The population of Galactic TeV γ-ray sources, and the search for Galactic PeV cosmic rays

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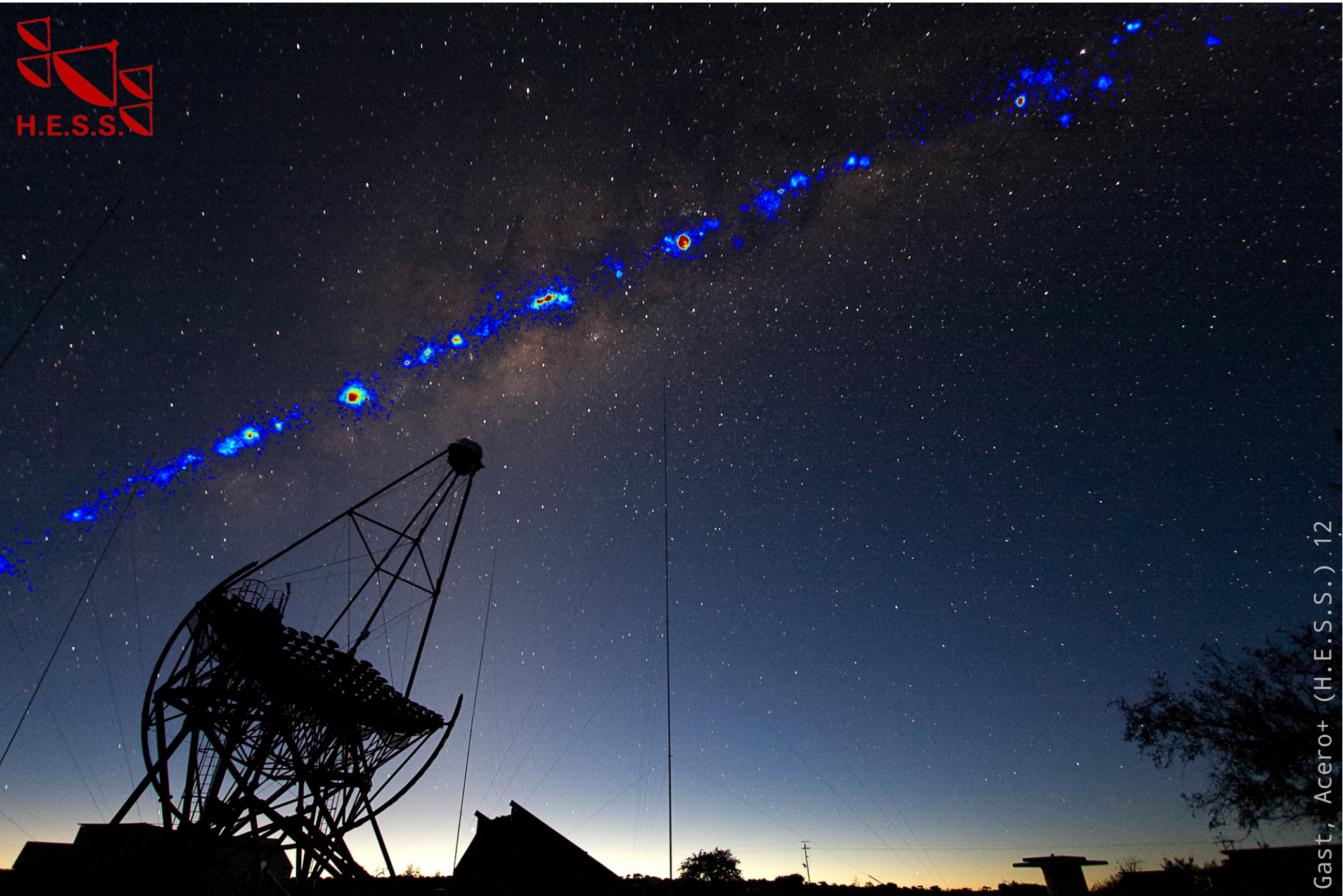
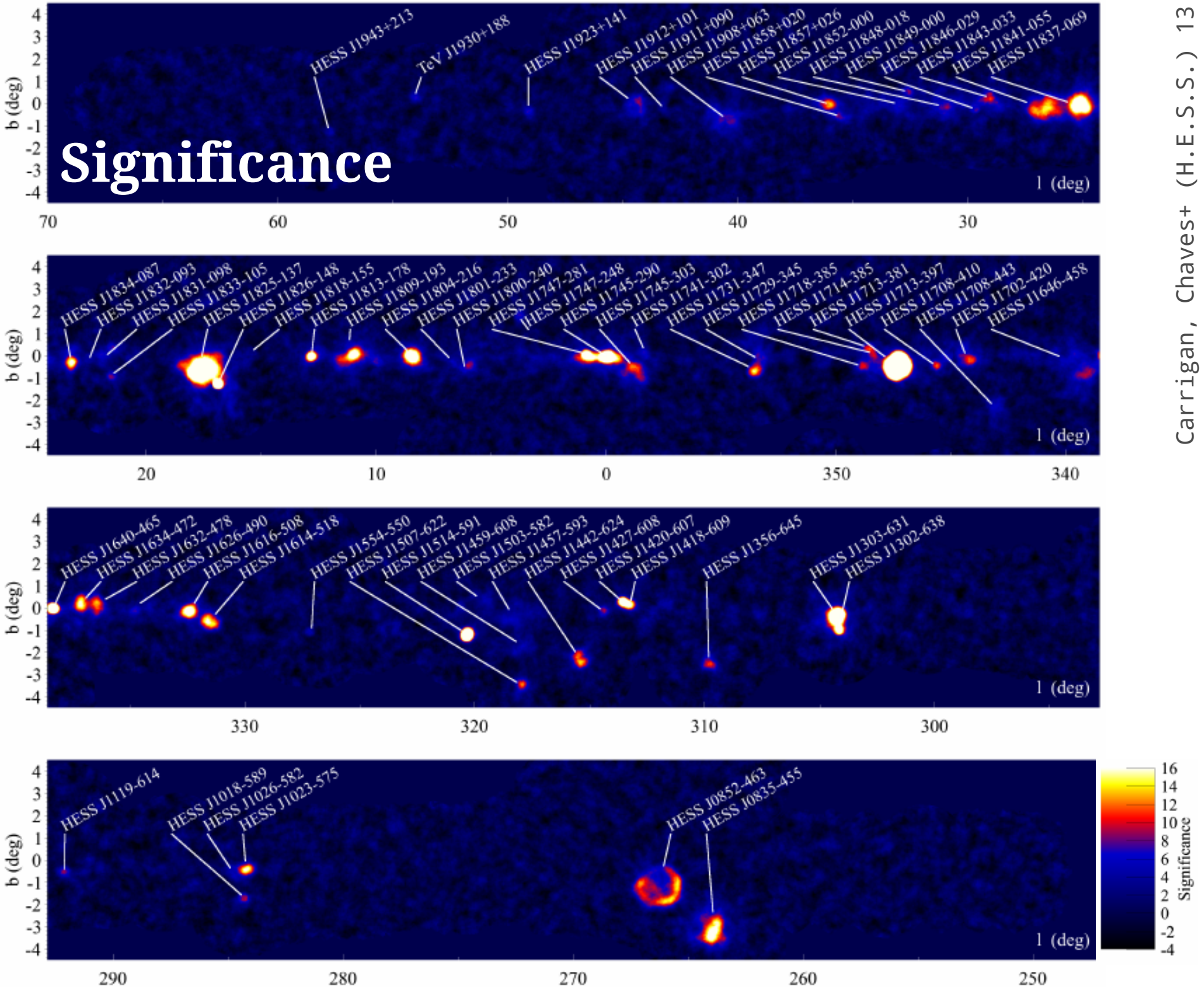
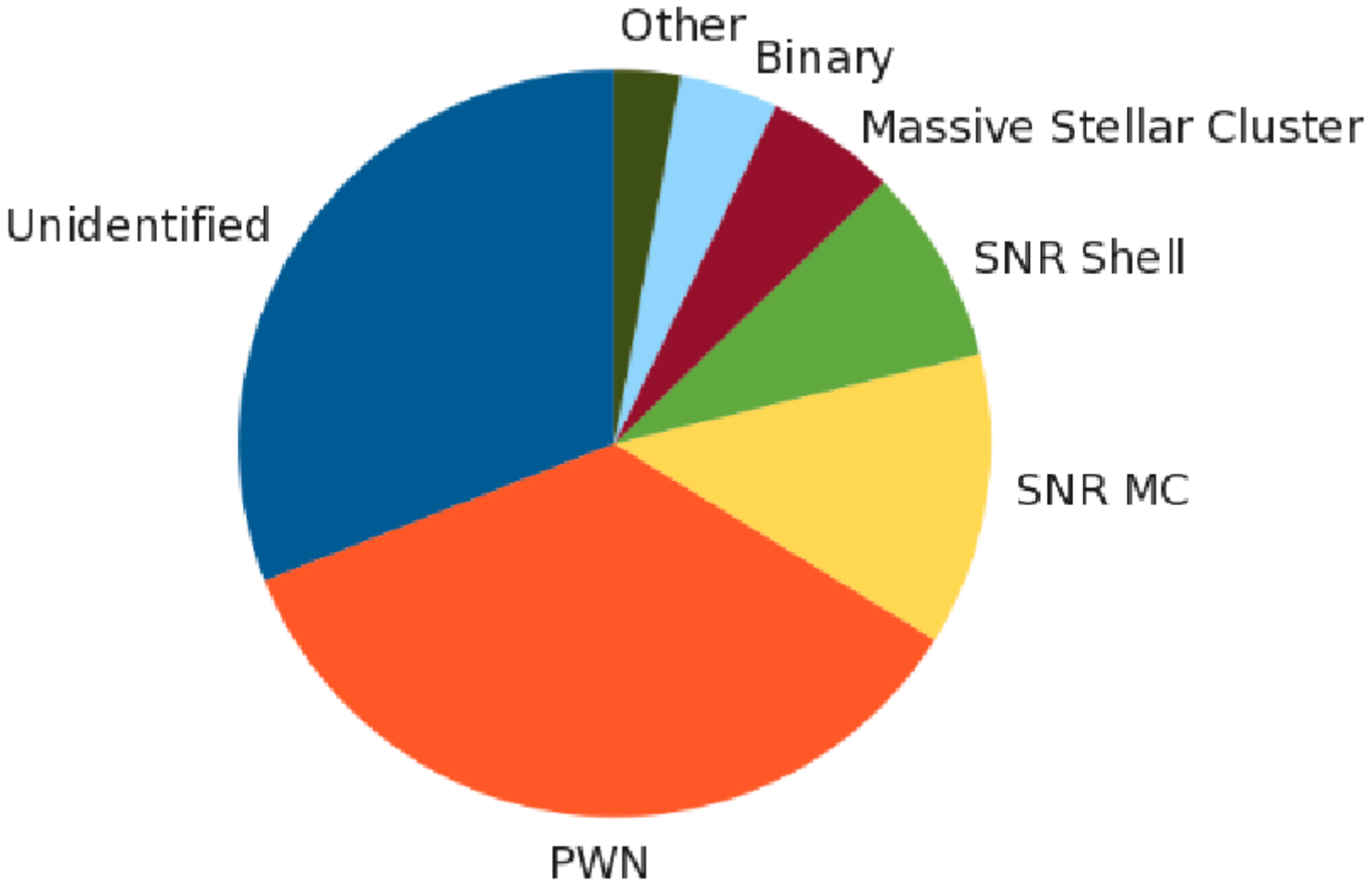
H.E.S.S. and the Galactic Plane Survey





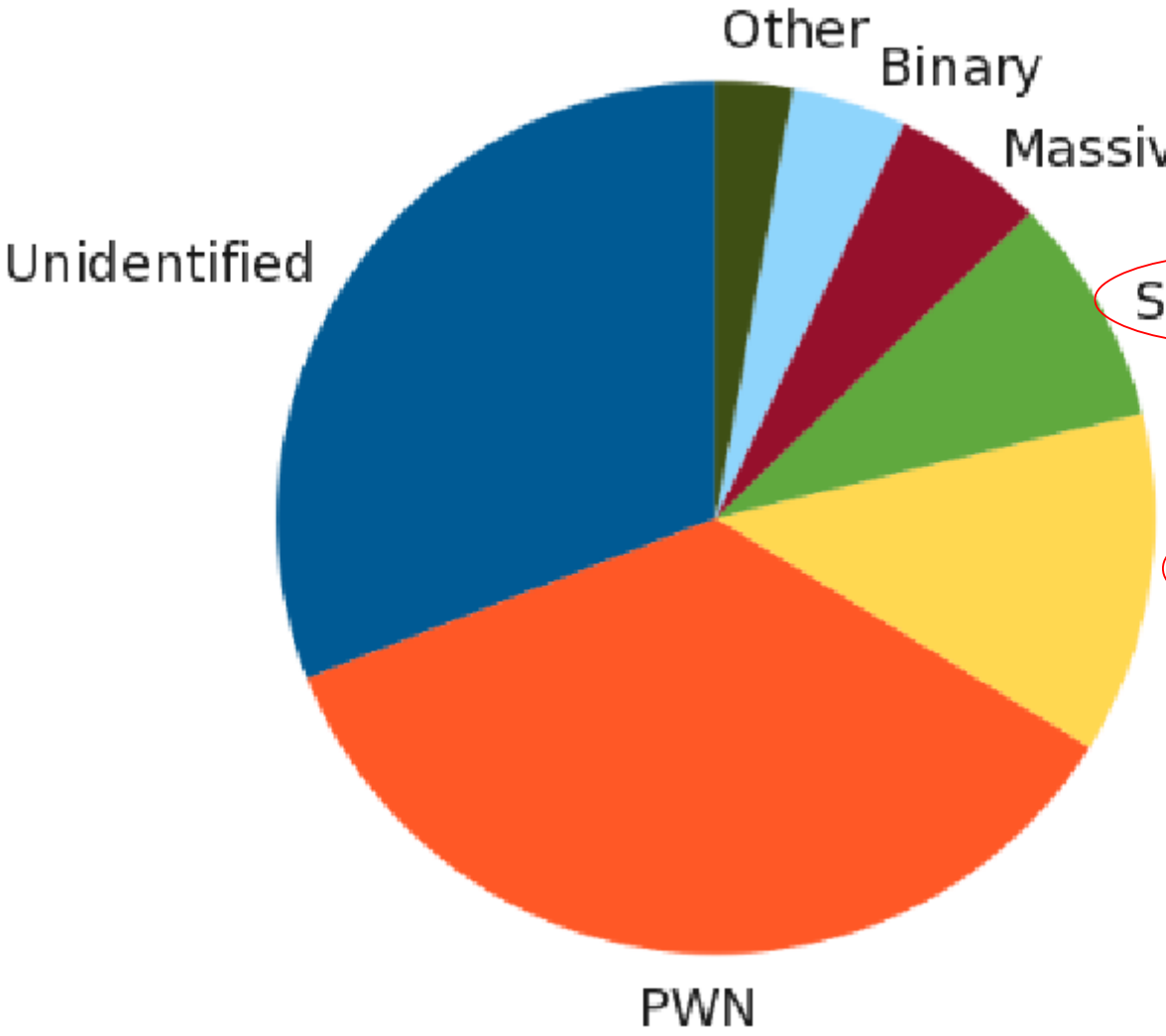
Carrigan, Chaves+ (H.E.S.S.) 13

Galactic TeV source populations



~70 sources total now known

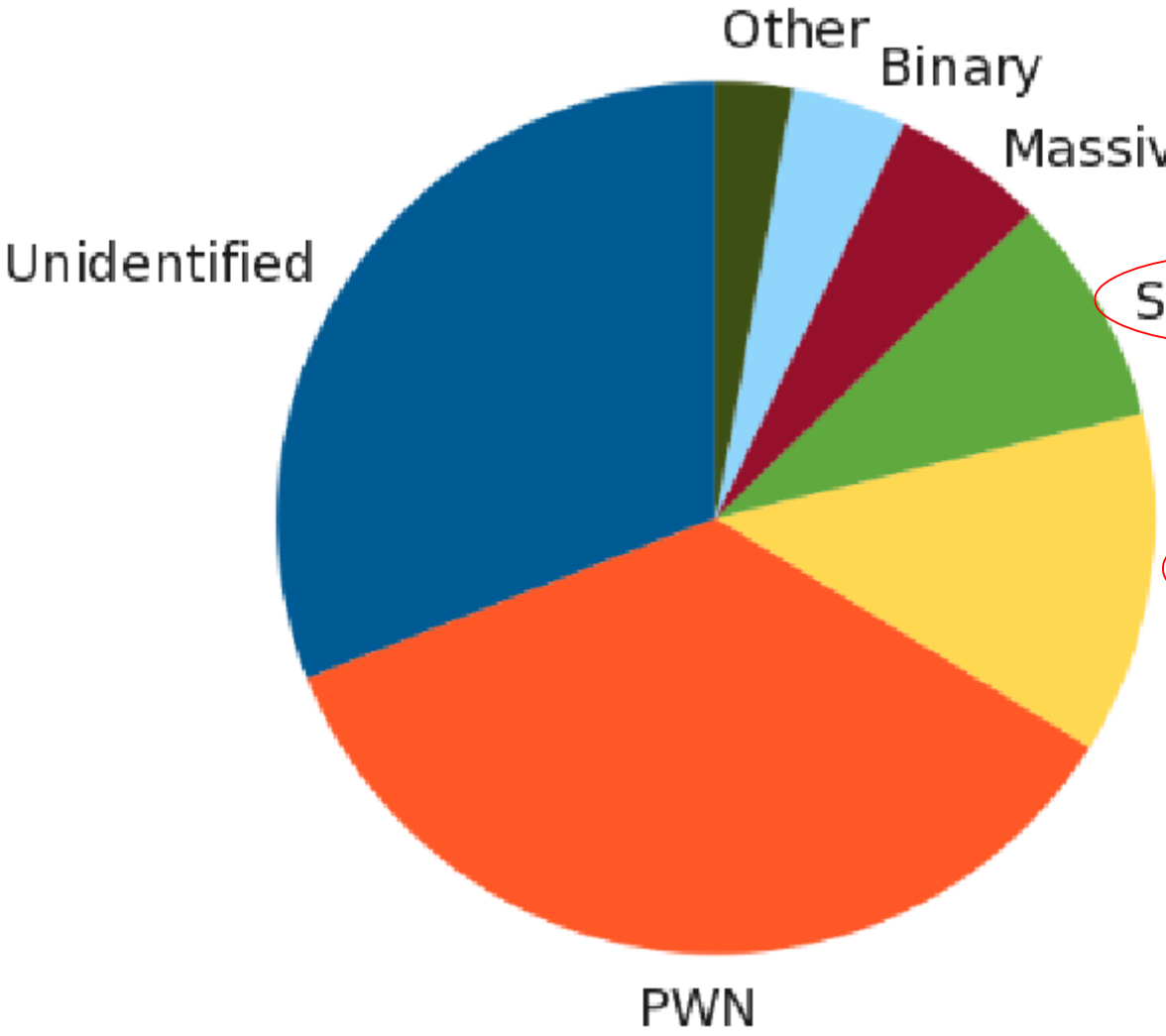
Galactic TeV source populations



Best PeVatron candidates?

π^0 bump discovery confirms hadronic interaction, but energies only up to ~300 GeV

Galactic TeV source populations



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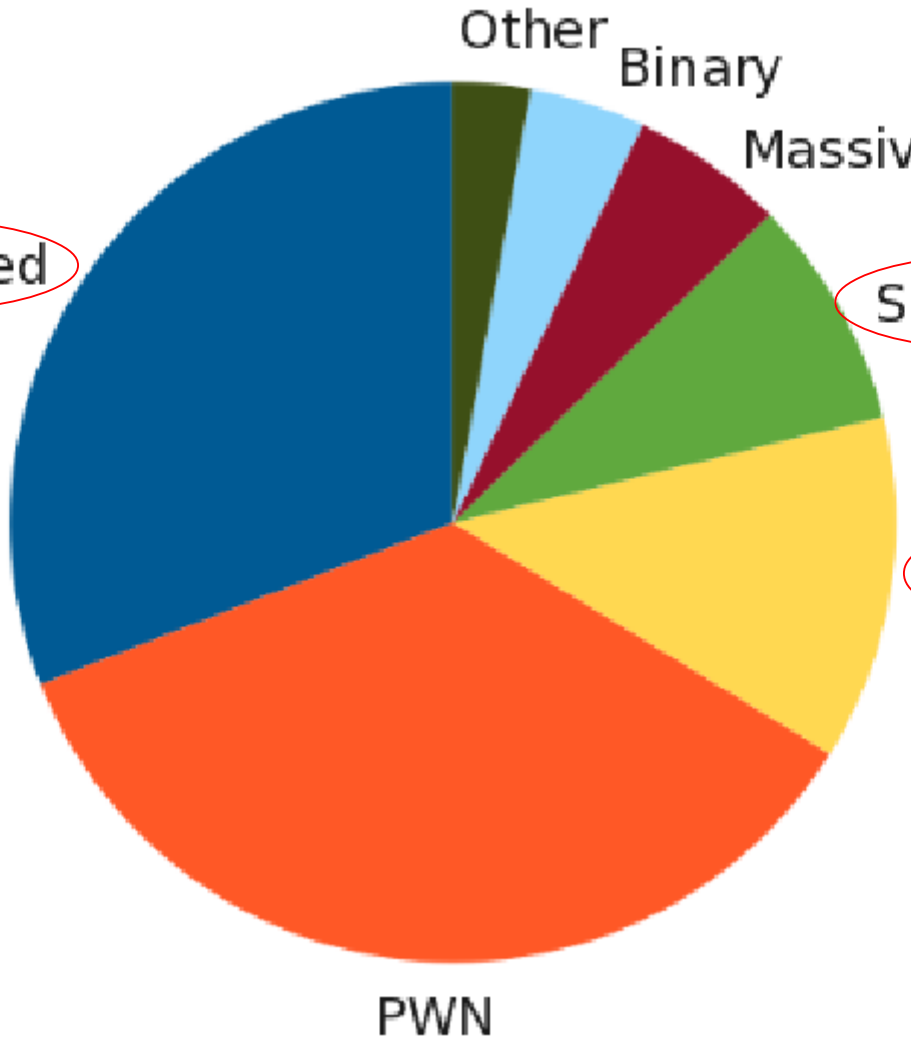
Galactic TeV source populations



Relic PWNe
or
missing SNRs?

Best PeVatron candidates?

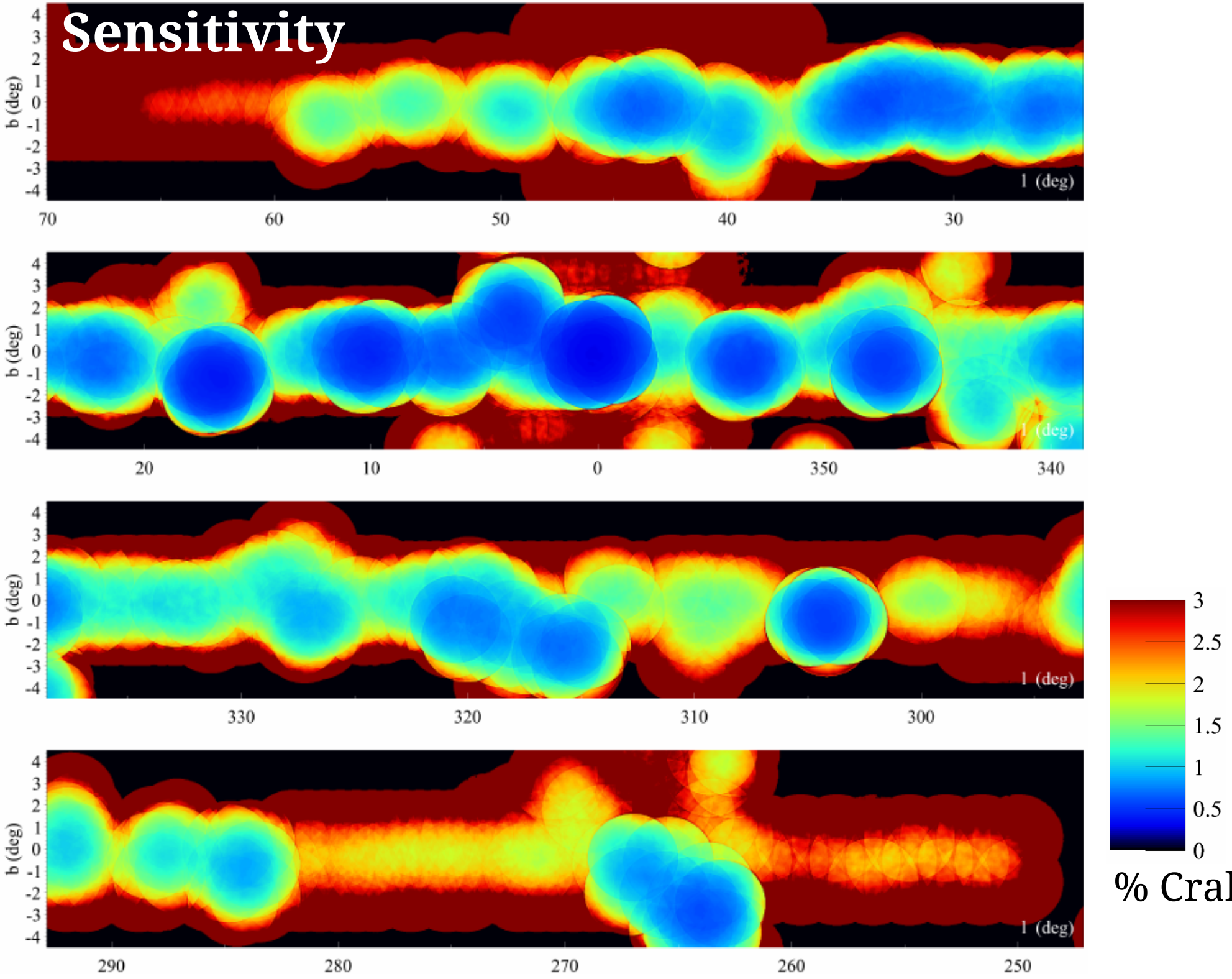
π^0 bump discovery confirms hadronic interaction, but energies only up to ~300 GeV

How to get to 3 PeV? Schure & Bell 2013 suggest:
Young SNR shock in dense wind (CSM), from a Type II SN and RSG progenitor
e.g. Cas A, but: Cas A photon spectrum cuts off at 20 TeV (→ E_{max} ~280 TeV).

How complete is the Survey?

or

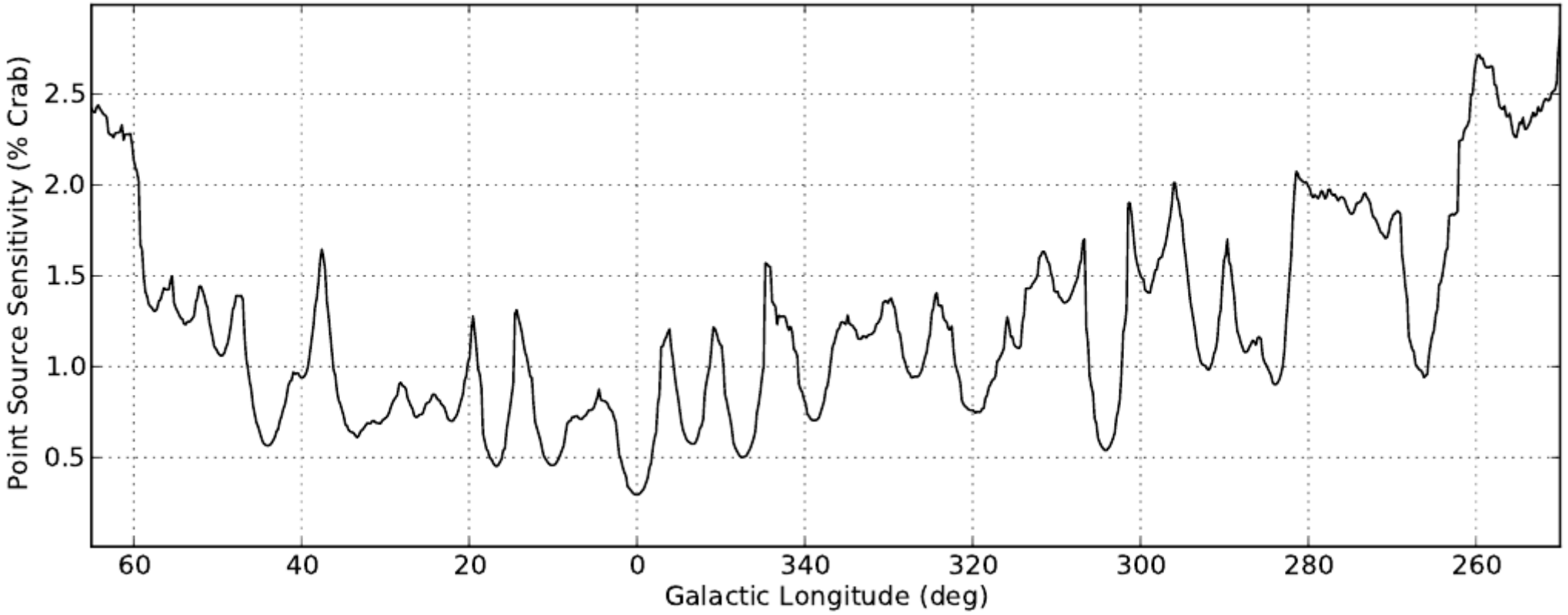
If there is a (bright) PeVatron out there,
would we have detected it already?



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

HGPS Sensitivity

along b = –0.3° for a 5-σ detection



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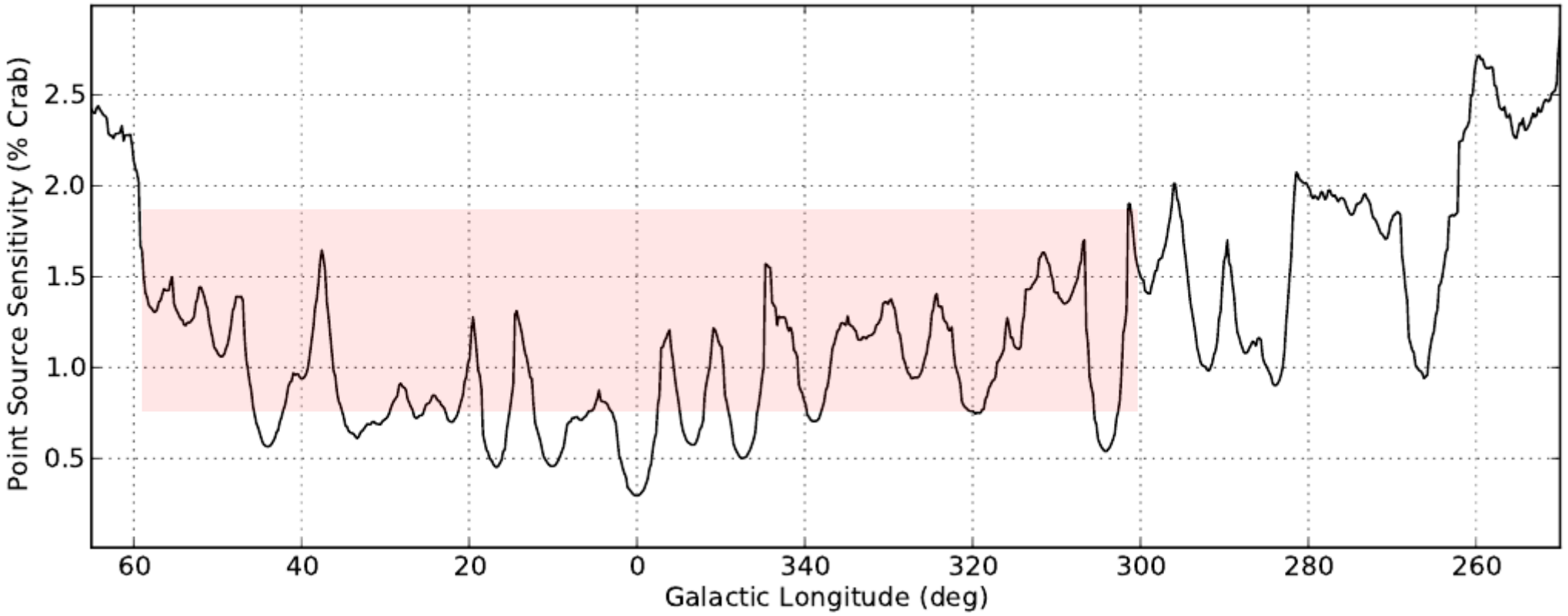

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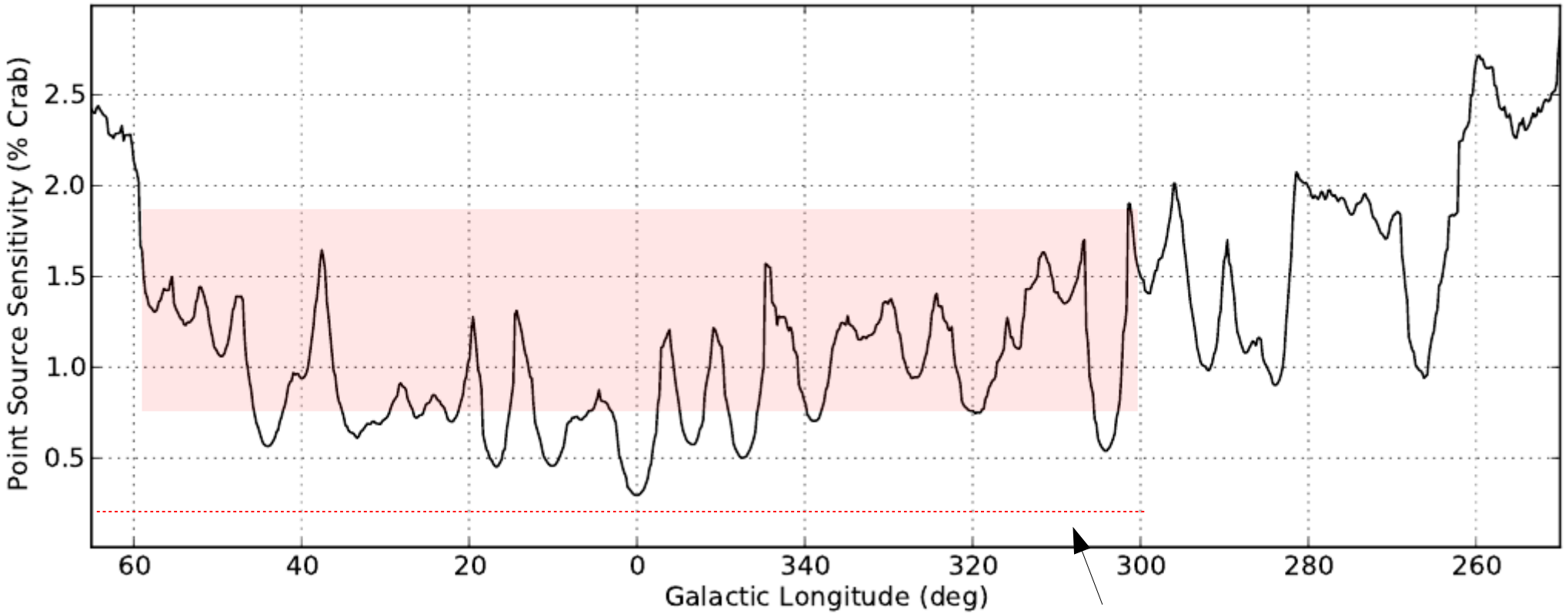
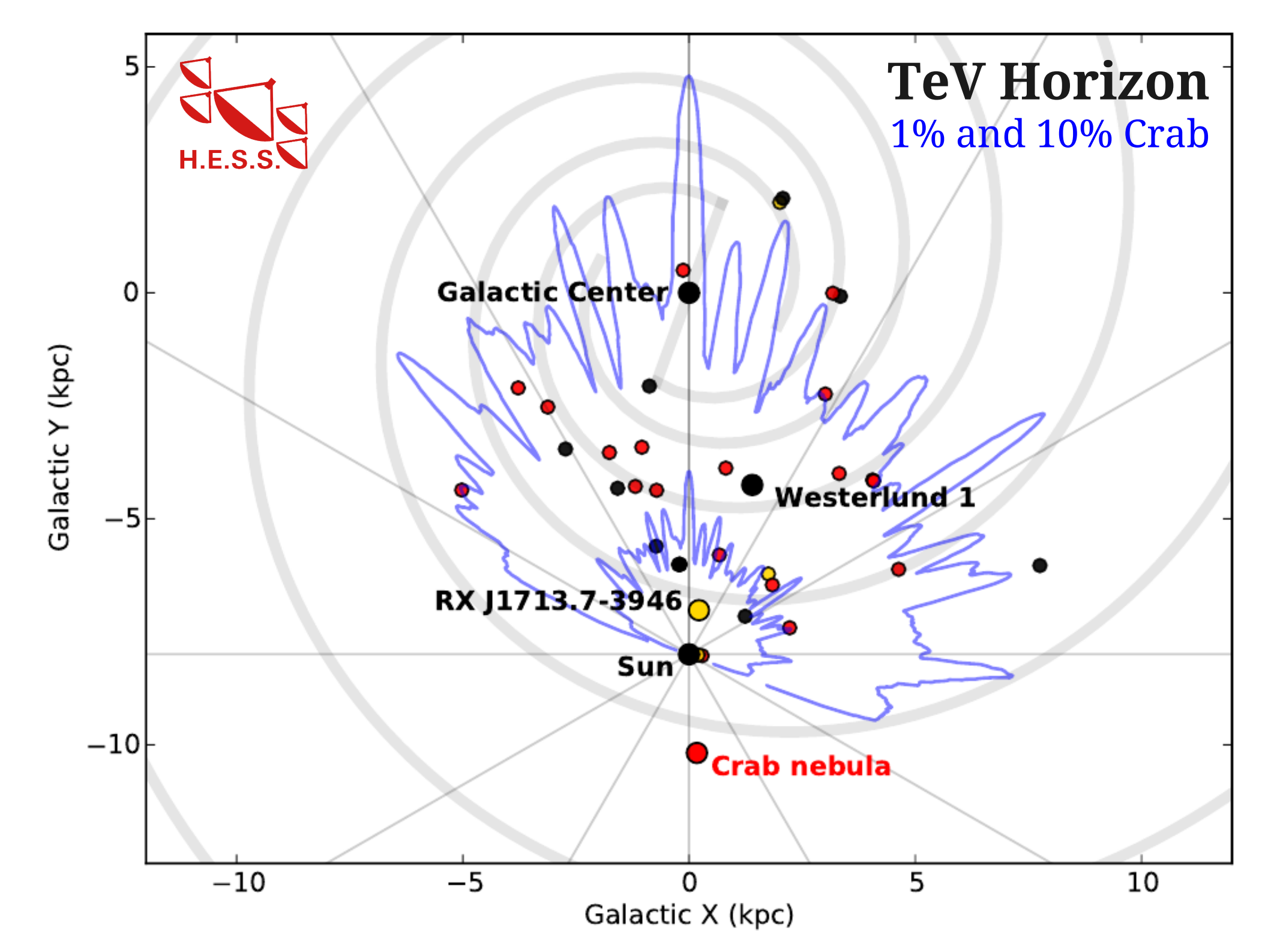
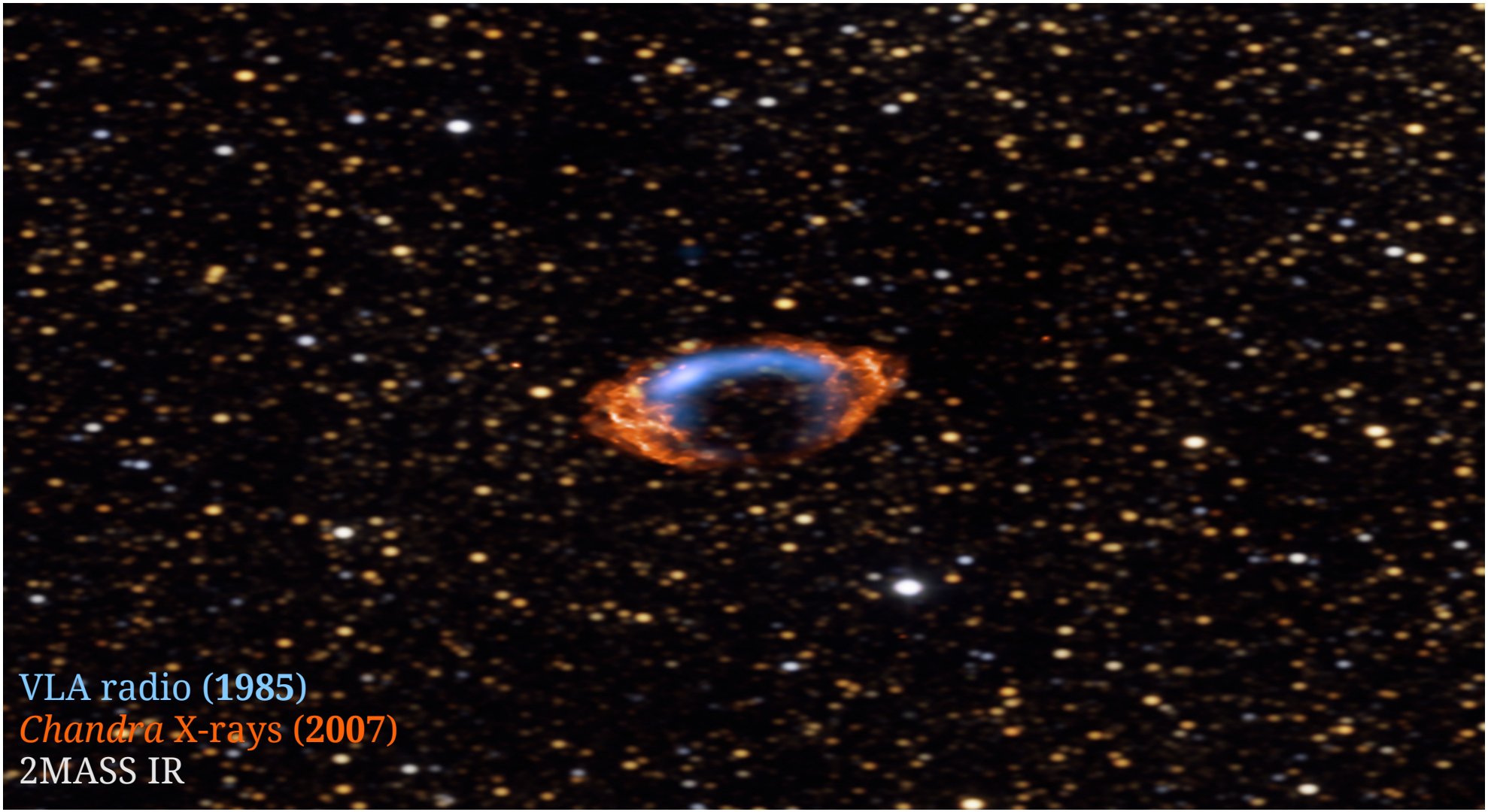


FYI: CTA GPS by ~2022


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

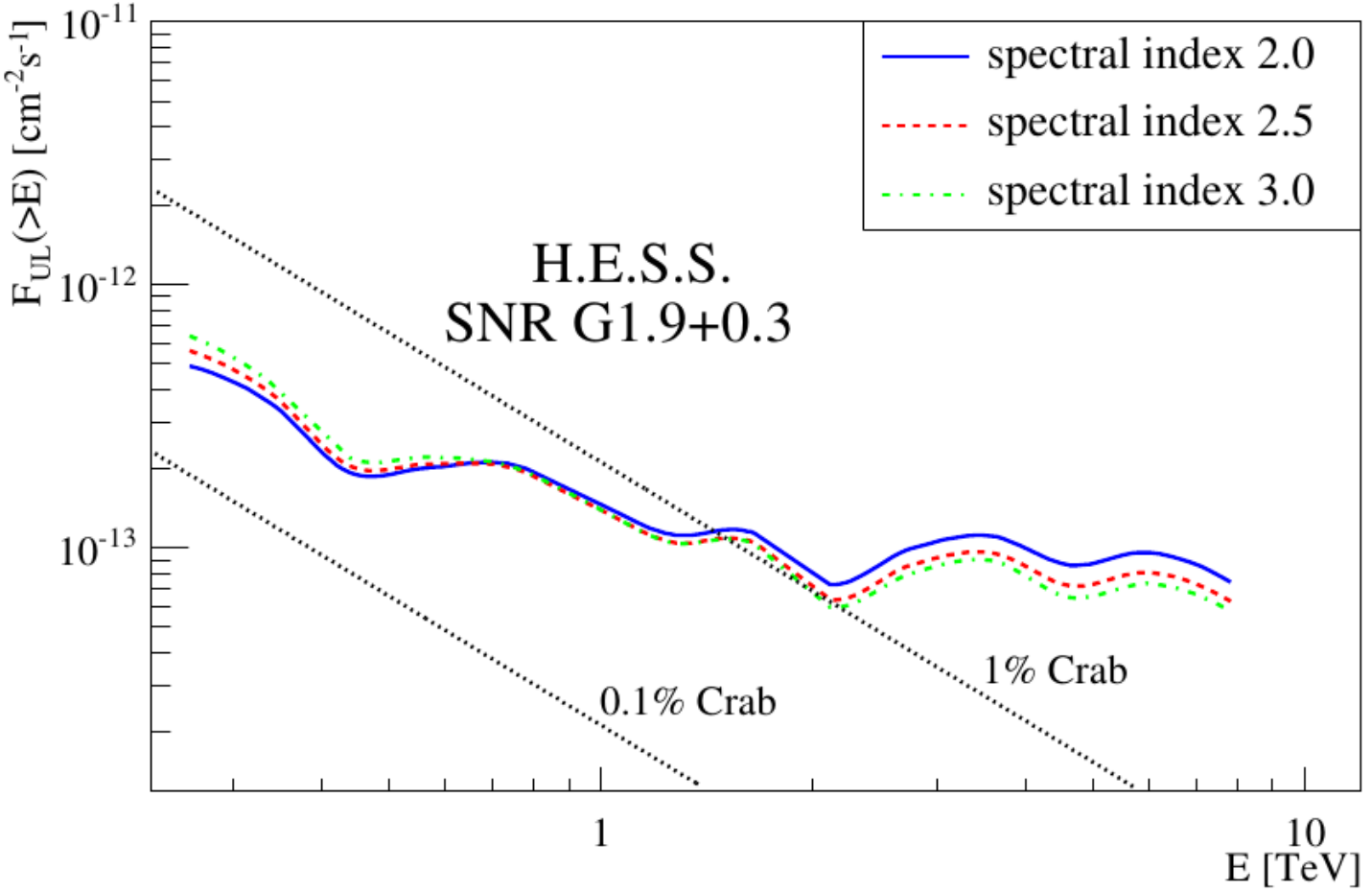
SNR G1.9+0.3:

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



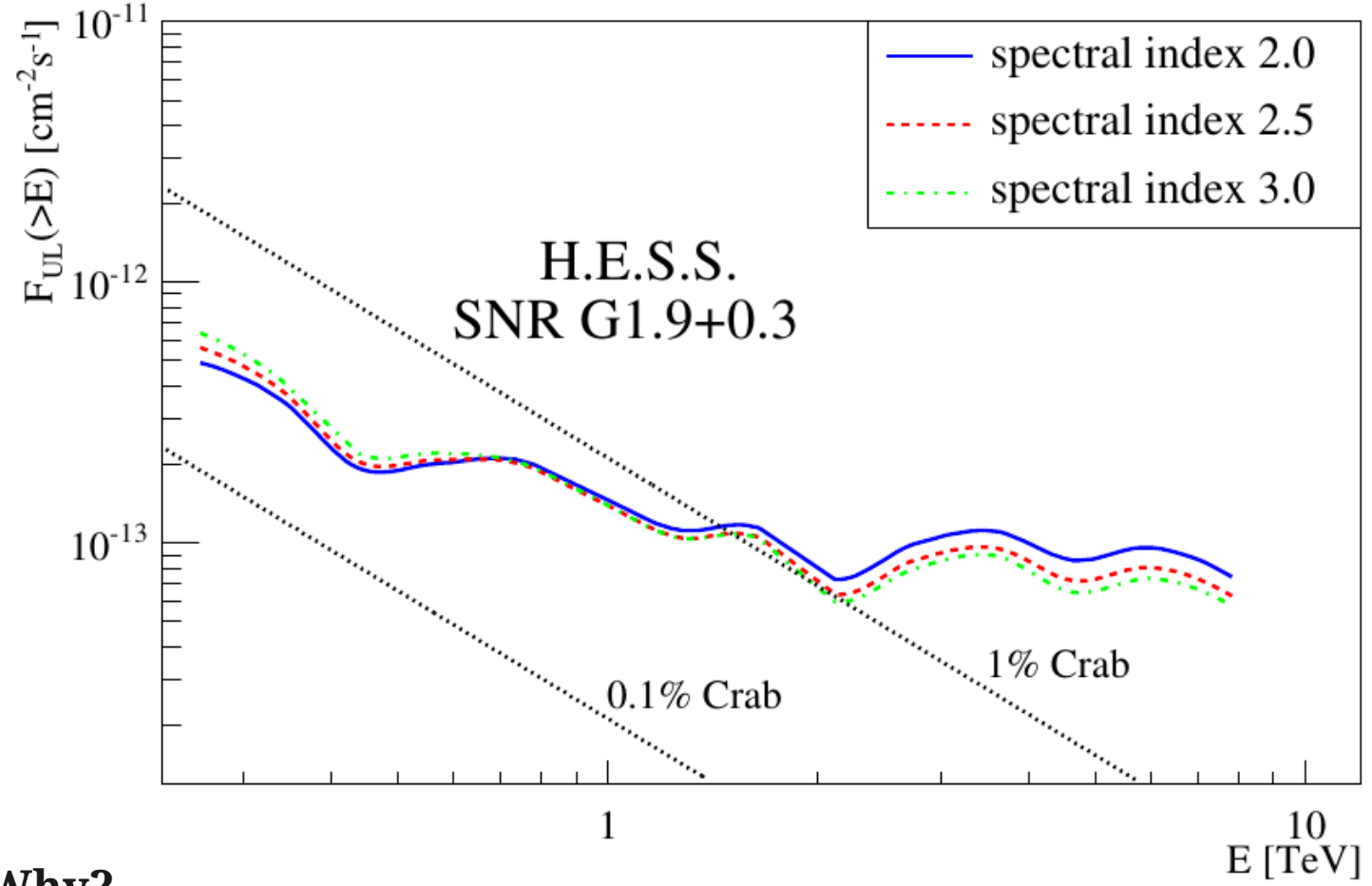
VHE limits → limits on:
magnetic field, density, CR conversion efficiency, cut-off energy, total energy

e.g.

B > 12 μG
E_{cut} < 44 TeV

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 ($e^{\pm}$)

Why?

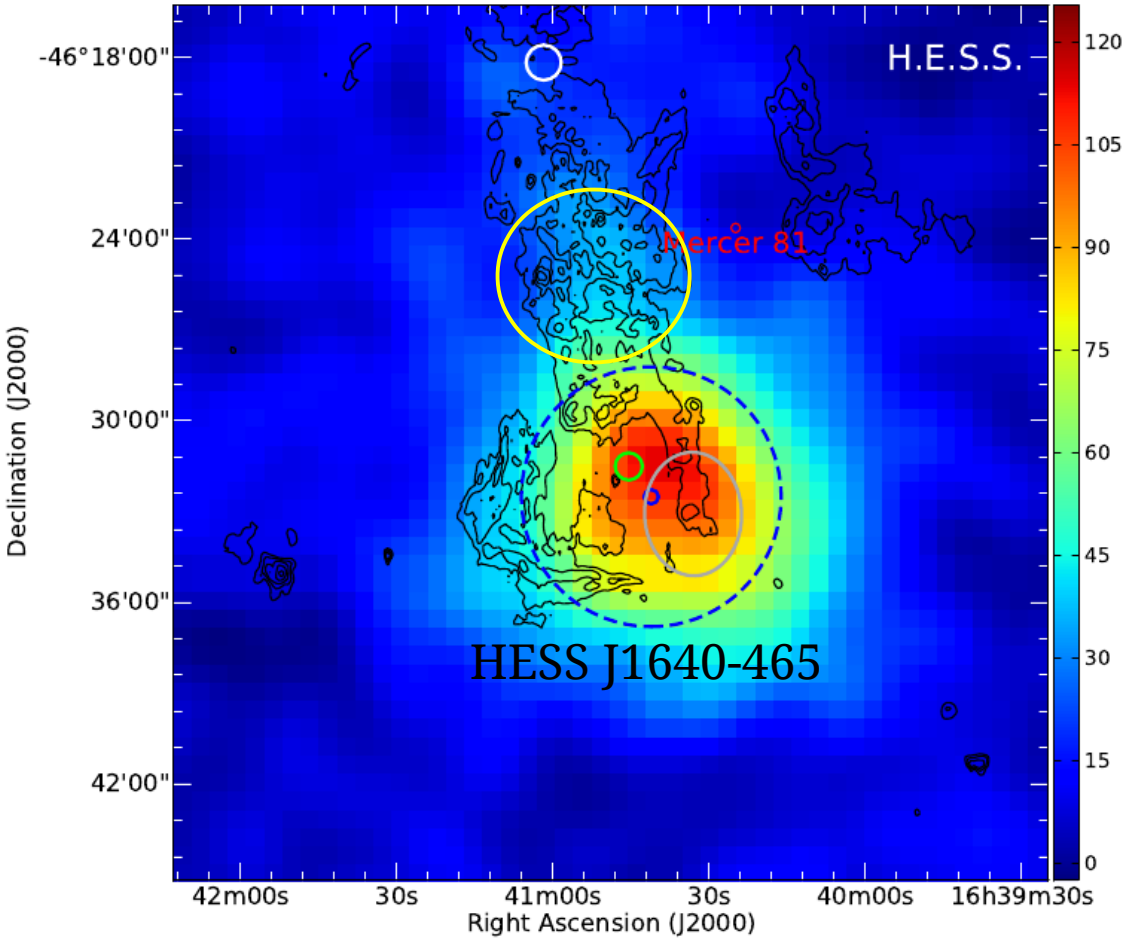
Circumstellar density expected to be low:

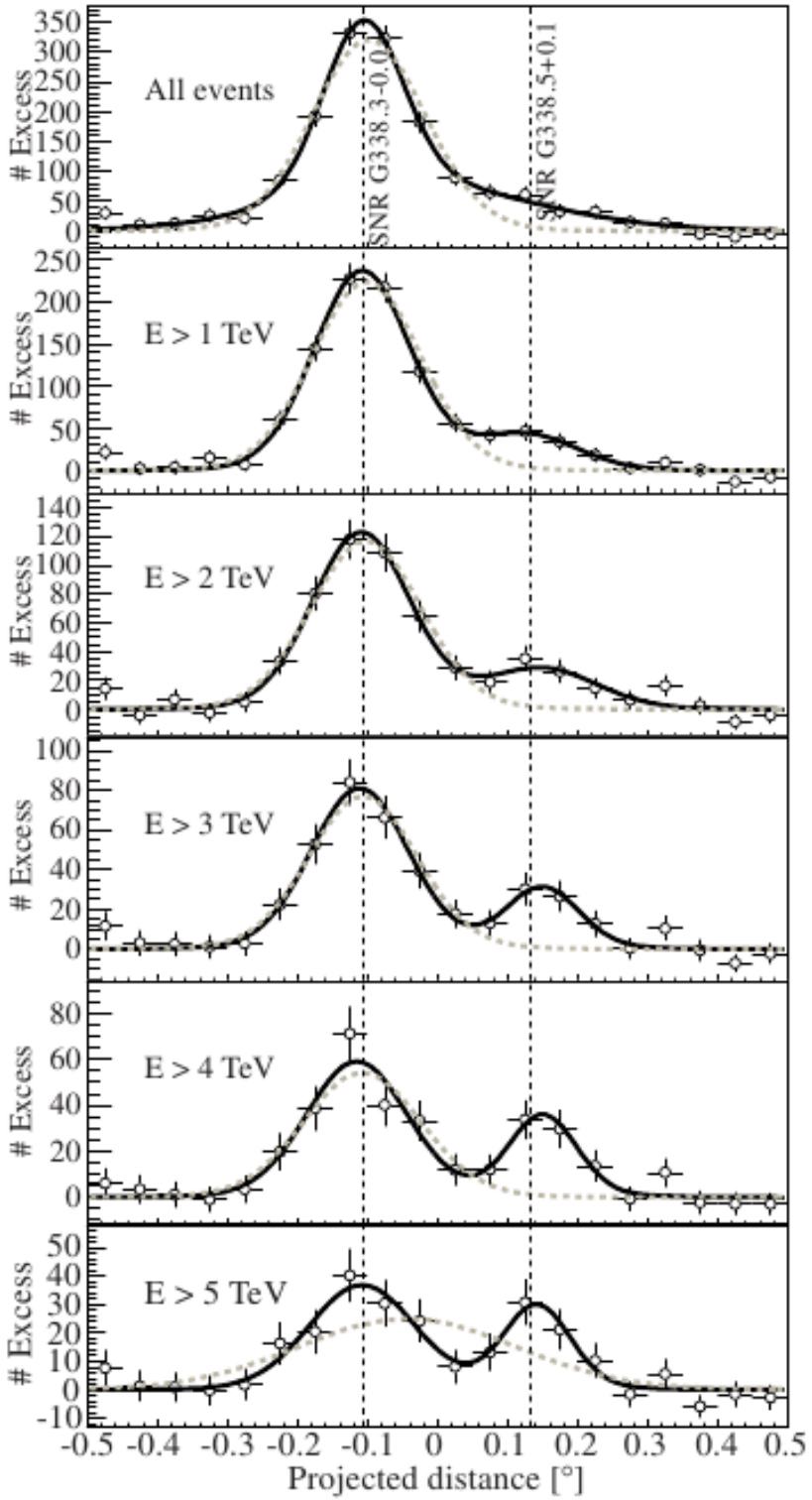
Estimated ~0.04 cm^{-3} (Reynolds+ 08). Constrained by VHE limits to < 1 cm^{-3} if θ = 0.1

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

Also moderately distant (8.5 kpc) & likely Type Ia SN.

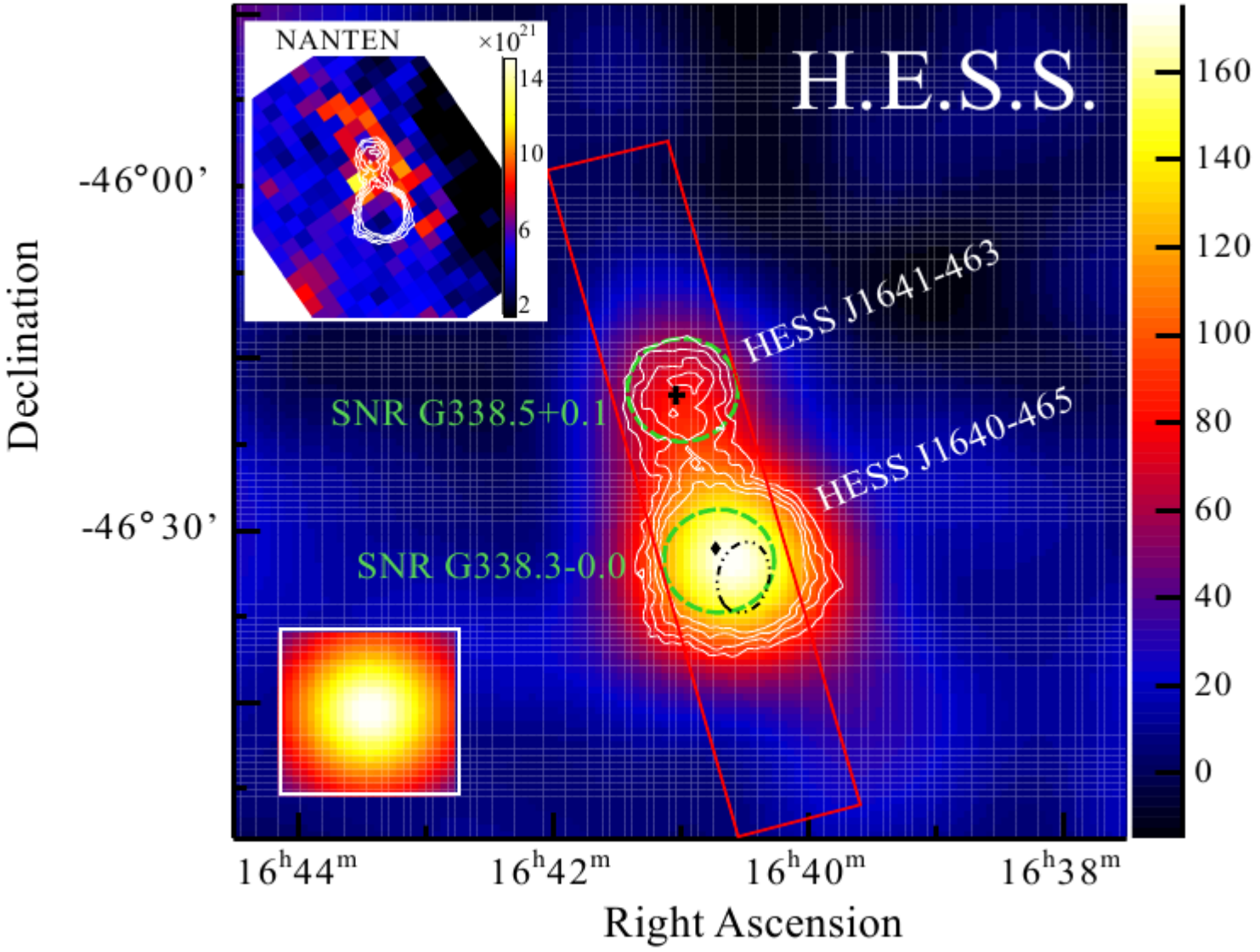
HESS J1641-463:
Brand-new,
serendipitous discovery…





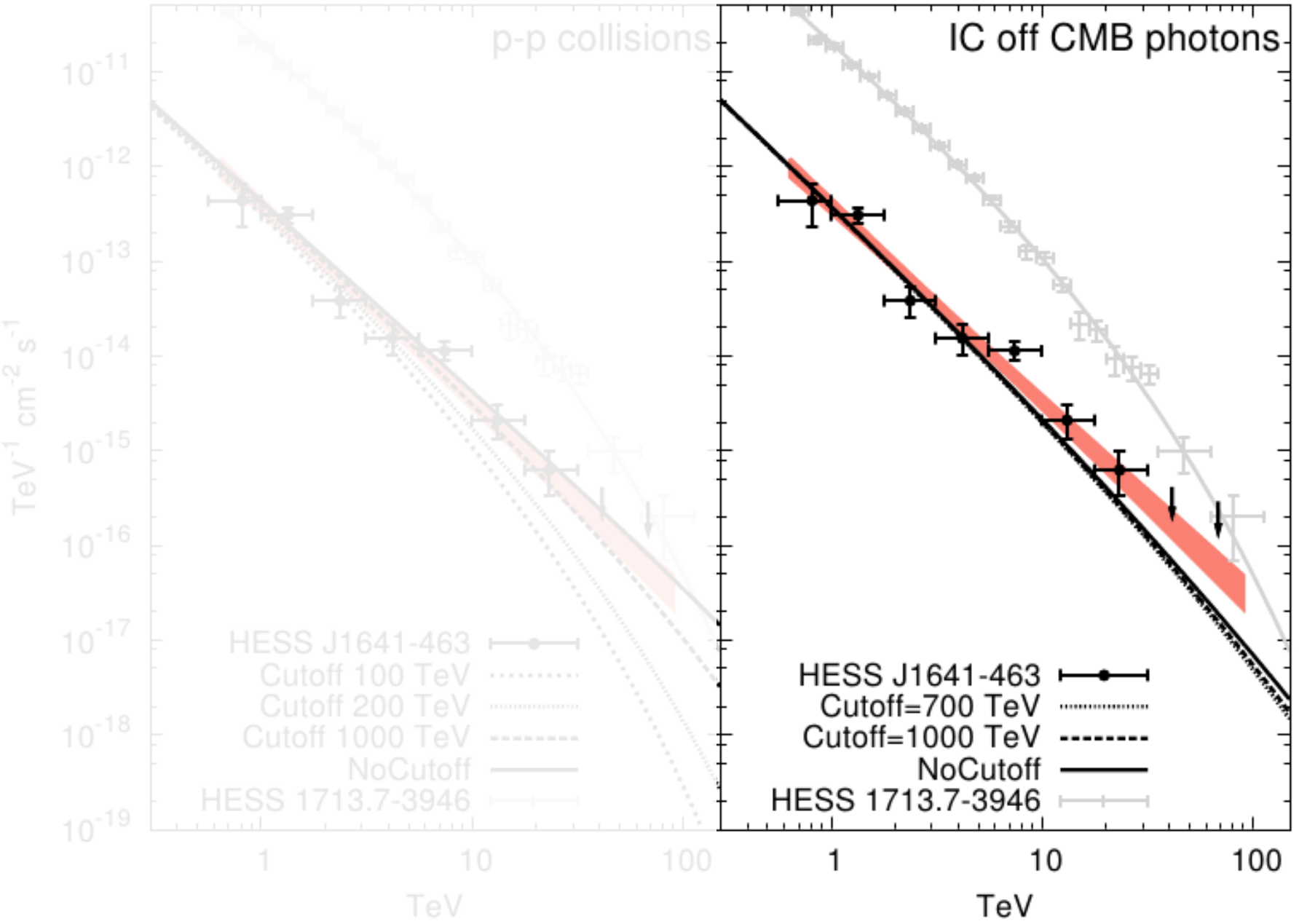
HESS J1641-463:

Hard Γ = 2.07 photon spectrum from little-known SNR



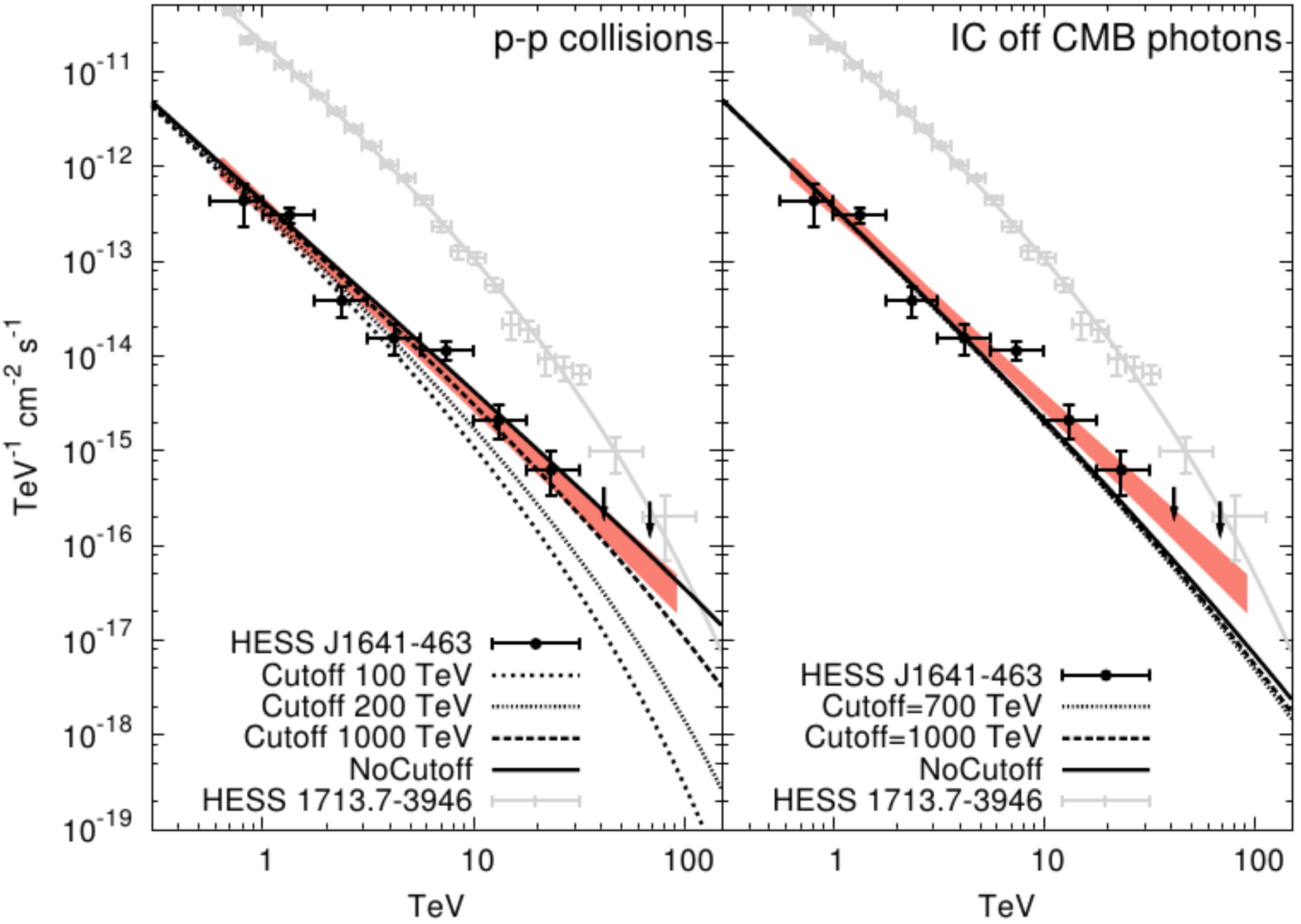
HESS J1641-463:

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

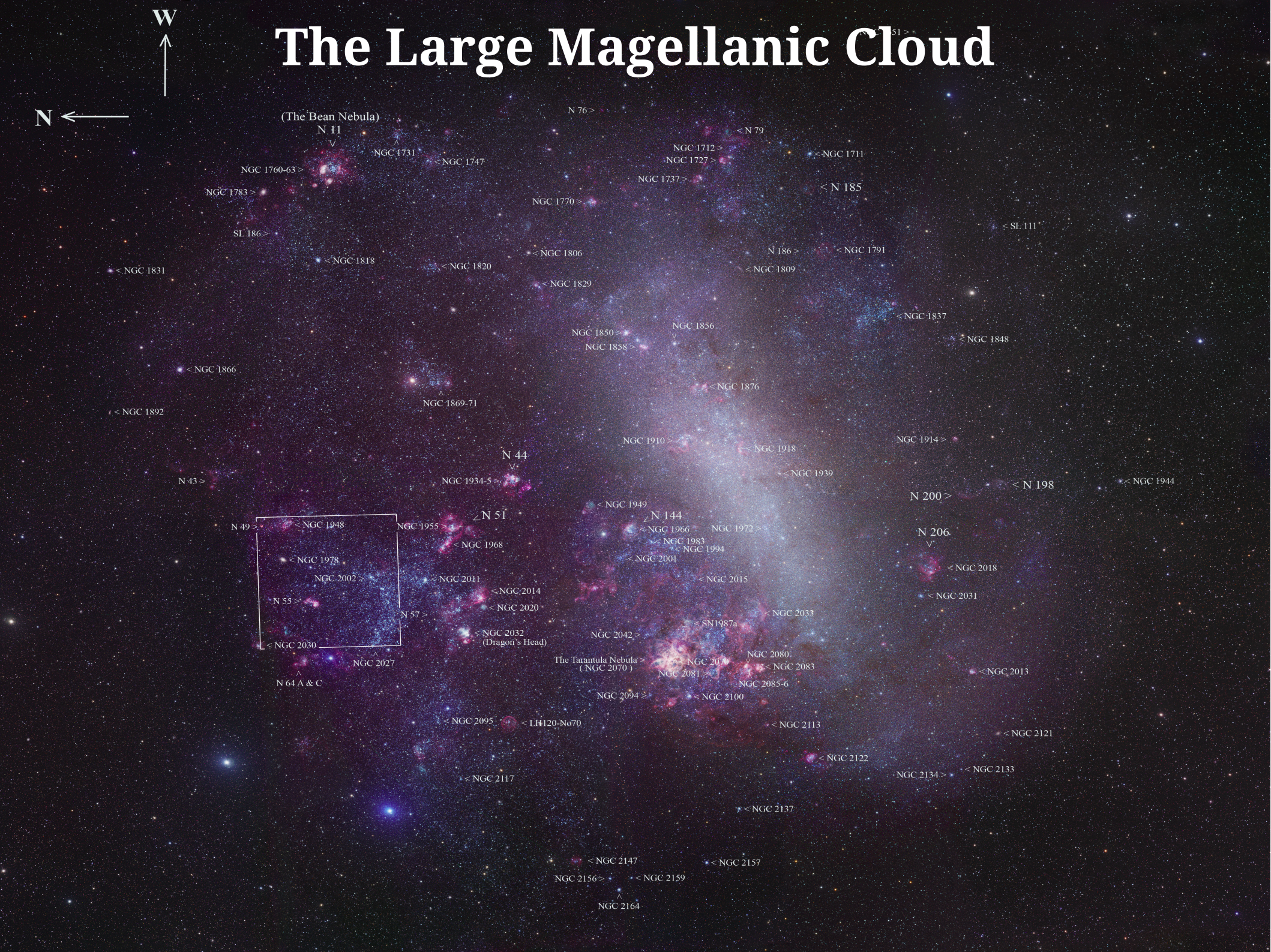


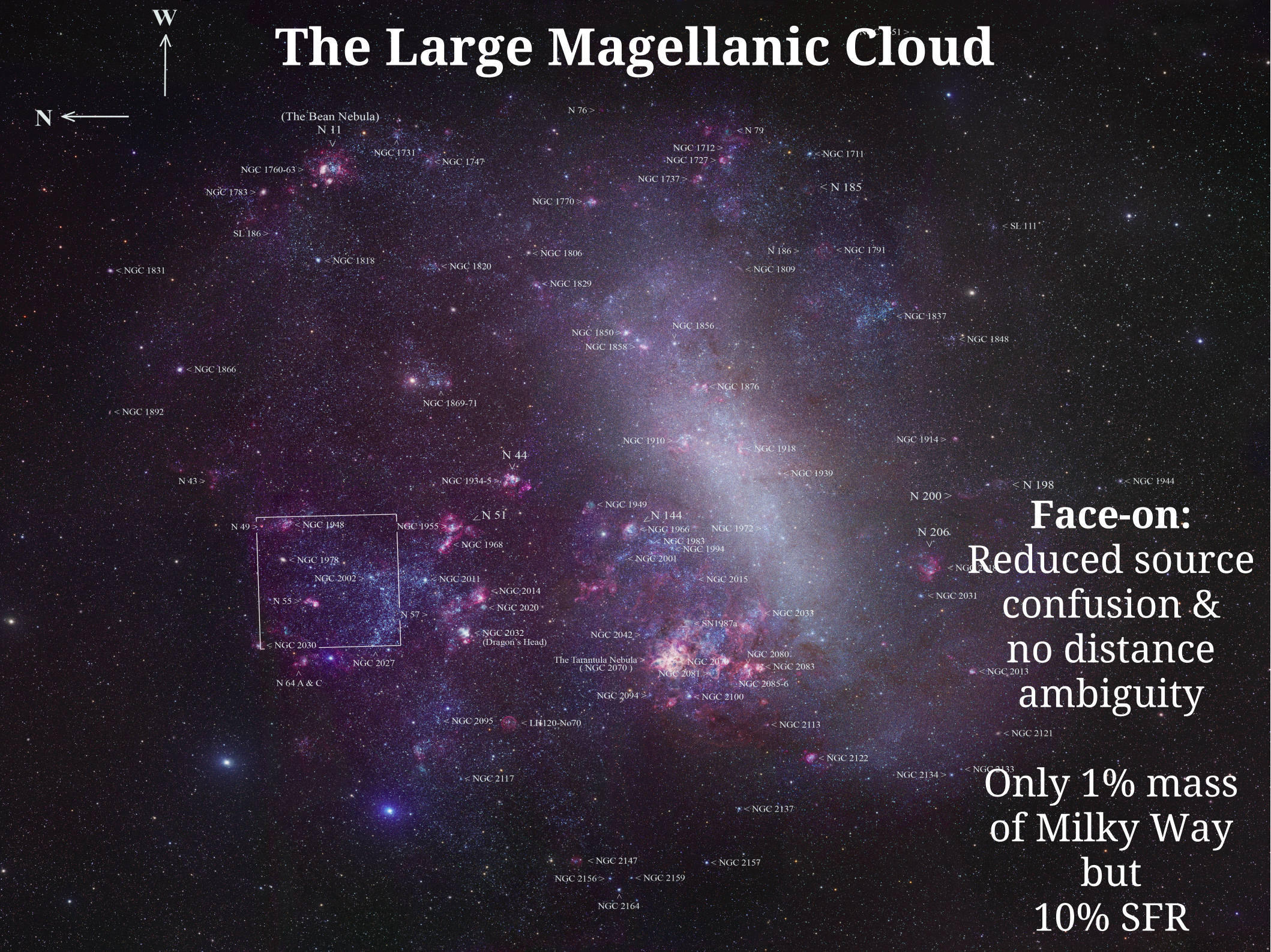
HESS J1641-463:

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



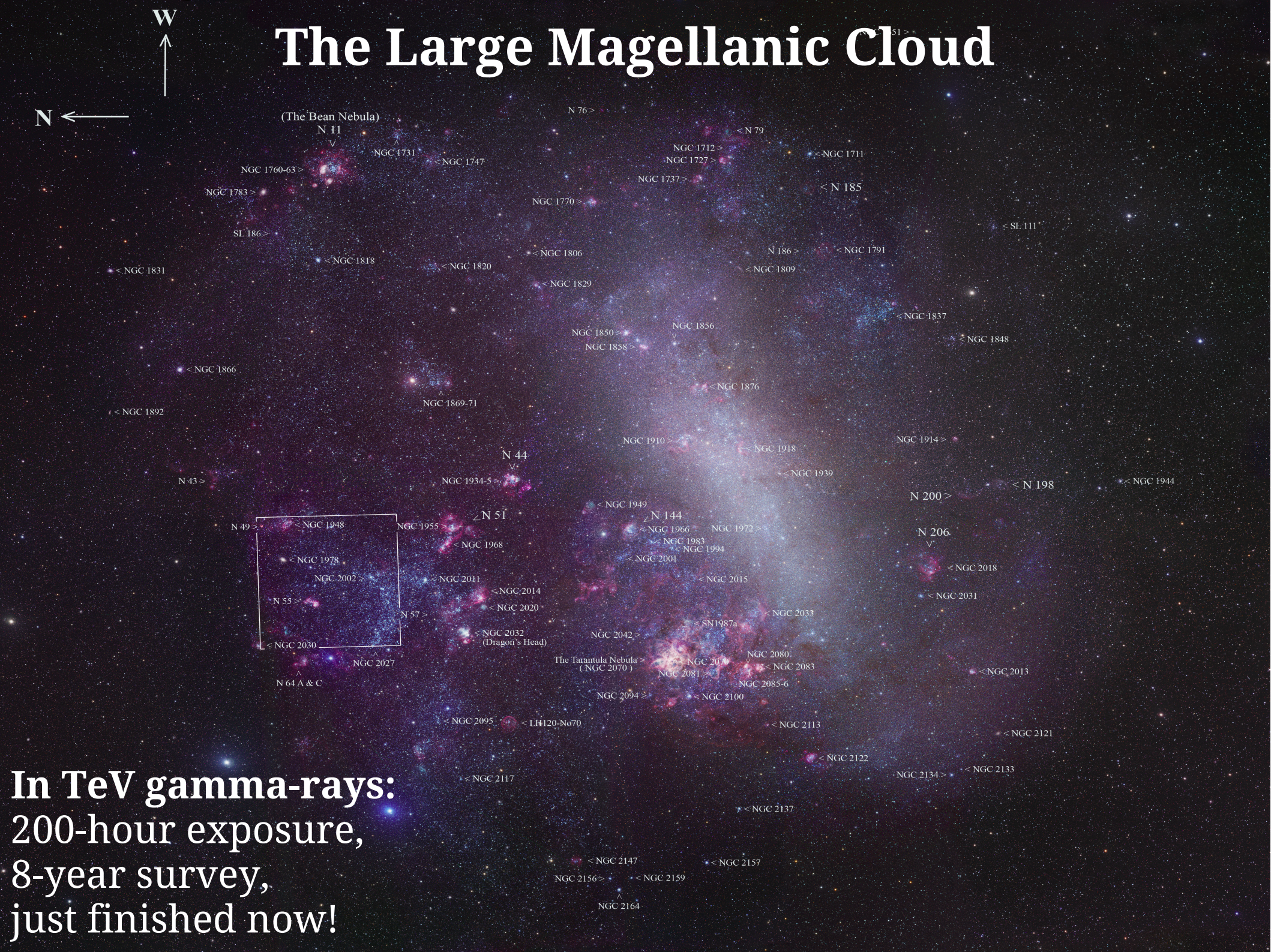
The other big H.E.S.S. survey
you probably haven't heard about (yet)


W
N
The Large Magellanic Cloud
(The Bean Nebula)
N 11
N 76 >
N 79
N 51 >
NGC 1731
NGC 1712 >
NGC 1727 >
NGC 1711
NGC 1747
NGC 1760-63 >
NGC 1737 >
NGC 1783 >
N 185
NGC 1770 >
SL 111
SL 186 >
NGC 1806
N 186 >
NGC 1791
NGC 1818
NGC 1820
NGC 1809
NGC 1831
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 2018
NGC 2002 >
NGC 2011
NGC 2015
NGC 2014
N 55 >
NGC 2031
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 2013
NGC 2027
NGC 2081
NGC 2085-6
N 64 A & C
NGC 2094 >
NGC 2100
NGC 2095
LH120-N70
NGC 2113
NGC 2121
NGC 2122
NGC 2133
NGC 2134 >
NGC 2117
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 10% SFR

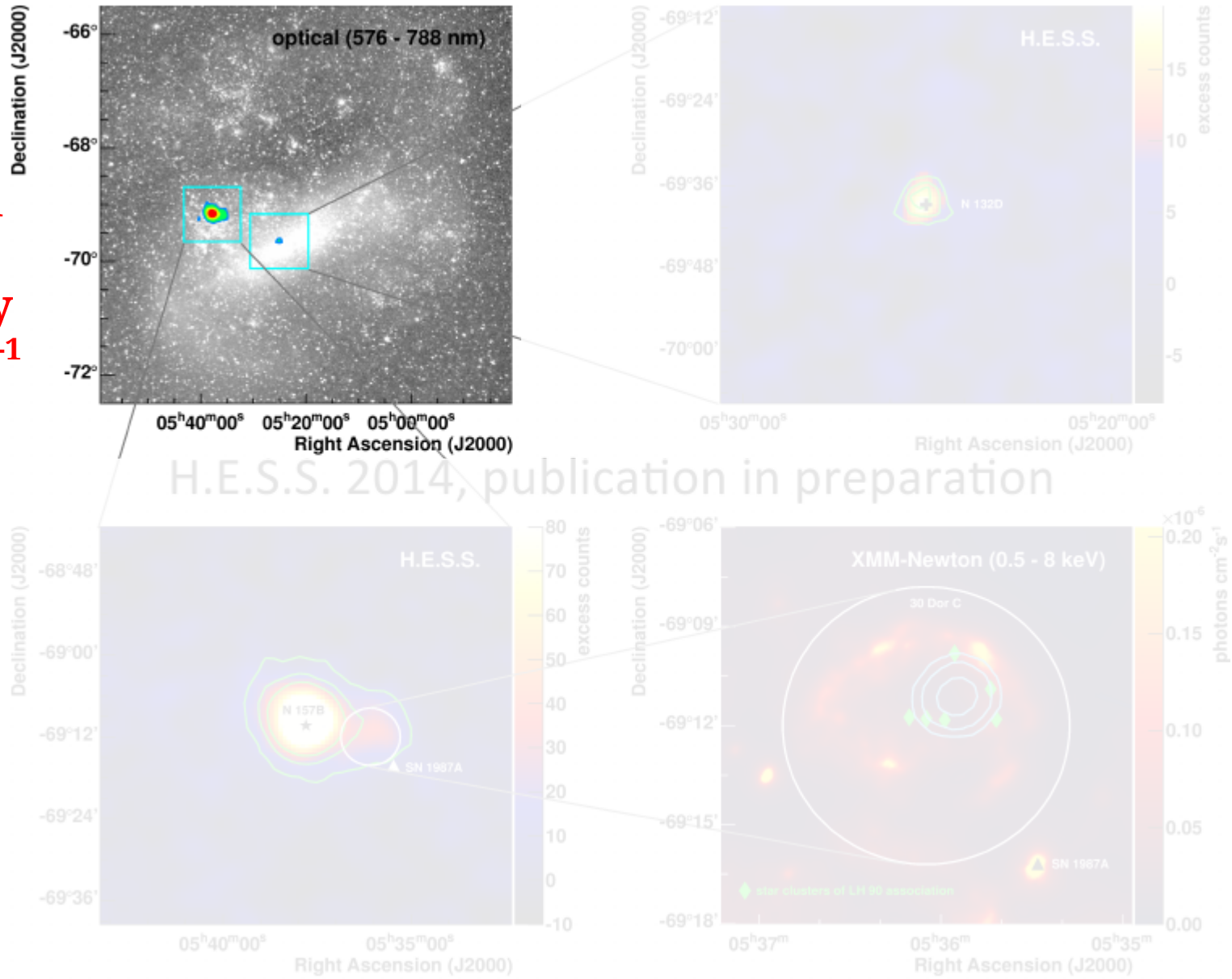


In TeV gamma-rays:
200-hour exposure,
8-year survey,
just finished now!

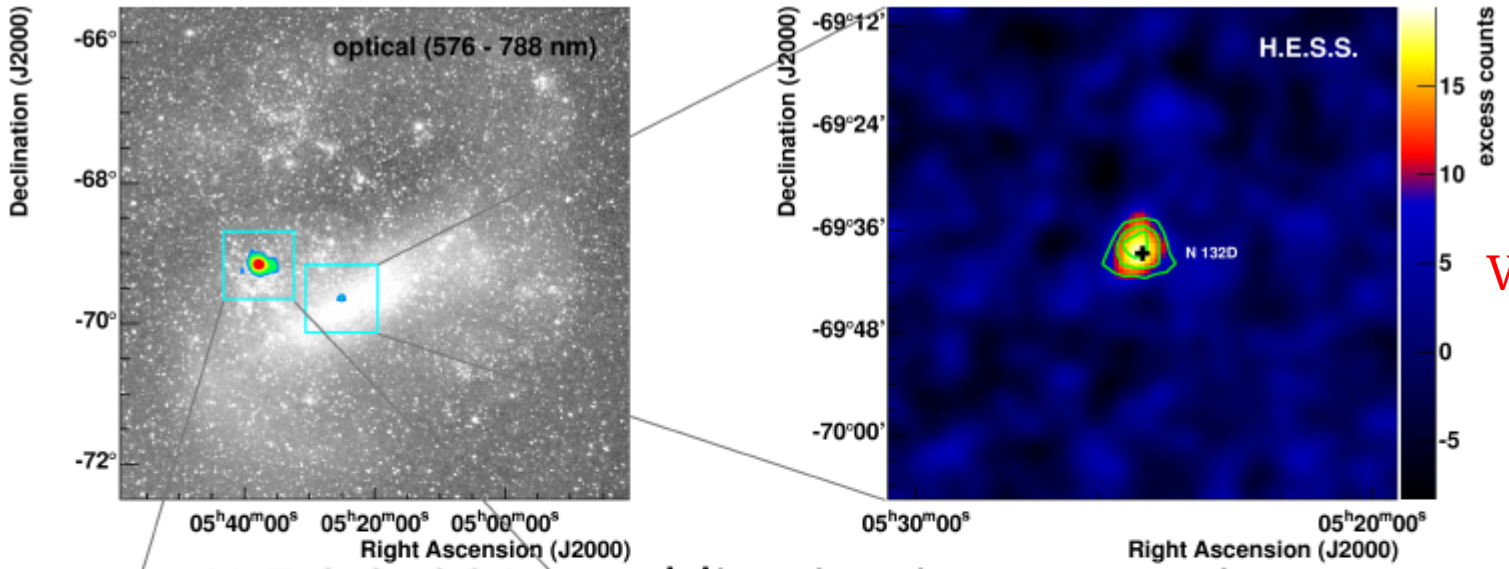
The Large Magellanic Cloud

0.05° ~ 3′ angular resolution

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



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

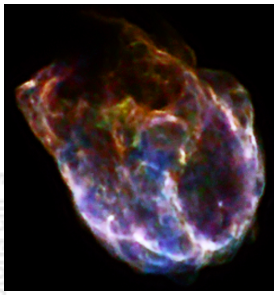


H.E.S.S. 2014, publication in preparation

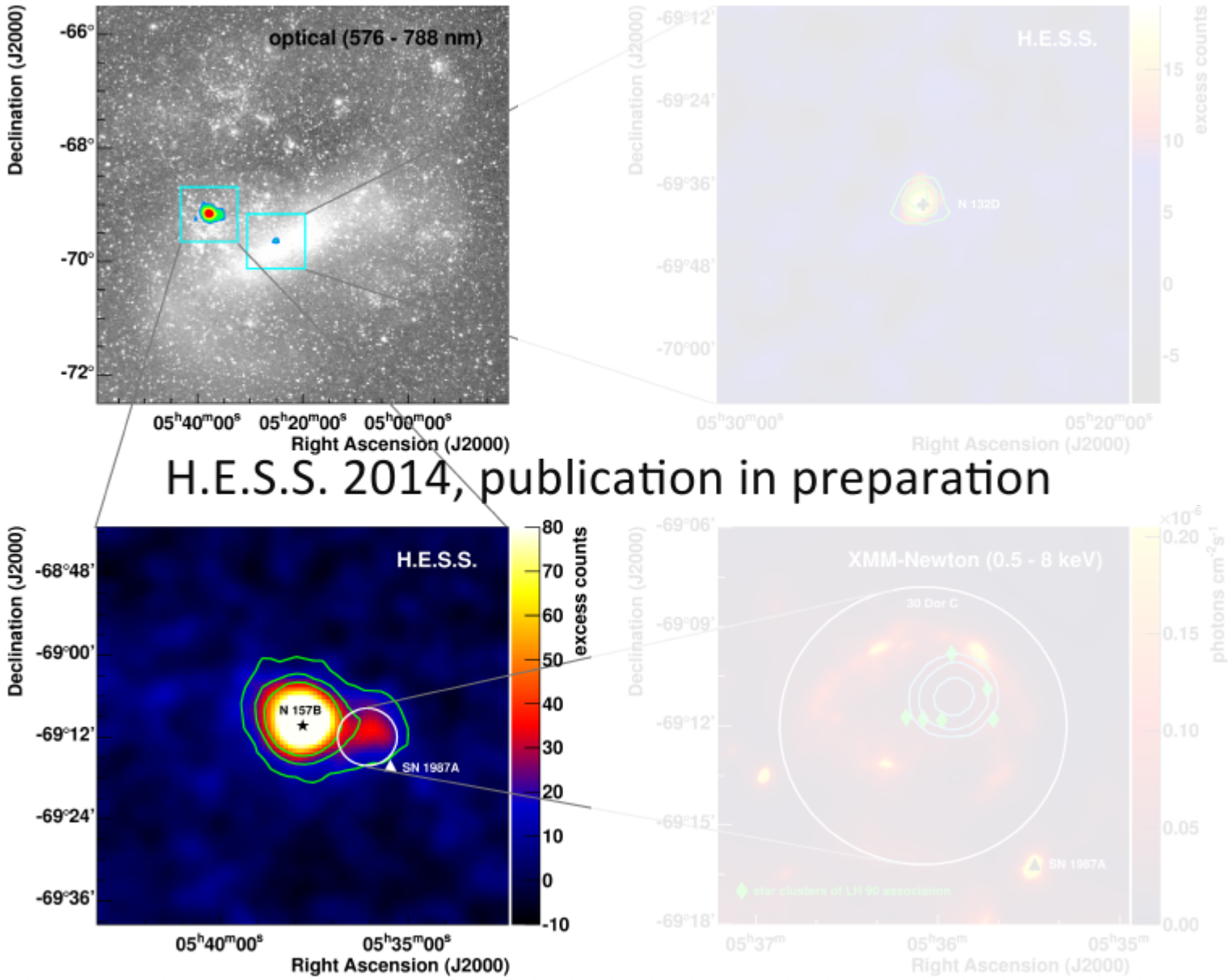
50% L_{radio} of Cas A

Not quite VHE detection ~5 σ

X-rays:



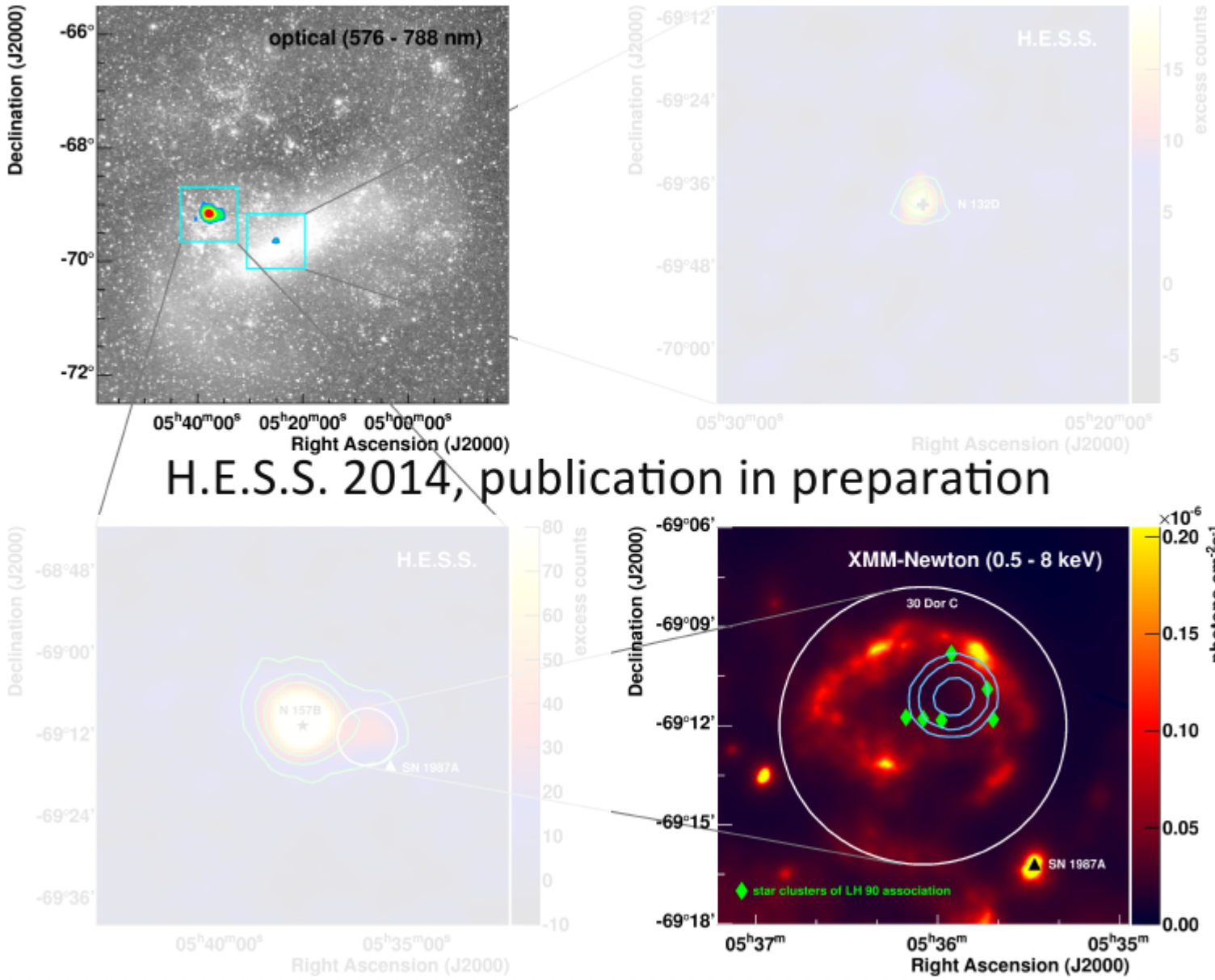
N 157B: The Crab Nebula's twin



Pulsar has **largest known Edot** ~ 4.8×10^{37} erg s^{-1}

Broadband SED model comparison w/ Crab in paper

30 Dor C: A TeV superbubble



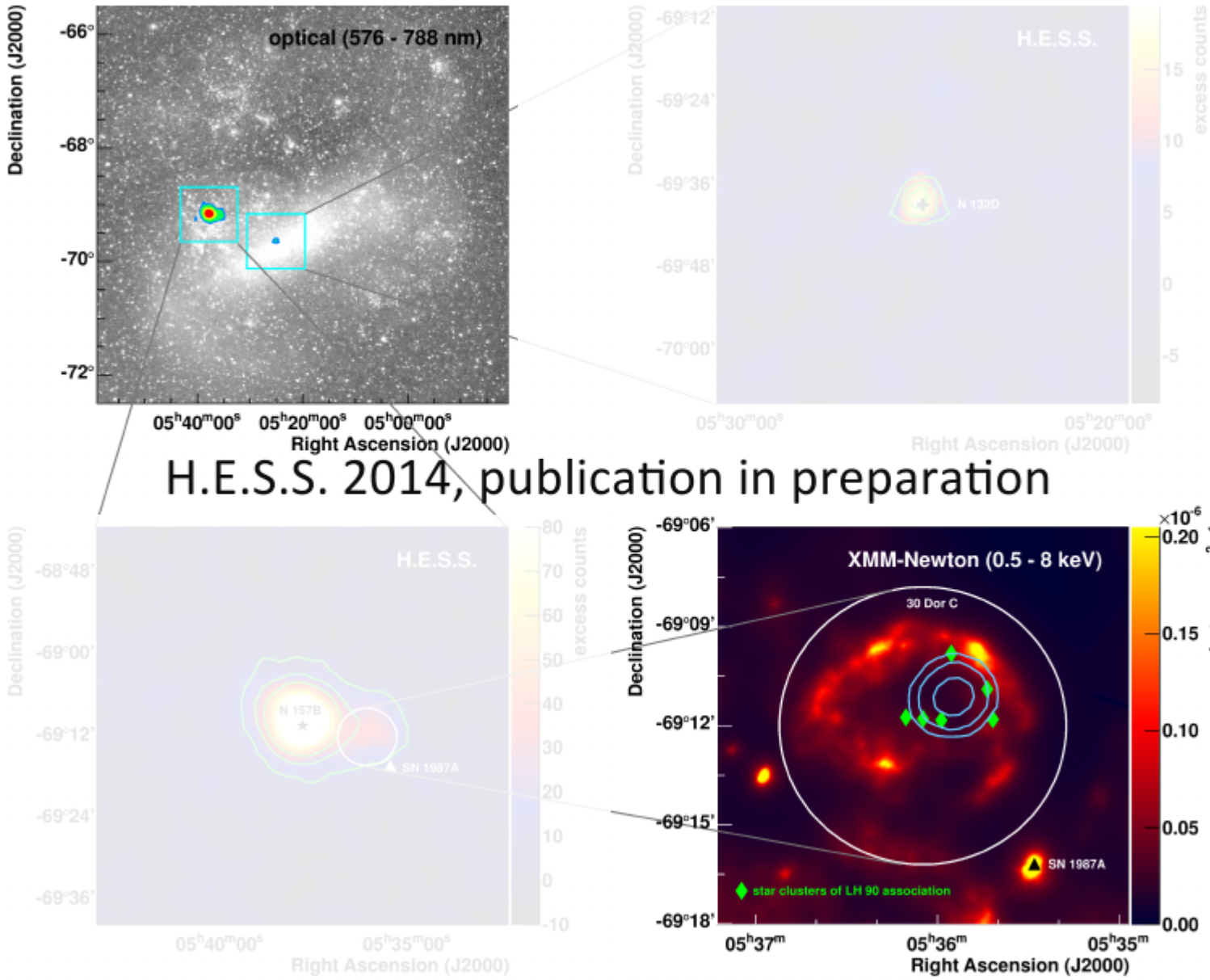
H.E.S.S. 2014, publication in preparation

Largest X-ray synchrotron shell known (47 pc)

10x as bright as SN 1006

Powered by stellar winds & SN explosions of LH 90, OB association

SN 1987A: The youngest SNR



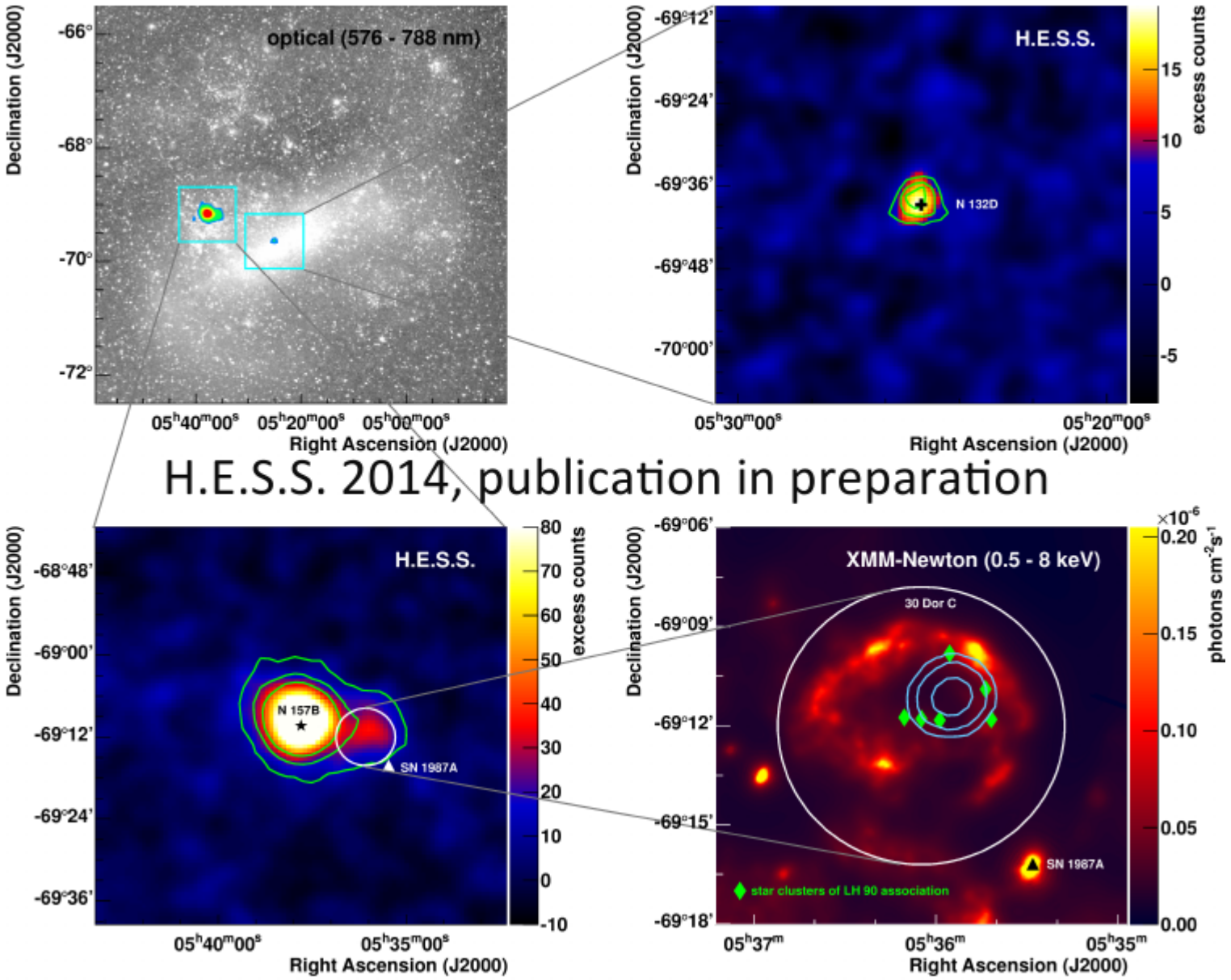
H.E.S.S. 2014, publication in preparation

High shock speed
High ambient density
Hadronic?

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

Already can constrain
CR efficiency < 1%

The LMC in VHE γ-rays



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

Paper accepted, in press at Science (under embargo)

Conclusions

H.E.S.S.-I Galactic Plane Survey & **LMC Survey completed in 2013**

Rich dataset continues to deliver new science
Most recently:

- **Investigating PeVatron candidates:**
  - young SNRs, but not only: multi-TeV data-driven approach
- **powerful Galactic-like sources in an external galaxy**

Coming out of H.E.S.S.-II commissioning phase
Closed the HE-VHE gap with *Fermi*/LAT
Detection of Vela pulsar

Since 2010, the H.E.S.S. array has undergone various major upgrades, to be completed in 2015.
Ready to hold the VHE torch until CTA in 2020.

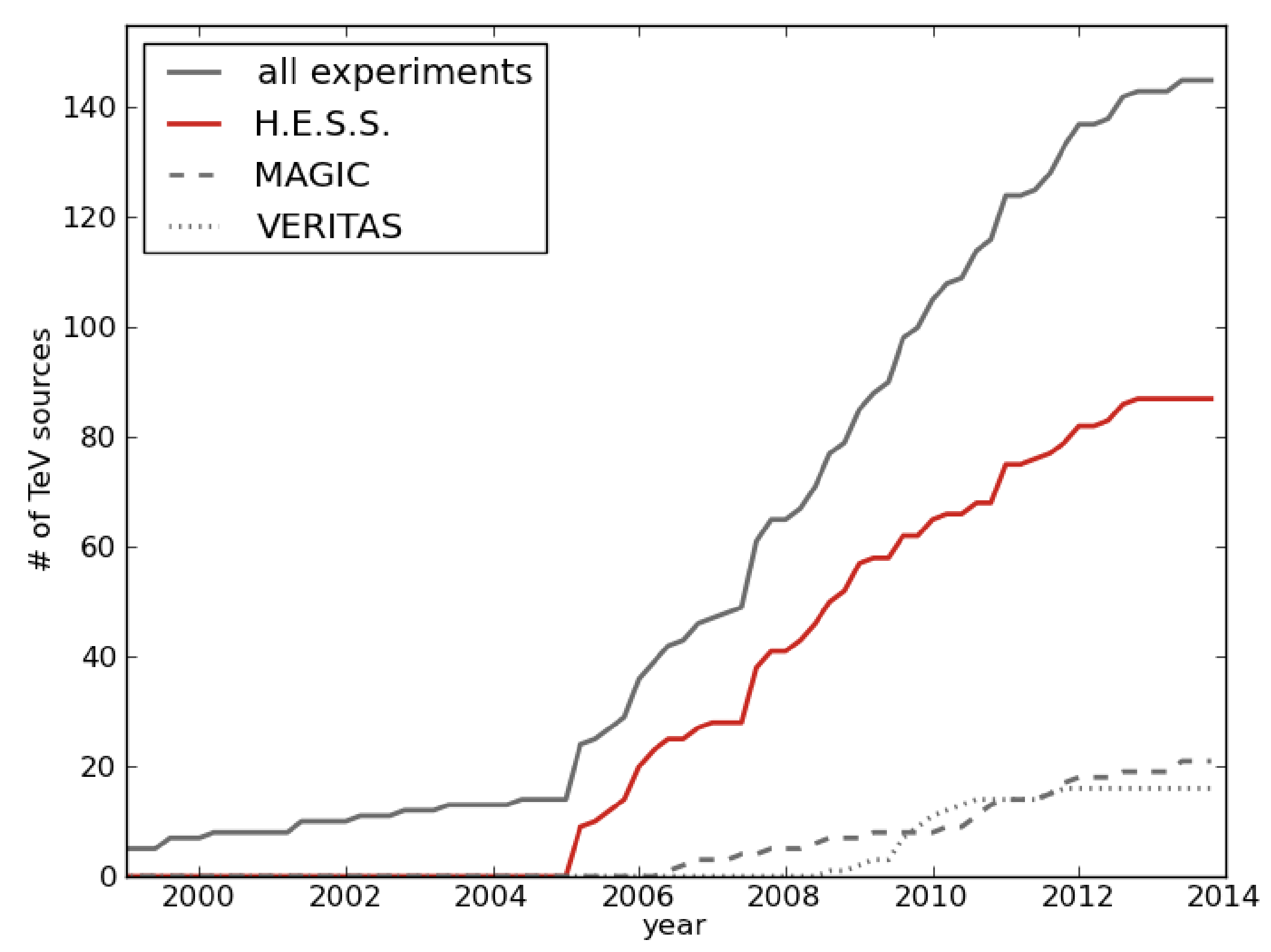
Backup slides

H.E.S.S. is now a 5-tel *hybrid* array

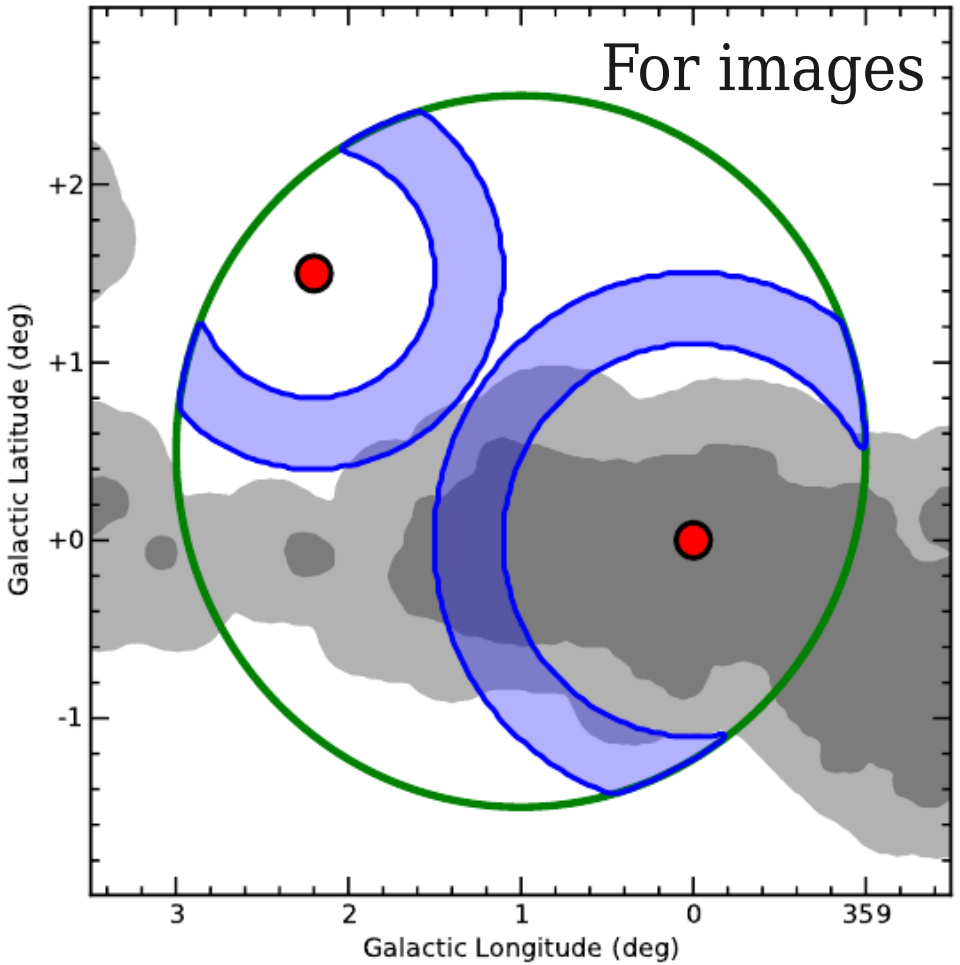
4 12-m IACTs w/ recoated mirrors + **1 28-m IACT**

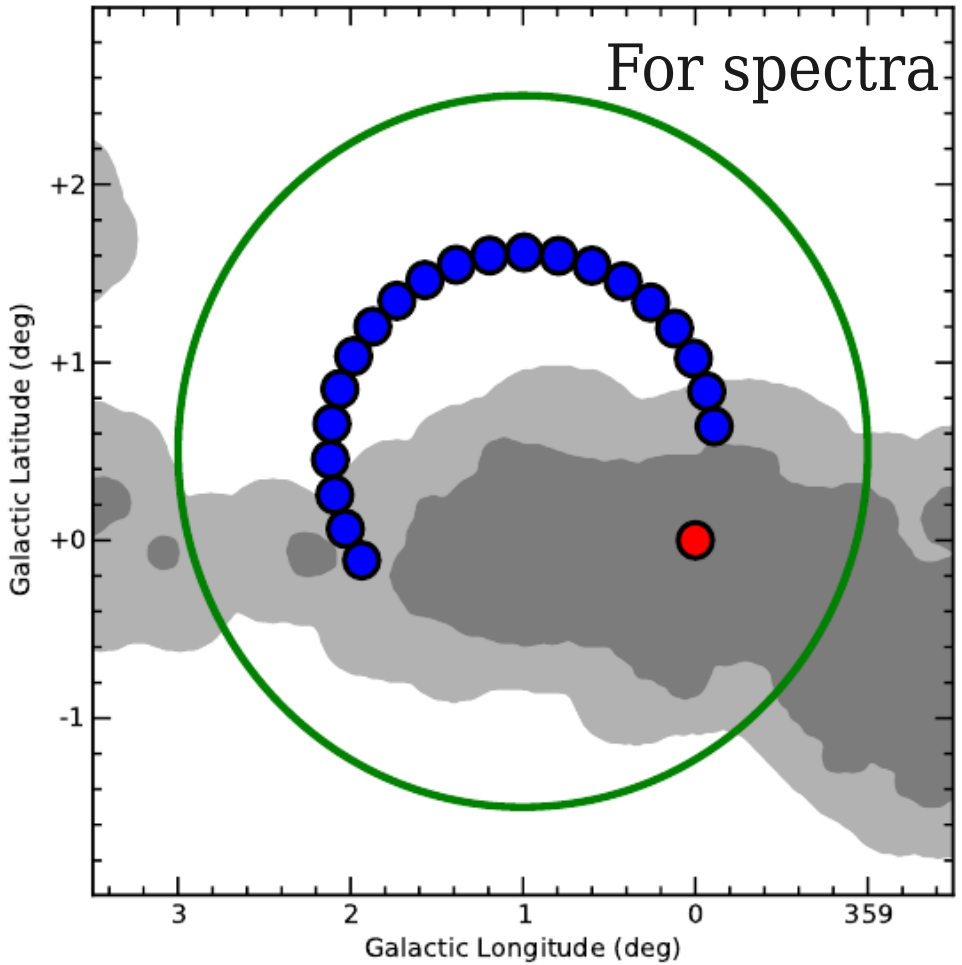
Multiple triggering & targeting schemes available

CT5: 2048 PMTs 614 m² 3.2° FoV E_{min} ~ 30 GeV f = 38 m

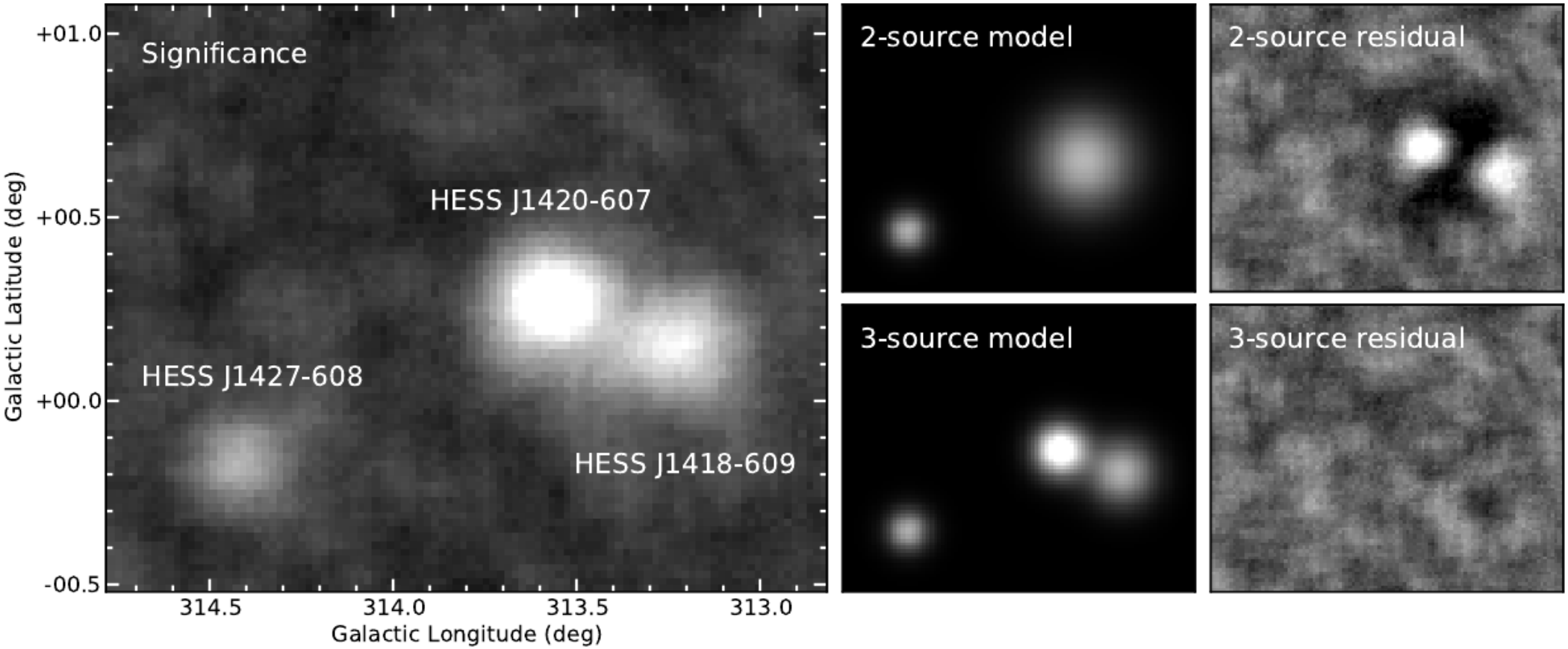

all experiments
H.E.S.S.
MAGIC
VERITAS
# of TeV sources
year
0
20
40
60
80
100
120
140
2000
2002
2004
2006
2008
2010
2012
2014

Challenges & solutions for analyzing complex source regions



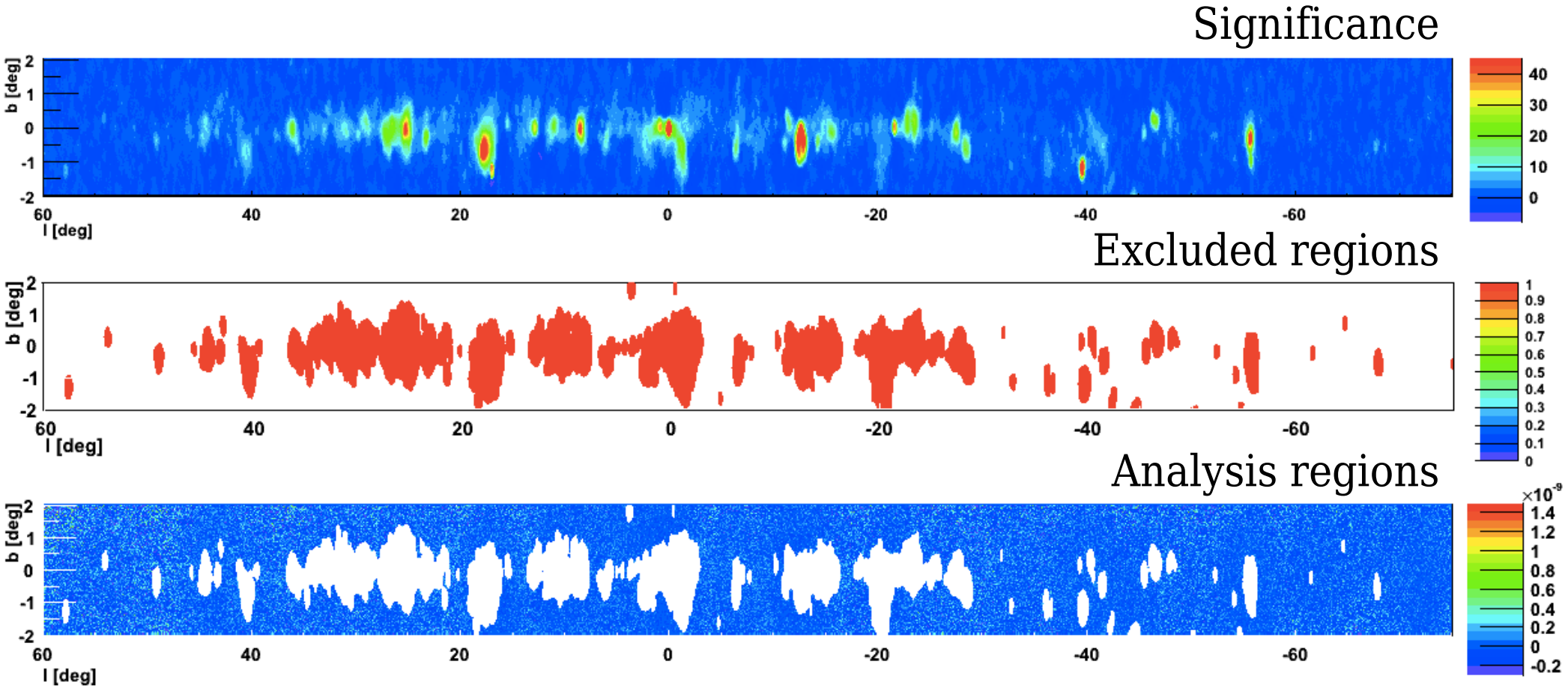


Background estimation with adaptive regions



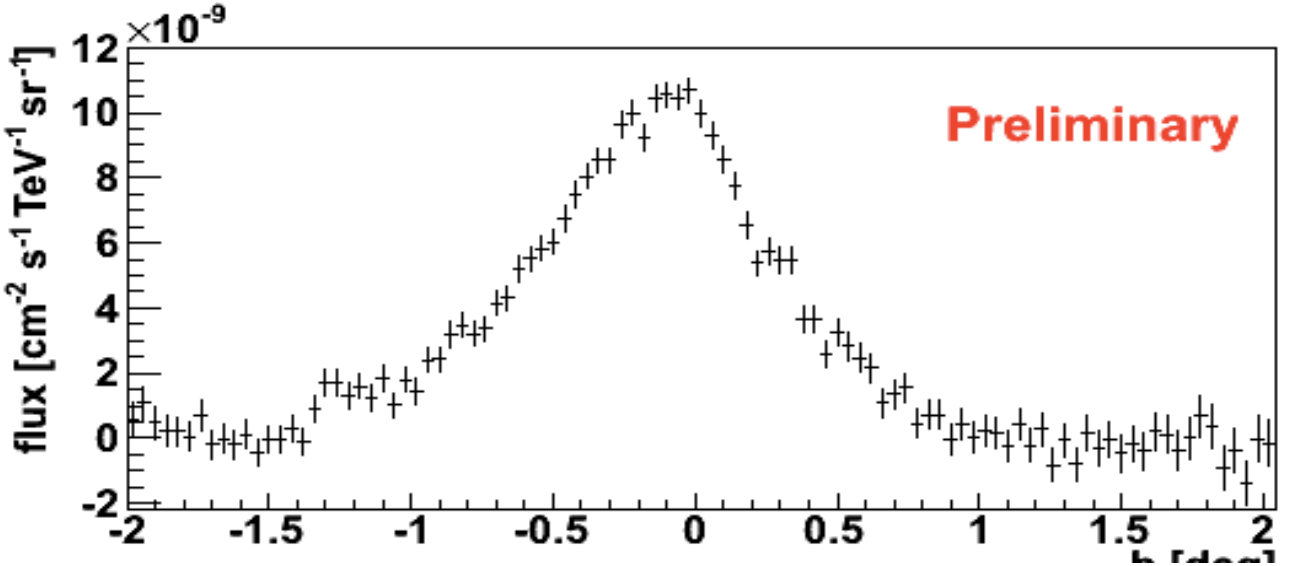
Automated source extraction with maximum likelihood techniques

Extracting a clean signal to search for diffuse TeV emission

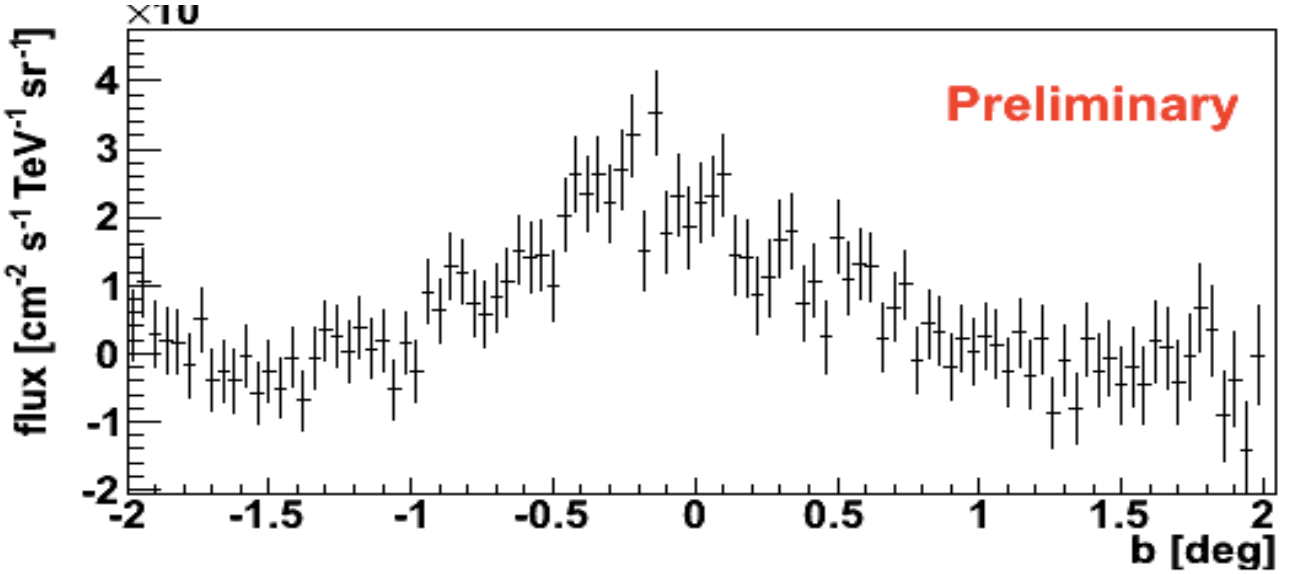


Extracting a clean signal to search for diffuse TeV emission

Total flux



Diffuse flux



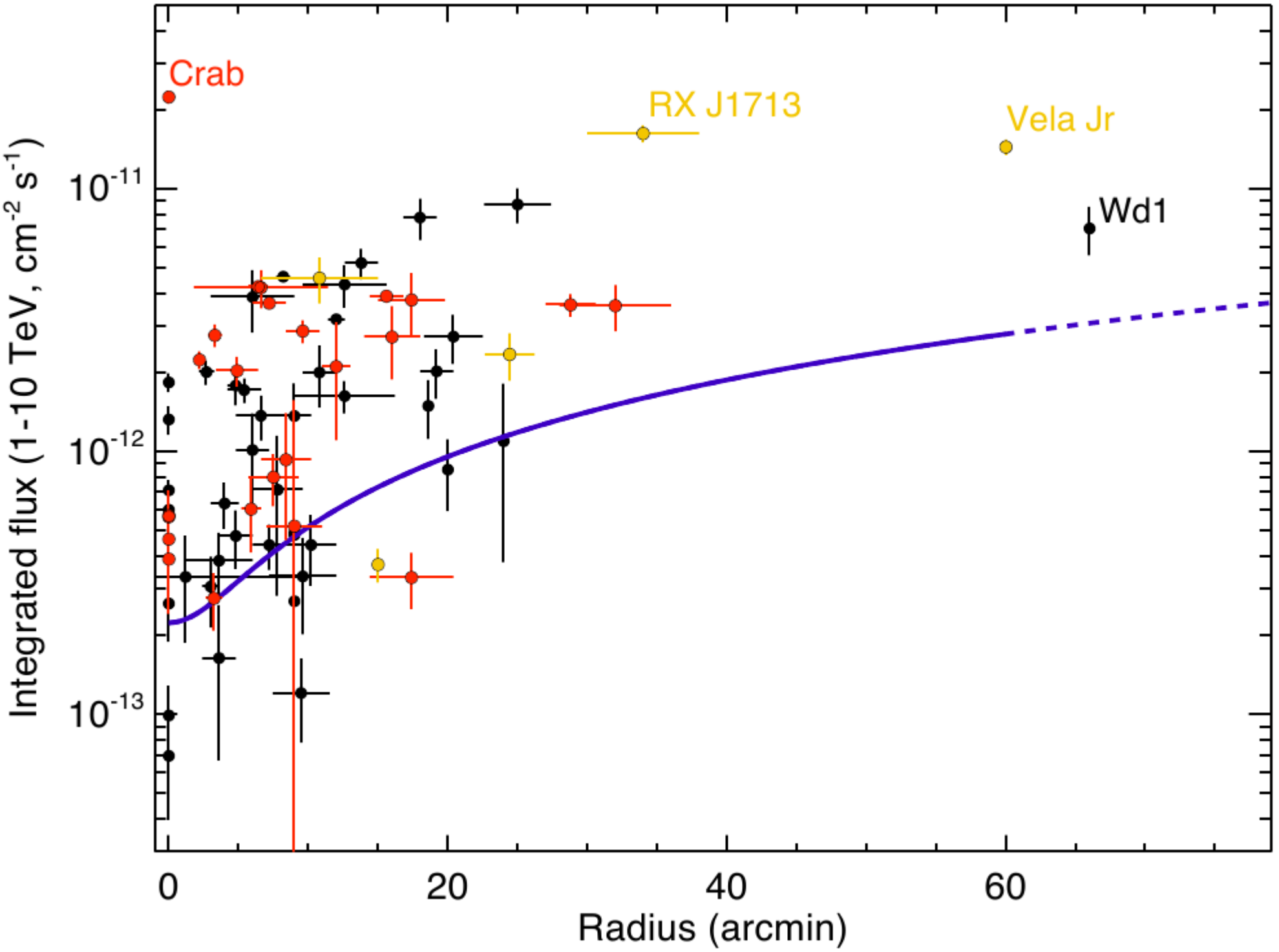
HESS J1640-465

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)

GRBs at VHE

Typical re-pointing time < 1 min

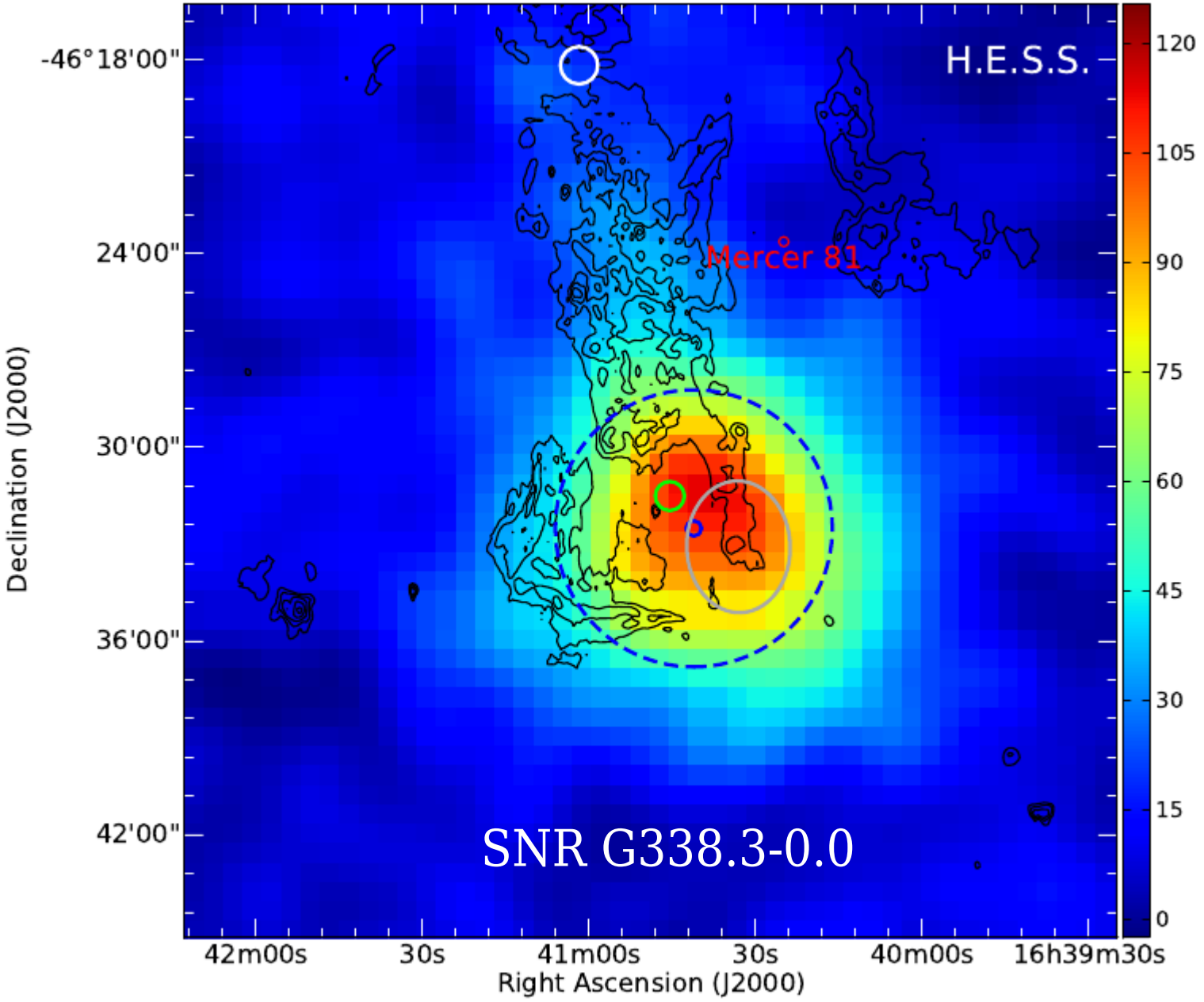
Fully automated GCN triggering & observations; highest priority

Currently observing ~5 GRBs/yr

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

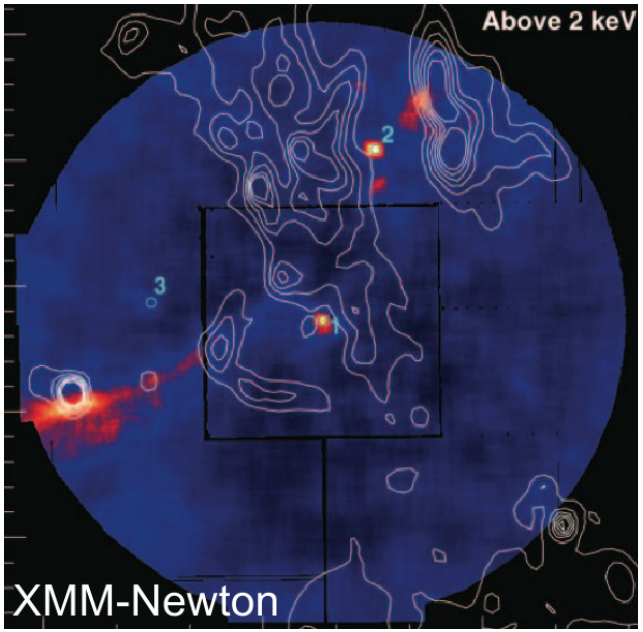
Abramowski et al. (H.E.S.S.) 2014 – MNRAS

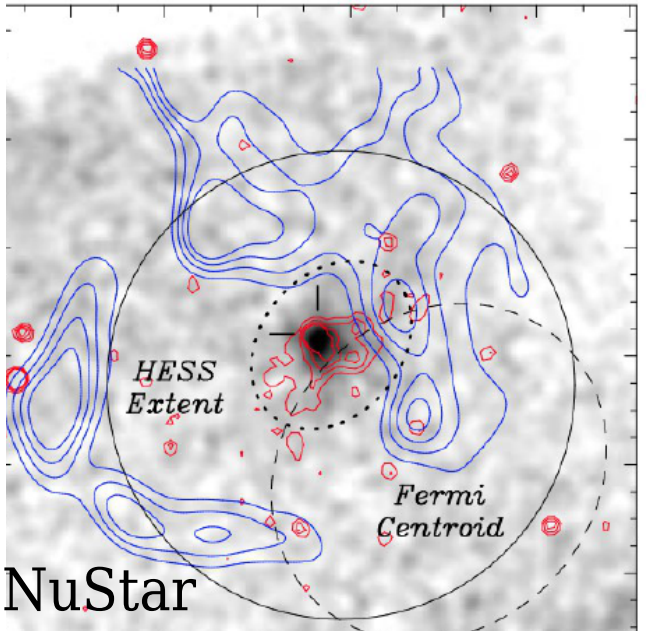
An exceptionally luminous TeV source & proton-accelerating SNR (which you probably haven't heard of yet)

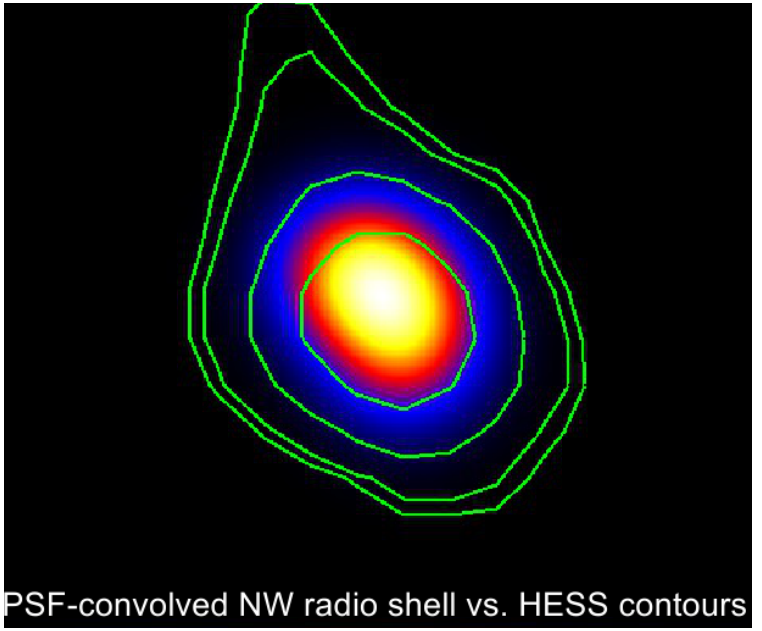


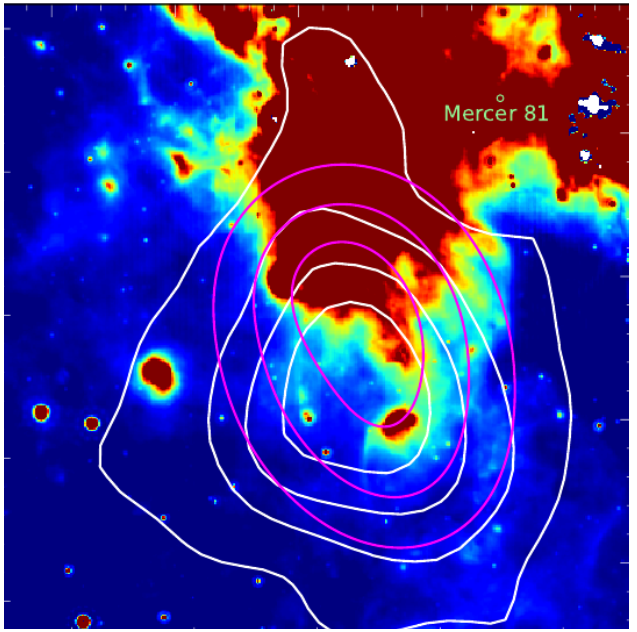
Abramowski et al. (H.E.S.S.) 2014 – MNRAS

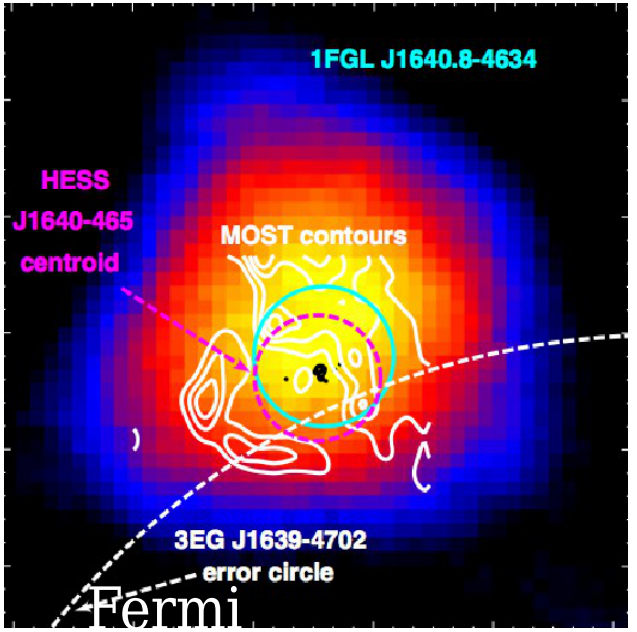
Synergies with other wavelengths: radio, IR, X-rays







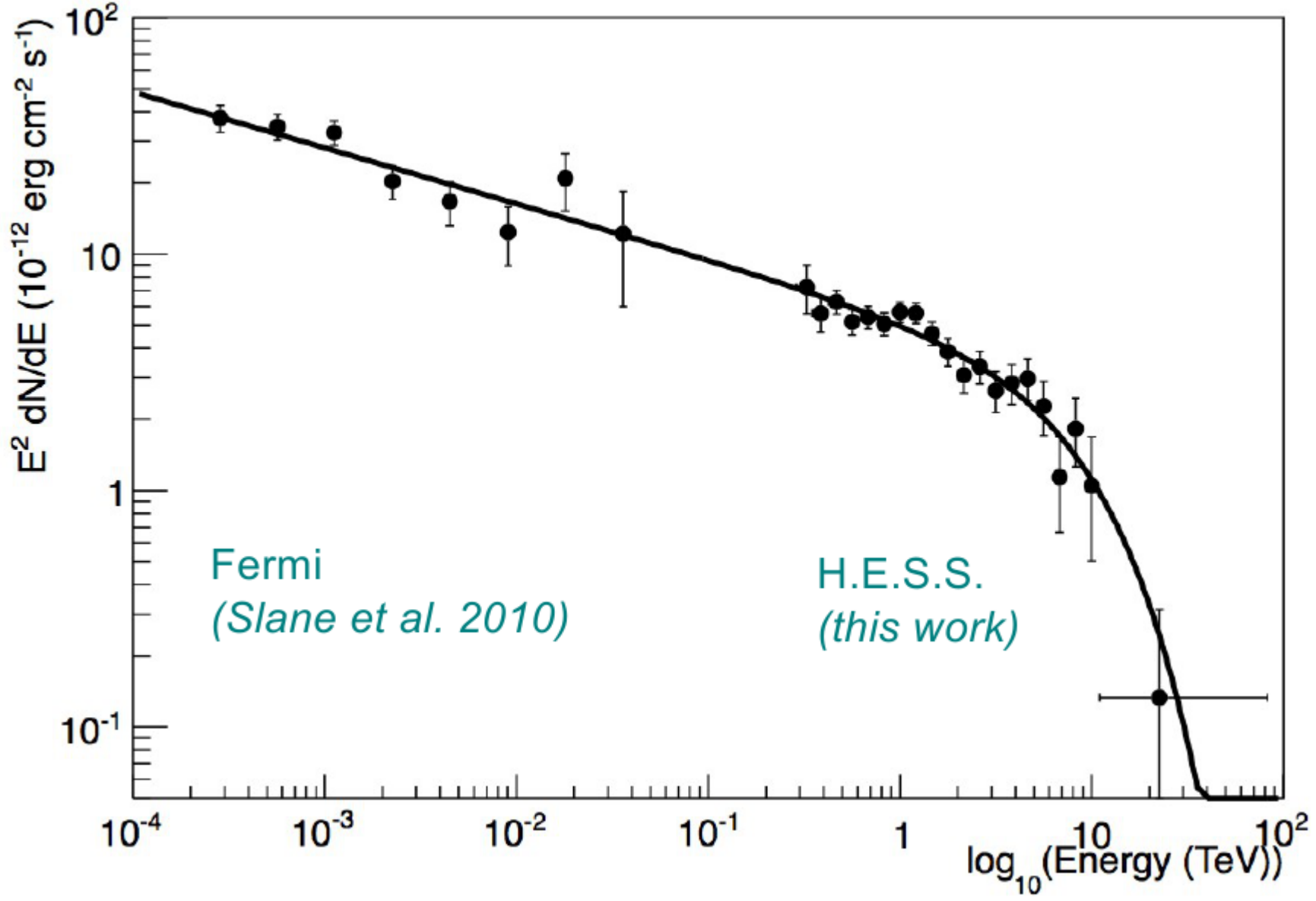




Abramowski et al. (H.E.S.S.) 2014
Adapted from Eger et al. (H.E.S.S.) 2014

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

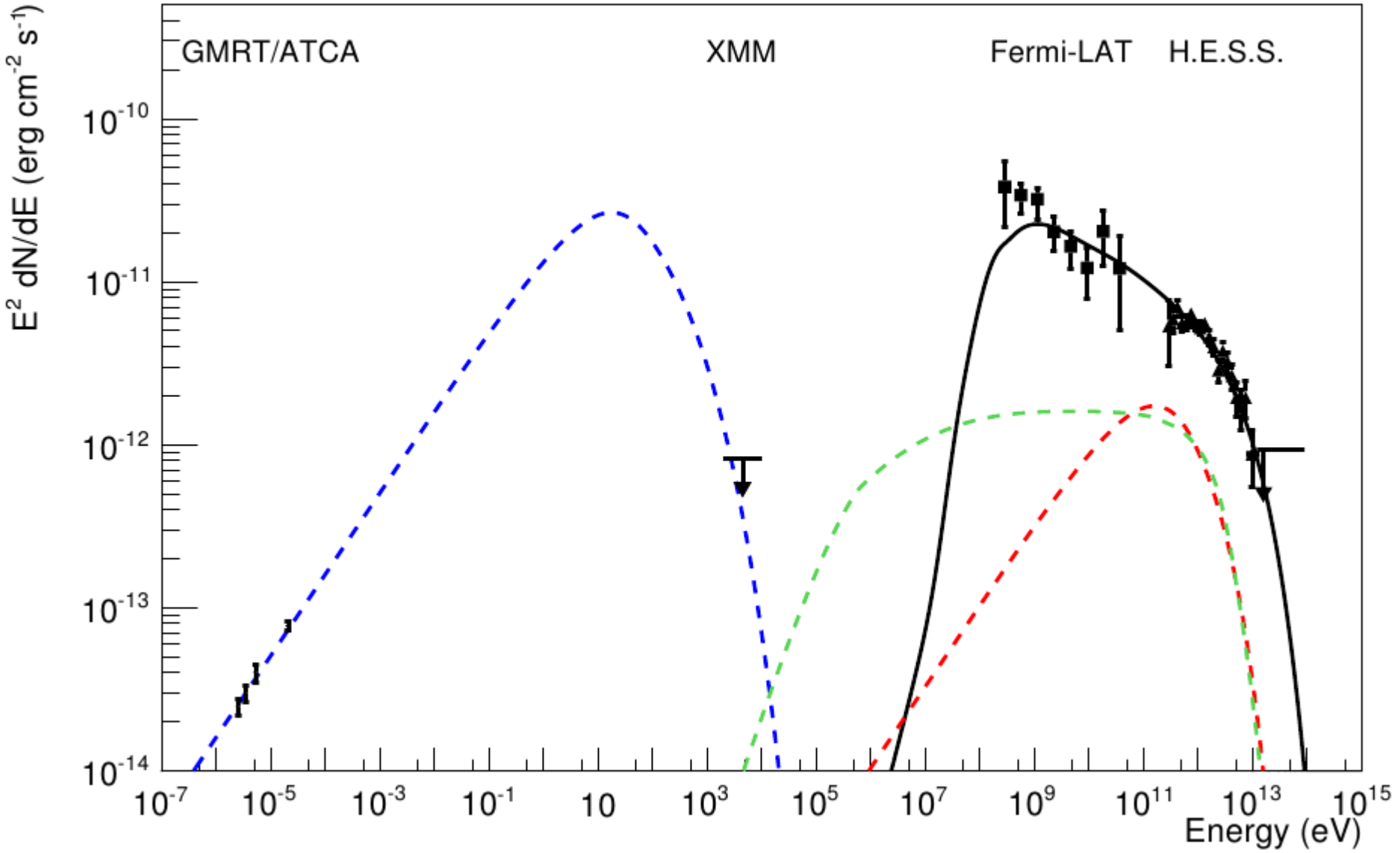
Challenging the previous PWN interpretation



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
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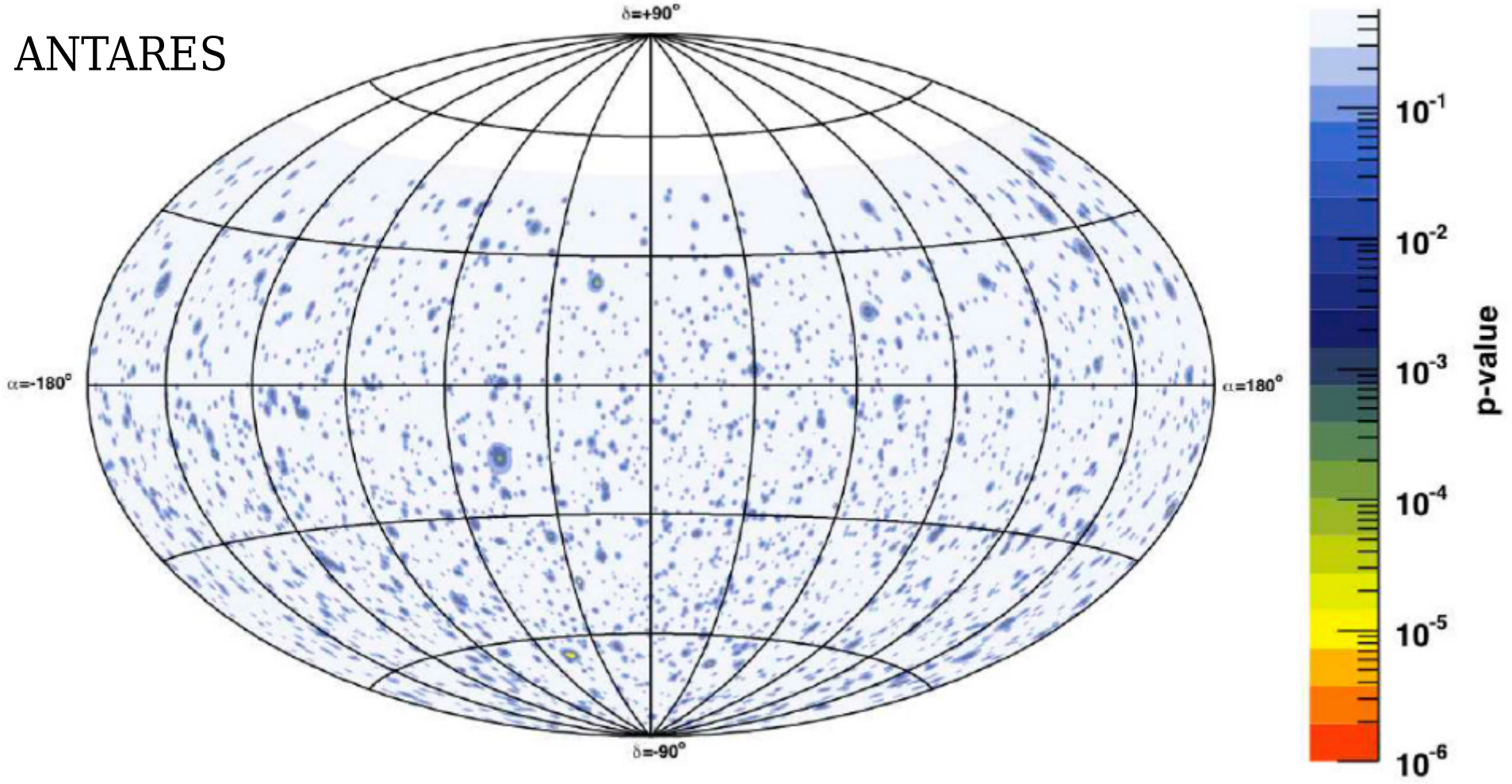
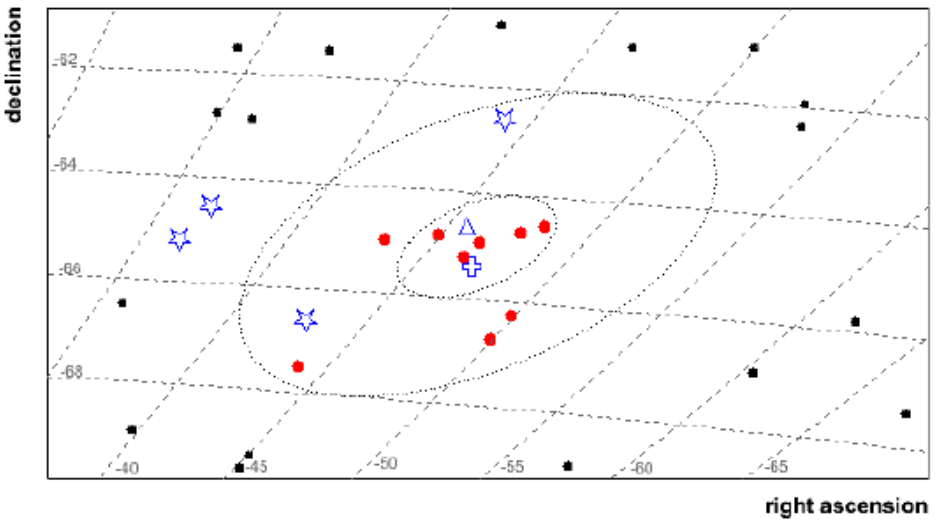
Synergies with different *messengers*: **neutrinos**

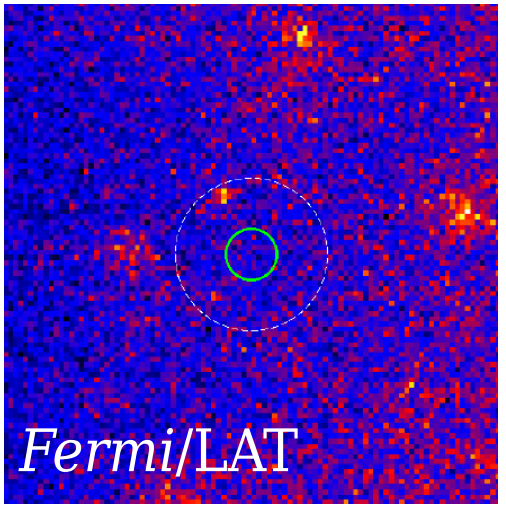
Synergies with different *messengers*: **neutrinos**

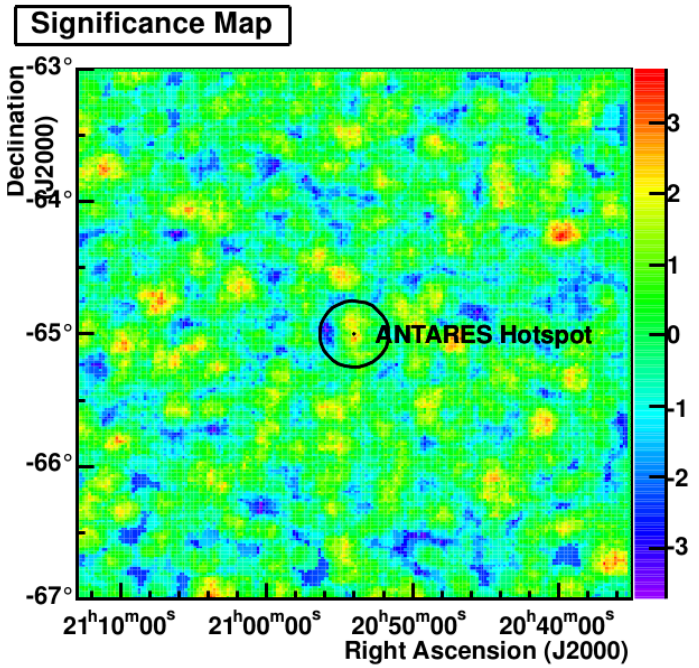
ANTARES

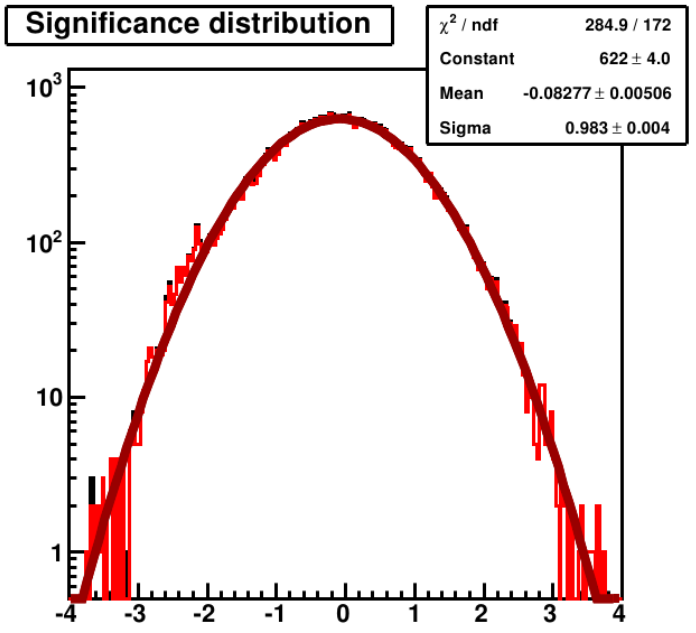


Synergies with different messengers: **neutrinos**



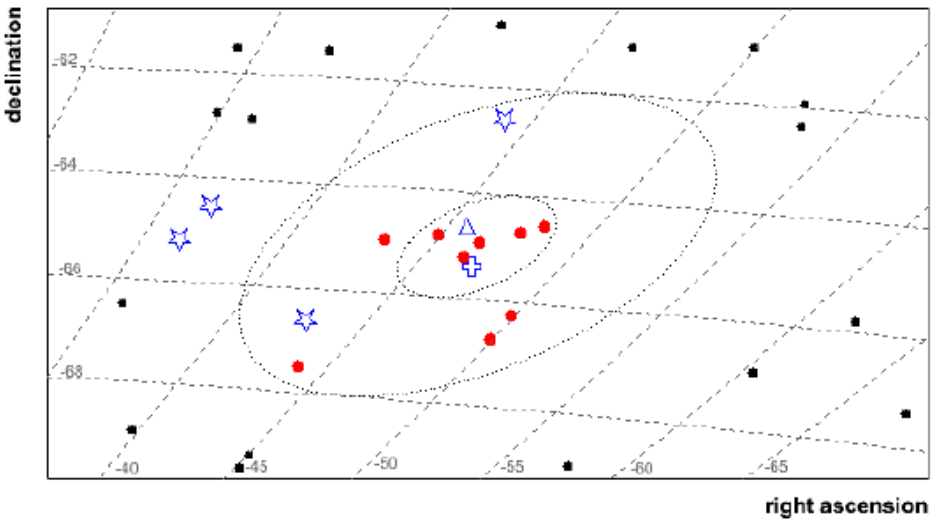


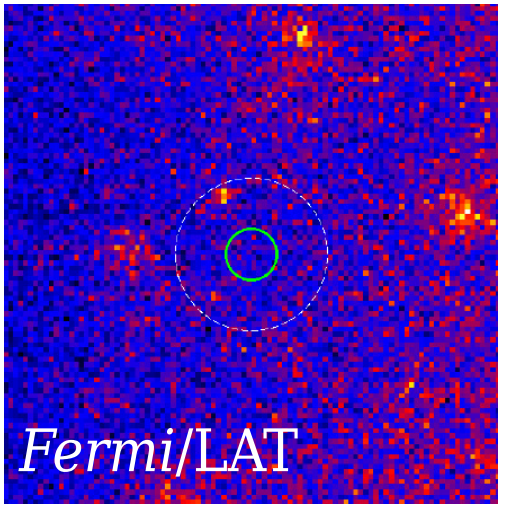




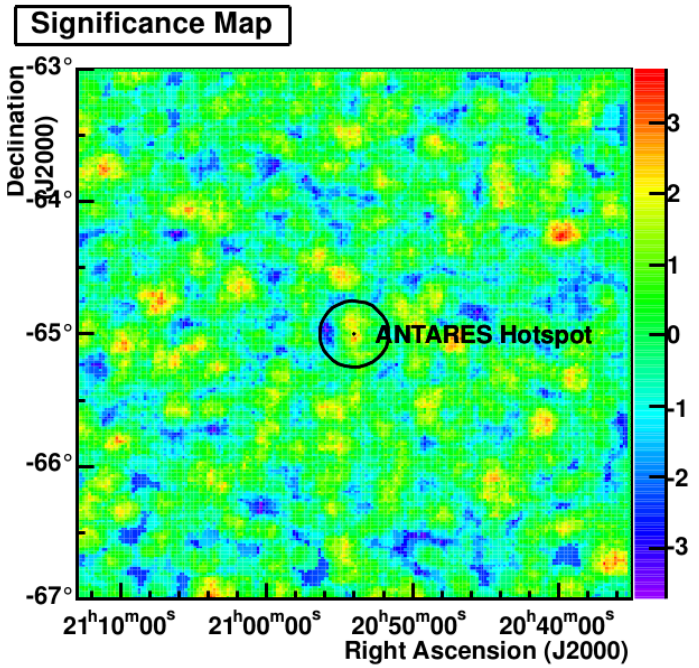
Schüssler, F., Brun, P., Chaves, R.C.G. et al. (H.E.S.S.) 2013

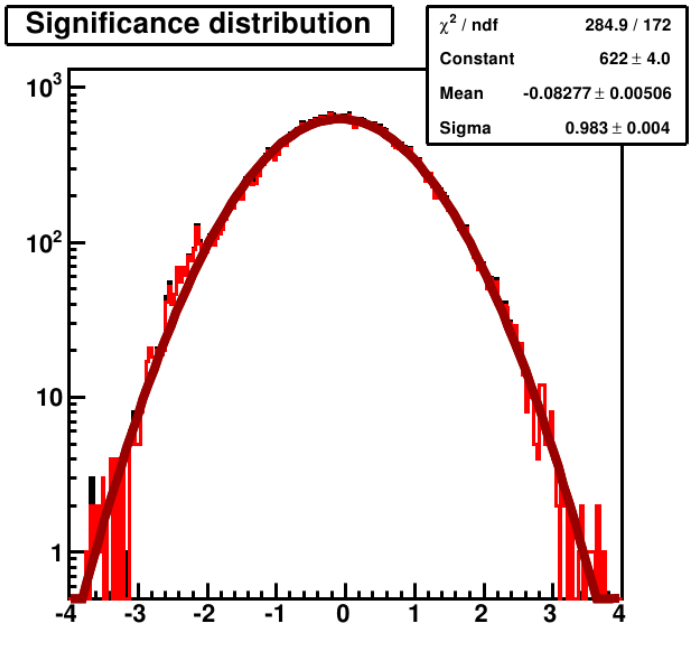
Synergies with different messengers: **neutrinos**





Also performed follow-up observations of **IceCube hotspot in 2009**





More formal partnerships with **astroparticle community**, including ToOs, currently under development

Schüssler, F., Brun, P., Chaves, R.C.G. et al. (H.E.S.S.) 2013

H.E.S.S.-II First Light, First Science

It's really big.

2.8 metric ton camera

580 metric ton total

largest “optical” telescope every built

875 90-cm mirror segments

slew speed 200° / min (GRBs!)

72 m height when pointed at zenith

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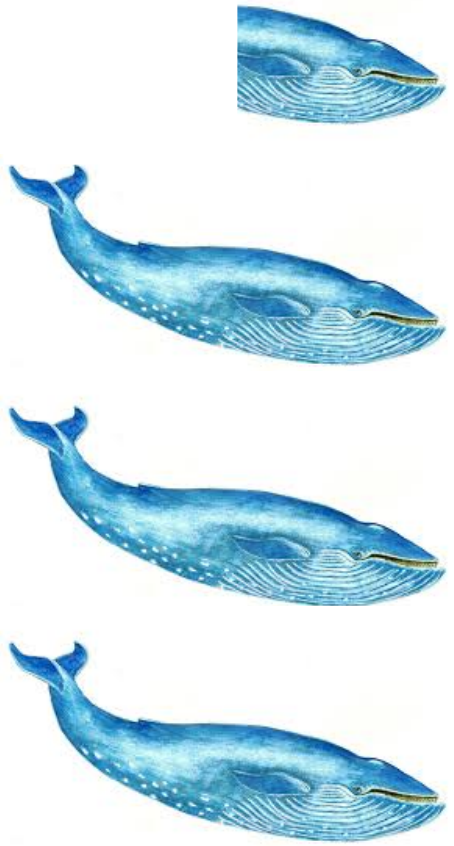
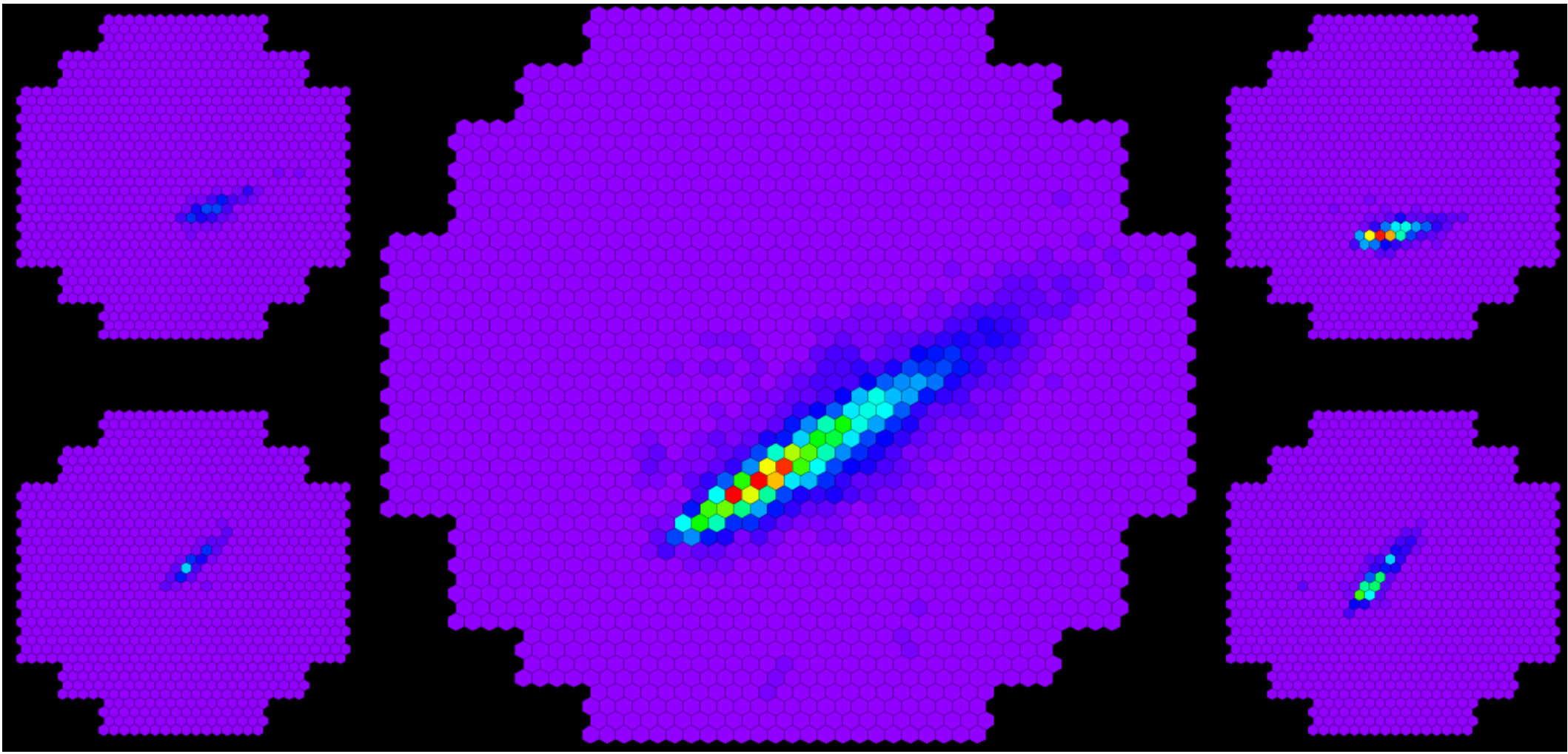
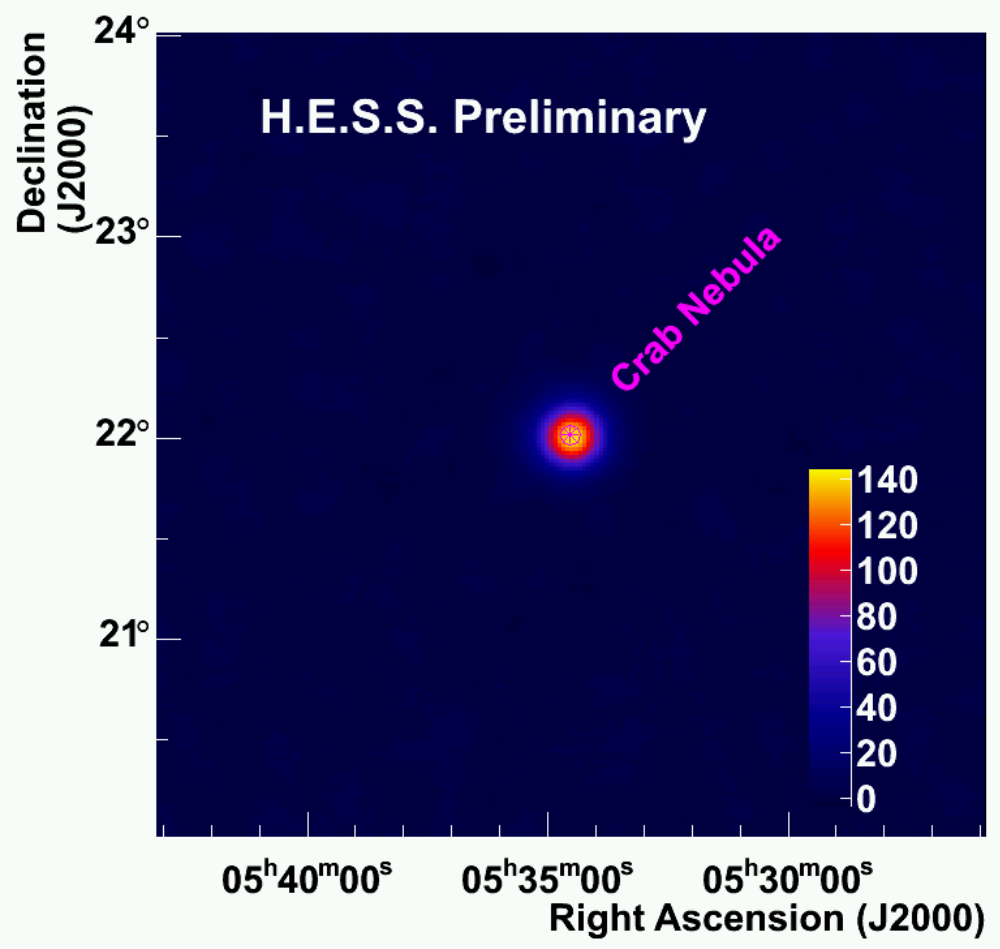
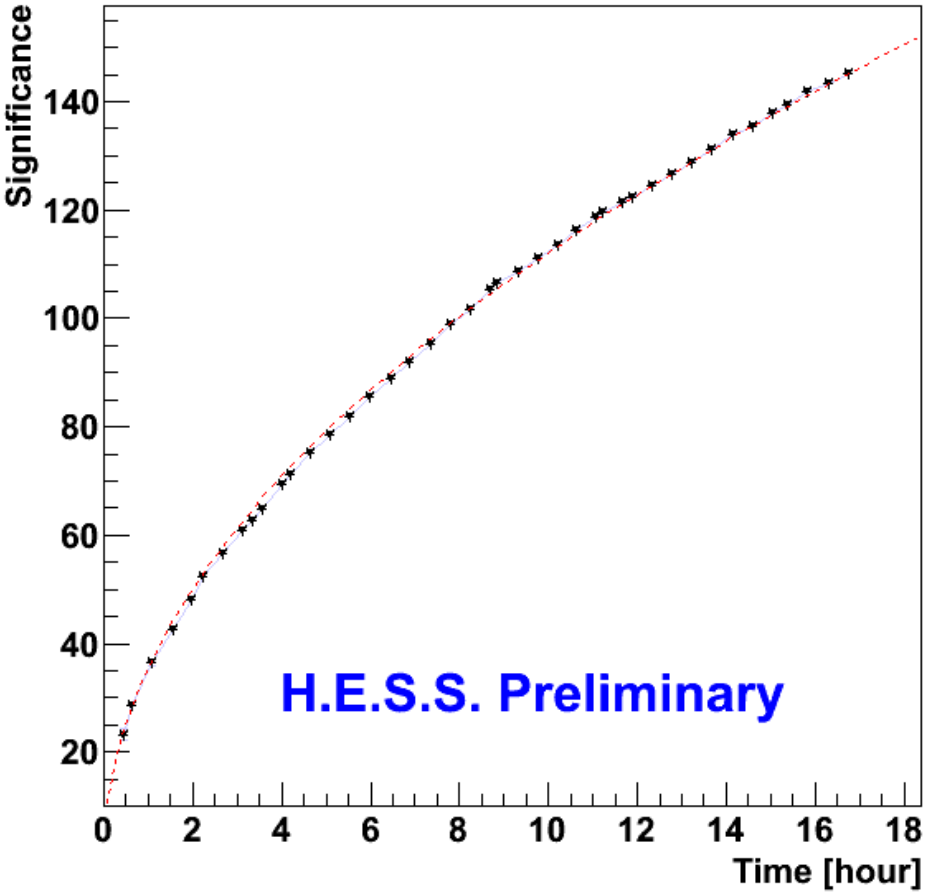


EAS Camera Images



Primary commissioning target for H.E.S.S.-II: **Crab Nebula**





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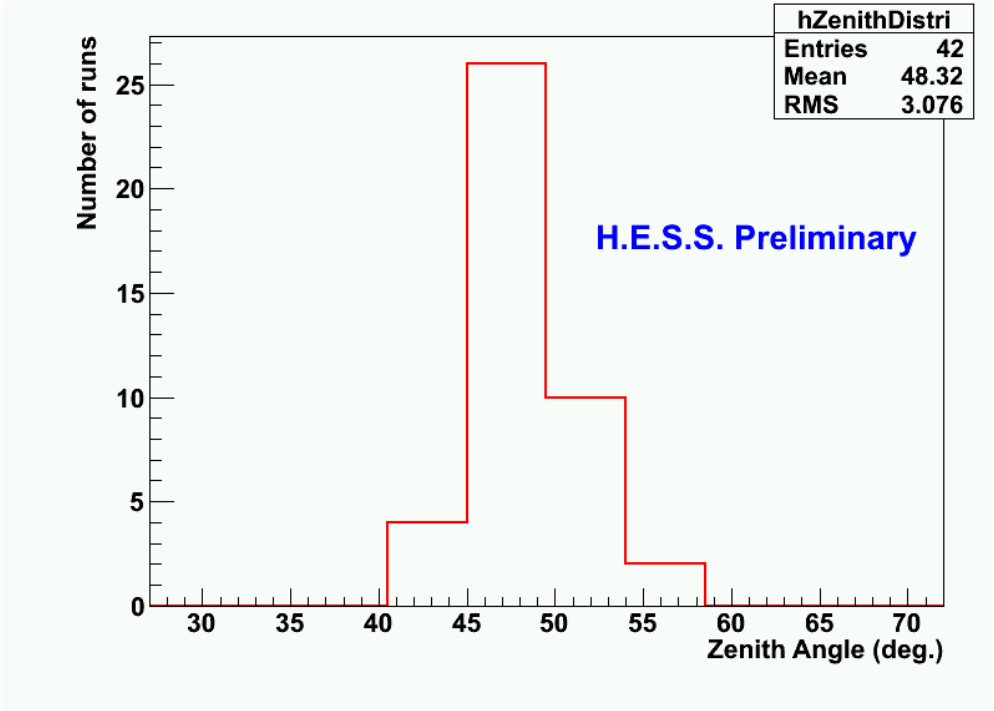
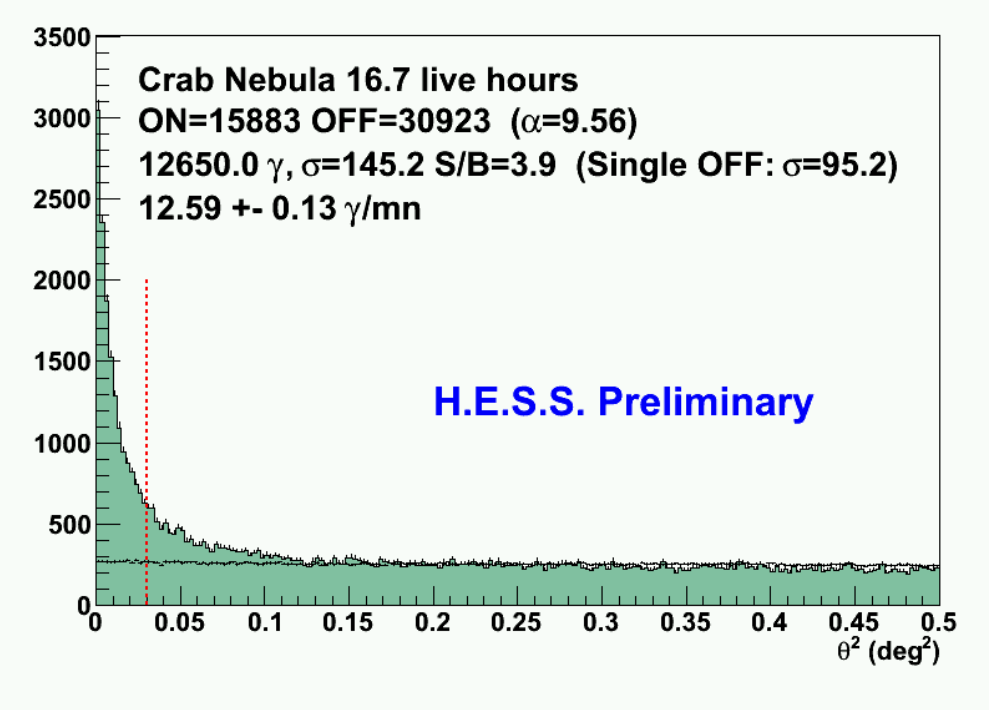
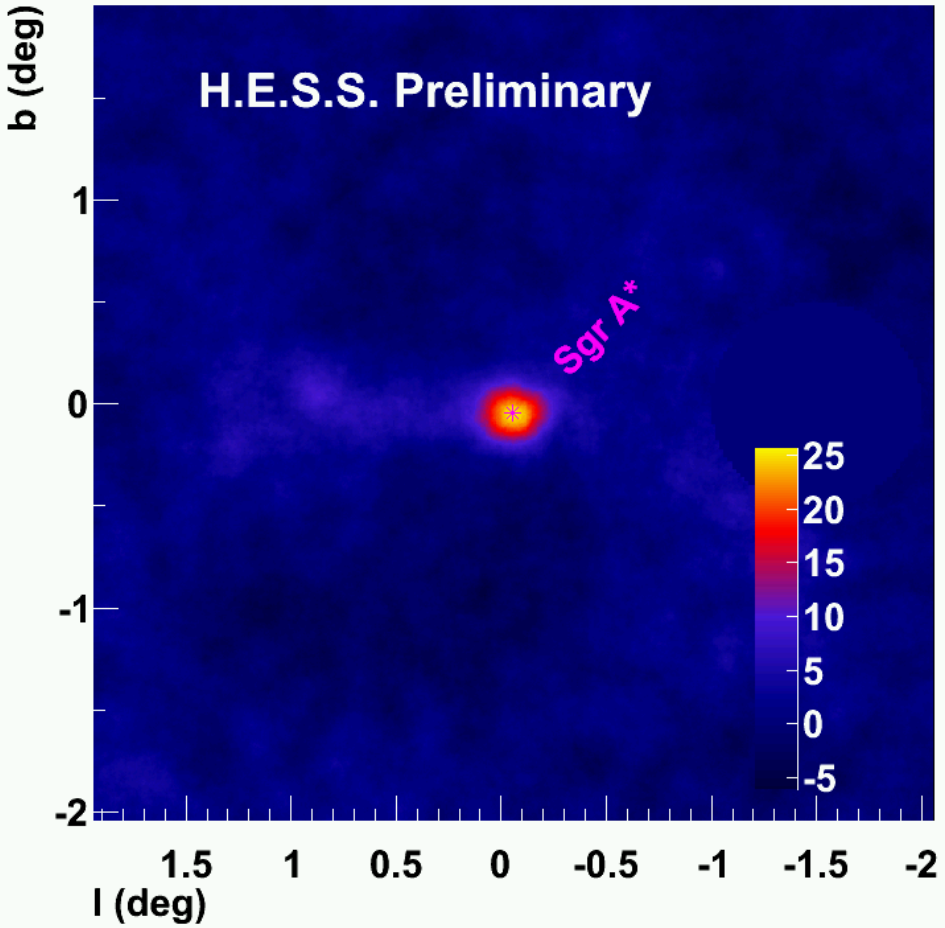
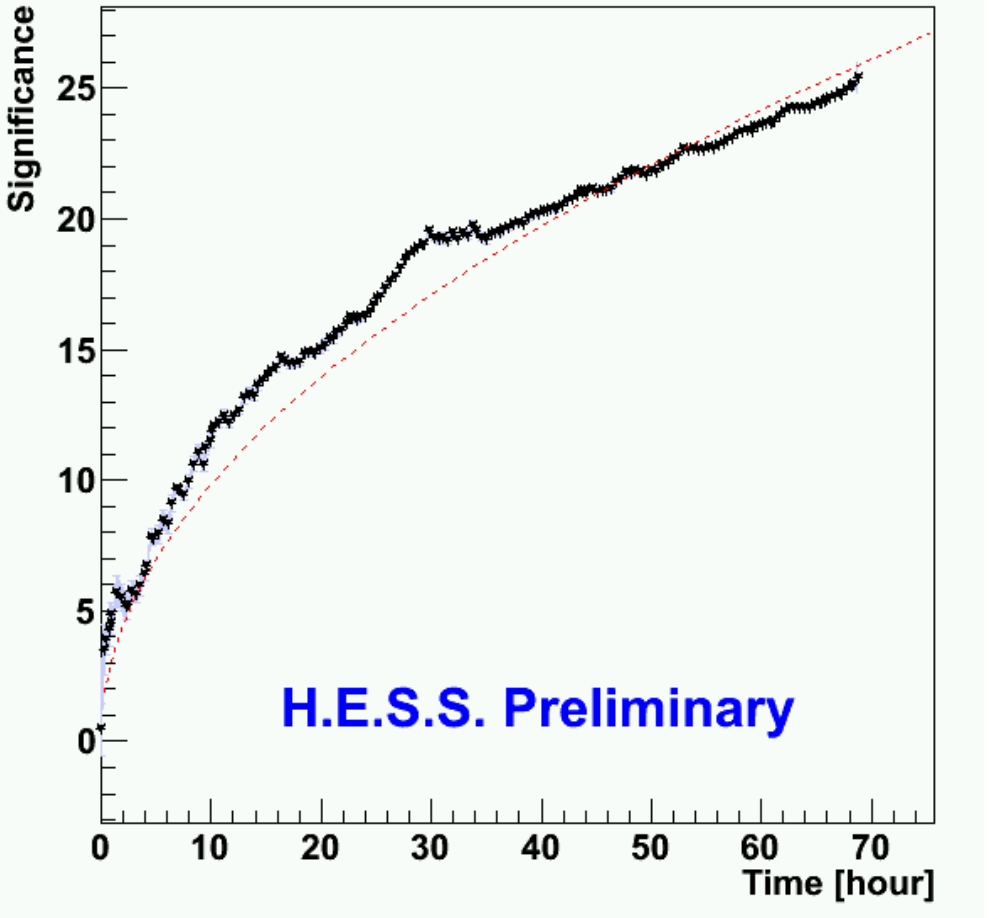


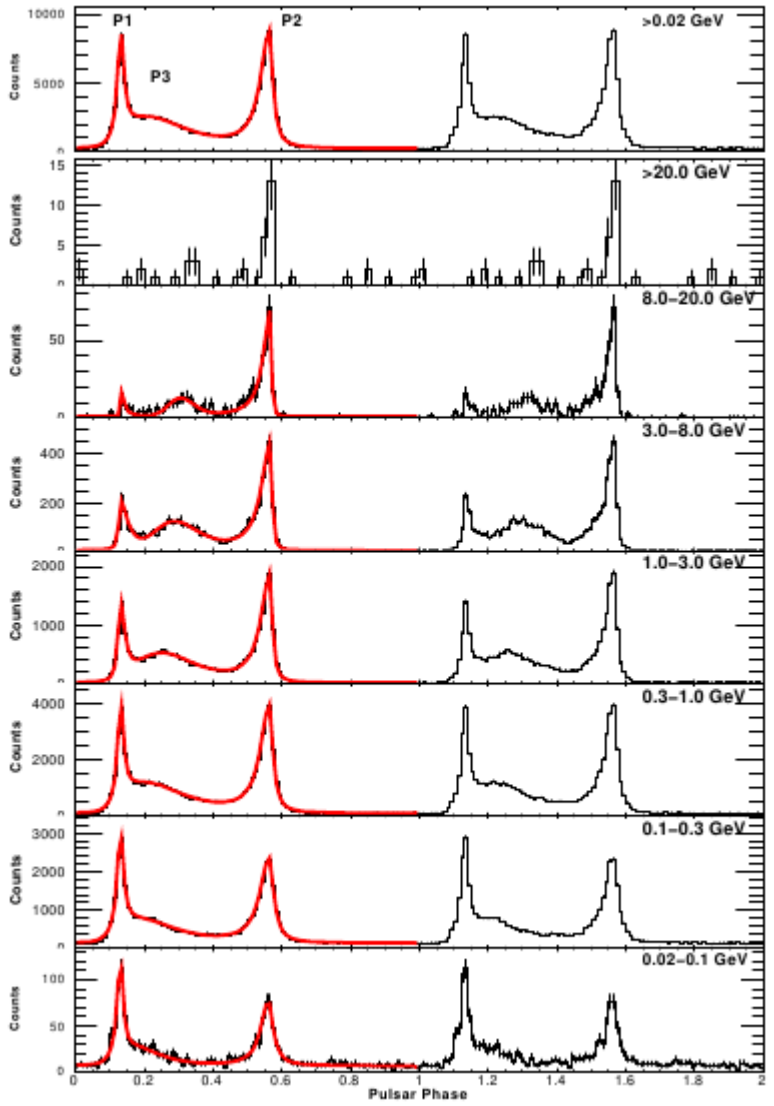


Primary commissioning target for H.E.S.S.-II: **Galactic Center**





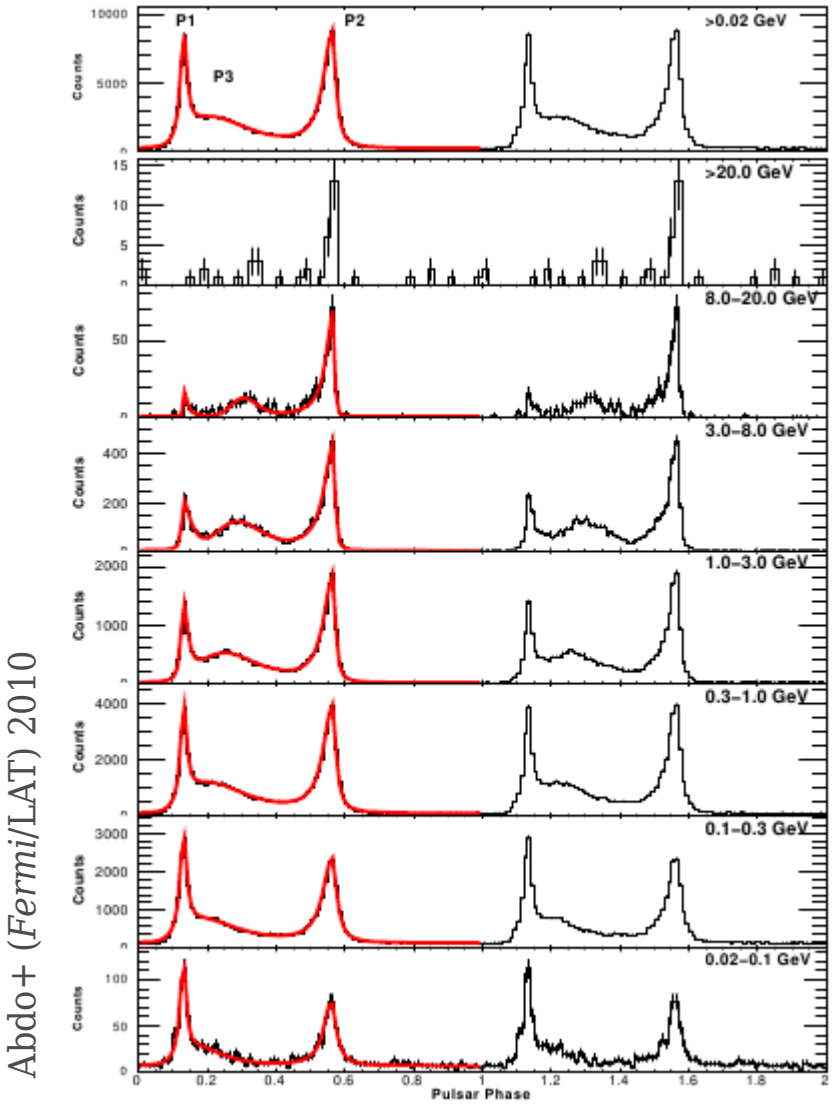
Vela PSR recap: *Fermi*/LAT view



E > 20 MeV

Abdo+ (*Fermi*/LAT) 2010

Vela PSR recap: *Fermi*/LAT view



Abdo+ (*Fermi*/LAT) 2010

E > 20 MeV

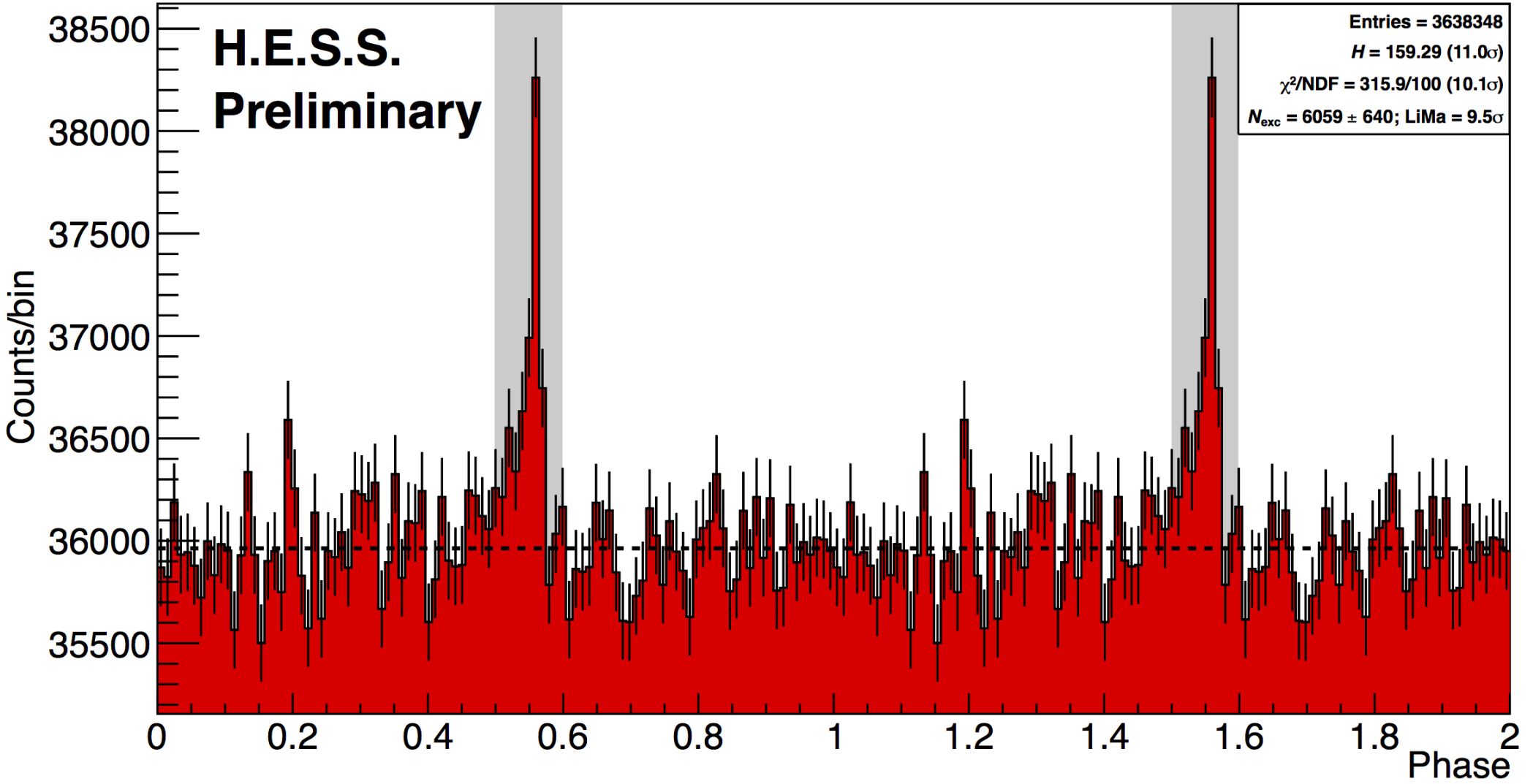
E > 20 GeV

E: 8-20 GeV

20-100 MeV

P2/P1 ratio increases with E: confirmed at VHE by H.E.S.S.?

Vela PSR detected by H.E.S.S.-II



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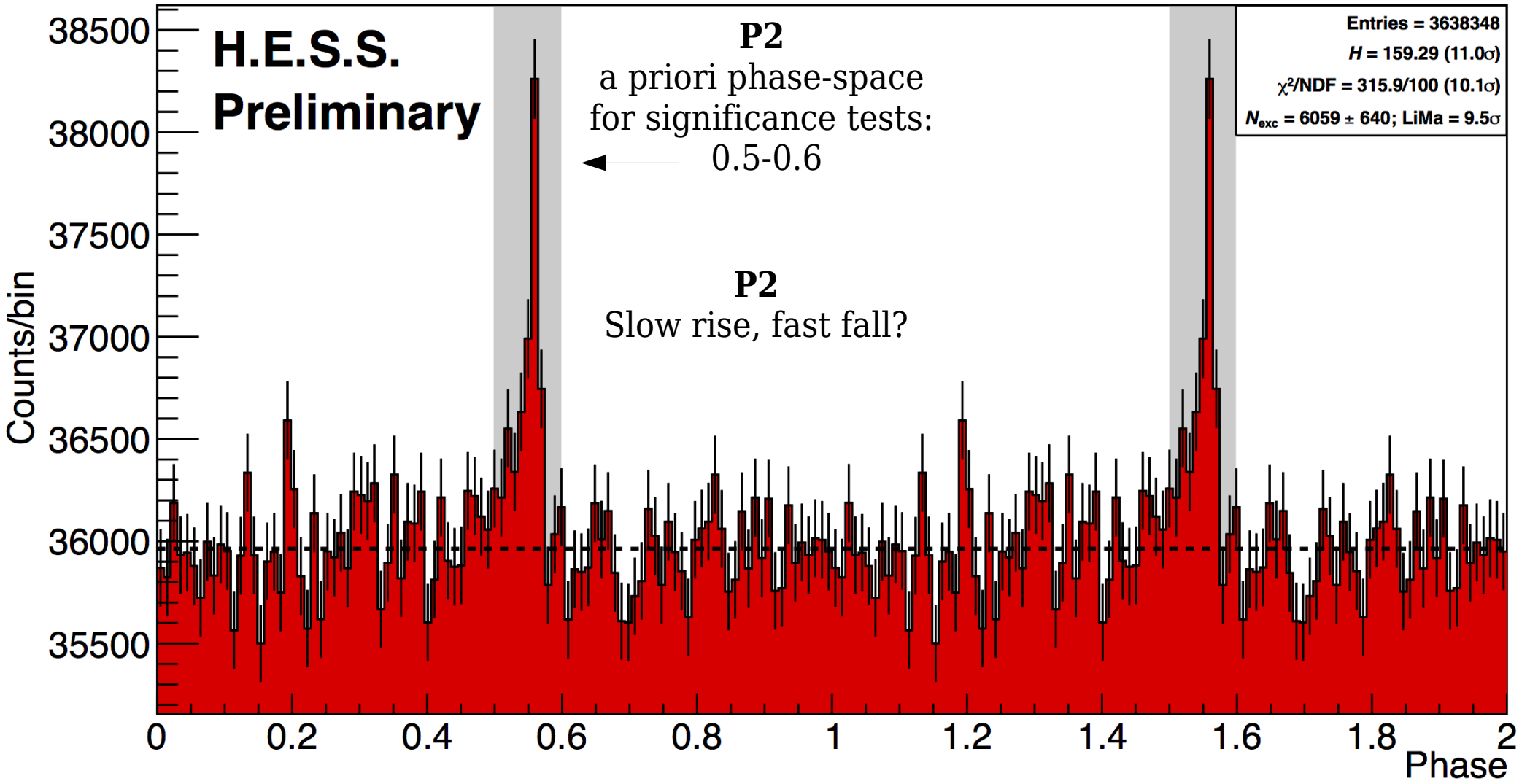
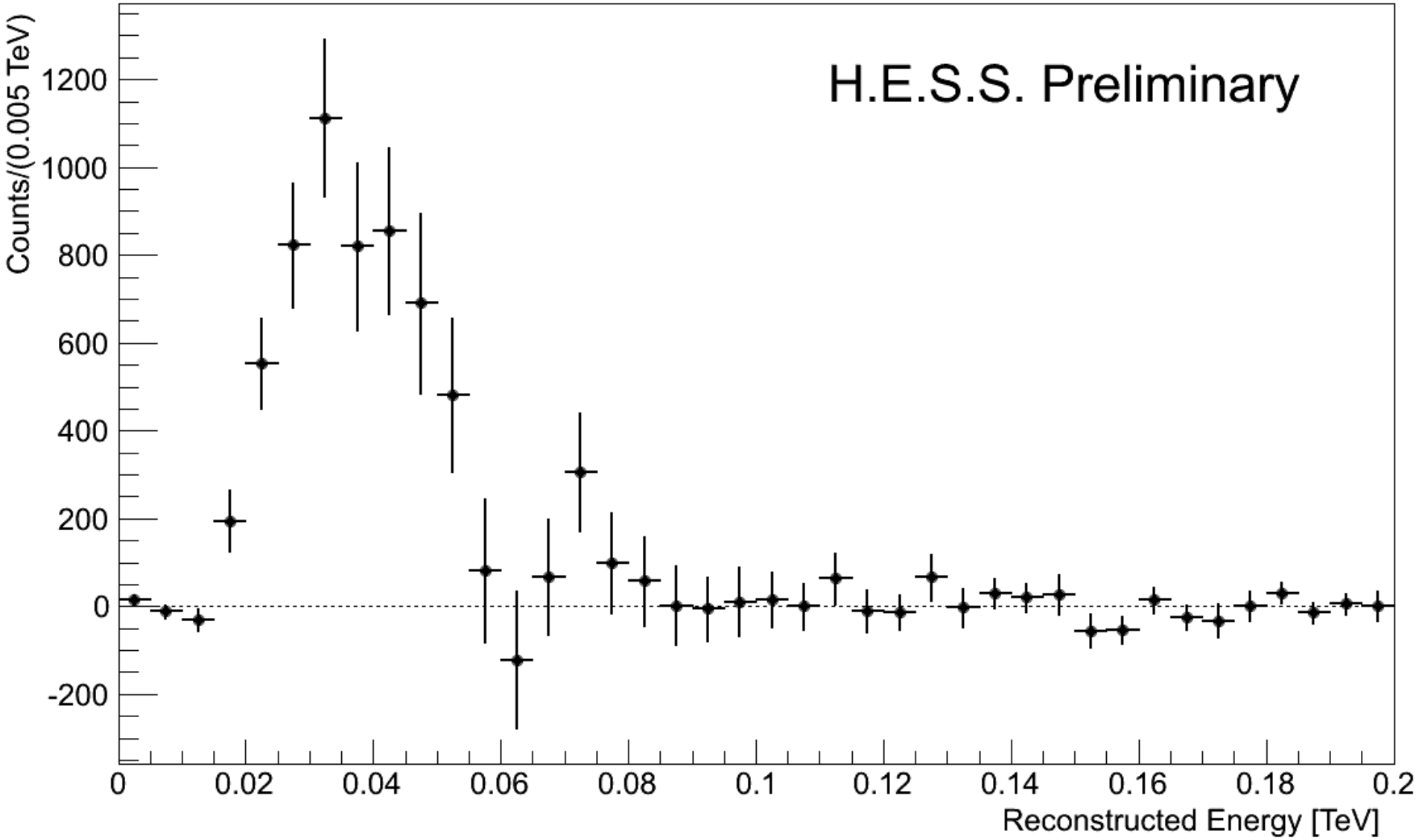


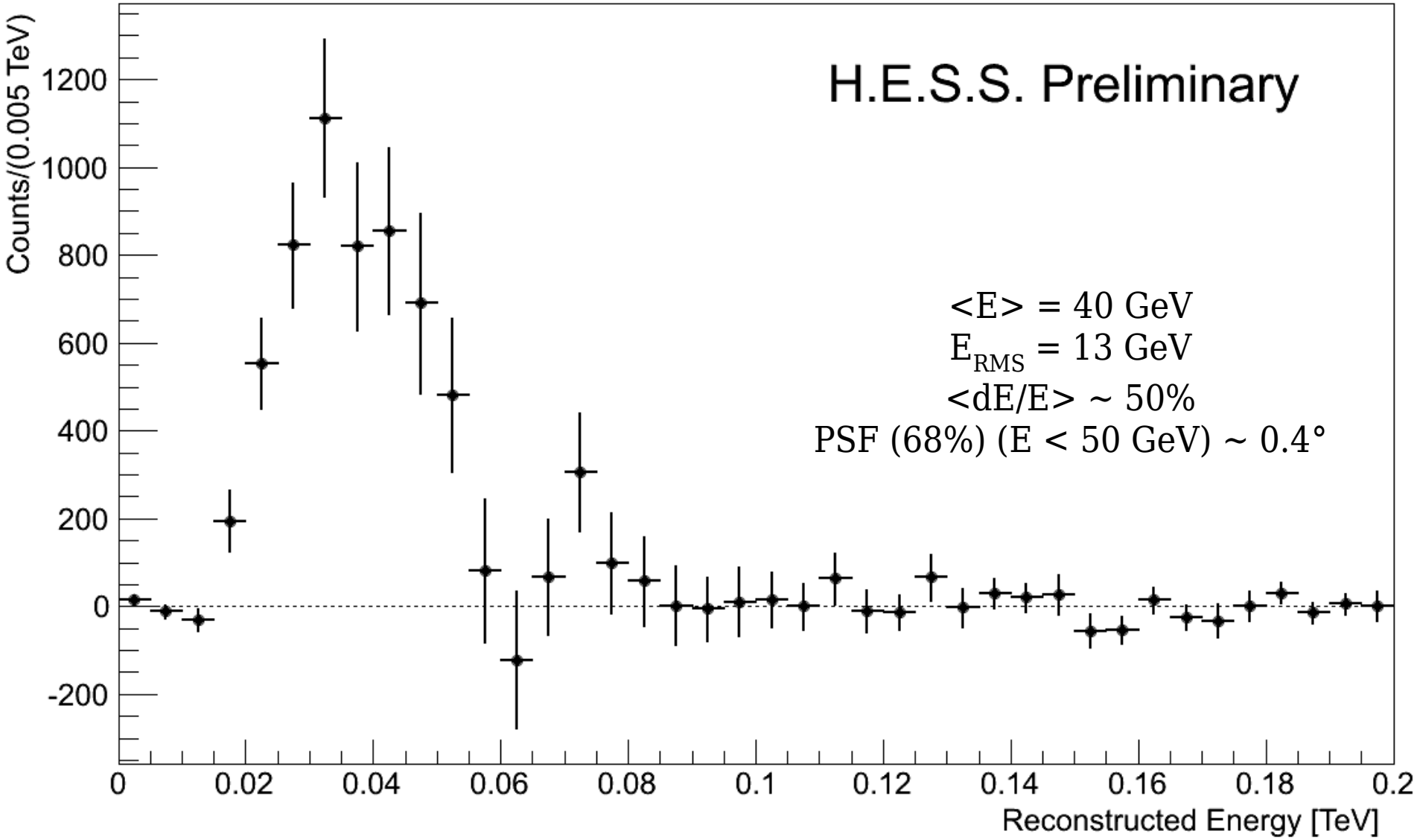
Phaseogram: Clear, high-significance detection of pulsation

Pushing down to new E thresholds



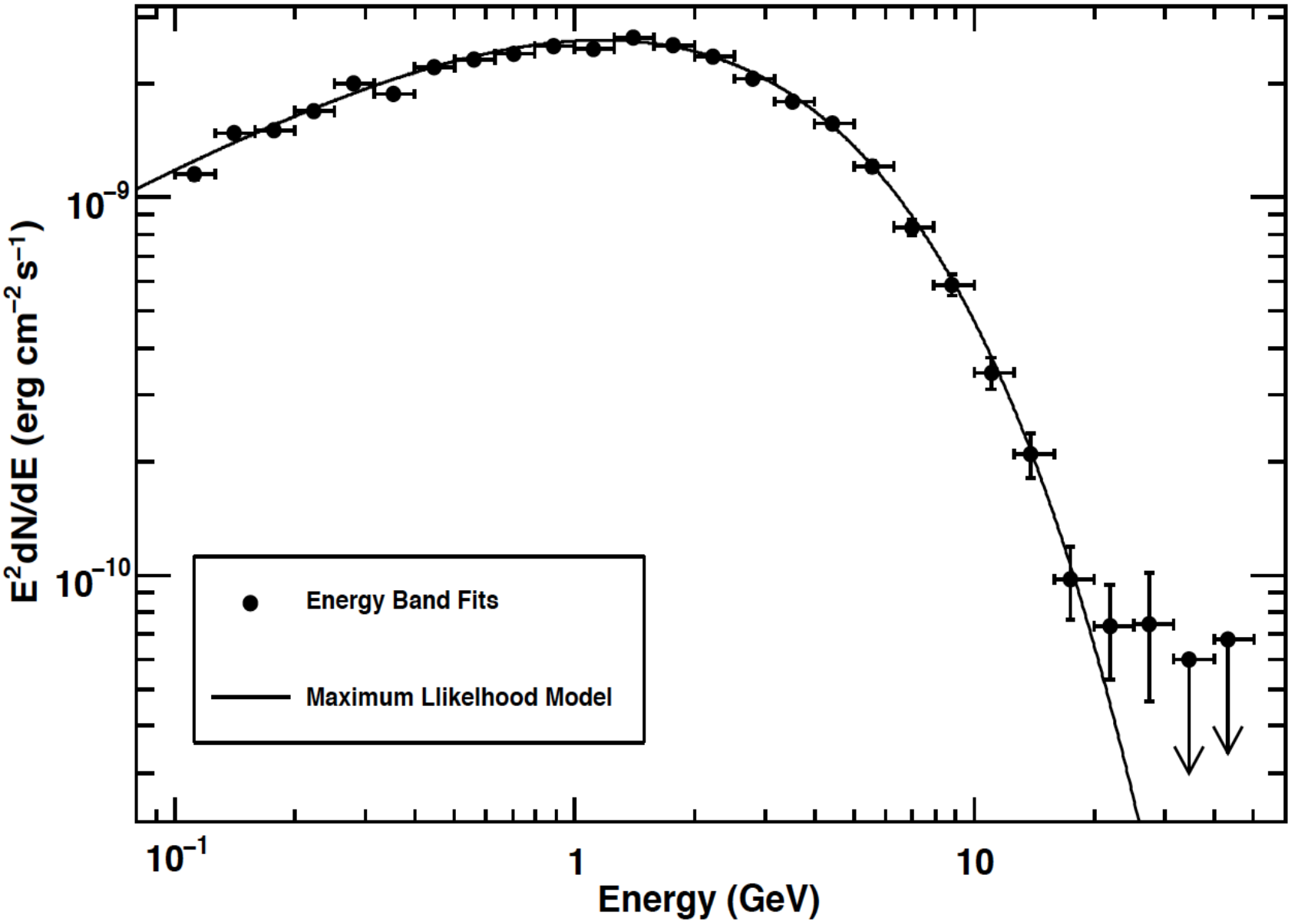
Energy distribution of pulsed events

Pushing down to new E thresholds



Energy distribution of pulsed events

Now on to VHE pulsar physics



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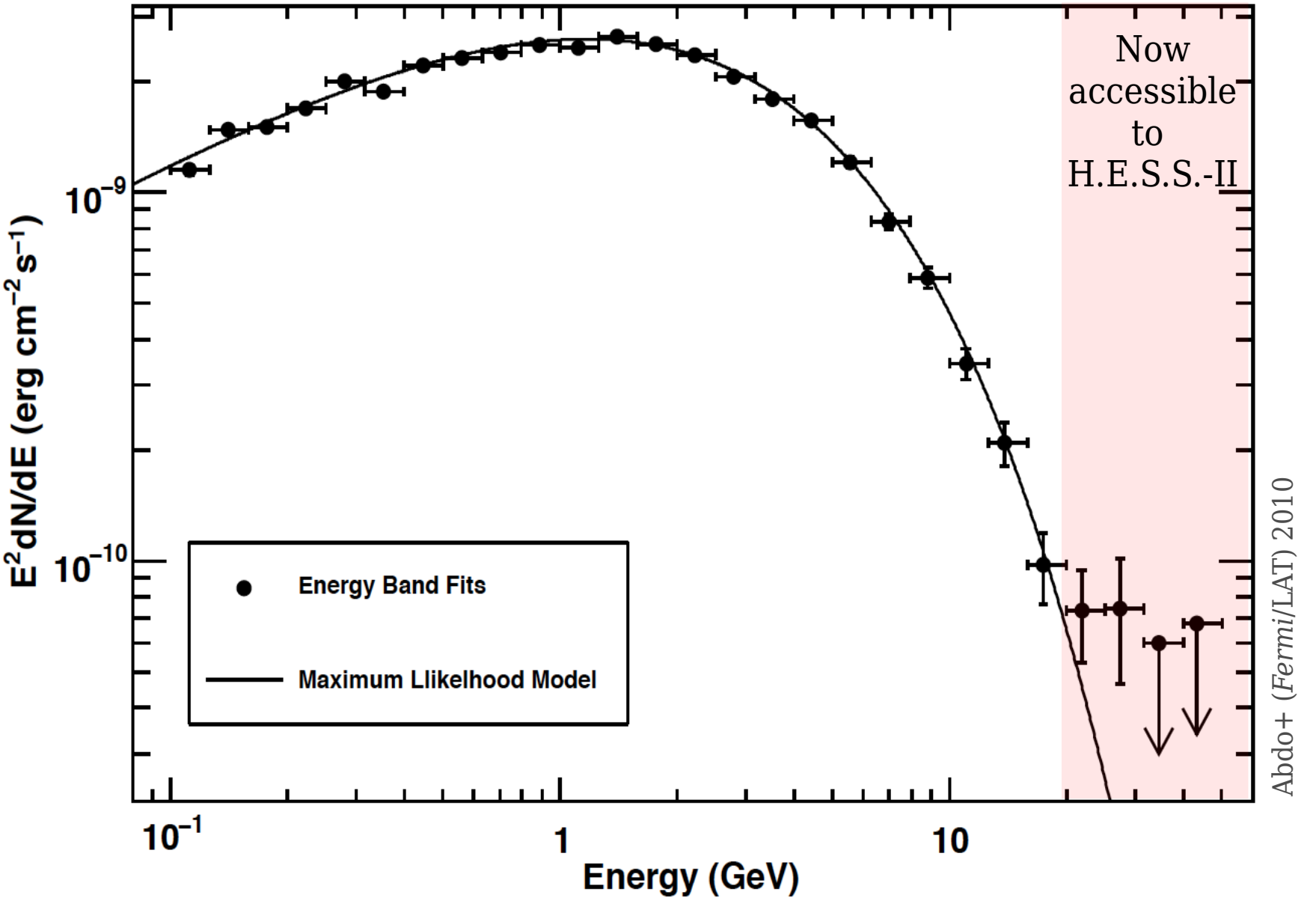

Constraining VHE spectrum & cutoff? Stay tuned...

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).