# Revealing multi-TeV particle accelerators in the Galaxy

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**CPPM Seminar**
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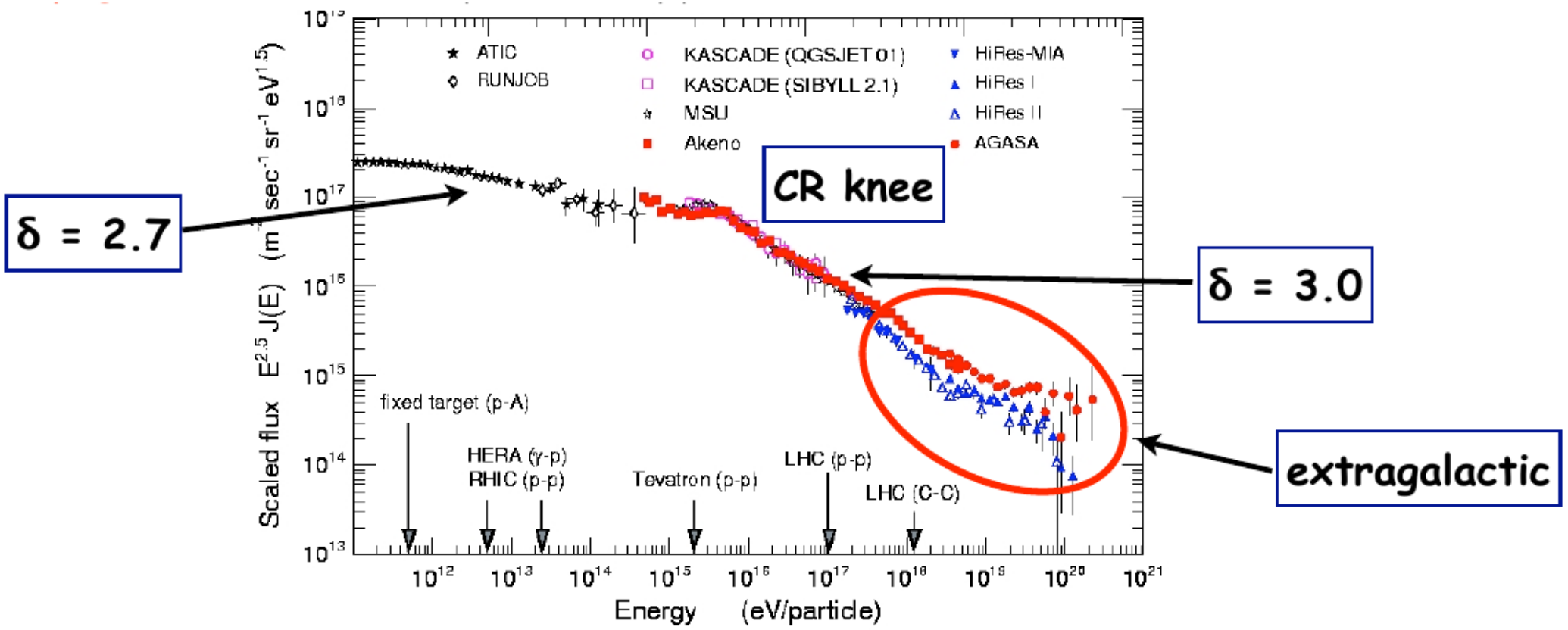
# **Primer:** The cosmic ray particle spectrum

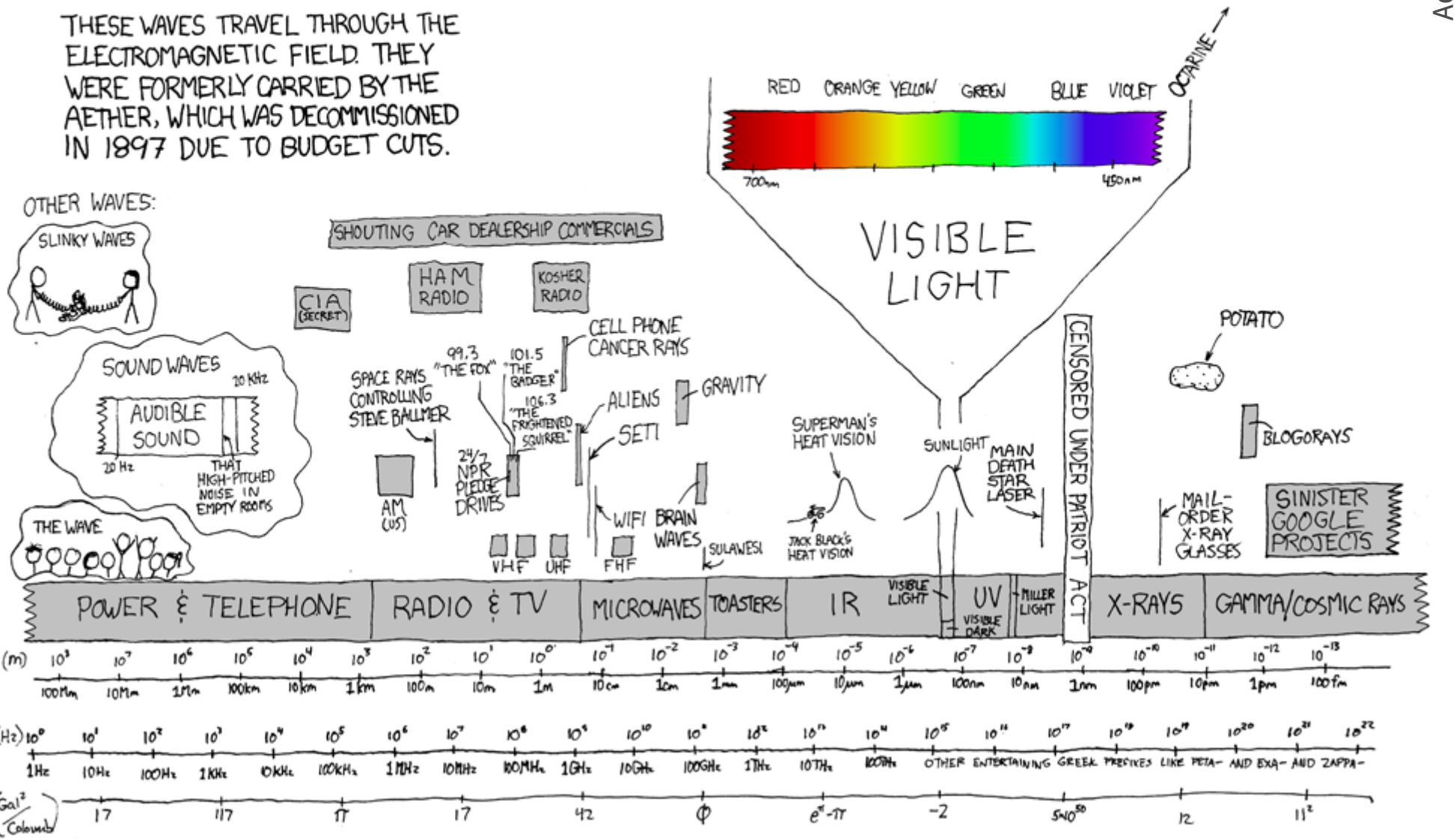
Energy density ~ starlight ~ 1 eV / $cm^3$
Single power law up to CR knee at a few PeV
Extremely isotropic, magnetic fields
*TeV-PeV hadrons produce GeV-TeV gamma rays via p-p → pion decay*

**Hadronic acceleration in supernova remnants?**
Diffusive shock acceleration predicts correct spectrum

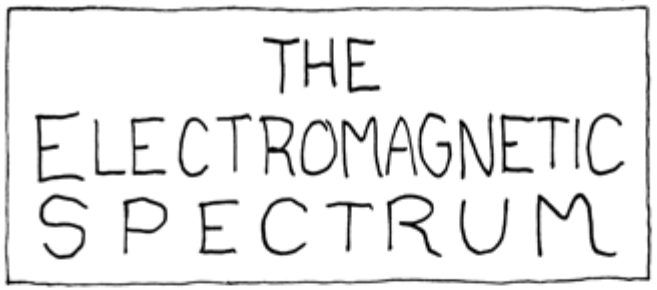


# THE ELECTROMAGNETIC SPECTRUM

THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.



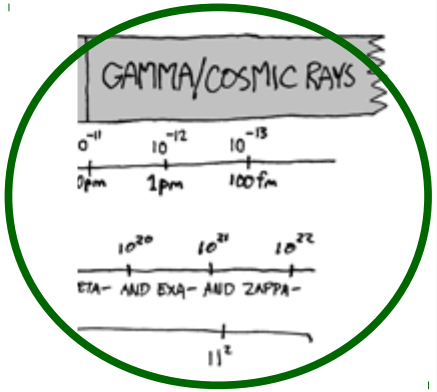

Adapted from XKCD



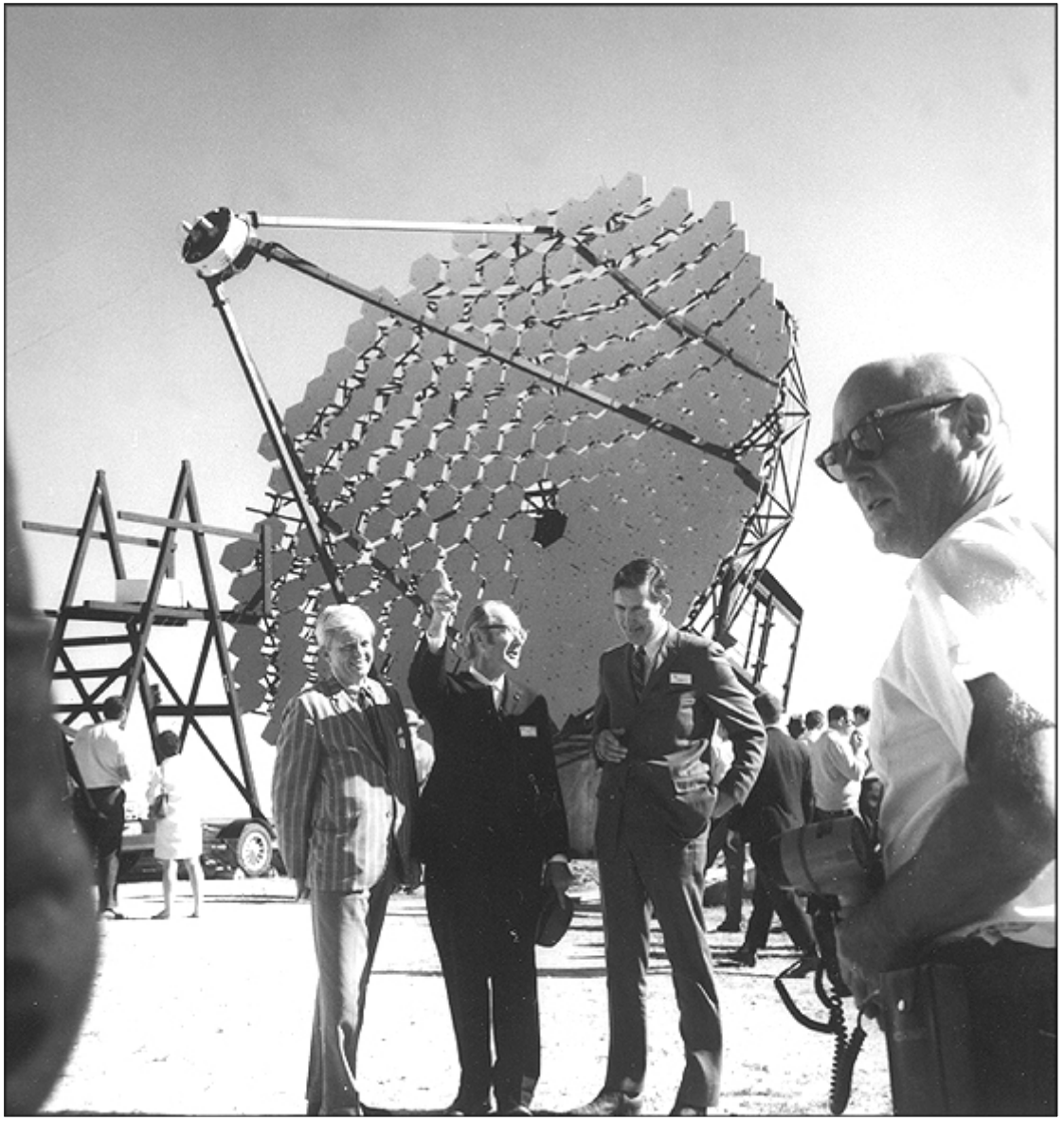

Adapted from XKCD

## *The VHE Domain*

~0.02 TeV → ~200 TeV

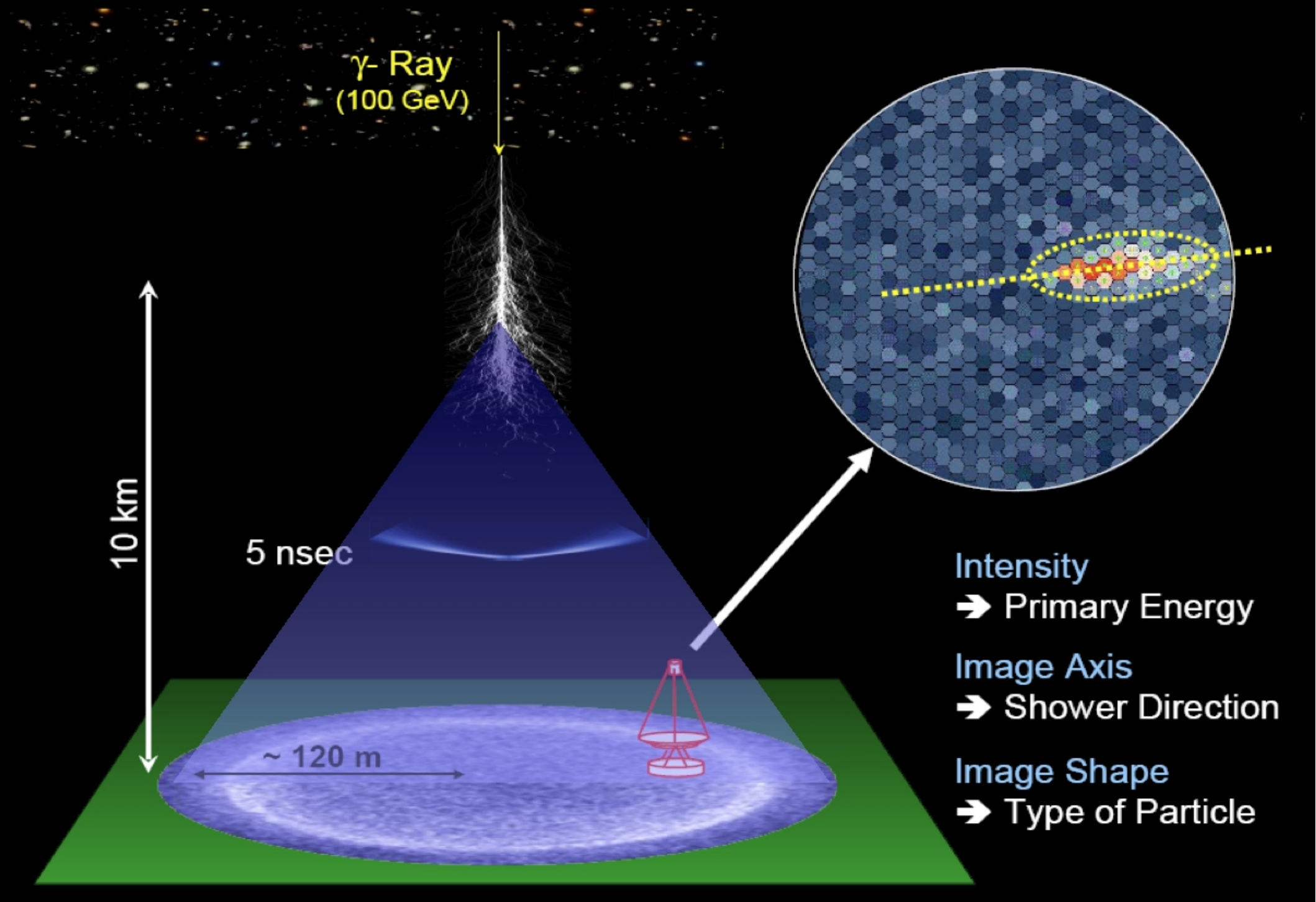


**Cherenkov telescope technique:**
Probing non-thermal processes at VHE since 1989

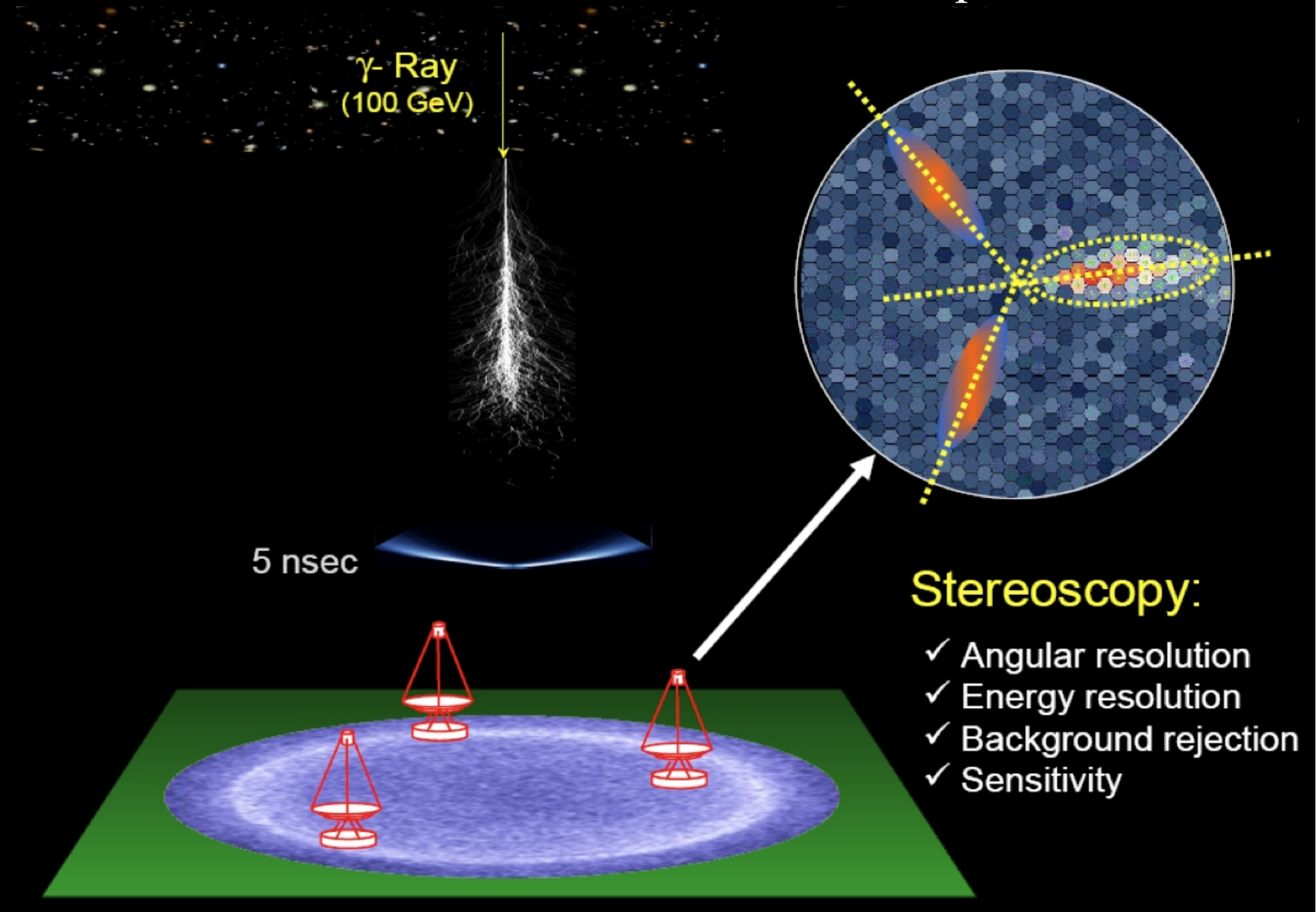


Smithsonian Institution 1968

# The Cherenkov technique in a nutshell



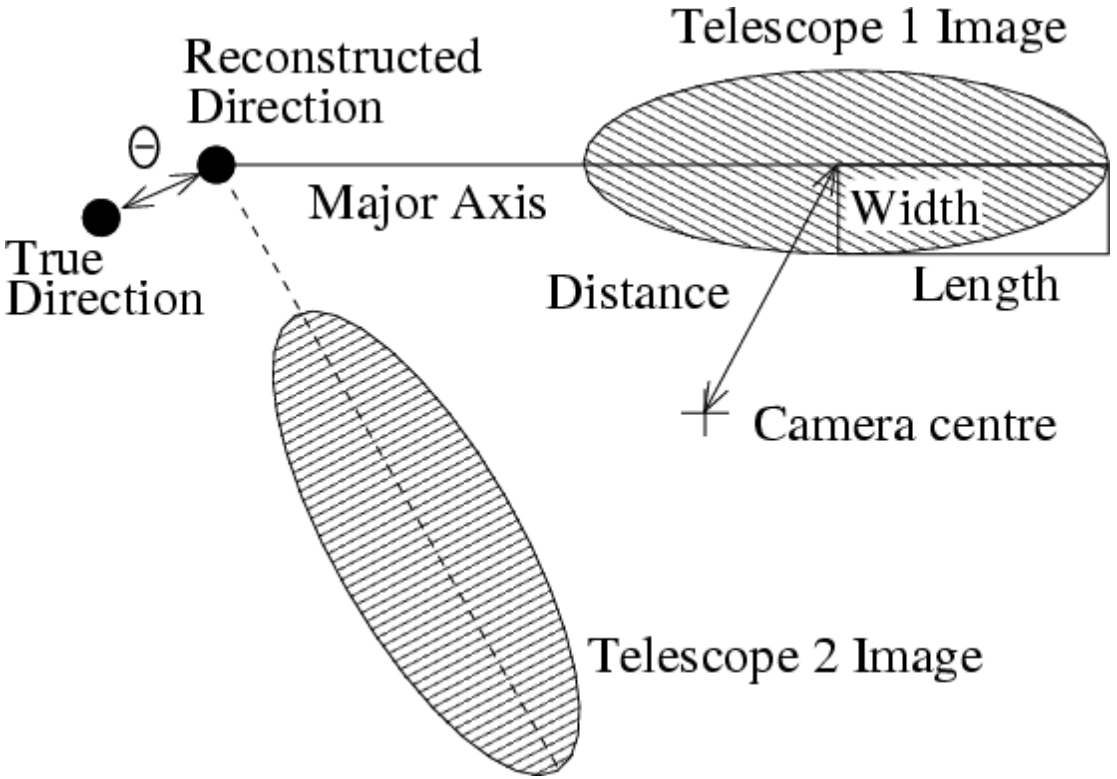
# The *stereo* Cherenkov technique in a nutshell



# **H.E.S.S.** phase I (2002-2013)


## Technical specs: snapshot

**Telescopes: 4**
Mirrors: 12 m diameter
Area: 107 $m^2$
**FoV: ~5° diameter**
Camera: 960 pixels (PMTs)
Angular resolution ≥ 0.06° (5')
Electronics: fast ~1 ns
Energy range: ~100 GeV to **~100 TeV**
Energy resolution ~15%
Background rejection > 99%
Duty cycle 10%



# The 5-tel hybrid Cherenkov telescope array

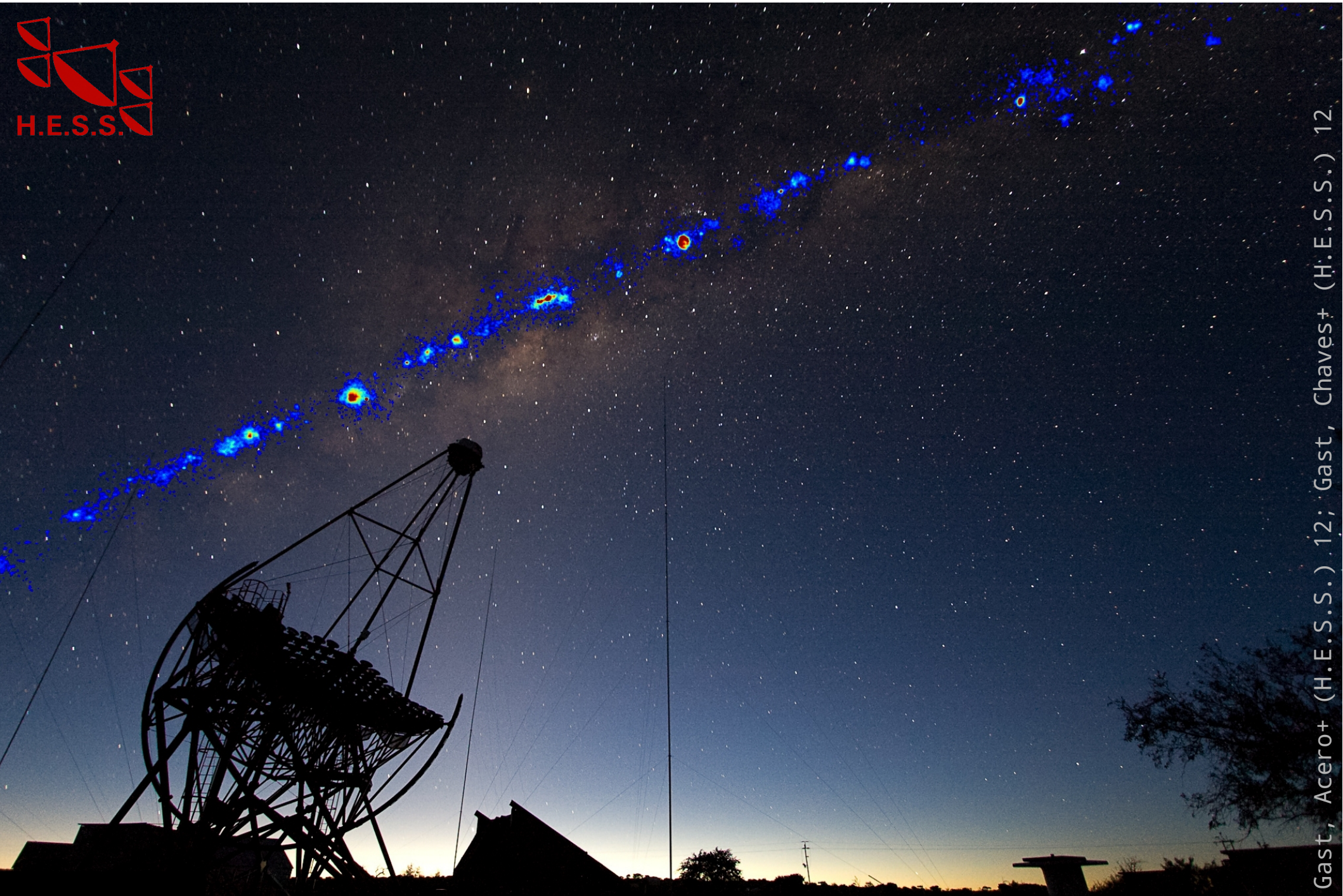
4 12-m IACTs w/ recoated mirrors + **1 28-m IACT**

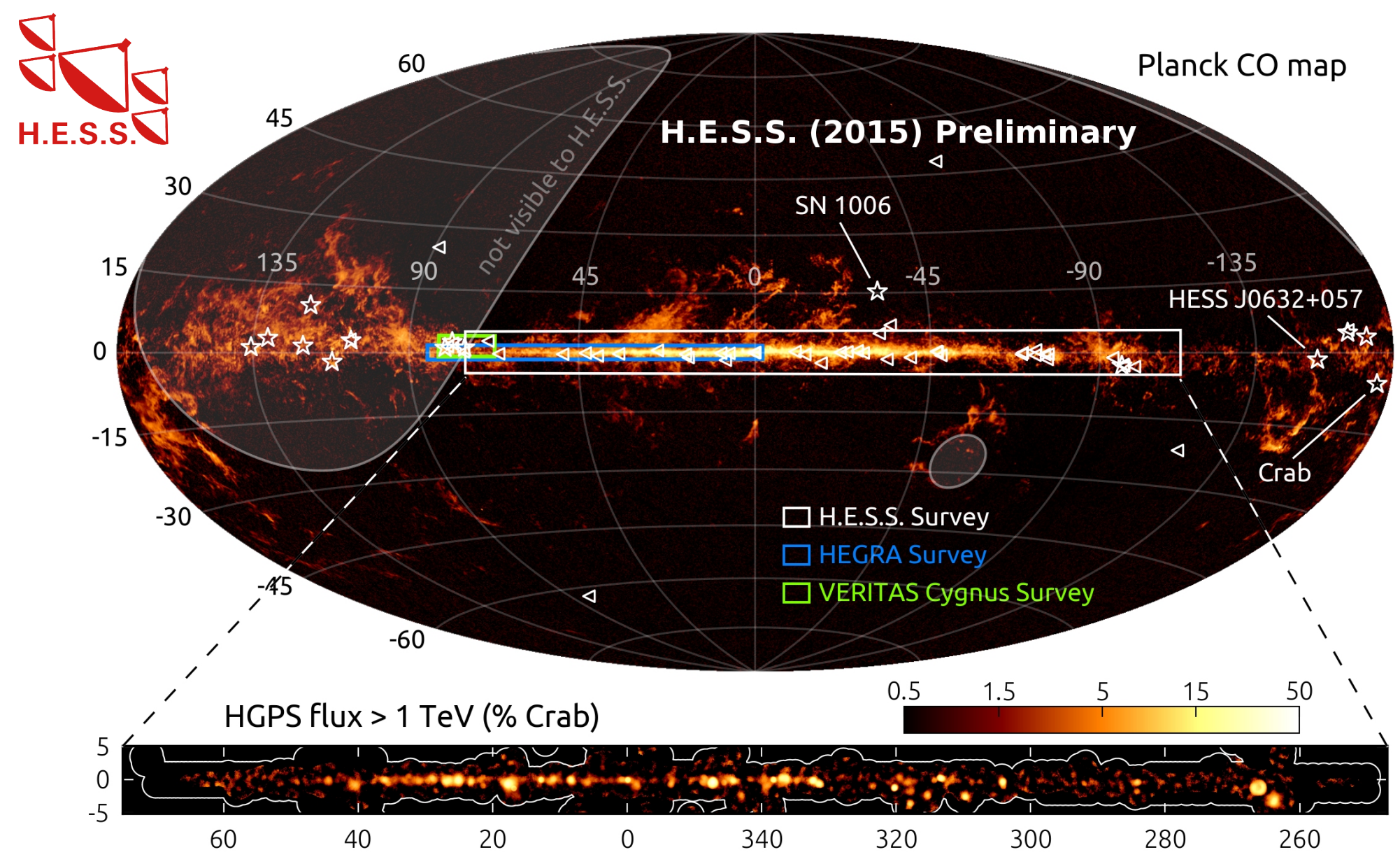
Multiple triggering & pointing schemes available

**CT5:** 2048 PMTs 614 $m^2$ **3.2° FoV** $E_{min}$ **~ 30 GeV** f = 38 m

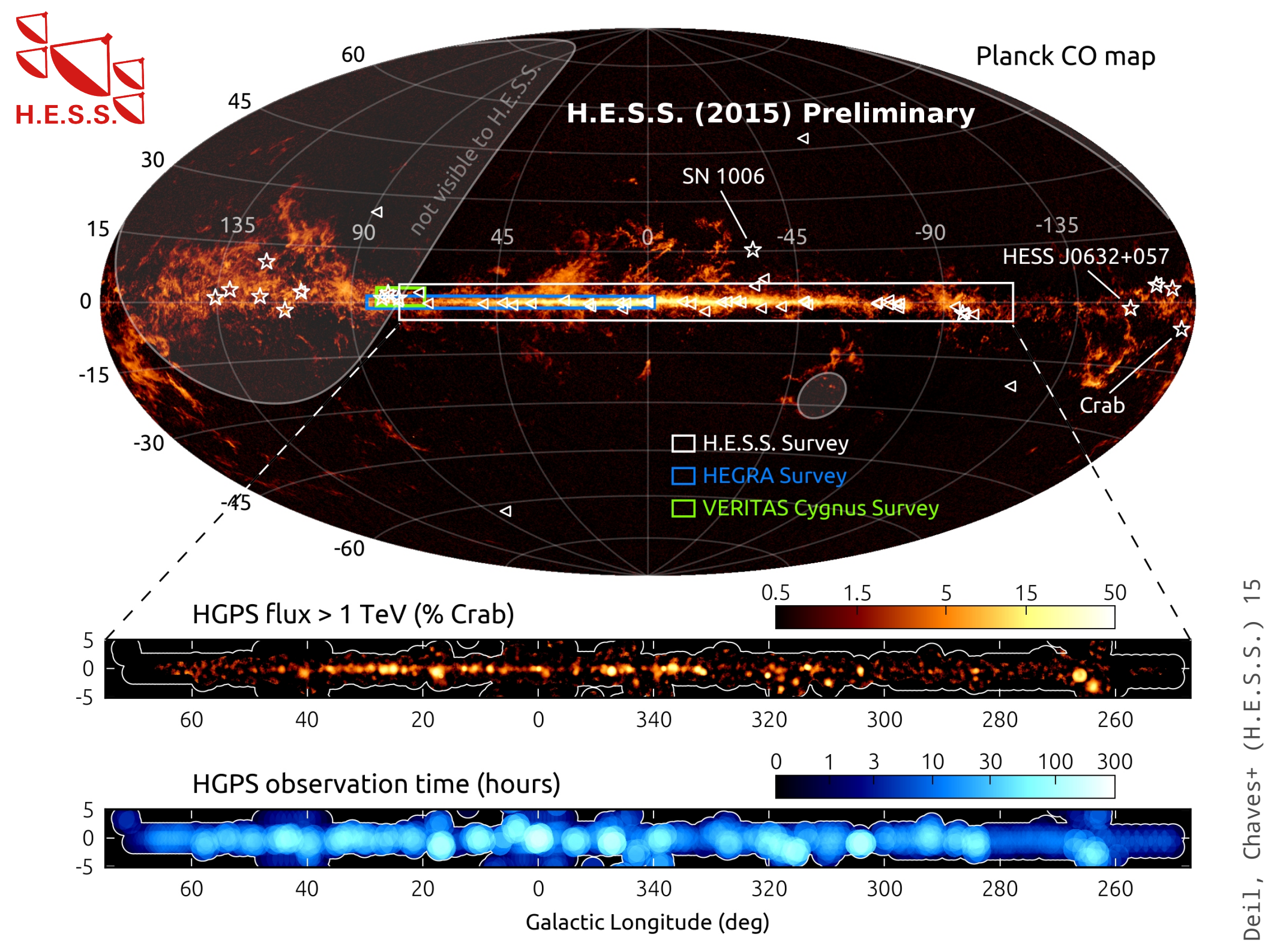
vs. **5.0°** FoV (CT1-4)

# The TeV Galactic Plane

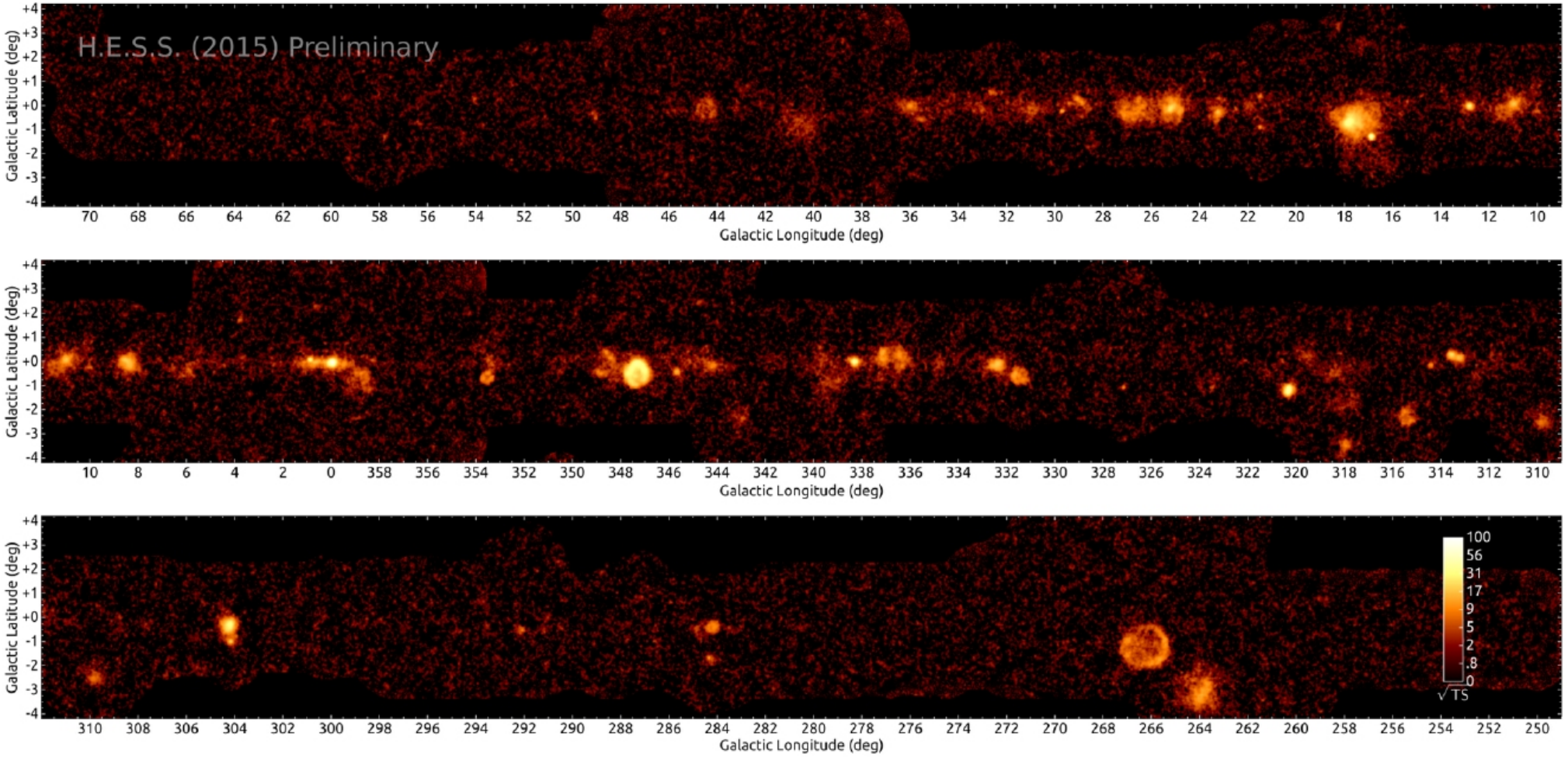





Deil, Chaves+ (H.E.S.S.) 15

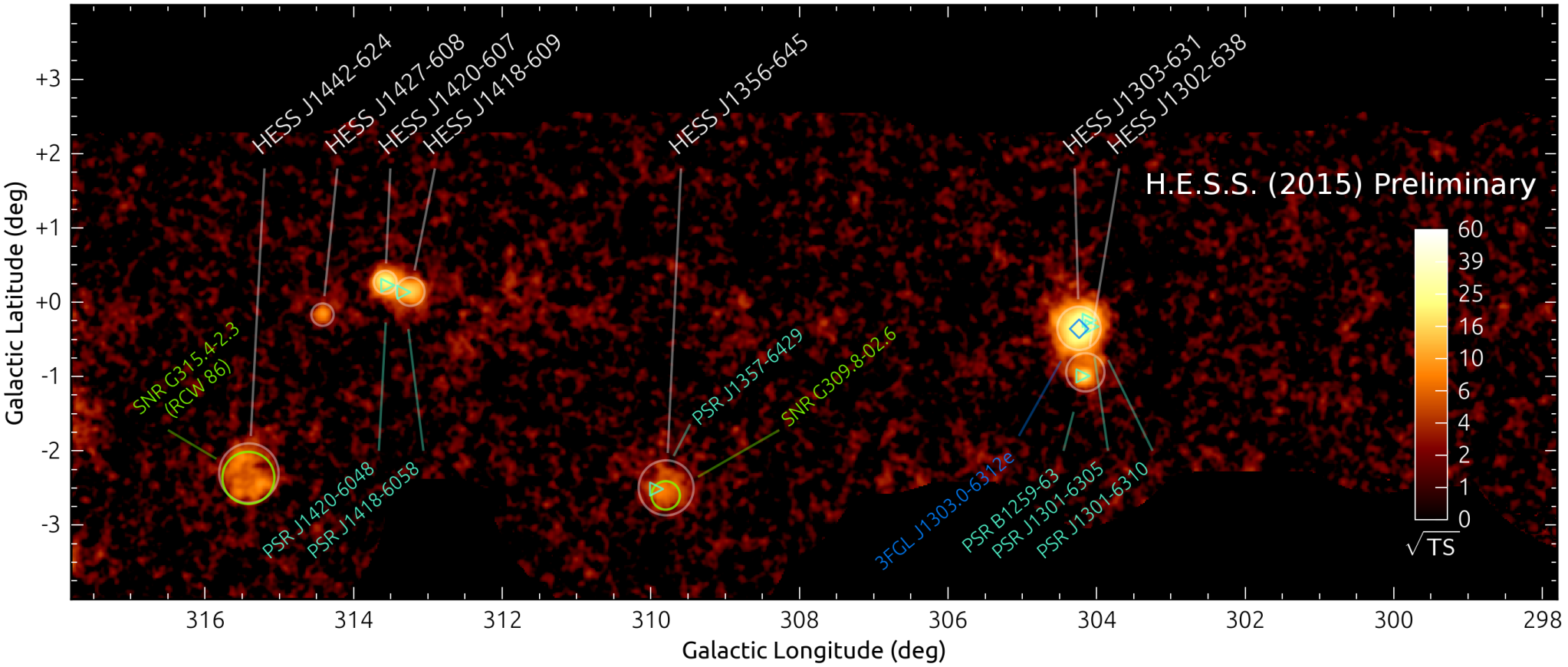

H.E.S.S.
Planck CO map
H.E.S.S. (2015) Preliminary
not visible to H.E.S.S.
SN 1006
HESS J0632+057
Crab
H.E.S.S. Survey
HEGRA Survey
VERITAS Cygnus Survey
HGPS flux > 1 TeV (% Crab)
0.5 1.5 5 15 50
HGPS observation time (hours)
0 1 3 10 30 100 300
Galactic Longitude (deg)
Deil, Chaves+ (H.E.S.S.) 15

# Significance, in full detail




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

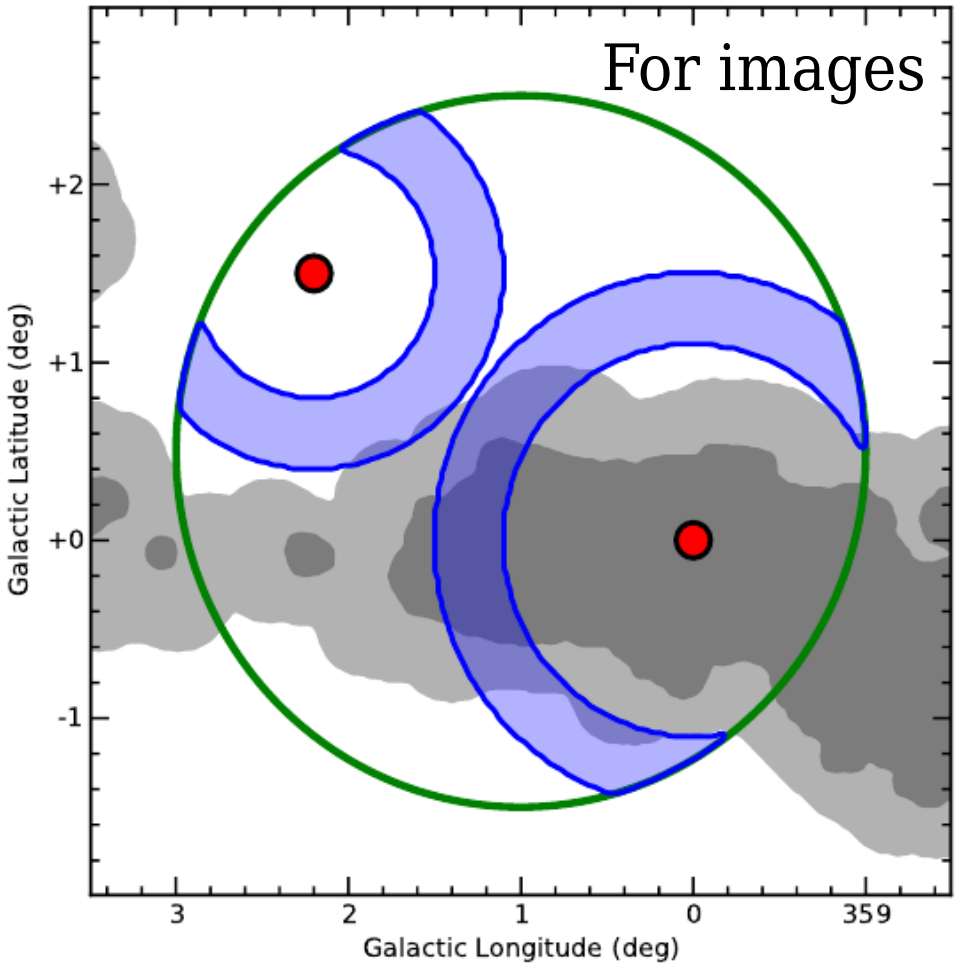
# Zoom-in

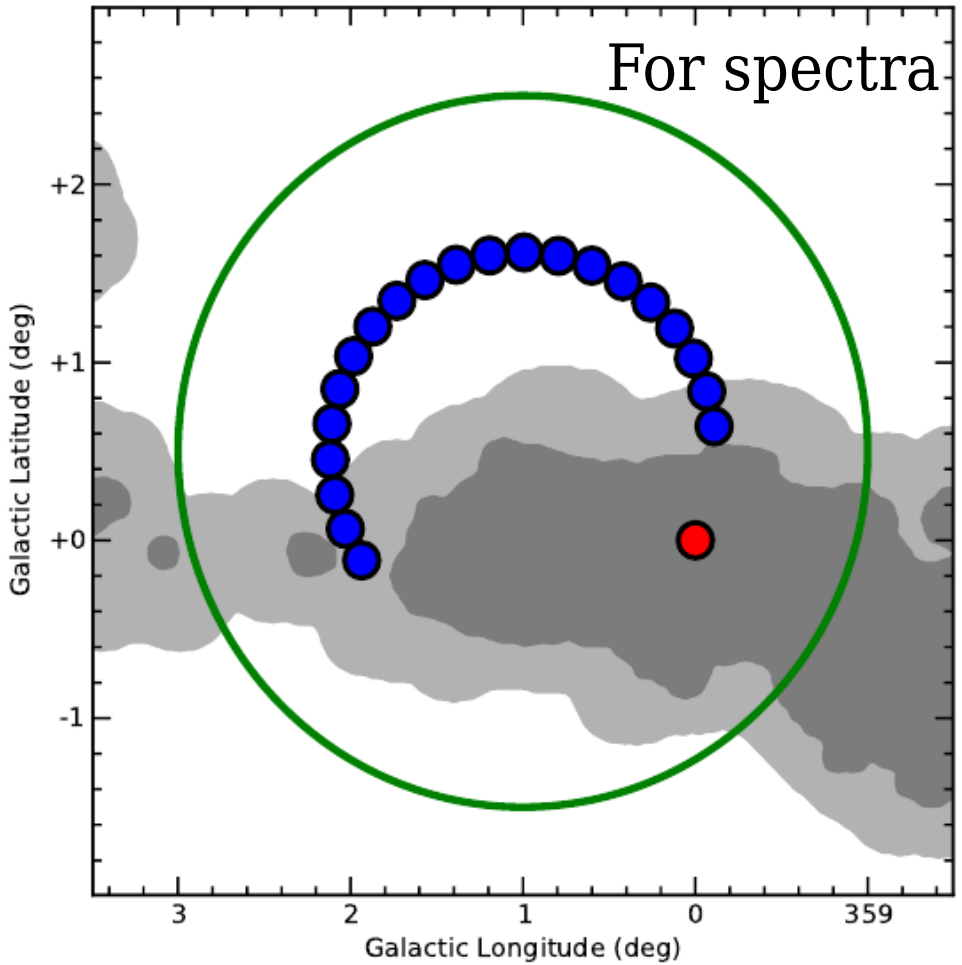



Full detail VHE sky images, catalog, and MWL associations

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

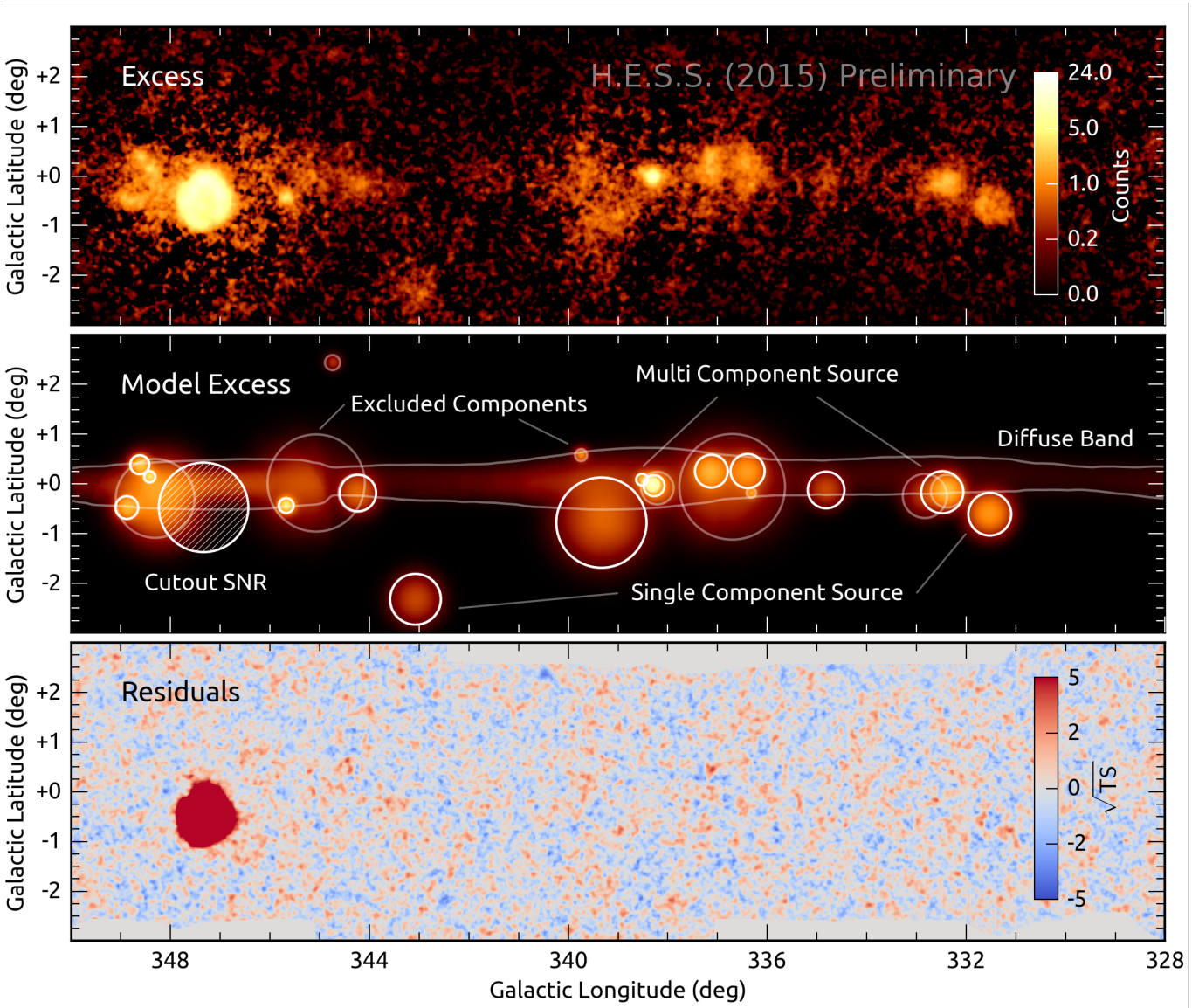
# Challenges & solutions for analyzing complex source regions



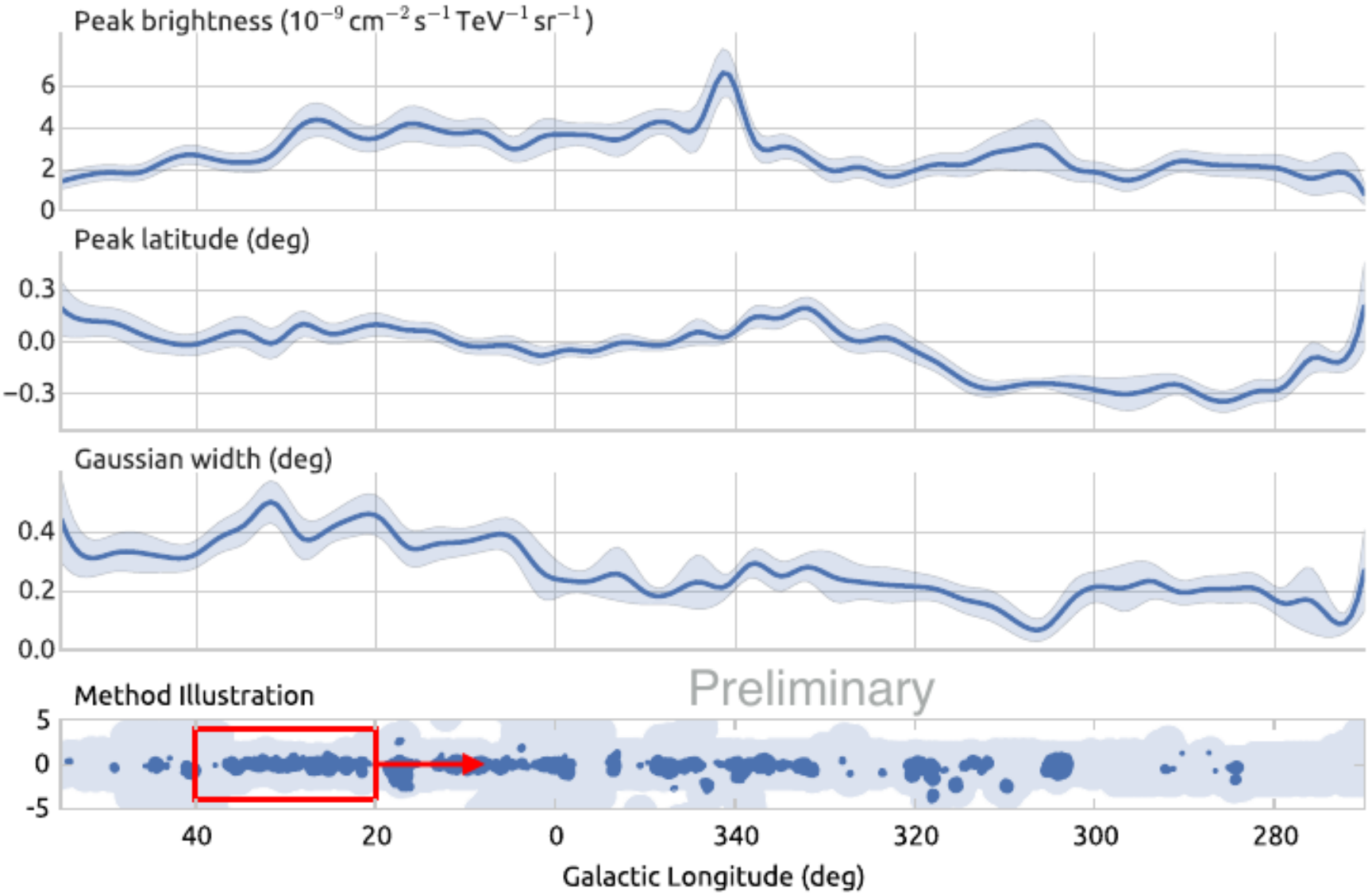

Background estimation with adaptive regions

# Catalog construction



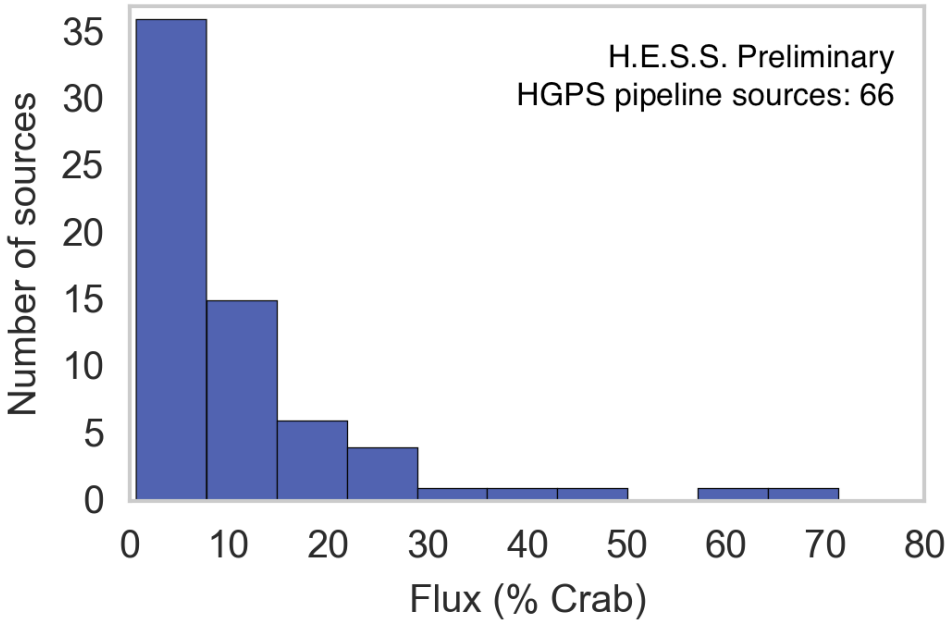

- Adaptive ring background estimation with exclusion region masks
- Semi-automated, MLE-based source detection & morphology fitting
- Model sources as Gaussian plus an underlying “diffuse” component

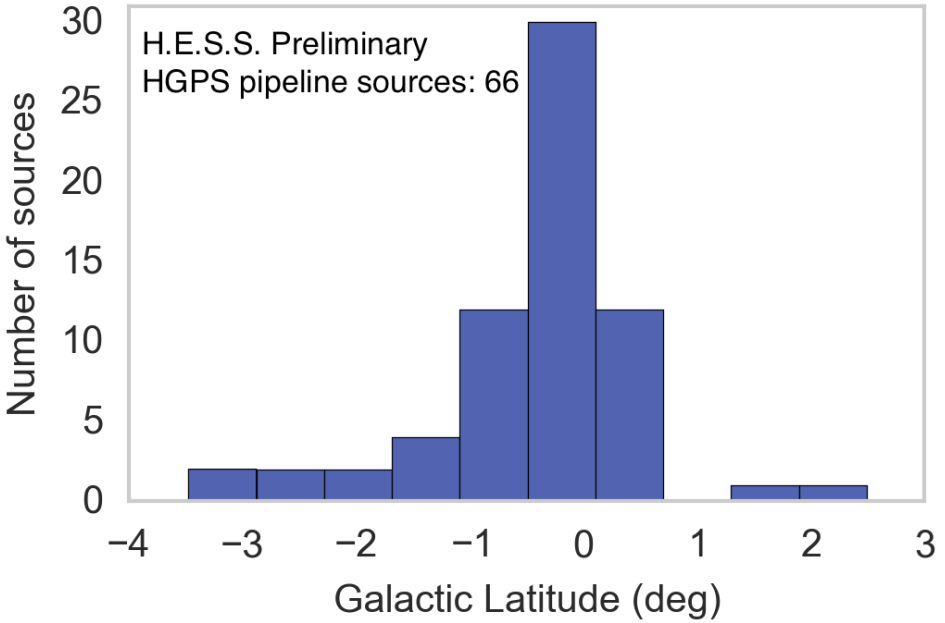
# Handling diffuse emission in the HGPS




*Empirical* not physical model: 20 deg sliding window w/ Gaussian in *b*

# Galactic TeV sources



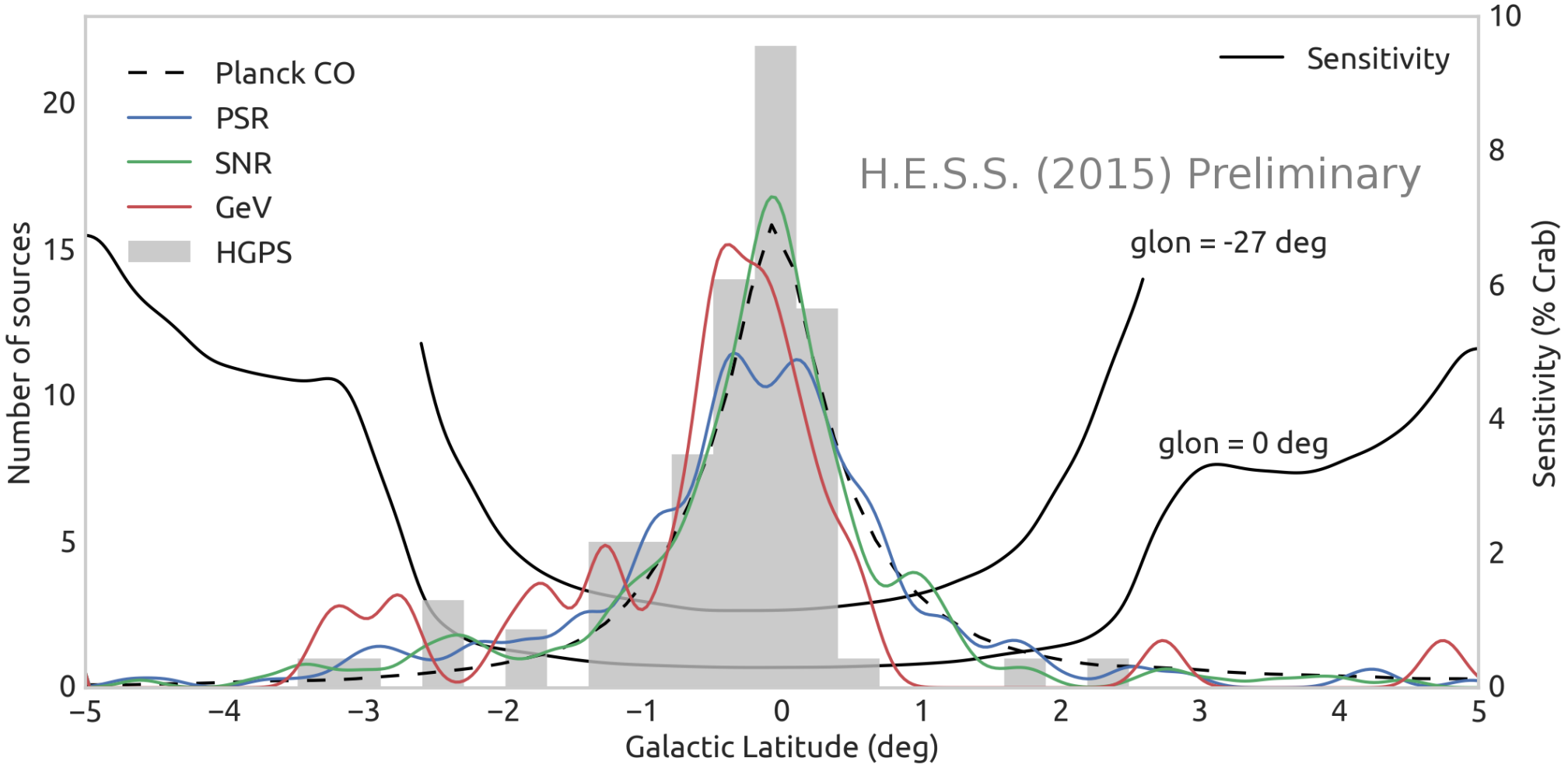

66 HGPS pipeline sources

+11 sources treated manually (Galactic center region, TeV shells)

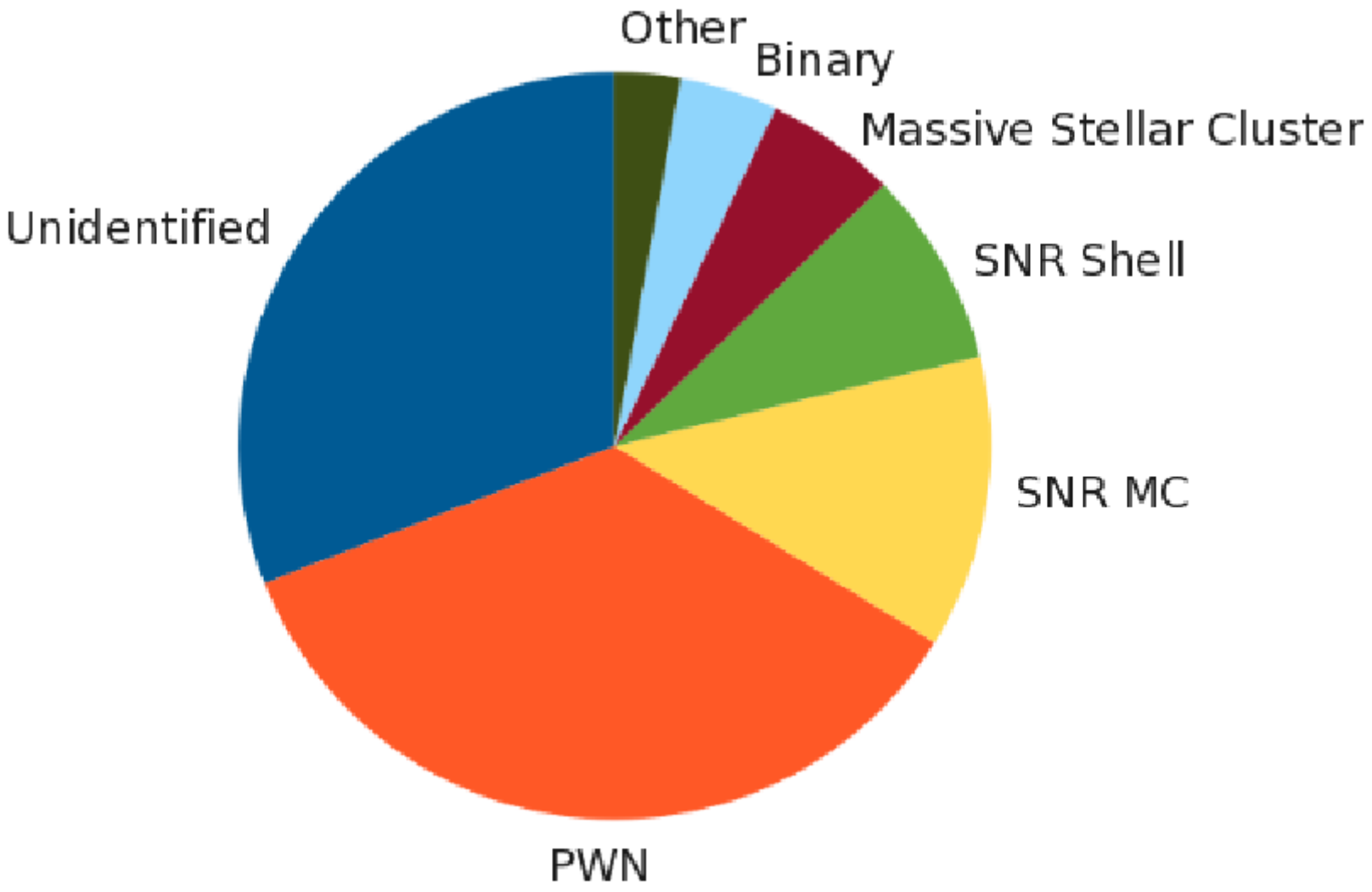
+3 sources outside HGPS region (Crab Nebula, SN 1006, HESS J0632)

=80 Galactic sources detected by H.E.S.S.

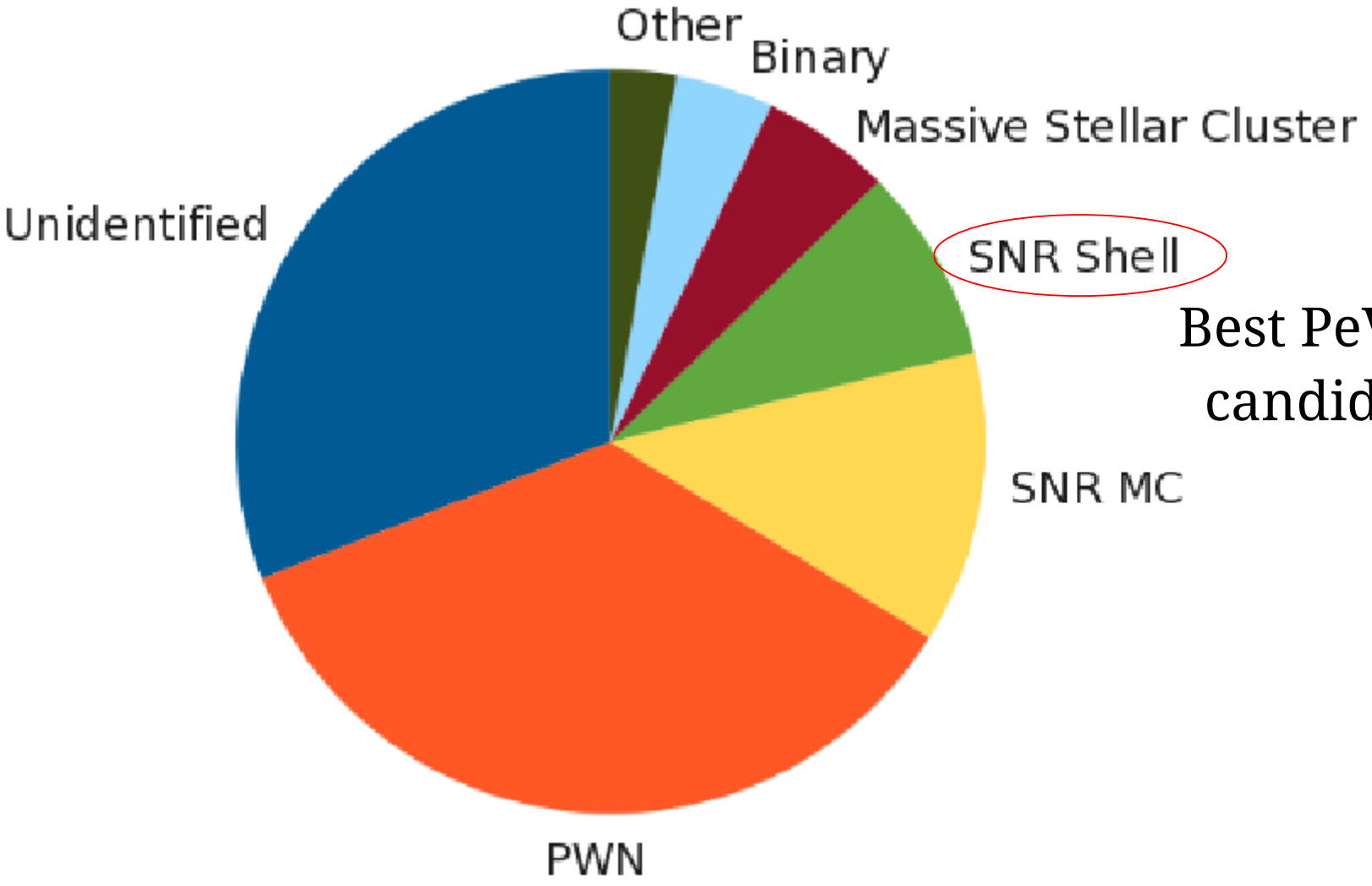
# VHE source distribution



# Galactic TeV source populations

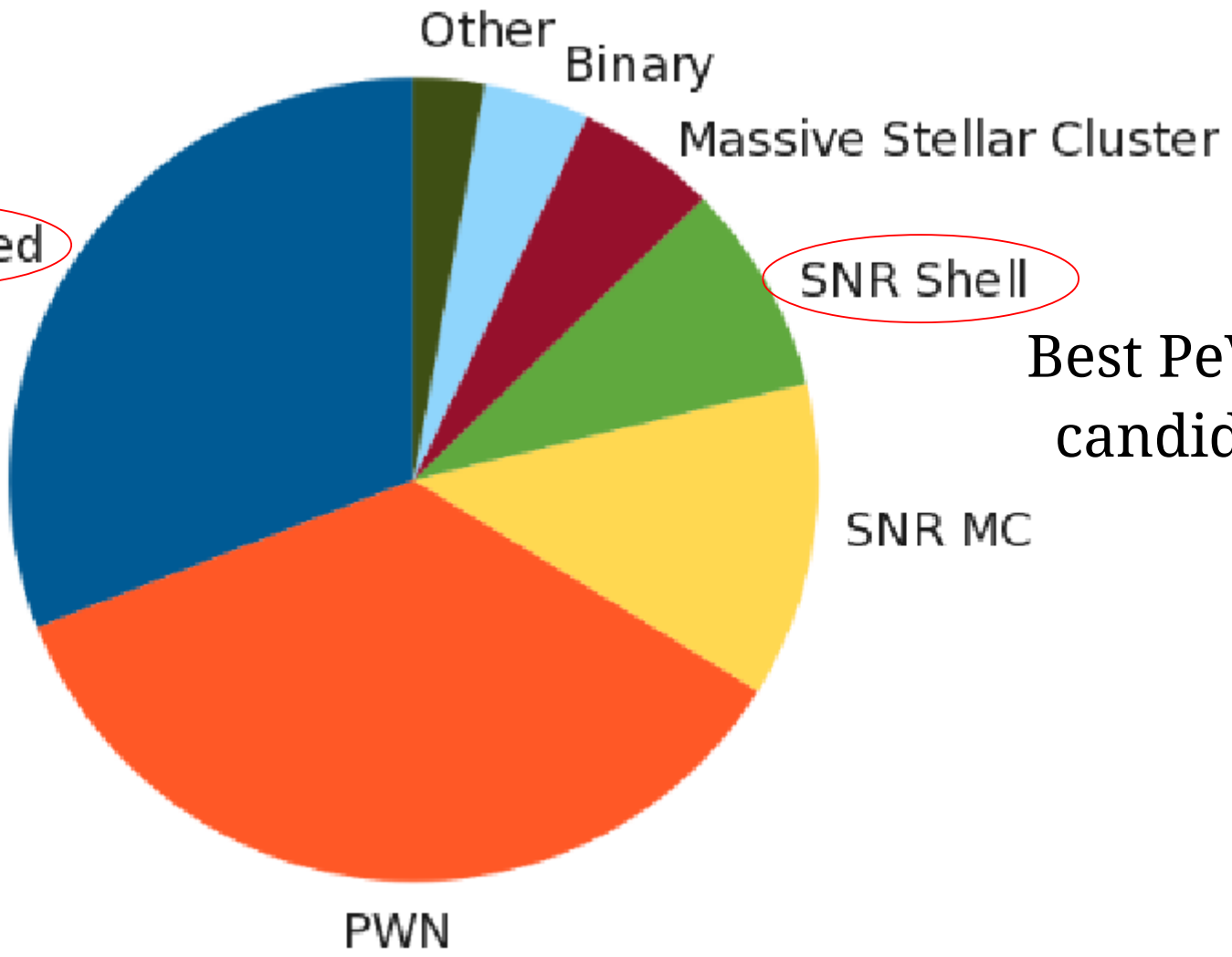


# Galactic TeV source populations




Best PeVatron candidates?

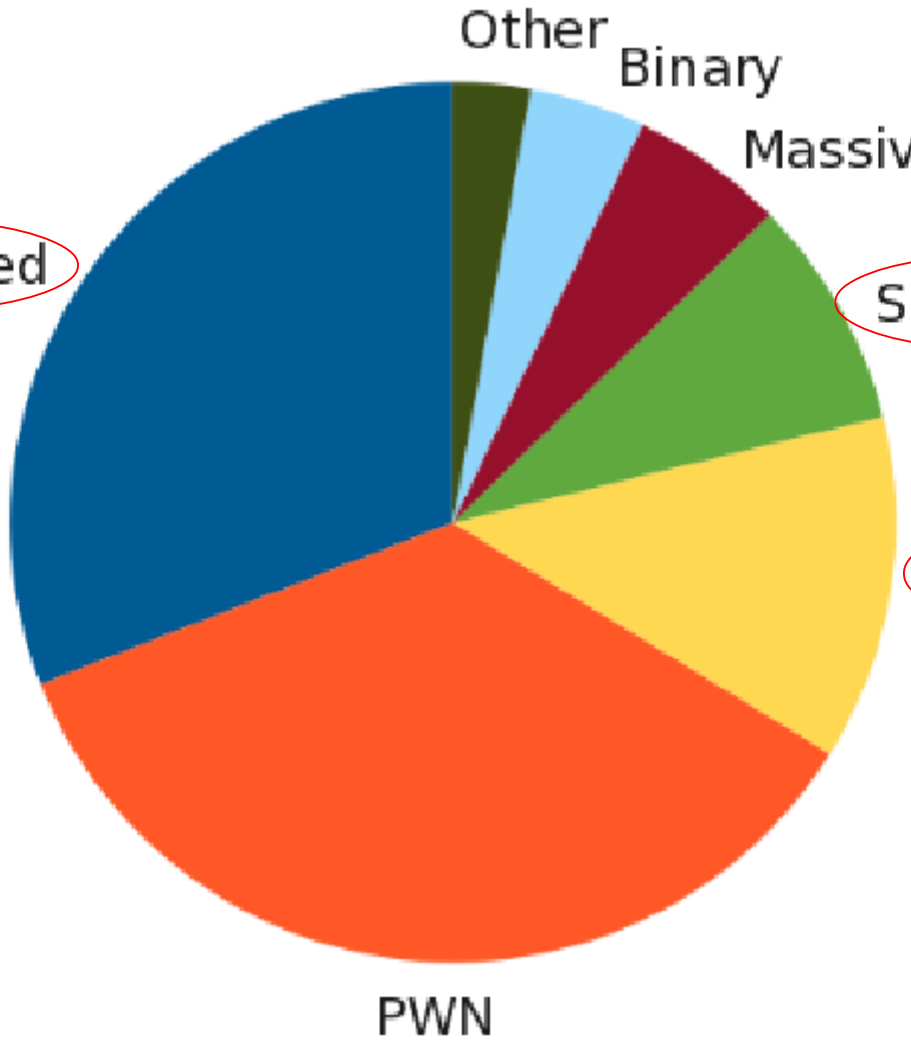
# Galactic TeV source populations




Relic PWNe
*or*
missing SNRs?

Best PeVatron candidates?

# Galactic TeV source populations

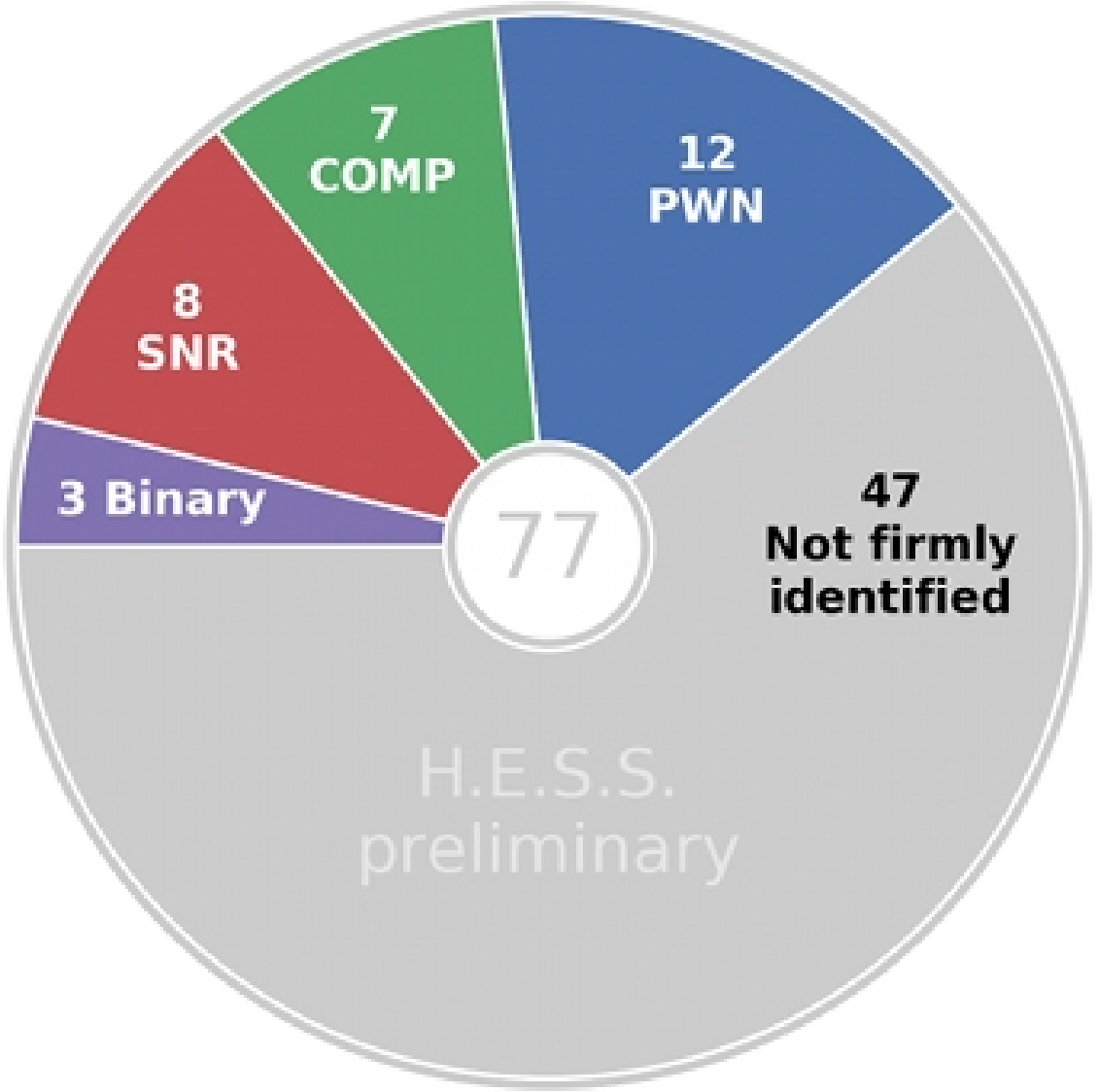



Relic PWNe
*or*
missing SNRs?

Best PeVatron candidates?

$\pi^0$ bump discovery confirms hadronic interaction, but particle energies only up to ~300 GeV (escape?) and steep spectra

# Firm identifications



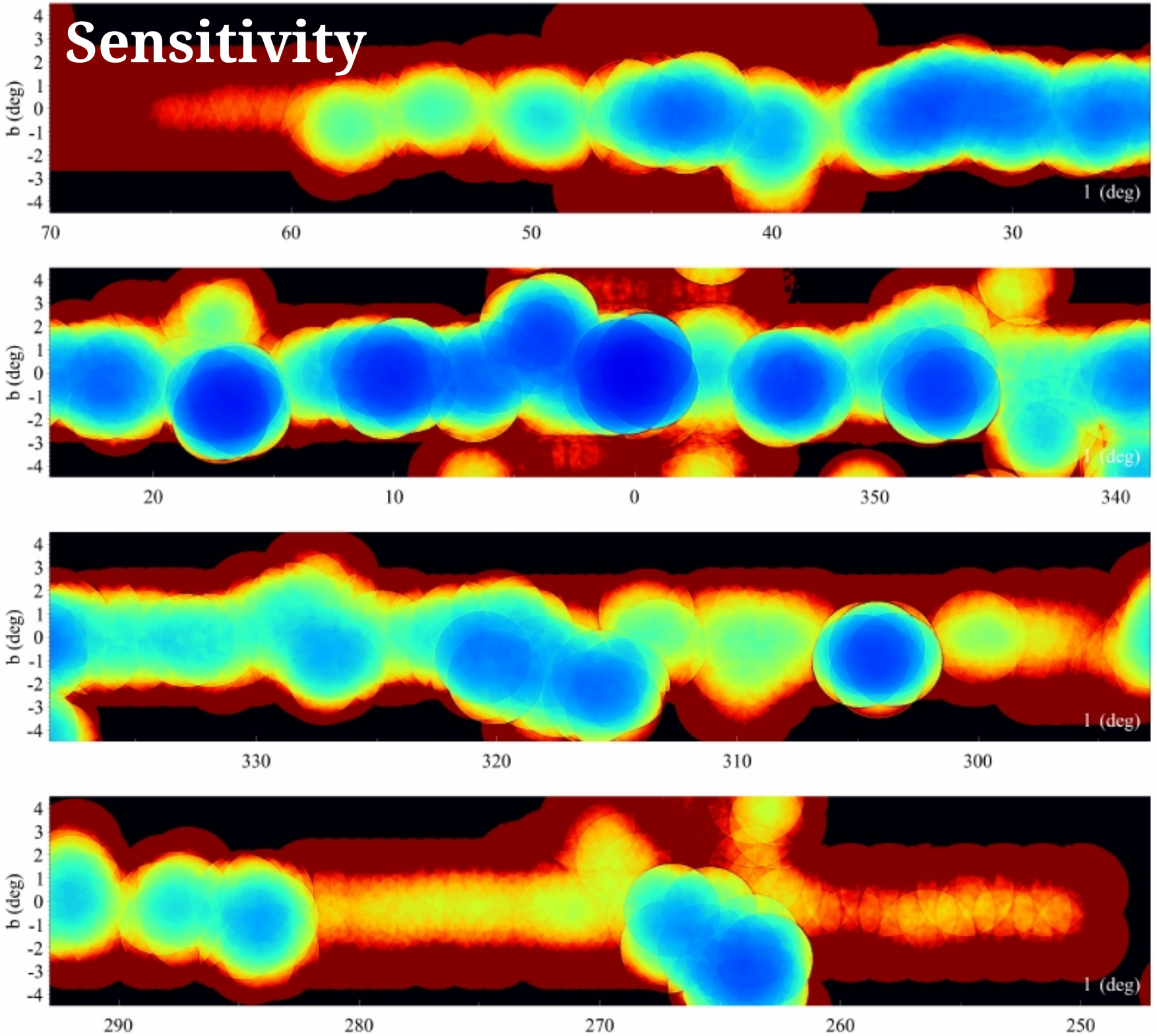

MWL counterparts:
**Pulsars** (ATNF), **PWN** (SNRcat), **SNRs** (SNRcat), **HE sources** (1FHL, 3FGL)

# How complete is the Survey?

*or*

If there is a (bright) ___(insert your favorite object here)___
out there in the Galaxy,
would we have detected it already?

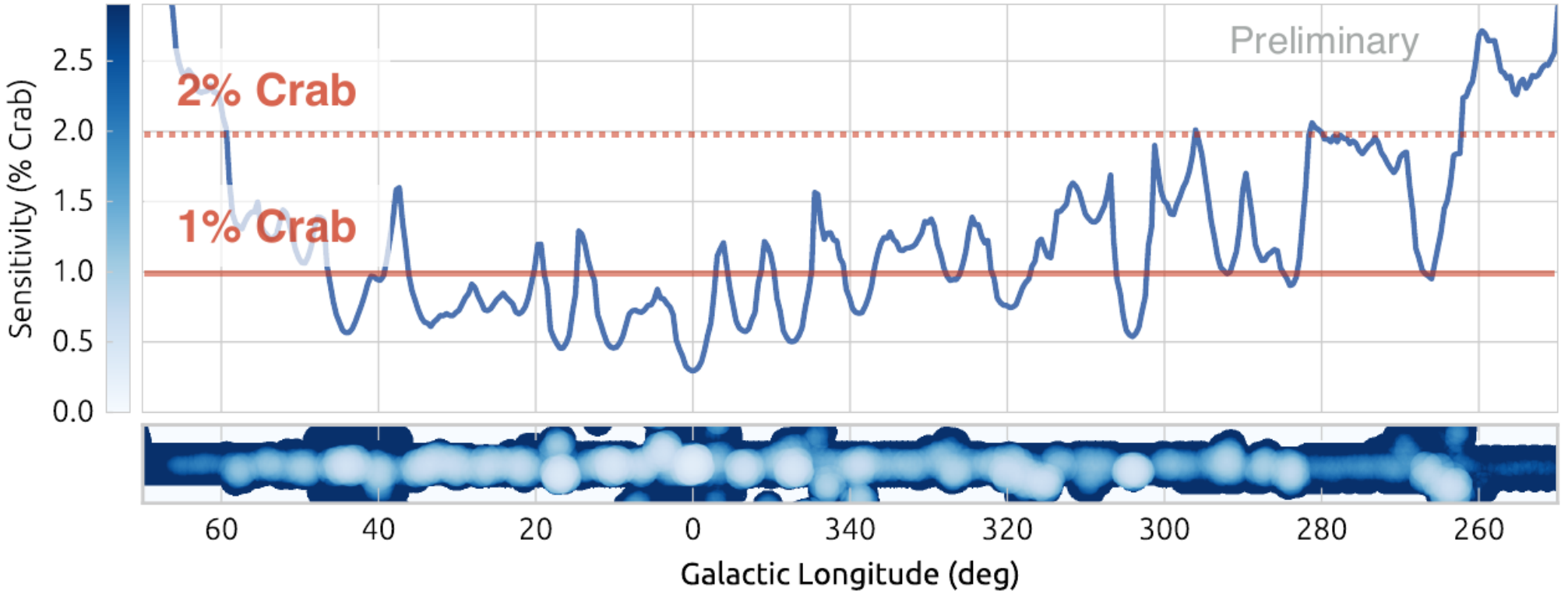
# Sensitivity

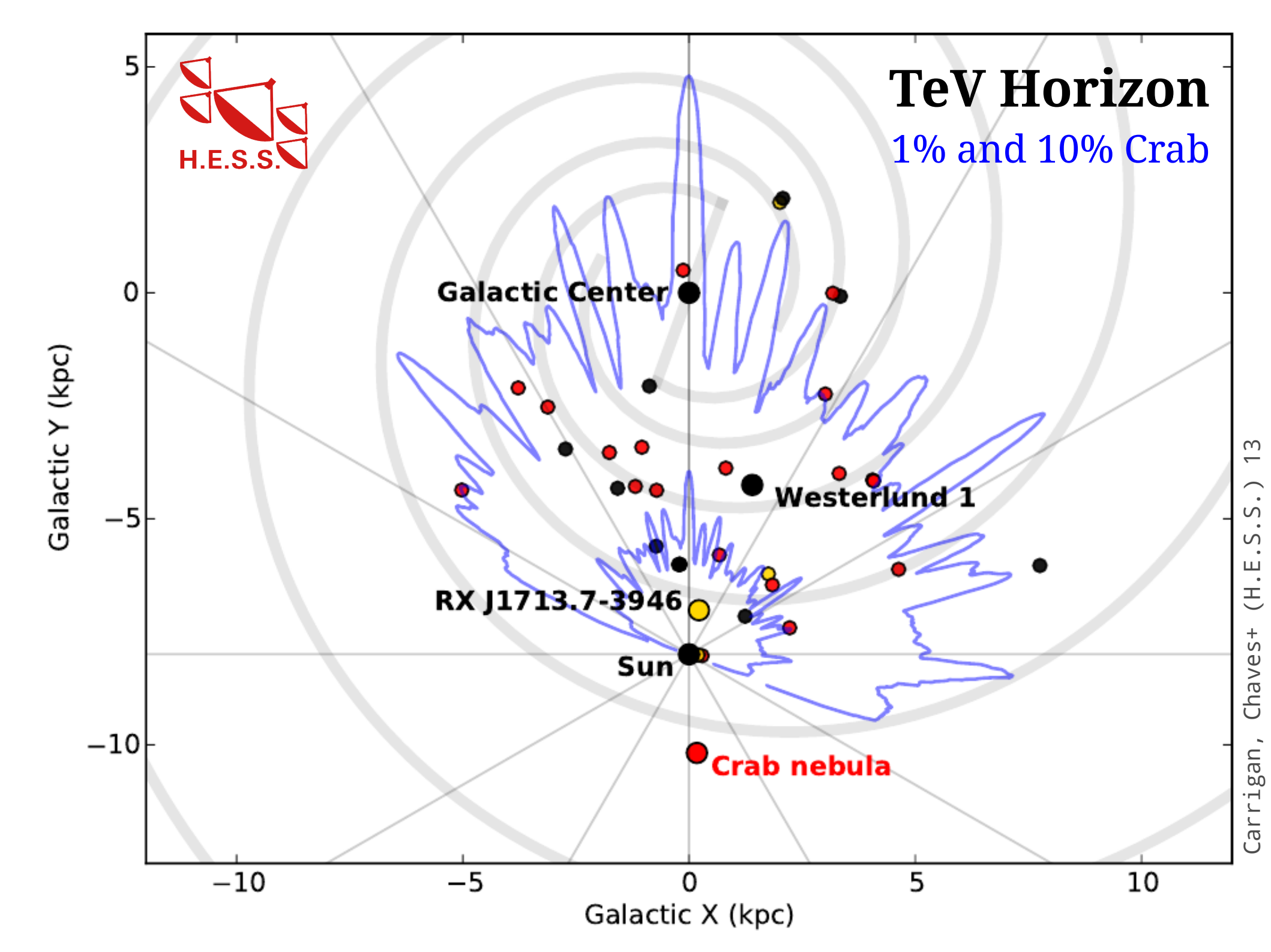



Carrigan, Chaves+ (H.E.S.S.) 13

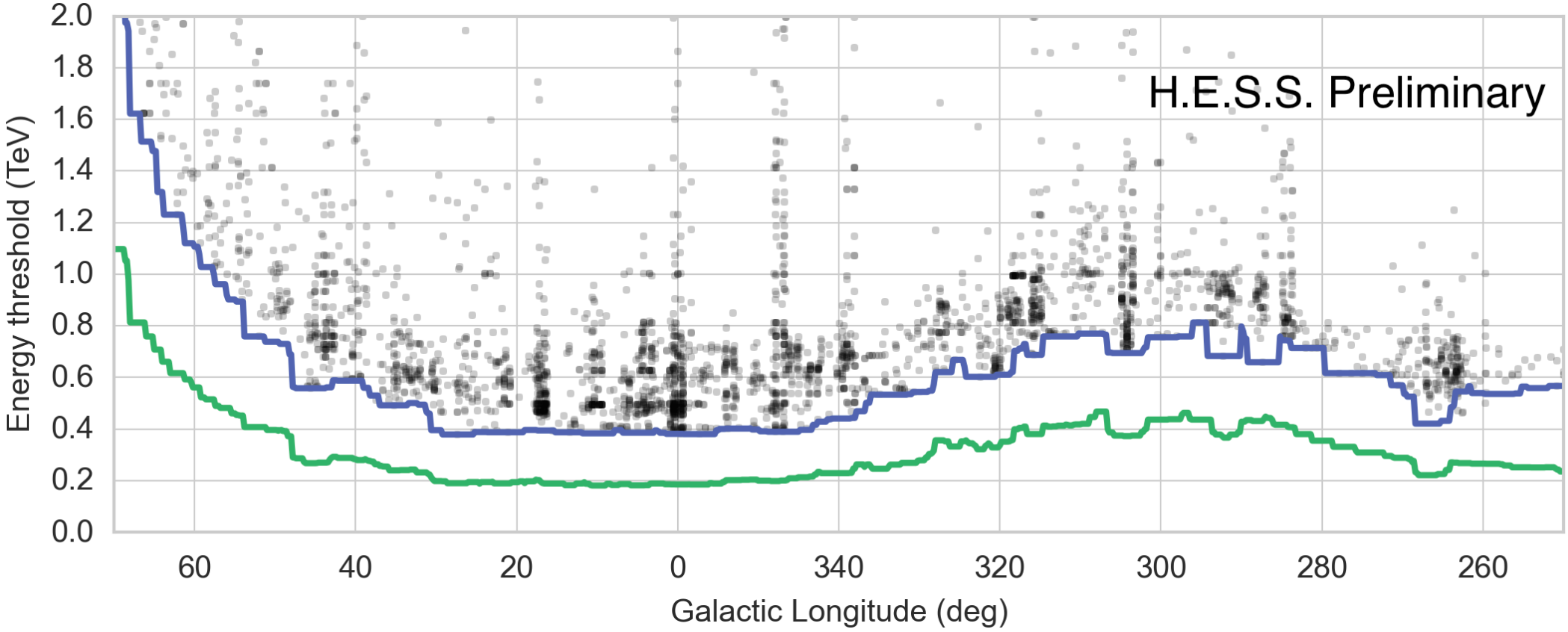
# HGPS Sensitivity

along b = 0° for a 5-σ detection




TeV Horizon
1% and 10% Crab
H.E.S.S.
Galactic Center
Westerlund 1
RX J1713.7-3946
Sun
Crab nebula
Galactic Y (kpc)
Galactic X (kpc)
5
0
−5
−10
−10
−5
0
5
10
Carrigan, Chaves+ (H.E.S.S.) 13

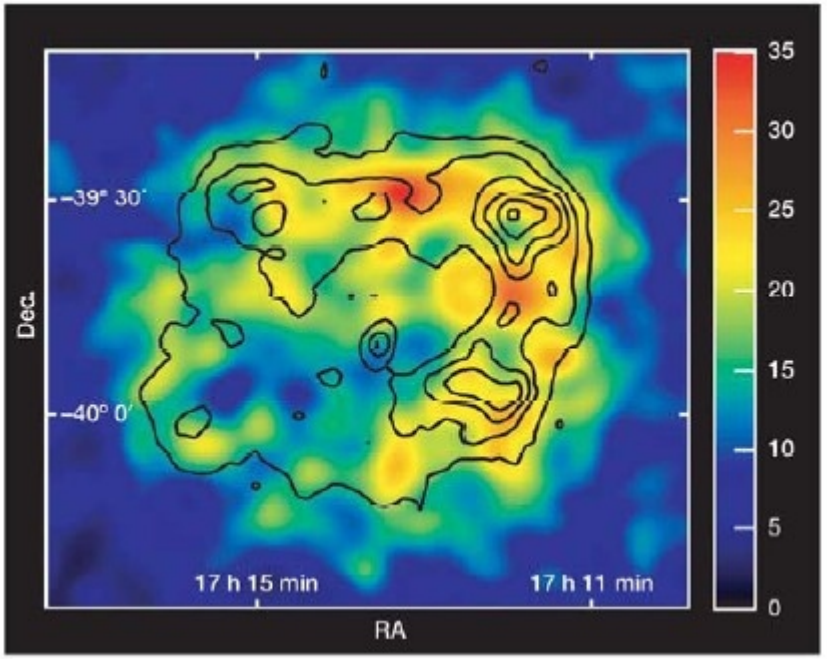
# Energy threshold



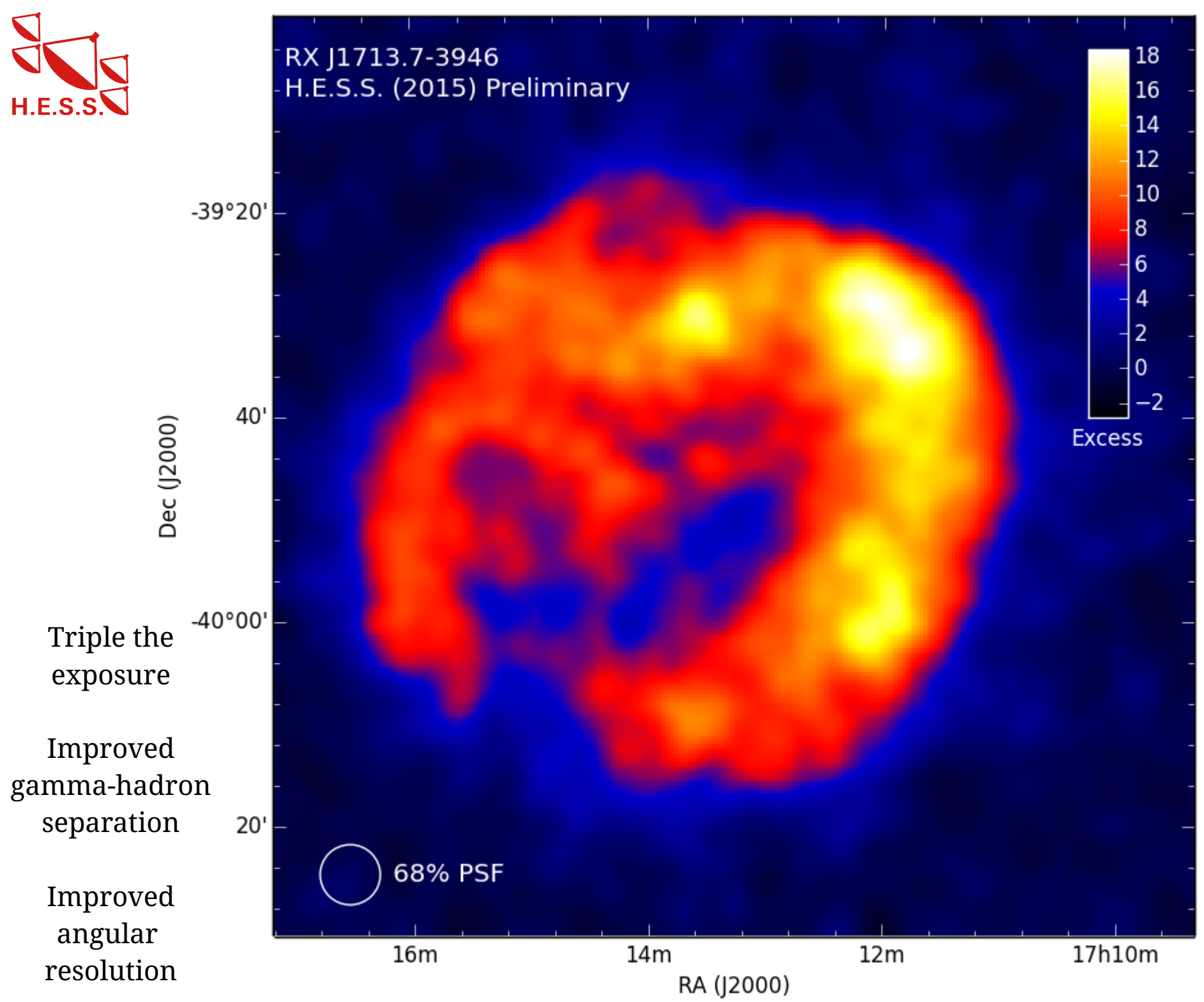

Reflects zenith angle longitude dependency

~6000 observations → ~3000 h dataset

# Revisiting the iconic TeV supernova remnant



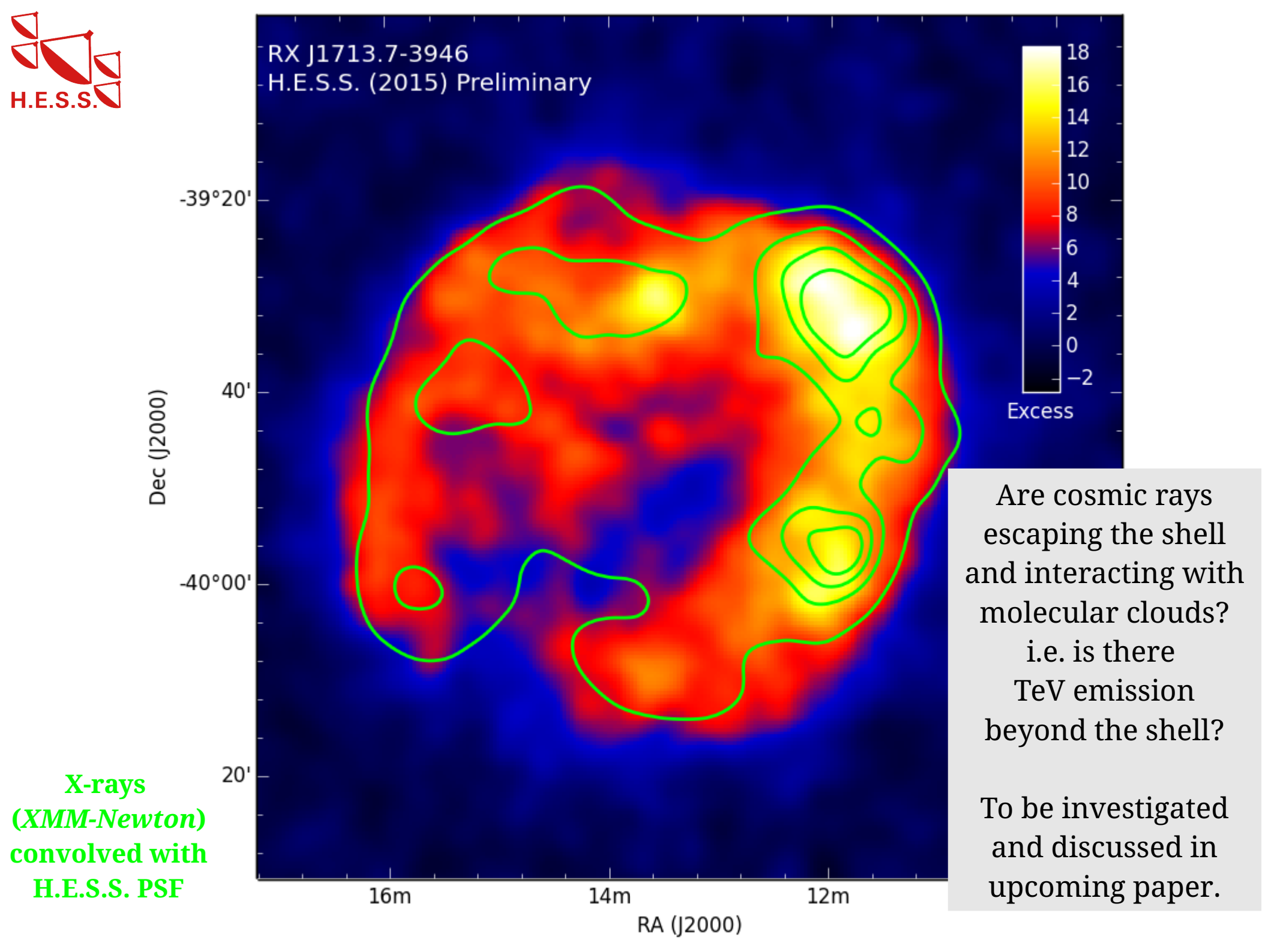

Aharonian+ (H.E.S.S.) 05




Triple the exposure

Improved gamma-hadron separation

Improved angular resolution

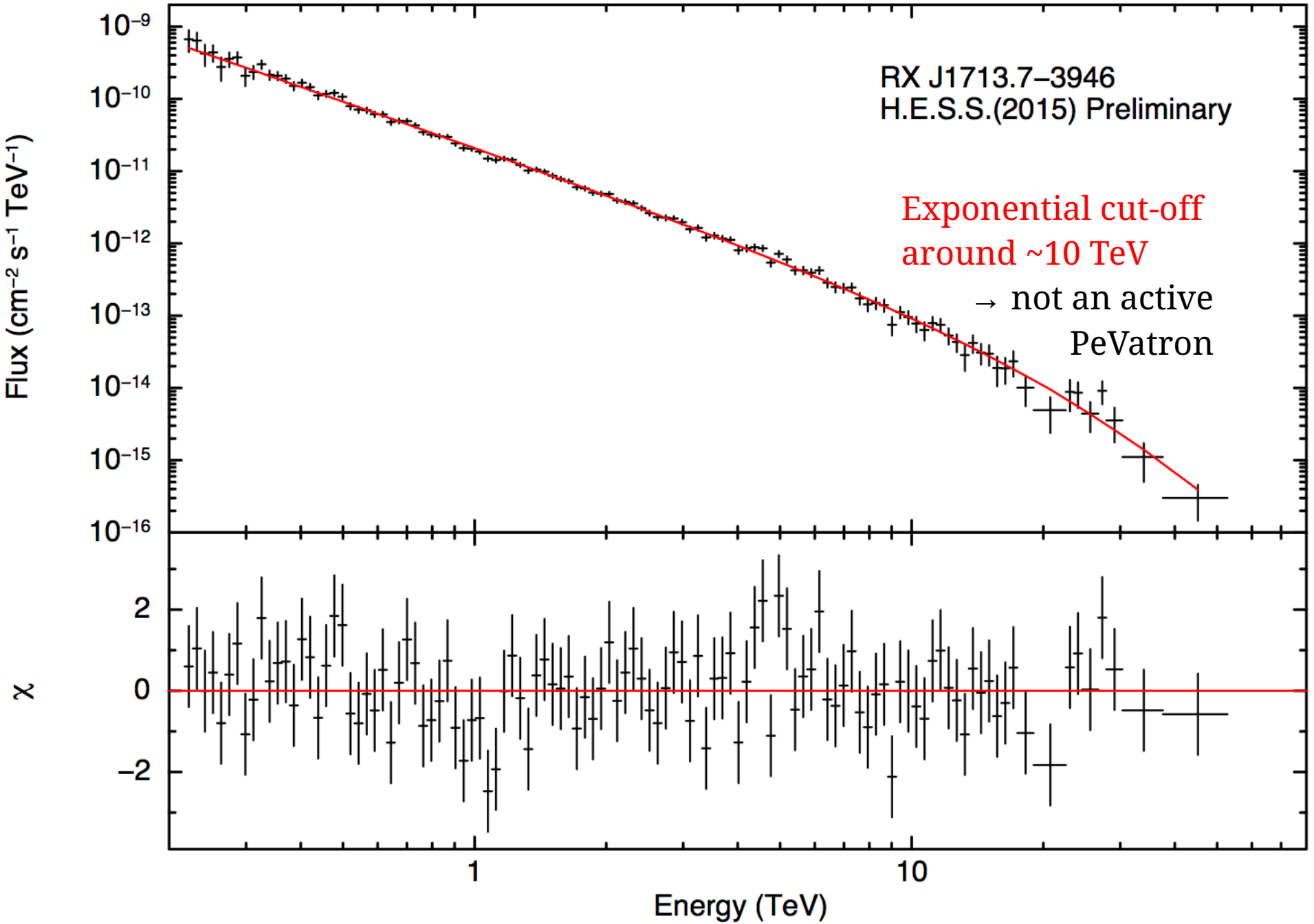


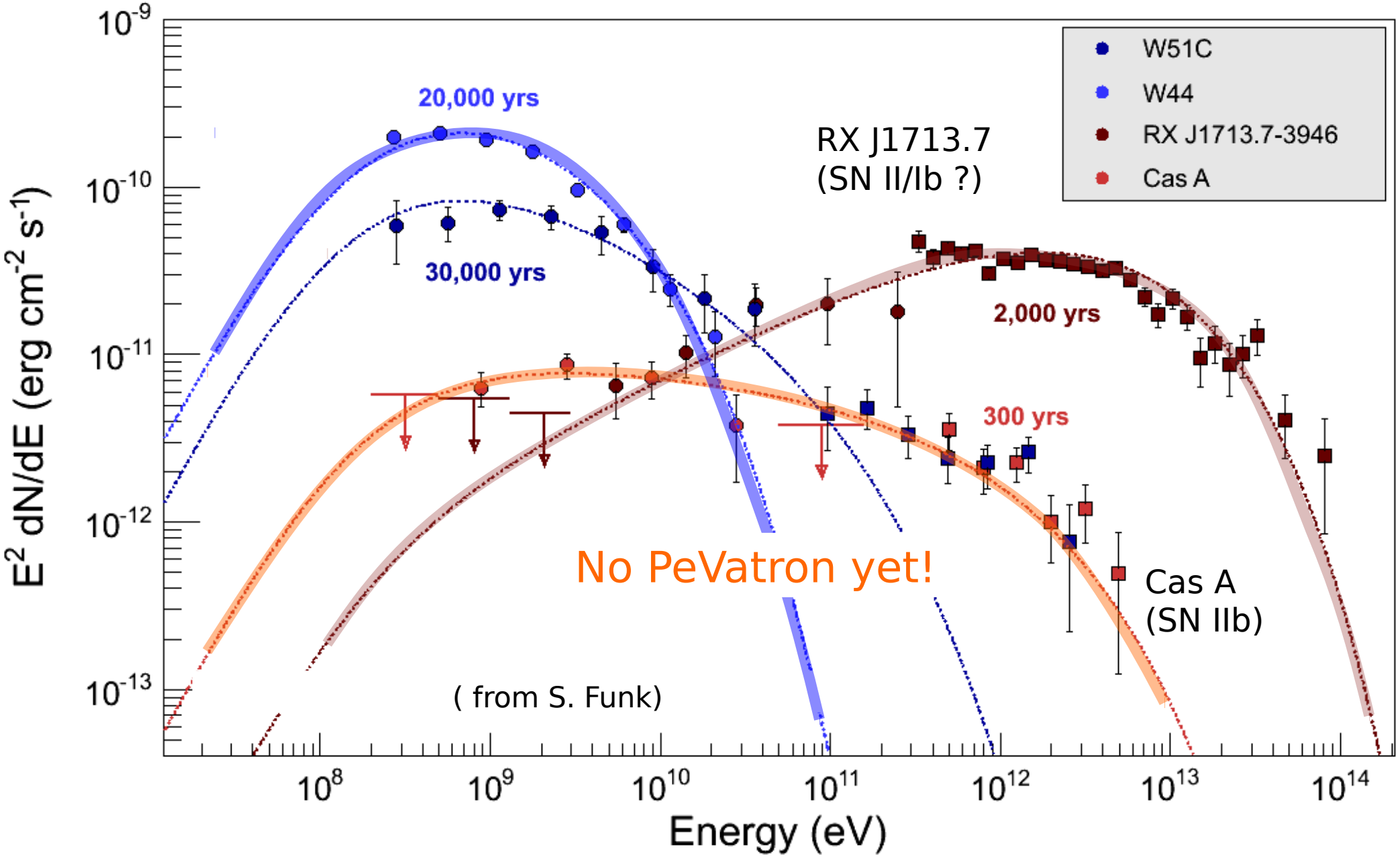

**X-rays (*XMM-Newton*) convolved with H.E.S.S. PSF**

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

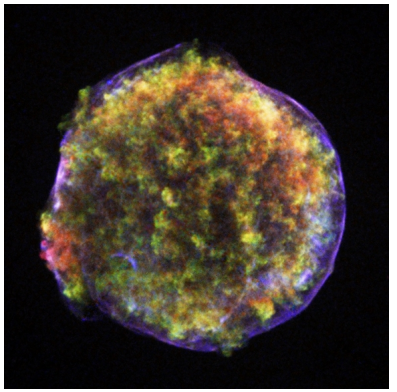
To be investigated and discussed in upcoming paper.

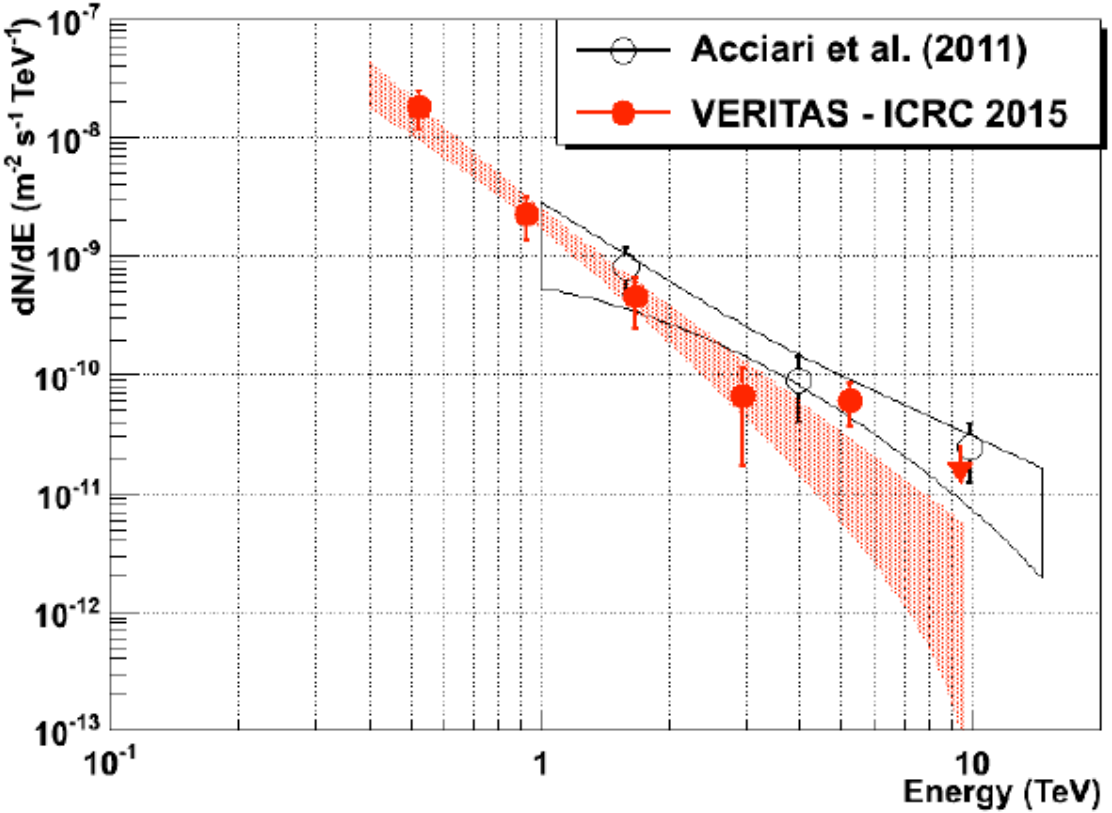
# Precision TeV spectral measurements

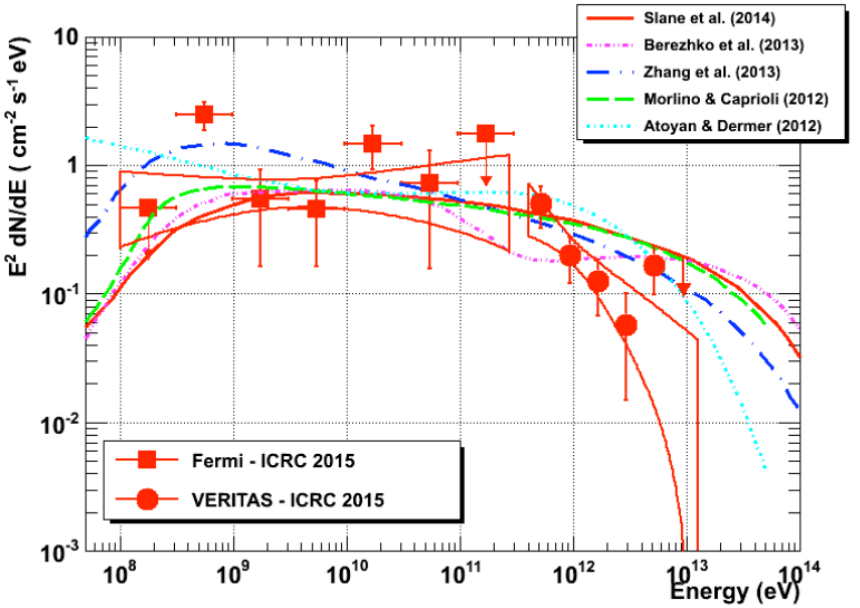



W51C
W44
RX J1713.7-3946
Cas A
20,000 yrs
30,000 yrs
RX J1713.7
(SN II/Ib ?)
2,000 yrs
300 yrs
No PeVatron yet!
Cas A
(SN IIb)
( from S. Funk)
$E^2$ dN/dE (erg cm$^{-2}$ s$^{-1}$)
Energy (eV)
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{8}$
$10^{9}$
$10^{10}$
$10^{11}$
$10^{12}$
$10^{13}$
$10^{14}$

# *Sorry Tycho...*



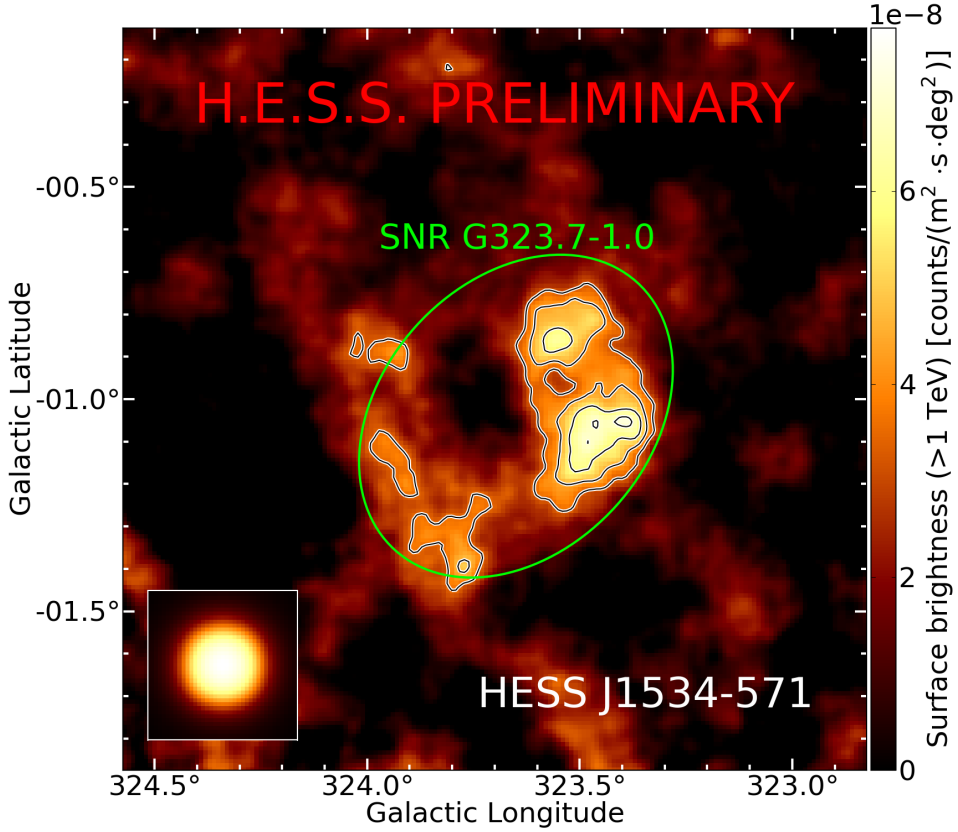


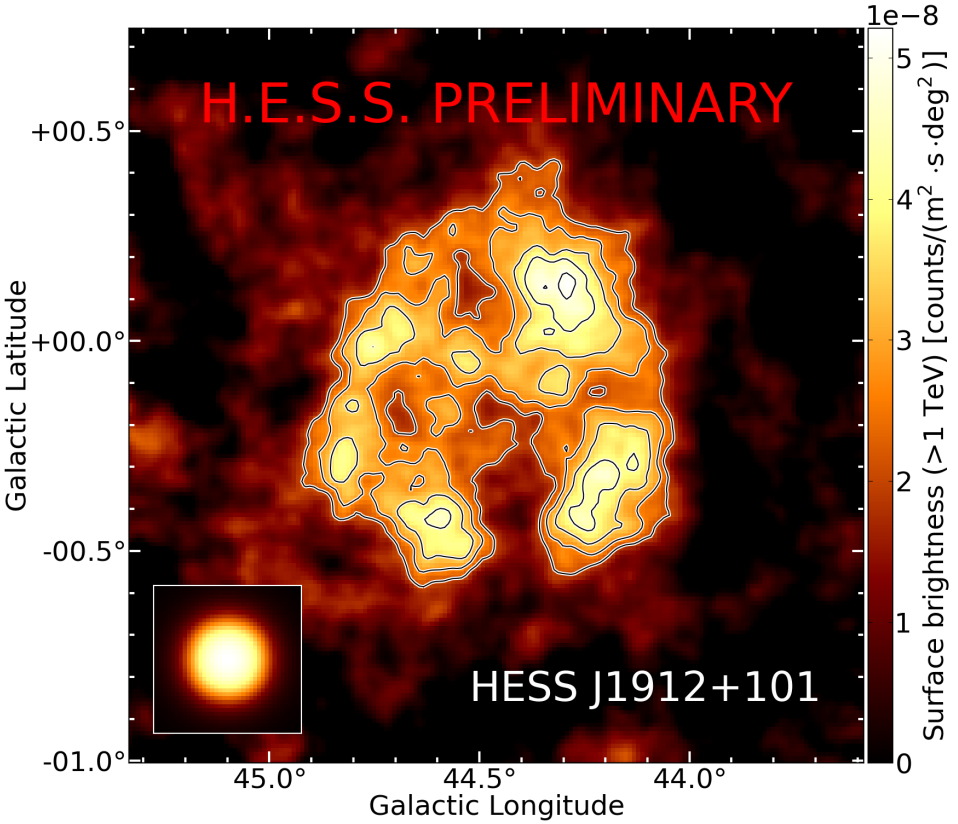




$\Gamma = \mathbf{1.95} \pm 0.51_{\text{stat}} \pm 0.30_{\text{syst}} \rightarrow \mathbf{2.92} \pm 0.42_{\text{stat}}$

No longer a promising PeVatron candidate

# What about missing SNRs?

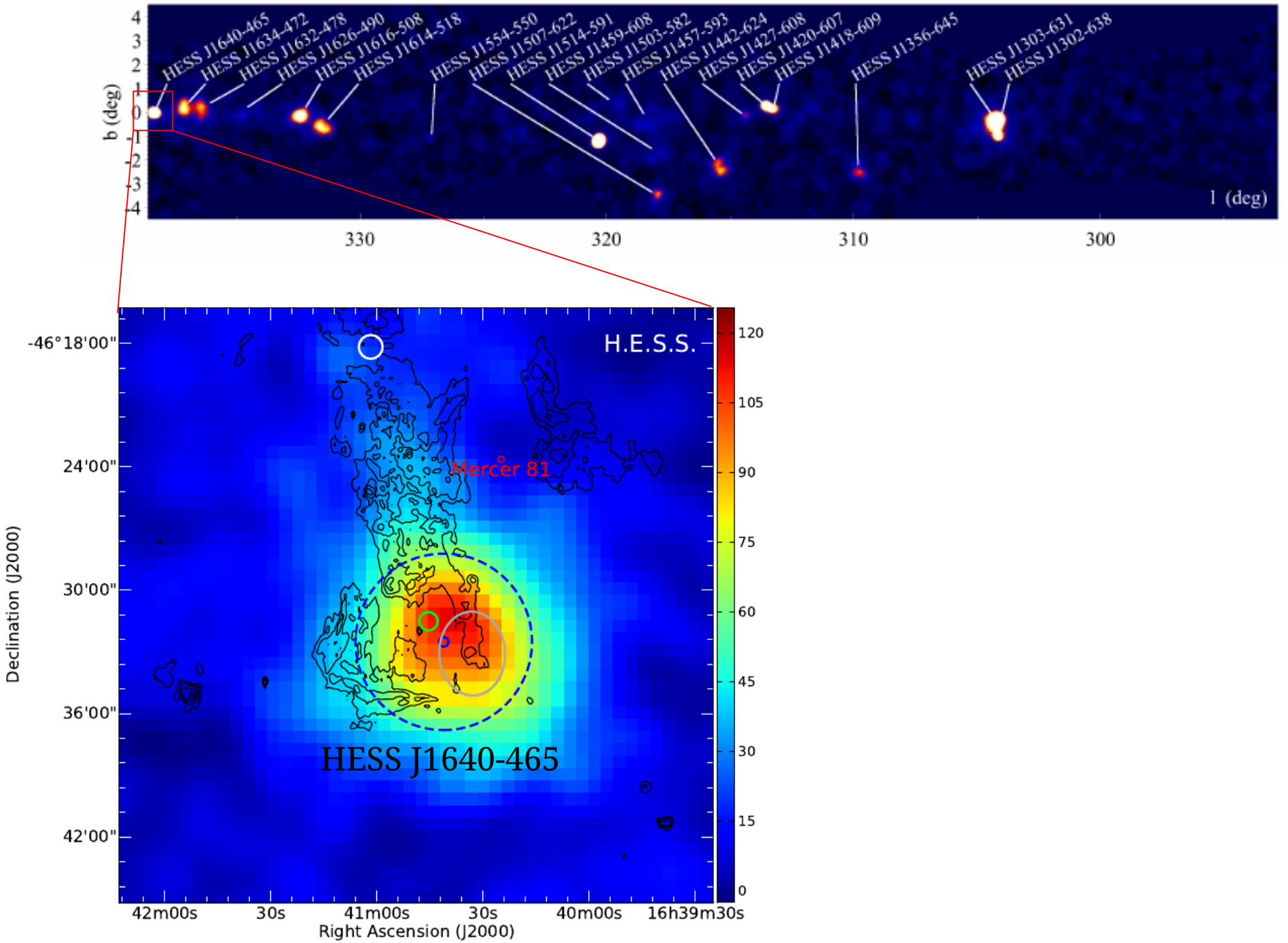



Statistically-significant TeV shell morphology discovered

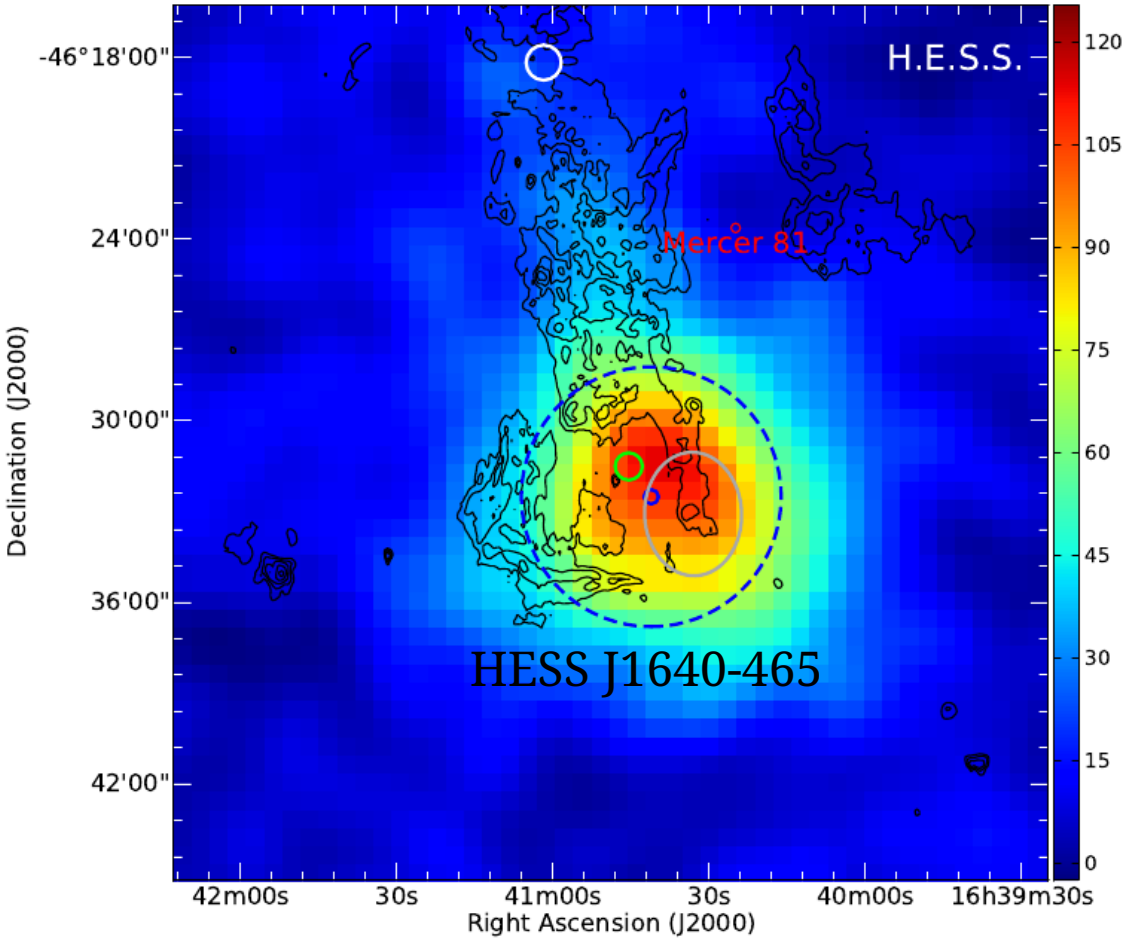
More like these hidden in the data?

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

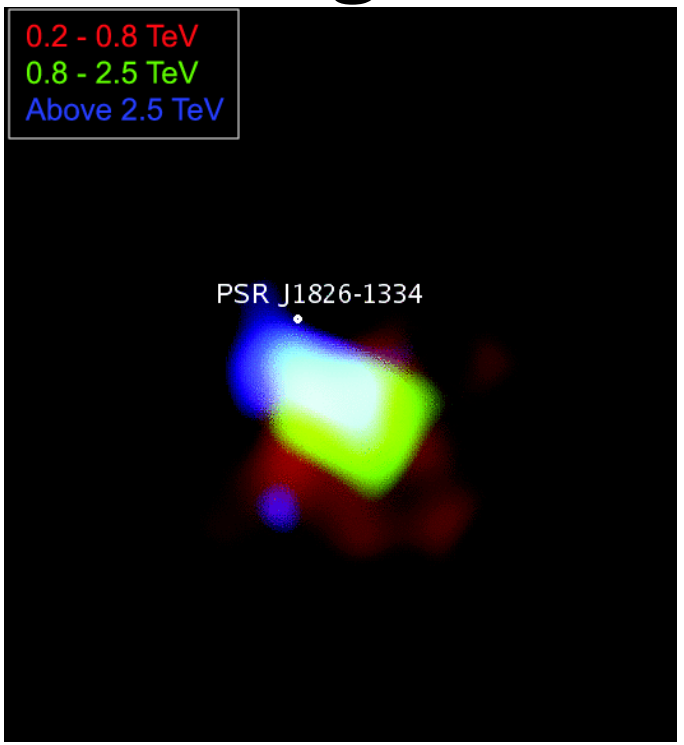


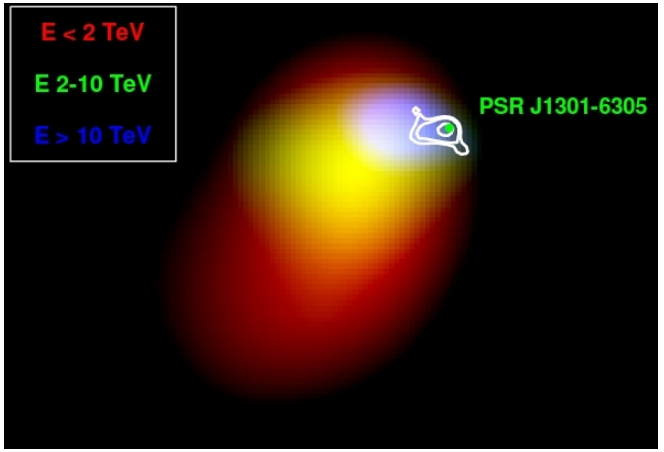

Abramowski+ (H.E.S.S.) 14

# Studying a possible pulsar wind nebulae for E-dep. morphology...




e.g.




Abramowski+ (H.E.S.S.) 14

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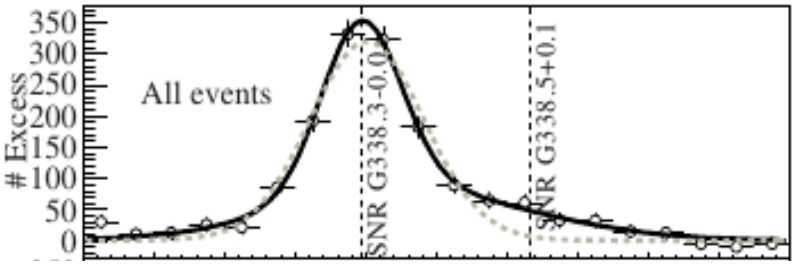


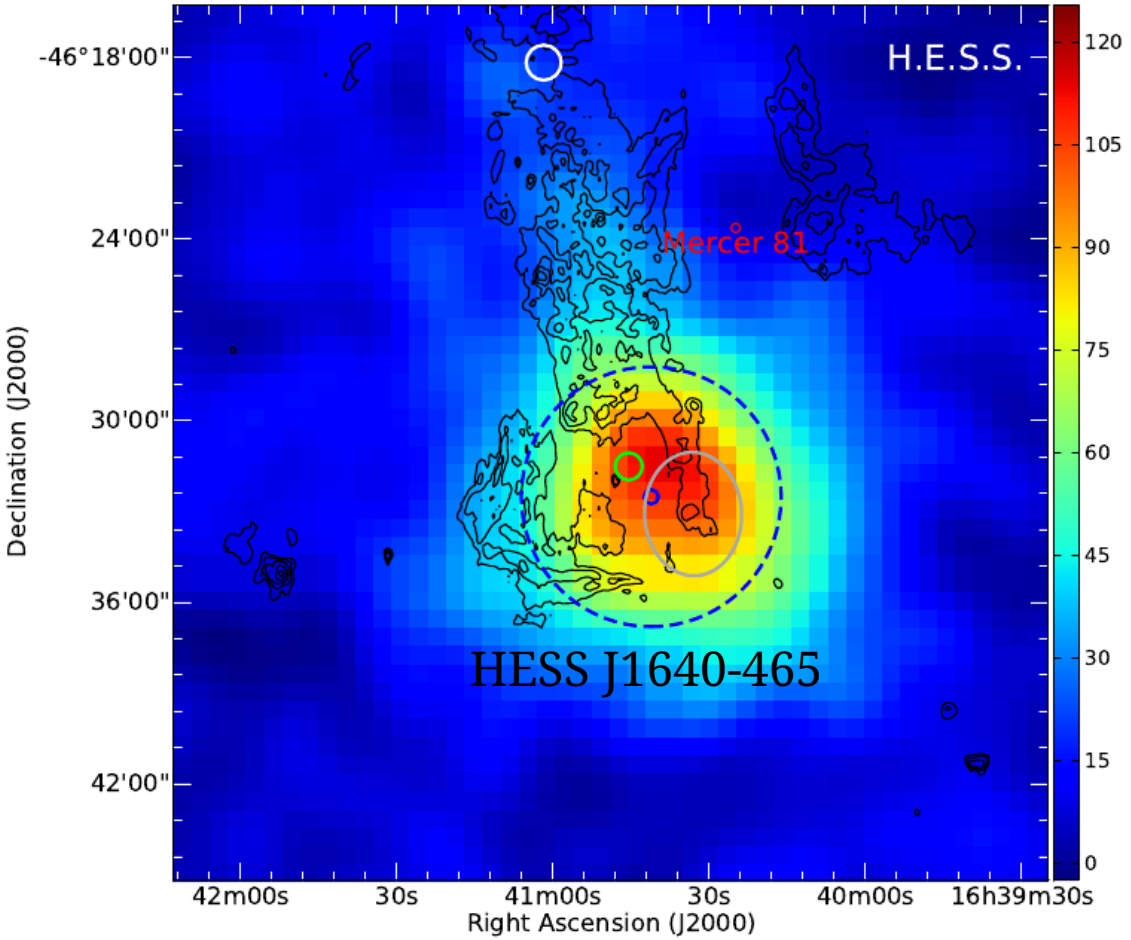


Abramowski+ (H.E.S.S.) 14

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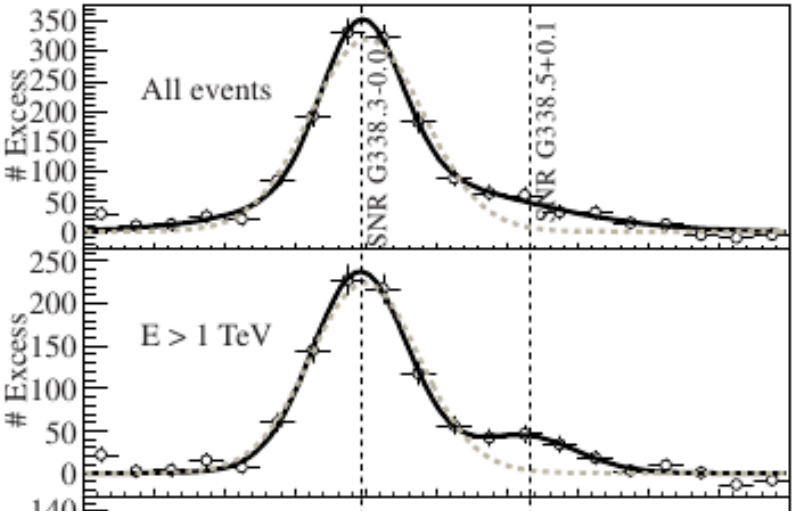
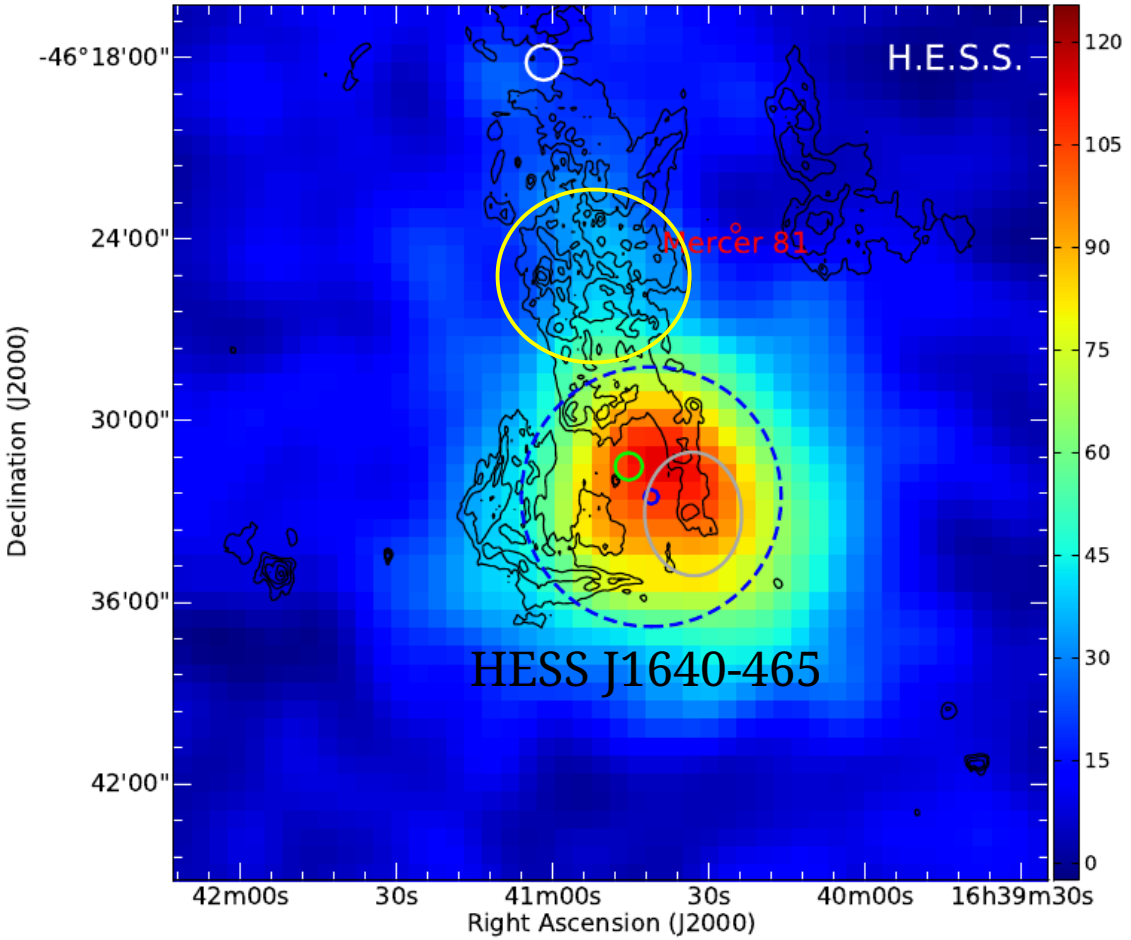
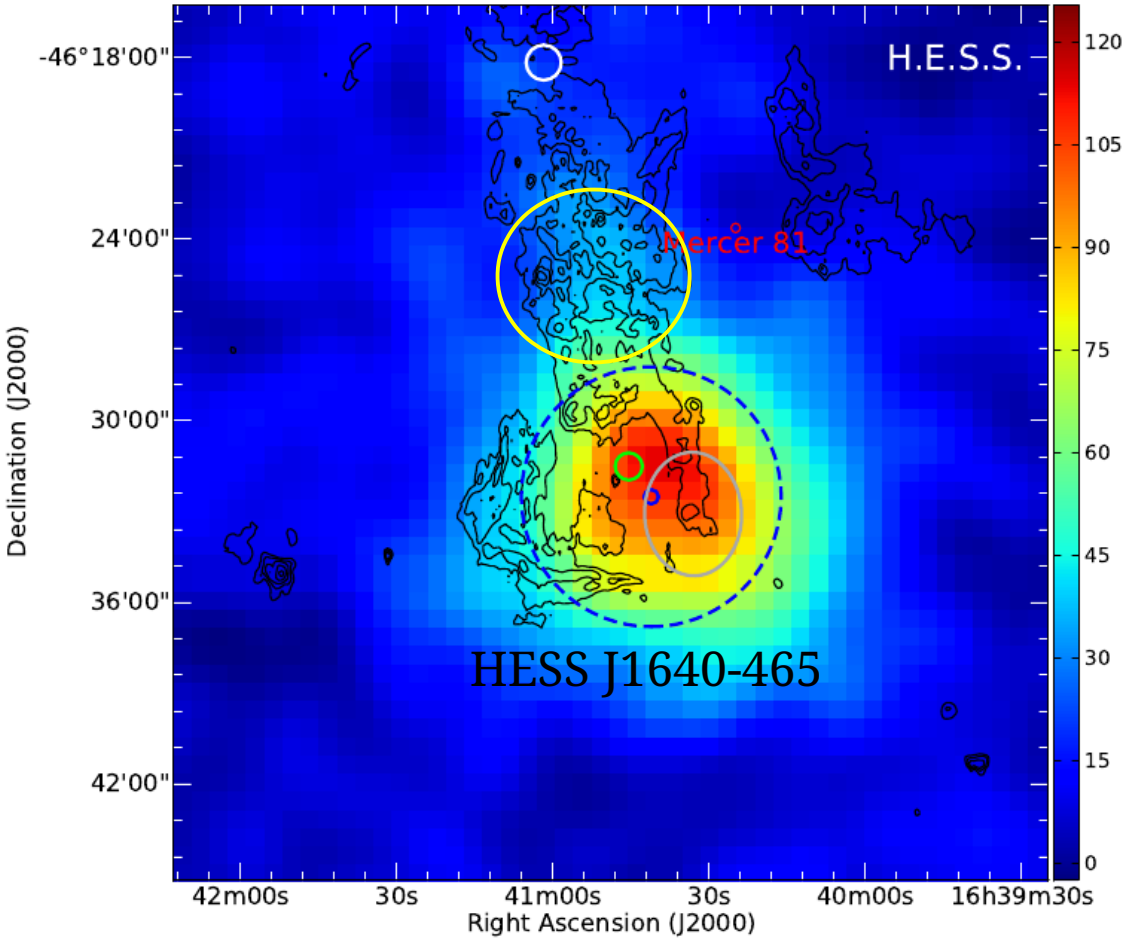
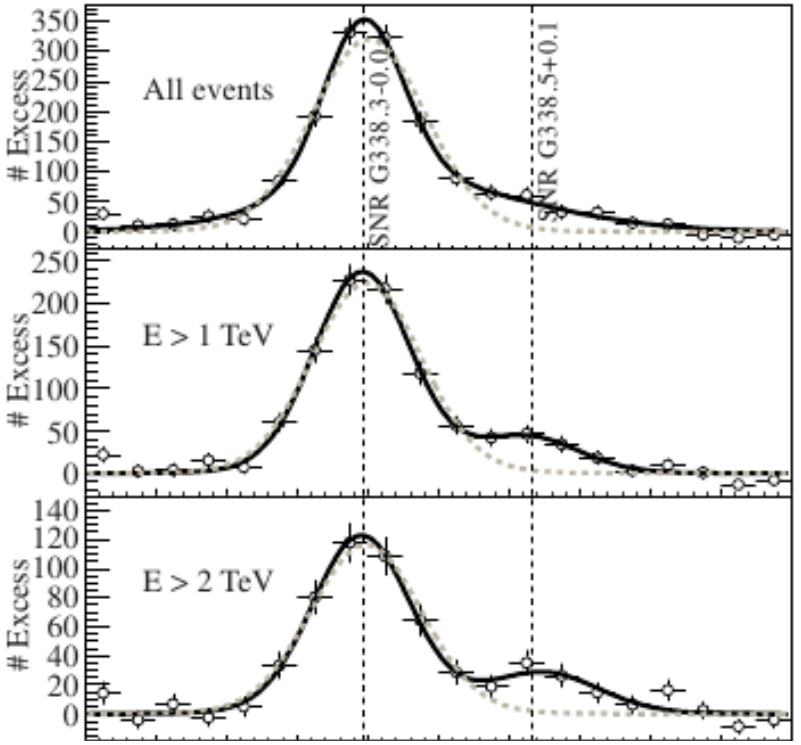


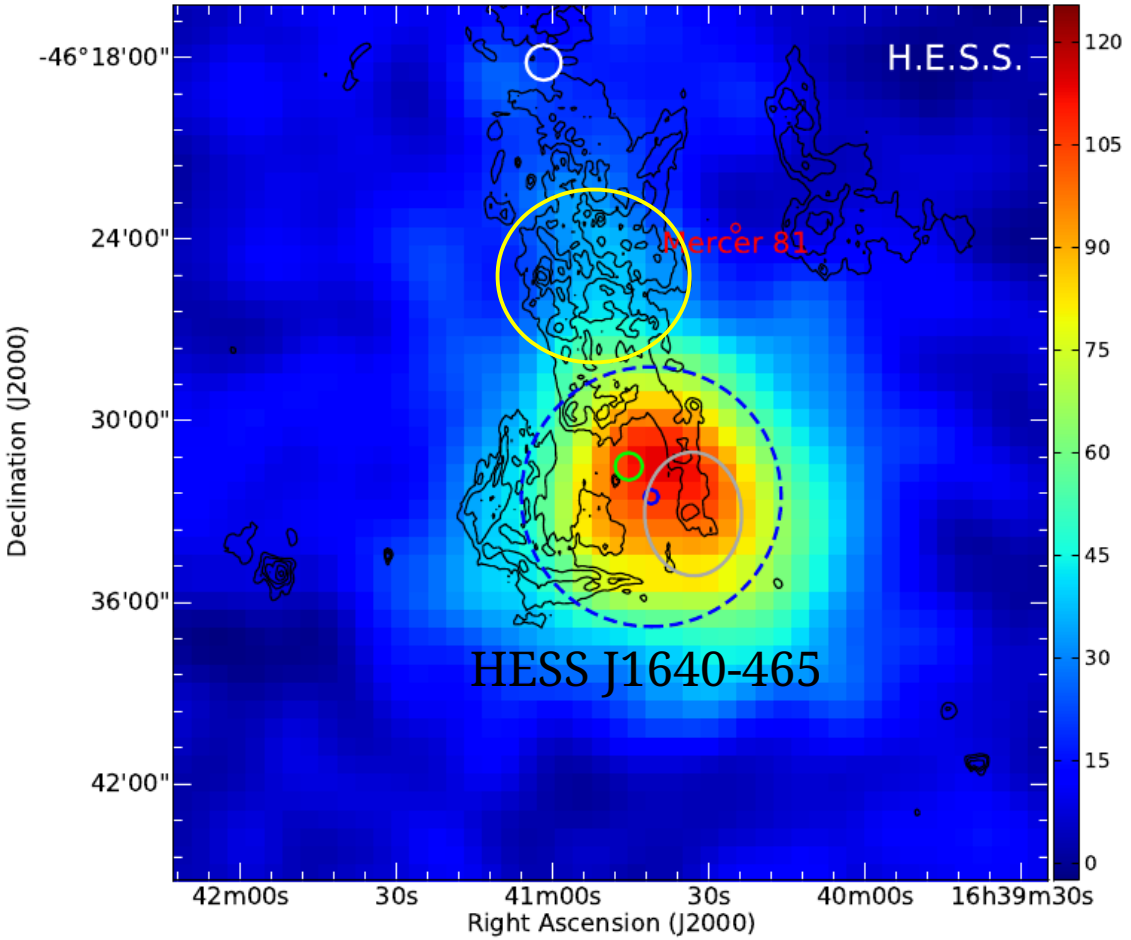
# Studying a possible pulsar wind nebulae for E-dep. morphology...

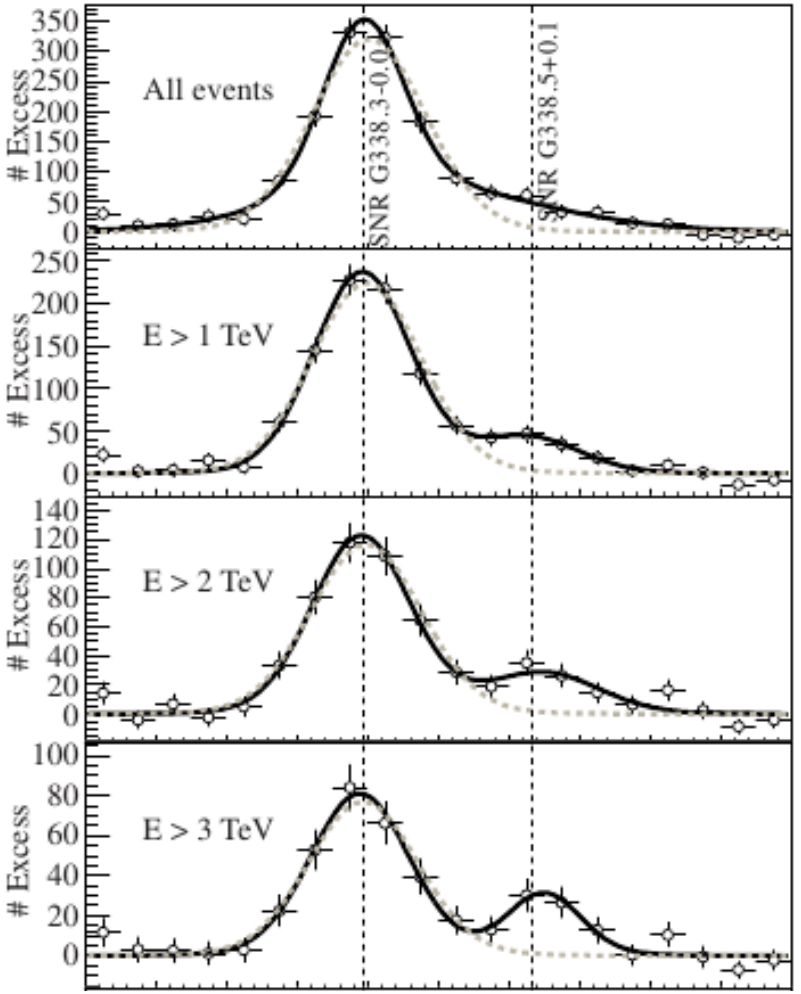



Abramowski+ (H.E.S.S.) 14

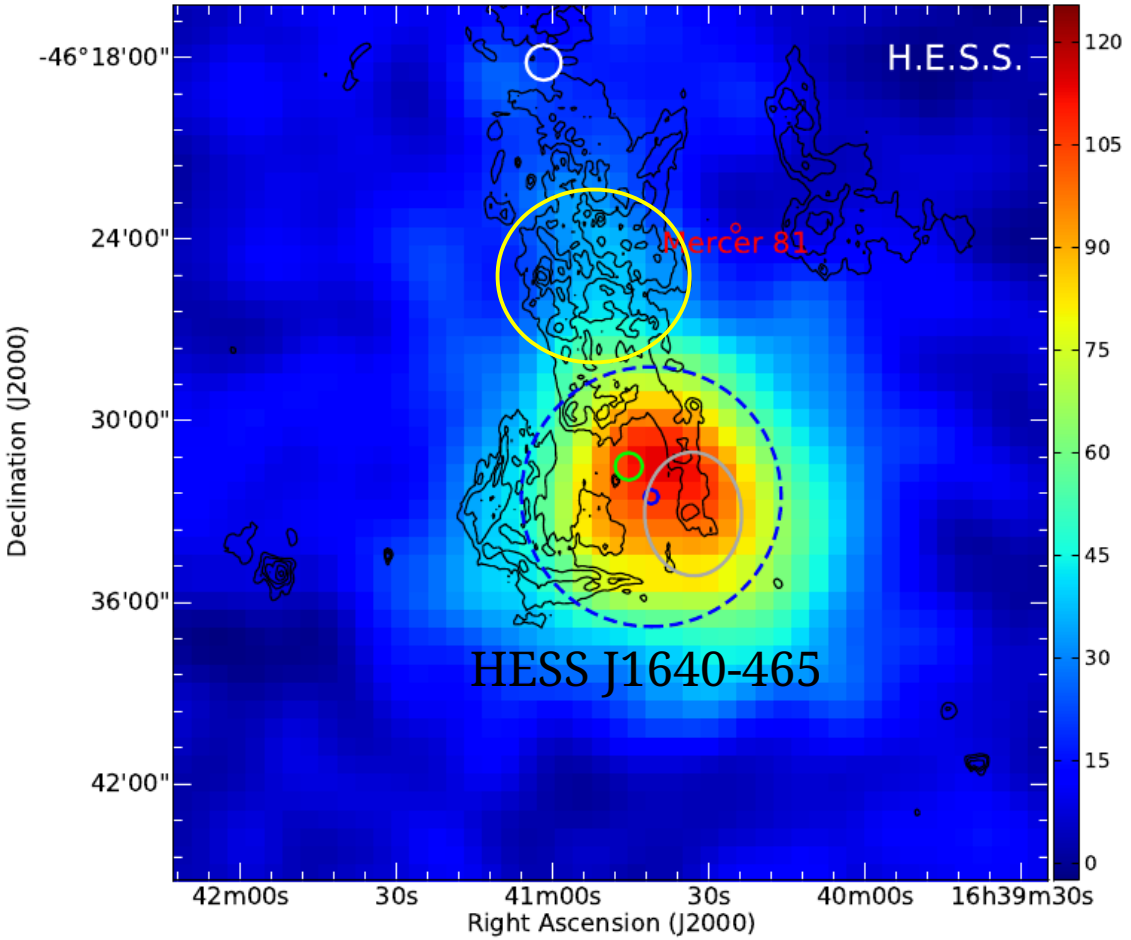
# Studying a possible pulsar wind nebulae for E-dep. morphology...

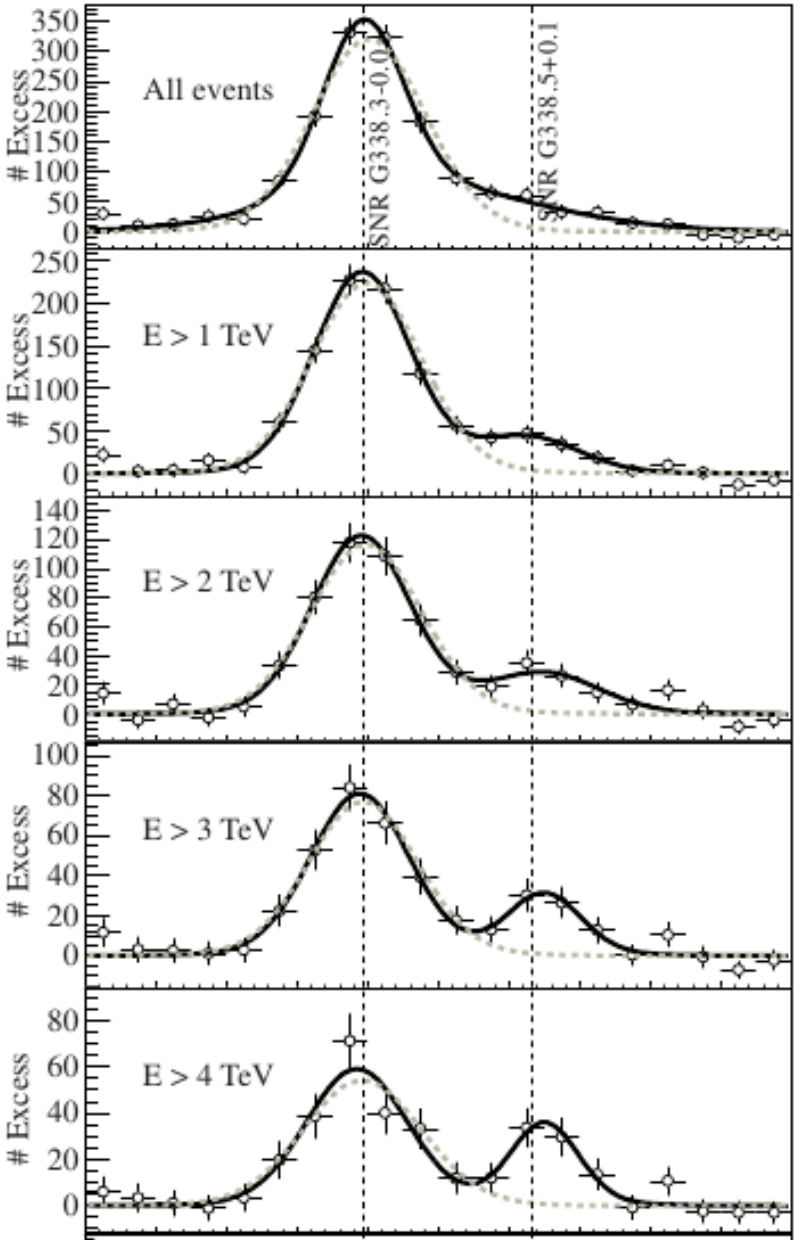



Abramowski+ (H.E.S.S.) 14

# Studying a possible pulsar wind nebulae for E-dep. morphology...

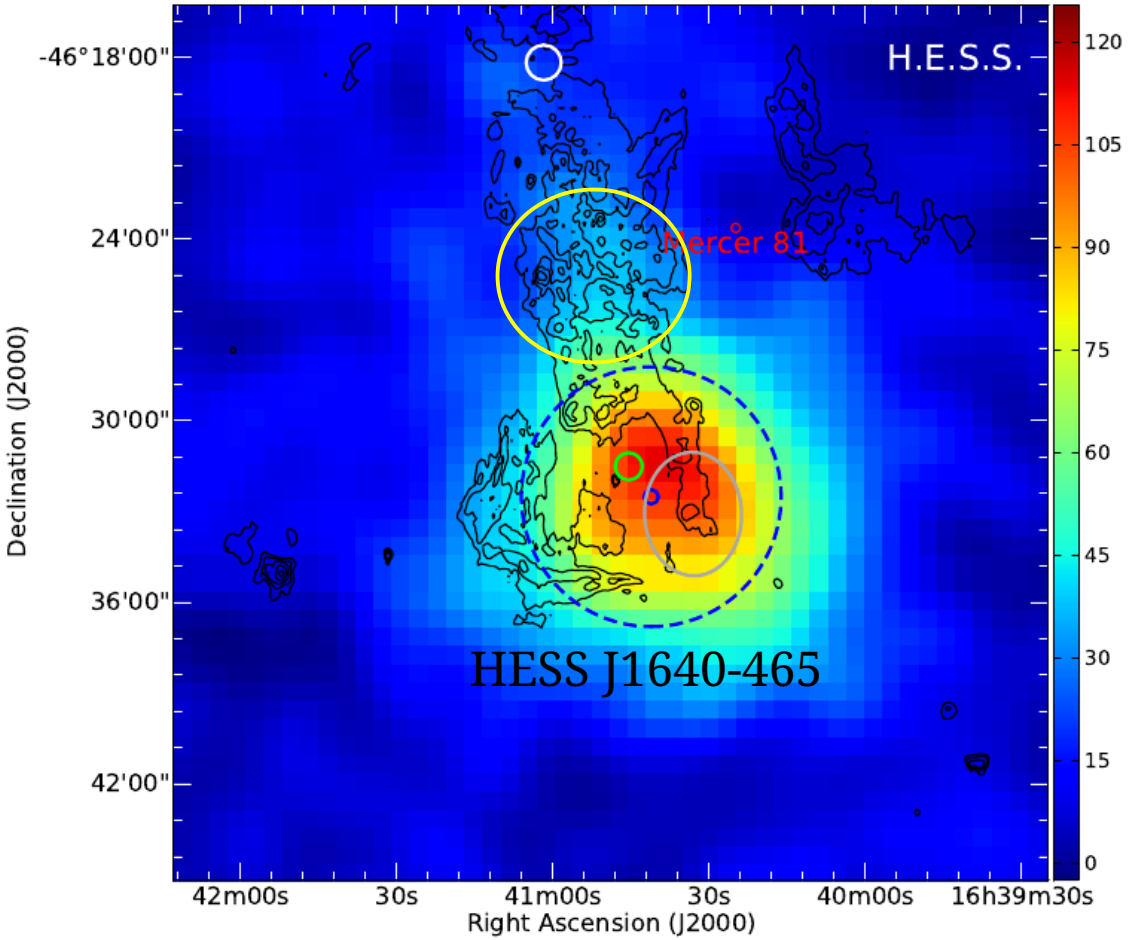


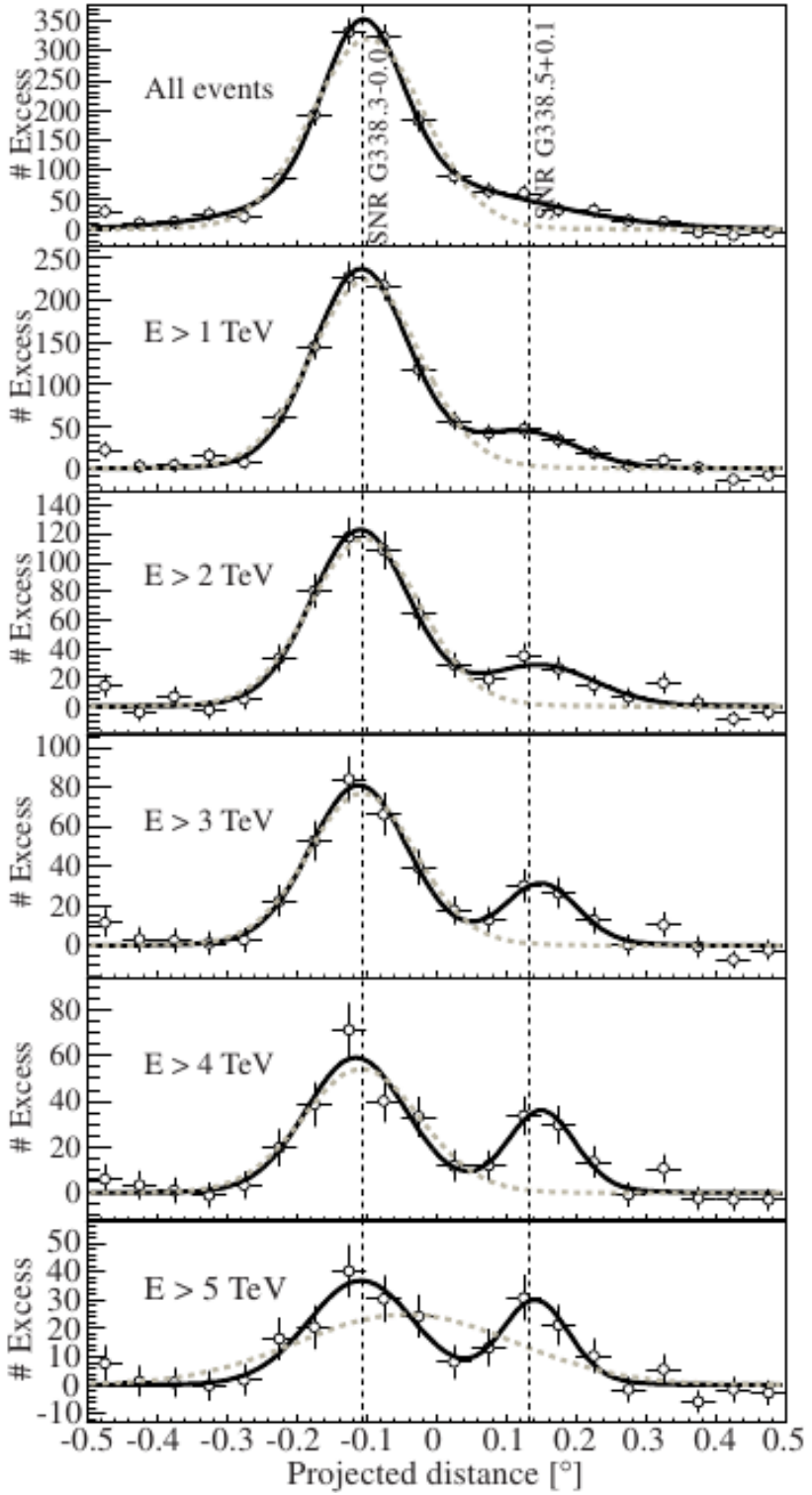




Abramowski+ (H.E.S.S.) 14

# HESS J1641-463:

Brand-new,
serendipitous discovery...



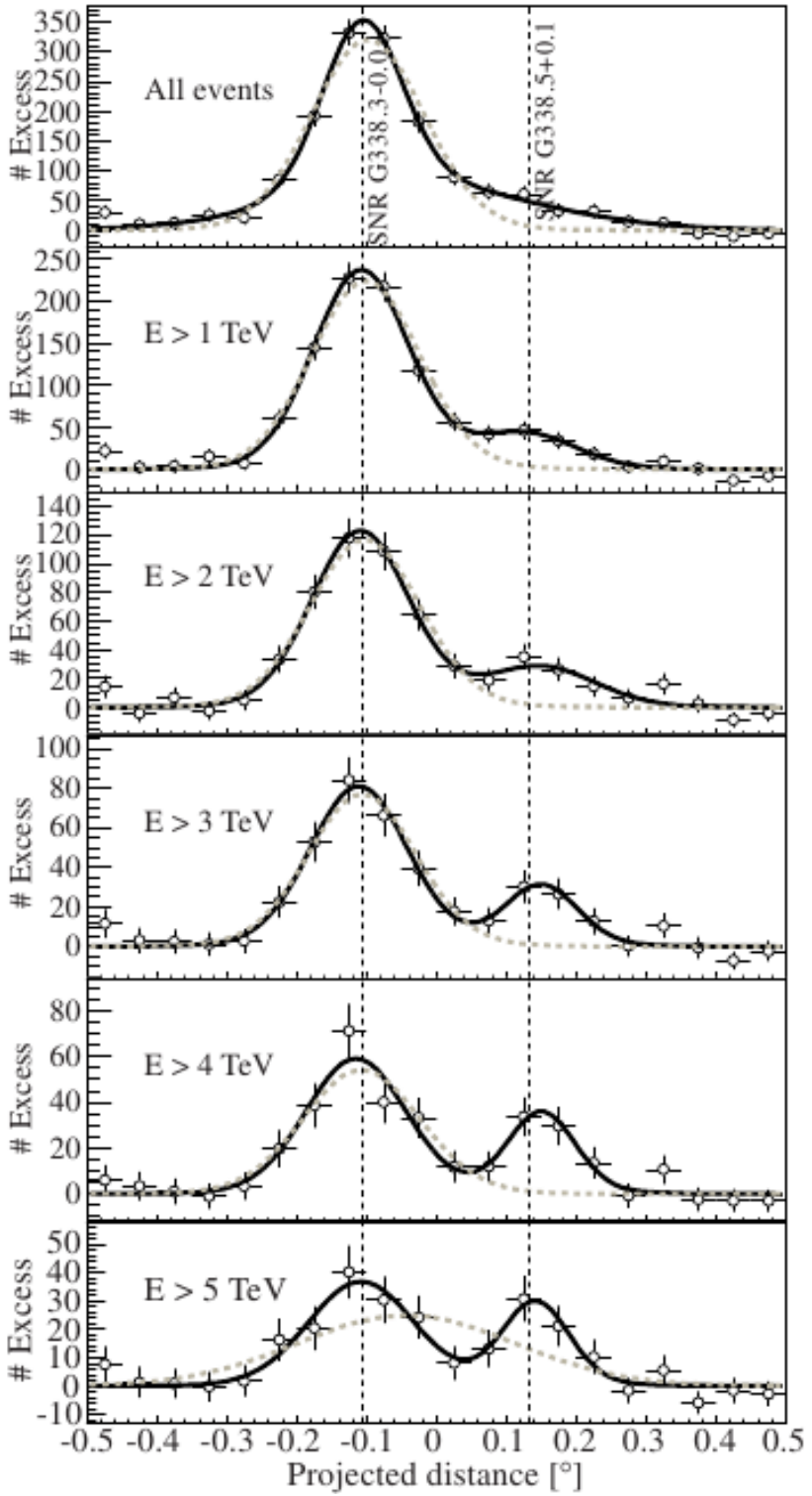




Abramowski+ (H.E.S.S.) 14

# **Deep exposures** (72 h) → **source confusion**

Side-step issue w/ high E cuts

especially if nearby sources have contrasting Γ



# **Deep exposures** (72 h) → **source confusion**

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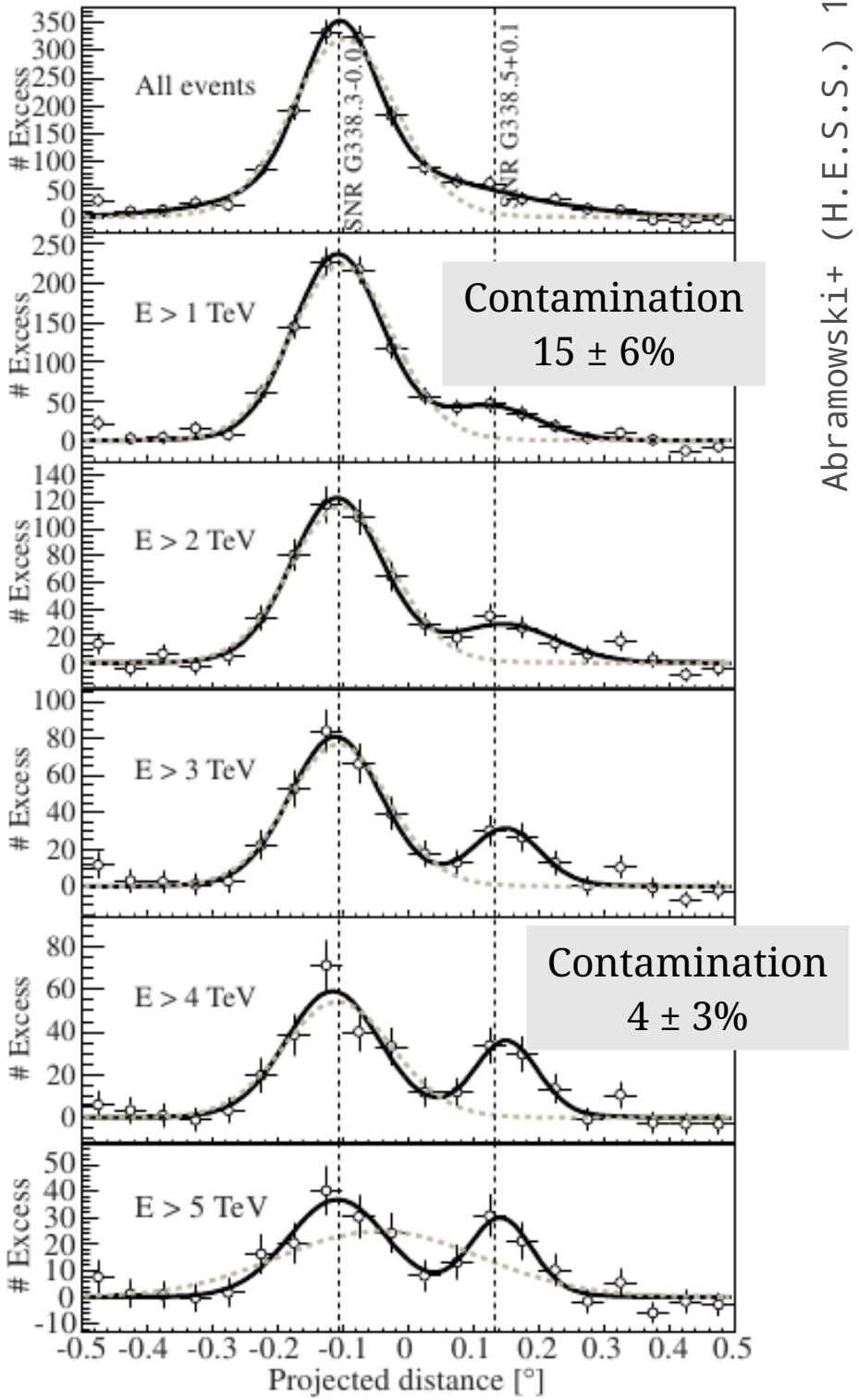
especially if nearby sources have contrasting Γ

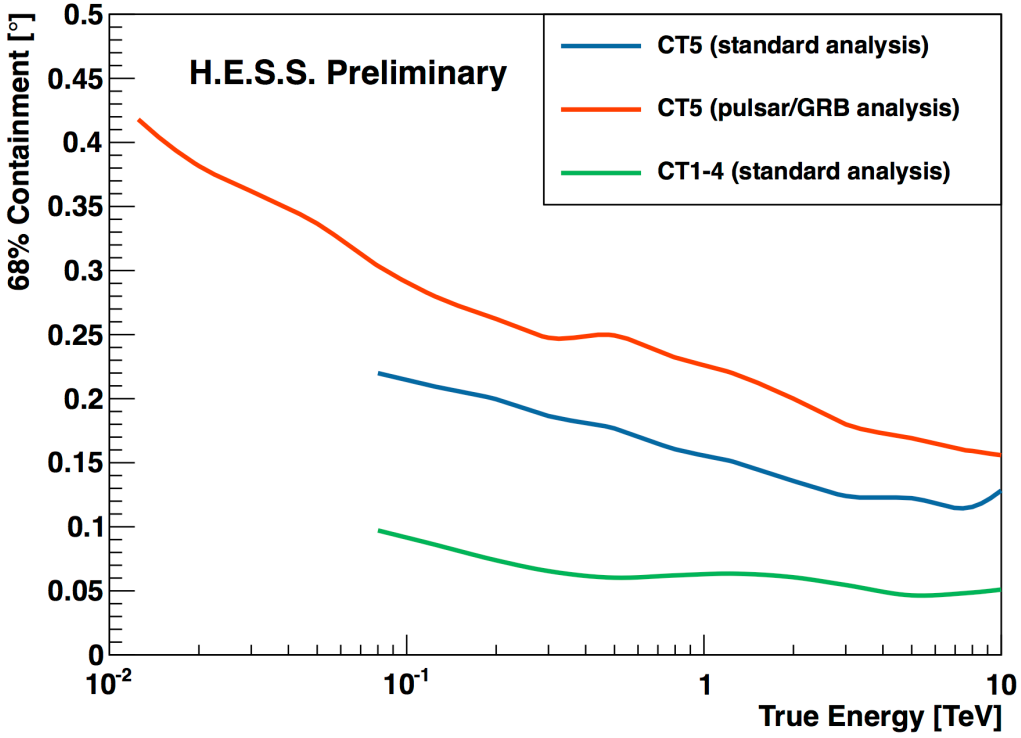


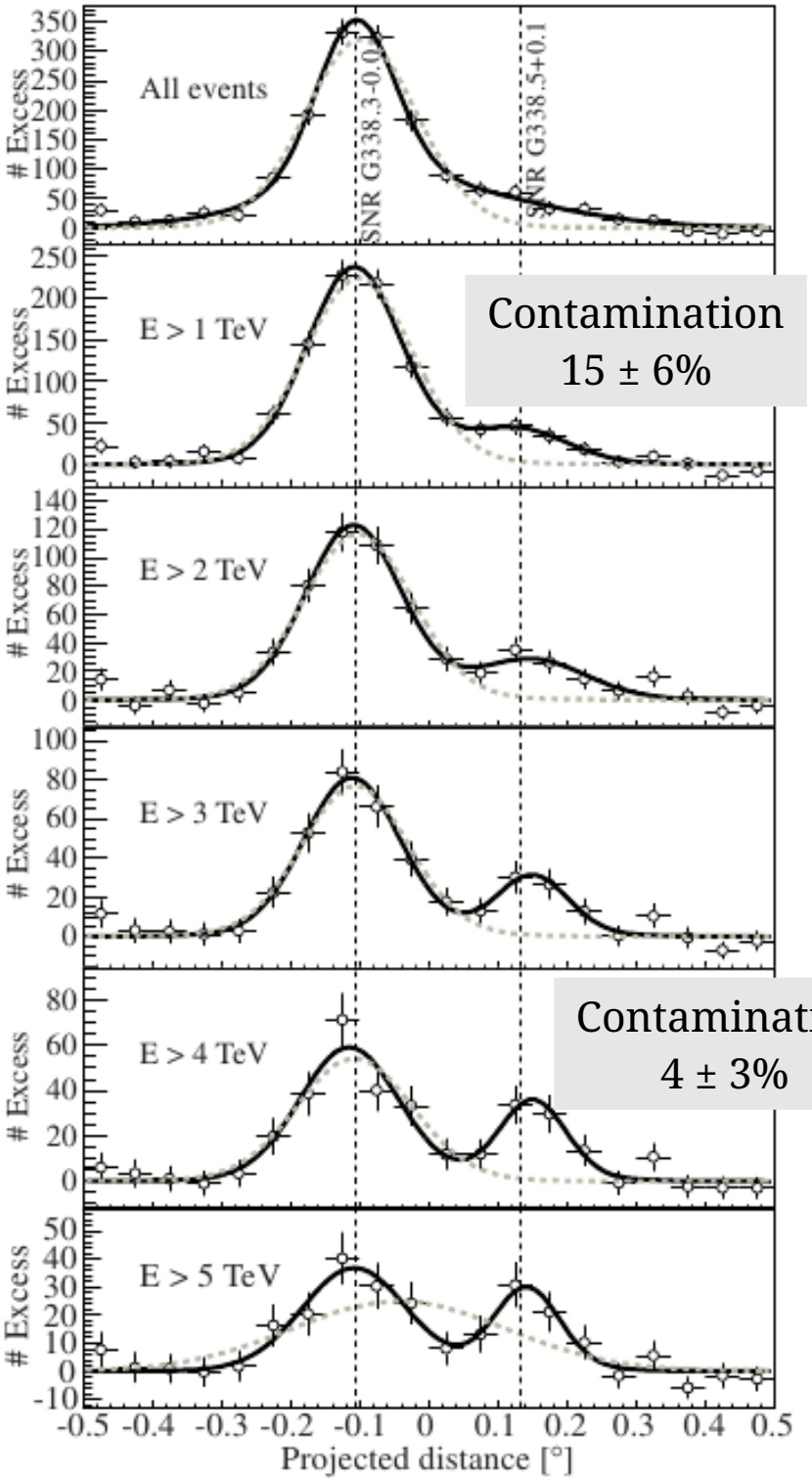
# **Deep exposures** (72 h) → **source confusion**

Side-step issue w/ high E cuts

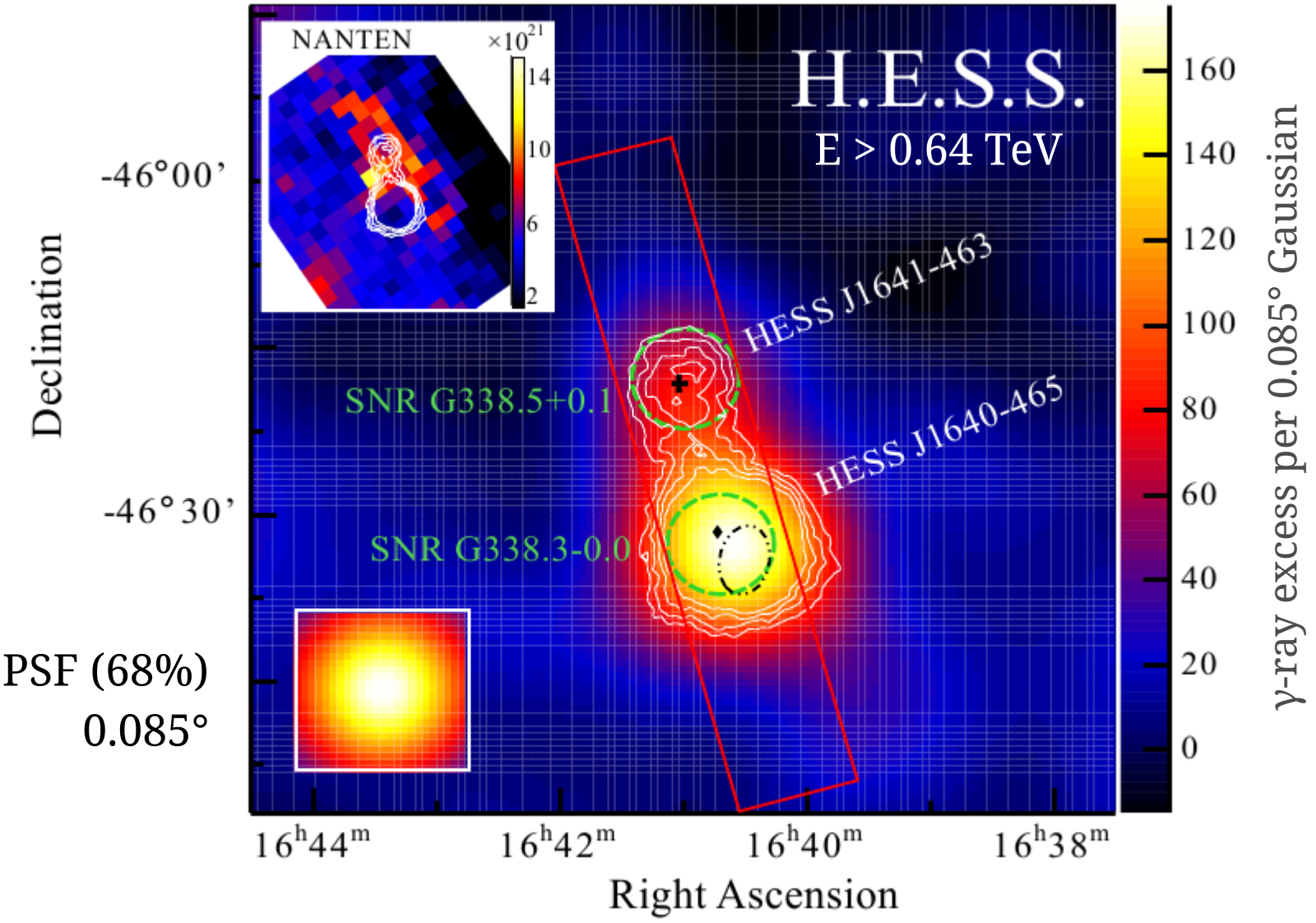
especially if nearby sources have contrasting Γ

Anyway, PSF also improves:



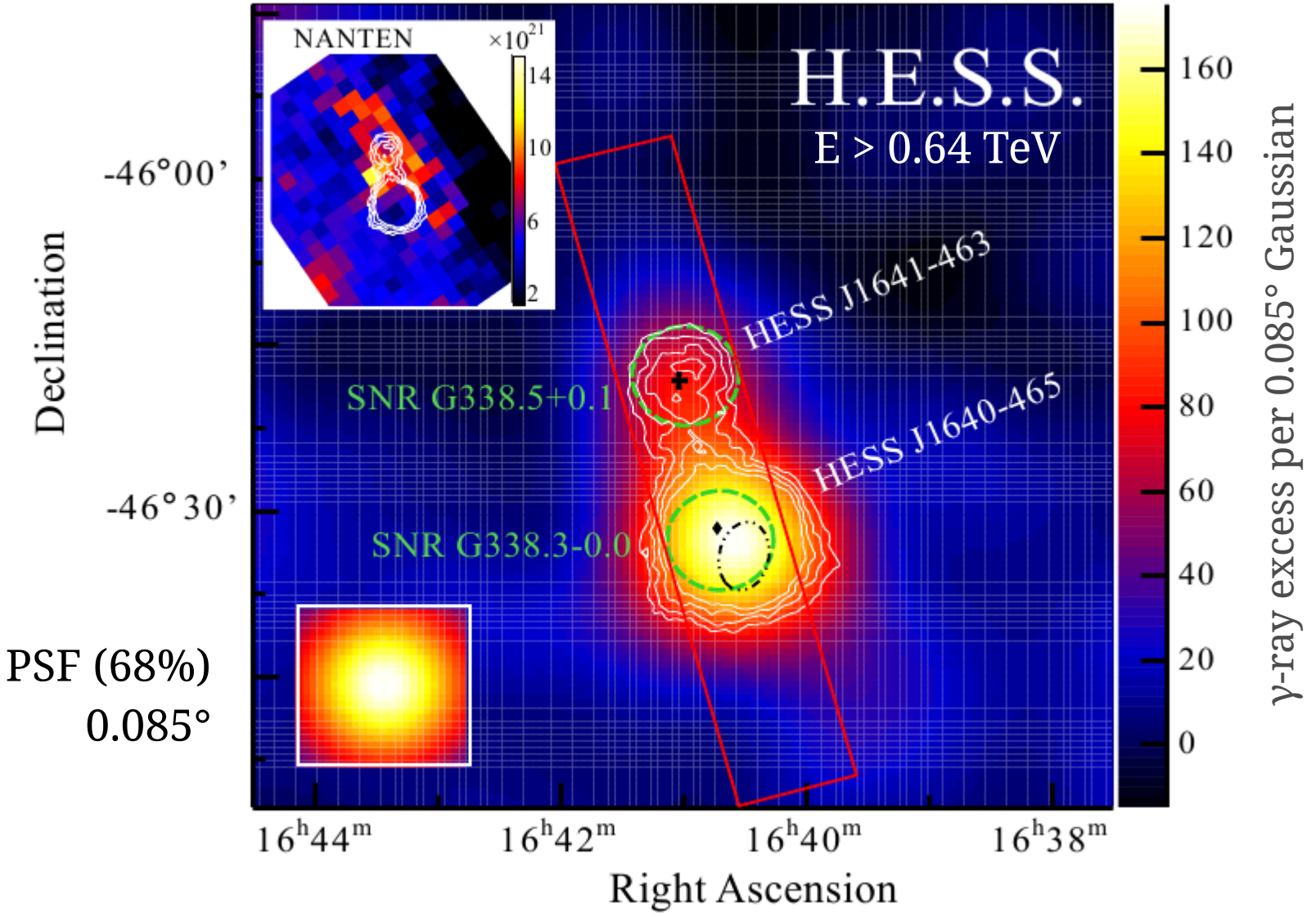
# **HESS J1641-463:** point-like, or diameter < 3'




Abramowski+ (H.E.S.S.) 14

# HESS J1641-463
# SNR G338.5+0.1

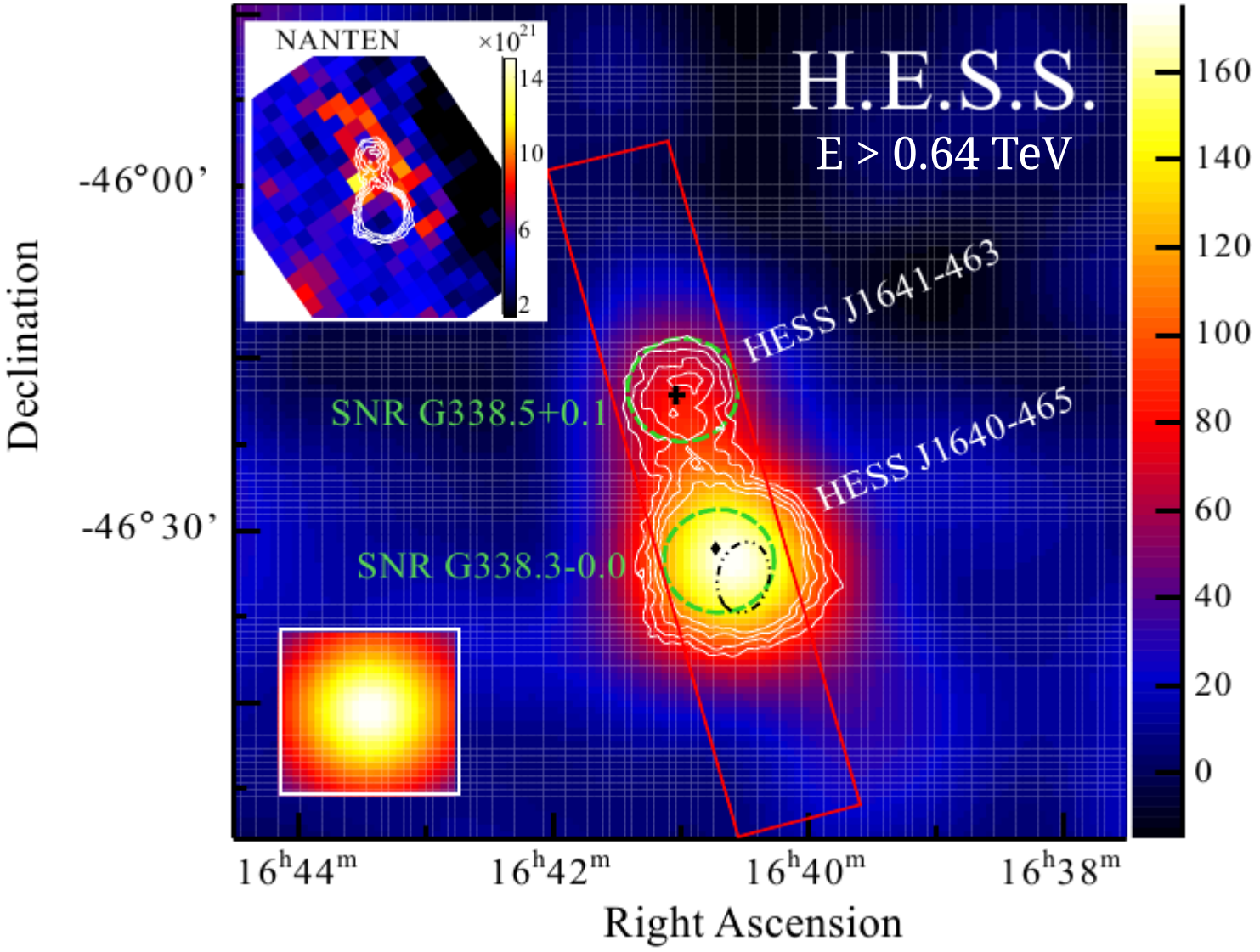
d = 11 kpc, d ~ 16-30 pc, Sedov age (n: 1-10 $cm^{-3}$) 1.1-3.5 kyr - 5-17 kyr




Abramowski+ (H.E.S.S.) 14

# HESS J1641-463:

Very hard photon spectrum: $\Gamma = 2.07 \pm 0.11_{stat} \pm 0.20_{syst}$




Integral flux:
1.8% Crab

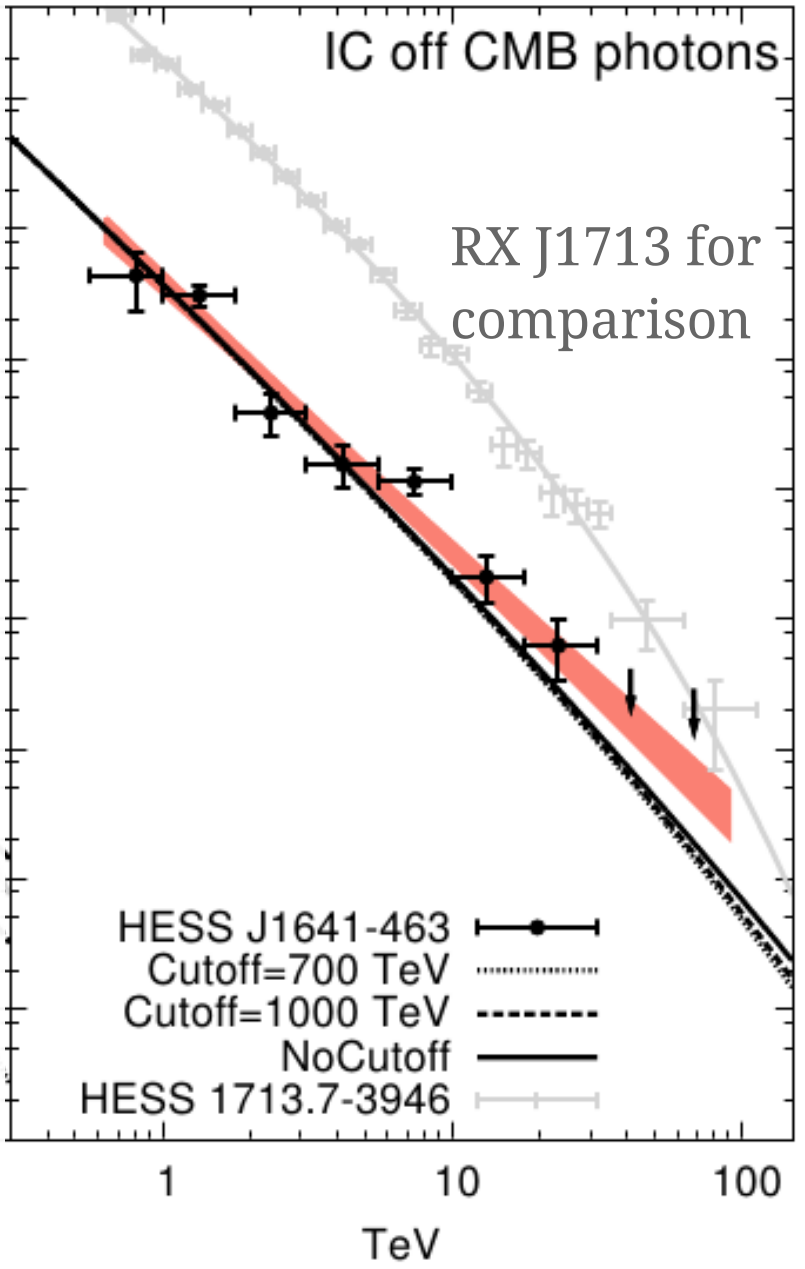
Abramowski+ (H.E.S.S.) 14

# HESS J1641-463:

leptonic model doesn't fit well (Klein-Nishina effect)

Assuming a PL for
primary electron spectrum

**Requires electron cutoff > 700 TeV (99% CL) to fit measured VHE spectrum**



# HESS J1641-463:

leptonic model doesn't fit well (Klein-Nishina effect)

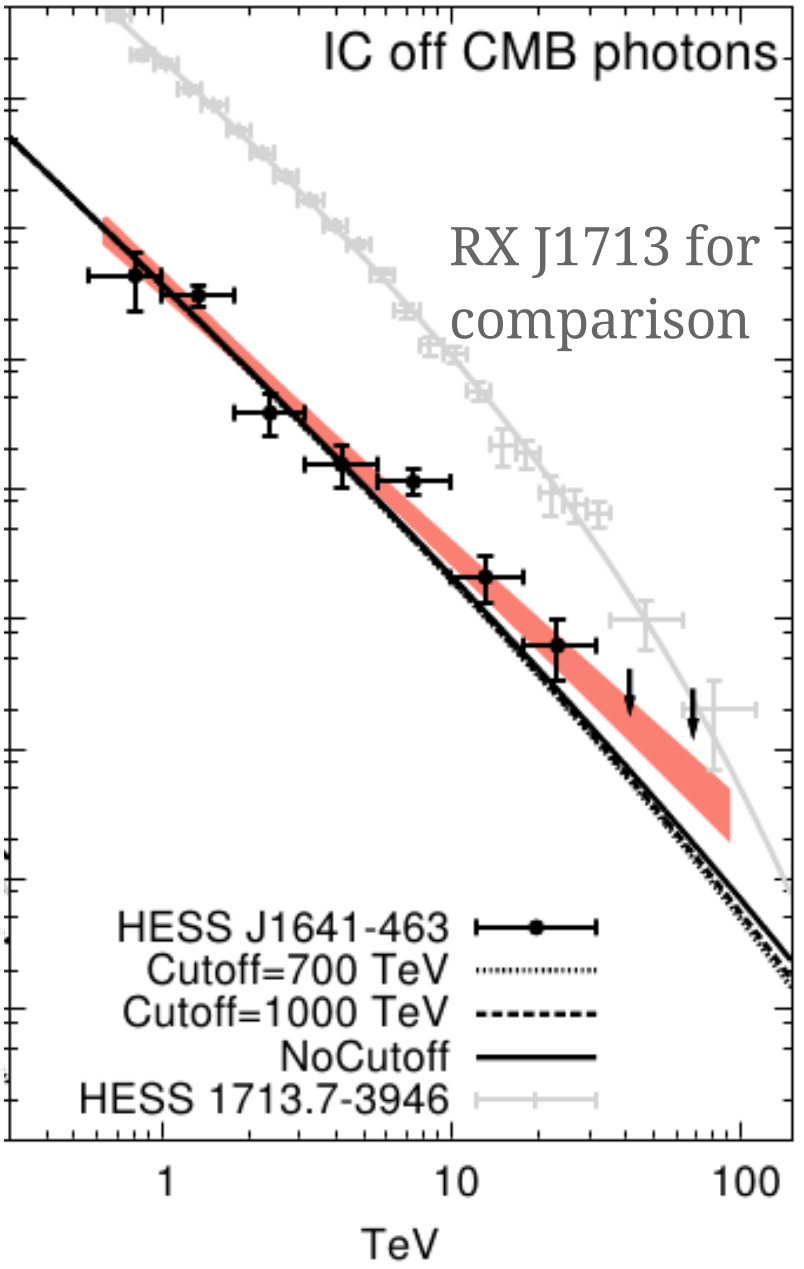
Assuming a PL for
primary electron spectrum

**Requires electron cutoff > 700 TeV (99% CL) to fit measured VHE spectrum**

Hundreds of TeV electrons suffer severe losses in amplified B-field

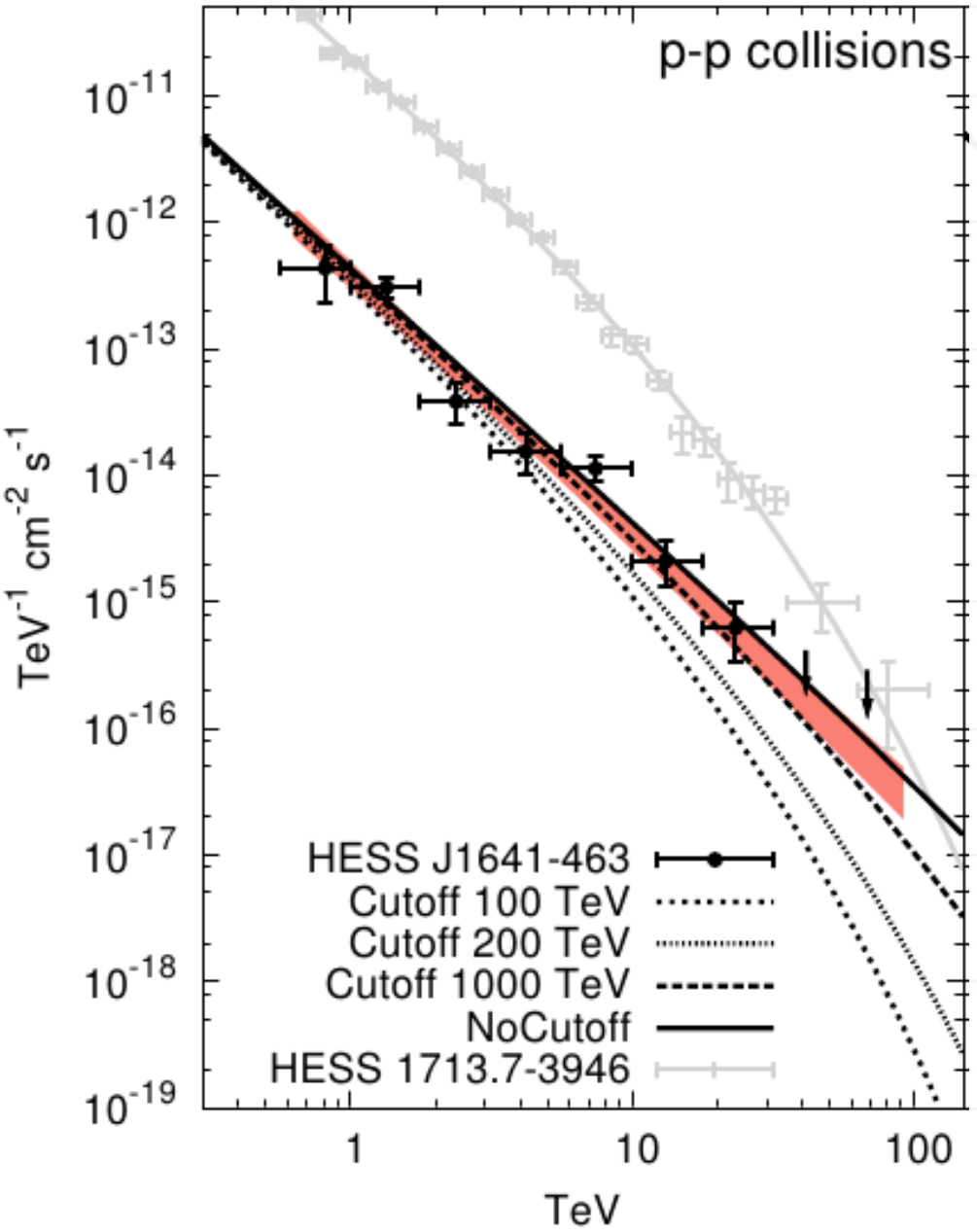
No break in photon spectrum

**Strongly disfavored scenario**



# HESS J1641-463:

p-p model fits data better → $\mathbf{E_{max} > 100\ TeV\ (99\%\ CL)}$



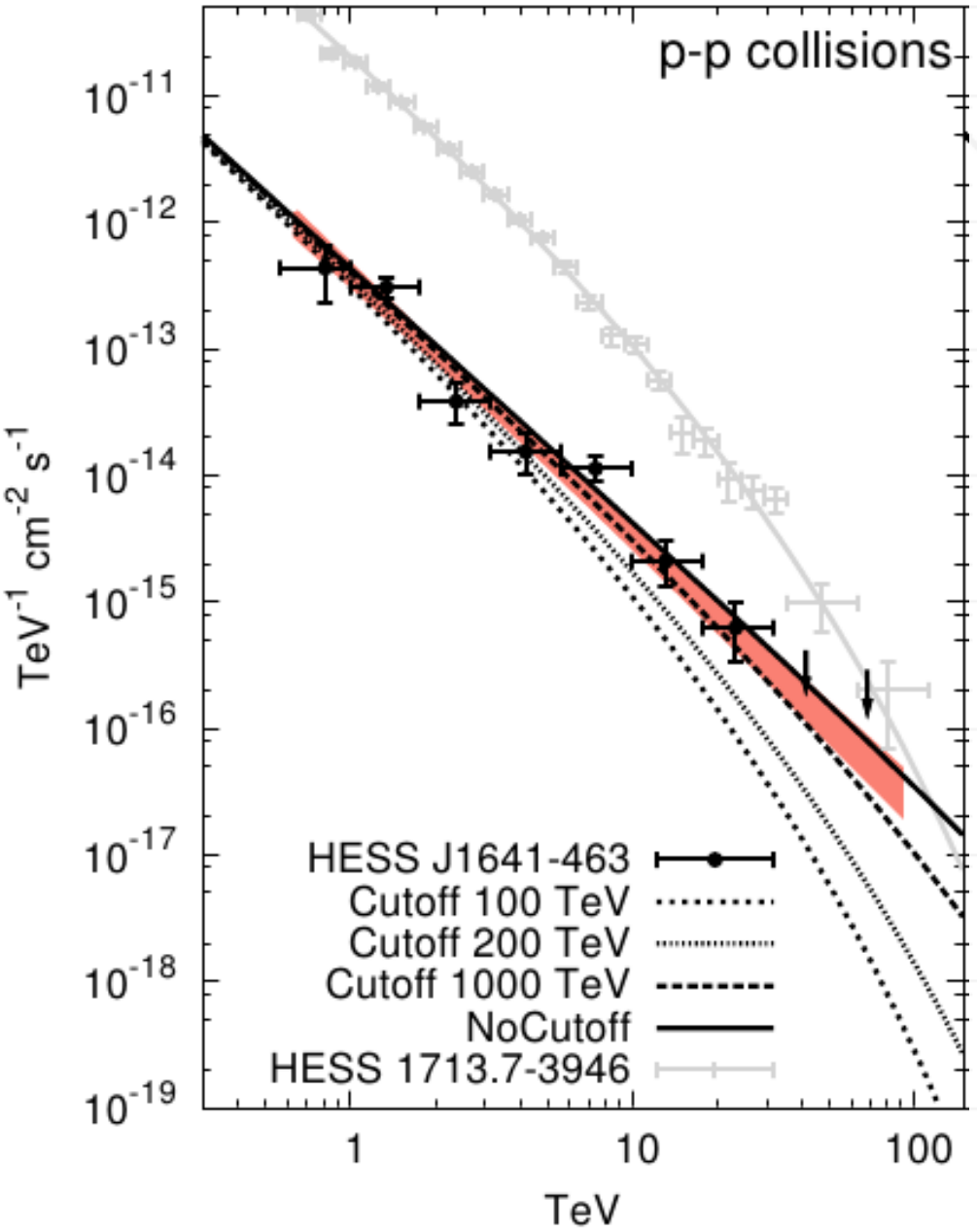

Kelner+06 parameterization

Assuming a PL with Γ = 2.1 primary proton spectrum

**One of the highest $E_{max}$ every inferred from VHE data**

# HESS J1641-463:

p-p model fits data better → $\mathbf{E_{max} > 100\ TeV\ (99\%\ CL)}$




Kelner+06 parameterization

Assuming a PL with $\Gamma = 2.1$ primary proton spectrum

**One of the highest $E_{max}$ every inferred from VHE data**

measured luminosity (d = 11 kpc)

$L_\gamma = 4 \times 10^{34}$ erg s$^{-1}$

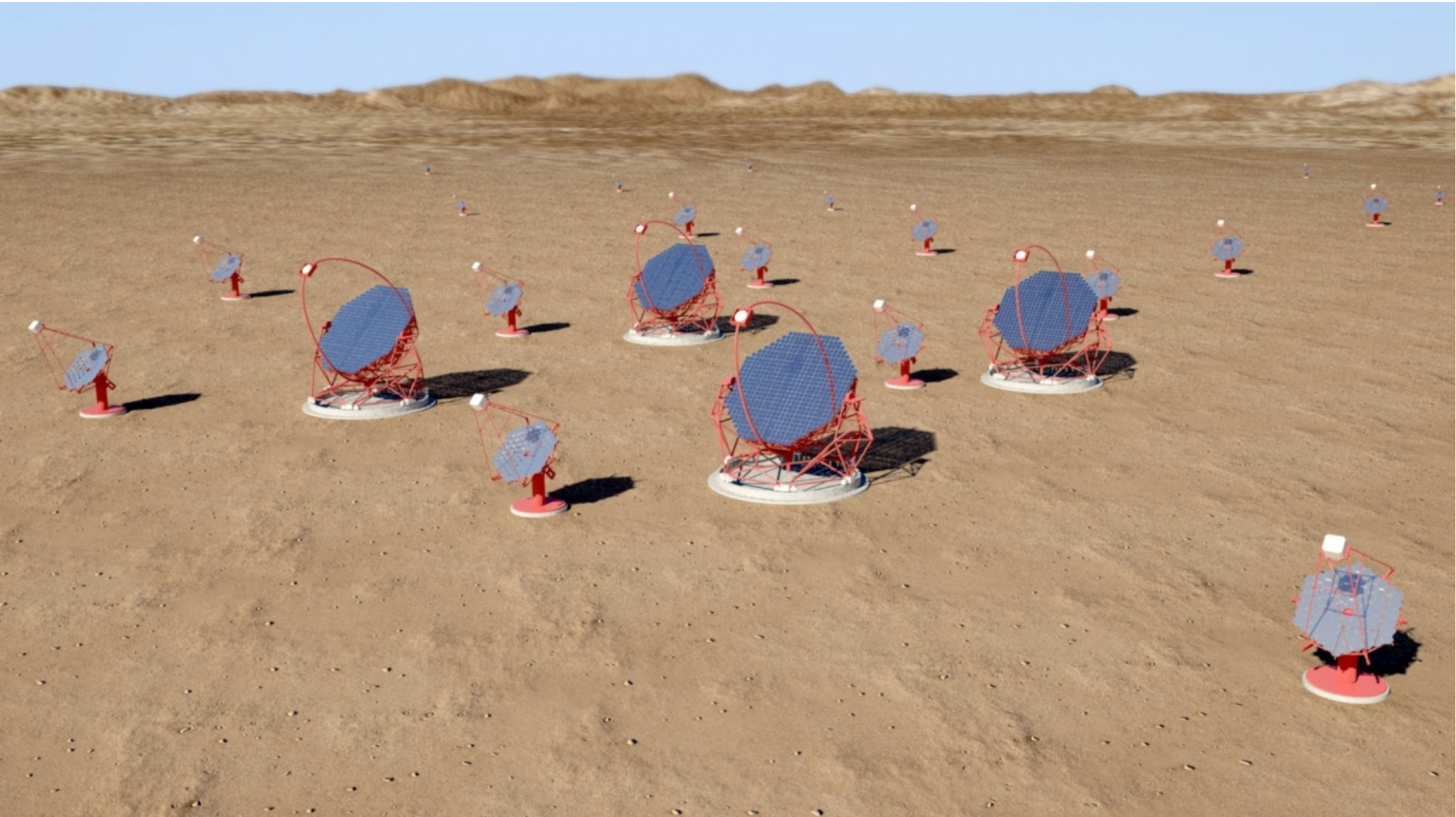
cooling time

$t_{\pi 0} \approx 5 \times 10^{15}\ (n\ /\ \mathrm{cm}^{-3})^{-1}$ s

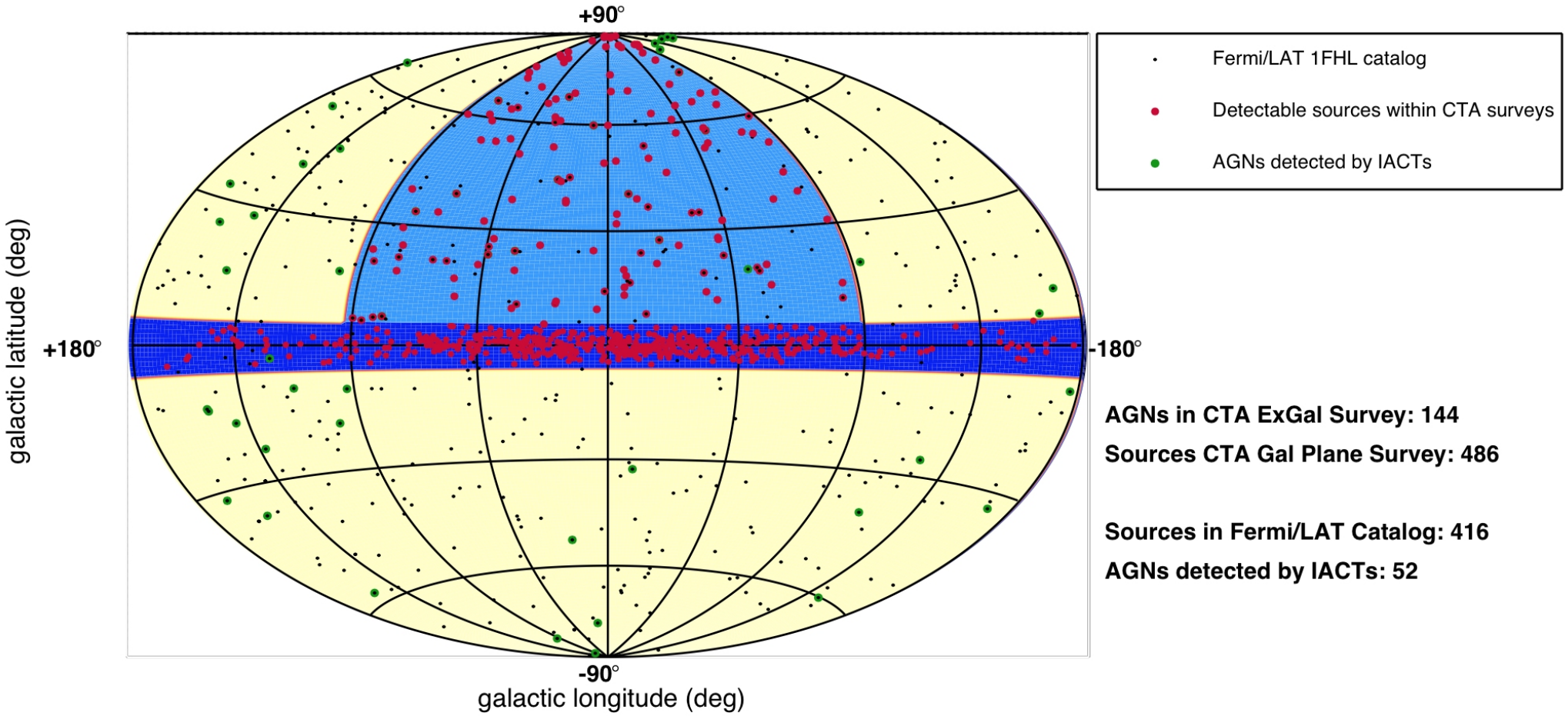
total energy SN → hadronic acc.

$W_p = L_\gamma\ t_{\pi 0} \approx 10^{50}\ (n\ /\ \mathrm{cm}^{-3})^{-1}$ erg

cherenkov telescope array



# Galactic (& Extragalactic Surveys)

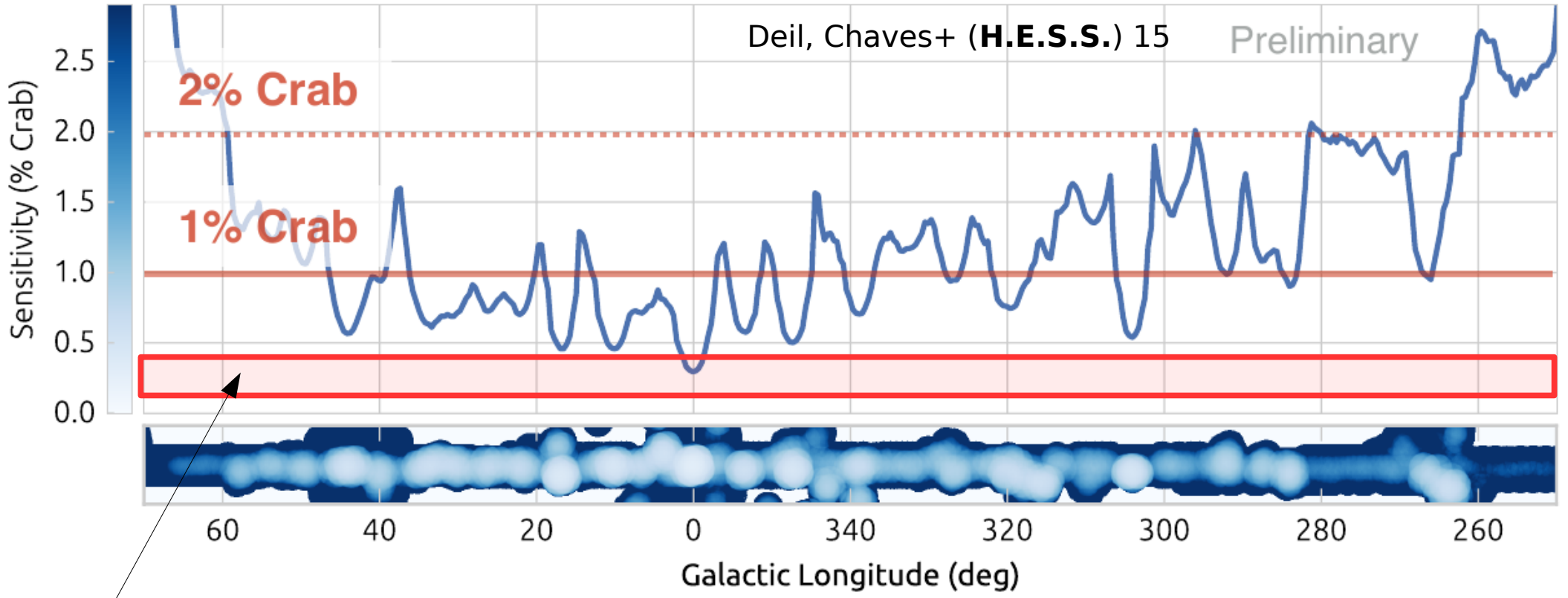



Target: < **2 mCrab Galactic**; ~6 mCrab Extragalactic

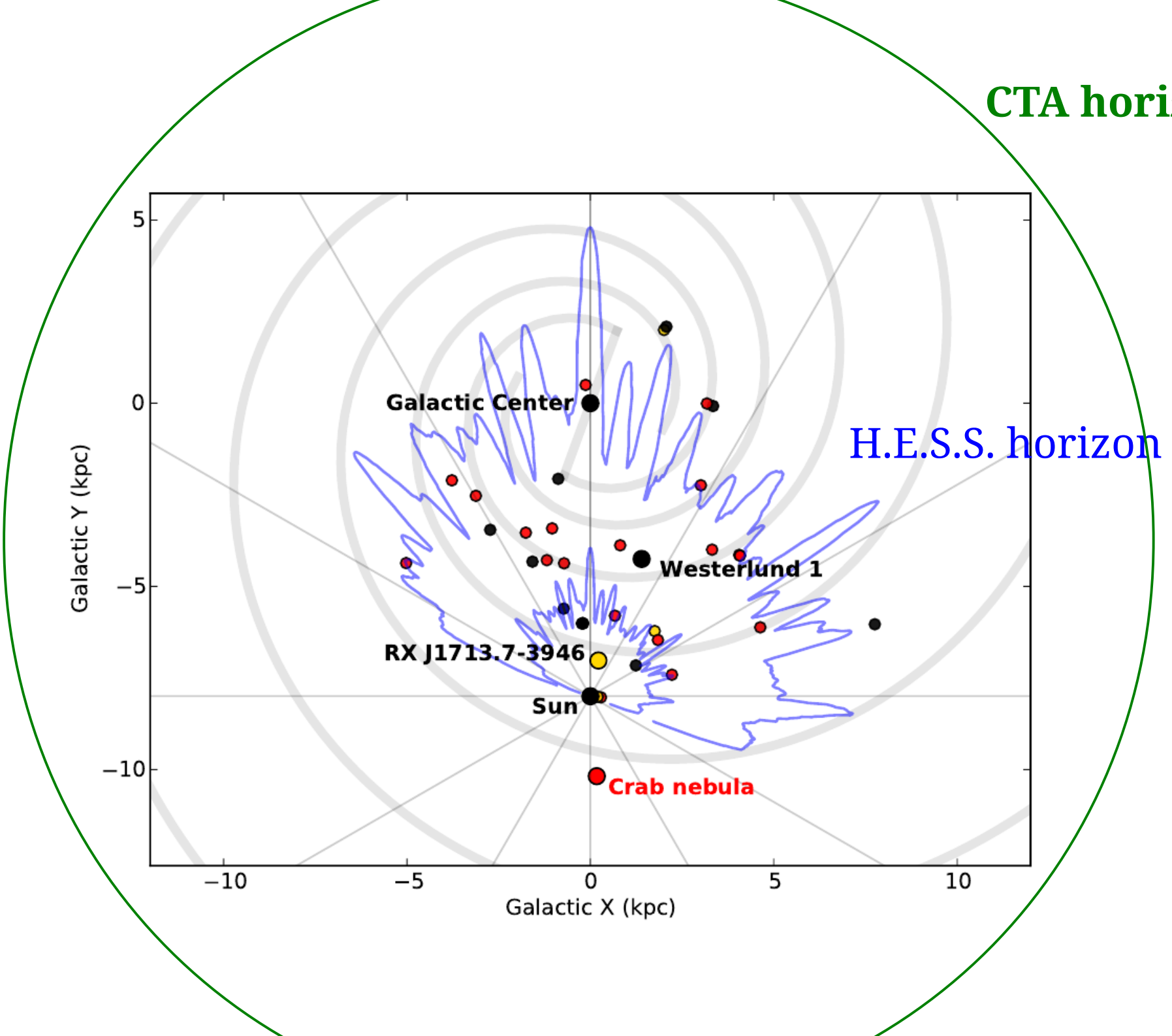
| Experiment | Hemisphere | Galactic Plane Coverage | Energy (GeV) | Sensitivity (mCrab) |
|---|---|---|---|---|
| H.E.S.S.-I | S | $-70^\circ < l < 60^\circ$, $\lvert b\rvert < 2^\circ$ | $>\sim 300$ | 10 – 30 |
| VERITAS | N | $67^\circ < l < 83^\circ$, $-1^\circ < b < 4^\circ$ | $>\sim 300$ | 20 –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

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

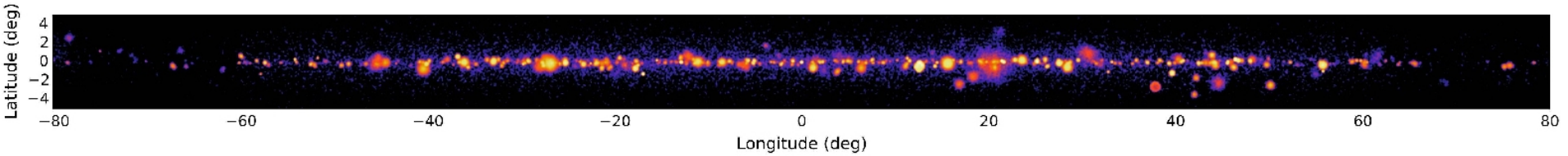
# GPS IN CONTEXT




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


CTA horizon
H.E.S.S. horizon
Galactic Center
Westerlund 1
RX J1713.7-3946
Sun
Crab nebula
Galactic Y (kpc)
Galactic X (kpc)
5
0
−5
−10
−10
−5
0
5
10

# GPS SIMULATIONS




Source populations modeled:

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

**Expected diffuse emission**: Both IC & $\pi^0$ components (GALPROP)

Energy range: 1-10 TeV

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

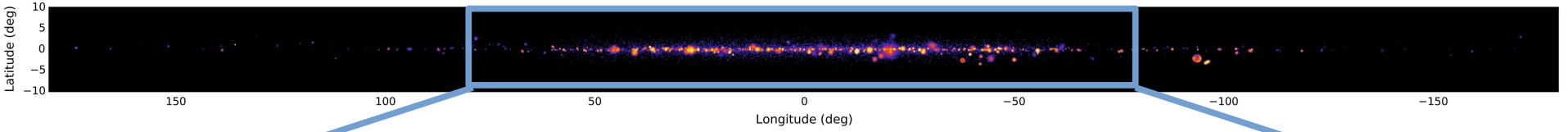
Actual GPS observation scheme (**1620 h**)

Most realistic simulations to date & work on-going

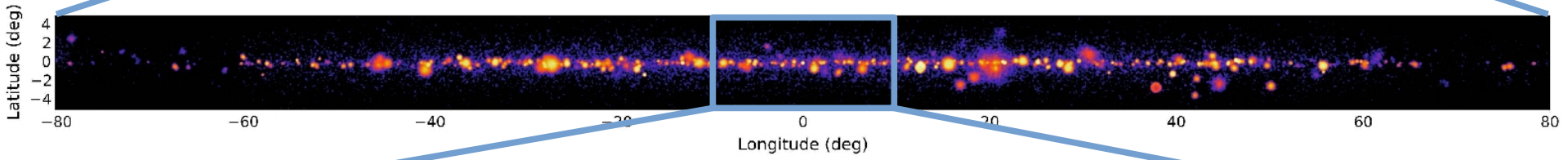
Knoedlseder, Martin+ (CTA)

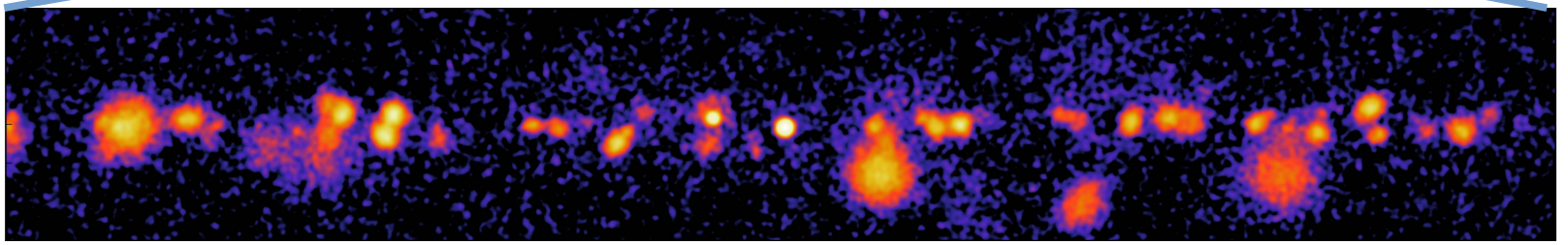
# GPS SIMULATIONS

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




**Deeper inner galaxy exposure:** $\ell$ ± 80°

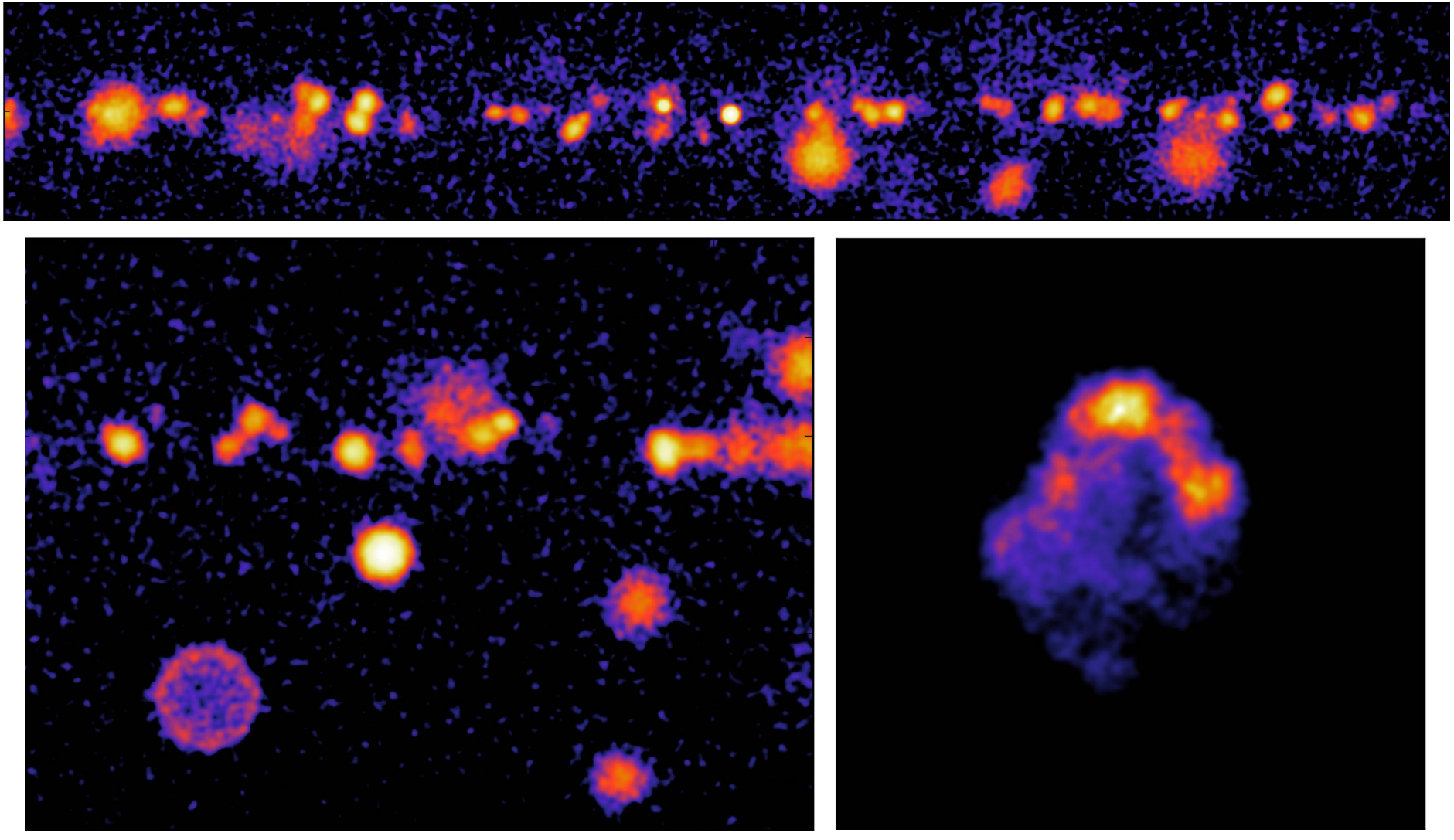


**Fine detail** revealed with **~arcmin PSF**

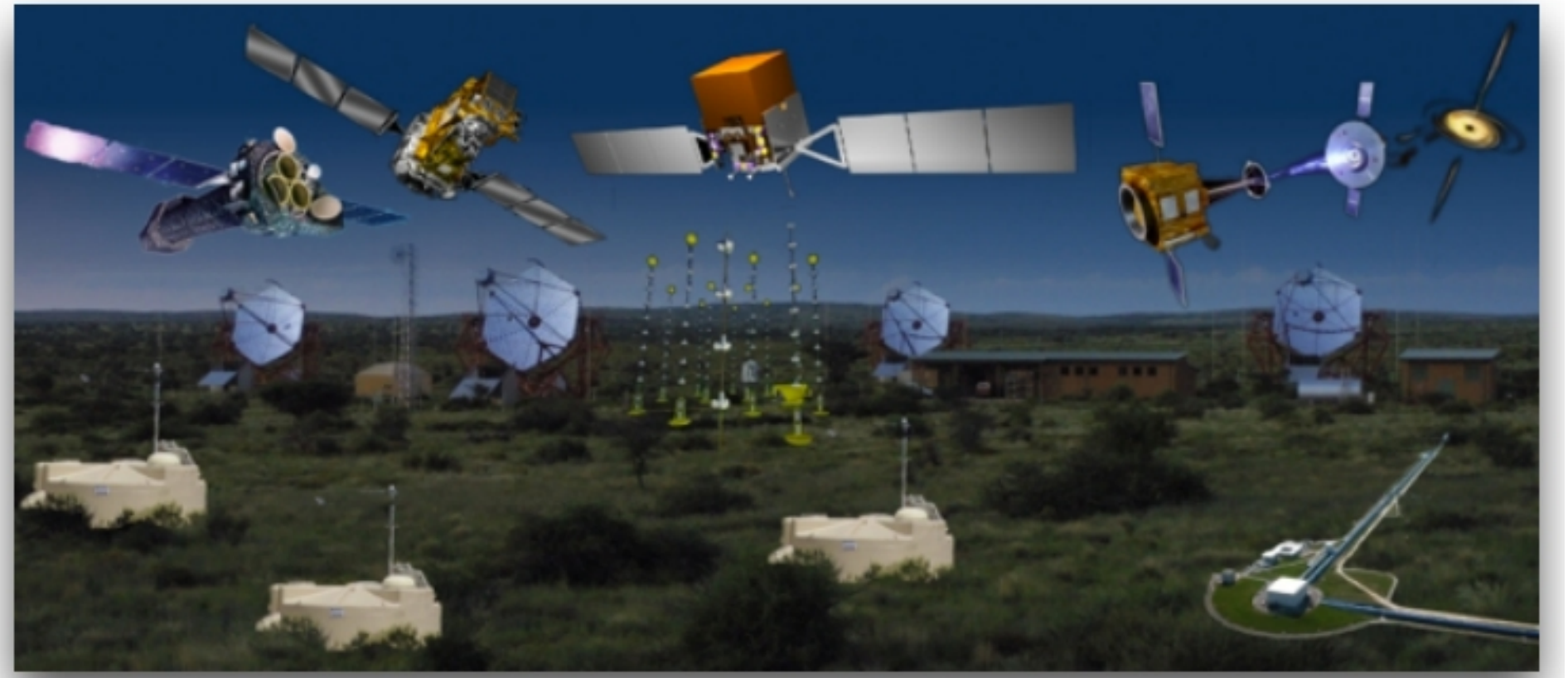
Knoedlseder, Martin+ (CTA)

# GPS SIMULATIONS: ZOOM



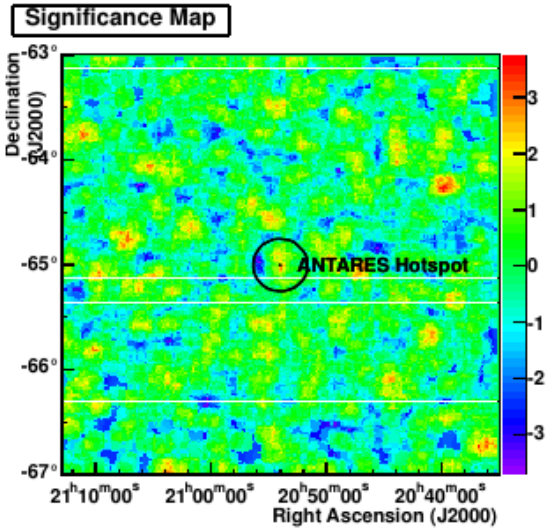
Knoedlseder, Martin+ (CTA)

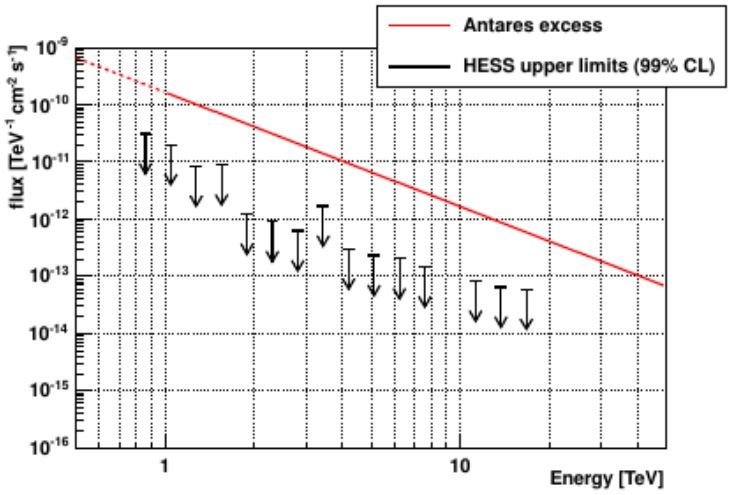
# Multi-messenger efforts

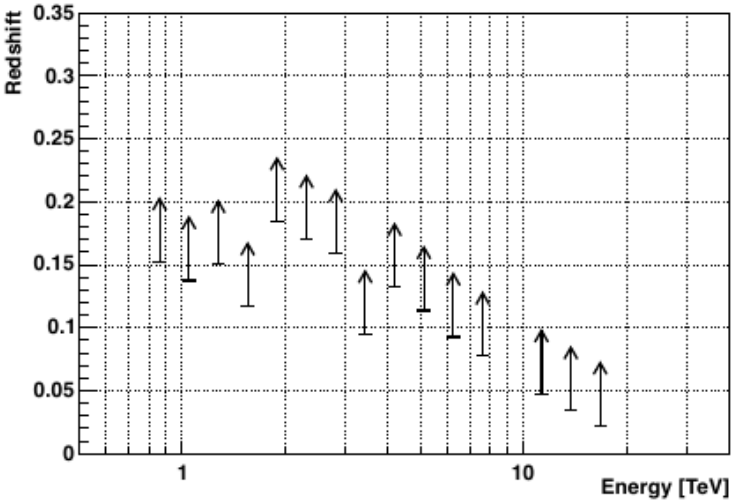


# Neutrinos & gamma-rays

**ANTARES** hotspot follow-up



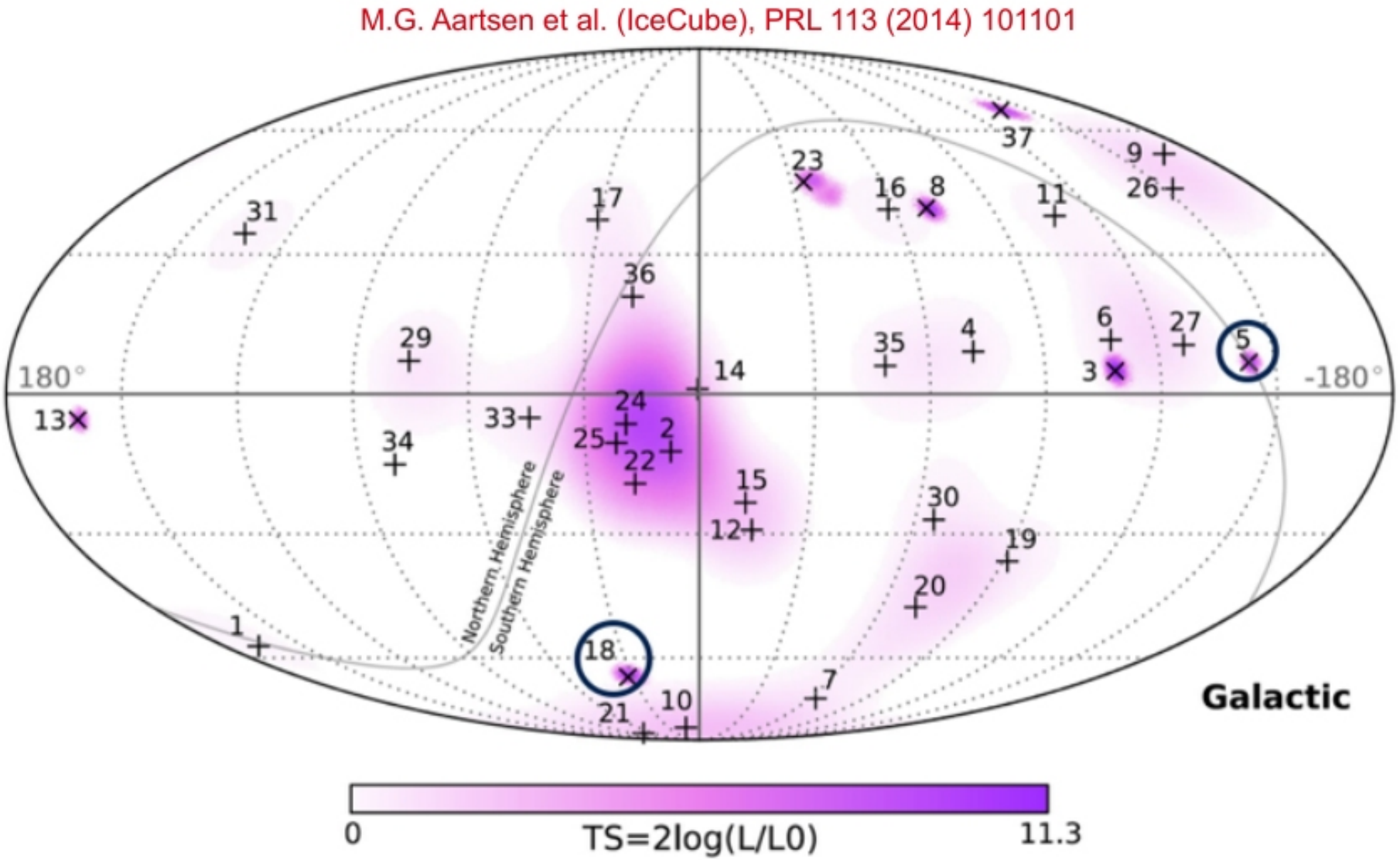

2.2 sigma neutrino signal
2 h of data during H.E.S.S. follow-up

Limits on possible source distance (redshift)

Schuessler, Chaves+ (H.E.S.S.) 2013

# Neutrinos and gamma-rays

**IceCube** HESE hotspot follow-up




Schuessler+ (H.E.S.S.) 2015

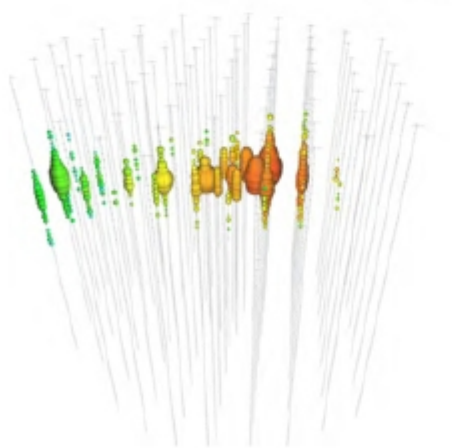
# Neutrinos and gamma-rays

Dr. Strangepork

## IceCube Event 5

- deposited energy: $71.4^{+9}_{-9}$ TeV
- Ra=110.6deg / Dec=-0.4deg

- H.E.S.S. observations
  - HESS-II 28m monoscopic mode
  - 0.9h effective livetime (acceptance corrected)

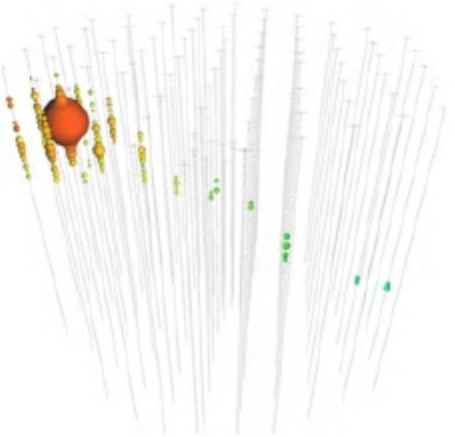


Zoot

## IceCube Event 18

- deposited energy: $31.5^{+4.6}_{-3.3}$ TeV
- Ra=345.6deg / Dec=-24.8deg

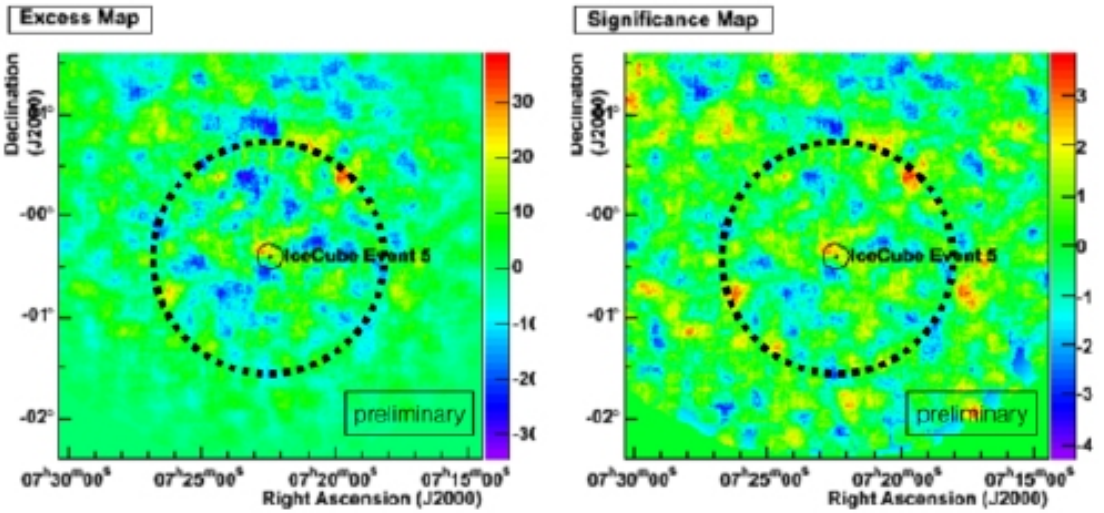
- H.E.S.S. observations:
  - HESS-II observations with full 5-telescope array
  - 9.5h effective lifetime (acceptance corrected)



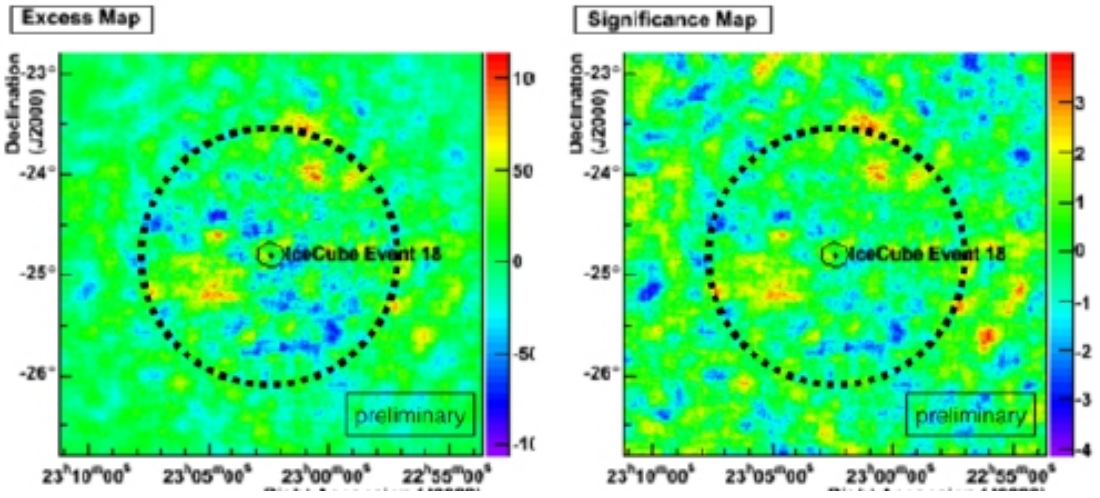
Schuessler+ (H.E.S.S.) 2015

# Neutrinos and gamma-rays

- IceCube 5




- IceCube 18




Schuessler+ (H.E.S.S.) 2015

# Conclusions

Particle physics meets gamma-ray astronomy
Demonstrated power of imaging atmospheric Cherenkov technique

**Decade-long H.E.S.S. I Galactic Plane Survey**

- Final catalog, high-level data release & new source discoveries
- Paper in preparation (internal review)
- Coupled with population studies on SNRs and PWNe

**Search for cosmic-ray accelerators (SNRs?) continues**

- Data-driven strategy seems most appropriate

**Follow-up of neutrino hotspots: multi-messenger cooperation**

- Complementary approach to discover hadronic accelerators
- Beginning ToO / alert capabilities for rapid response

**Preparing the way to the next-generation CTA Survey**

# Backup slides

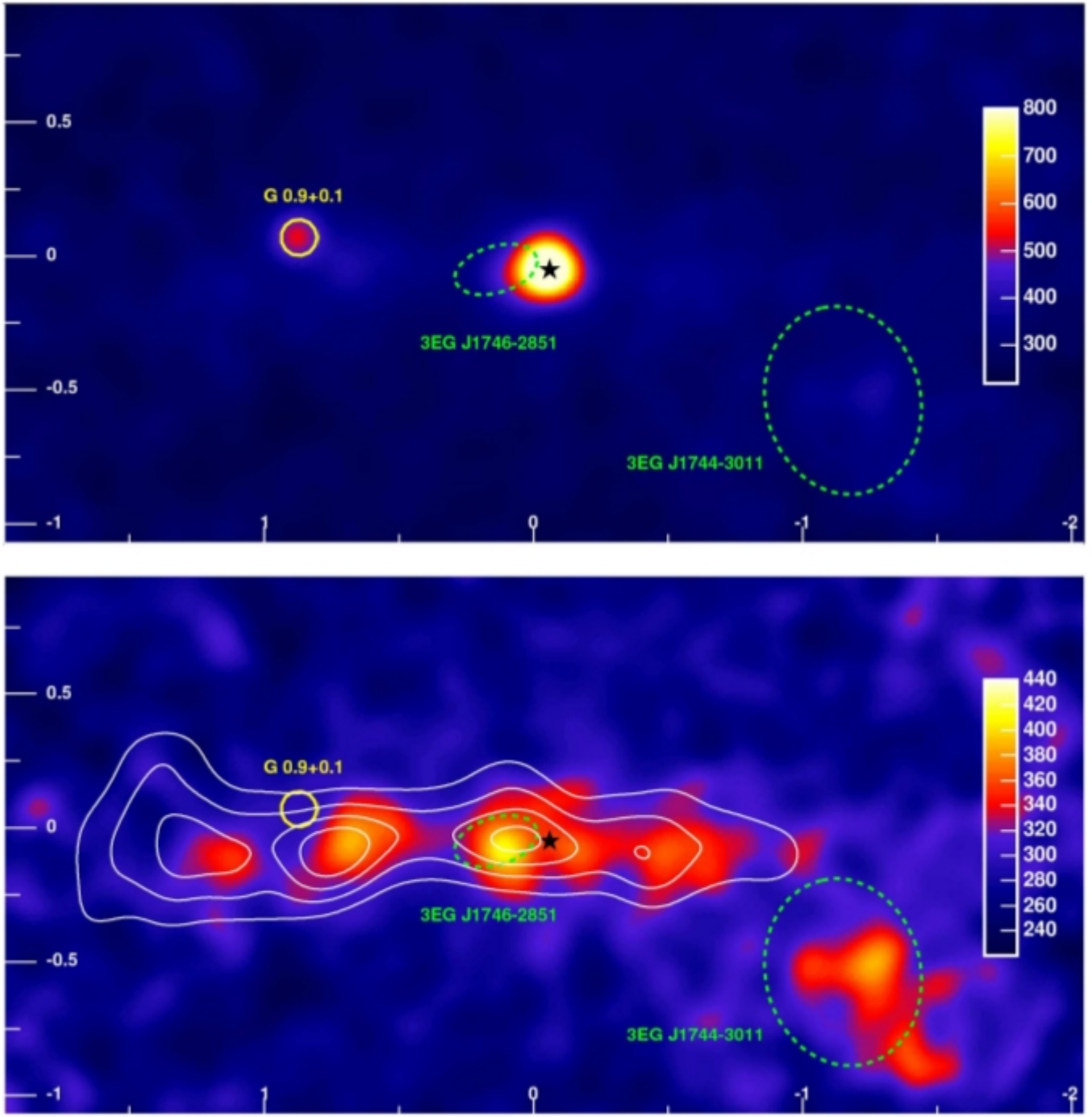
# Towards the next generation

2010-2012: Mirrors re-coated on all 4 telescopes.
Regained near-original optical efficiency.

2013: H.E.S.S.-II First Light
First hybrid IACT array. First LST.
Access down to ~30 GeV.
Increased effective area. Improved angular resolution.

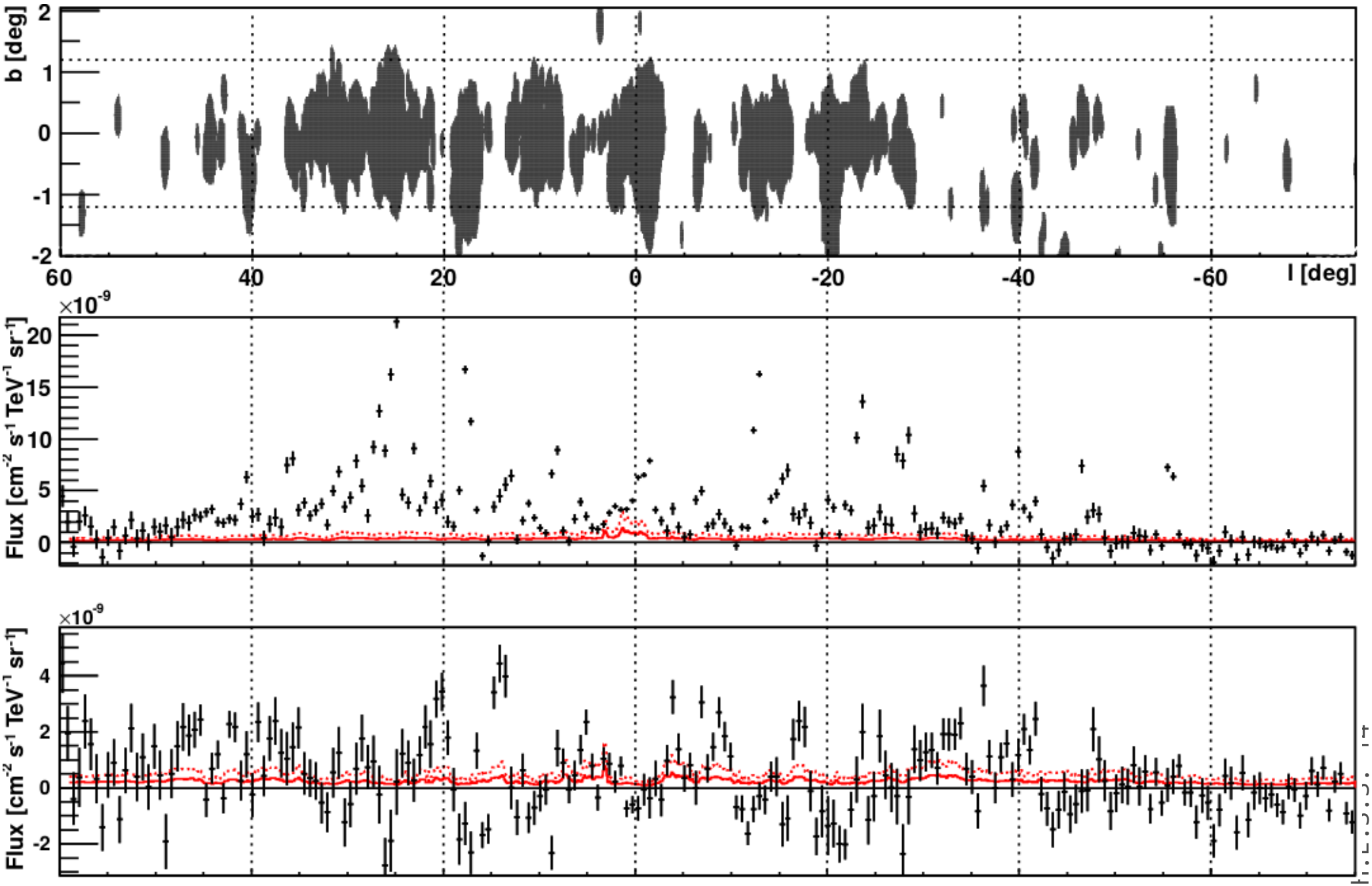
2014-15: H.E.S.S.-I camera electronics upgrade
Reduce deadtime. Increase robustness.
Greater integration.
Testbed for CTA tech (e.g. NectarCAM).

# The Galactic Center & diffuse TeV emission



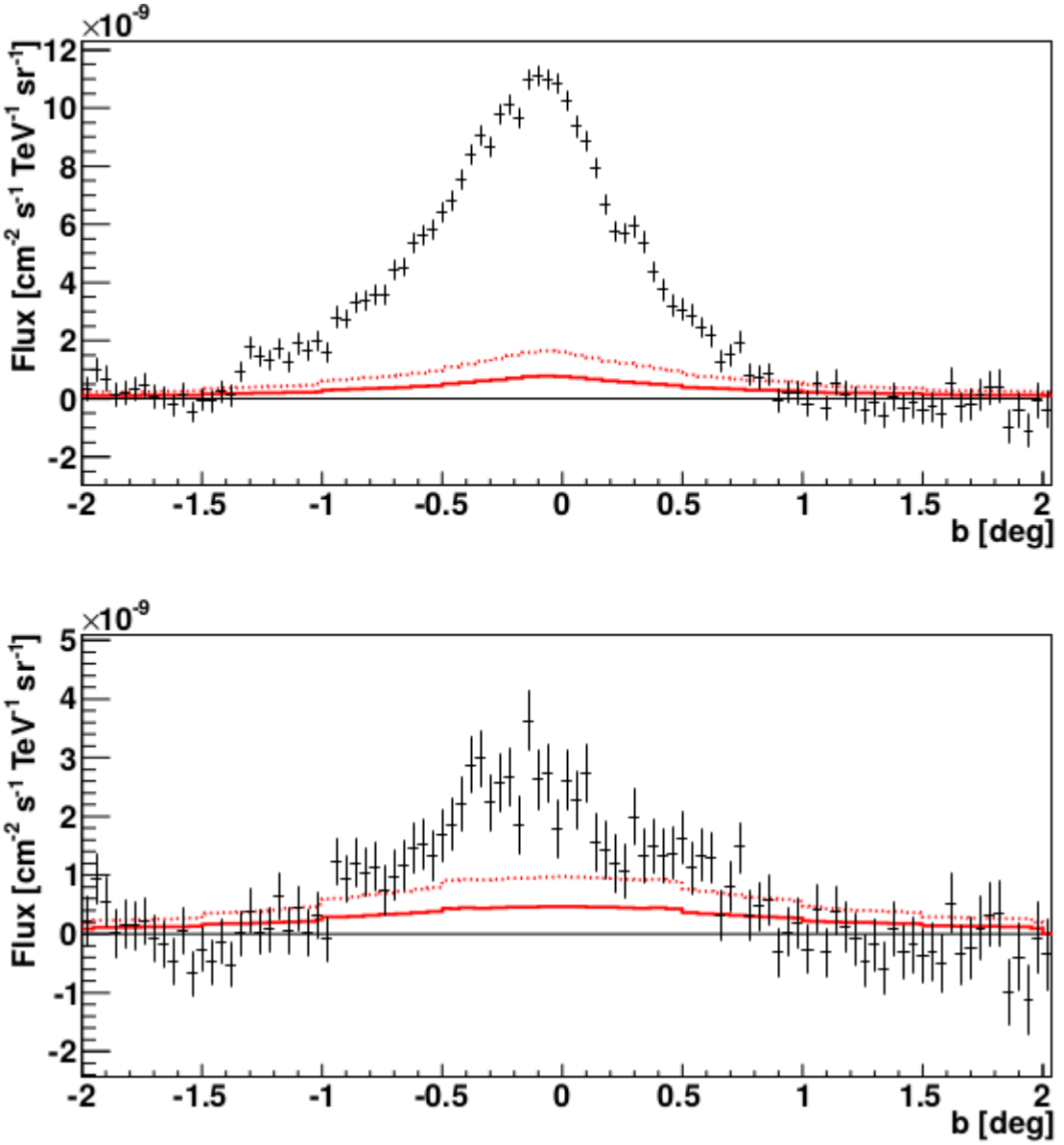

H.E.S.S. 06

# Diffuse TeV emission along the Galactic plane



# Diffuse TeV emission along the Galactic plane

Significant fraction (~50%) from hadronic p-p collisions ($\pi^0$ decay)

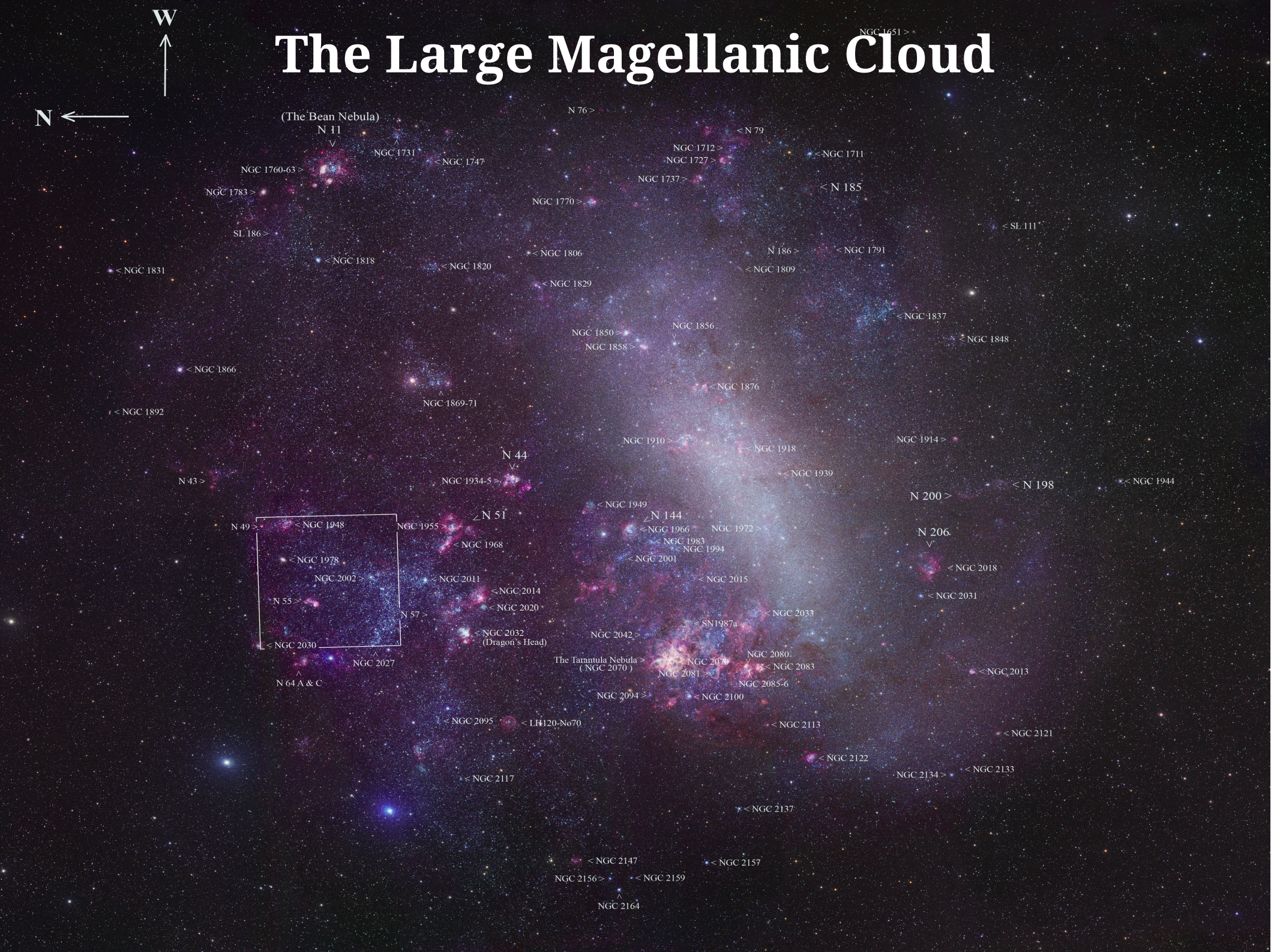



Additional contributions expected from inverse Compton & unresolved srcs (possibly accounts for difference in profile widths)

**Detected on a large scale for the first time.**

# **The other big H.E.S.S. survey**

you might not have heard about (yet)


W
N
The Large Magellanic Cloud
(The Bean Nebula)
N 11
N 76 >
NGC 1651 >
< N 79
NGC 1712 >
NGC 1727 >
< NGC 1711
NGC 1737 >
< N 185
NGC 1731
< NGC 1747
NGC 1760-63 >
NGC 1783 >
NGC 1770 >
< SL 111
SL 186 >
< NGC 1806
N 186 >
< NGC 1791
< NGC 1809
< NGC 1818
< NGC 1820
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NGC 1850 >
NGC 1856
NGC 1858 >
< NGC 1848
< NGC 1866
< NGC 1876
NGC 1869-71
< NGC 1892
NGC 1910 >
NGC 1914 >
< NGC 1918
N 44
N 43 >
NGC 1934-5 >
< NGC 1939
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< NGC 1944
N 200 >
< NGC 1949
N 51
N 144
N 49 >
< NGC 1948
NGC 1955 >
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NGC 1972 >
N 206
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N 55 >
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N 57 >
< NGC 2033
< SN1987a
< NGC 2032
(Dragon's Head)
NGC 2042 >
< NGC 2030
NGC 2080
The Tarantula Nebula >
( NGC 2070 )
NGC 2083
< NGC 2013
NGC 2081
NGC 2085-6
NGC 2027
N 64 A & C
NGC 2094 >
< NGC 2100
< NGC 2095
< LH120-No70
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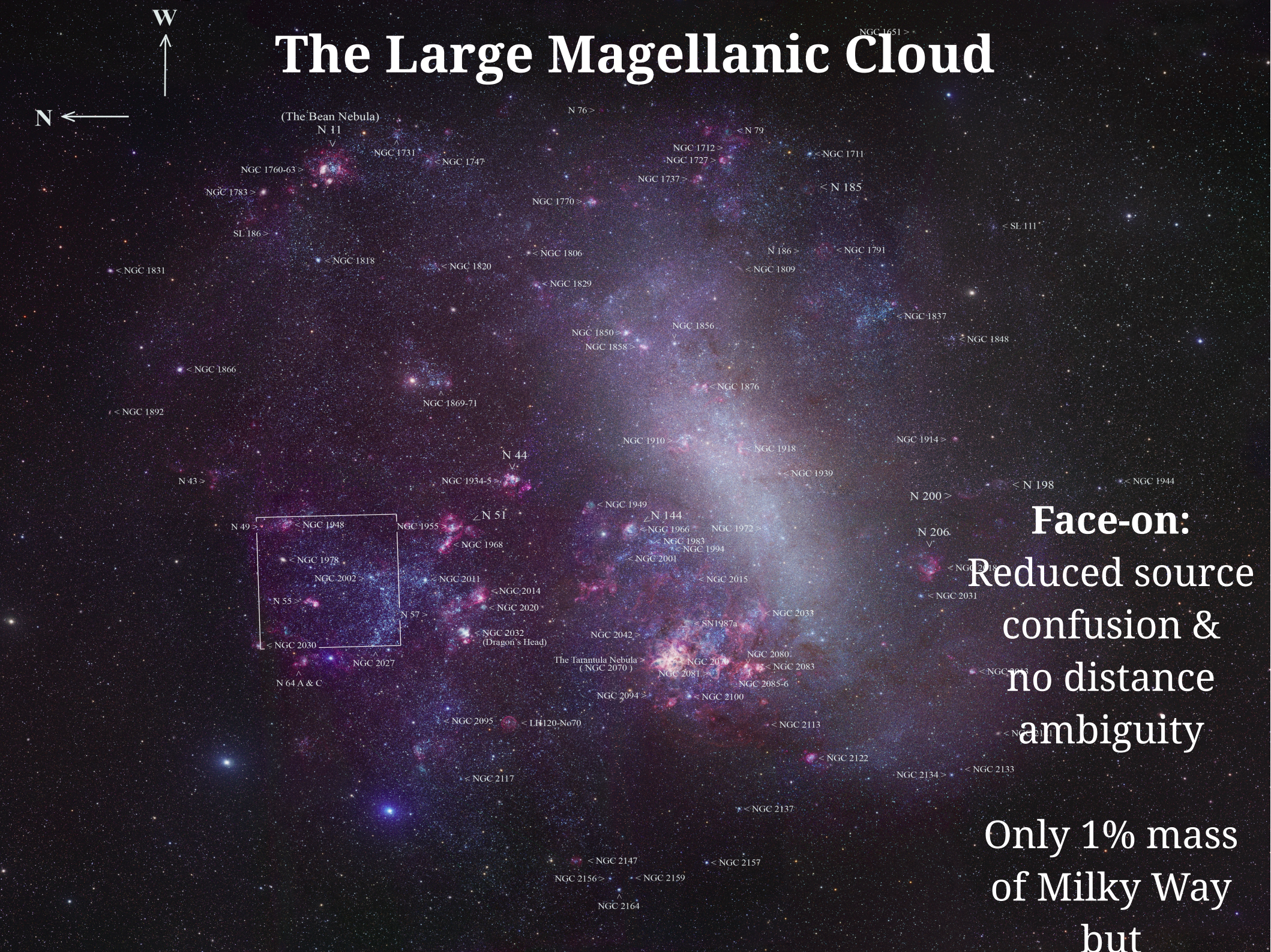
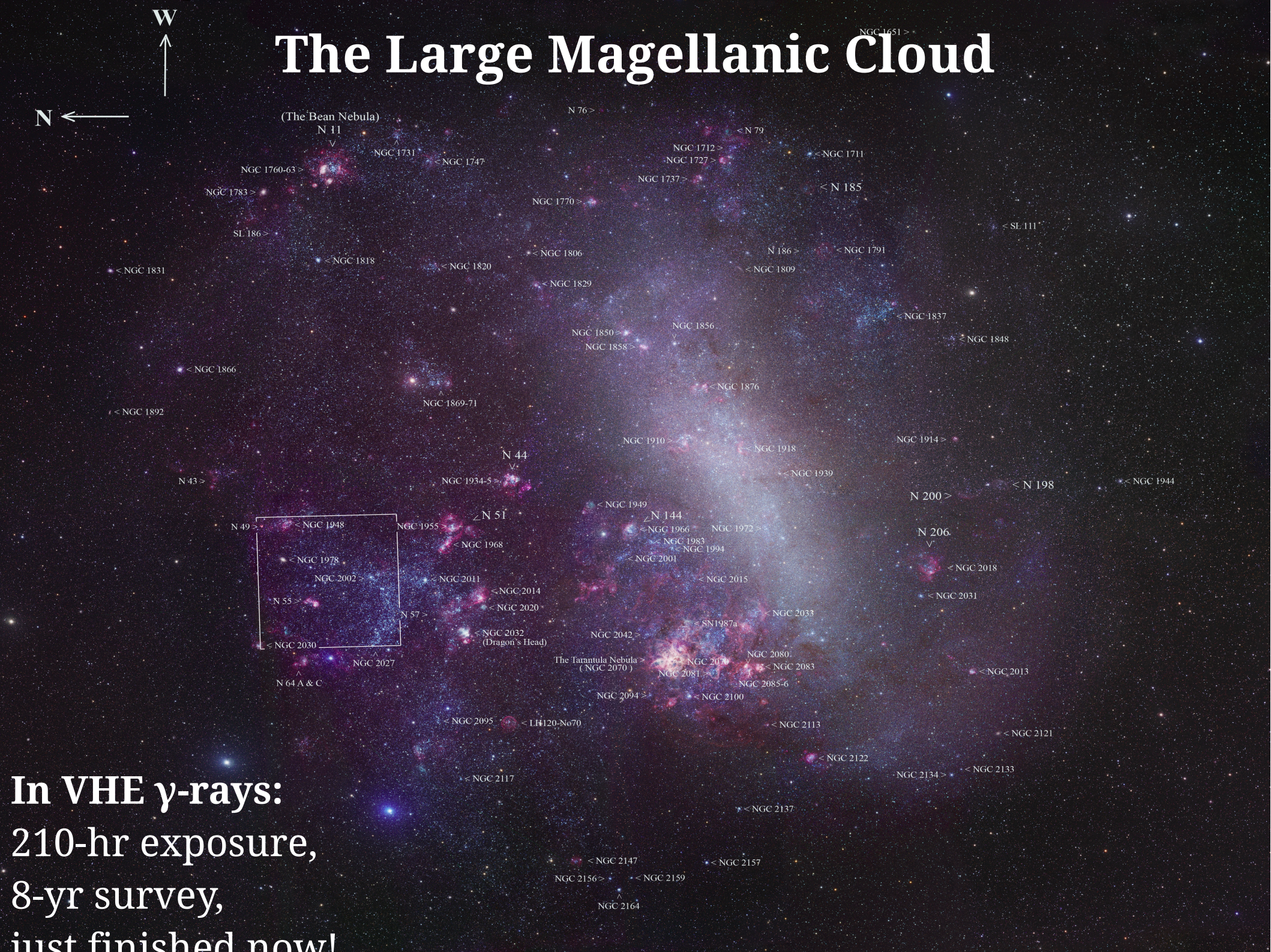
< NGC 2117
< NGC 2137
< NGC 2147
< NGC 2157
NGC 2156 >
< NGC 2159
NGC 2164


W
N
The Large Magellanic Cloud
(The Bean Nebula)
N 11
N 76 >
N 79
NGC 1651 >
NGC 1731
NGC 1747
NGC 1760-63 >
NGC 1712 >
NGC 1727 >
NGC 1711
NGC 1737 >
NGC 1783 >
N 185
NGC 1770 >
SL 111
SL 186 >
NGC 1806
N 186 >
NGC 1791
NGC 1818
NGC 1820
NGC 1831
NGC 1809
NGC 1829
NGC 1837
NGC 1850 >
NGC 1856
NGC 1858 >
NGC 1848
NGC 1866
NGC 1876
NGC 1869-71
NGC 1892
NGC 1910 >
NGC 1914 >
N 44
NGC 1918
N 43 >
NGC 1934-5 >
NGC 1939
N 198
NGC 1944
N 200 >
NGC 1949
N 51
N 144
N 49 >
NGC 1948
NGC 1955 >
NGC 1966
NGC 1972 >
N 206
NGC 1968
NGC 1983
NGC 1994
NGC 1978
NGC 2001
NGC 2002 >
NGC 2011
NGC 2015
NGC 2031
NGC 2014
N 55 >
NGC 2020
N 57 >
NGC 2033
SN1987a
NGC 2032
(Dragon's Head)
NGC 2042 >
NGC 2030
NGC 2080
The Tarantula Nebula >
( NGC 2070 )
NGC 2083
NGC 2027
NGC 2081
NGC 2085-6
N 64 A & C
NGC 2094 >
NGC 2100
NGC 2095
LH120-N70
NGC 2113
NGC 2122
NGC 2117
NGC 2134 >
NGC 2133
NGC 2137
NGC 2147
NGC 2157
NGC 2156 >
NGC 2159
NGC 2164
Face-on:
Reduced source confusion & no distance ambiguity
Only 1% mass of Milky Way but

# The Large Magellanic Cloud

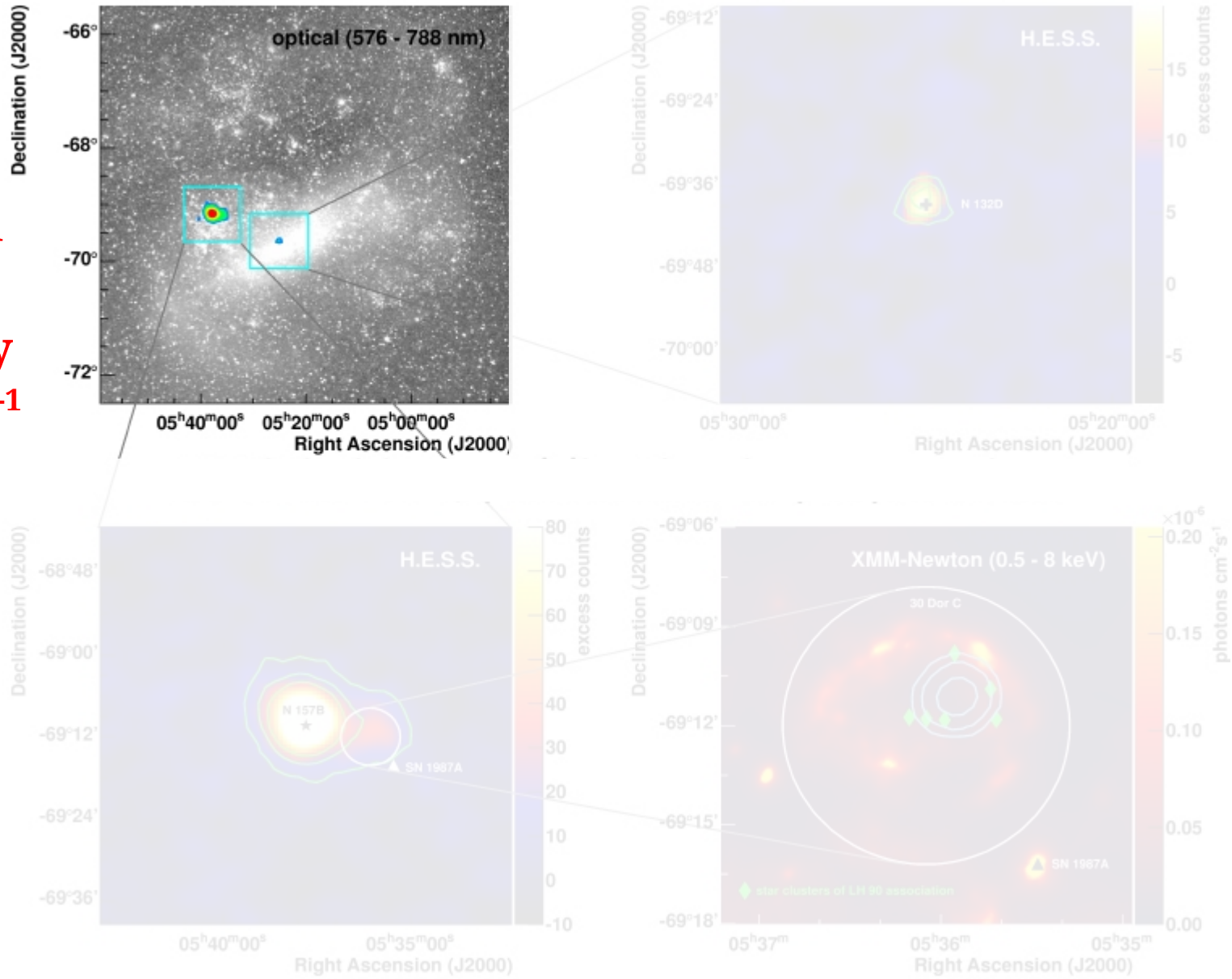



**In VHE γ-rays:**
210-hr exposure,
8-yr survey,
just finished now!

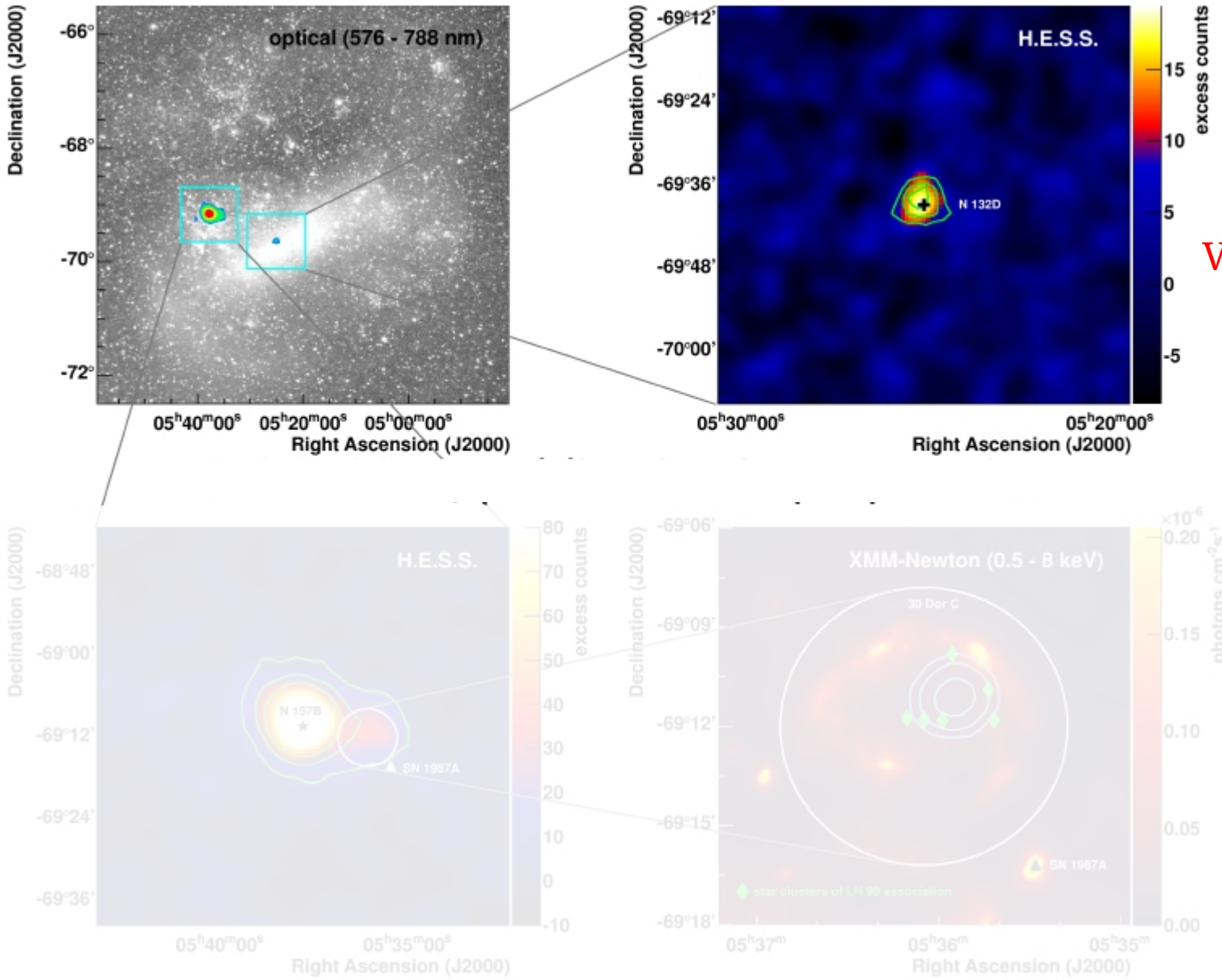
# The Large Magellanic Cloud

0.05° ~ 3′ angular resolution

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

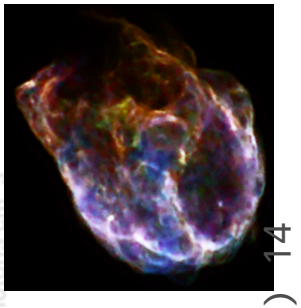


# **N 132D**: A radio-loud middle-aged SNR



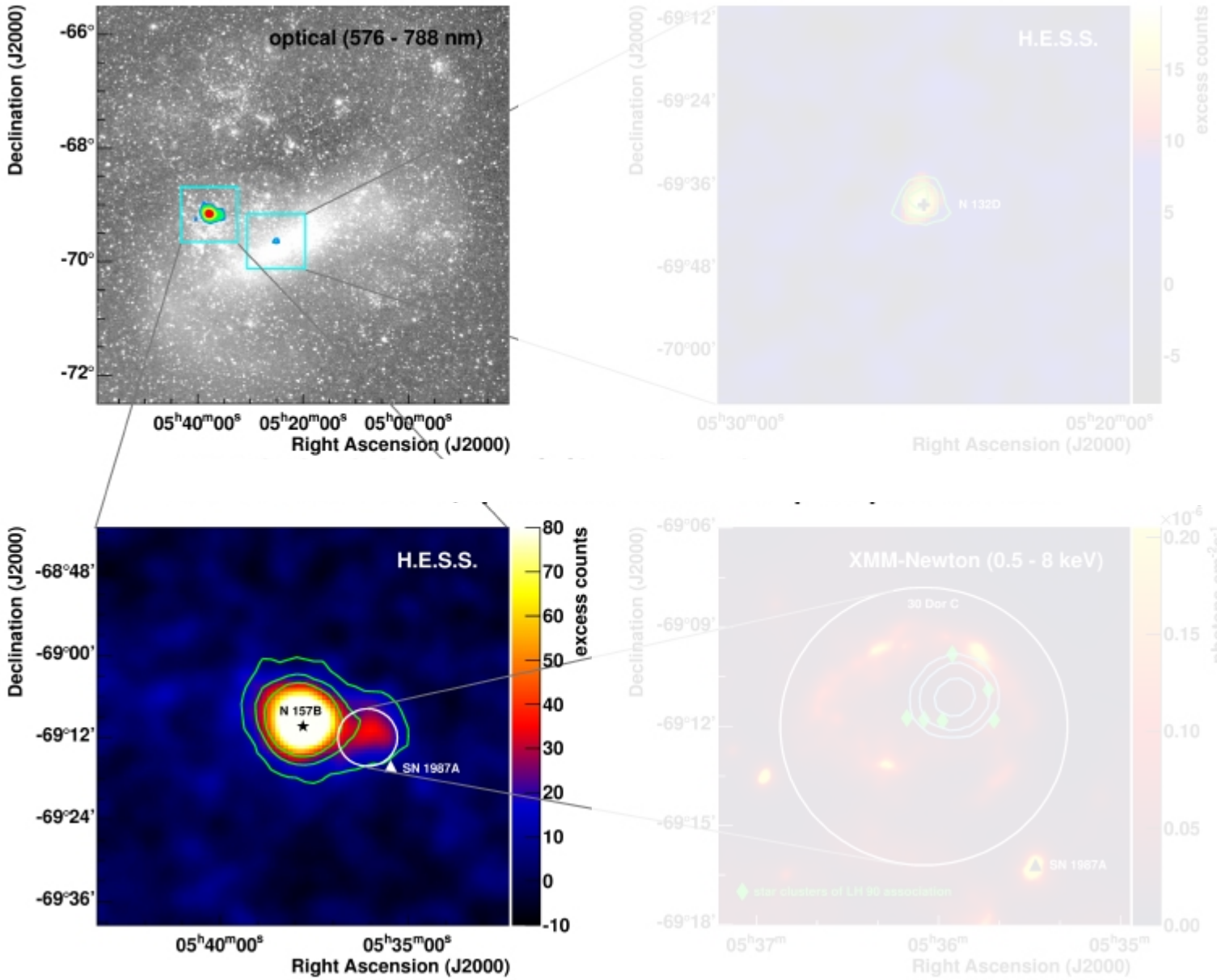

**50% $L_{radio}$ of Cas A**

Not quite VHE detection ~5 σ



Abramowski+ (H.E.S.S.) 14

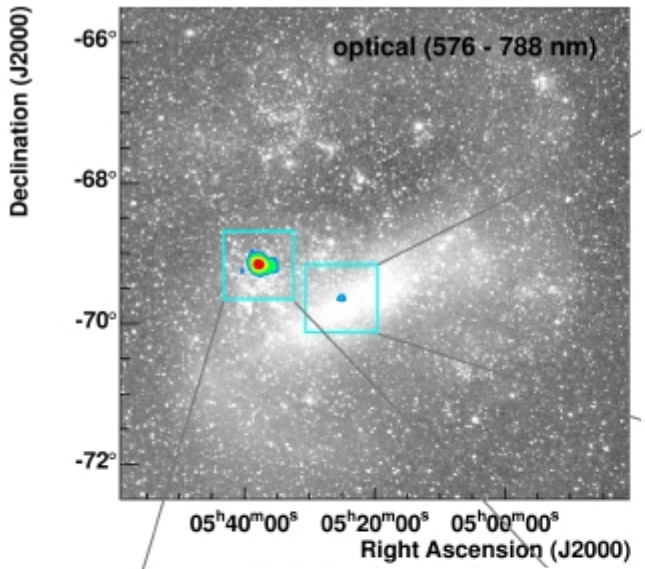
# **N 157B:** The Crab Nebula's twin




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

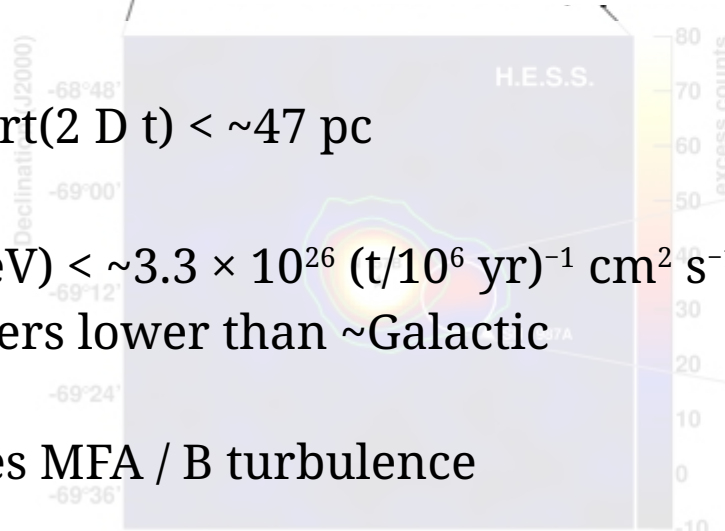
Abramowski+ (H.E.S.S.) 14

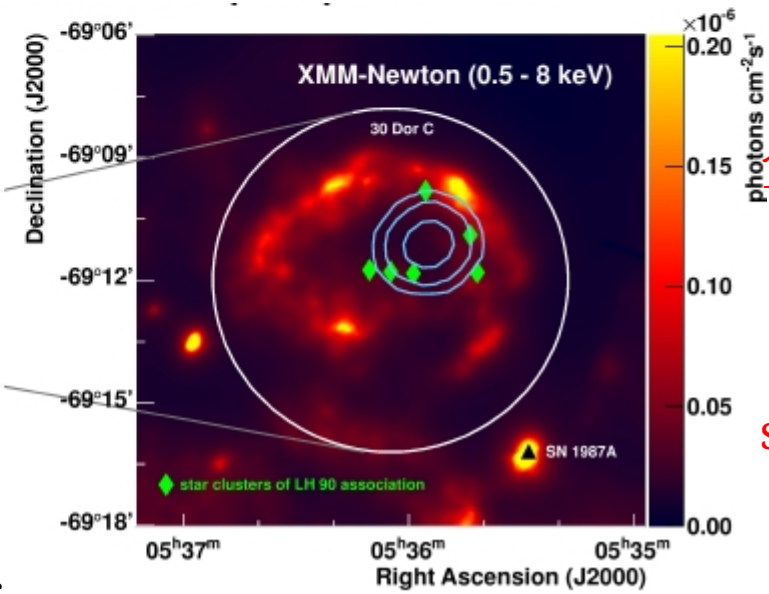
# **30 Dor C:** A TeV superbubble










$l_{diff}$ = sqrt(2 D t) < ~47 pc

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

requires MFA / B turbulence

still open question: leptonic vs. hadronic

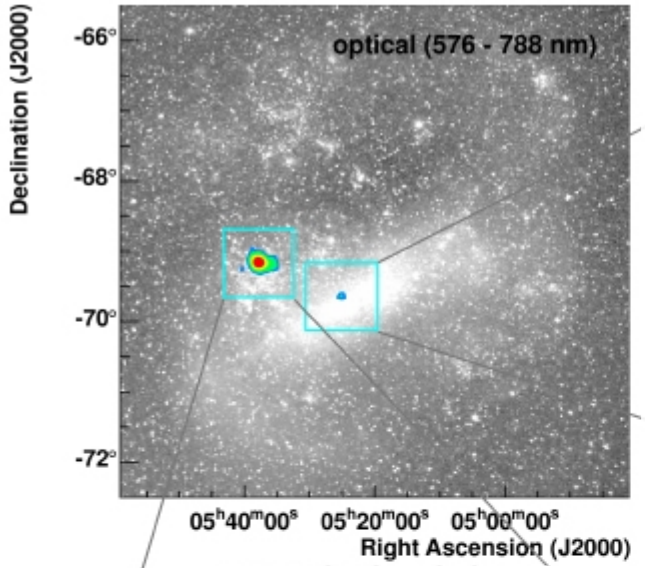
Largest SFR in Local Group

**Largest X-ray synchrotron shell known** (47 pc)

10x as bright as SN 1006

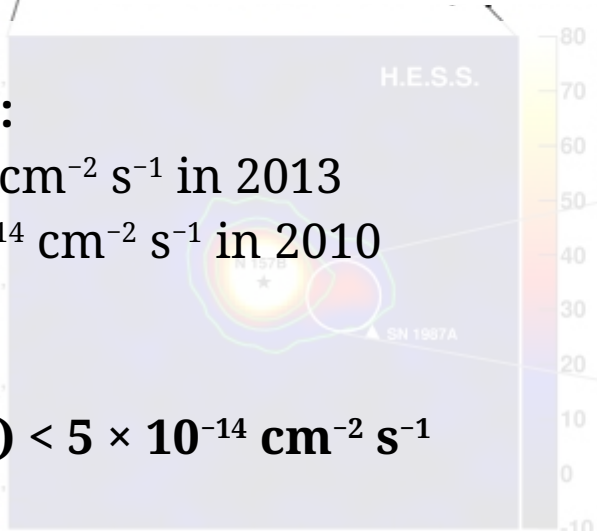
Powered by stellar winds & SN explosions of LH 90,

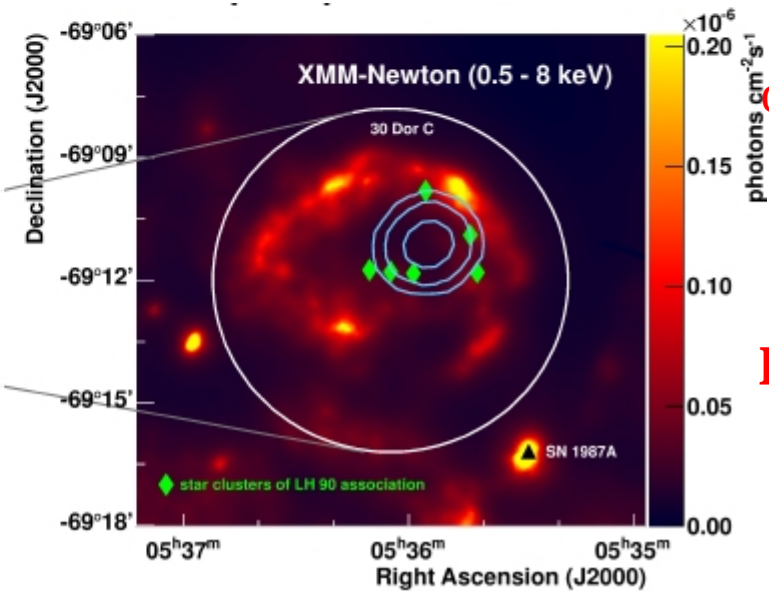
# **SN 1987A:** The youngest SNR










**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) < $5 \times 10^{-14}$ cm$^{-2}$ s$^{-1}$**

99% CL

during 2003-2012

High shock speed

High ambient density

**Hadronic?**

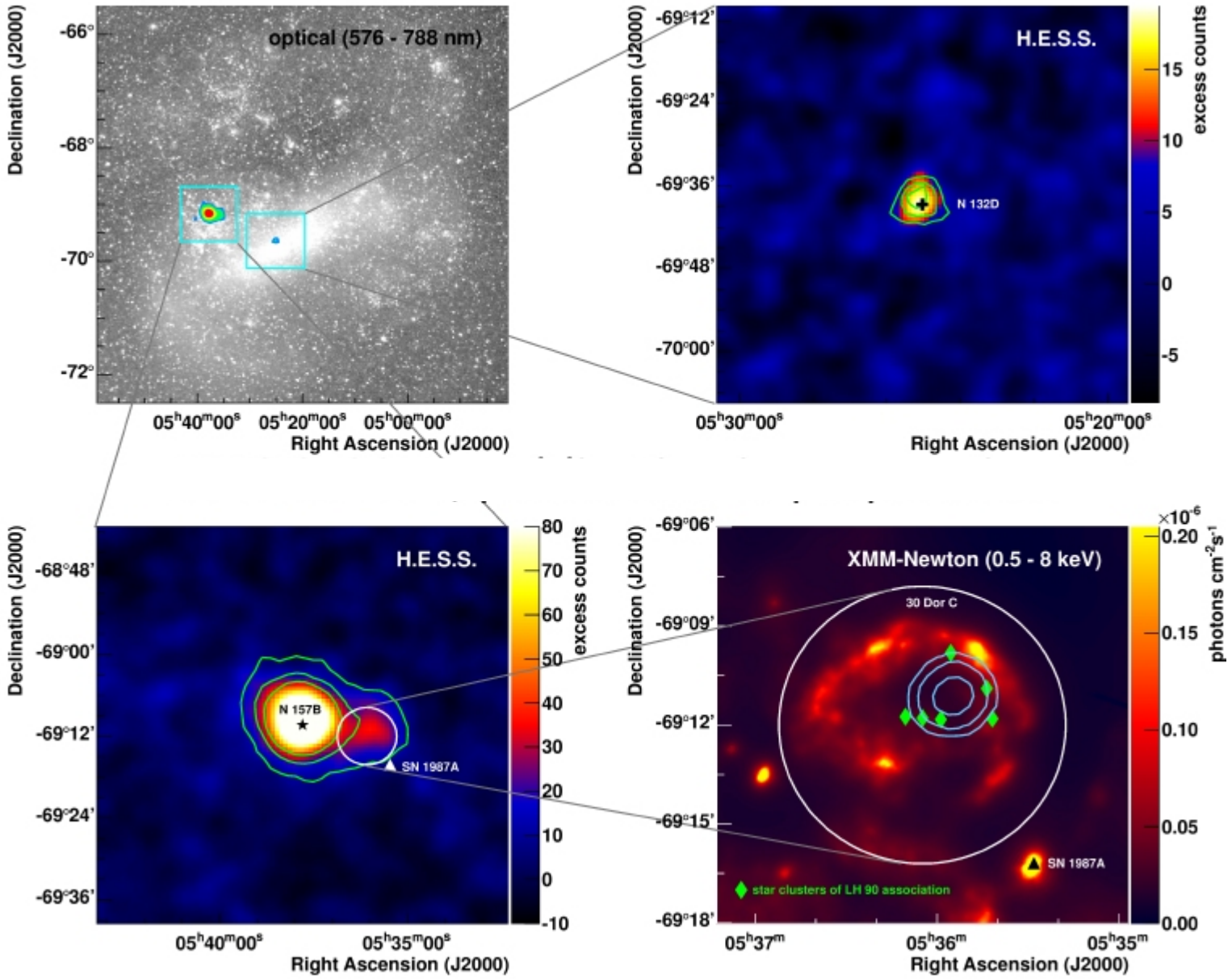
Upper limit only for now, but more observations planned

&

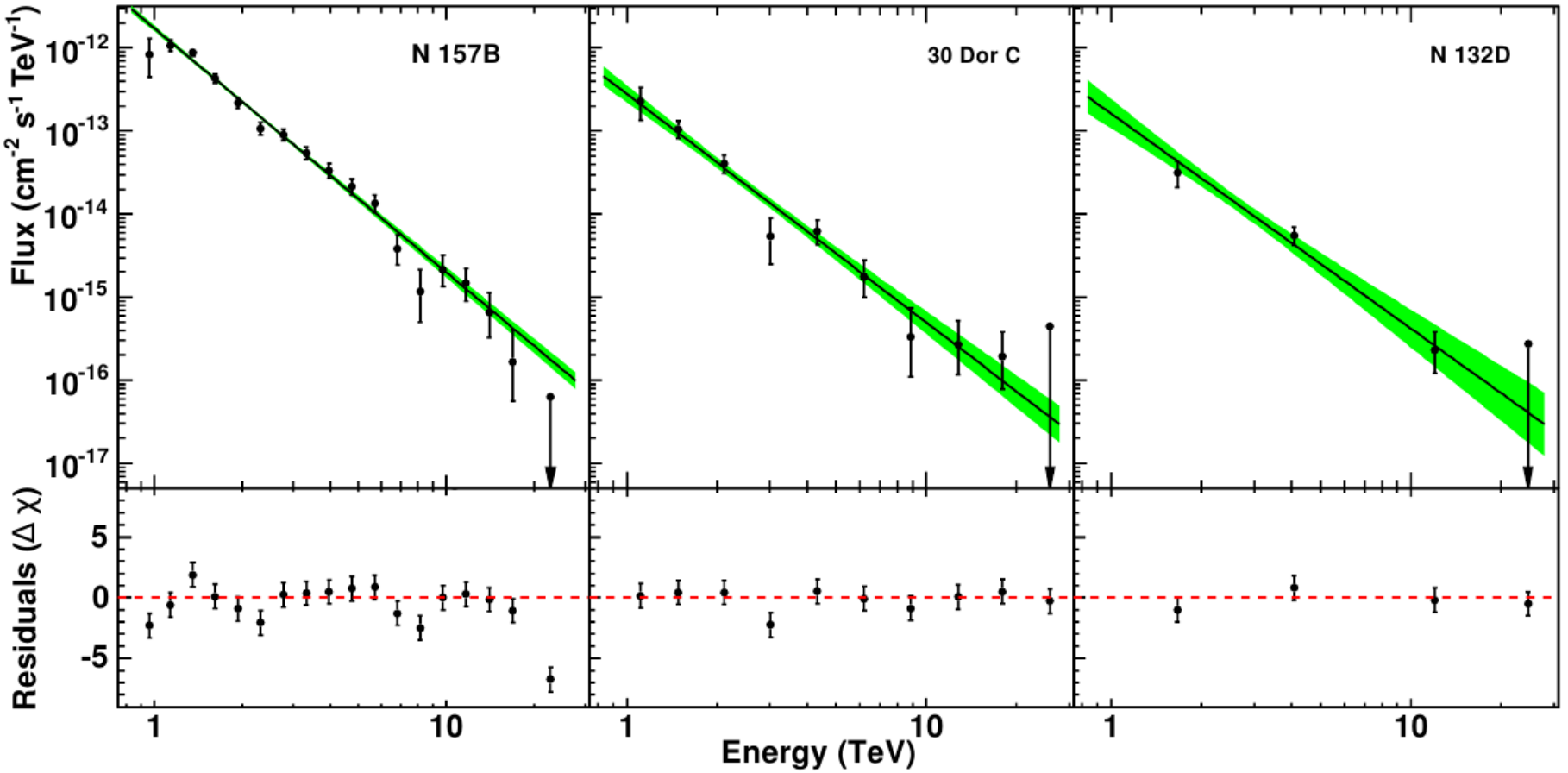
**emission predicted to increase in time**

Already can

# 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 |
| $\gamma$ rays | 613 | 74 | 43 |
| Significance | $33.0\,\sigma$ | $8.8\,\sigma$ | $4.7\,\sigma$ |
| Photon Index $\Gamma$ | $2.8 \pm 0.1$ | $2.6 \pm 0.2$ | $2.4 \pm 0.3$ |
| $\Phi(1\,\mathrm{TeV})$ $[10^{-12}\,\mathrm{cm^{-2}\,s^{-1}\,TeV^{-1}}]$ | $1.3 \pm 0.1$ | $0.16 \pm 0.04$ | $0.13 \pm 0.05$ |
| $L_\gamma(1-10\,\mathrm{TeV})$ $[10^{35}\,\mathrm{erg\,s^{-1}}]$ | $6.8 \pm 0.3$ | $0.9 \pm 0.2$ | $0.9 \pm 0.2$ |

# The LMC in VHE γ-rays

50-kpc-distant face-on satellite galaxy

**First detection of individual accelerators in an external Galaxy**

**Discovery of a new VHE source class:**

superbubble (*N.B.* a candidate source of Galactic CRs)

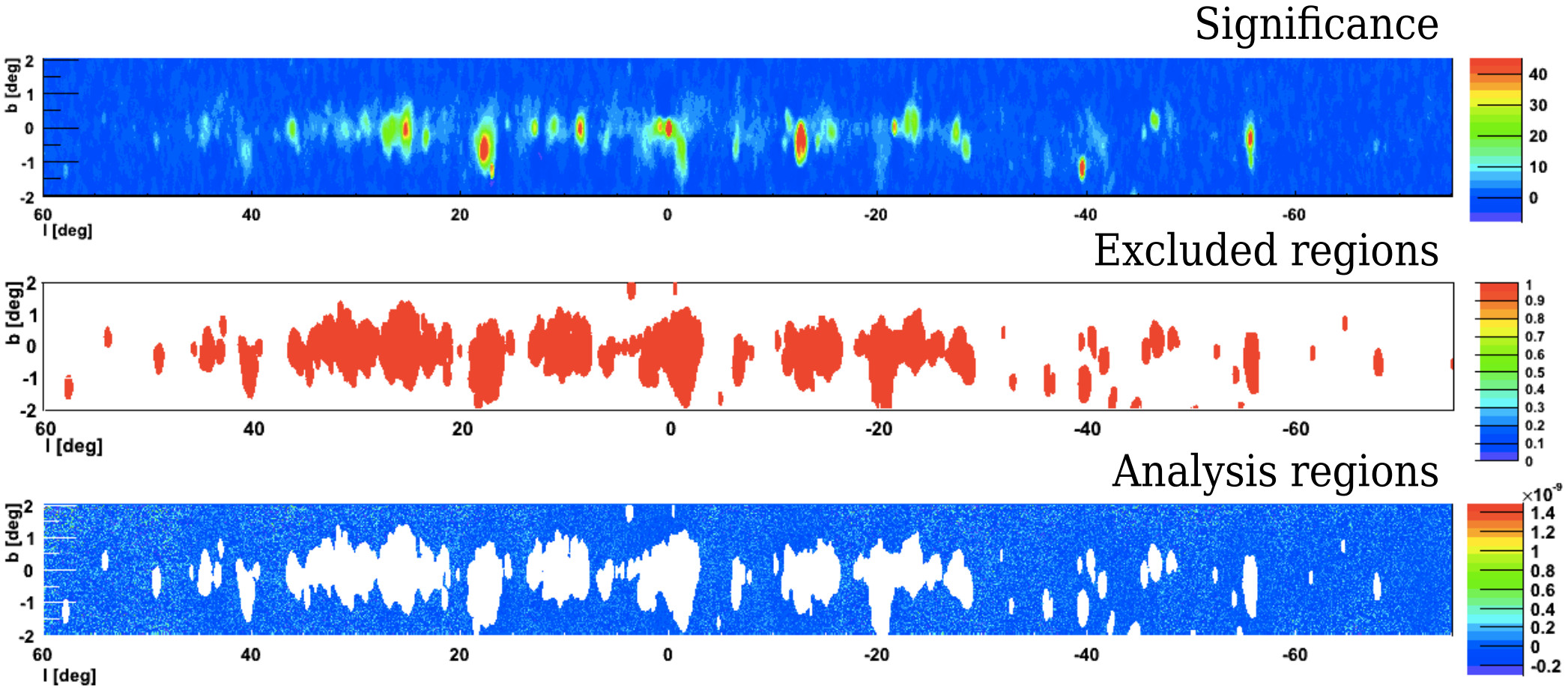
**Observing the extreme tip of the VHE population:**

two powerful sources: a Crab-like PWN and a unique SNR

**Upper limit on the youngest known SNR:**

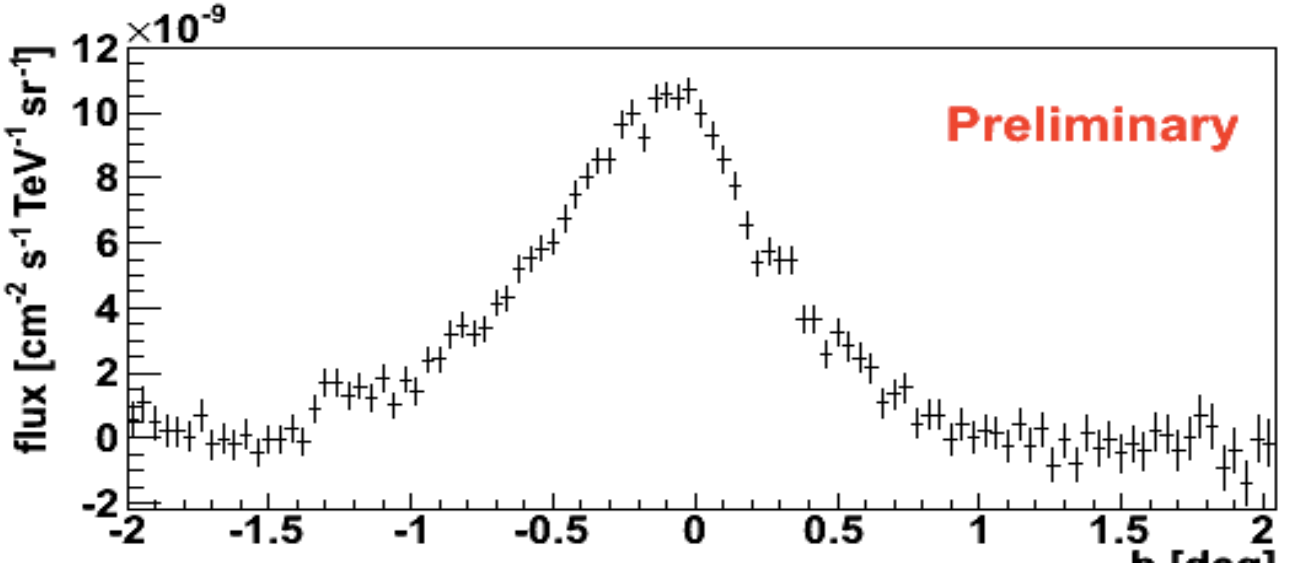
SN 1987A

# Extracting a clean signal to search for diffuse TeV emission

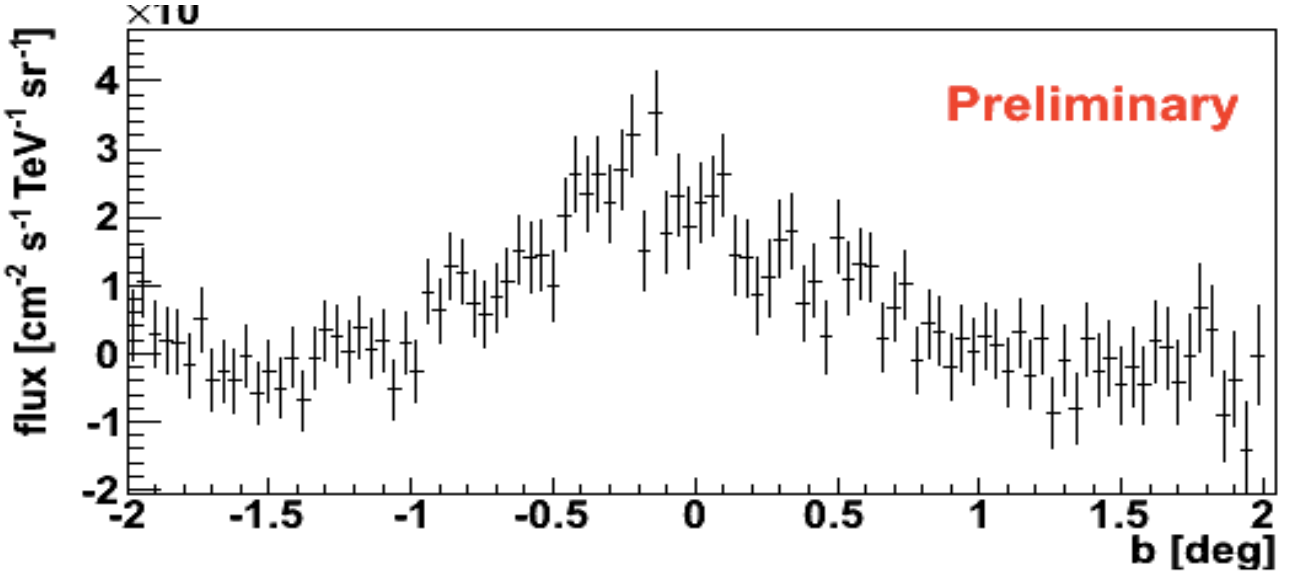


# Extracting a clean signal to search for diffuse TeV emission

Total flux




Diffuse flux



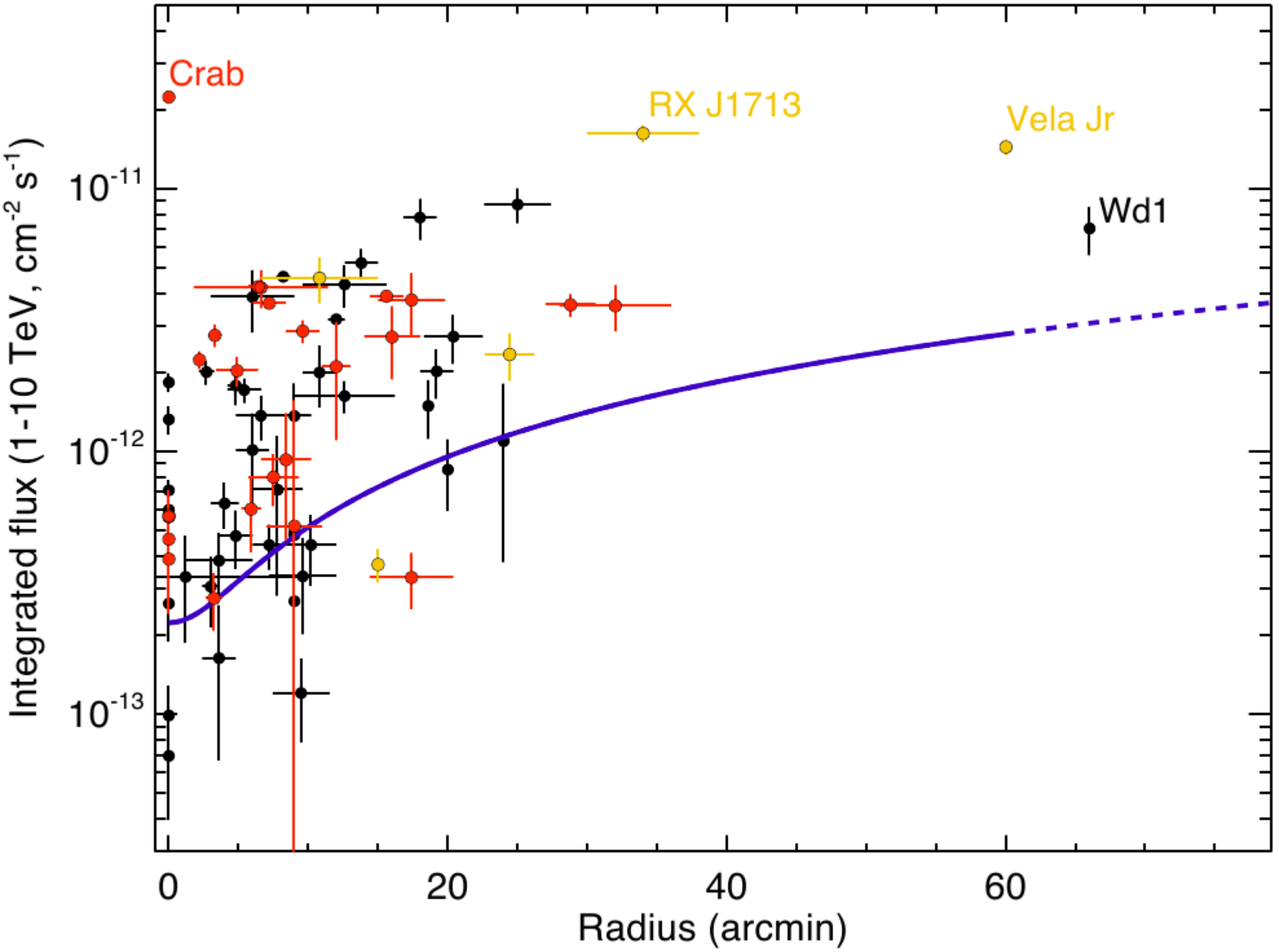
# HESS J1640-465

## Challenges for a PWN scenario

- No visible IC peak in GeV – TeV range:
  a) Very old lepton population, steep injection spectrum;
     - likely multiple emission zones
     - varying magnetic field within emission region
     - Complex spectra expected (i.e. Vela X, Hinton et al. 2011)
  b) Fine-tuned multi-component injection spectrum to mimic powerlaw: i.e. Relativistic Maxwell + powerlaw tail (Slane et al., 2010)

- Overlap of PWN IC emission with SNR shell
  a) Not observed for any other composite SNR so far
  b) Requires relic PWN and old system?

Abramowski et al. (H.E.S.S.) 2014 – MNRAS
Eger et al. (H.E.S.S.) 2014


Crab
RX J1713
Vela Jr
Wd1
$10^{-11}$
$10^{-12}$
$10^{-13}$
Integrated flux (1-10 TeV, cm$^{-2}$ s$^{-1}$)
0
20
40
60
Radius (arcmin)

# PeVatrons short lived… unfortunate

**But how to get to the *knee*?**
Young, fast (20,000 km $s^{-1}$) SNR shock in dense wind (CSM)
from a Type II SN & RSG progenitor

e.g. Cas A, but:

- Cas A photon spectrum cuts off at 20 TeV ($\rightarrow E_{max}$ ~300 TeV)
- $\Gamma = -2.6 \pm 0.2_{stat} \pm 0.2_{syst}$
- Tycho similar and Type Ia

NRH instability quenched after ~1000 yrs
$E_{max}$ ~ PeV for only ~50 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?

# GRBs at VHE

Typical re-pointing time < 1 min

Fully automated GCN triggering & observations; highest priority

Currently observing ~5 GRBs/yr

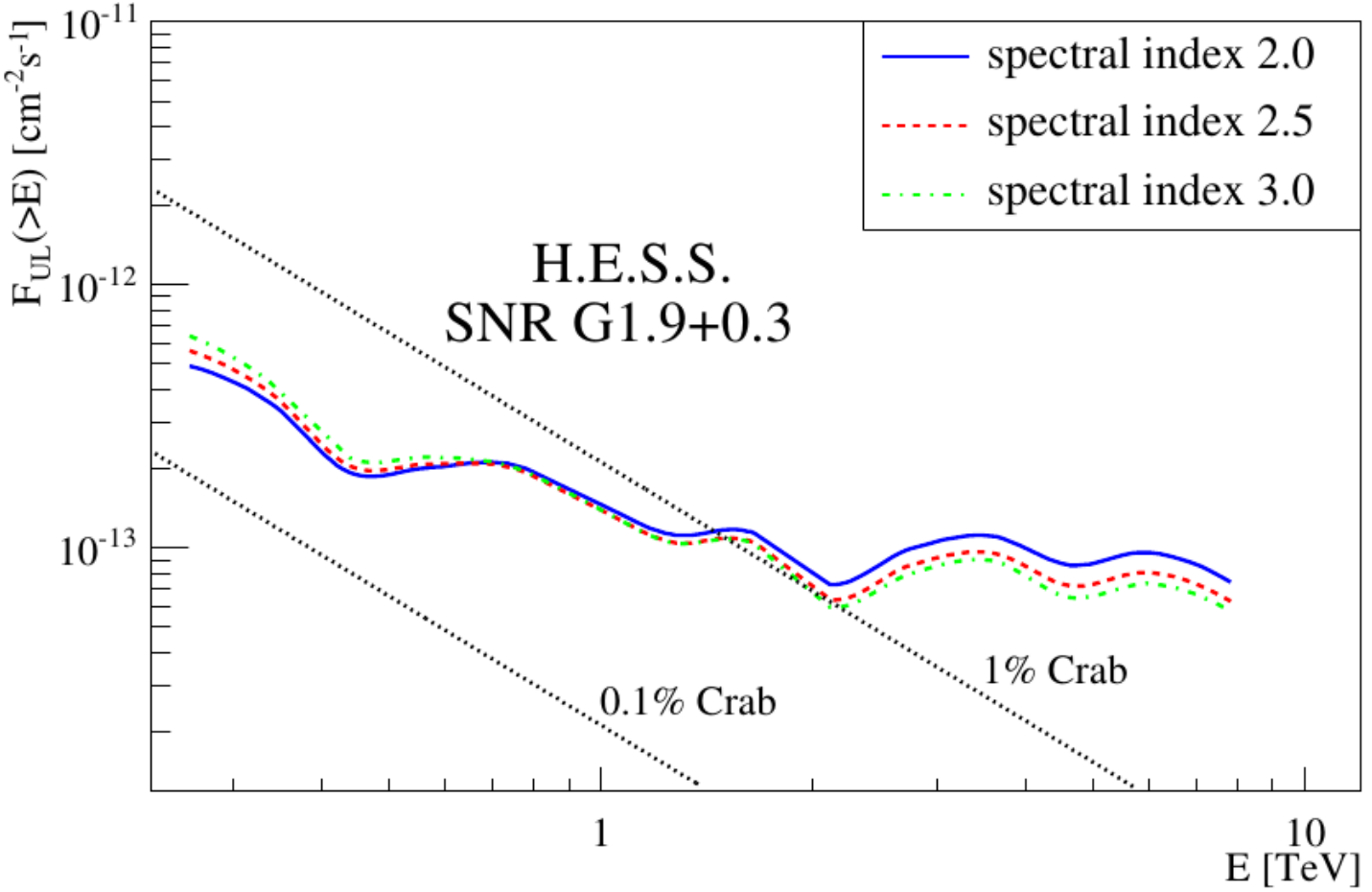
# SNR G1.9+0.3:

Youngest in the Galaxy, ultra-fast shock speed, close to Galactic Center, ... *PeVatron?*


Reynolds+ 08; Green+ 08

# SNR G1.9+0.3:

VHE quiet even after very deep observations




**VHE limits → limits on:**
magnetic field, density, CR conversion efficiency, cut-off energy, total energy

e.g.

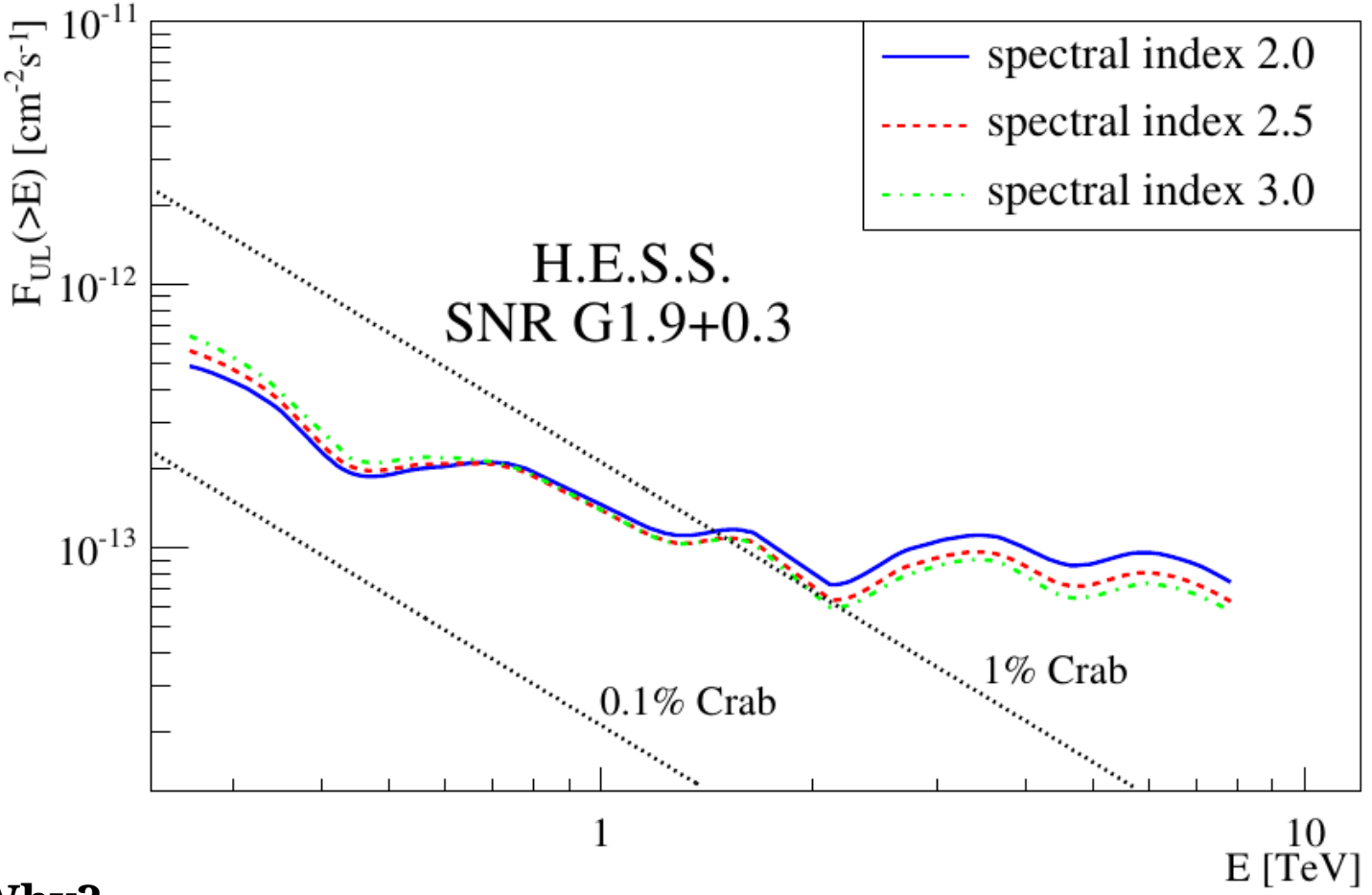
**B > 12 μG**

**$E_{cut}$ < 44 TeV**

Abramowski, Chaves+ (H.E.S.S.) 14

# SNR G1.9+0.3:

## VHE quiet even after very deep observations




**VHE limits → limits on:**
magnetic field, density, CR conversion efficiency, cut-off energy, total energy

e.g.

**B > 12 μG**
**$E_{cut}$ < 44 TeV**

**Why?**

Circumstellar density expected to be low:

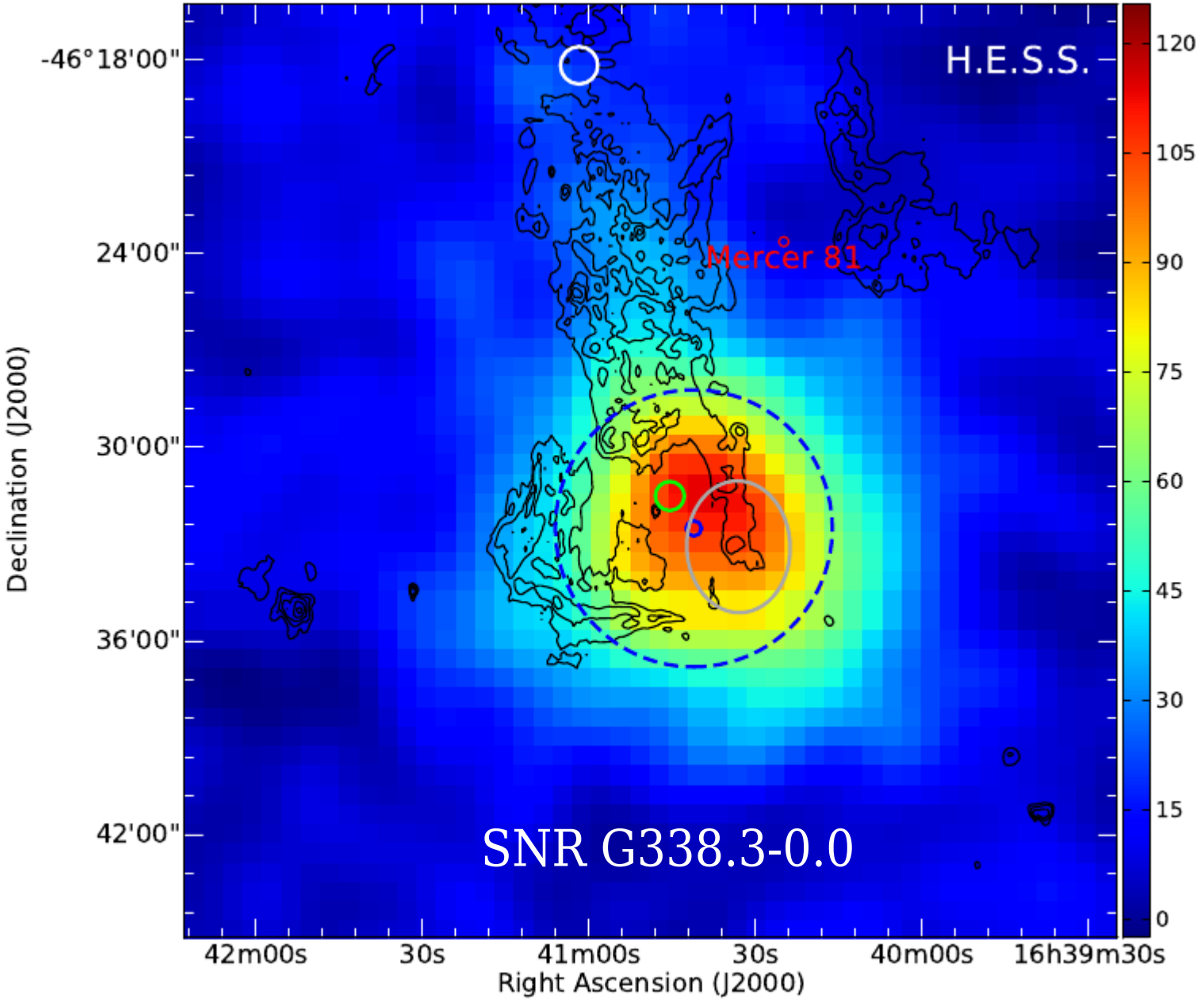
Estimated ~0.04 $cm^{-3}$ (Reynolds+ 08). Constrained by VHE limits to < 1 $cm^{-3}$ if θ = 0.1

Measured flux increase in radio/Xrays → not evolving in dense stellar wind.

# An exceptionally luminous TeV source & proton-accelerating SNR (which you probably haven't heard of yet)

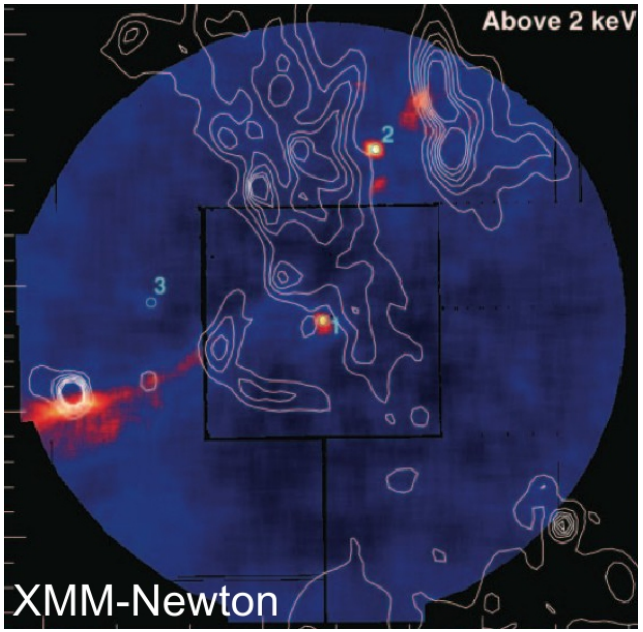
Abramowski et al. (H.E.S.S.) 2014 – MNRAS

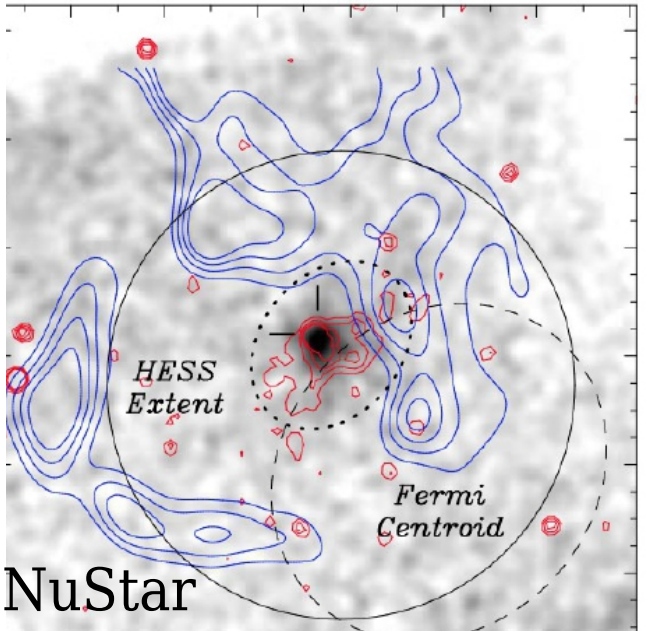
# An exceptionally luminous TeV source & proton-accelerating (?) SNR (which you probably haven't heard of yet)

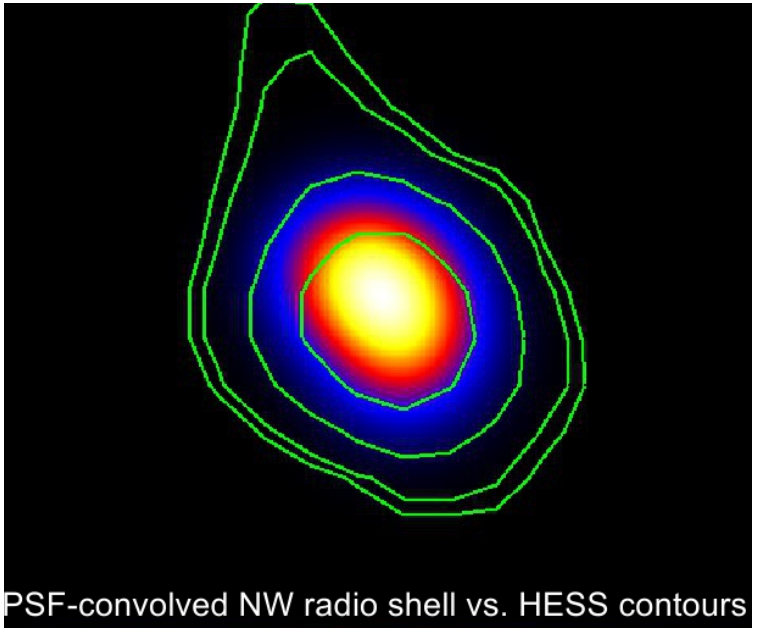


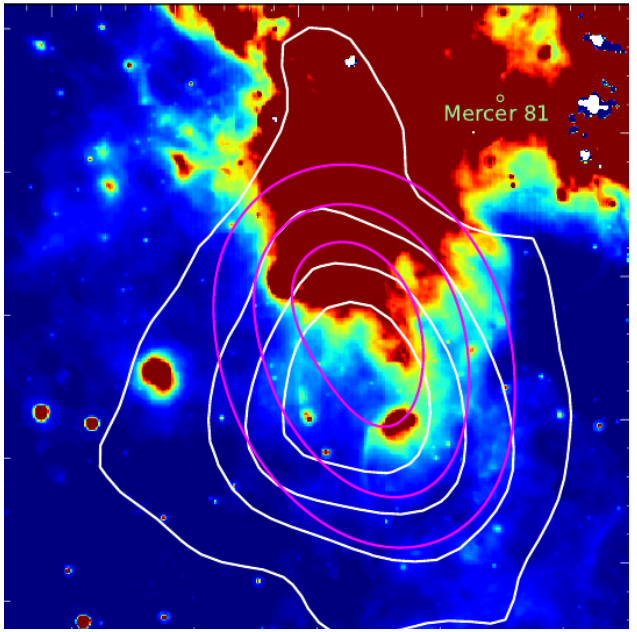

Abramowski et al. (H.E.S.S.) 2014 – MNRAS

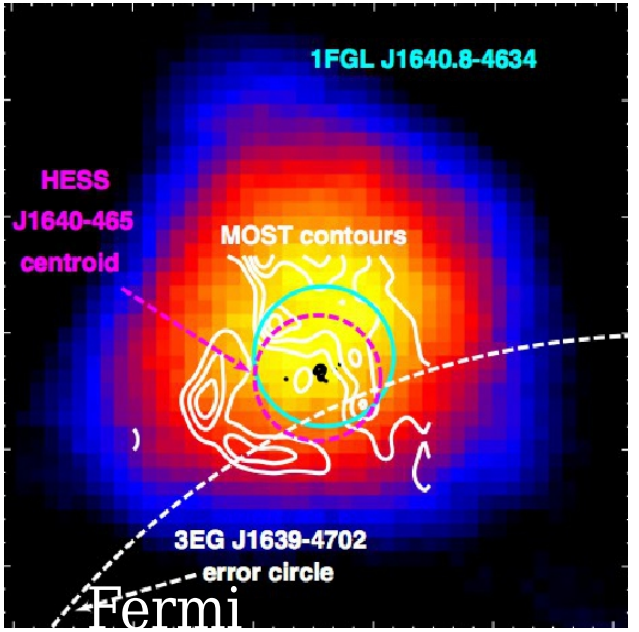
# **Synergies with other wavelengths:** radio, IR, X-rays



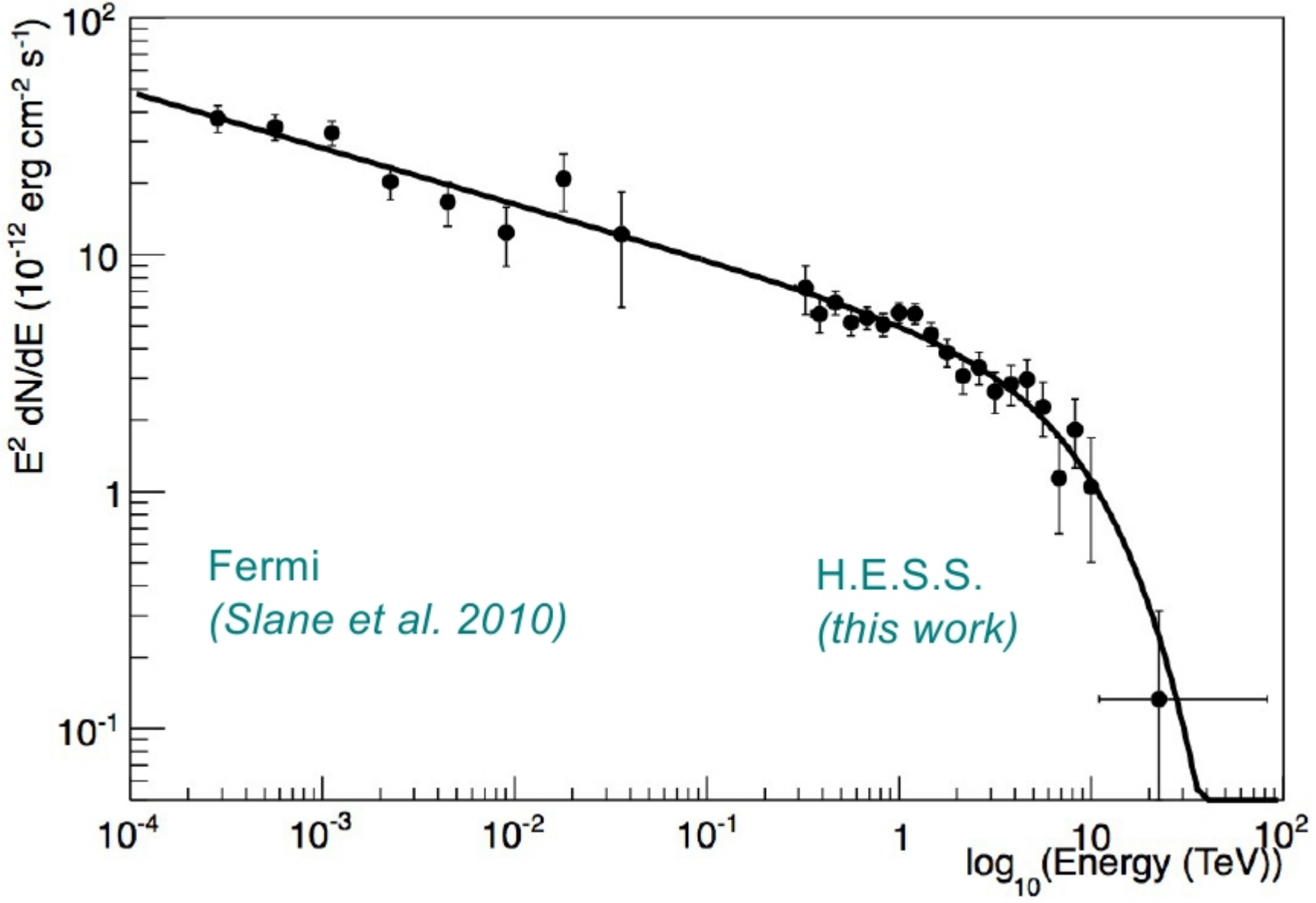




Abramowski et al. (H.E.S.S.) 2014
Adapted from Eger et al. (H.E.S.S.) 2014

**Synergies with other wavelengths:** HE (MeV-GeV) gamma-rays

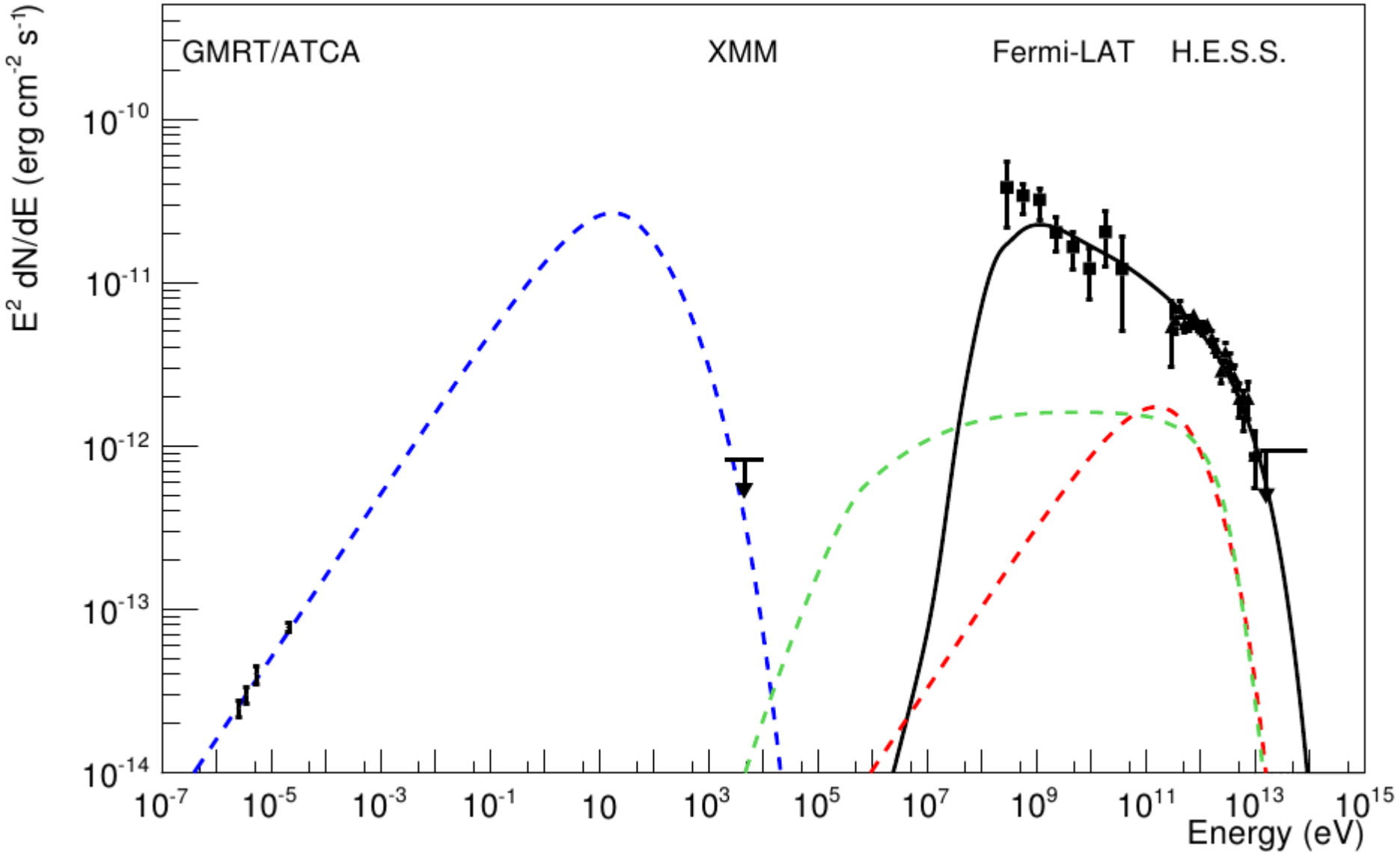
Challenging the previous PWN interpretation




Abramowski et al. (H.E.S.S.) 2014 – MNRAS
Eger et al. (H.E.S.S.) – Moriond

**Synergies with other wavelengths:** HE (MeV-GeV) gamma-rays

Challenging the previous PWN interpretation w/ new hadronic interpration




Abramowski et al. (H.E.S.S.) 2014 – MNRAS
Eger et al. (H.E.S.S.) – Moriond