Recent Results from the VHE Gamma-ray Observatories

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VERITAS collaboration

SLAC Summer Institute 2011

photo: P. Fortin

Outline

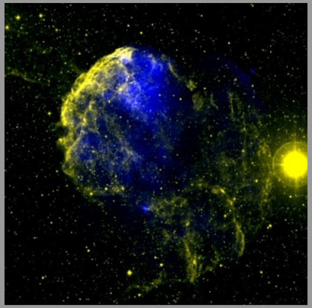
- VHE gamma-ray science drivers
- observational principles
- selected results from the 'big three' observatories
    - H.E.S.S.
    - MAGIC
    - VERITAS
- conclusions

VHE Gamma-ray Science

Study of very-high-energy gamma rays

(VHE: 100 GeV – 30 TeV)

known sources are:

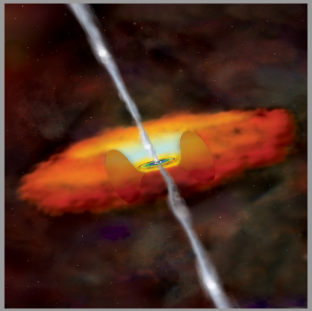


galactic

- pulsar wind nebulae (PWNe)
- supernova remnants (SNRs)
- binary systems

extra-galactic

- active galactic nuclei (AGNs)
- starburst galaxies



possible sources are:

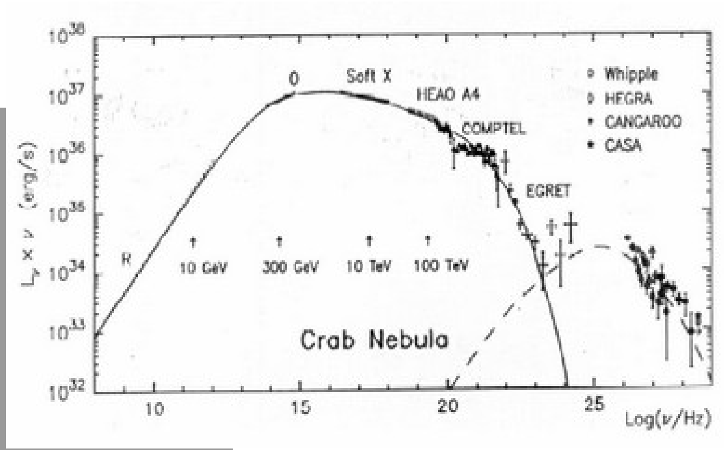
- WIMP annihilation in galaxy cores
- primordial black hole (PBH) evaporation

VHE Gamma-ray Science

Advantages of gamma rays:

- neutral – they point back to their origin (unlike charged cosmic rays)

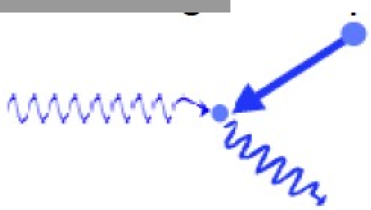
- interact electromagnetically – 'easy' to detect (unlike neutrinos)



Production of VHE gamma rays:

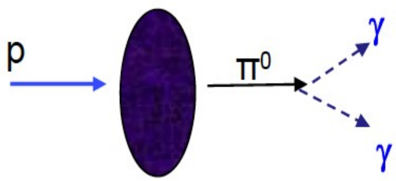
- charged particles get accelerated
    - shocks
    - pulsar fields

- electrons
    - emit synchrotron radiation (X-rays)
    - inverse-Compton scatter ambient photons to VHE
    -> double-hump feature in extended spectra



Inverse Compton Scattering

- protons
    - collide with ambient gas (beam-dumps)
    - $\pi^0 \rightarrow \gamma\gamma$



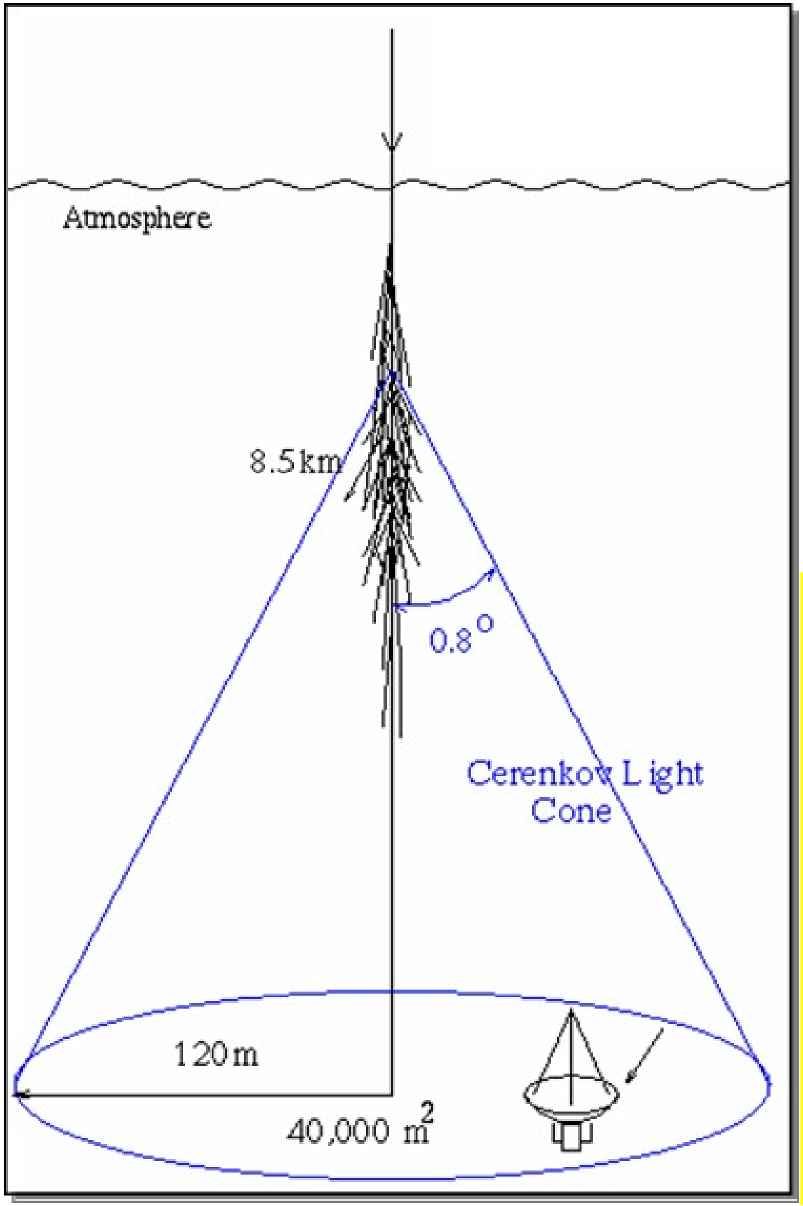
π^o and target material

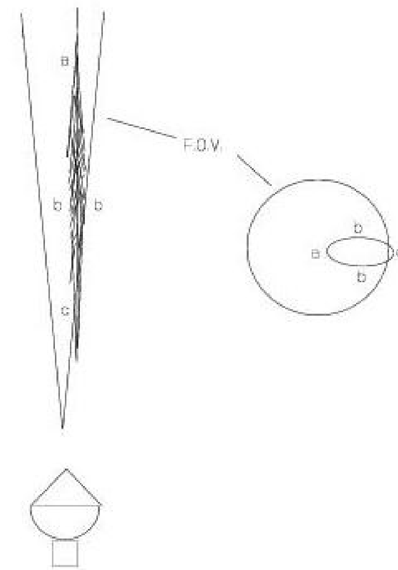
VHE Gamma-ray Science

Connection to (astro) particle physics

- instrumentation and techniques
- origin of cosmic rays
  - where are the accelerators?
  - how do they work? what energies?
  (relevant to Auger, HiRes, etc)
- understanding the nature of particle accelerators
  - what is being accelerated? (electrons, protons?)
  (relevant to IceCube, Antares, etc)
- astrophysical details of AGNs
  - can use flares to look for effects of quantum gravity
  but only if the start times are well understood
- increase discovery space
  - e.g. larger mass reach for WIMPs

Mechanics of TeV Gamma-ray Astronomy





air shower forms an image on the (pixellated) focal plane

images from gamma rays are different from images due to charged cosmic rays (good for background rejection)

stereo imaging using two or more telescopes offers better precision and background rejection

low duty-cycle and bad signal-to-noise are repaid by huge collection area (~10^5 m^2) - Fermi has ~1 m^2

H.E.S.S.
(High Energy Stereoscopic System)

- four 12-m (107 m^2) Davies-Cotton telescopes
- 5^O (diameter) field-of-view

~ 5' resolution for single gamma rays

- 5σ in 25 h for a source at 20^O zenith and flux 10^{-13} cm^{-2} s^{-1} > 1 TeV
- phase II - 600 m^2 dish at centre of array (under construction)

Germany

France

United Kingdom

Namibia

South Africa

Czech Republic

Ireland

Armenia

Poland

Australia

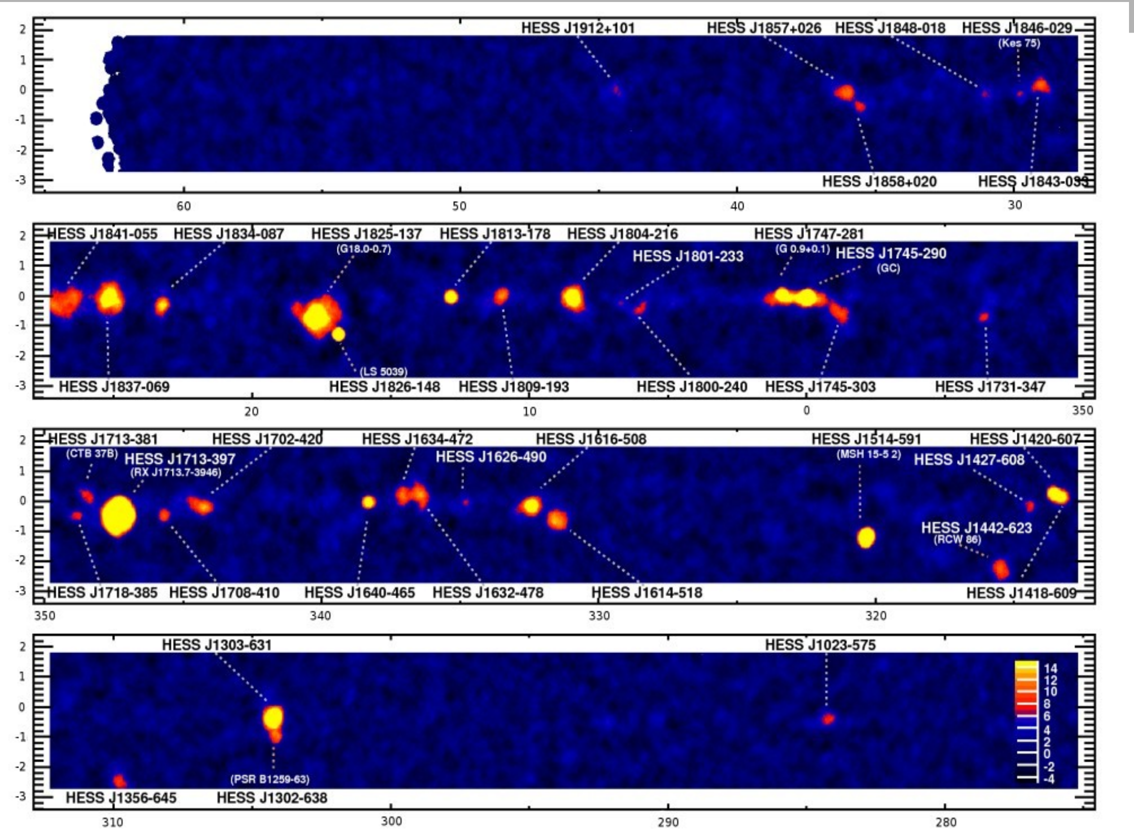
Sweden

Associate Members

(~ 200 authors)

H.E.S.S.

- located at 1800 m in Namibia → excellent view of Galactic Centre
- fully operational since December 2003
- more than 62 sources detected so far



H.E.S.S.

Gamma rays from direction of Terzan-5
(arXiv:1106.4069v2)

- globular clusters:
    - very high density of stars in their cores
        - 300,000 in 10 light-year sphere
        (10 in same volume near solar system)
    - very old (same age as galaxy)
    - ~150 in a halo around the galaxy
    - very old (same age as galaxy)
    - many millisecond pulsars (spun up in binary systems)
    - predicted to emit HE gammas
        - fields of MSPs
        - shocks at end of electron winds from pulsars

- Fermi LAT:
    - reports HE gammas from several GCs
    (Abdo et al 2009, 2010)

- Terzan 5 :
    - largest number of MSPs in radio
    - brightest at GeV energies (Fermi-LAT)
    - l.6 kpc distant
    - very compact
    - half-mass in << arc min
    - 1.7 degrees off Galactic plane a few degrees away from Galactic centre

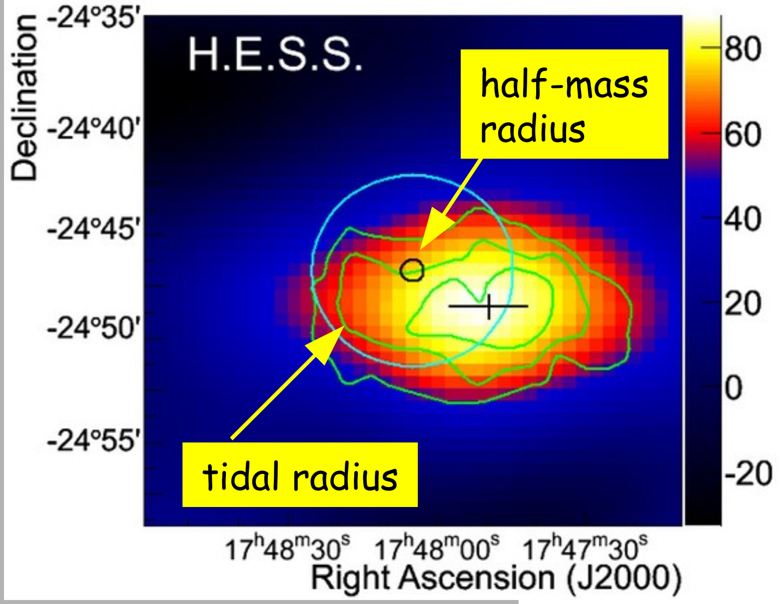
inner part of Terzan 5

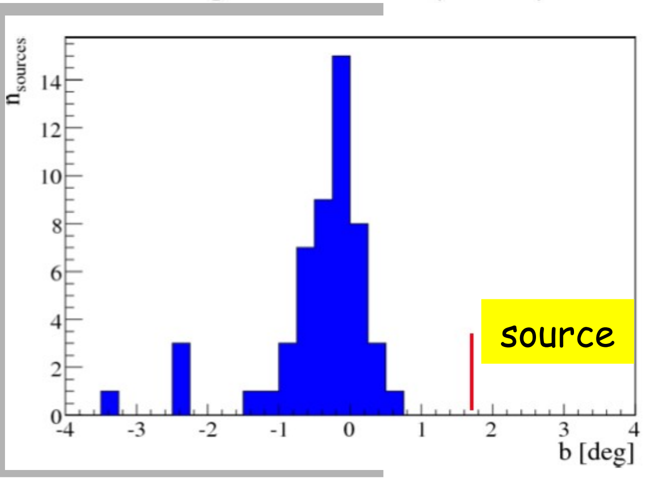
H.E.S.S.

Gamma rays from direction of Terzan-5

HESS results:

- 90 h of observations
- 7-sigma signal
- odd shape (see plot)
- marginally offset (4 arc minutes)
  - could it be a chance overlap with a less exotic source? (estimate is 0.01% prob by looking at galactic survey dist)
- source is more extended than expected by the two leading models
- first globular cluster to be seen in VHE gamma rays but puzzles need to be resolved





H.E.S.S.

A New SNR with TeV shell-type morphology: HESS J1731-347 (arXiv:1105.3206v2)

- initially discovered in the HESS galactic survey
  - not identified with any known sources at other wavelengths (eg PWNe, SNR, binary system - PWNe are the most common Galactic VHE sources)

- recent (2008) discovery (Tian et al) of radio SNR (G353.6-0.7) spatially coincident with HESS J1731-347 prompted more observations by HESS

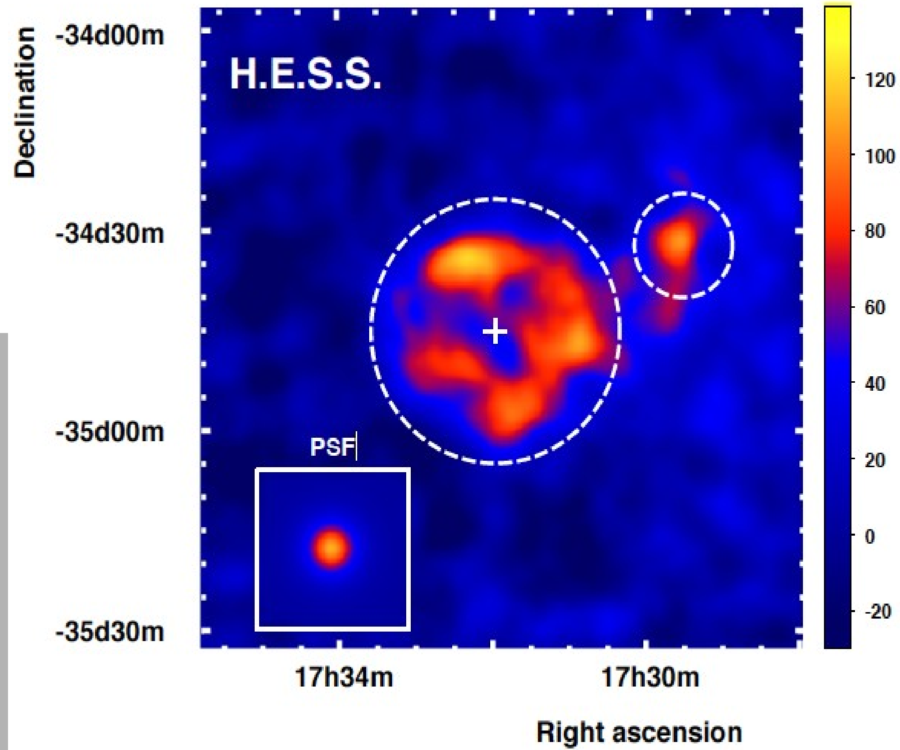
- X-ray data (Chandra, XMM, Suzaku, ROSAT) show morphology similar to the radio

- X-ray spectrum suggests synchrotron emission
  - SNR shock front is accelerating electrons to TeV energies

- compact object - possibly a pulsar (marginal evidence) - seen at the centre in X-rays

H.E.S.S.

HESS J1731-347



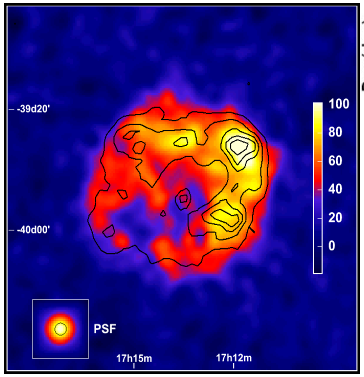
HESS results:

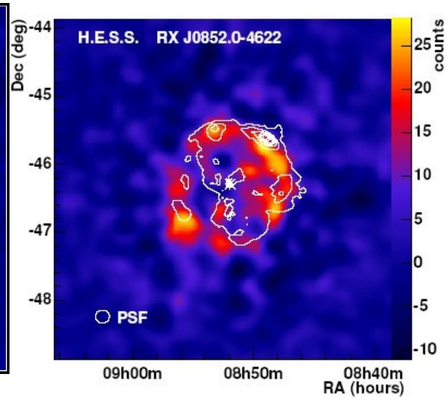
- 59 hours of data
  - 14 h in original survey
  - remainder in summer 2007, summer 2009
- E_{thresh} = 240 GeV
- 22 σ detection
- 8 σ detection of neighbouring structure HESS J1729-349

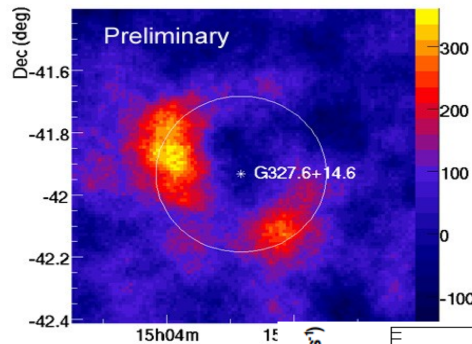
- spectrum is consistent with a power law (index 2.32 +/- 0.06)
- flux is about 16% of the Crab

H.E.S.S.

HESS J1731-347



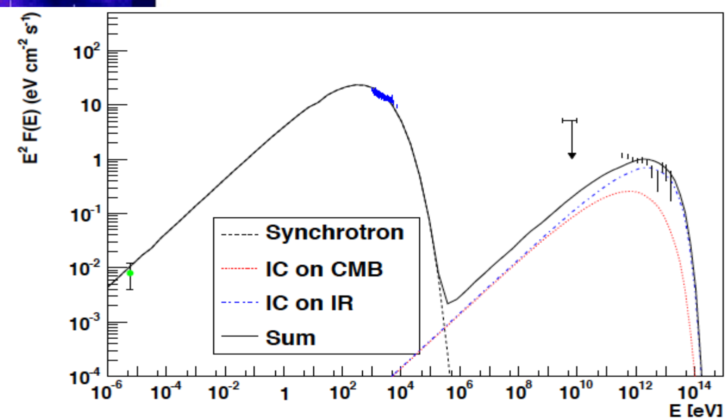


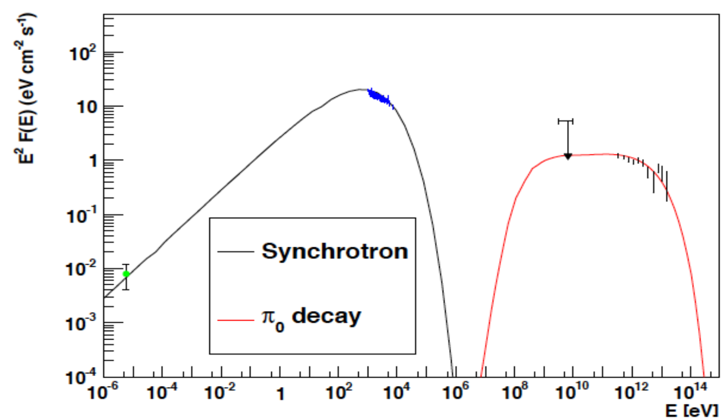


evidence favours shell-type SNR interpretation

- add to growing class consisting of
  RX J1713.7–3946
  RX J0852.0–4622
  SN 1006

difficult to model; electrons and protons
both have problems with minimal tuning





MAGIC
(Major Atmospheric Gamma Imaging Cherenkov telescope)

Germany

Spain

Italy

Poland

Bulgaria

Croatia

Finland

Associate Members

(~ 150 authors)

- two 17-m (227 m^2) parabolic (isochronous) telescopes
- 3.5^O (diameter) field-of-view
- 0.18^O @ 50 GeV → 0.08^O @ 1 TeV angular resolution (68% containment)
- sensitive to 1% Crab flux in 50 h at medium energies

MAGIC

- located at 2200 m on La Palma (Canary Islands)
- first telescope fully operational since 2004
- second 'clone' telescope operational since end of 2009
- MAGIC is the most technically aggressive of the big three
    - high quantum-efficiency PMTs
    - optical fibre analog signal transport
    - 2 GS/s FADC readout
    - ultra-light carbon-fibre structures for chasing gamma-ray bursts (GRBs)
        - fast slewing (< 20 s to arbitrary pointing)
    - low energy threshold (trigger and analysis)
        - big mirrors so more photons on-camera
        - isochronous so tight coincidences and short integration windows

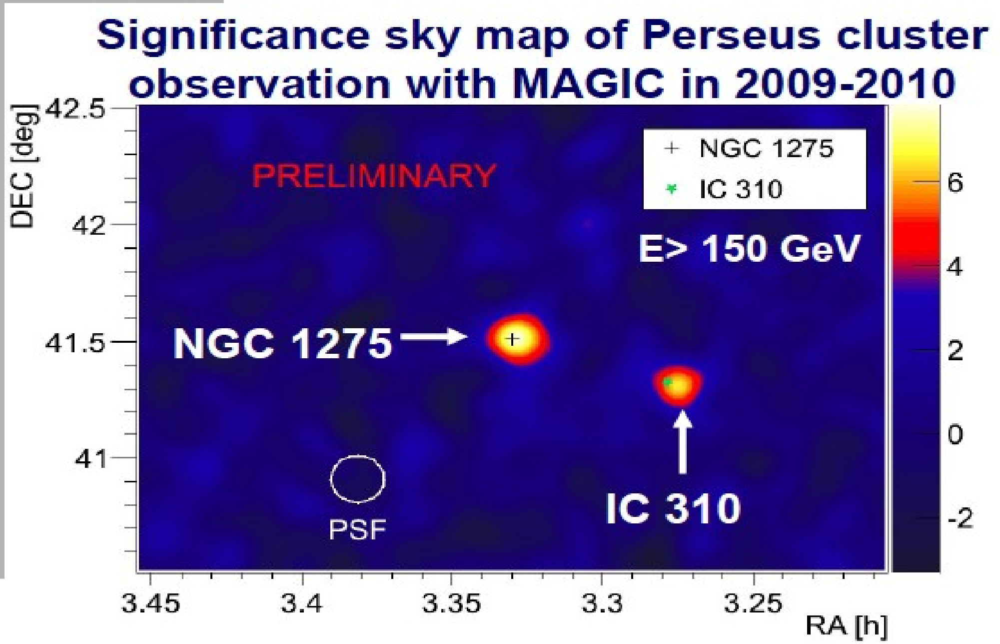
MAGIC

Detection of VHE emission from Head-tail Galaxy IC310 in the Perseus Cluster (ApJ Lett 723 L207)

Perseus Cluster (Abell 426)

- cluster of galaxies in the constellation Perseus
- one of the most massive objects in the universe
- thousands of galaxies immersed in a vast cloud of multimillion degree gas

- MAGIC detects two galaxies in VHE gamma rays
  - NGC 1275 (central galaxy of the cluster)
  - IC 310 (head-tail radio-galaxy)



MAGIC

IC 310

IC310

- along with NGC1265, one of the first two head-tail galaxies discovered by astronomers

- first head-tail to be seen at HE and VHE energies

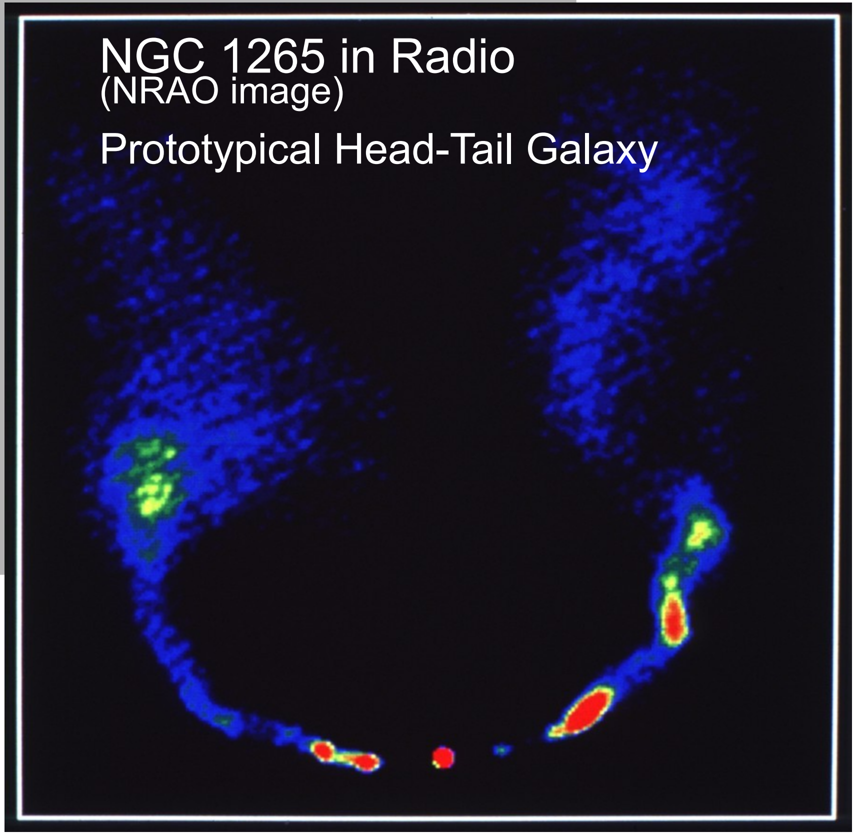
- first source to be discovered by stereo MAGIC

- head-tail: bright head, close to optical galaxy, fainter, elongated tail

- tail is illuminated (in radio) by radiation from particles accelerated by interactions with intracluster medium (ICM)

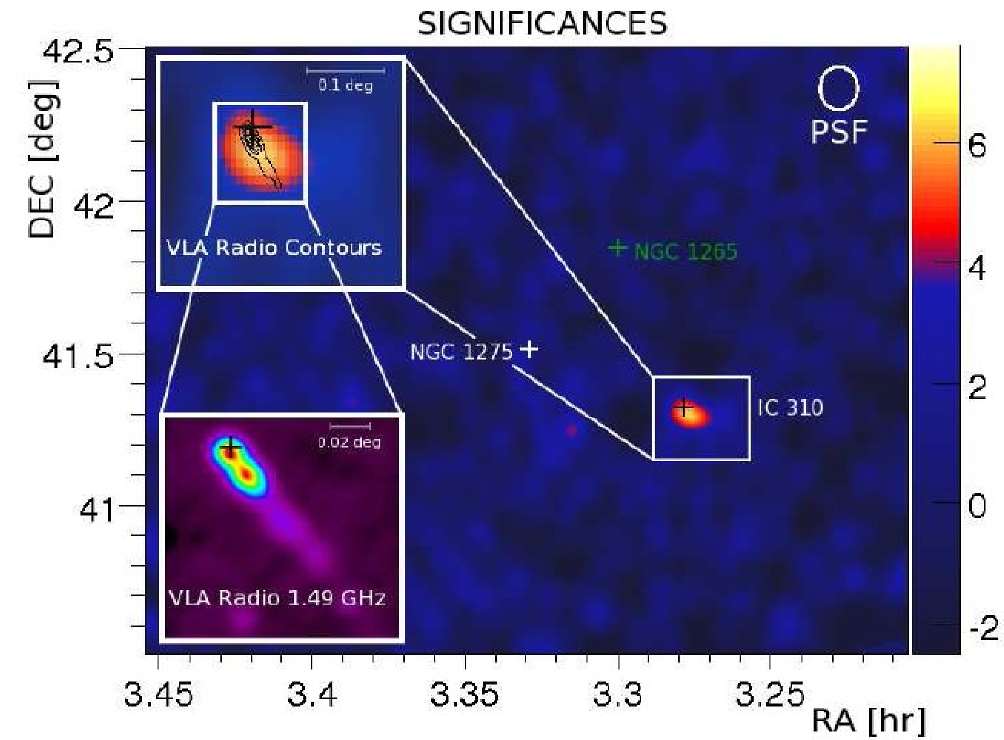
- X-ray data do not show the tail

- Fermi has detected IC310
    - 5 photons above 30 GeV (3 above 100)
    - no signal (0.1-1.0 GeV)

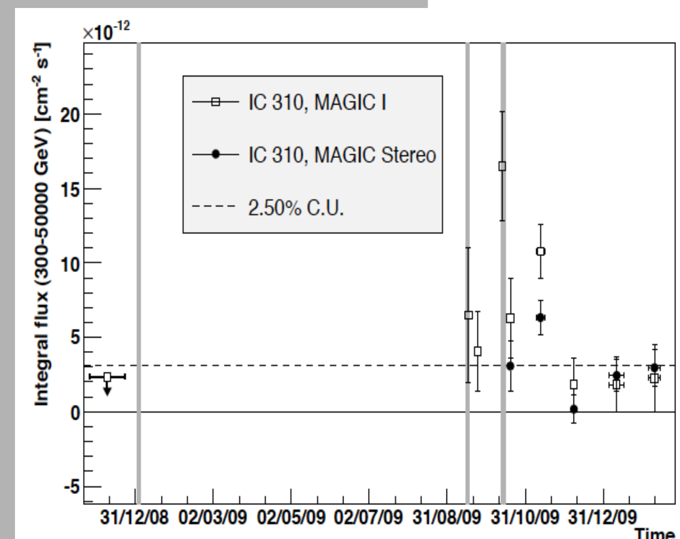


MAGIC

IC 310



- 94 h with MAGIC-1
- 21 h with MAGIC-2
- stereo results:
  106 excess events - 7.6 σ
  2.5% Crab flux above 300 GeV
  flat spectrum
  (power law with index -2.00+/-0.14)
- mono results in 2008 (11.2 h)
  no signal
  < 1.9% Crab UL (95% CL) -> time variability
- resolution not sufficient to tell if emission is from the tail or from the base of the jet (close to central engine)



production near the centre of the AGN is favoured
- time variability: one-week flare -> region < 2 10^{16} cm
- black-hole mass is 2.4 10^{8} solar masses
-> Schwarzschild Radius is 7 10^{13}cm)

(similar to M87 - see joint VERITAS, MAGIC, VLA paper in Science 324 p 444)

MAGIC

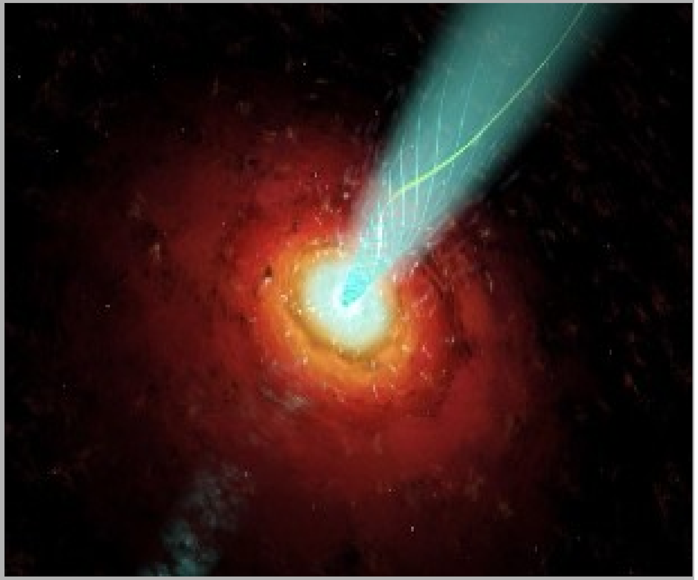
Flat-Spectrum Radio Quasars (FSRQs)

FSRQs

- AGNs with broad emission lines and 'big blue bump' in optical/UV part of spectrum likely from accretion disk

- only three detected at TeV energies (possible absorption on blue-bump photons)

- models are complicated and not entirely successful



- very far away:

  - study extra-galactic background light (EBL) via its effect on VHE gamma-ray propagation
    $\gamma_{TeV} + \gamma_{EBL} \rightarrow e+e-$

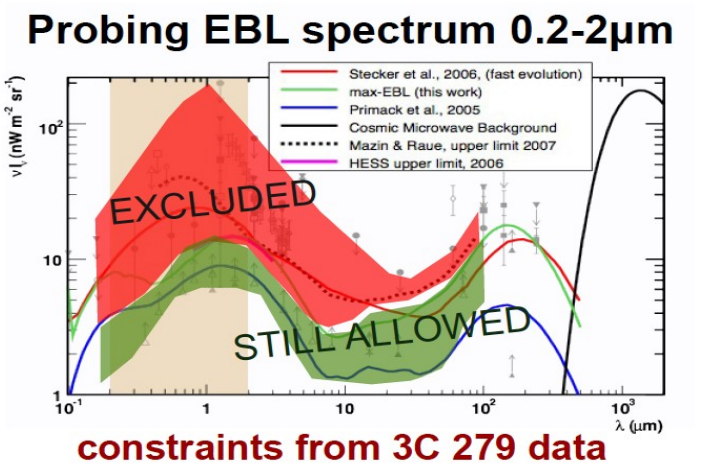
  - spectra should be suppressed at higher energies

  - use distortions to constrain models of EBL

MAGIC Flat-Spectrum Radio Quasars (FSRQs)

3C279

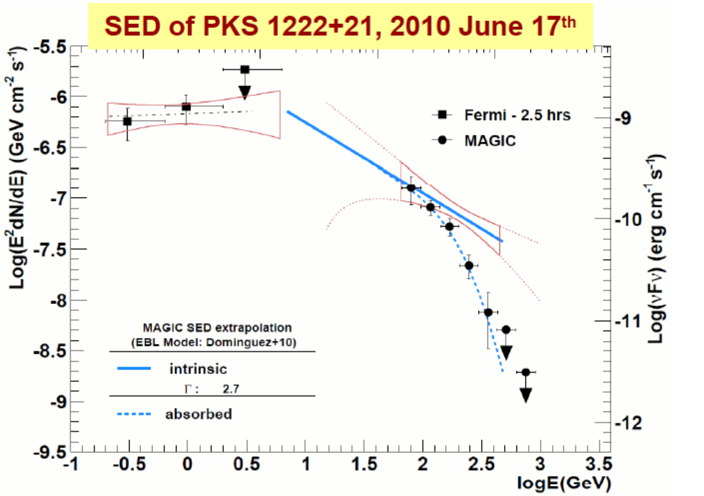
- discovered by MAGIC in Feb 2006 (single night flare)
- farthest TeV source so far (z=0.54)
  good for constraining EBL models
- flare detected on Jan 16, 2007
  (triggered by optical high state)



PKS 1222+21

- discovered by MAGIC in June 2010
- second farthest TeV source (z=0.432)
- rapid variability (doubling time = 8.6 min) → production close to centre?
- but no sign of cutoff in spectrum so production should be far from centre

→ challenge to models



VERITAS
(Very Energetic Radiation Imaging Telescope Array System)

USA

Canada

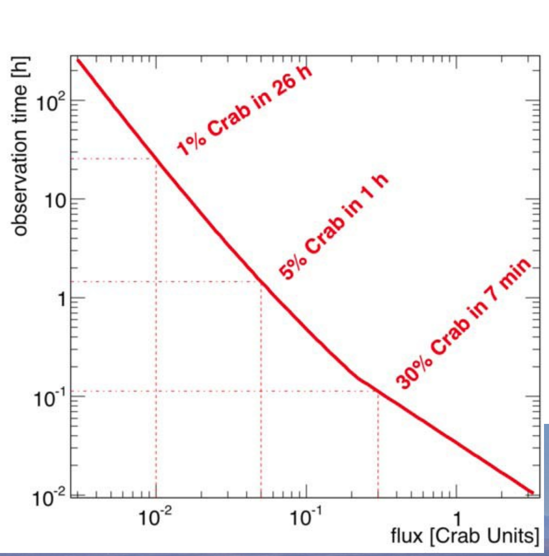
Ireland

United Kingdom

Associate Members

(~ 100 authors)

- four 12-m (113 m^2) Davies-Cotton telescopes
- 3.5^{O} (diameter) field-of-view
- angular resolution < 0.1^{O} (68% containment)
- energy resolution 15 – 25%
- energy range 100 GeV – 30 TeV
- 5 σ sensitivity – Crab Nebula 60 s
  - 1 % Crab < 30 h



VERITAS

located in southern Arizona

1300 m on Mt Hopkins (Whipple Observatory basecamp)

800 hours/year under dark skies

200 under partial moonlight

summer monsoon (July-August)
(handicap for galactic sources)

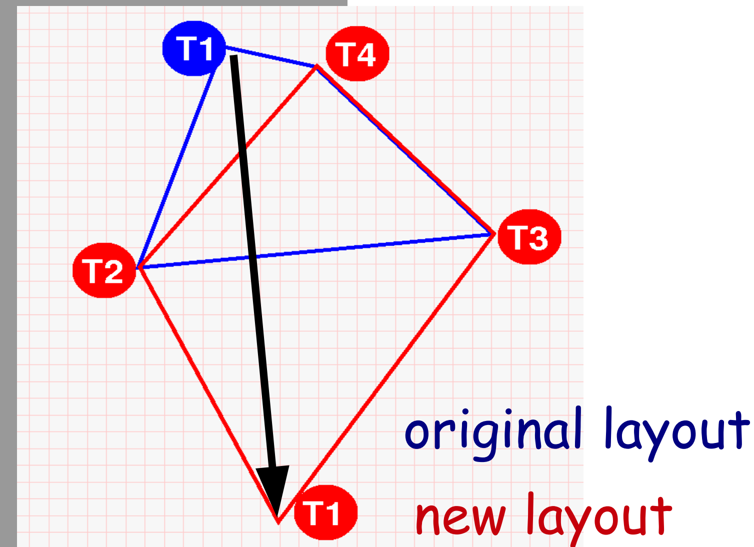
built between 2005 and 2007
(prototype in 2003)

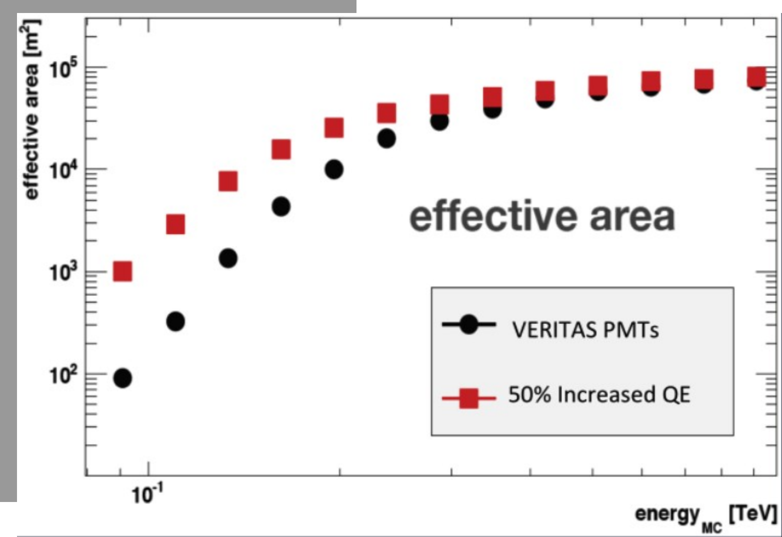
fully operational since September 2007

T1 moved during summer 2009
to improve sensitivity

> 40 sources detected so far
(8 classes)

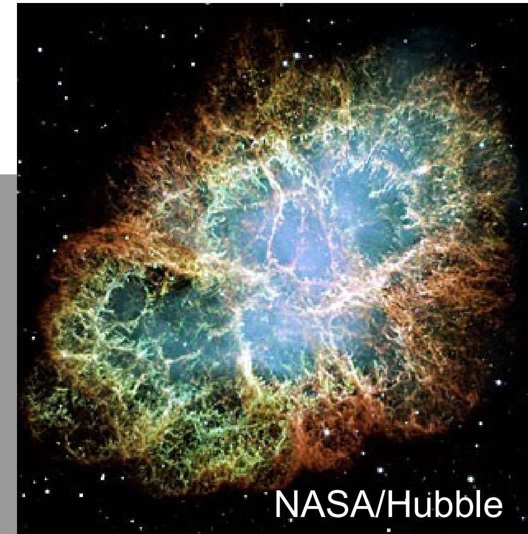
2012 – upgrade to higher QE PMTs





VERITAS

Detection of Crab Pulsar above 100 GeV



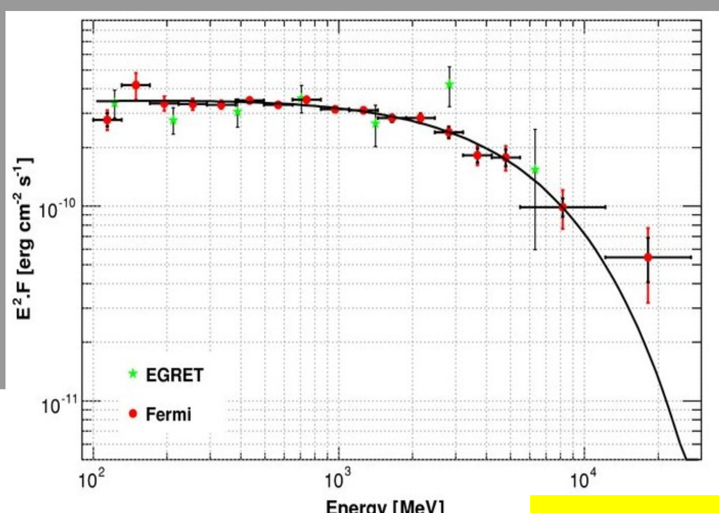
Crab Pulsar

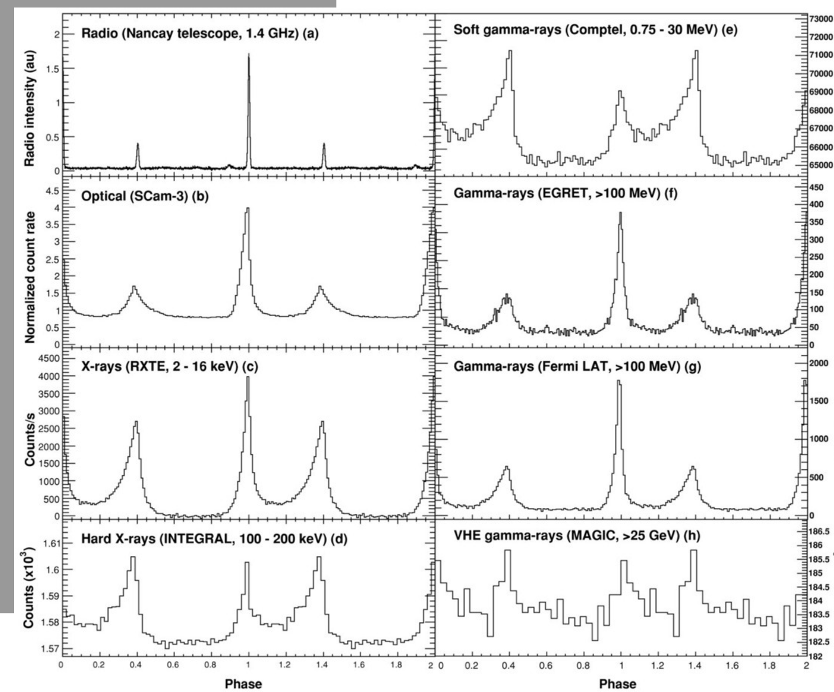
remnant of SN in 1054

seen at all wavelengths

most energetic pulsar
4.6×10^{38} erg s^{-1}

one of the brightest in gamma rays





Fermi-LAT energy spectrum suggests that there are few gamma rays above ~ 10 GeV

VERITAS

Detection of Crab Pulsar above 100 GeV

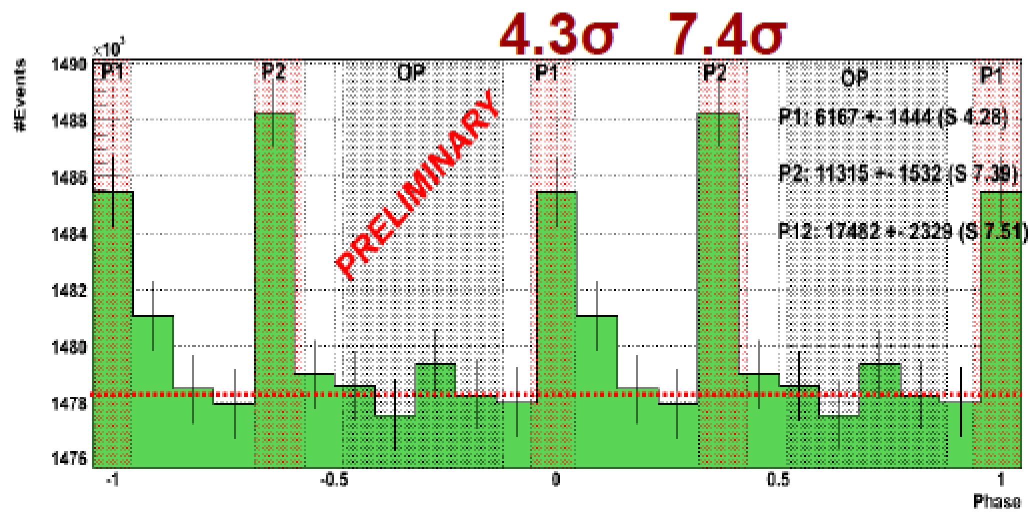
MAGIC

detection at E > 25 GeV

hints at E > 60 GeV

MAGIC: E >25 GeV

59 h of data from Oct-2007 to Jan-2009



VERITAS

Detection of Crab Pulsar above 100 GeV

VERITAS data:

2007-2009	45 hours
2010	62

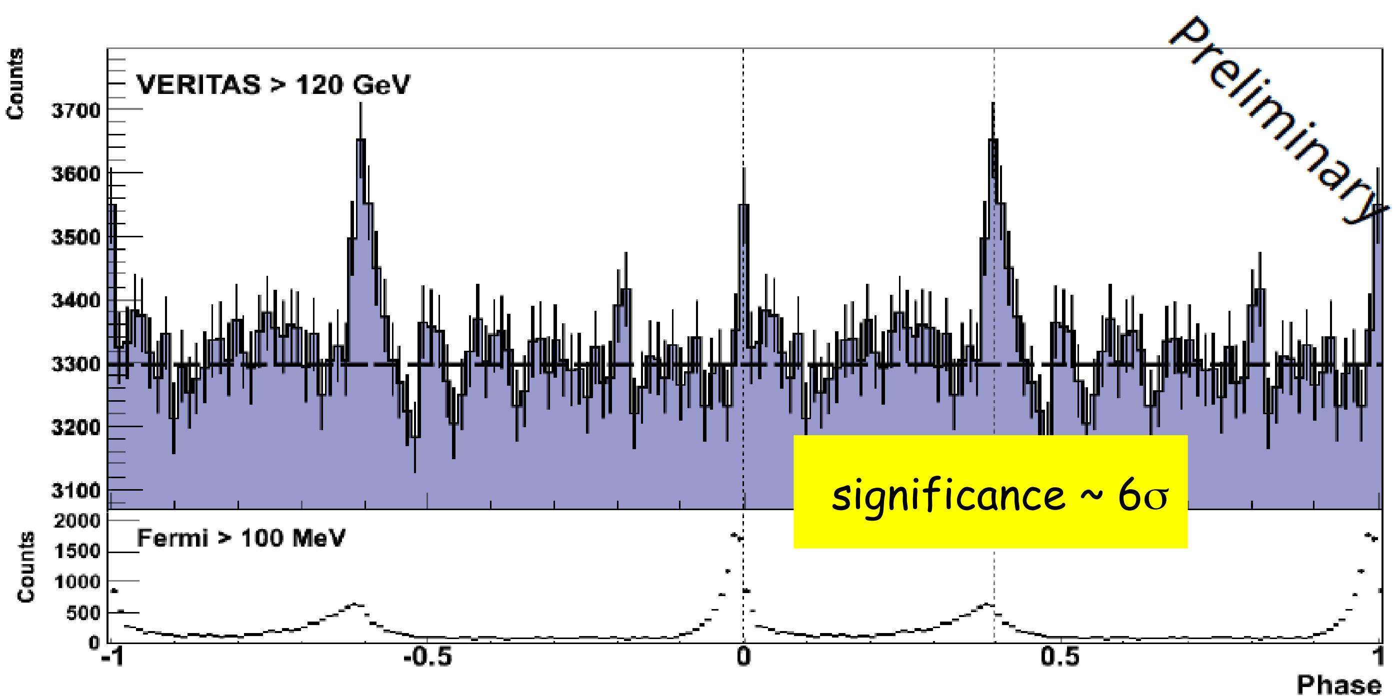
4 telescopes
zenith angle < 25 °

VERITAS analysis:

two independent analysis packages

analysis optimized for weak, soft source
- few-percent Crab flux
- power-law with index -4

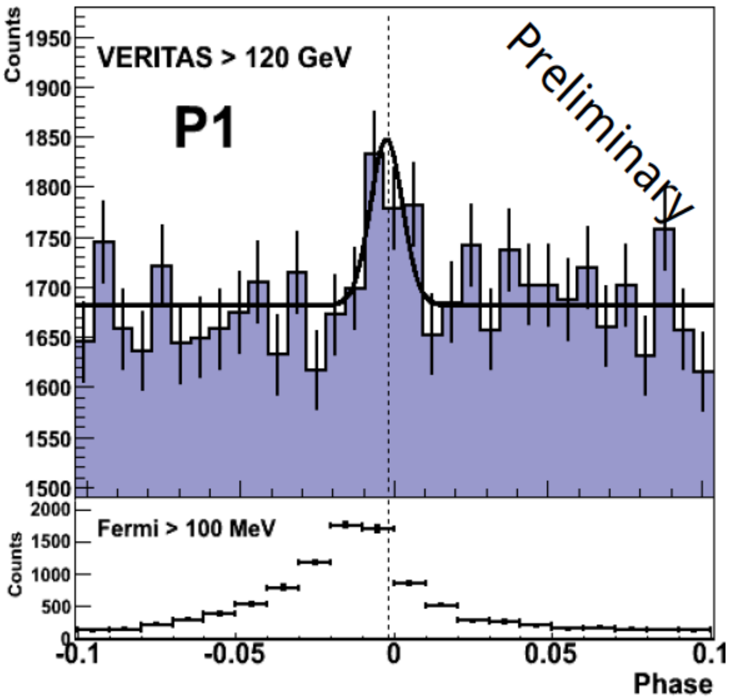
analysis threshold: 120 GeV

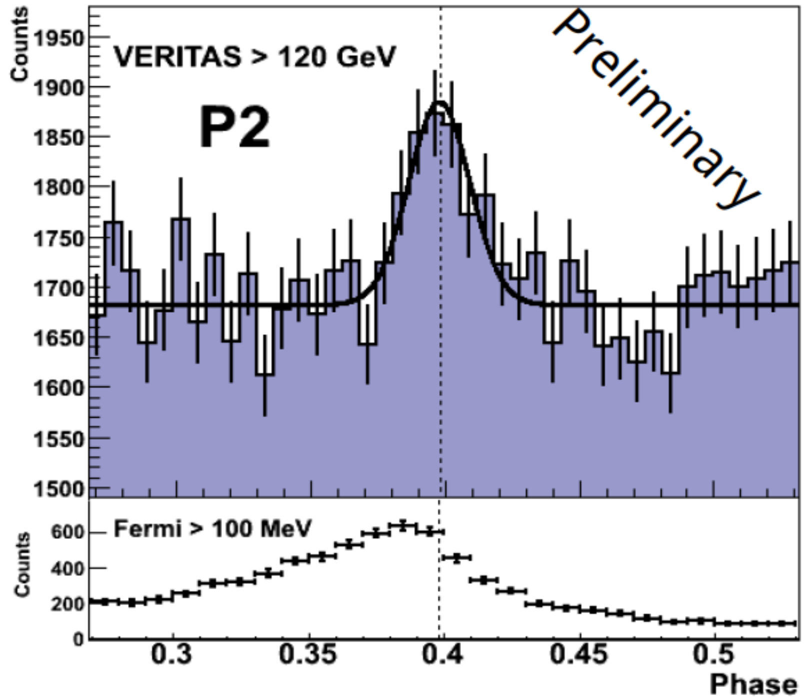


VERITAS

Detection of Crab Pulsar above 100 GeV

Pulse shapes evolve with energy --> useful clues/constraints for model builders





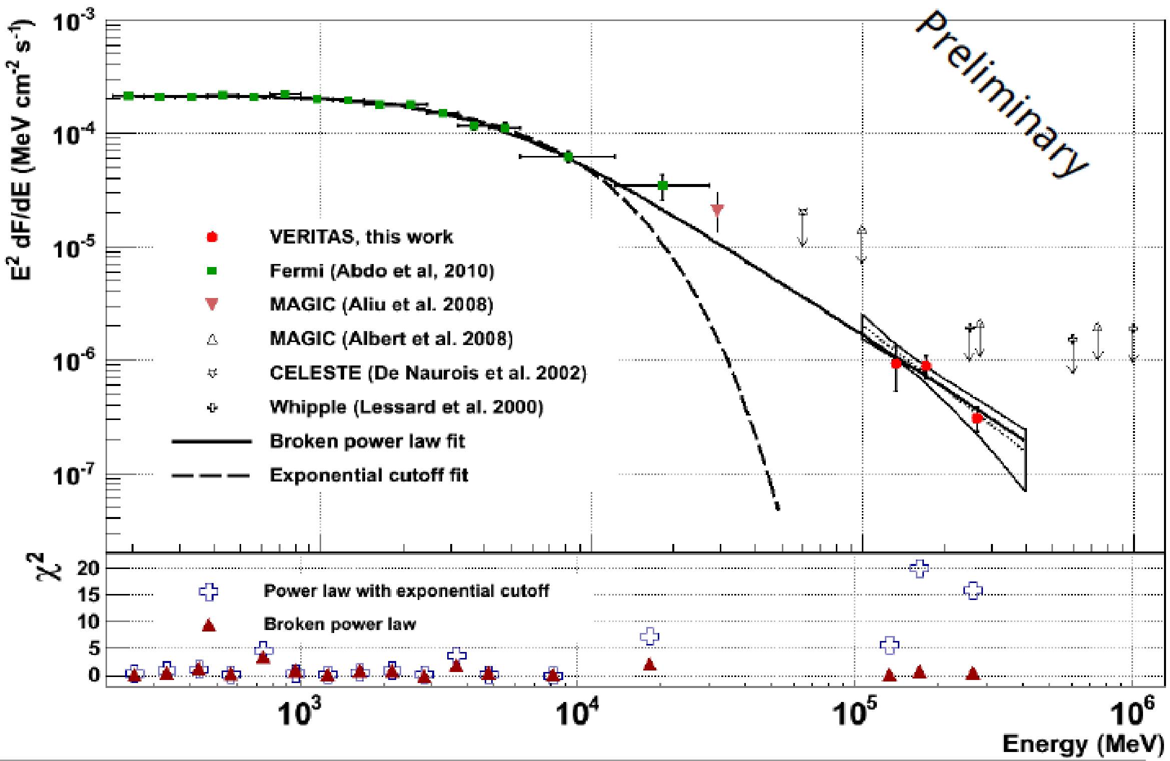
Gaussian fits:		mean	FWHM
	P1	-0.0023 +/- 0.0020	0.0132 +/- 0.0035
	P2	0.3975 0.0020	0.0268 0.0052

means match radio data – mismatch Fermi but likely an analysis/ephemeris effect

widths are 5 times narrower in VERITAS data than Fermi data → emission region tapers?

VERITAS

Detection of Crab Pulsar above 100 GeV

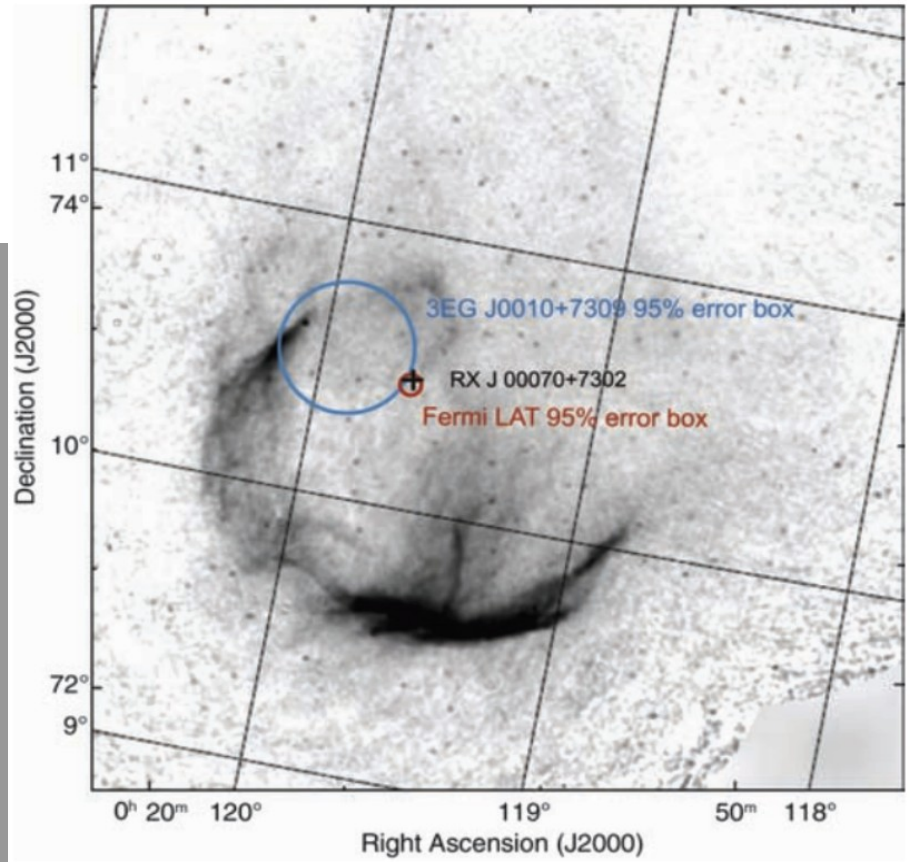


energy spectrum (combine P1 and P2)

- no exponential cutoff – power law with Γ = -3.8 +/- 0.5 +/- 0.3
- non-zero flux above 100 GeV (1% of Nebula at 150 GeV)
- curvature radiation cannot be the dominant mechanism
- the paradigm is shifting – stay tuned

VERITAS

CTA-1



Supernova Remnant (SNR)

- radio shell (1.8^{o} diameter)
- centre filled with X-ray emission

Pulsar

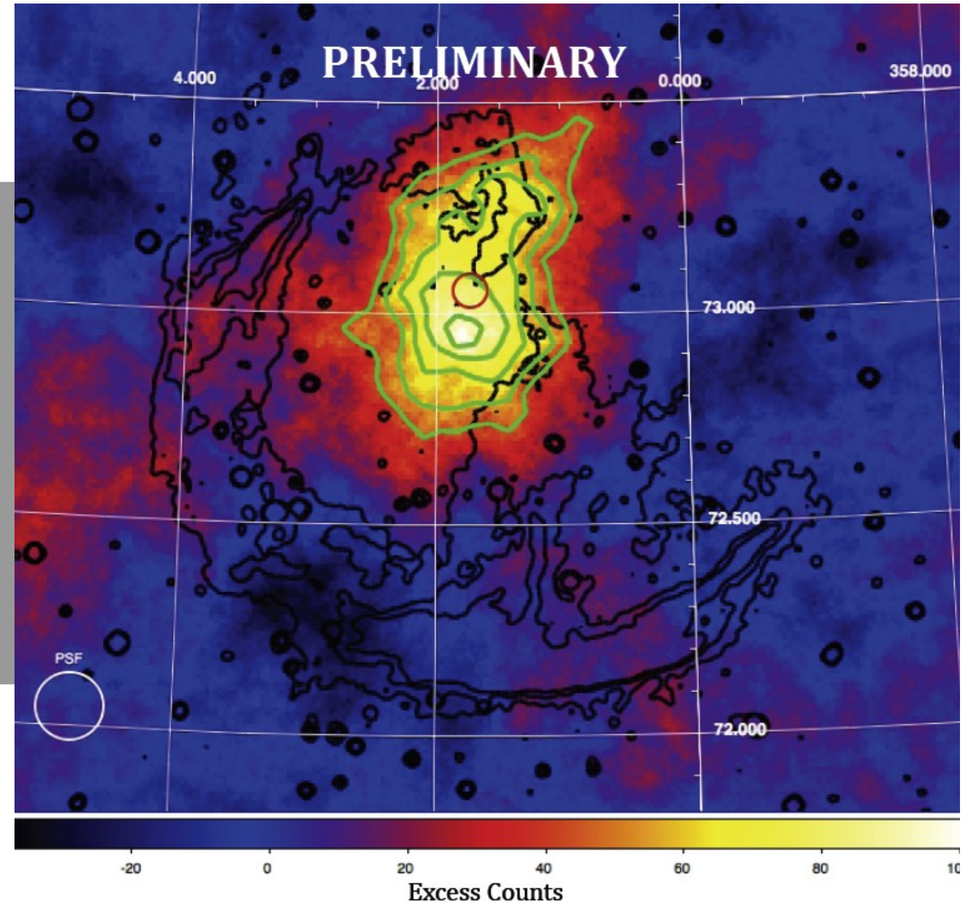
- discovered by Fermi-LAT (Abdo et al. 2008)
- blind search on first 4 months of data
- T = 316.9 ms
- E_{cutoff} ~ 5 GeV
- detected in X-rays by Chandra (Caraveo et al. 2010)

VERITAS

CTA-1

VERITAS Detection

- 26.5 hours (Oct 2010 -Jan 2011)
- 6.2σ detection, post trials
- flux = 4% Crab for E > 1 TeV
- very likely a young pulsar wind nebula (PWN)



green contours: 3 – 7σ – VERITAS

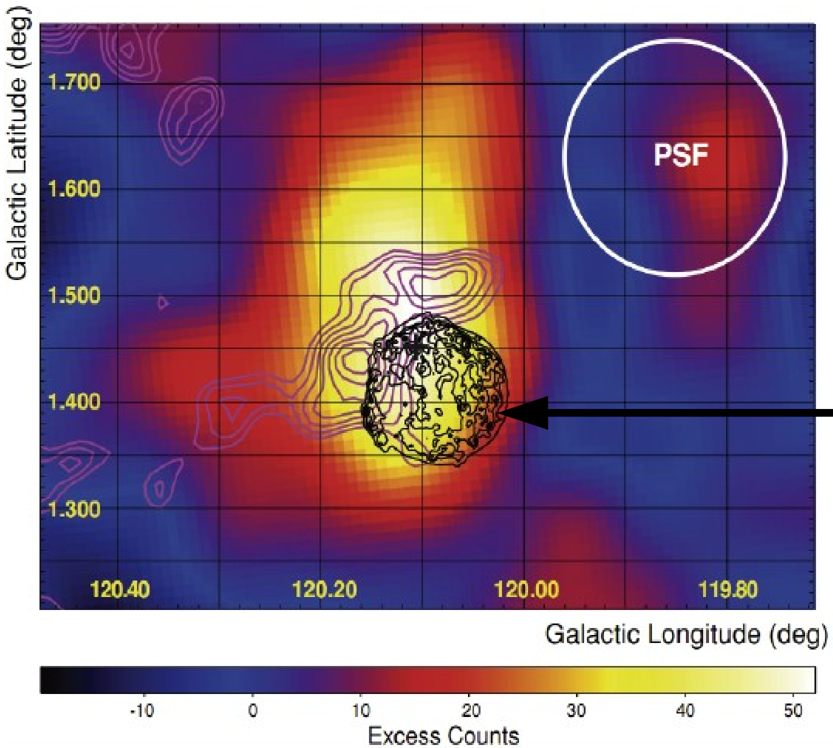
black contours: radio 1420 MHz – T. Landecker

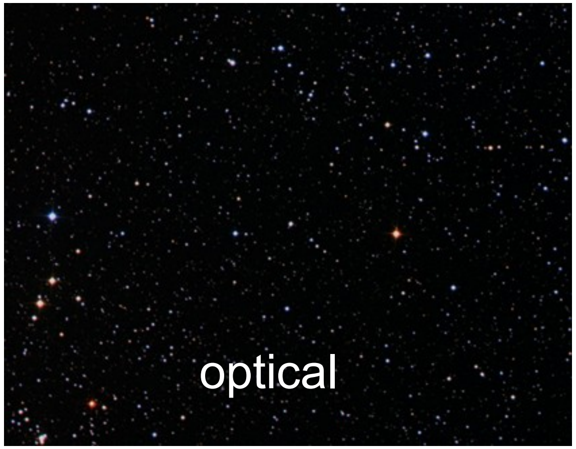
red circle: Fermi-LAT error circle

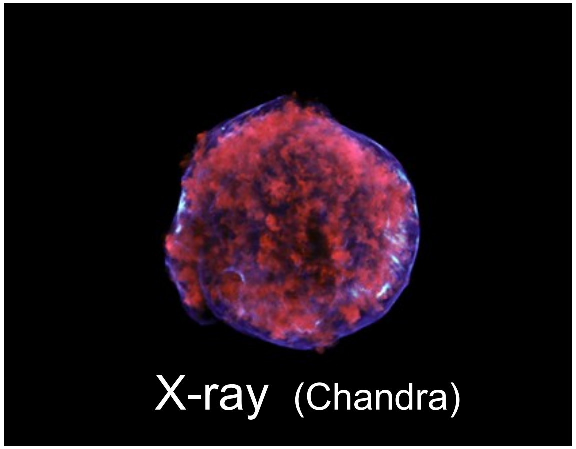
VERITAS

Detection of Tycho's Supernova Remnant

- remnant of a type 1A supernova event in 1572





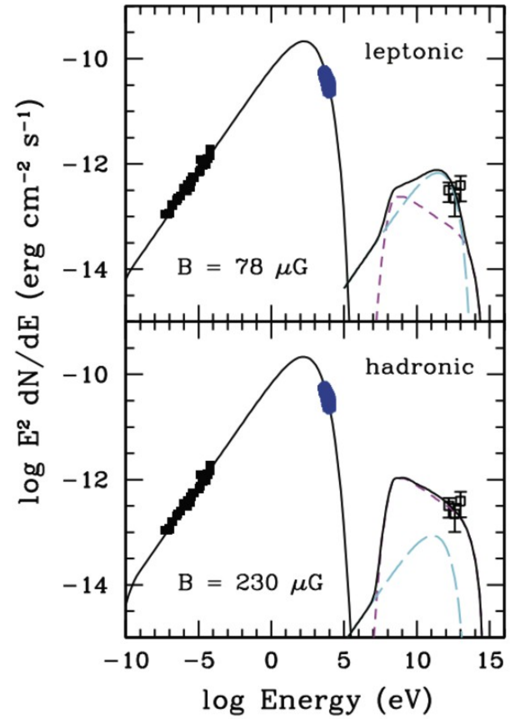


- VERITAS detection (2010):
  - 68 hours - 5σ
  - power law - $\Gamma = 1.95 +/- 0.51_{stat} +/- 0.30_{syst}$

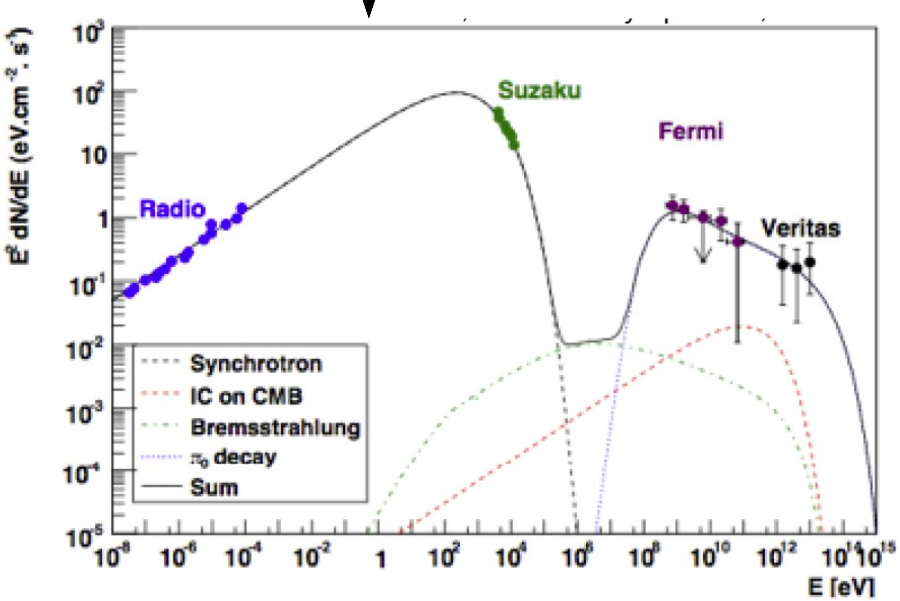
VERITAS

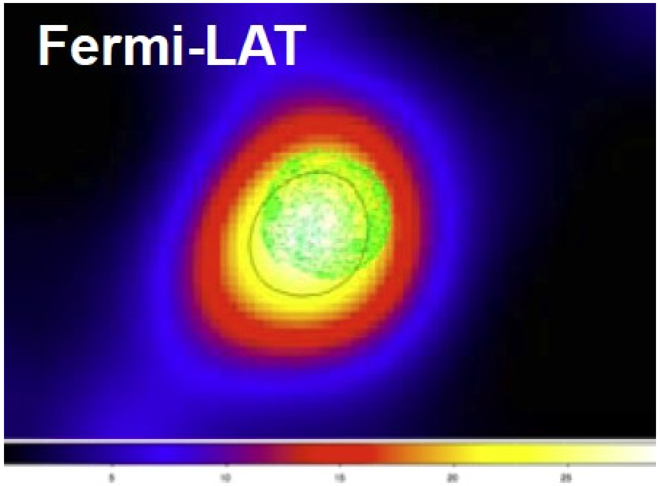
Detection of Tycho's Supernova Remnant

- VERITAS and radio/X-ray data are consistent with either leptonic or hadronic origin of TeV emission



- new results from Fermi-LAT favour hadronic
(M. Naumann-Godo, 3rd Fermi Symposium, Rome 2011)



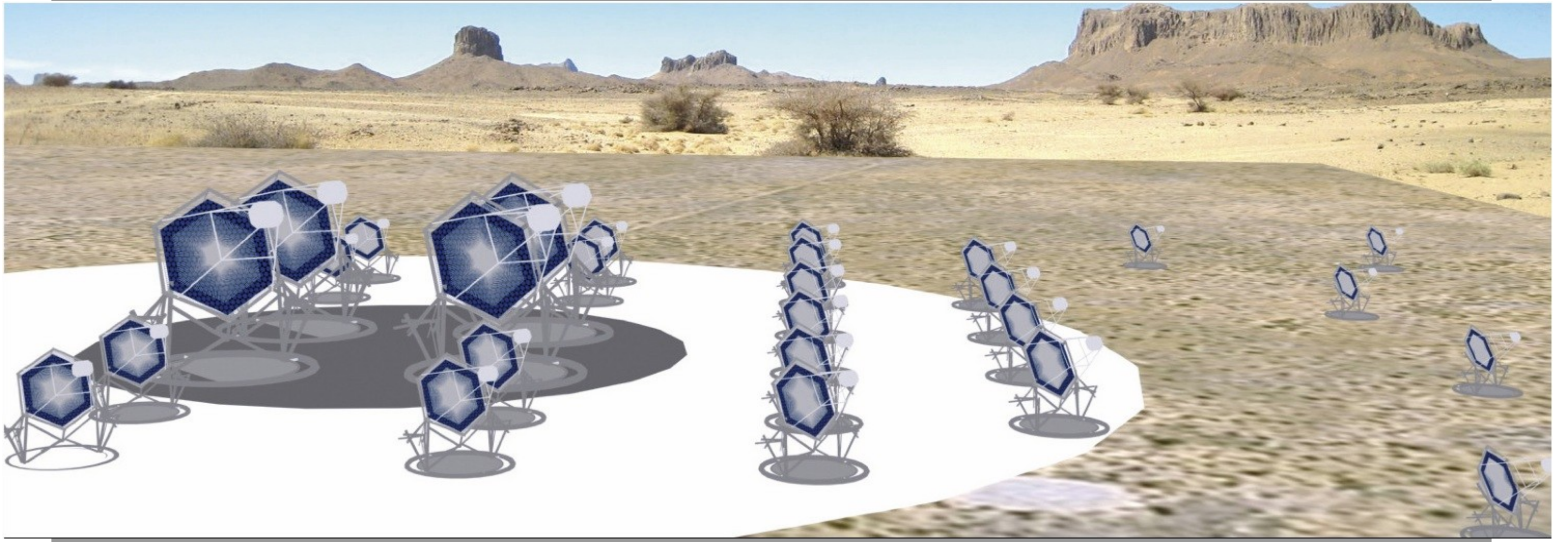


CTA – the future

- VHE gamma-ray astronomy has a well-defined and promising near-term future with VERITAS, MAGIC and H.E.S.S.

- the next-generation instrument is already in the design phase

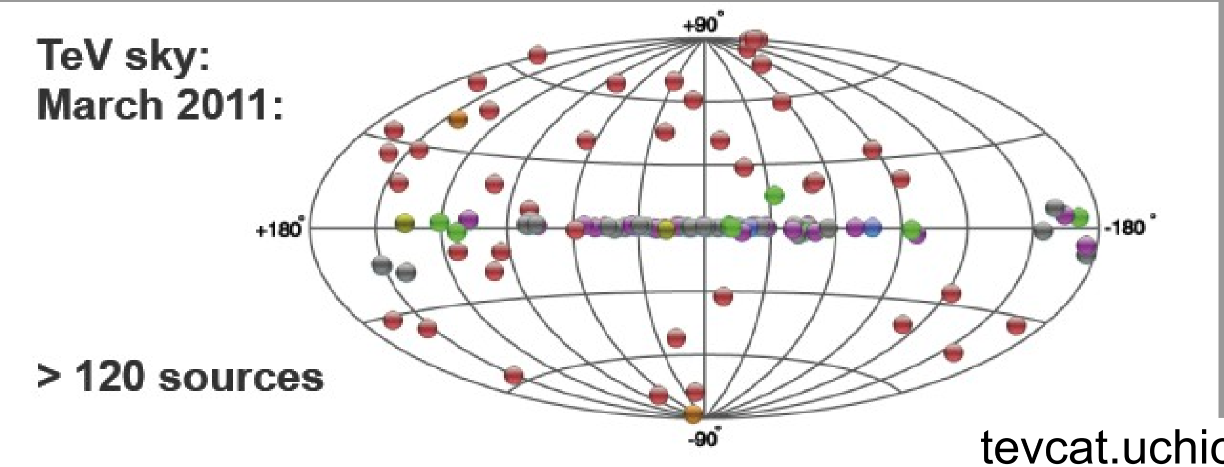
- Cherenkov Telescope Array (CTA)



see www.cta-observatory.org for details

Conclusions

- TeV gamma-ray astronomy is in a golden age
    - new instruments/improving analysis techniques
    - pathfinder guidance from Fermi
    - near-term upgrades to improve sensitivity
    - multi-wavelength campaigns
- TeV sky is highly populated with a variety of sources; strong, weak, stable, time-dependent → lots of physics



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