GALACTIC PHYSICS WITH CTA

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THE NEXT GENERATION: CTA

GALACTIC PHYSICS: CORE THEMES

THEME 1

Understanding the origin and role of relativistic cosmic particles

What are the sites of high-energy particle acceleration in the Galaxy?

What are the mechanisms for cosmic particle acceleration?

What role do accelerated particles play in feedback on star formation?

THEME 2

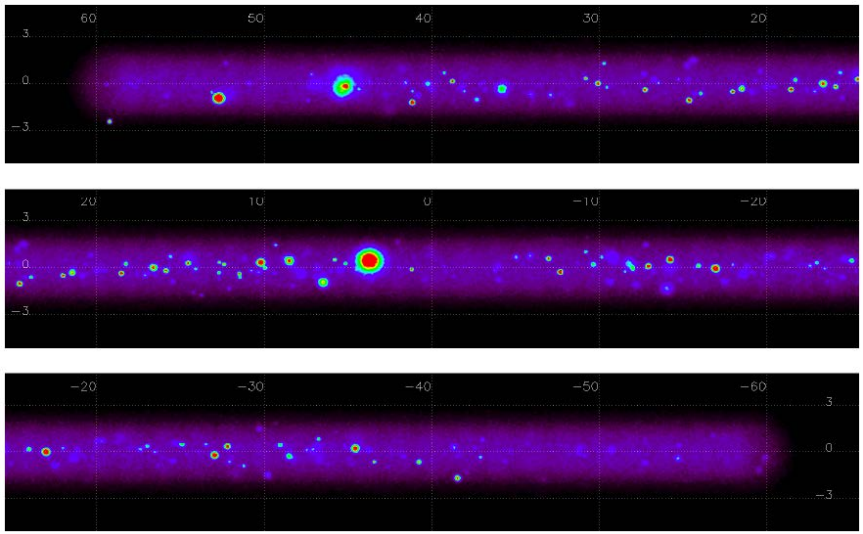
Probing extreme environments

What physical processes are at work close to neutron stars and black holes?

What are the characteristics of relativistic jets, winds, and explosions?

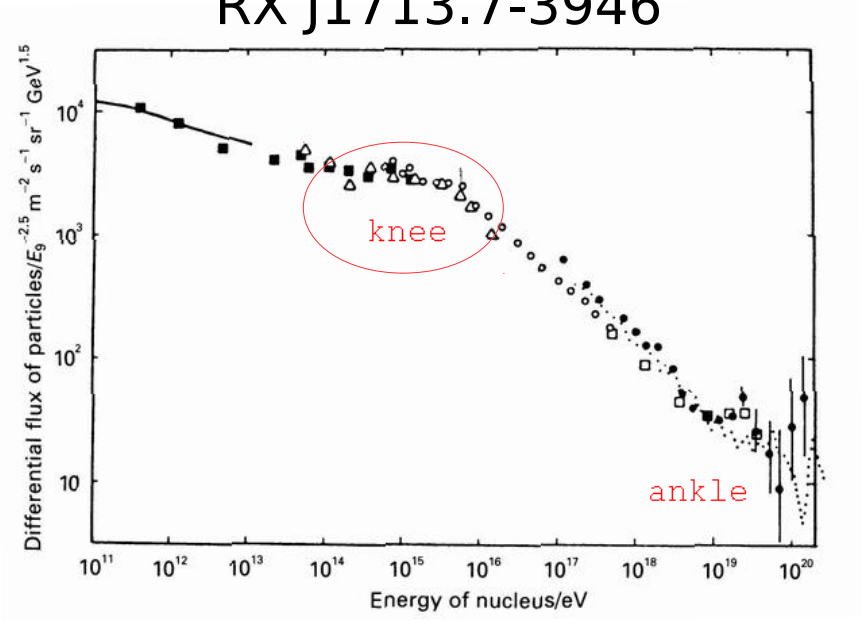
GALACTIC KEY SCIENCE PROGRAMS

Galactic Plane Survey



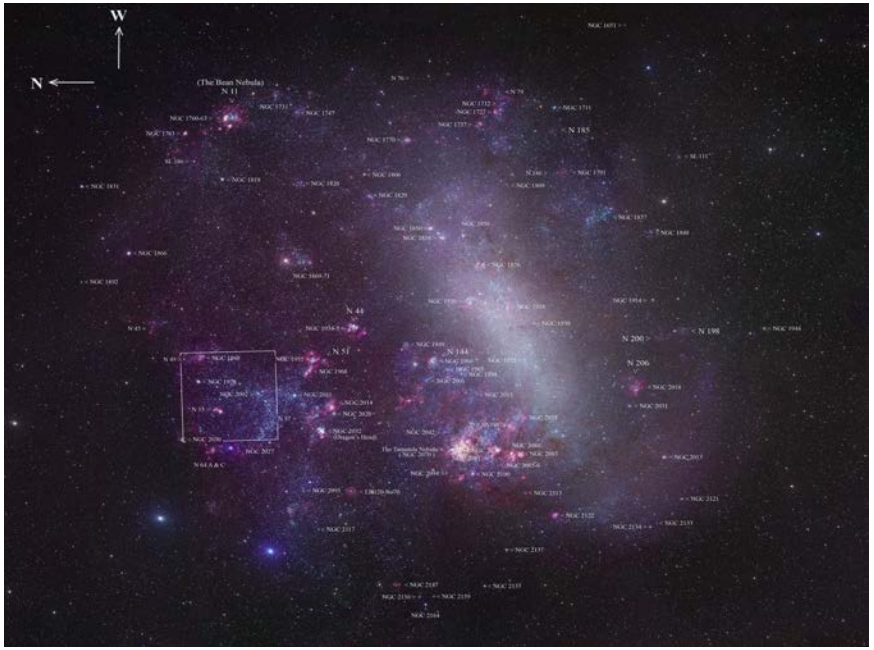
Dubus+ (CTA) 13

Cosmic-ray PeVatrons / Supernova remnant RX J1713.7-3946

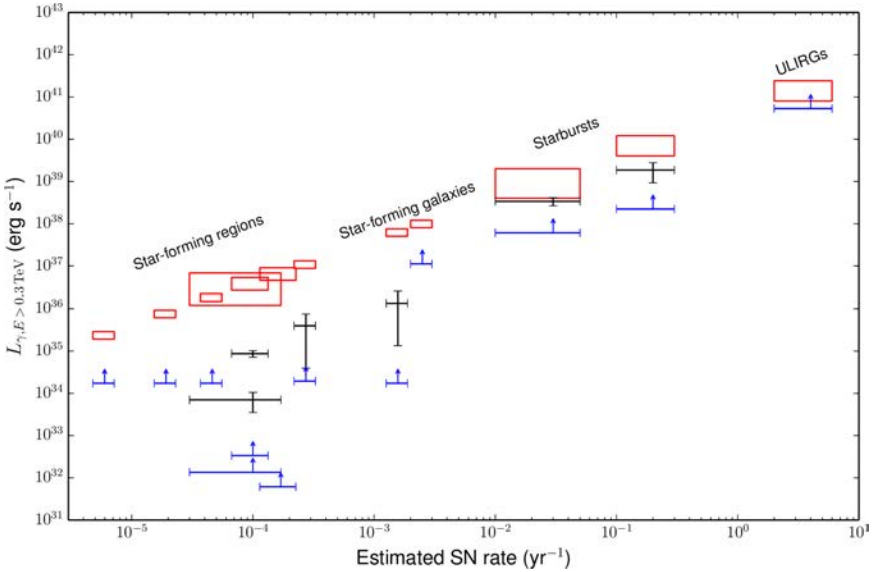


GALACTIC KEY SCIENCE PROGRAMS

Large Magellanic Cloud

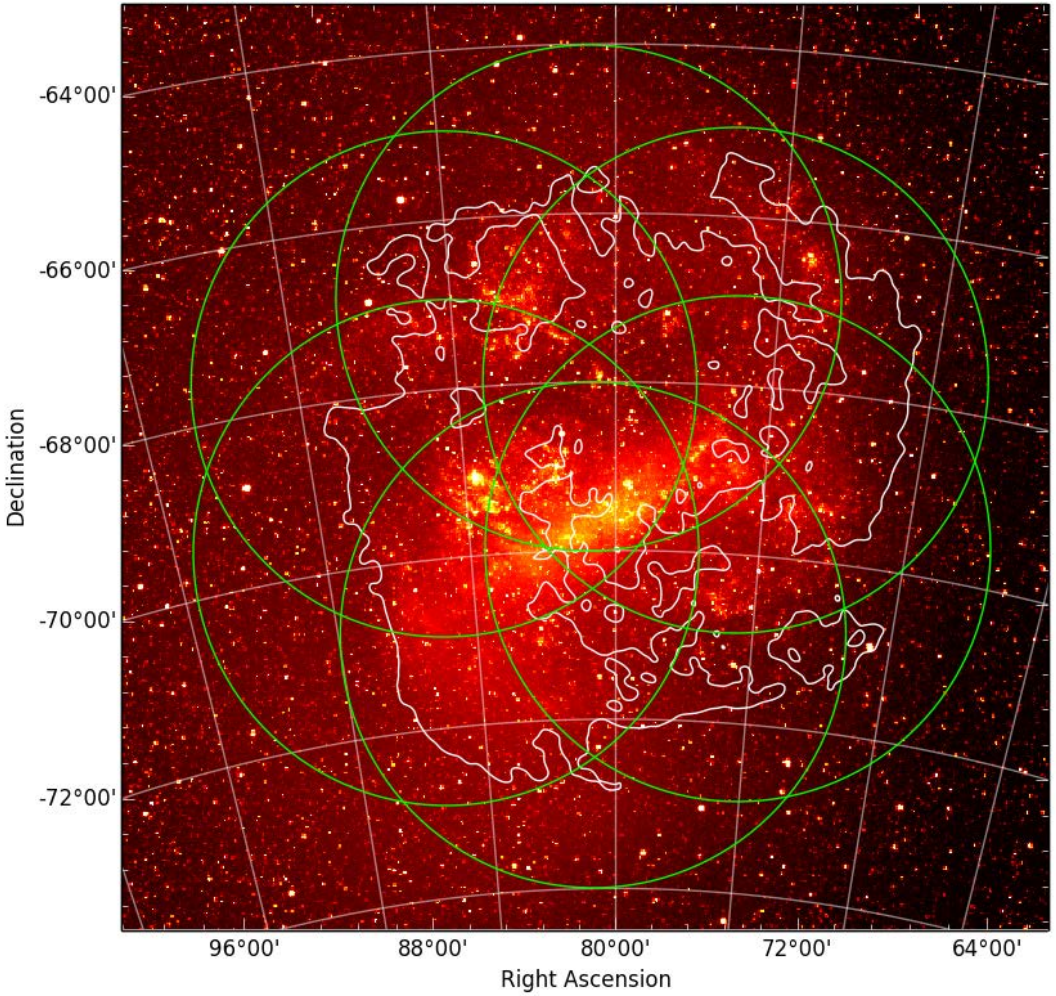


Star Forming Systems



Credit: R. Gendler

LMC



N.B. Advantage of large CTA FoV

A unique target to study extreme Galactic-type VHE sources & diffuse emission (CRs)

Face-on satellite galaxy:
- No source confusion
- Relatively nearby, and no distance ambiguity

Very active:
- Only 1% mass of the Milky Way
- Yet 10% the SFR

Potential pointing pattern overlaid on starry sky image

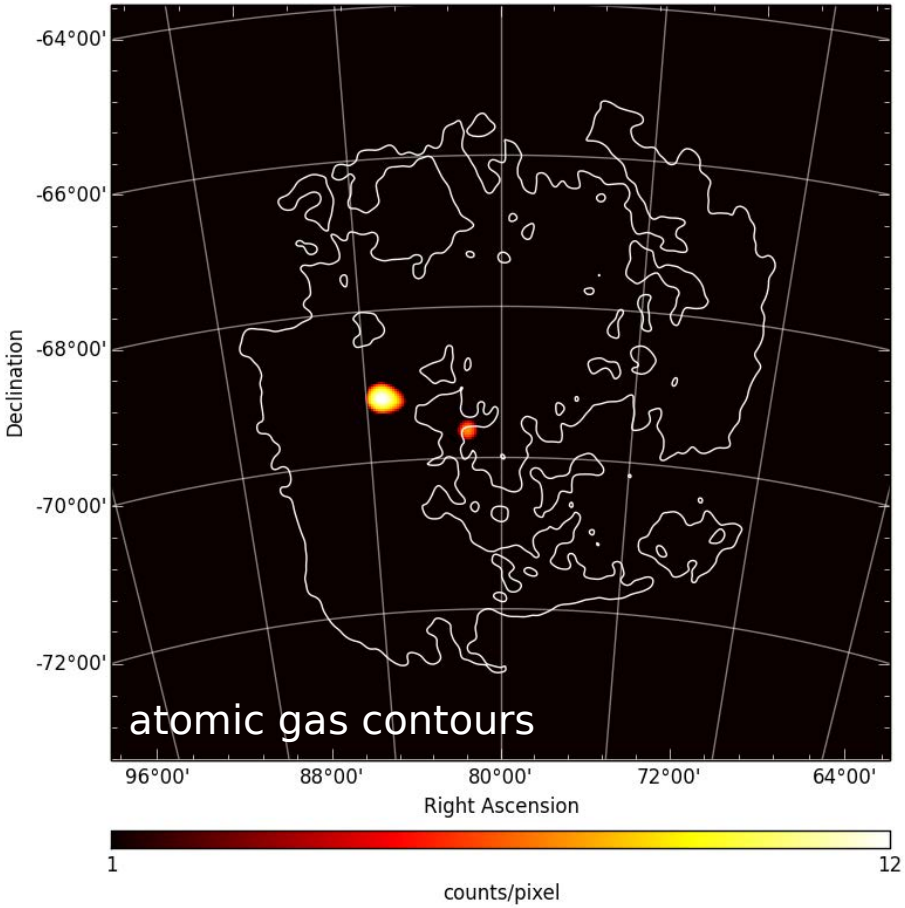
LMC SIMULATIONS

Include:

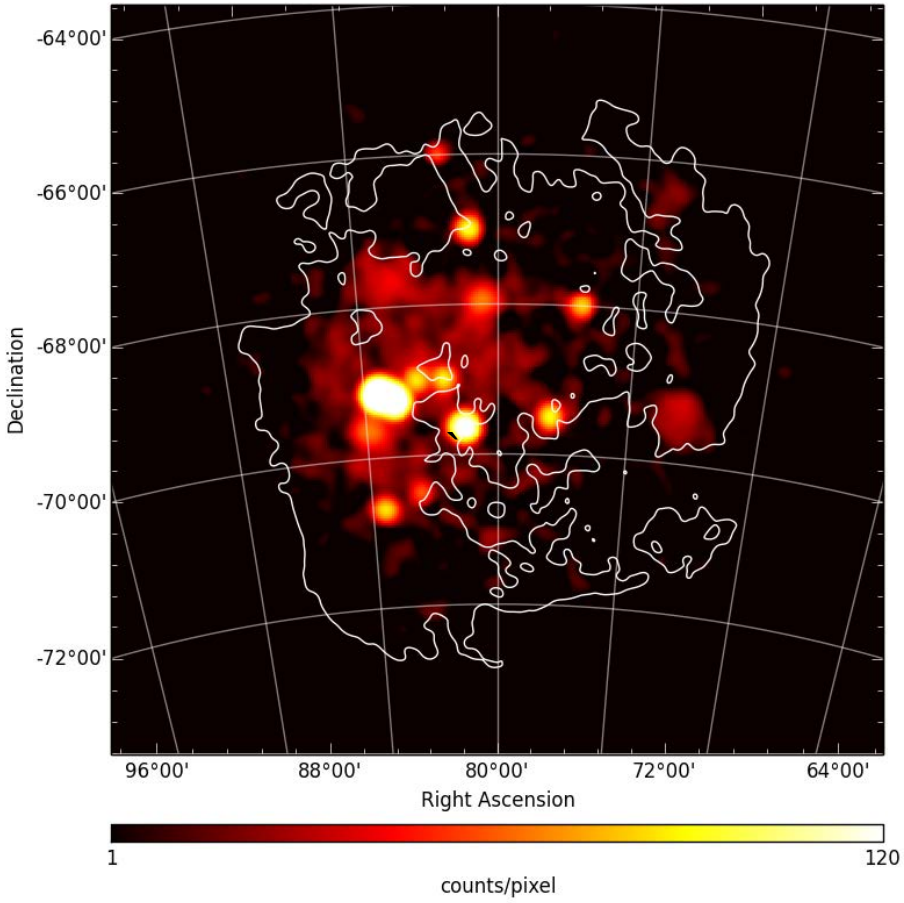
- known VHE sources
  - N 157B: most energetic pulsar, ~10^{38} erg/s
  - 30 Dor C: superbubble
  - N 132D: radio-loud SNR (50% L_{radio} Cas A)
- luminous point-like sources
- CR-enriched regions
- Youngest SNR: SN 1987A

LMC SIMULATIONS

H.E.S.S.-like performance
1 pointing, 16 h, 0.8-100 TeV



CTA performance
6 pointings, 340 h, 0.2-100 TeV



STAR FORMATION & COSMIC RAYS

Key science questions:

What is the impact of CRs on the ISM & how do they propagate?

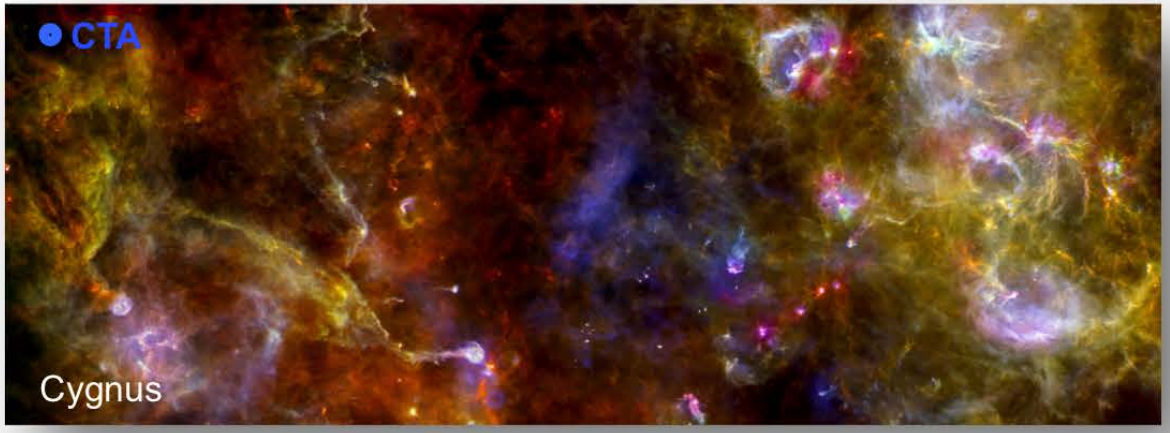
What is the relationship between star formation & particle acceleration in systems on different scales?

Motivated also by:

- well-established correlation in FIR
- correlation seen recently in GeV γ-rays

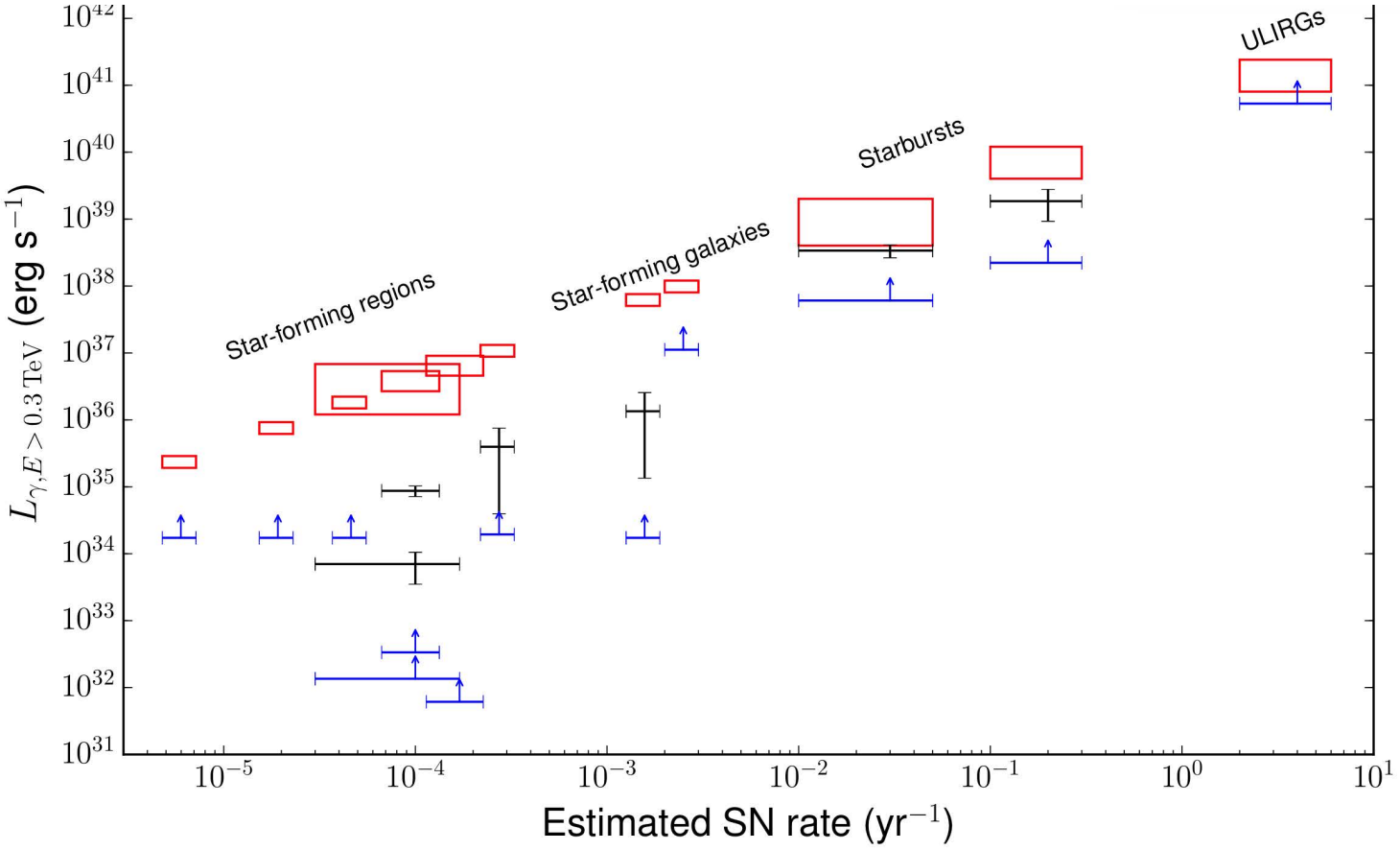
GALACTIC STAR FORMING SYSTEMS

Cygnus & Carina regions will be mapped at high resolution



TESTING UNIVERSAL RELATIONS

Complementary Galactic and extragalactic science

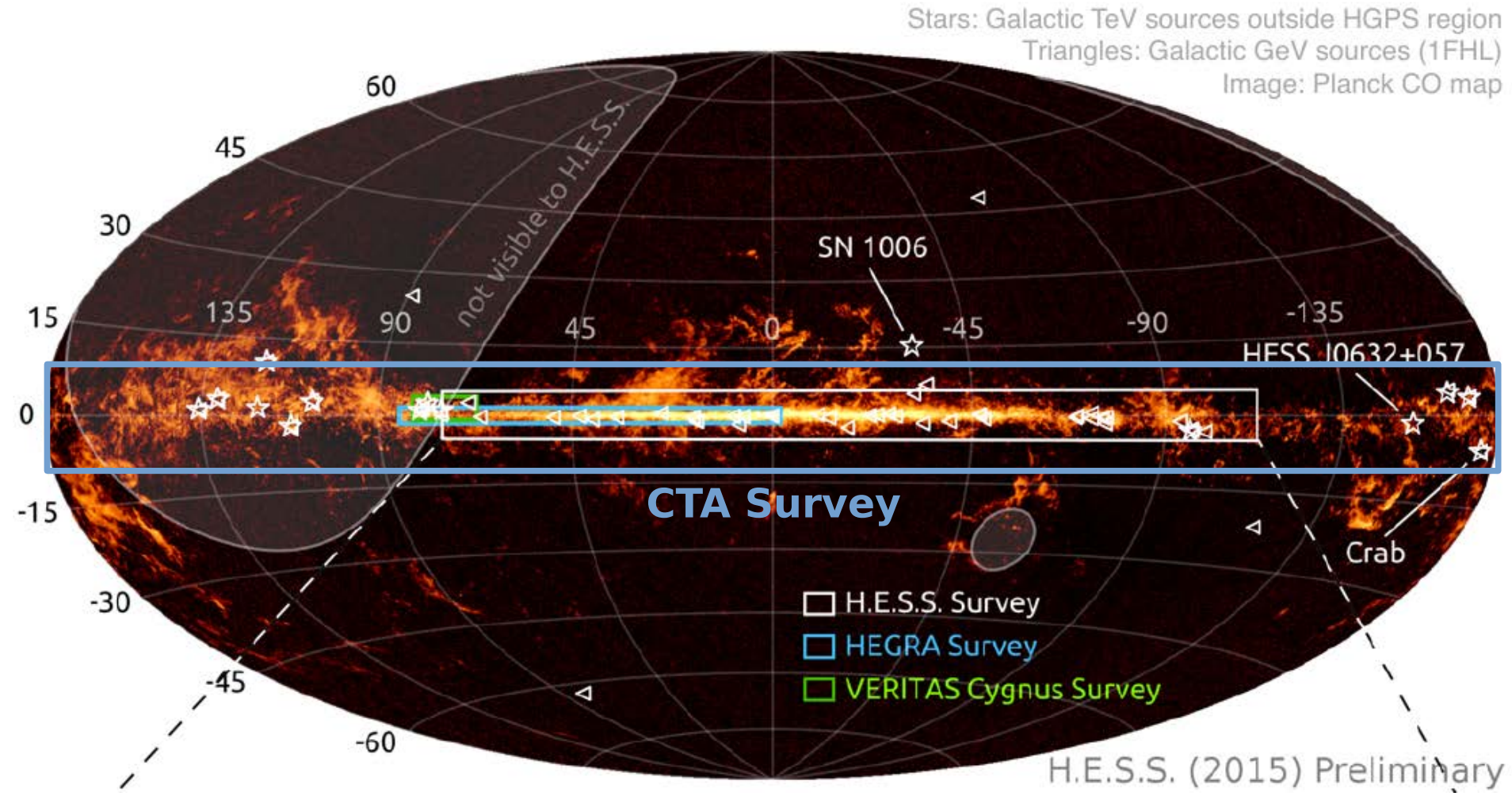


Estimated calorimetric gamma-ray flux

Estimated CTA sensitivity

Current detections

GPS IN CONTEXT



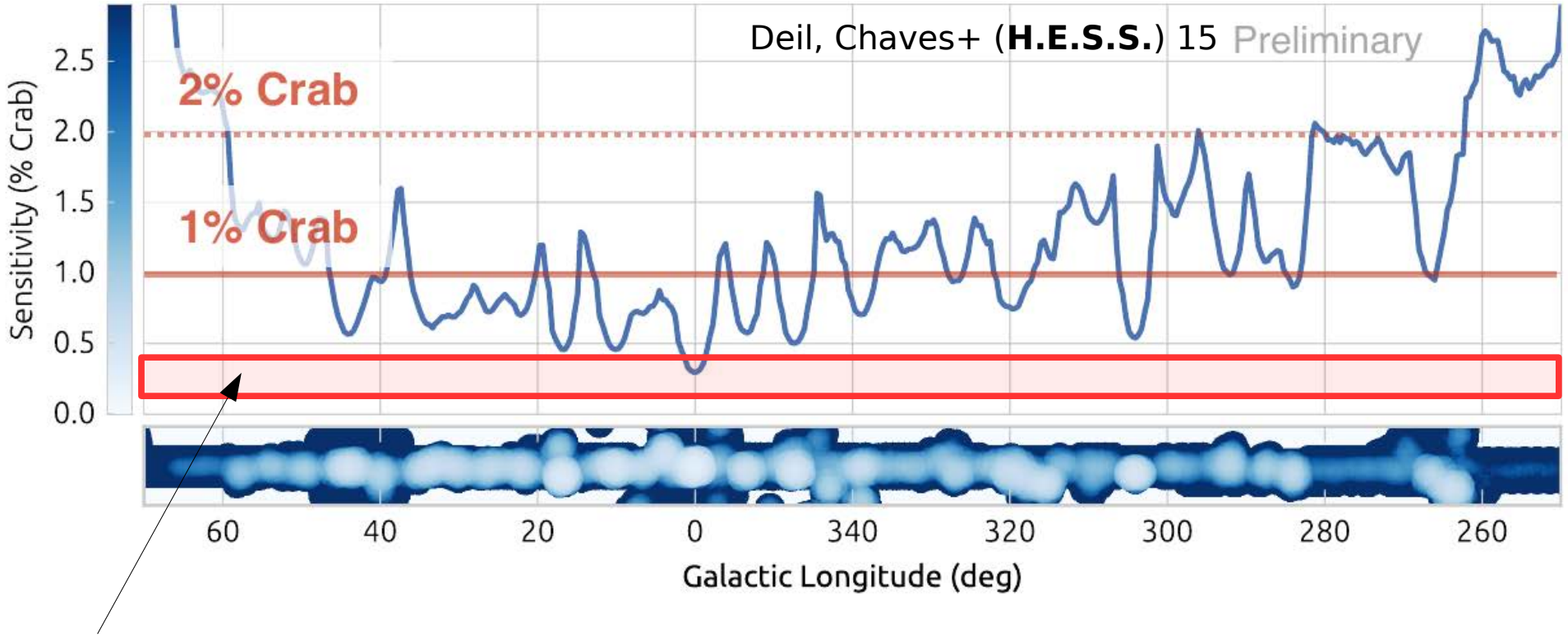
GPS IN CONTEXT

Experiment	Hemisphere	Galactic Plane Coverage	Energy (GeV)	Sensitivity (mCrab)
H.E.S.S.-I	S	$-70° < l < 60°$, $\|b\| < 2°$	$>\sim 300$	10 – 30
VERITAS	N	$67° < l < 83°$, $-1° < b < 4°$	$>\sim 300$	20 – 30
ARGO-YBJ	N	Northern Sky	> 300	240 – 1000
HEGRA	N	$-2° < l < 85°$, $\|b\| < 1°$	> 600	150 – 250
Milagro	N	Northern Sky	$> 10,000$	300 – 500

Observatory	Hemisphere	Energy Threshold	Angular Resolution	Pt. Source Sensitivity
CTA	N, S	125 GeV	$\sim 0.10°$ at 300 GeV	2 – 4 mCrab
HAWC	N	2 TeV	0.30°	20 mCrab

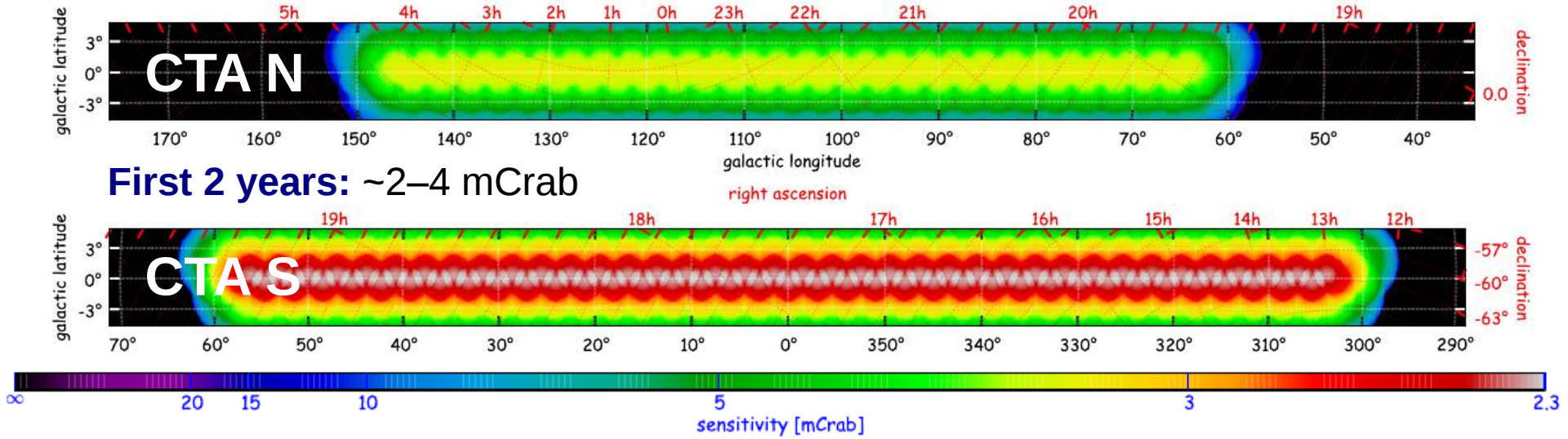
	STP (Years 1 – 2)		LTP (Years 3 – 10)	Total (Years 1 – 10)	
Galactic Longitude	**Hours**	**Sensitivity**	**Hours**	**Hours**	**Sensitivity**
SOUTH					
300° – 60° , Inner region	300	**2.7 mCrab**	480	780	**1.8 mCrab**
240° – 300° , Vela, Carina			180	180	**2.6 mCrab**
210° – 240°			60	60	**3.1 mCrab**
				1020	
NORTH					
60° – 150° , Cygnus, Perseus	180	**4.2 mCrab**	270	450	**2.7 mCrab**
150° – 210° , Anti-center, etc.			150	150	**3.8 mCrab**
				600	

GPS IN CONTEXT



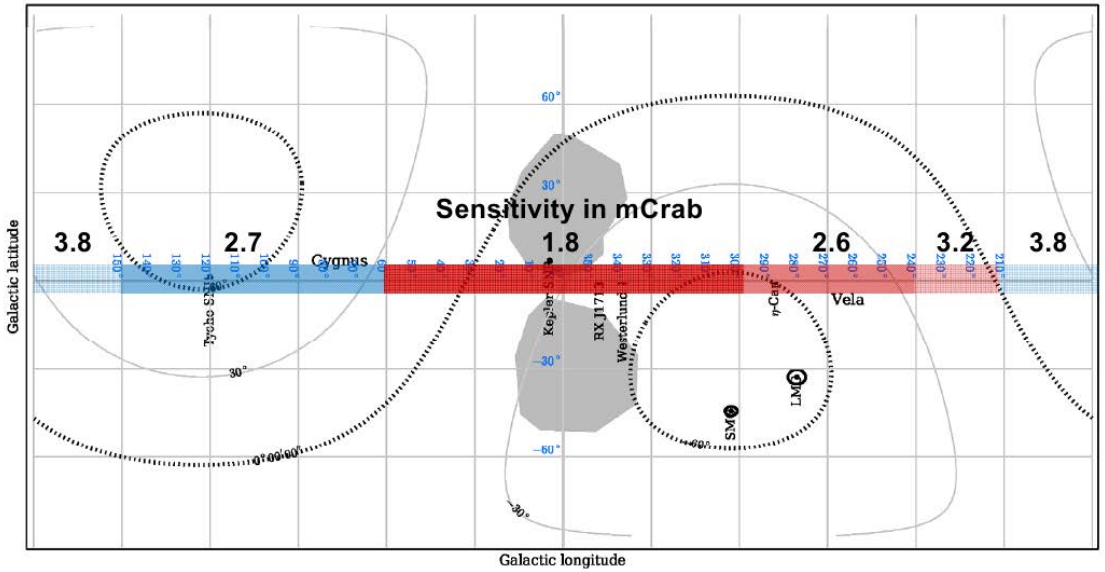
~mCrab and uniform sensitivity with CTA GPS in just 2 years

GRADED SENSITIVITY APPROACH



First 2 years: ~2–4 mCrab

10-yr program



GPS OBJECTIVES

Increase population of known Galactic VHE sources x 3–9+

Discover new VHE source classes and unexpected phenomena

Search for Galatic CR PeVatrons

Measure large-scale diffuse emission

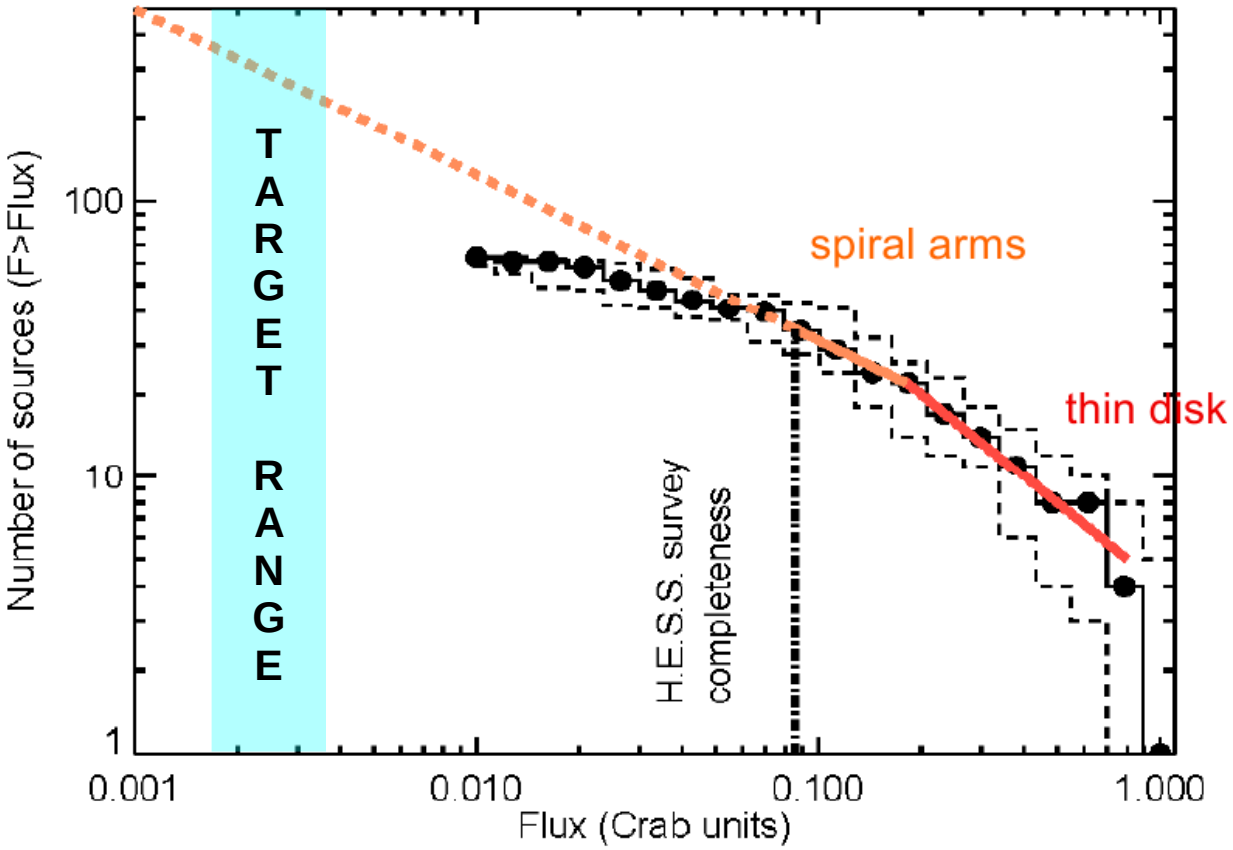
Detect new γ-ray binaries & other variable or transient sources

Provide first-look science data to other KSPs & General Observers

Produce a multi-purpose legacy dataset to MWL community

SOURCE POPULATION

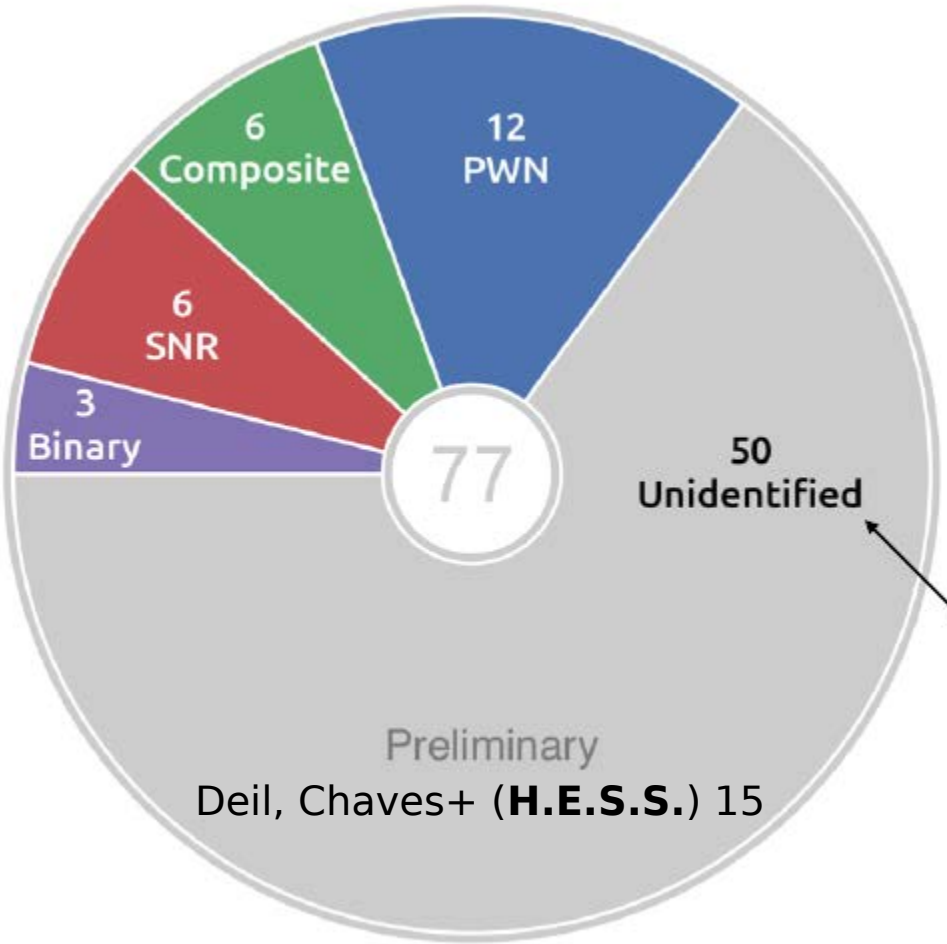
Increase population of known Galactic VHE sources x 3–9++



log N – log S plot
Renaud+09

NEW SOURCE CLASSES

Discover new VHE source classes and unexpected phenomena

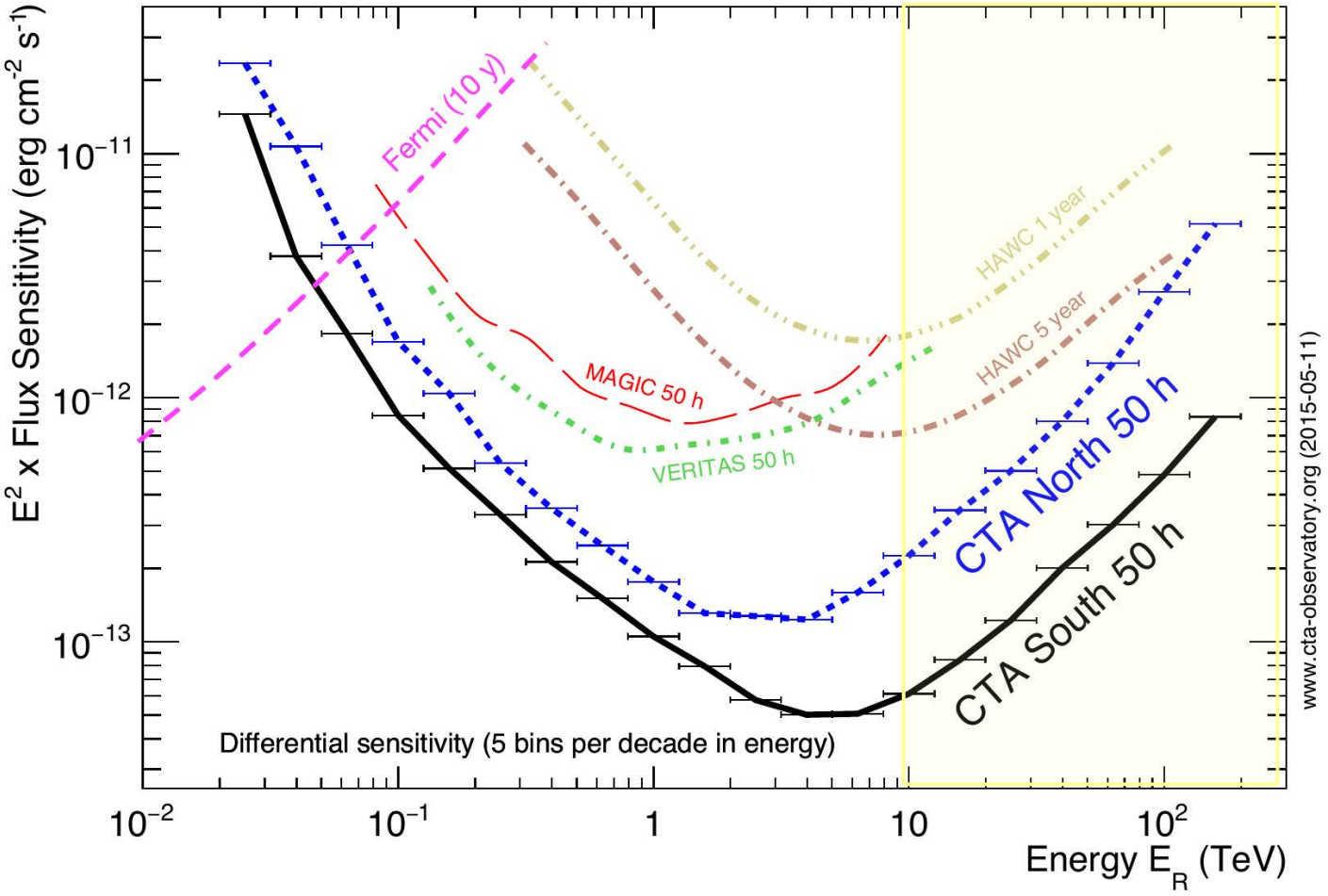


CTA discovery space

Mostly sources with multiple associations

PEVATRON SEARCH

Search for Galatic CR PeVatrons



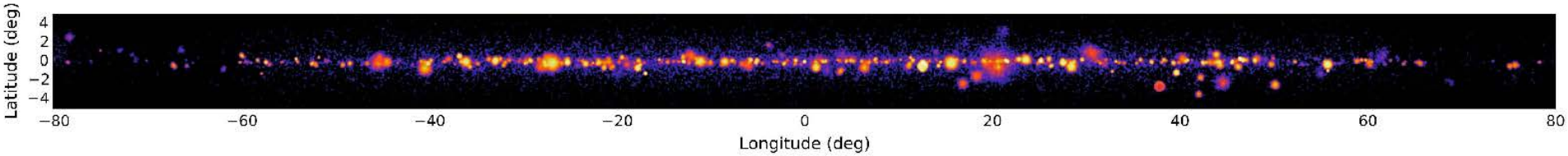
CTA South

SSTs further improve multi-TeV sensitivity

+

Access to inner Galaxy

GPS SIMULATIONS



Source populations modeled:

- Both **SNRs & PWNe**
- Fitted to known detections (TeVCat)

Expected diffuse emission: Both IC & π^0 components (GALPROP)

Energy range: 1-10 TeV

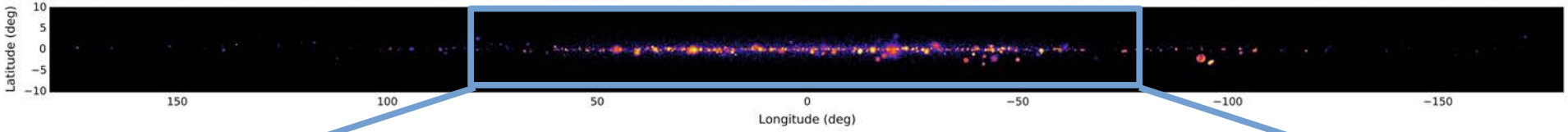
`ctools` open-source software with latest IRFs for North & South arrays

Actual GPS observation scheme (**1620 h**)

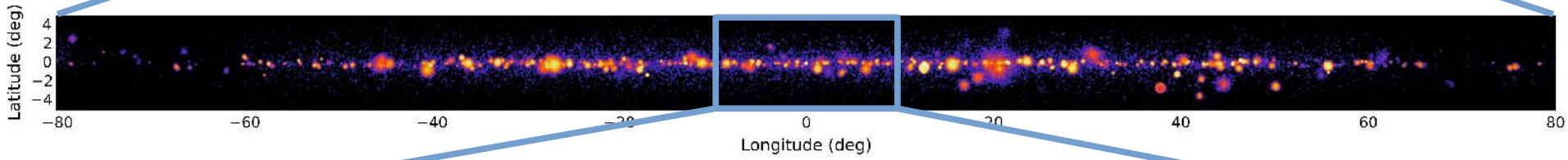
Most realistic simulations to date & work on-going

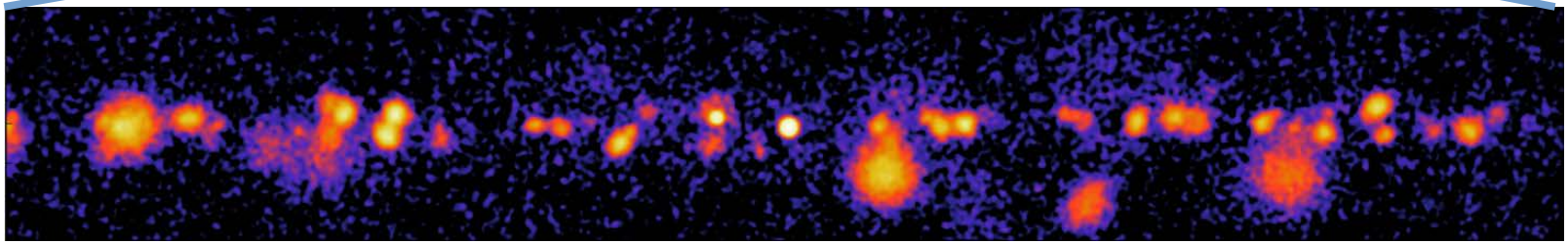
GPS SIMULATIONS

Full-plane coverage: longitude ± 180°, latitude b ± 10°



Deeper inner galaxy exposure: ℓ ± 80°

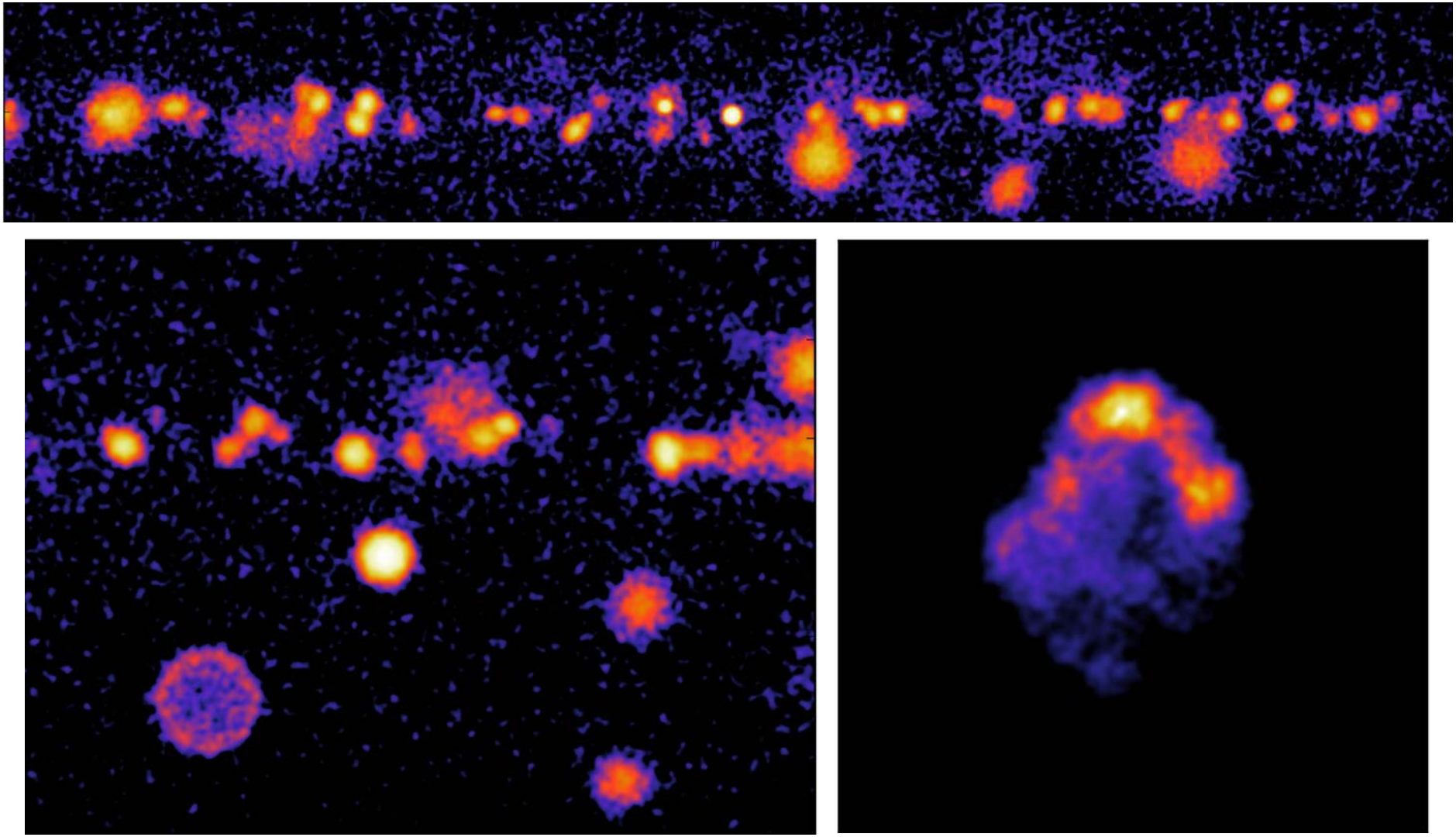




Fine detail revealed with **~arcmin PSF**

Knoedlseder+ (CTA)

GPS SIMULATIONS: ZOOM



CR/PEVATRON OBJECTIVES

Discover Galactic CR PeVatrons responsible for CR knee

Specifically:

Where & how in the Galaxy are CRs accelerated up to PeV energies?

What is the distribution of PeVatrons in the Galaxy?

Are we sitting in a particular location of the Galaxy, or is there a uniform CR sea within the whole Galaxy (understanding diffusion by observing gamma-ray accelerators and their surroundings)?

Do young shell-type SNRs accelerate hadronic CRs up to PeV energies?

If so, up to which energies, and how effective is this acceleration (probing the theory of non-linear DSA)?

WHERE ARE THE PEVATRONS?

One way to get to CR knee (~3 PeV) energies, quite specific:

Young, fast (20,000 km s^{-1}) SNR shock in dense wind (CSM) from a Type II SN & RSG progenitor

e.g. 330-yr-old Cas A, but $\Gamma = 2.6 \pm 0.2_{stat} \pm 0.2_{syst}$

Other historical SNRs are challenging as well, c.f. updated Tycho (SN Ia) spectrum from VERITAS ($\Gamma = 1.95 \pm 0.51_{stat} \pm 0.30_{syst} \rightarrow \Gamma = 2.92 \pm 0.41_{stat}$)

Are PeVatrons short lived?

MHD instability quenched after ~1000 yrs (~age RX J1713), e.g. Schure & Bell 2013

E_{max} ~ PeV for only ~100 yrs or less

Observation strategy for Cherenkov telescopes?

Hidden in the existing data but confused/obscured?

Just need more statistics / better sensitivity at multi-TeV E?

Not looking at the right objects, biased by well-known SNRs? Molecular clouds?

WHERE ARE THE PEVATRONS?

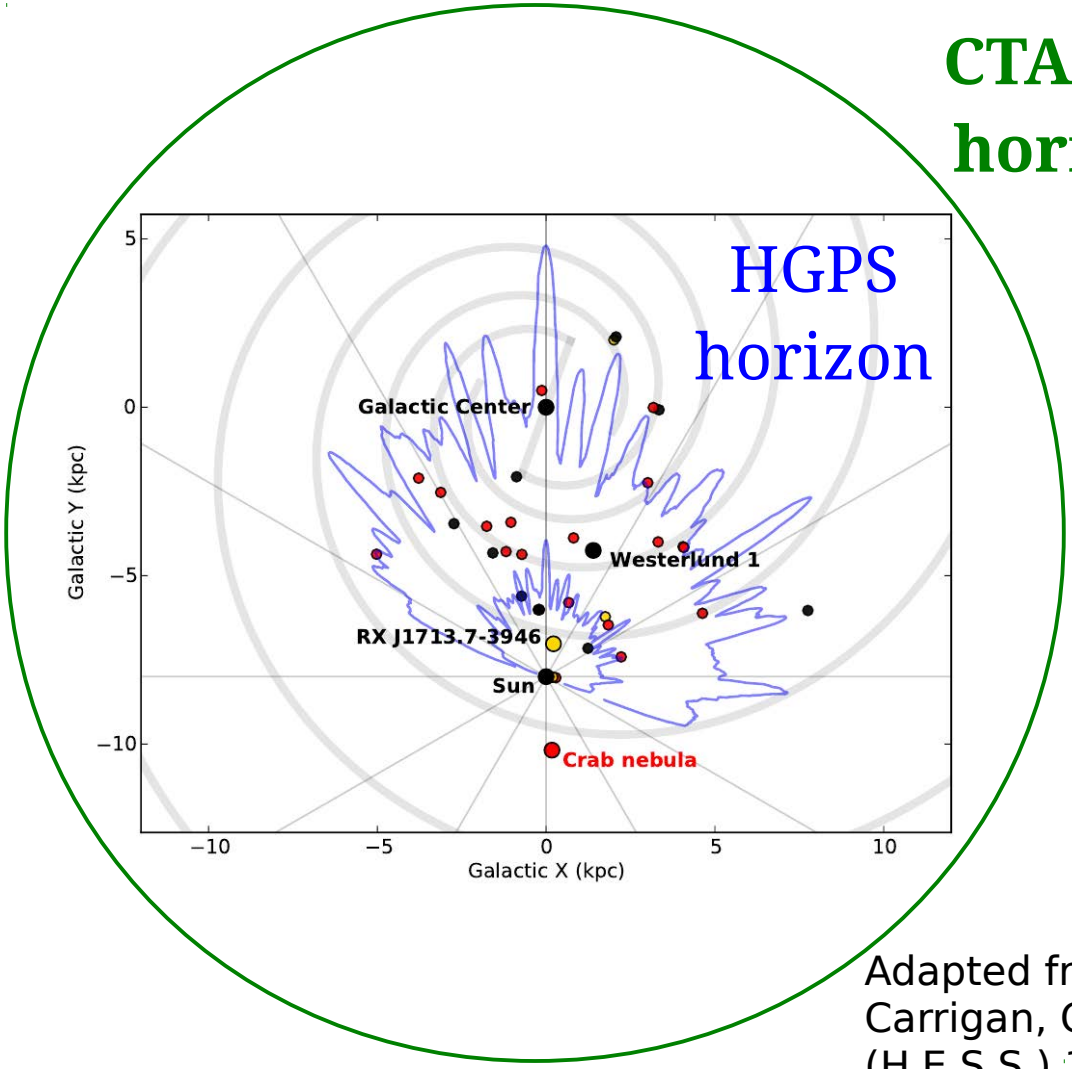
GPS ideal strategy to identify PeVatron candidates

- few mCrab sensitivity along entire plane

- E-range up to hundreds of TeV

- arcmin PSF to reduce source confusion

CTA GPS horizon

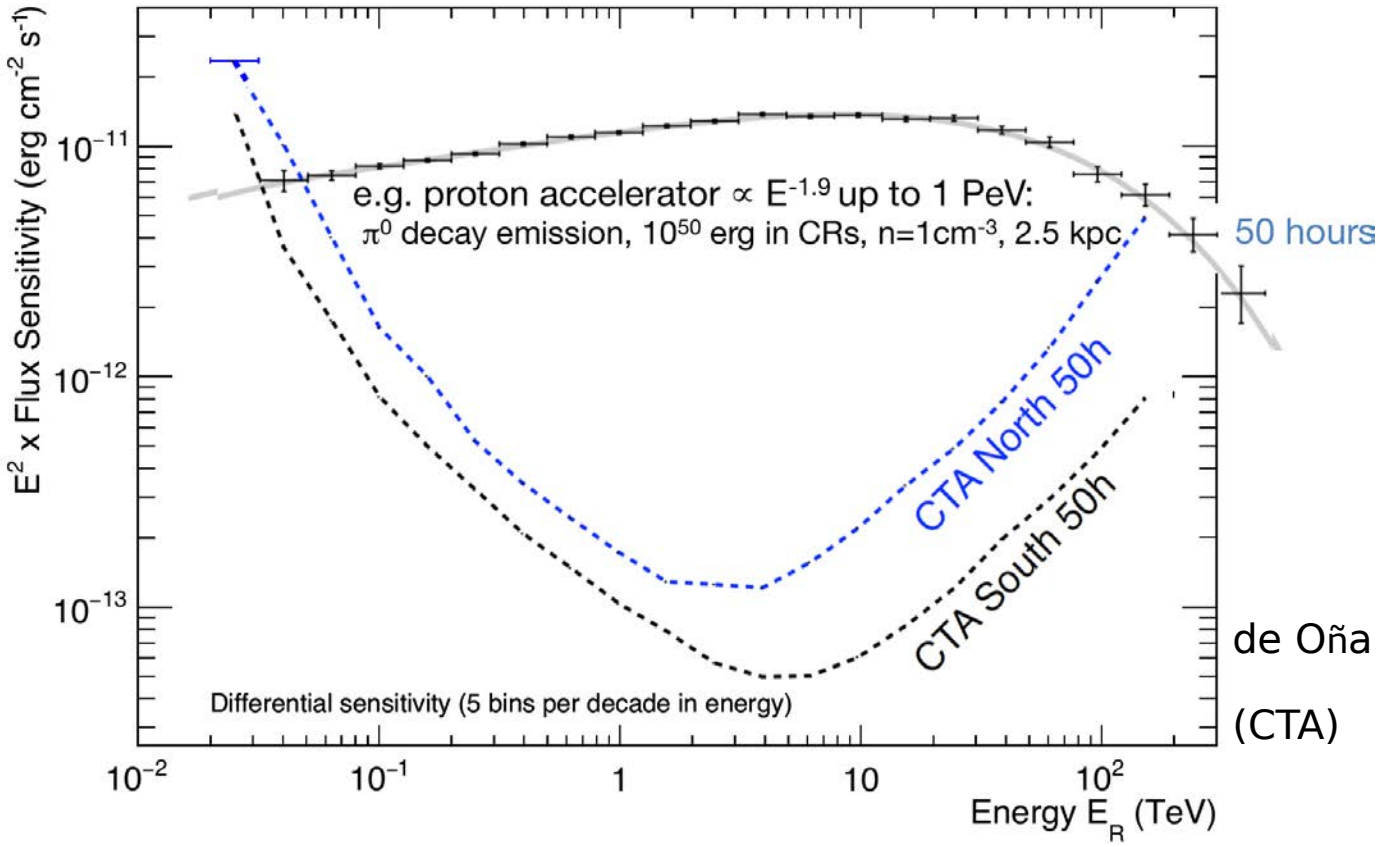


Adapted from Carrigan, Chaves+ (H.E.S.S.) 13

PEVATRON IDENTIFICATION

Specifically, candidates should exhibit:

- No VHE cut-off or break: 3-σ signal above 50 TeV
- Hard photon spectrum: $\Gamma \approx 2.0$

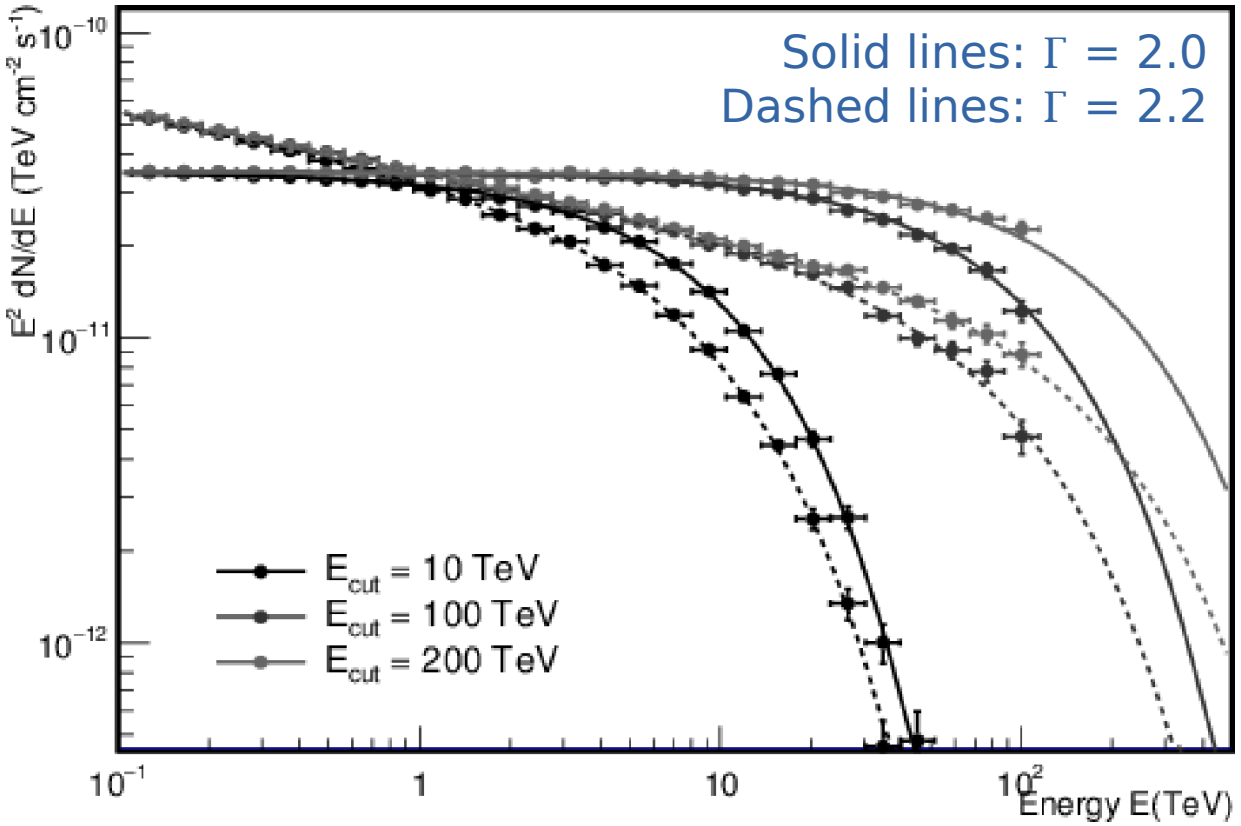


de Oña Wilhelmi+ (CTA)

PEVATRON CHARACTERIZATION

KSP follow-up of top 3 candidates:

+50 h deep observations of each to confirm & measure spectra



CTA simulations

de Oña Wilhelmi+

(CTA)

SNR RX J1713

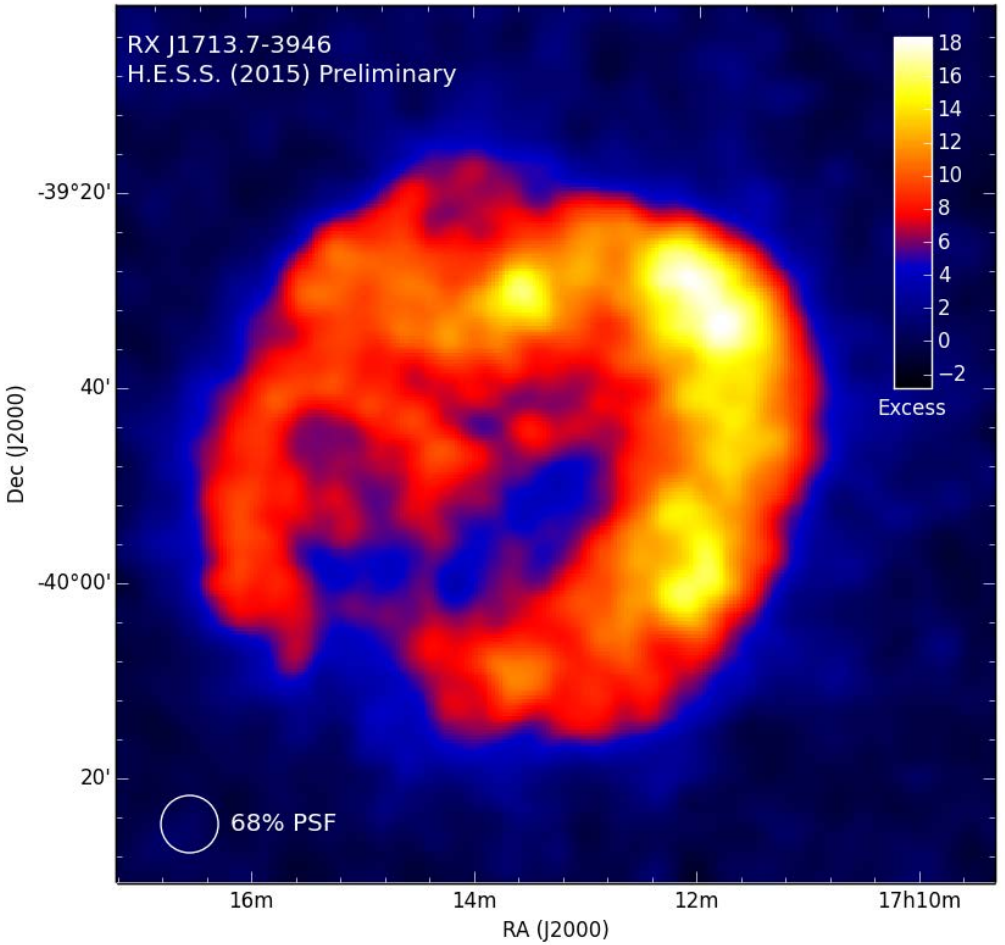
Deeper obs. (+50 h min.) of most prominent γ-ray SNR

To disentangle leptonic / hadronic acceleration

e.g. through precision imaging of shell morphology

To probe surrounding molecular environment (e.g. Gabici & Aharonian 07)

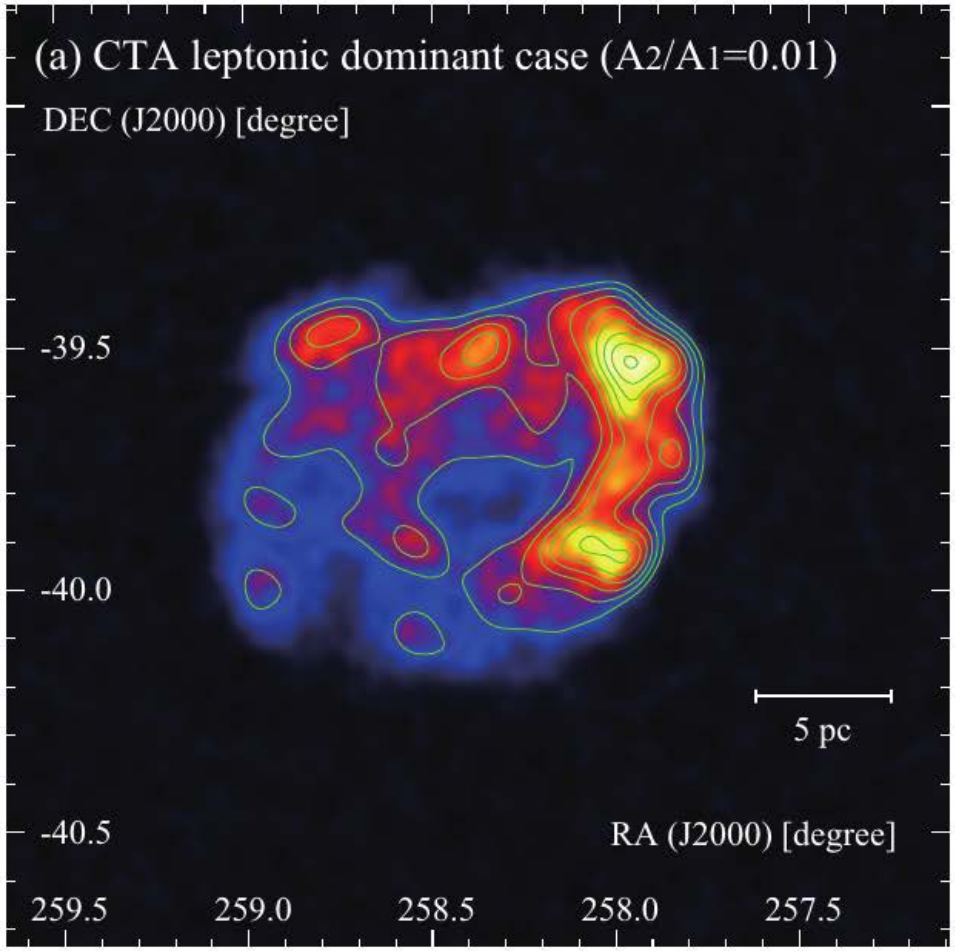
Leveraging next-gen PSF to better match gas studies

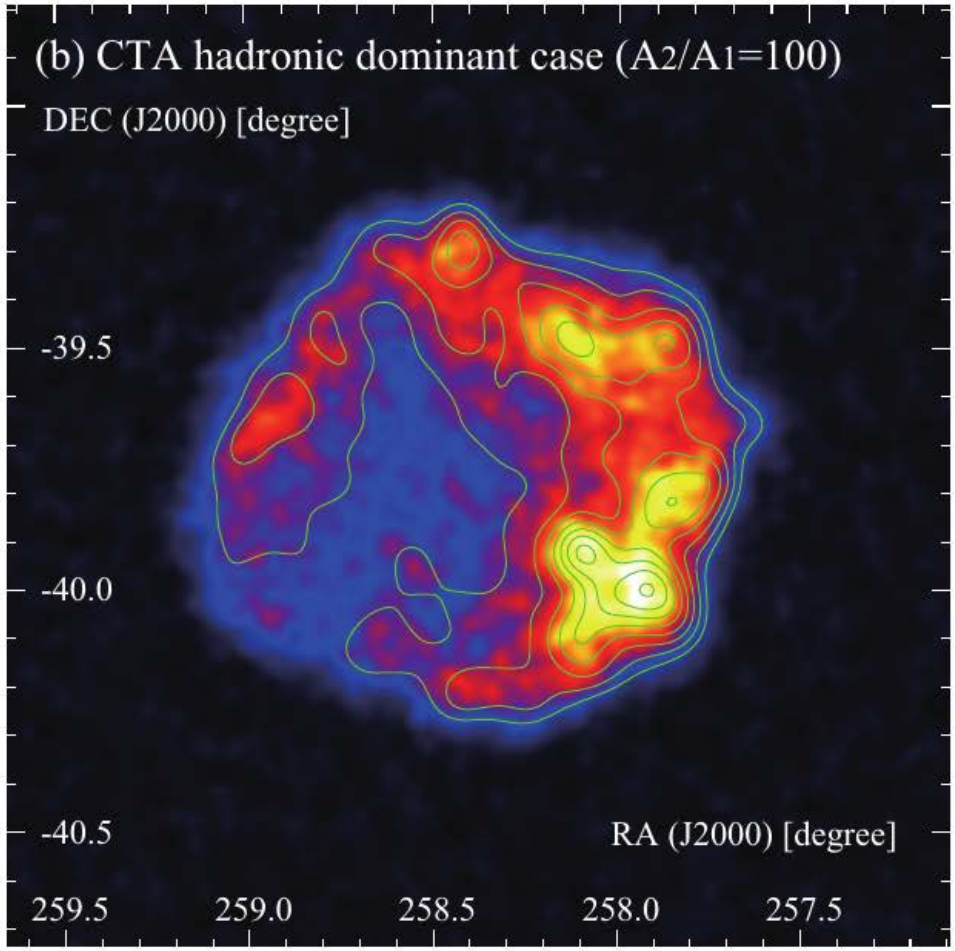


MORPHOLOGICAL APPROACH

50 h CTA simulation

Nakamori+ (CTA) 15

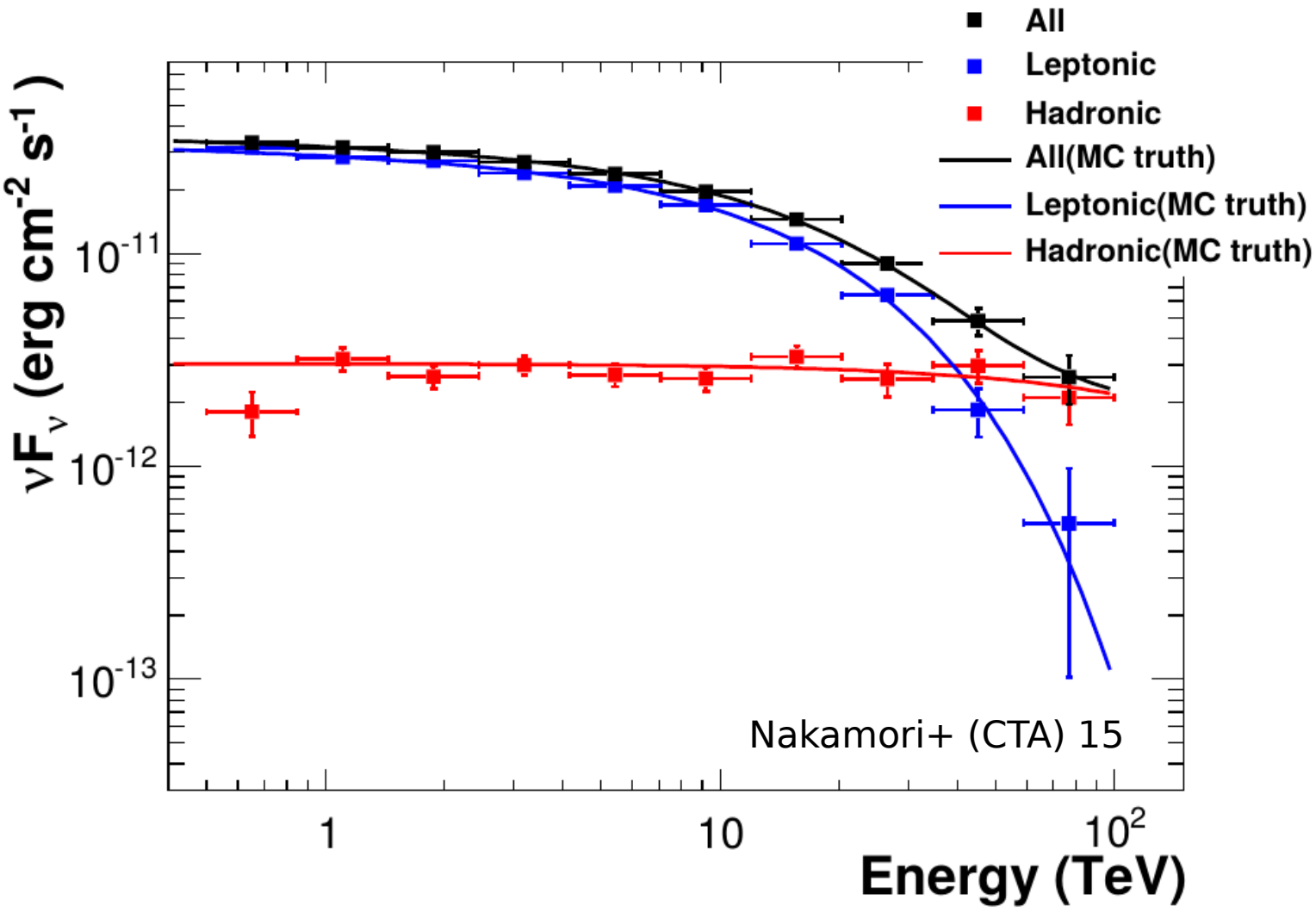




SPECTRAL APPROACH

If leptonic component dominant,

search for hidden hadronic component



CONCLUSIONS

CTA Galactic physics program to focus on:

Galactic Plane Survey for discovery, foundation for deeper observations, and legacy for MWL community

LMC to probe Galactic-type sources & diffuse CRs in face-on galaxy

PeVatrons, not only detection but characterization, and

SNR RX J1713 as unique SNR and potential hadronic accelerator

BACKUP

Galactic KSPs
Research questions

cta
cherenkov telescope array

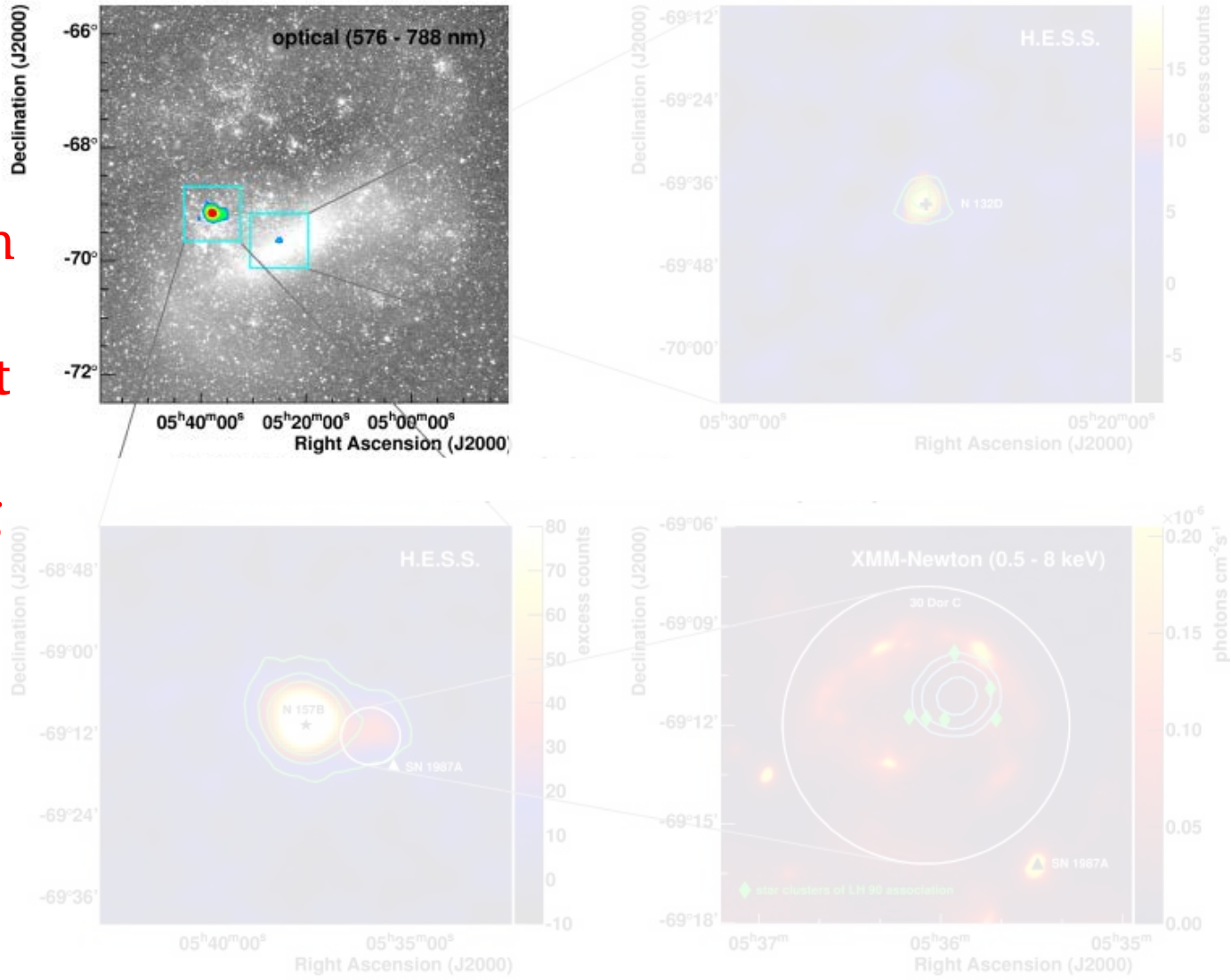
A wide coverage of core science themes that drive CTA

Theme		Question		Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
1	Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
		1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	
		1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
2	Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
		2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
		2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
3	Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
		3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
		3.3	Do Axion-like particles exist?					✔	✔			✔✔	

The Large Magellanic Cloud

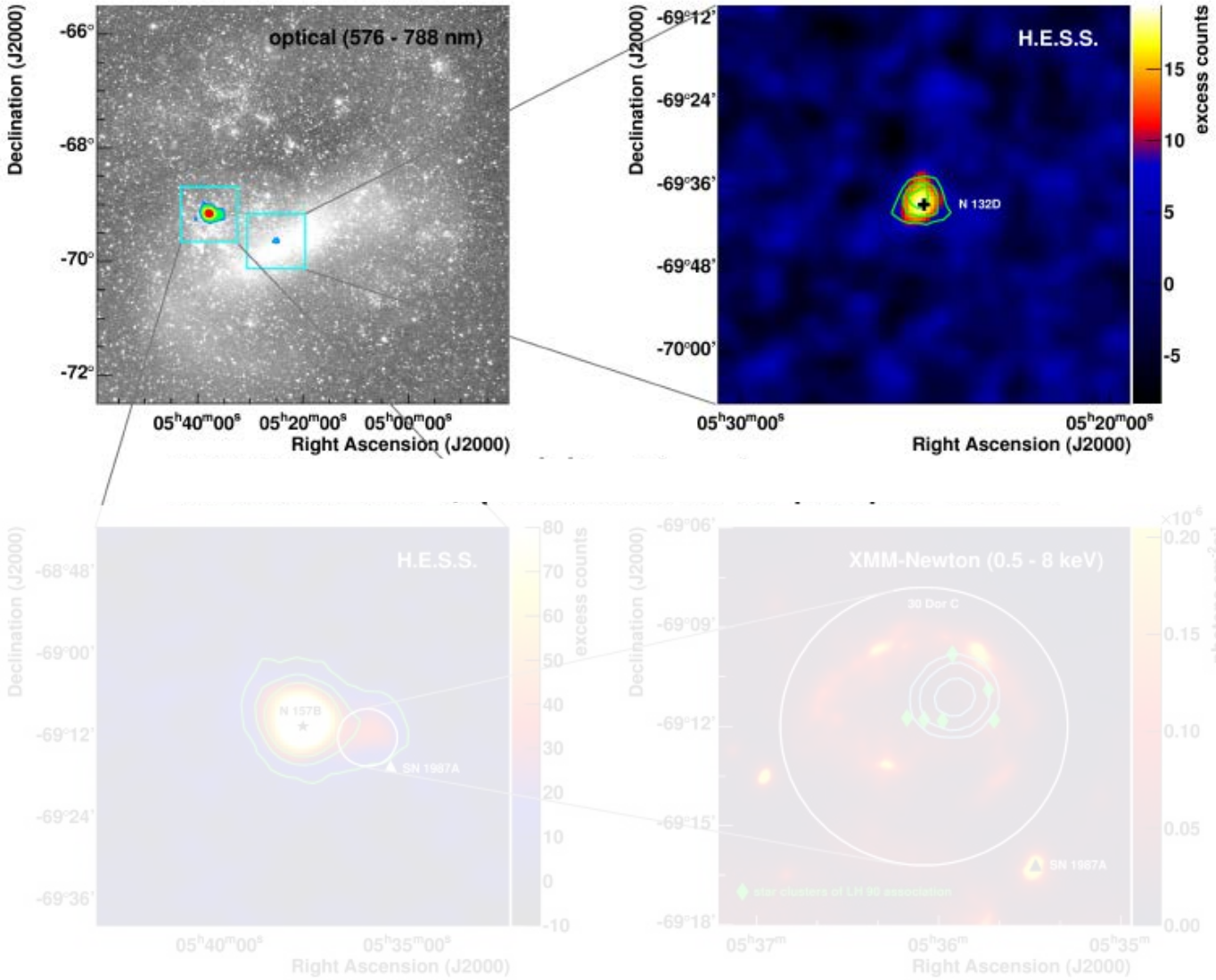
0.05° ~ 3′ angular resolution

sensitivity ~10^{35} erg s^{-1}



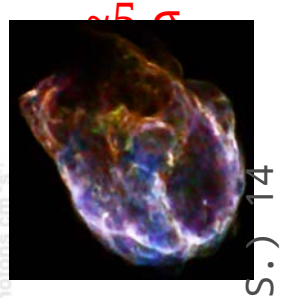
Abramowski+ (H.E.S.S.) 15

N 132D: A radio-loud middle-aged SNR

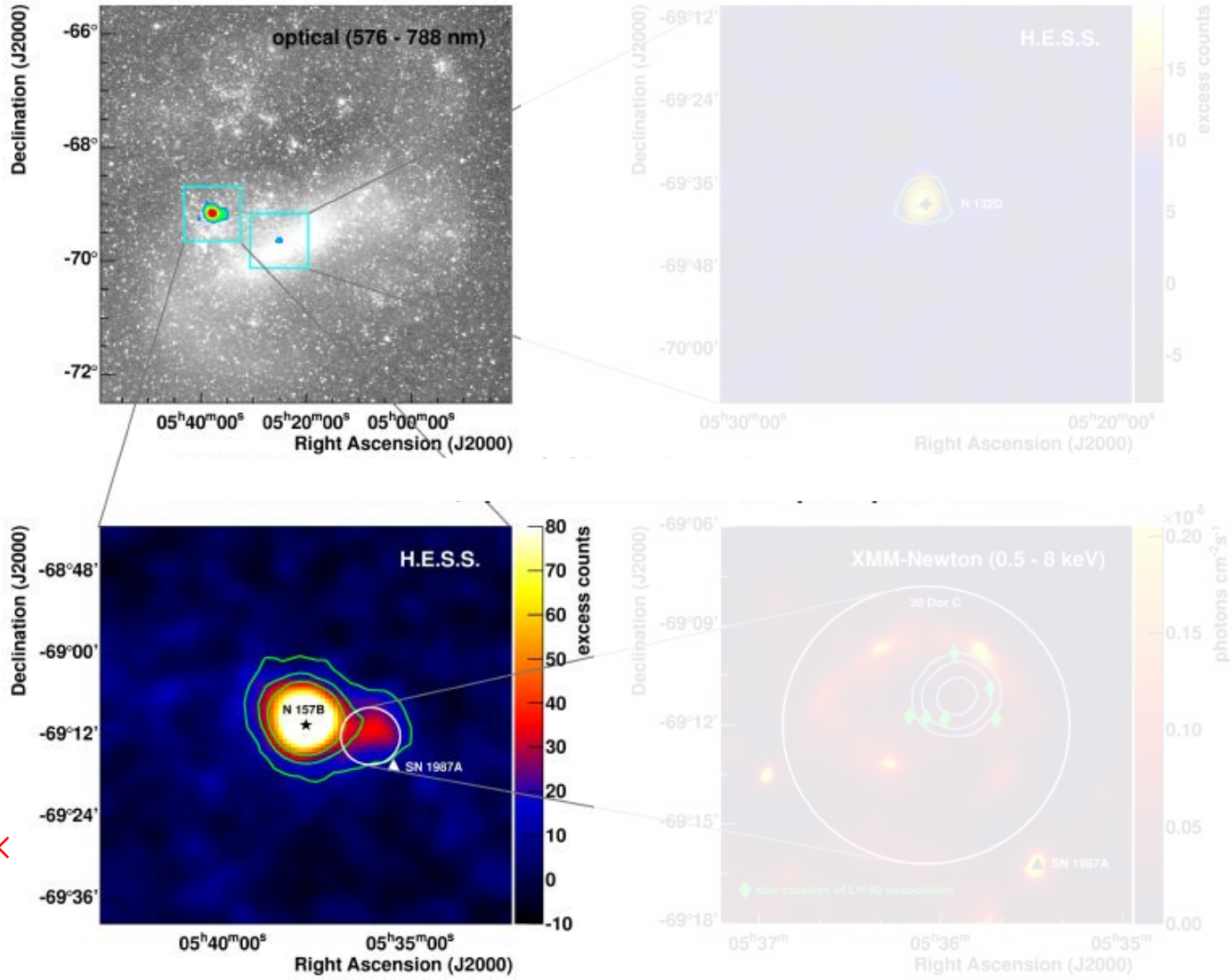


50% L_{radio} of Cas A

Not quite VHE detection ~5 σ

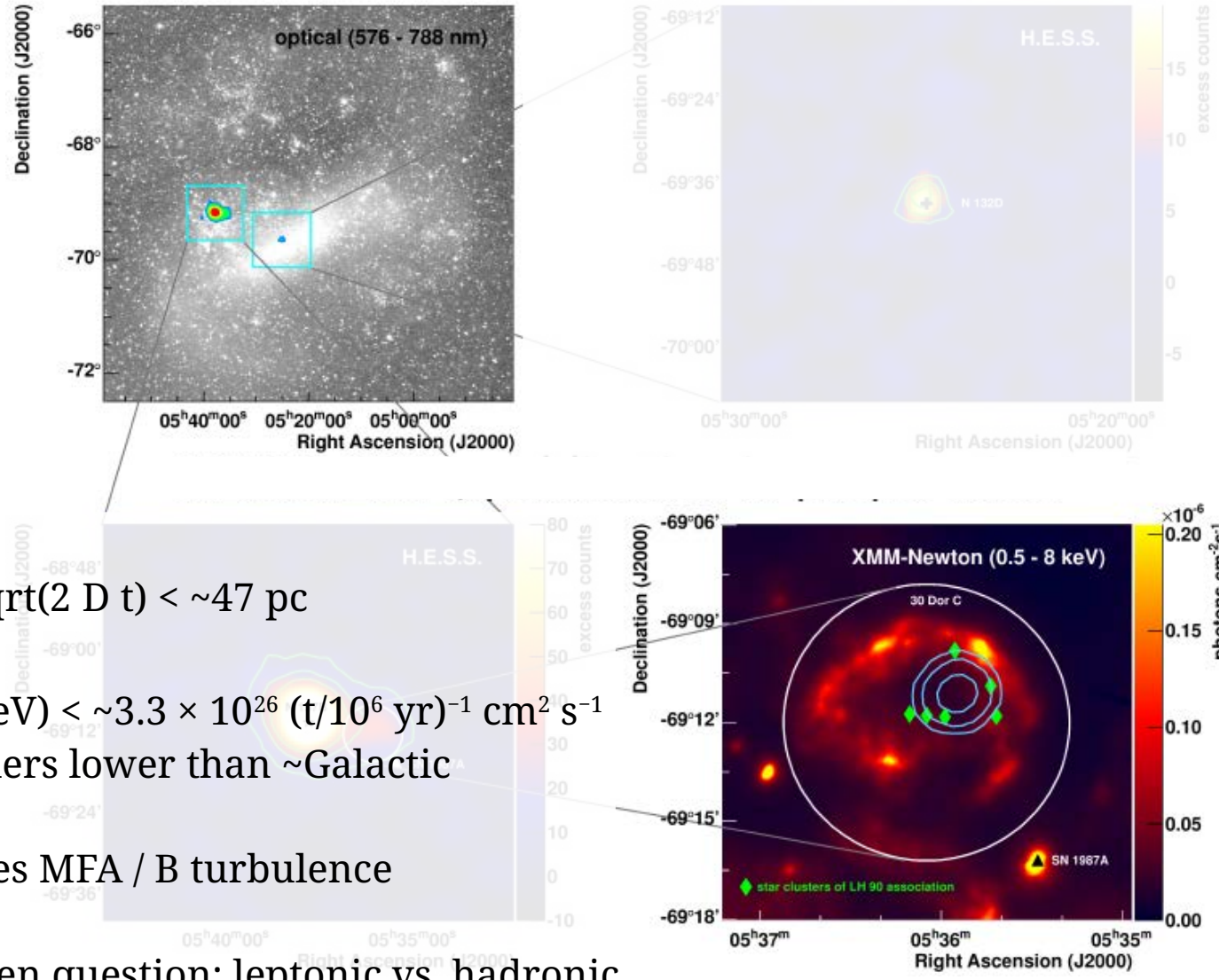


N 157B: The Crab Nebula's twin



Pulsar has **largest known Edot** ~ 4.8 × 10^{38} erg s^{-1}

30 Dor C: A TeV superbubble



$l_{diff} = \sqrt{2 D t} < \sim 47$ pc

$D(10\ \mathrm{TeV}) < \sim 3.3 \times 10^{26}\ (t/10^6\ \mathrm{yr})^{-1}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$
2-3 orders lower than ~Galactic

requires MFA / B turbulence

still open question: leptonic vs. hadronic

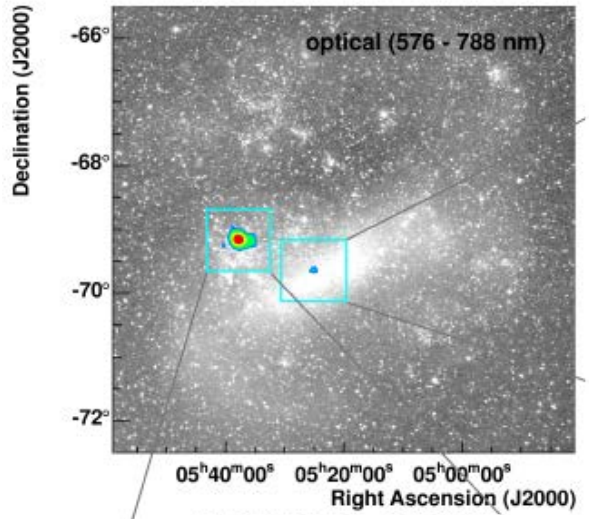
Largest SFR in Local Group

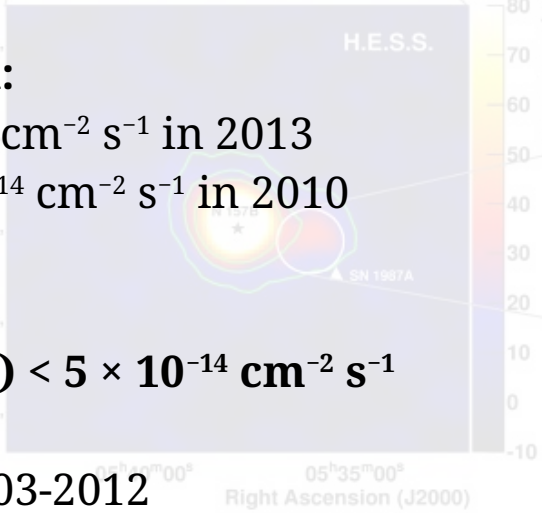
Largest X-ray synchrotron shell known (47 pc)

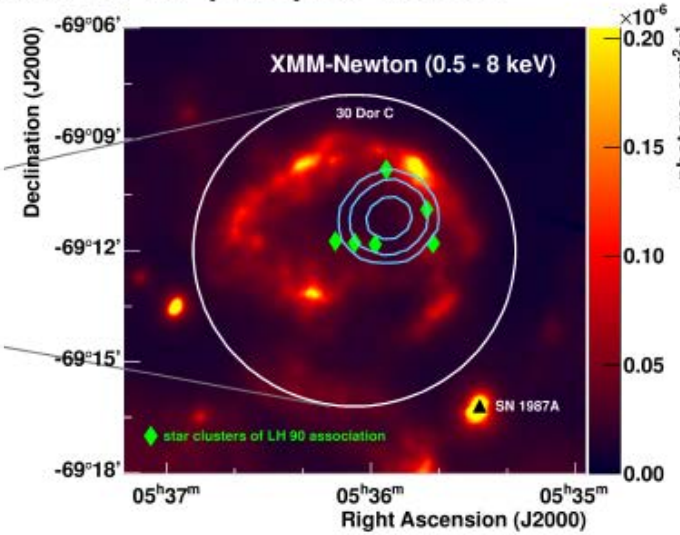
10x as bright as SN 1006

Powered by

SN 1987A: The youngest SNR







Predicted:

$\sim 8 \times 10^{-14}$ cm^{-2} s^{-1} in 2013

$\sim 2.5 \times 10^{-14}$ cm^{-2} s^{-1} in 2010

F (> 1 TeV) < 5 × 10^{-14} cm^{-2} s^{-1}

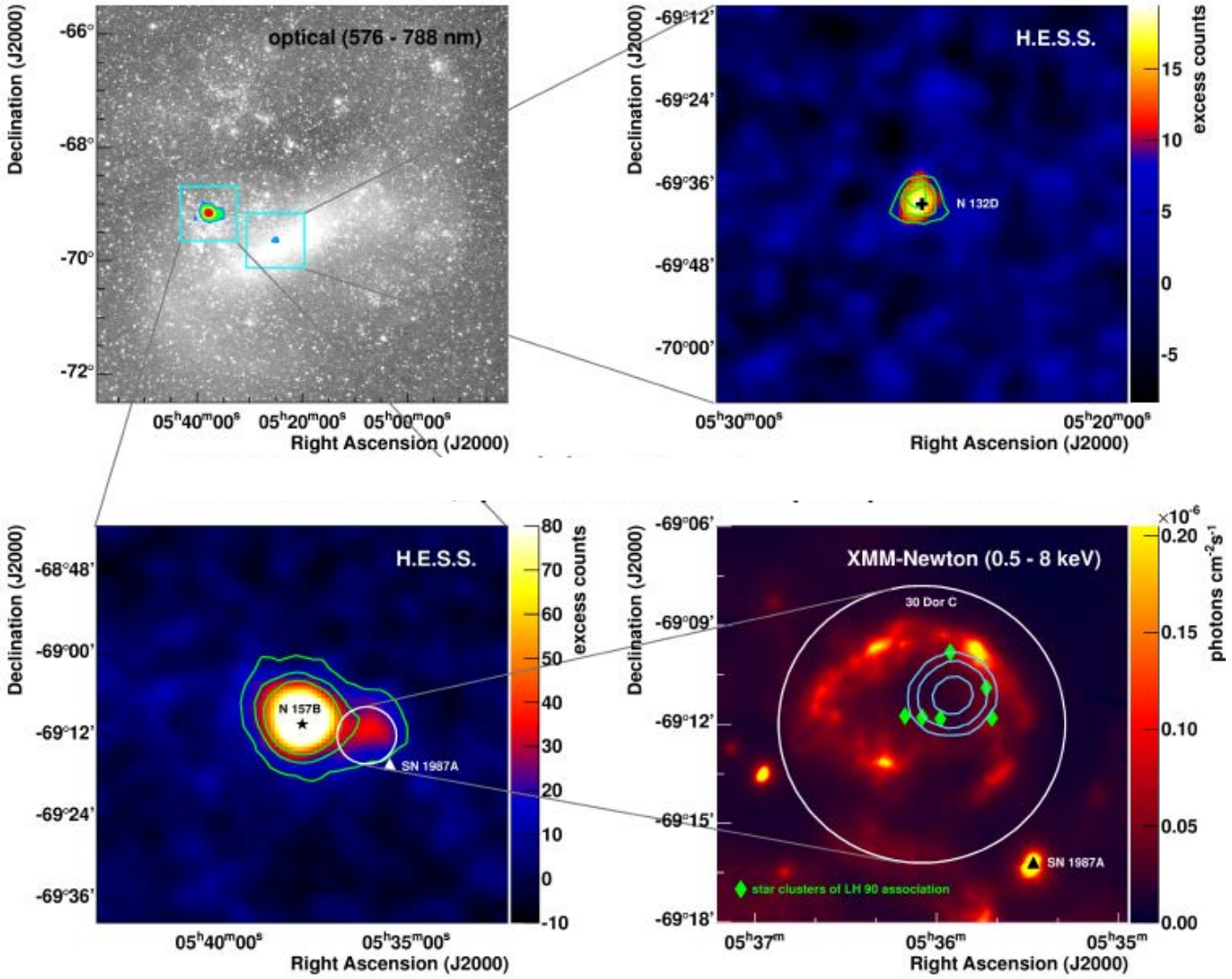
99% CL

during 2003-2012

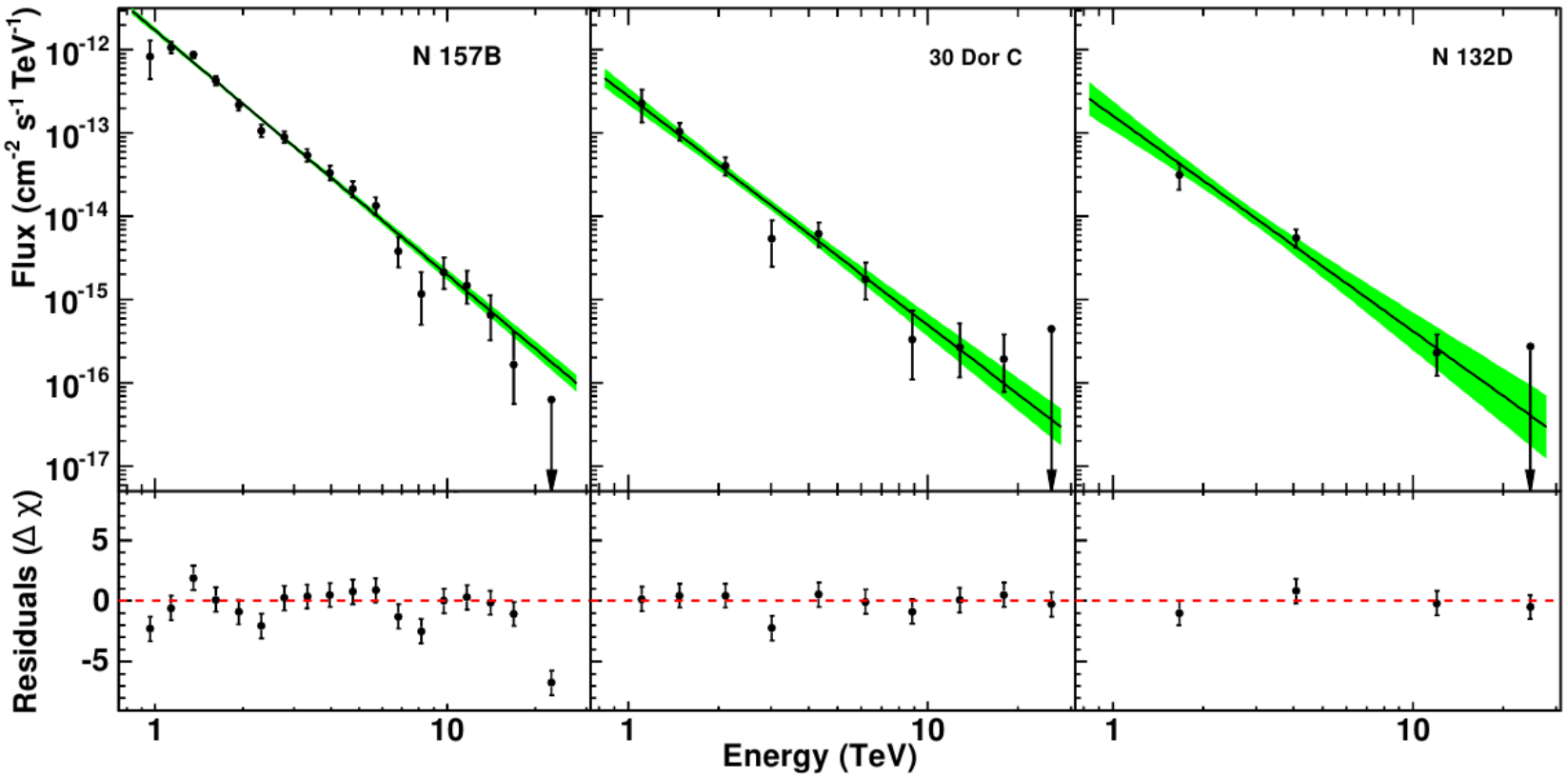
High shock speed
High ambient density
Hadronic?

Upper limit only for now, but more observations planned
&
emission predicted to increase

The LMC in VHE γ-rays: Recap

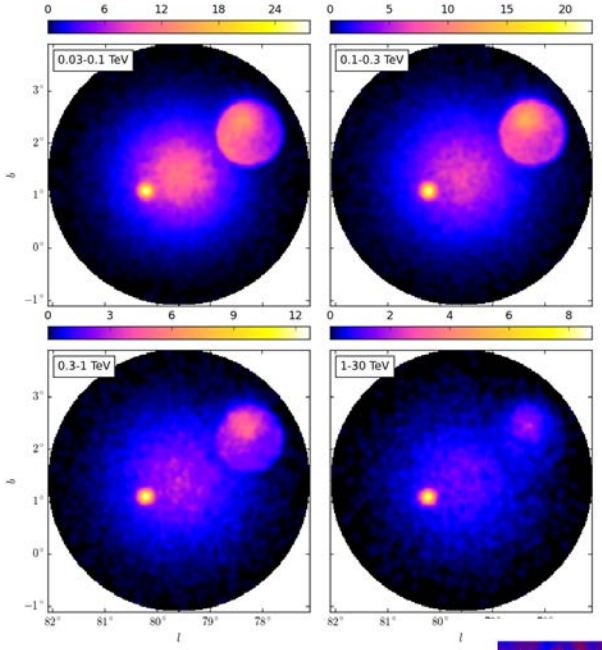


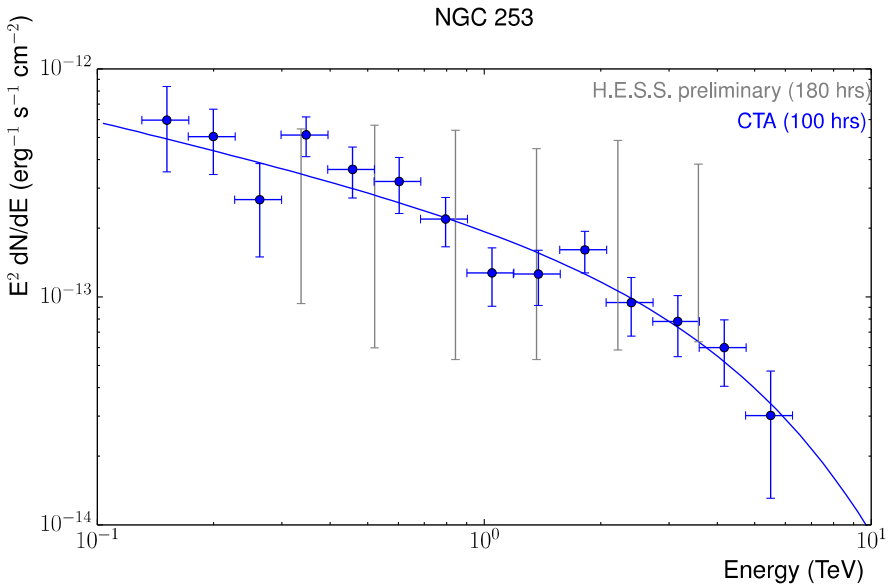
The LMC in VHE γ-rays: Spectra

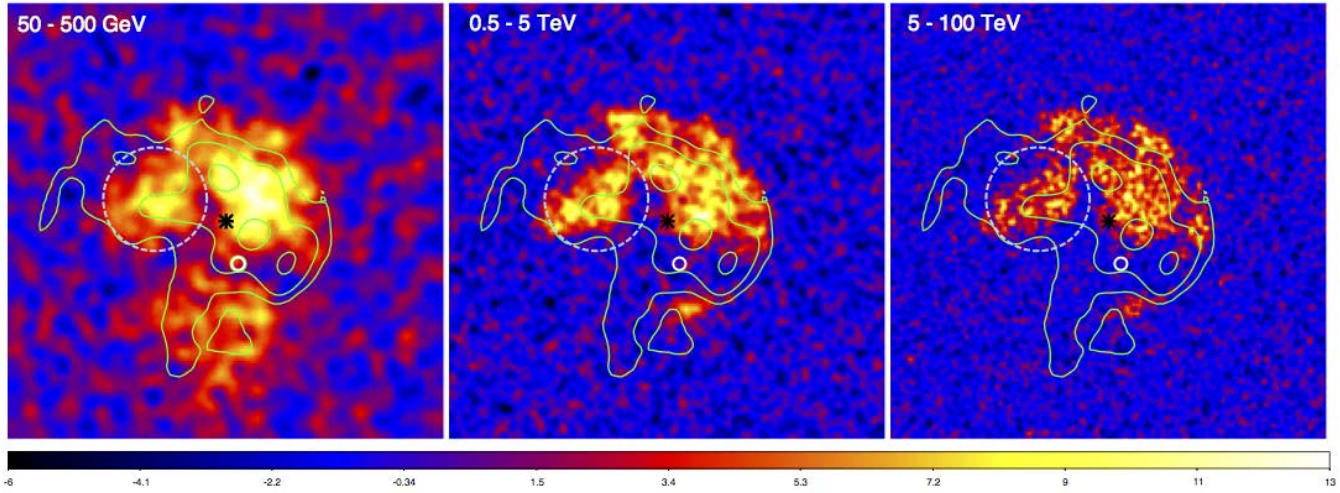


Source	N 157B	30 Dor C	N 132D
H.E.S.S. Identifier	HESS J0537−691	HESS J0535−691	HESS J0525−696
Exposure Time	181 h	183 h	148 h
γ rays	613	74	43
Significance	$33.0\,\sigma$	$8.8\,\sigma$	$4.7\,\sigma$
Photon Index Γ	2.8 ± 0.1	2.6 ± 0.2	2.4 ± 0.3
$\Phi(1\,\mathrm{TeV})$ $[10^{-12}\,\mathrm{cm^{-2}\,s^{-1}\,TeV^{-1}}]$	1.3 ± 0.1	0.16 ± 0.04	0.13 ± 0.05
$L_\gamma(1-10\,\mathrm{TeV})$ $[10^{35}\,\mathrm{erg\,s^{-1}}]$	6.8 ± 0.3	0.9 ± 0.2	0.9 ± 0.2

SFS KSP
New Simulations



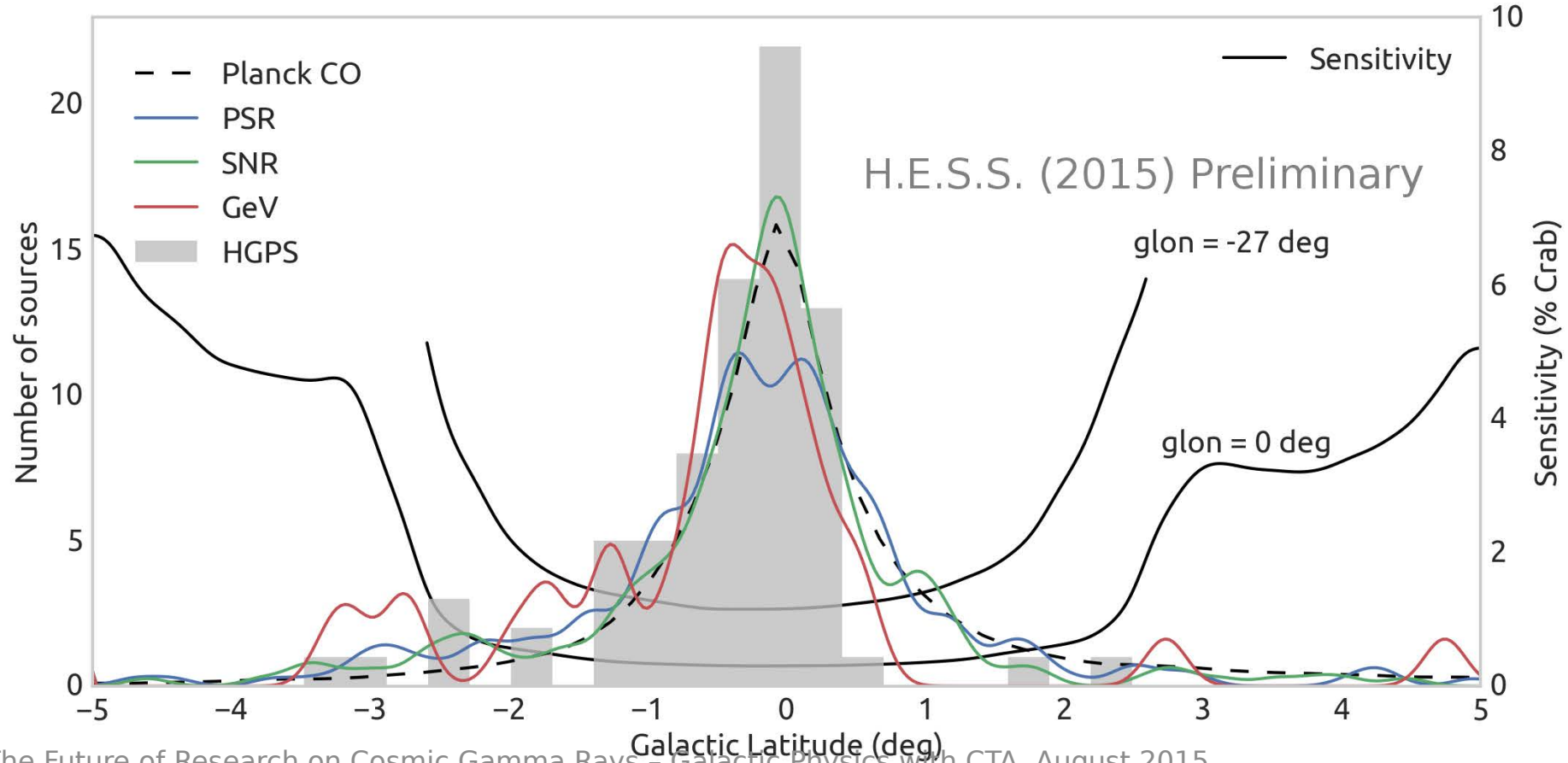




VHE source distribution

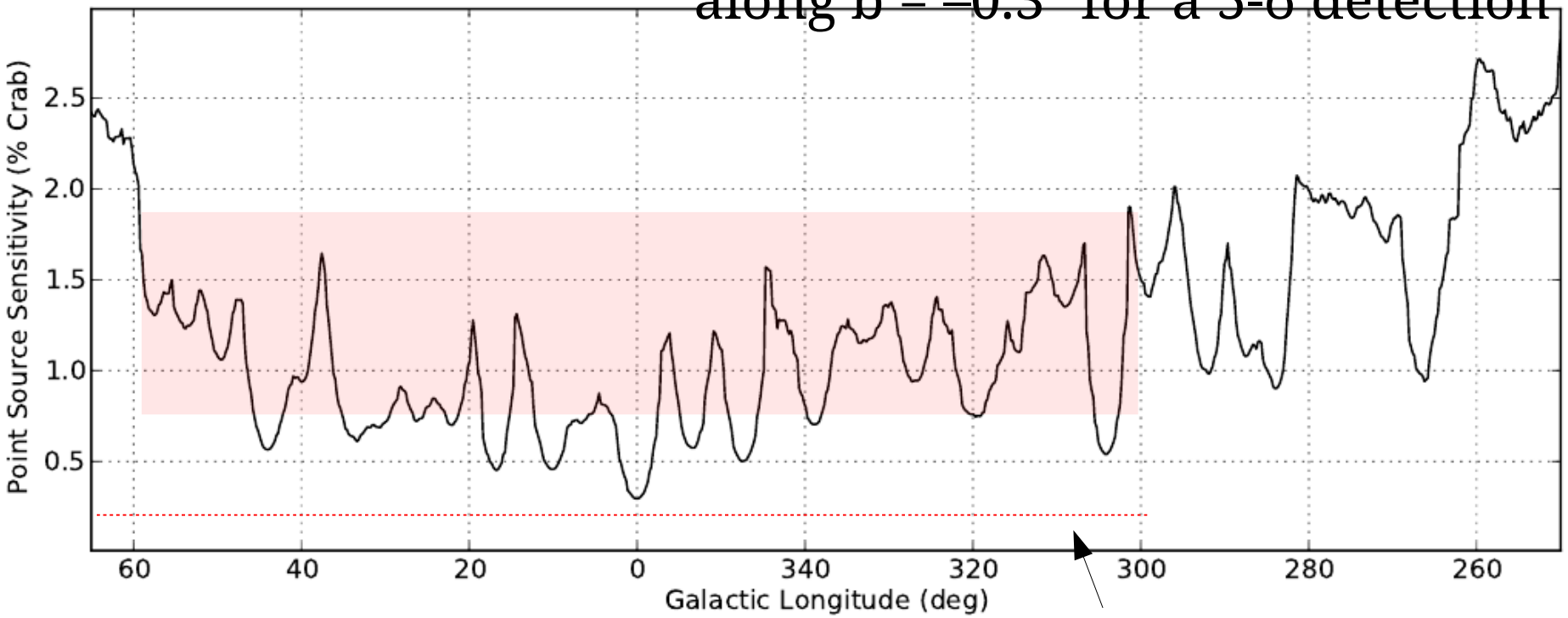
Roughly fits plausible counterpart distributions

Still lack statistics to disentangle? Not sensitivity limited in latitude?

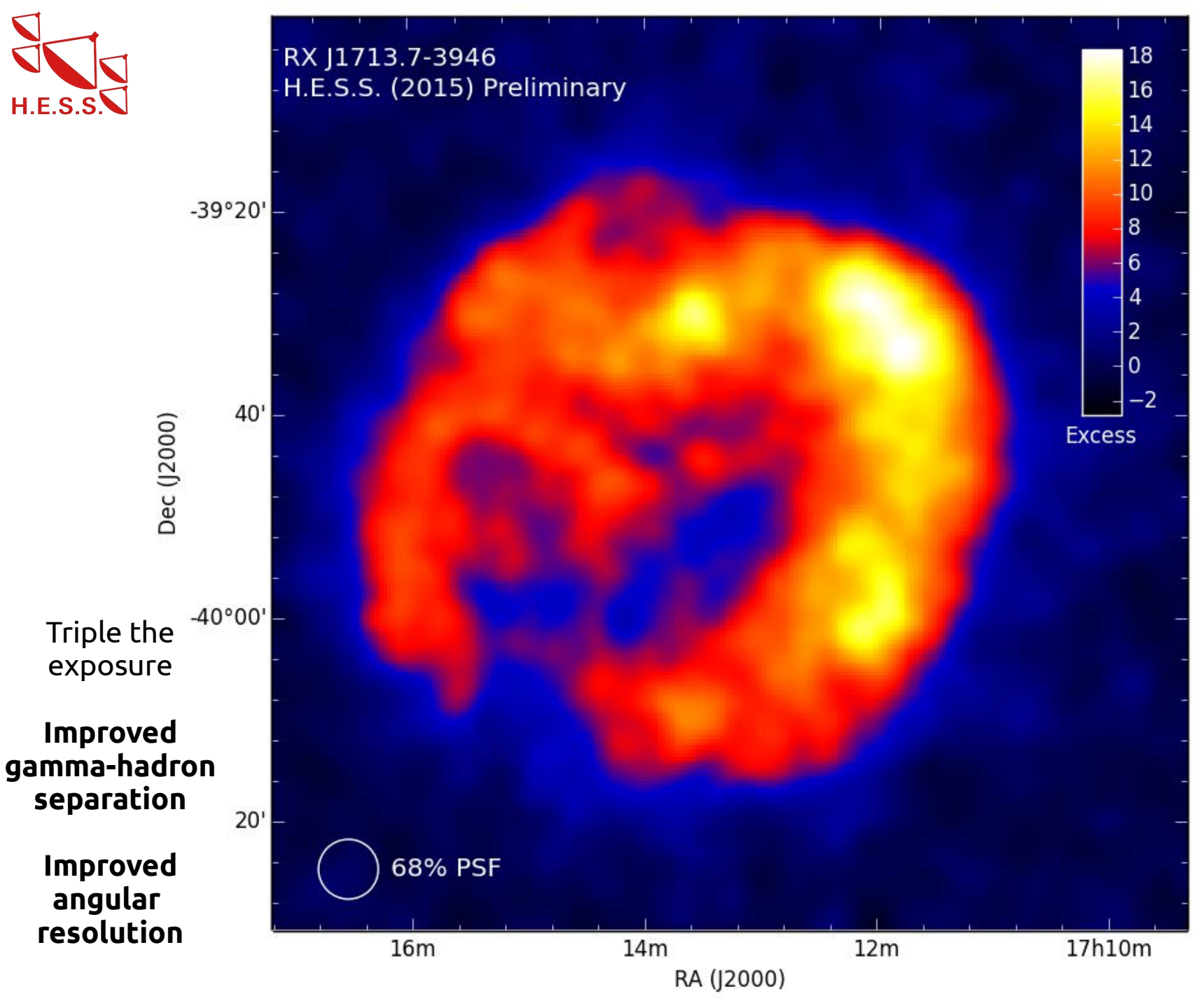


HGPS Sensitivity

along b = –0.3° for a 5-σ detection



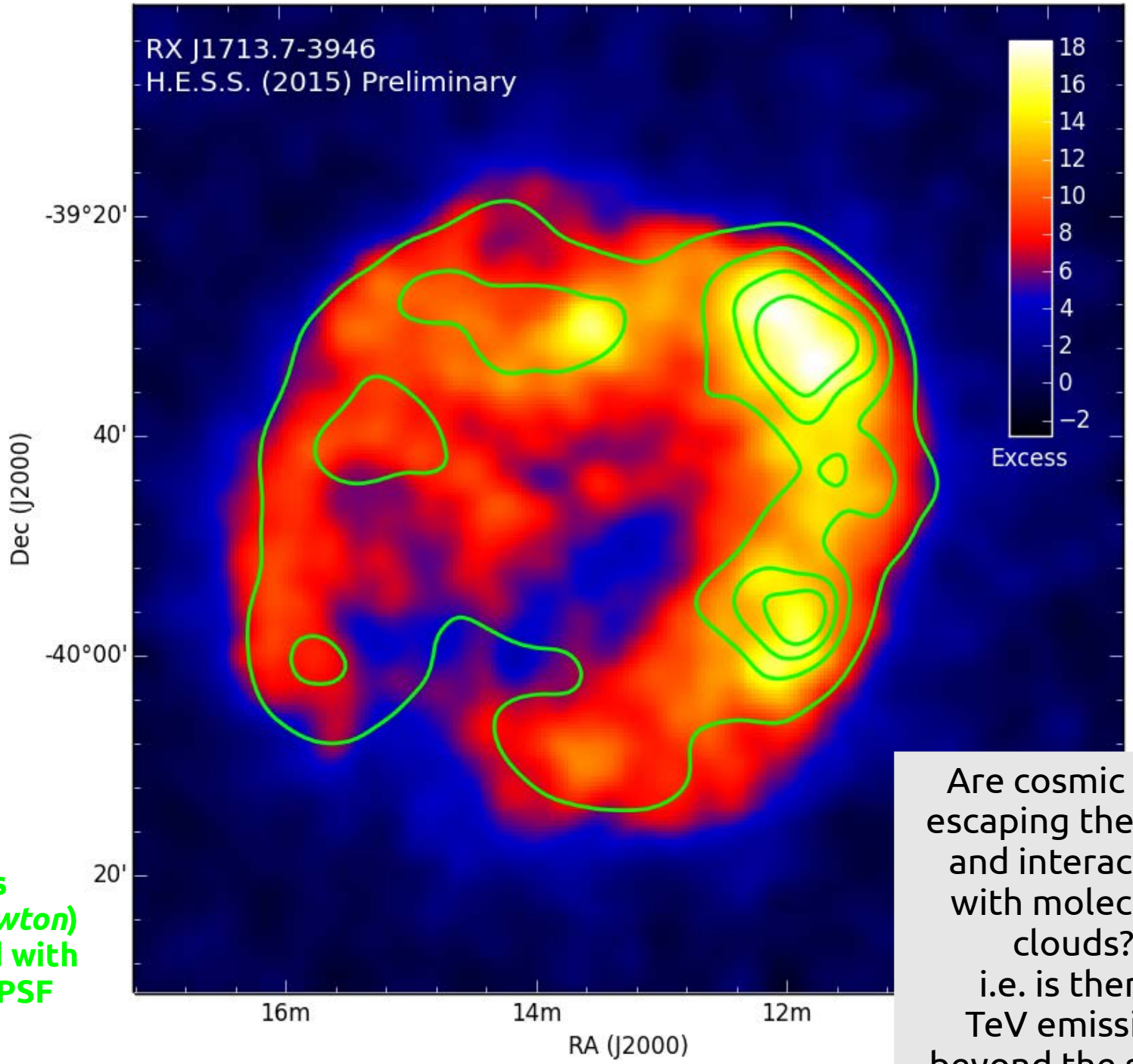
FYI: CTA GPS by ~2022



Triple the exposure

Improved gamma-hadron separation

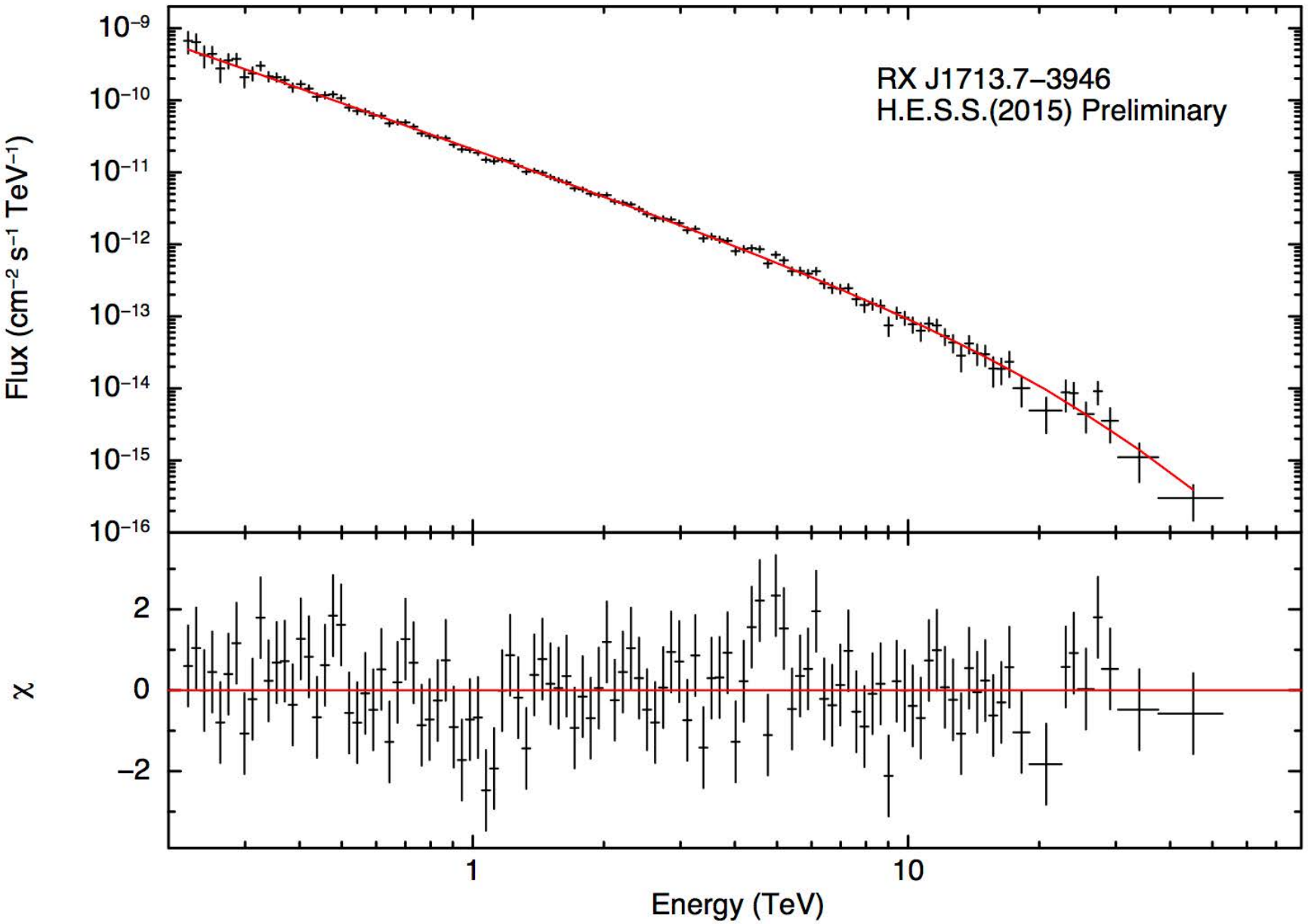
Improved angular resolution



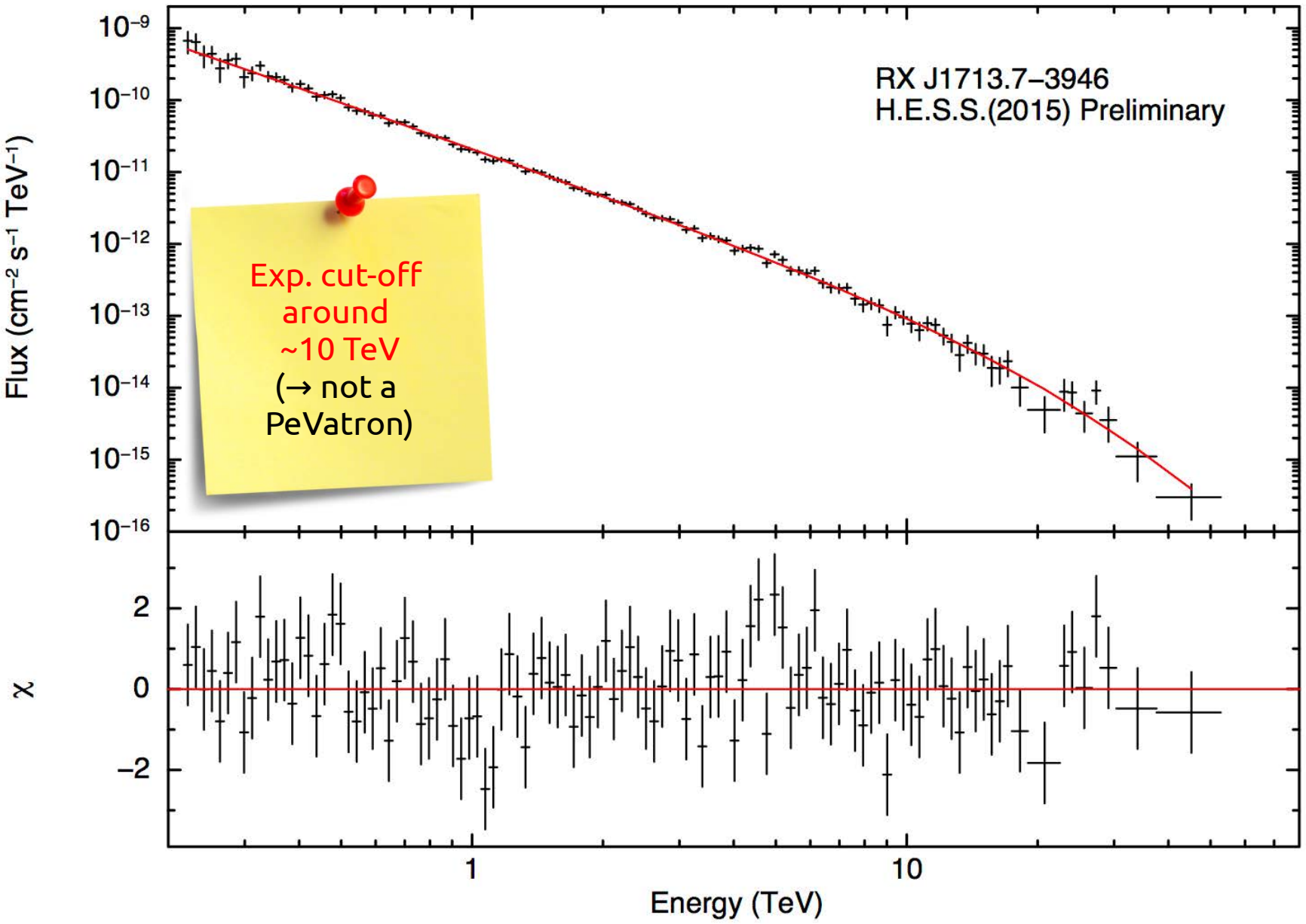
X-rays (*XMM-Newton*) convolved with H.E.S.S. PSF

Are cosmic rays escaping the shell and interacting with molecular clouds?
i.e. is there TeV emission beyond the shell?

Precision VHE spectra to ~50 TeV



Precision VHE spectra to ~50 TeV



START WITH SIMPLE CASES

May not be conclusive,
but can be an example of analysis strategy
based on 1-zone scenario

Determine the major component by **image analysis**

hadronic

This source wouldn't be a PeVatron

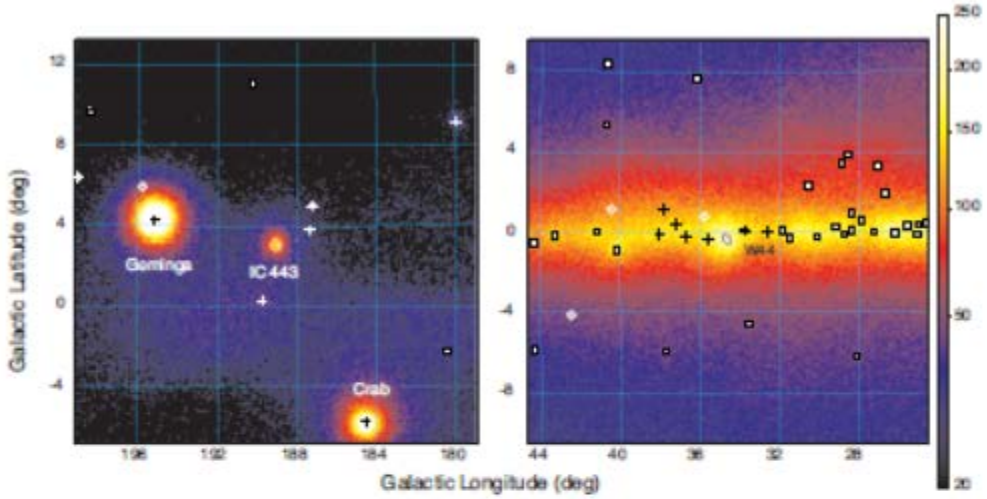
leptonic

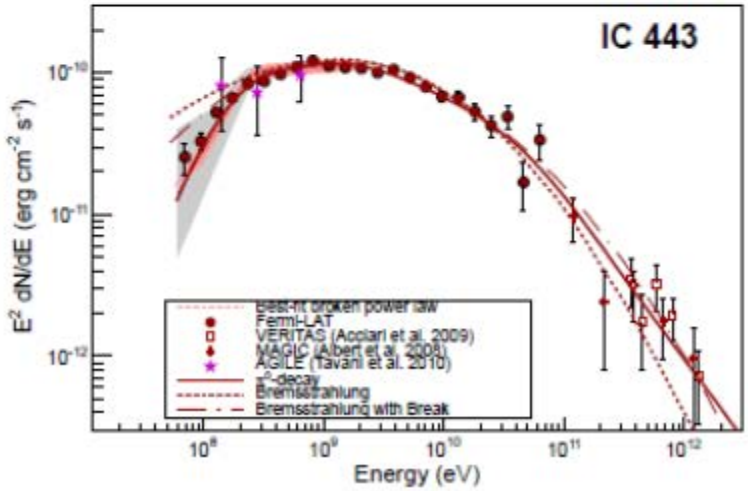
Search for hadronic component by **spectral analysis**

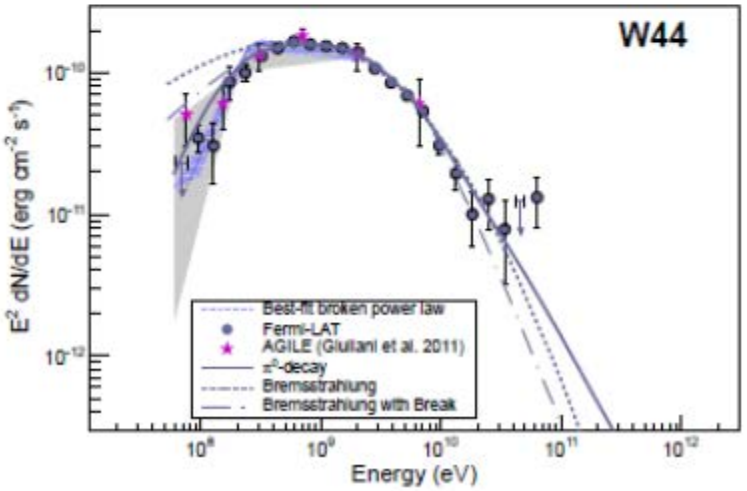
complimentary indication

Time evolution of E_c

(Knoedlseder+ 13)


Geminga
IC 443
Crab
W44
Galactic Latitude (deg)
Galactic Longitude (deg)


IC 443
Best-fit broken power law
Fermi-LAT
VERITAS (Acciari et al. 2009)
MAGIC (Albert et al. 2008)
AGILE (Tavani et al. 2010)
π0-decay
Bremsstrahlung
Bremsstrahlung with Break
E2 dN/dE (erg cm-2 s-1)
Energy (eV)


W44
Best-fit broken power law
Fermi-LAT
AGILE (Giuliani et al. 2011)
π0-decay
Bremsstrahlung
Bremsstrahlung with Break
E2 dN/dE (erg cm-2 s-1)
Energy (eV)