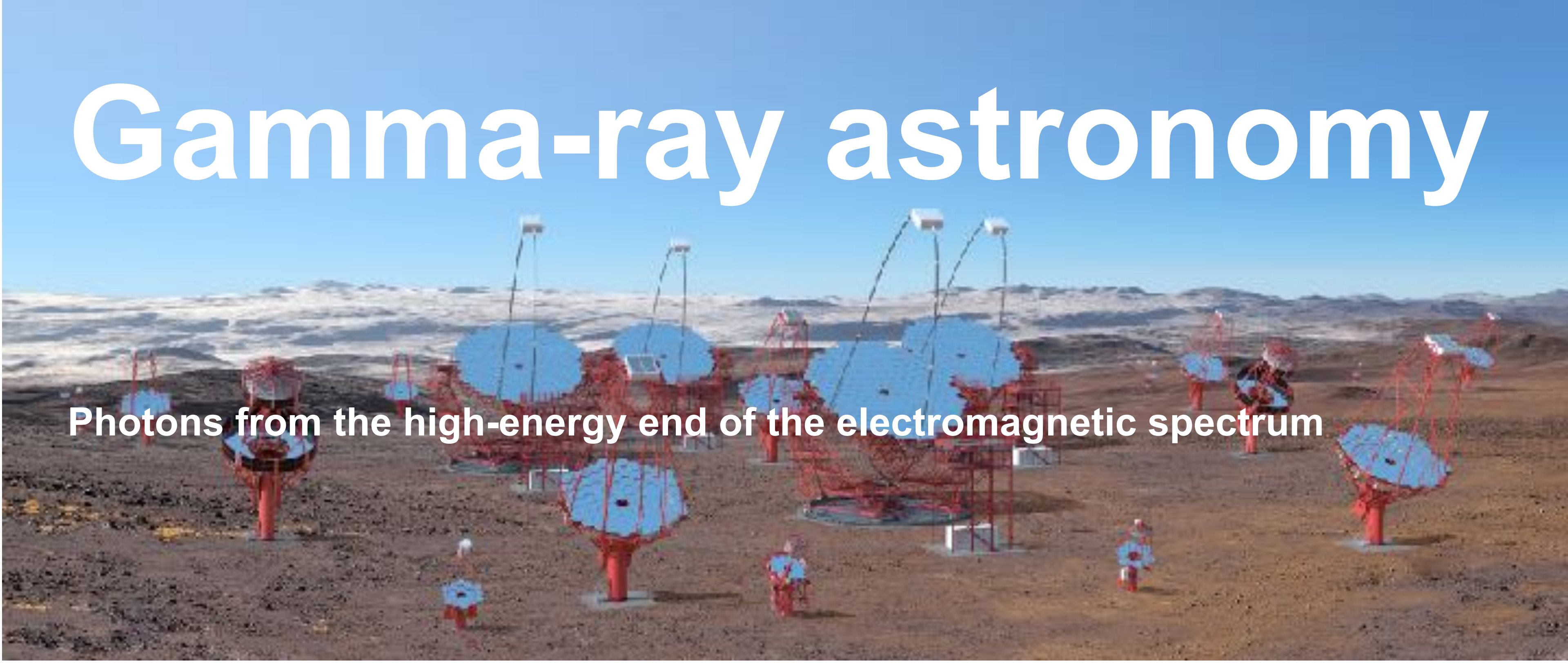
Gamma-ray astronomy



Photons from the high-energy end of the electromagnetic spectrum

Christian Stegmann
ISCRA
Erice, 2.8-7.8.2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Content

- Lecture 1: A bit of history and a focus on the instruments
- Lecture 2: Where do we stand

The discovery

American physical society

The 5th balloon flight – 7.8.1912

Georg Federmann, 2003

Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten

Von V. F. Hess
(Physik. Zeitschr. **14**, 1084, 1912)

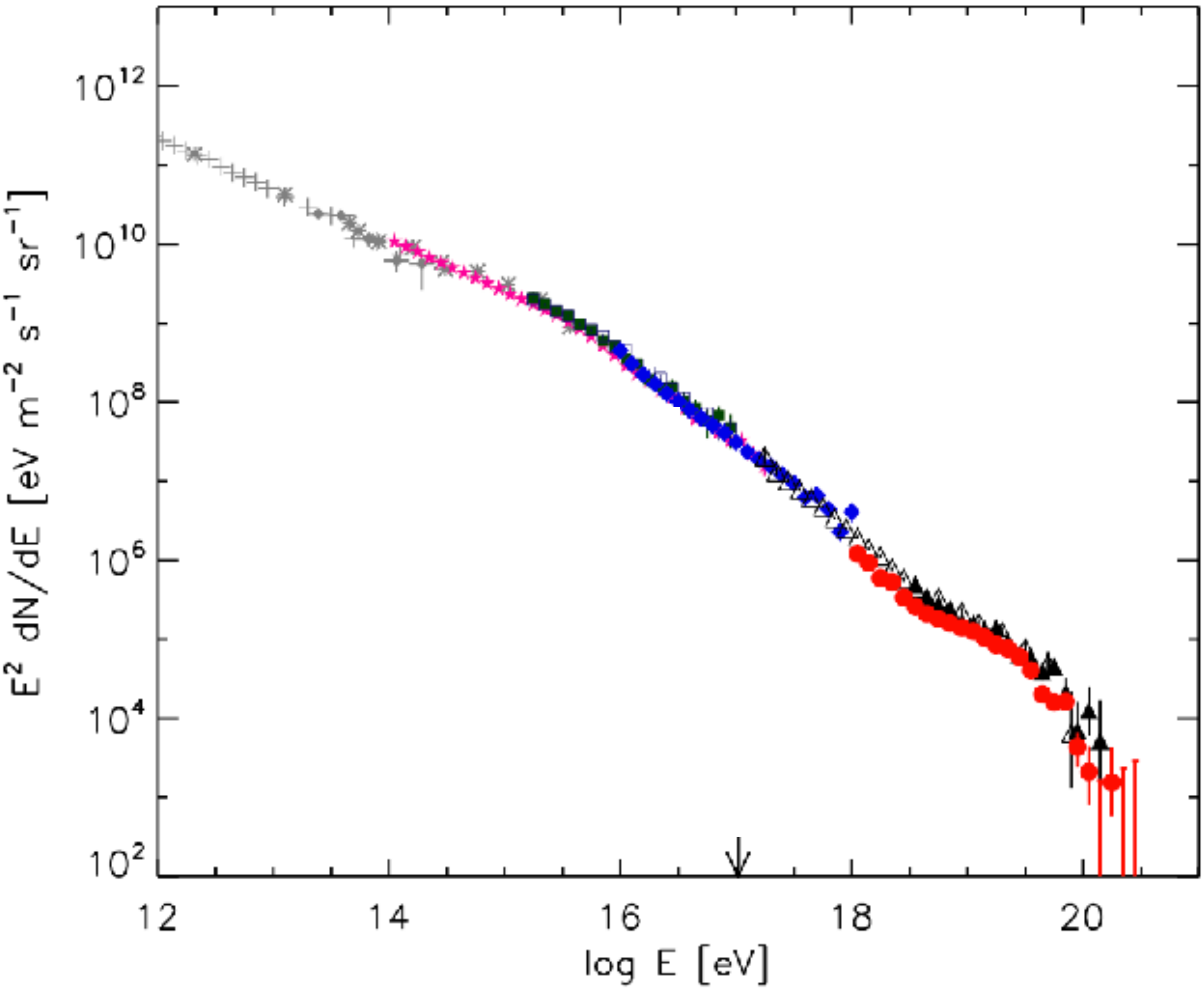
[...]

Die Ergebnisse der vorliegenden Beobachtungen scheinen am ehesten durch die Annahme erklärt werden zu können, daß eine Strahlung von sehr hoher Durchdringungskraft von oben her in unsere Atmosphäre eindringt und auch noch in den untersten Schichten einen Teil der in geschlossenen Gefäßen beobachteten Ionisation hervorruft.

[...]

The results of the available observations seem to be best explained by the assumption that a radiation of very high penetrating power penetrates our atmosphere from above and causes a part of the ionization observed in closed vessels even in the lowest layers.

K. Kotera, A. Olinto, ARAA 2011



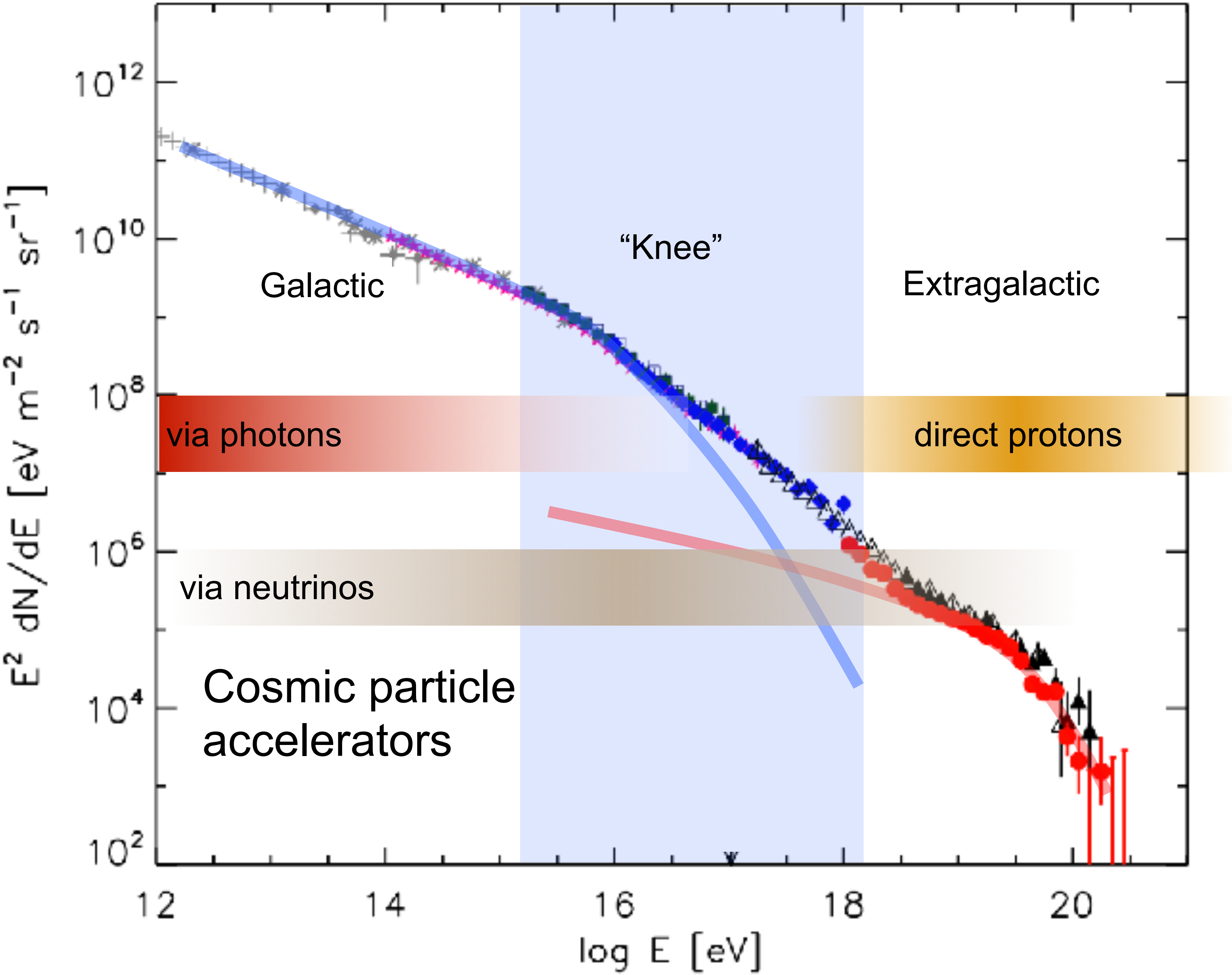
Why would anybody be interested in research
that does not concern
cosmology, inflation, dark energy?

My answer

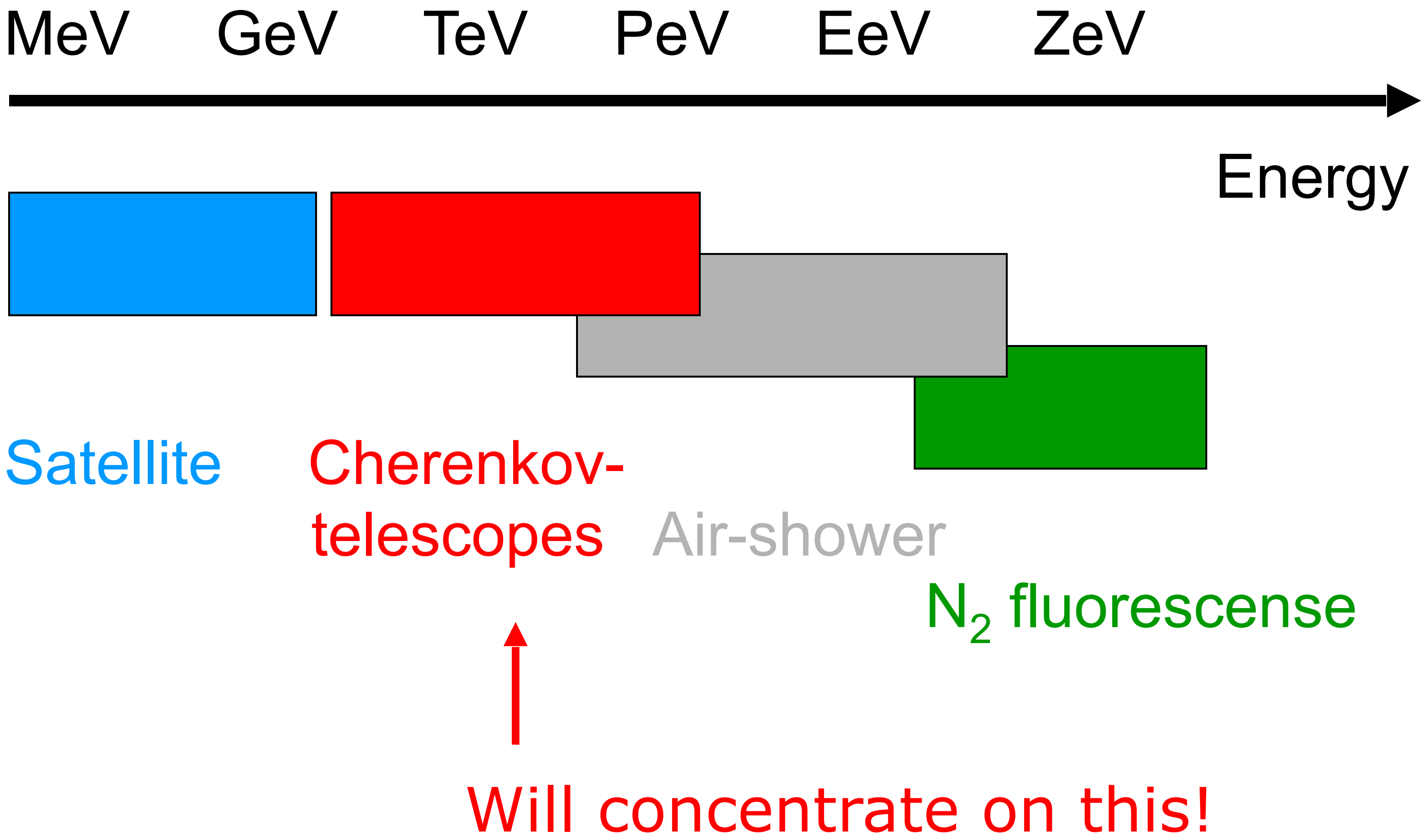
- 100 years after discovery of cosmic rays we still don’t fully understand how cosmic accelerators work
- Cosmic accelerators seem extremely efficient
  - in their energy conversion
  - in their speed of acceleration
- Cosmic rays probe some of the most extreme environments in the Universe
- Cosmic rays do influence galaxy evolution
- Need to understand cosmic-ray astrophysics before claiming new physics. e.g.
  - electrons/positrons from dark matter
  - effects of quantum gravity

Messengers

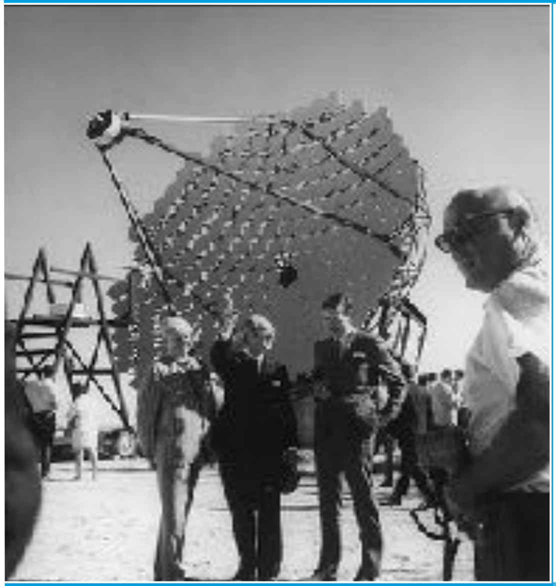
- Protons
  - directly produced in the sources
- **Photons (Gamma-rays)**
  - from protons: pion-decay: $\pi^0 \rightarrow \gamma\gamma$
  - from electrons: Inverse Compton Scattering: $e^{\pm}\,\gamma \rightarrow e^{\pm}\,\gamma$
- Neutrinos
  - from protons: pion-decay: $\pi^{\pm} \rightarrow \mu^{\pm}\,\nu_{\mu}$

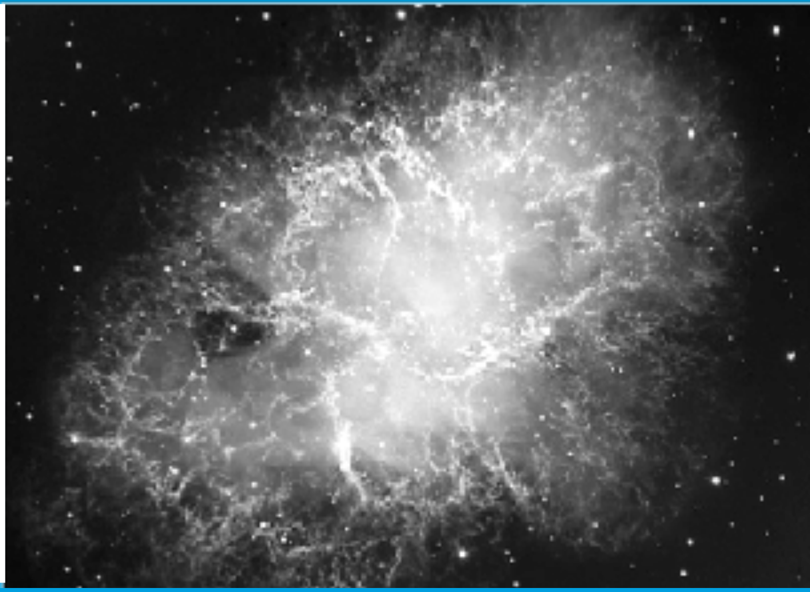

K. Kotera, A. Olinto, ARAA 2011
"Knee"
Galactic
Extragalactic
via photons
direct protons
via neutrinos
Cosmic particle
accelerators
E² dN/dE [eV m⁻² s⁻¹ sr⁻¹]
log E [eV]
10¹²
10¹⁰
10⁸
10⁶
10⁴
10²
12
14
16
18
20

Experimental Techniques

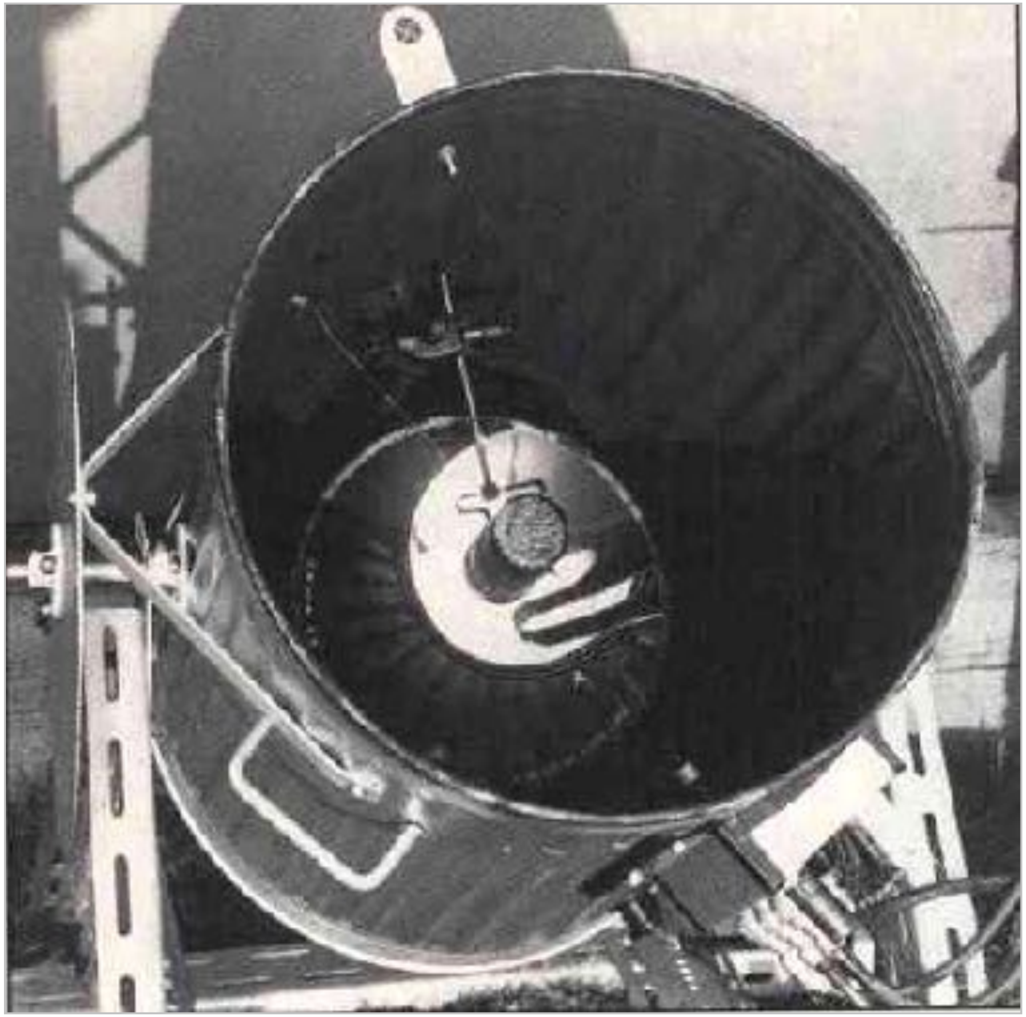


1953 – 2004
The beginnings



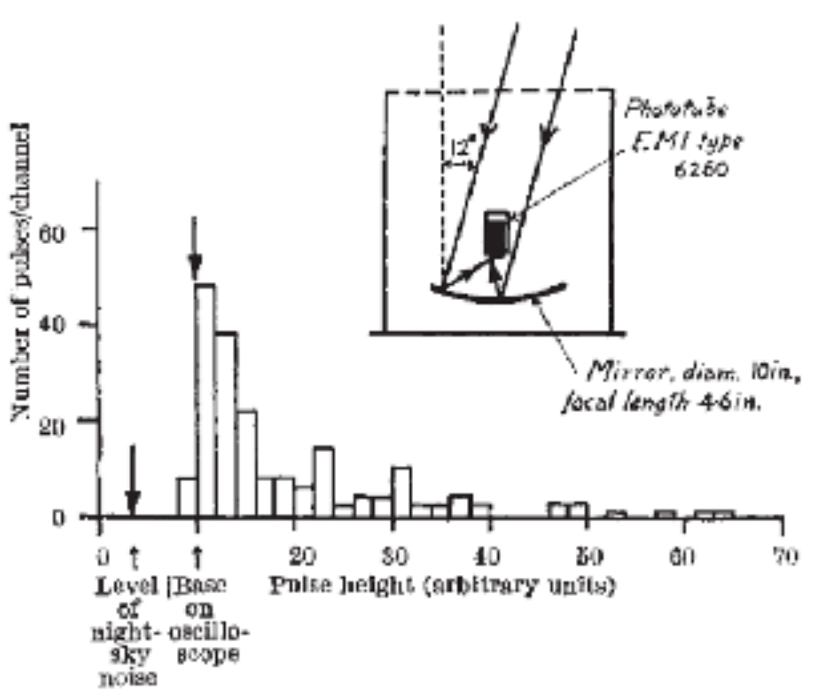


1953: The beginning



Galbraith & Jelly, 1953

1953: The beginning



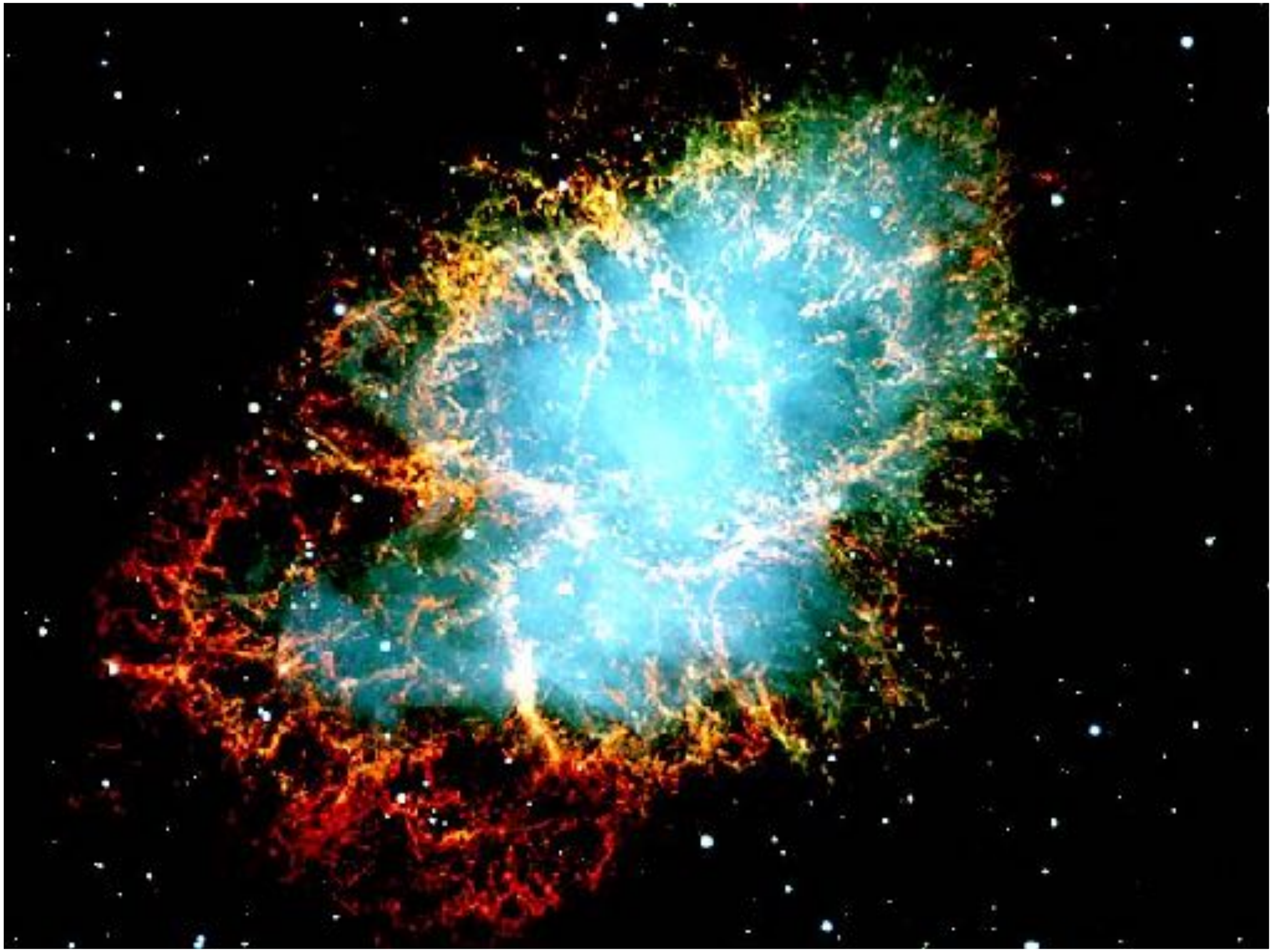
February 21, 1953 NATURE

Light Pulses from the Night Sky associated with Cosmic Rays

IN 1948, Blackett[1] suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation[2] produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the

Galbraith & Jelly, 1953

Crab Nebula: A gamma-ray source?



Useful units, numbers, dimensions

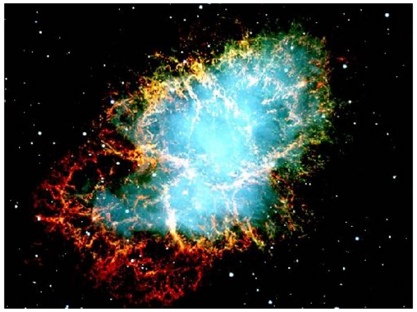
Energy and distance

- 1 erg = 10^{-7} J;   1 TeV ≈ 1.6 erg;
  - Supernova $E_{kin} \approx 10^{51}$ erg
- 1 yr ≈ π 10^7 s

- 1 pc ≈ 3.26 LJ ≈ $3.1 \cdot 10^{18}$ cm ≈ 1000 km/s x 1000 yr
  - Distance to center of Galaxy ≈ 8.5 kpc
  - Surface of kpc sphere ≈ $1.2 \cdot 10^{44}$ cm^2
  - Distance to M31 (Andromeda) ≈ 800 kpc
  - Distance to Centaurus A ≈ 4 Mpc
- Redshift z=0.1 ≈ 0.4 Gpc
- Surface of Gpc sphere ≈ $1.2 \cdot 10^{56}$ cm^2

- Gyroradius of (z=1) particles: $r_{pc} \approx E_{PeV}/B_{\mu G}$

Visibility of the Crab Nebula in gamma-rays



Crab pulsar

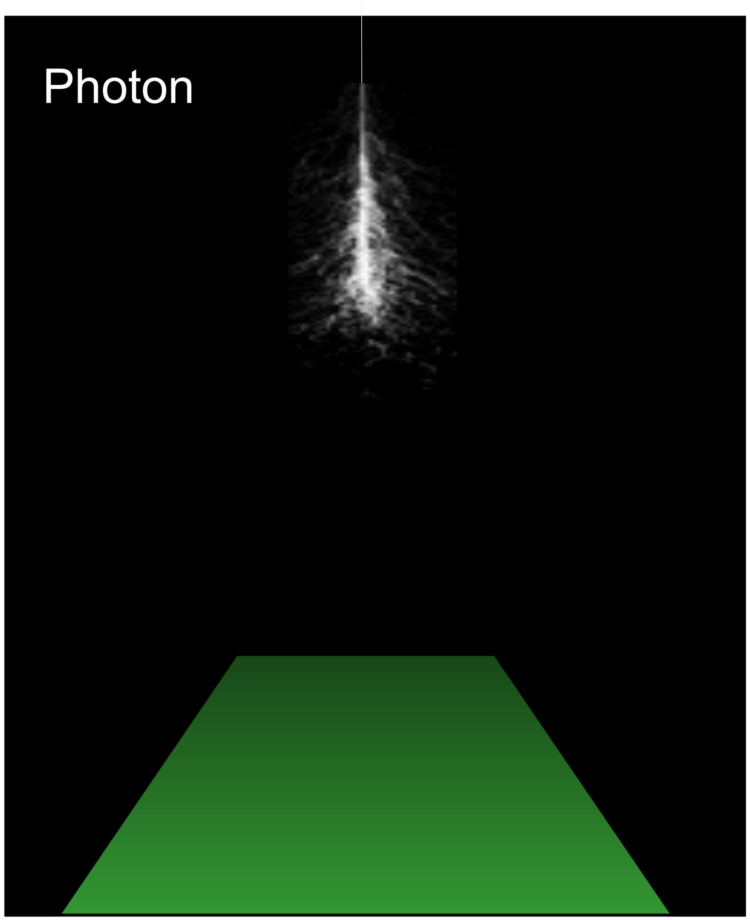
- Distance ~6500 Ly
- spin-down power erg/s = TeV/s

Assume

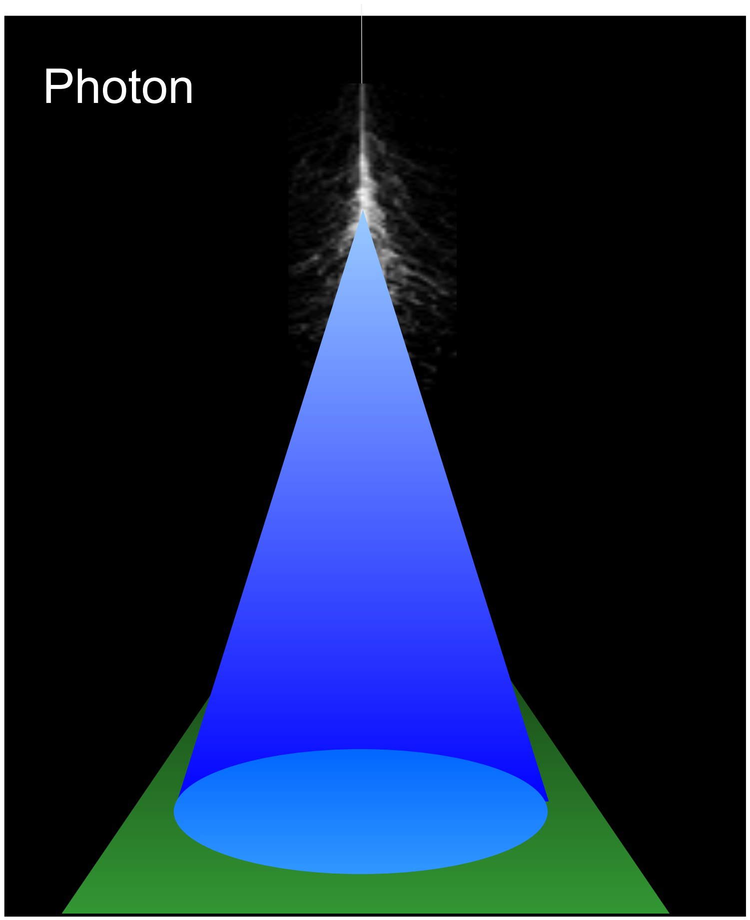
- Conversion efficiency in gamma-rays at VHE energies
- Isotropic emission
- 100 detected photons for detection (reasonable)
- background-free (somewhat optimistic)

We need a detector with detection area!

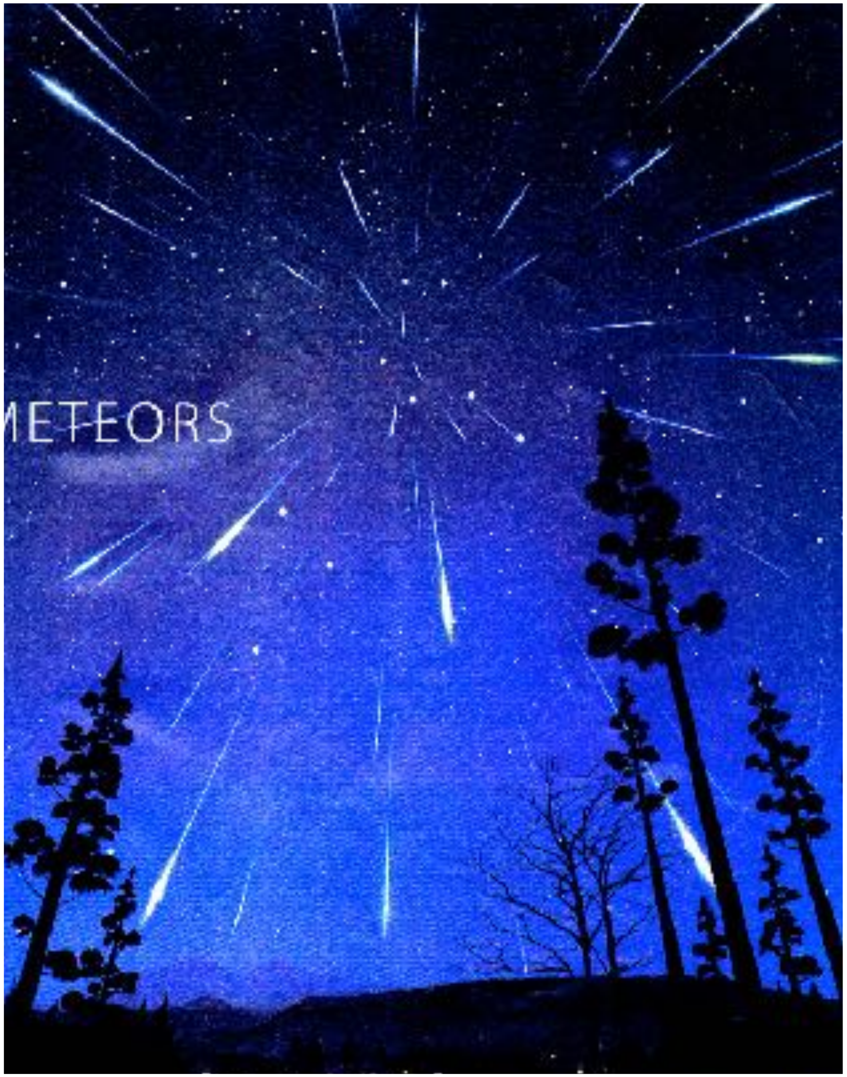
How to measure gamma-rays?



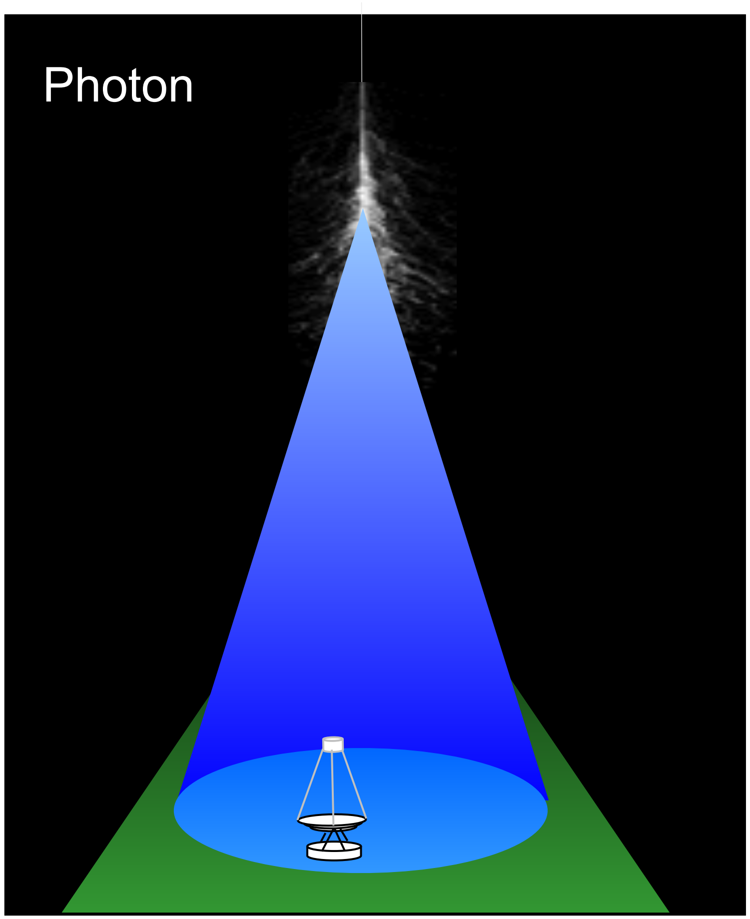
How to measure gamma-rays?

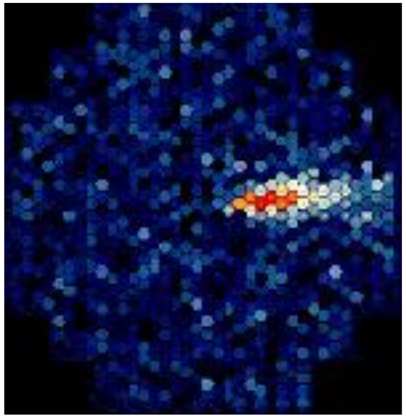


Showers look like meteors



How to measure gamma-rays?





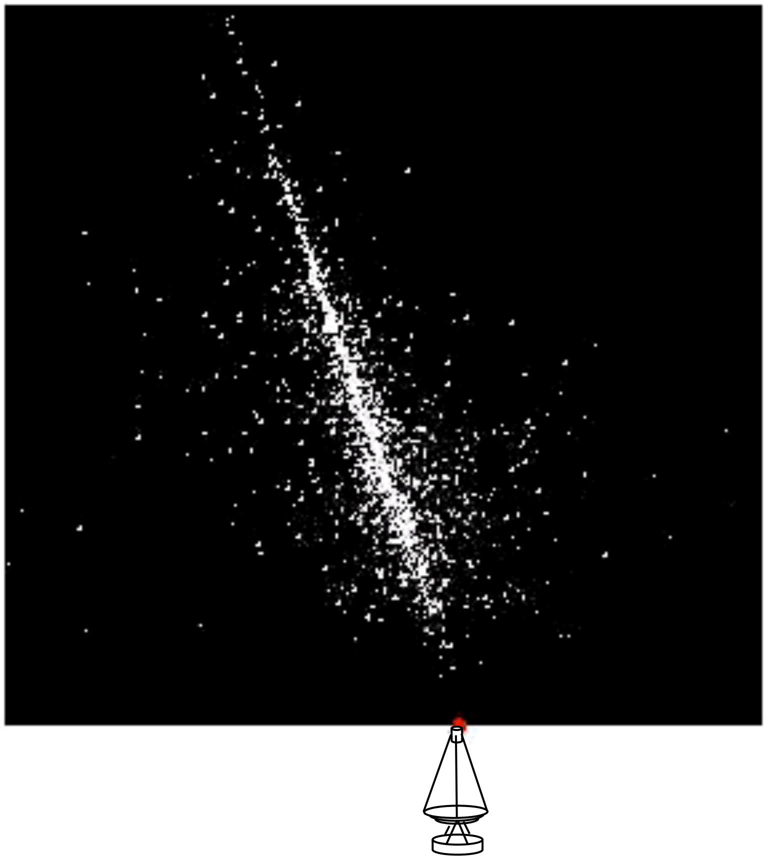
Camera image

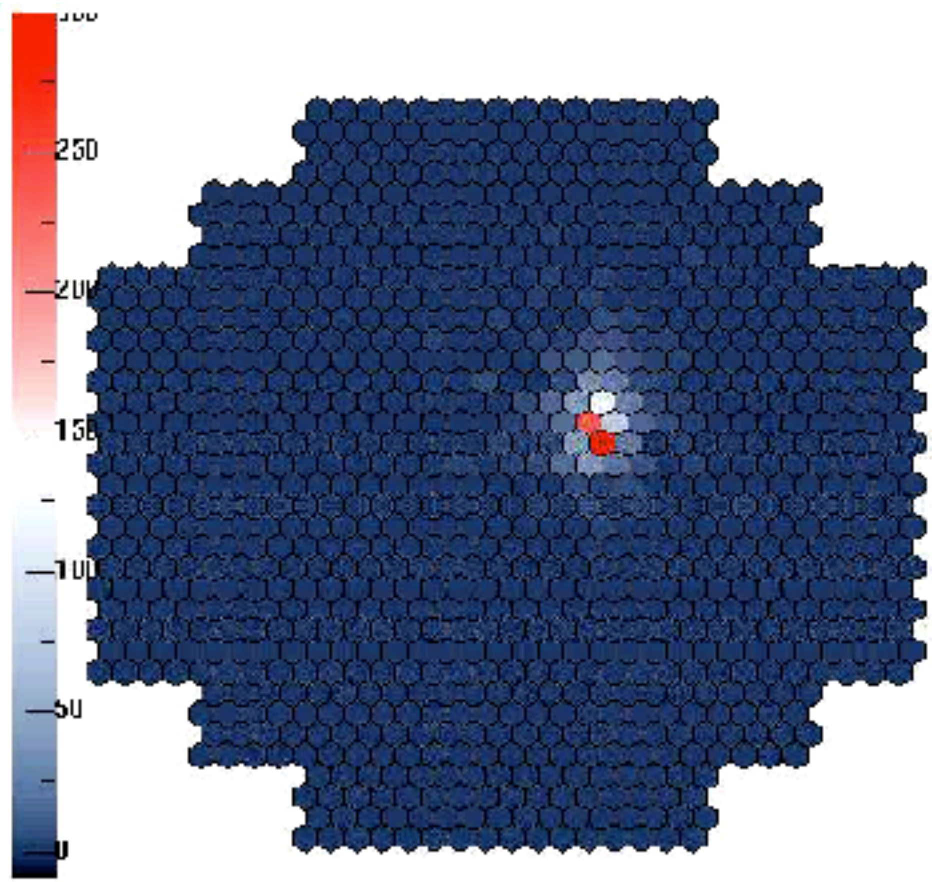
Intensity → Energy

Orientation → Direction

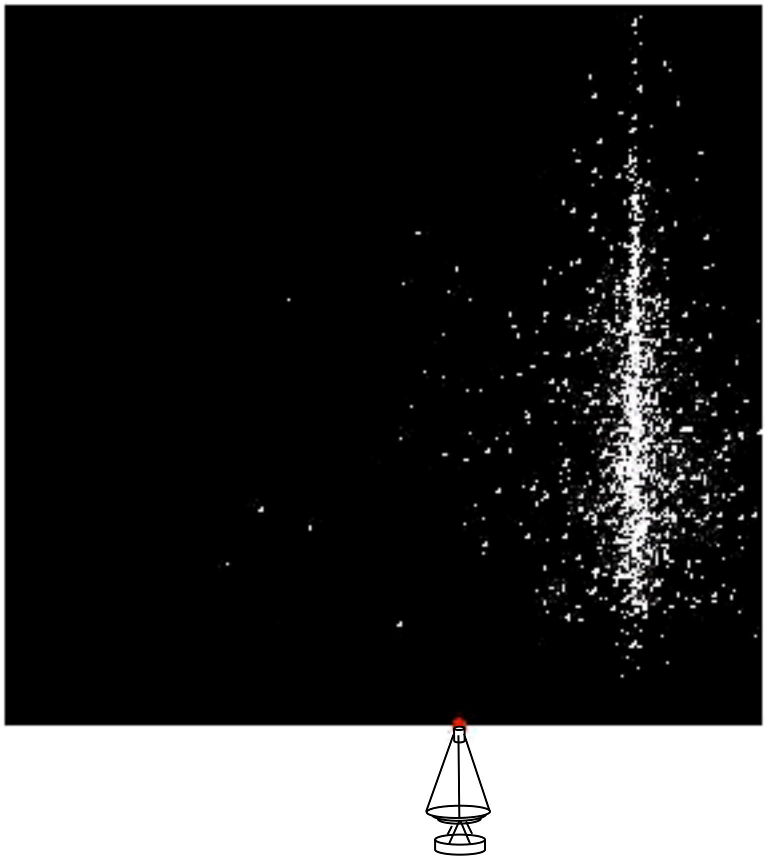
Shape → Primary

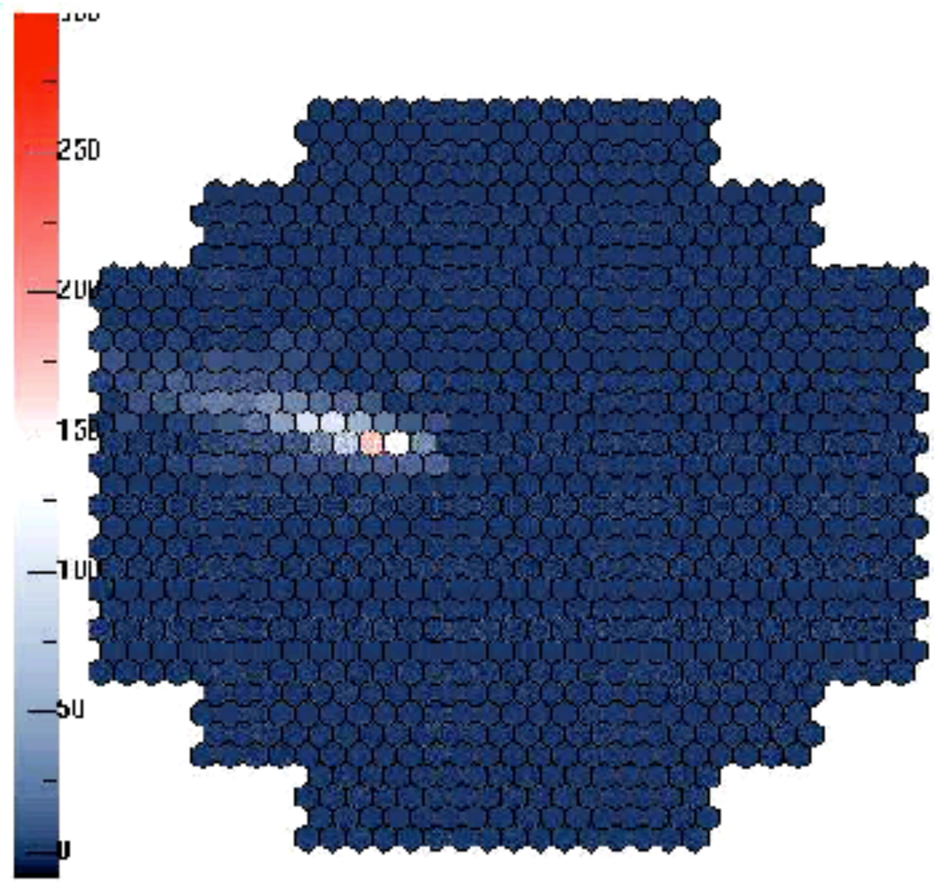
Showers in the camera



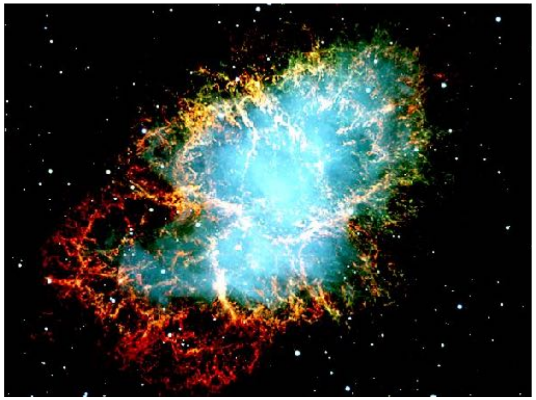


Shower in the camera

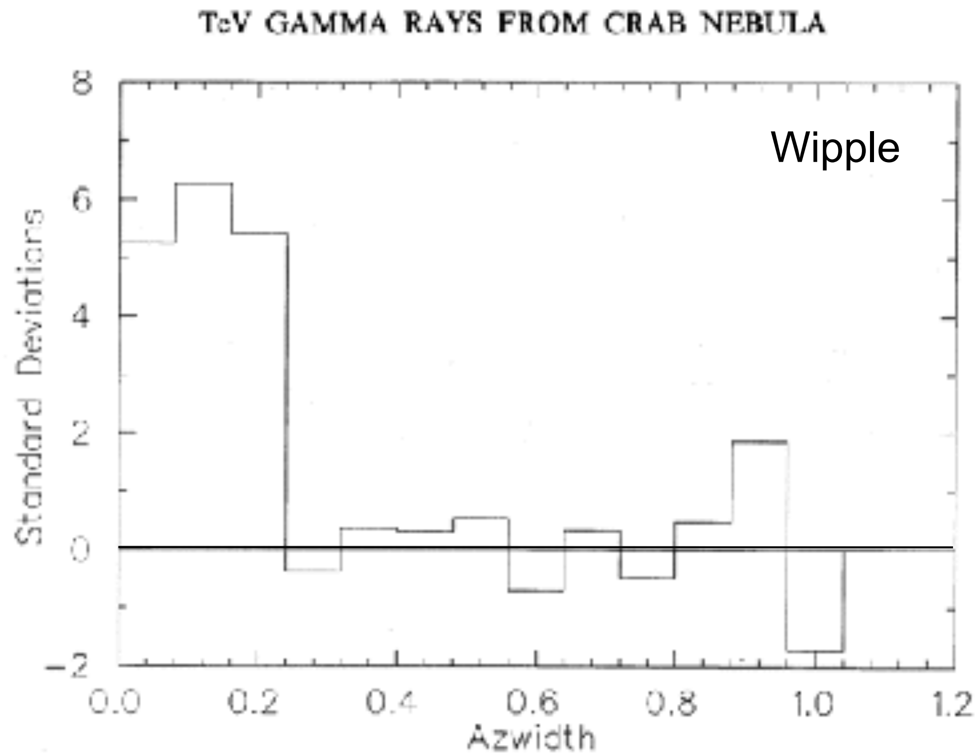




The discovery of the Crab Nebula in 1989



Wipple



The discovery of the Crab Nebula in 1989

THE ASTROPHYSICAL JOURNAL, 342:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[3] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[5] D. MACOMB,[5] N. A. PORTER,[3] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

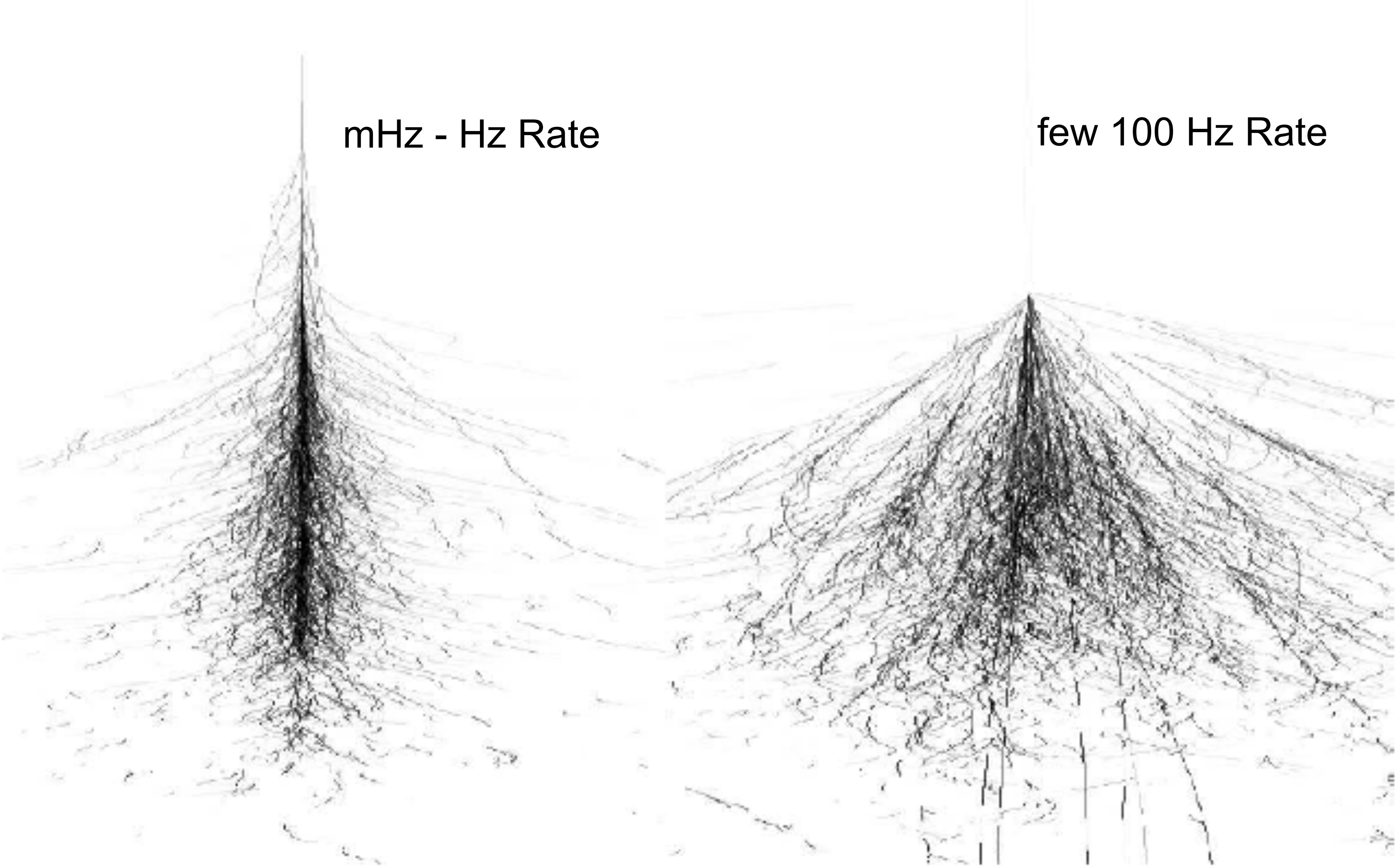
Received 1988 August 1; accepted 1988 December 9

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

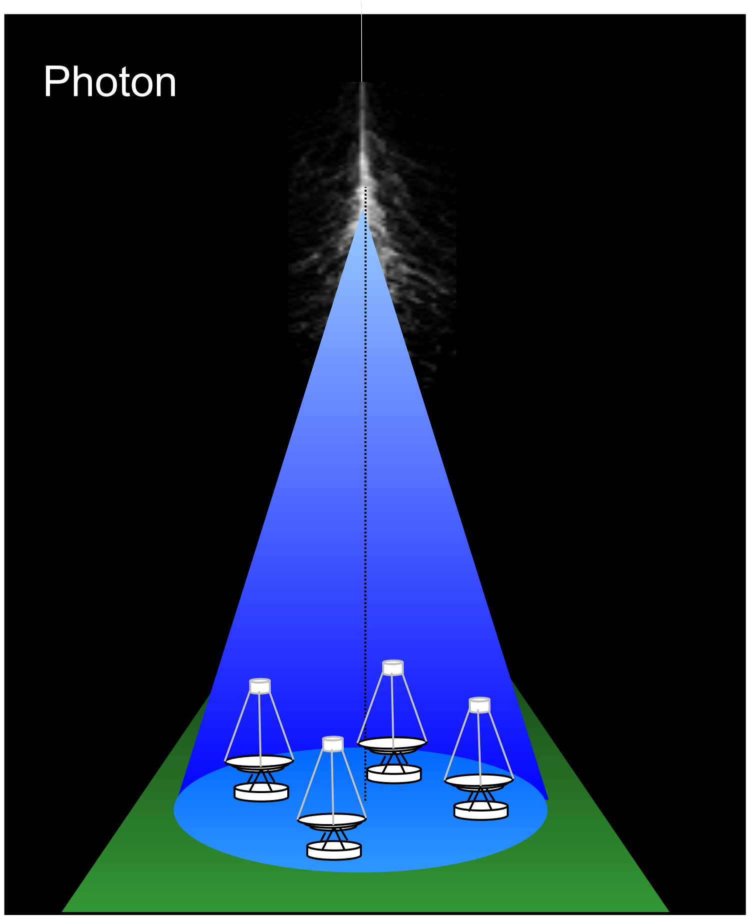
Cosmic ray veto using shower shape

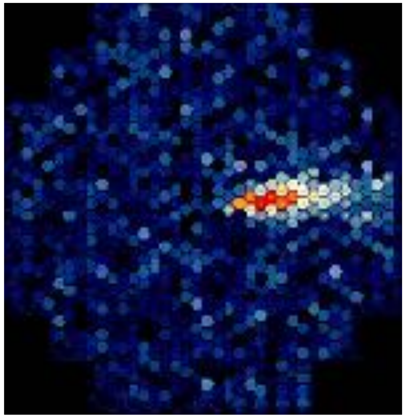


Gamma shower

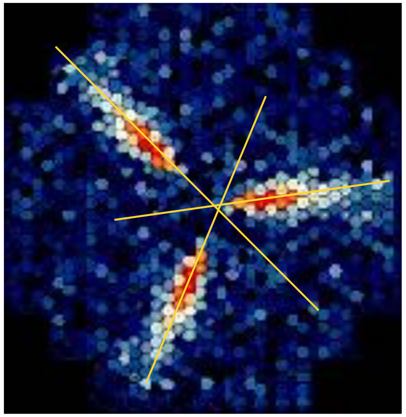
Hadronic shower

How to measure gamma-rays from the ground?





Single telescope event



3 telescope image in common camera plane

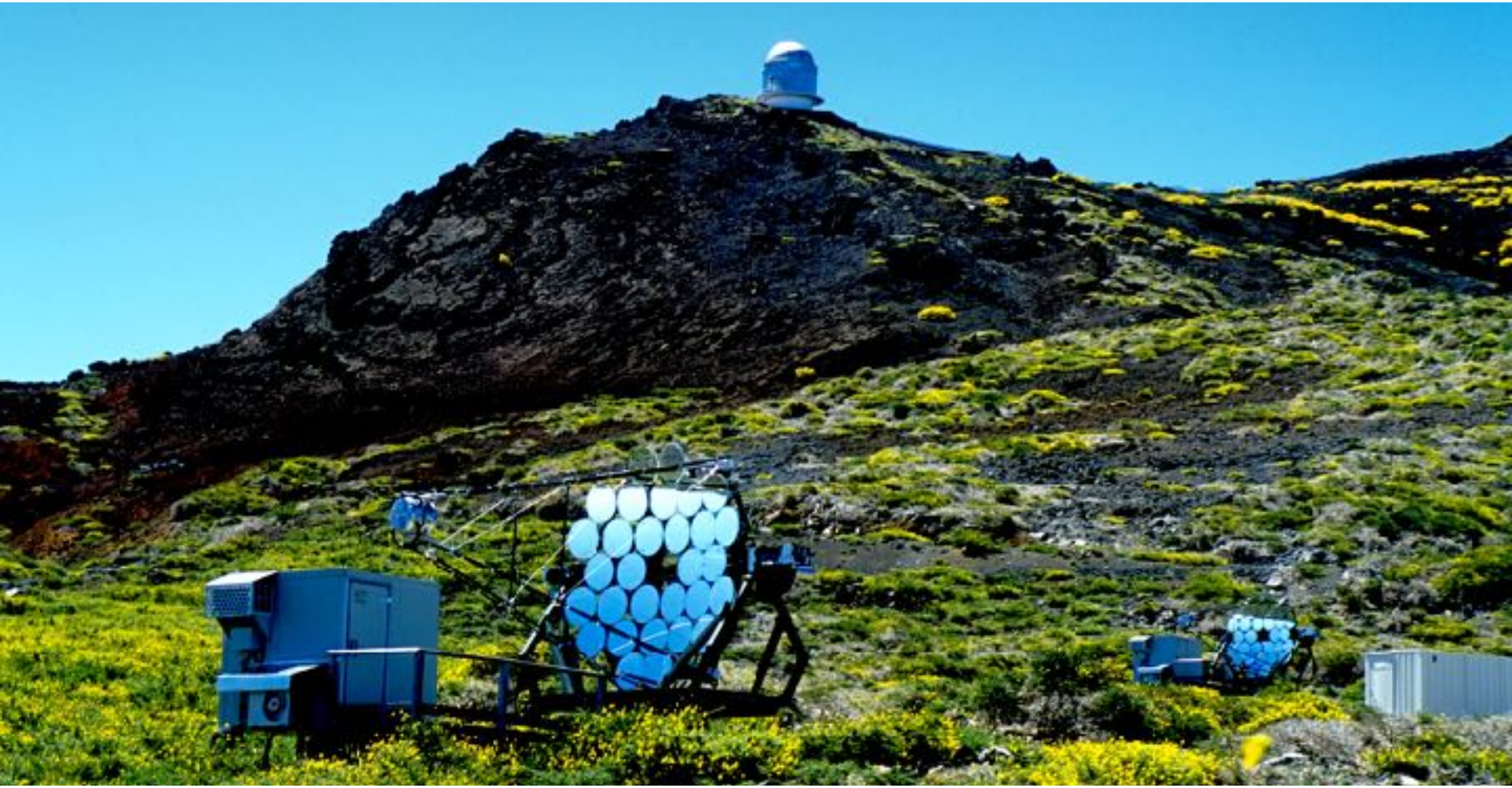
Intensity → Energy

Orientation → Direction

Shape → Primary particle

1992: HEGRA

Stereoscopic imaging technique



Useful units, numbers, dimensions

Instrument sensitivity

- assume
  - 100 detected photons for image (reasonable)
  - background-free (somewhat optimistic)

- **optical telescope** (few eV)
  - 10 m aperture, 1 h, 100% eff
  - $3 \cdot 10^{-8}$ ph/cm²s ~ 10^{-7} eV/cm²s ~ $2 \cdot 10^{-19}$ erg/cm²s
- **X-ray satellite** (keV)
  - 50 ks, eff. mirror aperture 500 cm² (Chandra)
  - $4 \cdot 10^{-6}$ ph/cm²s ~ 10^{-14} erg/cm²s
- **Fermi-LAT** (few 100 MeV)
  - 1 yr, 2 sr, eff. area 8000 cm²
  - $2 \cdot 10^{-9}$ ph/cm²s ~ 10^{-12} erg/cm²s
- **Cherenkov telescope** (few 100 GeV)
  - 50 h, eff. area 50000 m²
  - 10^{-12} ph/cm²s ~ $5 \cdot 10^{-13}$ erg/cm²s

required source luminosity @ 1 kpc:
~10^{32} erg/s
Sun thermal luminosity
~$4 \cdot 10^{33}$ erg/s
Crab pulsar spin-down
~$5 \cdot 10^{38}$ erg/s

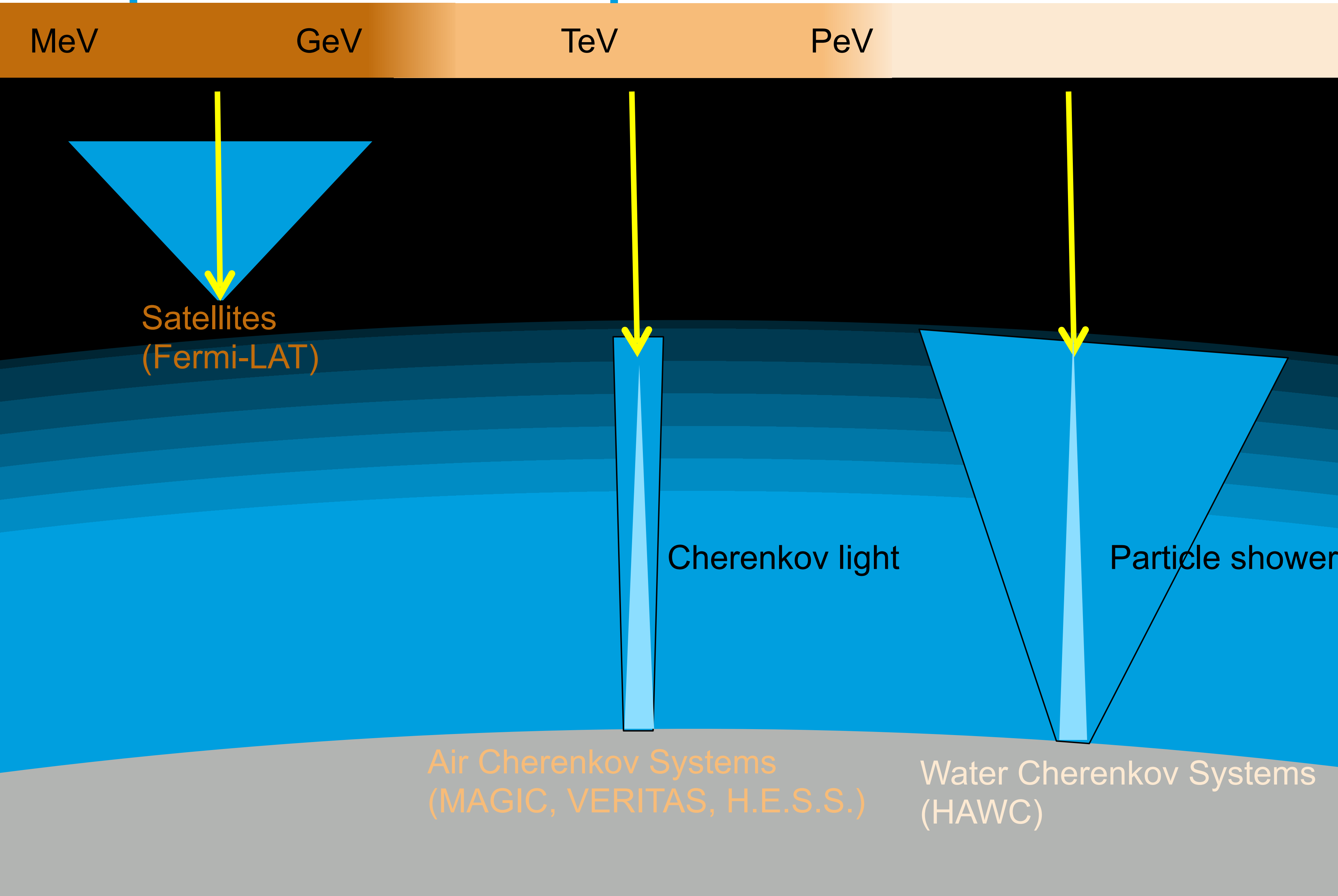
Useful units, numbers, dimensions

- Crab-like pulsar, assume 1% of spin-down (1% of $5 \cdot 10^{38}$ ergs/s) into radiation (note: actual Crab has 10^{-5} into VHE gamma rays)
  - at 1 kpc $4 \cdot 10^{-8}$ ergs/cm^{2}s
  - at center of Galaxy $5 \cdot 10^{-10}$ ergs/cm^{2}s
  - at LMC (50 kpc) $2 \cdot 10^{-11}$ ergs/cm^{2}s
  - at Andromeda $6 \cdot 10^{-14}$ ergs/cm^{2}s
- Dropping mass into BH, at 1% mc^2
  - 1 solar mass / yr @ 1 Gpc $5 \cdot 10^{-12}$ ergs/cm^{2}s

2004 – 2018
From source hunting to real astronomy

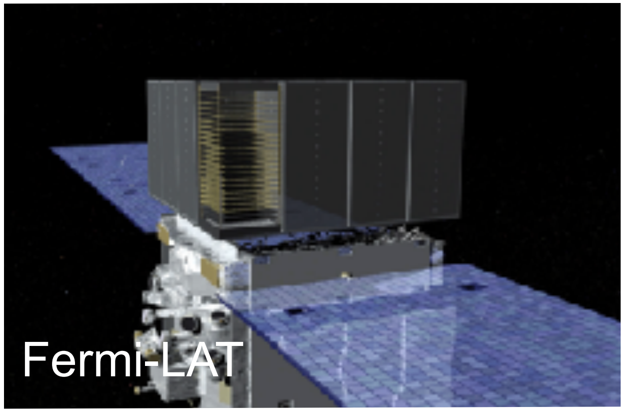


Experimental techniques



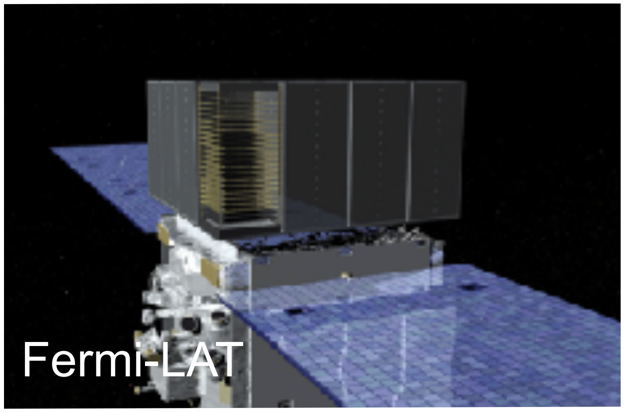
Experimental techniques

MeV GeV TeV PeV

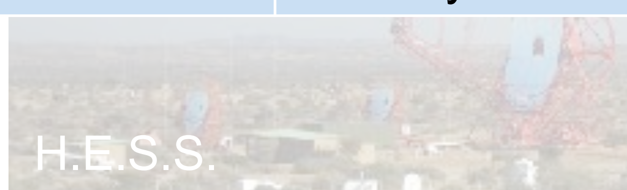


Experimental techniques

MeV GeV TeV PeV

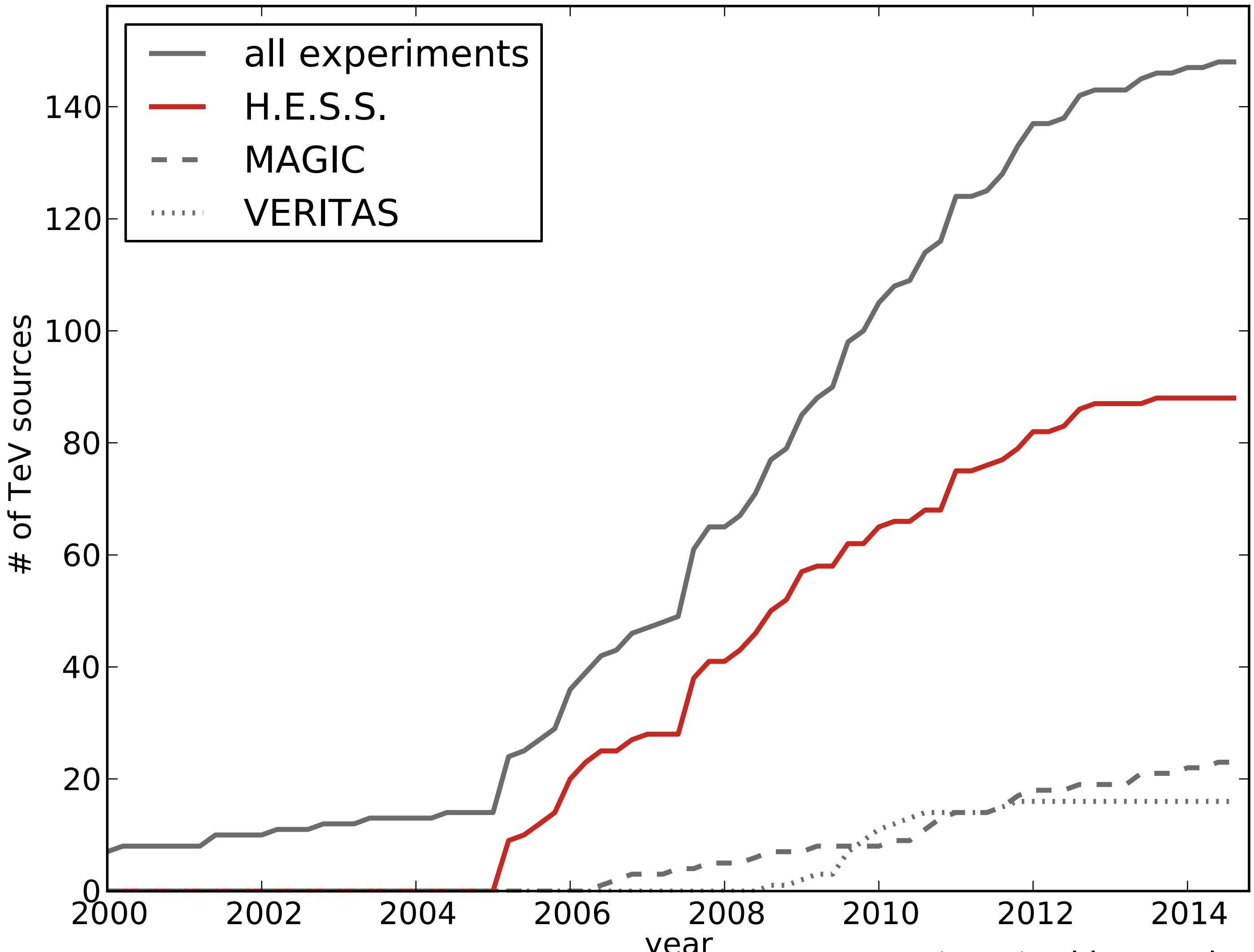


	Fermi LAT	IACTs	HAWC
Effective area	1 m^2	**10^5 m^2**	**10^5 m^2**
Field of view	**20% of the sky**	3^o – 5^o	**15% of the sky**
Energy res.	10%	**10%**	100% – 20%
Angular res.	6^o – 0.3^o	**0.1^o**	1^o – 0.2^o
Duty cycle	**Full year**	1400 h/year	**Full year**



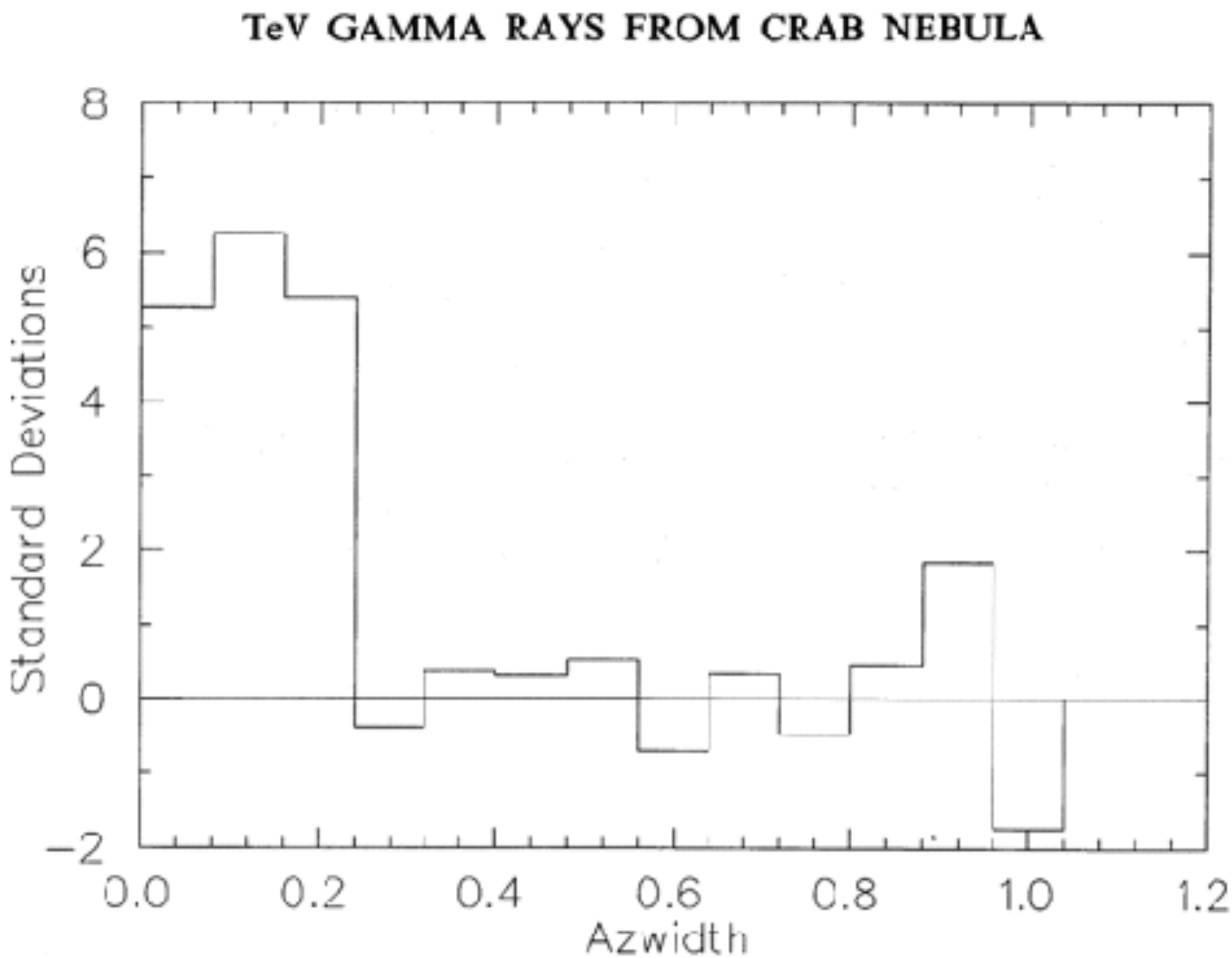
Gamma-ray astronomy – 3rd generation experiments

Source count



tevcat.uchicago.edu

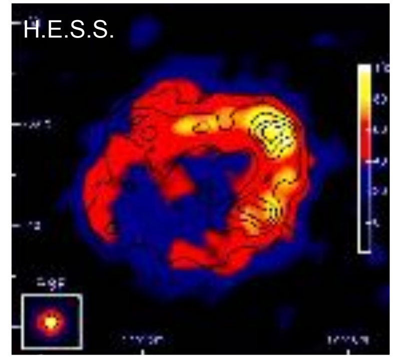
Data quality 1989



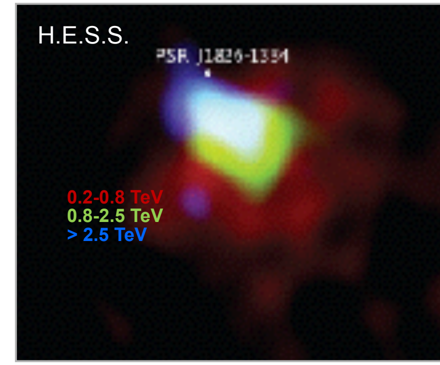
Data Quality today

- Morphologies
  - spacial
  - energy-dependent
- Periodicities/Variability
  - from ms to years
- Energy-coverage
  - over several decades
- Source positions and extensions
  - on the arc-second level

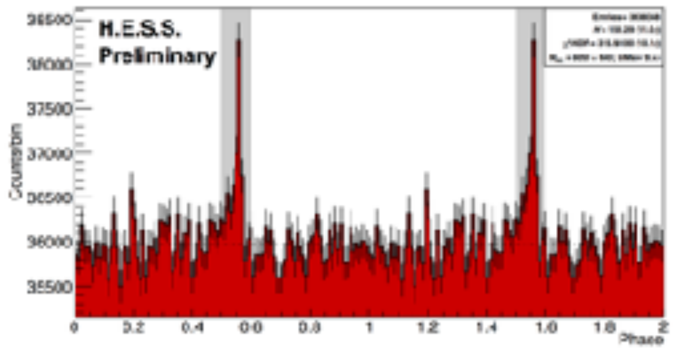
RX J1713-3946



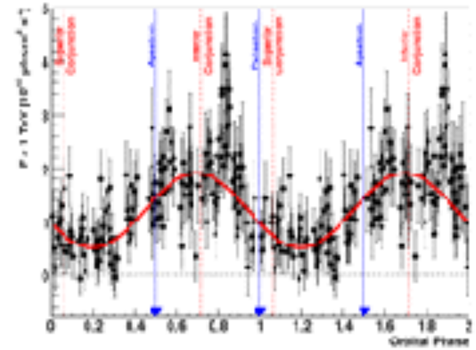
HESS J1825-137



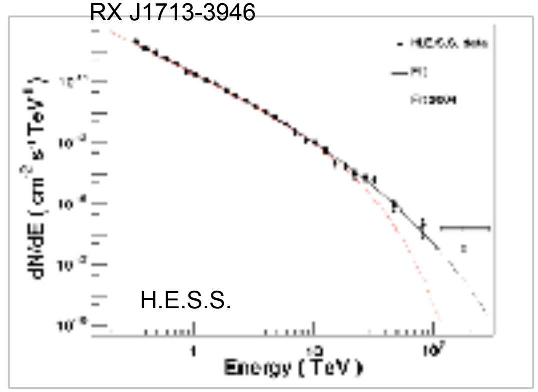
Vela pulsar



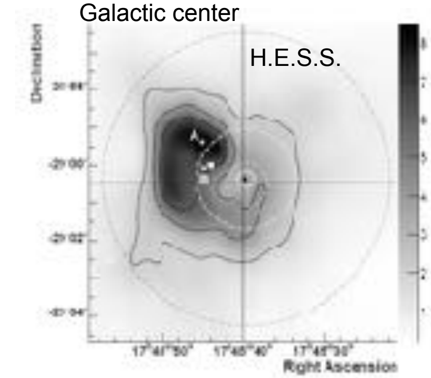
LS 5039



RX J1713-3946

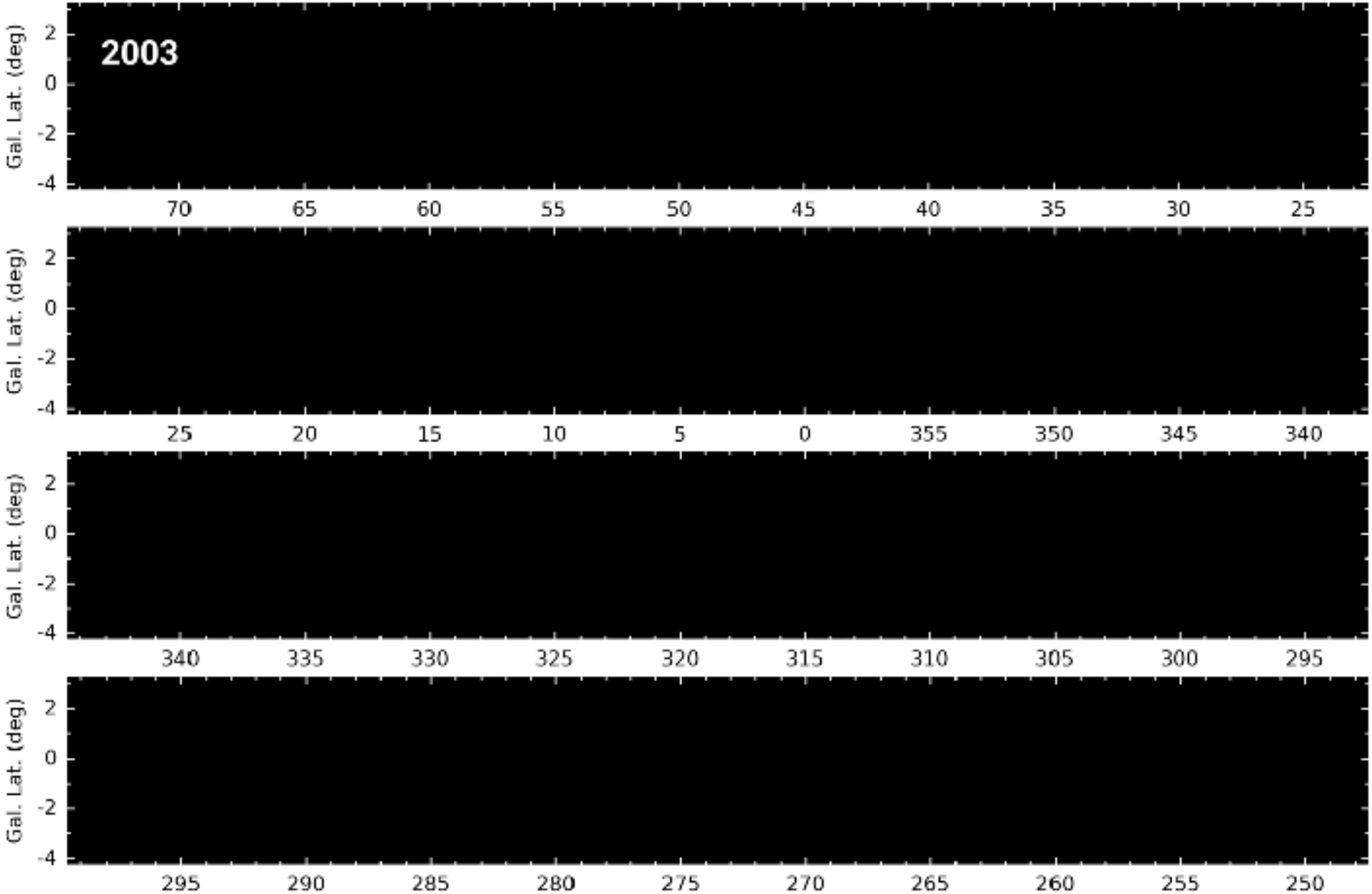


Galactic center



The Milky Way

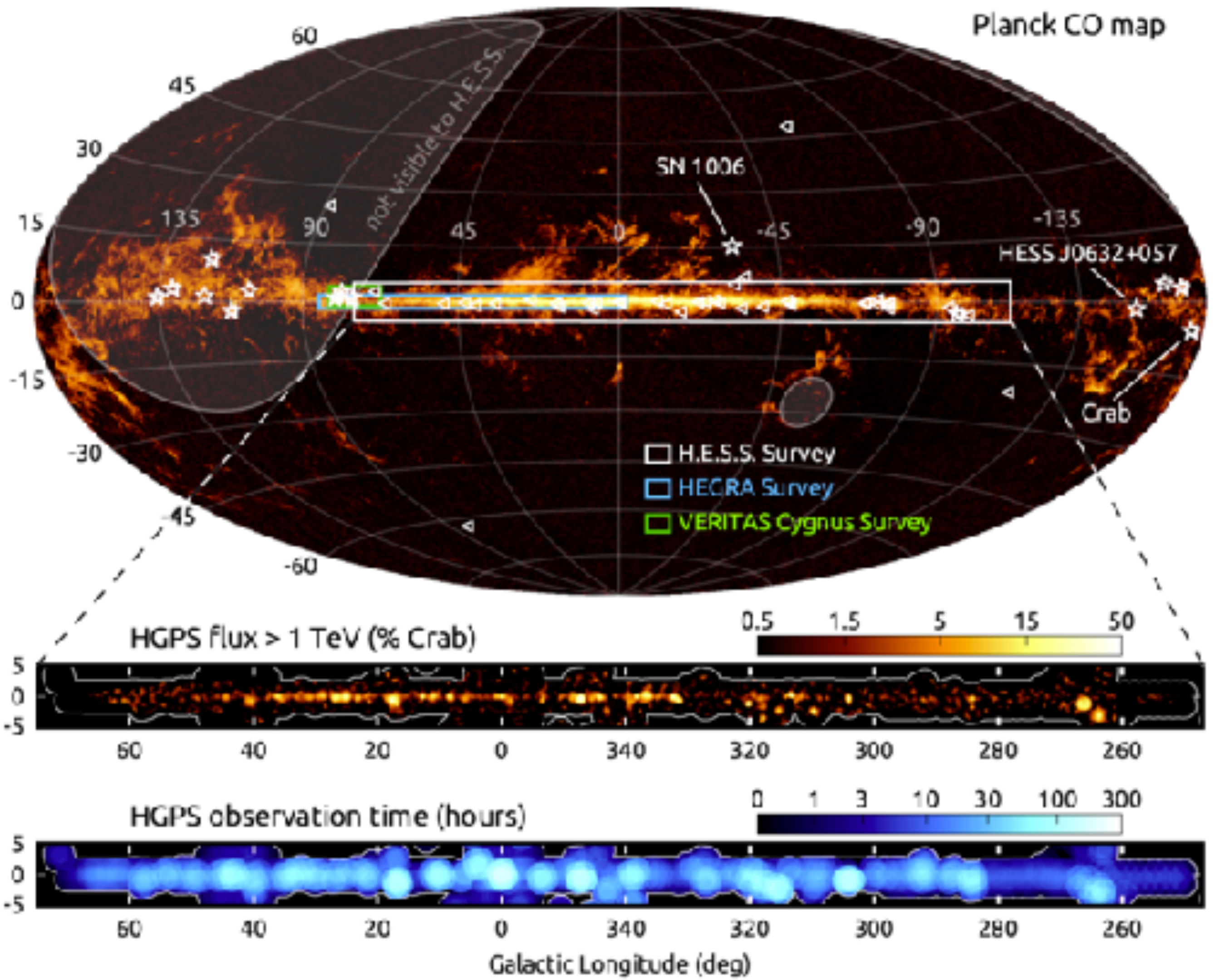
The H.E.S.S. Survey



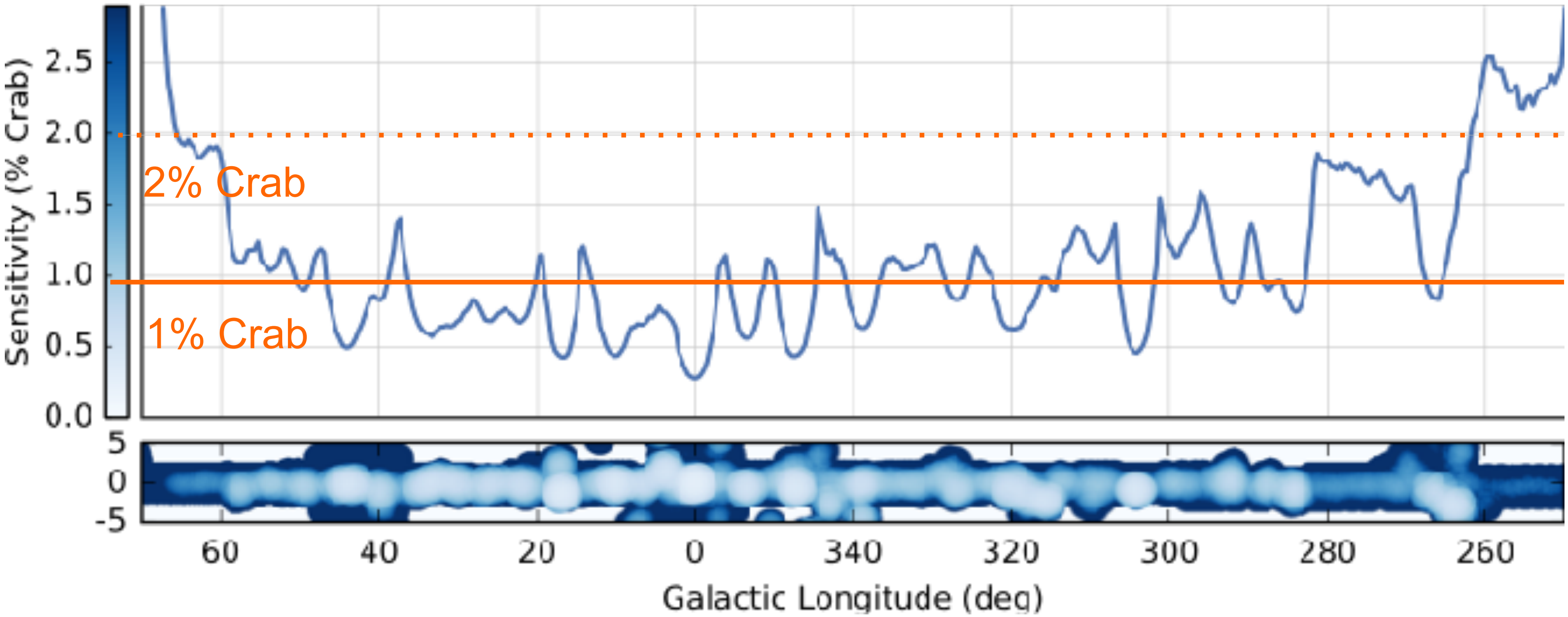
The Milky Way

The Milky Way in VHE gamma-rays

H.E.S.S. I Survey

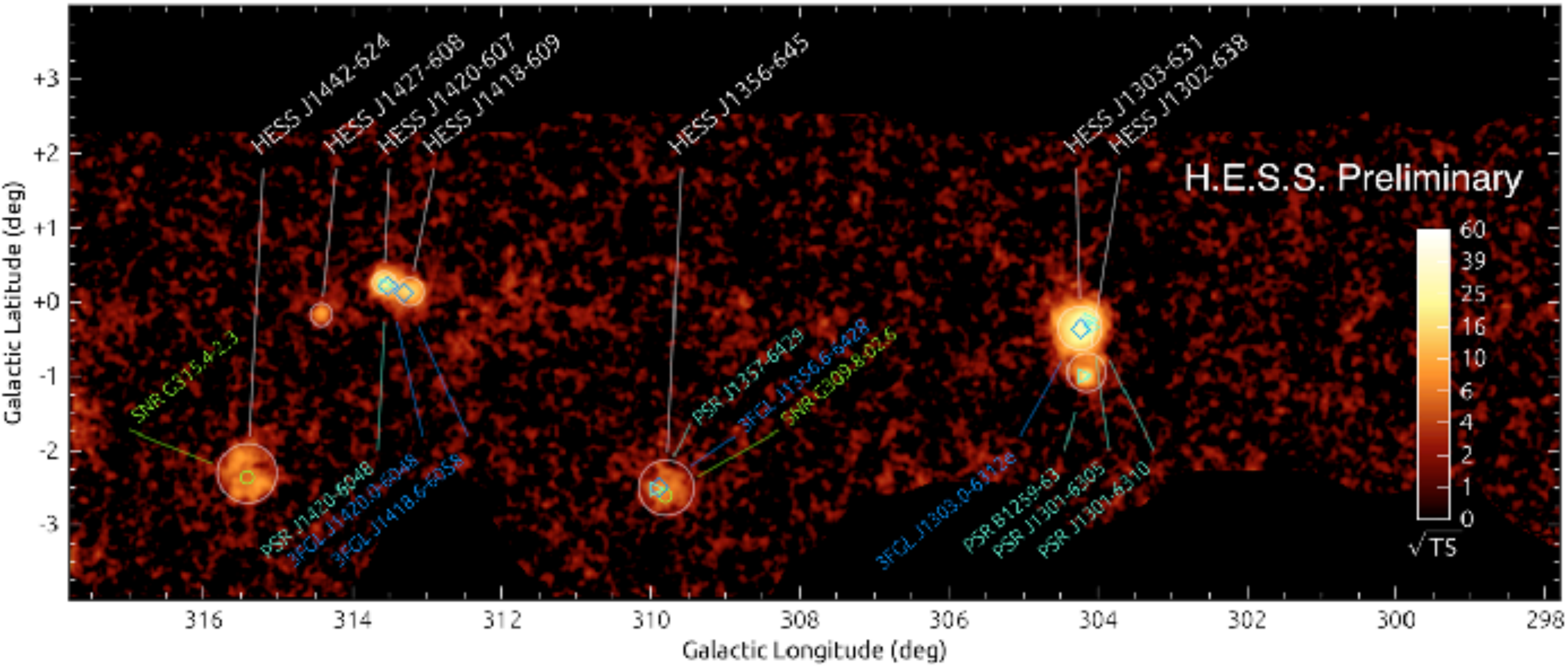


H.E.S.S. Galactic Plane Surveys



- 2673 hours of high-quality data, taken in the years 2004 to 2013.
  - Longitude l = 250 to 70 degrees, latitude |b| < 5 degrees
  - Sensitivity for the detection of point-like sources is at the level of 2% Crab or better

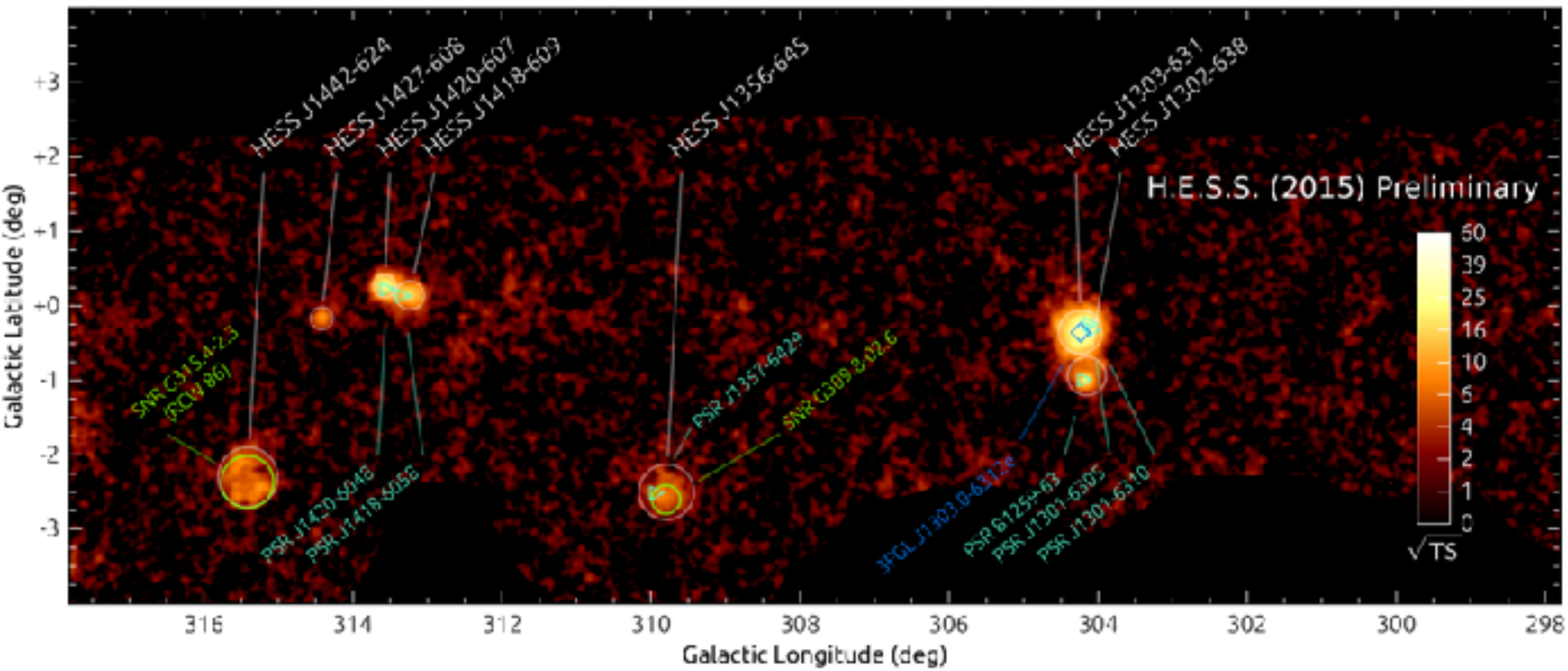
H.E.S.S. galactic plane survey



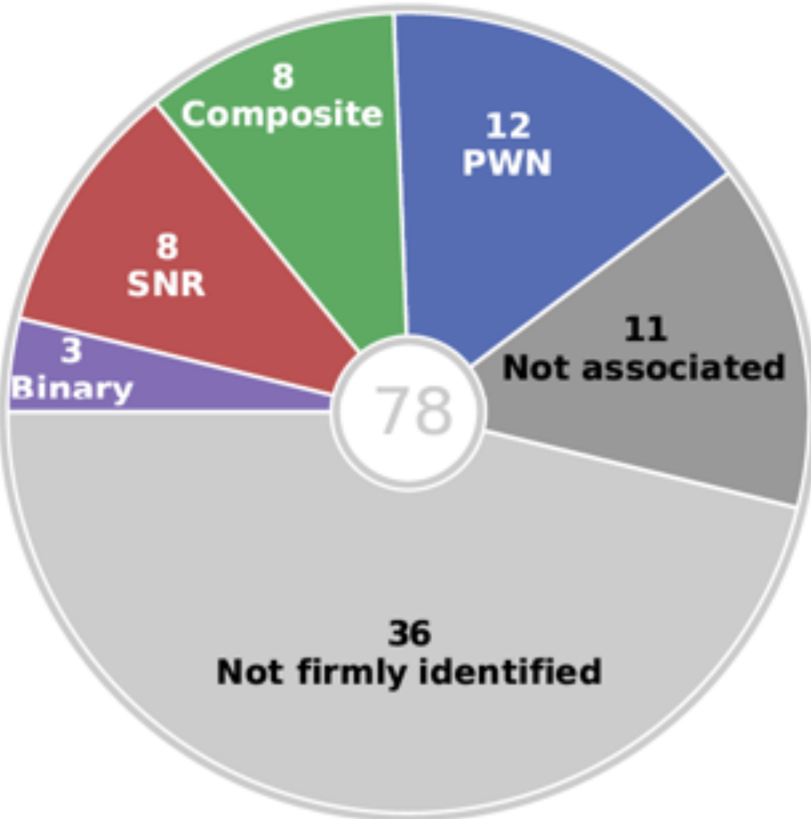
- Source extraction with automatic pipeline
- **67 VHE sources + 11 complex source**s (e.g. shell SNR) excluded from pipeline

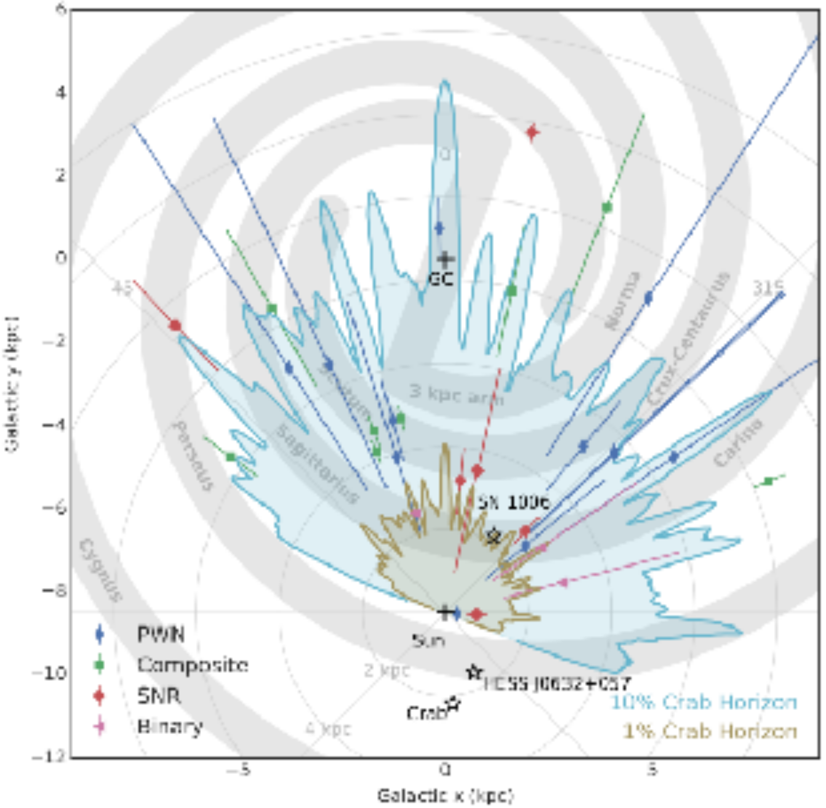
Associations

- Systematic association of HGPS sources with nearby PSR, SNR, PWN, GeV sources (3FGL and 1FHL)



Associations and Identifications





The Book of the Year 2018

A&A 612, E1 (2018)
https://doi.org/10.1051/0004-6361/201833049

Astronomy & Astrophysics
Special issue

Editorial

H.E.S.S. phase-I observations of the plane of the Milky Way

Of the three currently operating large Imaging Atmospheric Cherenkov Telescopes (IACT), the Namibia-based High Energy Stereoscopic System (H.E.S.S.) has the best access to the inner Galactic plane. Devoting 2700 hours to a survey of the Galactic plane, the H.E.S.S. Collaboration has covered the l = 250 deg to 65 deg longitude range for latitudes $|b|$ < 3 deg, with 5 arcmin angular resolution.

In this issue, we publish a series of papers that presents the observations, analyzes many of the 78 detected compact sources, and makes the sky maps available in FITS format. By covering a wide range of objects, from pulsar wind nebulae to gamma-ray binaries through supernova remnants, these papers illustrate the great potential of IACTs to study the most energetic phenomena in the Galaxy and what can be expected from the planned multinational Cherenkov Telescope Array (CTA).

Thierry Forveille, Sergio Campana, and Steve Shore
Astronomy & Astrophysics Editors

The Book of the Year 2018: Content

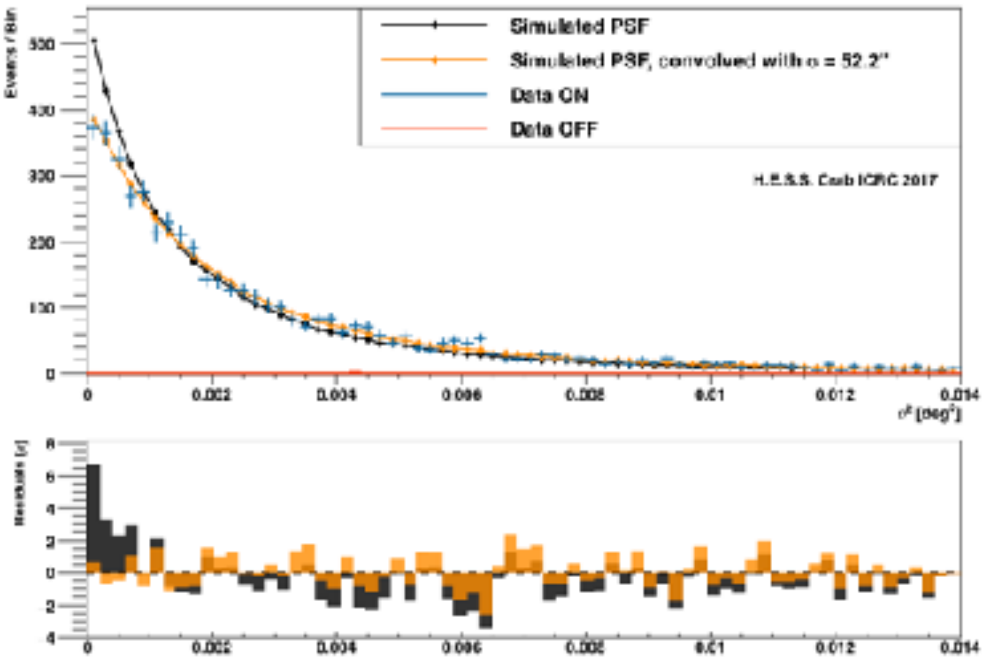
- **Population Studies:**
  - The population of TeV pulsar wind nebulae in the H.E.S.S. Galactic Plane Survey
  - Population Study of Galactic Supernova Remnants at Very High γ-Ray Energies with H.E.S.S.
  - Systematic search for very-high-energy gamma-ray emission from bow shocks of runaway stars
  - A search for new supernova remnant shells in the Galactic plane with H.E.S.S.

- **Galactic Centre Region:**
  - Characterising the VHE diffuse emission in the central 200 parsecs of our Galaxy with H.E.S.S

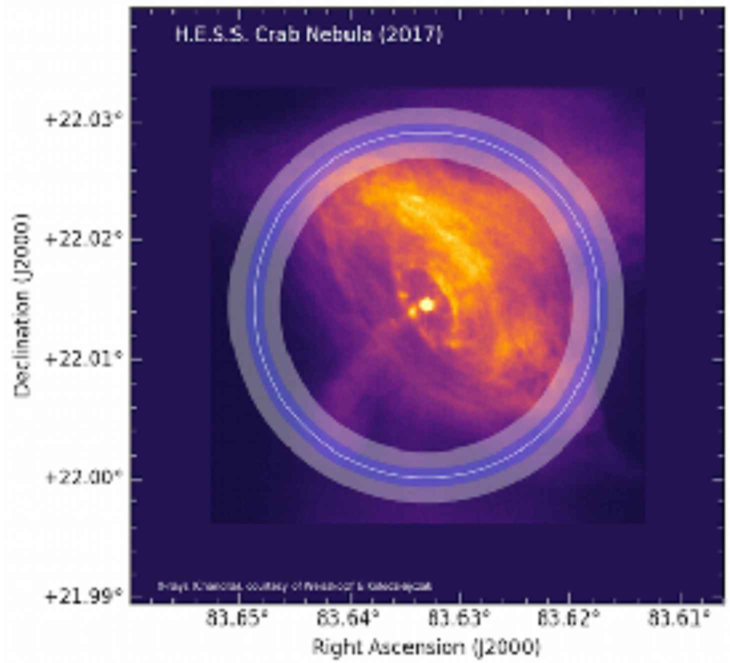
- **Precision studies of selected sources**
  - Detailed spectral and morphological analysis of the shell type SNR RCW 86
  - The supernova remnant W49B as seen with H.E.S.S. and Fermi-LAT
  - H.E.S.S. observations of RX J1713.7-3946 with improved angular and spectral resolution; evidence for gamma-ray emission extending beyond the X-ray emitting shell
  - Deeper H.E.S.S. Observations of Vela Junior (RX J0852.0-4622): Morphology Studies and Resolved Spectroscopy
  - A search for very high-energy flares from the microquasars GRS 1915+105, Circinus X-1, and V4641 Sgr using contemporaneous H.E.S.S. and RXTE observation
  - Extended VHE gamma-ray emission towards SGR1806-20, LBV1806-20, and stellar cluster Cl*1806-20
  - HESS J1741-302: a hidden accelerator in the Galactic plane
  - Constraints on particle acceleration in SS433/W50 from MAGIC and H.E.S.S. observations

The Size of the Crab Nebula

- Improved simulation techniques „aka run-wise simulation“ allow to push the limits of ground-based gamma-astronomy
- Major step in data analysis, important for CTA



H.E.S.S. collaboration, ICRC 2017



$\sigma_{2D,G} = 52.2'' \pm 2.9'' \pm 6.6''$