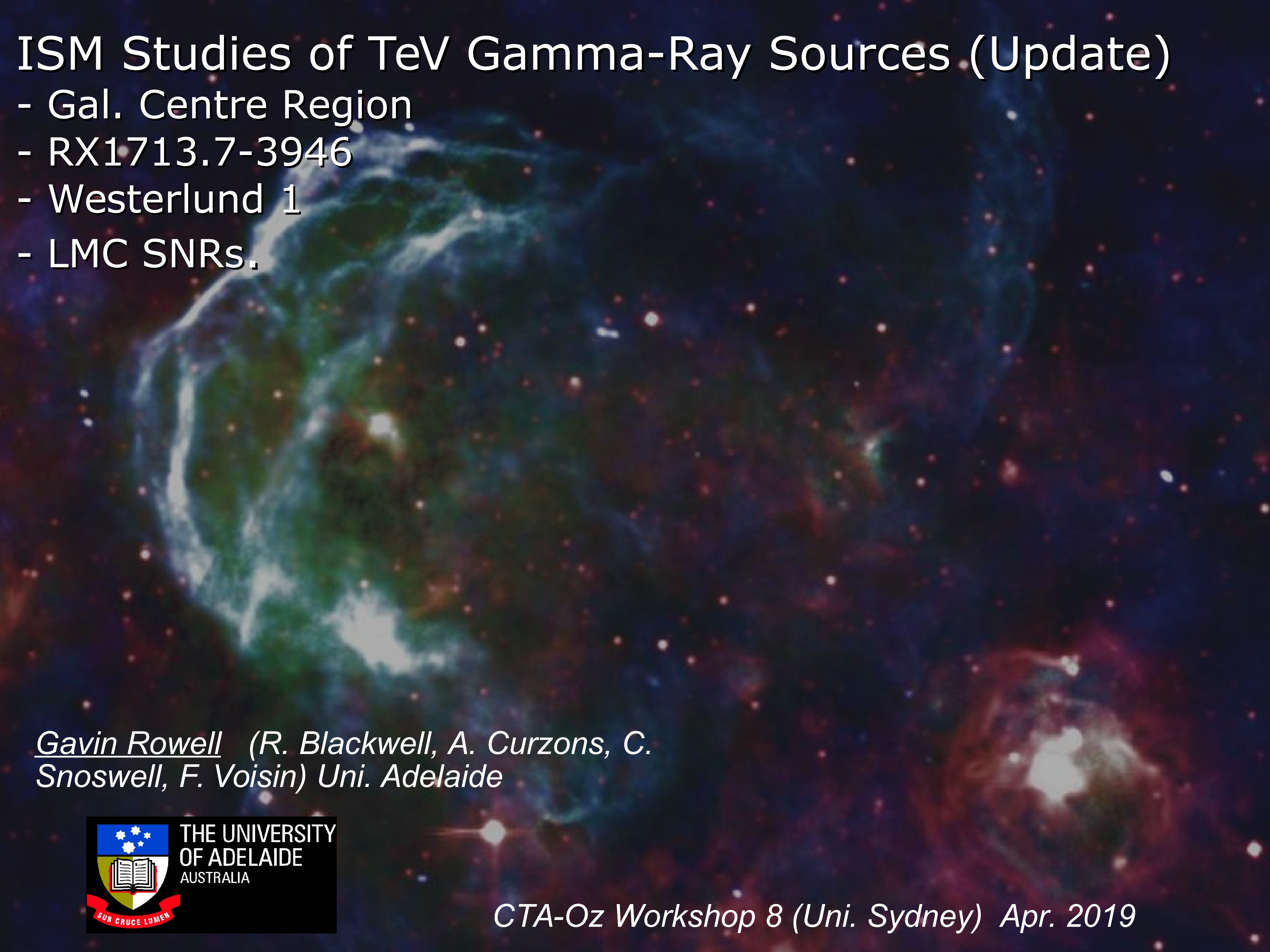


ISM Studies of TeV Gamma-Ray Sources (Update)

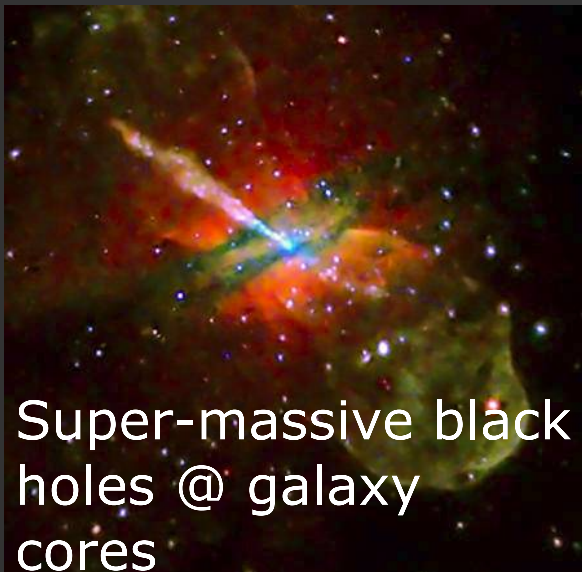
- Gal. Centre Region
- RX1713.7-3946
- Westerlund 1
- LMC SNRs.

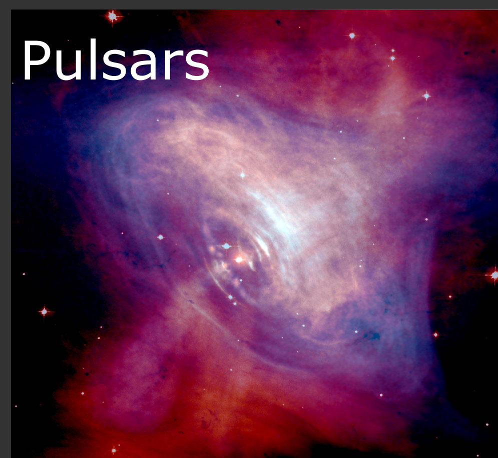
Gavin Rowell (R. Blackwell, A. Curzons, C. Snoswell, F. Voisin) Uni. Adelaide

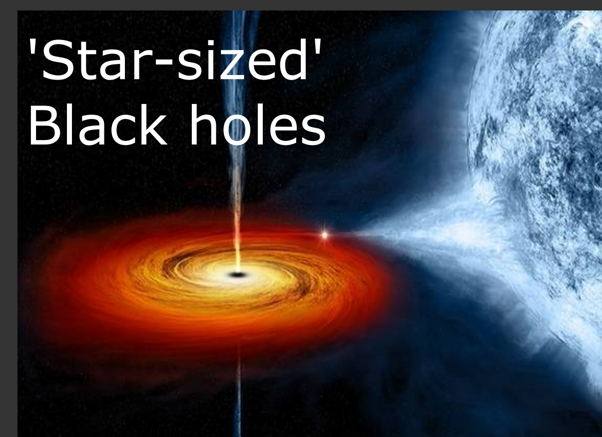
THE UNIVERSITY OF ADELAIDE AUSTRALIA

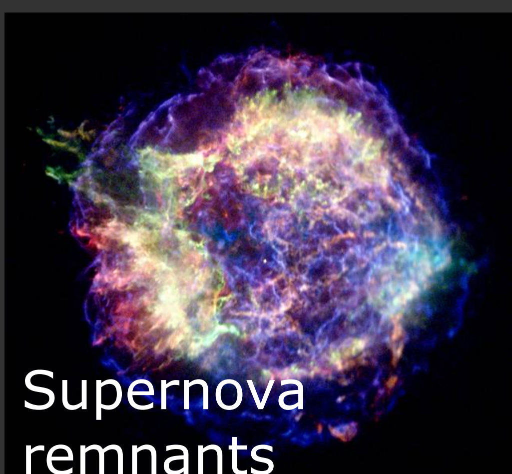
CTA-Oz Workshop 8 (Uni. Sydney) Apr. 2019

Some (potential) Cosmic-Ray and Electron Accelerators



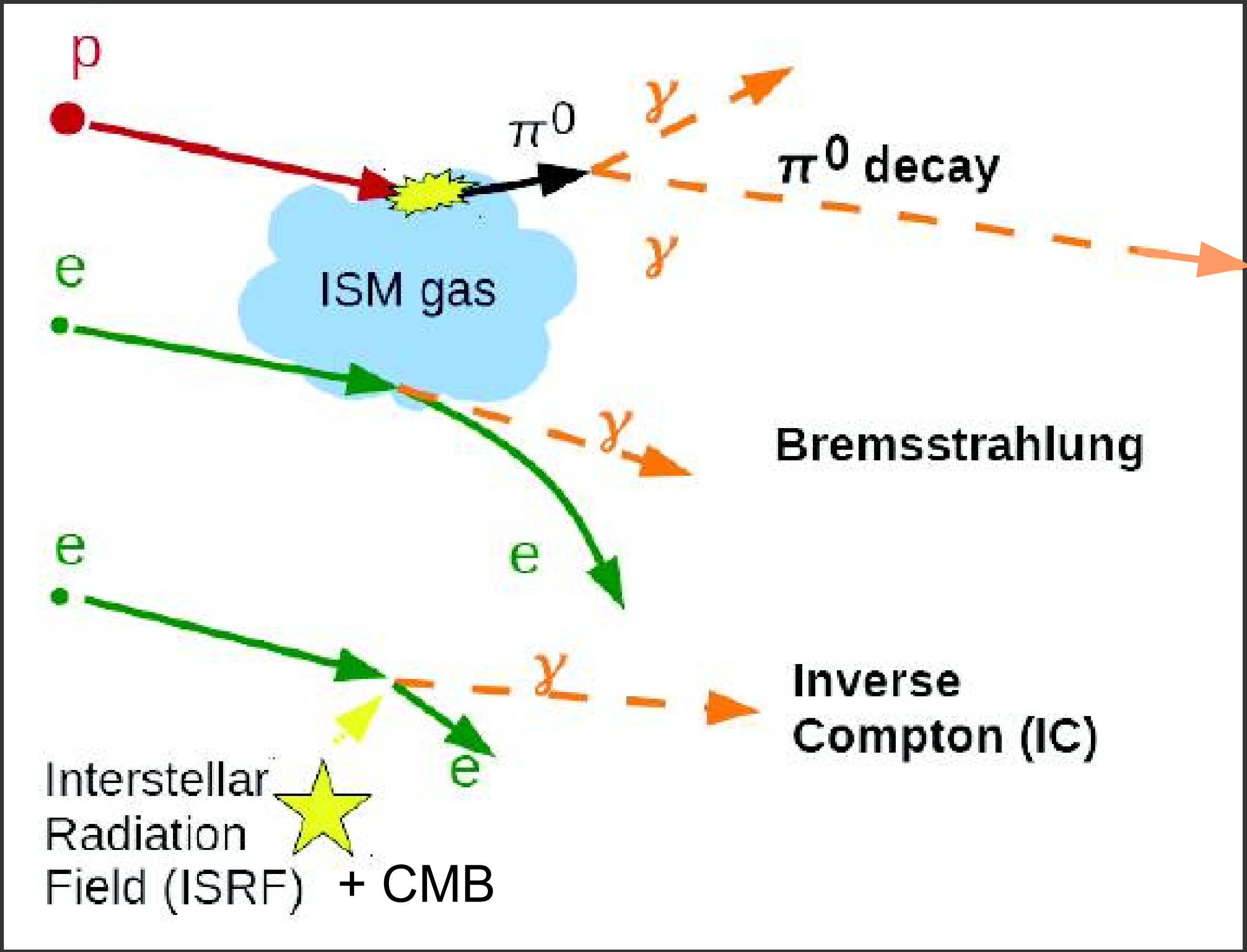






All are extreme environments!

Gamma Rays from multi-TeV particles



Protons: Gamma-rays and gas targets are generally spatially correlated (need to map atomic and molecular ISM → mm radio astronomy)

Electrons: Gamma-ray (IC) + non-thermal X-ray, radio emission (synchrotron) highly coupled

Synergies with interstellar gas surveys

www.atnf.csiro.au/research/HI/sgps

HI (atomic H), OH, CS

CO

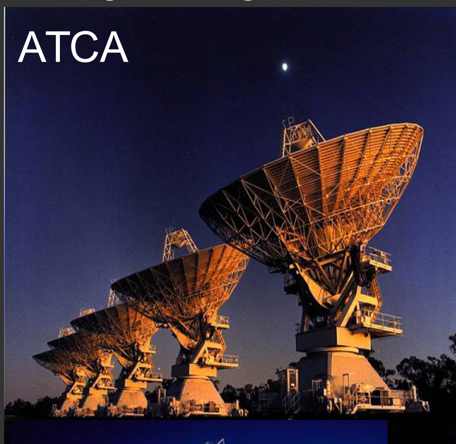
CO, NH_3, CS, SiO...

Gas density

$\sim10^{1 \text{ to } 4}$ cm^{-3}

$\sim10^{3}$ cm^{-3}

$>10^{3 \text{ to } 4}$ cm^{-3}



CSIRO

GAS KAP

The HI/OH/Recombination line survey of the Milky Way

THOR

NANTEN
Submillimeter Observatory
なんてん電波天文台

国立天文台
NAOJ
National Astronomical Observatory of Japan

THz (Antarctica & High-alt)

[CI] + [CII]

Mopra Telescope

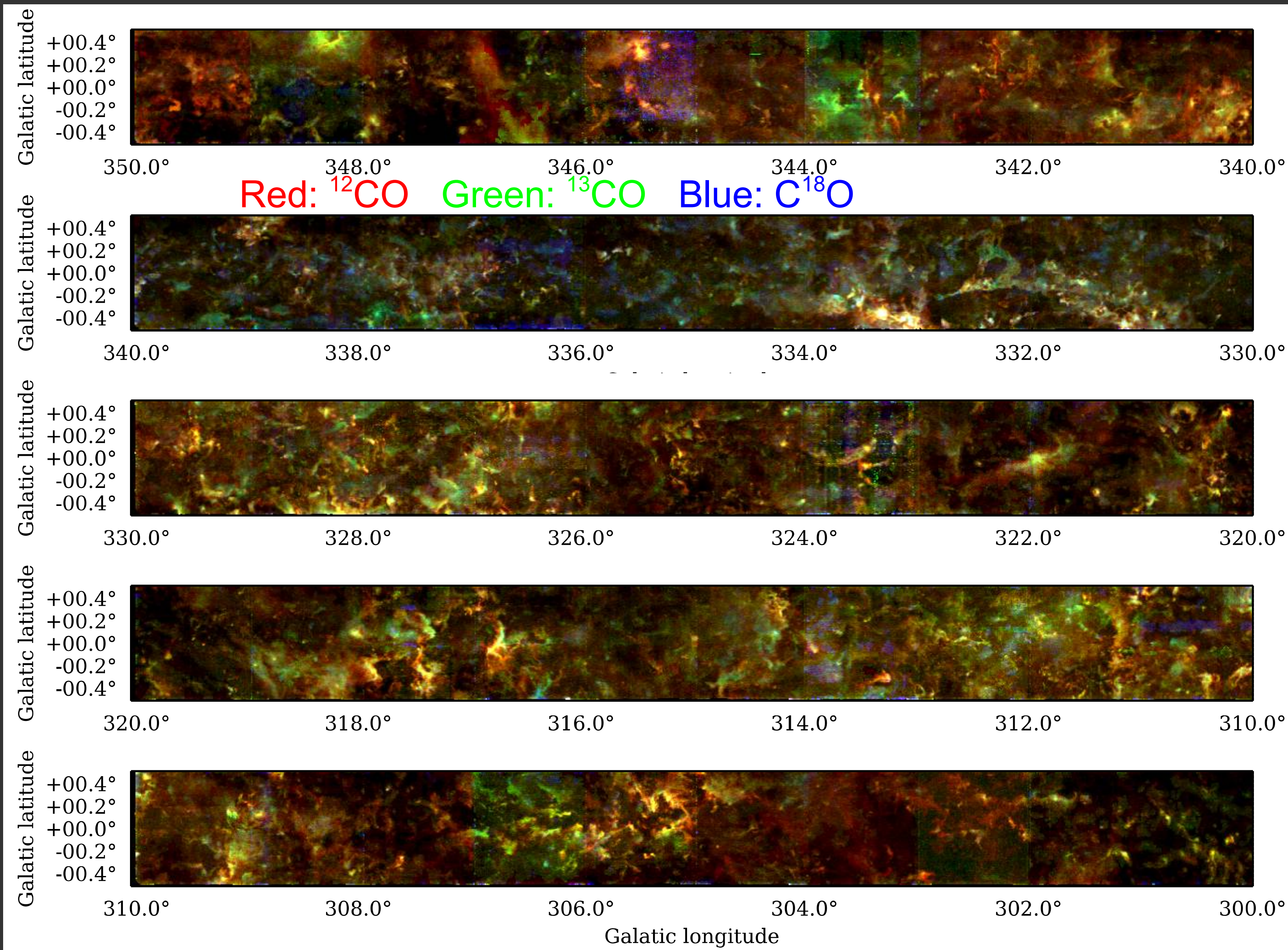
CSIRO

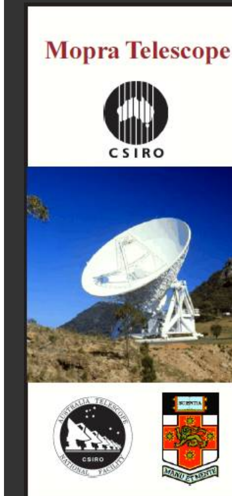
Australia Telescope National Facility CSIRO

SCIENTIA MANU ET MENTE

Mopra CO Peak Intensity (Braiding etal 2018) @ 35 arc-sec beam

Data download https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/LH3BDN

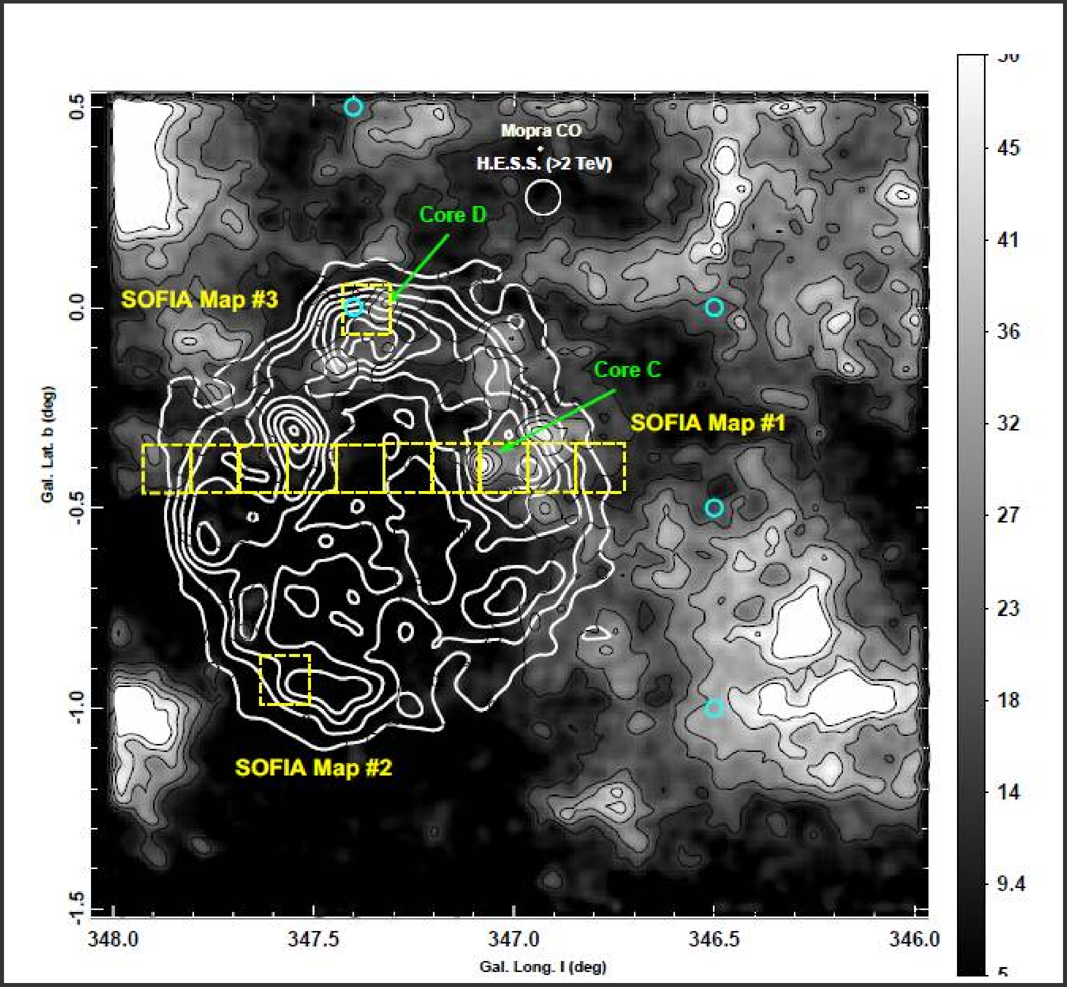




→ A legacy ISM survey for CTA's Galactic studies

Search for C^+ in a young SNR

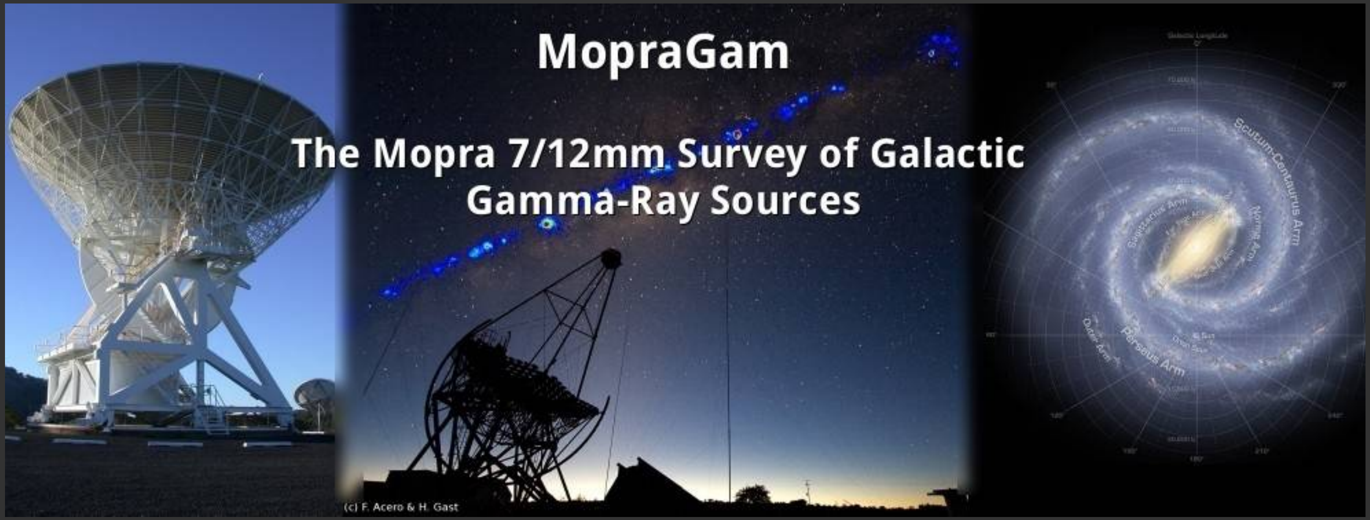
- CR energy density > 1000x at Earth
→ CR ionisation rate possibly
>100x galactic average



- SOFIA Observations 5hr In 2018 12 arc-sec res. (PI Rowell etal)

→ Compare C^+ vs CO across SNR shell.

→ Compare to C^+ across galaxy
Herschel GOT C+
(Pineda etal 2013, Langer et al 2014)



http://www.physics.adelaide.edu.au/astrophysics/MopraGam/

Main ISM Tracers

CS(1-0), SiO(1-0), CH_3OH

Targets

Since 2012 observed over ~40 bright UnID TeV gamma and high energy sources (>1500 hrs)

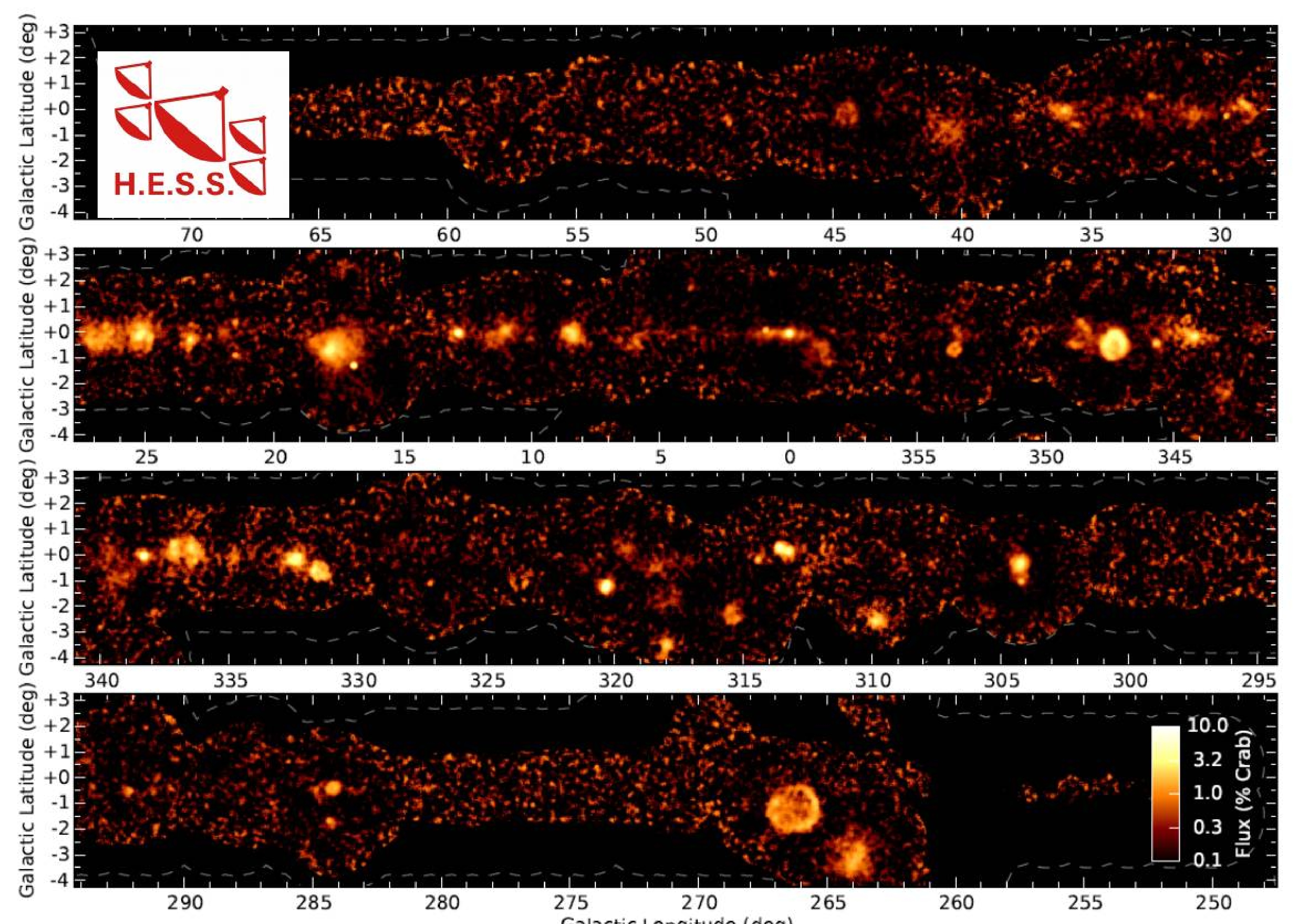
→ Determine distance to cloud components (often difficult with CO)
→ Understand particle propagation
→ Disentangle hadronic/leptonic components

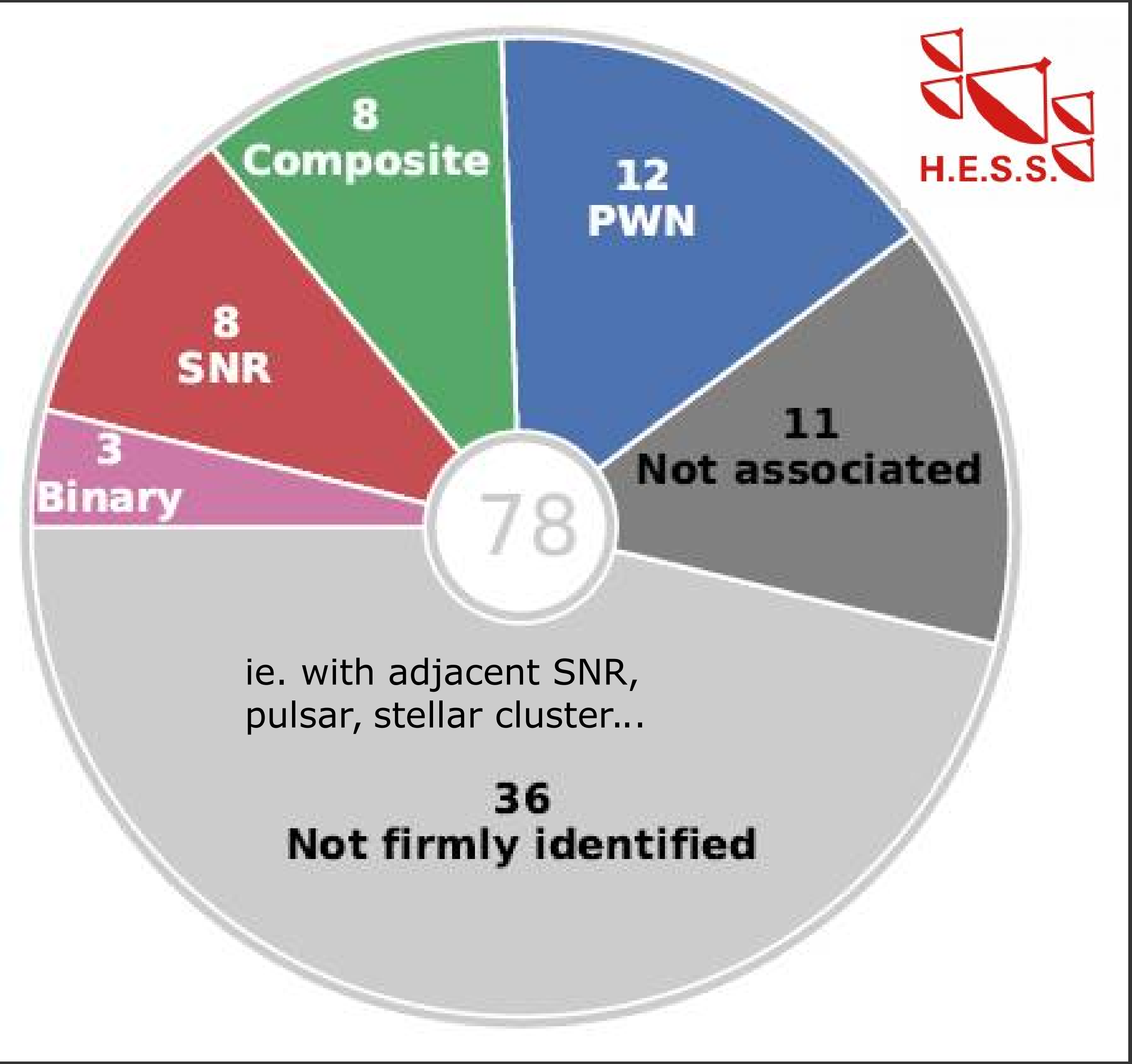
Coverage is limited to discrete sources → ATCA Systematic survey MALT45+

HESS Galactic Plane Survey (HGPS)

→ 78 sources (13 new sources)

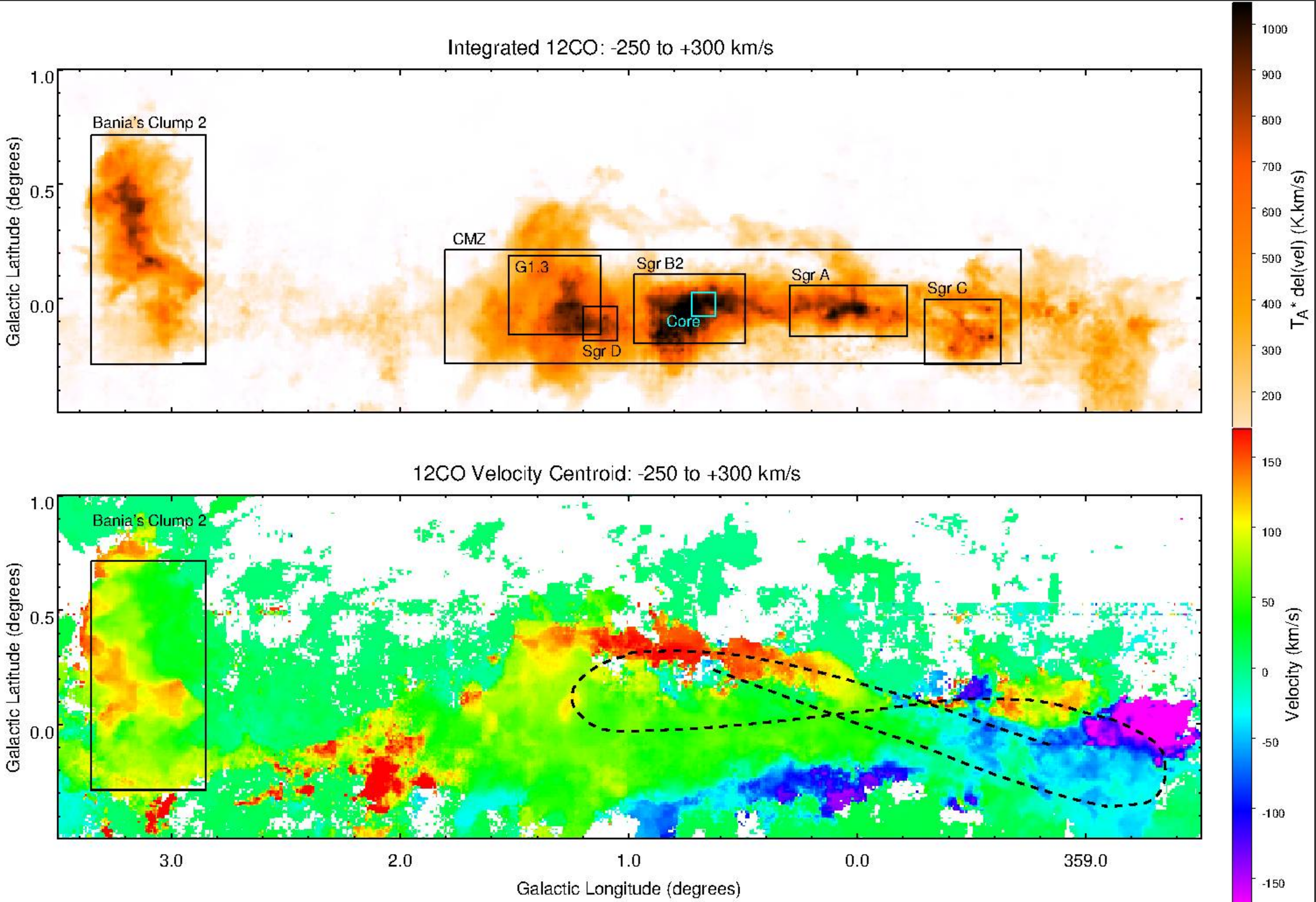
Deil et al 2015, HESS 2018

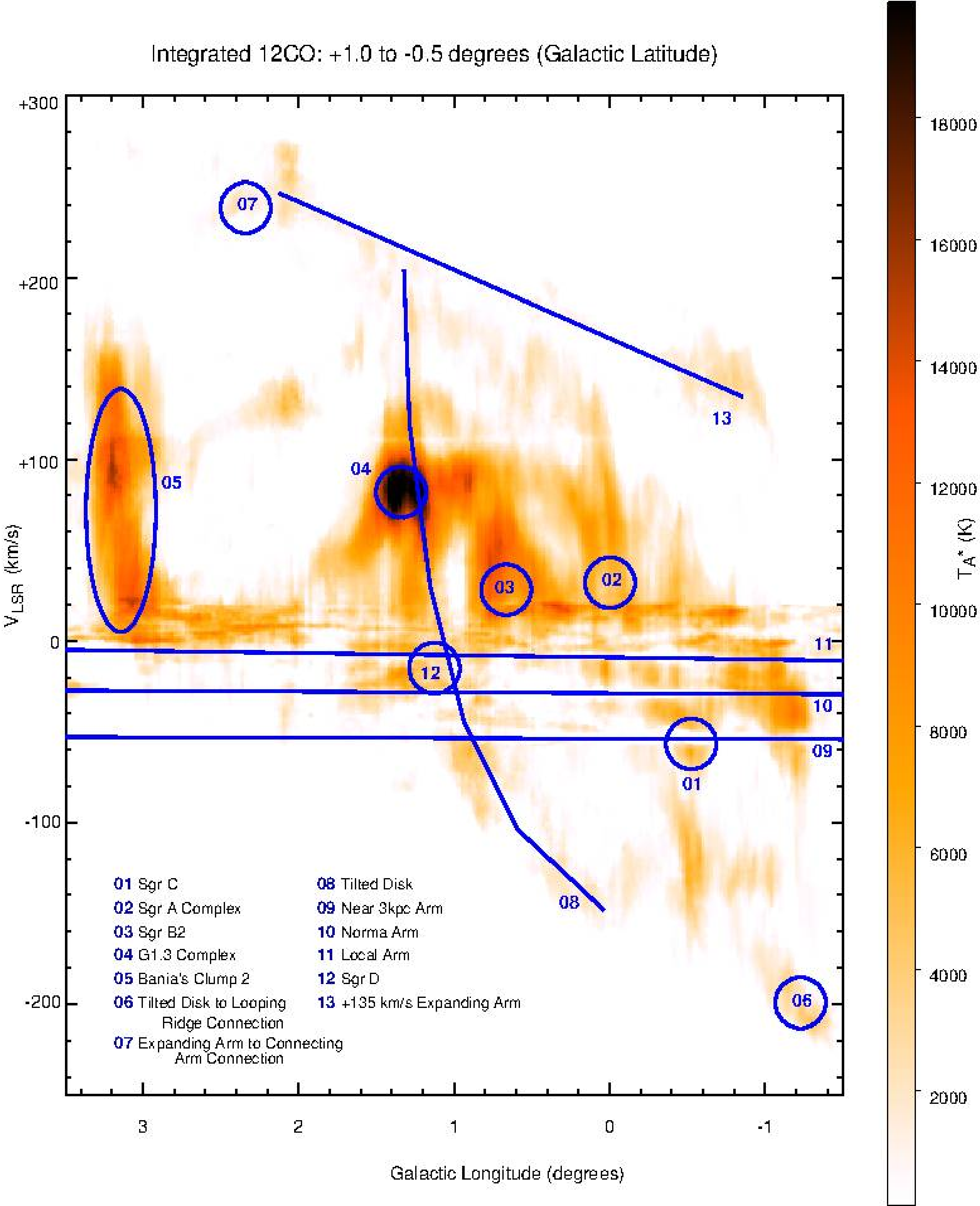




8
Composite
12
PWN
8
SNR
3
Binary
78
11
Not associated
ie. with adjacent SNR,
pulsar, stellar cluster...
36
Not firmly identified
H.E.S.S.

Mopra Galactic Centre CO Survey – Rebecca Blackwell

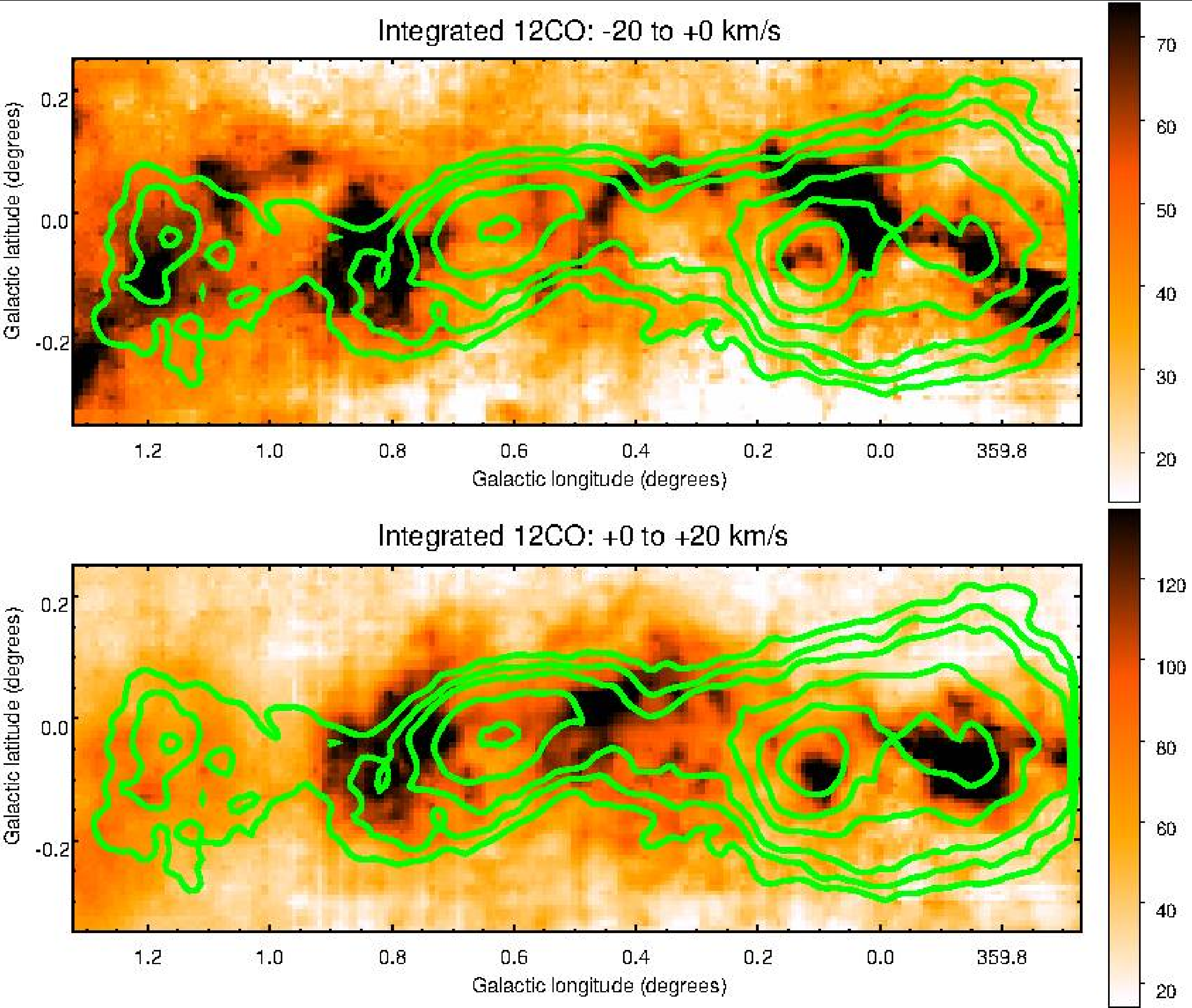




Broadly Distributed Diffuse Emission

- Detailed structure and many expected features seen, at 0.5 arc-min resolution
- Separation of individual features matters to being able to consider specific clouds as targets for CR interaction

The HESS TeV Diffuse Galactic Ridge vs 12CO

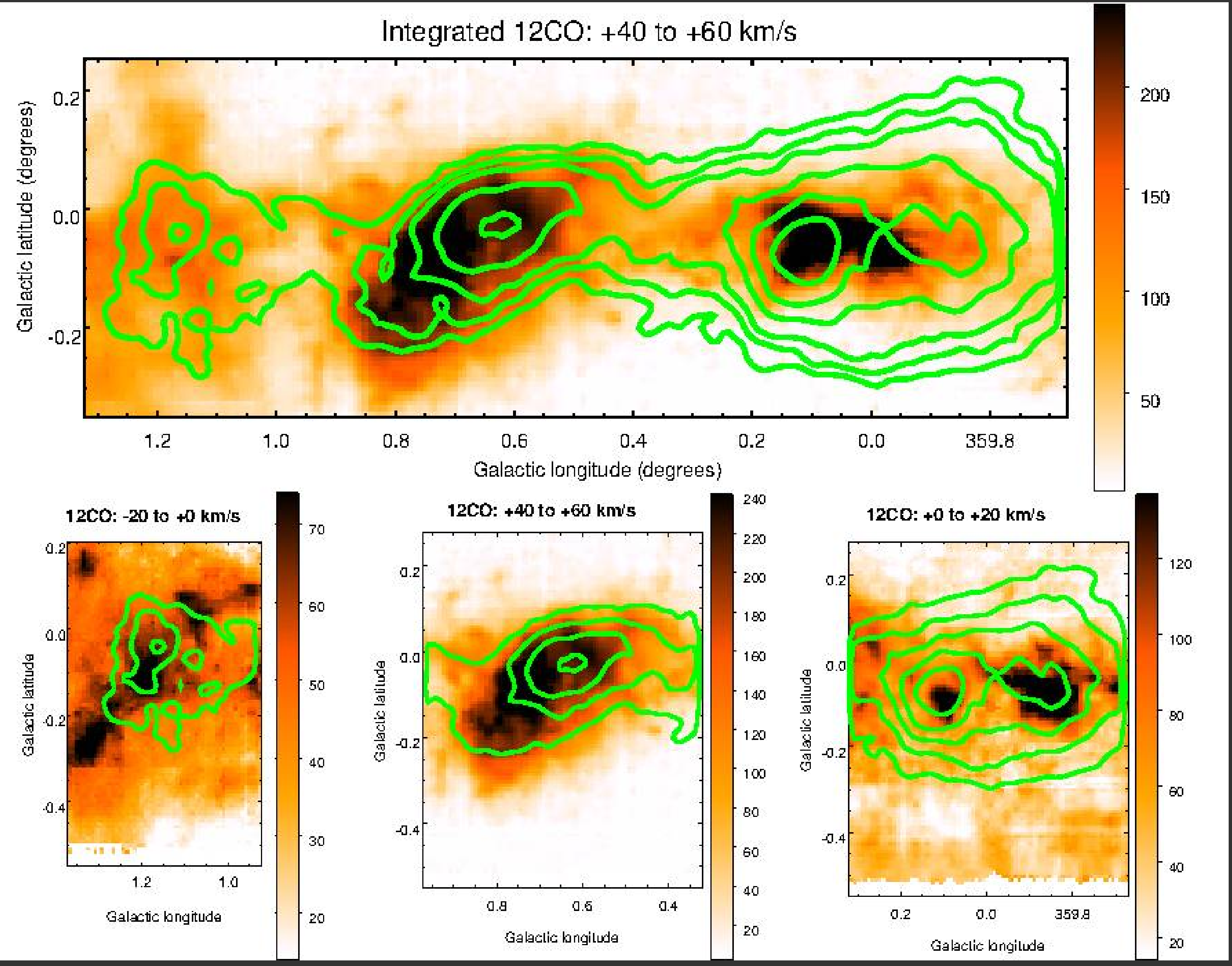


Two panels from a series of unbiased integrated 12CO maps, overlaid with the contours of the HESS diffuse Galactic Ridge.

Maps were integrated over 20km/s, and then stepped through to find the best 'by eye' matches to the peaks of the gamma-ray emission, as a first look.

Between these two panels, in adjacent velocity ranges, some significant changes in gas morphology are already visible.

The HESS TeV Diffuse Galactic Ridge vs. 12CO



A third 20km/s panel that 'by eye' agrees better with the central gamma-ray peak, toward SgrB2.

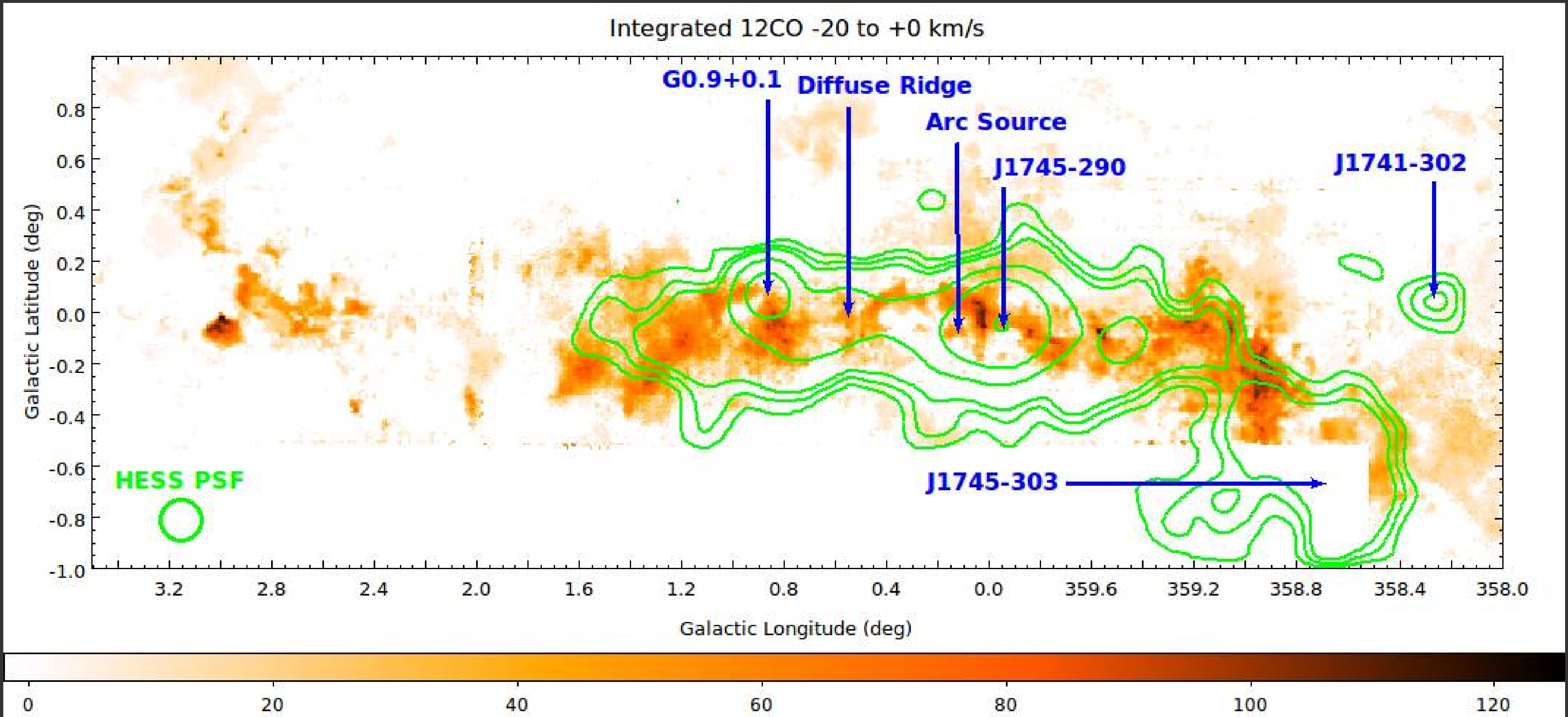
Three panels showing the best 'by eye' match to each of the three peak regions in the gamma-ray emission, towards

SgrD (left)

SgrB2, (centre)

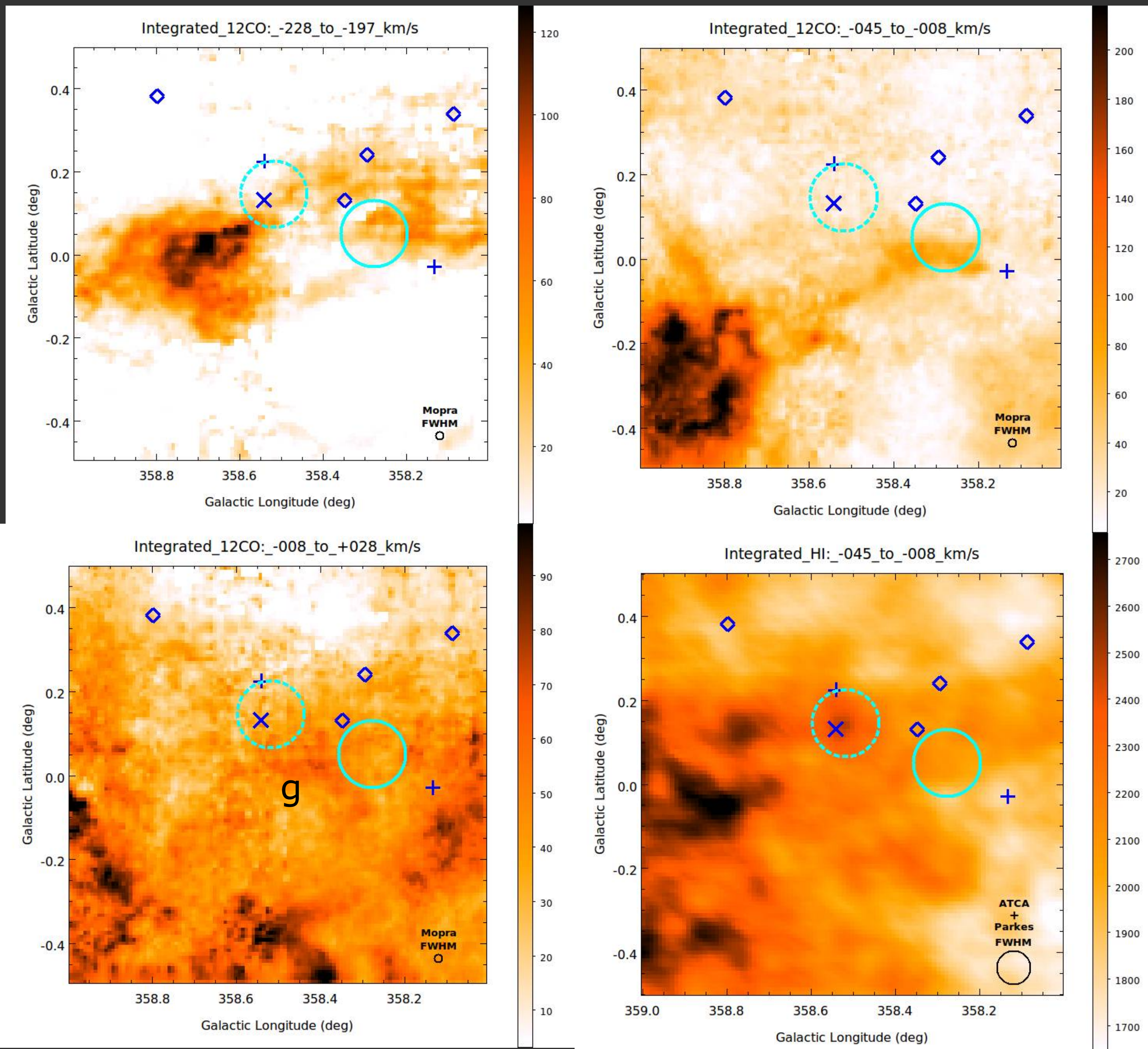
SgrA (right).

Another HESS Source near the GC – HESSJ1741-302



Part of the extended Mopra Central Molecular Zone CO survey region (4° > *l* > 358°, +1° > *b* > -1°) overlaps another interesting HESS sources near the Galactic Centre, HESS J1741-302.This source is a PeVatron candidate due to its hard spectrum at high energies, even though it is a faint source at only ~1% of the Crab flux.

HESS J1741-302



Key to Gas Panels:

Diamonds = Pulsars

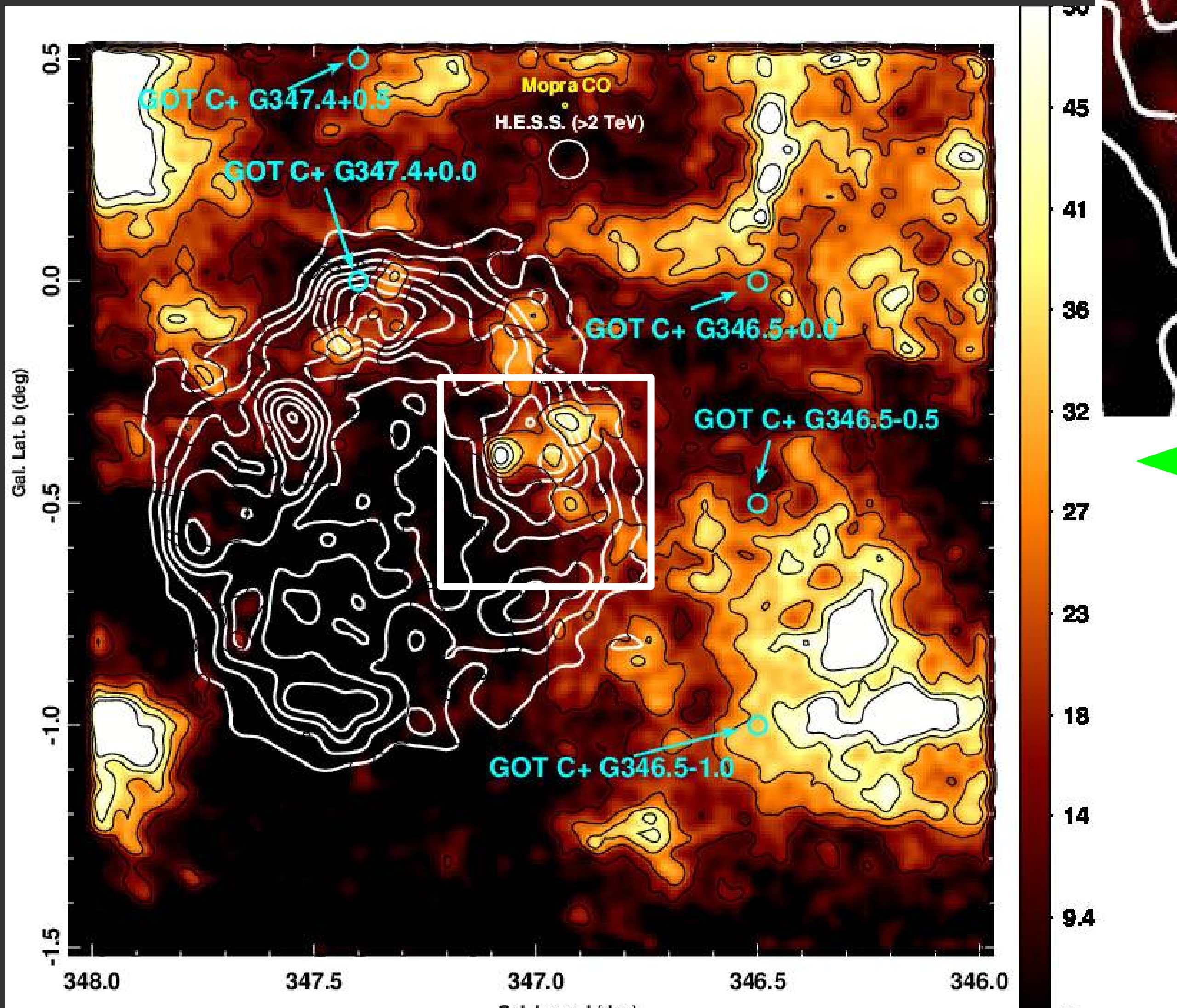
+ = Wolf-Rayet stars

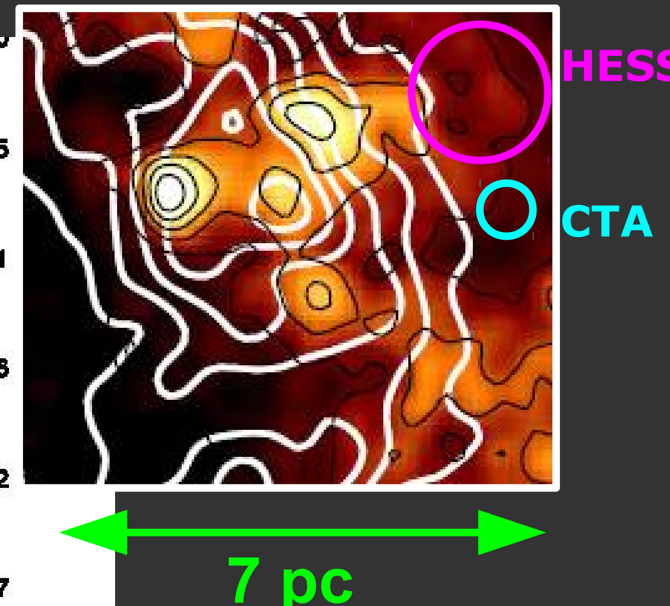
X = LBV star Wray 17-96

HESS TeV PSF (0.08°).
Same as the source (solid cyan circle) and hotspot (dashed cyan circle) regions

Young SNR : RXJ1713 TeV and ISM on Parsec Scales!

Mopra CO(1-0) Image + HESS > 2 TeV contours





CTA will finally be able to probe diffusion properties of hadronic cosmic rays

CR Diffusion *Into* Molecular Clouds

e.g. Gabici etal 2007, Inoue etal 2012

R = distance CR travels into molecular cloud core

R ~ sqrt[6 D(E_p, B) t]

$$D(E_P, B(r)) = \chi D_0 \left(\frac{E_P/\mathrm{GeV}}{B/3\,\mu\mathrm{G}} \right)^{0.5} \quad [\mathrm{cm}^2\,\mathrm{s}^{-1}],$$

$$B \sim 10(n\,/\,300\mathrm{cm}^{-3})^{0.65}\mu\mathrm{G}$$

Crutcher 2010

χ=diffusion suppression factor (~0.1)

→ Low energy CRs can't reach cloud core.

→ Harder TeV spectra from cores.

→ Depends on B-turbulence

(e.g. Morlino & Gabici 2015)

→ Don't expect electrons to penetrate!!

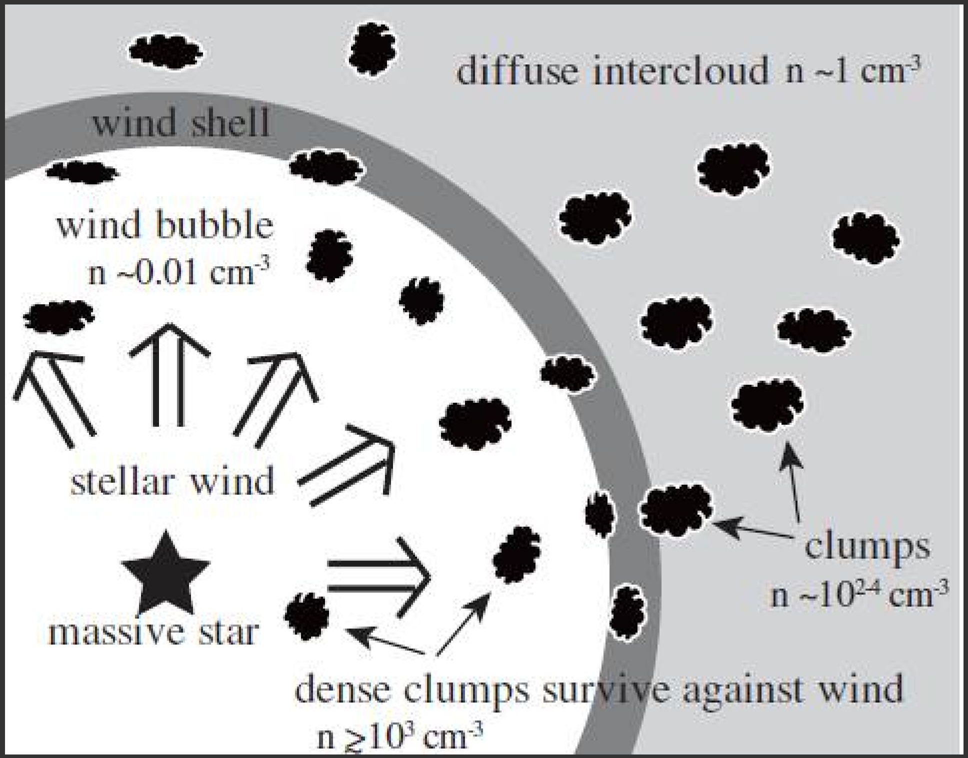
(due to sync. Losses)

→ Hadronic 'reservoir'

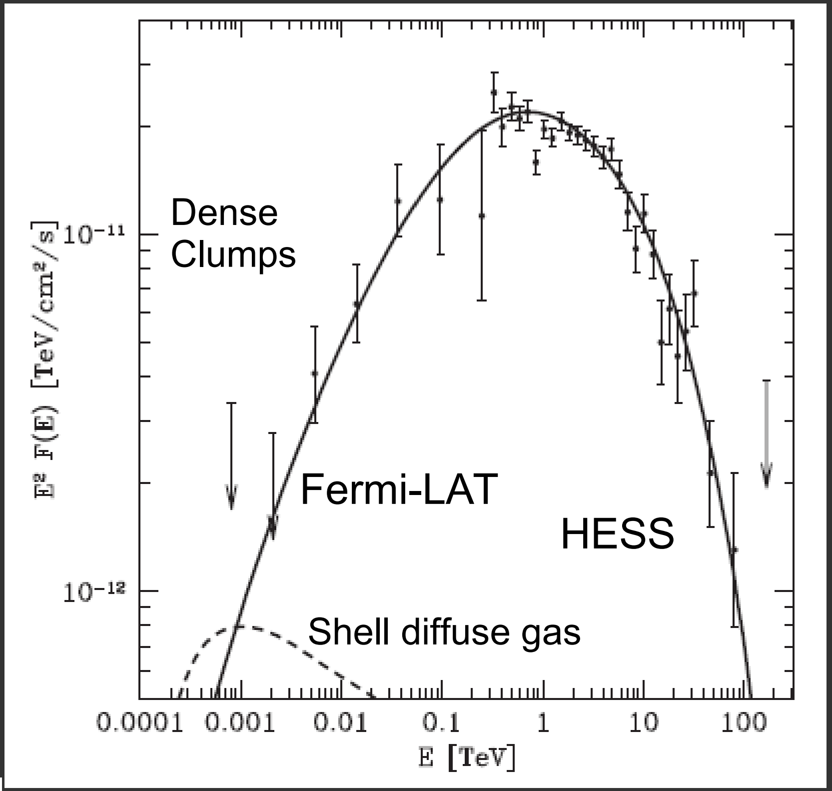
→ Need to map dense cloud cores ~1 arcmin or better

Hadronic Gamma-Rays from Clumpy ISM
SNR RXJ1713

Inoue et al. 2012



Gabici & Aharonian 2014
(also Celli et al. 2018)



CR penetration depth

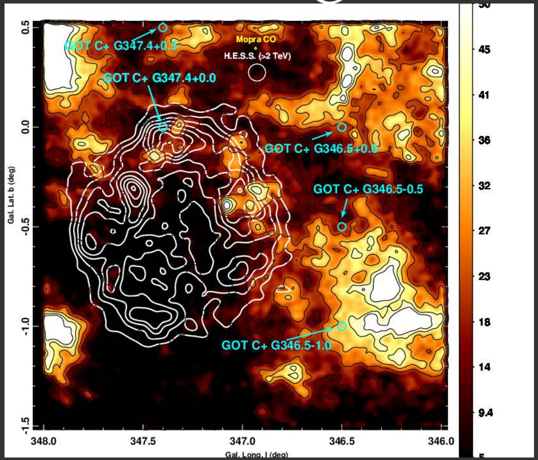
$$l_{\rm pd} \simeq (\kappa_{\rm d}\, t)^{1/2}$$
$$= 0.1\,\eta^{1/2} \left(\frac{E}{10\ {\rm TeV}}\right)^{1/2} \left(\frac{B}{100\ \mu{\rm G}}\right)^{-1/2} \left(\frac{t_{\rm age}}{10^3\ {\rm yr}}\right)^{1/2}\ {\rm pc}$$

$\eta = B^2/\delta B^2$ $\kappa_{\rm d} = 4\,\eta\, l_{\rm g}\, c/3\pi$ (Skilling 1975)

→ Dense clouds/clumps could play critical role in hadronic component

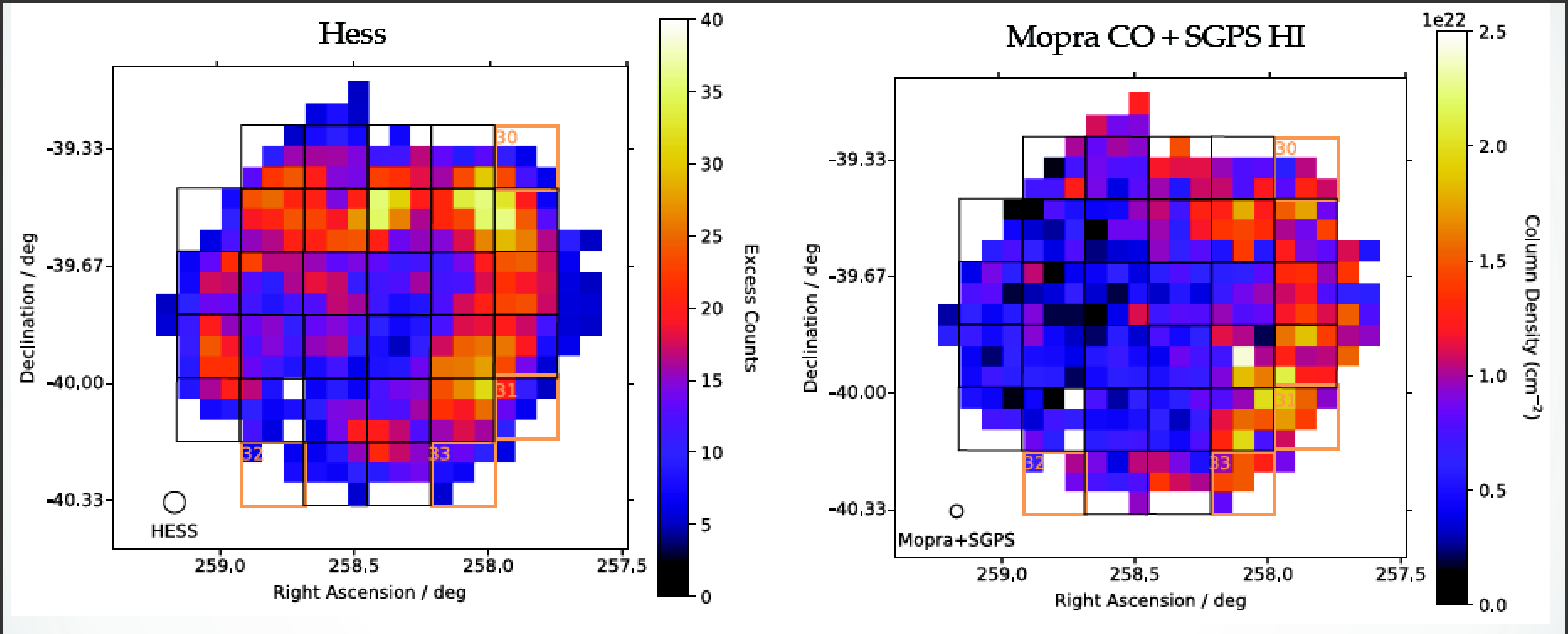
2D ISM/TeV Correlation and SED Modeling of RX1713

Andrew Curzons (MPhil project)



- Trying to understand what fraction of gamma-rays from RX J1713.7-3946 are hadronic and leptonic in origin. Diffusive shock acceleration theory suggests both should be present.
- Gamma-rays that are hadronic in nature or produced by electron Bremsstrahlung processes should spatially coincide with the ISM gas
- Inverse-Compton (leptonic) emission may generally anti-correlate with the ISM when synchrotron losses important.
- Compare the combined Mopra and SGPS ISM column density map with the HESS TeV gamma-ray map to produce a correlation coefficient over 2D.

Re-binning ISM Gas Data to HESS Resolution



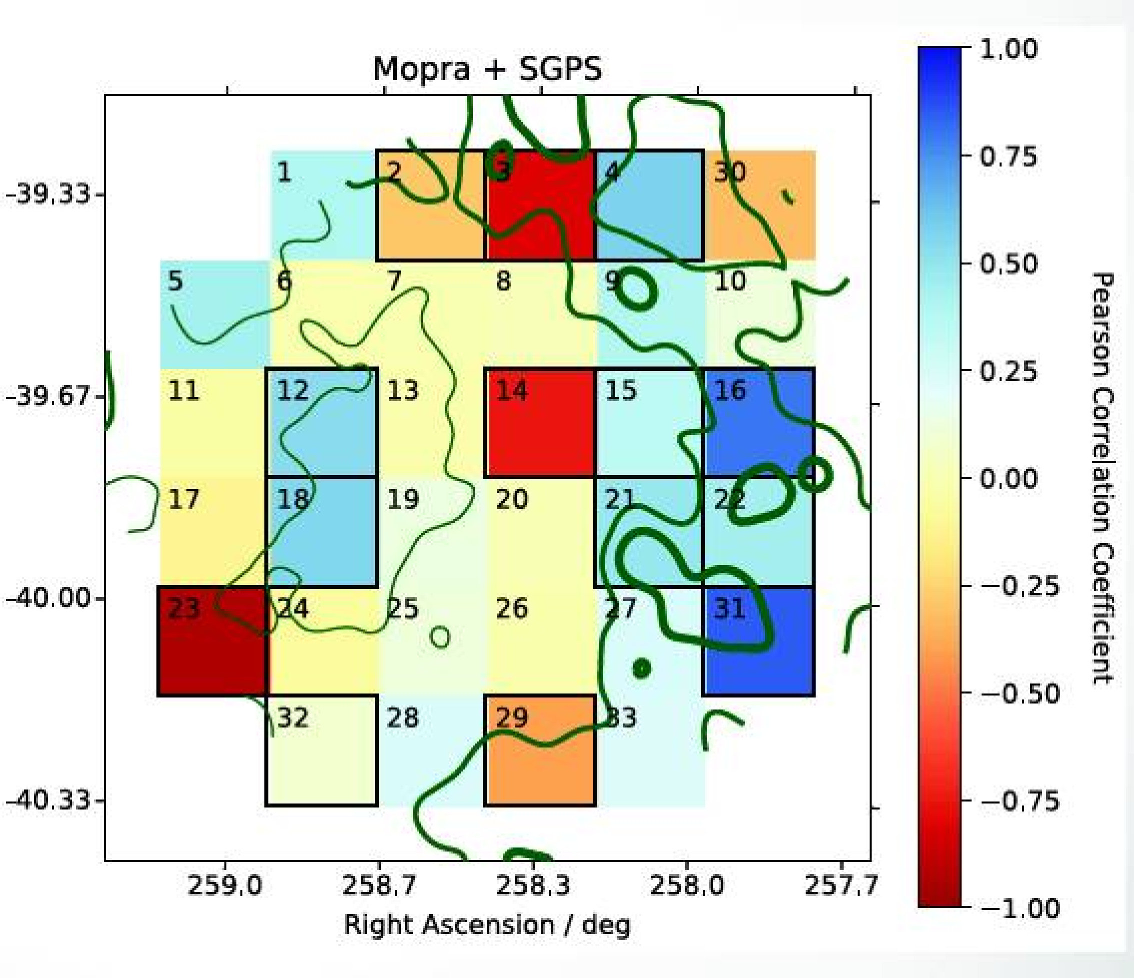
- Each of the 29 regions from Tanaka et al. 2008
- (+ 4 more with sufficient pixels)
- Pixel size is 3.6’ by 3.6’
- Removed pixels with gamma excess counts < 5
- Each region has up to 9 pixels

2D Map of Correlation Coefficients vs ISM

- Colour scale represents the Pearson correlation coefficient

$$\rho = \frac{\mathrm{Cov}(x, y)}{\sigma_x \sigma_y}$$

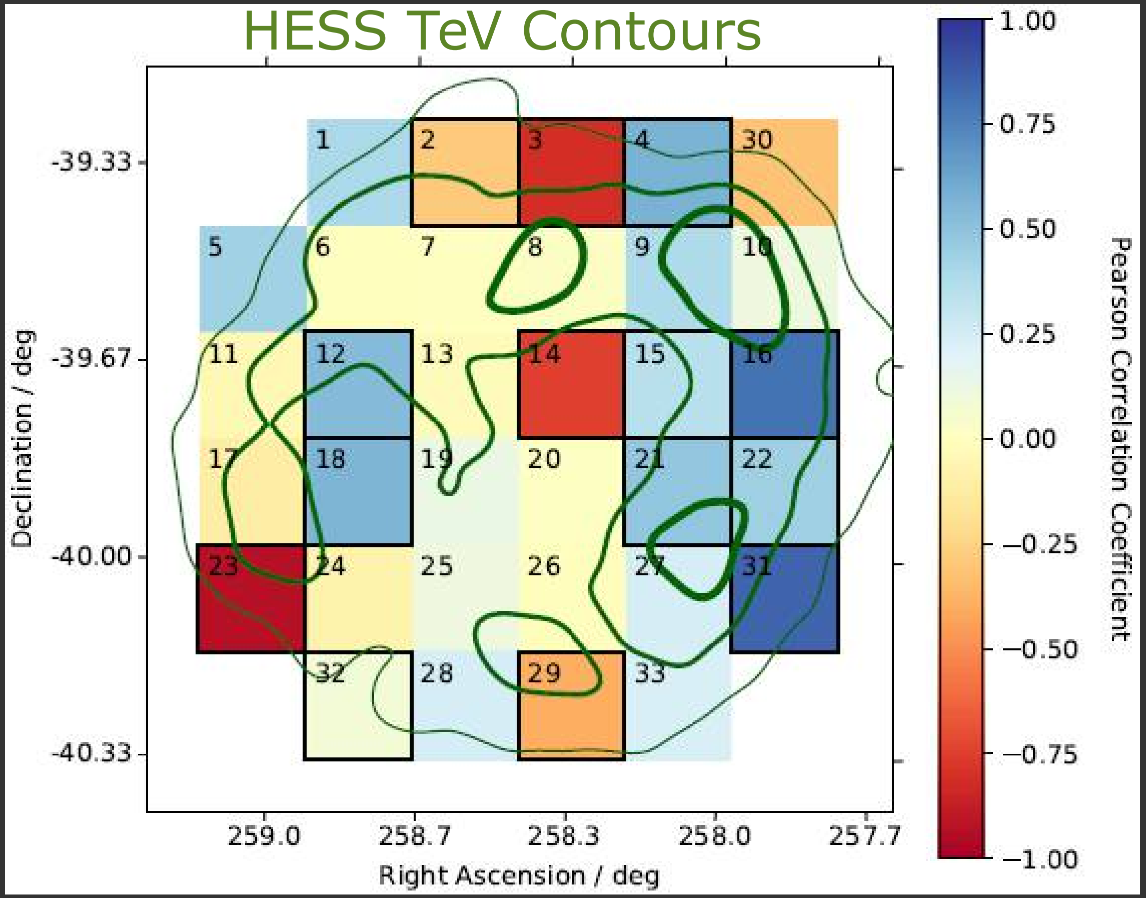
- Black boxes indicate regions with a significant correlation coefficient according to a bootstrap method



TeV/ISM

Anti-correlated Correlated

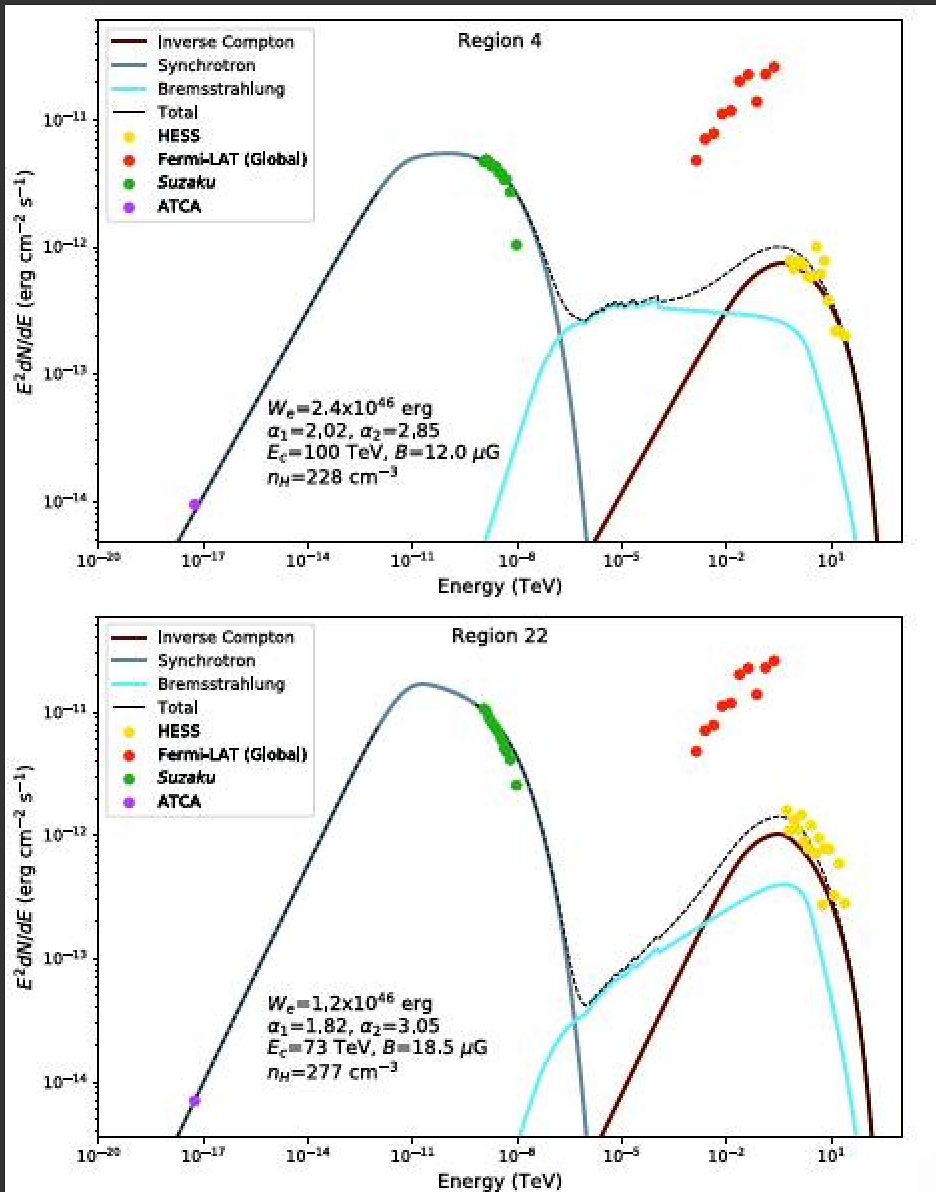
2D Map of Correlation Coefficients vs TeV



TeV/ISM

Anti-correlated Correlated

Role of Bremsstrahlung and hadronic fraction



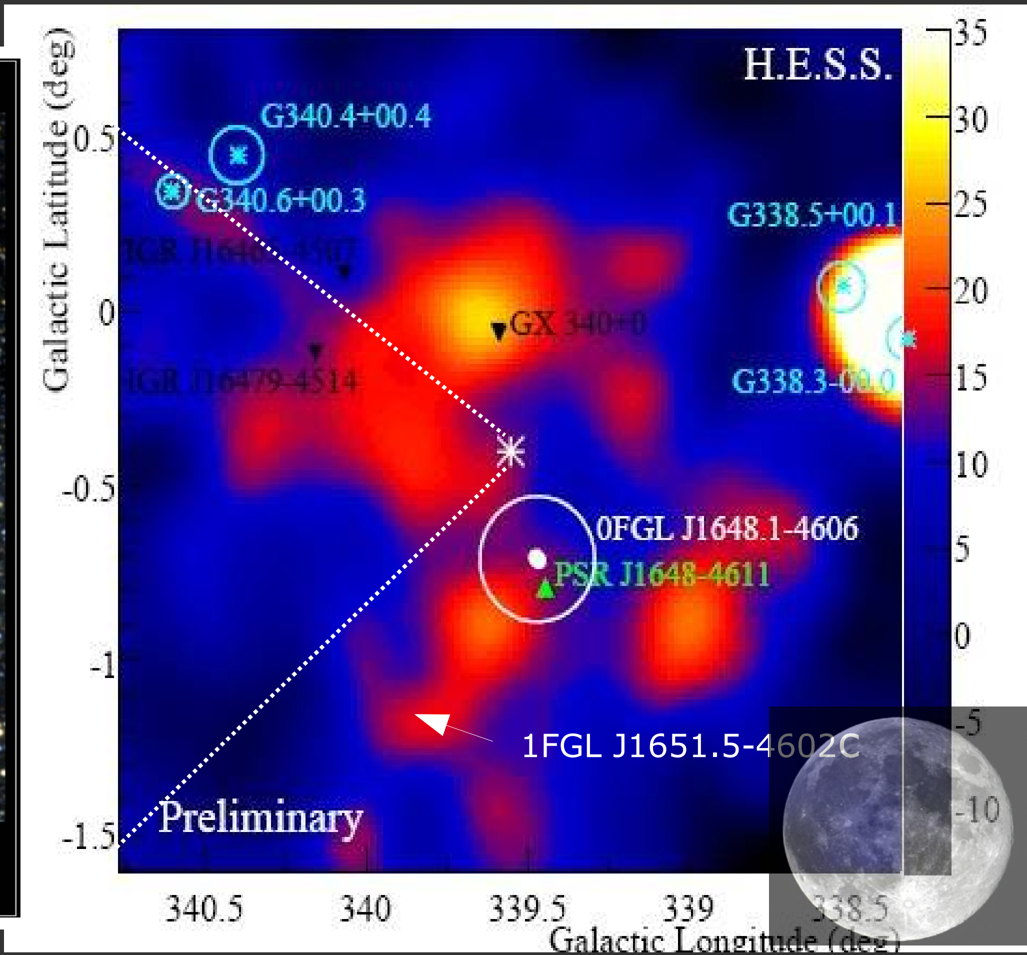
- Bremsstrahlung can contribute to the total leptonic spectrum based region-by-region SED modeling.
- In the blue (ISM correlated) regions Brem accounts for 6-26% of each region's TeV flux
- Assume remaining TeV flux from correlated regions (blue) is from hadronic interactions?

→ about 20% of SNR TeV emission is hadronic.

(the SNR flux fraction in the blue regions minus Brem)

Possibly lower limit?

Westerlund 1 – The Wolf-Rayet *Haven* Ohm etal 2009; HESS 2012

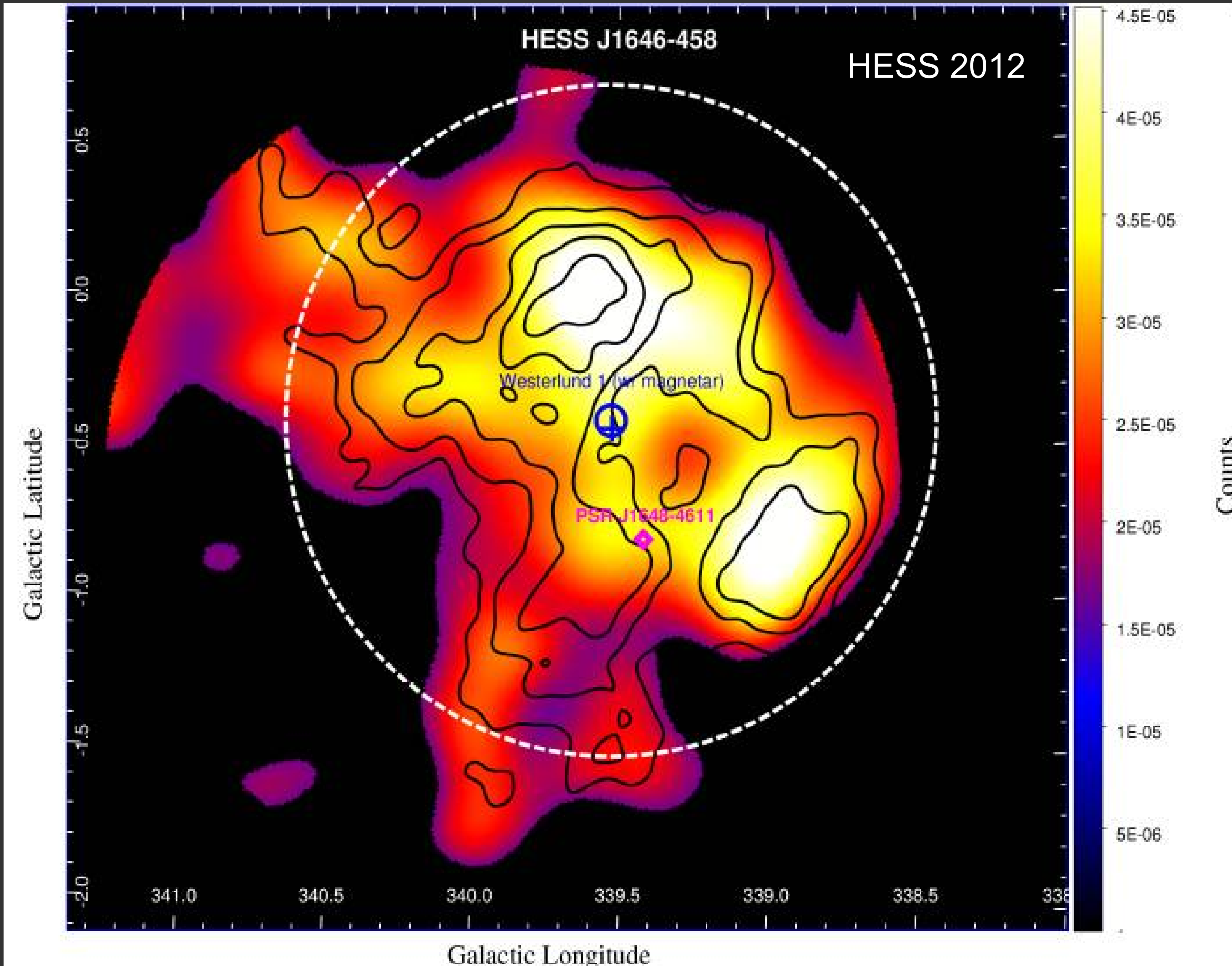


>24 WR stars, ~80 blue supergiants ! **L_w ~ 10^{40} erg/s; Age ~ 5 Myr**

(Crowther etal 2006)

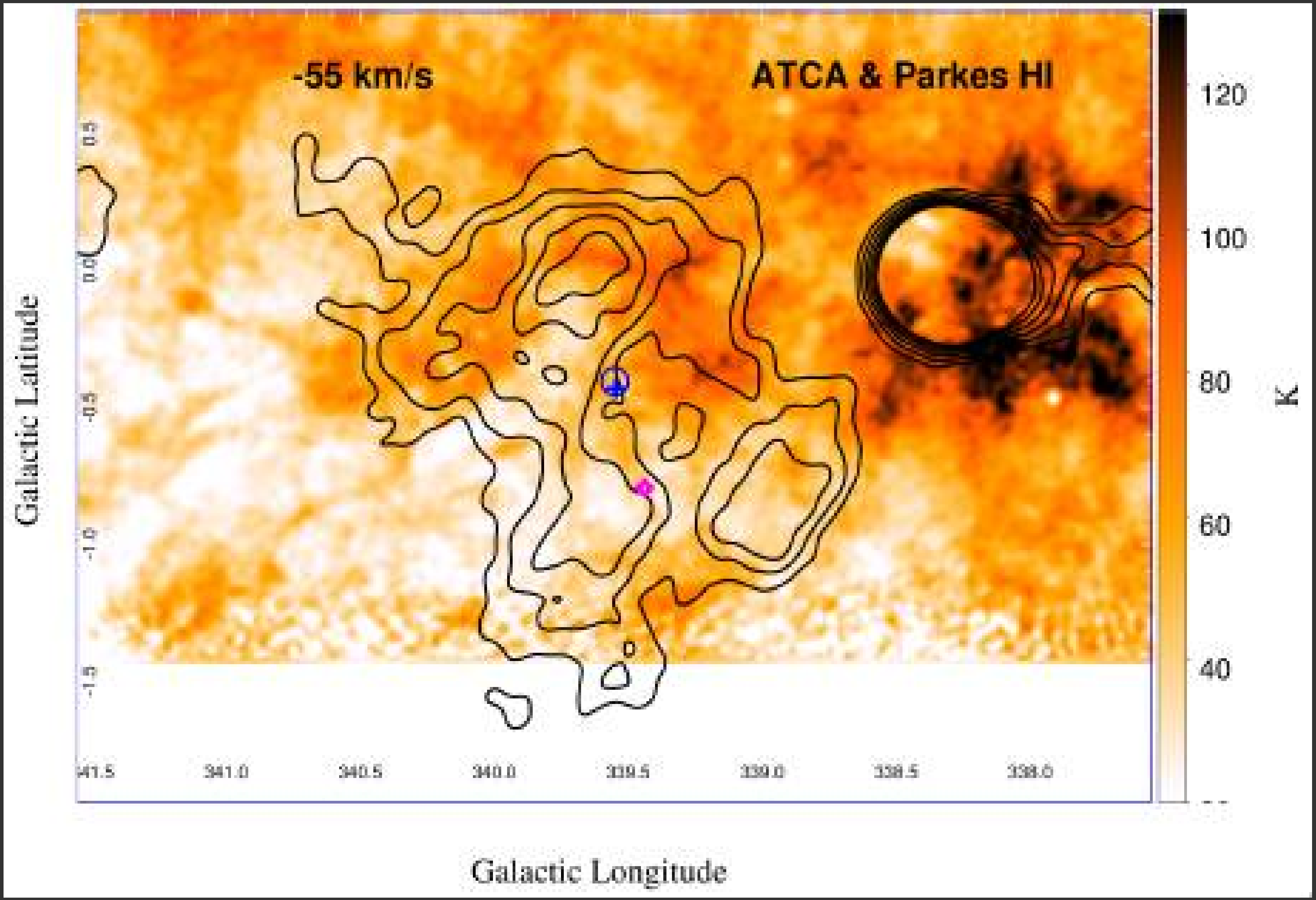
PSR J1648-4611 $P_{spindown}$ ~ 10^{33} erg/s/kpc^2

Magnetar! AXP CXOU J1647-4552 **Dist 4 – 5 kpc**

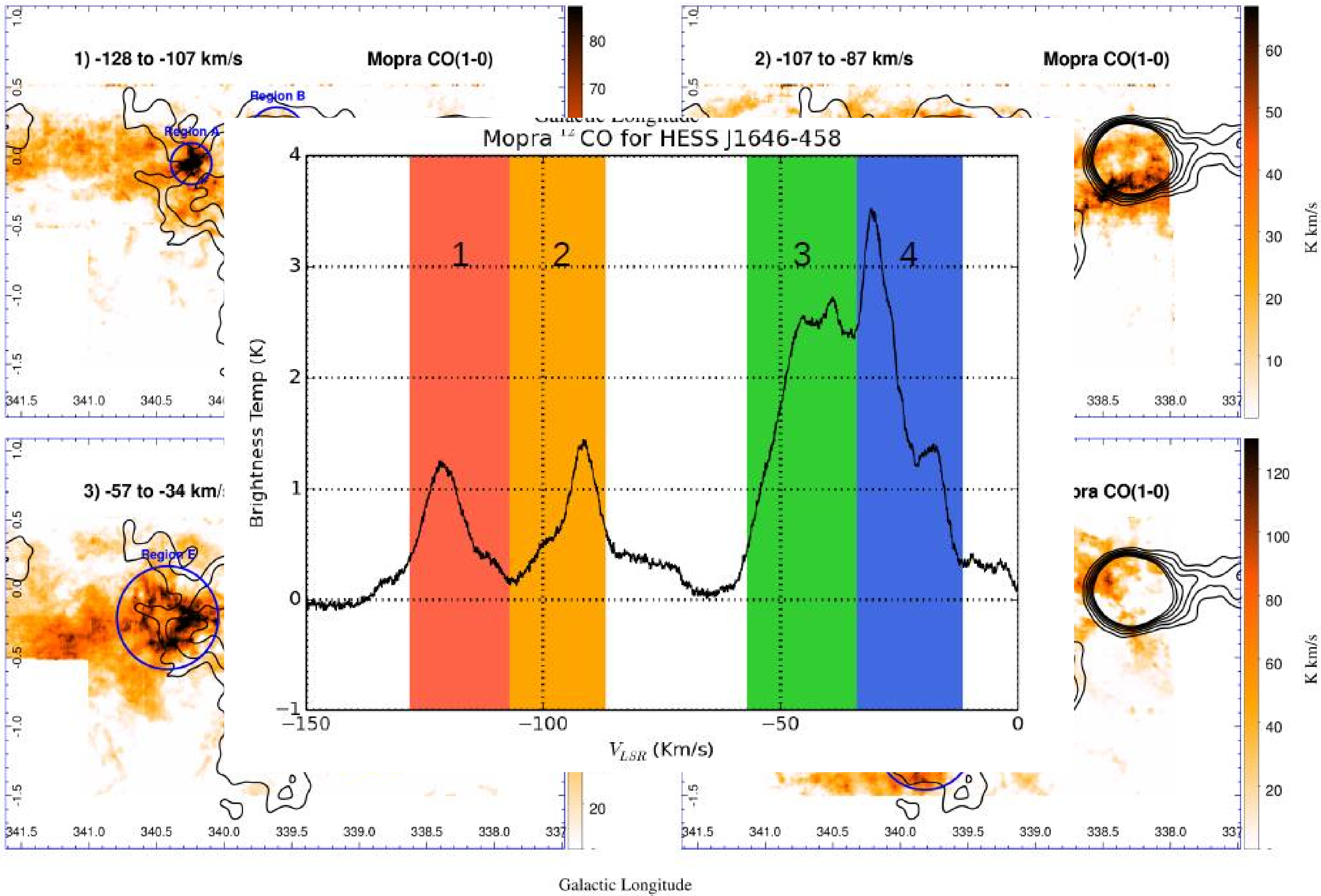


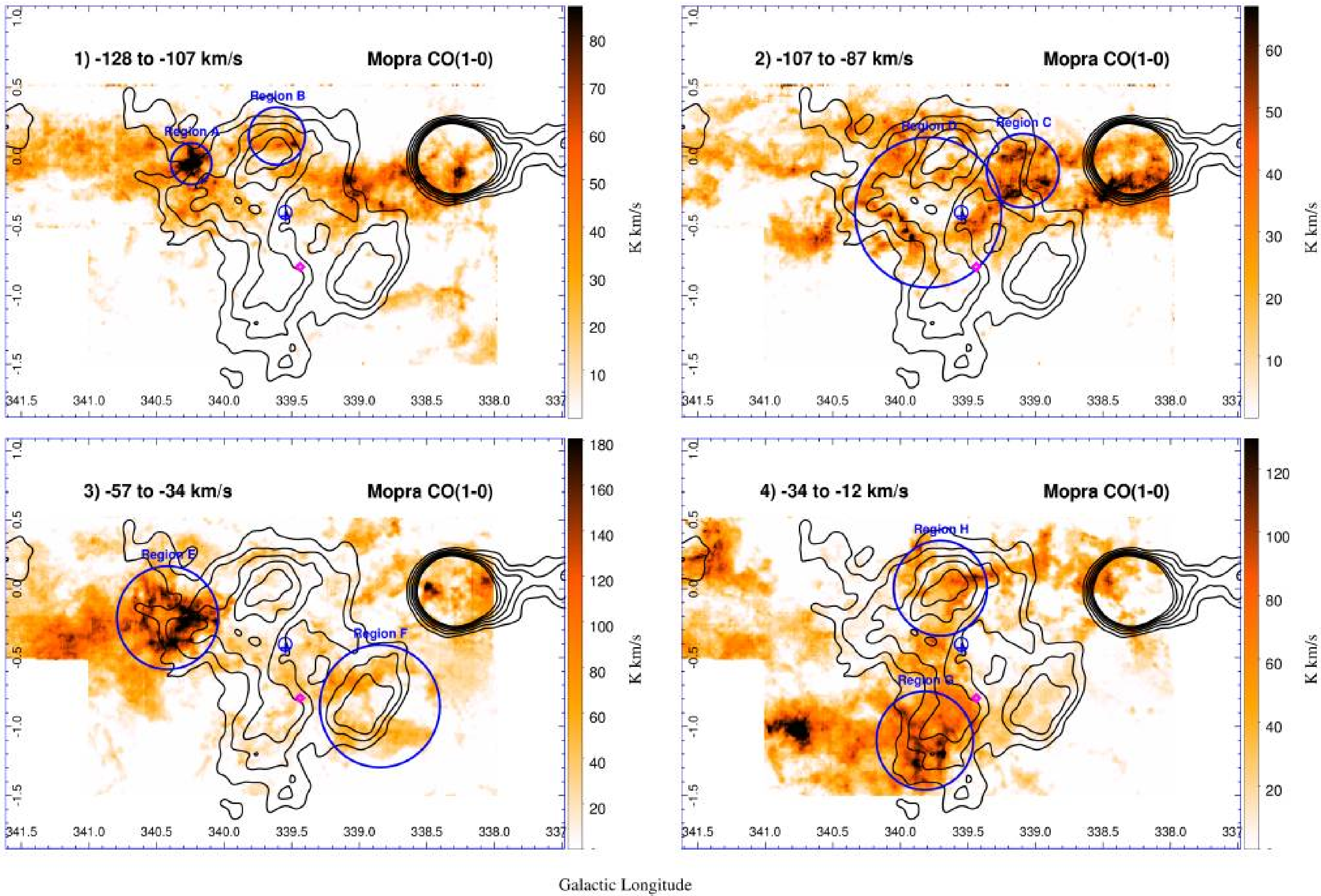
HESS J1646-458
HESS 2012
Westerlund 1 (w/ magnetar)
PSR J1648-4611
Galactic Latitude
Galactic Longitude
Counts
0.5
0.0
-0.5
-1.0
-1.5
-2.0
341.0
340.5
340.0
339.5
339.0
338.5
4.5E-05
4E-05
3.5E-05
3E-05
2.5E-05
2E-05
1.5E-05
1E-05
5E-06

HI bubble at -55 km/s Kothes & Dougherty (2007)



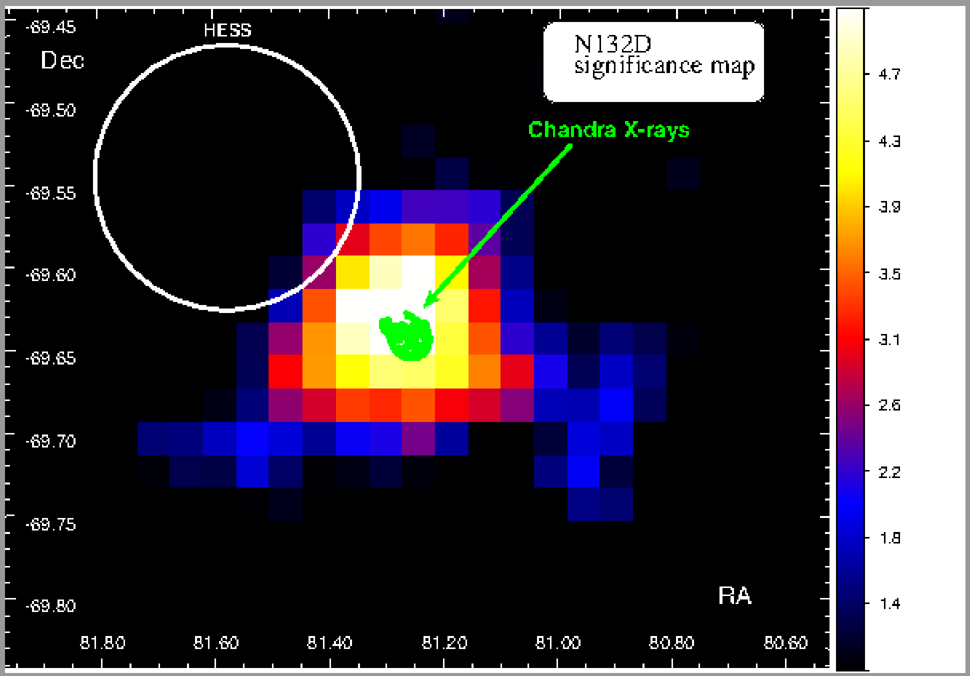
Mopra 12CO(1-0) studies by Cameron Snoswell (MPhil)

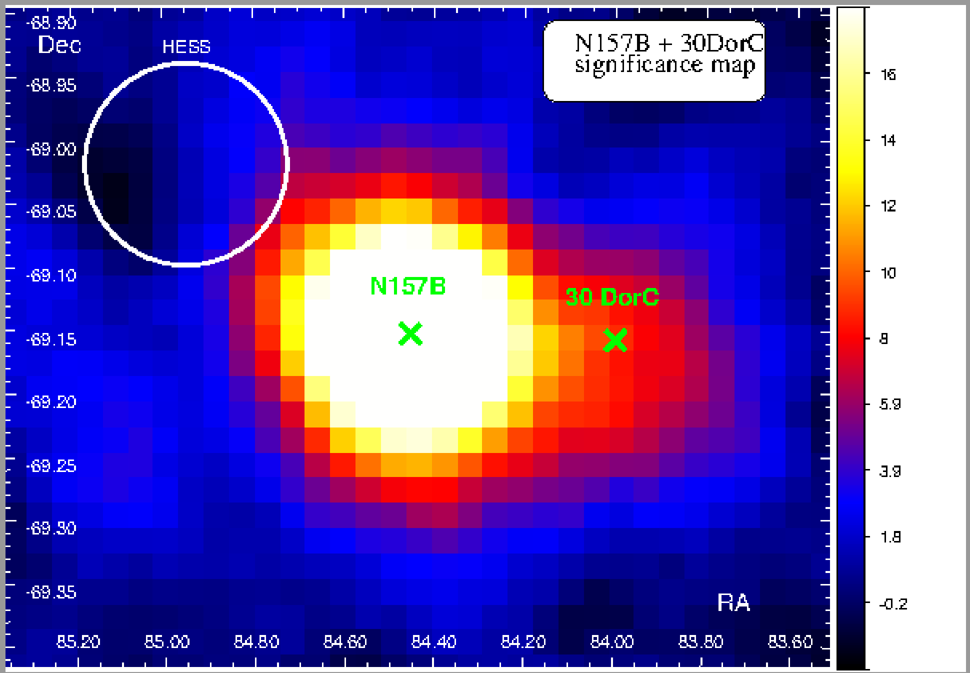


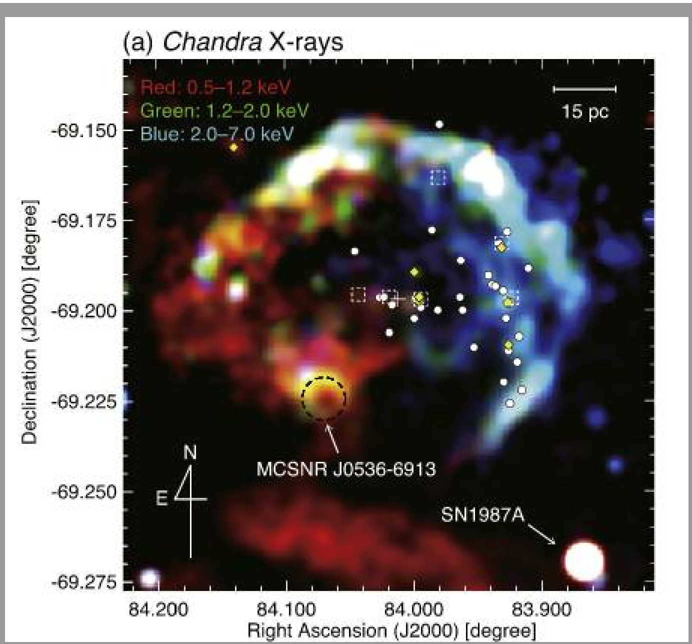

1) -128 to -107 km/s
Mopra CO(1-0)
Region A
Region B
2) -107 to -87 km/s
Mopra CO(1-0)
Region C
Region D
3) -57 to -34 km/s
Mopra CO(1-0)
Region E
Region F
4) -34 to -12 km/s
Mopra CO(1-0)
Region G
Region H
K km/s
K km/s
K km/s
K km/s
Galactic Longitude

CTA and LMC SNRs

- Fabien Voison, H. Sano, G. Rowell (in prep)
- LMC : perfect laboratory to study supernova remnants: > 20 SNRs.
- Powerful TeV gamma-ray emitters found in the LMC with HESS (Abramowski et al 2015)





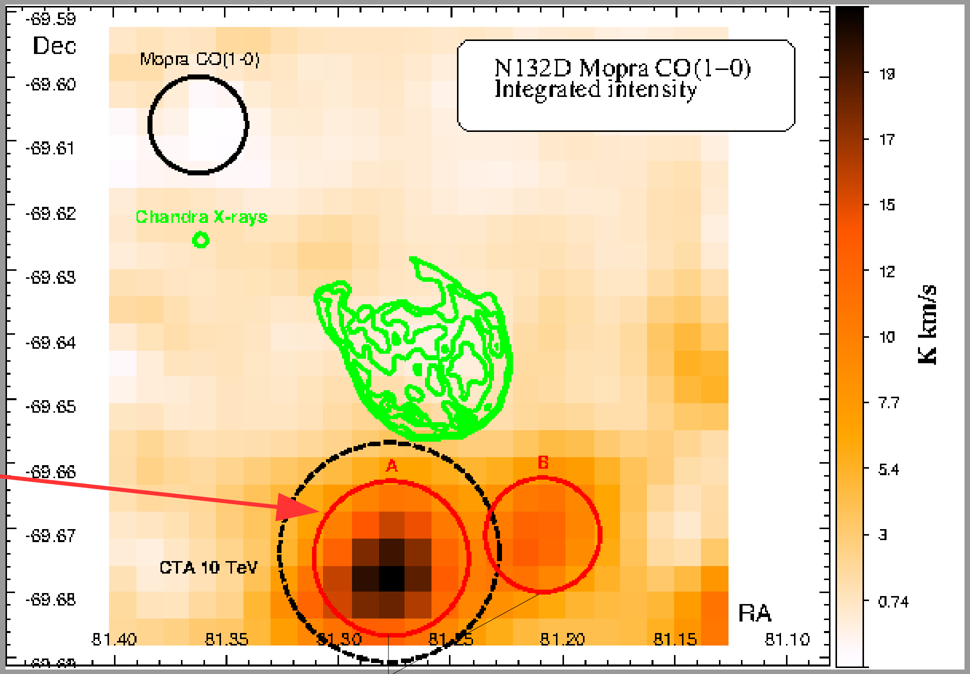


Sano et al (2017)

CTA and LMC SNRs

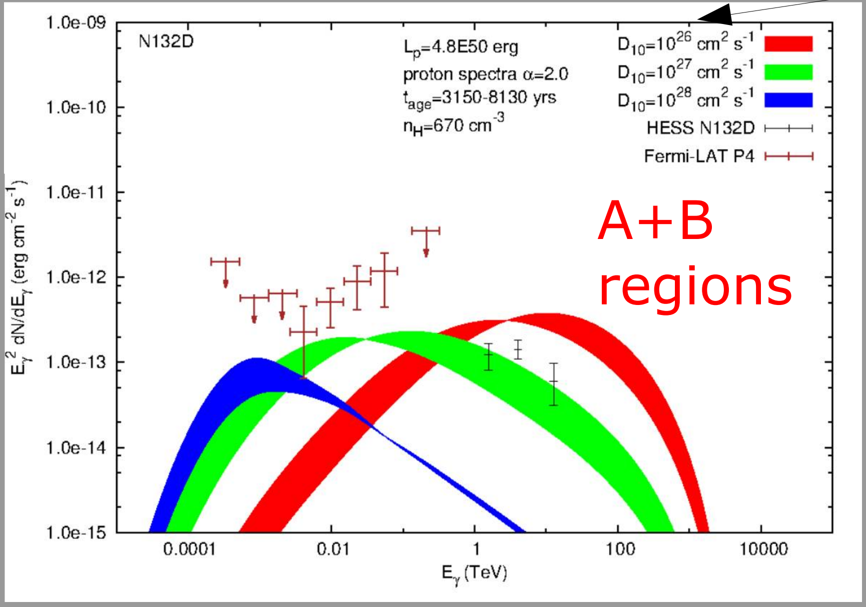
MOTIVATION :

- Identify suitable targets among the LMC SNRs to be observed with CTA.
- → Good candidates to have **molecular clumps resolvable** by CTA.
- Model the Hadronic gamma-ray emission overlapping the molecular clouds



Example suitable target : N132D

- 2 molecular clouds located in the vicinity of the SNR resolvable by CTA
- $E_{SNR}=4.6\times10^{51}$ erg (Leahy et al 2017),
- Using diffusion coefficient at 10 GeV $D_{10}=10^{27}$ $cm^{-2}s^{-1}$ → **modelled gamma-ray emission matches the HESS TeV gamma-ray flux point,** but below Fermi-LAT GeV emission by a factor of 2



CTA and LMC SNRs

MOTIVATION :

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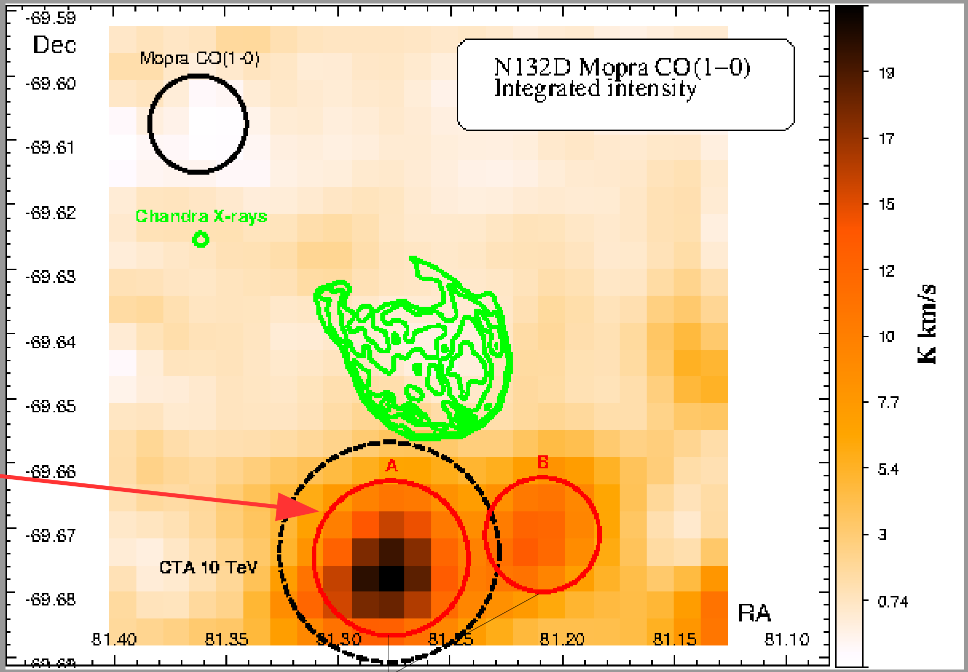
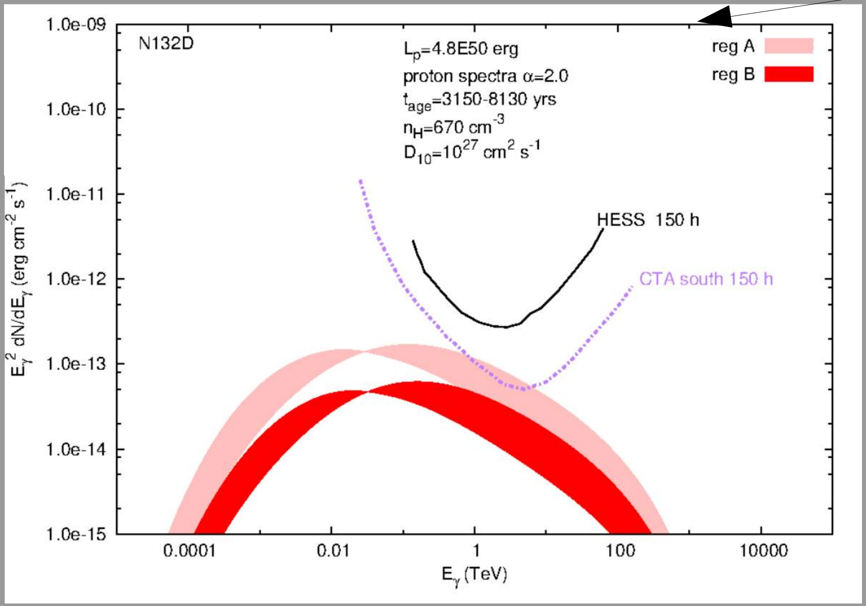




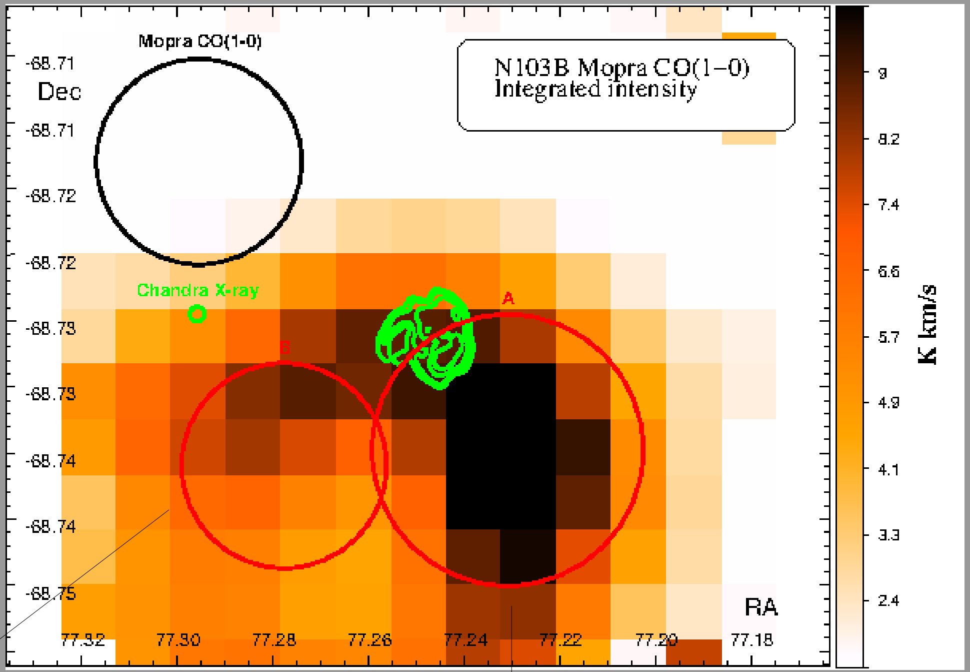
Example suitable target : N132D

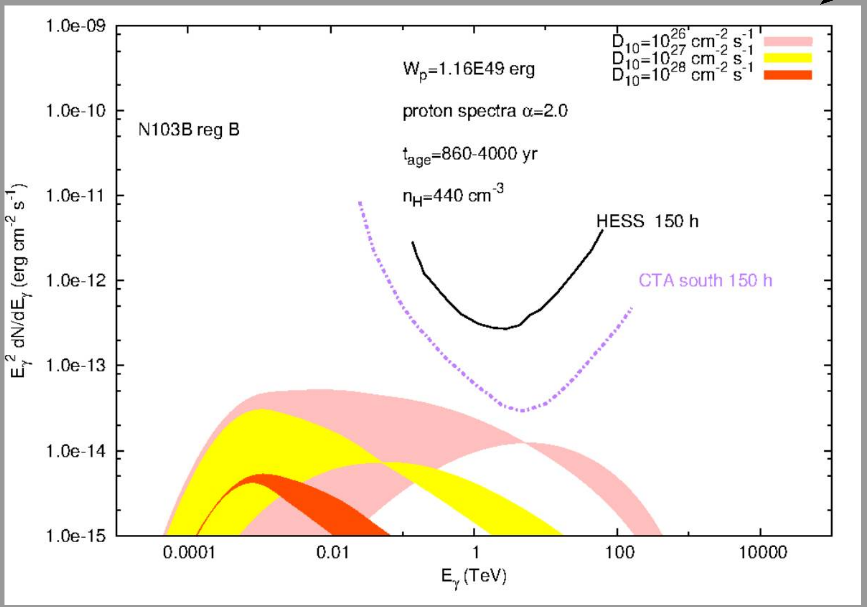
- ~10 TeV gamma-ray emission inside reg A could be detected by CTA after ~150h observations → Impose constraints on the diffusion coefficient.
- Potential TeV gamma-ray detections offset from the SNR could then help confirm its hadronic origin.

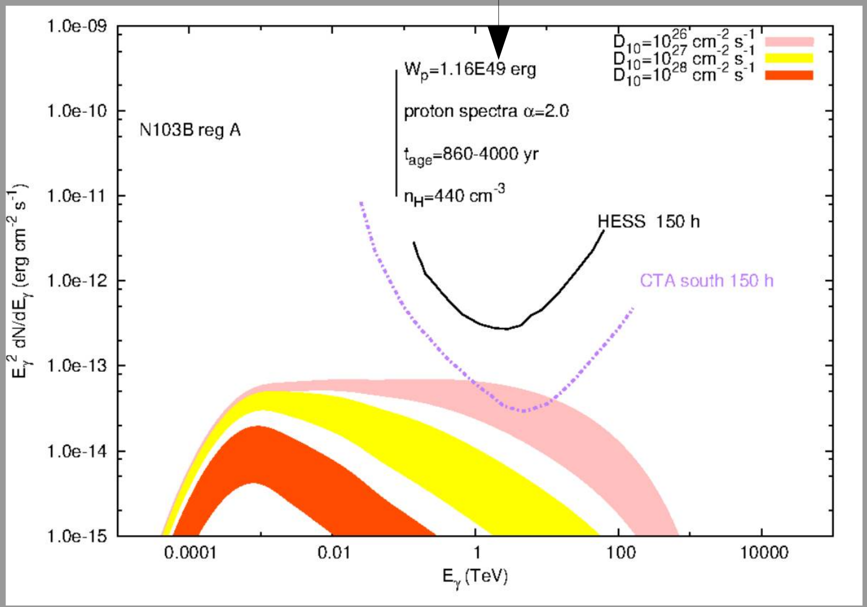
CTA and LMC SNRs

Another interesting source : N103B

- 2 molecular clouds found near SNR
- Potential TeV gamma-ray detection after 150 hours observations towards region A if the diffusion coefficent at 10 GeV is $D_{10}=10^{26}$ $cm^{-2}s^{-1}$ → slow diffusion

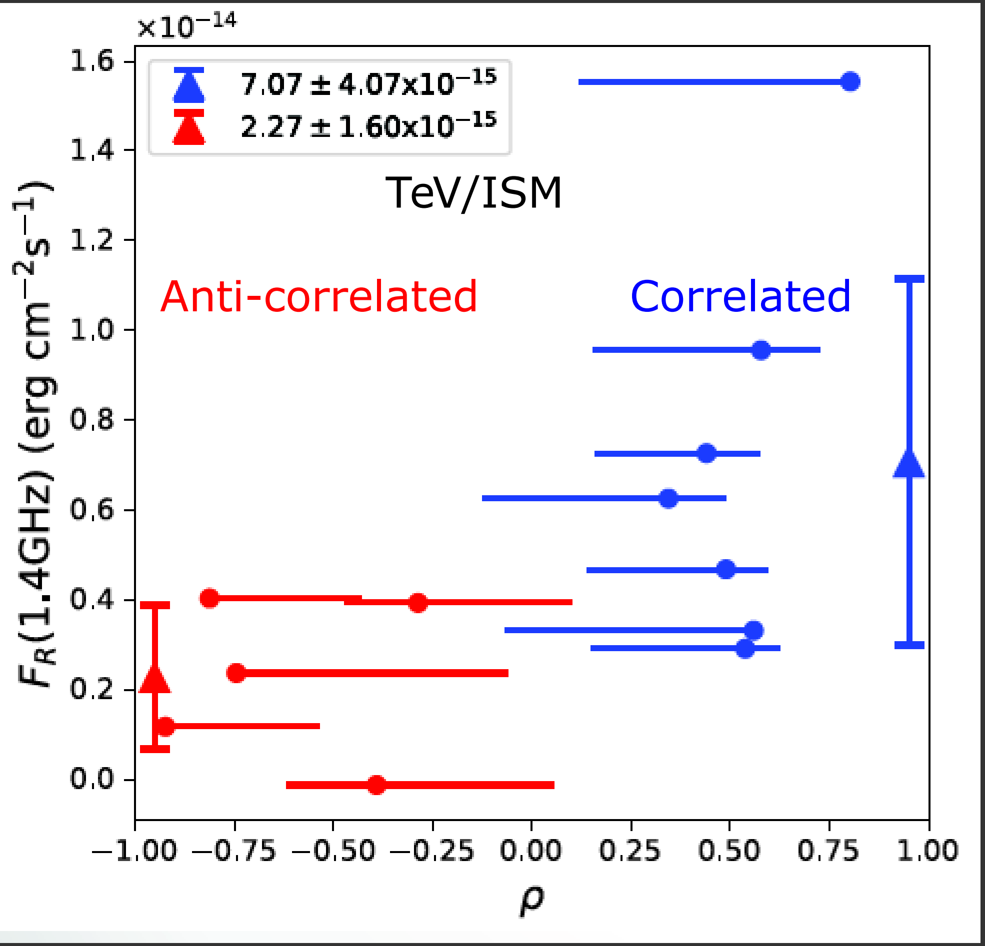






Thank you....

Radio Flux Difference?



- We compare the observations for the blue regions to those of the red regions by calculating a t-statistic for the samples
- We see a moderately significant difference between the ATCA radio flux ($t = 2.60$ and p-value $= 0.015$)
- Expected? Simplistically, red regions are inv-Compton-dominant or synchrotron-poor.