The Bright and Unknown:
Modelling the Cosmic-ray and Gamma-ray Morphology towards HESS J1804-216

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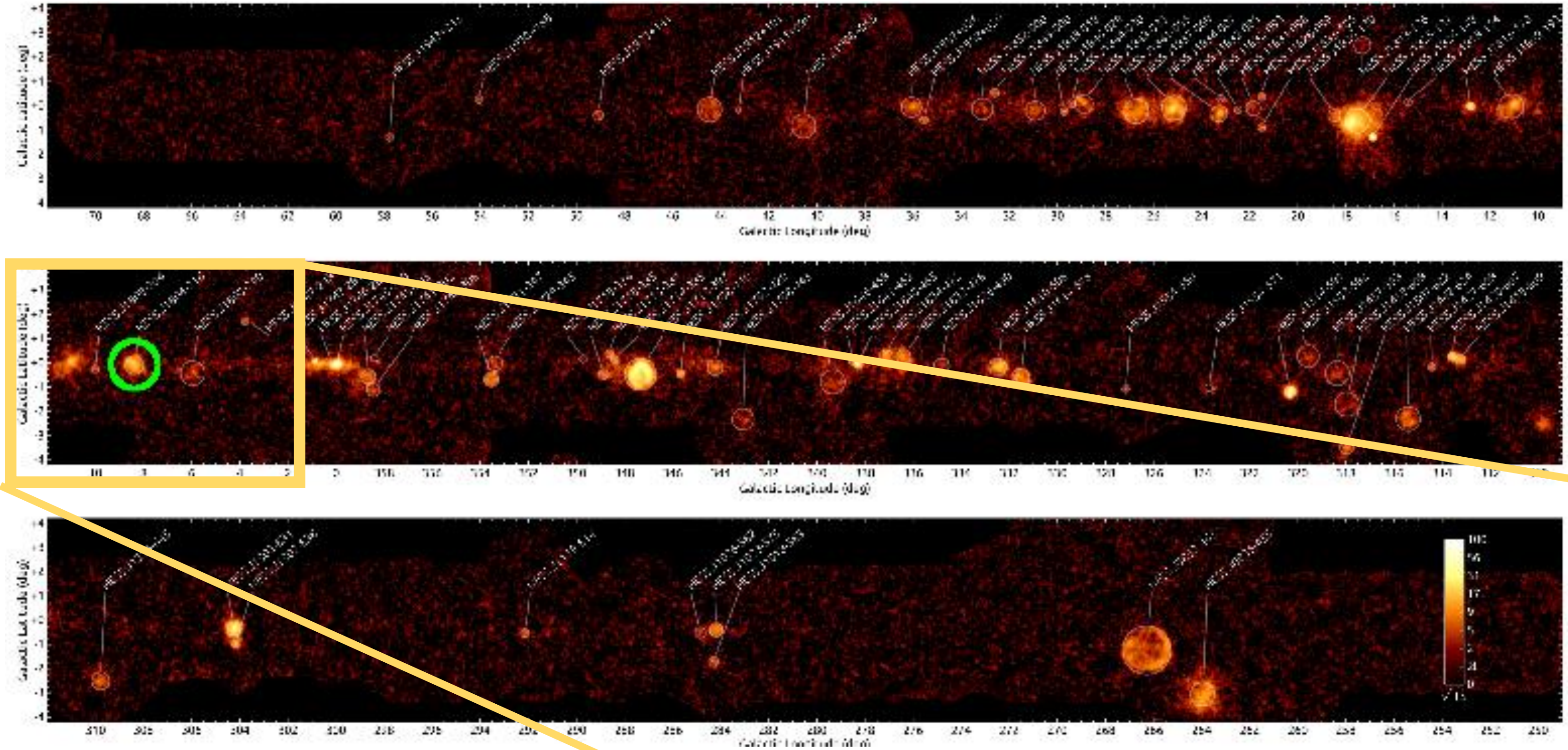
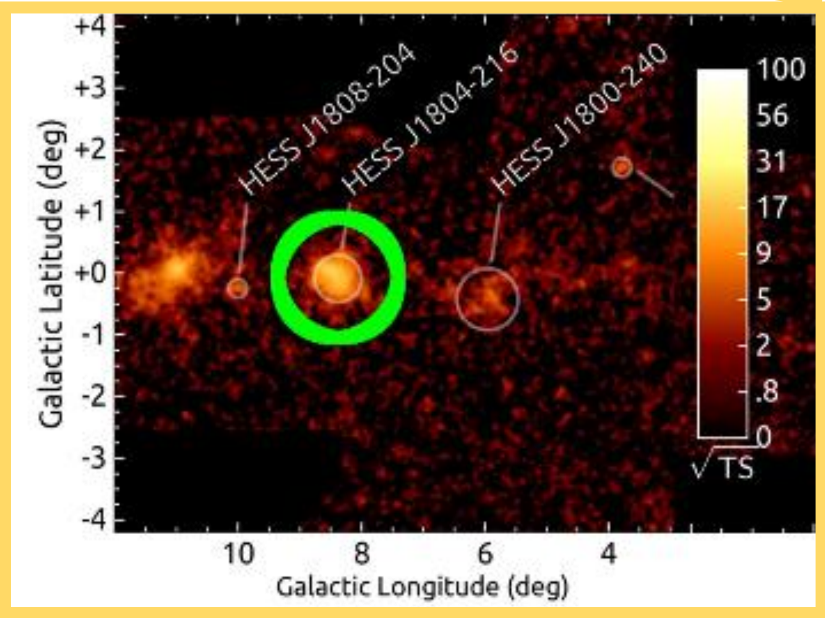
HESS Galactic Plane Survey - 2018

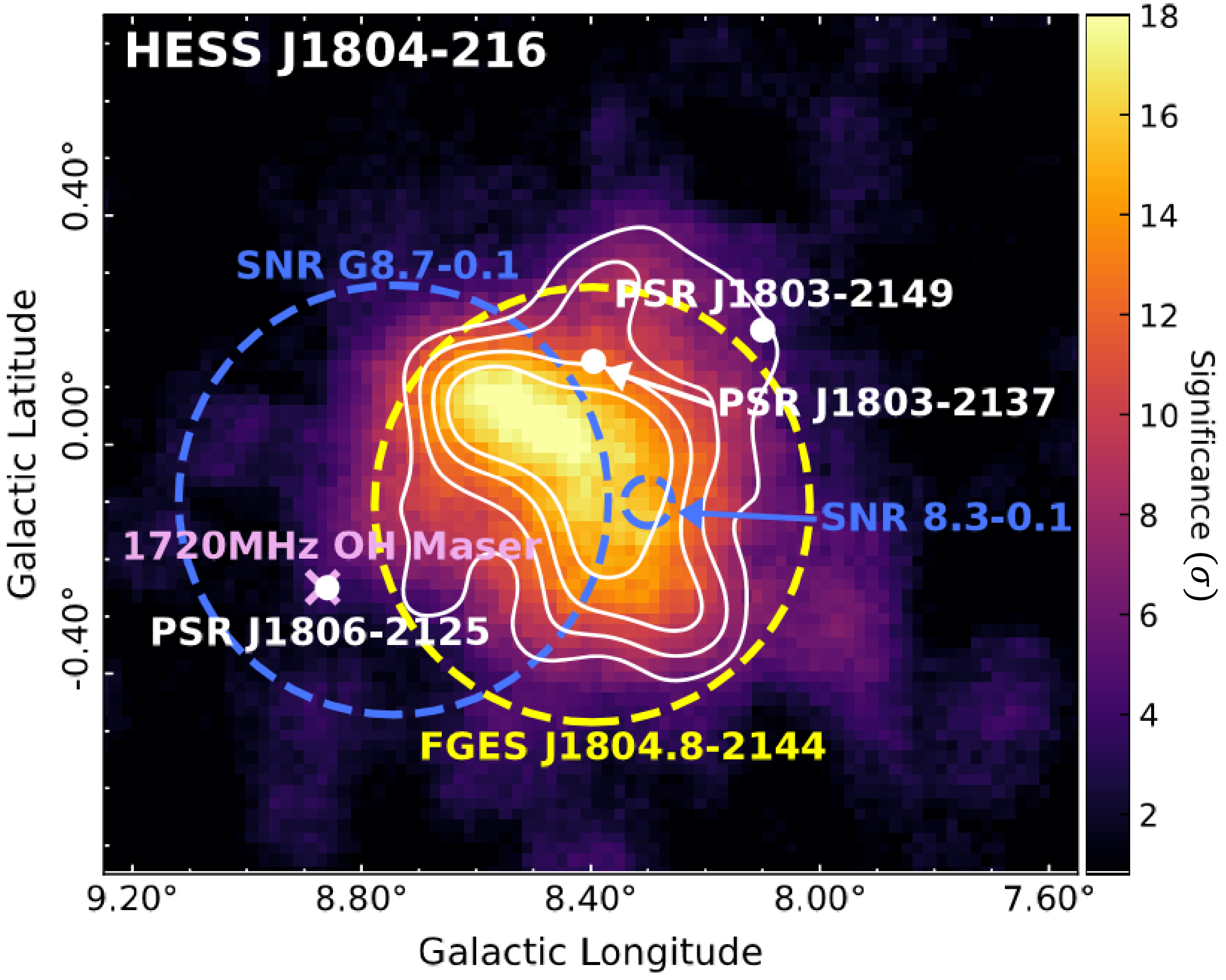


- 3 Binary
- 8 Composite
- 8 SNR
- 12 PWN
- **36 Unidentified**



2018 HGPS map: HESS Collaboration at https://arxiv.org/pdf/1804.02432.pdf

HESS J1804-216 – the bright and unknown



- $L_\gamma \sim 5 \times 10^{33} (d_{kpc})^2$ erg s^{-1}
- $\Gamma = 2.69 \pm 0.04$

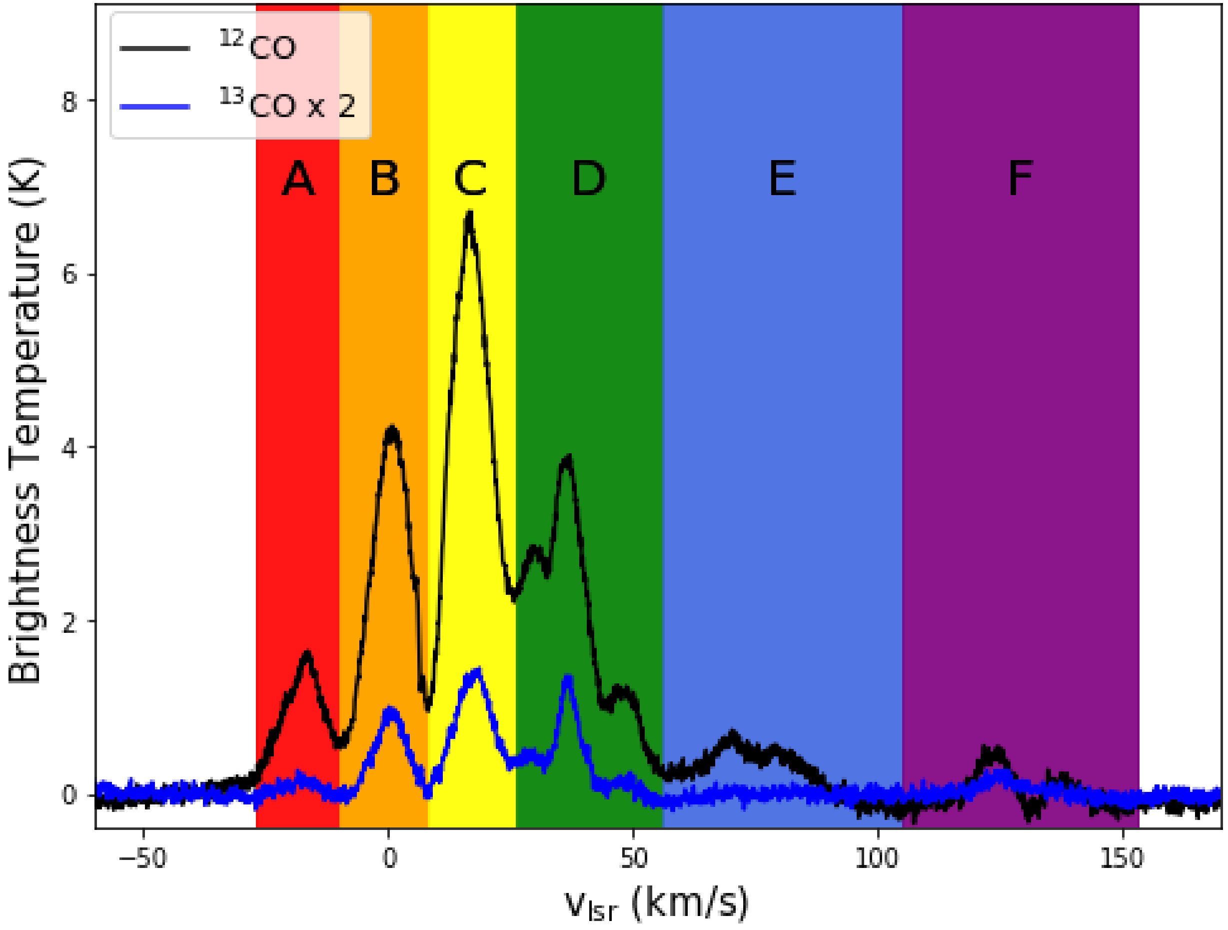
"Arc-minute-scale studies of the interstellar gas towards HESS J1804−216: Still an unidentified TeV Gamma-ray source", accepted for PASA

- Detailed ISM study with 3mm, 7mm and 12mm Mopra data
- Most potential accelerators:
  - **SNR G8.7-0.1**
    - Radius: 0.42°
    - Distance 4.5 kpc
    - Age: 15 kyr
  - **1720MHZ OH Maser**
    - Distance: 4.6 kpc
  - **PSR J1803-2137**
    - Distance: 3.8 kpc
    - Age: 16 kyr
    - Spin down power: 2.22×10^{36} erg s^{-1}
    - TeV gamma-ray efficiency: 3%

FGES = Fermi Galactic Extended Sources → one of the Fermi catalogs
Significance map: HESS Collaboration at https://arxiv.org/pdf/1804.02432.pdf

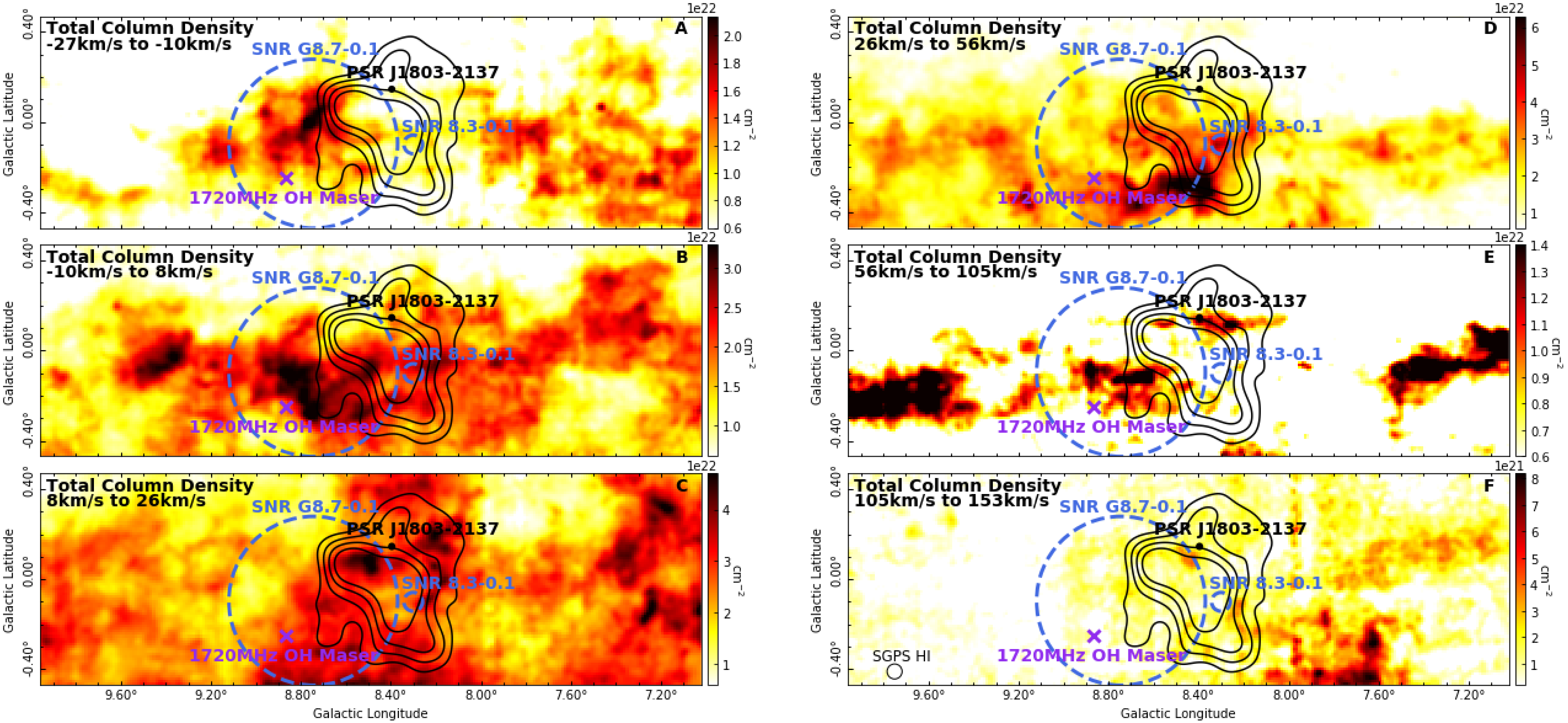
Mopra CO Survey

- 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



Total Column Density

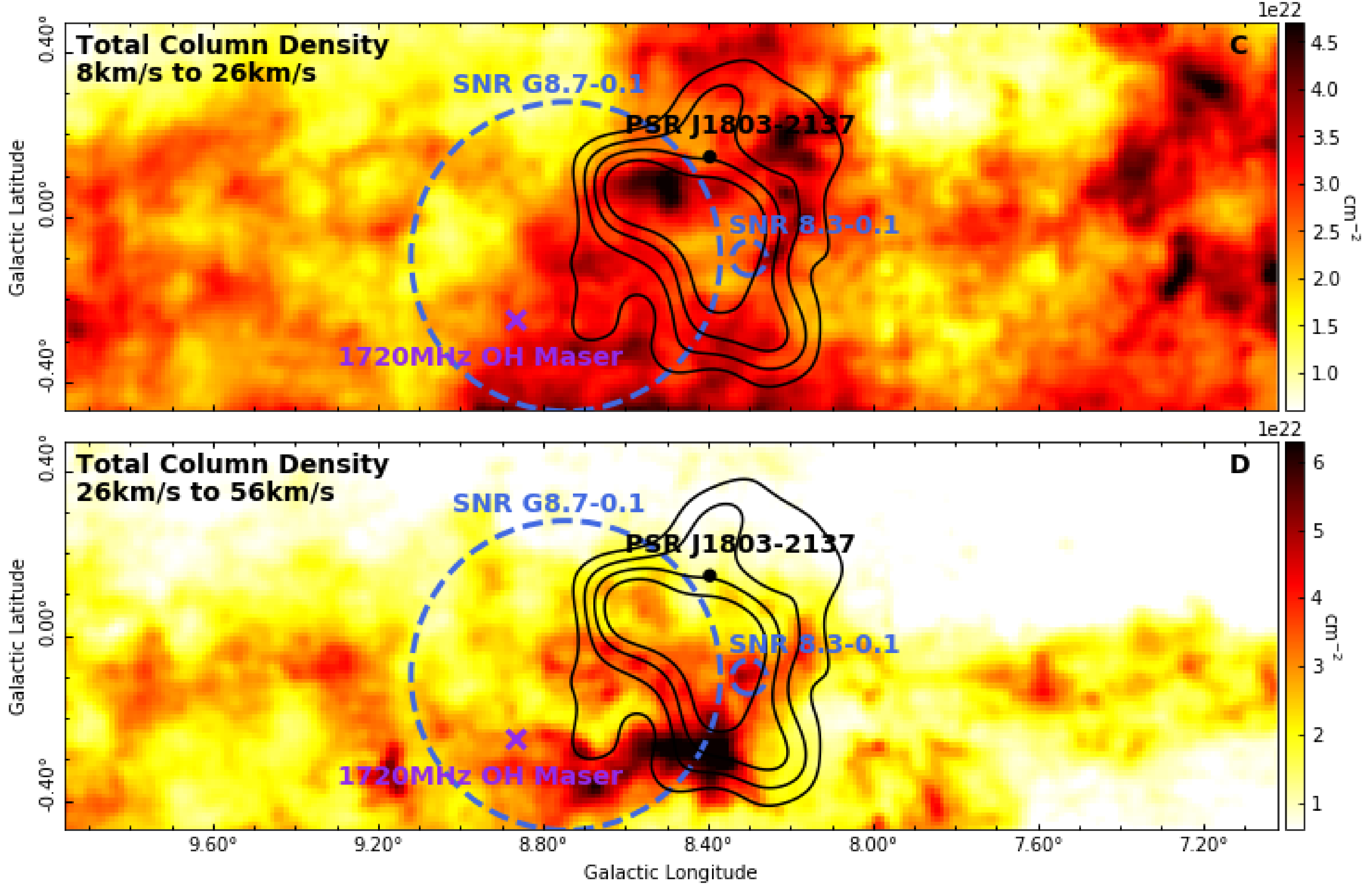
$$N(H) = N(HI) + 2N(H_2)$$



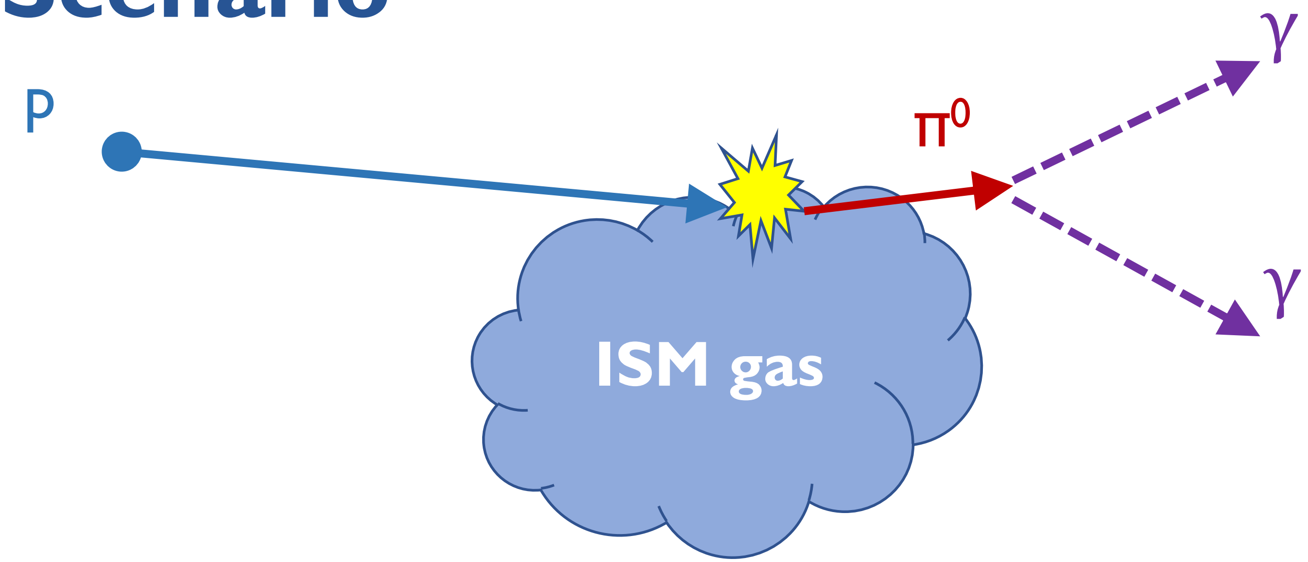
Components of Most Interest

PSR J1803-2137
at ~25km/s

SNR G8.7-0.1
at ~35km/s



Hadronic Scenario



- Older SNRs believed to have large enough hadronic contribution to account for TeV gamma–ray emission
- Two plausible candidates for the acceleration of CRs for the hadronic scenario
  - SNR G8.7-0.1
  - Progenitor SNR of PSR J1803-2137

Hadronic contribution: Yamazaki et al 2006 https://academic.oup.com/mnras/article/371/4/1975/1061316

Proton model

- Distribution of CR protons assuming time dependent escape of CR protons

$$J_p \equiv f(E,R,t) \approx \frac{N_0 E^{-\alpha}}{\pi^{3/2} R_{dif}^3} \exp\left(-\frac{(R-R_c)^2}{R_{dif}^2}\right) \qquad [\mathrm{cm^{-3}\,GeV^{-1}}]$$

- Diffusion radius:

$$R_{dif} = 2\sqrt{D(E)t' \frac{\exp(t'\delta/\tau_{pp})-1}{t'\delta/\tau_{pp}}}$$

  - $t' = t - t_{esc}$, N_0 is the normalisation factor
- The escape radius of particles with escape time t_{esc} is:

$$R_c = 0.31 \left(\frac{E_{51}}{n_0}\right)^{1/5} t_{esc}^{2/5} \quad \mathrm{pc}$$

- Escape time of CR protons:

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

- The cooling time for proton-proton collisions is $\tau_{pp} = 6 \times 10^7 (n/\mathrm{cm}^{-3})^{-1}$ yr
- The diffusion coefficient is:

$$D(E) = \chi D_0 \left(\frac{E/GeV}{B/3\mu G}\right)^{\delta} \quad \mathrm{cm^{-2}\,s^{-1}}$$

  - where $D_0 = 3 \times 10^{27}$ cm^{-2} s^{-1}, $B \sim 10\mu G$ and δ & χ are varied

f(E,R,t), Rdif, τ_{pp}: Aharonian and Atoyan, 1996, http://articles.adsabs.harvard.edu/pdf/1996A%26A...309..917A
Rc: Reynolds 2008, https://ui.adsabs.harvard.edu/abs/2008ARA%26A..46...89R/abstract
tesc: Gabici et al 2009, https://ui.adsabs.harvard.edu/abs/2009MNRAS.396.1629G/abstract
Diffusion: Gabici et al 2007, https://arxiv.org/pdf/astro-ph/0610032.pdf

Proton model

$$J_p \equiv f(E,R,t) \approx \frac{N_0 E^{-\alpha}}{\pi^{3/2} R_{dif}^3} \exp\left(-\frac{(R-R_c)^2}{R_{dif}^2}\right)$$

- For radii less than the R_c particles with energy less than E_{esc} are trapped inside a sphere (called the ‘bubble’)

$$E_{esc} = E_{p,\max\_100} \left(\frac{100\text{yr}}{t_{SNR}}\right)^{-\delta_p}$$

- The probability density function is the same through the entire bubble
  - Probability of particles within the bubble sphere is given by $\frac{1}{V_{sphere}} = \frac{1}{\frac{4}{3}\pi R_{bubble}^3}$
- Therefore the bubble is filled with the following function

$$f_{bubble} = \frac{N_0 E^{-\alpha}}{\frac{4}{3}\pi R_{bubble}^3}$$

Gamma-ray flux

- Gamma-ray production rate is computed through:

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

  - 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:

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

  - D is the distance to the source

- Note: the following slides show the preliminary results

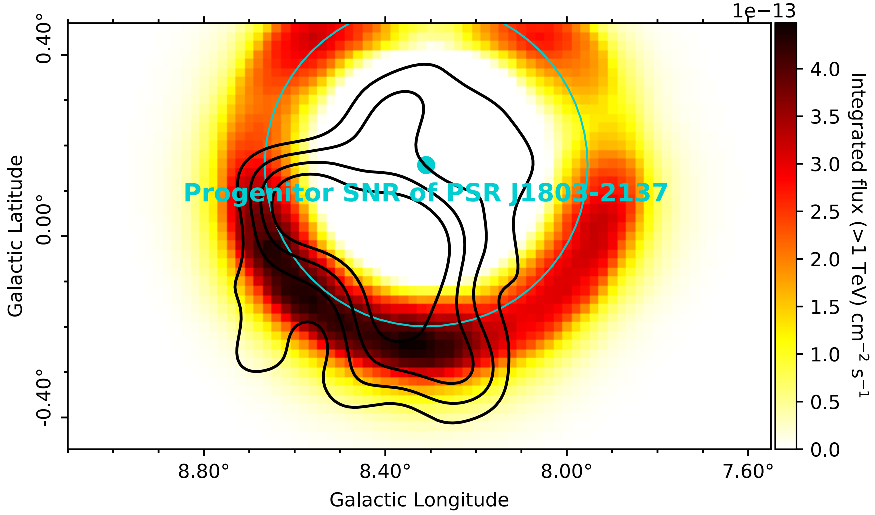
Gamma-ray production rate equation: Kelner et al, 2006: https://arxiv.org/abs/astro-ph/0606058

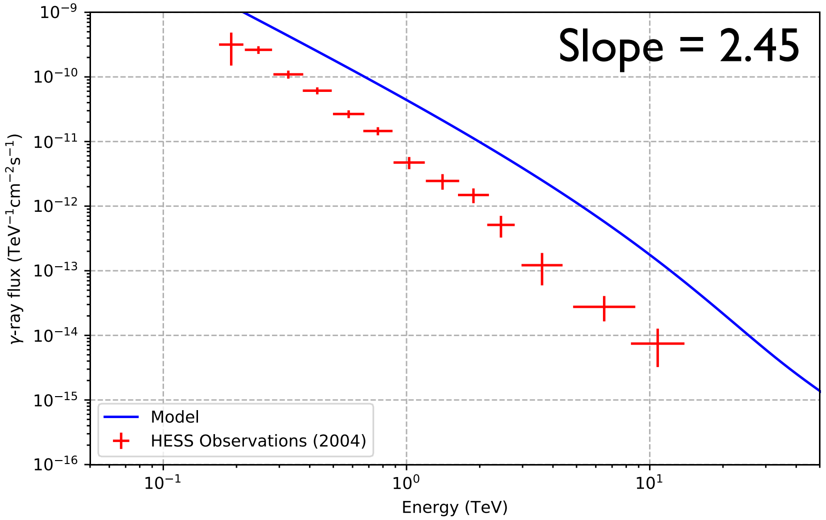
Parameter influence – δ

$$D(E) = \chi D_0 \left(\frac{E/GeV}{B/3\mu G}\right)^{\delta} \quad \mathrm{cm^{-2}\,s^{-1}}$$

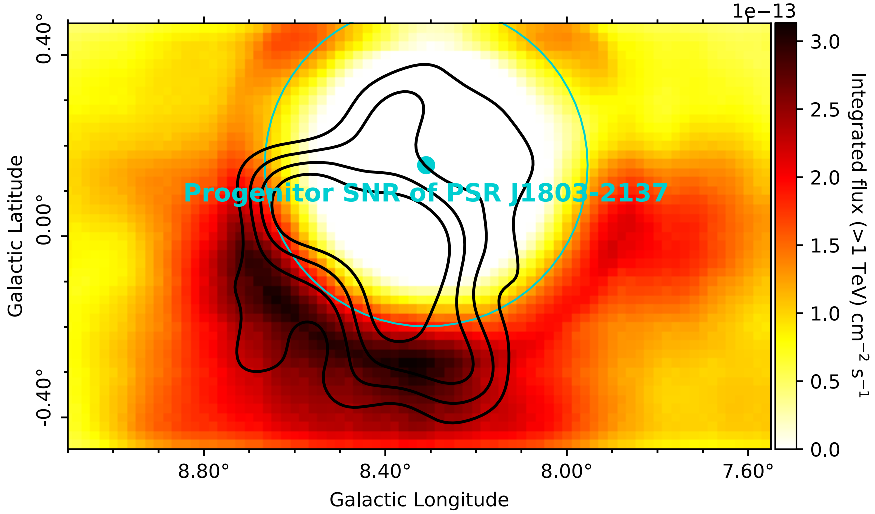
Preliminary

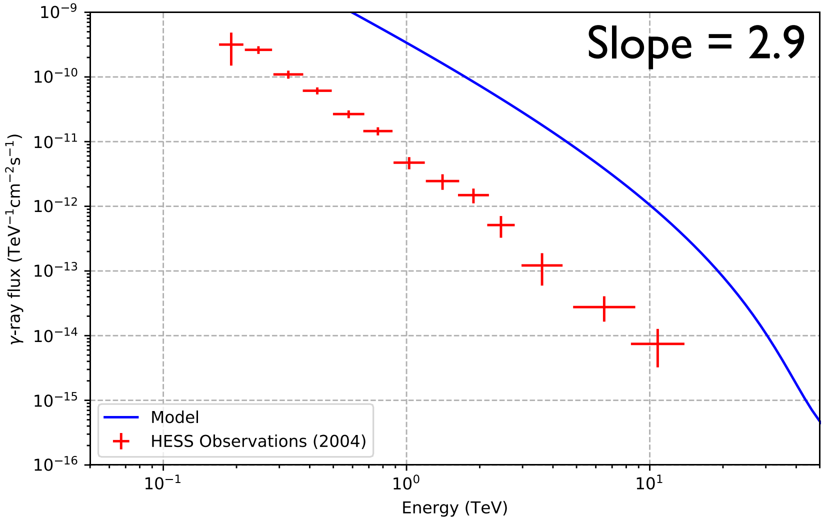
δ = 0.3





δ = 0.7





- Changes in morphology: as δ increases there is more spread
- Spectral index: increases as δ increases

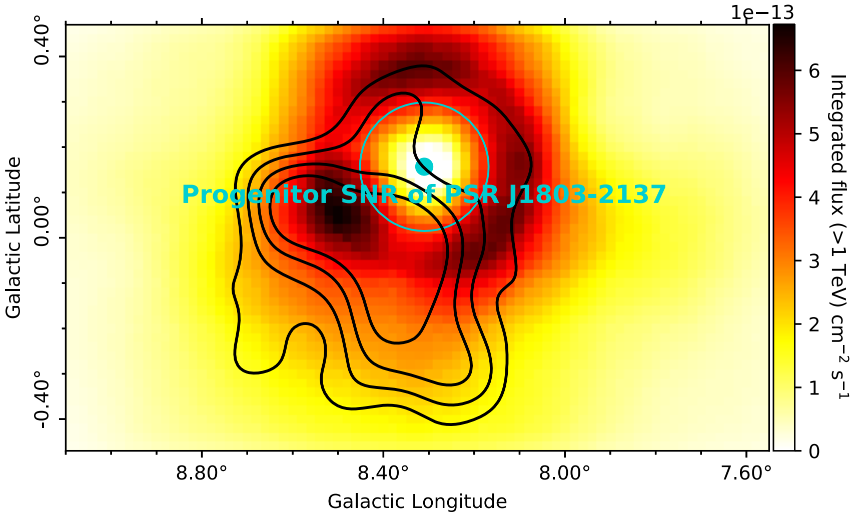
HESS observation data: Aharonian et al, 2006: https://arxiv.org/abs/astro-ph/0510397

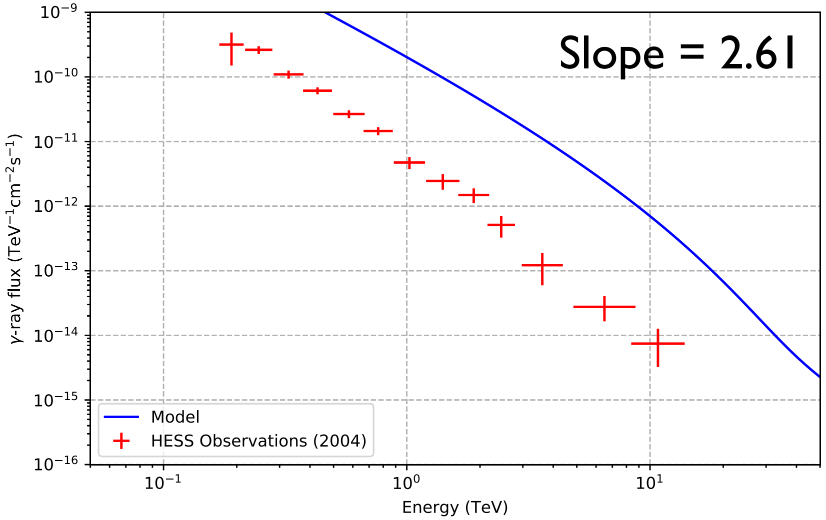
Parameter influence – χ

$$D(E) = \chi D_0 \left(\frac{E/GeV}{B/3\mu G}\right)^{\delta} \quad cm^{-2}\,s^{-1}$$

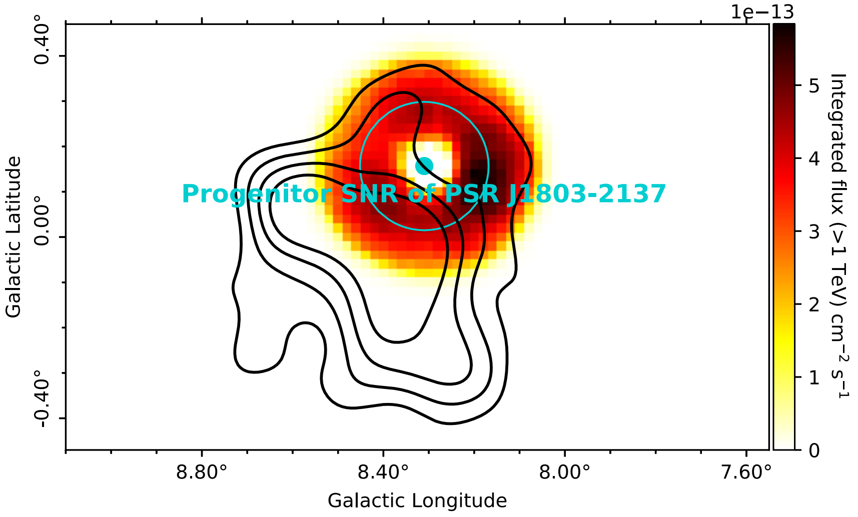
Preliminary

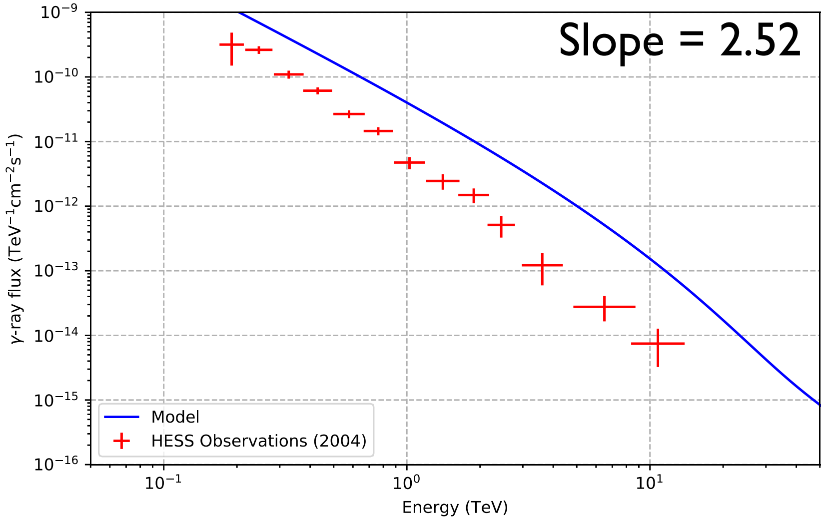
χ = 0.1





χ = 0.001





- Changes in morphology: as χ increases there is more spread
- Spectral index: increases as χ increases

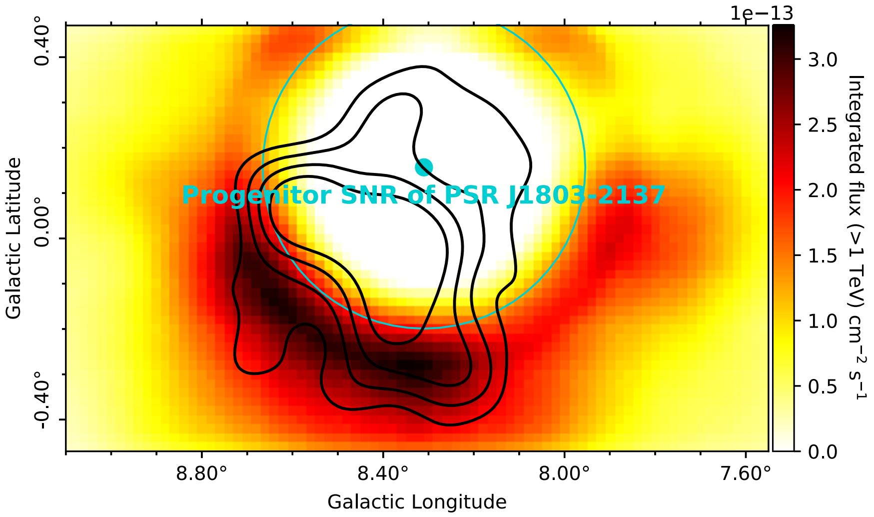
HESS observation data: Aharonian et al, 2006: https://arxiv.org/abs/astro-ph/0510397

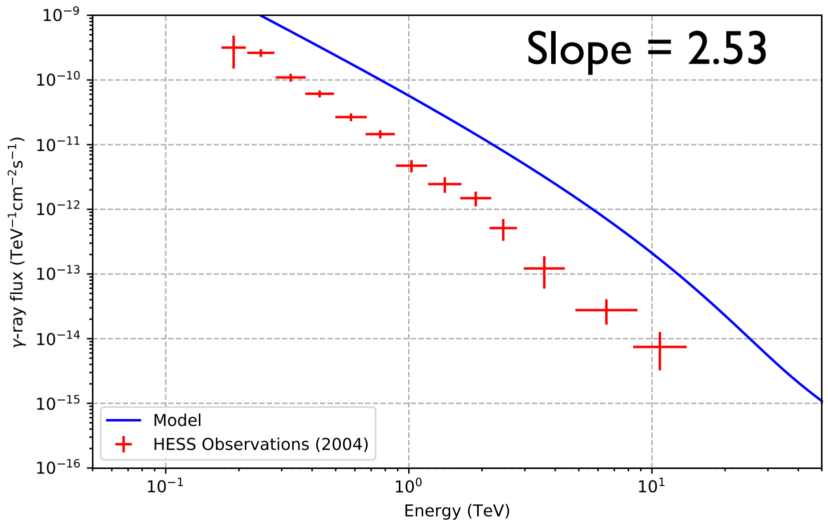
Parameter influence – n_0

$$R_c = 0.31 \left(\frac{E_{51}}{n_0}\right)^{1/5} t_{esc}^{2/5} \text{ pc}$$

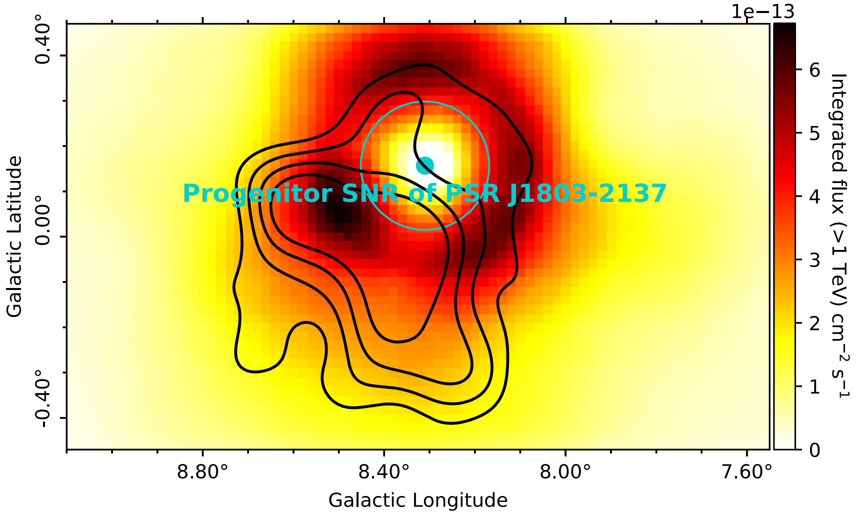
Preliminary

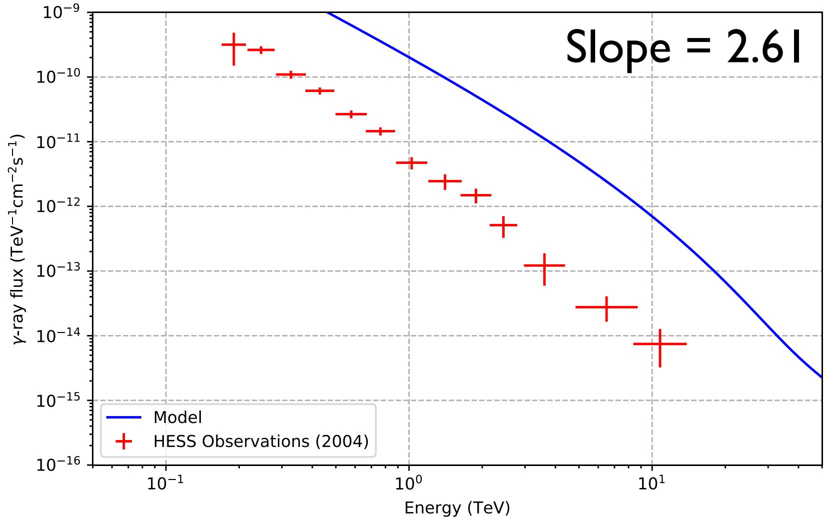
$n_0 = 0.1\ cm^{-3}$





$n_0 = 10\ cm^{-3}$





- Changes in morphology: lower value of n_0 shows a larger spread
- Spectral index: changes only slightly

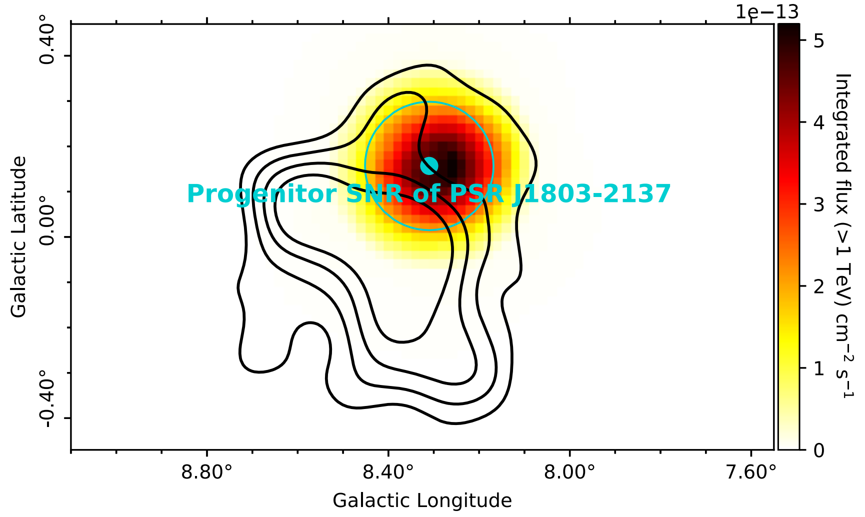
HESS observation data: Aharonian et al, 2006: https://arxiv.org/abs/astro-ph/0510397

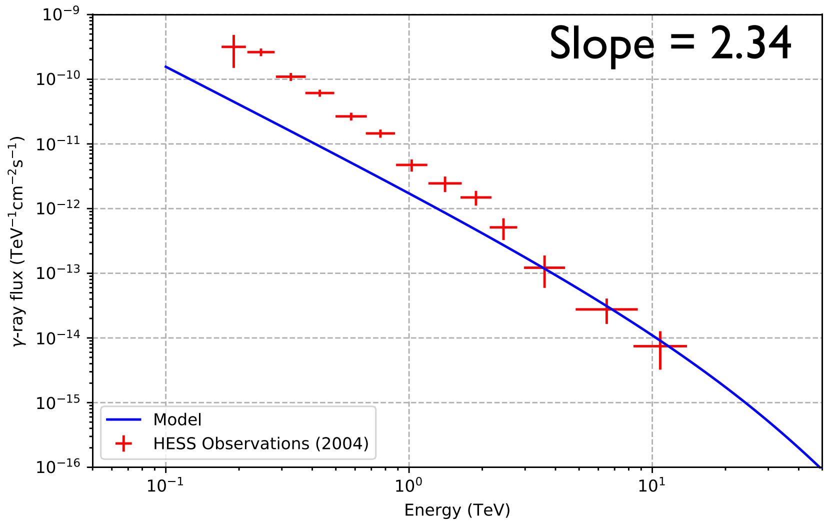
Parameter influence – δ_p

$$\delta_p = \frac{\ln(E_{p,\max\_SNR}/E_{p,\max\_100})}{\ln(100yr/t_{SNR})}$$

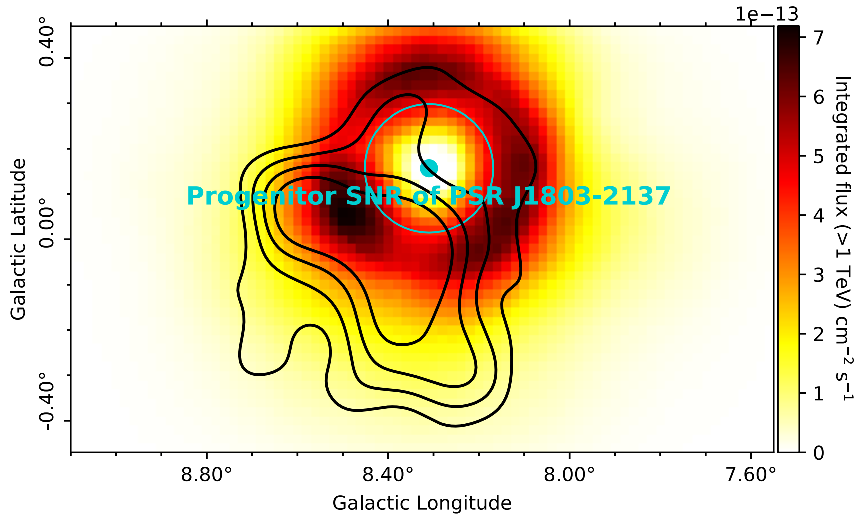
Preliminary

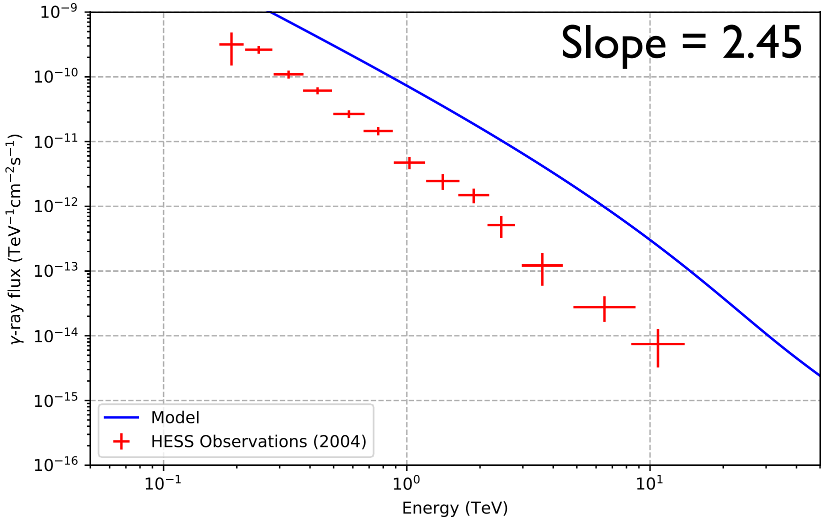
E_{p,max_snr} = 150 TeV
δ_p = 0.37





E_{p,max_snr} = 65 TeV
δ_p = 0.54





- Changes in morphology: δ_p increases the escape radius is different
- Spectral index: increases as δ_p increases

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

Model choice

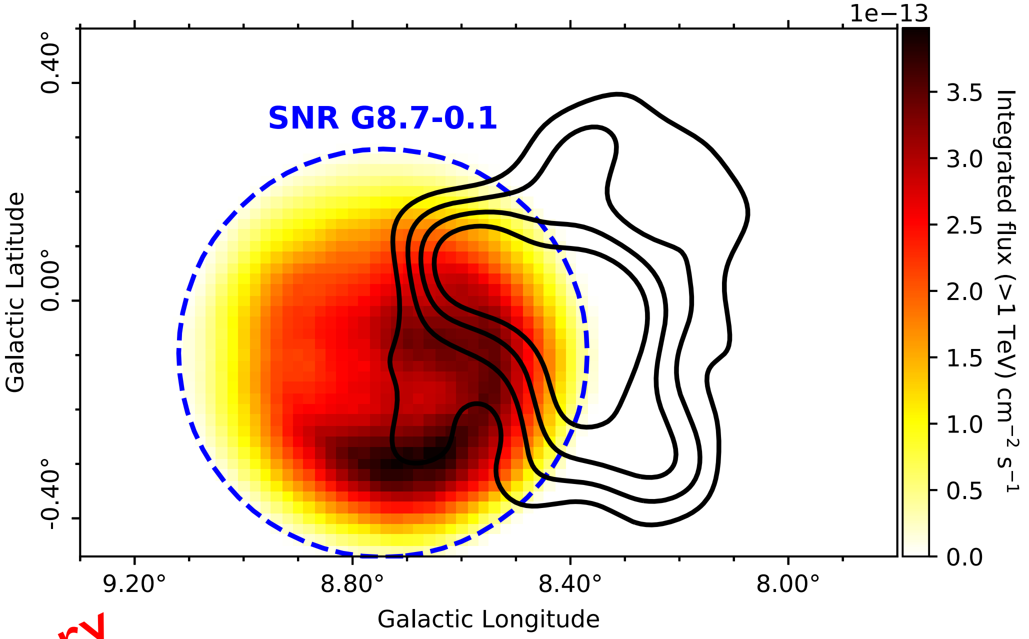
- To determine which model best matches the observations, use a residual sum method

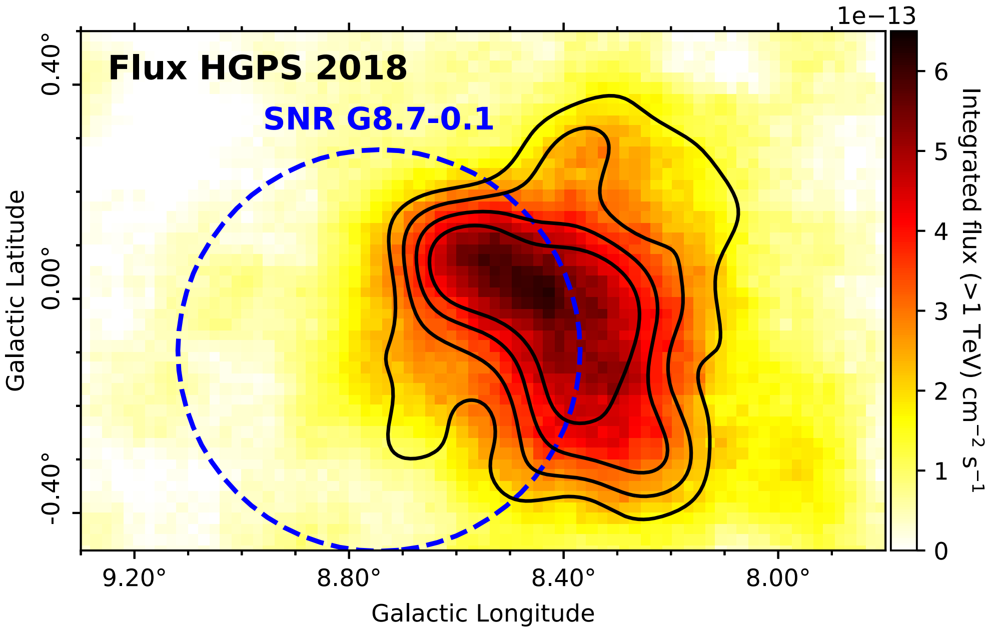
$$\mathrm{RSD} = \sum (\mathrm{observation} - \mathrm{model})$$

- The lowest value of the residual sum means the model is performing well
- Look at the values from observations as well as place some limits
  - HESS J1804-216 observations: $\Gamma = 2.69$, $\mathrm{F}(> 1\mathrm{TeV}) = 5.12 \times 10^{-12}$ cm^{-2} s^{-1}
- Limits for the model
  - $2.5 < \Gamma < 2.8$
  - $E_{budget} < 5 \times 10^{50}$ erg
  - 10^{-12}cm^{-2} s^{-1} $< F(> 1\mathrm{TeV}) < 10^{-11}$ cm^{-2} s^{-1}

Model – SNR G8.7-0.1 (15kyr)

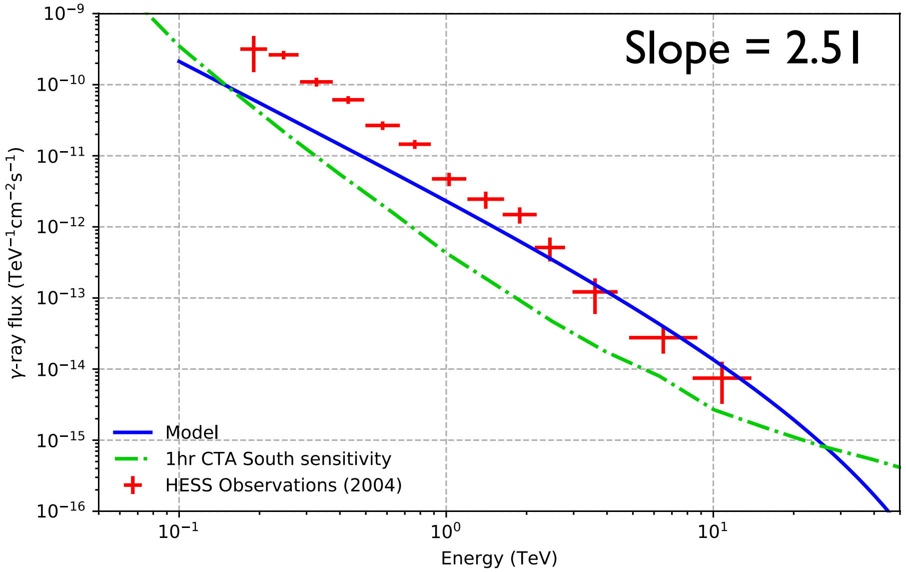
- HESS J1804-216 observations: $\Gamma = 2.69, \quad F(>1\mathrm{TeV}) = 5.12 \times 10^{-12}\ \mathrm{cm^{-2}\,s^{-1}}$

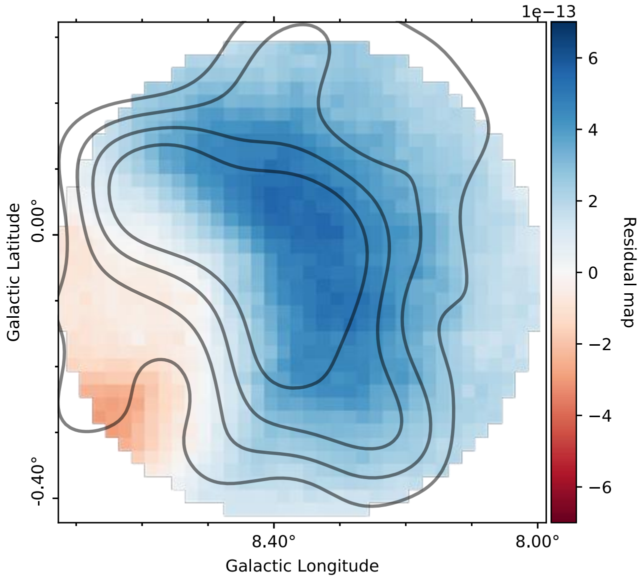




Preliminary

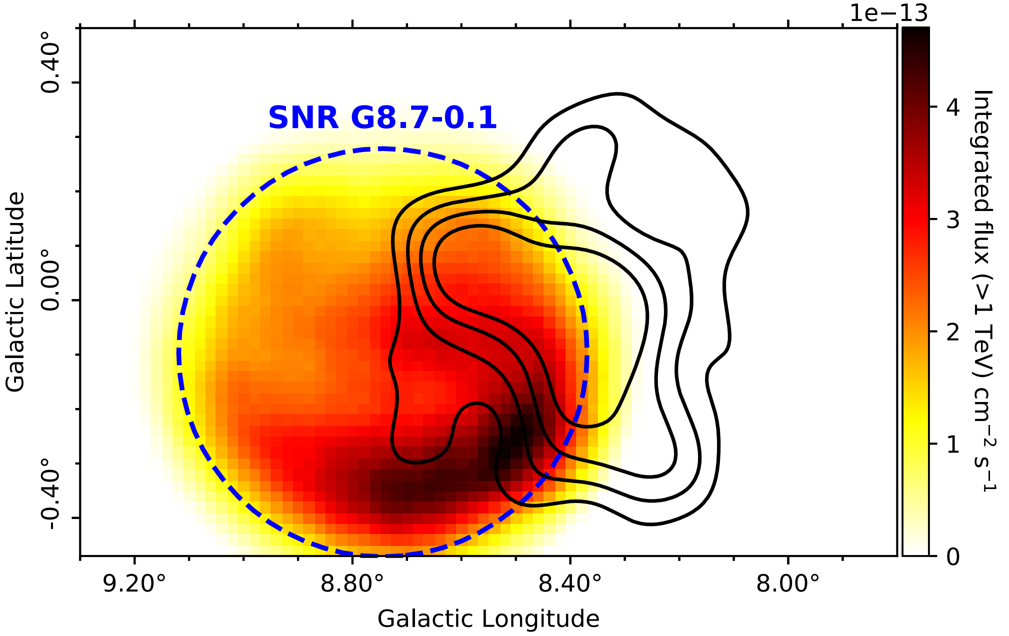
$\chi = 0.001$
$\delta = 0.3$
$n_0 = 0.1\ \mathrm{cm^{-3}}$
$\delta_p = 0.38$
$E_{budget} = 4.4 \times 10^{48}$ erg
$n_{avg} = 160\ \mathrm{cm^{-3}}$

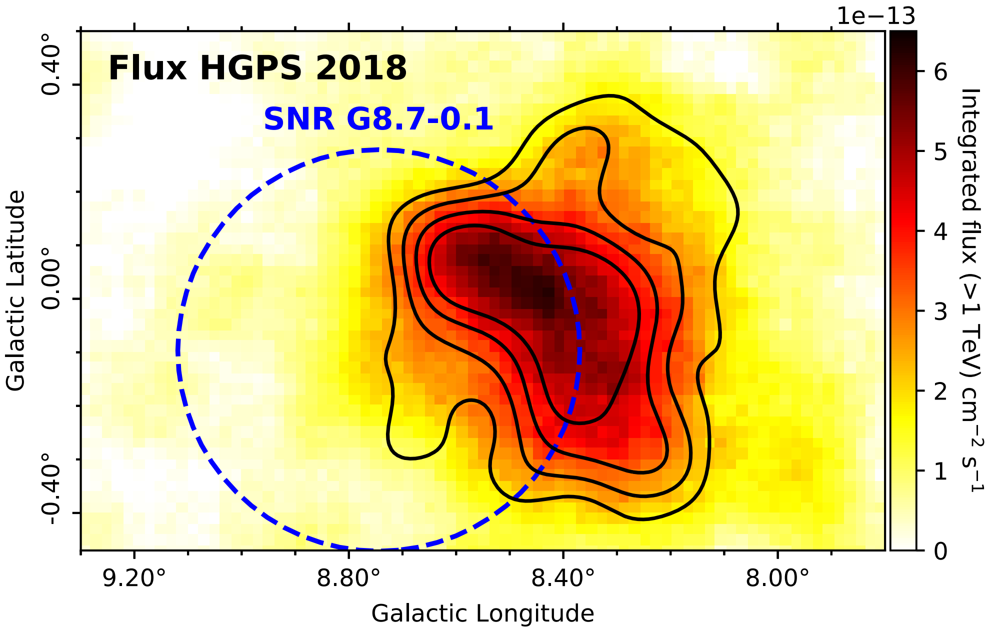




Model – SNR G8.7-0.1 (28kyr)

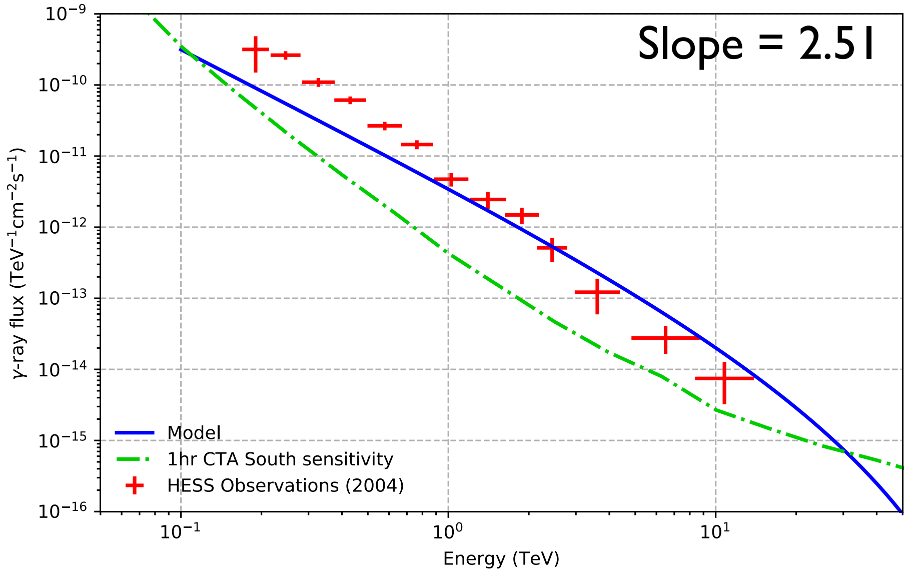
- HESS J1804-216 observations: $\Gamma = 2.69$, $F(> 1\text{TeV}) = 5.12 \times 10^{-12}\ \text{cm}^{-2}\,\text{s}^{-1}$

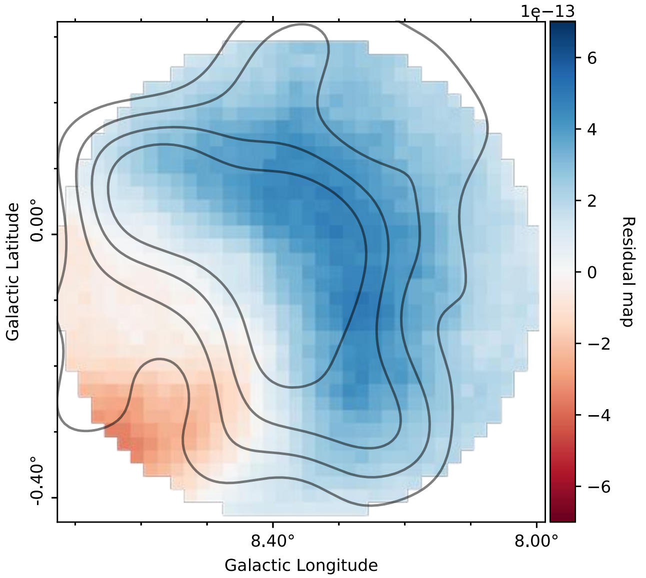




Preliminary

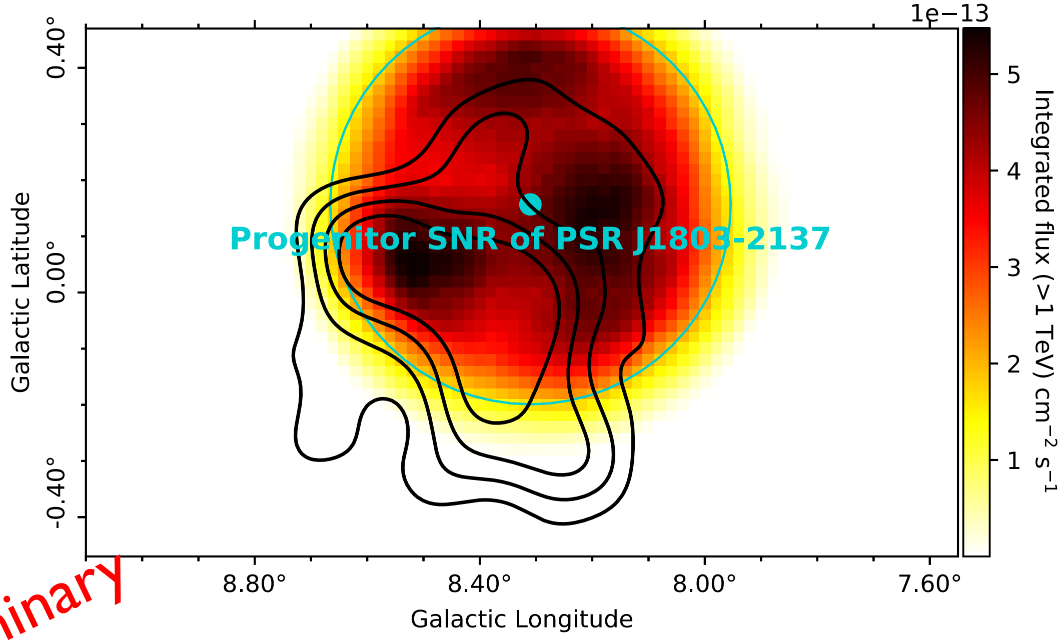
$\chi = 0.001$
$\delta = 0.3$
$n_0 = 0.1\ \text{cm}^{-3}$
$\delta_p = 0.34$
$E_{budget} = 9.1 \times 10^{48}$ erg
$n_{avg} = 160\ \text{cm}^{-3}$

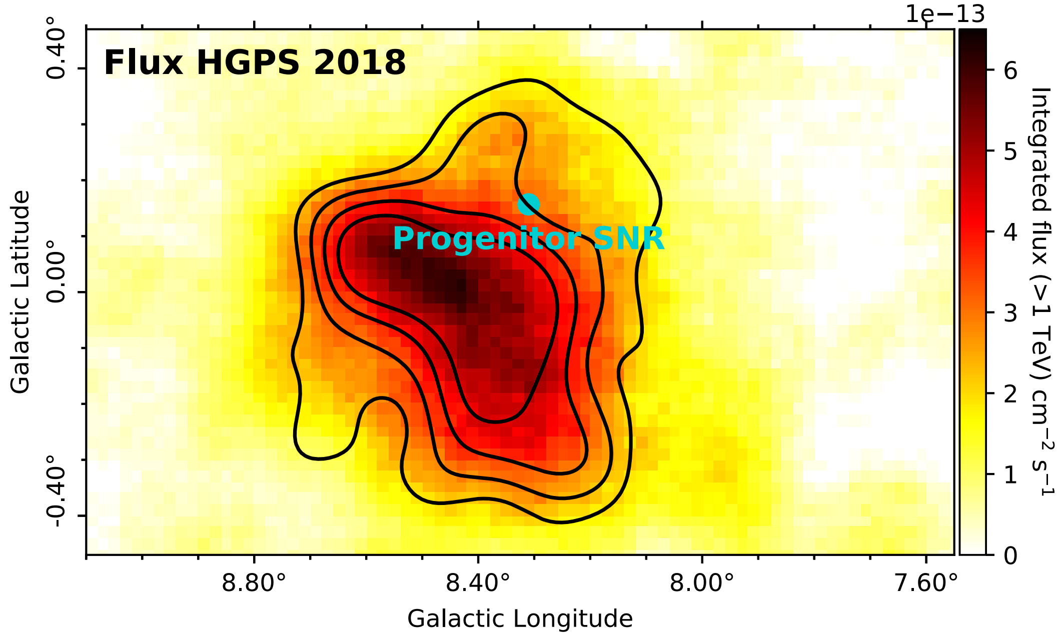




Model – PSR J1803-2137 progenitor SNR (16kyr)

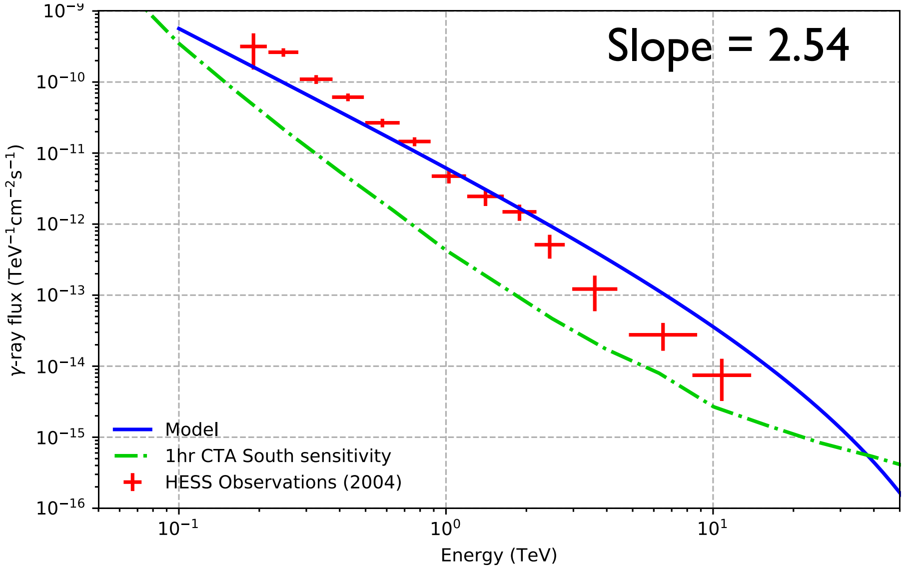
- HESS J1804-216 observations: $\Gamma = 2.69, \quad F(> 1\text{TeV}) = 5.12 \times 10^{-12}\ \text{cm}^{-2}\,\text{s}^{-1}$

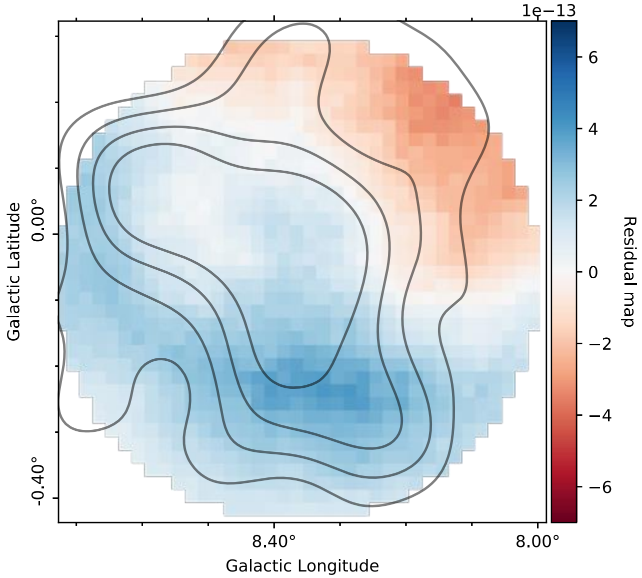




Preliminary

$\chi = 0.01$
$\delta = 0.7$
$n_0 = 0.1\ \text{cm}^{-3}$
$\delta_p = 0.37$
$E_{budget} = 7.1 \times 10^{48}$ erg
$n_{avg} = 325\ \text{cm}^{-3}$





HESS vs potential CTA – SNR G8.7-0.1 (15kyr)

Preliminary

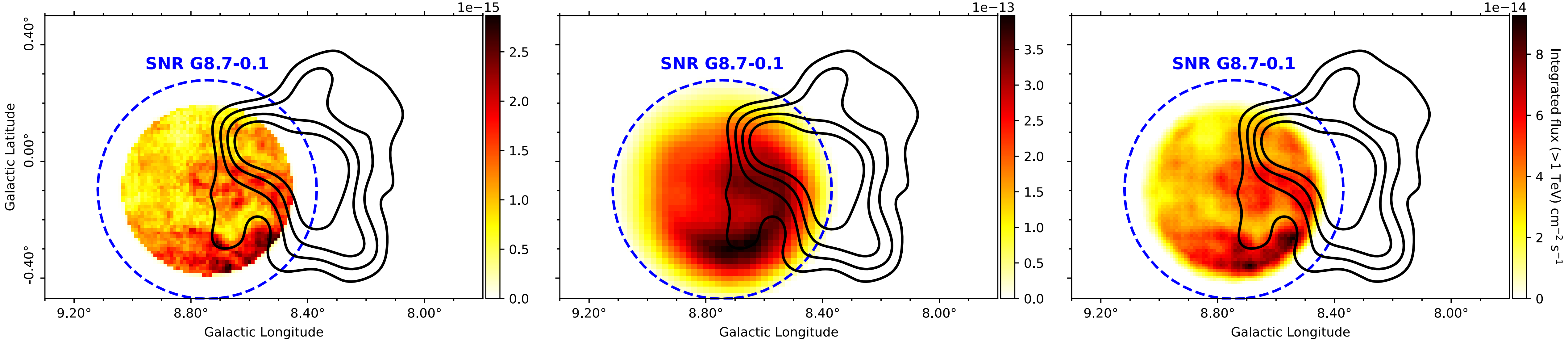
Data straight from gas map

HESS oversampled

- radius = 0.1°

CTA oversampled

- radius = 0.03°



HESS vs potential CTA – SNR G8.7-0.1 (28kyr)

Preliminary

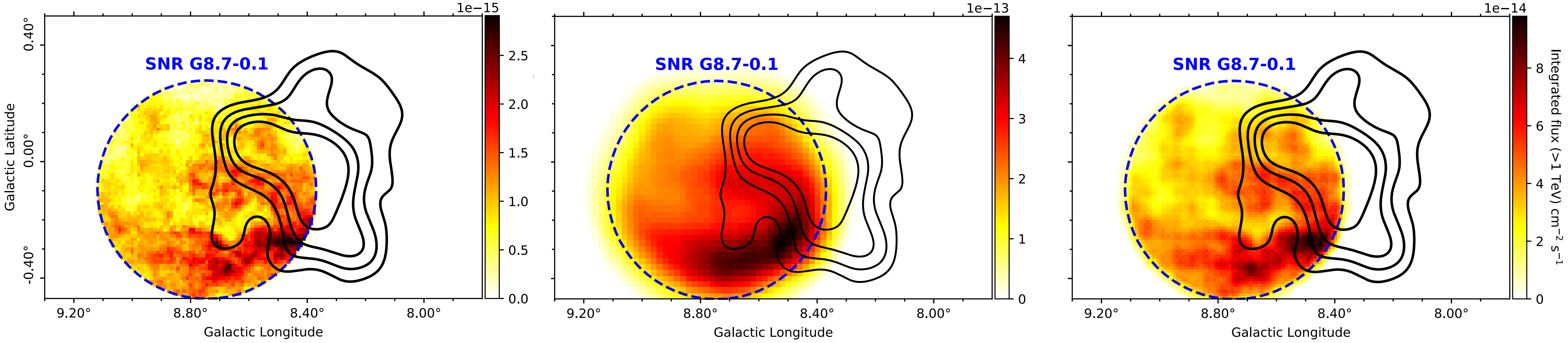
Data straight from gas map

HESS oversampled

- radius = 0.1°

CTA oversampled

- radius = 0.03°



HESS vs potential CTA – PSR J1803-2137 progenitor SNR (16kyr)

Preliminary

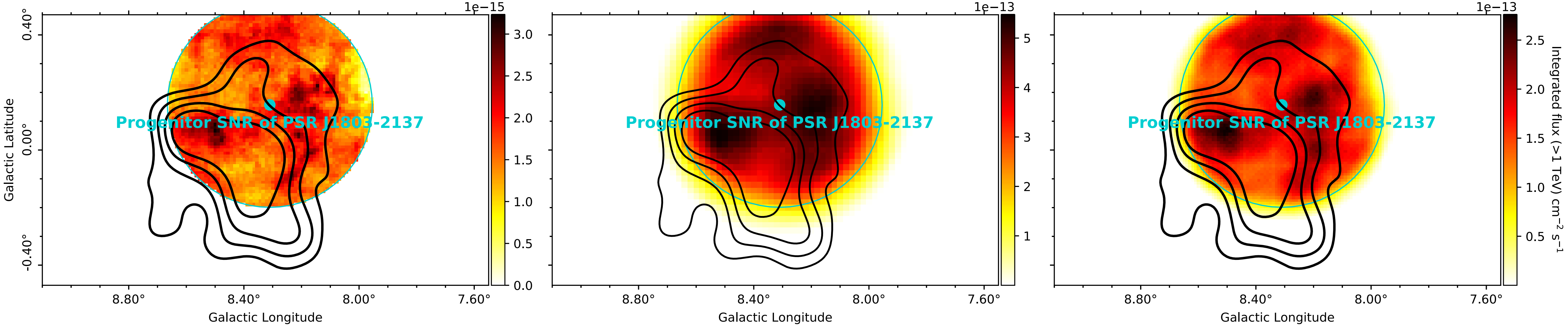
Data straight from gas map

HESS oversampled

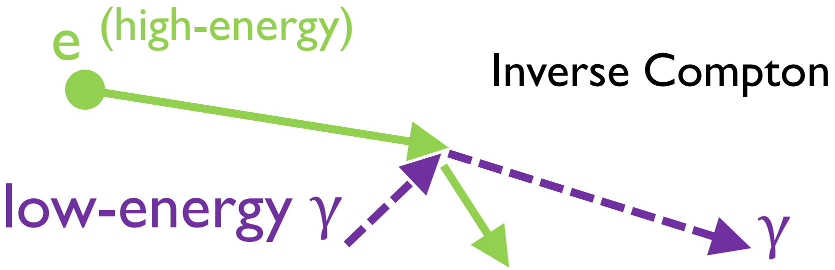
- radius = 0.1°

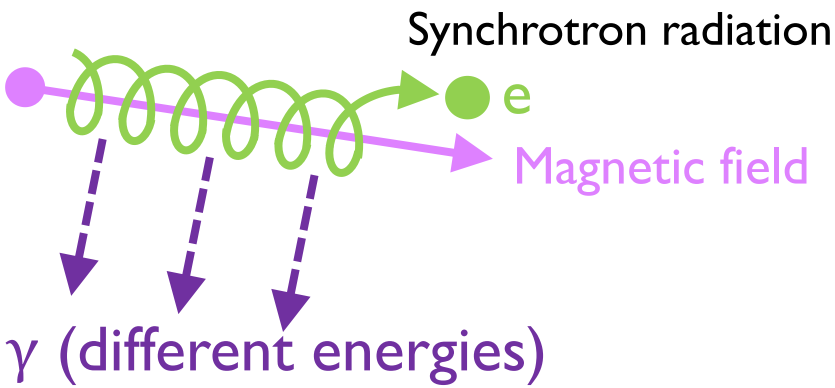
CTA oversampled

- radius = 0.03°



Leptonic Scenario





- In addition to protons, SNR are also believe to accelerate electrons at their shock fronts
- Distribution of electrons

$$f(\gamma, R, t) \approx \frac{N_0 \gamma^{-\alpha}}{\pi^{3/2} R_{dif}^3} (1 - \gamma p_2 t)^{\alpha-2} \exp\left(-\frac{R^2}{R_{dif}^2}\right)$$

- Diffusion radius:

$$R_{dif} = 2\sqrt{D(\gamma) t \frac{1-(1-\gamma/\gamma_{cut})^{1-\delta}}{\gamma/\gamma_{cut}(1-\delta)}}$$

  - This takes into account the losses due to synchrotron and inverse-Compton (p_2)

Electron equations: Atoyan et al 1995: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.52.3265

Electron model

- To convert from electron to gamma rays:

$$\frac{dN_{IC}}{dt\,d\epsilon_1} = \int\int \frac{3\sigma_T c}{4}\left(\frac{m_e c^2}{E_e}\right)^2 f(\gamma, R, t)\frac{I_{BB}(\epsilon)}{\epsilon} f(q) d\epsilon\, dE_e$$

  - I_{BB} is the blackbody distribution:

$$I_{BB}(\epsilon) = \frac{2\epsilon^3}{h^2c^2}\frac{1}{\exp\left(\epsilon/kT\right) - 1}$$

  - σ_T is the Thomson cross section and

$$f(q) = 2q\ln q + (1+2q)(1-q) + \frac{1}{2}\frac{(4q\epsilon E_e/m_e^2c^4)^2}{1+4q\epsilon E_e/m_e^2c^4}(1-q)$$

  - where

$$q = \frac{E_\gamma}{4\epsilon E_e/m_e^2c^4(1-E_\gamma/E_e)}$$

- ϵ is the initial photon energy, E_γ is the gamma-ray energy and E_e is the electron energy

Gamma-ray production rate equation: Manolakou et al 2007 https://arxiv.org/abs/0708.1516

Future work – counts model

- The predicted gamma–ray flux maps can be 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

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

- 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

Summary / Next Steps

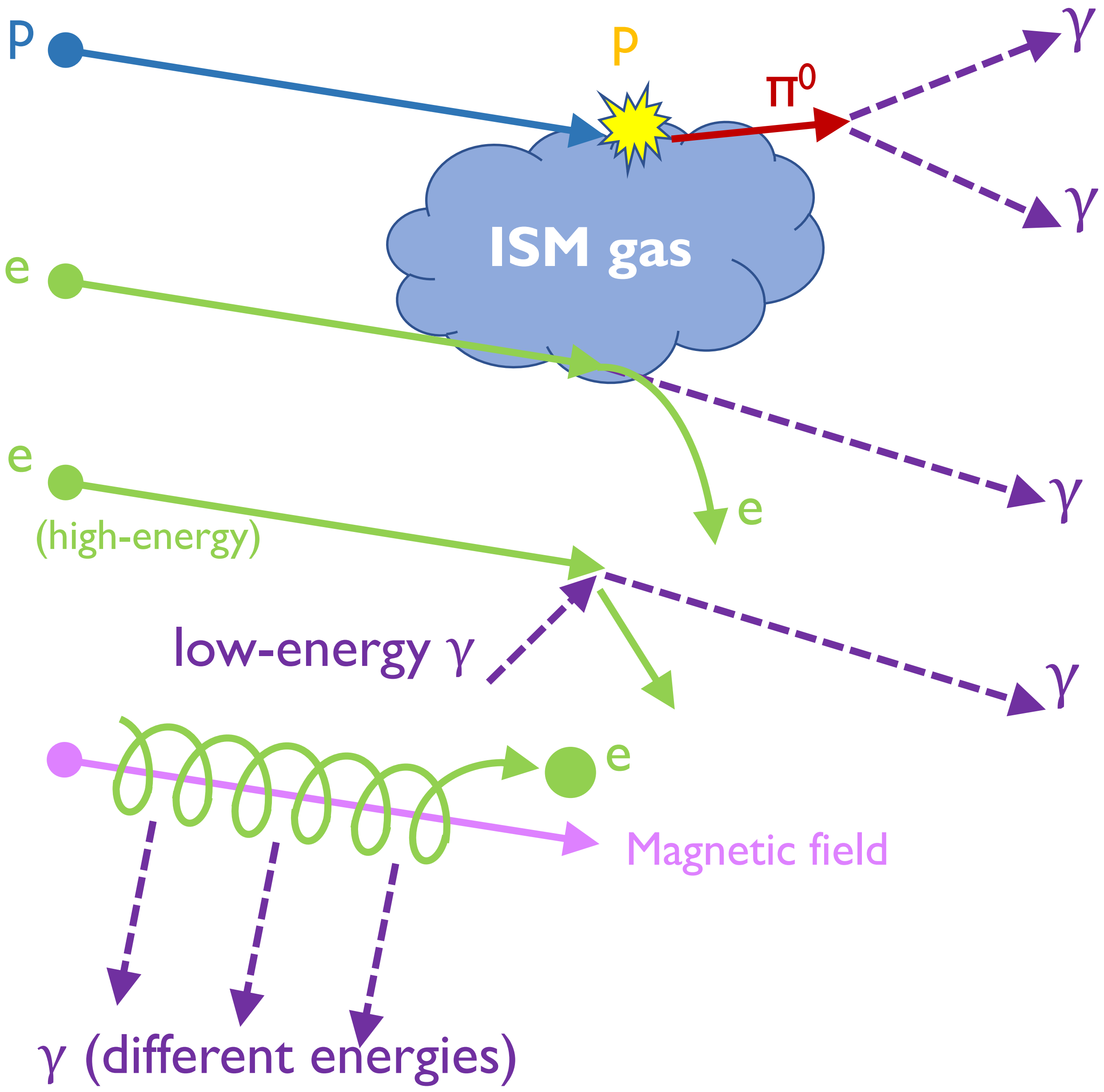
- Molecular clouds provide insight to the complex nature of gamma–ray sources
- Two counterparts for HESS J1804-216 are currently investigated
  - SNR G8.7-0.1
  - Progenitor SNR of PSR J1803-2137
- Optimisation of the hadronic model

Future steps

- Implementation of leptonic model
- Comparison of maps in different energy bands
  - Re-analysis of HESS data
- Hybrid model
- **Simulations of CTA counts maps**

Backup slides

Production of gamma-rays



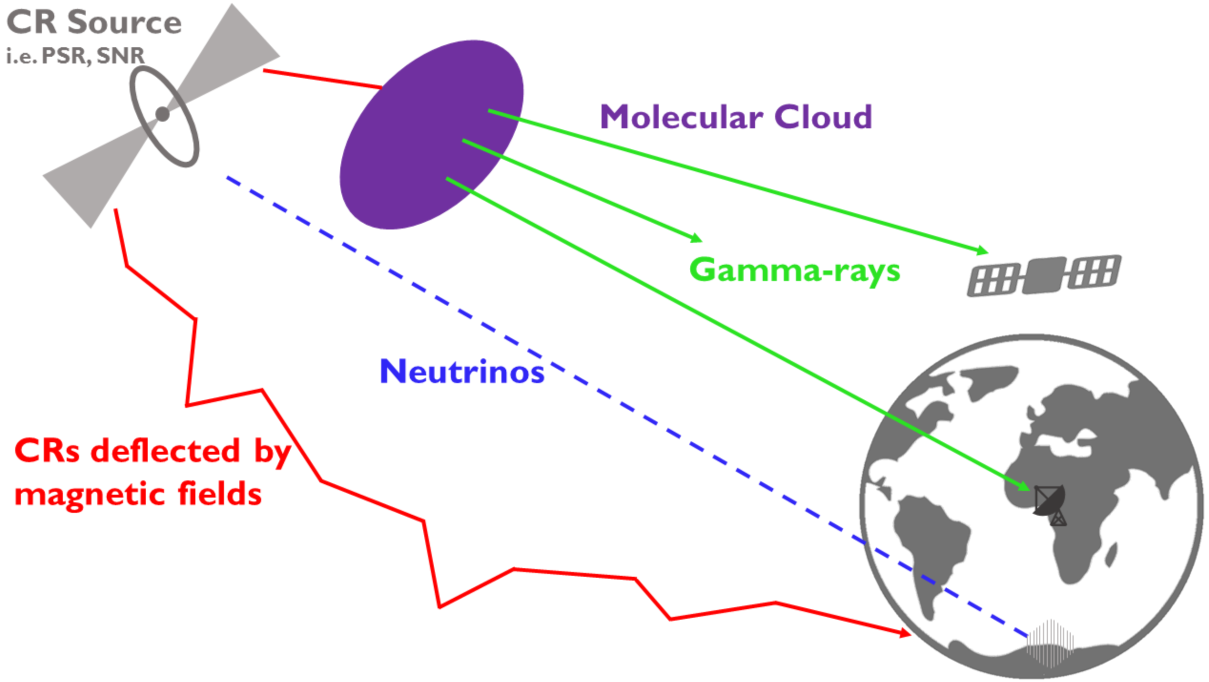
HADRONIC

- π_0 decay

LEPTONIC

- Bremsstrahlung
- Inverse Compton
- Synchrotron Radiation

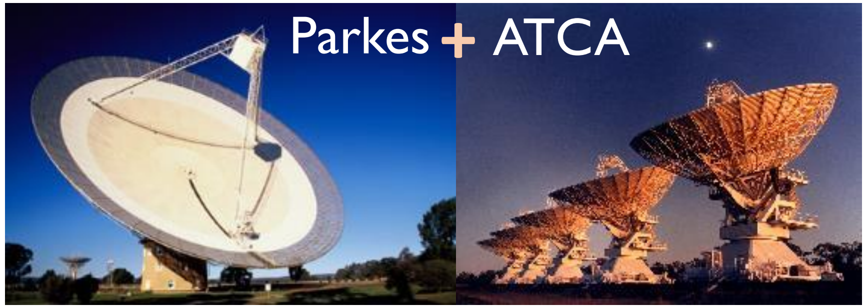
Molecular Clouds



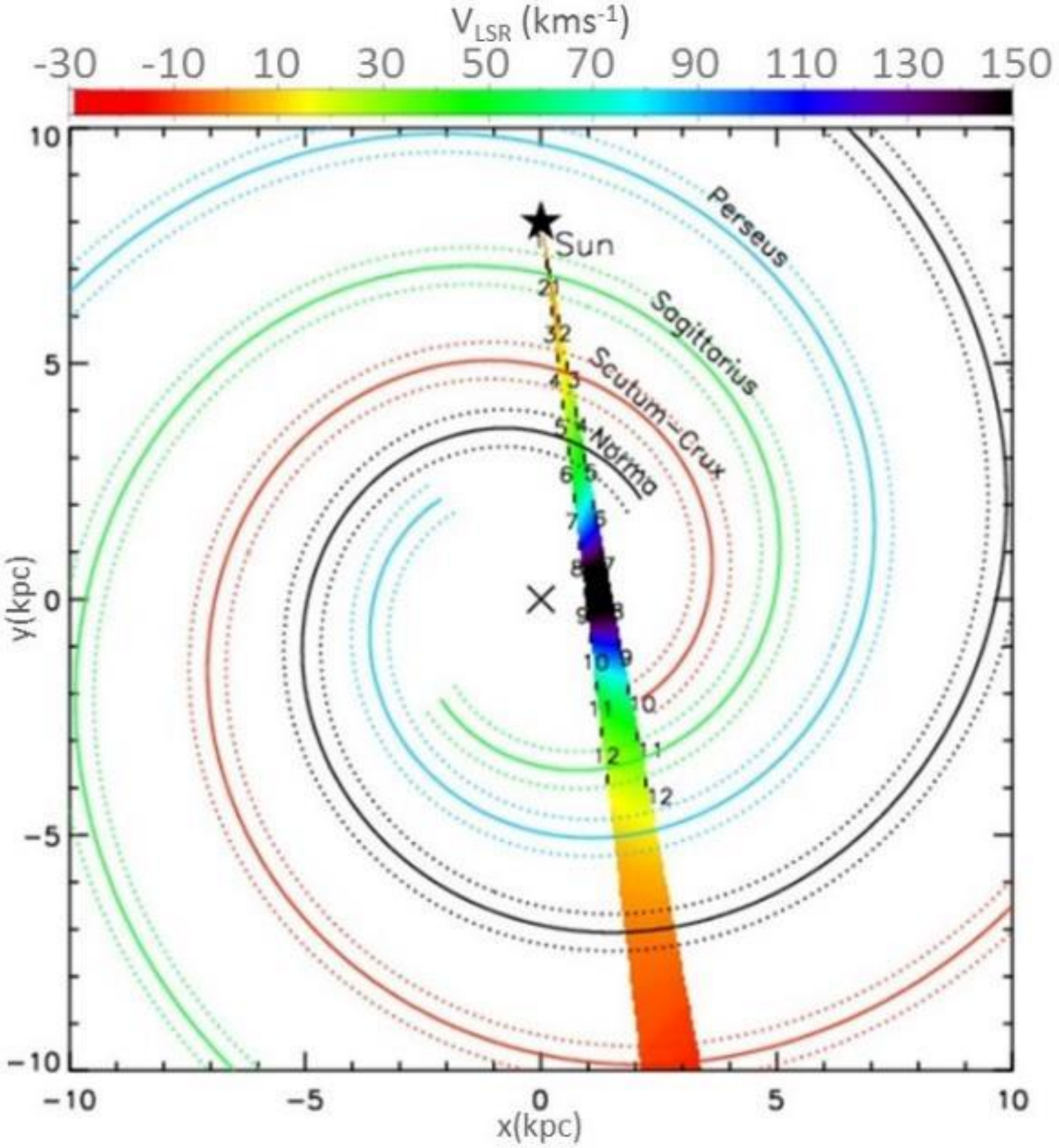
- Clouds serve as a target for cosmic ray (CR) collisions
  - Dense regions of gas give information about gamma-ray sources
- Important to understand the interstellar gas surrounding a source
- Different gas tracers include:
  - Carbon monoxide (CO)
  - Atomic hydrogen (HI)

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



Galactic Rotation Curve

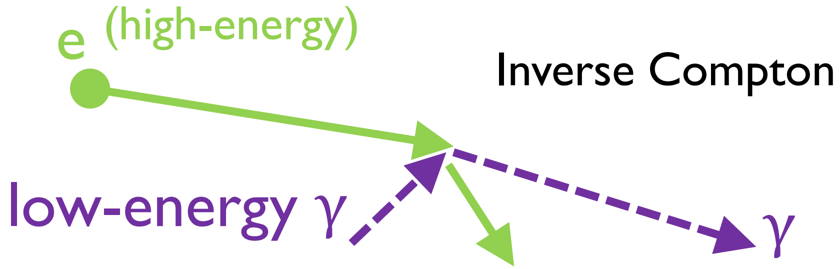


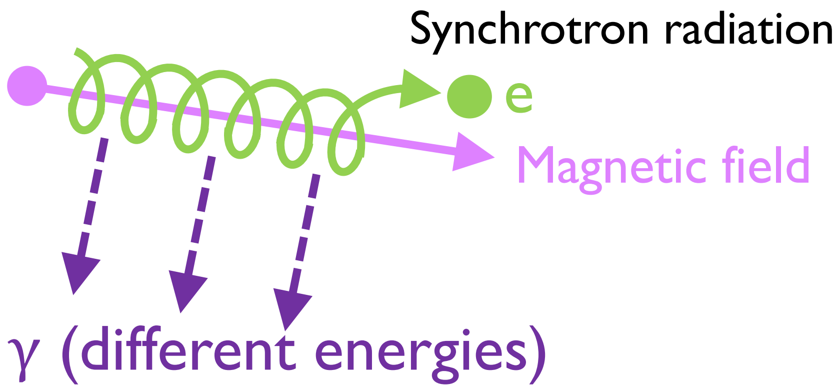
- Distances to sources not easily resolved
- Doppler shifting of spectral lines allows us to estimate these distances
- The Galactic Rotation curve is used to find the various distances related to objects in the local region of HESS J1804-216

Left: Galactic Rotation Curve model for HESS J1804-216

GRC map/code: Courtesy of Nigel Maxted

Leptonic Scenario





- Lorentz factor is $\gamma = E/m_e c^2$ where $m_e = 511$ keV/c^2 $\gamma_{cut} = (p_2 t)^{-1}$, if $\gamma > \gamma_{cut}$ then $f = 0$
- The term due to synchrotron and inverse-Compton losses is

$$p_2 = 5.2 \times 10^{20} \frac{w_0}{\text{eV cm}^3} \ \text{s}^{-1}$$

  - where $w_o = w_B + w_{MBR} + w_{opt}$, is energy density due to the magnetic field (at $B = 5\ \mu$G) , microwave background and optical-IR radiation respectively
    - $w_B = 0.5$ eV/cm³, $w_{MBR} = 0.25$ eV/cm³, $w_{opt} = 0.6$ eV/cm³

Electron equations: Atoyan et al 1995: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.52.3265