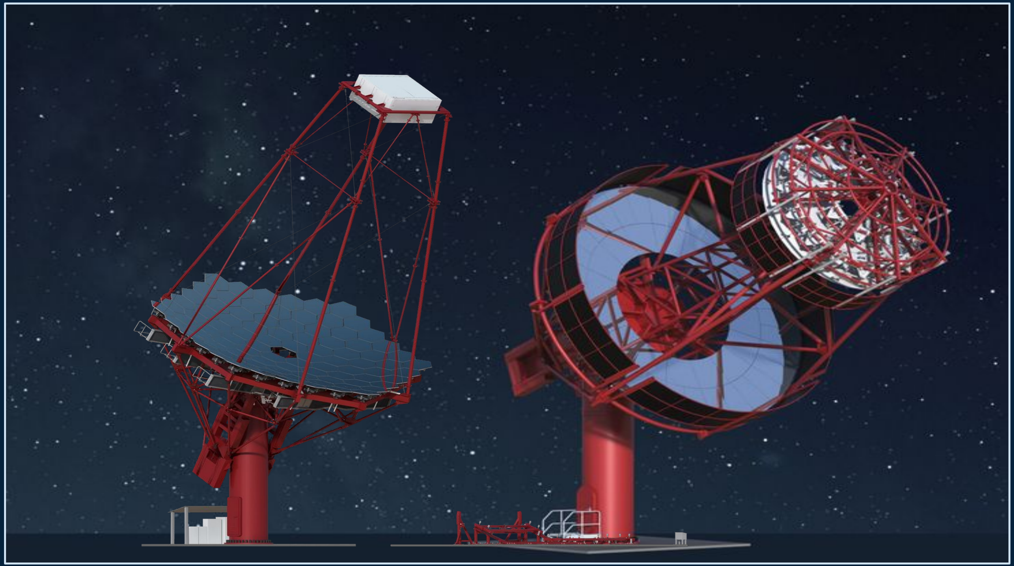
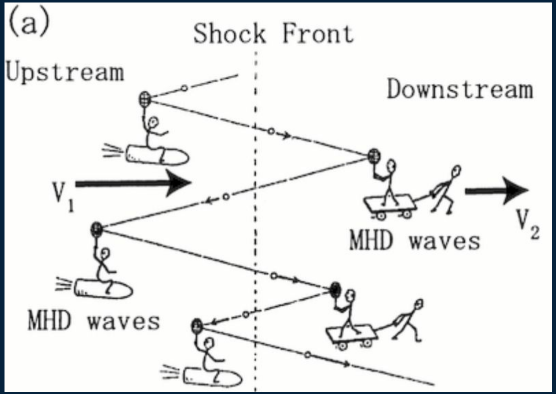


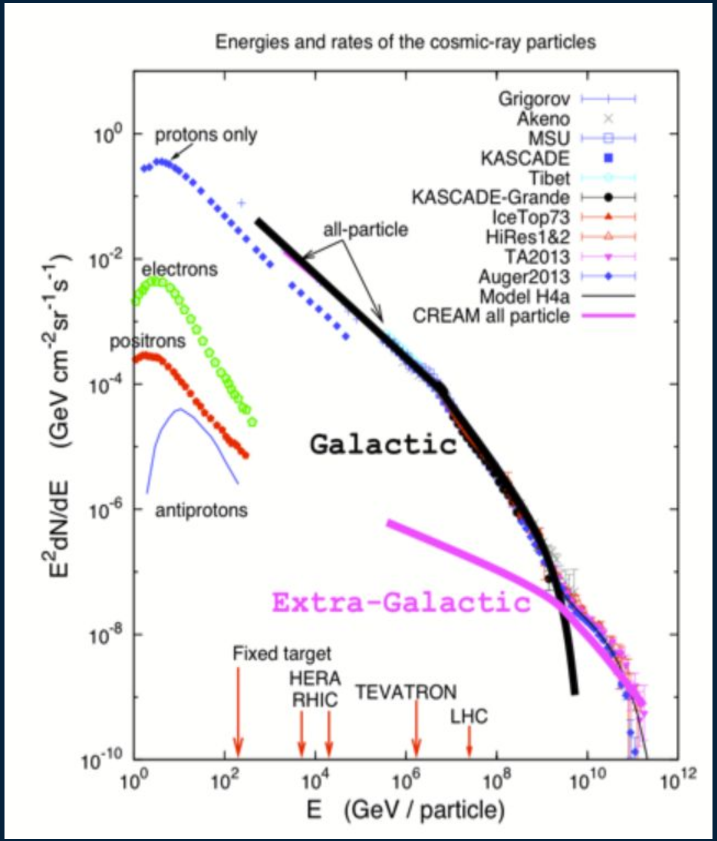
Simulating the Galactic Centre: A Comparison of Medium-Sized Telescopes and Schwarzschild-Couder Telescopes

Anna Wong
Wellesley College
Columbia Nevis Labs REU Program, Summer 2023
VERITAS Group

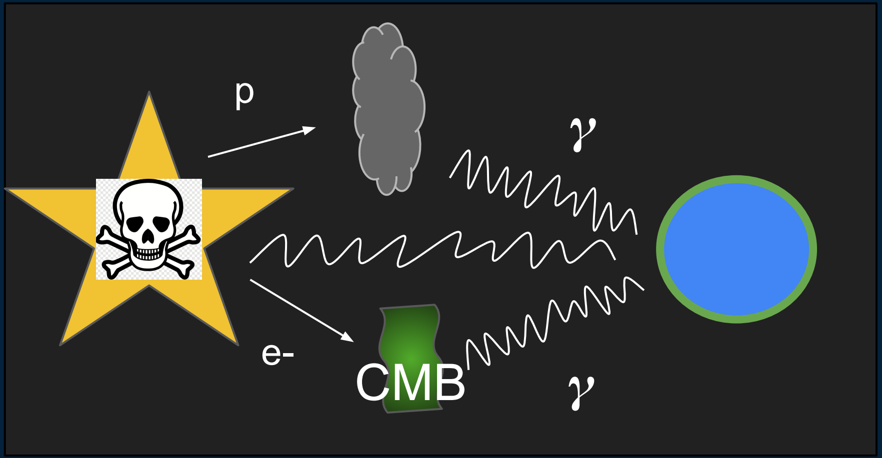
Cosmic ray sources

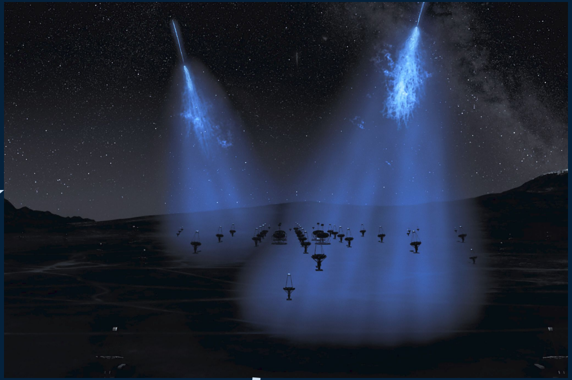
- Ultra-high energy particle accelerators
- Extremely violent environments: black holes, pulsar wind nebulae, supernova remnants (SNRs)
  - Acceleration mechanisms unknown
- Supernova remnants: diffusive shock acceleration

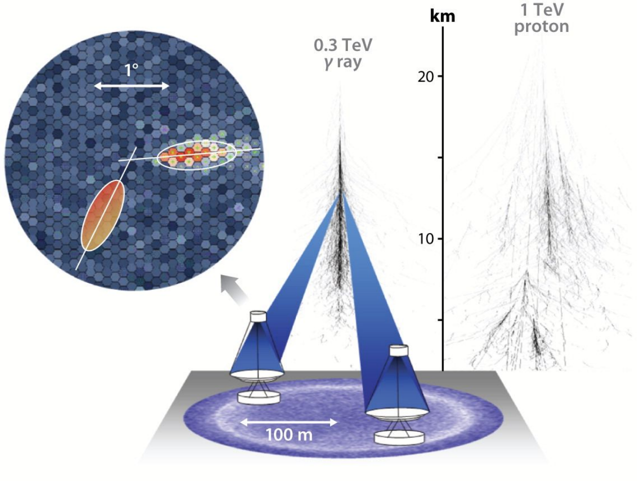




Cosmic ray detection







Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

Imaging Atmospheric Cherenkov Technique (IACT)

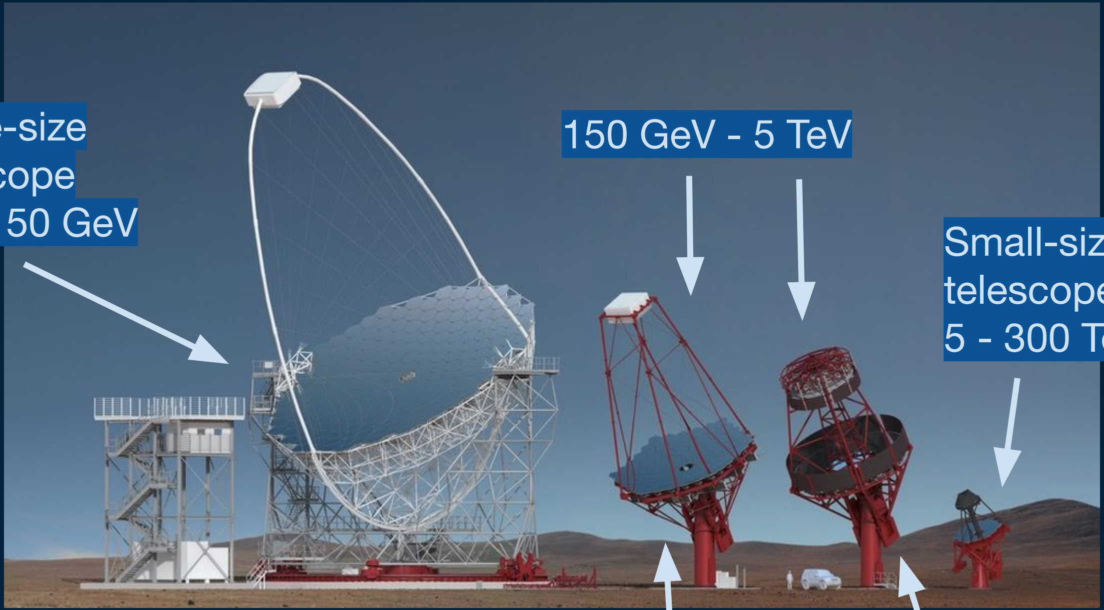
- MAGIC, HESS, VERITAS

Cherenkov Telescope Array Observatory

Large-size telescope
20 - 150 GeV

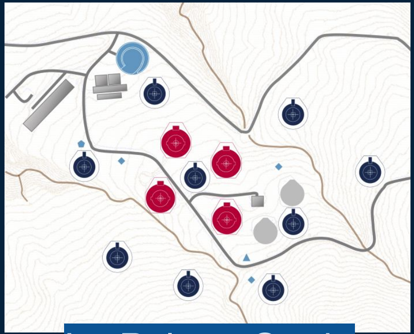
150 GeV - 5 TeV

Small-size telescope
5 - 300 TeV

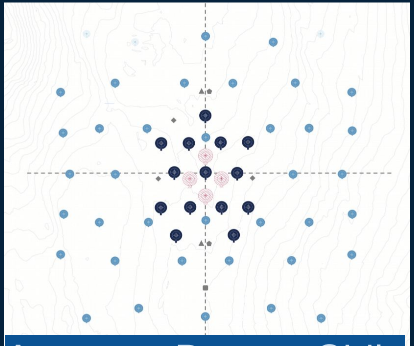


Medium-size telescope

Schwarzschild-Couder telescope



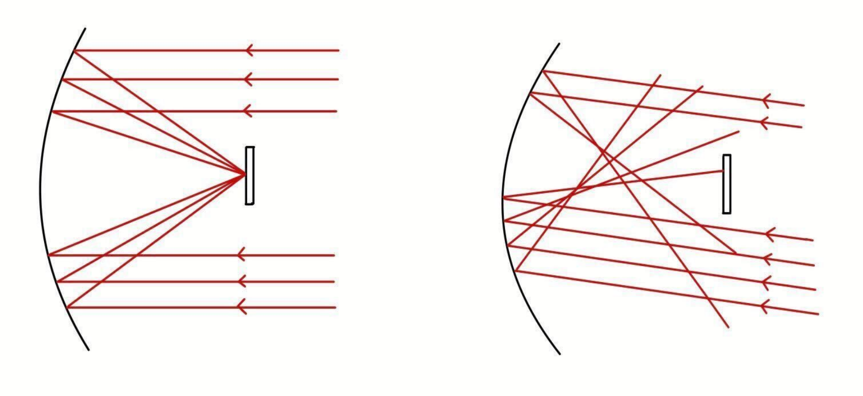
La Palma, Spain

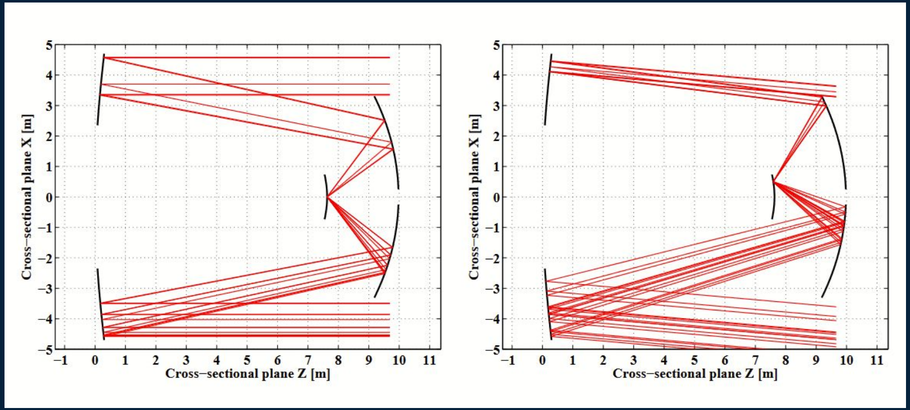


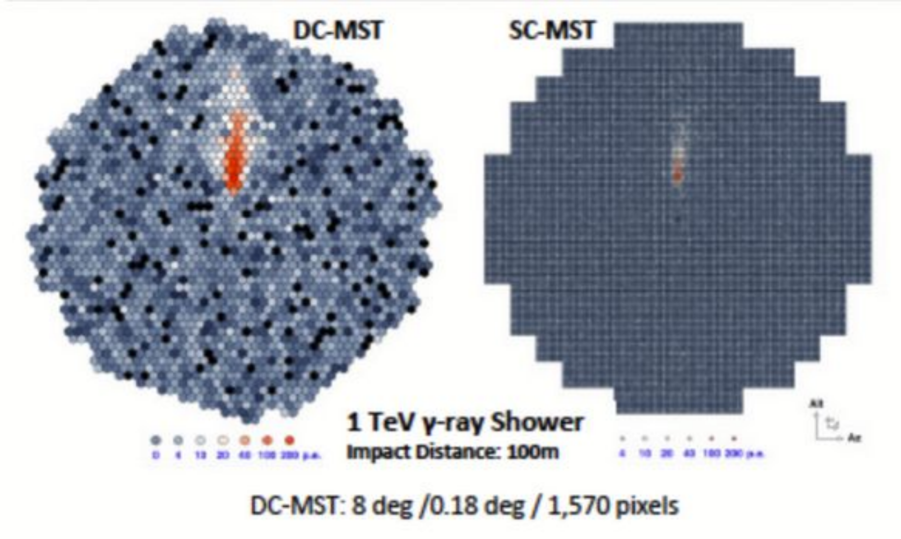
Atacama Desert, Chile

MST and SCT optics

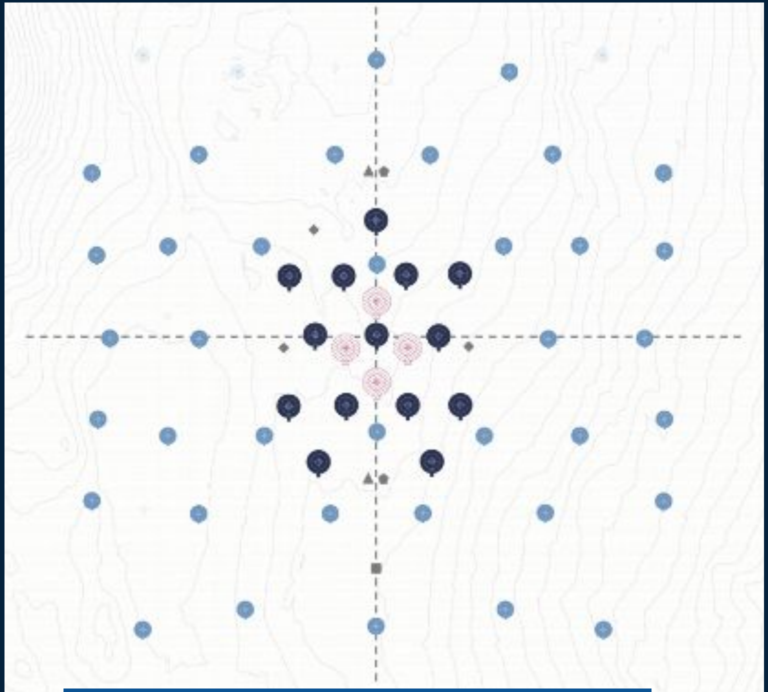
	MST	SCT
Effective FOV	3.5°	7.6°
Number of pixels	1855	11328



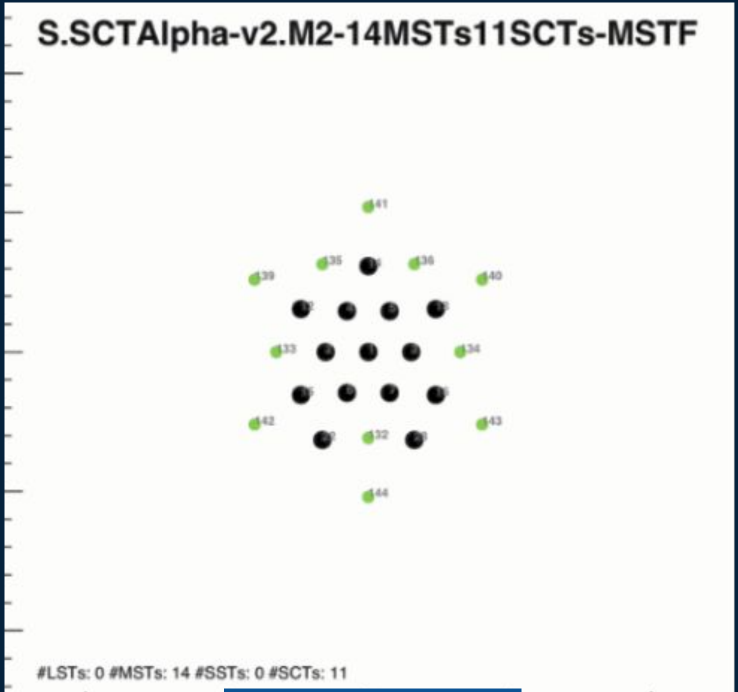




Alpha and Alpha-V2 configurations

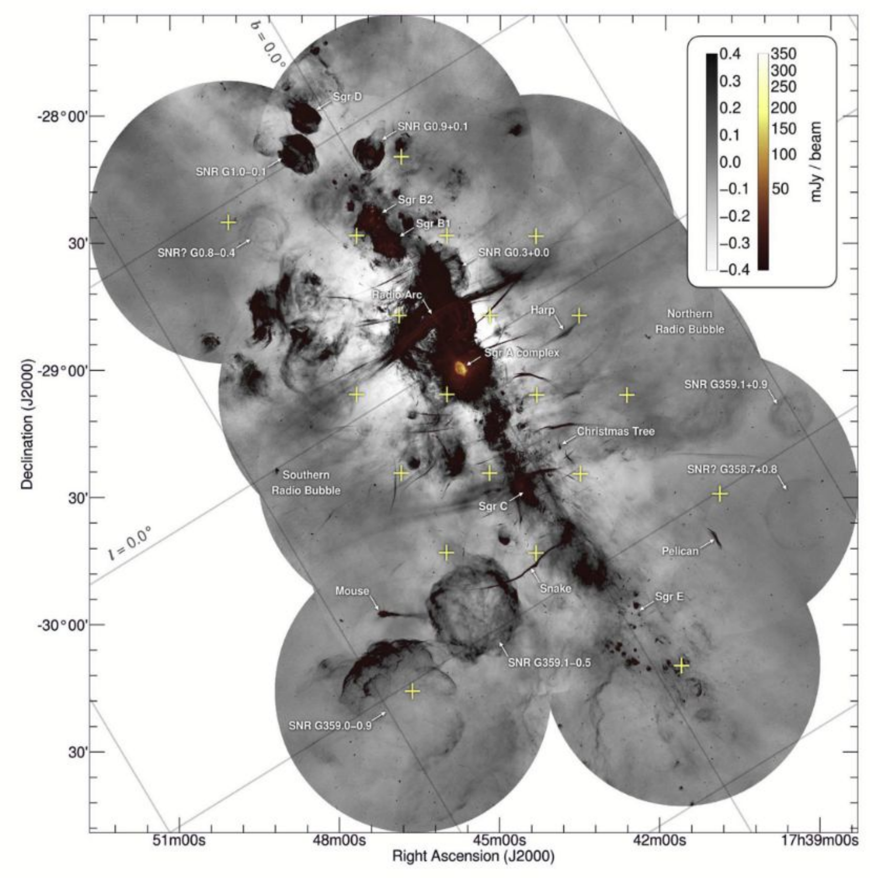


37 SSTs, 14 MSTs, 4 LSTs



… + 11 SCTs

Project objective



To simulate gamma-ray events from the Galactic Centre using three different arrays:

- 14 MSTs
- 14 MSTs + 11 SCTs
- 25 MSTs

and show how the SCTs improve the image.

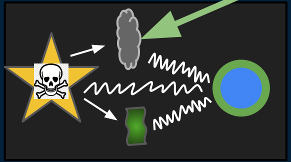
Mosaic of twenty pointings from the South African MeerKAT radio telescope

Conversion

Equation from Aharonian et. al describes gamma-ray flux as dependent on an A factor:

$$F_\gamma(\geq E) = f_\alpha \times 10^{-10} \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\alpha+1} A\ \mathrm{cm}^{-2}\mathrm{s}^{-1},$$

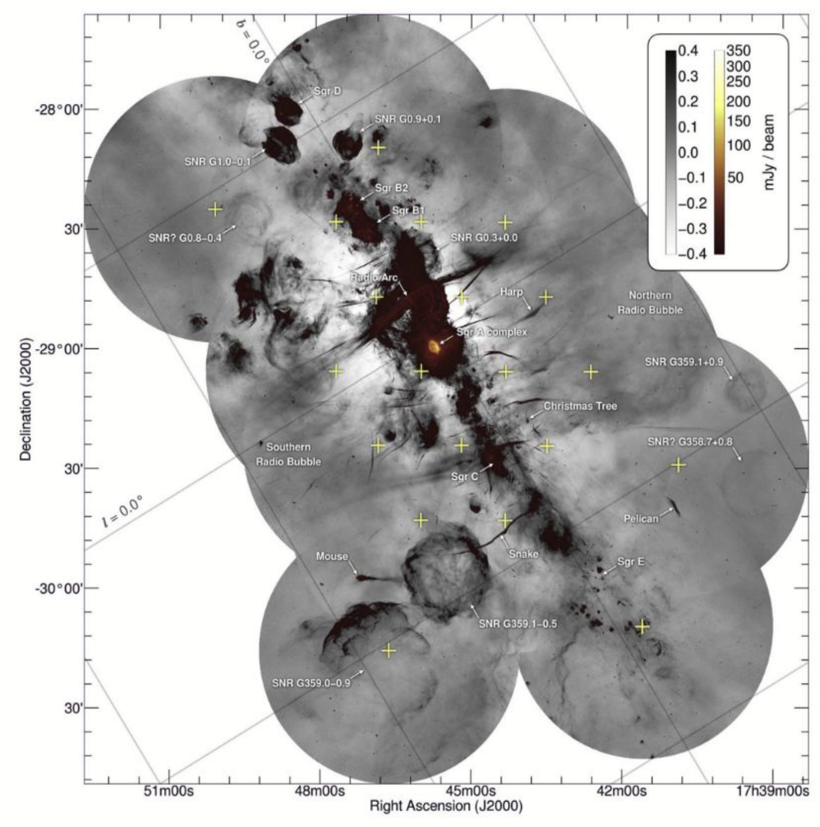
$$A = \boxed{\theta \left(\frac{E_{SN}}{10^{51}\,\mathrm{erg}}\right)} \left(\frac{d}{1\ \mathrm{kpc}}\right)^{-2} \left(\frac{\boxed{n}}{1\ \mathrm{cm}^{-3}}\right)$$



$$A = \boxed{(E_{CR})} \left(\frac{1\mathrm{kpc}}{d}\right)^2 \boxed{\left(\frac{N_{total}}{V}\right)}$$

$$A = \boxed{\left(\frac{E_{CR}}{V}\right)} \left(\frac{1\mathrm{kpc}}{d}\right)^2 \boxed{(N_{total})}$$

Finding N

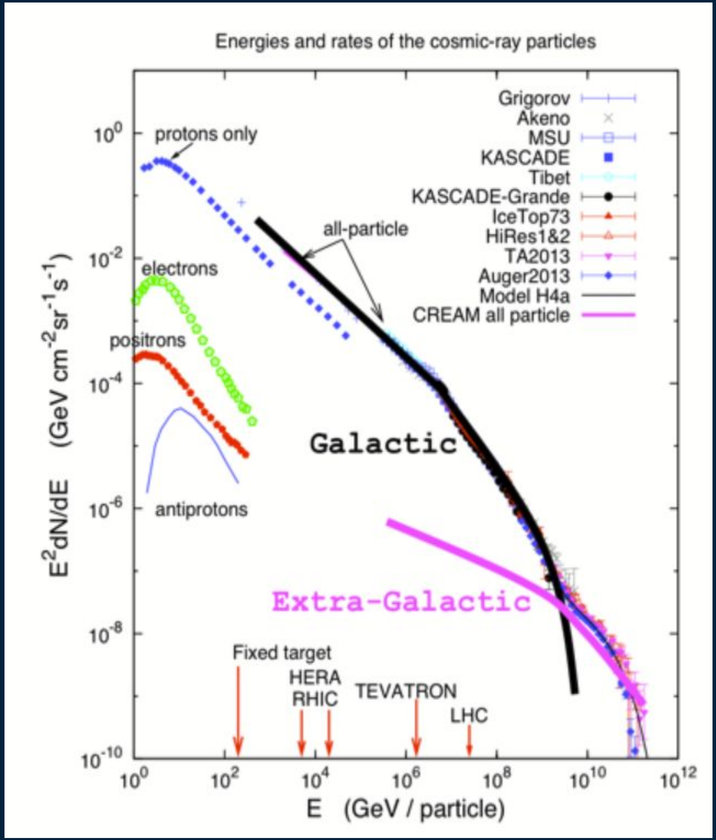


$$N_{column} \approx (2.33 \times 10^{20})(1+z)^4(\theta^{-2}) \int S df$$

- Hydrogen line (21 cm line)
- N = 8 x 10^{66} (total)

Equation from Westmeier 2023

Finding E_{CR} / V



<u>Assuming uniform cosmic ray flux:</u>

- Gamma rays detected are 1 TeV (MST range)
- Cosmic rays only transfer ~10% energy to gamma rays
- 1 TeV x 10 = 10^4 GeV

Flux of cosmic rays with 10^3 GeV = 10^{-2} GeV/cm^{2}s

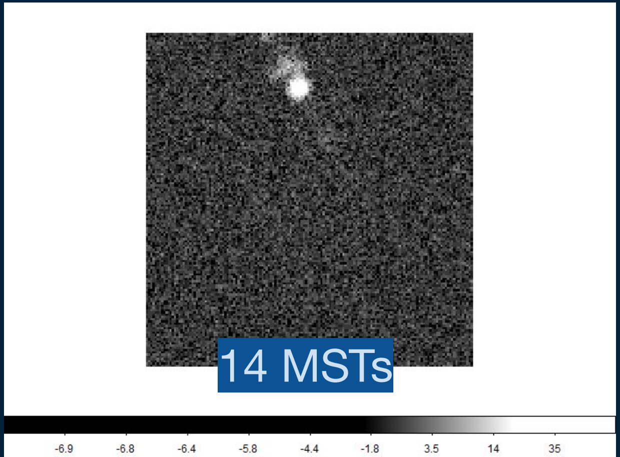
$$\frac{F_{CR}}{c} = \boxed{\frac{E_{CR}}{V}}$$

$$A = \boxed{\left(\frac{E_{CR}}{V}\right)}\left(\frac{1\text{kpc}}{d}\right)^2 (N_{total})$$

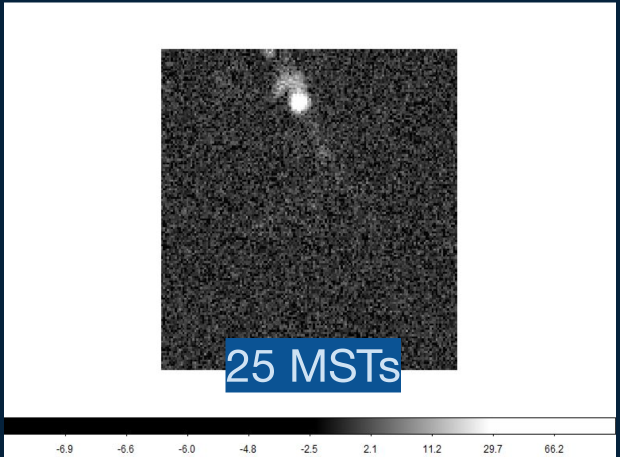
$$A = 1.54 \times 10^{-17}$$

Simulation setup

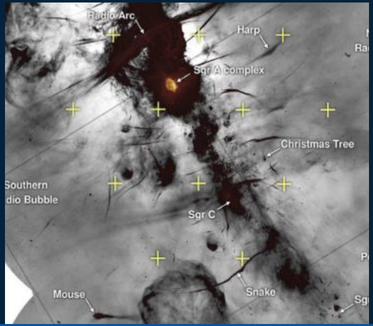
- Ctools: gamma ray event simulation software
- Using calculated A value for prefactor
- 10-hour pointing with three different arrangements of telescopes
- SCT provides better resolution of morphology surrounding Sagittarius A*
- …Have to mask Sagittarius A*



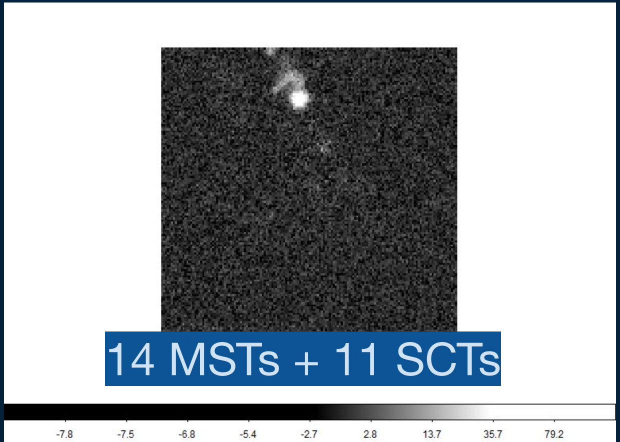
14 MSTs



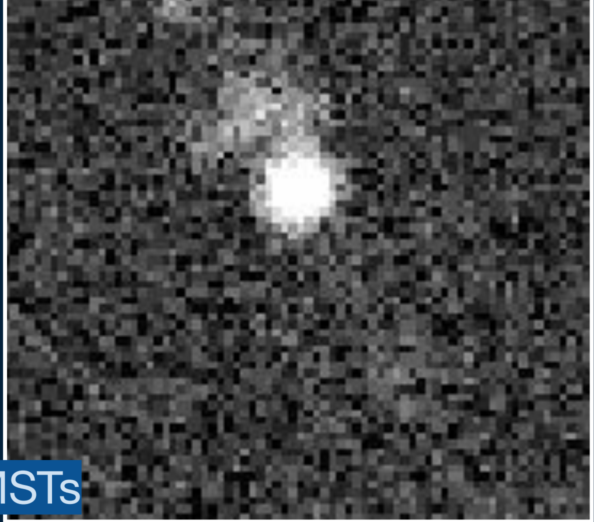
25 MSTs



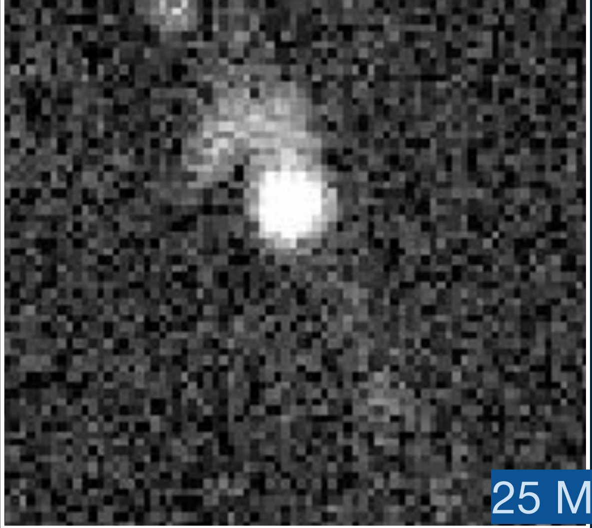
MeerKAT radio data



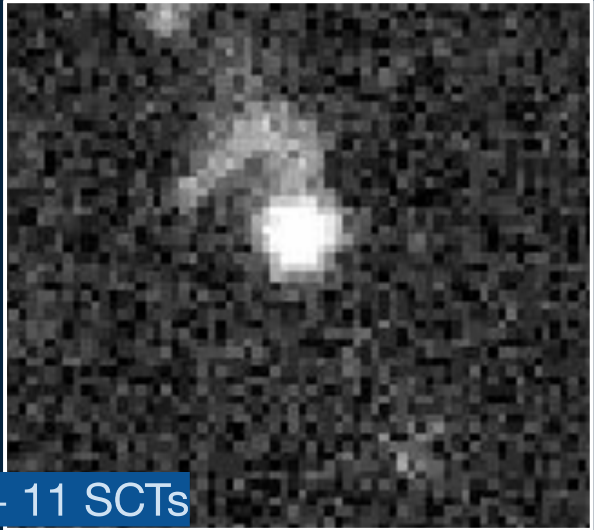
14 MSTs + 11 SCTs



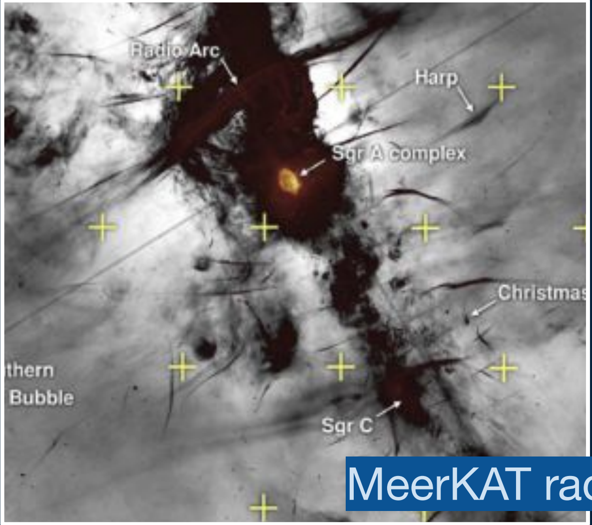
14 MSTs



25 MSTs



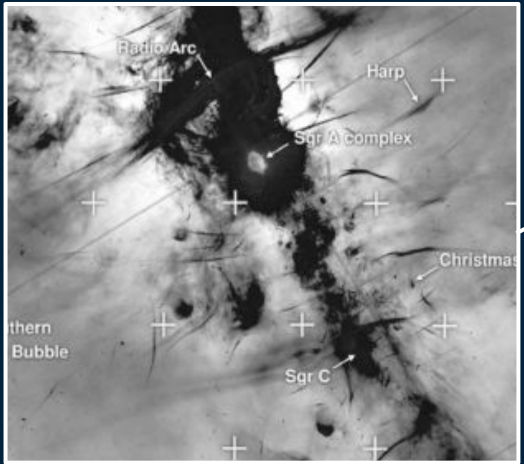
14 MSTs + 11 SCTs

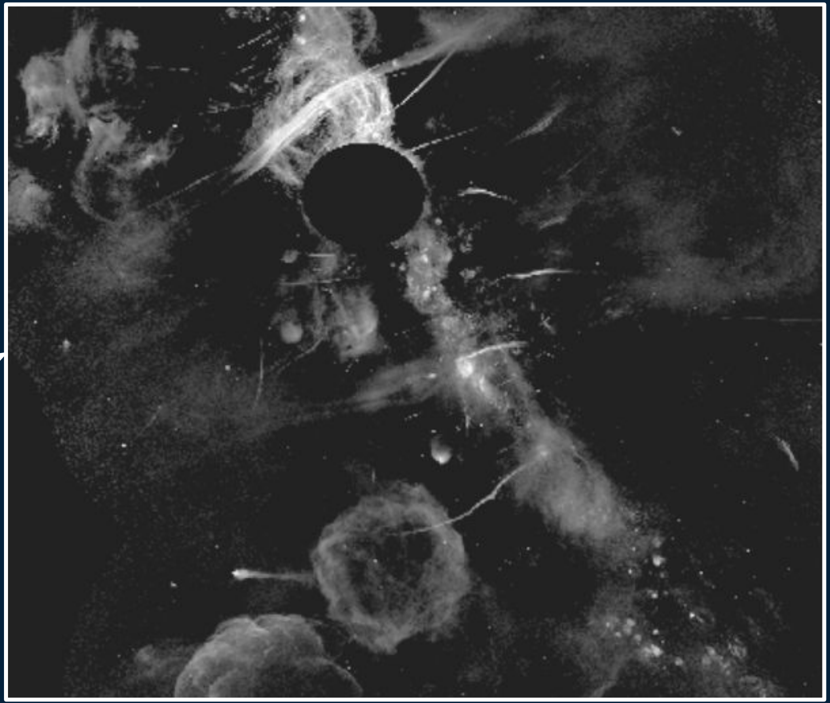


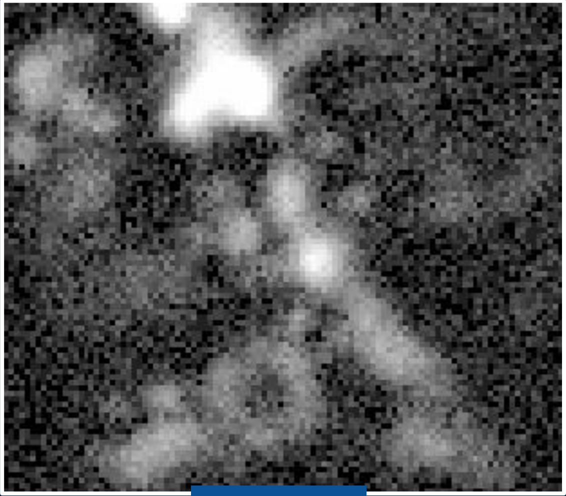
MeerKAT radio data

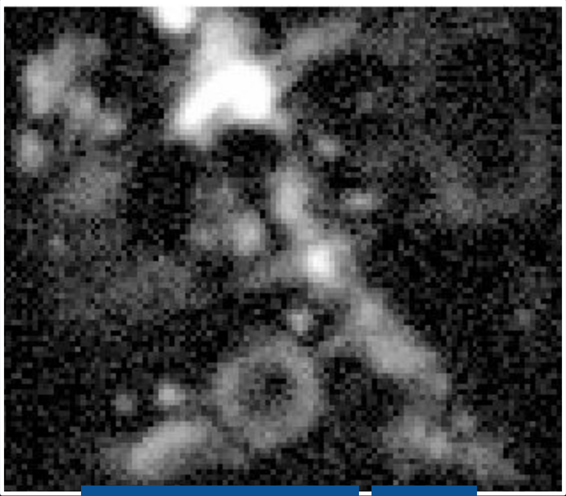
Simulation setup pt. 2

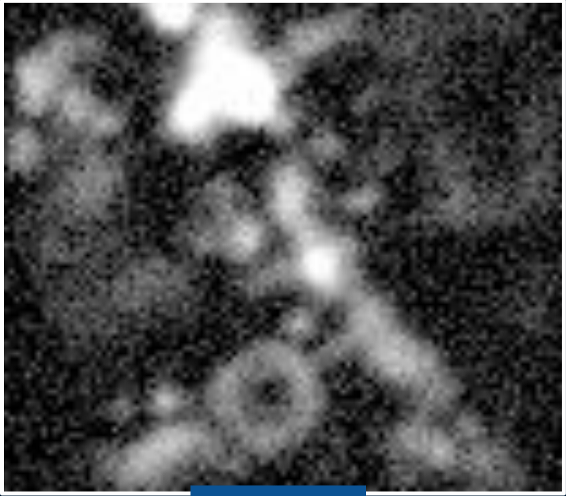
- Still using A as normalization for power law spectrum but masked Sagittarius A*
- 20 hour pointing instead of 10 hour

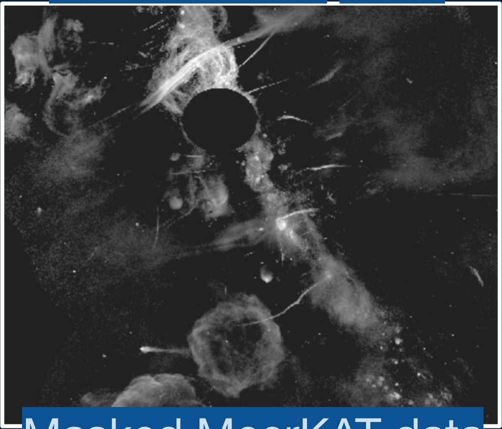


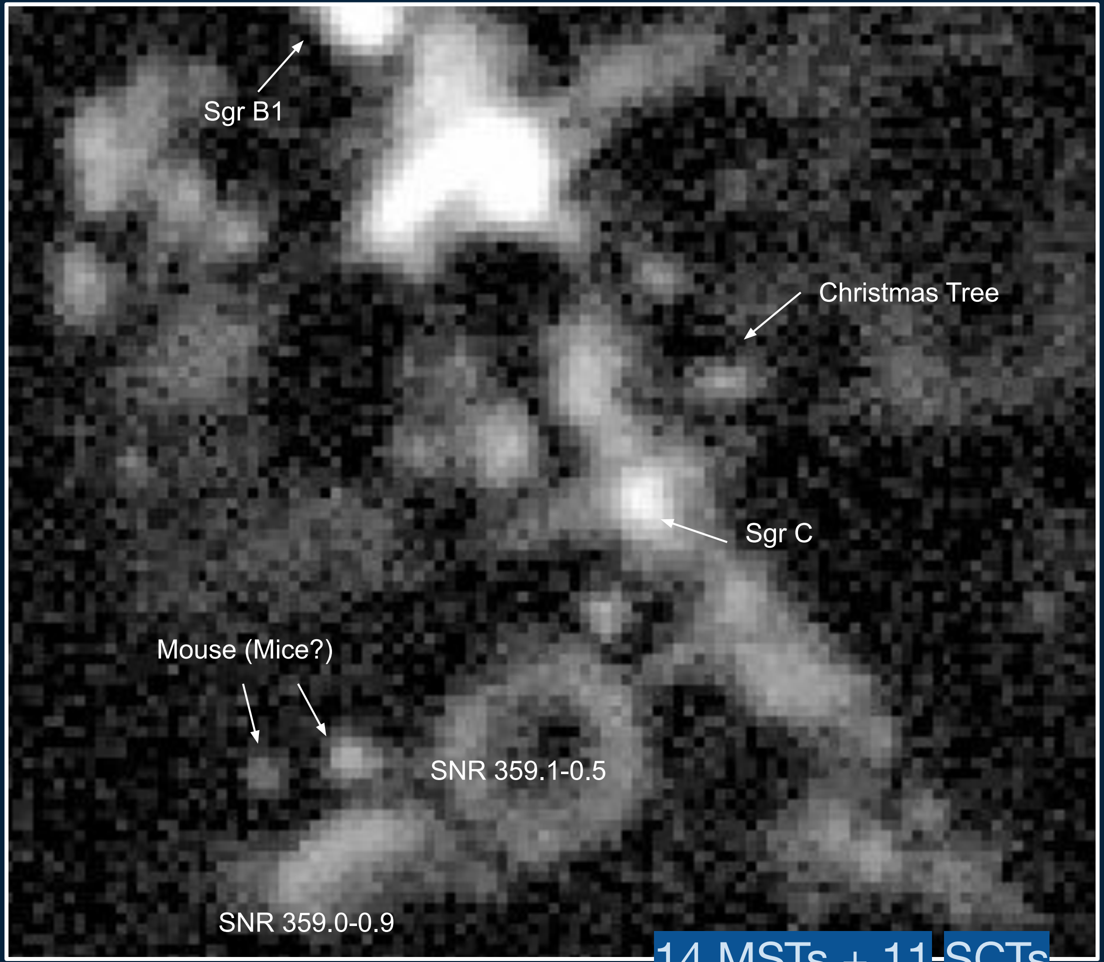



14 MSTs

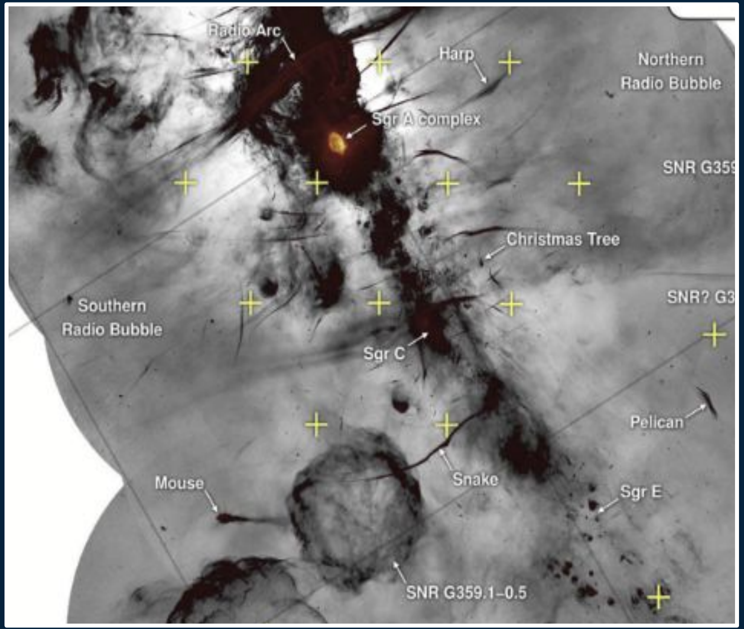

14 MSTs + 11 SCTs

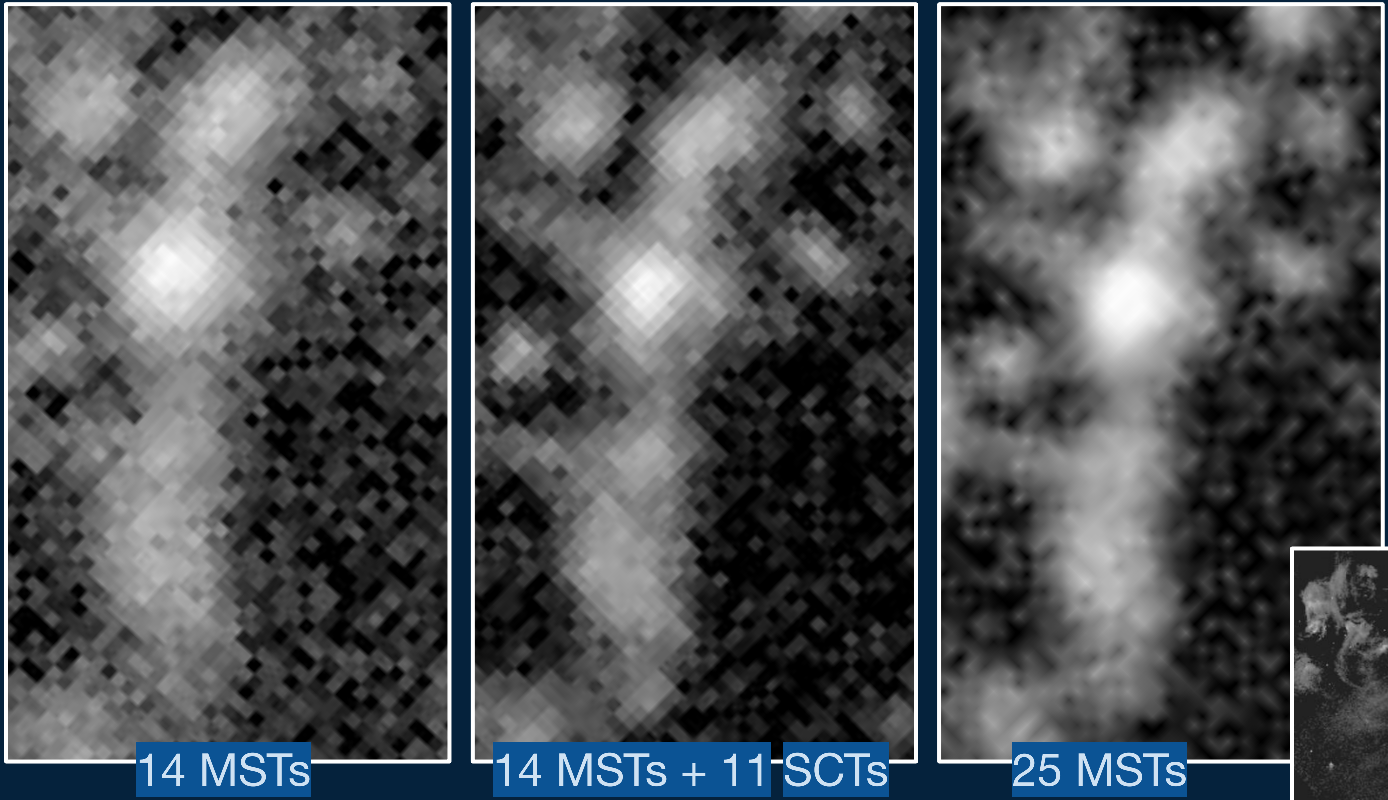

25 MSTs

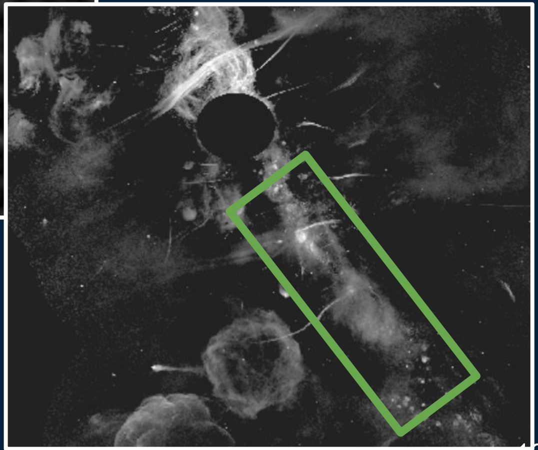

Masked MeerKAT data



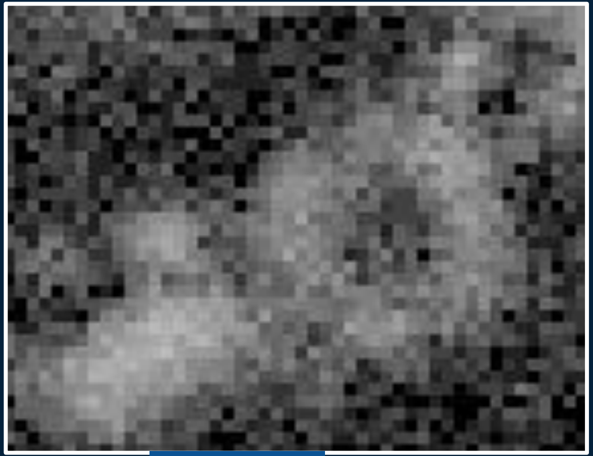
14 MSTs + 11 SCTs



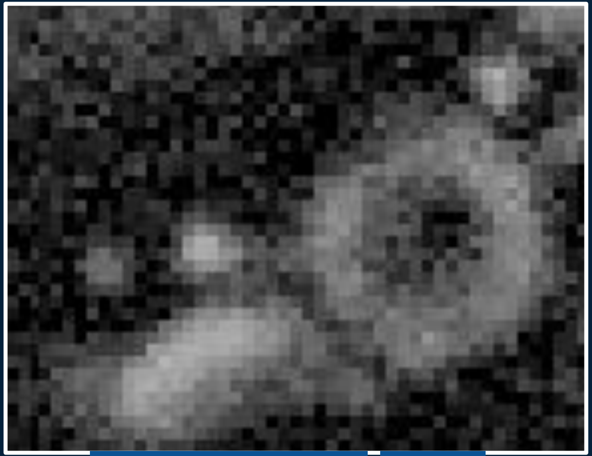




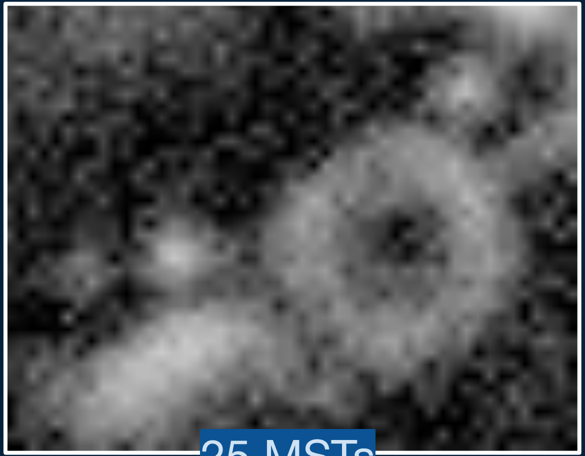
Sagittarius C, Christmas Tree



14 MSTs

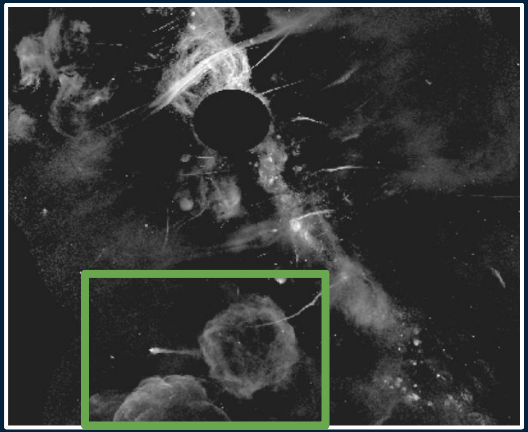


14 MSTs + 11 SCTs



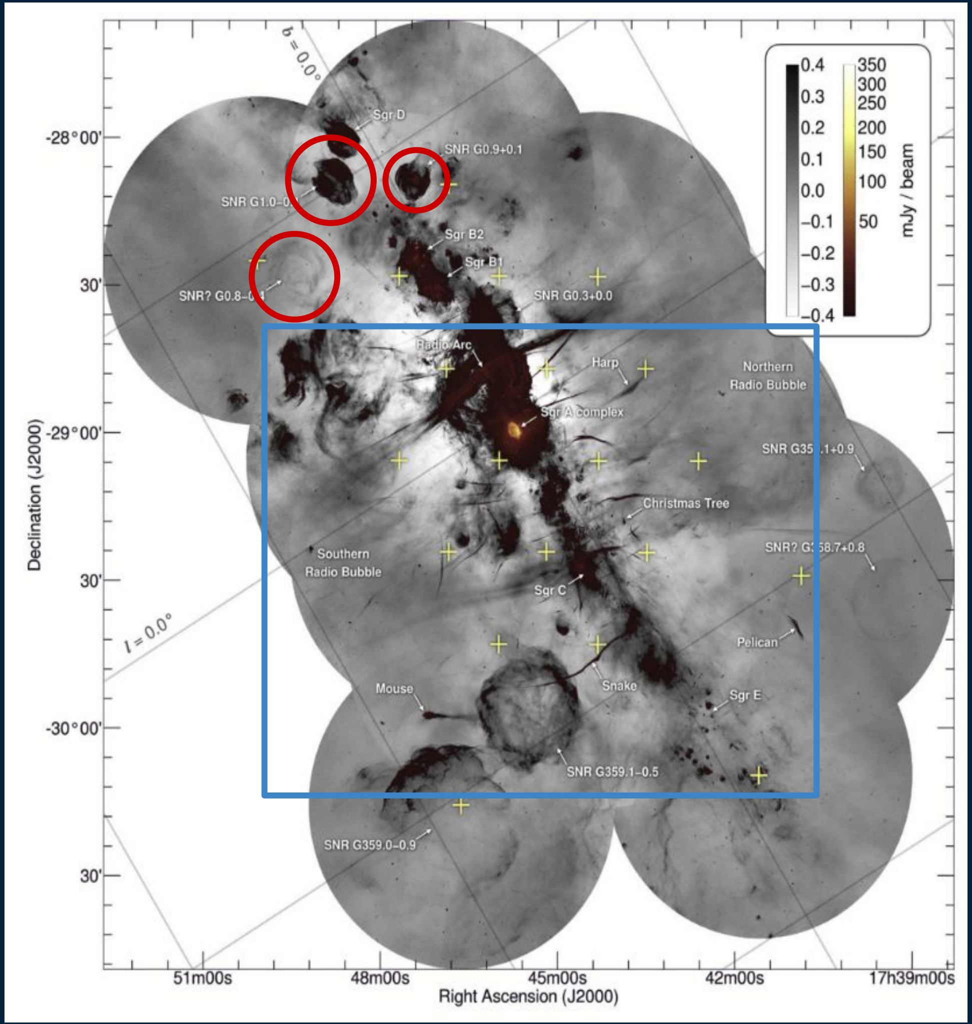
25 MSTs

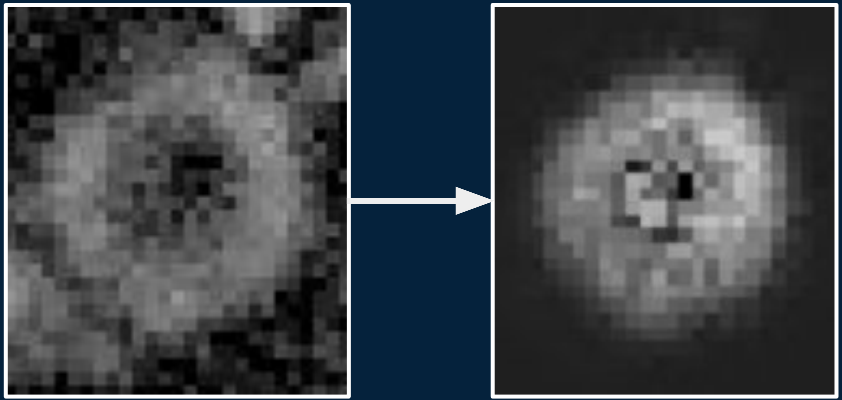
SNR 359.1-0.5
Upper half of SNR 359.0-0.9



Further investigation

- Simulate events from upper SNRs
- Incorporate 'local' SNR flux
    - Apply Gaussian scaling proportional to distance

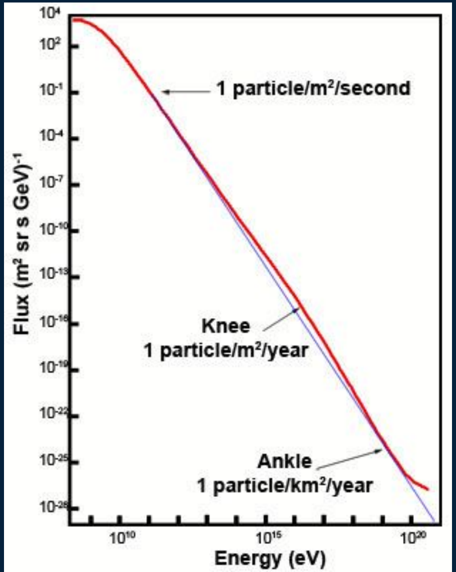




SNR 359.1-0.5

Conclusion

- 11 SCTs greatly improve CTAO's ability to image the Galactic Centre
  - High-density of sources
- High-energy physics implications
  - Acceleration mechanisms
  - Ankle, knee
- Astronomy implications
  - Most detailed gamma-ray image of GC
  - New sources, PeVatron confirmations



Acknowledgements

I would like to thank Professor Reshmi Mukherjee, Dr. Ruo Shang, and the rest of the VERITAS group at Columbia and Barnard for their guidance and support of my research this summer. I'd also like to thank Amy Garwood, Professor Georgia Karagiorgi, and Professor John Parsons for the opportunity to do research at Nevis Labs, and for their support of Columbia's REU program.

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NEVIS LABORATORIES
COLUMBIA UNIVERSITY

VERITAS

cta
cherenkov telescope array

$$F_\gamma(\geq E) = f_\alpha \times 10^{-10} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-\alpha+1} A\,\mathrm{cm}^{-2}\mathrm{s}^{-1},$$

E = 300 MeV

f_α = 0.9, 1.43, and 0.19 for α = 2.1, 2.2, 2.3 respectively

$$A = \theta \left(\frac{E_{\mathrm{SN}}}{10^{51}\,\mathrm{erg}}\right) \left(\frac{d}{1\,\mathrm{kpc}}\right)^{-2} \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)$$

E_{SN} = SNR's total explosion energy

θ = fraction of E_{SN} converted to CR energy (typical values 0.1 - 0.2)

d = distance to SNR

n = column density (volume)

$$N_{H1} \approx (2.33 \times 10^{20})(1+z)^4(S)\left(\frac{1}{\theta^2}\right)$$

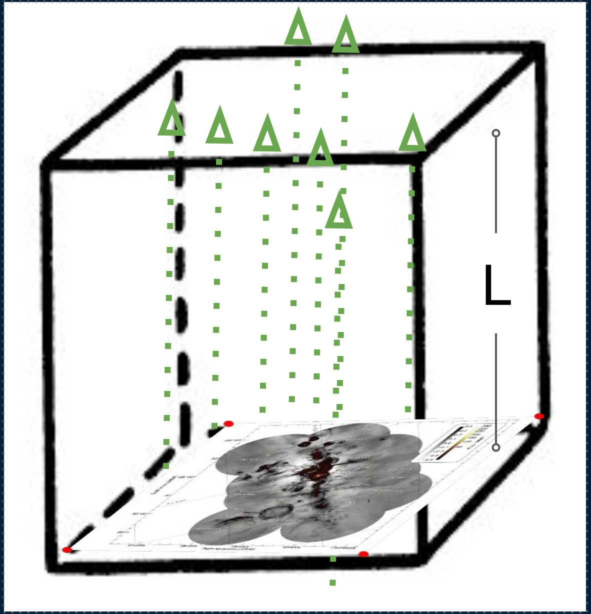
N_{H1} =-column density (area)

z = redshift

S = integrated spectral flux

θ = beam width (arcsec)

Finding E_{CR} / V



$$F_{CR} = \frac{E_{CR}}{A \times \Delta t}$$

$$\frac{E_{CR}}{V} = \frac{E_{CR}}{A \times L} = \frac{E_{CR}}{A \times (c\Delta t)} = \frac{E_{CR}}{c(A \times \Delta t)} = \frac{F_{CR}}{c}$$

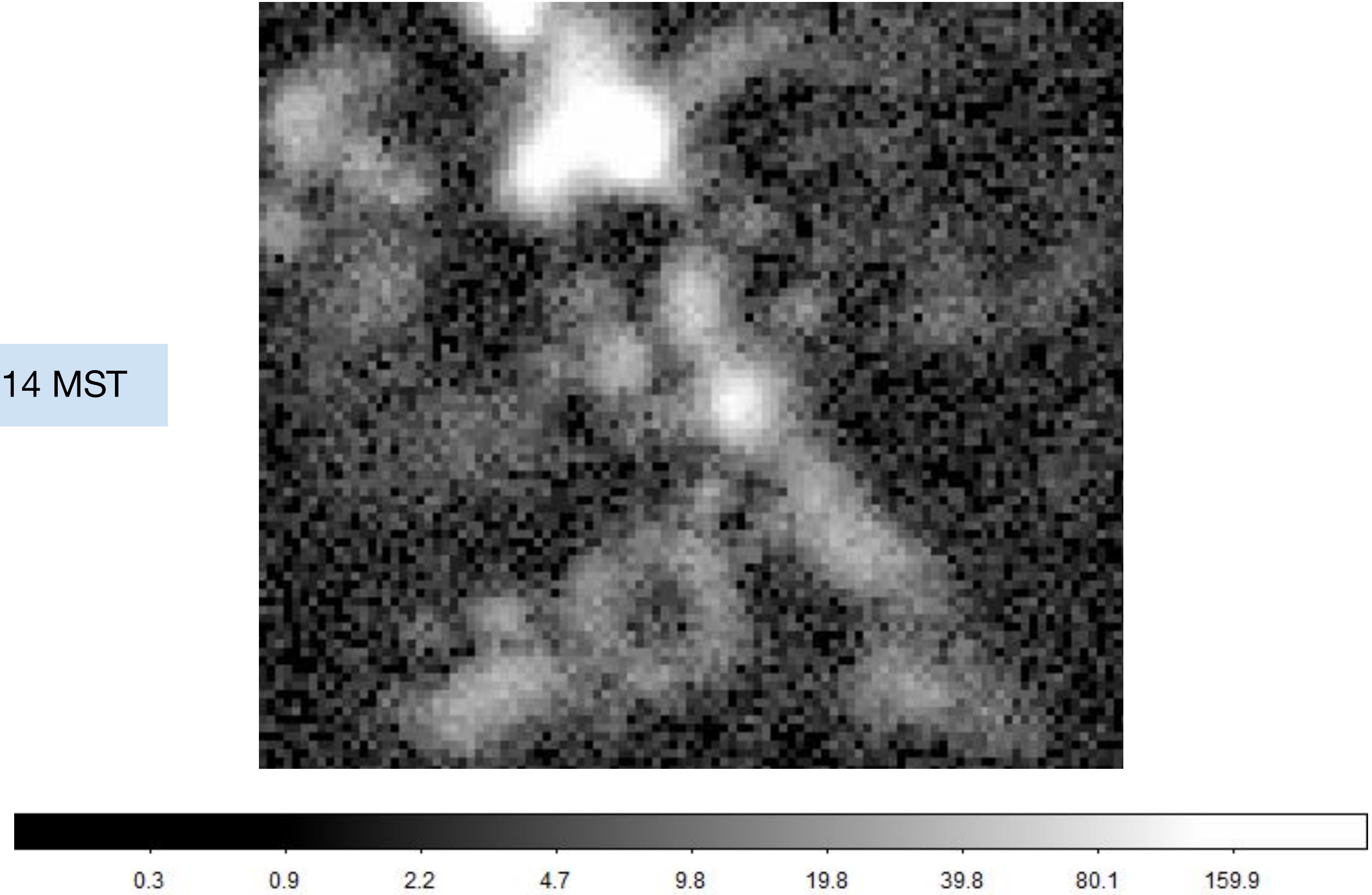
$$A = \boxed{\left(\frac{E_{CR}}{V}\right)}\left(\frac{1\text{kpc}}{d}\right)^2 (N_{total})$$

$$A = 1.54 \times 10^{-17}$$

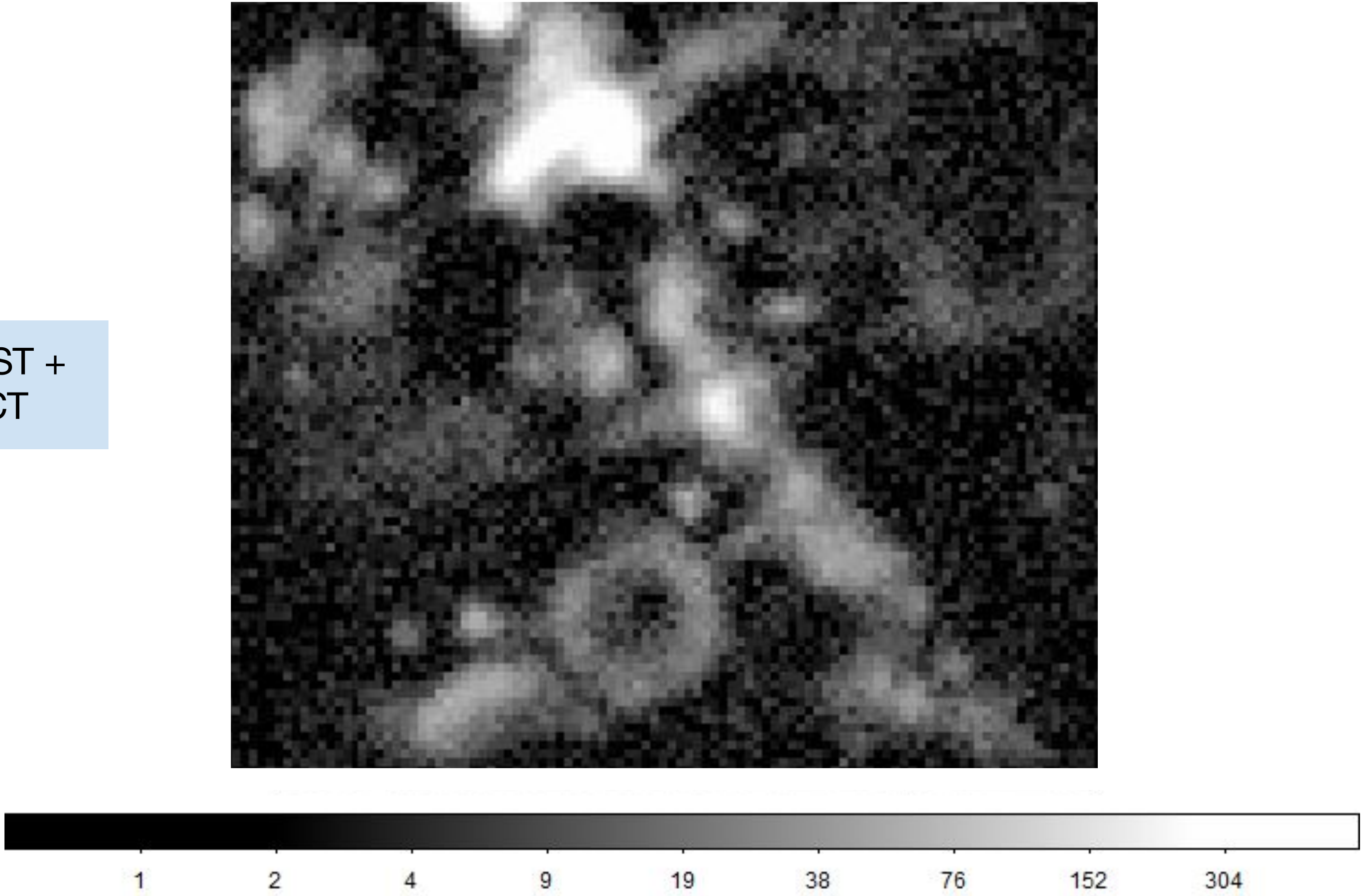
The "Christmas Tree" catalogued by Thomas 2000:
"These authors explain this morphological configuration in terms of a massive star or pulsar that is ejecting cosmic rays as it moves along Galactic magnetic field lines, which are then sequentially emitting synchrotron emission."

- CTAO Science

14 MST



14 MST +
11 SCT



25 MST