Very High-Energy Gamma-Ray Astrophysics

David A. Williams

Santa Cruz Institute for Particle Physics

UC Santa Cruz

Quarknet

July 12, 2013

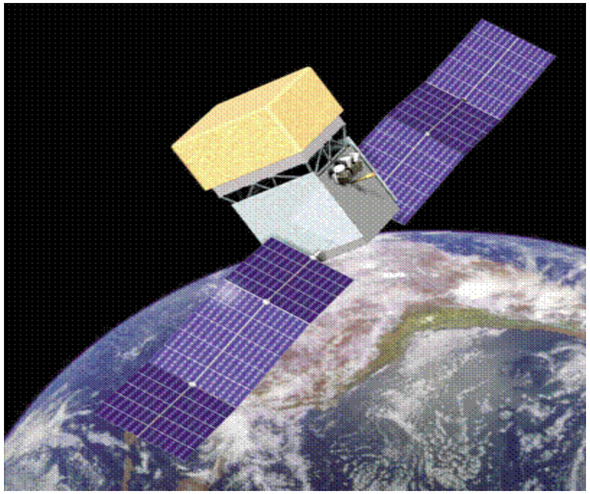
Detecting High Energy Gamma Rays

<u>High Sensitivity</u>
HESS, MAGIC, CANGAROO, VERITAS, CTA

<u>Low Energy Threshold</u>
Fermi

<u>Large Aperture/High Duty Cycle</u>
Milagro, Tibet, ARGO, HAWC

Large Effective Area
Excellent Background Rejection (>99%)
Low Duty Cycle/Small Aperture
>50 GeV (5 x 10^{10} eV)



Space-based (small area)
"Background Free"
Large Duty Cycle/Large Aperture
100 MeV – 300 GeV

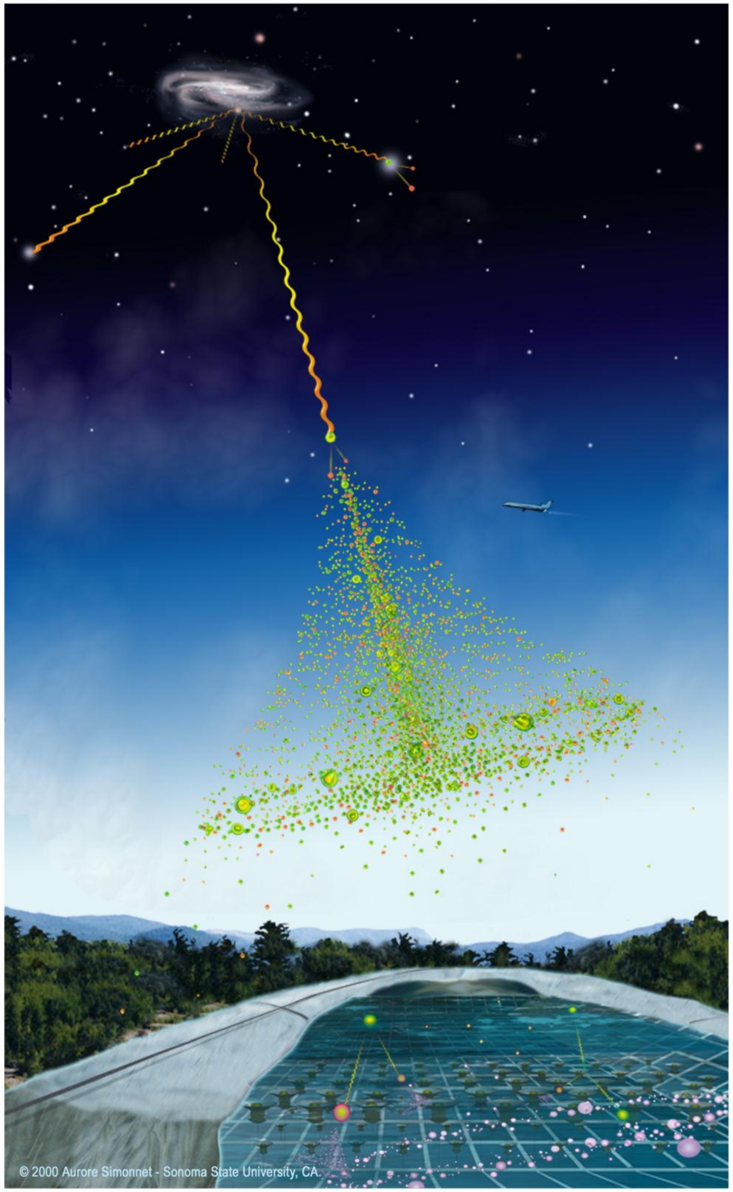
Large Effective Area
Good Background Rejection
Large Duty Cycle/Large Aperture
> 1 TeV (10^{12} eV)

Detecting >100 GeV γ-Rays

Detect shower in the atmosphere

What reaches the ground?

- Some particles
- Cherenkov light



Development of a 2TeV Gamma Ray Shower
from first interaction to the Milagro Detector

Viewed from below the shower front -
Color coded by Particle Type

This movie views a CORSIKA simulation of a gamma ray initiated shower. The purple grid is 20m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.

Blue - electrons and gammas

Yellow - muons

Green - pions and kaons

Purple - protons and neutrons

Red - other, mostly nuclear fragments

http://scipp.ucsc.edu/milagro/Animations/AnimationIntro.html

Development of a 2TeV Proton Shower from first interaction to the Milagro Detector

Viewed from below the shower front -
Color coded by Particle Type

This movie views a CORSIKA simulation of a proton initiated shower. The purple grid is 20m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.

Blue - electrons and gammas
Yellow - muons
Green - pions and kaons
Purple - protons and neutrons
Red - other, mostly nuclear fragments

http://scipp.ucsc.edu/milagro/Animations/AnimationIntro.html

Cherenkov Radiation

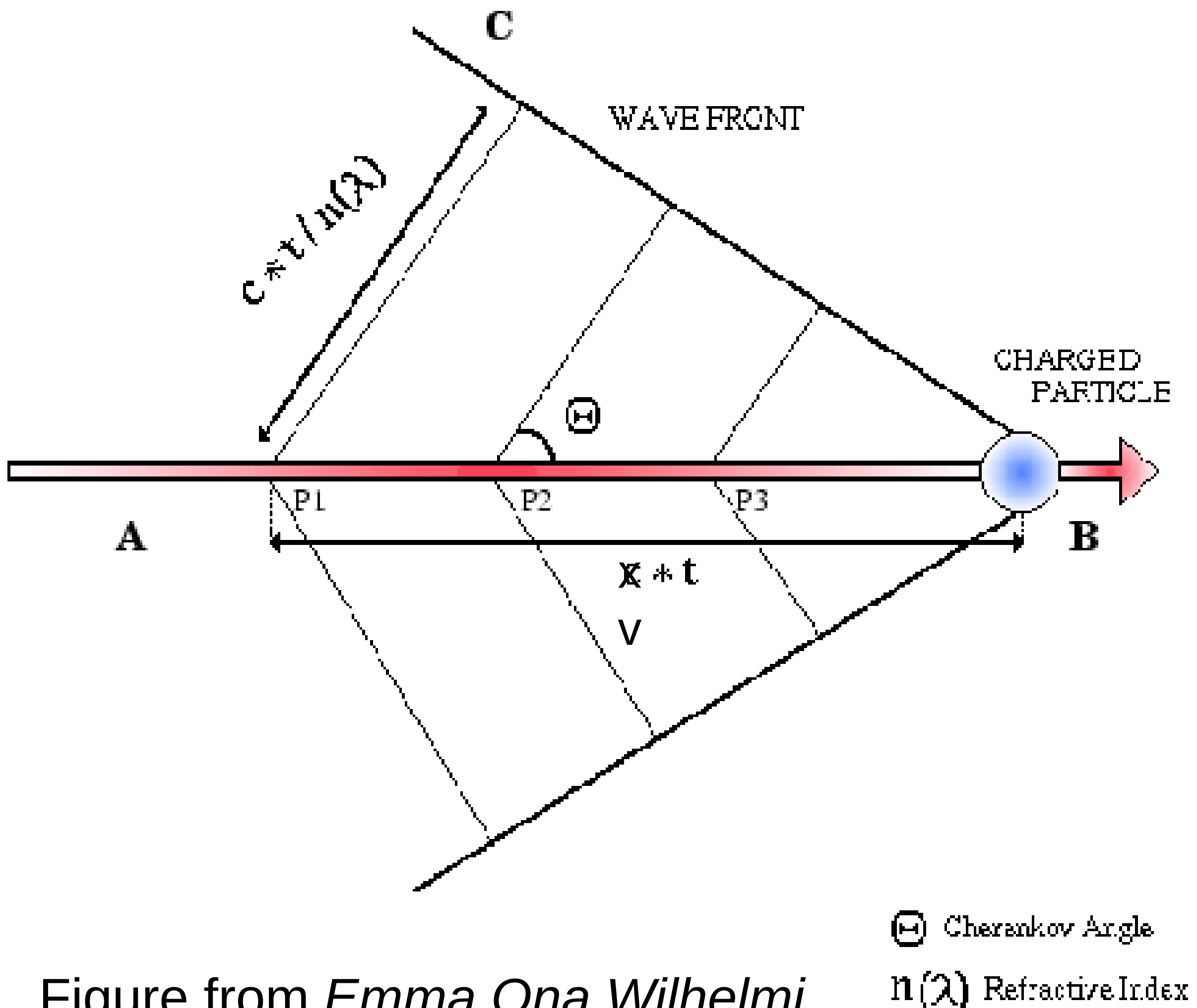


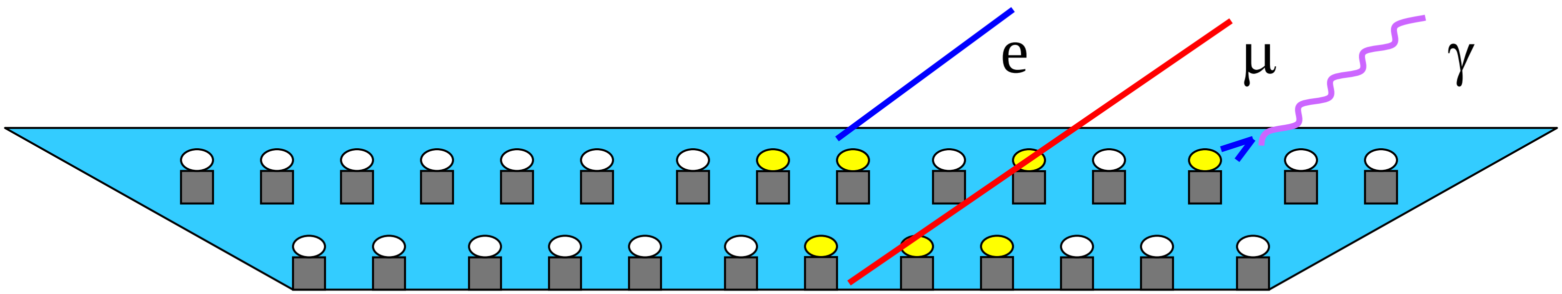
Figure from *Emma Ona Wilhelmi*

http://www.gae.ucm.es/~emma/tesina/node4.html

$\cos\theta = (c/\eta)/v = 1/(\beta\eta)$

$v/c = \beta > 1/\eta$

Milagro: Water Cherenkov Detector



Shower from a vertical 2TeV Gamma Ray Primary

Side View

Note the penetration of the shower core almost to the second layer of detectors (6m) and the formation of the bowl and ring structure by the shower core. The ring is the classic Cherenkov radiation pattern, and the bowl is formed by multiple scattering - many small rings from highly scattered particles adding up to form a bowl. In the Milagro pond the probability density of Cherenkov light emission from an entering particle is in this bowl-ring distribution.

Red - electrons and positrons

Green - secondary gammas

Blue - Cherenkov Photons

http://scipp.ucsc.edu/milagro/Animations/AnimationIntro.html

Shower from a vertical 2TeV Gamma Ray Primary

Bottom View

This shower is seen from below the Milagro pond. Note the small Cherenkov rings from the peripheral particles and the prominent bowl and ring structure formed by the core. The boxes are the same size, but the white box is at the water surface, and the purple box moves with the shower front.

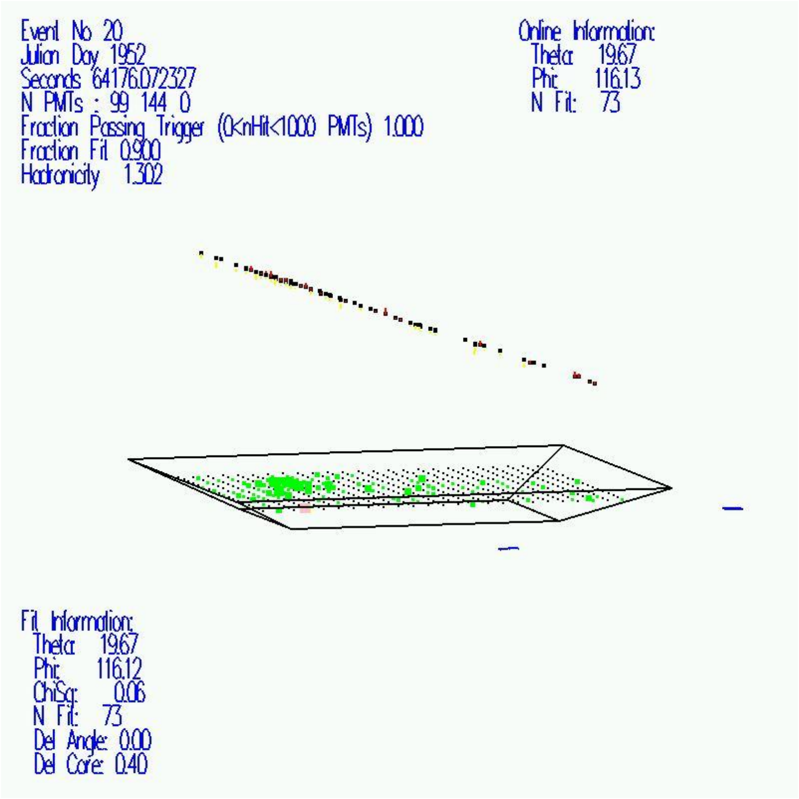
Red - electrons and positrons

Green - secondary gammas

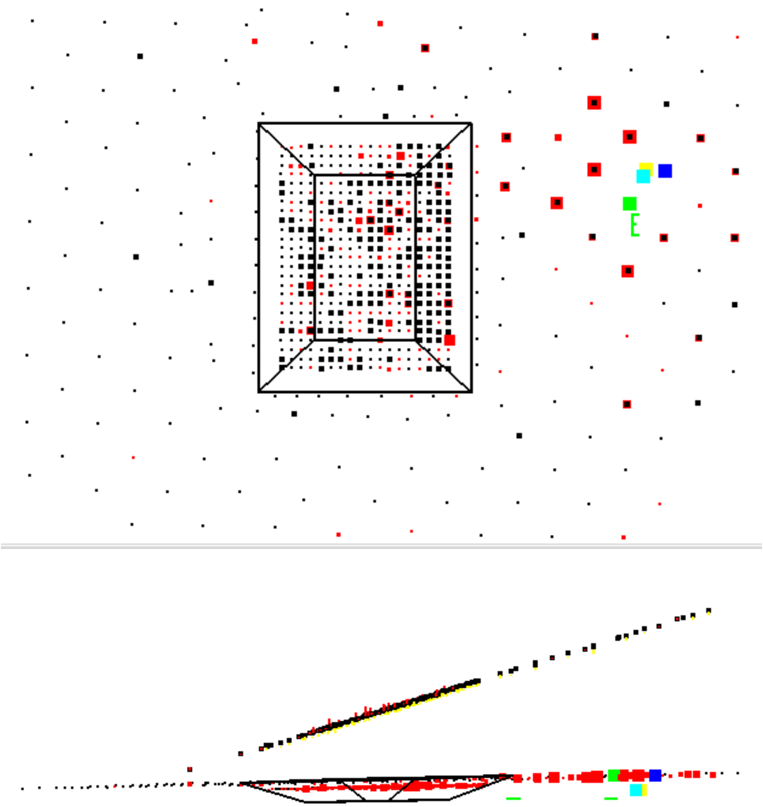
Blue - Cherenkov Photons

http://scipp.ucsc.edu/milagro/Animations/AnimationIntro.html

Shower Direction & Core Position



Real air shower event



Simulated gamma-ray shower

Shower from a vertical 2TeV Proton Primary

Side View

At this energy proton showers tend to have many fewer particles hitting the pond - as seen by the wide particle spacing in this relatively strong proton shower. Notice the very distinctive Cherenkov cone left by a muon.

Red - electrons and positrons

Green - secondary gammas

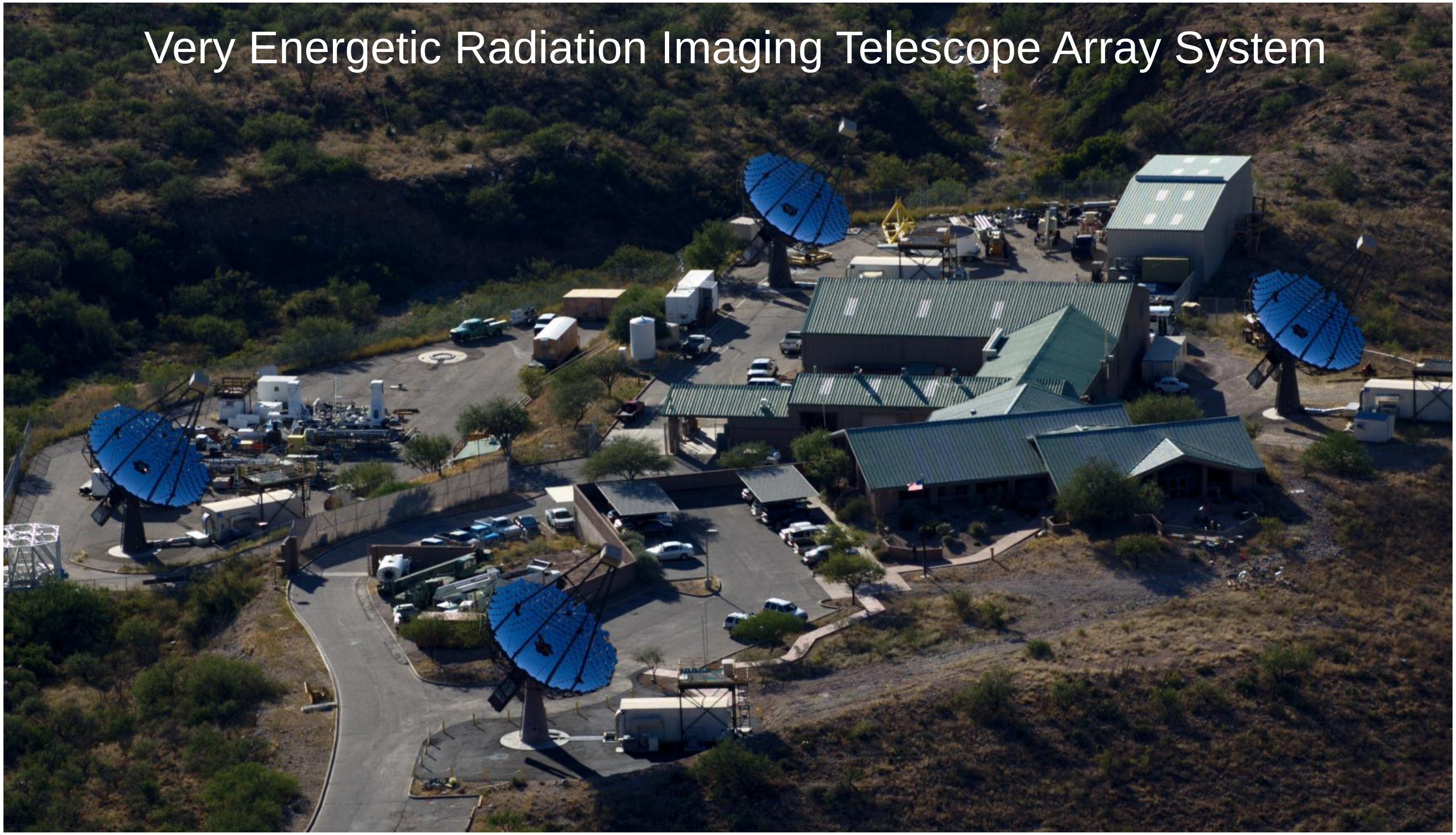
Yellow - muons

Blue - Cherenkov Photons

http://scipp.ucsc.edu/milagro/Animations/AnimationIntro.html

Milagro's Successor: HAWC

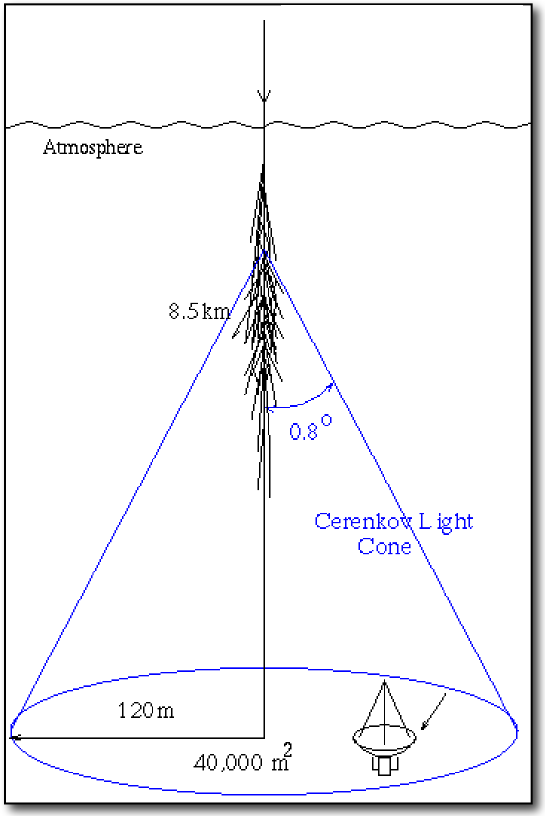
VERITAS: Imaging Atmospheric Cherenkov Telescope



Whipple Observatory Basecamp (el. 1275 m) at foot of Mt. Hopkins

Atmospheric Imaging Technique

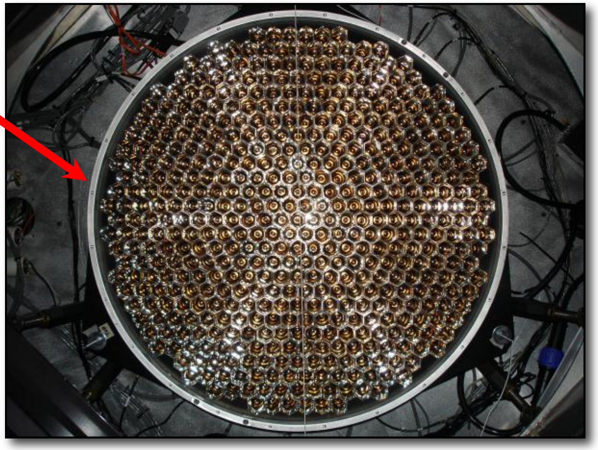
γ–ray



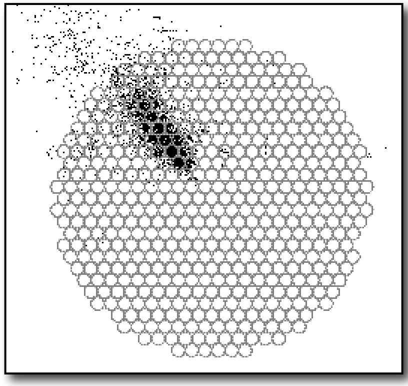
Area = $10^4 - 10^5$ m^2
~60 optical photons/m^2/TeV

γ-rays above ~100 GeV

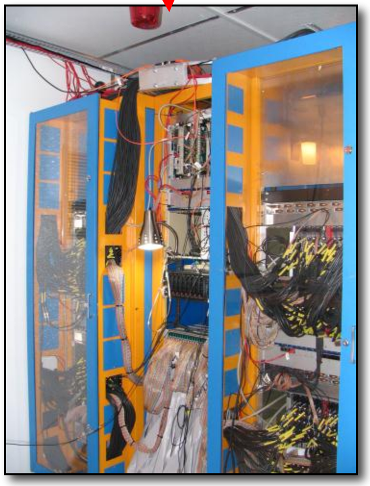
12 m Mirror



499-PMT camera

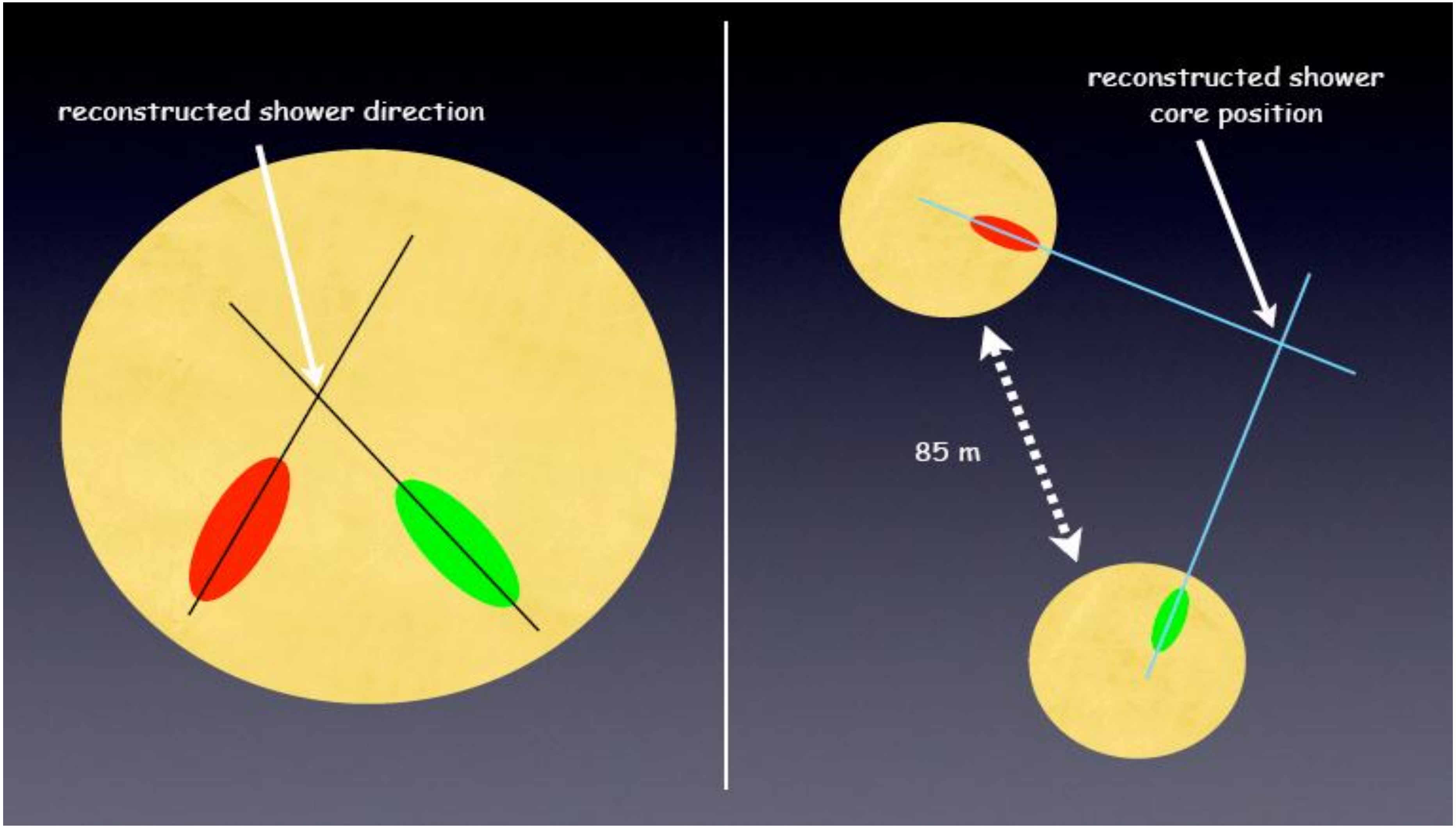


Cherenkov image



500-MHz FADC electronics

Shower Direction & Core Position



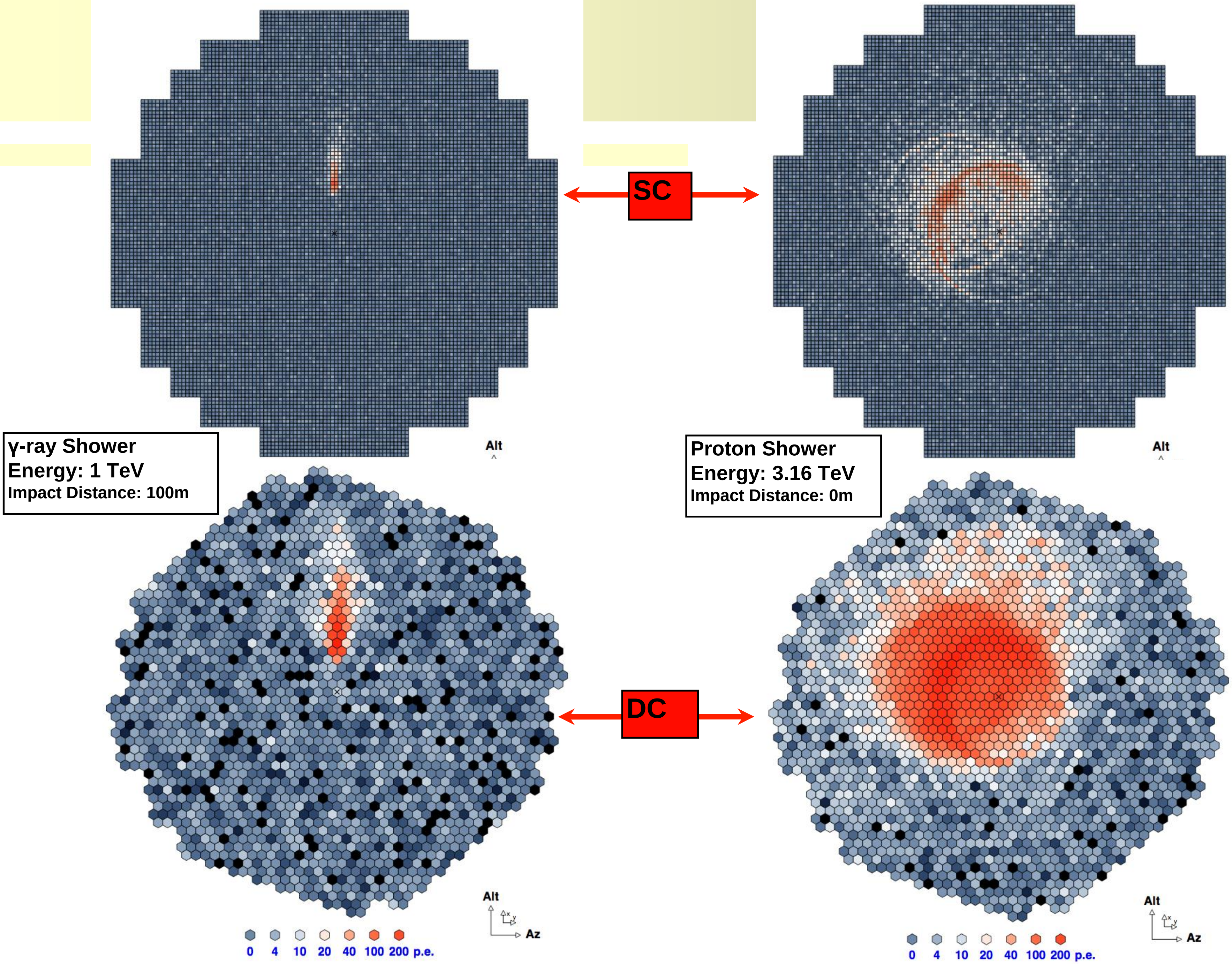
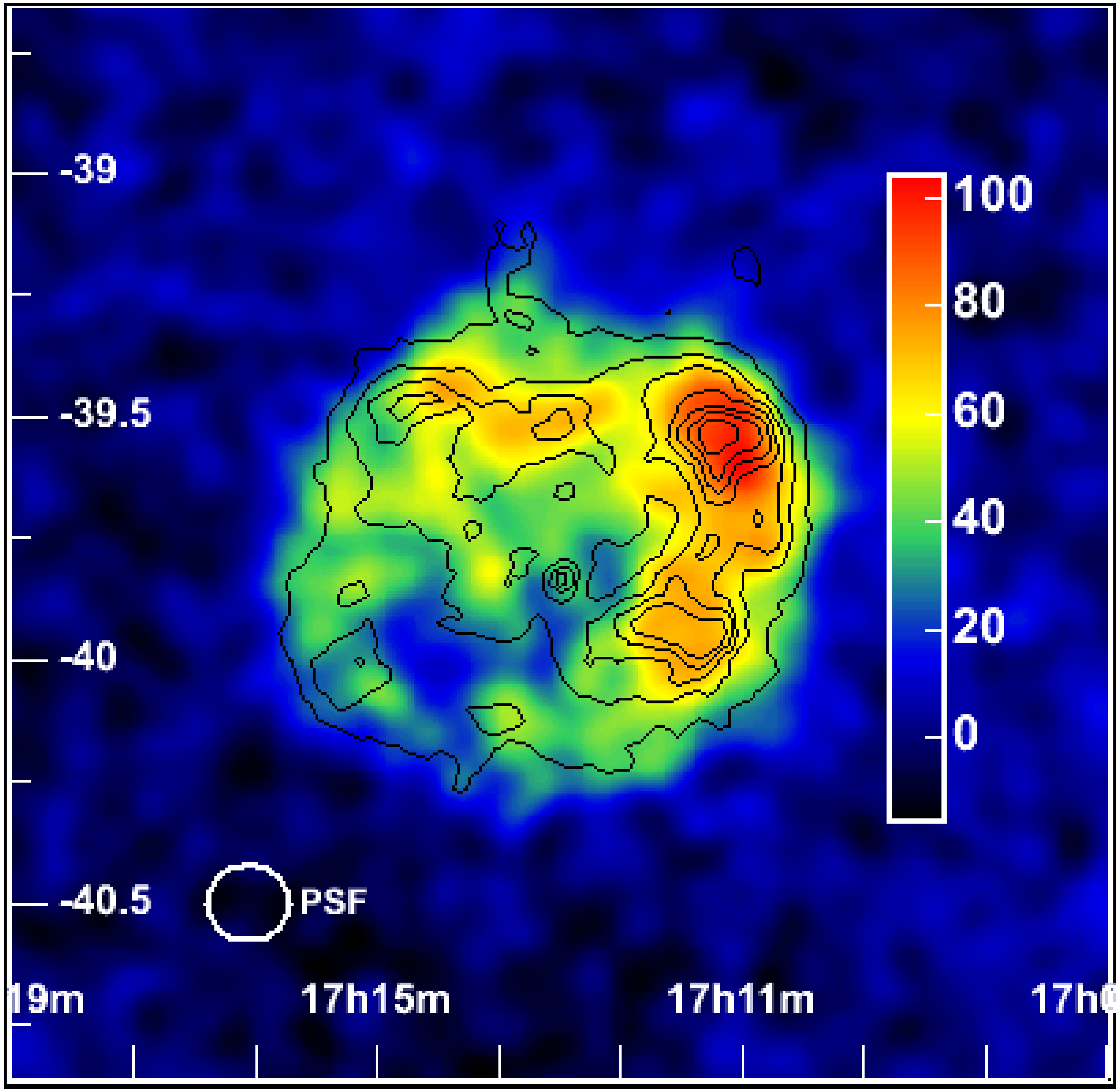

γ-ray Shower
Energy: 1 TeV
Impact Distance: 100m
SC
DC
Proton Shower
Energy: 3.16 TeV
Impact Distance: 0m
Alt
Az
0 4 10 20 40 100 200 p.e.

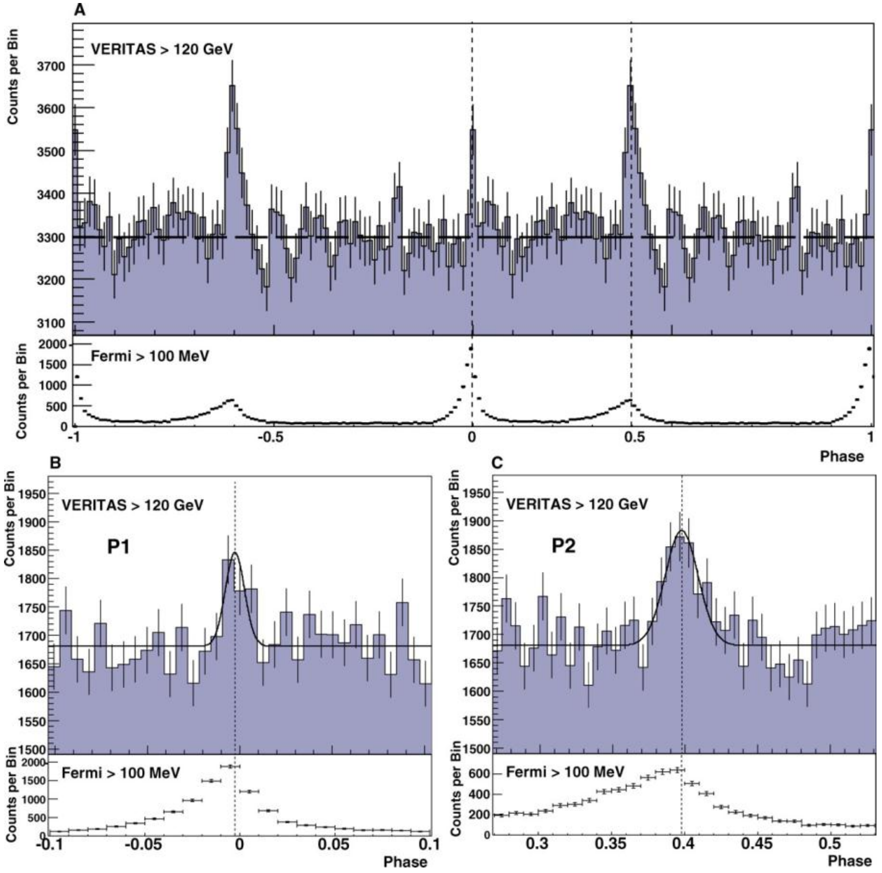
Image of a Supernova Remnant

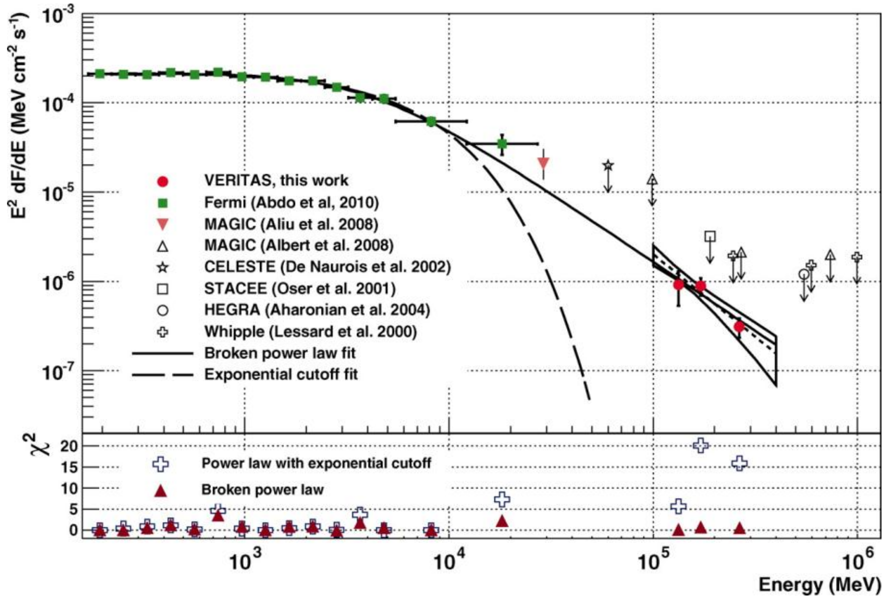
RX J1713.7 -3946

- First image of a γ-ray source –HESS result
- Contours are ASCA 1–3 keV
- Color is VHE γ-rays
- Acceleration of particles ($e^{\pm}$? p?) to >100 TeV



Discovery of VHE Crab Pulsar

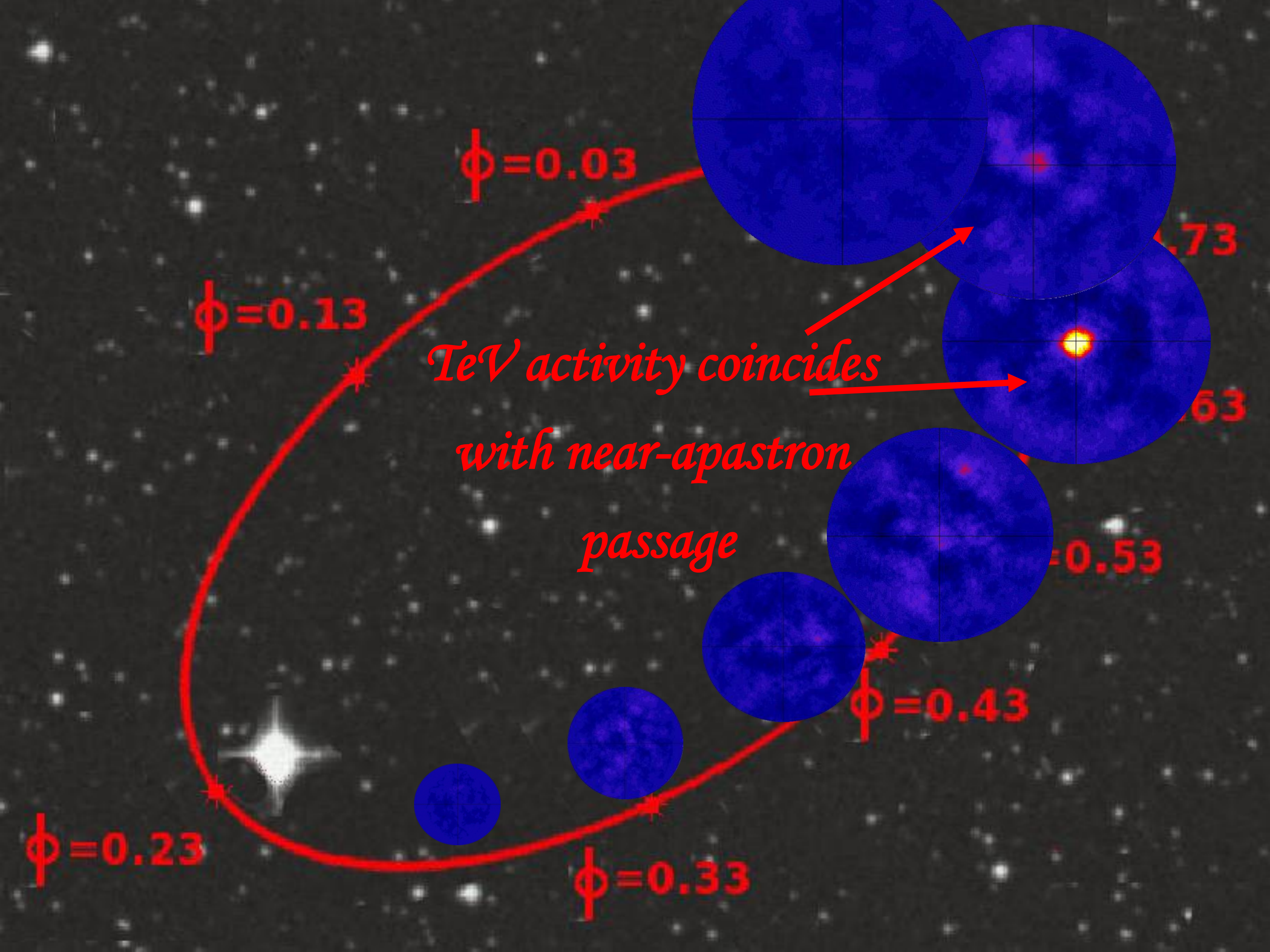




E. Aliu et al. 2011, *Science* 334, 69–72

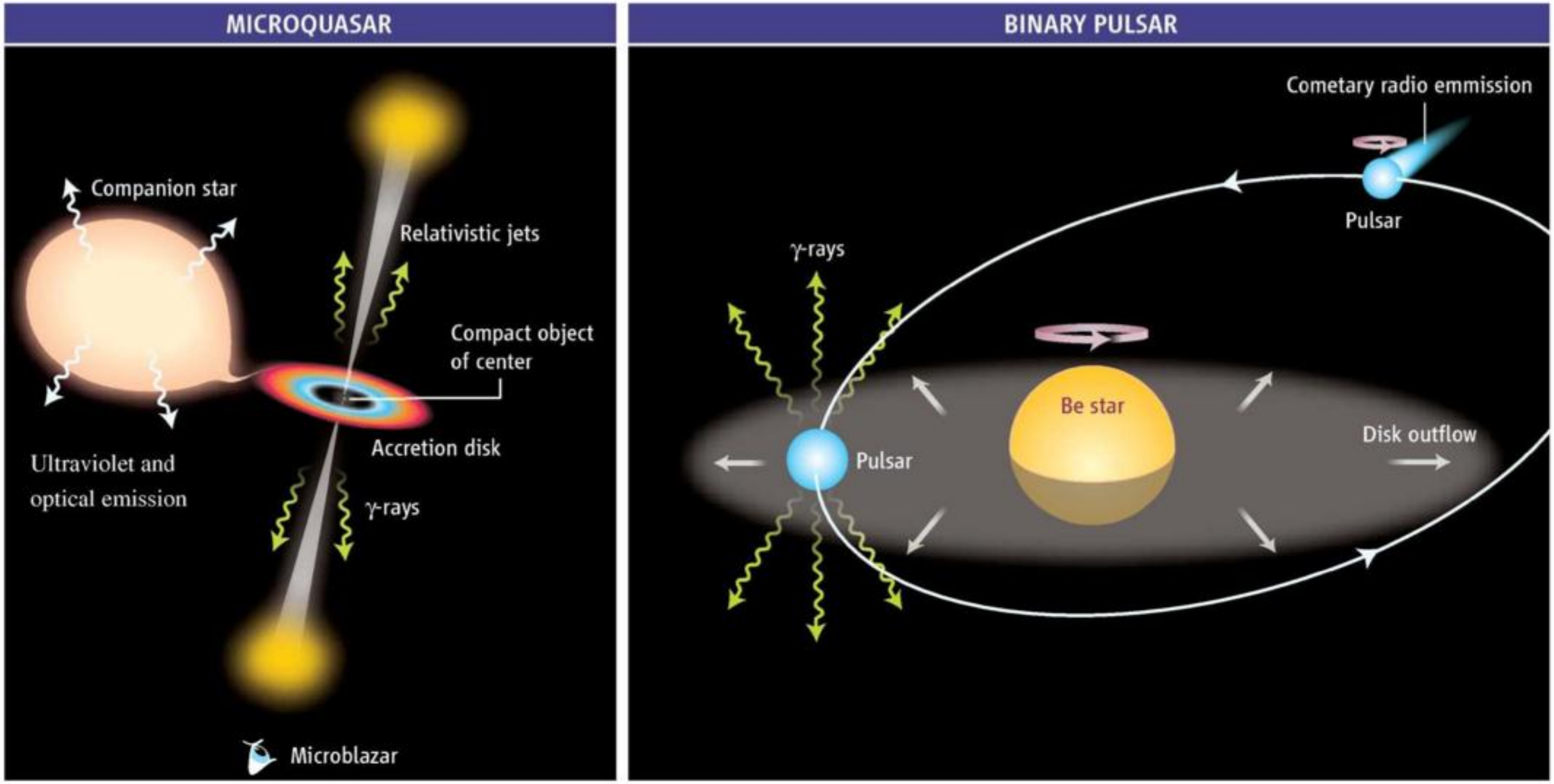
Work led by, A. Nepomuk Otte

UCSC postdoc, now asst. prof. at Georgia Tech



ϕ=0.03
ϕ=0.13
ϕ=0.23
ϕ=0.33
ϕ=0.43
0.53
.63
.73
TeV activity coincides with near-apastron passage

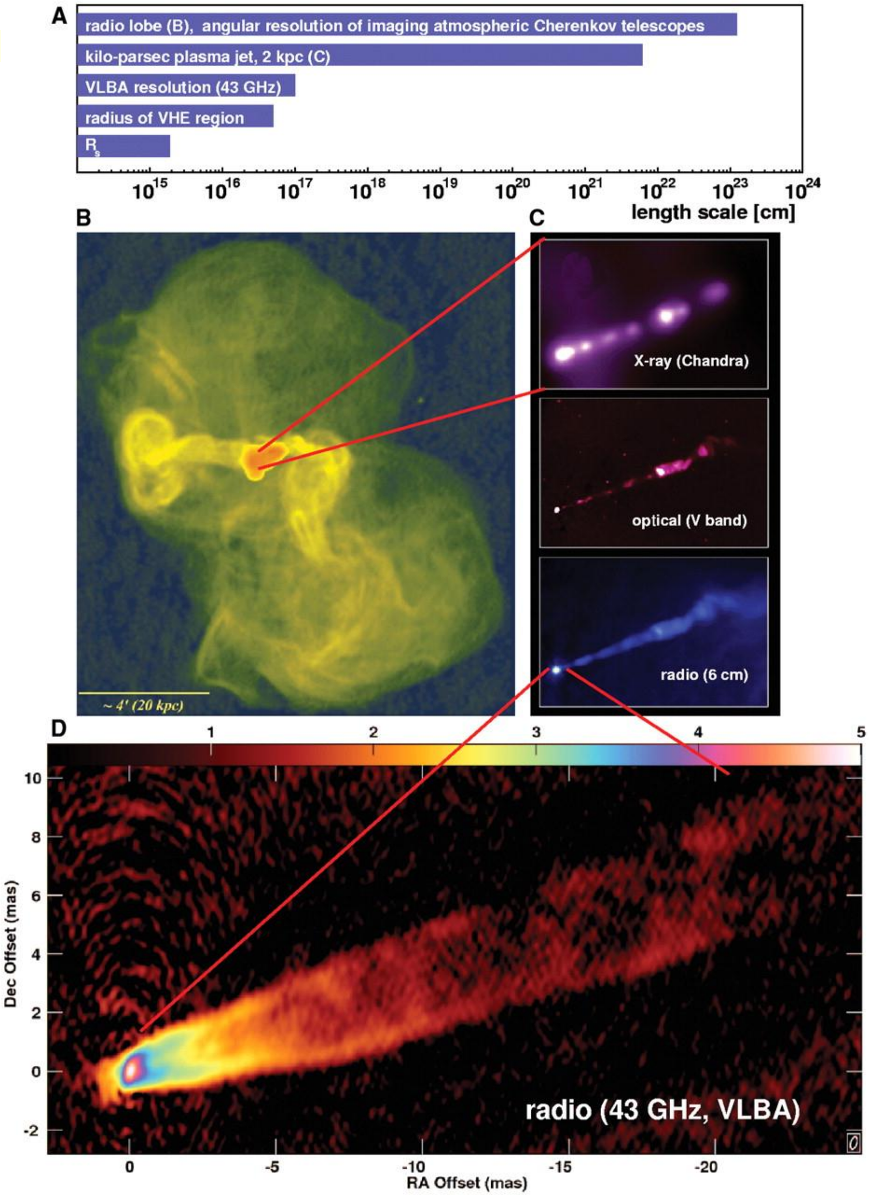
Microquasar or binary pulsar?



From Mirabel 2006, Science 312, p. 1759

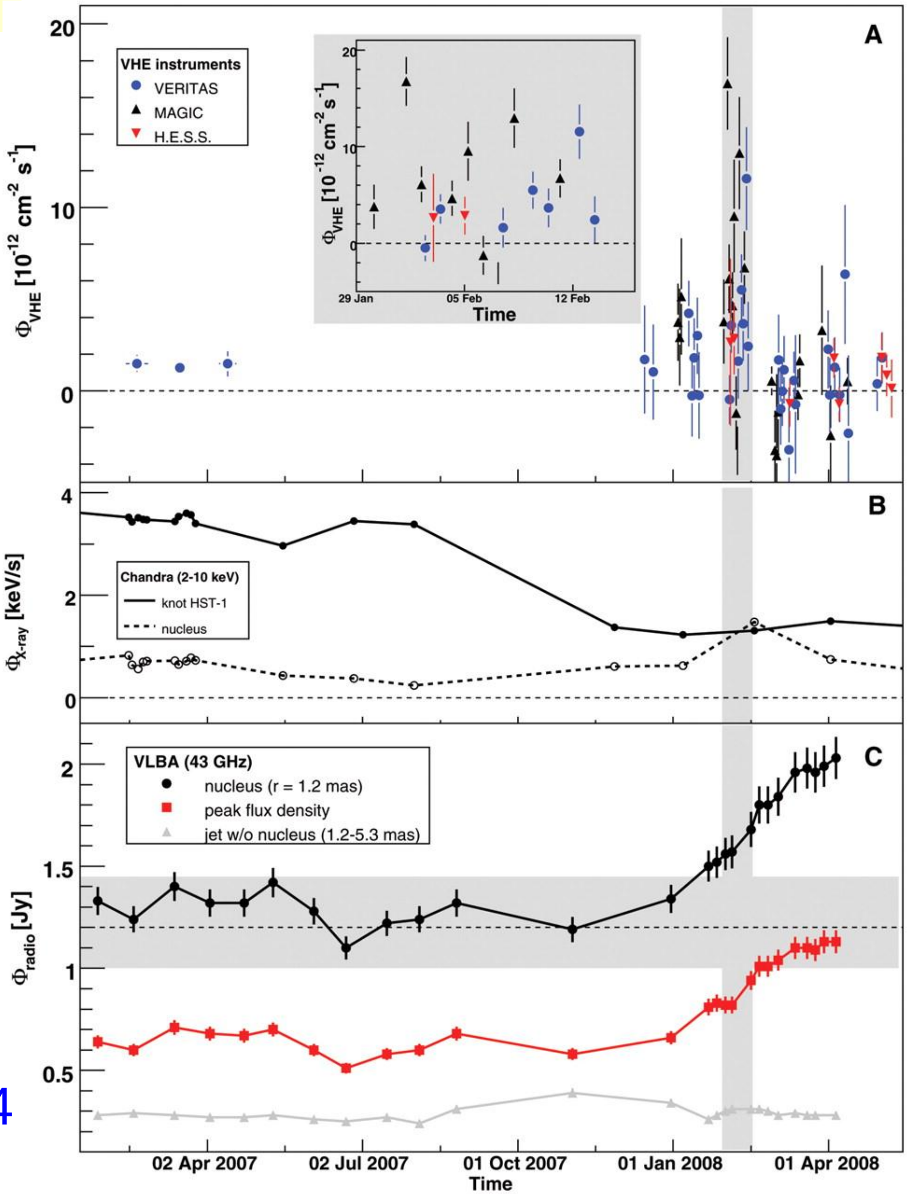
Radio Galaxy: M 87

- Giant radio galaxy (class of AGN)
- Distance ~16 Mpc, redshift 0.004
- Central black hole ~6 x 10^9 M_{sun}
- Jet angle 15° – 30°
- Knots resolved in the jet
- Jet is variable in all wavebands



M 87 – Radio and TeV flares

- Rapid TeV flares coincident with the core brightening
- TeV particles accelerated within ~100 R_s of BH
- Best determination so far of location of particle acceleration

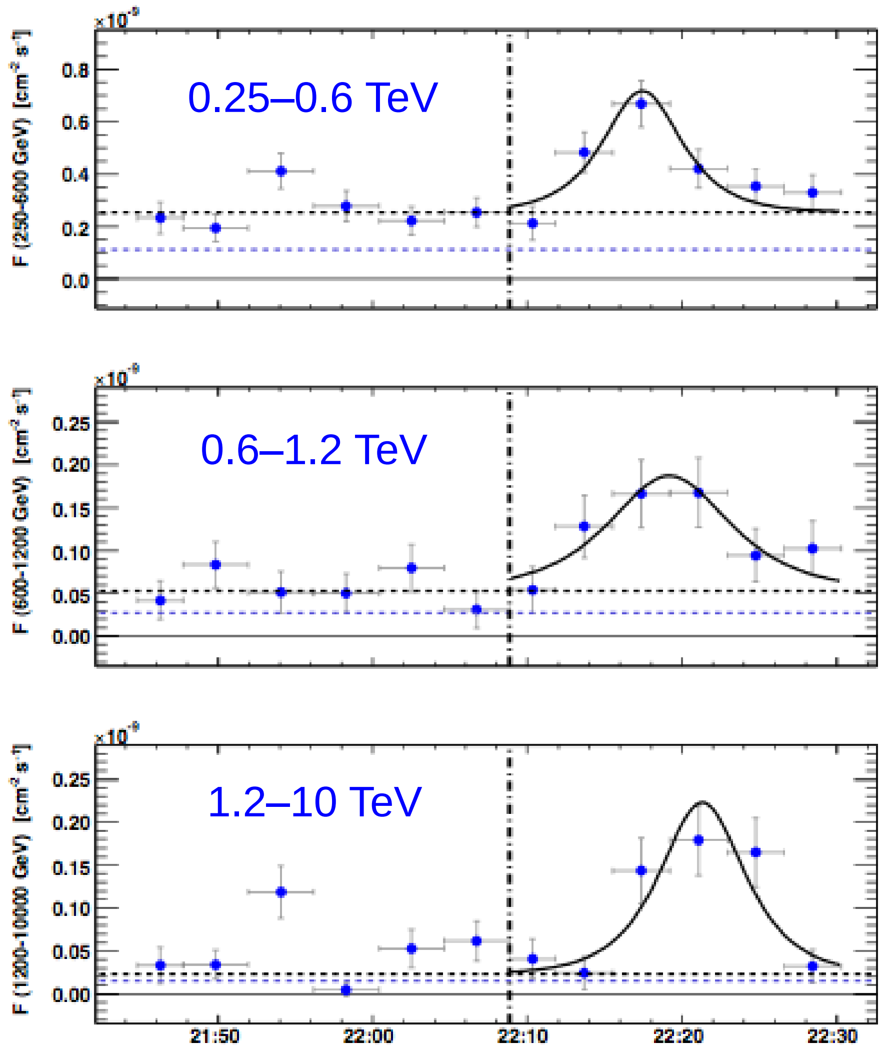


V. Acciari *et al*. 2009, Science 325, 444

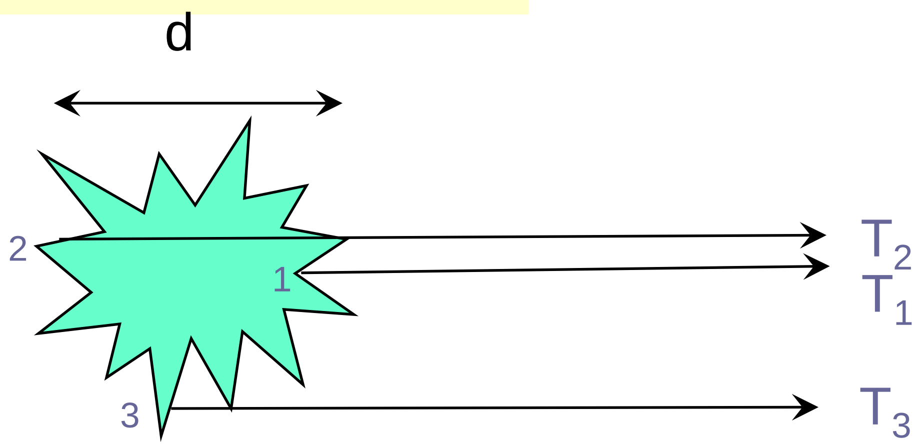
Markarian 501 – July 9, 2005

Rapid flare

- MAGIC telescope (Albert et al., submitted to Astrophys. J.)
- Flux doubling times ~2 minutes
- Indication of a 4±1 minute lag between lowest and highest E events
- Constrains details of emission



Size of Emission Region

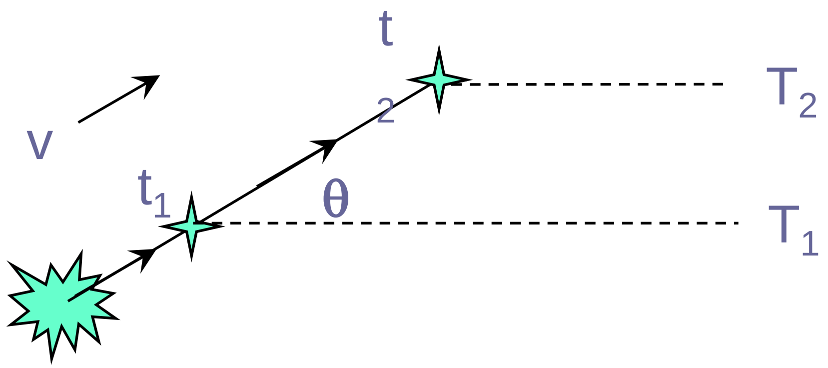


- Instantaneous flash emits photons from 1, 2, and 3 at the same time
- Observer sees them arrive at different times:

  $T_2 – T_1 \sim d/c$

  $T_3 – T_1 \sim d/2c$
- Duration of flash seen by observer is *at least* of order d/2c long for opaque emission region; d/c for transparent one
- Short bursts must come from small regions

Emission Region in Motion



$$\Delta t_{lab} = t_2 - t_1$$

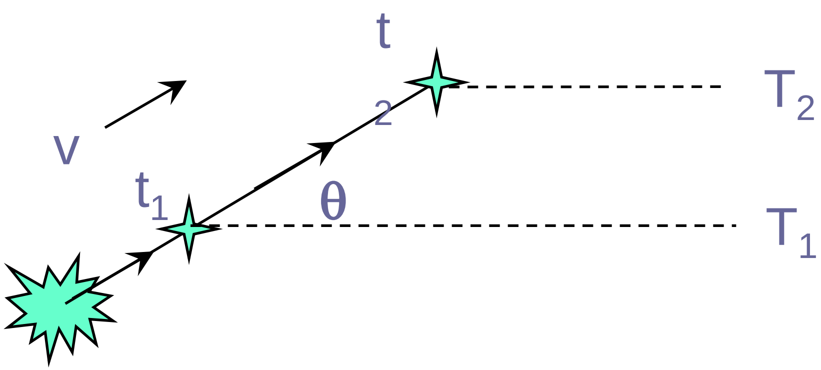
$$\beta = v/c$$

$$\Gamma = 1/(1 - \beta^2)^{1/2}$$

$$\Delta T_{obs} = T_2 - T_1$$

- If emission region is moving towards observer, apparent time between events is reduced
- Limiting case: $v = c$ & $\theta = 0 \rightarrow \Delta T_{obs} = 0$
- *Apparent* motion can be superluminal

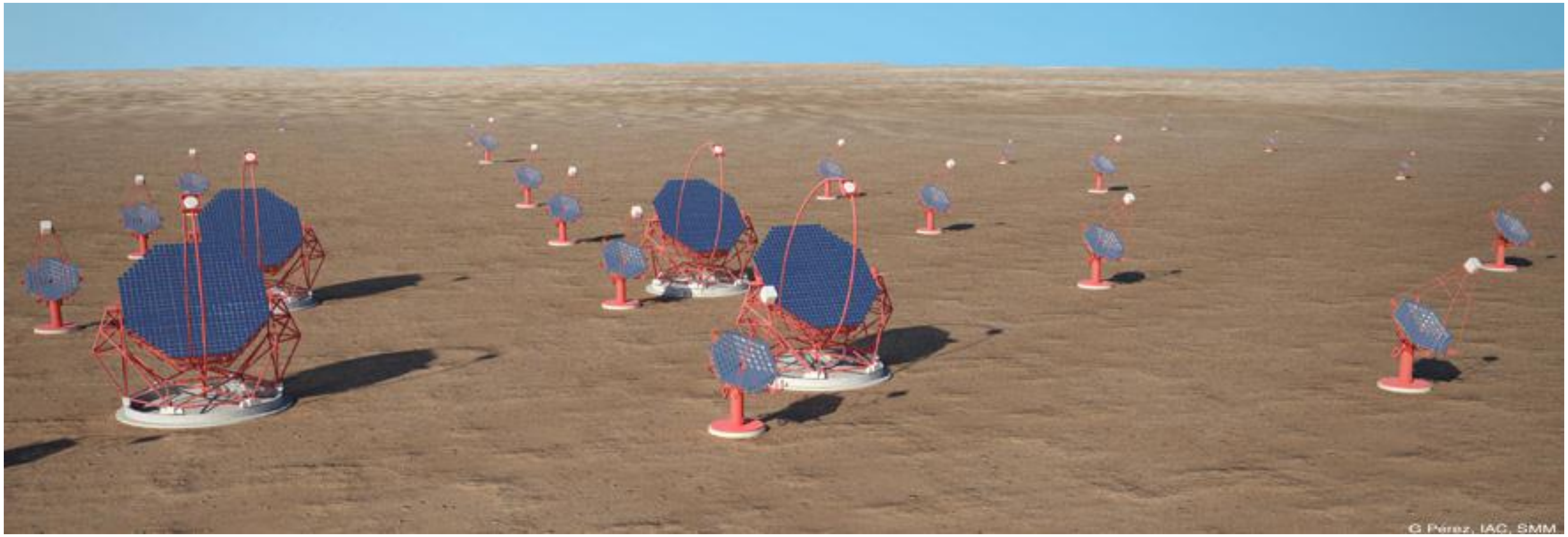
Emission Region in Motion



$$
\begin{aligned}
T_2 - T_1 &= (t_2 - t_1) - (v\,(t_2 - t_1)\cos\theta)/c \\
&= \Delta t_{lab}\,(1 - \beta\cos\theta) \\
&\approx \Delta t_{lab}\,(1 - \beta) \qquad (\text{for } \cos\theta \sim 1) \\
&\approx \Delta t_{lab}\,(1 - \beta)(1 + \beta)/2 \qquad (\text{for } \beta \sim 1) \\
&\approx \Delta t_{lab}\,(1 - \beta^2)/2 \\
\Delta T_{obs} &\approx \Delta t_{lab}\,/(2\,\Gamma^2)
\end{aligned}
$$

- Time intervals seen by observer are $\sim 2\Gamma^2$ times shorter than intervals at source
- Lorentz factors of 10 to 50 not uncommon
- Emission region not ~2 light minutes across, but still small

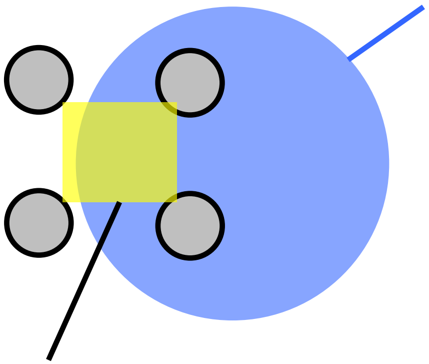
The CTA Concept



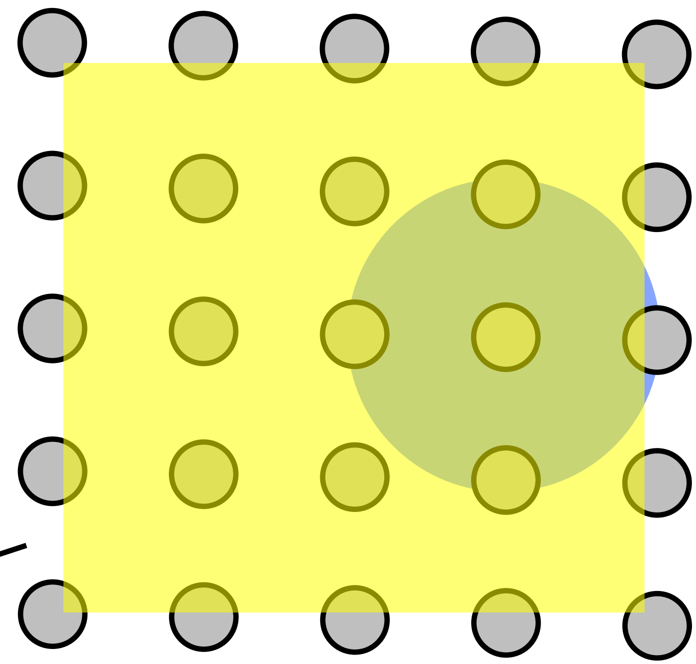
- Arrays in northern and southern hemispheres for full sky coverage
- 4 large (~23 m) telescopes in the center (LSTs)
  - Threshold of ~30 GeV
- ≥25 medium (9–12 m) telescopes (MSTs) covering ~1 km^2
  - Order of magnitude improvement in 100 GeV–10 TeV range
- Small (~4 m) telescopes (SSTs) covering >3 km^2 in south
  - >10 TeV observations of Galactic sources
- Construction begins in ~2015

From current arrays to CTA

Light pool radius
R ≈100-150 m
≈ typical telescope spacing

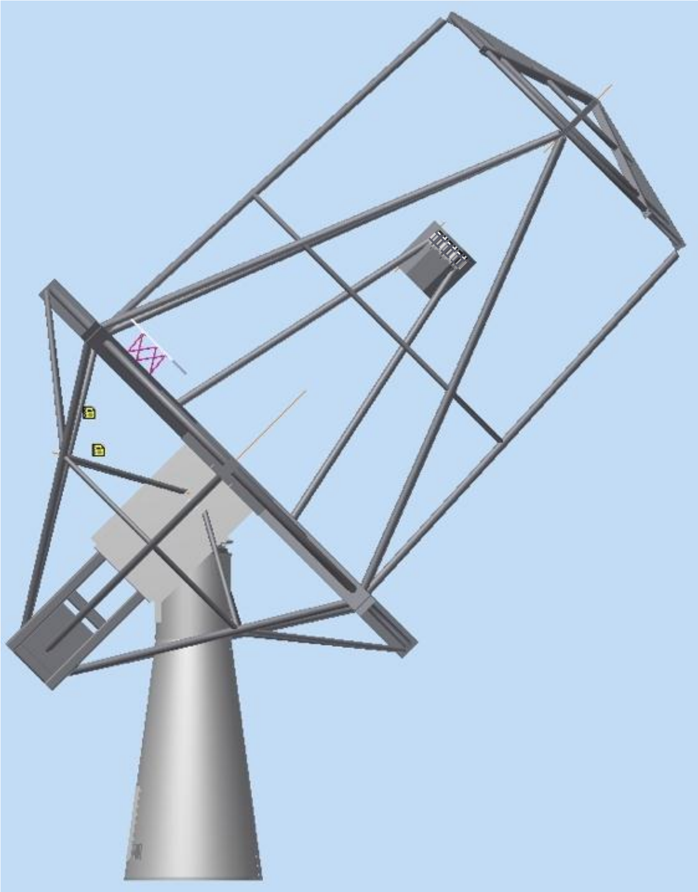


Sweet spot for
best triggering
and reconstruction:
Most showers miss it!

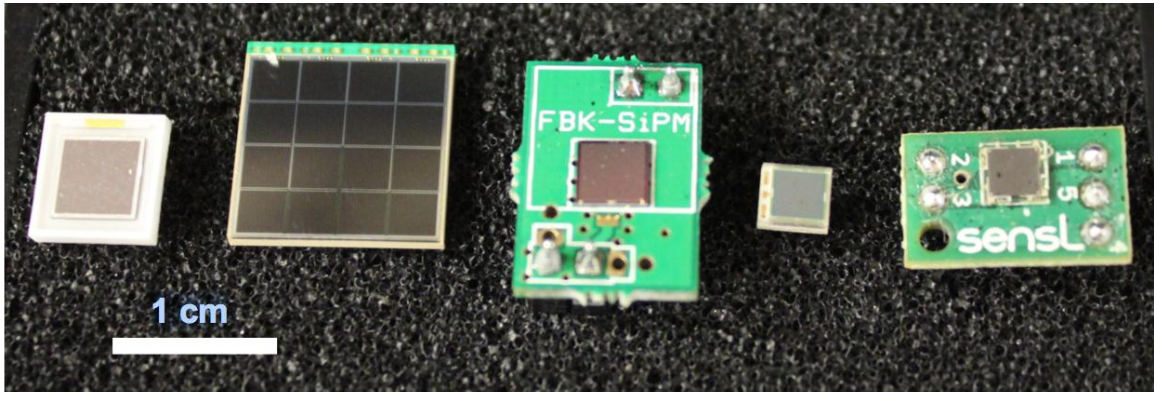


Large detection area
More images per shower
Lower trigger threshold

A Novel Telescope for CTA



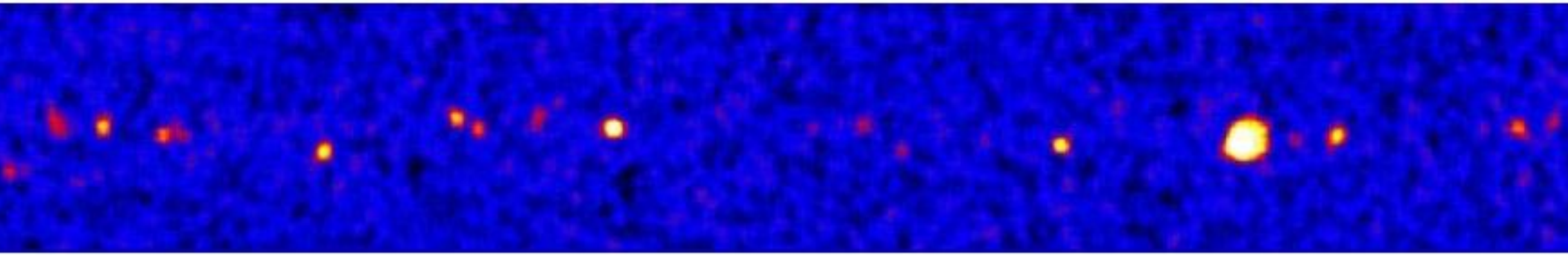
Schwarzschild-Couder optics



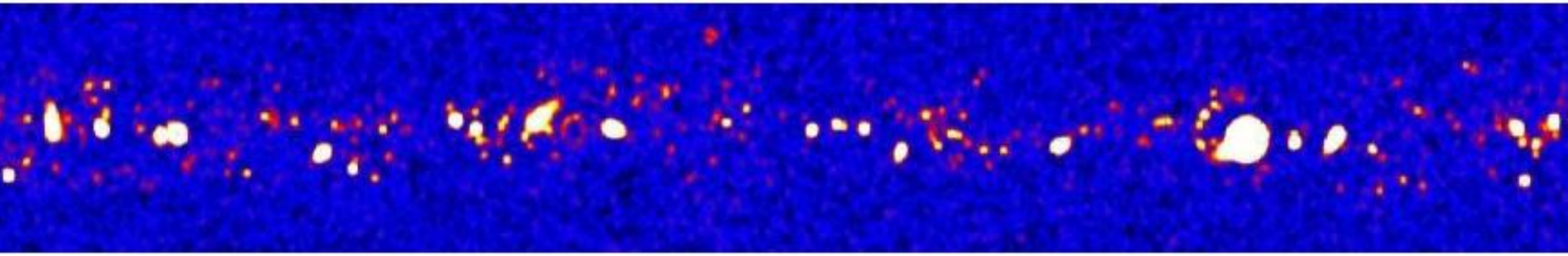
Camera using multianode photomultiplier tubes or Geiger-APDs with integrated electronics

Simulated Galactic Plane surveys

H.E.S.S.



CTA, for same exposure



Expect ~1000 detected sources over the whole sky

Dark matter searches with Fermi & CTA

Fermi dwarf spheroidal and CTA Galactic Center searches are complementary

Assuming b b-bar decay channel

LAT 2-year result from Ackermann et al. 2011, *Phys. Rev. Lett.* **107**, 241302.