Simulations of the Morphology of HESS J1804-216 for observations with HESS and CTA

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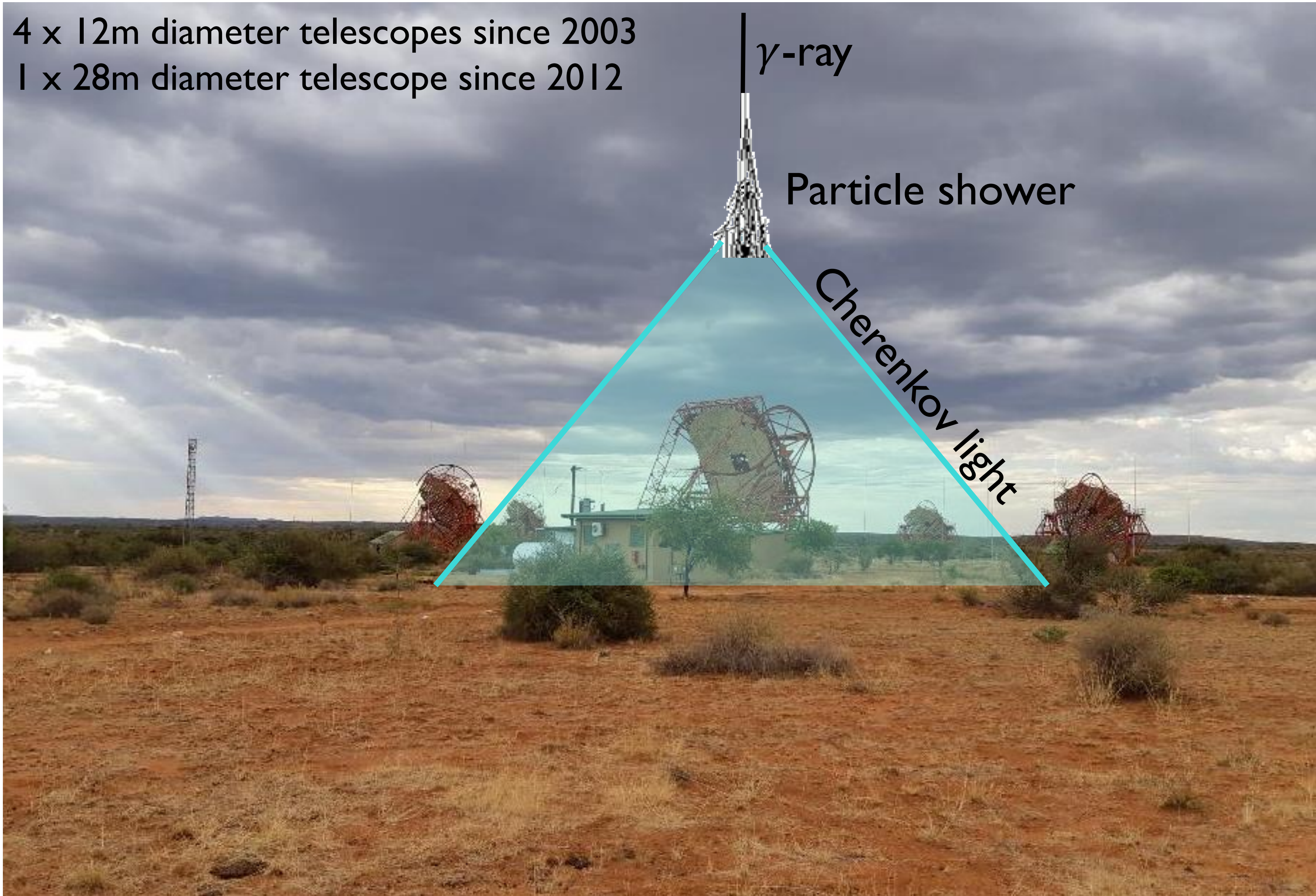
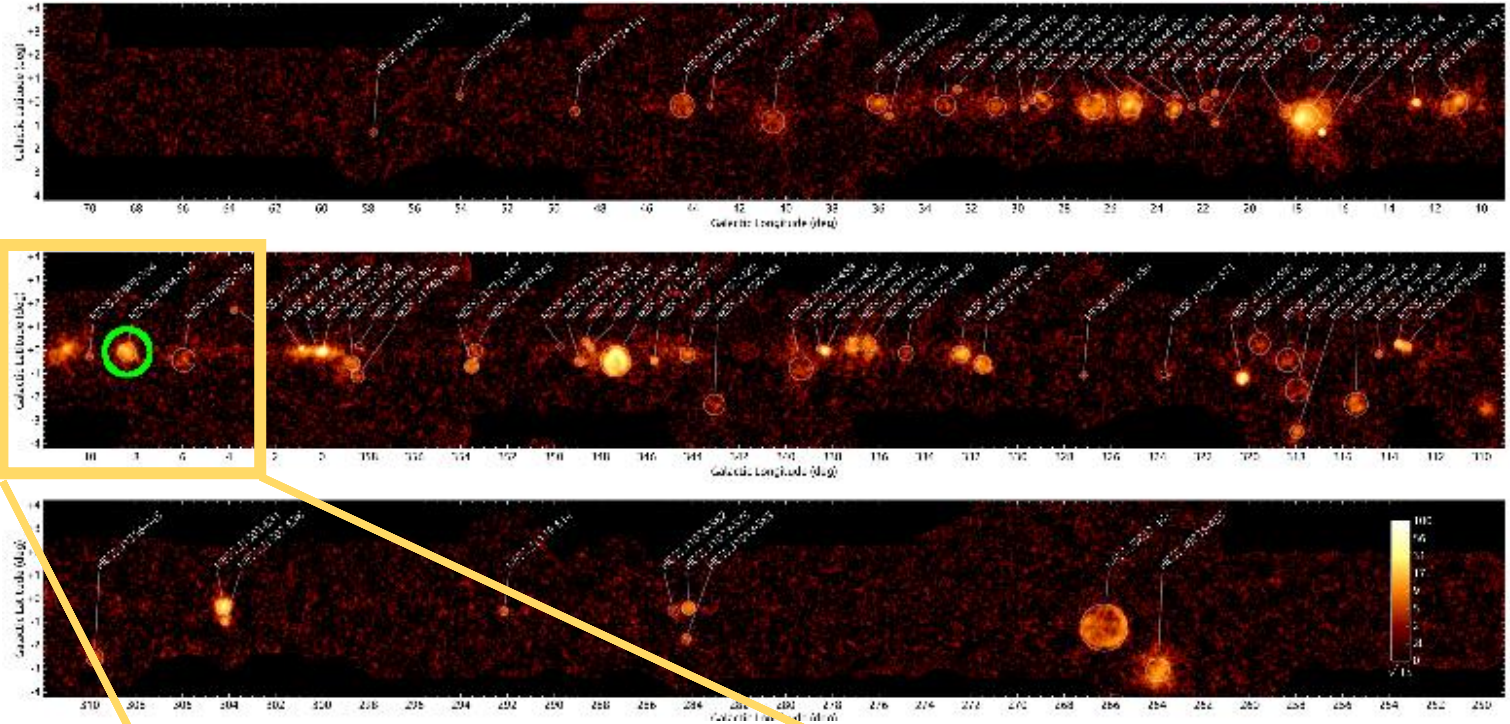
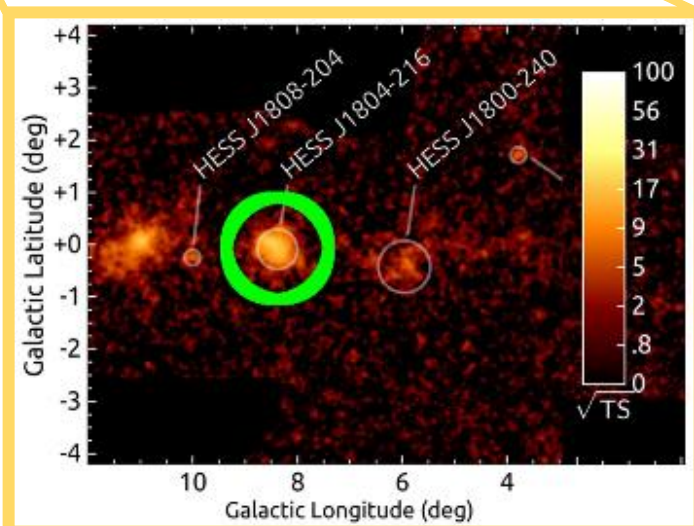
THE UNIVERSITY *of* ADELAIDE

High Energy Stereoscopic System



HESS Galactic Plane Survey - 2018

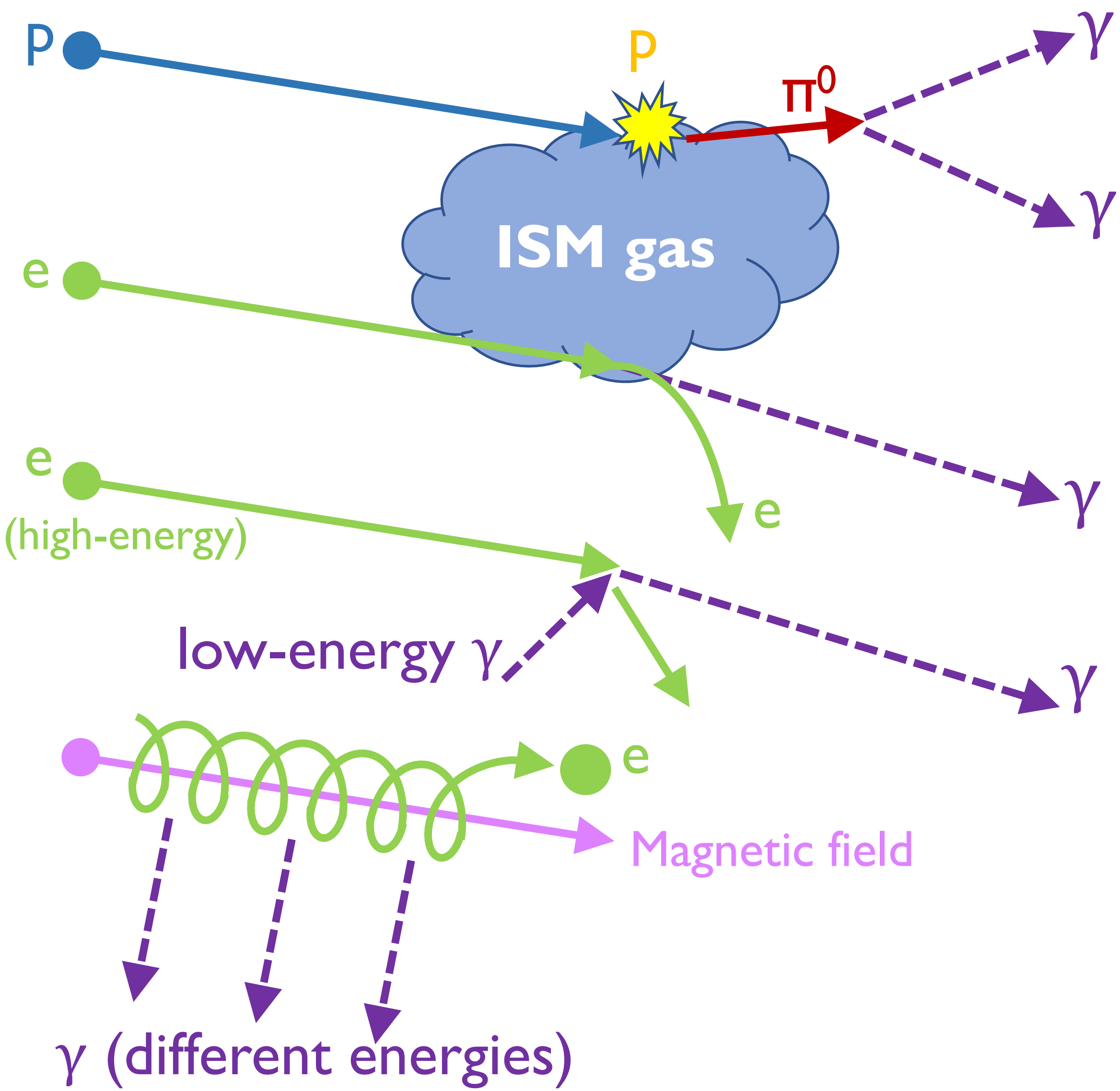




- 3 Binary
- 8 Composite
- 8 SNR
- 12 PWN
- **36 Unidentified**

HGPS map: HESS Collaboration at https://arxiv.org/pdf/1804.02432.pdf

Production of gamma-rays



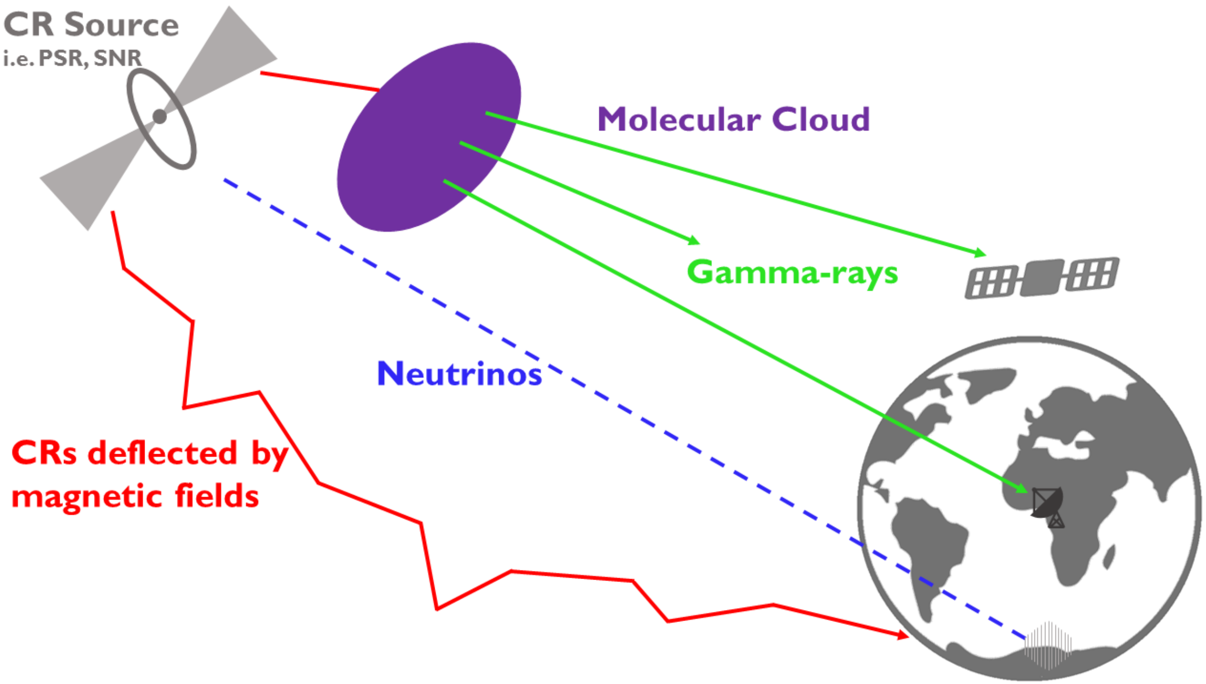
HADRONIC

- π_0 decay

LEPTONIC

- Bremsstrahlung
- Inverse Compton
- Synchrotron Radiation

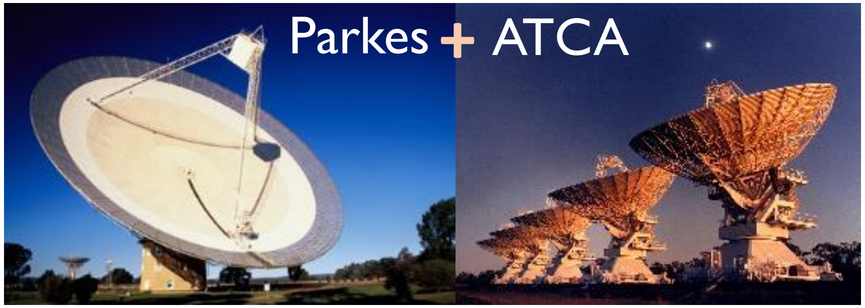
Molecular Clouds



- Clouds serve as a target for cosmic ray (CR) collisions
  - Dense regions of gas give information about gamma-ray sources
- Important to understand the interstellar gas surrounding a source
- Different gas tracers include:
  - Carbon monoxide (CO)
  - Atomic hydrogen (HI)

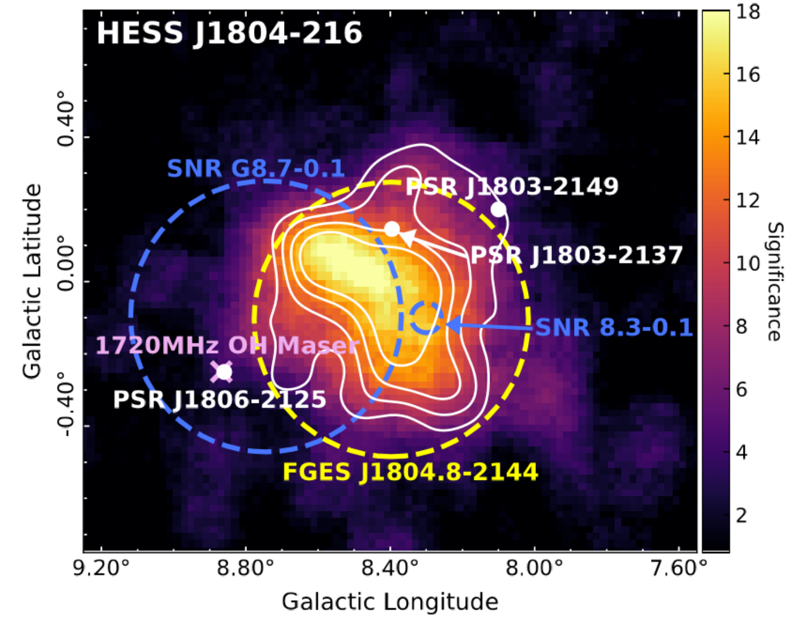
3mm: ^{12}CO, ^{13}CO, $C^{18}O$, $C^{17}O$
7mm: CS, SiO, HC_3N
12mm: NH_3

Parkes + ATCA = Southern Galactic Plane Survey (SGPS) of HI



HESS J1804-216

- HESS J1804-216 is one of the most mysterious and brightest TeV gamma–ray sources discovered
  - $F_\gamma(> 200\text{GeV}) = 5.32 \times 10^{-11}$ cm^{-2}s^{-1}
  - $L_\gamma \sim 5 \times 10^{33}(d_{kpc})^2$ erg s^{-1}
  - $\Gamma = 2.69 \pm 0.04$
- No objects coincide exactly
- **SNR 8.3-0.1**
  - Radius: 0.04°
  - Distance: 16.4 kpc
- **1720MHZ OH Maser**
  - Distance: 4.6 kpc
- **SNR G8.7-0.1**
  - Radius: 0.42°
  - Distance 4.5 kpc
  - Age: 15 kyr



Top: TeV gamma-ray significance map of HESSJ1804−216, along with potential counterparts

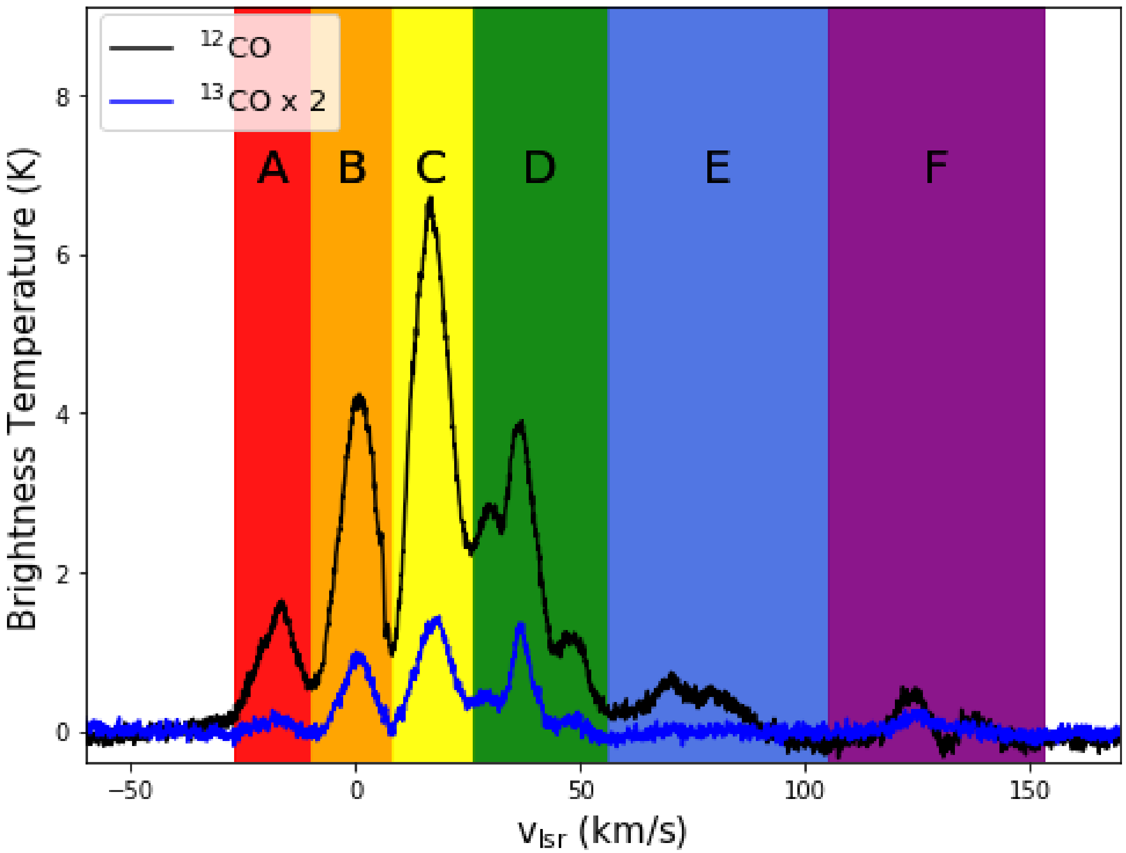
FGES = Fermi Galactic Extended Sources → one of the Fermi catalogs

PSR	J1803-2137	J1803-2149	J1806-2125
Distance (kpc)	3.8	1.3	10
Age (kyr)	15.8	86.4	65
Spin down power, $\dot{E}$ (10^{35} erg s^{-1})	22.2	6.41	0.41
TeV gamma-ray efficiency ($L_\gamma/\dot{E}$)	3%	1%	120%

Significance map: HESS Collaboration at https://arxiv.org/pdf/1804.02432.pdf

Spectra

- Region taken to encompass the 5σ level of HESS J1804-216 on the Mopra ^{12}CO cube
  - Cube is Doppler-shifted velocity along the z-axis
  - This is used to create a spectrum
- The Mopra Galactic Plane CO survey data: ^{12}CO and ^{13}CO



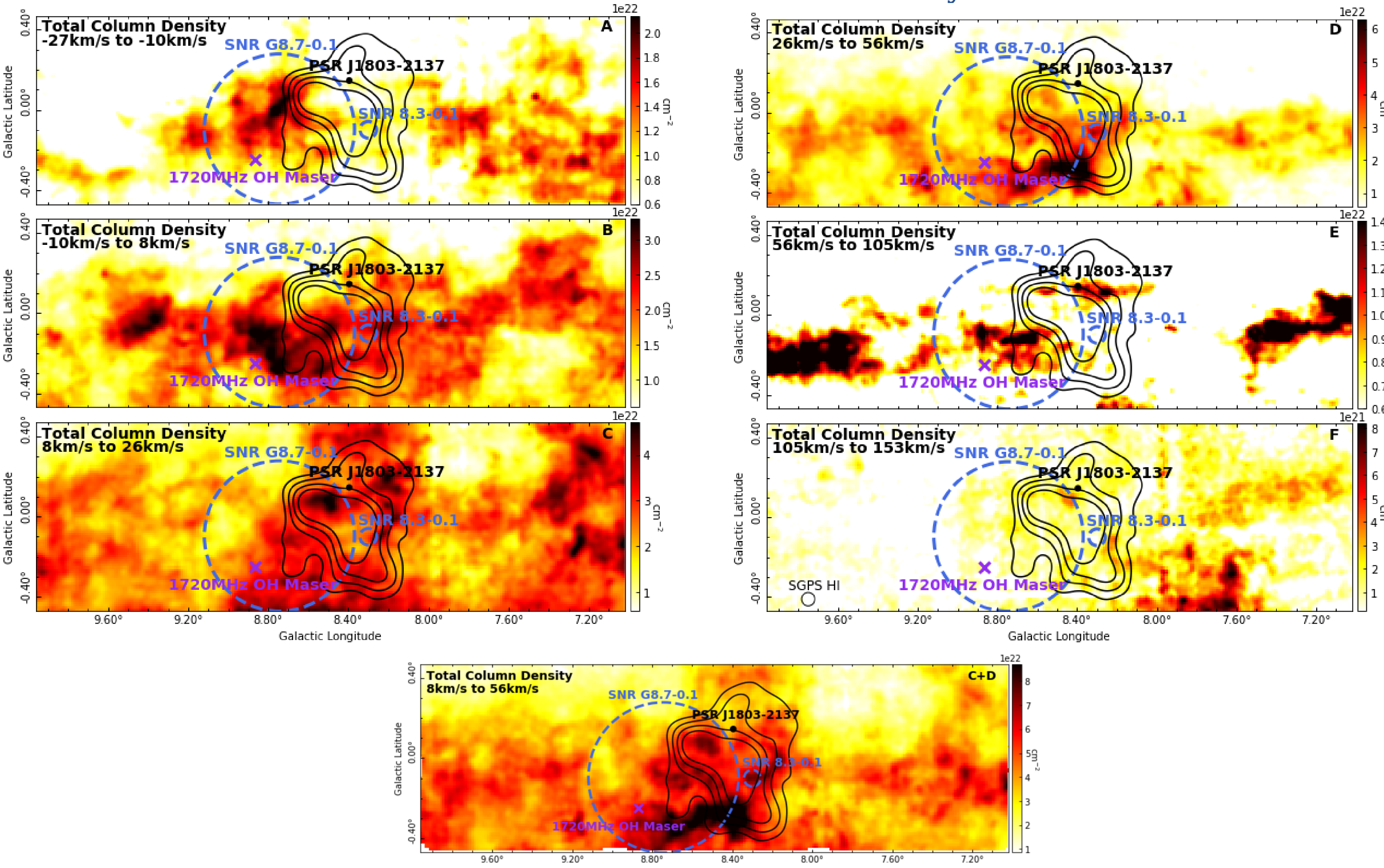
Left: Mopra ^{12}CO and ^{13}CO spectra towards HESS J1804-216

Bottom: Velocity components from left plot

Velocity range (km/s)	Component
-27 to -10	A
-10 to 8	B
8 to 26	C
26 to 56	D
56 to 105	E
105 to 153	F

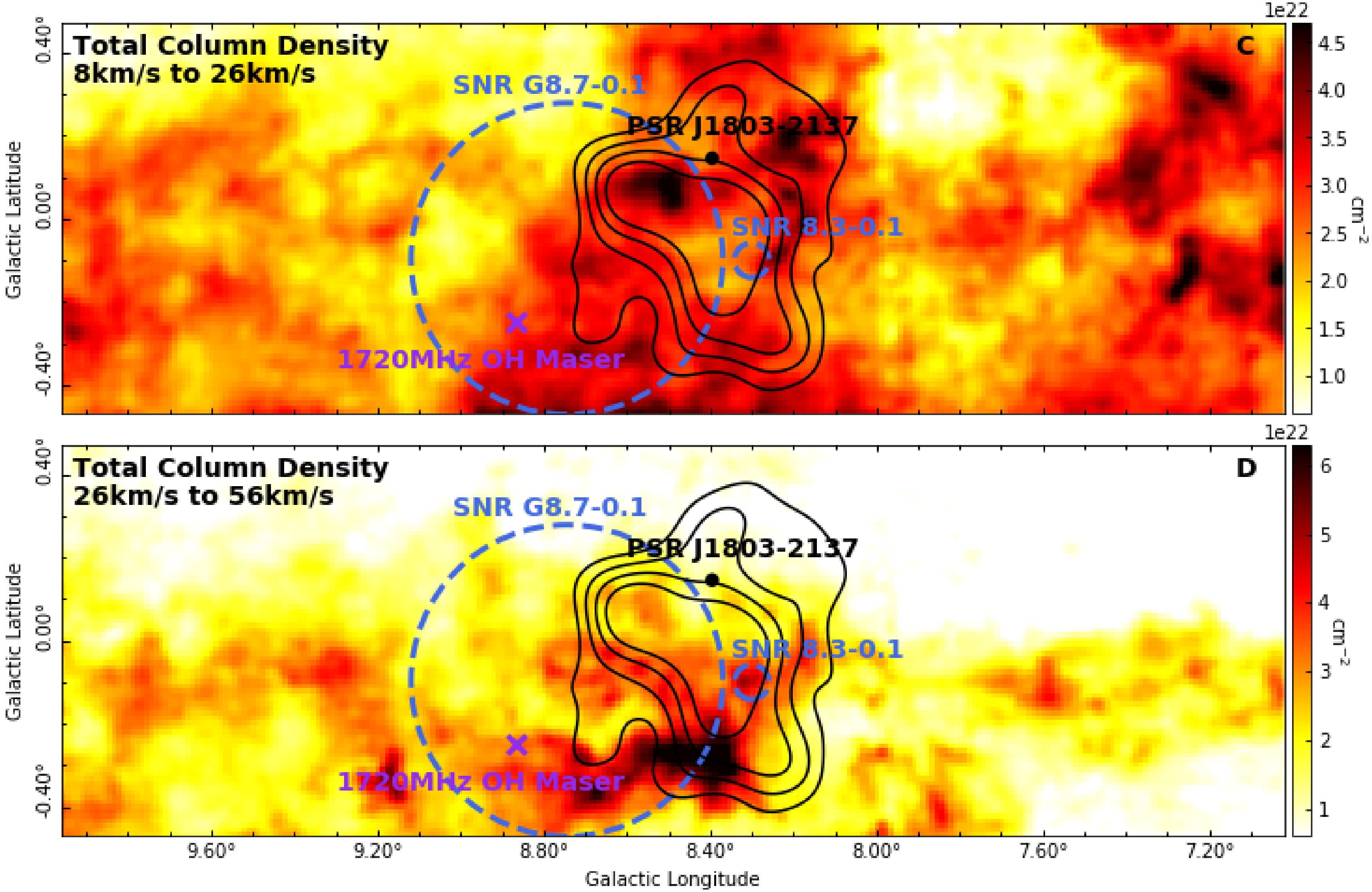
Total Column Density

Column density of HI → $$N(H) = N(HI) + 2N(H_2)$$ ← Column density of CO

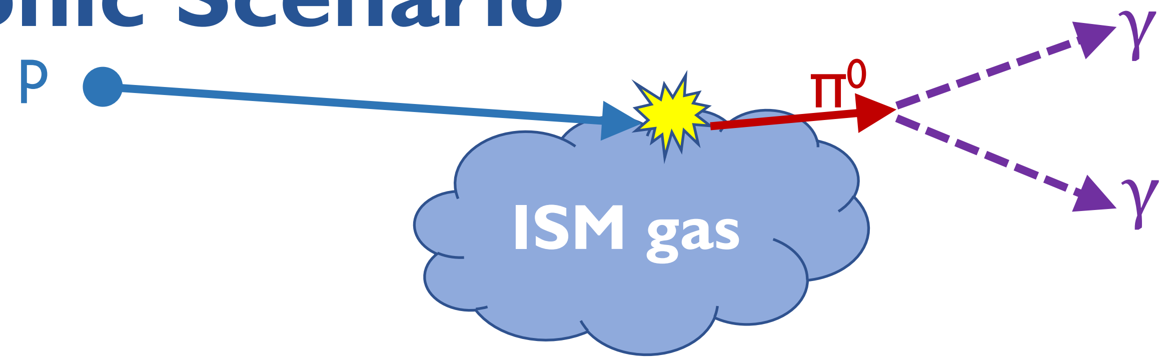


Components of Most Interest

- PSR J1803-2137 ~25km/s (component C) from the dispersion measure of the pulsar
- SNR G8.7-0.1 ~35km/s and 1720MHZ OH maser 36km/s (component D)



Hadronic Scenario



- Older SNRs are believed to have a large enough hadronic (proton-proton) contribution to account for TeV gamma–ray emission
- SNR G8.7-0.1 and the progenitor SNR of PSR J1803-2137 are two plausible candidates for the acceleration of CRs for the hadronic scenario
- The CR enhancement factor (k_{CR}) is given through:
  - $F(\geq E_\gamma) = \begin{cases} 2.85 \times 10^{-13} E_{TeV}^{-1.6} \left(\frac{M_5}{d_{kpc}^2}\right) k_{CR} & \text{cm}^2\text{s}^{-1} \\ 1.45 \times 10^{-13} E_{TeV}^{-1.75} \left(\frac{M_5}{d_{kpc}^2}\right) k_{CR} & \text{cm}^2\text{s}^{-1} \end{cases}$
- SNR G8.7-0.1: for TeV energies $k_{CR} \sim 37$ and for GeV energies is $k_{CR} \sim 9$
- Progenitor SNR: for TeV energies $k_{CR} \sim 57$ and for GeV energies is $k_{CR} \sim 14$

Gamma-ray flux equation: Aharonian, 1991: http://adsabs.harvard.edu/abs/1991Ap%26SS.180..305A

Hadronic Scenario – CR model

- The isotropic distribution of CR protons

$$f(E,R,t) \approx \frac{N_0 E^{-\alpha}}{\pi^{3/2} R_{dif}^3} \exp\left(-\frac{(\alpha-1)t}{\tau_{pp}} - \frac{R^2}{R_{dif}^2}\right) \quad [\text{cm}^{-3}\,\text{GeV}^{-1}]$$

- Diffusion radius is for CR protons of energy E propagating through the ISM during time t:

$$R_{dif} \equiv R_{dif}(E,t) = 2\sqrt{D(E)t\,\frac{\exp(t\delta/\tau_{pp})-1}{t\delta/\tau_{pp}}}$$

- N_0, determined assuming the SNR is at early epoch of evolution (~1yr)→ $R_{dif} = R$, and 10^{50}erg in CRs is contained within the SNR
- The cooling time for proton-proton collisions is:

$$\tau_{pp} = 6 \times 10^7 (n/\text{cm}^{-3})^{-1} \quad \text{yr}$$

- The diffusion coefficient is:

$$D(E) = \chi D_0 \left(\frac{E/GeV}{B/3\mu G}\right)^{\delta}$$

  - where $D_0 = 3 \times 10^{27}, B{\sim}10\mu G$ and δ & χ are varied

Particle distribution, Rdif, τ_{pp}: Aharonian and Atoyan, 1996, http://articles.adsabs.harvard.edu/pdf/1996A%26A...309..917A
Diffusion: Gabici et al 2007, https://arxiv.org/pdf/astro-ph/0610032.pdf

Hadronic Scenario – CR model

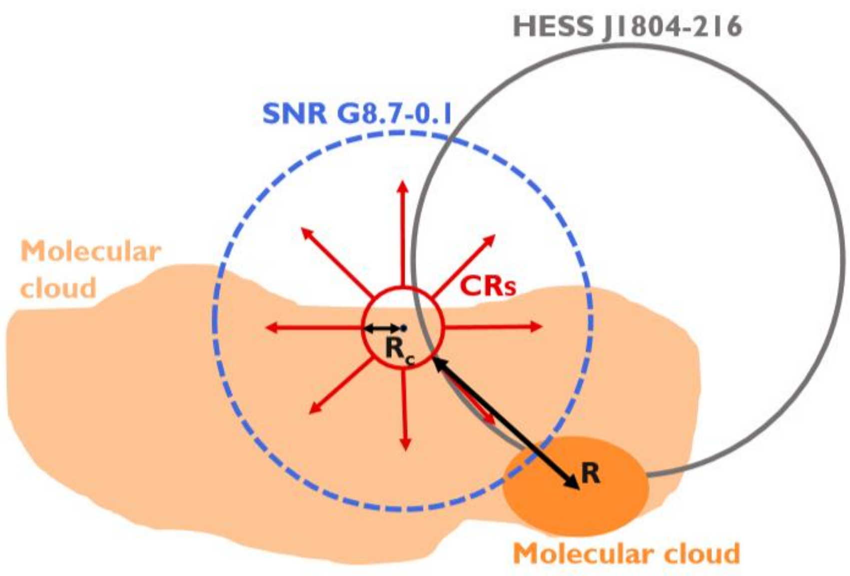
- The differential flux of protons is then given by:

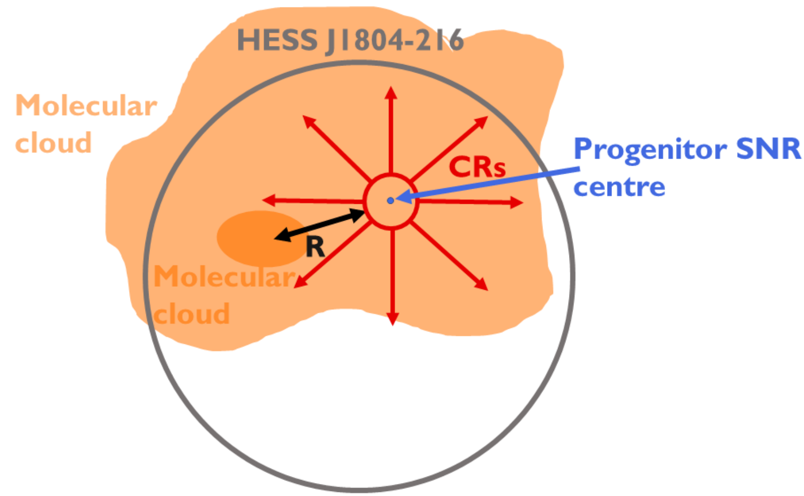
$$J(E,R,t) = (c/4\pi) f(E,R,t) \quad [\mathrm{cm^{-3}\,s^{-1}GeV^{-1}\,sr^{-1}}]$$

- For HESS J1804-216 the spectral index is $\alpha = 2.69$
- Contribution from the spectrum of CR protons observed at Earth is given by:

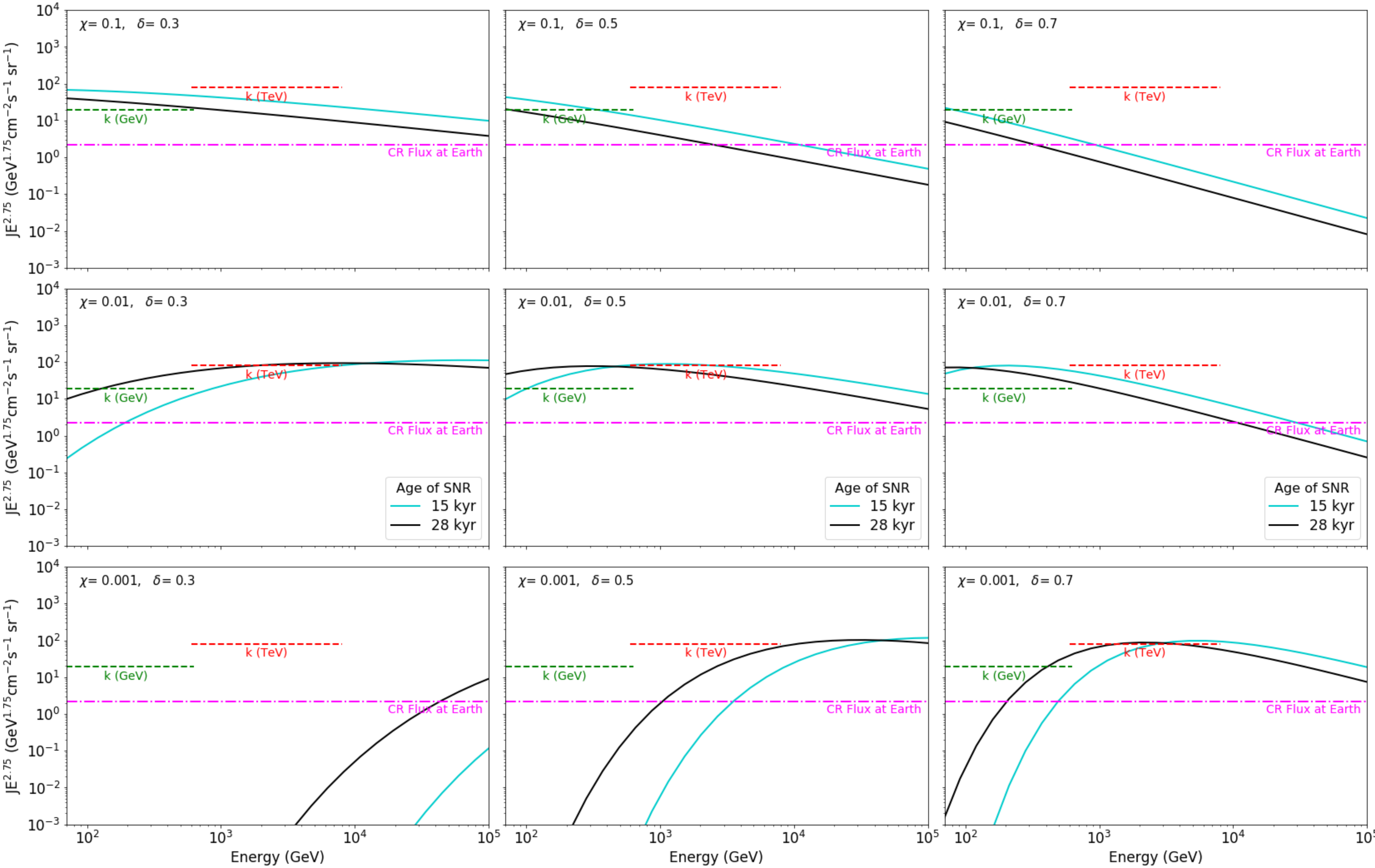
$$J(E) = 2.2\,E^{-2.75} \quad [\mathrm{cm^{-3}\,s^{-1}GeV^{-1}\,sr^{-1}}]$$

- SNR G8.7-0.1: in component D ($d = 4.5$kpc $\therefore v \sim 35$km/s) the distance from the accelerator to the cloud is ~12pc
- Progenitor SNR: in component C ($d = 3.8$kpc $\therefore v \sim 25$km/s) the distance from the accelerator to the cloud is ~10pc

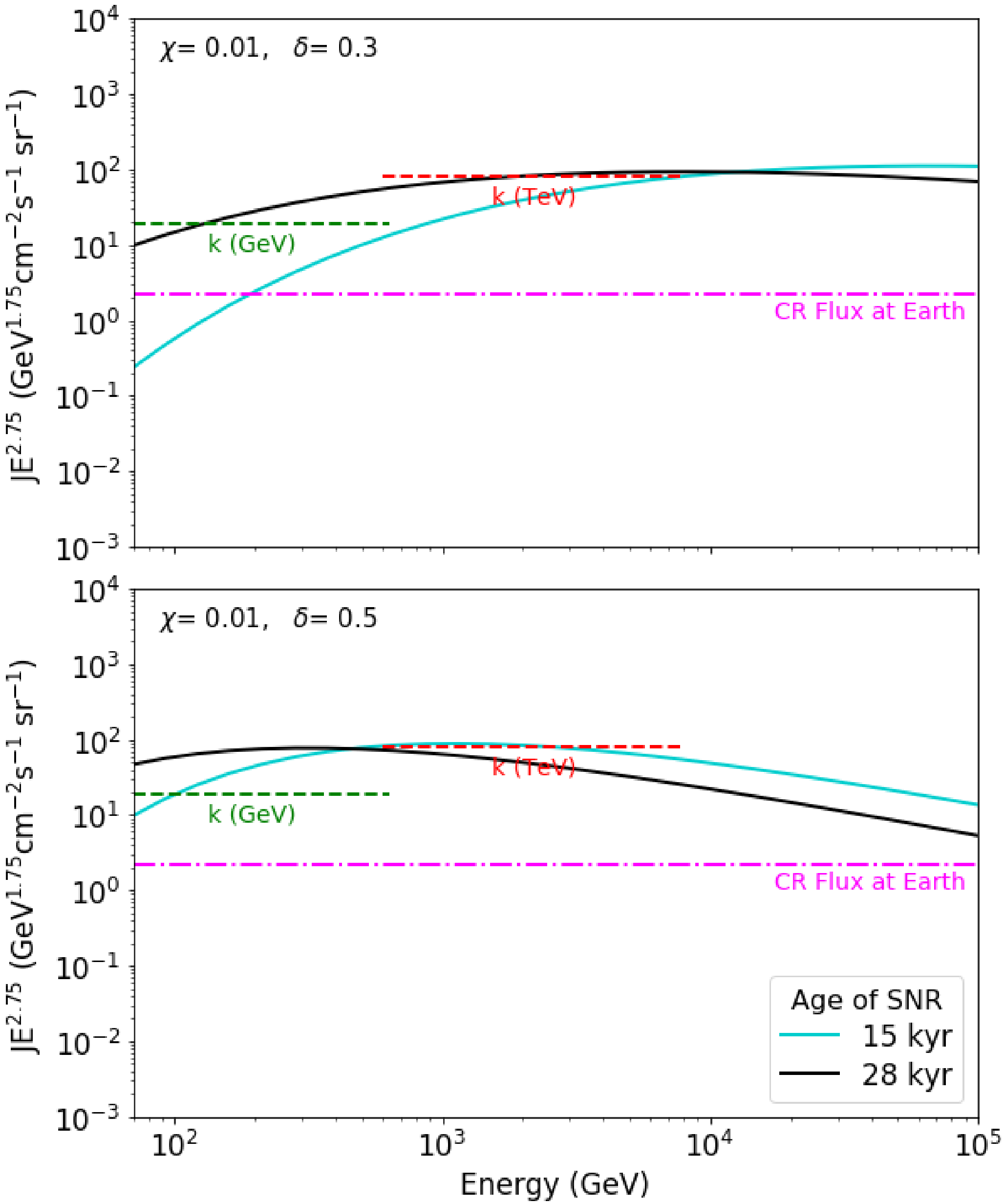




Proton spectra – SNR G8.7-0.1

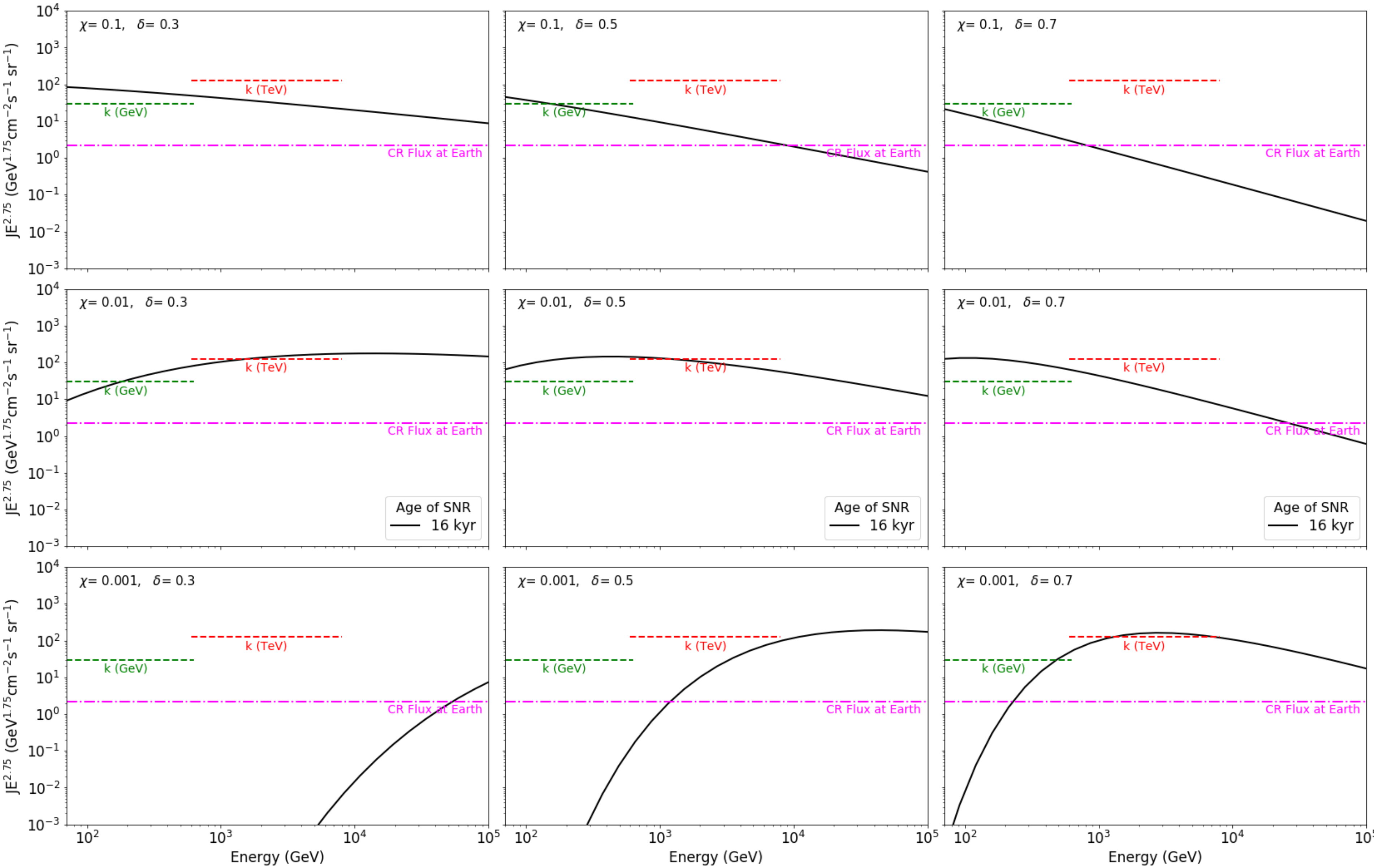


Proton spectra – SNR G8.7-0.1

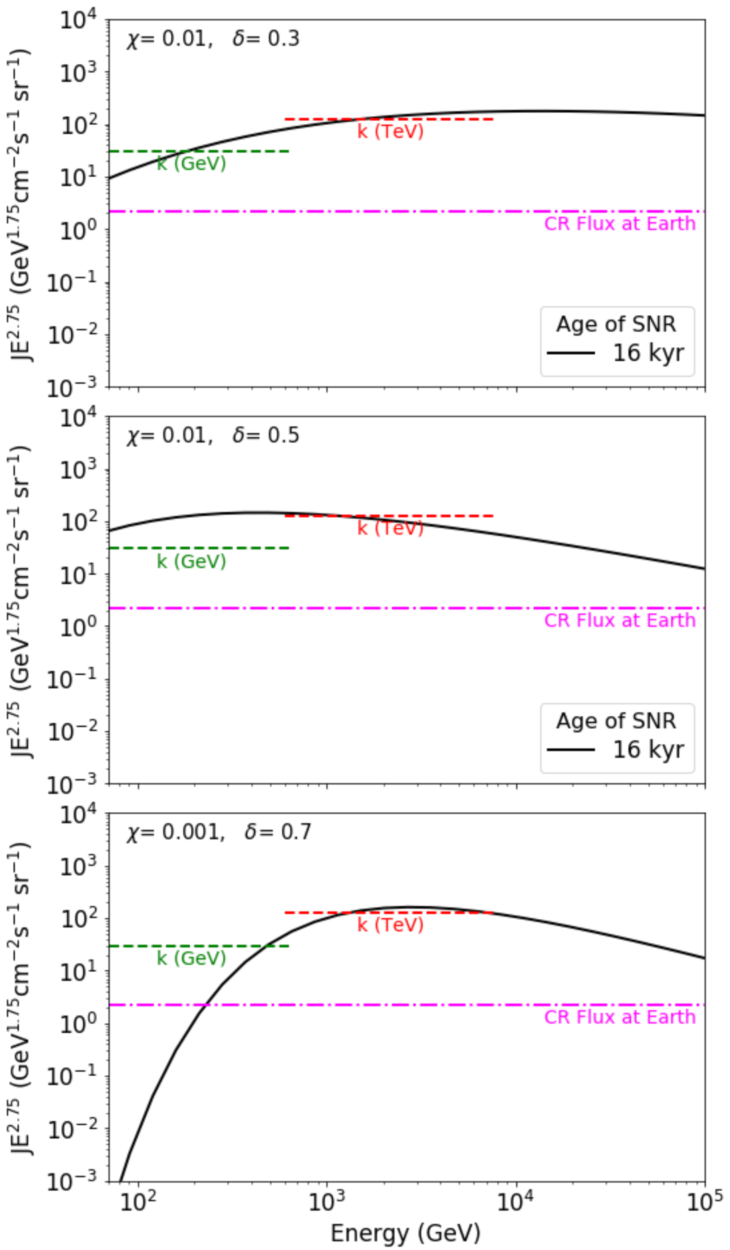


- Consider source specific model where the age of SNR G8.7-0.1 is taken to be 15-28kyrs
- Figure shows that the two cases broadly match the GeV and TeV CR enhancement factors for $\chi = 0.01$ and δ set to 0.3 or 0.5
- Trend shows lower energy population of CRs for older age
- Higher energy CRs are seen to escape first, as expected
- Evident that CRs require slow diffusion ($\chi = 0.01$) in order to contribute to the gamma-ray emission from HESS J1804-216

Proton spectra – PSR J1803-2137 progenitor SNR



Proton spectra – PSR J1803-2137 progenitor SNR



- Consider source specific model where the age of the progenitor SNR of PSR J1803-2137 is taken to be 16 kyr (the age of PSR J1803-2137)
- Figure shows that the three cases broadly match the GeV and TeV CR enhancement factors for $\chi = 0.01$ and $\delta = 0.3$ or 0.5 and $\chi = 0.001, \delta = 0.7$
- Slow diffusion consistent with other studies on the W28 SNR and IC443

Small chi : Li and Chen, 2008: https://arxiv.org/pdf/1108.4541.pdf

Gamma-ray flux predictions

- Gamma-ray production rate is computed through:

$$\Phi_\gamma(E_\gamma) = c n_H \int_{E_\gamma}^{\infty} \sigma_{inel}(E_p) J_p(E_p) F_\gamma\left(\frac{E_\gamma}{E_p}, E_p\right)\frac{dE_p}{E_p} \quad [\mathrm{cm^{-3}\,TeV^{-1}\,s^{-1}}]$$

  - Where $J_p = f(E, R, t)$ is the production rate of CR protons, n_H is the number density of hydrogen gas, $\sigma_{inel}(E_p)$ is the elastic cross-section of proton-proton interactions, F_γ is the total gamma-ray spectrum

- The differential gamma-ray spectrum is given through:

$$\mathcal{F} = \frac{1}{4\pi}\int_0^{l_{max}} \Phi_\gamma(E_\gamma)dl = \frac{\Phi_\gamma(E_\gamma)}{4\pi} dl_{max} \quad [\mathrm{cm^{-2}\,TeV^{-1}\,s^{-1}\,sr^{-1}}]$$

- Must account for the steradian per pixel:

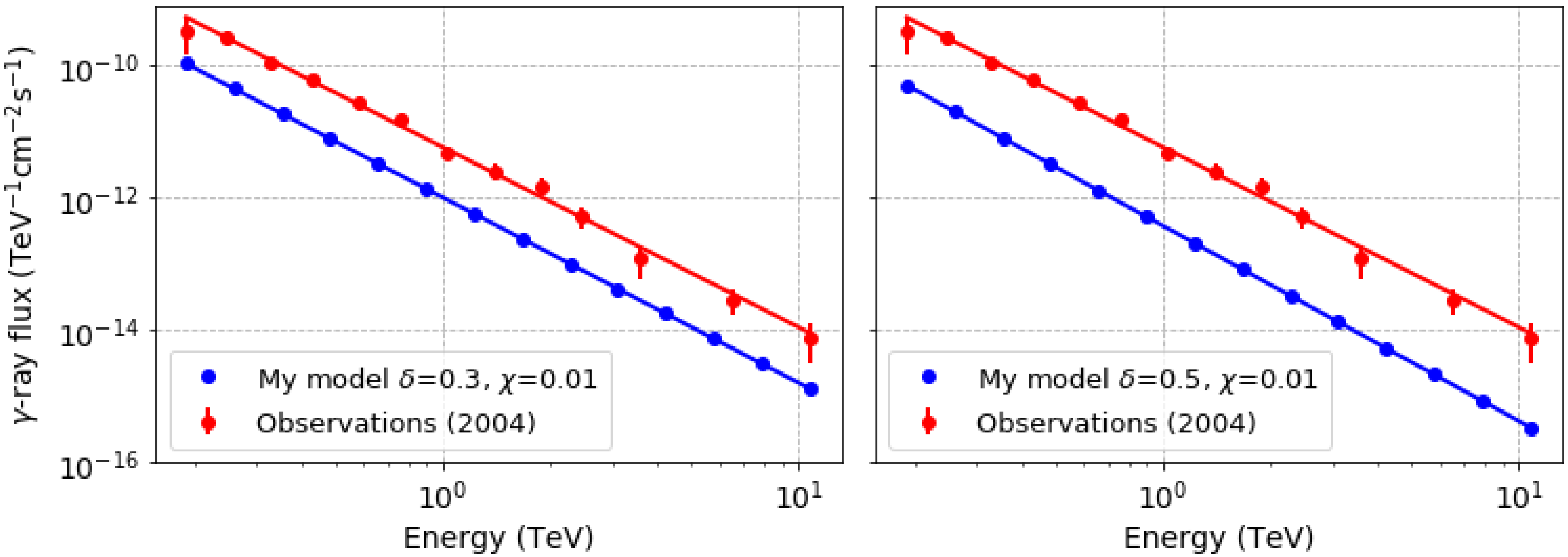
$$\mathrm{F} = \frac{\Phi_\gamma(E_\gamma)}{4\pi} dl_{max}\left(\frac{A}{D^2}\right) \quad [\mathrm{cm^{-2}\,TeV^{-1}\,s^{-1}}]$$

  - Where A=area of pixel= $(D tan\theta_{pixel})^2$, D=distance to the source

Gamma-ray production rate equation: Kelner et al, 2006: https://arxiv.org/abs/astro-ph/0606058

Flux comparison model – SNR G8.7-0.1

- The data taken of HESS J1804-216 was in a region of ~0.4° radius
- To compare the gamma-ray flux obtained from the 2004 observations to my model, the flux is summed in this 0.4° region
  - This gives a flux value for each energy in the gamma-ray flux cube

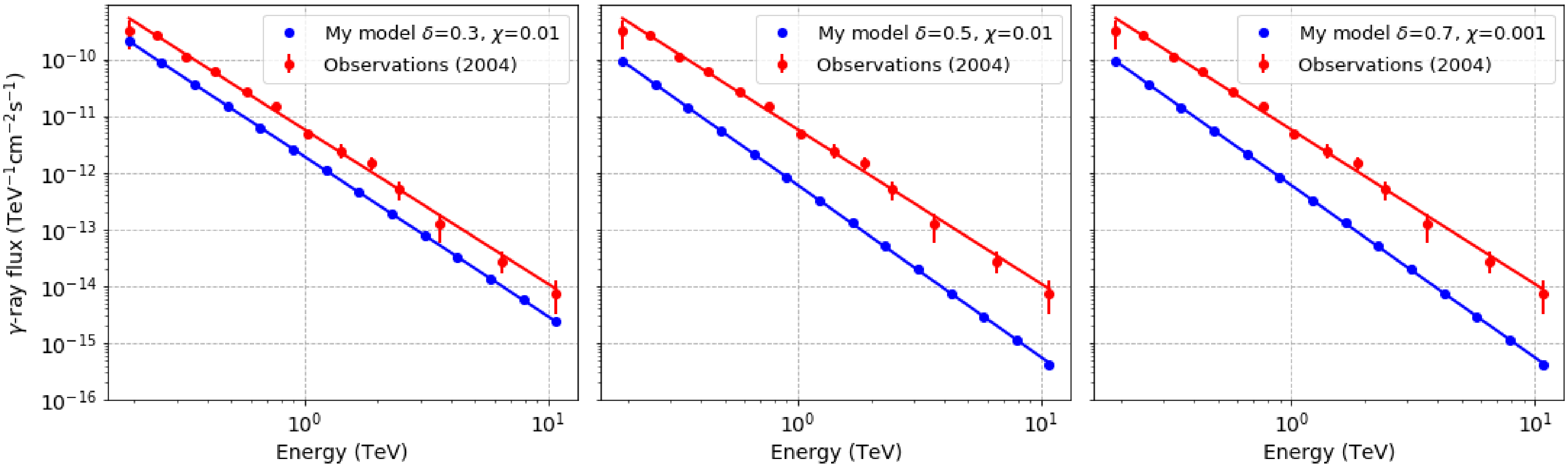


	HESS Observations	My model ($\delta = 0.3, \chi = 0.01$)	My model ($\delta = 0.5, \chi = 0.01$)
Amplitude (TeV^{-1} cm^{-2} s^{-1})	5.44×10^{-12}	9.98×10^{-13}	3.71×10^{-13}
Index	2.72 ± 0.04	2.80	2.95

HESS observation data: Aharonian et al, 2006: https://arxiv.org/abs/astro-ph/0510397

Flux comparison model – PSR J1803-2137 progenitor SNR

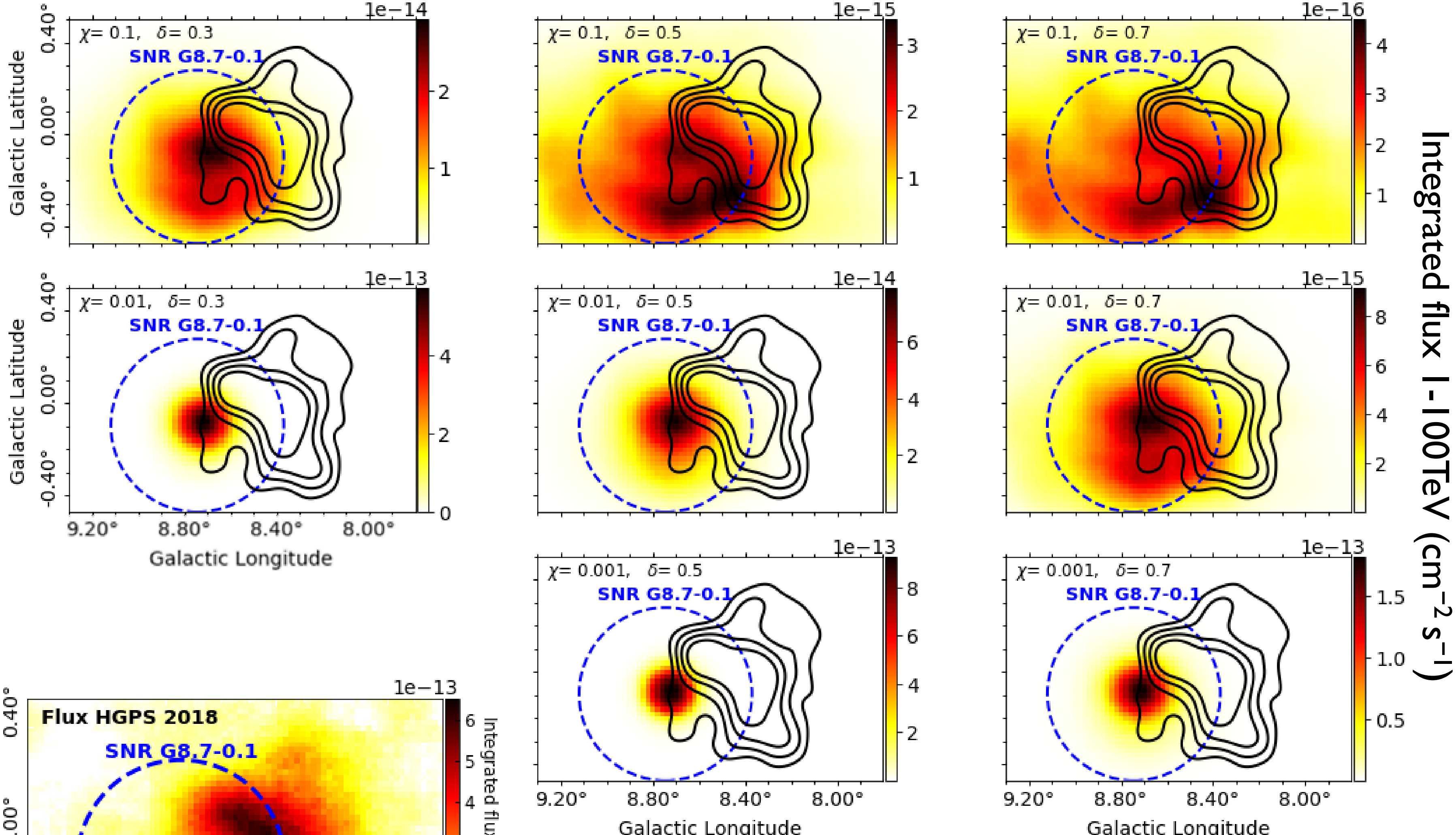
- The data taken of HESS J1804-216 was in a region of ~0.4° radius
- To compare the gamma-ray flux obtained from the 2004 observations to my model, the flux is summed in this 0.4° region
  - This gives a flux value for each energy in the gamma-ray flux cube

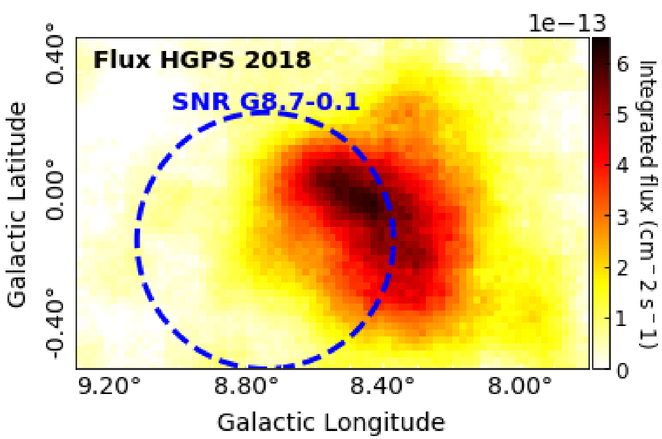


	HESS Observations	My model $(\delta = 0.3, \chi = 0.01)$	My model $(\delta = 0.5, \chi = 0.01)$	My model $(\delta = 0.7, \chi = 0.001)$
Amplitude (TeV^{-1} cm^{-2} s^{-1})	5.44×10^{-12}	1.92×10^{-12}	6.02×10^{-13}	1.11×10^{-12}
Index	2.72 ± 0.04	2.82	3.03	3.15

HESS observation data: Aharonian et al, 2006: https://arxiv.org/abs/astro-ph/0510397

Model Map Integral flux (>1 TeV) – SNR G8.7-0.1





Power law: $f(E) = \phi_0 E^{-\Gamma}$

Integral: $F(E) = \frac{\phi_0}{1-\Gamma} E^{-\Gamma}$

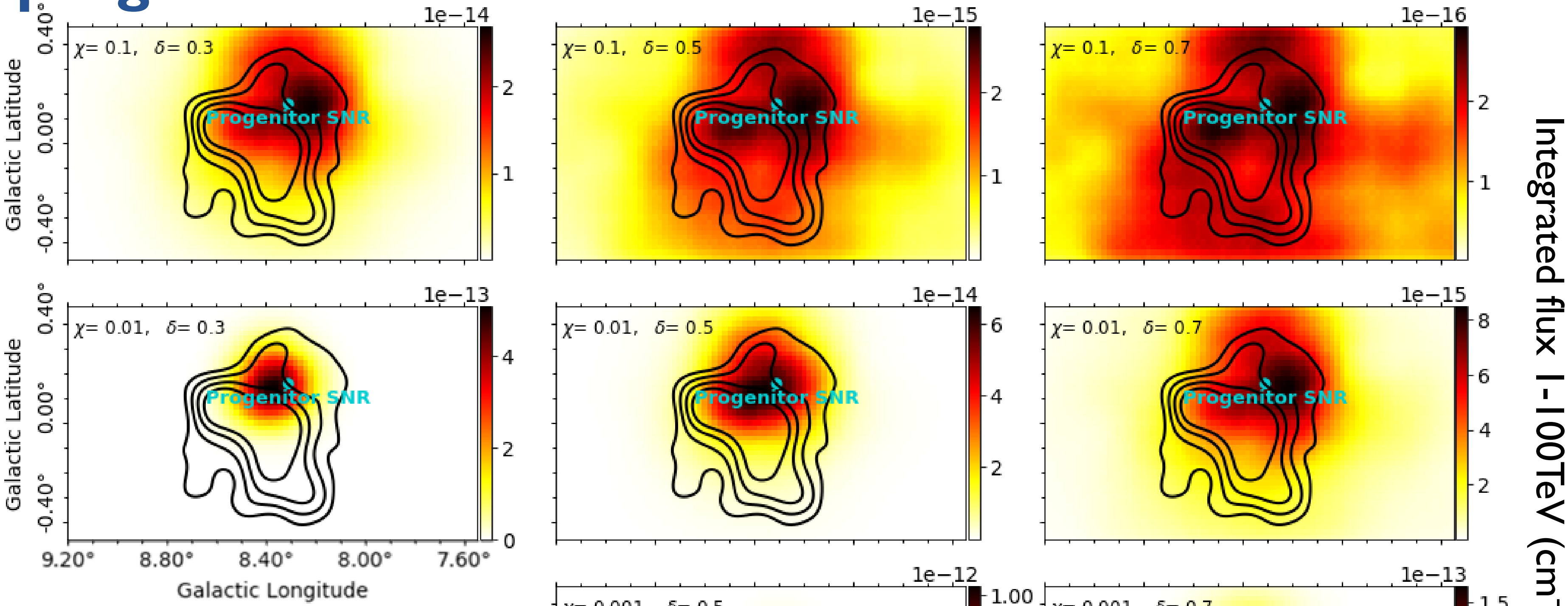
Amplitude

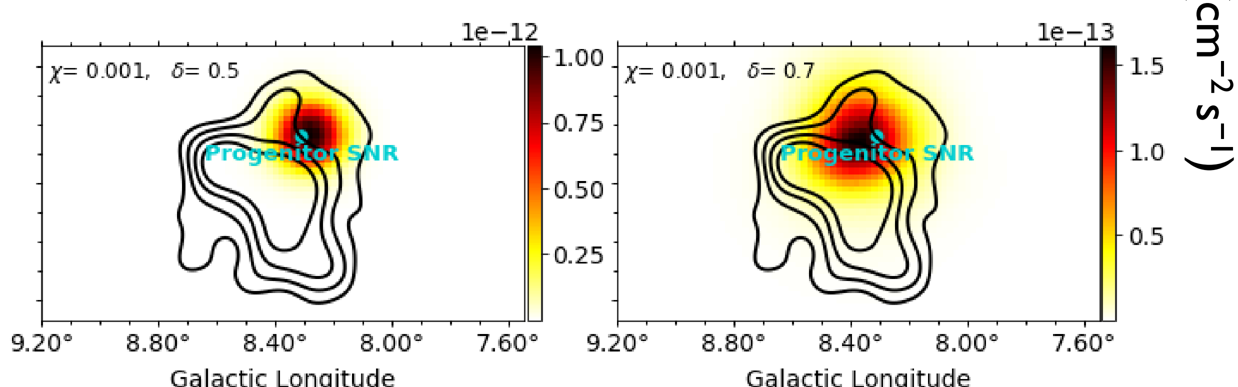
Index

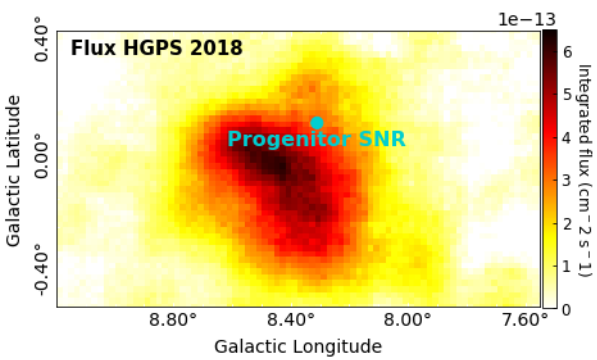
∴ Integrated power law: $F(E) = F(E_{\text{max}}) - F(E_{\text{min}})$

HGPS flux map: HESS Collaboration at https://arxiv.org/pdf/1804.02432.pdf

Model Map Integral flux (>1 TeV) – PSR J1803-2137 progenitor SNR







Power law: $f(E) = \phi_0 E^{-\Gamma}$ ← Amplitude

Integral: $\mathrm{F(E)} = \frac{\phi_0}{1-\Gamma} E^{-\Gamma}$ ← Index

∴ Integrated power law: $F(E) = F(E_{\max}) - F(E_{\min})$

Counts explanation

- Predicted gamma–ray flux maps are used to produce gamma–ray counts maps for both HESS and CTA
- Use the open-source python package Gammapy
- The simulations require a spectral model for each gamma-ray flux cell
- The current two spectral models used for the simulations are a power law and log-parabola

$$\Phi_{\mathrm{PL}}(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \qquad \Phi_{\mathrm{LP}}(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta \log\left(\frac{E}{E_0}\right)}$$

- The spectral model used for each pixel is the one that matches the data closest, which is found through:

$$\mathrm{RSD\_dof} = \mathrm{RSD}/\mathrm{dof}$$

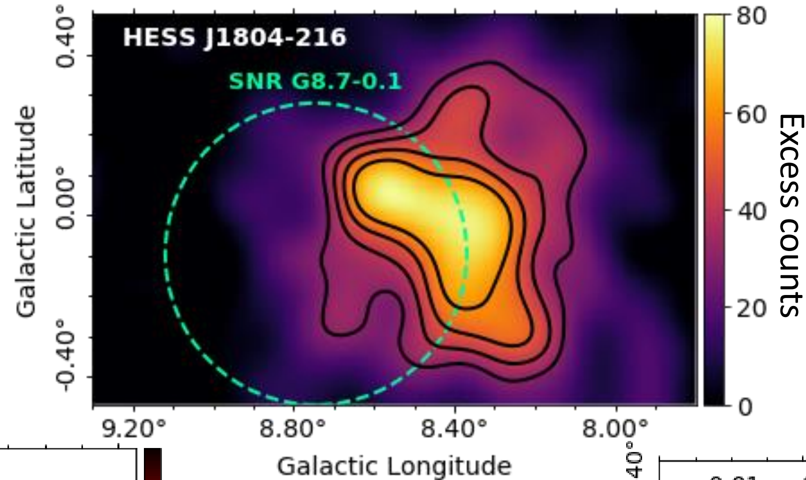
where $\mathrm{RSD} = \sum \frac{(\mathrm{obs}-\mathrm{fit})^2}{\mathrm{obs}}$, dof=number of fit params

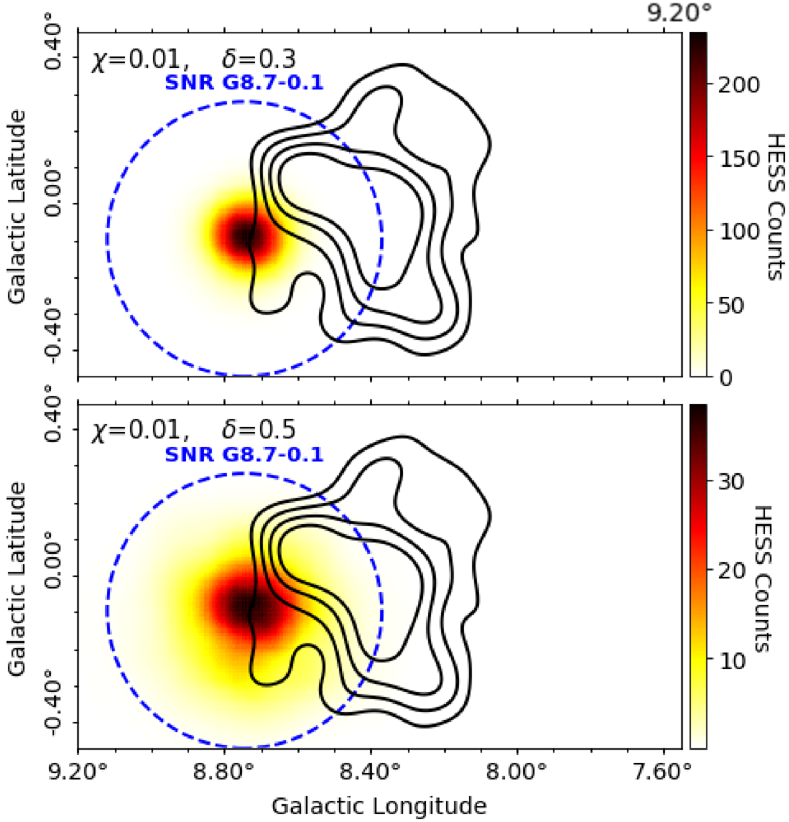
- The fit for each cell is used along with the effective area, energy dispersion of the telescope, the offset and livetime for the observations
- The effective area and energy dispersion can be found through the instrument response functions (IRFs) for various gamma–ray observatories

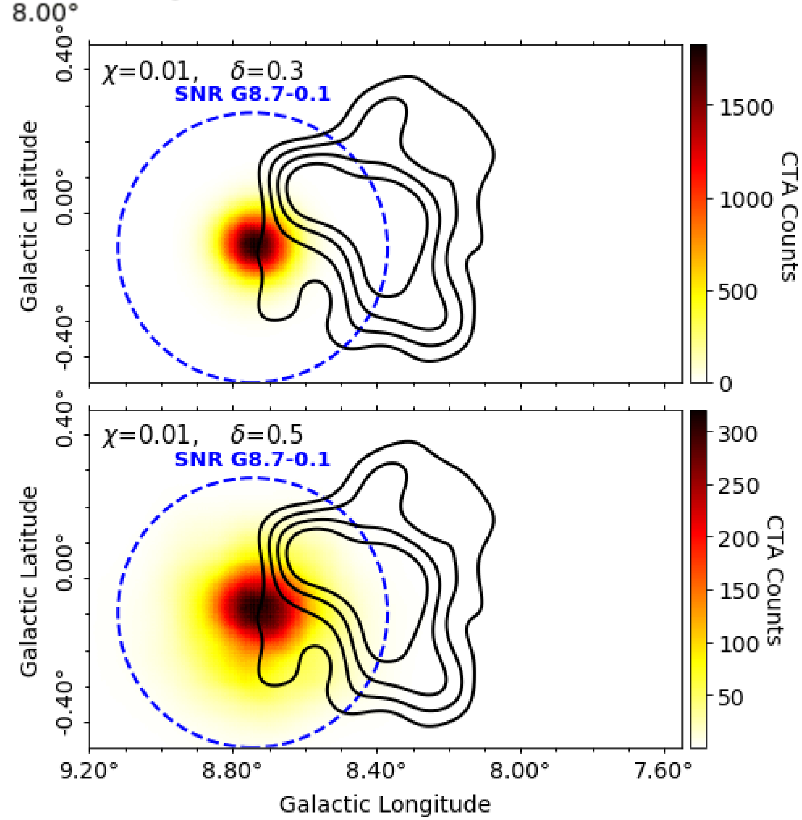
RSD – relative squared distances

Counts – SNR G8.7-0.1

- Energy = 0.19- 10.78 TeV
- Offset = 0.5°
- Livetime = 15.7 hr



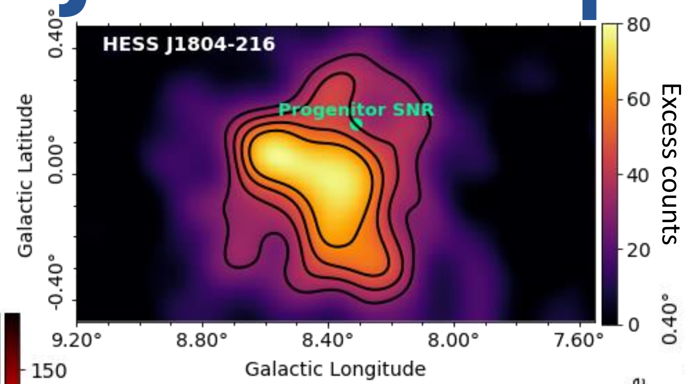


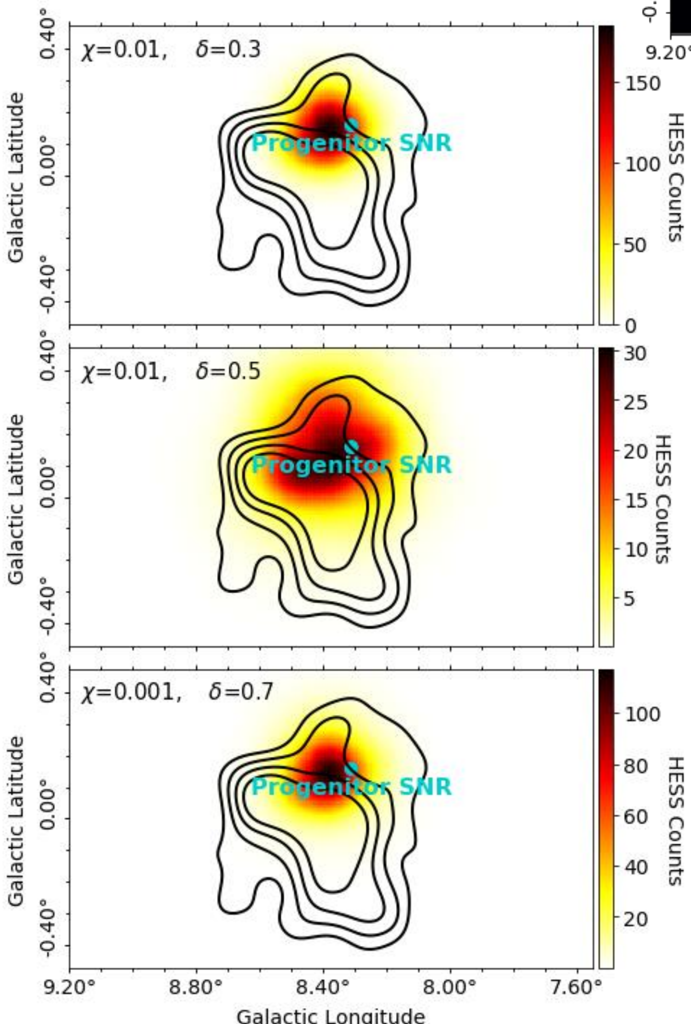


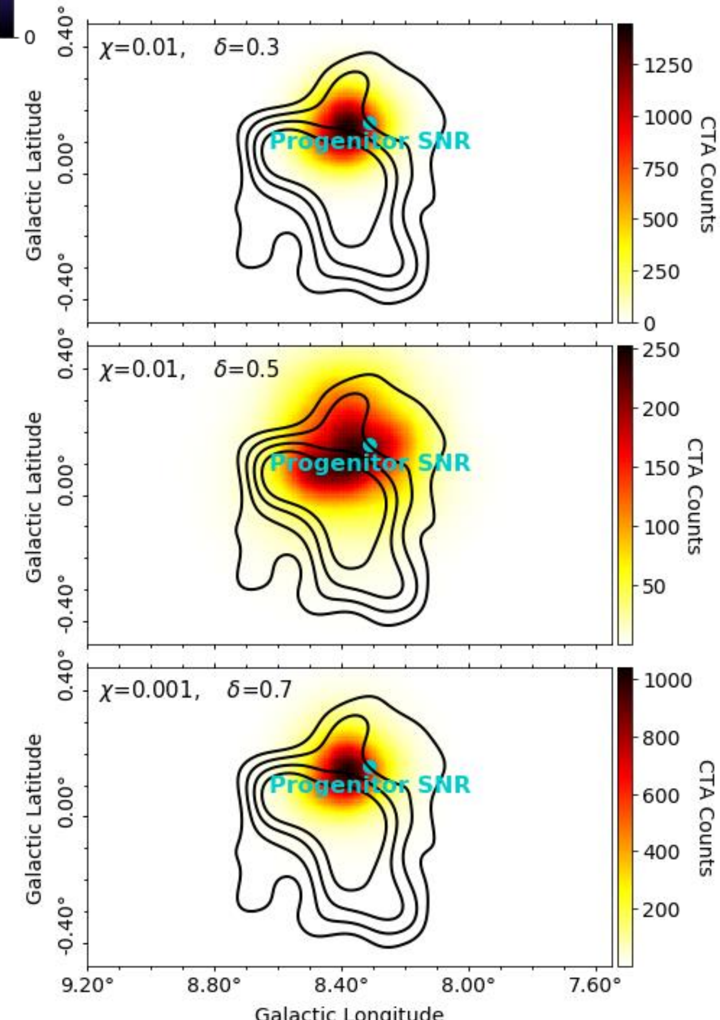
HGPS excess counts map: Aharonian et al, 2006: https://arxiv.org/abs/astro-ph/0510397

Counts – PSR J1803-2137 progenitor SNR

- Energy = 0.19- 10.78 TeV
- Offset = 0.5°
- Livetime = 15.7 hr







HGPS excess counts map: Aharonian et al, 2006: https://arxiv.org/abs/astro-ph/0510397

Leptonic Scenario

- PSR J1803-2137 is assumed as the accelerator of CRs for the leptonic scenario
- TeV gamma–ray efficiency for PSR J1803-2137 is $\eta_\gamma = \frac{L_\gamma}{\dot{E}} \sim 3\%$
  - Spin down power of the pulsar ($\dot{E} = 2.2 \times 10^{36}\mathrm{erg\ s^{-1}}$) and luminosity of HESS J1804-216 at 3.8kpc ($L_\gamma = 7.09 \times 10^{34}\mathrm{erg\ s^{-1}}$)

→ Leptonic TeV gamma–ray emission is supported from an energetics point of view

- Assuming that only electrons are being accelerated by PSR J1803-2137, the three leptonic cooling times are calculated:
- $t_{diff} = 12$ kyr, $t_{brem} = 120$ kyr, $t_{IC} = 230$ kyr, $t_{sync} = 22$ kyr
  - At the assumed distance to PSR J1803-2137 ($d = 3.8\mathrm{kpc}\ \therefore v \sim 25\mathrm{km/s}$)
- Diffusion time (12 kyr) is similar to that of the pulsars age (16 kyr), hence electrons can diffuse the required distance of 30pc
- $age_{PSR} < t_{cool} \rightarrow$ energy losses from each effect are negligible
- Component C (corresponding to the distance of PSRJ1803−2137) shows gas structures which anti-correlate with the TeV emission from HESSJ1804−216, typical of a PWN driven TeV source

Summary

- Molecular clouds provide insight to the complex nature of gamma–ray sources
- Comparisons between gas and the TeV gamma–ray data allows us to, potentially, categorise the gamma–ray source
- Two solutions for HESS J1804-216 are currently investigated:
  - A completely hadronic source
  - A completely leptonic source
- Modelled CR proton spectra for the hadronic scenarios with SNR G8.7-0.1 and the progenitor SNR of PSR J1803-2137 to predict gamma-ray flux maps
  - These maps are used to predict what both HESS and CTA might see
- Leptonic scenario is not completely ruled out, with PSR J1803-2137 as the accelerator
- It is also possible to have a mixture of hadronic and leptonic, which will be investigated in time
- Future work therefore aims for detailed spectral model for the electrons