Surveys with Imaging Atmospheric Telescopes

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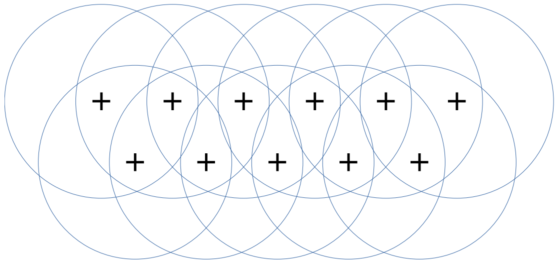
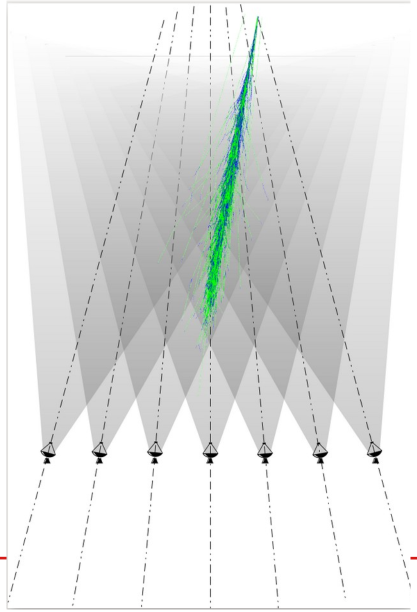
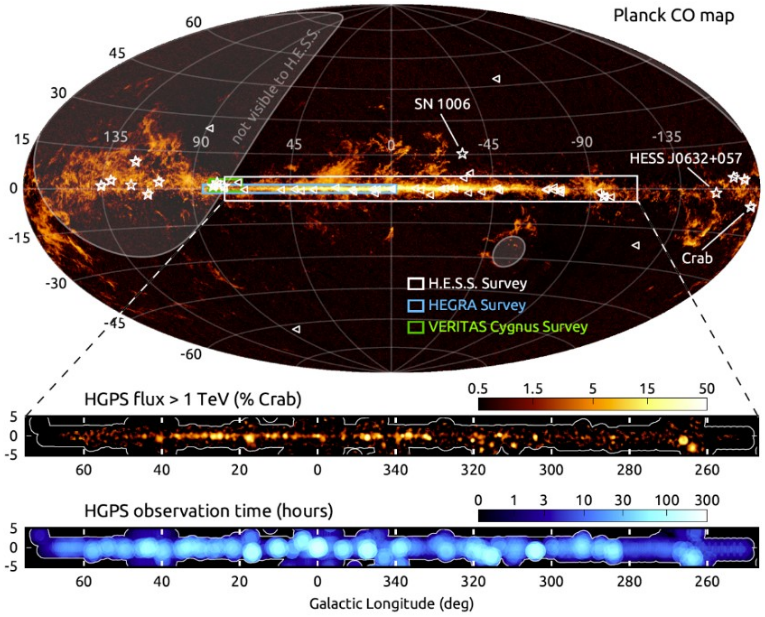


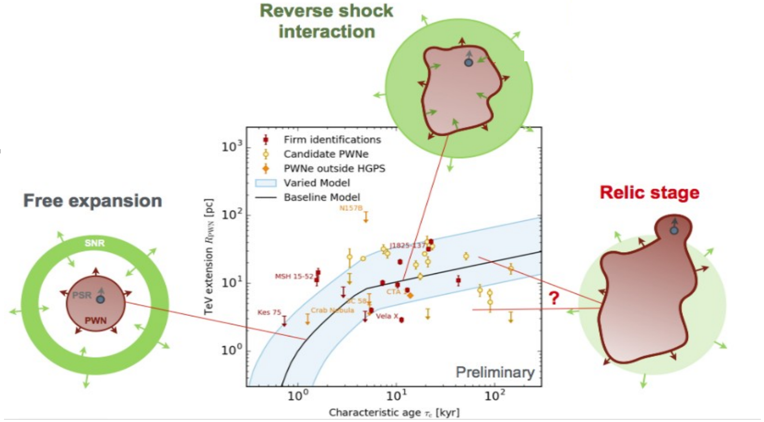




Surveys & IACTs

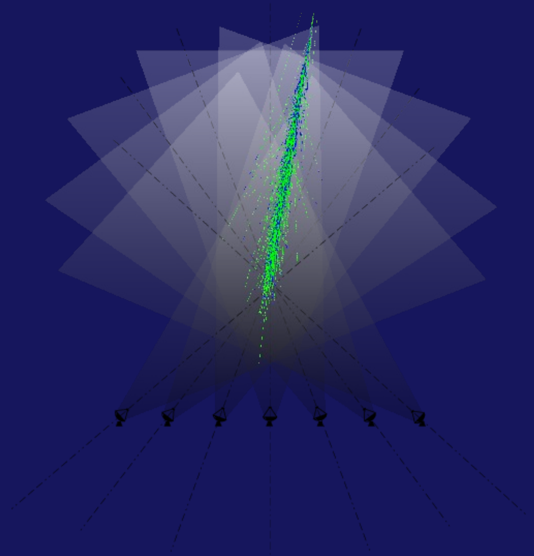
- What are survey good for?
  - Systematic, unbiased source searches
  - Source catalogues (completeness, etc)
  - Population studies (Evolution of sources, log(N) - log(S), …
    Examples:
    - Population of TeV Pulsar Wind Nebulae in the H.E.S.S.
    - Population & evolution of SNR ⇒ Search for Pevatrons

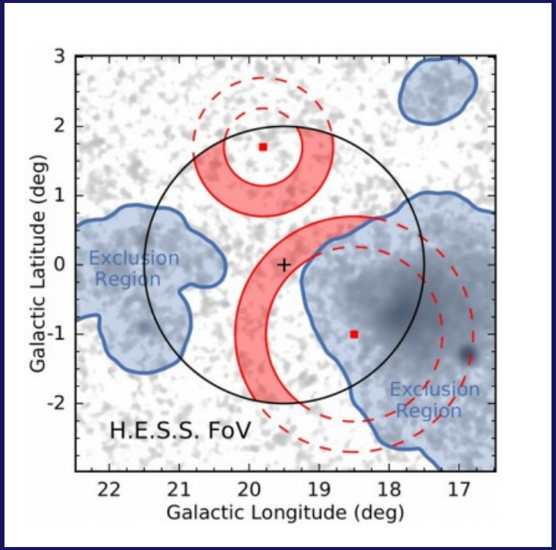
H.E.S.S. Collaboration - A&A. 612 (2018) A2



- Specific aspects of IACTs
  - Narrow field of view (a few ° ∅)
    ⇒ Stacking of large number of observations with different observation conditions (threshold, …)
  - Large acceptance gradients
  - Background (and eventually systematics) dominated
    ⇒ Need for very accurate determination of acceptance
    ⇒ Need to exclude any true γ-ray source, tricky in some regions

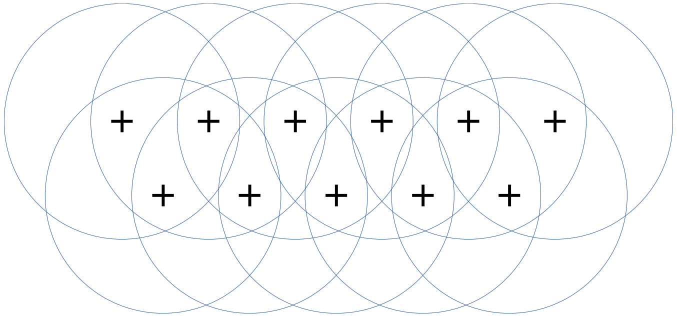
Technical aspects

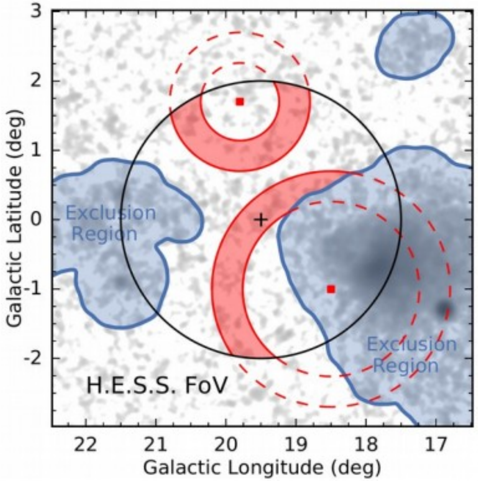


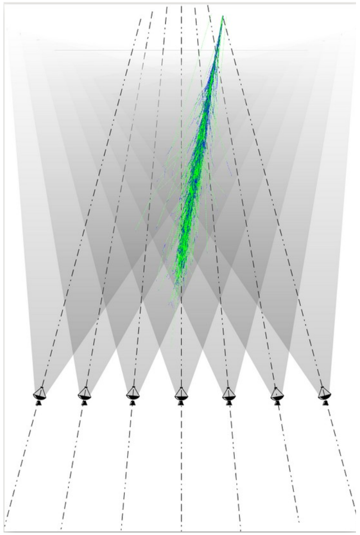


Ingredients of surveys

- Observation strategy
  - Pointing positions: spacing, time per pointing, recurrence, …
  - Pointing strategy: parallel-, convergent-, divergent pointing, array splitting, etc.
- Data analysis
  - Event selection - hard vs soft cuts, …
  - Background subtraction
  - Catalogue pipelines
  - Open-source tools
- Data release
  - Catalogues
  - FITS release
  - Legacy data





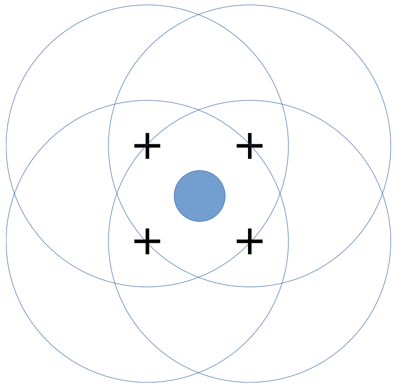


Observations strategies

- Traditional IACTs observations where using the “wooble” observation mode
  - Putative source at a fixed offset in FoV, alternating pointing in RA/Dev

    ⇒ Background from symmetric region in FoV, similar acceptance

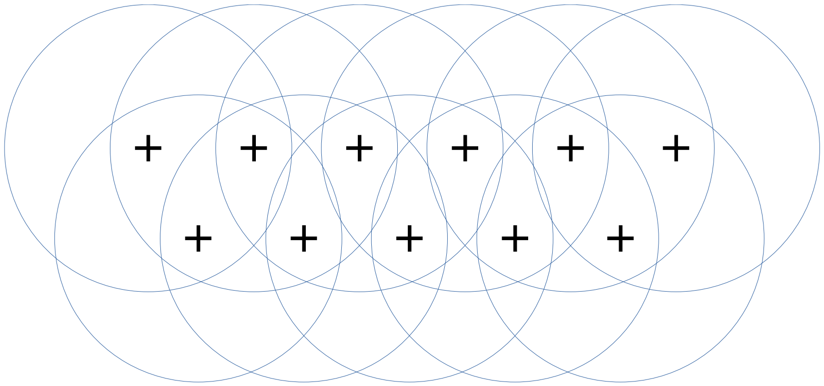
    ⇒ Good control of systematic
  - Not applicable for surveys (multiple sources, etc) and/or for very extended source



- Scanning mode: regularly spaced grid on the sky
  Applicable to large regions of the sky
  - Need overlapping FoV to mitigate acceptance gradients
  - Several row, in parallel or one after the other
  - Regular visit of regions of specific interest

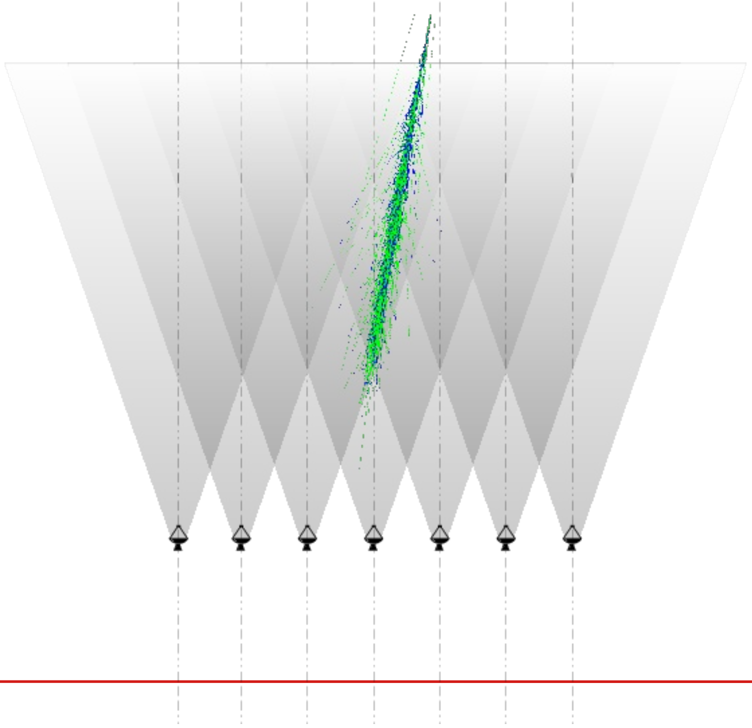
    ⇒ Data acquired over large time intervals are stacked together

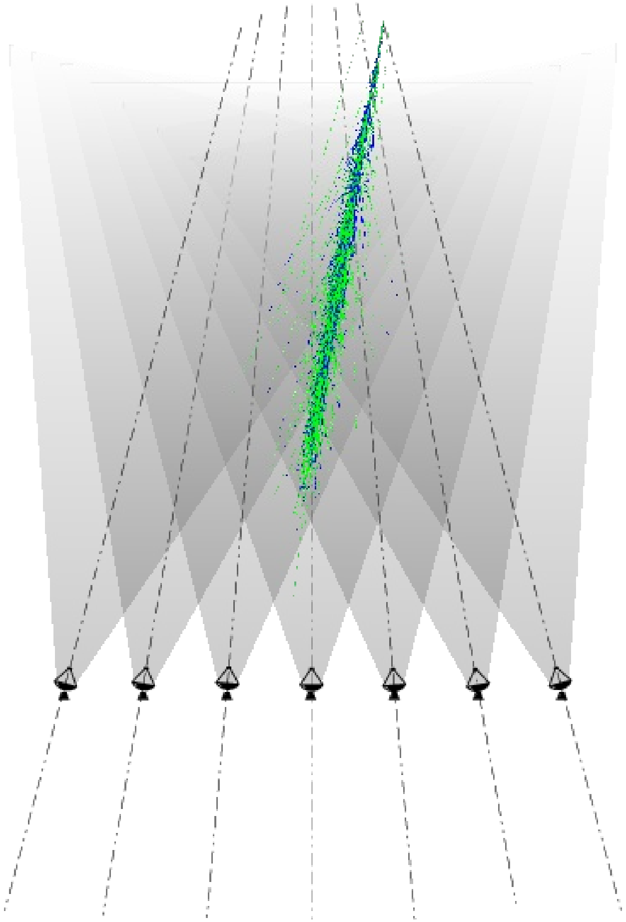
    ⇒ Need to keep track of observation conditions (array configuration, atmospheric transparency, condition, ...)



Pointing Strategies

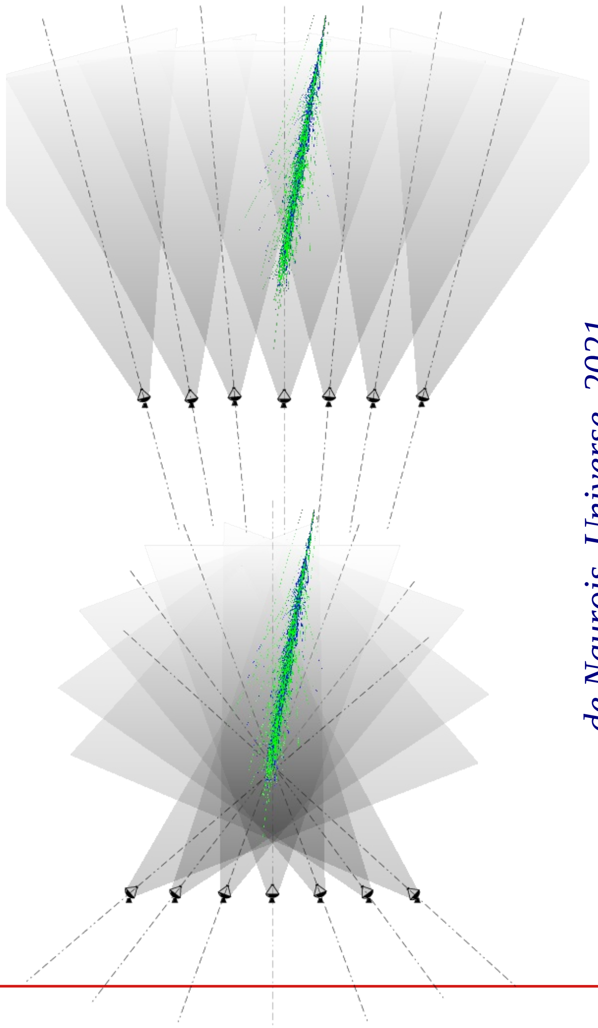
- Traditional IACTs observations optimized on point-like sensitivity
  ⇒ Parallel or slightly convergent pointing (at ~ 10 km)





Pointing Strategies - II

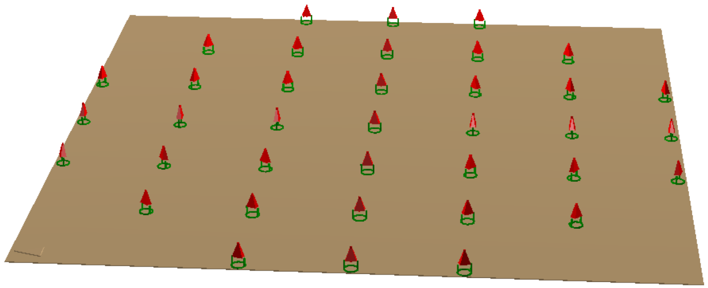
- Different pointing scheme suitable for surveys
- "Divergent pointing" increases effective FoV
  - Easily implemented as convergent pointing at negative altitude
  - Increased effective FoV ⇒ faster coverage of survey region
  - Comes at the expense of sensitivity and accuracy (reduced telescope multiplicity)
  - More complicated background determination
- "Skewed pointing" (convergent at very low altitude)
  - Also increases the effective FoV
  - Keeps a large multiplicity for well contained events
  - But comes at the expense of a reduced effective area
- Quantitative study of merits/drawbacks needed



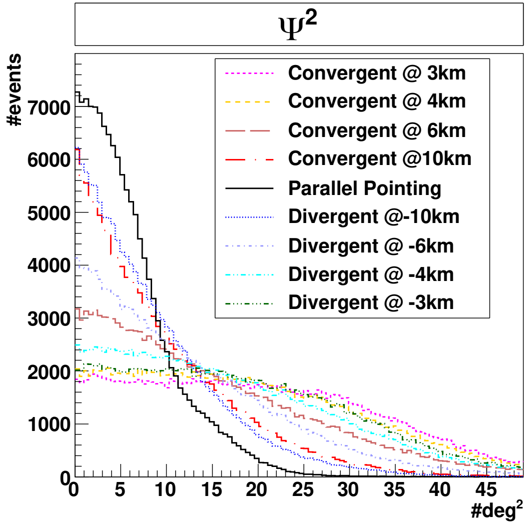
de Naurois, Universe, 2021

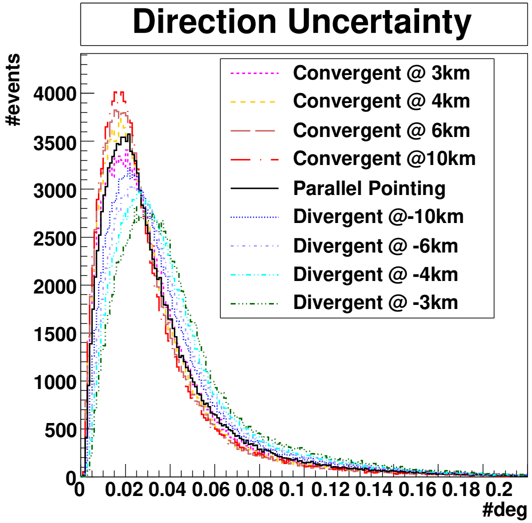
Pointing Strategies - III

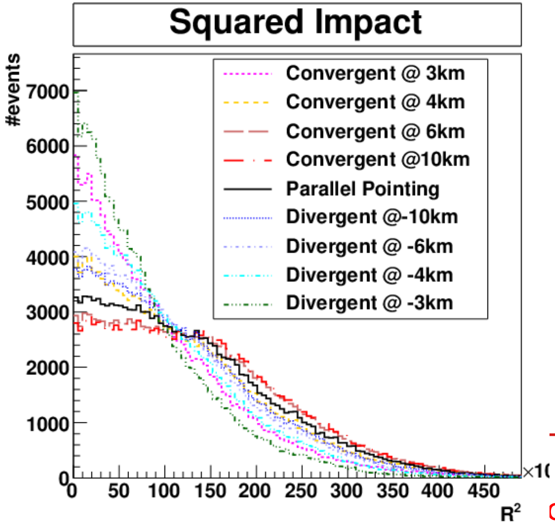
de Naurois, Universe, 2021



- Quantitative evaluation:
  - Test array of 37 HESS-I telescopes
  - Diffuse simulation + full reconstruction (Model++)
  - No background simulation yet
- Confirmed expectations:
  - Larger FoV for both divergent & skewed pointing
  - Better accuracy for convergent pointing @ 10 km
  - Larger effective area for convergent pointing @ 10 km







Pointing Strategies - III

de Naurois, Universe, 2021

- Quantitative evaluation:
  - Test array of 37 HESS-I telescopes
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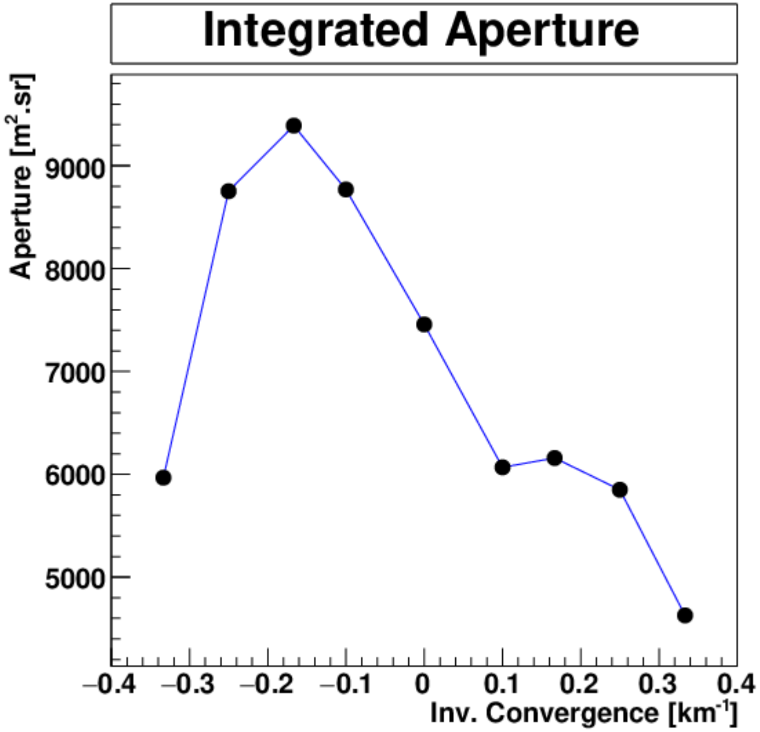
- Confirmed expectations:
  - Larger FoV for both divergent & skewed pointing
  - Better accuracy for convergent pointing @ 10 km
  - Larger effective area for convergent pointing @ 10 km
- Integrated aperture (effective area × solid angle) maximized for divergent pointing at ~ -6 km

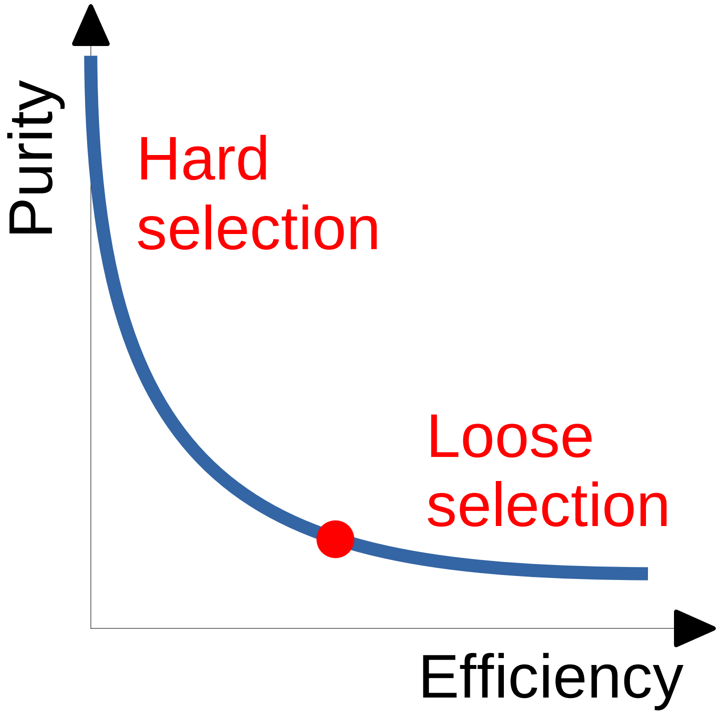
  ⇒ Maximal γ-ray detection rate
  - To be repeated with realistic array (CTA South)
  - Effect on background subtraction to be investigated



Event Selection

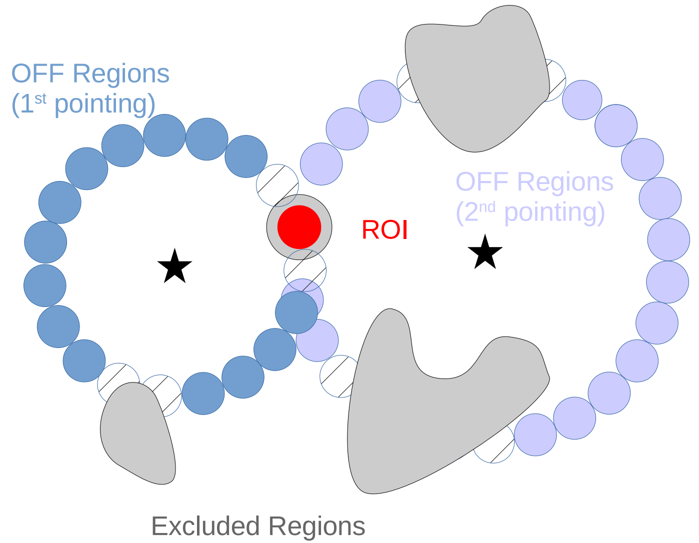
- IACTs are background dominated
  ⇒ Significance of signal depends on abilities to
  - Keep a maximum number of γ's (efficiency)
  - Reject the largest fraction of background events (purity)

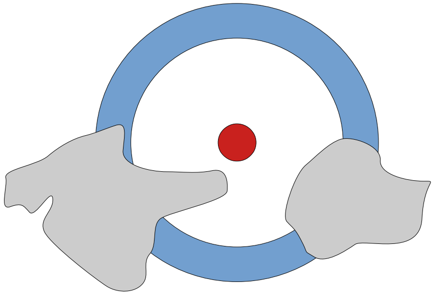
- Choice of operation point in a efficiency-purity plot depends on goals
  - Statistical optimal differs for every source (depends on spectral shape)
  - Hard selection improves sensitivity to high energy sources (PeVatrons, …) & angular resolution, with reduced background systematics
  - Loose selection usually reduced energy threshold
- Future surveys to be released with several configurations?

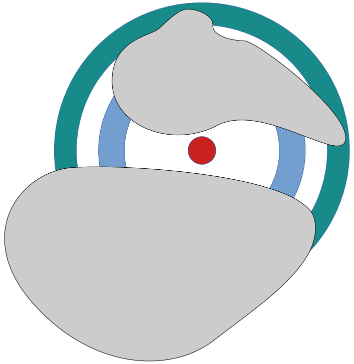


Background Subtraction Techniques

- Classical "reflected regions" background not suitable for survey maps
  - Can however be used for spectral determination of identified sources
- Ring Background well suited for background maps
  - Adaptive Ring Background needed in very crowded regions, to keep constant ON/OFF areas
- Template Background (using hadron-like events as background estimator) barely used any-more
  - More prone to systematics
  - Not allowing derivation of spectra
- Field-of-view Background (using acceptance as background estimator) recently successfully used
  - Suitable to very extended sources
  - But more prone to systematics
- Fully simulated background seem promising
  - Relies on simulation of diffuse γ + corrections

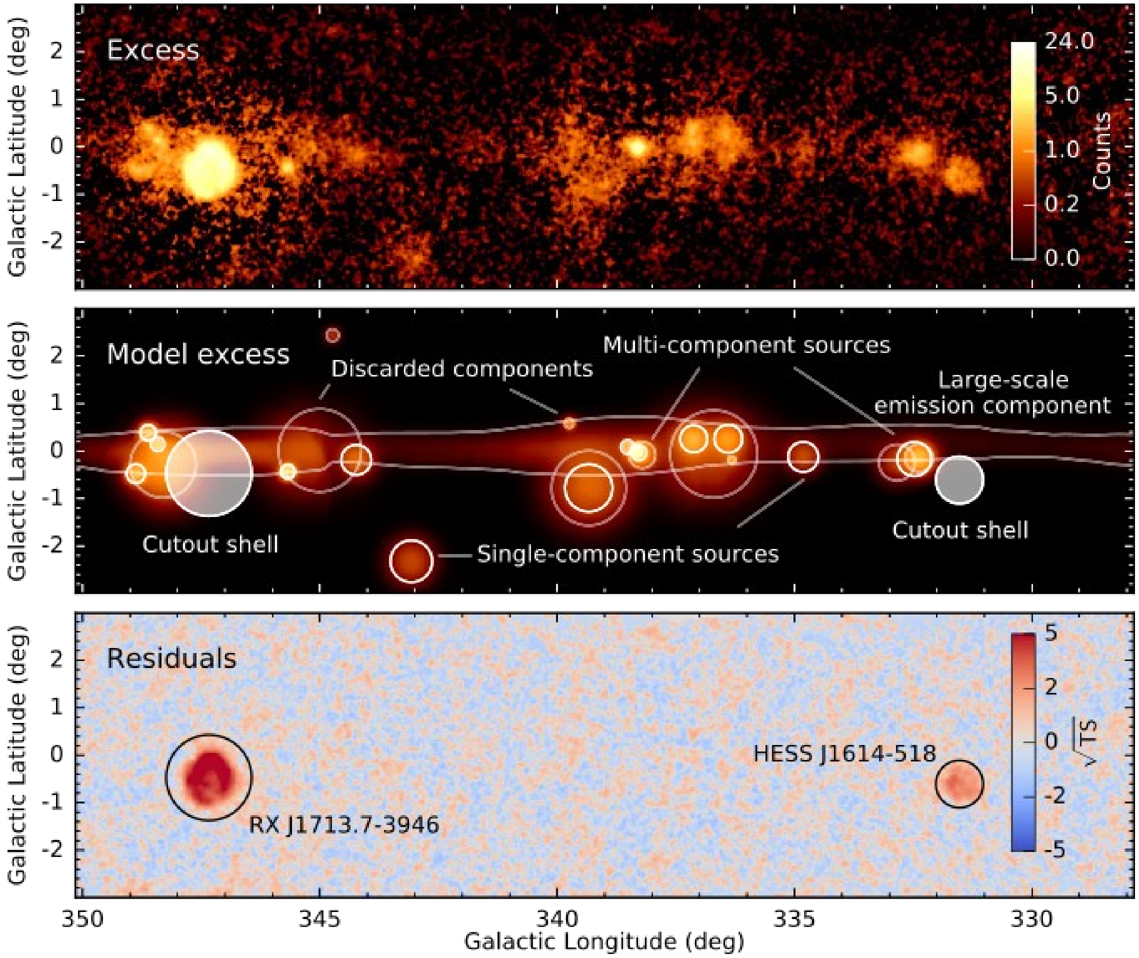




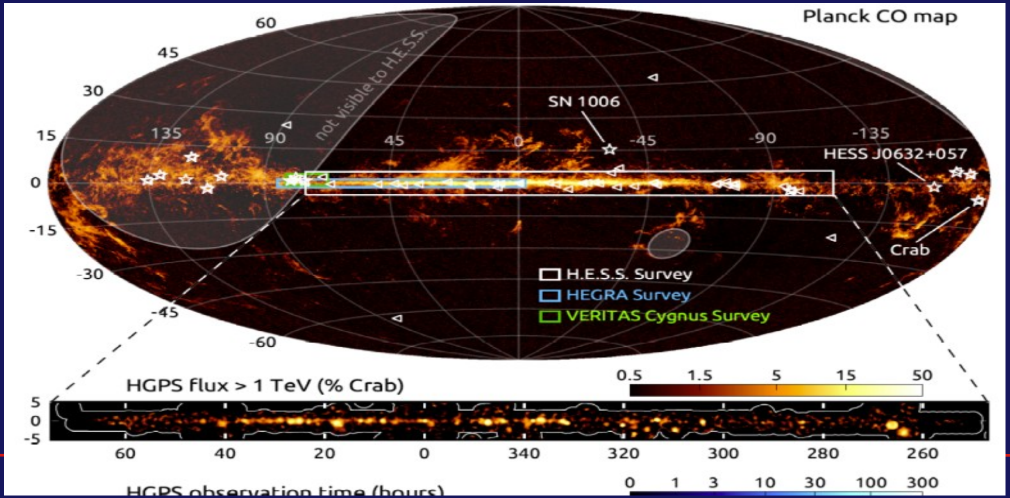


Final analysis pipeline

- Acceptance determination from γ-ray free data set:
  - Use EGAL fields, but different conditions (e.g. NSB)
  - Iterative procedure to remove identified sources + margin
- Iterative construction of source catalogue
  - Use of large scale diffuse emission components
  - Identification of regions with significance emission
  - Separation into (gaussian) components

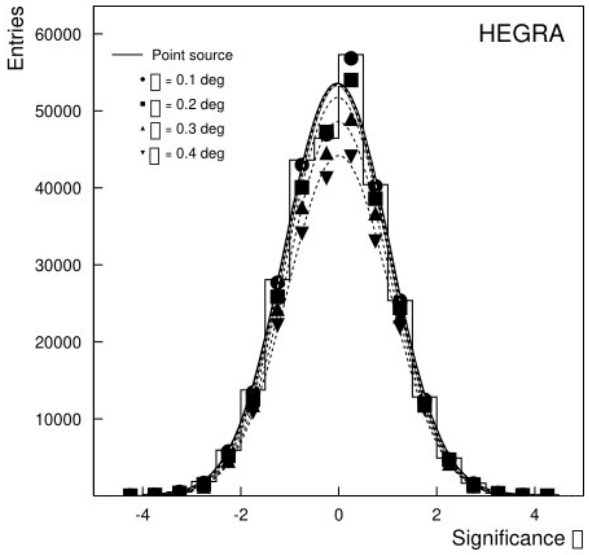


Existing Surveys



HEGRA Survey

- First systematic survey in history of VHE γ-rays
- 176 hr in -2° ≤ l ≤ 85°
- No source detection, constraining upper limits used for some population studies (SNRs & Pulsars)



HEGRA Collaboration - A&A. 395 (2002)

A&A 395, 803–811 (2002)
DOI: 10.1051/0004-6361:20021347

Astronomy & Astrophysics

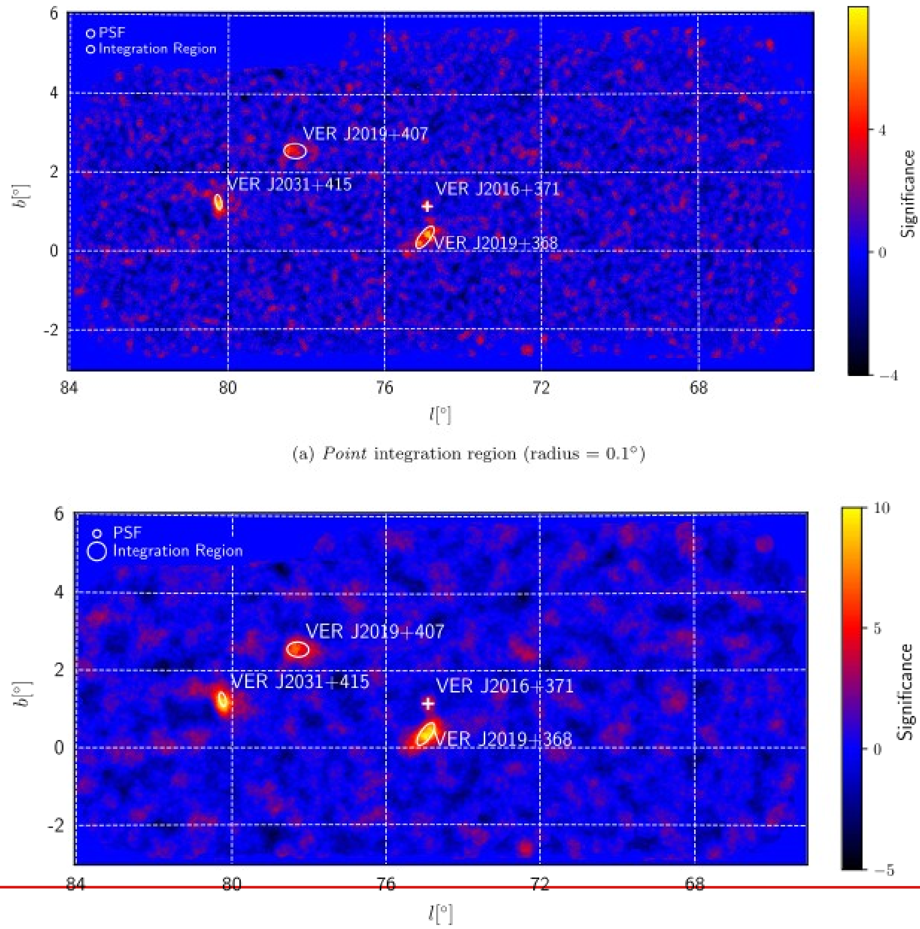
A search for TeV gamma-ray emission from SNRs, pulsars and unidentified GeV sources in the Galactic plane in the longitude range between −2° and 85°

F. A. Aharonian[1], A. G. Akhperjanian[7], M. Beilicke[4], K. Bernlöhr[1], H. Bojahr[6], O. Bolz[1], H. Börst[5], T. Coarasa[2], J. L. Contreras[3], J. Cortina[2], S. Denninghoff[2], V. Fonseca[3], M. Girma[1], N. Götting[4], G. Heinzelmann[4], G. Hermann[1], A. Heusler[1], W. Hofmann[1], D. Horns[1], I. Jung[1], R. Kankanyan[1,7], M. Kestel[2], J. Kettler[1], A. Kohnle[1], A. Konopelko[1], H. Kornmeyer[2], D. Kranich[2], H. Krawczynski[1,%], H. Lampeitl[1], M. Lopez[3], E. Lorenz[2], F. Lucarelli[3], O. Mang[5], H. Meyer[6], R. Mirzoyan[2], A. Moralejo[3], E. Ona[3], M. Panter[1], A. Plyasheshnikov[1,§], G. Pühlhofer[1], G. Rauterberg[5], R. Reyes[2], W. Rhode[6], J. Ripken[4], A. Röhring[4], G. P. Rowell[1], V. Sahakian[7],

VERITAS Survey of the Cygnus region

- 300hrs of data over 7 years
- 15° × 5° region, tangent to Cygnus Arm
- ≤ 3% Crab point-like sensitivity
- 4 sources, 3 of which extended

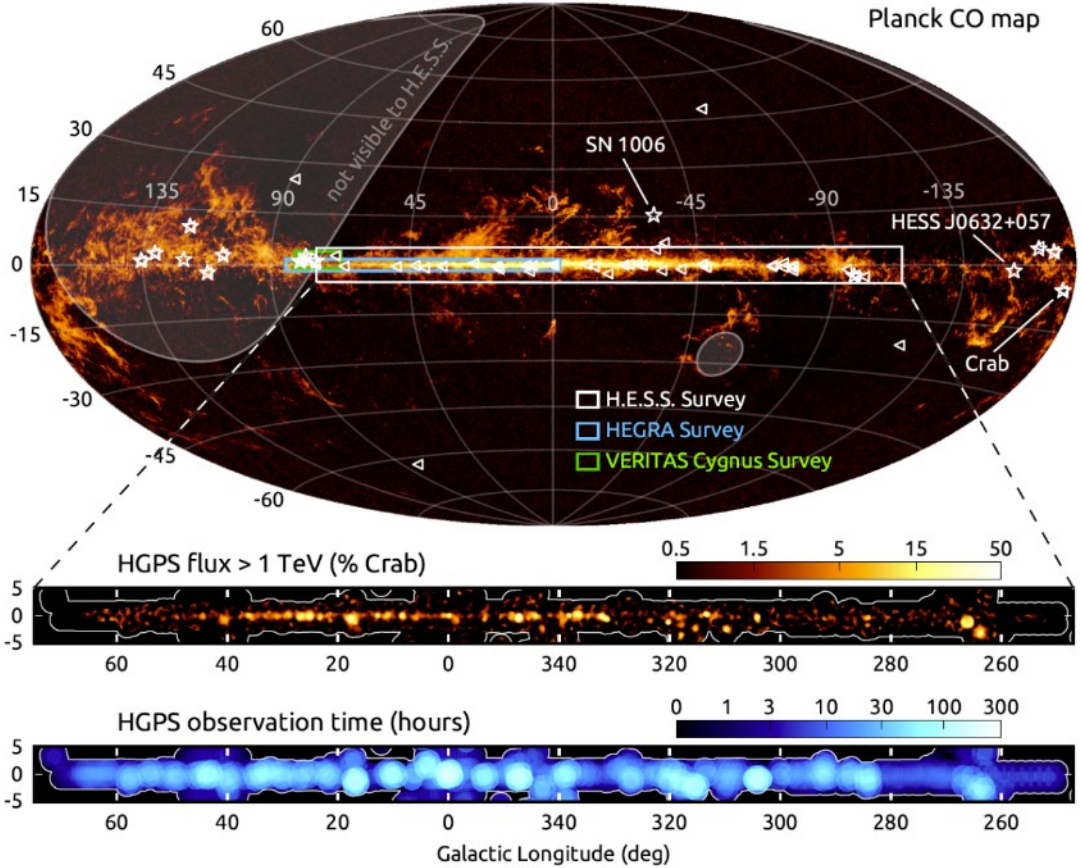
VERITAS Collaboration - ApJ 861 (2018)



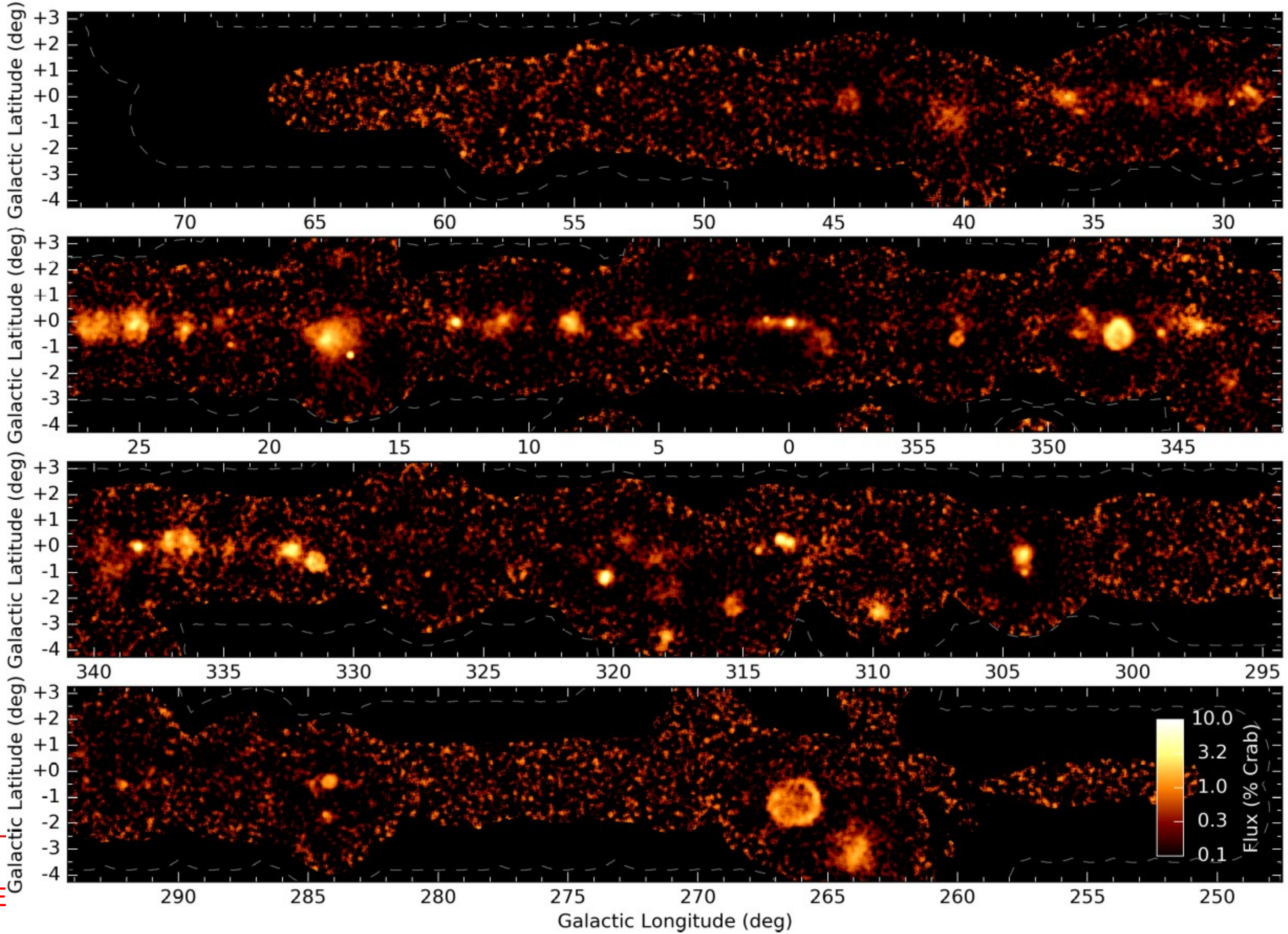
HEGRA Collaboration - A&A. 395 (2002)

H.E.S.S Legacy Survey

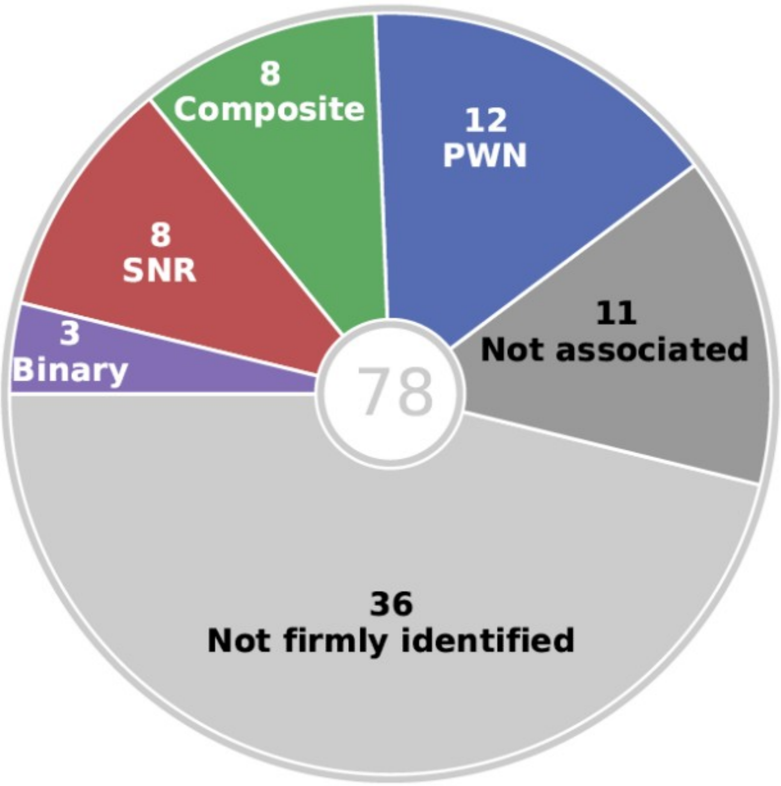
- Major H.E.S.S. project
- Data collected 2004 – 2013
  - 2673 h after quality selection
  - l in [-110°, 70°]
  - b in [-5°, 5°]
  - Inhomogeneous exposure (sources of particular interest)
- Largest VHE survey so far done by IACTs
- Maps released in FITS format



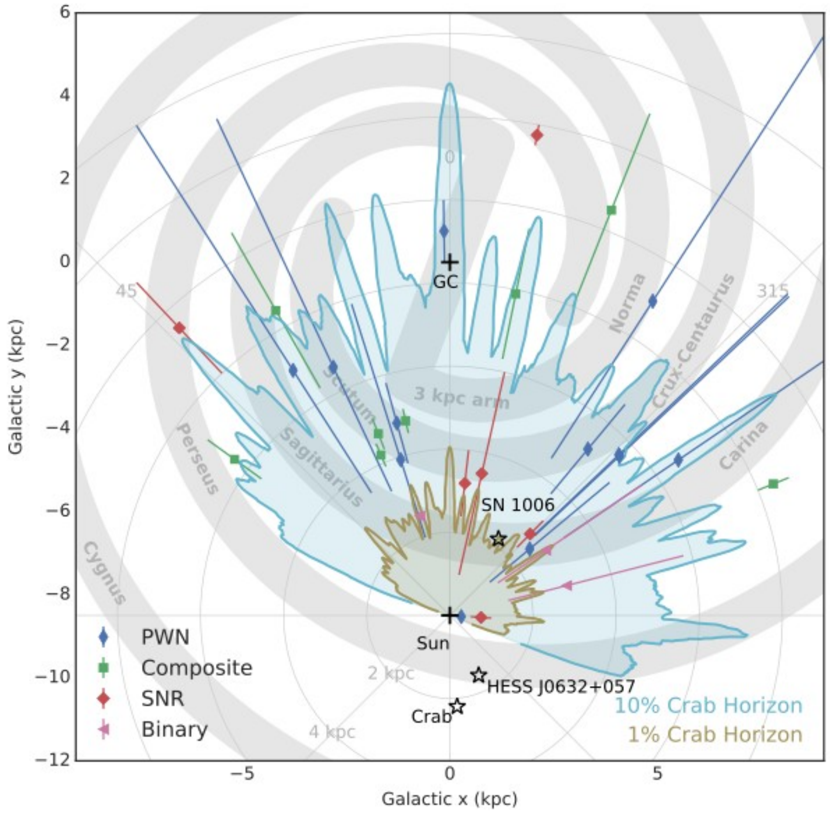
H.E.S.S. Collaboration - A&A 612 (2018)


Galactic Latitude (deg)
+3
+2
+1
+0
-1
-2
-3
-4
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
355
350
345
340
335
330
325
320
315
310
305
300
295
290
285
280
275
270
265
260
255
250
Galactic Longitude (deg)
10.0
3.2
1.0
0.3
0.1
Flux (% Crab)

Association and Identification

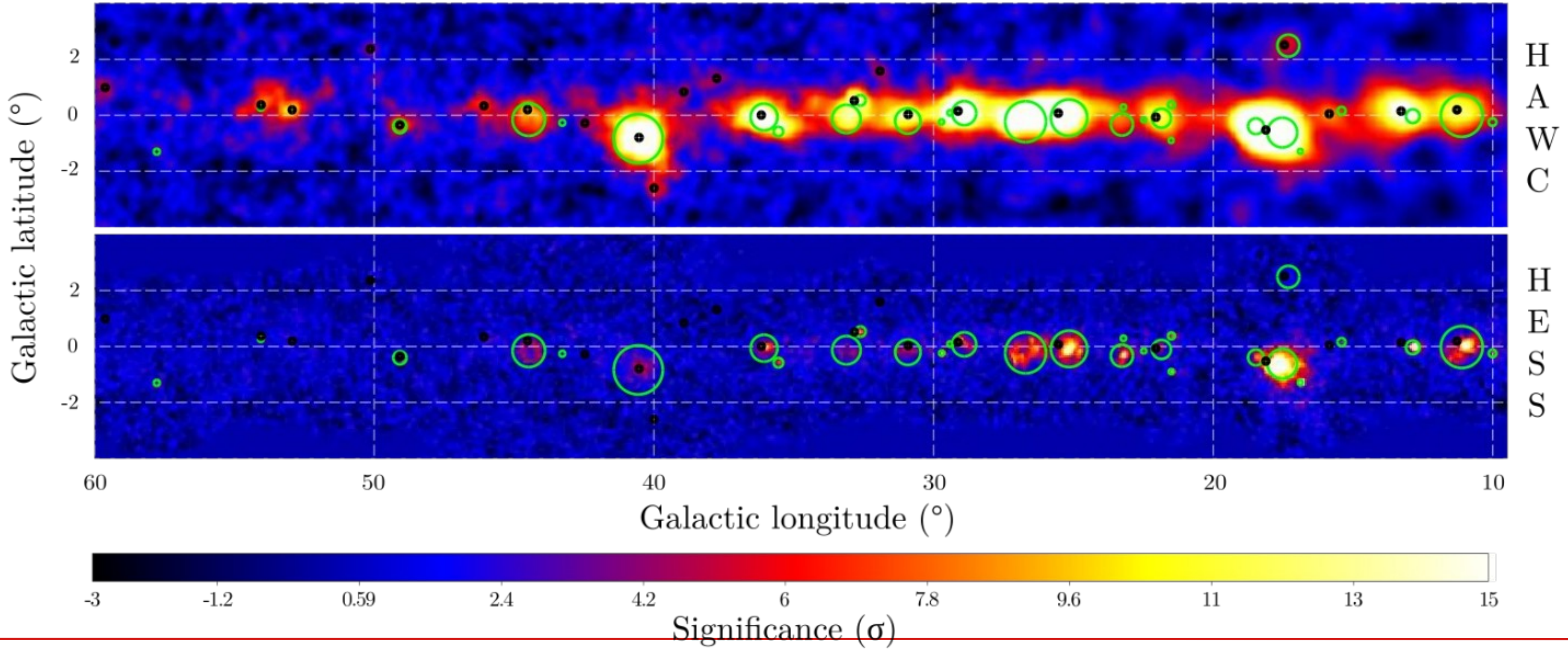


Horizon



Comparison between H.E.S.S. and HAWC

- 0.1° correlation radius: completely different pictures, due to different PSFs

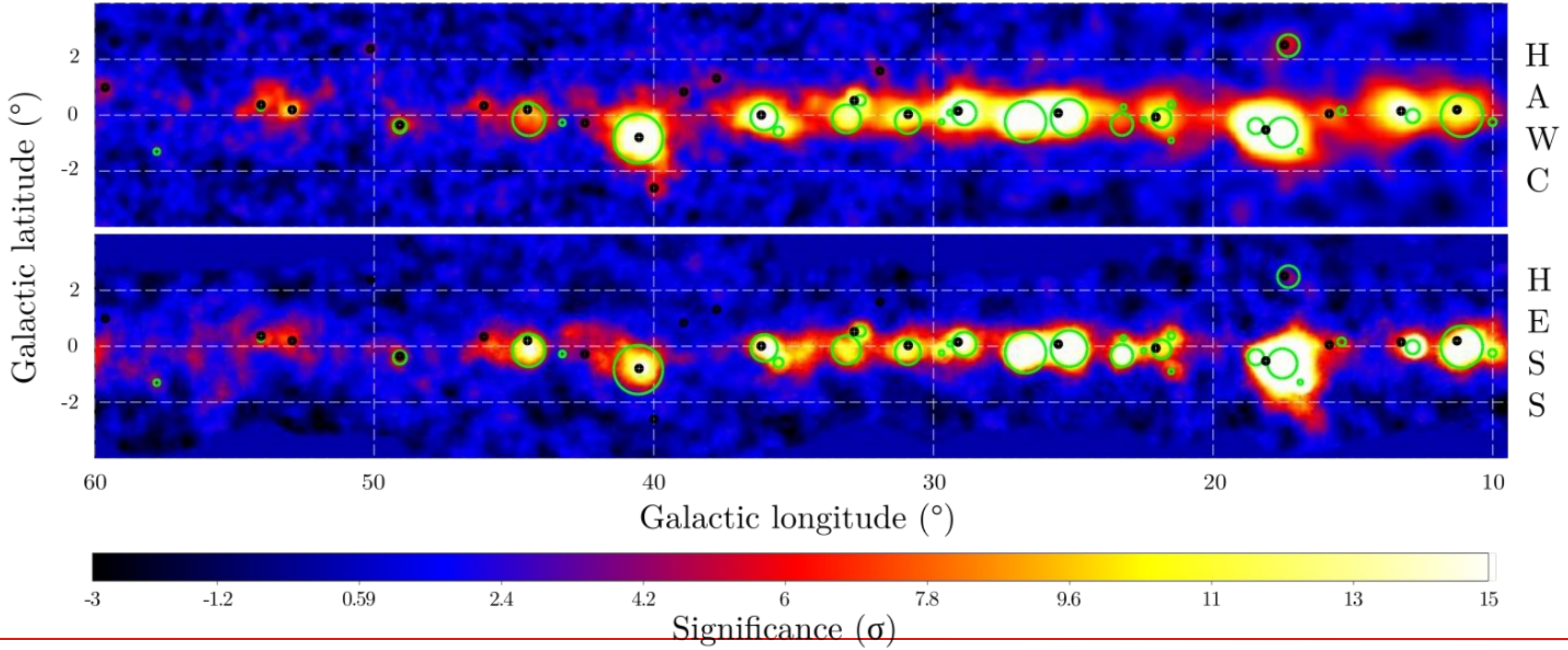


0.1° correlation radius

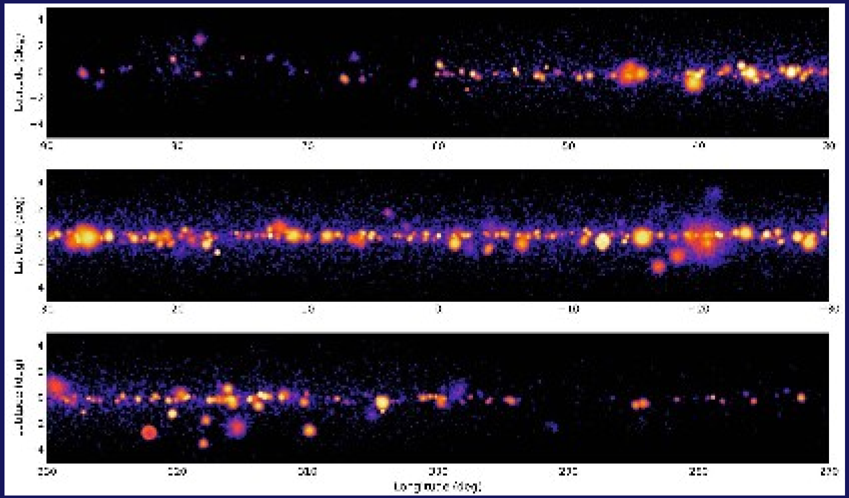
Comparison between H.E.S.S. and HAWC

Jardin-Blicq, ICRC 2019

- 0.4° correlation radius
- > 1 TeV, FieldOfView Background (comparable to HAWC)



Conclusions and outlooks



Lesson learned

- Surveys with IACTs are not easy and need:
  - Dedicated observation planning (pointing scheduling, pointing strategy, ...)
  - Specific analysis pipelines, able to deal with large amount of data acquired under vastly different conditions
  - Special care of various systematics (acceptance gradient, etc)
- Surveys are very useful and generate many results (unbiased surveys, population studies, ...)
- Mandatory for next generation of instruments (see talk by Jim Hinton)
- Given the phase-space, several analysis configurations might be useful (low & high energy, etc)
- Opensource software are the next step to go (reproducibility, combination, etc).

Role of open-source tools in future

- Automatized procedure (to be implemented!)
- 3D analysis (energy dependant maps)
- Template fitting
- Combination of several experiments in same survey

GammaPy