The HESS experiment - Status, Results and Future

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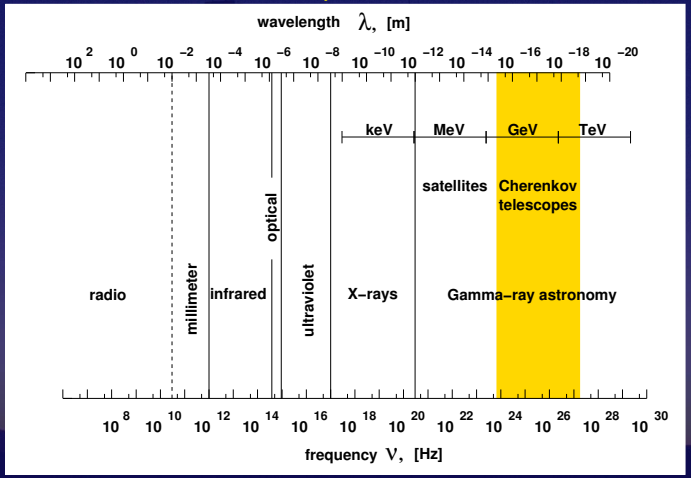
LLR Ecole Polytechnique

SCIPP-Seminar, October 1^{st} 2004, Santa Cruz

- GeV/TeV-Astronomy
- The era of the Next Generation has begun
- The HESS detector (Phase 1)
- Galactic Sources
- Extragalactic Sources
- The future: Phase 2
- Summary

Overview: GeV/TeV-Astronomy



The Pioneering Era

Whipple, HEGRA, CAT, CANGAROO, Durham Mark 6, 7TA

Object	Flux level (approx.) [Crab]	First detection	Confirmation
Crab Nebula	1.00	Whipple	Many
Vela	0.50	CANGAROO	–
PSRB 1706-44	0.50	CANGAROO	–
SN 1006	0.50	CANGAROO	–
Cas A	0.03	HEGRA	–
RXJ 1713.7-3946	0.70	CANGAROO	–
Cen X-3	0.40	Durham	–
Sgr A*	0.1-0.4	CANGAROO	(Whipple)
TeV J2035+415	0.03	HEGRA	–
RCW 86	0.2	CANGAROO	–
RX J0852.0-4622	?	CANGAROO	–
Mkn 421	0.2->1	Whipple	Many
Mkn 501	0.2->1	Whipple	Many
1ES 1959+650	0.06-1	7TA	Whipple/HEGRA/CAT
H 1426+428	0.03-0.1	Whipple	HEGRA/CAT
1ES 2344+514	0.2-0.6	Whipple	HEGRA
PKS 2155-304	?	Durham	–
NGC 253	?	CANGAROO	–

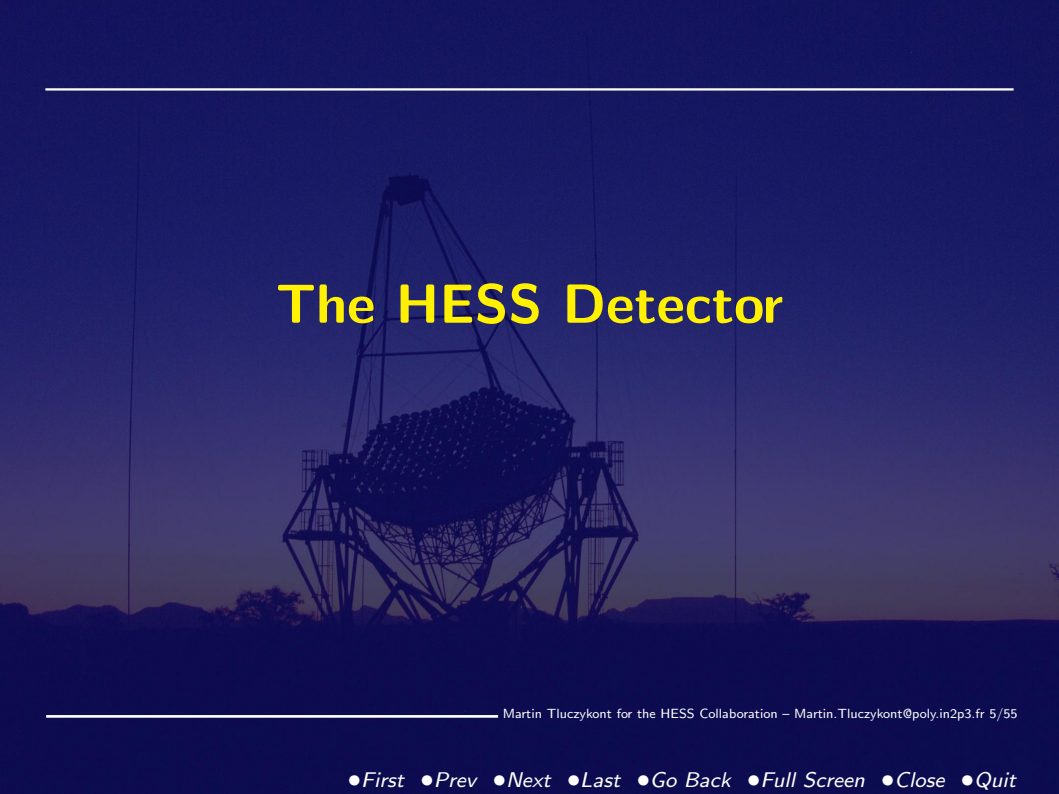
The Era of the Next Generation has begun

HESS, VERITAS, MAGIC, CANGAROO III

Object	Flux level [Crab]	First detection	Conf.	Contradiction (HESS)
Crab Nebula	1.00	Whipple	Many	–
Vela	0.50	CANGAROO	–	Flux
PSRB 1706-44	0.50	CANGAROO	–	Flux
SN 1006	0.50	CANGAROO	–	Flux
Cas A	0.03	HEGRA	–	–
RXJ 1713.7-3946	0.70	CANGAROO	HESS	–
Cen X-3	0.40	Durham	–	–
Sgr A*	0.1-0.4	CANGAROO	HESS	Spectrum
TeV J2035+415	0.03	HEGRA	–	–
HESS J1303-63	0.10	HESS	–	–
PSR B1259-63/SS2823	0.05	HESS	–	–
RCW 86	0.2	CANGAROO	–	–
RX J0852.0-4622	?	CANGAROO	–	–
Mkn 421	0.2->1	Whipple	Many	–
Mkn 501	0.2->1	Whipple	Many	–
1ES 1959+650	0.06-1	7TA	Whipple/HEGRA/CAT	–
H 1426+428	0.03-0.1	Whipple	HEGRA/CAT	–
1ES 2344+514	0.2-0.6	Whipple	HEGRA	–
PKS 2155-304	?	Durham	HESS	–
NGC 253	?	CANGAROO	–	Flux

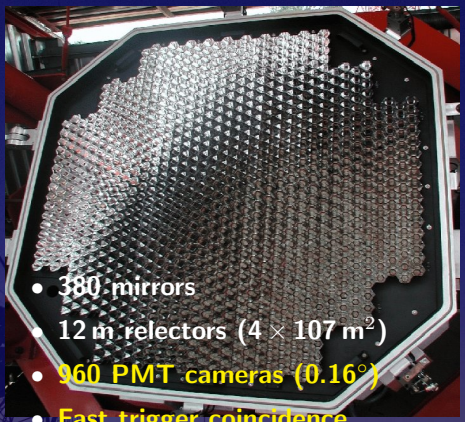
currently: work to understand contradictions (simultaneous observations)

The HESS Detector



HESS 1: Stereoscopic System of 4 Cherenkov Telescopes

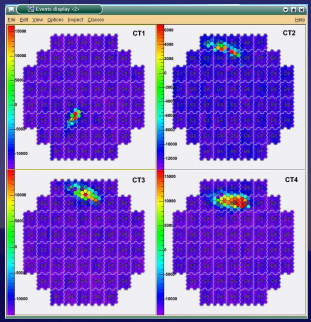
- Namibia, Khomas Highlands (23°S, 15°E)
- Altitude 1800 m



- 380 mirrors
- 12 m relectors ($4 \times 107\,m^2$)
- 960 PMT cameras (0.16°)
- Fast trigger coincidence
- Electronics integrated in Cameras
- 5.3° FoV
- Energy threshold 100 GeV

HESS I – Phase 1 Completed

First light telescope 1	:	June 2002
Two telescopes	:	March 2003
Stereoscopy	:	July 2003
Three telescopes	:	September 2003
Four telescopes	:	December 2003

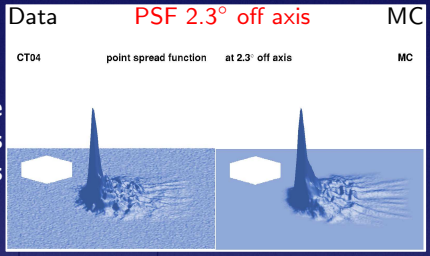


Phase 1 completed & fully operational !

- 0.01 Crab in 25 h
- $E_{thr} = 100\,\mathrm{GeV}$

The Mirror Alignment

Individual mirror facets steerable
Alignment of facets using stars
PSF well within specifications



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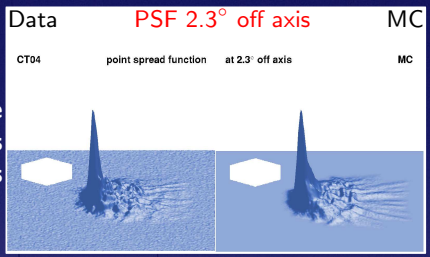

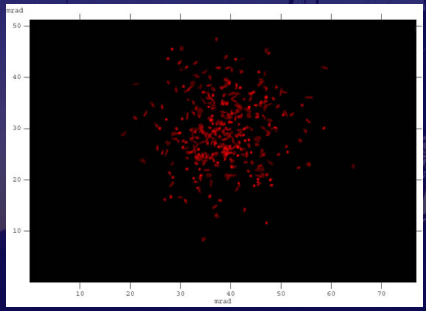

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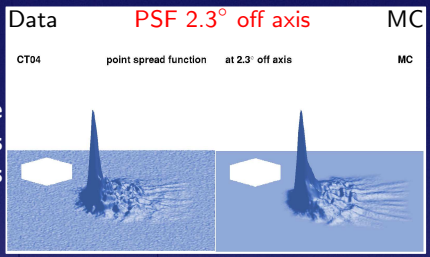
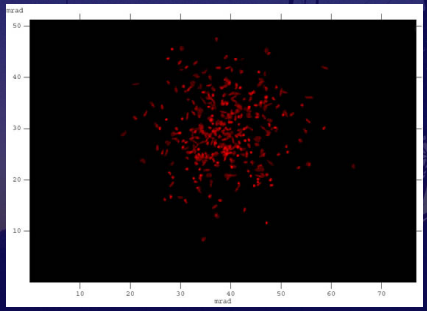
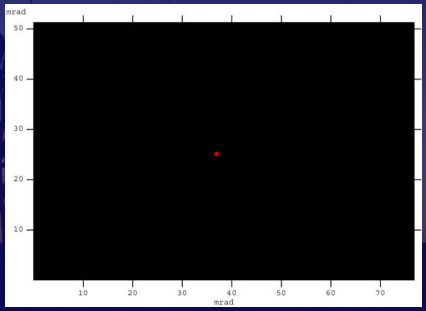
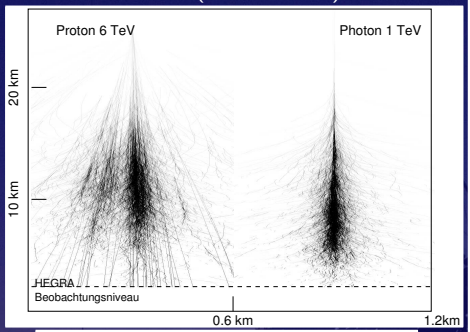


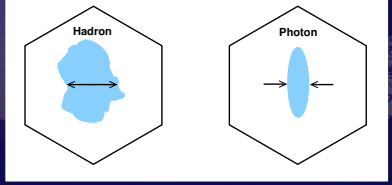


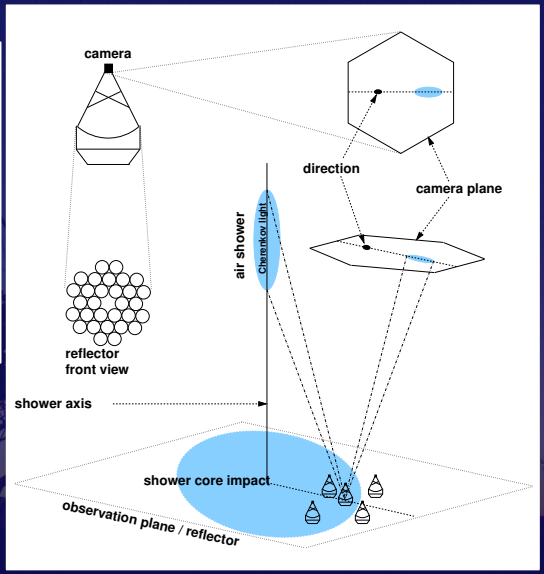


Imaging Air Shower Cherenkov Technique (Pioneered by Whipple)

MC simulation (Horns 2000):

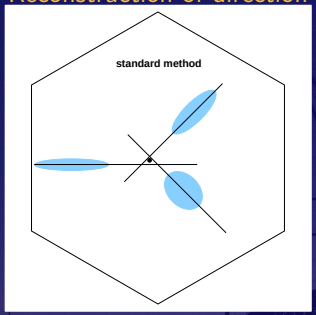






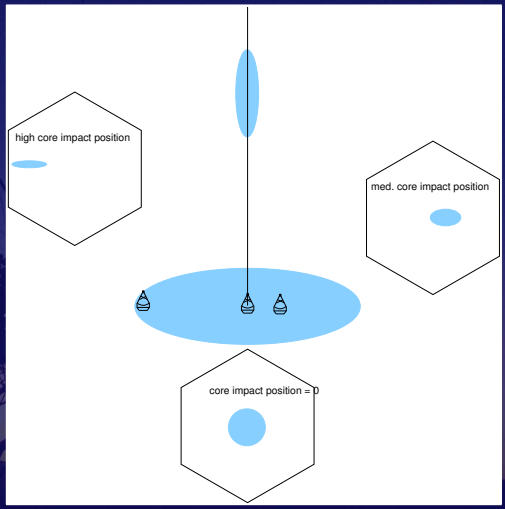
The Basic Stereoscopic Reconstruction Principles

Reconstruction of direction

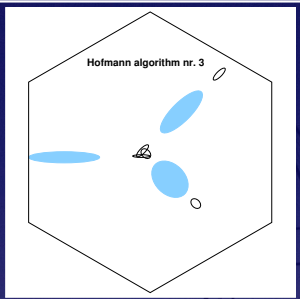


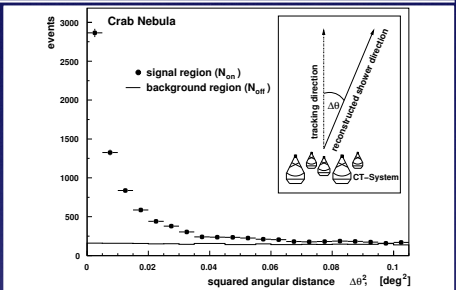
Scaling the image width: Mean Scaled Width Parameter

- Reconstruct: $core$ + amplitude + zenith angle
- MC lookup tables for width $\longrightarrow$ scaling of the width



Stereoscopic Observation Technique - Pioneered by HEGRA

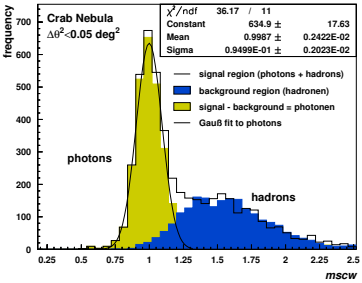




$\geq$ 2 images $\rightarrow$ superposition:

- ... in the camera $\rightarrow$ direction (θ)
- ... at observation level
  $\rightarrow$ core impact position

Hadron rejection:
$core$ + amplitude + zenith angle
$\rightarrow$ $m$ean scaled $w$idth ($mscw$)



Simulation, Calibration & Analysis

Monte Carlo simulations

- CORSIKA + sim_hessarray
- KASKADE + smash

2 Calibration chains

- Heidelberg
- Paris

Background subtraction

- Geometric models
- Template-model
- Likelihood-based model

Different Calibration methods

- Single ph.e.
- Muon rings
- Laser System

Shower reconstruction methods

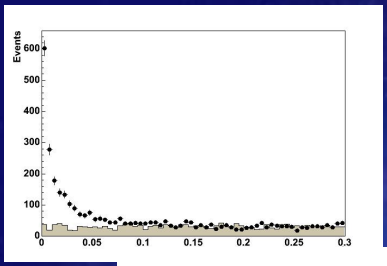
- Standard Hillas reconstruction
- Semi-analytical model
- 3D-Model

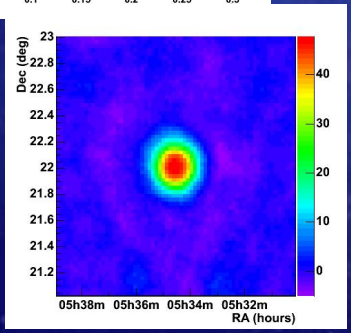
Redundance gives confidence: Robust results

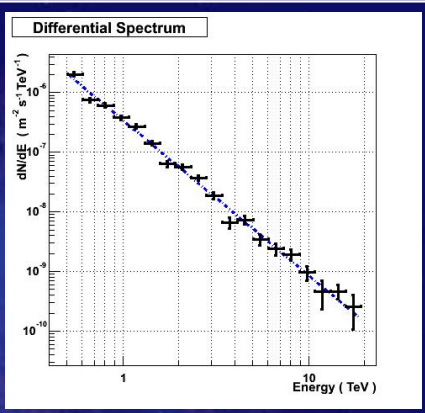
Galactic Sources

Physics: Origin/acceleration of Cosmic Rays, new sources, Dark matter ...

The Crab Nebula as seen by HESS (preliminary)







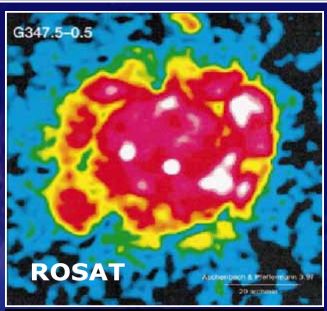
- High zenith angle ($E_{thr} \approx 325$ GeV)
- Independent analyses give consistent results
- Spectral index: $\alpha = 2.62 \pm 0.02$
- Compatible with previous results

Shell-type Supernova remnants

The Shell-Type Supernova Remnant RXJ 1713-3946

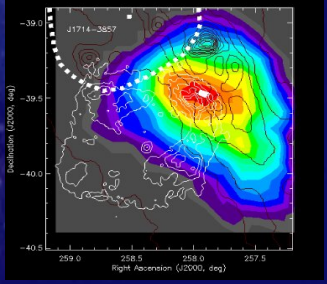
Discovery in X-rays

- ROSAT All-Sky survey source
- Non-thermal X-rays
- Distance: 1 kpc (CO survey)
- Angular extension: 1 deg



First TeV-detection: CANGAROO II
(Muraishi, A. et al. 2000; Enomoto, R. et al. 2002)

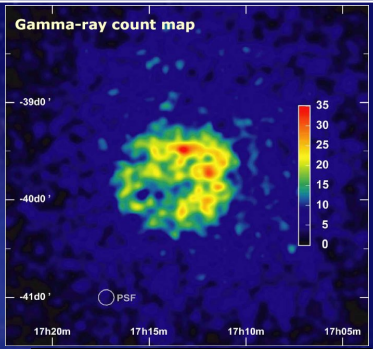
- ≈0.7 Crab
- Question of Cosmic ray acceleration ⟶ controversial discussions (Pohl et al. 2002)



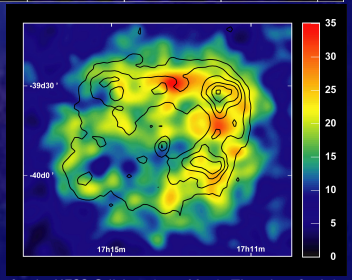
RXJ 1713.7-3946 as seen by HESS

Recent GeV/TeV-confirmation: HESS 2004
(D. Berge, Gamma 2004 & Nature acc. f. publ.)

- High quality data 18.1 h
- $>20\,\sigma$ total remnant
- *The first ever astronomical TeV-image*
- Shown here: High resolution data sub-sample (E>800GeV)



Superposition:
ASCA X-ray data contours



RXJ 1713.7-3946 – The spectrum

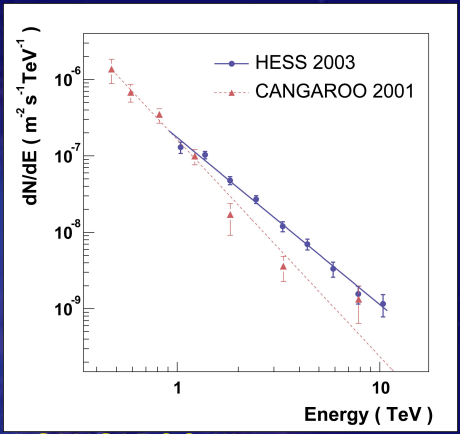
Spectrum: inconsistent spectral indices

HESS:

- $\alpha = 2.19 \pm 0.09 \pm 0.15$
- consistent results in independent analyses

CANGAROO II:

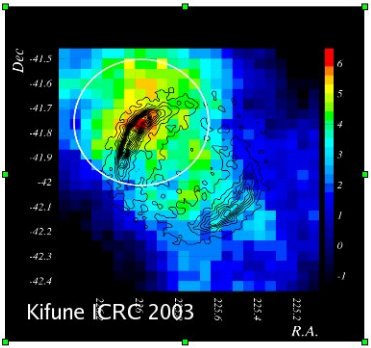
- $\alpha = 2.84 \pm 0.15 \pm 0.20$



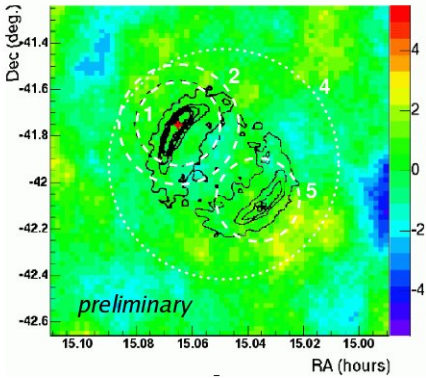
$\longrightarrow$ Further observations by HESS and CANGAROO III
$\longrightarrow$ GLAST observations of 70 MeV bump ?

The shell-type Supernova Remnant SN 1006: Inconsistency

CANGAROO SN 1006



H.E.S.S. significance map



Tanimori et al., Ap J 497 (1988) L25
3.8 m telescope
+ conference proceedings

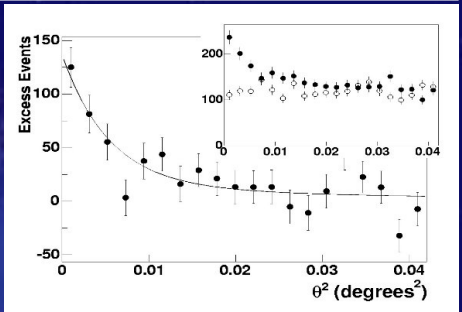
Hofmann, Gamma 2004

A unique type of GeV/TeV-emitter

The Galactic Center (Sgr A*): HESS data

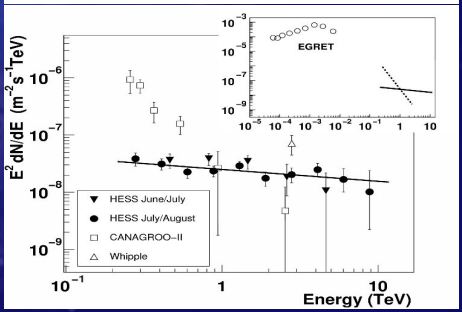
The Signal:

- 2-Telescope data
- Average zenith angle: 20°
- Two detector configurations
  - 4.7 h at $E_{thr} = 255$ GeV
  - 11 h at $E_{thr} = 165$ GeV
- Total significance: $9.2\,\sigma$

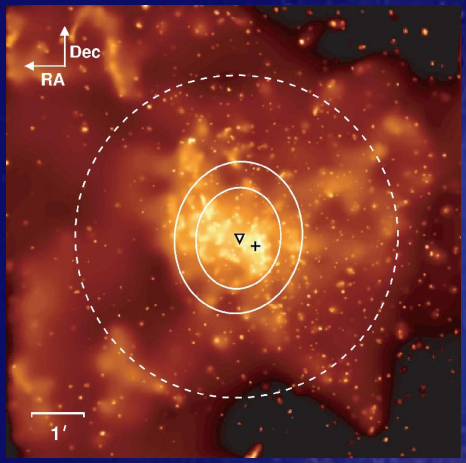


Spectrum:

- Power-law, $\alpha = 2.21 \pm 0.09 \pm 0.15$
- Steady state 0.05 % (E> 165 GeV)
- Strong contradiction to CANGAROO II



The Galactic Center (Sgr A*)



Chandra X-ray image

HESS superimposed:

- 68 % & 95 % confidence regions for source position
- 95 % upper limit on rms source size
- Position compatible within errors (30") with SgrA*
- $\Omega_{\mathbf{err}}$ reduced by 100 (as cmp to previous measurements)

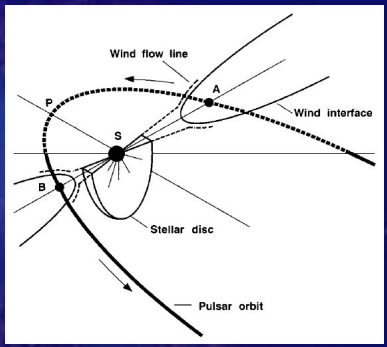
Dark Matter hypothesis: HESS spectrum + angular distribution $\Longrightarrow$ $M\chi > 12\,\mathrm{TeV}$ (90 % C.L.) (Horns, astro-ph/0408192, also: Aharonian & Neronov, astro-ph/0408303)

A new unique type of GeV/TeV-emitter

PSRB 1259-63 / SS 2883

The Binary Pulsar system PSRB 1259-63 / SS 2883 at 1.5 kpc

- 10 $M_\odot$ Be star $L = 3\times10^{30}$ W
  dense stellar disk, high mass outflow
- 48 ms radio Pulsar
  $L_{spindown} = 8\times10^{28}$ W
- Pulsar orbit around Be star
  - 3.4 years
  - Periastron : 23 $R_\odot$
  - Apastron : 331 $R_\odot$
  - Inclination : 35 deg
  - Diameter: 350 $R_\odot$ (Point-like)



CANGAROO 3.8 m: 4.8 σ (1994), 10 m: Upper limits (2000), after periastron
HESS-observations at last periastron passage : 7^{th} of March 2004

PSRB 1259-63 / SS 2883 – HESS Results (S. Schlenker, Gamma 2004)

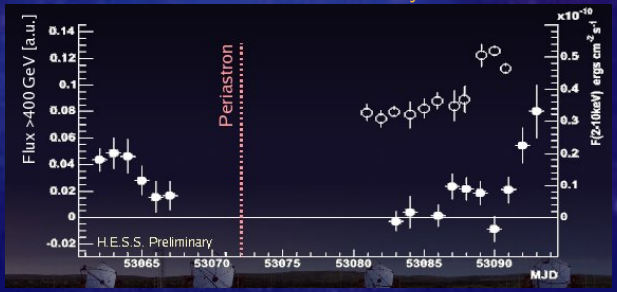
Pre-Periastron

- High quality data : 7.8 h
- Significance : $9.1\,\sigma$
- Excess rate : $\approx 0.4\,\gamma$/min

Post-Periastron

- High quality data : 17.4 h
- Significance : $6.3\,\sigma$
- Excess rate : $\approx 0.2\,\gamma$/min

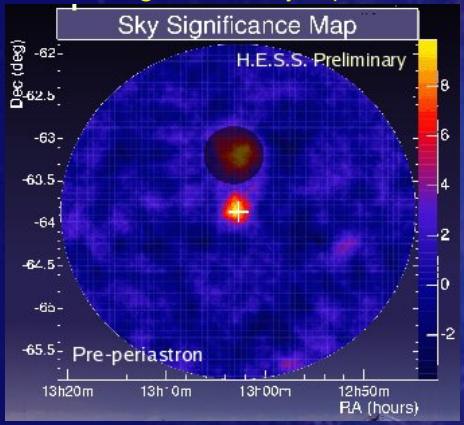
Overall $> 10\sigma$ detection by HESS



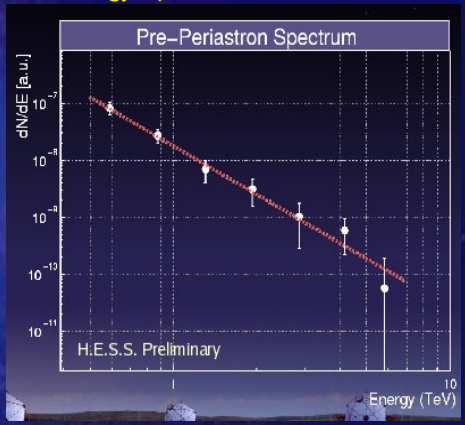
Flux E>400 GeV $\approx 5\,\%$ Crab

PSRB 1259-63 / SS 2883 – HESS Results (S. Schlenker Gamma 2004)

Significance Skymap



Energy Spectrum $\alpha = 2.8 \pm 0.3$



PSRB 1259-63 / SS 2883 – The Next Periastron passages

- July/August 2007
- Christmas 2010
- ...

Simultaneous observations with GLAST already in 2007 ?
Or nice Christmas present in 2010 ?

Non-identified GeV/TeV-Sources

Physics: what? how? where?

HESS J1303-63 (M. Beilicke, Gamma 2004)

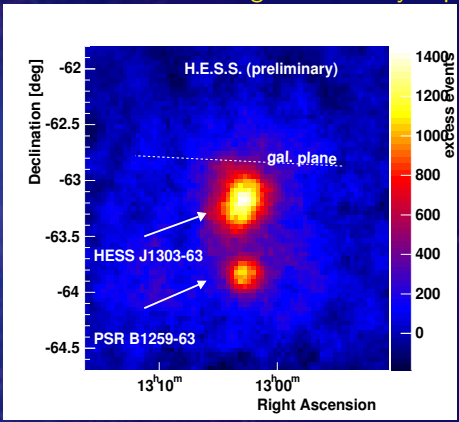
Surprise in PSRB 1259-63 observations:

- Second signal in FoV !
- 0.7 deg from Pulsar position
- Steady state signal ($18\,\sigma$)

Calibration or Physics ?

- High data quality
- Consistent results for different algorithms
- ...

Significance Skymap

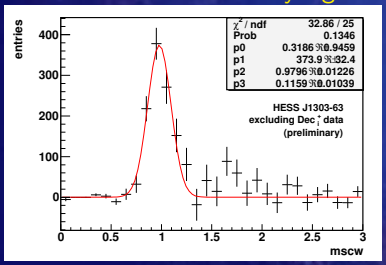


HESS J1303-63 (M. Beilicke, Gamma 2004)

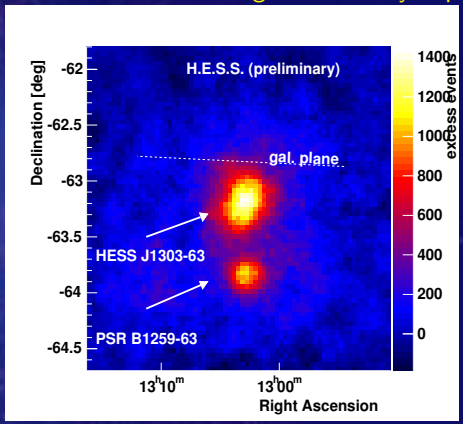
Surprise in PSRB 1259-63 observations:

- Second signal in FoV !
- 0.7 deg from Pulsar position
- Steady state signal (18σ)

HESS 1303-63: Gamma-ray signature

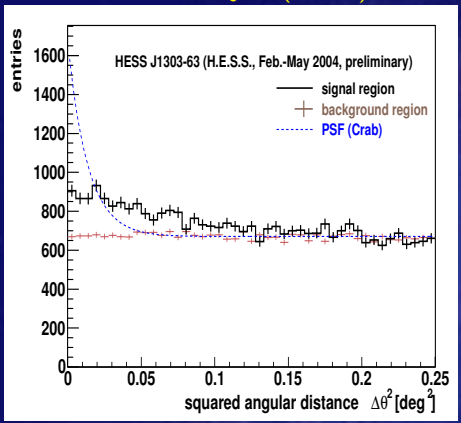


Significance Skymap

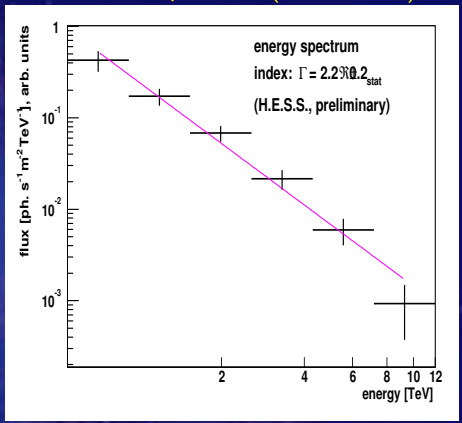


HESS J1303-63: The 2^{nd} unidentified TeV-source

Extended object ($\approx 0.2°$)



Powerlaw spectrum ($\alpha = 2.2 \pm 0.2$)

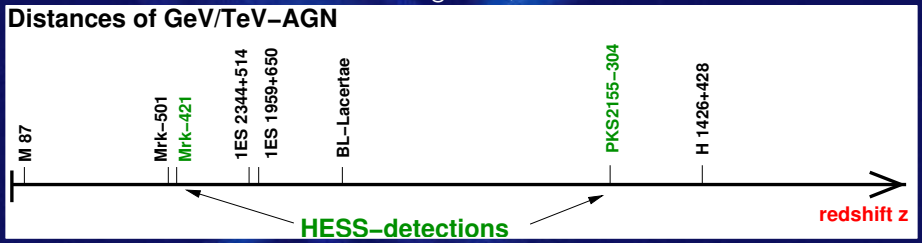


Populated corner of the sky but ...
No obvious radio / optical / X-ray counterpart found

$\longrightarrow$ Further HESS & Future GLAST observations

Extragalactic Sources

Physics: Production mechanisms, understanding the AGN family, Extragalactic Background, ...

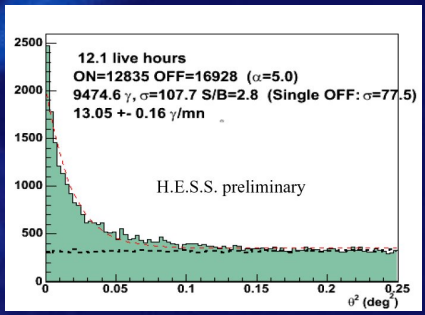


Mrk 421: HESS Detection

First Detection: Whipple (Punch et al. 1992), subsequently confirmed by many

HESS observations

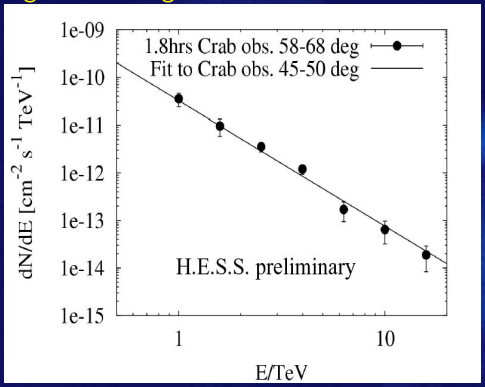
- 13.6 h observation full 4-telescope-system
- Average zenith angle: 63 deg
- Low state: 01/2004 - 6σ (2.1 h)
- High state: 04/2004 - $\approx 100\,\sigma$ 11.5 h, 11 γ/minute
- More than 8000 γ-ray events



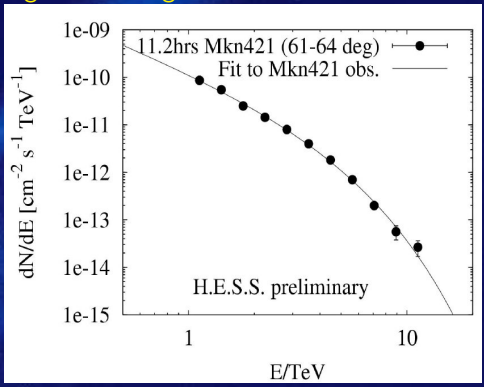
See contributions to GAMMA 2004 by D. Horns & A. Lemière

Mrk 421: Energy Spectrum

High zenith angles: Crab



High zenith angles: Mrk 421

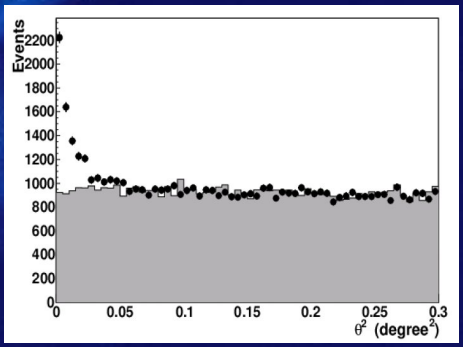


PKS 2155-304

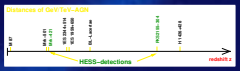
- High Frequency Peaked BL-Lac Object
- First detection: Durham Mark 6 Telescope
- $z = 0.116 \longrightarrow$ second most distant GeV/TeV emitter so far

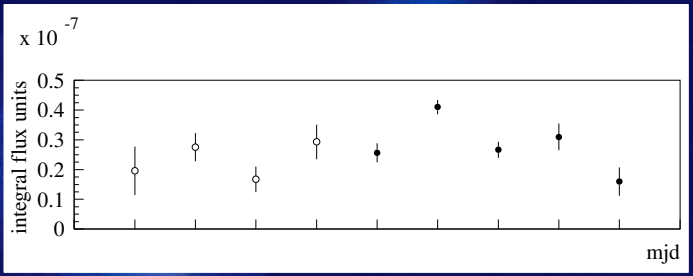
HESS Data

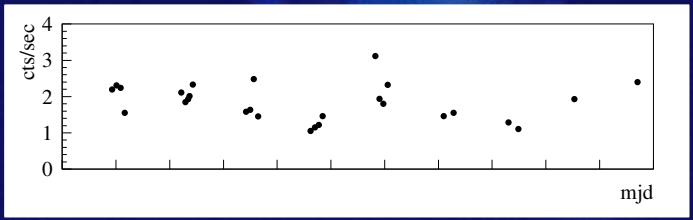
- Observation time ≈60 h
- Different data sets: varying Energy threshold 165 GeV - 305 GeV
- Significance: $>50\,\sigma$
- Many photons collected (>4000)
- Flux level consistent with Durham Mark6 detection
- No strong flux variations observed



PKS 2155-304: Multi Wavelength Campaigns

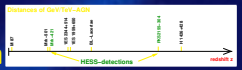


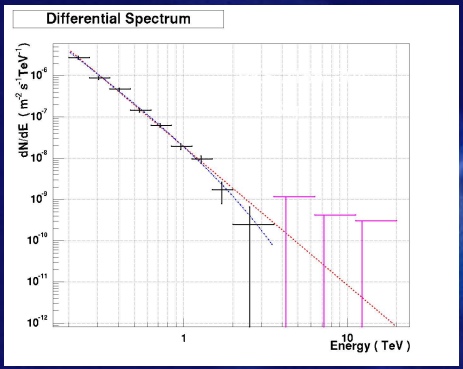




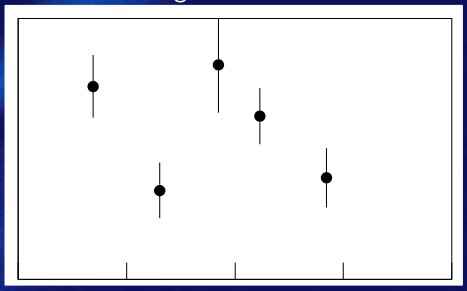
Multiwavelength campaigns carried out, results in preparation (B. Giebels)

PKS 2155-304: Energy Spectrum & Flux Variation





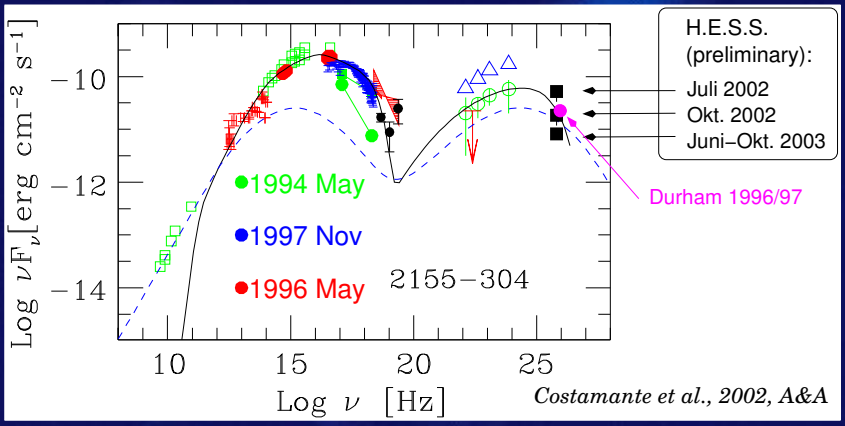
Intra-night flux variation:



No strong flux variations observed

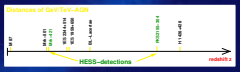
Object is detected *every night* $\longrightarrow$ Observation of a ≪ground state≫(first ever!)

PKS 2155-304: SSC model

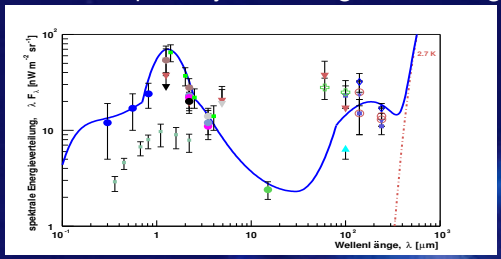


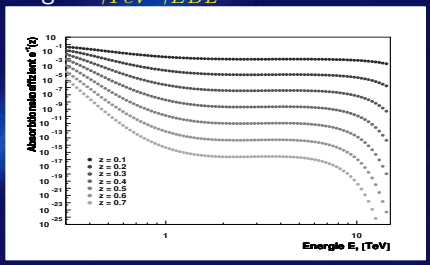
One-zone homogeneous SSC-model, Costamante et al. 2002

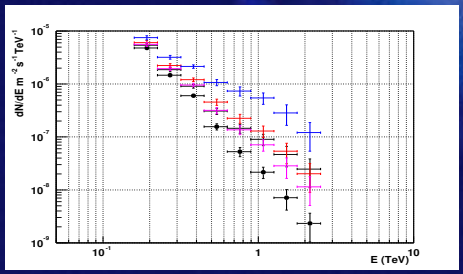
PKS 2155-304 & EBL Absorption



Absorption by the Extragalactic Background Light: $\gamma_{TeV}\,\gamma_{EBL} \longrightarrow e^+e^-$





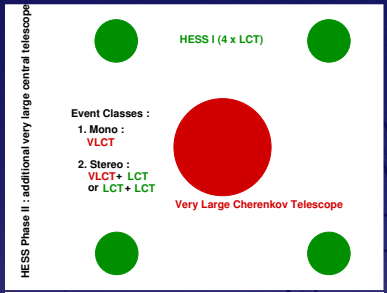


← PKS 2155-304 by HESS

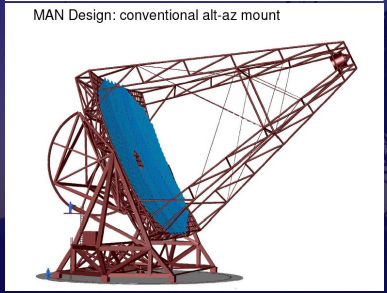
- $z = 0.116$
- Several EBL models tried
- No cutoff seen yet
- Wait for higher statistics (2004) at high energies (?)

The Near Future: HESS Phase 2

HESS Phase 2 = HESS 1 + Very Large Telescope



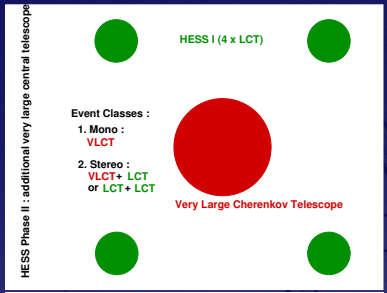
MAN Design: conventional alt-az mount



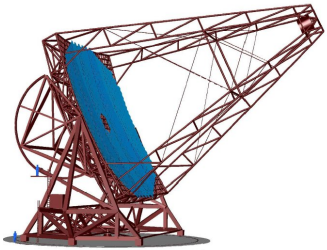
Very Large Cherenkov Telescope:

- Reflector : 28 m ($\approx 600\,m^2$)
- Focal distance $\approx$ 35 m
- Camera: diam. 2.5 m ($\approx$ 2000 kg)
- 2048 PMTs (0.07°/pixel)
- FoV : 3.5°
- Trigger rate $\approx$ 2.5-20 kHz
- Faster memories needed ($\approx$500 kHz)
- Minimize data flow: 2nd level trigger

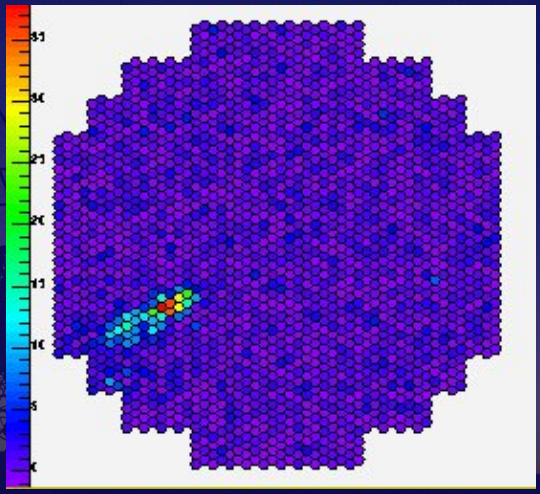
HESS Phase 2 = HESS 1 + Very Large Telescope



MAN Design: conventional alt-az mount



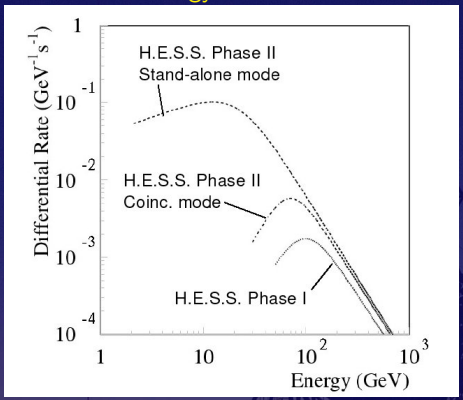
MC Simulation: 30 GeV γ-ray



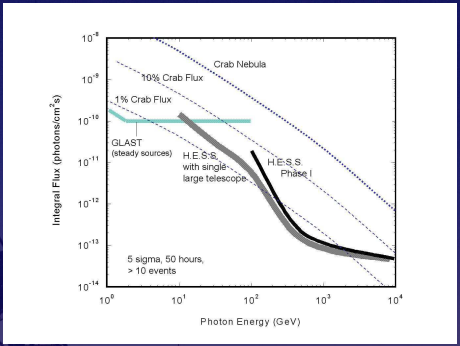
HESS Phase 2 in Namibia

HESS Phase 2 : Expectations

Energy threshold



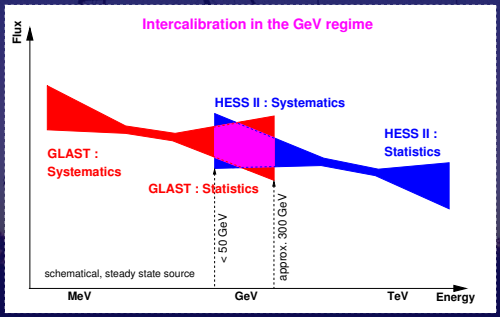
Sensitivity: Stereoscopic mode



- New HESS event class: E $\approx$ 10-50 GeV
- Increase sensitivity for E $\approx$ 50-100 GeV
- Improve resolution for E $>$ 100 GeV

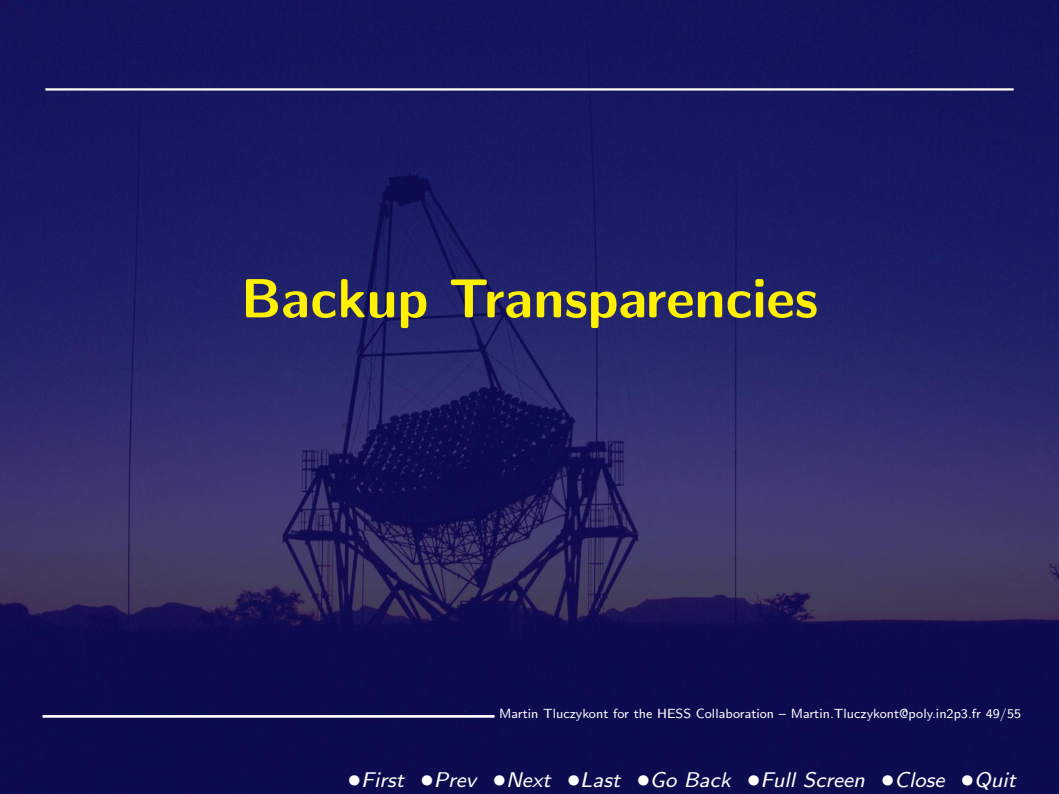
Future collaboration with GLAST

- Overlapping energy regime : Observations of the same particle population
  - GLAST trigger for HESS-observations
  - HESS will produce sensitive variability studies
- Simultaneous observations of a steady source $\longrightarrow$ Intercalibration



Summary

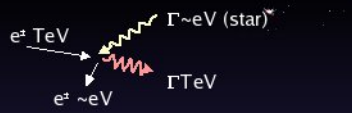
- HESS Phase I completed and fully operational
- Planned performance achieved
  ($E_{thr} = 100$ GeV, Sensitivity 0.05 Crab in 1 h)
- Outstanding new results
  - 1^{st} astronomical GeV/TeV image (RX J1713.7)
  - New object class (Psr B1259-63)
  - 1^{st} time two sources in one FoV
  - 1^{st} observation of BL Lac at low state? (PKS 2155-304)
- $\longrightarrow$ Potential for more
- HESS Phase II is being planned:
  - Objective: close the gap to GLAST
  - Method: additional Very Large Central Telescope



Backup Transparencies

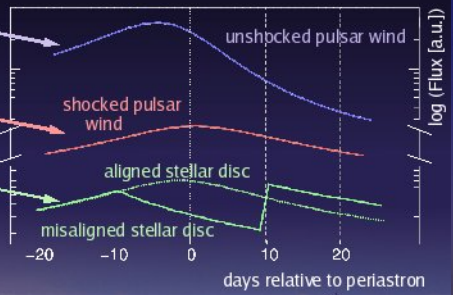
Gamma Ray Emission Models

TeV gamma ray production via Inverse Compton Scattering of the star's photon field and accelerated particle populations from:



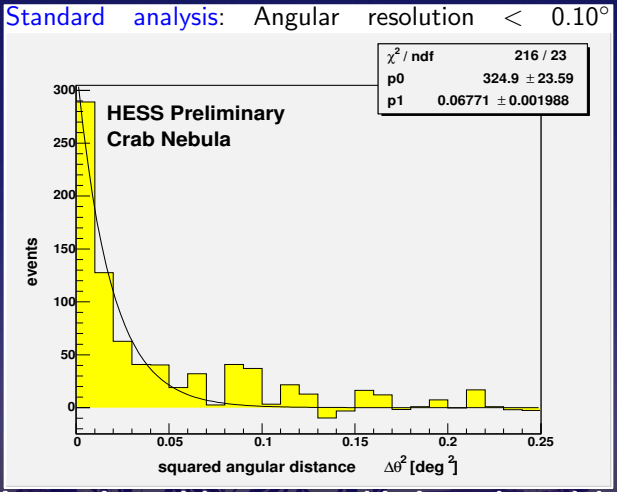
5) Unshocked pulsar wind *Ball, Kirk* 2000
6) Pulsar wind termination shock induced by star's photon field *Ball, Dodd* 2001
7) Interaction region of star mass outflow and pulsar wind *Kawachi et al.* 2004

All models predict flux variation dependent on orbital phase



Probe particle acceleration with star's photon field!

HESS 1 Performance: Angular resolution



Improving with more sophisticated models (Semi-Analytical model & 3D-Model)

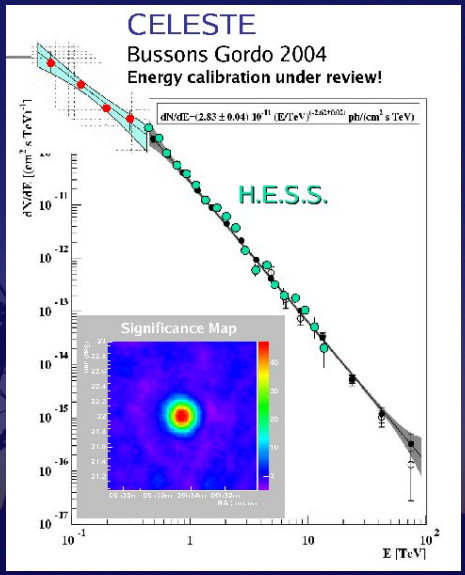
HESS 1 Performance: Energy Reconstruction

MC

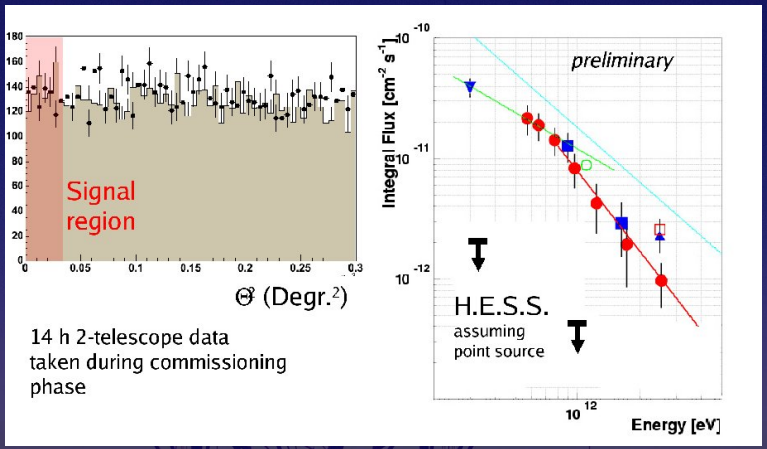
- Energy resolution: 10-20 %
- Reconstruction bias $< 10\,\%$

Crab Nebula Spectrum

- $\alpha = 2.59 \pm 0.04^{stat}$
  - Whipple: $\alpha = 2.49 \pm 0.07$
  - HEGRA: $\alpha = 2.62 \pm 0.05$
  - CAT: $\alpha = 2.76 \pm 0.04$
- Flux (E>1 TeV): $2.16 \pm 0.08 \times 10^{-7}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$
  - Whipple: $2.15^{\pm 0.43} \cdot 10^{-7}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$
  - HEGRA: $1.75^{\pm 0.37} \cdot 10^{-7}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$
  - CAT: $1.78^{\pm 0.39} \cdot 10^{-7}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$

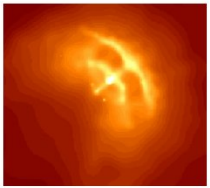


PSR B1706-44 by HESS



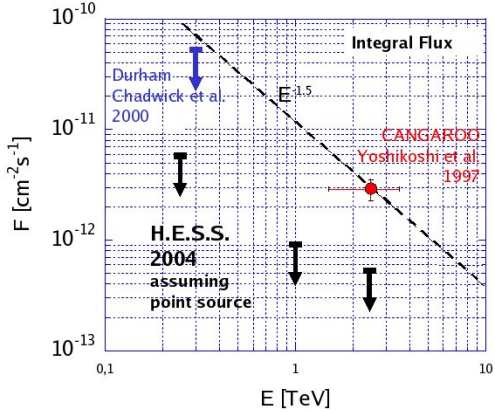
Hofmann, Gamma 2004

Vela by HESS



Chandra

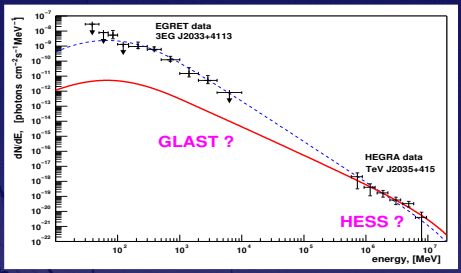
- CANGAROO source 0.13° off pulsar
- H.E.S.S. limits similar for both CANGAROO and pulsar location

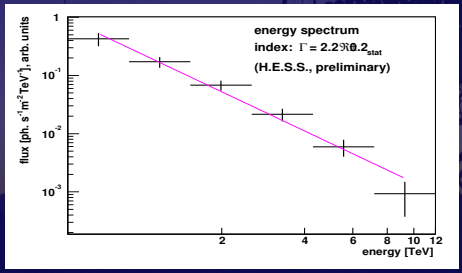


Hofmann, Gamma 2004

What kind of objects to observe for inter calibration?

- Steady state source: simplifies a lot
- Hadronic
  - Naive: straight power law
  - More efficient acceleration at GeV energies ?
- Leptonic ?





Possible Candidate: HESS 1303-63

- Power law: $\alpha = 2.2$
- Flux: 0.1 Crab (E>1 TeV)
- GLAST-detection: O(days)