

VHE γ -rays from Galactic SNRs of ccSN origin

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The logo for the International Astronomical Union (IAU) is the letters 'IAU' in a stylized white font on a black background.

IAU

SN 1987A, 30 years later - Cosmic Rays and Nuclei from Supernovae and their aftermaths

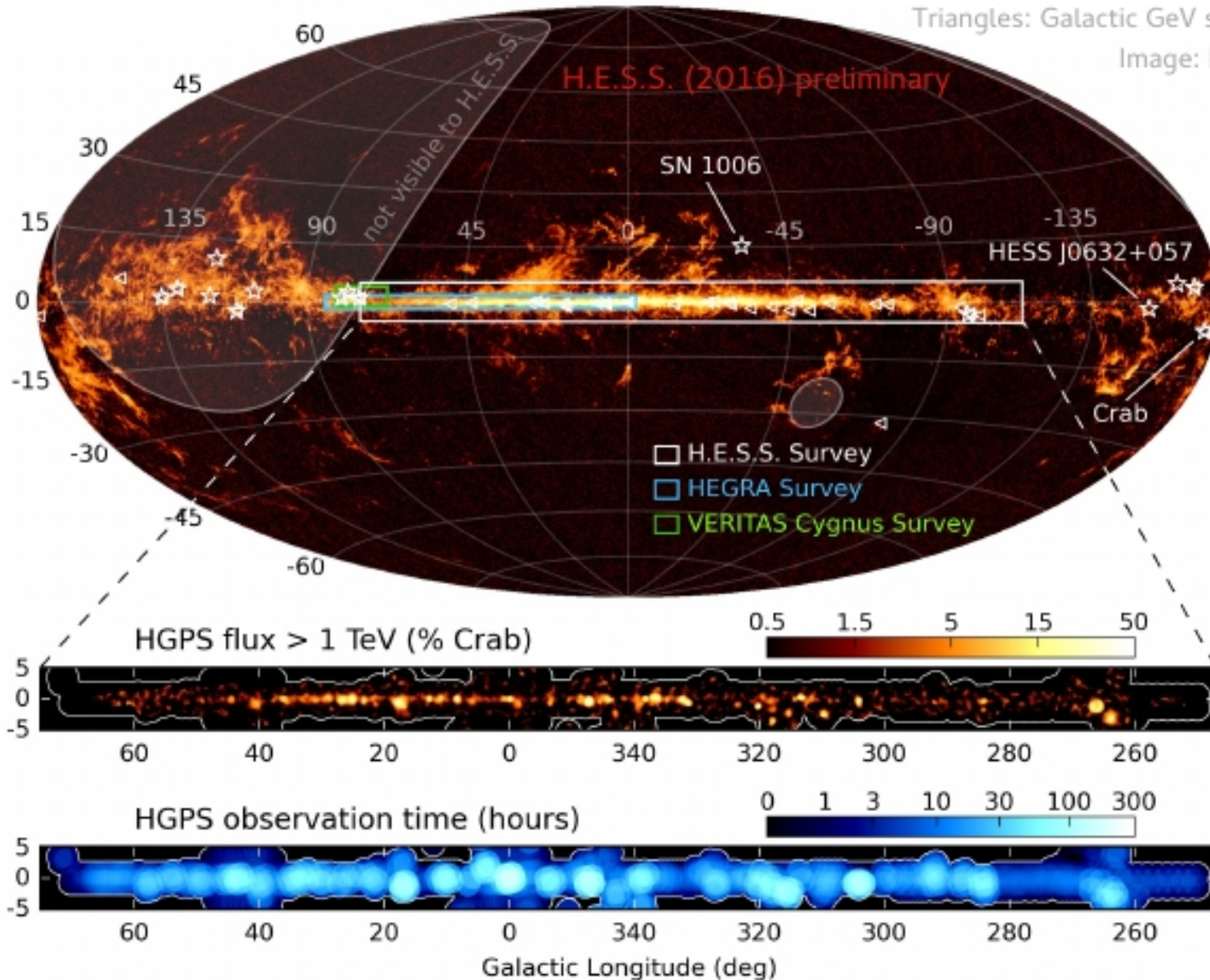
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Galactic Plane Survey in VHE γ -rays

Stars: Galactic TeV sources outside HGPS region

Triangles: Galactic GeV sources (2FHL)

Image: Planck CO map



Aharonian+(H.E.S.S.)06

Chaves+(H.E.S.S.)08

Chaves(H.E.S.S.)09

Gast,...,Chaves+(H.E.S.S.)11

Deil,...,Chaves+(H.E.S.S.)12

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

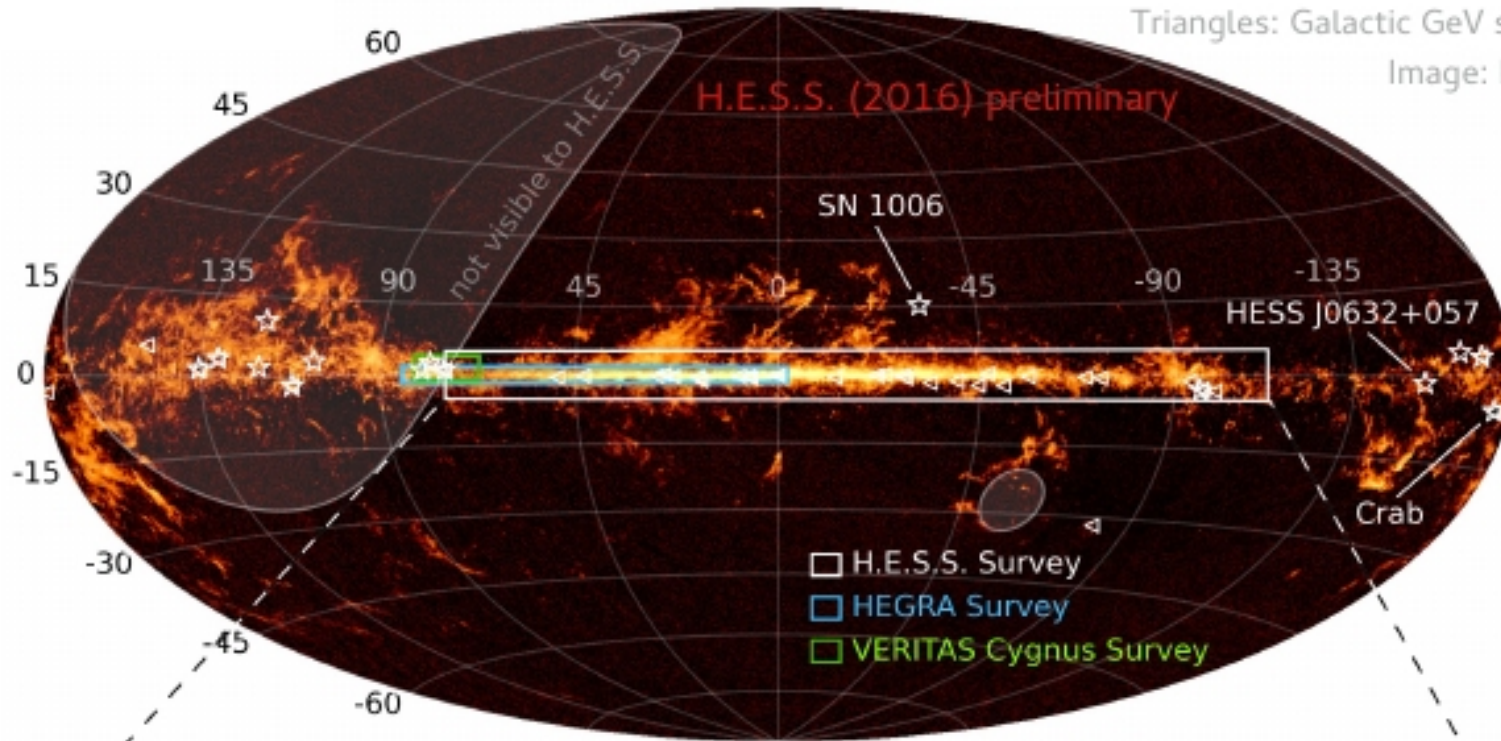
Abdalla,...,Chaves+(H.E.S.S.)17 in prep

Galactic Plane Survey in VHE γ -rays

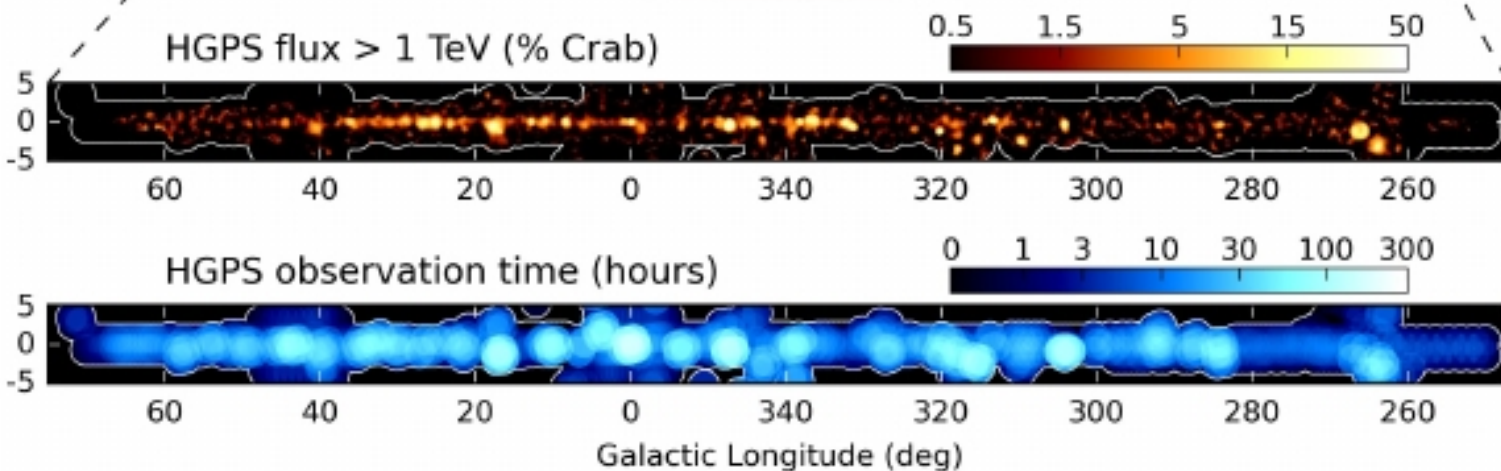
Stars: Galactic TeV sources outside HGPS region

Triangles: Galactic GeV sources (2FHL)

Image: Planck CO map



~300 SNRs in Galaxy
 ~2/3 in HGPS region
**majority of ccSNe
 origin**



Aharonian+(H.E.S.S.)06

Chaves+(H.E.S.S.)08

Chaves(H.E.S.S.)09

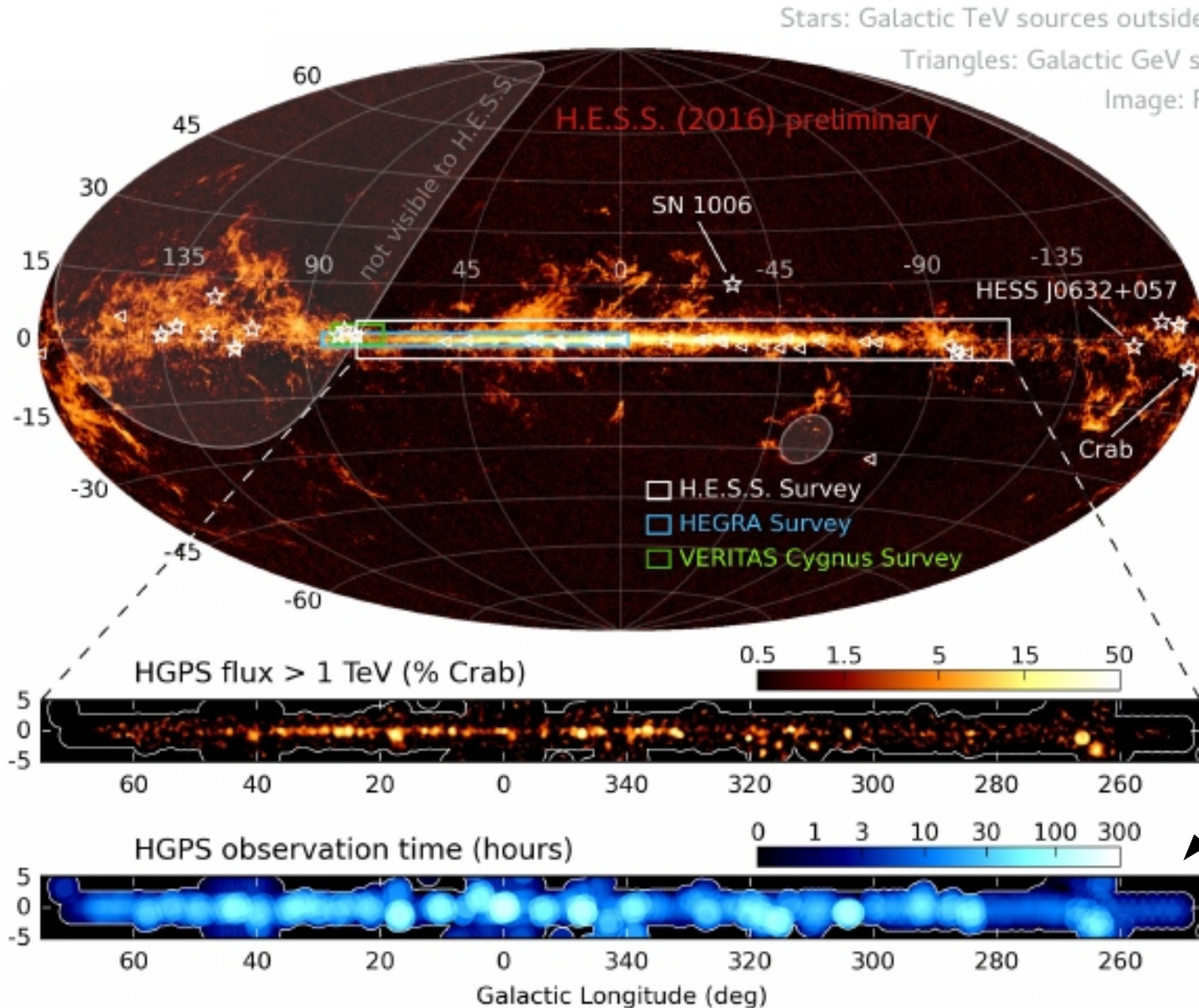
Gast,...,Chaves+(H.E.S.S.)11

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Galactic Plane Survey in VHE γ -rays

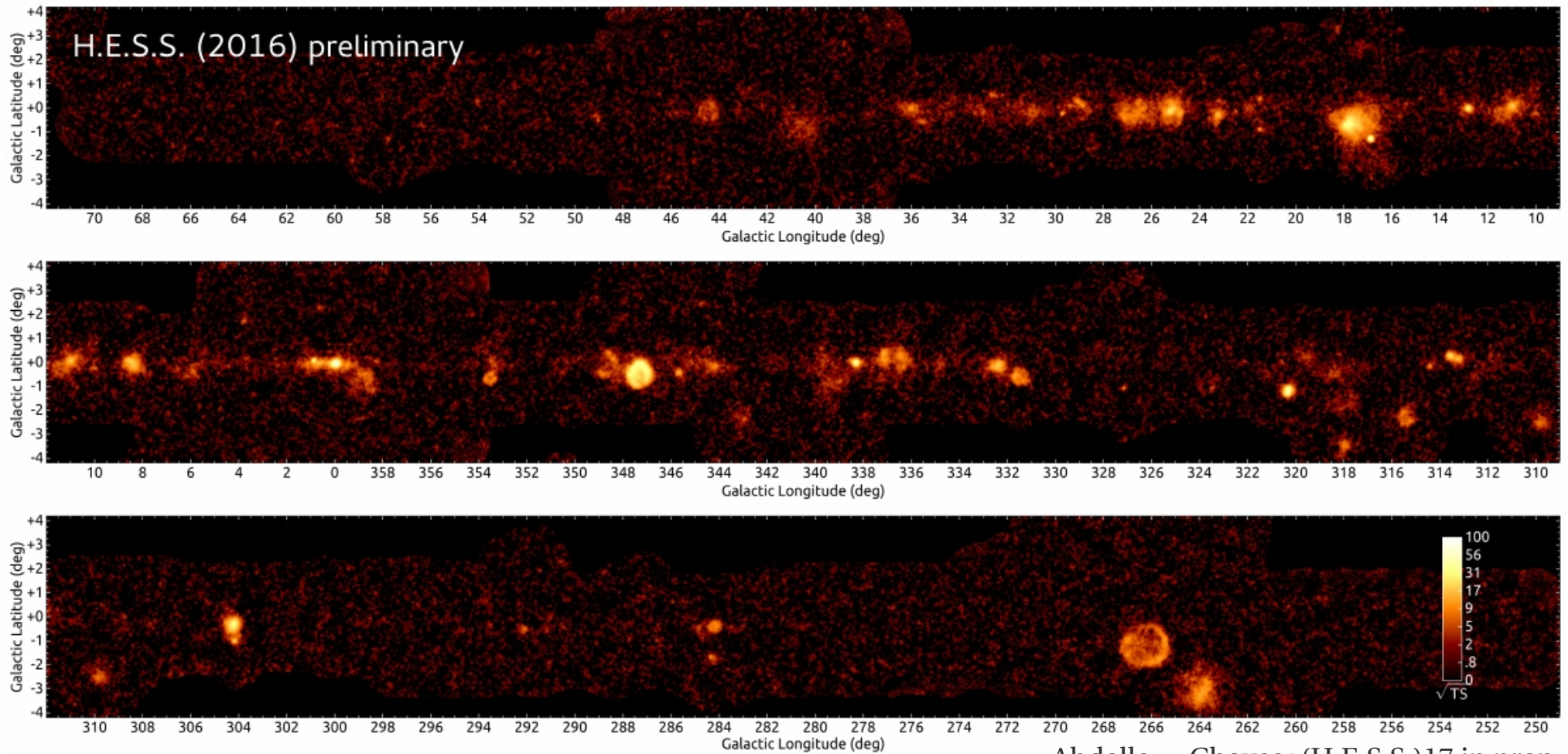


~300 SNRs in Galaxy
 ~2/3 in HGPS region
majority of ccSNe origin

N.B. survey sensitivity not uniform

- Aharonian+(H.E.S.S.)06
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- Carrigan,...,Chaves+(H.E.S.S.)13
- Abdalla,...,Chaves+(H.E.S.S.)17 in prep

The Galaxy in VHE γ -rays

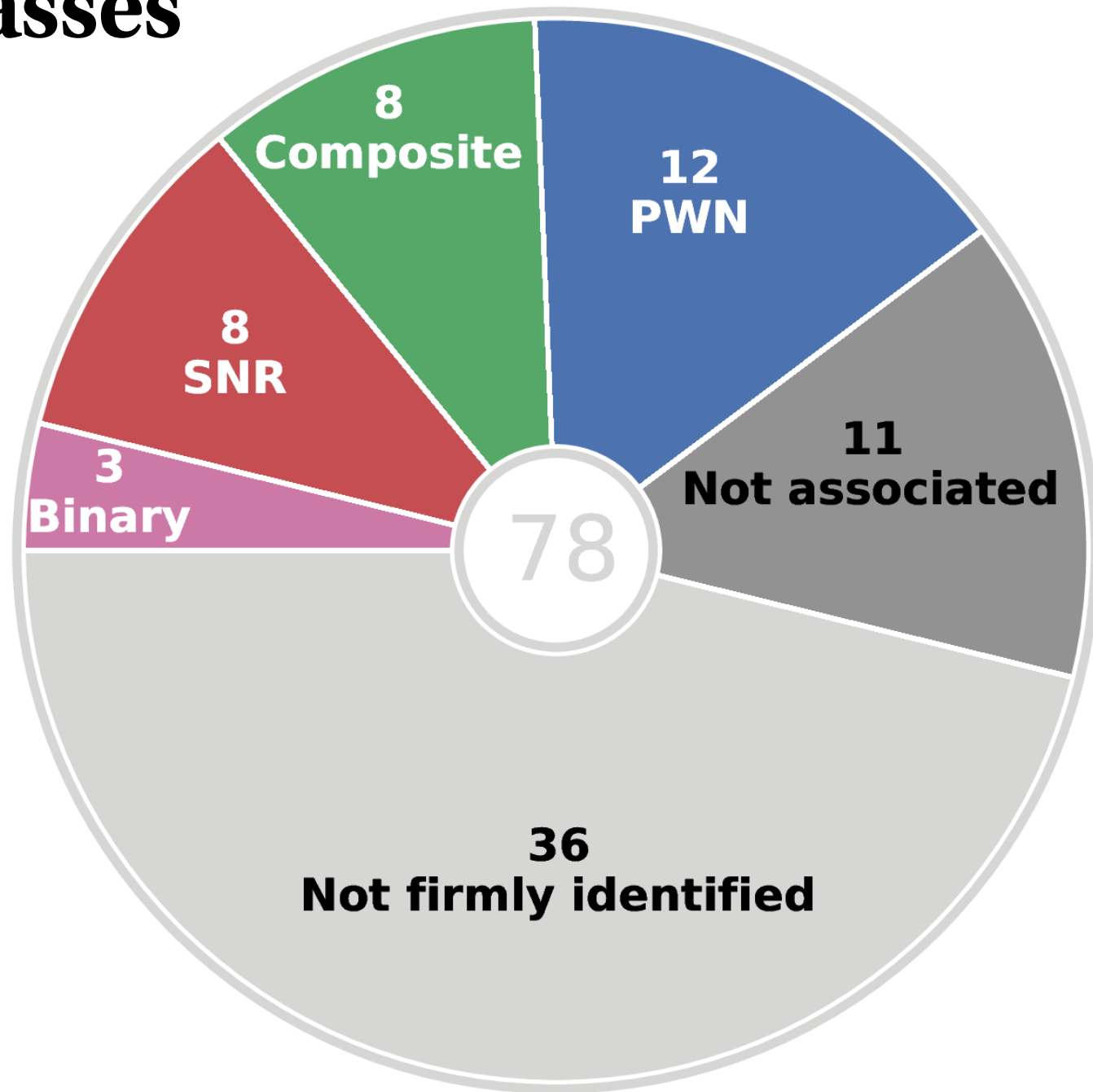


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2700 h of H.E.S.S. observations and 10 years later
78 sources detected in HGPS (of ~100 total known)

VHE source classes

(HGPS region only)

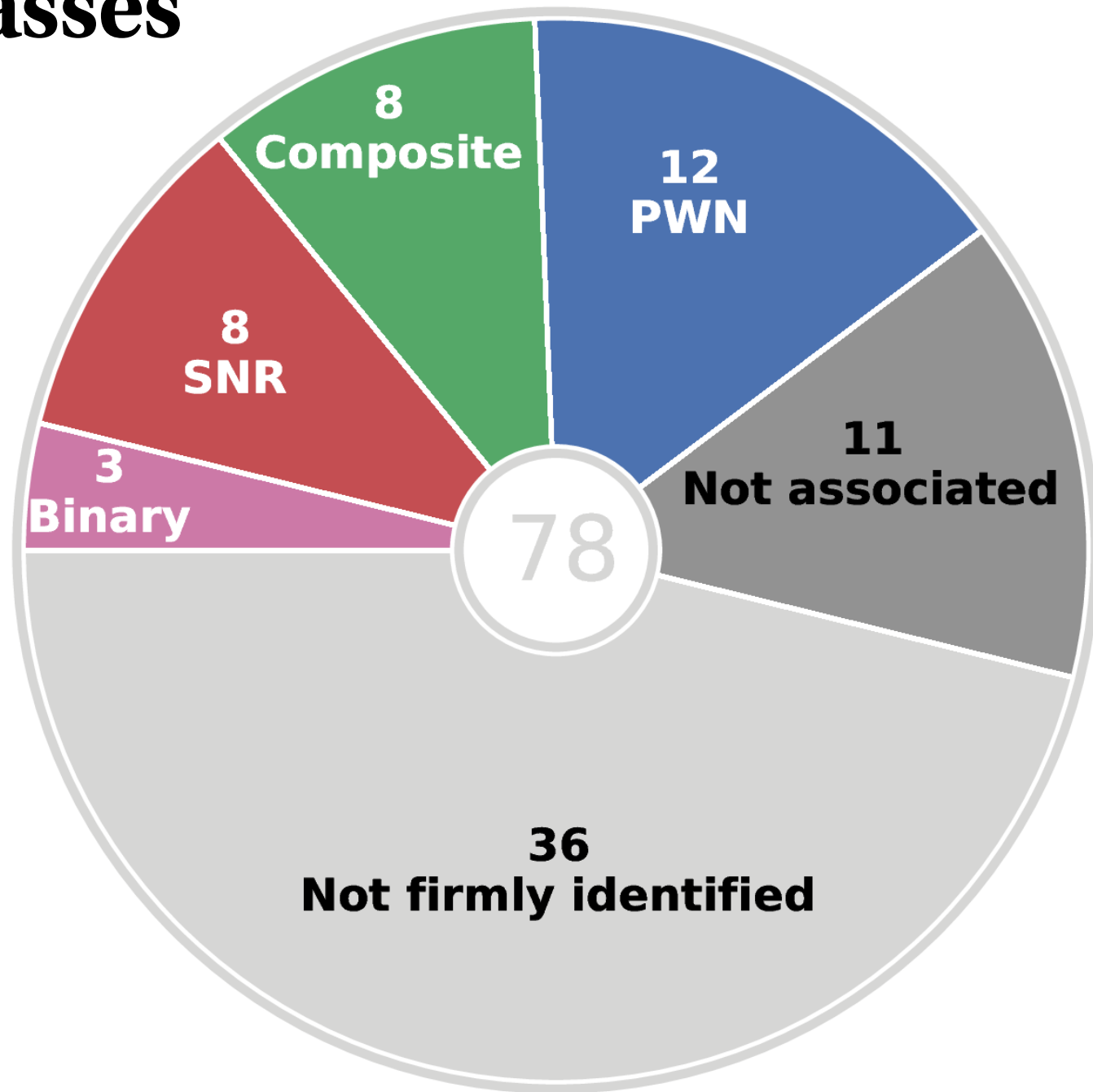


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VHE source classes

(HGPS region only)

8 SNRs firmly ID'd
incl. 3 certain
CC SNRs:
RX J1713.7-3946
W49B
HESS J1731-347
(W51C ?)
(W28?)



Abdalla,...,Chaves+(H.E.S.S.)17 in prep

VHE source classes

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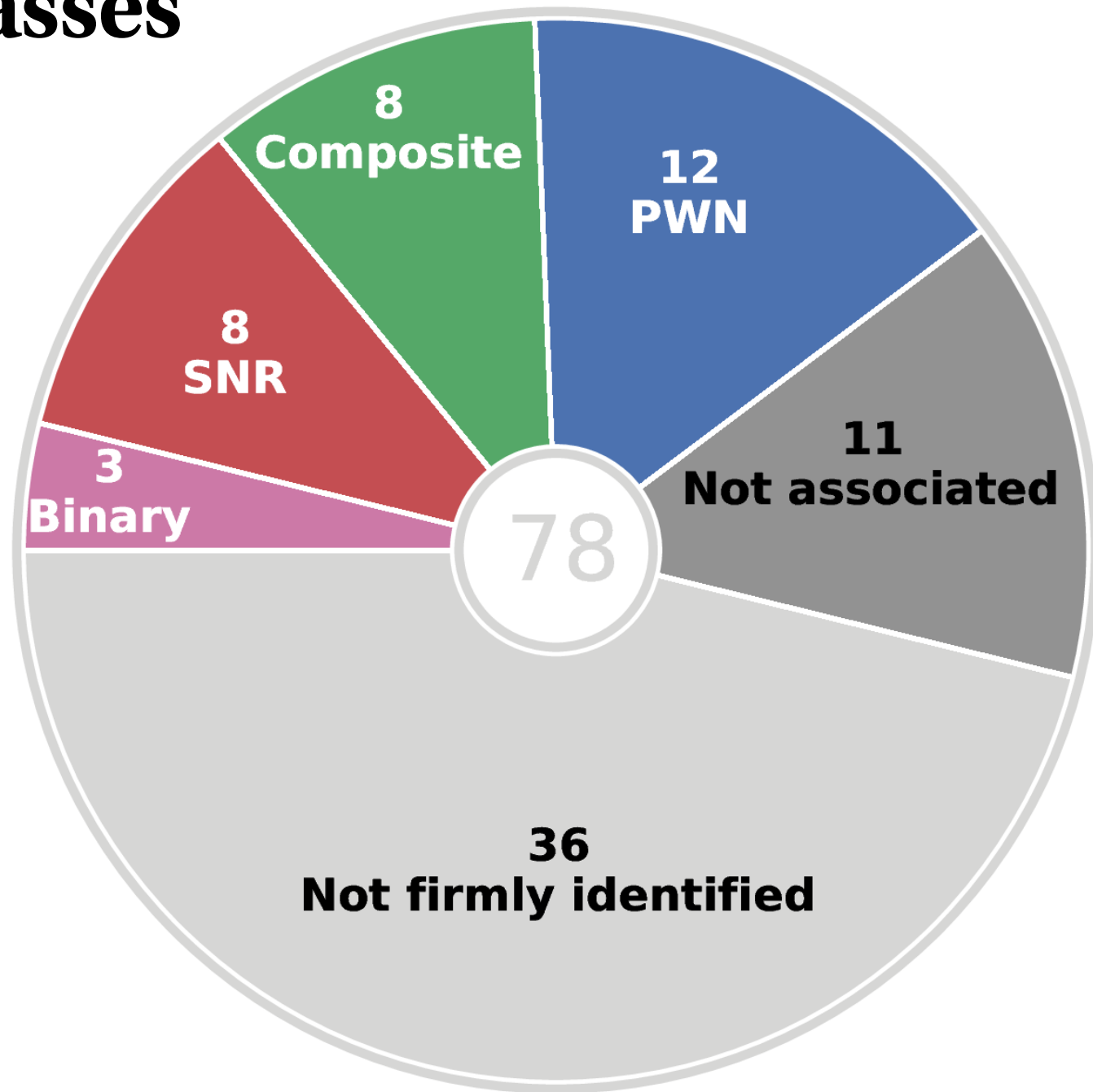
(W28?)

Other notable
CC SNRs outside
HGPS region:

+ **Cas A**

+ **IC 443**

+ **Gamma Cygni**
(VERITAS/MAGIC)

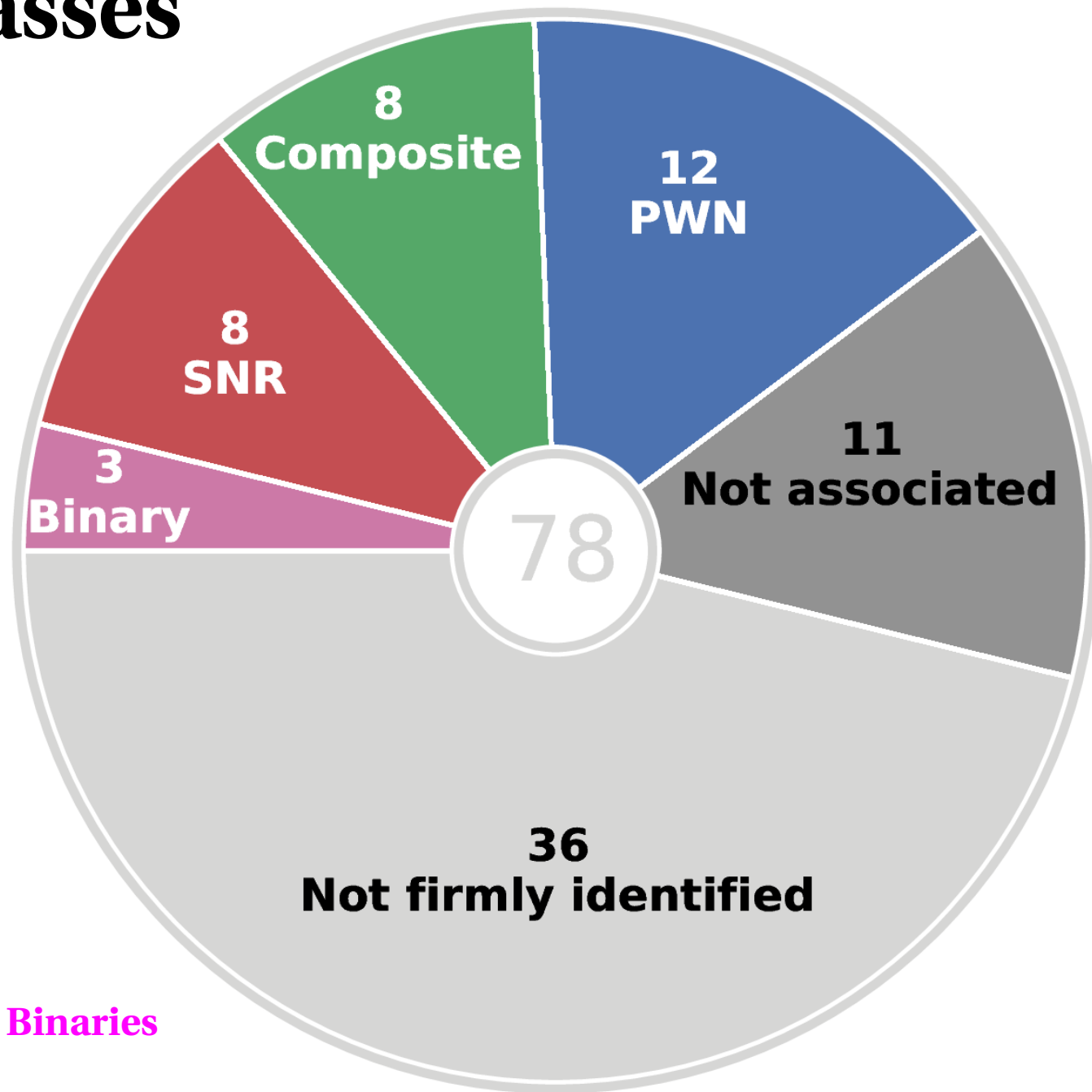


Abdalla,...,Chaves+(H.E.S.S.)17 in prep

VHE source classes

(HGPS region only)

Composite:
Cannot disentangle
between SNR shell
origin and PWN origin



MWL counterparts:

PWNe (SNRcat), **SNRs** (SNRcat), **Binaries**

HE sources (2FHL, 3FGL)

PSRs (ATNF)

Abdalla,...,Chaves+(H.E.S.S.)17 in prep

VHE source classes

(HGPS region only)

Composite:
Cannot disentangle
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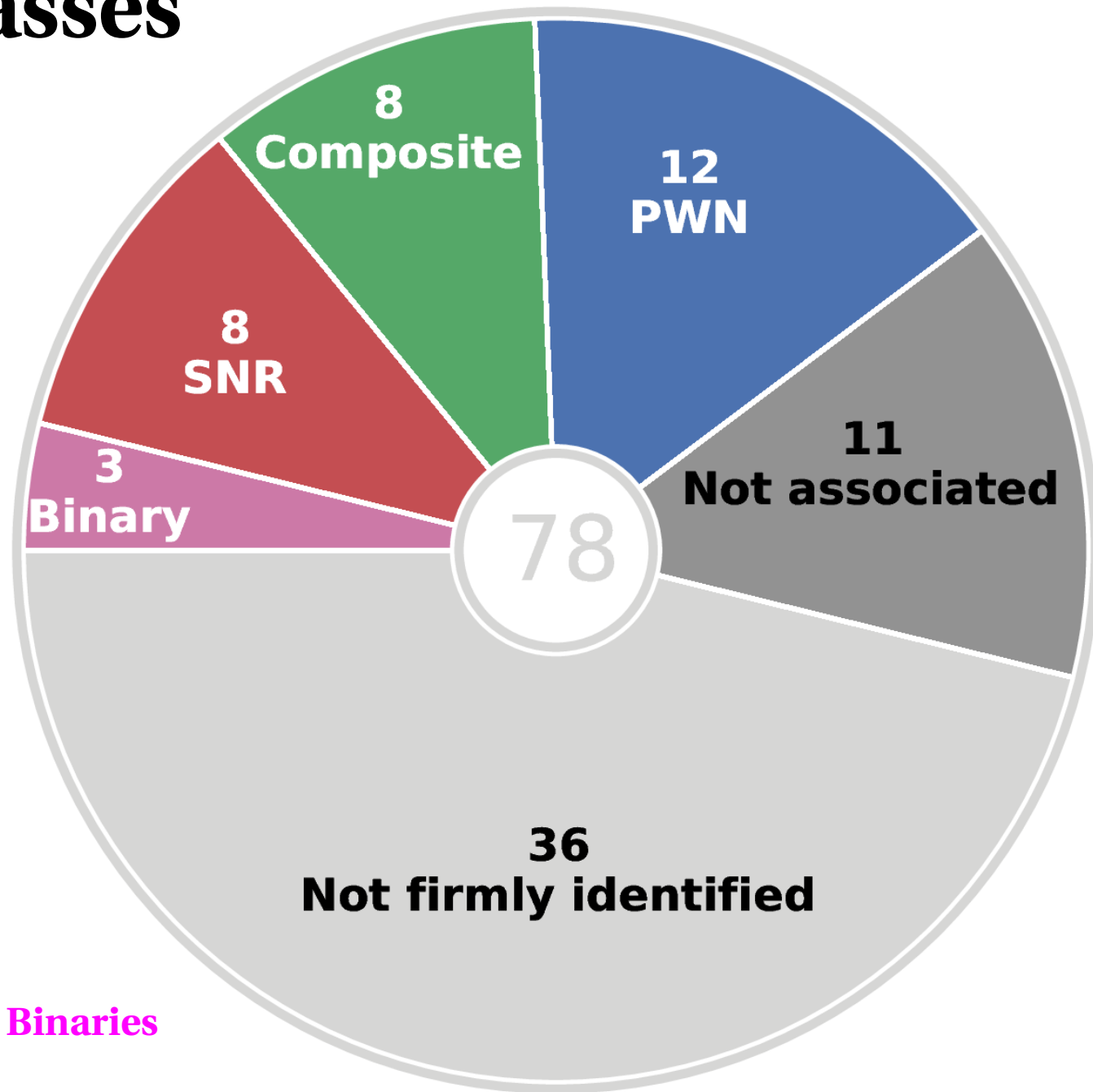
Not firmly ID'd:
But spatial
associations exist
(often multiple)

MWL counterparts:

PWNe (SNRcat), **SNRs** (SNRcat), **Binaries**

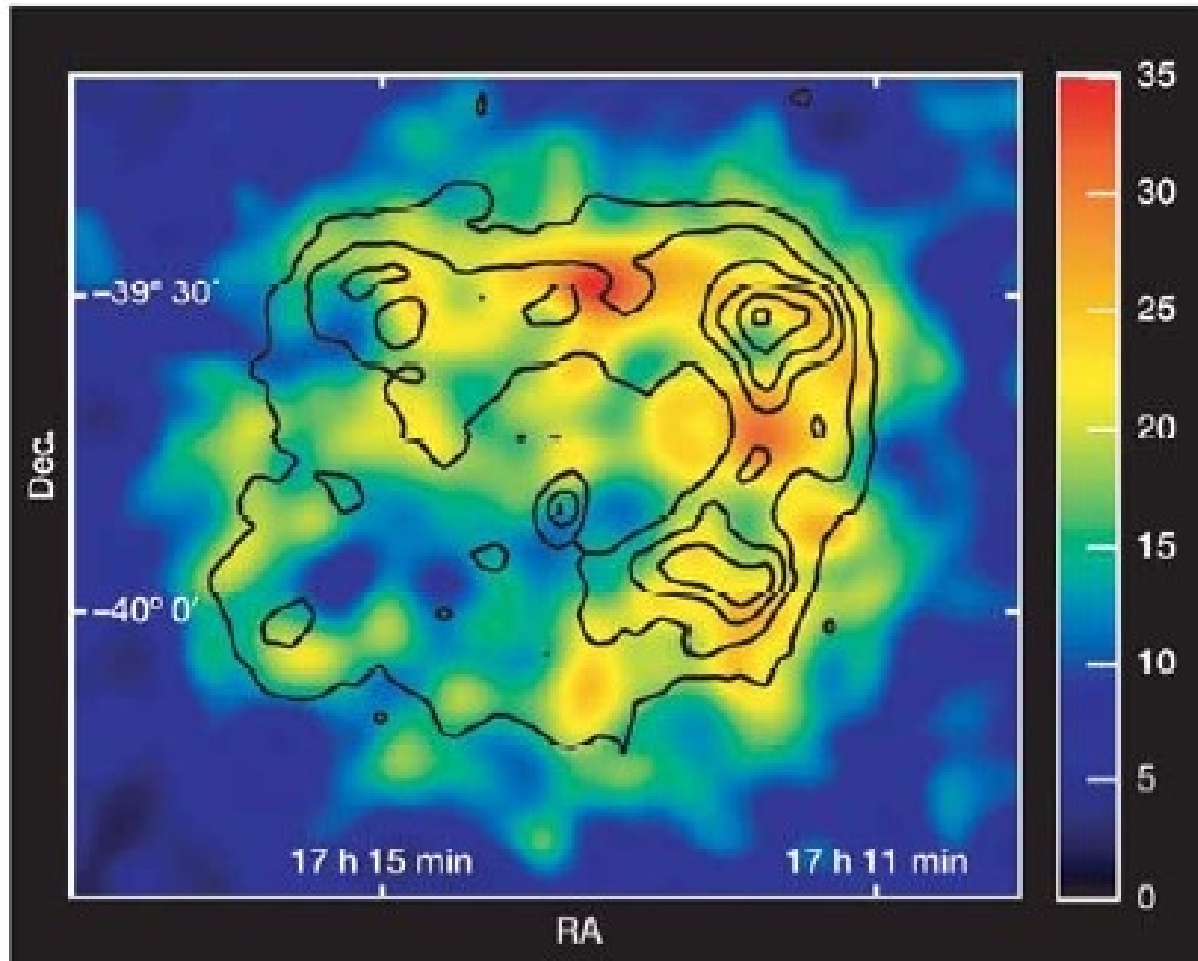
HE sources (2FHL, 3FGL)

PSRs (ATNF)



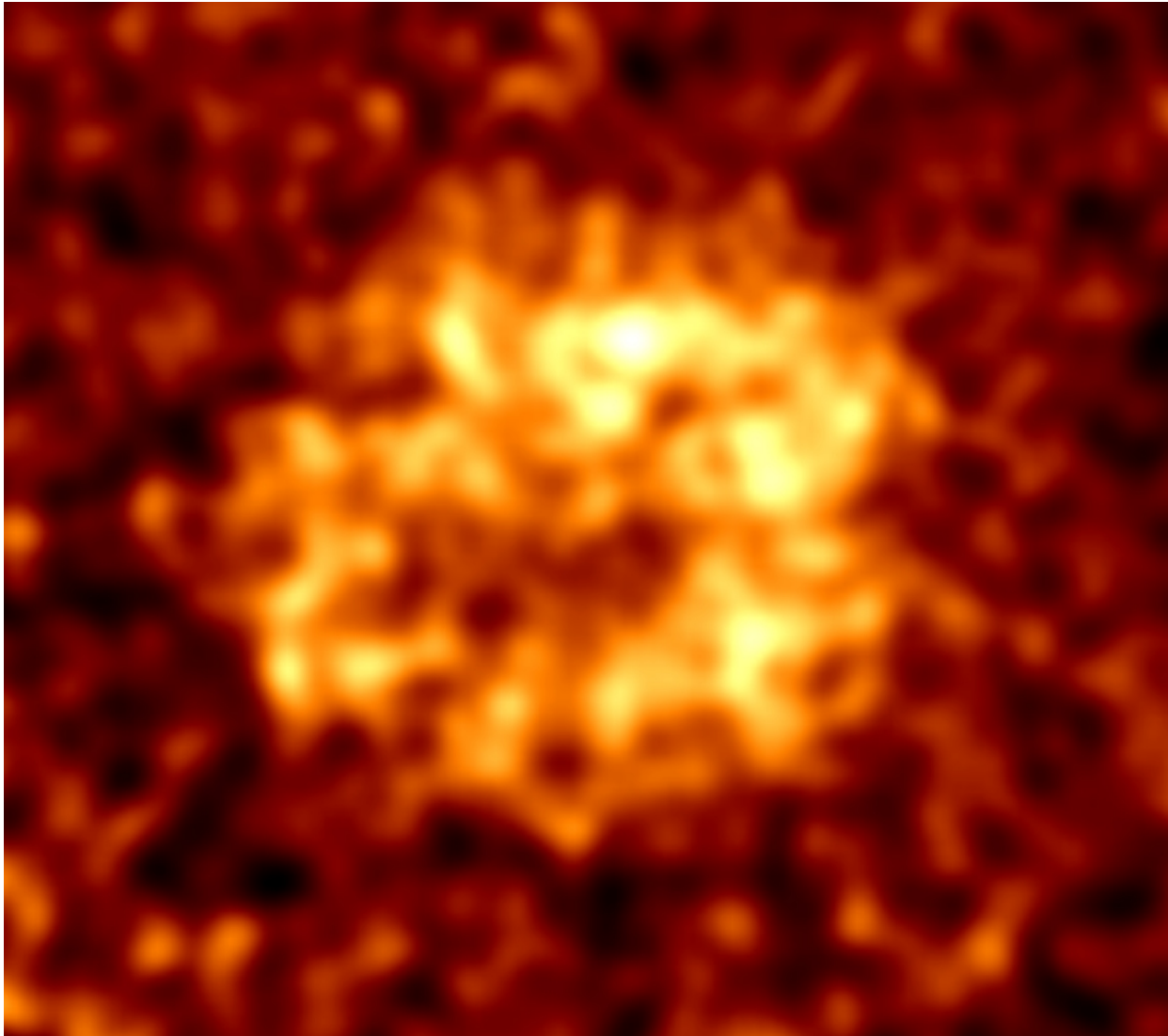
Abdalla,...,Chaves+(H.E.S.S.)17 in prep

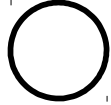
RX J1713.7-3496



Aharonian+(H.E.S.S.)05

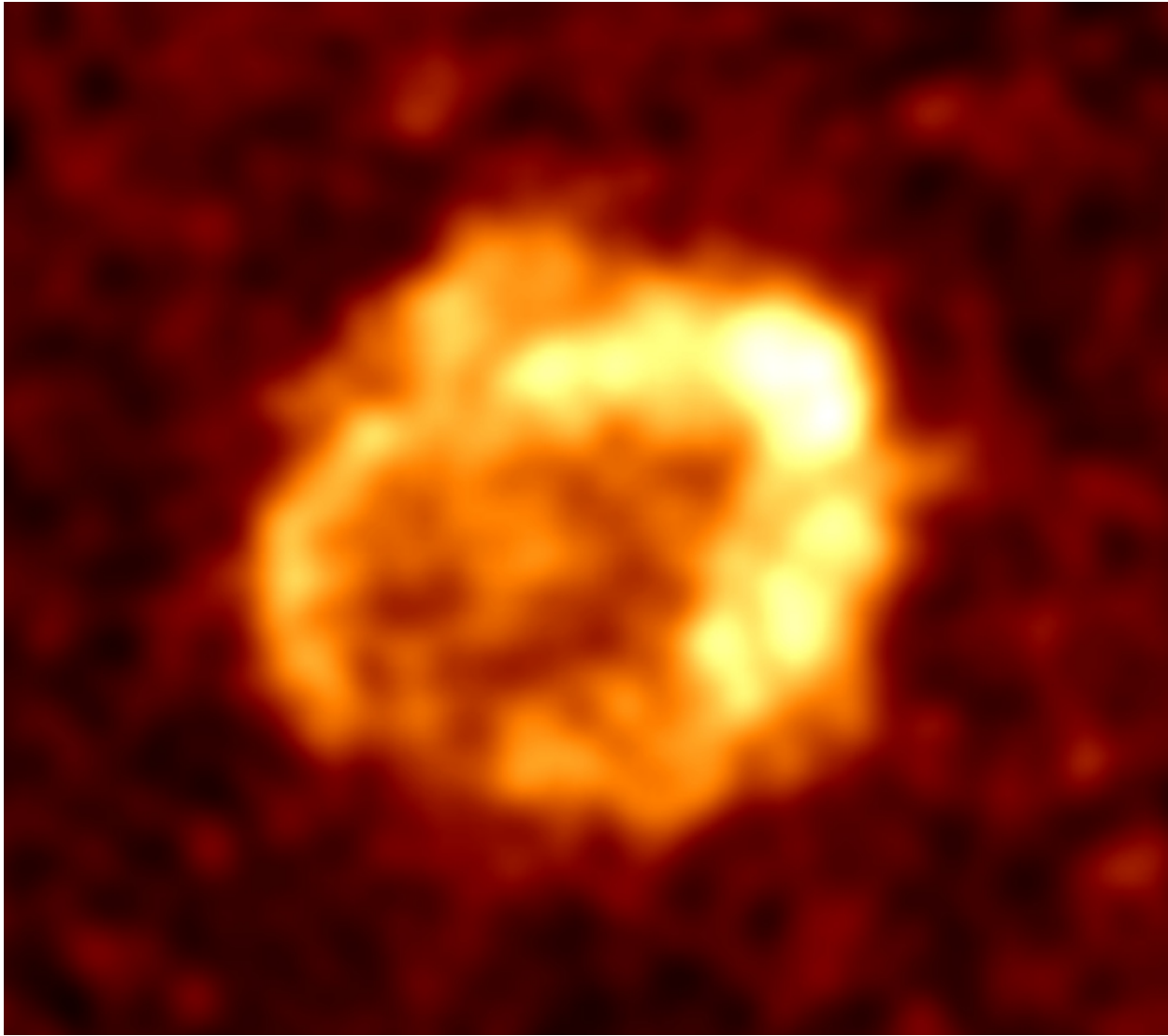
RX J1713.7-3496



- 18 h livetime
- $E_{\min} = 1 \text{ TeV}$
- γ -ray excess: 1430
- 2004
- 
- PSF (R_{68}): 4.8'

Abdalla,...,Chaves+(H.E.S.S.)17
See also IAU talks by Ballet, others

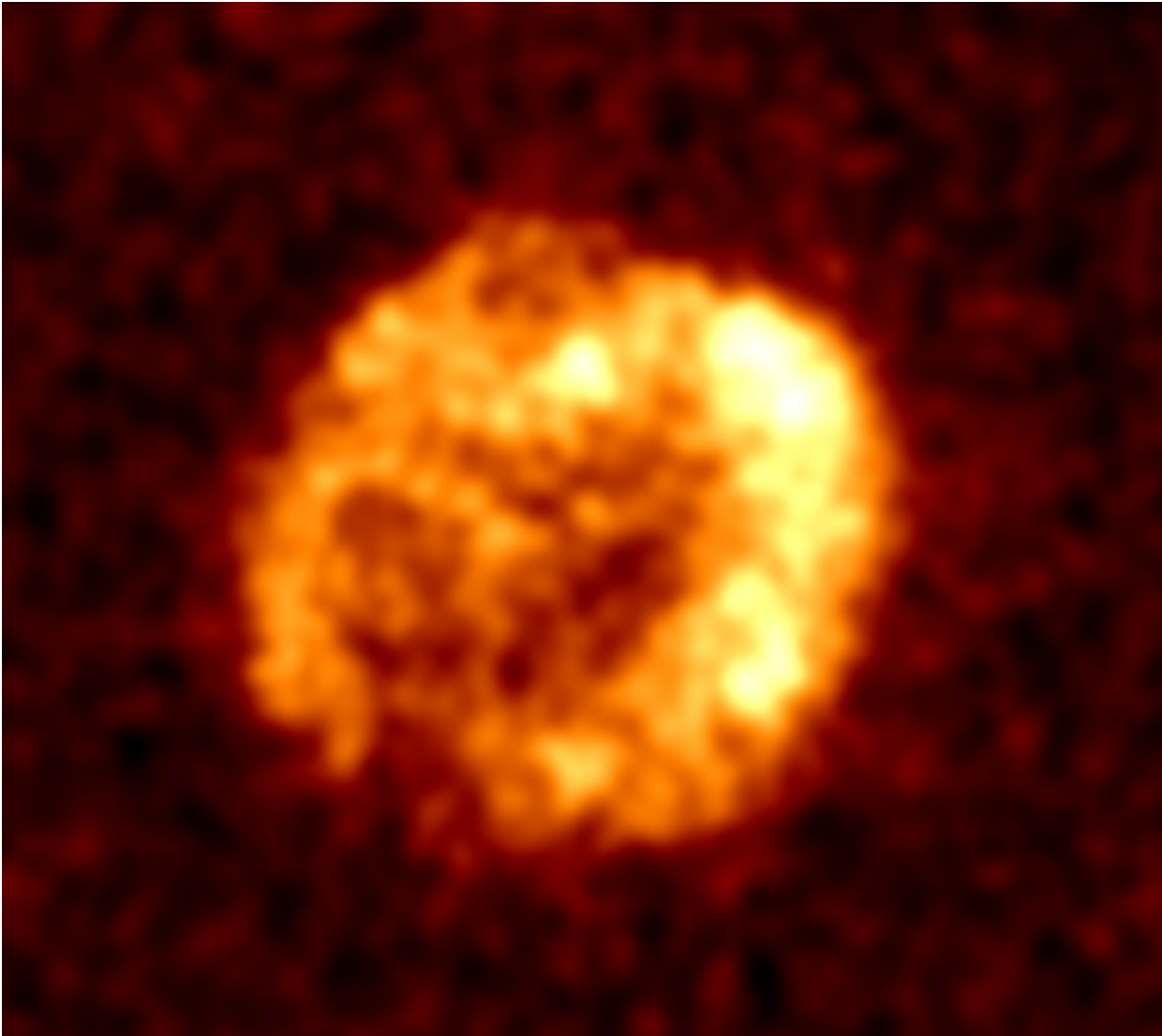
RX J1713.7-3496

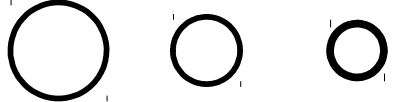


- **63 h** livetime
- $E_{\min} = \mathbf{0.3 \text{ TeV}}$
- γ -ray excess: **6700**
- 2004 **2006**
- PSF (R_{68}): **3.6'**

Abdalla,...,Chaves+(H.E.S.S.)17
See also IAU talks by Ballet, others

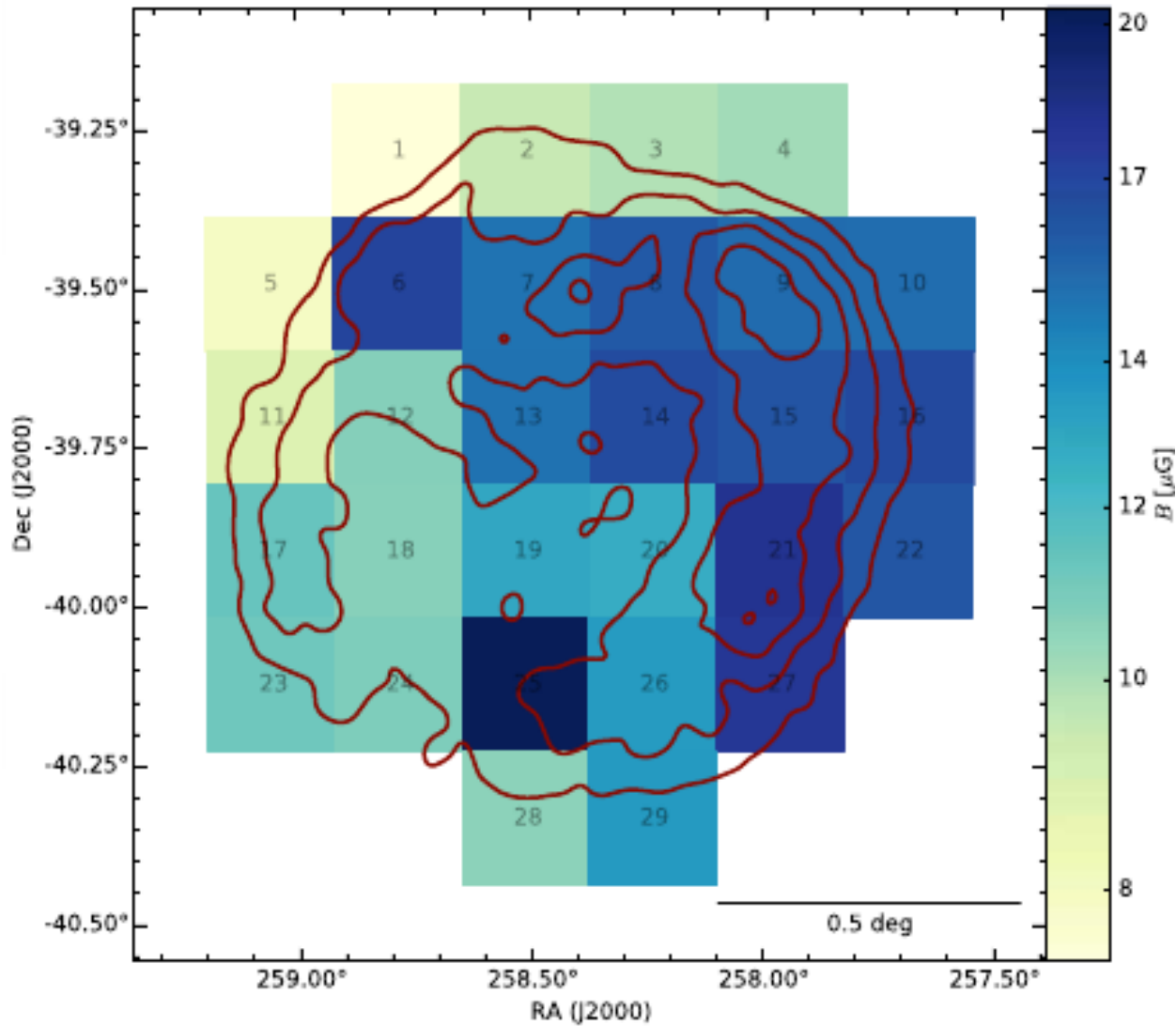
RX J1713.7-3496



- **164 h** livetime
- $E_{\min} = \mathbf{0.25 \text{ TeV}}$
- γ -ray excess: **31000**
- 2004 2006 **2016**

- PSF (R_{68}): **2.9'**
- **Deep observations** and systematics control leading to **precise measurements:**
smallest PSF ever achieved in VHE
*PSF ($E > 2 \text{ TeV}$): **2.2'***

Abdalla,...,Chaves+(H.E.S.S.)17
See also IAU talks by Ballet, others

RX J1713.7-3496: B-field mapping

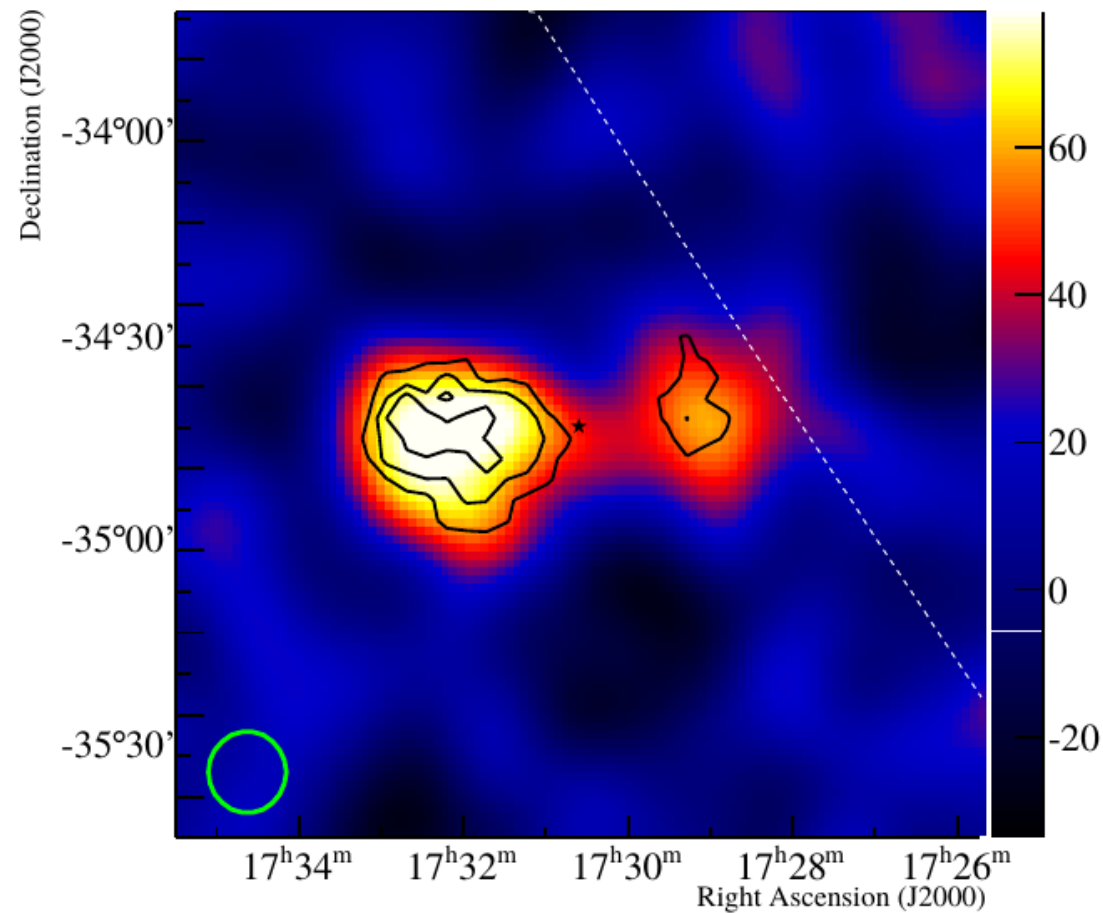


Evolving capabilities
in VHE astronomy

Allows more detailed
model comparisons

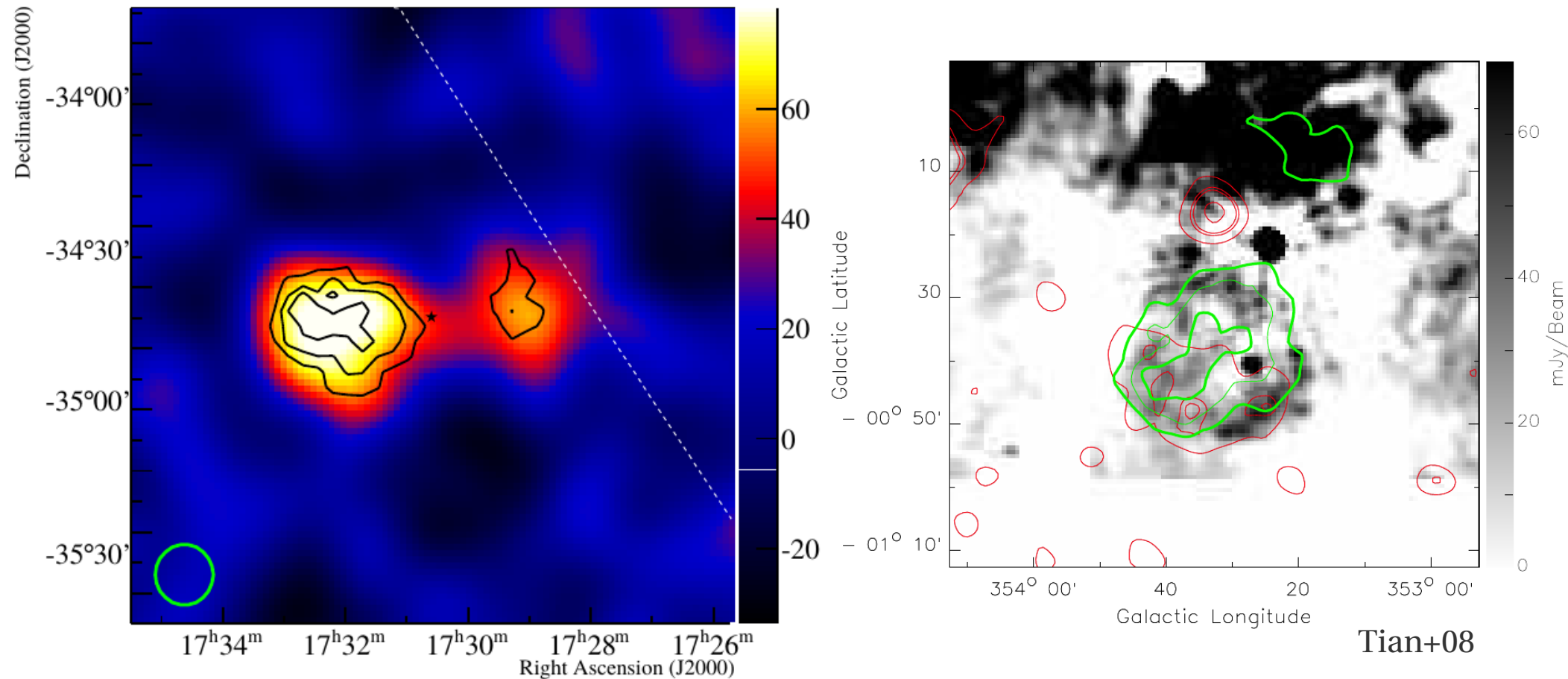
Abdalla, ..., Chaves+ (H.E.S.S.) 17
See also IAU talks by Ballet, others

UNID'd source (2008): HESS J1731-347



Aharonian+(H.E.S.S.)08

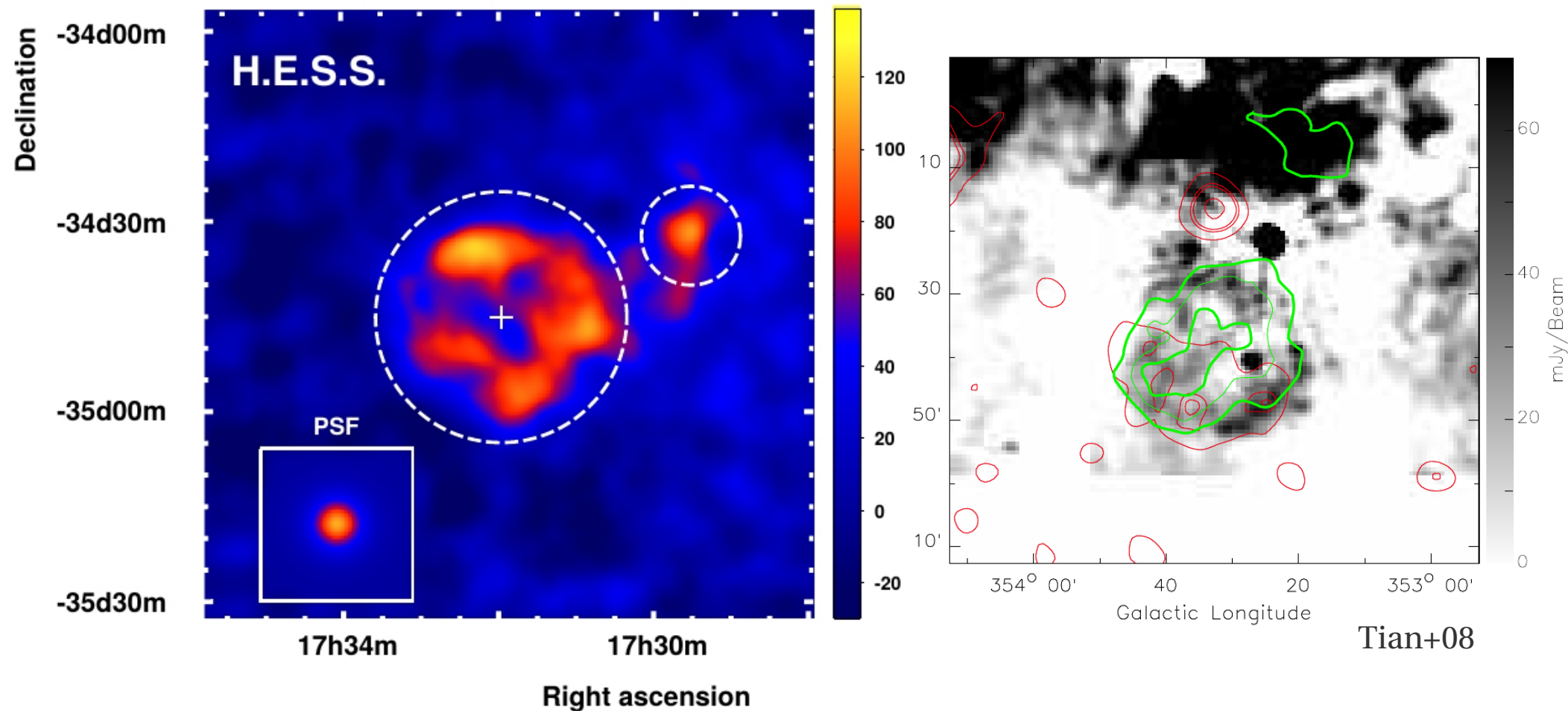
VHE leads to SNR discovery: HESS J1731-347



Aharonian+(H.E.S.S.)08

First time SNR discovery initiated by VHE channel

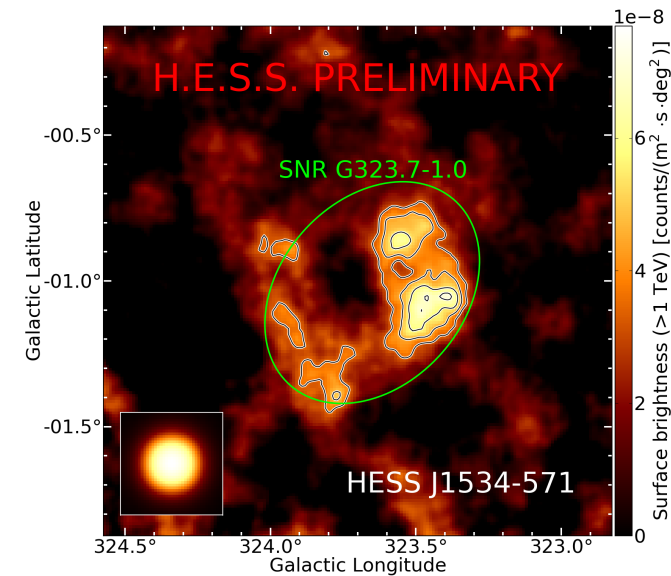
VHE leads to SNR discovery: HESS J1731-347



Abramowski,...,Chaves+(H.E.S.S.)11

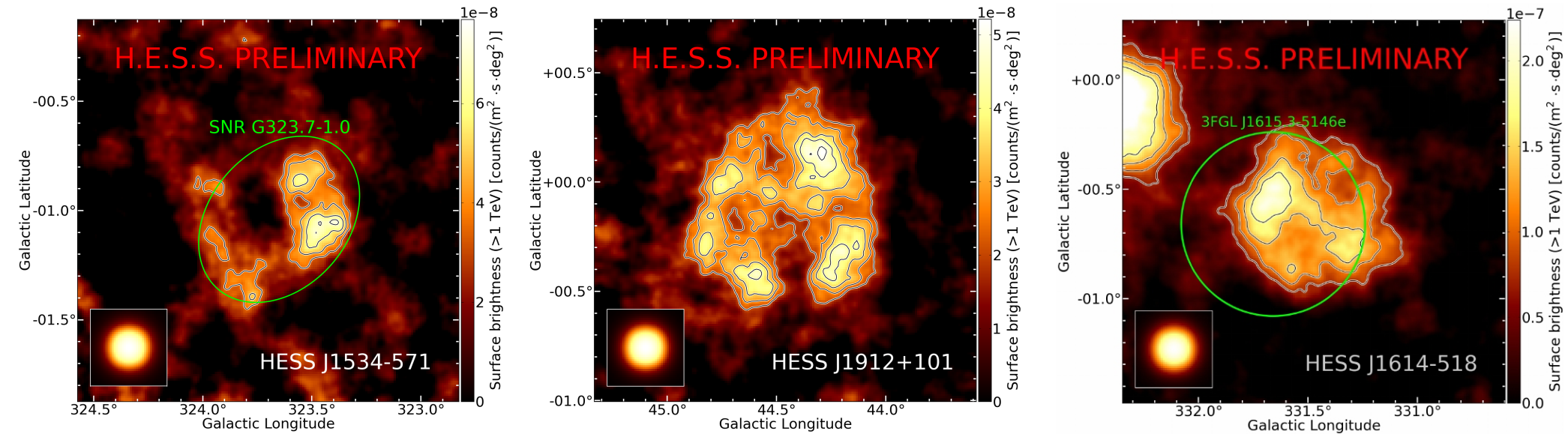
First time SNR discovery initiated by VHE channel
VHE shell morphology significant
Many studies now of SNR-MC scenario w/ nearby HESS J1729-345

New VHE shells, now 9 total



1 SNR confirmed (coincident with radio SNR candidate)

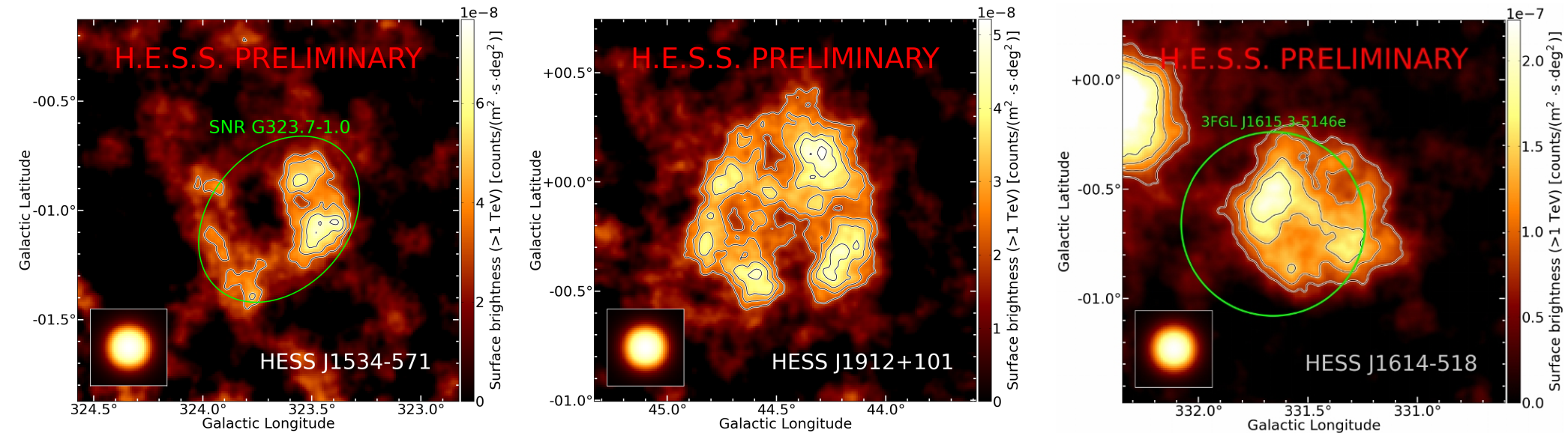
New VHE shells, now 9 total



1 SNR confirmed (coincident with radio SNR candidate)
2 new SNR candidates

Puelhofer, ..., Chaves+ (H.E.S.S.) 15
Abdalla, ..., Chaves+ (H.E.S.S.) 17 in prep

New VHE shells, now 9 total



1 SNR confirmed (coincident with radio SNR candidate)
2 new SNR candidates

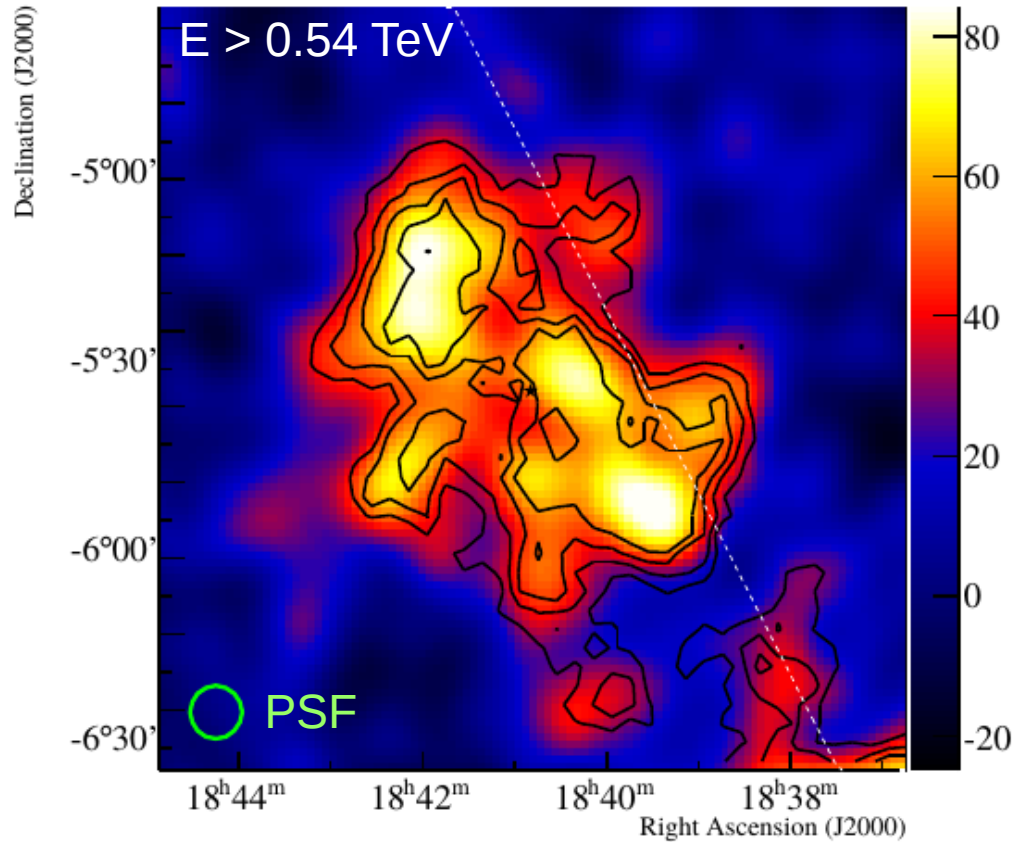
Following **systematic search for shell-like* morphologies** in HGPS
*azimuthally-symmetric, homogeneous, projected 3D shells

*Can we find “missing” SNRs via VHE observations?
Does assumed symmetry bias us toward Type Ia SNRs?*

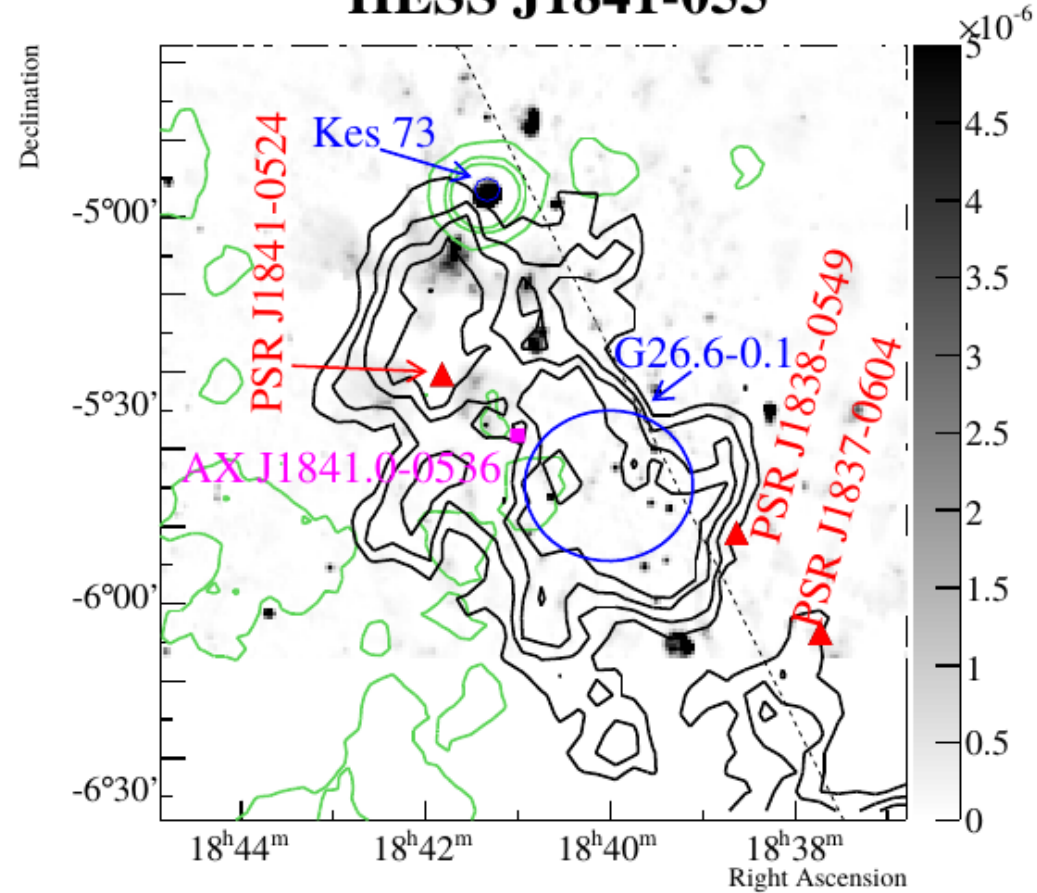
Puelhofer,...,Chaves+(H.E.S.S.)15
Abdalla,...,Chaves+(H.E.S.S.)17 in prep

Source confusion

HESS J1841-055



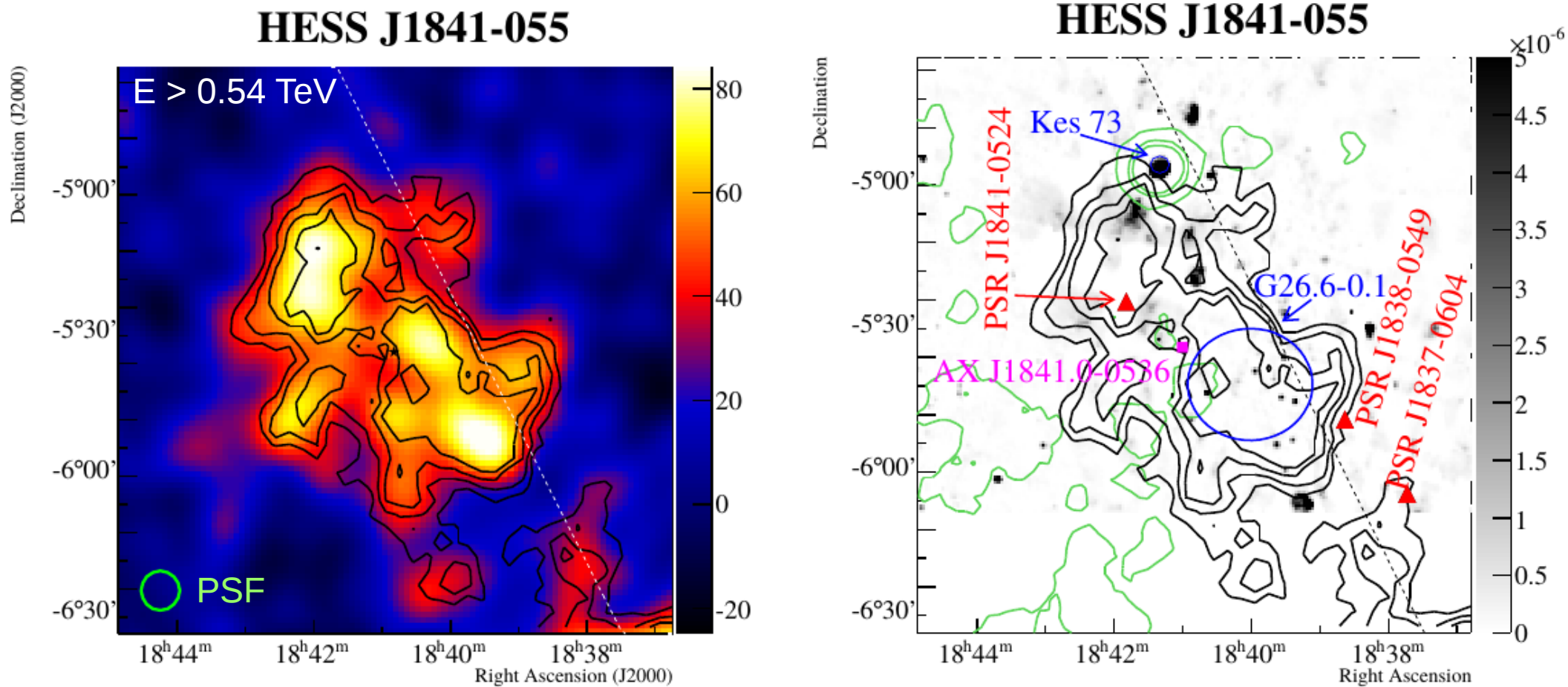
HESS J1841-055



Aharonian+(H.E.S.S.)08

Very complex VHE emission near rim of CC SNR **Kes 73** (age 500-2200 yr)

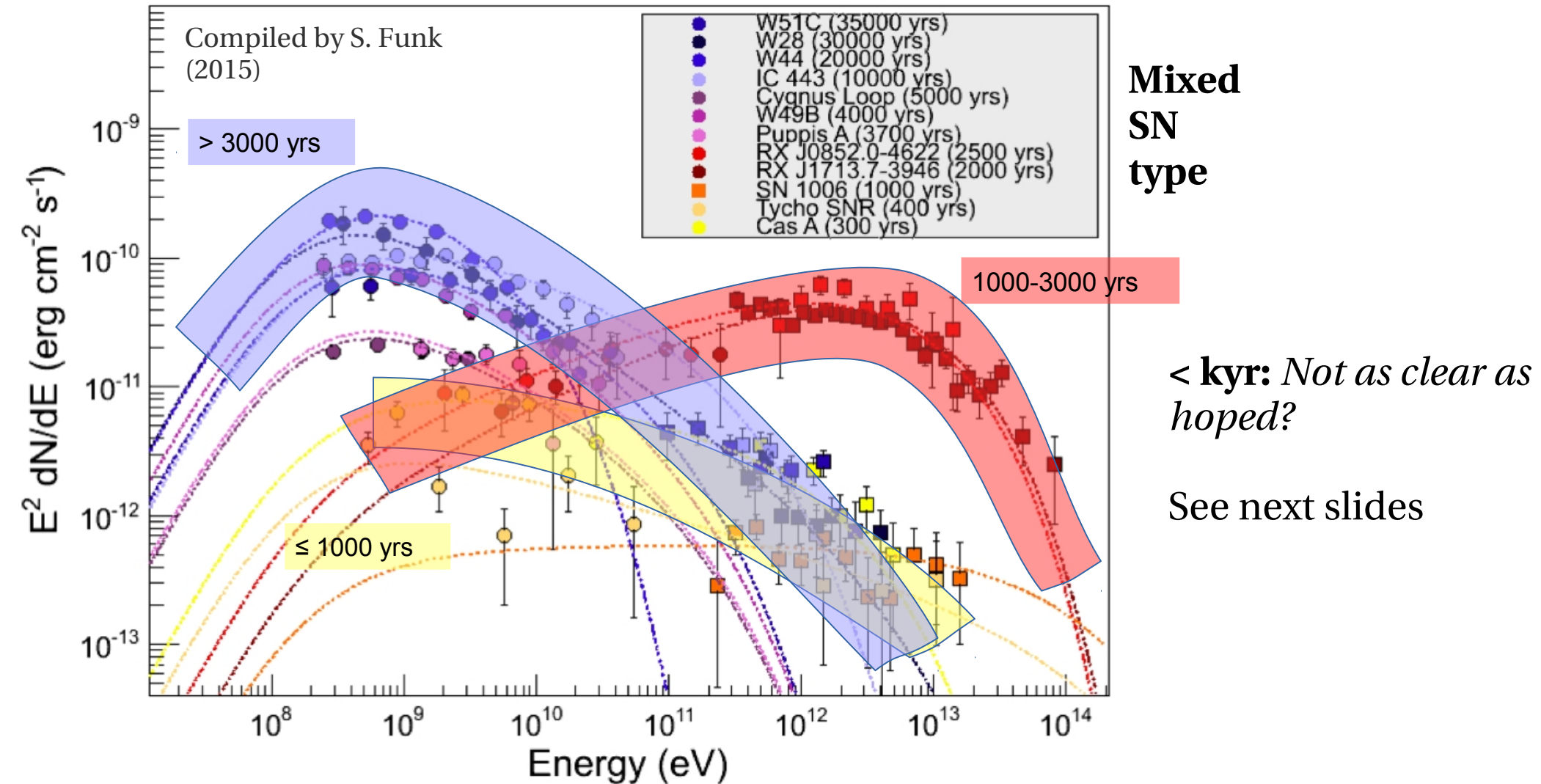
Source confusion



Aharonian+(H.E.S.S.)08

Very complex VHE emission near rim of CC SNR **Kes 73** (age 500-2200 yr)
Hadronic emission from SNR-MC interaction possible (e.g. Kilpatrick+16)
But bulk of γ -rays seen above more likely to originate in nearby PWN(e)
Source confusion + SNR too distant ($d = 7.5-9.8$ kpc) vs. HGPS sensitivity

Clear spectral trends vs. SNR age?



~3+ kyr: Relatively clear
 Soft spectra
 Pion bumps (IC 443, W44, W 51C, W49B)
 (but SNR-MC...)

~1-3 kyr: Clear but only ~2 detected
 Spectral cut-offs 7-15 TeV
 RX J1713 (CC), Vela Jr (Ia)

ccSN link to search for CR PeVatrons

How to get to the cosmic-ray knee?

Young:

- $E_{\max} \sim \text{PeV}$ for only ~ 50 yr or less
- NRH instability quenched after $\sim \text{kyr}$ for $B \sim 5 \mu\text{G}$

Very fast:

- $20,000 \text{ km s}^{-1}$ SNR shock

In dense wind (CSM):

- from ccSN & RSG progenitor

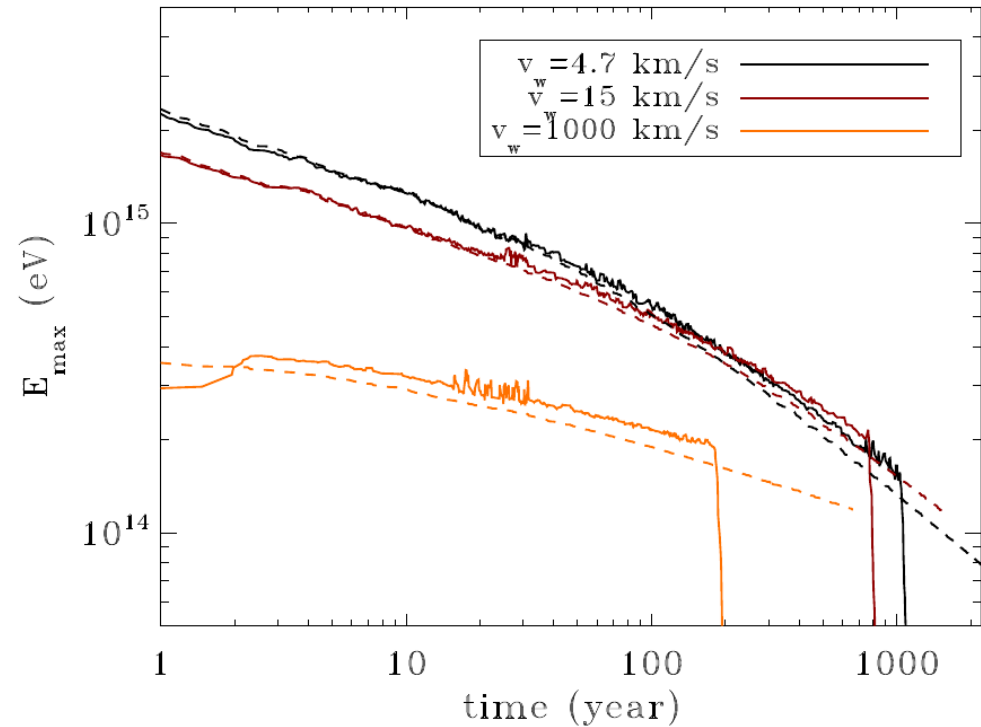
4 youngest Galactic SNRs:

ccSN: **Cas A** (340 yr)

Ia: **G1.9** (~ 150 yr)

Tycho (445 yr)

SN 1006 (1011 yr)



e.g. Schure&Bell+13
See also IAU talk by Morlino

ccSN link to search for CR PeVatrons

Cas A

$$E_{\gamma,\max} > 7 \text{ TeV} \rightarrow E_{p,\max} > \sim 100 \text{ TeV}$$

$$\Gamma = -2.75 \pm 0.10_{\text{stat}} \pm 0.20_{\text{syst}} \quad \text{Acciari+(VERITAS)10}$$

G1.9

mCrab VHE upper limits after deep exposure
(low density?) Abramowski,...,Chaves+(H.E.S.S.)13

SN 1006 also not hard (-2.4), extends to ~ 10 TeV

Acero,...,Chaves+(H.E.S.S.)10

Tycho:

next slide

Observation strategy for Cherenkov telescopes?

- Not looking at the right objects, biased by well-known SNRs?
- Hidden in the existing VHE data but confused / obscured?
- Need more statistics / better sensitivity at multi-TeV?
- Nearby / very large and background subtracted?

Aside: Tycho (Type Ia)

$\Gamma =$

- 2.9 (VHE),
- 2.3 (HE-VHE PL), or
- 2.1 (HE-VHE ECPL) ?

vs.

-2.0 (standard DSA prediction)

$E_{\gamma, \text{cut}}$

- > ~8 TeV (VHE or HE-VHE PL) or
- = 1.7 ± 1.2 TeV (HE-VHE ECPL) ?

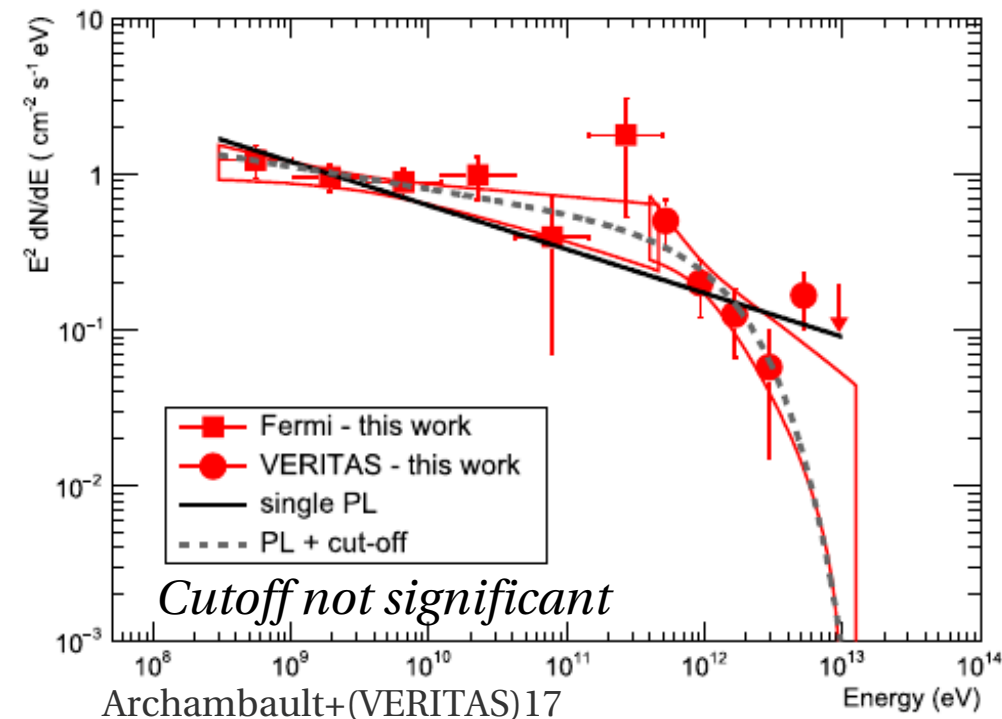
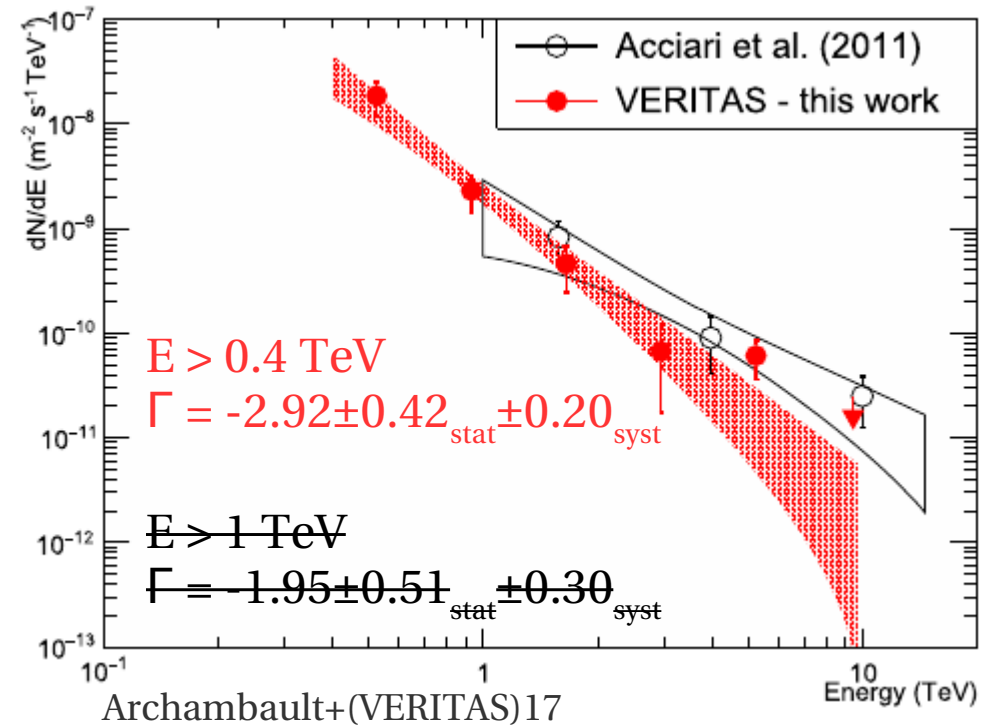
vs.

~ 100 TeV

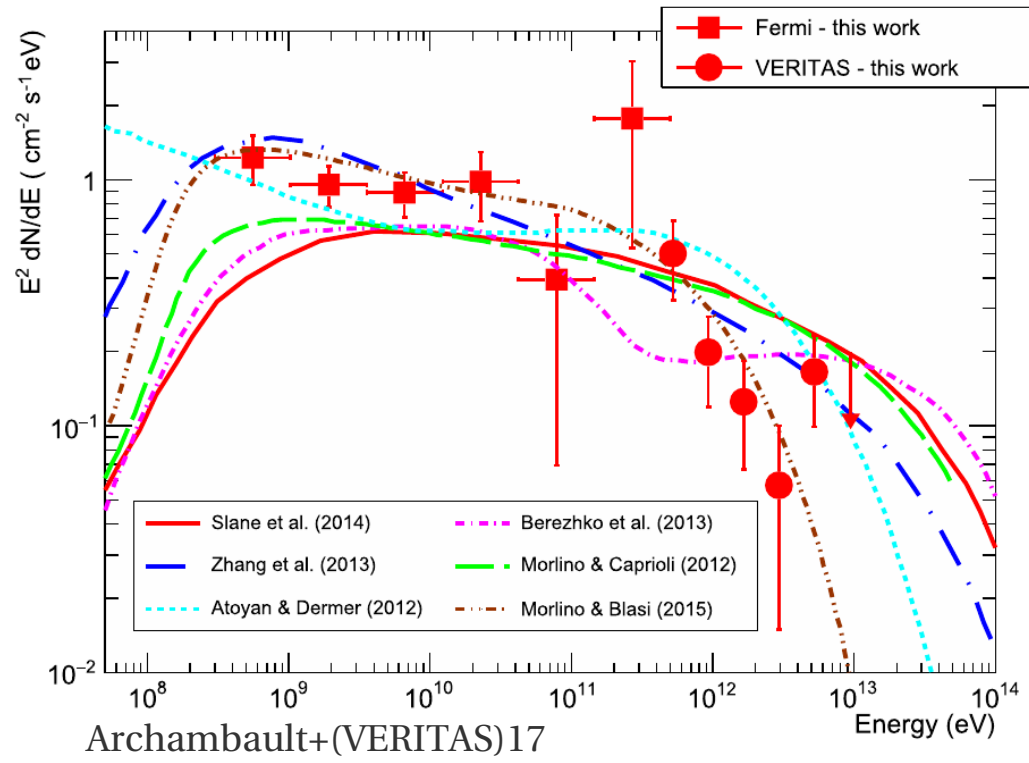
(DSA+, to reach $E_{p, \text{max}} \sim \text{PeV}$)

+ Type Ia

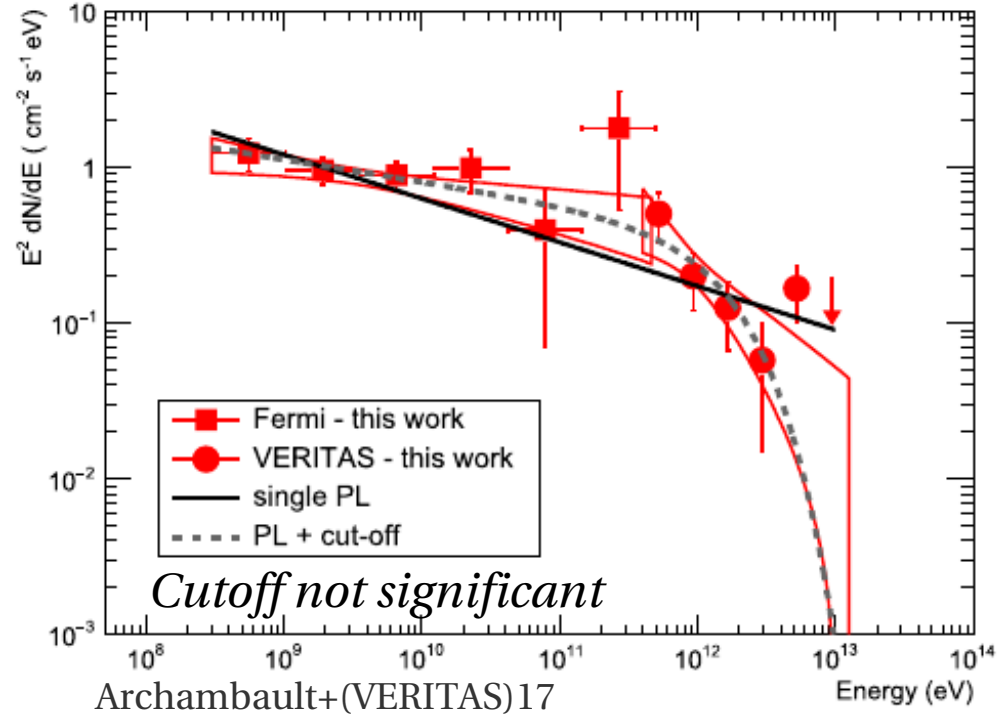
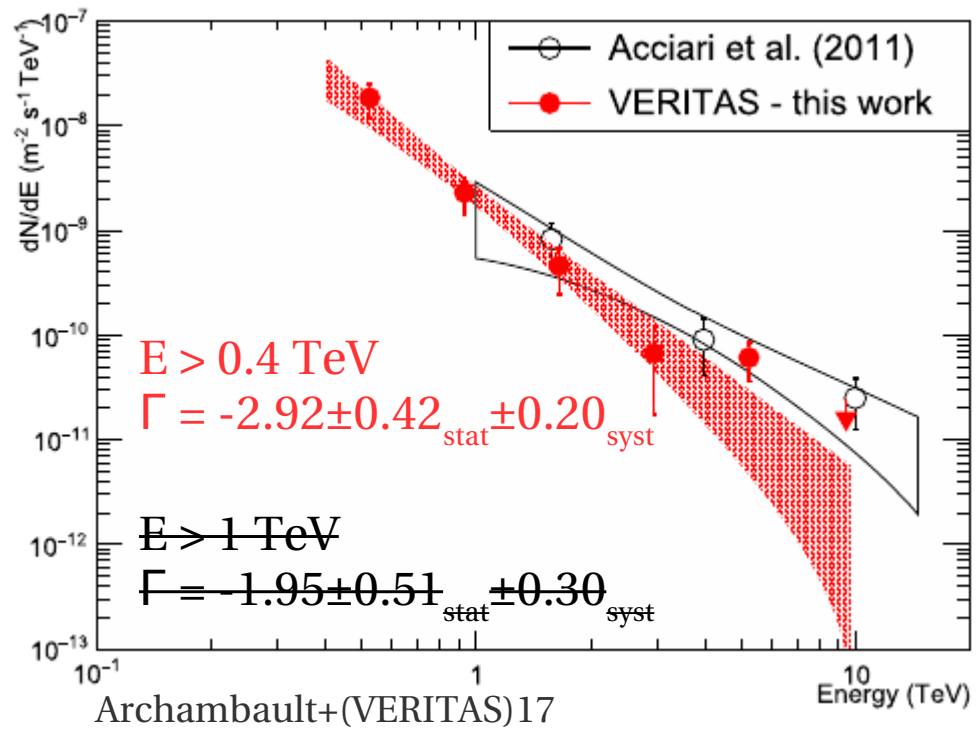
→ Not a good CR PeVatron candidate & will very likely need CTA to do better



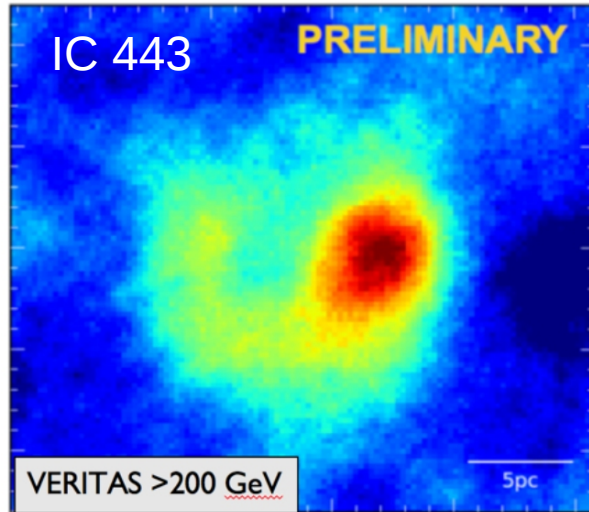
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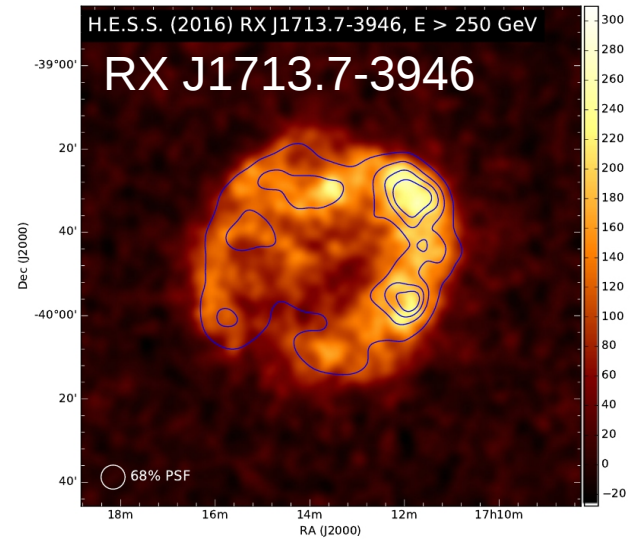
→ **Hadronic-dominated model**
seems favored but not yet
definitive: most modeling
 based on first VERITAS result



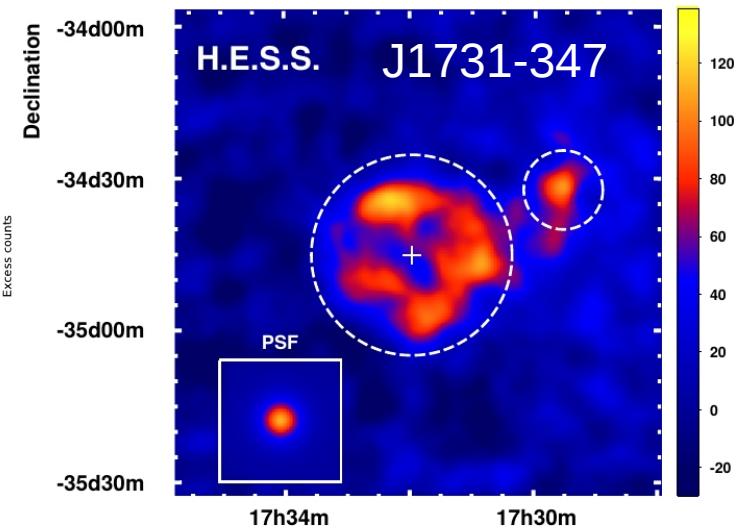
VHE SNRs from ccSNe: Resolved



Holder+(VERITAS)16



Abdalla,...,Chaves+(H.E.S.S.)17

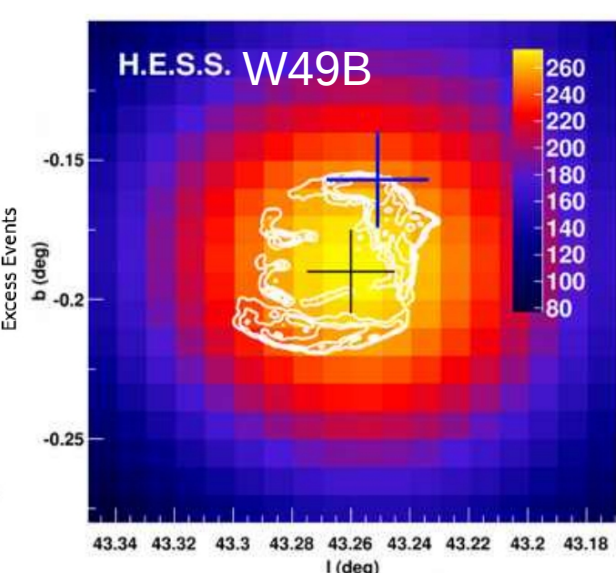
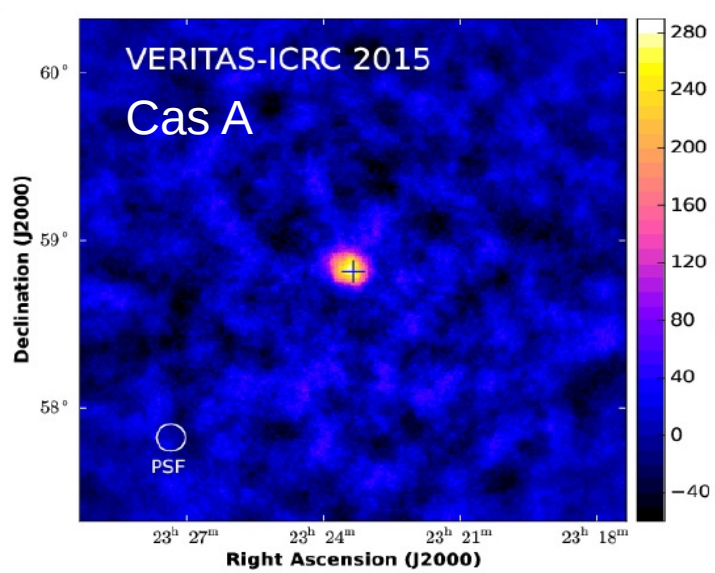
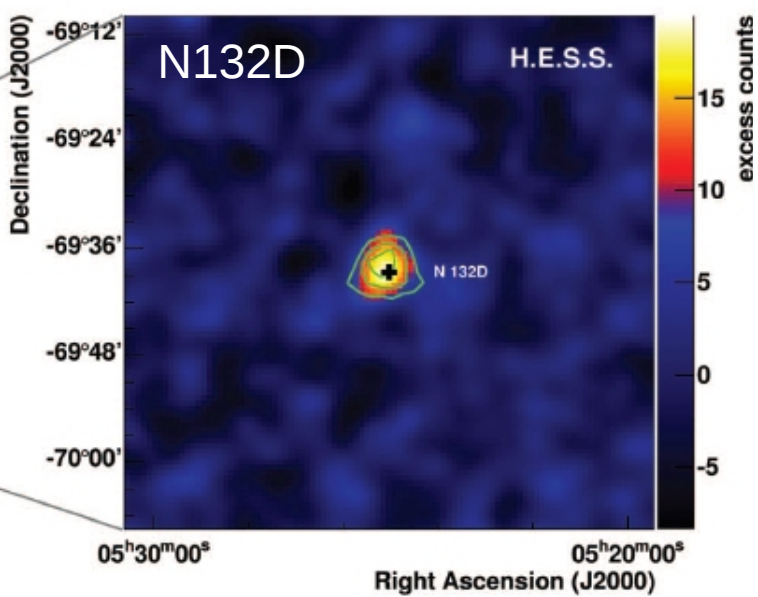


Abramowski,...,Chaves+(H.E.S.S.)11

Prospects for studying VHE shell asymmetries vs. SN type
(but source sample very small, $N \sim 9$)
Inhomogeneities in pre-SN CSM/ambient medium still influential?

VHE SNRs from ccSNe: Point-like

D

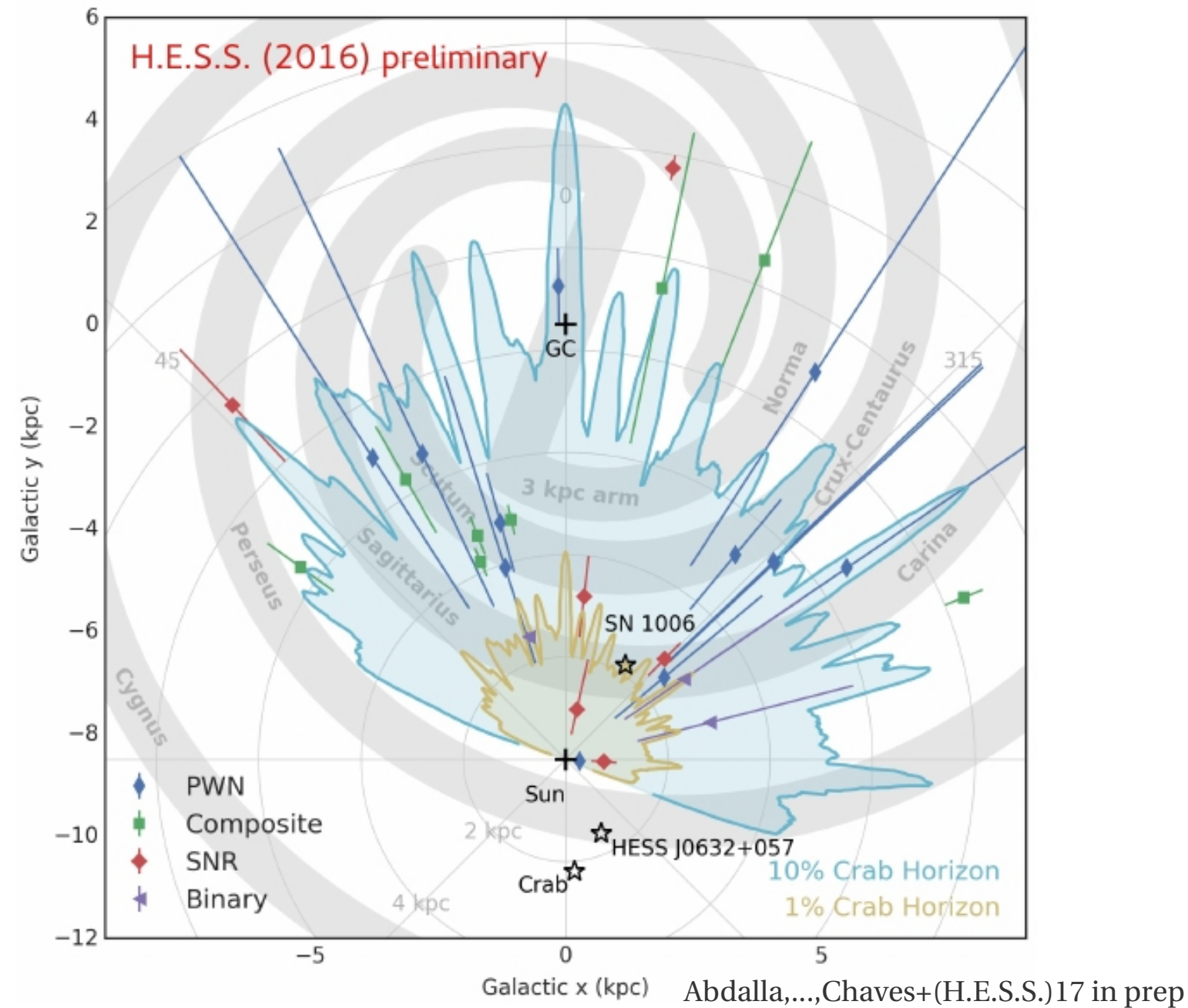


Abramowski,...,Chaves+(H.E.S.S.)14
See IAU talks by Komin, Martin

Ghiotto+(VERITAS)16

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

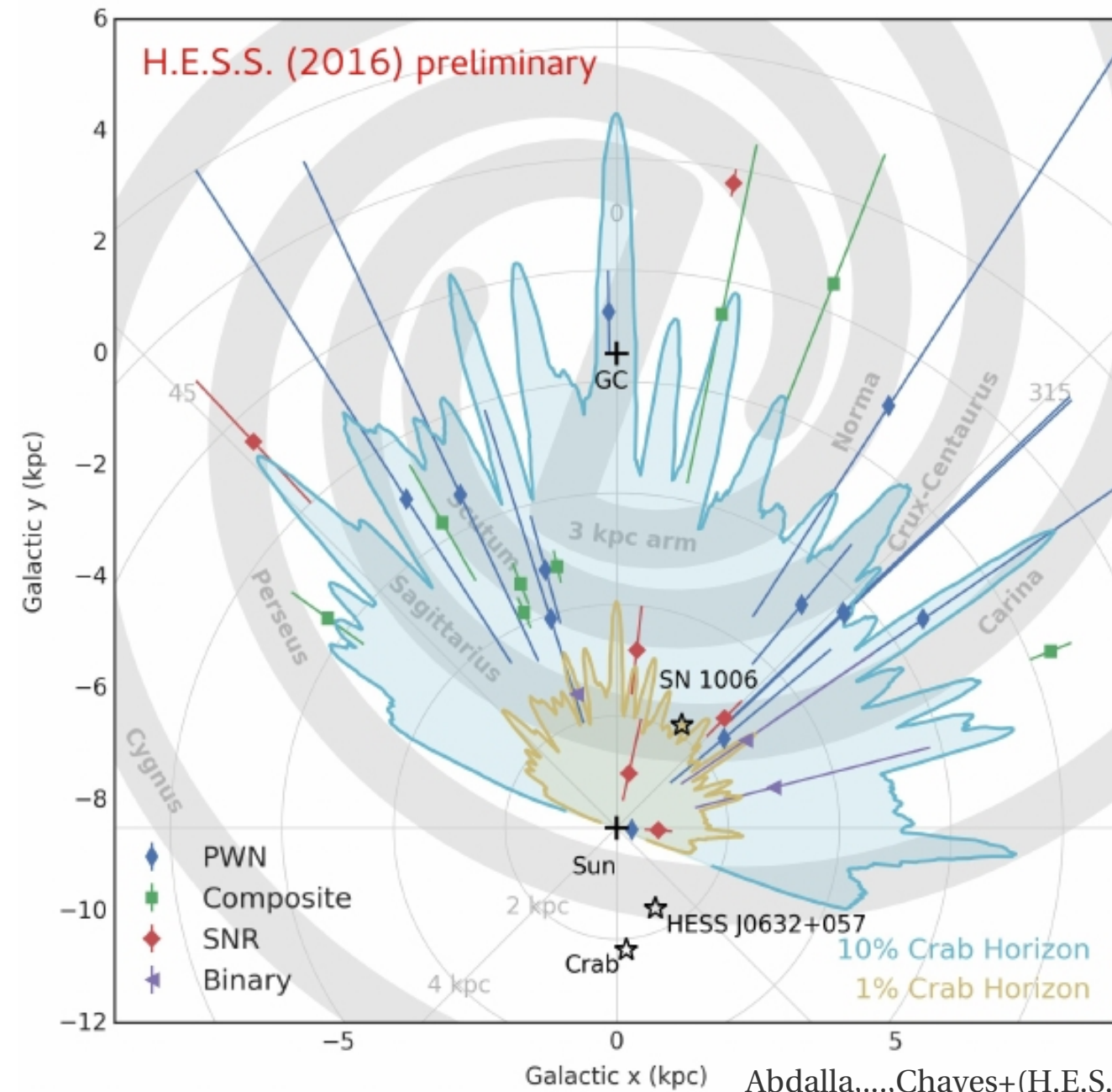
VHE horizon



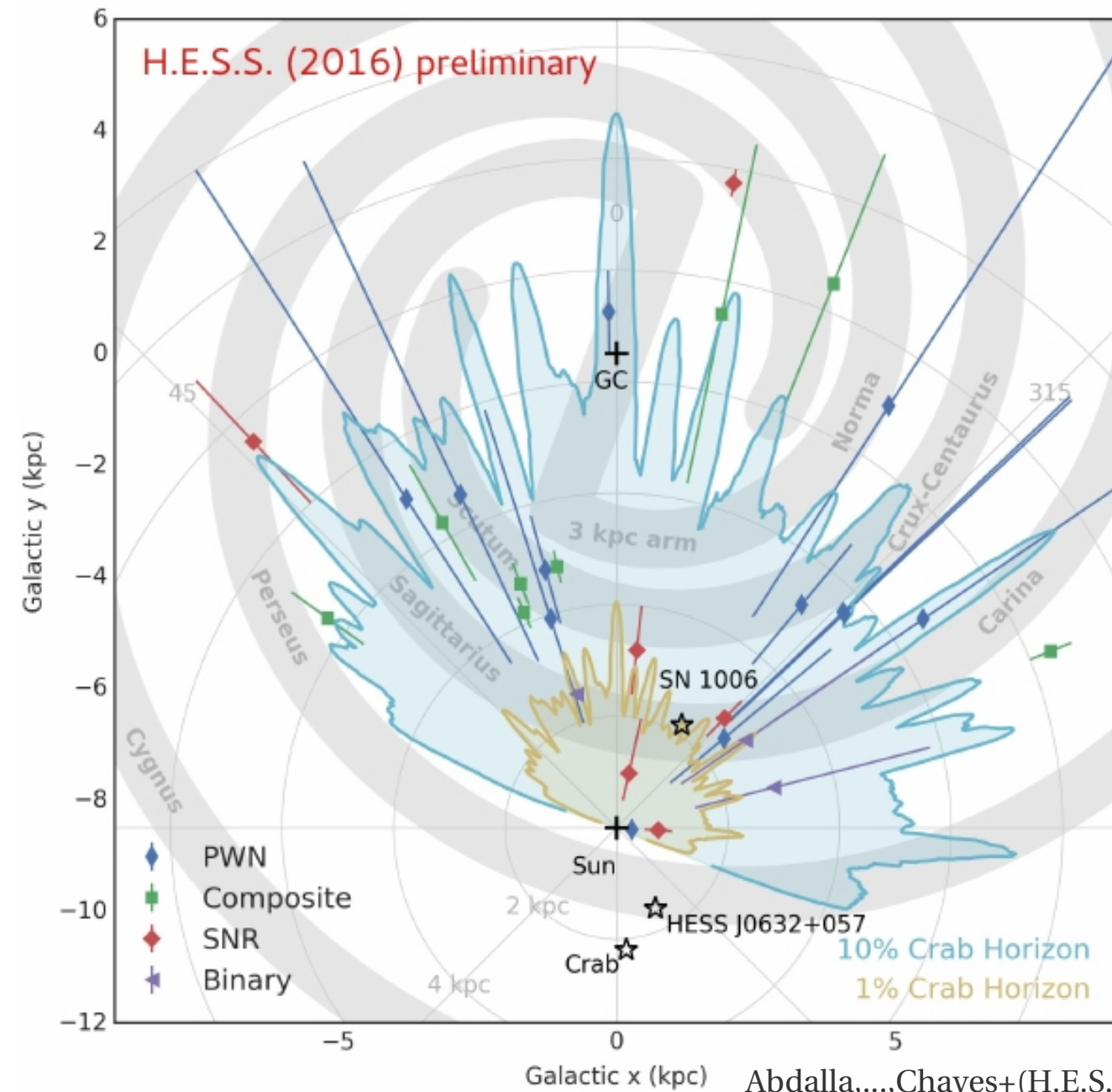
VHE horizon

Current generation
of IACTs:

covered Galaxy
out to ~6-9 kpc for
bright sources



VHE horizon



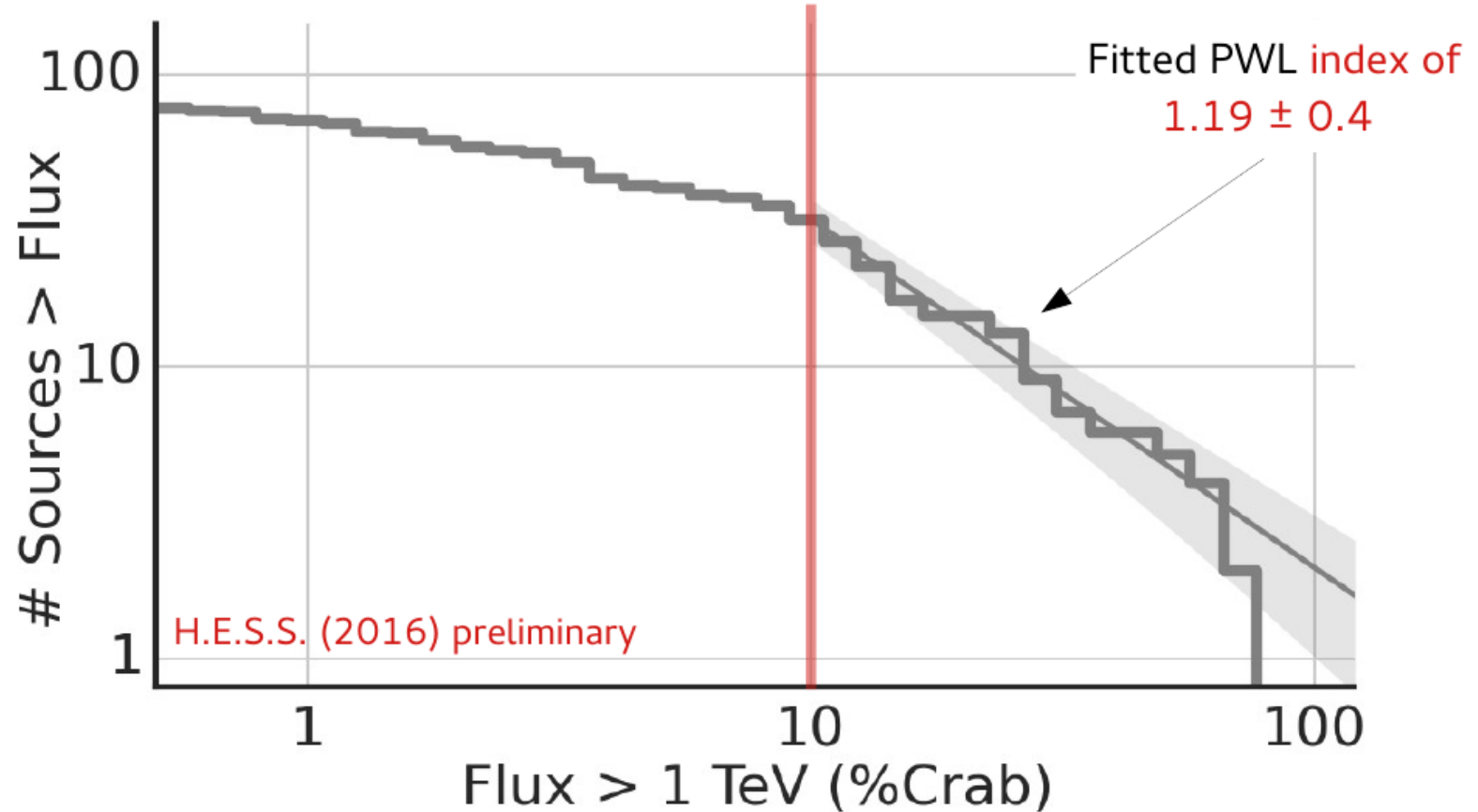
Current generation
of IACTs:

covered Galaxy
out to ~6-9 kpc for
bright sources

but typically
only probe
faint sources within
~2-3 kpc

(notable exception:
ccSNe **N132D** in LMC
detected after 148 h)

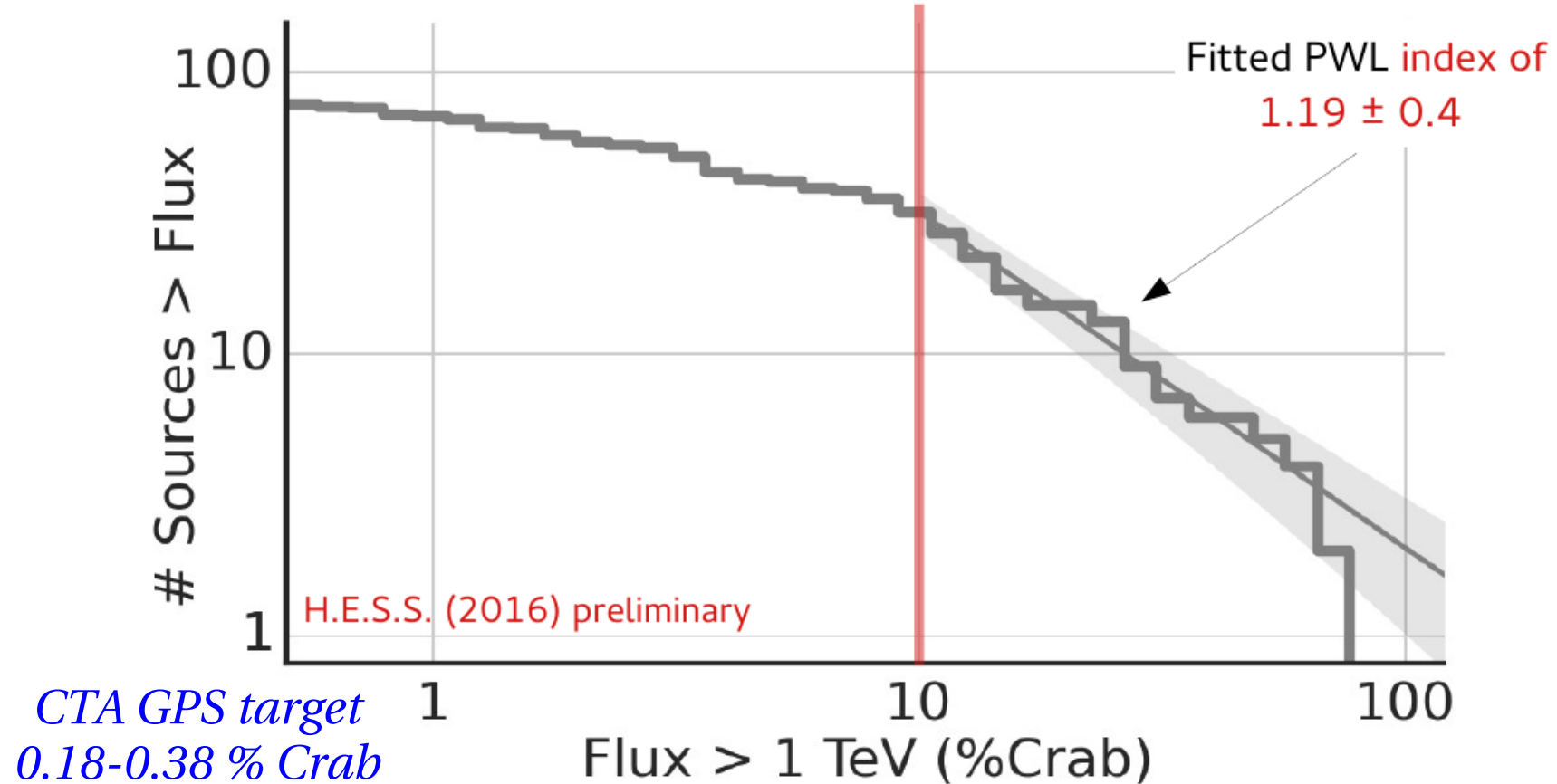
VHE log N – log S



Abdalla,...,Chaves+(H.E.S.S.)17 in prep

HGPS complete for **all source sizes down to 10%**
for **point sources in inner Galaxy down to 1.5%**

VHE log N – log S



Abdalla,...,Chaves+(H.E.S.S.)17 in prep

HGPS complete for **all source sizes down to 10%**
for **point sources in inner Galaxy down to 1.5%**

CTA will detect hundreds of Galactic sources in its 10-yr GPS

Renaud09, Dubus+13, Chaves,Mukherjee,Ong+(CTA)17 in prep

Conclusion: VHE astronomy, not “experiments”

Increasing sample of significant VHE γ -ray emission from numerous SNRs of CC SNe origin in the Galaxy (and one in LMC)

So far no clear VHE signatures for distinguishing CC vs. Type Ia Population (upper limit) studies on-going

Hahn,...,Chaves+(H.E.S.S.)ICRC15
Abdalla,...,Chaves+(H.E.S.S.)17 in prep

Current challenges

Disentangling PWN from shell emission

Multiple source (and counterpart) confusion, incl. SNR-MC

Determining dominant acceleration mechanism (regardless of SN type)

Small (detected) sample size

...

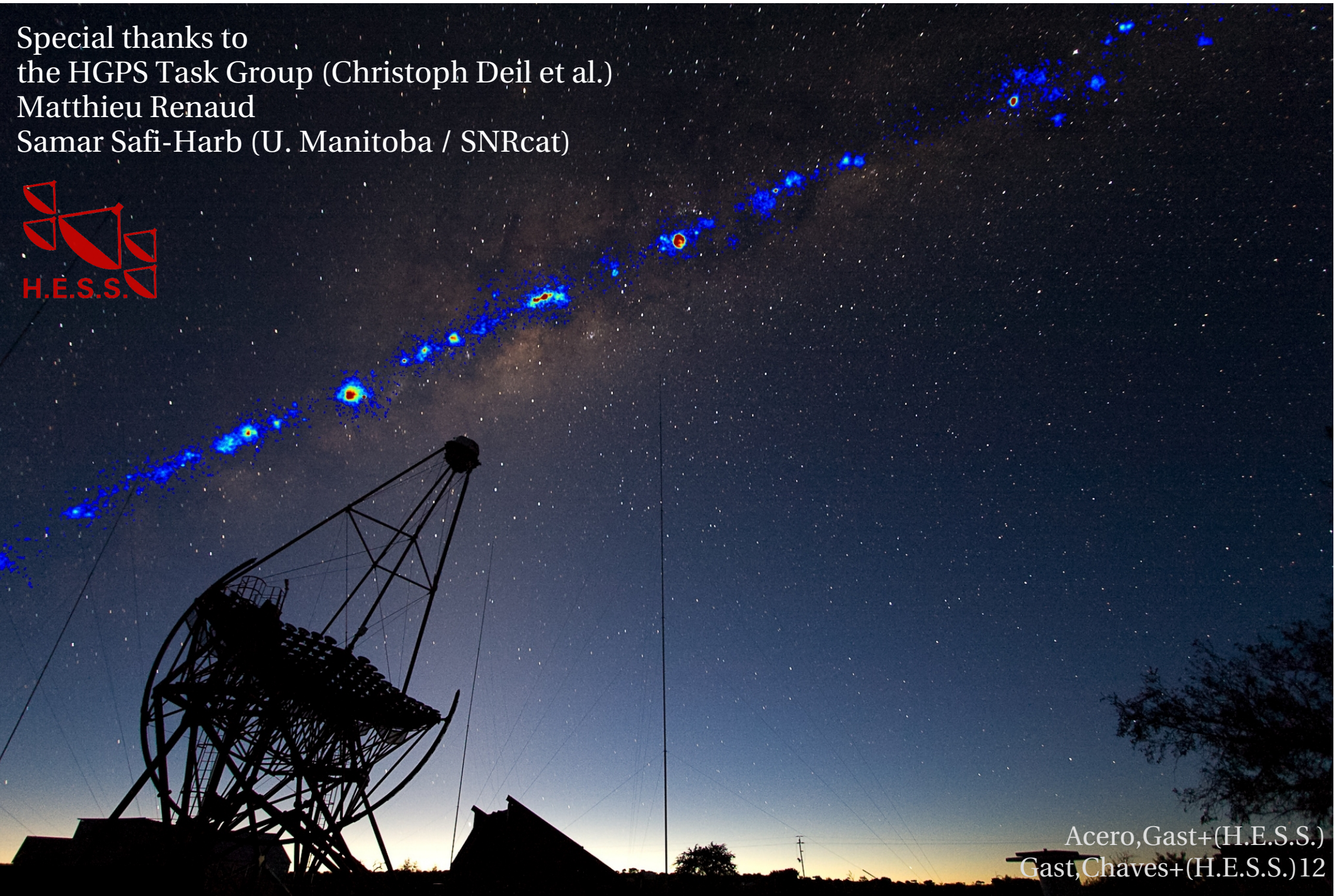
CTA future

PSF $\sim 5' \rightarrow \sim 2'$

Complete coverage of Galactic plane + uniform sensitivity

Spectra over wider range (0.02 – 300 TeV)

Special thanks to
the HGPS Task Group (Christoph Deil et al.)
Matthieu Renaud
Samar Safi-Harb (U. Manitoba / SNRcat)



Acero, Gast+(H.E.S.S.)
Gast, Chaves+(H.E.S.S.)12