10 years with H.E.S.S.
Highlights and perspectives

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LAPP
13 Mars 2015

H.E.S.S. : High Energy Stereoscopic System

An array of telescopes for very-high energy gamma ray astronomy

- Mont Khomas, Namibia

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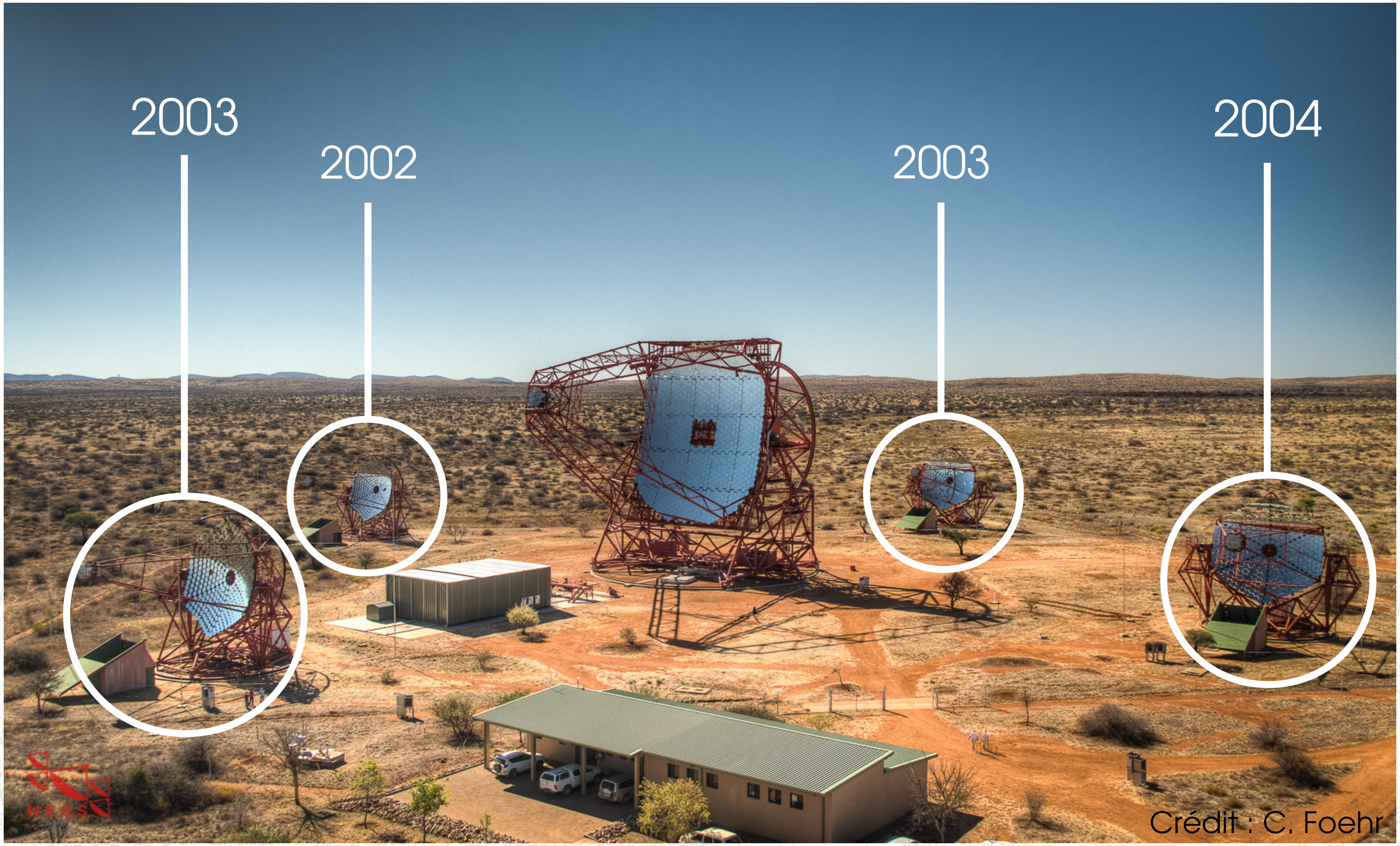

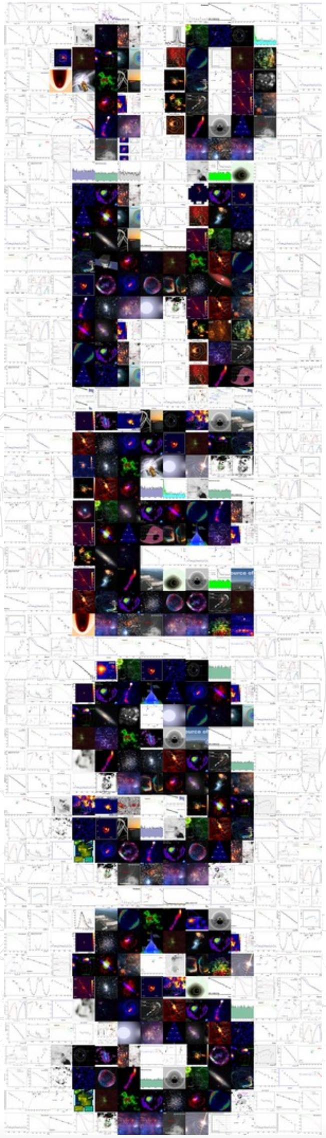

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- H.E.S.S. I : 4 telescopes – 2004

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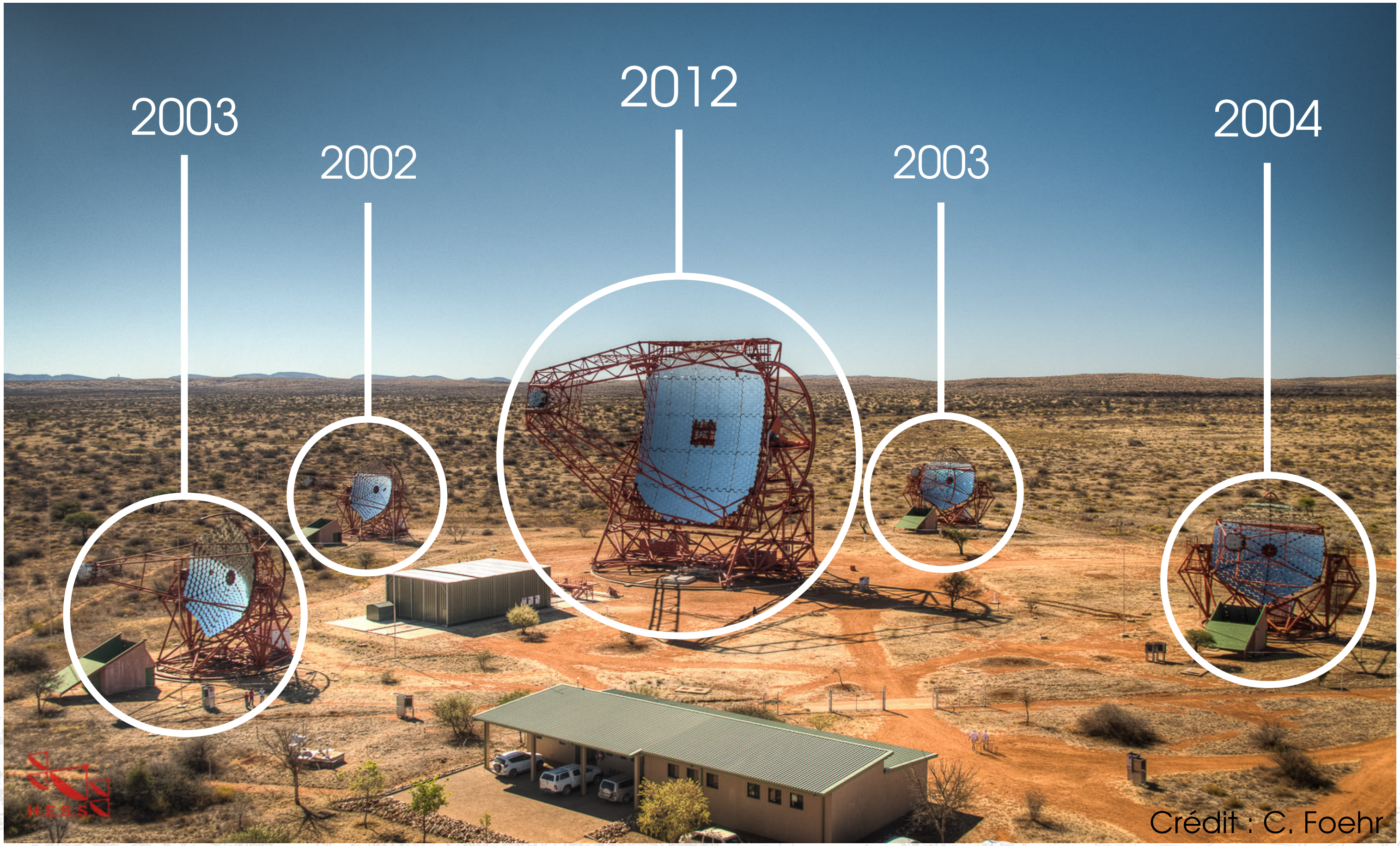

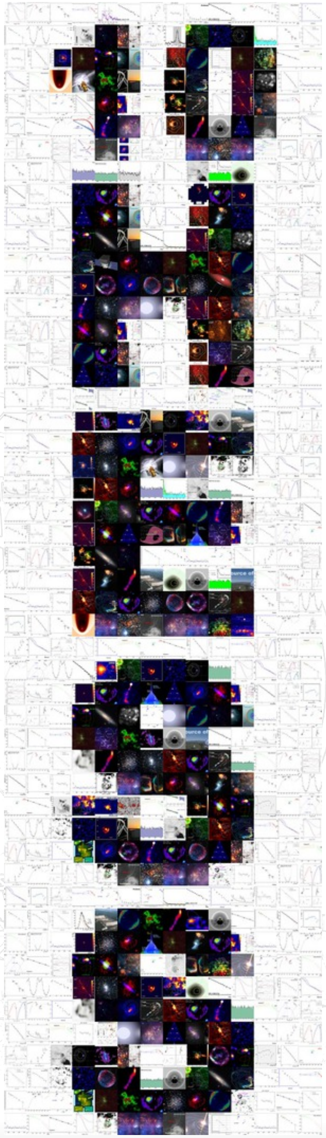

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- H.E.S.S. II : 5 telescopes - 2012

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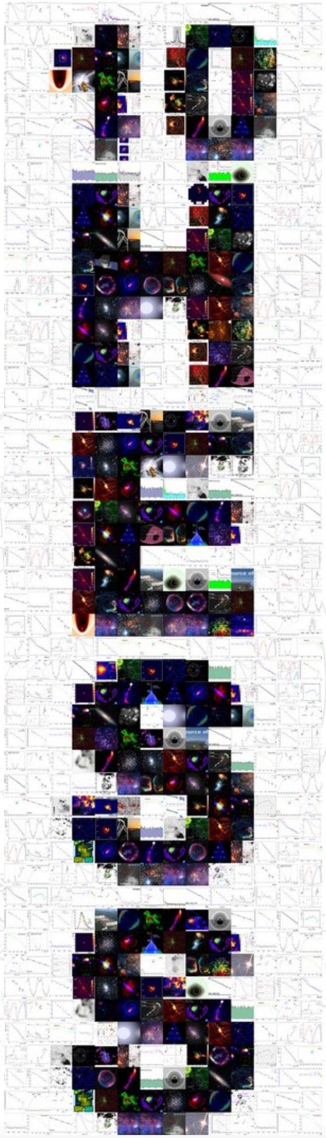

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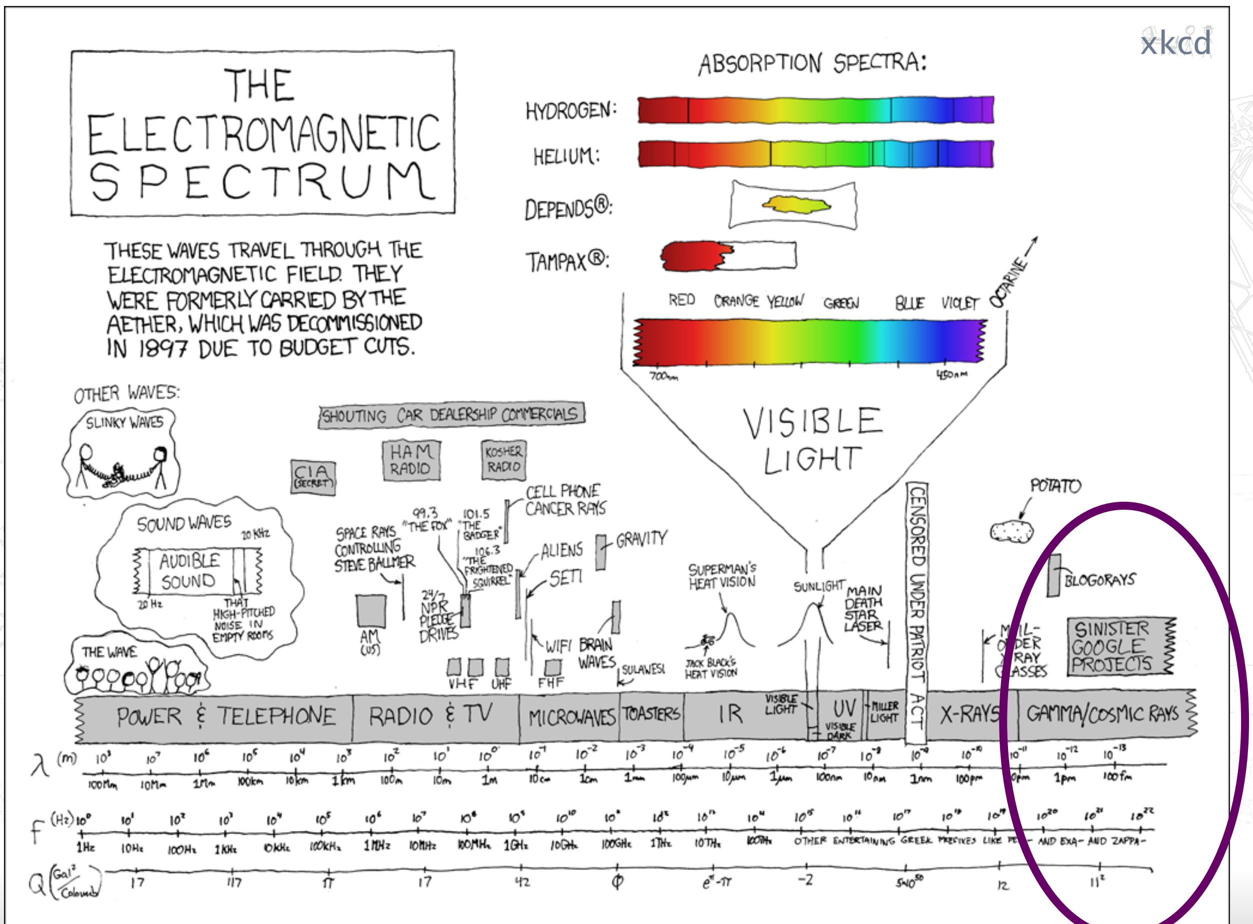
Outline

1. Very high energy gamma ray astronomy and the H.E.S.S. experiment
2. The Galactic plane survey
3. The extragalactic sky
4. H.E.S.S. phase II
5. CTA

Very high energy gamma ray astronomy

- Gamma-rays :
  - Cosmic photons with energy E > 10^5 eV
  - Very high energies : E > 100 GeV

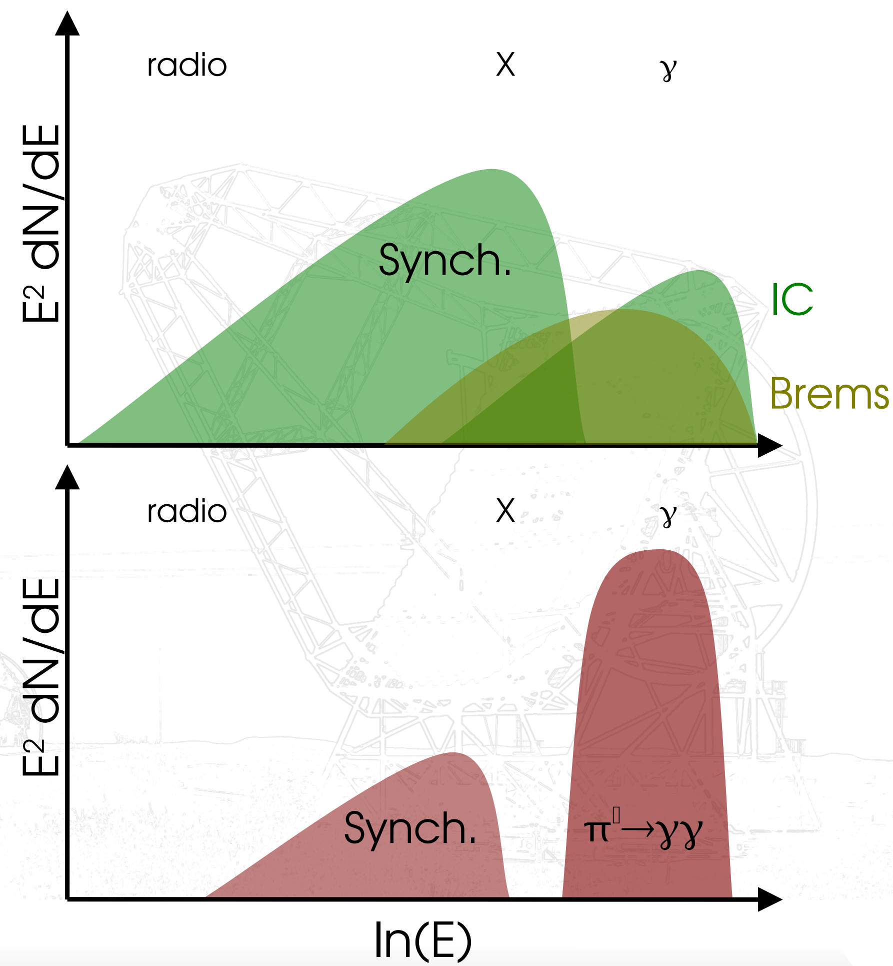


Observation of the non-thermal Universe

Cosmic particles accelerators !

Very high energy gamma ray astronomy

- Gamma-rays :
  - Production by ultra-relativistic charged particles
- Leptons :
  - γ : Inverse Compton on radiation fields (or Bremsstrahlung)
  - radio – X : Synchrotron of accelerated electrons
- Hadrons :
  - γ : neutral pions decay, from interaction with surrounding matter
  - radio – X : Synchrotron from secondary electrons



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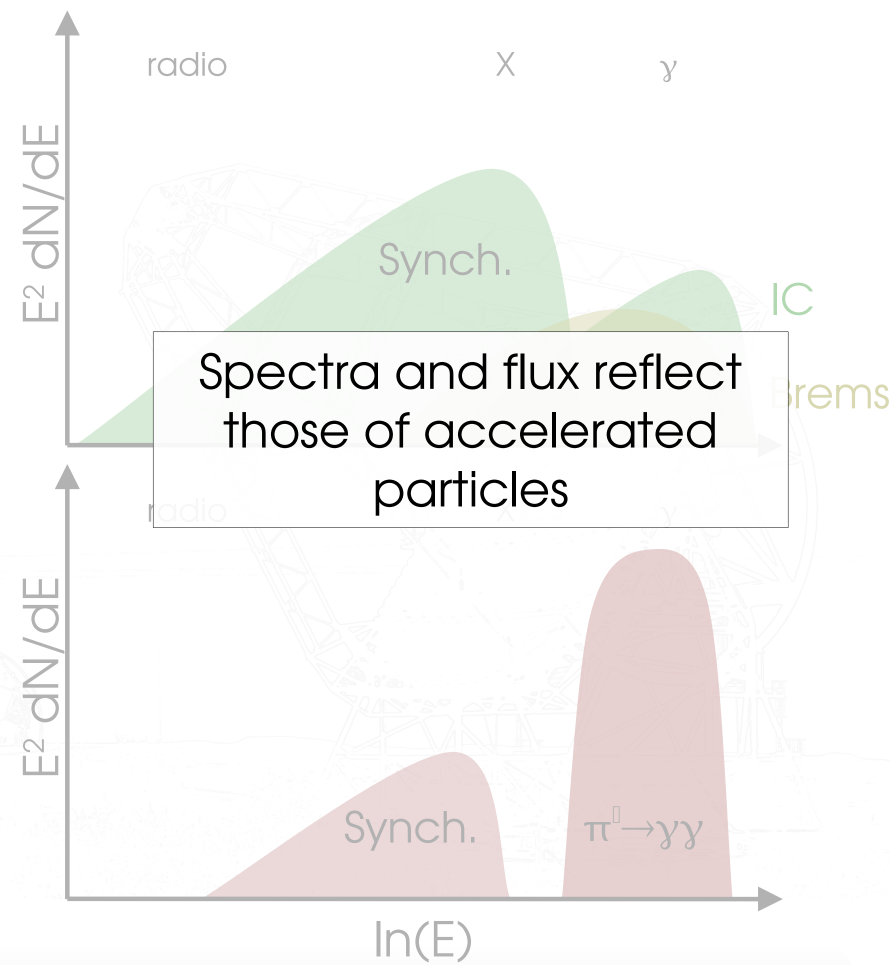
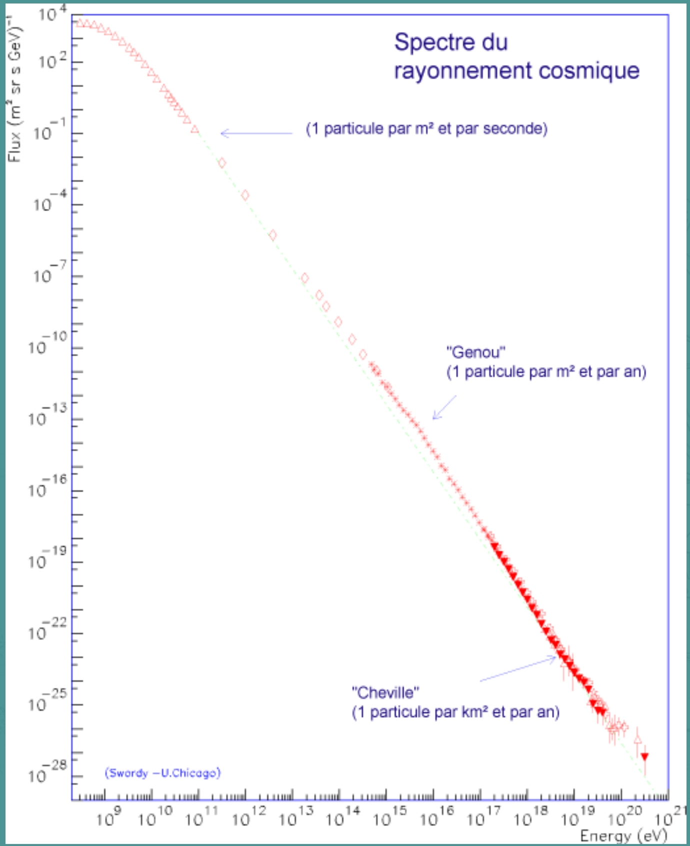


Very high energy gamma ray astronomy

- Study of charged particle acceleration in astrophysical sources
- Search for the sources of cosmic rays

- ~90% protons
- Deviation by magnetic fields :
  - ➞ impossible to identify the sources
  - ➞ Production of **neutral** tracers : high & very high energy photons !



Very high energy gamma ray astronomy

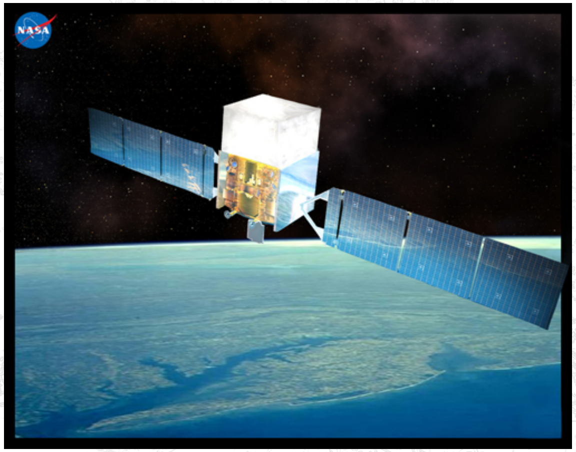
- Study of charged particle acceleration in astrophysical sources
- Search for the sources of cosmic rays

- Study the processes at play in AGNs or binary systems
- Study extragalactic background light
- Search for dark matter, LIV, axions...

Very high energy gamma ray astronomy

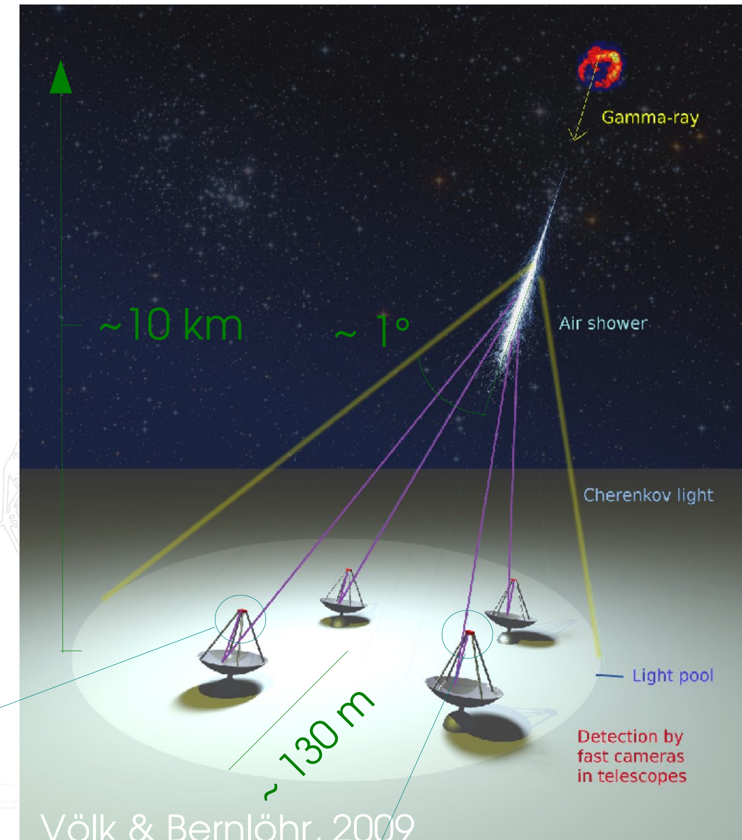
- Detection

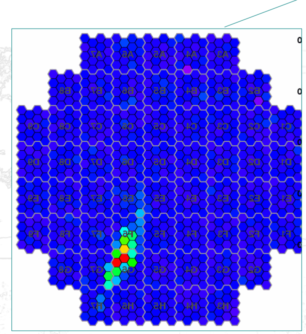
< 100 GeV : detection from satellite (Fermi)
> 100 GeV : detection from ground (H.E.S.S.) :
➔ Imaging atmospheric Cherenkov technique

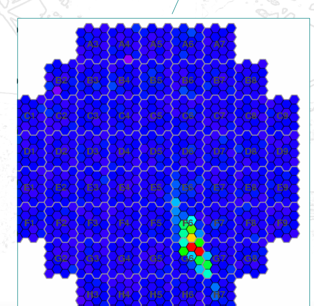


The imaging atmospheric Cherenkov technique

- γ interacts in the atmosphere
- Development of a particle shower
- Emission of a brief (~ few ns) and weak flash of Cherenkov light
- Image of the shower with cameras at the focal plane of telescopes : stereoscopy



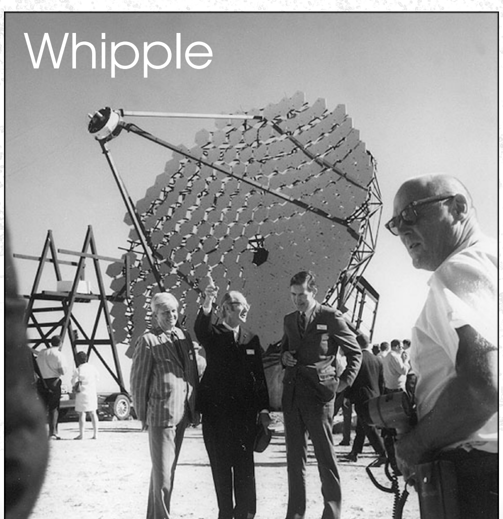




The imaging atmospheric Cherenkov technique

- The technique works best with :
  - **Large mirrors**
  - **Fast** and **finely pixelated** cameras
  - **Stereoscopy**

H.E.S.S. combines these advantages, inherited from the previous generations of instruments



The imaging atmospheric Cherenkov technique

First detection of a TeV gamma-ray source (1989) : The Crab nebula
5σ detection in 50h

Opening of a new astronomical window !

The imaging atmospheric Cherenkov technique

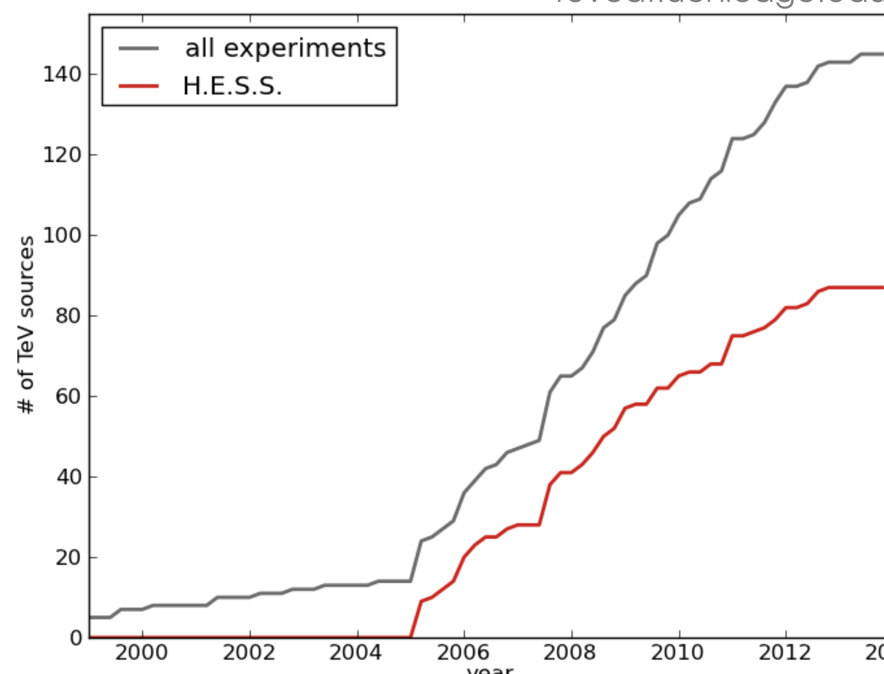
First detection of a TeV gamma-ray source (1989) : The Crab nebula
5σ detection in 50h

Sensitivity : 1% of the Crab nebula flux in 25h

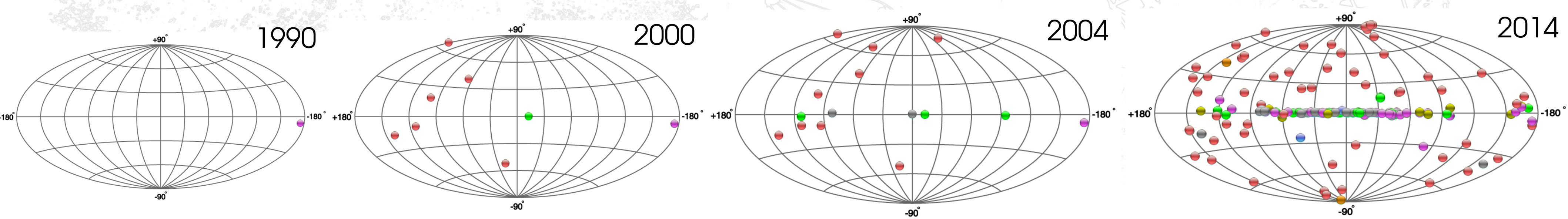
H.E.S.S. : 10 years of operation

- ~ 10 000 hours of observations
  - ~50% Galactic / 50% extragalactic
  - $6x10^9$ events
- ~ 90 new sources
  - ~ 60 Galactic / ~ 30 extragalactic

tevcat.uchicago.edu

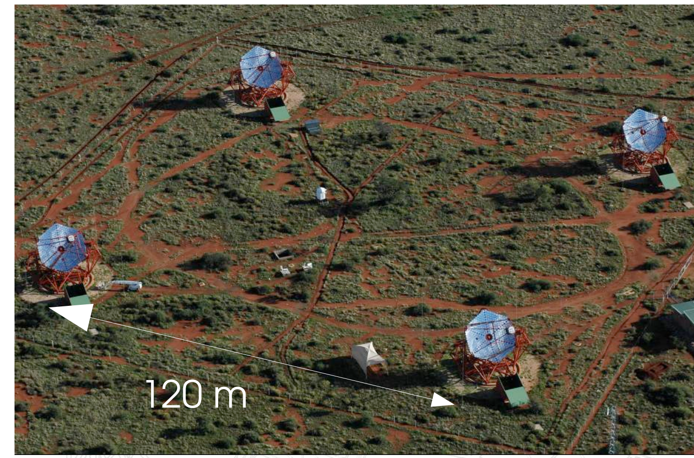


All: Whipple, Crimea, Telescope Array, Durham, MAGIC, VERITAS, H.E.S.S.



The H.E.S.S. array

- High Energy Stereoscopic System
  - 4 telescopes of 107 m²
  - Cameras with 960 PMTs
  - Field of view : 5°
  - 100 GeV – 50 TeV (resolution ~ 10%)
  - Angular resolution < 0.1°



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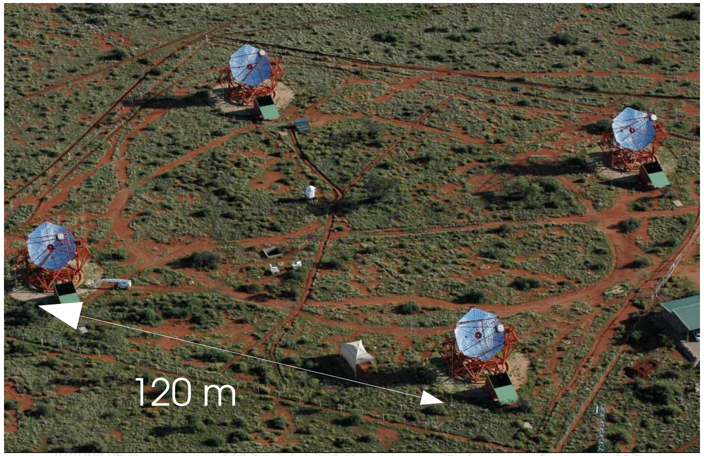

« Real » astronomy in a new energy band

- A sensitive instrument (1 % « Crab ») ...

  ... on more than 2 orders of magnitude in energy
- Morphology studies
- Survey capabilities
- Detailed light-curves

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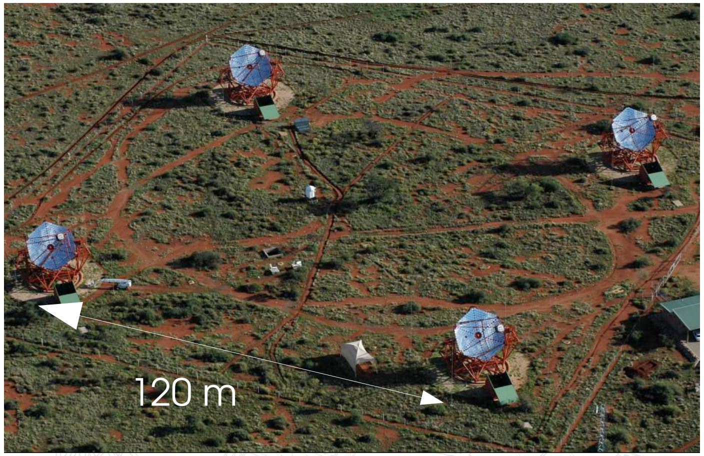


MPI Kernphysik, Heidelberg, Humboldt Univ. zu Berlin, Ruhr-Univ. Bochum, Univ. Erlangen-Nürnberg, Univ. Hamburg, LSW Heidelberg, Univ. Potsdam, Univ. Tübingen, DESY,

Ecole Polytechnique, Palaiseau, APC Paris, Univ. Paris VI-VII Paris, Univ. Bordeaux, Observatory, Meudon, LAPP Annecy, LUPM Montpellier, CEA Saclay,

Durham Univ., Univ. Leceister, Dublin Inst. for Adv. Studies,

Polish Academy of Sciences, Warsaw Jagiellonian Univ., Cracow Charles Univ., Prague, Yerewan Physics Inst.

Univ. Adelaide, North-West Univ. Potchefstroom, Univ. of Namibia, Windhoek

...

38 institutes from 13 countries

The H.E.S.S. array

F. Aharonian[1], A.G. Akhperjanian[2], K.-M. Aye[3], A.R. Bazer-Bachi[4], M. Beilicke[5], W. Benbow[1], D. Berge[1], P. Berghaus[6], K. Bernlöhr[1,7], O. Bolz[1], C. Boisson[8], C. Borgmeier[7], F. Breitling[7], A.M. Brown[3], J. Bussons Gordo[9], P.M. Chadwick[3], V.R. Chitnis[10,20 ⋆], L.-M. Chounet[11], R. Cornils[5], L. Costamante[1,20], B. Degrange[11], A. Djannati-Ataï[6], L.O'C. Drury[12], T. Ergin[7], P. Espigat[6], F. Feinstein[9], P. Fleury[11], G. Fontaine[11], S. Funk[1], Y. Gallant[9], B. Giebels[11], S. Gillessen[1], P. Goret[13], J. Guy[10], C. Hadjichristidis[3], M. Hauser[14], G. Heinzelmann[5], G. Henri[15], G. Hermann[1], J.A. Hinton[1], W. Hofmann[1], M. Holleran[16], D. Horns[1], O.C. de Jager[16], I. Jung[1,14 ⋆⋆], B. Khélifi[1], Nu. Komin[7], A. Konopelko[1,7], I.J. Latham[3], R. Le Gallou[3], M. Lemoine[11], A. Lemière[6], N. Leroy[11], T. Lohse[7], A. Marcowith[4], C. Masterson[1,20], T.J.L. McComb[3], M. de Naurois[10], S.J. Nolan[3], A. Noutsos[3], K.J. Orford[3], J.L. Osborne[3], M. Ouchrif[10,20], M. Panter[1], G. Pelletier[15], S. Pita[6], M. Pohl[17⋆⋆⋆], G. Pühlhofer[1,14], M. Punch[6], B.C. Raubenheimer[16], M. Raue[5], J. Raux[10], S.M. Rayner[3], I. Redondo[11,20†], A. Reimer[17], O. Reimer[17], J. Ripken[5], M. Rivoal[10], L. Rob[18], L. Rolland[10], G. Rowell[1], V. Sahakian[2], L. Saugé[15], S. Schlenker[7], R. Schlickeiser[17], C. Schuster[17], U. Schwanke[7], M. Siewert[17], H. Sol[8], R. Steenkamp[19], C. Stegmann[7], J.-P. Tavernet[10], C.G. Théoret[6], M. Tluczykont[11,20], D.J. van der Walt[16], G. Vasileiadis[9], P. Vincent[10], B. Visser[16], H.J. Völk[1], and S.J. Wagner[14]

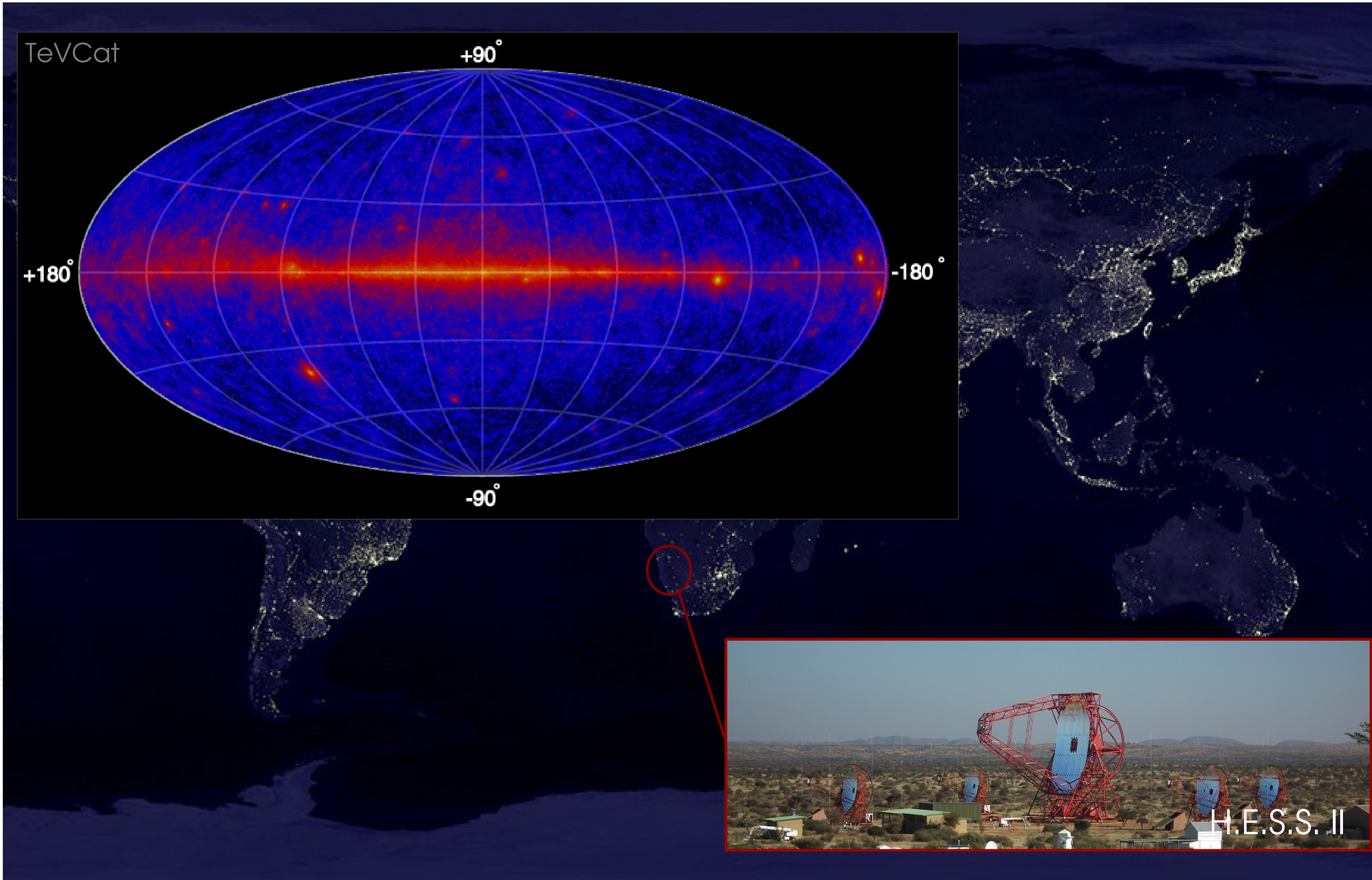
2004
~100 co-authors

H.E.S.S. Collaboration, A. Abramowski[1], F. Aharonian[2,3,4], F. Ait Benkhali[2], A.G. Akhperjanian[5,4], E. Angüner[6], G. Anton[7], S. Balenderan[8], A. Balzer[9,10], A. Barnacka[11], Y. Becherini[12], J. Becker Tjus[13], K. Bernlöhr[2,6], E. Birsin[6], E. Bissaldi[14], J. Biteau[15,16], M. Böttcher[17], C. Boisson[18], J. Bolmont[19], P. Bordas[20], J. Brucker[7], F. Brun[2], P. Brun[21], T. Bulik[22], S. Carrigan[2], S. Casanova[17,2], M. Cerruti[18,23], P.M. Chadwick[8], R. Chalme-Calvet[19], R.C.G. Chaves[21], A. Cheesebrough[8], M. Chrétien[19], S. Colafrancesco[24], G. Cologna[25], J. Conrad[26,27], C. Couturier[19], Y. Cui[20], M. Dalton[28,29], M.K. Daniel[8], I.D. Davids[17,30], B. Degrange[15], C. Deil[2], P. deWilt[31], H.J. Dickinson[26], A. Djannati-Ataï[32], W. Domainko[2], L.O'C. Drury[3], G. Dubus[33], K. Dutson[34], J. Dyks[11], M. Dyrda[35], T. Edwards[2], K. Egberts[14], P. Eger[2], P. Espigat[32], C. Farnier[26], S. Fegan[15], F. Feinstein[36], M.V. Fernandes[1], D. Fernandez[36], A. Fiasson[37], G. Fontaine[15], A. Förster[2], M. Füßling[10], M. Gajdus[6], Y.A. Gallant[36], T. Garrigoux[19], G. Giavitto[9], B. Giebels[15], J.F. Glicenstein[21], M.-H. Grondin[2,25], M. Grudzińska[22], S. Häffner[7], J. Hahn[2], J. Harris[8], G. Heinzelmann[1], G. Henri[33], G. Hermann[2], O. Hervet[18], A. Hillert[2], J.A. Hinton[34], W. Hofmann[2], P. Hofverberg[2], M. Holler[10], D. Horns[1], A. Jacholkowska[19], C. Jahn[7], M. Jamrozy[38], M. Janiak[11], F. Jankowsky[25], I. Jung[7], M.A. Kastendieck[1], K. Katarzyński[39], U. Katz[7], S. Kaufmann[25], B. Khélifi[32], M. Kieffer[19], S. Klepser[9], D. Klochkov[20], W. Kluźniak[11], T. Kneiske[1], D. Kolitzus[14], Nu. Komin[37], K. Kosack[21], S. Krakau[13], F. Krayzel[37], P.P. Krüger[17,2], H. Laffon[28], G. Lamanna[37], J. Lefaucheur[32], A. Lemière[32], M. Lemoine-Goumard[28], J.-P. Lenain[19], D. Lennarz[2], T. Lohse[6], A. Lopatin[7], C.-C. Lu[2], V. Marandon[2], A. Marcowith[36], R. Marx[2], G. Maurin[37], N. Maxted[31], M. Mayer[10], T.J.L. McComb[8], J. Méhault[28,29], P.J. Meintjes[40], U. Menzler[13], M. Meyer[26], R. Moderski[11], M. Mohamed[25], E. Moulin[21], T. Murach[6], C.L. Naumann[19], M. de Naurois[15], J. Niemiec[35], S.J. Nolan[8], L. Oakes[6], S. Ohm[34], E. de Oña Wilhelmi[2], B. Opitz[1], M. Ostrowski[38], I. Oya[6], M. Panter[2], R.D. Parsons[2], M. Paz Arribas[6], N.W. Pekeur[17], G. Pelletier[33], J. Perez[14], P.-O. Petrucci[33], B. Peyaud[21], S. Pita[32], H. Poon[2], G. Pühlhofer[20], M. Punch[32], A. Quirrenbach[25], S. Raab[7], M. Raue[1], A. Reimer[14], O. Reimer[14], M. Renaud[36], R. de los Reyes[2], F. Rieger[2], L. Rob[41], C. Romoli[3], S. Rosier-Lees[37], G. Rowell[31], B. Rudak[11], C.B. Rulten[18], V. Sahakian[5,4], D.A. Sanchez[2,37], A. Santangelo[20], R. Schlickeiser[13], F. Schüssler[21], A. Schulz[9], U. Schwanke[6], S. Schwarzburg[20], S. Schwemmer[25], H. Sol[18], G. Spengler[6], F. Spies[1], L. Stawarz[38], R. Steenkamp[30], C. Stegmann[10,9], F. Stinzing[7], K. Stycz[9], I. Sushch[6,17], A. Szostek[38], J.-P. Tavernet[illegible], [illegible] Tavernier[32], A.M. Taylor[3], R. Terrier[32], M. Tluczykont[1], C. Trichard[37], K. Valerius[7], C. van Eldik[7], B. van Soelen[40], G. Vasileiadis[36], C. Venter[17], A. Viana[2], P. Vincent[19], H.J. Völk[2], F. Volpe[2], M. Vorster[17], [illegible], M. Ward[8], M. Weidinger[13], Q. Weitzel[2], R. White[34], A. Wierzcholska[illegible], [illegible] Wouters[21], V. Zabalza[2], M. Zacharias[13], A. Zajczyk[11,36], A.A. Zdziarski[11], A. Zech[18], and H.-S. Zechlin[1]

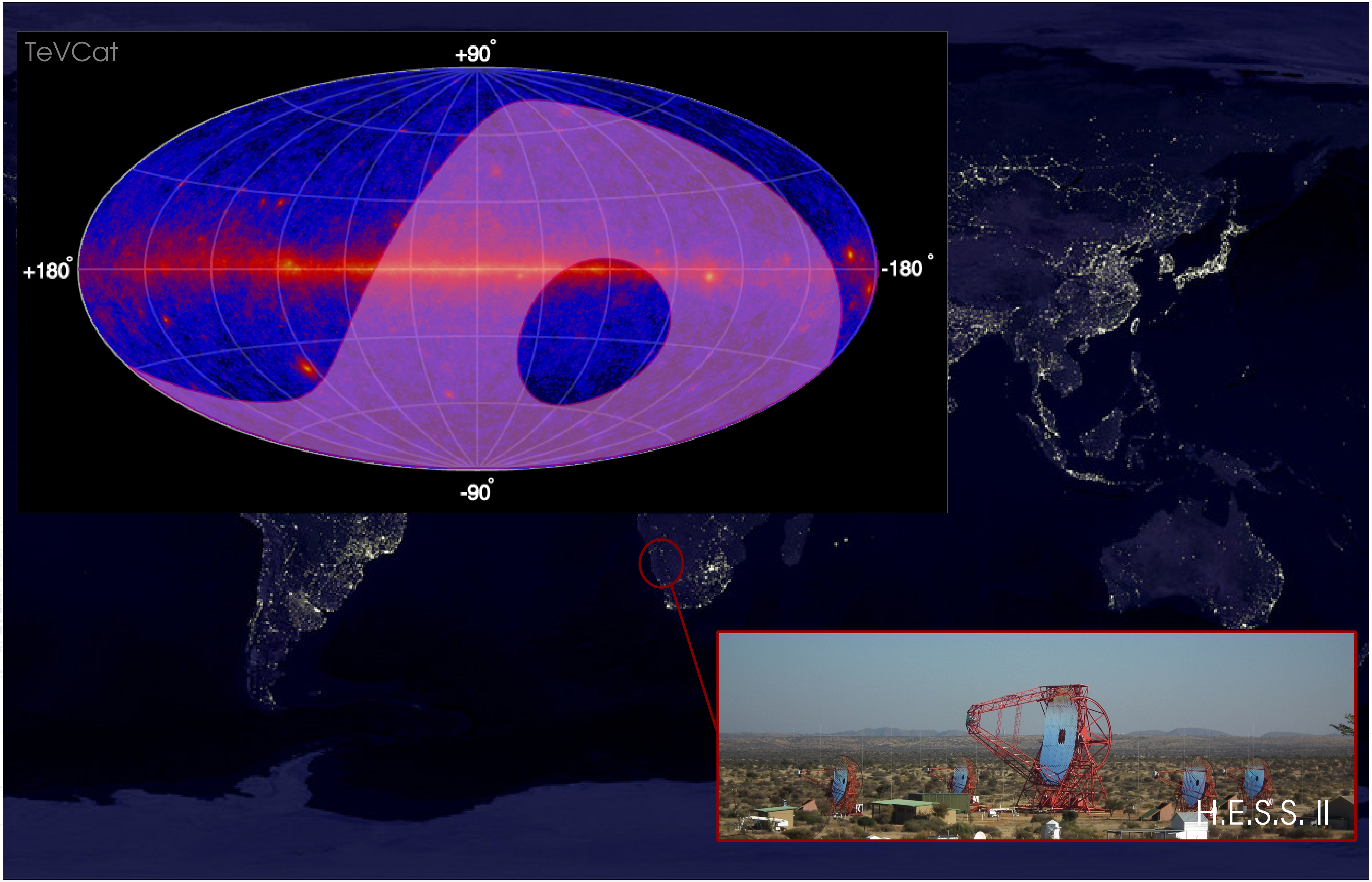
2014
~200 co-authors

Instruments currently in operation

A southern hemisphere observatory



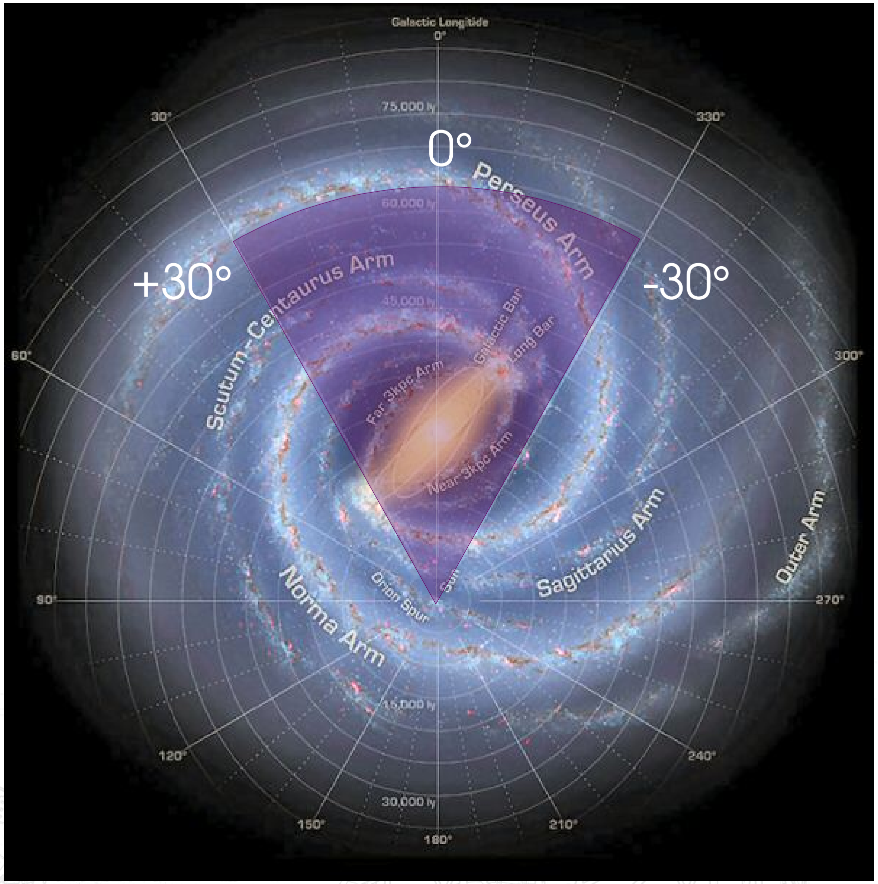
A southern hemisphere observatory

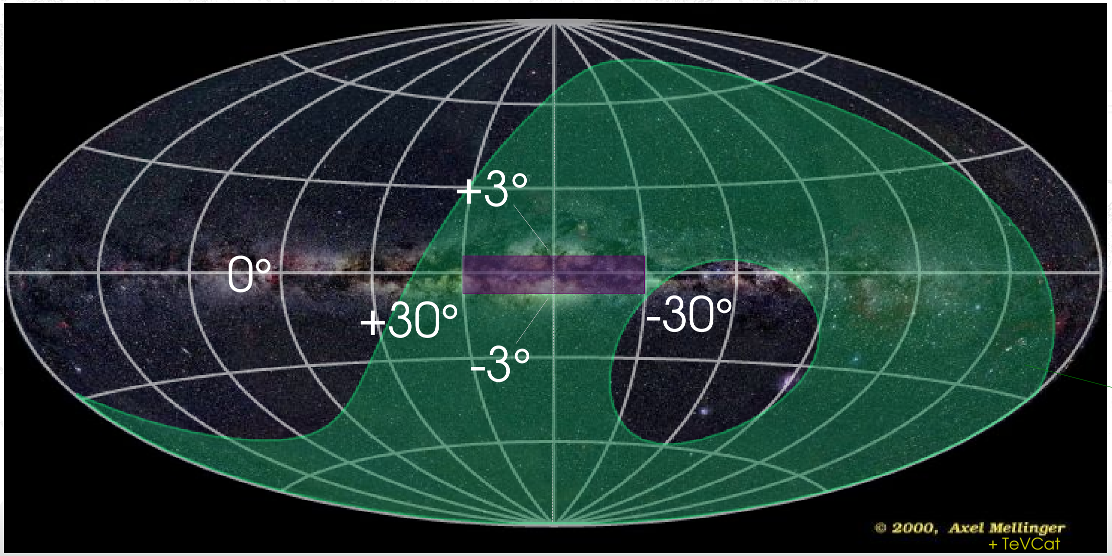


The Galactic Plane Survey

The Galactic plane survey

- **Goal** : Map the inner regions of the Galaxy to discover new TeV sources
- **First survey (2004)** :
  - ~ 230 hours of observation
  - -30° to +30° in longitude
  - -3° to +3° in latitude





Optimal H.E.S.S. visibility

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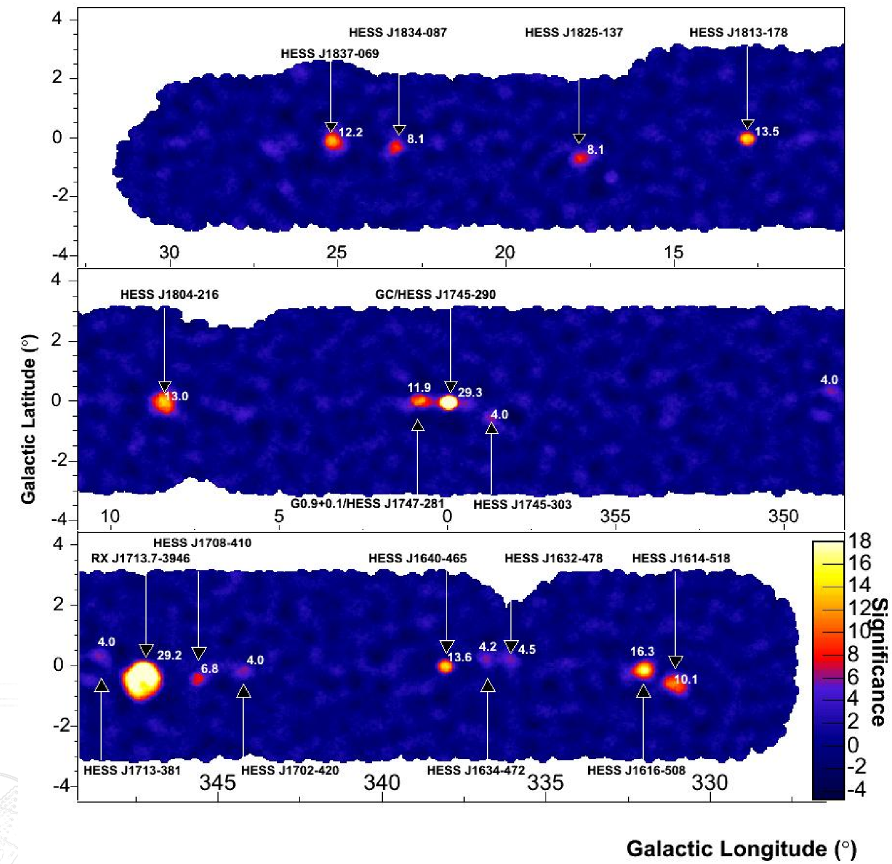
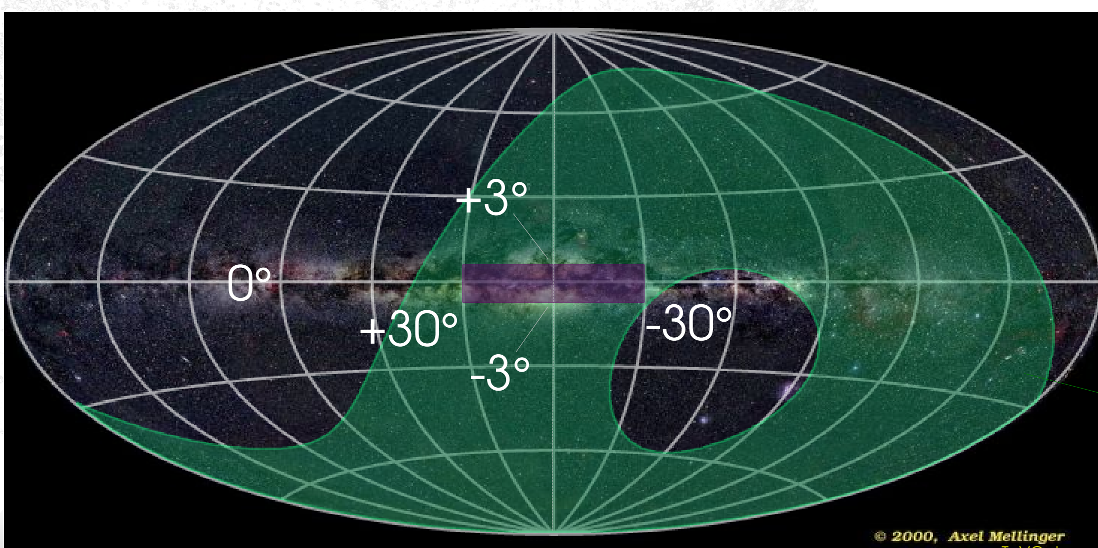
HESS Collaboration (2005)



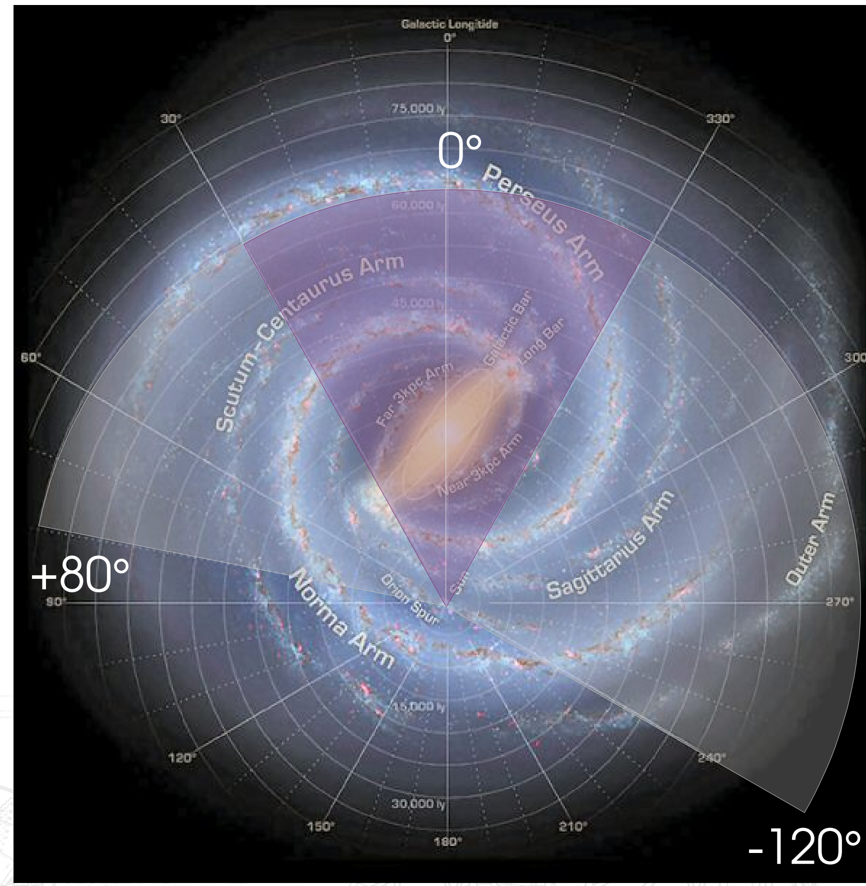


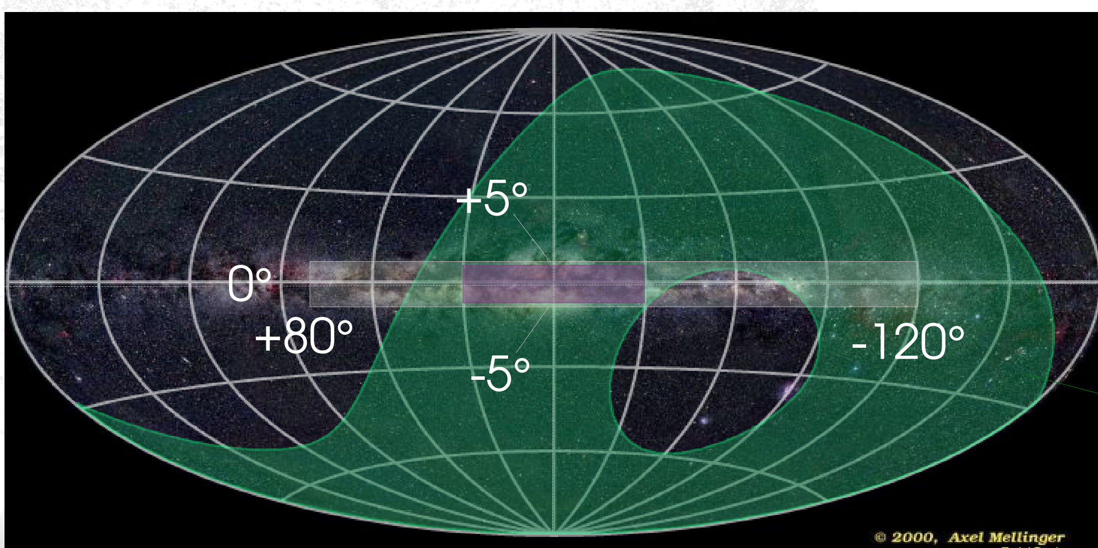
Optimal H.E.S.S. visibility

The Galactic plane survey

- **Goal** : Map the inner regions of the Galaxy to discover new TeV sources

- **Since 2004** :
  - ~ 2800 hours of observation
  - -120° to +80° in longitude
  - -5° to +5° in latitude

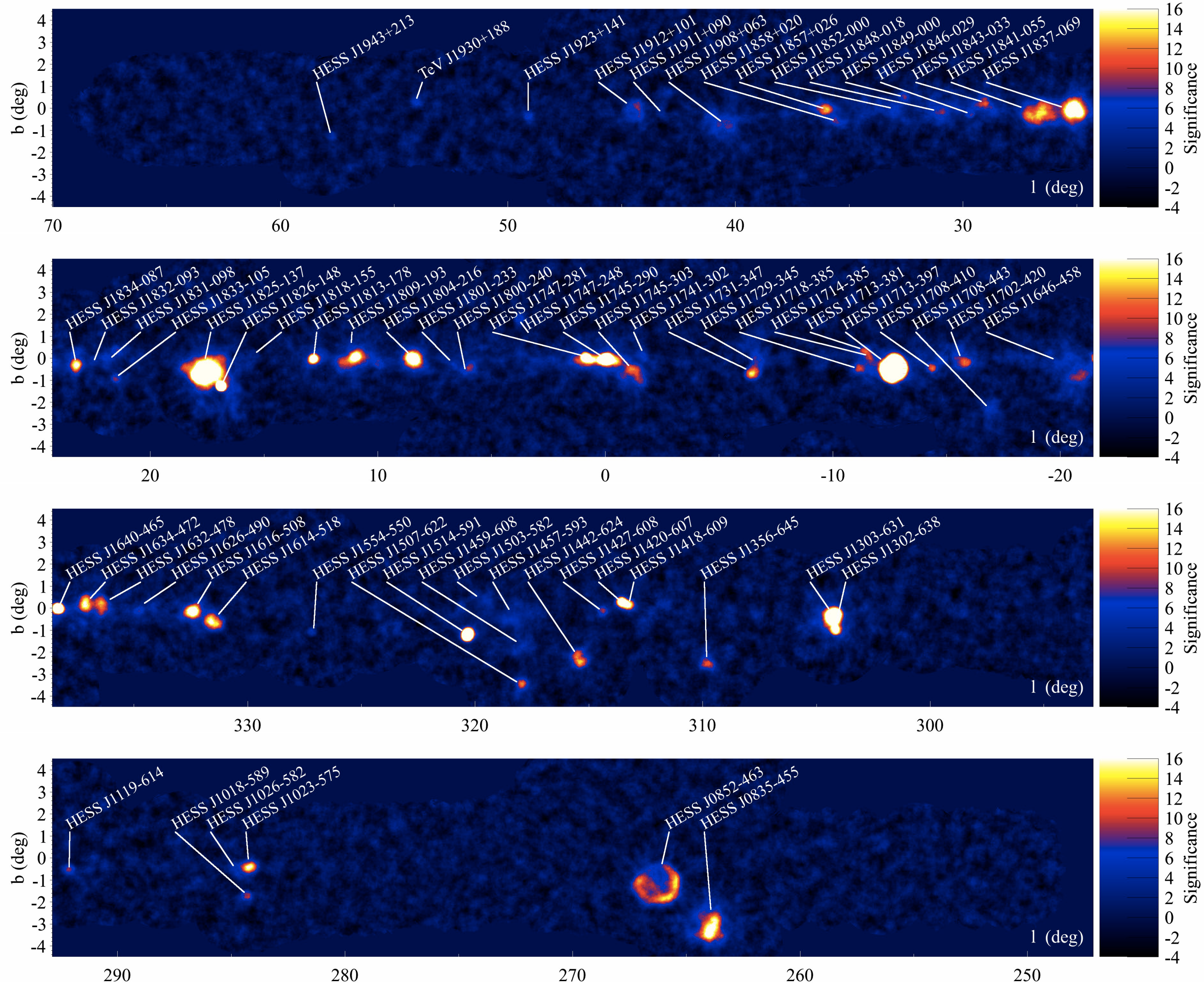




Optimal H.E.S.S. visibility

The Galactic plane survey

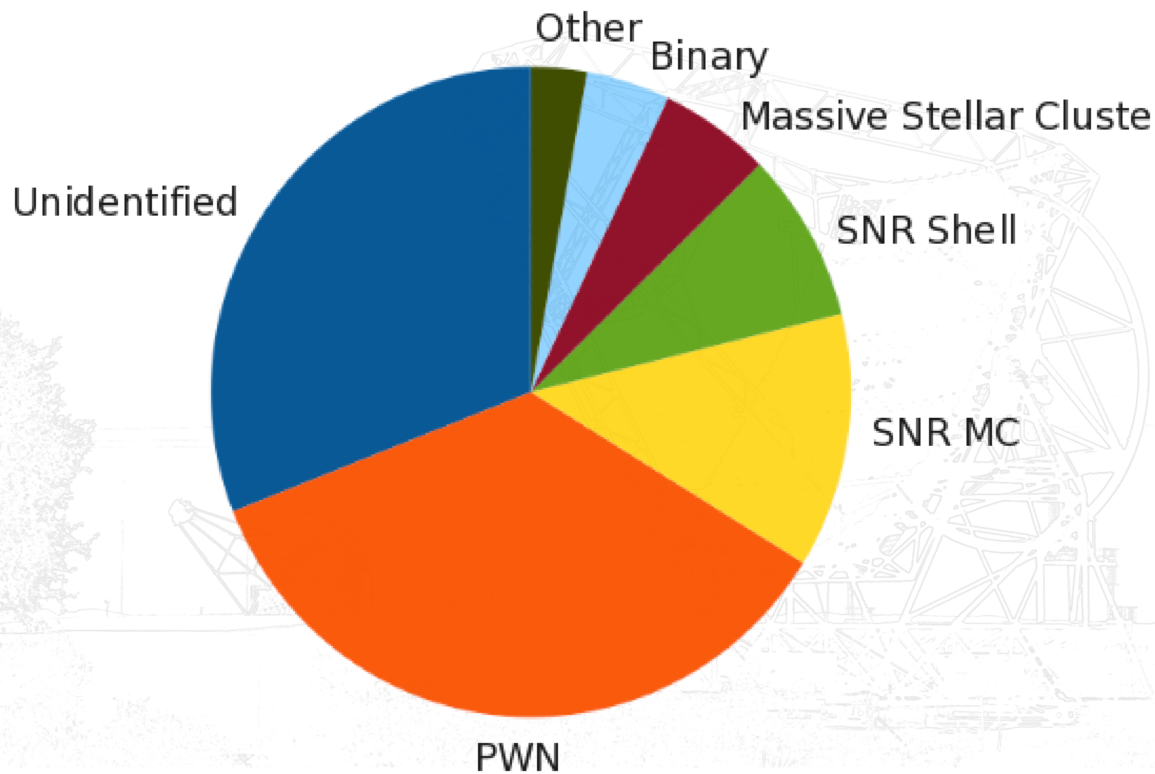
Significance map (pre-trials),
correlation radius : 0.1°
blue-red transition ~ 5σ post-trials



S. Carrigan, **F. Brun** et al., 2013 (ICRC)

The Galactic plane survey

- More than **60 new sources detected** at very high energies with H.E.S.S.
  - Large variety of source types : supernova remnants, pulsar wind nebulae, binaries...



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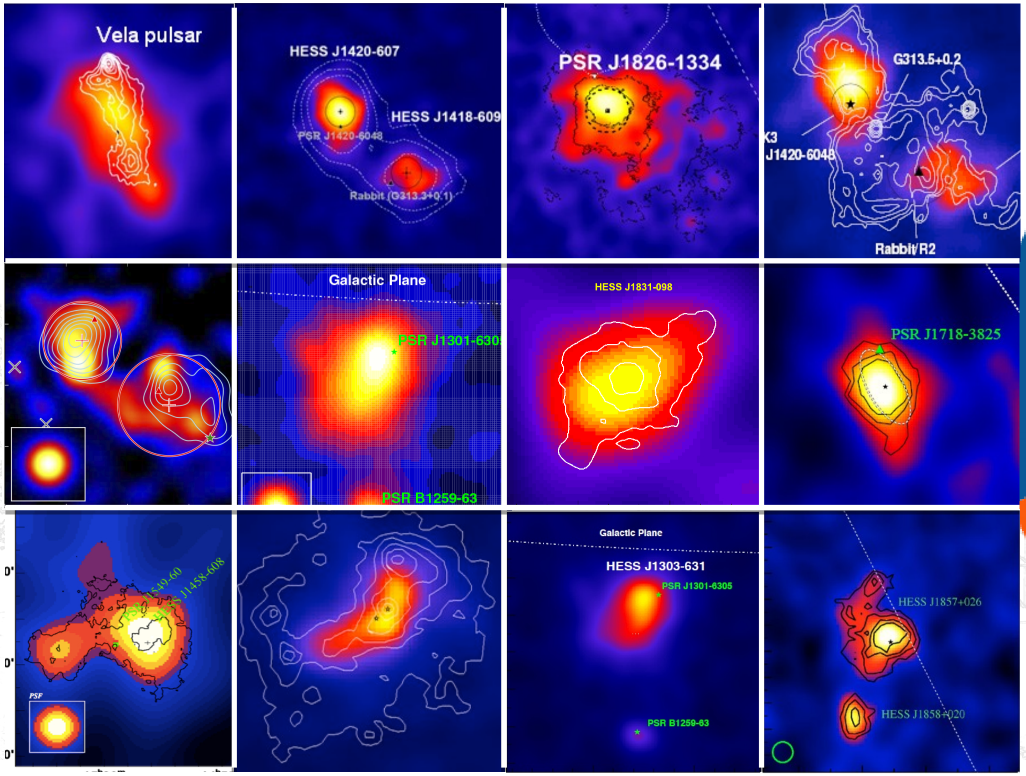

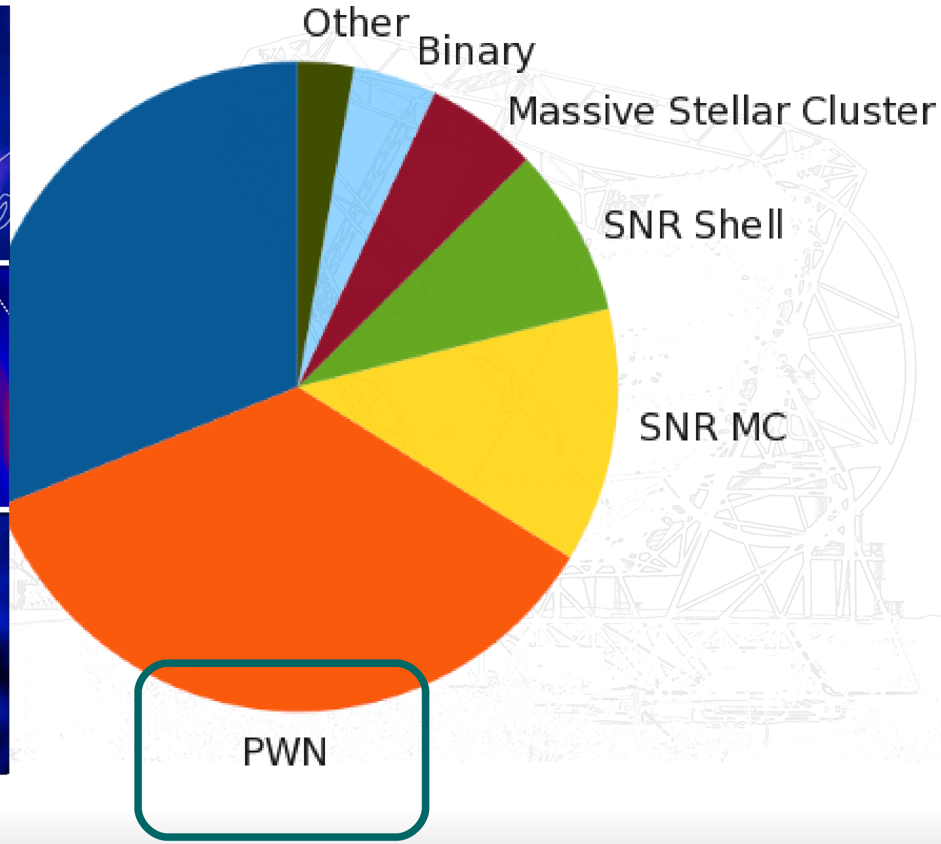

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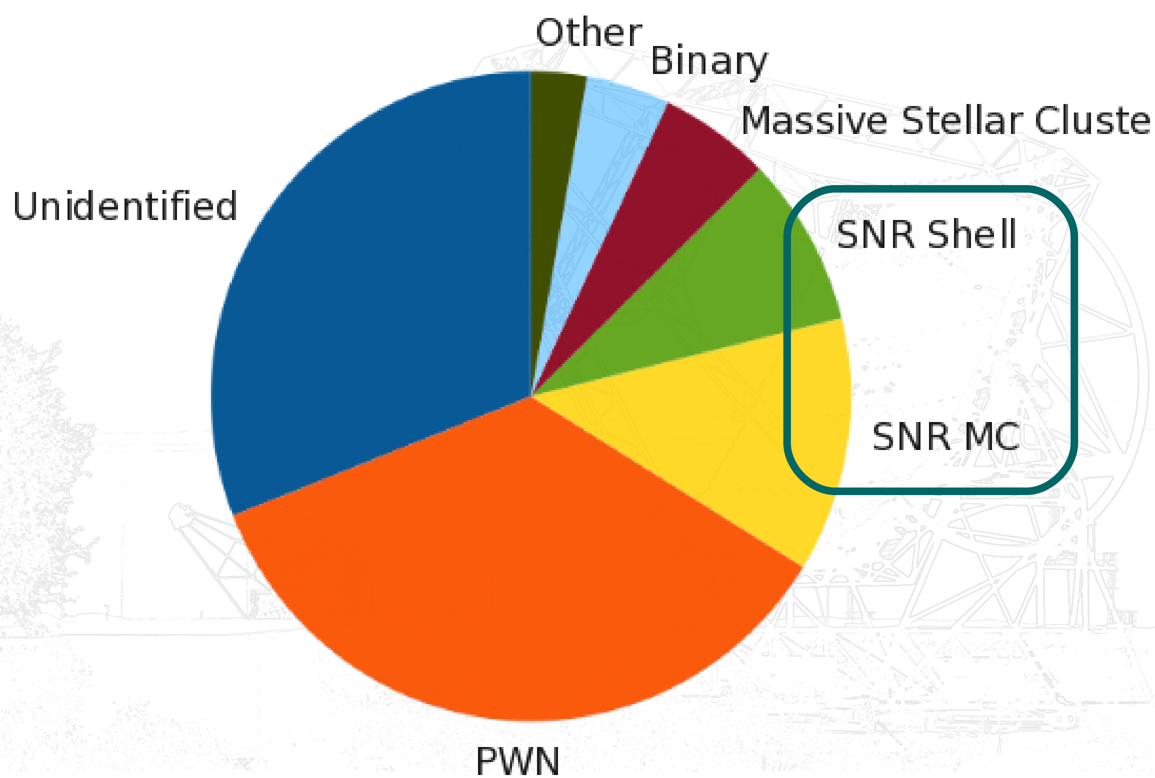
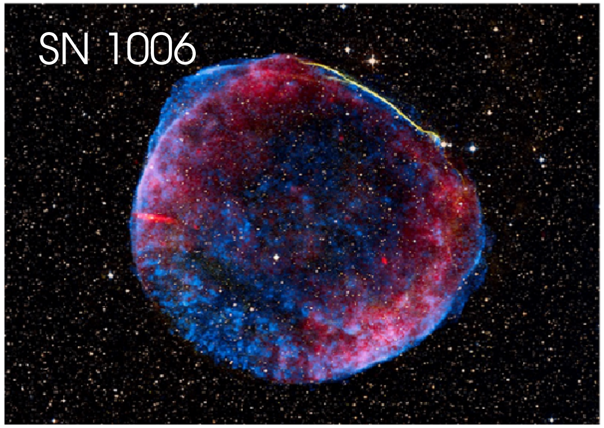


Supernova remnants

- **Good candidates as sources of Galactic cosmic rays (< 10^{15} eV)**
  - Remnants of massive stars explosions ($E \sim 10^{51}$ erg)
  - Shockwave (shell) : stochastic acceleration of charged particles (Fermi mechanism)

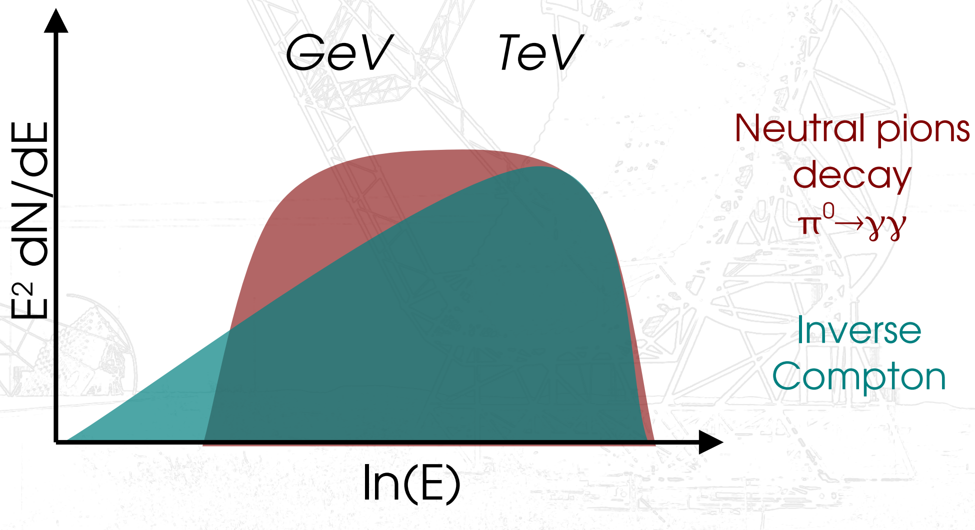


Radio (red) + X (blue) + Optical (yellow)
Credits : NASA/ESA/Zolt Levay (StScI)

γ rays detected -> charged particles acceleration

Nature of these particles : leptons or hadrons ?

- Expected spectra in γ rays are different
- Models/observations comparison to (try to) discriminate



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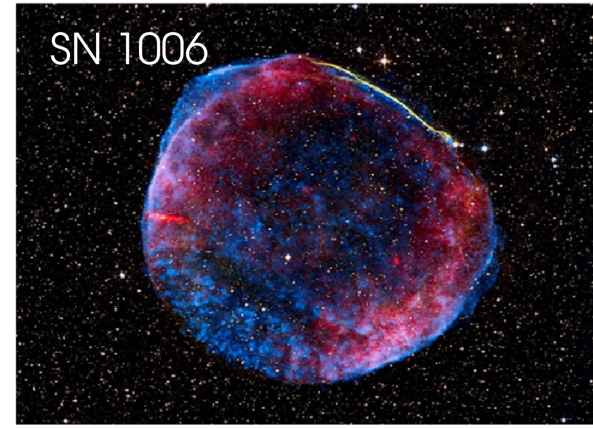

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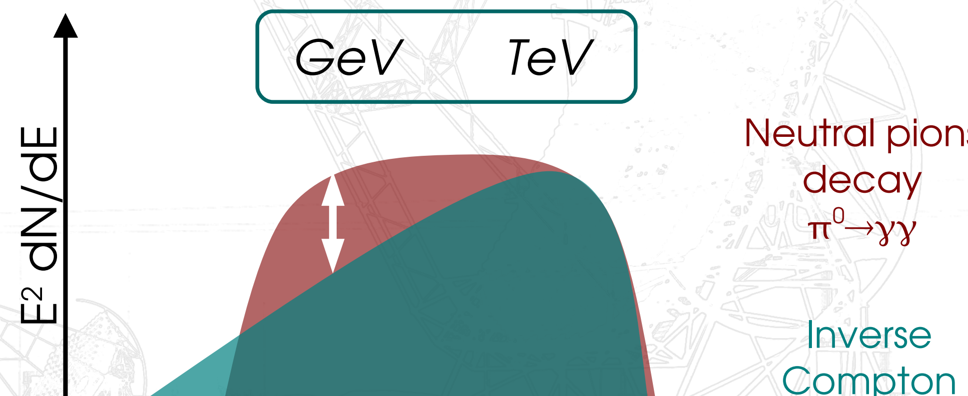
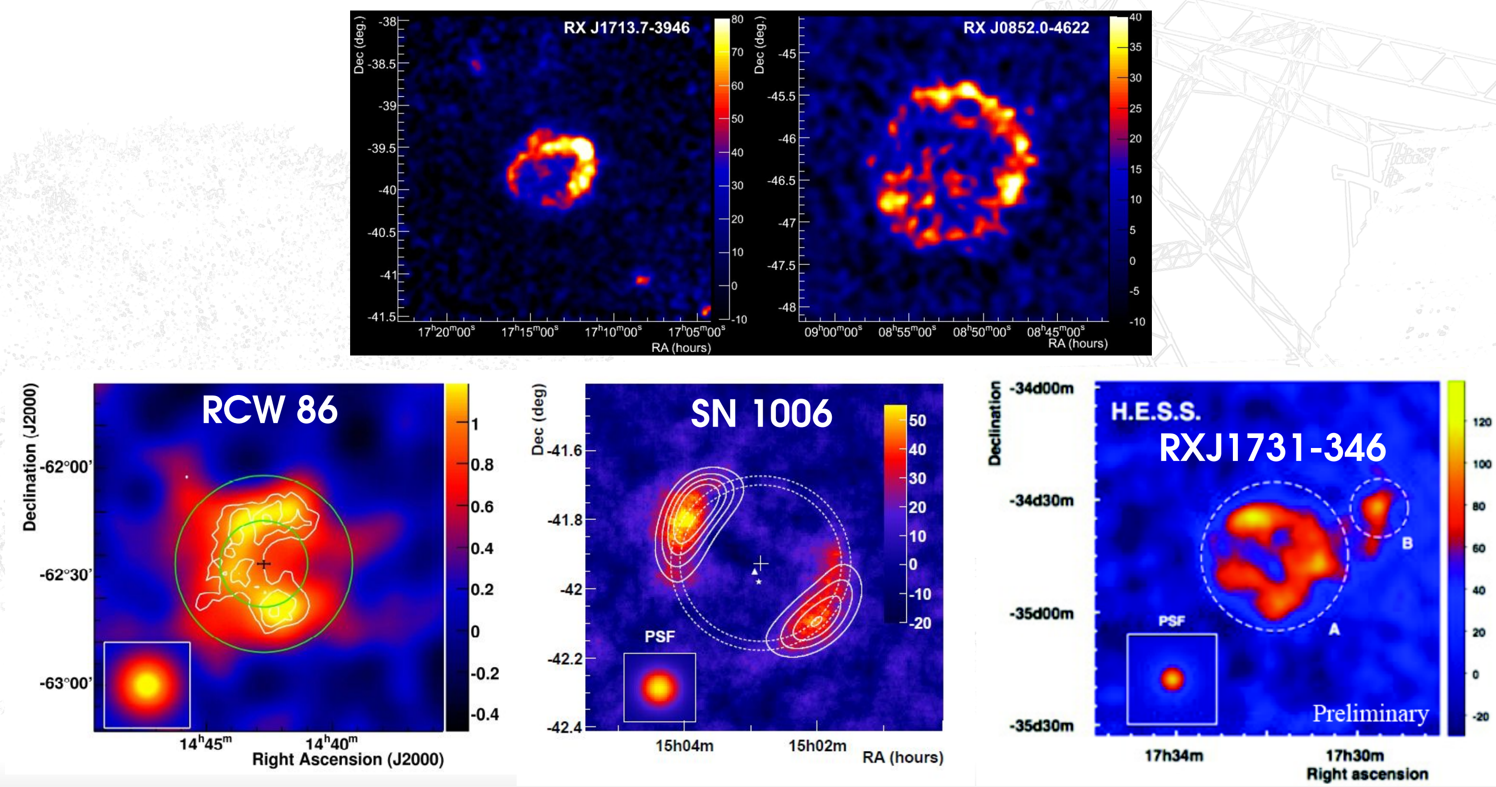


Multi-wavelengths observations particularly useful to constrain the emission processes

Supernova remnants at high energies

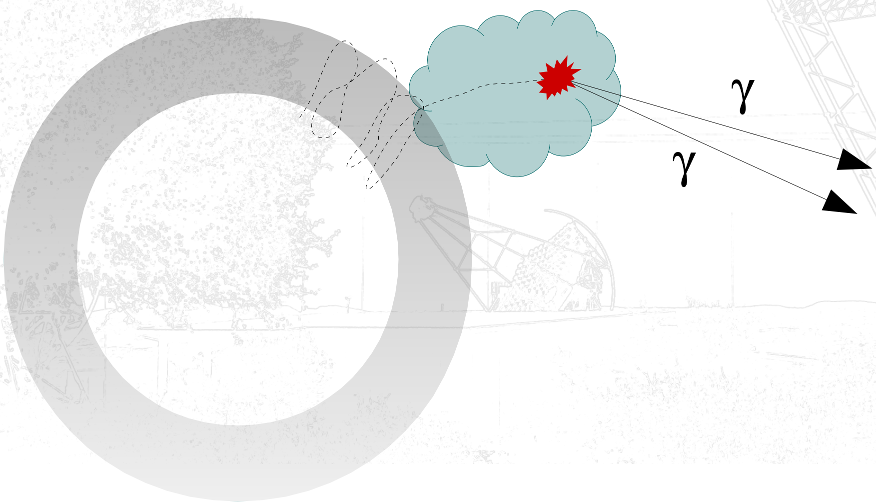
- « Young » remnants : 1st shells resolved at TeV with H.E.S.S.
  - RXJ 1713-3946, Vela Jr, RCW 86, SN 1006, RXJ 1731-347
  - Particles accelerated at more than 100 TeV in the shell
  - Nature of the particles not clear



Supernova remnants at high energies

- Older remnants, interacting with molecular clouds
  - Molecular cloud
    - ➔ overdensity in the interstellar medium
    - ➔ target material for the hadronic processes

Bringing to light the hadronic processes



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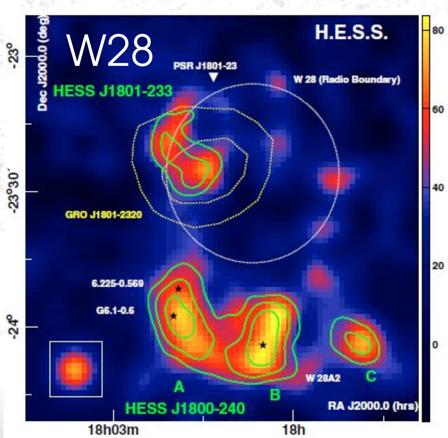
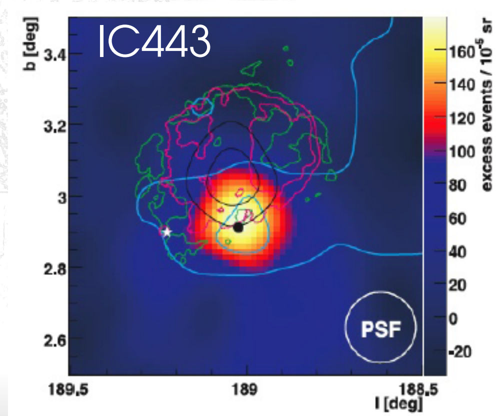
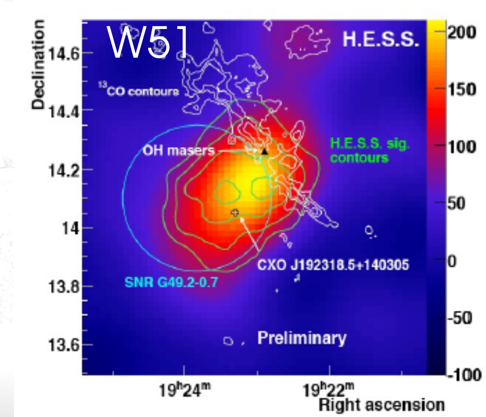
Bringing to light the hadronic processes

  - Several objects detected in GeV and TeV
    - W28, CTB 37A, W51C, G359.1-0.5, IC 443, W49B (**F. Brun** et al., 2011)







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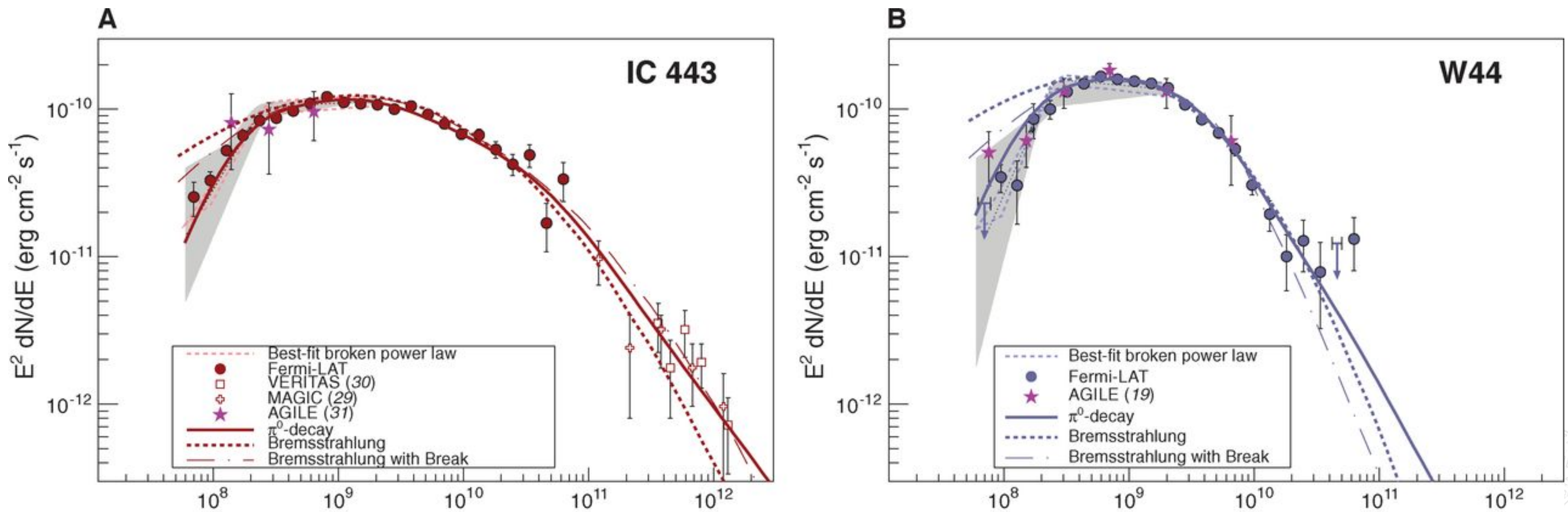
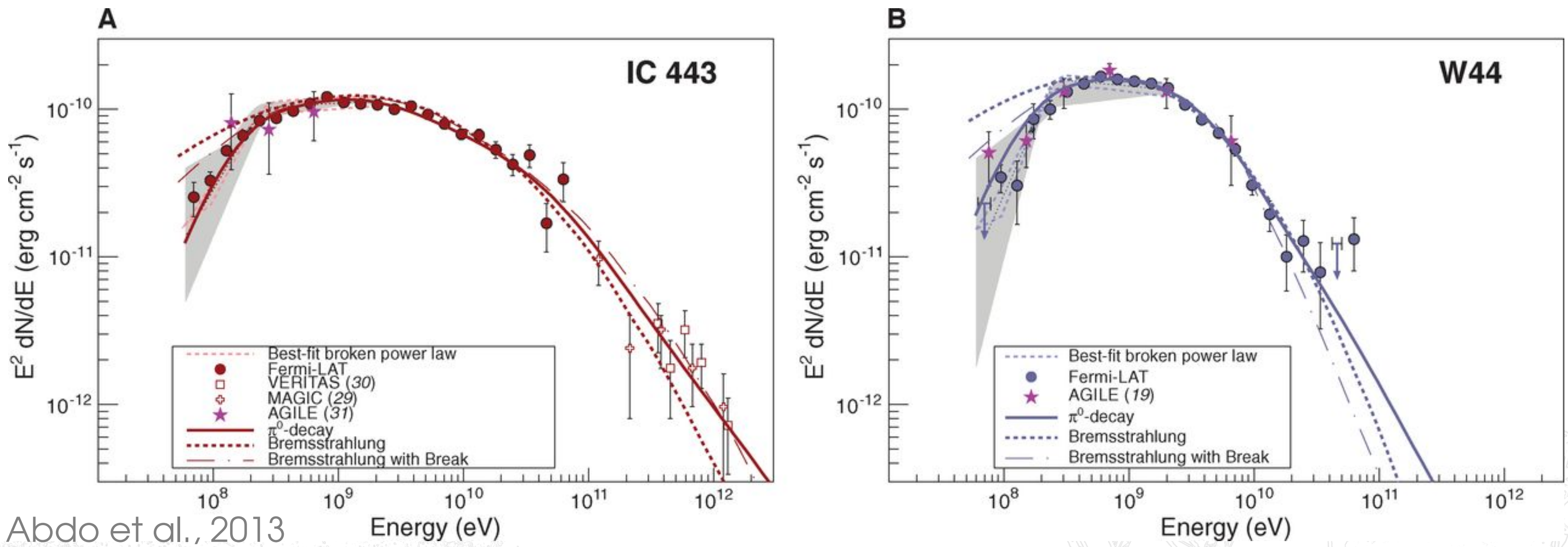


Abdo et al., 2013

GeV detection with Fermi :
Spectral shape -> characteristic signature of pion decay !

Supernova remnants at high energies



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W49B spectrum : similar feature
Currently working on the H.E.S.S.+Fermi publication

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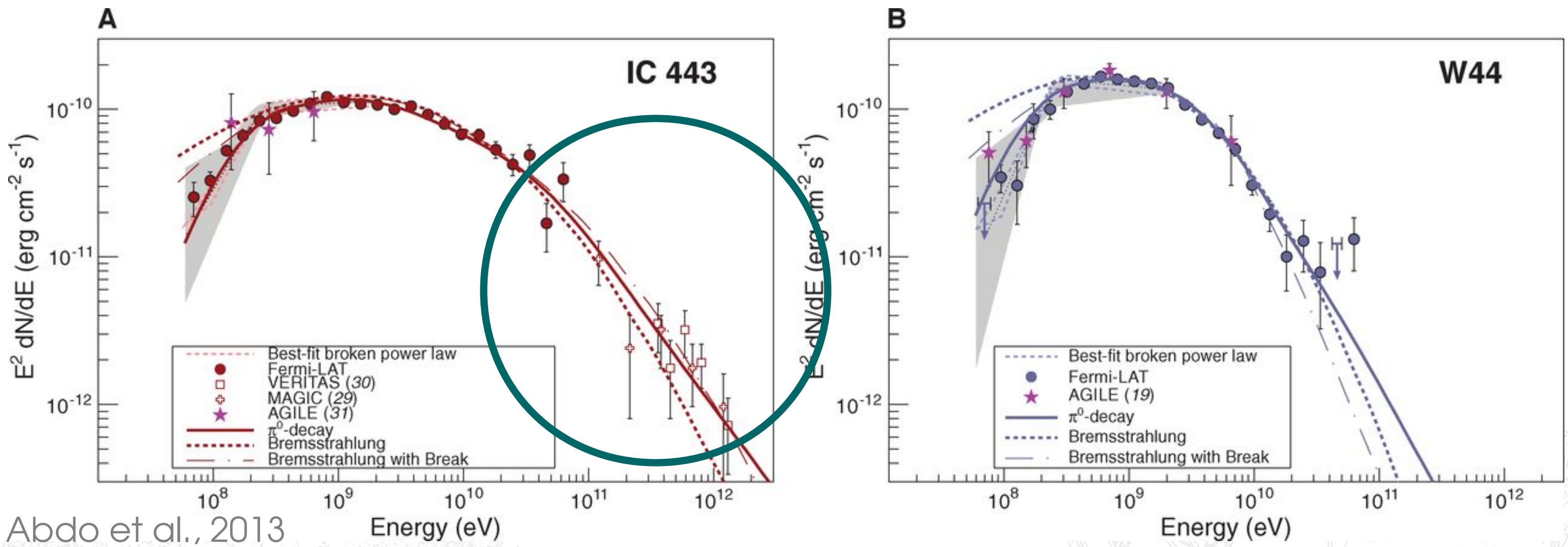

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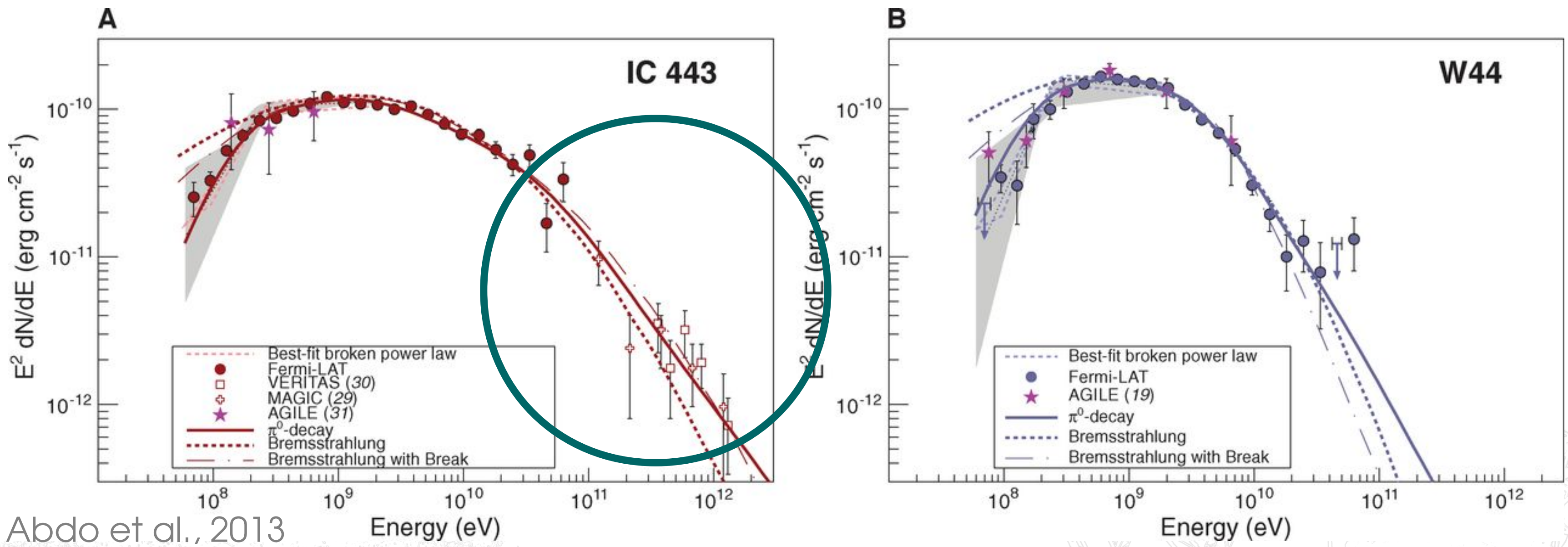

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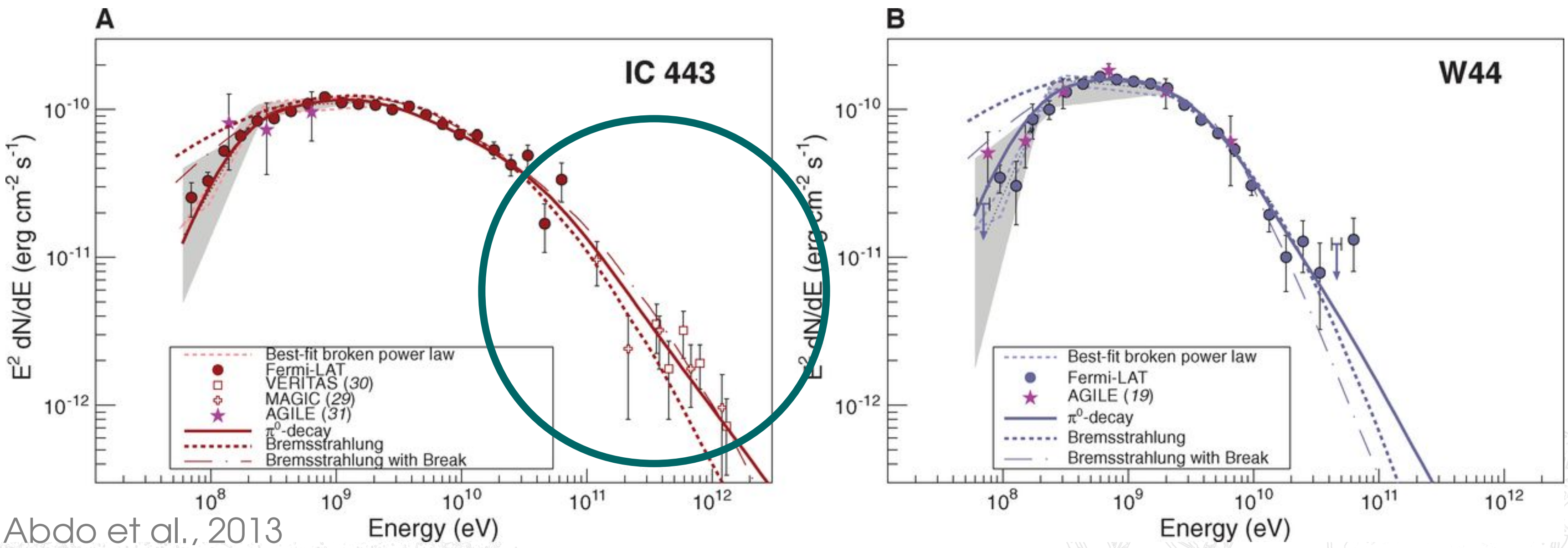
- SNRs are sources of cosmic rays !
- Are they the (dominant) sources of cosmic rays ?

Supernova remnants at high energies



Abdo et al., 2013

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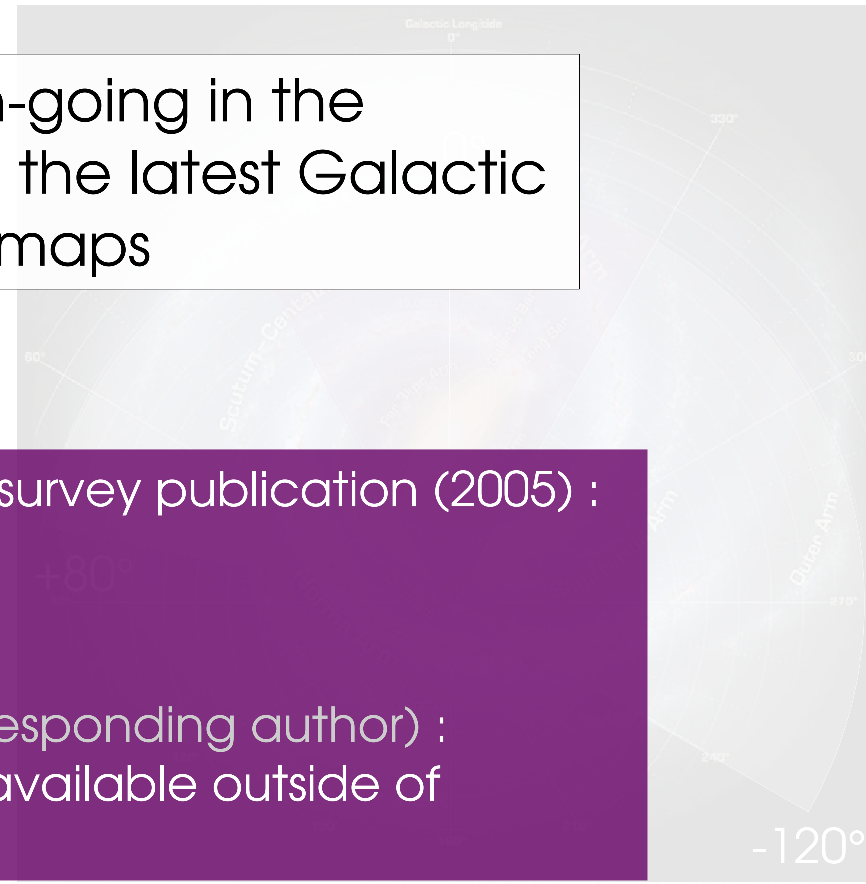
→ Population studies

The Galactic plane survey

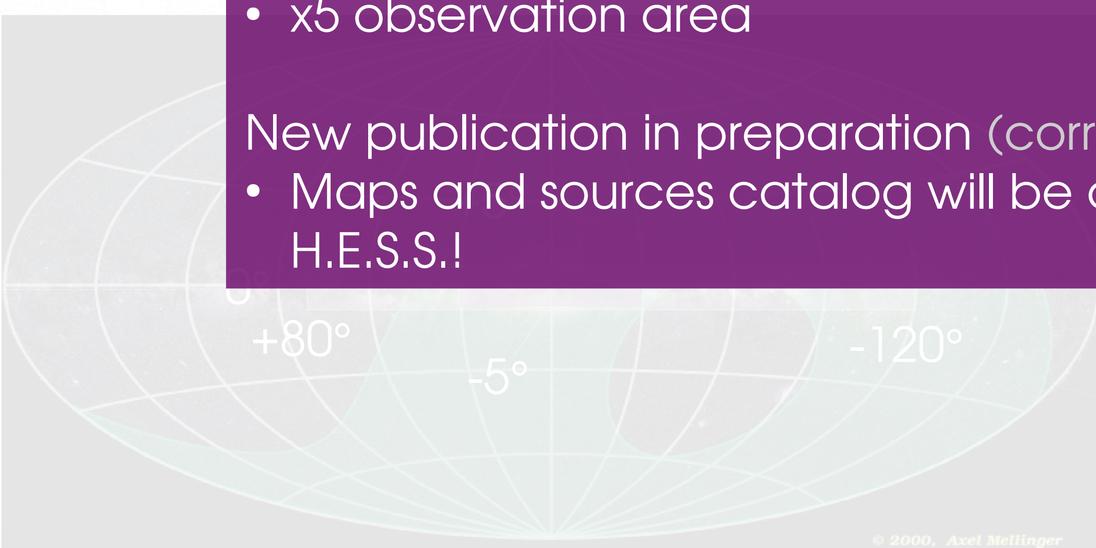
- **Goal** : Map the inner regions of the Galaxy to discover new TeV sources
- **Since 2004** :
  - ~ 28
  - -120° to +80° in longitude
  - -5° to +5° in latitude

Population studies on-going in the collaboration are based on the latest Galactic plane survey maps



Since the first H.E.S.S. Galactic plane survey publication (2005) :
- x10 observation time
- x5 observation area

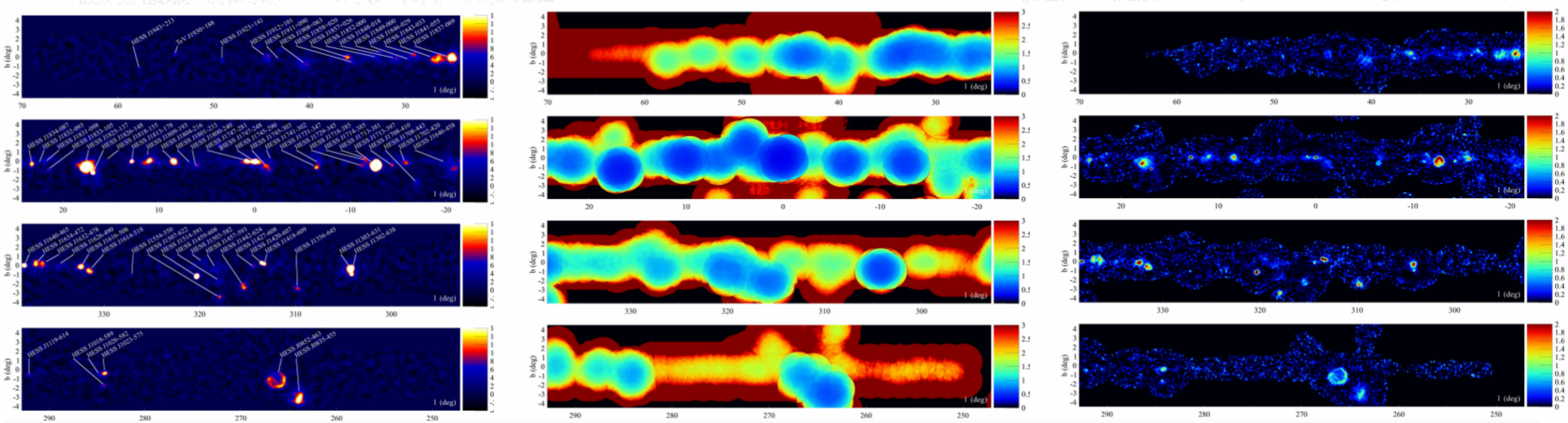
New publication in preparation (corresponding author) :
- Maps and sources catalog will be available outside of H.E.S.S.!



Optimal H.E.S.S. visibility

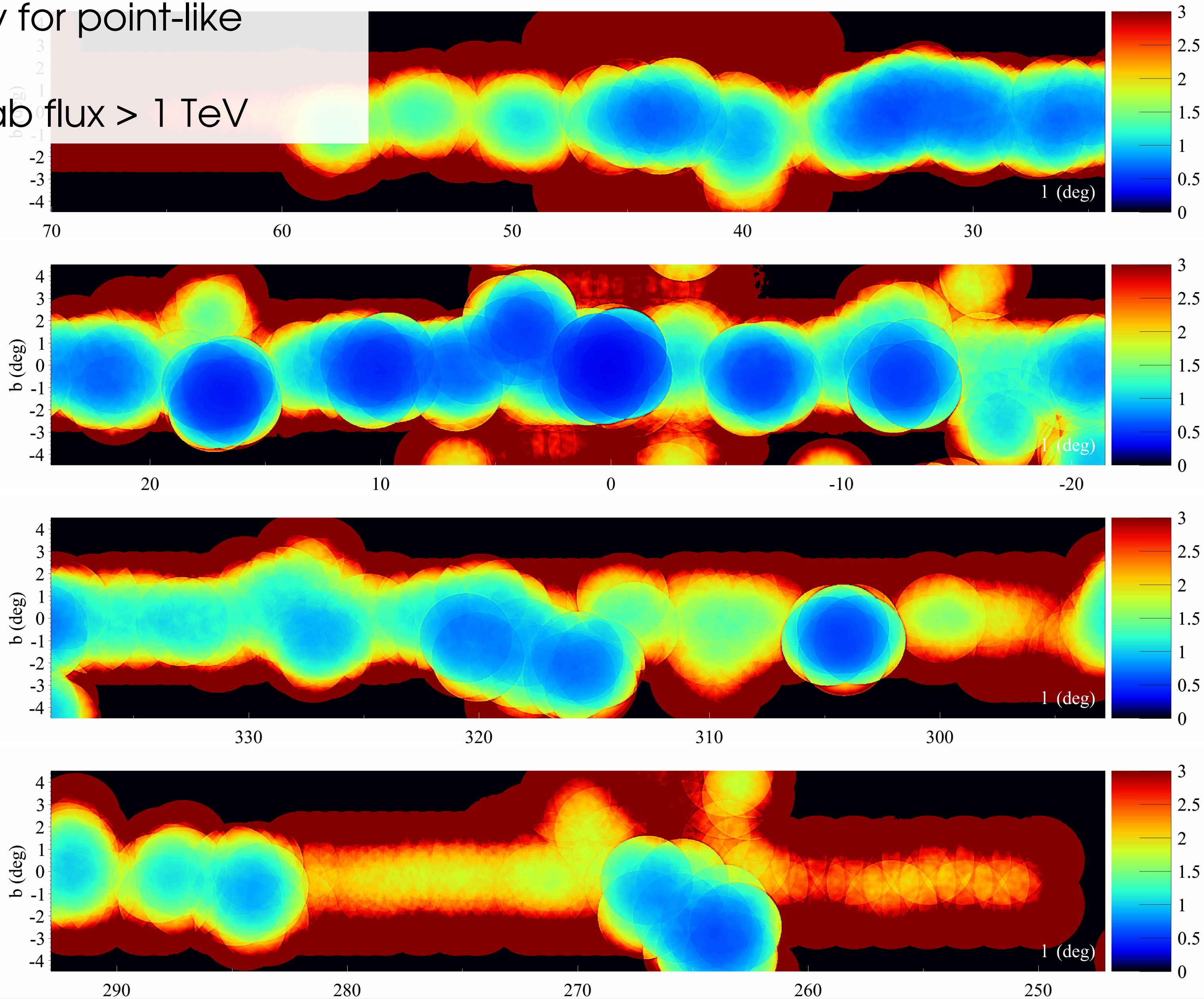
The Galactic plane survey : latest version

- Maps :
  - New tools for the background substraction
    - ➔ Adaptive ring background method
    - ➔ Automated alogorithm to find exclusion regions
- Available soon :
  - Significance, sensitivity, flux (+errors) and upper limits maps



The Galactic plane survey : latest version

5σ sensitivity for point-like sources.
Units : % Crab flux > 1 TeV



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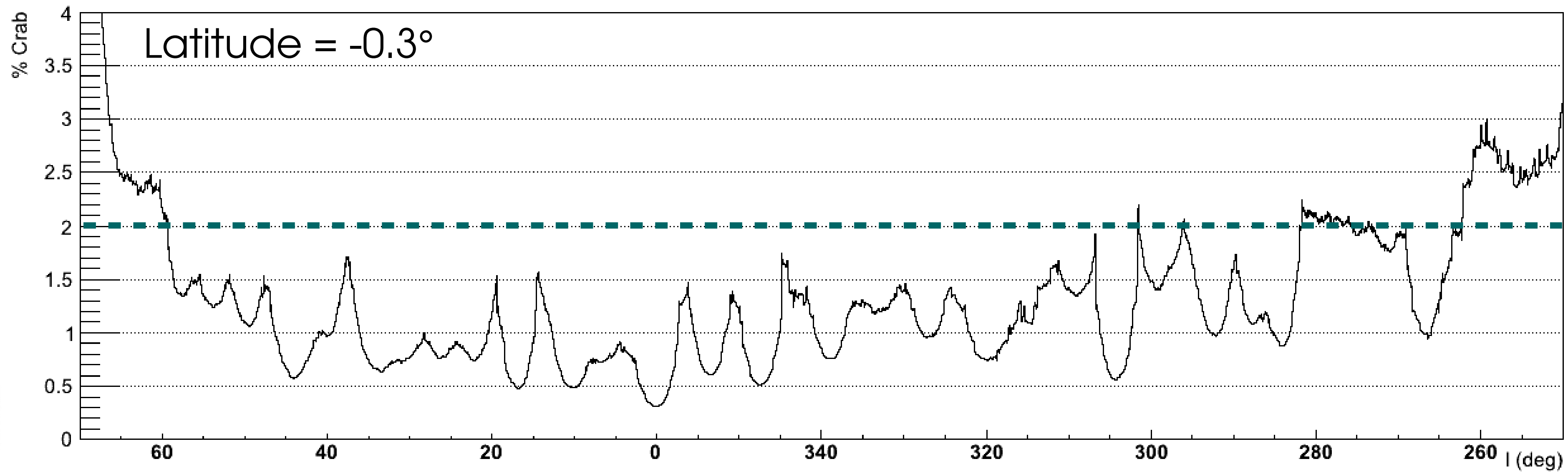

Sensitivity at 2 % Crab or better !

The Galactic plane survey : latest version

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- Catalog :
  - Uniform analysis of all the Galactic plane sources
  - Maximum likelihood fit of the photons maps, taking exposure, PSF and background model into account
  - Spectral analysis of the obtained sources

The Galactic plane survey : complementary studies

- Maps : basis for complementary studies
- **Populations studies** on-going in H.E.S.S. :
  - Supernova remnants Fernandez et al., 2013 (ICRC)
  - Pulsar wind nebula Klepser et al., 2013 (ICRC)

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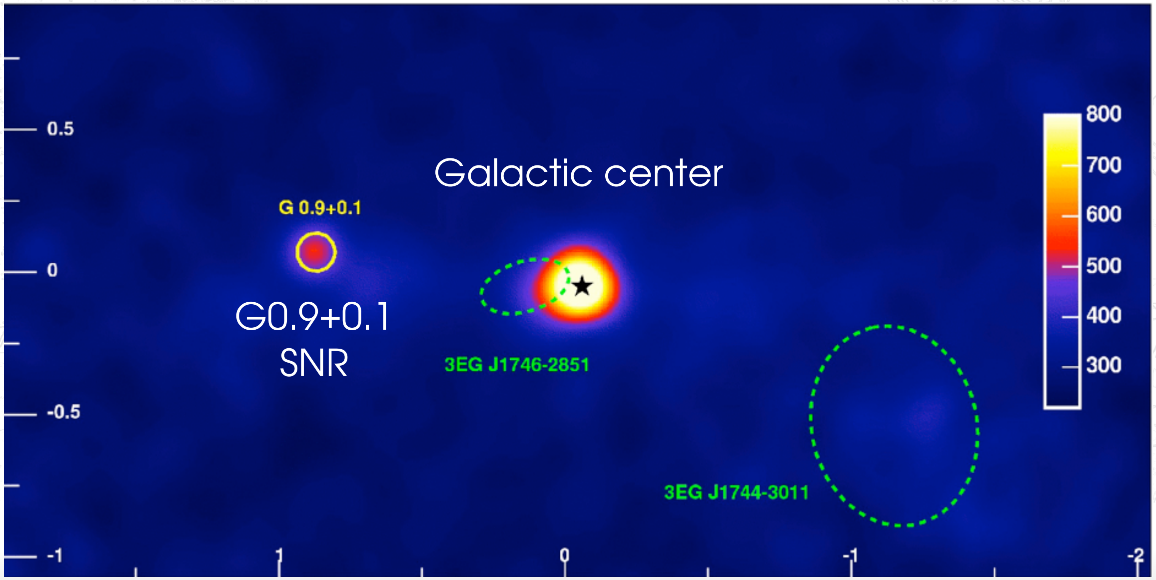
Excess map



HESS Collaboration, 2007

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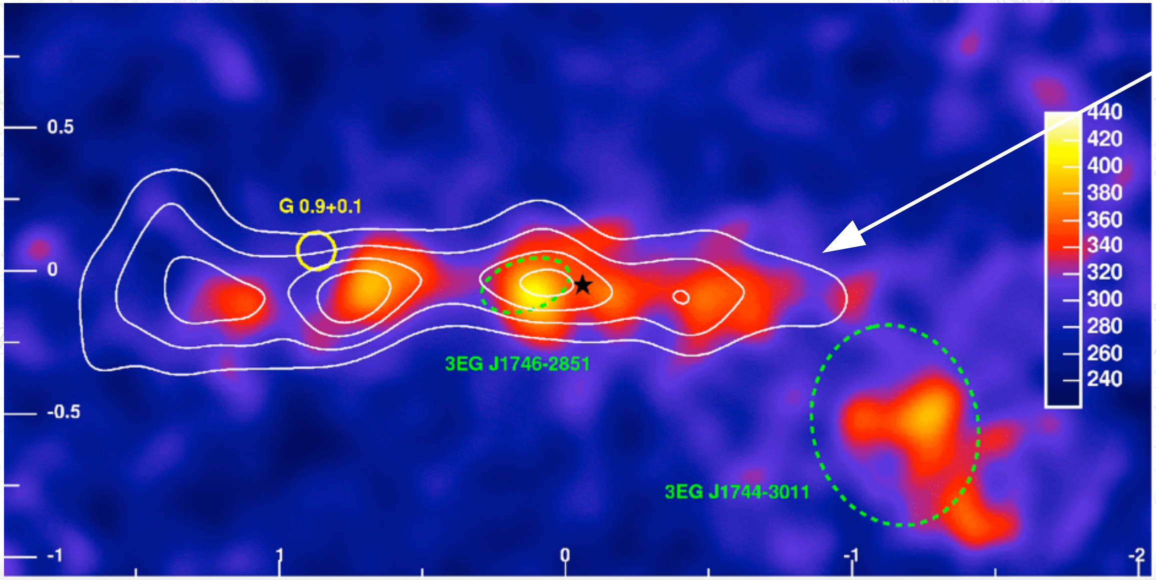
TeV map after sources substraction



Contours (CS) = matter density

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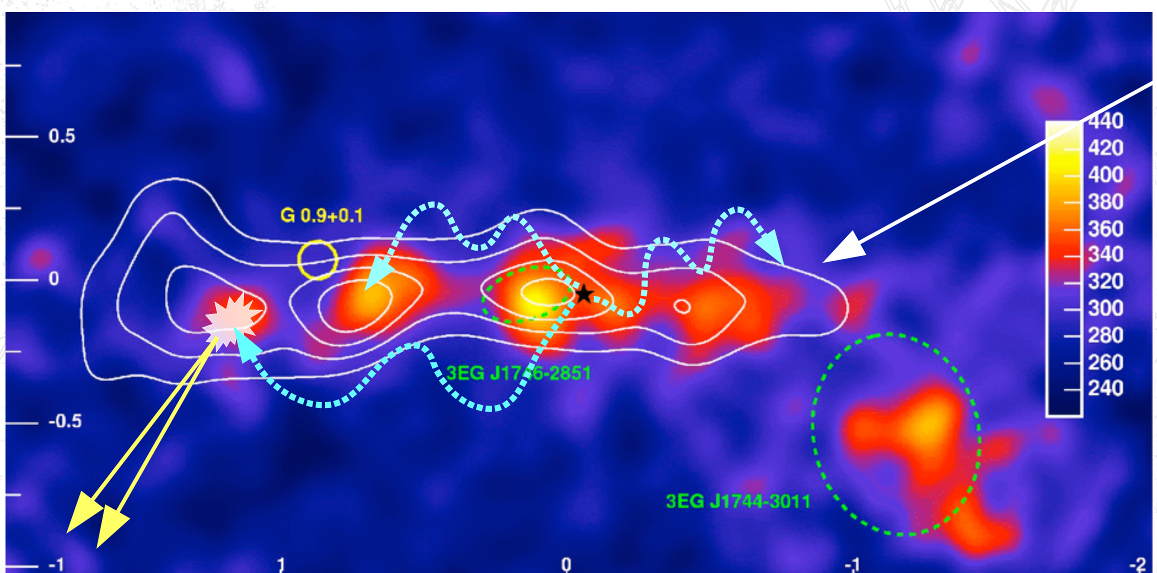

HESS Collaboration, 2007

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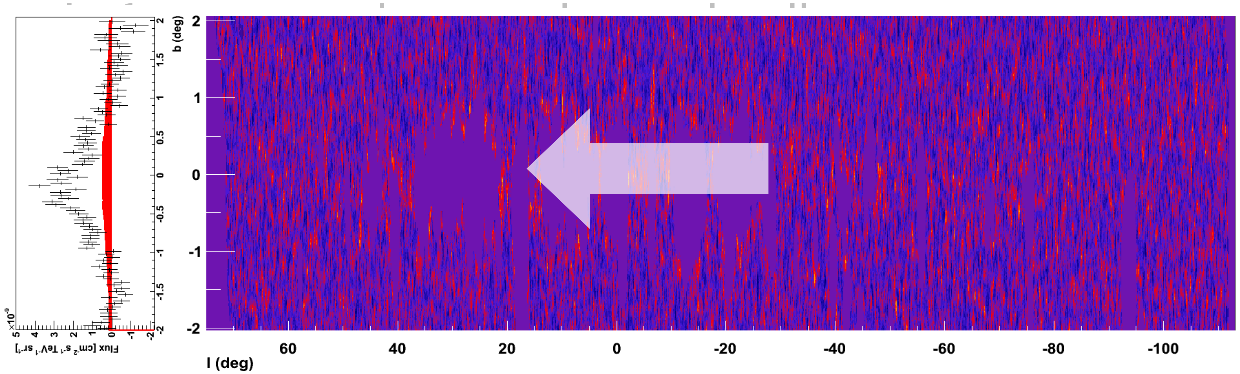
Cosmic ray interacting with molecular material

The Galactic plane survey : complementary studies

- Maps : b
- **Populati**
  - Super
  - Pulsar



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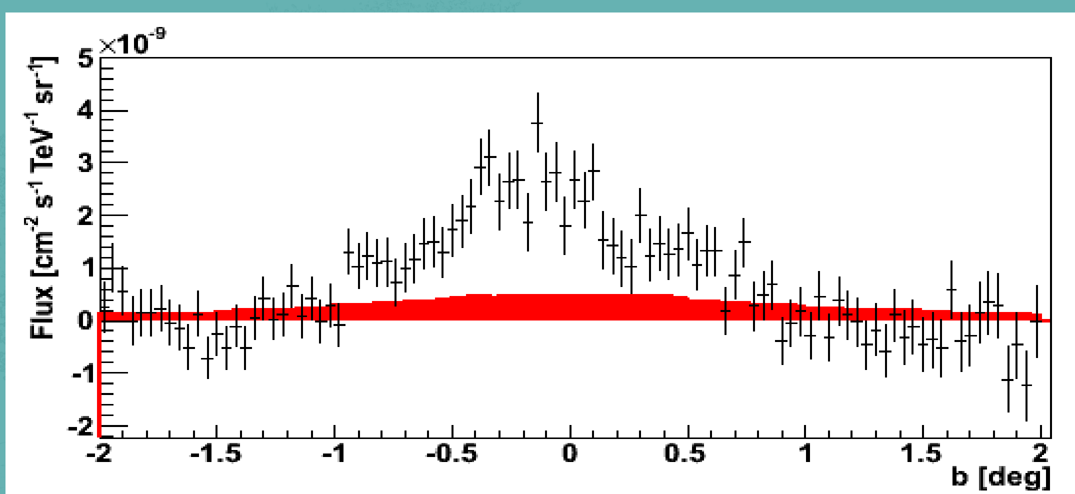


Total flux outside sources regions versus Galactic latitude :

~ 25% = Galactic cosmic rays

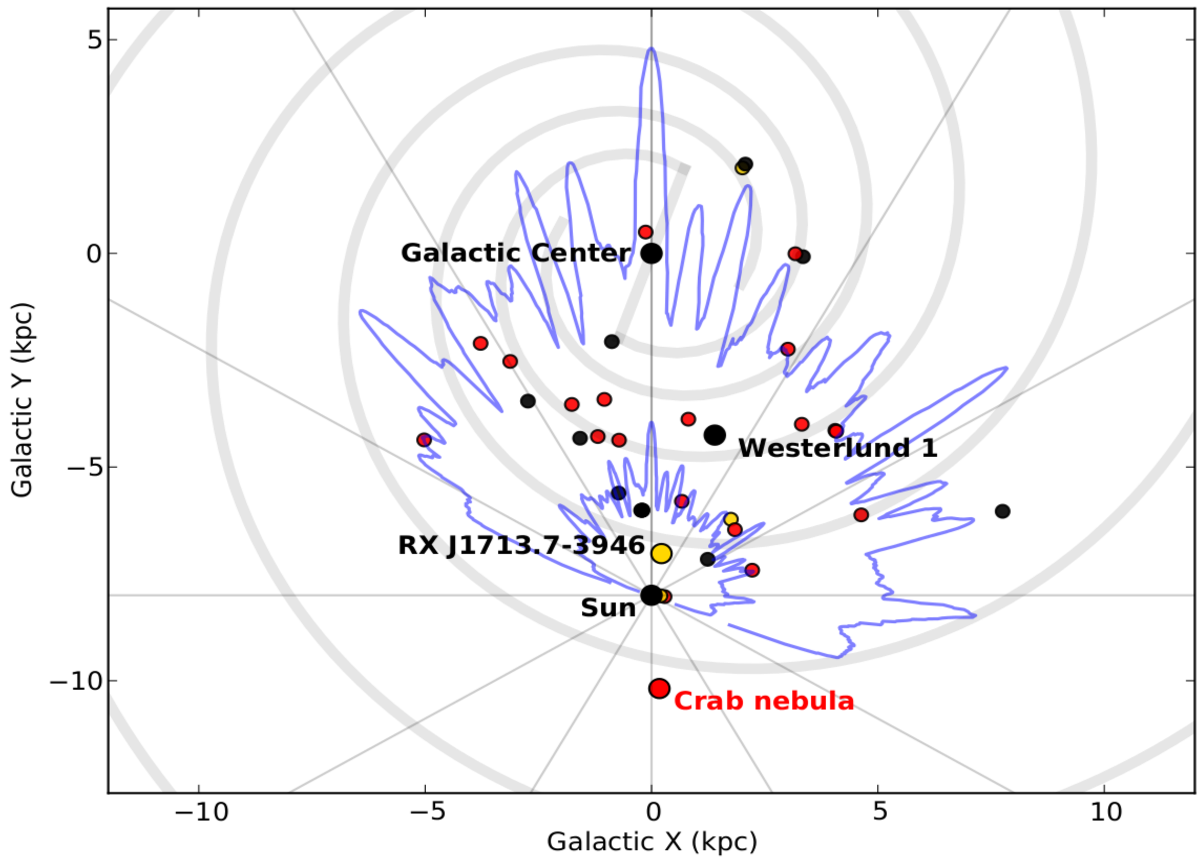
~ 75% = Unresolved sources

K. Egberts, **F. Brun** et al., 2013 (ICRC)

HESS Collaboration, **published** in December 2014

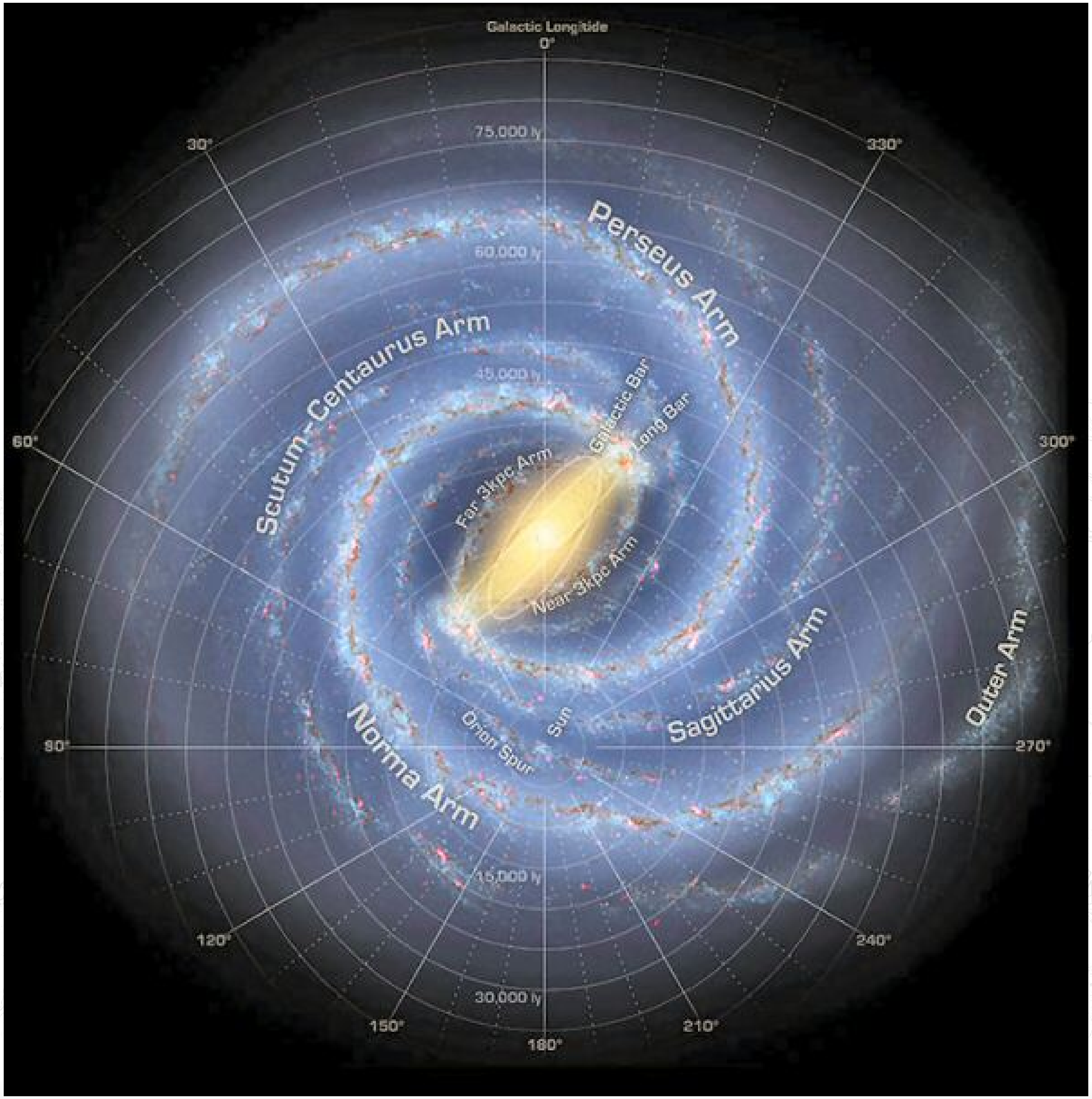
The Galactic plane survey : complementary studies

Horizons for 10% and 1% of the Crab luminosity



S. Carrigan, **F. Brun** et al., 2013 (ICRC)

The Galactic plane survey : complementary studies



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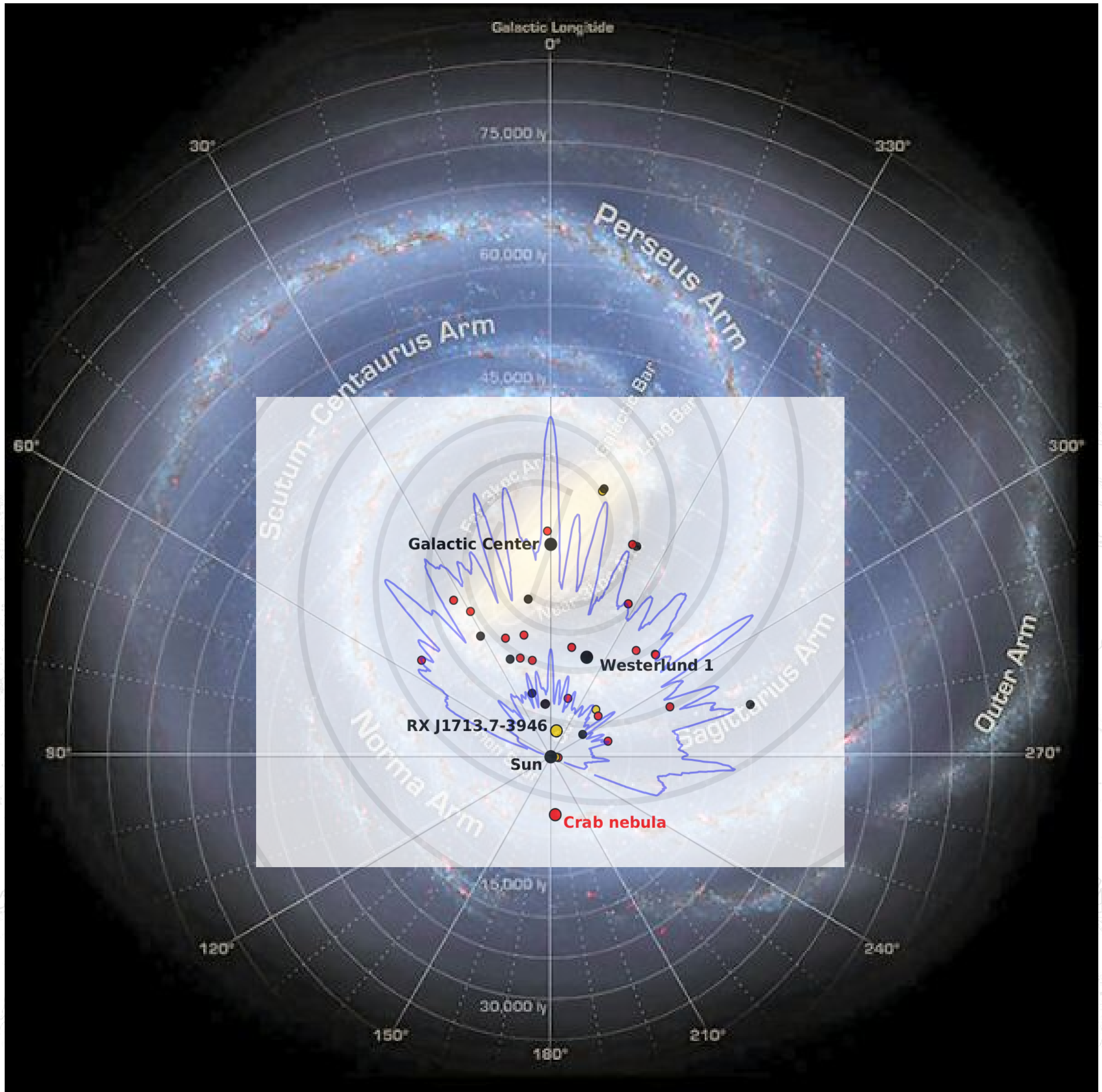

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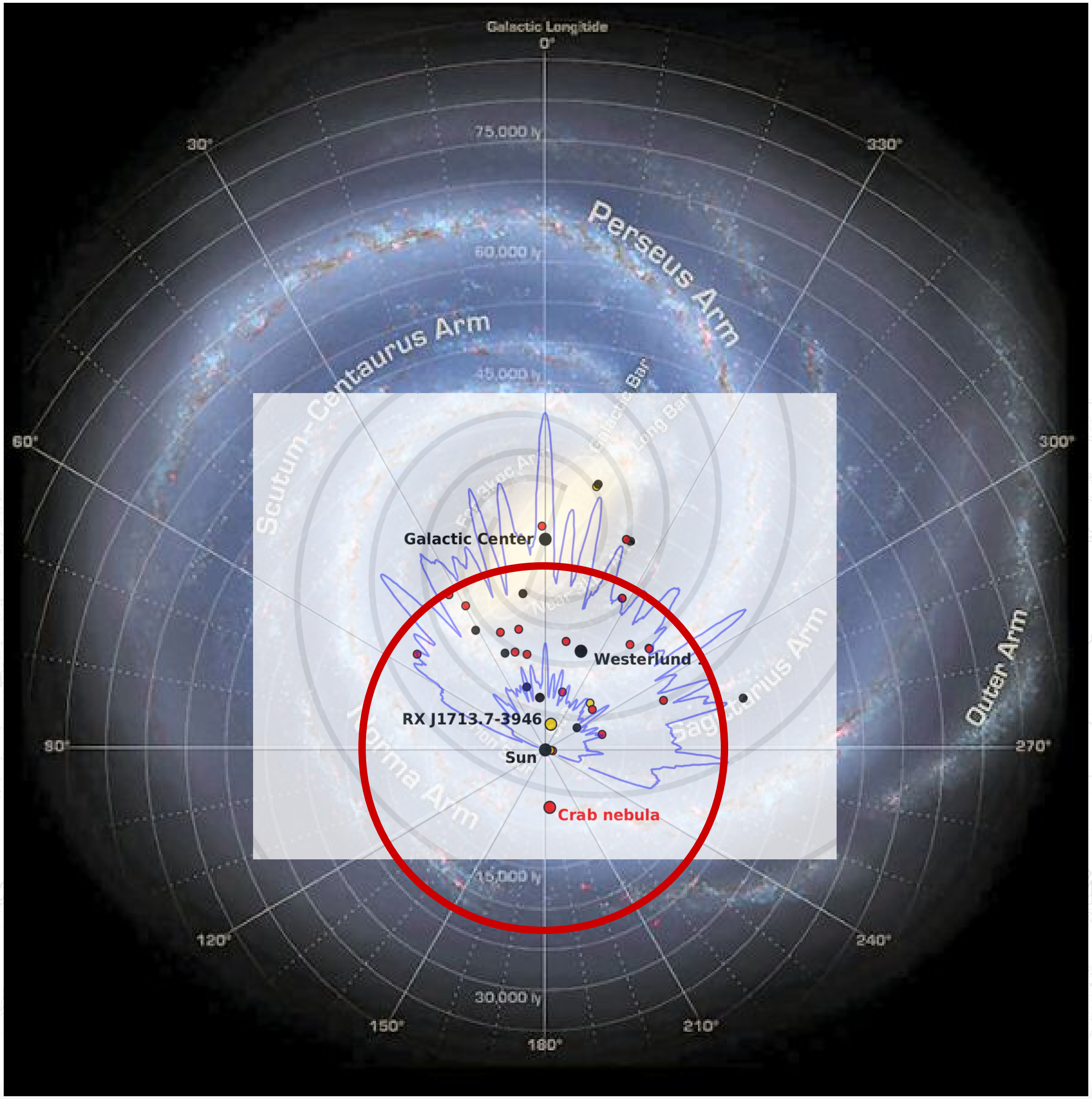

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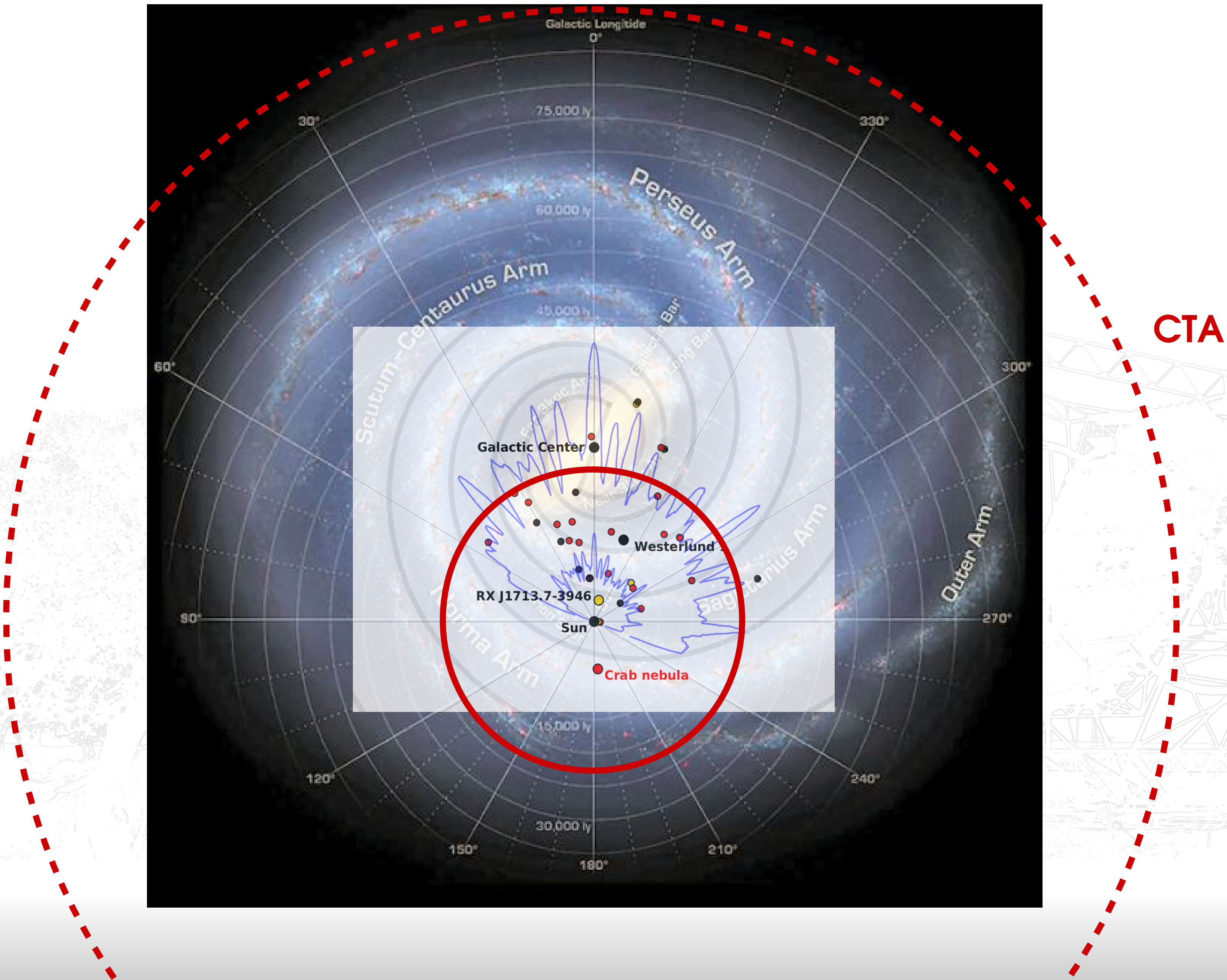
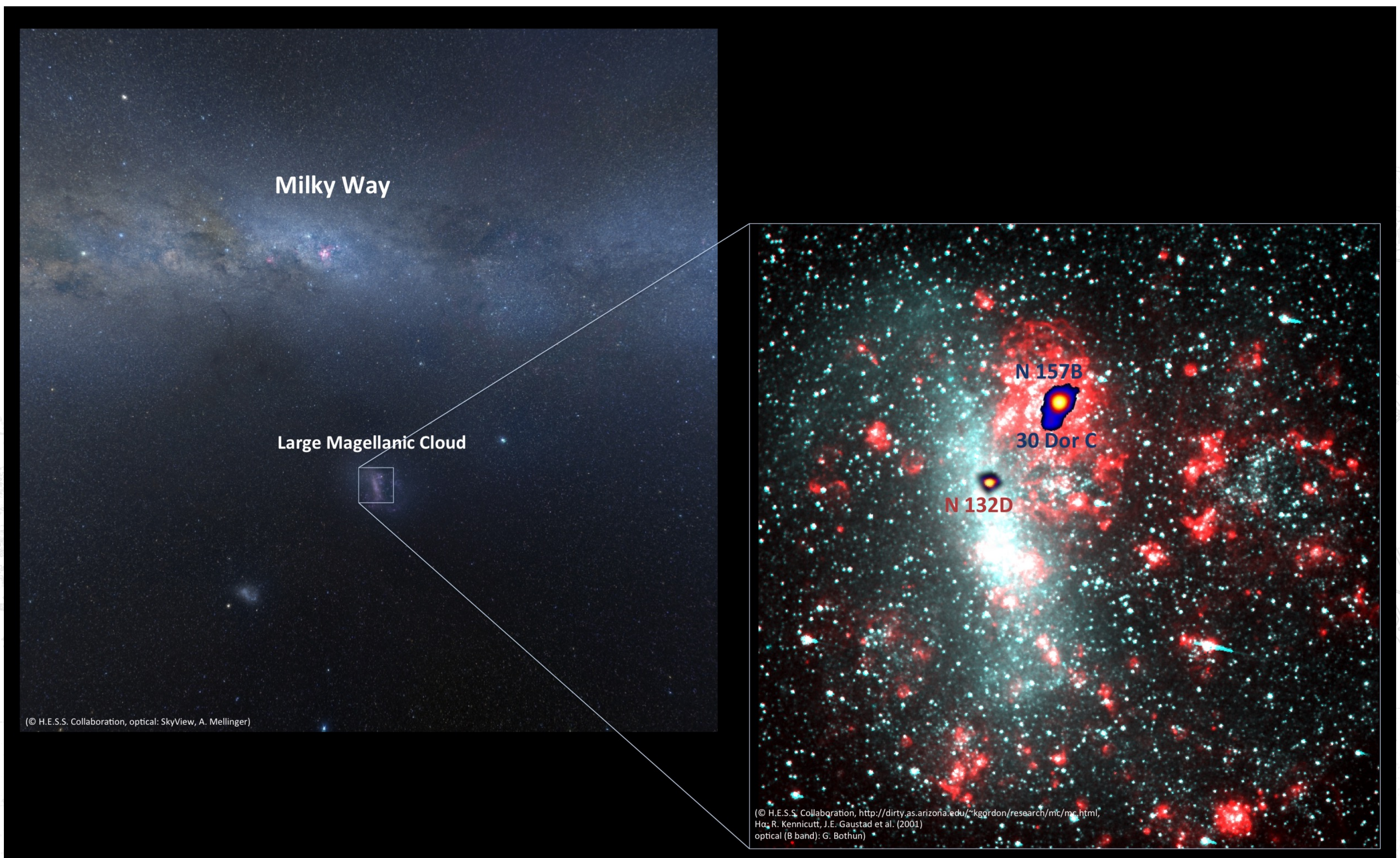


The extragalactic sky

Beyond the Milky way

- Cosmic accelerators in the Large Magellanic Cloud
  - Galaxie of the local group (d = 50 kpc)



Science 347 (2015) 406 (contribution : internal review of the analysis)

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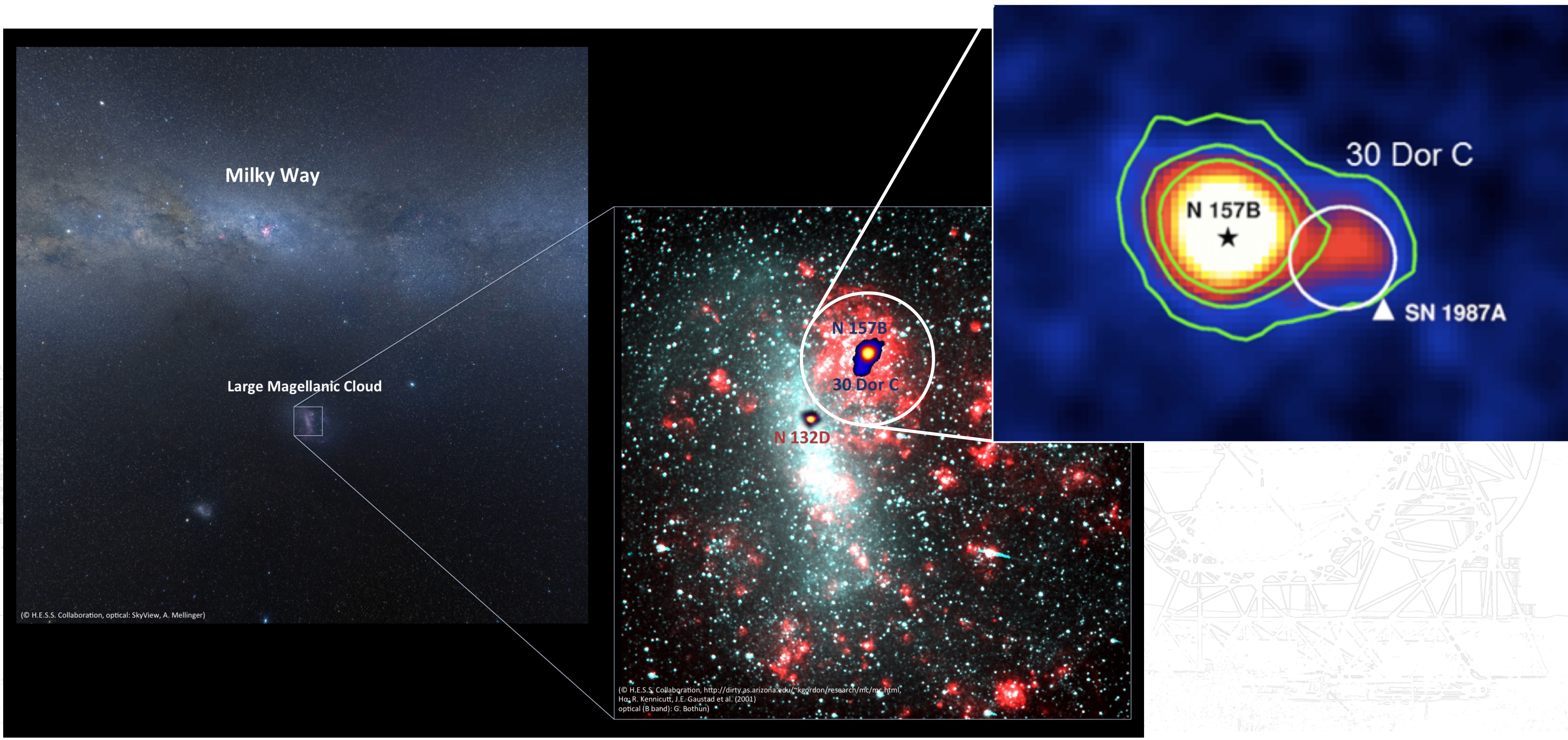
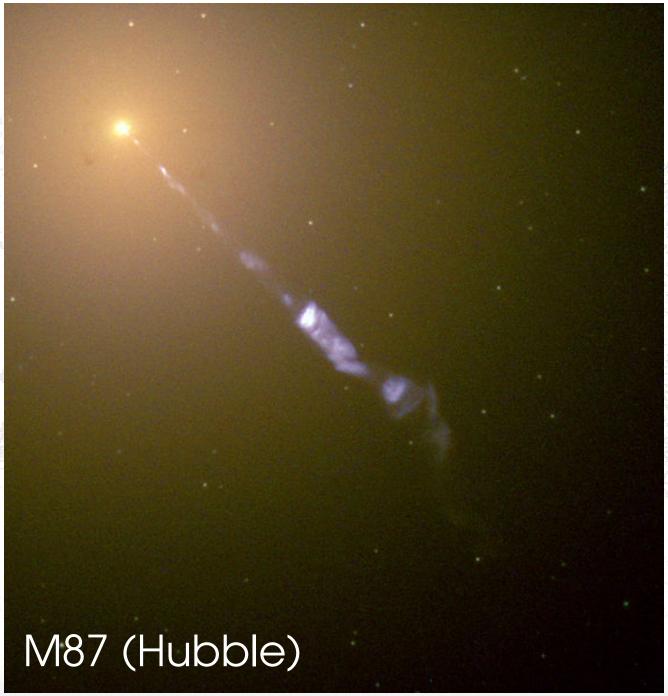


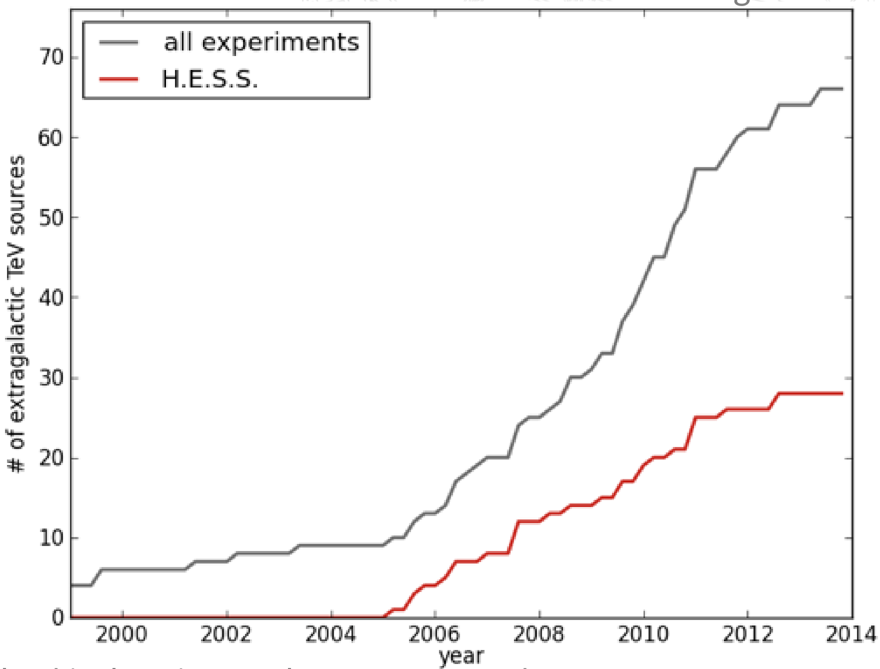
Science 347 (2015) 406 (contribution : internal review of the analysis)

The extragalactic sky with H.E.S.S.

- ~ 50 % observation time
- ~ 30 sources
  - Mainly active galactic nuclei
  - Starburst galaxy
  - Measurement of extragalactic background light, LIV, axions



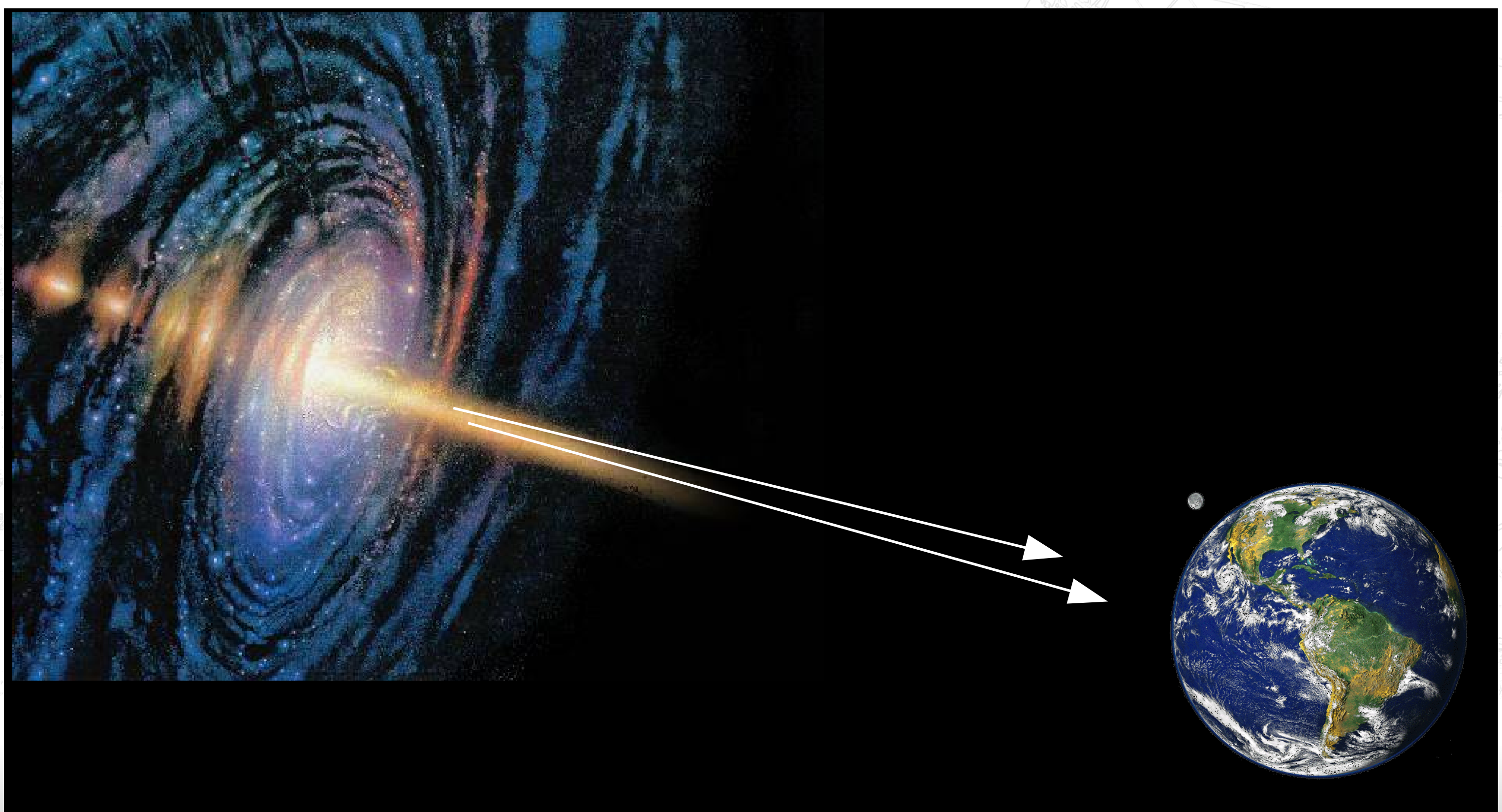
tevcat.uchicago.edu



All: Whipple, Crimea, Telescope Array, Durham, MAGIC, VERITAS, H.E.S.S.

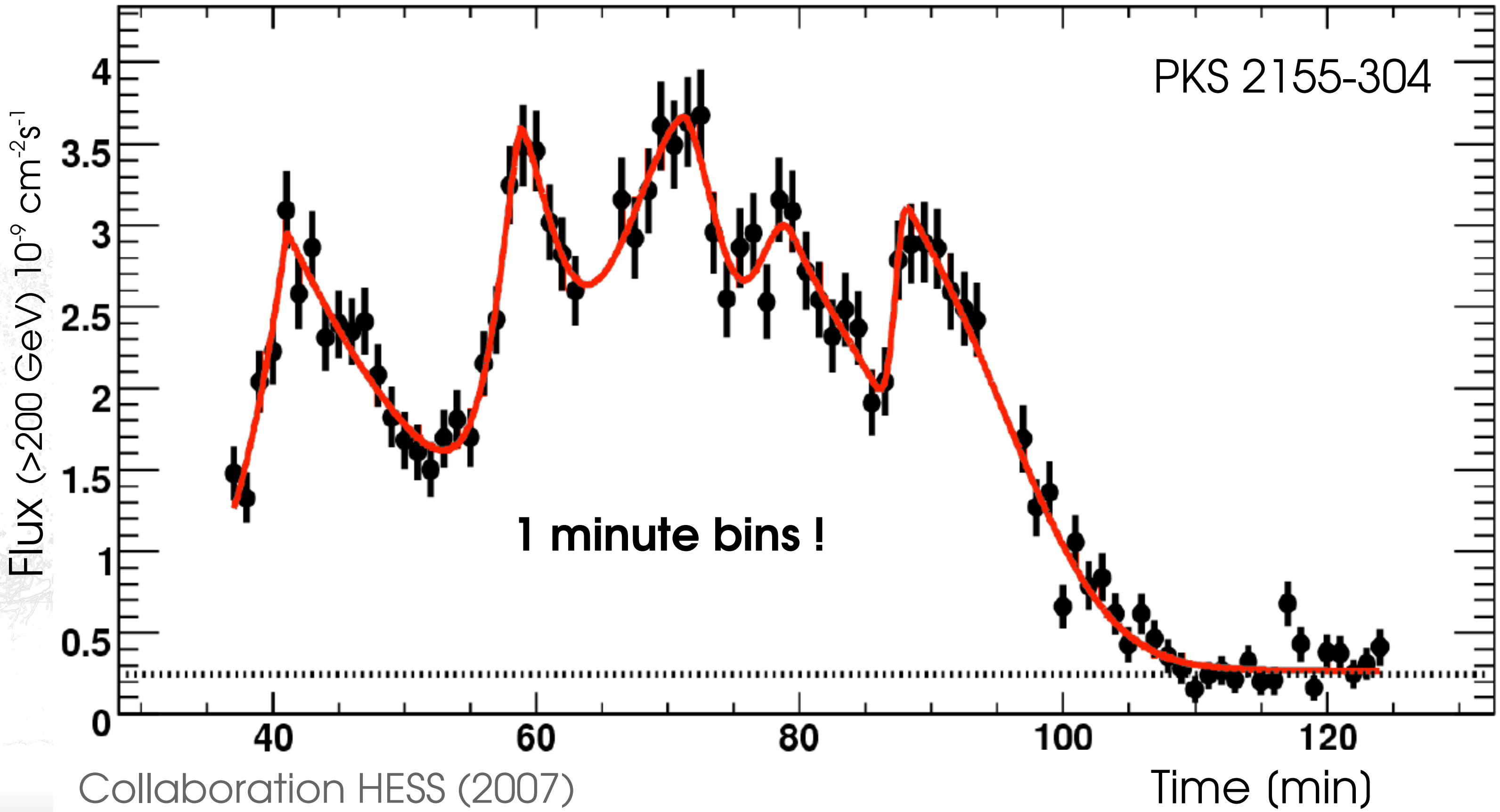
The extragalactic sky with H.E.S.S.

- Active Galactic Nuclei (z < 0.5)
  - Supermassive black hole, jets
  - Blazar : observer looking into the jet



The extragalactic sky with H.E.S.S.

- Active Galactic Nuclei (z < 0.5)
- Particularly variable objects



Collaboration HESS (2007)

The extragalactic sky with H.E.S.S.

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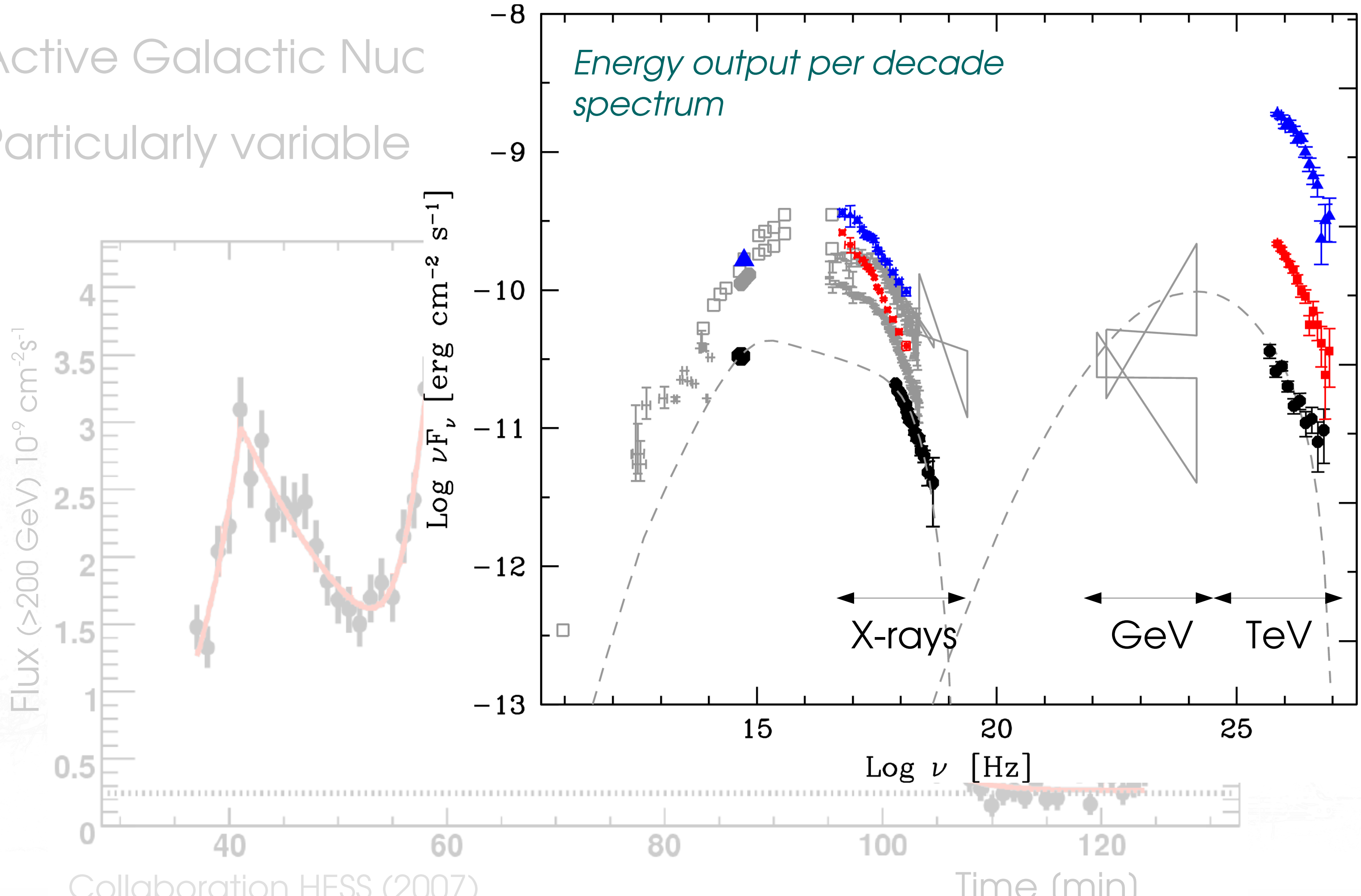
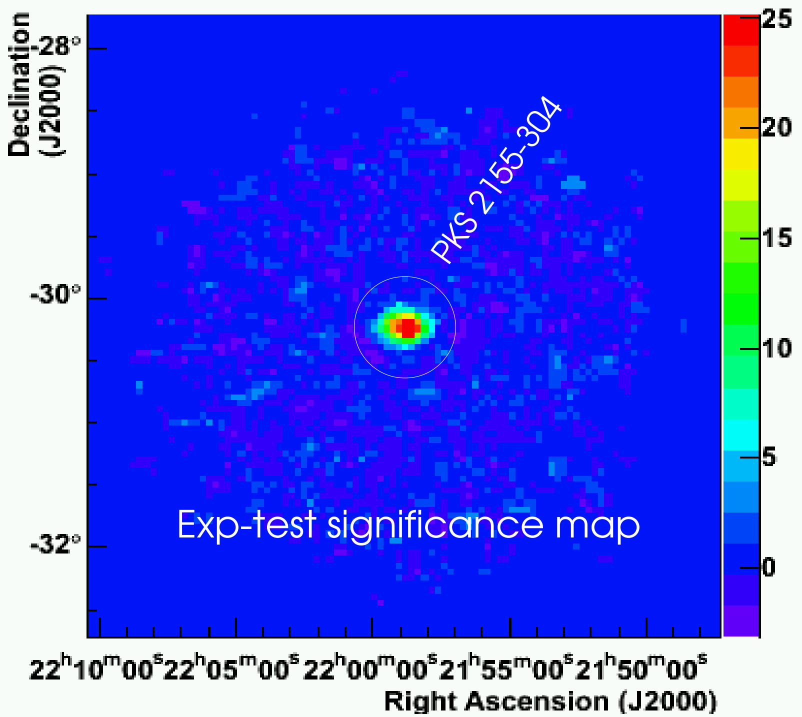


Analysis methods to search for transient/variable sources

- Development of analysis methods based on the time intervals between individual events (F. Brun, PhD thesis)
  - Source detection and characterization
  - Production of variability maps : allowing for blind searches

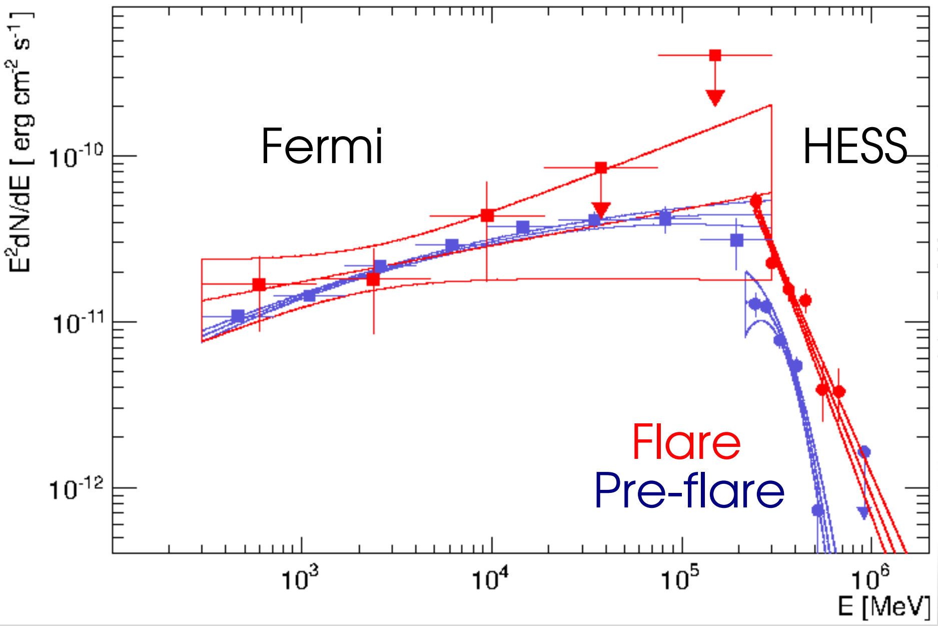


Analysis methods to search for transient/variable sources

- Development of analysis methods based on the time intervals between individual events (F. Brun, PhD thesis)
- On-going analysis for the whole H.E.S.S. dataset

Identification of a flare in the active galactic nucleus PG 1553+113

Collaborations HESS+Fermi, **published** in December 2014 (corresponding author)



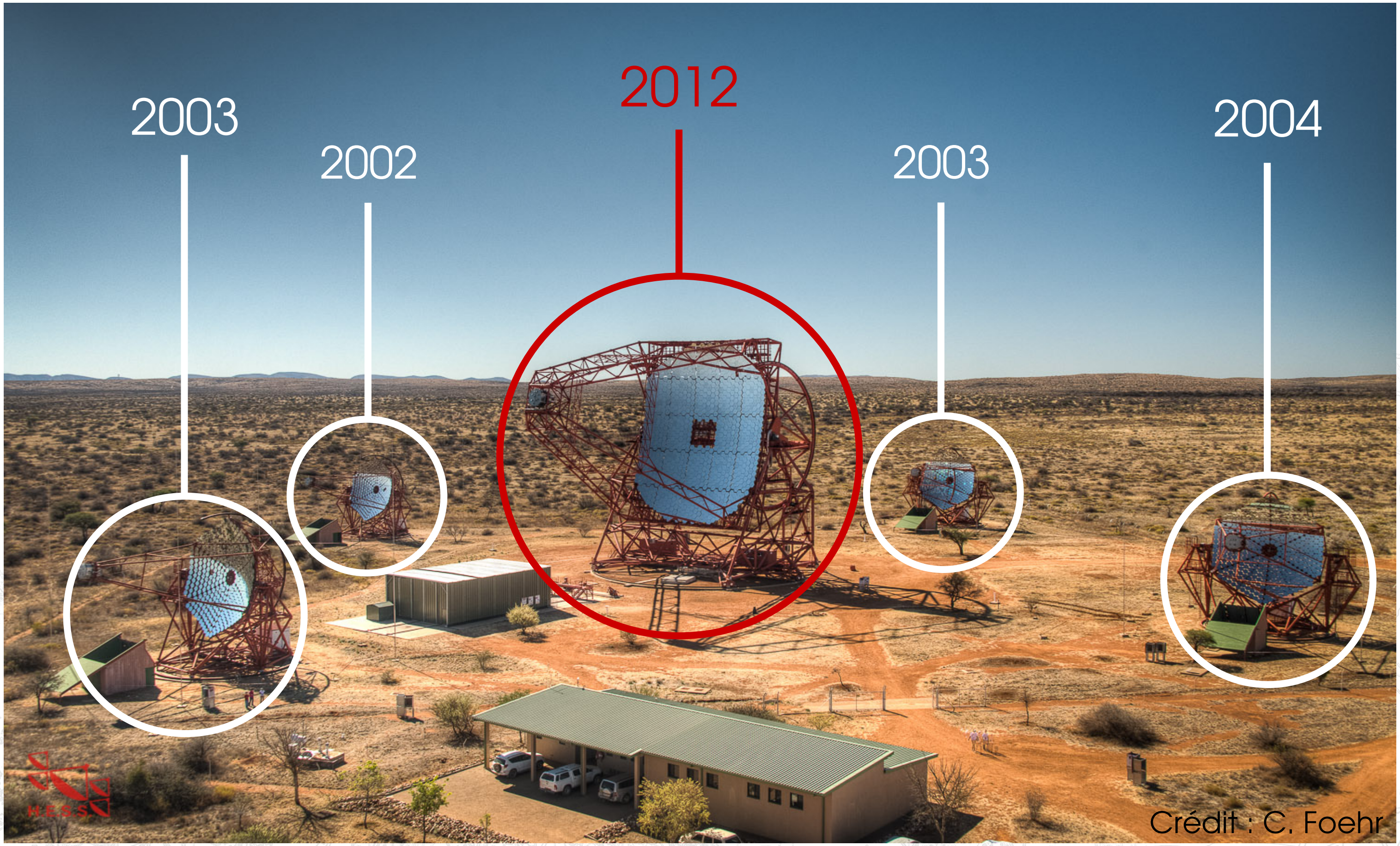
Developpement of new methods to :

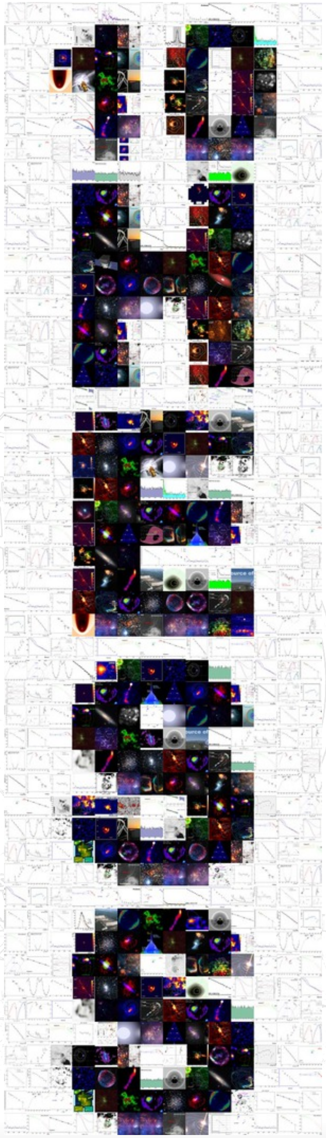
- Estimate the redshift of the source
- Constrain a potential Lorentz invariance violation

H.E.S.S. Phase II

H.E.S.S. : High Energy Stereoscopic System

An array of telescopes for very-high energy gamma ray astronomy

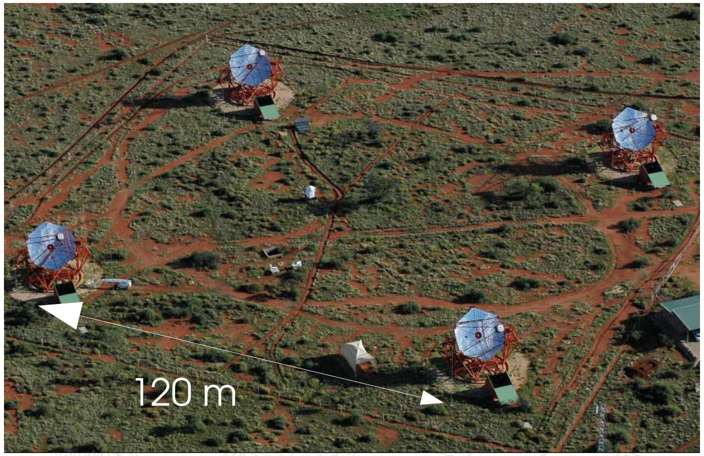


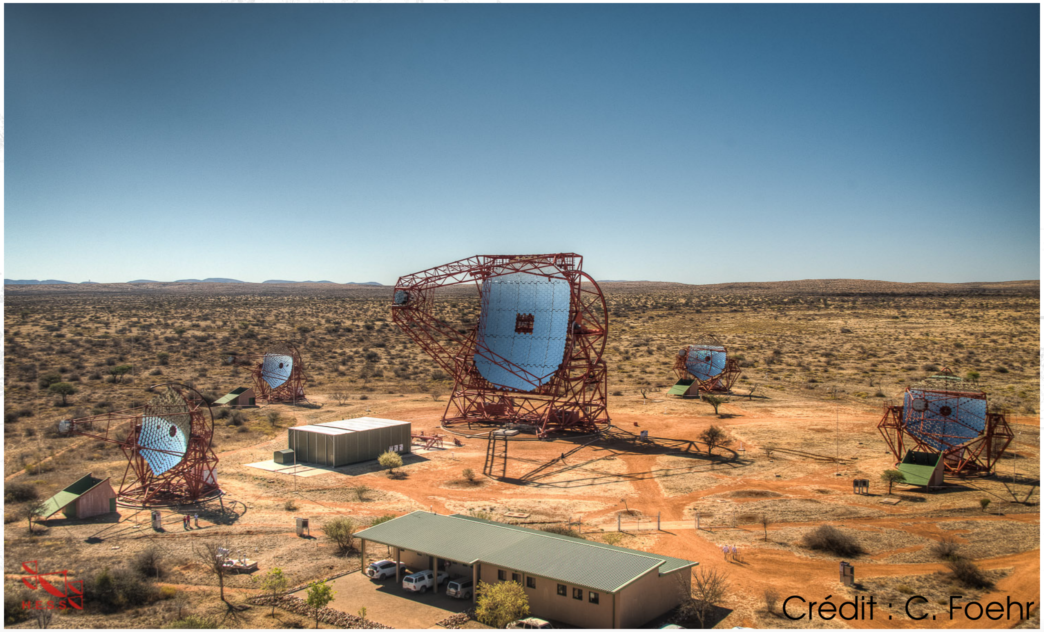


- Mont Khomas, Namibia
- H.E.S.S. I : 4 telescopes – 2004
- H.E.S.S. II : 5 telescopes - 2012

The H.E.S.S. array

- High Energy Stereoscopic System
  - 4 telescopes of 107 m²
  - Cameras with 960 PMTs
  - Field of view : 5°
  - 100 GeV – 50 TeV (resolution ~ 10%)
  - Angular resolution < 0.1°

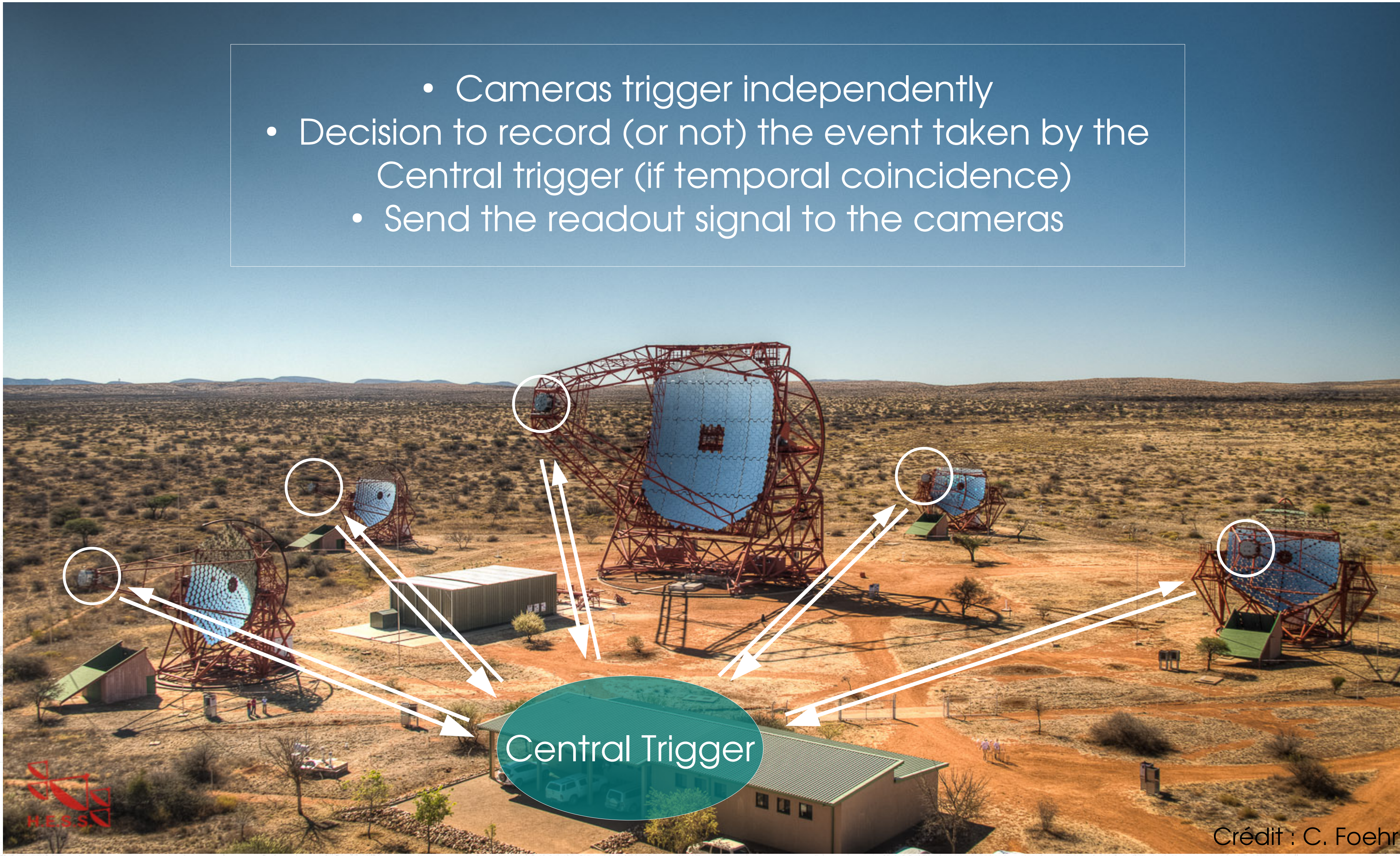




- H.E.S.S. II : additionnal 5th telescope at the center
  - 28 m in diameter, 600 m^2
  - Energy threshold lowered to ~ 50 GeV
  - Improved sensitivity and angular resolution

H.E.S.S. II

H.E.S.S. II : Central trigger



Responsible for the system from December 2011 to June 2014

H.E.S.S. II : Central trigger

- Tests, implementation and on-site installation for H.E.S.S. II
- Hardware upgrade

New electronic boards / firmware modifications

➔ Coordination of MPIK's electronicians

Optical Fibers converter boards

Delay boards

Central Trigger board

Monitoring boards

Scaler board

+ possibility to take data no matter the location of the camera (dish/shelter)

H.E.S.S. II : Central trigger

- Tests, implementation and on-site installation for H.E.S.S. II
- Hardware upgrade

  New electronic boards / firmware modifications

  ➔ Coordination of MPIK's electronicians

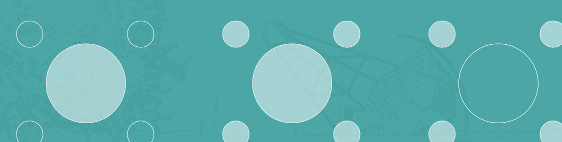
- Software upgrade

  Management of the new pieces of hardware

  Communication and data streams from/to the central data acquisition software

  New capabilities :

  - Different event types : Mono, Hybride, HESS I

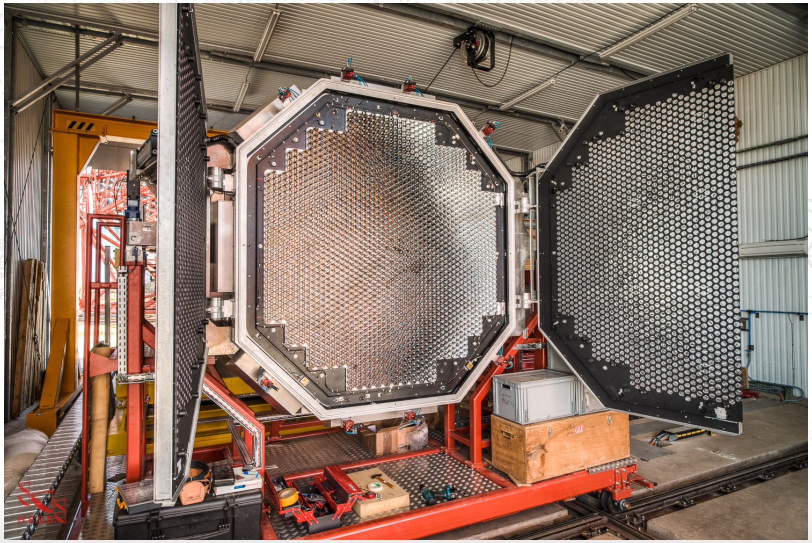
  

  - Possibility to split HESS II and HESS I observations (subarrays)

- Documentation

H.E.S.S. II : Camera

- A better camera (IN2P3)
  - 100 times smaller dead time (compared to H.E.S.S. I)
  - 2048 pixels instead of 960
  - ~ 2 kHz (H.E.S.S. I ~ 500 Hz)
  - Smaller field of view… but better sampled



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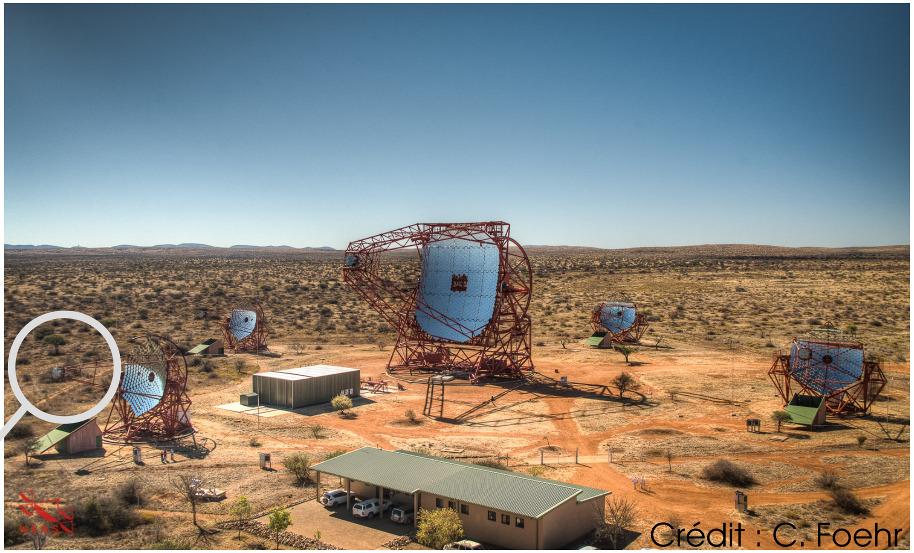
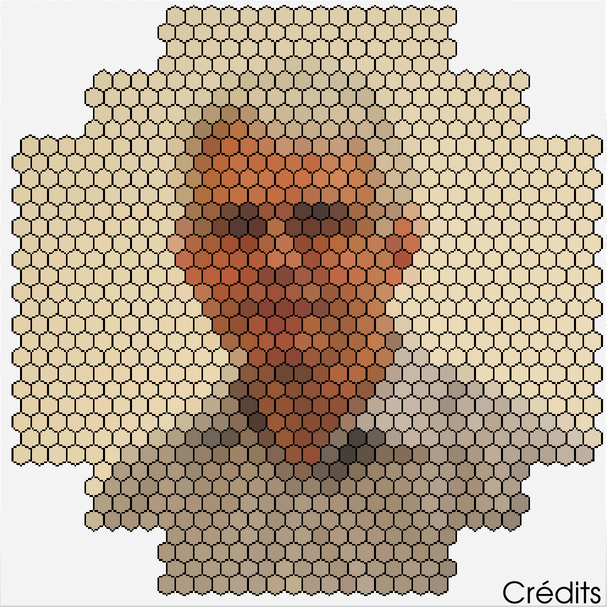


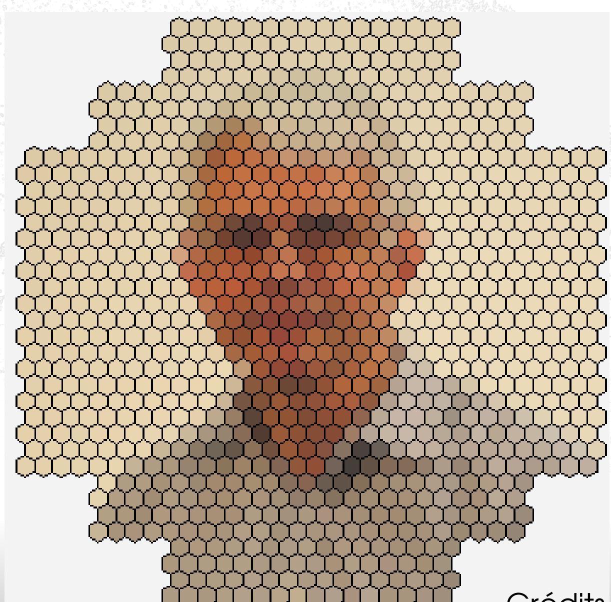
Crédit : C. Foehr

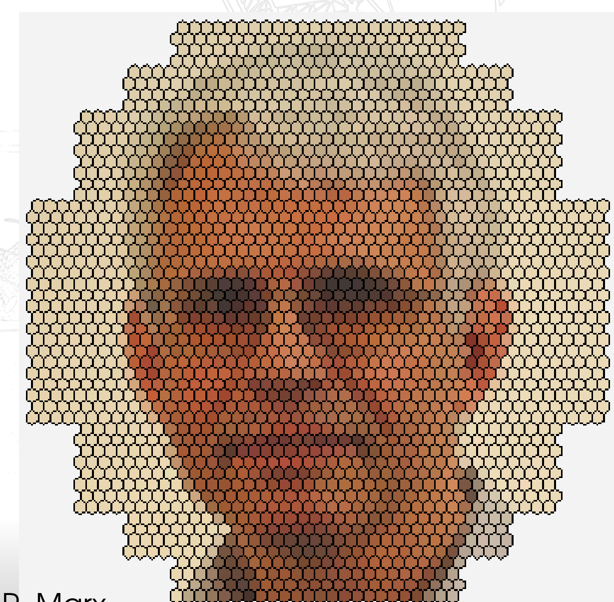


Crédits : V. Marandon, R. Marx

H.E.S.S. II : Camera

- A better camera (IN2P3)
  - 100 times smaller dead time (com
  - 2048 pixels instead of 960
  - ~ 2 kHz (H.E.S.S. I ~ 500 Hz)
  - Smaller field of view… but better sampled

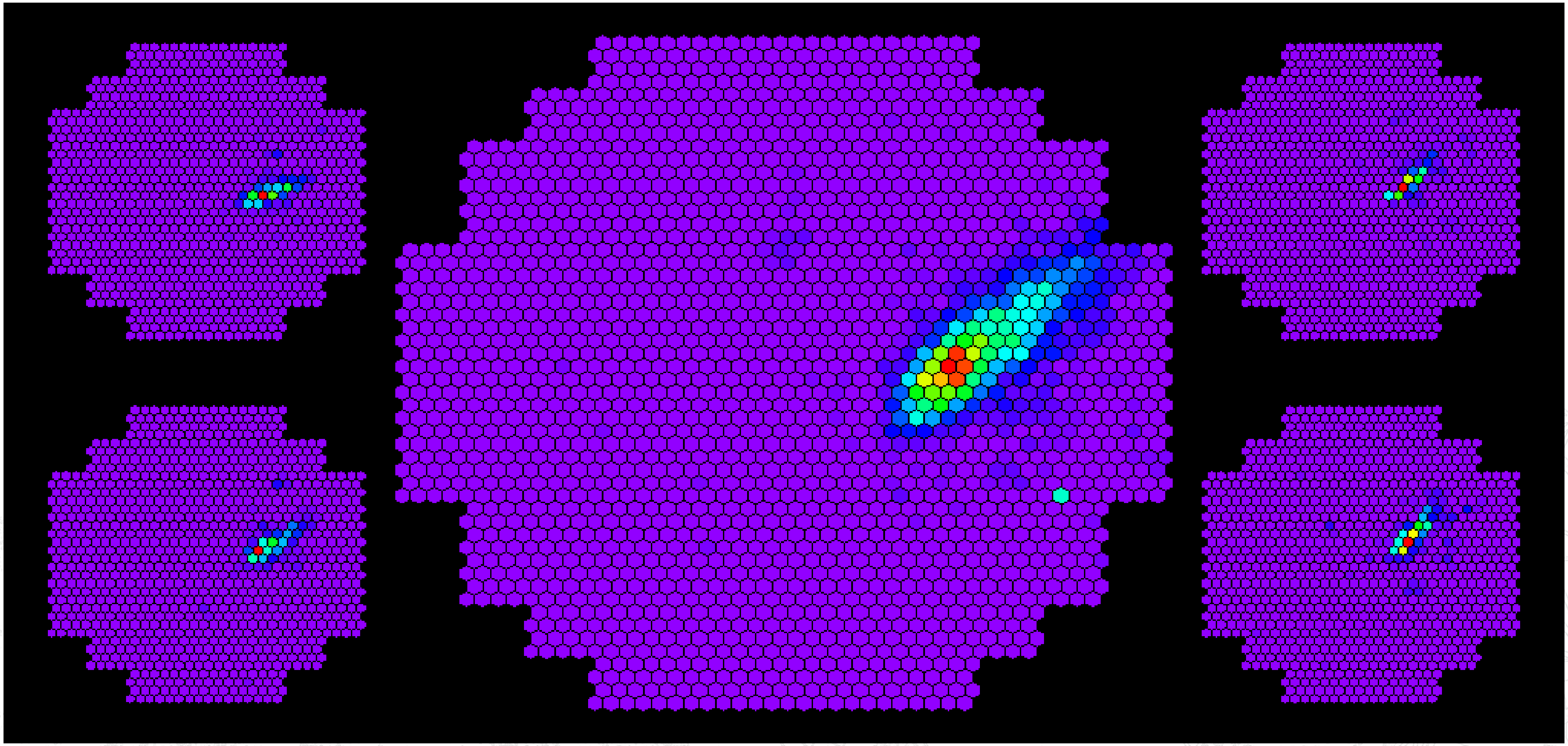




Crédits : V. Marandon, R. Marx

H.E.S.S. II

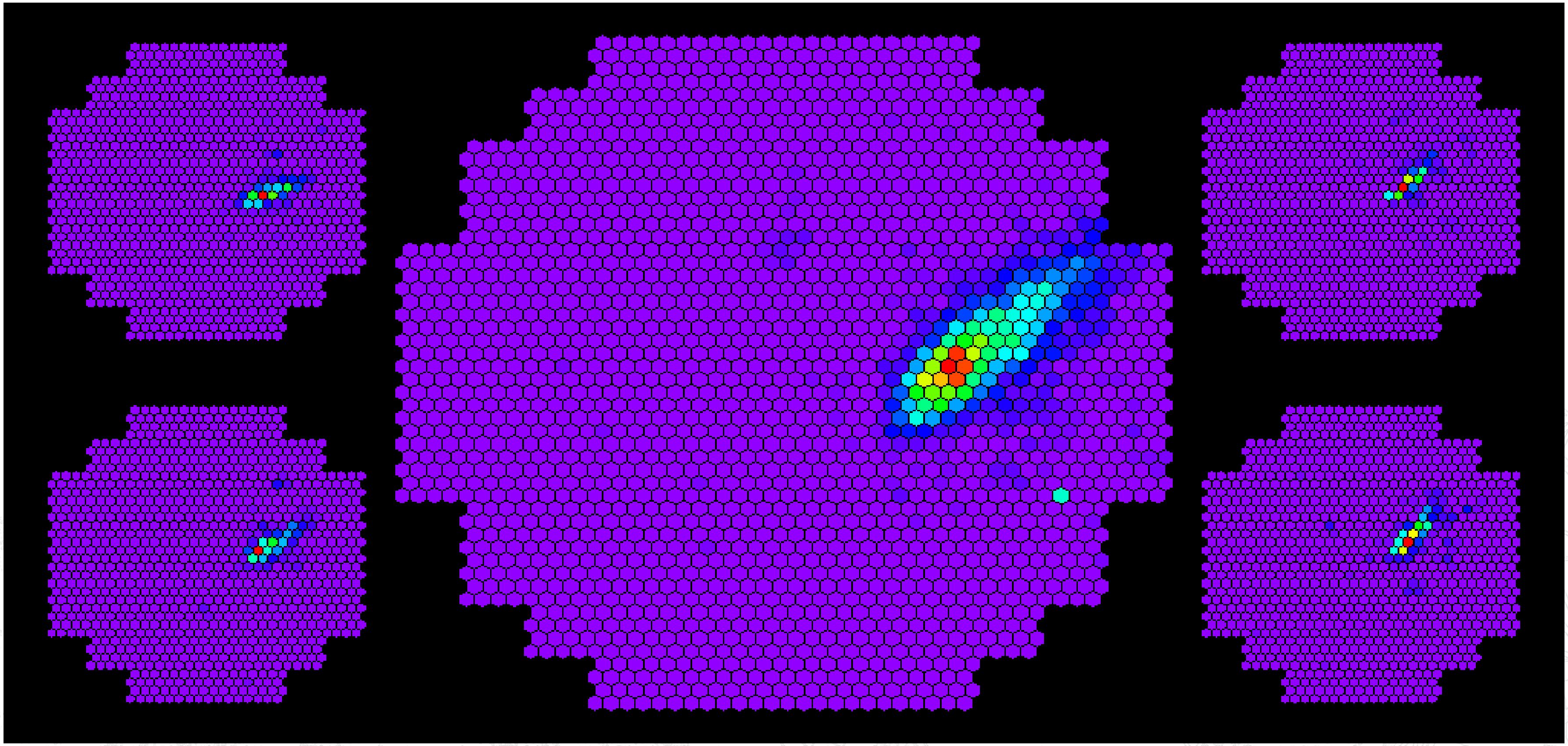
Event seen by the 5 telescopes in coincidence



First « hybrid » array of Cherenkov telescopes !

H.E.S.S. II

Event seen by the 5 telescopes in coincidence



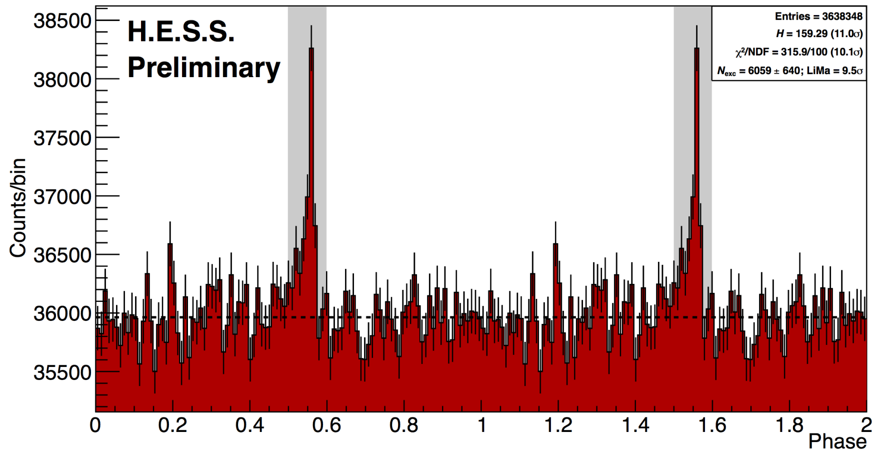
First « hybrid » array of Cherenkov telescopes !

Upgrade of the H.E.S.S. I cameras planned in 2015

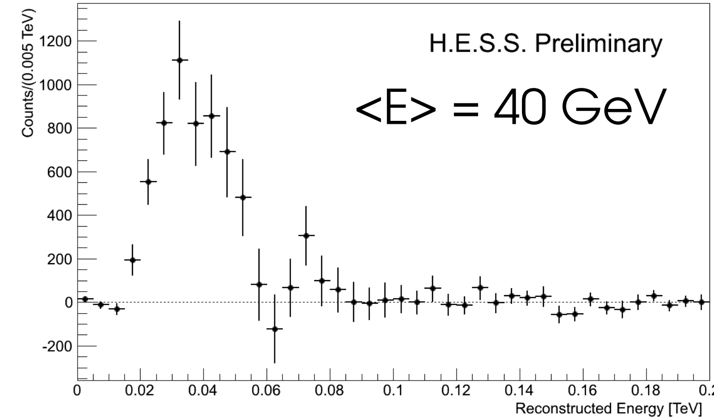
Science with H.E.S.S. II

- Lower energy threshold :
  - Pulsars (MAGIC & VERITAS detection of the pulsed emission of the Crab)
  - Supernova remnants
  - Dark matter ?
  - AGN less absorbed by EBL
    - → More objects
  - Part of the energy range common with Fermi
- Faster structure : re-pointing < 2 minutes
  - GRB detection ?
- Increased sensitivity to variable/transient sources

Vela Pulsar
8σ detection of the pulsed signal

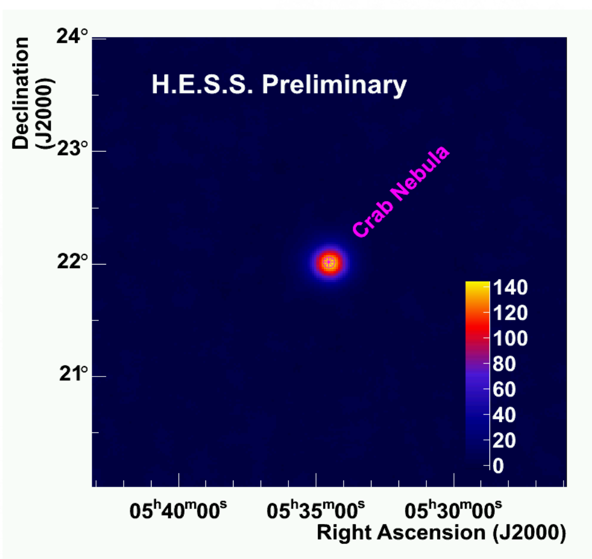


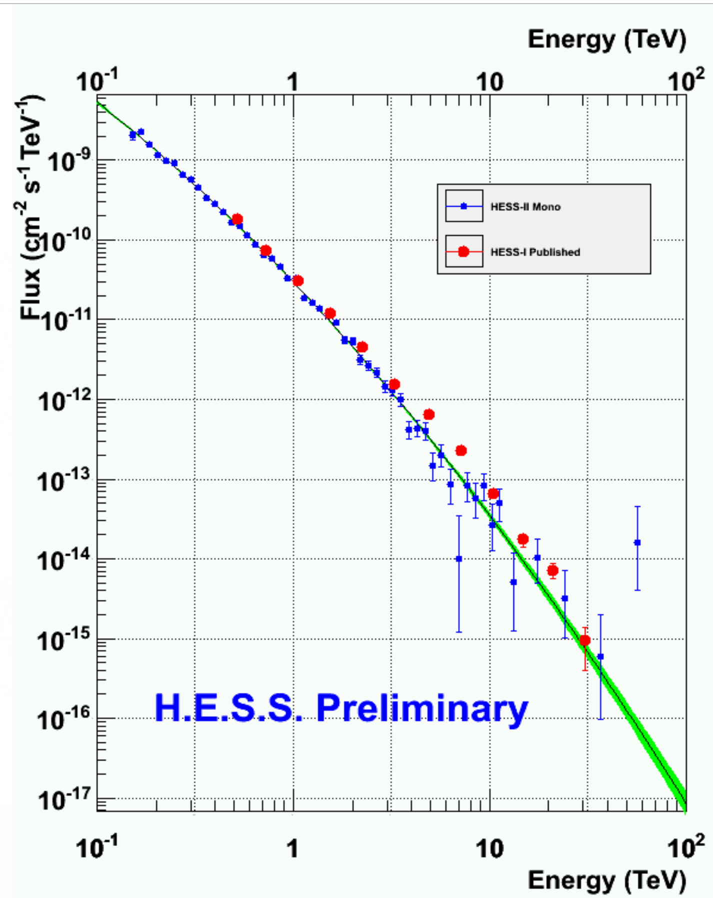
Energy distribution

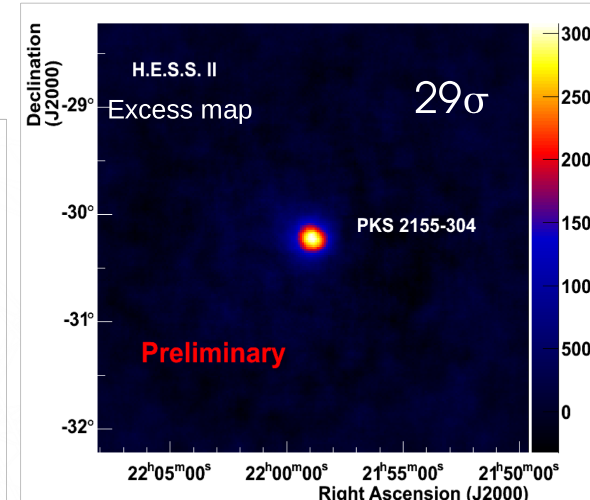


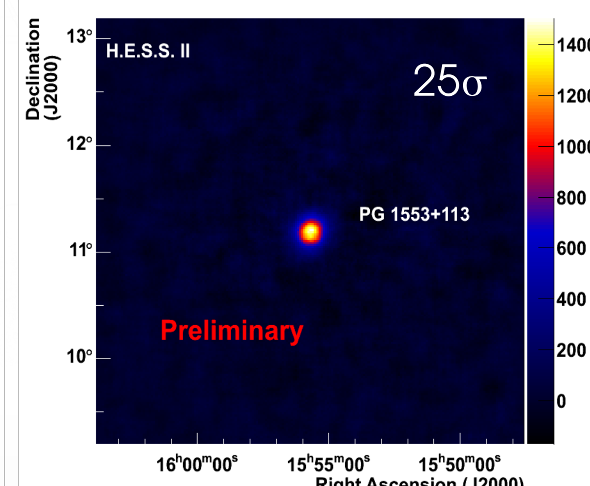
First H.E.S.S. II results (Conferences, summer 2014)

Crab nebula





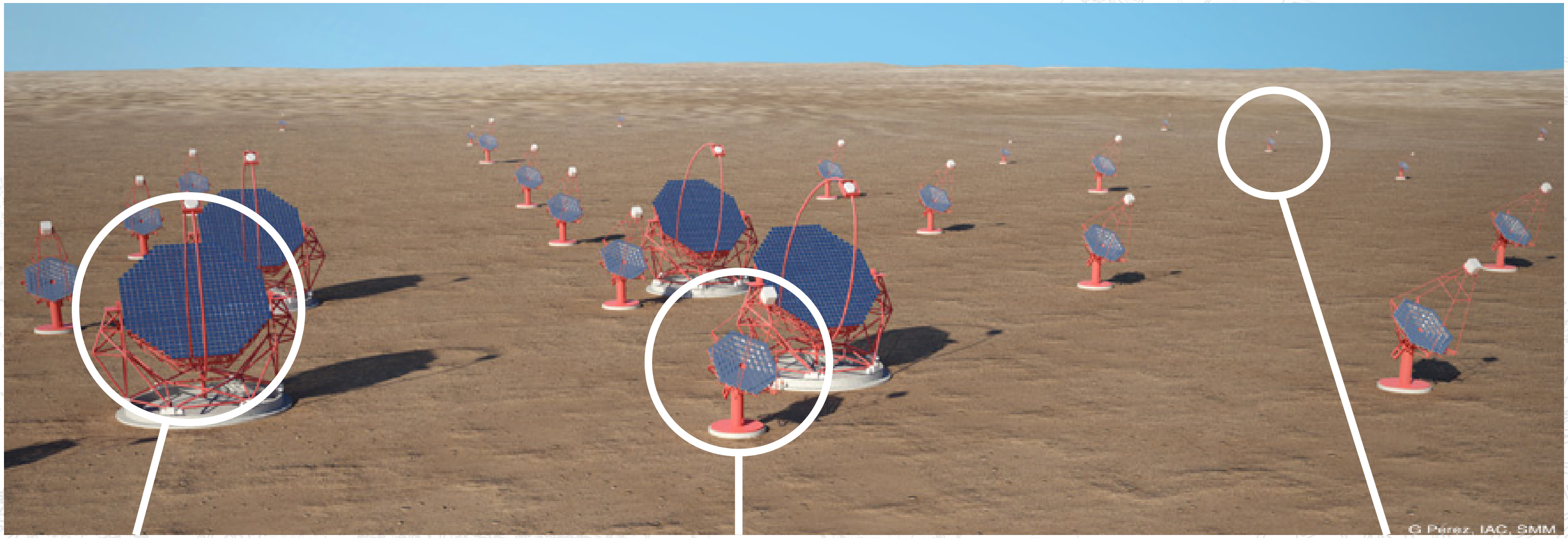




Cherenkov Telescope Array

The next step : CTA

- CTA (Cherenkov Telescope Array) : several number of telescopes (~2020)
  - 10 GeV – 100 TeV
  - Better sensitivity on the whole energy range (x10 at 1 TeV)
  - Better angular resolution



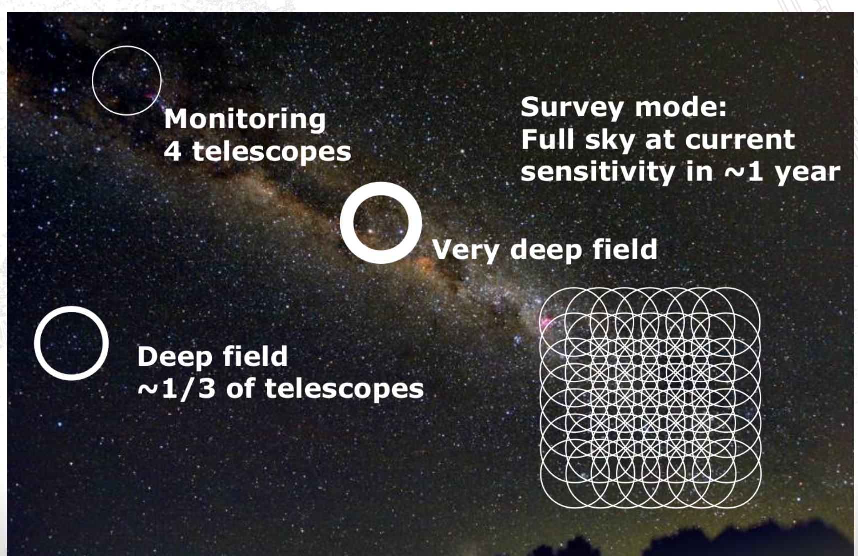
A few H.E.S.S. II -like : low énergies

Several H.E.S.S. I-like telescopes : sensitivity and energy reconstruction

Field of small telescopes (~6 m) : collection area + very high energies

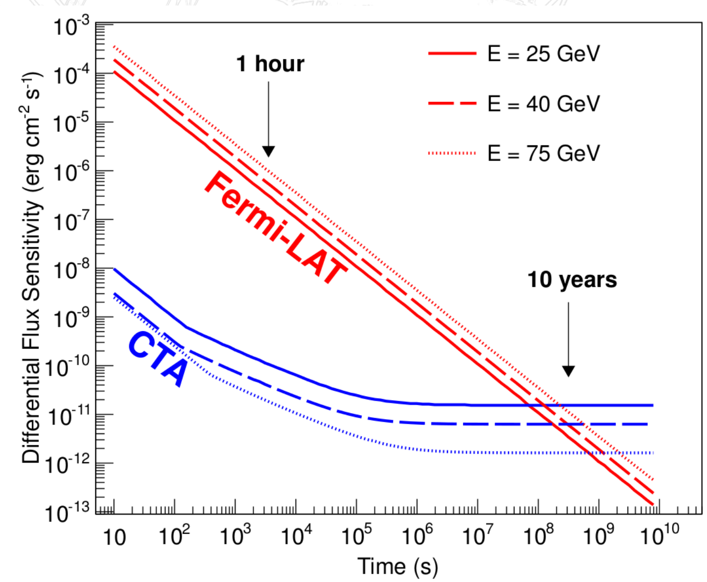
The next step : CTA

- CTA (Cherenkov Telescope Array) : several number of telescopes (~2020)
  - 10 GeV – 100 TeV
  - Better sensitivity on the whole energy range (x10 at 1 TeV)
  - Better angular resolution
- Southern + Northern sites : complete sky coverage
- Flexible observatory :
  - Surveys, deep fields, monitoring...



The next step : CTA

- CTA (Cherenkov Telescope Array) : several number of telescopes (~2020)
  - 10 GeV – 100 TeV
  - Better sensitivity on the whole energy range (x10 at 1 TeV)
  - Better angular resolution
- Southern + Northern sites : complete sky coverage
- Flexible observatory :
  - Surveys, deep fields, monitoring...
  - Sensitive to transient events
    - ➔ Alerts !

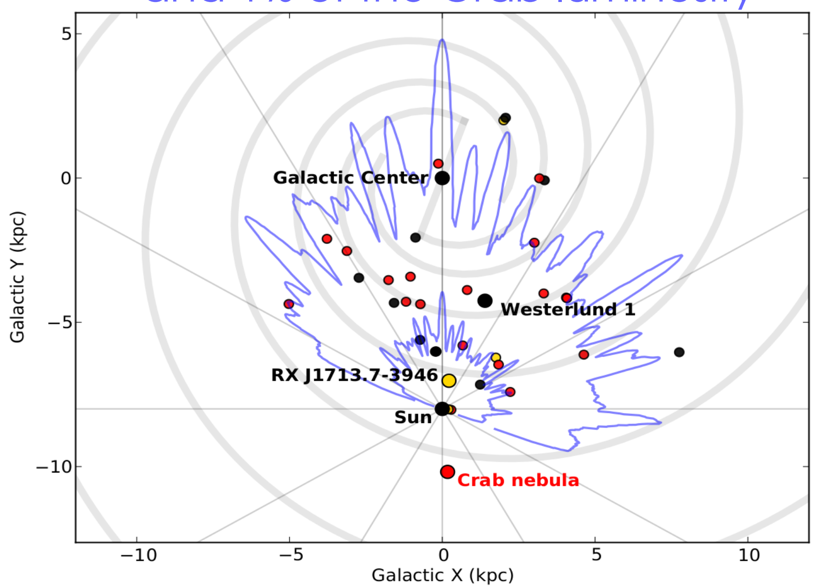


Funk & Hinton, 2013

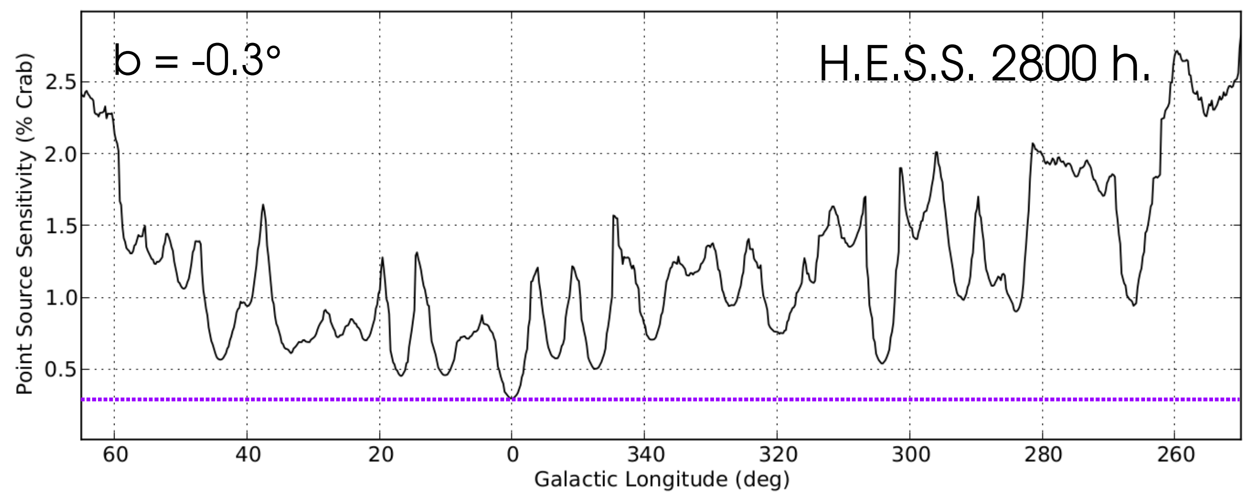
The Galactic plane survey with CTA

- ~ 75% unresolved sources

Horizon (H.E.S.S.) for sources at 10% and 1% of the Crab luminosity



S. Carrigan, **F. Brun** et al., 2013 (ICRC)



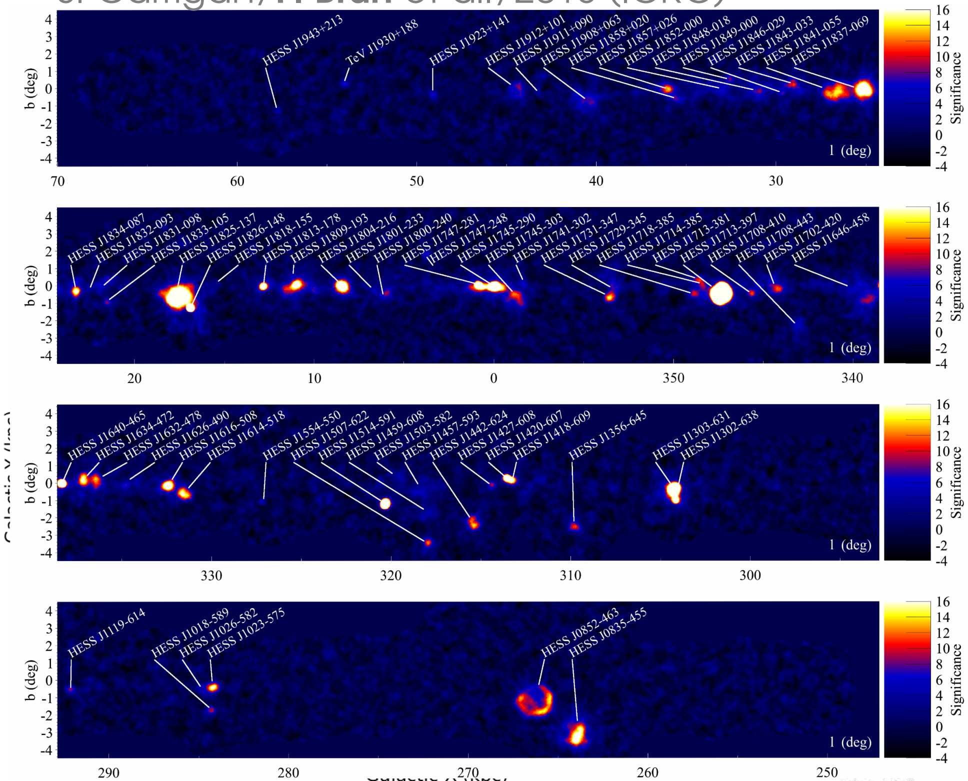
3 mCrab in 250 h. With CTA

(G. Dubus et al. 2012)

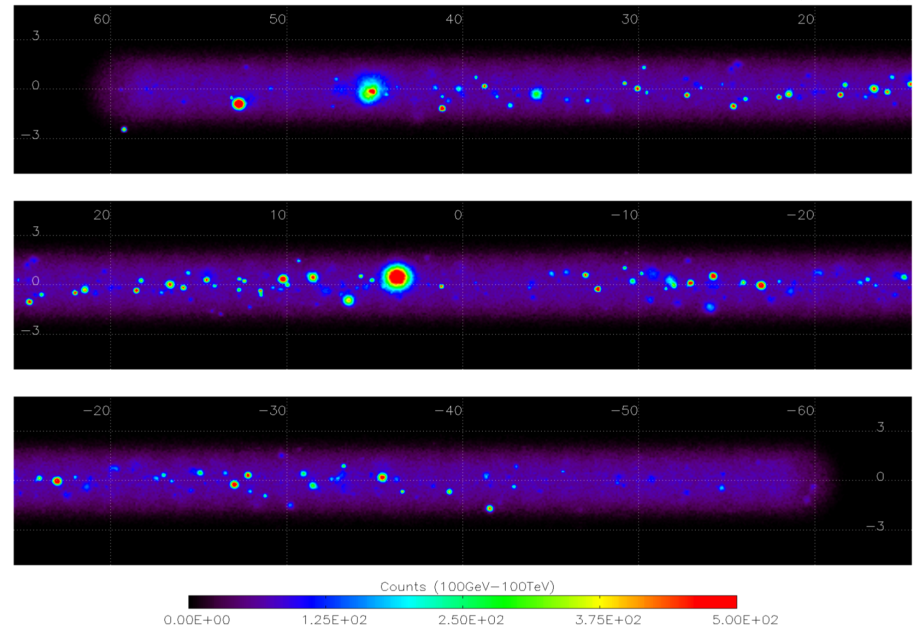
- Extragalactic sky survey capabilities :
  - 1/4 sky at 30 mCrab in ~ 370 h. (G. Dubus et al. 2012)

The Galactic plane survey with CTA

S. Carrigan, **F. Brun** et al., 2013 (ICRC)



G. Dubus et al.(2012)



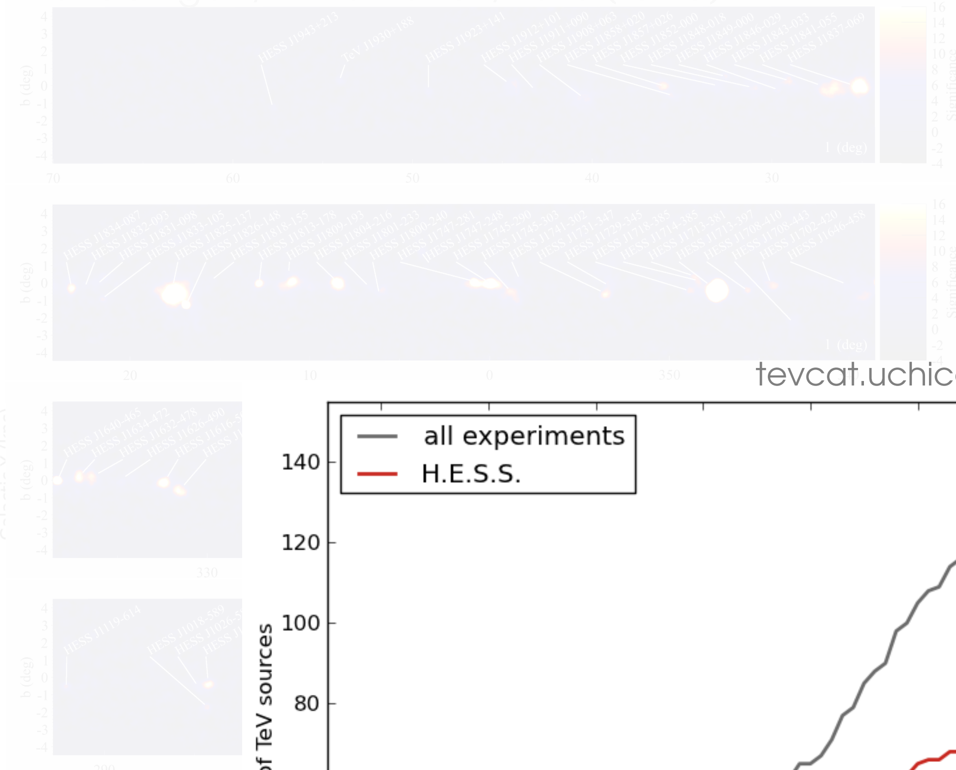
Study sources with (intrinsic) spectral breaks

Population studies, Detailed analysis of interesting sources

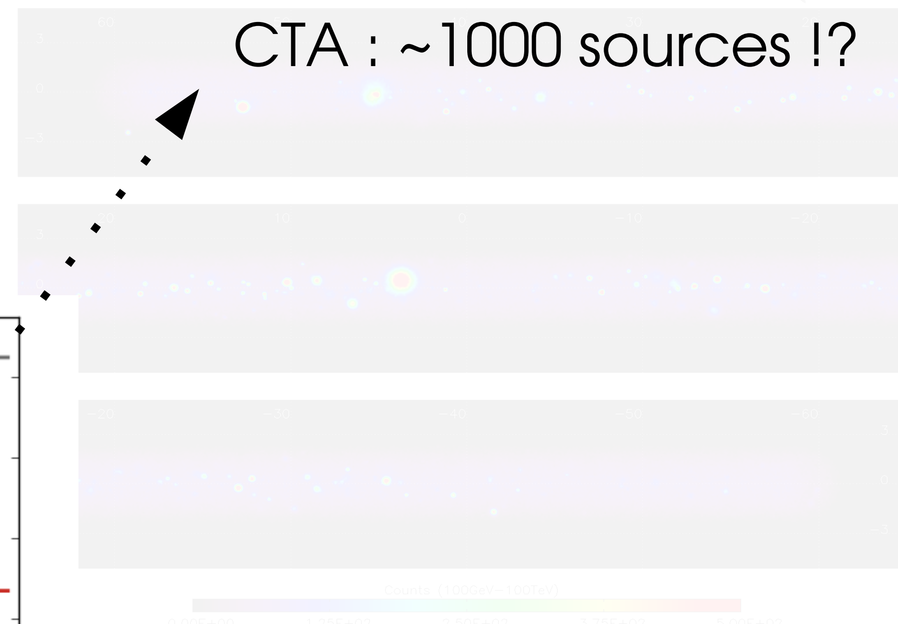
Highest energy limit of cosmic accelerators

The Galactic plane survey with CTA

S. Carrigan, F. Brun et al., 2013 (ICRC)

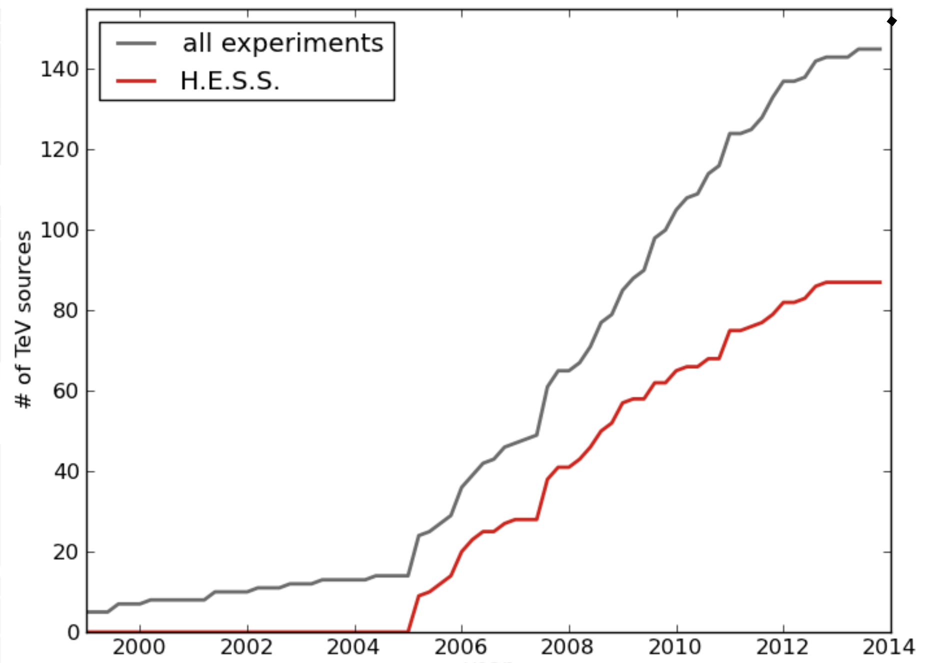


G. Dubus et al.(2012)



CTA : ~1000 sources !?

tevcat.uchicago.edu



All: Whipple, Crimea, Telescope Array, Durham, MAGIC, VERITAS, H.E.S.S.

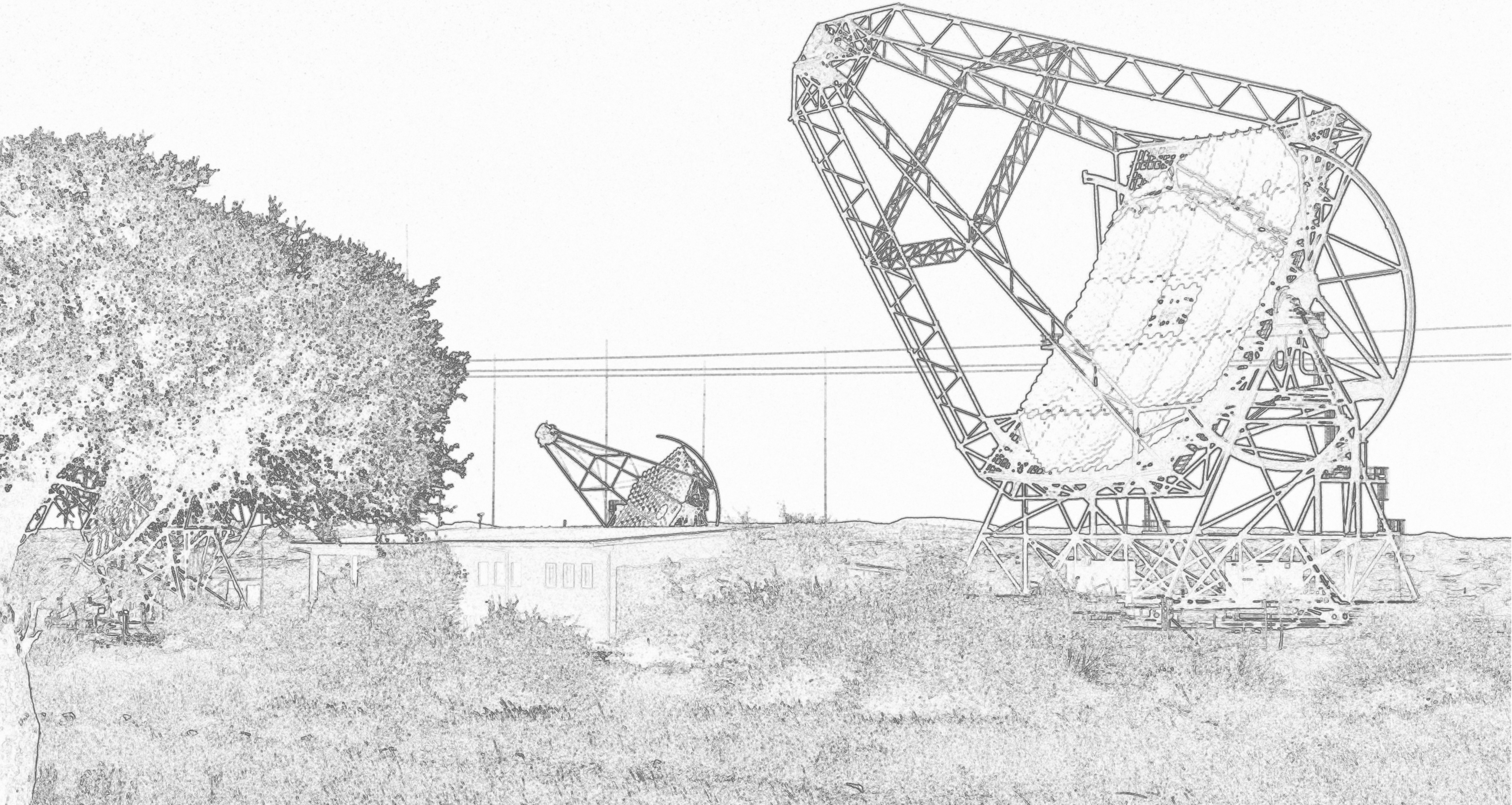
Highest energy limit of cosmic accelerators

Summary

- Gamma ray sources are cosmic particle accelerators
- Accelerating particles at multi-TeV energies is easy (for Nature)
- H.E.S.S. first 10 years of operation
  - 10 times increase in number of known TeV sources (same as at GeV)
  - Real astronomy : detailed sky maps, detailed spectra and light curves
- Large variety of acceleration mechanism, often related to life cycle of massive stars
- Qualitative understanding of some mechanisms but still many open issues
- Near to addressing fundamental issues in cosmology, DM, axion searches, LIV...

→ *Stay tuned for the upcoming H.E.S.S. II results !*

Thanks for your attention !

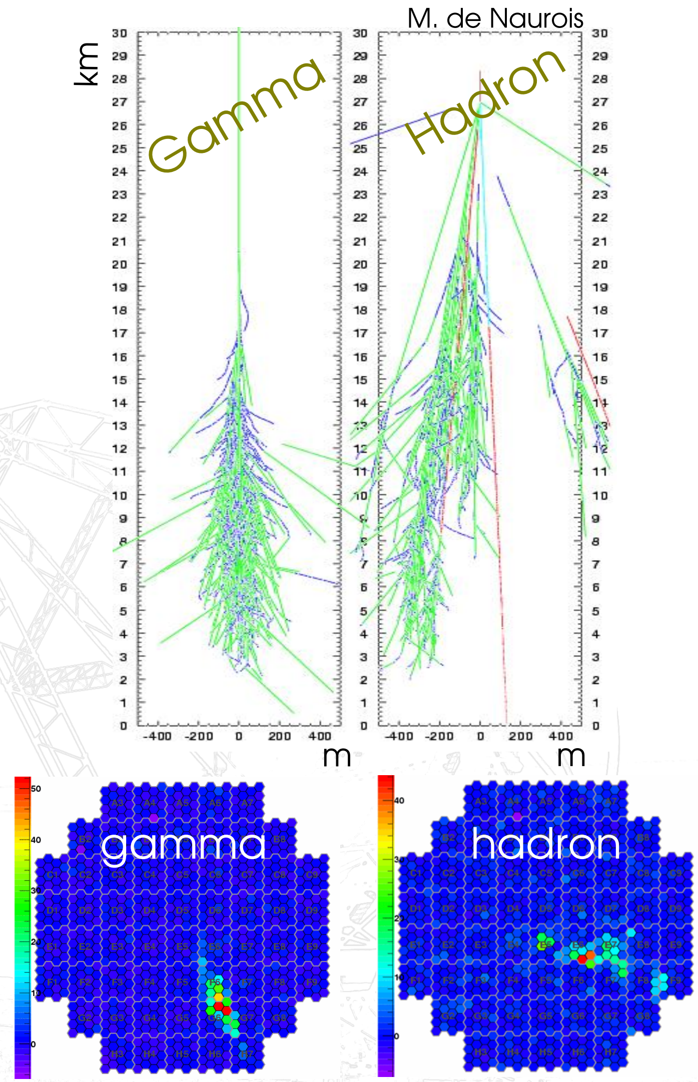


Imaging atmospheric Cherenkov technique

- ~ 1 γ for 1000 hadrons
  - EM Showers : smooth, symetrical
  - hadronic showers : irregular + isolated

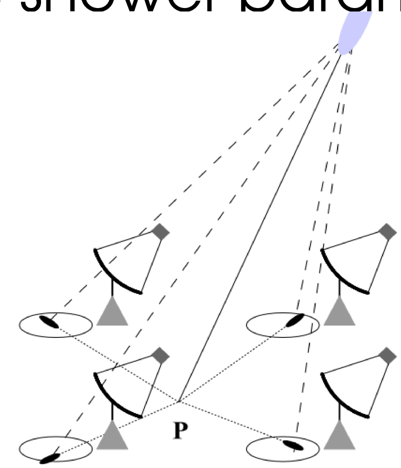
- **Fast** and **finely pixelated** cameras
- **Large mirors** and **stereoscopy**
- **Analysis :**

  Image shape -> discrimination
  Images orientation -> direction
  Intensity -> energy

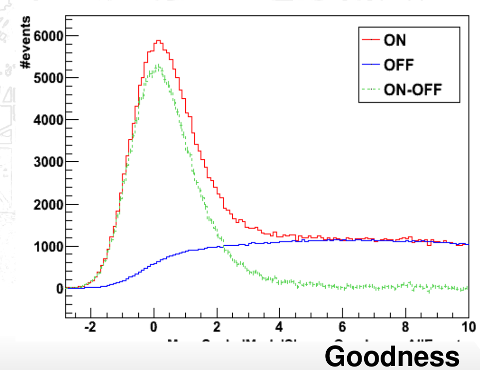


Analyse des données : reconstruction & discrimination gamma/hadron

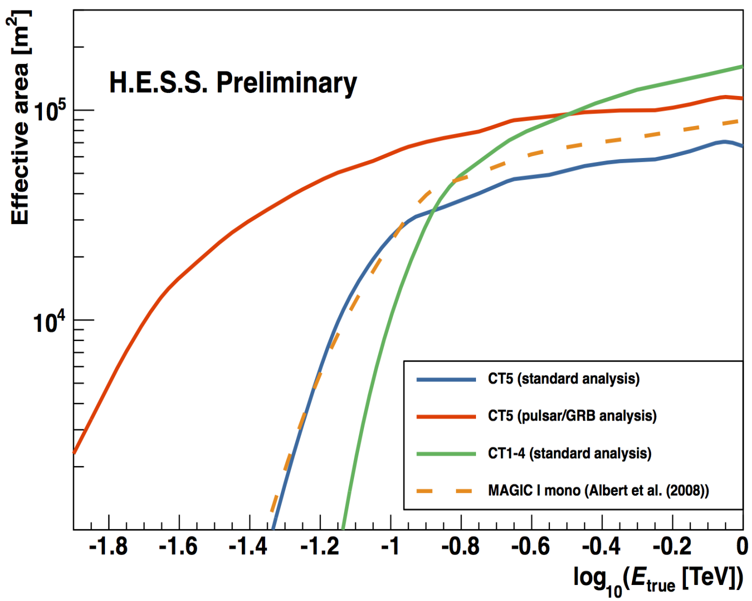
- « **Model** » analysis :
  - Comparison (pixel per pixel) of detected images to pre-calaculated images, computed from a semi-analytical model
- Maximum likelihood fit to reconstruct the shower parameters :
  - **Energy**
  - **Direction**
  - **Impact parameter (P)**
  - **First interaxtion depth**

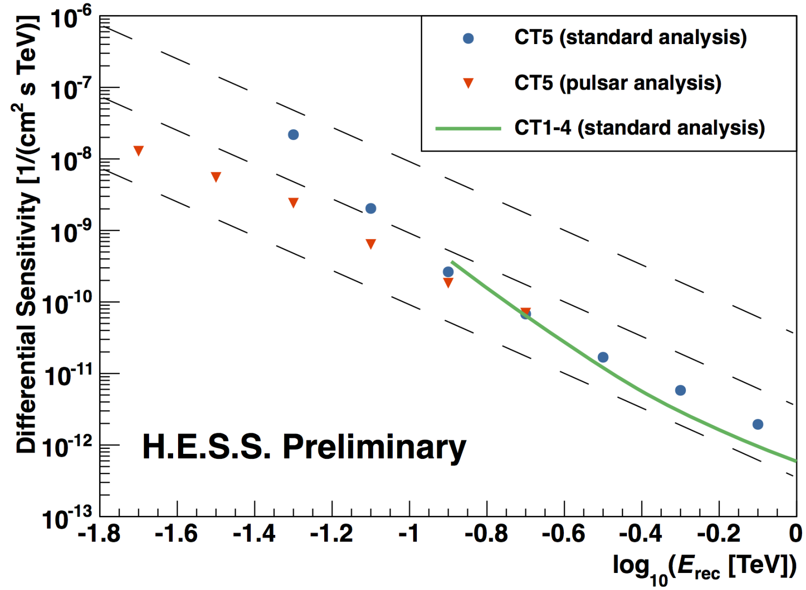


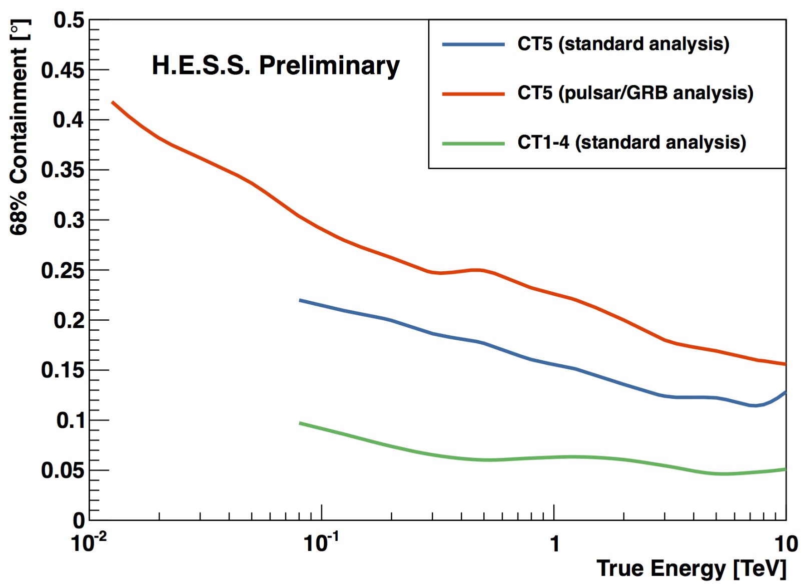
- Goodness of fit allows for the **gamma/hadron discrimination**

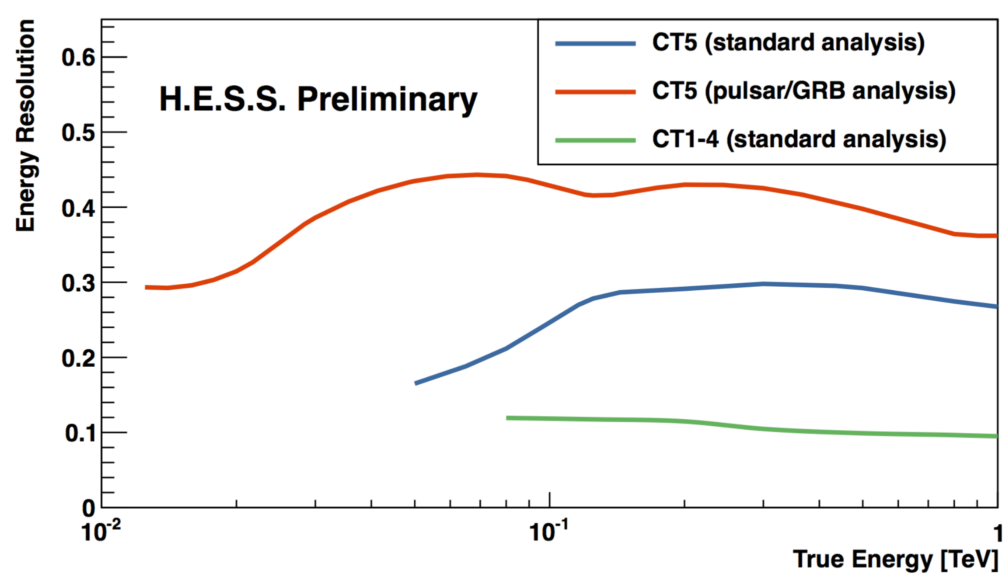


H.E.S.S. II : Performances



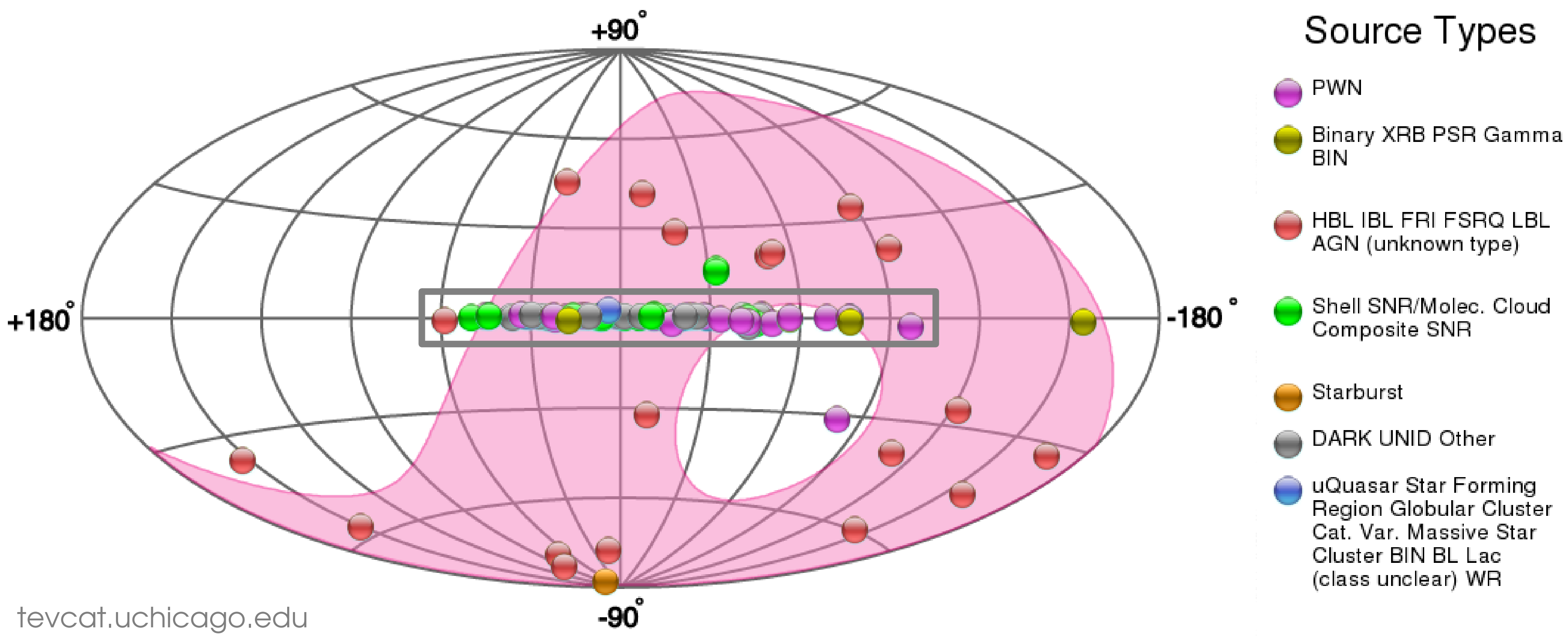






A southern hemisphere observatory

➡ Access to a large part of the Galactic plane



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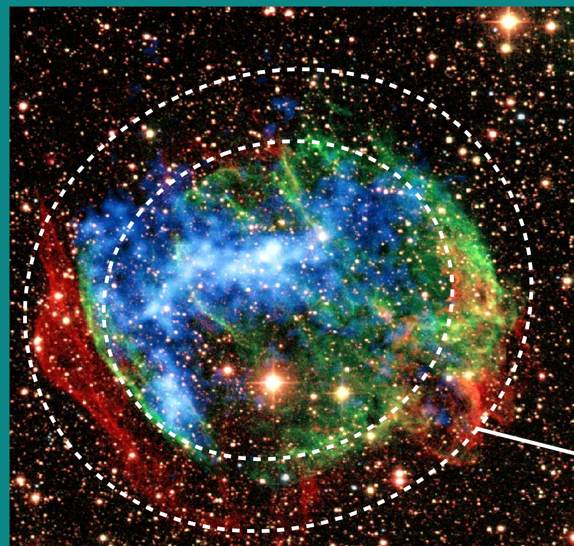
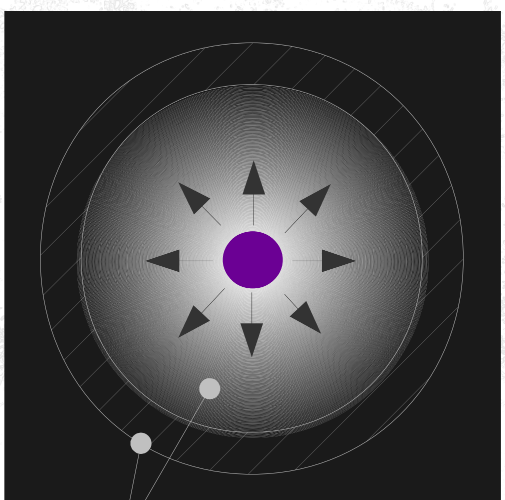
W49B – SNR/MC interaction

Composite image (Reach et al. 2006)

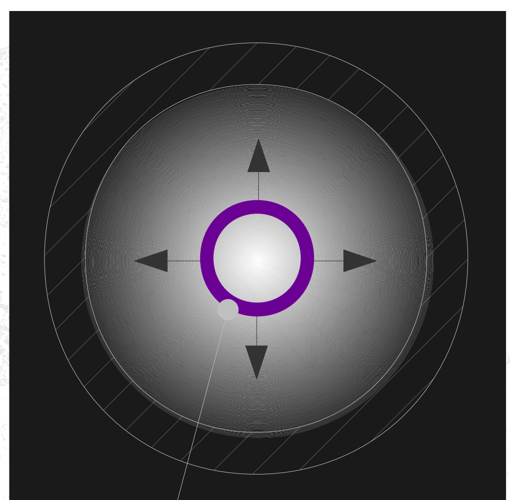


2.12 μm (IR) : Shocked molecular hydrogen (Palomar)

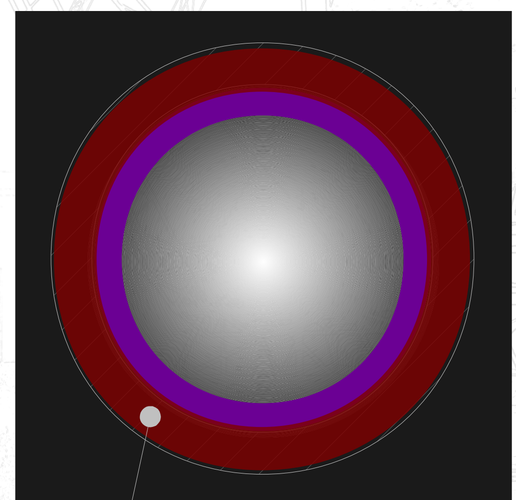
~ 1 – 3 x 10^3 cm^{-3}
~ 14 – 550 $M_\odot$



Cavity + overdensity created by the progenitor's wind

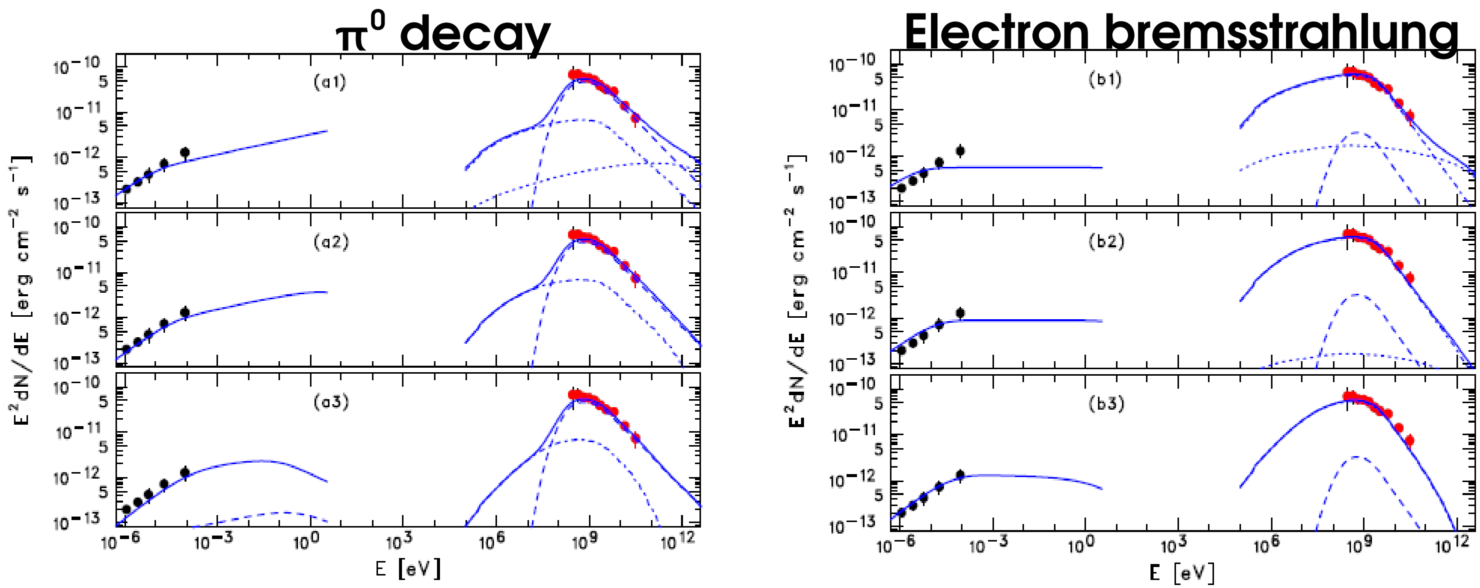


Shock wave



Shock in interaction with the overdensity

W49B – Models (Abdo et al. 2011)



Abdo et al. 2010

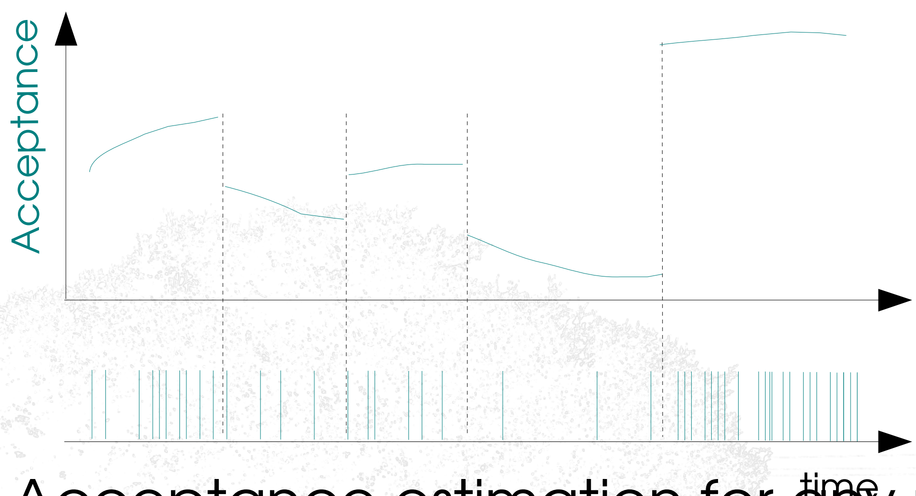
TABLE 1
PARAMETERS OF MULTIWAVELENGTH MODELS

Model	Parameters						Energetics		
	a_e/a_p	Δs	p_{br} (GeV c^{-1})	B (μG)	n_H (cm^{-3})	f	(a)W_p or (b)W_e (10^{50} erg)	(a)U_p or (b)U_e (eV cm^{-3})	U_B (eV cm^{-3})
(Case a1) π^0-decay	0.01	0.7	4	15	10	0.6	11	1.1×10^5	5.6
(Case a2) π^0-decay	0.01	0.7	4	60	100	0.06	1.1	1.1×10^5	90
(Case a3) π^0-decay	0.01	0.7	4	240	1000	0.006	0.10	1.0×10^5	1400
(Case b1) Bremsstrahlung	1.0	1.0	4	5	10	0.6	2.6	2.6×10^4	0.62
(Case b2) Bremsstrahlung	1.0	1.0	4	20	100	0.06	0.23	2.3×10^4	10
(Case b3) Bremsstrahlung	1.0	1.0	4	80	1000	0.006	0.016	1.6×10^4	160

NOTE. — Seed photons for IC include infrared ($kT_{IR} = 3 \times 10^{-3}$ eV, $U_{IR} = 1$ eV cm^{-3}), optical ($kT_{opt} = 0.25$ eV, $U_{opt} = 1$ eV cm^{-3}), and the CMB. The total energy, $W_{e,p}$ and energy density $U_{e,p}$ of radiating particles are calculated for $p > 10$ MeV c^{-1}

Correction of the temporal acceptance variations

- Acceptance evolves with observation conditions (Zenith angle, atmospheric conditions...)
  - Higher acceptance induces lower time intervals
    - Needs to be corrected → $d\tau = a(t)dt$



Events : variable background (instrument) + possible variable source

↓

- Predict the background variability : **acceptance estimation**

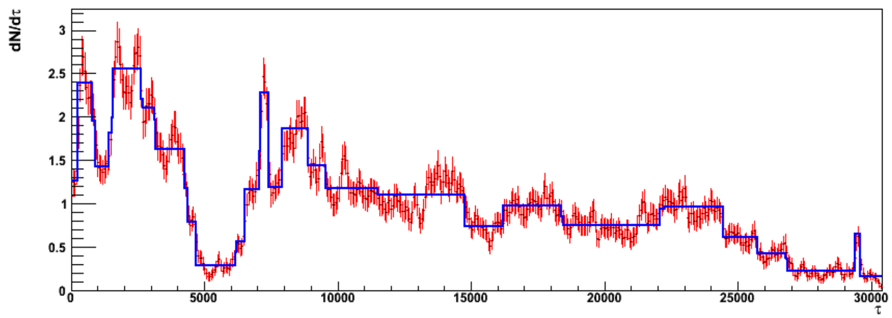
- Suppress instrumental variability : **acceptance correction**

- Acceptance estimation for any position and date during observations ✓

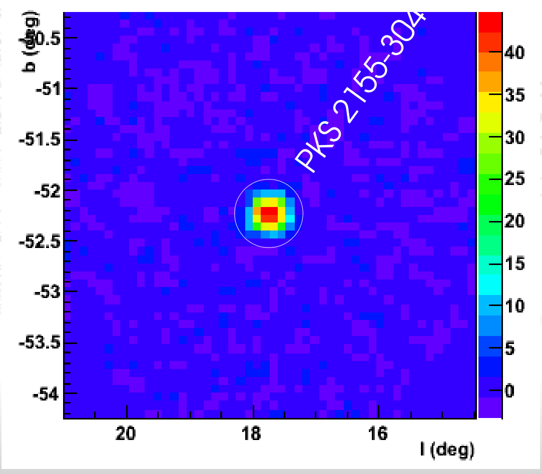
- Correction of the temporal acceptance variations and normalization (mean rate = 1) ✓

Implemented tests

- Once acceptance estimation and correction is performed, any kind of test can be applied
  - **Exp-test, Inter-events test (Prahl, 1999)**
  - **Running Exp-test**
  - **Bayesian blocs (Scargle 1998)**
  - **Cumulative sum**
  - **ON/OFF**

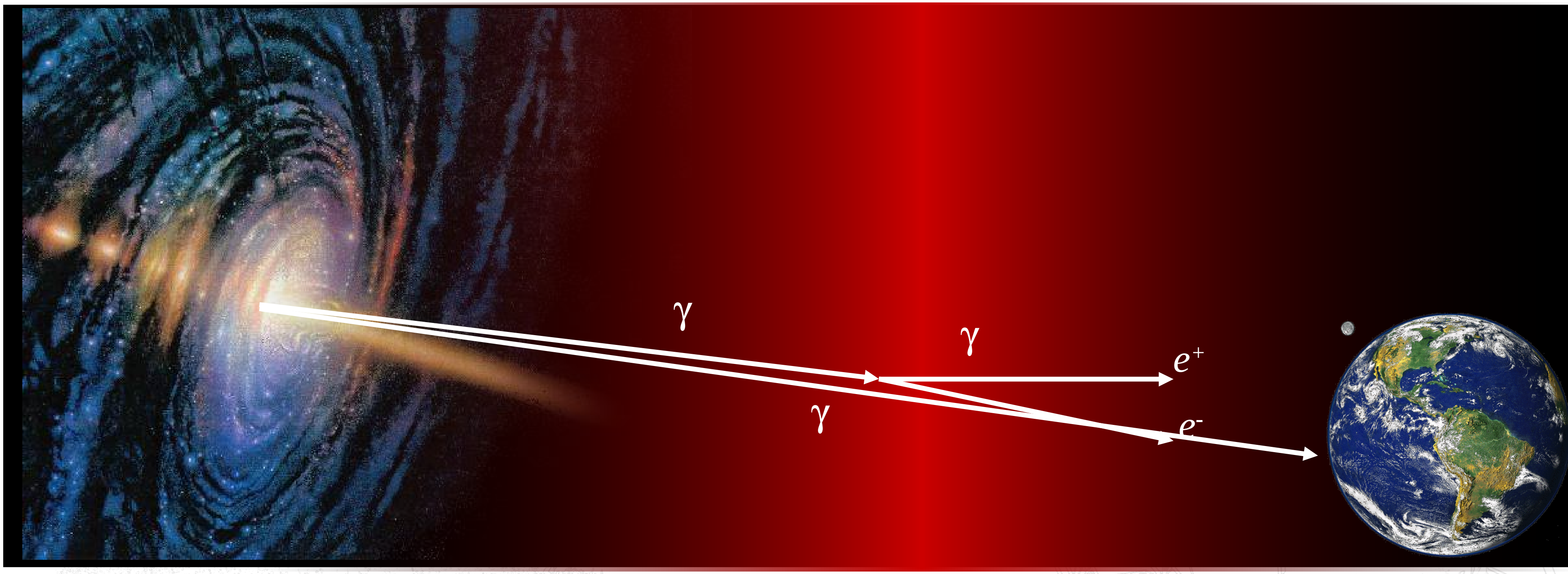


→ Production of variability maps possible

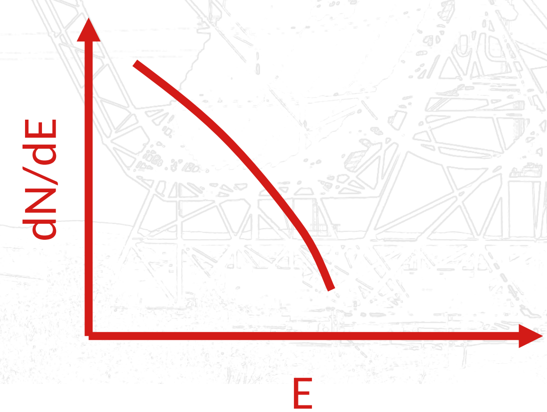


Significance map of the Exp-test

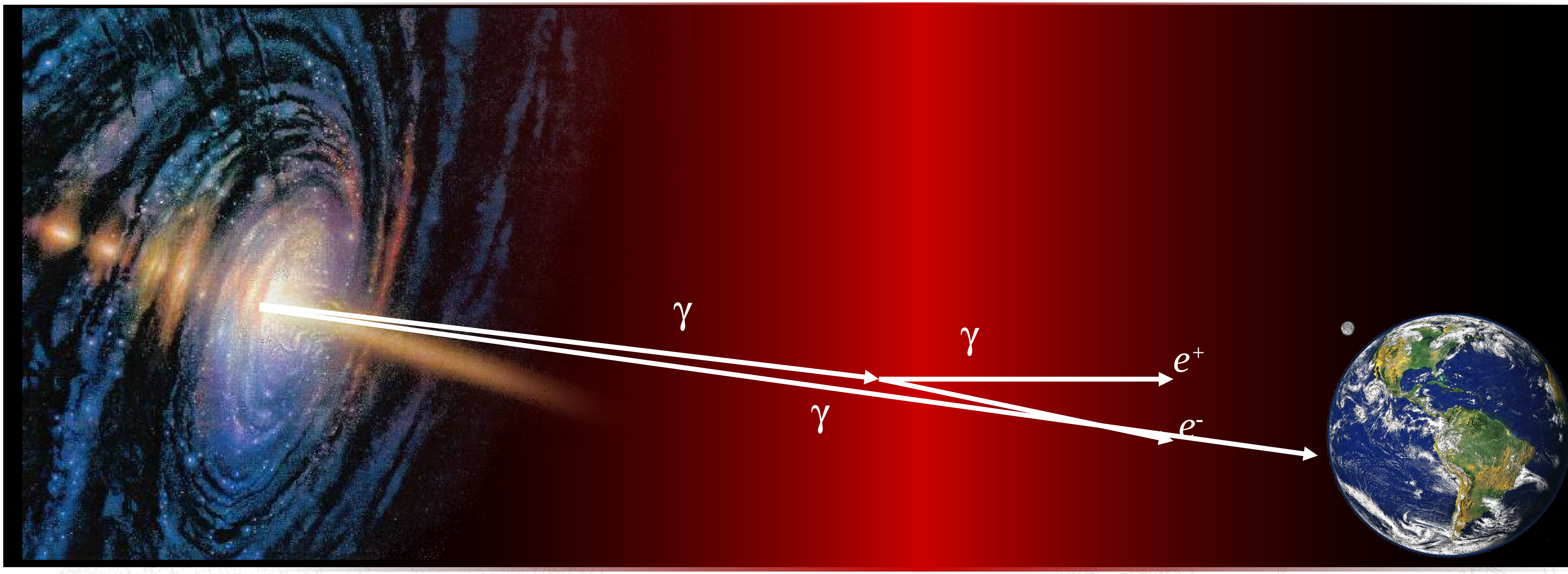
Extragalactic Background Light (EBL)



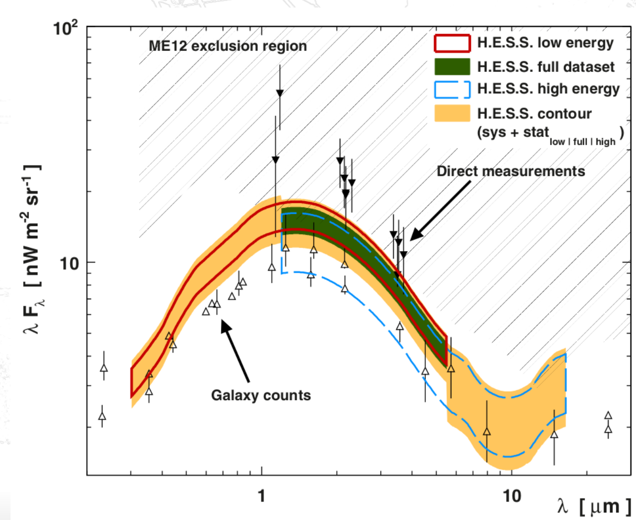
Absorption by pair creation
TeV + O/IR -> $e^+ e^-$



Extragalactic Background Light (EBL)

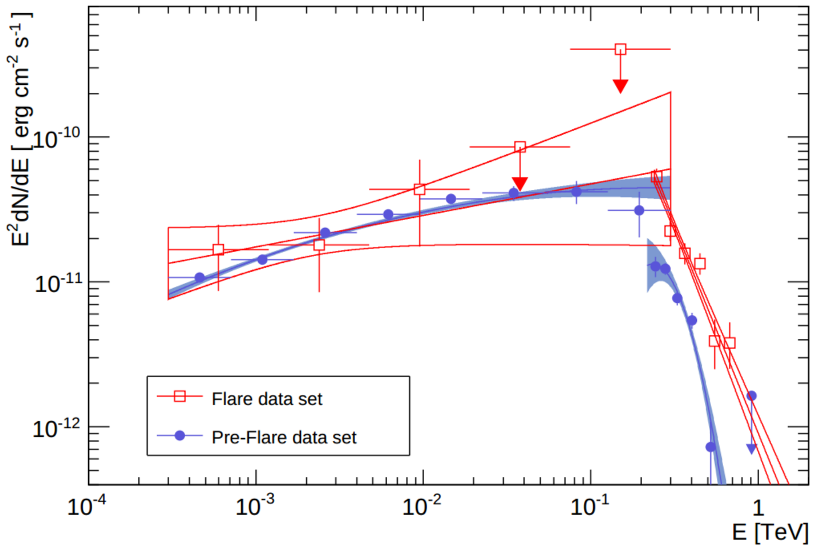


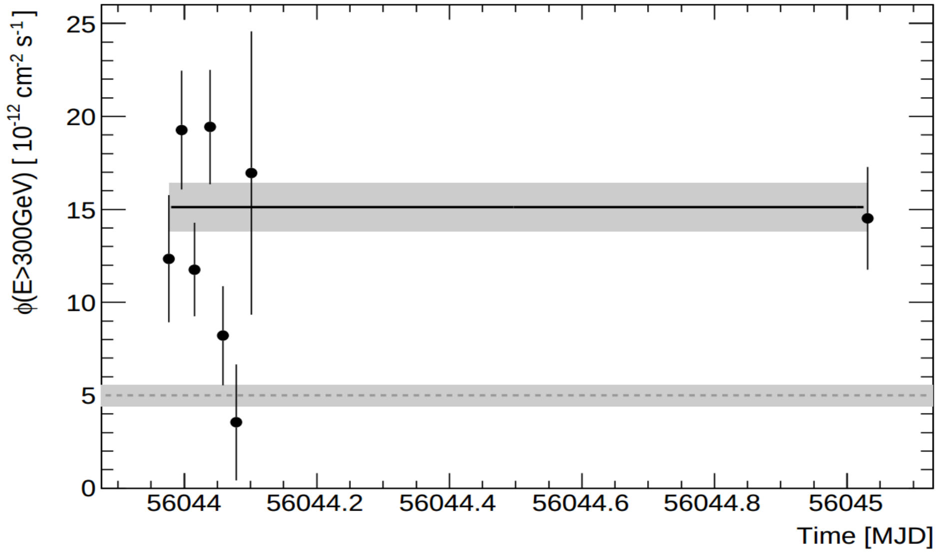
EBL detected by H.E.S.S. at ~ 8.8σ taking into account the absorption directly at the spectrum reconstruction step



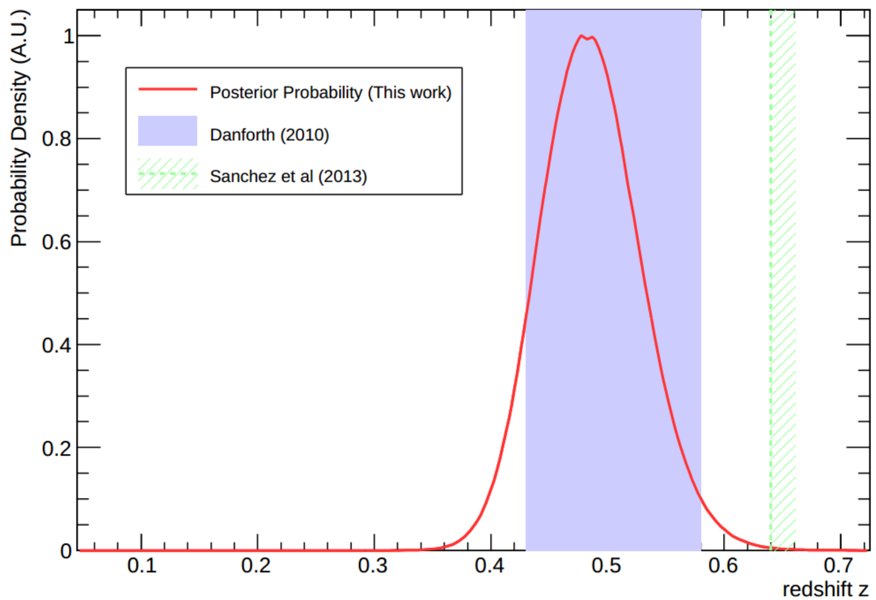
Collaboration H.E.S.S., 2013

PG 1553+113





HESS Collaboration (2015)



Bayesian approach : Introduction

- Aim : derive an UL on the redshift of PG 1553+113 using a bayesian approach. We assume that the source spectrum is a power-law from 300 MeV to TeV energies absorbed by the EBL.

$$\phi = N \times (E/E_0)^{-\Gamma} \times e^{-\tau}$$

- bayesian approach ⇒ need to specify:
  - Data : H.E.S.S. data
  - Model parameters : N, Γ, z
- writing the Bayes Theorem, the posterior probability is :

$$P(\theta|Y) \propto P(\theta)P(Y|\theta)$$

  - All the normalization factors have been dropped in the following

Likelihood and Prior

- P(Y | Θ) is the likelihood and is estimated using the H.E.S.S. data
  - Likelihood that the H.E.S.S. soft minimizes is mapped
  - The parameters of the likelihood -> models parameters : N, Γ, z
- P(Θ) is the prior
  - Assume a PL in the whole energy range
  - intrinsic parameters: Fermi data
- We assume that all the parameters are independents

$$P(\theta) = P(z)P(N)P(\Gamma)$$

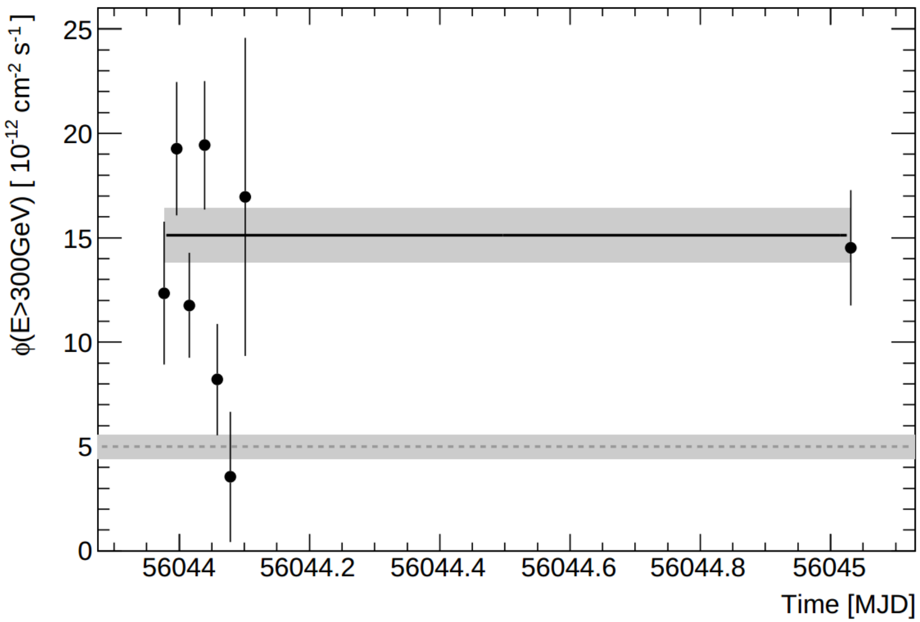
$$P(N) = \text{cst}$$

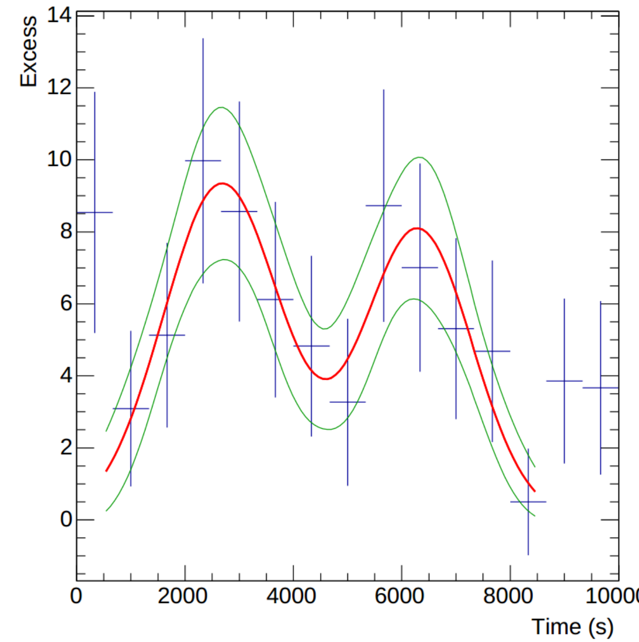
$$P(\Gamma) \propto N(\Gamma, \Gamma_{\rm Fermi}, \sigma_\Gamma) \text{ if } \Gamma < \Gamma_{\rm Fermi} \text{ or } P(\Gamma) = \text{cst}$$

$$P(z) \propto exp(-\tau(z))$$

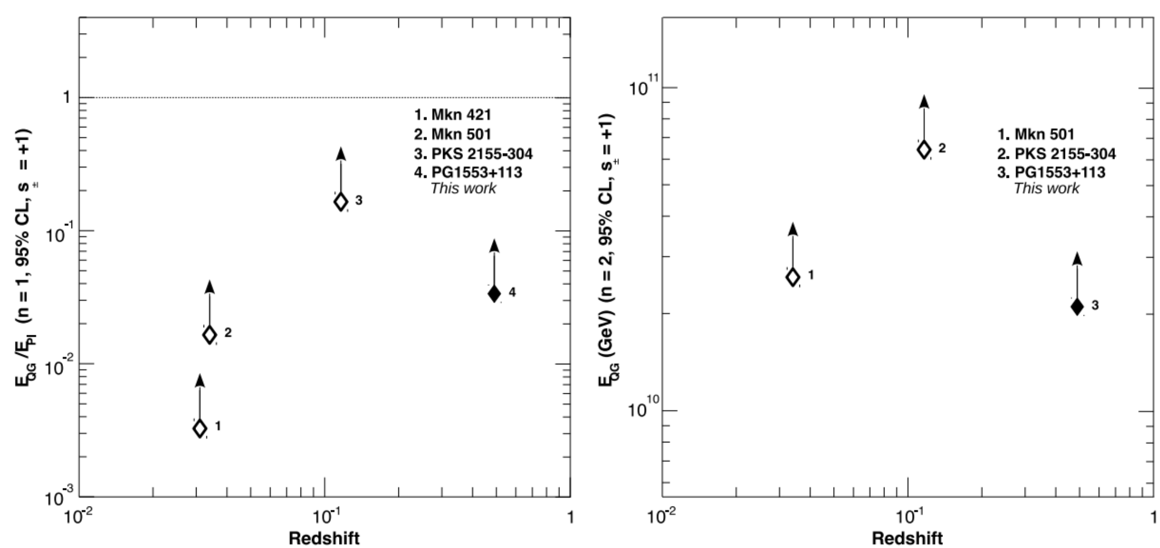
  - Fermi and H.E.S.S. uncertainties included in σ_Γ

PG 1553+113





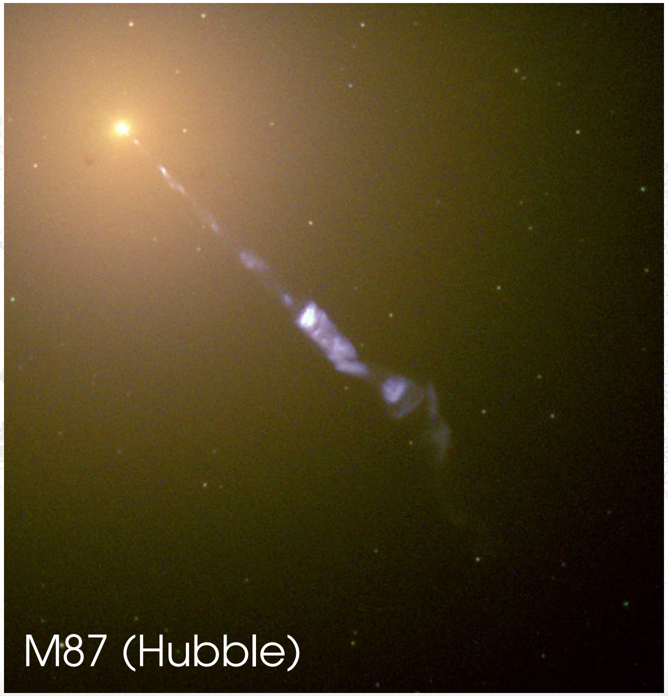
HESS Collaboration (2015)



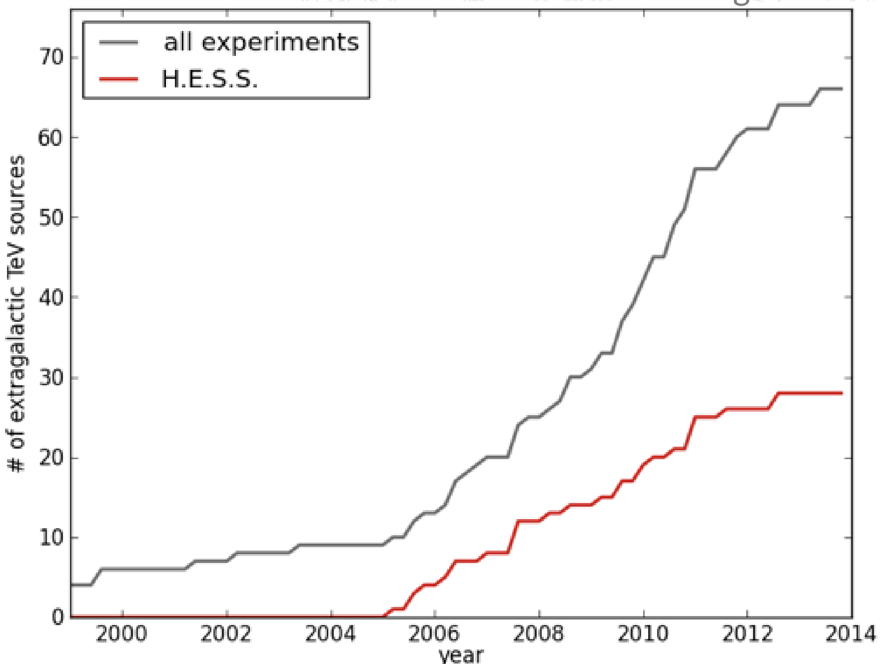
The extragalactic sky with H.E.S.S.

- ~ 50 % observation time
- ~ 30 sources
  - Mainly active galactic nuclei
  - Starburst galaxy
  - Measurement of extragalactic background light, LIV, axions

Information on CR acceleration : associated with massive stars or their remnants



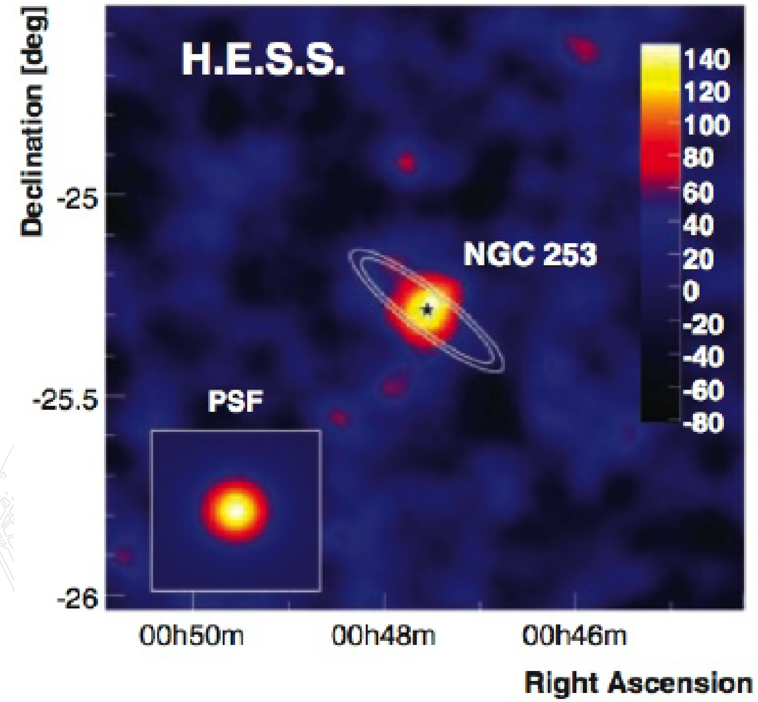
tevcat.uchicago.edu

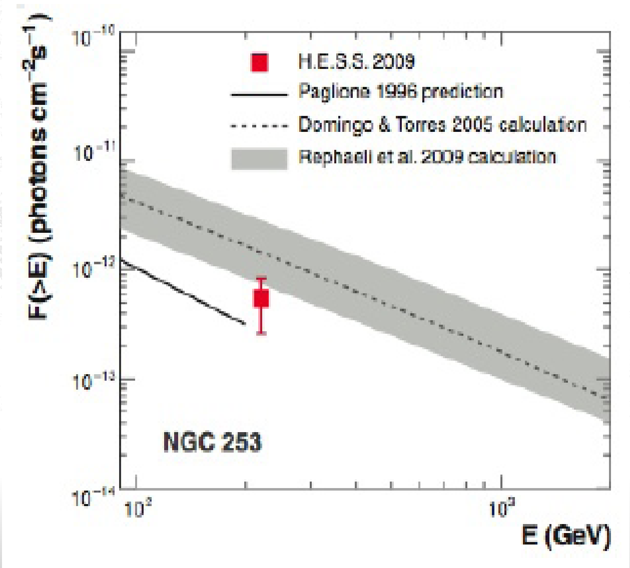


All: Whipple, Crimea, Telescope Array, Durham, MAGIC, VERITAS, H.E.S.S.

GeV/TeV Emission from Starburst Galaxies

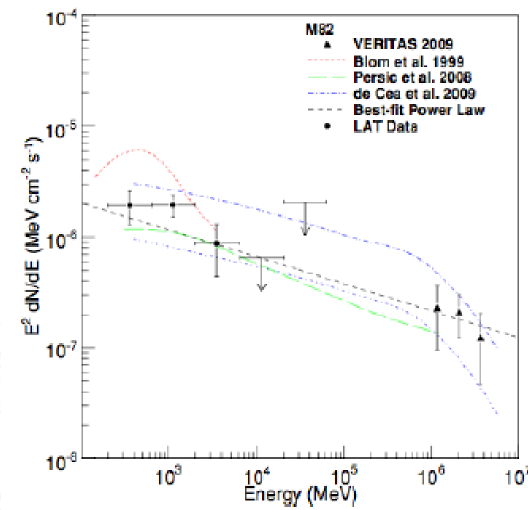
- Unresolved source consistent with NGC 253 starburst region
  - Compact starburst region (100 pc)
  - enhanced SN rate (0.3 yr^{-1})
    - ➔ high CR density
  - enhanced gas density ~ 600 cm^{-3}
- Detected flux (0.3% Crab Nebula) close to model predictions

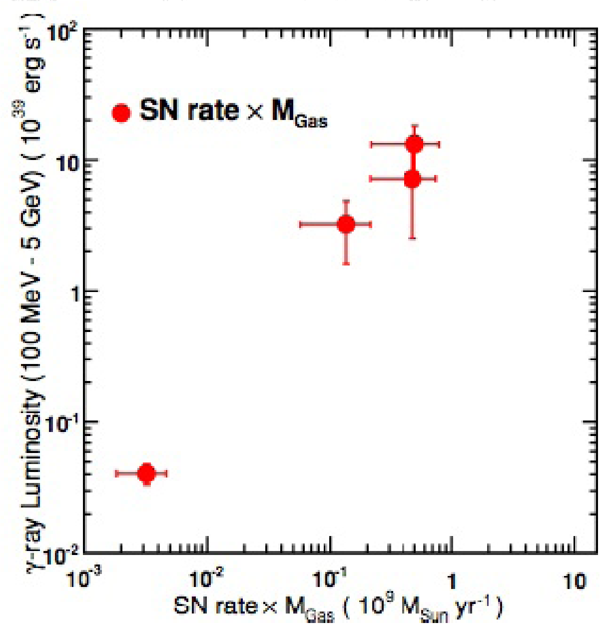




GeV/TeV Emission from Starburst Galaxies

- VERITAS detection of TeV g-ray emission from the starburst galaxy M82
- FERMI detection of GeV g-ray emission from NGC 253 and M82
- CRs + ISM gas
  - ➔ hadronic interactions
- g-ray luminosity ∝ $n_{CR}.M_{gas}$
  - Consistent with $n_{CR} \propto$ SN rate
  - Suggests association of CR production with massive stars or their remnants





Check runs

- Runs taken with the calibrated delay value :