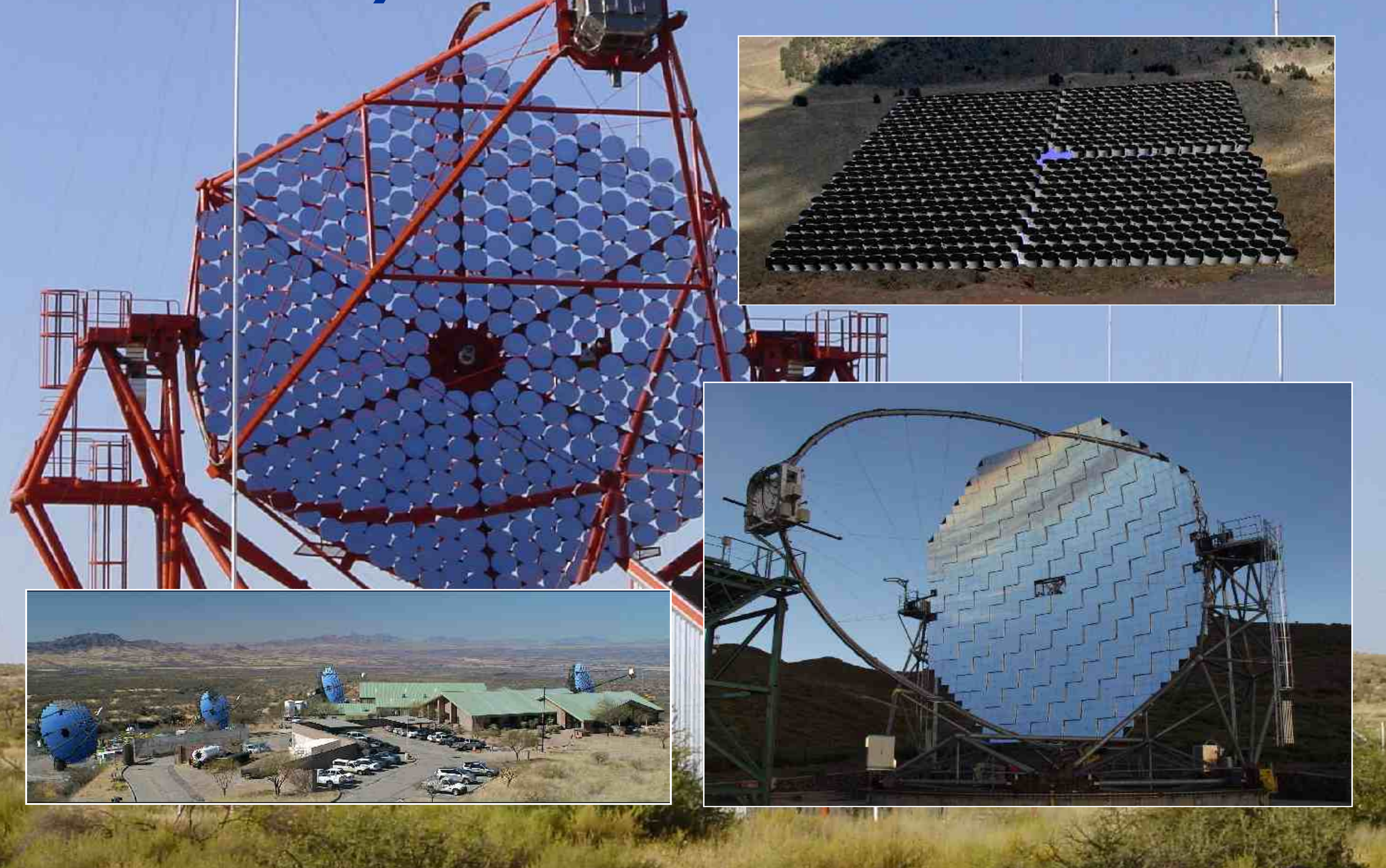
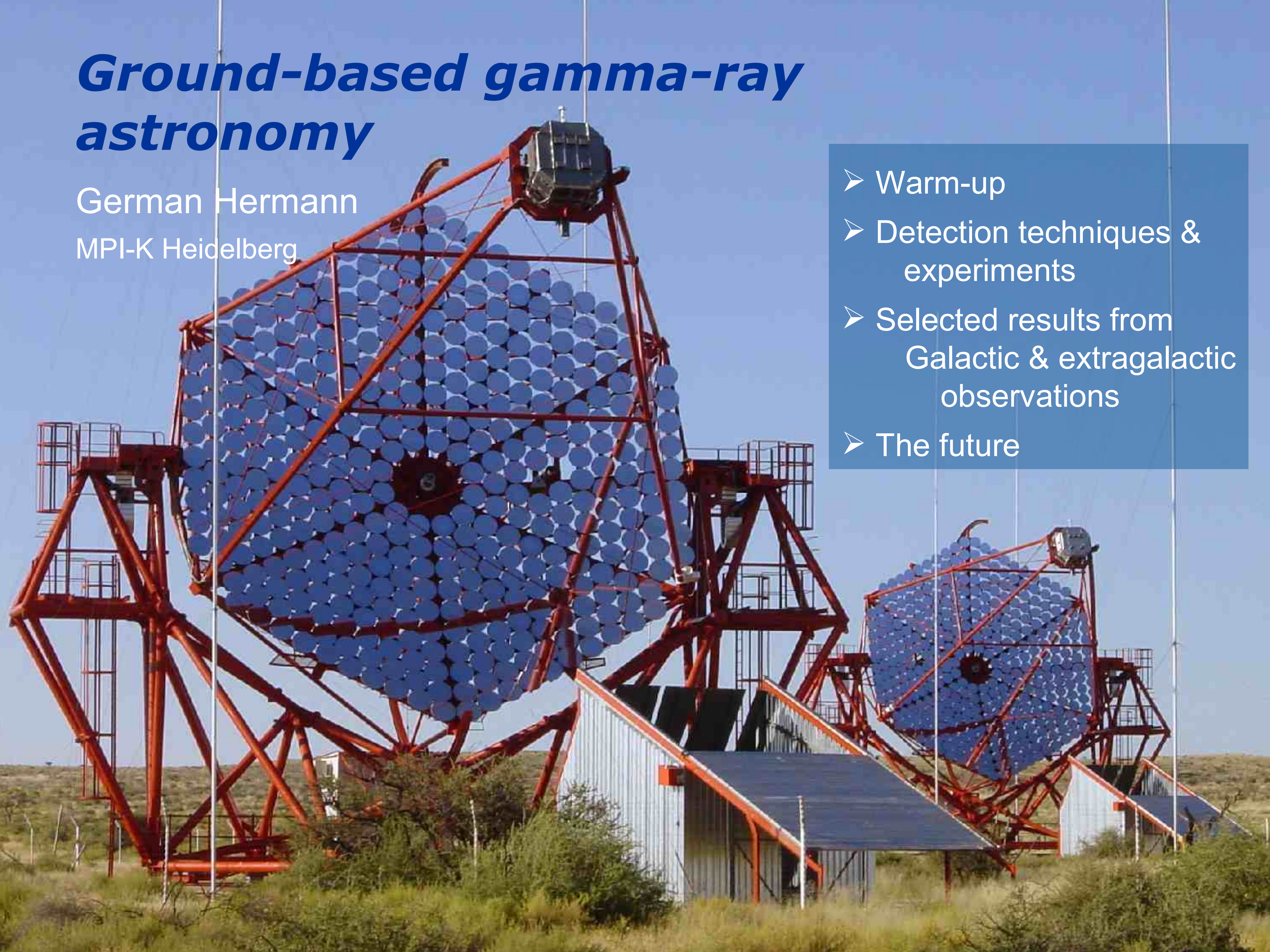
Ground-based gamma-ray astronomy



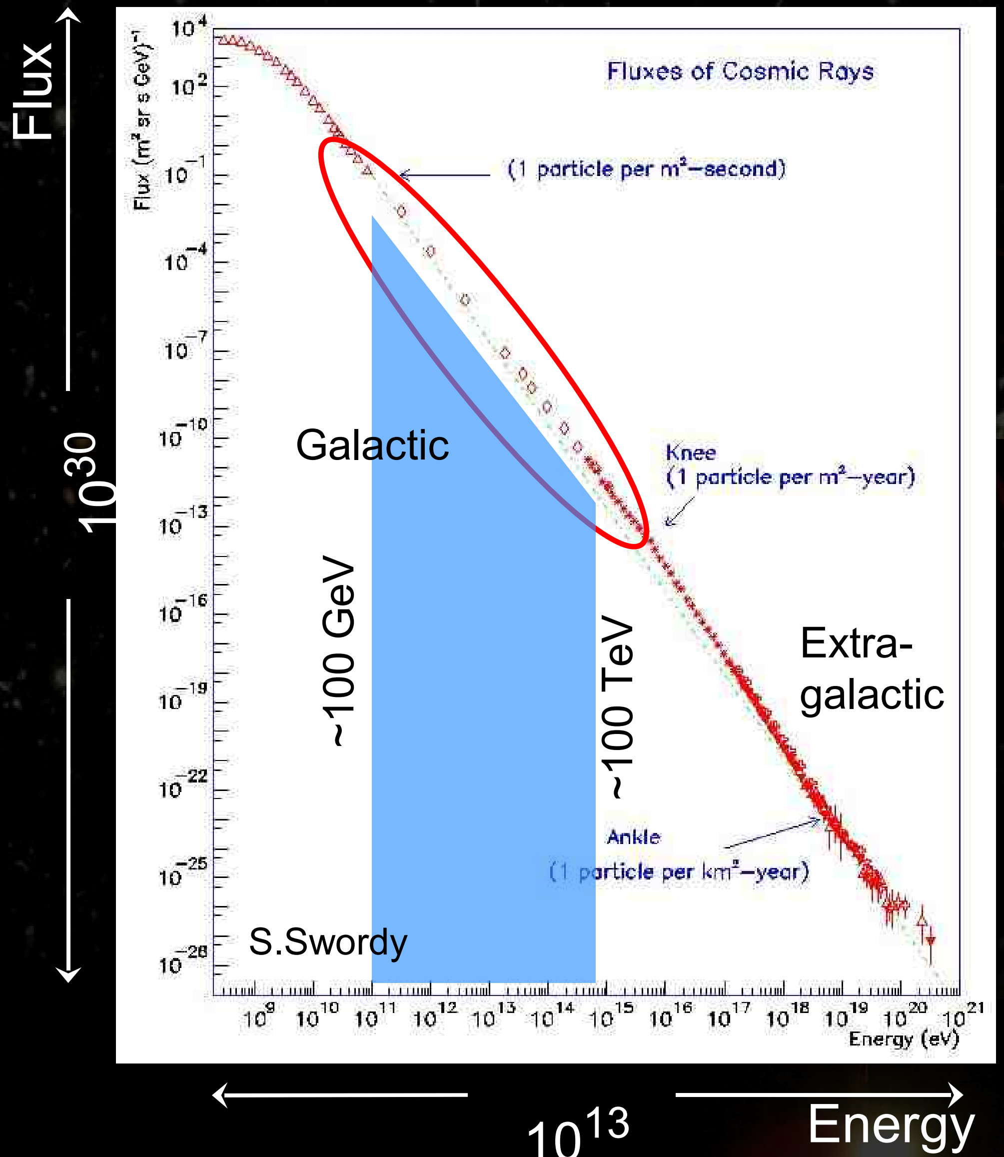
Ground-based gamma-ray astronomy

German Hermann
MPI-K Heidelberg

- Warm-up
- Detection techniques & experiments
- Selected results from Galactic & extragalactic observations
- The future



The Cosmic Ray Puzzle



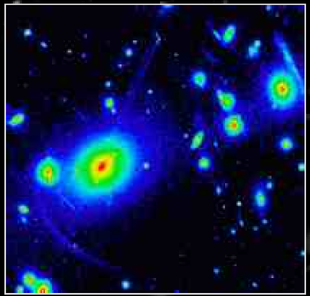
- Mostly nuclei p, He, … Fe
  also $e^{\pm}$
  few γ, ν
- Non thermal spectrum
  $dN/dE \sim E^{-\alpha}$
- Isotropic distribution

Discovery in 1912, but

- Cosmic ray origin ?
- Sources ?
- Processes ?

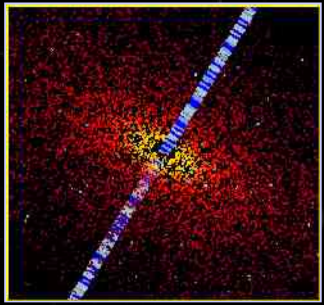
Potential Sources and Processes

Clusters of Galaxies



Dark Matter

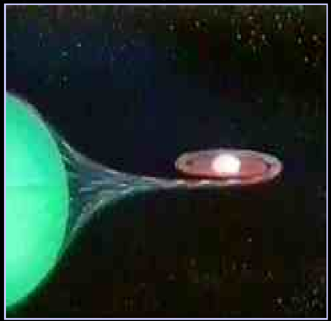
Active Galactic Nuclei (AGN)



Super Nova Remnants (SNR)

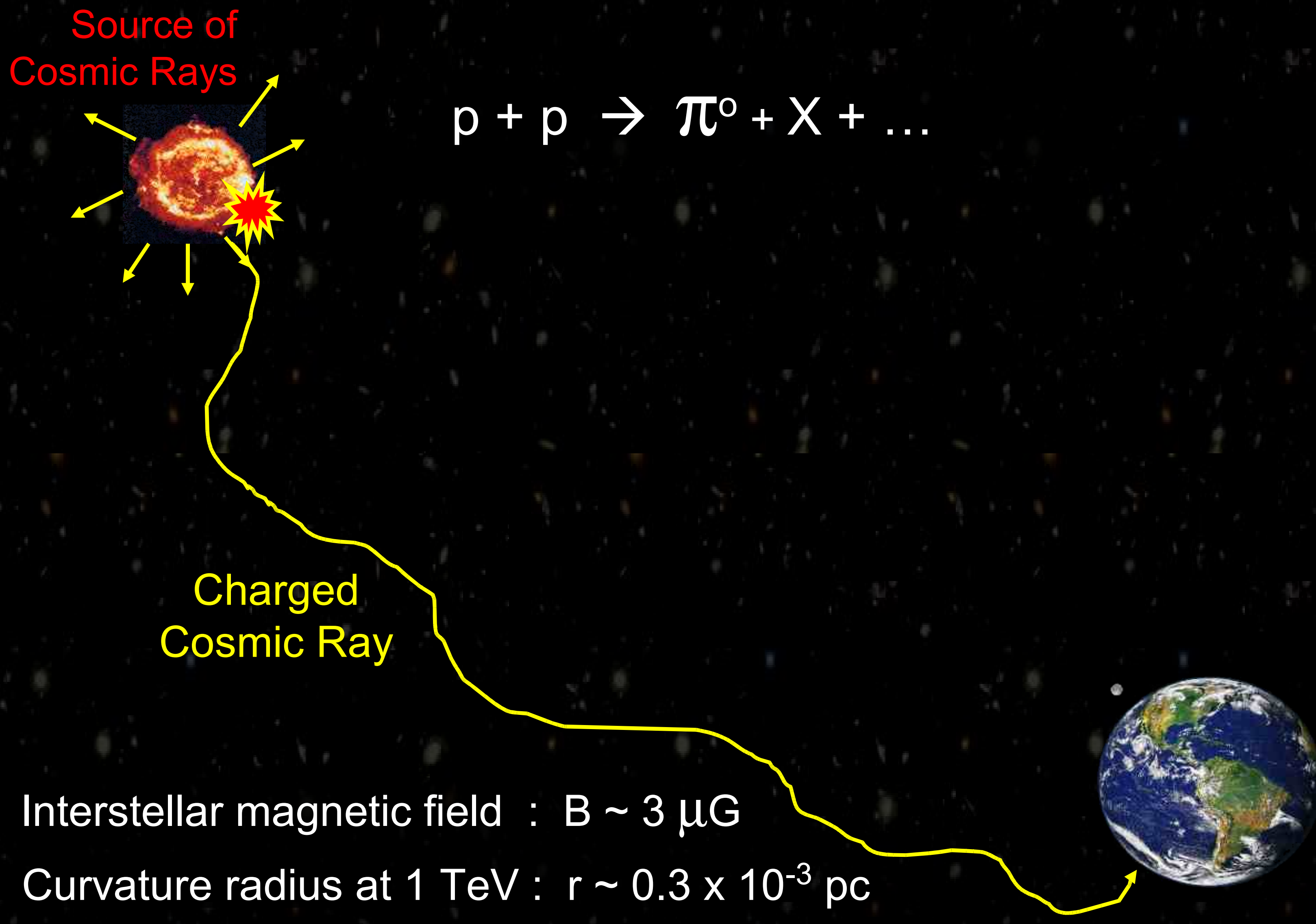
Pulsar Nebula

Binary Systems



- SNR as sources of CR
- Acceleration of relativistic particles
- Energy transfer in pulsars
- Environment of neutron stars and Black Holes
- Properties of relativistic jets
- Indirect search for DM
- Cosmology: diffuse EBL GRBs and GRBRs

Tracers to Cosmic Ray Accelerators

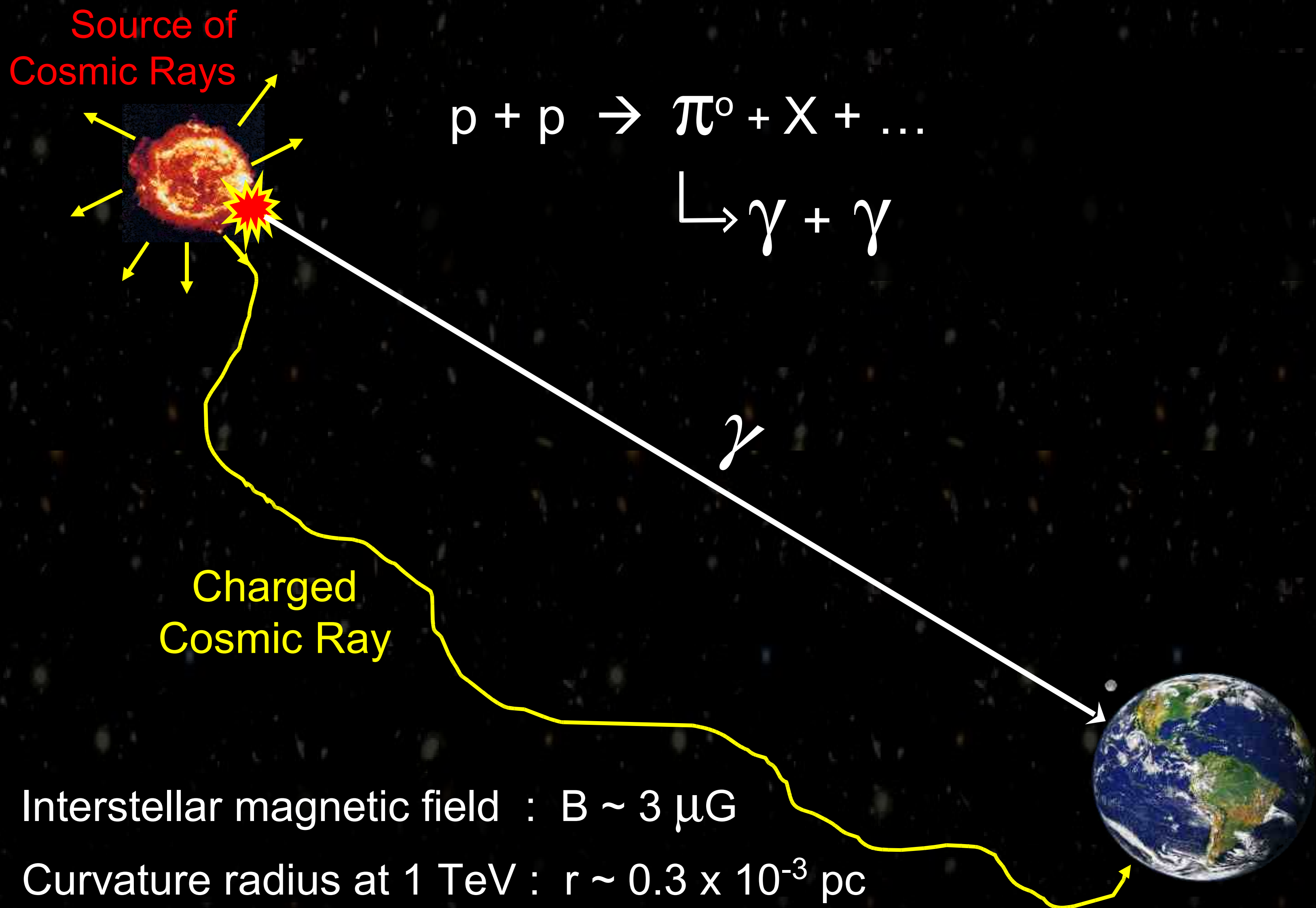


$p + p \rightarrow \pi^o + X + \ldots$

Interstellar magnetic field : $B \sim 3\ \mu G$

Curvature radius at 1 TeV : $r \sim 0.3 \times 10^{-3}$ pc

Tracers to Cosmic Ray Accelerators



Interstellar magnetic field : B ~ 3 μG

Curvature radius at 1 TeV : r ~ 0.3 x 10^{-3} pc

Tracers to Cosmic Ray Accelerators

Source of Cosmic Rays

$$p + p \rightarrow \pi^{o} + X + \ldots$$
$$\hookrightarrow \gamma + \gamma$$

γ

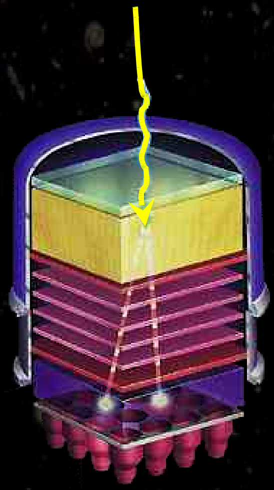
Infer properties of *primary particle distribution* in the sources and their *interactions*

Observables

- Energy Spectra
  flux, range, shape
- Source Morphology
- Variability/Periodicity

+ Multi-Wavelength (radio, IR, optical, X-ray)

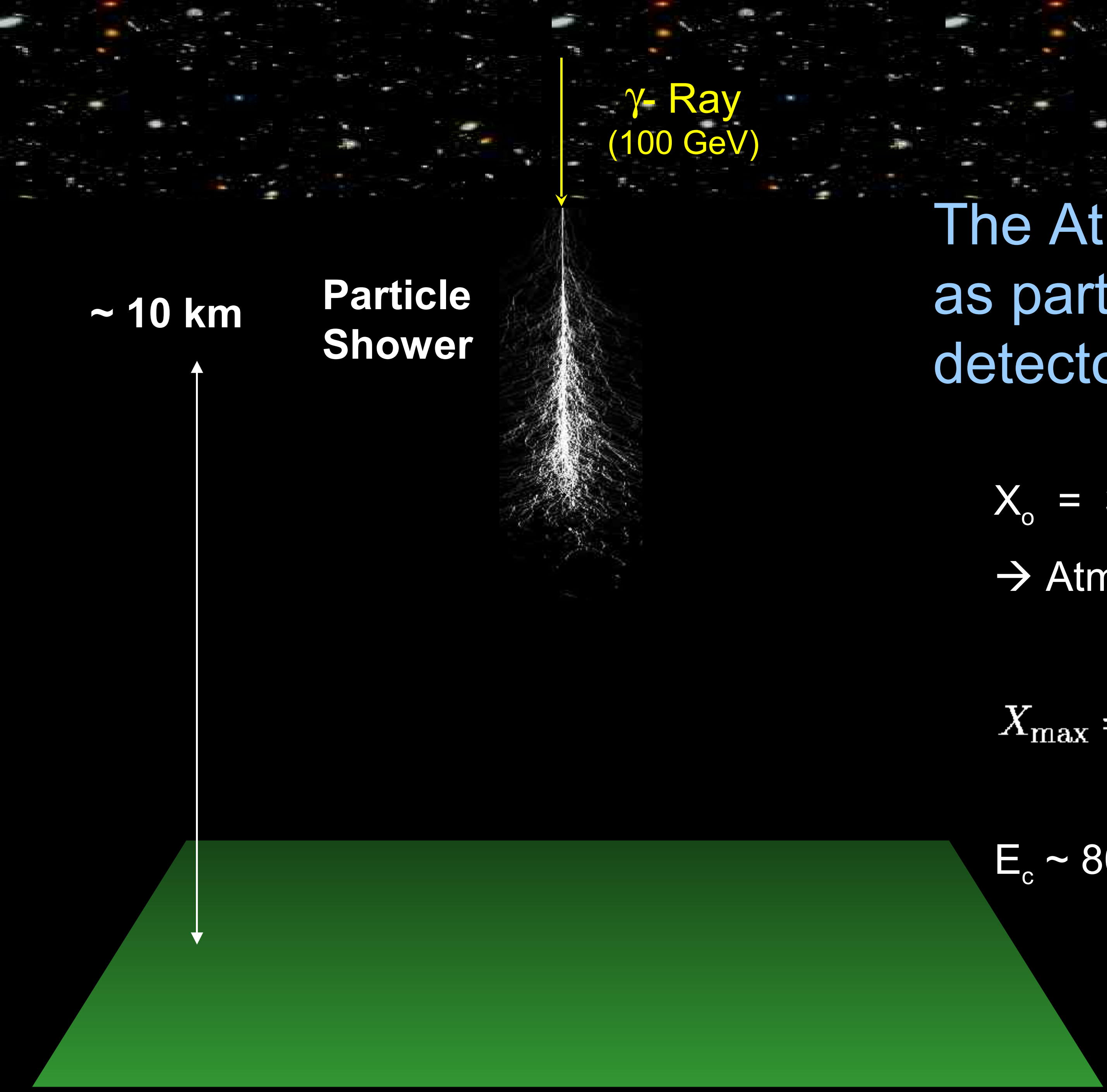
Detection rate for (very) high energy gamma-rays



Rate from Crab (E>1 TeV):

2.3×10^{-6} / m^2/ sec

(need a pretty large rocket)



The Atmosphere as part of the detector

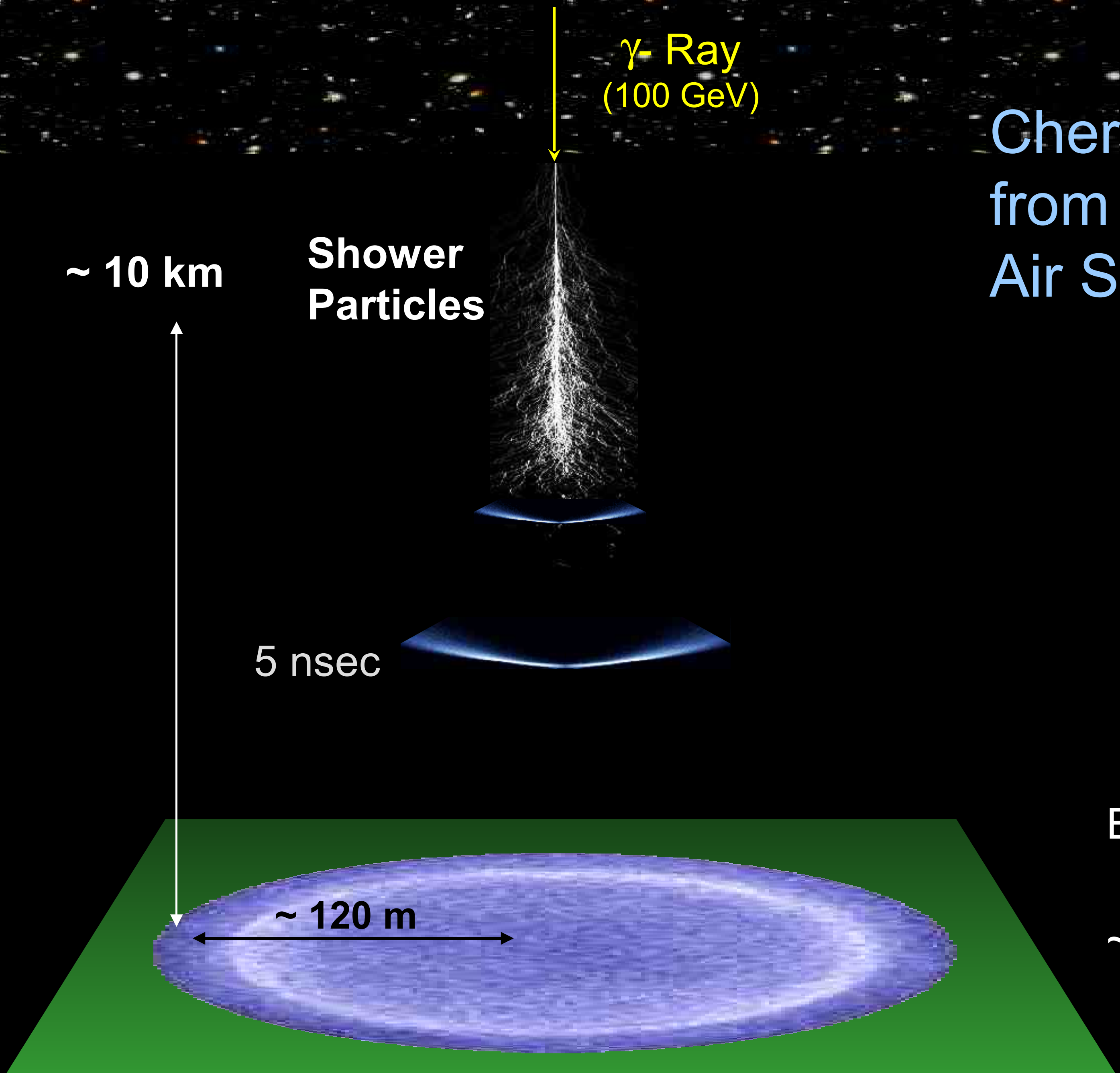
$X_o = 37.2\ g/cm^2$

→ Atmosphere ~ 27 X_o

$$X_{\rm max} = \frac{\ln E_0/E_{\rm c}}{\ln 2} \cdot X_0$$

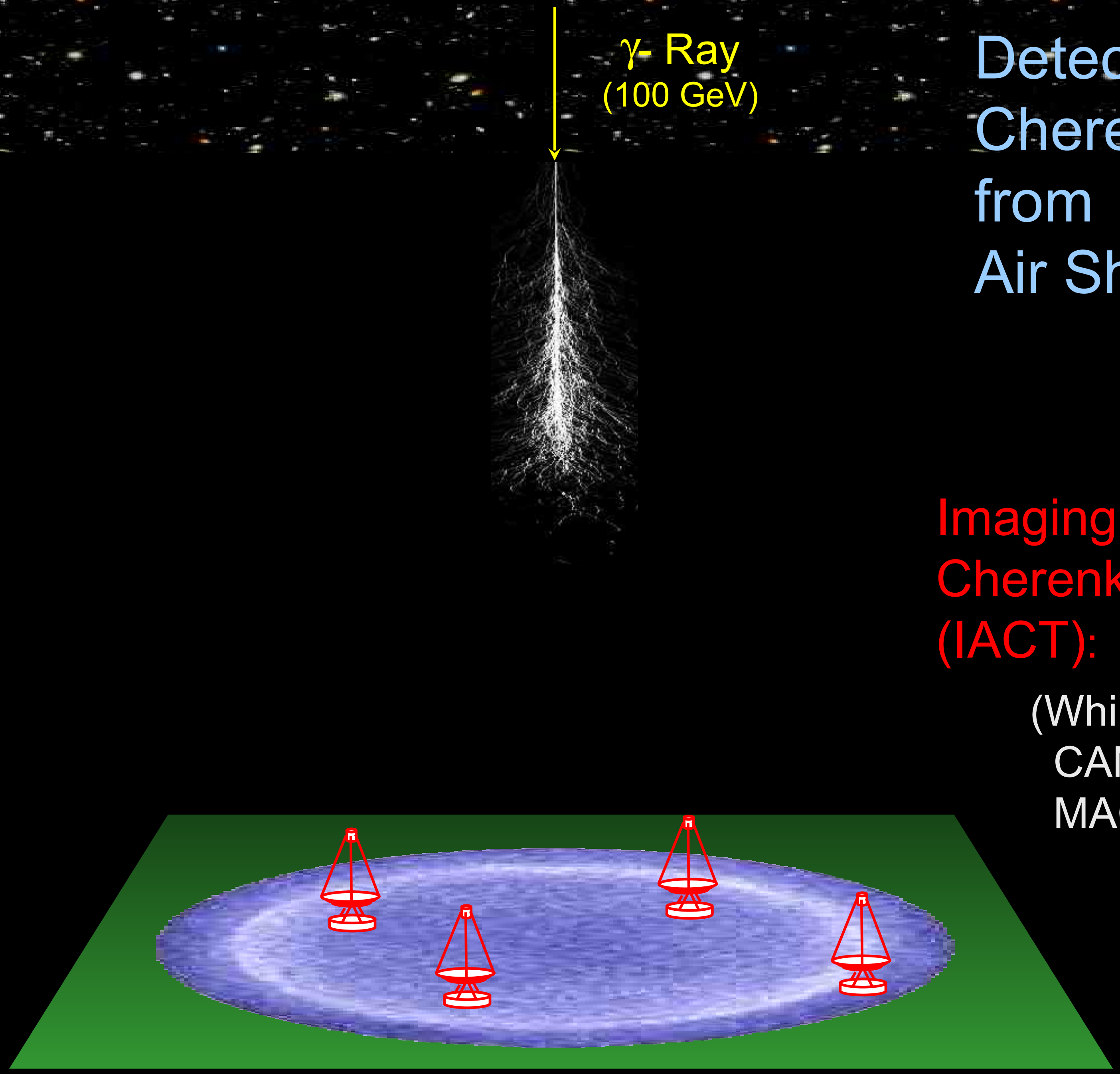
E_c ~ 80 MeV

Cherenkov Light from Air Showers



E_γ : 100 GeV

~ 10 Photons/m^2
(300 – 600 nm)



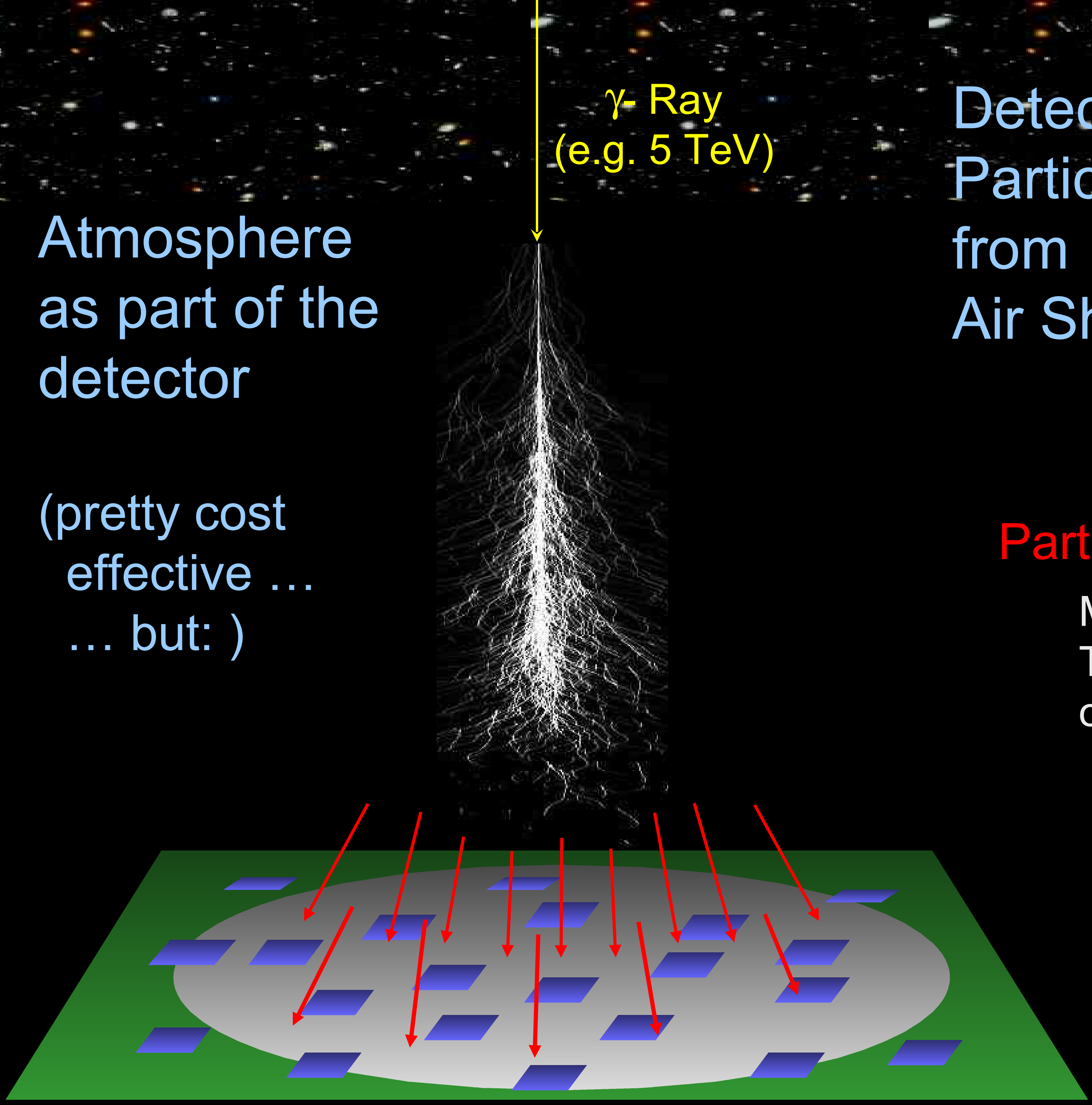
Detection of Cherenkov Light from Air Showers

Imaging Atmospheric Cherenkov Telescopes (IACT):

(Whipple, HEGRA, CAT)
CANGAROO, H.E.S.S., MAGIC, VERITAS

Atmosphere as part of the detector

(pretty cost effective …
… but:)

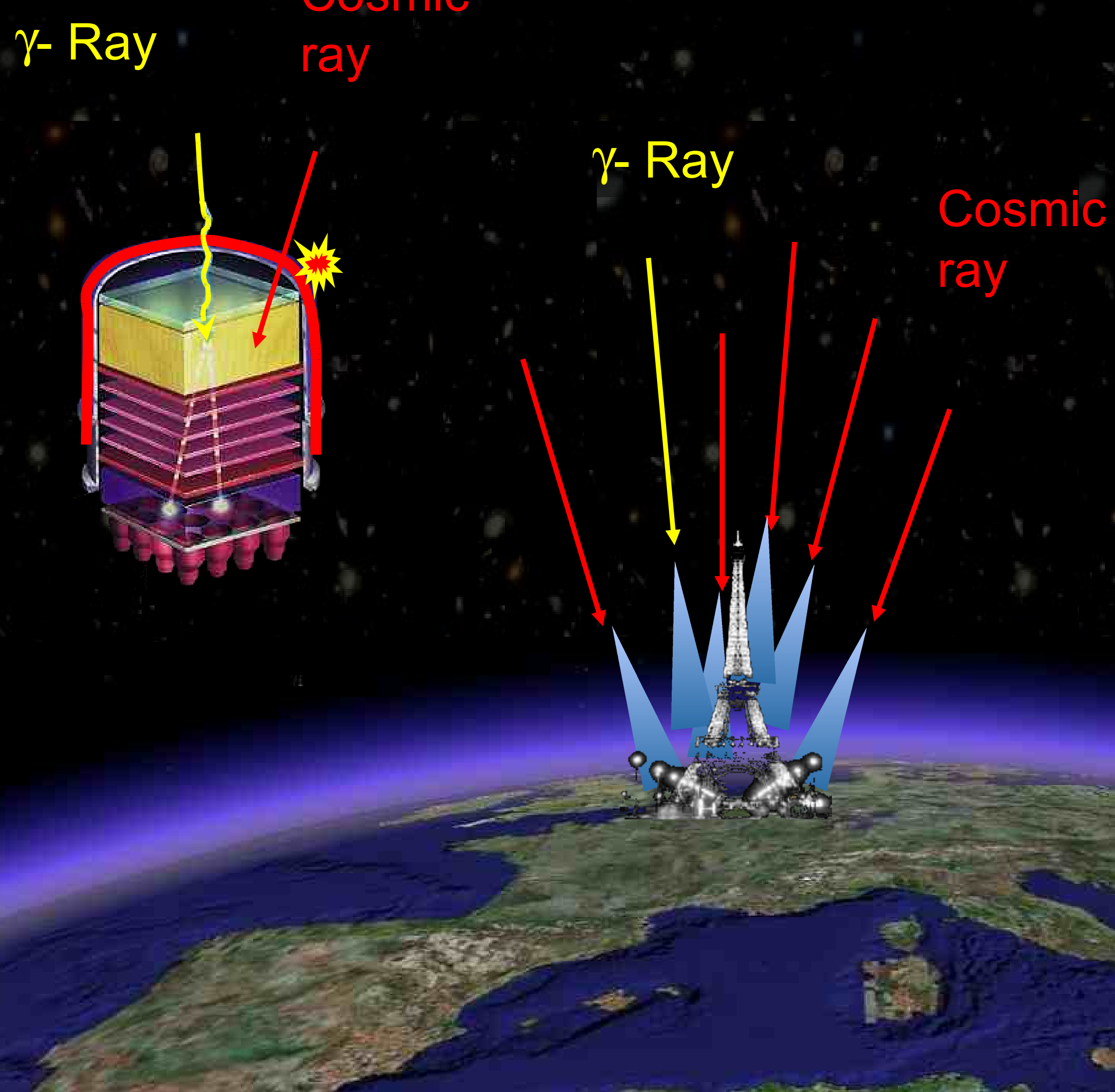


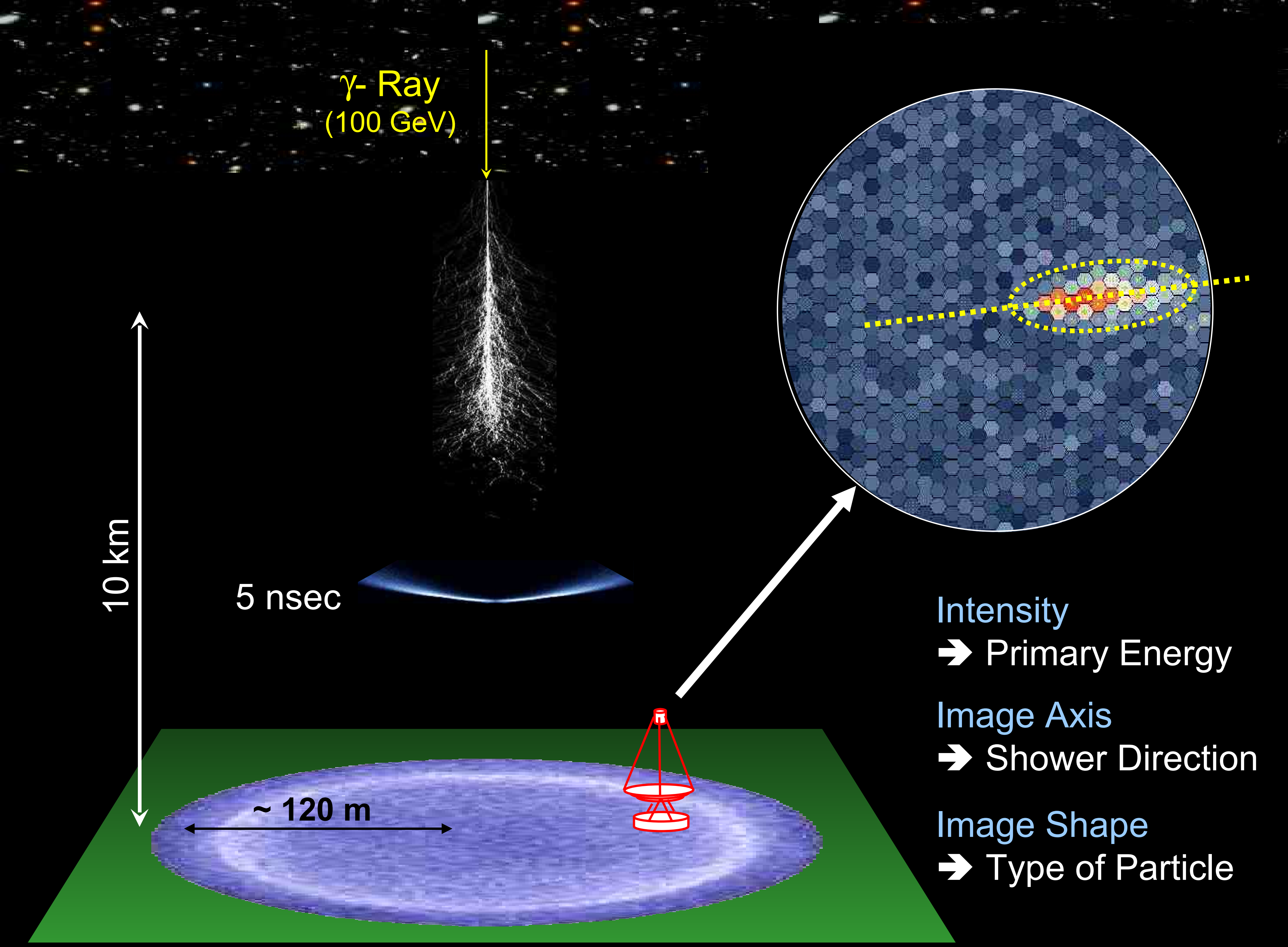
Detection of Particles from Air Showers

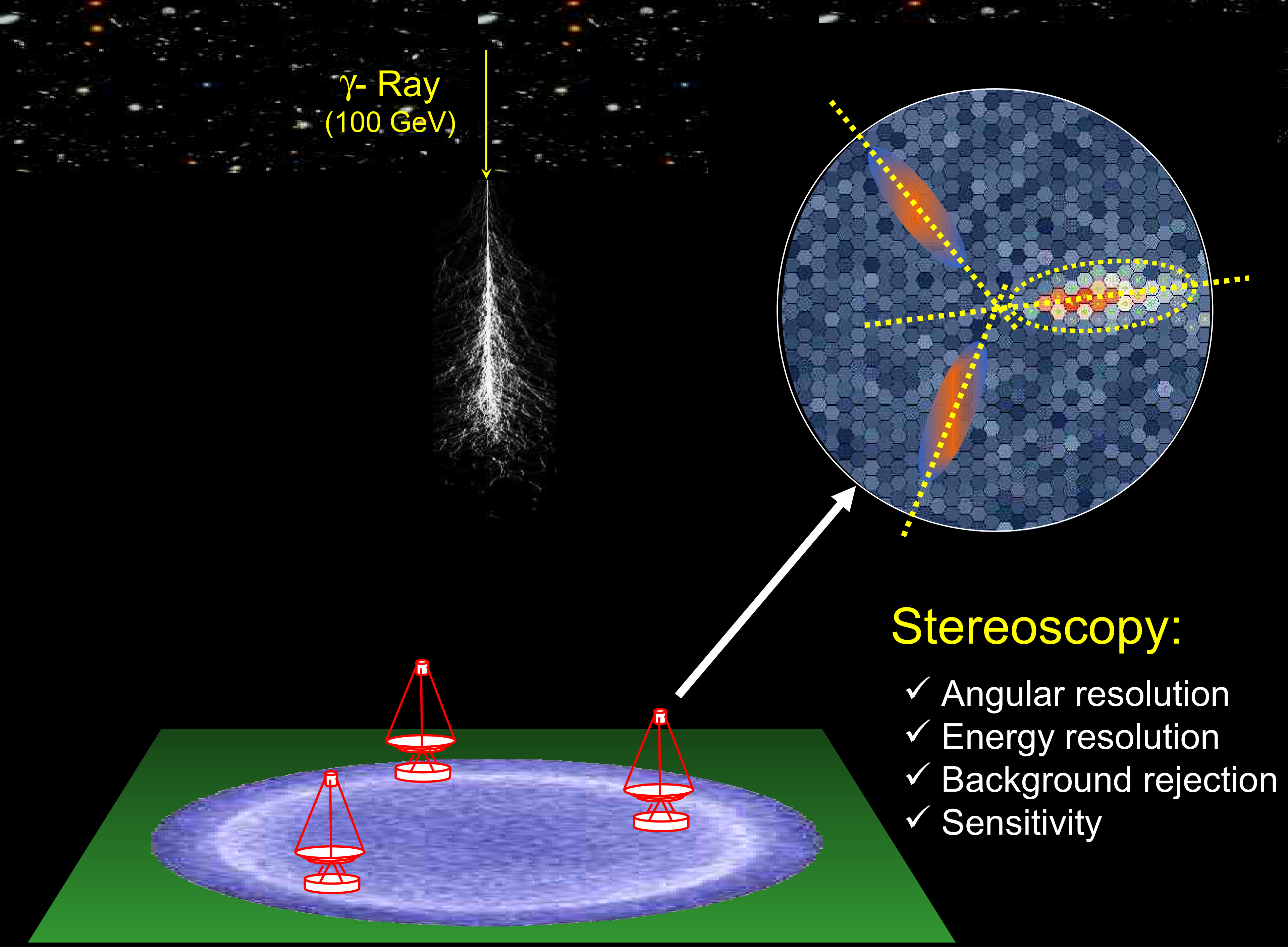
Particle Arrays:

Milagro
Tibet Array
others, …

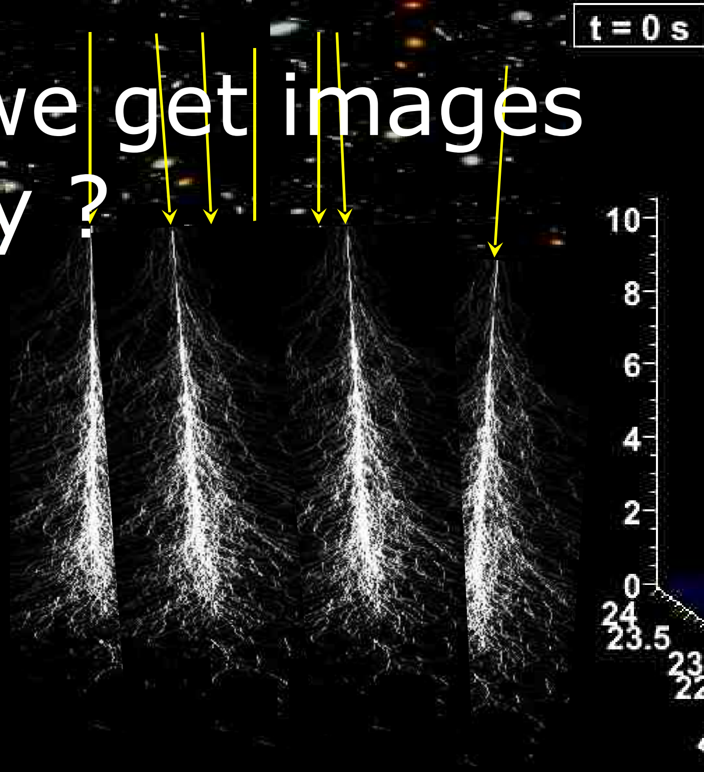
Background from Charged Cosmic Rays



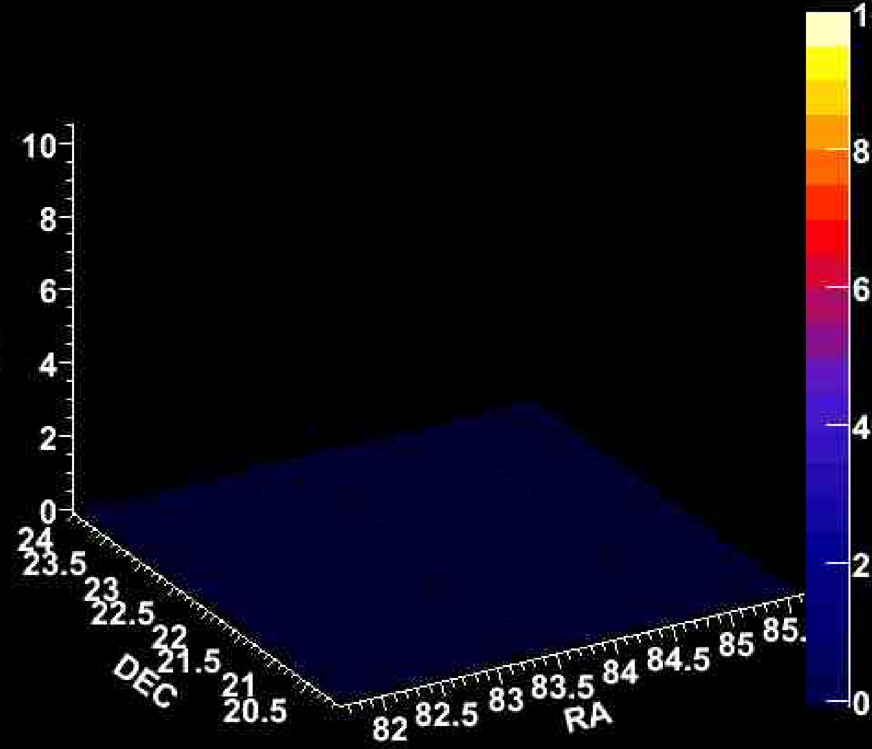

γ- Ray
(100 GeV)
10 km
5 nsec
~ 120 m
Intensity
➔ Primary Energy
Image Axis
➔ Shower Direction
Image Shape
➔ Type of Particle


γ- Ray
(100 GeV)
Stereoscopy:
✓ Angular resolution
✓ Energy resolution
✓ Background rejection
✓ Sensitivity

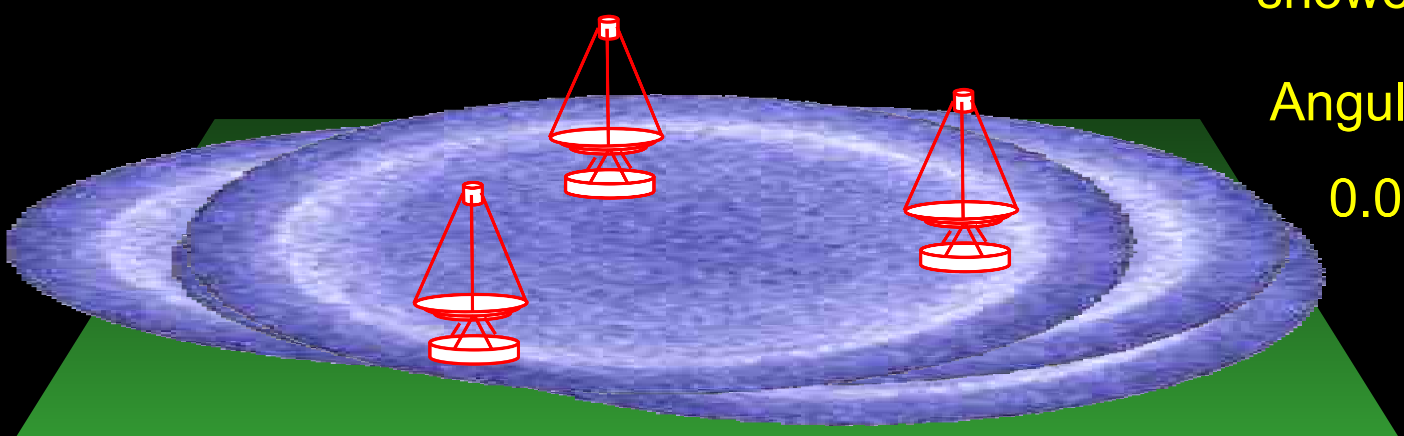
How do we get images of the sky ?



From T.Weeks (VERITAS)



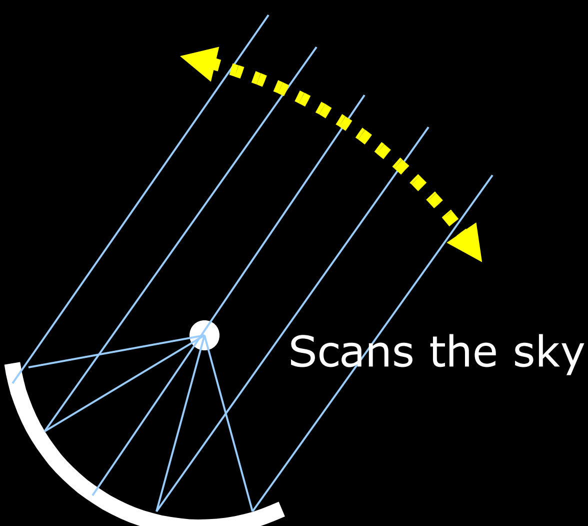
Sky map of reconstructed shower directions

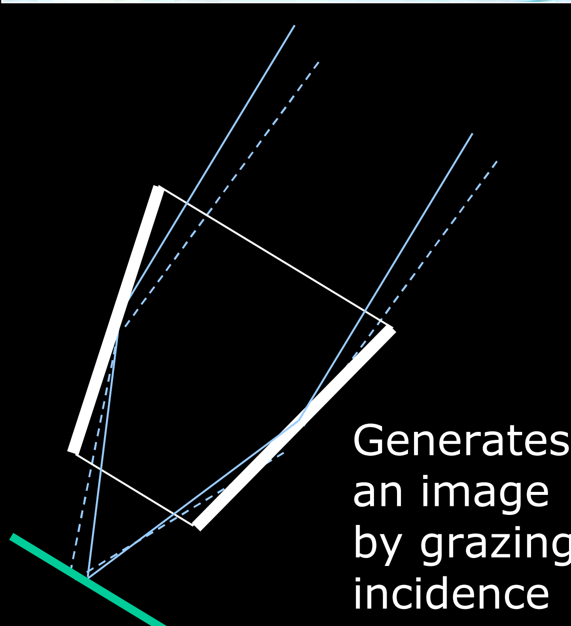


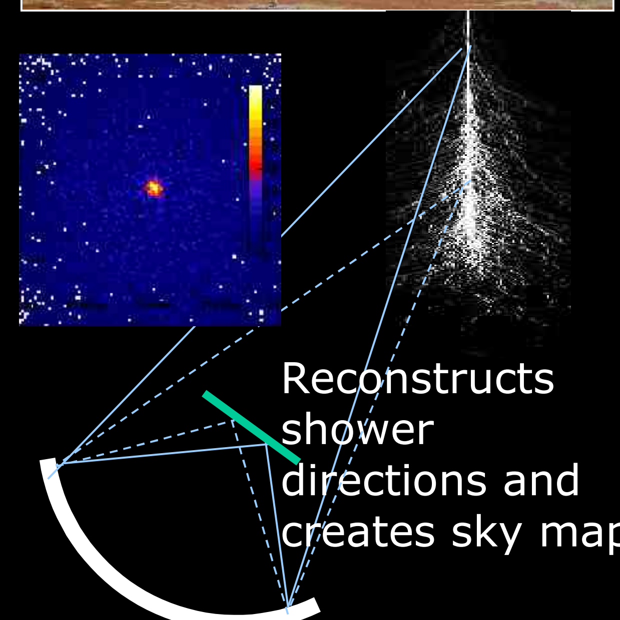
Angular resolution:

0.05 …. 0.1°

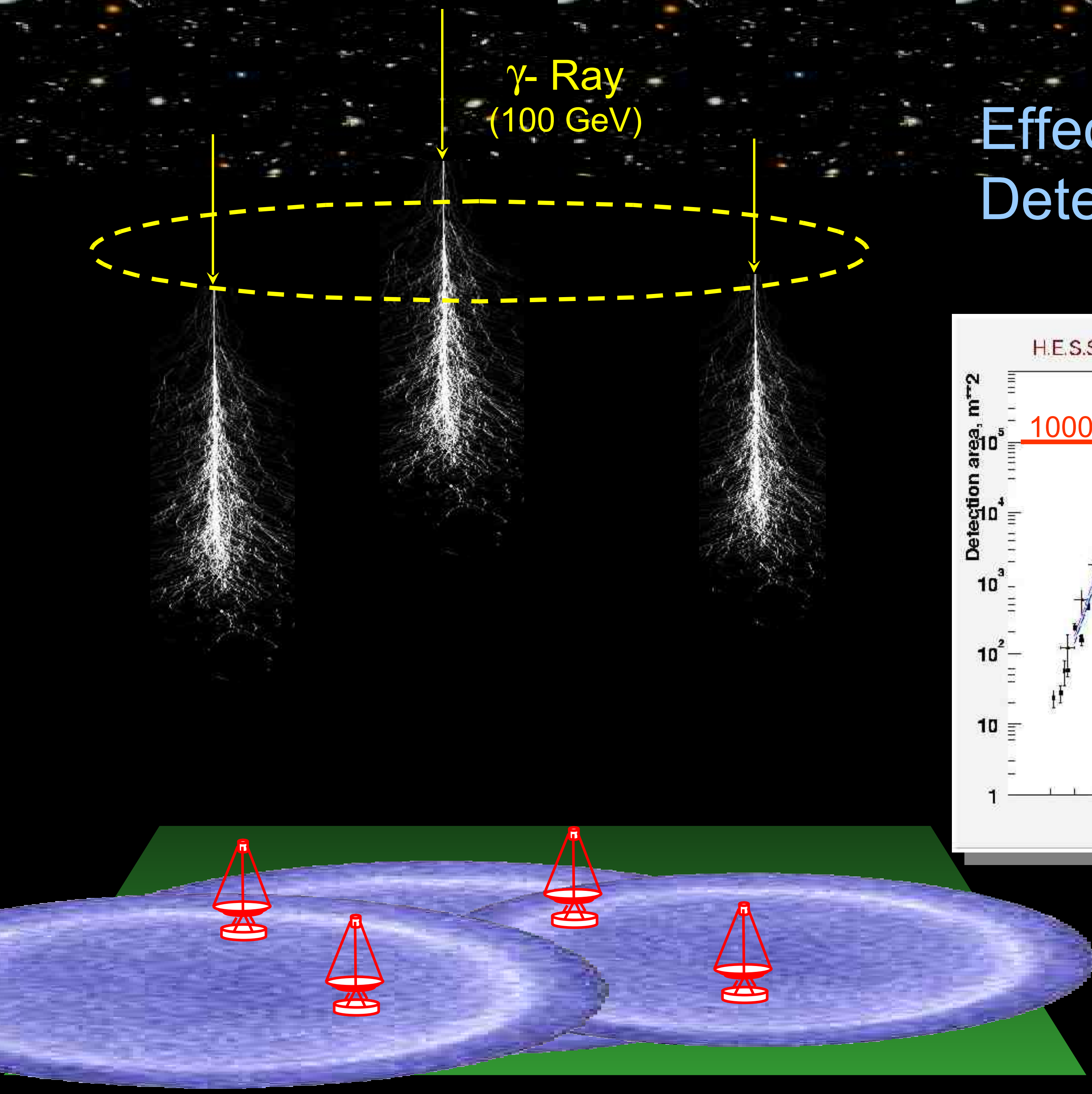
How do we get images of the sky ?

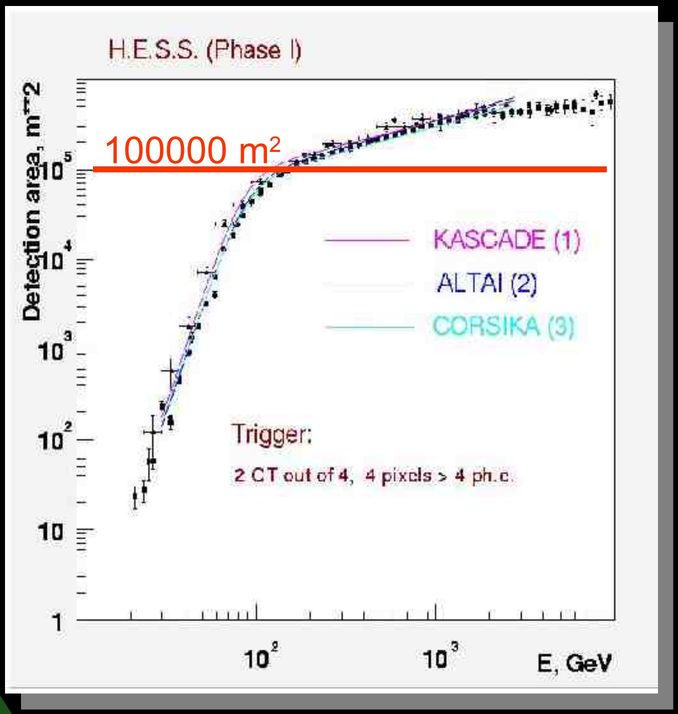




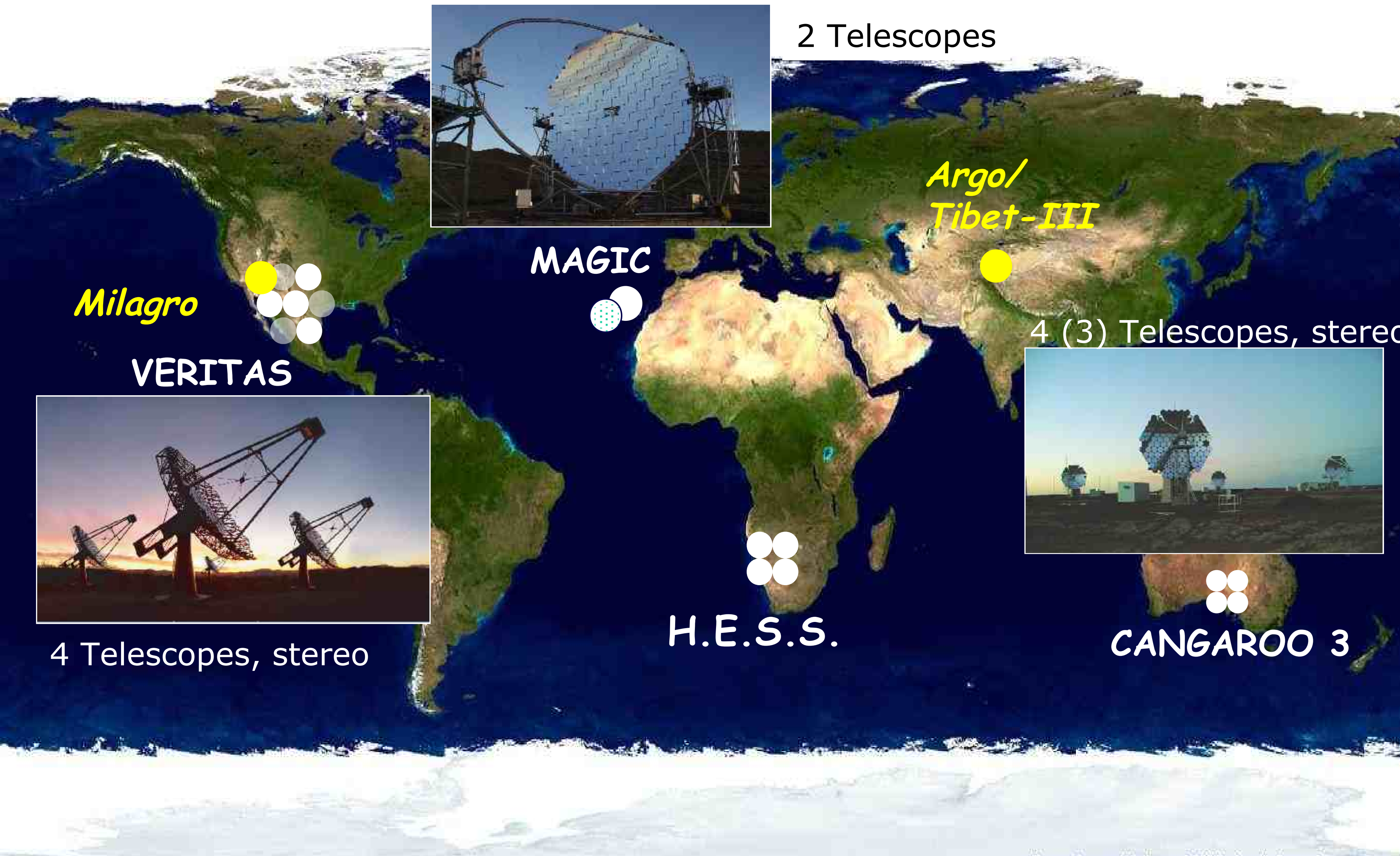


Effective Detection Area





Major Ground-Based γ-Ray Installations



The MAGIC Telescope(s)

17 meter diameter
236 m^2 mirror area

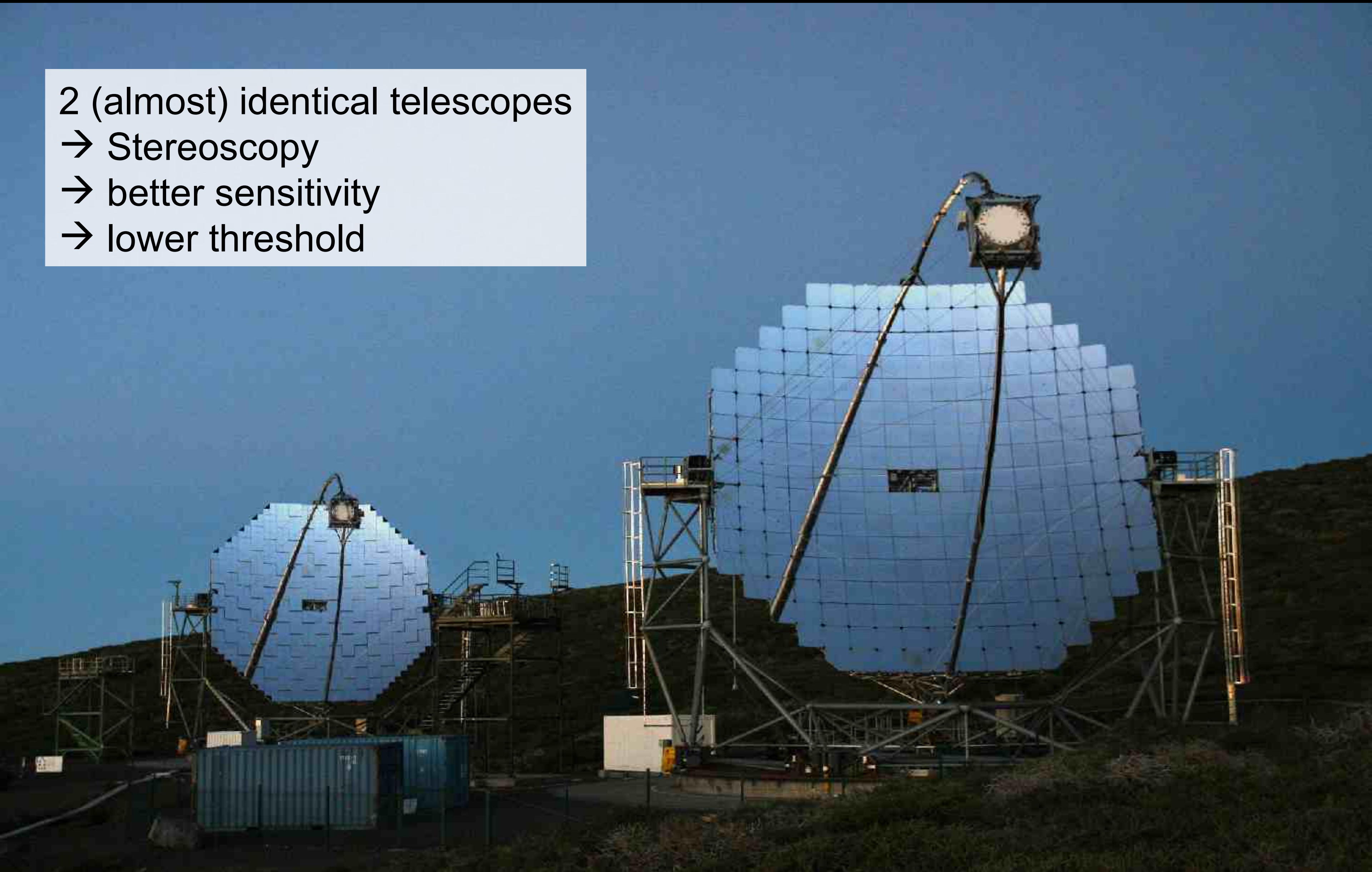
Camera:
3.5 deg FoV

Energy threshold :
~50 GeV (<100 GeV analysis)

First telescope operational since 2004

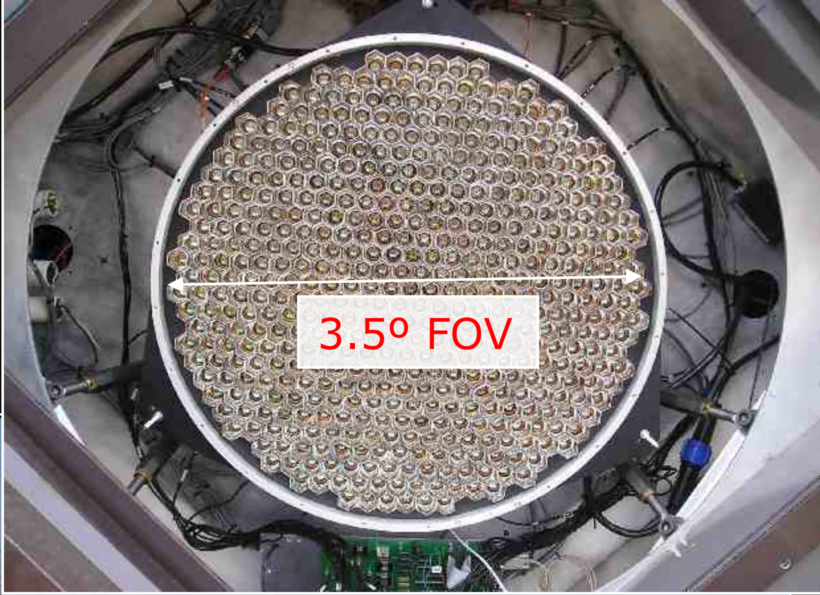
MAGIC : stereo observations since 2009

2 (almost) identical telescopes
→ Stereoscopy
→ better sensitivity
→ lower threshold



VERITAS: since 2007

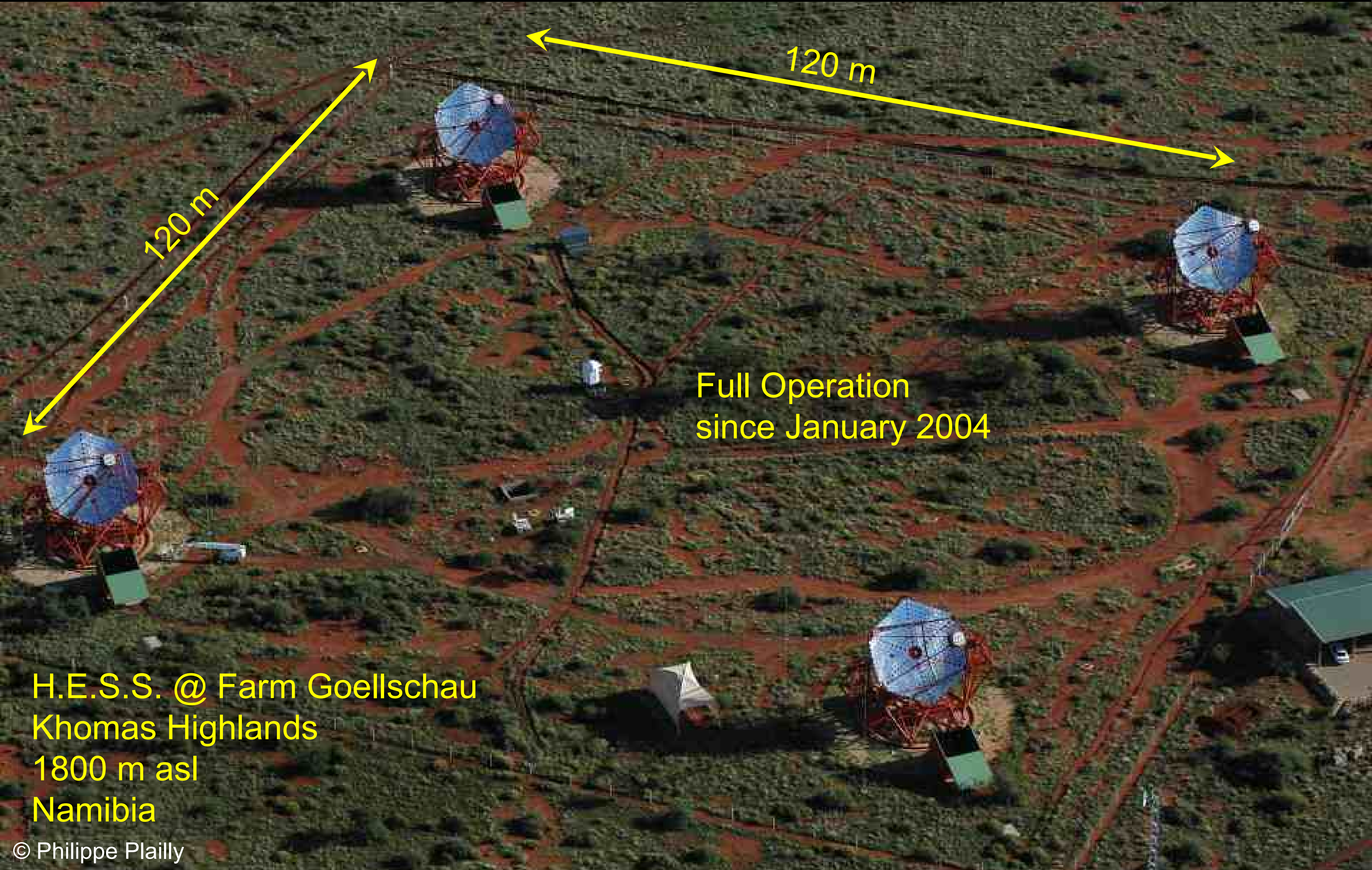
499 PMT camera



Situated at the Whipple Observatory
near Tucson, Arizona
1268m altitude

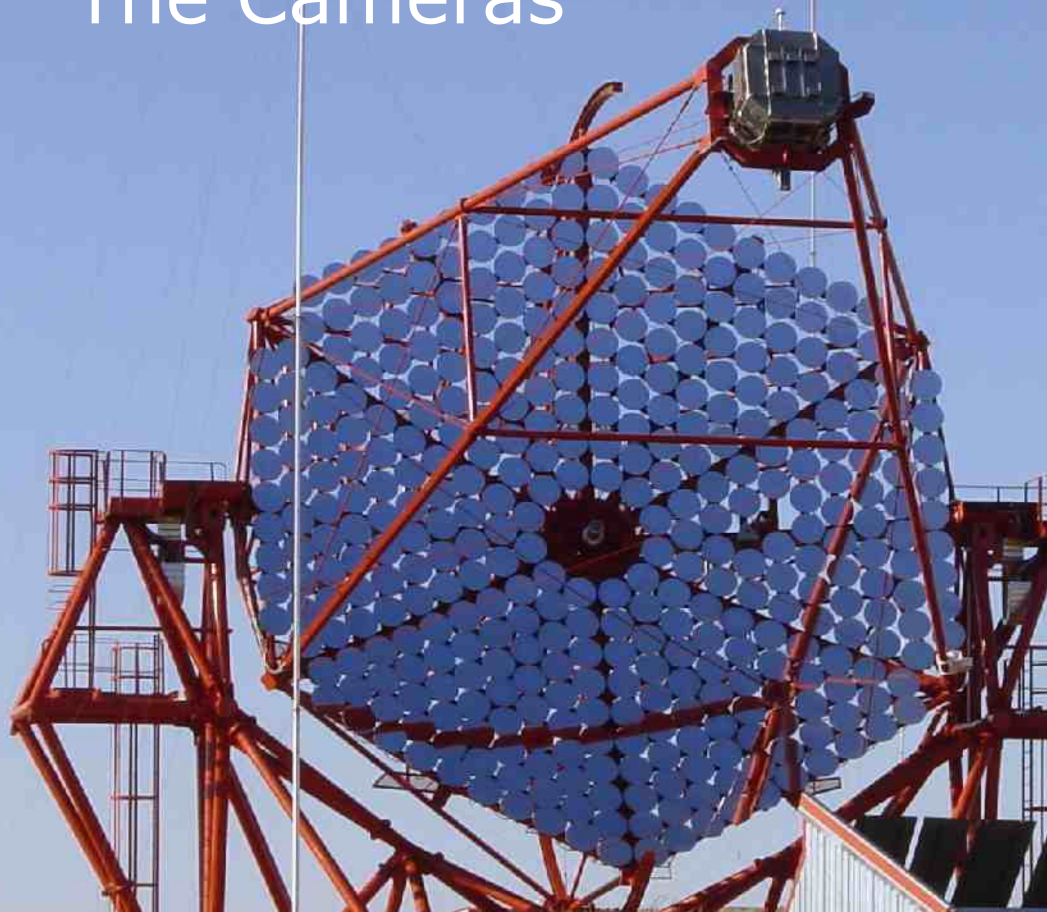
4 telescopes
100 m2 each

High Energy Stereoscopic System

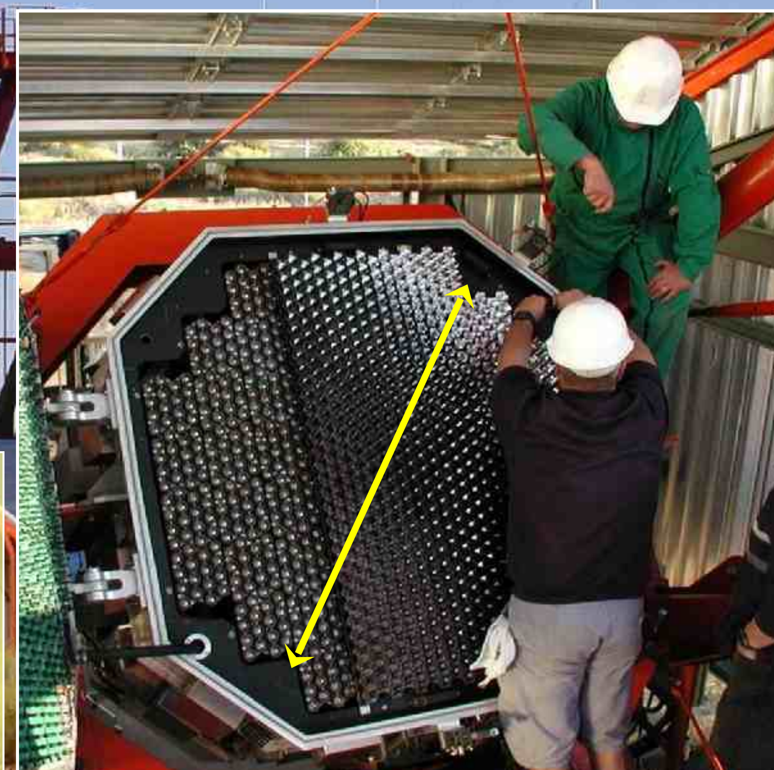


The Cameras

Alt-Azm mount
107 m² mirror area
380 mirrors each
15 m focal length
Rigid mount
Optical PSF
~ 0.5 mrad (r80)

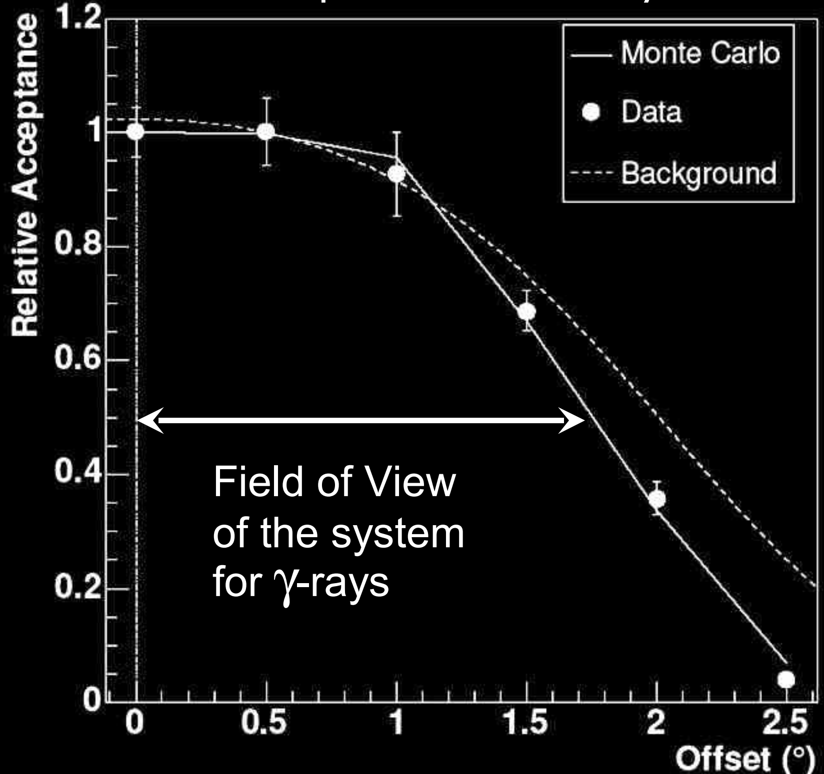


5 deg FoV
960 Pixels / PMTs
Fast Trigger [nsec]
GHz sampling, 16 nsec Int.



Field of View on the Sky

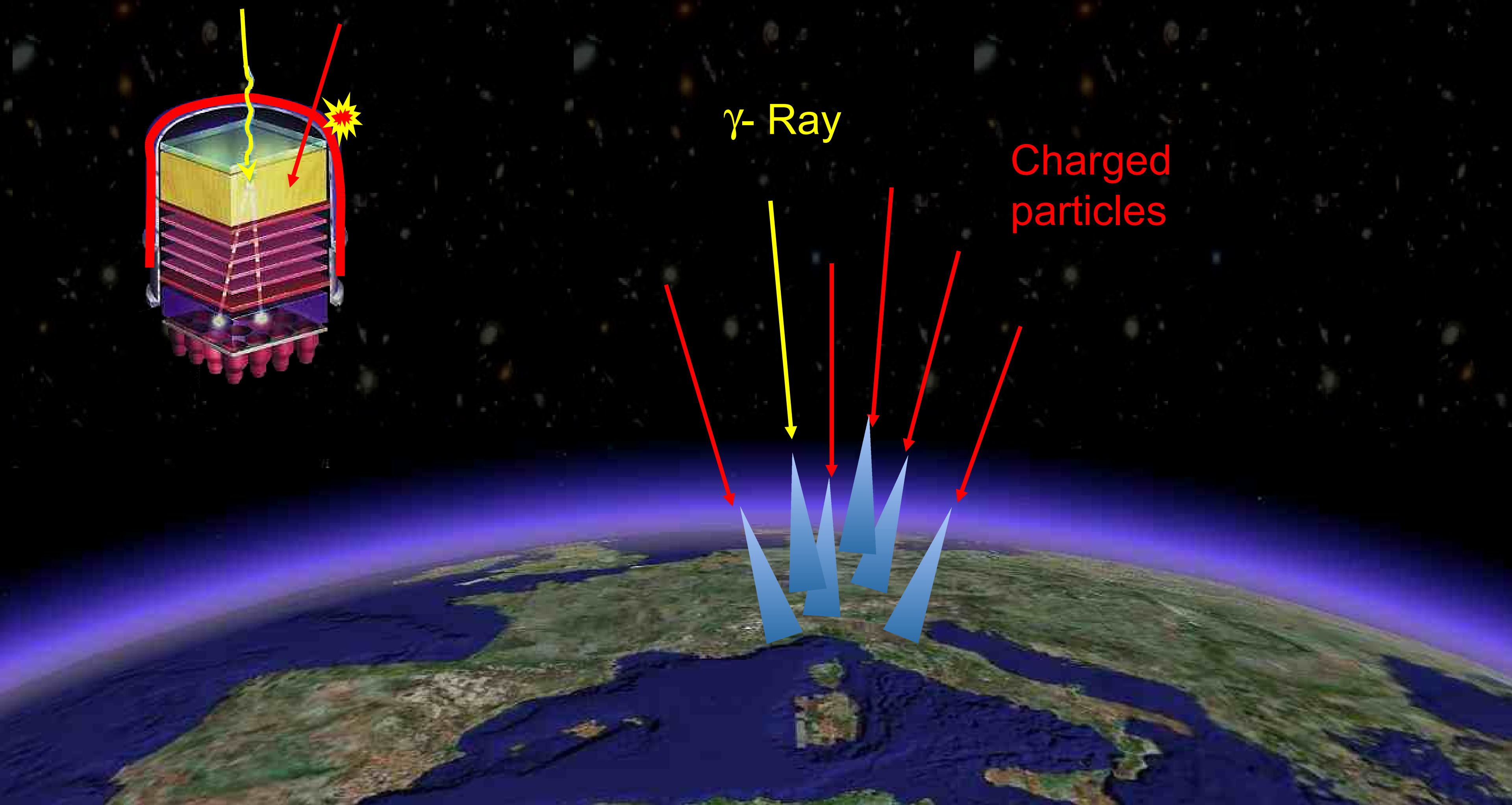
Rel. acceptance of the system



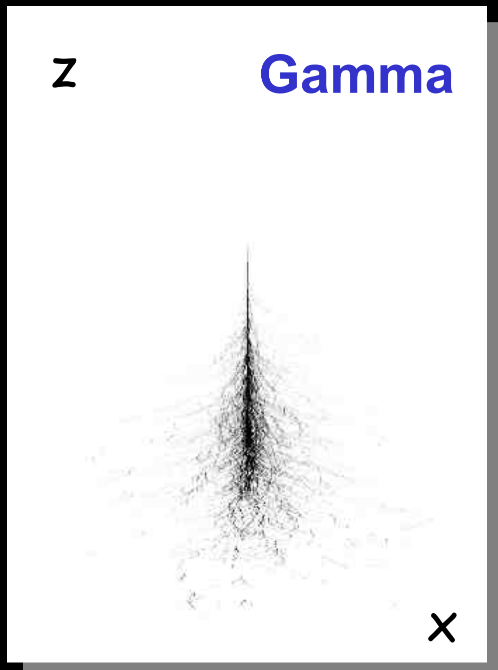
50 % acceptance : 3 deg
20 % acceptance : >4 deg

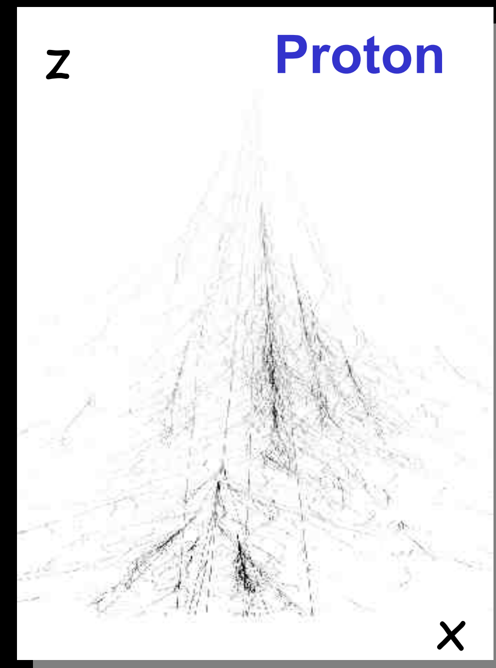
→ Sky Surveys
→ Extended sources
→ Serendipitous discoveries
→ High energy performance

Background from Charged Cosmic Rays



Who is who ? Gamma-Hadron Separation

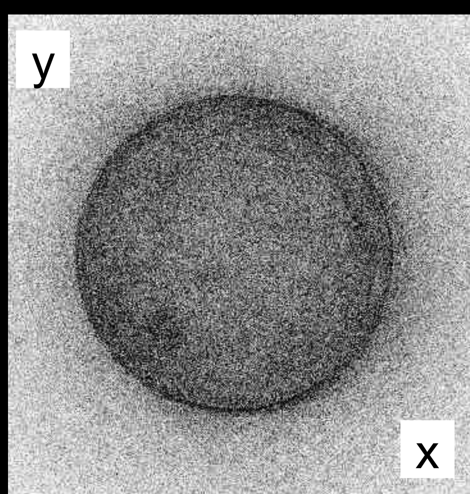


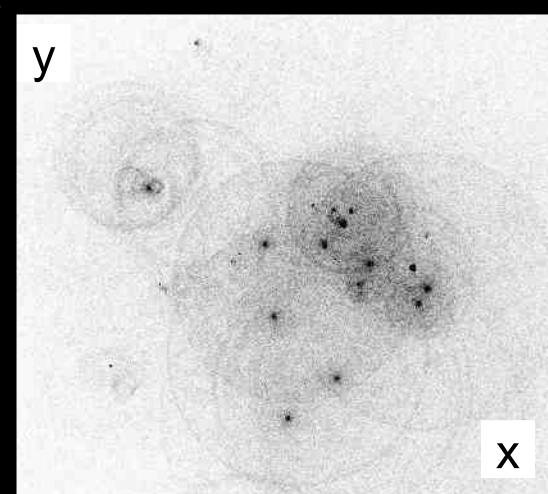


Particle tracks in the air

Not to scale

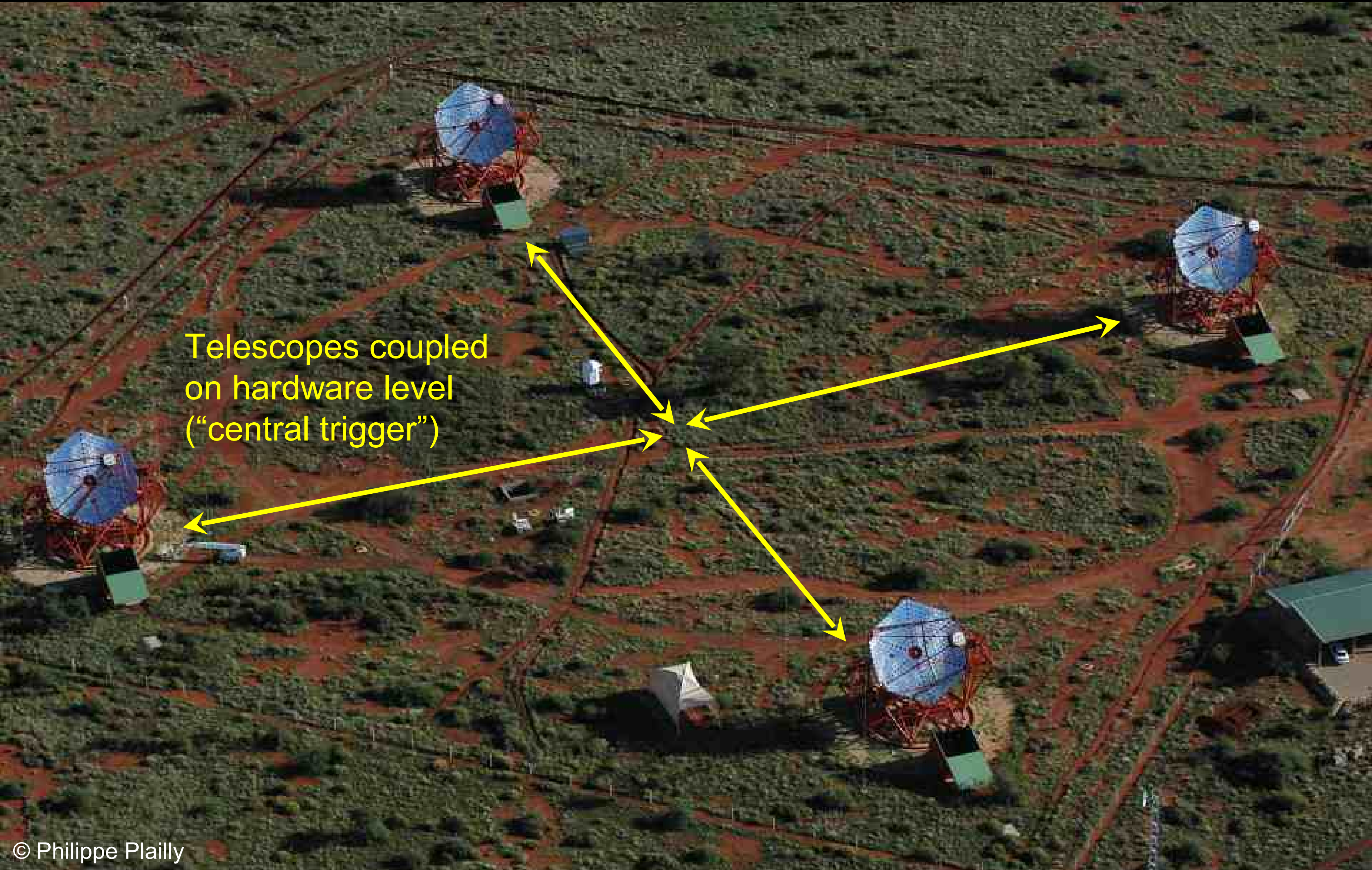
Not to scale



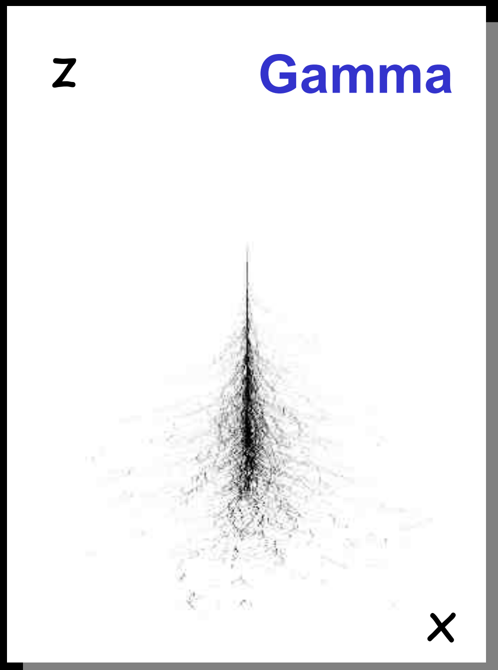


C-photon density on ground

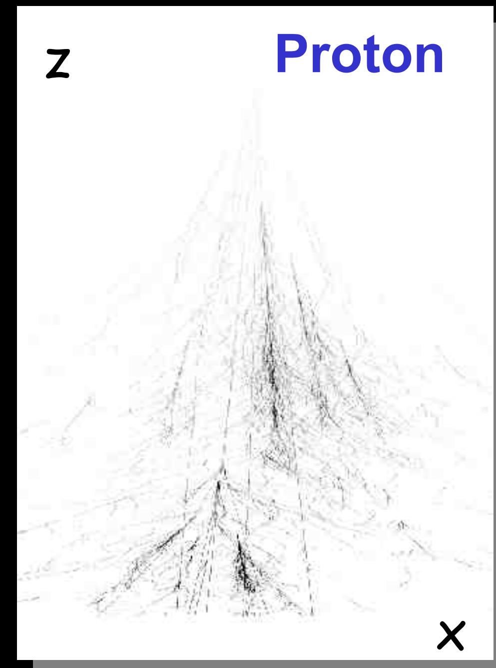
Stereoscopic Hardware Trigger

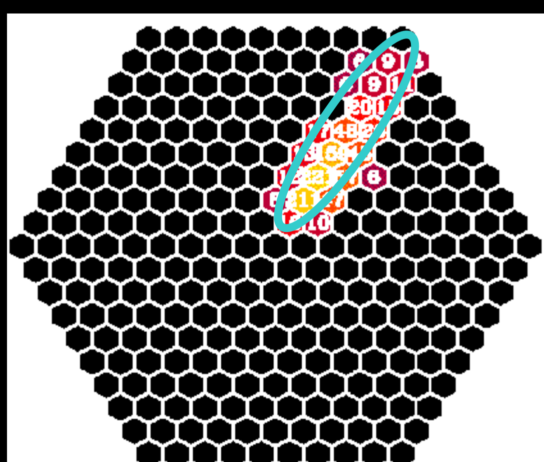


Who is who ? Gamma-Hadron Separation



Particle tracks in the air





Camera plane: angular space

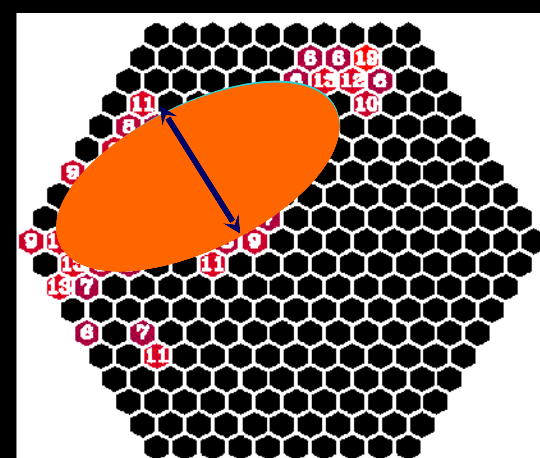
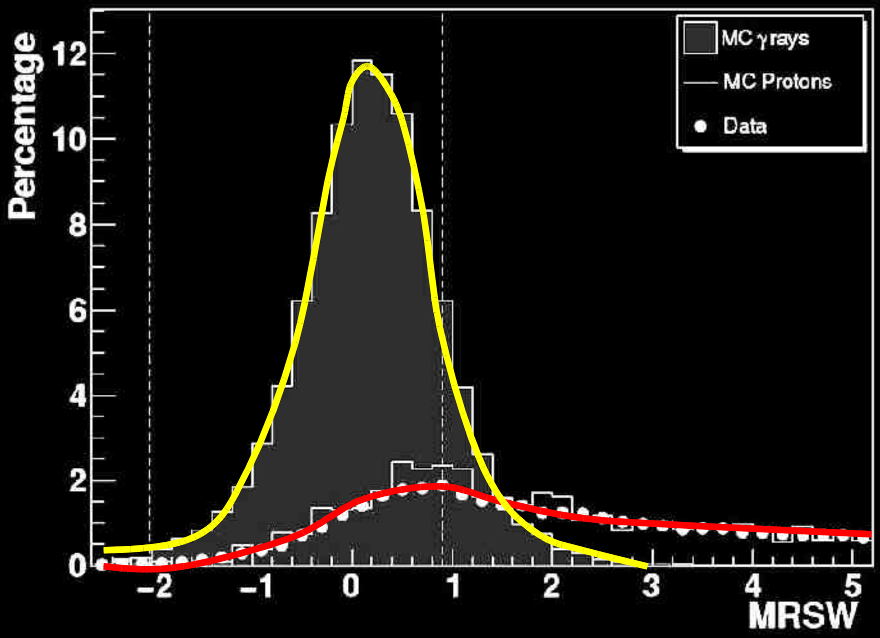
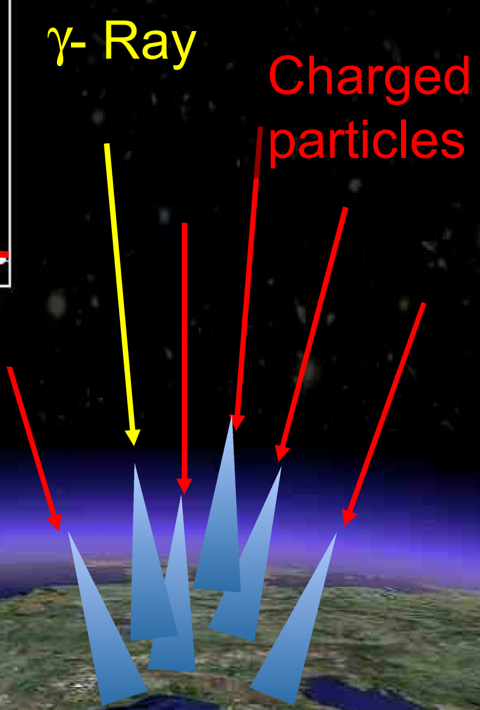


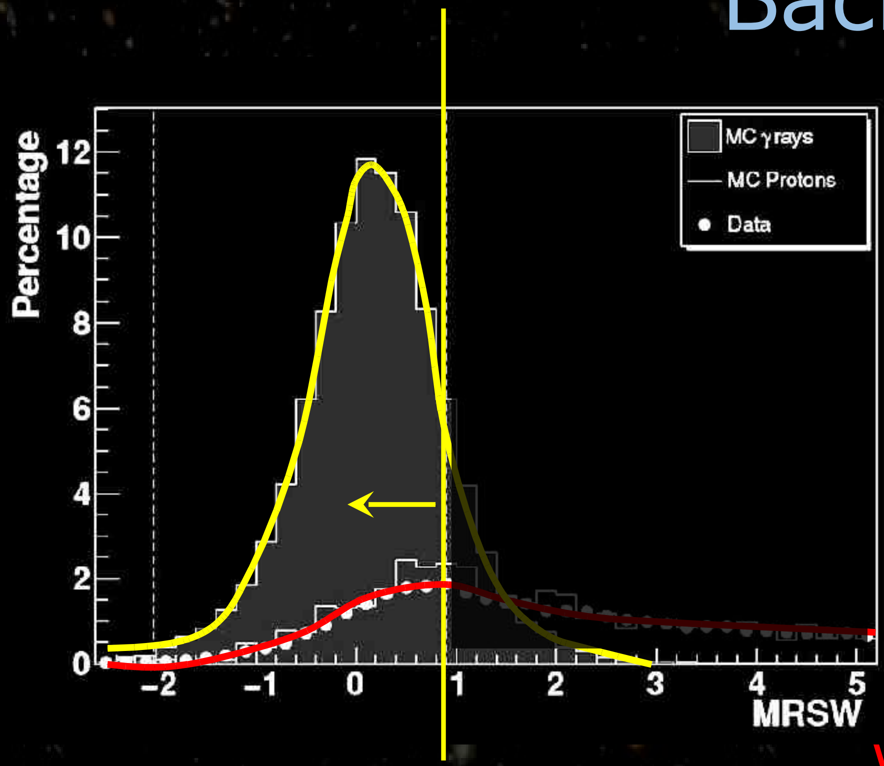
Image Width

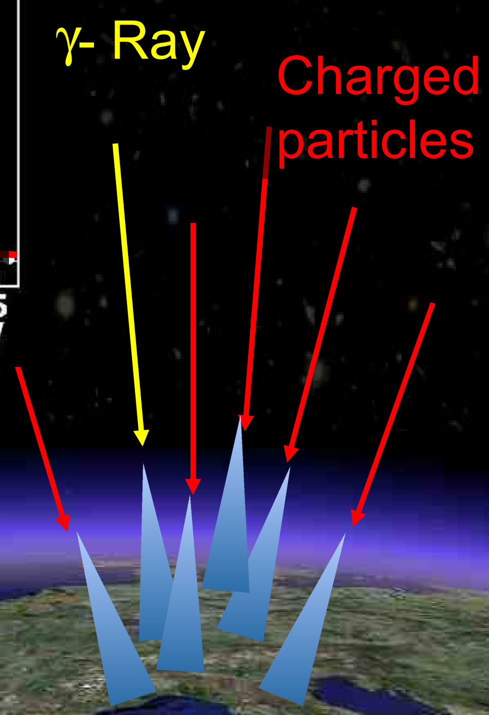
Background from Charged Cosmic Rays





Background from Charged Cosmic Rays





ε_γ = 0.56 … 0.28

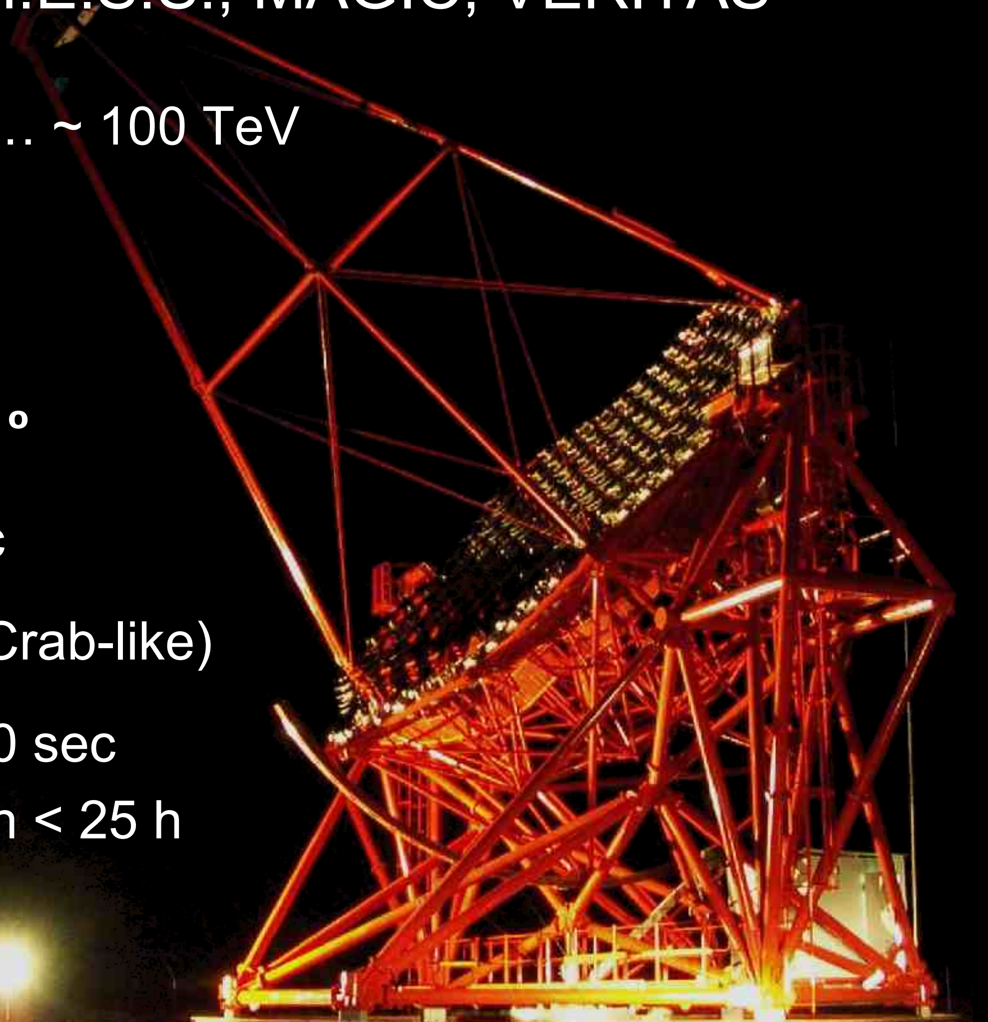
ε_b = 0.03 … 0.004

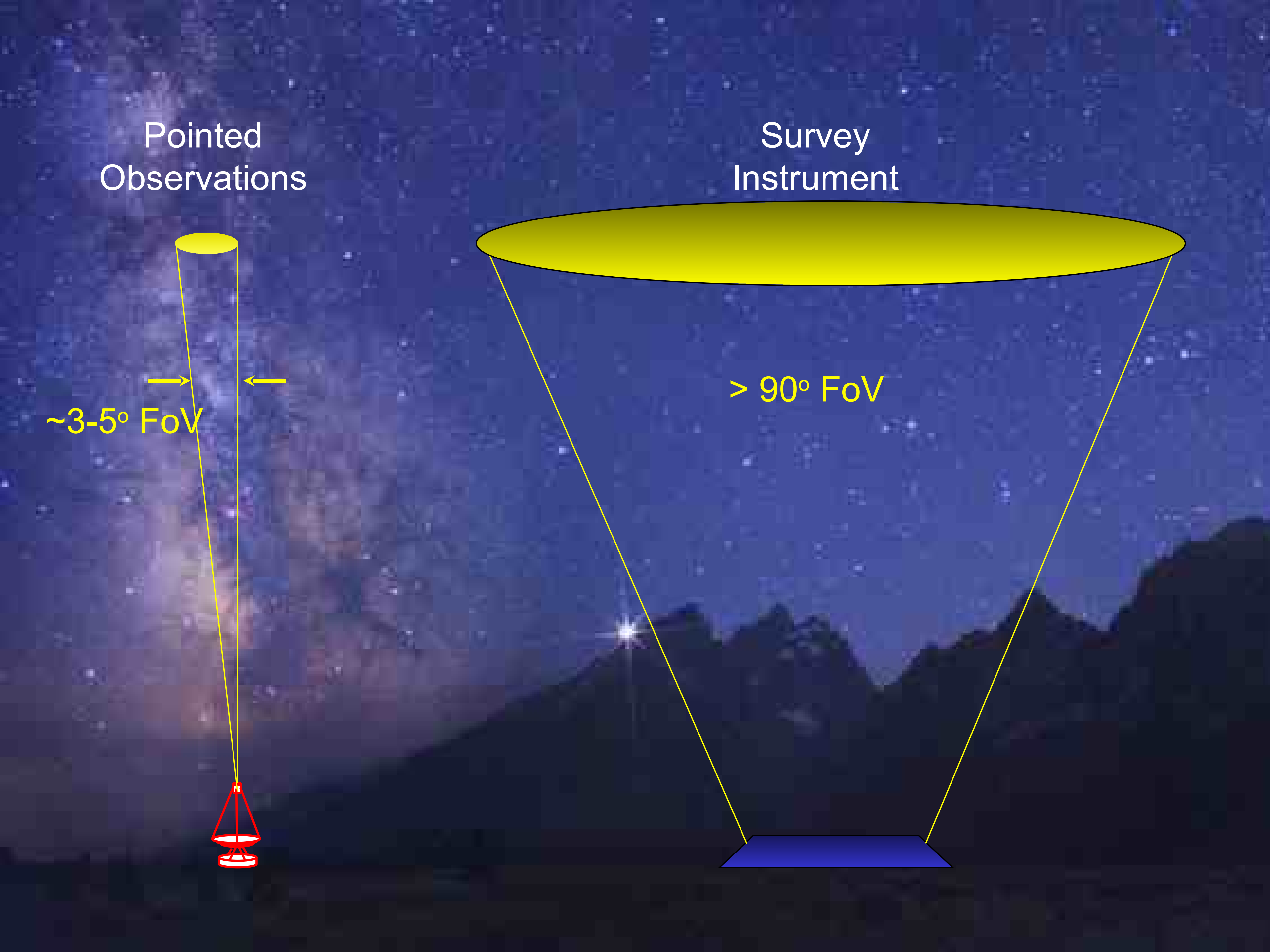
(10 - 20 / h)

State of the Art Performance Parameters

Within a factor 2-3 same for H.E.S.S., MAGIC, VERITAS

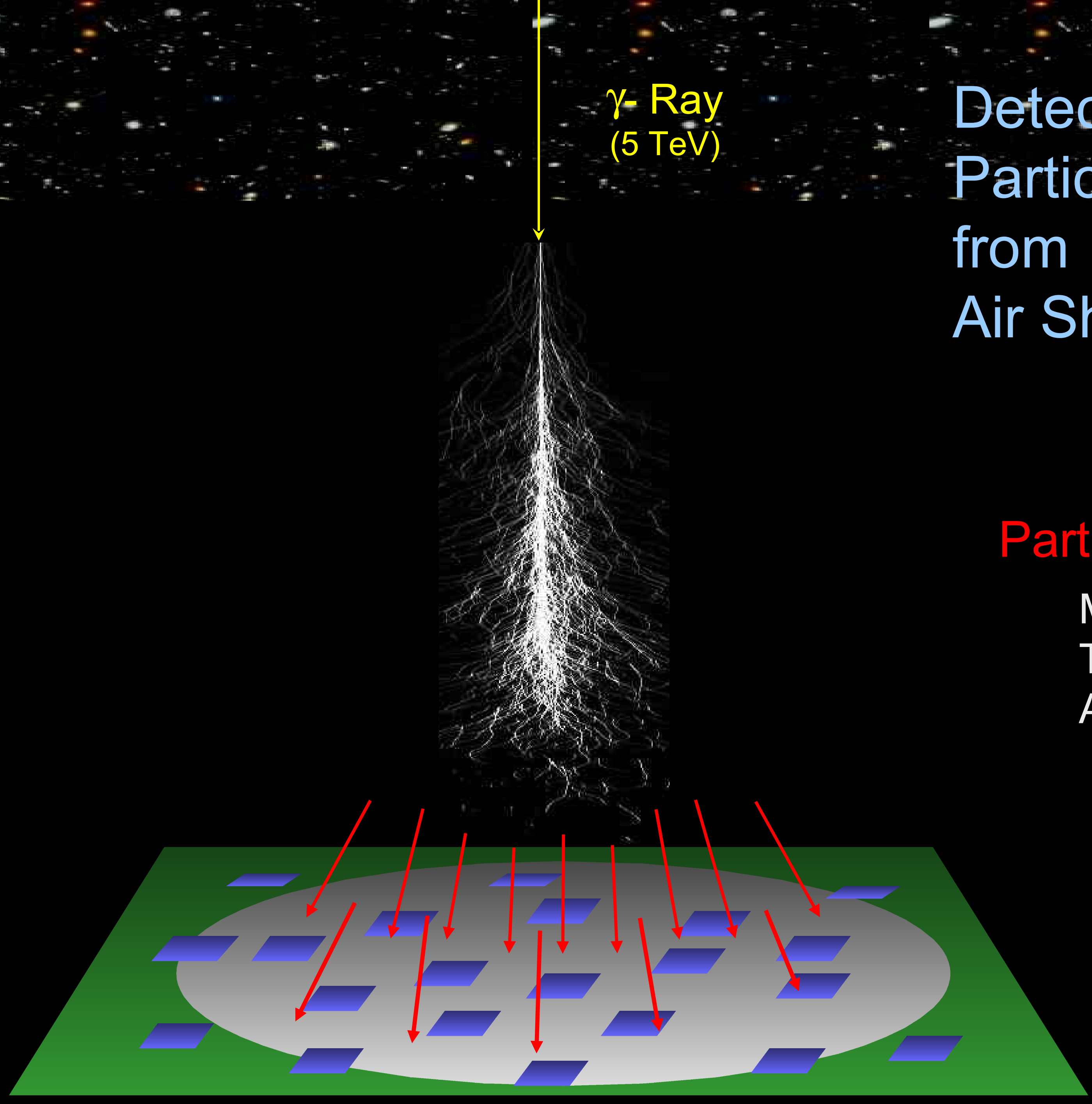
Energy range:	~100 GeV … ~ 100 TeV
Energy resolution:	15 %
Field of view:	~ 4 deg
Angular resolution:	0.05° - 0.1°
Pointing accuracy:	~ 10 arcsec
Signal Rate:	~55 / min (Crab-like)
Sensitivity:	1 Crab in 30 sec 0.01 Crab in < 25 h





Pointed Observations
~3-5° FoV
Survey Instrument
> 90° FoV

Detection of Particles from Air Showers



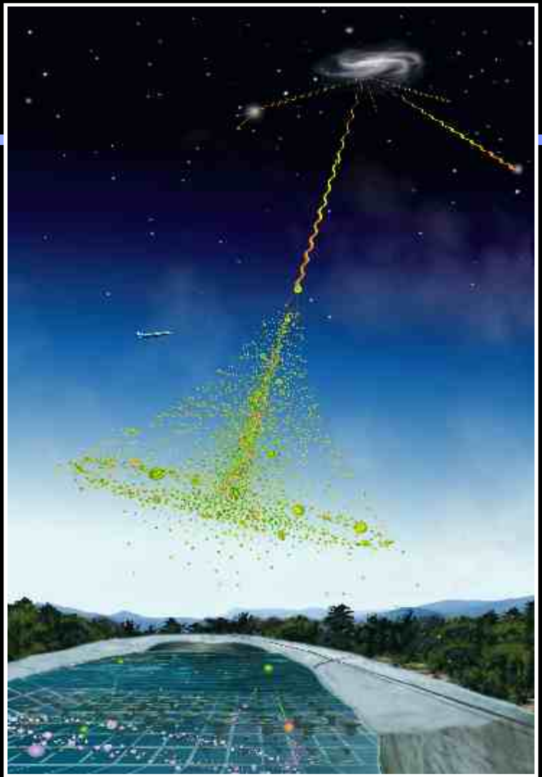
Particle Arrays:

Milagro
Tibet Array
Argo-YBJ, …

Major Ground-Based γ-Ray Installations

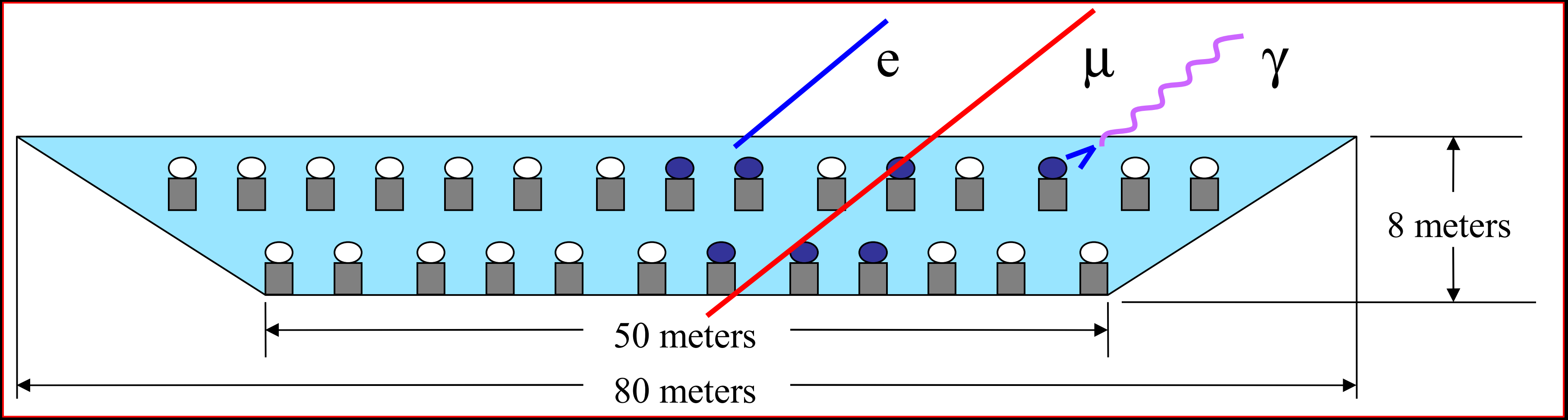
MILAGRO (… - 2007)

MILAGRO: the principle



Water Cherenkov detector

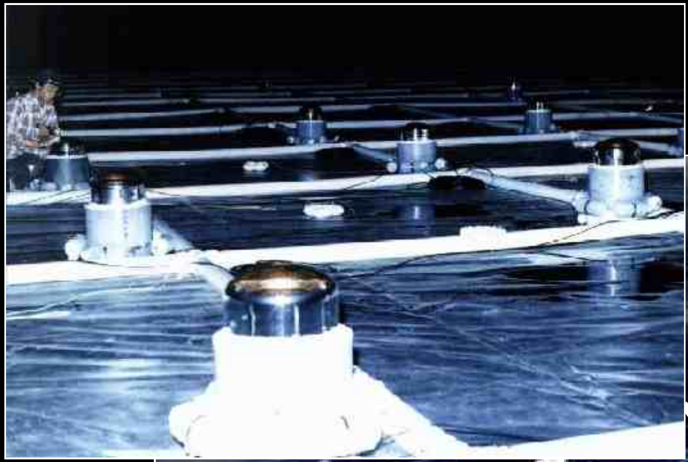
- Use big water pond as particle detector
- Cherenkov light of from air showers particles detected with PMTs

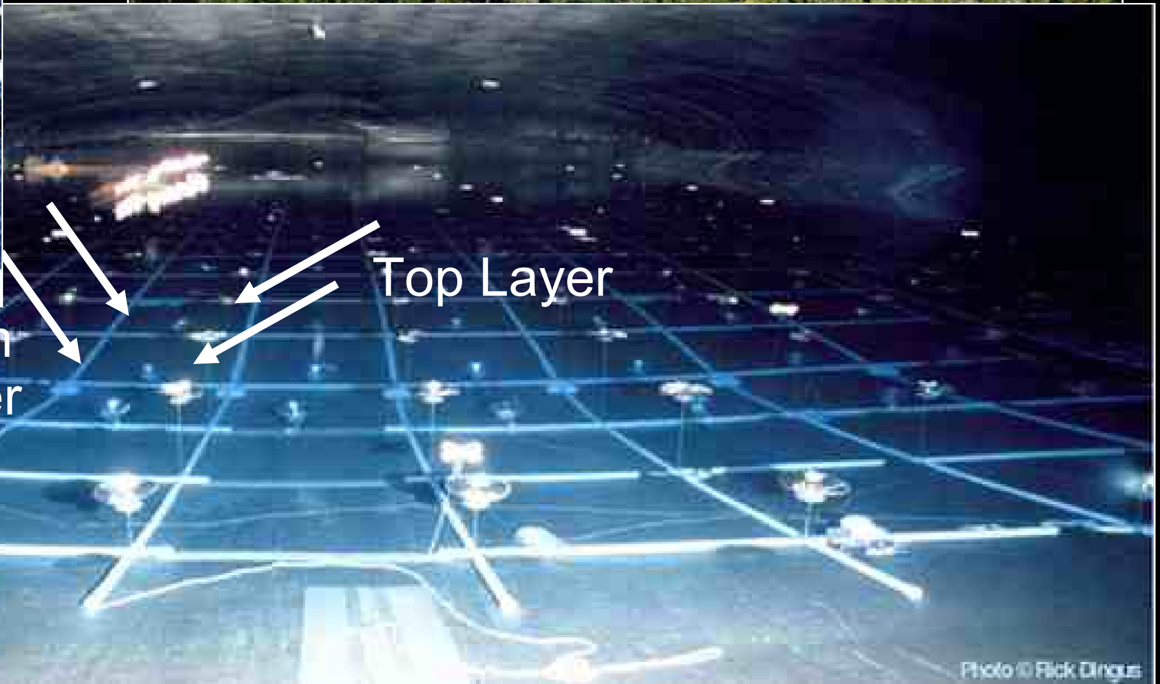


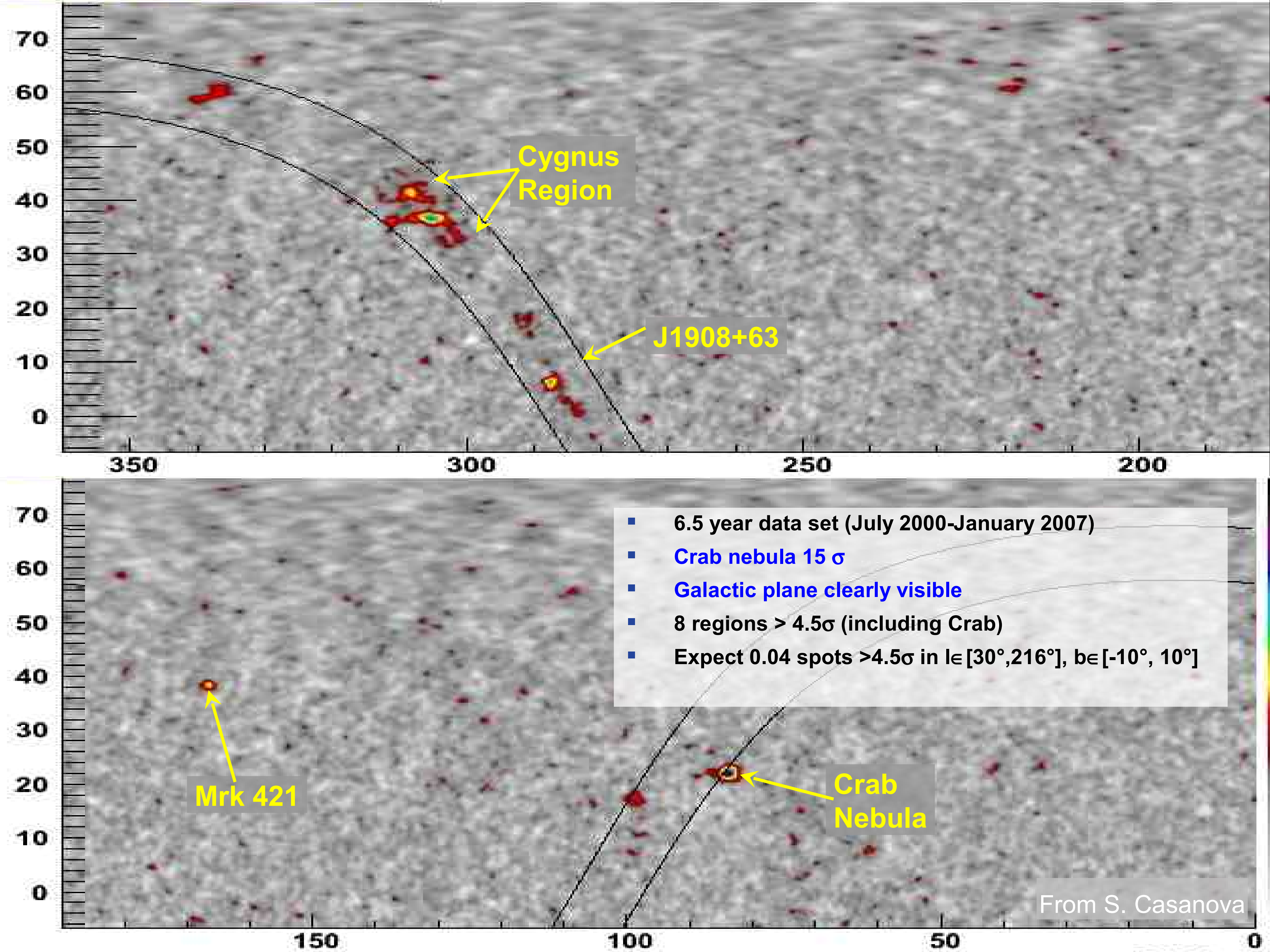
MILAGRO

Near Los Alamos (1999-2007)

2-12 TeV median energy
1700 Hz trigger rate
0.5^o-1.4^o resolution
1 Crab: 5 σ / sqrt(year)



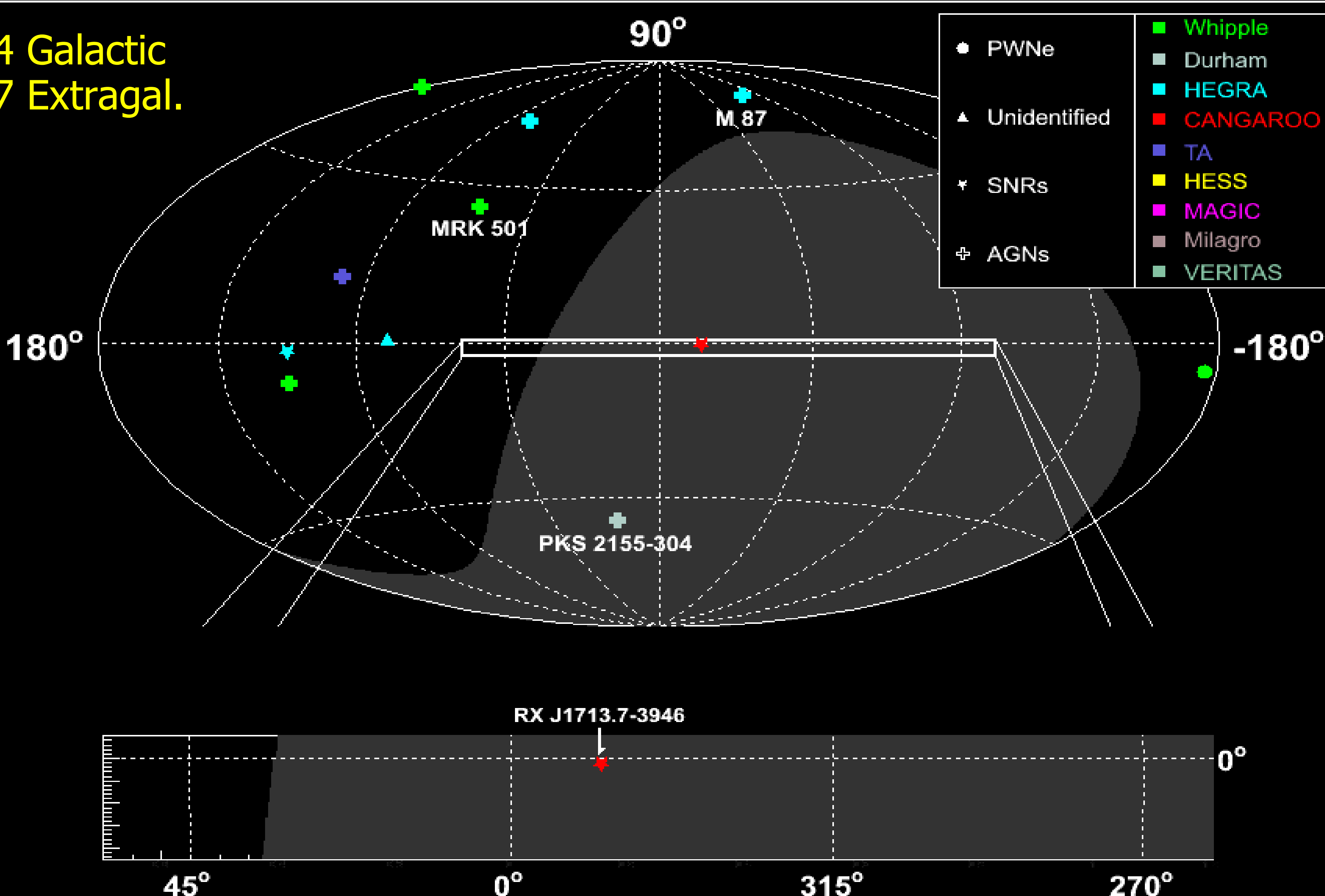



Cygnus Region
J1908+63
Mrk 421
Crab Nebula
6.5 year data set (July 2000-January 2007)
Crab nebula 15 σ
Galactic plane clearly visible
8 regions > 4.5σ (including Crab)
Expect 0.04 spots >4.5σ in l∈[30°,216°], b∈[-10°, 10°]
From S. Casanova
70
60
50
40
30
20
10
0
350
300
250
200
150
100
50
0

Observational results

The TeV Sky in 2003

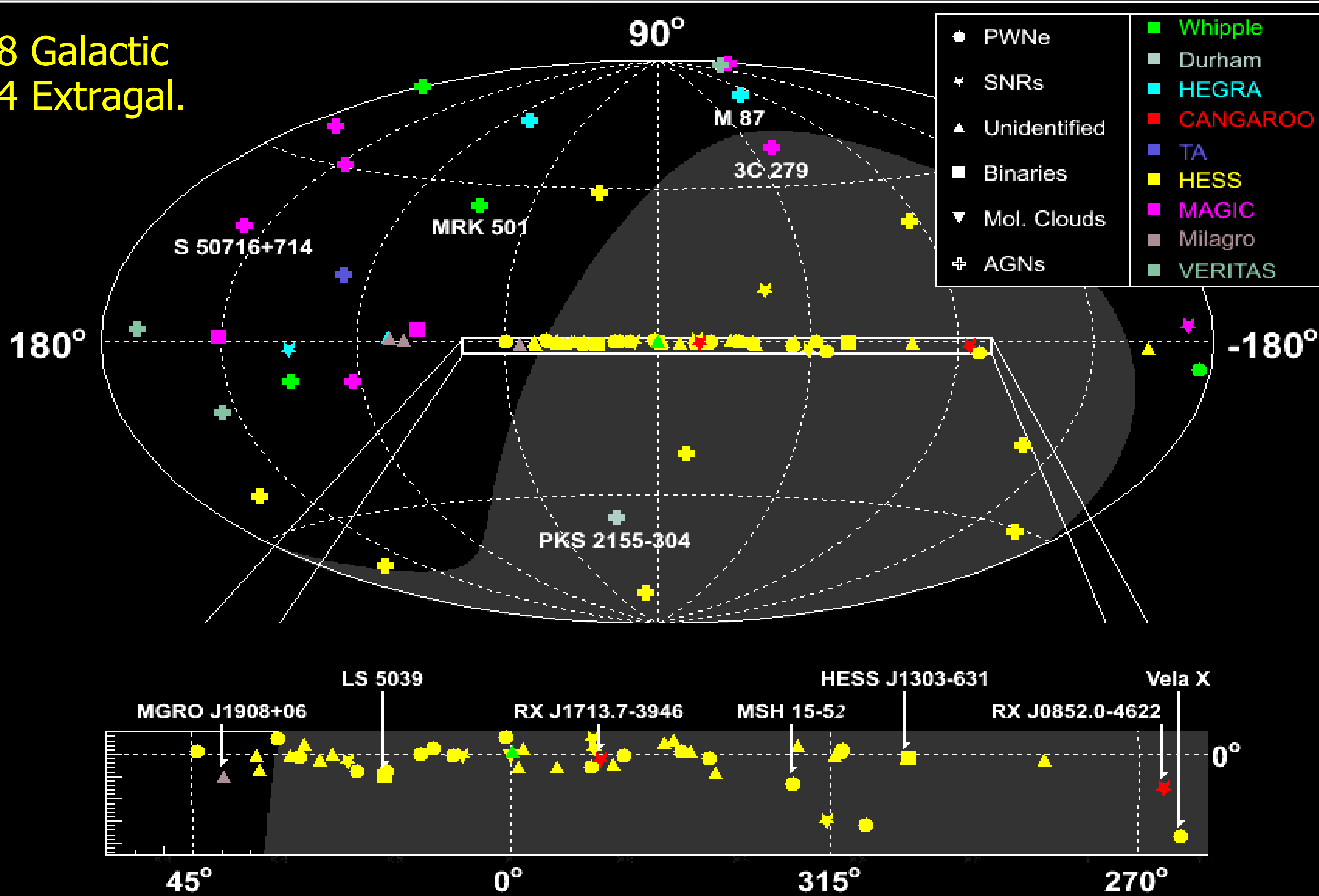
4 Galactic
7 Extragal.



from J. Hinton

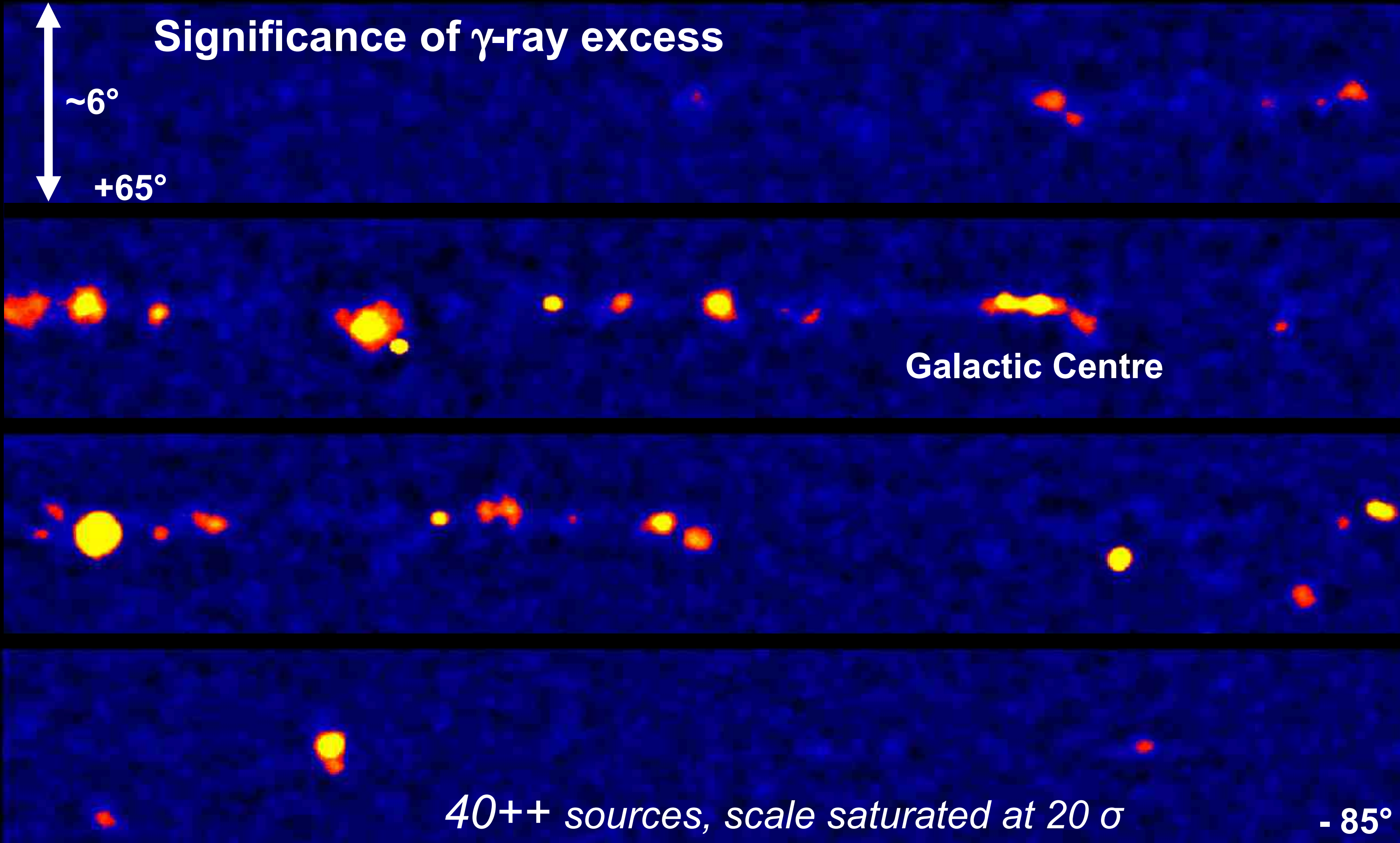
The TeV Sky in February 2009

58 Galactic
24 Extragal.

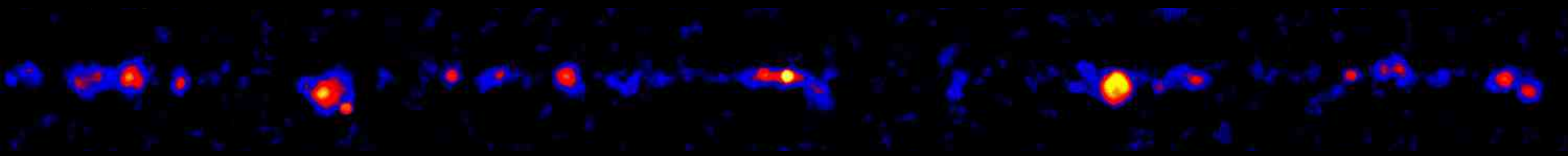


from J. Hinton

H.E.S.S. Galactic Plane Survey

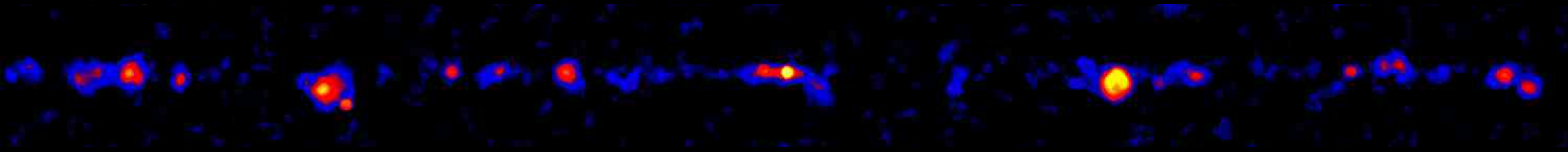


Classes of Galactic Sources



- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Molecular Clouds
- Star cluster
- Pulsar
- Galactic center
- "Dark sources"

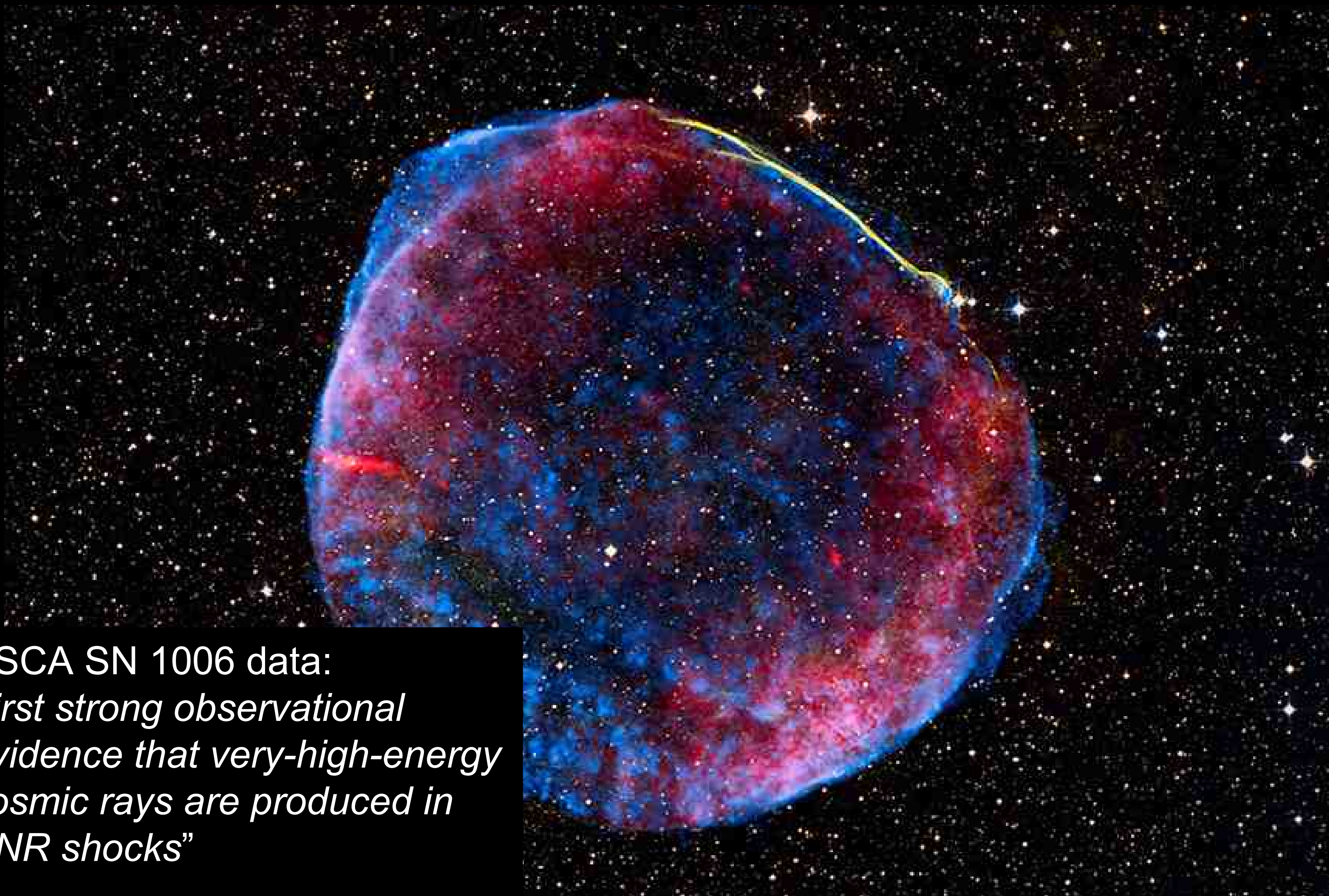
Classes of Galactic Sources



- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Molecular Clouds
- Star cluster
- Pulsar
- Galactic center
- “Dark sources”

→ See links to review articles

SNRs as Sources of Galactic Cosmic Rays



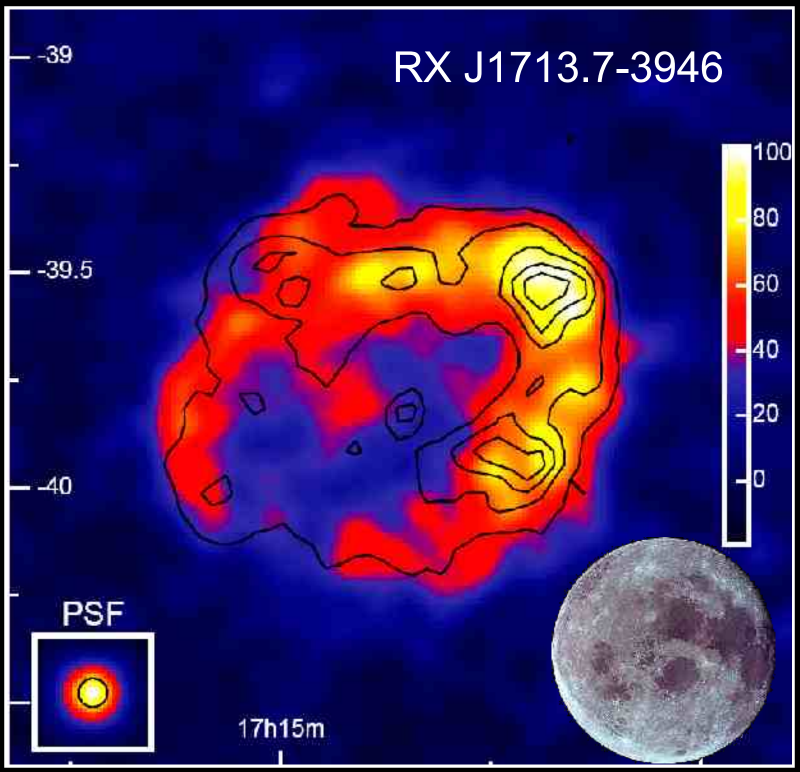
ASCA SN 1006 data:
"*first strong observational evidence that very-high-energy cosmic rays are produced in SNR shocks*"

(Koyama, Nature 1995)

Credit: NASA, ESA, Zolt Levay (STScI)

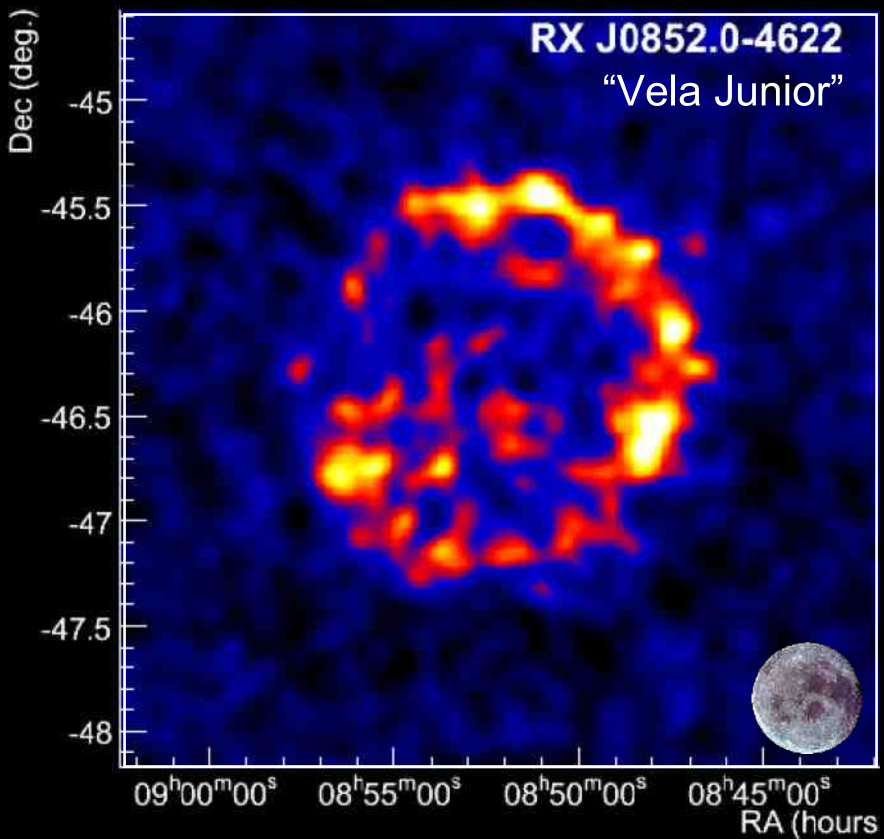
TeV Gamma-Rays from SNRs

See also: H.E.S.S., Nature (2004)



2004-2006 Data

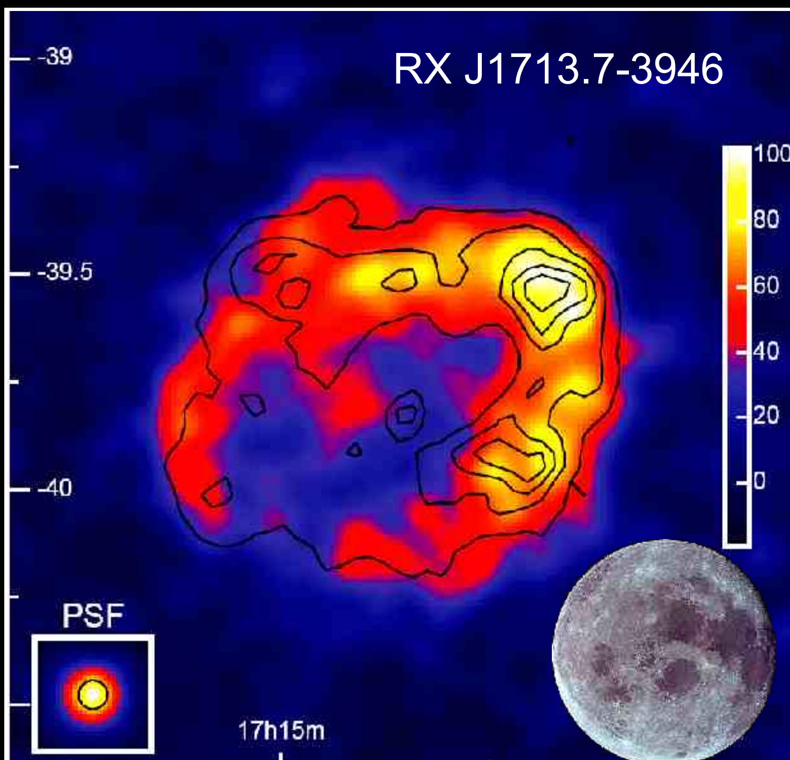
Largest TeV source: ~2 deg diameter



Proof of TeV emission from the shell of SNRs

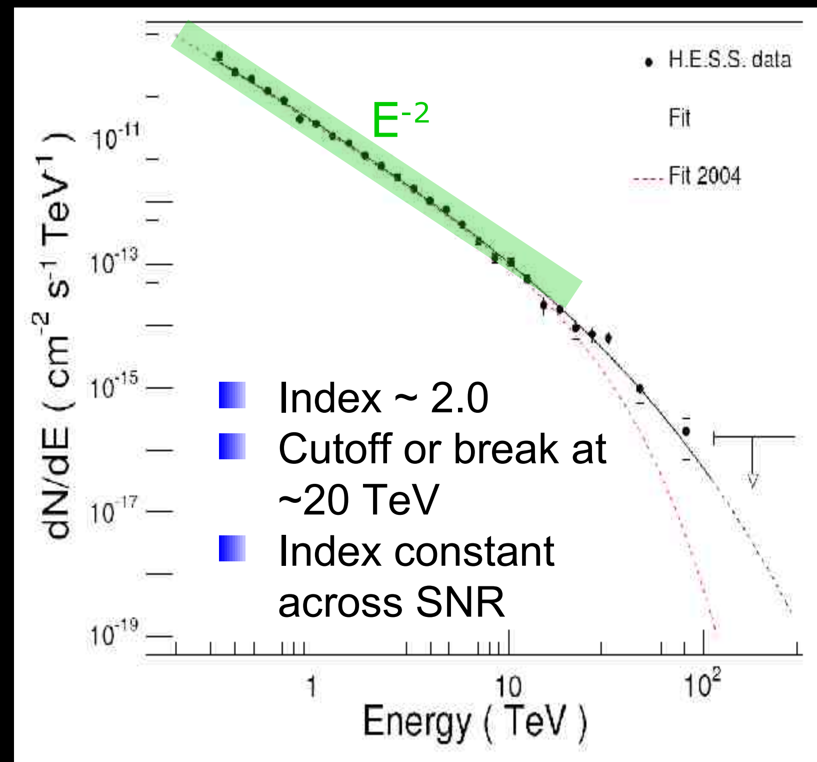
TeV Gamma-Rays from SNRs

See also: H.E.S.S., Nature (2004)



2004-2006 Data

Particle acceleration to beyond 100 TeV



- Index ~ 2.0
- Cutoff or break at ~20 TeV
- Index constant across SNR

Proof of TeV emission from the shell of SNRs

What particles are accelerated … ?

Source of Cosmic Rays

γ

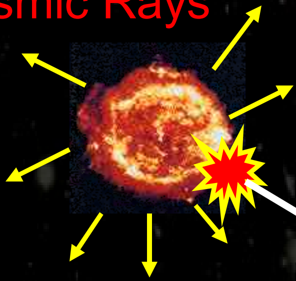
Infer properties of *primary particle distribution* in the sources and their *interactions*

Observables

- Energy Spectra
  flux, range, shape
- Source Morphology
- Variability/Periodicity

+ Multi-Wavelength (radio, IR, optical, X-ray)

What particles are accelerated … ?



… protons ?

$$p + p \rightarrow \pi^{o} + X + \ldots$$
$$\hookrightarrow \gamma + \gamma$$

γ

Infer properties of *primary particle distribution* in the sources and their *interactions*

Observables

- Energy Spectra
  flux, range, shape
- Source Morphology
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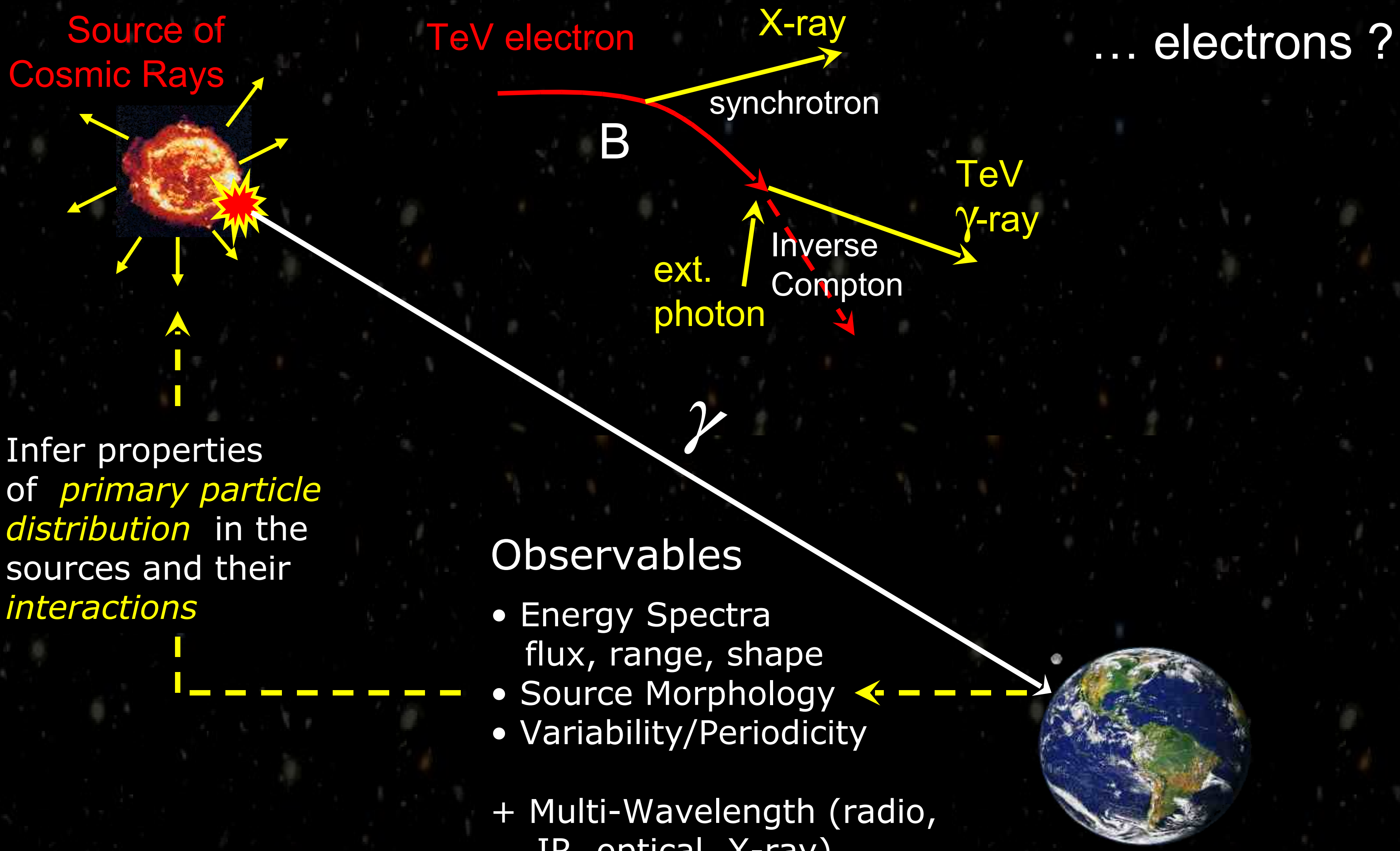
What particles are accelerated … ?



Infer properties of *primary particle distribution* in the sources and their *interactions*

Observables

- Energy Spectra
  flux, range, shape
- Source Morphology
- Variability/Periodicity

+ Multi-Wavelength (radio, IR, optical, X-ray)

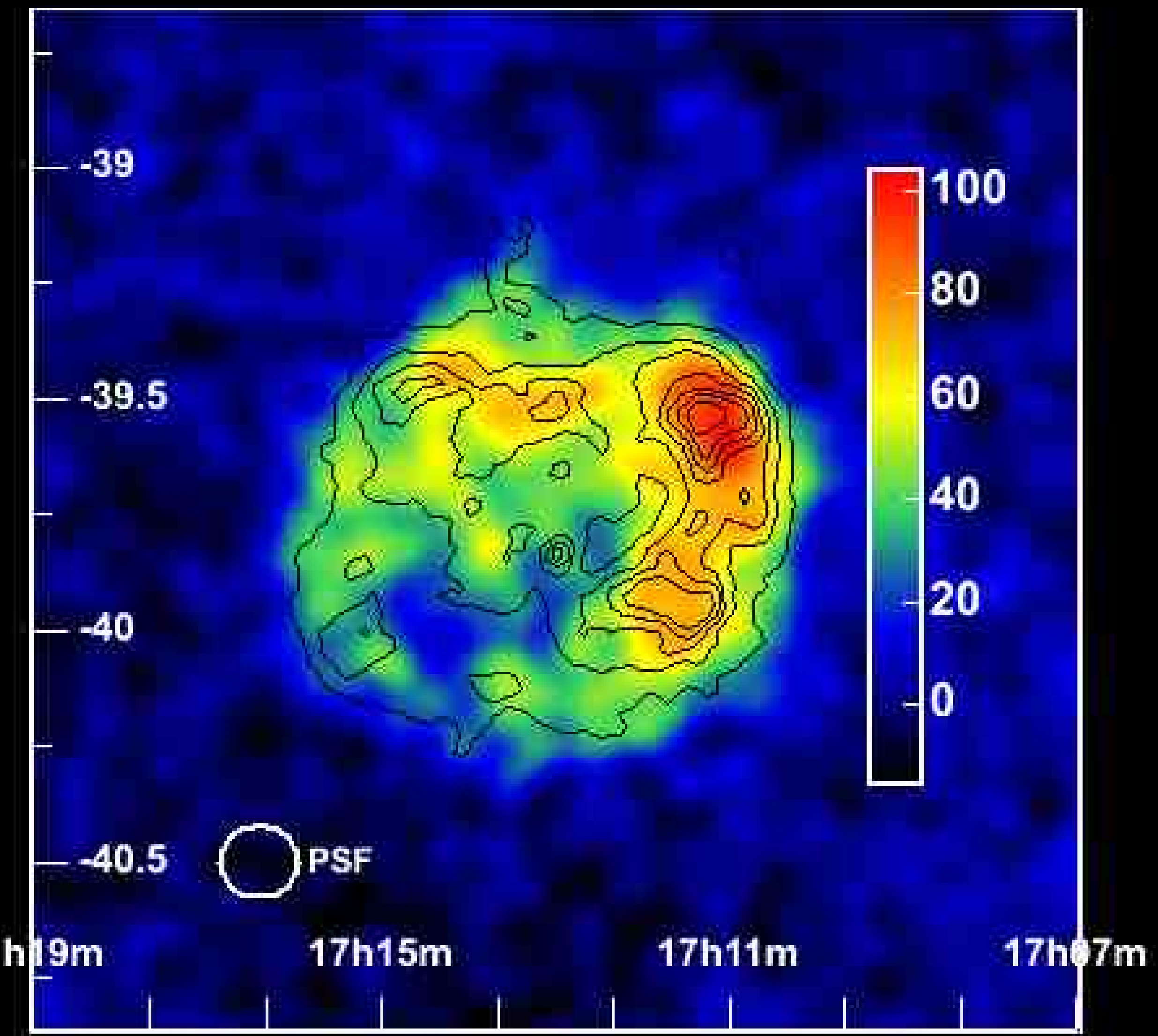
RX J1713.7: TeV / X-ray Correlation

What are the primary particles ?

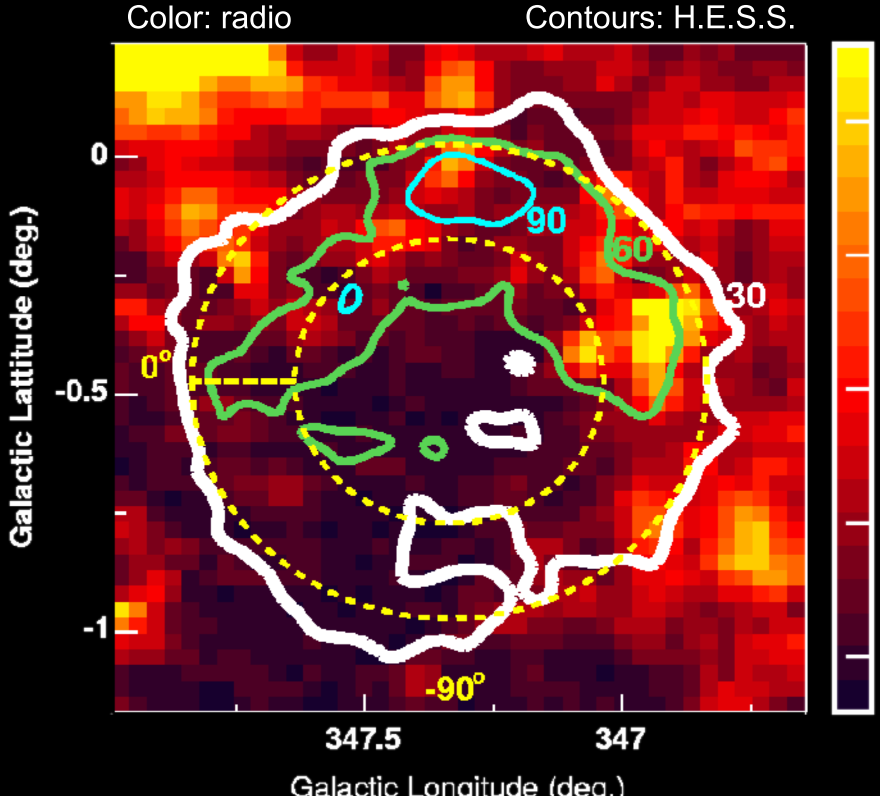
Almost perfect
X-ray <–> gamma-ray correlation !

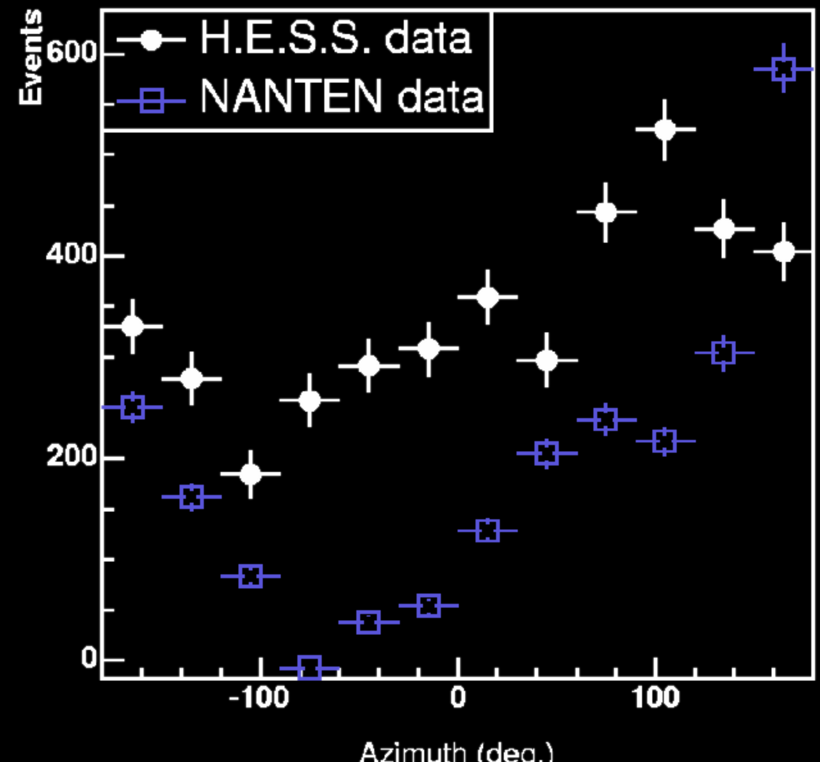
Are the primary particles electrons ?

X-ray contours:
ASCA



RX J1713: Correlation TeV - CO Data ?



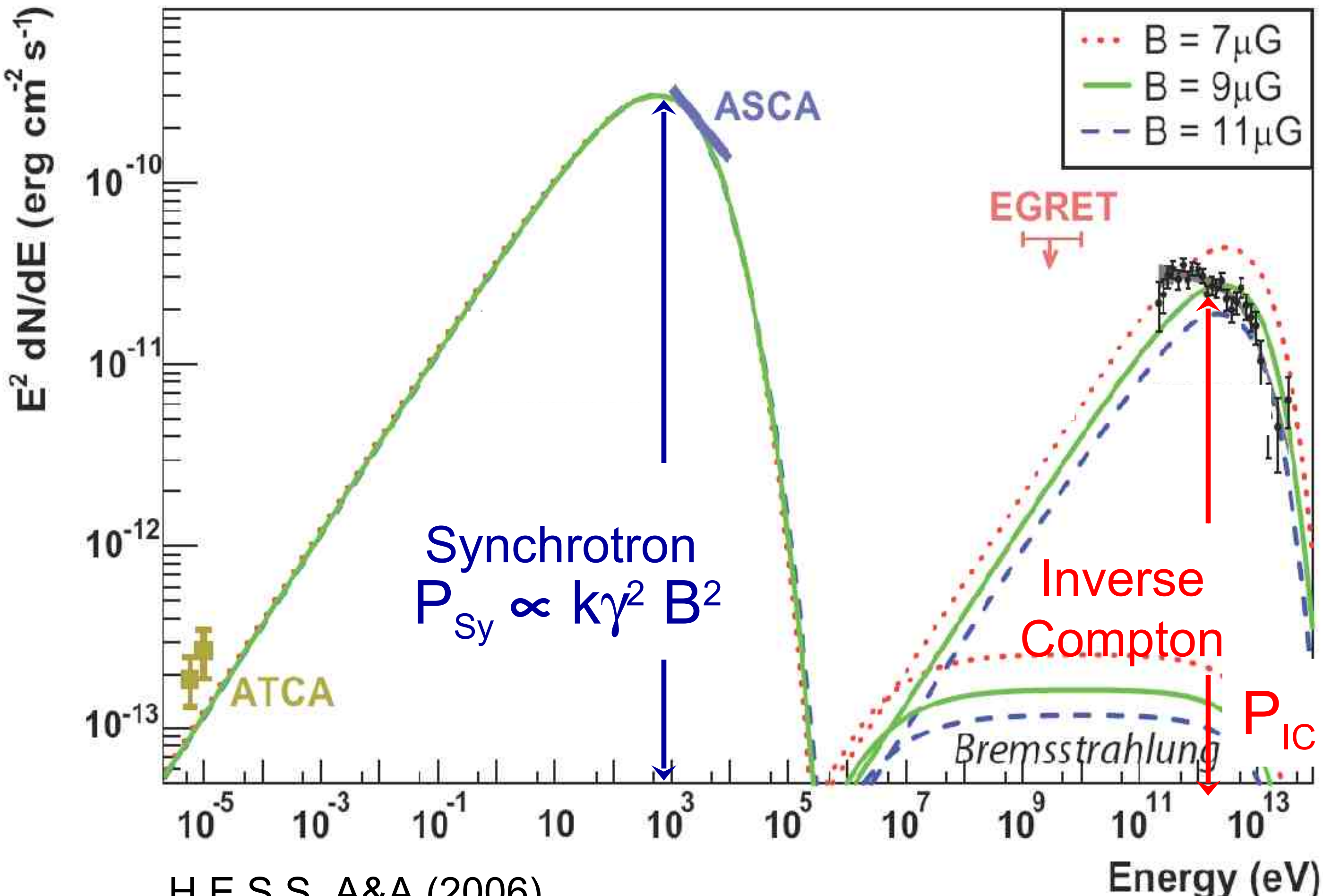


Nanten CO – data @
-11 km/sec … -3 km/sec
(0.4 …. 1.5 kpc)

Some correlation between gas density and TeV emission

Leptonic emission model for RXJ 1713

Assume Electrons: Synchrotron + Inverse Compton

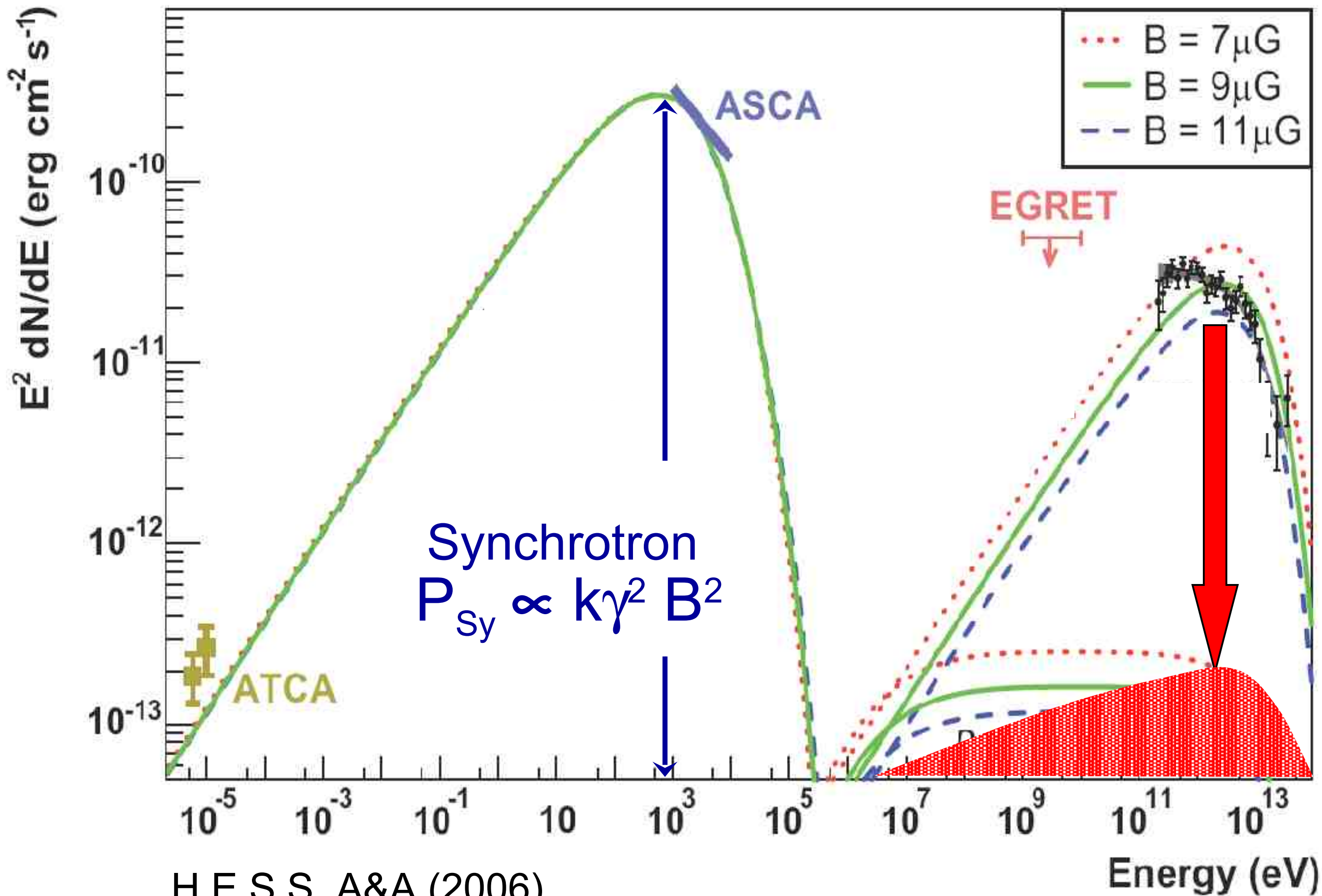


$P_{IC} / P_{Sy} \propto 1 / B^2$

H.E.S.S. A&A (2006)

Leptonic emission model for RXJ 1713

Assume Electrons: Synchrotron + Inverse Compton

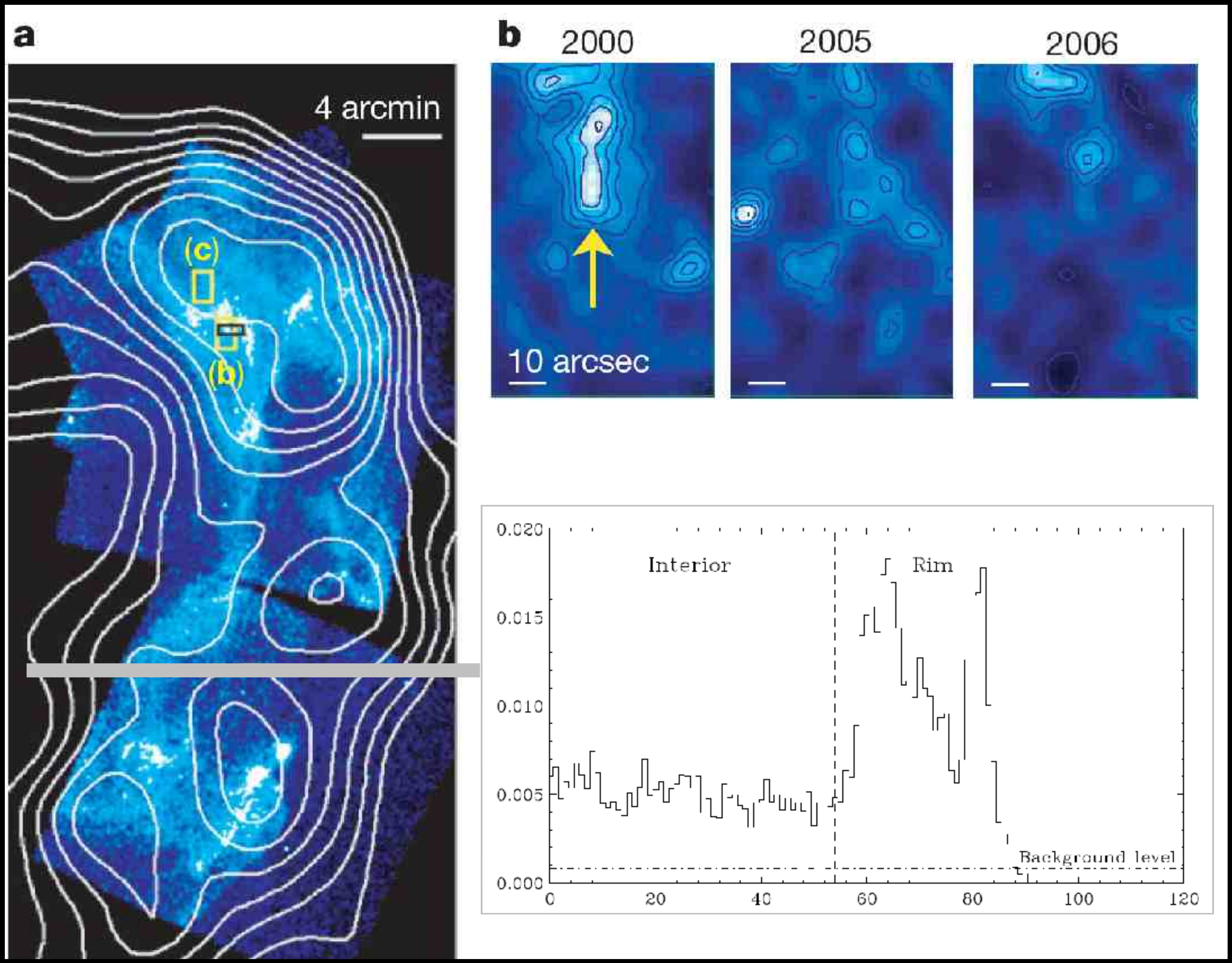


$P_{IC} / P_{Sy} \propto 1 / B^2$

High B-Field

H.E.S.S. A&A (2006)

RX J1713: X-rays indicate high B-field



RX J1713.7
Chandra
Uchiyama et al. 2007

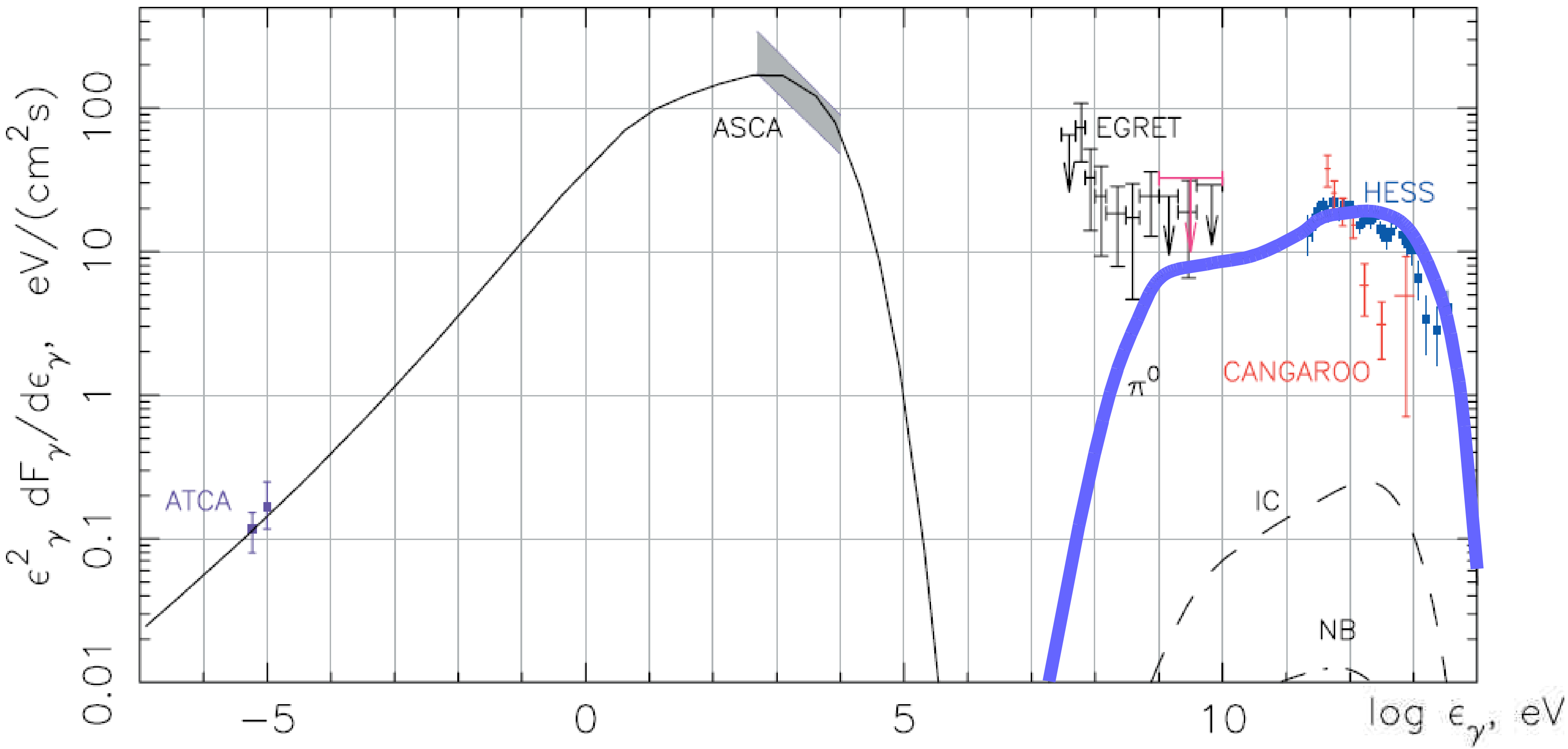
Need B > 1 mG

XMM
Hiraga et al. 2004

Need B > 65 μG
Berezkho, Völk 2008

Hadronic emission model for RXJ 1713

Collision of protons w/ ambient gas : $p + p \rightarrow \pi^o + X$

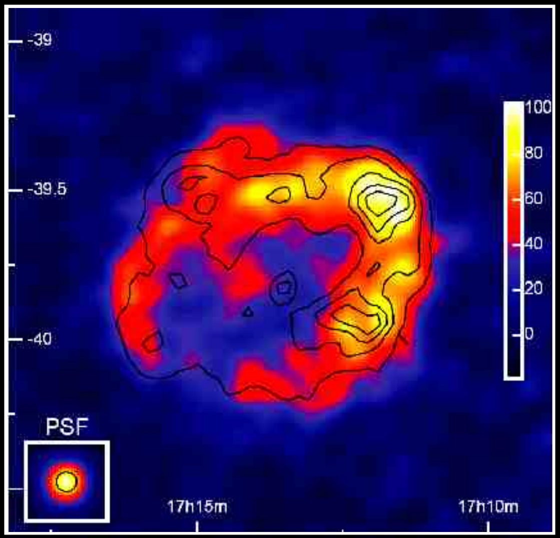


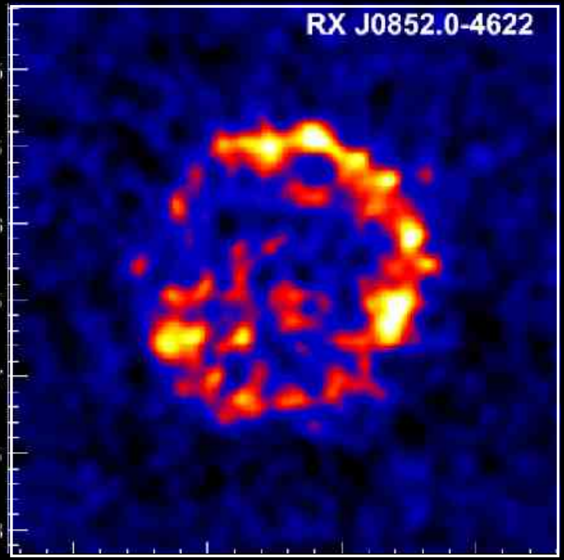
Berezkho, Völk (2006)

Hadronic models describe data reasonably well !

Are SNRs *the* sources of Galactic cosmic rays ???

Found *the* CR accelerators ?



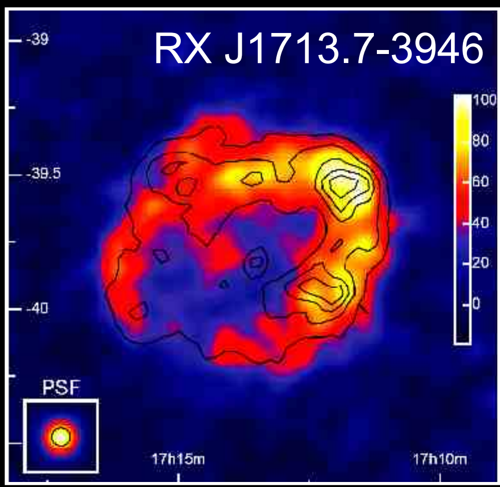


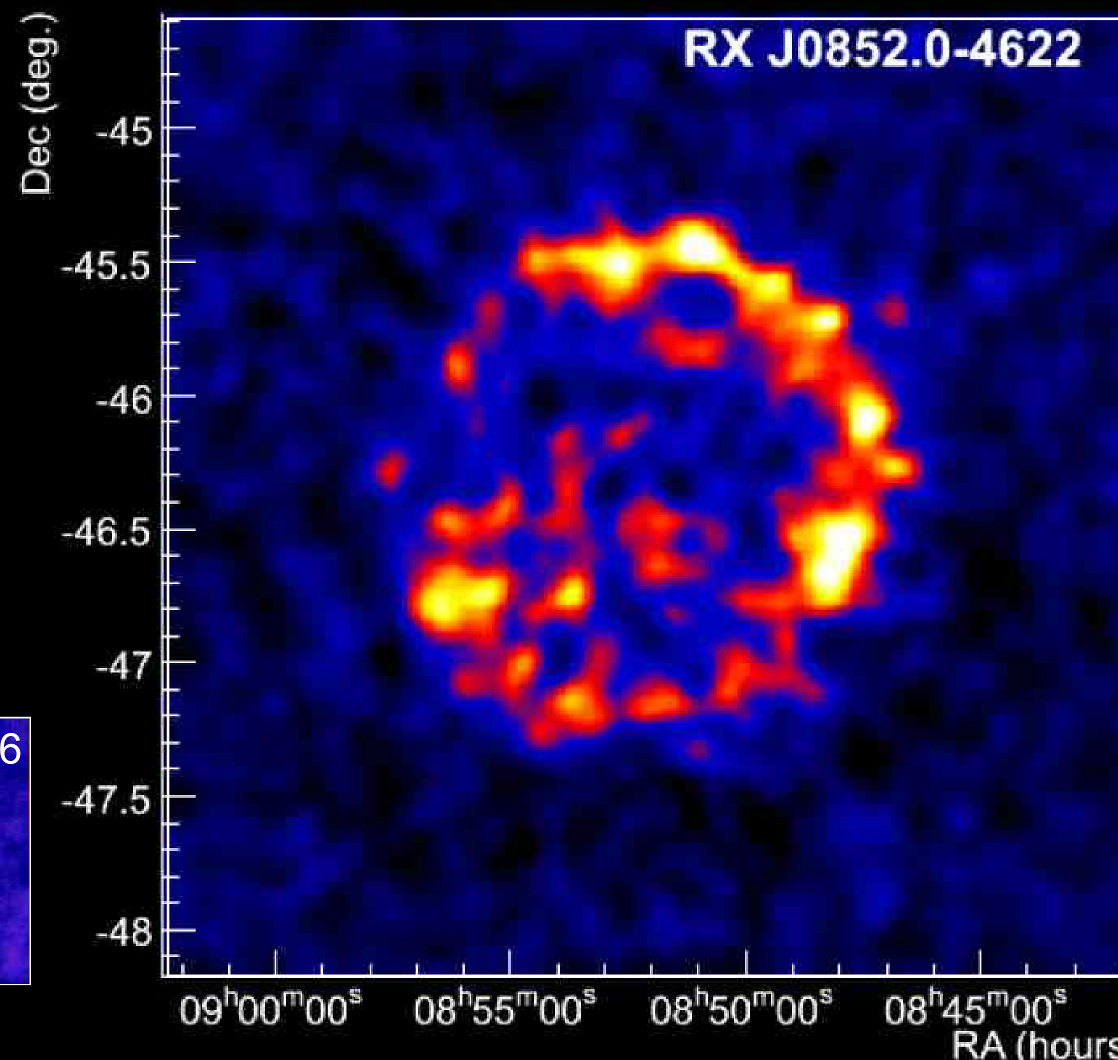
Unambiguous proof that
SNR shock waves are cosmic
accelerators up to energies of O(100 TeV)

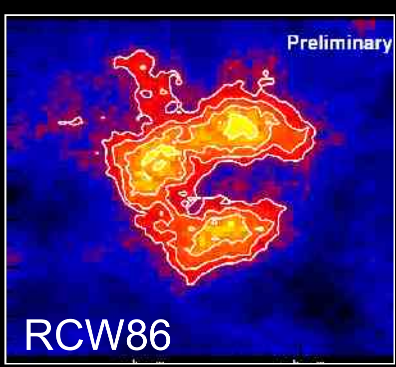
What is the efficiency of energy conversion from SNR explosion into CR
Uncertainty of parameters:
distance ?, gas density ?

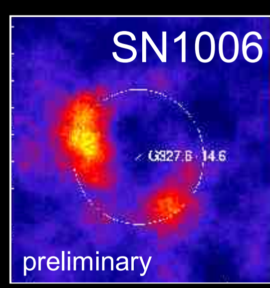
- *Large lever arm from O(50 GeV) to O(100 TeV)*
- *Further multi-λ studies (also GLAST)*
- *Better angular resolution (filaments)*
- *More sources …*

Towards a case by case population study of shell-type TeV SNRs …



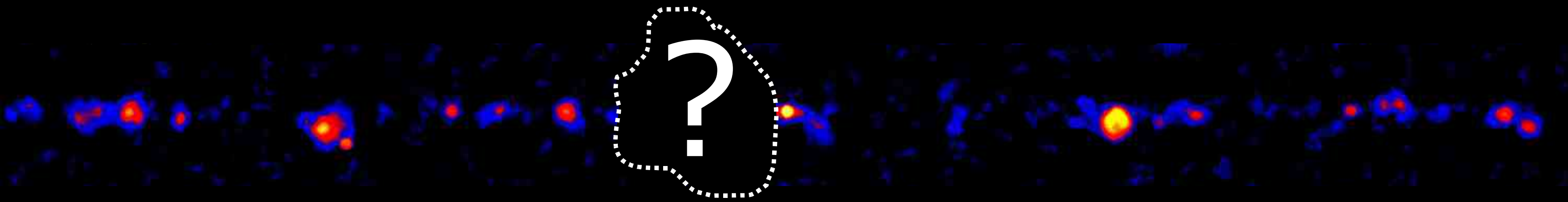






Maps ~ to scale

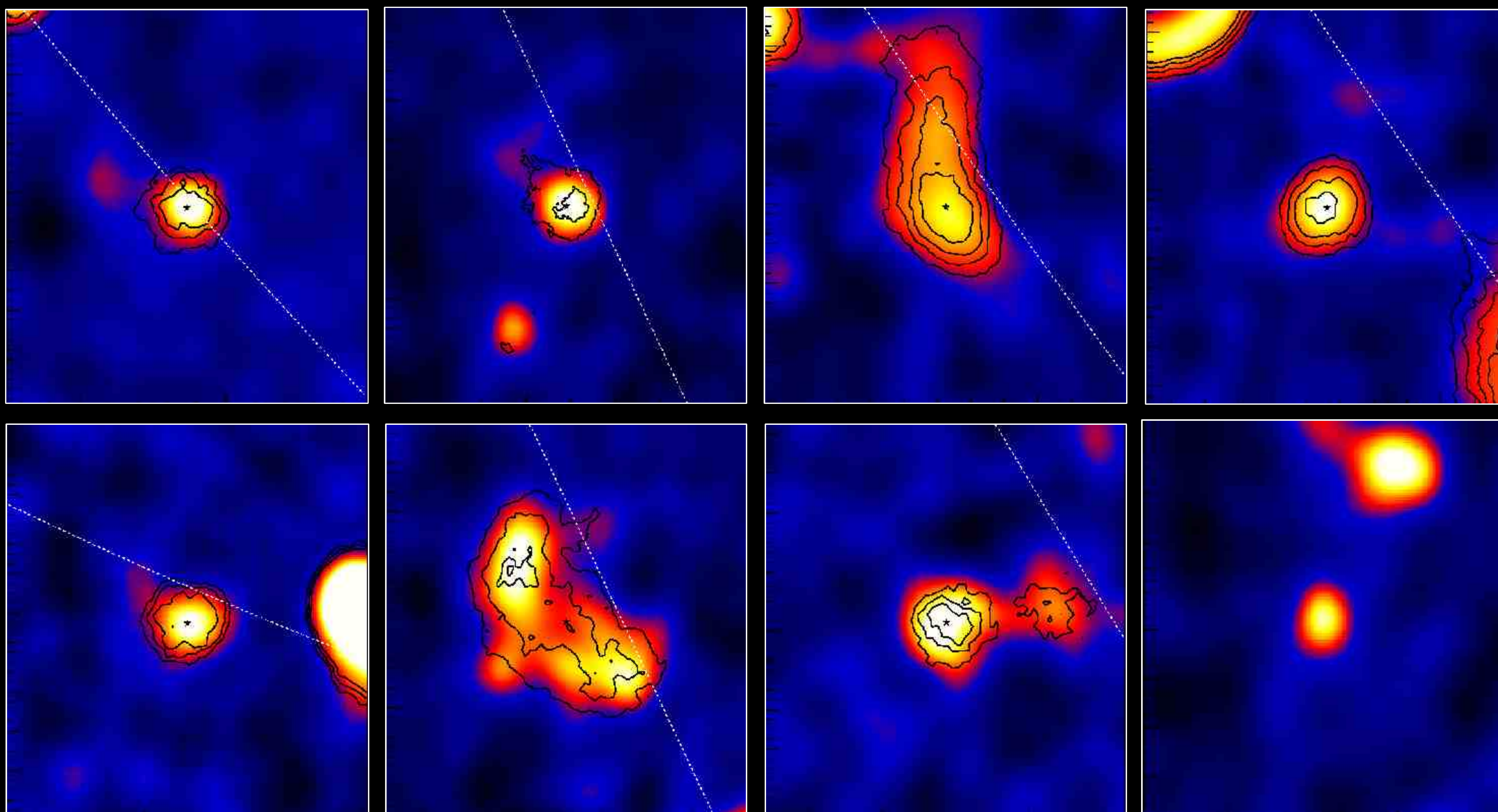
Classes of Galactic Sources



- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Molecular Clouds
- Star cluster
- Pulsar
- Galactic center
- “Dark sources”

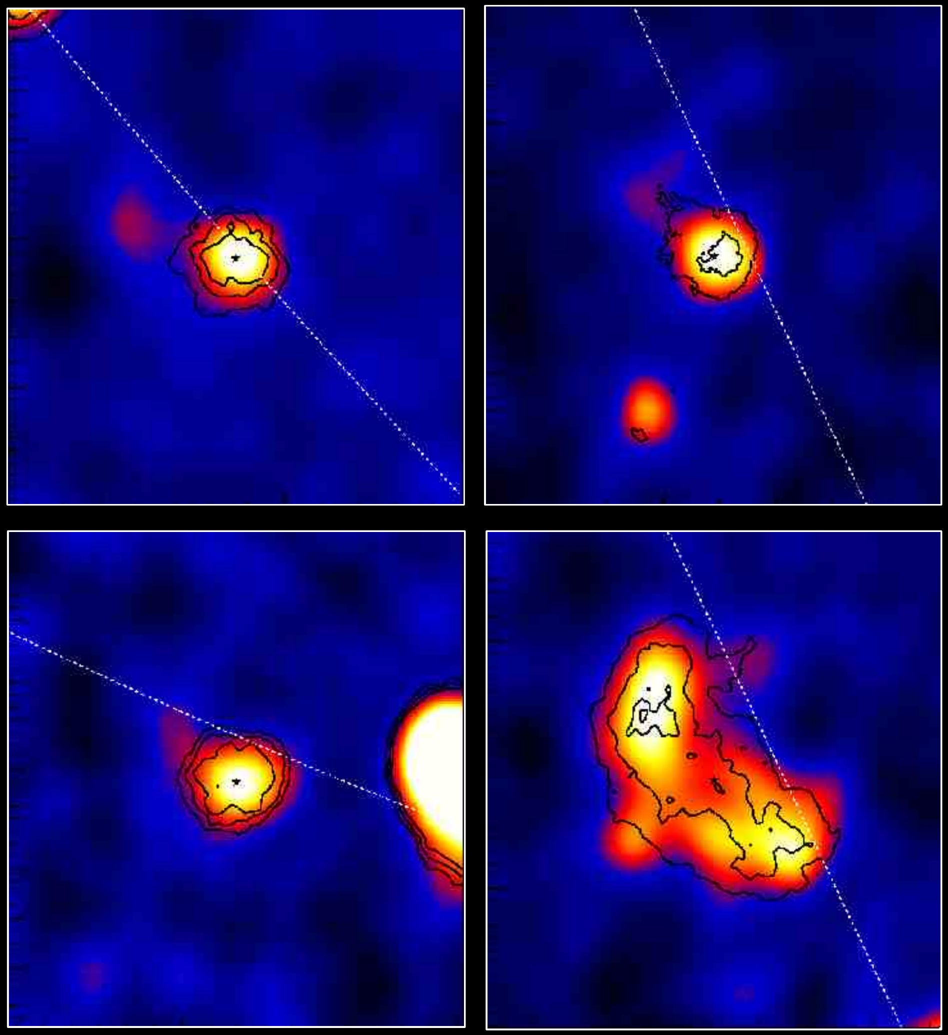
Discovery Potential: “Dark Sources”

A bias free view on the sky: → new class of TeV sources



Discovery Potential: "Dark Sources"

A bias free view on the sky: → new class of TeV sources



No counterparts in other energy bands seen (radio, IR, optical, X-ray, …)

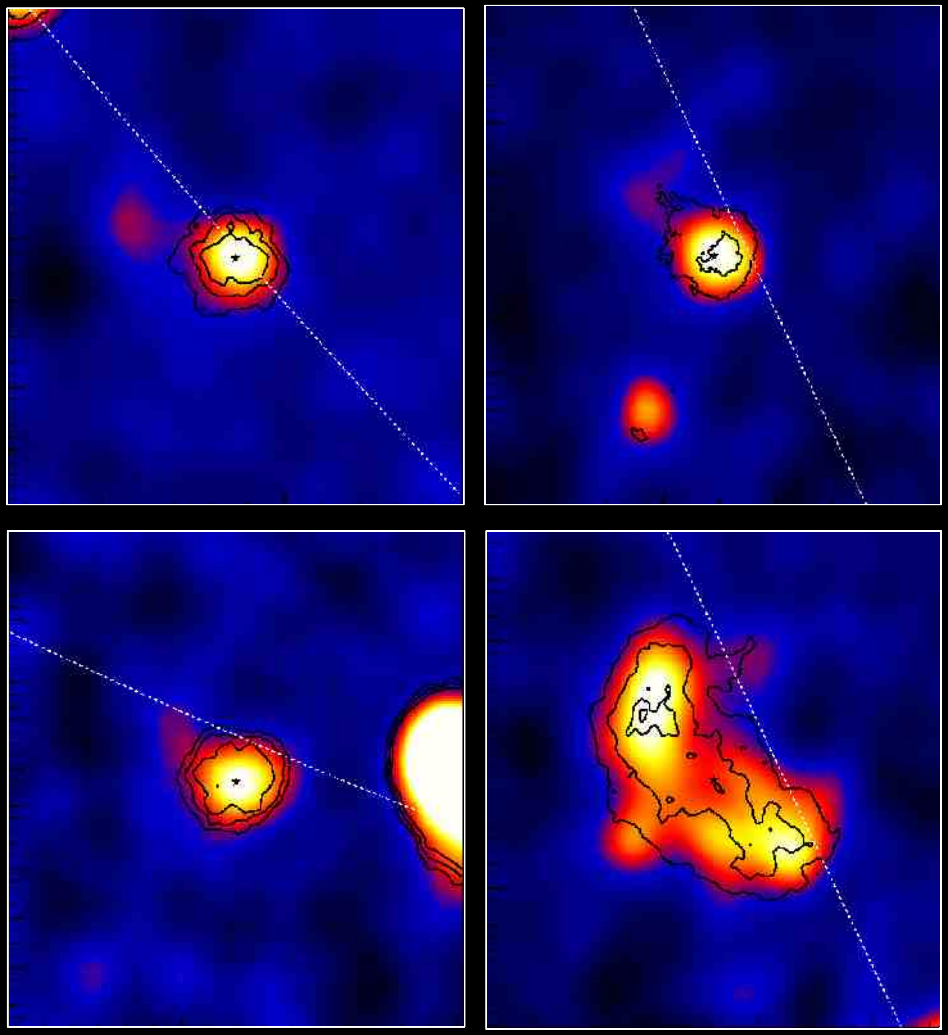
Aligned with Galactic plane
All are extended: O (10 arcmin)
Hard spectrum: $\Gamma \sim$ 2.1 … 2.5

→ Maximum energy output of these sources in TeV γ-rays
→ Hadron accelerator ?
→ Old PWN ?
→ GRB remnant ?
→ Dark Matter ?

HESS A&A 477 (2008)

Discovery Potential: “Dark Sources”

A bias free view on the sky: → new class of TeV sources



No counterparts in other energy bands seen (radio, IR, optical, X-ray, …)

→ More sensitive X-ray and radio observations following the TeV detection

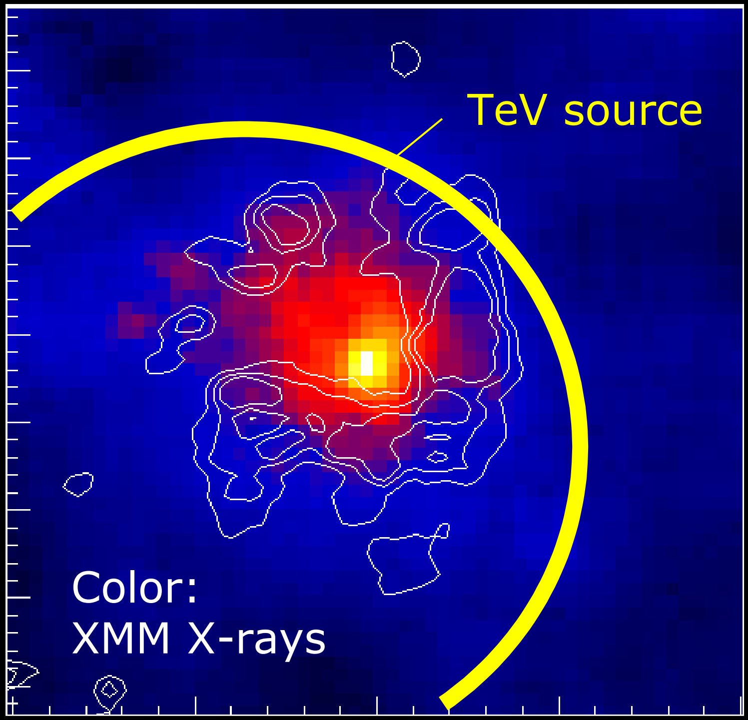
HESS A&A 477 (2008)

Enlightening "Dark Sources"

→ More sensitive X-ray and radio observations following the TeV detection

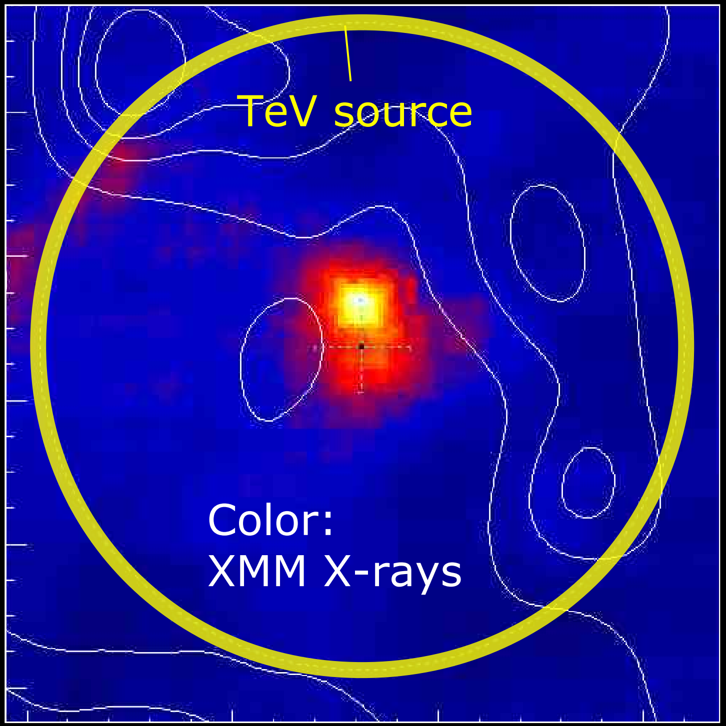
→ Association / identification as *composite SNR* (1813) and *PWN* (1640)

HESS J1813-178 Funk et al. 2007



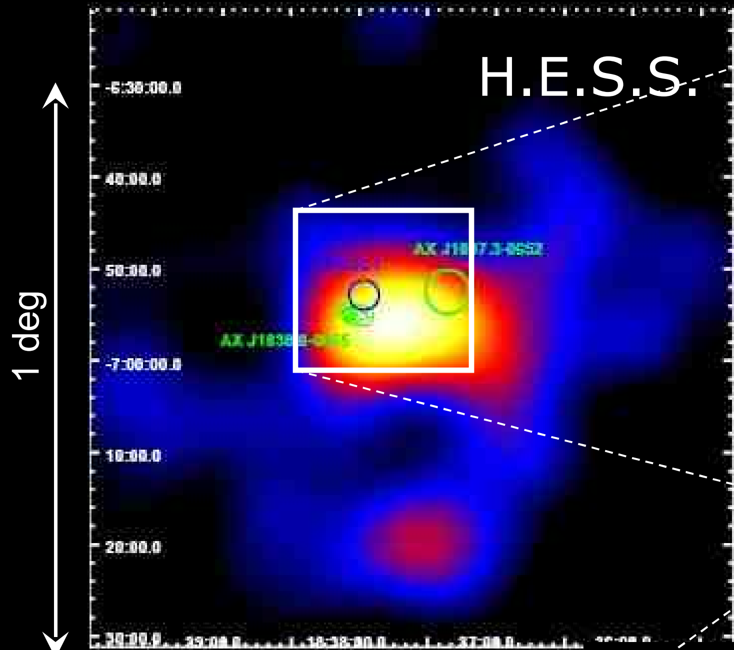
Radio shell: Helfand et al., 2005, Brogan et al., 2005

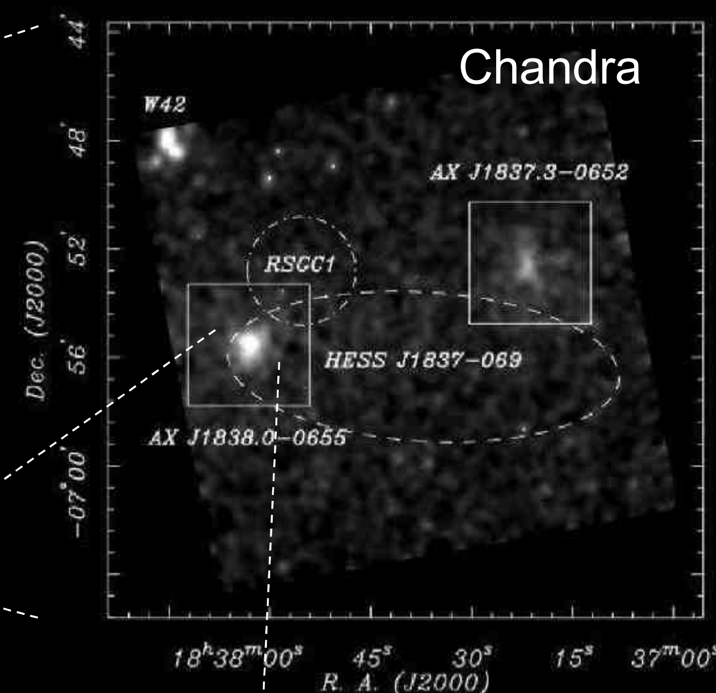
HESS J1640-465 Funk et al. 2007



radio contours

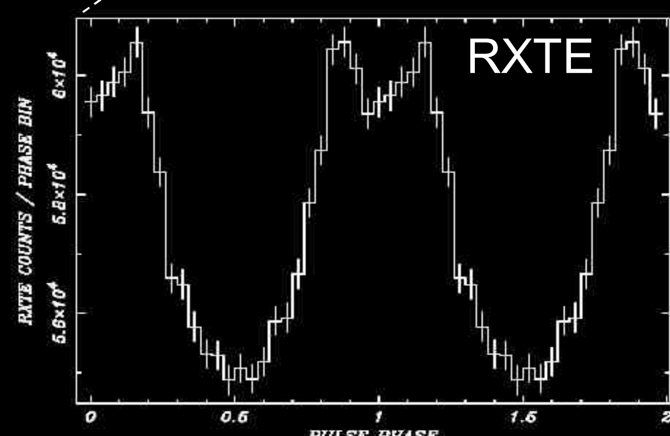
Pulsar discovery triggered by H.E.S.S.





HESS J1837-069:
7 ‘ x 3 ‘ extension
Flux ~ 0.13 Crab

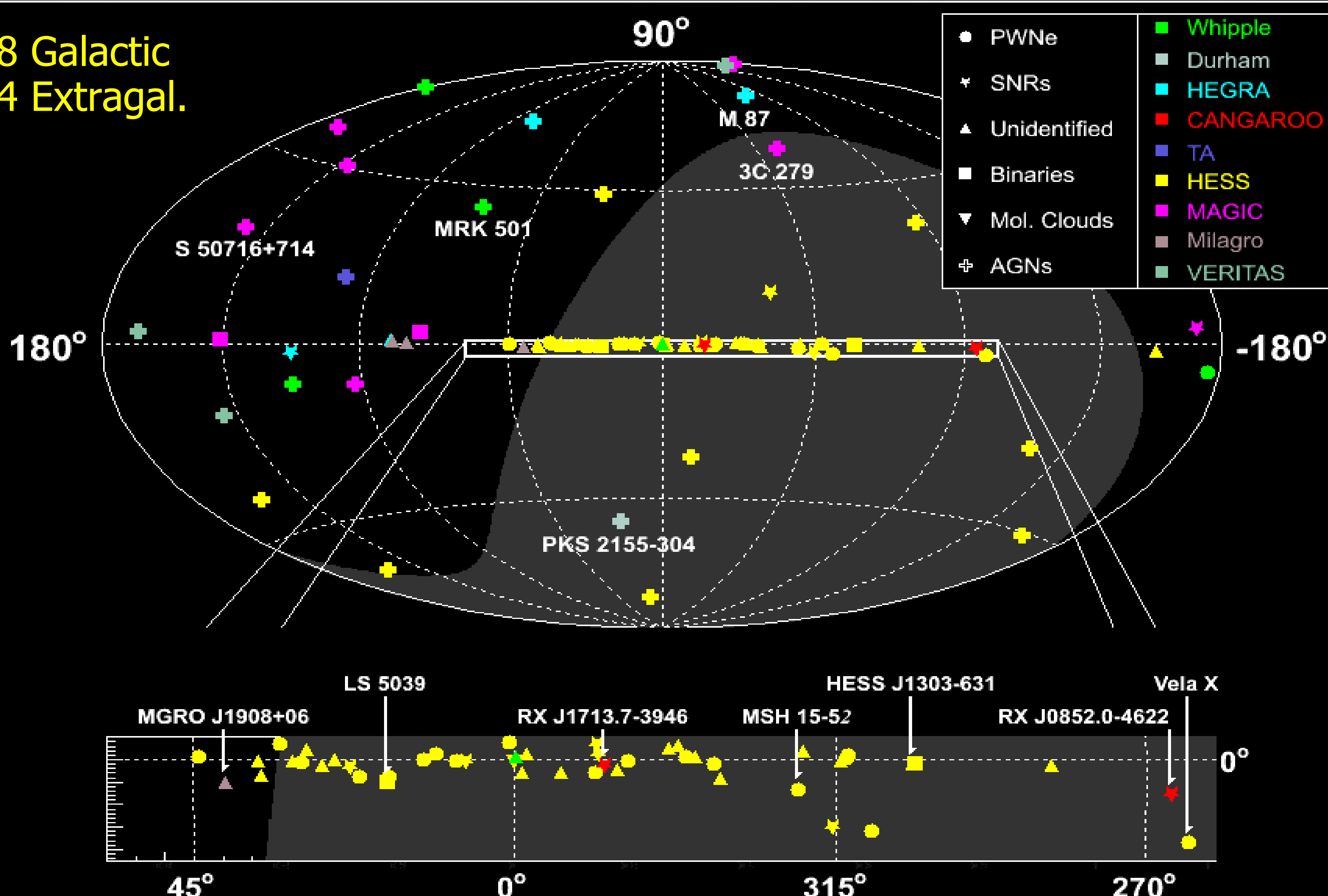
2 % of dE/dt of Pulsar needed to power TeV flux !



Discovery of
PSR J1838−0655
Gotthelf & Halpern (2008)
period 70.5 ms,
spin-down energy loss
~5.5 x 10^{36} ergs/s

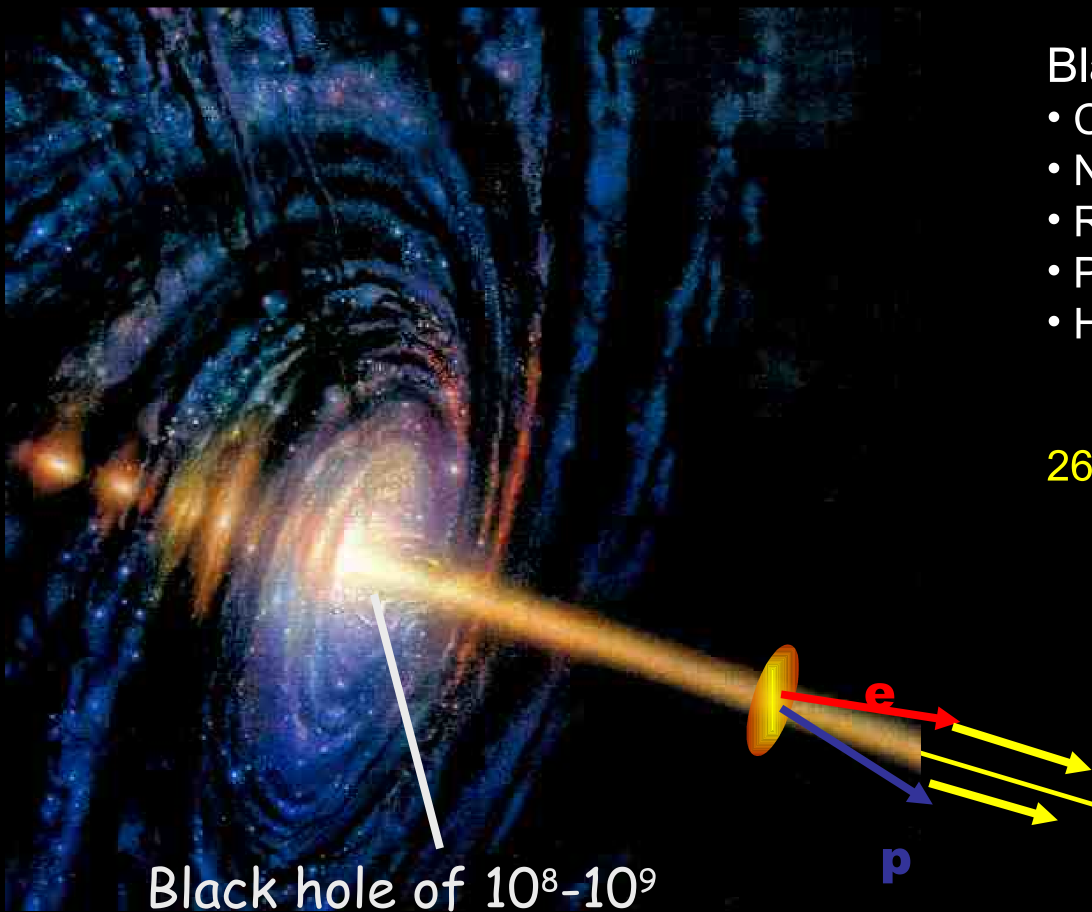
The TeV Sky in February 2009

58 Galactic
24 Extragal.



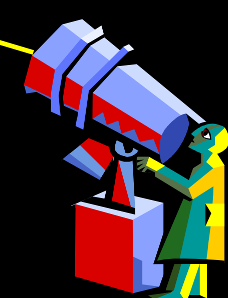
from J. Hinton

Active Galactic Nuclei (AGN)



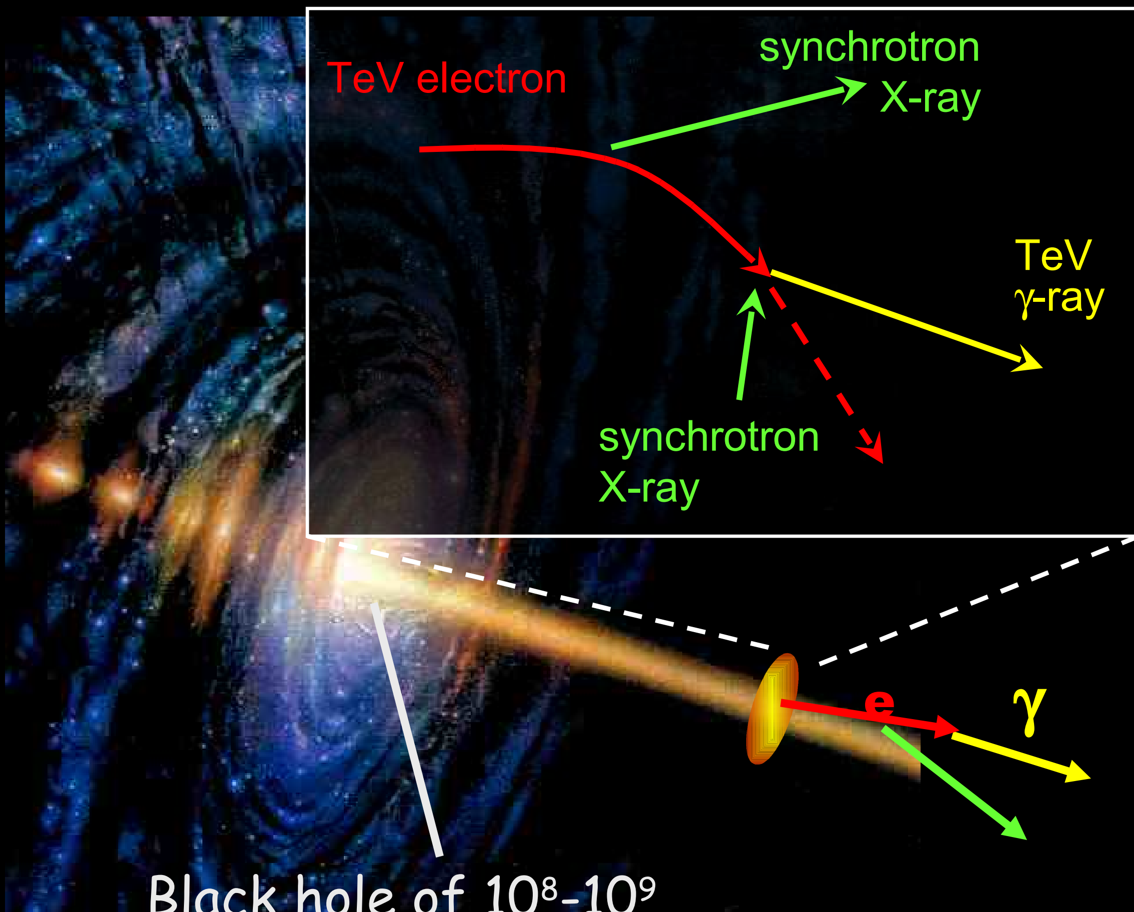
Blazars:
- Compact core, high luminosity
- Non-thermal spectrum
- Radioloud
- Polarized -> synchrotron
- Highly variable (~ h…y)

26 extragalactic objects detected
- z = 0.002 …. 0.56 (or higher ?)
- almost all are Blazars
- 2 radio galaxies



Beamed Radiation
„amplified“ intensity
shorter timescales

Synchrotron Self Compton (SSC) Model

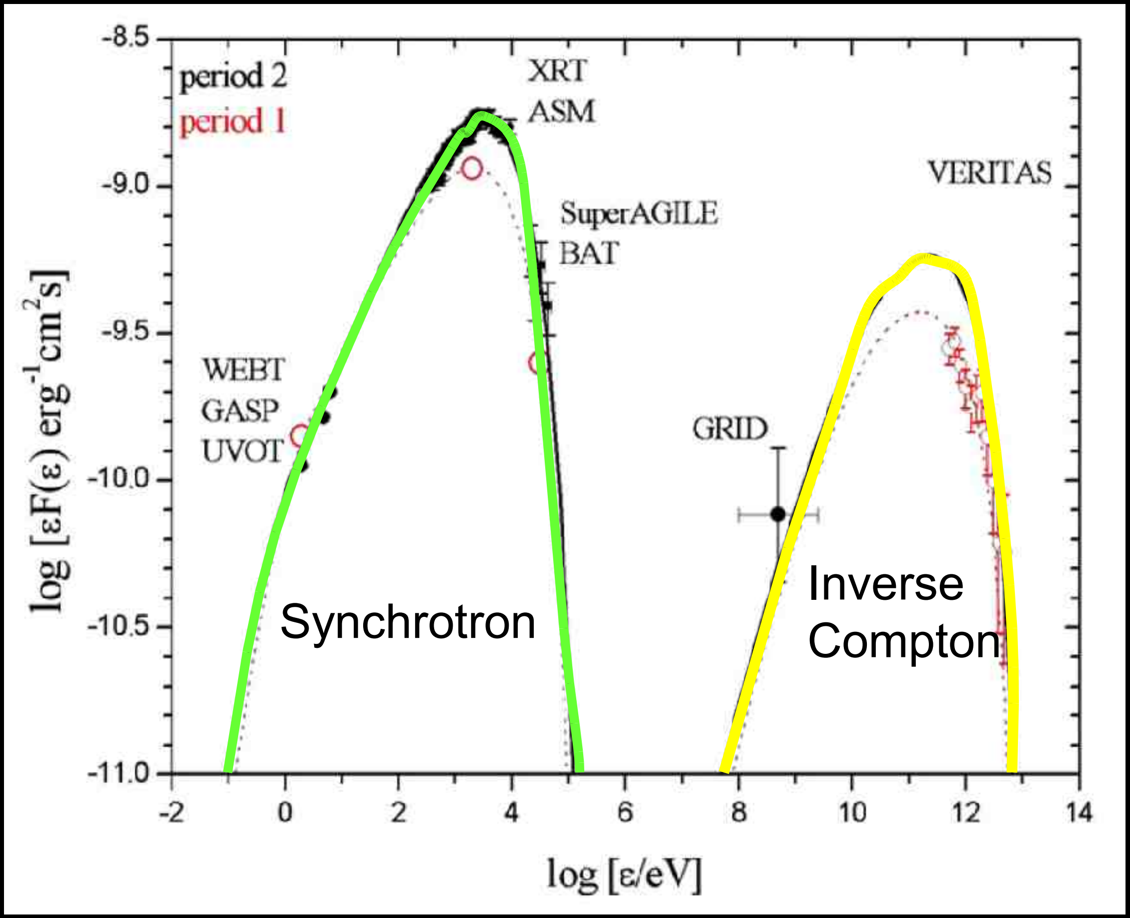


Black hole of 10^8-10^9 solar masses

Electrons emit Synchrotron Radiation in radio - X-Ray

Same Population of Electrons upscatter Synchrotron Photons to GeV-TeV Energies via Inverse Compton

Synchrotron Self Compton (SSC) Model



MRK421: VERITAS, MAGIC, ApJ 691 (2009)

Electrons emit Synchrotron Radiation in radio - X-Ray

Same Population of Electrons upscatter Synchrotron Photons to GeV-TeV Energies via Inverse Compton

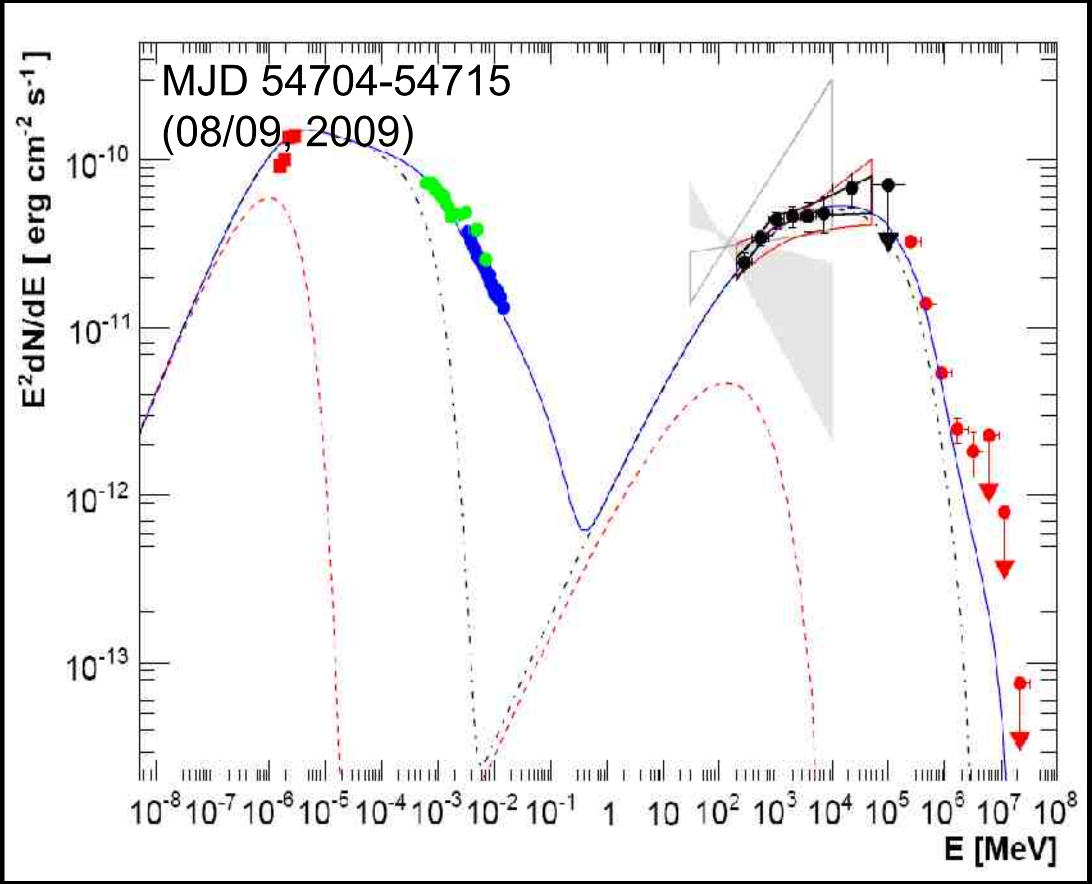
Main Ingredients:
→ Electron Spectrum
K, n1, E_{break}, n2

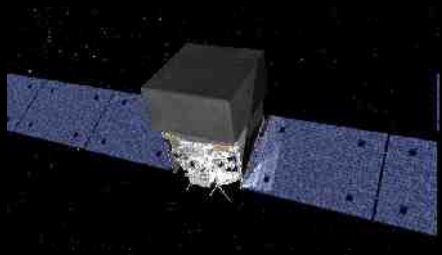
→ Size of Source
→ Magnetic Field B
→ Doppler factor

Strong X-ray / TeV-correlation expected

Catching the IC-Peak of PKS 2155

Multi wavelength campaign
ATOM, RXTE, Swift, Fermi, H.E.S.S. (ApJ 2009)



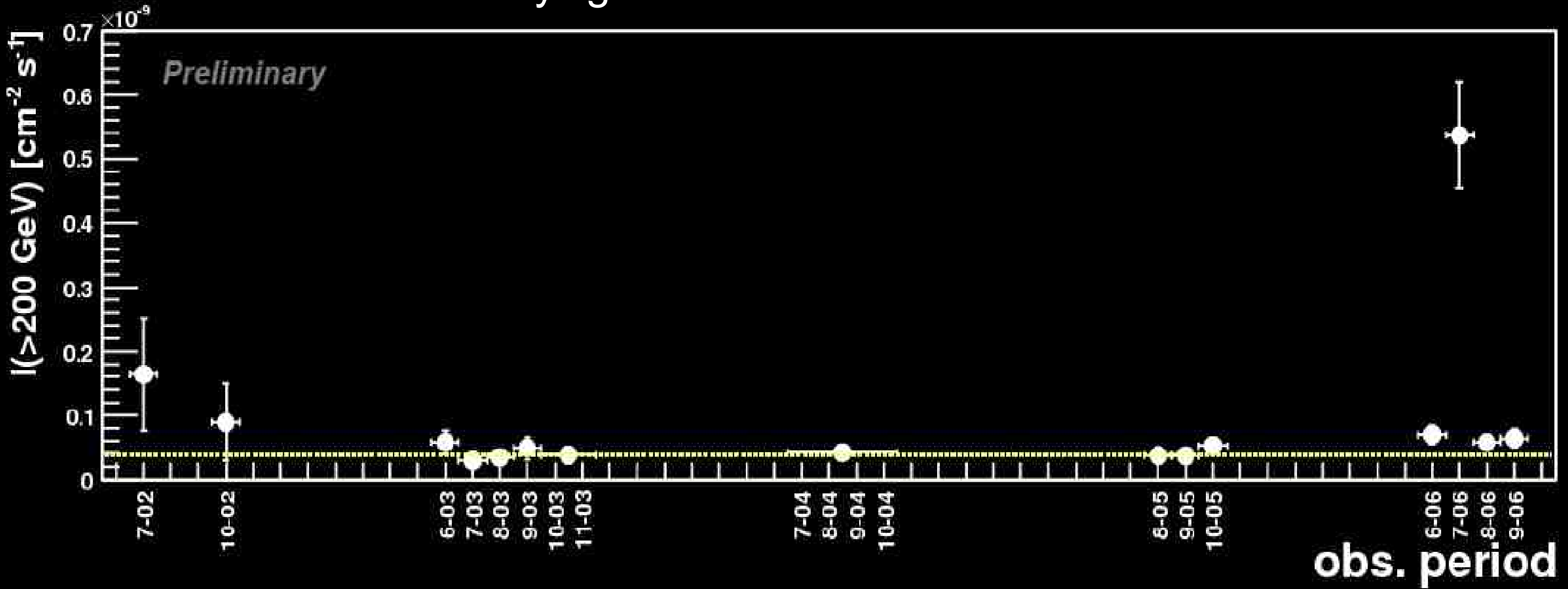


- Flux close to lowest archival level at X-ray and TeV-energies
- High level of optical flux
- Only little variability (~ 30 %)
- No correlation between X-rays and TeV gamma rays

→ First time, IC peak could be measured for an AGN
→ One zone model fits
→ Highest energetic electrons responsible for hard X-rays, but little impact on TeV gammas

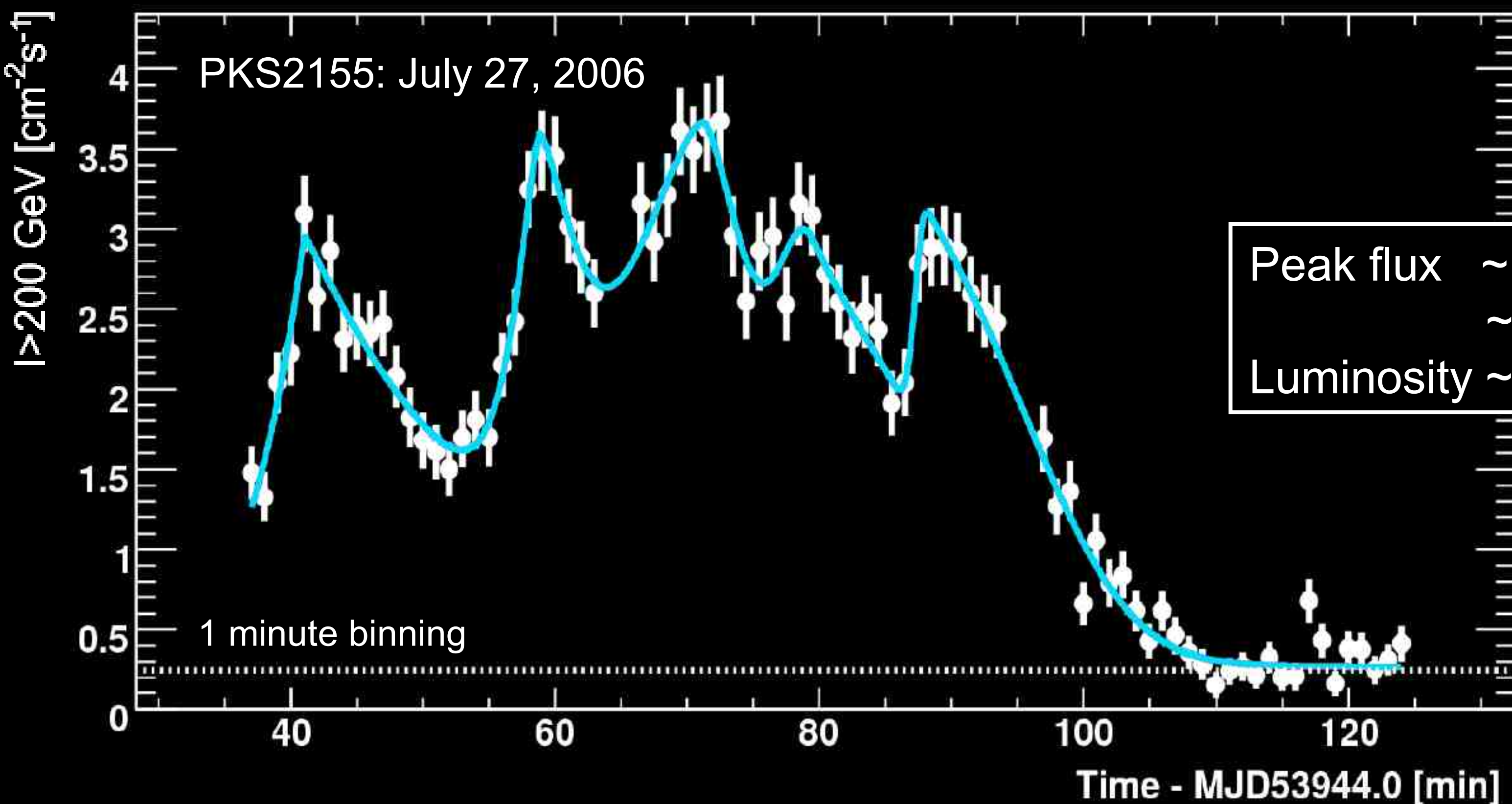
PKS 2155 Monitoring

Monthly light curve: 2002 … 2006



- Source monitored since 2002 (~240 h)
- Average flux : 3.95 +- 0.39 10^{-11} cm^{-2} s^{-1}
- Huge outburst in July 2006 - two main flares of 27 and 29 July

“Photons from hotter hell” (T.Weekes)

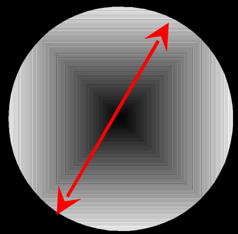


Peak flux ~15 x Crab
~50 x average
Luminosity ~10^{12} x Crab

→ Variability on timescales 2-3 minutes

→Characteristic length scale R_{BH}

→ R_{BH} / c ~ 1...2 · 10^4 s

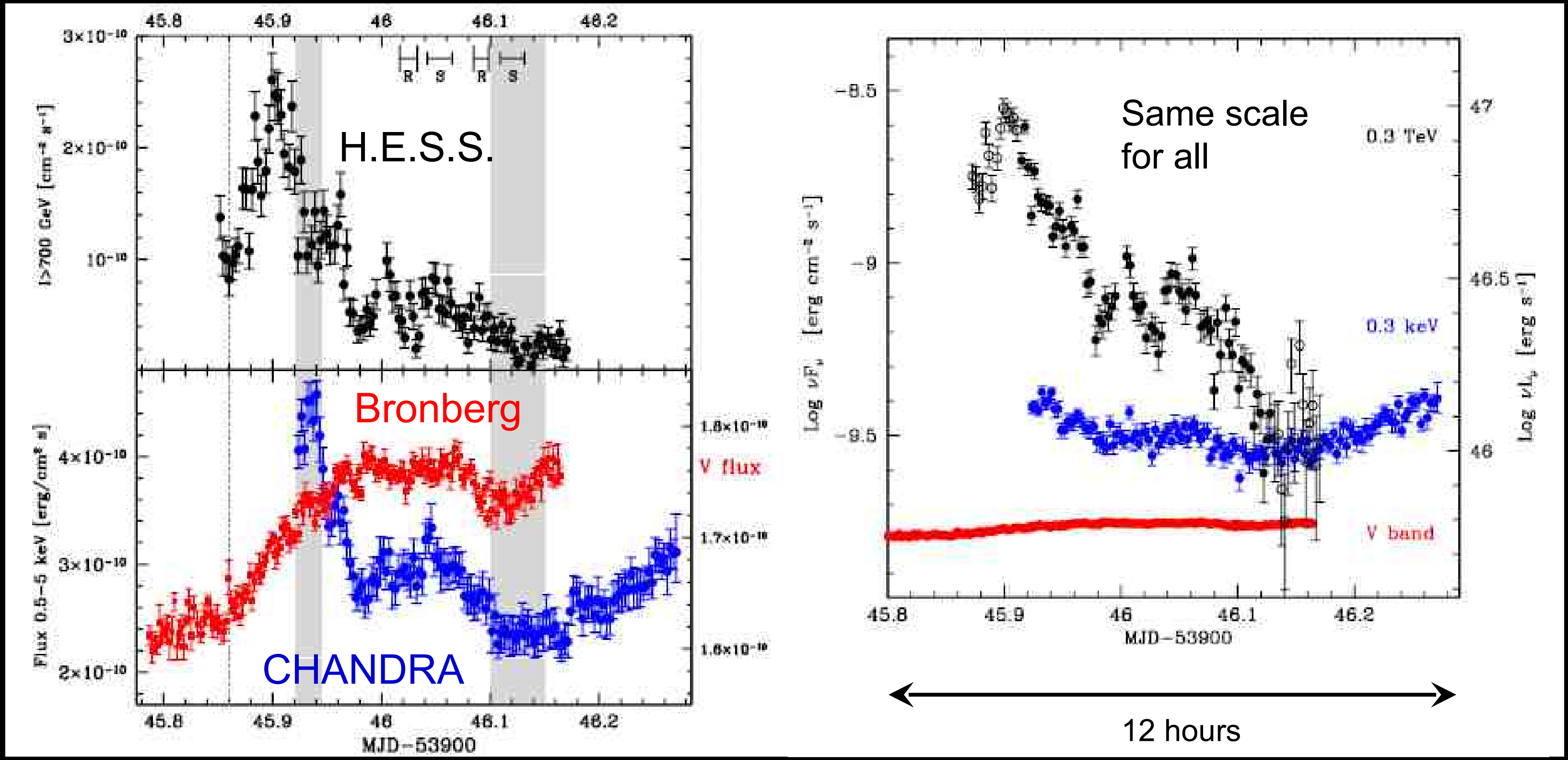


Emission region
region Doppler
boosted w/
Γ ~ 100

HESS, A&A (2007)

PKS2155: the Chandra campaign

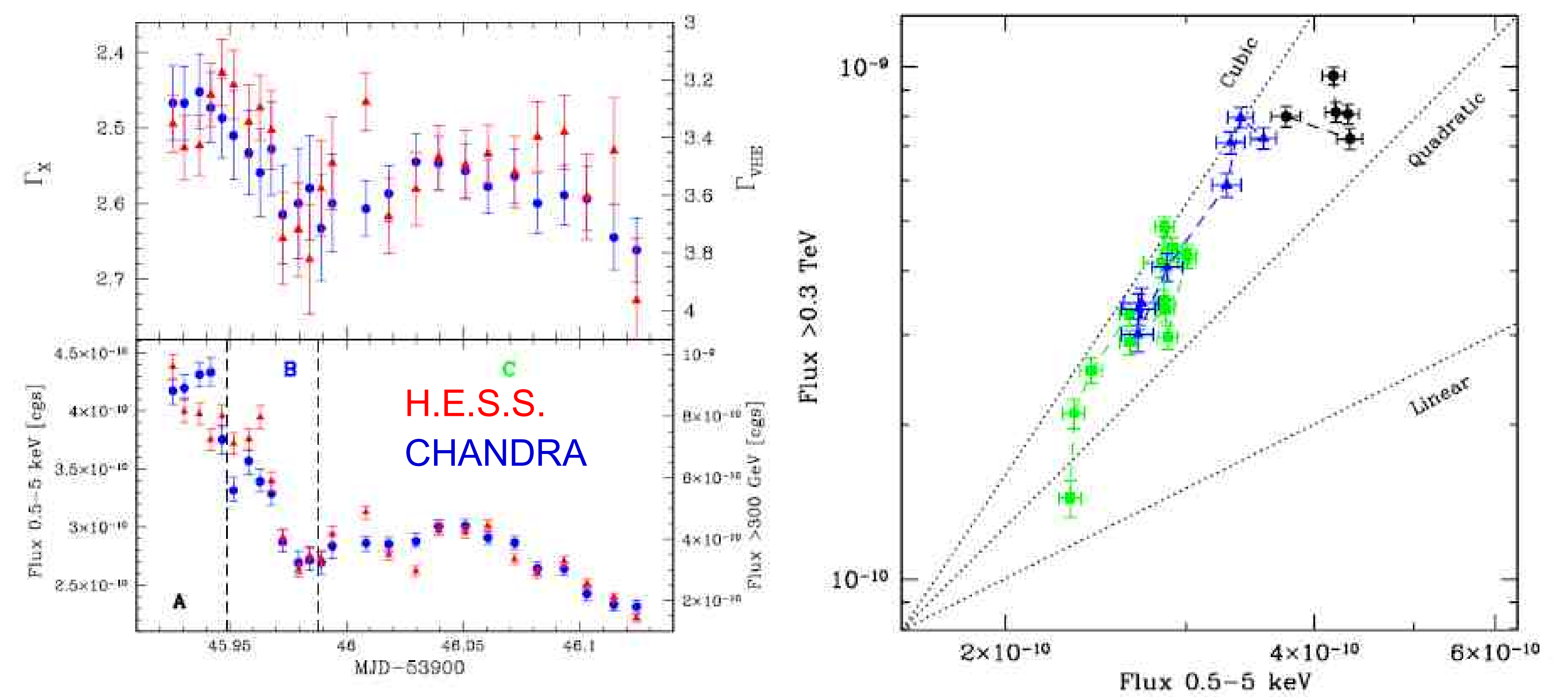
Multi wavelength campaign : Chandra, RXTE, Swift, Fermi, H.E.S.S. (July 29, 2006)



- Larger flux variations in VHE compared to X-rays and optical
  (1 order of magnitude vs factor ~2 vs <15%)
- VHE / X-ray correlation
- Max luminosity » 10^{47} erg/s & L_{IC}/L_S from 10 to <1 during the night

H.E.S.S. (ApJ 2009)

PKS2155: spectral variability



Spectral index:

VHE / X-ray correlation

$\Delta\Gamma$ ~ 0.2 in X-rays and ~ 0.6 in VHE

Flux:

Cubic VHE / X-ray flux correlation

→ a real challenge for SSC models

The future

Near Future: H.E.S.S. Phase II

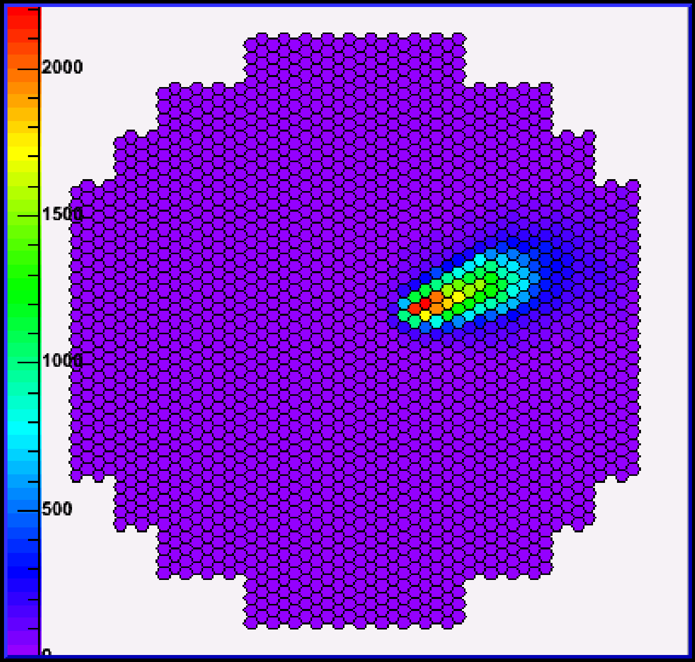
Improved sensitivity (x1.5 - 2) in current regime up to ~ 1 TeV

Energy range down to ~50 GeV will finally become accessible

Near Future: H.E.S.S. Phase II

Near Future: H.E.S.S. Phase II

H.E.S.S. Phase II Camera



2048 Pixels

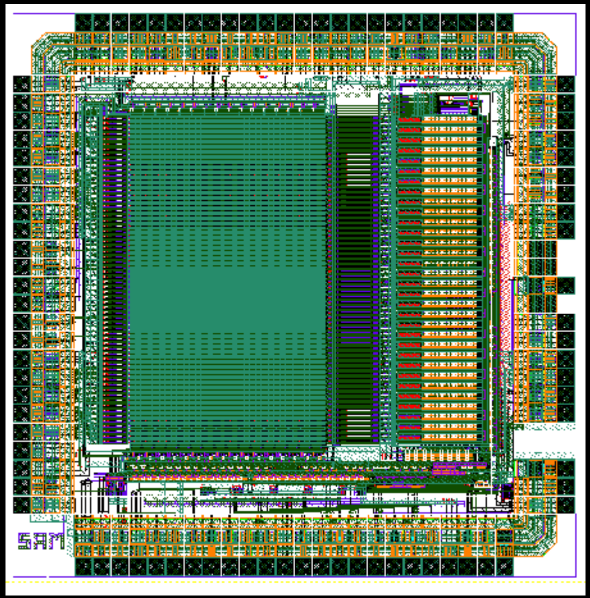
Pixel size: 0.07°

FoV : ~ 3.6°

Same principle as in Phase I:

- Analog pipeline for signal buffering
- On board signal integration

Sampling Analog Memory



SAM

Sampling:	1 GS/sec
Depth	256 cells
Bandwidth	> 300 MHz
Dyn. Range	> 11 bit

Last fall in Annecy …

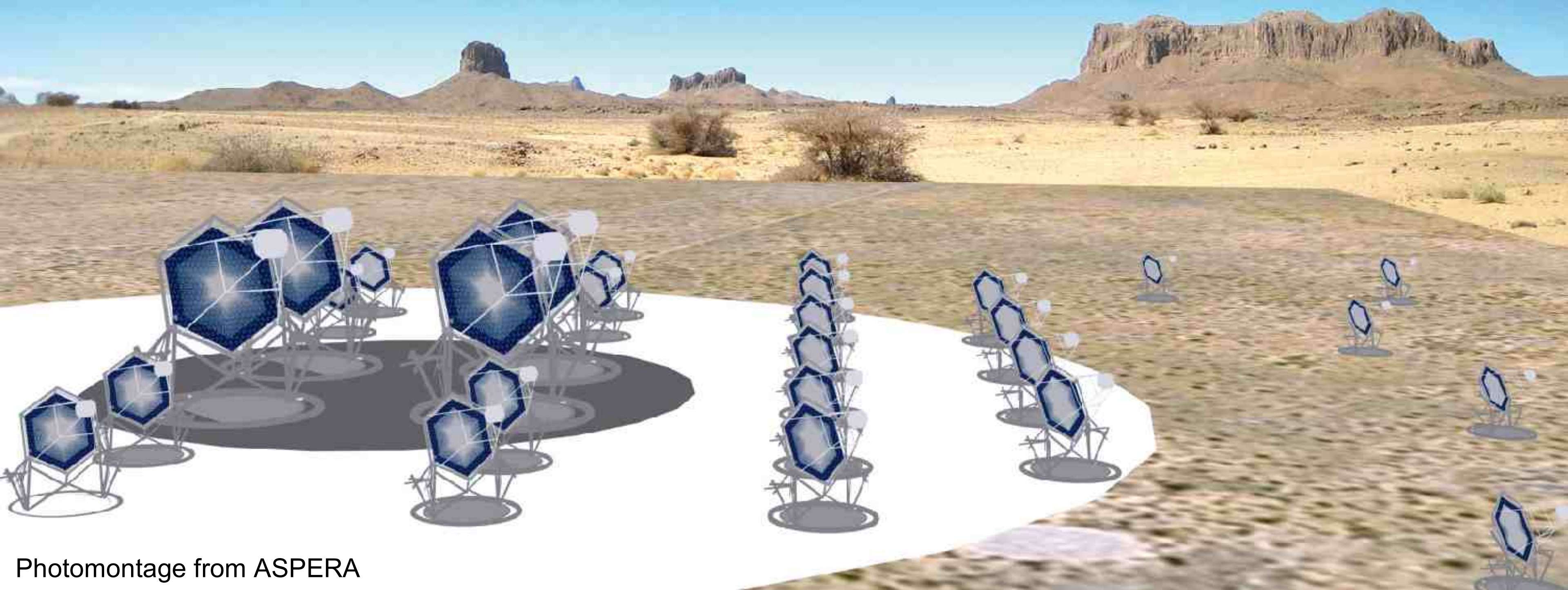
H.E.S.S. collaboration in front of camera mechanics test setup (09/2008)

Cherenkov *T*elescope *A*rray

The very-high-energy

ground-based

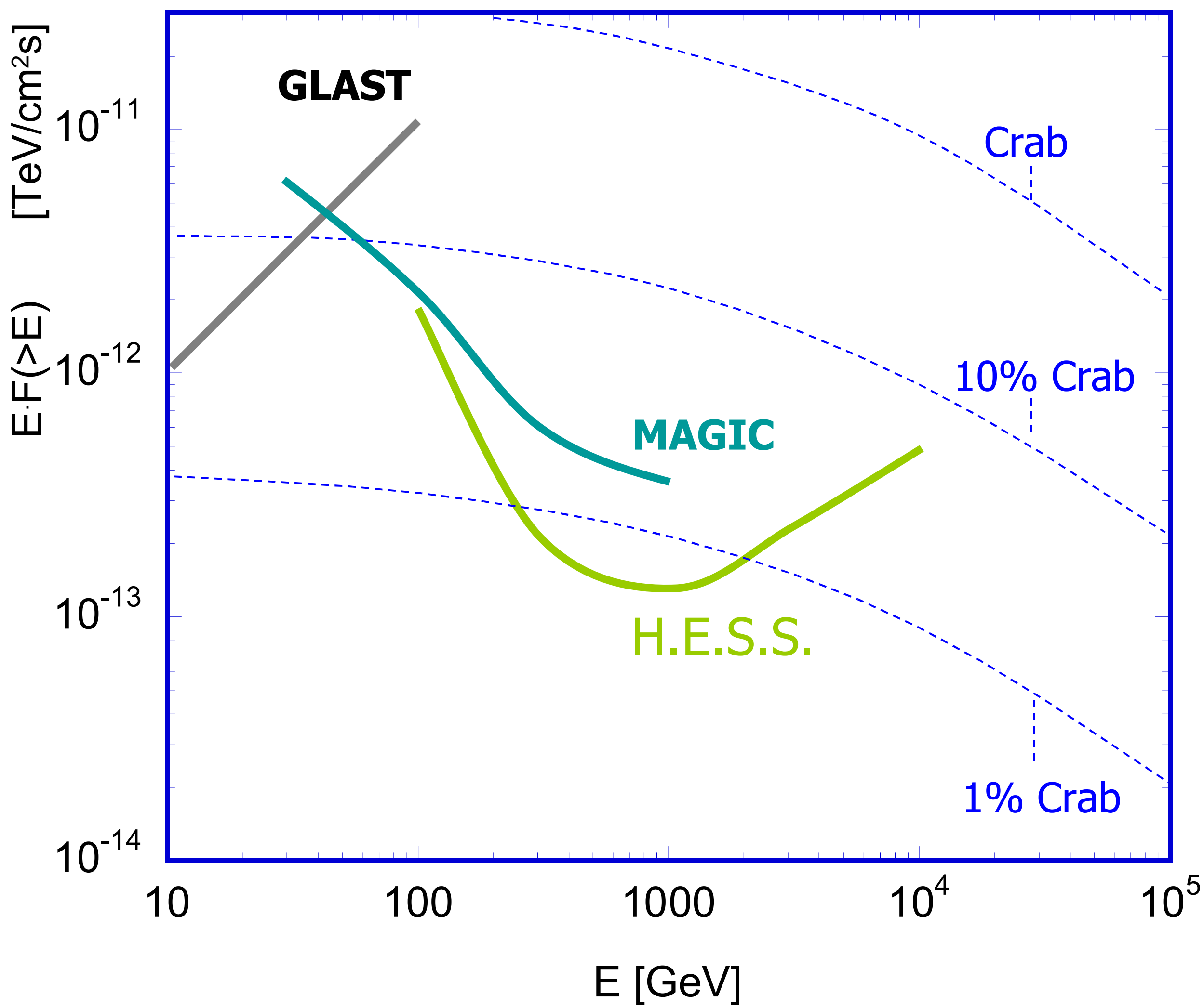
Gamma-Ray Observatory



Photomontage from ASPERA

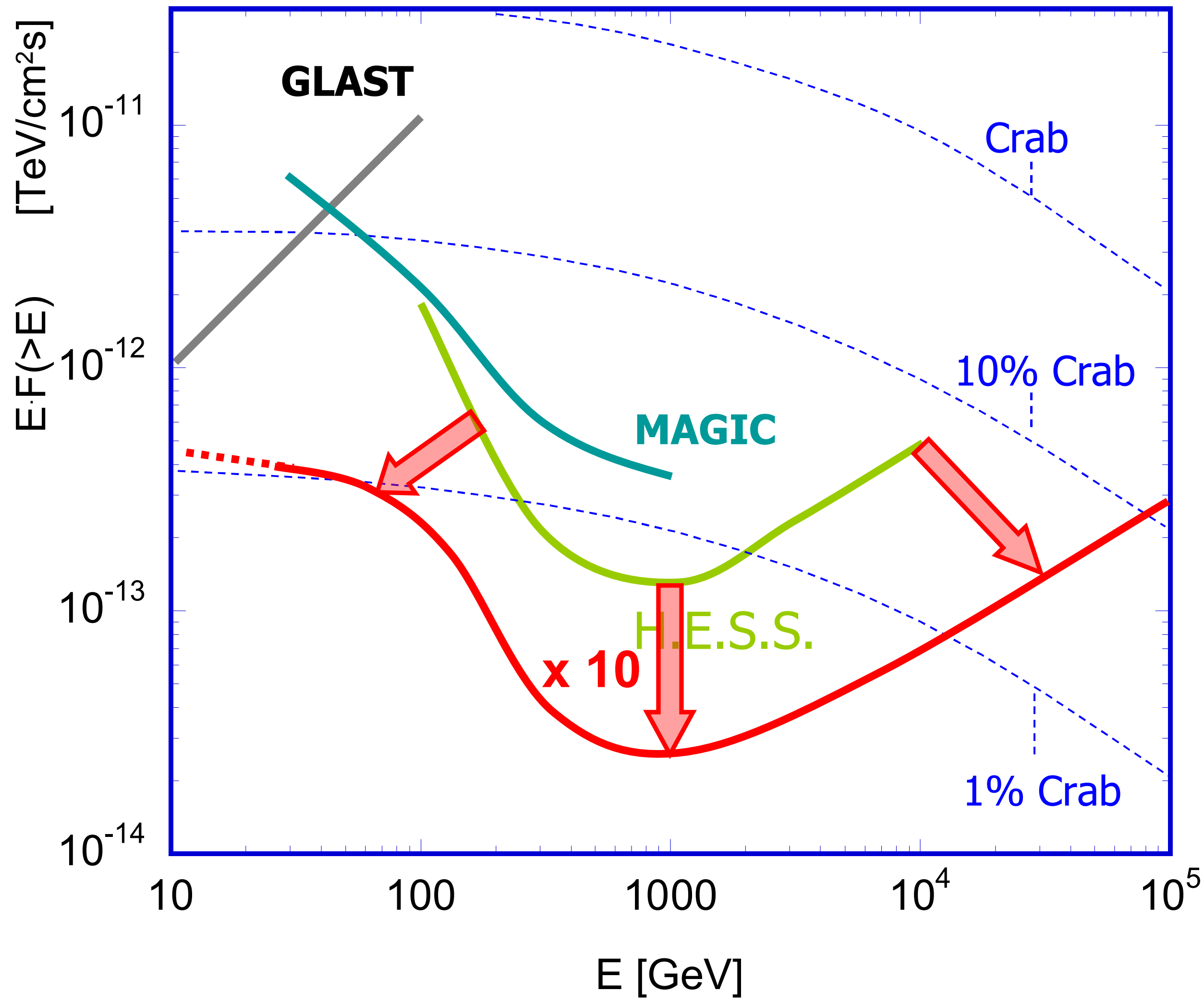
Next Generation: Wish list

An advanced Facility for ground-based gamma-ray Astronomy



Next Generation: Wish list

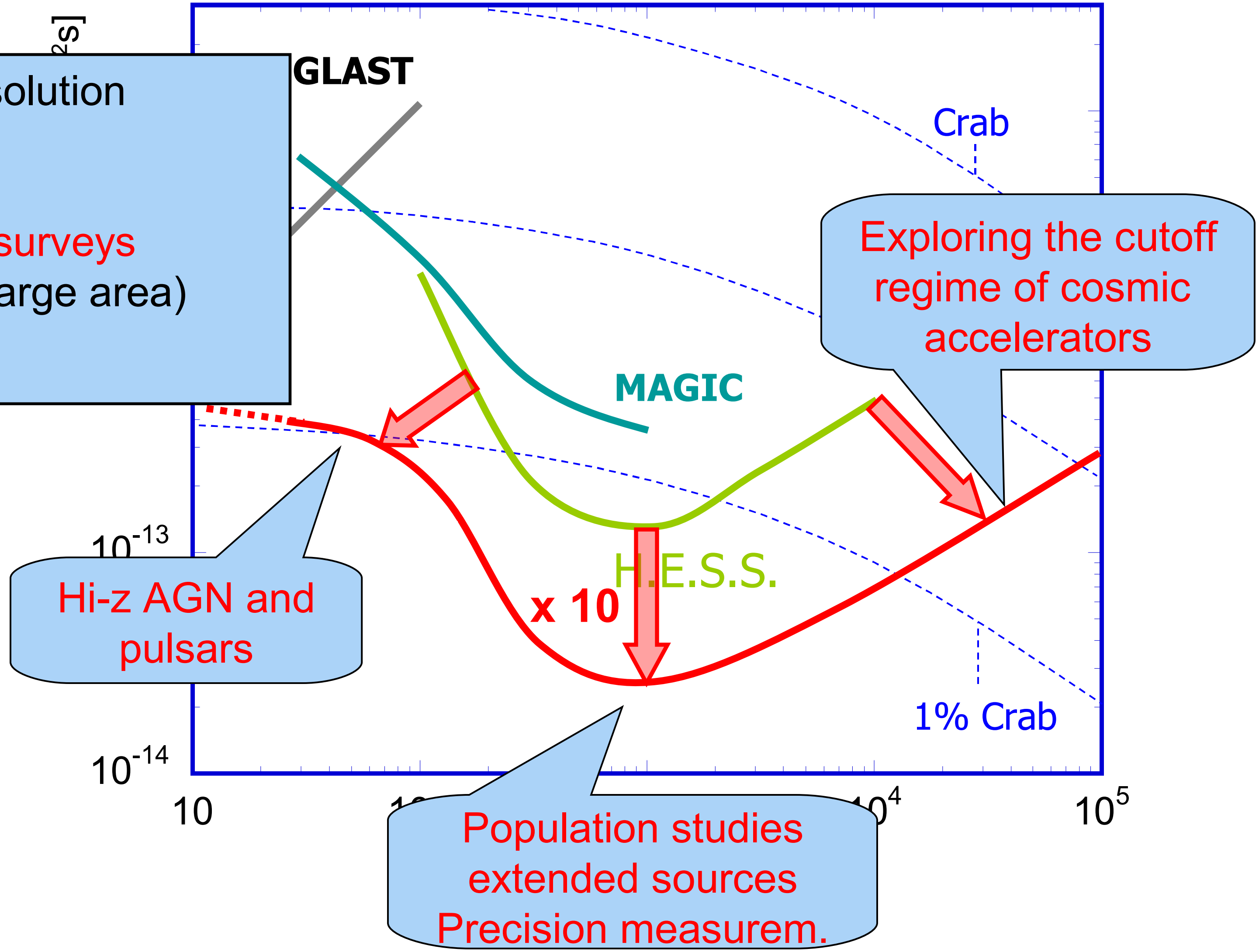
An advanced Facility for ground-based gamma-ray Astronomy

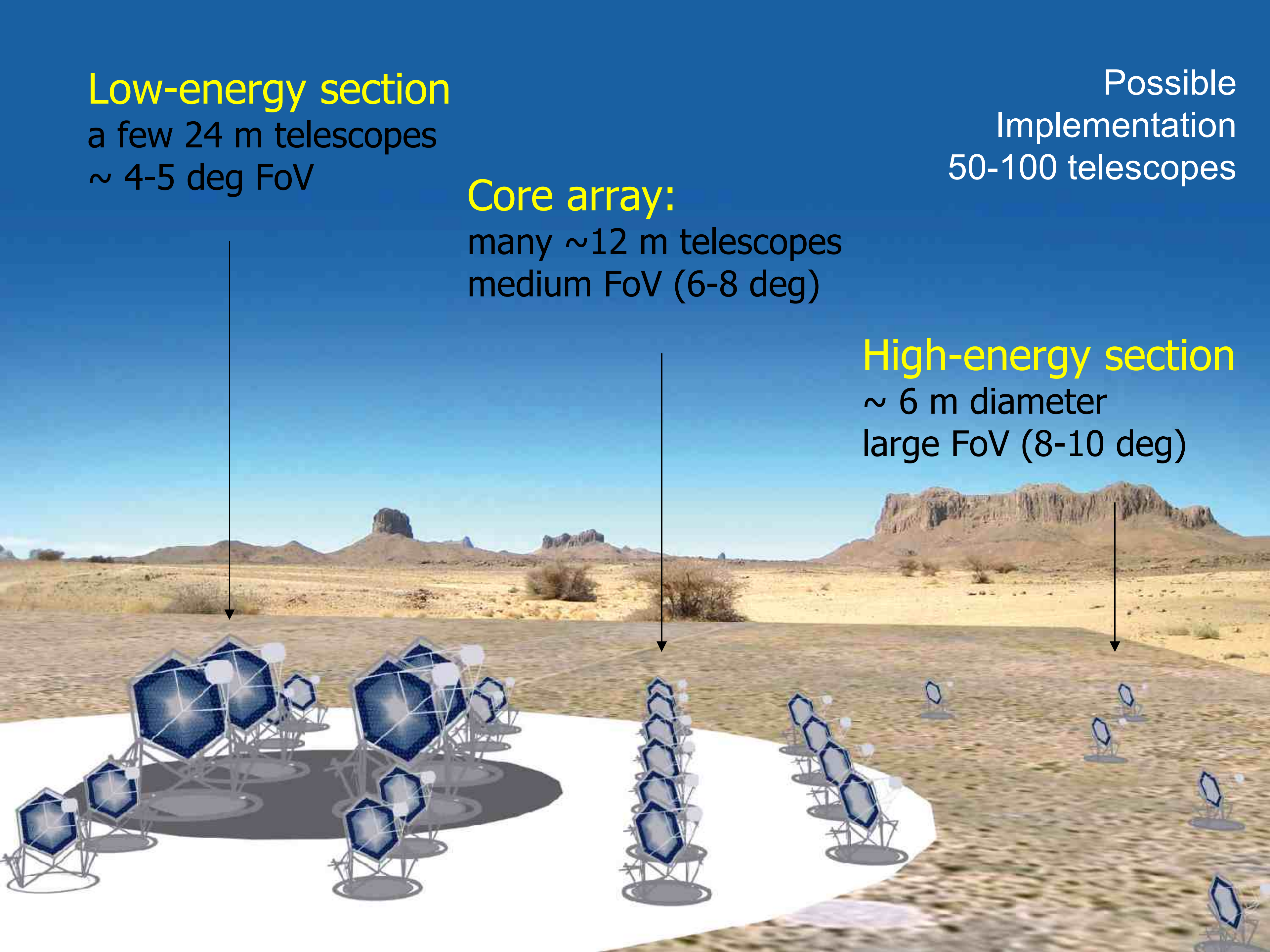


Next Generation: Wish list

An advanced Facility for ground-based gamma-ray Astronomy

- Improved angular resolution
  source morphology
- large FoV (6-8 deg)
  extended sources, surveys
- High detection rate (large area)
  transient sources

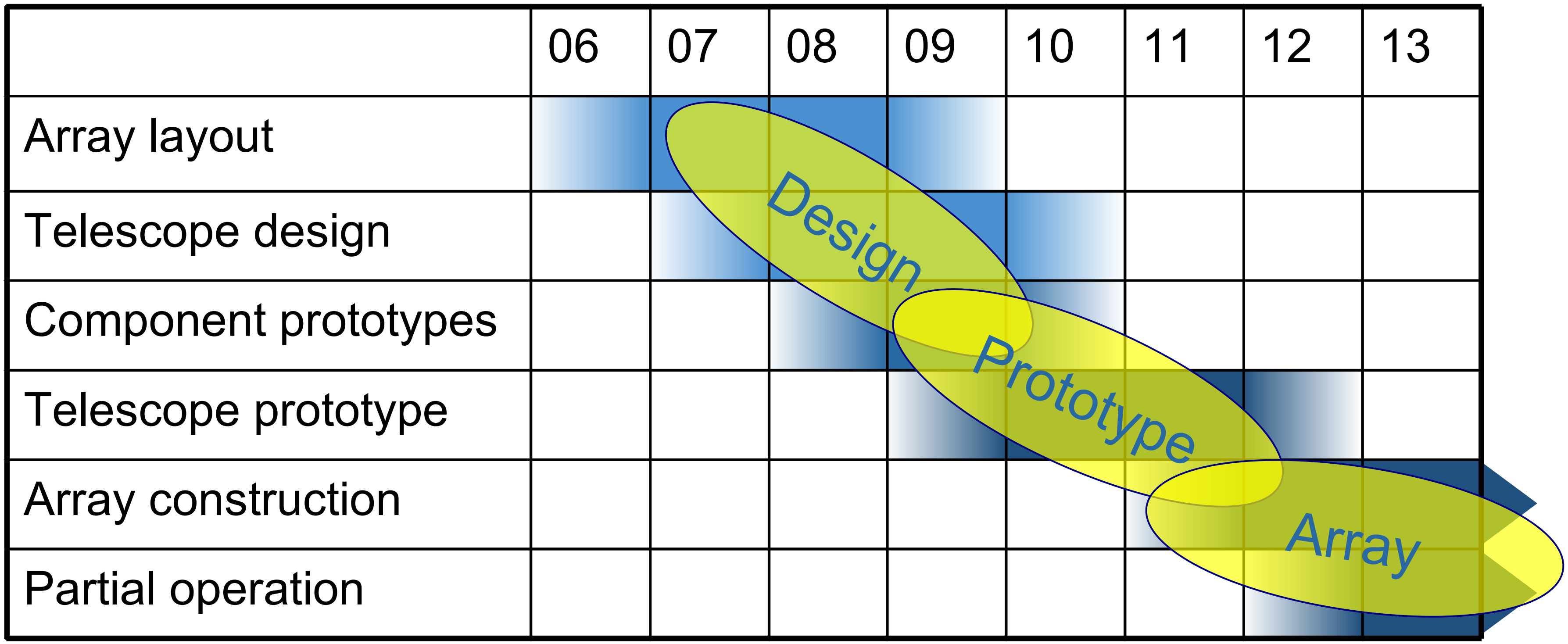




Low-energy section
a few 24 m telescopes
~ 4-5 deg FoV
Possible
Implementation
50-100 telescopes
Core array:
many ~12 m telescopes
medium FoV (6-8 deg)
High-energy section
~ 6 m diameter
large FoV (8-10 deg)

Tentative Timeline

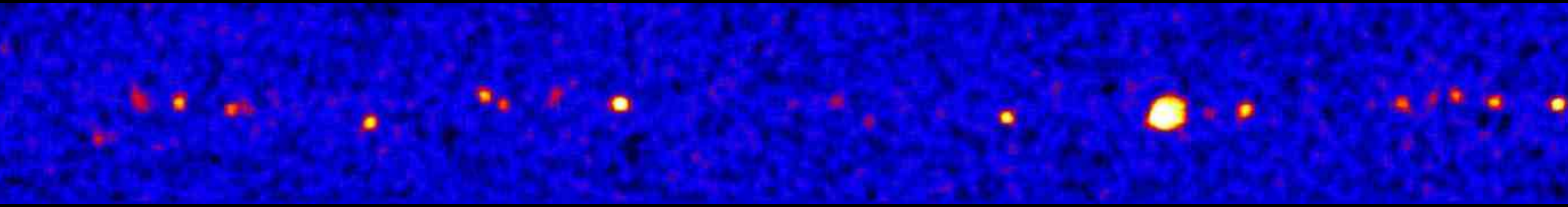
An advanced Facility for ground-based gamma-ray Astronomy



The ‘Galactic Plane’ with CTA

- Toy Simulation:
  - b, l object distribution from Parkes, Green & H.E.S.S. catalogues
  - Log (N) = -log (S)
  - Angular size distribution of objects from H.E.S.S.
  - Detector properties (ang. res, S/BG rates) from simulation & data
  - Normalized to HESS measurements

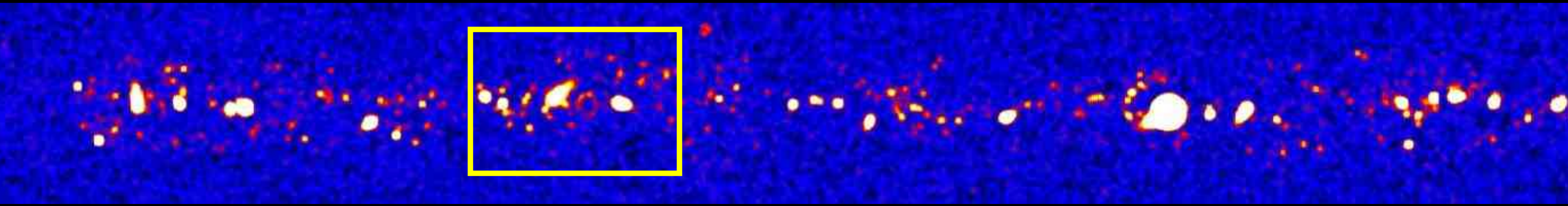
‘HESS’ : ~500 hours



The ‘Galactic Plane’ with CTA

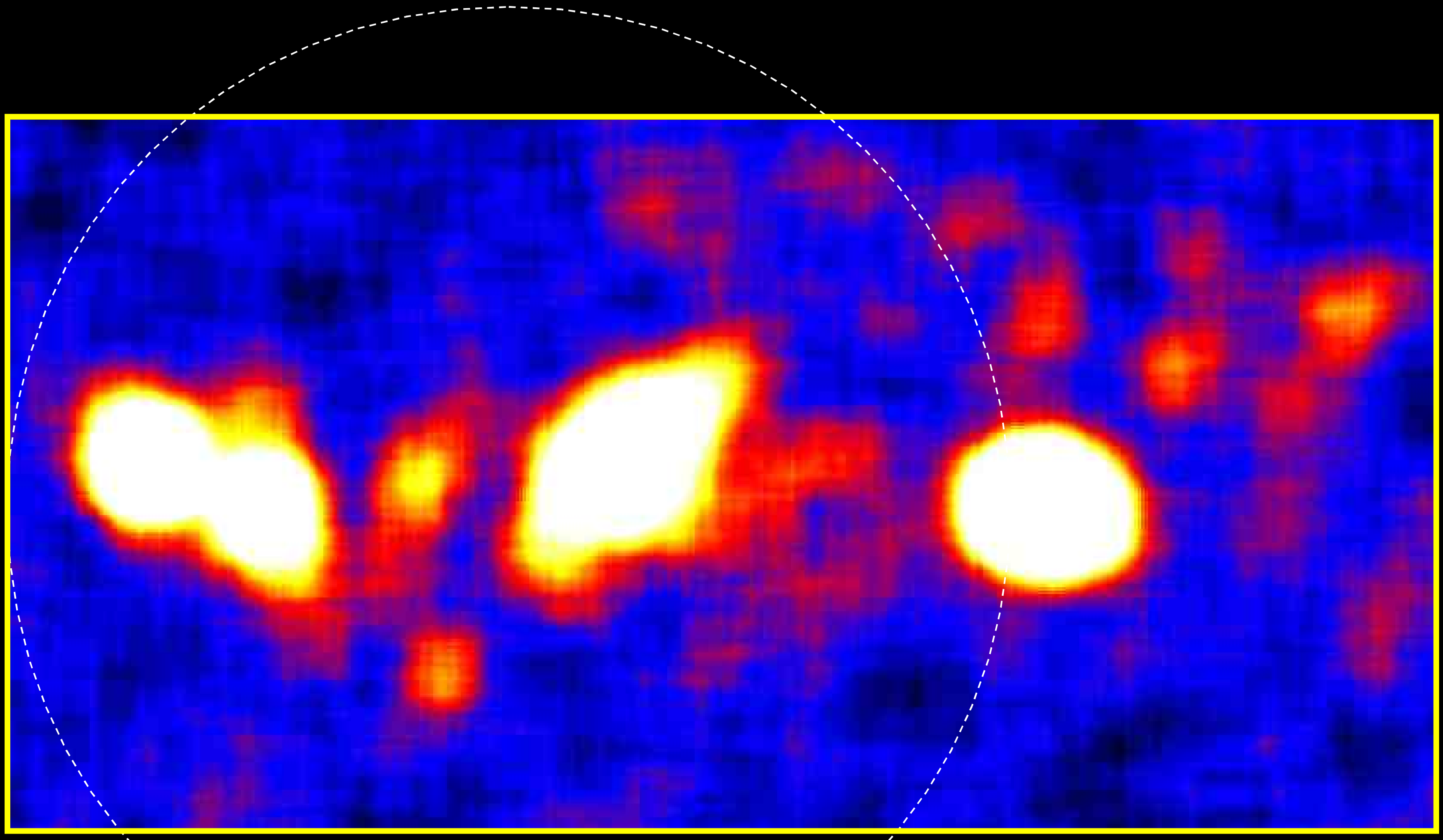
- Toy Simulation:
  - b, l object distribution from Parkes, Green & H.E.S.S. catalogues
  - Log (N) = -log (S)
  - Angular size distribution of objects from H.E.S.S.
  - Detector properties (ang. res, S/BG rates) from simulation & data
  - Normalized to HESS measurements

‘CTA’ : ~500 hours



Expecting / hoping for :   O(1000) sources (galactic + extragalactic)

The ‘Galactic Plane’ with CTA

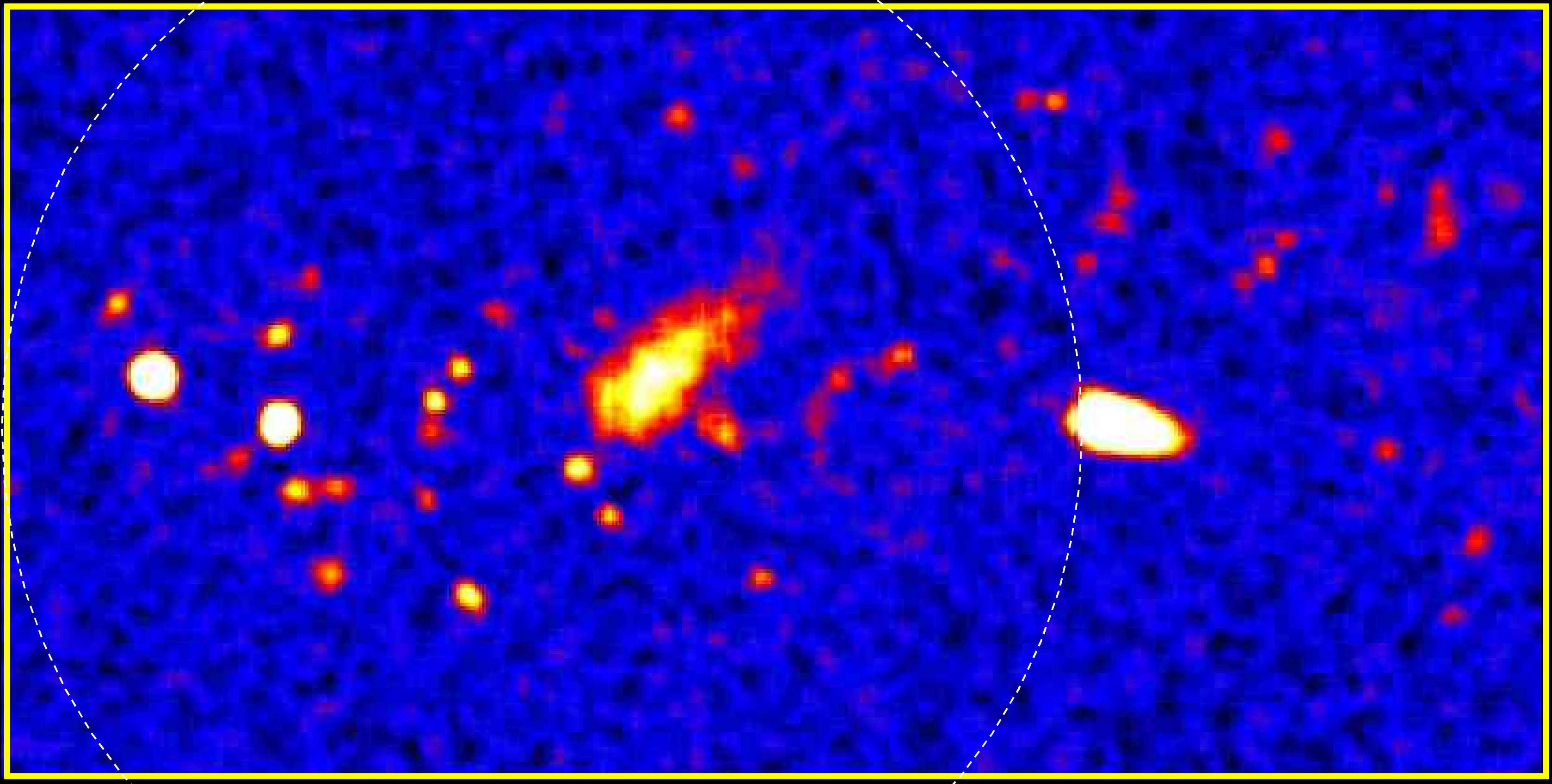


6 deg FoV

angular resolution: 0.2 deg (~ 50 GeV)

The 'Galactic Plane' with CTA

CTA : a "microscope" for Galactic Accelerators



6 deg FoV

angular resolution: 0.05 deg (> 1TeV)