PeVatrons in the very high energy gamma ray sky: current status and perspective for CTA

Searching for the sources of Galactic CRs, 11-14 Dec 2018

Sabrina Casanova, MPIK and IFJ PAN

Outline

- The search for CR PeVatrons : state of the art
  - Testing the SNR paradigm
  - Gamma-ray signatures of PeVatrons in MC close to SNRs
  - Galactic Centre
  - Star Clusters
- Searching for PeVatrons with CTA
- Conclusions & Outlook

The Cosmic Ray Spectrum at Earth

- 90% protons, 9% helium, 1% electrons
- Almost featureless spectrum and isotropically distributed up to very high energies
- CRs up to the knee are believed to have a Galactic origin
- Galactic accelerators have to inject particles up to at least the knee at PeV (10^{15} eV) energies, maybe 10^{17} eV.
- The knee for protons might be earlier at about 400-500 TeV (ARGO Collaboration 2015).
- CR production rate = (0.3-1) 10^{41} erg/s or cosmic-ray energy density roughly 1 eV cm^{-3}
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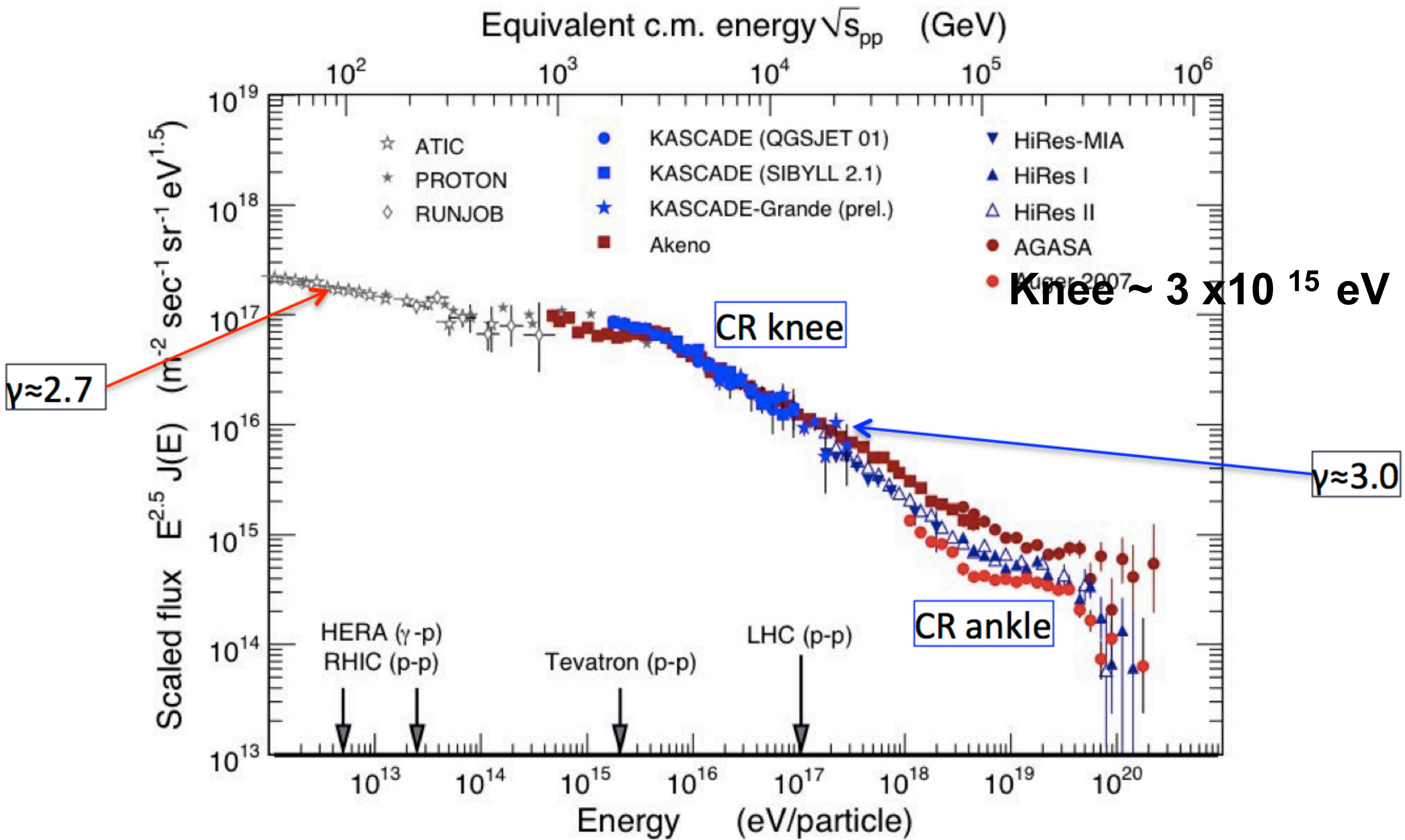


Relevant tests of candidate PeVatrons

- The candidate PeVatron emits VHE γ-ray. Its $\gamma-$ ray spectrum is relatively hard and extends up at least several tens of TeV without a break
- The γ radiation is hadronic
- We can quantify the energetic input in accelerated protons

$$L_\gamma \propto W_p t^{-1} \propto W_p n$$

SNR Paradigm

- Theoretically SNRs provide adequate conditions to have efficient CR acceleration through Diffusive Shock Acceleration -> 10% efficiency and hard E^{-2} type particle spectrum continuing up to very high energies

- SN explosions provide the necessary amount of available energy – 10^{51} erg – to sustain the Gal CR population

- Is there any observational evidence of CR acceleration up to PeV energies in SNRs ?
- Can we constrain how much of the SN burst energy goes in CRs ? Can we prove that each SNR inject 10^{50} erg ?

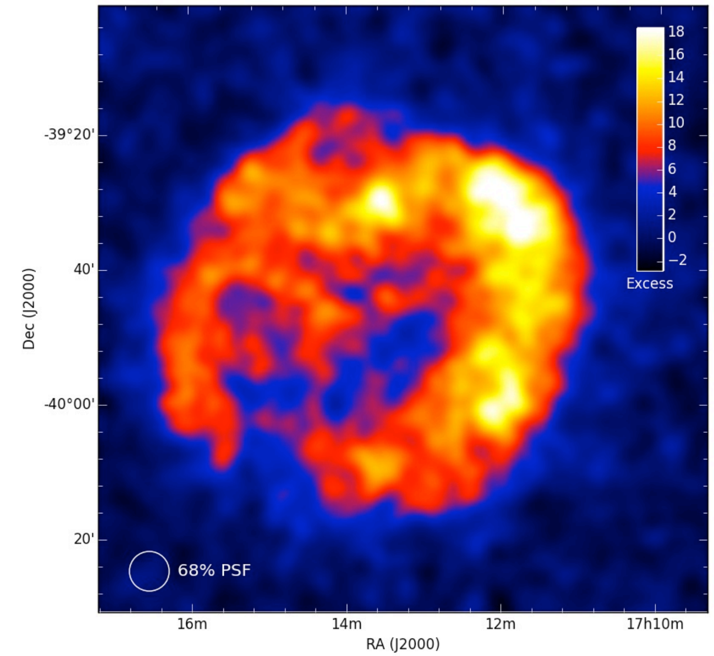
SNR RX J1713-3946

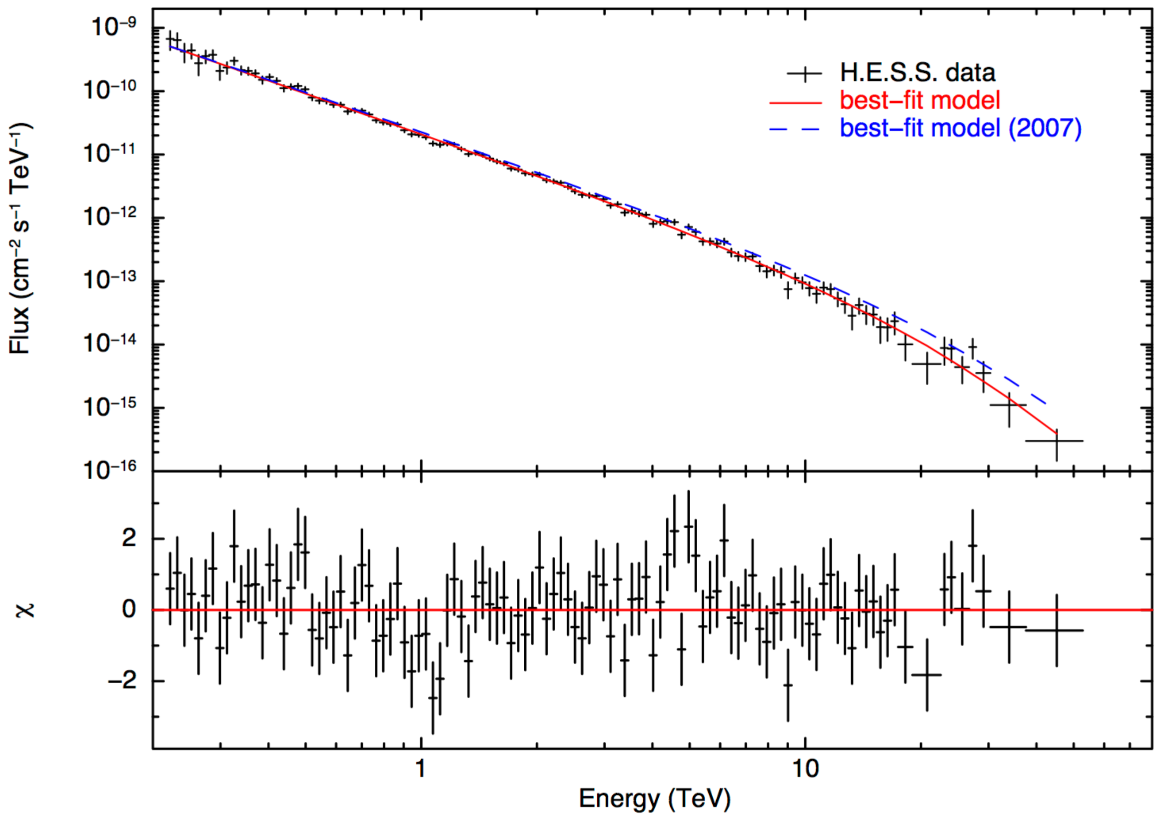
Young (~1.5 kyr) and nearby (~1 kpc) SNR

First, and brightest resolved TeV shell

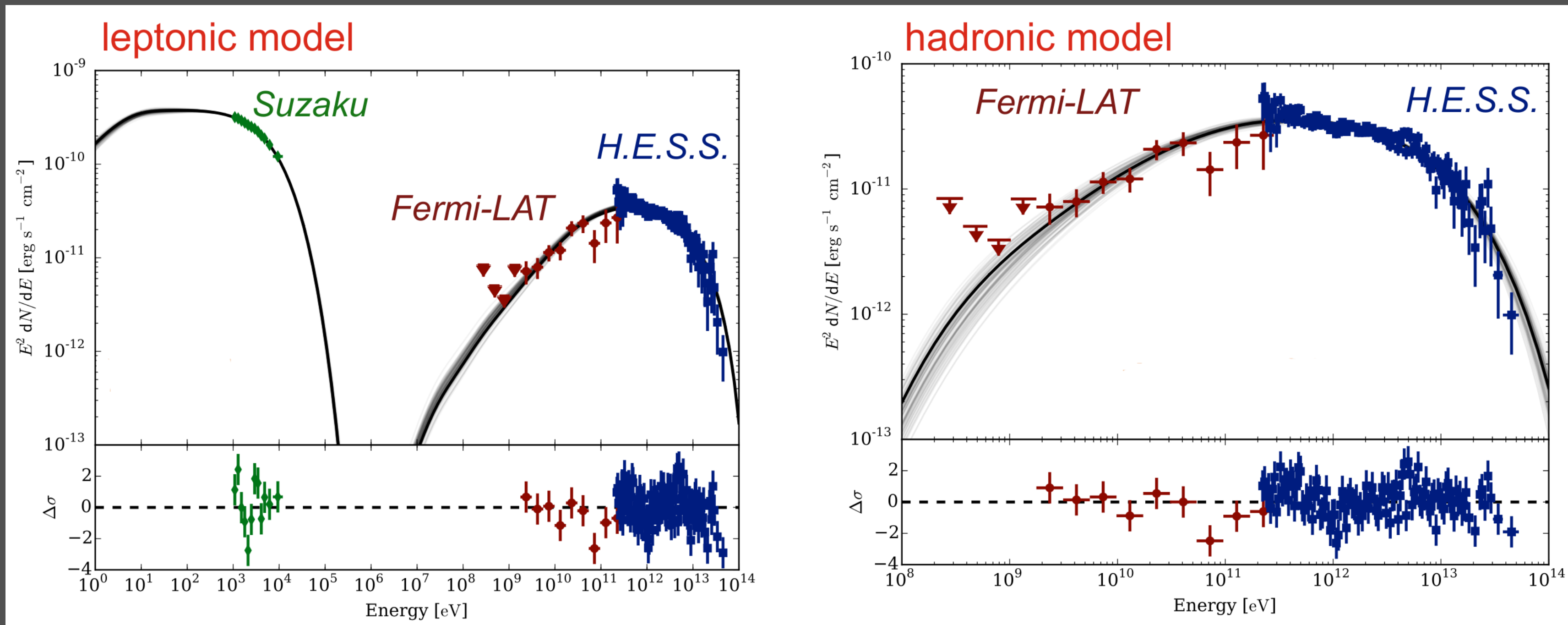
10 years of H.E.S.S. data

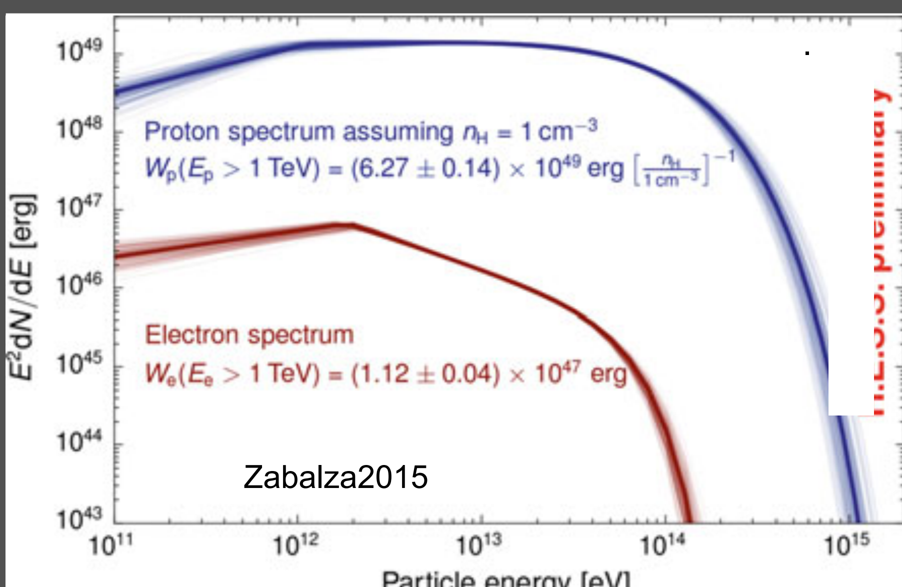
- Factor 2 improvement in statistics over last publication (> 27 000 γ's)
- Spectrum up to ~50 TeV: cuts off ~ 12 TeV





Hadronic or leptonic ?



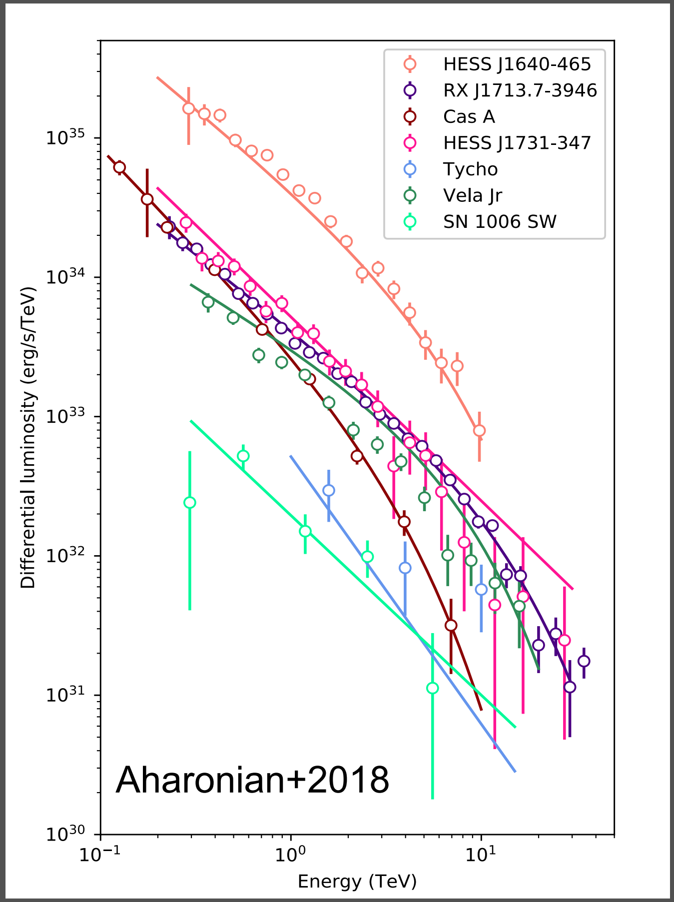


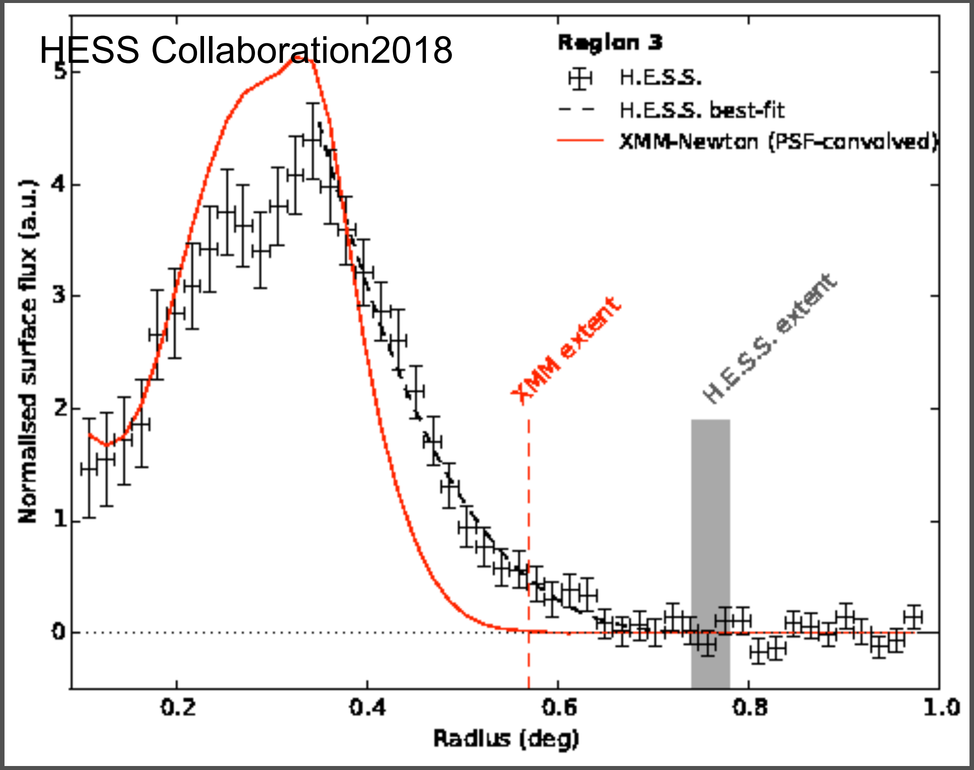
Both hadronic and leptonic can explain the GeV to TeV emission

The content in accelerated hadrons in unknown because of the uncertainty in the estimate of the gas density

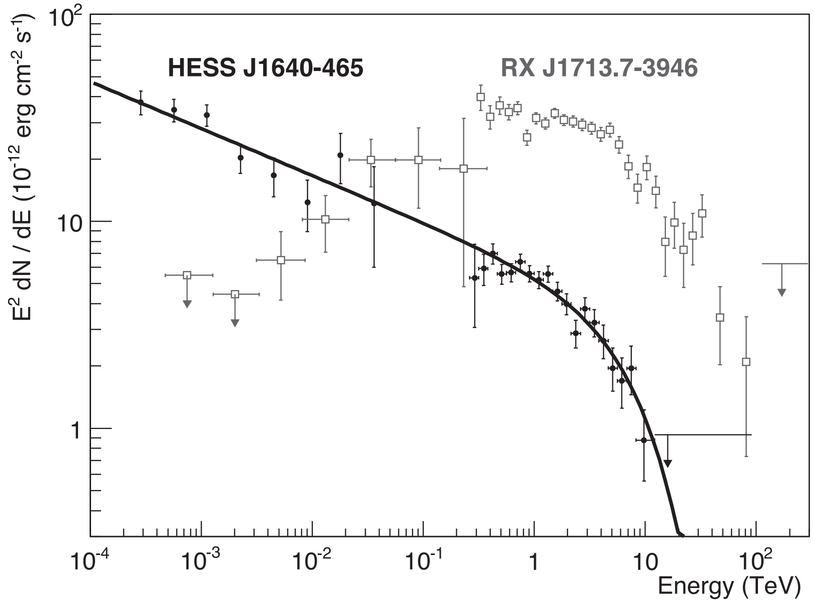
Spectra of young SNRs

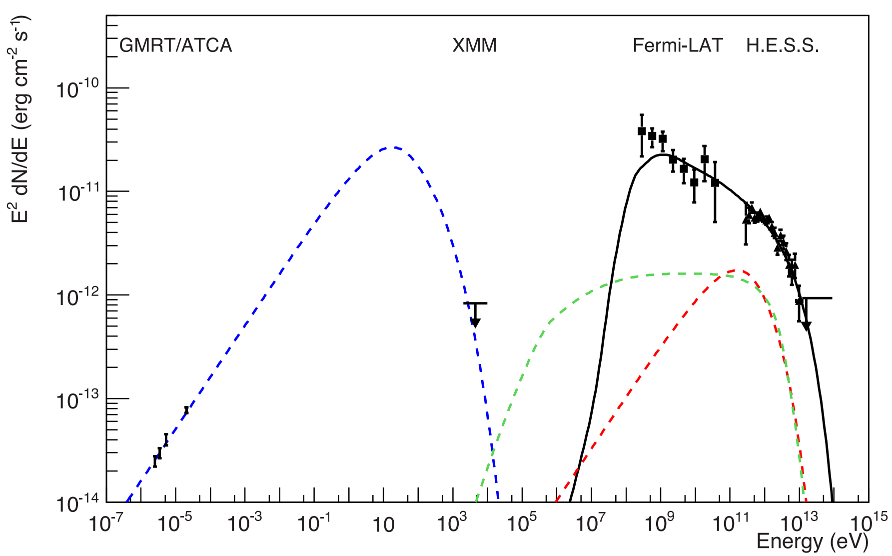
- Cutoffs in the spectra of famous young SNRs at few TeVs. Particle acceleration proceeds up to 100 TeV. No indication of particle acceleration proceeding up to the knee
- SNRs thought to act as PeVatrons only during the early phases. Small chance to detect SNRs when they are PeVatrons. Maybe PeVatron gamma-ray signatures from nearby clouds illuminated by runaway CRs





An exceptionally bright SNR G338.3-0.0

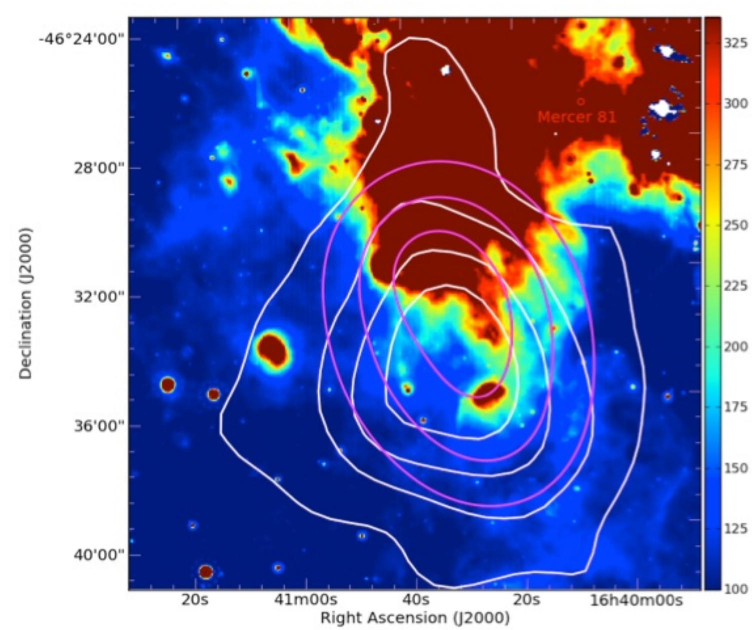




Core collapse SNR from a massive star. Strong winds have created a cavity surrounded by high density shell

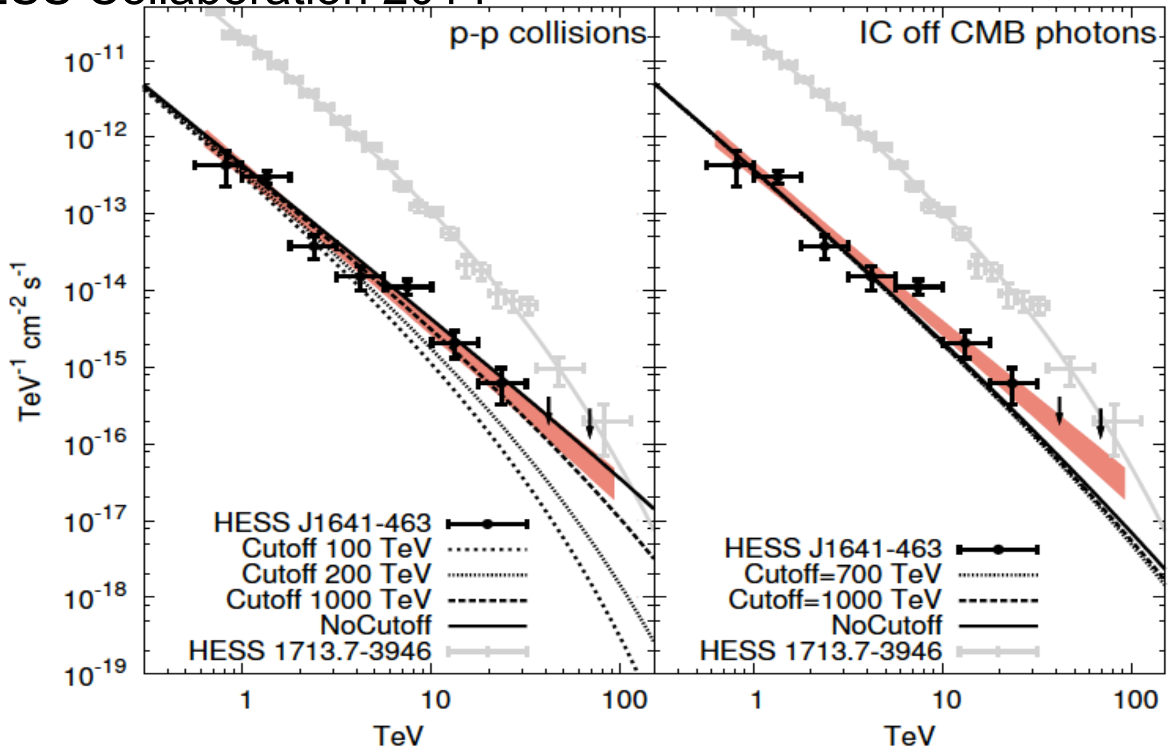
L_γ at TeV close to 10^{35} erg/s
$W_p = 4\ 10^{52}$ (d/10 kpc) $(n/1cm^3)^{-1}$ erg -> rich target density -> optimism for detecting more of these objects with CTA

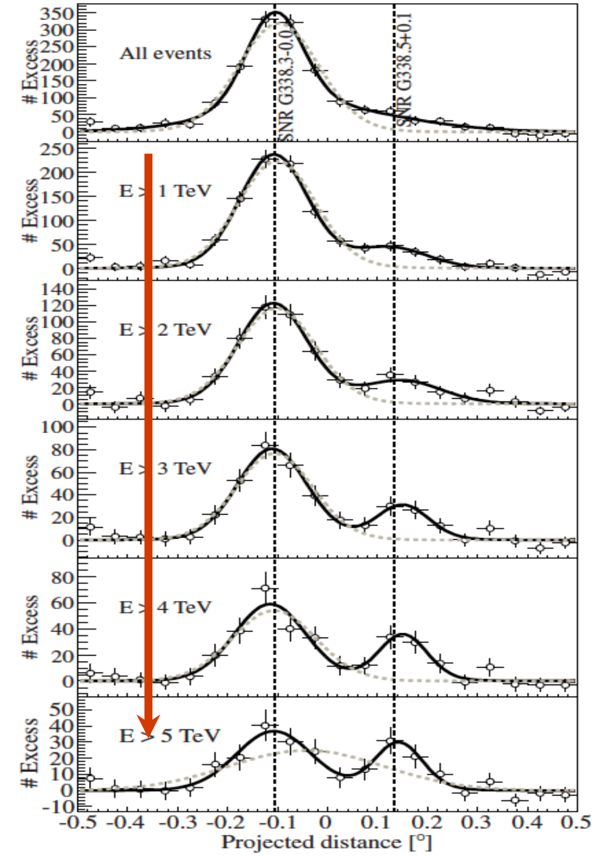
The Spitzer MIPS 24μm images show abundance of interstellar dust and HII region. Gas density up to 600 cm^{-3}



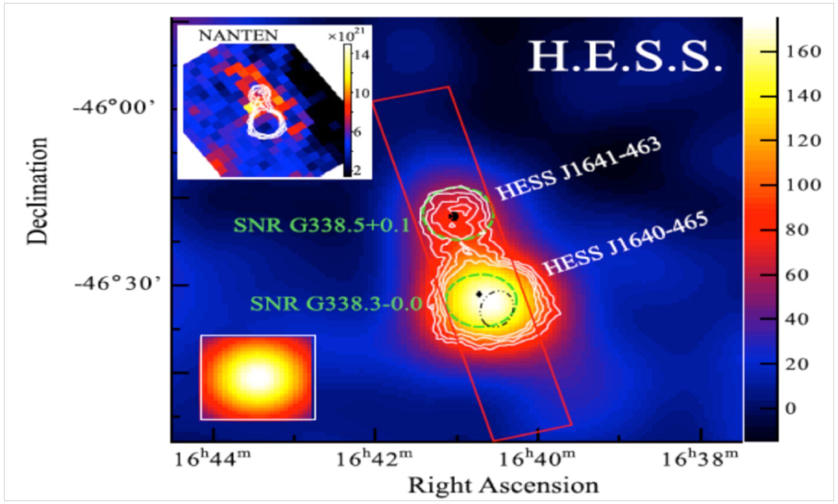
Runaway cosmic rays ?

HESS Collaboration 2014

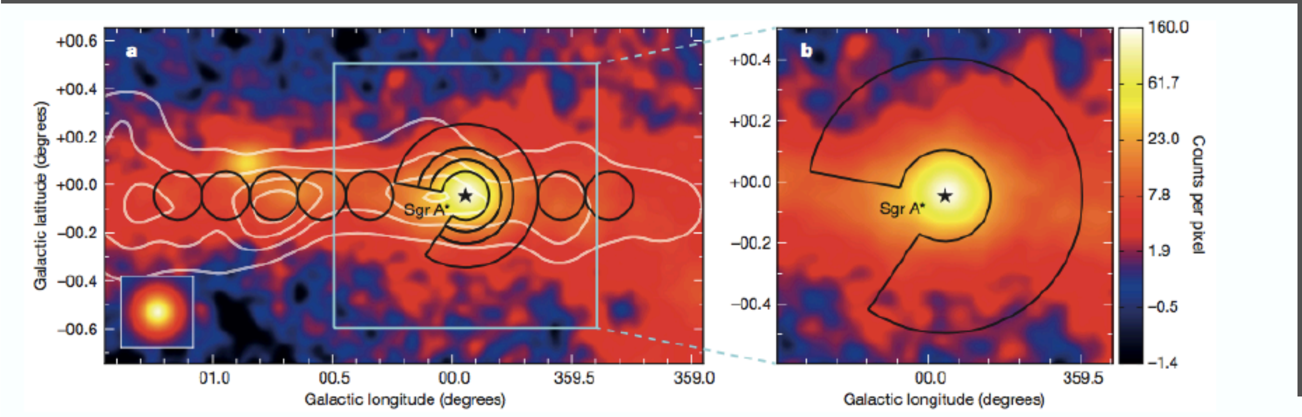




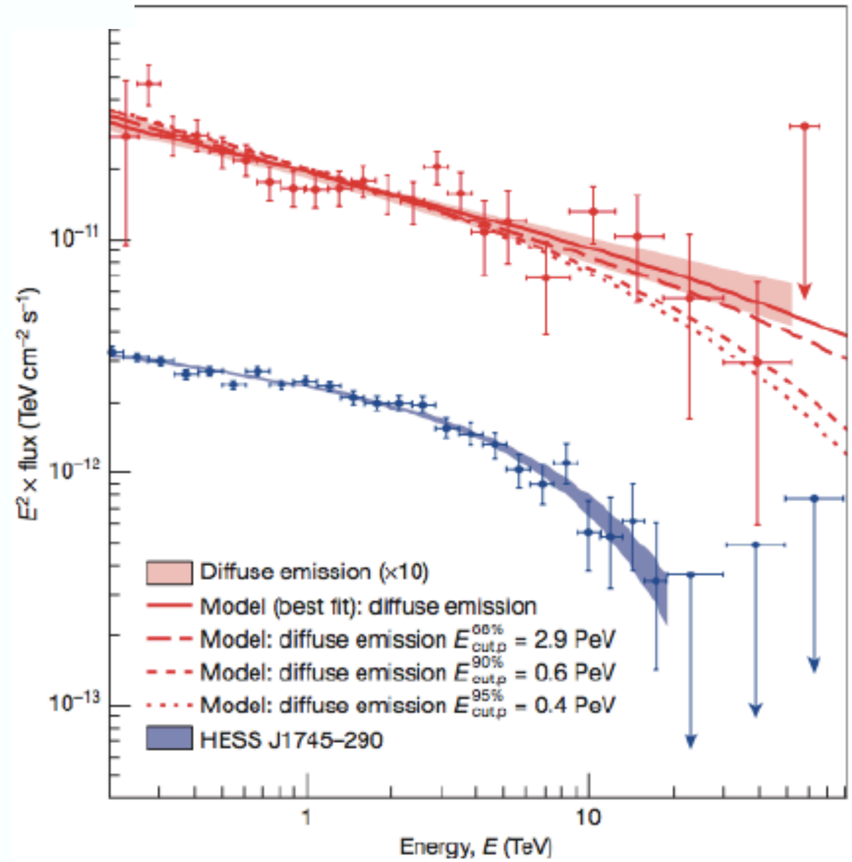
- Very hard spectrum, index 2.07
- No preference for a cutoff
- Data points until 20 TeV
- Lower limit on proton cutoff energy: 100 TeV
- $W_p = 10^{50}\, n^{-1}$ erg
- Leptonic scenario implies particle spectra up to at least 700 TeV
- Several sources like HESS J1641–463 needed



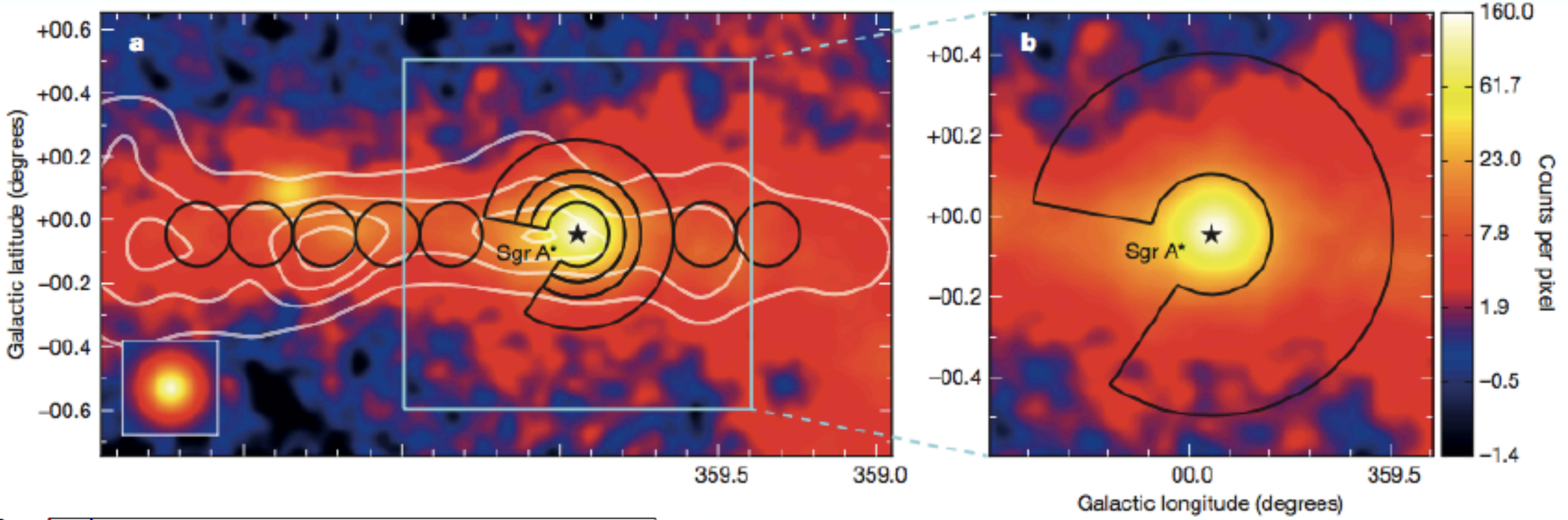
GC PeVatron : Spectral Studies with H.E.S.S.

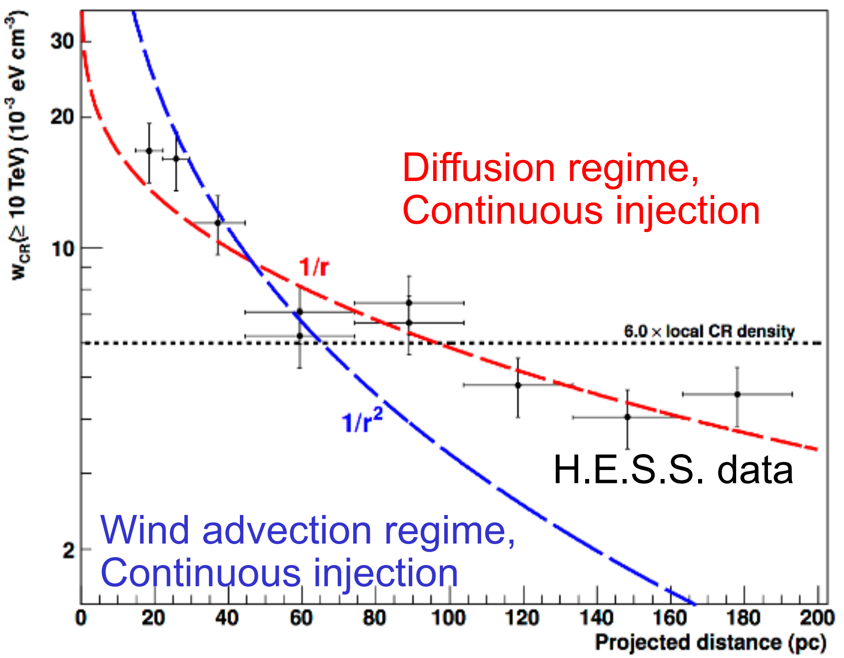


- Point-like, central source on top of extended (ridge) emission
- Central point source: cut-off @ 10 TeV
- Diffuse emission shows no cut-off well > 10 TeV
- Origin of diffuse emission:
  - Interaction of CR (from central BH) with interstellar medium ?
  - CR acceleration in CMZ (and in particular star forming regions) ?
  - …



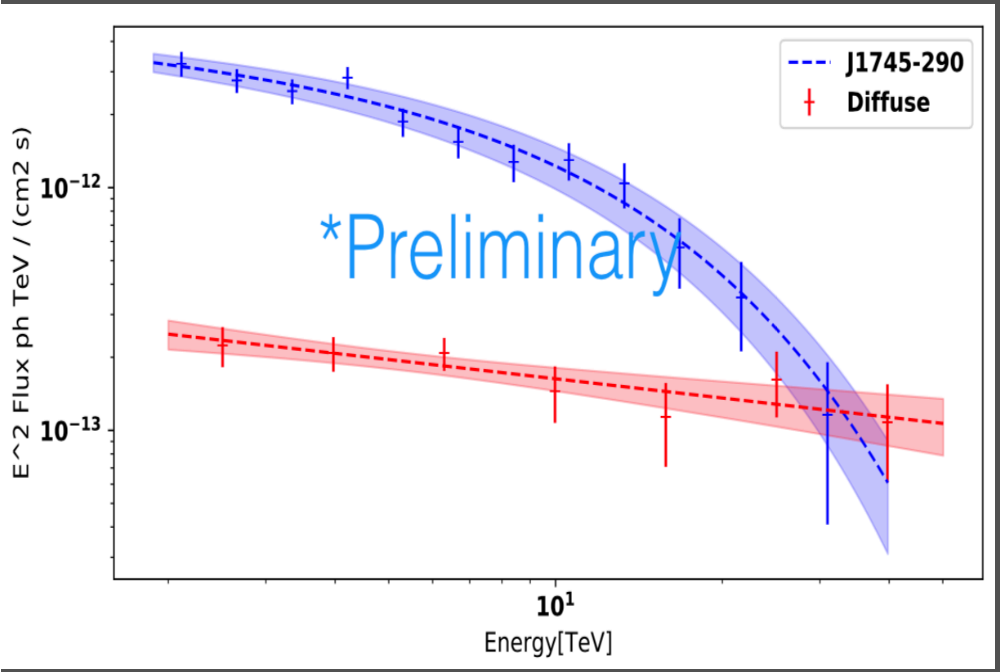
GC PeVatron : Morphological studies



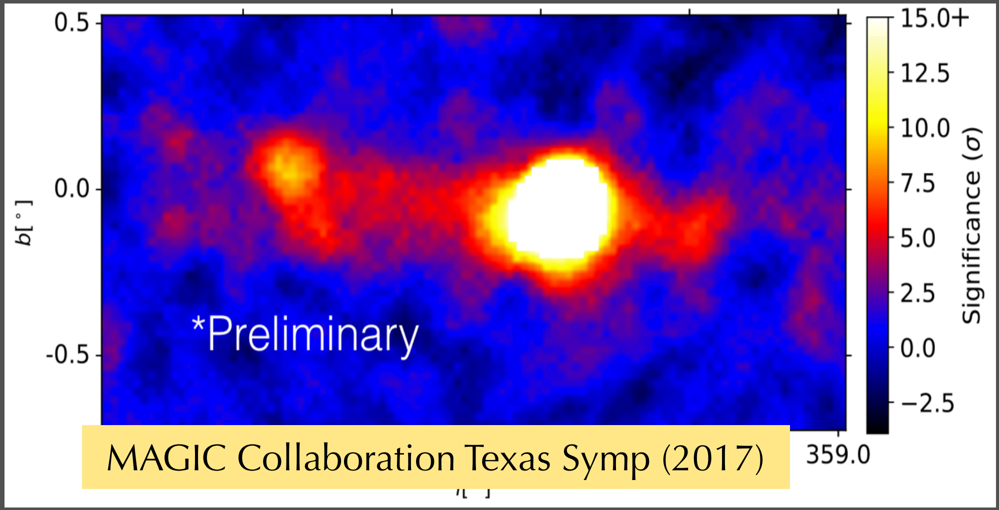


- Emission profile consistent with propagation of protons accelerated continuously from a region < 10 pc from GC
- Current bolometric lum of Sgr A* is 100-1000 times less than required to support CR population. PeVatron more powerful in the past ? Other PeVatrons in the Galaxy ?

Large Zenith Angle Observations of the GC



VERITAS Collaboration, COSPAR (2018)



MAGIC Collaboration Texas Symp (2017)

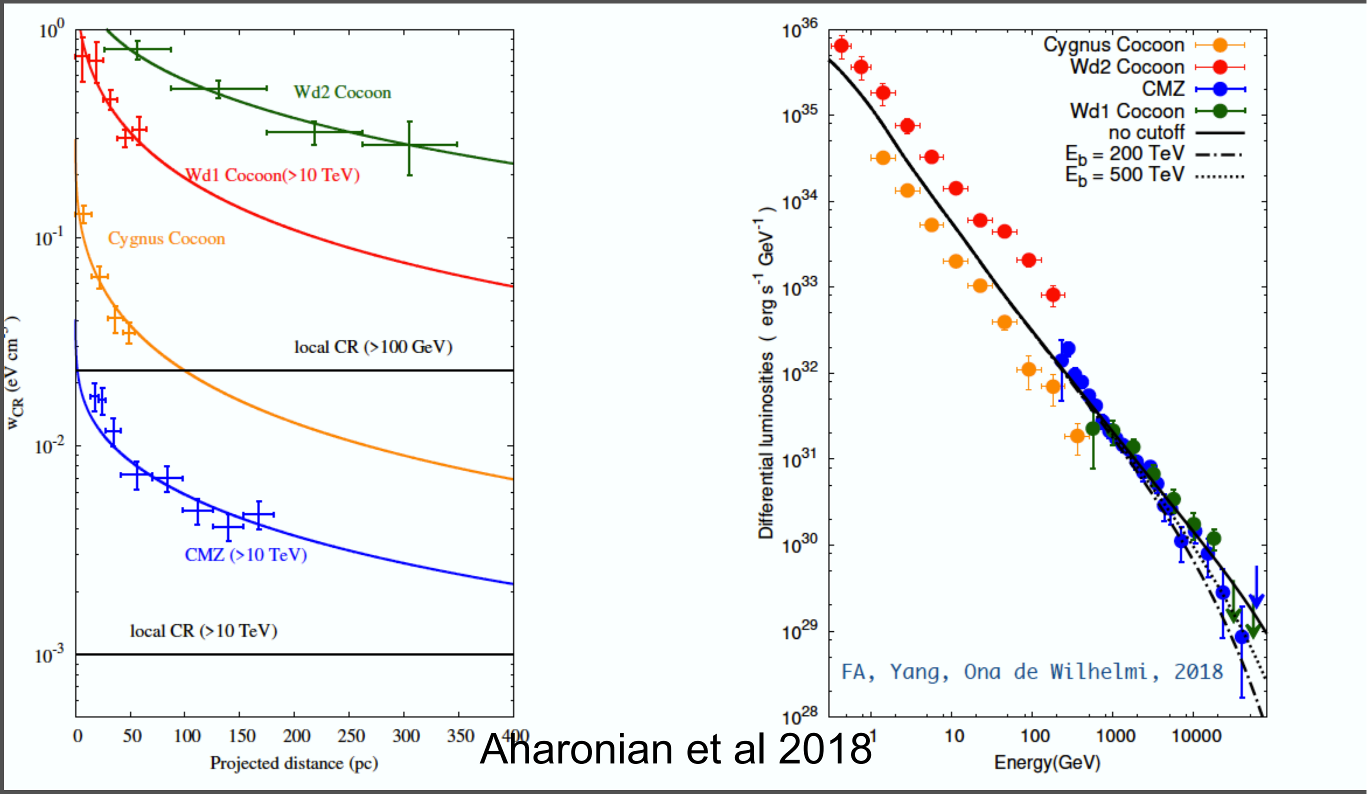
- No cutoff observed up to 40 TeV.
- Further observations planned at LZA.

Young Stellar Clusters

Extended gamma-ray emissions around young star clusters (50 ~ 200 pc). Gamma-ray luminosity ~ 1e36 erg/s.

Each source has hard spectrum ~ 2.2, without cutoff

CR distribution derived by gamma-ray profile and gas distributions. 1/r profile implies a continuous injection in the lifetime of clusters



Aharonian et al 2018

A survey for PeVatrons

Source class approach: select a source (GC) or a source class (SNRs or YSCs) and investigate the feasibility of such class as contributors to the cosmic ray flux.

Survey approach : look for powerful gamma-ray emitters in the multi TeV range and investigate how these different particles factories contribute to the spectrum of cosmic rays. We expect the contribution of different sources or source classes to be different

For each of the PeV candidates we wish to determine

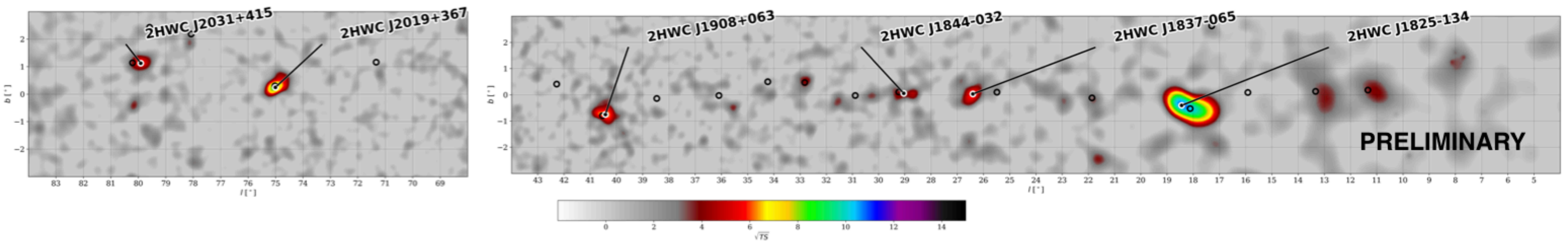
1) fraction of available energy converted to nonthermal particles

2) maximum possible energy achieved

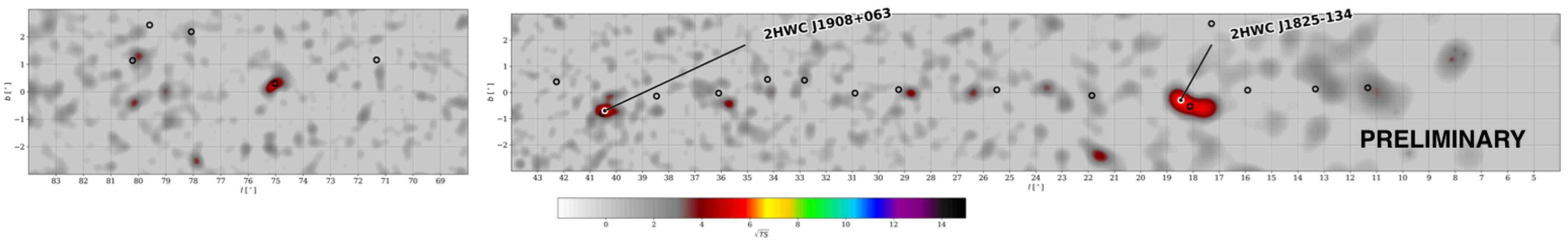
The tip of the iceberg : HAWC high energy sky

HAWC sky above 56 TeV

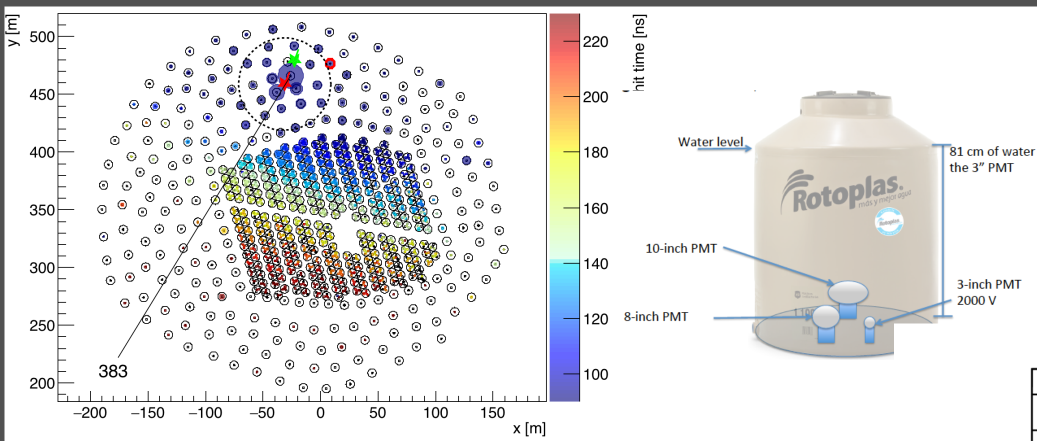
K. Malone I TeVPA 2018



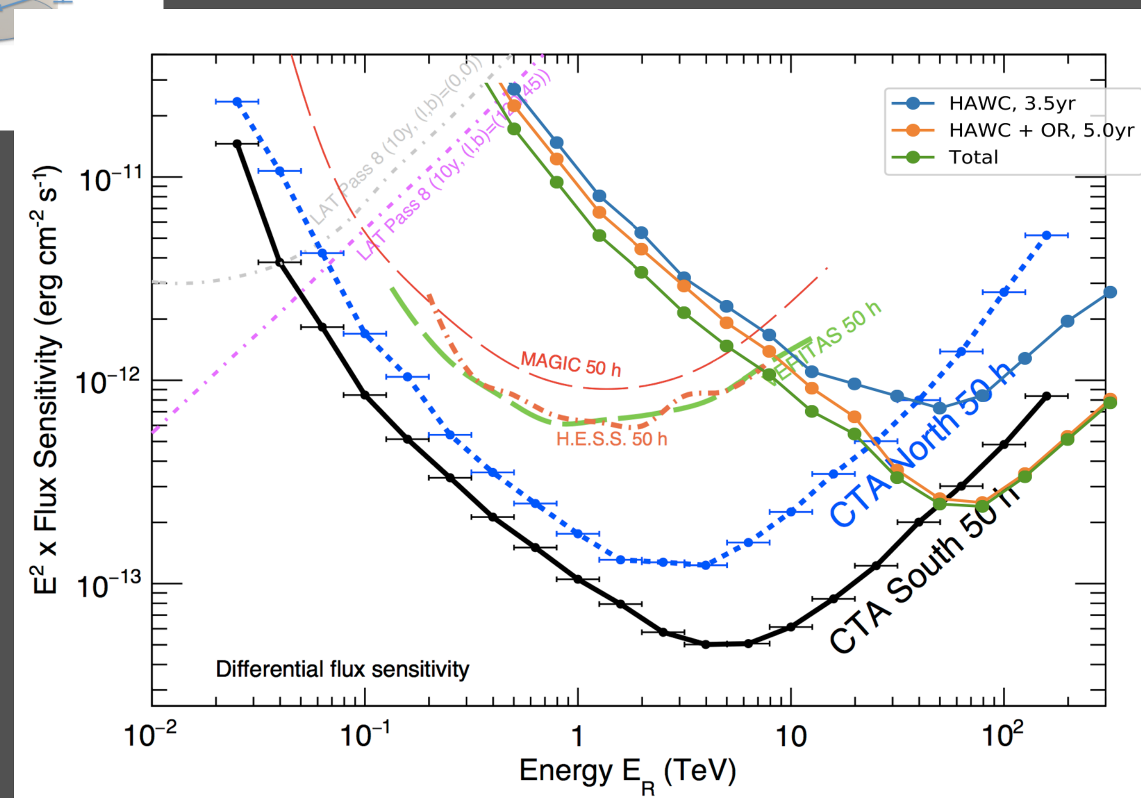
HAWC sky above 100 TeV



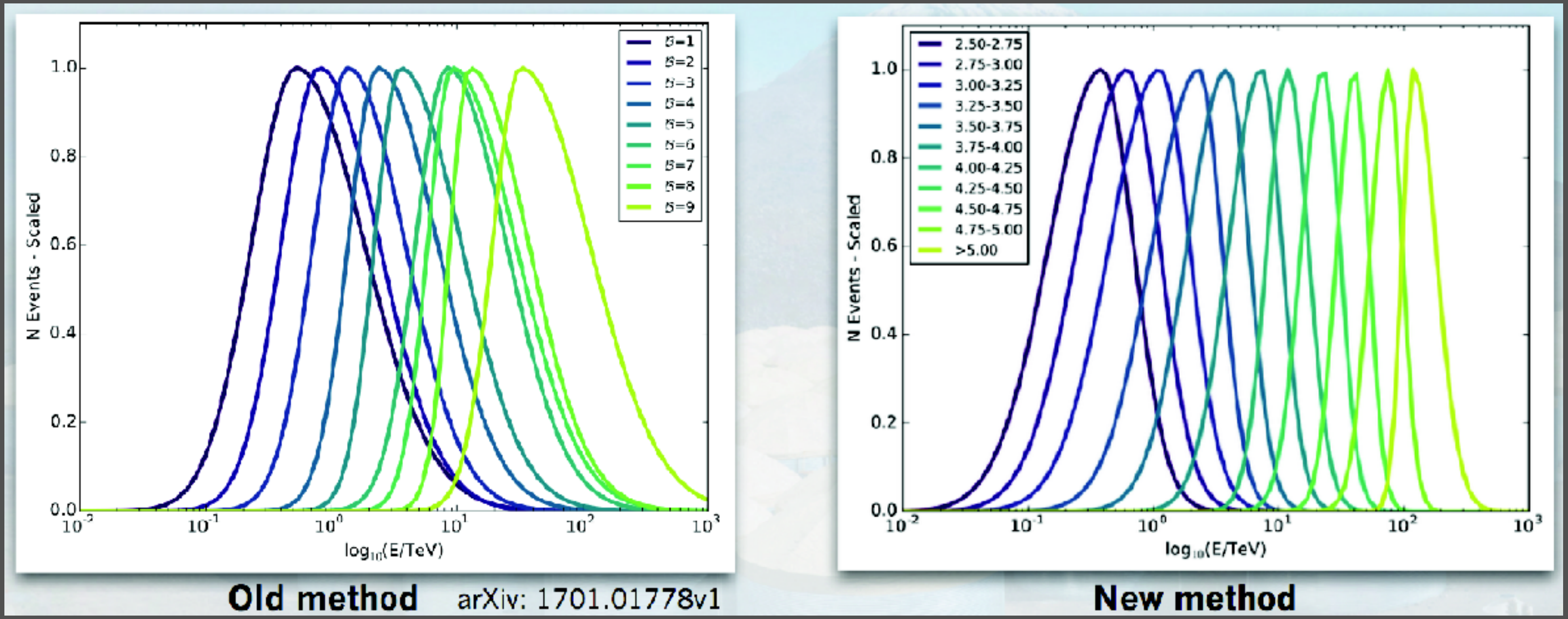
Extending the energy range: HAWC outriggers

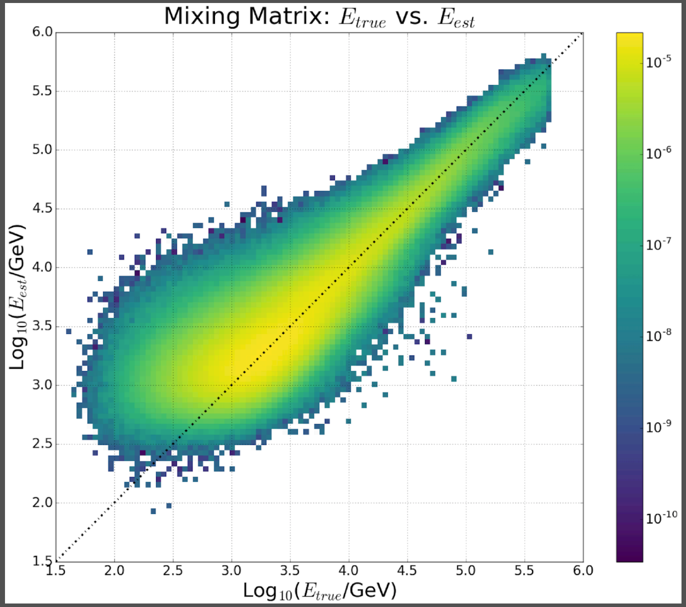


Collection area of several 10^4 m^2 above 10 TeV



Energy resolution in HAWC





Even with an event by event energy reconstruction not ideal spectroscopy !
Surely room for improvement !

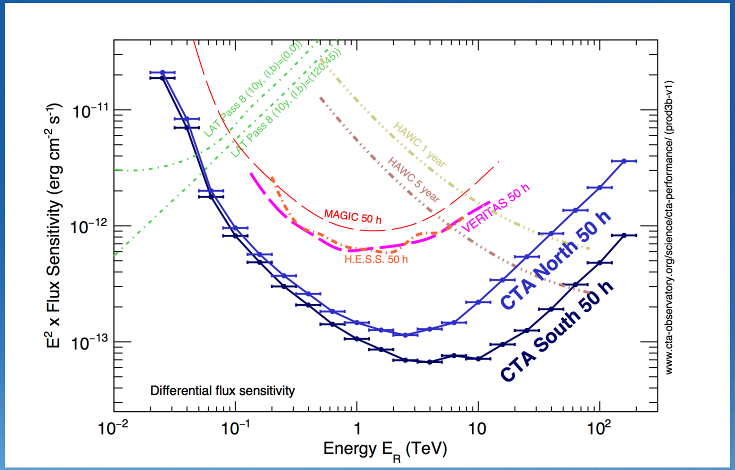
A PeVatron survey with CTA

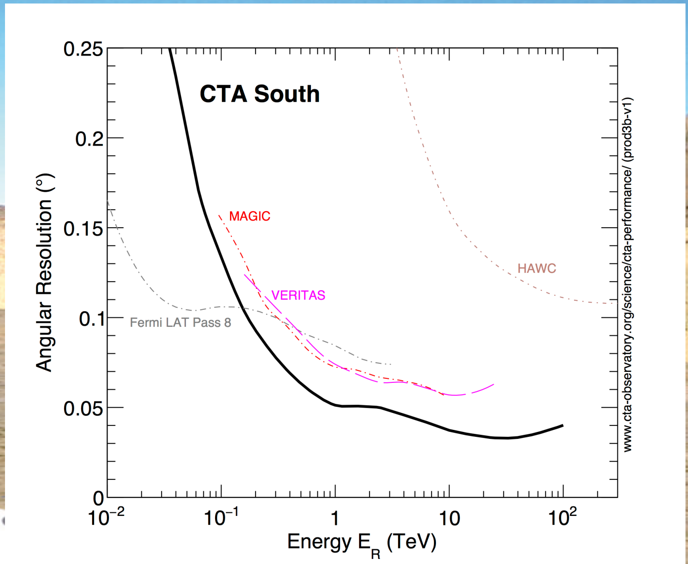
Search for sources of cosmic rays close to PeV energies → High sensitivity at 10-100 TeV

Resolve hadronic-leptonic degeneracy. → Good energy resolution at TeVs

Search for different and possibly unexpected classes of sources → Survey

Resolve sources which might be hidden in the tails of bright sources and compare and correlate with gas surveys → Good angular resolution at arcmin level





Strategy for PeVatron searches with CTA

- CTA will perform a survey of the GPS with unprecedented sensitivity in the unknown 50 to 300 TeV range observing each location on average for 15hr
- PeV selection criteria (PeVatron metrics) based on the lower limit of cut-off energy with 40 hours of CTA observations (obtained by extrapolating 10 h obs).
- Deep observations (50 hr) devoted to the best candidates

Towards a PeVatron metrics

- Simulate CTA Events. (spectra : Power-law, morphology : Point source)
- Perform fit to spectral models. (Power-law and Exp. Cutoff Power-law)
- Derive 95% lower limits on the cut-off parameter for each simulation.
- The outcome distribution spreads are due to statistical fluctuations. We take the median of the distributions as estimate of the cut-off energies lower limits.

The final selection of promising candidates is made by estimating parental proton spectra parameters (proton Ec) with NAIMA. ISM gas density (n_{gas}) and distance estimations are needed.

Anguner + 2018

Results

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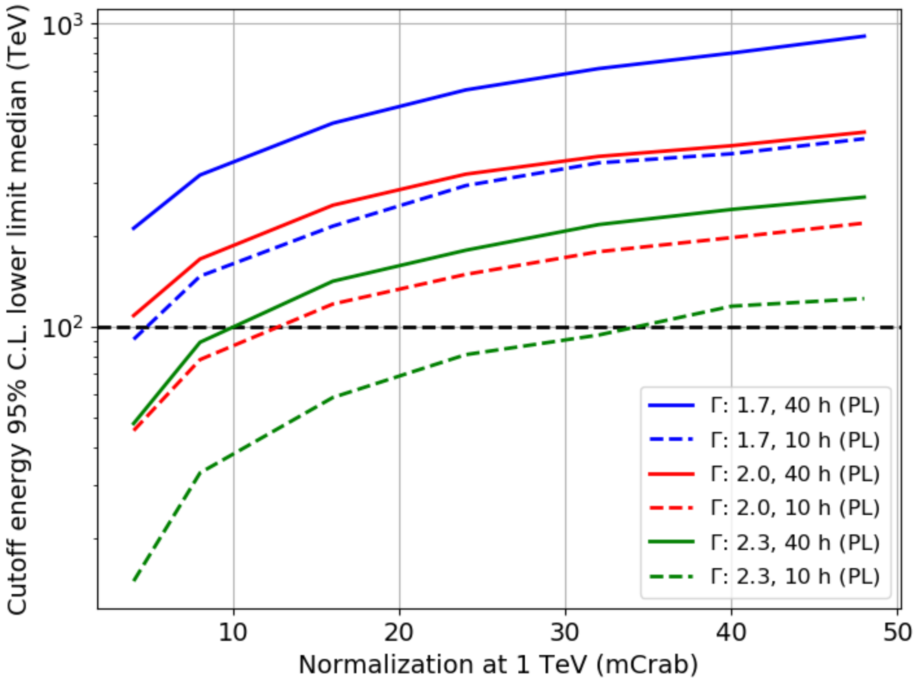
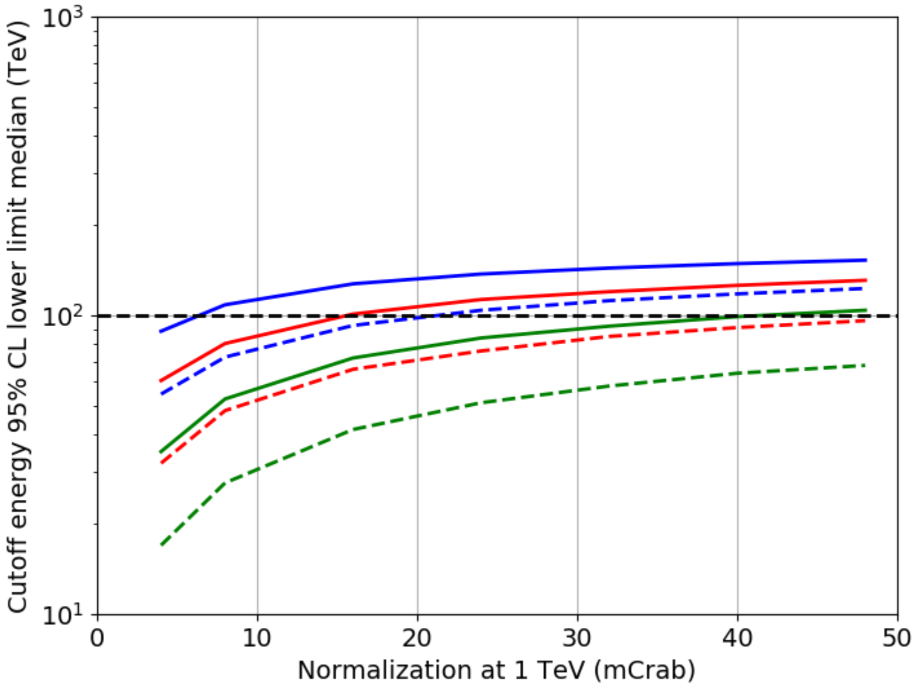
Pure Power-law (intrinsic)



ECPL 200 TeV (intrinsic)



- The black dashed lines show a conservative 95% lower-limit of 100 TeV for determining a source as a PeVatron candidate. Ep / Eg = 10 (can go up to 30-40).

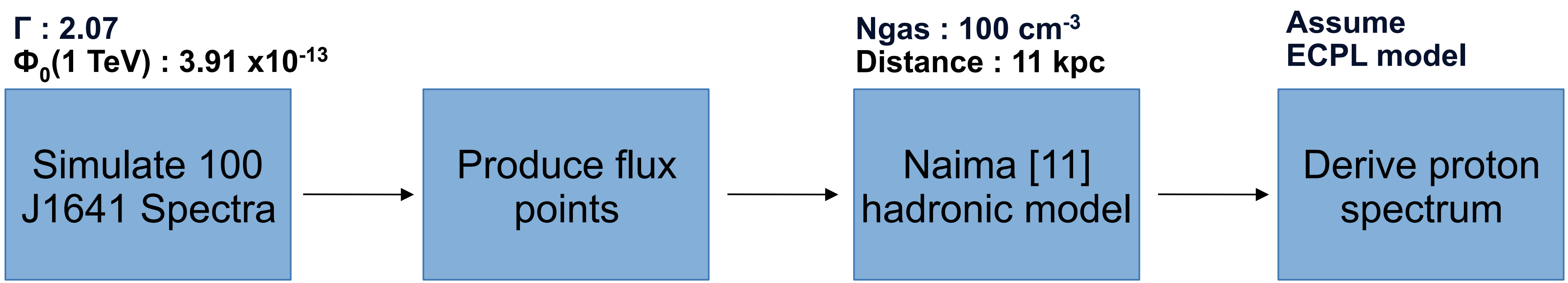
	1.7 Index	2.0 Index	2.3 Index
Pure PL	5 mCrab	13 mCrab	34 mCrab
Ecut 200 TeV	21 mCrab	48 mCrab	-

Required minimum flux at 1 TeV (mCrab) of a source for being tagged as a PeVatron candidate after 10h of CTA observation (assuming a conservative limit of 100 TeV).

Hadronic Modeling

Anguner+2018

- We simulated (100 times) the spectrum of the PeVatron candidate source HESS J1641–463 [10] using the published results, assuming different γ–ray cut-off energies at 50 TeV, 100 TeV and 200 TeV (40 hr observation time) to investigate parent proton spectrum properties.



	Ecutoff 200 TeV	Ecutoff 100 TeV	Ecutoff 50 TeV
Gamma-ray Ecutoff 95% L.L. Median	**83 TeV**	**53 TeV**	**31 TeV**
Proton Ecutoff Median	**6.16 PeV**	**2.33 PeV**	**0.81 PeV**
Proton Index Mean	**2.13**	**2.14**	**2.14**

Conclusions and outlook on the PeV metrics

- The results for different PL and ECPL models show that as the source spectrum gets harder and/or as the source brightness increases, the lower limits on the γ–ray cut-off energies increase.

- Preliminary investigation based on hadronic modeling of HESS J1641-463 suggest that setting a conservative lower limit (95%) on the cutoff energy of 100 TeV may leave promising PeVatron candidate sources unnoticed.

- The studies under PeVatron TG is extending for being able to determine efficient selection criteria. The future studies include :

(On-going studies)
→ Generation of the PeVatron metric for extended sources
→ Investigation of Large zenith angle observations.
→ Number of PeVatrons expected in the CTA GPS, using population model described in the study (Cristofari et al. 2018).

(Future studies)
→ Application on the known PeVatron candidate sources (hadronic modeling).
→ Investigation of Moon nights observations (SSTs, increase duty cycle).

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Constraining the energy content in CRs

Upcoming high resolution (<arcmin) ISM surveys :

Southern Hemisphere:

Mopra CO(1-0) http://newt.phys.unsw.edu.au/mopraco/

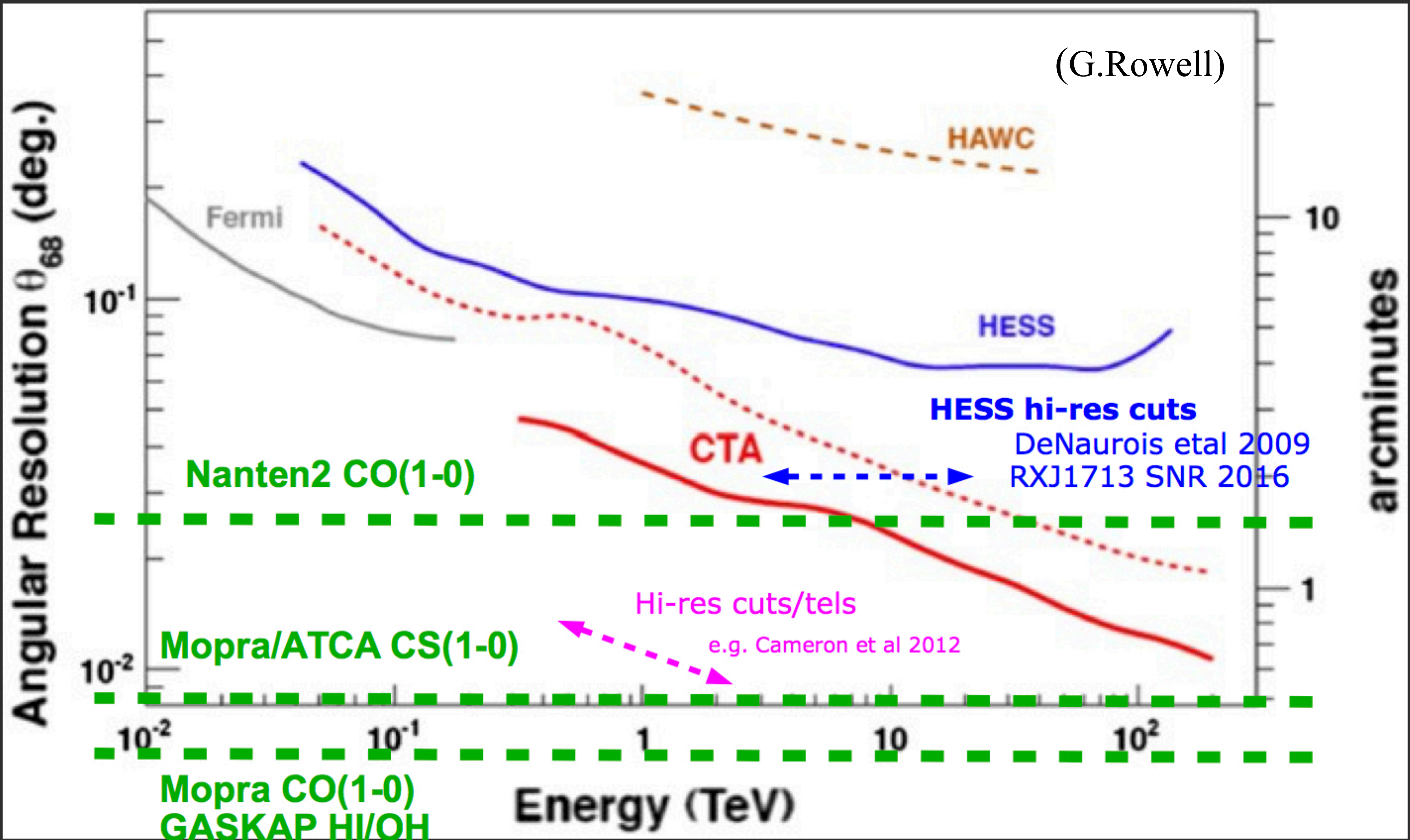
ASAKP (GASKAP) HI/OH – https://www.atnf.csiro.au/research/GASKAP/index.html

Northern Hemisphere:

Nobeyama FUGIN CO(1-0) - https://academic.oup.com/pasj/article/69/5/78/4060573
VLA THOR HI - http://www2.mpia-hd.mpg.de/thor/Overview.html

Angular Resolution 68% PSF (HESS, CTA..)

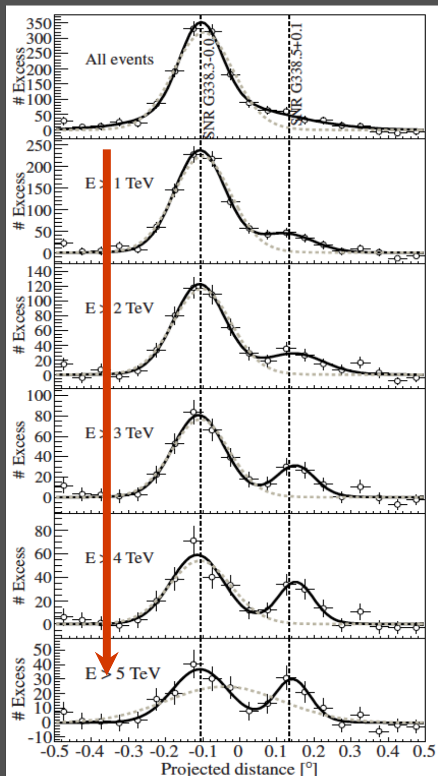
Acharyara etal 2013

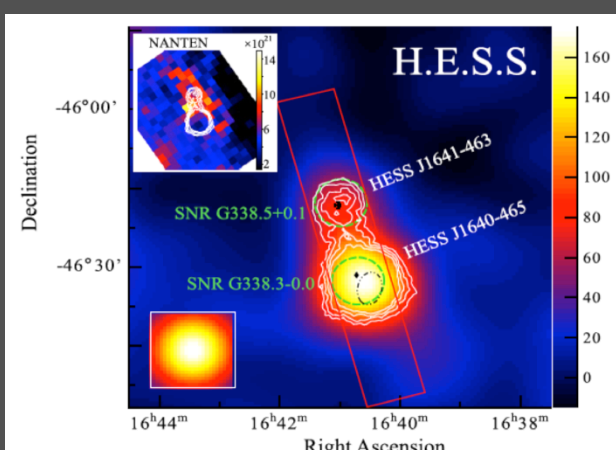


Beam Sizes 68% containment radius

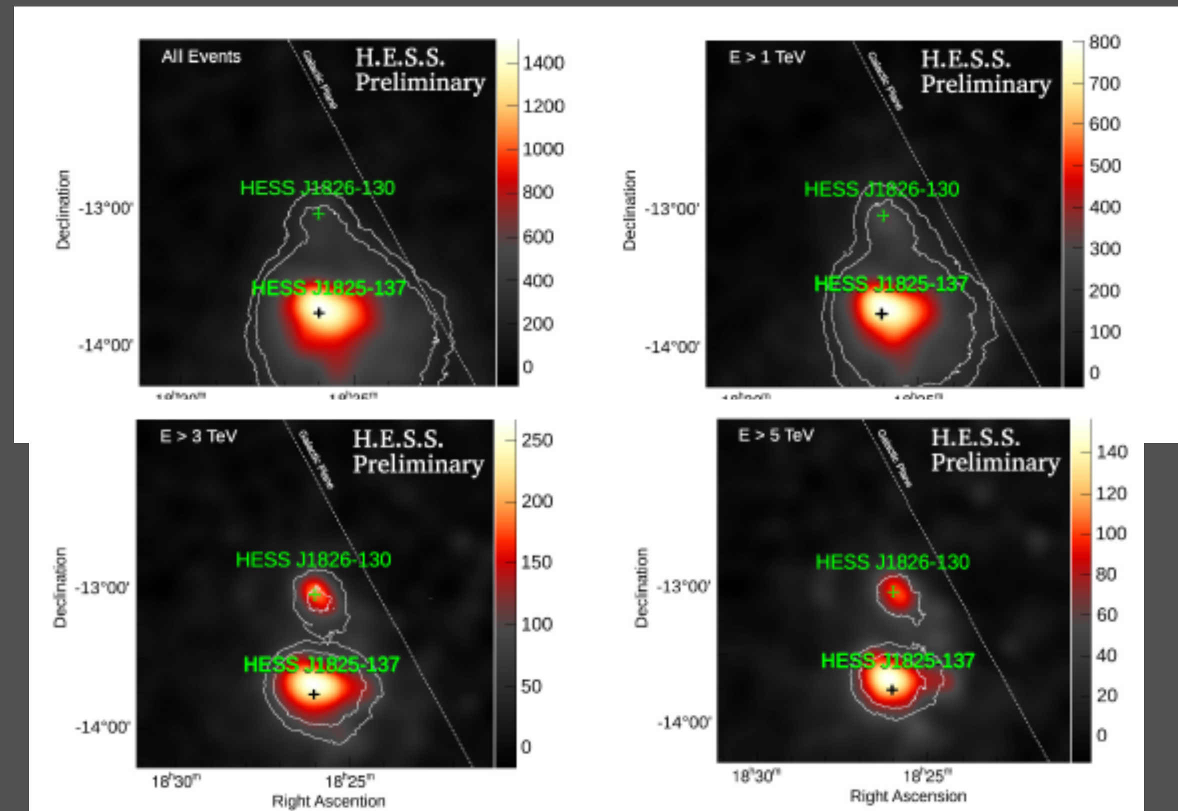
Source confusion and contamination

- **HESS J1641–463** (15% > 0.64 TeV)



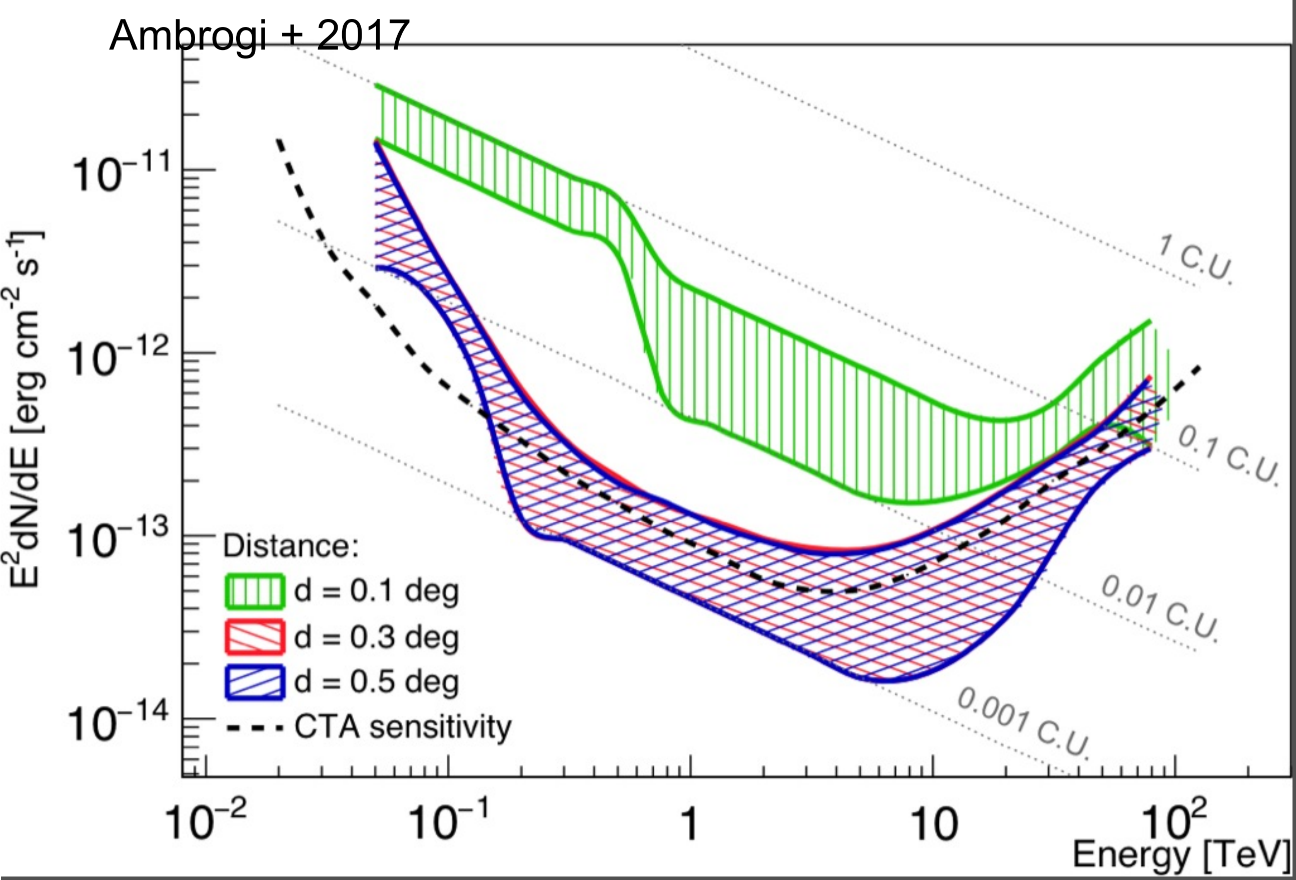


- **HESS J1826–130** (40% > 0.4 TeV) TeV)



- Source confusion, especially for the ones located in the vicinity of bright sources.
- Analysis in energy bands is a powerful technique for new discoveries. Contamination decreases with the increasing energy threshold.

CTA sensitivity for crowded regions



CTA sensitivity estimated for isolated sources. CTA observations will increase the number of detected sources. What about source confusion in regions dense of sources? The effective sensitivity reduced by background from nearby gamma-ray sources

PeVatrons searches above 10 TeV

PSF optimal

More compact tails of bright sources

Limited number of multi Tev sources

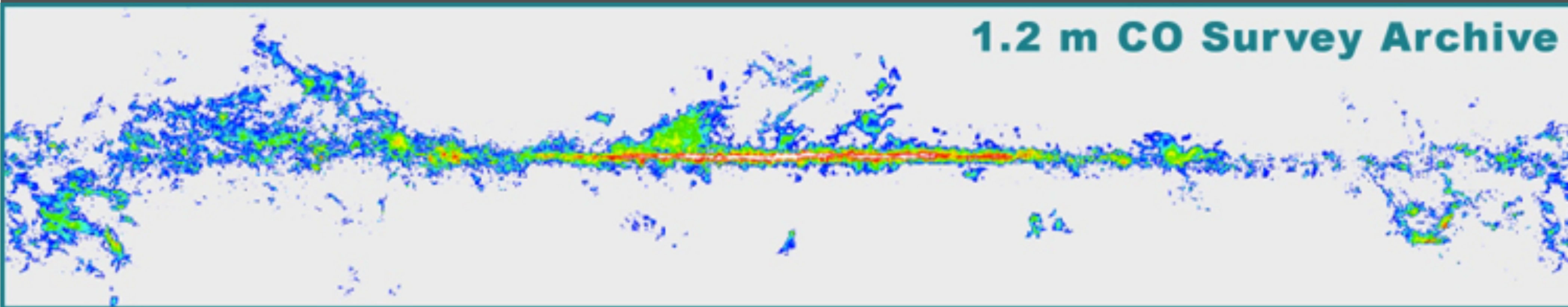
Summary and outlook

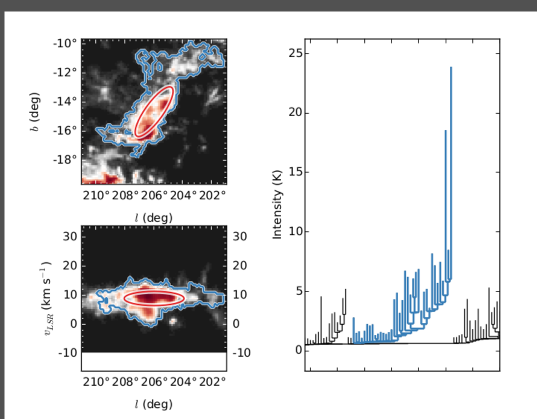
- Source class approach
- Survey approach (unexpected PeVatron sources, population studies of SNRs to estimate the energy content in CRs for different classes of SNRs)
- Selection criteria for PeVatrons from CTA GPS survey
- Upcoming high resolution ISM surveys

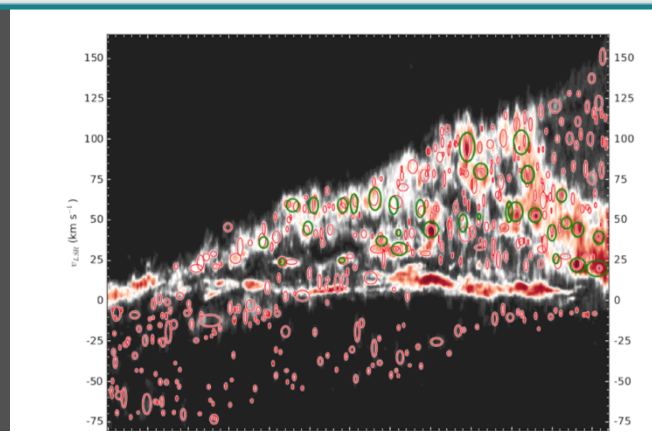
Backup Slides

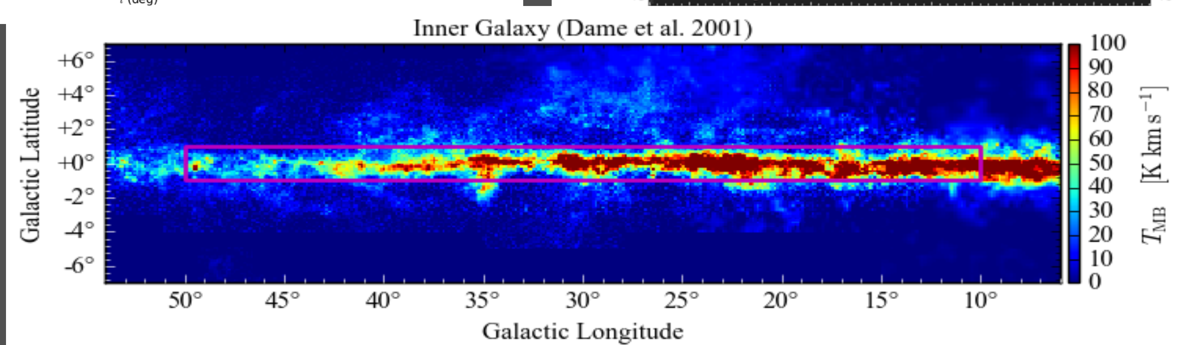
The CfA Survey of Molecular Gas

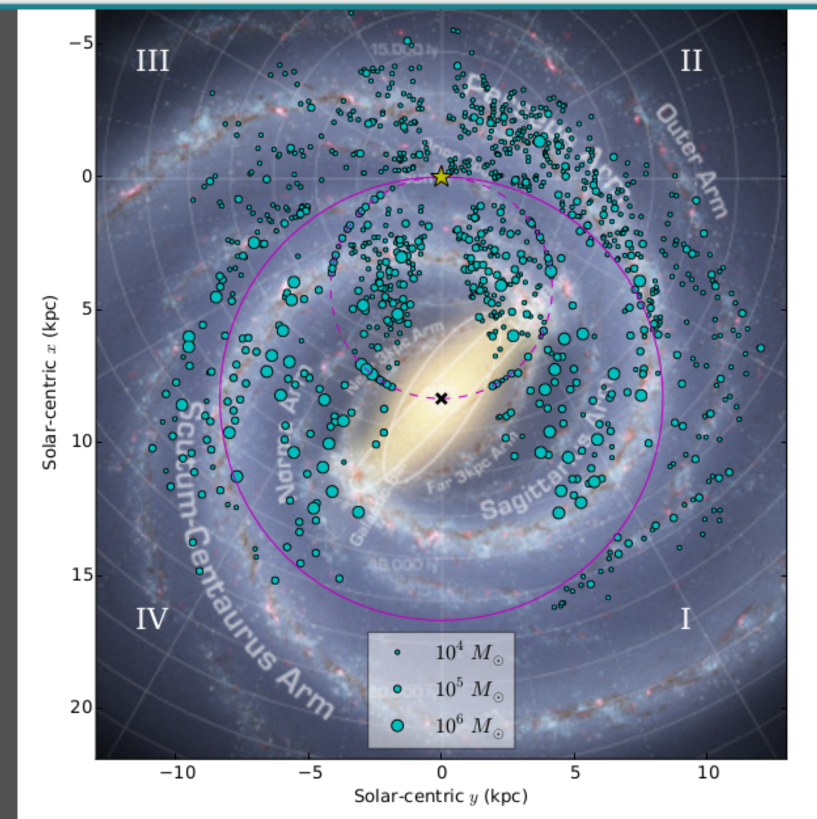
Dame+1987, Dame+2001,Rice+2016



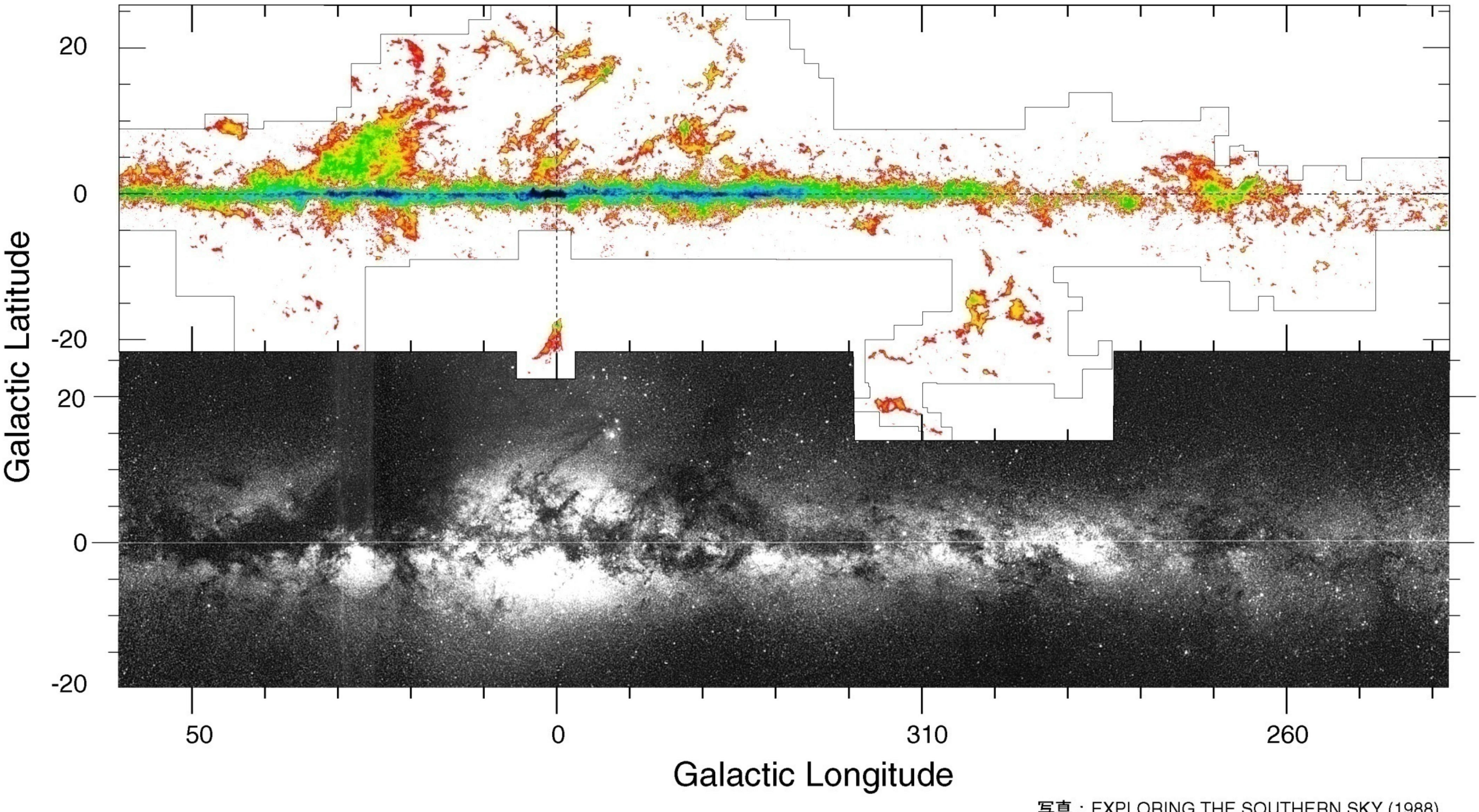






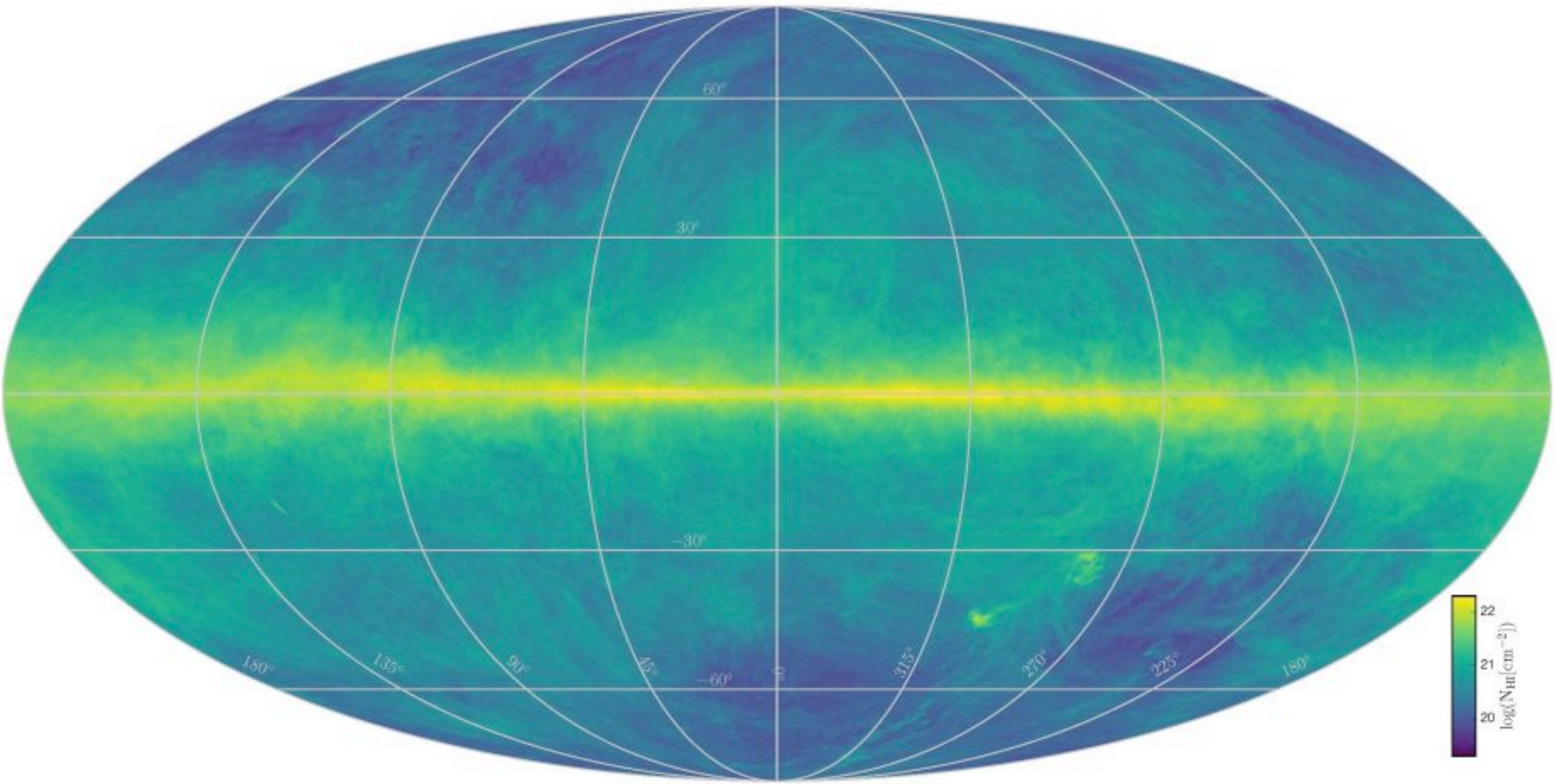


The Milky Way in Molecular Clouds (Nanten survey)



(courtesy: Y. Fukui)

The 4PiHI Survey of Atomic Gas



Interstellar gas tracers & telescopes

HI (atomic H), OH, CS

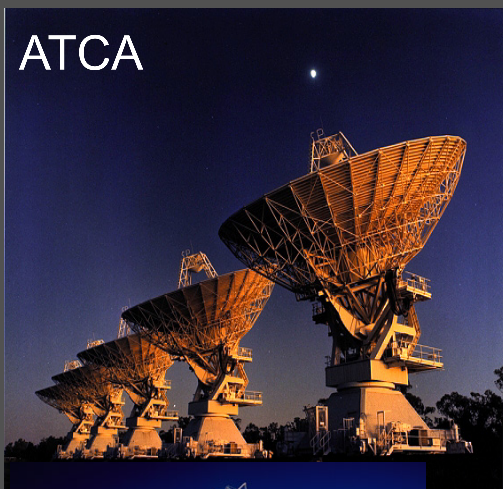
$\sim 10^{1\text{ to }4}$ cm^{-3}

CO

$\sim 10^{3}$ cm^{-3}

CO, NH,CS, SiO...

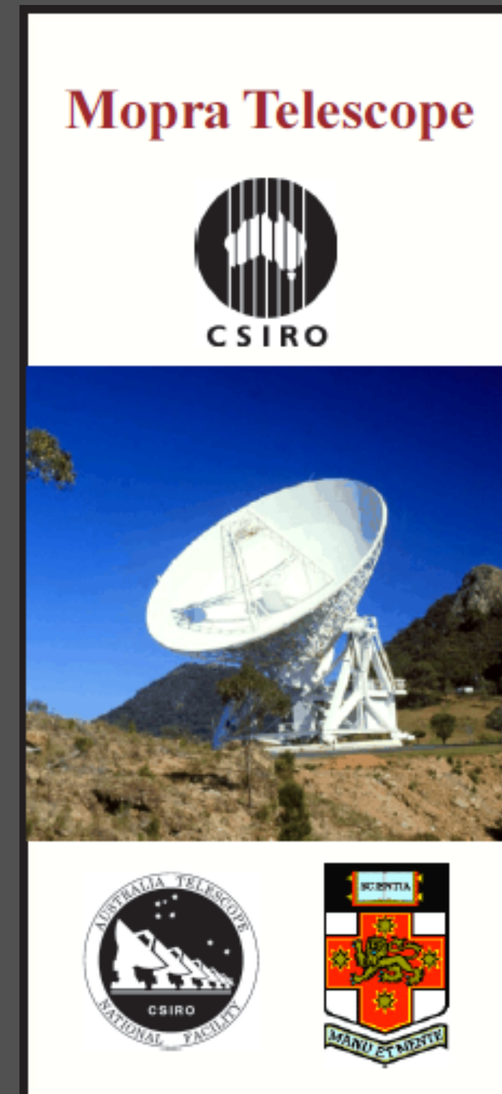
$>10^{3\text{ to }4}$ cm^{-3}



ASKAP-GASKAP

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

HEAT – THz (Antarctica)
[CI] + [CII]

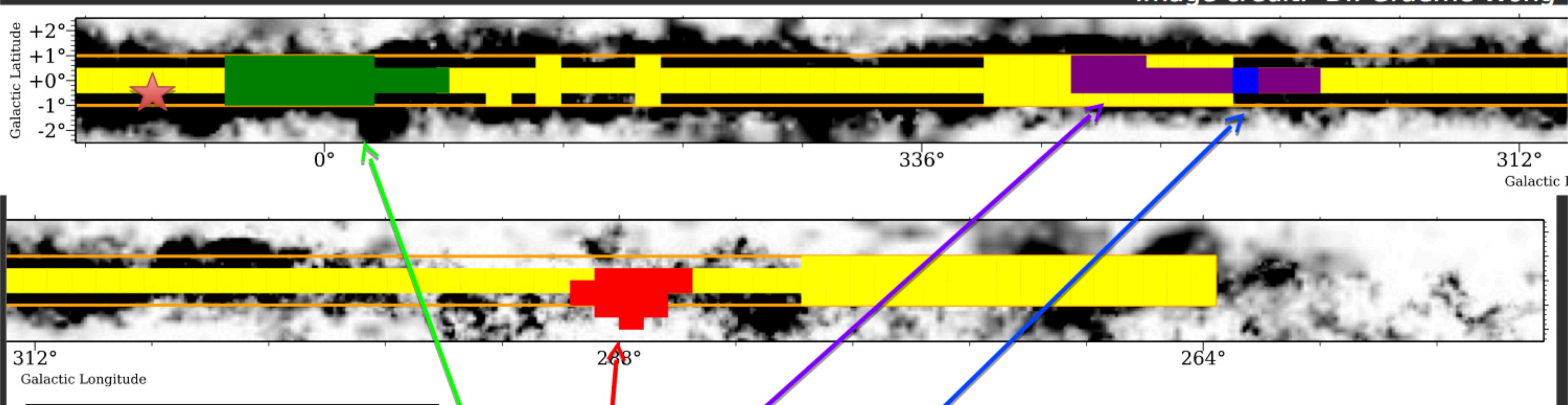


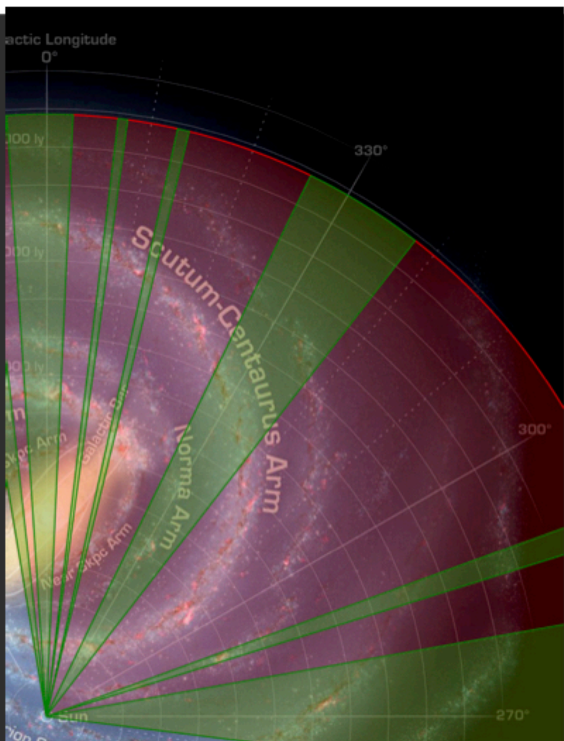
Mopra CO survey (South): Current Status

30 arc-sec resoluton

www.phys.unsw.edu.au/MopraCO/

Image credit: Dr. Graeme Wong





Pilot region G328 (Burton et al 2013)

Data release I (Braiding et al 2015)

Data release II: Carina (Rebolledo et al 2016)

Central Molecular Zone (Blackwell, R et al, in prep)

Data release III: l: 300 -> 350, |b| < 0.5
(Braiding et al, in prep.)

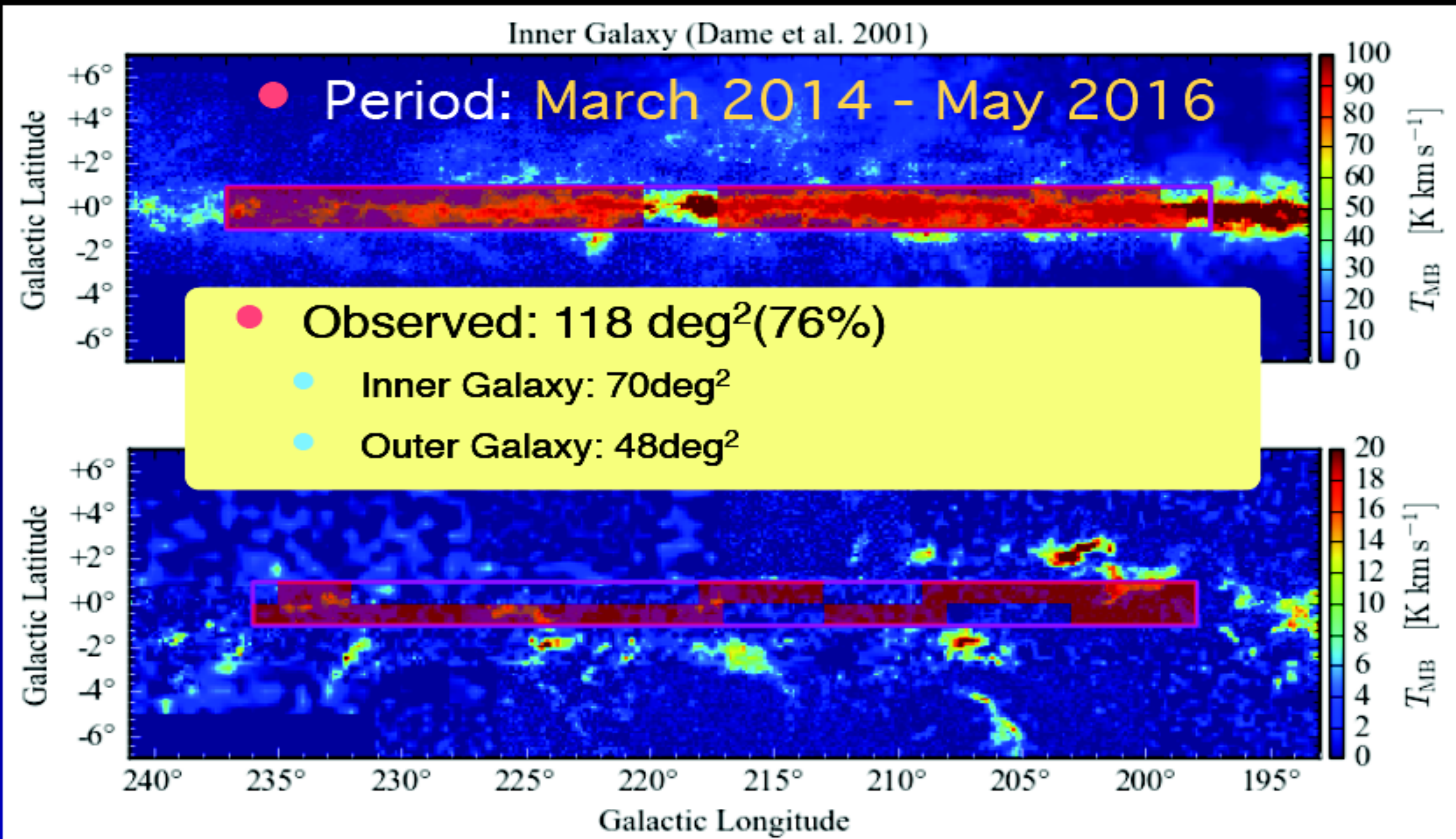
Survey to completed by 2018

+ Mopra dense gas studies of HESS TeV sources
http://www.physics.adelaide.edu.au/astrophysics/MopraGam/

Nobeyama CO survey (North): Current Status

20 arc-sec resolution Torii et al 2016

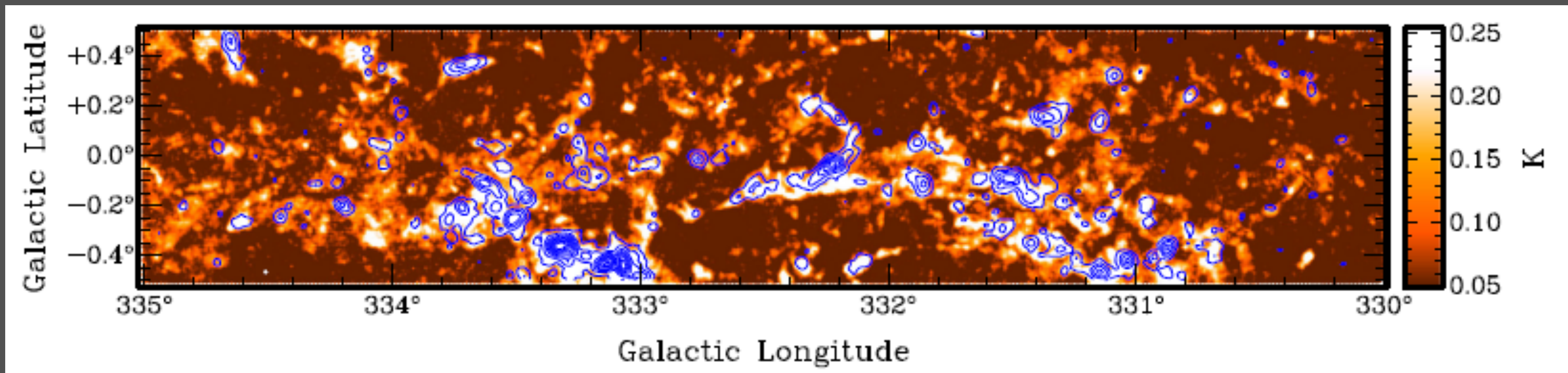
- magenta: planned, red: observed



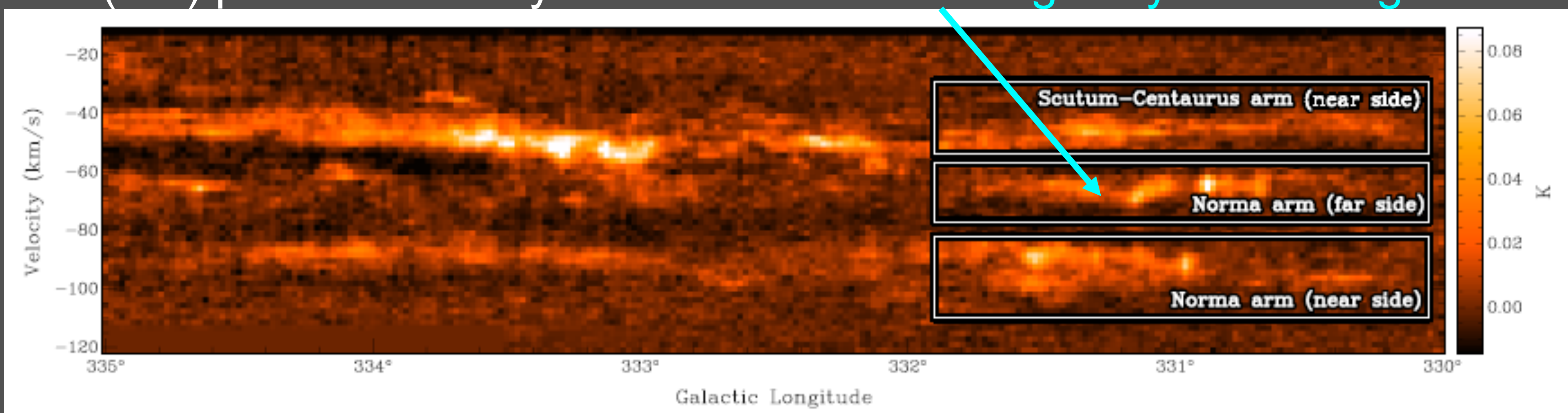
MALT45 7mm Survey with ATCA

> 5x more sensitive than Mopra (1 arc-min resolution)

CS(1-0) peak pixel image with HOPS NH3(1,1) contours (Jordan etal 2013, 2015)



CS(1-0) position/velocity → can see far side of galaxy in dense gas!



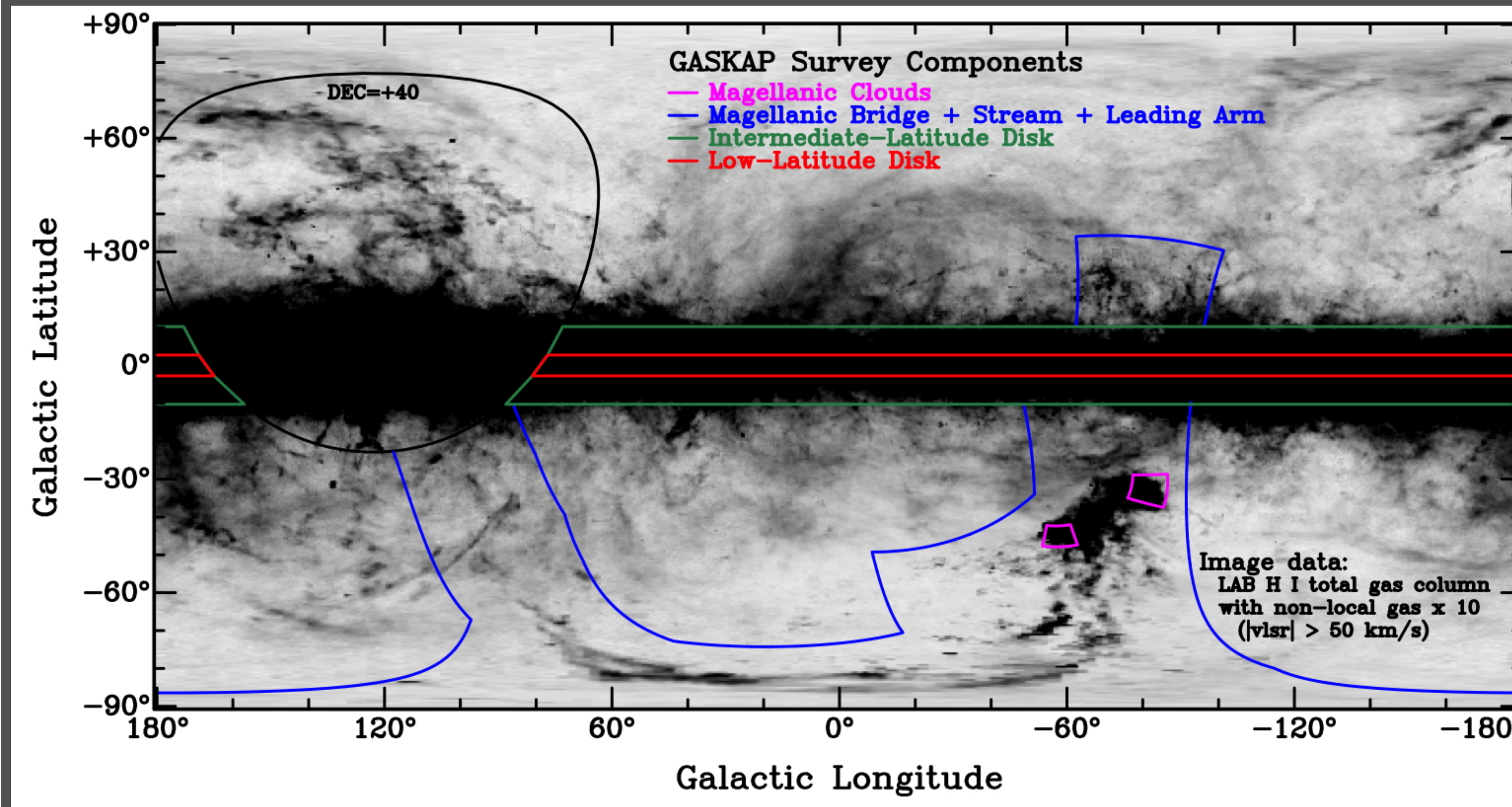
From 2017 "Full Strength MALT 45" l = 300 to 360 (Breen et al..)

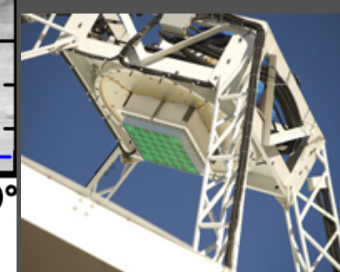
→ dense gas ISM survey over southern gal. plane

GASKAP

New HI + OH survey with the ASKAP
- 30 arc-sec resolution
- Commencing 2018

www.atnf.csiro.au/research/GASKAP/





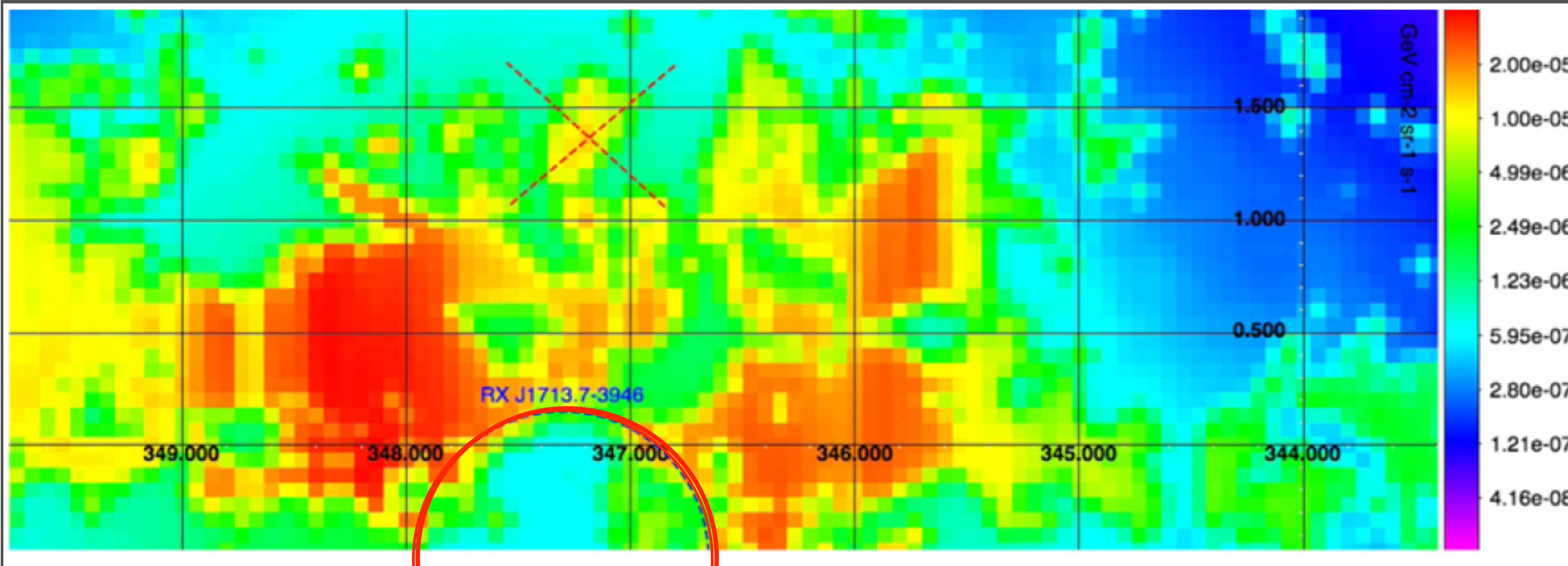
ASKAP - Australian Square Kilometre Array Pathfinder

Phased array feeds (PAFs) *30-beams*

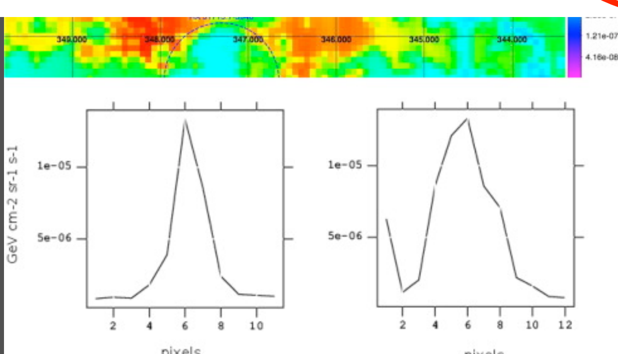
- Continuum survey, HI & OH lines, B-field strength & turbulence, transients

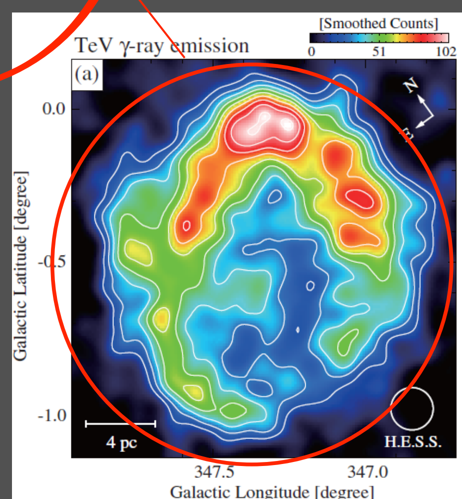
CRs escaping SNR RXJ1713.7-3946 (Casanova et al 2010)

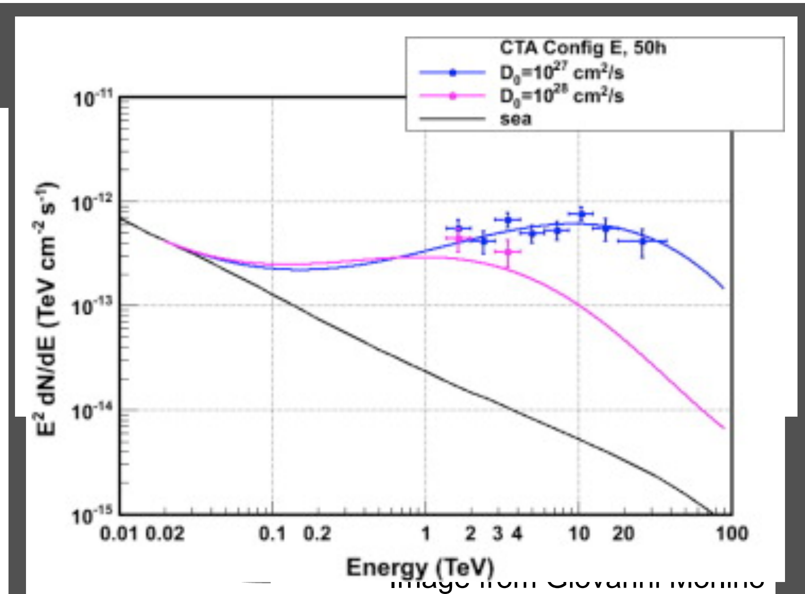
Particle escape from young SNRs: RX J1713.7-3946



Acero+2013



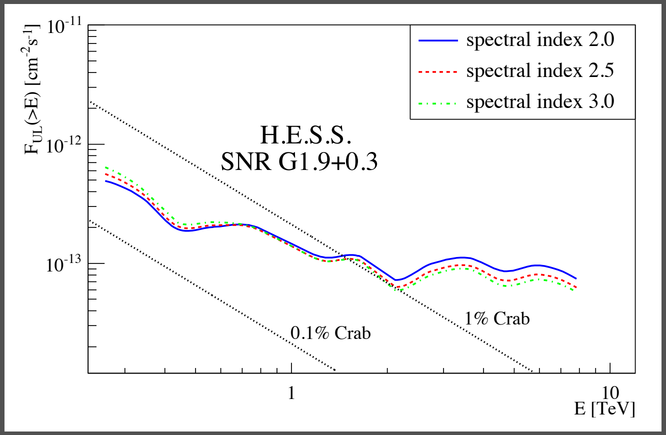




SNR energy input in accelerated hadrons

- Each SNR is expected to inject about 10^{50} erg in protons. This is what we wish to test with our gamma-ray observations but :
  - ✧ hadronic-leptonic degeneracy (unknown density, magnetic and radiation fields)
  - ✧ Even if emission is hadronic, $W_{pp} \propto n^{-1} L_{gamma}$
  - ✧ Maybe not all SNR classes inject the same amount of explosion energy in accelerated cosmic rays

High energy acceleration is believed to proceed very efficiently only at the very early stages. For the non thermal dominated youngest SNR in the Galaxy: G1.9+0.3, age~ 100 yr and highest energy protons cannot propagate beyond several pc. L_{HESS}(>1 TeV) < 1e32 erg/s -> <10^{45} erg in protons. Shock speed 14000km/s, Expected synch peak at 20 keV instead only 1 keV _> not efficient accelerator (Sun et al, 2018)



Prompt X-rays from a PeVatron