HESS Galactic Plane Survey and Implications for CTA

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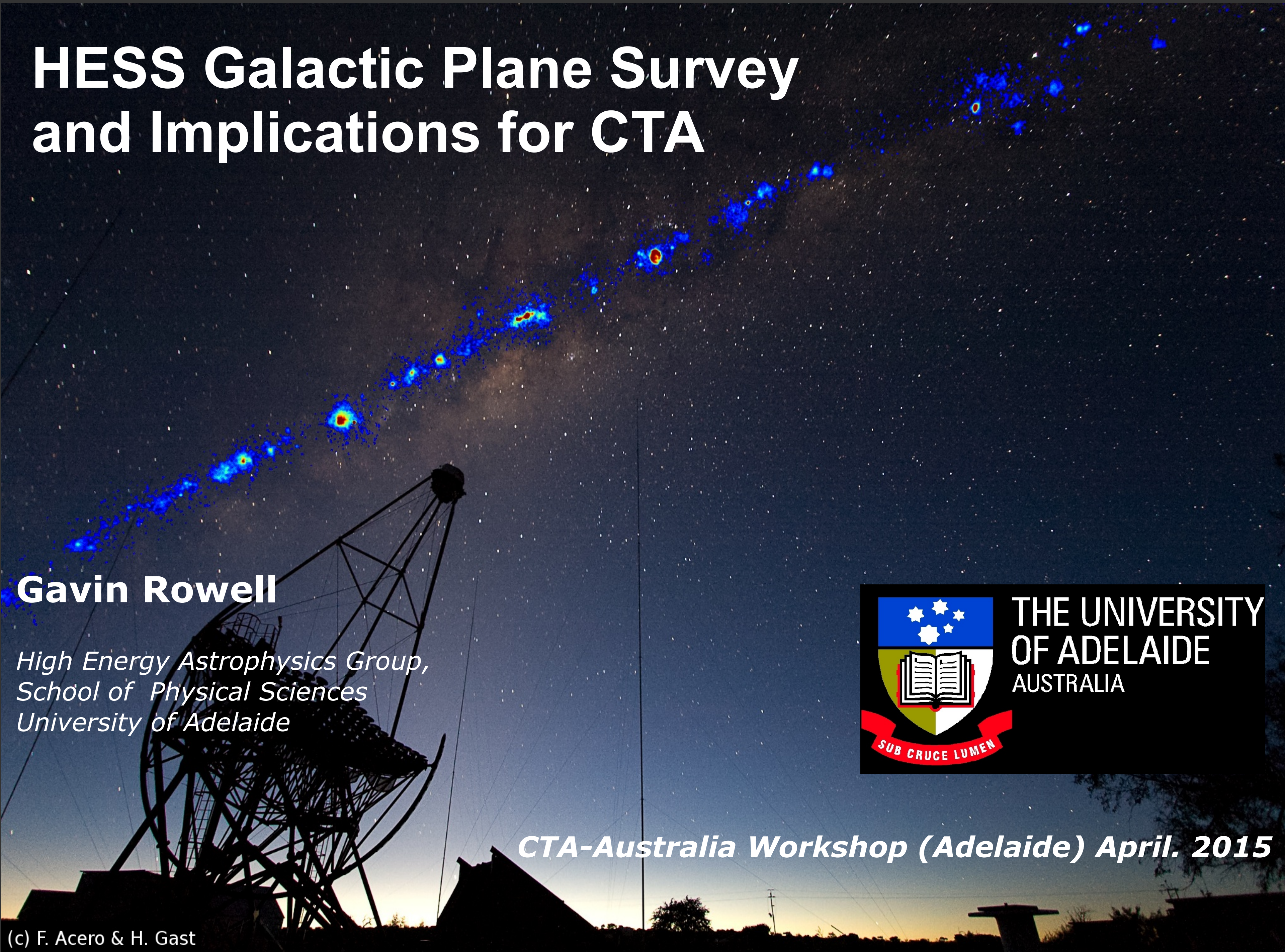
SUB CRUCE LUMEN

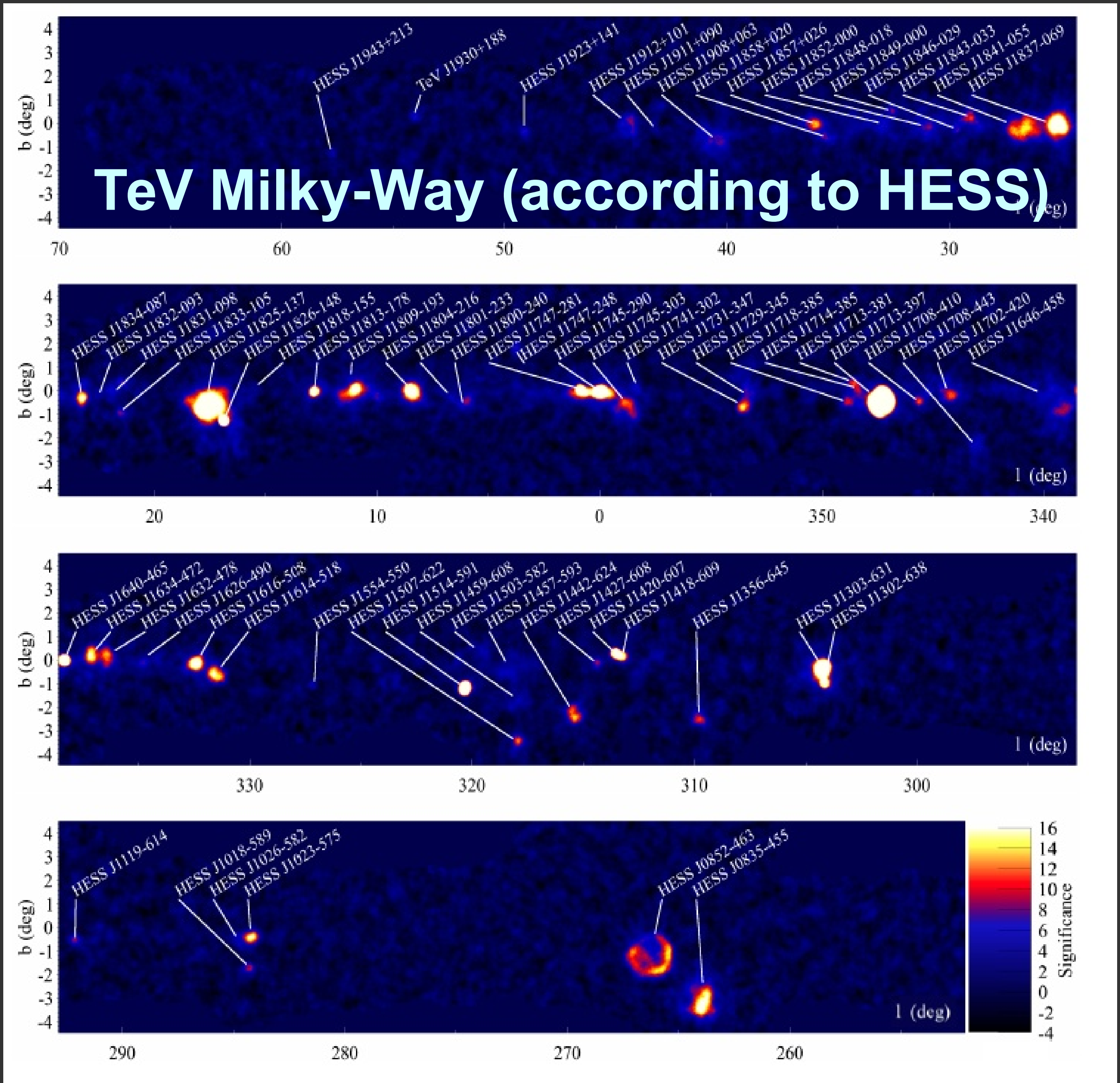
CTA-Australia Workshop (Adelaide) April. 2015



(c) F. Acero & H. Gast

TeV Milky-Way (according to HESS)

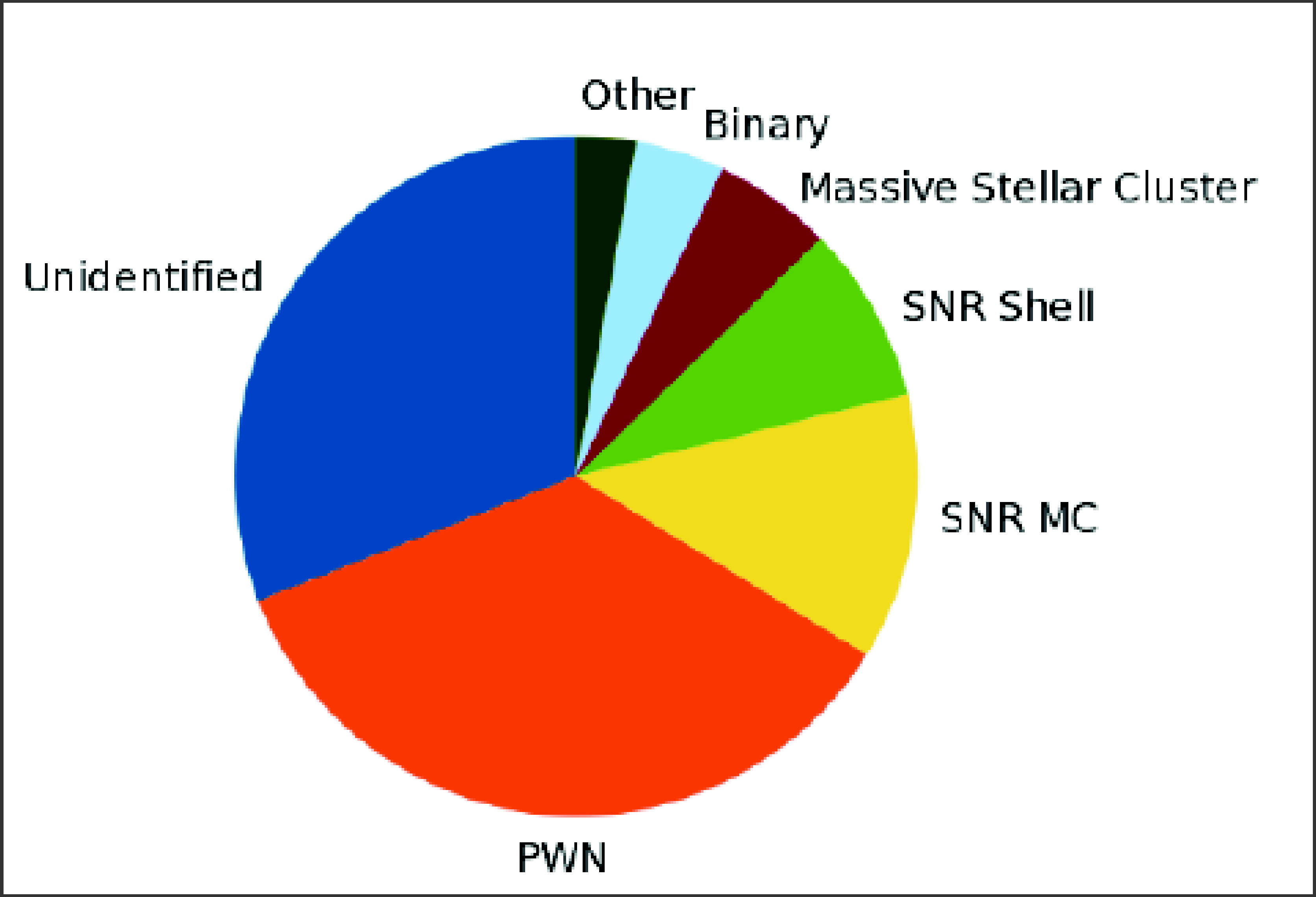
Carrigan et al 2013



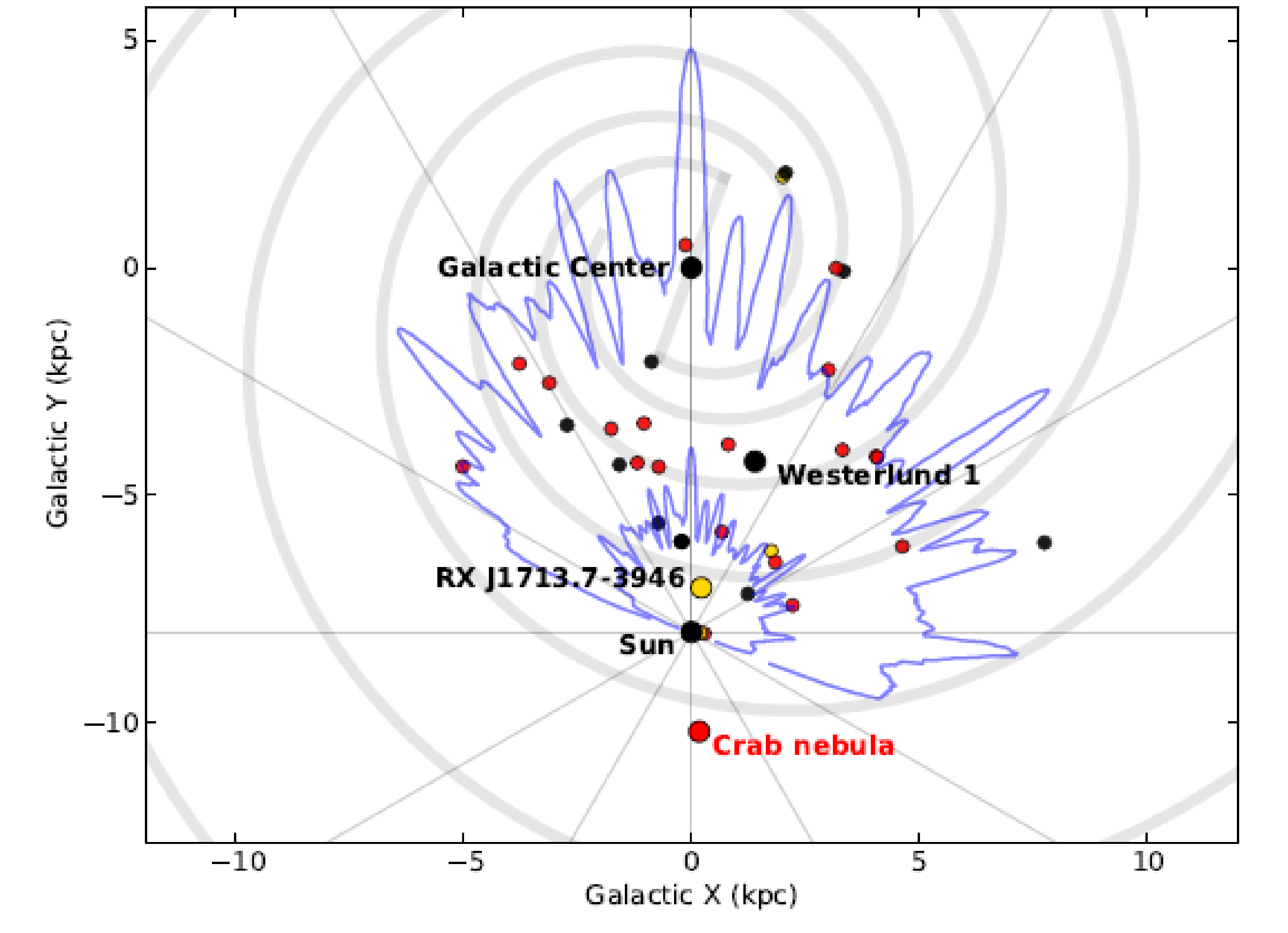
$L_{TeV} \sim 10^{32\text{-}34}$ erg/s <d>~3kpc

Carrigan et al 2013

TeV Milky-Way (according to HESS)

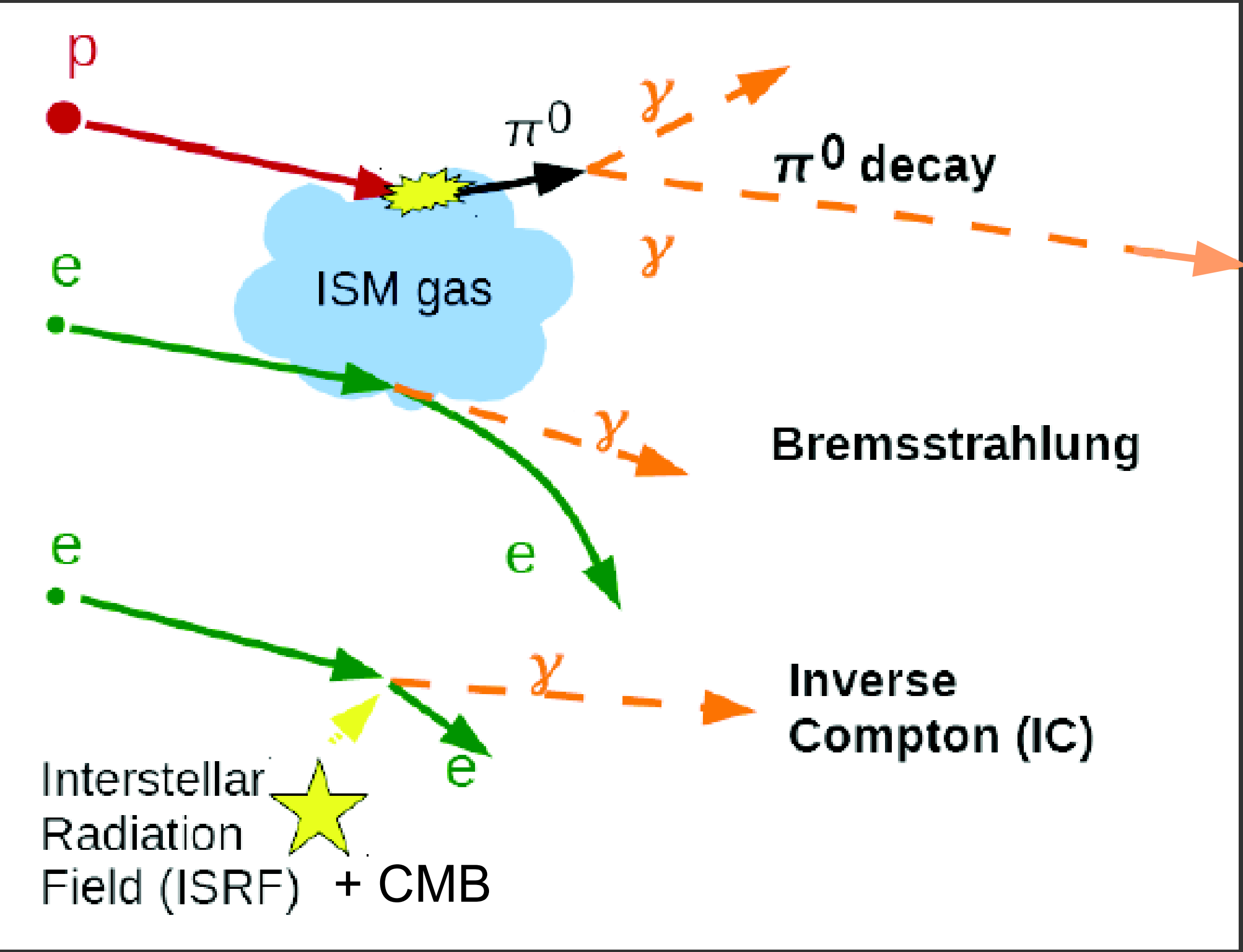


HESS TeV horizon 1% & 10% Crab flux > 1 TeV



Carrigan et al 2013

Gamma Rays from multi-TeV particles



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

Electrons: Gamma-ray (IC) + X-ray, radio emission (synch.) coupled (Bremss. usually minor)

TeV gamma-ray production:

Cooling time $t = E/\dot{E}$

Pi-zero decay: $t_{pp} = (n\sigma_{pp} f c)^{-1} \approx 5.3 \times 10^7 (n/\mathrm{cm}^3)^{-1}$ yr

IC scattering: $t_{IC} \approx 3 \times 10^8 (U_{rad}/\mathrm{eV/cm}^3)^{-1} (E_e/\mathrm{GeV})^{-1})$ yr

Bremsstrahlung: $t_{br} \approx 4 \times 10^7 (n/\mathrm{cm}^3)^{-1}$ yr

Synchrotron: $t_{sync} \approx 12 \times 10^6 (B/\mu\mathrm{G})^{-2} (E_e/\mathrm{TeV})^{-1}$ yr

Cooling times: Excellent first-order evaluation of dominant processes in particle accelerators $E_\gamma \equiv \sim 0.1 E_{\text{proton or electron}}$

For ISM, B and U_{rad} parameters in many sources, TeV gamma-ray production can be slow: t > 10^4 yrs especially for pi-zero decay

Slower than X-ray synchrotron (t < 10^4 yr) but similar to radio synchrotron from GeV electrons.

TeV gammas and non-thermal radio → relic emission in old sources e.g. ancient SNRs and PWNe

Galactic **TeVatrons** and **PeVatrons**

What are the particle accelerators to E ~ 10^{15} eV (1 PeV)?

- Shell Type Supernova Remnants?
W_{CR} ~ 10^{50} erg per SNR

$L_{All-SNR} \sim$ few $\times 10^{42}$ erg s^{-1}

- Pulsar Wind Nebulae?
Pulsar *spin-down* power

$\dot{E} = I\omega\dot{\omega} \sim 10^{32}$ to $\sim 10^{39}$ erg s^{-1}

- Pulsars? Rotating dipole B

$E_{max} \approx 8 \times 10^{20} Z (B/10^{13}\mathrm{G})(\omega/3000\mathrm{Hz})^2$ eV

- WR, O & B stars, Massive Stellar Clusters, Massive Star Formation?
Stellar wind KE

$$L_w = \frac{1}{2}\dot{M} v_\infty^2$$

B-star ***L_w ~$10^{34\text{-}35}$ erg/s***

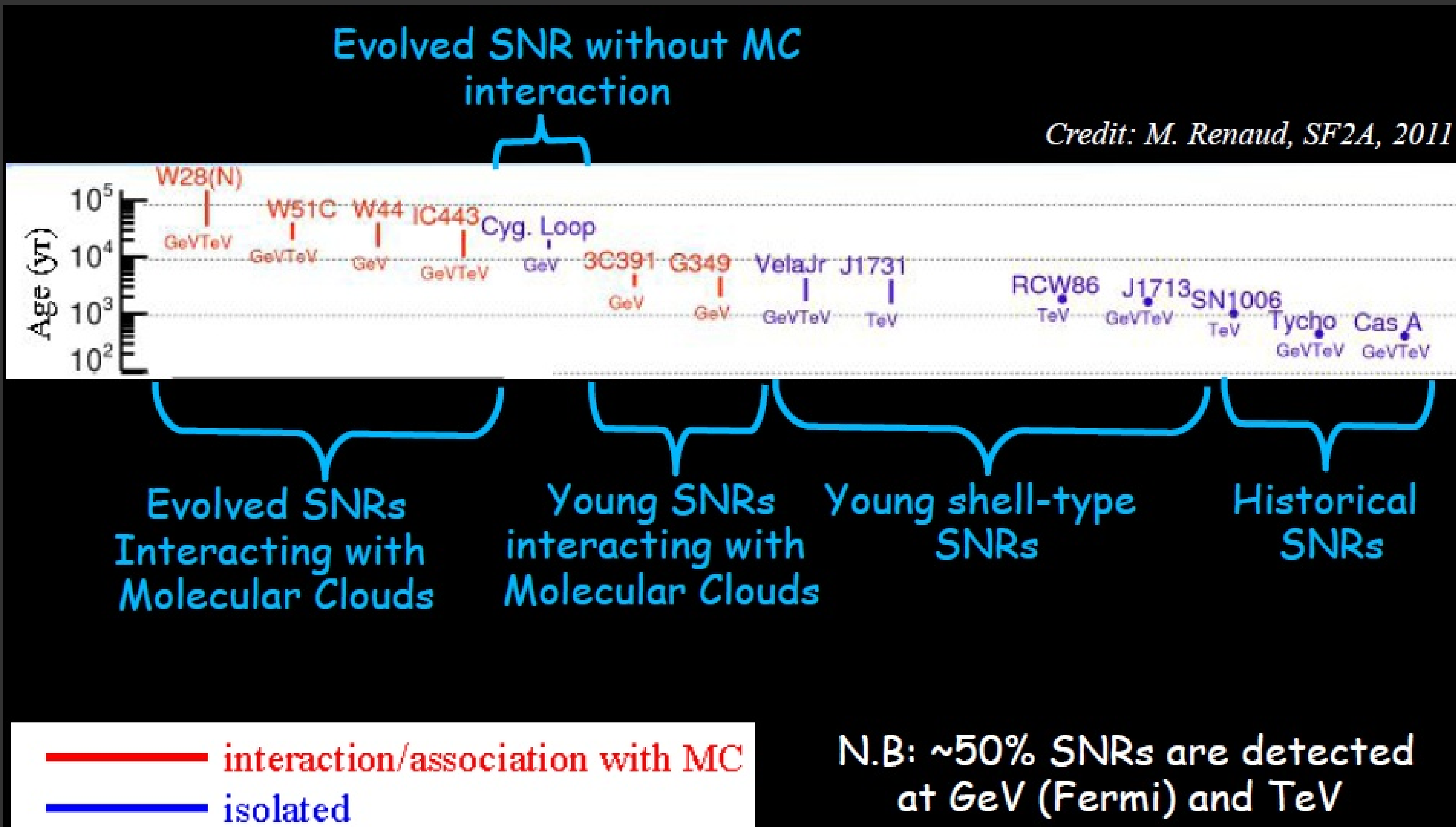
WR star **L_w ~ $10^{38\text{-}39}$ erg/s**

- X-Ray Binaries, Microquasars, Active galaxies (AGN)?
Accretion power

$L_{acc} = \eta c^2 \dot{M}/2$ η=10 to 20%

Galactic $L_{acc} \sim 10^{40}$ erg s^{-1}

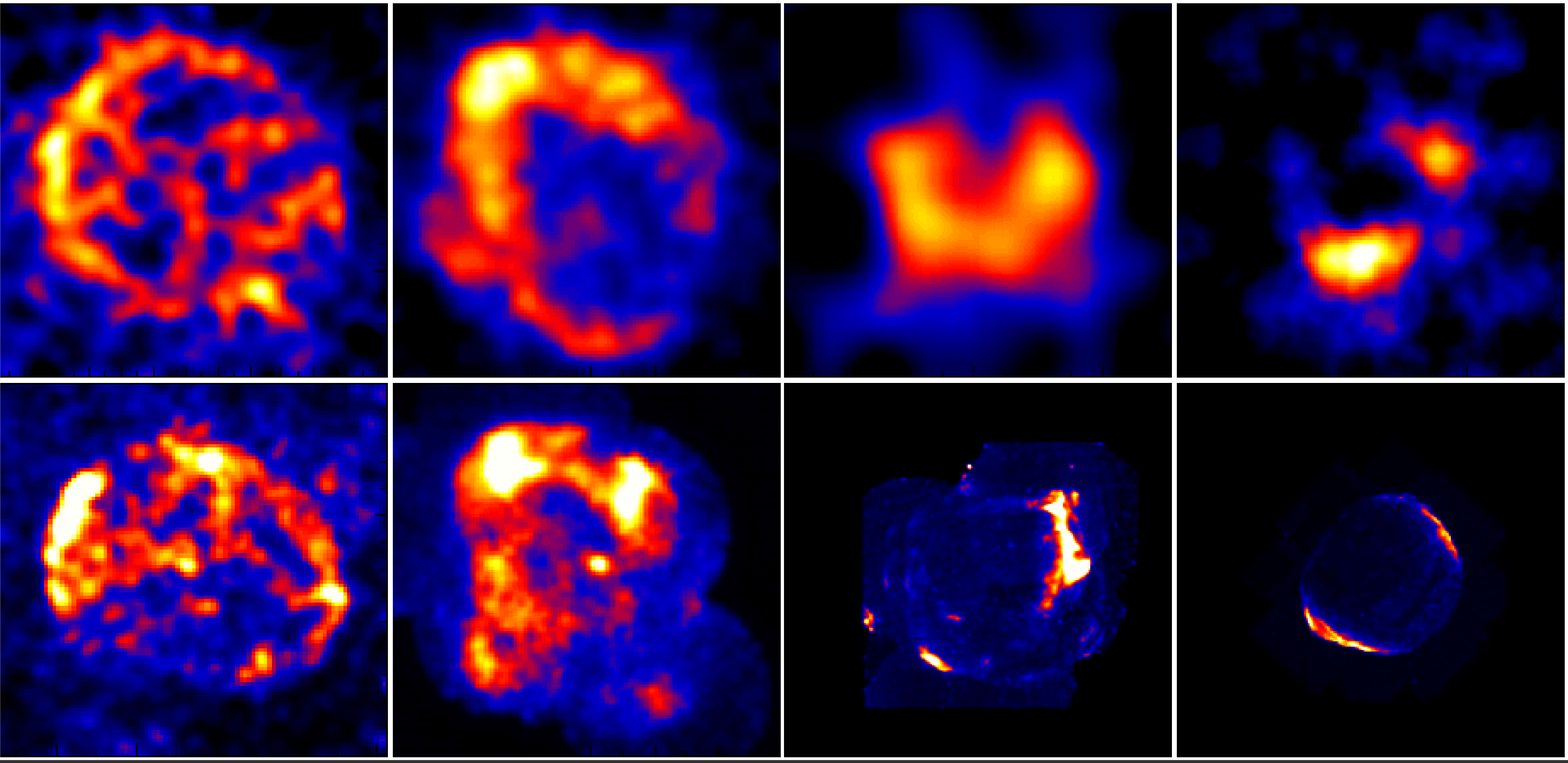
AGN $L_{acc} \sim 10^{46}$ erg s^{-1}

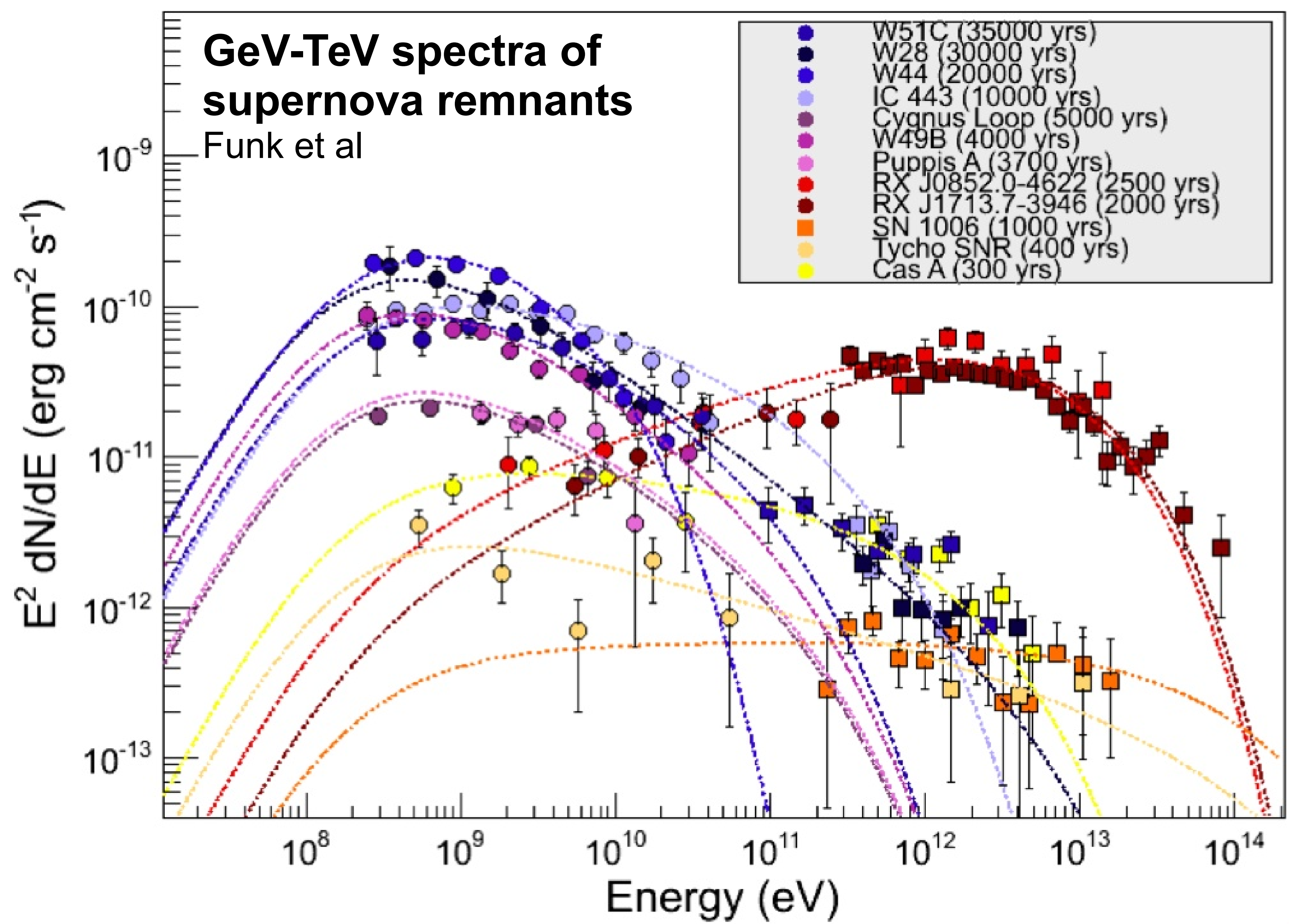


From M. Lemoine-Gourmard

X-Ray-Bright Shell-Type Supernova Remnants

age < few 1000 yr



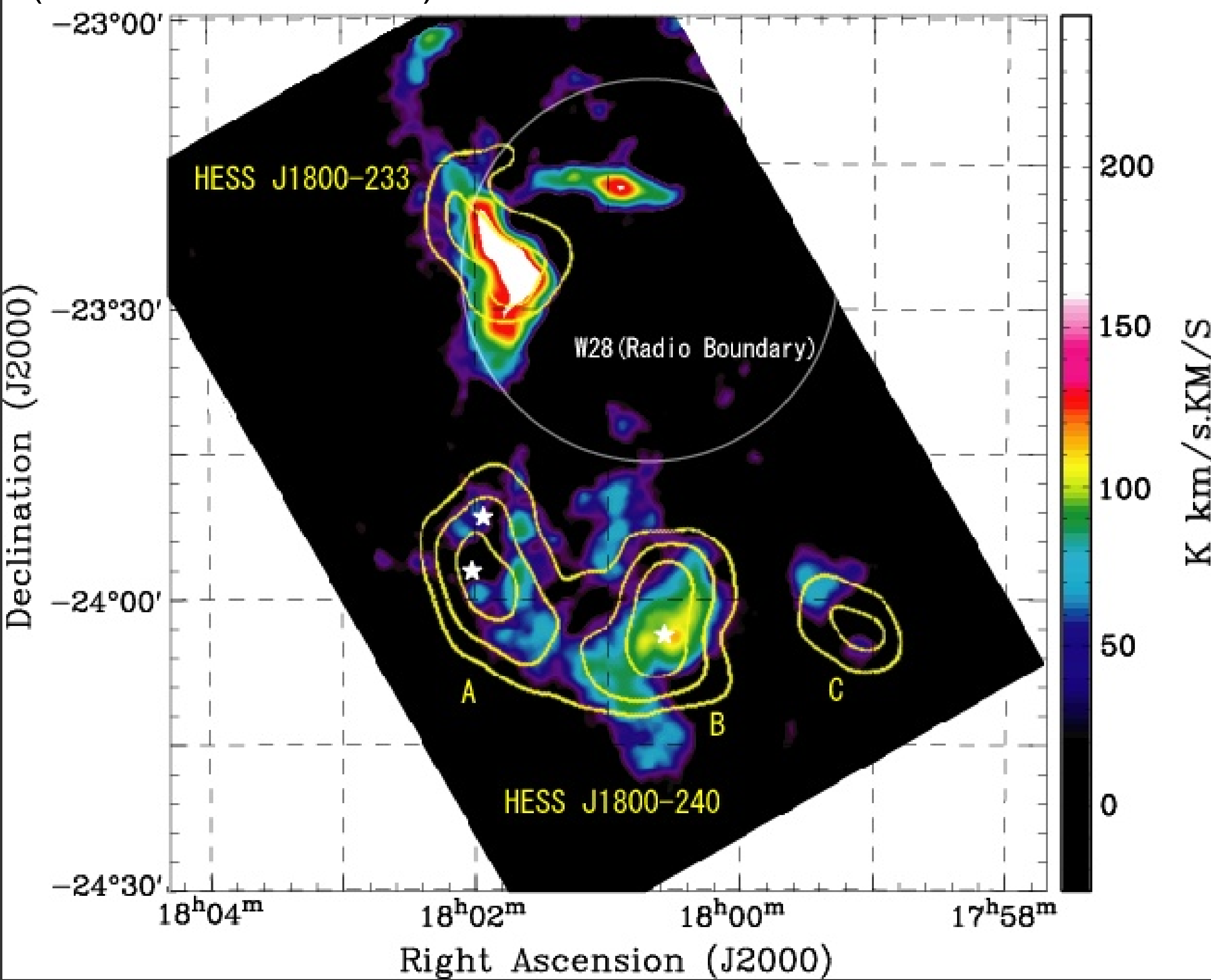


GeV-TeV spectra of supernova remnants
Funk et al
W51C (35000 yrs)
W28 (30000 yrs)
W44 (20000 yrs)
IC 443 (10000 yrs)
Cygnus Loop (5000 yrs)
W49B (4000 yrs)
Puppis A (3700 yrs)
RX J0852.0-4622 (2500 yrs)
RX J1713.7-3946 (2000 yrs)
SN 1006 (1000 yrs)
Tycho SNR (400 yrs)
Cas A (300 yrs)
E^2 dN/dE (erg cm^{-2} s^{-1})
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
Energy (eV)

Old SNR (>10^4 yr) W28 + Molecular Gas

Aharonian et al 2008

Nanten2 ^{12}CO(J=2-1) image -10 to 25km/s
(Nakashima etal 2008)



Excellent TeV & Molecular Cloud spatial match

→ best indication for CRs from SNRs!

CR density k_{CR}
~7 to 30 x local value

HESSJ1801-233
SNR shock/mol cloud interaction

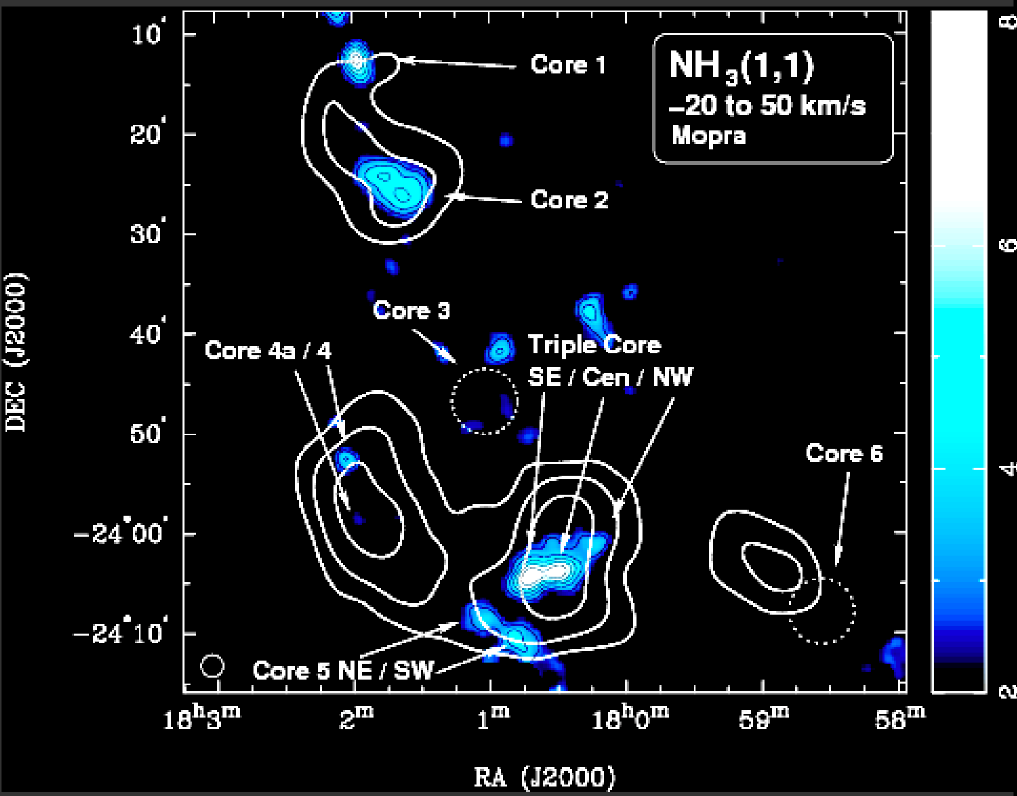
HESSJ1800-240
Also CRs from W28

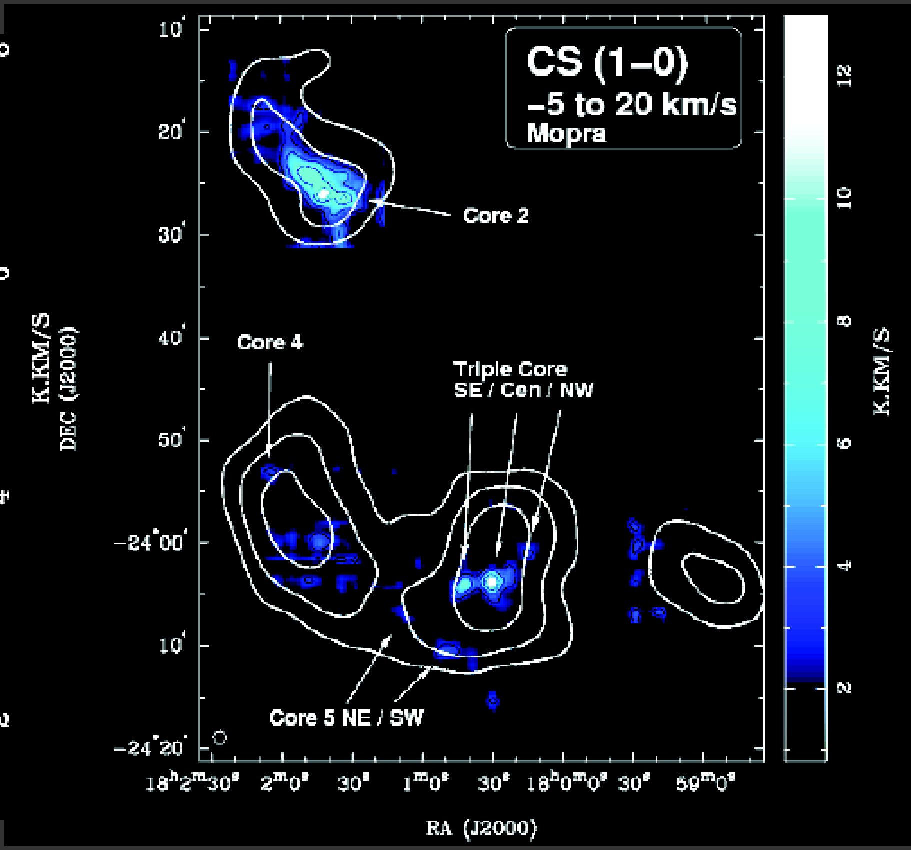
+ HII regions?

Dense (>10^4 cm^{-3}) Cores of W28 Molecular Clouds (Nicholas etal 2011a, 2011b)

NH_3 (23 GHz) & CS(1-0) (48 GHz) with Mopra

→ probe for cloud disruption and connection with W28
→ cosmic-ray diffusion properties (ala Core C in RXJ1713)
→ star formation properties of southern cores.





CR Diffusion *Into* Molecular Clouds

Gabici etal 2007

R = distance CR travels into molecular cloud core

$$R = 0.62 - \sqrt{6D(E_P, B)[1600 - t_0]} \quad [\mathrm{pc}]$$

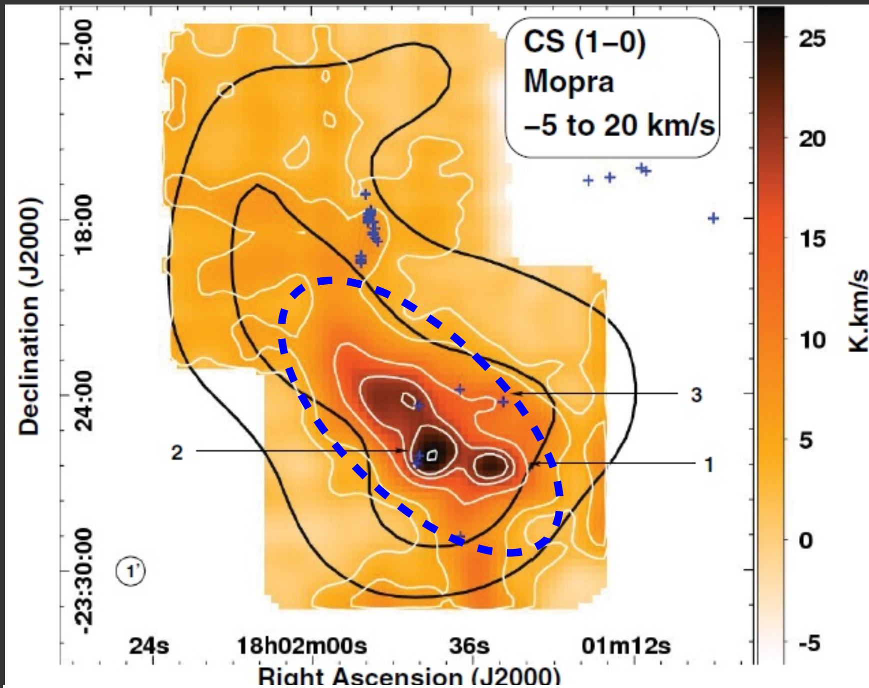
$$D(E_P, B(r)) = \chi D_0 \left(\frac{E_P/\mathrm{GeV}}{B/3\,\mu\mathrm{G}} \right)^{0.5} \quad [\mathrm{cm}^2\,\mathrm{s}^{-1}],$$

$$B(n_{H_2}) \sim 100 \sqrt{\frac{n_{H_2}}{10^4\ \mathrm{cm}^{-3}}} \quad [\mu\mathrm{G}]$$

χ=diffusion suppression

→ Low energy CRs can't reach cloud core
→ Expect harder TeV spectra from cores.
→ Don't expect electrons to penetrate!!
(due to sync. losses)

→ Need to map dense cloud cores



NE Shocked Cloud

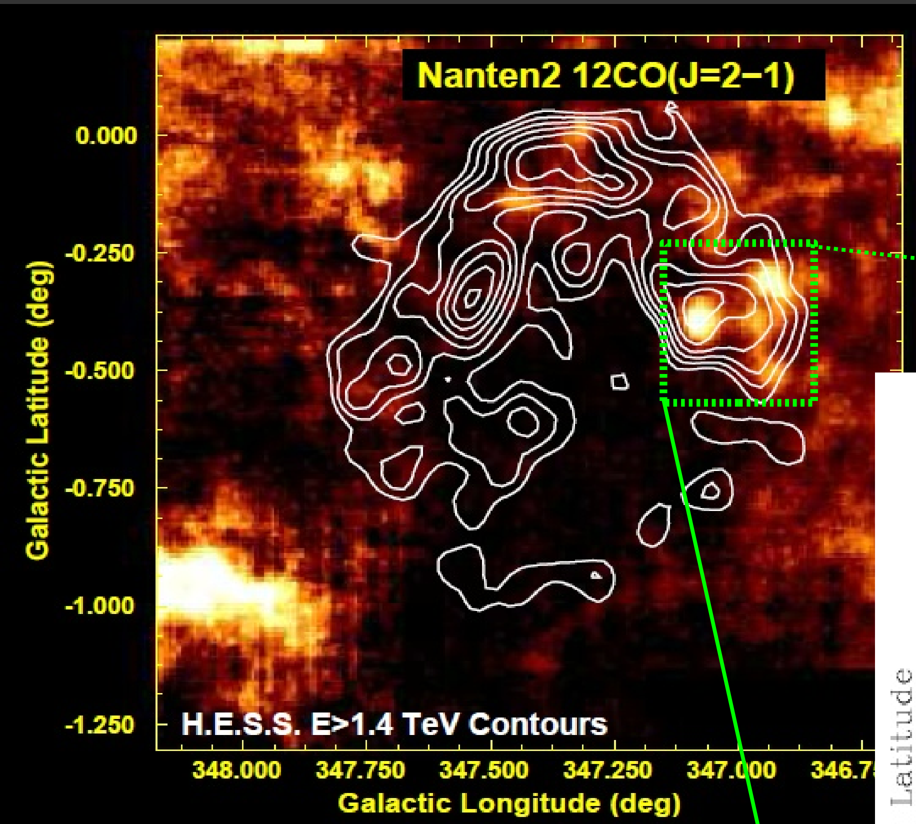
Mass of dense core ~10^4 M_{sun}

→ **Gamma-rays from CS clumps ($10^{-14 \text{ to } -13}$ ph/cm^2/s)**

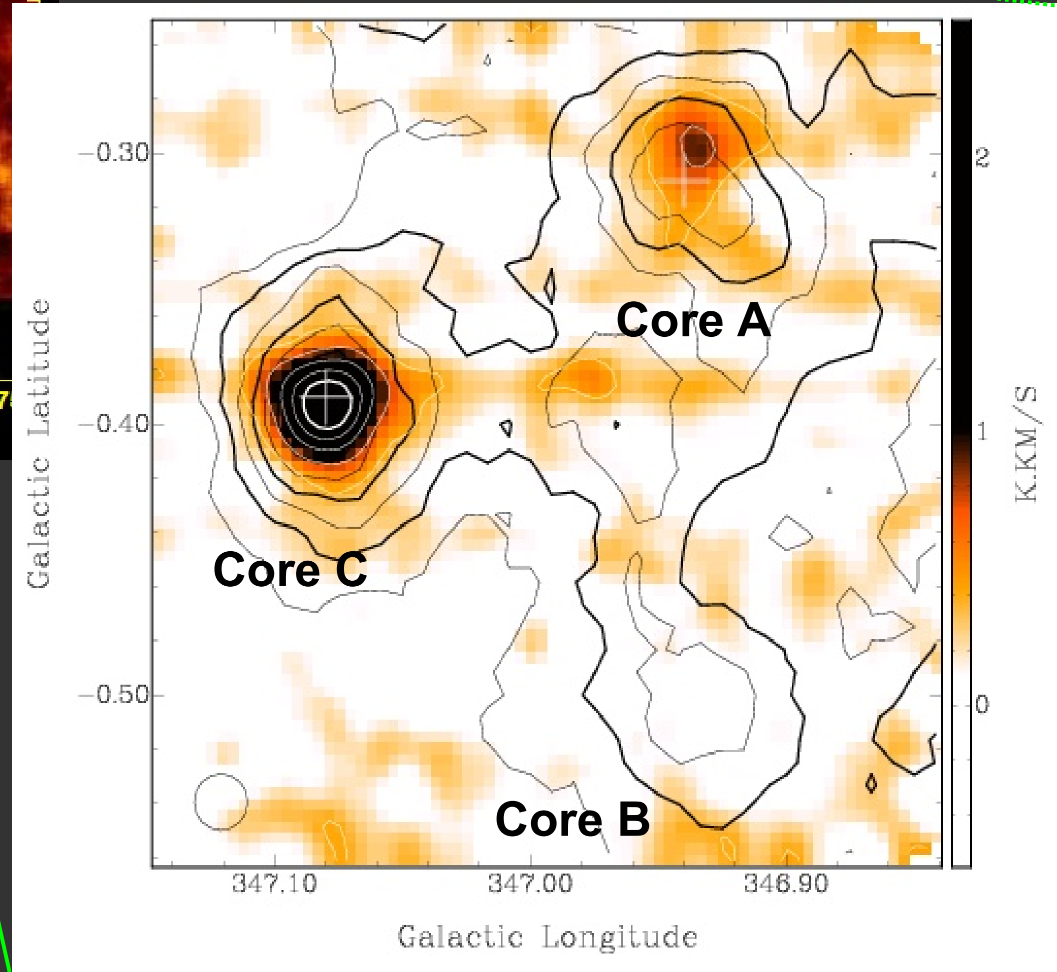
→ **Detectable & maybe resolvable by CTA**

Region	k_{CR}	Expected flux $F(E \geq 1$ TeV) (photons cm^{-2} s^{-1})
NE shocked cloud	13	$< 5.1 \times 10^{-13}$
G5.89−0.39 H II region	18	7.0×10^{-13}
G5.89−0.39 NW arm	18	5.4×10^{-14}
G5.89−0.39 SE ridge	18	1.6×10^{-13}
G6.1−0.6 region	14^a	6.5×10^{-14}
G6.225−0.569 region	14^a	1.6×10^{-14}
HESS J1800−240 C	35^b	4.7×10^{-15}

RXJ1713.7-3946: Molecular Cloud Cores (Mopra Obs.)



Mopra observations CS(1-0)
(N. Maxted)



→ dense gas $10^{4\text{-}5}$ cm^{-3}

→ mass 50 – 100 M_{sun}

CR diffusion *into* 'Core C'

2D Slices of CR diffusion depth vs E and χ

Assume average B ~ 17 μG

→ For χ <= 10^{-3}, can expect exclusion of
> 1 TeV CRs from centre

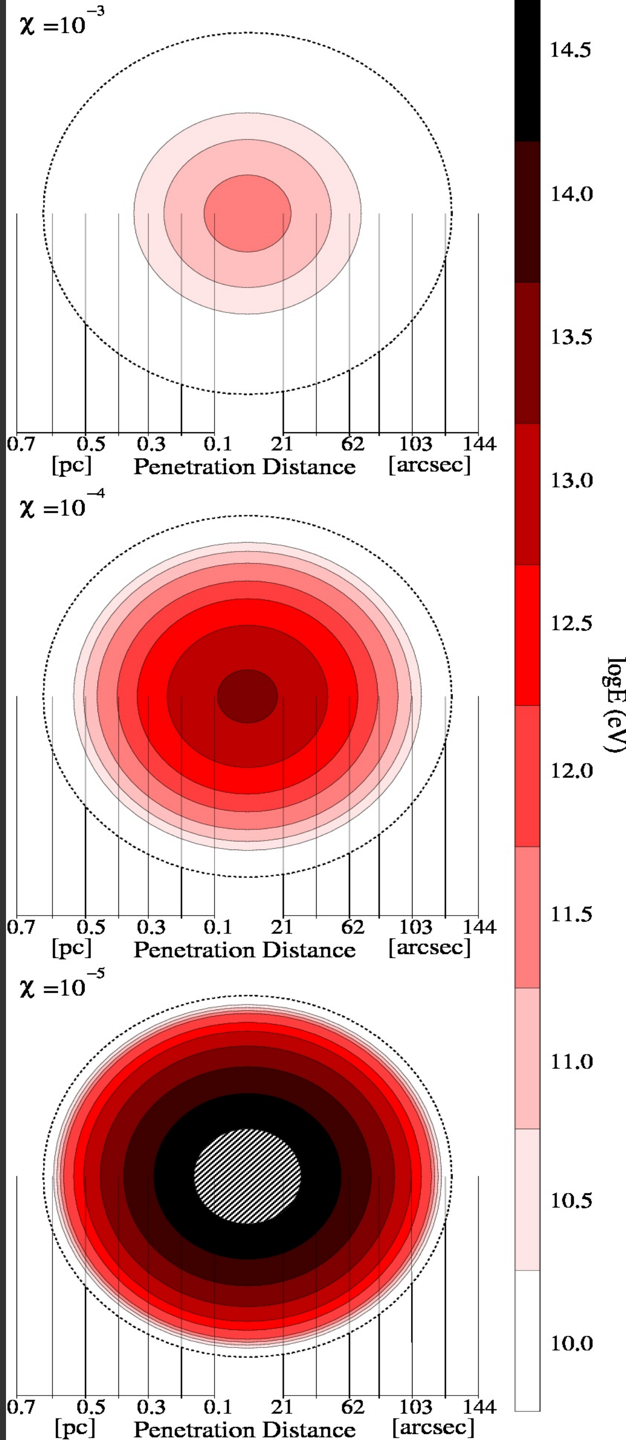
→ Similar trends for gamma-rays ($E_\gamma \sim E_p/10$)

→ Need <2 arc-min gamma-ray observations to resolve inner and outer regions.

→ New way to determine CR vs. electron nature of gamma-rays!

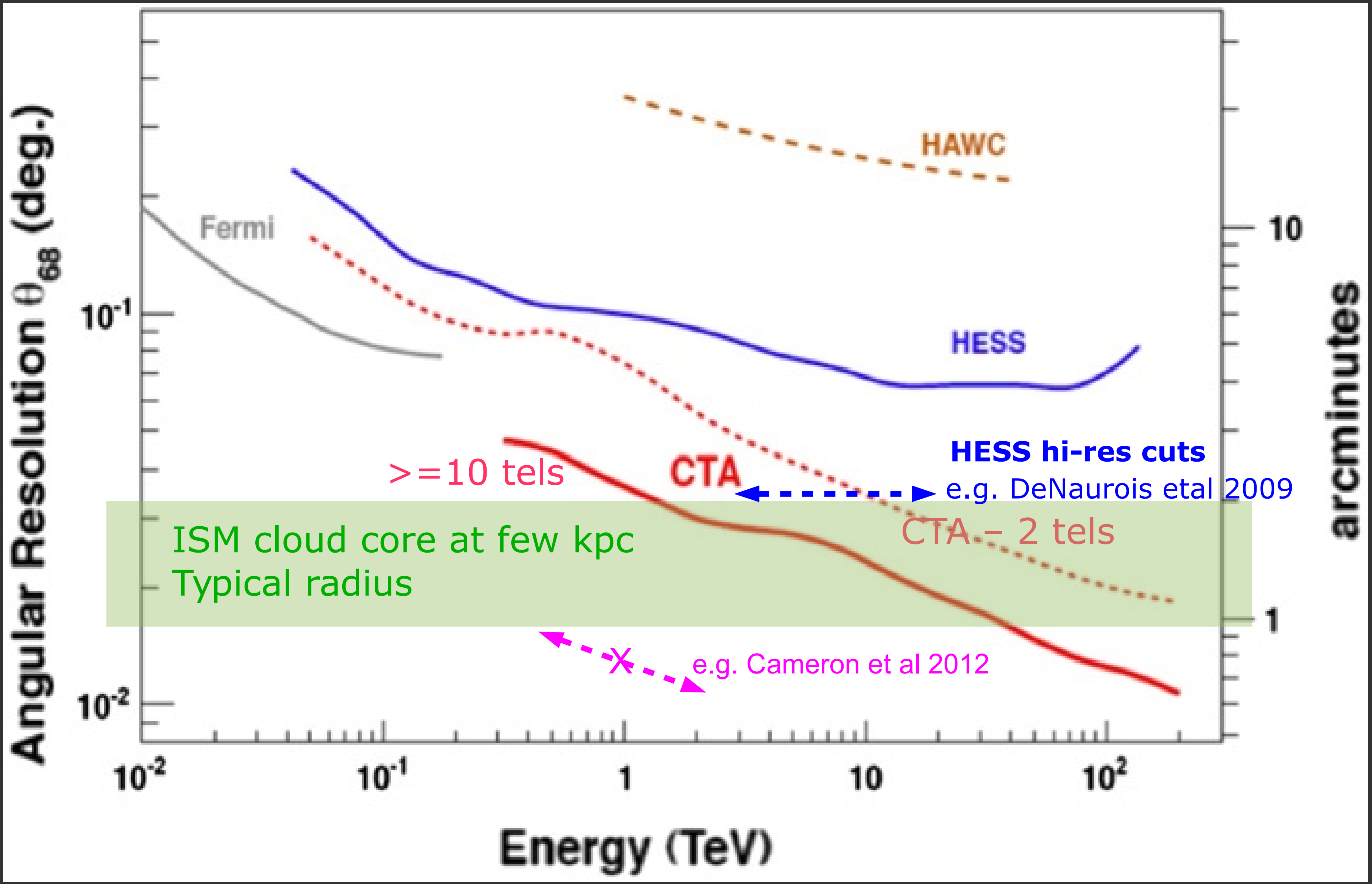
Deeper obs. With HESS (2015/2016)

→ many SNRs with CTA



Angular Resolution (HESS, CTA..)

Acharyara etal 2013



CTA MST-SCTs with small pixels and/or hi-res cuts → resolve cloud cores!

Arc-min Angular Resolution

0.004°
XMM 10 keV

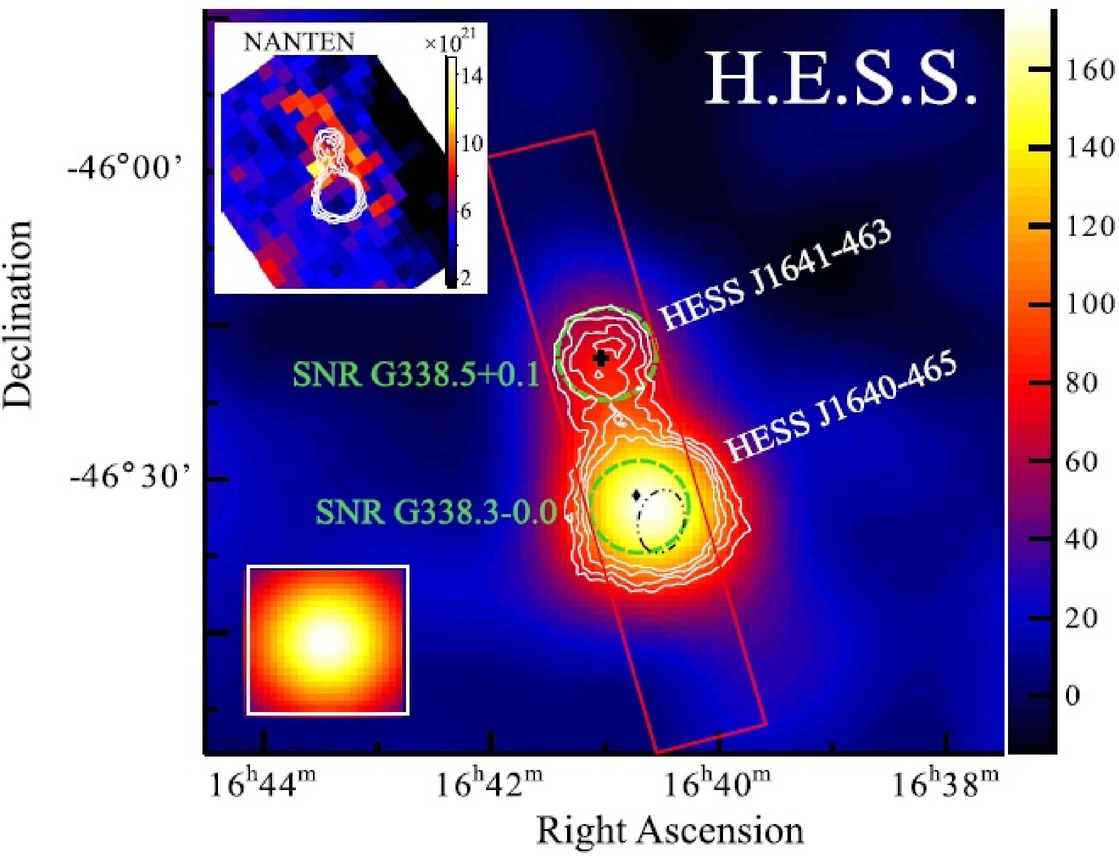
0.1°
Simulation with current IACT

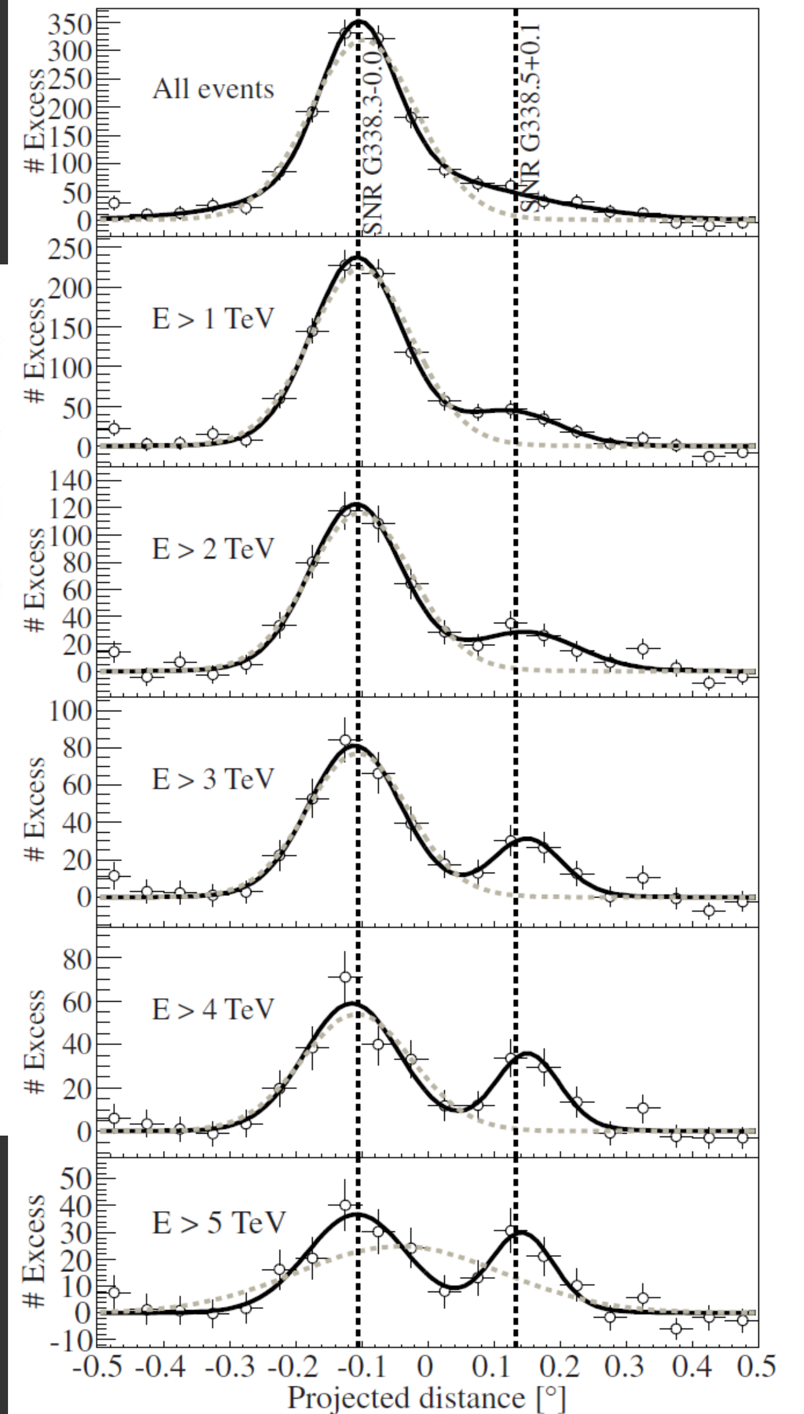
0.02°
CTA @ few TeV

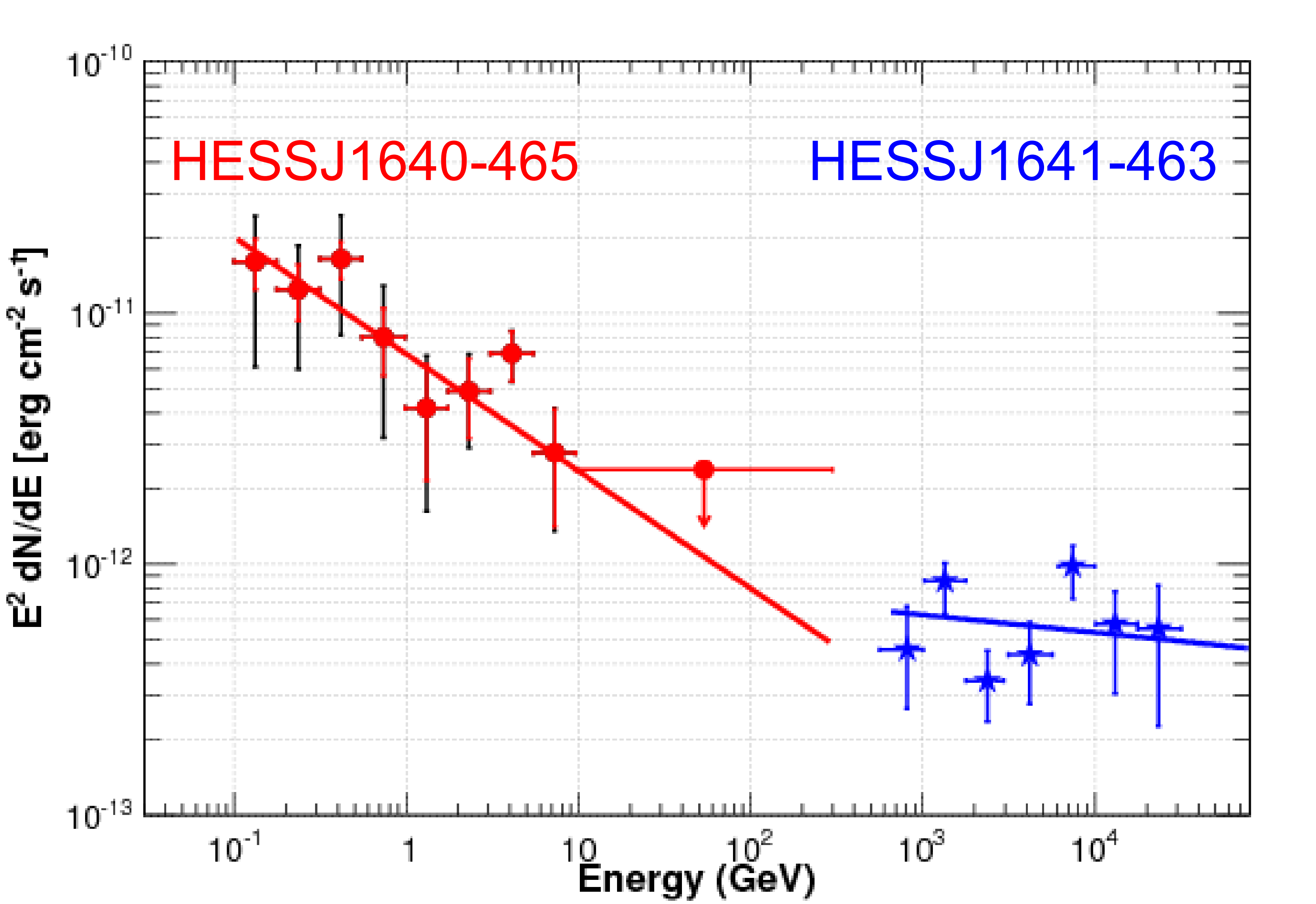
➡ *sub-structure of SNR shock fronts will become visible at TeV energies;*

➡ *source morphologies*

HESSJ1641-463
A Galactic PeVatron?






HESSJ1640-465
HESSJ1641-463
E^2 dN/dE [erg cm^{-2} s^{-1}]
Energy (GeV)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-1}
1
10
10^2
10^3
10^4

Acceleration of CRs above the knee (10^{15}~10^{18} eV)

A Major Mystery in High Energy Astrophysics...

- Diffusive Shock Acceleration Theory E_{max} ~ few x 10^{15} eV
  (Drury 1983, Lagage & Cesarsky 1983, Hillas 2006 for review)

Some ideas..... eg.

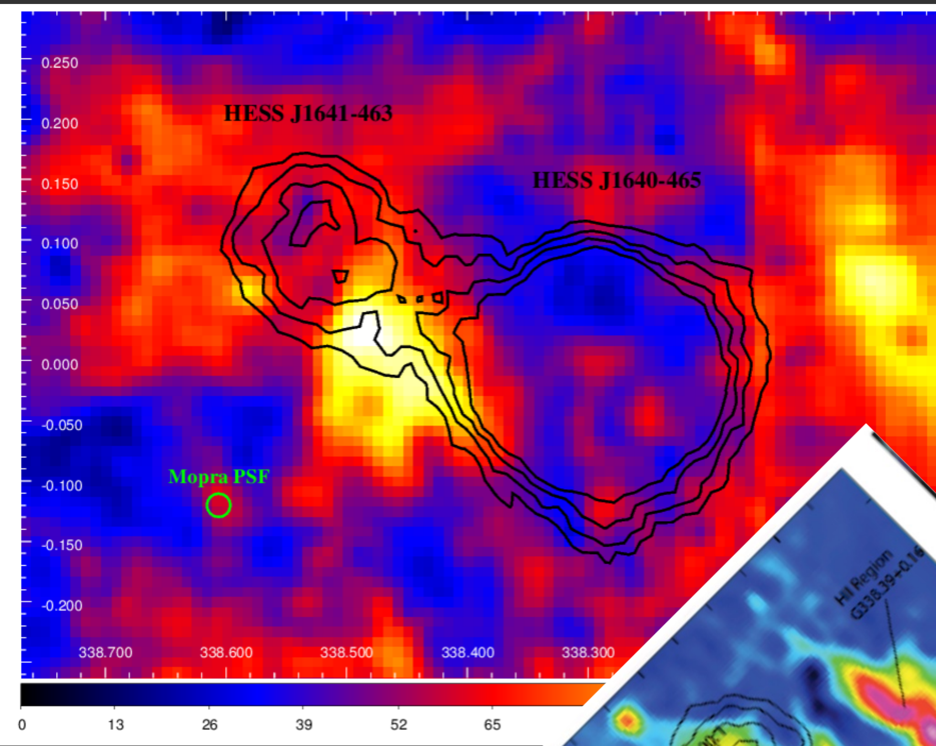
- Magnetic field modification B>100 μG (Bell & Lucek 2001)
  → Young SNRs

- Re-acceleration of Galactic Cosmic Rays (Jokipii & Morphill 1985, Voelk & Zirakashvili 2001)

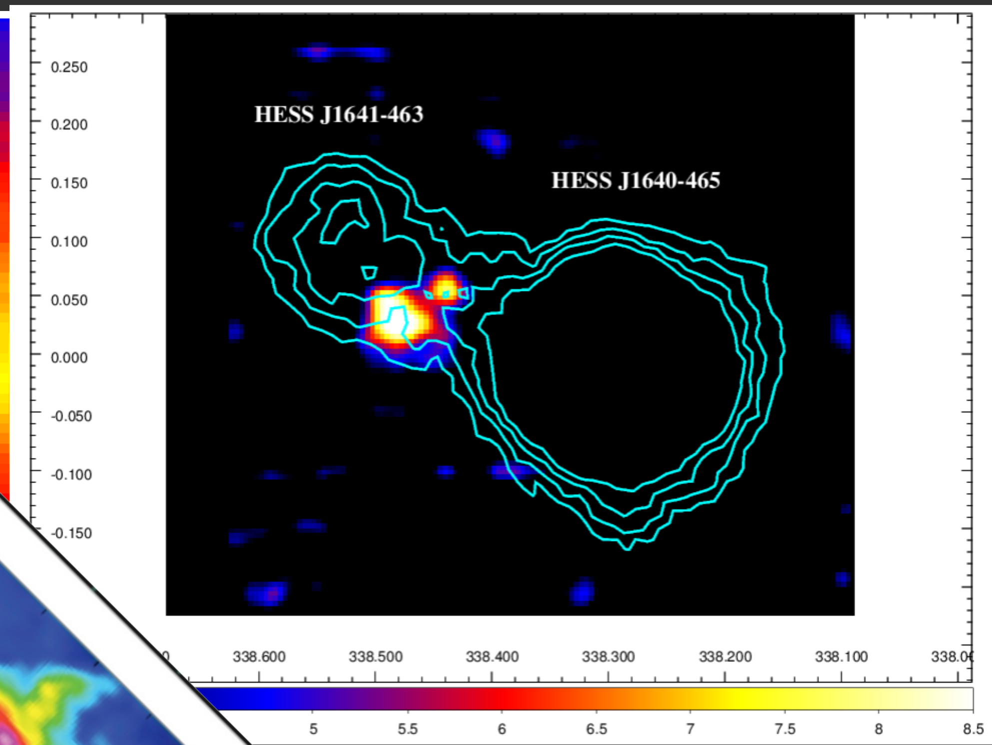
- Acceleration by Galactic GRBs – Hypernovae
  (Wick, Dermer, Atoyan 2004)

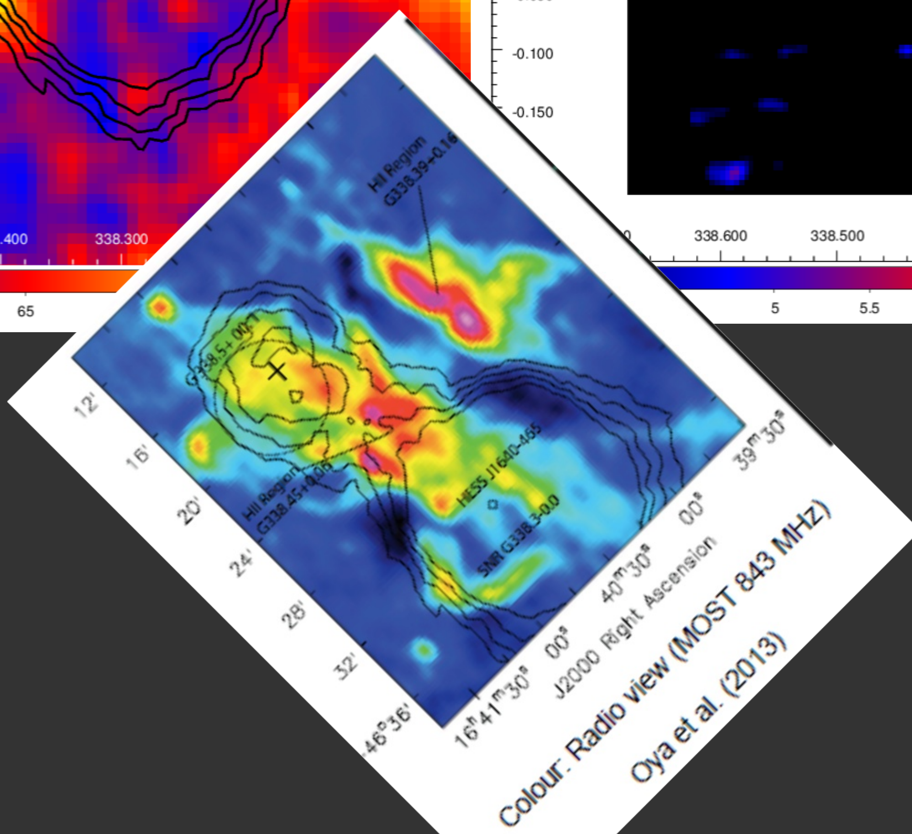
- Large-scale galactic shocks from Superbubbles via
  multi SNR, multi stellar winds from OB assoc.
  (Drury 2001, Bykov 2001, Parizot 2004)

Mopra CO(1-0)



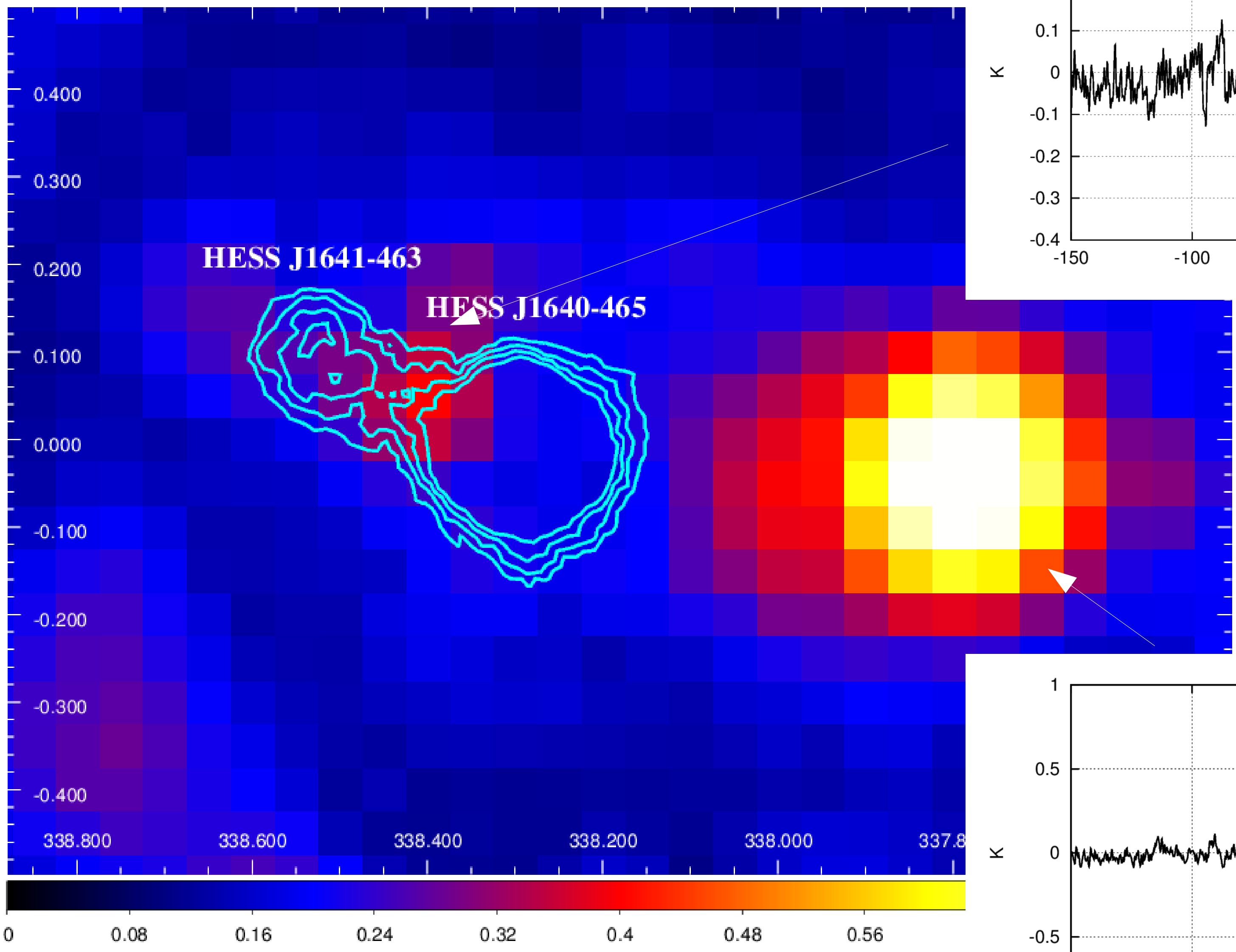
Mopra CS(1-0)

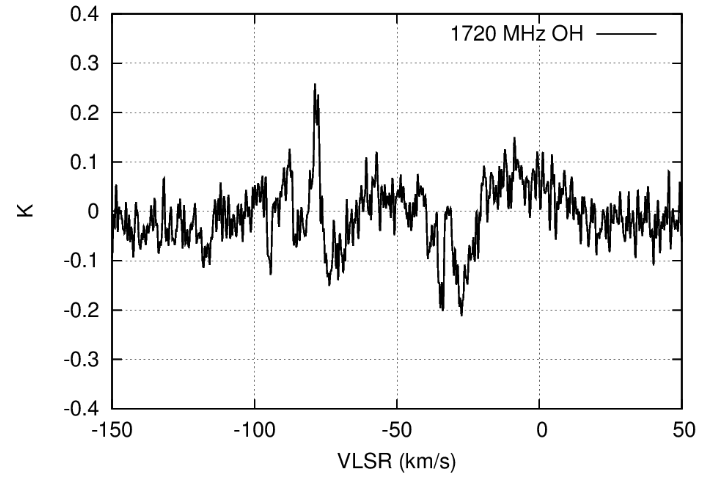


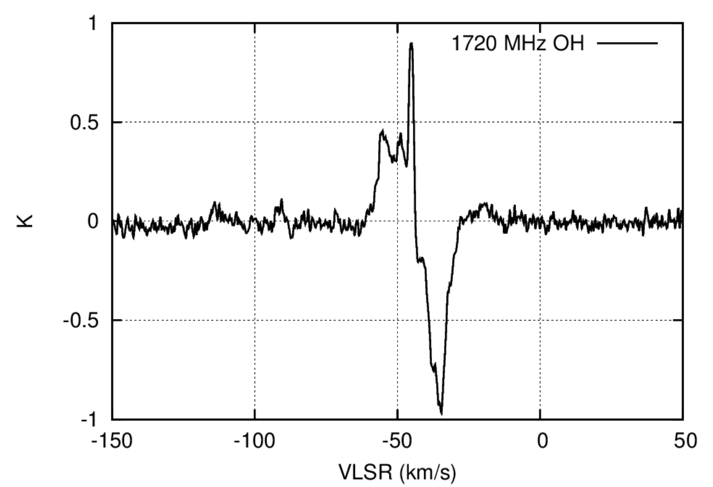


Parkes SPLASH 1720 MHz OH

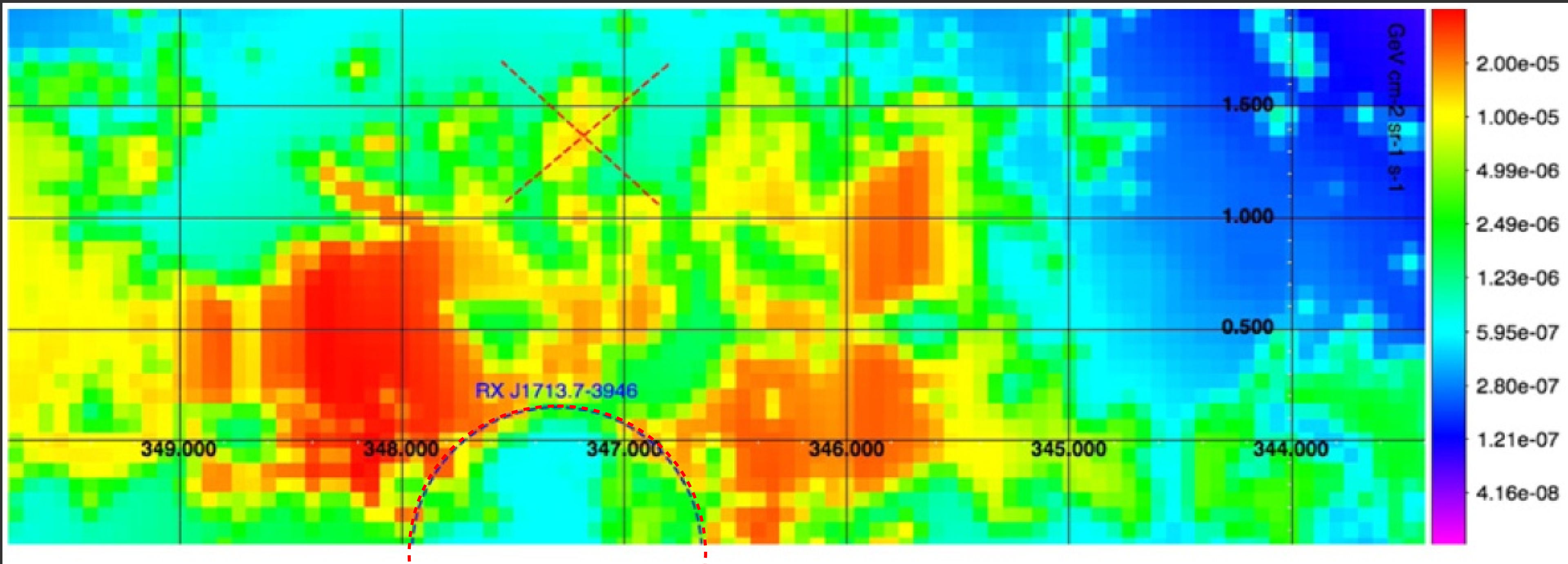
(data courtesy Jo Dawson)







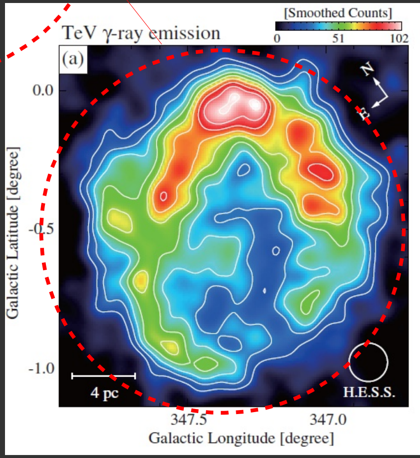
Simulated TeV gamma-ray emission (units GeV/cm^2/s/sr) from CRs escaping SNR RXJ1713.7-3946 (Acero etal 2013)

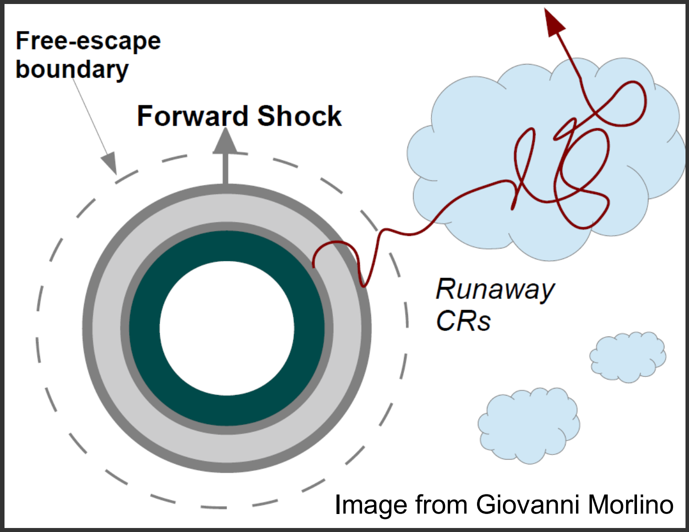


Based on Casanova etal 2010 (with Nanten CO(1-0) data)

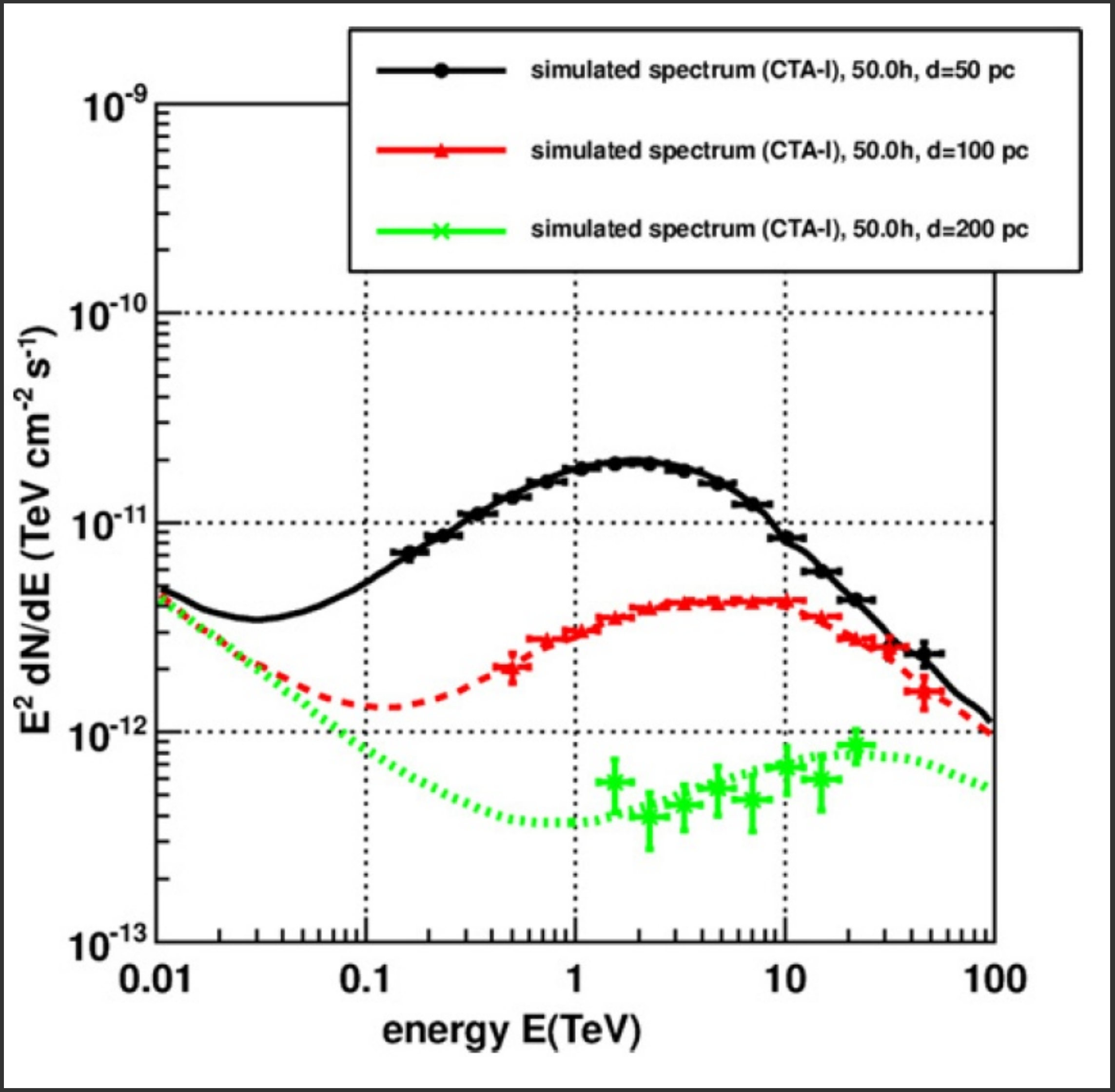
$D = 10^{28}(E/10GeV)^{0.5}$ cm^2/s

$E_{escape} \sim 500\ (t/100\ yr)^{-0.43}$ TeV





CTA 50h Observation - CRs escaping SNR



SNR age 2000 yr

Cloud mass 10^5 M_{sun}

d = 1 kpc

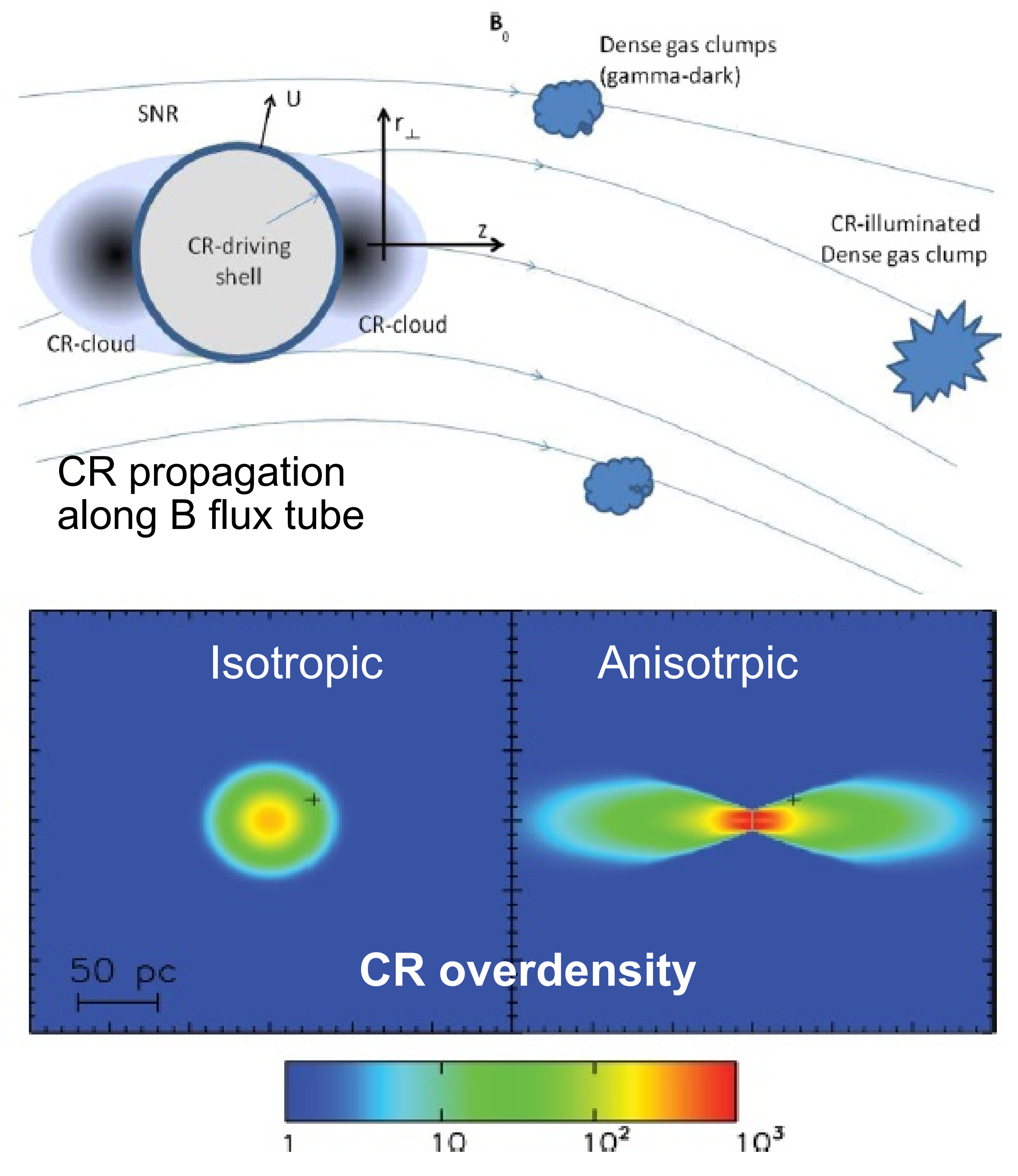
$D=10^{28}(E/10GeV)^{0.5}$ cm^2/s

PeV CRs escape first and arrive at the cloud first!

Ideal way to probe CR PeVatrons

CR diffusion – not necessarily Isotropic!

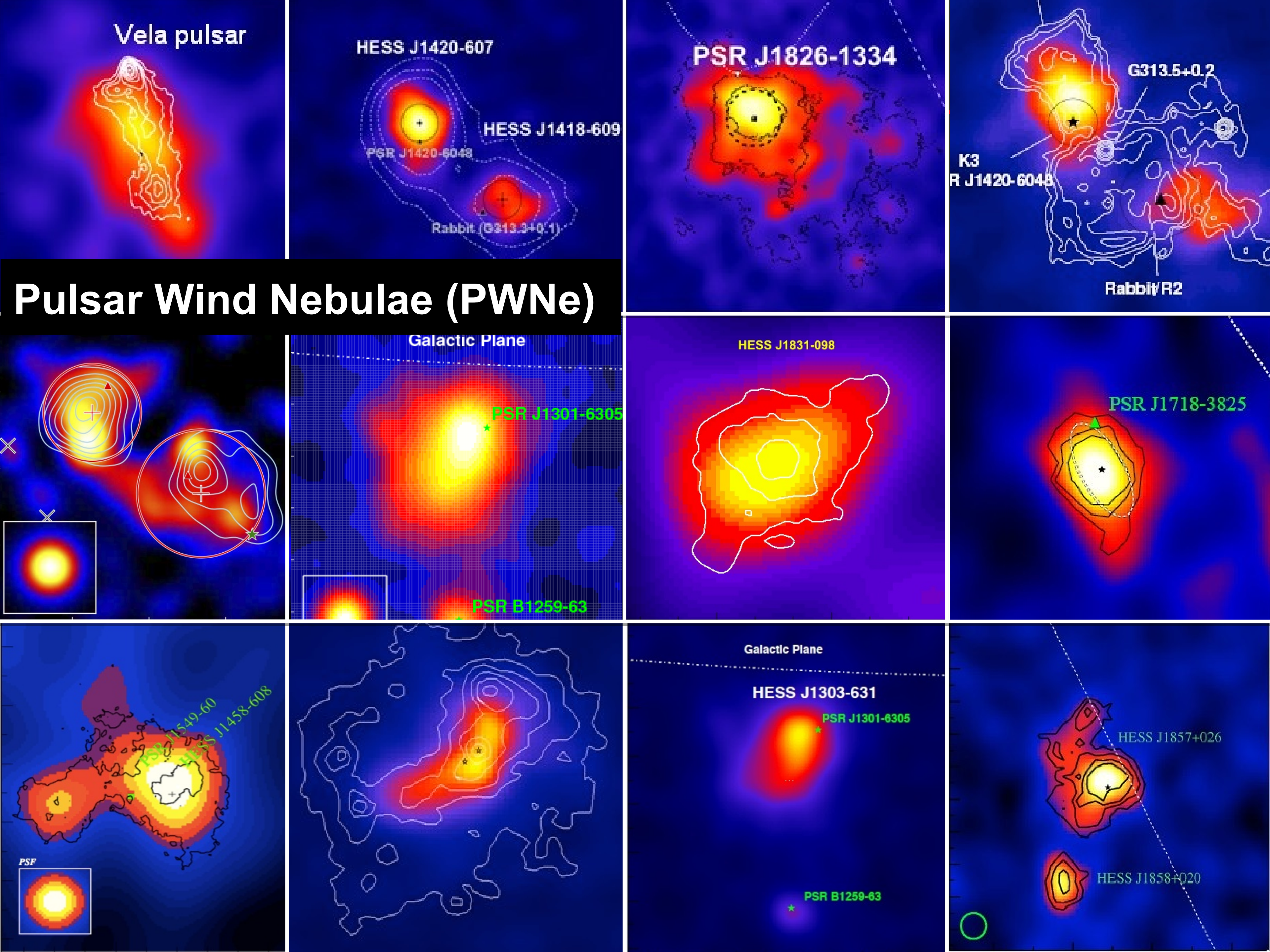
Malkov etal 2013
Nava & Gabici 2013



→ Nearby clouds will see different CR densities

→ Need detailed maps of ISM gas + B-field direction

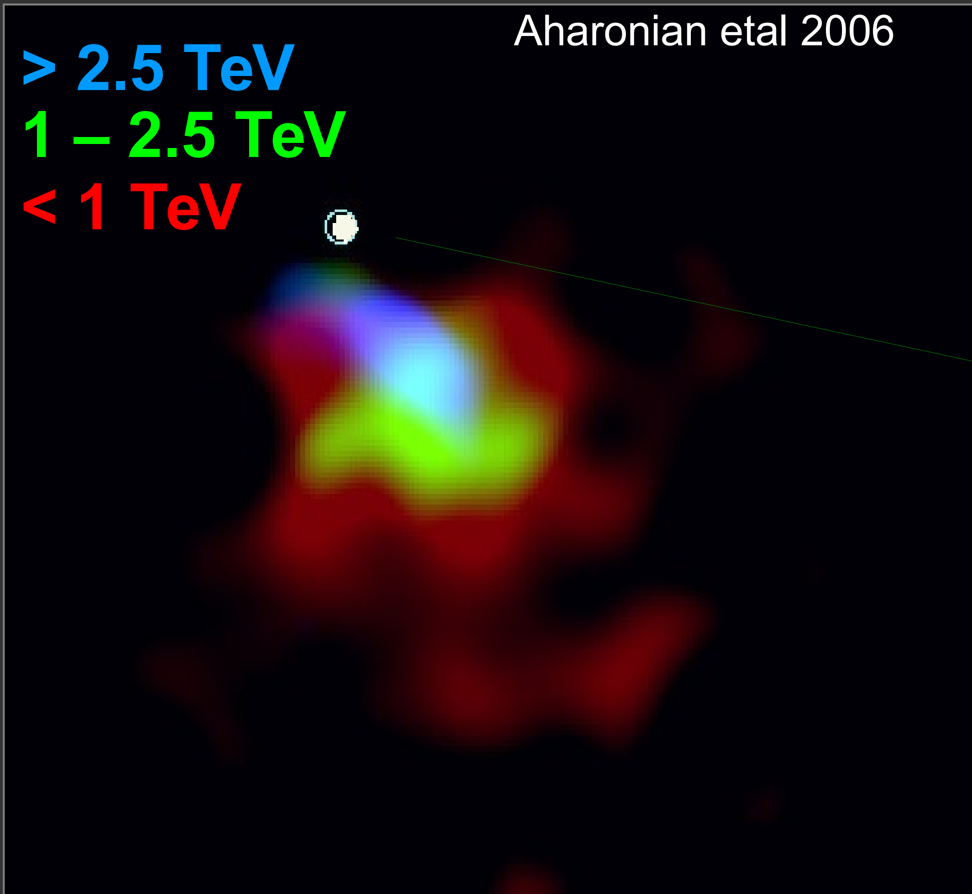
Pulsar Wind Nebulae (PWNe)

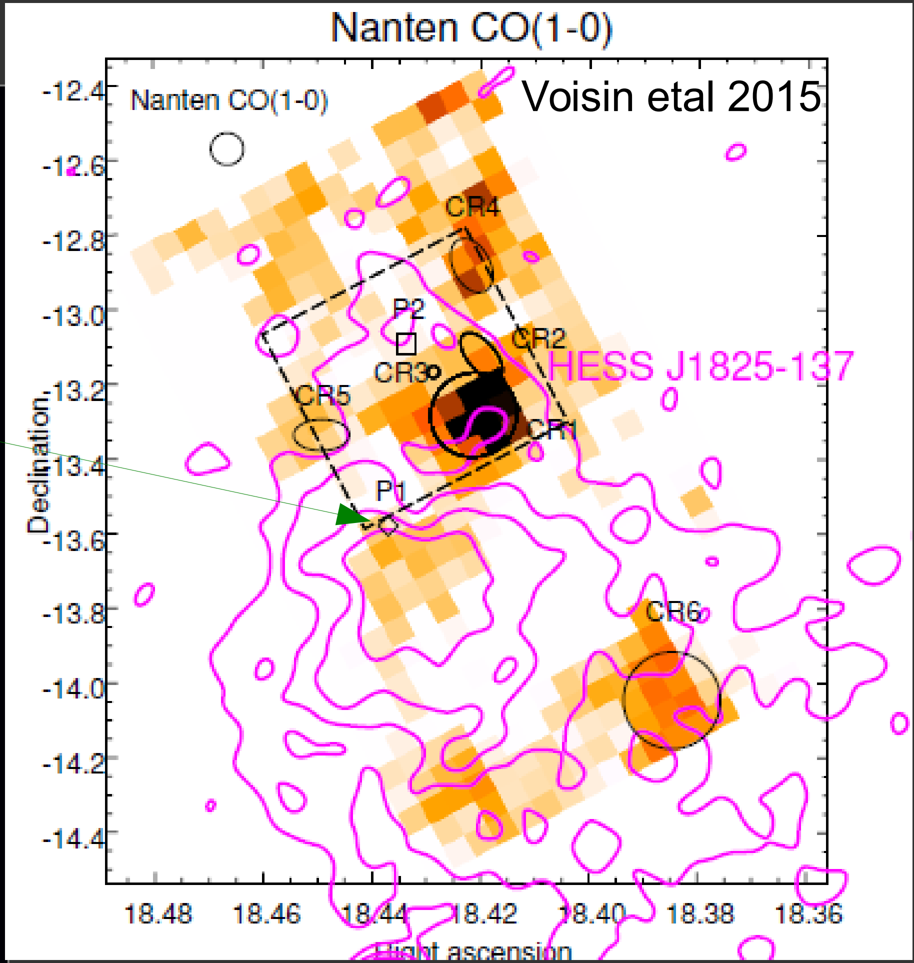


PWN HESS J1825-137

Energy-resolved morphology → particles are electrons (+ HESSJ1303-631)

Dense molecular cloud to north



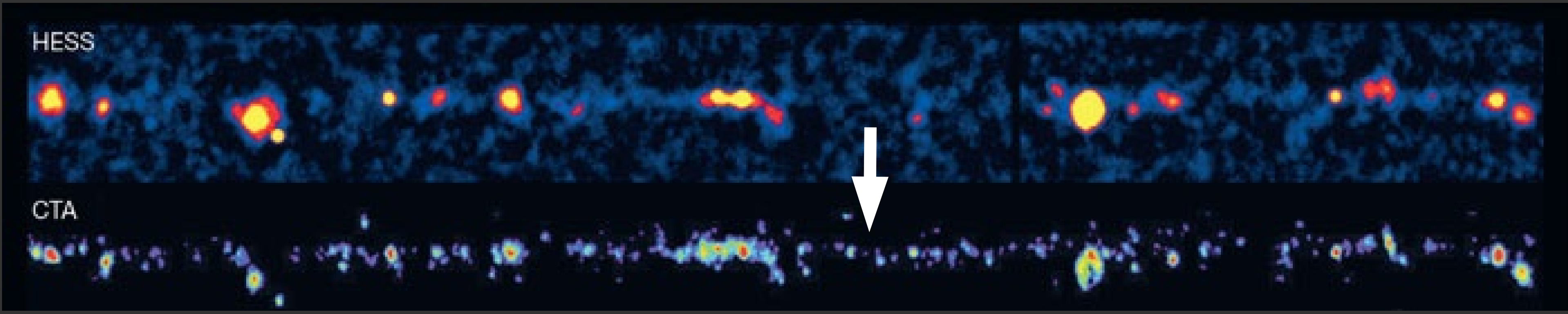


TeV spectral evolution consistent with electron origin : Synchrotron & IC cooling vs. distance from pulsar!

Can search for hadronic pulsar winds !

(Hoshino etal 1992, Gallant etal 1994, Amato etal 2003, Horns etal 2007)

Galactic Plane TeV Surveys : HESS → CTA

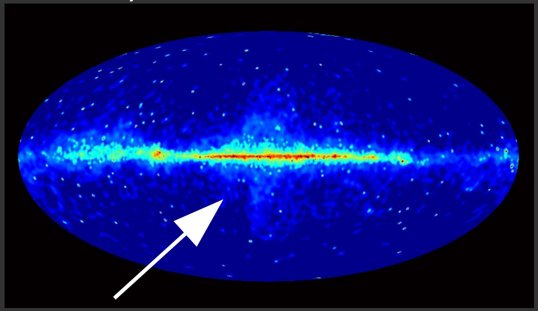


Funk et al 2012

- CTA will provide Galactic Plane TeV Gamma-ray maps
  on ~1-3 arc-min scales
  (~0.5 arc-min possible – high quality cuts)

- >3 sources per deg^2 |b|<0.2° |l|<30° (Dubus etal 2013)

- Diffuse TeV components visible?
  from CR 'sea' – maybe
  local CR accelerator enhancements – yes

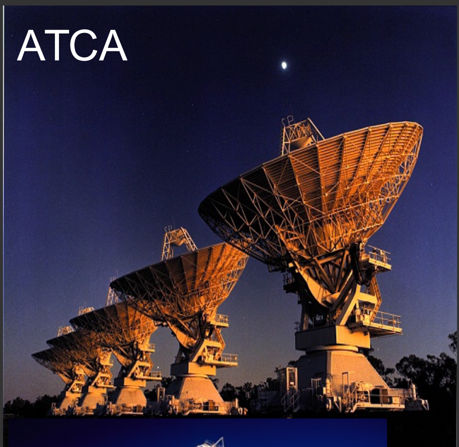


Confusion guaranteed (same as for Fermi-LAT at GeV energies!)

- Mapping the ISM on arc-min scales over the plane will be essential
Mopra (CO, CS), Nanten2 (CO), ASKAP (HI, OH), THz (CI, C+)

We need to map the interstellar gas to discriminate hadronic vs. leptonic gamma-rays!

HI (atomic H), OH	CO	CO, NH_3, CS, SiO...
Gas density $\sim 10^{1\text{ to }2}$ cm^{-3}	$\sim 10^{3}$ cm^{-3}	$>10^{3\text{ to }4}$ cm^{-3}



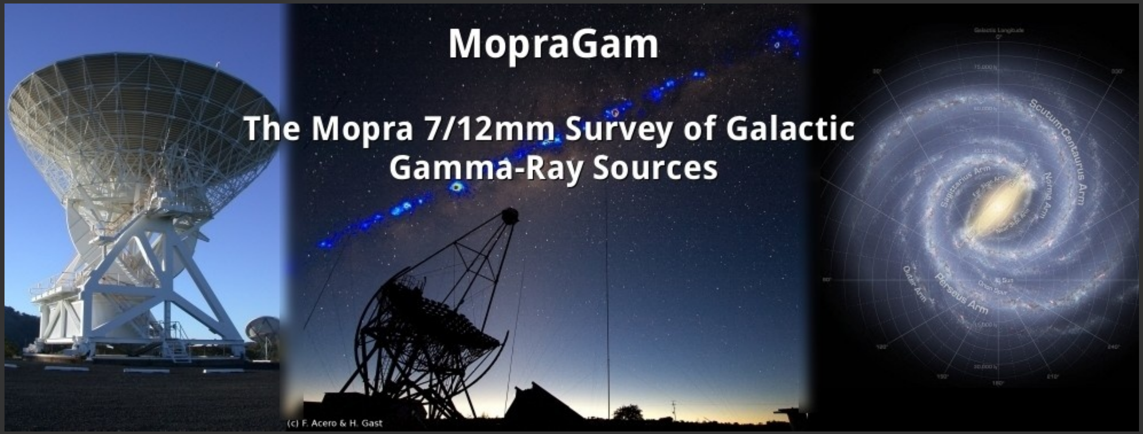
CSIRO

NANTEN
Submillimeter Observatory
なんてん電波天文台

HEAT – THz telescope (Antarctica) [CI] + [CII]
→ tracing the complete C budget!

Mopra Telescope

CSIRO



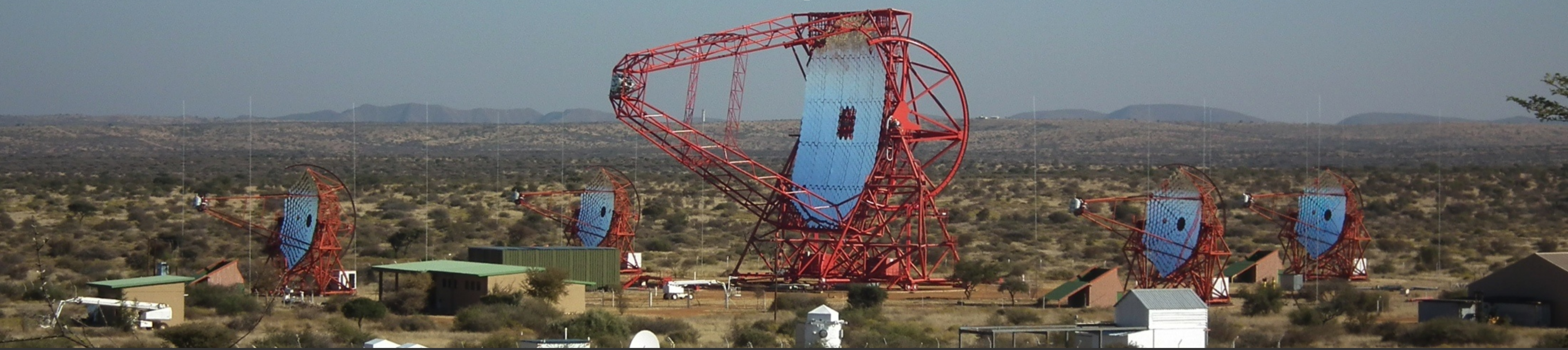
http://www.physics.adelaide.edu.au/astrophysics/MopraGam/

<u>Team Members</u>
Gavin Rowell (lead, Adelaide), Michael Burton (UNSW), Yasuo Fukui (Nagoy), Bruce Dawson (Adelaide), Andrew Walsh (Curtin), Felix Aharonian (DIAS/MPIK), Stefan Ohm (Leicester)
Adelaide PhD students: Brent Nicholas (now at DSTO), Nigel Maxted (now at Montpellier), Phoebe de Wilt, Jarryd Hawkes, Fabien Voisin, Jame Lau, Rebecca Blackwell, Stephanie Pointon (MPhil student).

<u>Targets</u>
Since 2012 observed over ~40 TeV gamma and high energy sources, > 1500 hrs.

<u>Student Projects</u>
Phoebe deWilt – ISM survey of unidentified TeV sources, TeV+HII regions
Jarryd Hawkes – Outflow sources (e.g. XRBs) and magnetars
Fabien Voisin – Pulsar Wind Nebulae
James Lau – SNR/MC associations / G328 filament
Rebecca Blackwell – CMZ
Stephanie Pointon – Two bright unidentified TeV sources

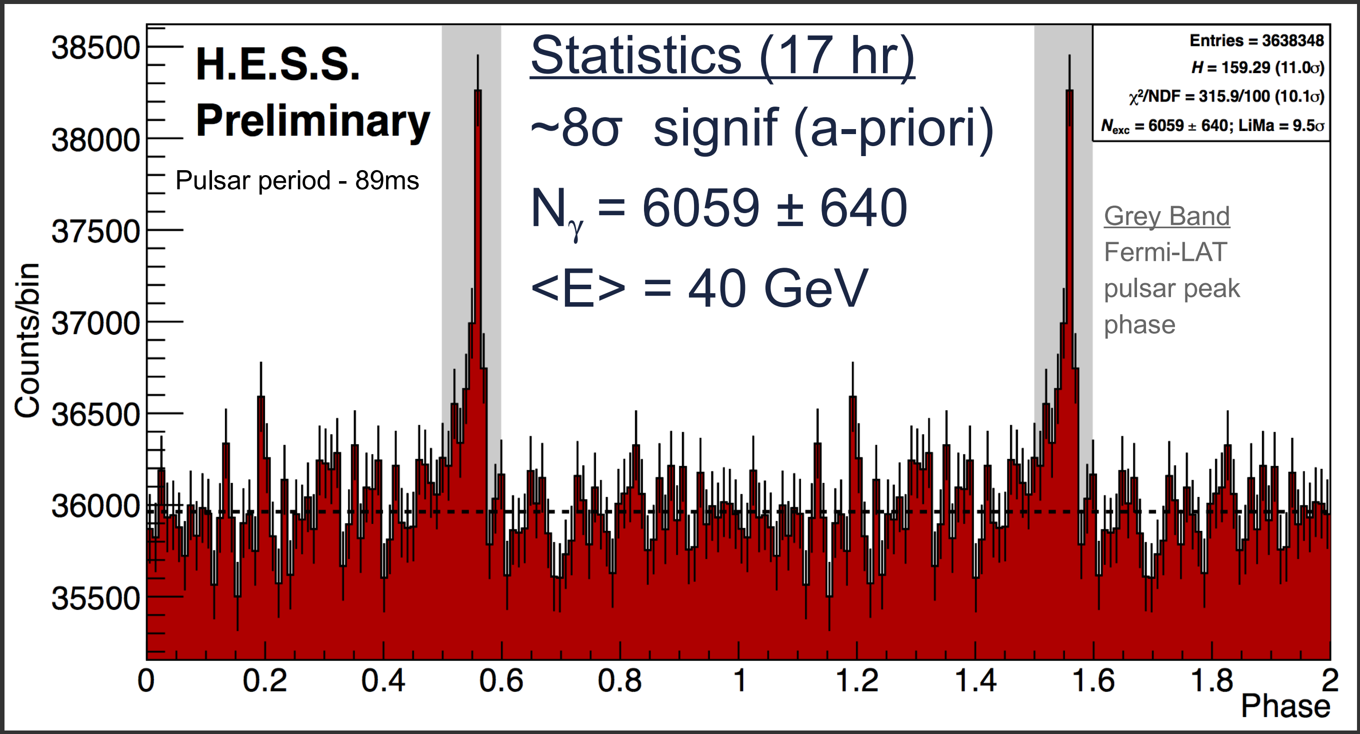
First Results from HESS phase II



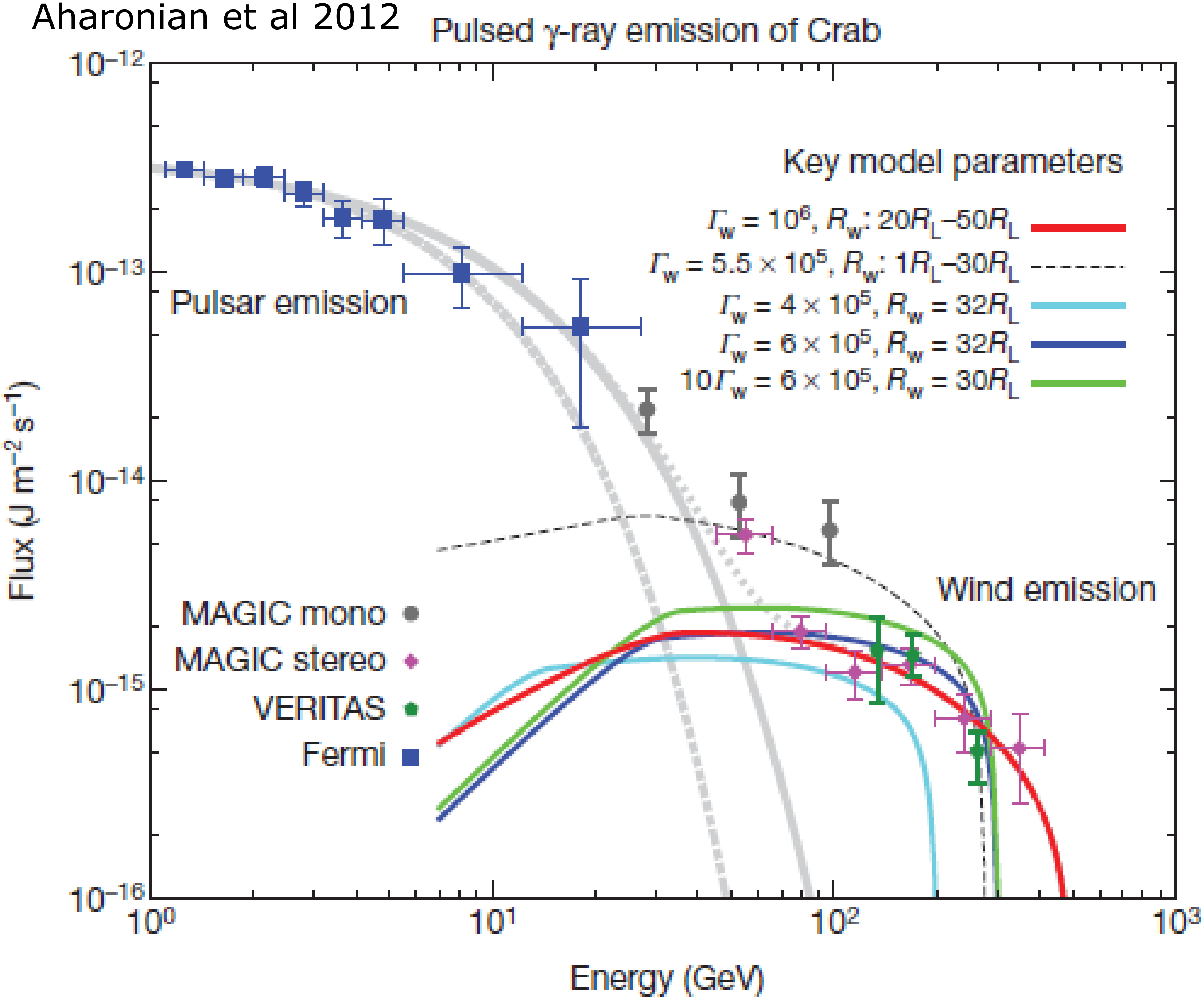
First "Mono" Results from New 28metre Telescope

~30 GeV threshold

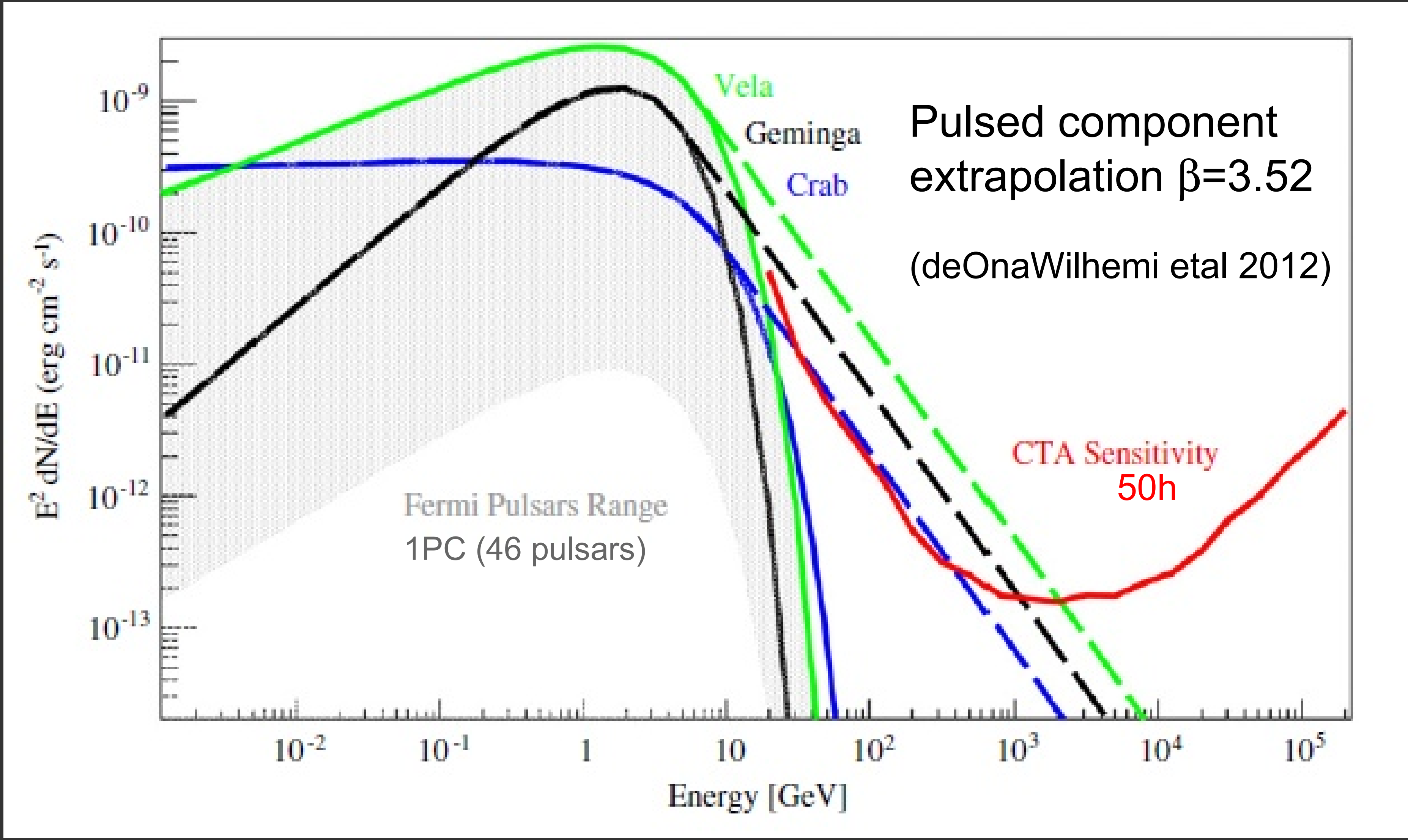
Vela Pulsar: 1st Detection of pulsed Gammas from the Ground



Aharonian et al 2012



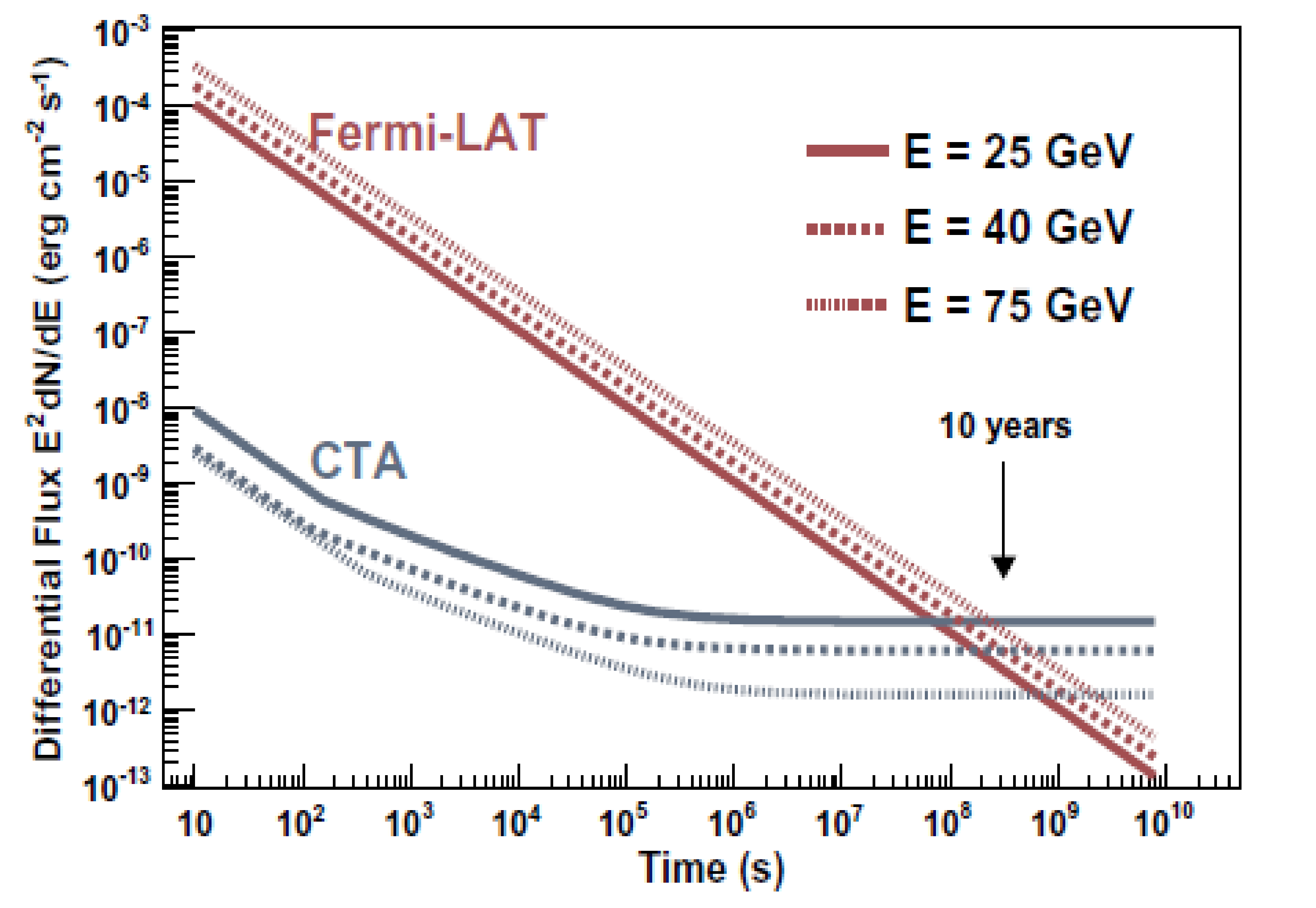
CTA : Prospects for pulsed emission studies



Assume Crab-like power law extension

→ ~40% of Fermi 1PC pulsars potentially detectable

CTA Sensitivity vs. Time (HESS-II is similar!) Funk etal



CTA (& HESS-II) >1000 times more sensitive than Fermi-LAT

→ GRBs, giant pulses, PWNe variability, FRBs, SGR bursts


Thank you..
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