Very High Energy Astrophysics

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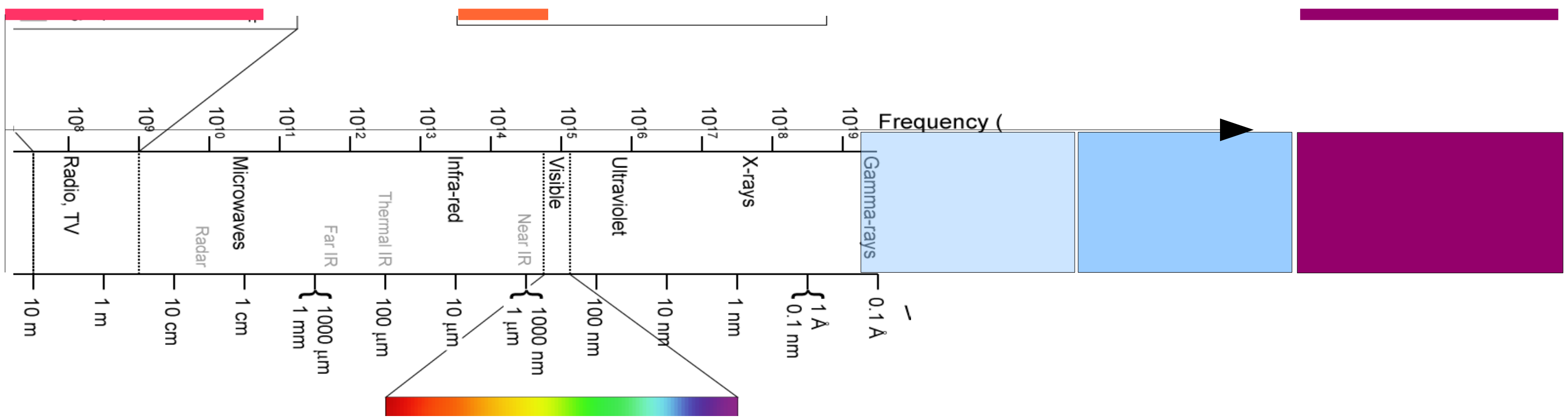
What is VHE Astrophysics?
Technical Aspects
Galactic sources

Extragalactic studies
The near future
CTA

What is 'Very High Energy' ?



Gamma-ray astrophysics covers ~9 orders of magnitude in energy

Low-E gamma-rays:	511 keV – 100 MeV	INTEGRAL, CGRO
High-E gamma-rays:	100 MeV – 30 GeV	FGST, AGILE
Very High Energy (VHE):	30 GeV – 100 TeV	IACTs, WCTs

Why do we care?

Curiosity of explorers: What are VHE fluxes of sources?

Are there any new classes of sources in the VHE sky?
(Many previously unknown phenomena in other wavebands)

Physical models of non-thermal sources can be tested and constrained using measurements (and limits) at VHE.
(Synchrotron-models are often not well constrained, joint studies of synchrotron and IC processes help)

99-year old mystery of High-Energy Cosmic Radiation.
CR include α, β, γ-rays, relativistic hadrons and leptons generate VHE photons by a number of processes.

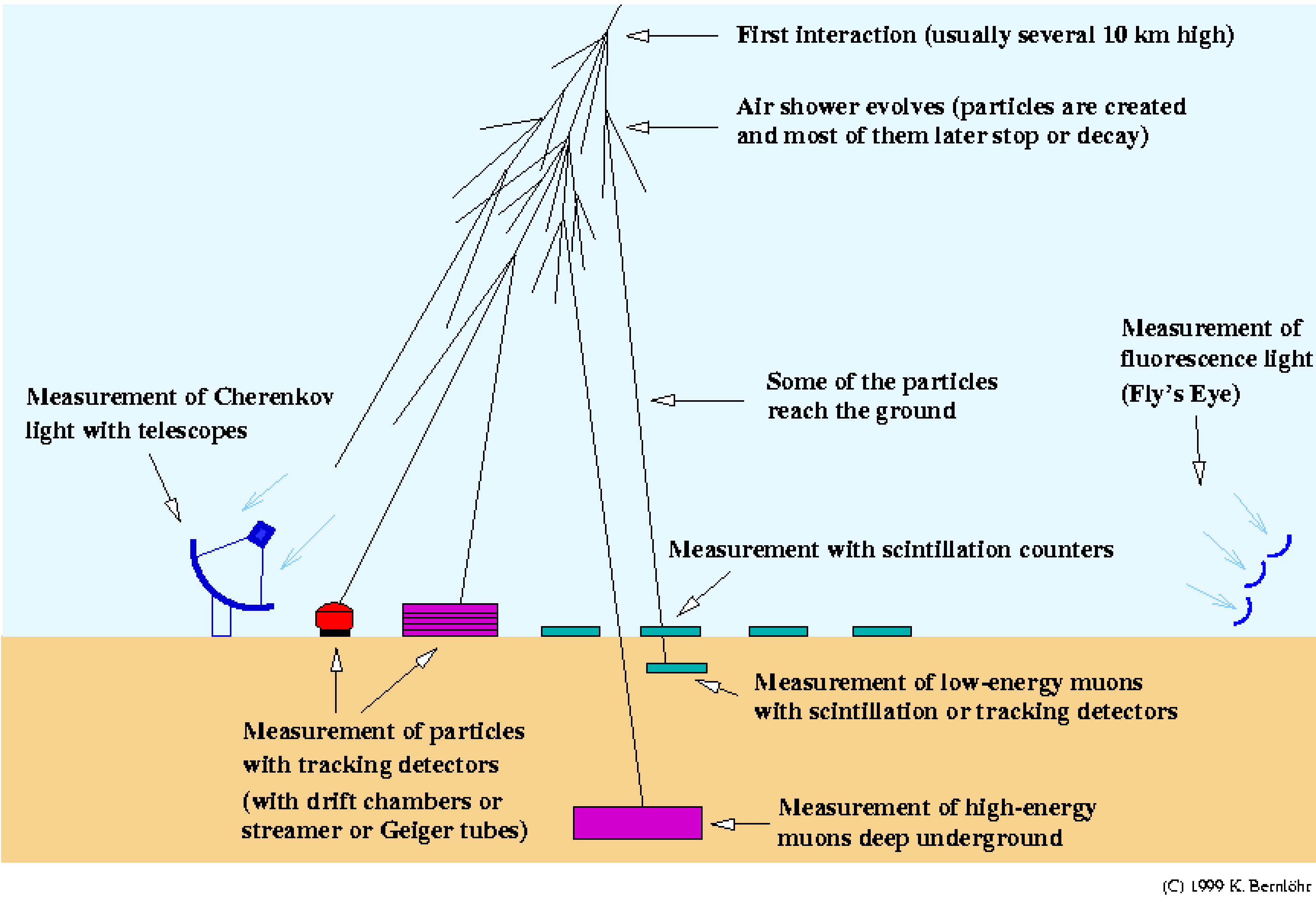
How are VHE photons detected?

Above a few MeV high energy photons
are detected by pair conversion.

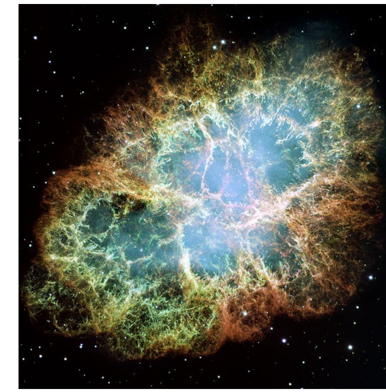
EGRET (spark chamber), Fermi-LAT (silicon strips).

The atmosphere may also be used as a detector:
(1) VHE photons spark atmospheric showers;
(2) Secondary particles may be detected directly;
(3) Relativistic secondary particles emit Cerenkov radiation

Measuring Air Showers



Photon Fluxes



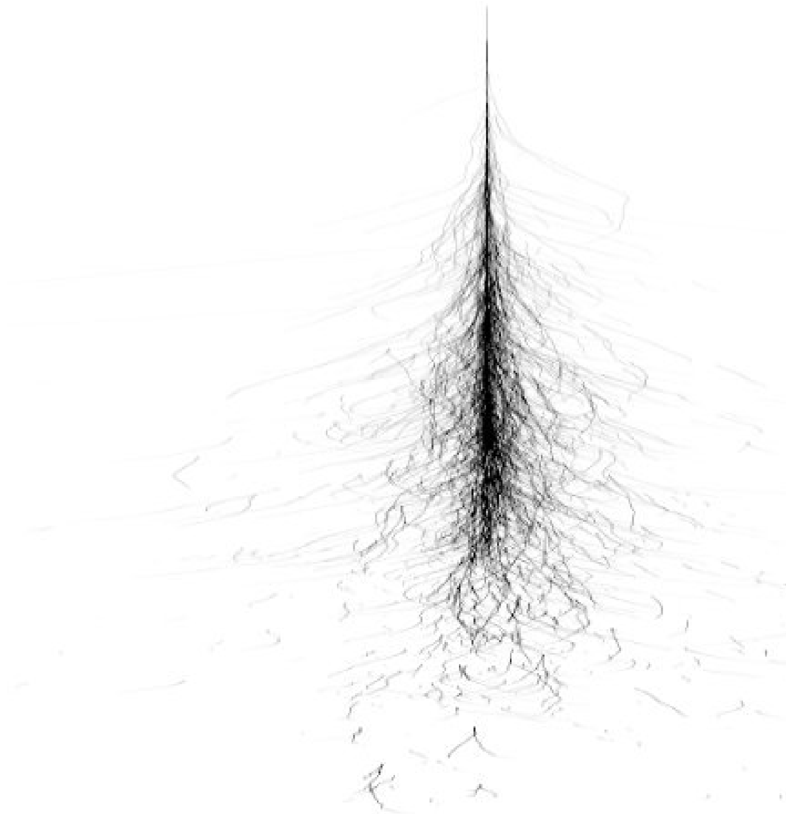
The 'standard' candle
of high energy astrophysics
is the Crab SNR
(SN 1054)

GeV domain: 3 photons/day/sq.m./GeV
(Fermi-LAT has an effective area of 1 sq.m.)

Spectra fall as $N \sim E^{-2}$

$\nu S \sim 3\ 10^{-13}$ erg cm^{-2} s^{-1}
at 1 TeV
~ 1 photon/yr/sq.m./TeV
(not possible with space-borne detectors)

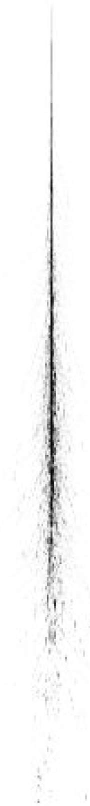
Cerenkov Detection



1TeV Photons interact in air
at an altitude of ~ 10 km,
launching an atmospheric shower.

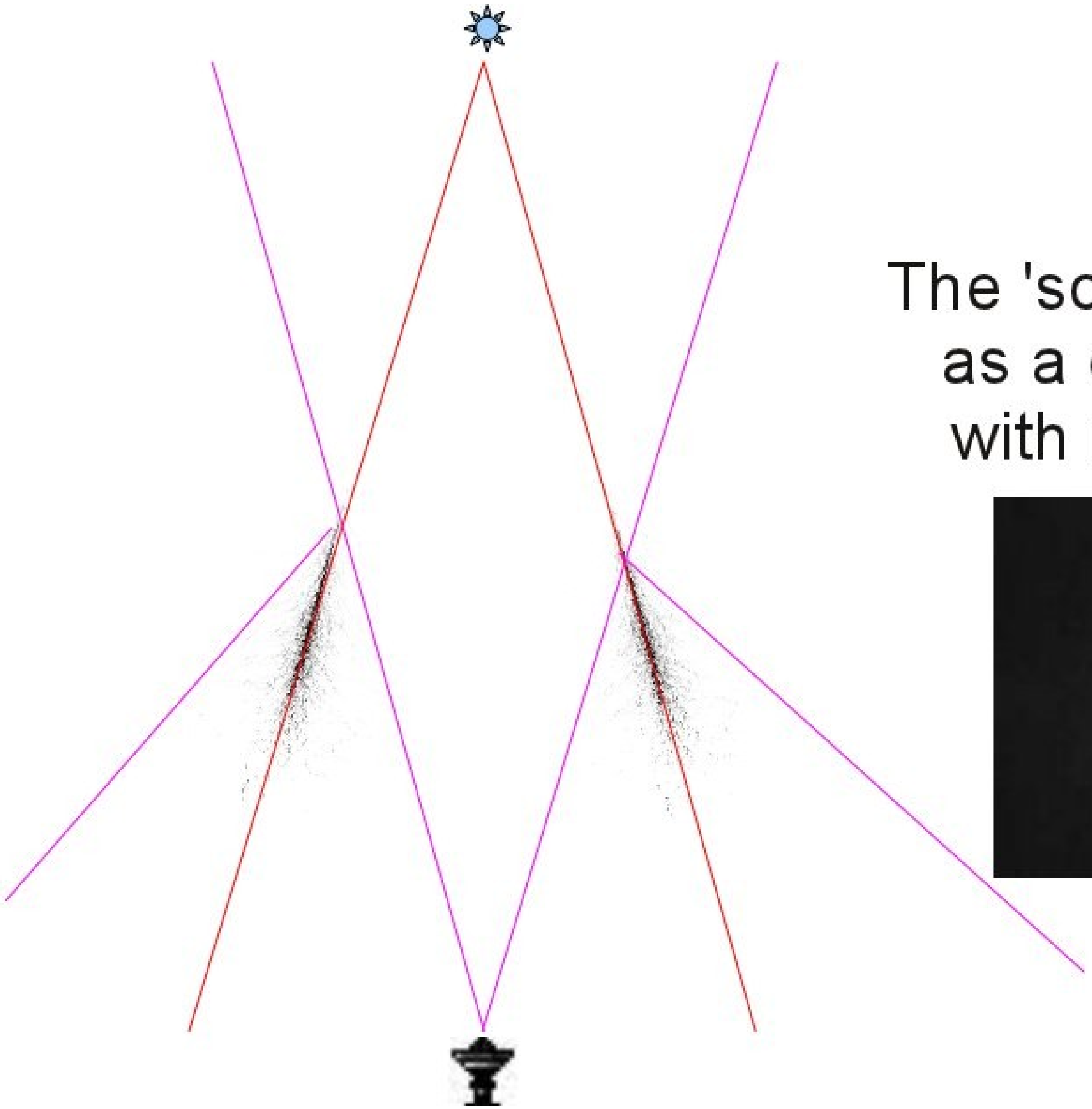
Secondary particles emit
Cerenkov radiation within
cone of opening angle ~ 1°.

← Stretched 1:20 True scaling →

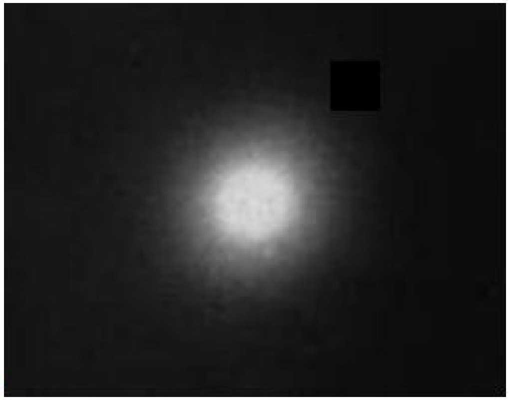


All shower images: K. Bernlöhr, MPIK

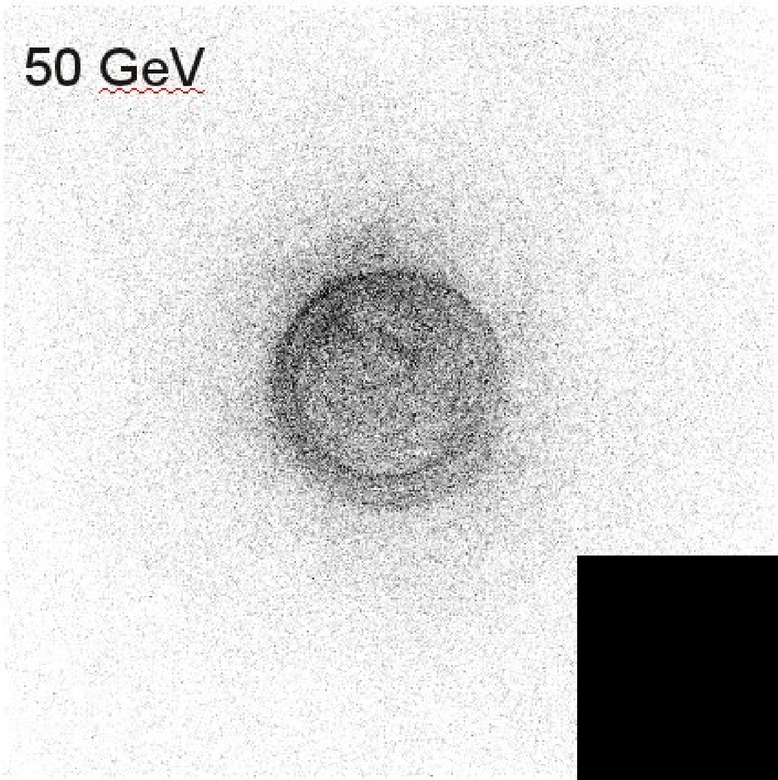
The image in the sky

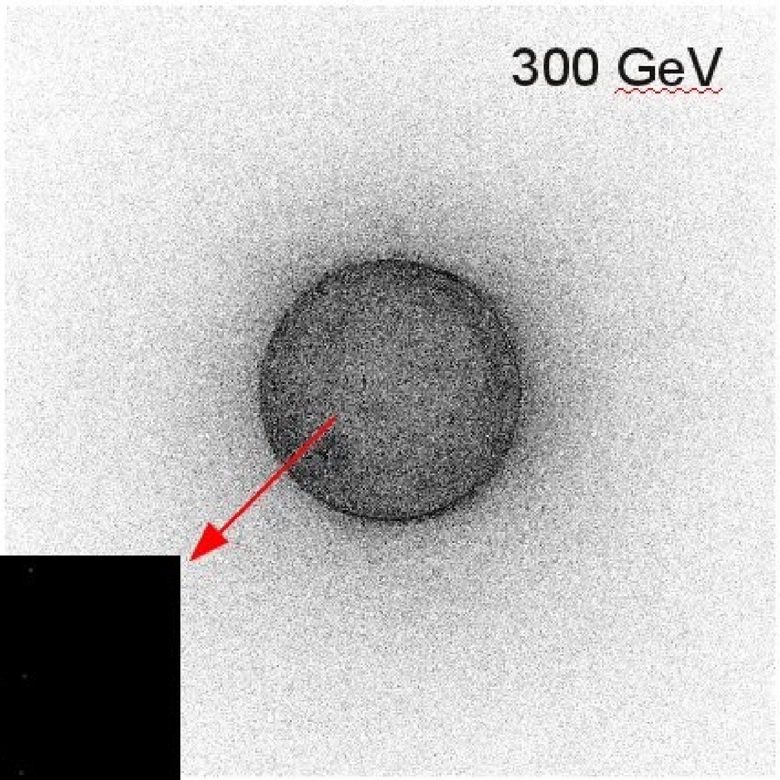


The 'source' appears as a diffuse 'halo' with radius r ~ 1°.



The image on the ground



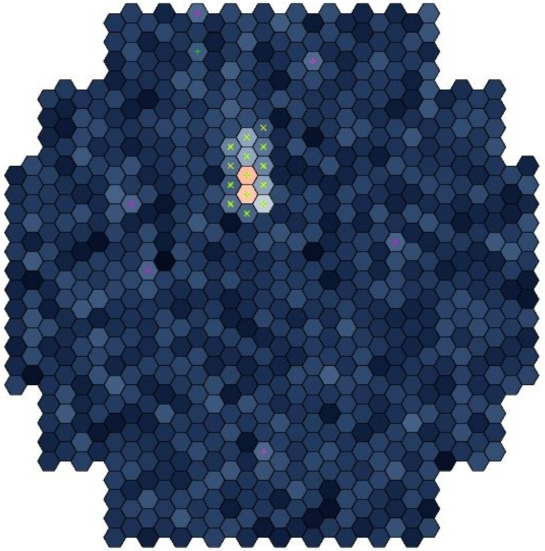


The image in the camera

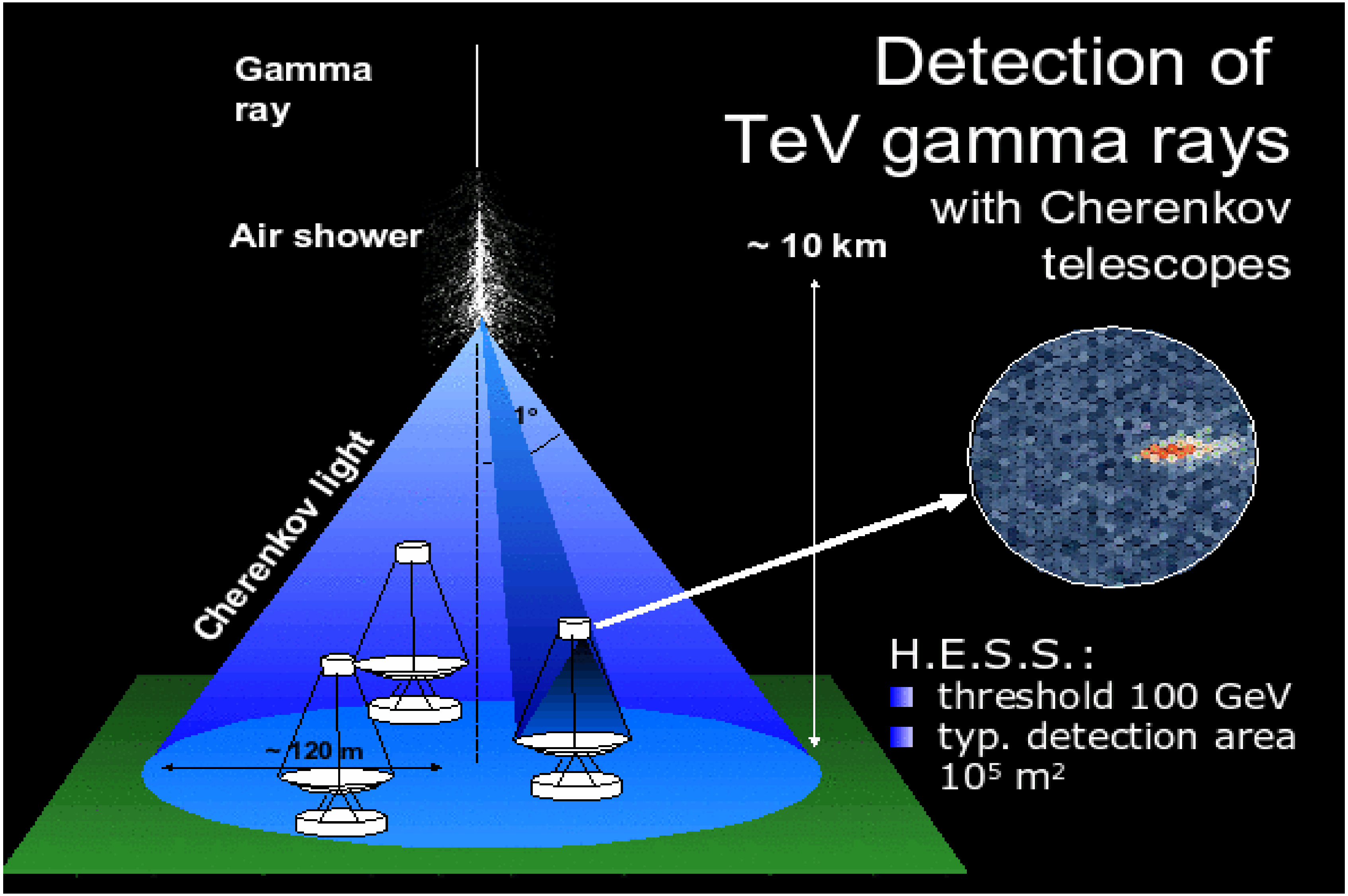
The Cerenkov (optical) halo around the line-of-sight towards a VHE gamma-ray source is very faint.

1) The shower front is thin, the footprint is illuminated for a few nsec, nsec-sampling of images.

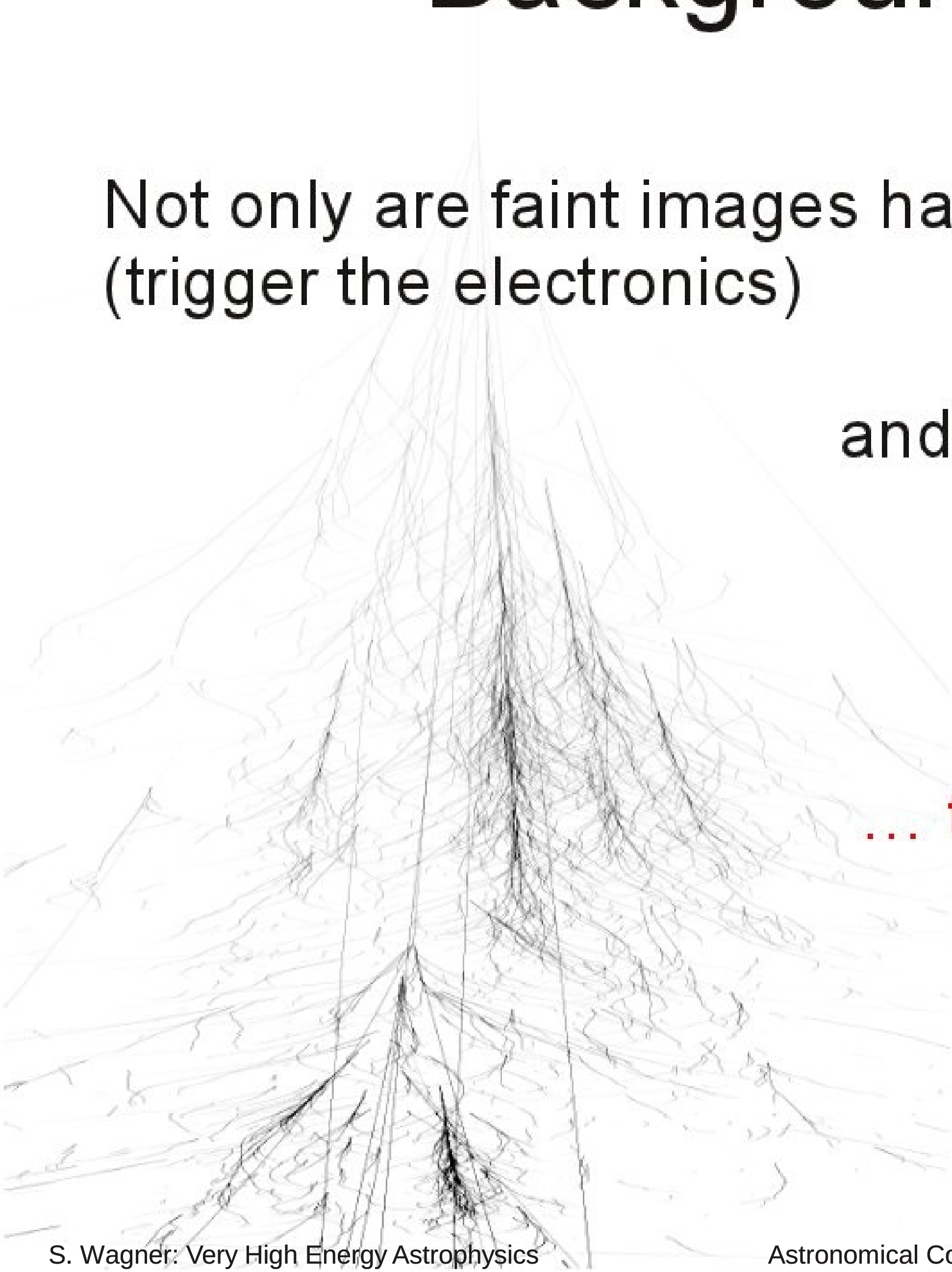
2) Recording of individual photons; each shower image samples a fraction of the time-integrated Cerenkov cone.



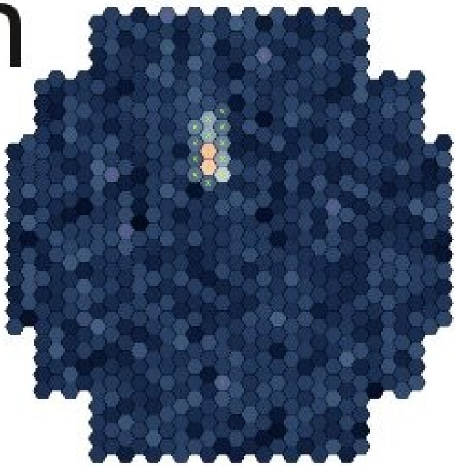
Stereoscopic imaging



Background subtraction



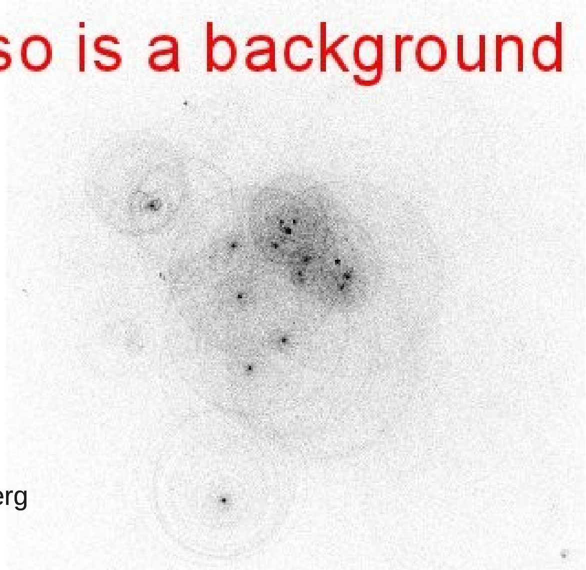
Not only are faint images hard to identify
(trigger the electronics)



and even more difficult to reconstruct
(uncertainty in flux, position)

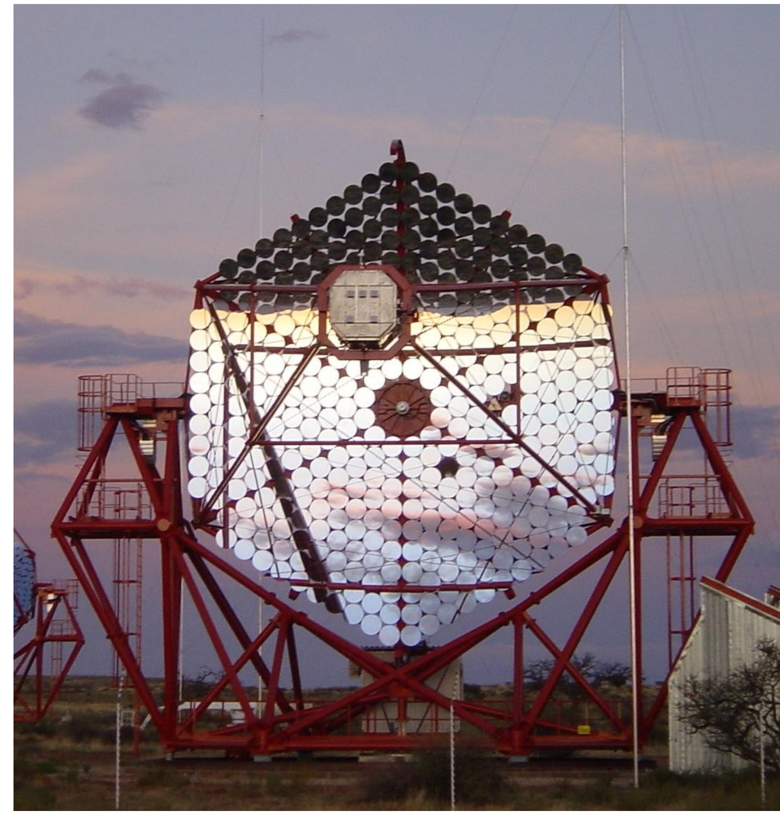
against night-sky fluctuations...

... there also is a background of CRs

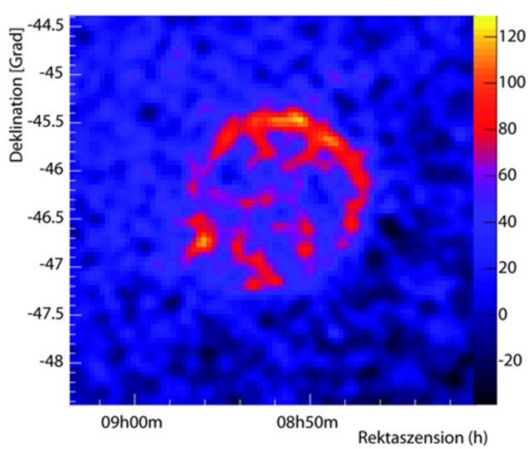


Imaging Cerenkov Astronomy

Sample Camera images;
Identify shower;
Trigger other telescopes;
Record images;
Measure image parameters;
Discriminate photons;
Reconstruct shower
(energy, location, time);
→ Record **one** VHE photon
(every 100 sec)



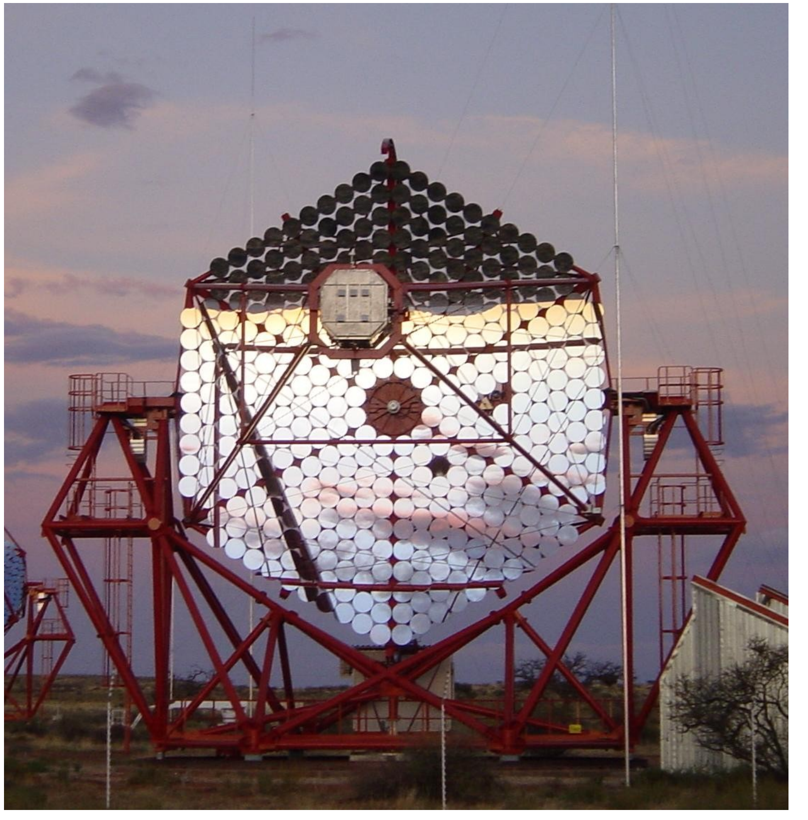
Integrate images:



The H.E.S.S. array

4 telescopes
108 sq.m. mirror area each
382 movable mirrors
120 m square array
960 PMT cameras
60t each

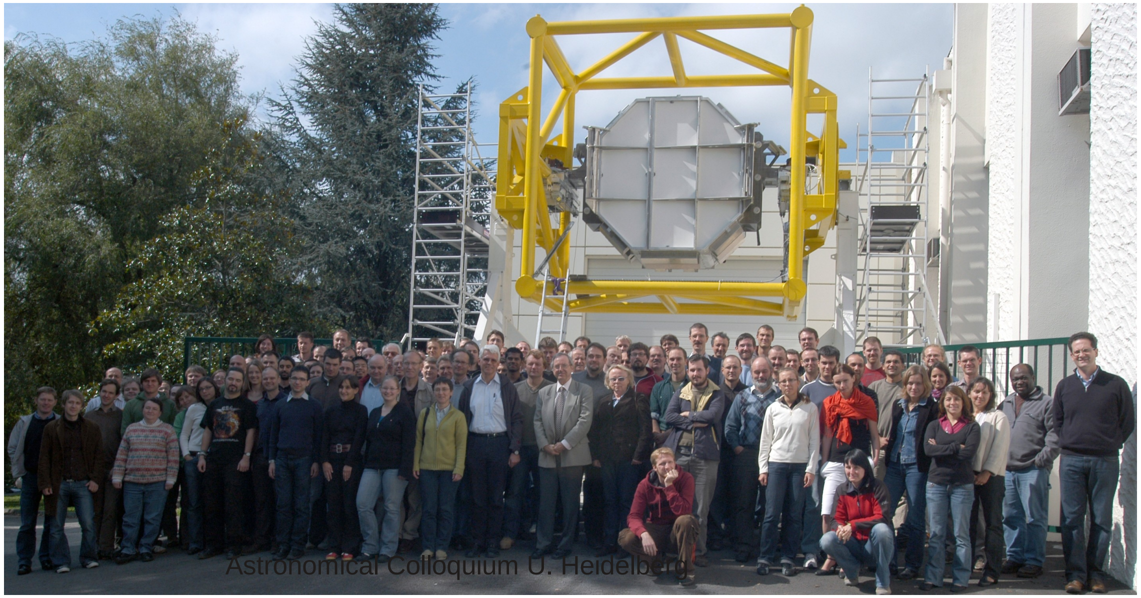
FoV 5 degrees
in Namibia (-23 deg lat)
> 100 GeV
1% Crab in 25h
(3 10^{-13} erg cm^{-2} s^{-1}) at 1 TeV
3' individual photon
10” localisation
Energy resolution 15%



The H.E.S.S. consortium

The High Energy Stereoscopic System H.E.S.S.
is operated by the H.E.S.S. Consortium, formed by
25 institutes in Austria, Armenia, CR, France, Germany,
Ireland, Namibia, Poland, South Africa, Sweden, UK

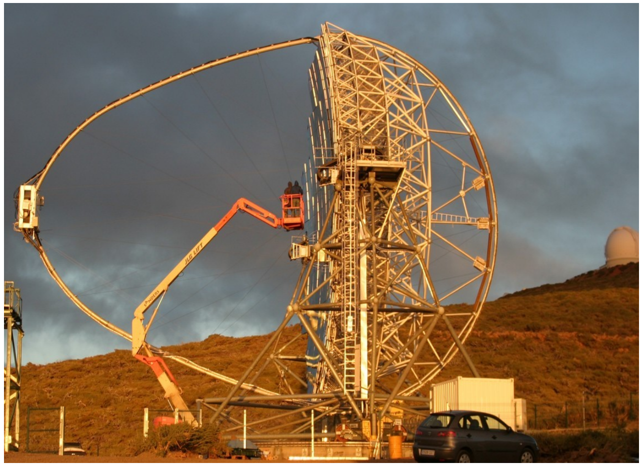
An experimental facility with continuous improvement of
observation, calibration and analysis techniques



Status of facilities

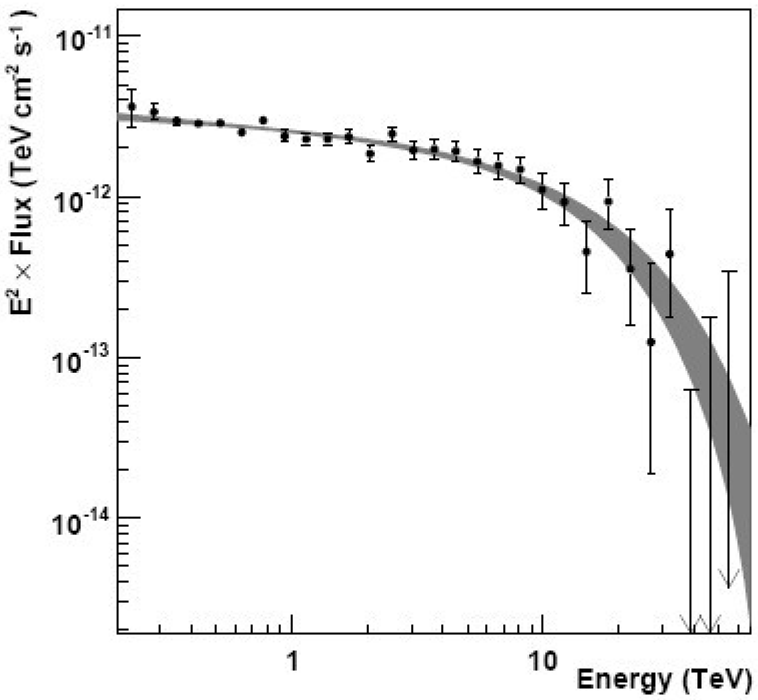
Proof of concept (IACT) in 1990s
(Whipple, HEGRA) → few sources

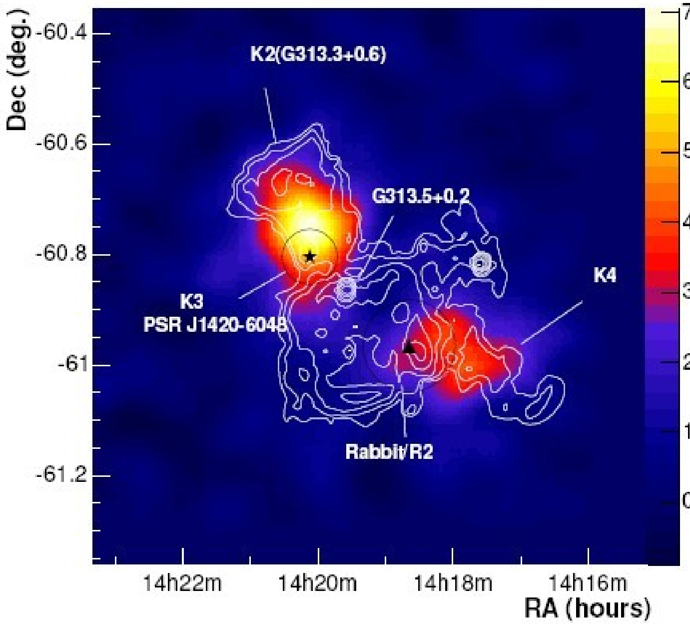
Pioneers in last decade:
Sensitive stereoscopy: HESS (2004+), VERITAS (2007+)
Lower energies → MAGIC (2005+)

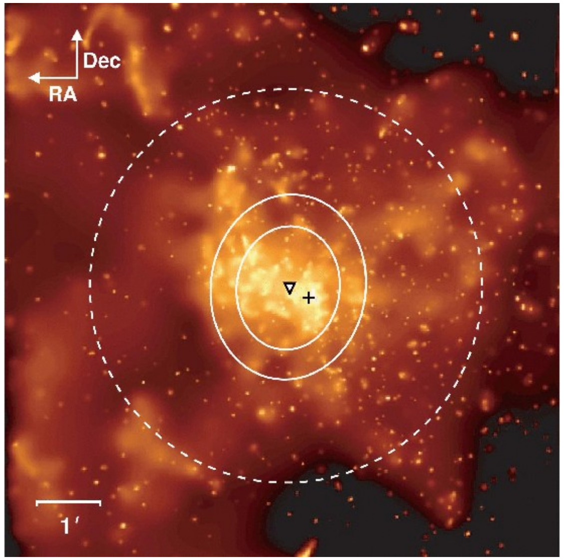


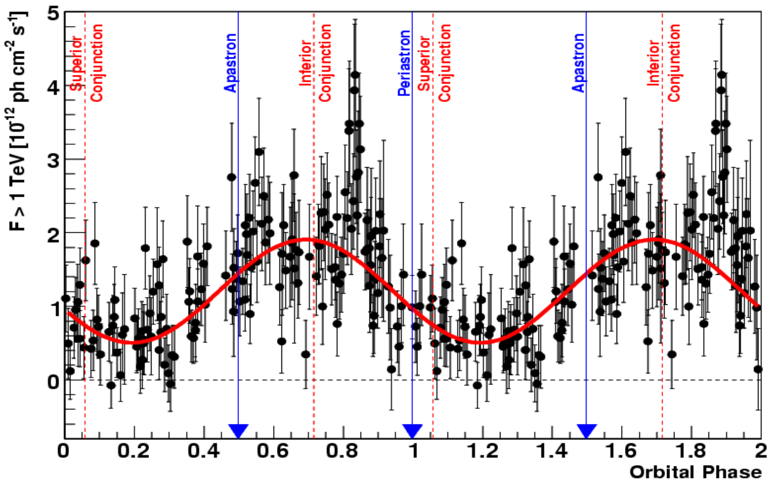
Status VHE γ-ray astronomy

In the last years the field joined mainstream astrophysics:
Images: Morphology, Astrometry
Spectra, Broad-band Coverage
Lightcurves (msec - years)
Surveys, Populations, Catalogs
VHE-dominated sources

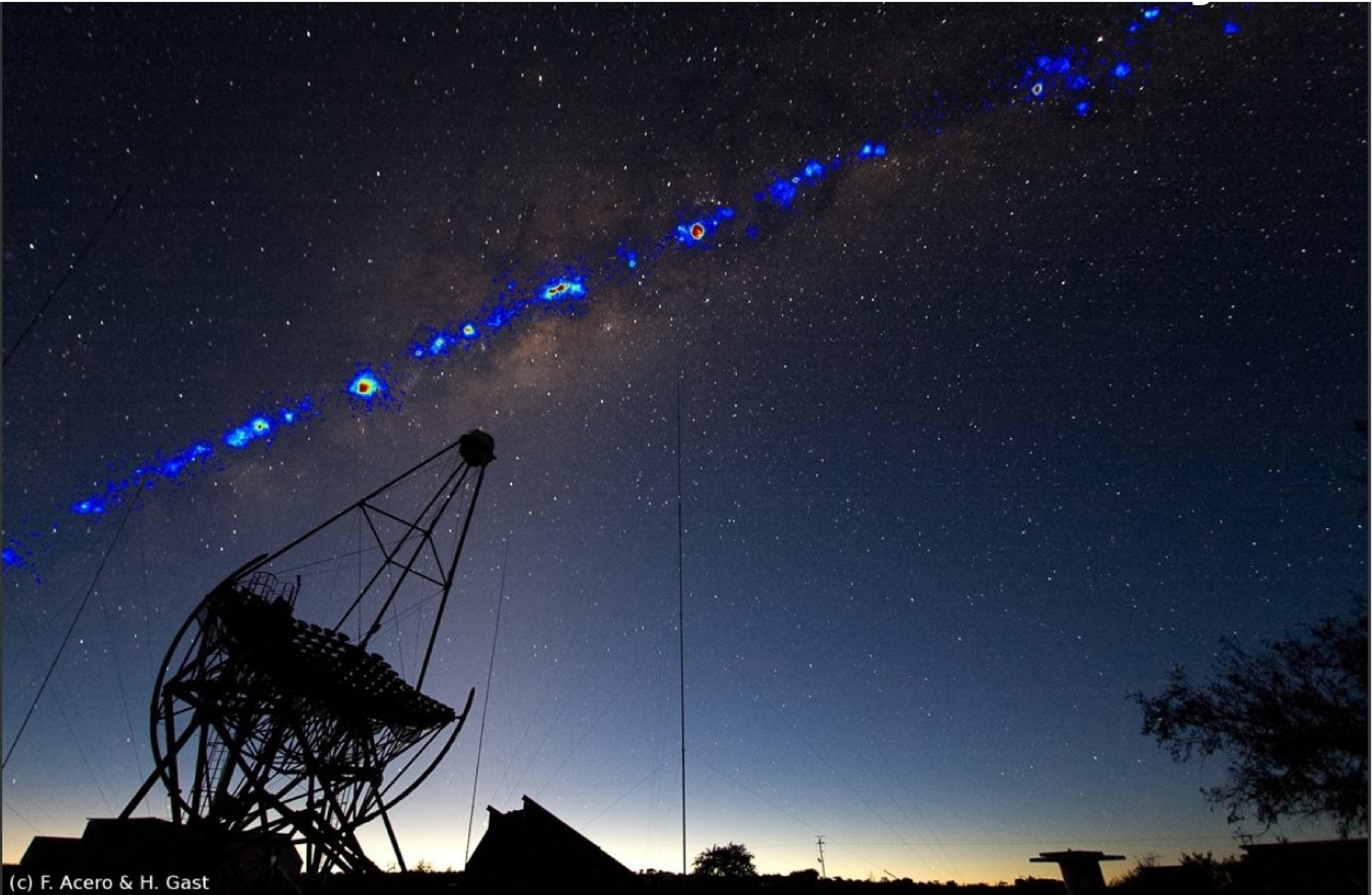




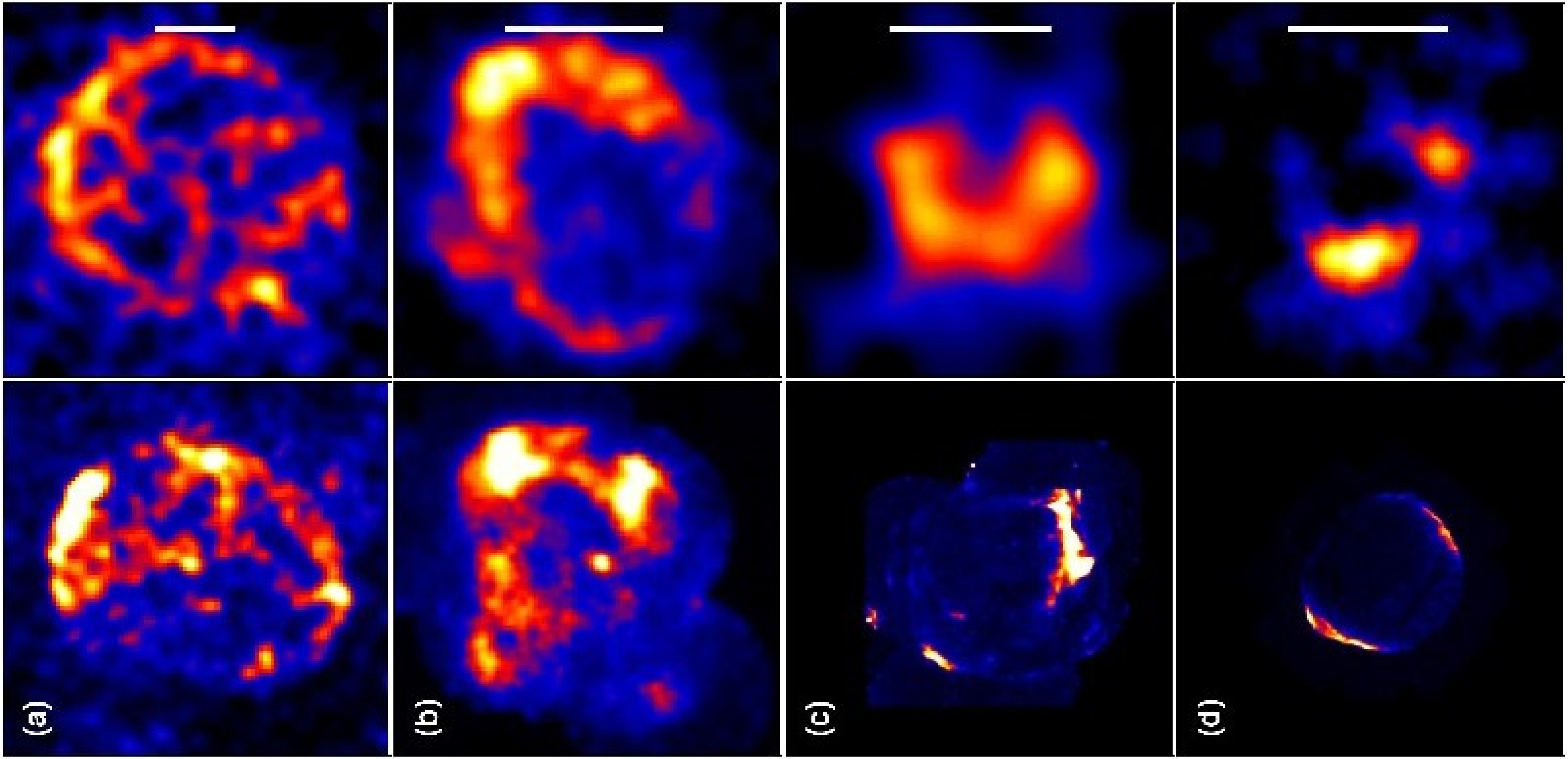




Galactic VHE astronomy

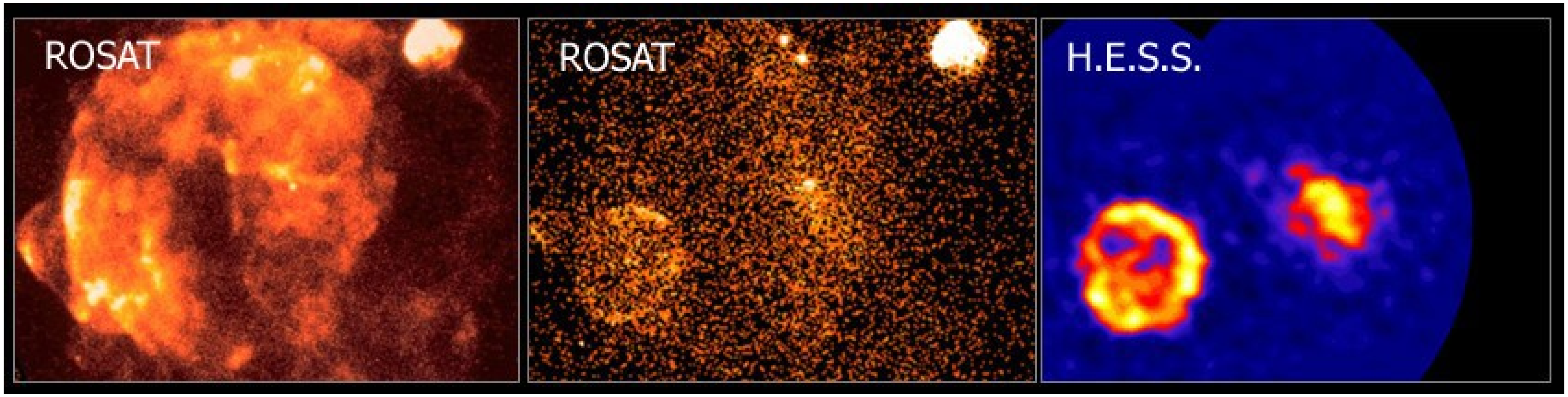


Shell-type Supernova-Remnants

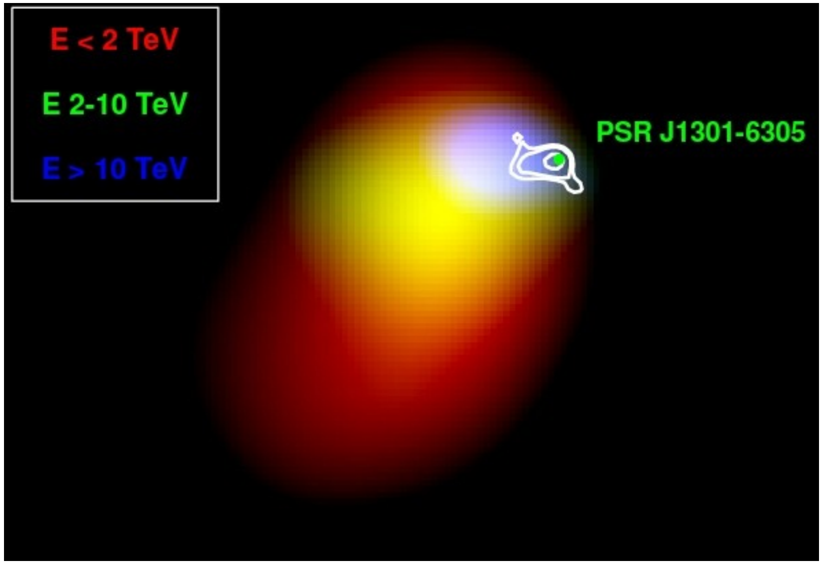


RXJ 1713.7-3946, Vela Jr., RCW 86, SN 1006 – 30' bars

Plerionic Supernova Remnants



PWNe = 'bags' of highly relativistic electrons, escaping from spinning neutron star (independent of pulsar orientation)



IC scattering of ambient radiation fields (0.3 eV/ccm)
Extreme non-thermal SZ effect.

Sample distribution of electrons f(E), tracing diffusion

Other Galactic sources

Binary systems
(many emission sites and processes, variable absorption)

Stellar Clusters
(young open clusters, globular clusters with ms pulsars)

Diffuse ISM
(in particular dense MC near SNR)

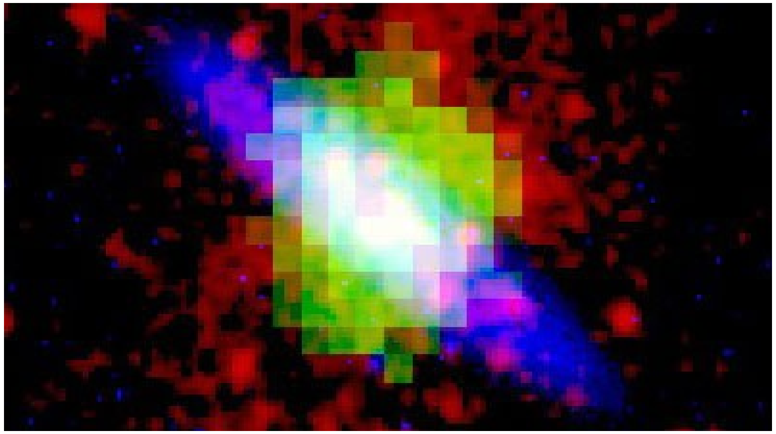
Dark accelerators
$(\nu S_{VHE} / \nu S_{<VHE}) > 100$, extreme PWNe?

The Galactic Center
(many astrophysical scenarios, Dark Matter signal)

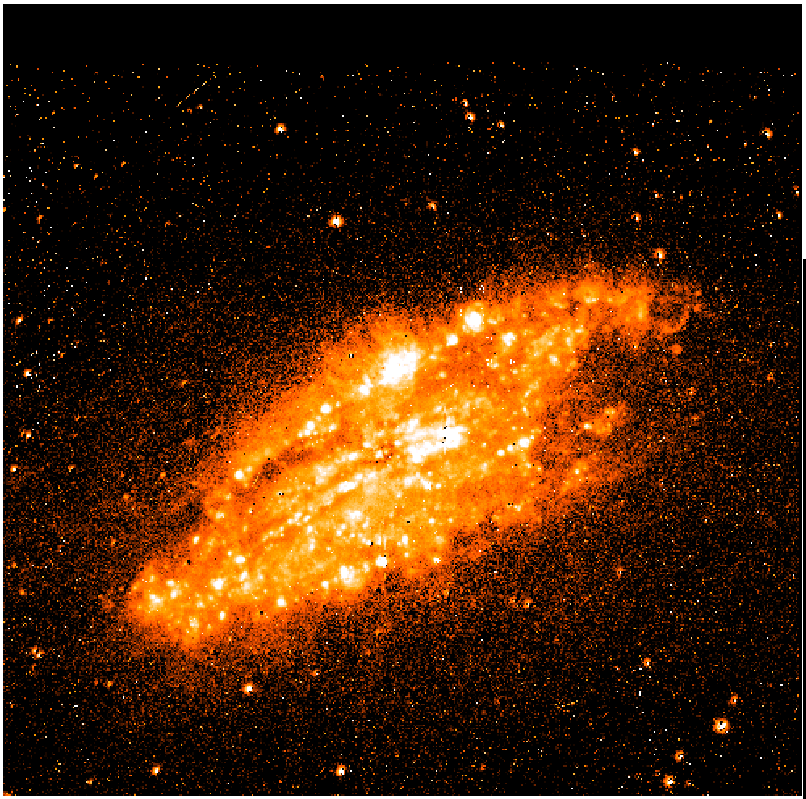
Stellar Populations, Galaxies

Individual stellar sources
have been detected in
nearby galaxies (LMC)
[SNR N 157B (HESS)]

Integrated signal of population?
Starbursting galaxies
HESS: NGC 253, VERITAS: M82

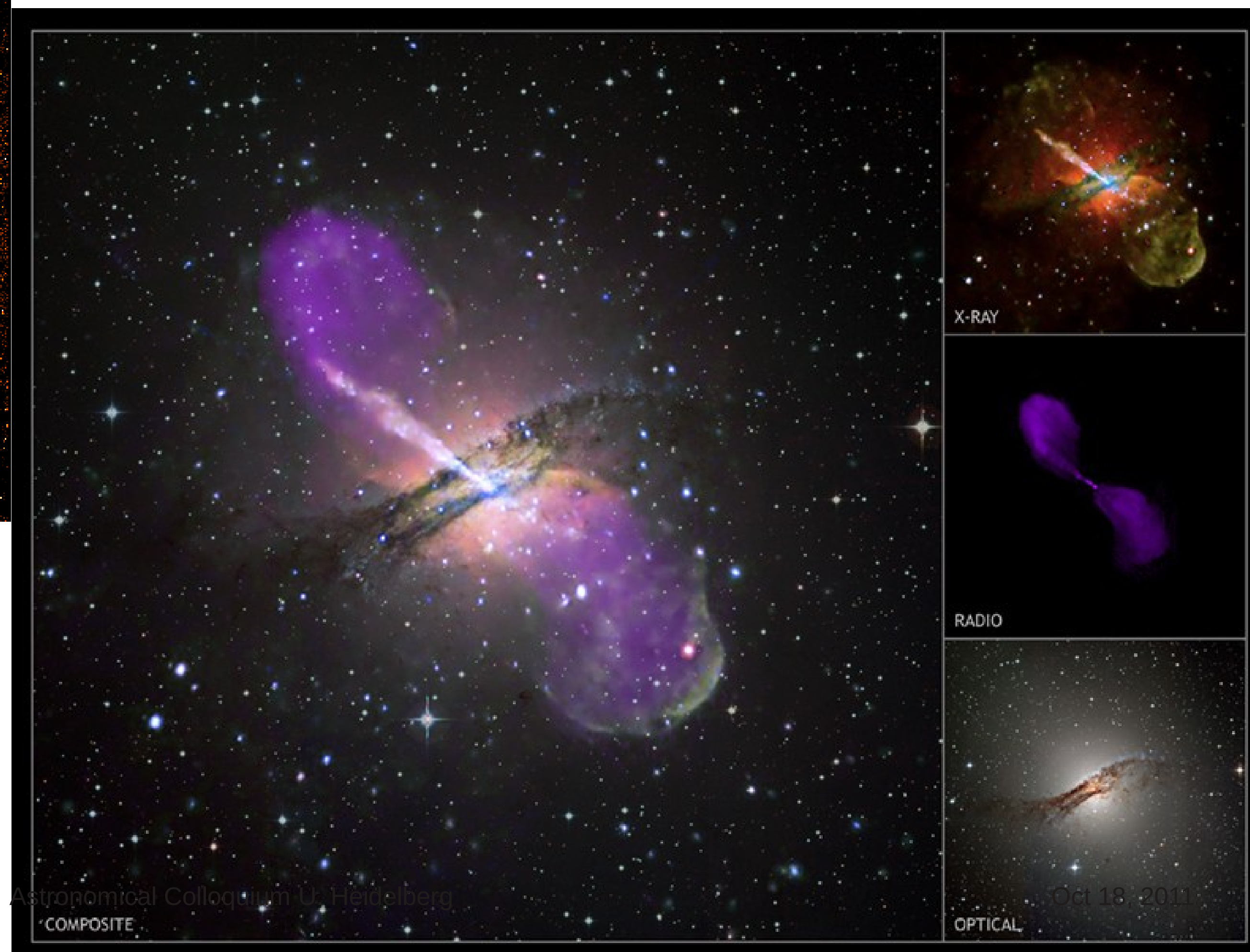


Identification of VHE processes



Radio galaxies?
(Vir A = M87,
Per A = NGC 1275)

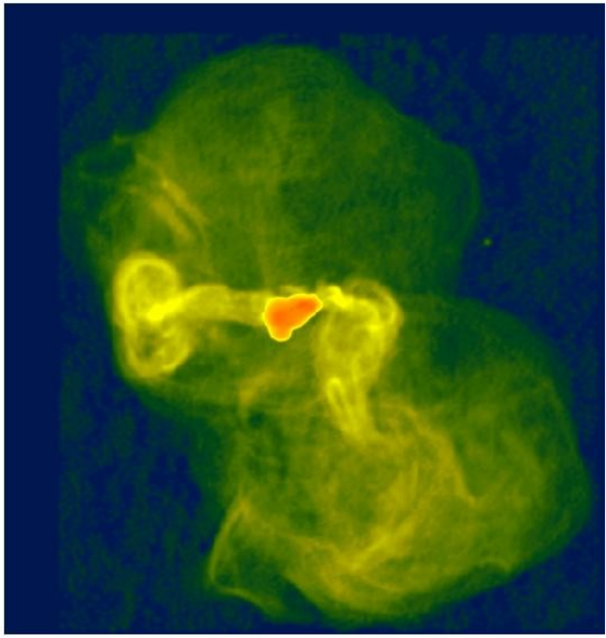
Other nearby galaxies (3.4 Mpc)
(among the faintest VHE sources)



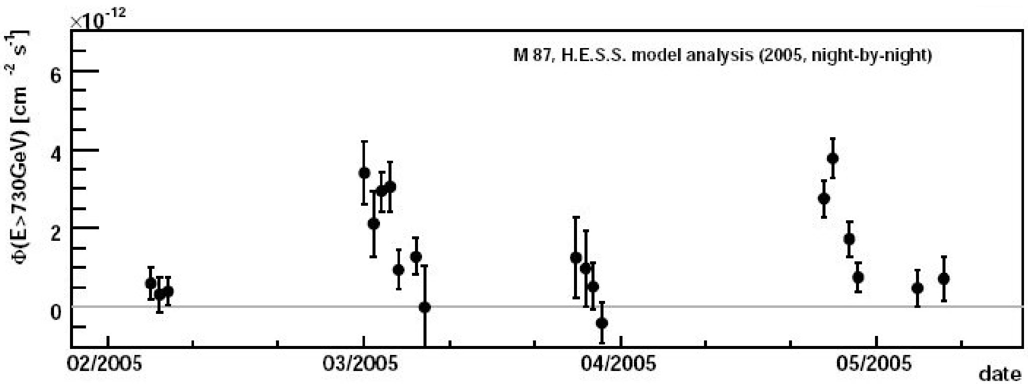
Radio Galaxies

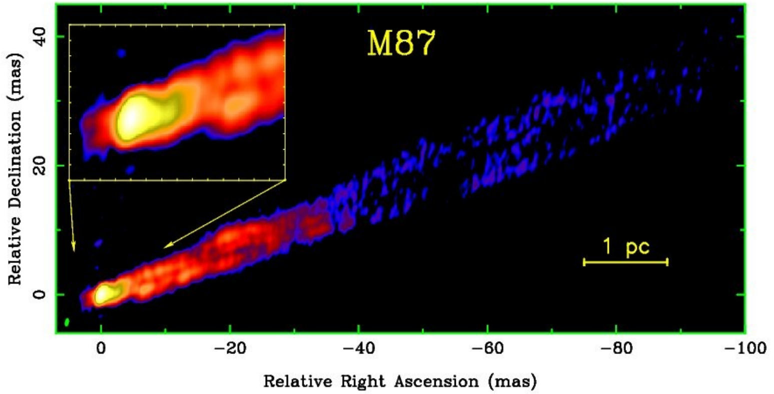
M87: A radio galaxy but an inconspicuous AGN

Jets inclined by ~ 30 deg?
Moderate Doppler beaming



Rapid VHE variability → Compact emission region
Correlation with other events → Several emission sites?
Large beaming?
AGN unification?





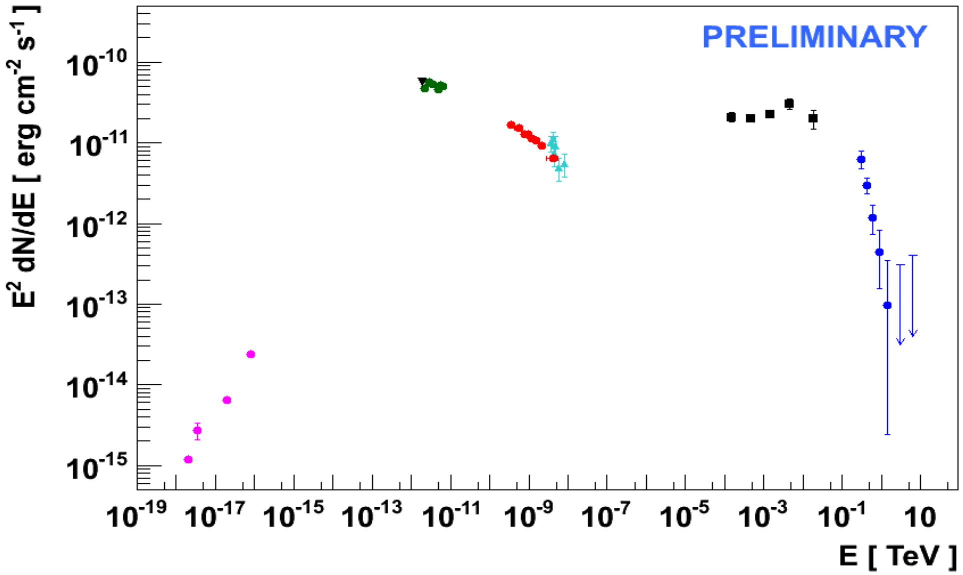
Blazars

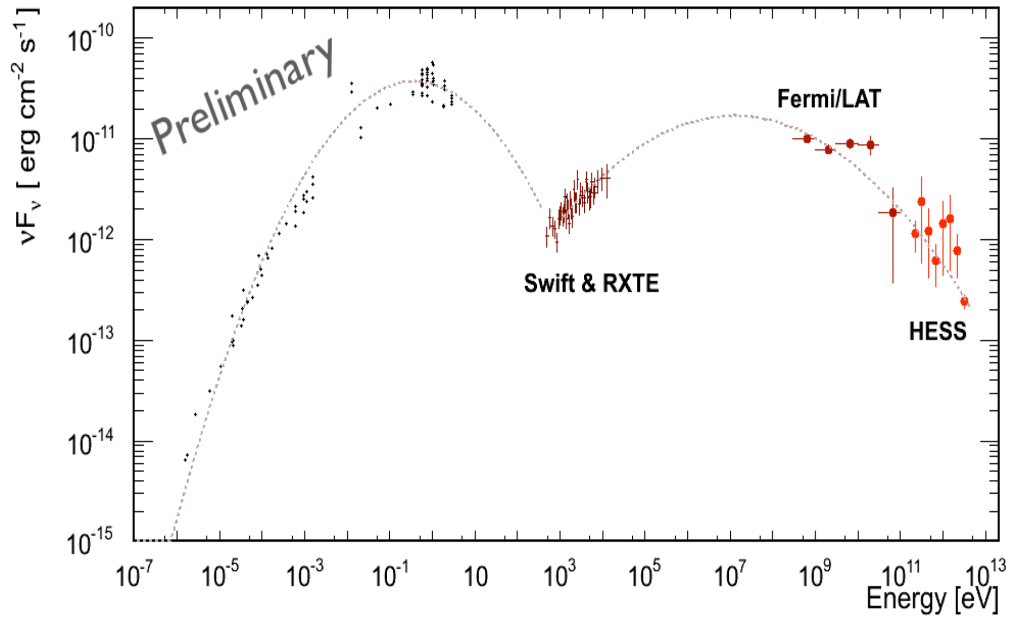
Blazars (BL Lac Objects & Quasars (Radio-loud QSOs)) are AGN dominated by non-thermal emission. Long known to have broad-band SEDs, they were the first population of gamma-ray sources detected by EGRET (>85% of Fermi sources are thought to be Blazars).

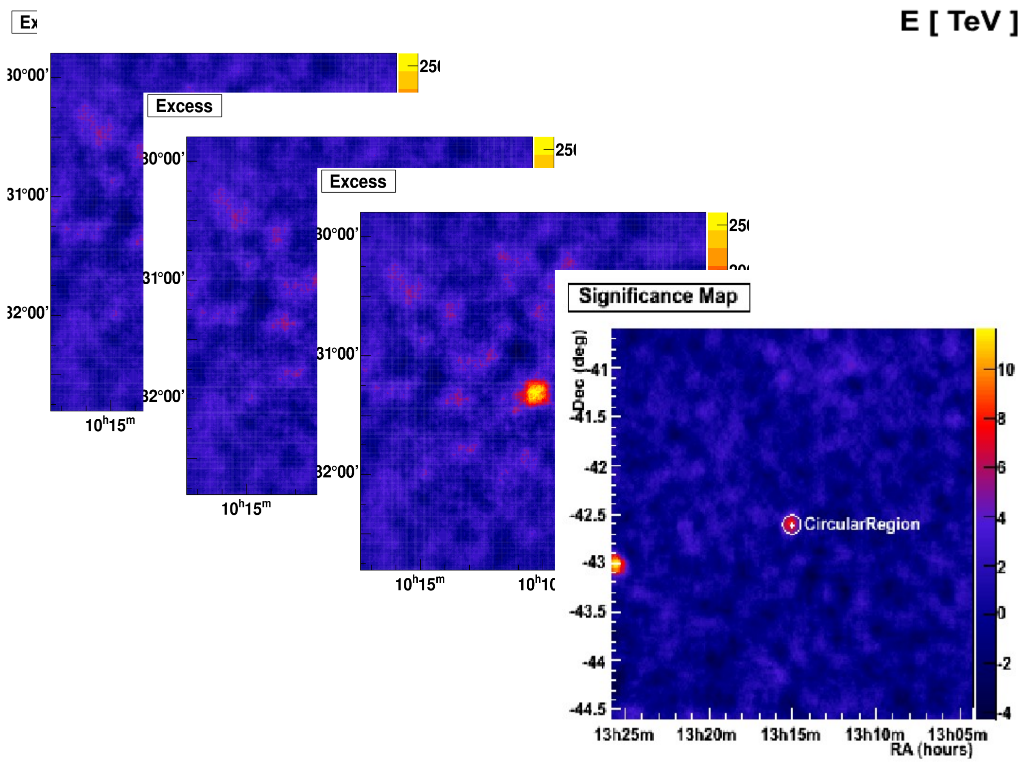
Rapid variability suggests compact source size and high Doppler factor ($D = 1/[\gamma(1+\beta)]$)
$\rightarrow$ Superluminal motion, flux amplification, small fraction

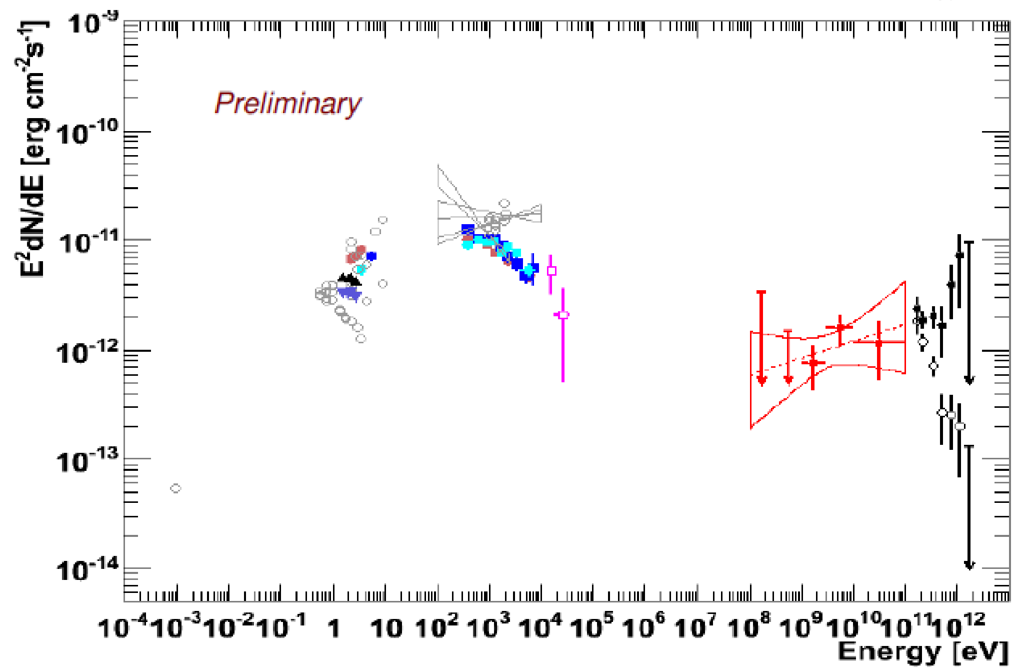
IDV, discovered in early 1990s suggested very high D, in conflict with population studies and source energetics. Bright gamma-ray emission expected.

Blazar population

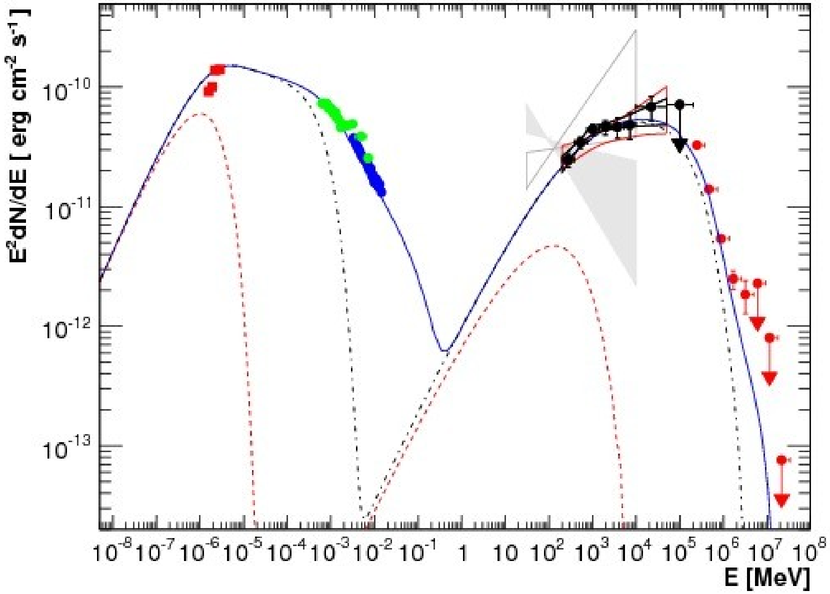




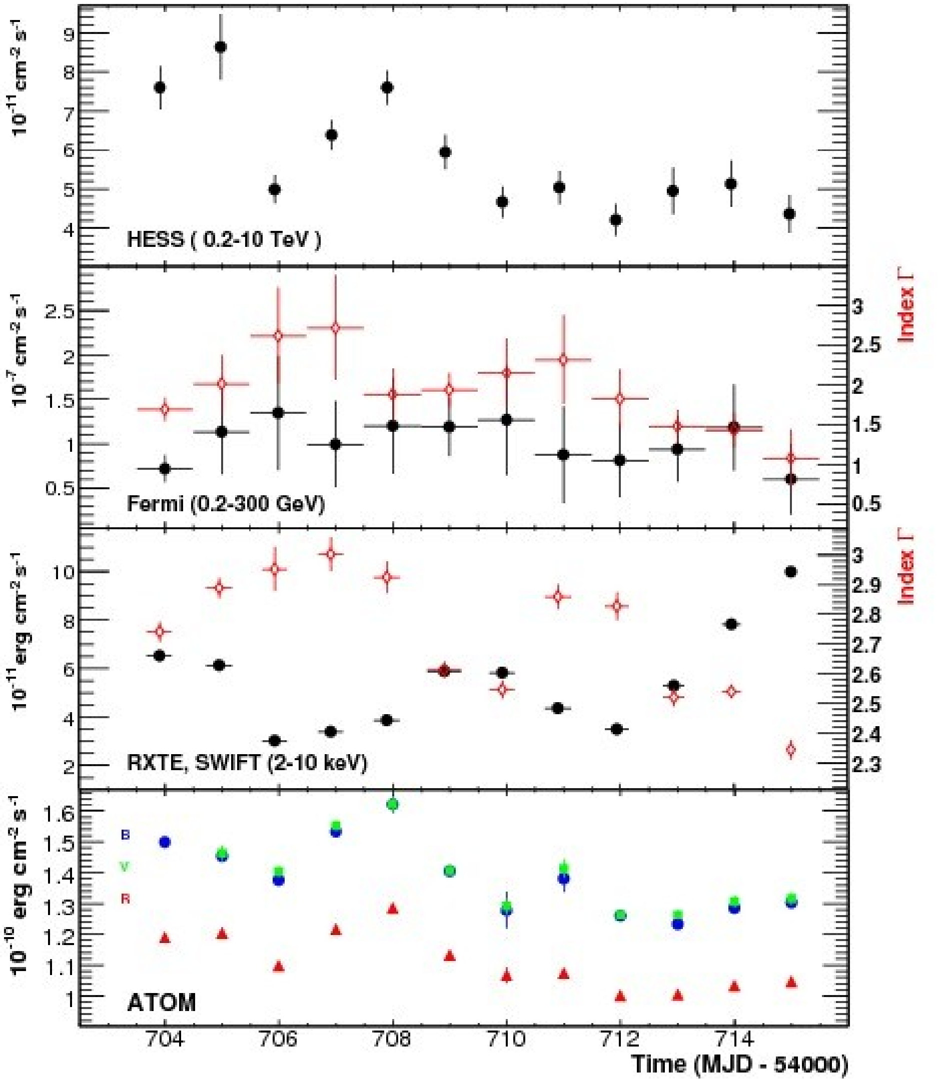




Variability - a promise and a curse



Prototypical PKS 2155-304

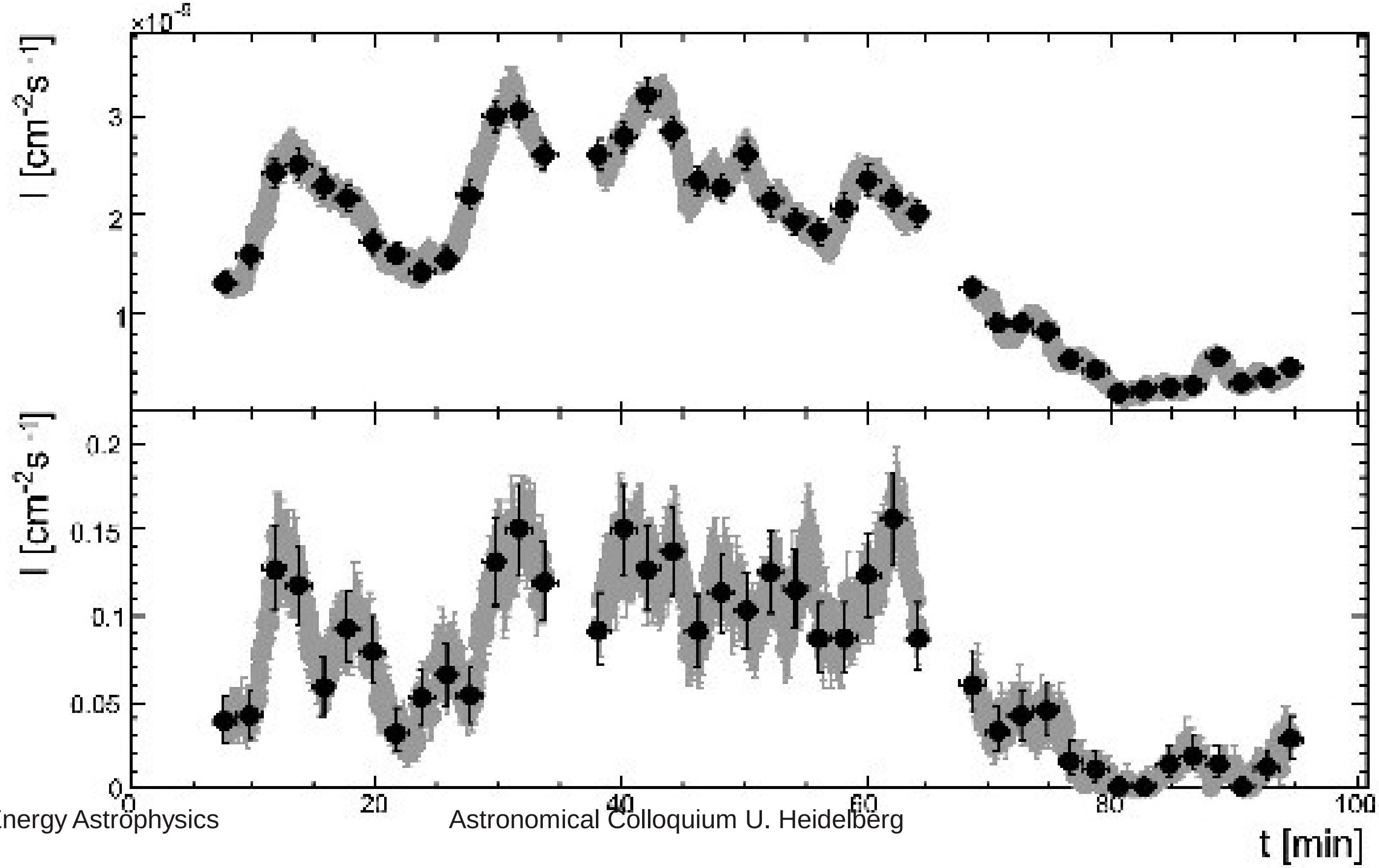


Multifrequency coverage
SED description by cospatial, multicomponent e distribution.

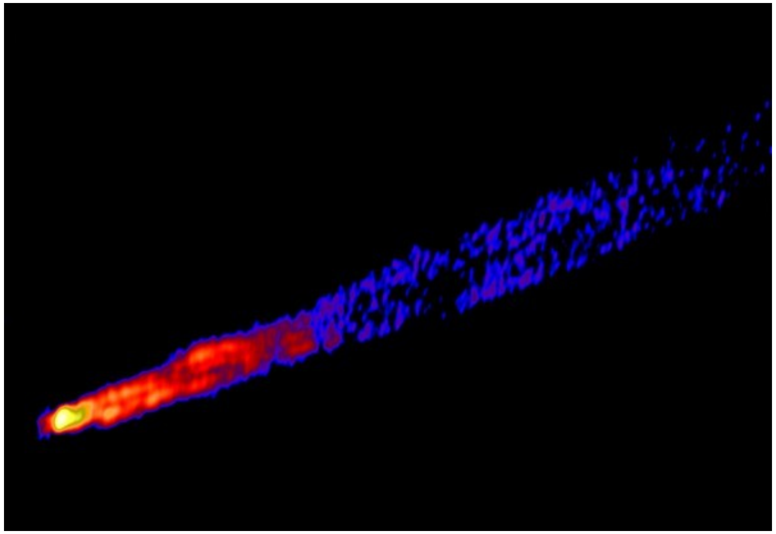
Does not fit variability patters

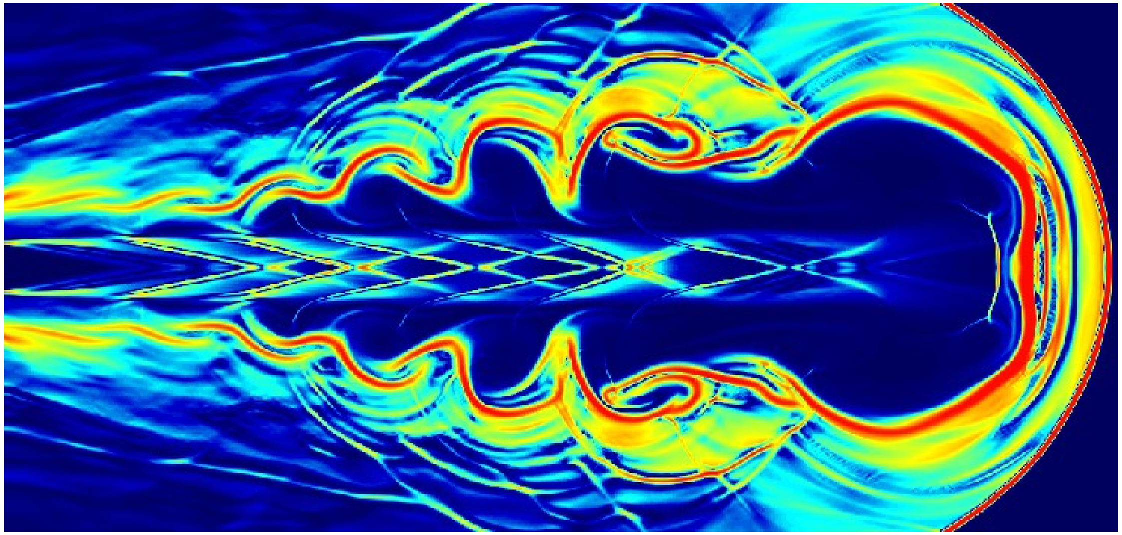
“Persistent GRBs”

Flares by factors > 100 on time-scales of minutes
(PKS 2155-304, HESS; Mrk 501, MAGIC; Mrk 421, VERITAS)



Structured jets & beaming statistics



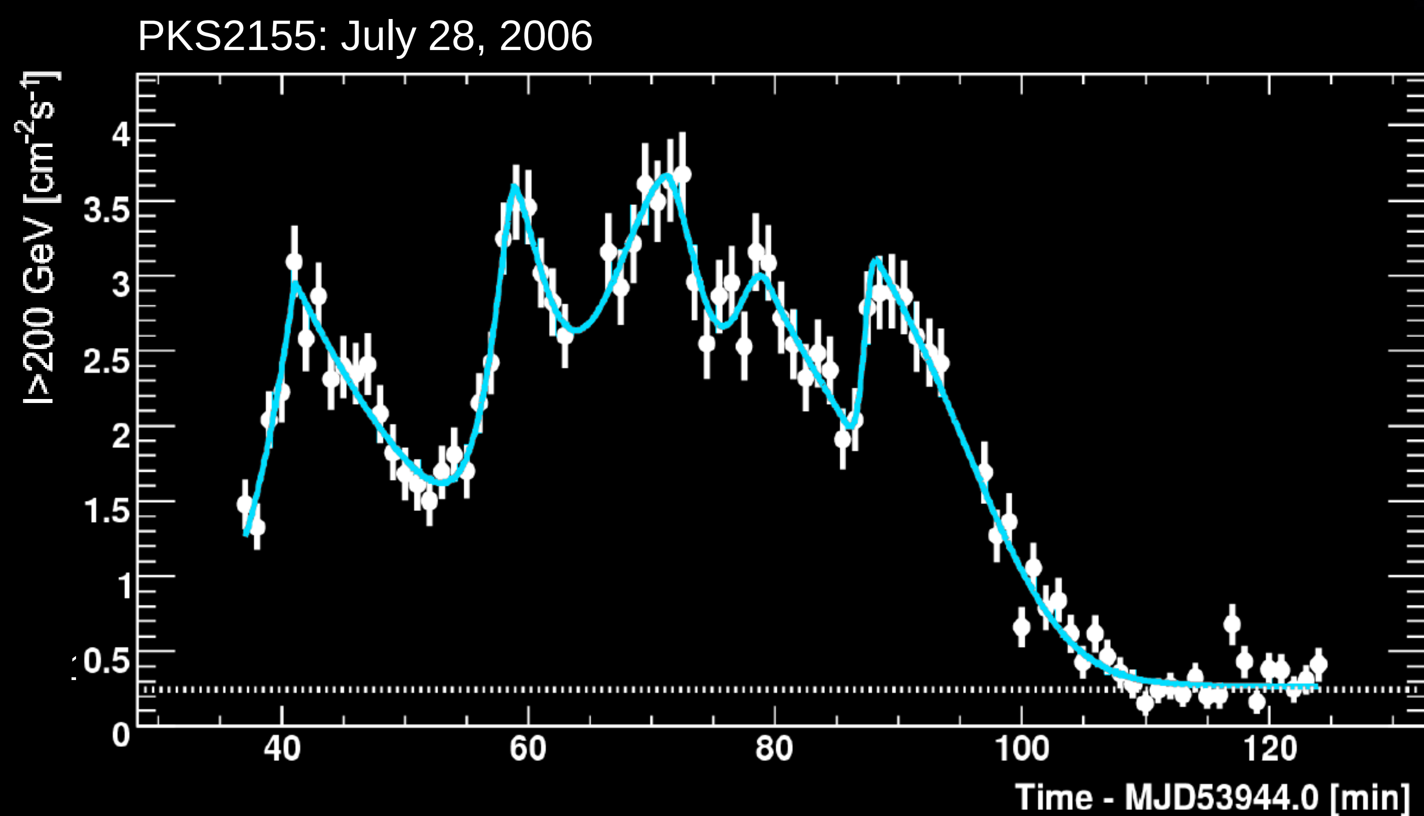


Jets are expected to display substructure.

Diameter of emitting volume < $10^{-12} D^2 r_{jet}$.
Energy density (low D) vs. beaming statistics (high D).

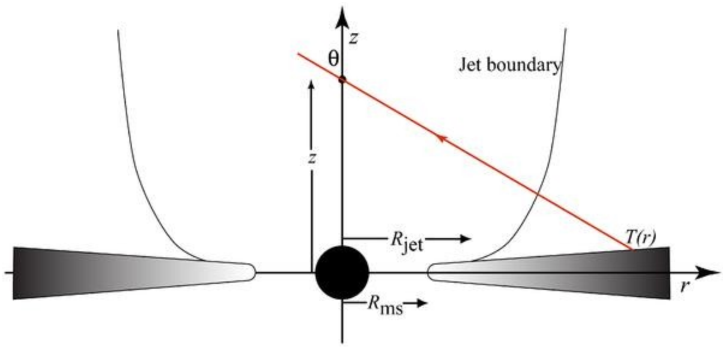
Random velocity vectors?
Instantaneous beaming cone small (rare events)
Envelope of beaming cones wide (expect many events)?
Power-law spectrum of flares (confirming optical data)

Grazing the horizon?



- → Timescale x c << Rs
- → Doppler factors > 100 near SMBH?
- → Jet acceleration
- → Statistics, Isotropy
- → Opacity problem

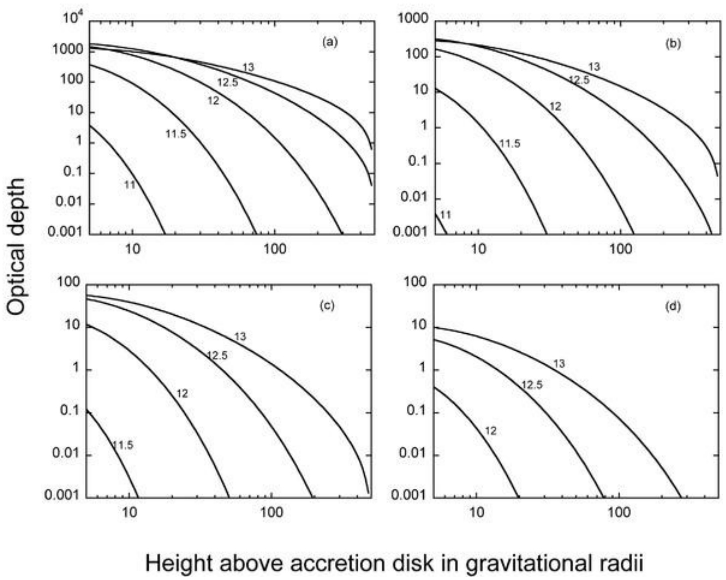
Gamma-ray opacity

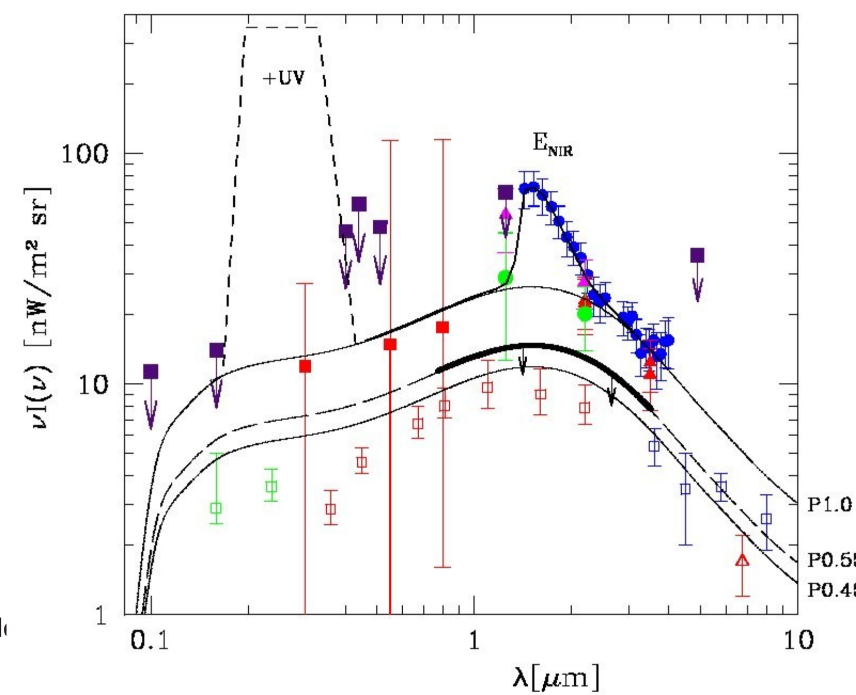


TeV and eV photons annihilate in pair creation.

VHE photons cannot penetrate high $u_{\rm rad}$

Radiation fields near SMBH high for most disks



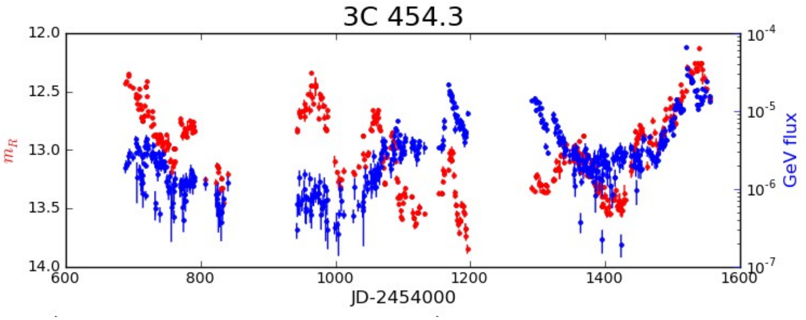


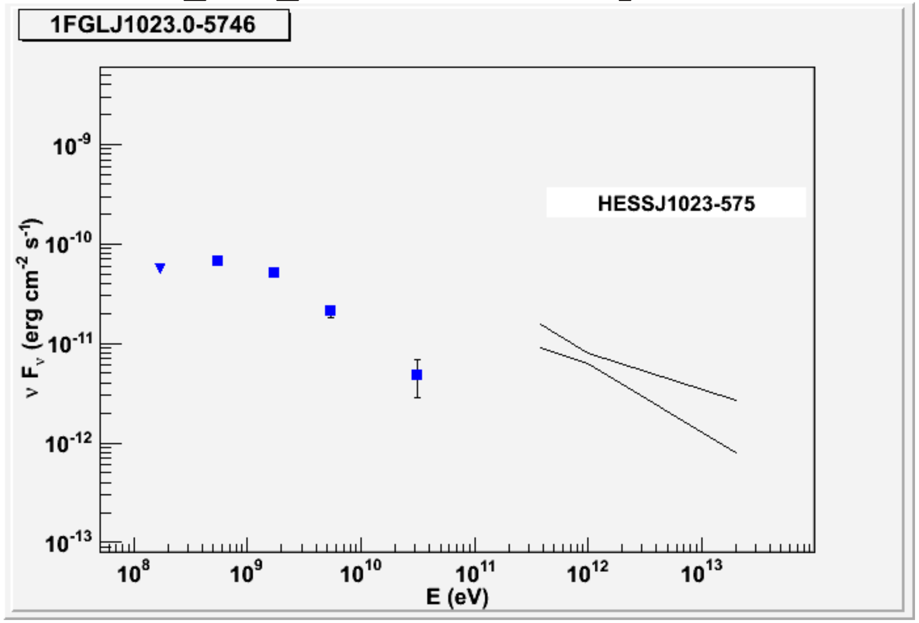
Probing universal EBL found low $u_{\rm rad}$. → larger z

The case for low energies

Extending the cosmological gamma-ray horizon requires an extension to lower energies.

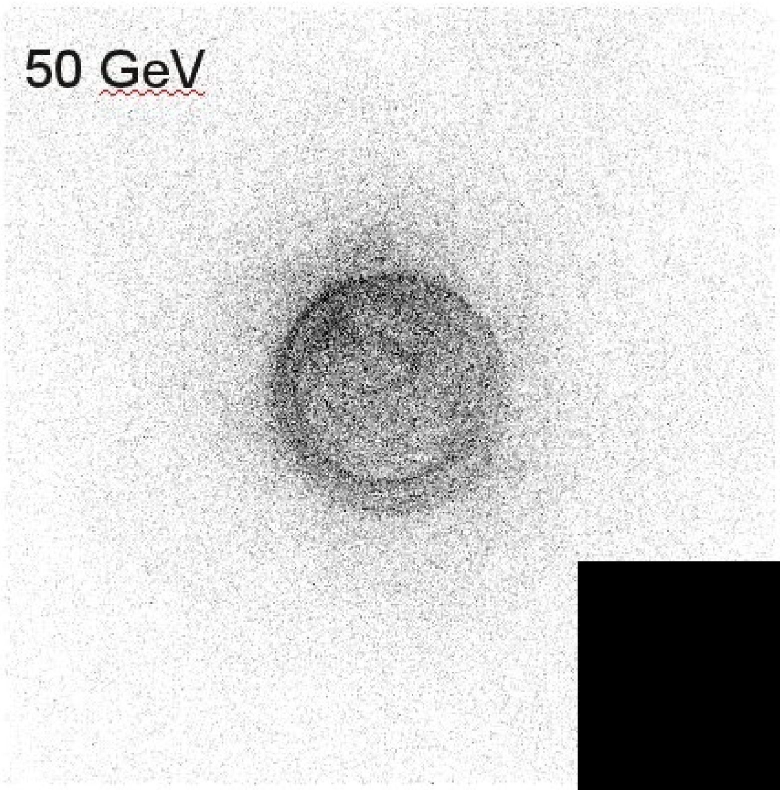
Fermi can reach tens of GeV (mostly after years of integration, averaging over many different flares)

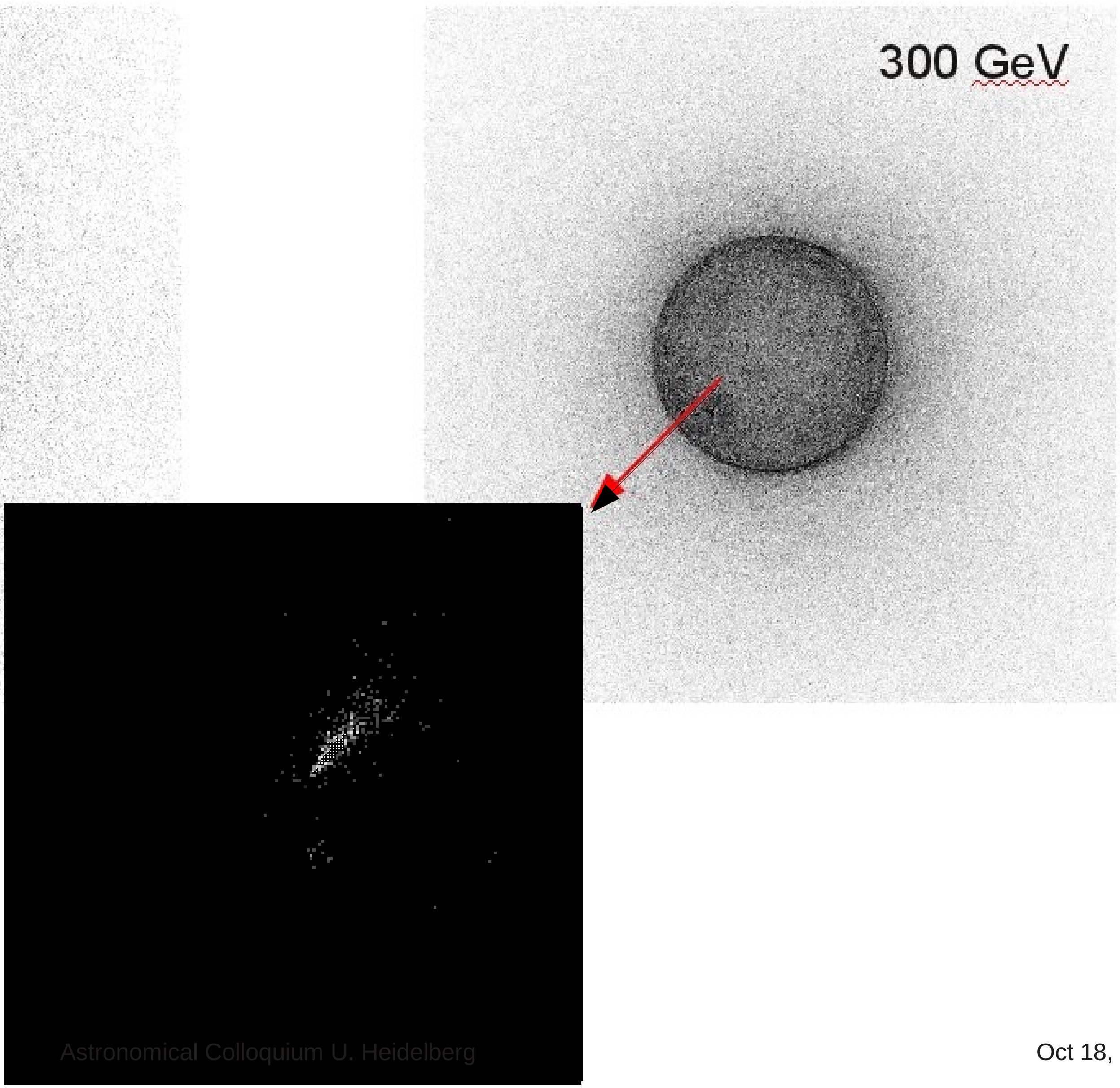




For many Galactic sources Fermi and HESS spectra do not join seamlessly

Low Energies = Faint Showers

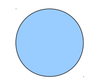




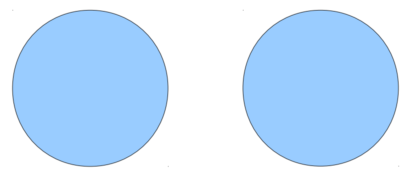
Building BIG telescopes

Optical telescopes:

3.5m Calar Alto/ NTT/3.6m ESO

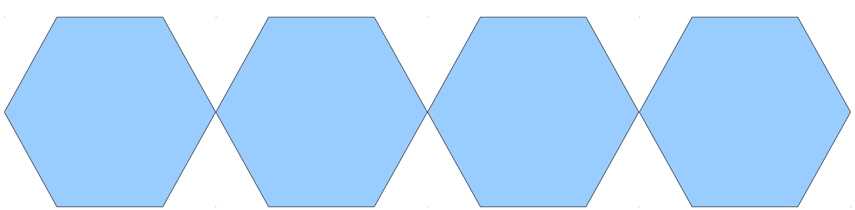


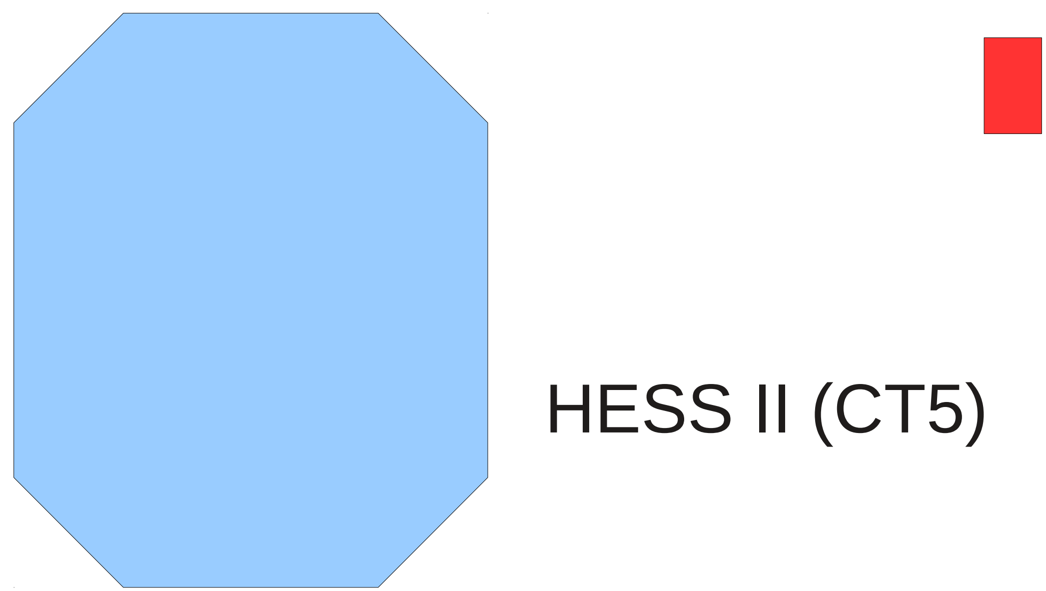
VLT, LBT (8.2m)



Cerenkov telescopes:

HESS CT1 - CT4





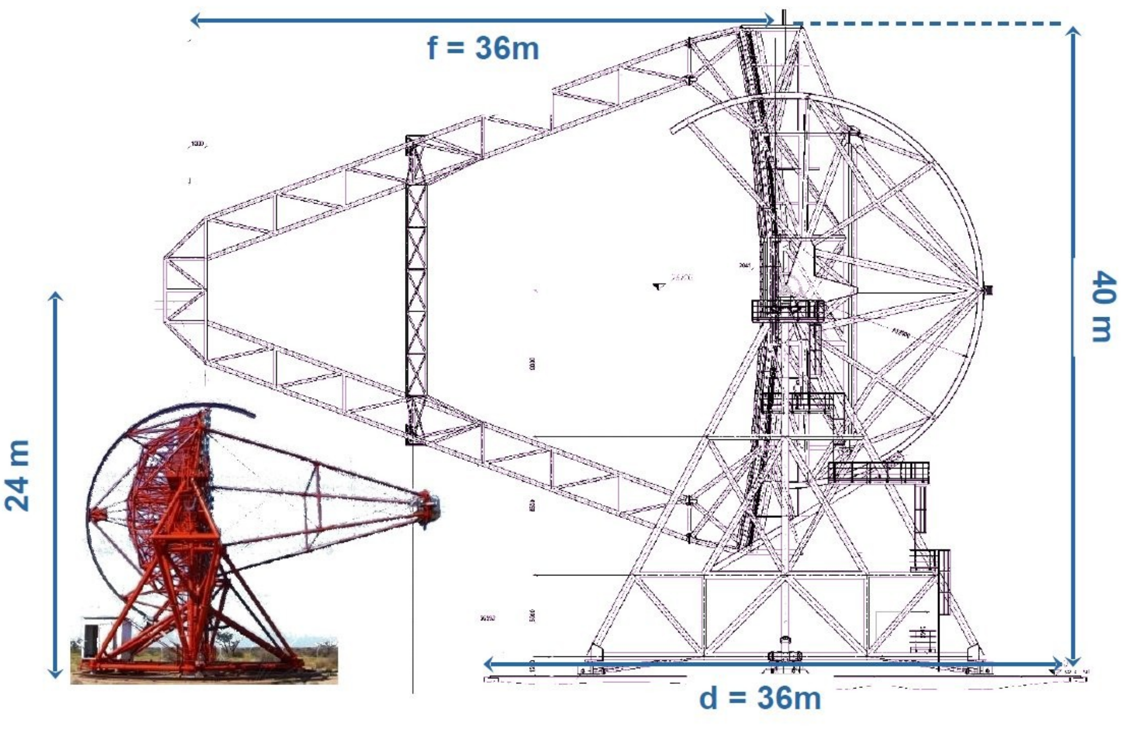
HESS II (CT5)

Extension - HESS II

CT5 (28m) will lower energy threshold by factor 2-4
It will improve the overall sensitivity by a factor of 2-4
First Light in June 2012.

Science Goals:

HE end of pulsed emission
Extending VHE horizon
Exploring GRBs
Sampling Binaries
Extending DM searches
Broad-band links to Fermi



Errecting HESS II

Lifting 30m dish support structure in August 2011 ...

... changes the scene at the HESS site.

Completing HESS II

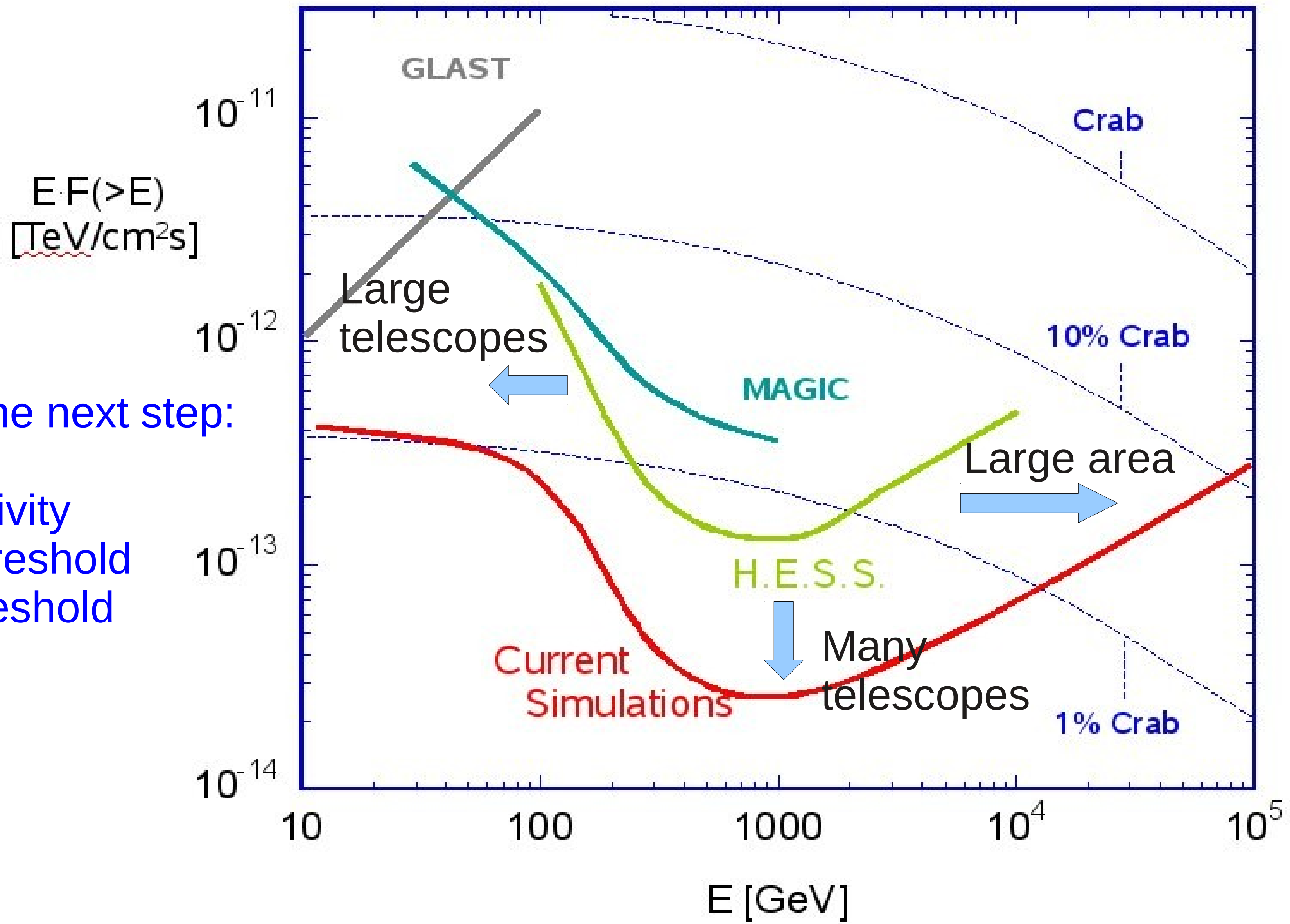
Completing installation of telescope in September-November '11

850 mirrors to be integrated on site in spring 2012

HESS II … and beyond

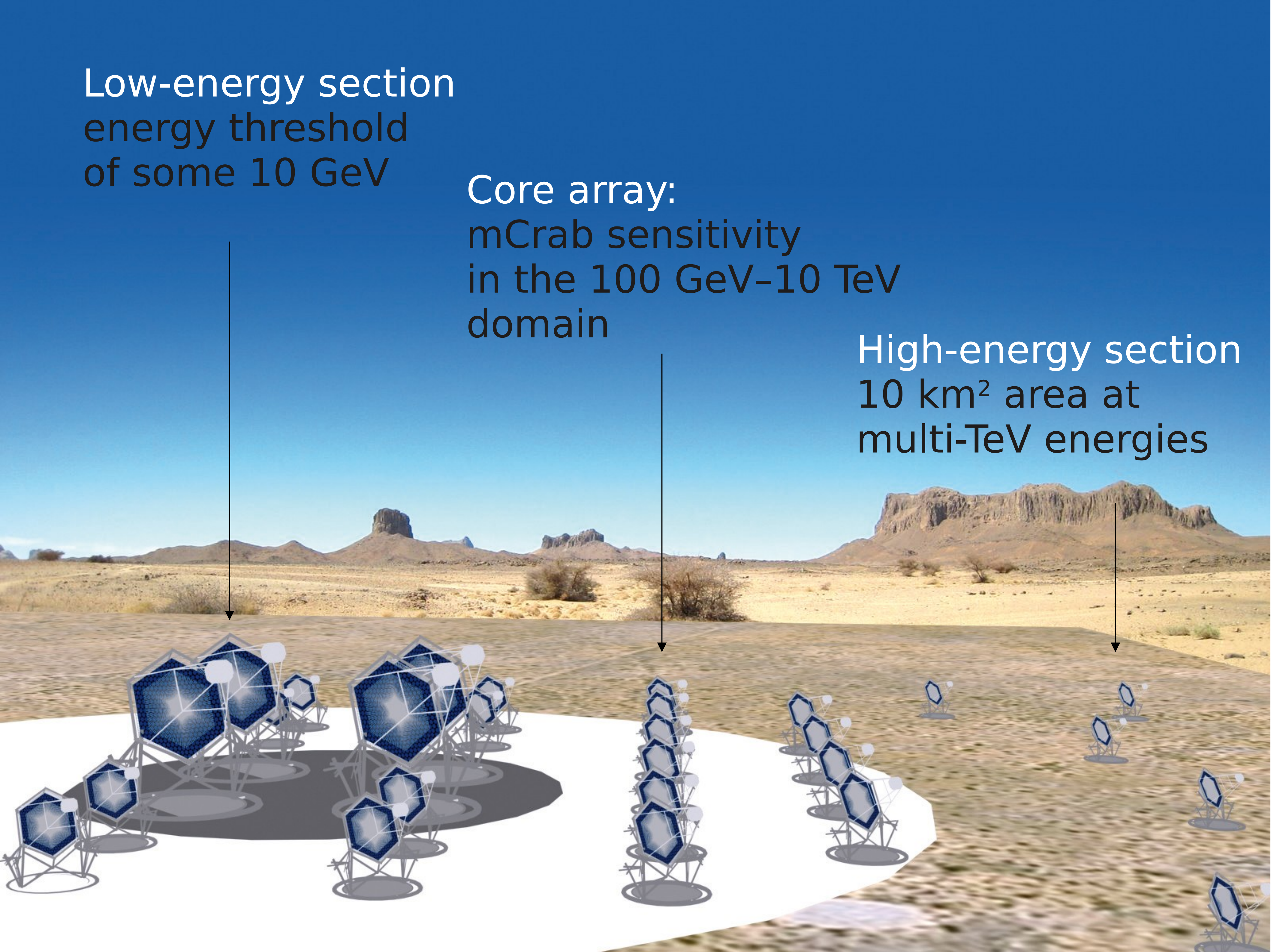
Beyond pioneering:



Original idea for the next step:

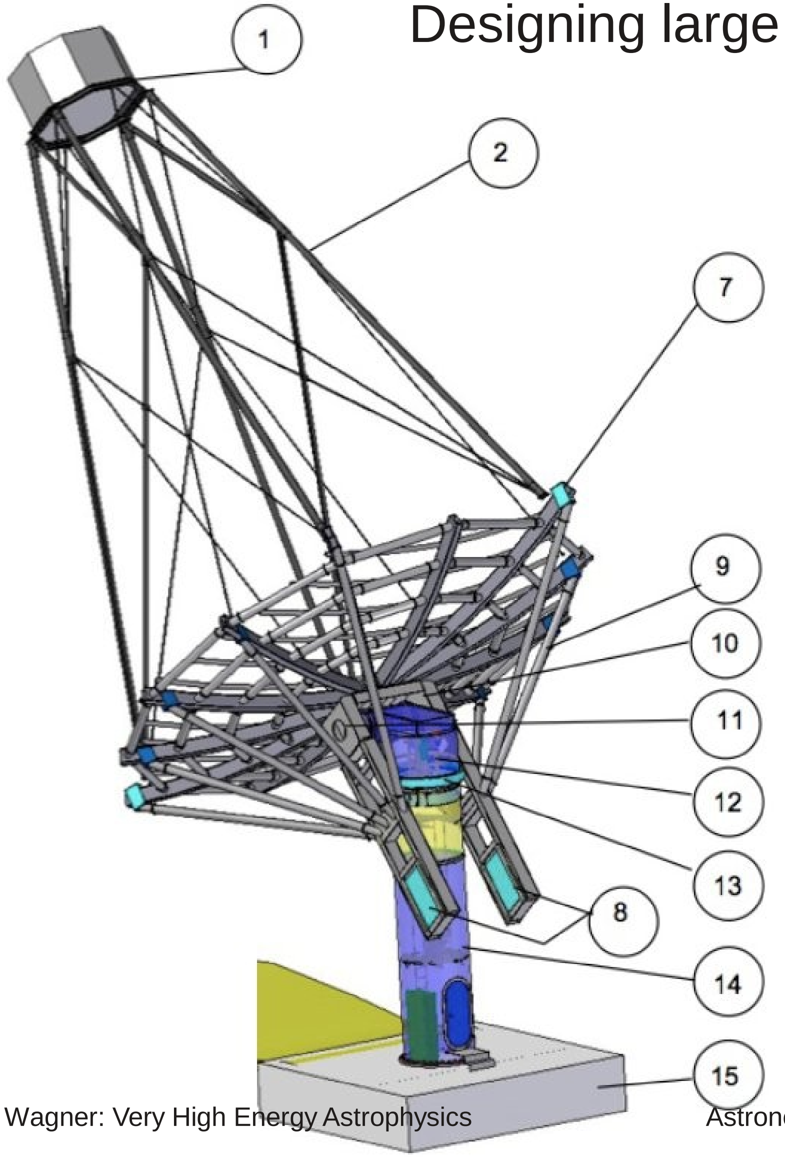
Factor 10 in sensitivity
Factor 5 in high threshold
Factor 2 in low threshold

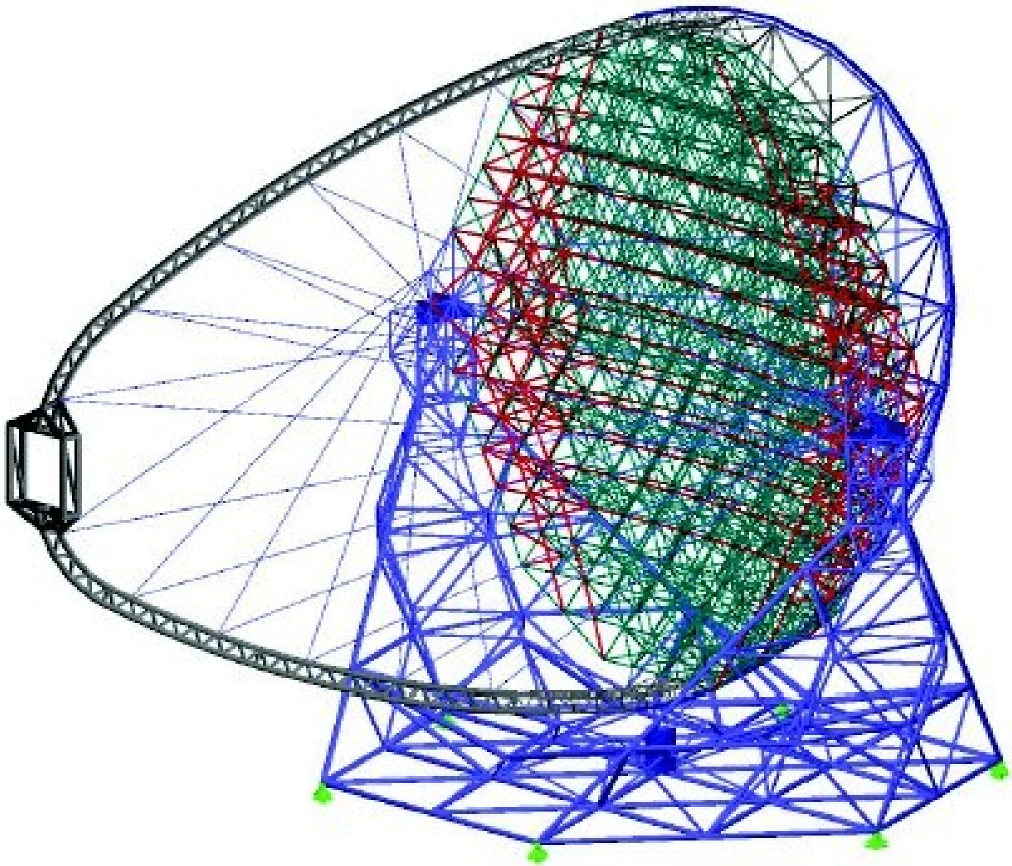
150 ME budget


Low-energy section
energy threshold
of some 10 GeV
Core array:
mCrab sensitivity
in the 100 GeV–10 TeV
domain
High-energy section
10 km² area at
multi-TeV energies

Optimizing the telescopes

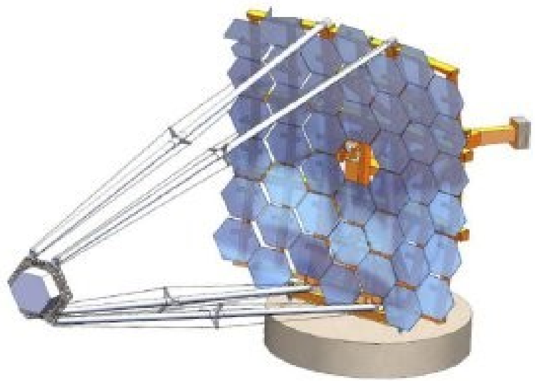
Designing large and medium-sized telescopes:

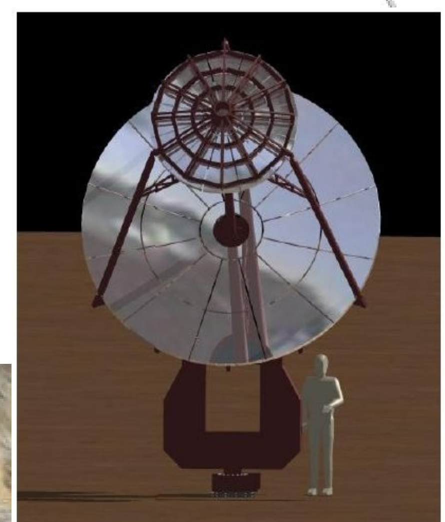


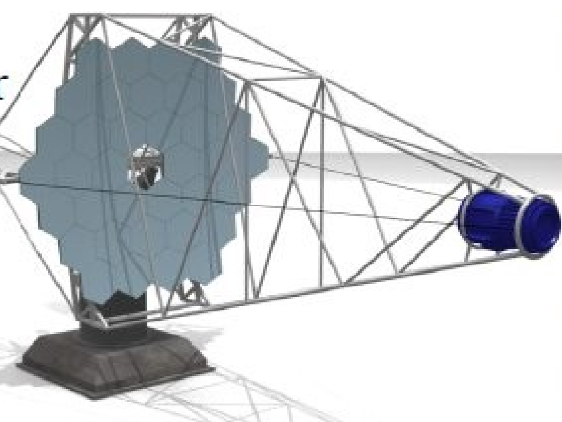


Several different designs tested

Candidate designs for small-scale telescopes:



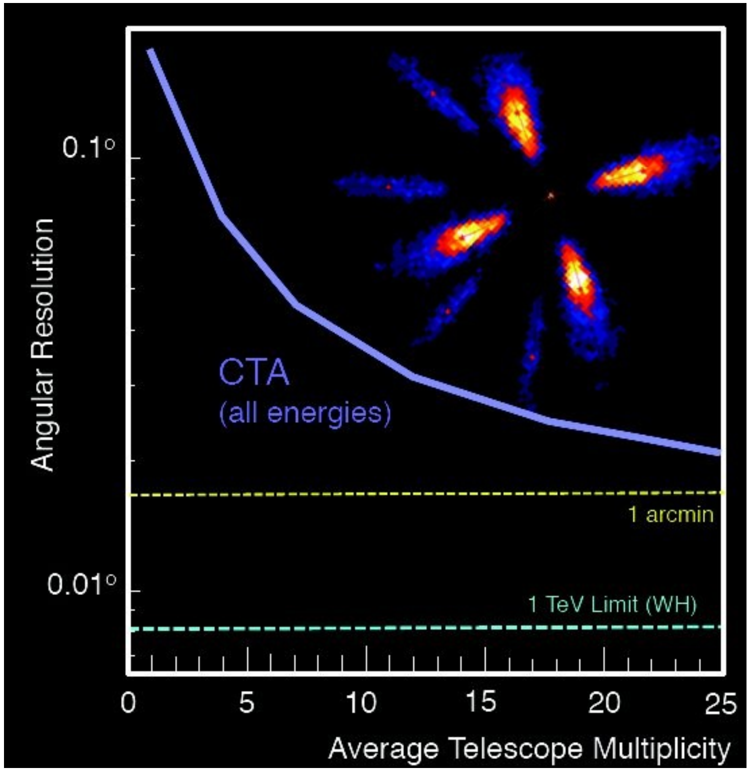


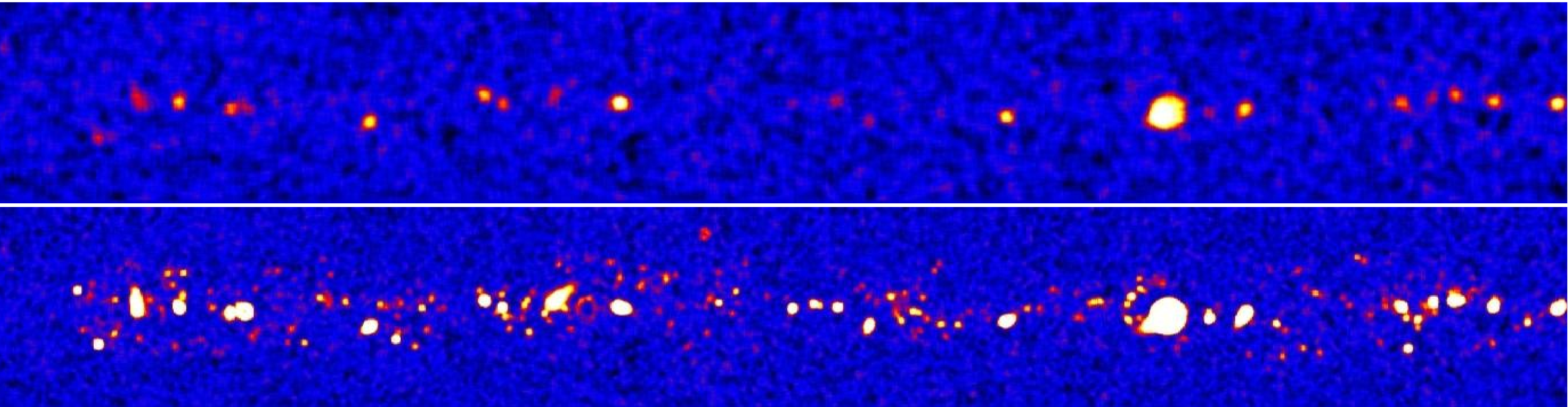


What to expect?

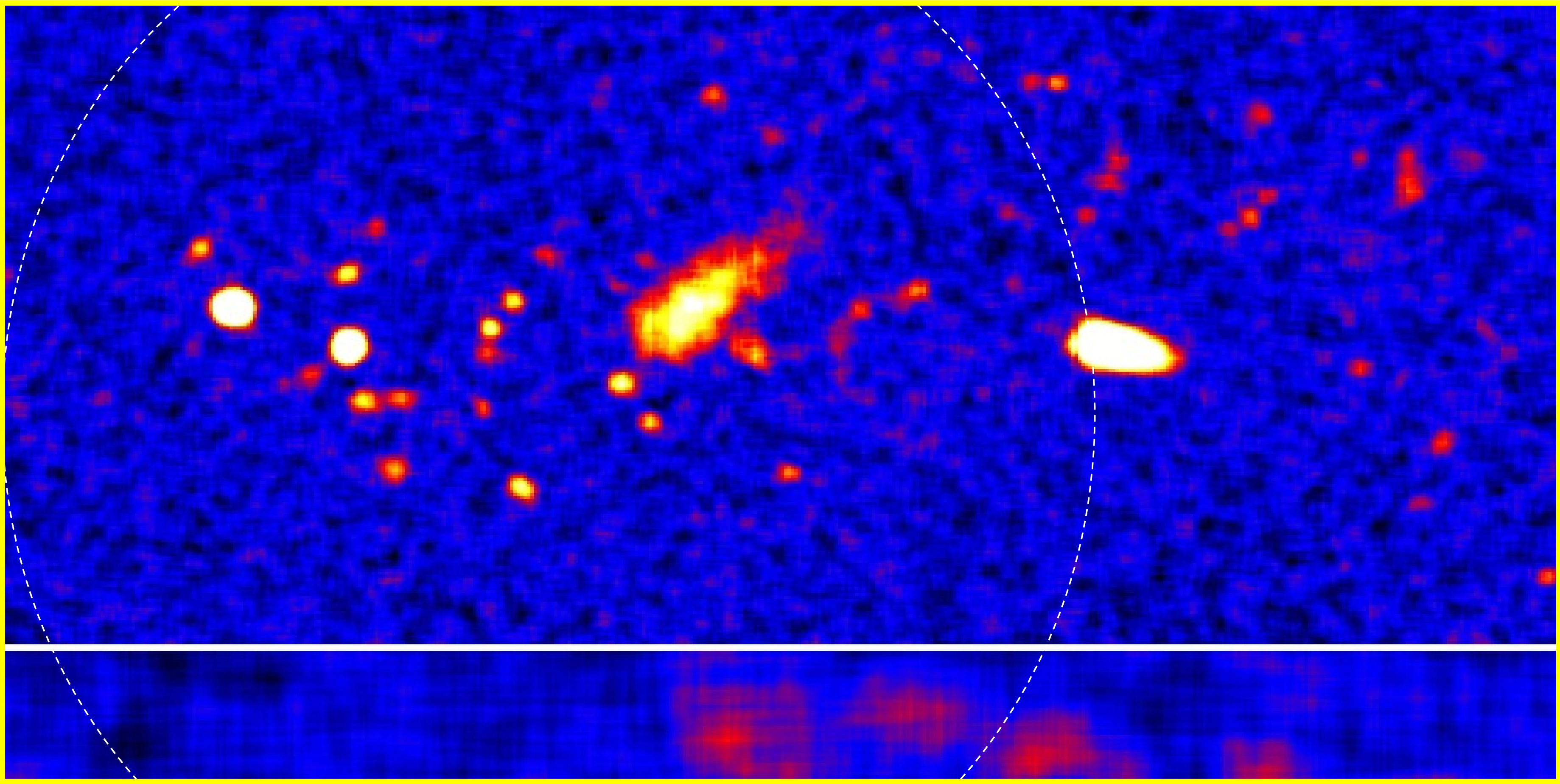
Performance goals:

Improved sensitivity (> factor 10)
Increased Energy range (0.03 - 100 TeV)
Improved Energy Resolution
Improved Angular Resolution
Larger Field-of-view (Survey)





What to expect?



6 deg FoV

angular resolution: 0.05 deg (> 1TeV)

Who is behind this?

CTA planning was started by HESS and MAGIC collaborations.
Now ~50 groups, 280 people, mostly European

CTA is an open collaboration of groups/institutes (Astro-/Particle Physics)

Several European groups have joined 2006-2010

Partners in most European countries

Germany: HGF (DESY-Zeuthen), MPG (MPIK, Munich), 9 university groups

Non-European partners: Japan, US, potential hosts (SA, Namibia, Argentina)

Now ~800 people in 130 institutes.

PI: Werner Hofman, MPIK, CTA-Germany: SW

How are we going to do this?

Preparatory Phase 2010 – 2013
Prepare array and components
Define legal structure
Identify sites
Project Office at LSW Heidelberg
Coordinator: W Hofmann, MPIK

cta
cherenkov telescope array

Observatory operation: open access

VO-usable (FITS) data format

MC simulations and calibration data

Summary I

Imaging Atmospheric Cherenkov Telescopes provide access to very high energy (>0.1 TeV) studies.

A third 'window' for ground-based astronomy is open.

VHE Gamma-ray studies joined astrophysics:
> 100 sources of many diff. types with high quality data (positions, morphology, spectra, lightcurves);
dark accelerators, diffuse emission, populations;
SEDs over 20 orders of magnitude.

Summary II

Supernova shells trace energetic particle acceleration in shocks to 100 TeV (cosmic super-colliders)

Milky Way survey unreveals a zoo of Galactic sources (Pulsars and Plerions, Microquasars, Stellar Clusters).

Galactic Starbursts are gamma-ray bright.

VHE from nearby, low-luminosity SMBH challenge models

Blazar properties (sizes of emission regions, Doppler challenges) turn out to be more extreme than expected.

The bright non-thermal universe provides bolometric limit on photons generated through cosmic nucleosynthesis.

Summary III

First light for HESS II expected in June 2012:
A new frontier (for science and technology) -
The biggest optical telescope ever built.
A first mixed-size array of IACTs.
Closing the gap to satellite-borne GeV instruments.

From pioneering experiments to community observatories:
A preparatory phase for a Cerenkov Telescope Array (CTA),
Studying and prototyping telescopes and electronics for
a ~100-telescope two-stations global facility for 2018+
The international Project Office is operated at LSW.