Short Course on High Energy Astrophysics

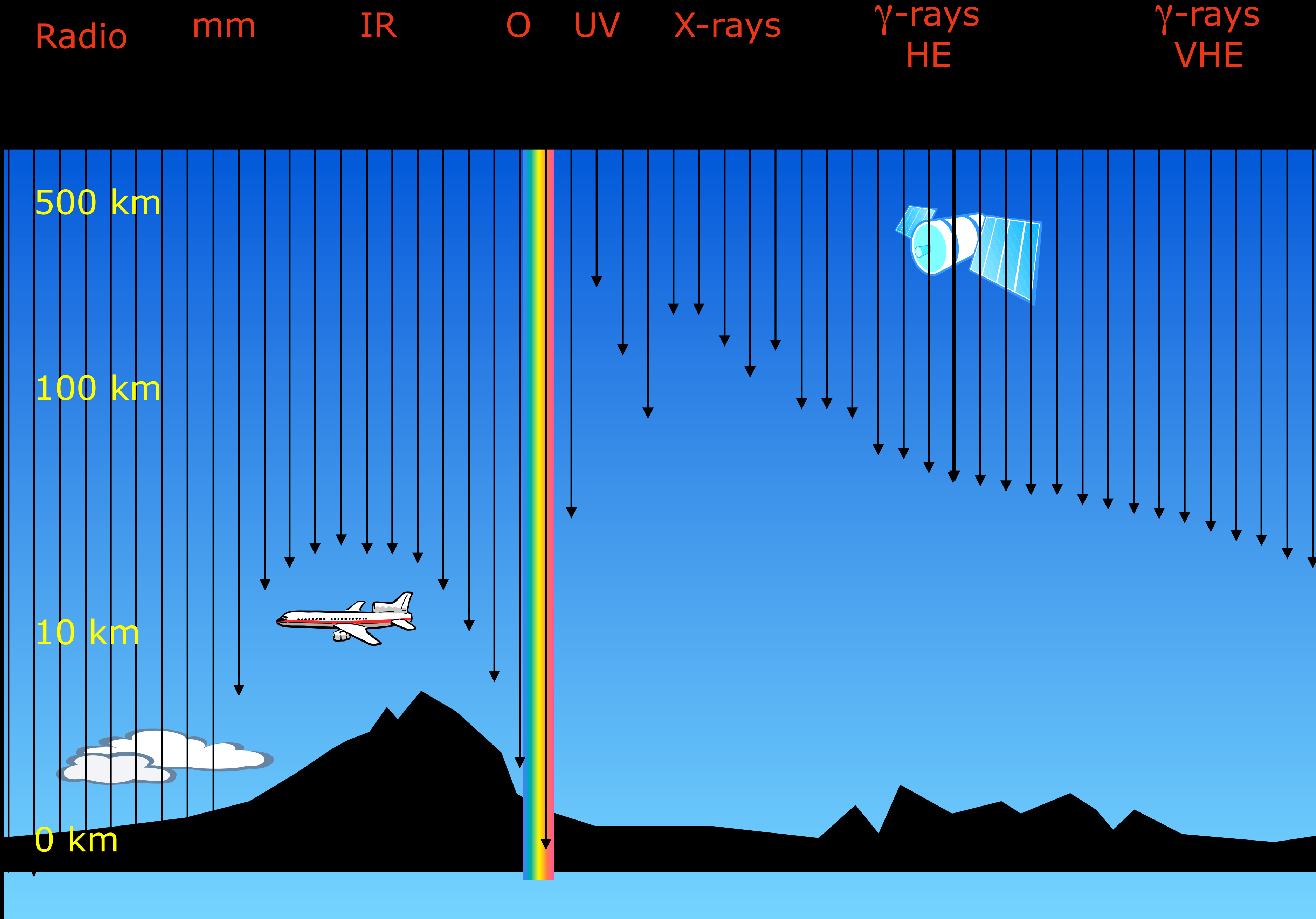
Exploring the Nonthermal Universe with High Energy Gamma Rays

Lecture 4: **Ground-based gamma-ray detectors: status and future**

Felix Aharonian
Dublin Institute for Advanced Studies, Dublin
Max-Planck Institut fuer Kernphysik, Heidelberg

Florianopolis, Brazil, March 2016

Transparency of the Earth's atmosphere for cosmic E-M radiation



detecting γ-rays from ground and from space

"direct" detection of LE/HE gamma-rays - possible from space, but is effective only at enertgies below 100 (10?) GeV

"indirect" detection of VHE gamma-rays - possible from ground, but is effective only at energies above 100 (10?) GeV

recently: detection of gamma-rays from Crab Nebula:
up to 100 GeV by *Fermi* LAT and down to <50 GeV by MAGIC and HESS

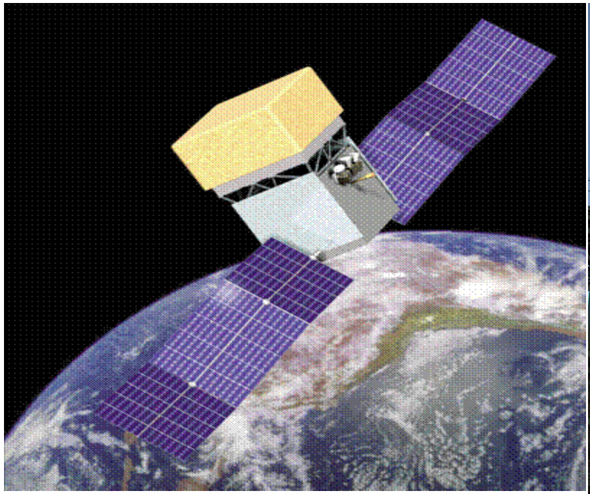
very good agreement of measured fluxes around 100 GeV !

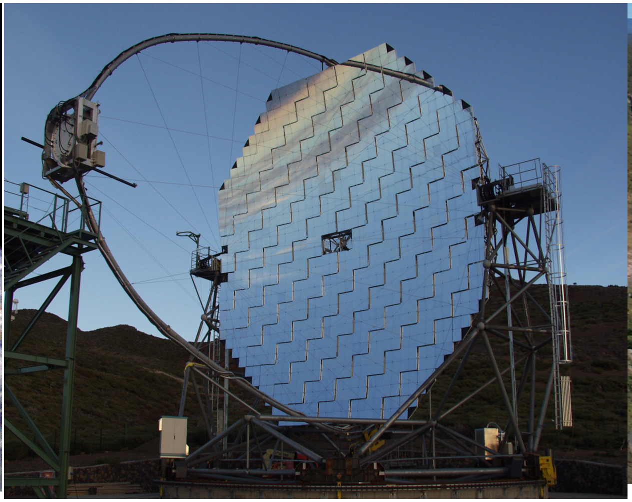
HE, VHE, and UHE Gamma-Ray Detectors

HE

VHE

UHE





direct

Cherenkov light

EAS particles

Ground Based Gamma-Ray Astronomy

presently provides the VHE window in the spectrum of cosmic E-M radiation

0.1 TeV and 100 TeV => TeV (VHE) γ-ray Astronomy

with a potential for extension of the energy domain

- below 100 GeV down to 10 GeV: multi-GeV (HE) Astronomy
- above 0.1 PeV up to 1 PeV: PeV (UHE) Astronomy

in foreseeable future (hopefully) => GeV-TeV-PeV astronomy

Status of ground-based gamma-ray astronomy

after several decades of struggles and controversial reports/claims ground-based gamma-ray astronomy became an observational discipline - part of modern astronomy/astrophysics with:

- *two viable detection techniques:*
  (i) Imaging Atmospheric Cherenkov Telescope Arrays
  (ii) Low-threshold EAS arrays/Water Cherenkov Detectors

brief history

1950-1970s: first ideas about detection of gamma-rays using ground based detectors - Cherenkov-light telescopes and EAS arrays; first theoretical estimates, first meaningful upper limits; first claims of possible/marginal detections of TeV gamma-ray sources, including Crab (Fazio et al. 1969), and radiogalaxy Centaurus A (Grindlay et al. 1972)

mid 1980s: interesting times with X-ray binaries - exciting reports about detections of TeV/PeV signals (of non-photonic origin?!) from Cyg X-3, Her X-1, …but… unfortunately…

1989: first reliable detection of a TeV gamma-ray signal from the Crab Nebula by the Whipple collaboration (Weekes et al. 1989)
=> finally! ASTRONOMY!
although "a single-source gamma-ray astronomy"

1990s:

- Exciting discoveries by CANGAROO, CAT, HEGRA and Whipple groups (in particular exceptional flares of Mkn 501 in 1997!), but not yet a breakthrough; gamma-ray astronomy recognized as the most advanced area of Astroparticle Physics, but not yet a nominal astronomical discipline; a standard question of opponents: "*how many sources do you have?*".

  very important - HEGRA group demonstrated the power of the stereoscopic IACT technique with detection of sources at the level of "a few % of Crab", including two "superstars" on the sky Cas A and M87, as well as and the first unidentified (slightly extended !) TeV source => an (obvious?) path towards HESS:
  (i) HEGRA concept (stereoscopy and large FoV)
  (ii) Whipple type (10m-diameter class) reflectors
  (iii) CAT type imagers (multi-hundred channel, fine pixels)

- CASA-MIA - giant EAS array: no >100 TeV gamma-ray sources at the level of energy flux 1eV/cm^{2}s

2000s

TeV gamma-ray astronomy - a success story

over last several years the field has bee revolutionized

before – “astronomy“ with several sources
(Astroparticle Physics rather than Astronomy)

now – a truly astronomical discipline with characteristic key words:
energy spectra, images, lightcurves, surveys…

with tens (> 150) detected G & EXG sources
and two well established detection techniques
in the energy interval between 0.1 TeV to 100 TeV

the major factors which make possible this success ?

several factors… but basically thanks to the lucky combination of two:

- ✓ *great potential of the detection technique*
- ✓ *effective acceleration of TeV/PeV particles on all astronomical scales (coupled with favourable conditions for production of gamma-rays)*

ground-based technique:

"indirect" - based on the detection of secondary products of air showers or their Cherenkov light

Earth's atmosphere is not a full absorber, but

can be used as a part of perfect γ-ray detector

Why Cherenkov telescopes ?

[CT = an optical reflector with a PMT in focus + fast (ns) electronics]

- large detection area – typically 0.1 km2,
  potentially up to 10km^2 or more

- energy threshold – typically 1 TeV,
  potentially down to a few GeV

but it is a <u>cosmic ray detector</u>

rather than a <u>gamma-ray telescope</u>...

Why Imaging ?

it allows reconstruction of shower parameters!

- certain information about arrival direction
- capability to separate gamma- and proton induced showers

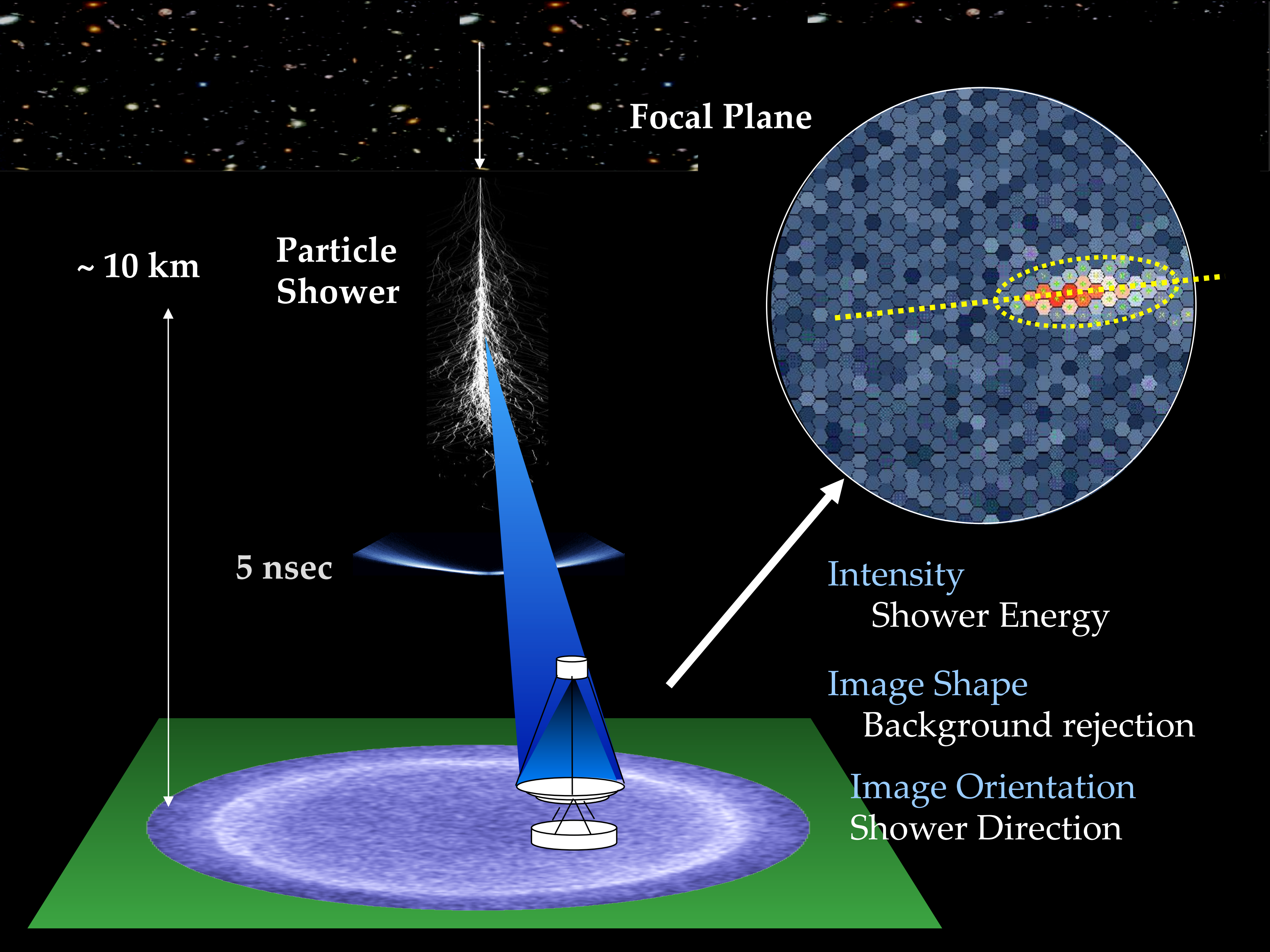
first result: detection of 10 sigma signal from Crab with Whipple 10 m telescope (1989)

a good gamma-ray detector but not yet a perfect telescope ...

Why Stereoscopy ?

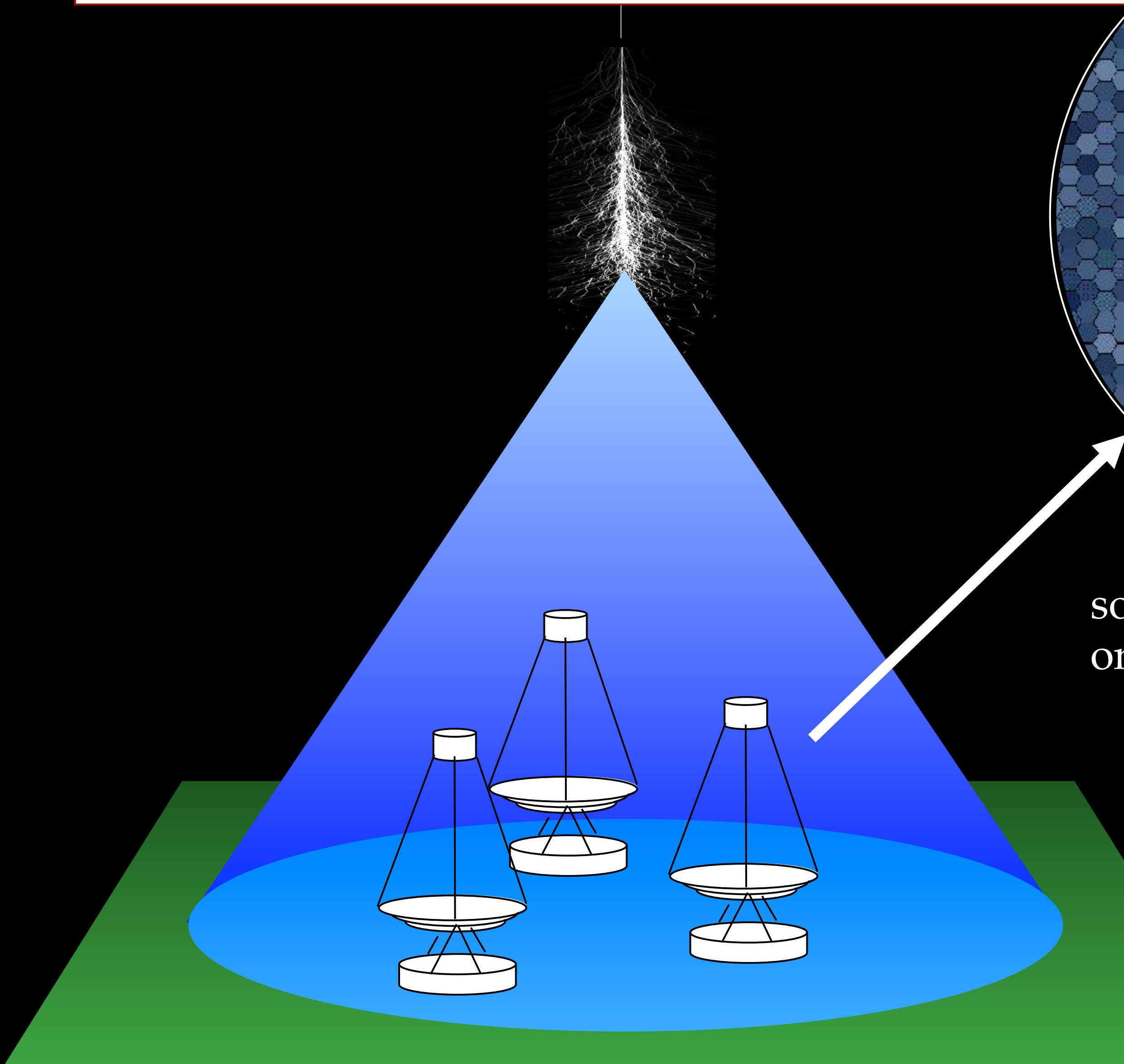
- ✓ better separation of hadronic and E-M showers
  - → confidence/reliability, sensitivity
- ✓ angular resolution of about 3 arcmin
  - → sensitivity, source localization, morphology
- ✓ energy resolution 10 to 15 per cent
  - → spectrometry
- ✓ rejection of local muons, better rejection of N.S.B.
  - → low energy threshold, systematics under control
- ✓ quite large (up to 5 degree) FoV
  - → extended sources, effective surveys, larger collection areas ()

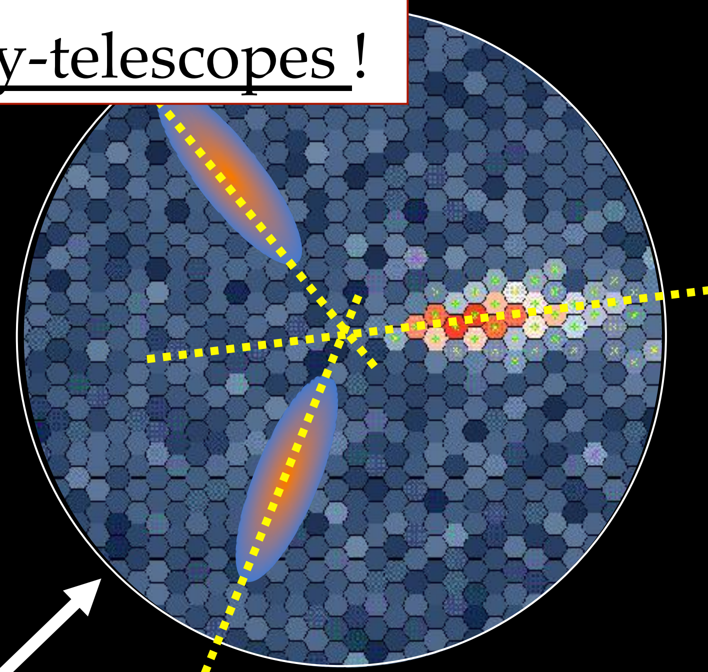
IACT arrays are perfect gamma-ray telescopes !



Focal Plane
~ 10 km
Particle
Shower
5 nsec
Intensity
Shower Energy
Image Shape
Background rejection
Image Orientation
Shower Direction

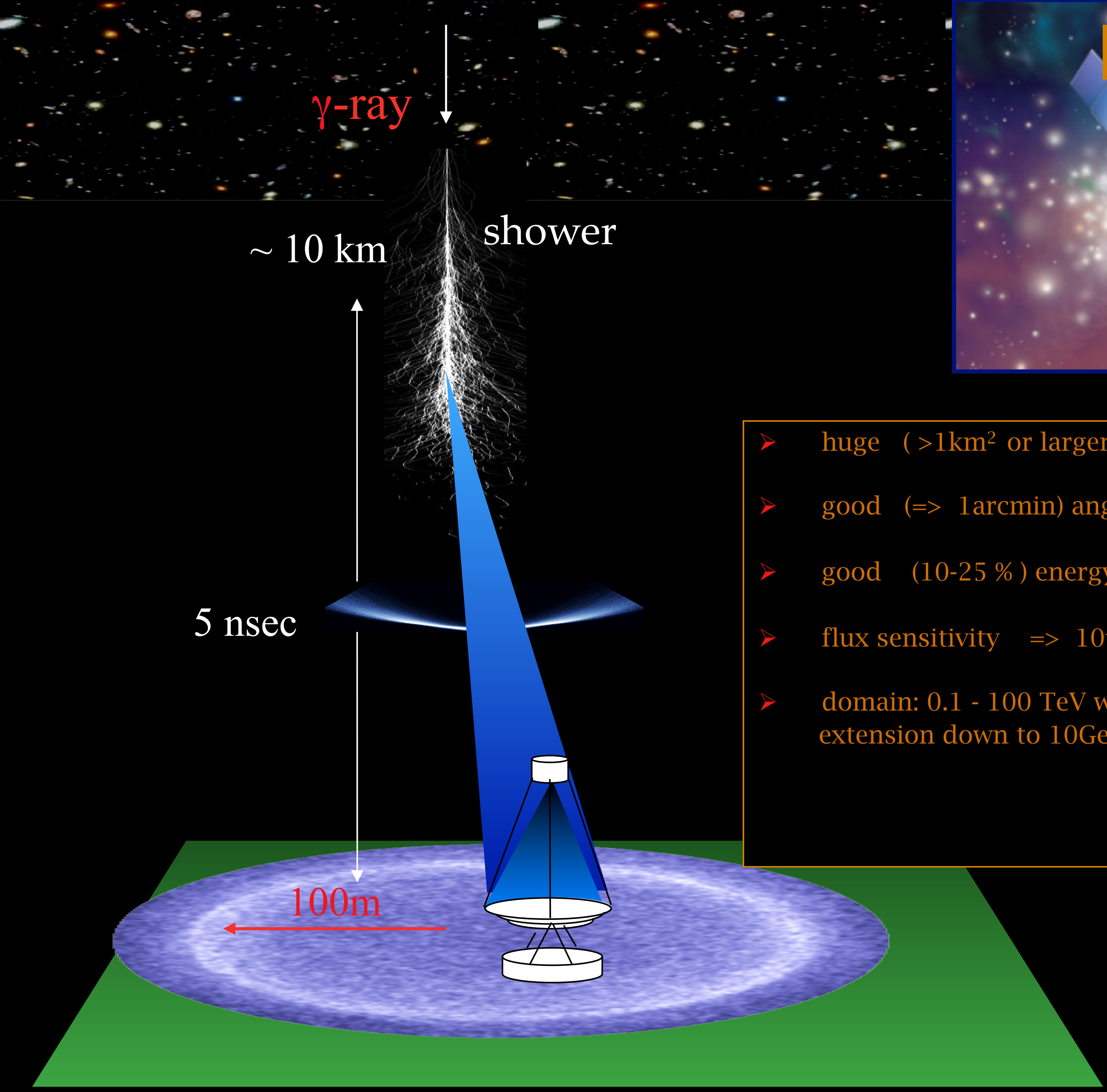
Stereoscopic IACT arrays
as perfect <u>γ-ray-telescopes</u>!





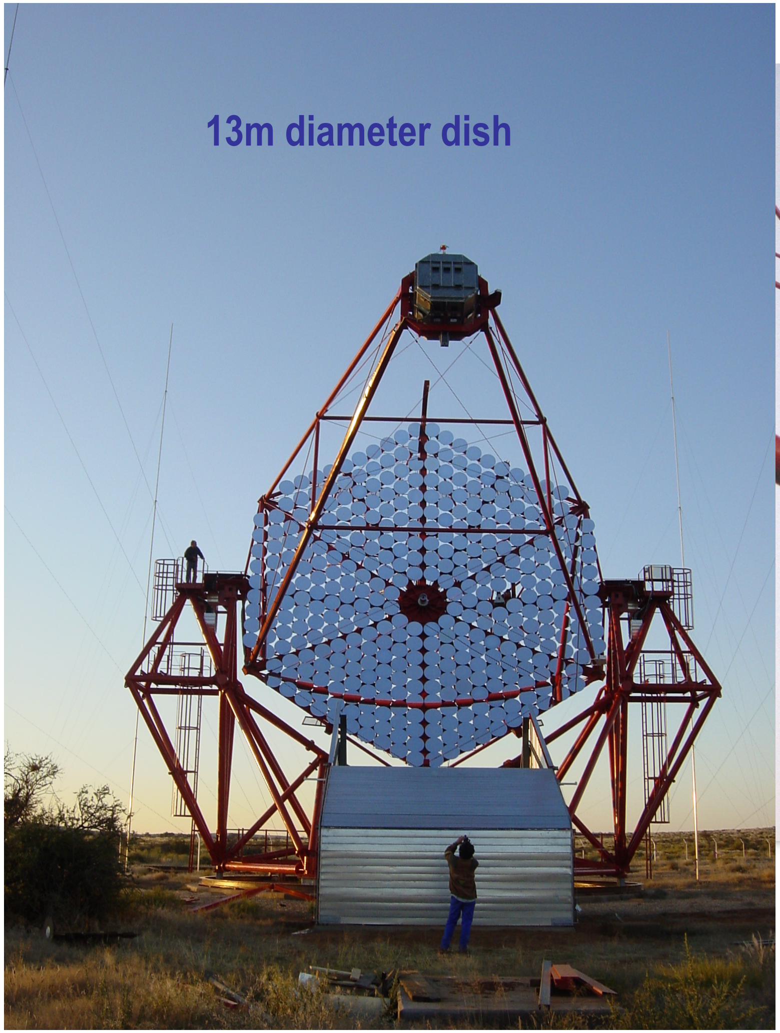
source is located (somewhere)
on the image axis …

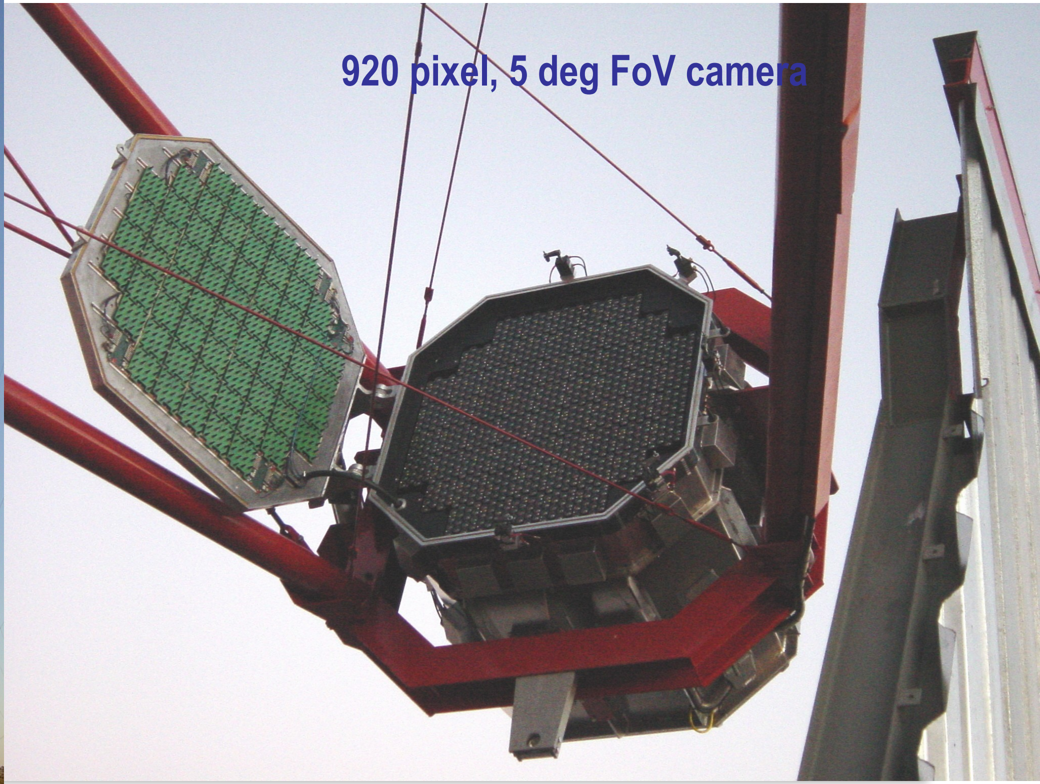
need several views
to get unambiguous
shower direction



- huge (>1km^2 or larger) detection area
- good (=> 1arcmin) angular resolution
- good (10-25 %) energy resolution
- flux sensitivity => 10^{-14} erg/cm^2 s
- domain: 0.1 - 100 TeV with a potential of extension down to 10GeV and up to 1PeV

H.E.S.S. - *High Energy Stereoscopic System*





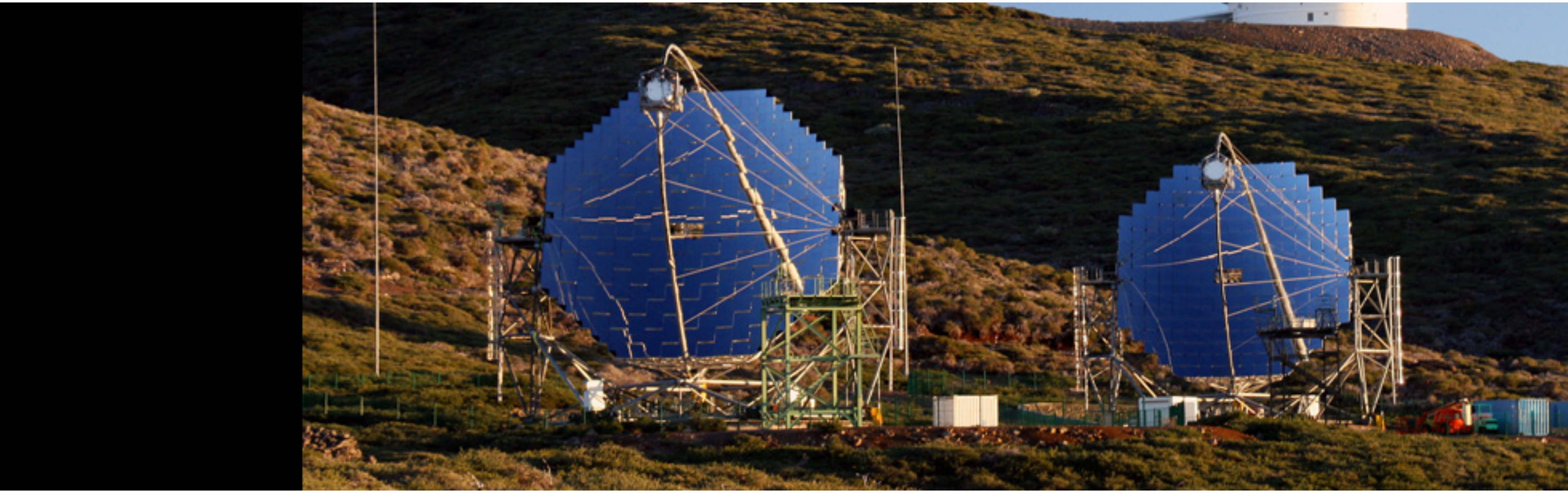
the first representative of the new generation of IACT arrays

HESS II- lower threshold

VERITAS

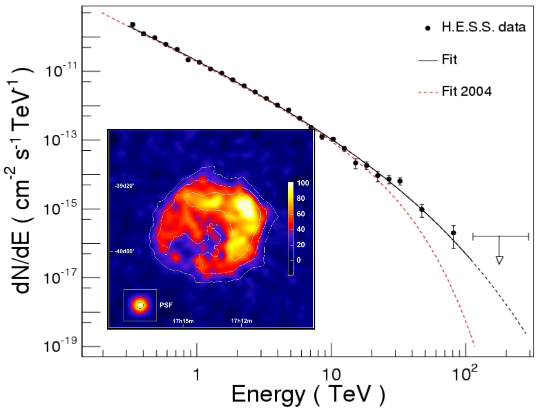
South Arizona

MAGIC II



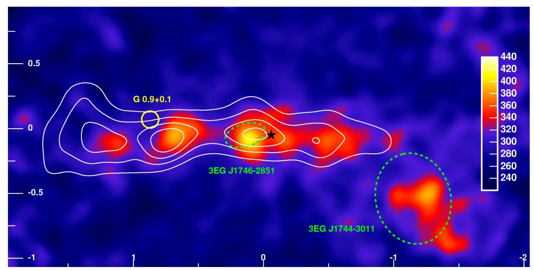
good performance => high quality data => solid basis for theoretical studies

RXJ 1713.7-3946



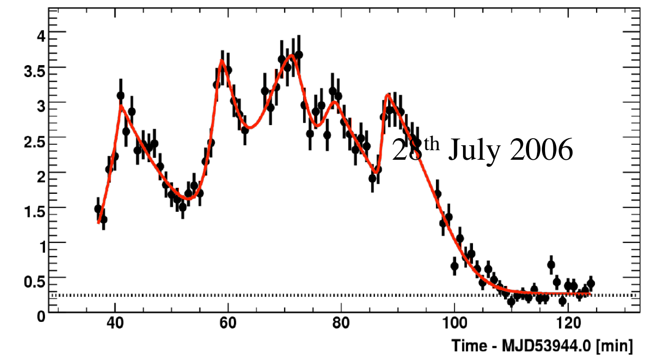
TeV image and energy spectrum of a SNR

Galactic Center



resolving GMCs in the Galactic Center 100pc region

PKS 2155-309



variability of TeV flux of a blazar on minute timescales

multi-functional tools: *spectrometry* *temporal studies* *morphology*

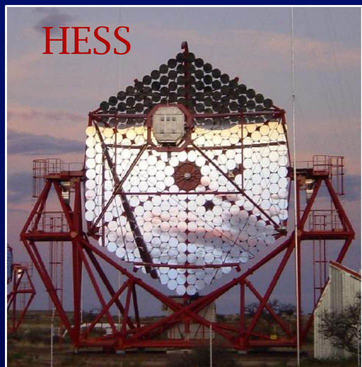
✓ extended sources: *from SNRs to Clusters of Galaxies*

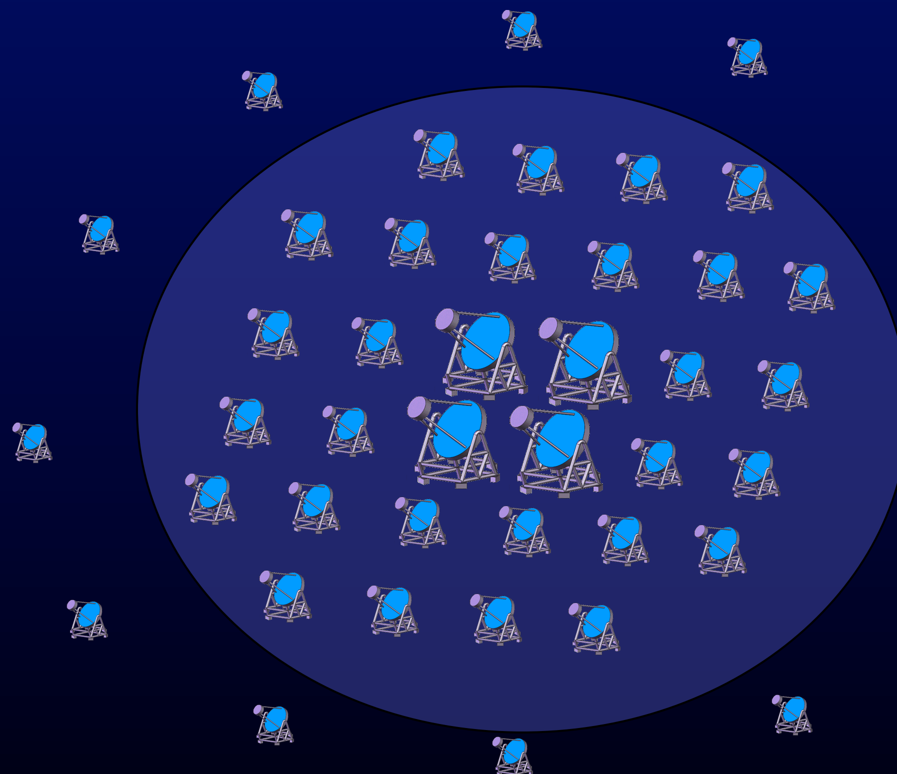
✓ transient phenomena *μQSOs, AGN, GRBs, ...*

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology

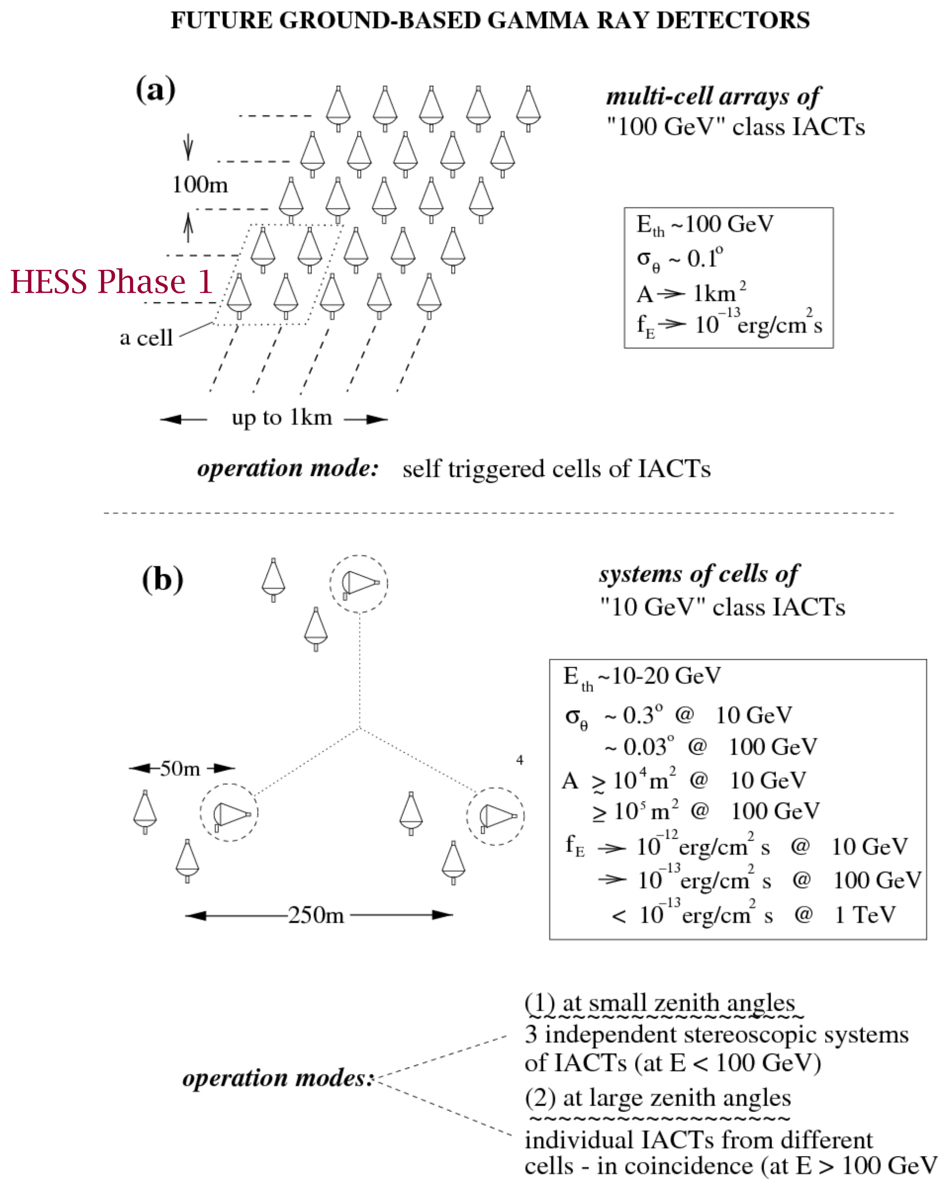
towards next generation IACT Arrays:

- ✓ an order of magnitude better sensitivity
- ✓ broader energy coverage: 10^{10} to 10^{15} eV





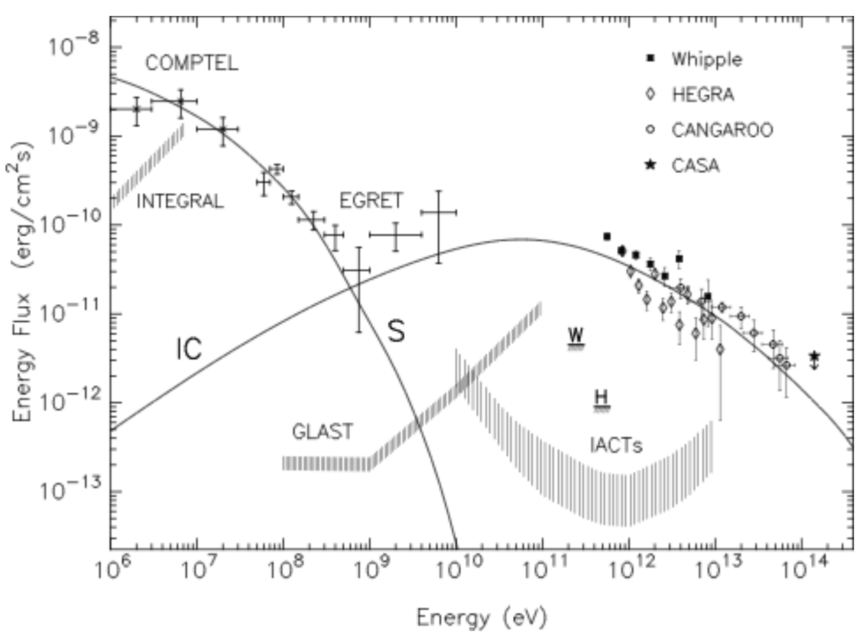
from HESS/MAGIC/VERITAS to CTA…



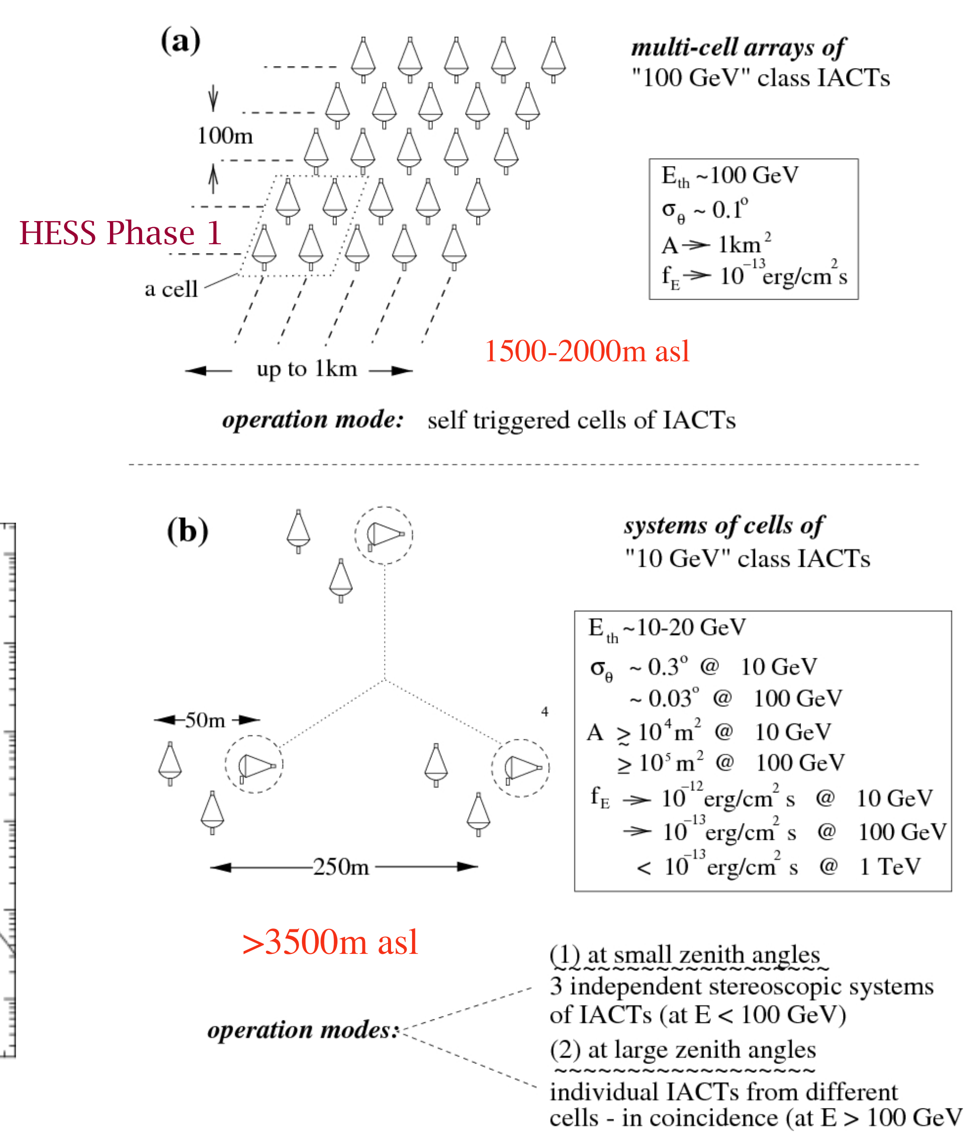
two possible designs of IACT arrays (Aharonian 1997, LP97, Hamburg 1997)

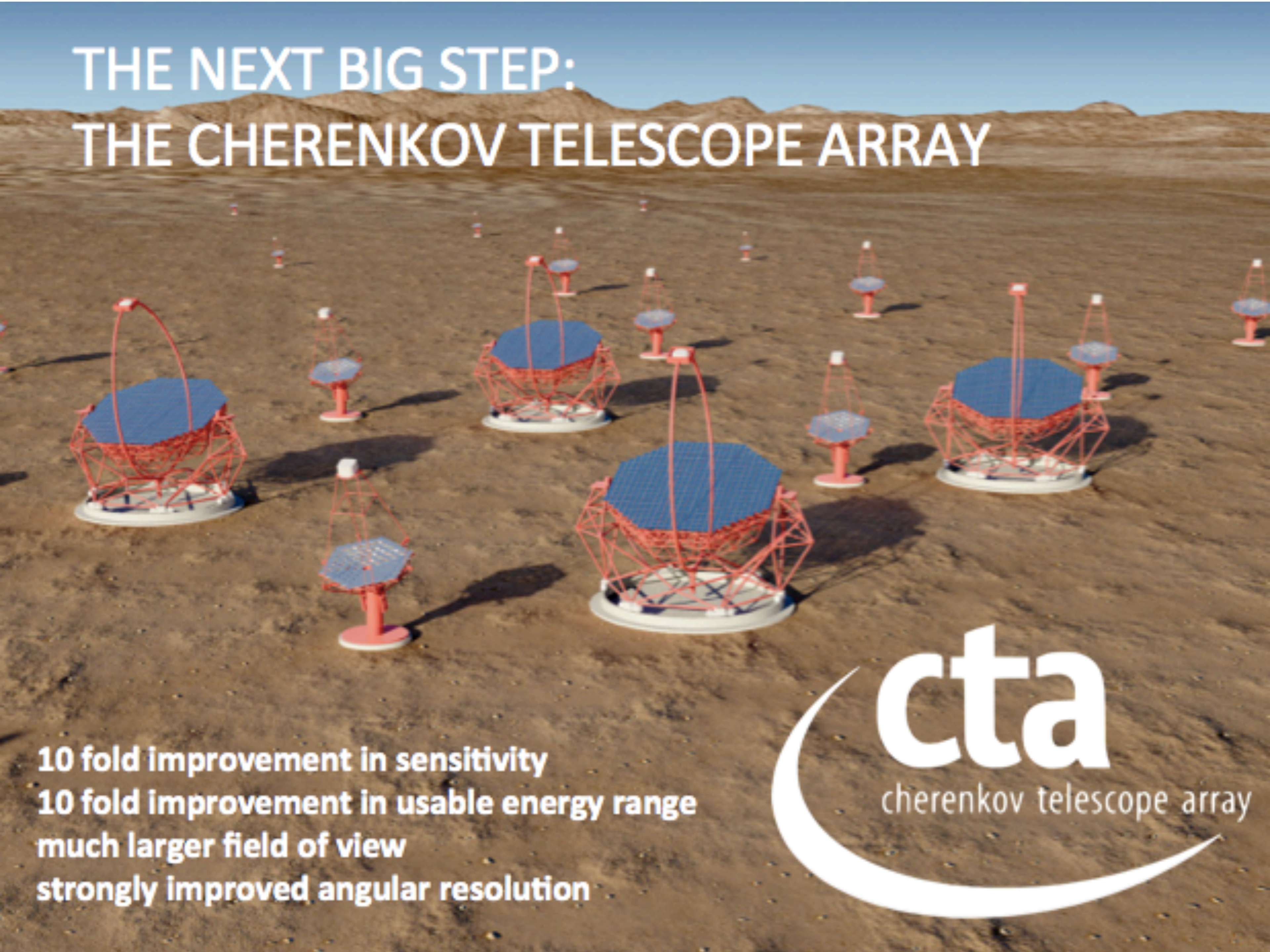
two possible designs
of IACT arrays =>

the slide shown first time in Padova in 1995 at the 4th “Towards a major …” workshop published 2years later, in: FA 1997, LP97 (Hamburg)



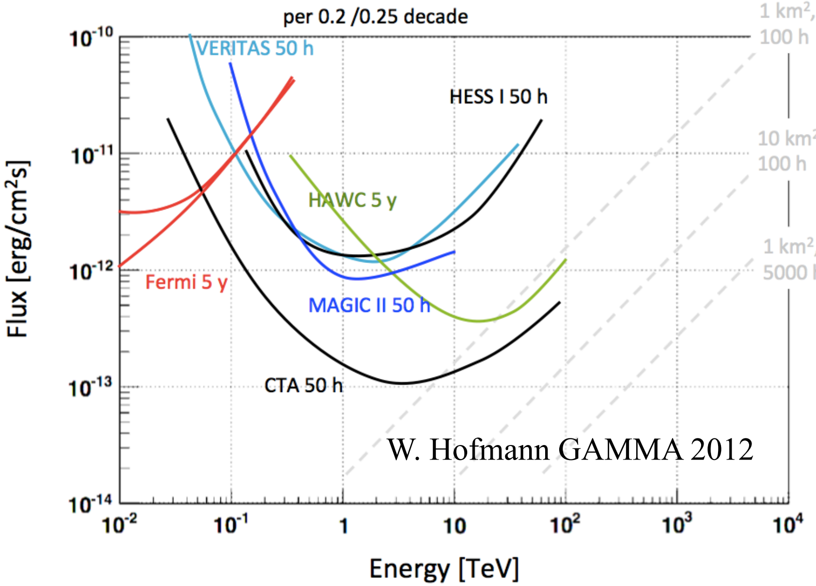
FUTURE GROUND-BASED GAMMA RAY DETECTORS



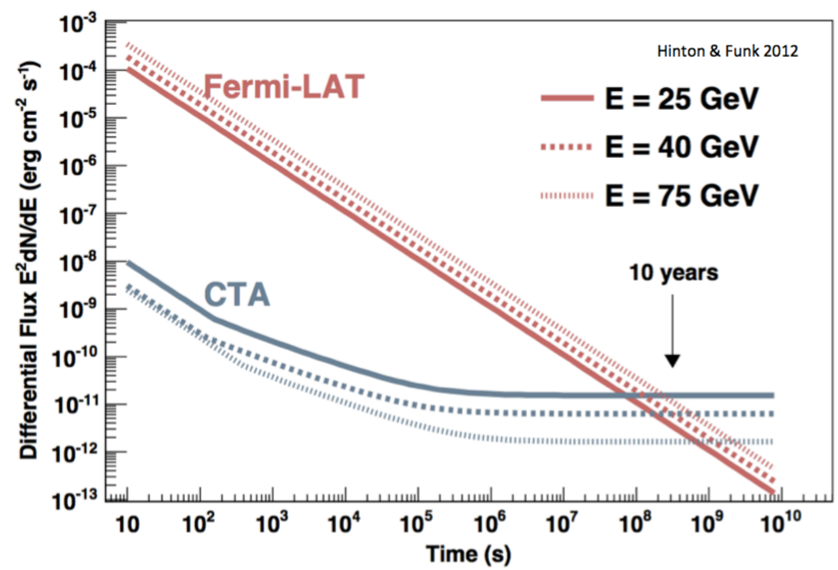

THE NEXT BIG STEP:
THE CHERENKOV TELESCOPE ARRAY
10 fold improvement in sensitivity
10 fold improvement in usable energy range
much larger field of view
strongly improved angular resolution
cta
cherenkov telescope array

CTA – a powerful tool for exploration of the Nonthermal Universe

DIFFERENTIAL SENSITIVITY



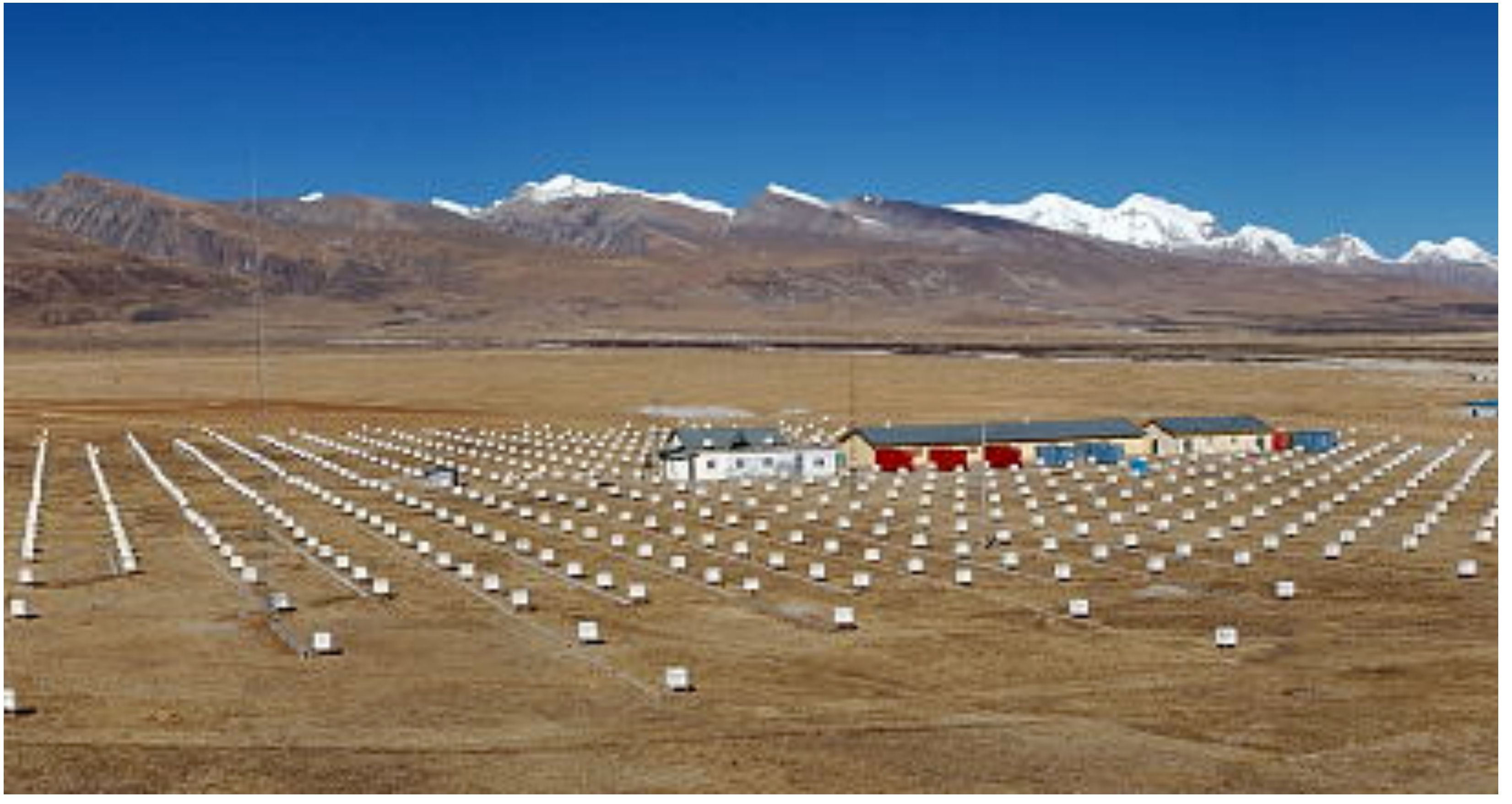
CTA VERSUS FERMI – TRANSIENT SOURCES



- detection of `nominal' (Fermi/AGILE) AGN for just 1min,
- detection of >10,000 gamma-rays from (Fermi LAT) GRBs with >10-GeV tails

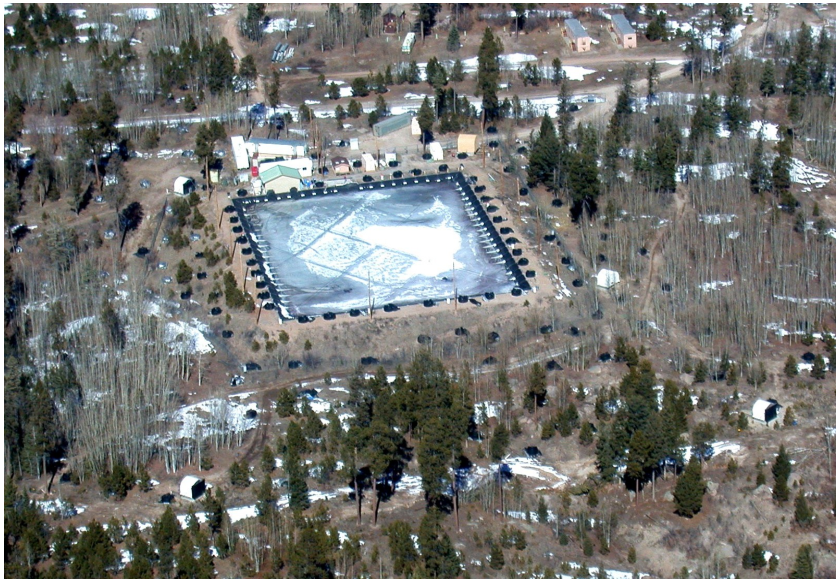
but above several tens of GeV, the emission could be suppressed at tens of GeV
=> low threshold is critical (as low as 10 GeV is possible!)

Air shower detectors



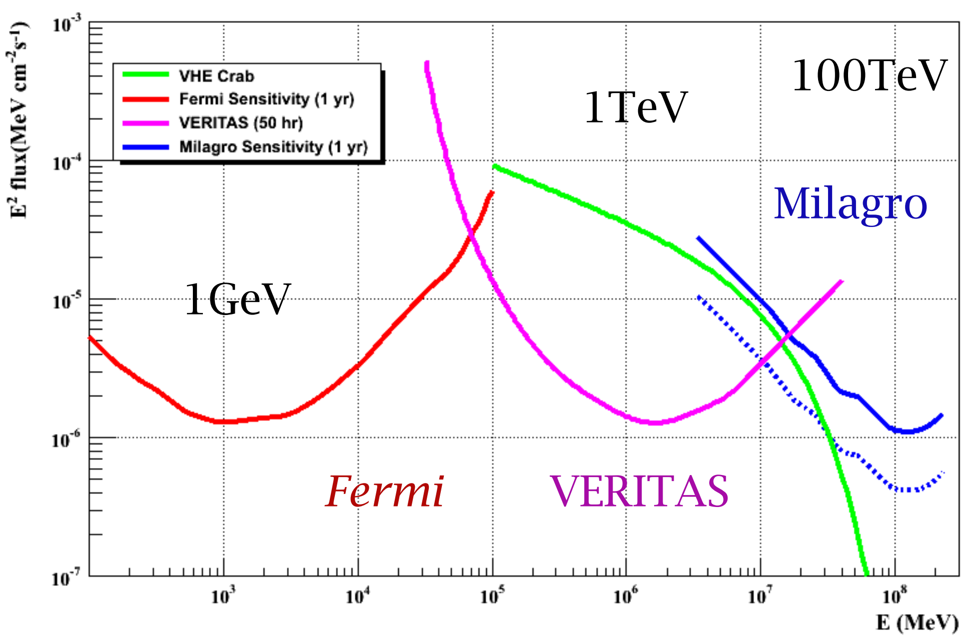
Tibet AS-gamma Experiment

Milagro Detector



- Central Water Pond (80x60 meter)
- 450 PMTs under 1.5 m water
- 273 PMTs under 6 m water
- 2640 meters a.s.l. elevation

- 1700 Hz Trigger Rate
- angular resolution $0.35^{o} – 1.0^{o}$
- energy range: 100 GeV – 100 TeV
  median energy 10 – 40 TeV
  (depending on cuts, weights etc)
- Operated from 2000-2008

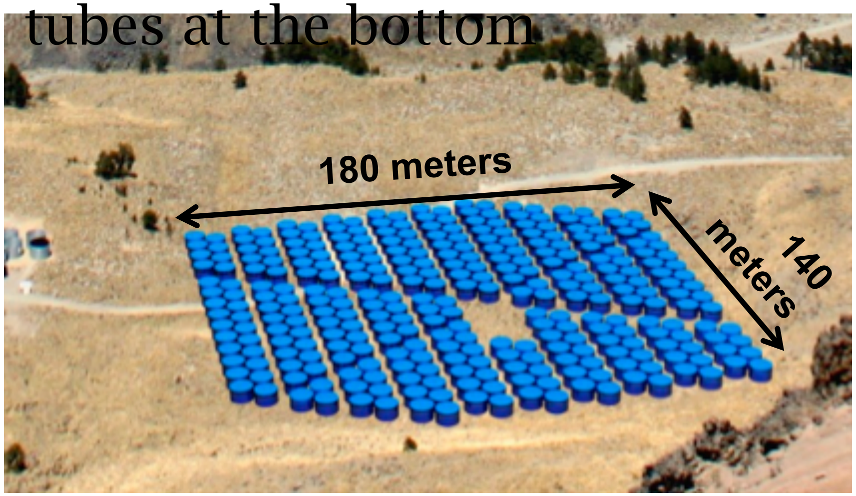


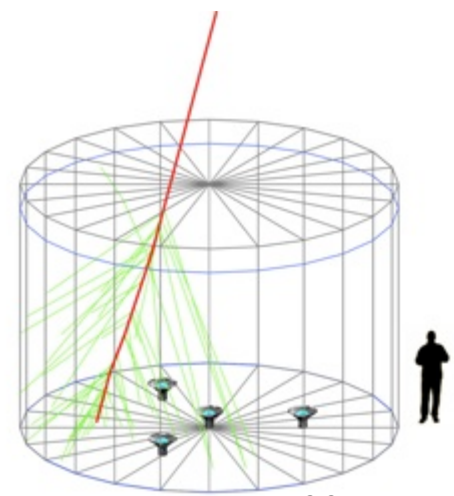
energy flux sensitivity compared to Fermi and VERITAS but at 100TeV

Milagro is a quite sensitive instrument!

next step: HAWC (High Altitude Water Cherenkov)

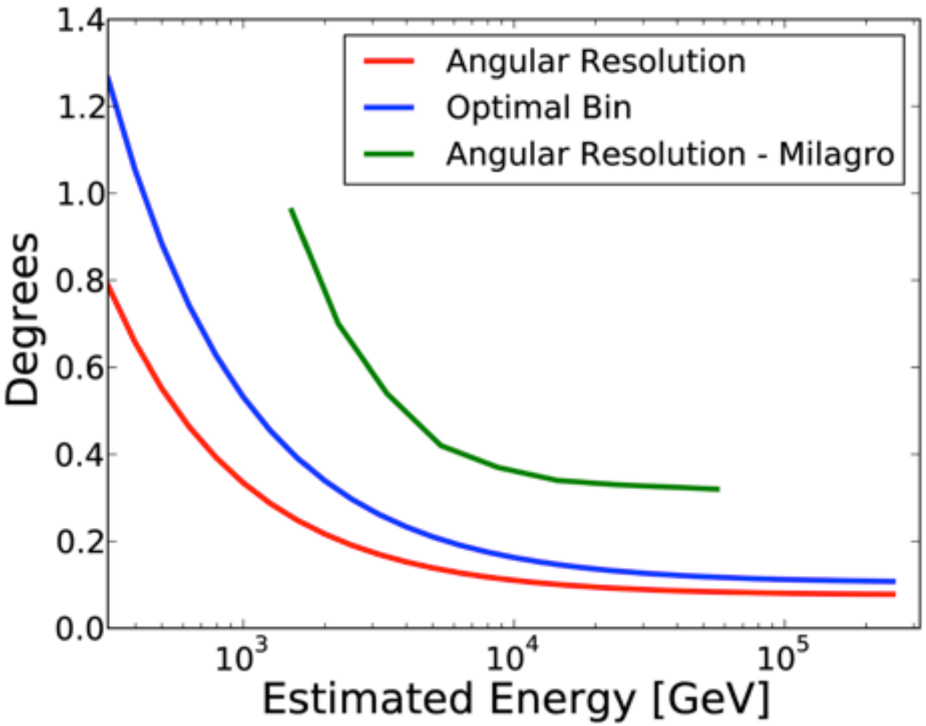
300 close packed water tanks (7.3m dia x 4.5 m deep of 200,000 liters) each with 4 upward facing photomultiplier tubes at the bottom



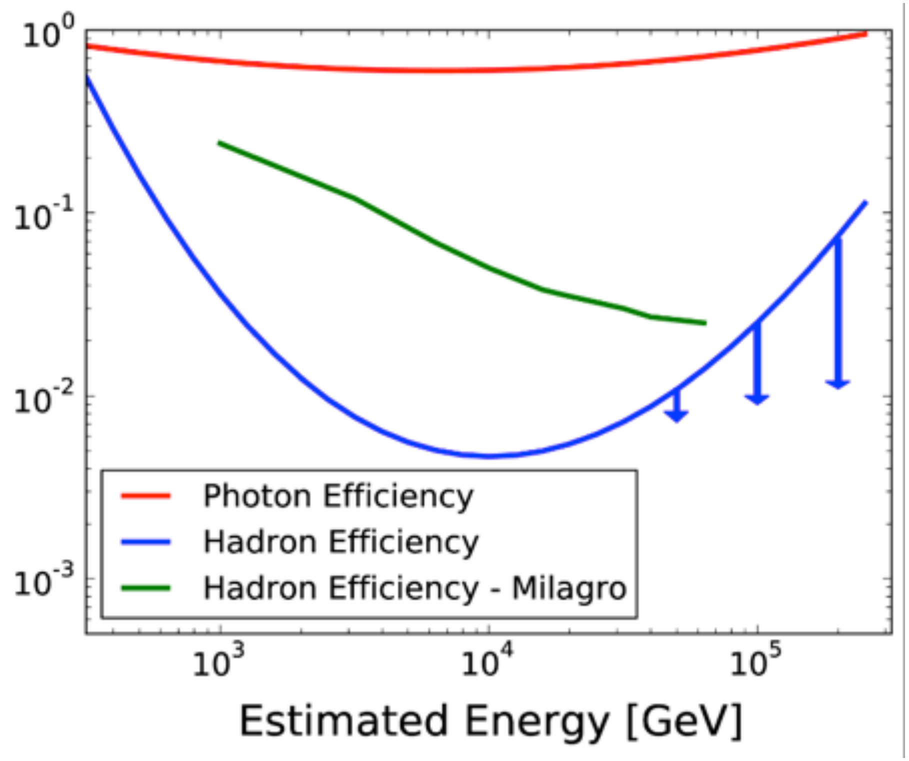


HAWC performance

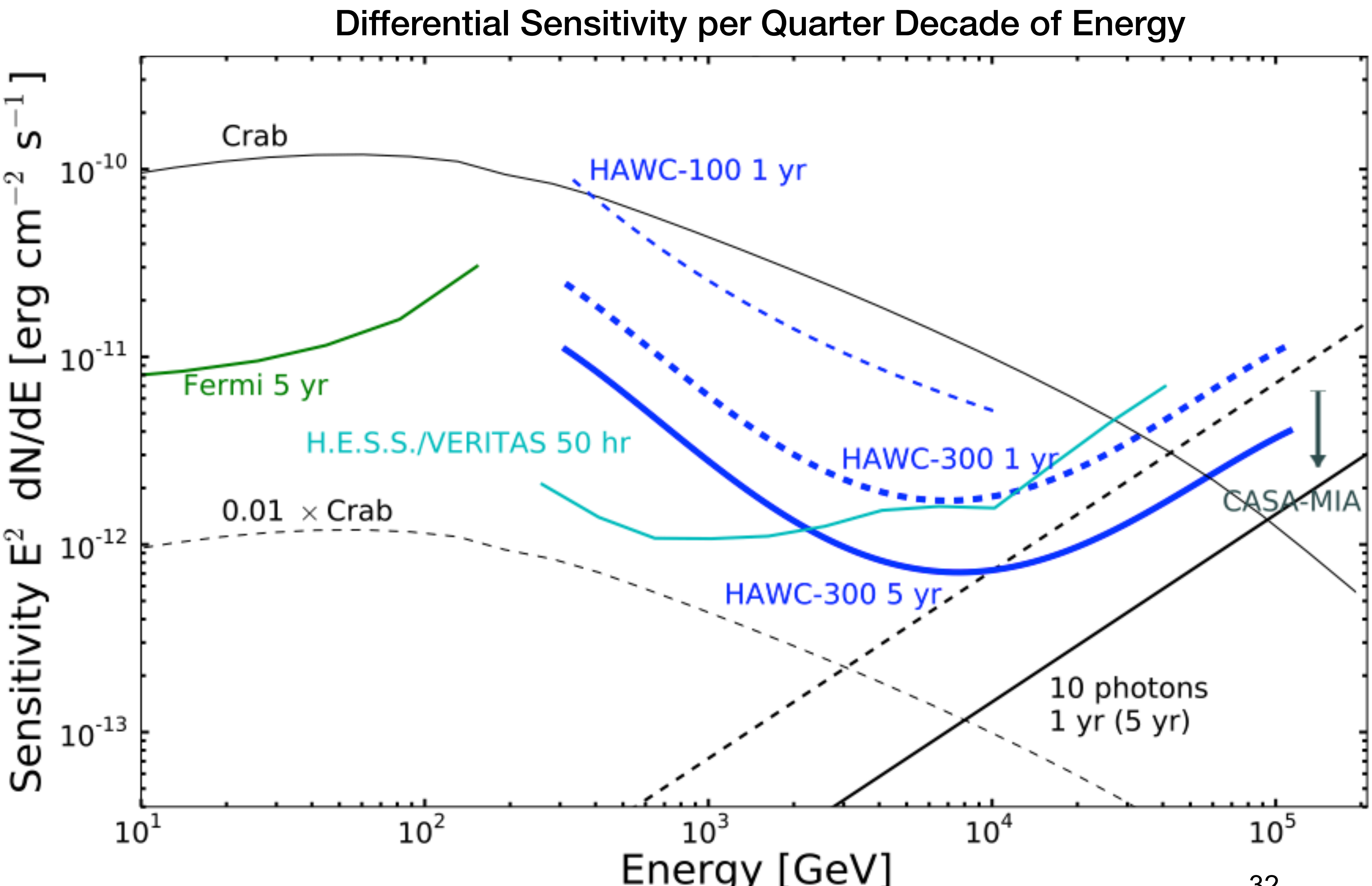
Angular Resolution



Hadron Rejection



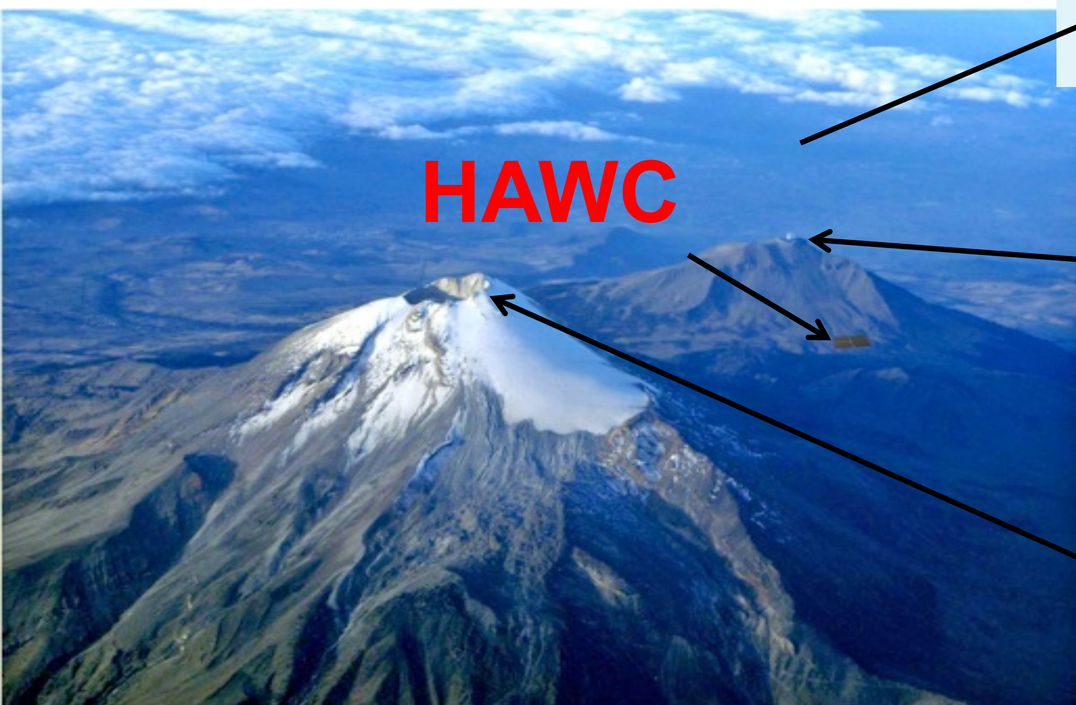
HAWC Sensitivity



http://arxiv.org/abs/1306.5800

from Milagro to HAWC - bigger and higher:
to reduce energy threshold and increase sensitivity

HAWC Site Location



Large Millimeter Telescope (50m dia. dish)

Pico de Orizaba 5600 m (18,500')

beyond HAWK …

objectives?

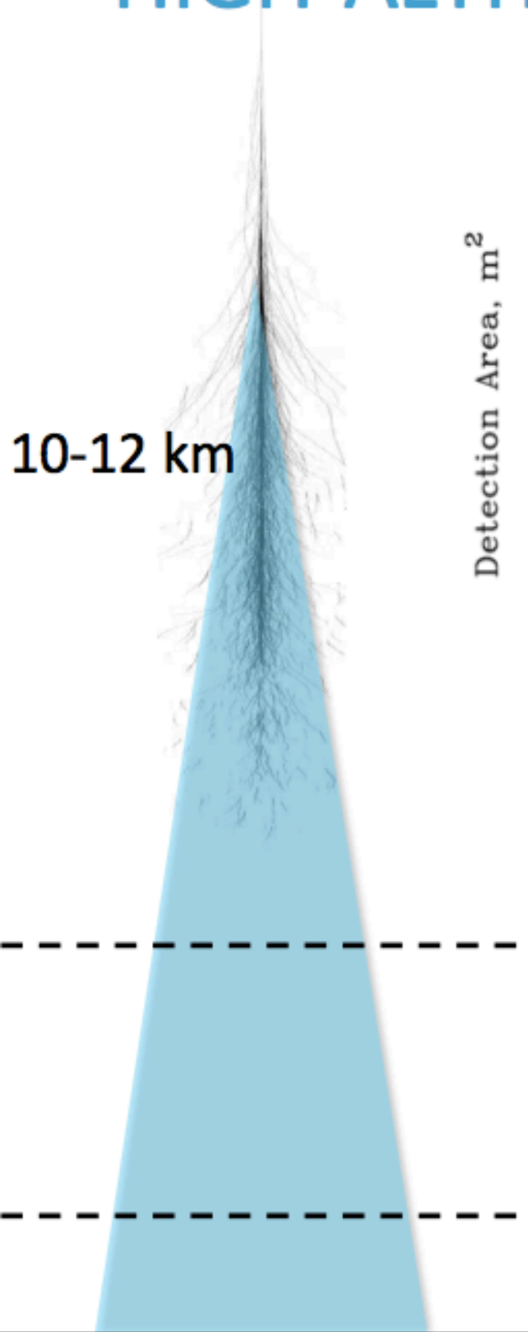
- more sensitive – larger array
- lower threshold – higher altitude

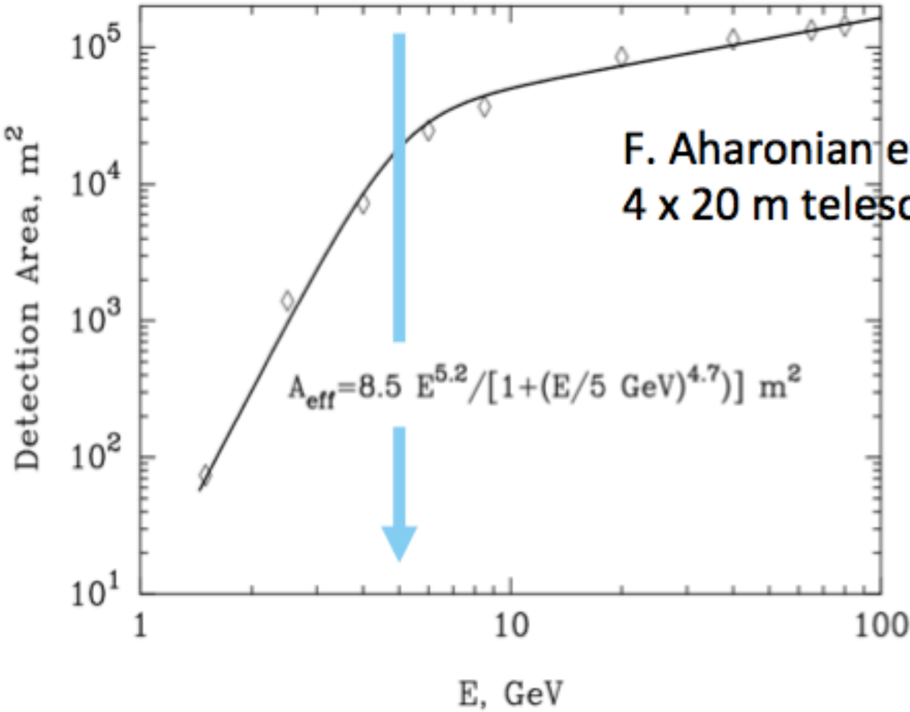
purpose?

- all sky monitor with flux sensitivity
  10^{-12} erg/cm^2 s - similar to *Fermi LAT*
  but in VHE domain
- transient VHE gamma-ray source "hunter"

plans? LATTES… (ALMA site, 5km a.s.l.)

HIGH-ALTITUDE CHERENKOV TELESCOPES





F. Aharonian et al., astro-ph/0006163
4 x 20 m telescopes @ 5000 m asl

higher light intensity (5000 m: x2)
➔lower threshold
smaller light pool area (5000 m: /2)

Reference height ~2000 m

W. Hofmann GAMMA 2012

5@5 - a GeV timing explorer

- Detector : **several 15 to 25m diameter IACTs to study the sky at energies from several GeV to several 100 GeV with unprecedented** ***photon and source statistics***

- Potential: **can detect EGRET/Fermi sources with spectra extending beyond 5 GeV for exposure time from** ***1 sec to 10 minutes***

- Targets: **Gamma Ray Timing Explorer for study of nonthermal phenomena:** ***AGN, Microquasars, GRBs,, Pulsars ...***

5@5 is complementary to GLAST
in fact due to small FoV needs very much GLAST
and ... GLAST certainly needs a 5@5 type instrument

"The rapid development and successful operation of 5@5 during the lifetime of GLAST would represent a major observational coup"

Gamma Ray Group Summary Report, Snowmass "The future of particle Physics" (astro-ph/0201160)

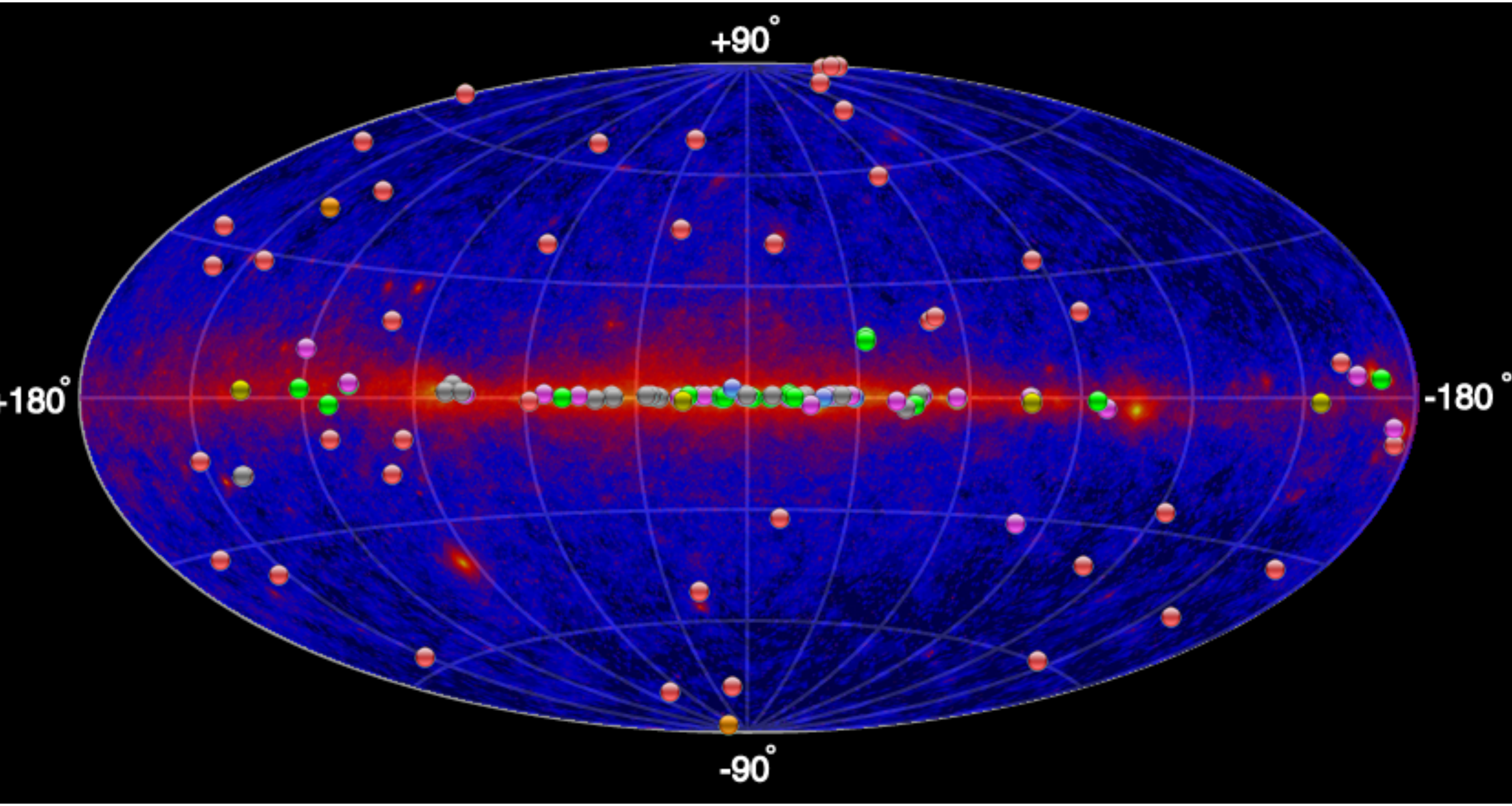
5@5 – a Gamma Ray Timing Explorer

Future of ground-based gamma-ray astronomy

- aim? sensitivity: F_E => 10^{-14} erg/cm^2 s (0.03-30TeV)
- realization 1 to 10 km^2 scale 10m+ diameter IACT arrays
- timescales short (years) - no technological challenges
- price no anymore cheap 100+ MEuro
- expectations guaranteed success - great results/discoveries
- first priority: "classical" 0.1-30 TeV IACT array with possible extension towards 30 GeV and 100 TeV
- next step: (parallel?) <100 GeV threshold all-sky monitor (LATTES?)
  <10 GeV threshold IACT array (5@5?)

Current Status

>150 TeV sources on the *Fermi* LAT map



[TeVCAT homepage]

VHE Gamma Ray Sources:

not many but representing many source populations

Extended Galactic Objects

- ✓ Shell Type SNRs
- ✓ Giant Molecular Clouds
- ✓ Star formation regions
- ✓ Pulsar Wind Nebulae

Compact Galactic Sources

- ✓ Binary pulsar PRB 1259-63
- ✓ LS5039, LSI 61 303 ?
- ✓ Cyg X-1 (a microquasar)

Galactic Center

Extragalactic objects

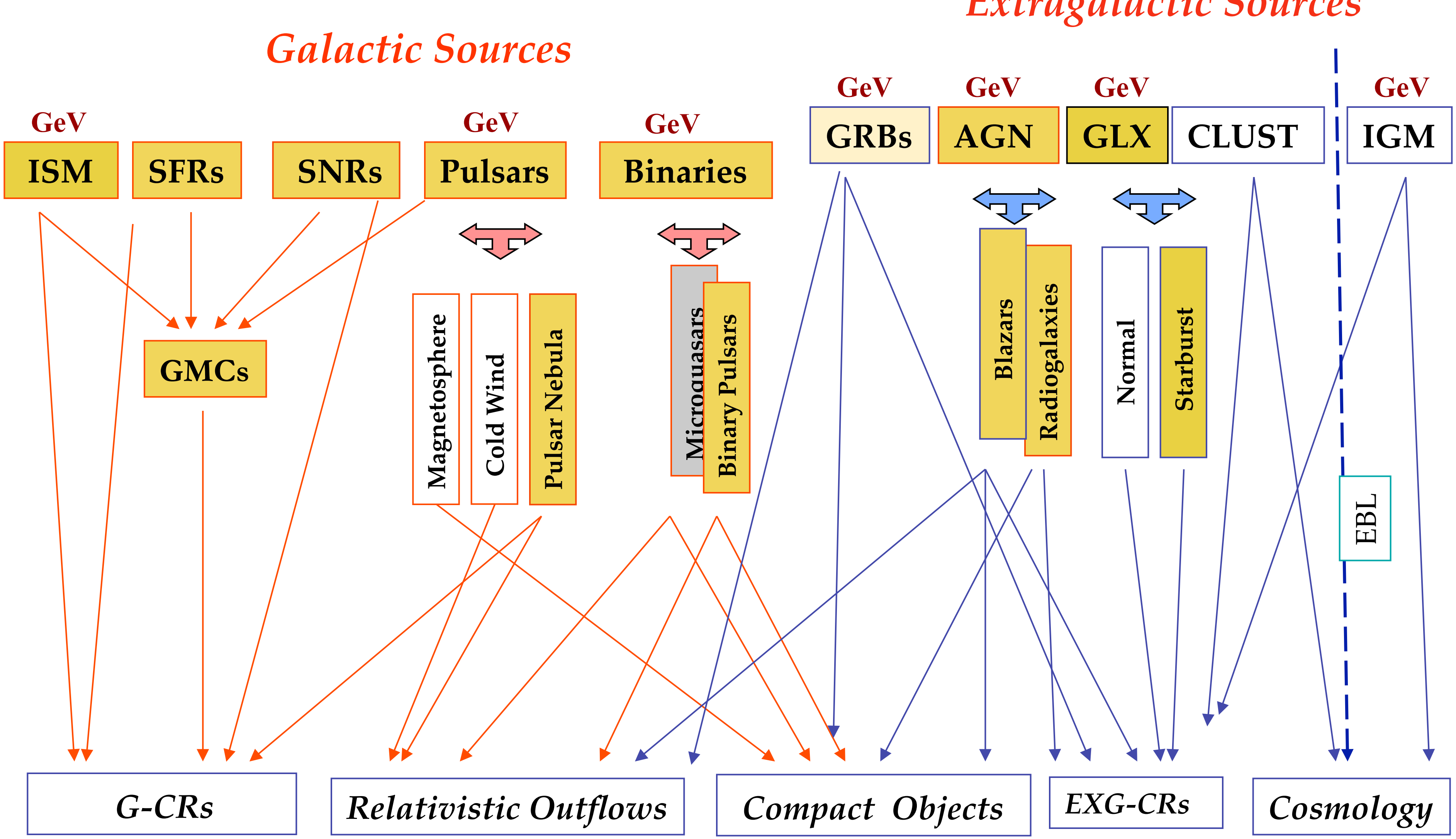
- ✓ M87, Cen A - radiogalaxies
- ✓ TeV Blazars – with redshift from 0.03 to 1
- ✓ NGC 253 and M82 - starburst galaxies

- ✓ GRBs (Fermi LAT; photons of tens of GeVs at $z > 1$)

and a large number of yet unidentified TeV sources …

VHE gamma-ray source populations

Potential Gamma Ray Sources



Major Scientific Topics