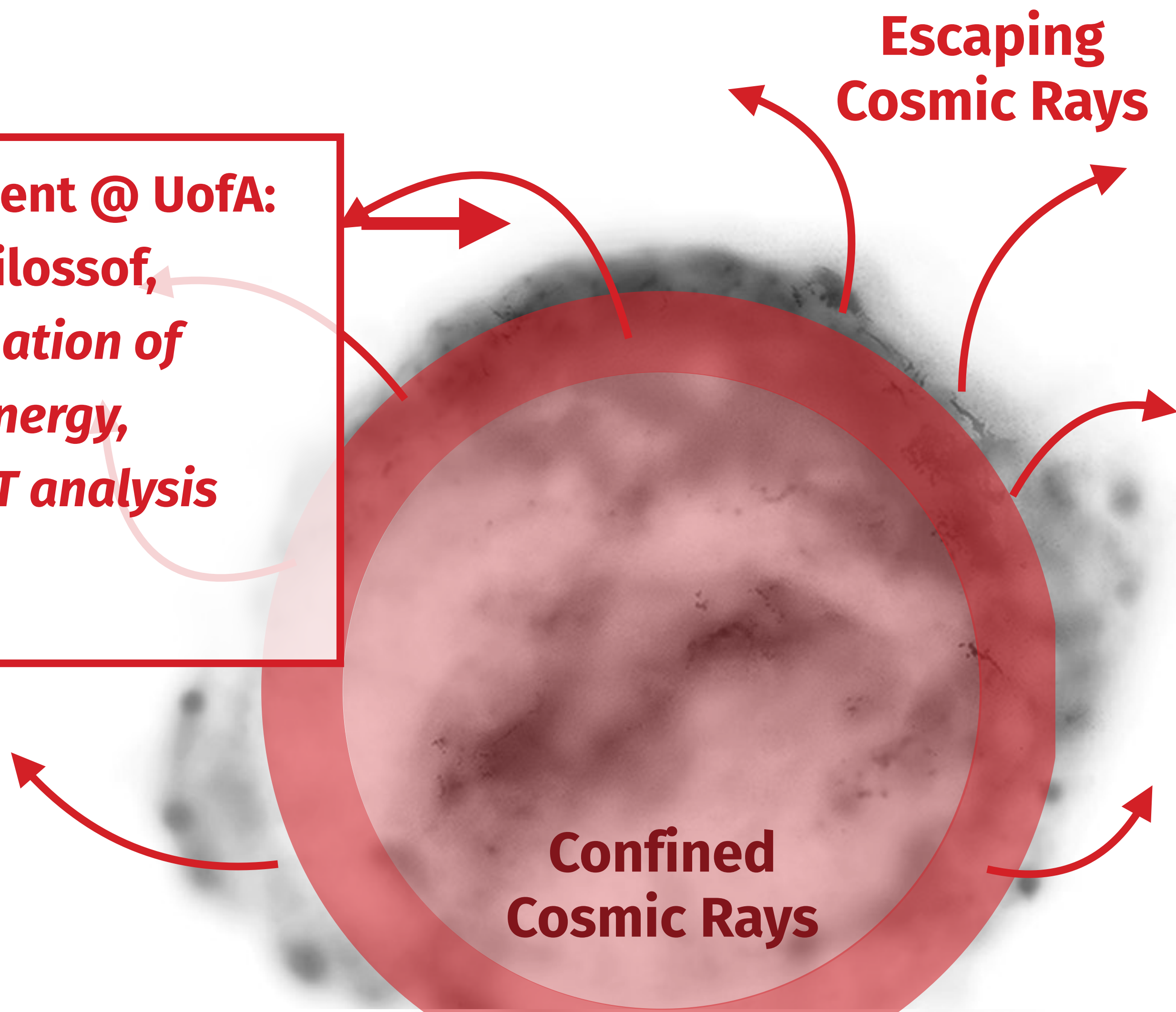
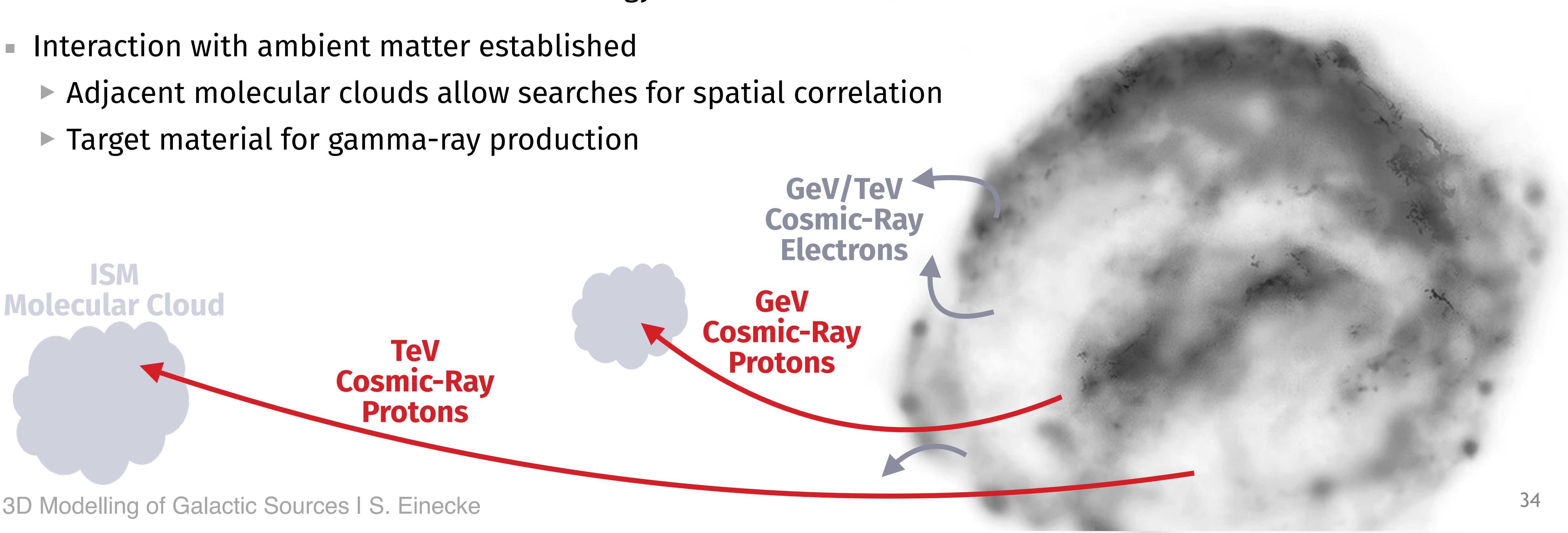
PhD student @ UofA:
Jemma Pilossof,
Determination of escape energy,
Fermi-LAT analysis



The Supernova Remnant W28

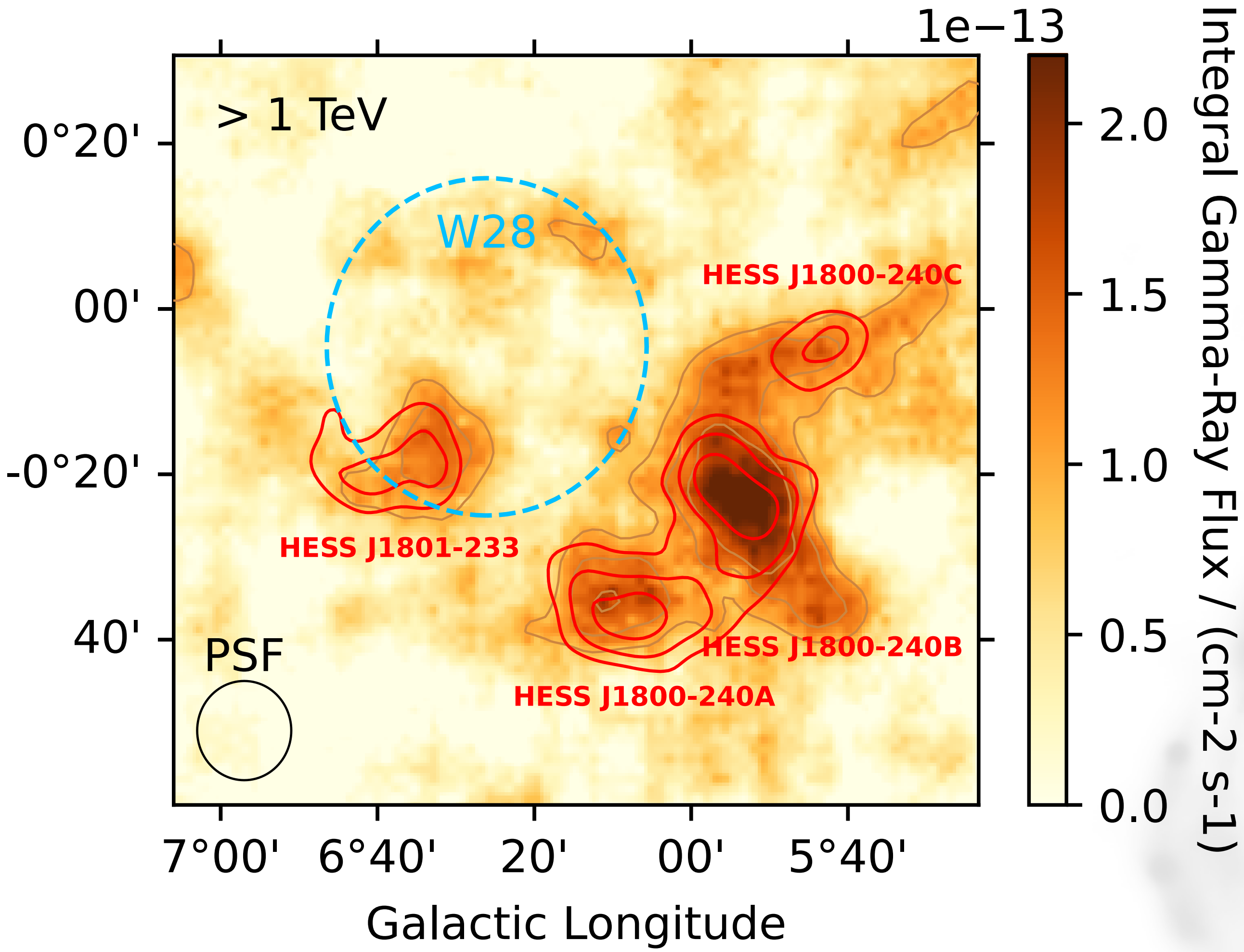
- Mixed-morphology SNR in relatively close distance to Earth (1.8 - 3.3 kpc)
- Old age of 35 - 150 kyrs
  - Most cosmic rays (CRs) have escaped into Interstellar Medium (ISM)
  - CR protons escaped during early phase have diffused substantial distance
  - CR electrons have lost most of their energy
- Interaction with ambient matter established
  - Adjacent molecular clouds allow searches for spatial correlation
  - Target material for gamma-ray production



Gamma-Ray Observations

Detection of GeV and TeV gamma-ray emission with distinct energy-dependent morphologies

HESS



- Detection of 4 HESS sources: HESS J1801-233, HESS J1800-240A, B, C
- Spatial match of TeV gamma rays with molecular clouds
- Gamma-ray emission beyond 10pc from shell

⇒ Most likely hadronic CRs accelerated in W28

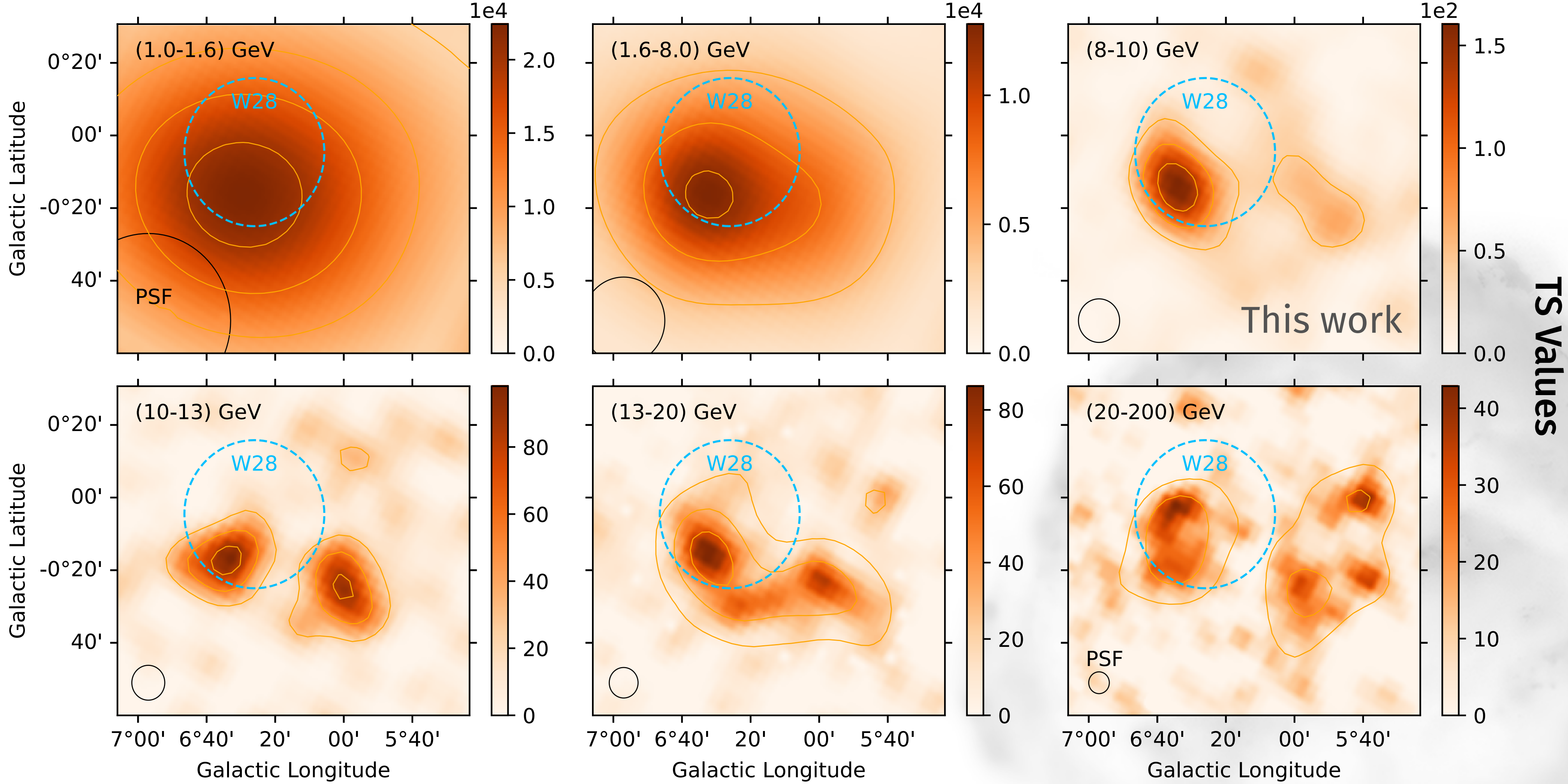
HESS Collab., A&A 612 (2018) A1
Aharonian et al., A&A 481 (2010) 401

Gamma-Ray Observations

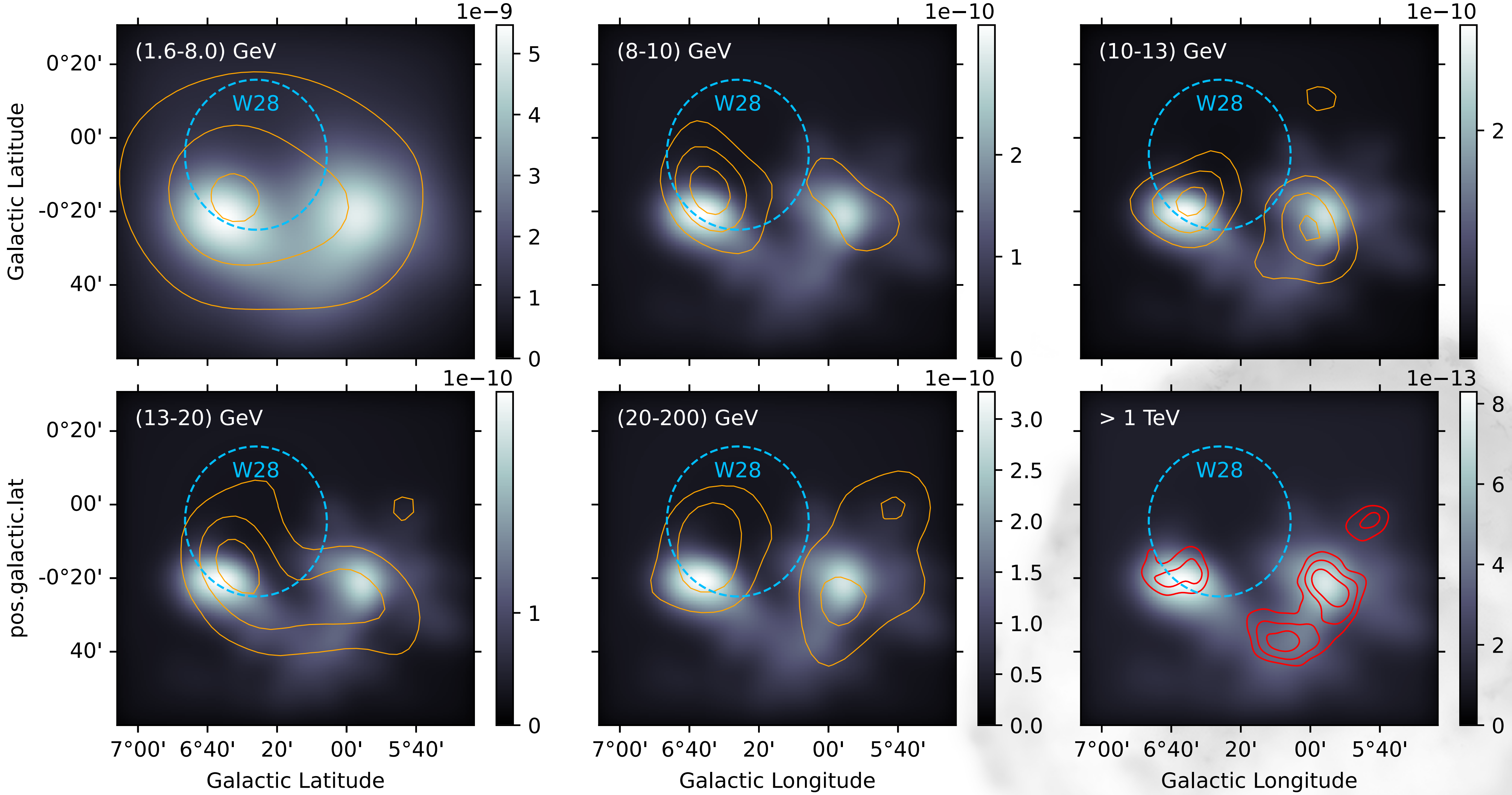
Detection of GeV and TeV gamma-ray emission with distinct energy-dependent morphologies

***Fermi*-LAT**

(~14.5 years from 2008 to 2023)

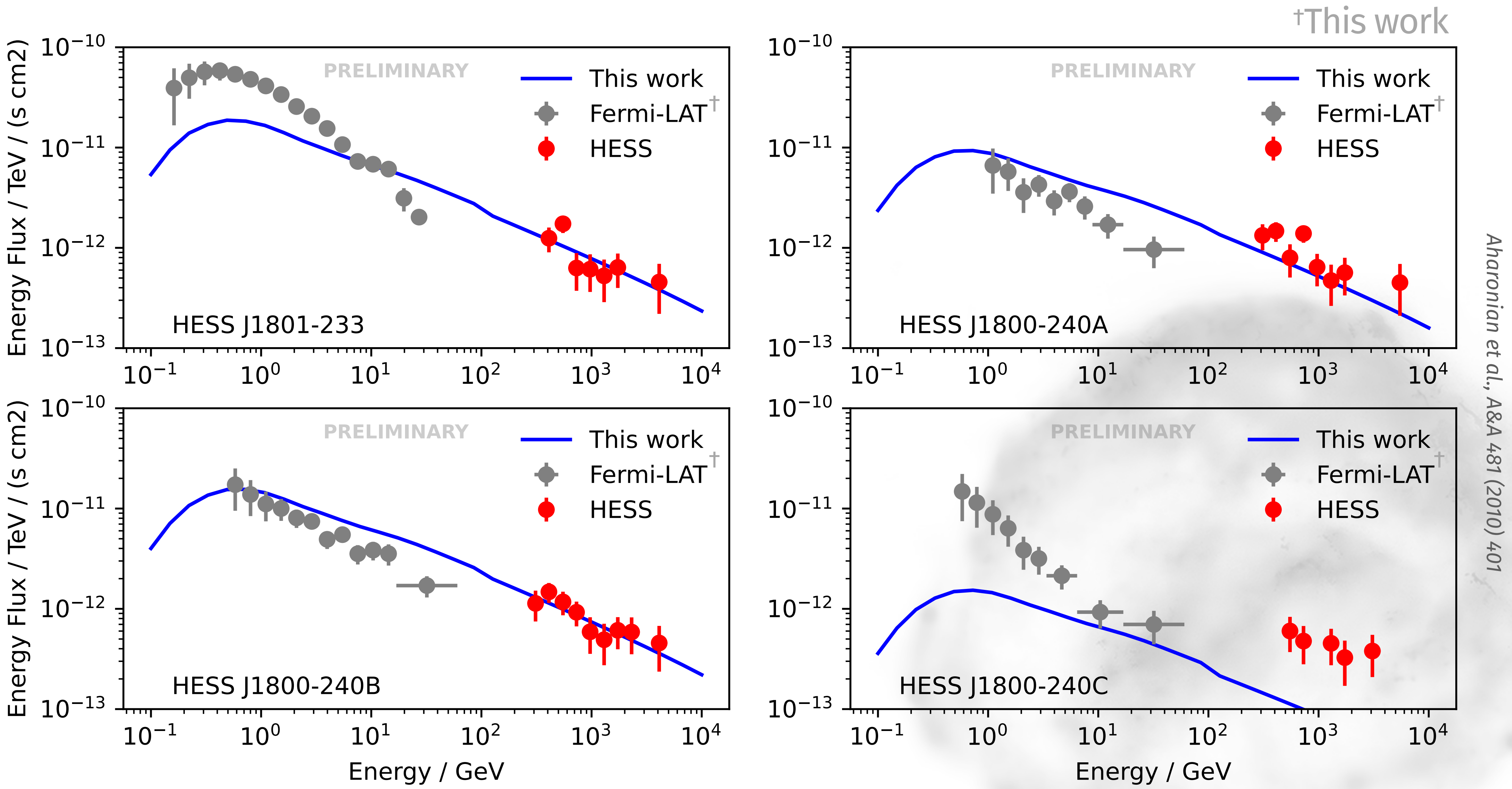


Results



α=2.1, E_{max}=5PeV E_{SN}=2e51erg, η=0.3, M_{ej}=1.4M_{sol},
δ=0.3, χ=0.5, D_0=3e27cm^2/s, B=10μG, δ_p=2.5

Results



†This work
Energy Flux / TeV / (s cm2)
Energy / GeV
PRELIMINARY
This work
Fermi-LAT†
HESS
HESS J1801-233
HESS J1800-240A
HESS J1800-240B
HESS J1800-240C
Aharonian et al., A&A 481 (2010) 401

Conclusion

- To shed light on the origin of cosmic rays, the origin of neutrino emission along Galactic plane, the most energetic gamma-ray sources, we need to understand particle accelerators and their environment
- To understand particle accelerators and their environments, we need to be able to reproduce their gamma-ray spectra **and** their morphologies
- New 3D modelling "task force"
  - Many PhD students already involved…
  - … and still more projects available for further students!
  - Many synergies with large Australian surveys, specifically in radio
- Next-generation observatories will be essential
  - CTAO will have unprecedented sensitivity and angular resolution
  - SKAO will provide essential surveys of the environment, required to model transport and gamma/neutrino production

CTAO