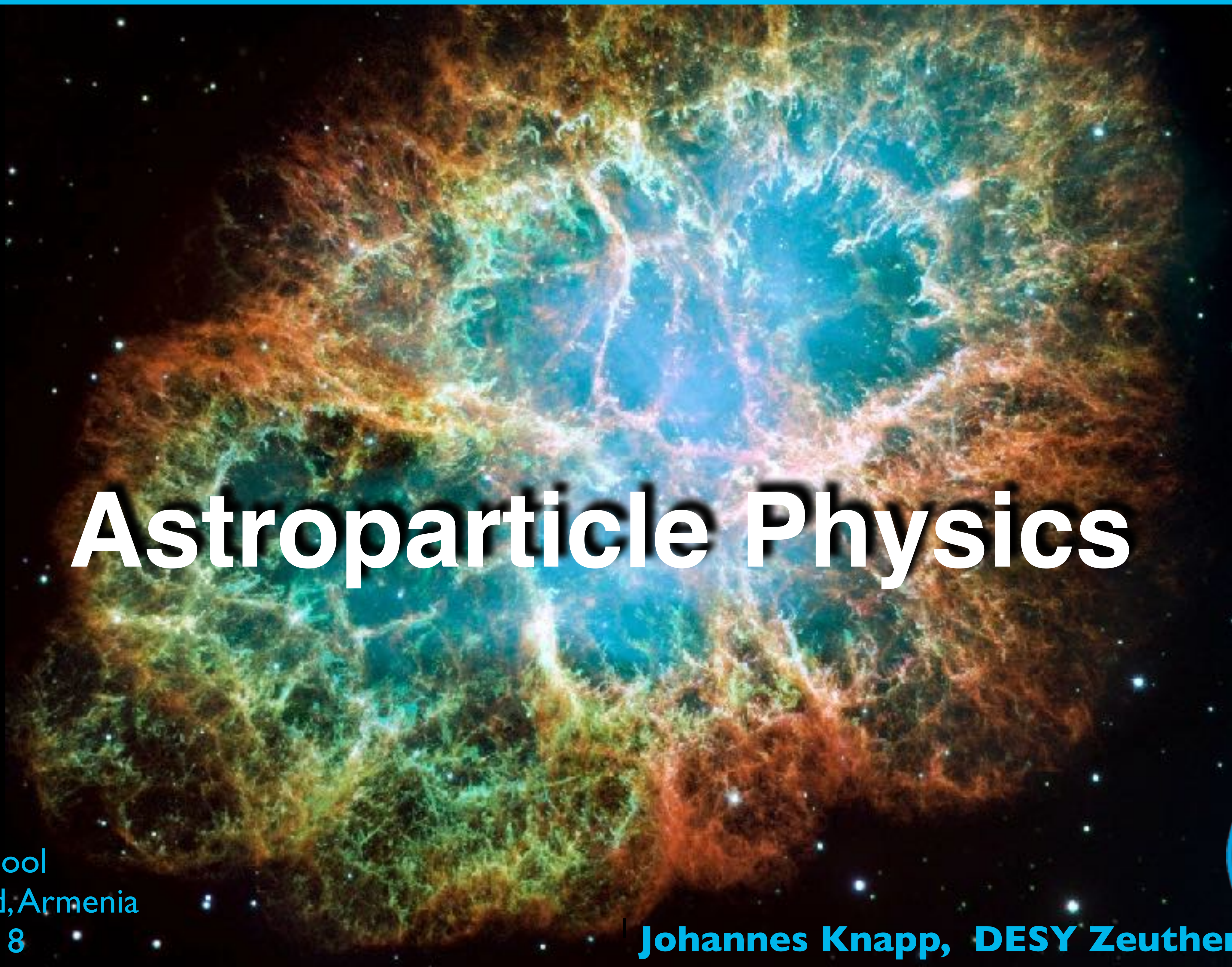
From Measurement to Discovery – The Scientific Method in Physics



Summer School
Nor Amberd, Armenia
5-8 June, 2018

Johannes Knapp, DESY Zeuthen

From Measurement to Discovery

My Plan for APP:

Discovery
Discovery

Lecture 1: Cosmic Rays: discovery, techniques, spectra & spectral features

Lecture 2: Neutrinos ν: neutrino hypothesis & detection, the solar model, solar neutrino problem, neutrino oscillations

Lecture 3: Neutrino astronomy: the idea, techniques atmospheric neutrinos, sources

Discovery

Lecture 4: Gamma Rays γ: early ideas, techniques, path to maturity, sources & successes

very many discoveries

From Measurement to Discovery

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Lecture 4: Gamma Rays γ: early ideas, techniques, path to maturity, sources & successes **very many discoveries**

Much of this is what we call today "Astroparticle Physics"

4. Gamma Rays

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Gamma Rays

point back
easy to detect
some absorption

Energy scale:

radio IR visible light UV X rays γ rays

the range of astroparticle physics

meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

10^{-3} ... 1 ... 10^{3} ... 10^{6} ... 10^{9} ... 10^{12} ... 10^{15} ... 10^{18} ... 10^{21} eV

non-thermal processes

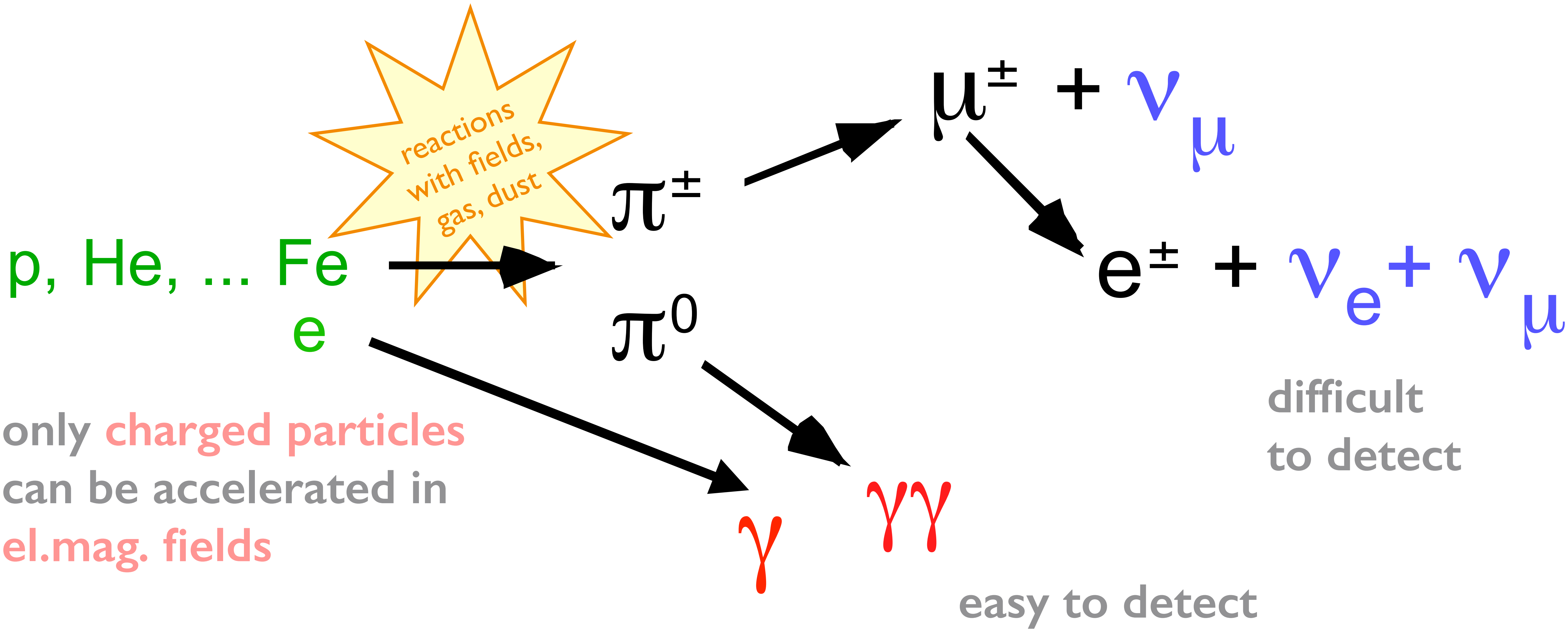
Photons: astronomy

charged: p, He, ... Fe, ... completely ionised nuclei

electrons

Neutrinos:

Cosmic rays, gamma rays and neutrinos come likely from the same sources



"multi-messenger astrophysics"

but gamma rays are currently the most "productive" messengers.

γ, ν

point back to sources (good for astronomy)
but serious backgrounds

γ Rays:

pick them out of the CR background
point back at sources

< 100 GeV: direct observations on satellites

γ via direct identification

> 100 GeV: indirect obs. via air showers

γ via shower shape, muon content

or via localised excess of events
from certain sky positions

Historic Development

Many slides and historic information from talks by:

R Mirzoyan (HESS Centenary Meeting, Bad Saarow, 2012)

S Sarkar (School for Cosmic Ray Astrophysics, Erice, 2012)

Historic Timeline – Part 1

1910: E Curie observes bluish light in water with Radium salt

1912: V Hess discovers Cosmic Rays
1912: CTR Wilson invents the cloud chamber

1934: P Cherenkov's brilliant experimental work
to explain the bluish light (Cherenkov effect)

1938: P Auger discovers air showers (CR energies up to 10^{15} eV
a total mystery at the time)

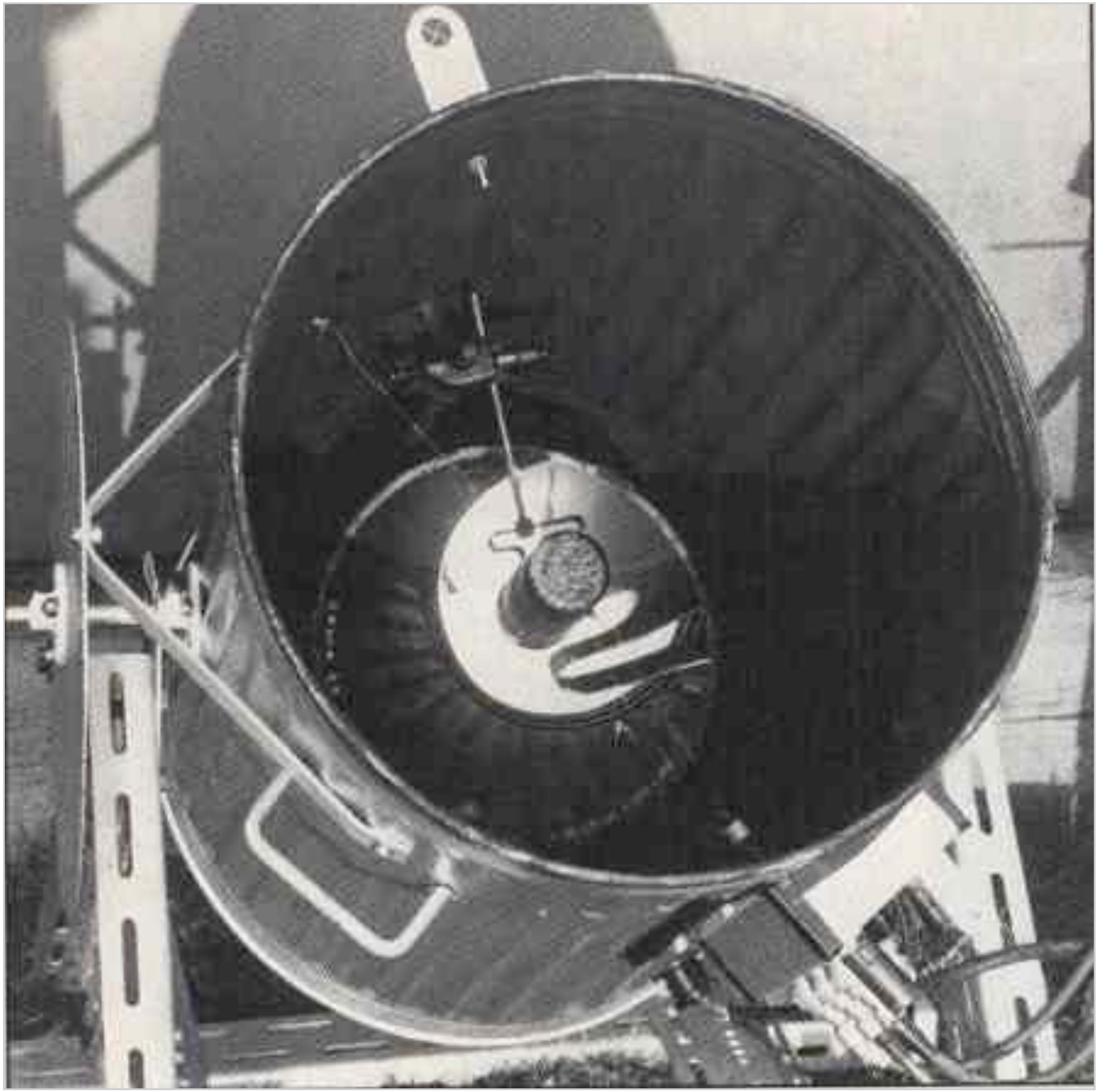
many discoveries in particle physics using CRs and
cloud chambers; interactions, particle production, ...

1948: E Fermi publishes acceleration theory of cosmic rays
(... and if protons are accelerated, then there should also be secondary γ rays)

1948: P Blackett recognised that Cherenkov light from relativistic particles
in air showers ($e^{\pm}$, $\mu^{\pm}$) should contribute to the light of night sky (~10^{-4} ?).

... ingredients ready for gamma-ray astronomy
with Cherenkov telescopes.

Cherenkov light from showers



garbage can, 60 cm search light mirror,
1 PMT (fast light flashes)

Galbraith, Jelley (Harwell, UK)
record Cherenkov flashes from air showers

February 21, 1953 NATURE

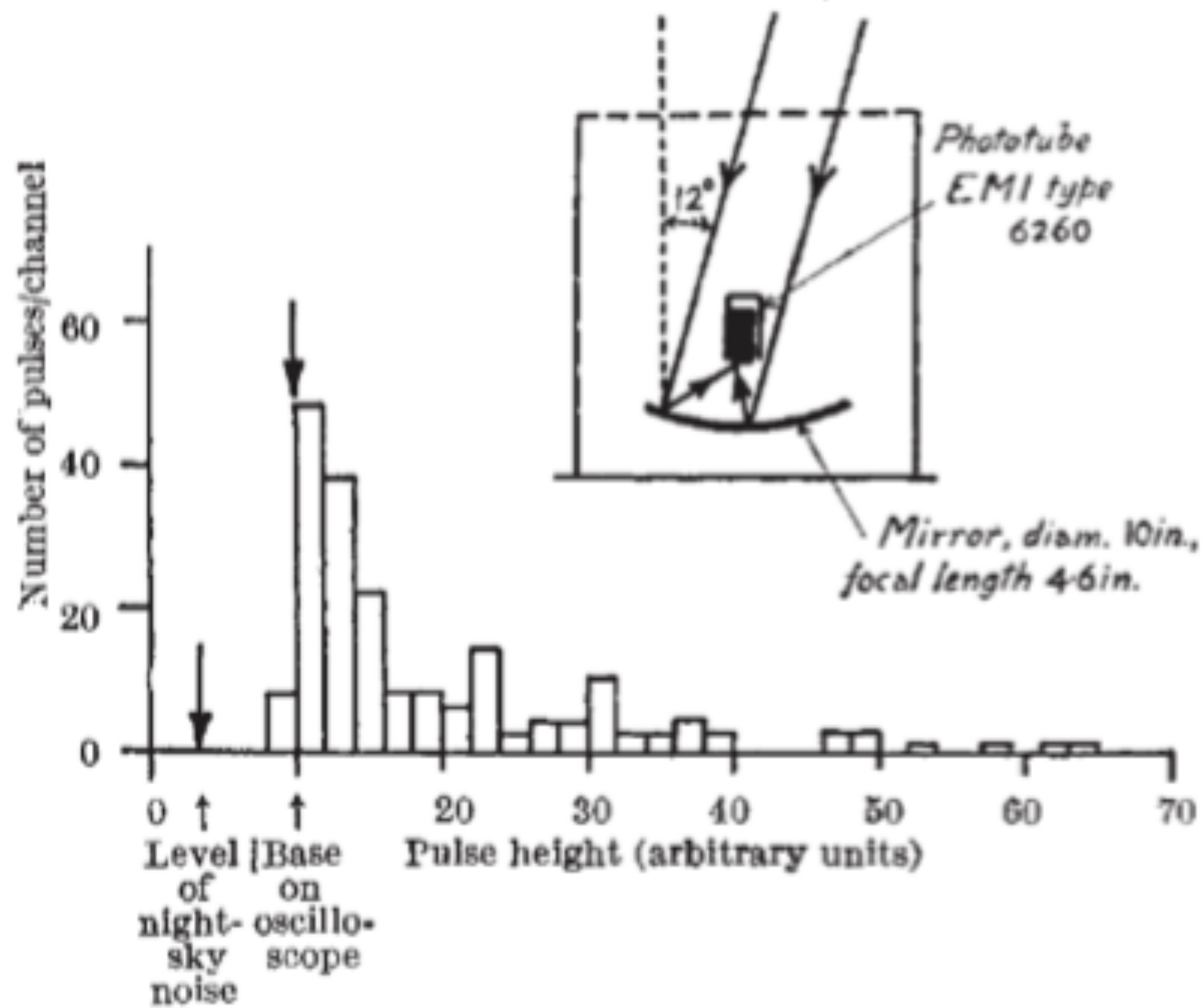
Light Pulses from the Night Sky associated with Cosmic Rays

IN 1948, Blackett[1] suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation[2] produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the

....

thank Mr. W. J. Whitehouse and Dr. E. Bretscher for their encouragement, and Dr. T. E. Cranshaw for the use of the extensive shower array.

W. GALBRAITH
J. V. JELLEY



Gamma Ray Astronomy

requires separation of photons from the cosmic ray background

1958: seminal paper by P Morrison

1959: G Cocconi (CERN) suggests to observe the Crab Nebula (ICRC 1959 Moscow)

AN AIR SHOWER TELESCOPE AND THE DETECTION OF 10^{12} eV PHOTON SOURCES

Giuseppe Cocconi *

CERN - Geneva.

1) This paper discusses the possibility of detecting high energy photons produced by discrete astronomical objects. Sources of charged particles are not considered as the smearing produced by the magnetized plasmas filling the interstellar spaces probably obliterates the original directions of movement.

Crab Nebula

1 TeV

The Crab Nebula: Visual magnitude of polarized light m = 9.
Magnetic field in the gas shell $H \simeq 10^{-4}$ gauss.
Therefore: $U_\nu = 10^{12}$ eV and $R(10^{12} eV) \approx 10^{-3.2}\ m^{-2} s^{-1}$.
The signal is thus about 10^{3} times larger than the background (2). Probably in the Crab Nebula the electrons are not in equilibrium with the trapped cosmic rays, and our estimate is over-optimistic. However, this source can probably be detected even if its efficiency in producing high energy photons is substantially smaller than postulated above.

407, the Jet Nebula: m = 13.5 $H \simeq 10^{-4}$ gauss.
$R(10^{12} eV) \simeq 10^{-5} m^{-2} s^{-1}$, still well above the background (2). For this object our evaluation is probably not fundamentally wrong.

Military surplus of
- parabolic search-light mirrors 1-2 m in diameter
- gun mounts with drive systems

G.T. Zatsepin (from GZK cutoff) asked Chudakov
to measure the predicted gamma-ray sources.
Crimea: Chudakov got 12 parabolic mirrors of 1.5 m
made measurements for almost 4 years.

Crimea Experiment
1959-1965

only upper limits

Cocconi's estimate
far too optimistic

First mention of the potential of the stereo imaging

SOVIET PHYSICS JETP VOLUME 20, NUMBER 2 FEBRUARY, 1965

THE ANGULAR DISTRIBUTION OF INTENSITY OF CERENKOV RADIATION FROM EXTENSIVE COSMIC-RAY AIR SHOWERS

V. I. ZATSEPIN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 2, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) 47, 689-695 (August, 1964)

The angular distribution of intensity is calculated for the Cerenkov radiation produced in the terrestrial atmosphere by extensive air showers of cosmic rays. Calculations are made for showers arriving from the zenith and for conditions of observation at sea level and at an altitude of 3860 m above sea level. Photographic observation of the shape of the flash of light against the celestial sphere, as obtained in [2,3] is evidently in satisfactory agreement with the calculations.

1. INTRODUCTION

In the registration of extensive air showers (EAS) by means of Cerenkov counters,[1,2] a knowledge of the angular distribution of the Cerenkov radiation is important primarily from the methodological point of view (choice of the angle subtended by the Cerenkov counters to obtain optimal signal-to-noise ratio, estimates of the accuracy of the angular coordinates of high-energy primary particles, and so on). Besides this, the angular distribution of the light from showers is already itself the object of physical investigation,[3] and therefore it is important to ascertain what kind of information about a shower can be obtained from such data. The present calculation has been made for this purpose, and is based on the following ideas.

Cerenkov radiation is mainly caused by the electronic component, which makes up the bulk of the charged particles in a shower. Owing to multiple Coulomb scattering by the nuclei of atoms in the air, electrons of energy E at a depth t have a Gaussian distribution of distances r from the axis of the shower, and a Gaussian distribution of angles relative to a mean angle ϑ, which depends on r. The dispersions of the transverse and angular distributions depend on E. The energy spectrum of the electrons is an equilibrium one and does not depend on the degree of development of the shower in depth. For the case of primary photons the variation of the electrons with height is taken to be that given by the electromagnetic cascade theory,[4] and for the case of primary protons, that given by the calculations of Nikol'skii and Pomanskii.[5] The light emitted by the electrons is at the angle ϑ_{Cer} with the direction of their motion. Neither the scattering of the light by density inhomogeneities in the air nor absorption of the light is taken into account.

2. STATEMENT OF PROBLEM AND METHOD OF CALCULATION

The purpose of the calculation is to determine the number I of light quanta in the frequency range from λ_1 to λ_2 that fall on unit area of the earth's surface at distance R from the axis of the shower, and in the direction from any given point of the celestial sphere.

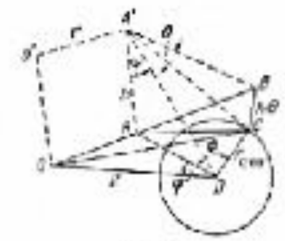


FIG. 1

Let us turn to Fig. 1. Here O is the trace of the axis of the shower on the earth's surface, D is the point of observation, and A' is an arbitrary point which is at height h over the level of observation and is characterized by the angular coordinates ψ (the zenith angle) and φ (the azimuthal angle). We agree to measure the azimuthal angle from the direction from the point of observation D to the trace O of the axis of the shower on the earth's surface. The figure OBCD lies in the plane of the drawing, and OO'A'B in the perpendicular plane. We shall determine for the neighborhood of

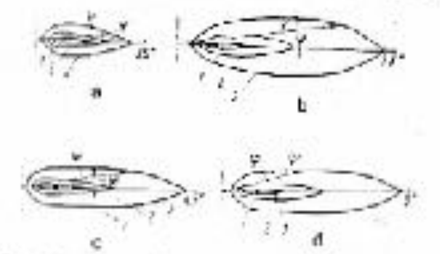
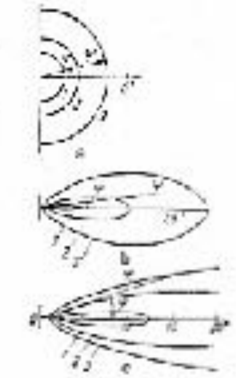


FIG. 6. Contours of equal intensity in light flashes from showers from primary protons and primary photons of various energies, for sea level and R = 100 m from the axis. The curves 1, 2, 3 correspond to intensity values $10^{-1} I_{max}(100)$, $10^{-2} I_{max}(100)$, and $10^{-3} I_{max}(100)$. Diagrams a and b cor-



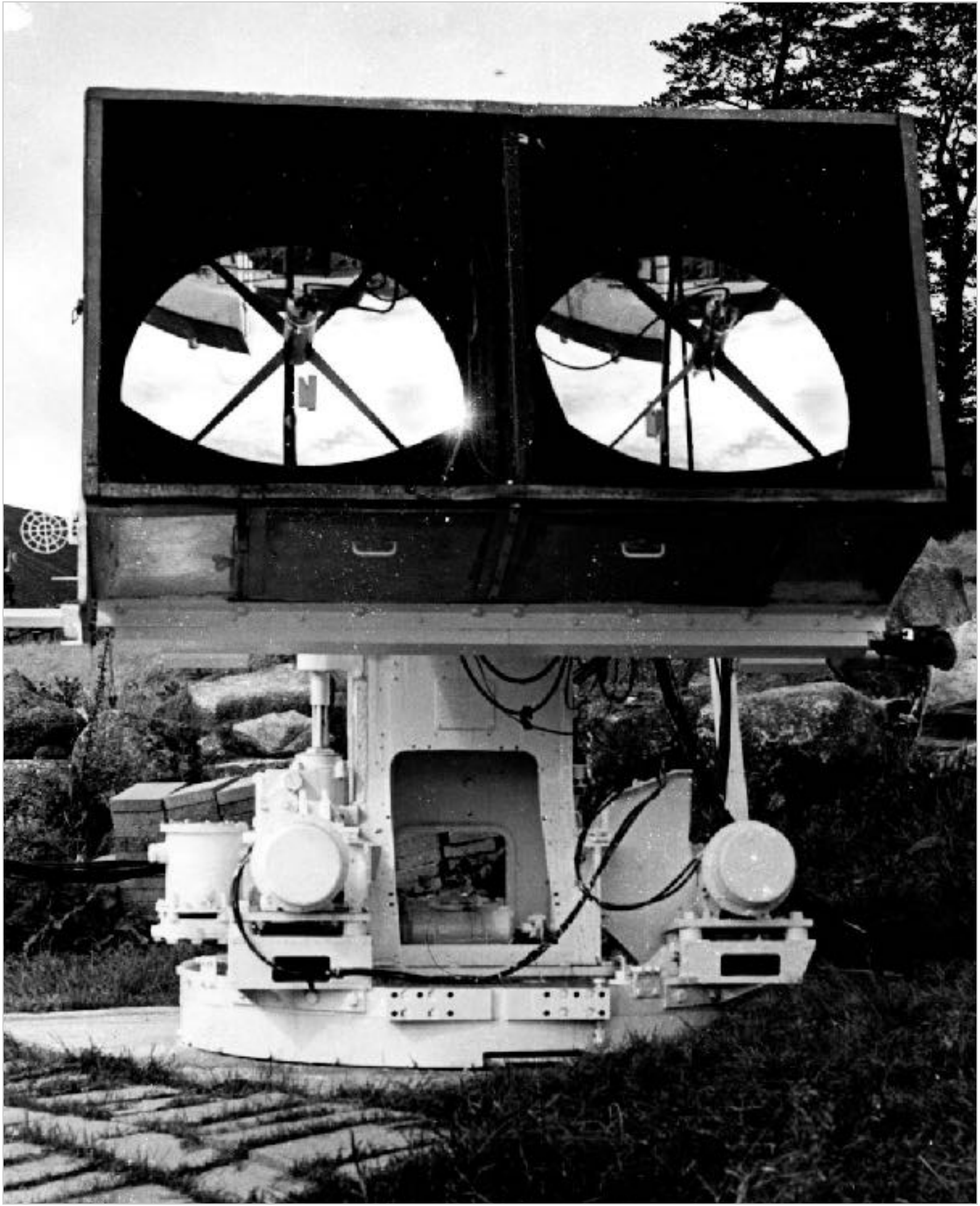
CONCLUSION

The calculations that have been made enable us to draw the following conclusions:

1. Since the maximum intensity of the light from a shower does not coincide with the direction of arrival of the primary particle, in researches in which the determination of the angular coordinates of the primary particle is made by photographing the light flash from the shower one should seek improved accuracy in this determination by photographing the shower simultaneously from several positions.

2. If the distance from the axis of the shower to the detector is determined from independent data, then an analysis of the shape of the light flash from the shower and its total intensity gives information both about the initial energy of the primary particle and about the position in the atmosphere of the maximum of the shower, and can thus be used for the analysis of fluctuations in the development of showers in the atmosphere.

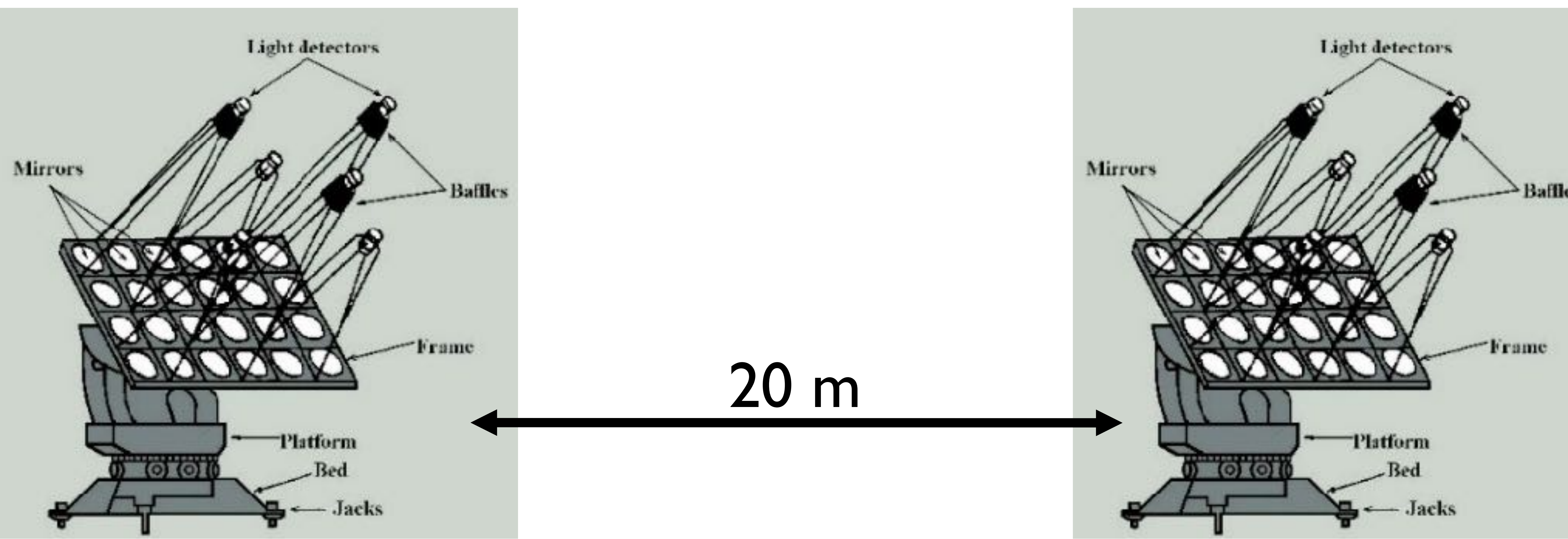
V.I. Zatsepin 1965



Ireland:
Porter & Jelley
1962-66

First imaging "stereo" telescopes: GT-48 in Crimea 1985-89

A Stepanian



First gamma-ray experiment at Whipple Observatory, 1967-68

Work on the Mt. Hopkins Observatory proceeds at an astonishing pace. The laser and Baker-Nunn systems are now installed and operating and the large optical reflector is scheduled to arrive by the end of next month. In preparation for the LOR installation, Trevor Weekes (above, left) and George Rieke have conducted seeing tests with two movable searchlight reflectors. Look carefully — some outcroppings at the base of Mt. Hopkins are visible upside-down in the reflector.

THE ASTROPHYSICAL JOURNAL, Vol. 154, November 1968

1968

A SEARCH FOR DISCRETE SOURCES OF COSMIC GAMMA RAYS OF ENERGIES NEAR 2×10^{12} eV

G. G. FAZIO AND H. F. HELMKEN
Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Massachusetts

G. H. RIEKE
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona, and Harvard University, Cambridge, Massachusetts

AND

T. C. WEEKES*
Mount Hopkins Observatory, Smithsonian Astrophysical Observatory, Tubac, Arizona

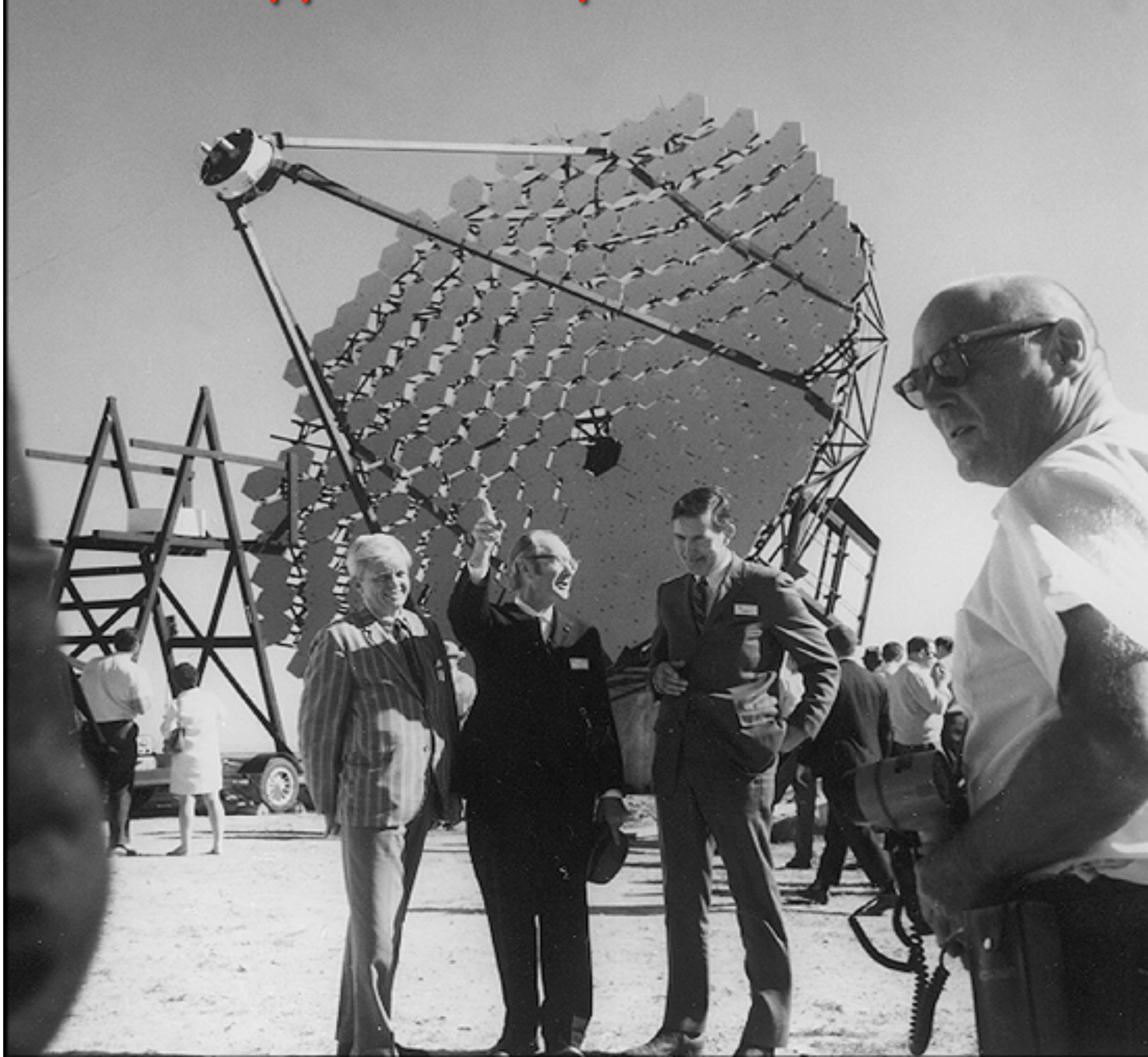
Received September 3, 1968

ABSTRACT

By use of the atmospheric Čerenkov nightsky technique, a study has been made of the cosmic-ray air-shower distribution from the direction of thirteen astronomical objects. These include the Crab Nebula, M87, M82, quasi-stellar objects, X-ray sources, and recently exploded supernovae. An anisotropy in the direction of a source would indicate the emission of gamma rays of energy 2×10^{12} eV. No statistically significant effects were recorded. Upper limits of $3–30 \times 10^{-11}$ gamma ray cm^{-2} sec^{-1} were deduced for the individual sources.

10 m Whipple Telescope

built in 1968



1970-80's: plenty of "discoveries" on 3-4 **σ** level

A.M. Hillas, University of Leeds:

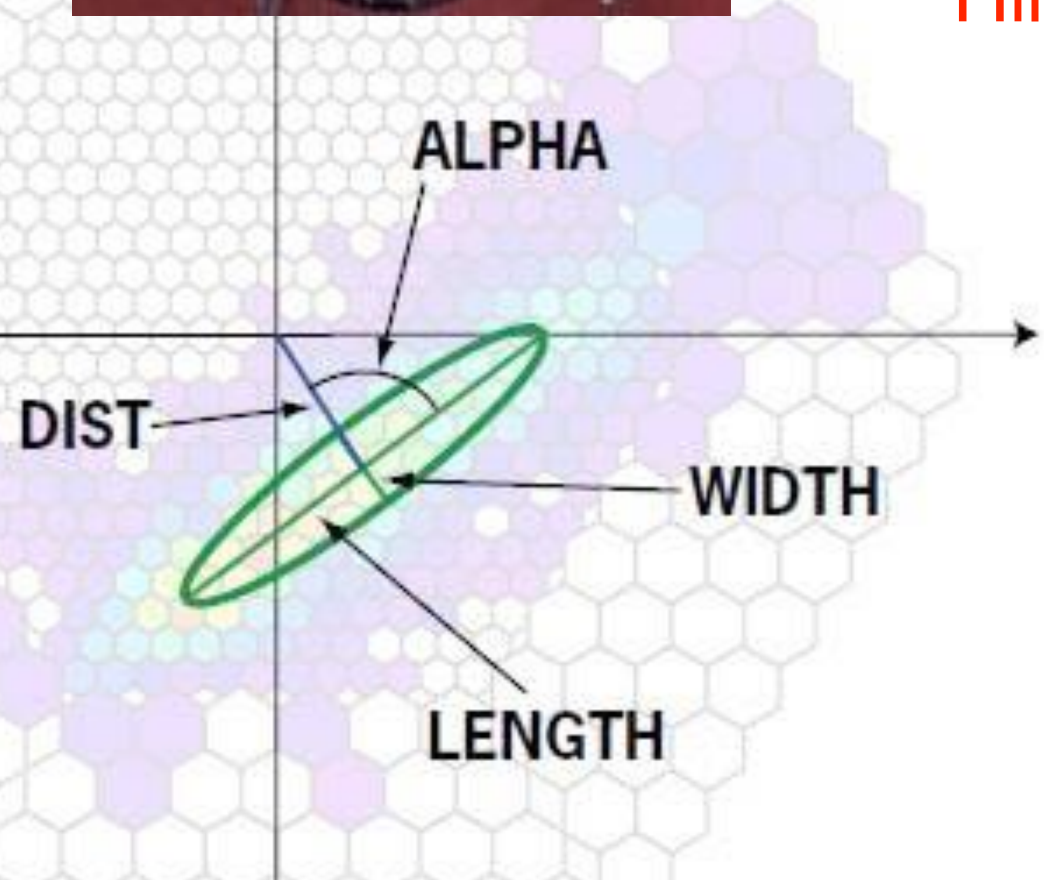
"A physicist's apparatus gradually learns what is expected of it. It has a dog-like desire to please."

"Concentration" is a good parameter

(>75% of light is concentrated in 2 pixels)

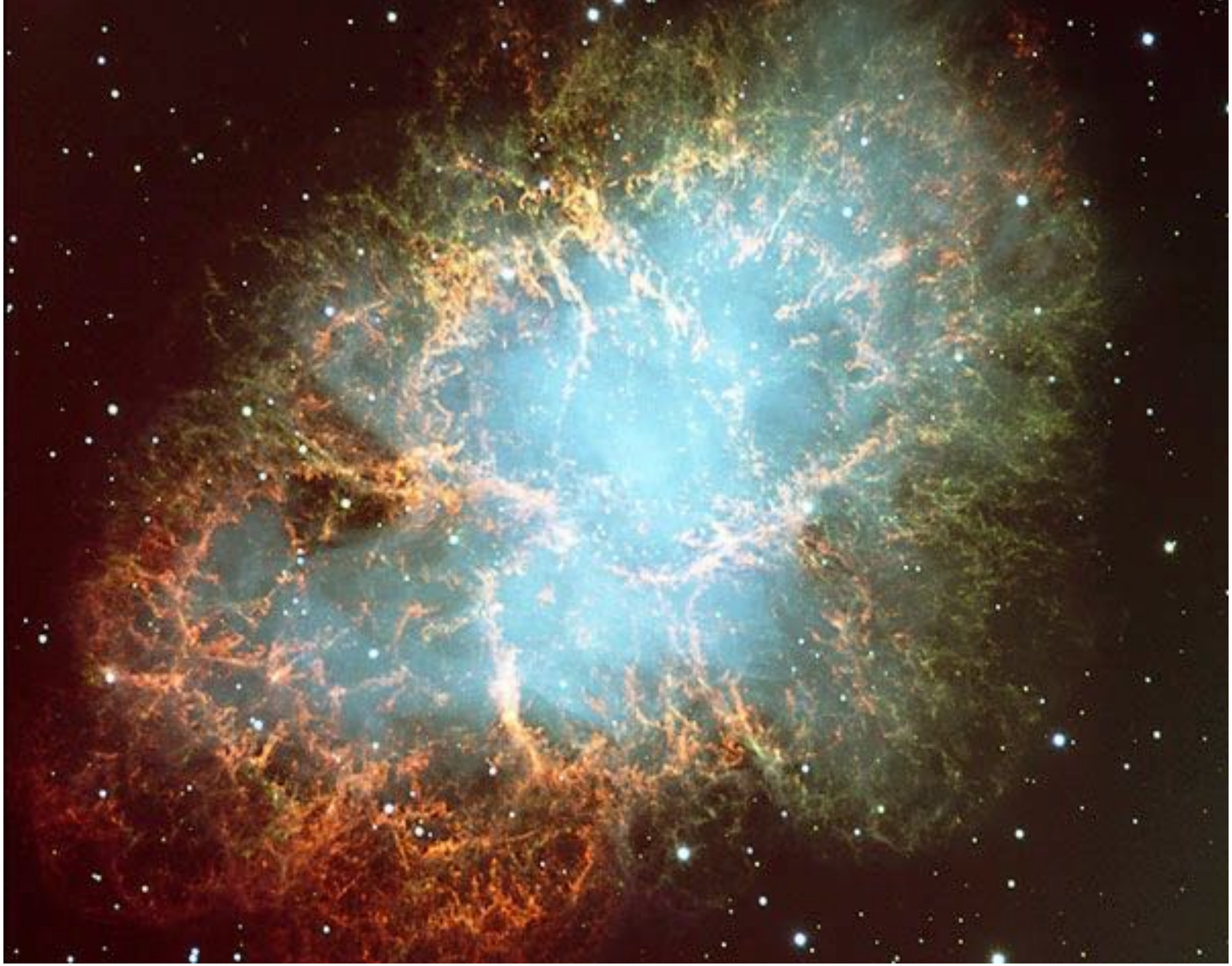
Plyasheshnikov, Bignami (1985) showed that α is a useful parameter

La Jolla, 1985: Hillas suggests to use the "Hillas image parameters"



gamma showers are:

- slimmer,
- more concentrated
- oriented towards source



1989:
Detection of the Crab Nebula

9σ significance

5σ signal in 50 h,
with 159 pixel camera
and Hillas image analysis.

1990's: sources were seen everywhere, up to 10^{15} eV

e.g.

CONCLUSIONS

It was shown that Vela X-1 emits steady, pulsed TeV emission over five years of observations, at a period corresponding with the expected X-ray period. No orbital modulation could be established. For Cen X-3 pulsed emission was found only in a part of the orbit, corresponding with the known accretion wake. It also seems that the emission in the wake is steady over time scales of years. In both cases weak evidence for a period shift was found. With the detection of AE Aqr as a possible source of TeV gamma-rays, a new area of candidate sources has been opened up for TeV astronomy. In all cases it will be imperative to observe sources over a number of years, and if possible, make use of multiwavelength observations to investigate the behaviour of these objects.

... which could not be confirmed.

Reliable source detection needs $>5\sigma$ significance and independent confirmation.

1985:
Yerevan Physics Institute
Plan for 5 imaging Cherenkov Telescopes:

Nor Amberd CR station
2000 m a.s.l.
mount Aragats, Armenia

90.

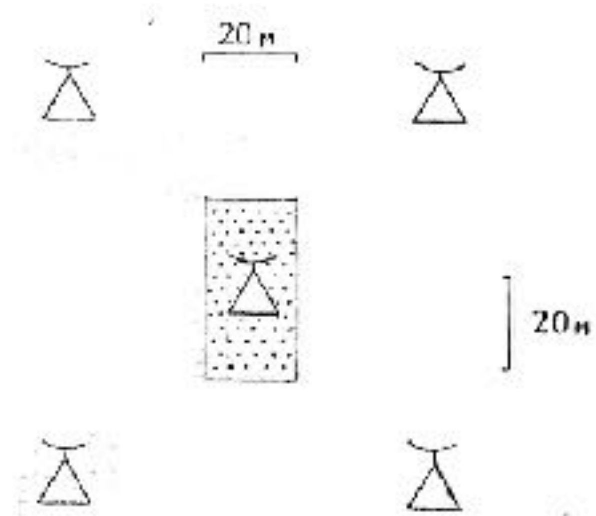


Рис. 38. Установка I.

– телескопы для регистрации ЧС ливней с ПЧД.

– детекторы мюонов ШАЛ.

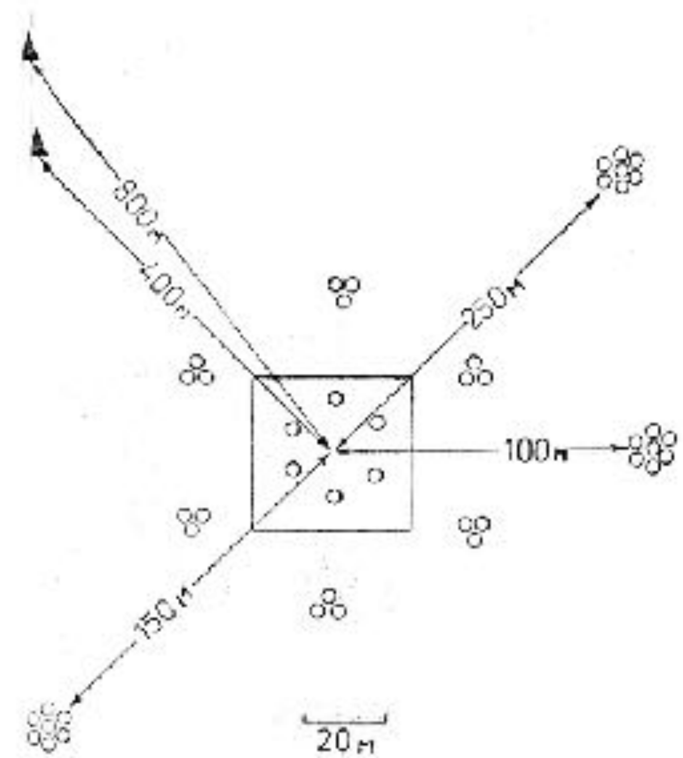


Рис. 39. Установка 2.

– центральная часть АНИ для регистрации компонент ШАЛ.

– детекторы для определения поперечного распределения ЧС ШАЛ

– детекторы для определения формы импульсов ЧС ШАЛ.

only one was built

Hegra, La Palma

31.

Proposal
for
Imaging Air Cherenkov Telescopes in the HEGRA Particle Array

F.A. Aharonian, A.G.Akhperjanian, A.S. Kankanian,
R.G. Mirzoyan, A.A. Stepanian*

Yerevan Physics Institute

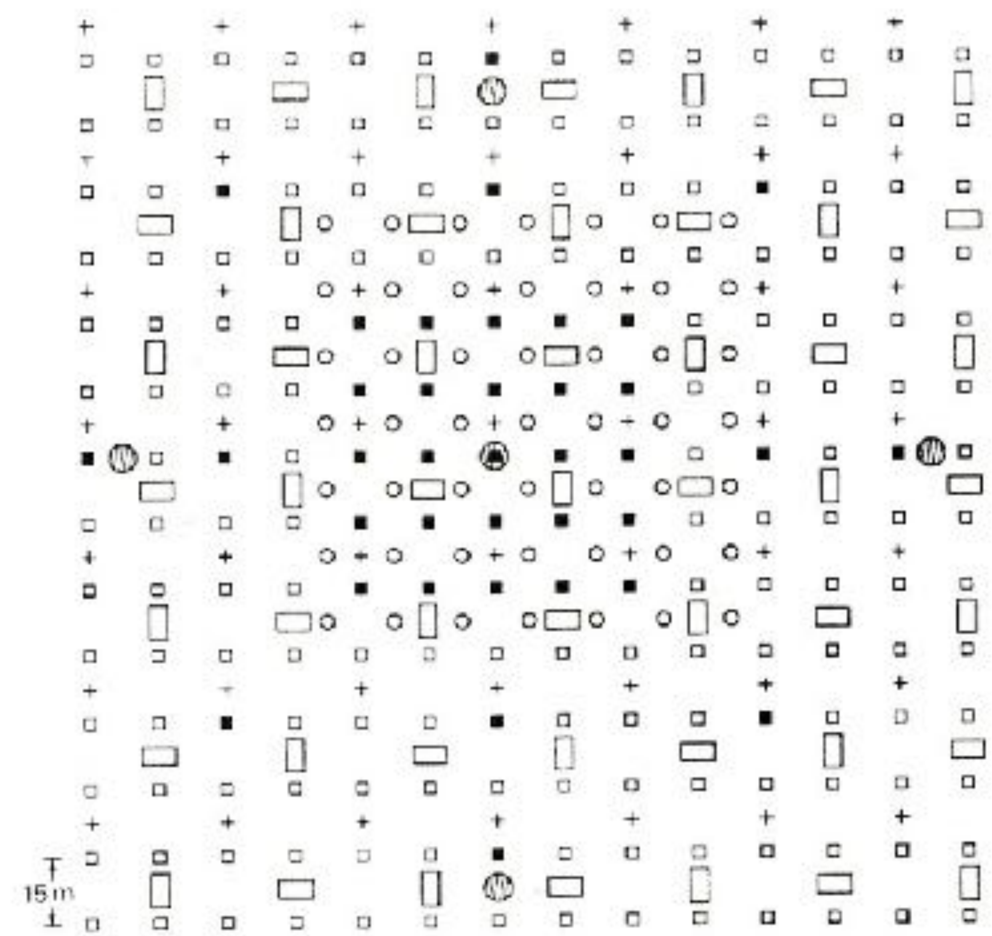
* Crimean Astrophysical Observatory

M. Samorski, W. Stamm

Institut für Kernphysik, University of Kiel

M. Bott-Bodenhausen, E. Lorenz, ?. Sawallisch

Max-Planck-Institute for Physics and Astrophysics
Munich



ELECTRON DETECTORS: 1 m^2 scintillation counters for particle density and fast-timing measurements (2 PM's each), with 5 mm of lead for photon conversion.

- ■ 37 detectors in operation since July 1988 (University of Kiel)
- □ 159 additional detectors, 90 of them in operation since July 1989, the rest since December 1990 (MPI Munich together with University of Madrid)
- ○ 49 further detectors to increase the detector density in the centre of the array, planned for 1991 (University of Hamburg)

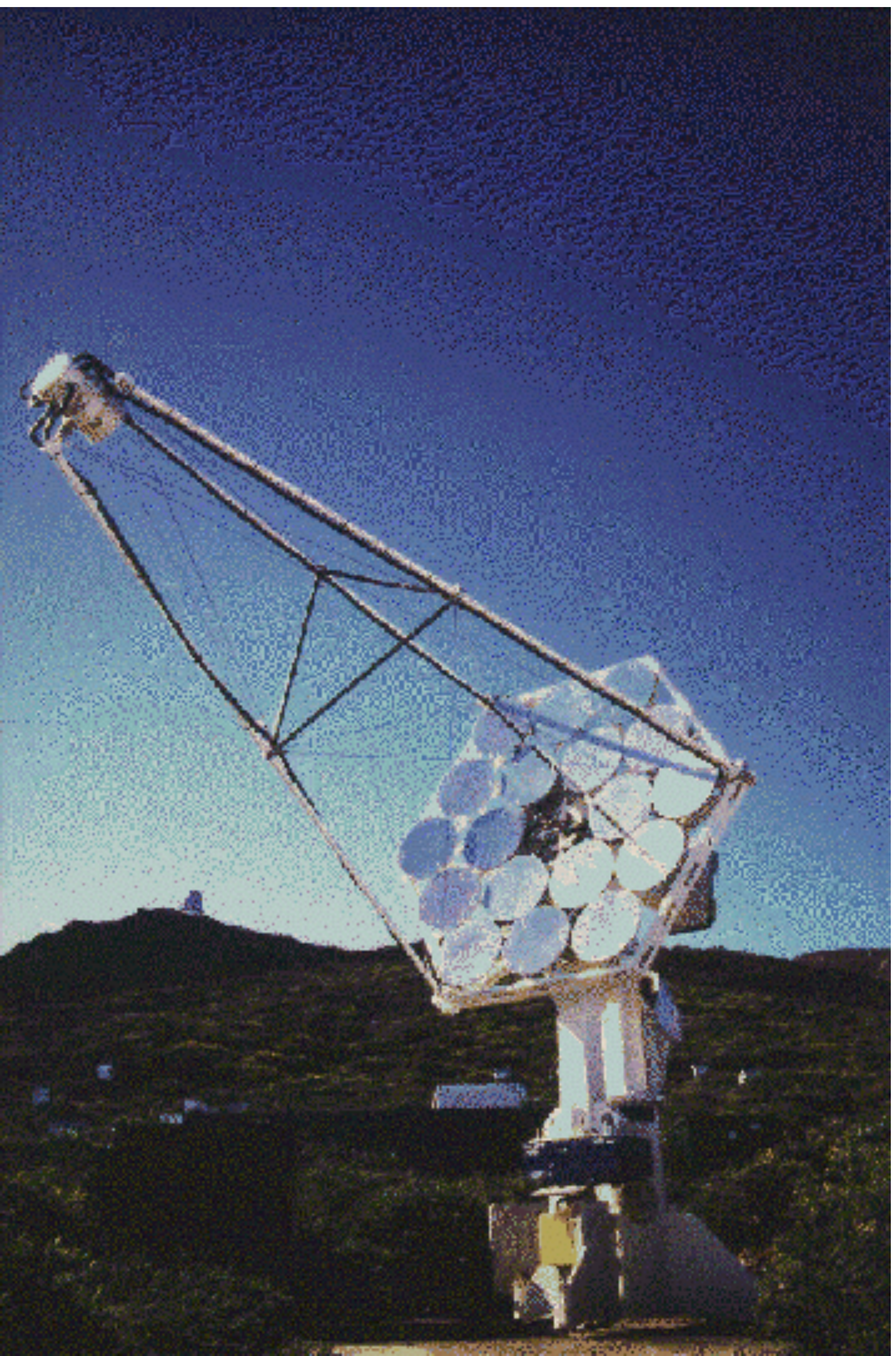
▭ 49 MUON DETECTORS: 15 m^2 each, consisting of sandwiches of Geiger tube and absorber layers, planned for 1991/92 (University of Wuppertal together with University of Kiel)

\+ 49 CHERENKOV-LIGHT DETECTORS: each consisting of a 20 cm diameter PM and a light-collecting cone, planned for 1991 (MPI Munich together wit h University of Madrid)

◍ 5 CHERENKOV TELESCOPES: 3 m in diameter with 19 mirrors and 37 PM's each, imaging technique, planned for 1991/92 (Yerevan Institute of Physics together with MPI Munich and University of Kiel)

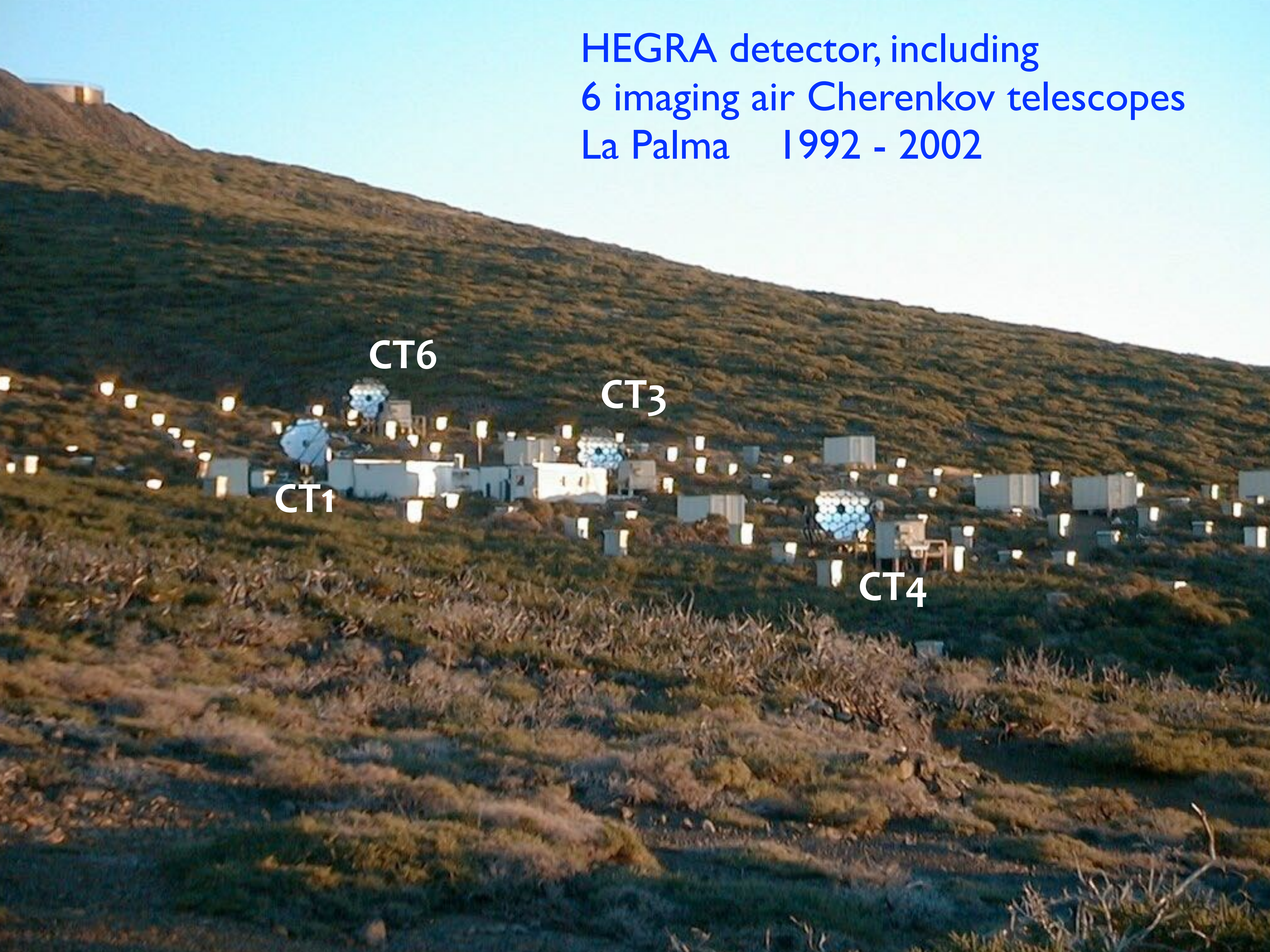
Fig. 1: Status and planned extensions of the HEGRA detector array.

CT1 (3 m diam.)
1992 first signal from
Crab Nebula

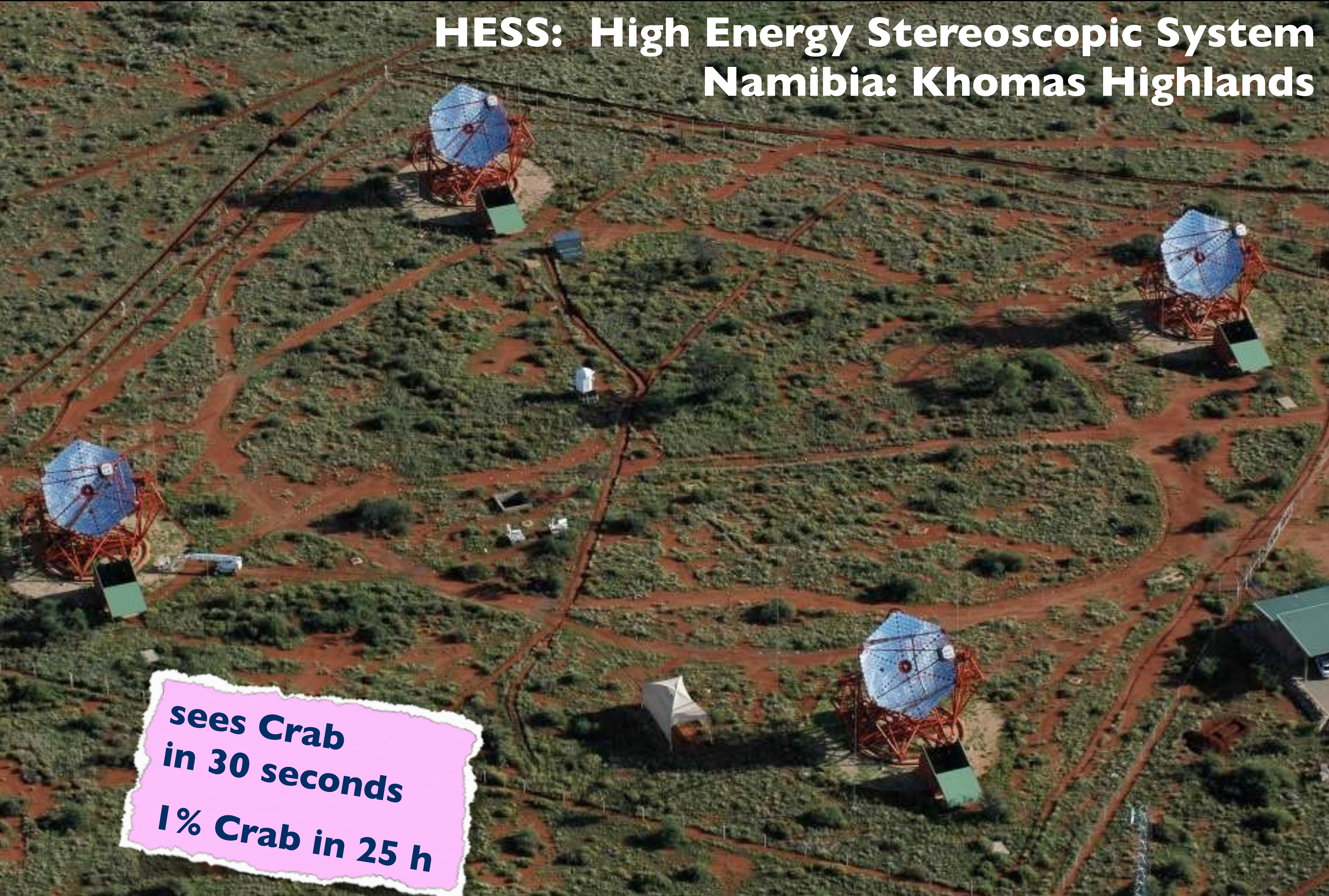


CT2 – CT6: (4 m diam.)
5 more telescopes until 1997.

first successful
stereo detection of γ-ray sources


HEGRA detector, including
6 imaging air Cherenkov telescopes
La Palma 1992 - 2002
CT6
CT3
CT1
CT4

HESS: High Energy Stereoscopic System
Namibia: Khomas Highlands



Four 12-m telescopes, 5° field of view
960 pixels / camera, Data taking since 2004

… a major step forward

Historic Timeline – Part 2

Ingredients ready		1948	
Whipple 10-m telescope built		1968	

~40 years

first detection

Crab Nebula	PWN	1989	Whipple
Markarian 421	HBL	1992	Whipple
Markarian 501	HBL	1996	Whipple
3C66A	IBL	1998	Crimea
1ES 2344+514	HBL	1998	Whipple
PKS 2155-304	HBL	1999	Durham Mark 6
1ES 1959+650	HBL	1999	Telescope Array
RX J1713.7-3946	Shell	2000	Cangaroo
Cas A	Shell	2001	HEGRA
BI Lac	IBL	2001	Crimea
H 1426+428	HBL	2002	Whipple
TeV J2032+4130	UNID	2002	HEGRA
M87	FR I	2003	HEGRA
Galactic Centre	UNID	2004	Cangaroo

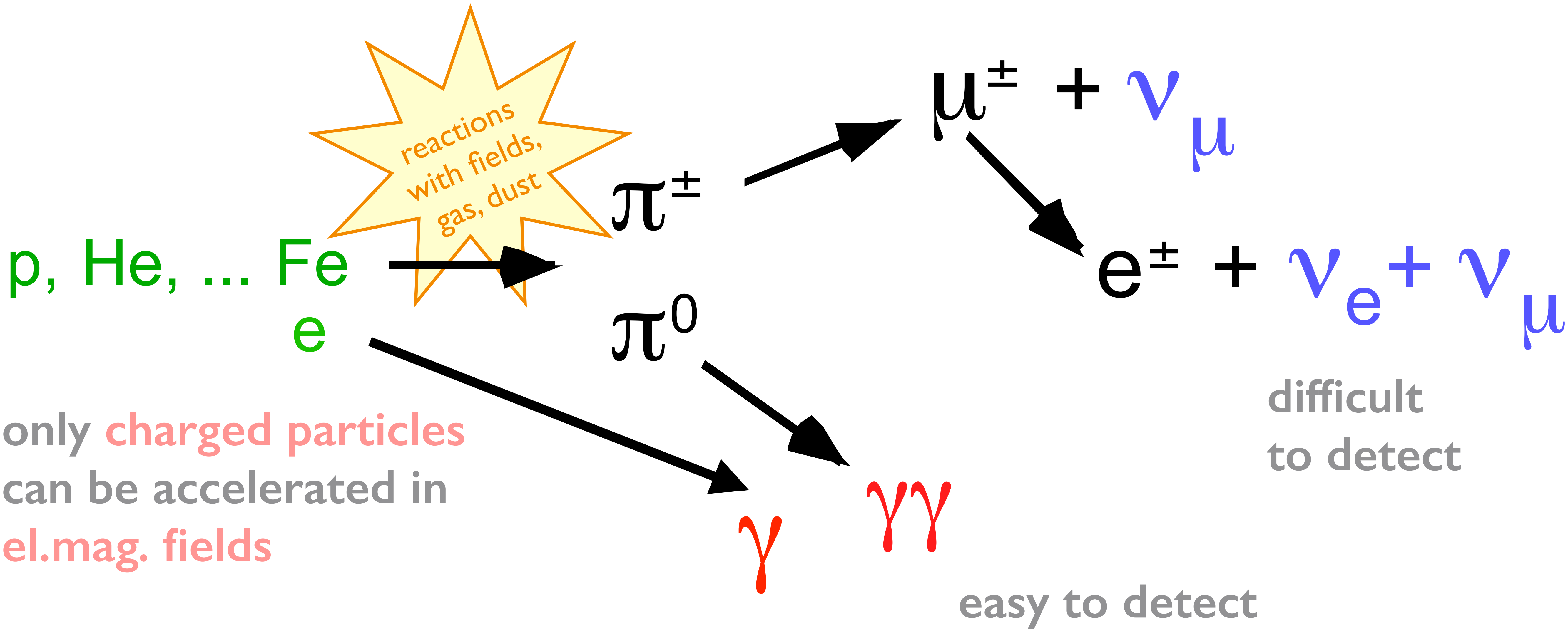
~10 years

~5 years

HESS started observations

... 16 new sources	2005
... 17 new sources	2006

Cosmic rays, gamma rays and neutrinos come likely from the same sources



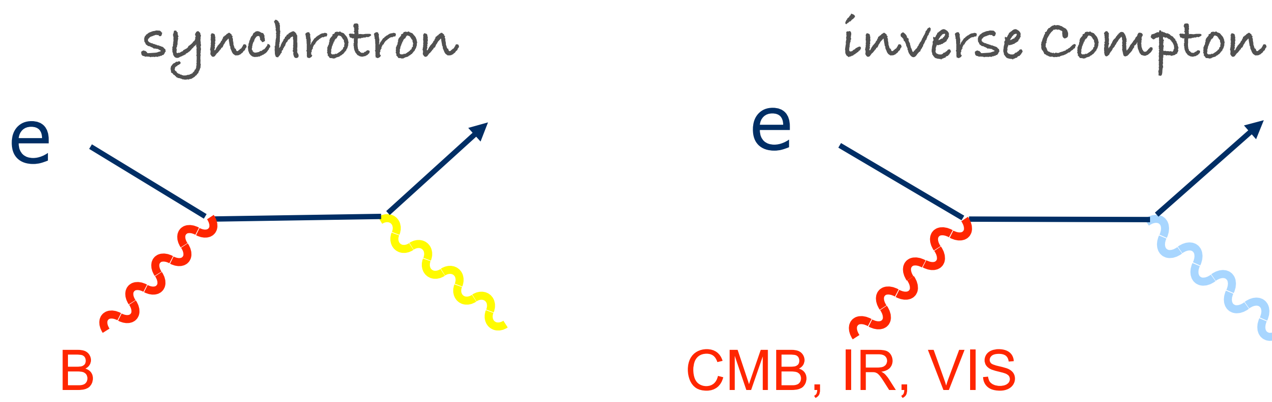
"multi-messenger astrophysics"

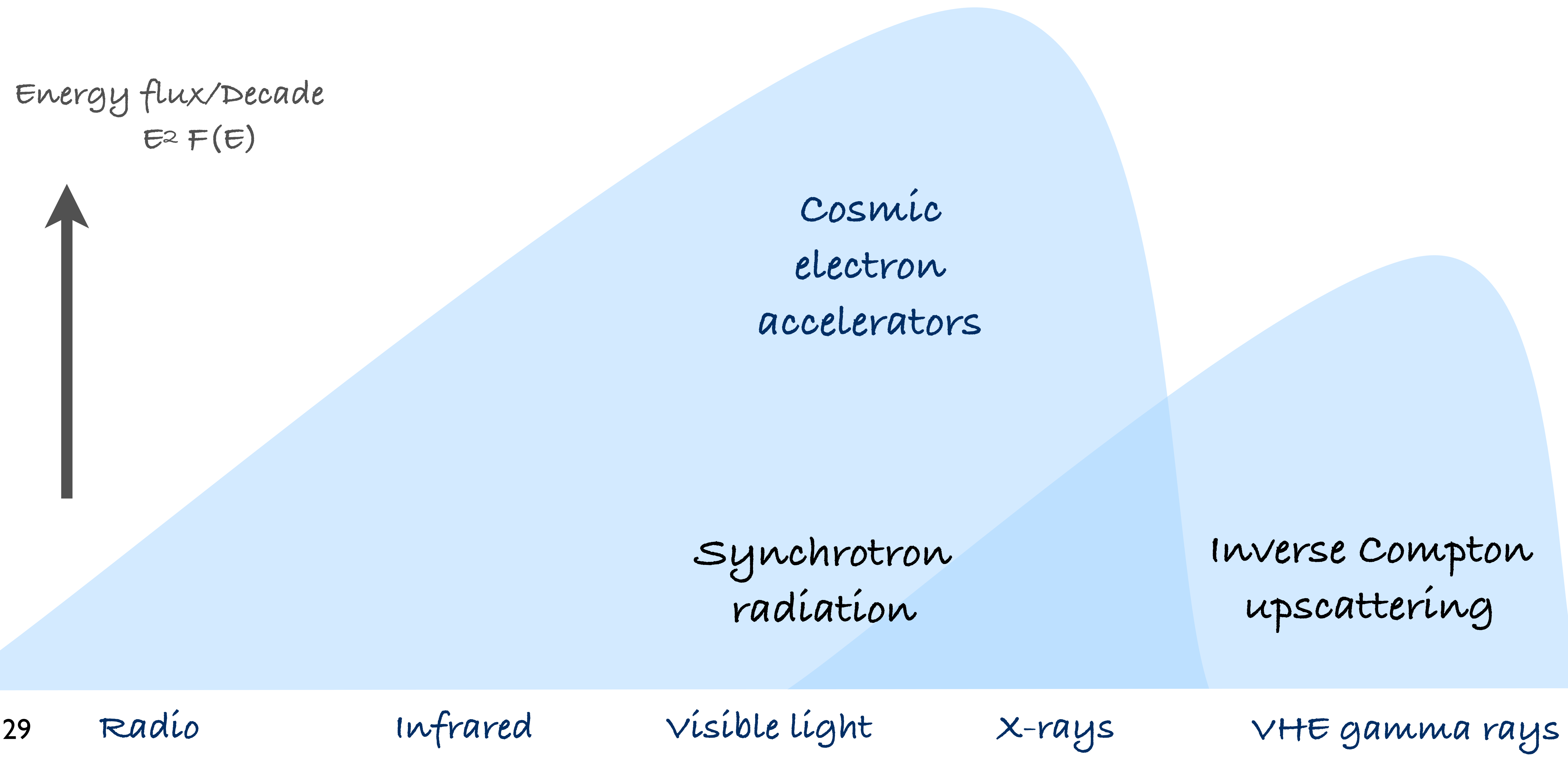
but gamma rays are currently the most "productive" messengers.

γ,ν

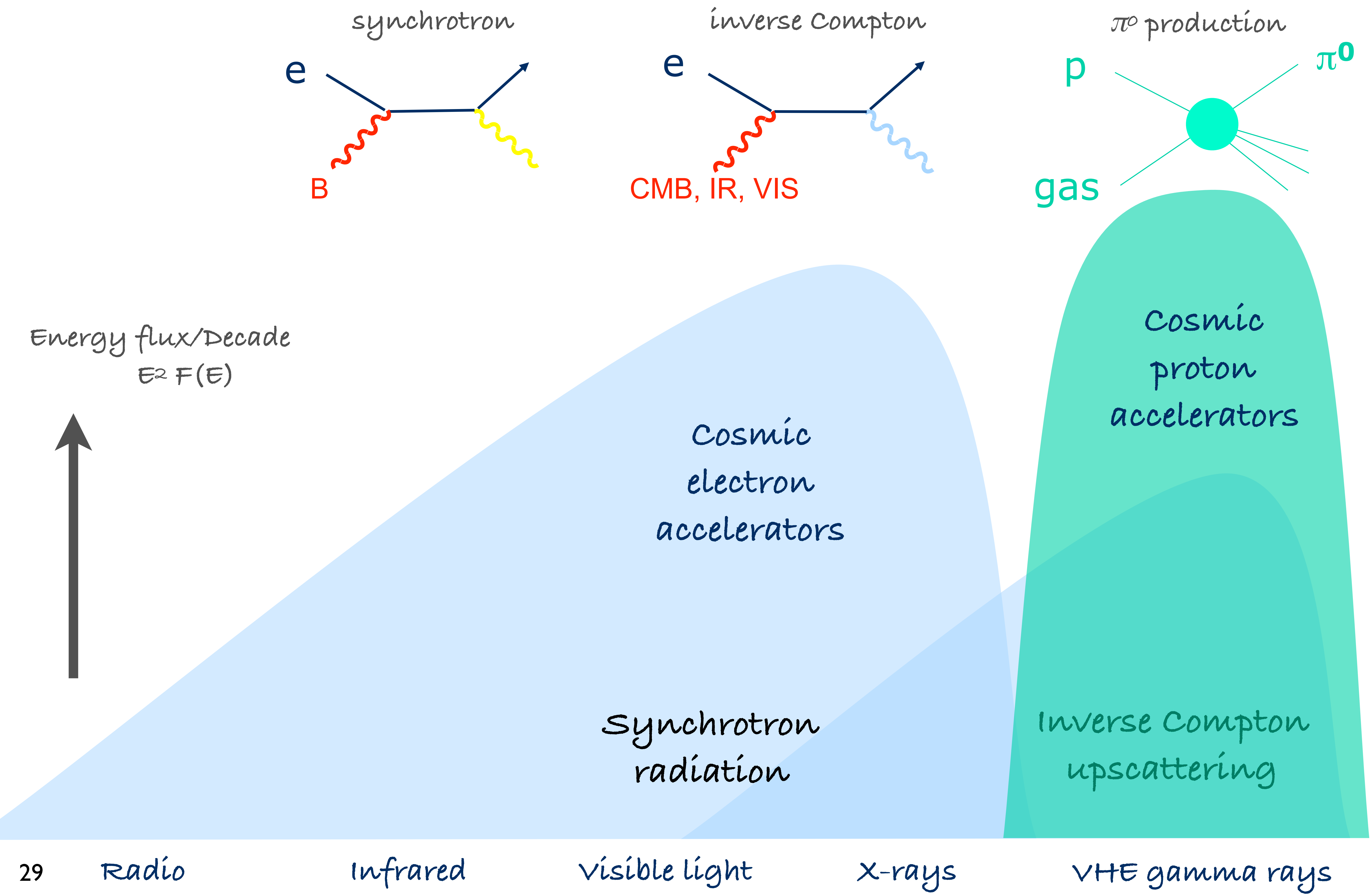
point back to sources (good for astronomy)
but serious backgrounds

Gamma Ray Production





Gamma Ray Production



Recent Experiments

Fermi Satellite

≈ 1 m² 2.5 sr
30 MeV - 300 GeV

Fermi - LAT

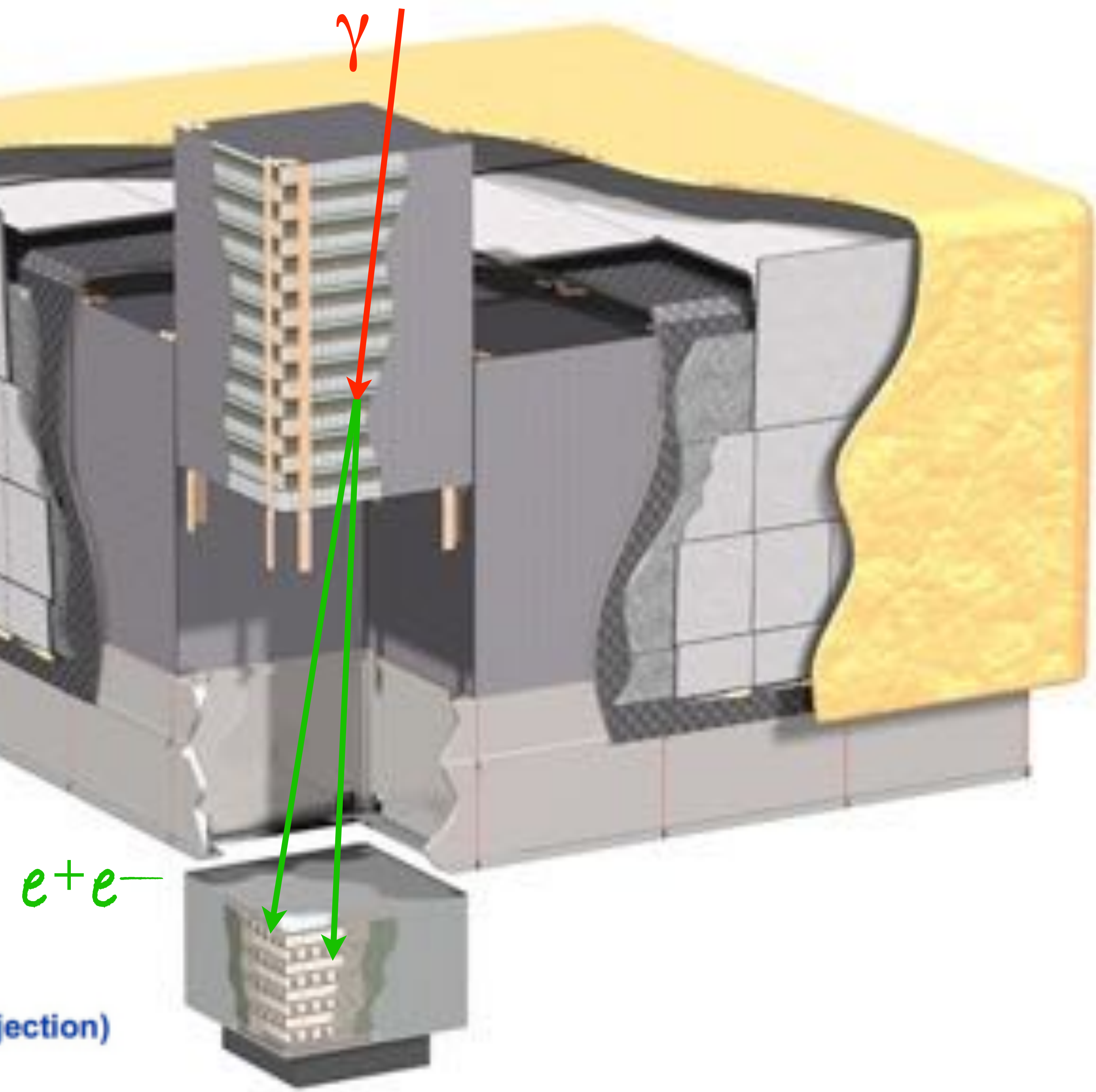
large angle
telescope

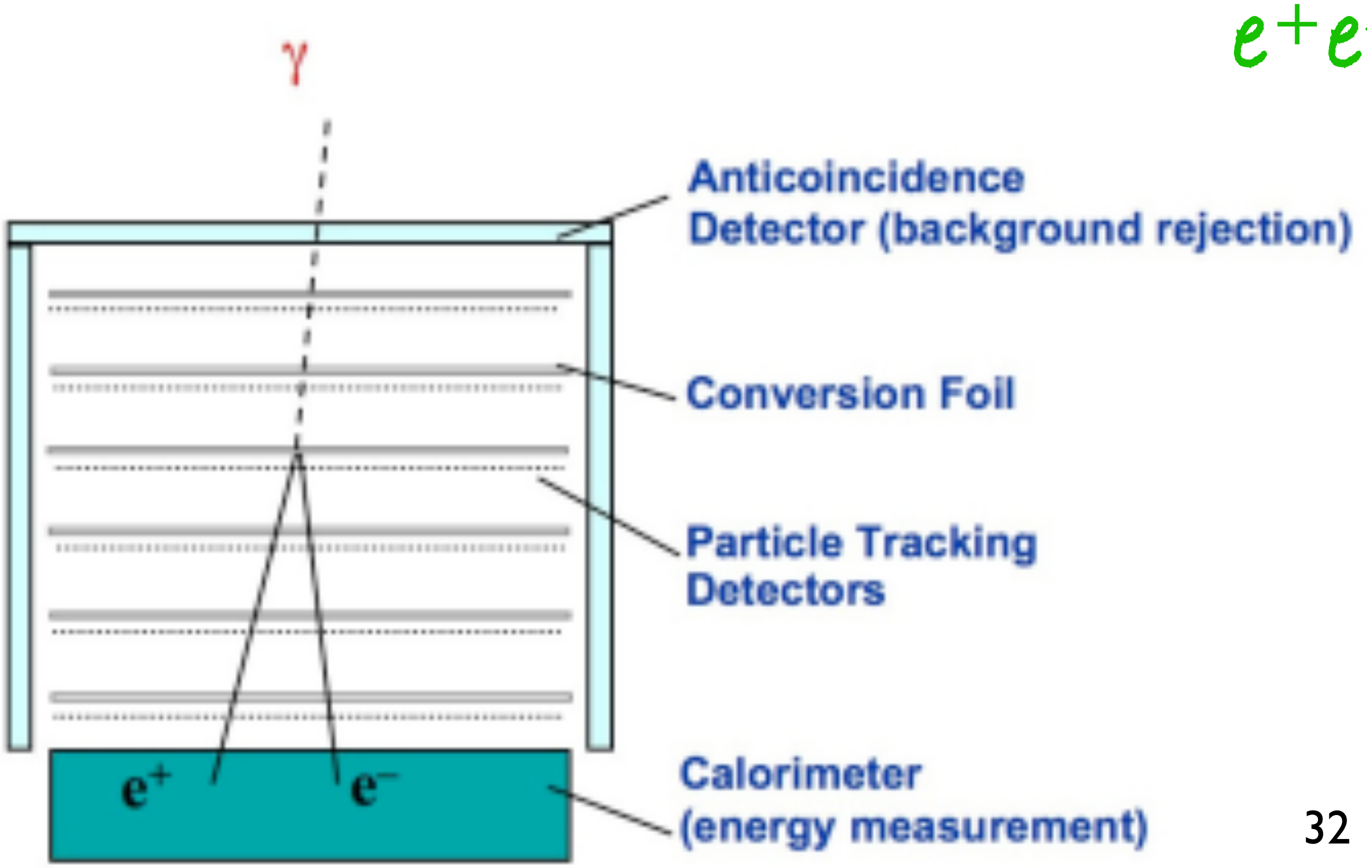
pair-conversion telescope with:

precision trackers
- 18 layers tungsten converters and x, y silicon strip detectors.

calorimeter
- 96 CsI(Tl) crystals in an 8 layer hodoscope (depth: 8.6 X_0)

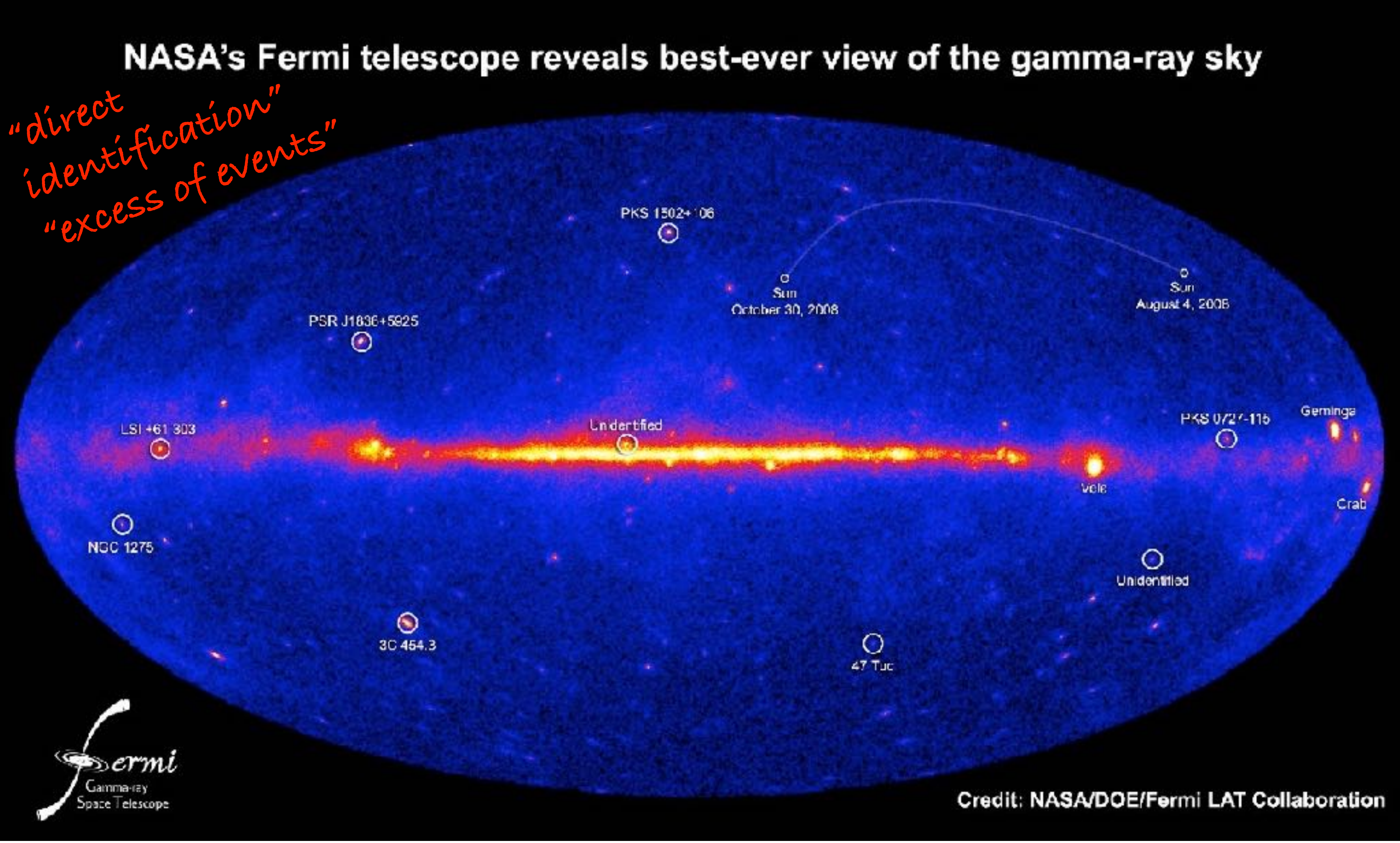
4x4 modules covered by anti-coincidence shield





≈ 1 m² 2.5 sr

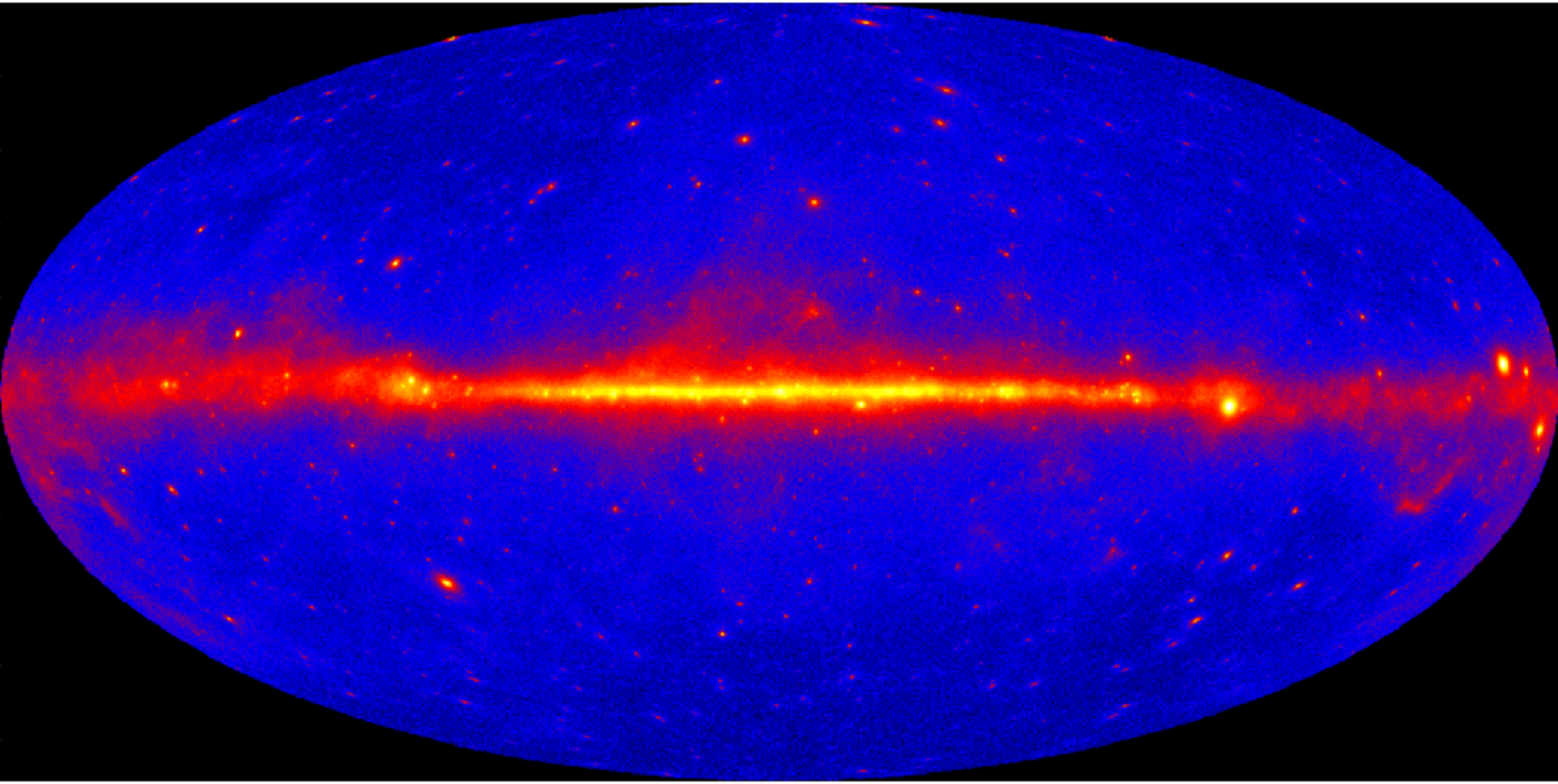
near-perfect rejection of charged primaries



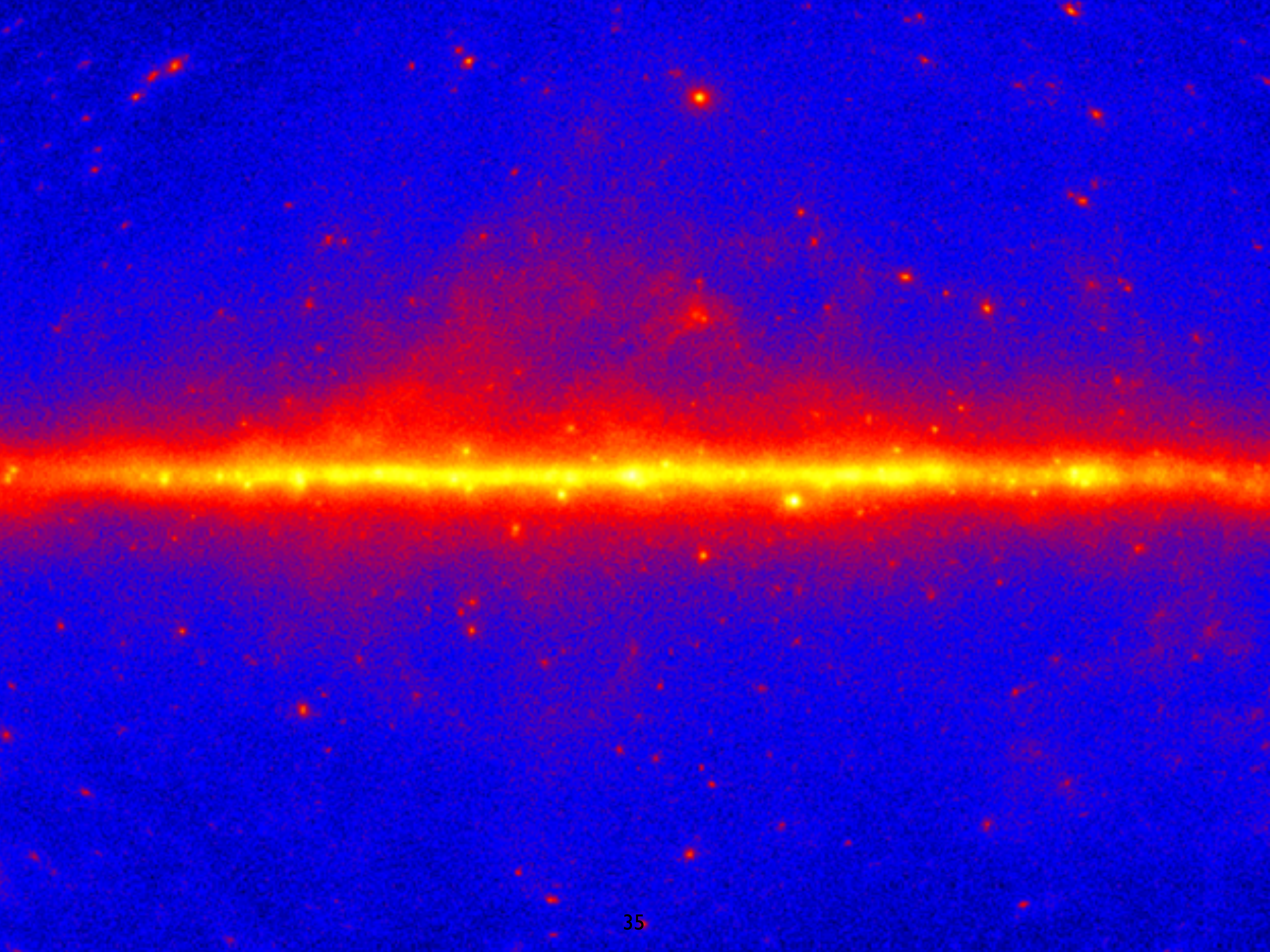
Satellite experiment: 100 MeV - 100 GeV

point sources, extended sources and diffuse emission, ...

Fermi-LAT: 2-year catalog

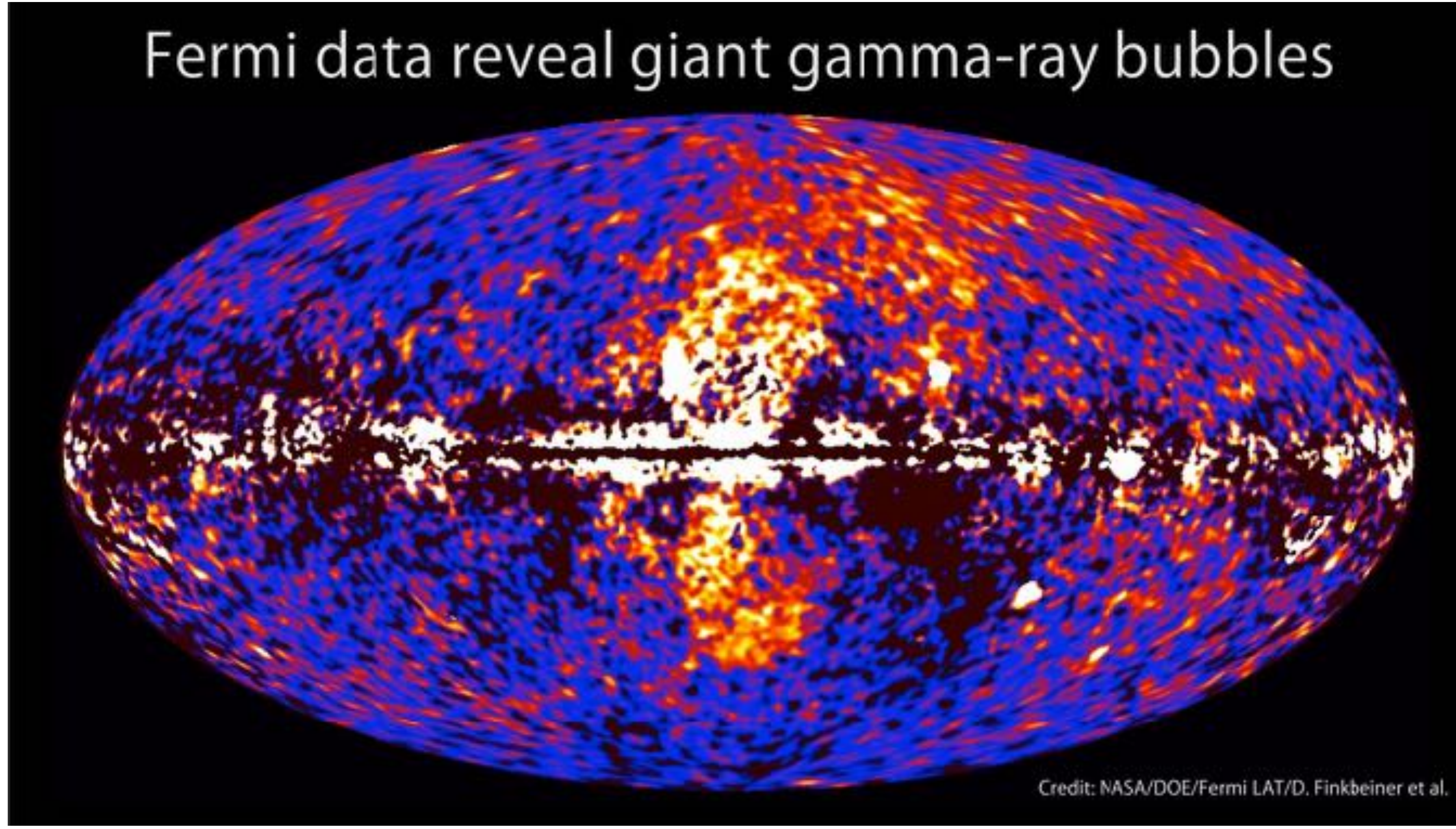


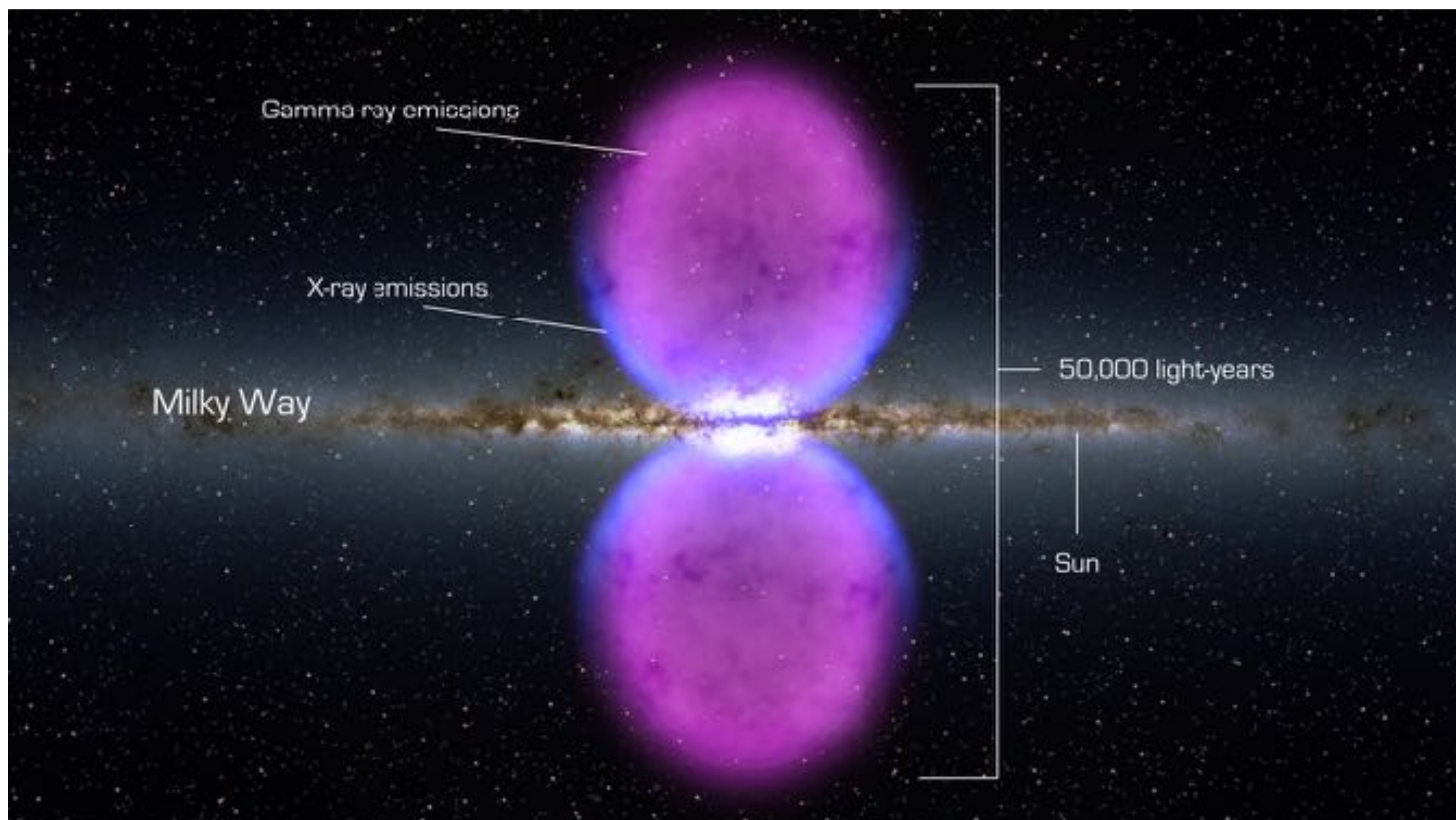
Satellite experiment: 100 MeV - 100 GeV
point sources, extended sources and diffuse emission, ...



The Fermi Bubble

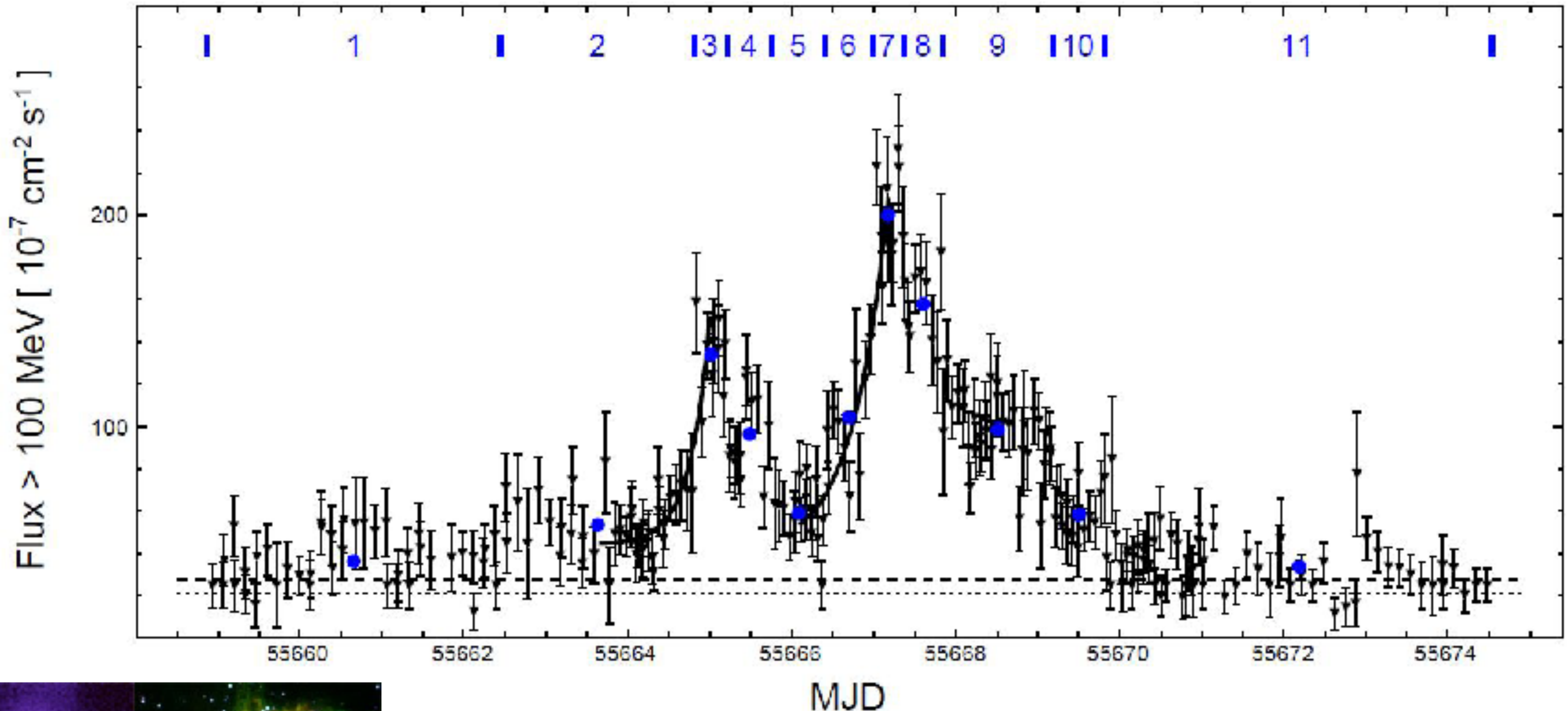
... a remnant of recent activity of our galaxy ?

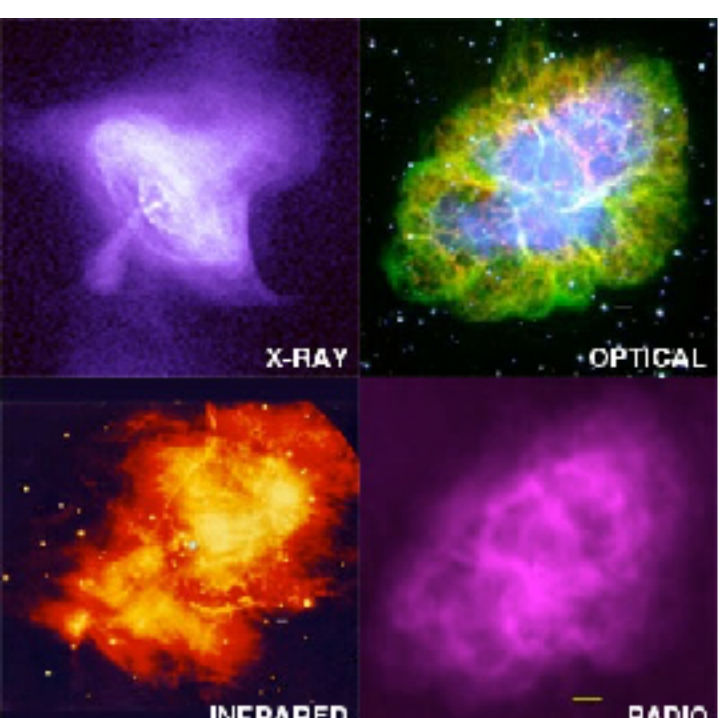


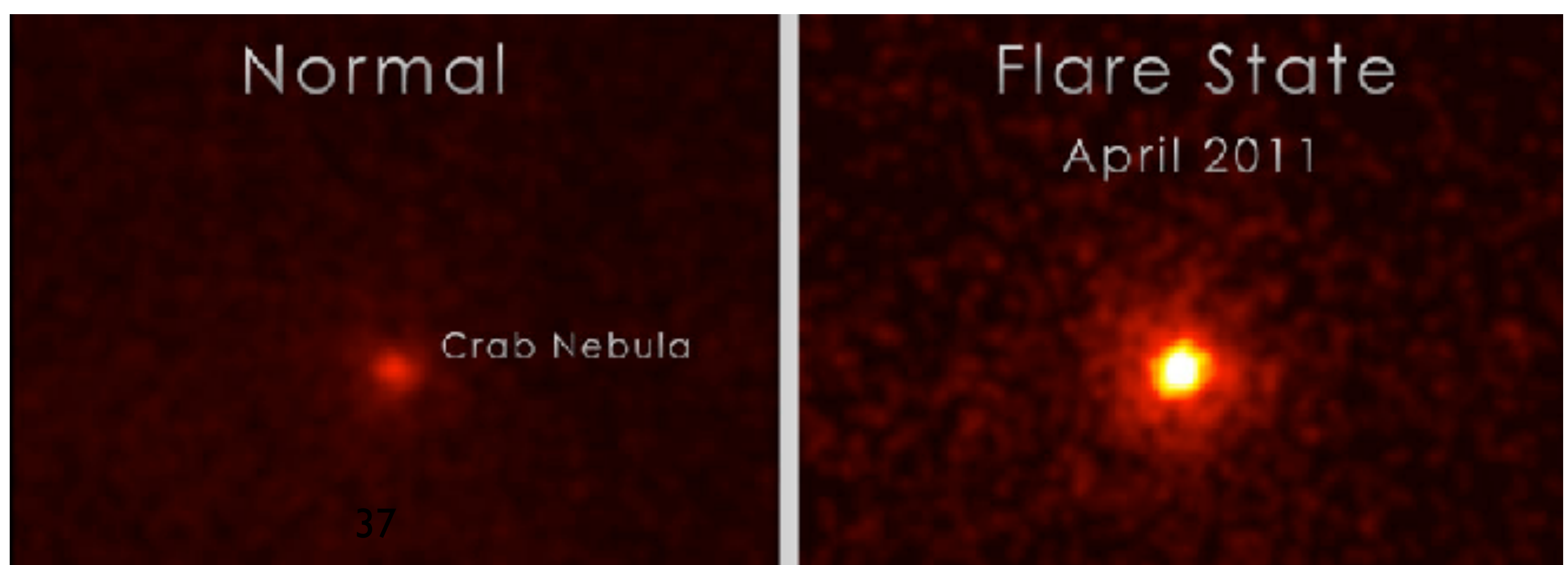


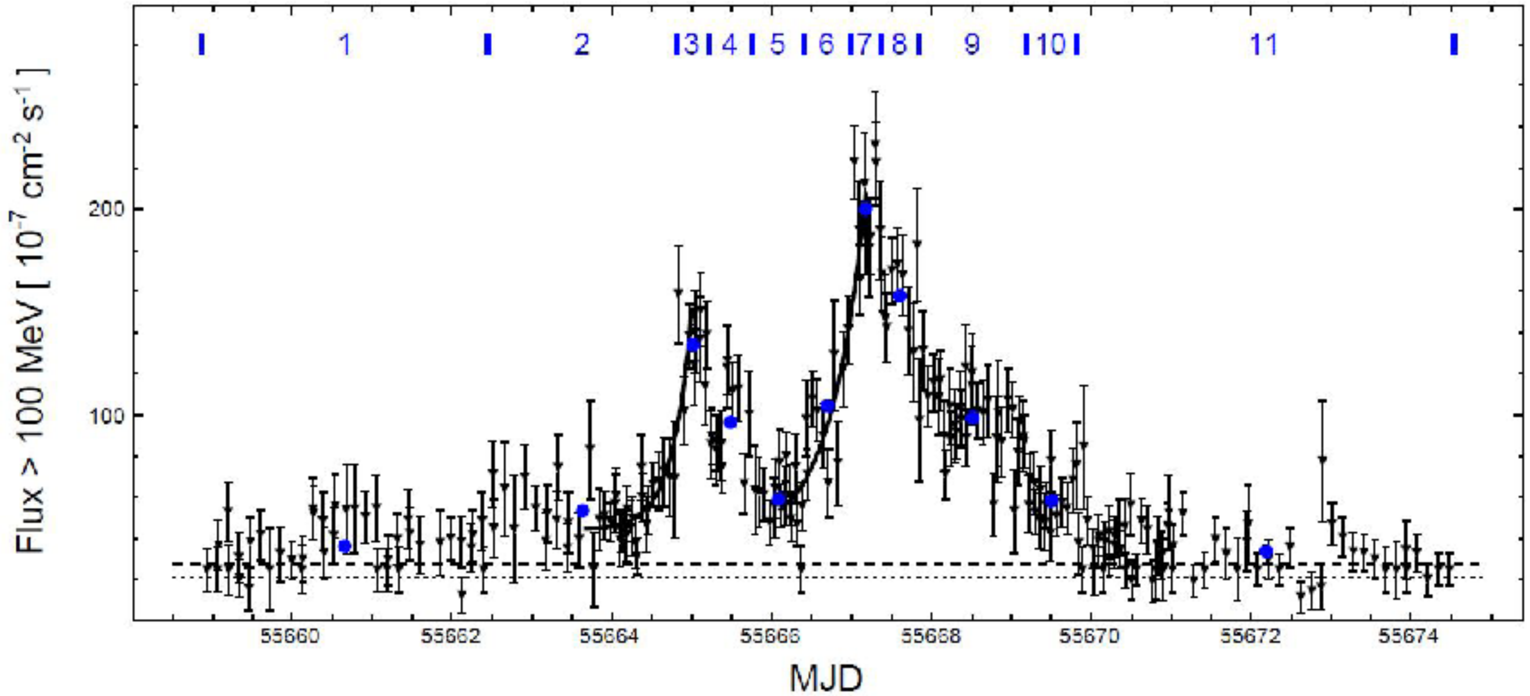
Major gamma-ray flare from Crab Nebula (April 2011)

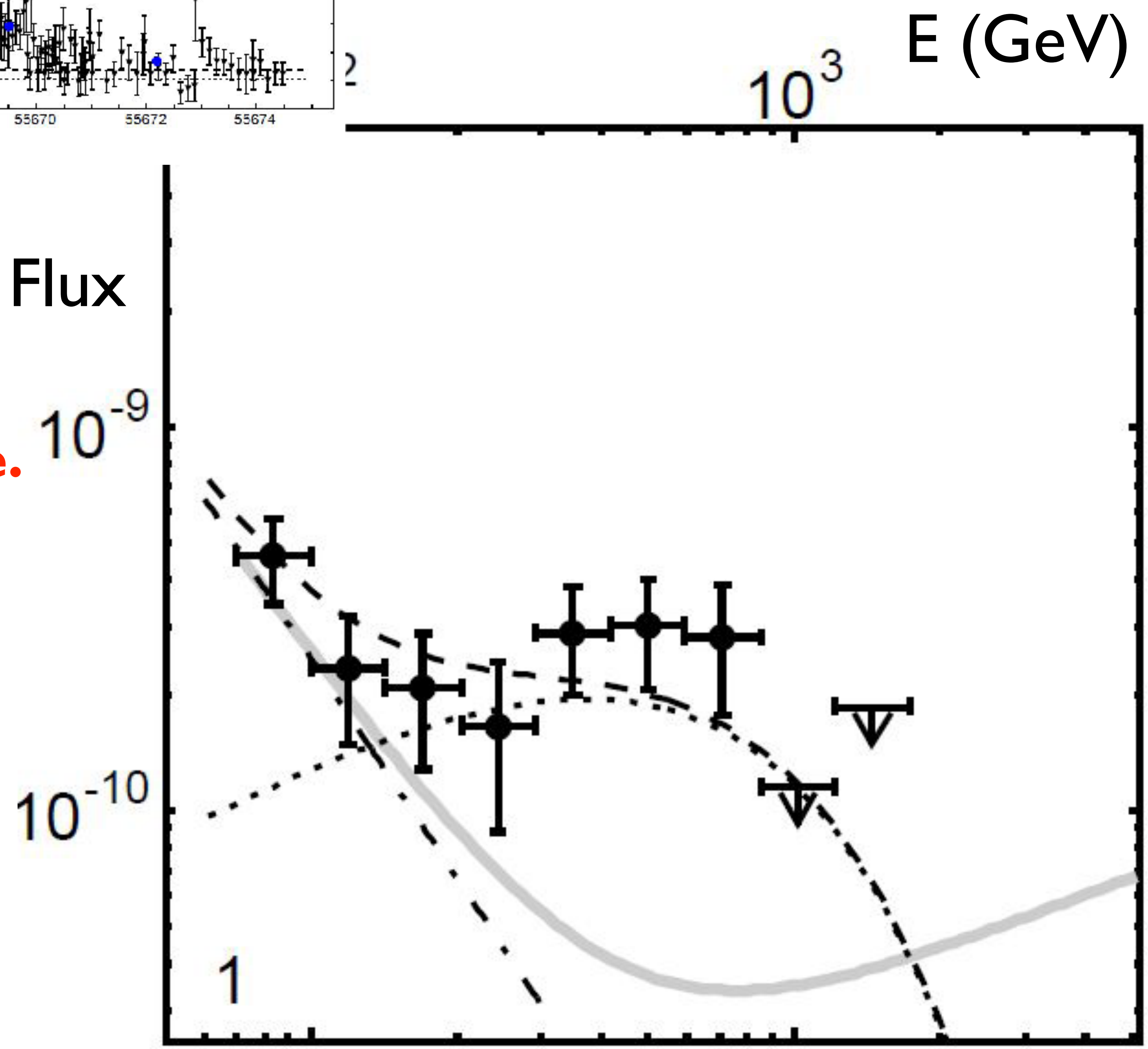
Crab was always seen as the "standard candle"



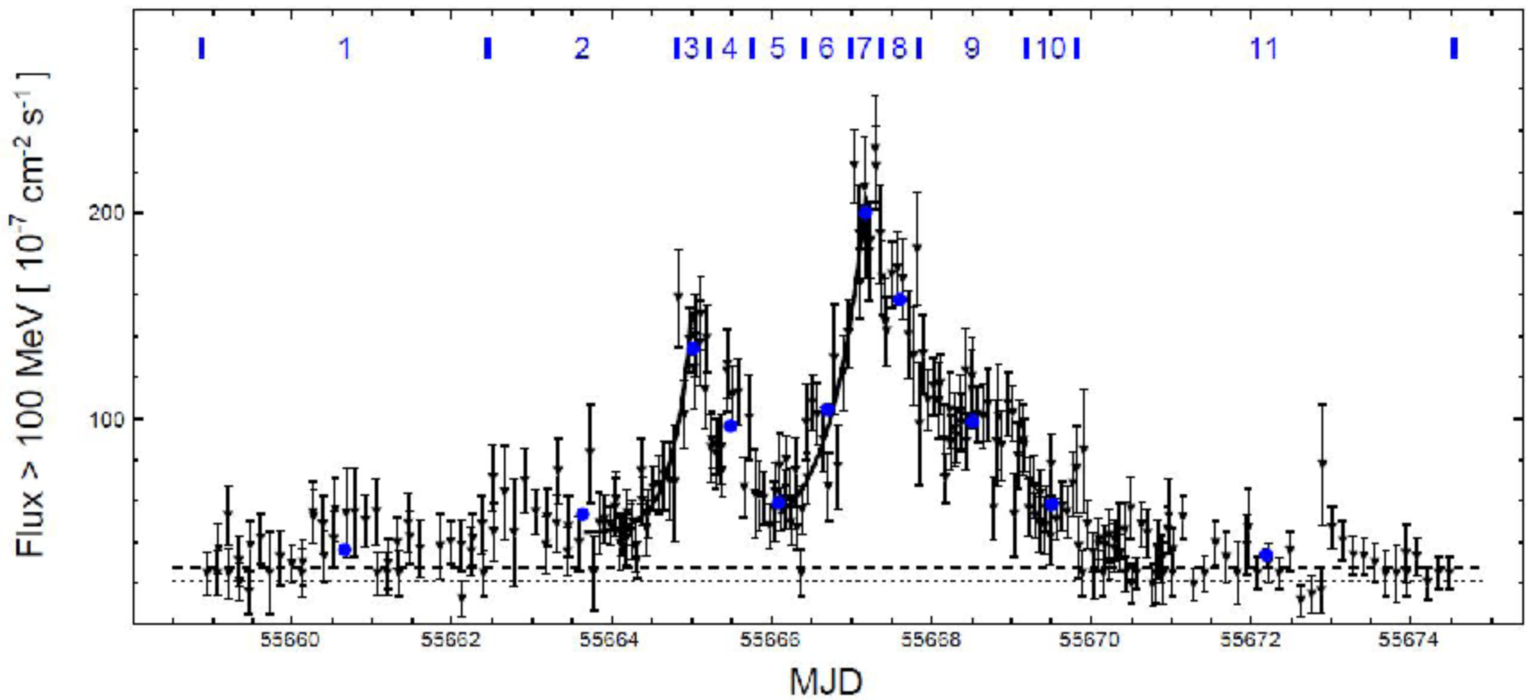


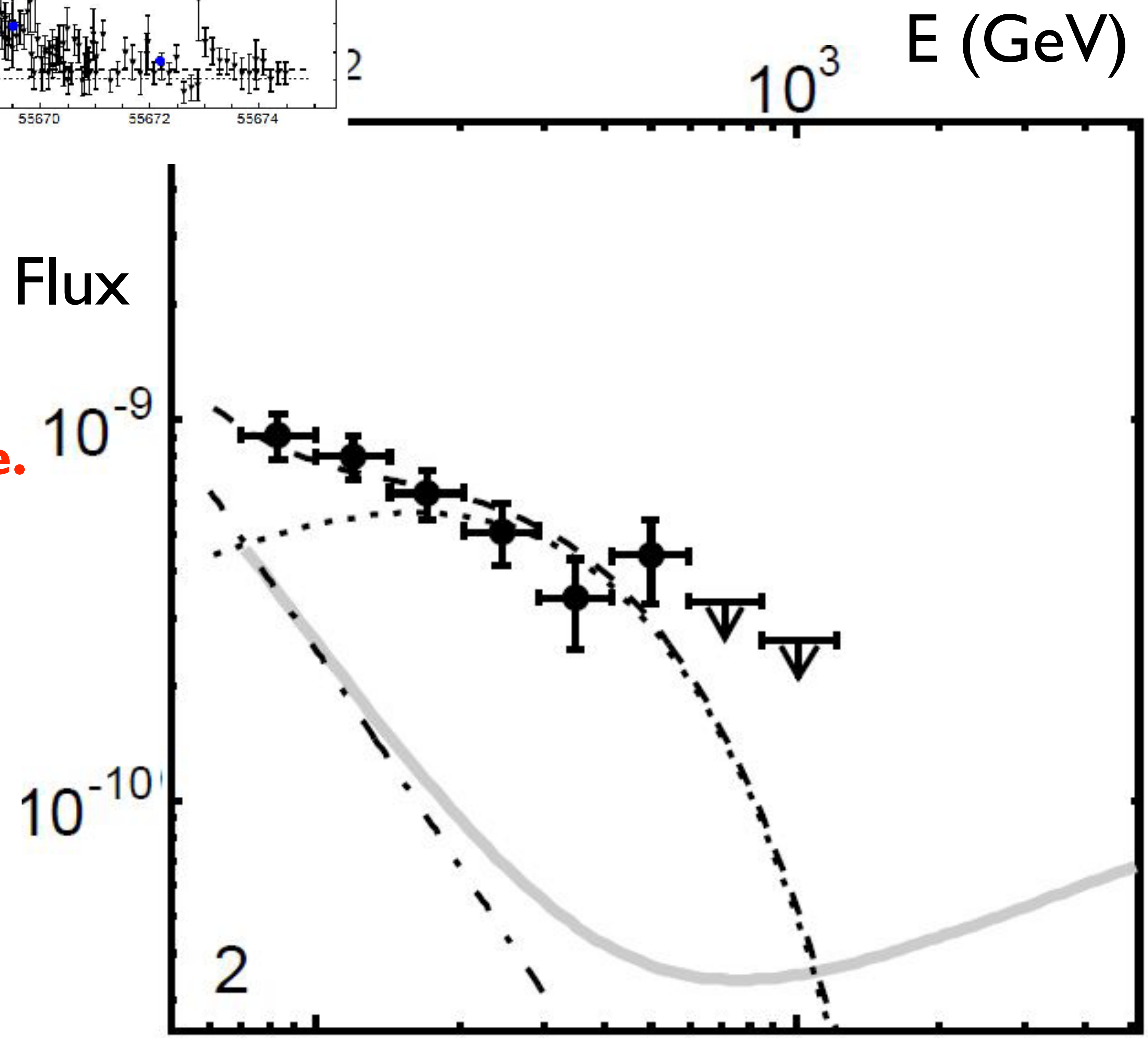






Spectrum varies with time.
Allows study of the
"dynamic processes"
of particle acceleration.





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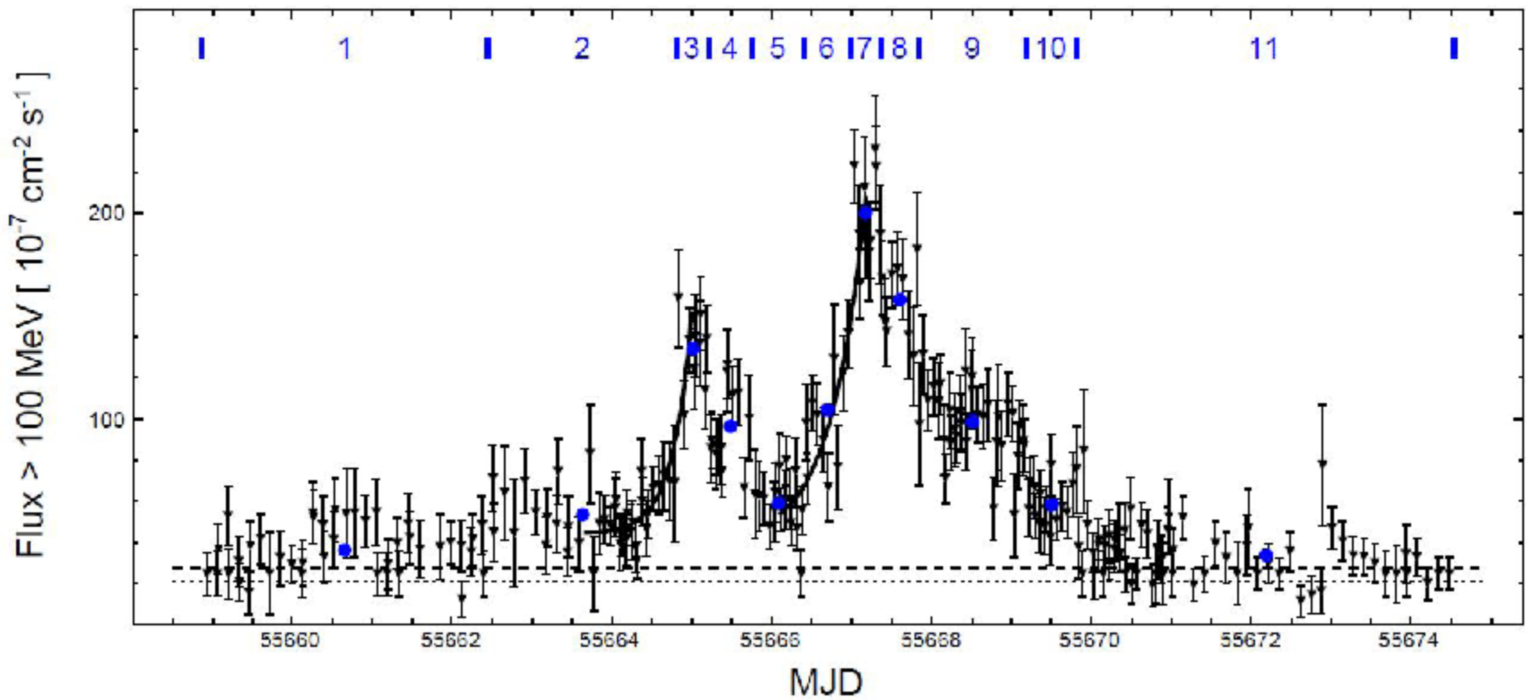

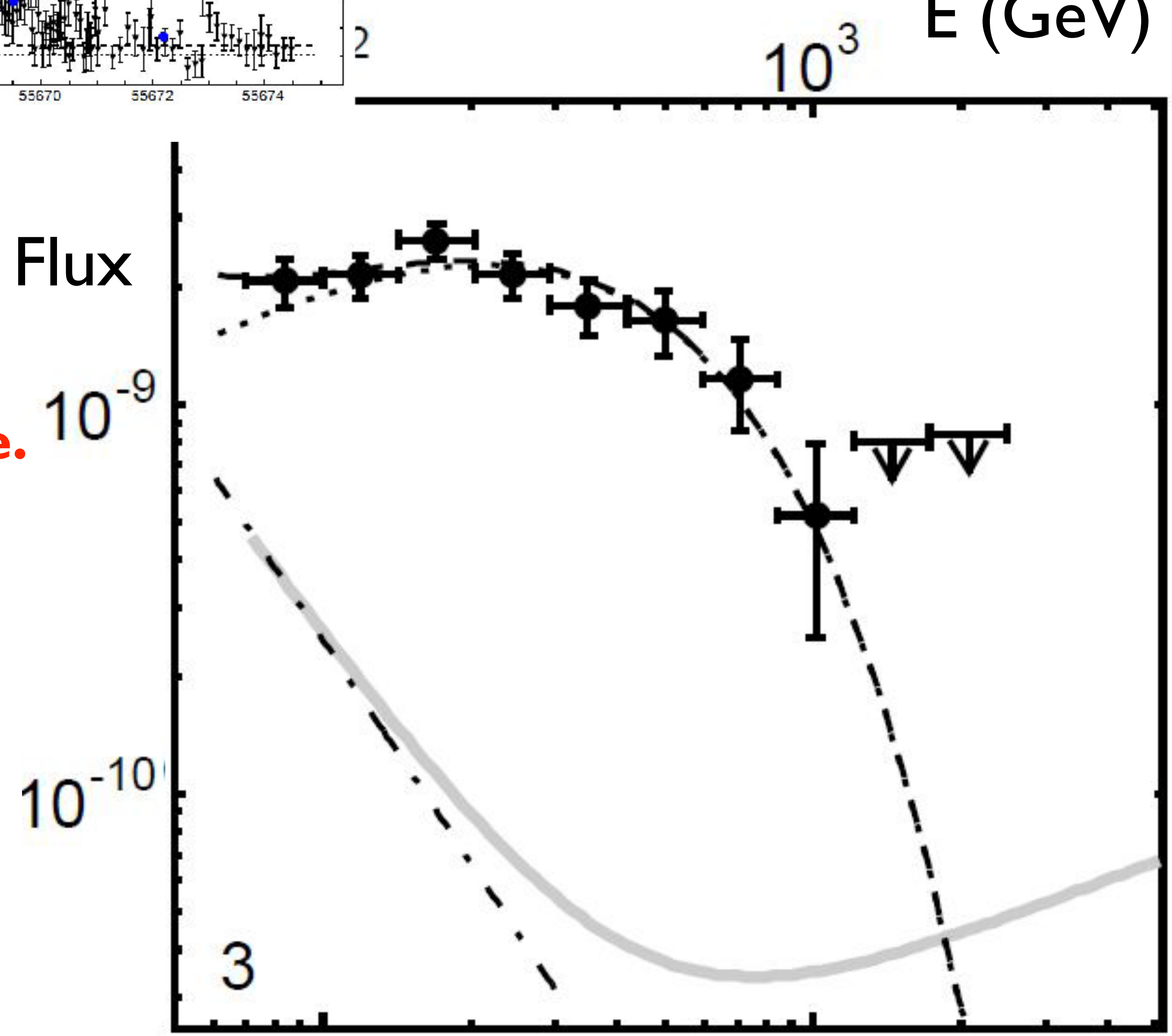

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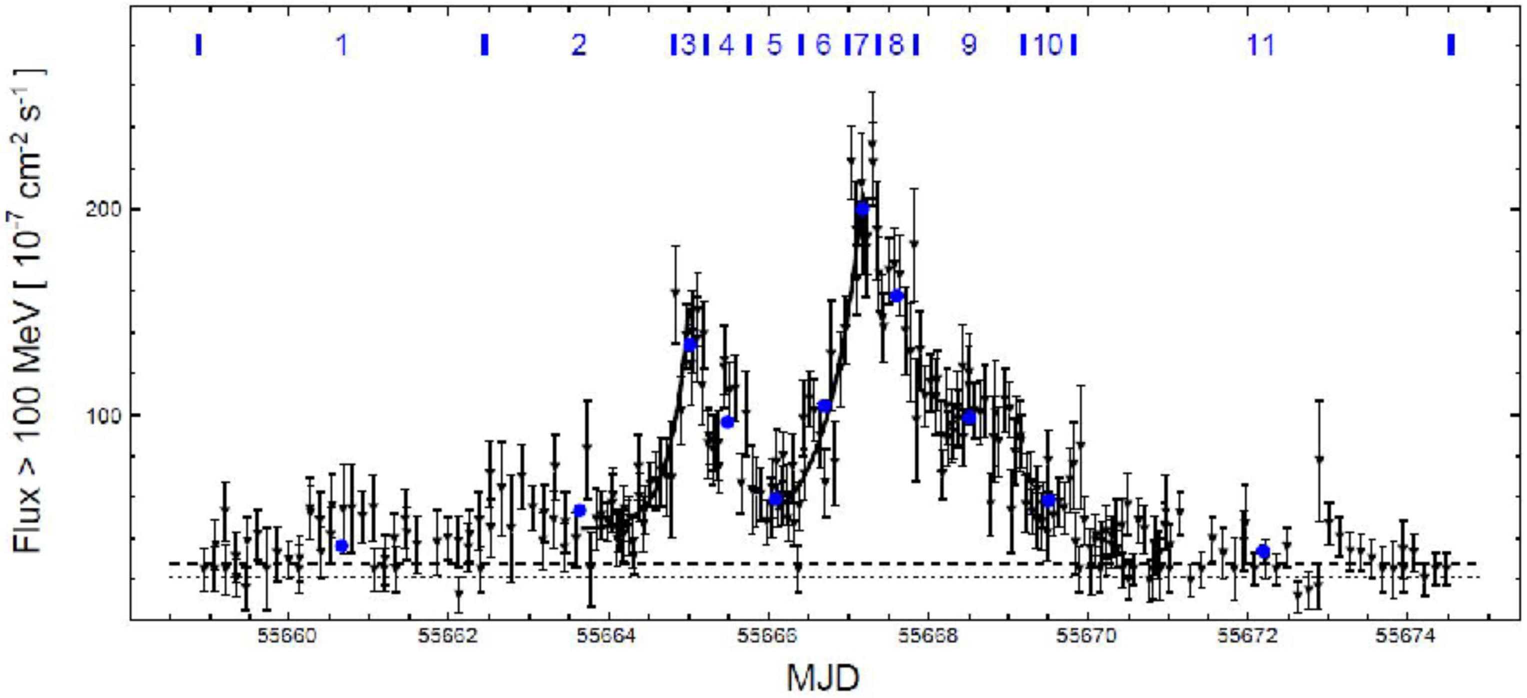

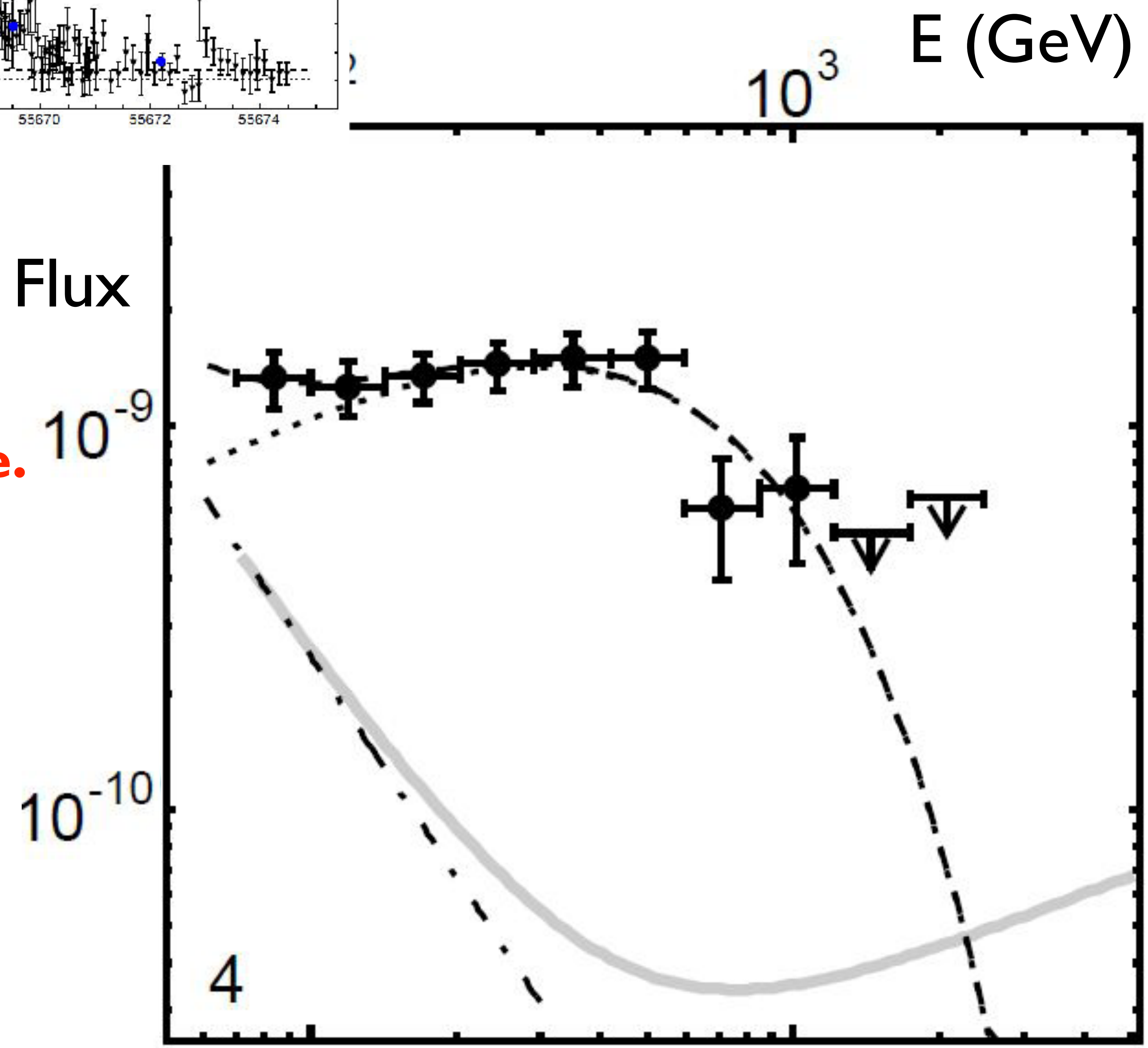

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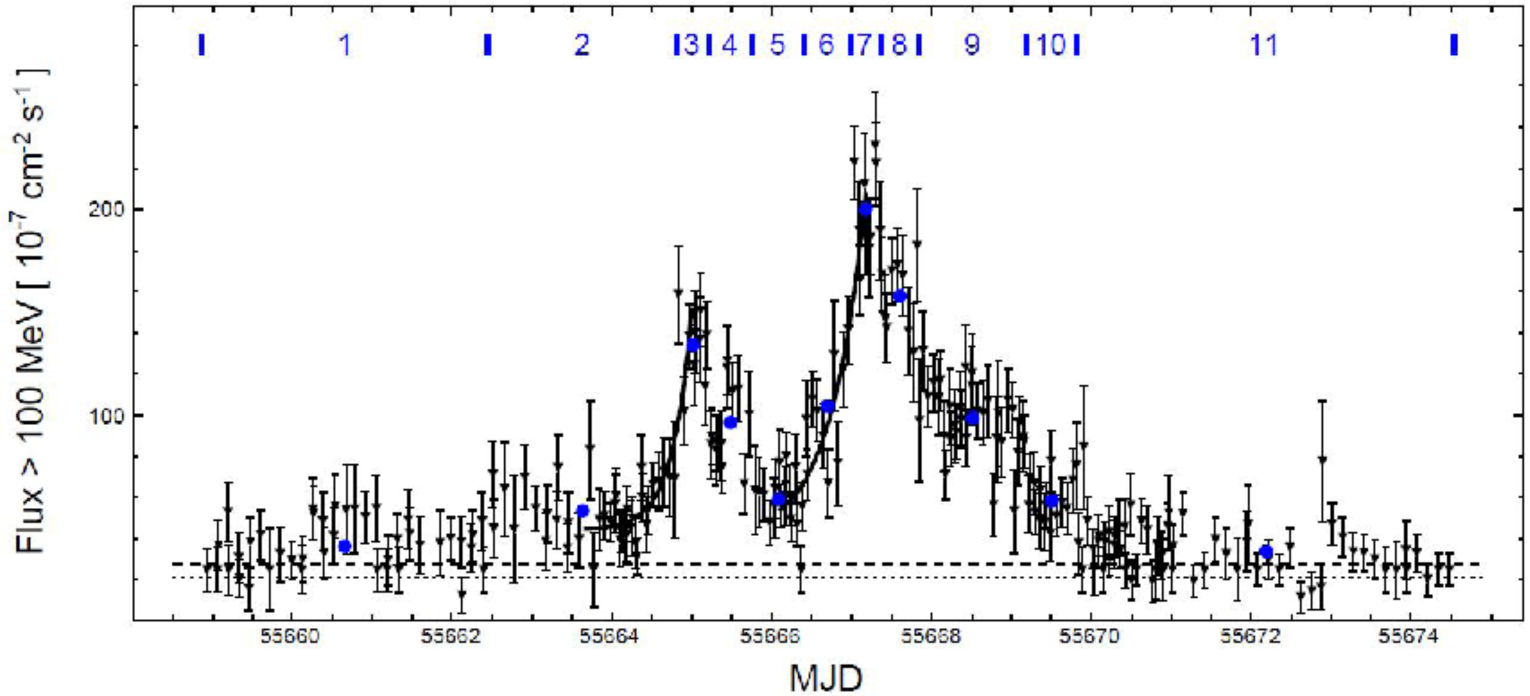

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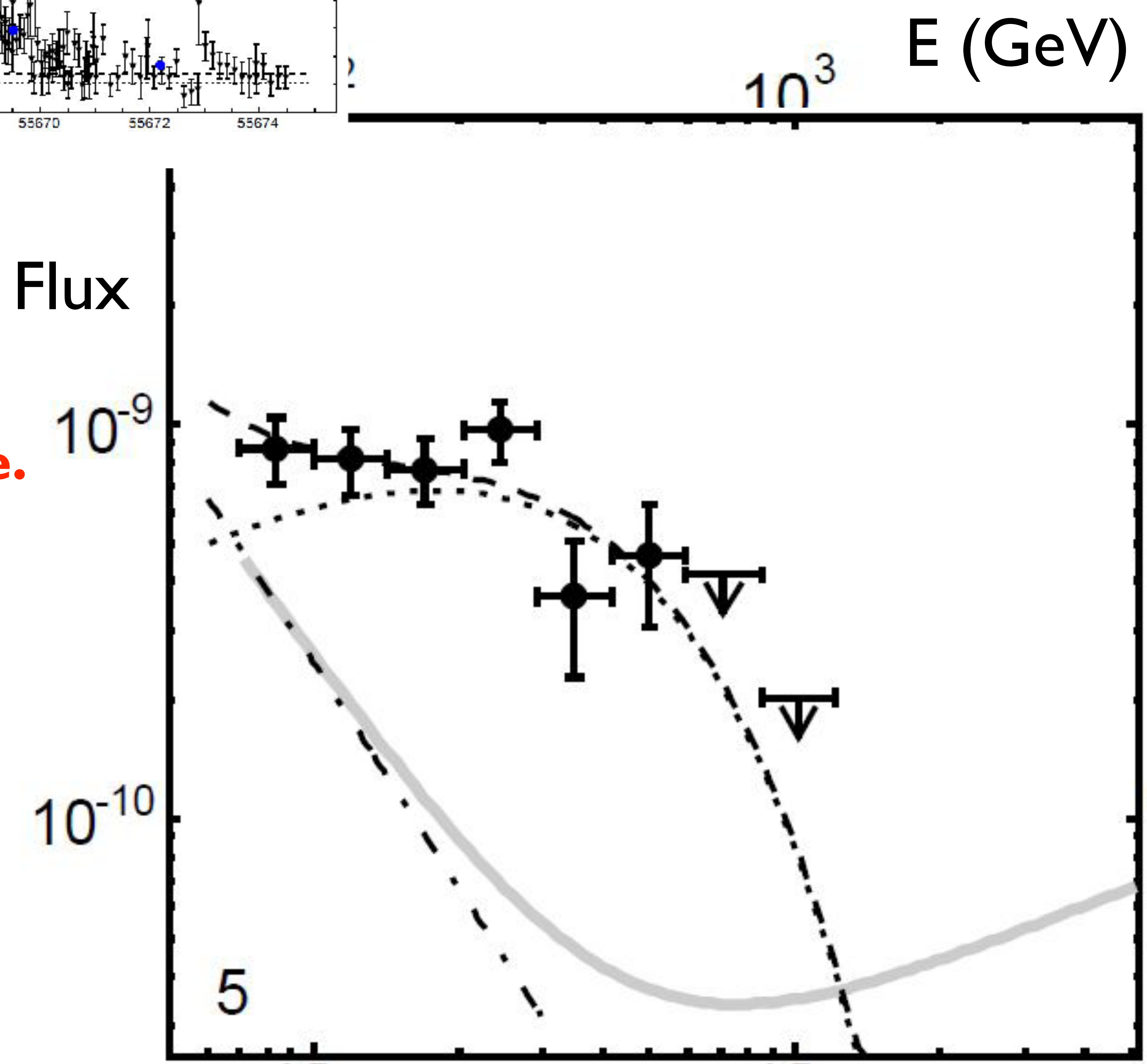

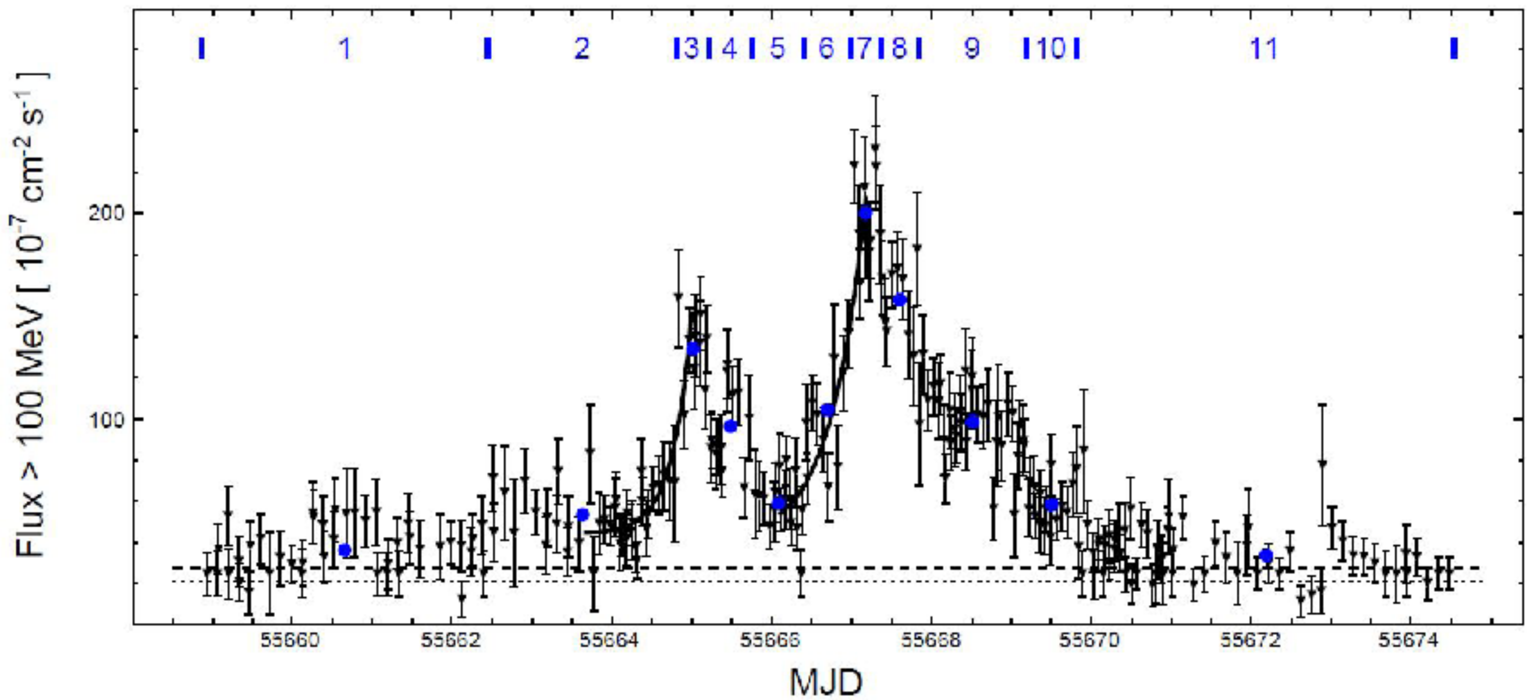

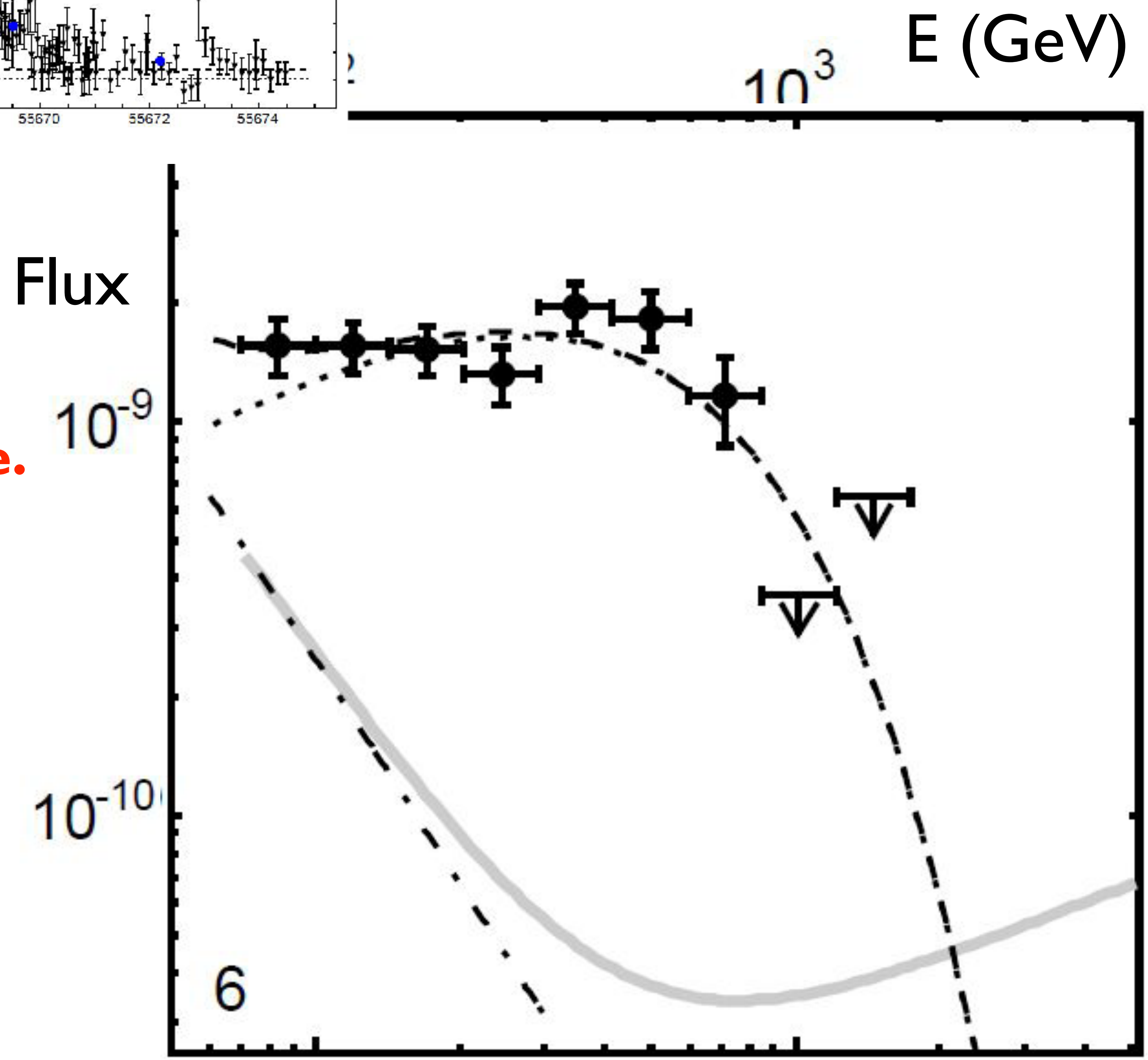

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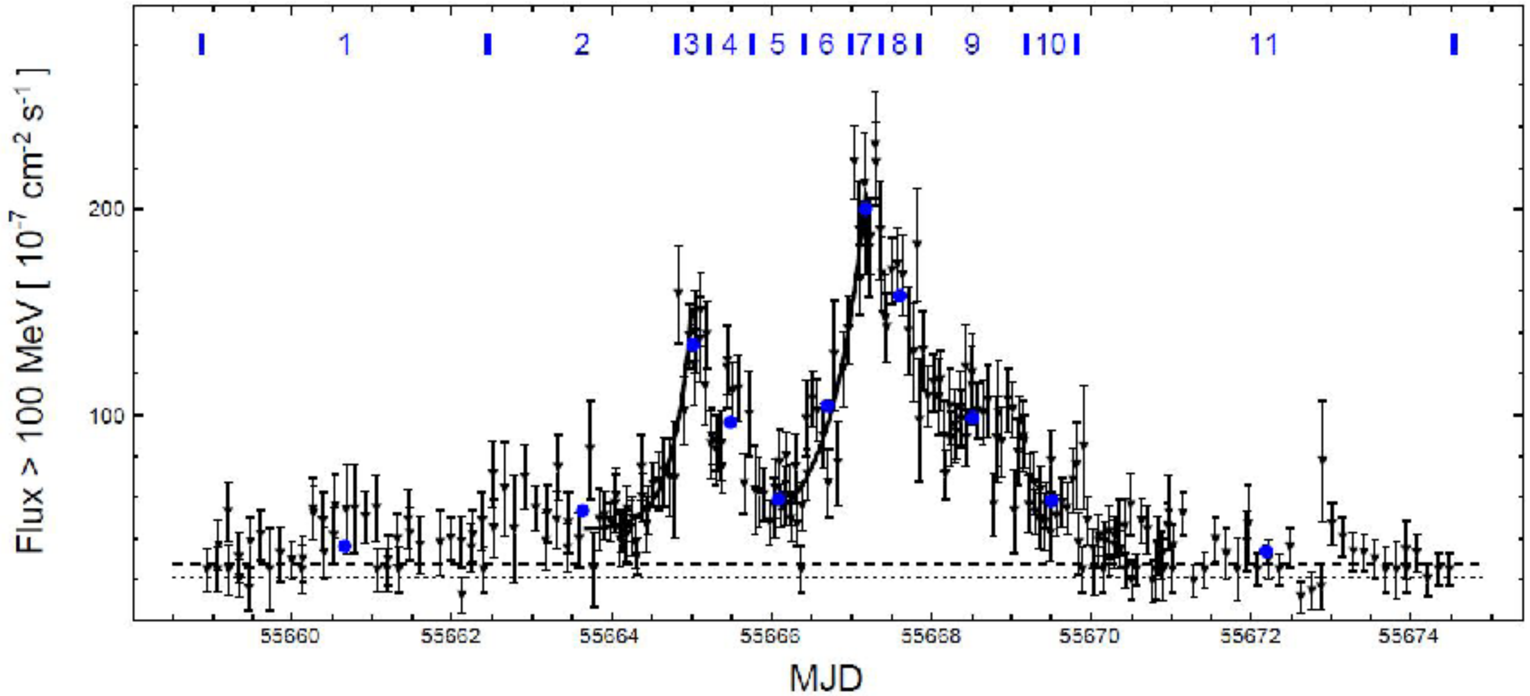

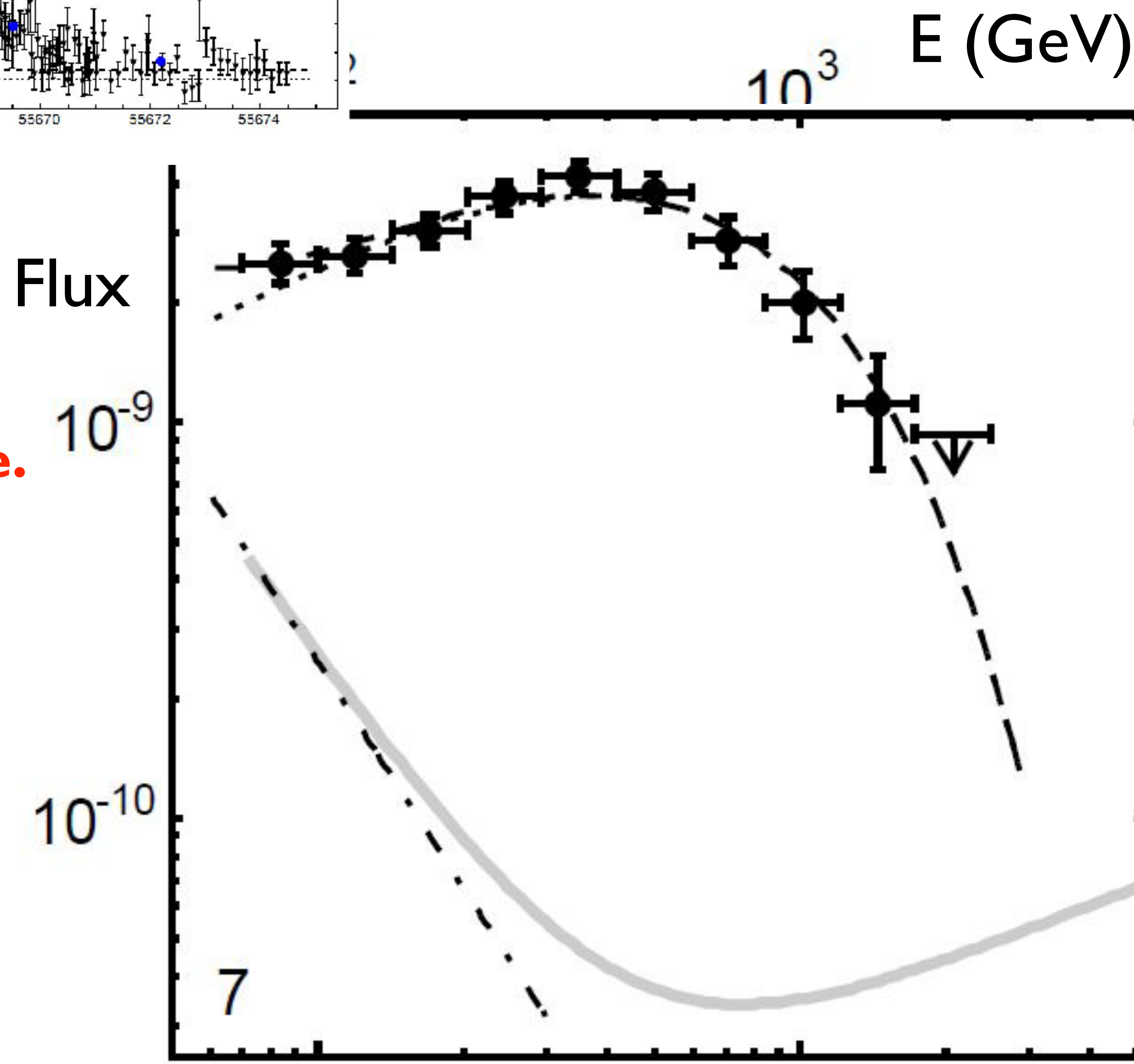

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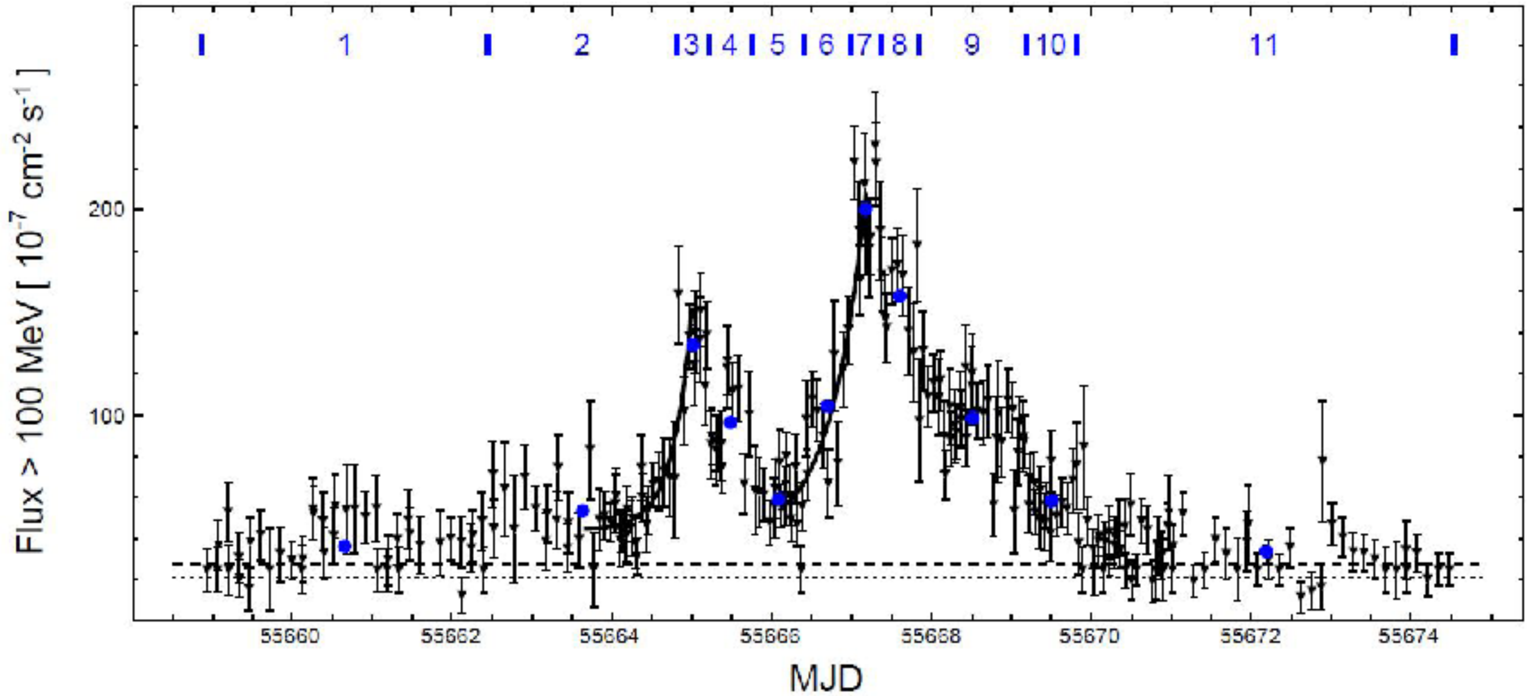

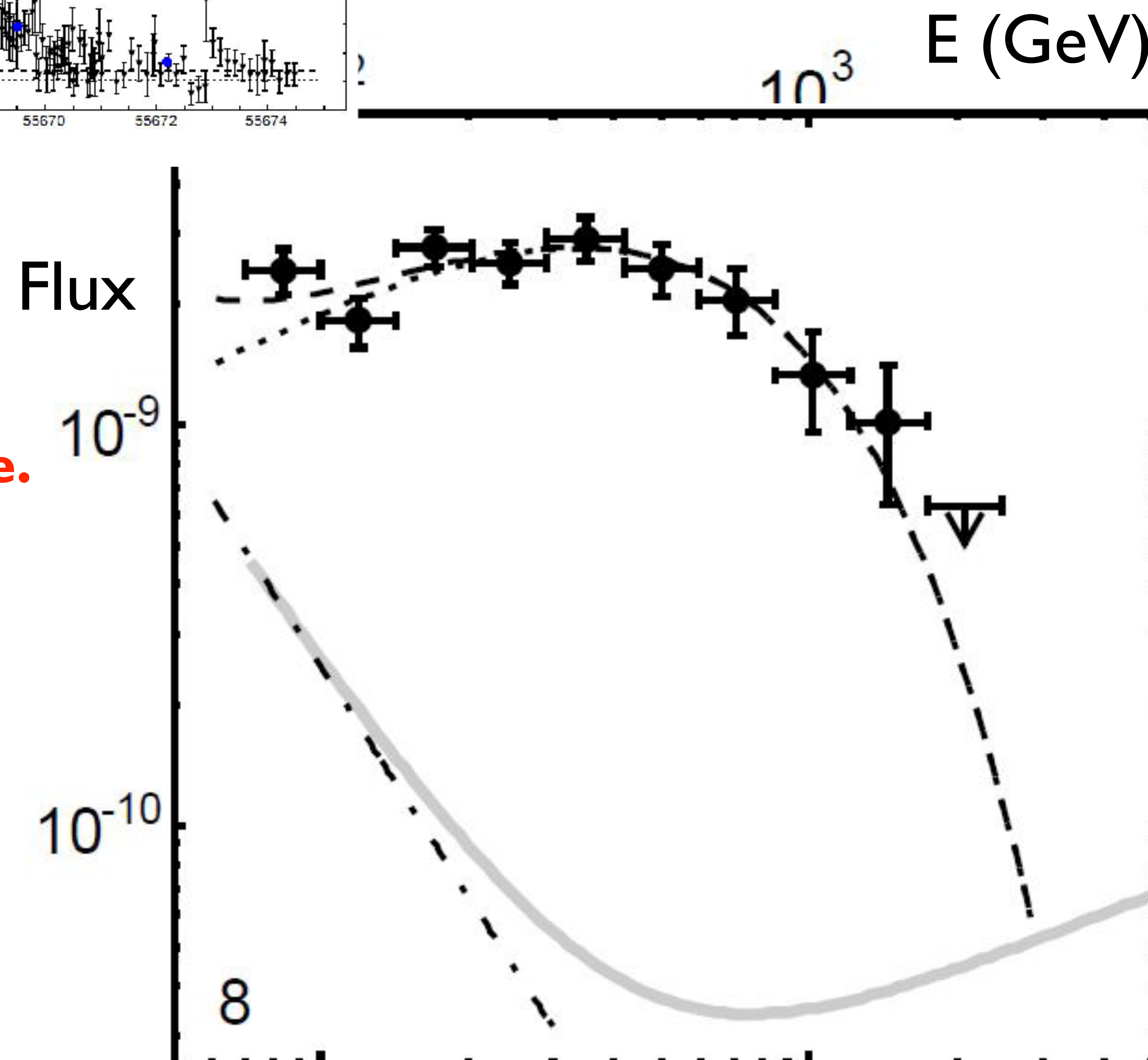

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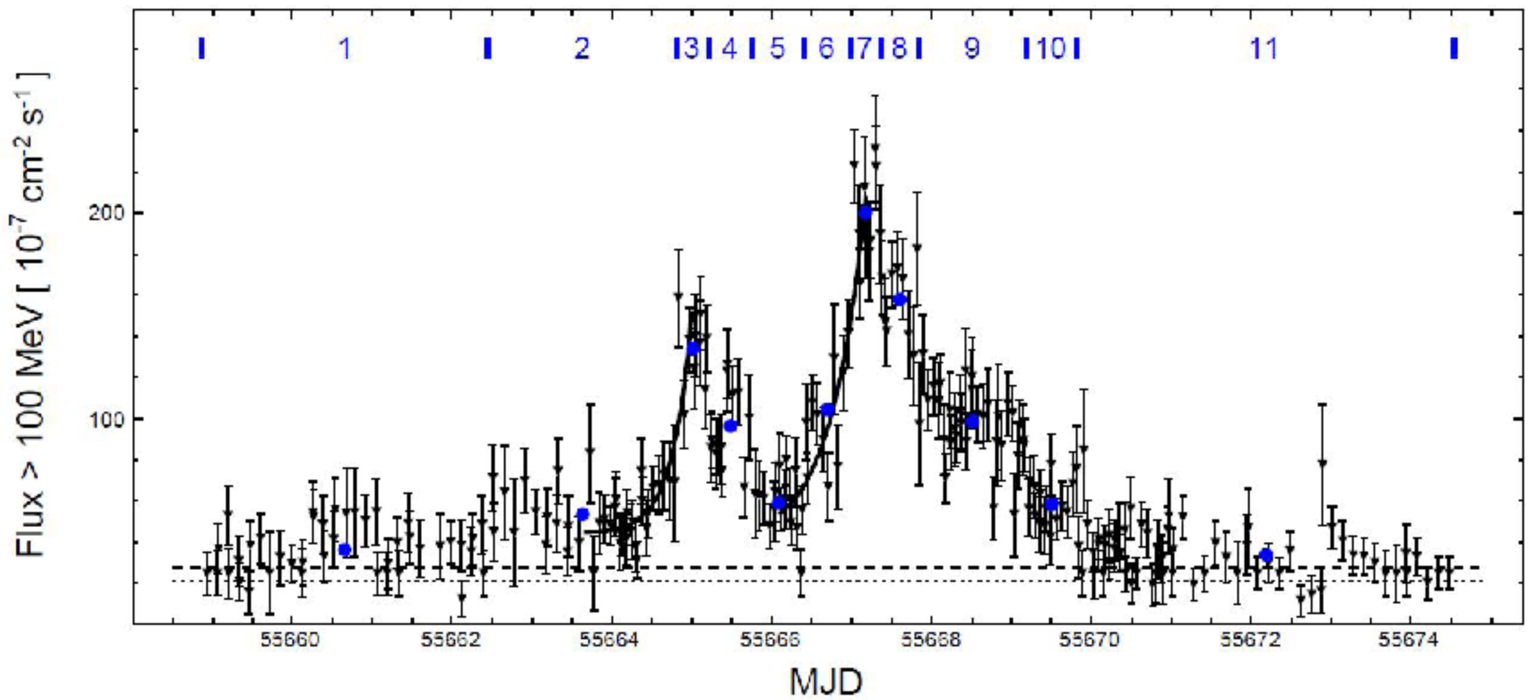

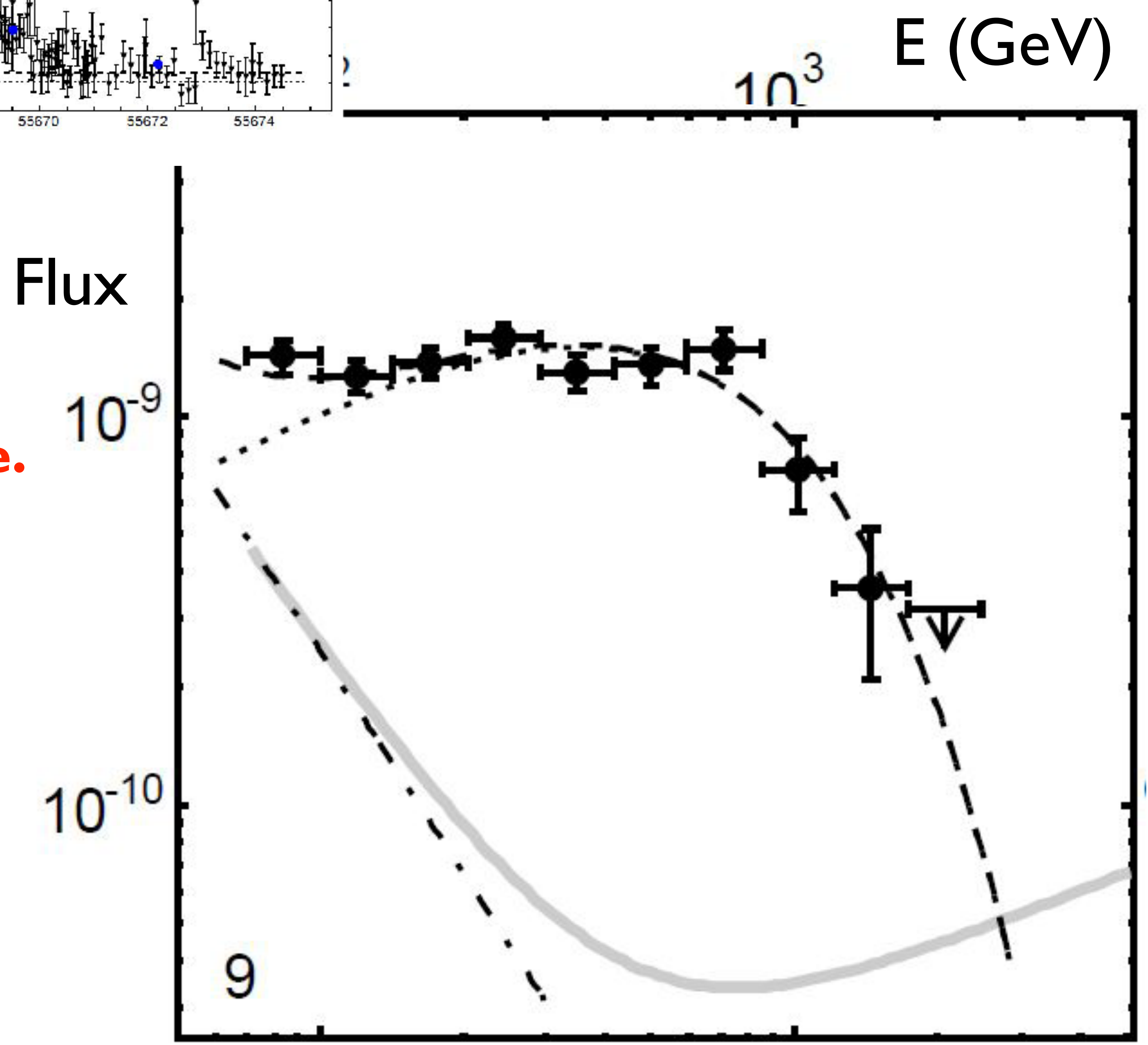

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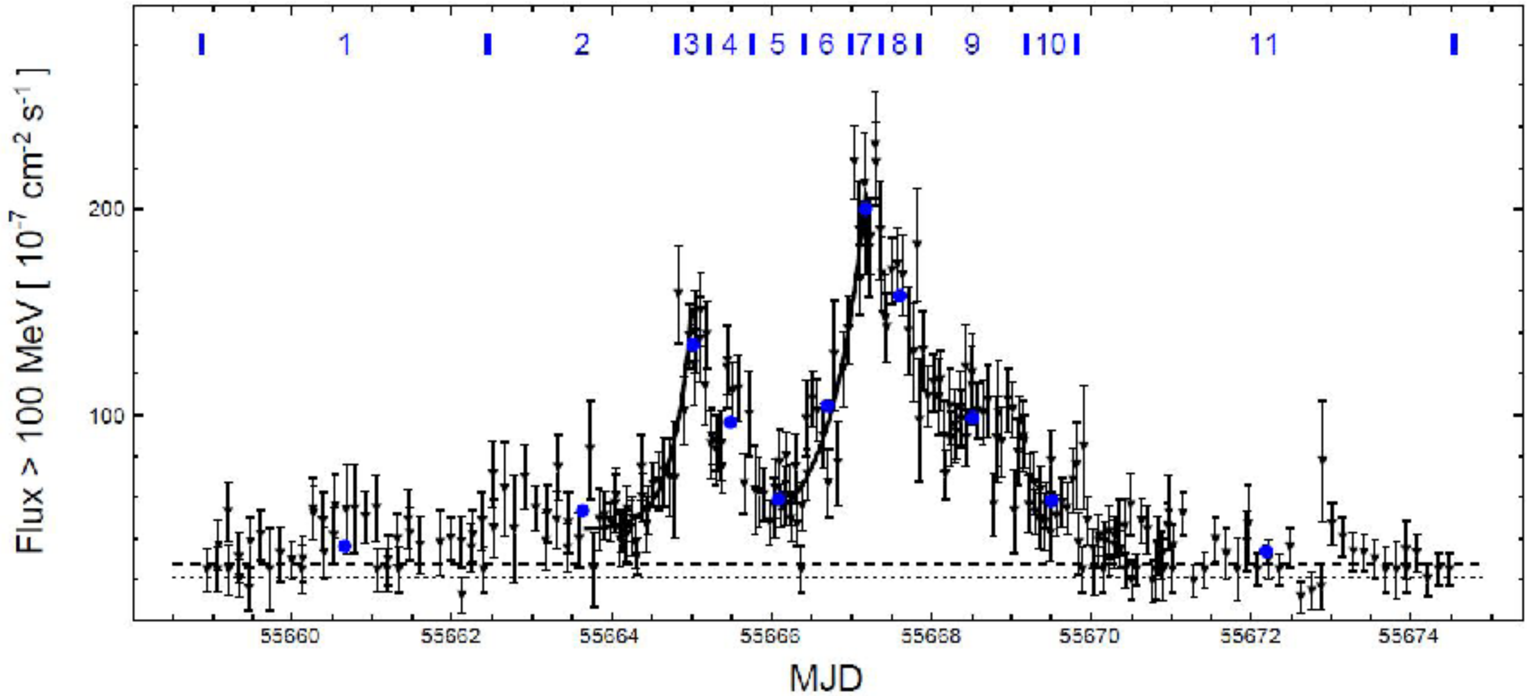

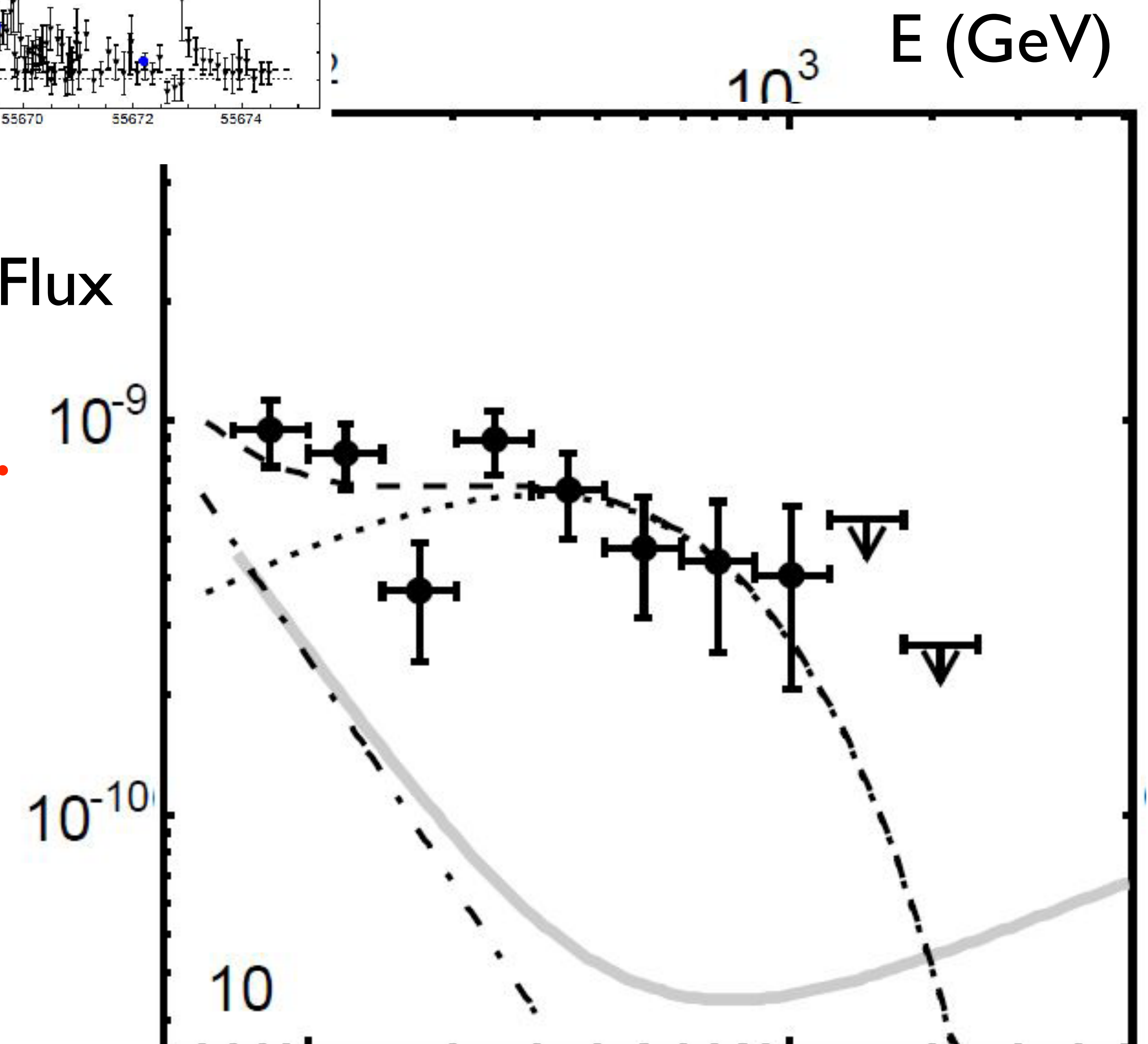

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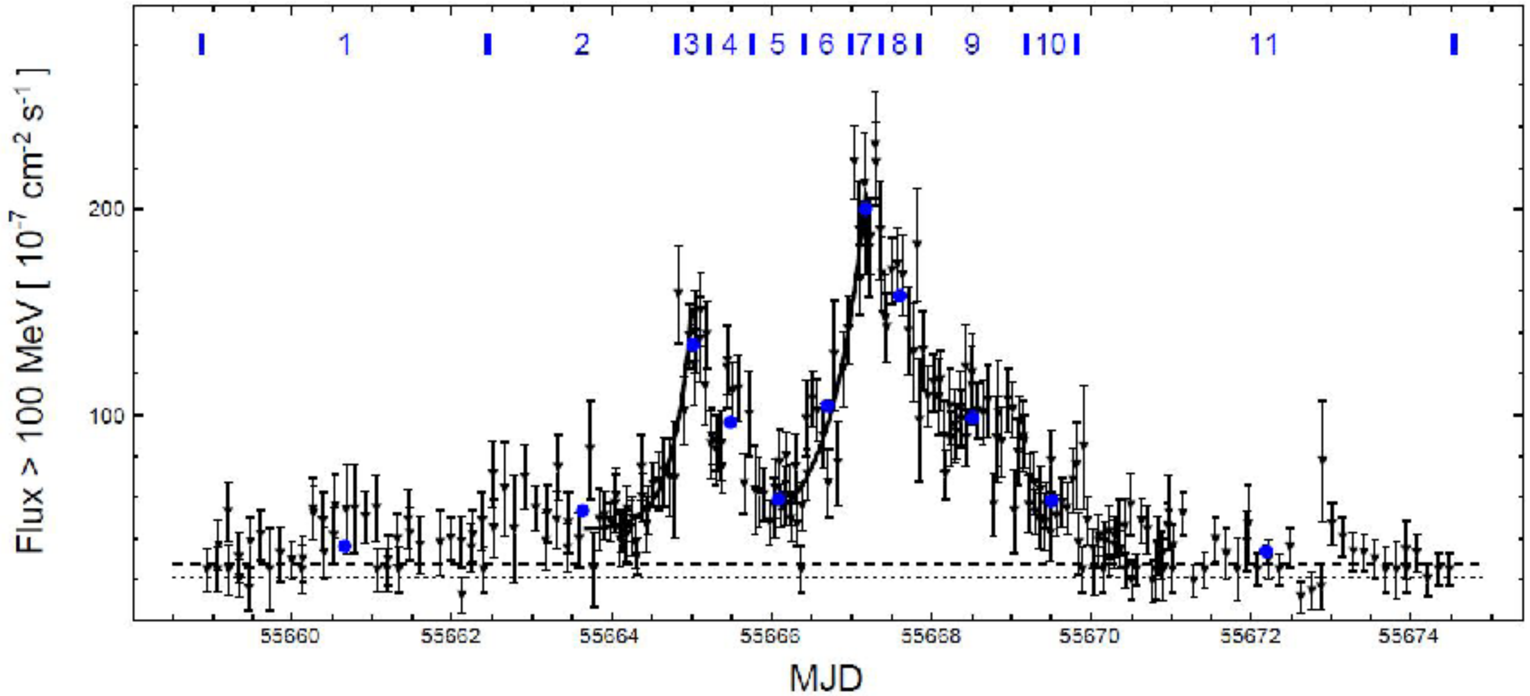

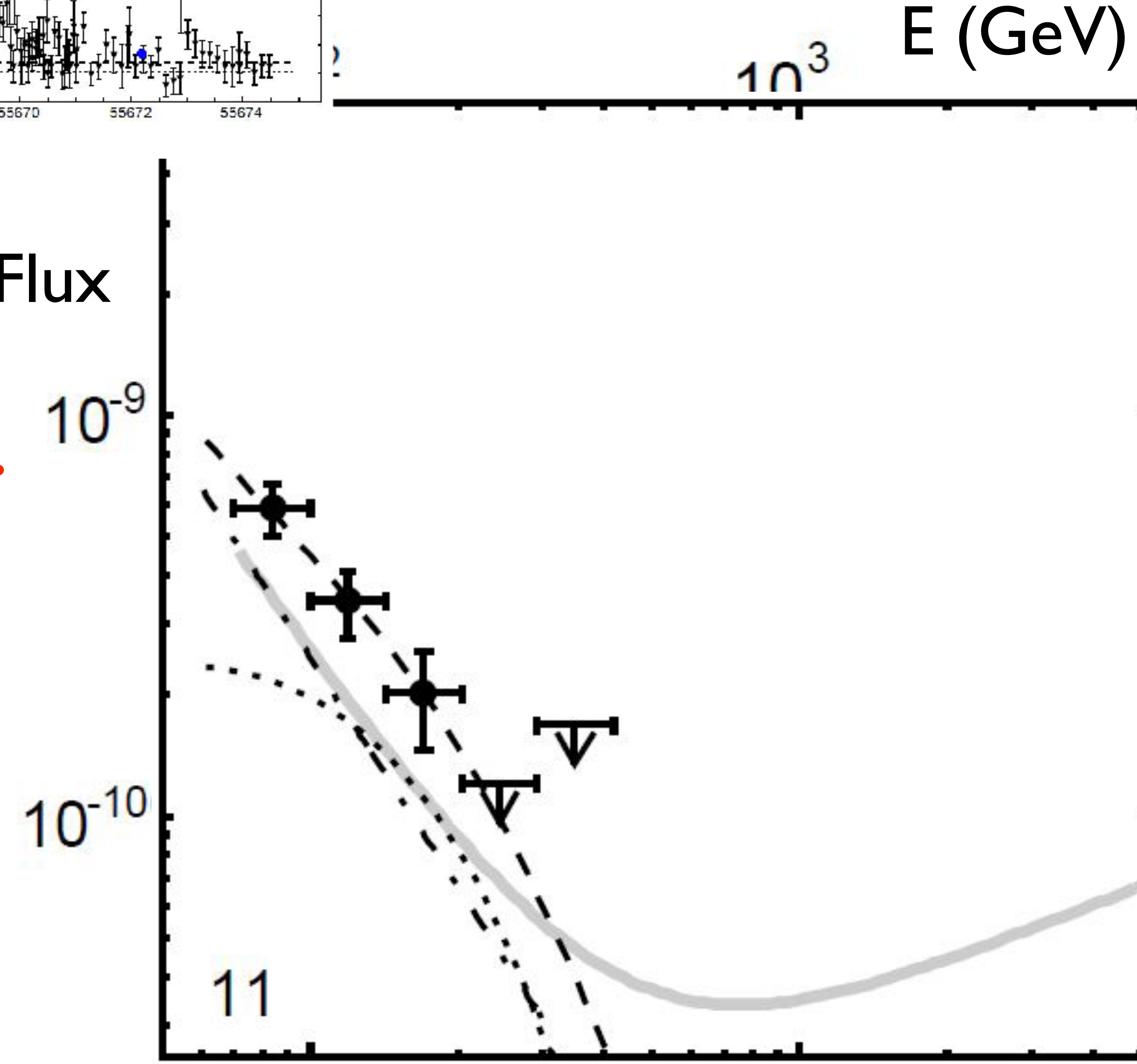

Spectrum varies with time.
Allows study of the
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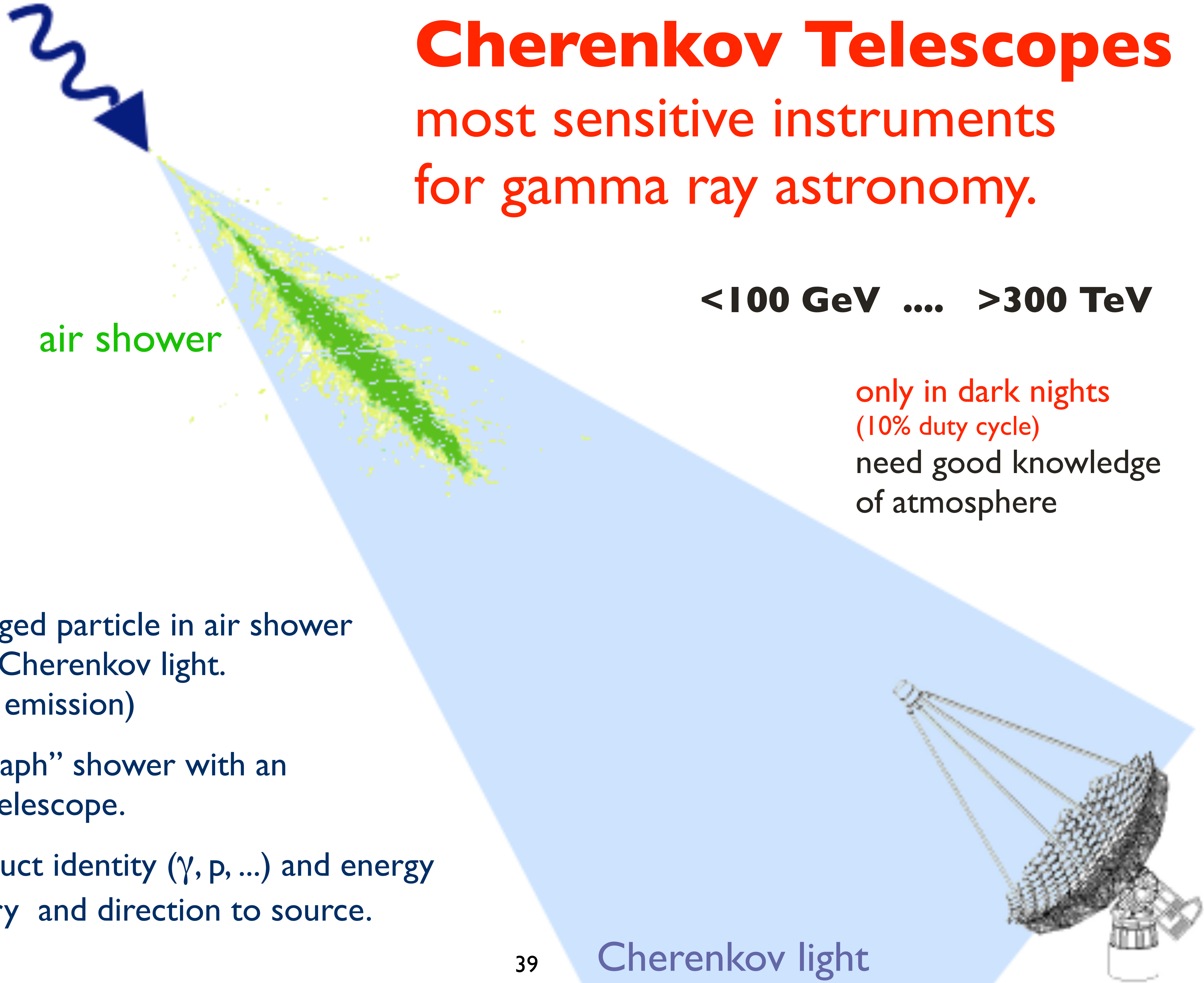
of particle acceleration.

Cherenkov Telescopes

most sensitive instruments for gamma ray astronomy.

<100 GeV .... >300 TeV

only in dark nights
(10% duty cycle)
need good knowledge of atmosphere

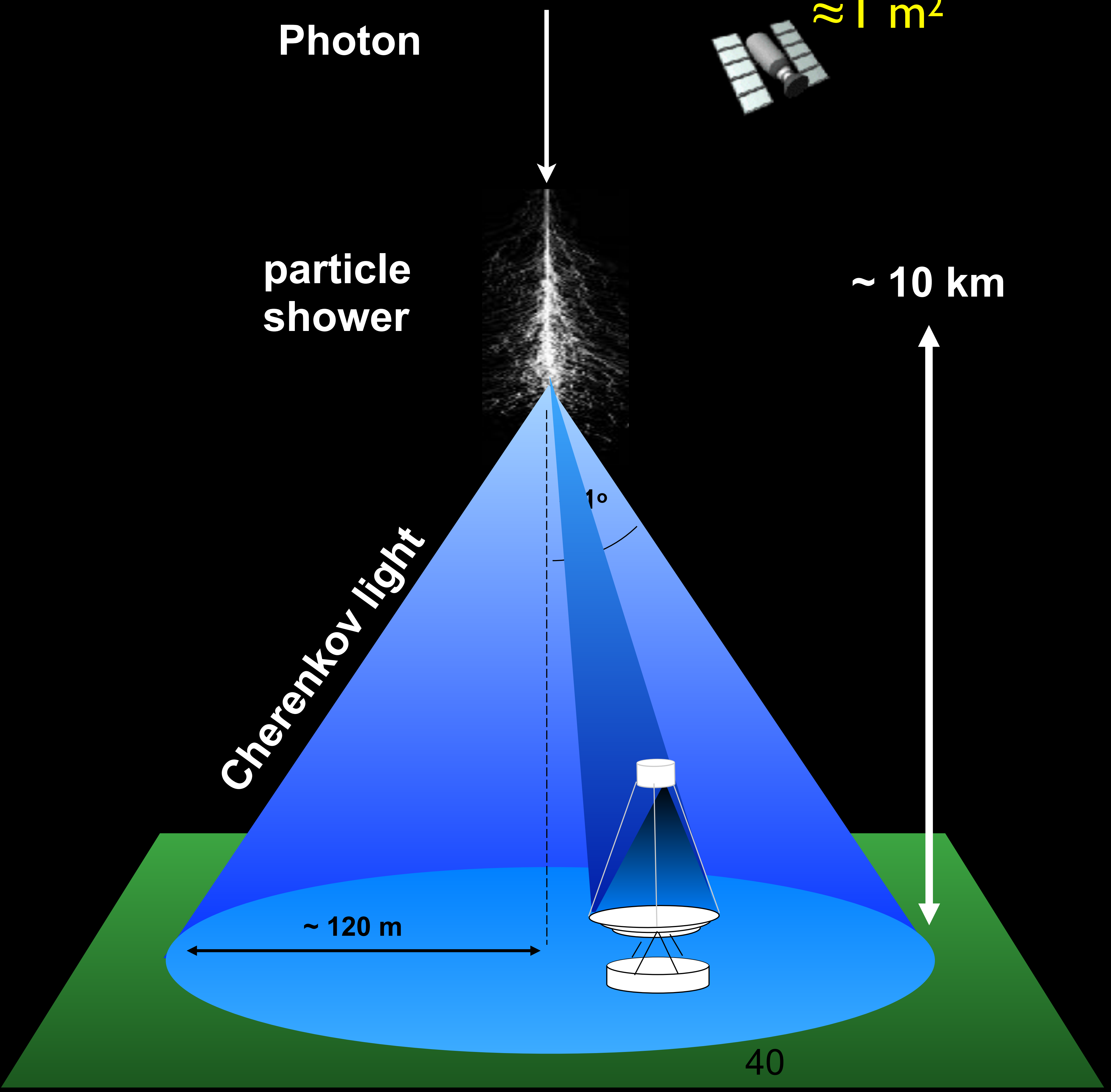


Fast charged particle in air shower produce Cherenkov light.
(forward emission)

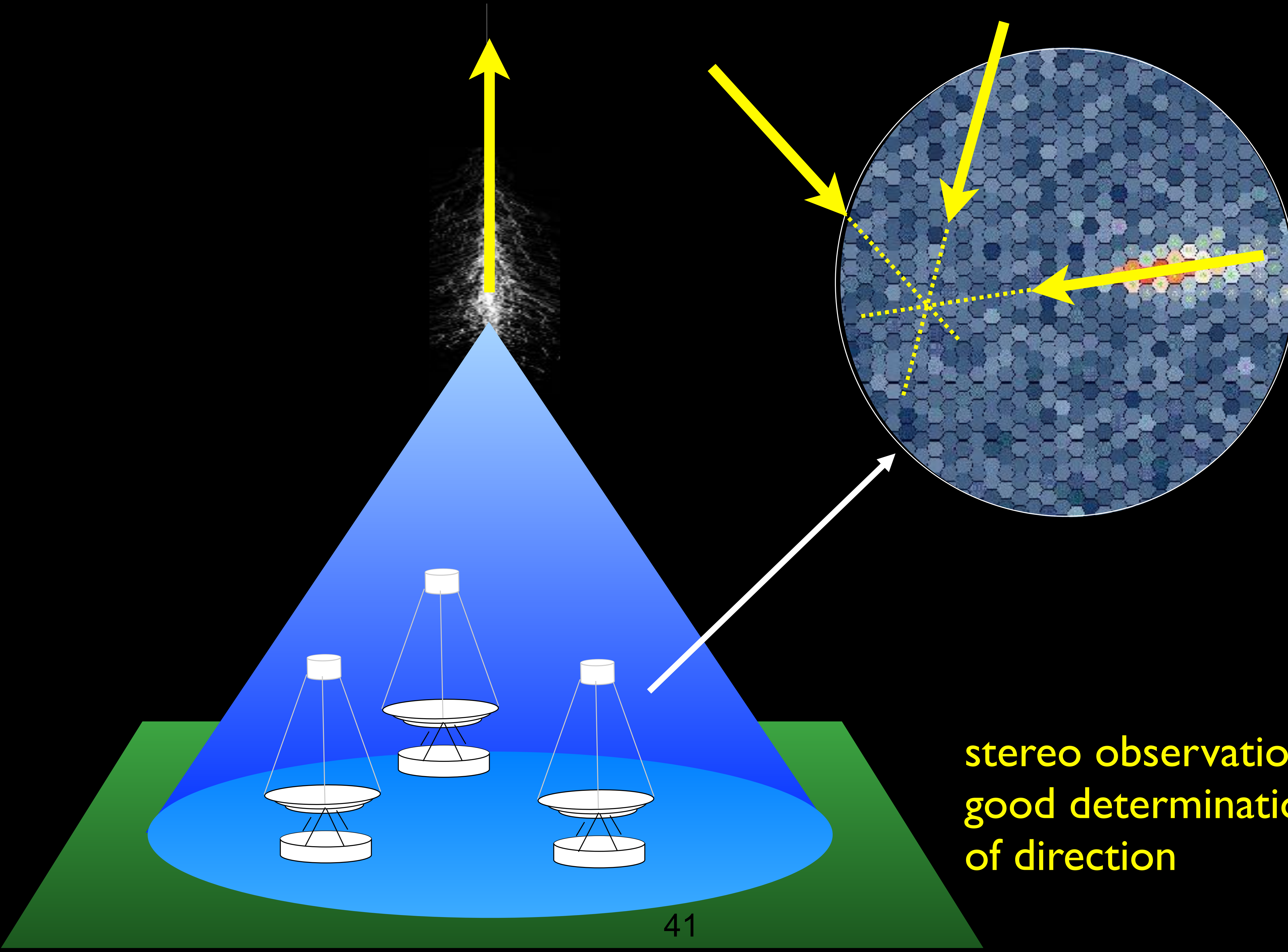
"Photograph" shower with an imaging telescope.

Reconstruct identity (γ, p, ...) and energy of primary and direction to source.

Detection principle

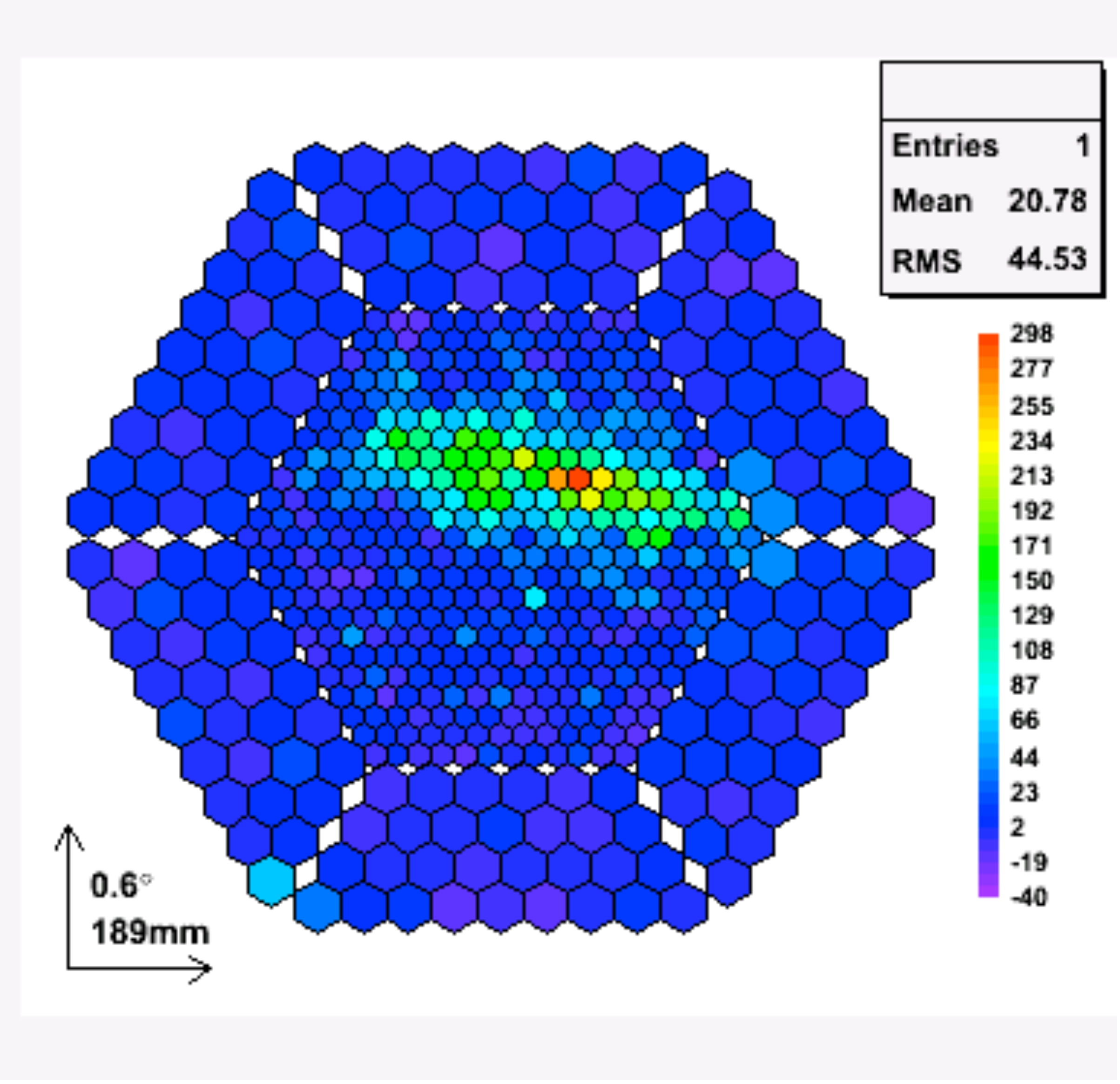


large effective detector area $\approx 10^5$ m²



stereo observation:
good determination
of direction

MAGIC camera



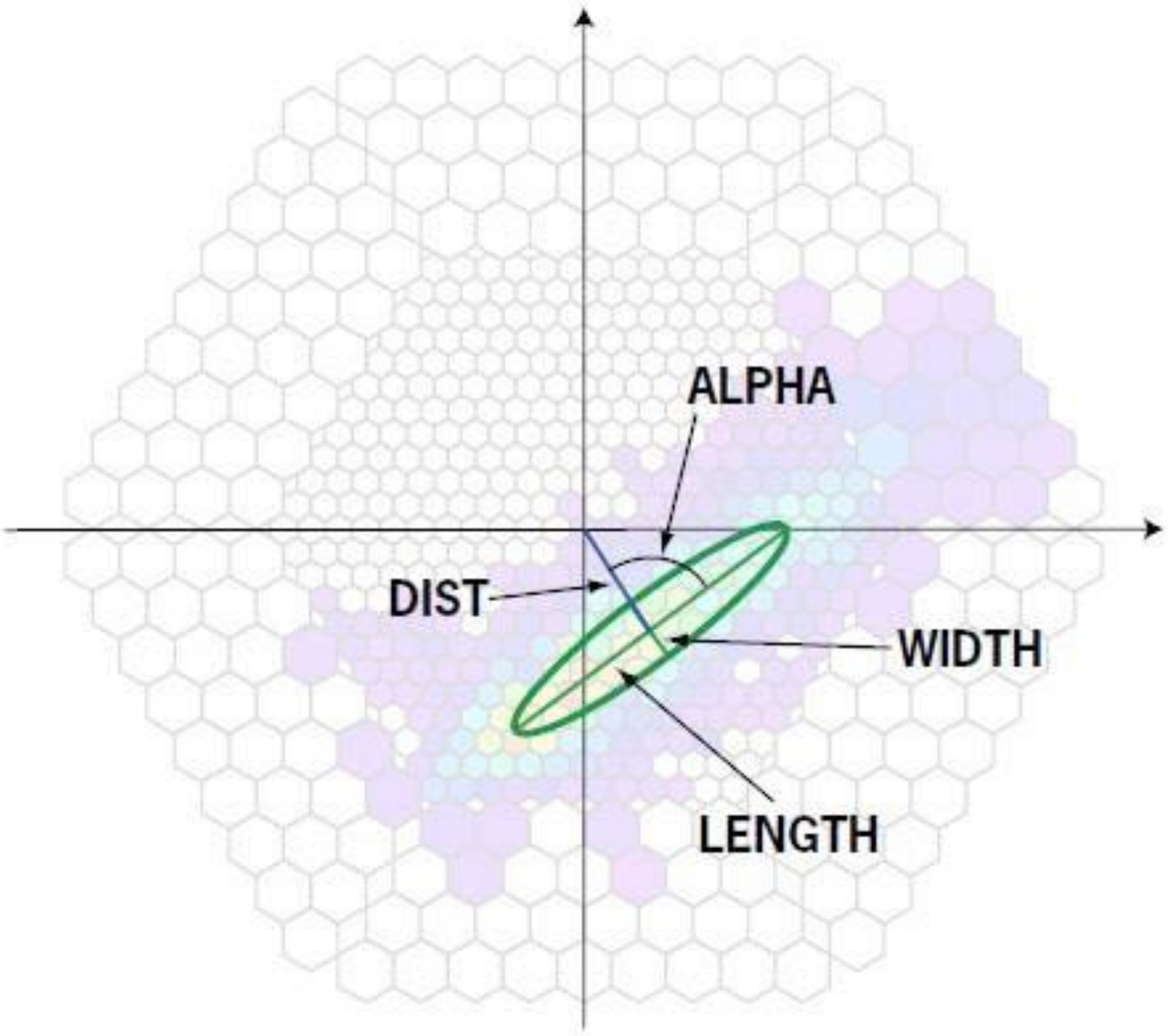
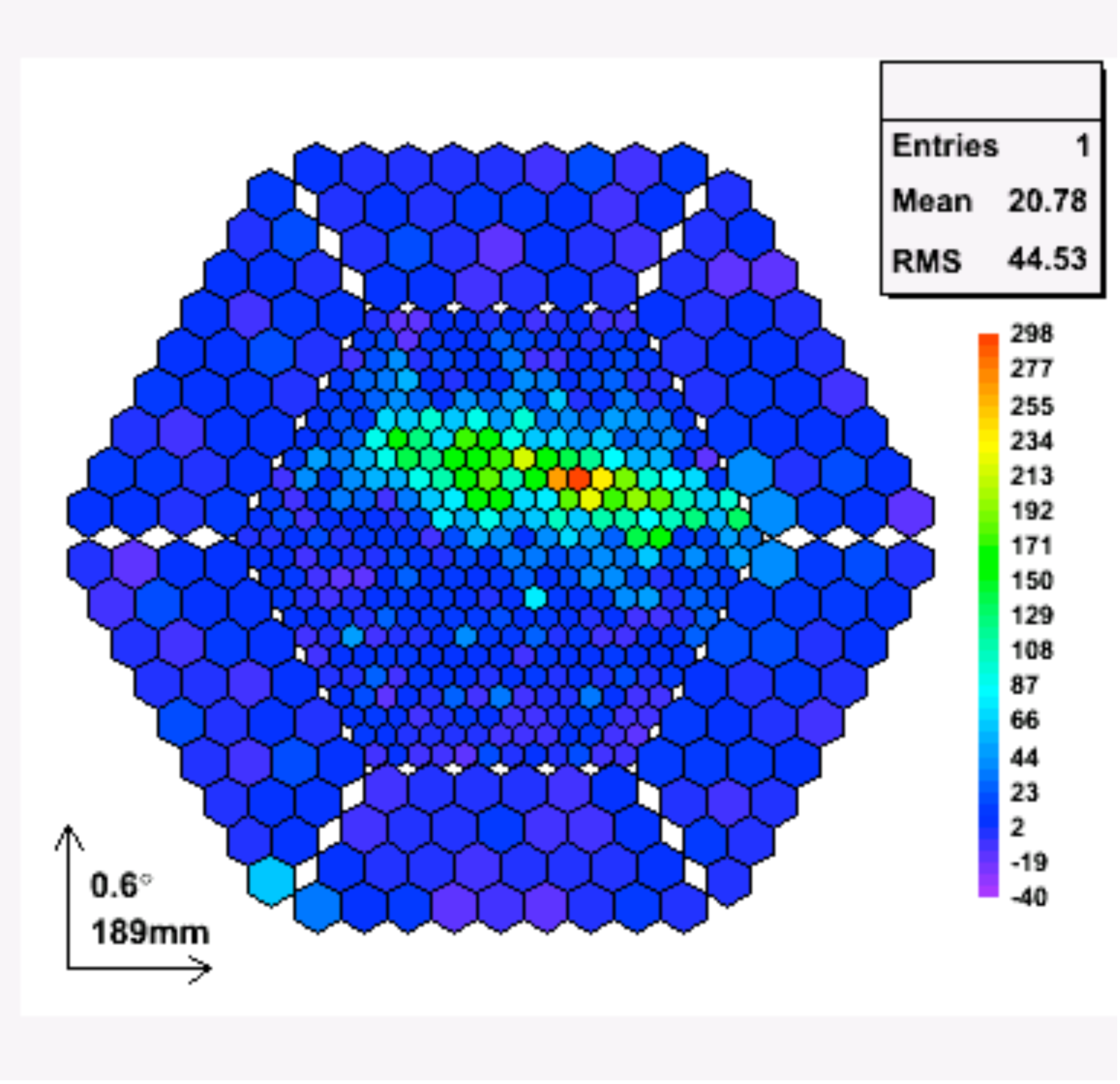


image analysis:
form and orientation

MAGIC camera



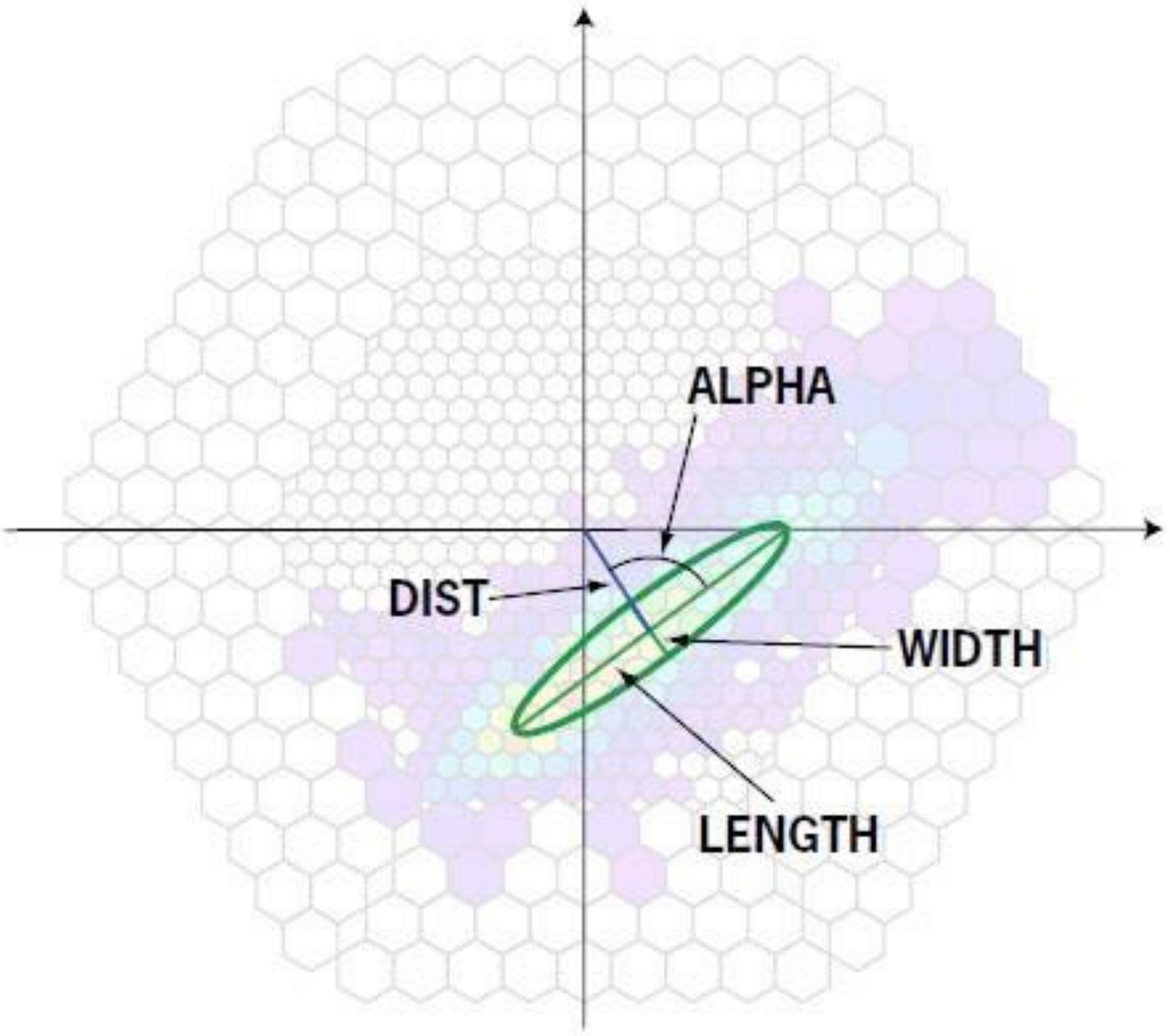
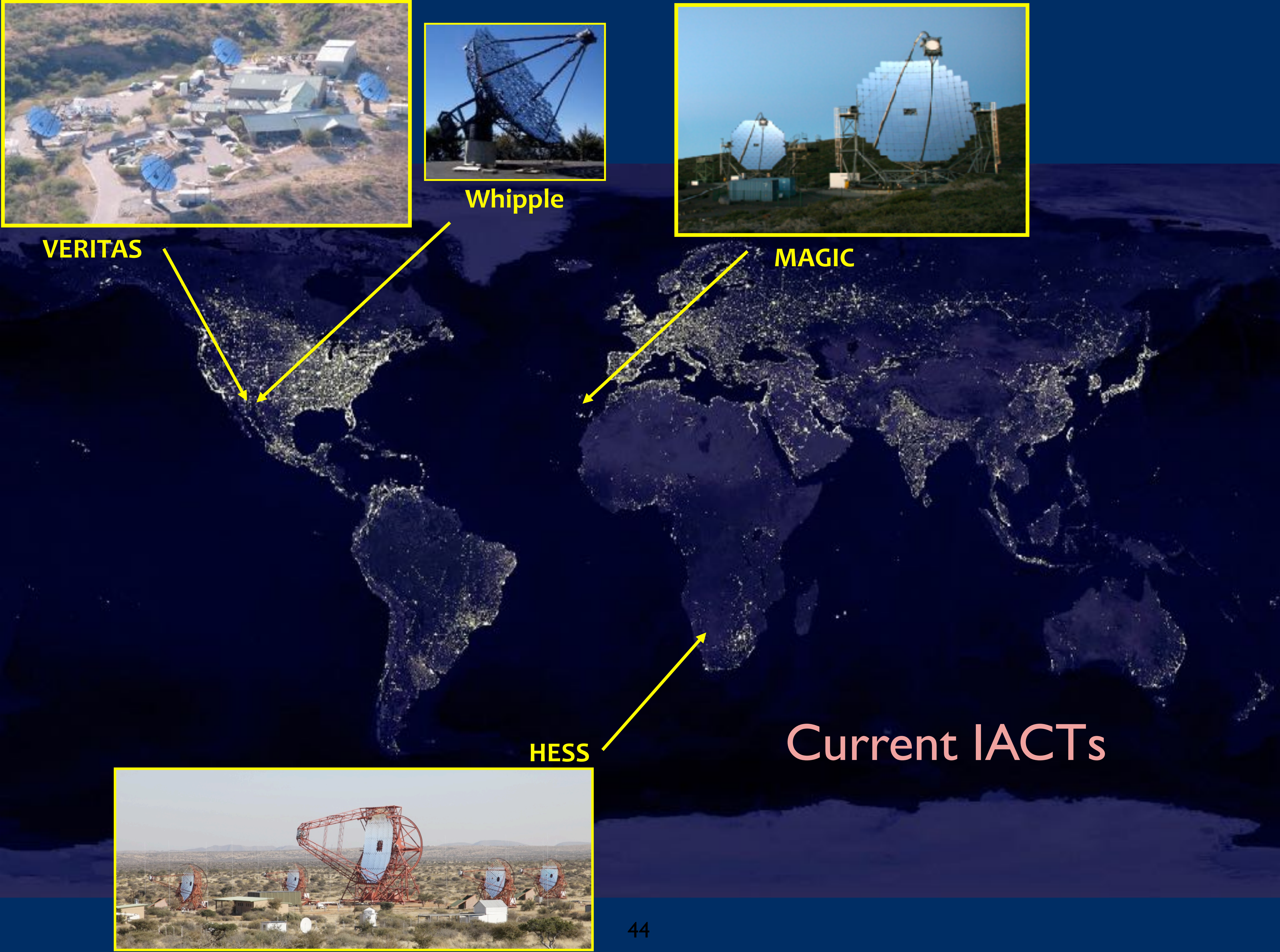


image analysis:
form and orientation

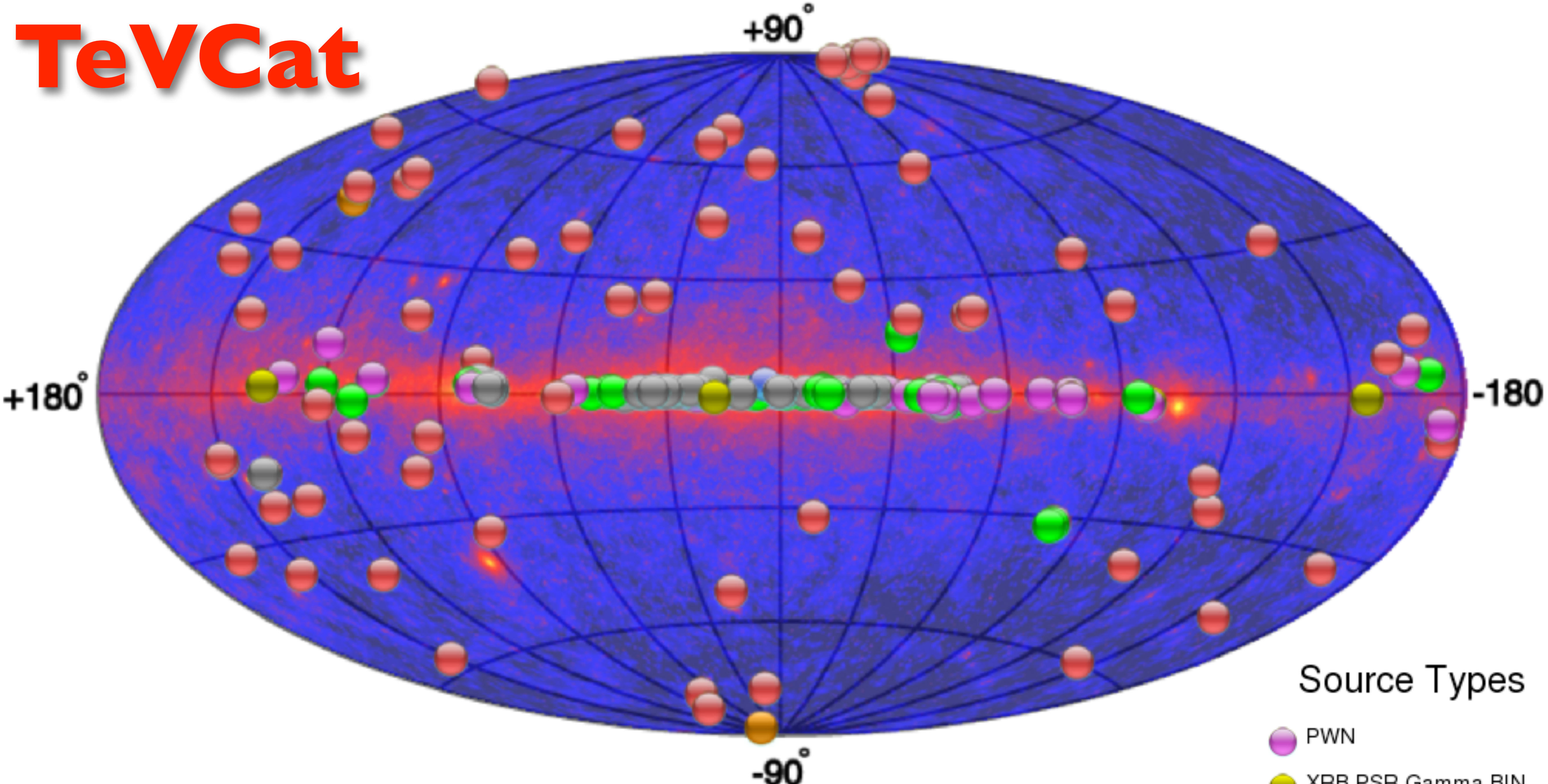
e.g. HESS Observatory (28-m Telescope added in 2012)
Namibia: 0.5 km^2
5 imaging Cherenkov telescopes

TeV-Gamma rays
($E \approx 10^{11}$–10^{14} eV)

Current IACTs



TeVCat



background image:
Fermi sky map (MeV-GeV)

now: >170 sources (> 100 GeV)
gal. / extragal. / unid.

gamma ray emission is present
wherever there are shocks and relativistic flows

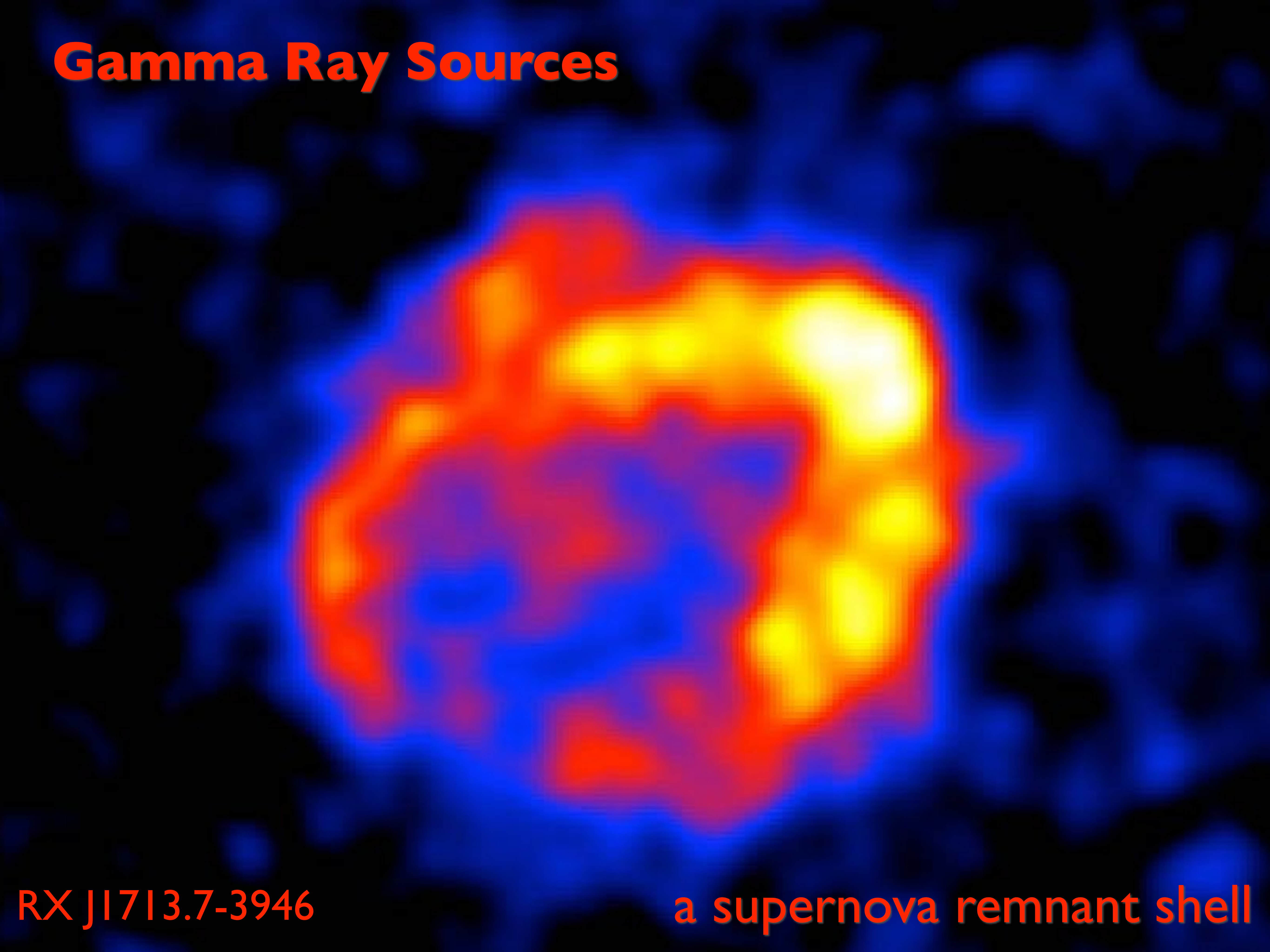
TeV astronomy highlights

from **HESS, MAGIC** and **VERITAS**
Descartes & Rossi Prize for HESS

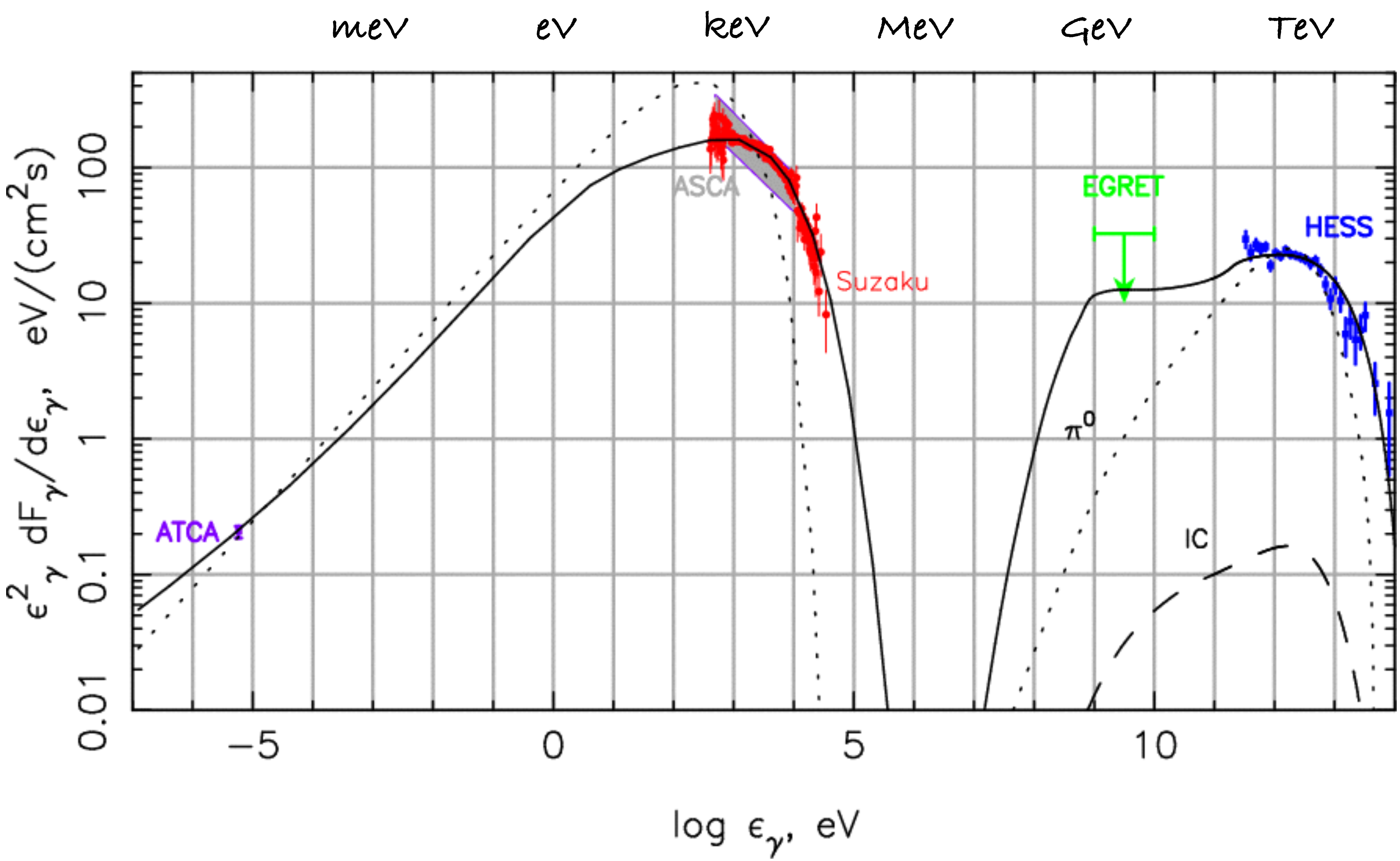
Supernova remnants:	Nature	432 (2004) 75		
Microquasars:	Science	309 (2005) 746	Science	312 (2006) 1771
Pulsars:	Science	322 (2008) 1221	Science	334 (2011) 69
Galactic Centre:	Nature	439 (2006) 695	Nature	531 (2016) 476
Galactic Survey:	Science	307 (2005) 1839		
LMC:	Science	347 (2015) 406		
Black Holes:	Science	346 (2014) 1080		
Starbursts:	Nature	462 (2009) 770	Science	326 (2009) 1080
Active Galactic Nuclei:	Science	314 (2006) 1424	Science	325 (2009) 444
EBL:	Nature	440 (2006) 1018	Science	320 (2008) 752
Dark Matter:	PRL	96 (2006) 221102	PRL	106 (2011) 161301
	PRL	114 (2015) 081301	PRL	110 (2013) 41301
Lorentz Invariance:	PRL	101 (2008) 170402		
Cosmic Ray Electrons:	PRL	101 (2008) 261104		

+ many papers in other journals
… a booming field.

Gamma Ray Sources

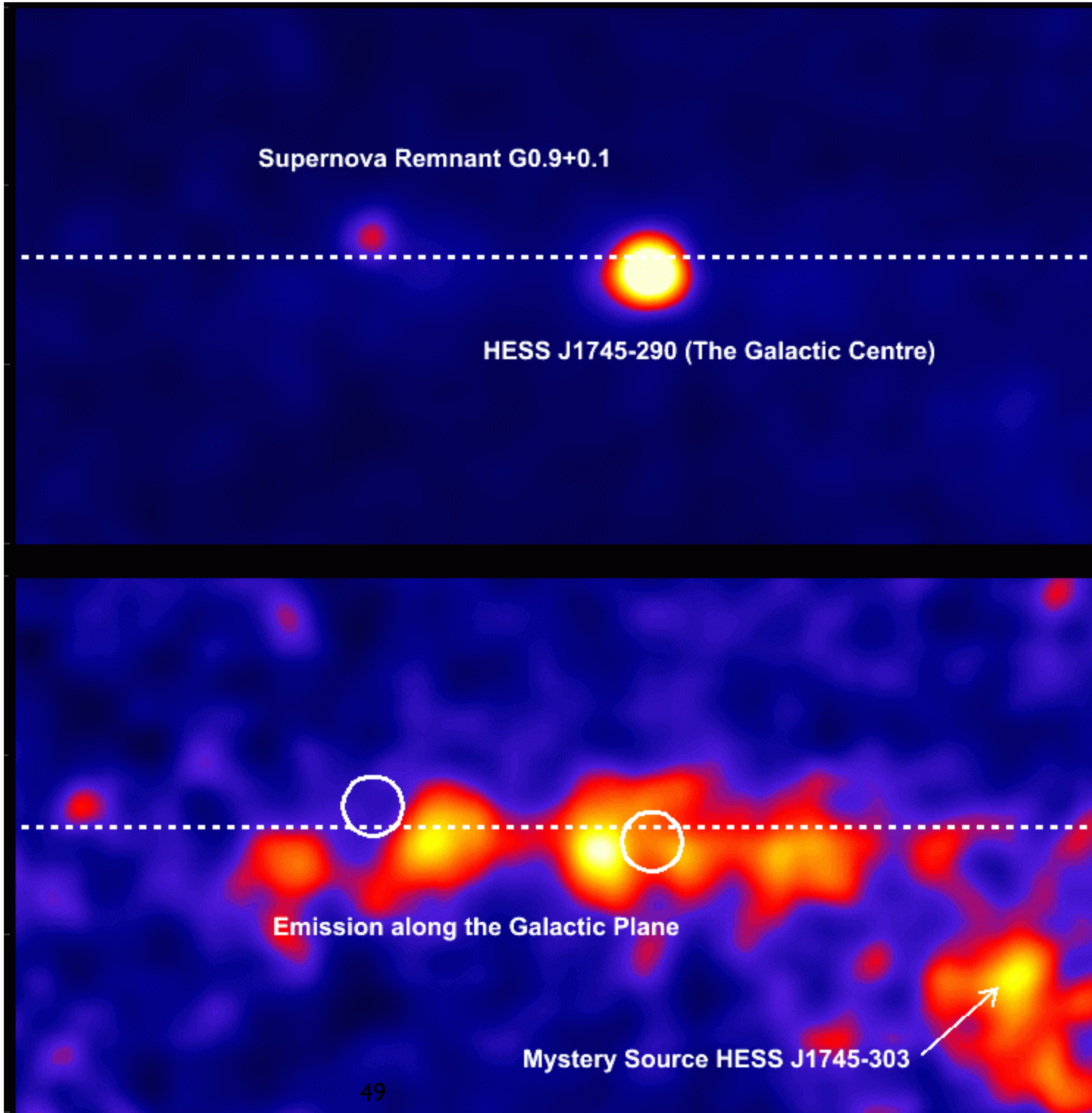


Supernova Remnant RX J1713.7-3946



HESS:
gal. centre

CRs with
mol. clouds



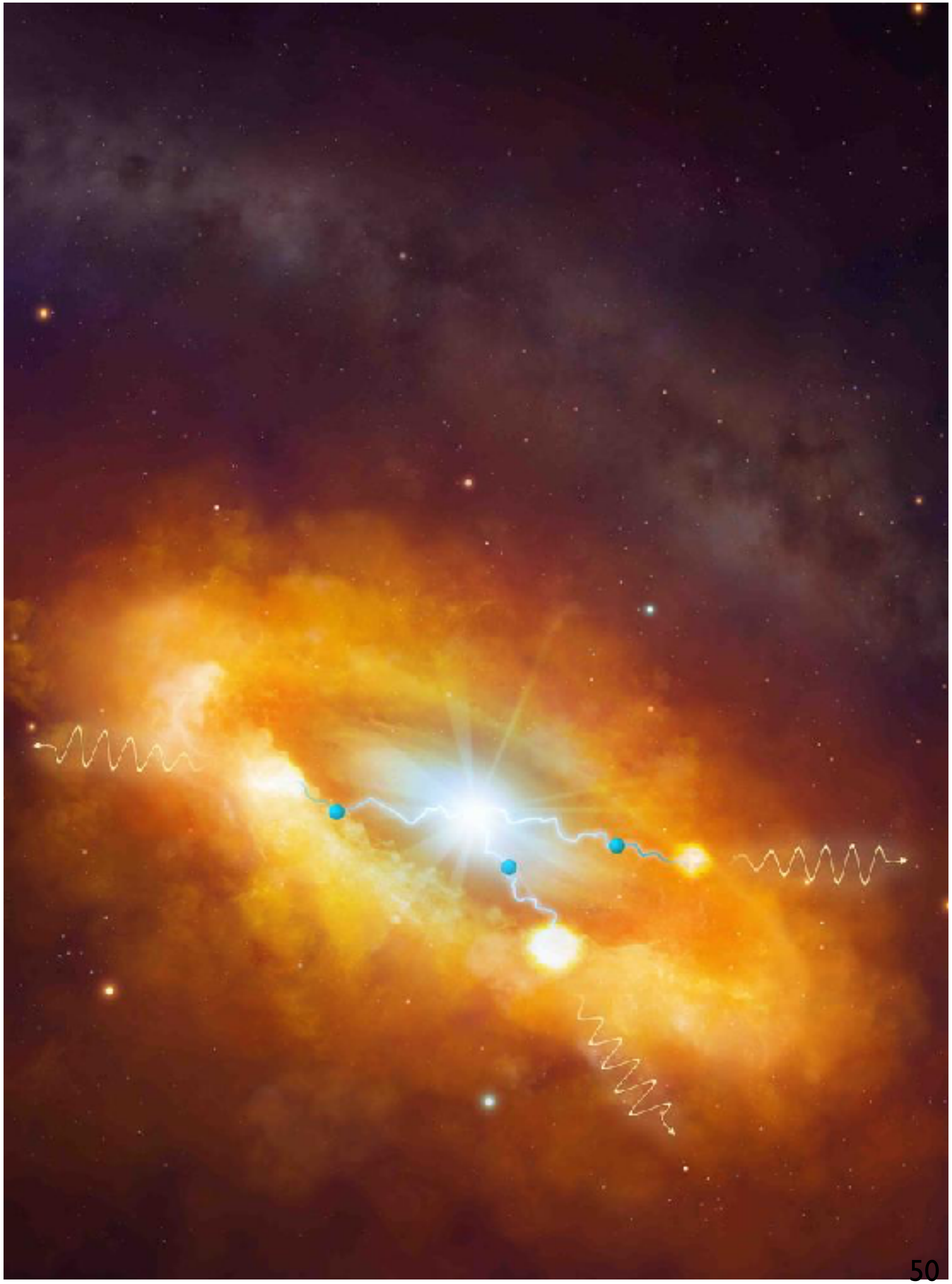
A PeV-atron in the Galactic centre

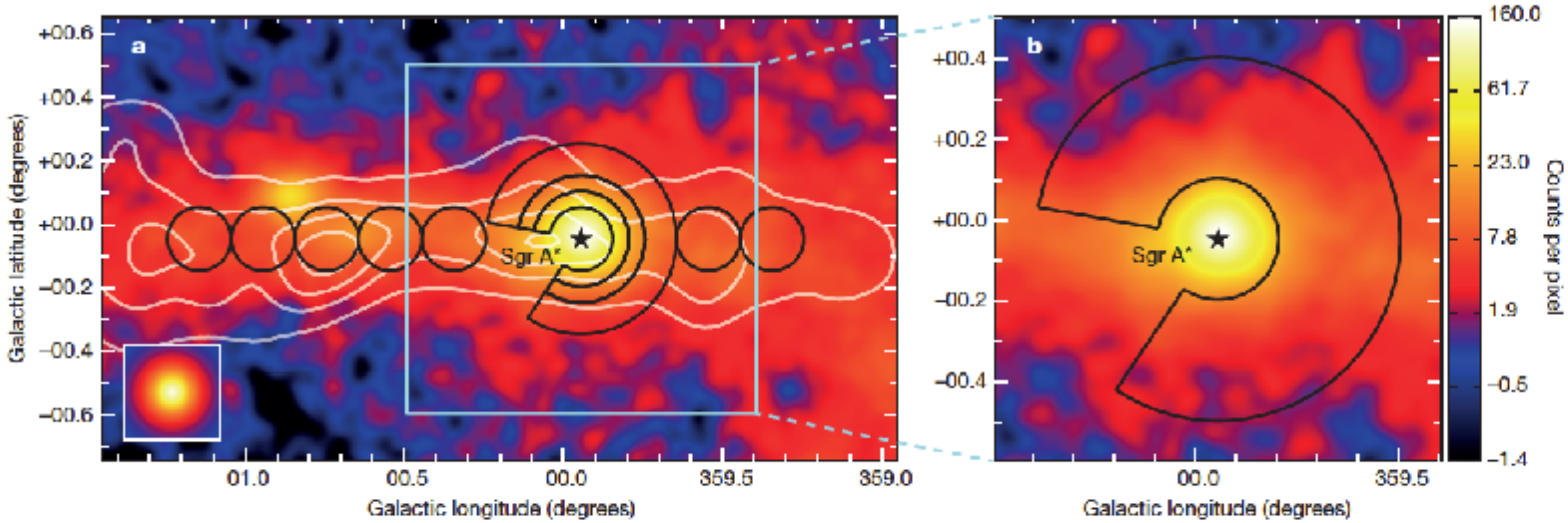
Nature 531, 476-479 (2016

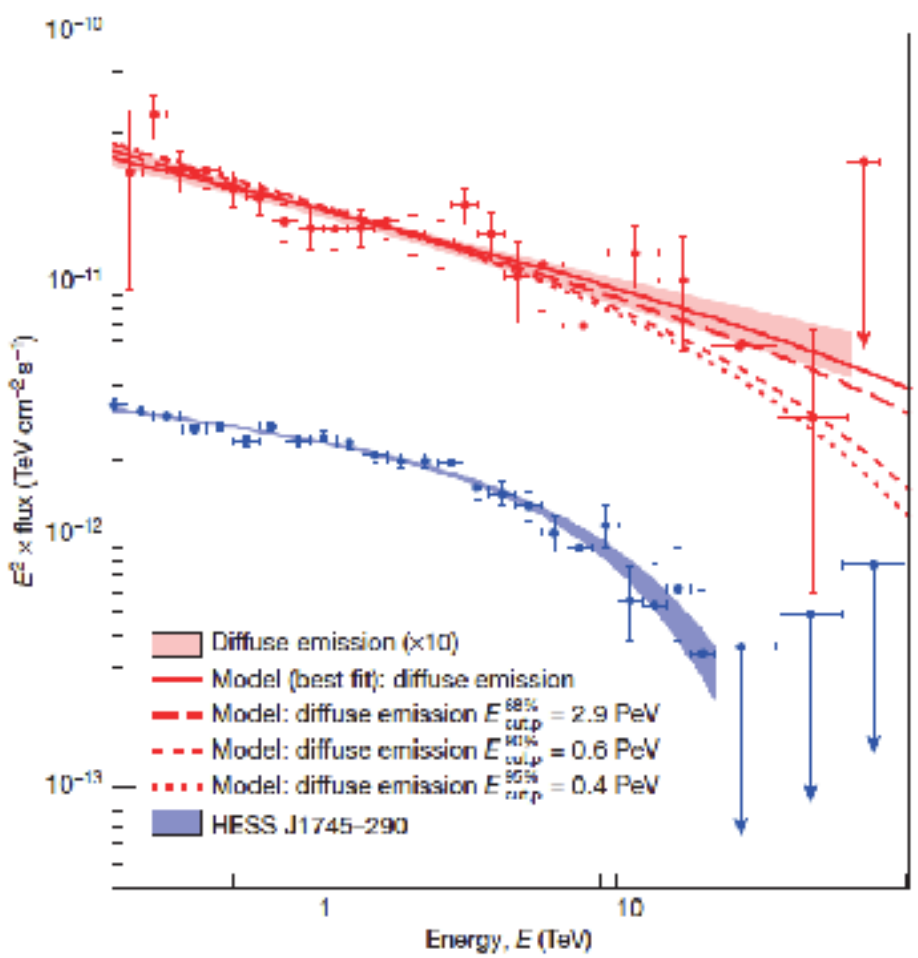
H.E.S.S. 2016:
diffuse emission in
Galactic Centre Ridge region

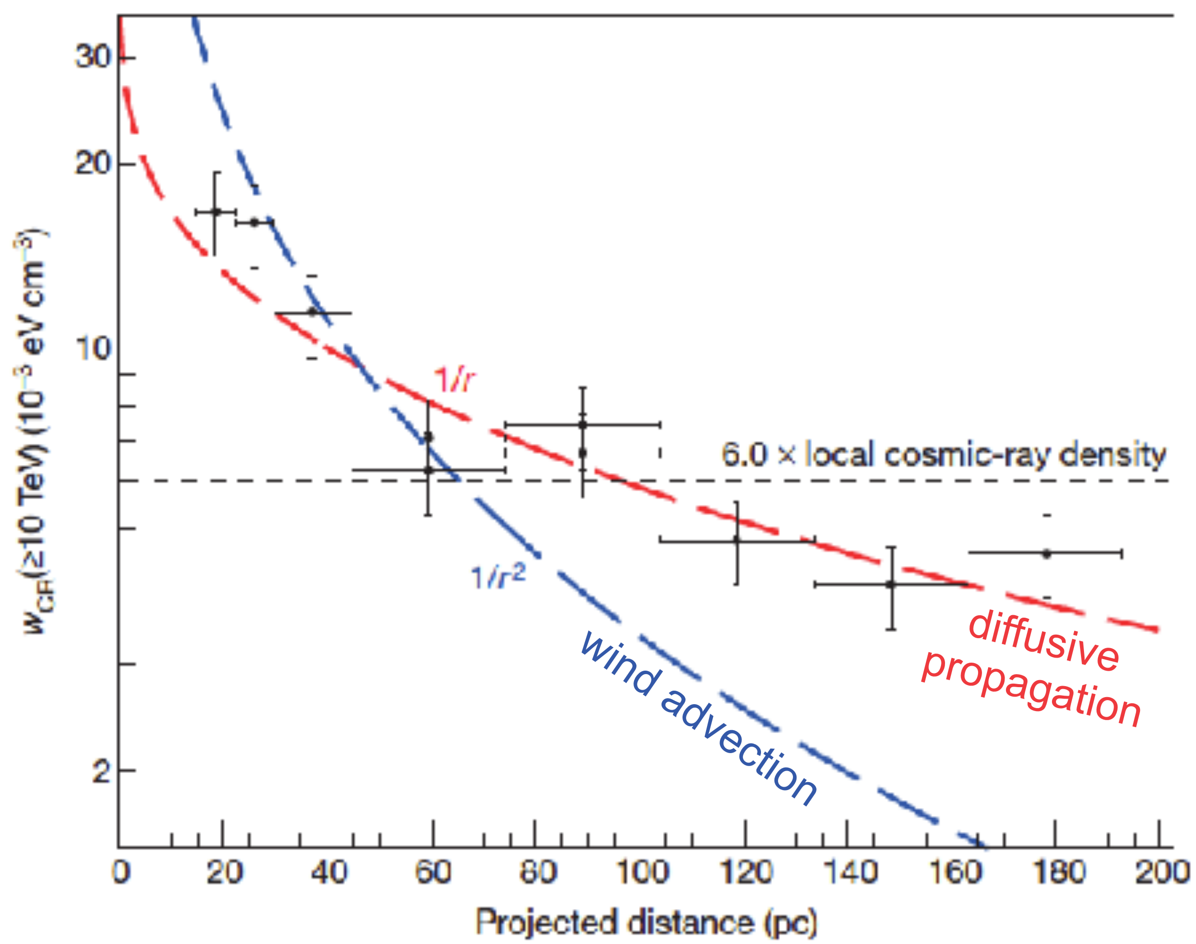
Presence of protons of ≈ 10^{15} eV

Dataset: 2004 - 2015



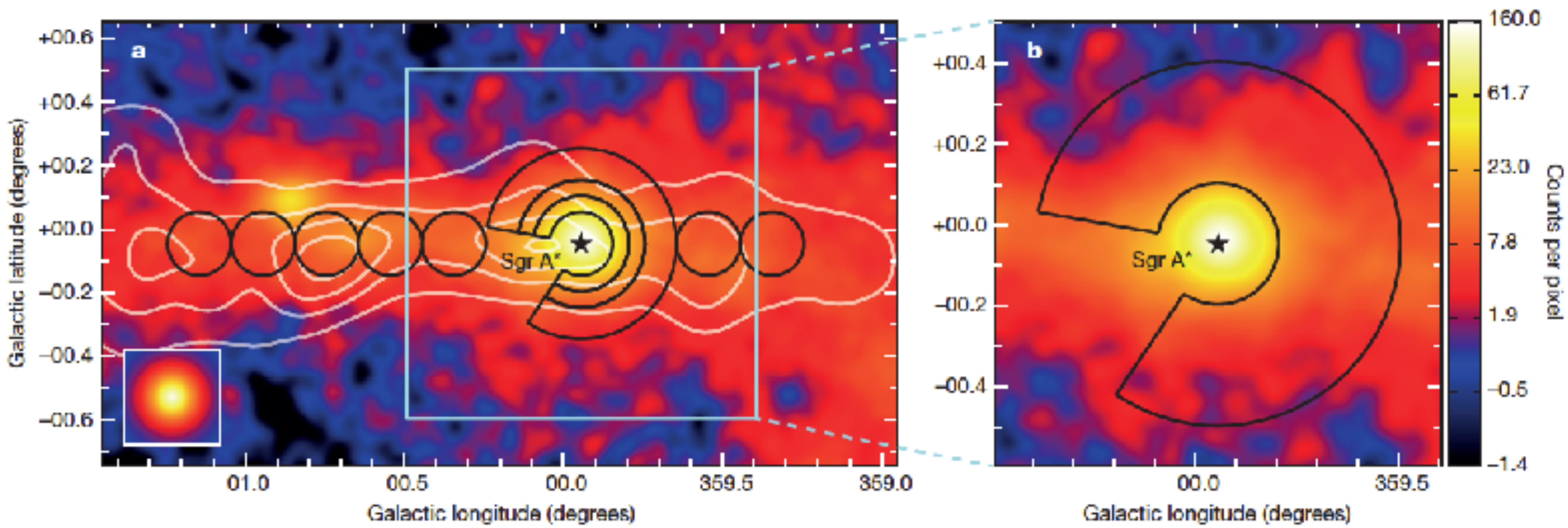


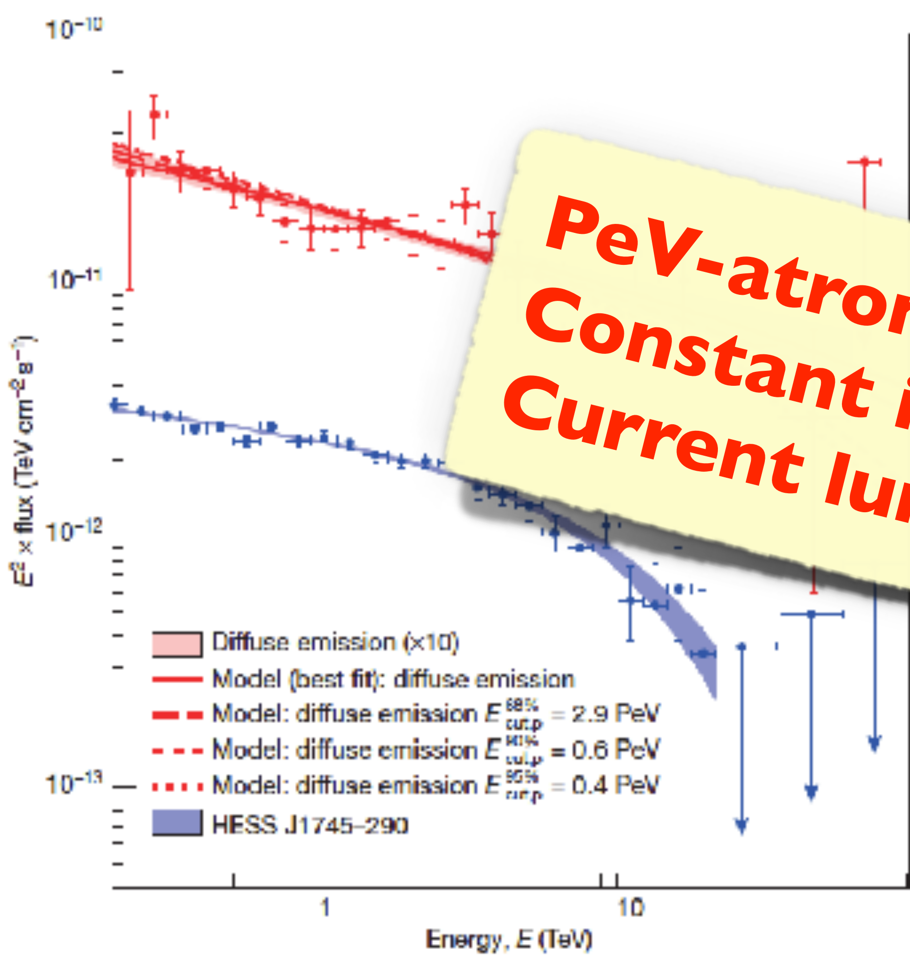




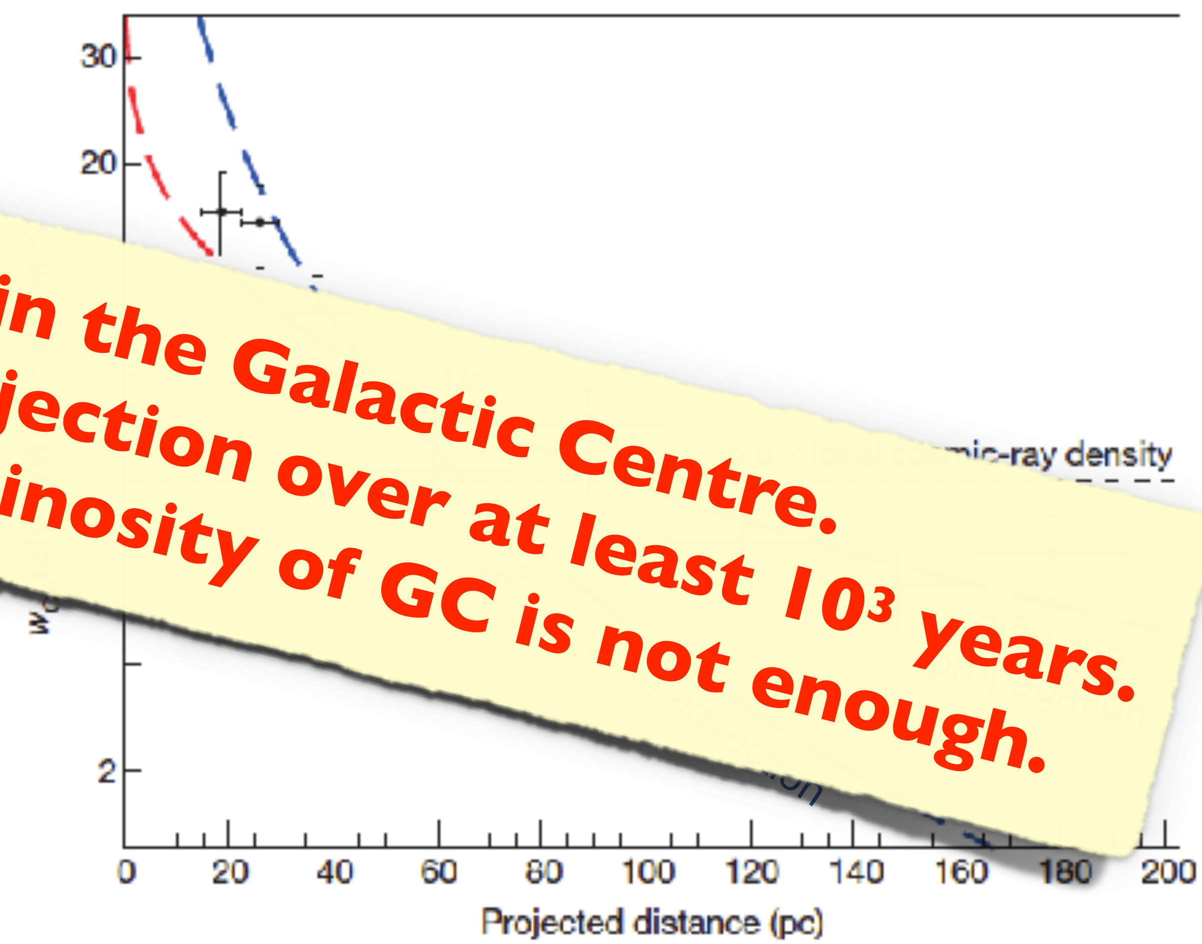
Very hard emission, no cutoff, untypical for extended emission

Cosmic ray density profile using matter densities from molecular line surveys.





PeV-atron in the Galactic Centre.
Constant injection over at least 10^3 years.
Current luminosity of GC is not enough.



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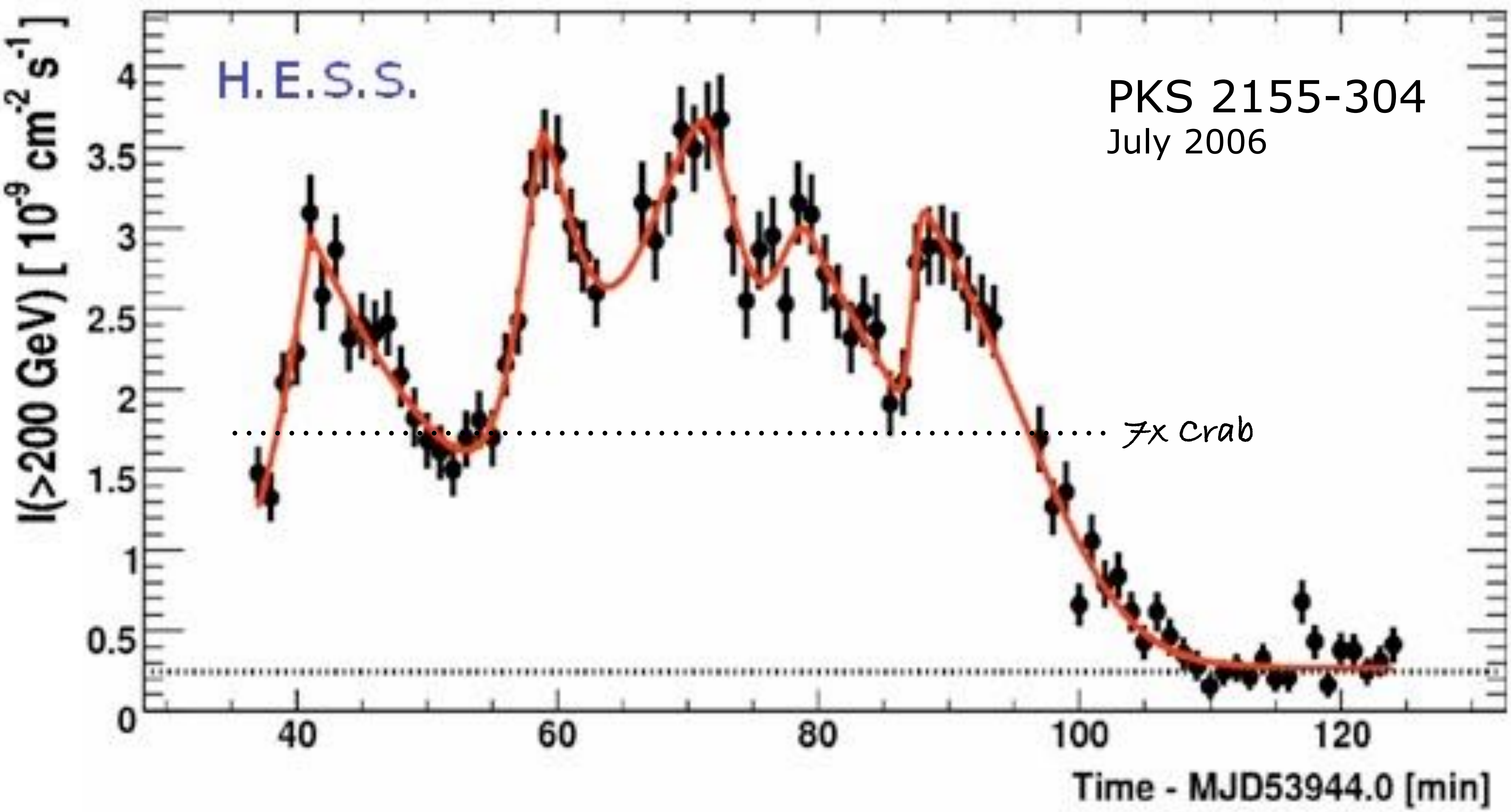


BL Lac object $z = 0.116$
bursts on minute scales
$\Gamma \geq 100$ are required

Gamma Rays are ubiquitous:

many sources / source types
complex structures in space, time and energy

test extreme end of high-energy phenomena
complement observations at longer wavelengths
with other particles

The Imaging Atmospheric Cherenkov technique
is not yet at its limit:

Big improvements are possible with existing technology.

Science Scope:

Cosmic energetic particles

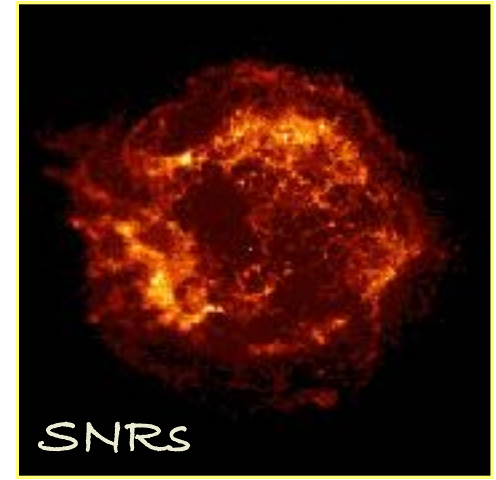
- Origin of the galactic cosmic rays
  - Also UHECR signatures
- Role of ultra-relativistic particles in in clusters of galaxies, AGN, Starbursts…
- The physics of (relativistic) jets and shocks

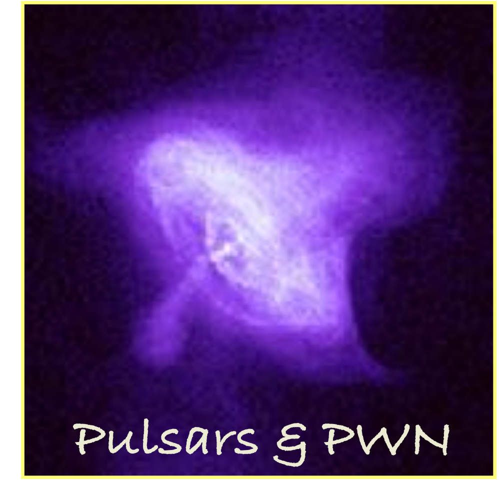
Fundamental Physics

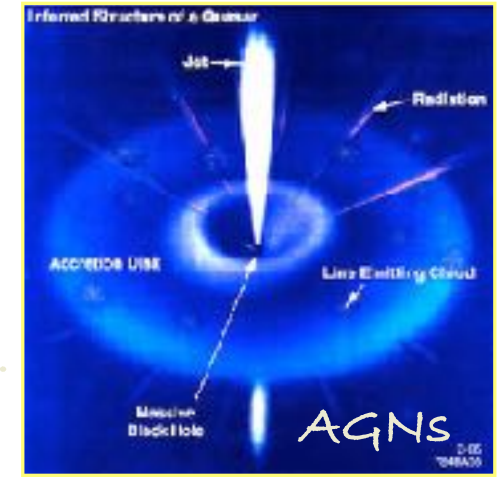
- Dark Matter annihilation / decay
- Lorentz Invariance violation

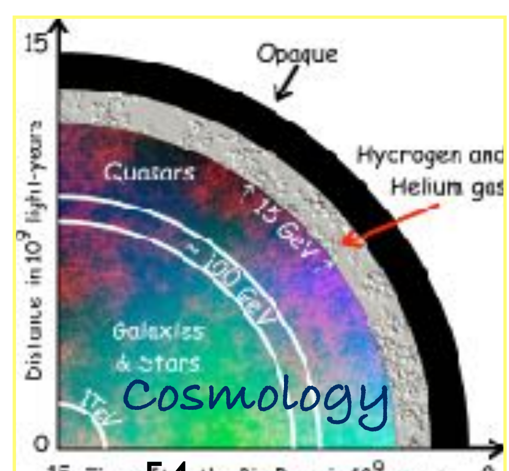
Cosmology

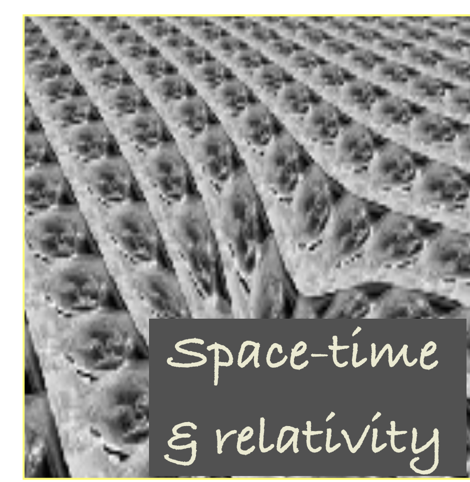
- cosmic FIR-UV radiation,
- cosmic magnetism











The future with cta

cherenkov telescope array

An advanced facility for ground-based gamma-ray astronomy.

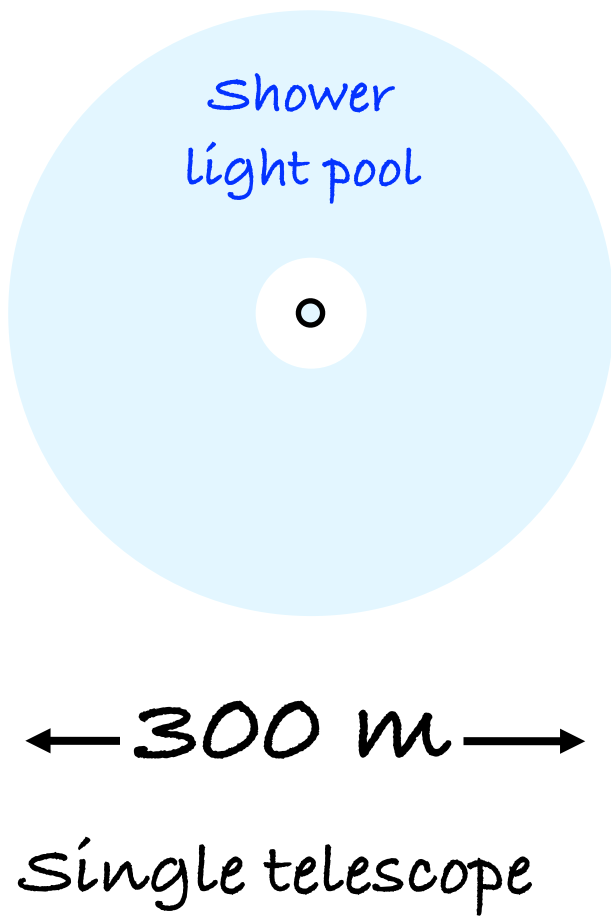
CTA is the global, next-generation project
with largely enhanced performance and energy range
two observatories (South and North),

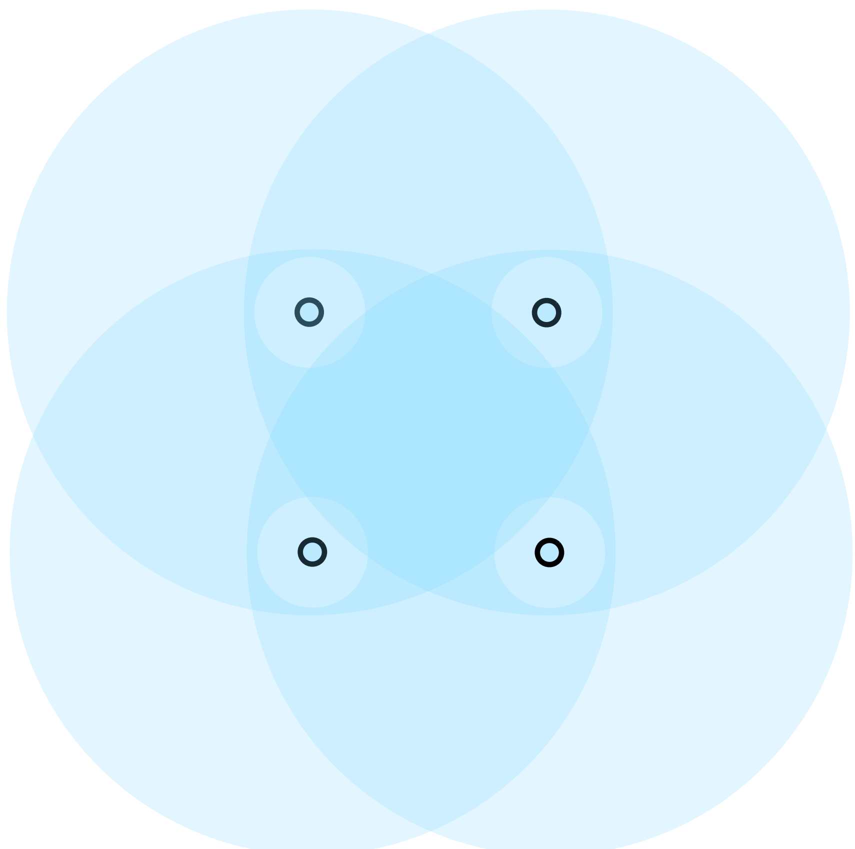
probing the **extreme universe** with huge potential for
high-energy astronomy and fundamental physics.

Boosting sensitivity & resolution: Arrays of Cherenkov telescopes

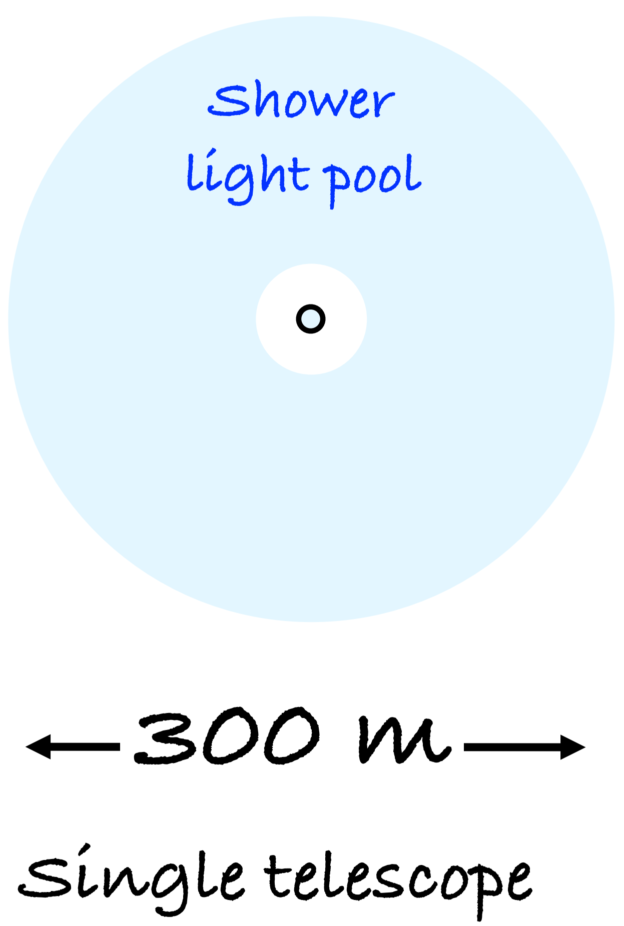
Single telescope

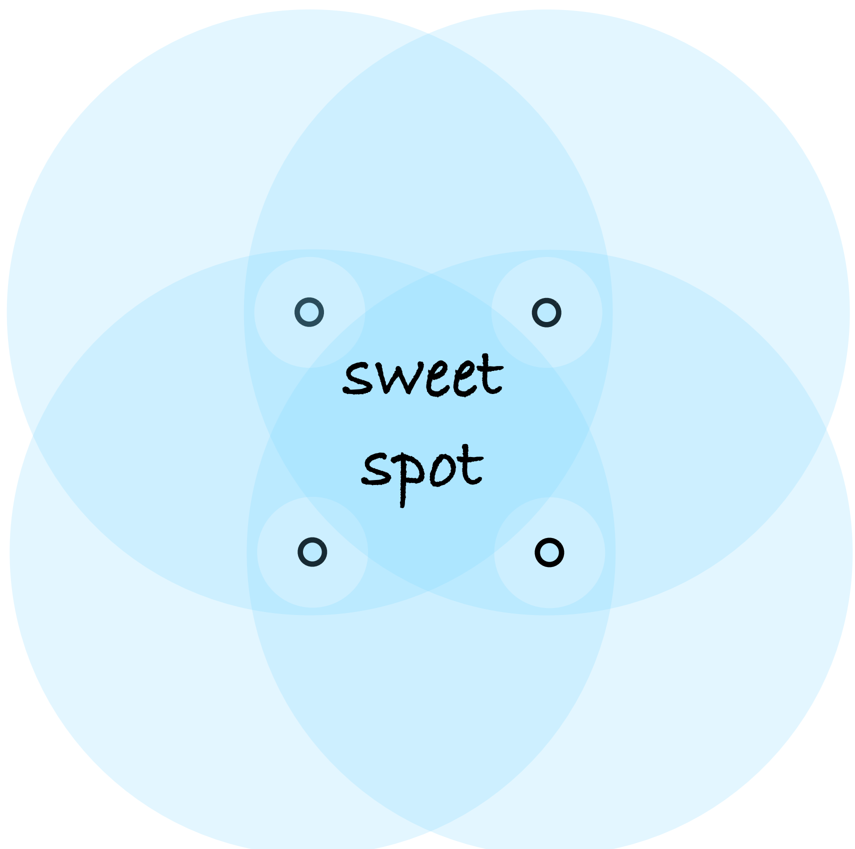
Boosting sensitivity & resolution: Arrays of Cherenkov telescopes



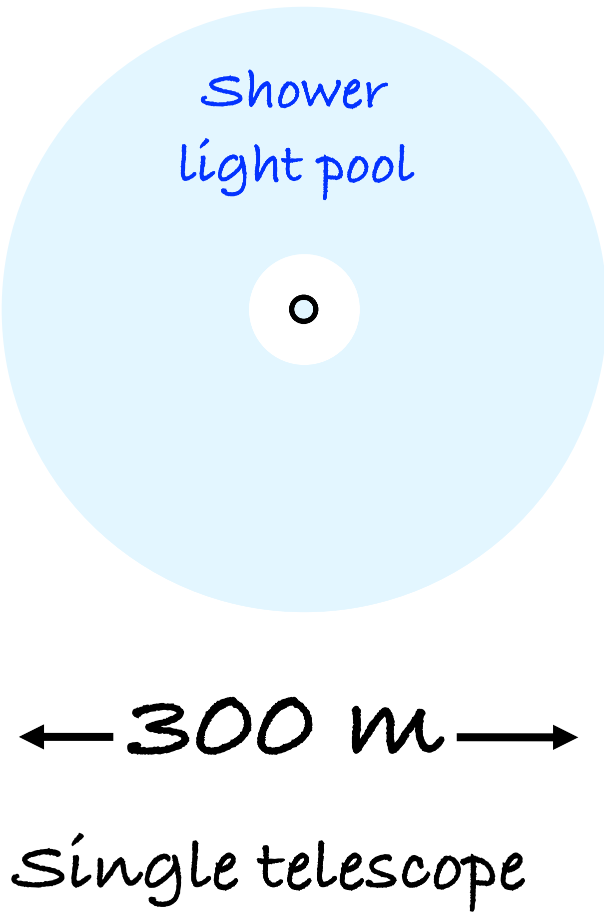


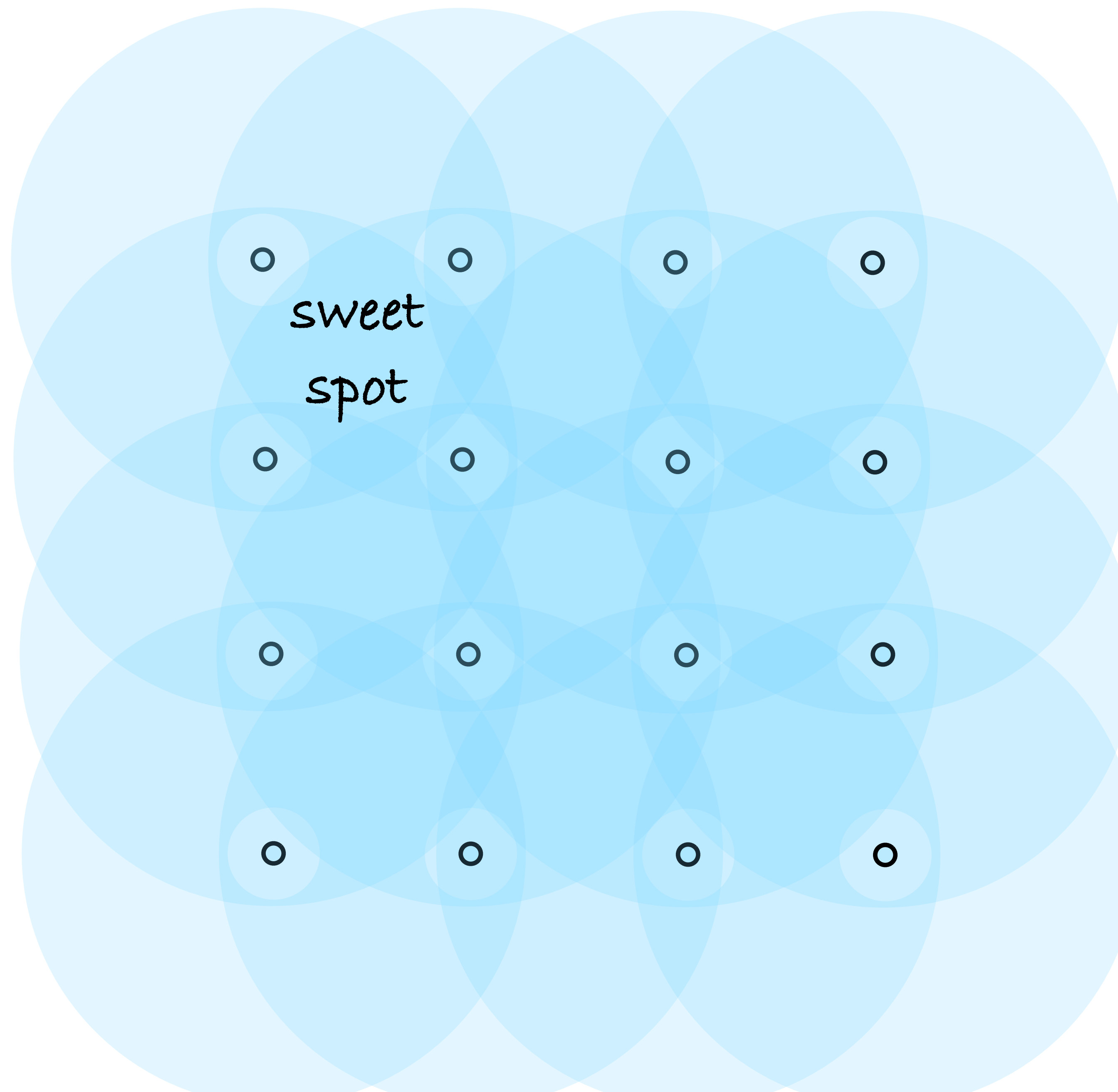
Boosting sensitivity & resolution: Arrays of Cherenkov telescopes



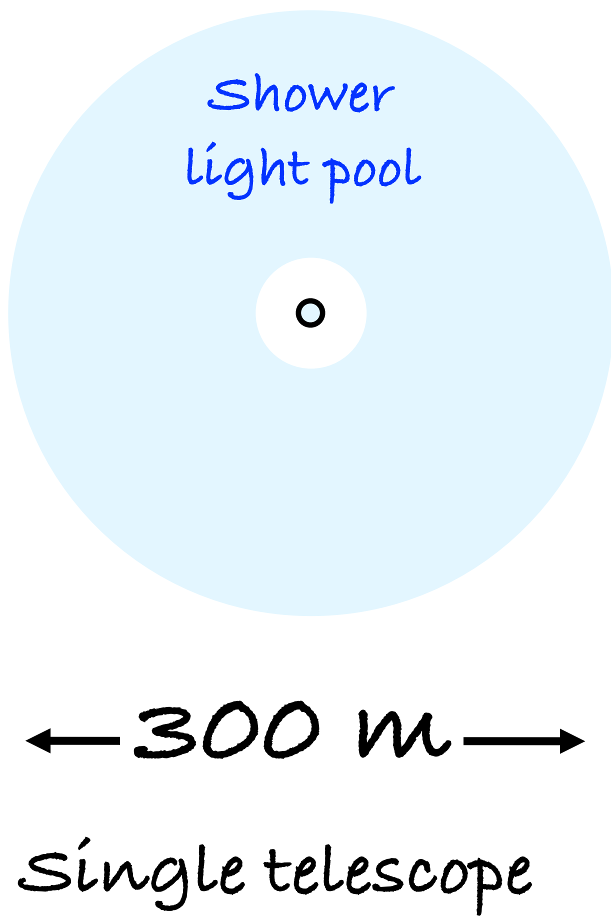


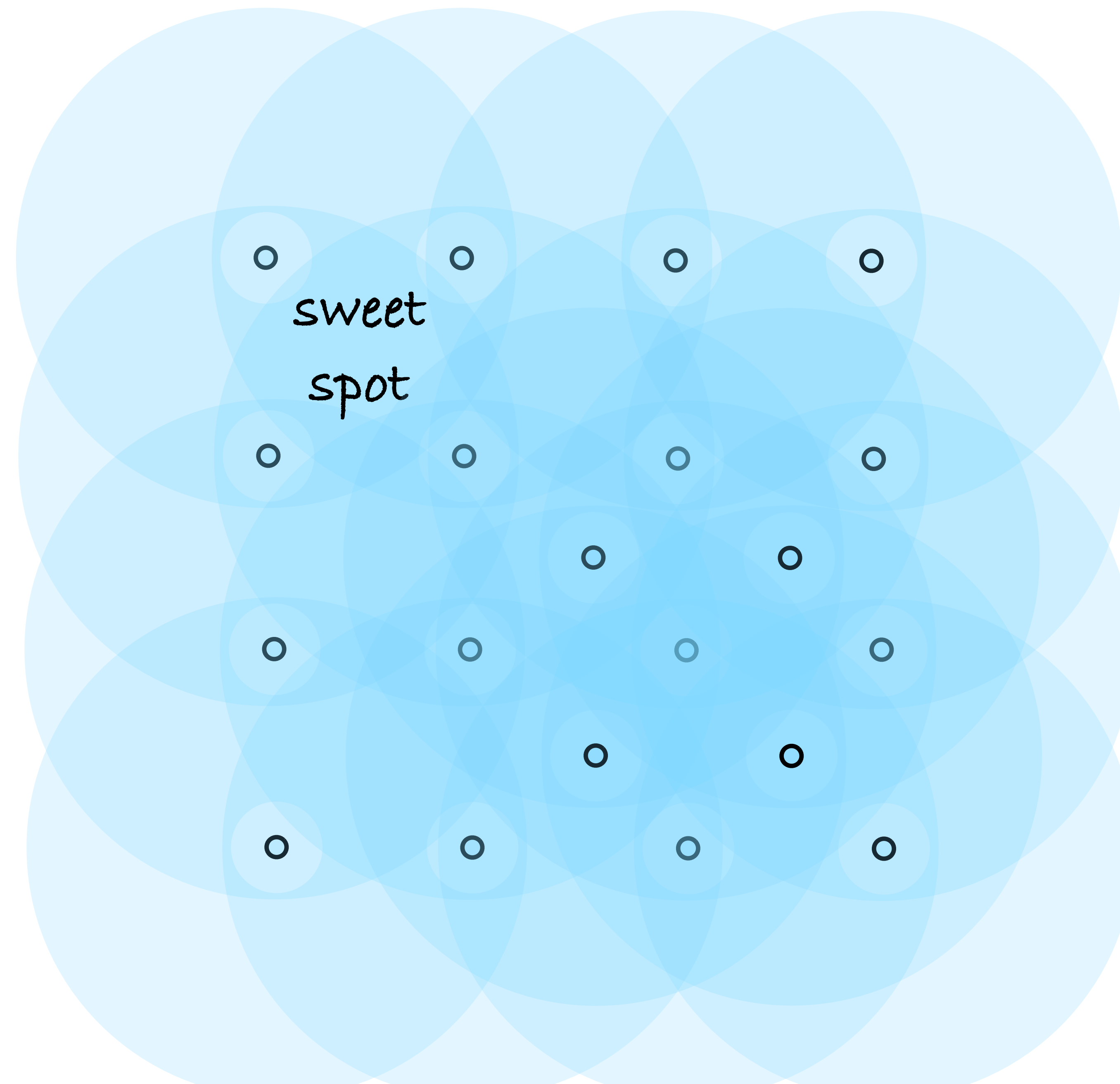
Boosting sensitivity & resolution: Arrays of Cherenkov telescopes

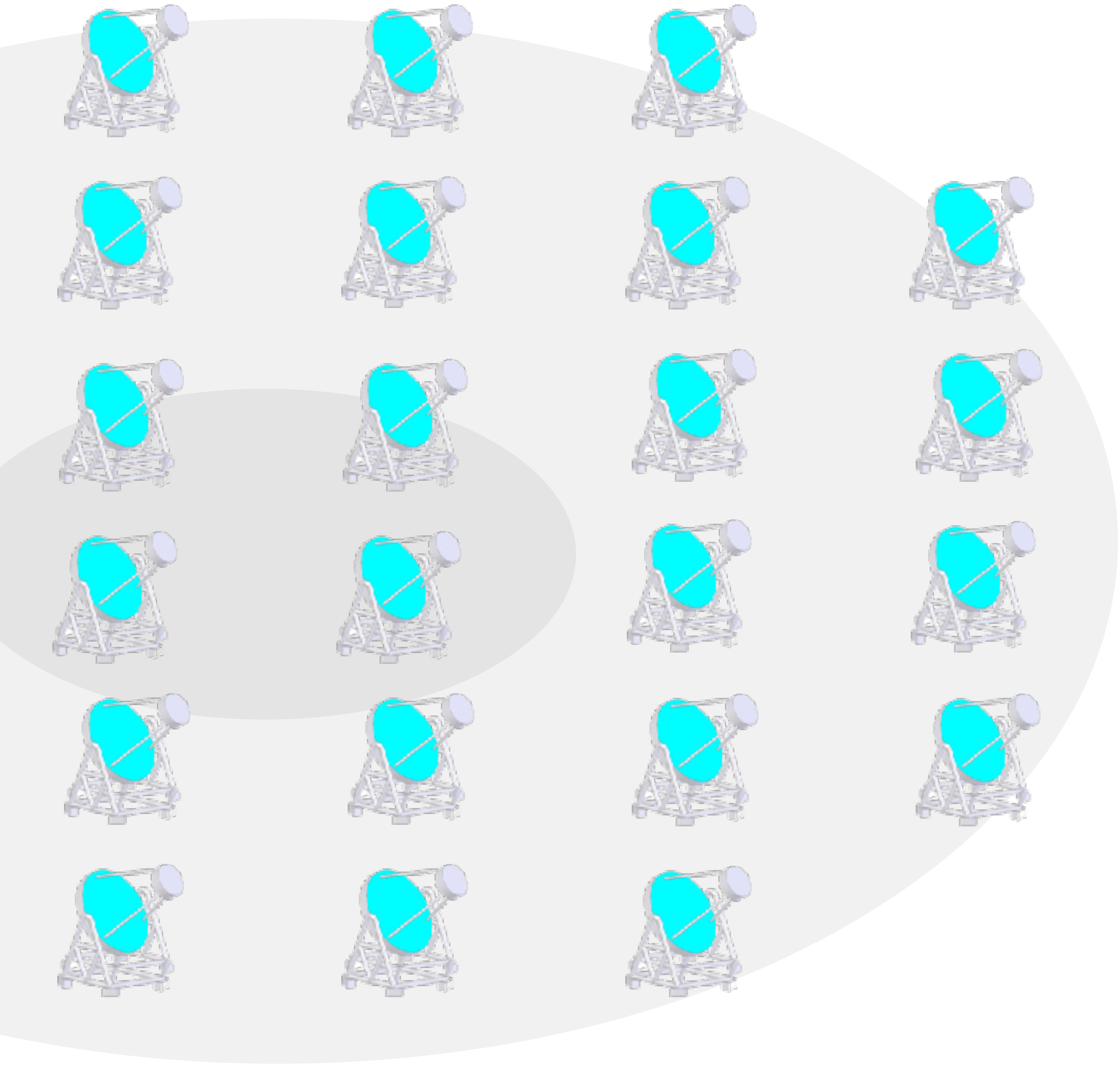




Boosting sensitivity & resolution: Arrays of Cherenkov telescopes



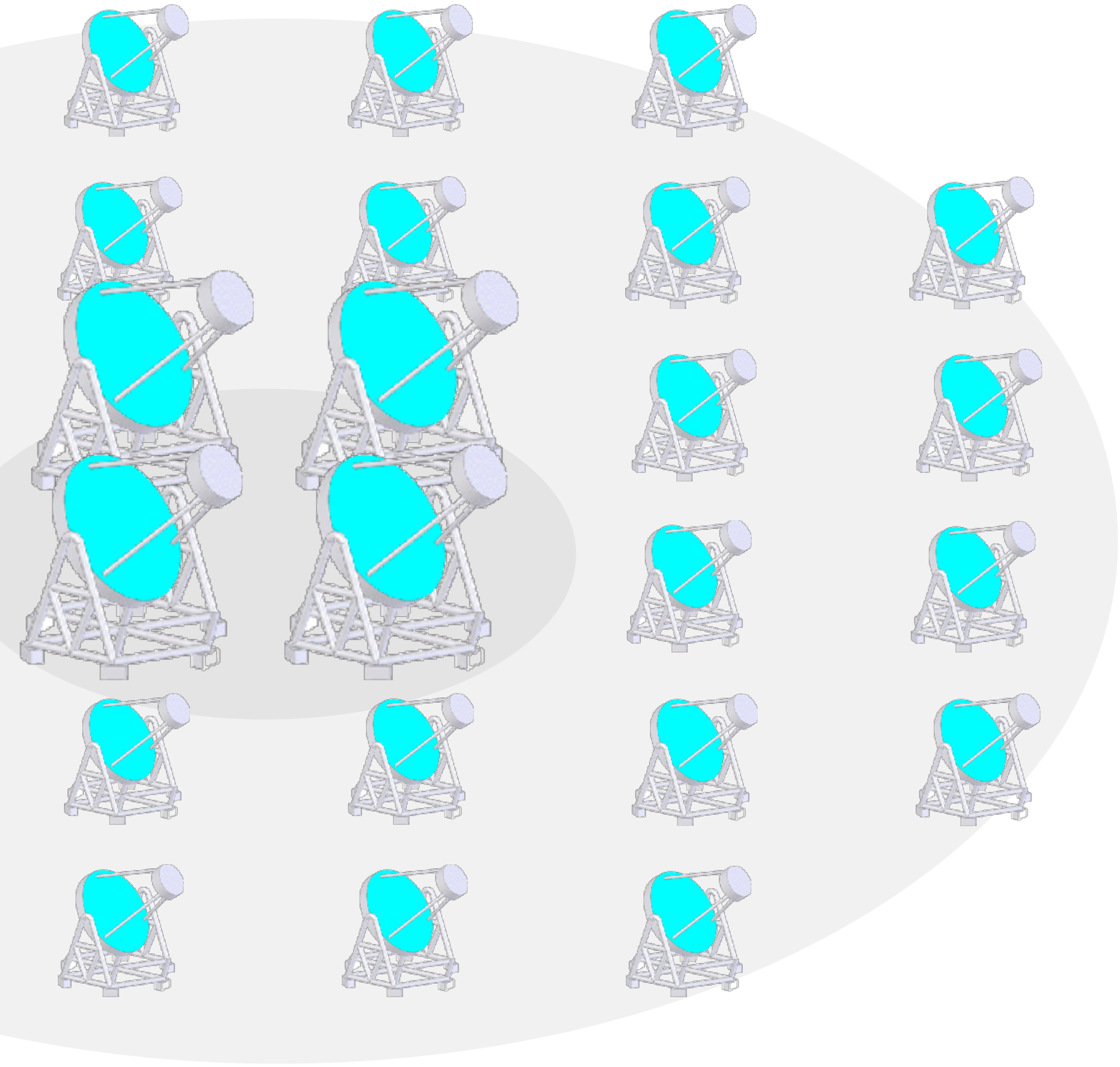




Core array:

mCrab sensitivity
in 0.1–10 TeV range

Not to scale !



Low-energy section

energy threshold

of some 10 GeV

(a) bigger dishes or

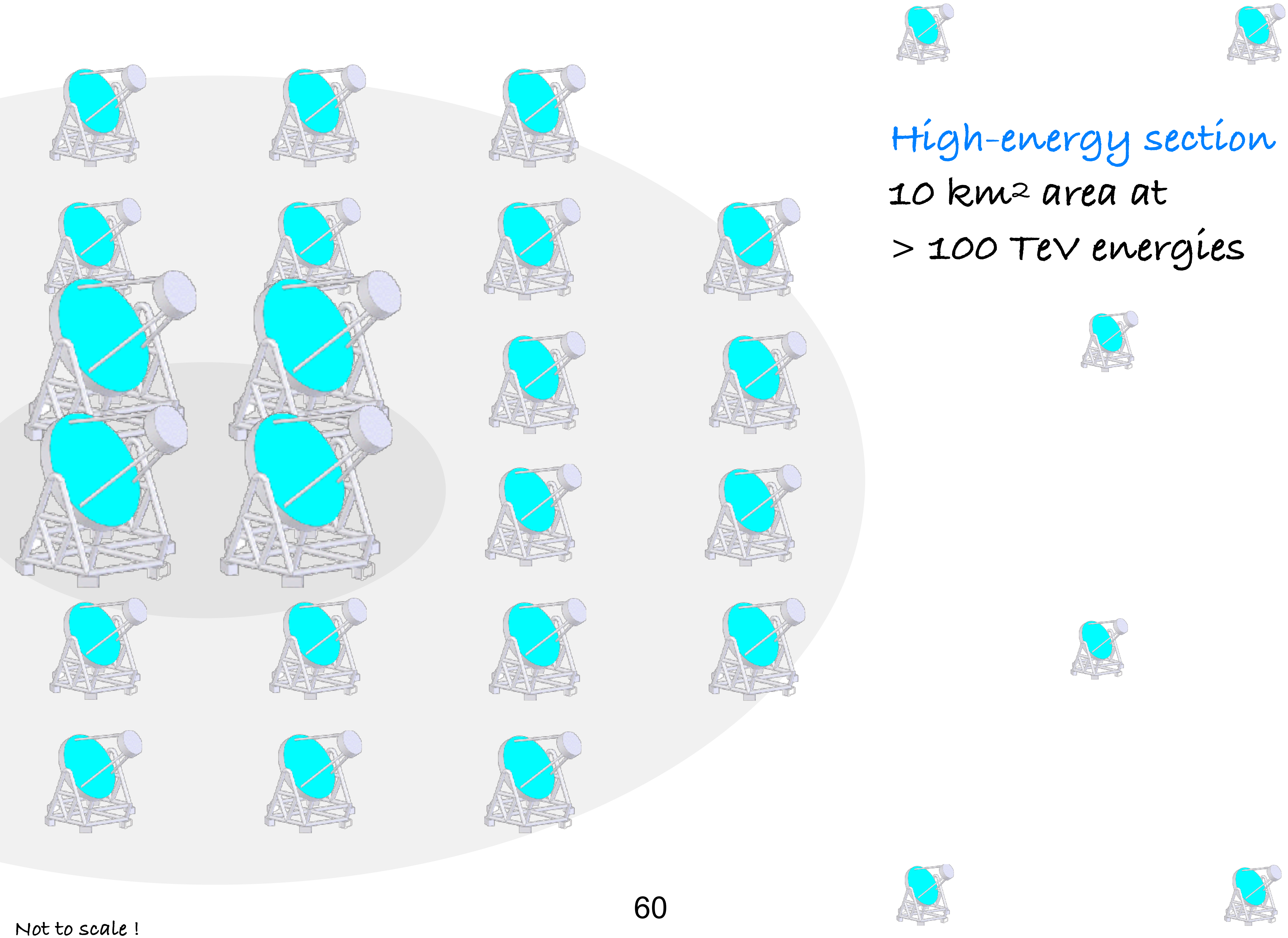
Not to scale !

Low-energy section

energy threshold
of some 10 GeV

(a) bigger dishes or
(b) dense packing / high-QE sensors

Not to scale !



High-energy section

10 km² area at

> 100 TeV energies

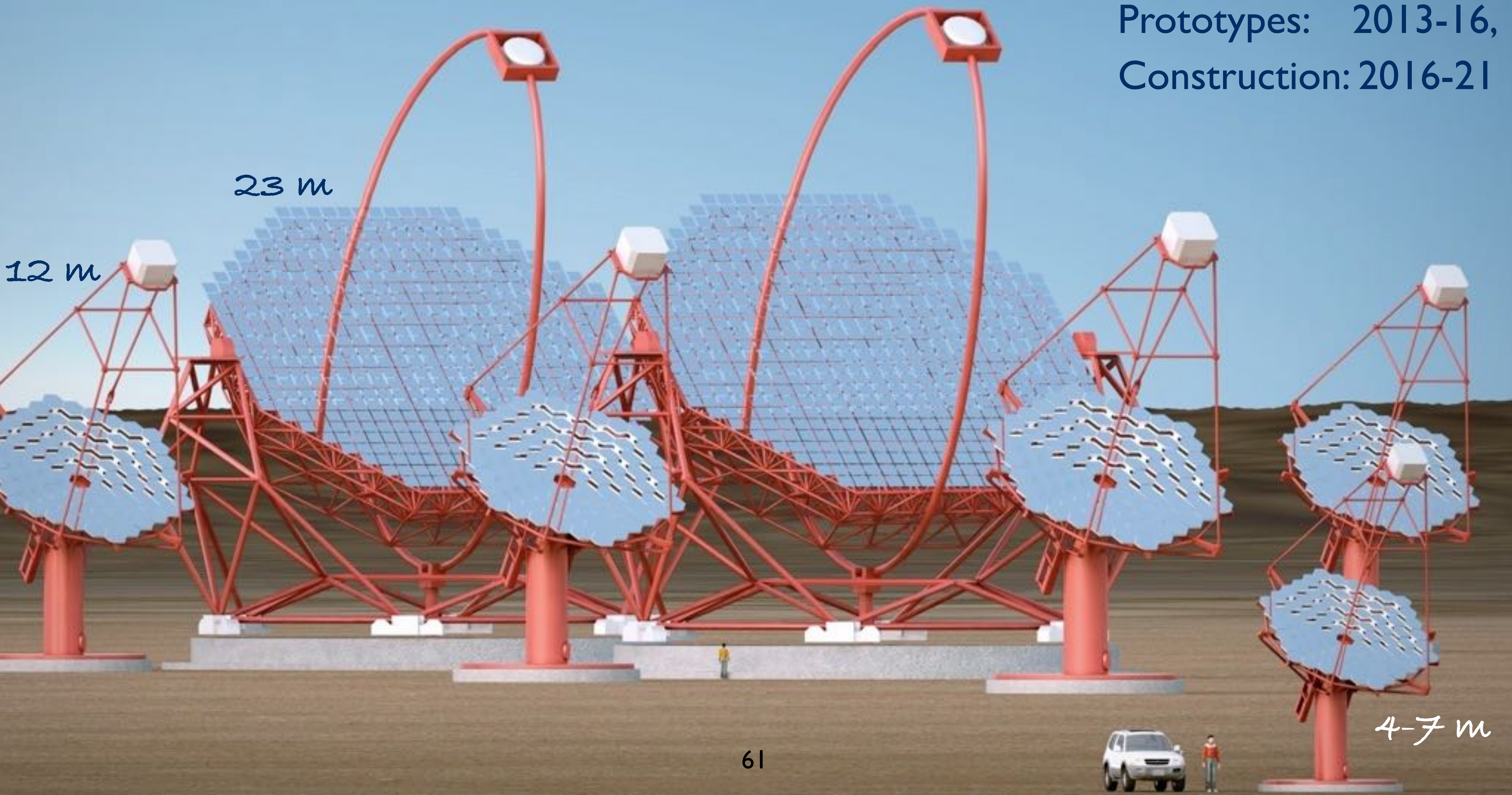
Not to scale !

CTA

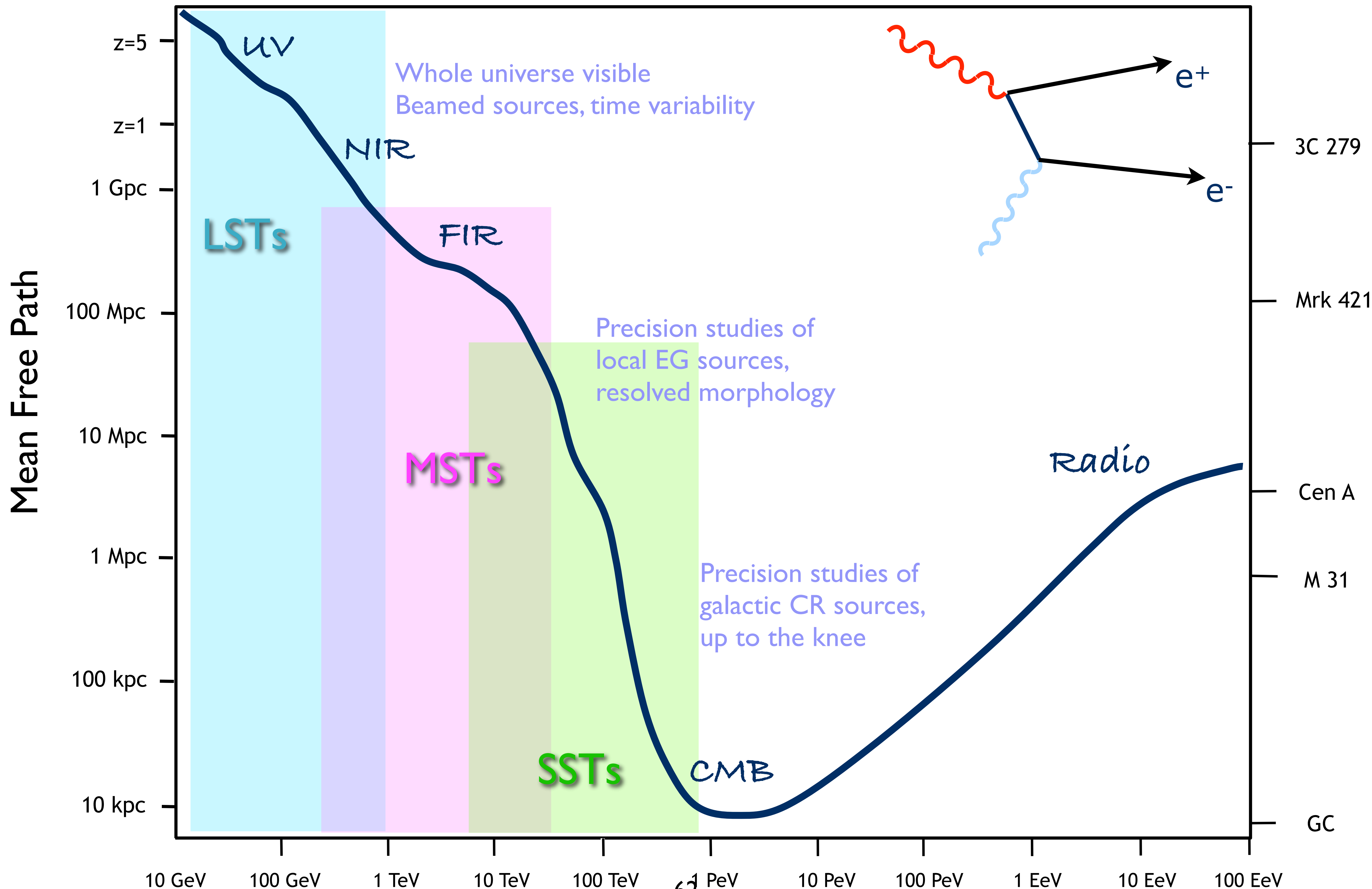
10x more sensitive than current instruments
+ much wider energy coverage and field of view
substantially better angular and energy resolution

telescopes: ~100 (3 sizes)

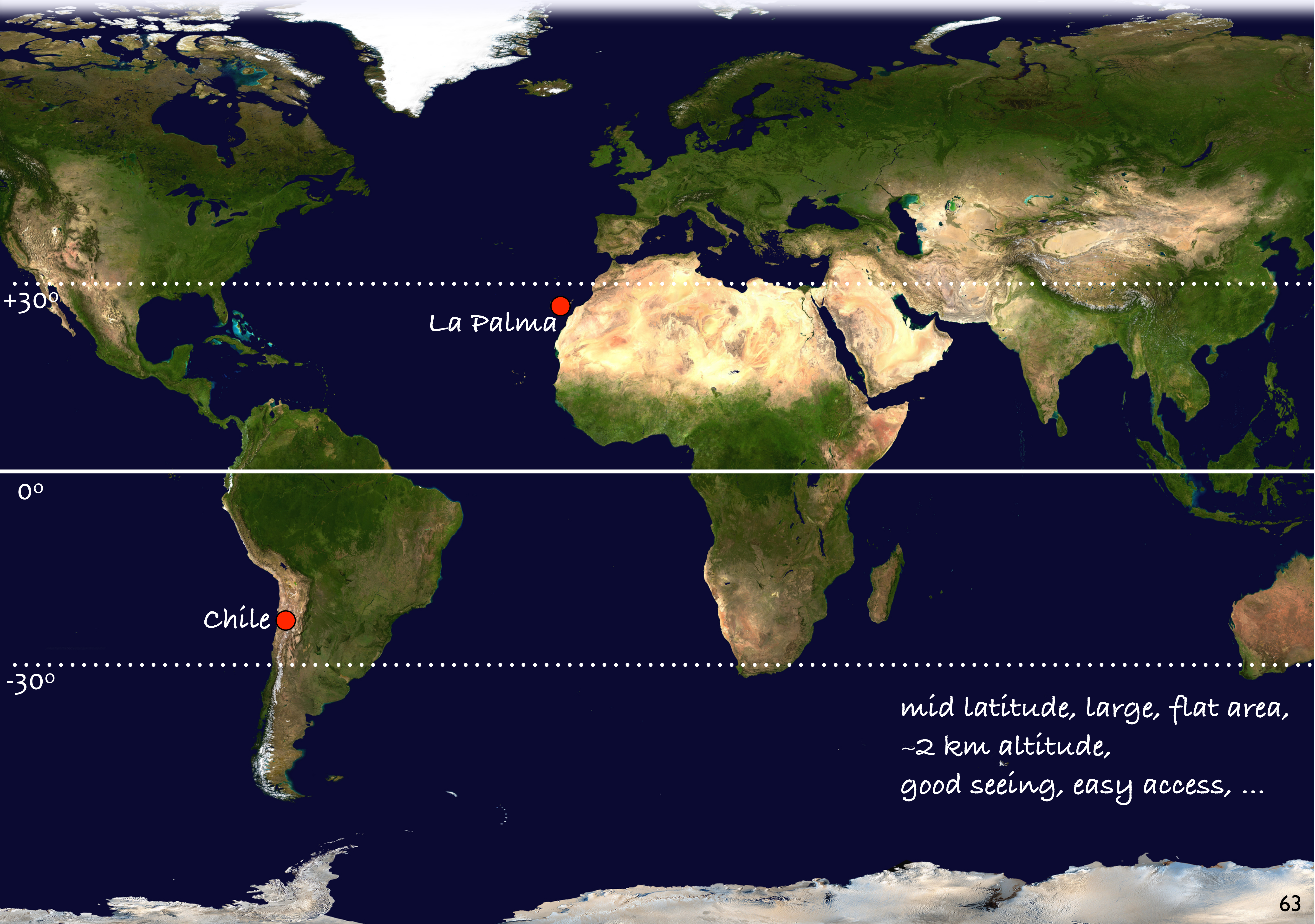
Design: 2008-12,
Prototypes: 2013-16,
Construction: 2016-21



The Gamma-Ray Horizon $\gamma_{VHE} + \gamma \longrightarrow e^+e^-$



One observatory with two sites

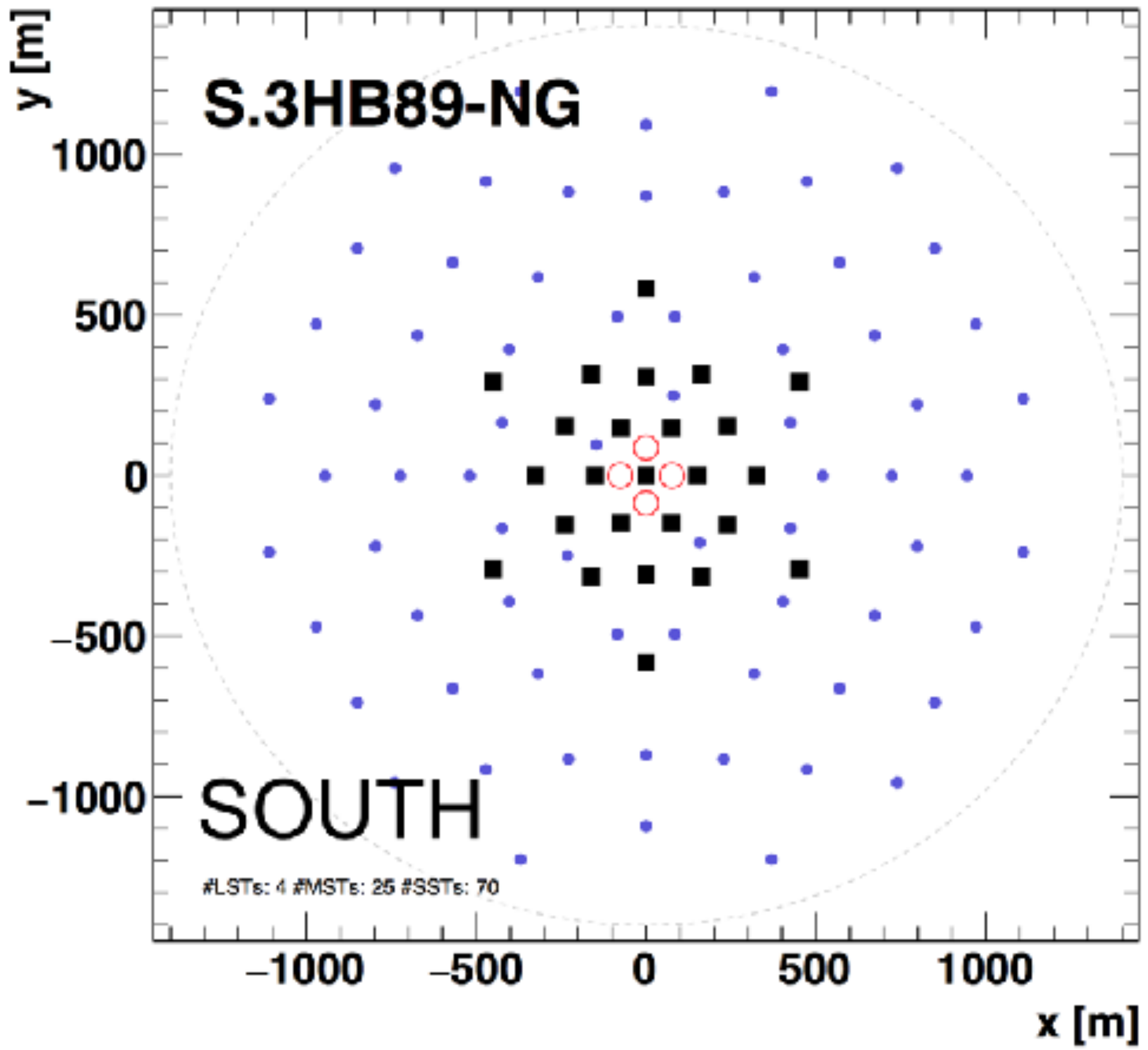


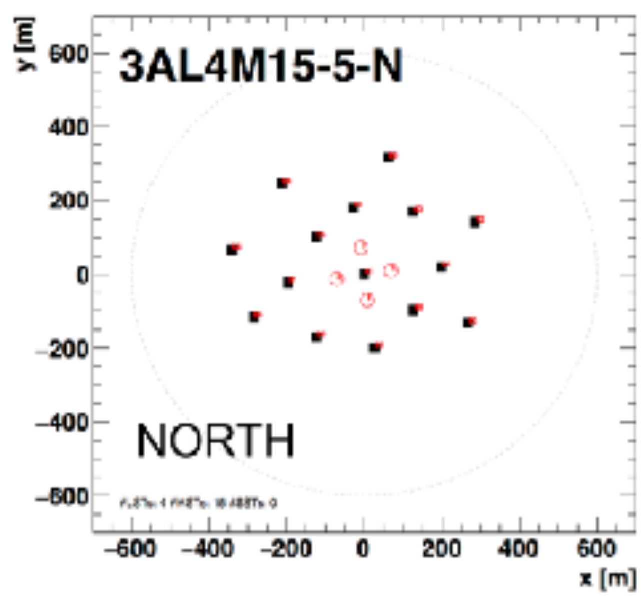
La Palma, Spain (near MAGIC site)

Paranal, Chile (ESO site, Atacama desert)

Baseline Arrays

South: 4 LSTs 25 MSTs 70 SSTs **North: 4 LSTs 15 MSTs**



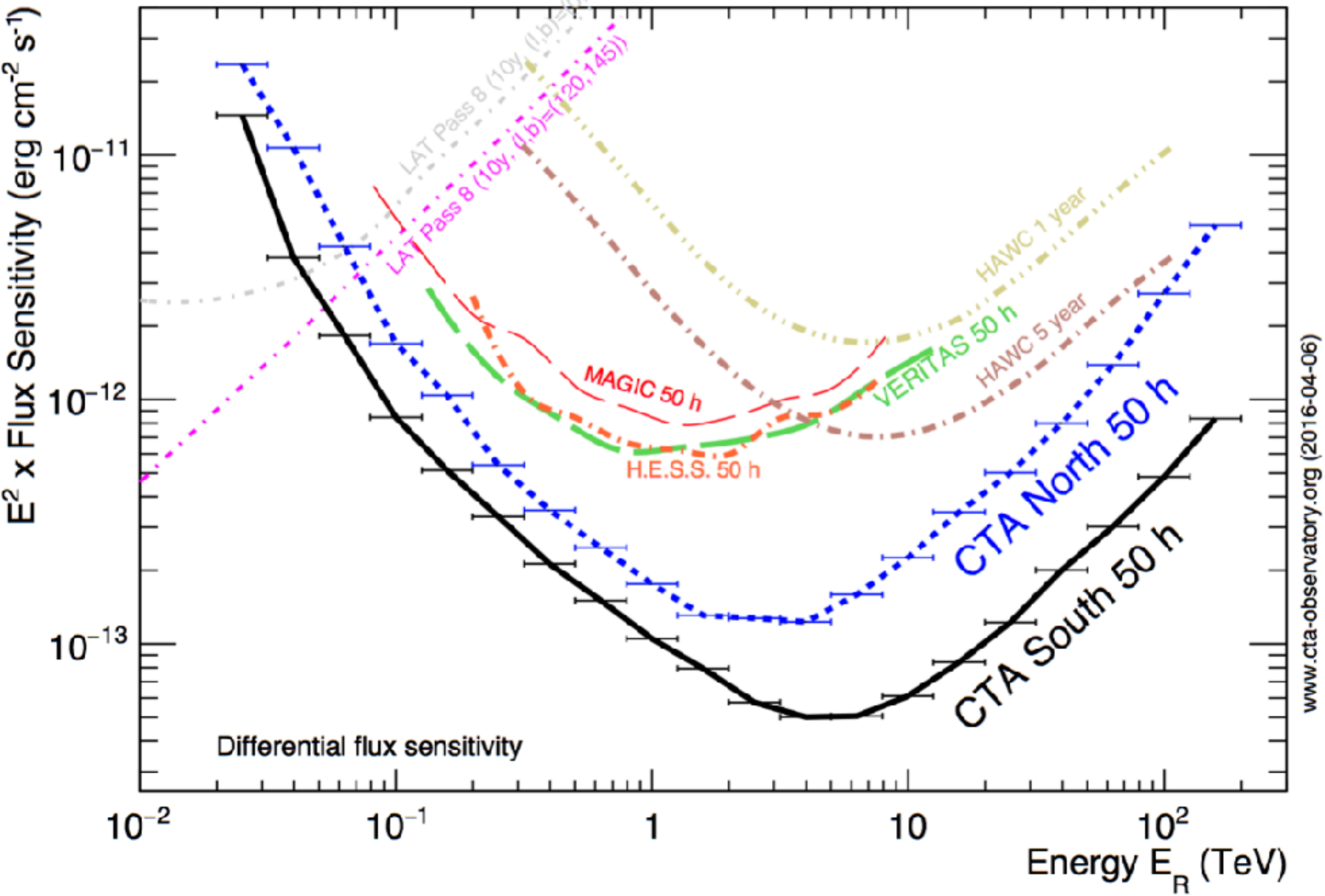


to scale

full energy range

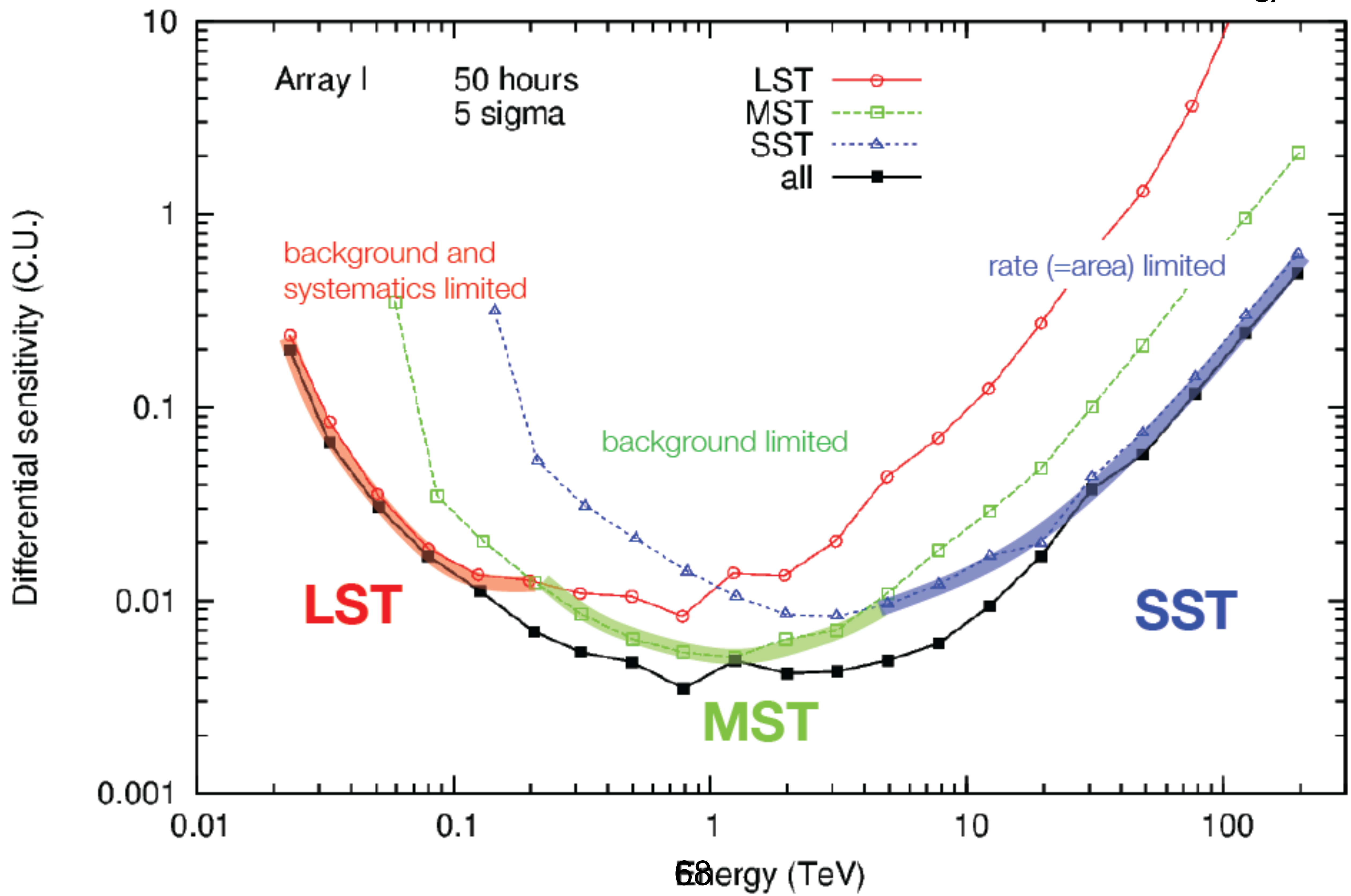
mainly low energies

Sensitivity to point sources



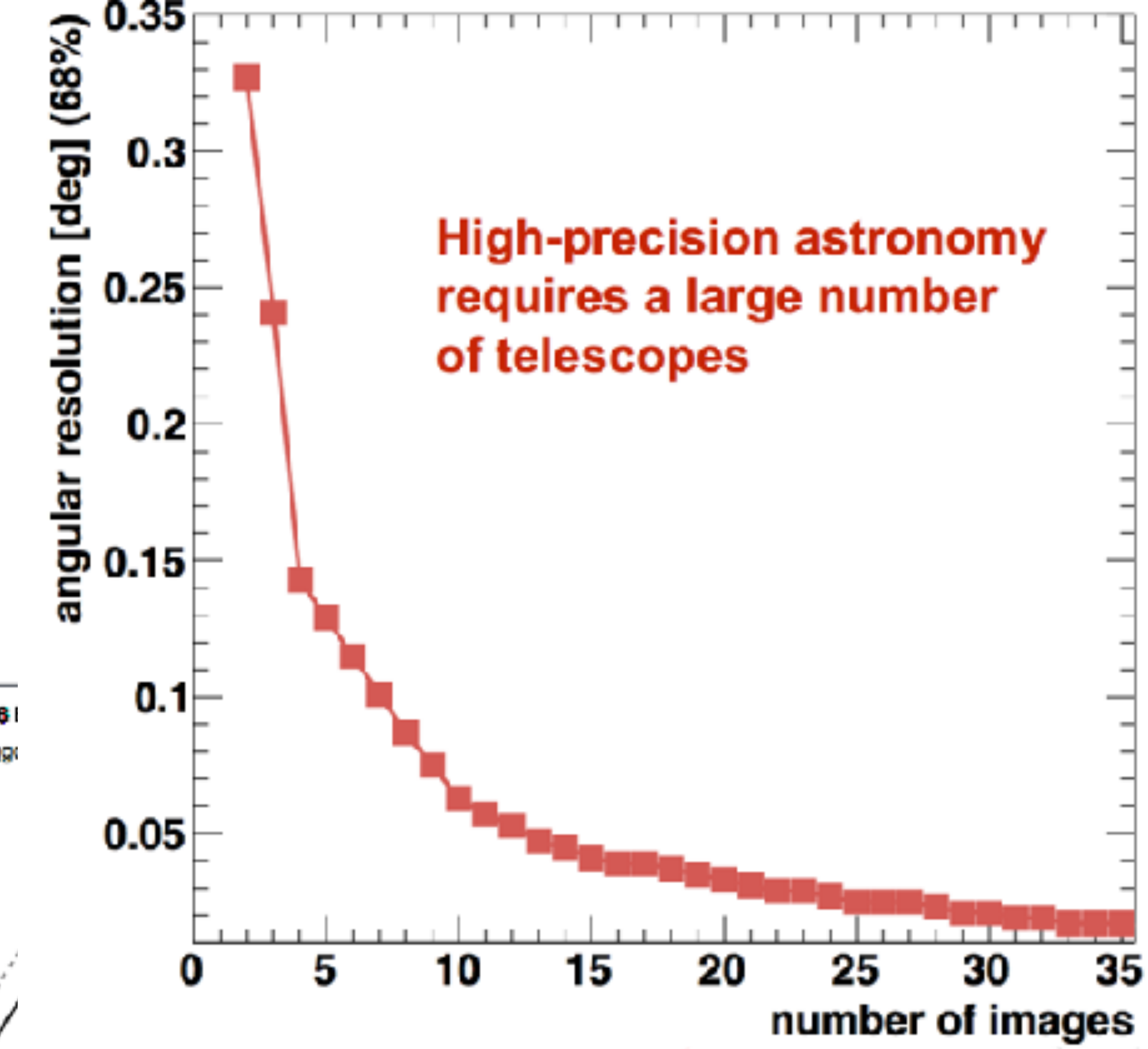
3 telescope sizes for a wide energy coverage

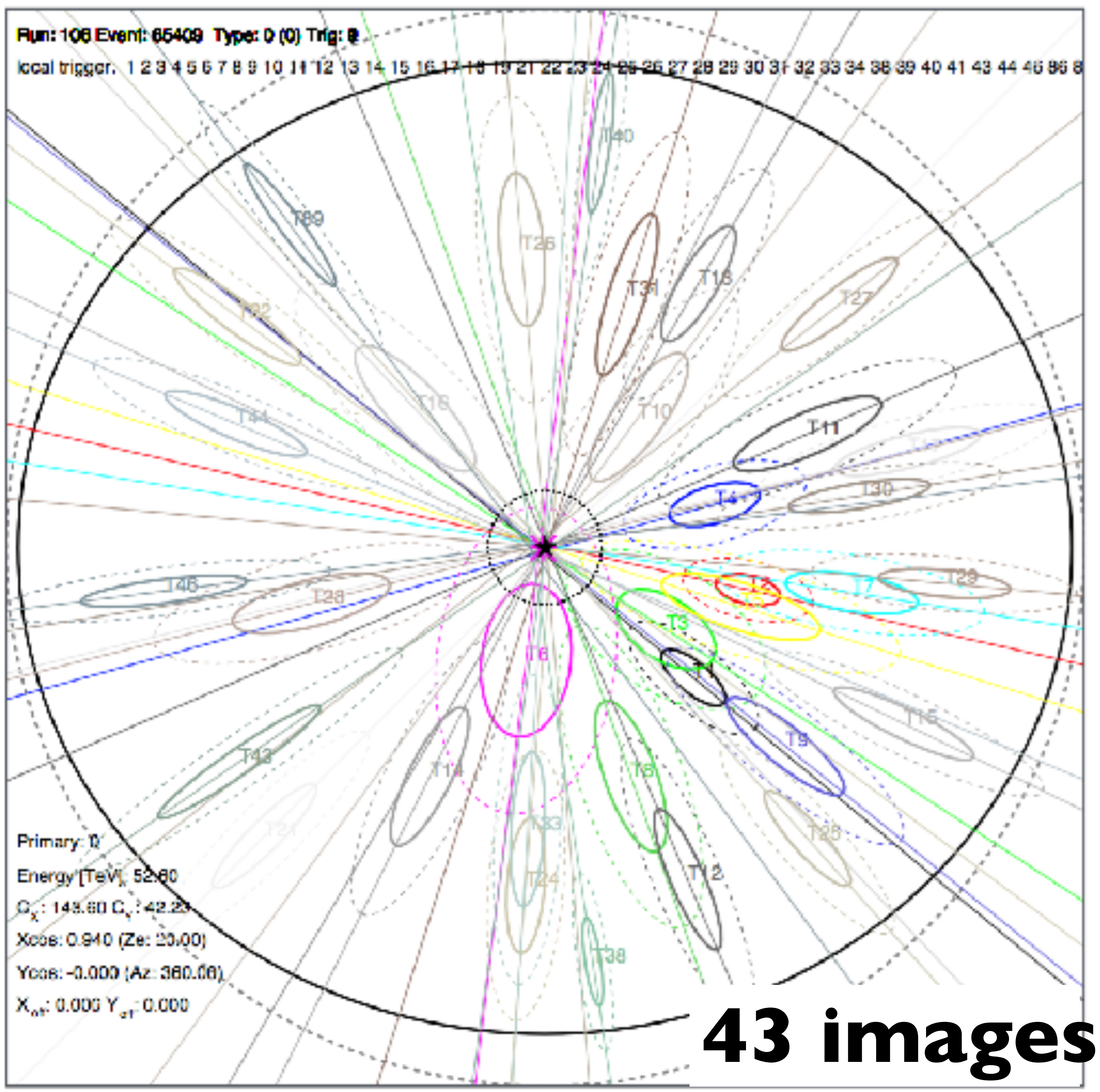
Sensitivity (in units of Crab flux)
for detection in each 0.2-decade energy band



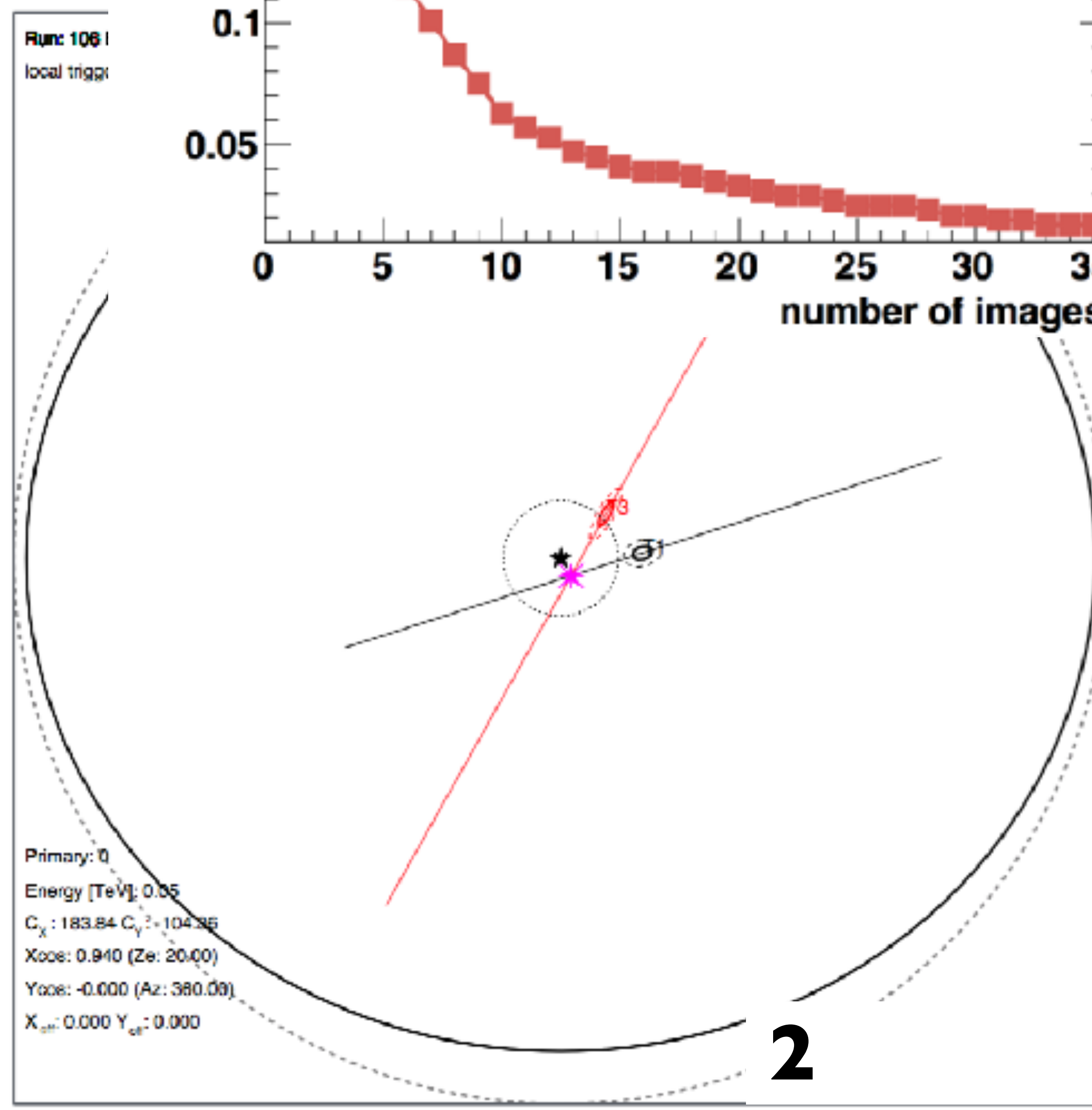
Angular Resolution:

< 0.1° for ≥ 5 images
or for E > 100 GeV (≥ 4 images)





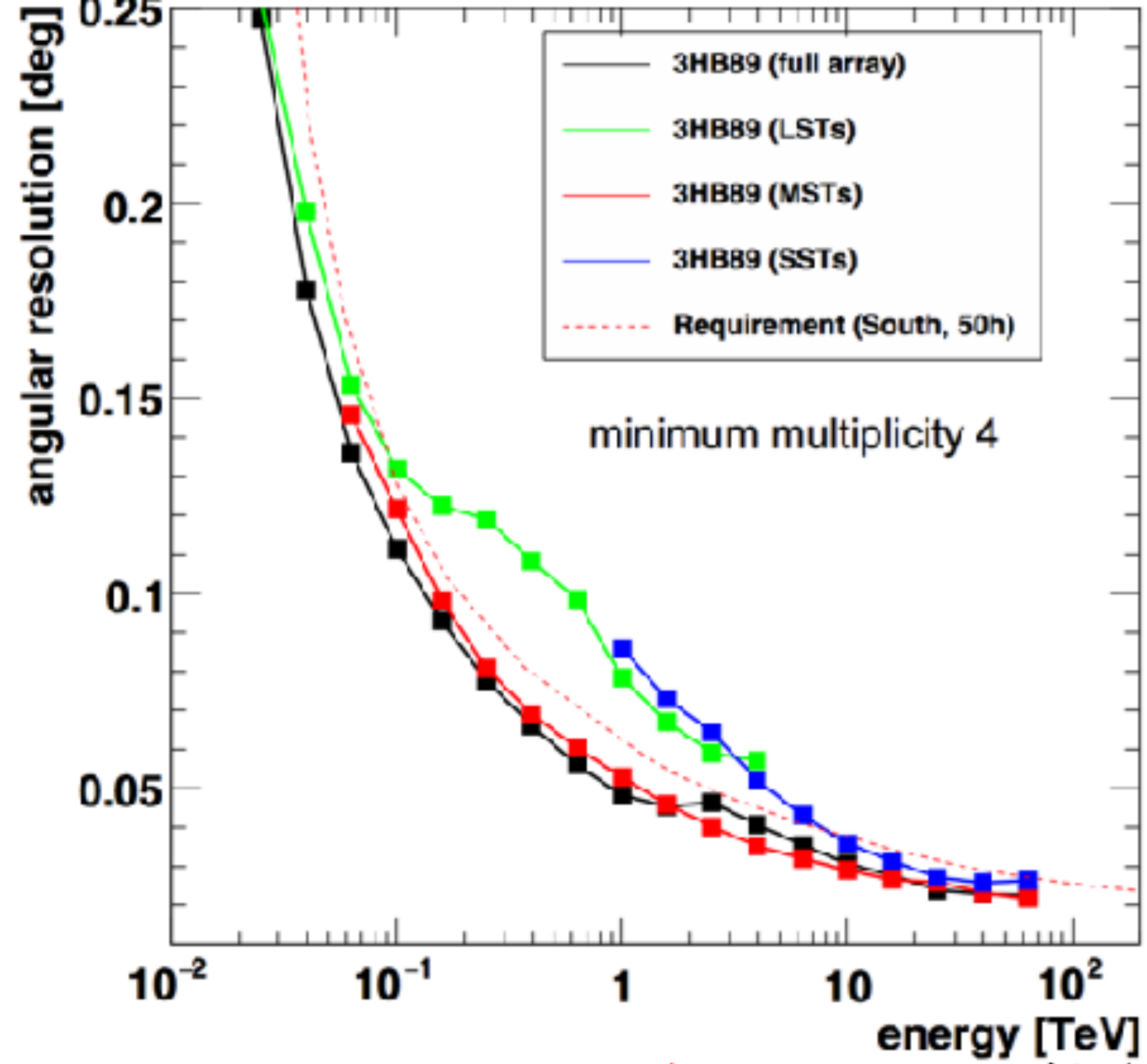
43 images

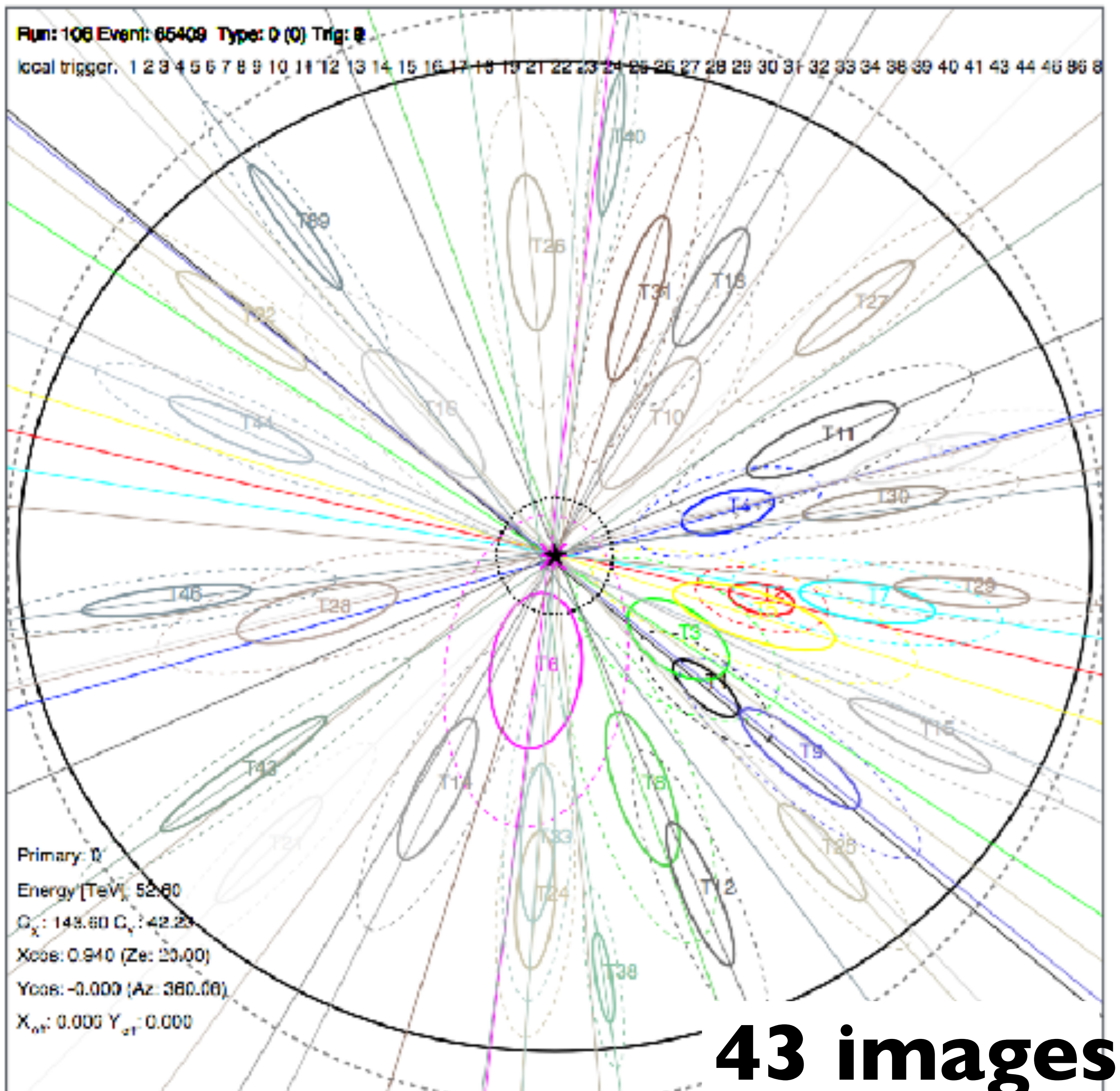


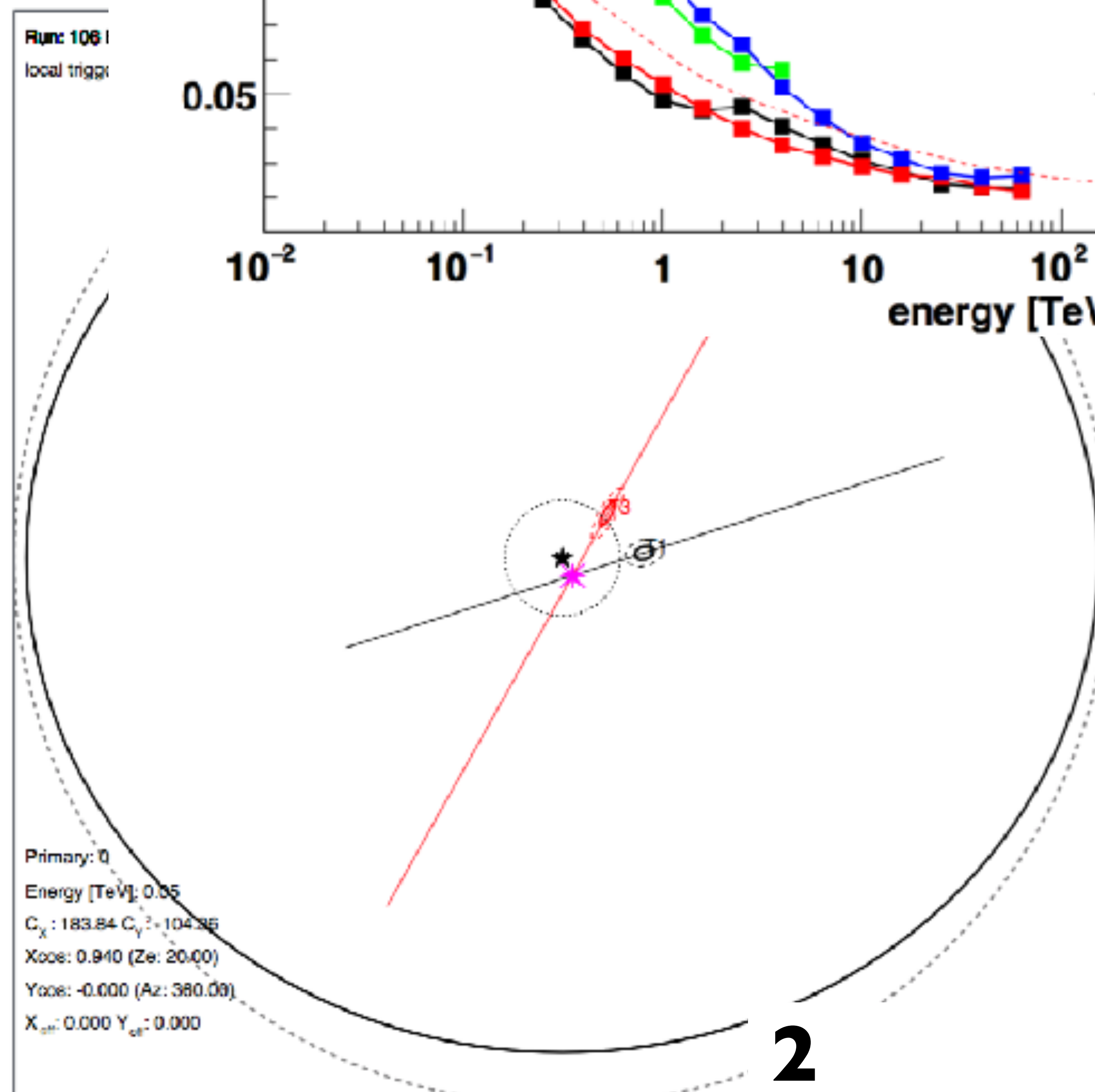
2

Angular Resolution:

< 0.1° for ≥ 5 images
or for E > 100 GeV (≥ 4 images)







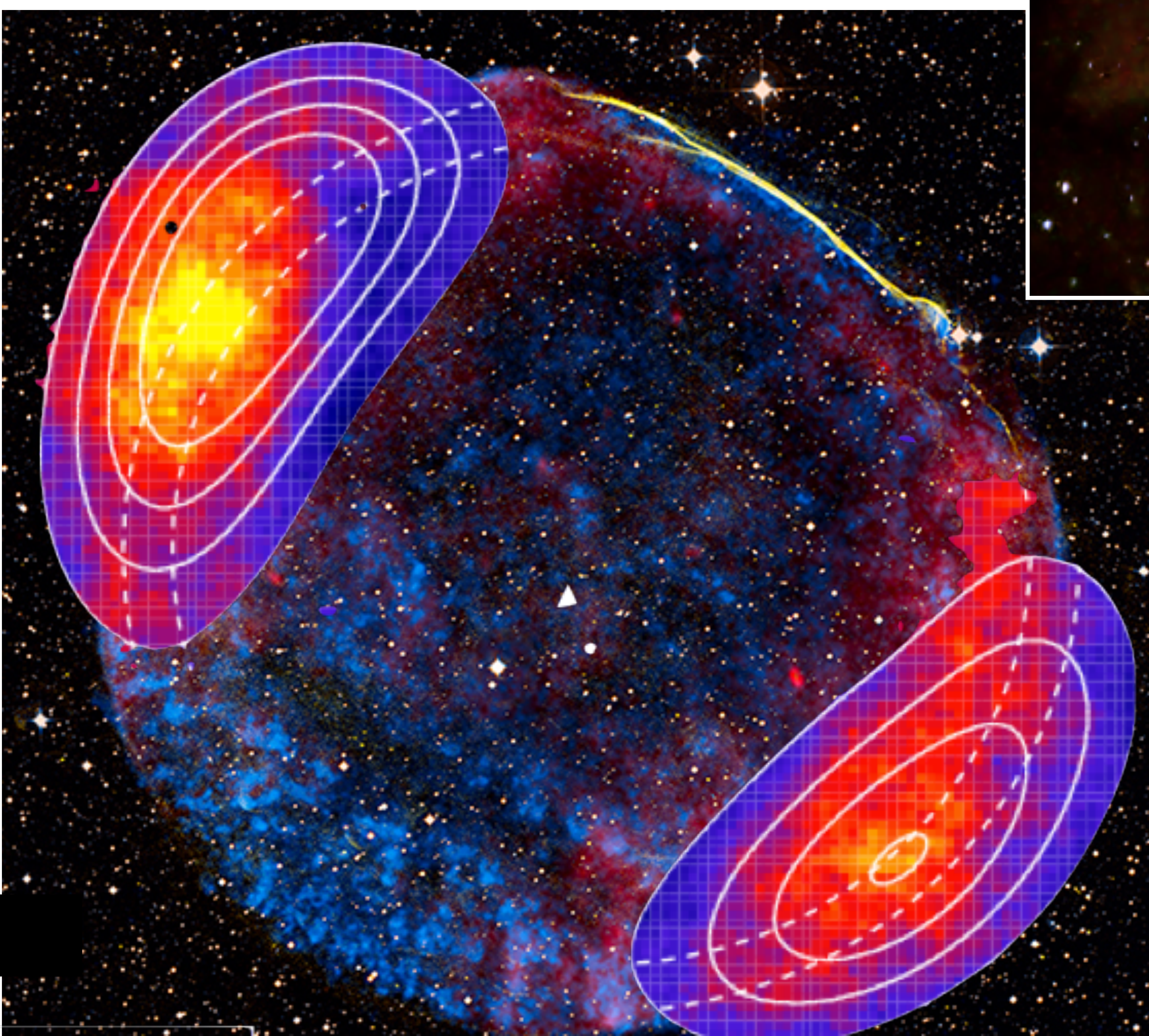
... allows study of morphologies

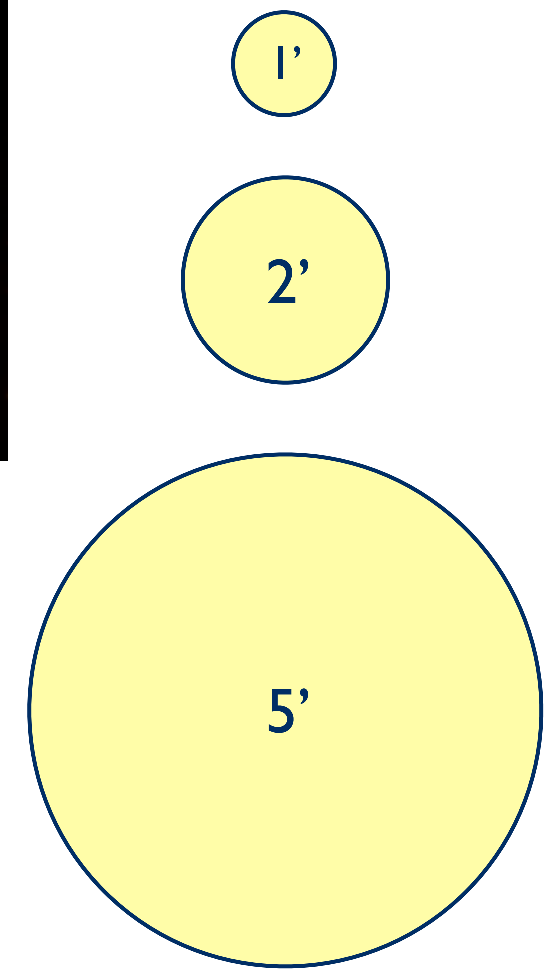
Hydra A

M 82

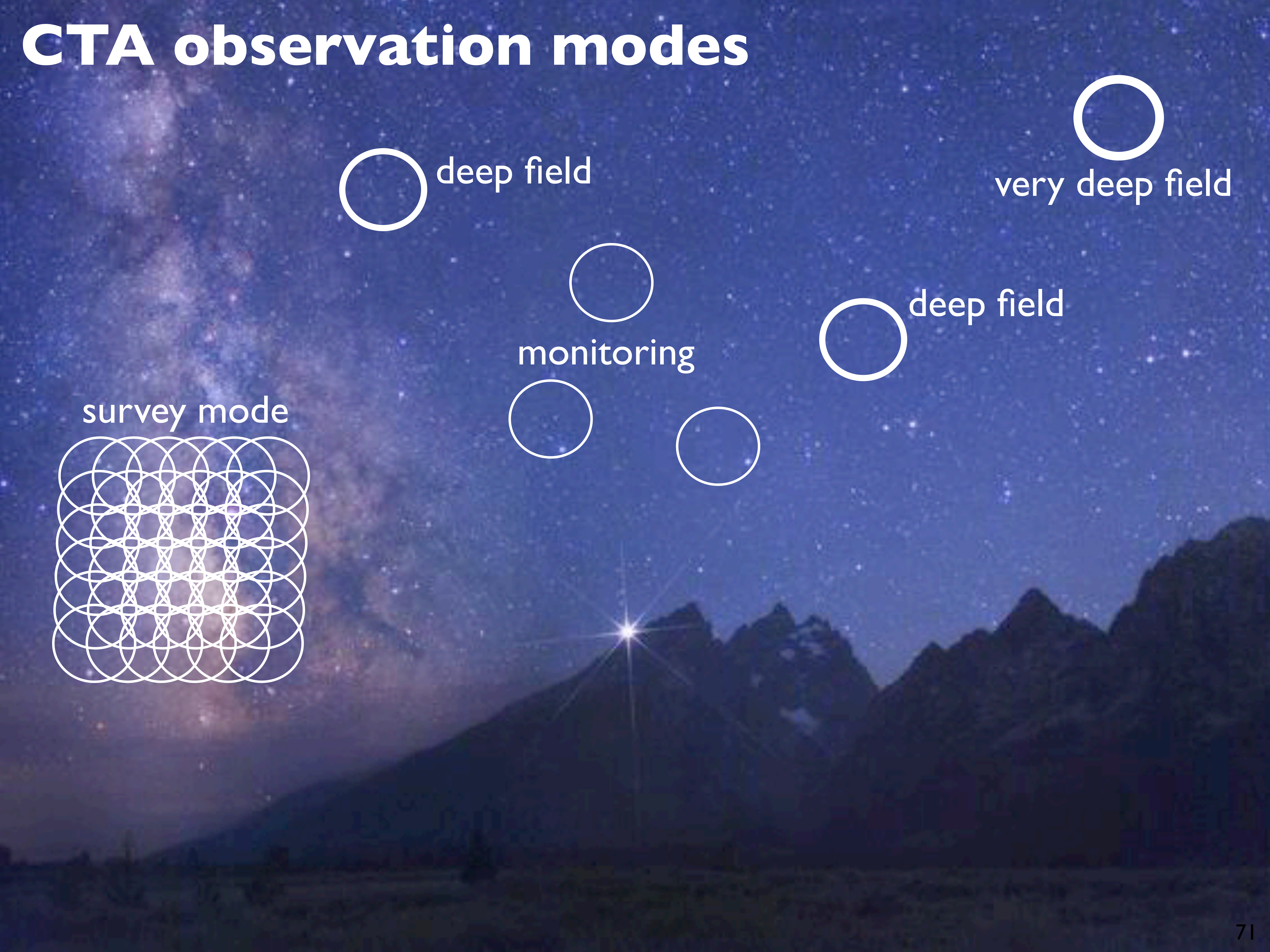
Cen A

SN 1006



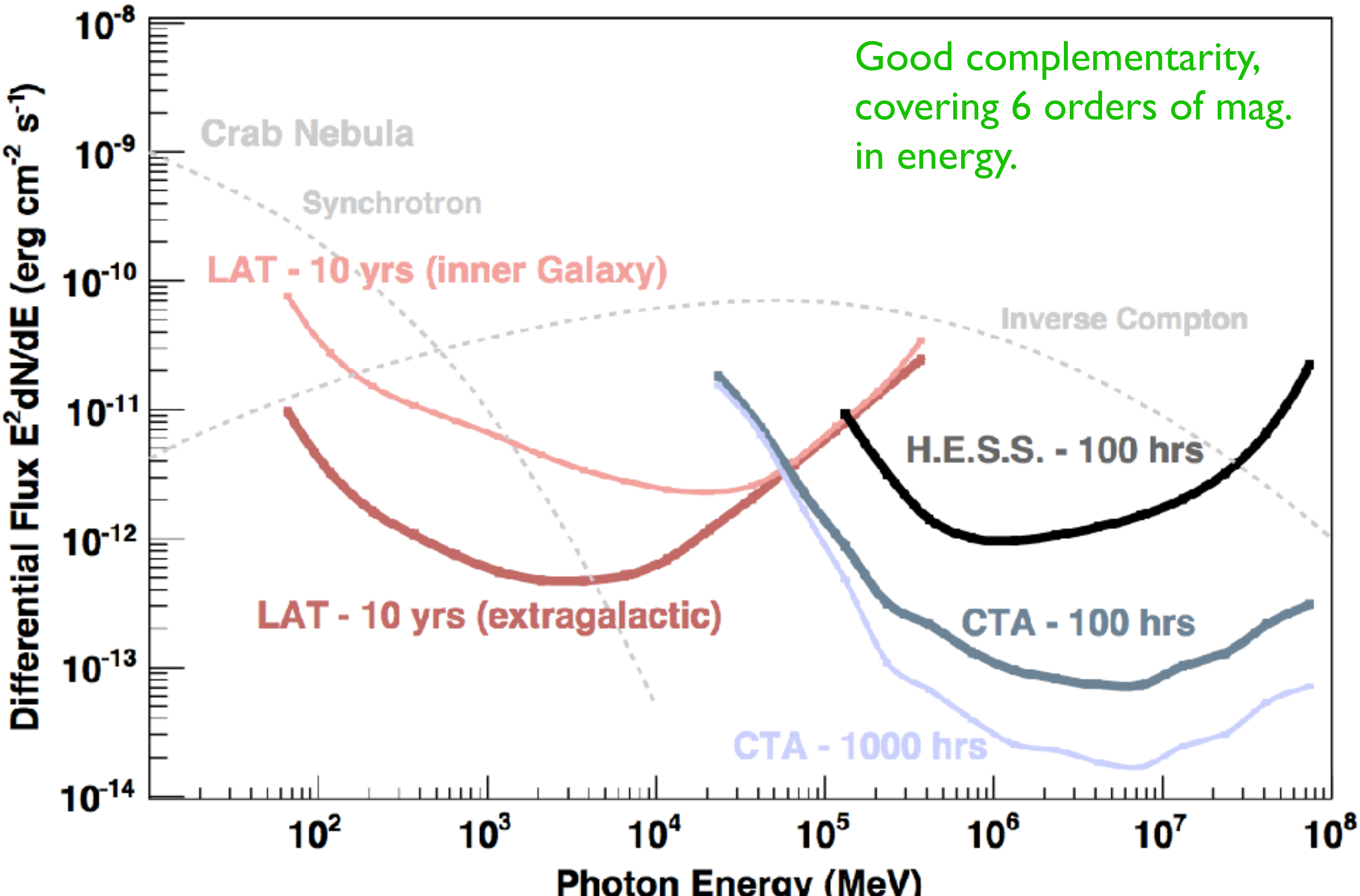


CTA observation modes



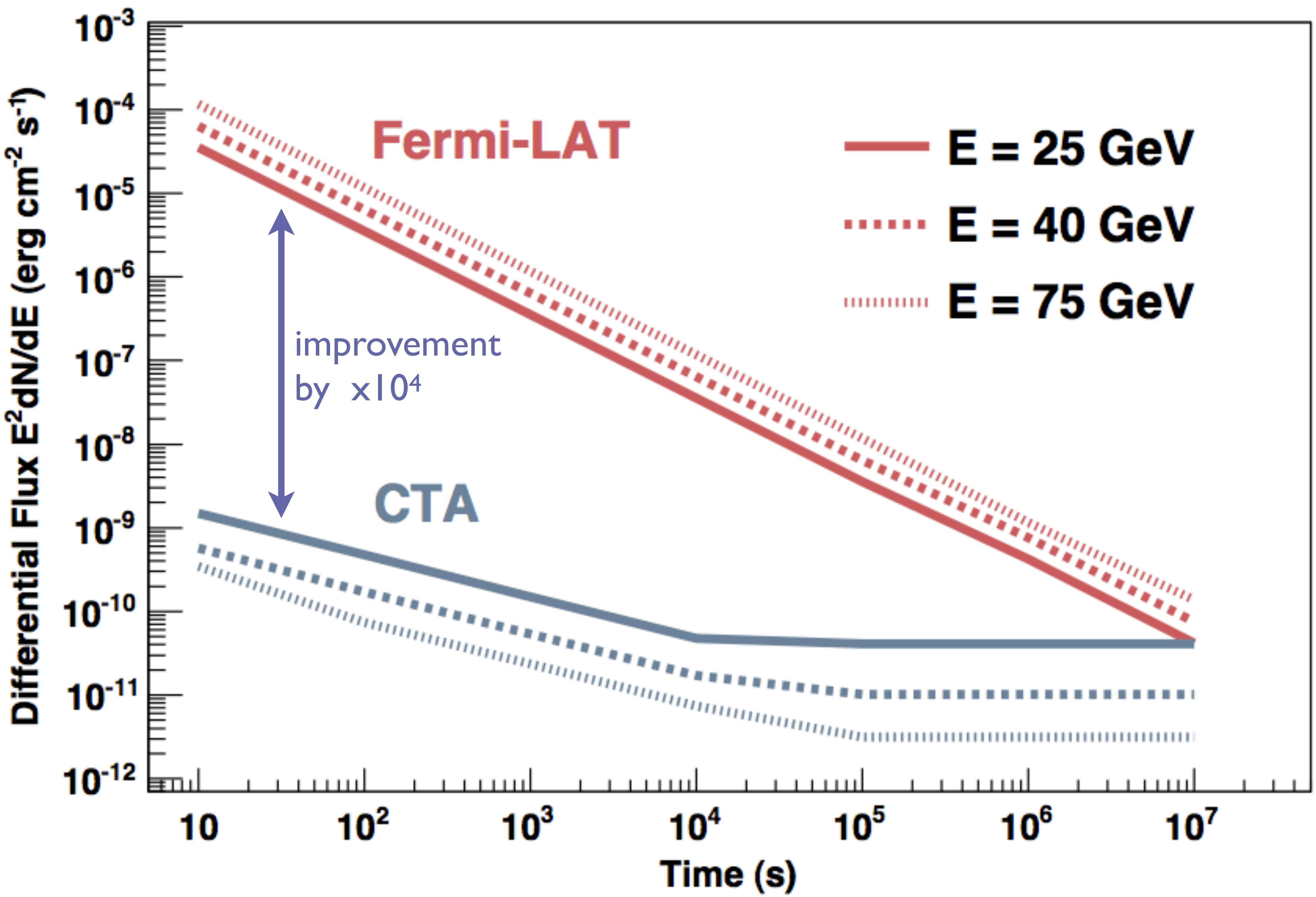
CTA and Fermi

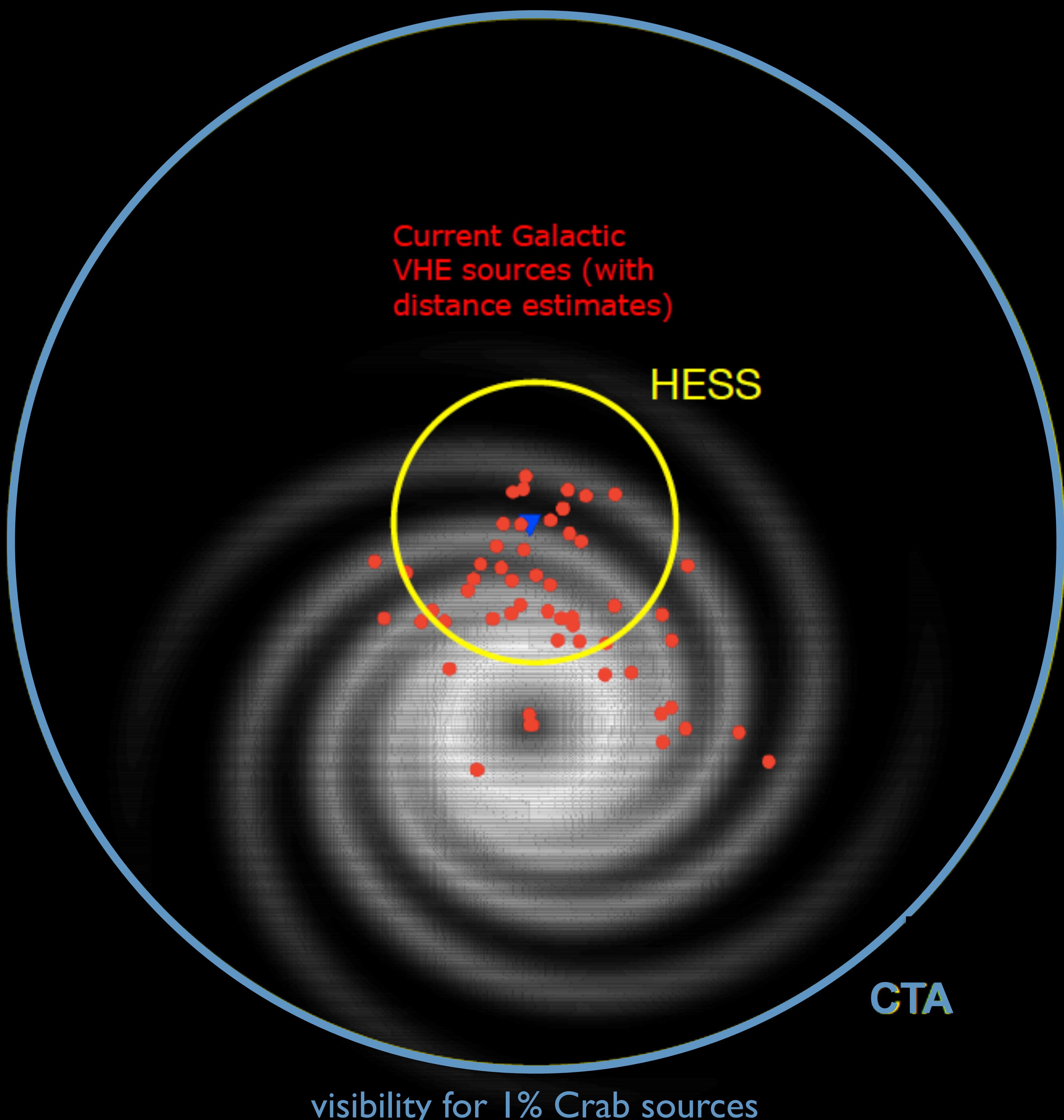
(Steady sources)



Variability and Short-Timescale Phenomena

(flares, GRBs, ... all sorts of transients)





CTA will be the ultimate instrument …

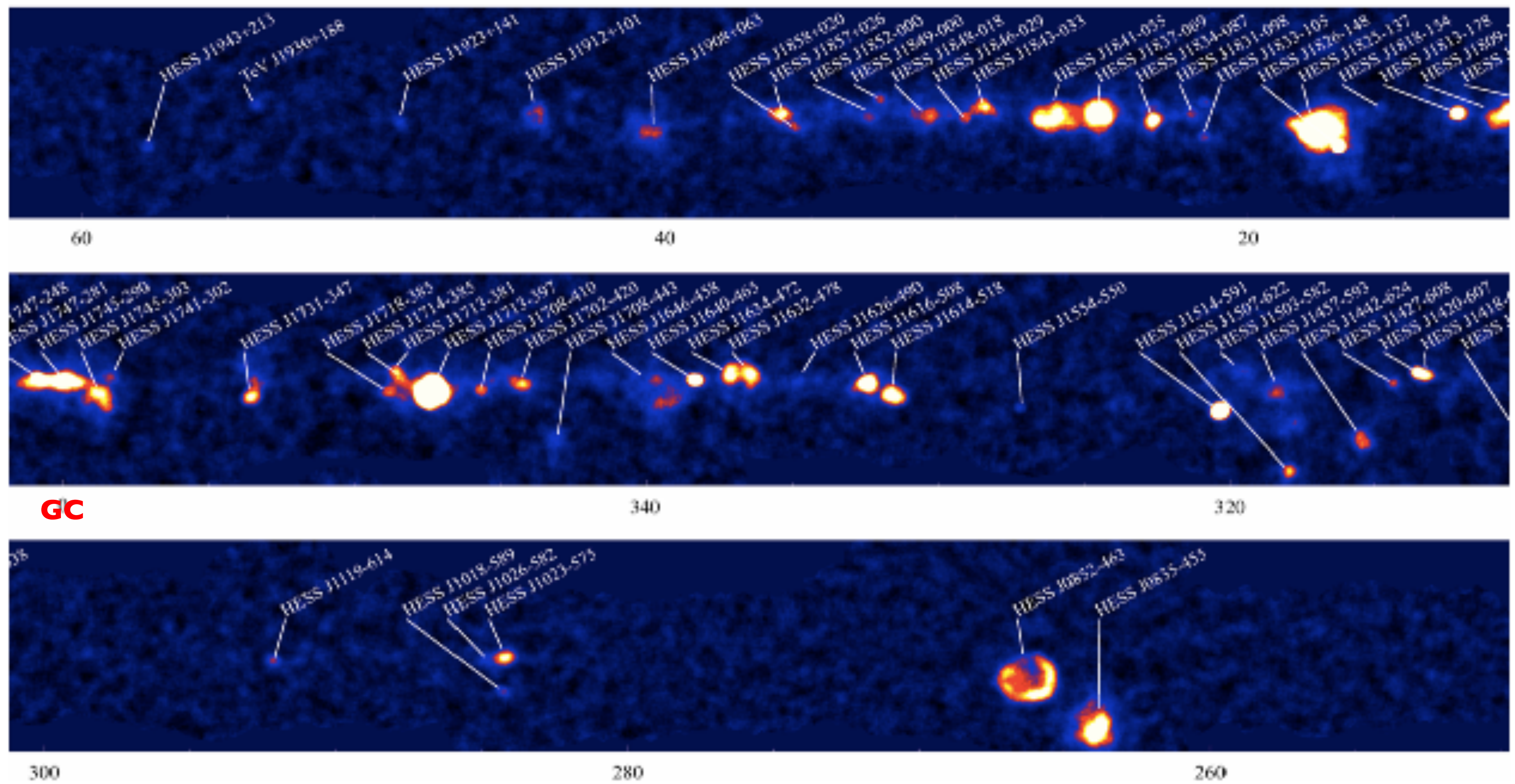
… for surveys
~400x faster than H.E.S.S.

… for transients
at 25 GeV,
10^4x better than Fermi

CTA prognosis: >1000 new sources

galactic disc

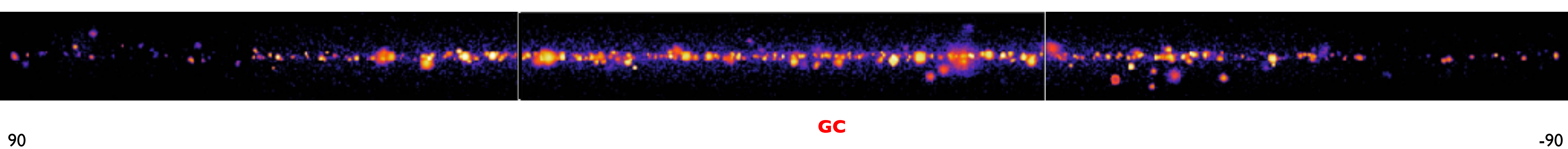
HESS
+60 … -120°



58 sources

CTA prognosis:

~600 sources



galactic + extragalactic: ≥ 1000 sources

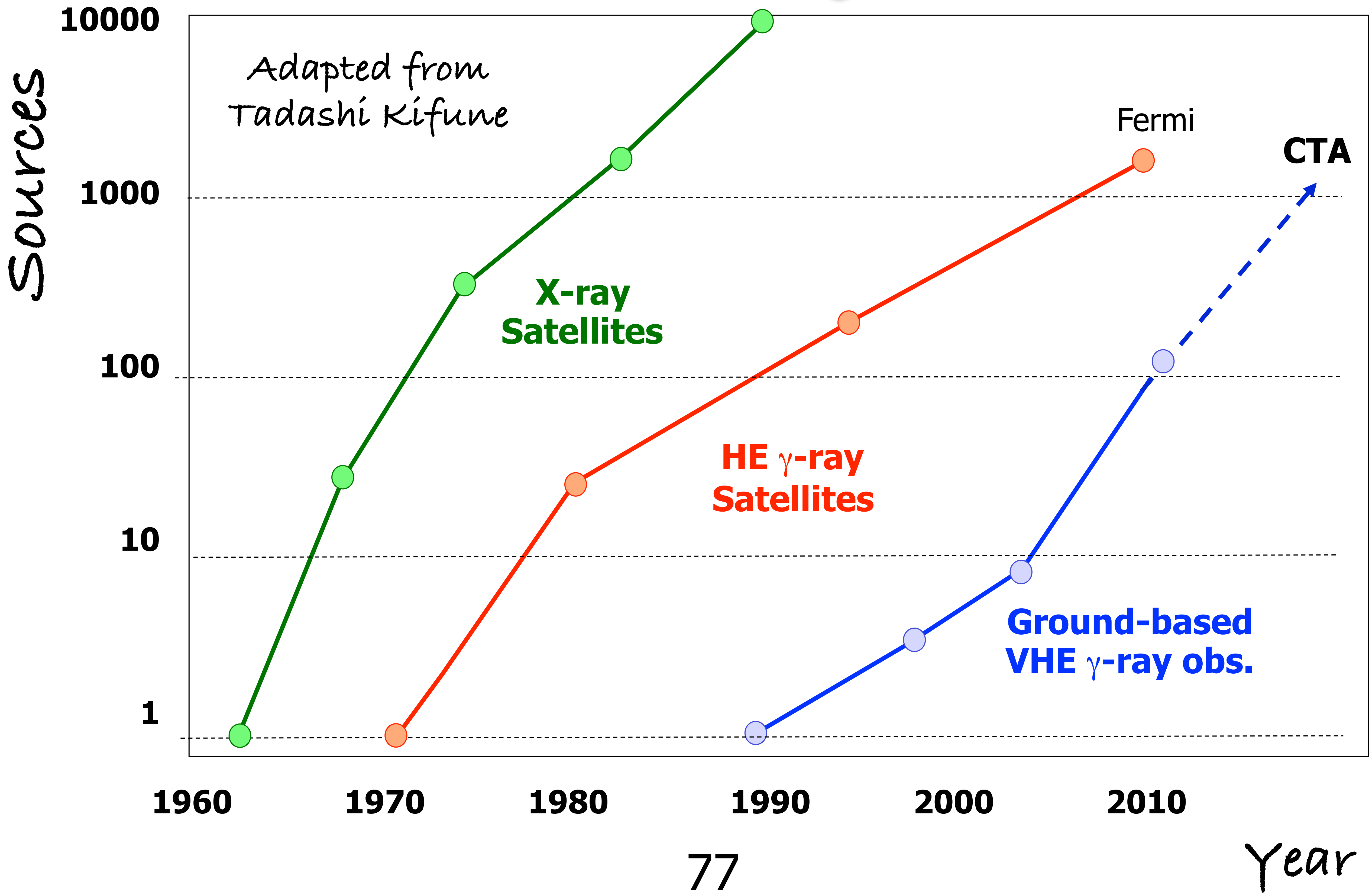
Multi-Messenger Physics:

Radio	LOFAR, ALMA, SKA …
optical	VLT, GMT, eELT, LSST, …
X-rays	SWIFT, XMM, SVOM, …
Gamma rays (keV-GeV)	Fermi, DAMPE, …
(TeV)	HAWC, LHAASO, **CTA**
neutrinos	IceCube/Gen2, KM3NeT
gravitational waves	Adv Ligo, KAGRA, Ligo-India

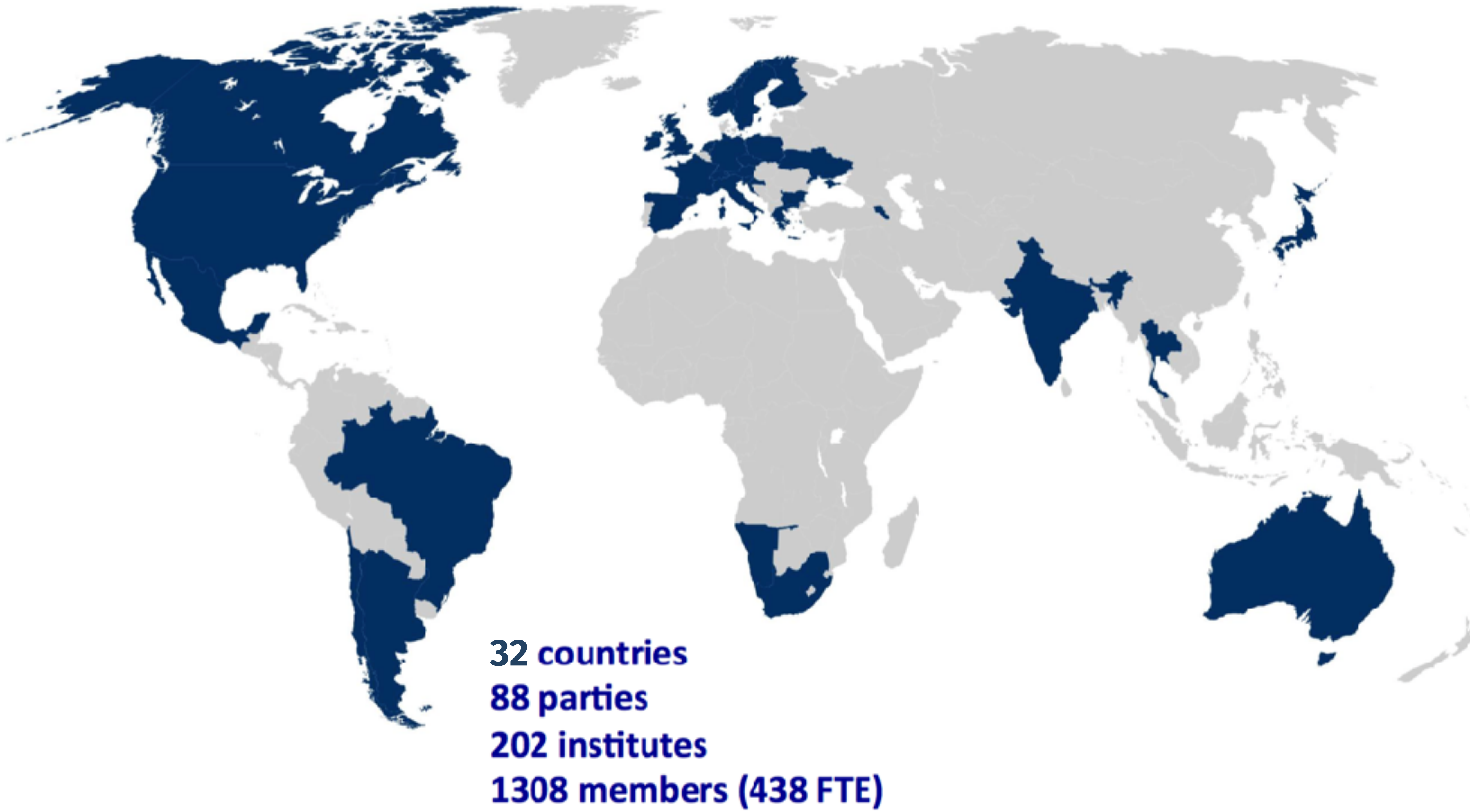
many complementary / contemporary experiments

Source Number

Gamma-Ray Astronomy goes "mainstream"



CTA Consortium



Argentina, **Armenia**, Australia, Austria, Brazil, Bulgaria, Canada, Chile, Czech Republic, Croatia, Finland, France, Germany, Greece, India, Italy, Ireland, Japan, Mexico, Namibia, Netherlands, Norway, Poland, Slovenia, Spain, South Africa, Sweden, Switzerland, Thailand, UK, Ukraine, USA

Main Science Themes:

Cosmic Particle Acceleration

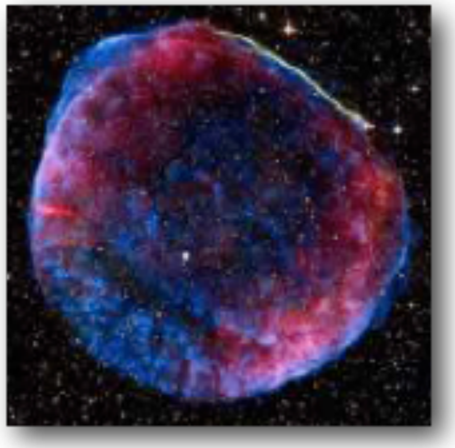
- Particle acceleration
- Particle propagation
- Impact of rel. particles on their environment

Probing Extreme Environments

- Processes close to neutron stars and black holes
- Processes in relativistic jets, winds and explosions
- Cosmic voids

Physics frontiers

- Nature & distribution of Dark Matter
- Lorentz-Invariance at high energies
- Axion-like particles
- Exotics



CTA is a new, powerful observatory for ground-based gamma-ray astronomy

- has a huge science potential (for a moderate price)
- offers an attractive mix of discovery potential and
  a wealth of "guaranteed" good astrophysics,
- complements data from other wavelengths / messengers
- is almost production ready,
- first funding is in hand / construction start very soon ...

CTA will considerably advance our knowledge on high-energy astrophysics and cosmic accelerators.

https://www.cta-observatory.org

Gamma Ray Astronomy

– 1948: first ideas
– 1989: first source

41 years!
(thanks to very dedicated physicists)

– 2000:	~10 sources	~10 collaborators
– 2010:	~100 sources	~100 collaborators
– 2030:	~1000 sources	~1000 collaborators

– Cherenkov Telescopes are the best means of studying γ-rays at energies 50 GeV ... 300 TeV

– Astrophysics in the GeV ... >300 TeV range will see major scientific progress with
Fermi and CTA

Summary:

- Astroparticle Physics is an exciting field.
- Highest energy particles are rare & difficult to detect

  ... but new experiments (with increased sensitivity) are getting better in detecting these particle and identifying their sources.
- The most-energetic CRs, gamma rays & neutrinos come likely from the same, most violent environments in the universe. (Multi-messenger approach)
- Three new windows in Astronomy:

  TeV gamma rays, Neutrinos, UHECRs
- Bright future with many challenges for bright young scientists

Astroparticle Physics poses many puzzles

Experimental findings and theoretical ideas
do not (yet) form a coherent and clear image.
The situation may seem messy.

Steven Weinberg,
Four golden lessons (for young physicists)
Nature 426 (2003) 389

"My advice is to go for the messes - that's where the action is."

Experiments & analyses are challenging and require
bright young students (i.e. you ?)
to answer some of the most exciting questions in physics.