γ

e

p

Photons in Astroparticle Physics: Gamma Ray Astronomy and the Future with

cta
cherenkov telescope array

1. basics and history
2. status and future

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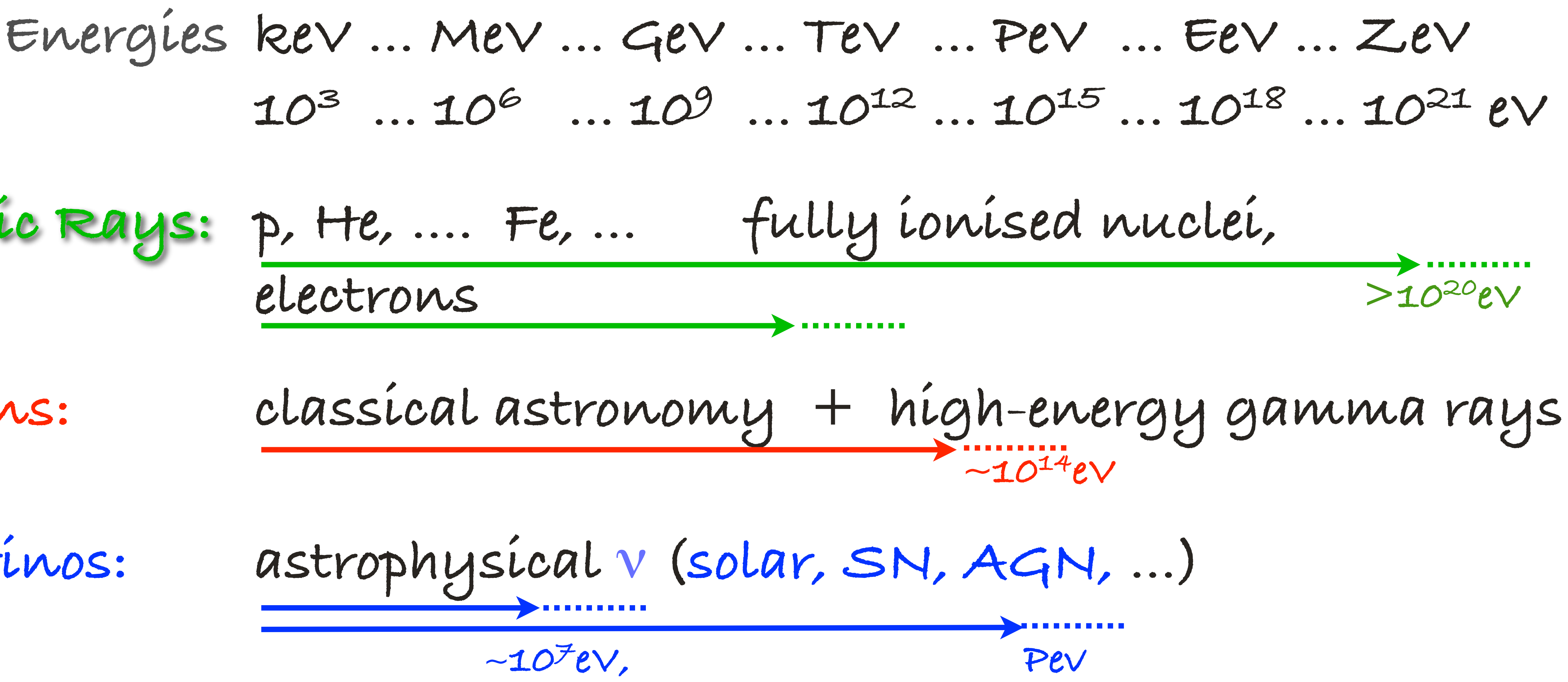
DESY Zeuthen, Germany

WAPP 2013
Darjeeling

Astroparticles: particles from astrophysical sources

… The highest energy particles in the universe !!!!!



Energies keV … MeV … GeV … TeV … PeV … EeV … ZeV

10^3 … 10^6 … 10^9 … 10^{12} … 10^{15} … 10^{18} … 10^{21} eV

Cosmic Rays: p, He, …. Fe, … fully ionised nuclei,

$>10^{20}$eV

electrons

Photons: classical astronomy + high-energy gamma rays

$\sim 10^{14}$eV

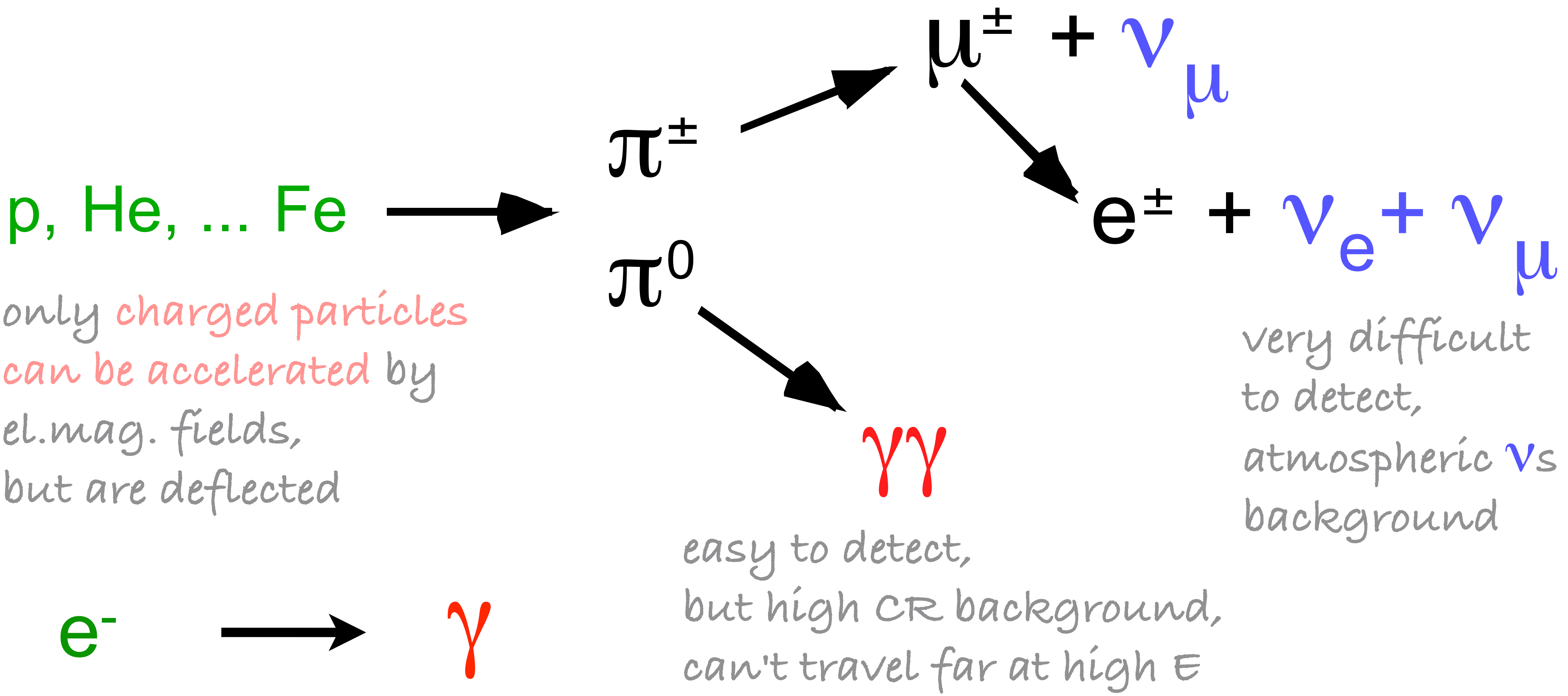
Neutrinos: astrophysical ν (solar, SN, AGN, …)

$\sim 10^7$eV, PeV

highest energies particles –

acceleration in most extreme environments

Cosmic Rays, Gamma Rays and Neutrinos are linked



$$\text{p, He, ... Fe} \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

$$\pi^{0} \rightarrow \gamma\gamma$$

$$e^{-} \rightarrow \gamma$$

only charged particles can be accelerated by el.mag. fields, but are deflected

easy to detect, but high CR background, can't travel far at high E

very difficult to detect, atmospheric νs background

high-energy CRs produce also high-energy γs and neutrinos νs

γs and νs travel in straight lines, i.e. point back at source.

If Cosmic Rays exist,
then also γ and ν must exist
at similar energies.

But:

Can γ and ν be detected above backgrounds ???

γ : 10^3-10^4 x more charged cosmic rays

ν : low interaction cross section
atmospheric neutrinos from atmosphere

γ Rays

pick them out of the CR background

γ : 10^3-10^4 x more charged cosmic rays

point back at sources

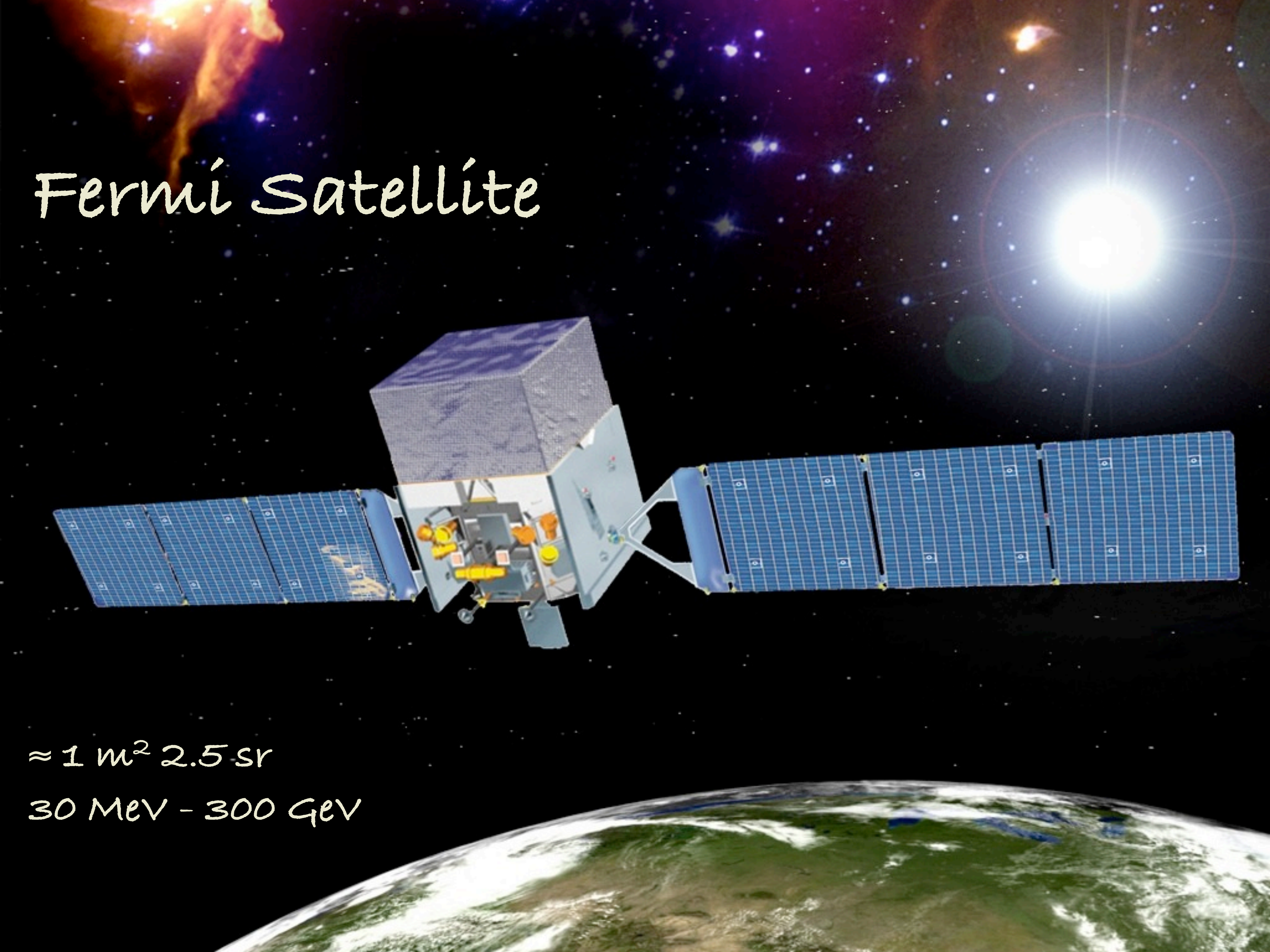
< 100 GeV: direct observations on satellites

> 100 GeV: indirect observations via air showers

γ via shower shape, muon content

or via excess of events from certain sky positions

Fermi Satellite



$\approx 1\ \mathrm{m}^2\ 2.5\ \mathrm{sr}$

30 MeV - 300 GeV

Fermi - LAT

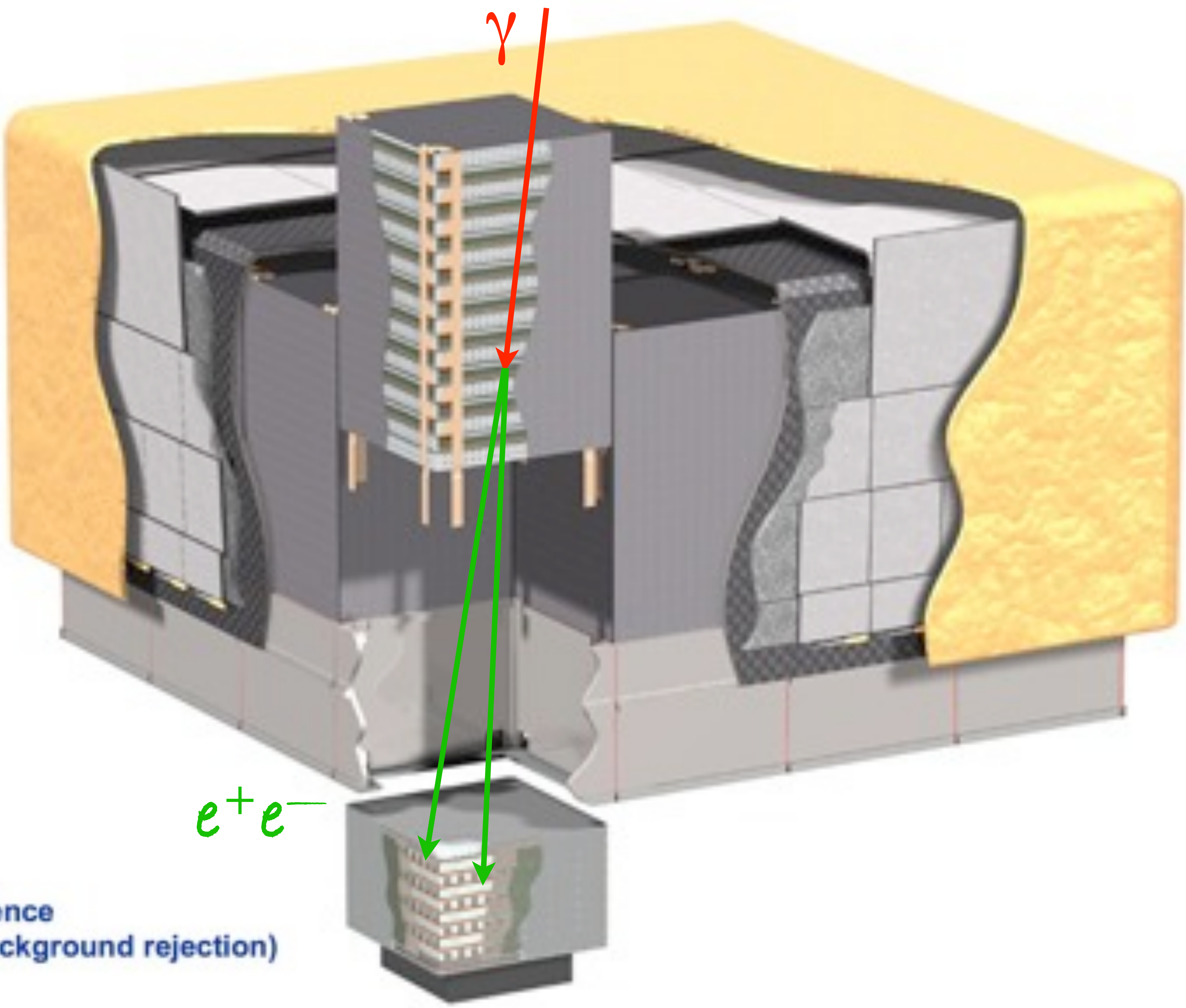
large angle
telescope

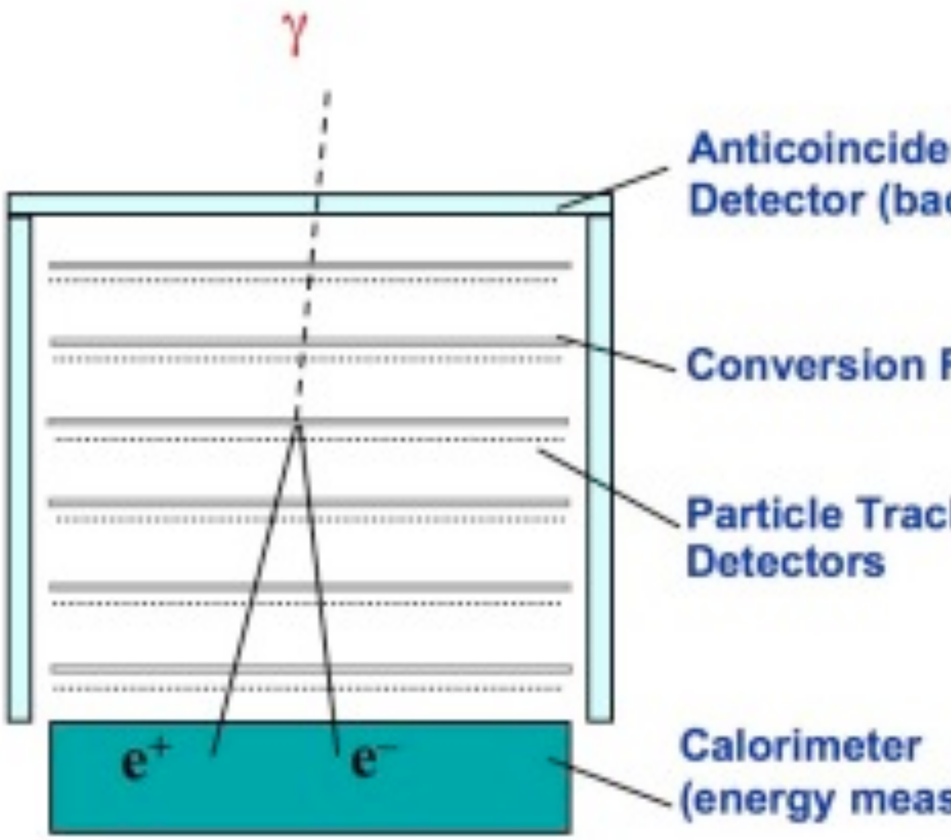
pair-conversion telescope with:

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)

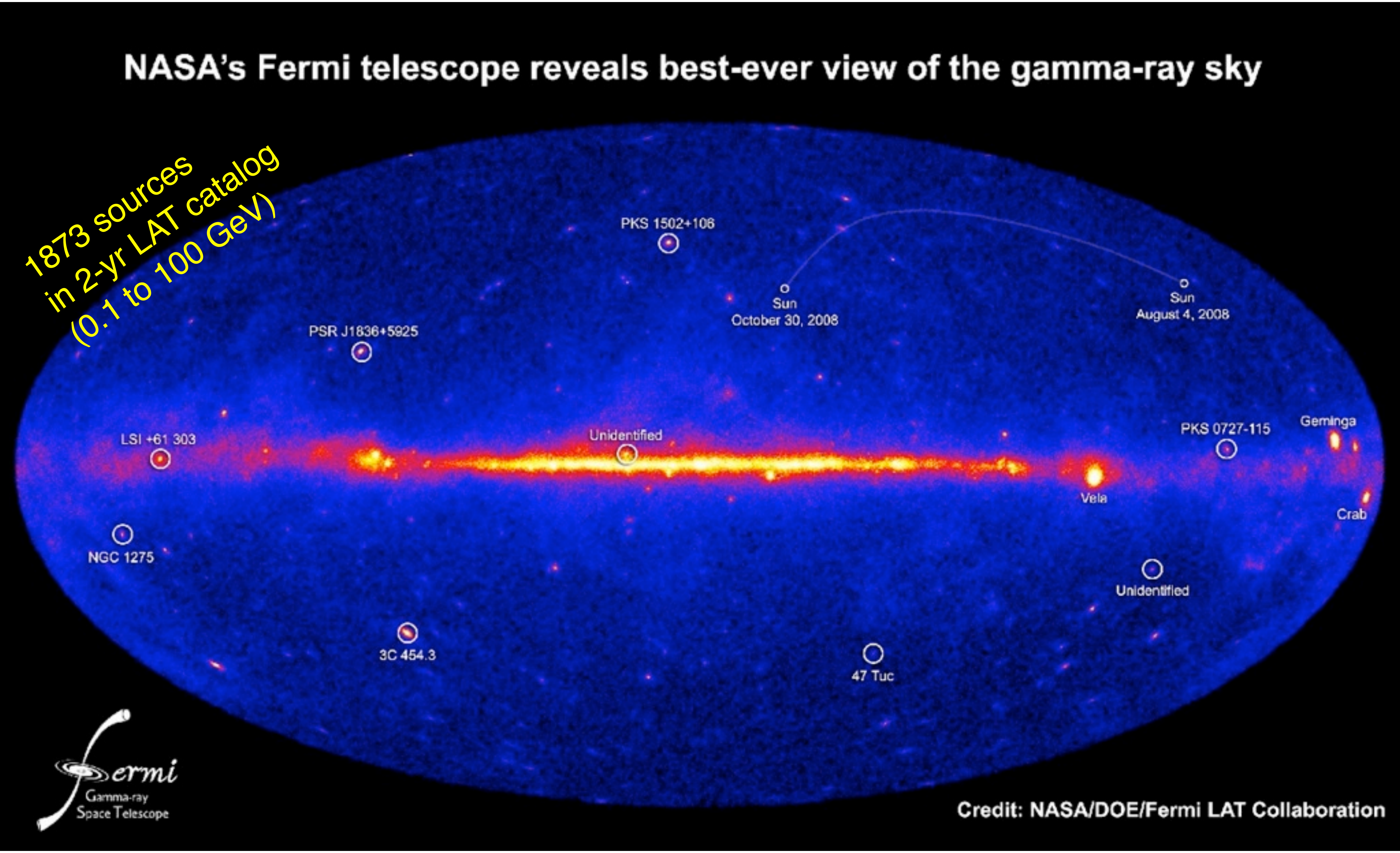
4x4 modules covered by
anti-coincidence shield





≈ 1 m^2 2.5 sr

near-perfect rejection of
charged primaries



NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

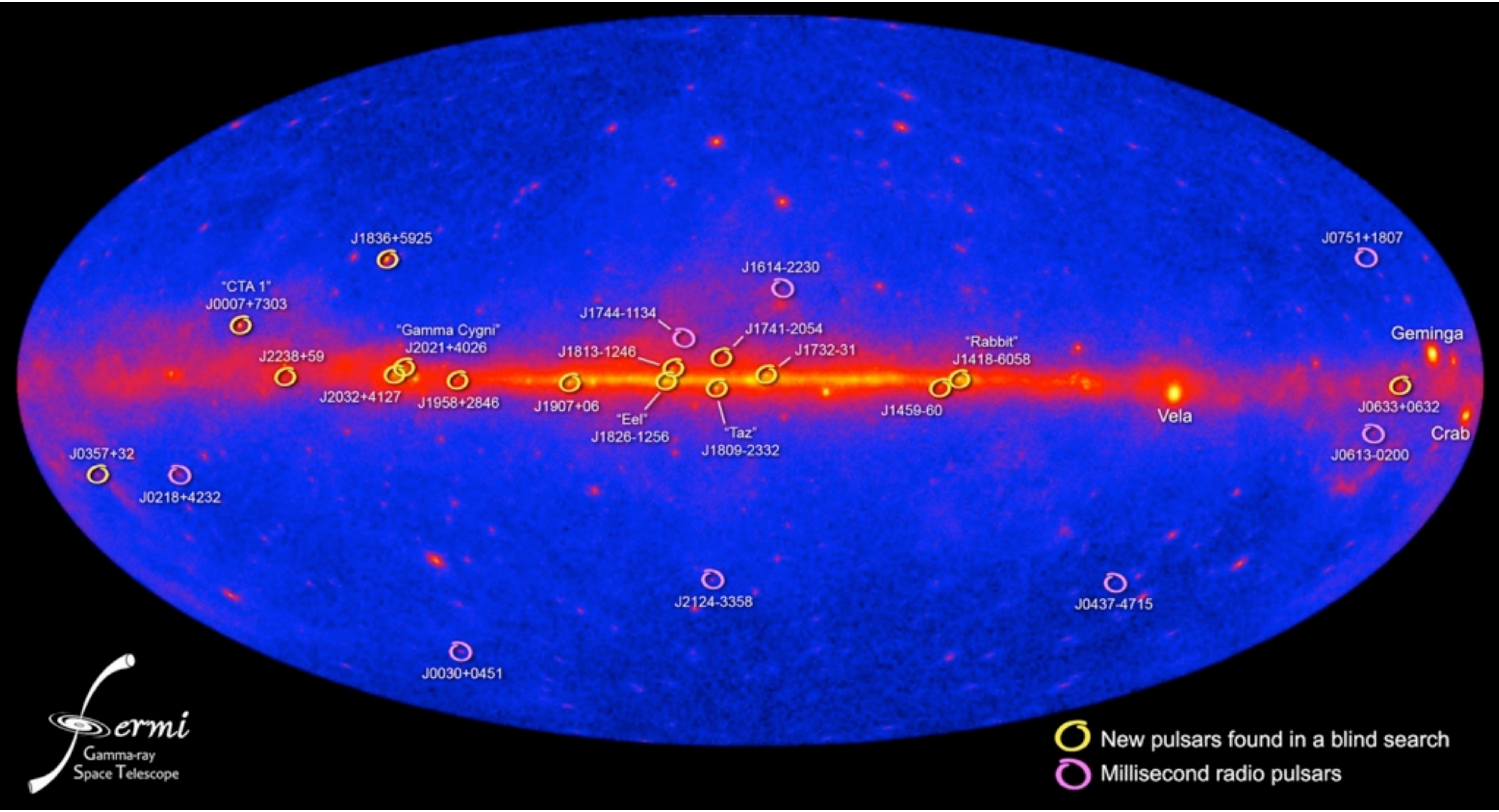
1873 sources
in 2-yr LAT catalog
(0.1 to 100 GeV)

Credit: NASA/DOE/Fermi LAT Collaboration

point sources, extended sources and diffuse emission

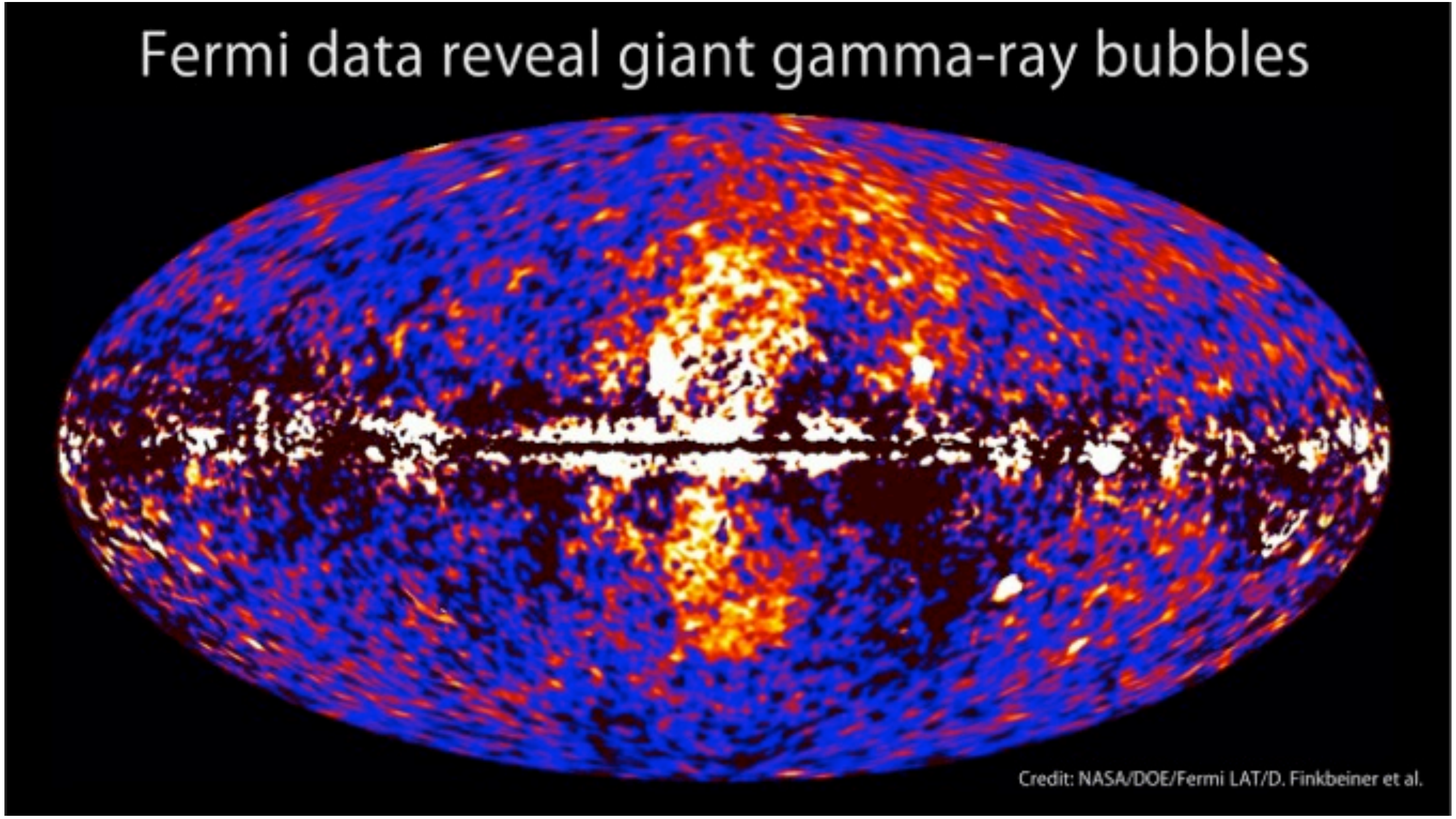
.... hundreds of papers on all sorts of objects and their emission.

… many old and new gamma ray pulsars



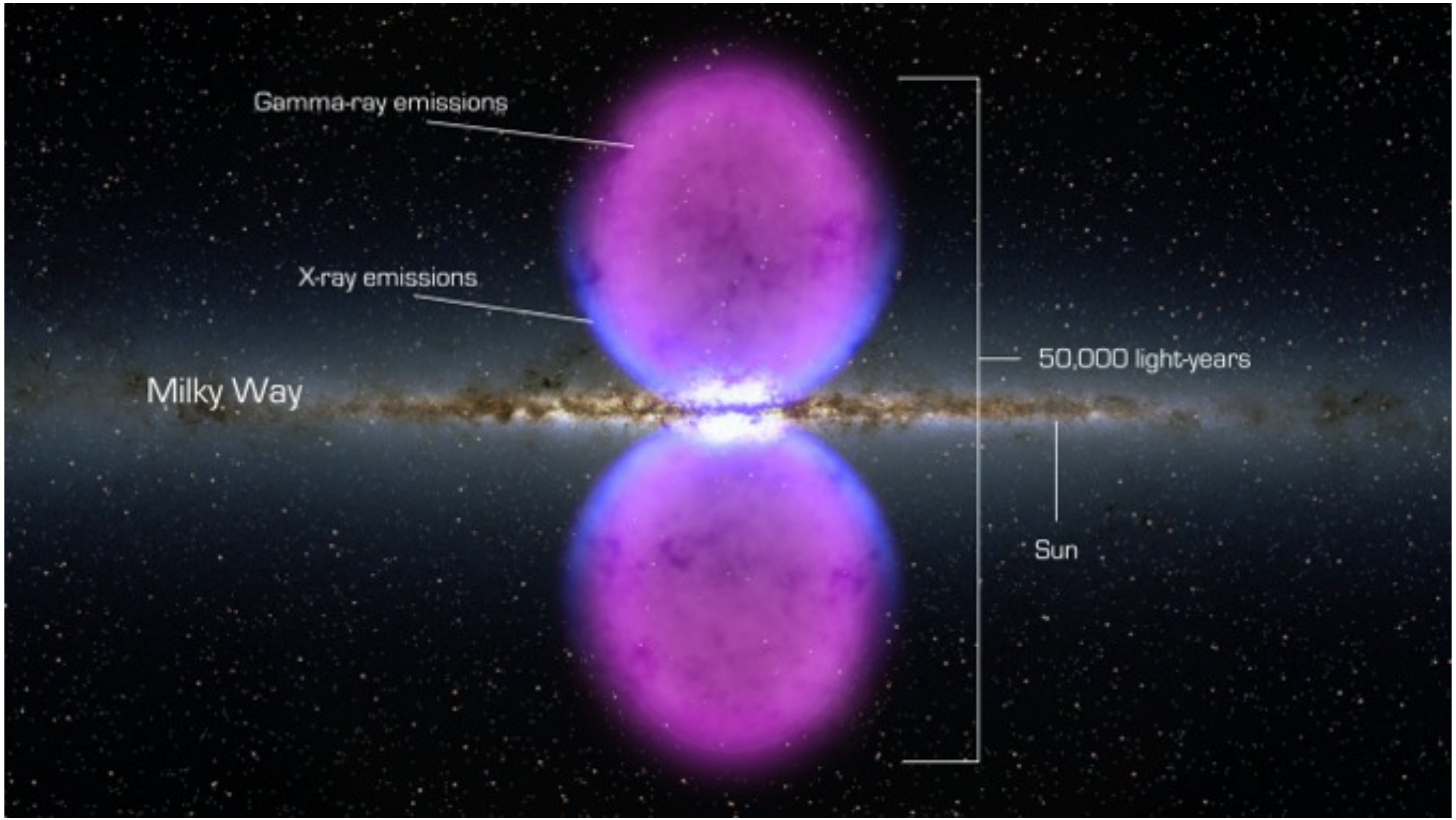
The Fermi Bubble

… a remnant of
recent activity
of our galaxy ?

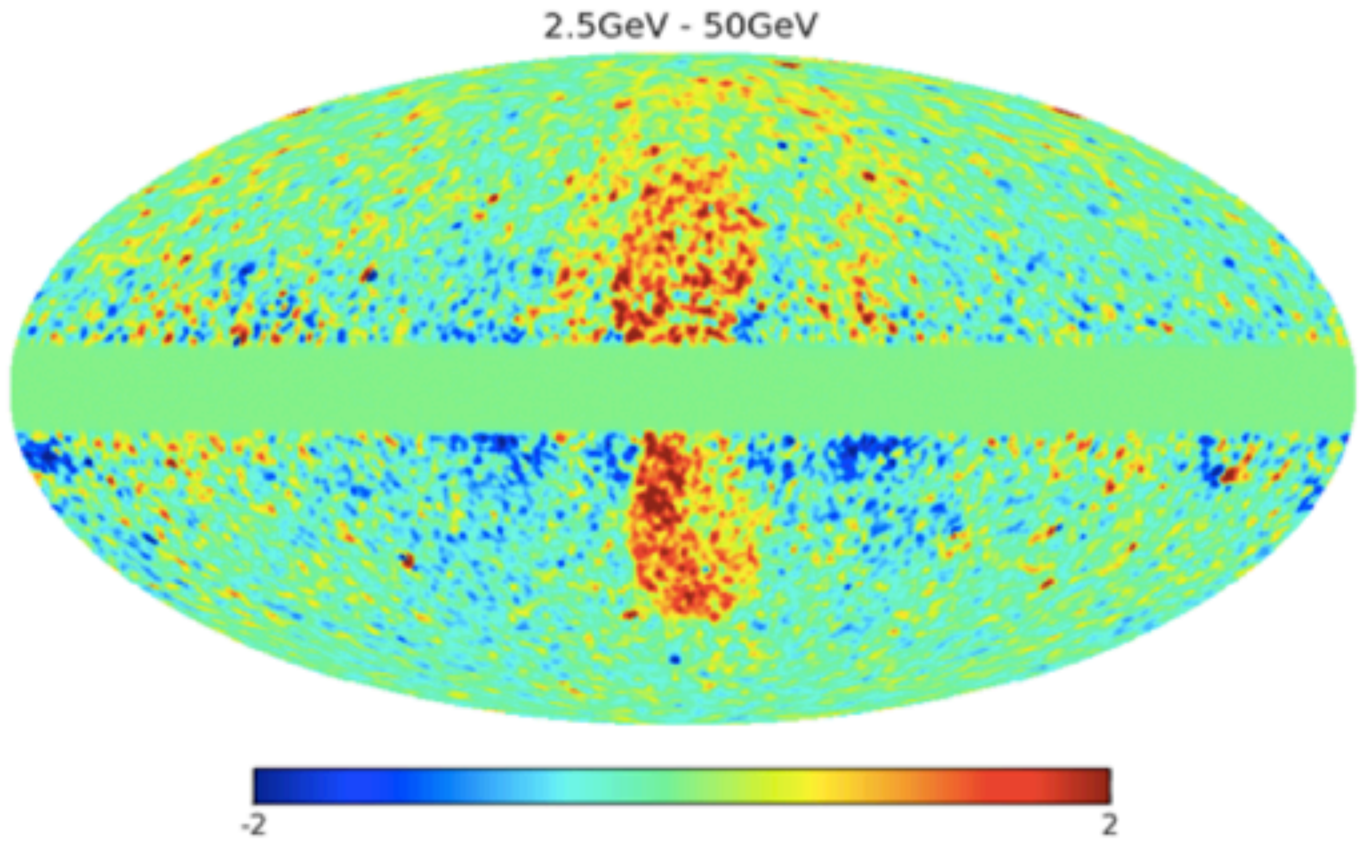


Fermi data reveal giant gamma-ray bubbles

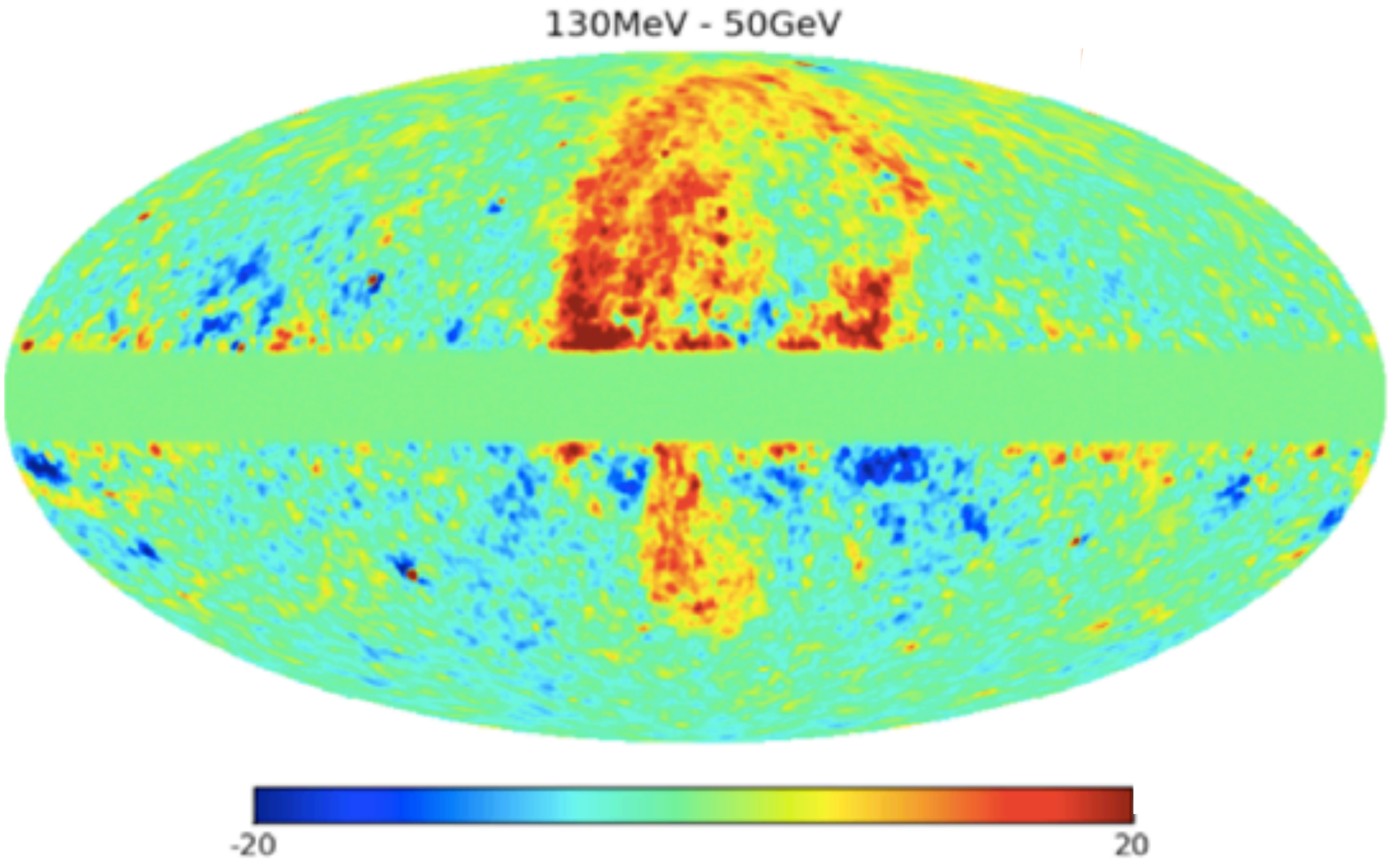
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.



Fermi Bubble

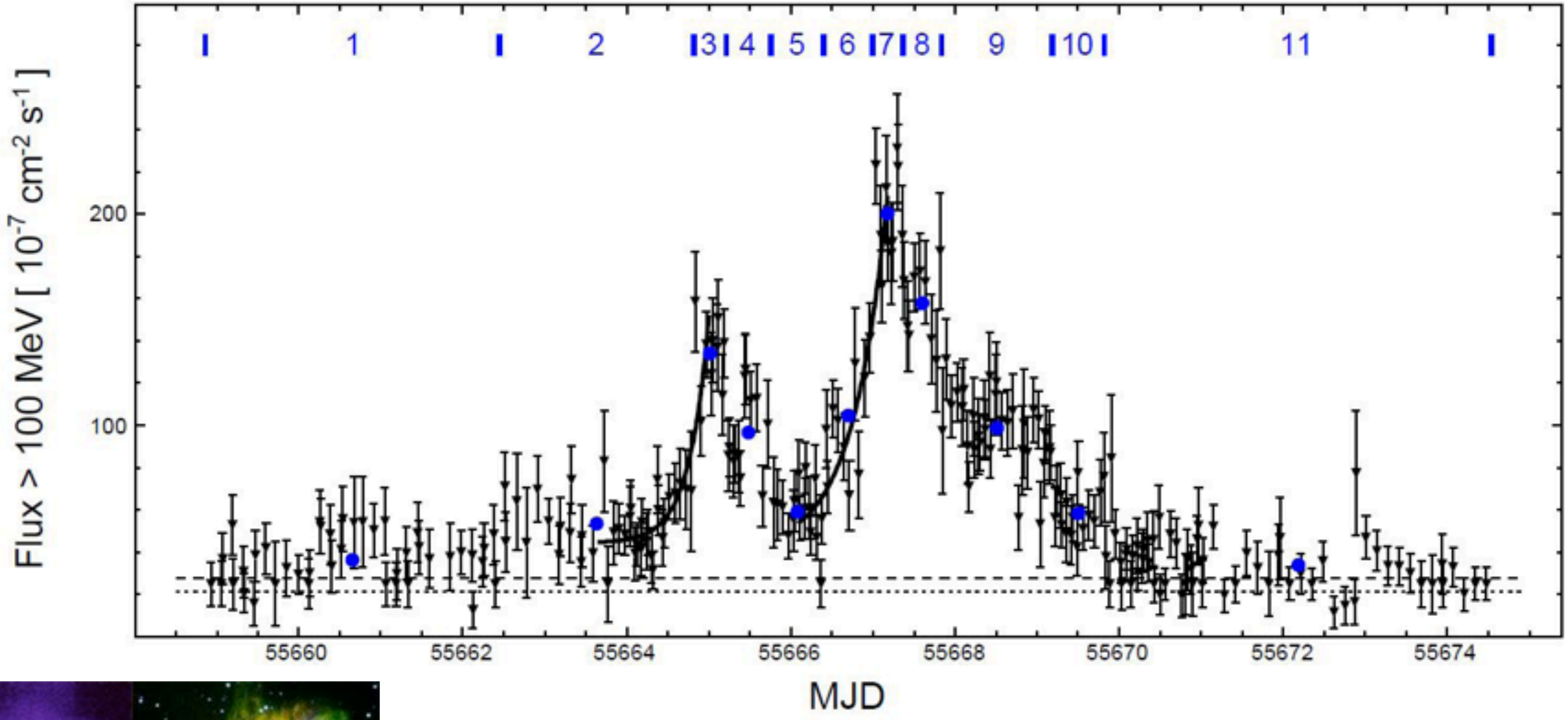


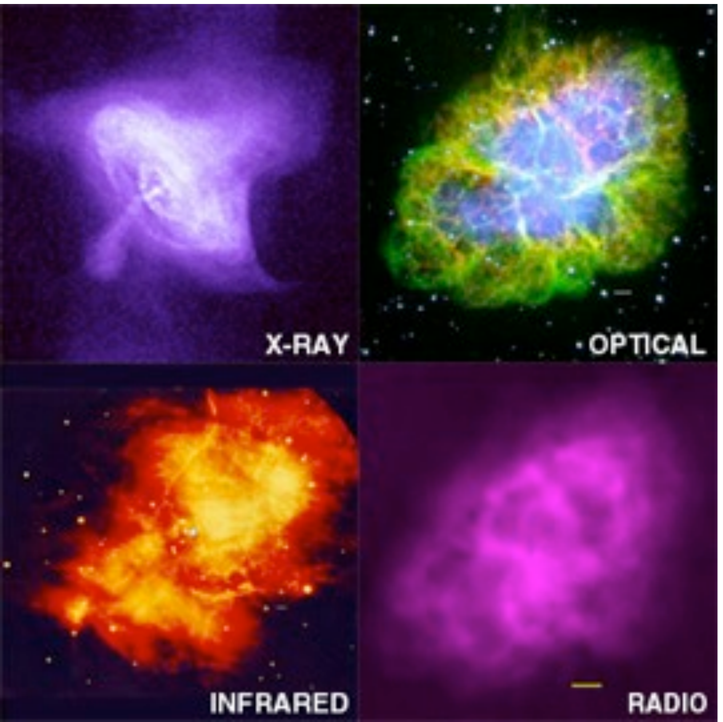
Fermi Loop

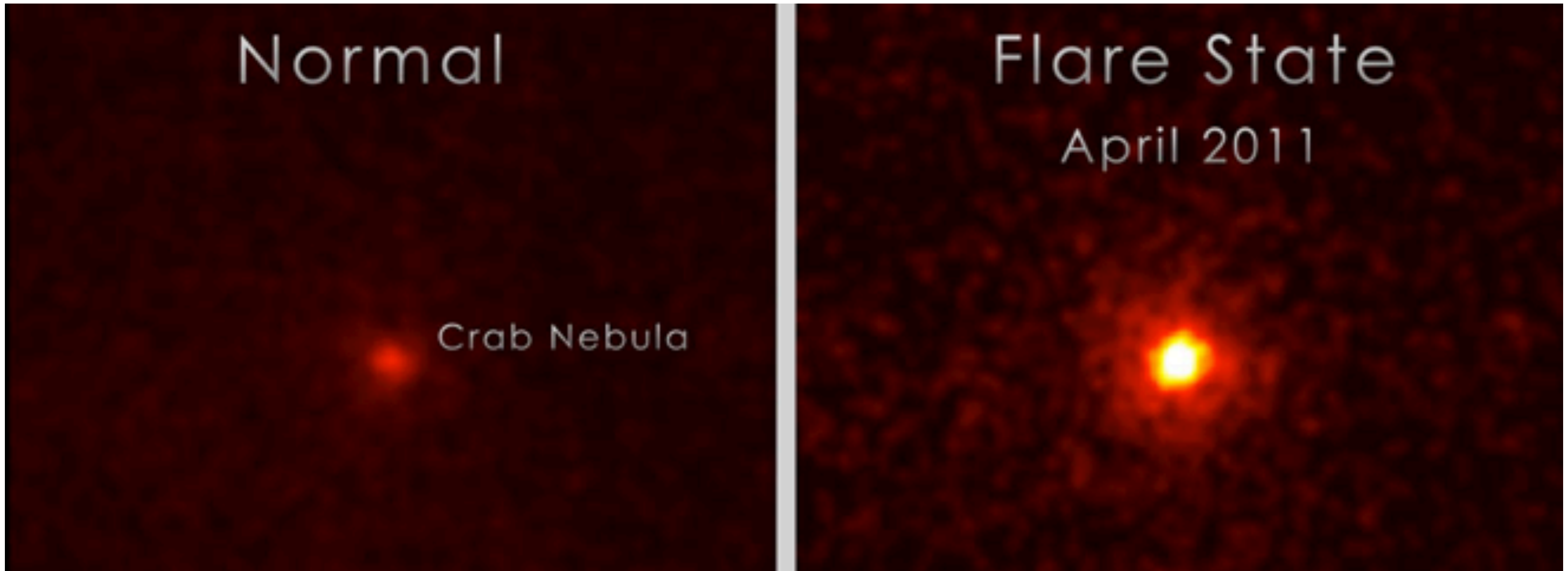


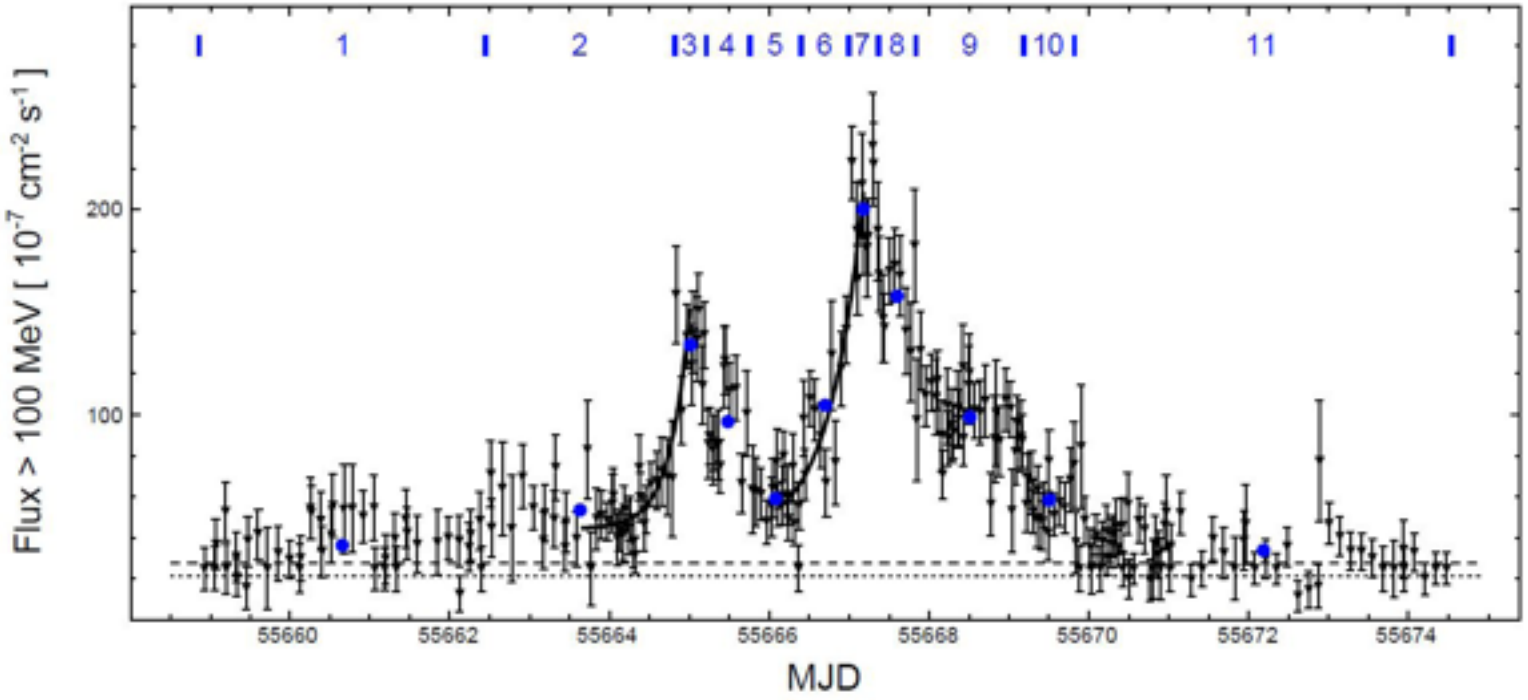
Major gamma-ray flare from Crab Nebula (April 2011)

Crab was always seen as the "standard candle"



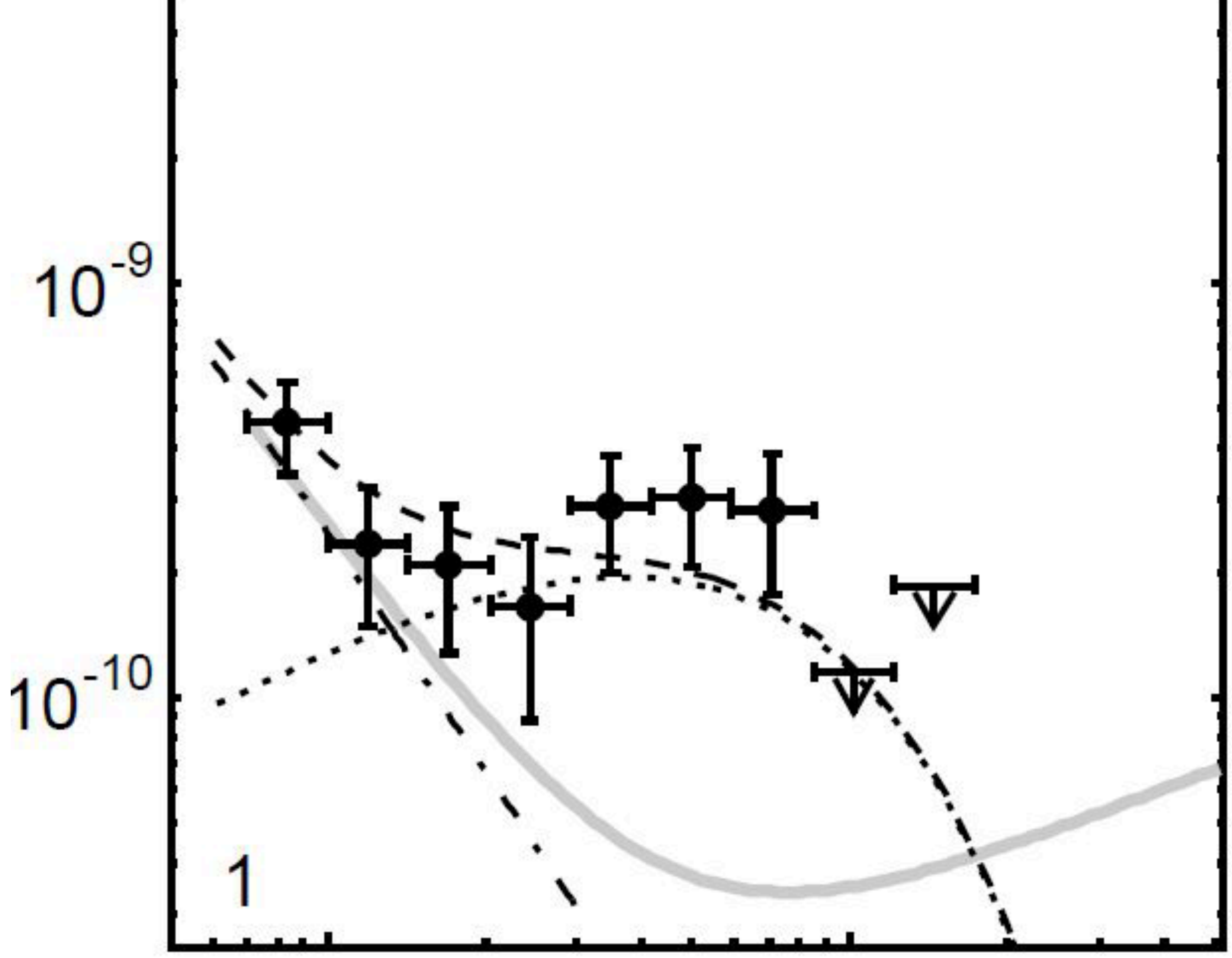


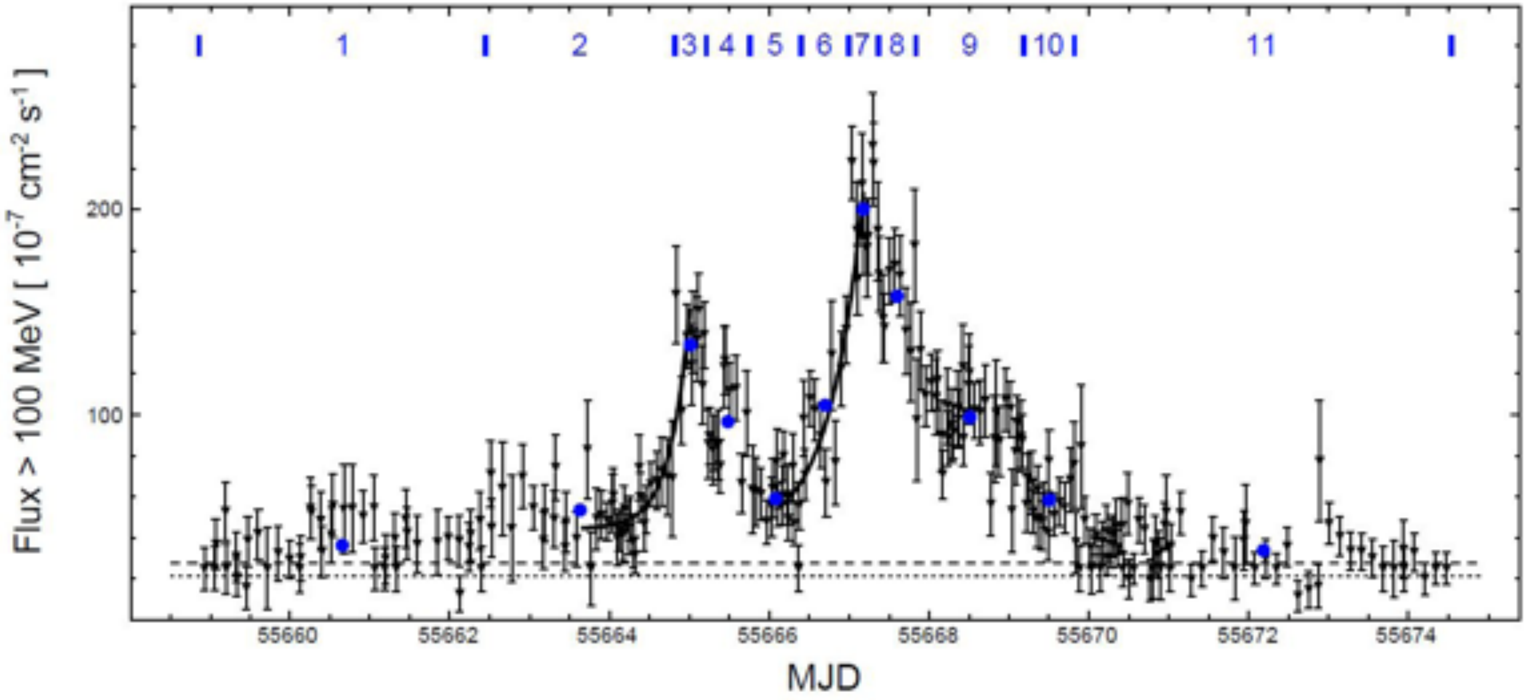


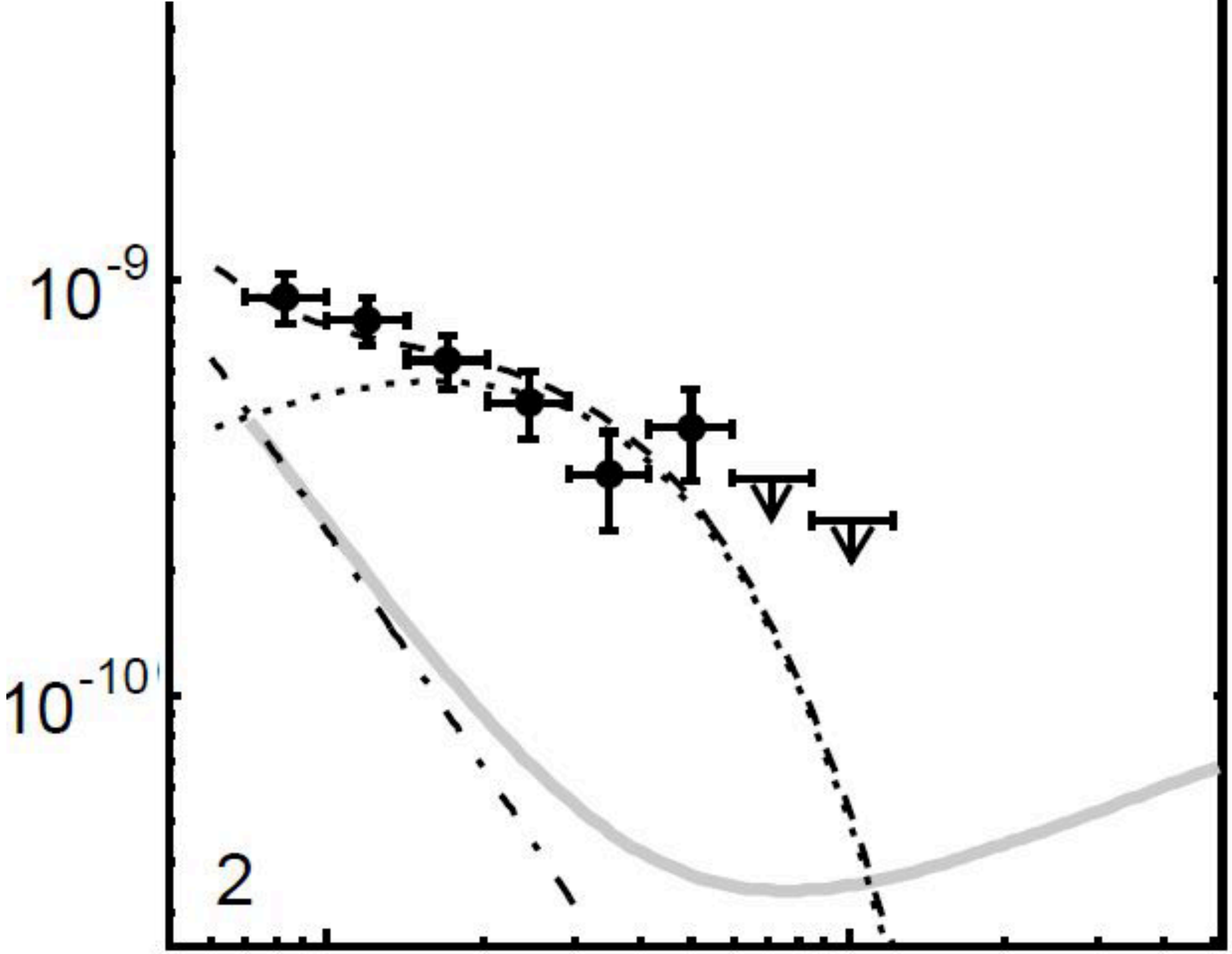


Spectrum varies with time.
Allows study of the
"dynamic processes"
of particle acceleration.

GeV







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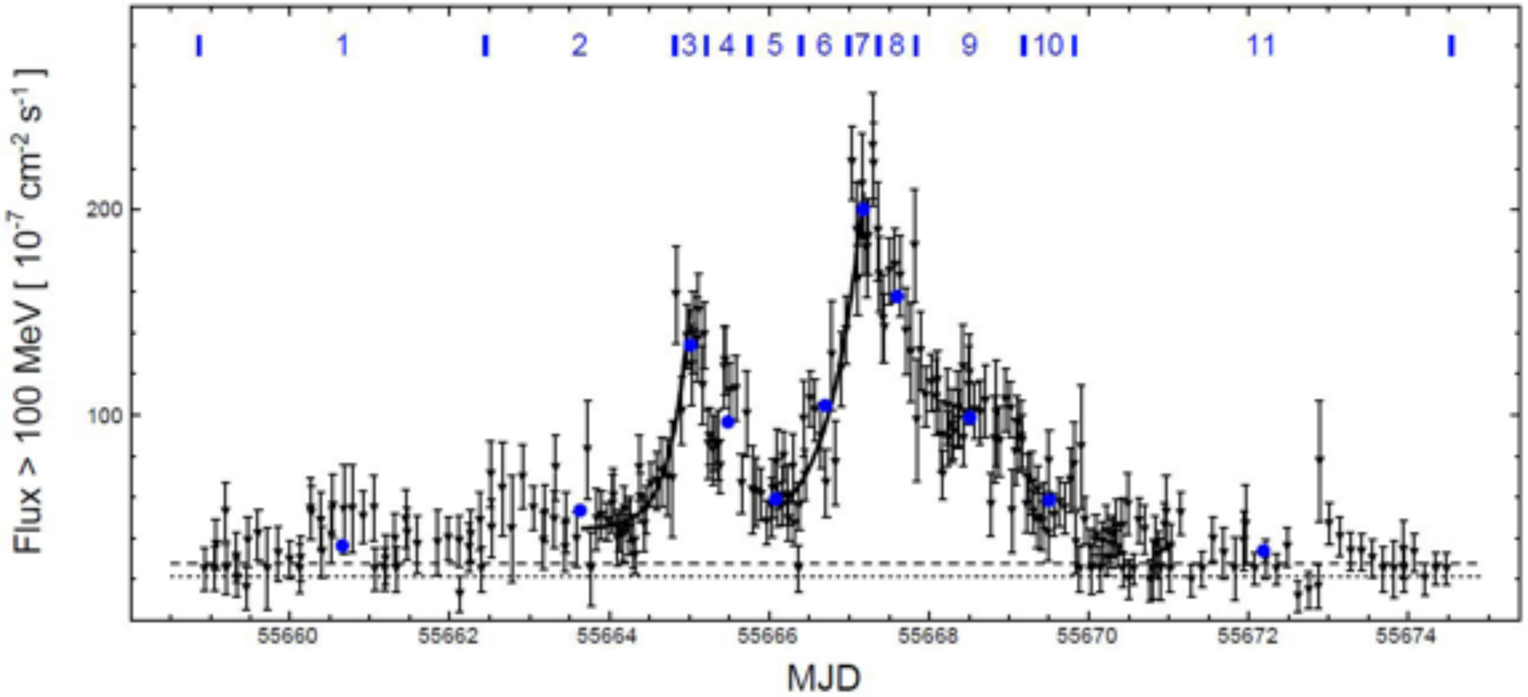

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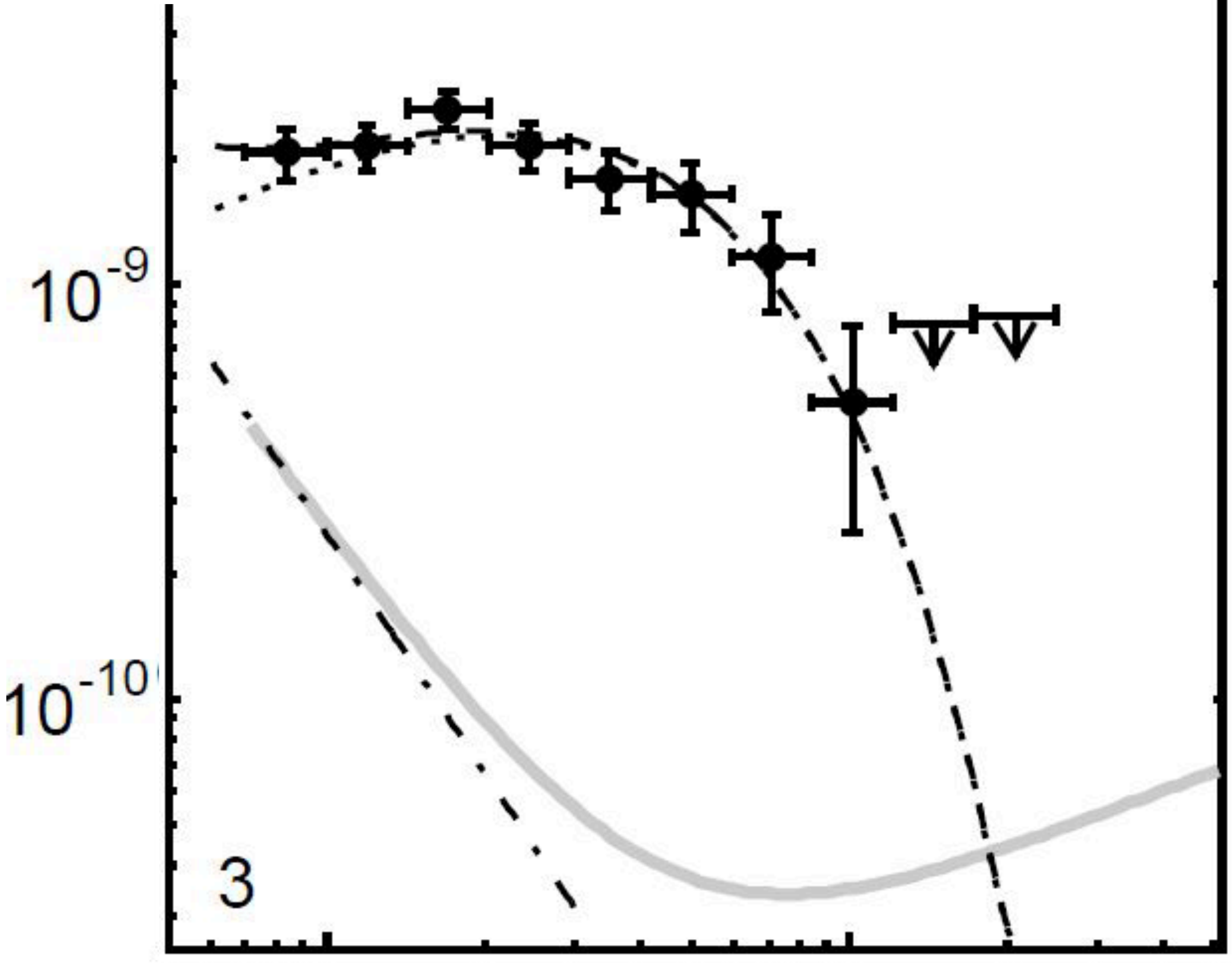
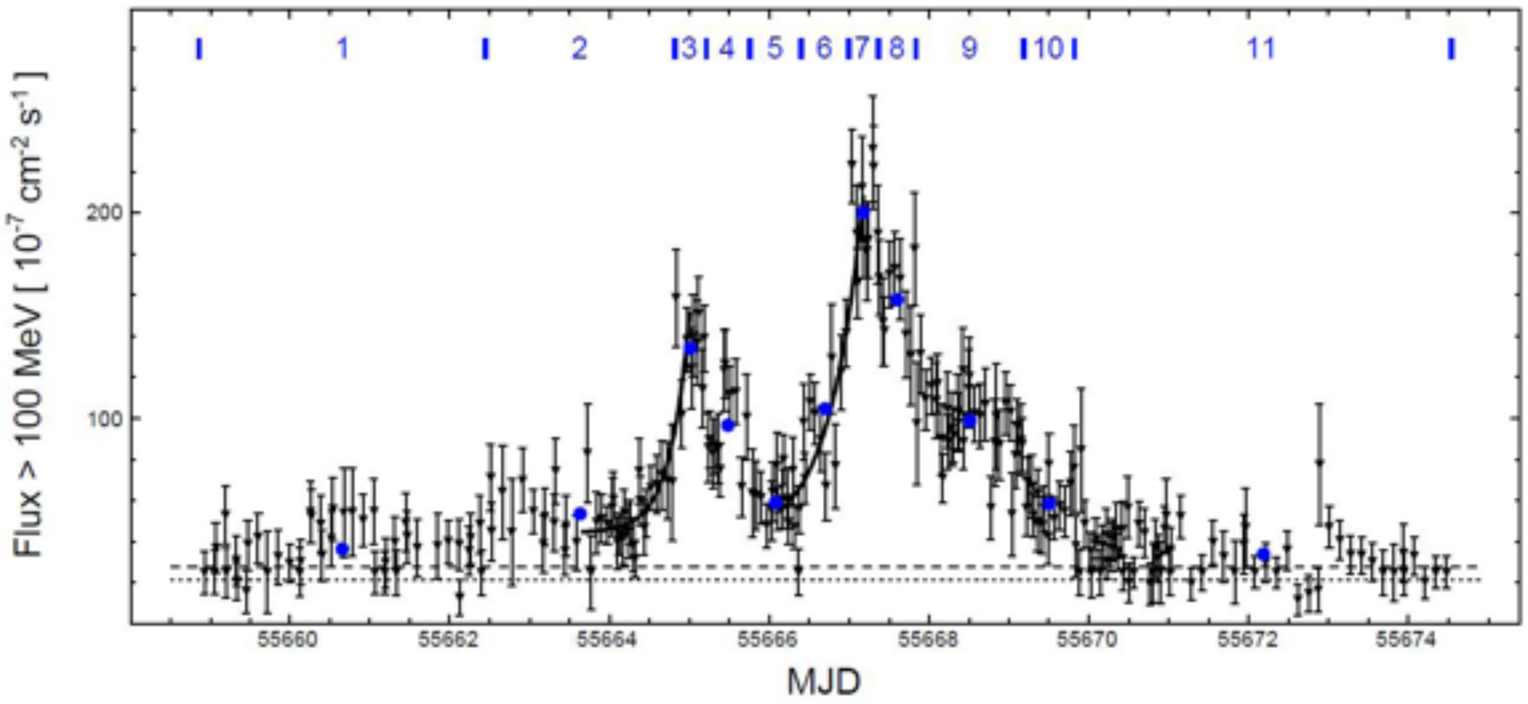
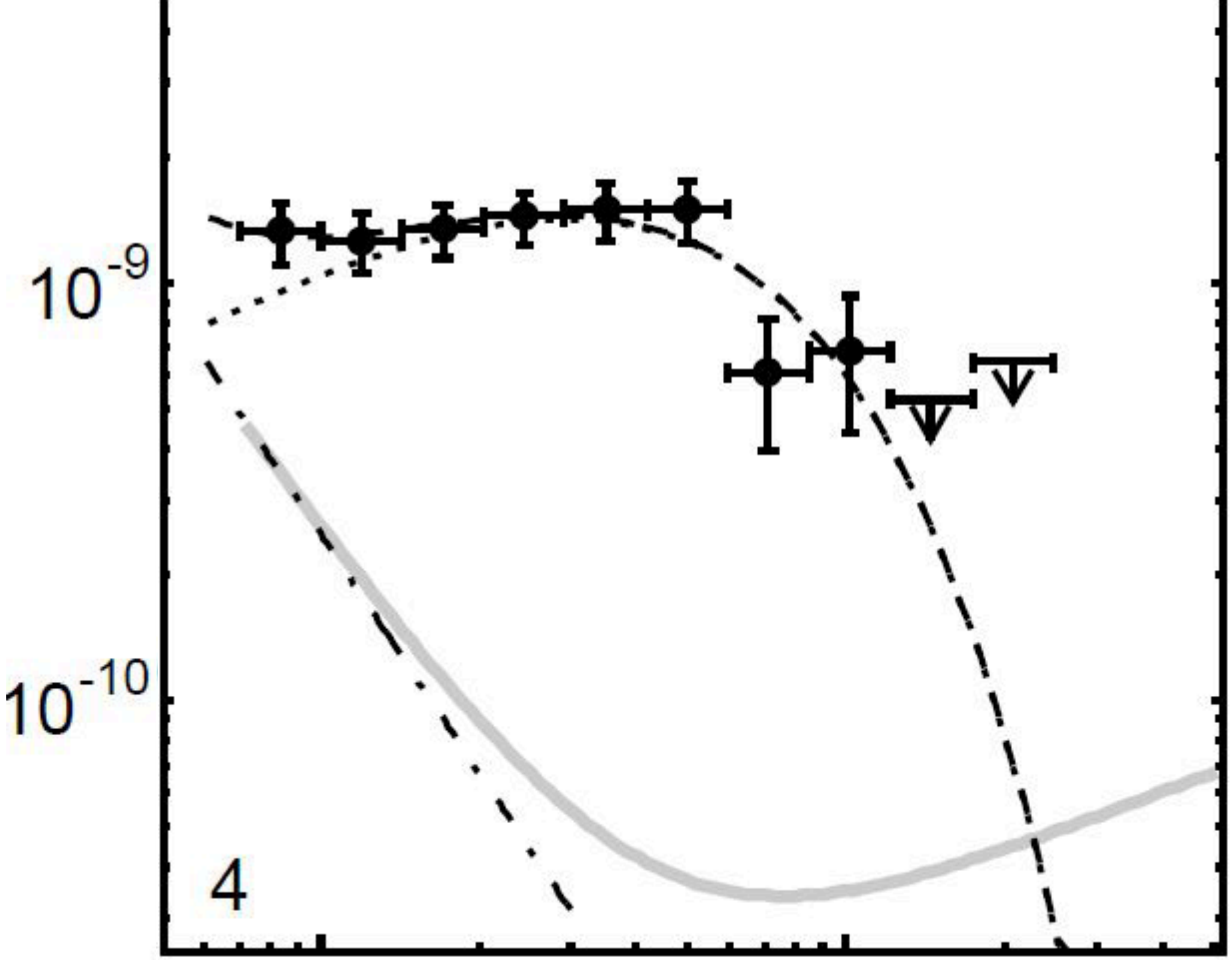




GeV



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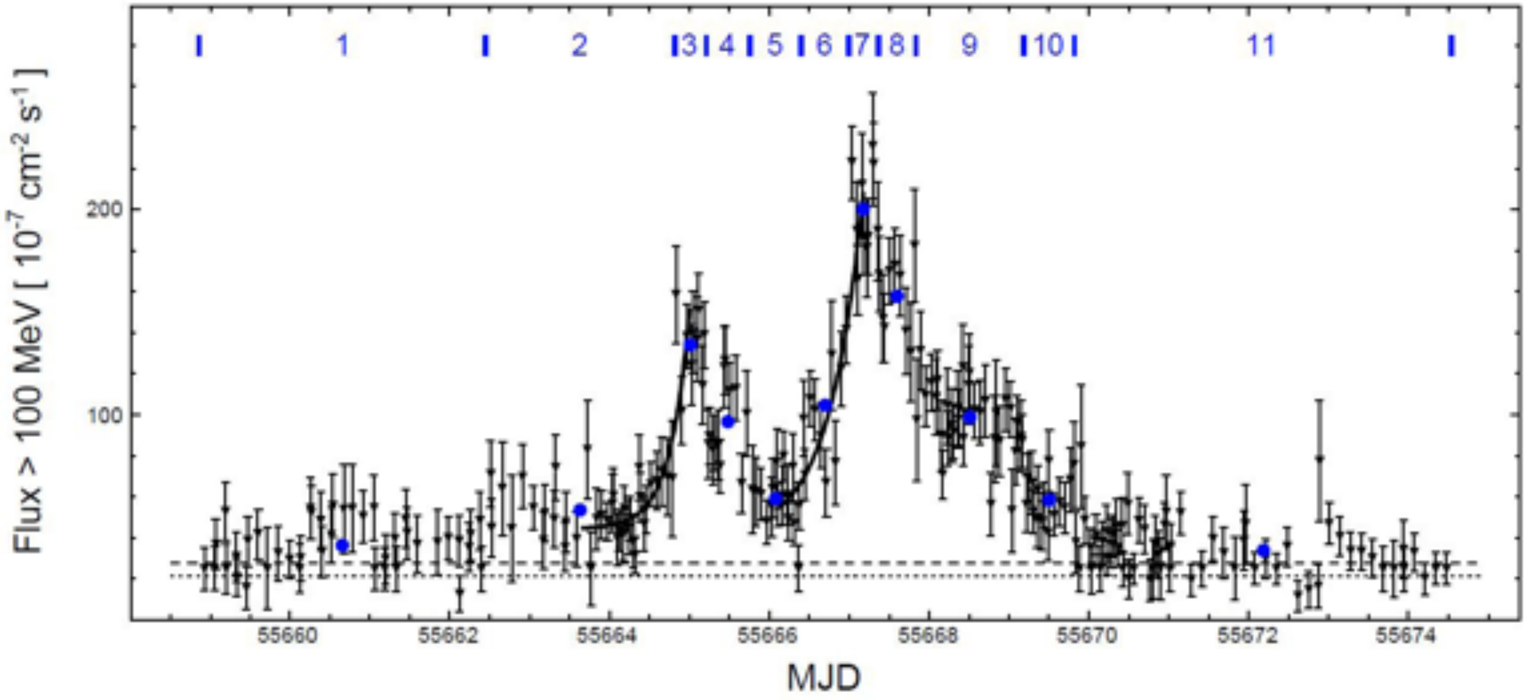

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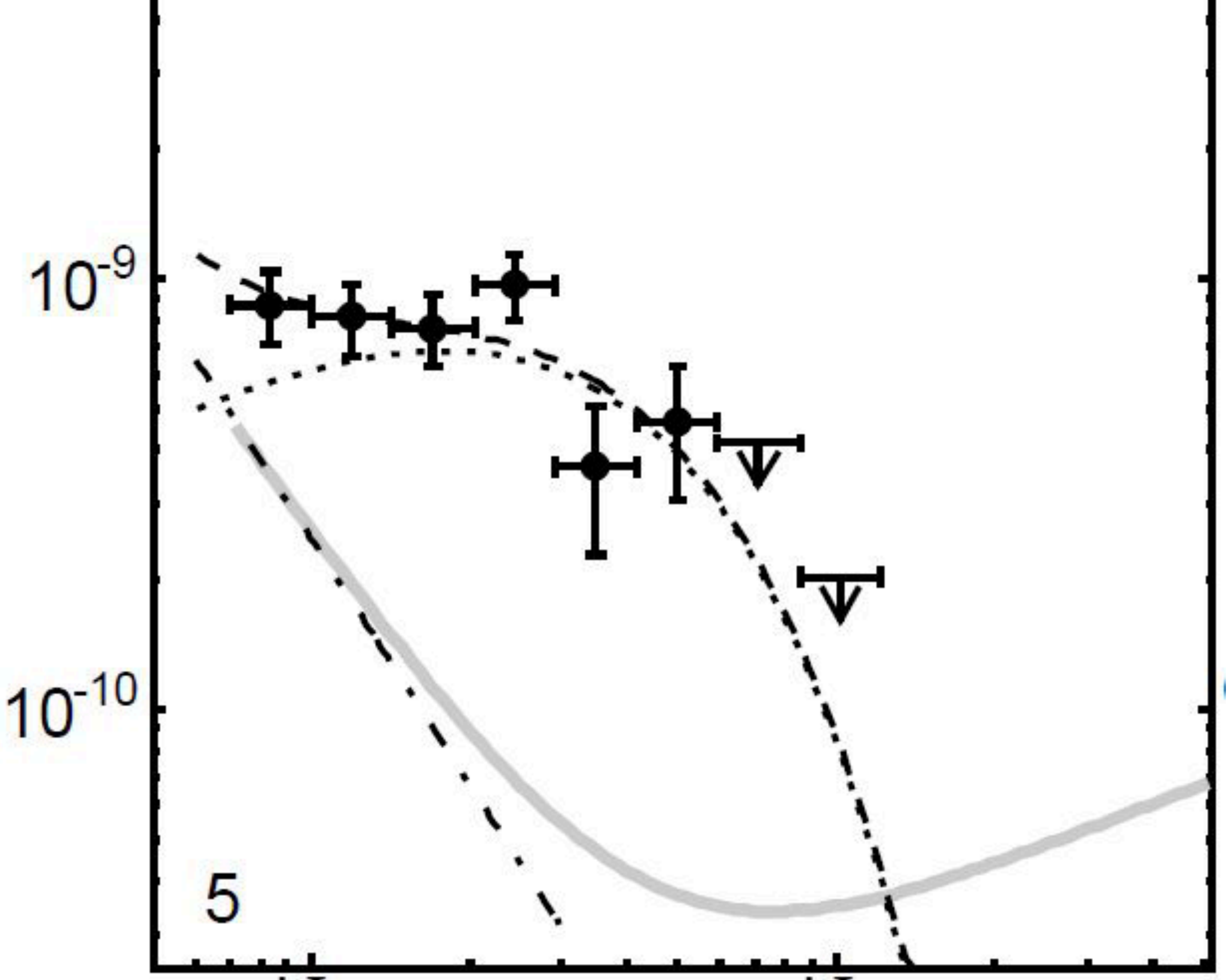

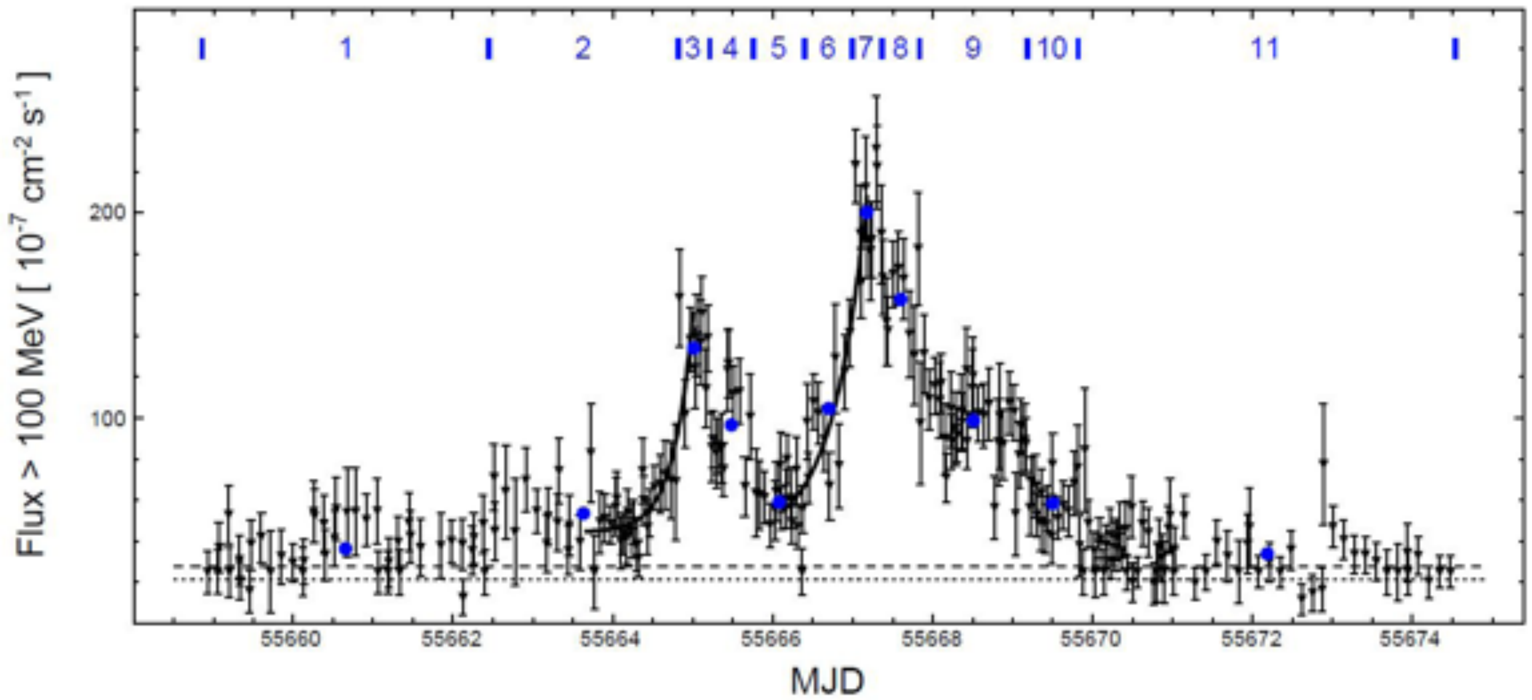

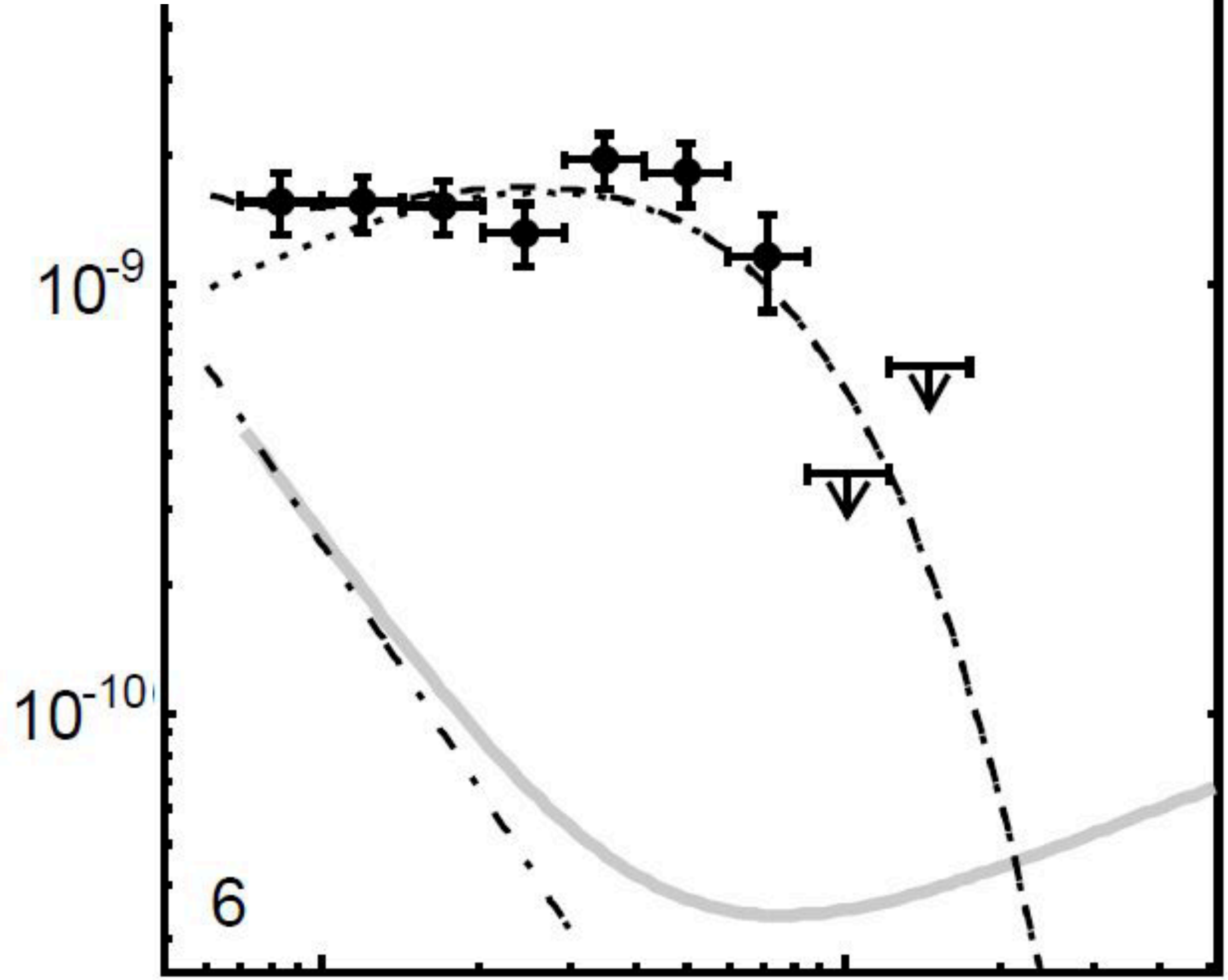

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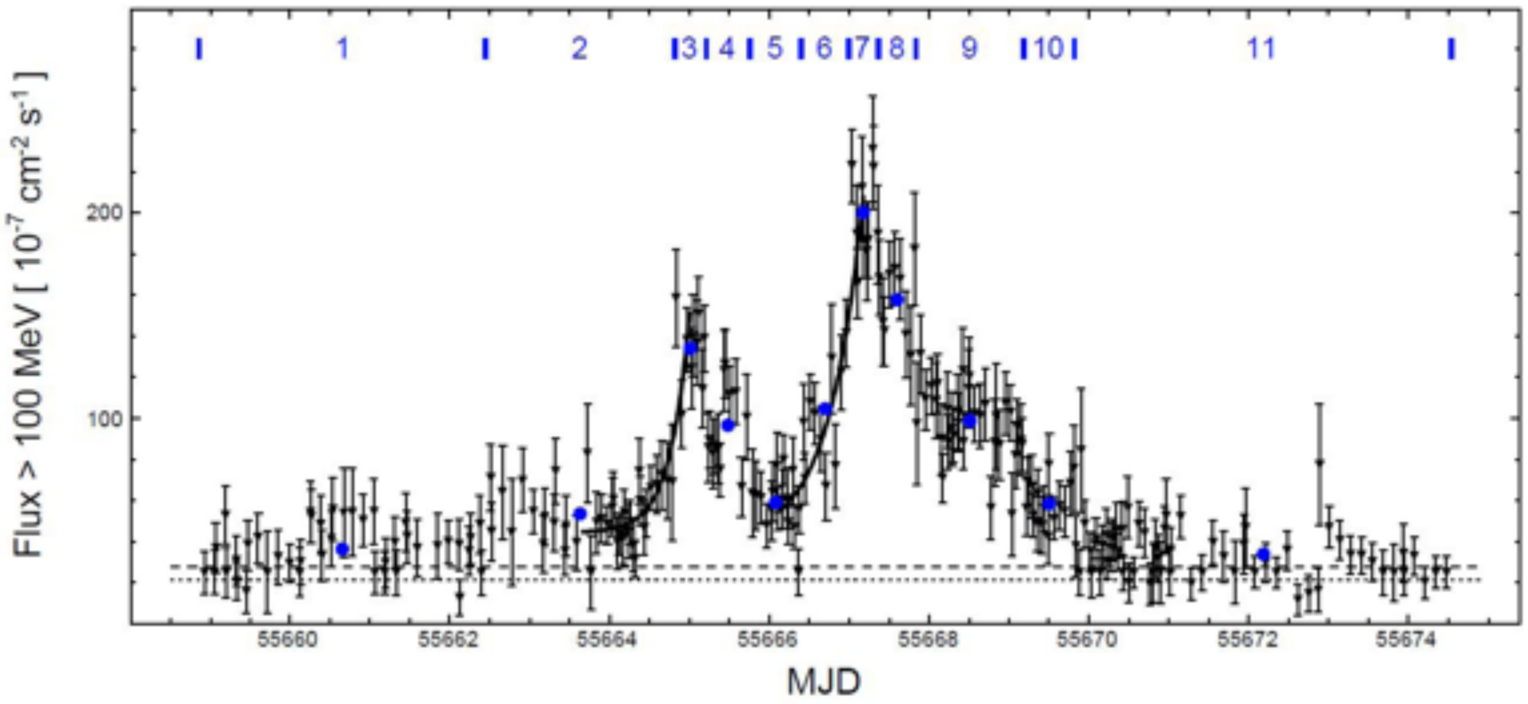

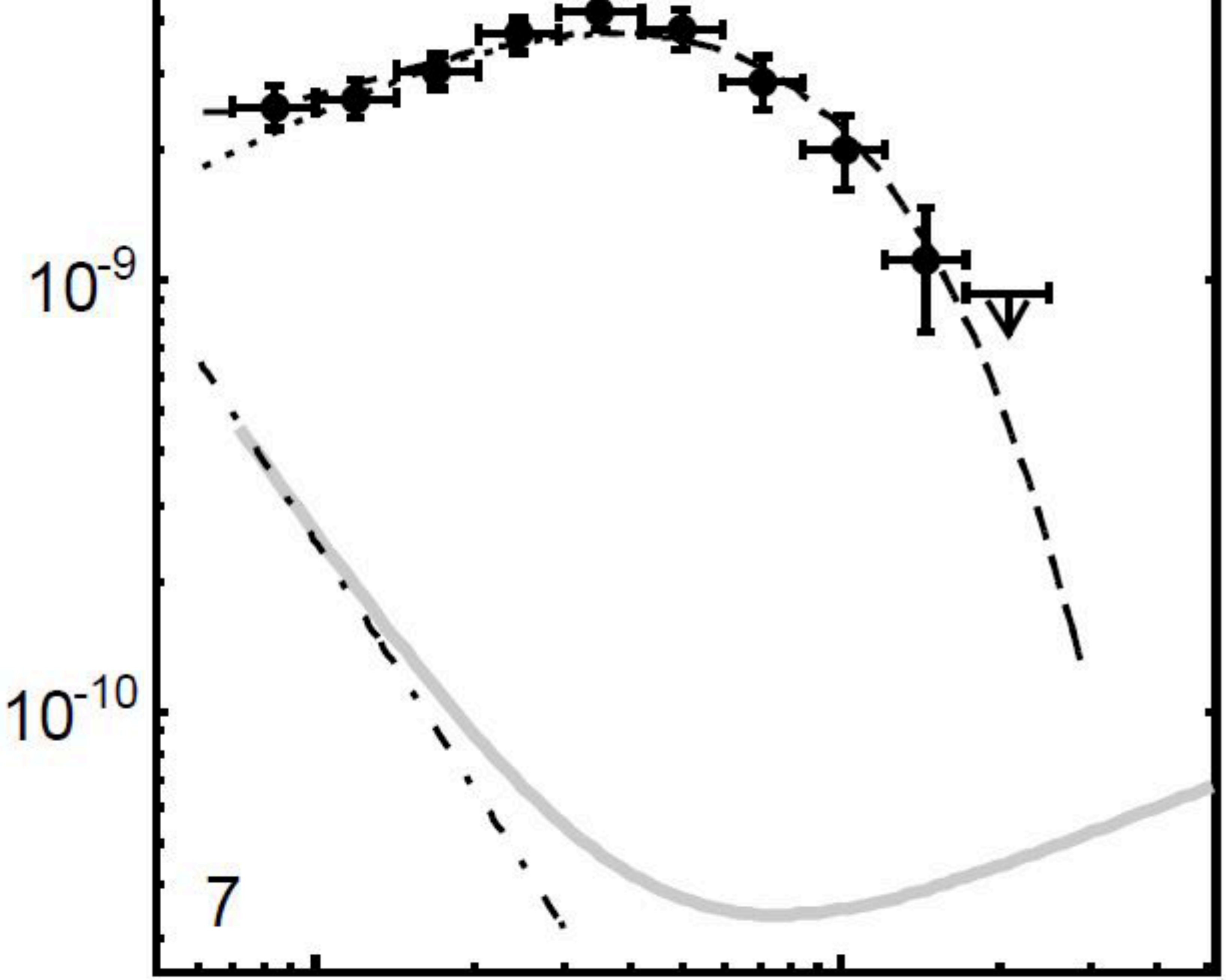

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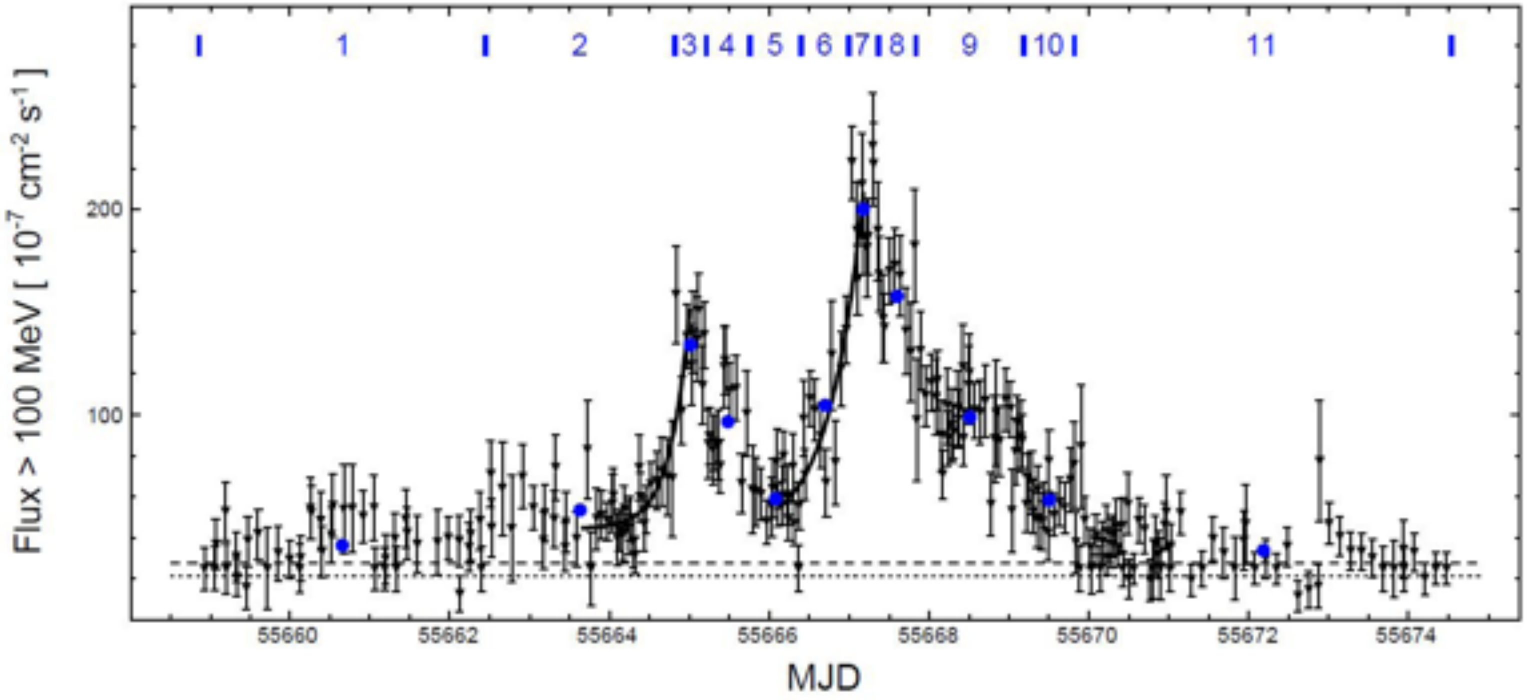

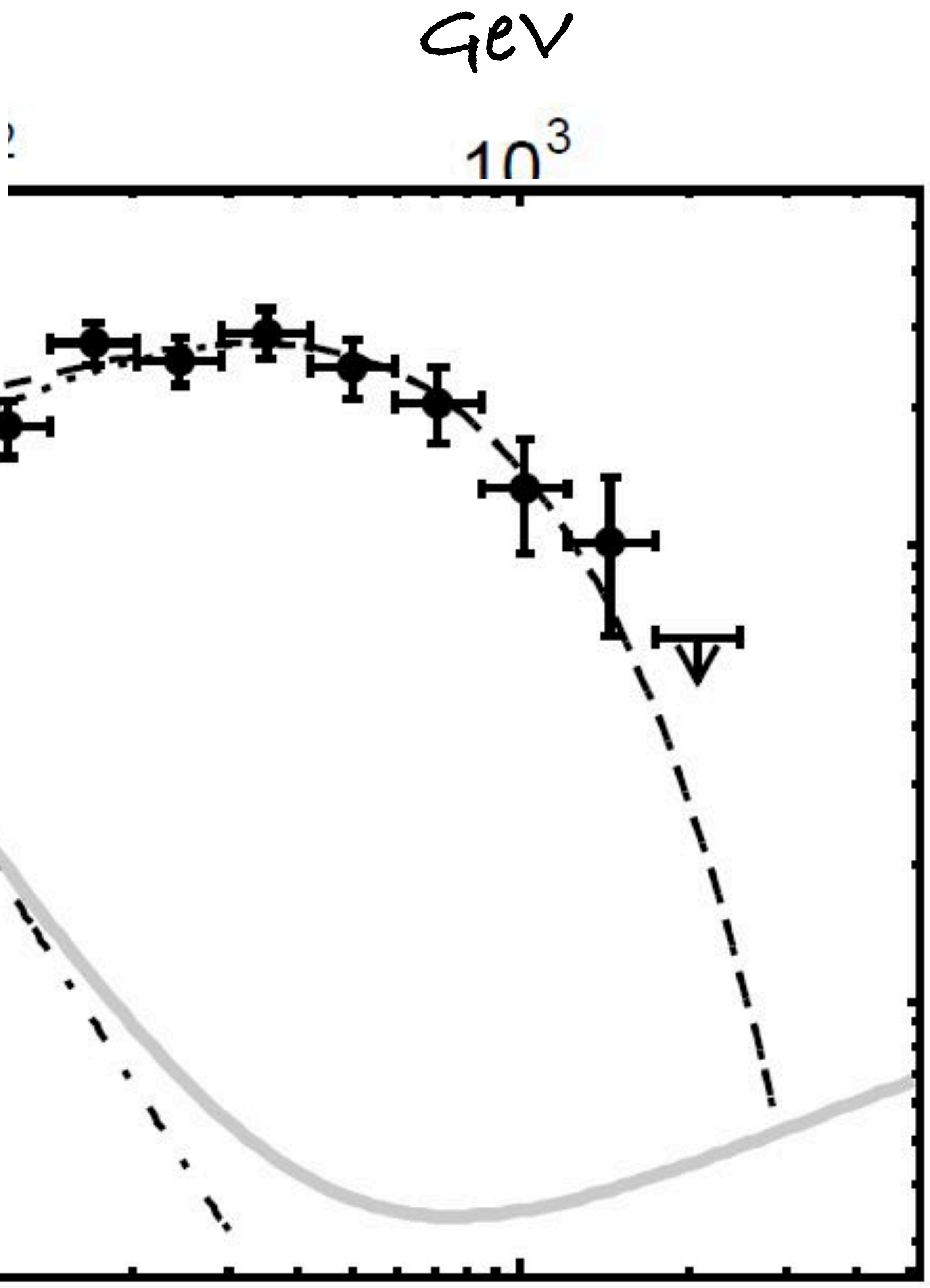

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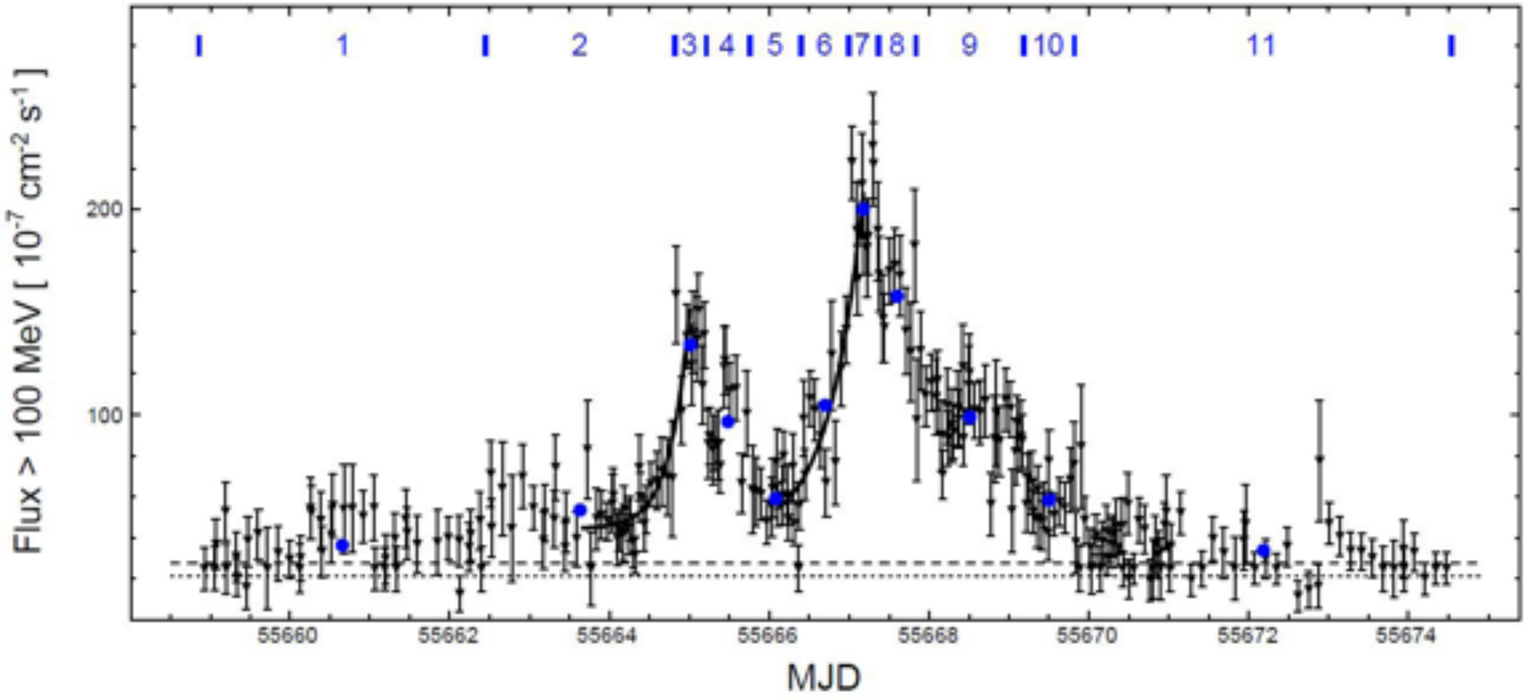

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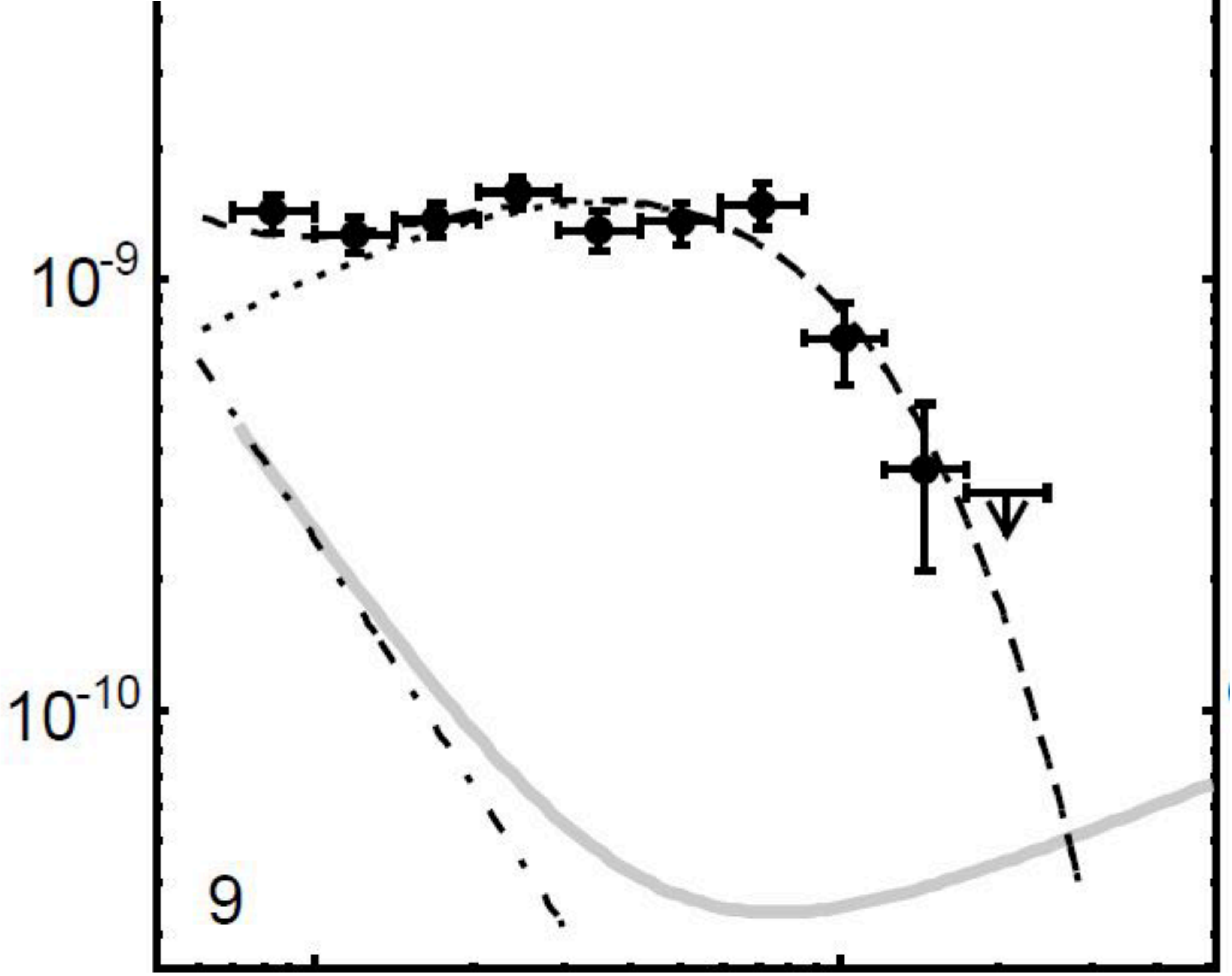

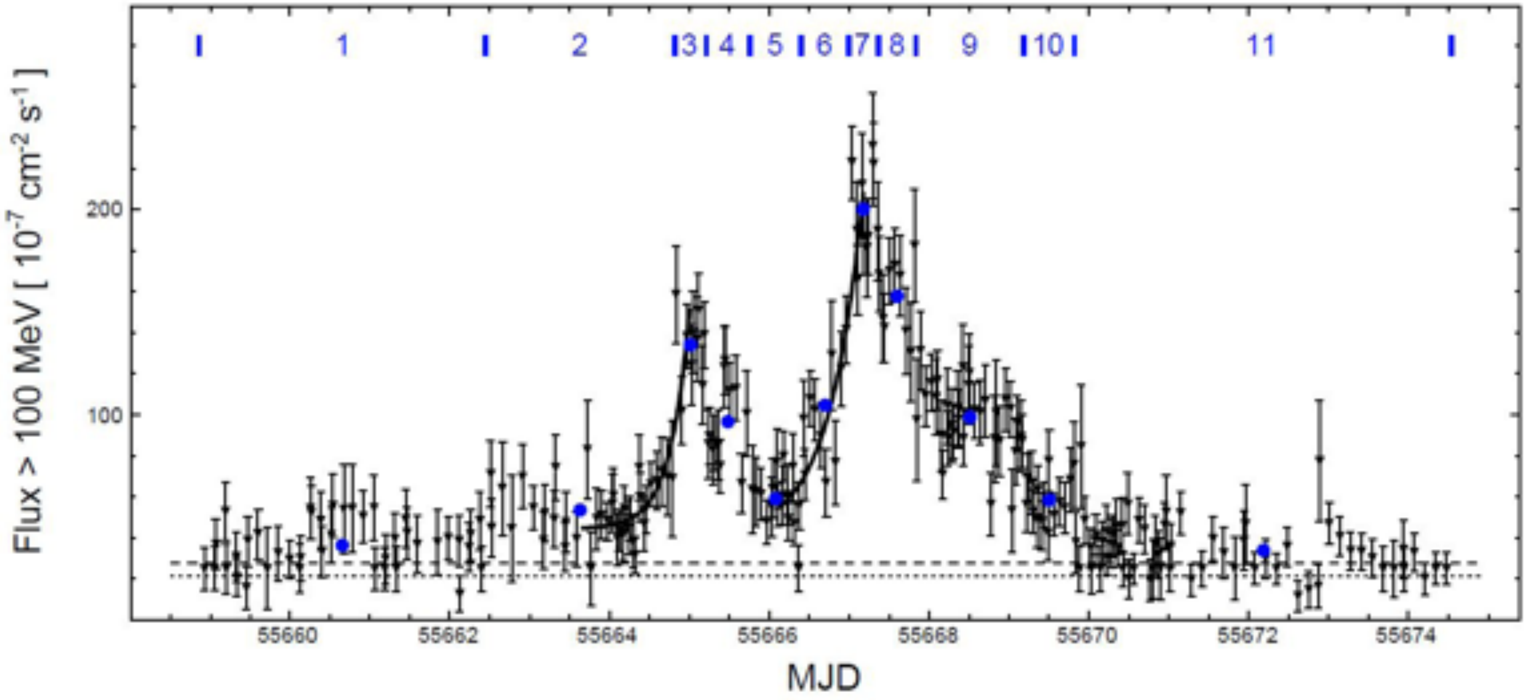

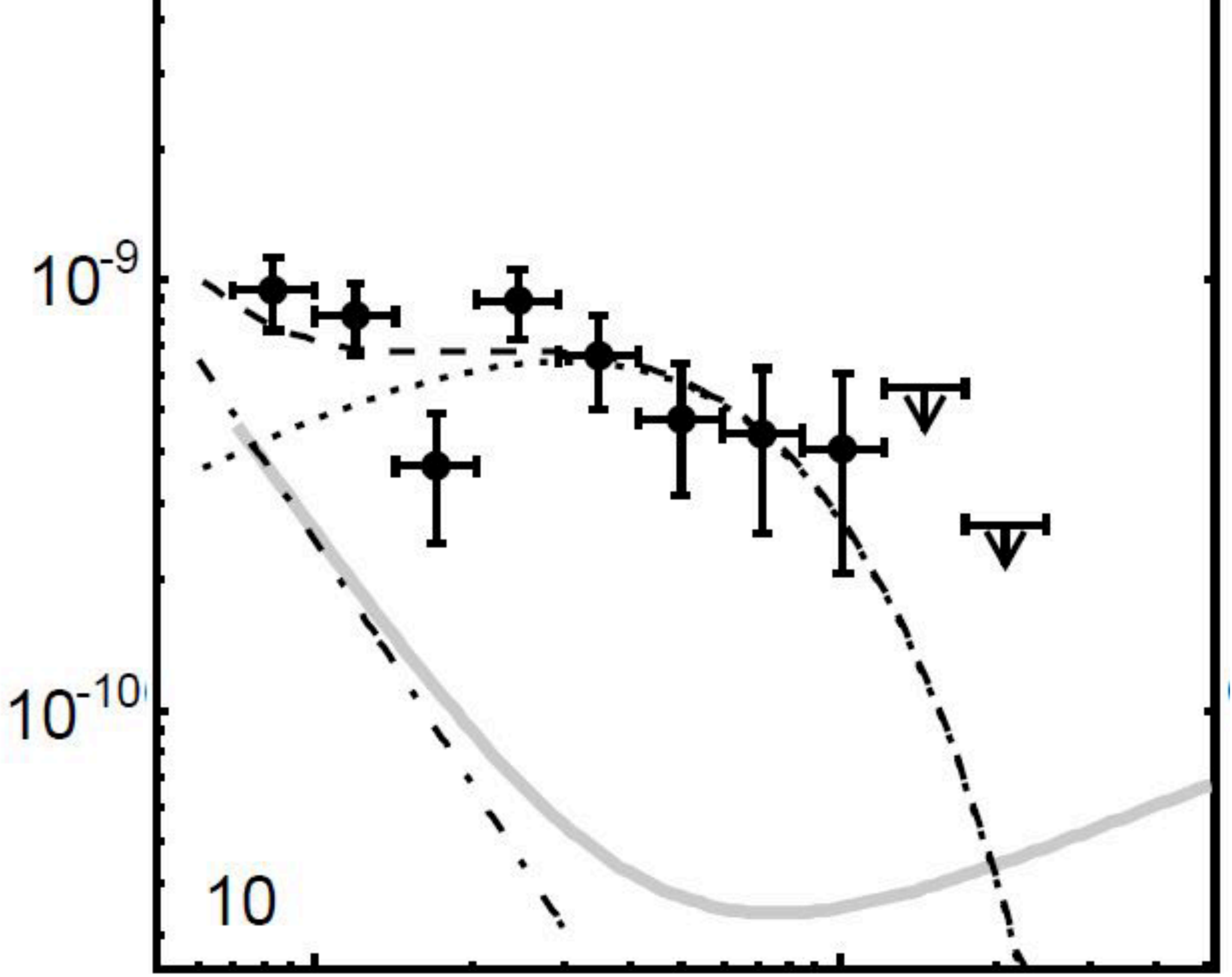

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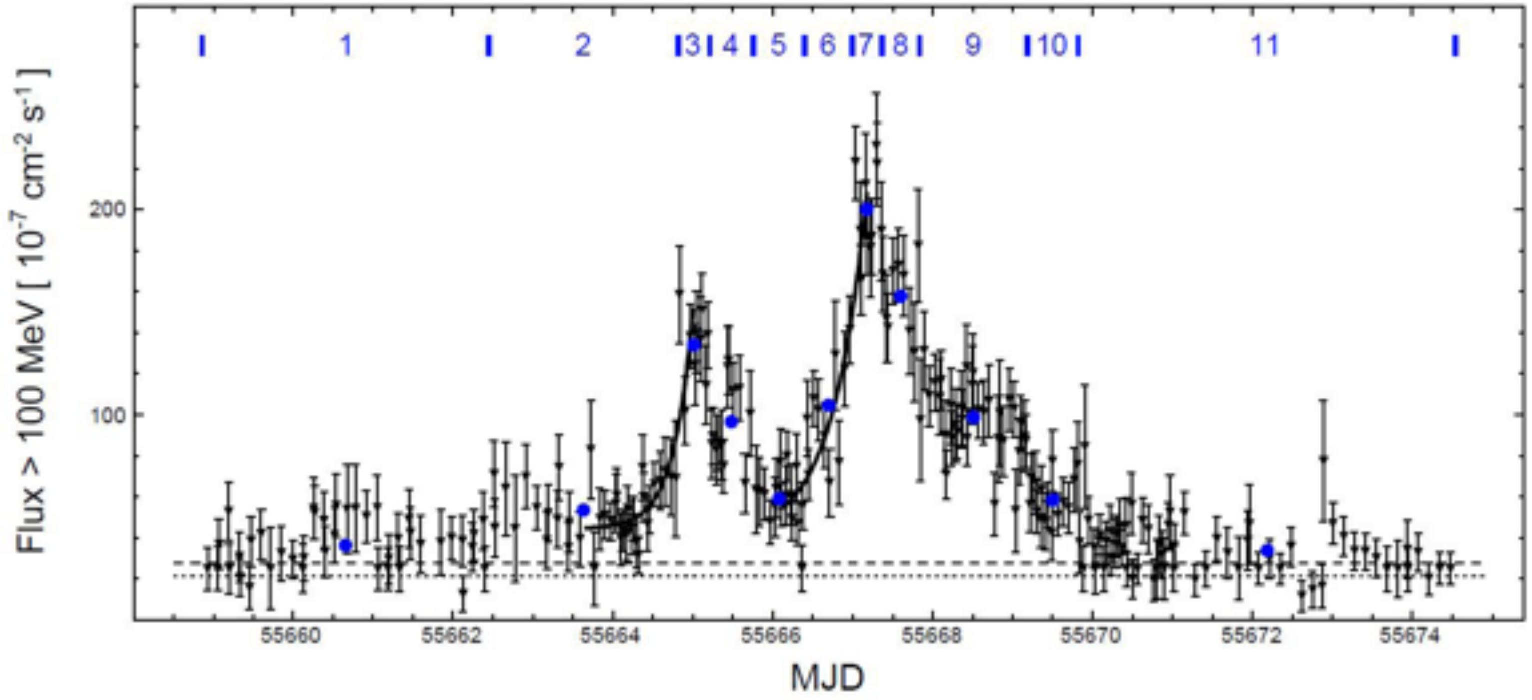

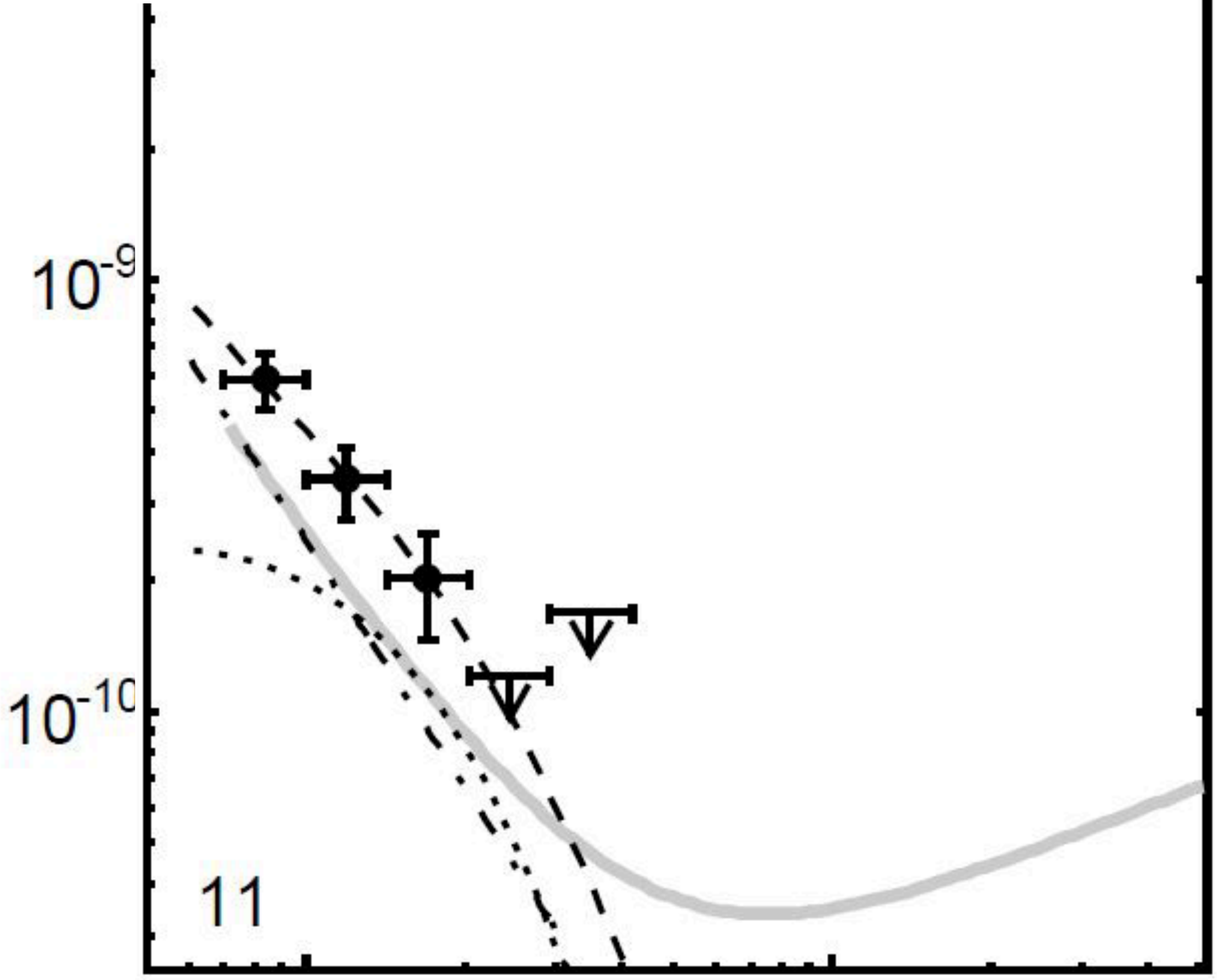

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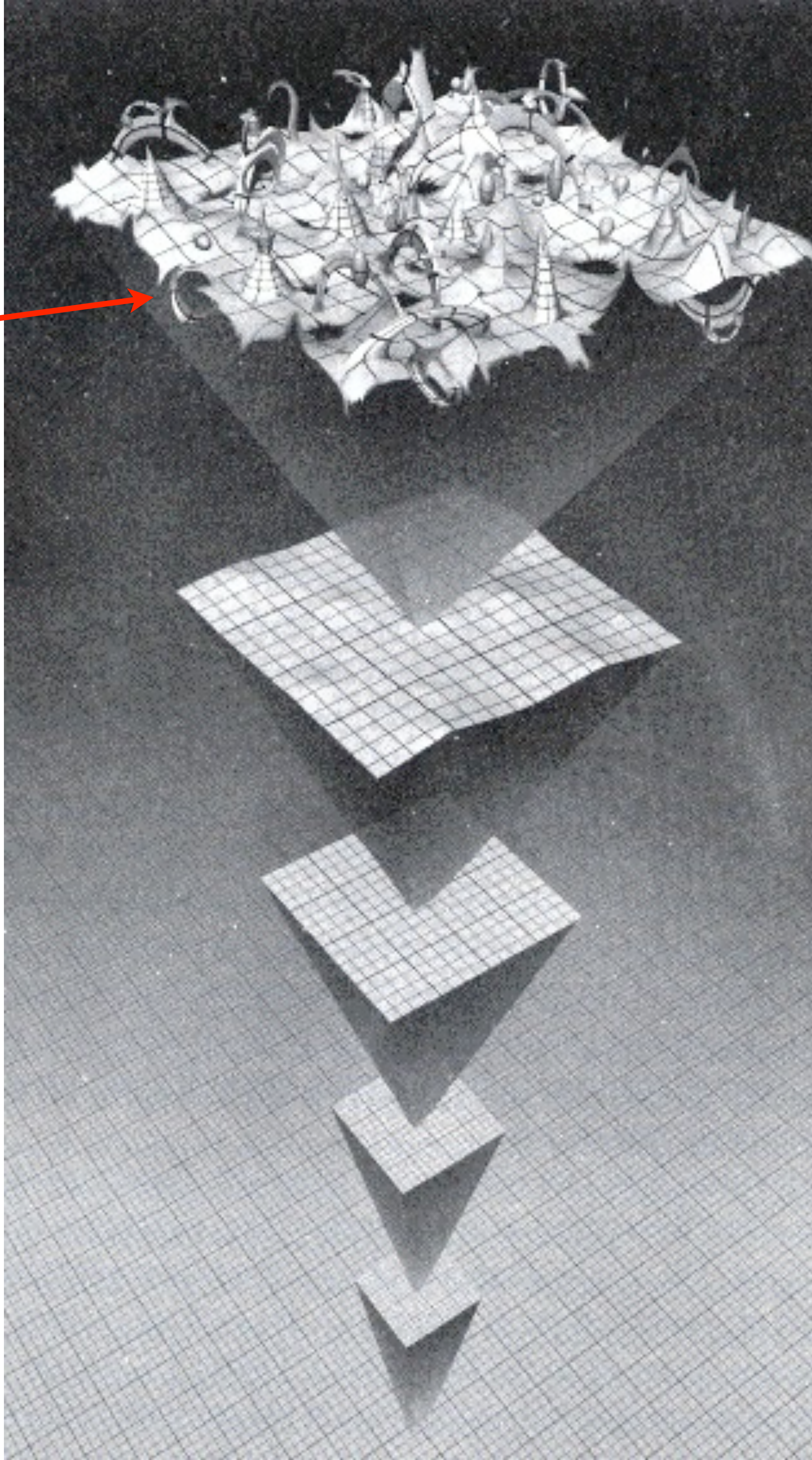
Lorentz invariance violation @ high energies ?



space-time becomes granular on smallest scales (quantum-Gravity effects)

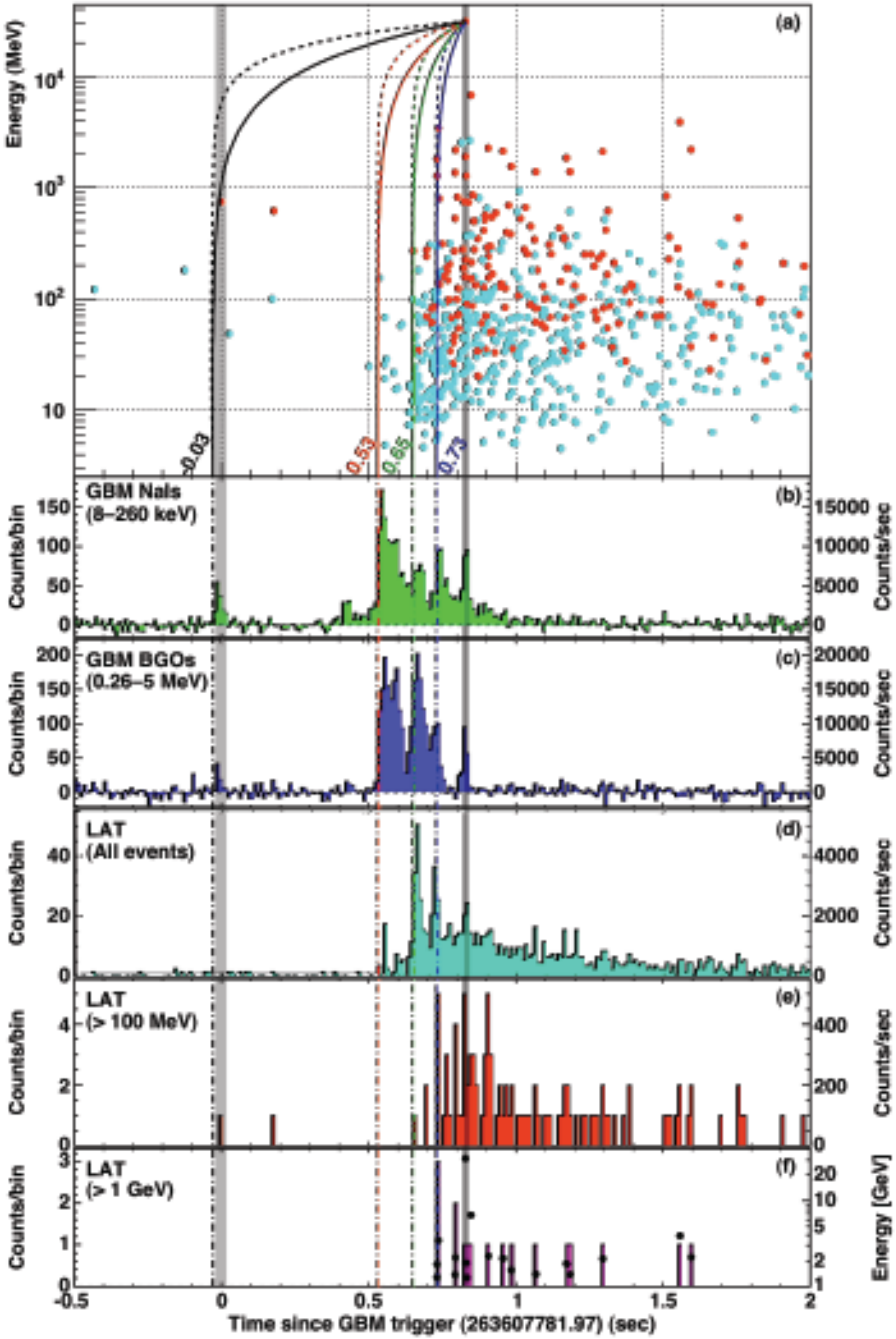
high energy photons resolve structures and travel on curly paths, i.e. they are slower than c

Fermi:
LIV test: GRB

Fermi LAT+GBM:

QG energy scale $> 1.2\ E_{\text{Planck}}$

(linear dep. of the speed of light on energy)



... plus many more exciting results. 100s of papers...

Beyond 100 GeV...

Steeply falling spectrum:

10x in energy /100-500 in flux !

$$N_{evts} = \text{flux} \times \text{area} \times \text{time}$$

> 100

for <10% stat. error

low, given by nature

$\approx 1\ \text{m}^2$

for space exp.

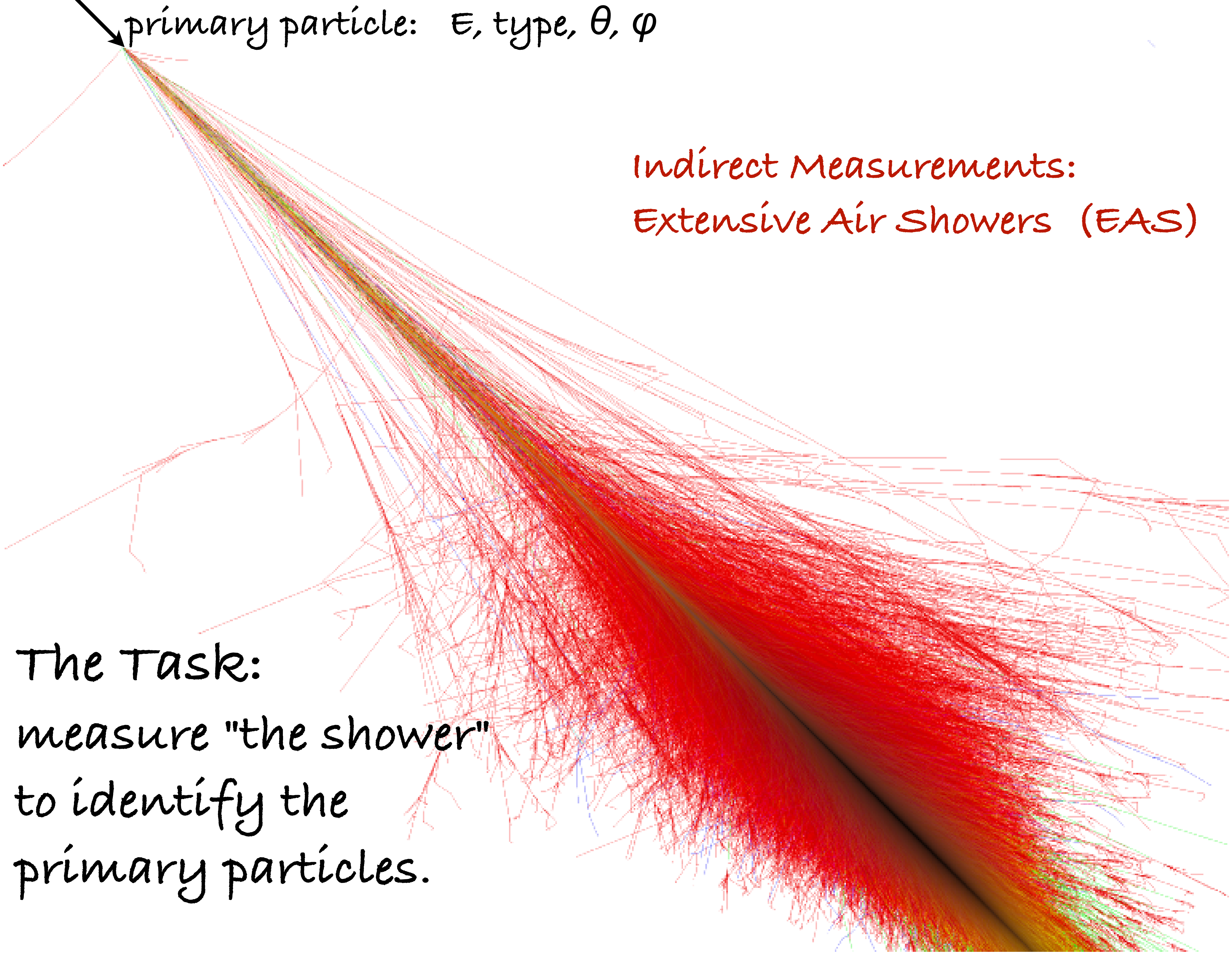
≈ 3 yrs

for a PhD

Size of detector limits the fluxes that can be observed

Therefore, HUGE detection volumes (i.e. target materials) need to be instrumented

Natural detector: the atmosphere is first target for particles from space



Indirect Measurements:
Extensive Air Showers (EAS)

The Task:

measure "the shower"
to identify the
primary particles.

+ Particle Multiplication:

Instead of 1 particle (the primary) one has to detect
a shower with many particles scattered over a wide area.
much easier to detect !

- Indirect Measurements:

Deduce properties of primary particles from
the shape and particle content of the shower of secondaries.

- particles (e, γ , μ , …) at ground level
- Cherenkov light from charged secondaries (forward)
- Fluorescence light from ionised air (isotropic)
- Radio emission from charges in Earth magnetic field (forward)

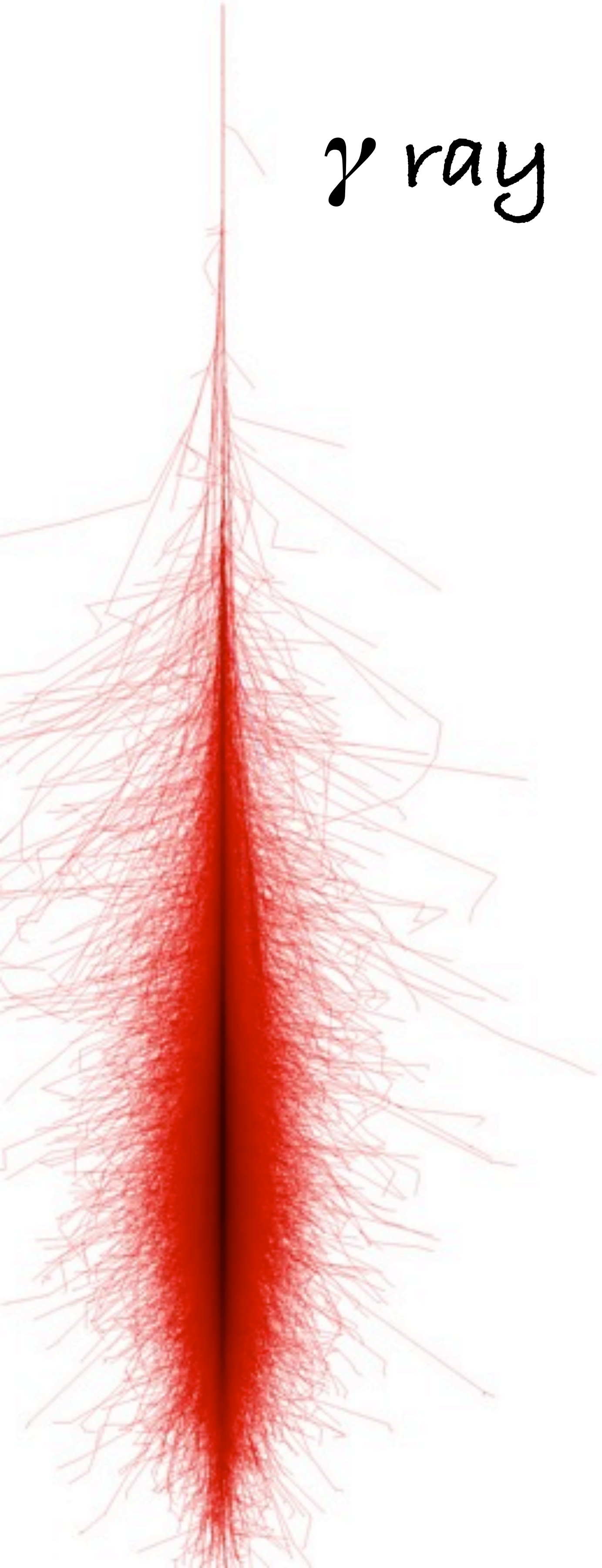
for all: density, lateral-, energy-, time distributions

This is tricky:
it requires knowledge on how a shower develops
depending on its primary, energy, angle,
el.mag. / hadronic interactions, ….

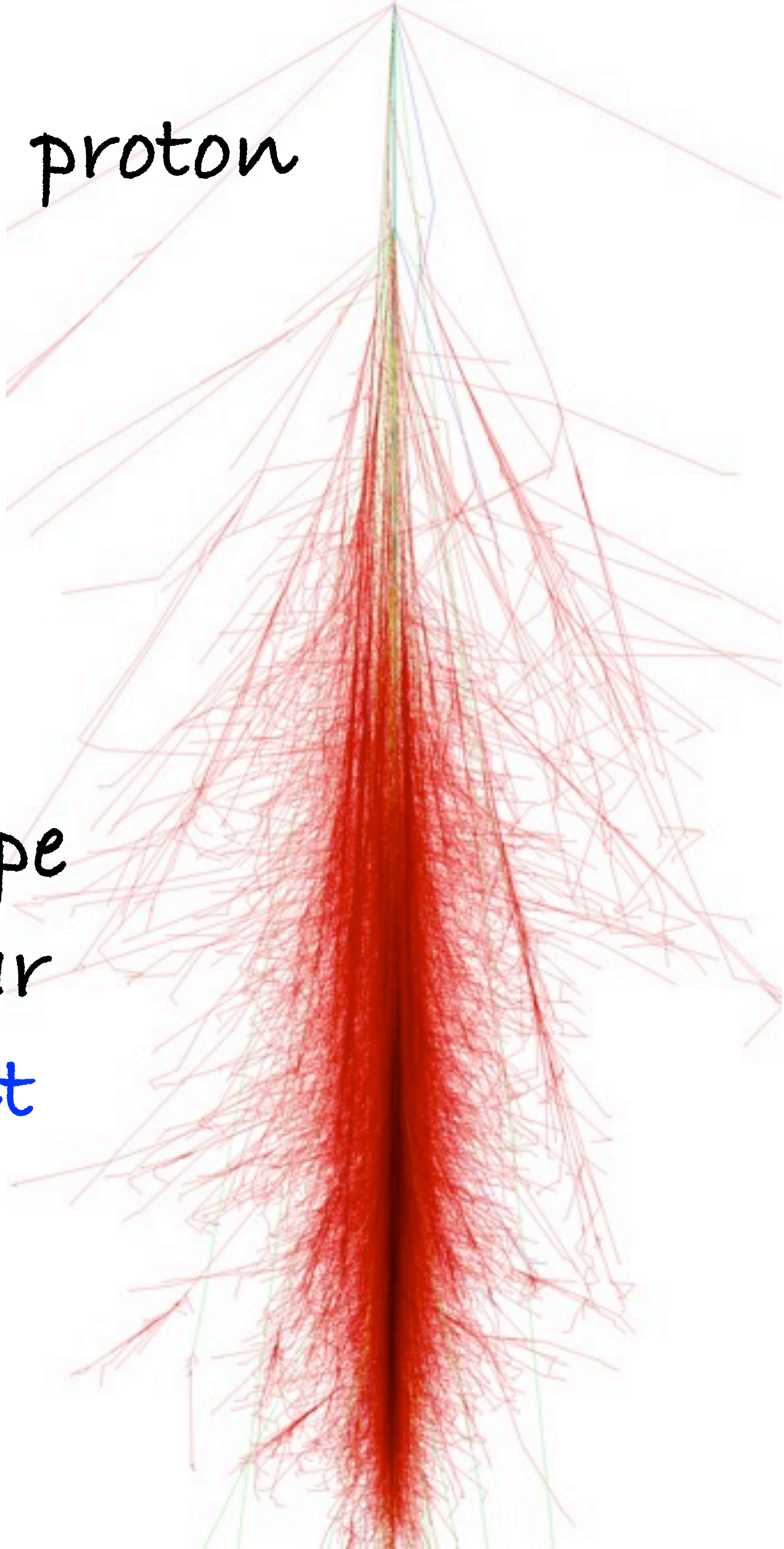
MC sims!

10^{12} eV γ ray vs hadronic showers

γ ray



proton



different shape

more irregular

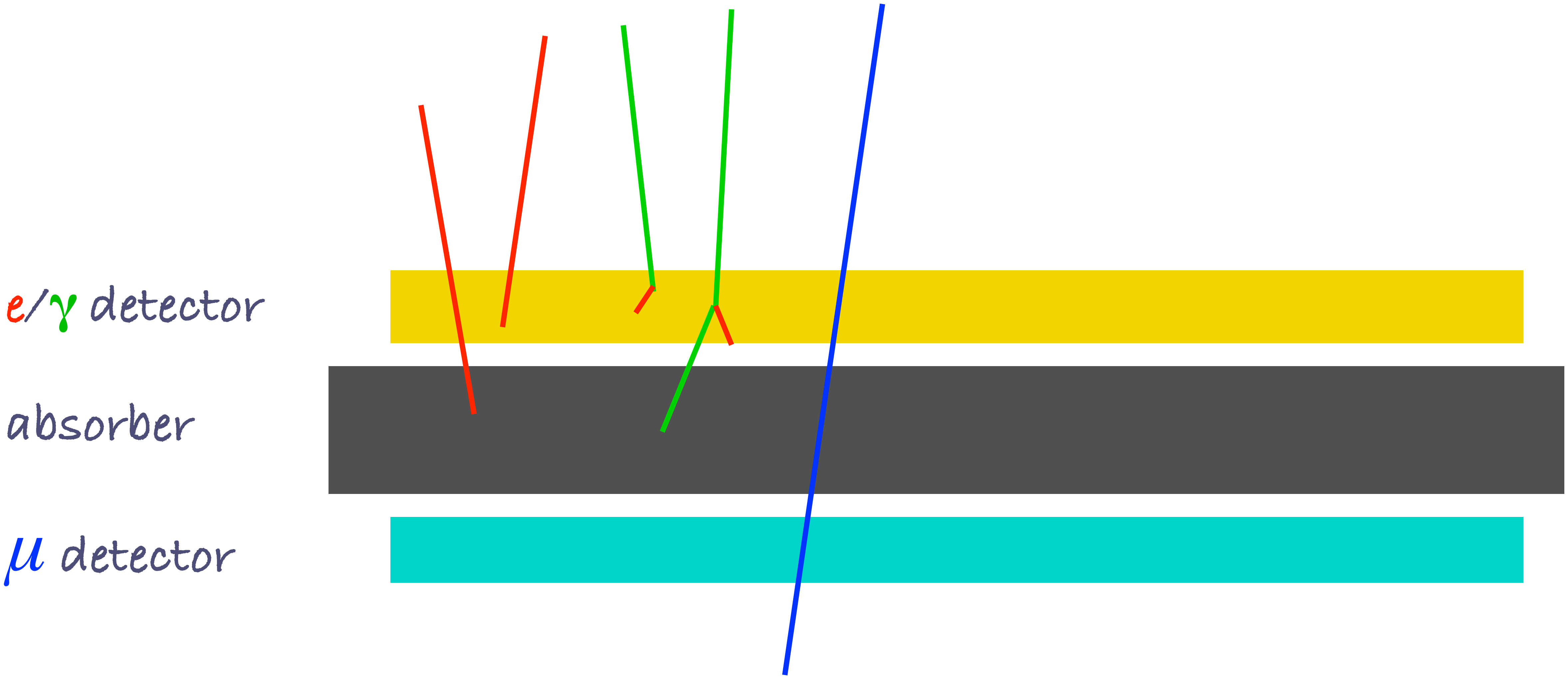
muon content

all particles

Different detectors for different purposes ...

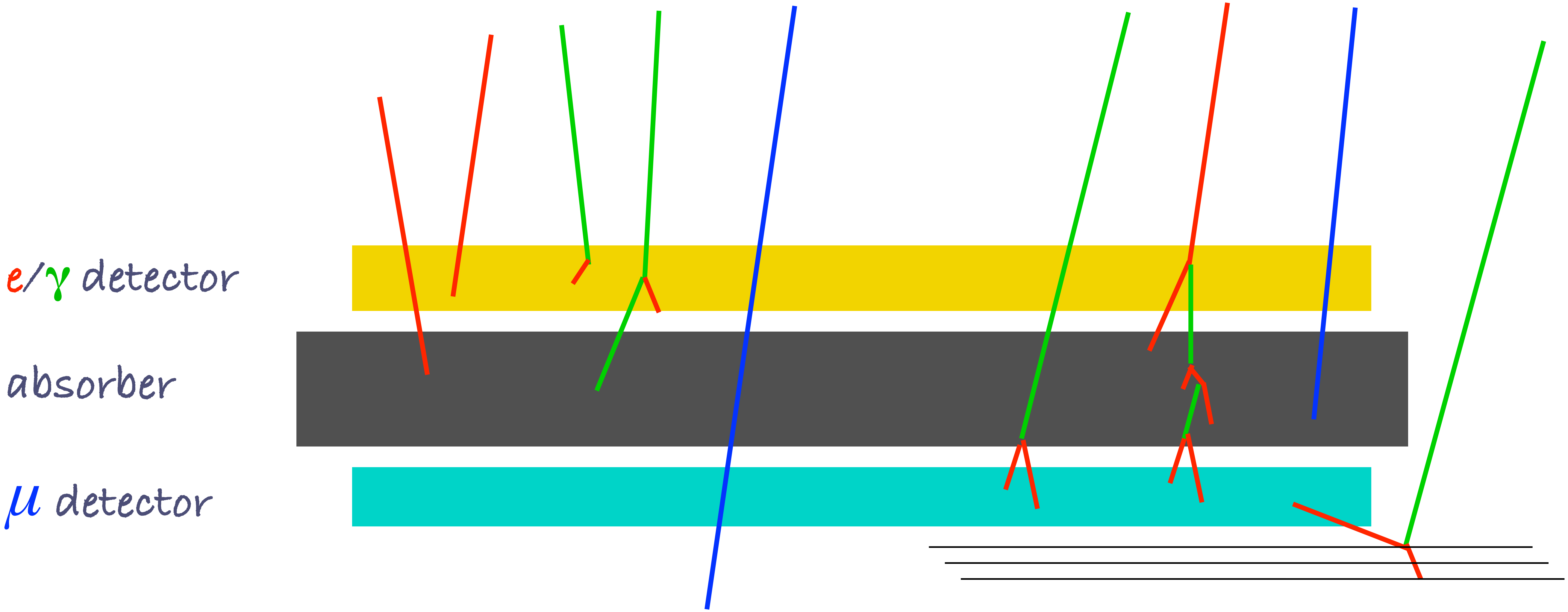
EAS Observables:	Suitable Detectors:
Number, distribution, fluctuation of electrons arrival times	arrays of scintillators, water Cherenkov detectors or gas chambers
Number, distribution, angle, energy, fluctuation of μ	buried detectors, tracking chambers
Number, distribution and energy of hadrons	deep hadronic calorimeters
Number and distribution, angular distribution of Cherenkov photons	wide angle and imaging Cherenkov detectors
angular distribution of fluorescence photons	fluorescence telescopes
Depth of shower maximum	Cherenkov or fluorescence detectors

Identifying secondaries is not so easy ....



detector response is crucial

Identifying secondaries is not so easy ....



detector response is crucial

Gamma ray sources can be detected

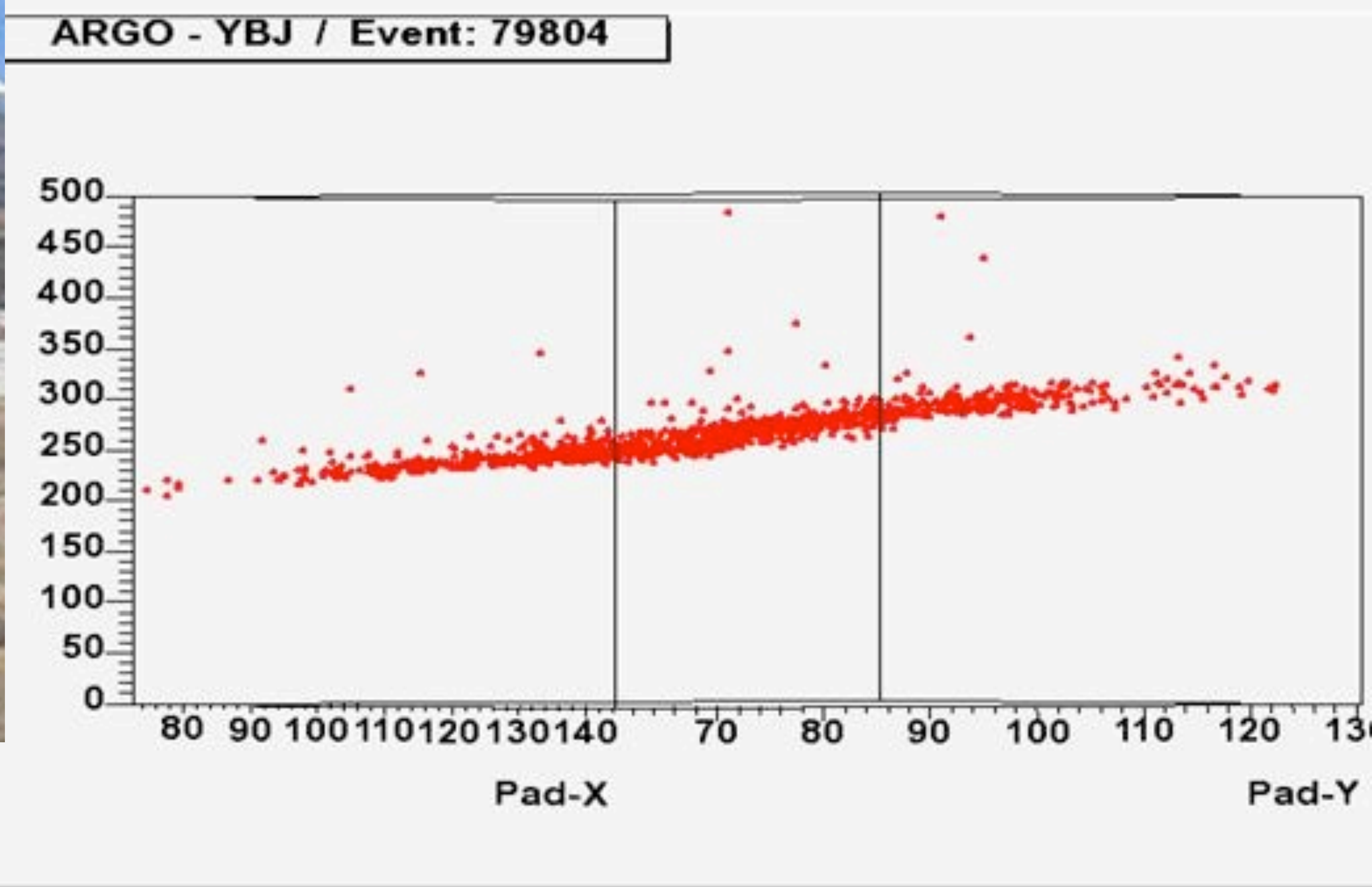
—if you can identify a single photon event from the sea of background events

(shower shape, muon content)

—if they emit so many photons that the number of particles from this direction stands out of the background.

(excess of events from a position in sky)

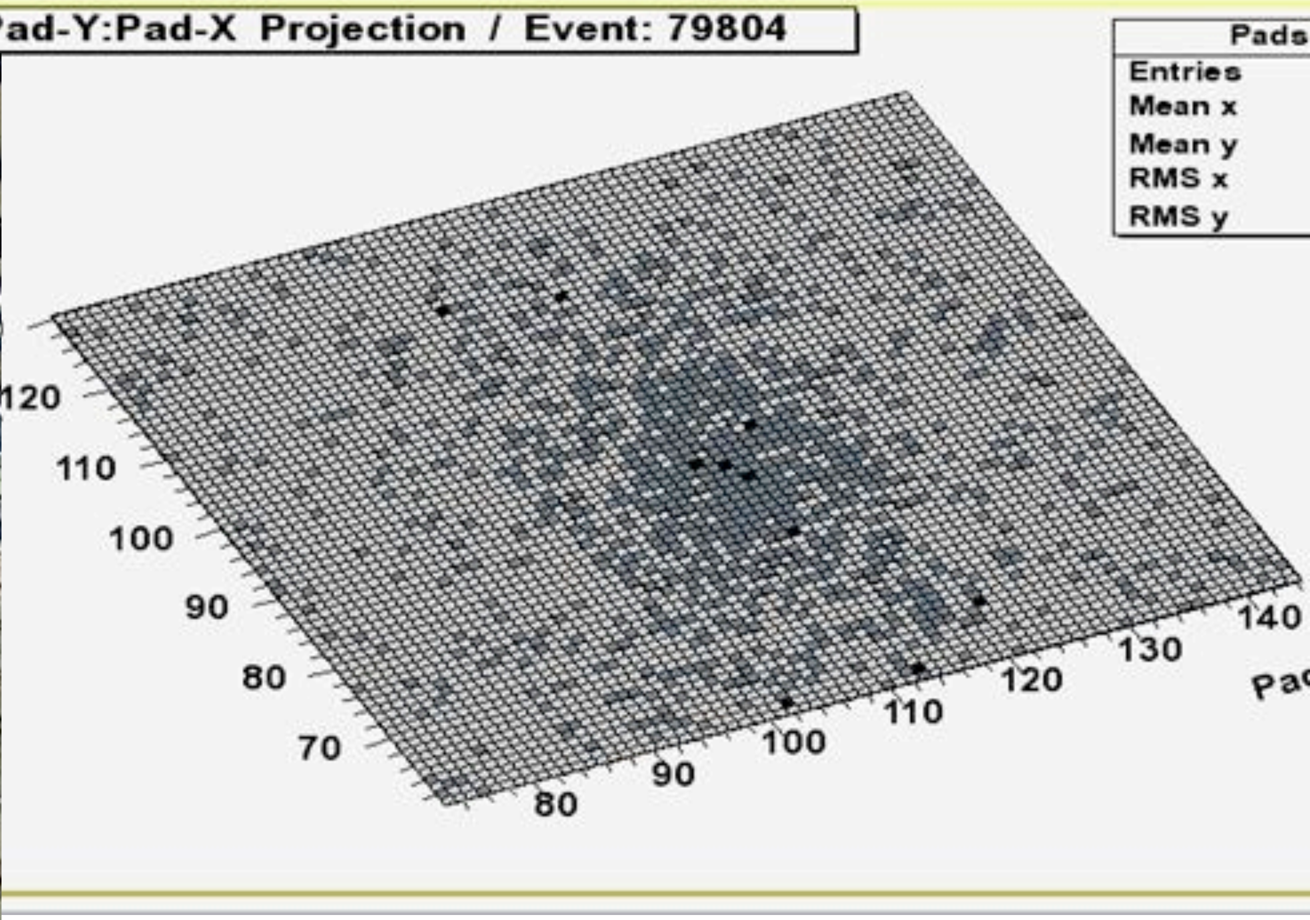
4200 m.a.s.l.



Argo

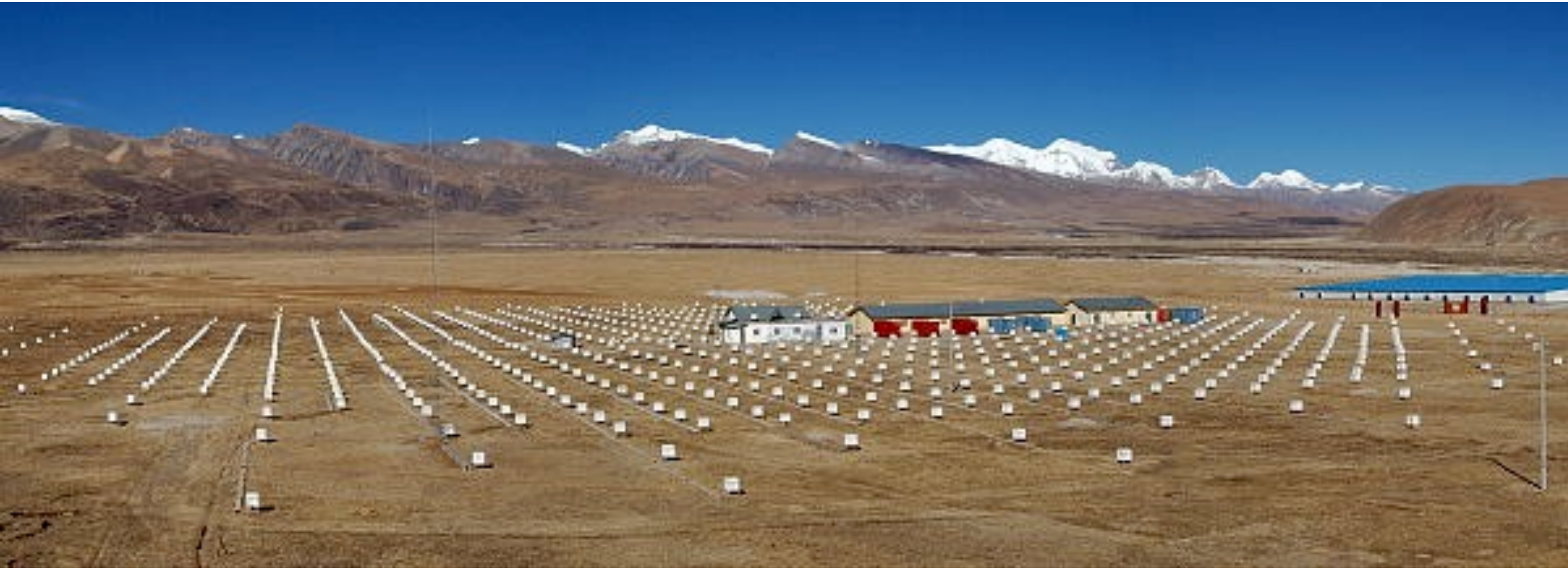
gamma sources

RPCs full coverage



Tibet AS Gamma

4200 m.a.s.l.



Milagro

2650 m.a.s.l.

New Mexico

80 m x 60 m water pond
8 m deep.

Detect shower particles via
Cherenkov light in water

PMTs in 2 layers for
el.mag. and muons.

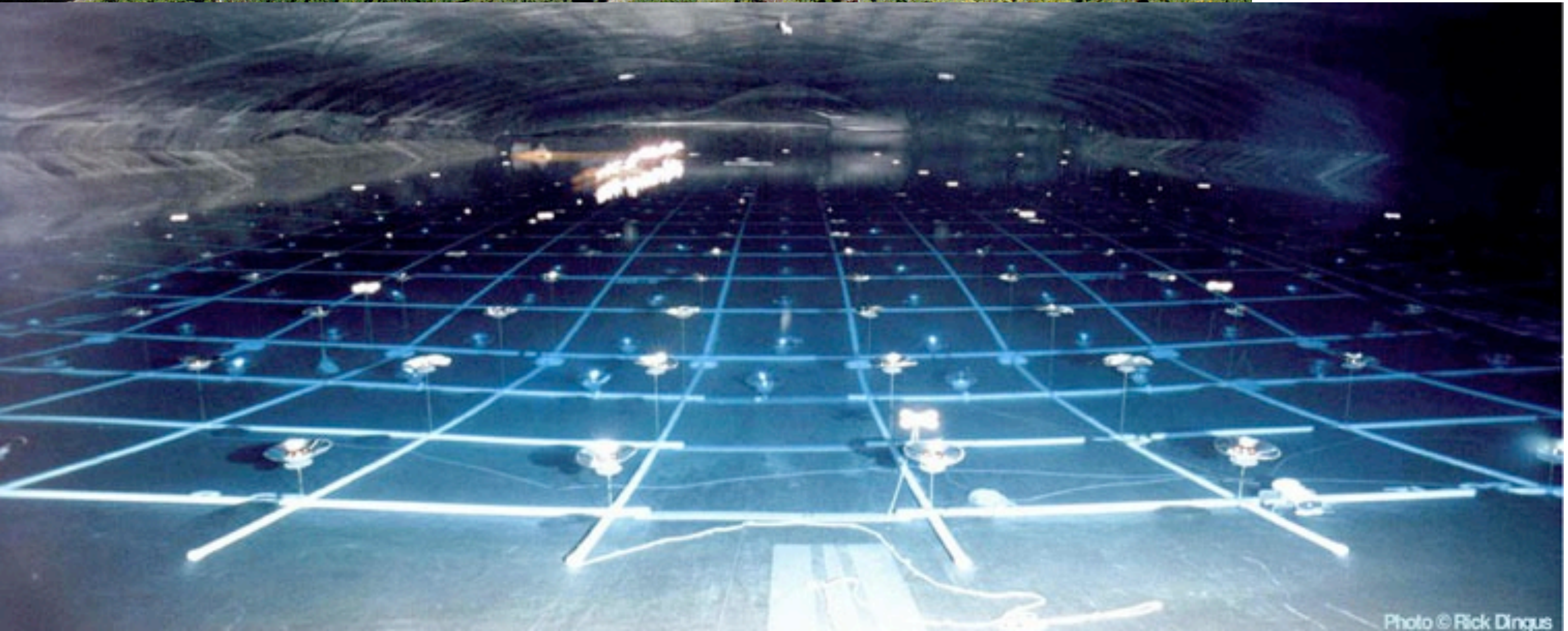


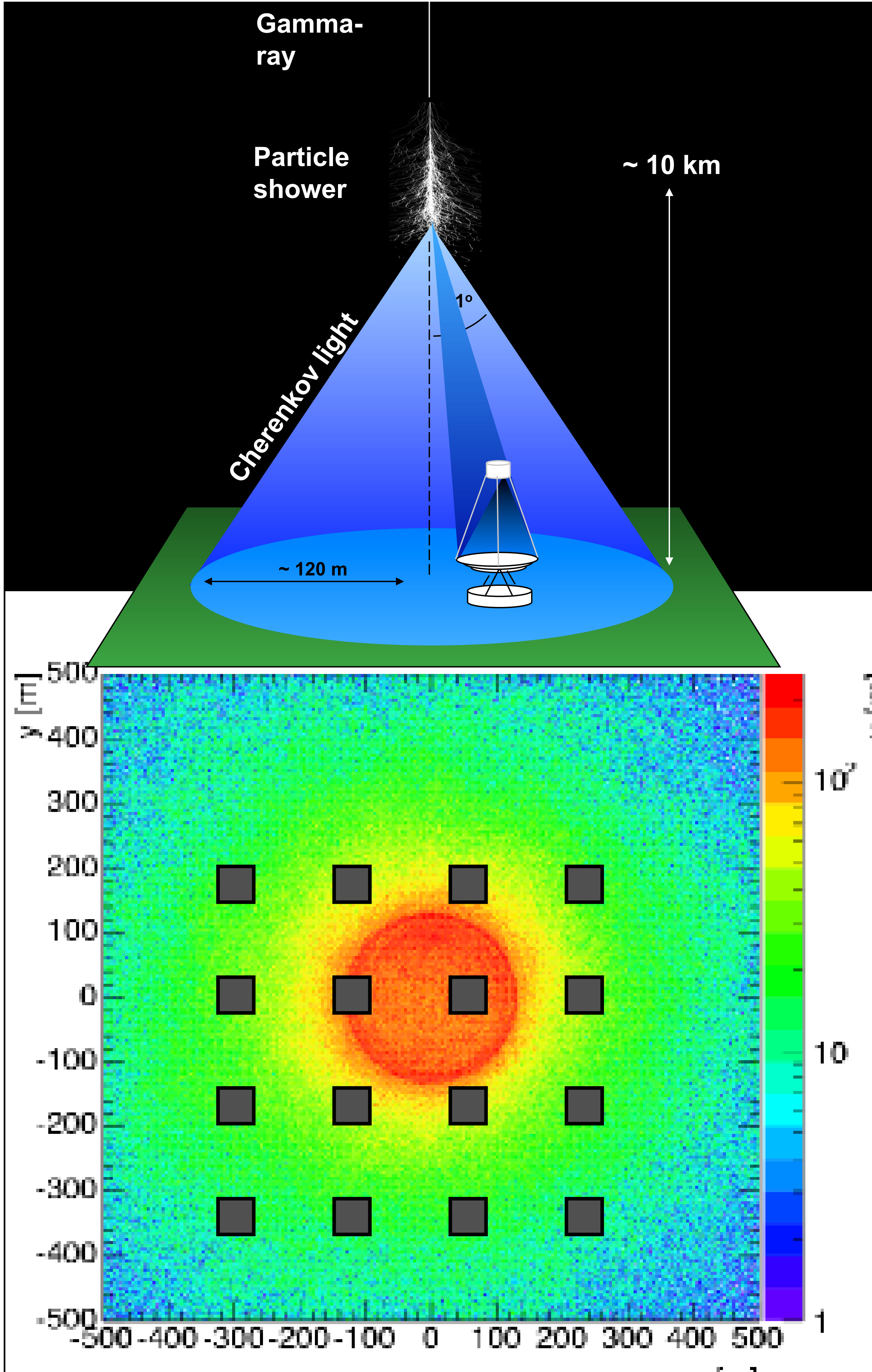
Photo © Rick Dingus

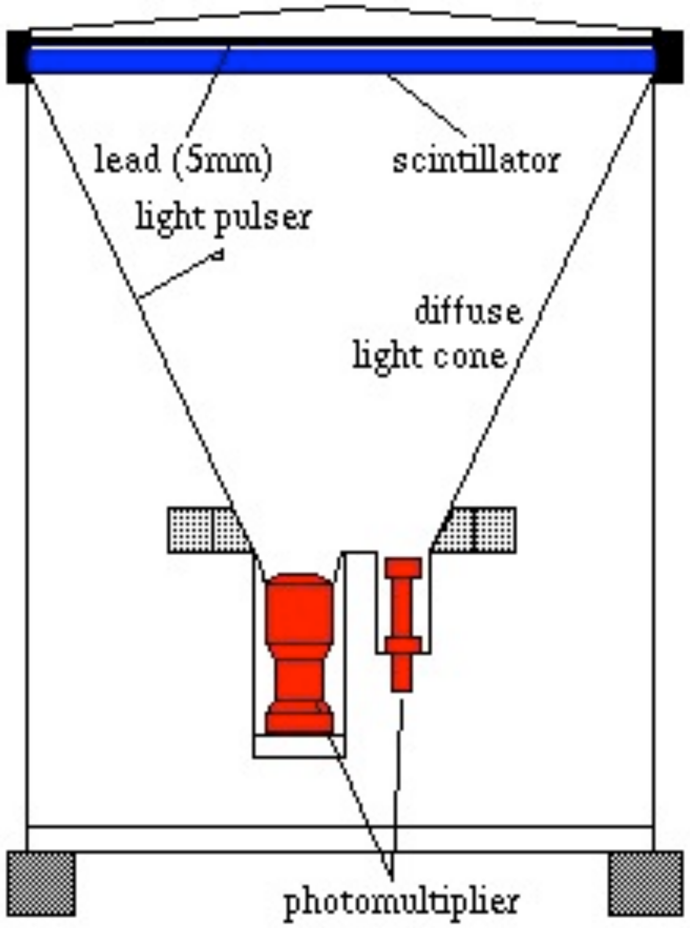
look for excess:
gamma sources

2π sky view

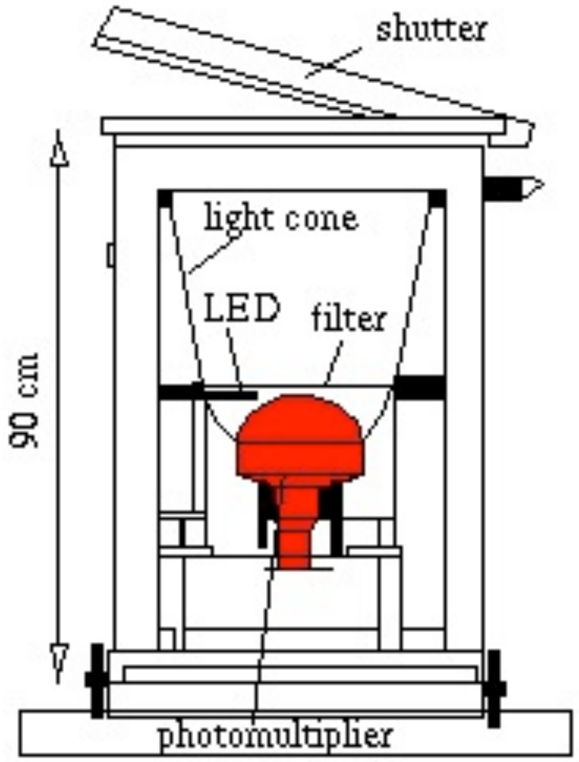
… or sample the light pool
and measure the lateral distribution

good, calorimetric
energy measurement





scintillation counter



AIROBICC counter

Hegra, Airobicc
La Palma

scintillator array
Muon detectors
Cherenkov counter

poor γ- hadron separation

via muon content or particle pattern at ground

γ sources detected by excess counts
from certain directions

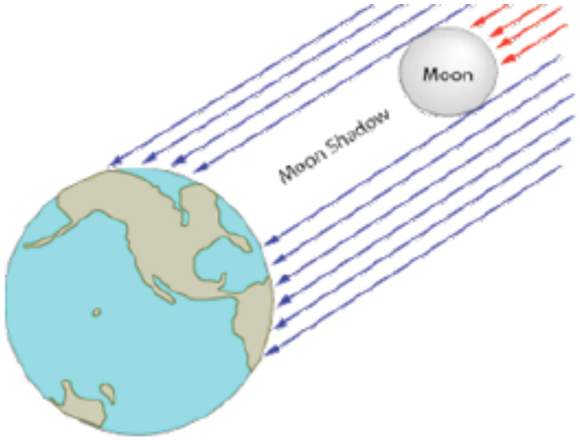
sources: Moon, Sun shadow

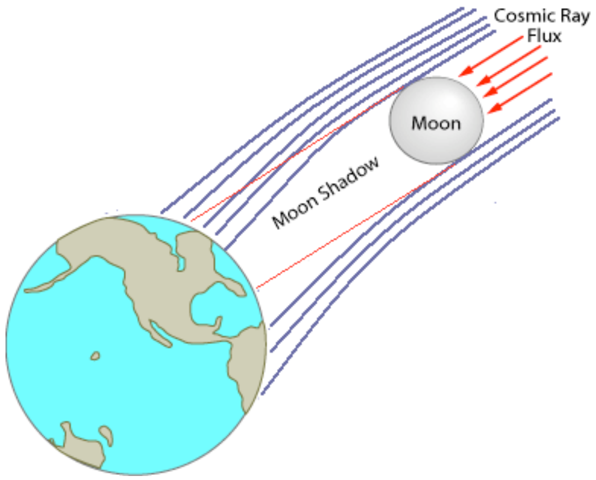
Crab nebula

few strong γ sources

Moon Shadow … calibration of direction reconstruction

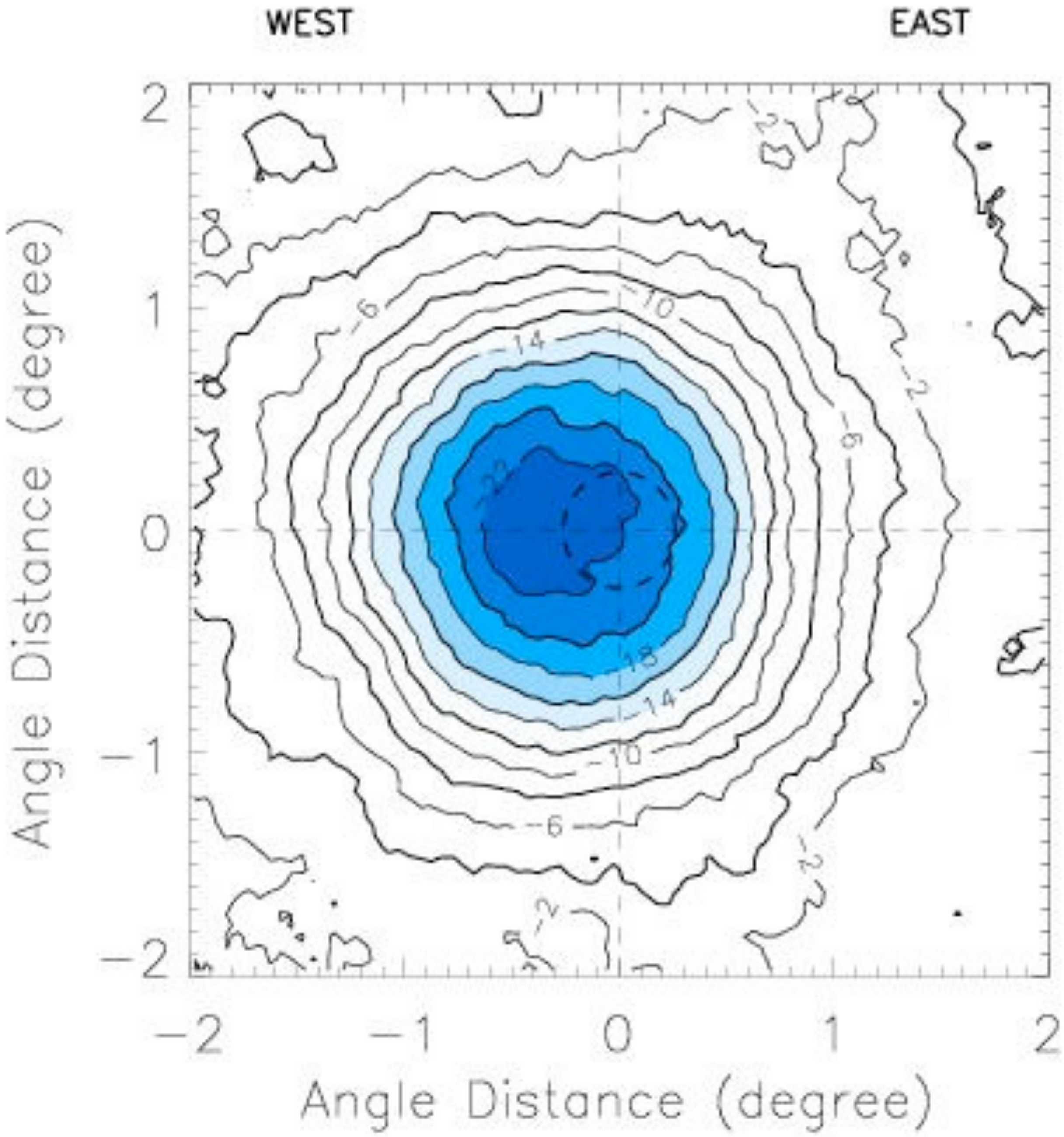
$E \approx \mathrm{TeV}$

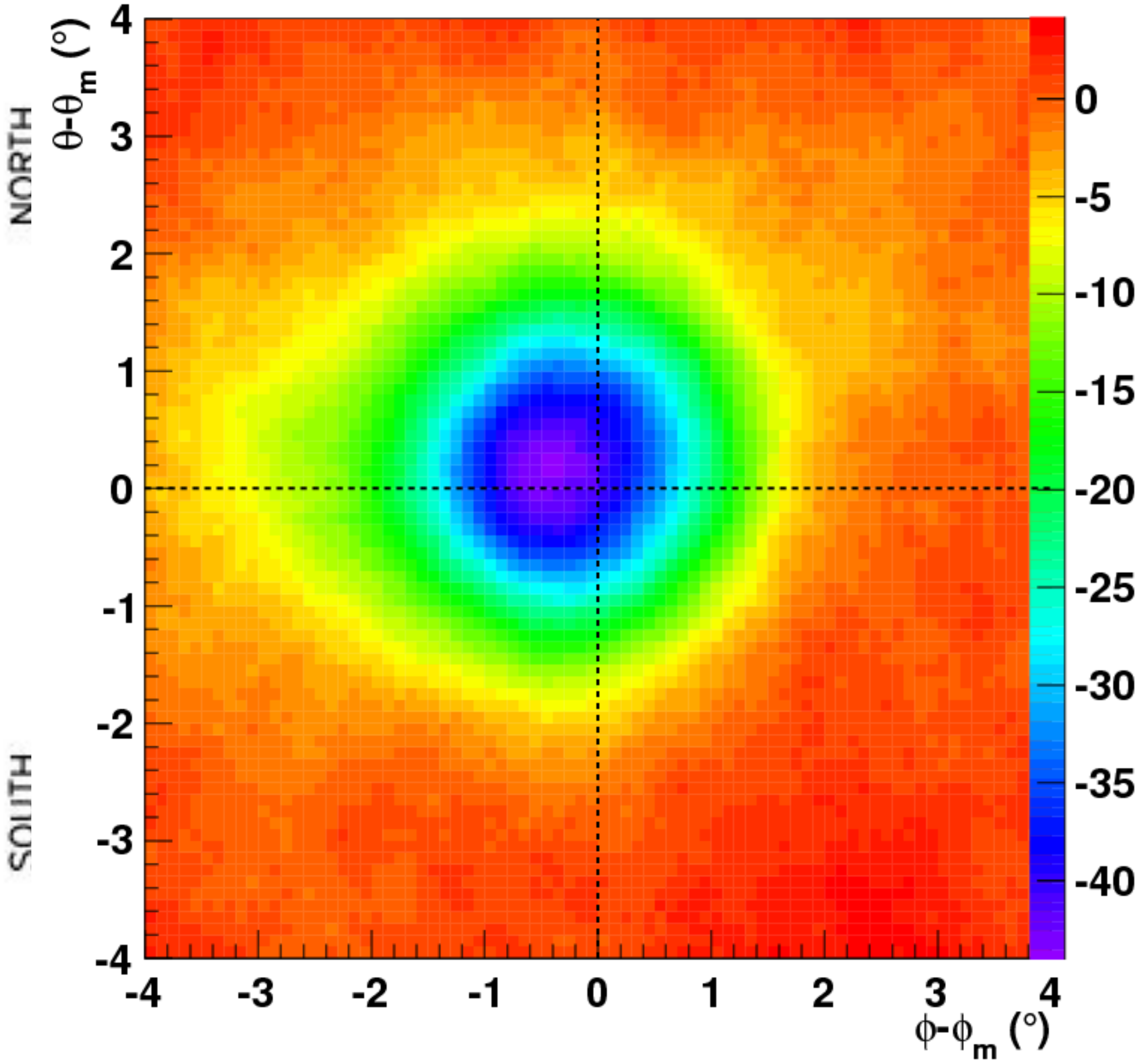




Tibet ASγ

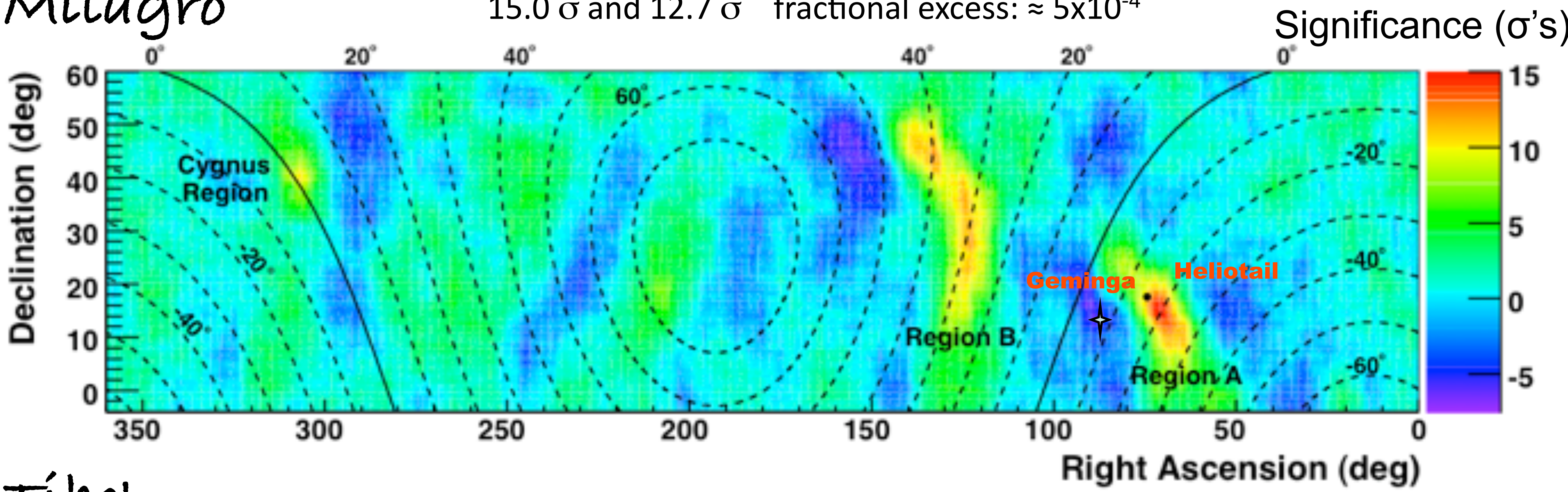
Argo



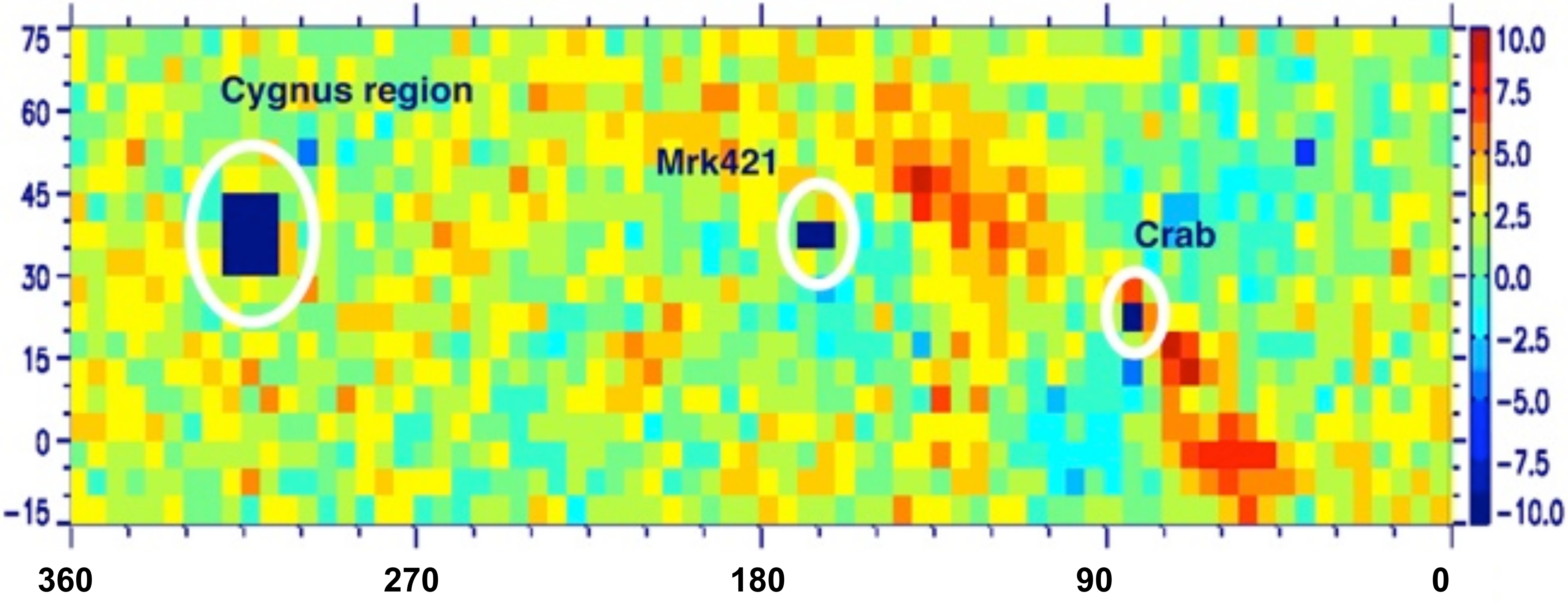


Milagro

15.0 σ and 12.7 σ fractional excess: ≈ 5×10^{-4}

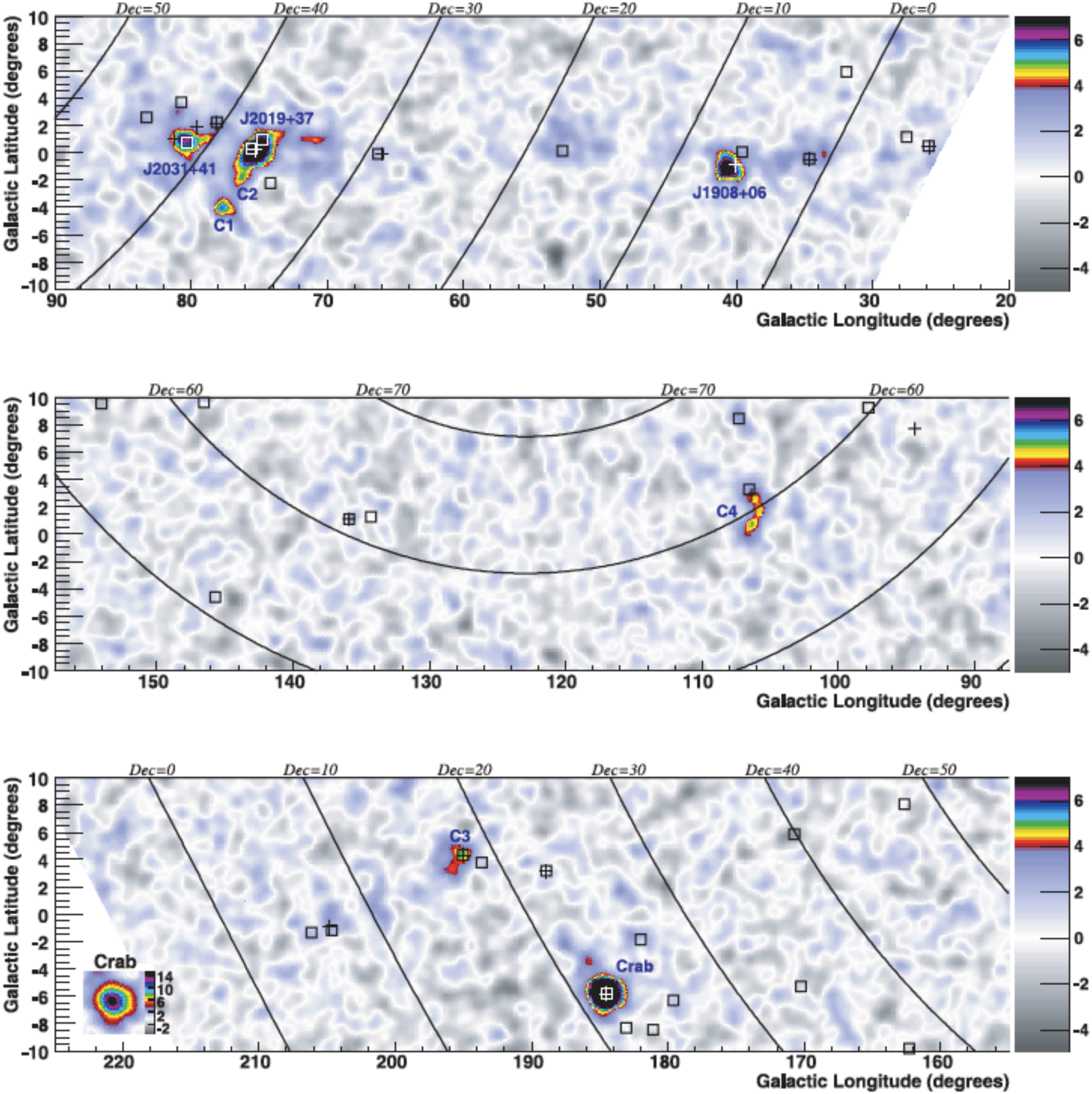


Tibet



MILAGRO gal. plane

□ EGRET sources



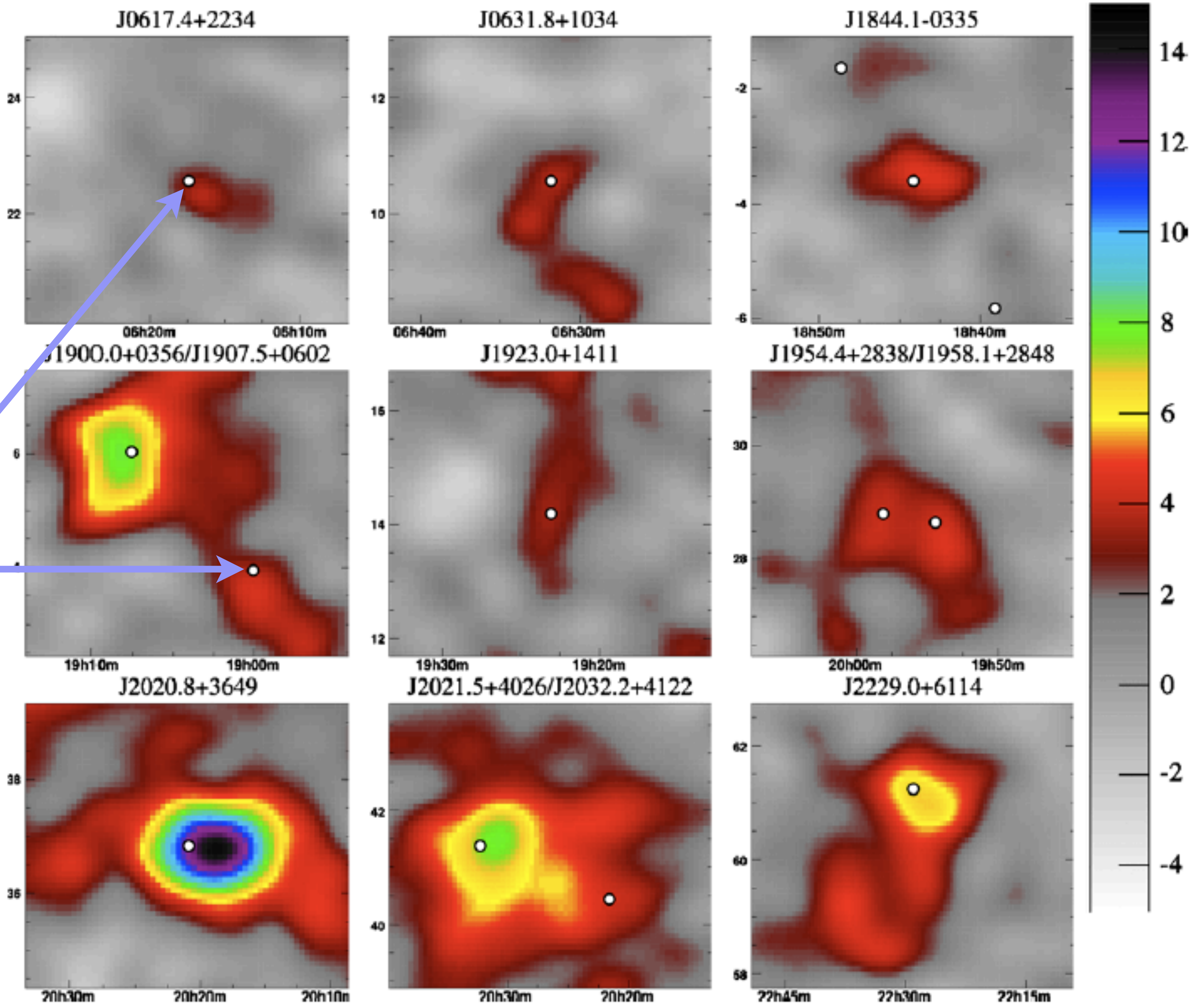
MILAGRO

(3 σ)

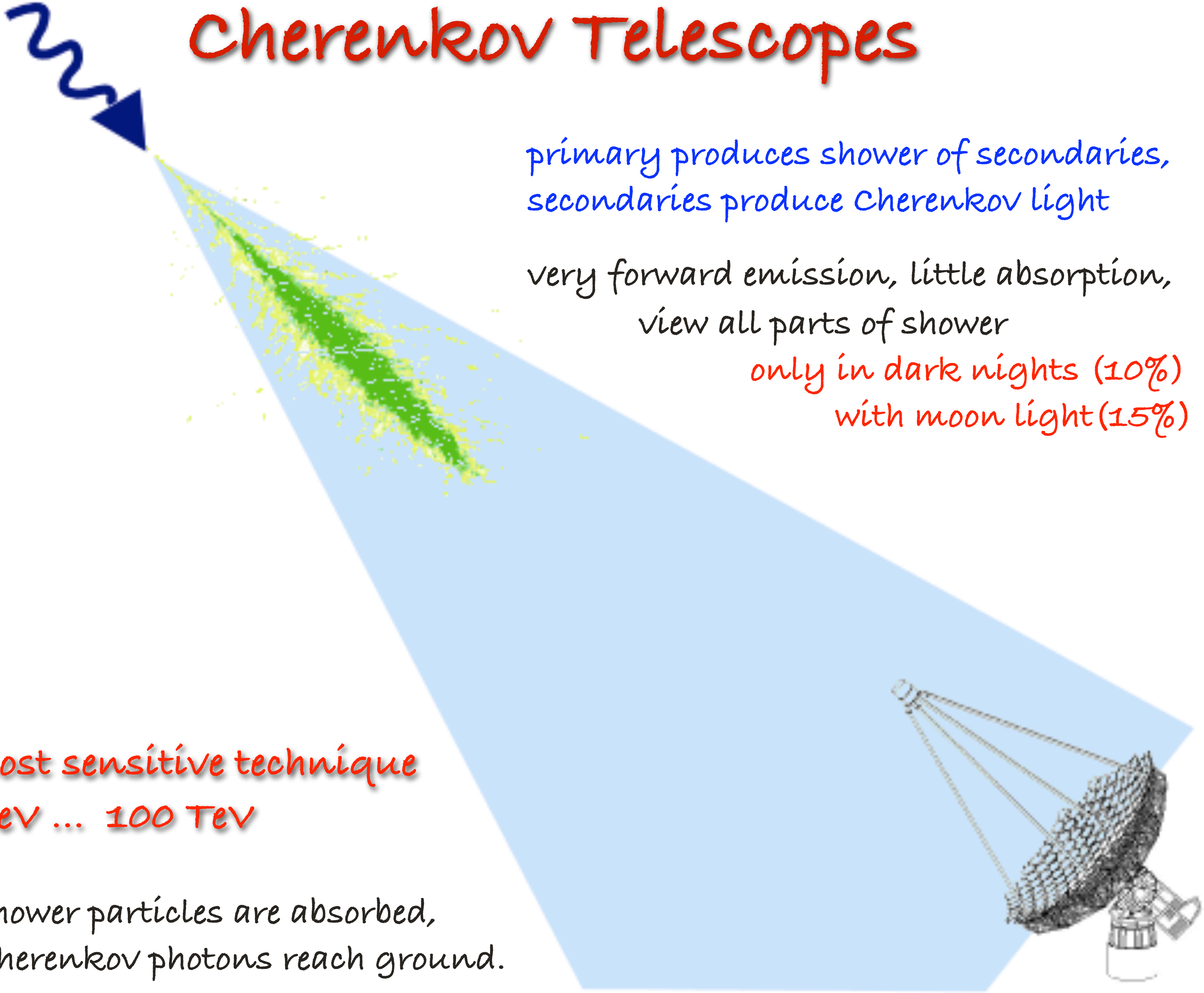
strong

Fermi

sources



Cherenkov Telescopes



primary produces shower of secondaries,
secondaries produce Cherenkov light

very forward emission, little absorption,
view all parts of shower
only in dark nights (10%)
with moon light (15%)

The most sensitive technique
100 GeV ... 100 TeV

Most shower particles are absorbed,
only Cherenkov photons reach ground.

The Early Days

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

1934-38: 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)

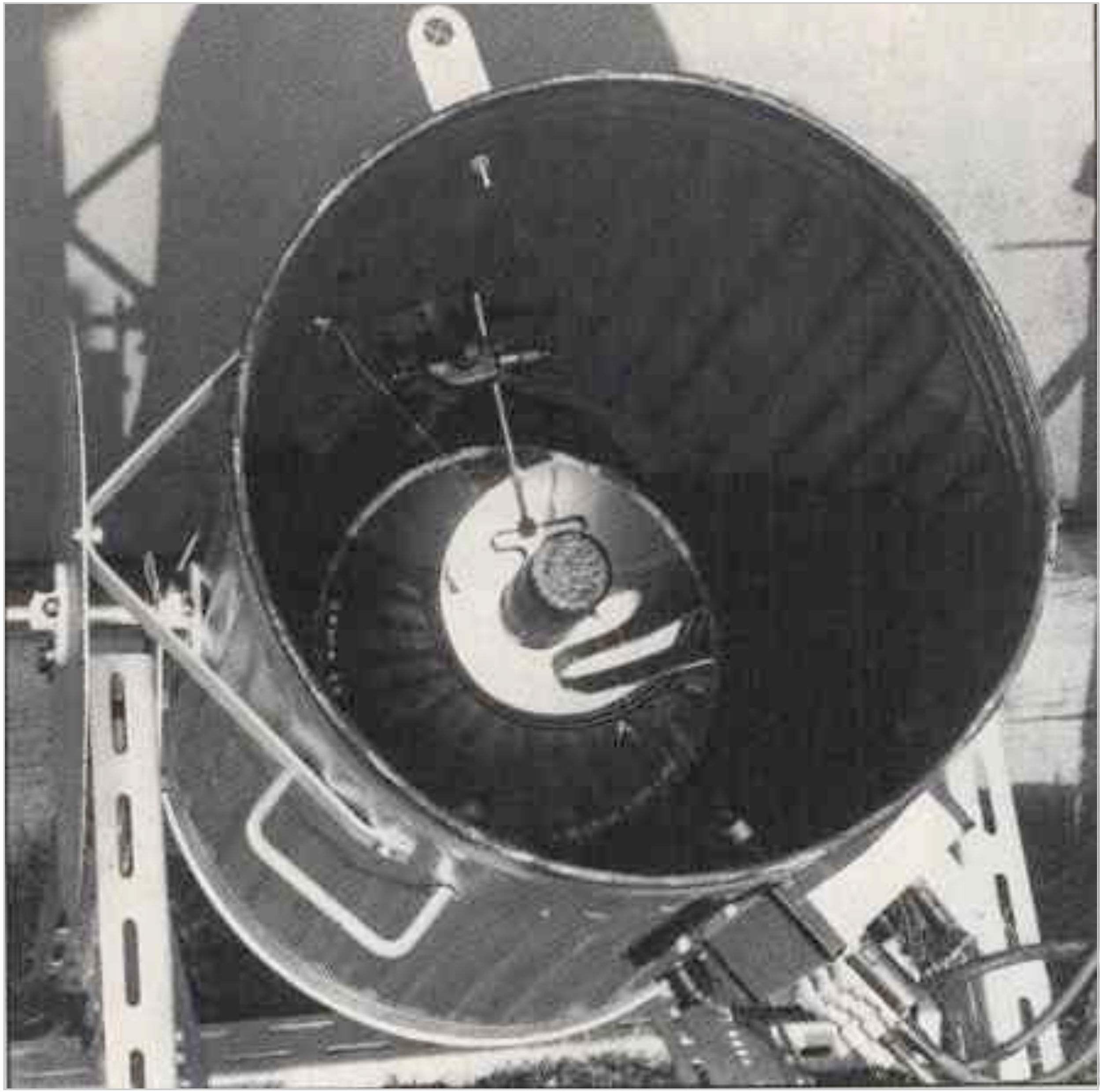
many discoveries in particle physics using CRs and
cloud chambers; interactions, particle production, ...

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 ($\sim 10^{-4}$?).

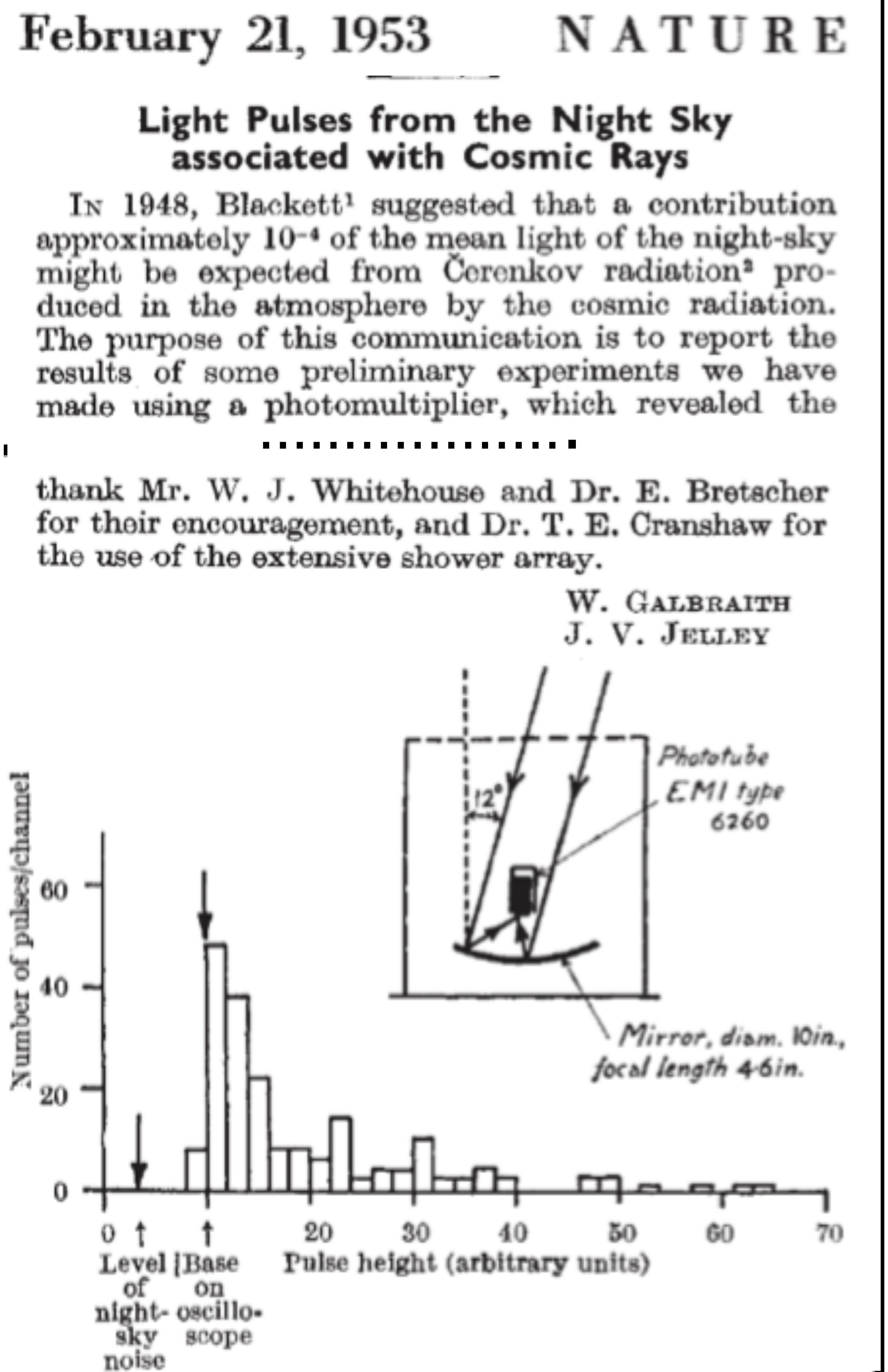
... ingredients ready for astronomy with Cherenkov tels.

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

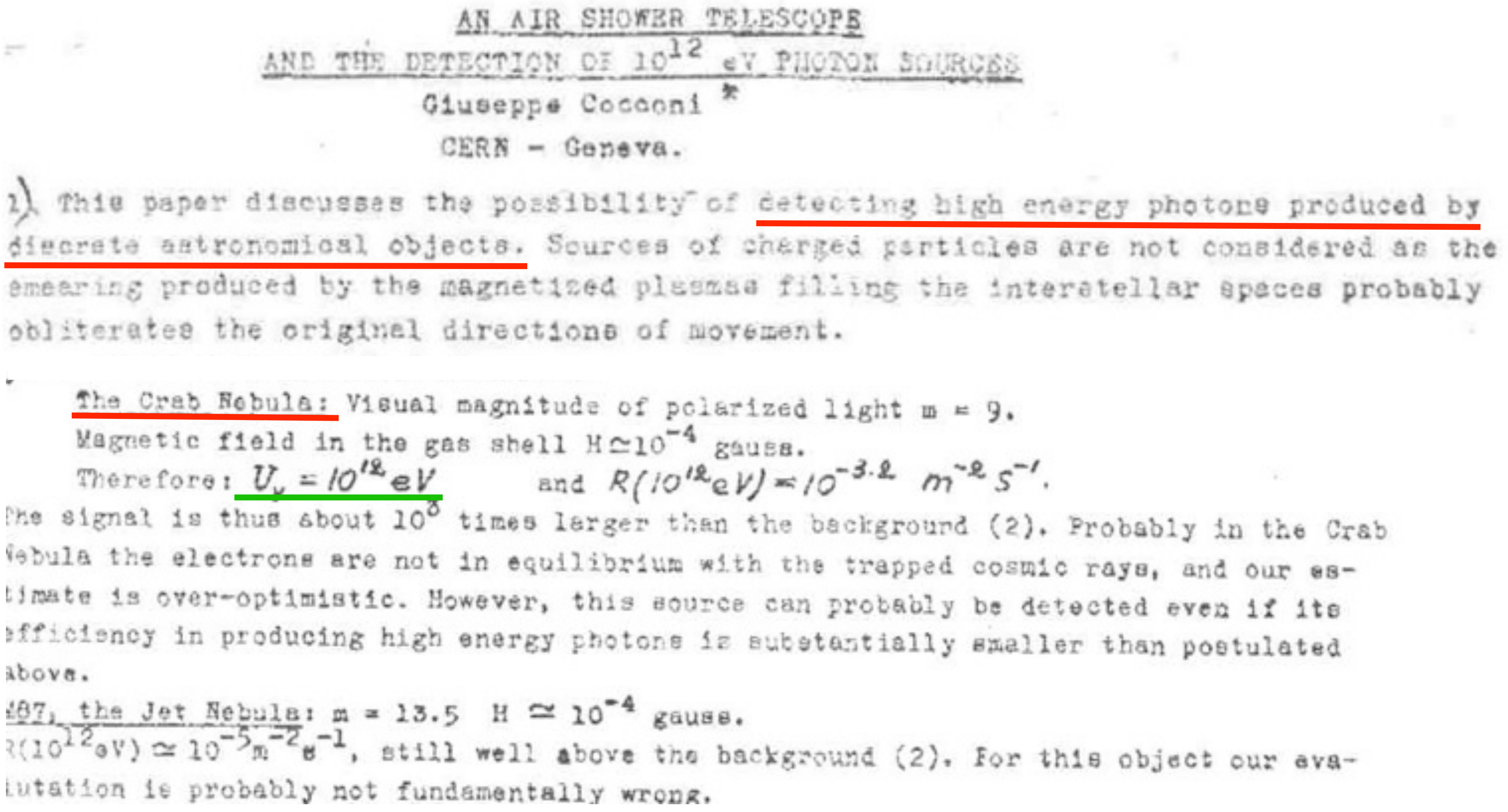
Gamma Ray Astronomy

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 $R(10^{12}\,\mathrm{eV}) \approx 10^{-3.2}\ m^{-2}\,s^{-1}$.

The signal is thus about 10^{8} 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.

M87, the Jet Nebula: m = 13.5 $H \simeq 10^{-4}$ gauss.
$R(10^{12}\,\mathrm{eV}) \simeq 10^{-5} m^{-2} s^{-1}$, still well above the background (2). For this object our evalutation 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.

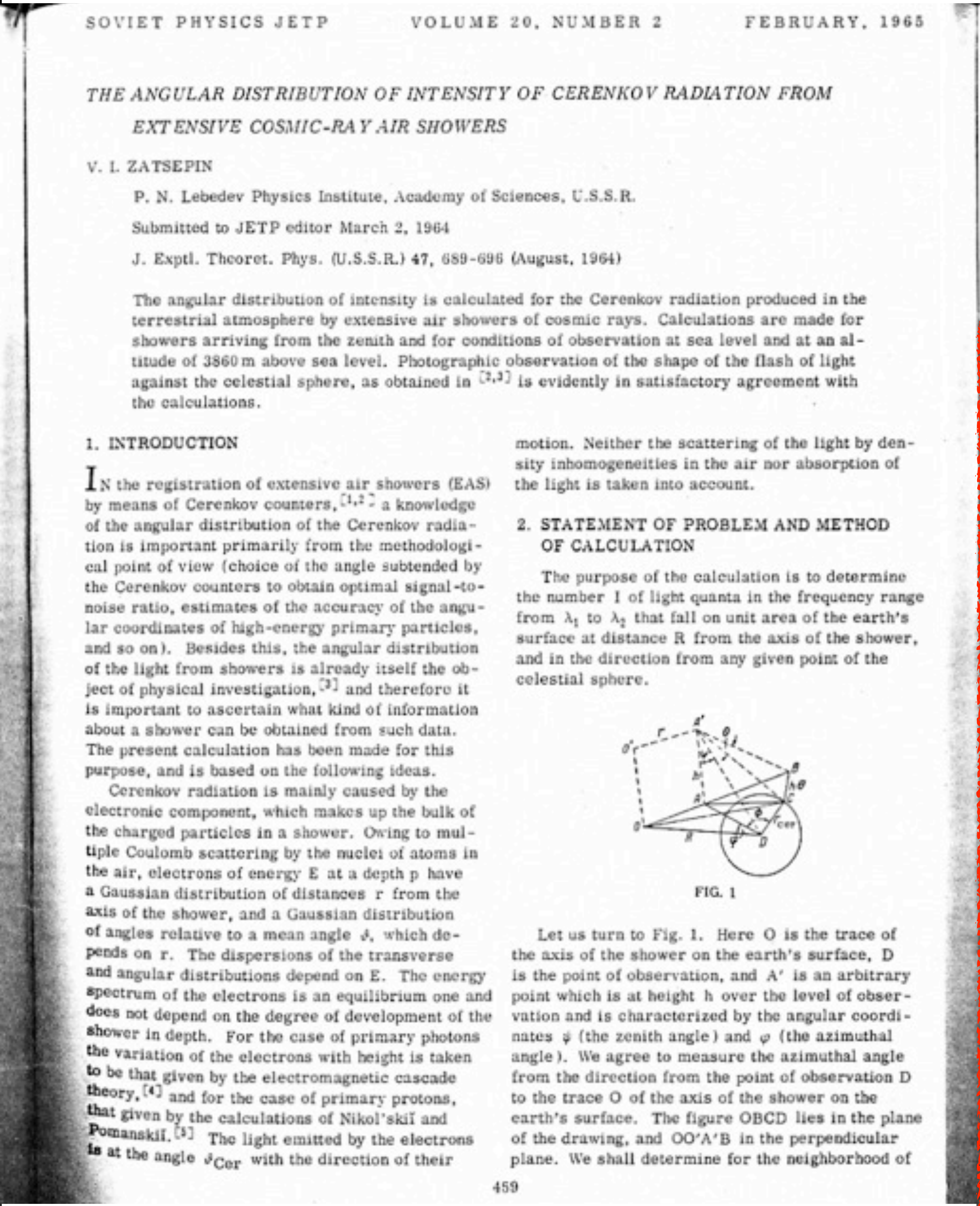
Crimea: Chudakov got 12 parabolic mirrors of 1.5 m
made measurements for almost 4 years.

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, 689-696 (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 p 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'skiĭ and Pomanskiĭ.[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.

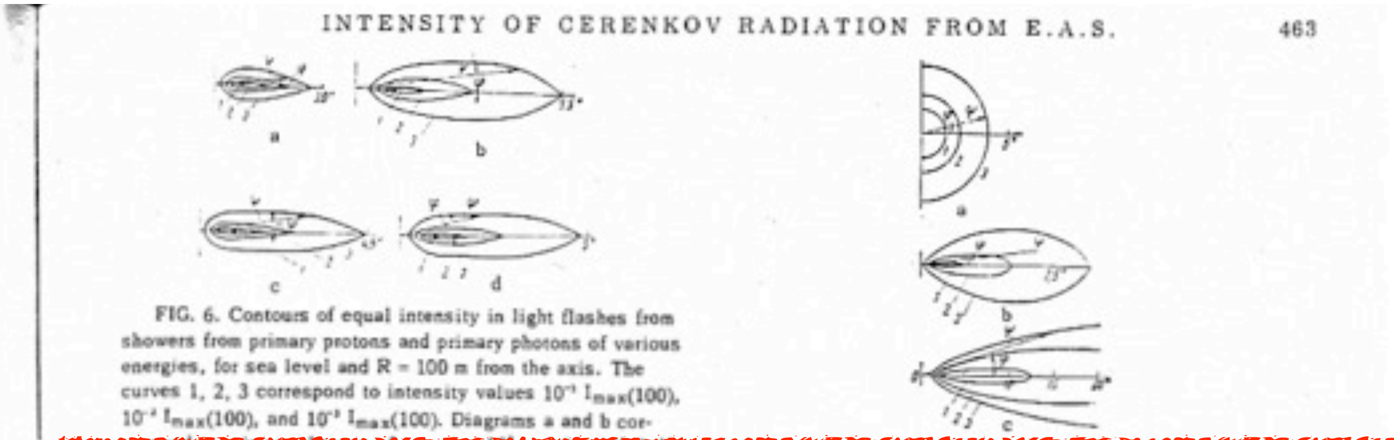
2. STATEMENT OF PROBLEM AND METHOD OF CALCULATION

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

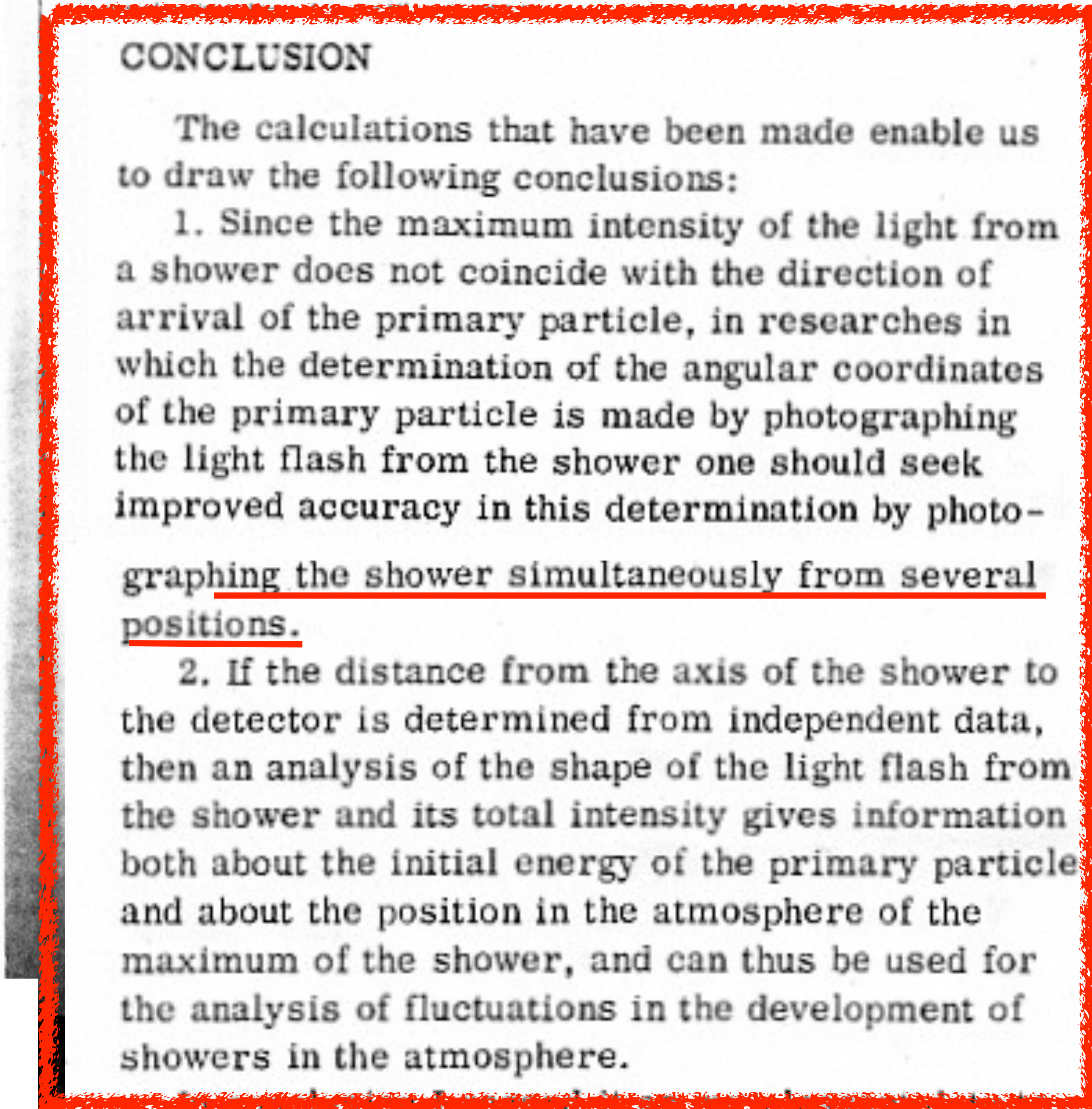
Let us turn to Fig. 1. Here O is the trace of the axis of the shower on the earth's surface, D is the point of observation, and A' is an arbitrary point which is at height h over the level of observation and is characterized by the angular coordinates ψ (the zenith angle) and φ (the azimuthal angle). 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

459



INTENSITY OF CERENKOV RADIATION FROM E.A.S. 463

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.

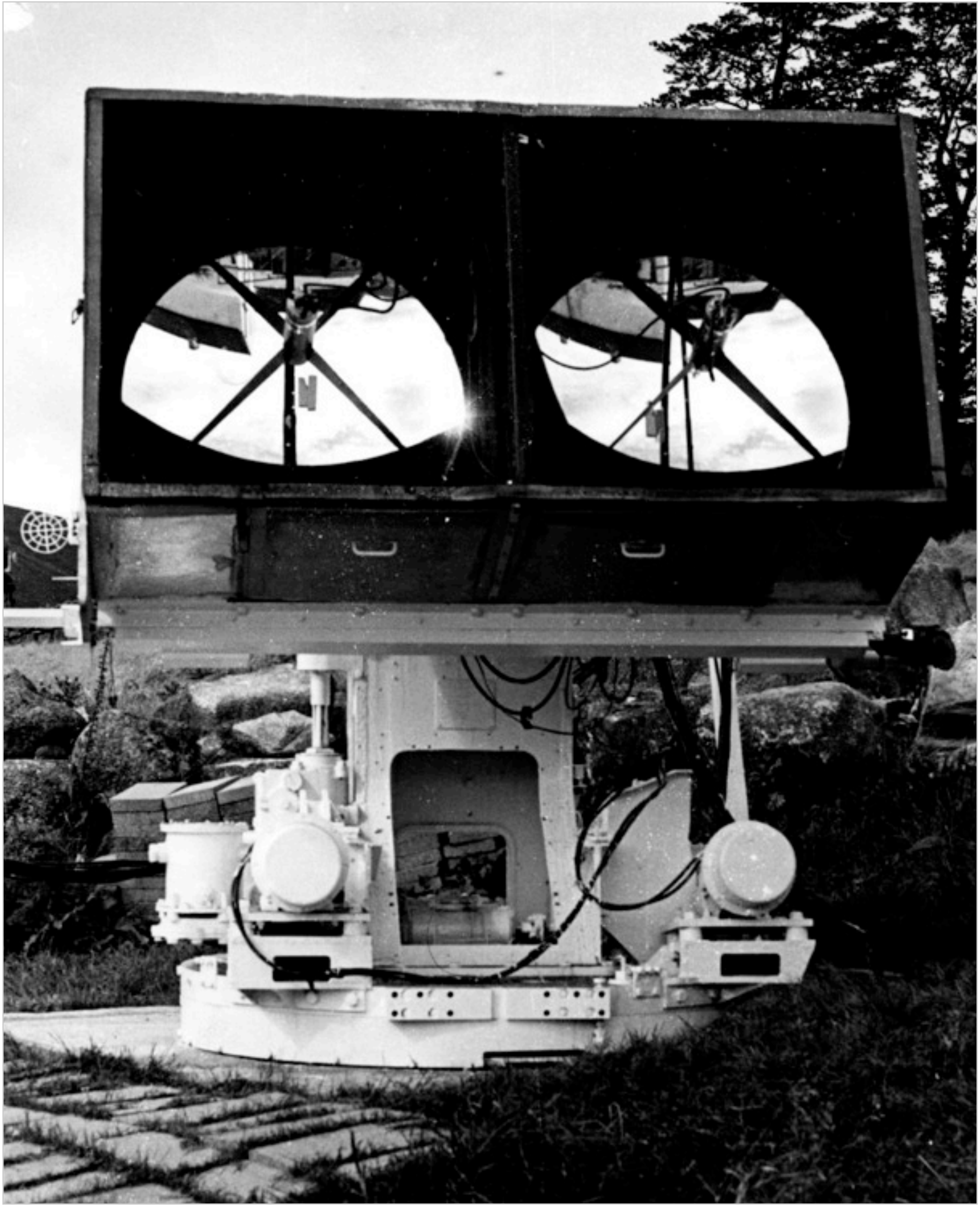
2. If the distance from the axis of the shower to the detector is determined from independent data, then an analysis of the shape of the light flash from the shower and its total intensity gives information both about the initial energy of the primary particle and about the position in the atmosphere 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 gamma-ray experiment at Whipple Observatory, 1967-68

Trevor Weekes

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 10 m Whipple Telescope

built in 1968

Fred Lawrence Whipple

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 $3\text{–}30 \times 10^{-11}$ gamma ray cm^{-2} sec^{-1} were deduced for the individual sources.

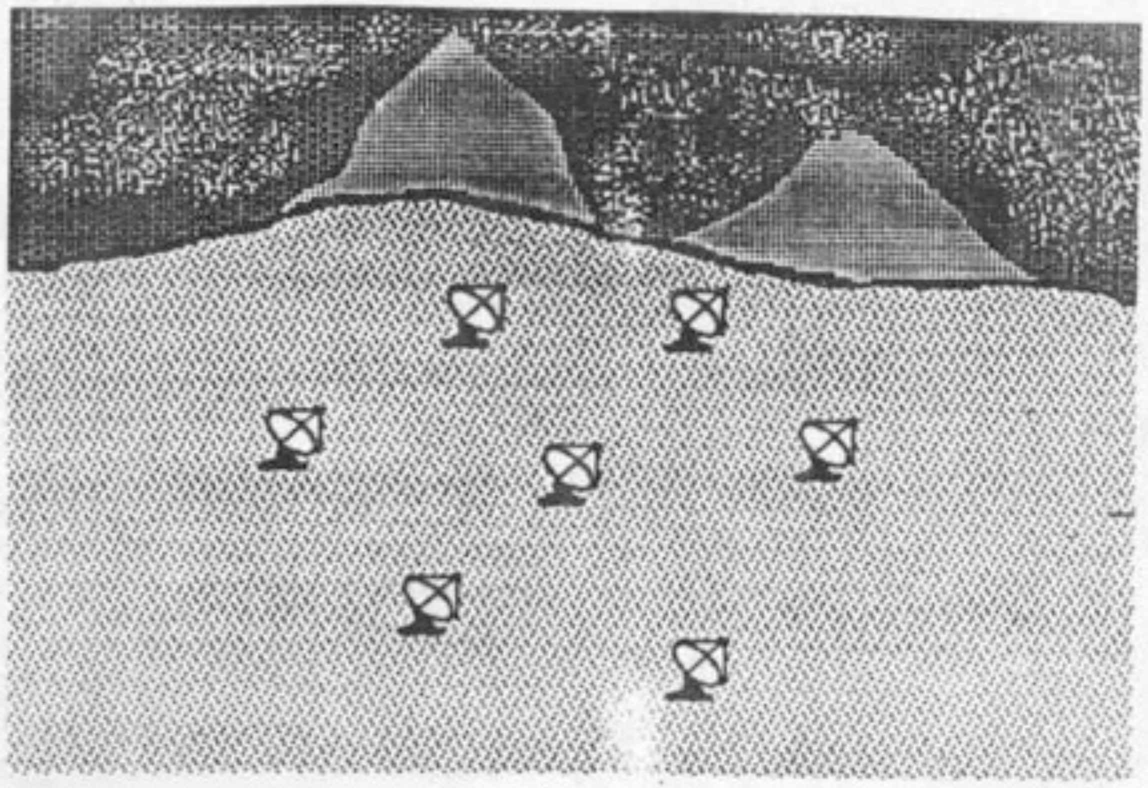
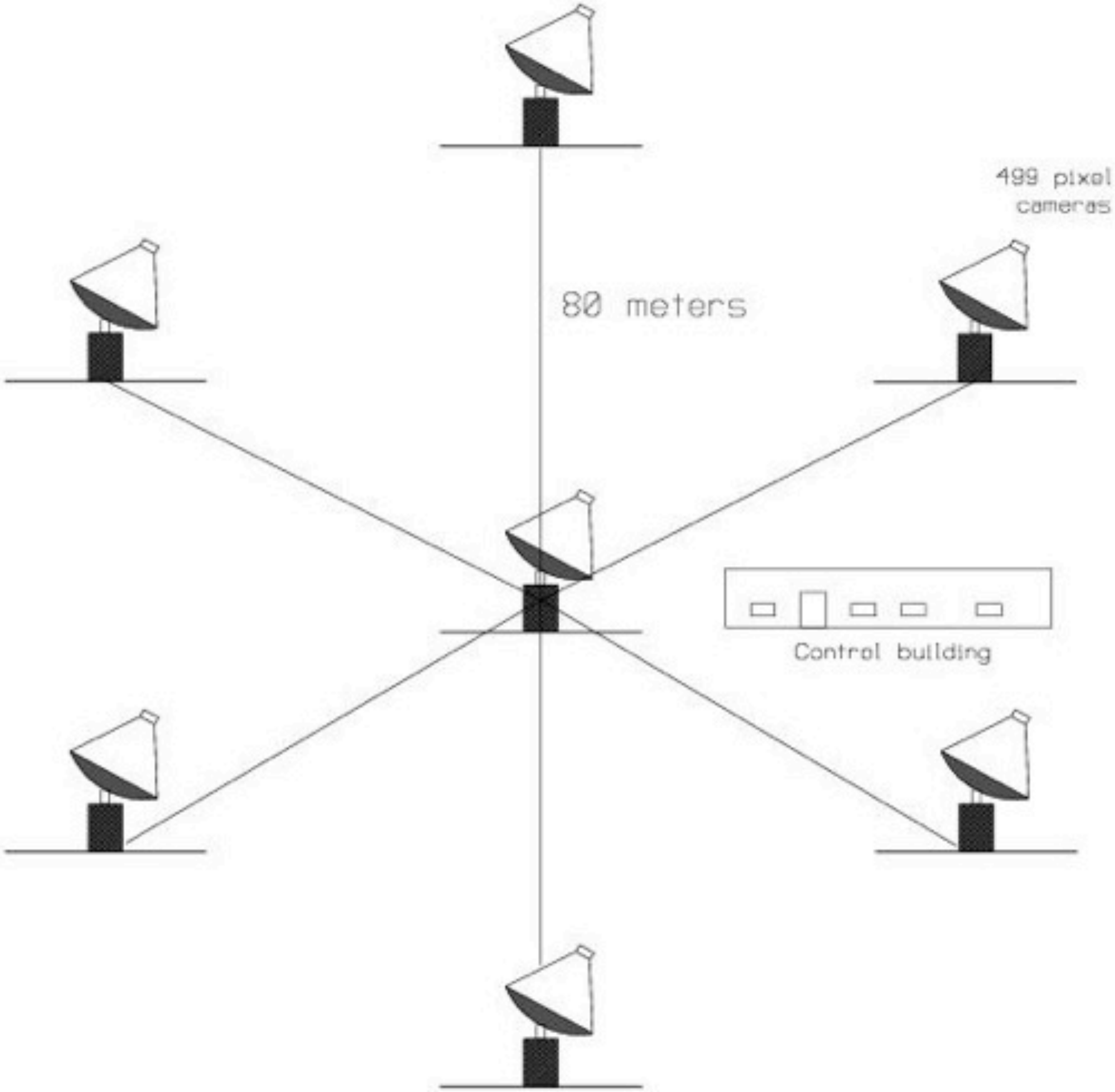
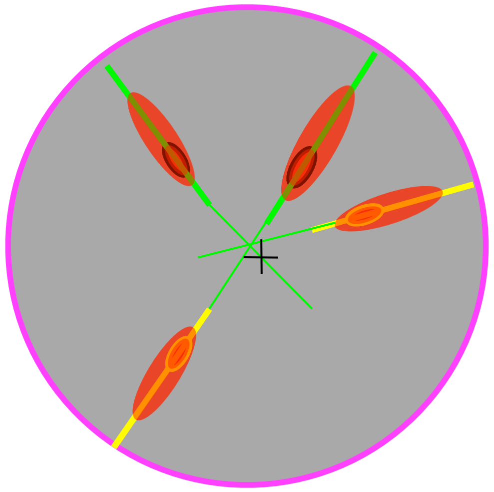


Figure 1a. Artist's concept of VHE Gamma Ray Observatory showing seven 15 m aperture atmospheric Cherenkov cameras with spacing of 75 m.

1984: proposed at NASA Workshop, Space Lab. Science, Baton Rouge

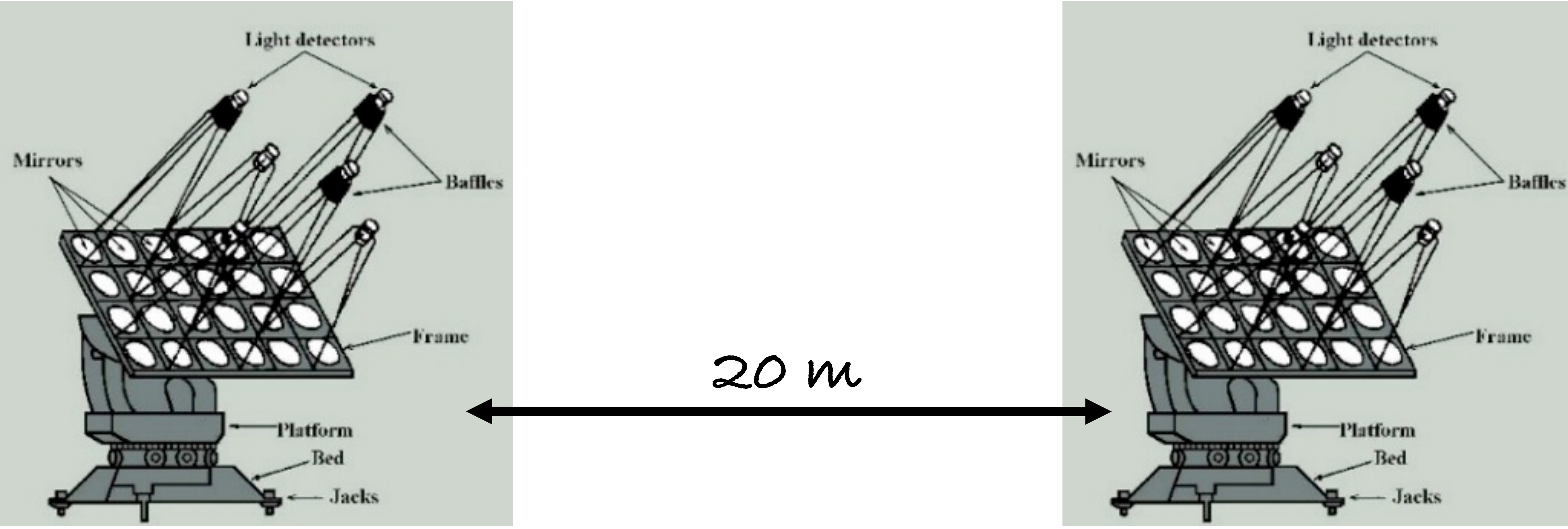


2000: layout for VERITAS



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

A Stepanian



1970-80ies: plenty of “discoveries” on 3-4 σ level
but instruments were not sensitive enough ....

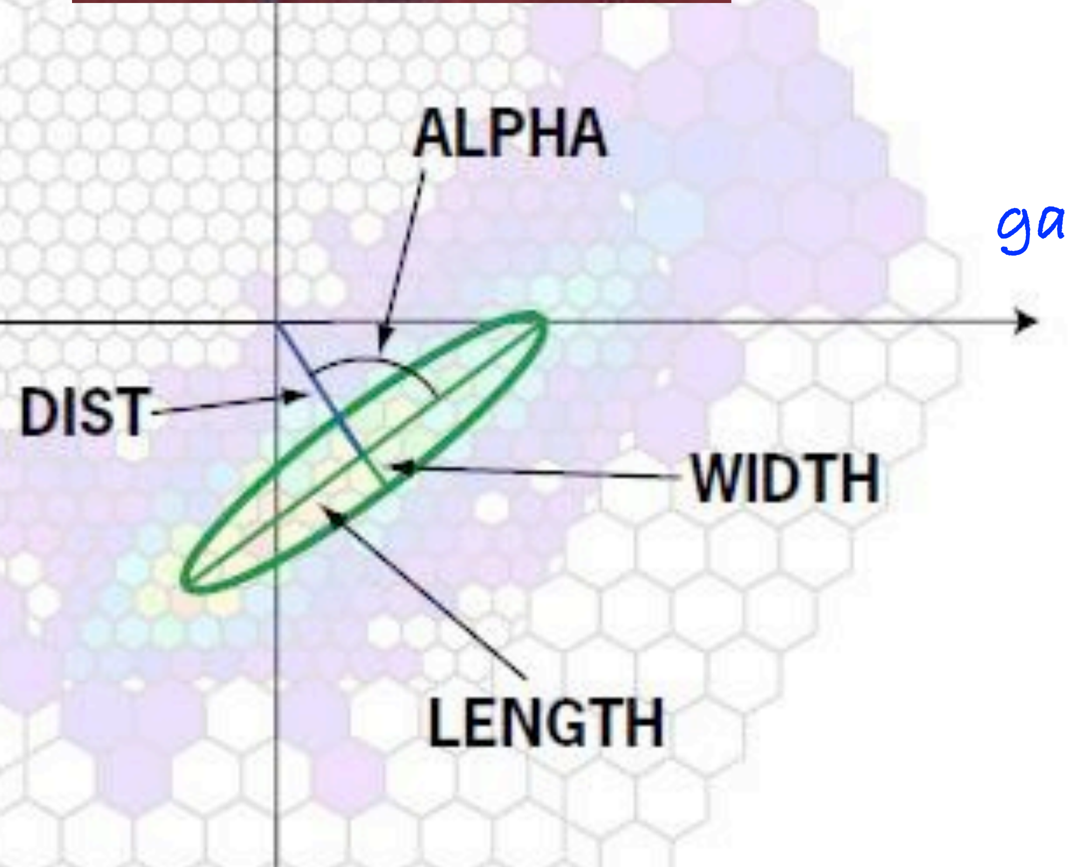
1970-80ies: plenty of "discoveries" on 3-4 σ level
but instruments were not sensitive enough ....

A.M. Hillas, University of Leeds:
good MC simulations &
image analysis,

"Concentration" is a good parameter
(>75% of light is concentrated in 2 pixels)

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

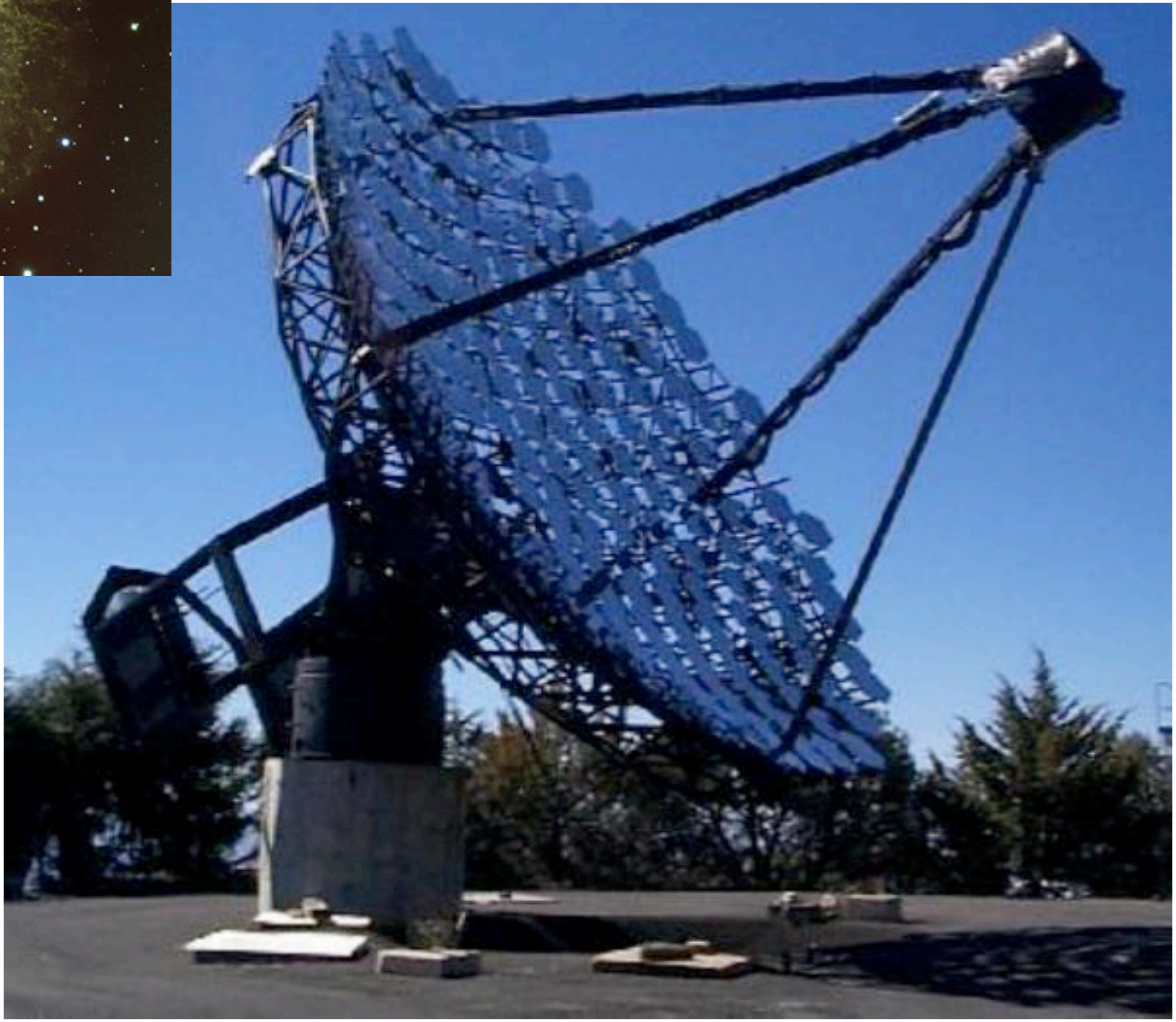
La Jolla, 1985: Hillas suggests to use the
"Hillas image parameters"



gamma showers are:
- slimmer,
- more concentrated
- oriented towards source

1989: Whipple discovers
9σ signal from Crab !!!

10 m Whipple Telescope

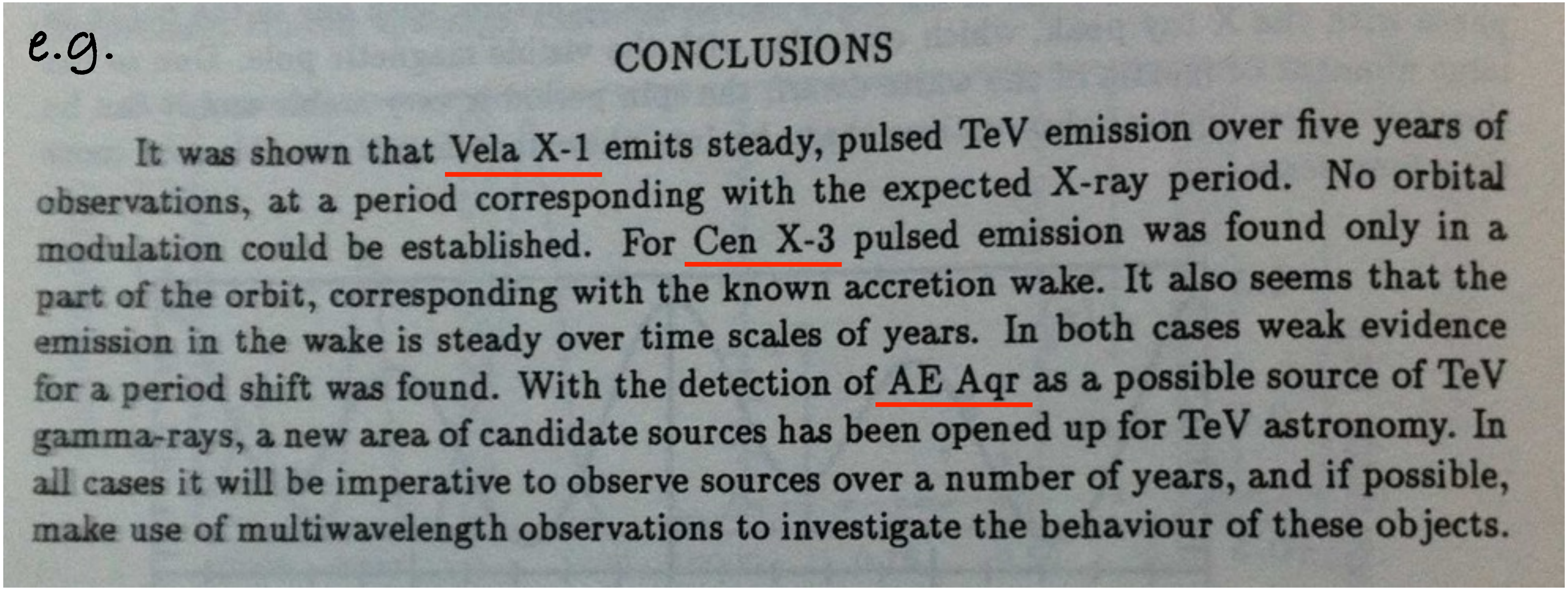


1989:
Detection of the Crab Nebula

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.

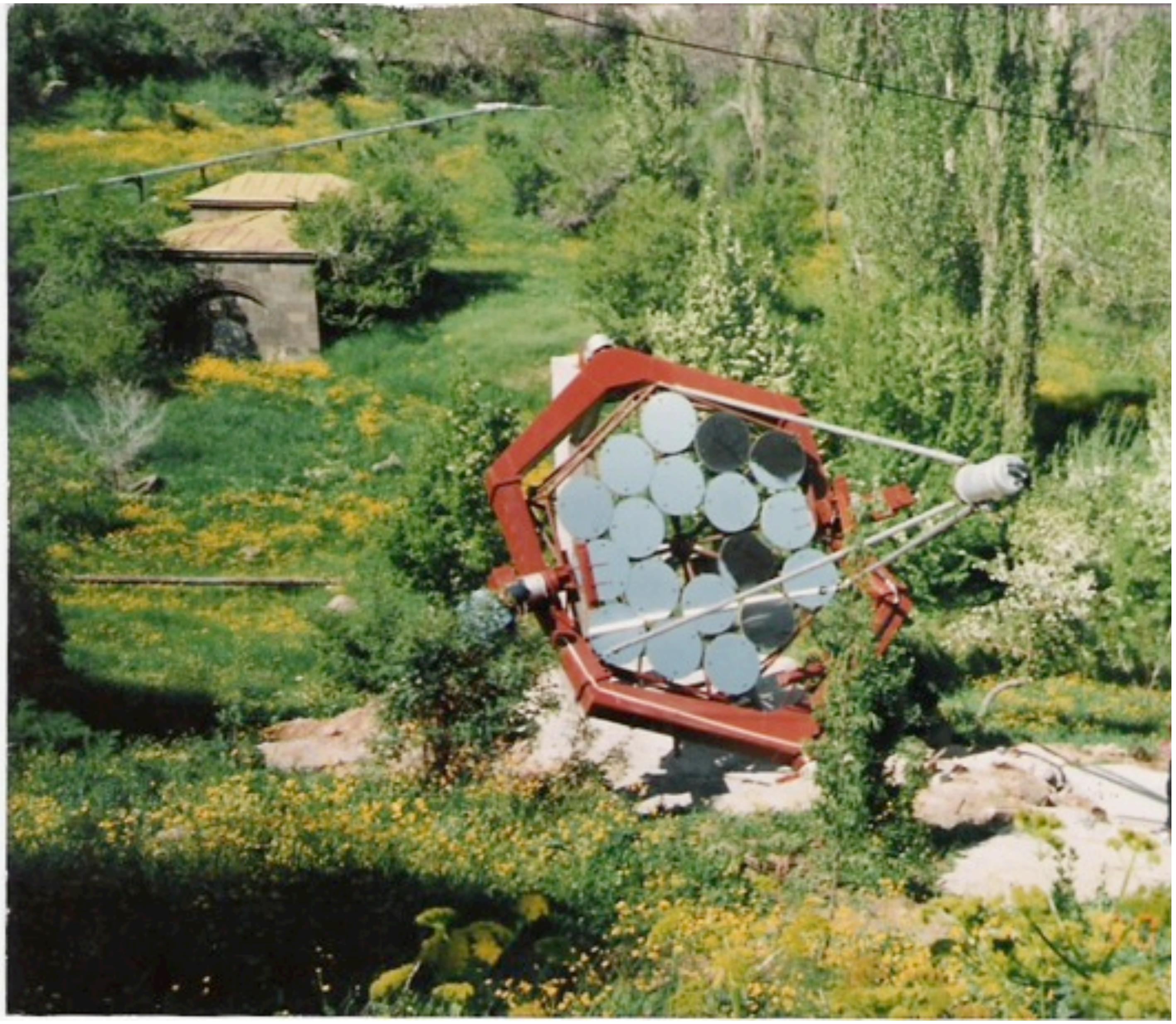
… which could not be confirmed.

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

many new exptl. activities were started …

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

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



only one was built

90.

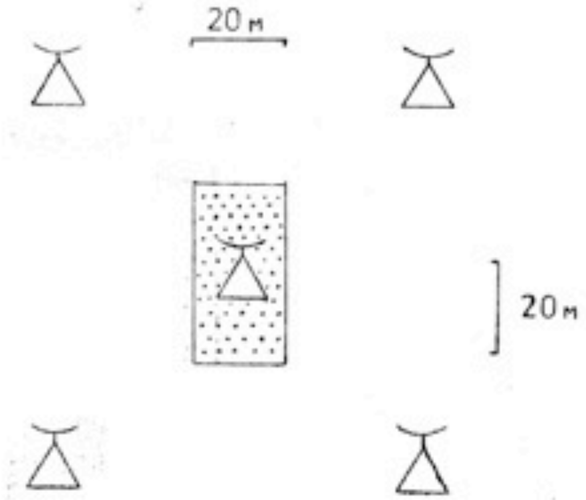


Рис. 38. Установка I,

Δ – телескопы для регистрации ЧС ливней с ПЧД.

▢ – детекторы мюонов ШАЛ.

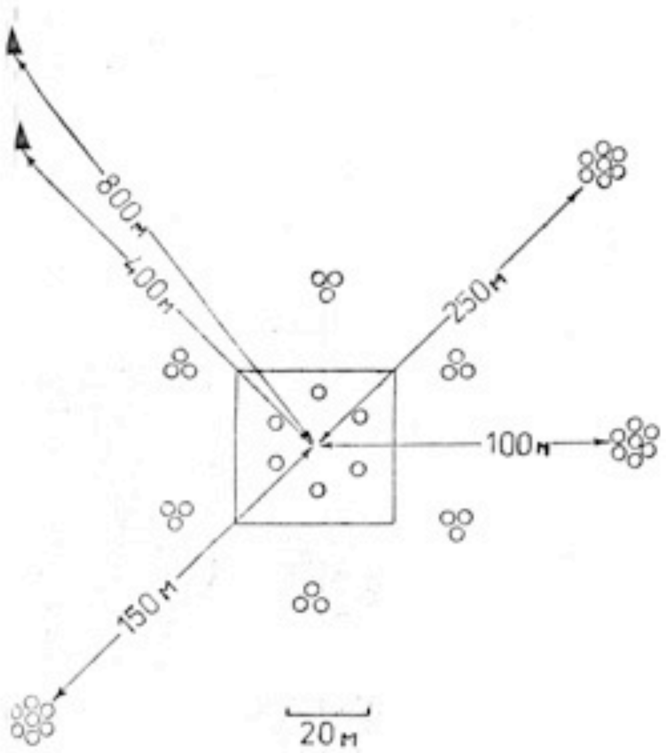


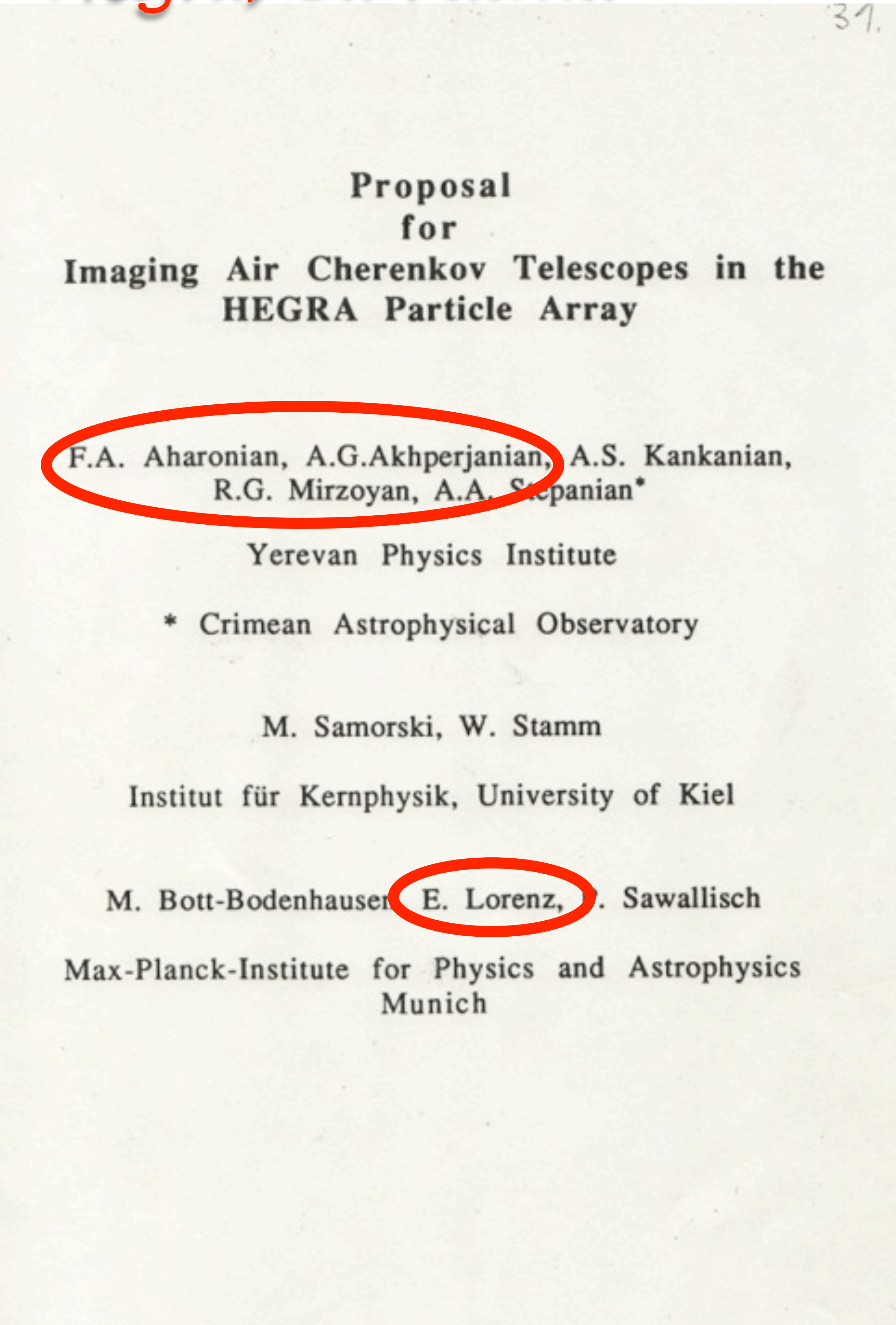
Рис. 39. Установка 2.

□ – центральная часть АНИ для регистрации компонент ШАЛ.

○; ⚬⚬; ✿-детекторы для определения поперечного распределения ЧС ШАЛ

▲ – детекторы для определения формы импульсов ЧС ШАЛ.

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

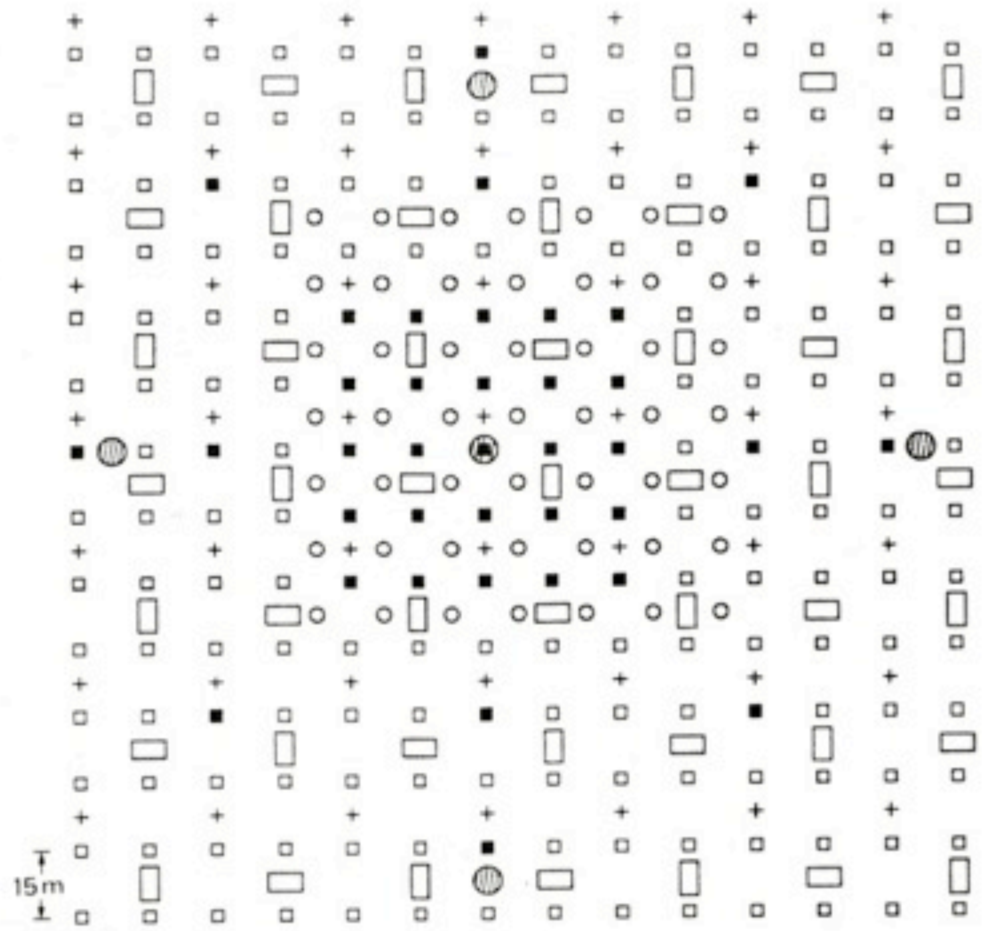
* Crimean Astrophysical Observatory

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)

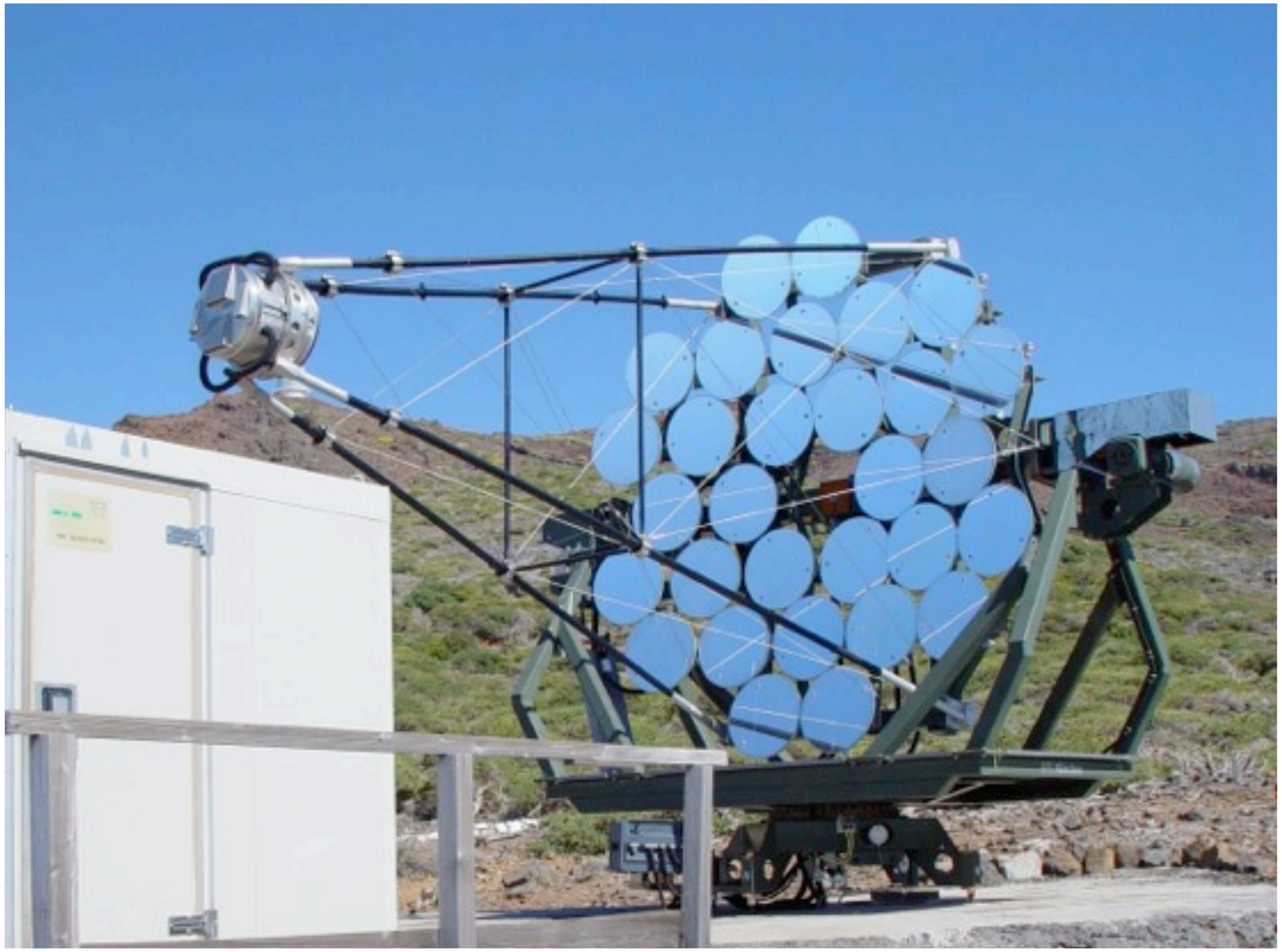
▨ 5 CHERENKOV TELESCOPES: 3 m in diameter with 19 mirrors and 37 PM's each, imaging technique, planned for 1991/92 (Yerevan Institute of Physics together with MPI Munich and University of Kiel)

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

Hegra, La Palma

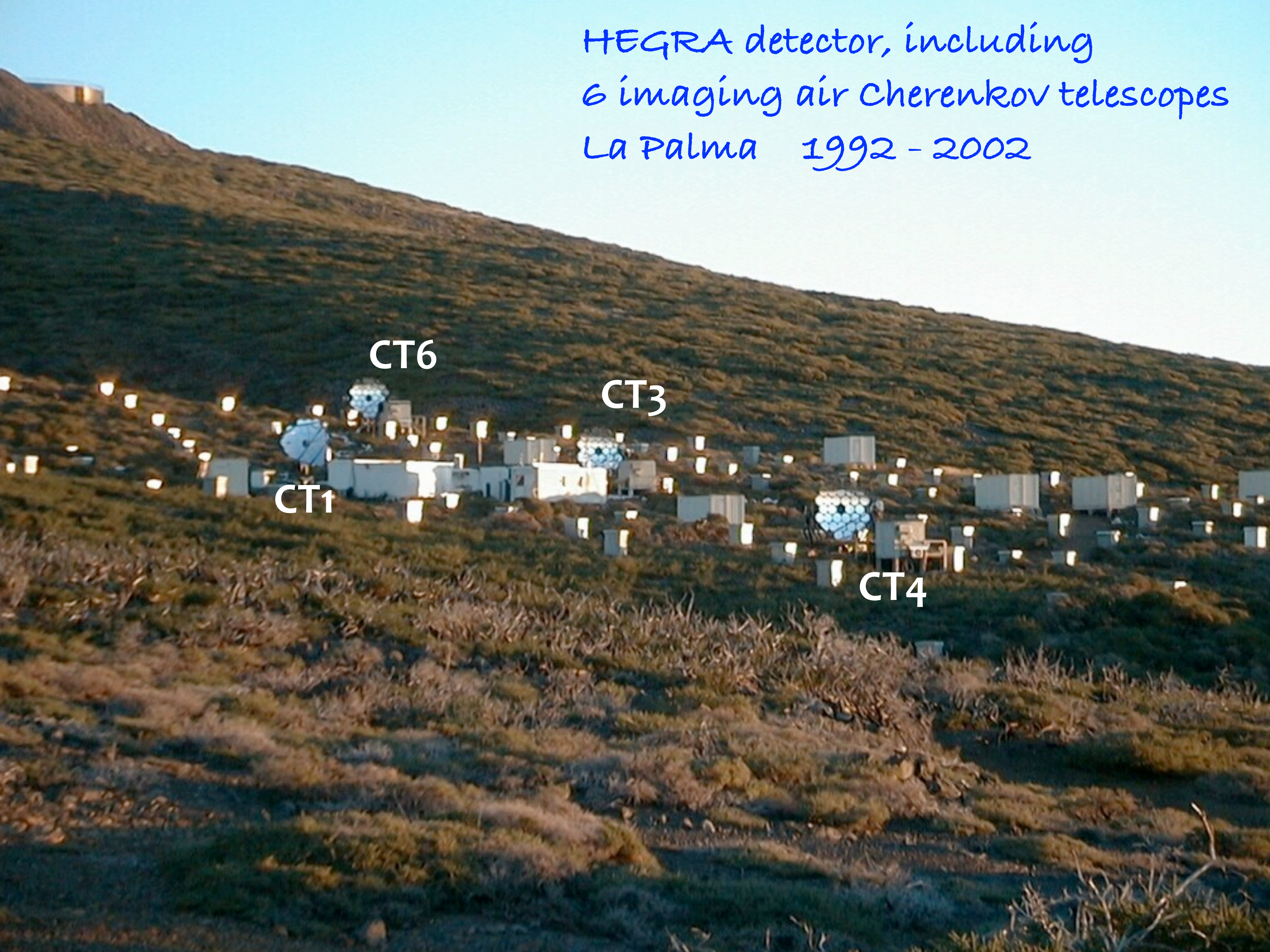
CT1 (3 m diam.)
1992 first signal from
Crab Nebula

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



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

~10 years

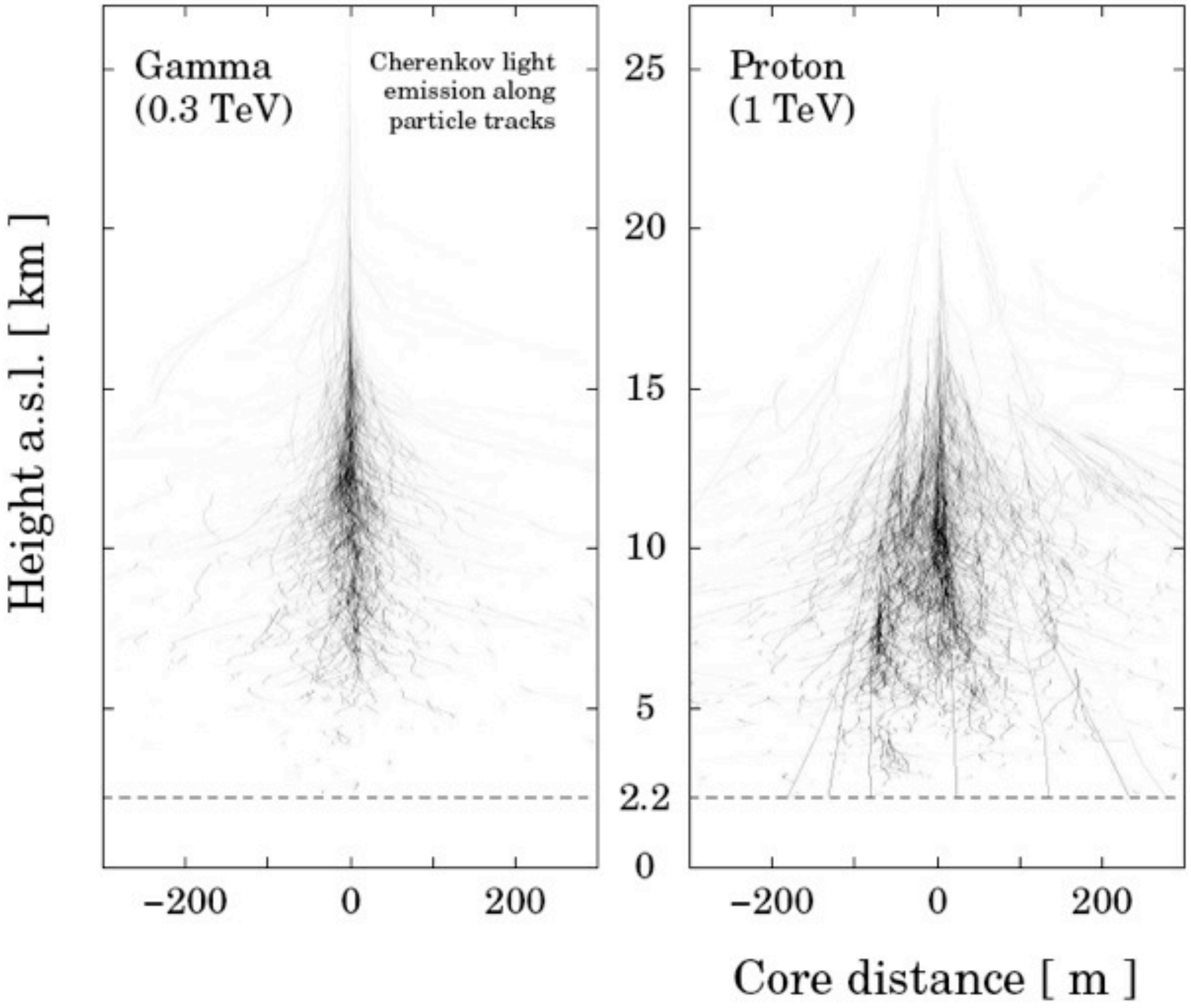
RX J1713.7-3946	Shell	2000	Cangaroo
Cas A	Shell	2001	HEGRA
Bl Lac	IBL	2001	Crimea
H 1426+428	HBL	2002	Whipple
TeV J2032+4130	UNID	2002	HEGRA
M87	FR1	2003	HEGRA
Galactic Centre	UNID	2004	Cangaroo

~5 years

HESS started observations

… 16 new sources	2005
… 17 new sources	2006

Part II



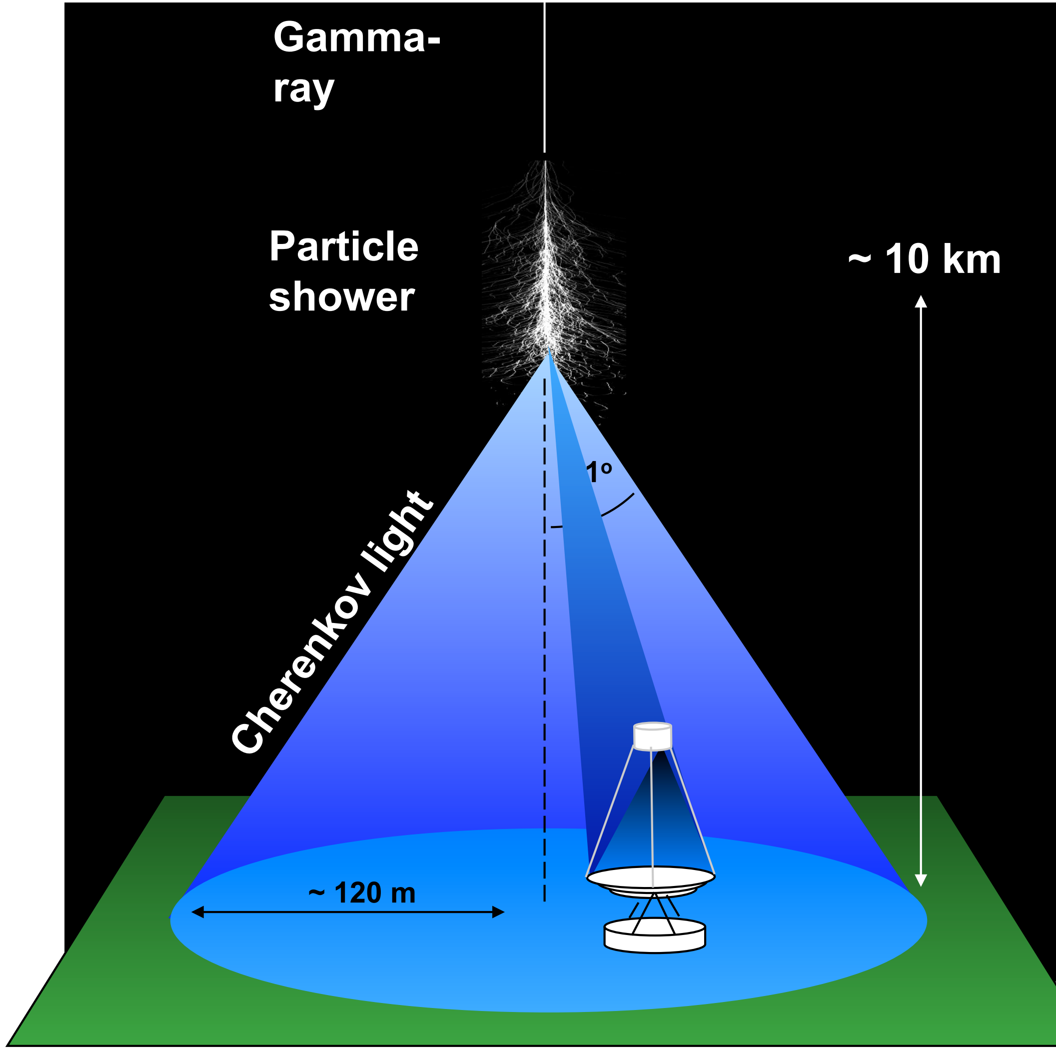


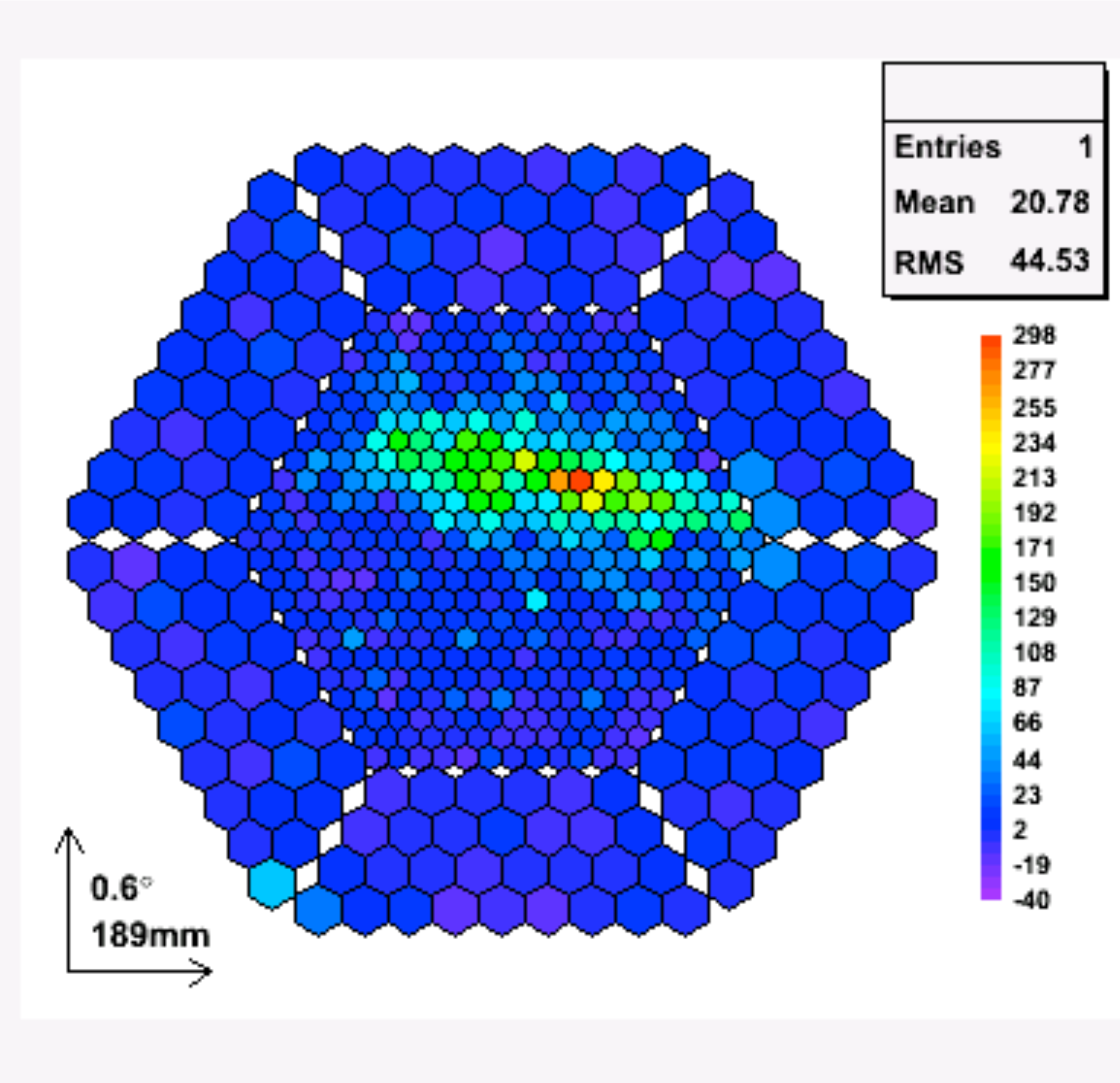
Image the shower,

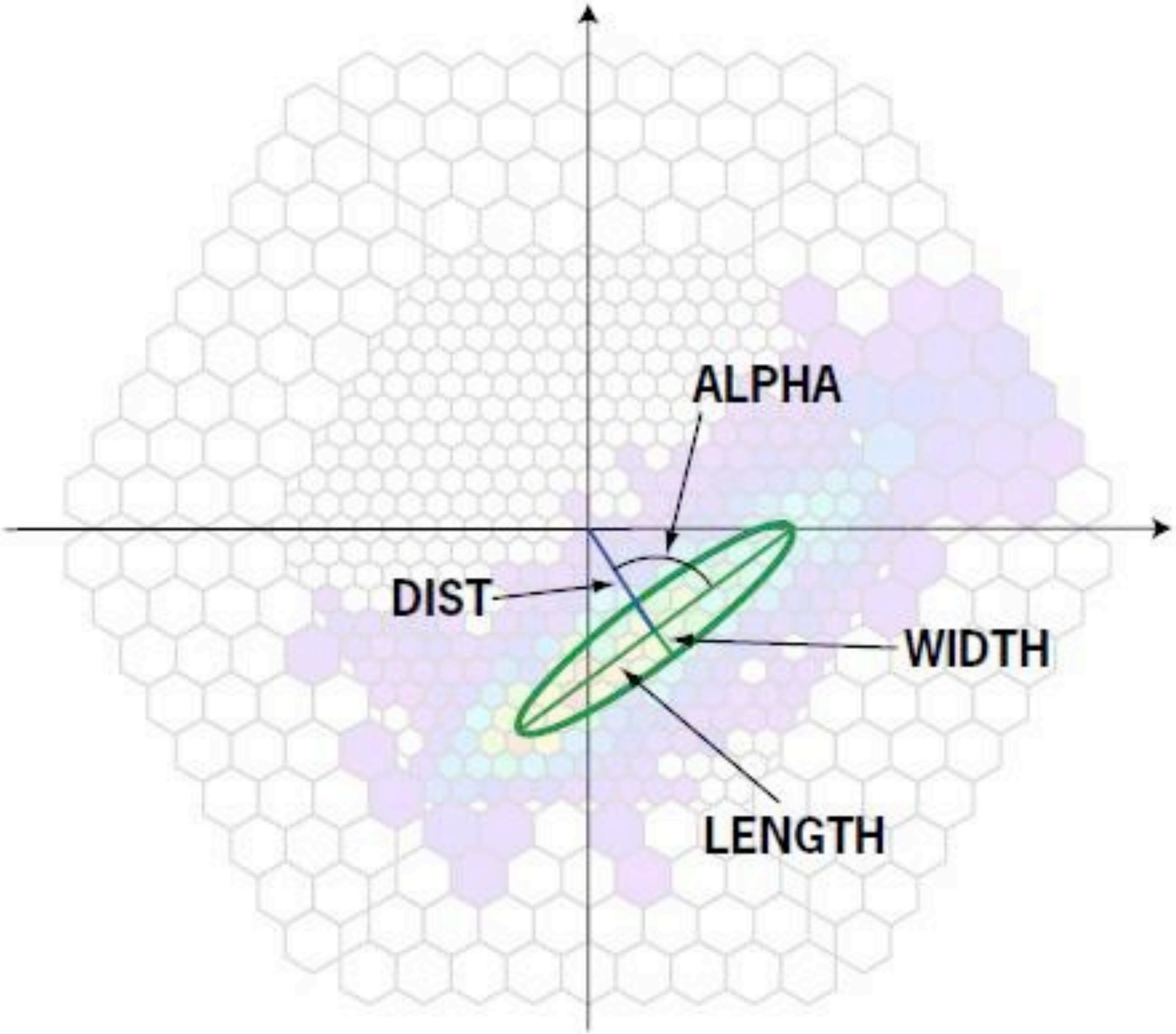
distinguish protons and photons from the shape of their images.

.... very successful technique

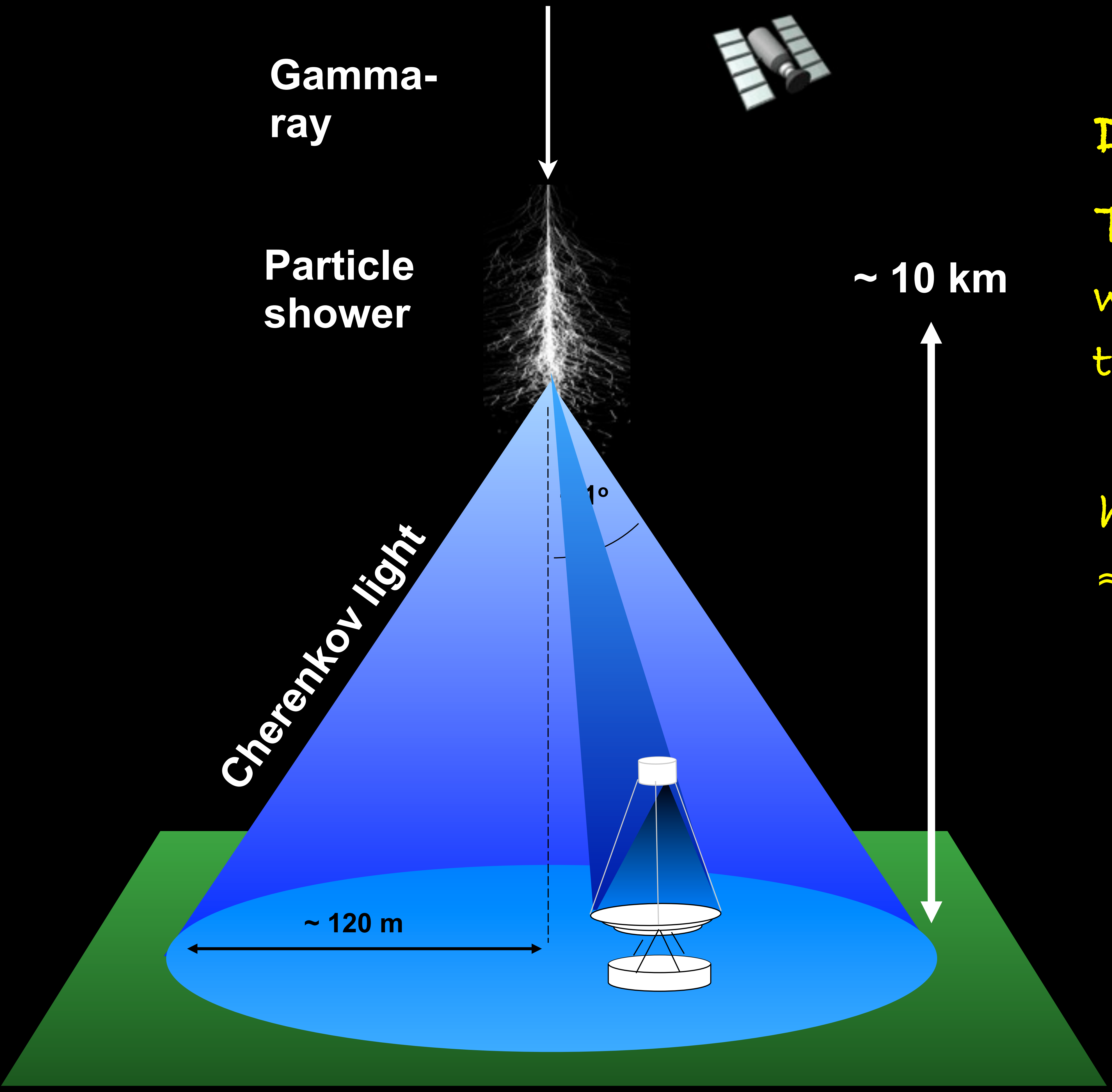
also possible to identify e^- and Fe

MAGIC Camera



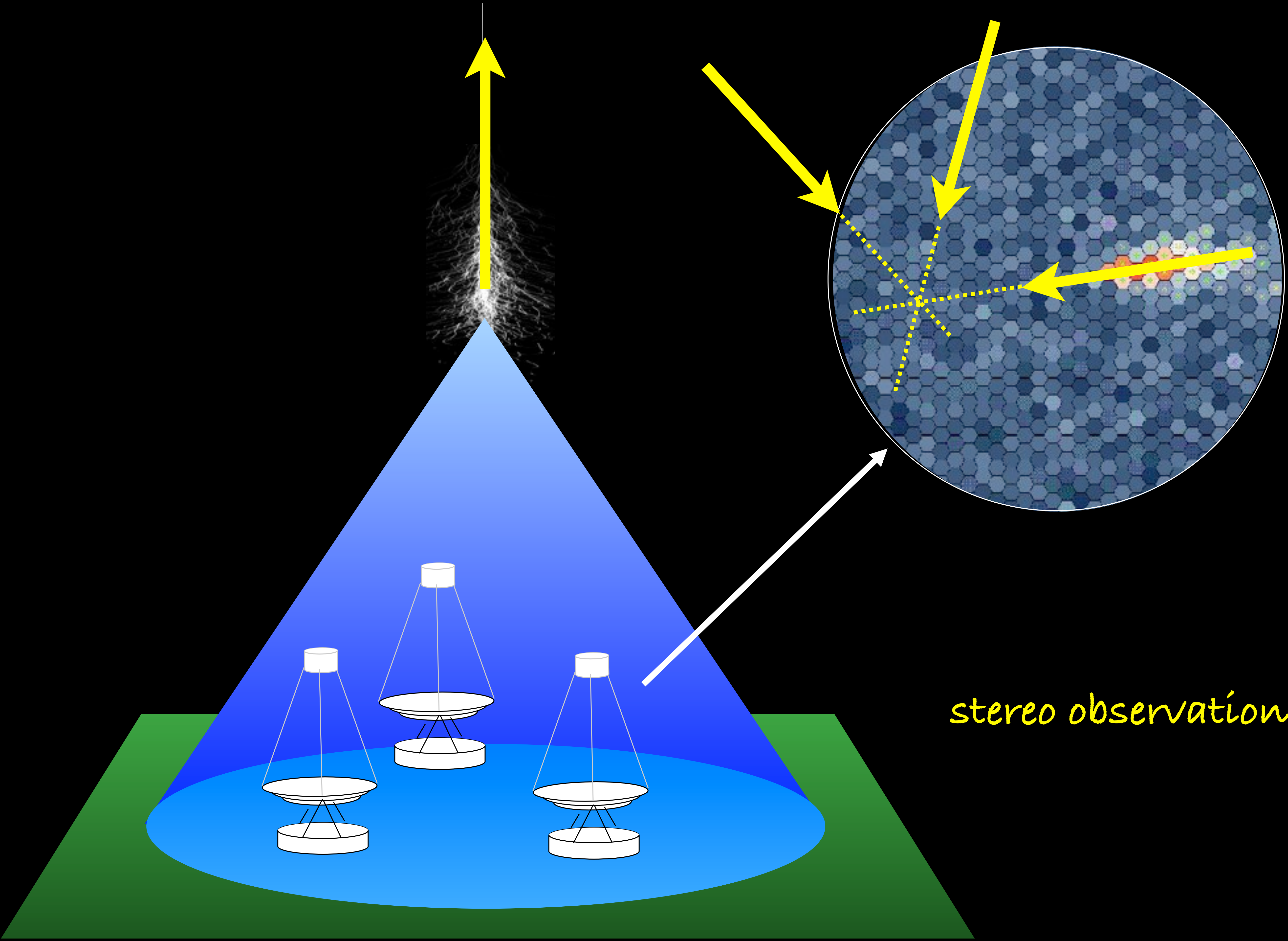


Hillas image analysis



Detection of TeV γ rays with Cherenkov telescopes

huge detection area $\approx 10^5\ m^2$



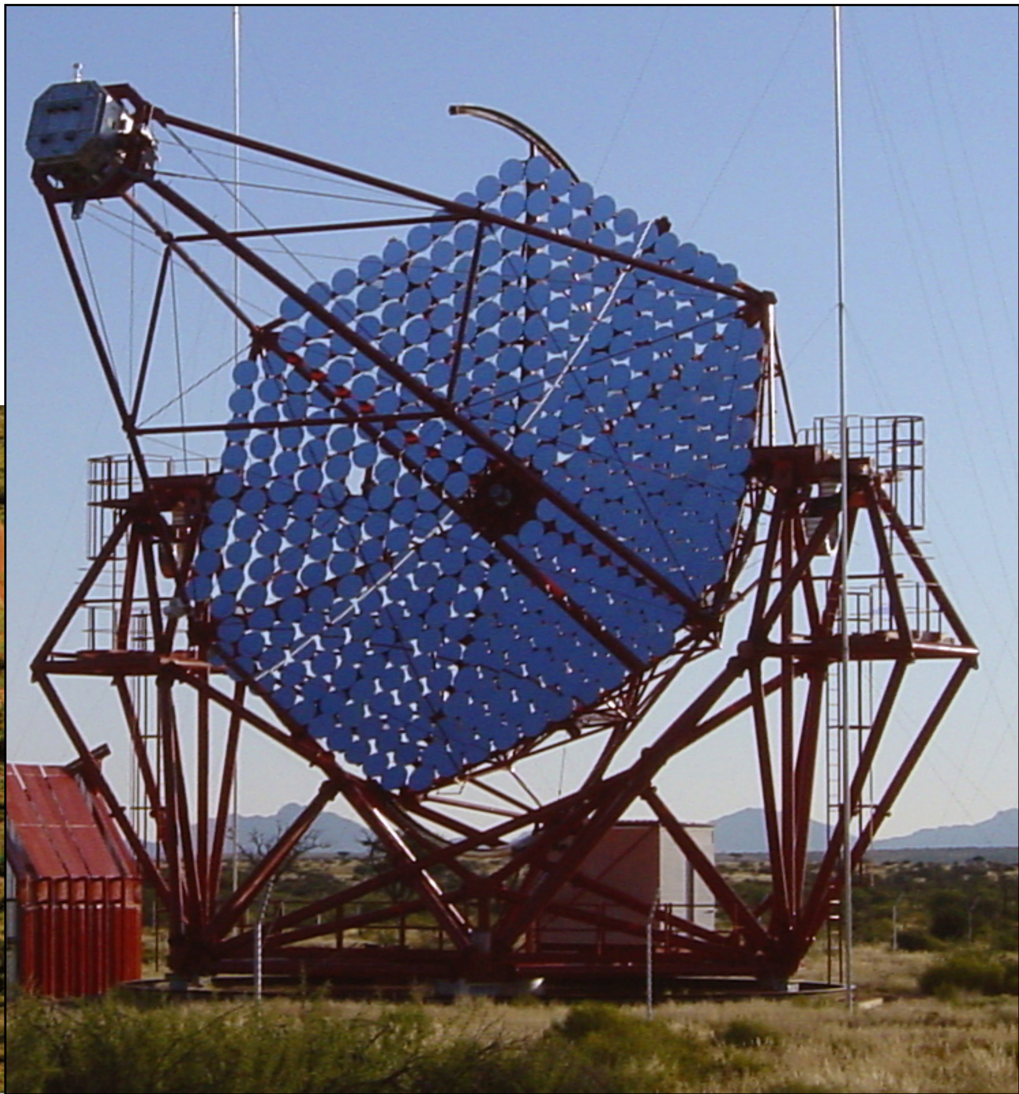
stereo observations

Imaging Cherenkov Telescopes

TeV gamma ray astronomy (100 GeV - 50 TeV)
requires good knowledge of atmospheric conditions

Imaging Atmospheric Cherenkov Telescopes:

e.g. HESS, MAGIC, VERITAS,

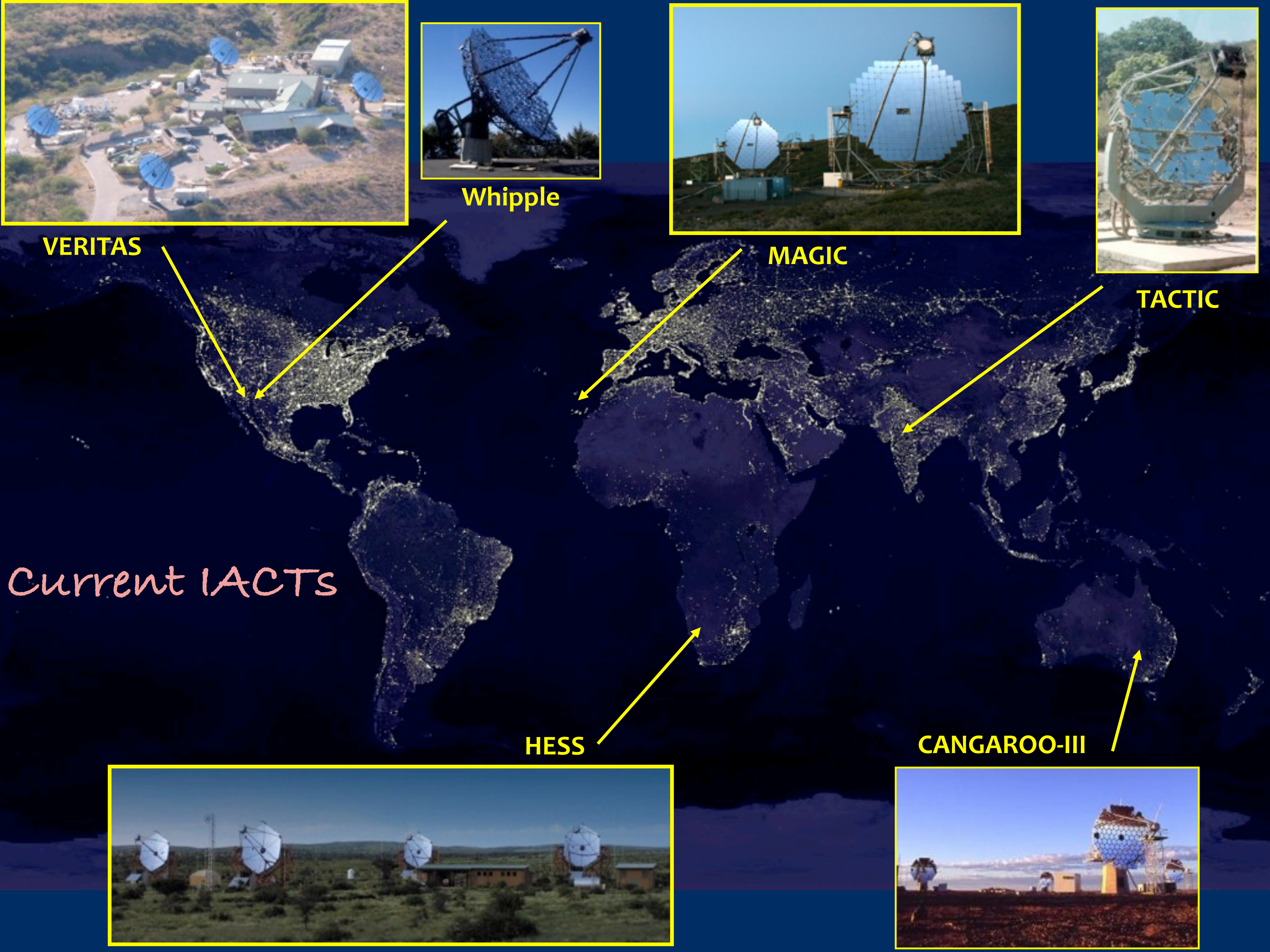


HESS, Namibia
detects Crab
in 30 seconds

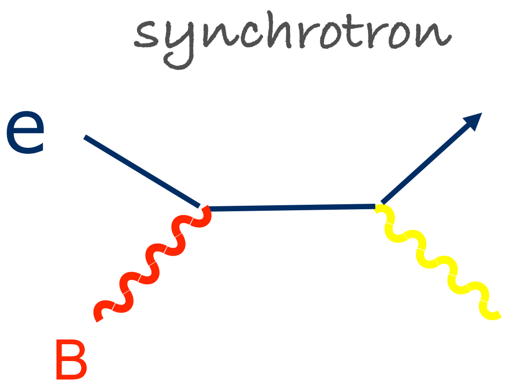
1% Crab in 25 h

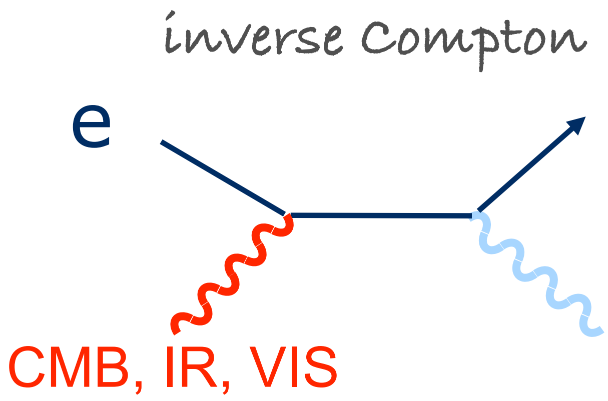
4 x 12m telescopes
5° FOV, 0.16°
960 pixels

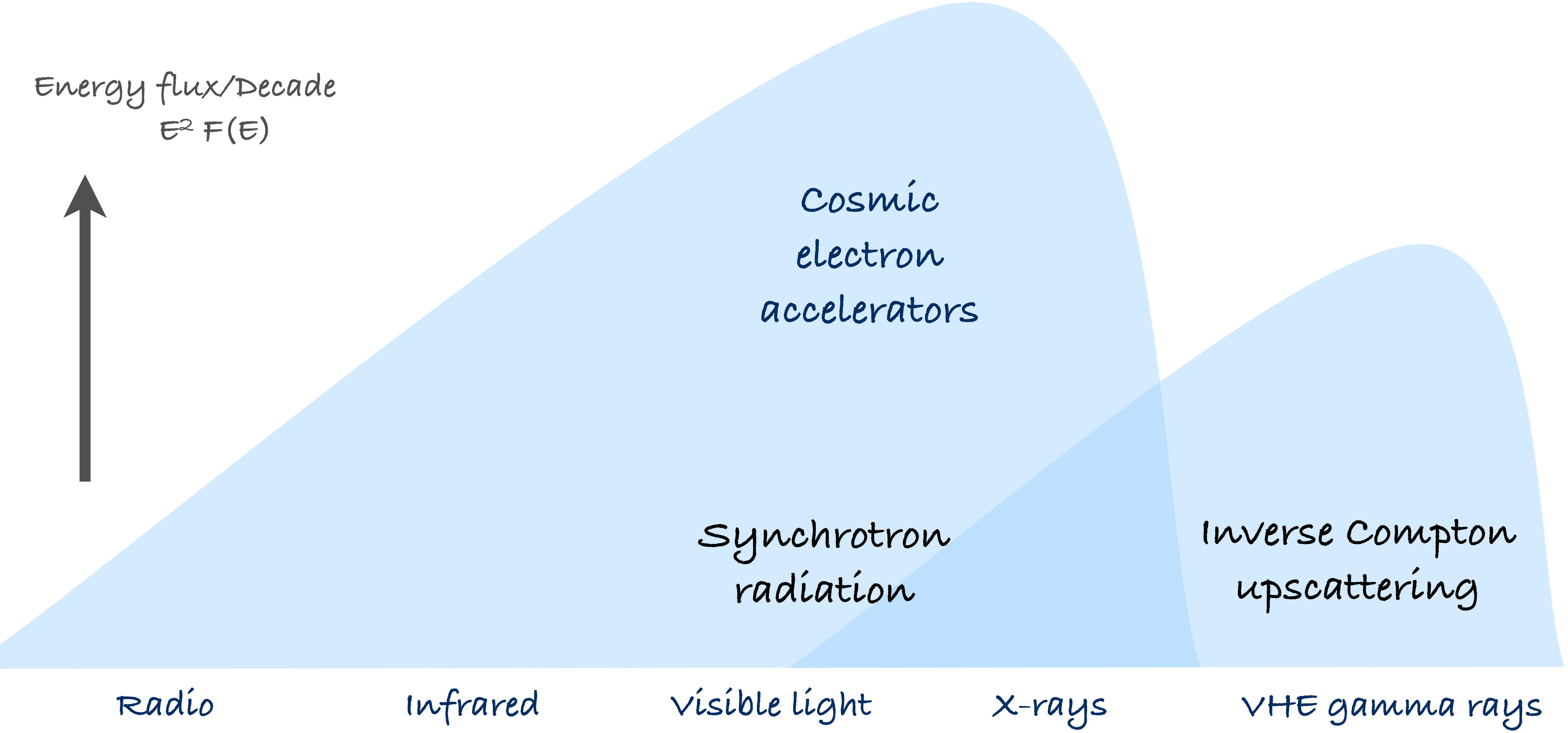
Current IACTs



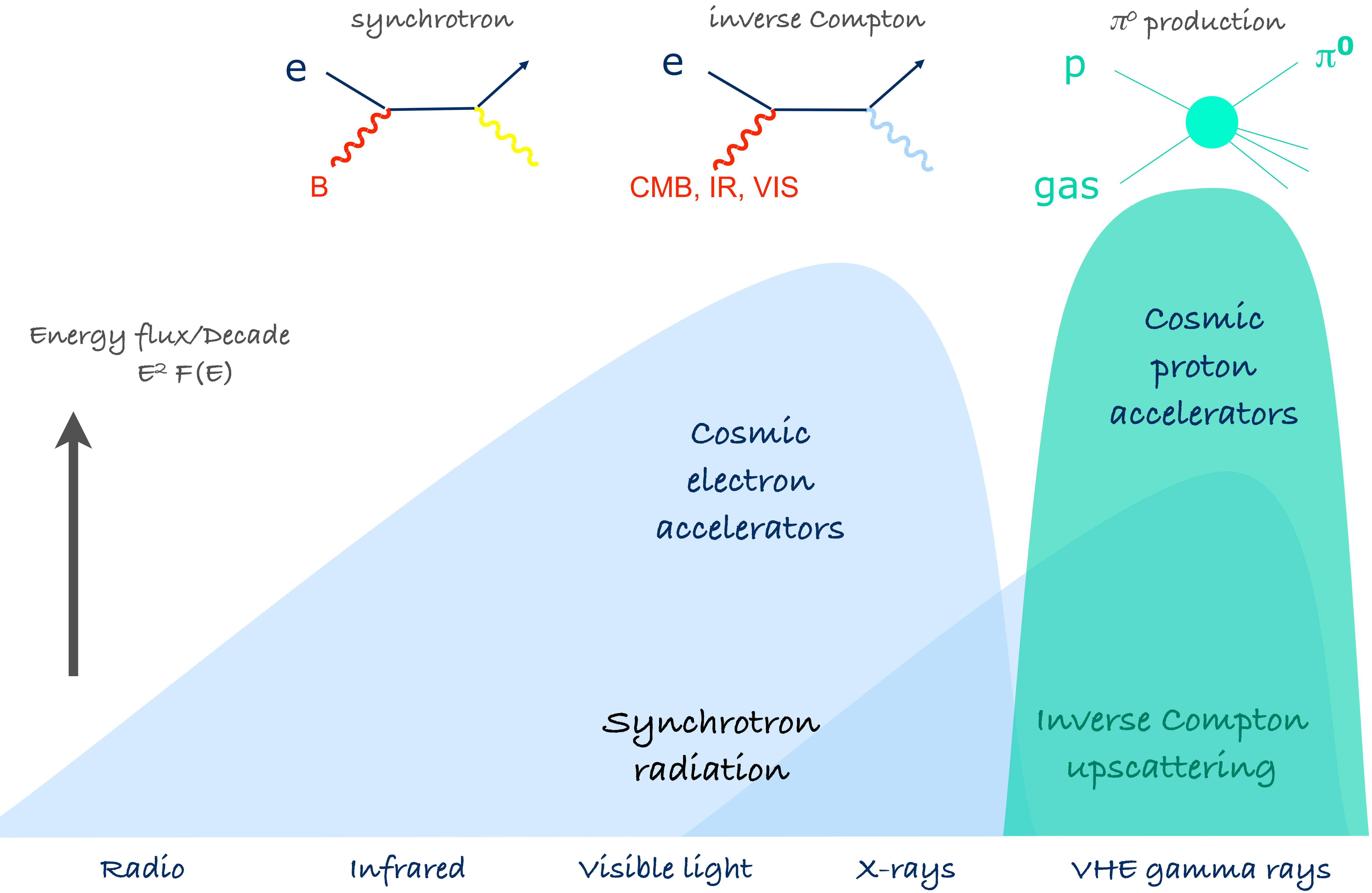
From particles to radiation







From particles to radiation



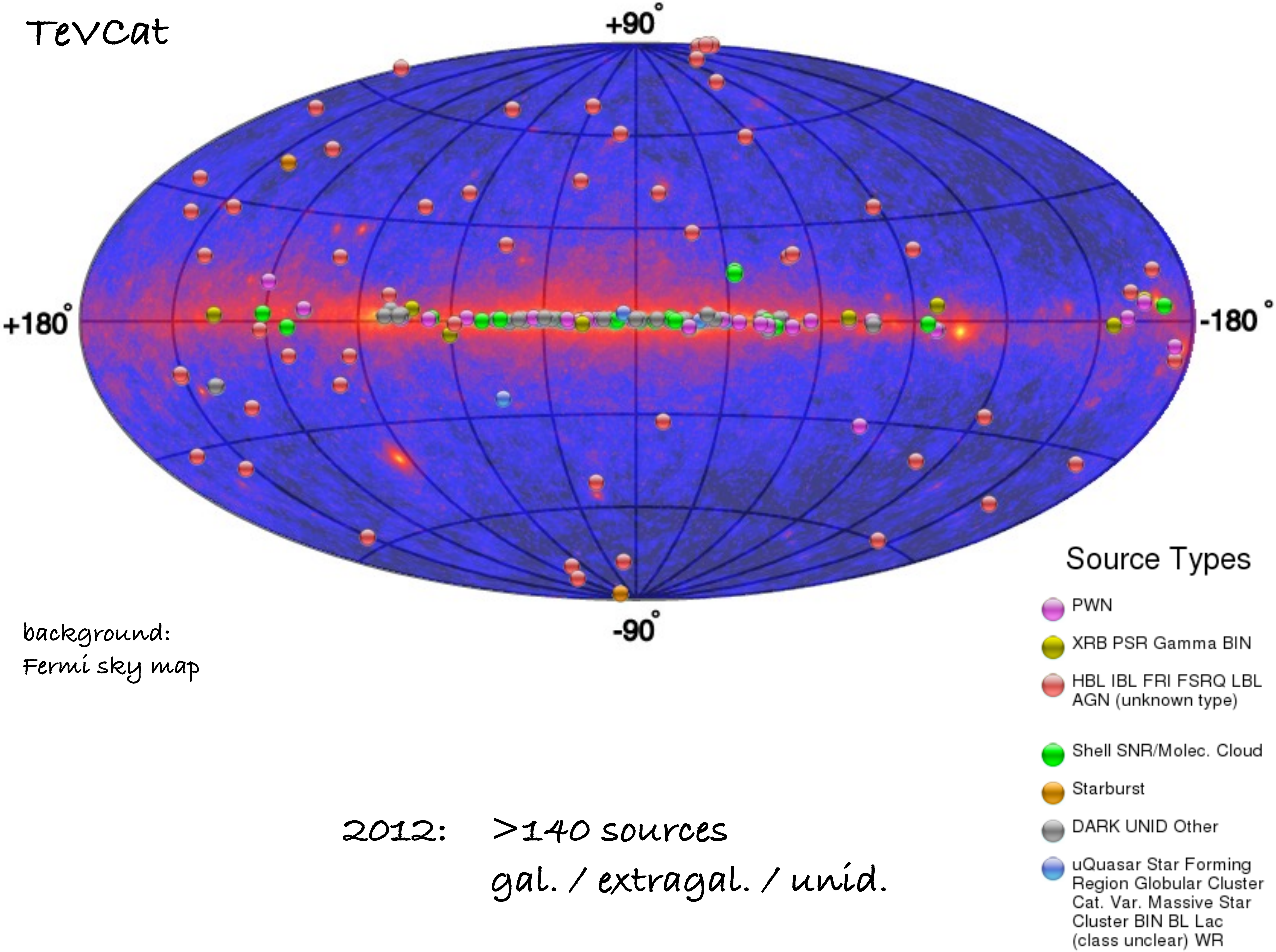
Cosmic
electron
accelerators

Synchrotron
radiation

Cosmic
proton
accelerators

Inverse Compton
upscattering

TeVCat



background:
Fermi sky map

2012: >140 sources
gal. / extragal. / unid.

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
Galactic Survey:	Science 307 (2005) 1839
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, 161301 (2011)
Lorentz Invariance:	PRL 101 (2008) 170402
Cosmic Ray Electrons:	PRL (2009)

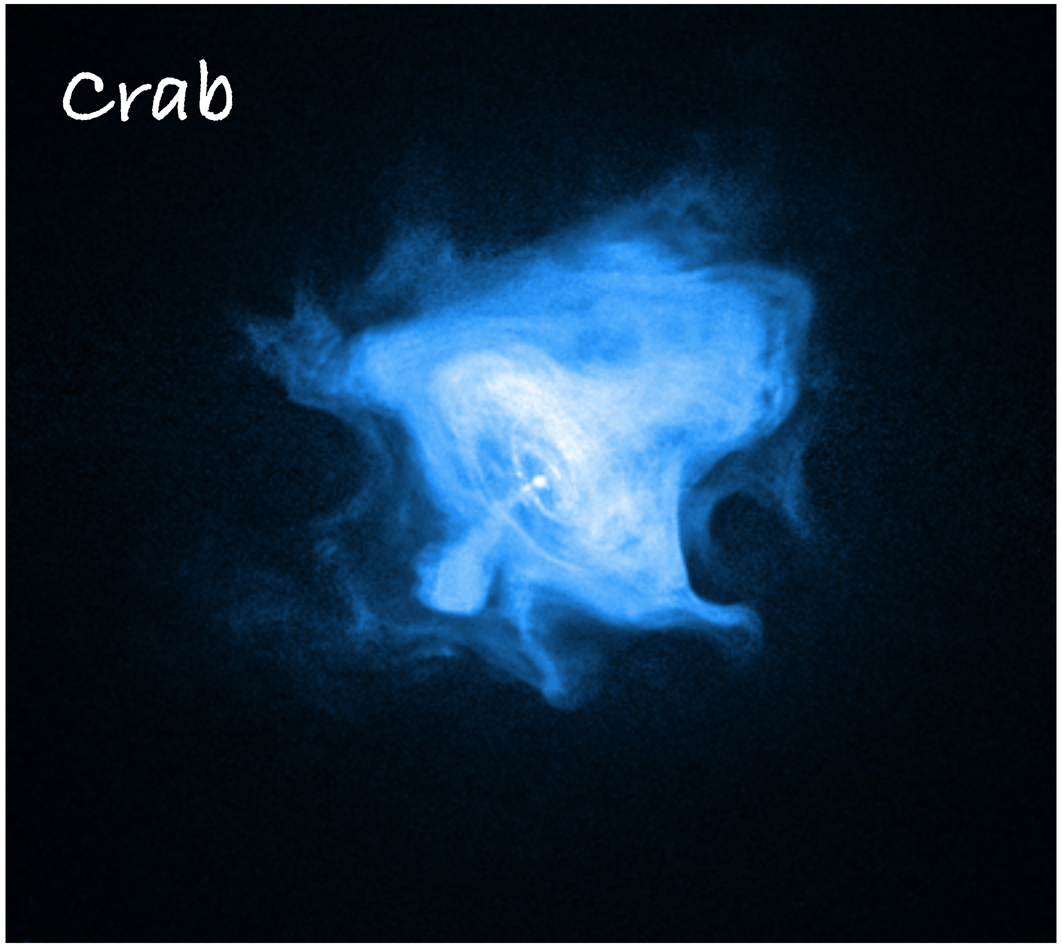
... a booming field.

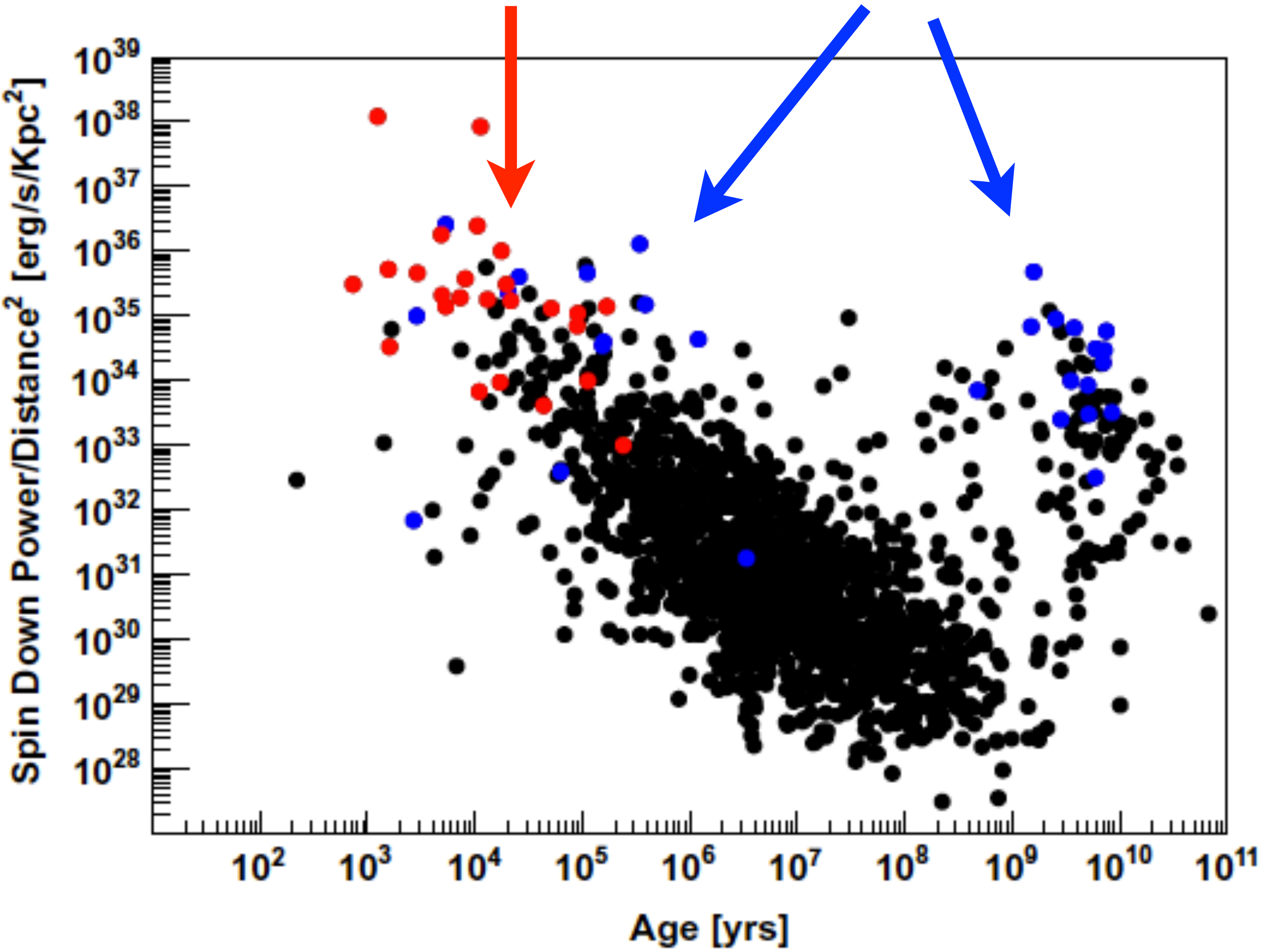
and the technique is not yet maxed out.

~30 pulsar wind nebulae (PWN)

young (~10 ky) pulsars with large spin-down power
magnetised relativistic winds

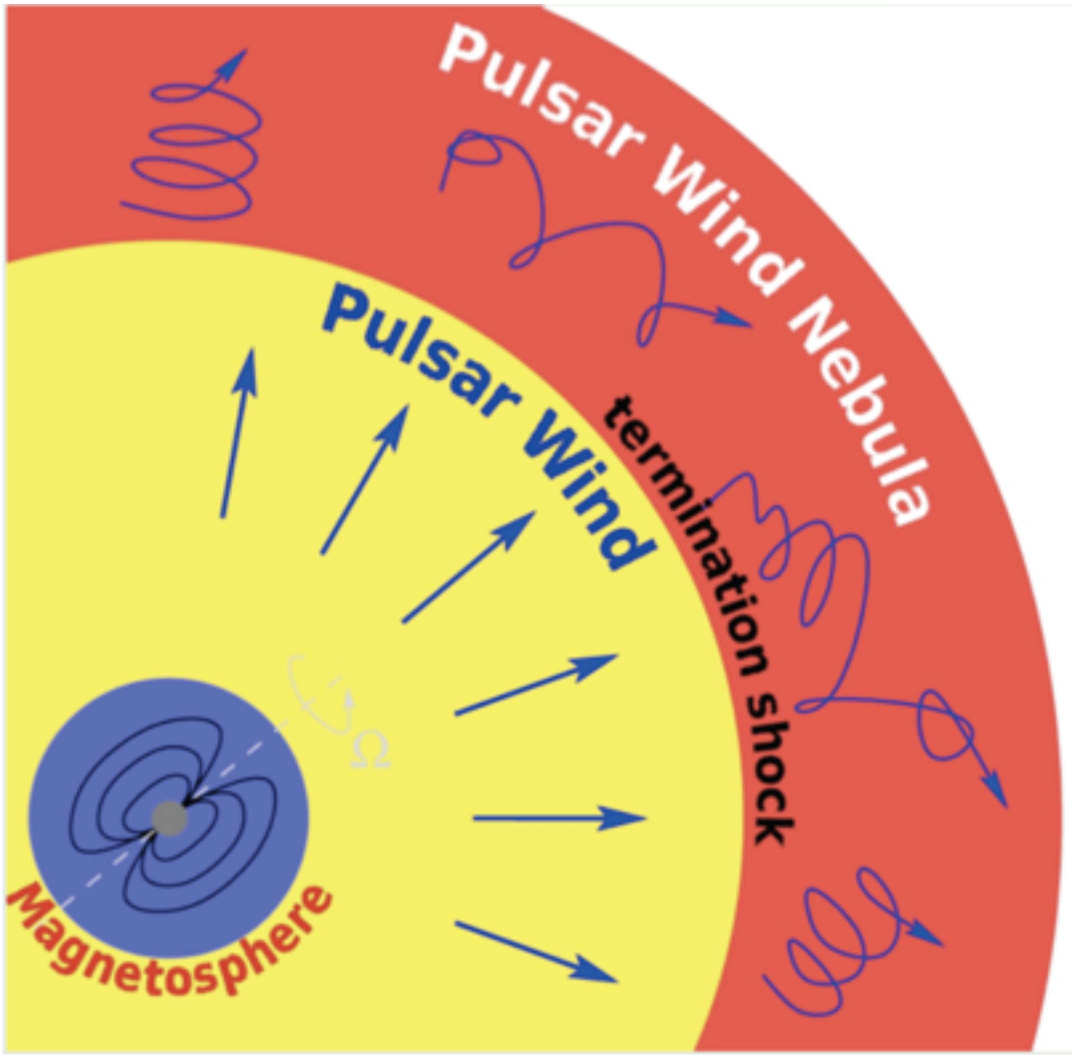
morphology
SED: GeV - TeV connection
SNR - PWN connection
electron cooling
population studies



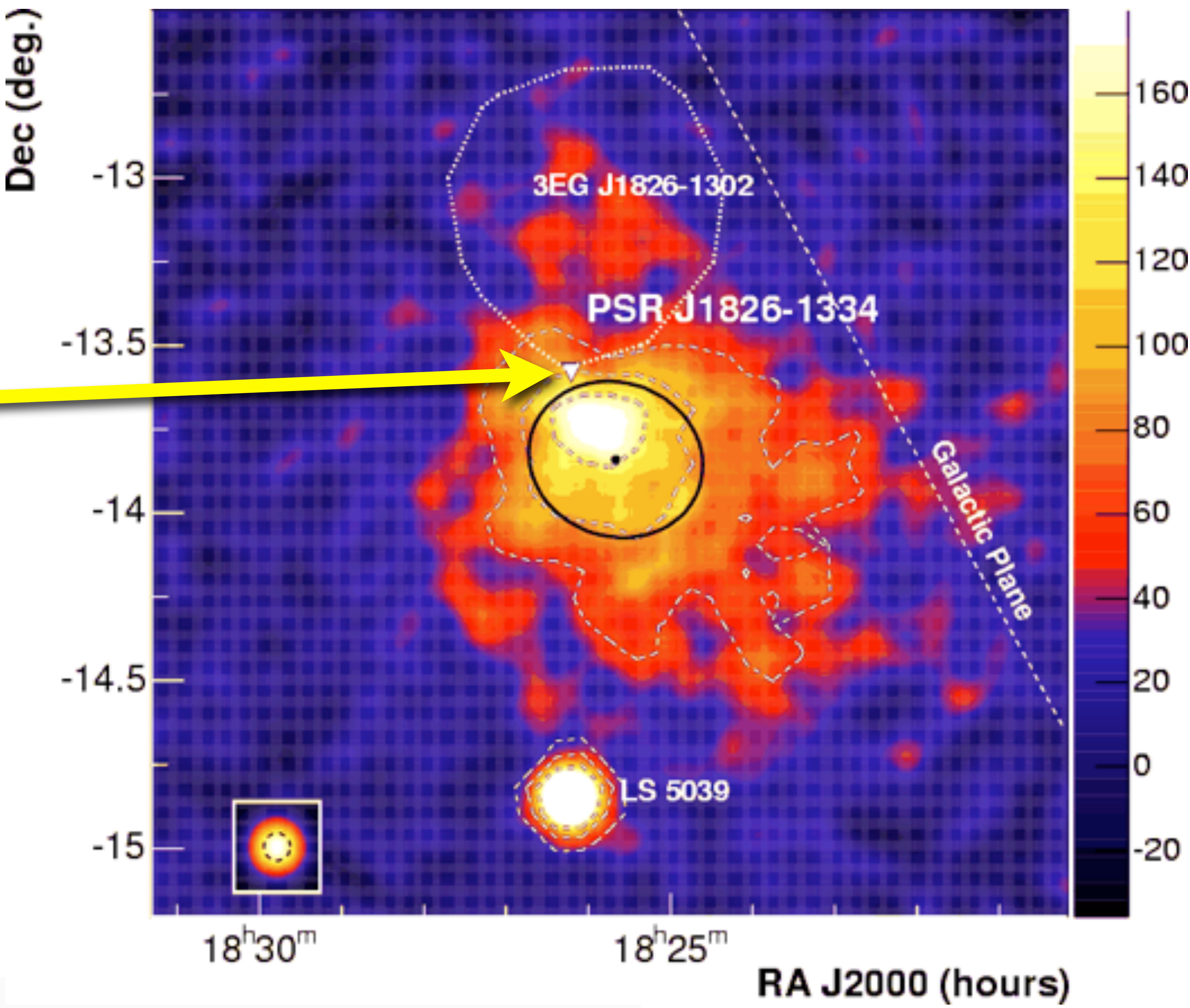


TeV PWNe

GeV PWNe

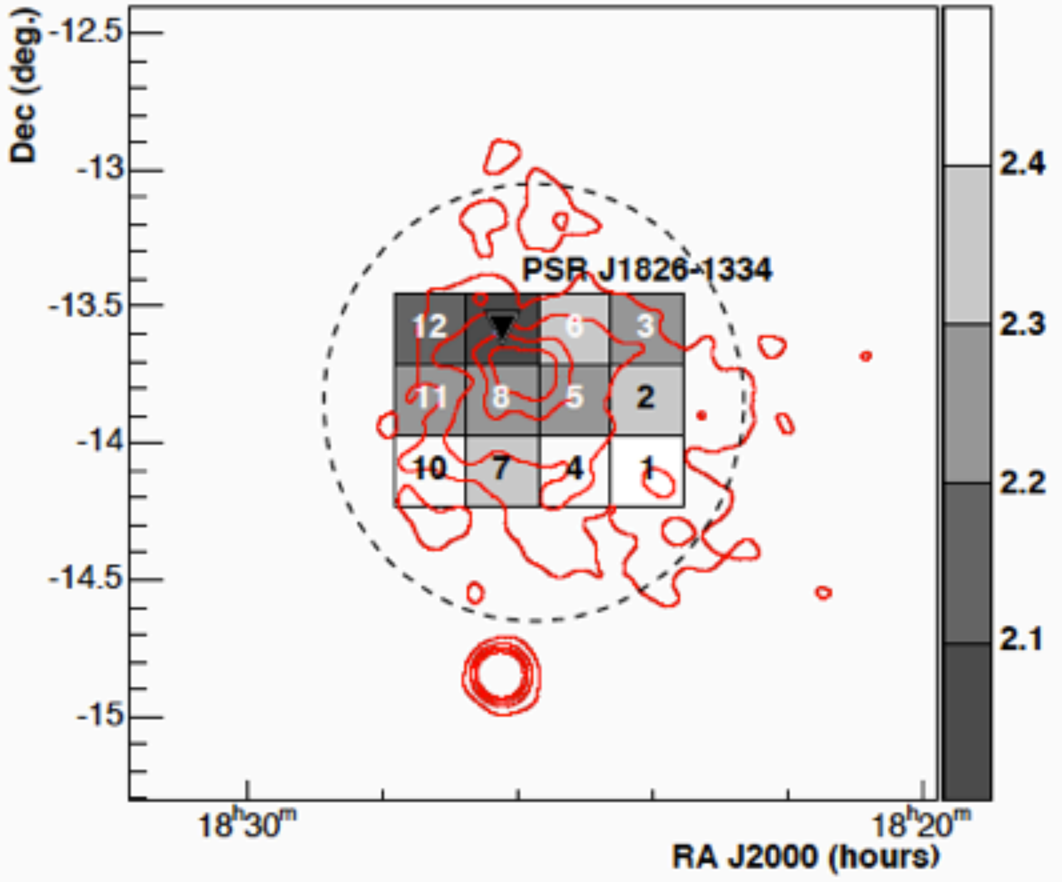


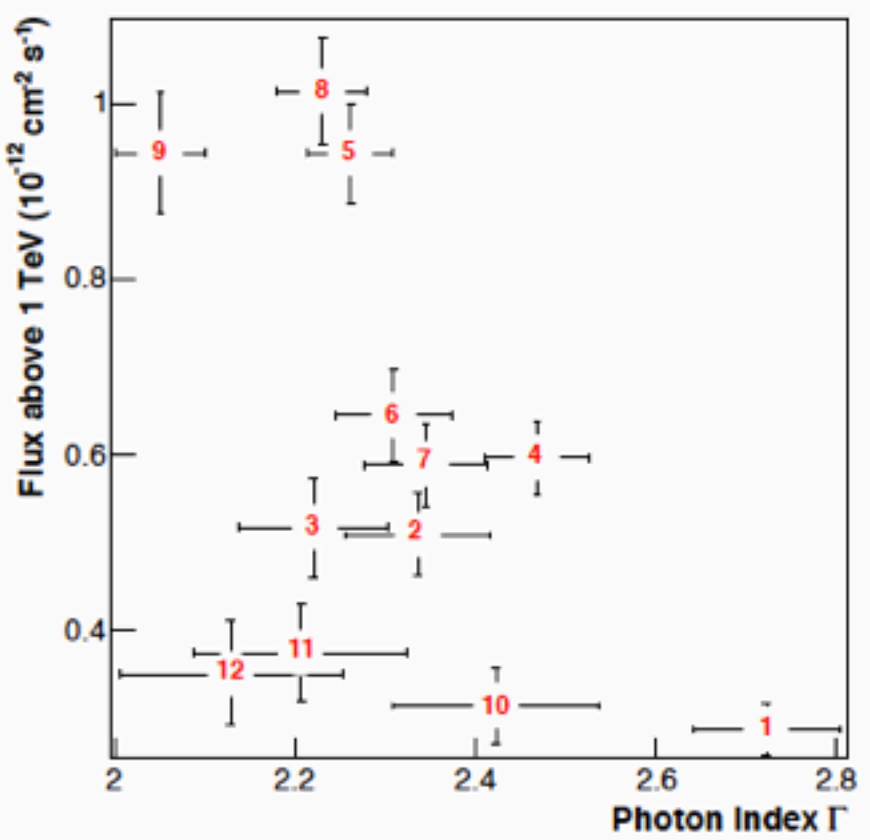
e.g. HESS J1825-137



source of wind

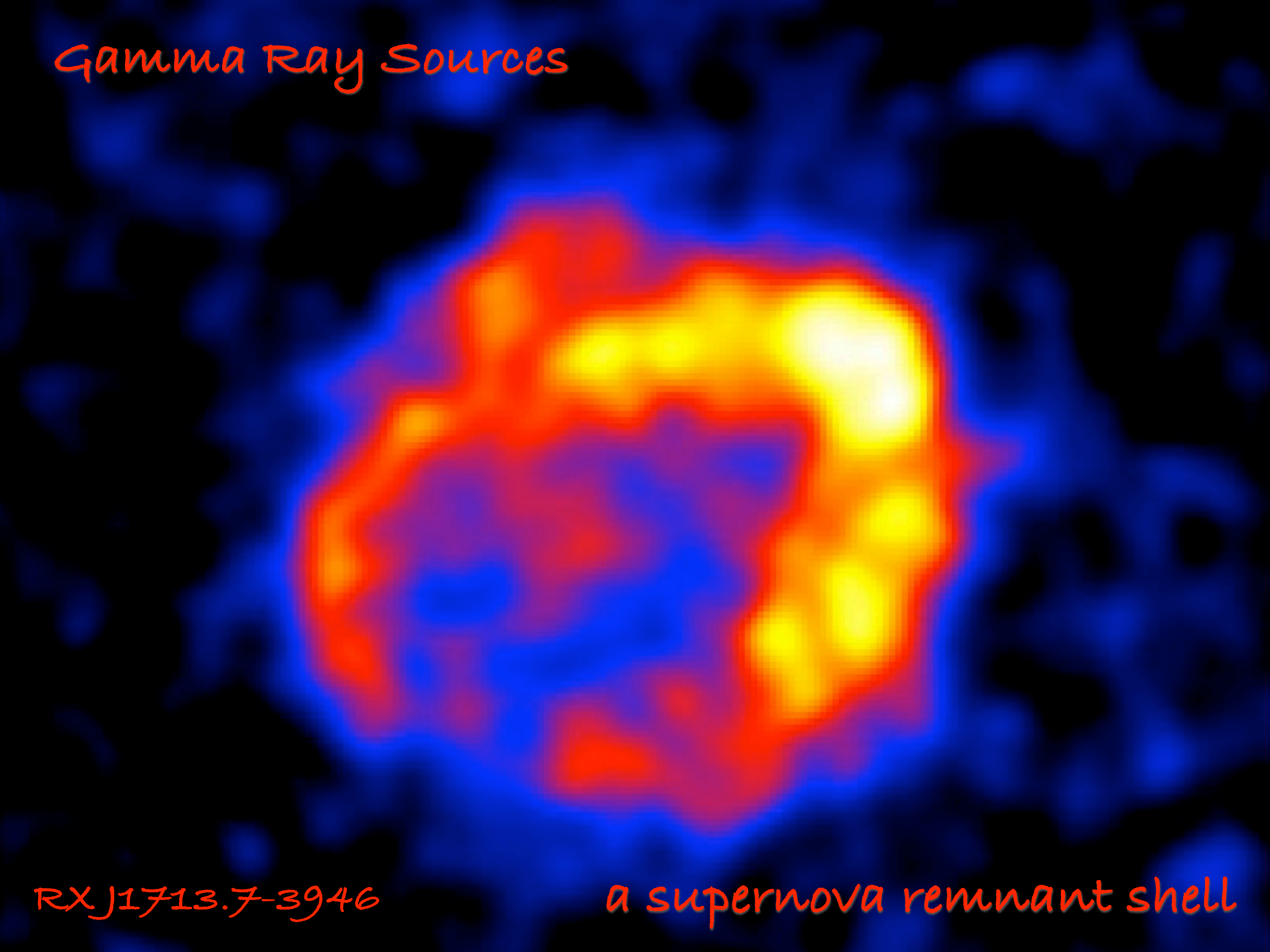
270 GeV to 35 TeV





spatially resolved spectra

Gamma Ray Sources

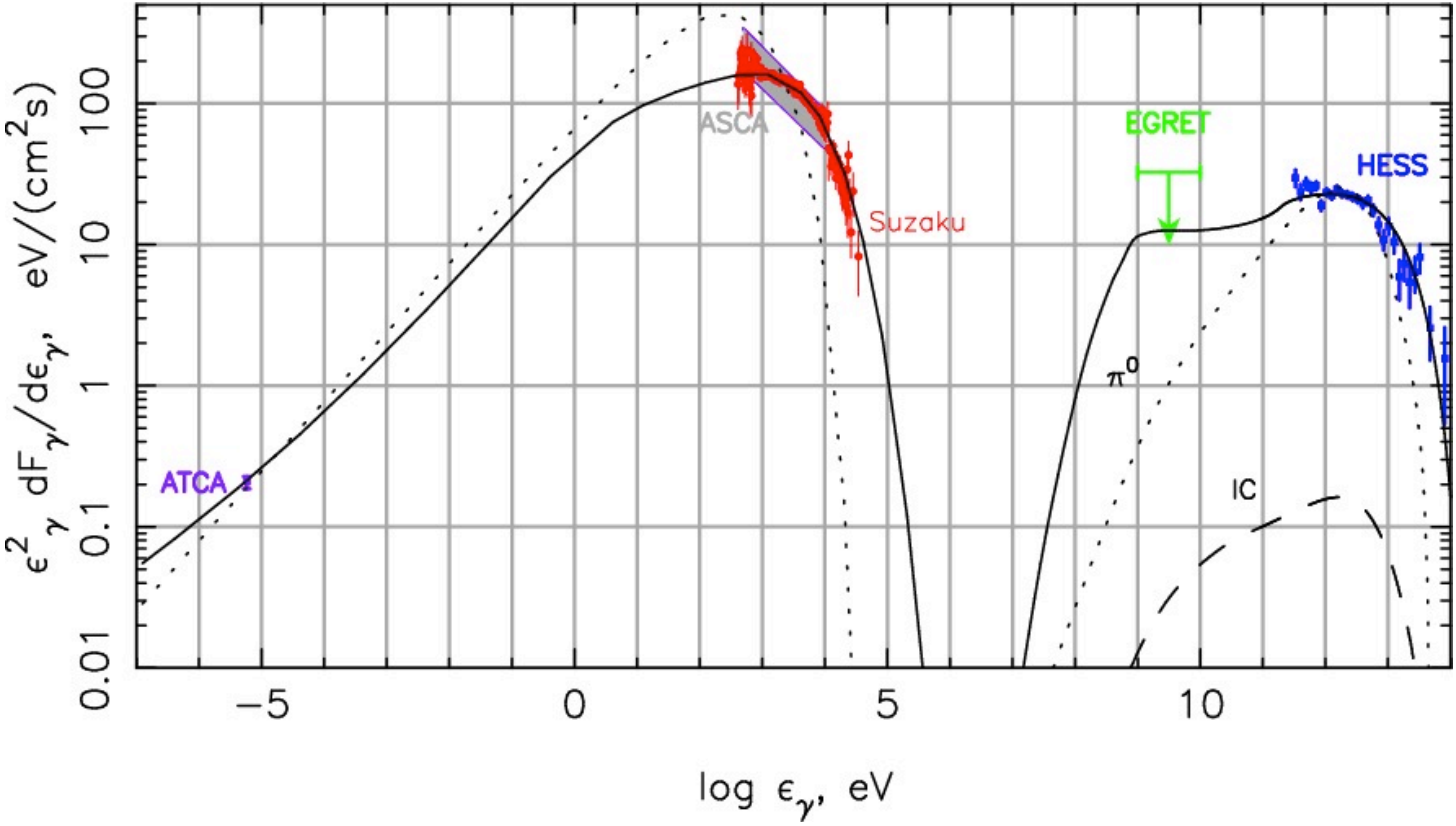


RXJ1713.7-3946

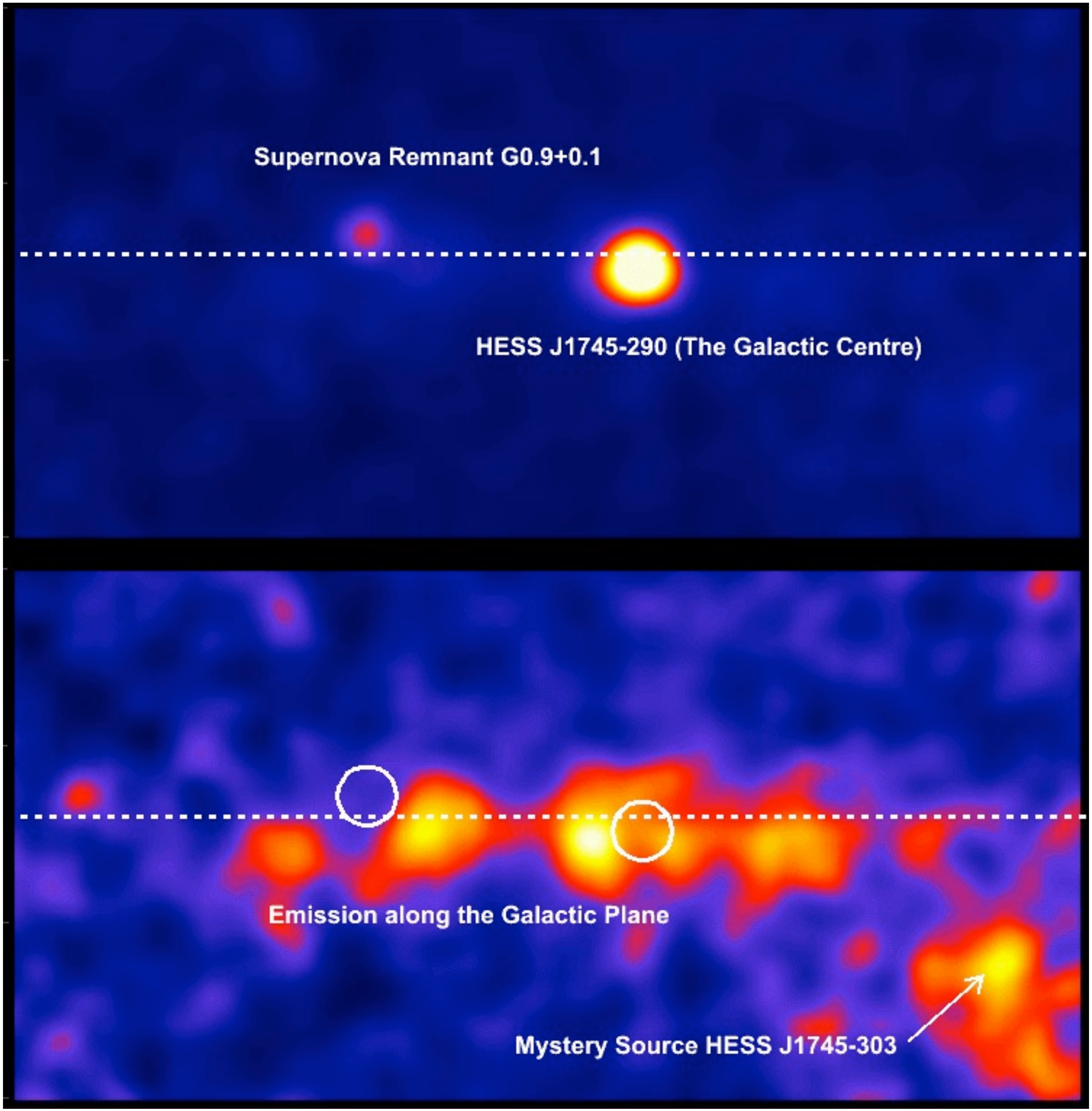
a supernova remnant shell

Supernova Remnant RX J1713.7-3946

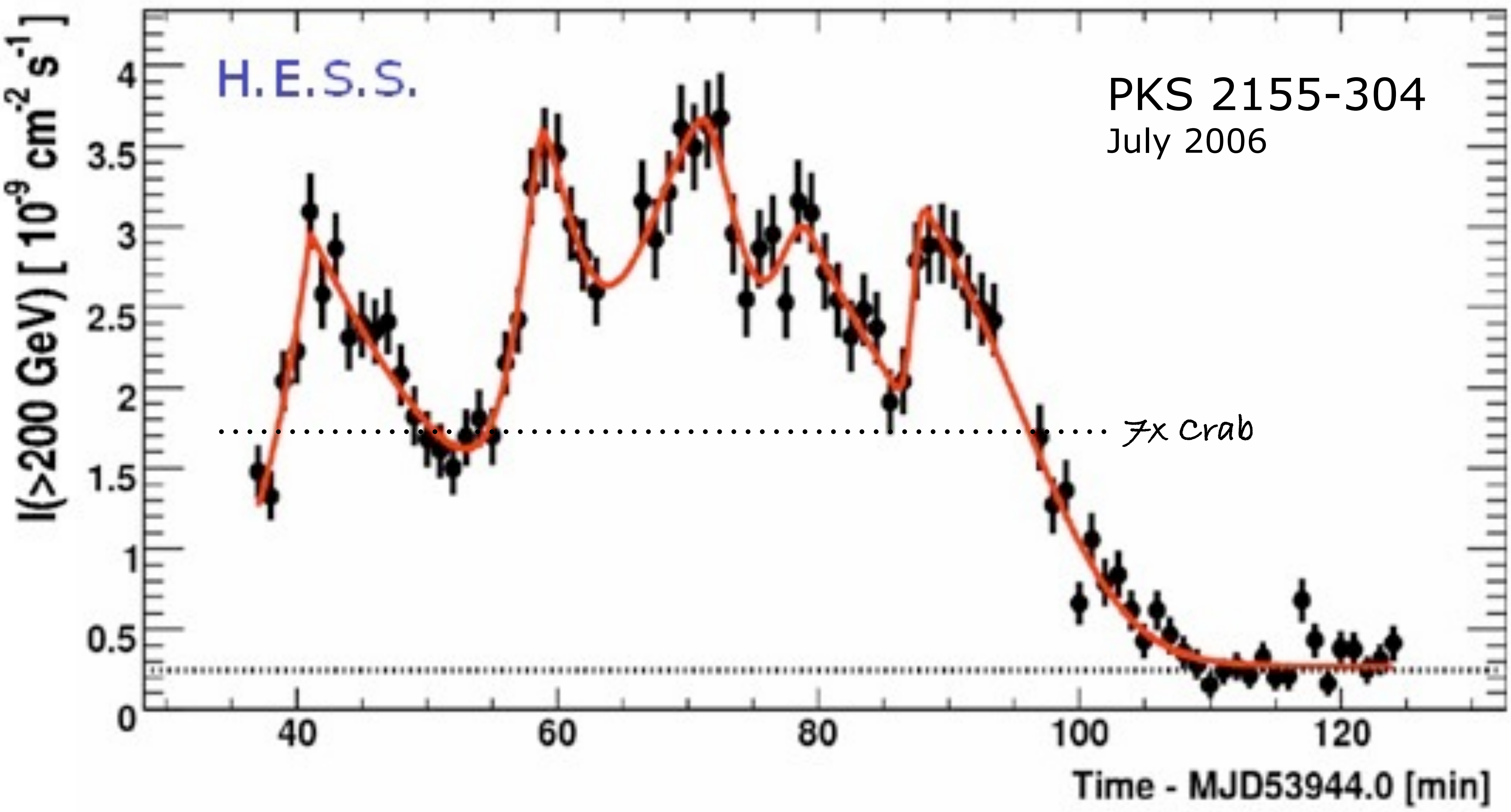
meV eV keV MeV GeV TeV



HESS:
gal. centre



CRs with
mol. clouds

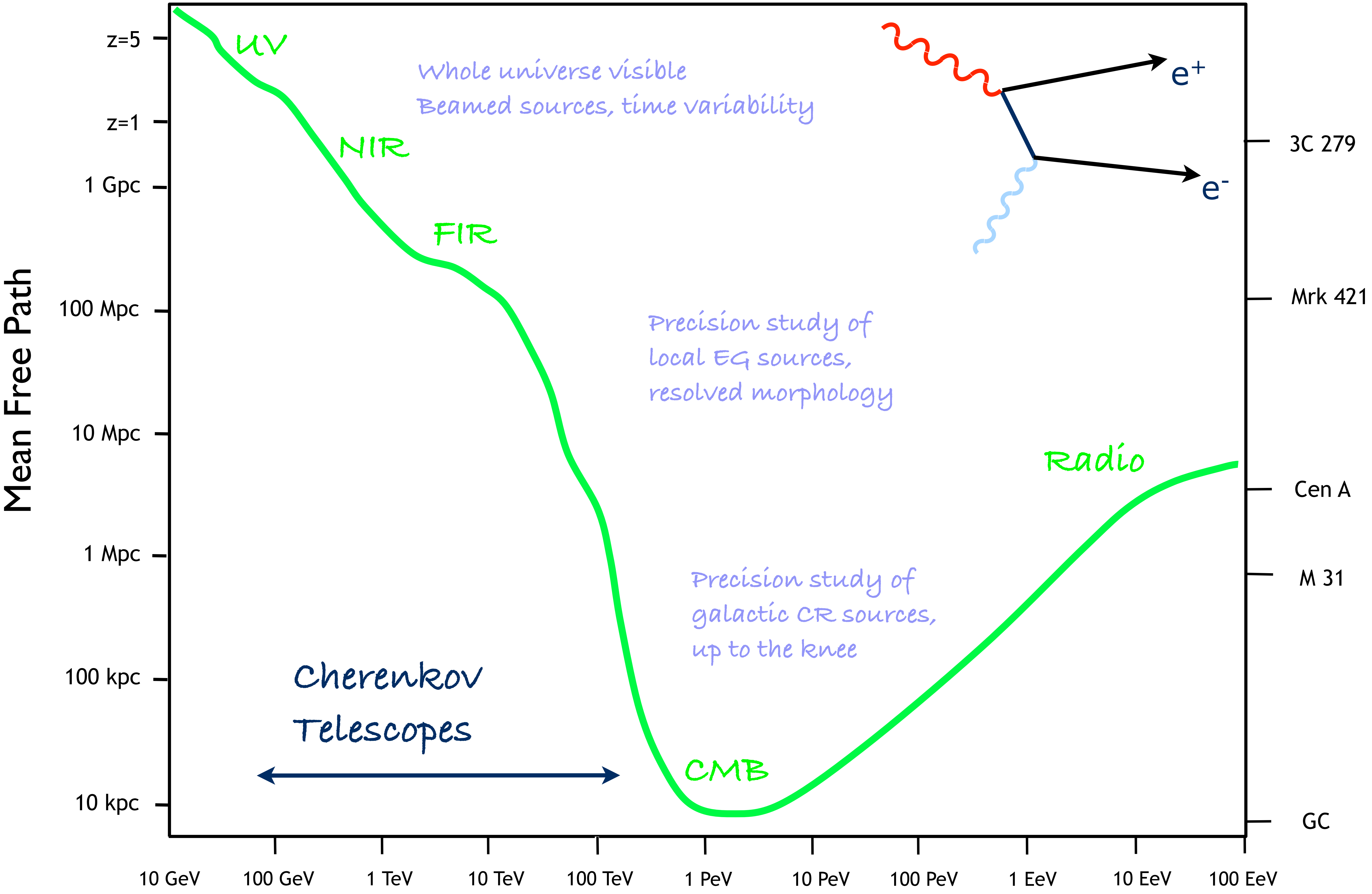


BL Lac object $z = 0.116$
bursts on 200 s scales
$\Gamma \geq 100$ are required

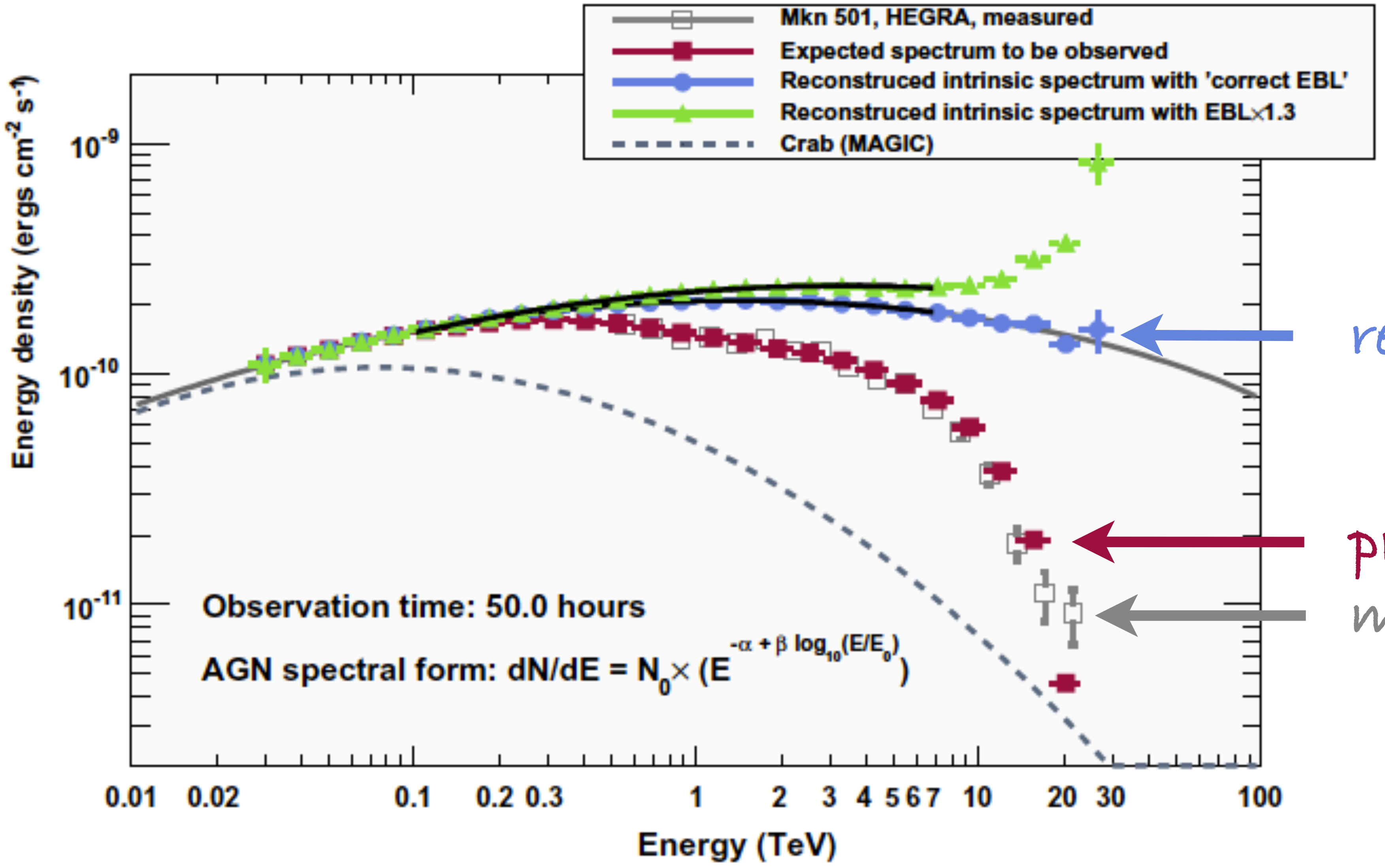
volume of emission can only be
≈ light minutes across (sun-earth)

Extragalactic Background light

The Gamma-Ray Horizon $\gamma_{TeV} + \gamma_{IR} \longrightarrow e^+e^-$



Mazin et al. 2012



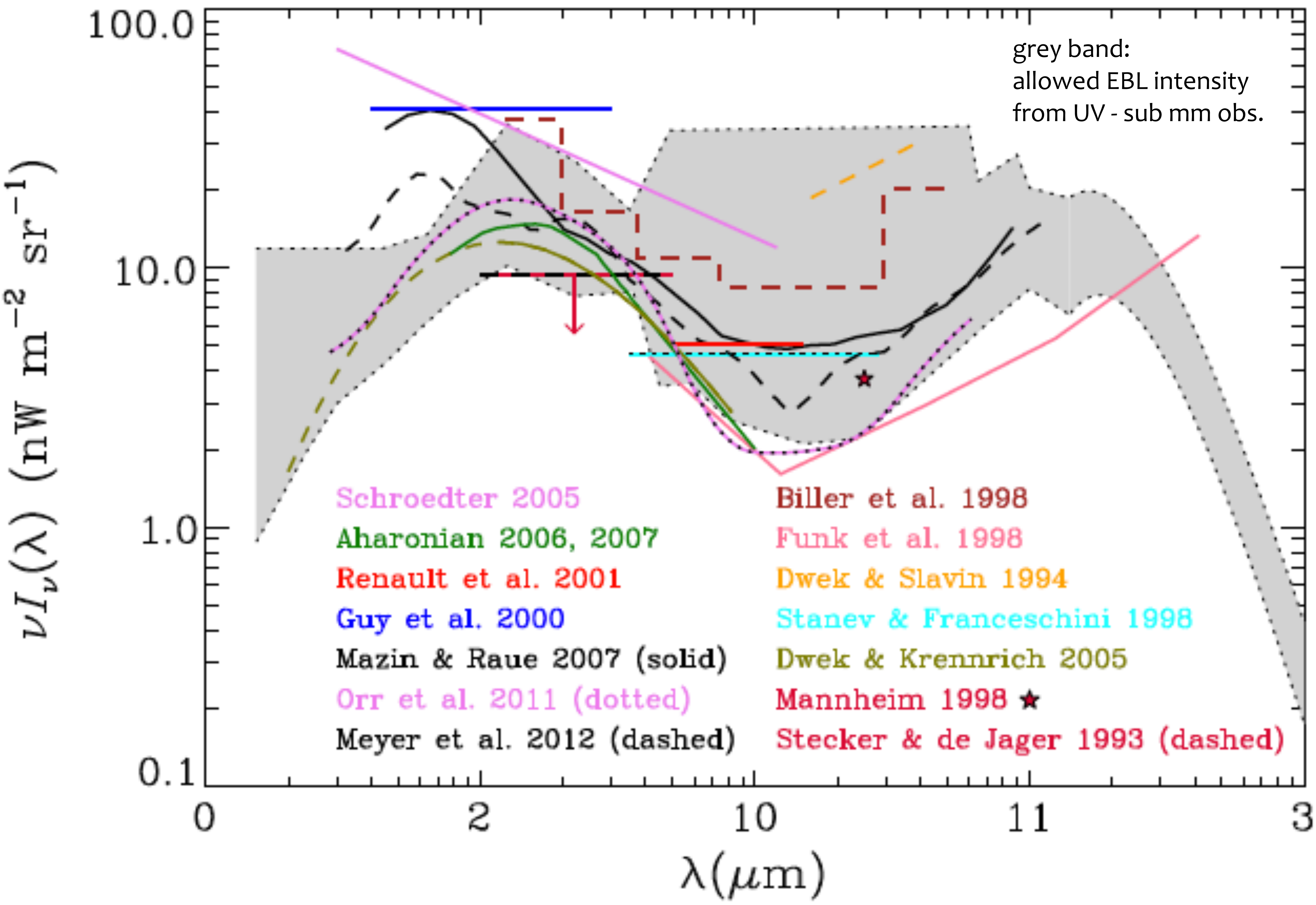
reconstructed

predicted (CTA)

measured (Hegra)

analyse absorption features in the spectra of distant sources.

Dwek & Krennrich 2012



grey band:
allowed EBL intensity
from UV - sub mm obs.

universe is surprisingly transparent.

Scientific Objectives:

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

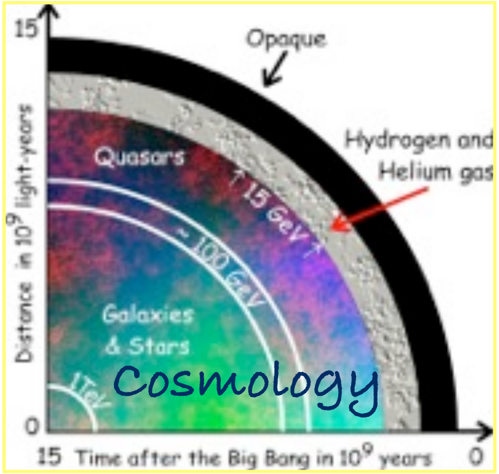
Dark Matter annihilation / decay

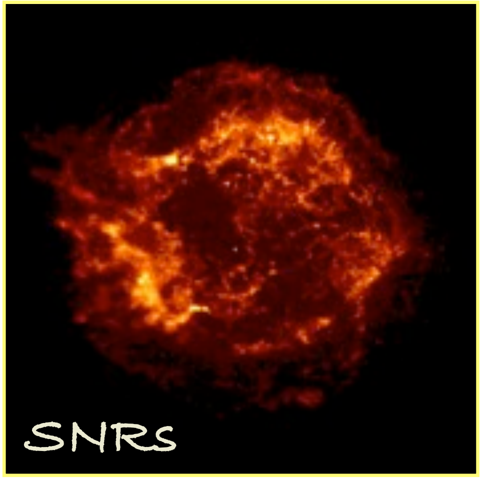
Lorentz Invariance violation

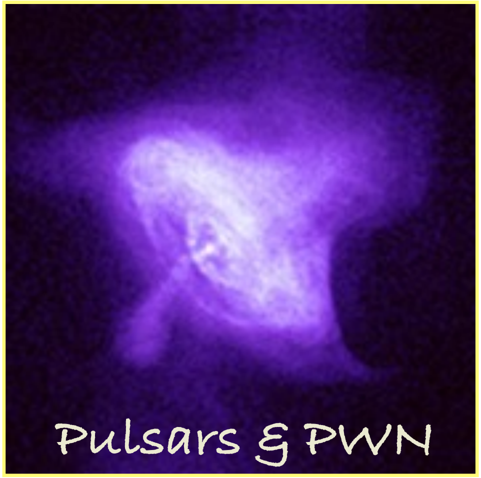
Cosmology

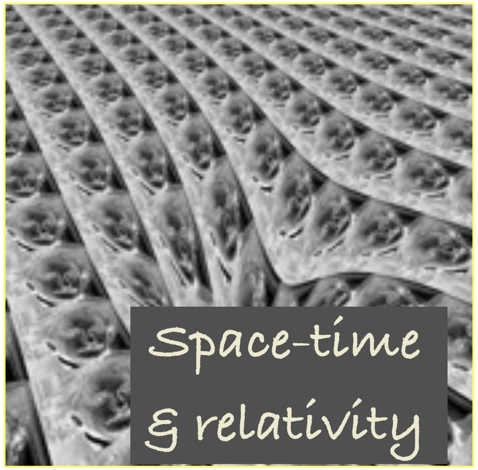
cosmic FIR-UV radiation,

cosmic magnetism









The Future with

cta

cherenkov telescope array

How to do even better with Ch. telescopes ?

A future Cherenkov observatory needs:

for E > TeV:

bigger collection area
(i.e. large array of telescopes, wider FOV)

more events

for E < TeV:

better background rejection
(i.e. large array of telescopes, wider FOV
for multiple shower images)

better events

cta
cherenkov telescope array

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

CTA is the global next generation project.

A precise and sensitive probe of the extreme universe,
with huge potential for extreme astronomy and
fundamental physics with TeV photons

Very Good reviews for CTA:

ASPERA:

ASTROPARTICLE PHYSICS

the European strategy

ASPERA

http://www.aspera-eu.org

ASTRONET:

The ASTRONET Infrastructure Roadmap: A Strategic Plan for European Astronomy

ASTRONET
www.astronet-eu.org

The ASTRONET Infrastructure Roadmap:

A Strategic Plan for European Astronomy

ESFRI:

European Strategy Forum
on Research Infrastructures

ESFRI

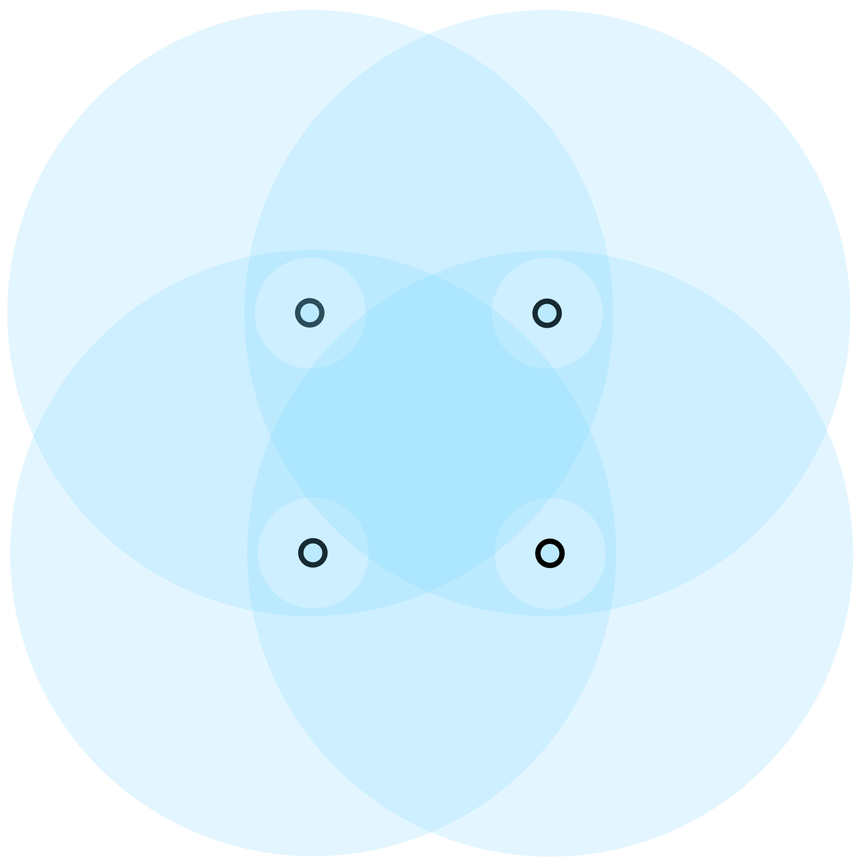
EUROPEAN ROADMAP
FOR RESEARCH
INFRASTRUCTURES

Boosting sensitivity & resolution: Arrays of Cherenkov telescopes

Single telescope

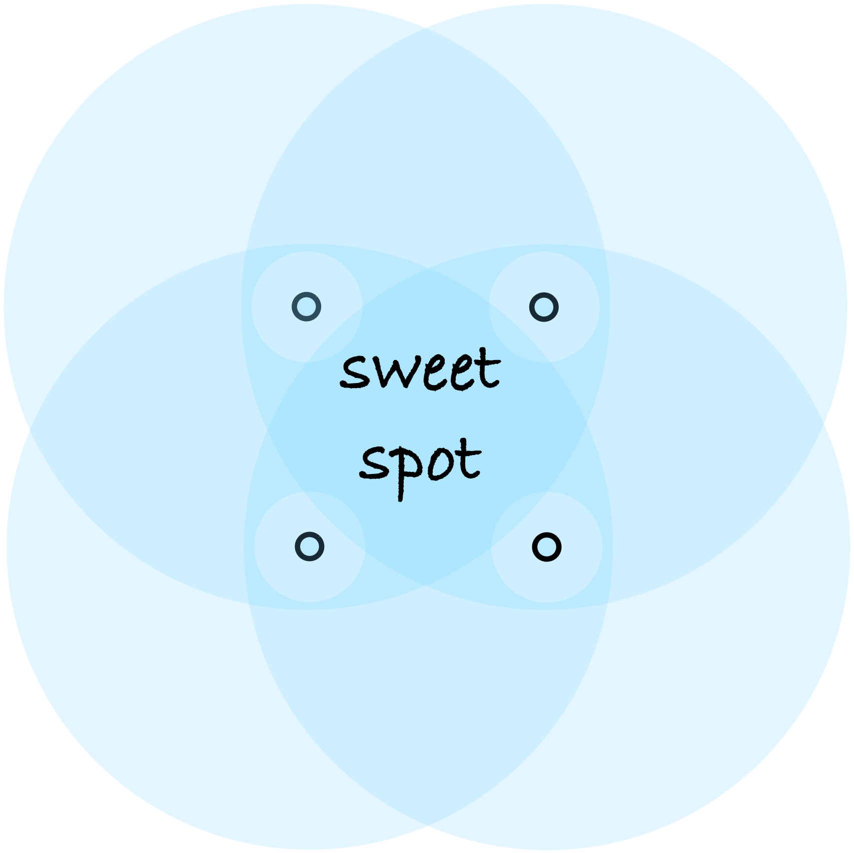
Boosting sensitivity & resolution:
Arrays of Cherenkov telescopes

Single telescope



Boosting sensitivity & resolution: Arrays of Cherenkov telescopes

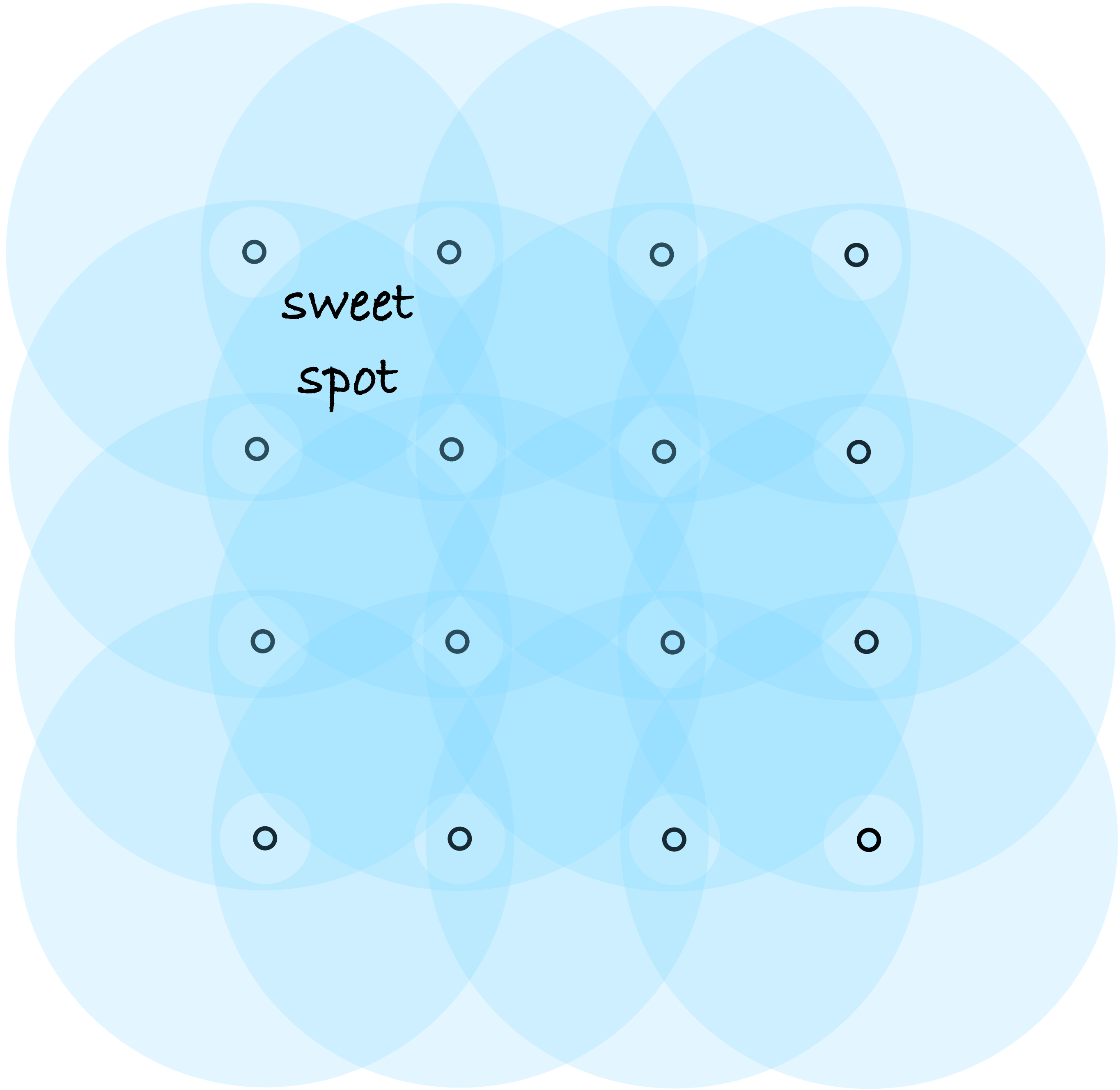
Single telescope



Boosting sensitivity & resolution:
Arrays of Cherenkov telescopes

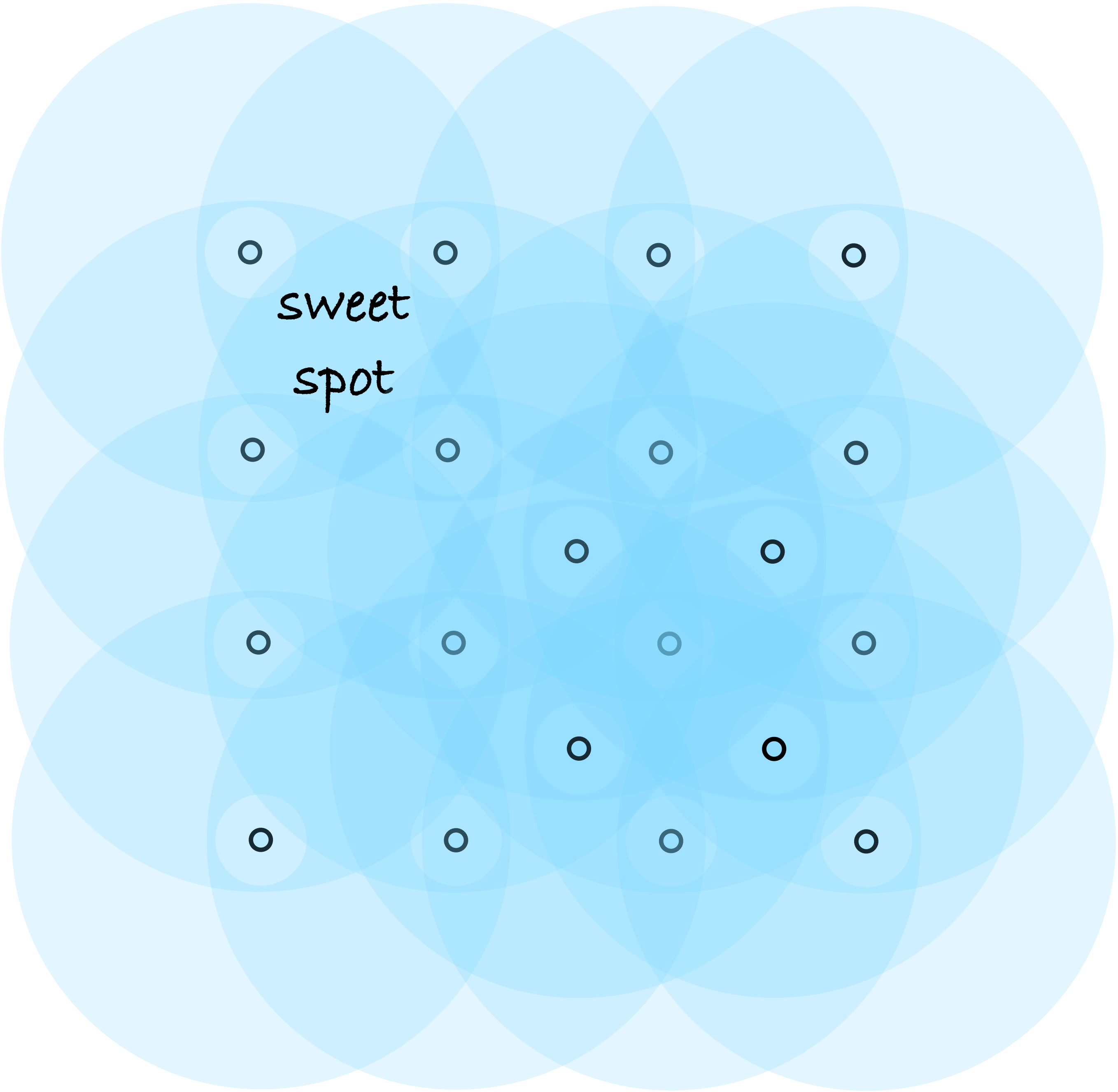
←300 m→

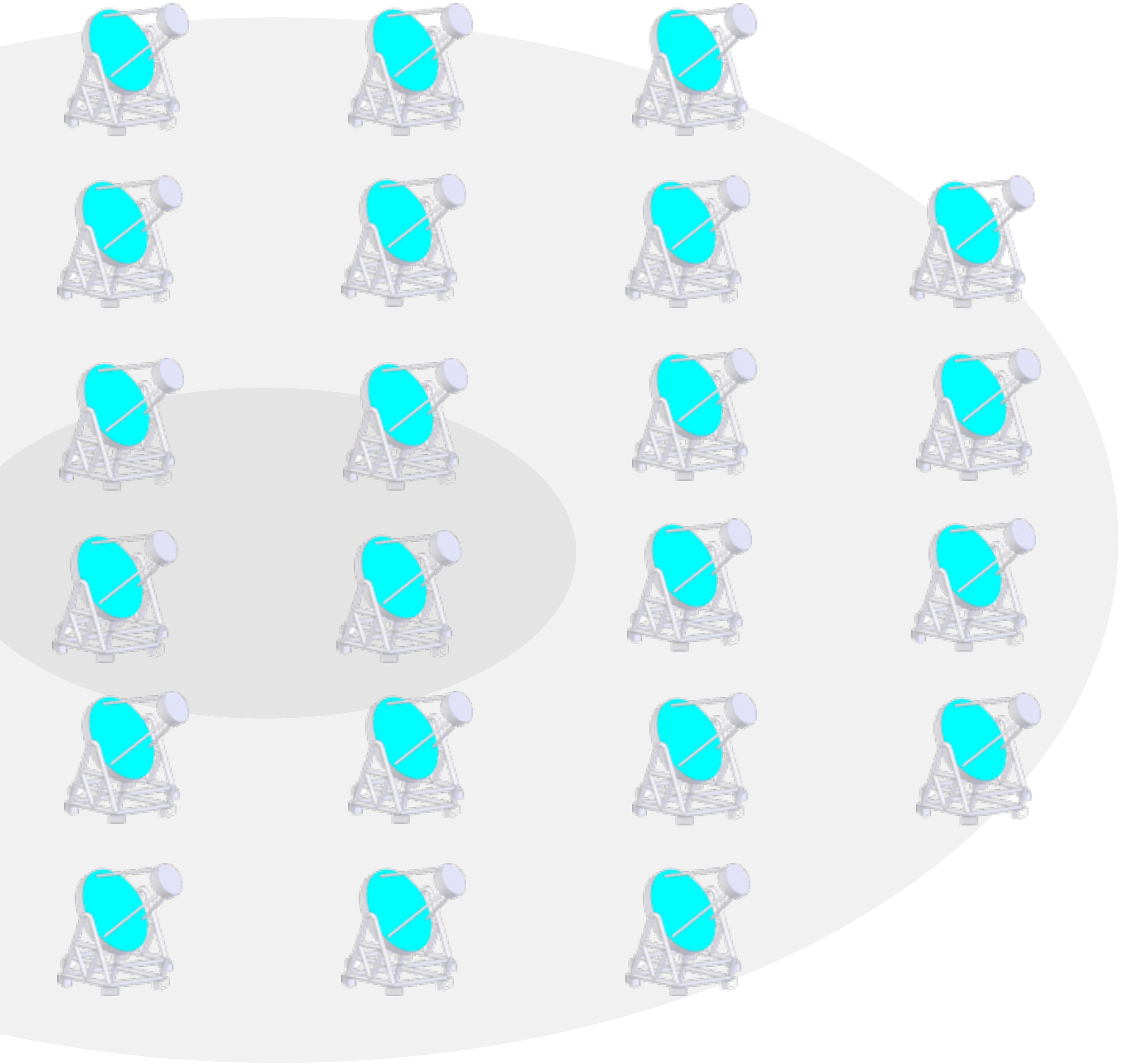
Single telescope



Boosting sensitivity & resolution: Arrays of Cherenkov telescopes

Single telescope





Core array:

mCrab sensitivity
in 0.1–10 TeV range

Not to scale !

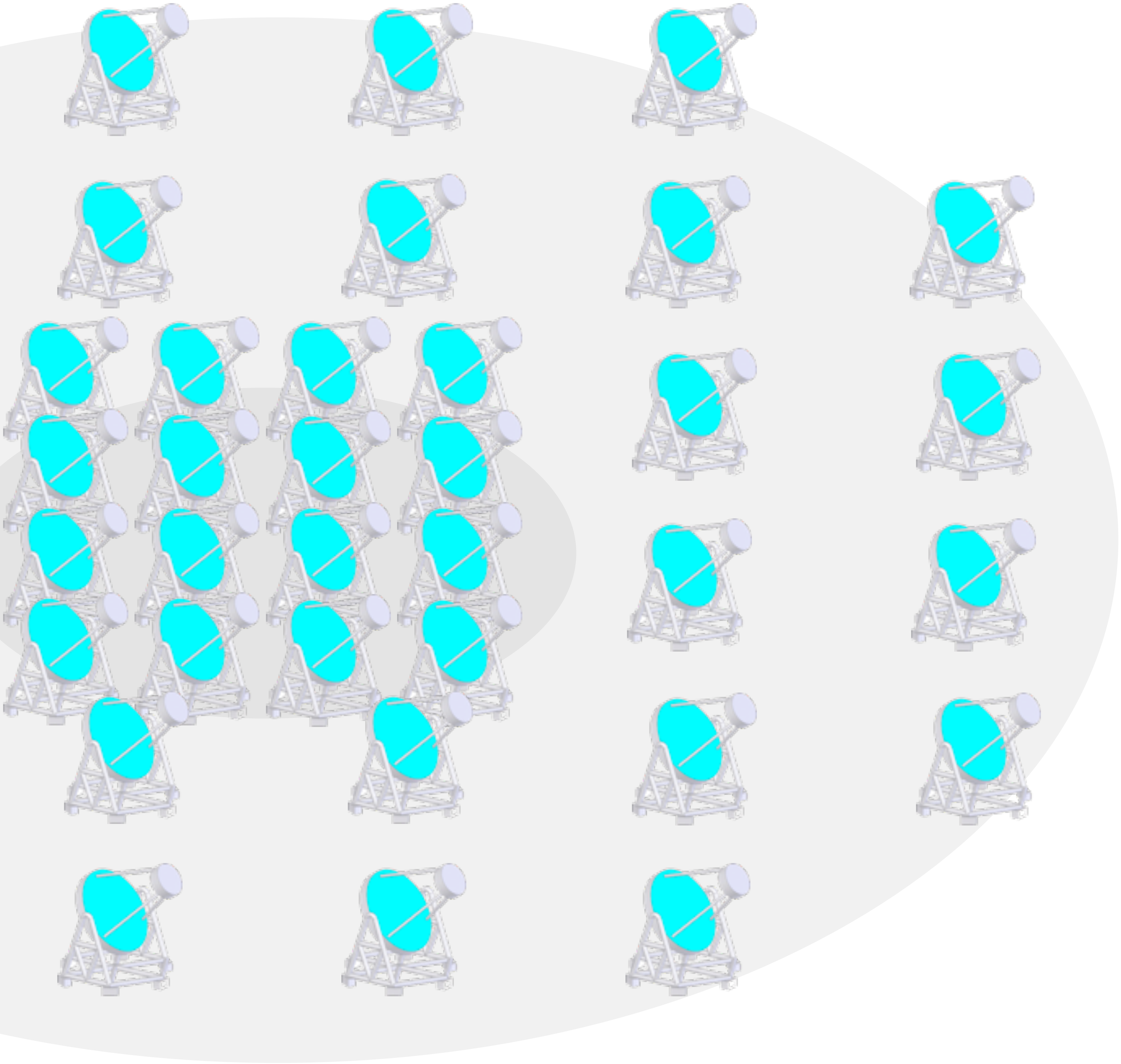
Low-energy section

energy threshold

of some 10 GeV

(a) bigger dishes or

Not to scale !



Low-energy section

energy threshold

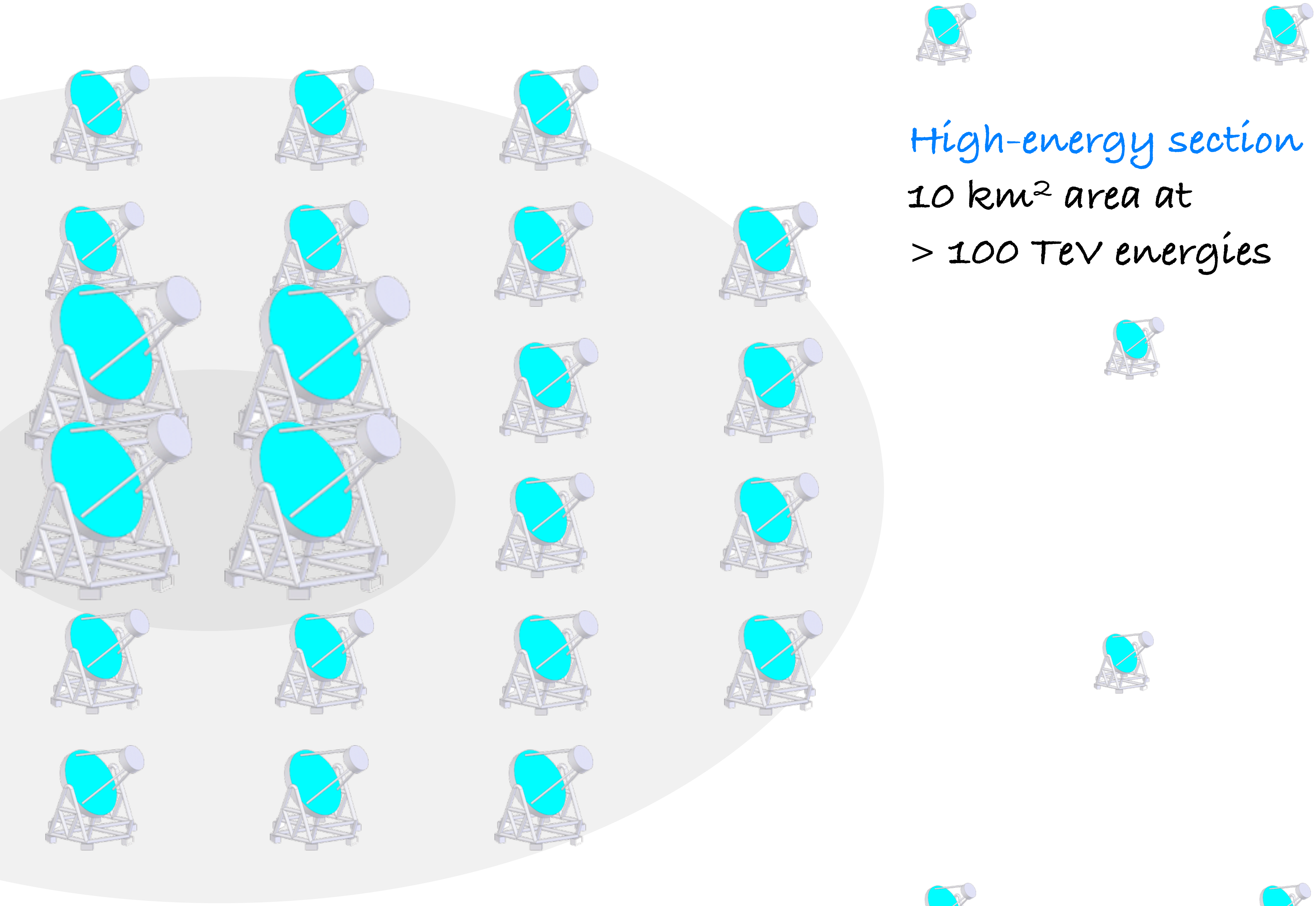
of some 10 GeV

(a) bigger dishes or

(b) dense packing /

high-QE sensors

Not to scale !



High-energy section

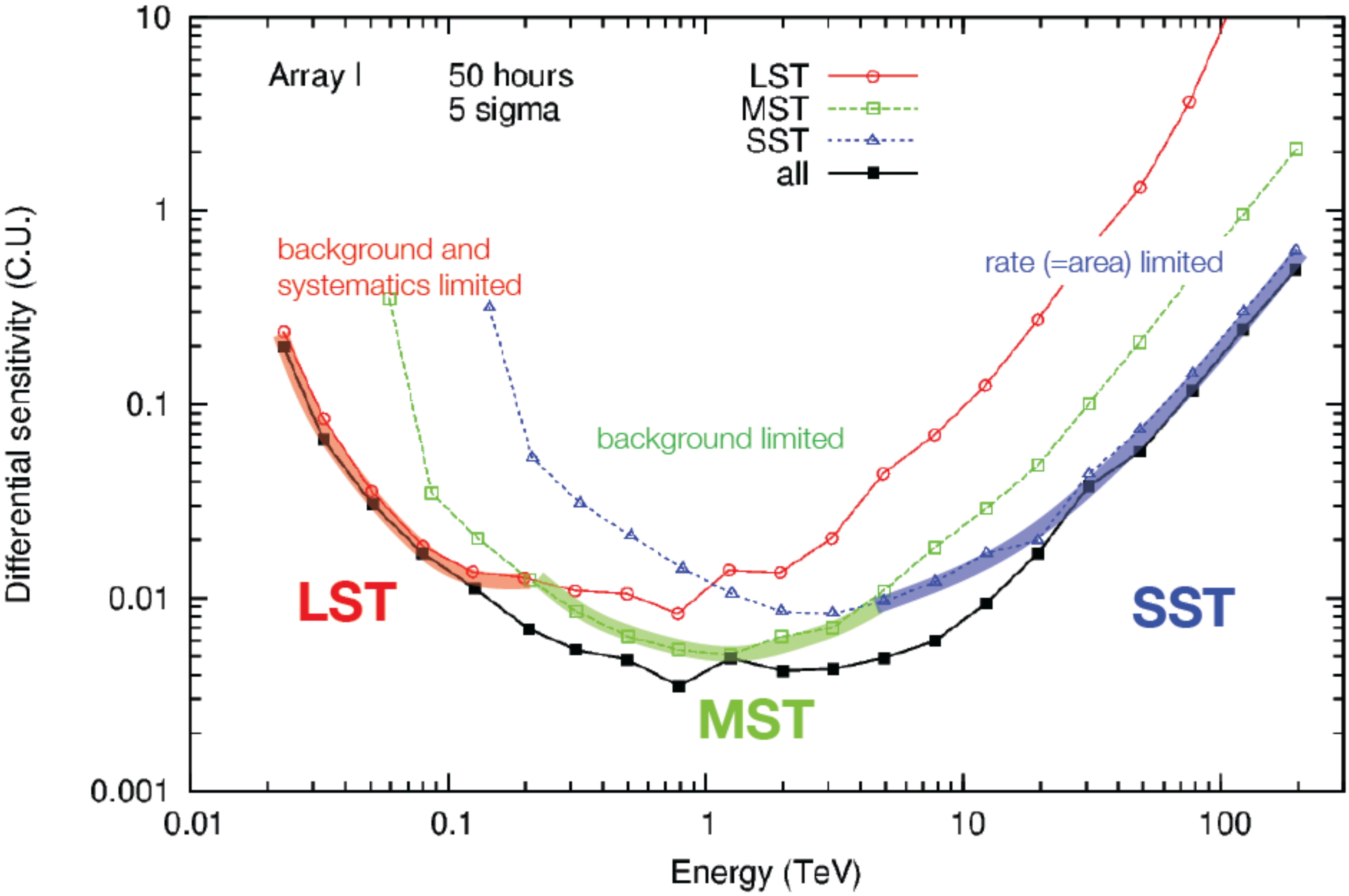
10 km^2 area at

> 100 TeV energies

Not to scale !

Sensitivity (in units of Crab flux)

for detection in each 0.2-decade energy band



CTA

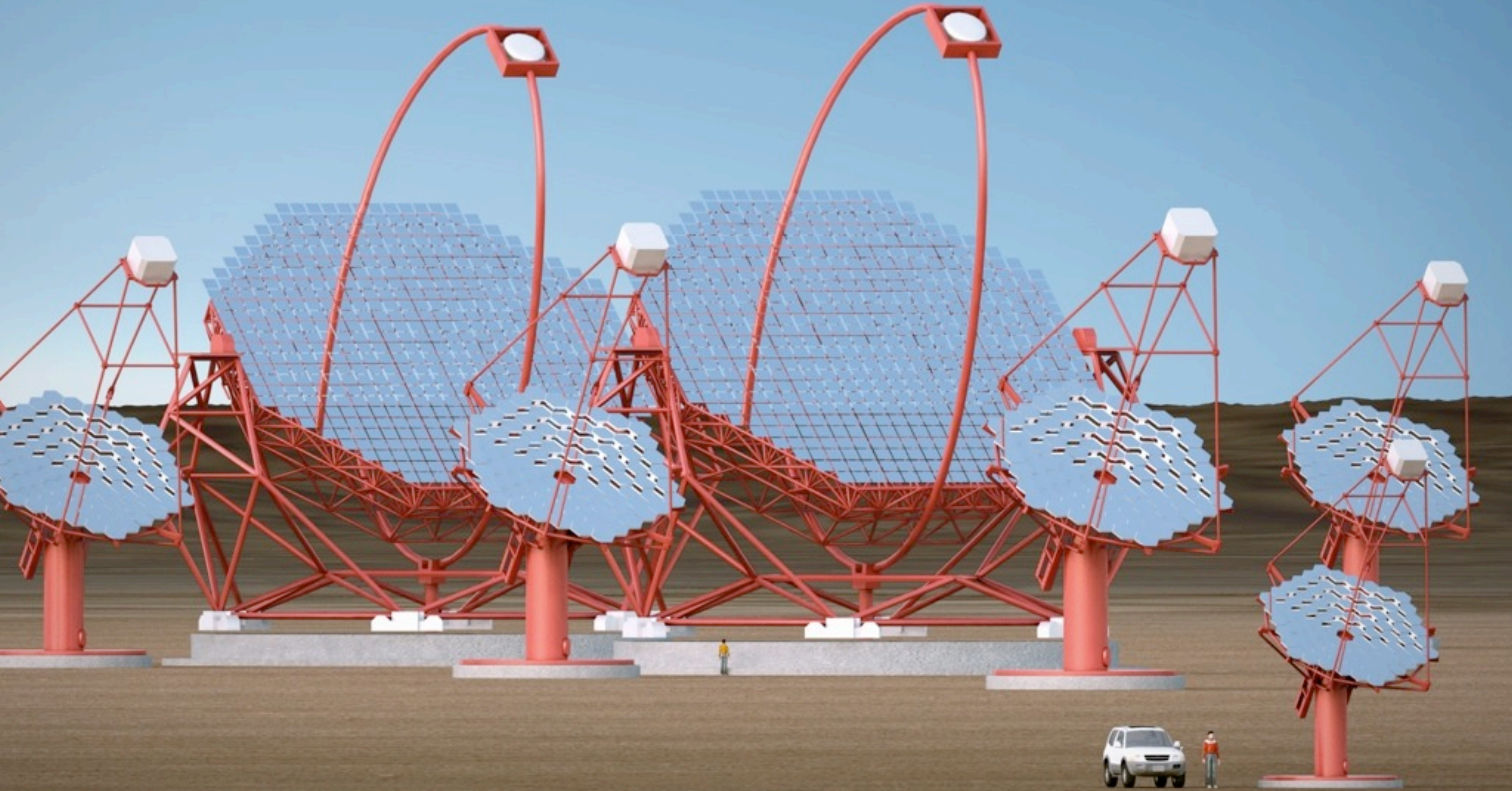
10x more sensitive than current instruments

+ much wider energy coverage and field of view

substantially better angular and energy resolution

International project: 50-100 telescopes

Design: 2008-12, Prototyping: 2011-14, Construction: 2015-19



Price Tag: € 100 + 50 M

South North

(2006 Euros)

What is the best instrument for this money?

Science / €

Optimise performance (within budget),

(parameters: telescope size, type, pixel size, FoV, array layout)

design for mass production, long-term operation
and low maintenance

i.e. cheap, reliable, modular ...

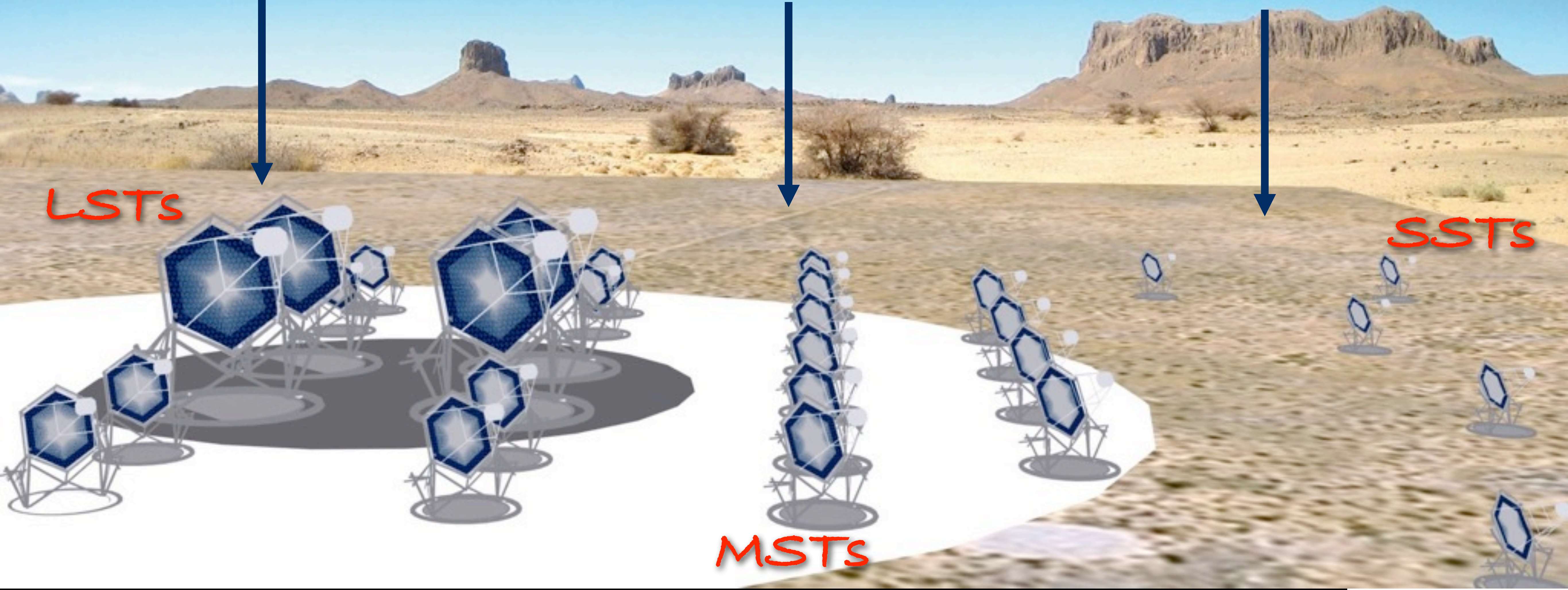
A real observatory with ≈ 100 telescopes.

Low-energy section
energy threshold
of 20-30 GeV
~23m telescopes

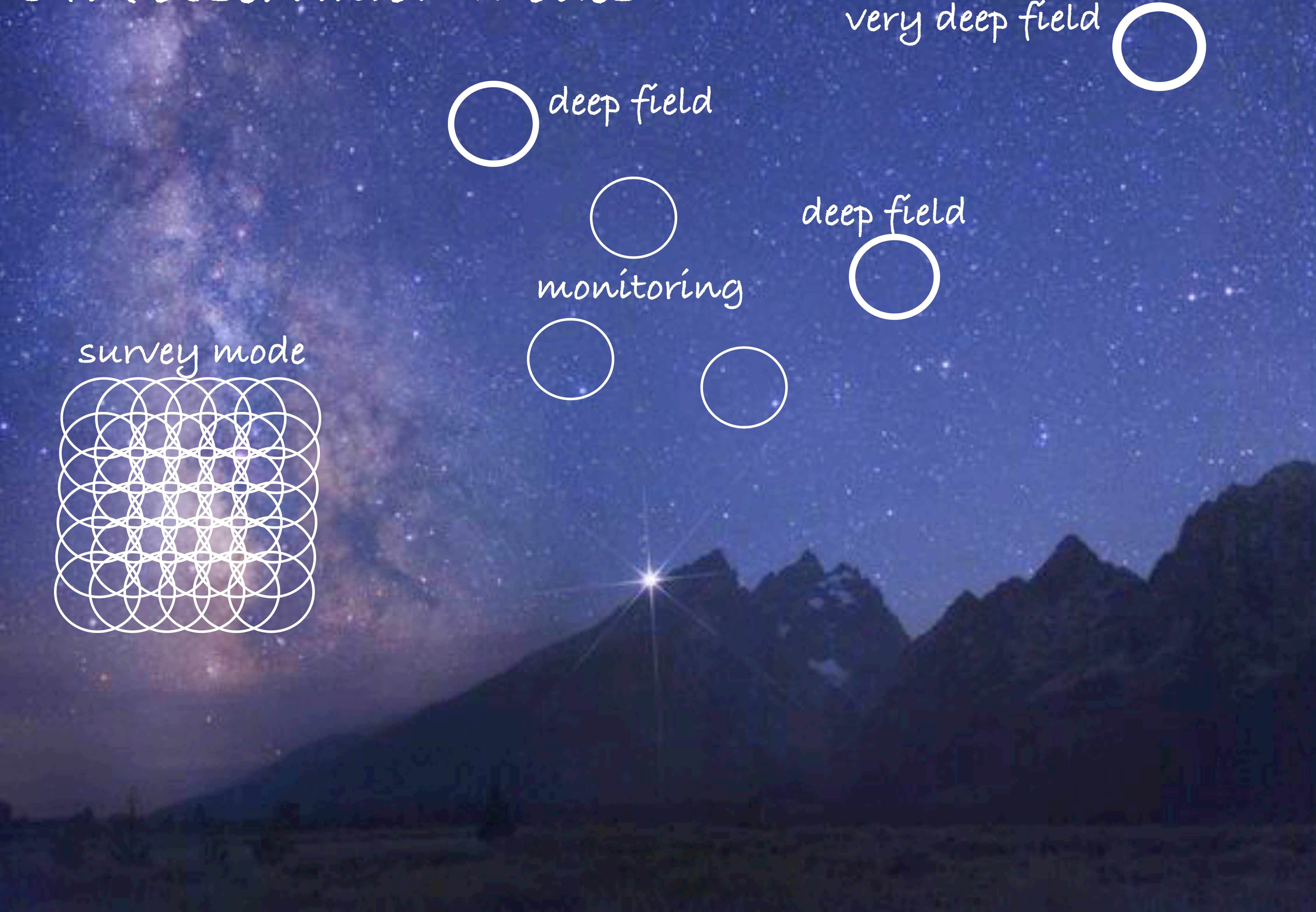
Medium Energies:
mCrab sensitivity
0.1–10 TeV
~12m telescopes
(+9m SC option)

(South Only)

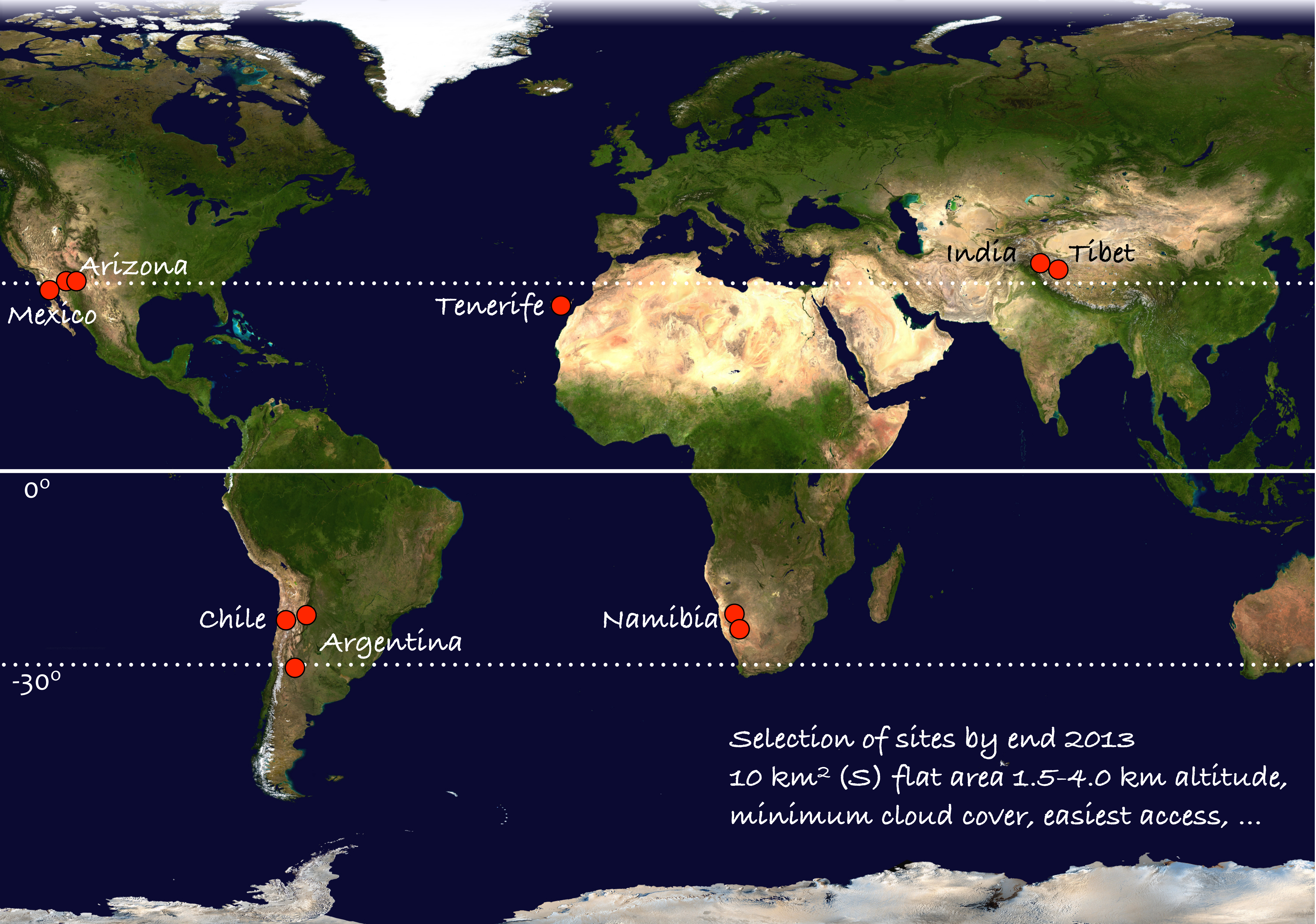
High-energy section
10 km² area for up to
energies ≈300 TeV
~4-7 m telescopes



CTA observation modes

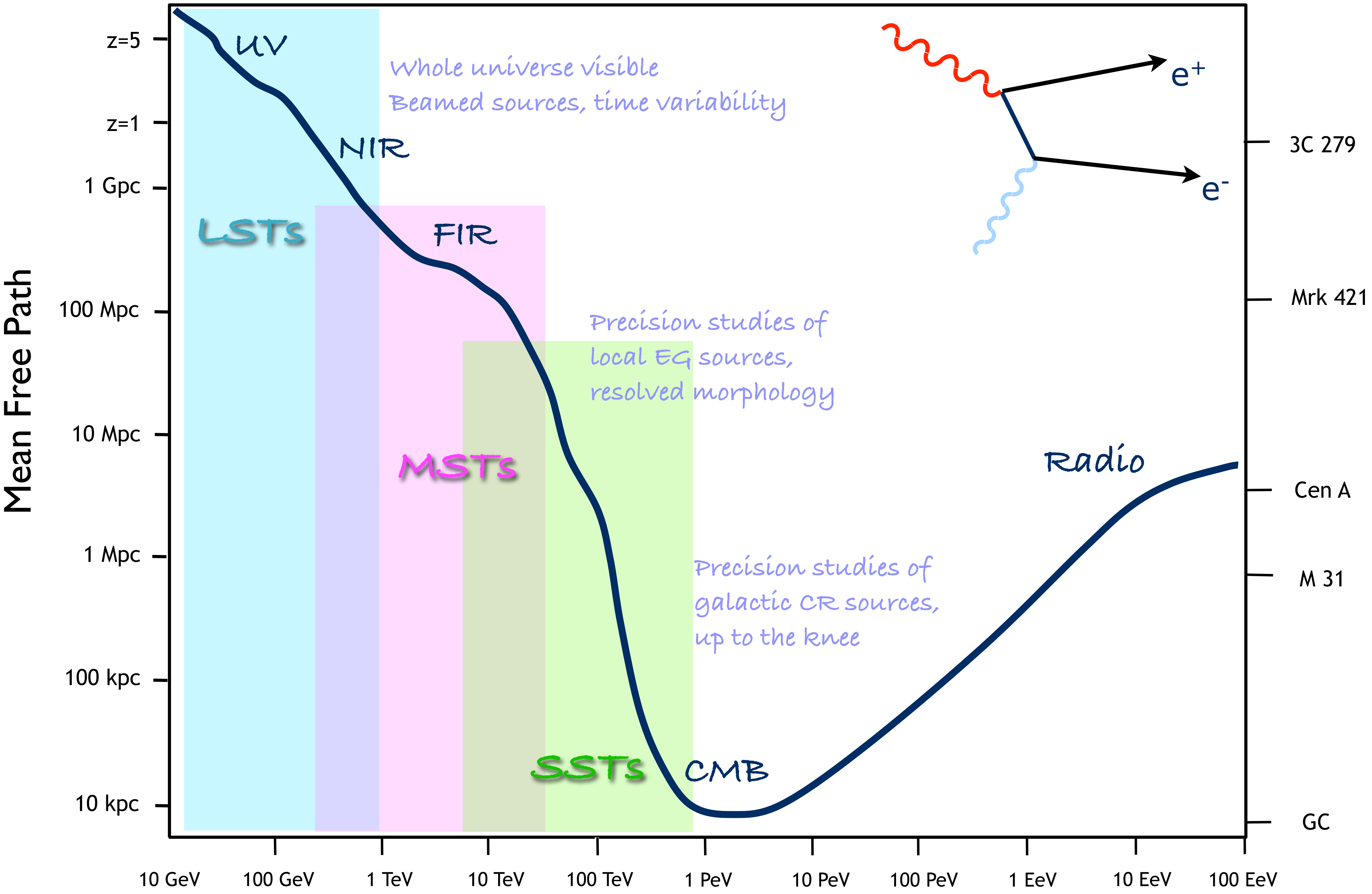


One observatory with two sites - operated by one consortium

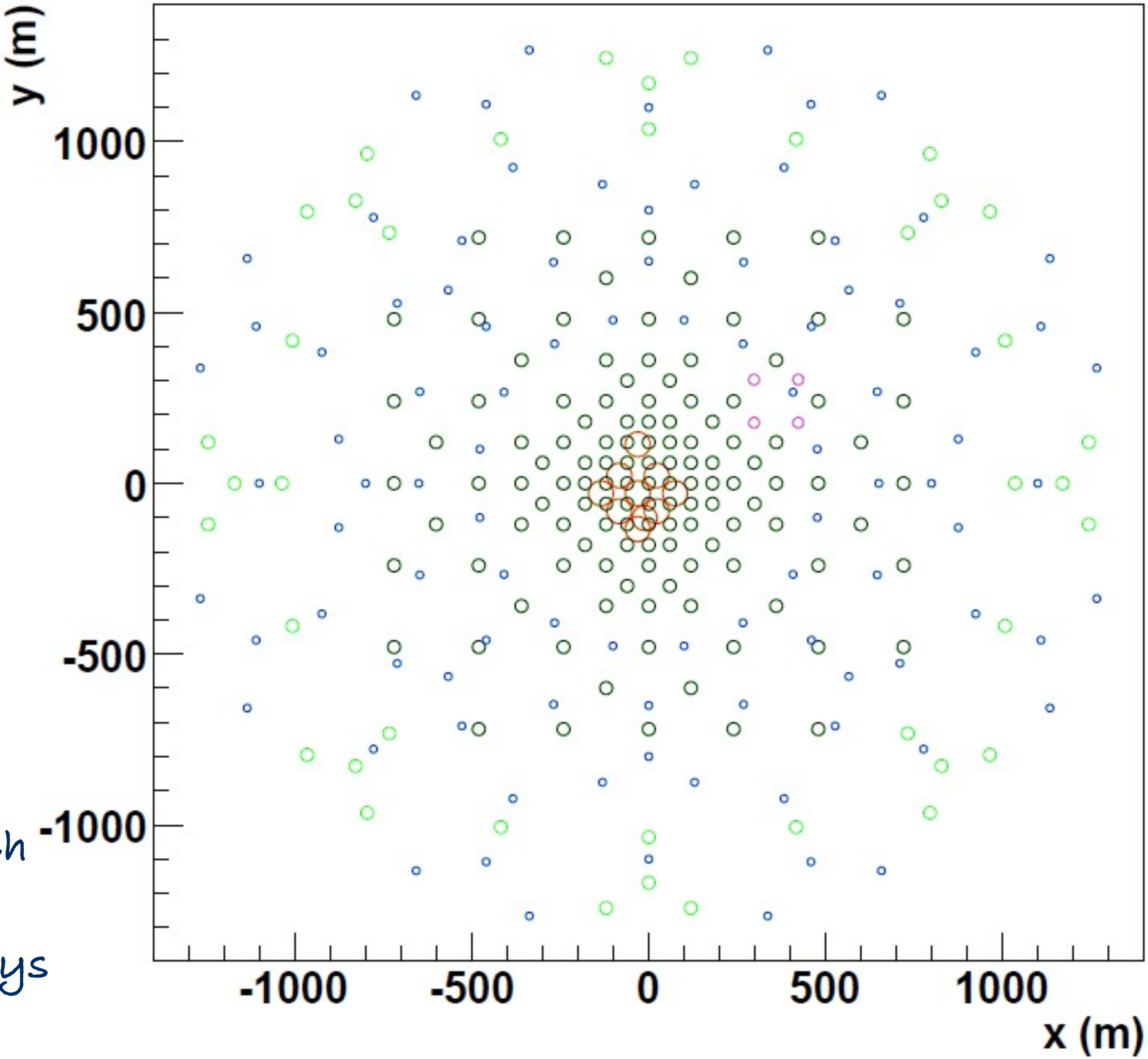


Selection of sites by end 2013
10 km² (S) flat area 1.5-4.0 km altitude,
minimum cloud cover, easiest access, ...

The Gamma-Ray Horizon $\gamma_{VHE} + \gamma_{..} \rightarrow e^+e^-$



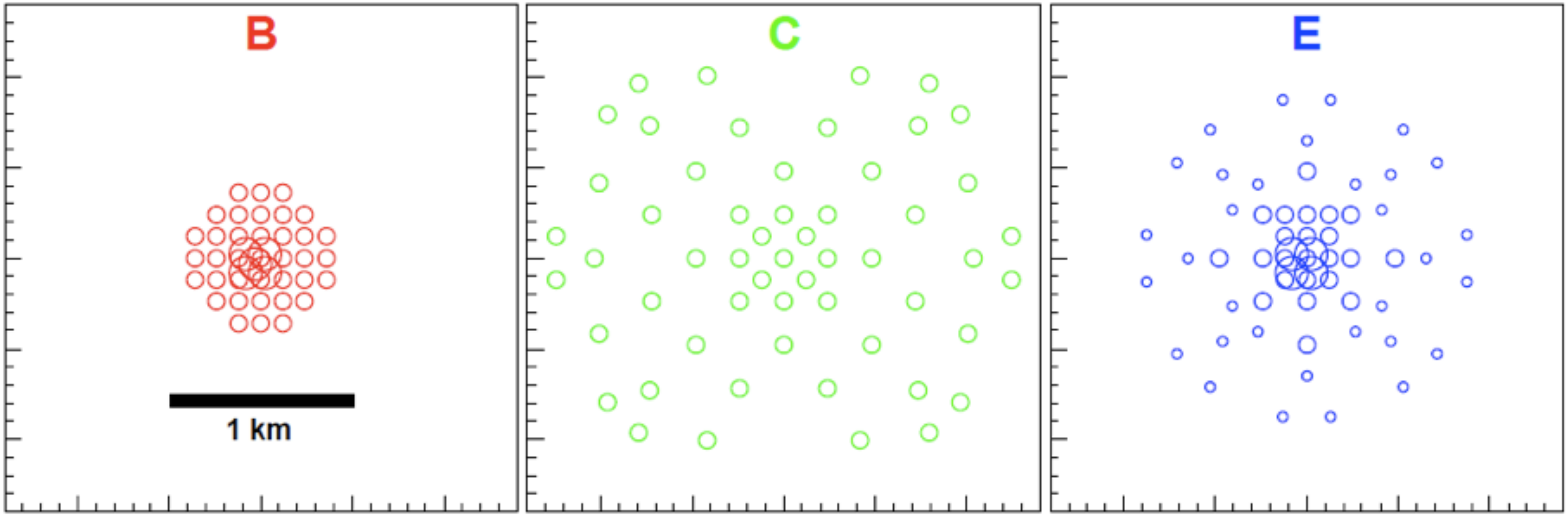
Performance Calculations



273 telescopes, subsets of which are actual candidate arrays

Examples of subarrays

(of same cost)



dense array of
12 & 24 m tels.

+ low E
– high E

low density array of
12 m telescopes

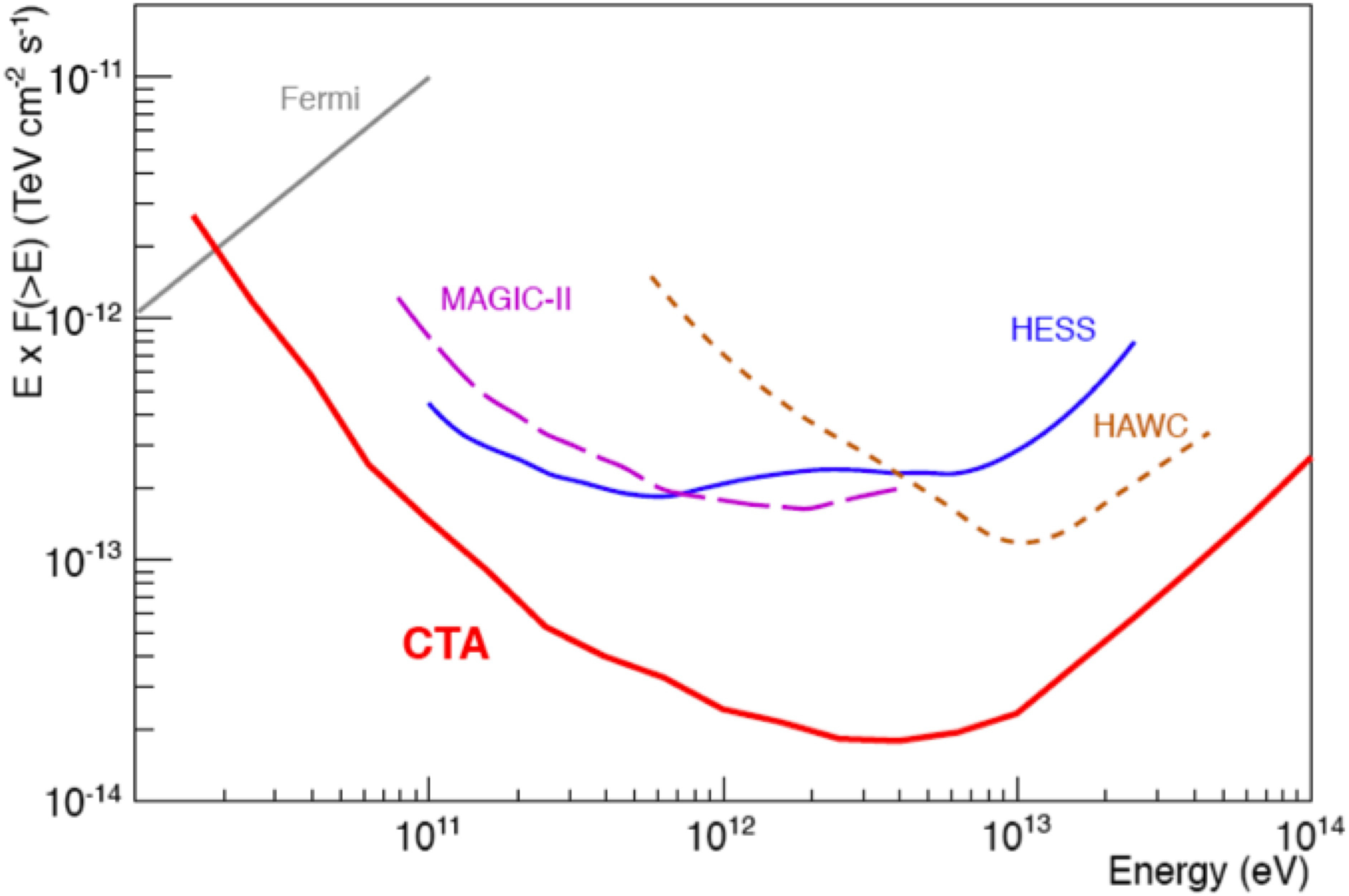
+ high/medium E
– low E

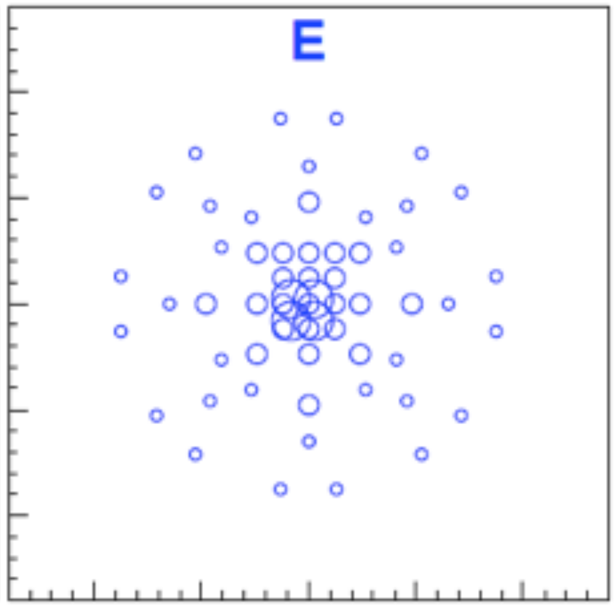
array of 7, 12 and
24 m telescopes

+ good sensitivity
across full energy
range

main trade-off: quantity vs quality of events

Point Source Sensitivity

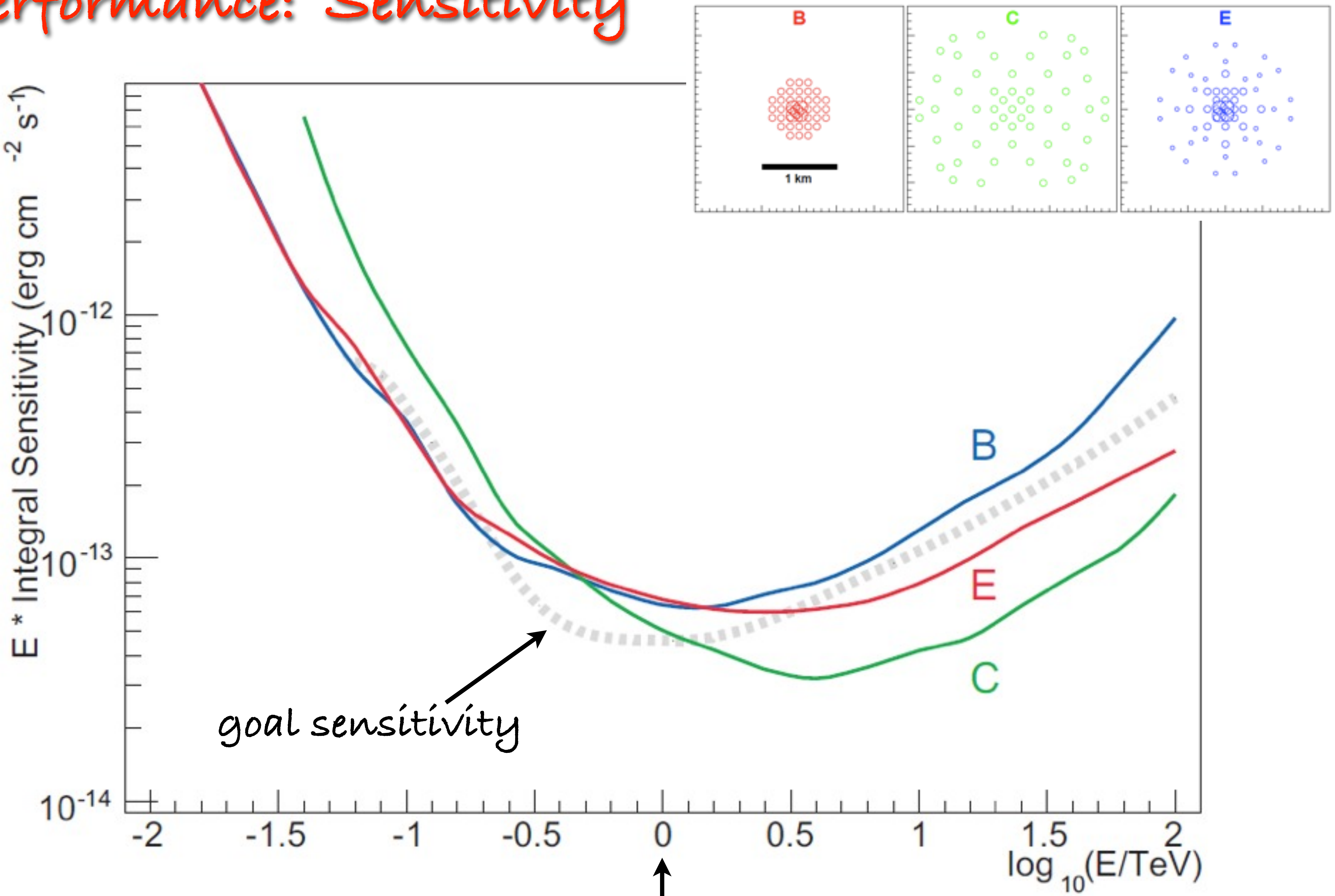




array "E" :
59 telescope config.
(analysis & layout
not optimised yet)

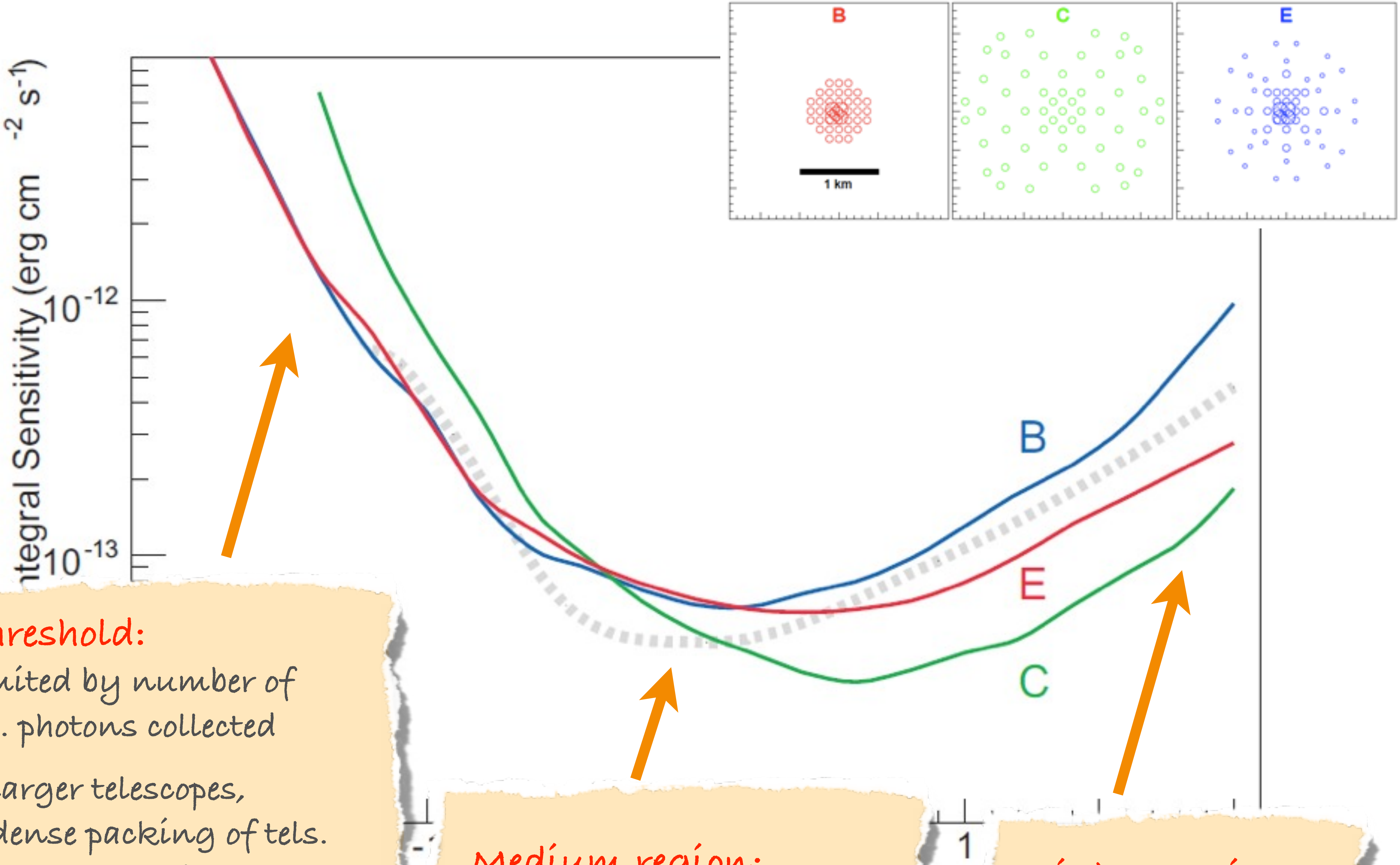
€80M nominal cost

Performance: Sensitivity



goal sensitivity

1 TeV



Threshold:
limited by number of Ch. photons collected

- larger telescopes,
- dense packing of tels.
- better photo detectors

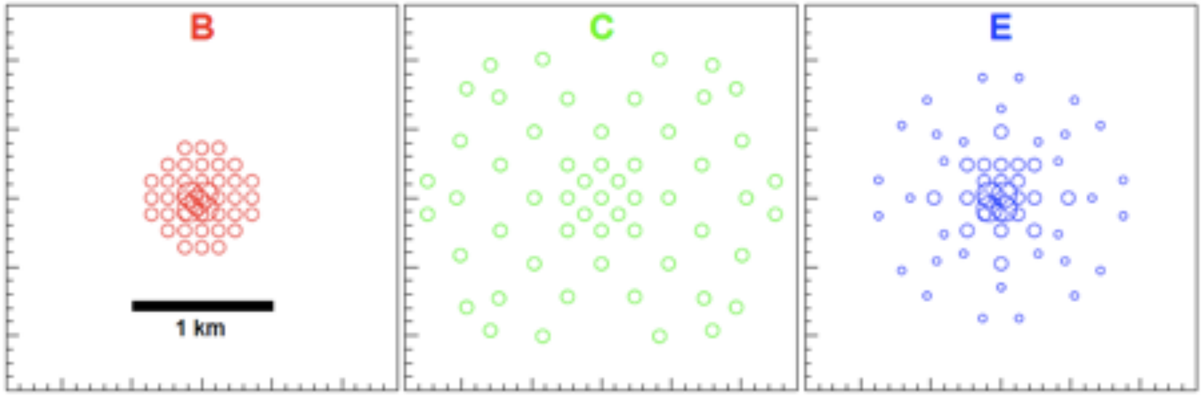
Medium region:
limited by signal / BG

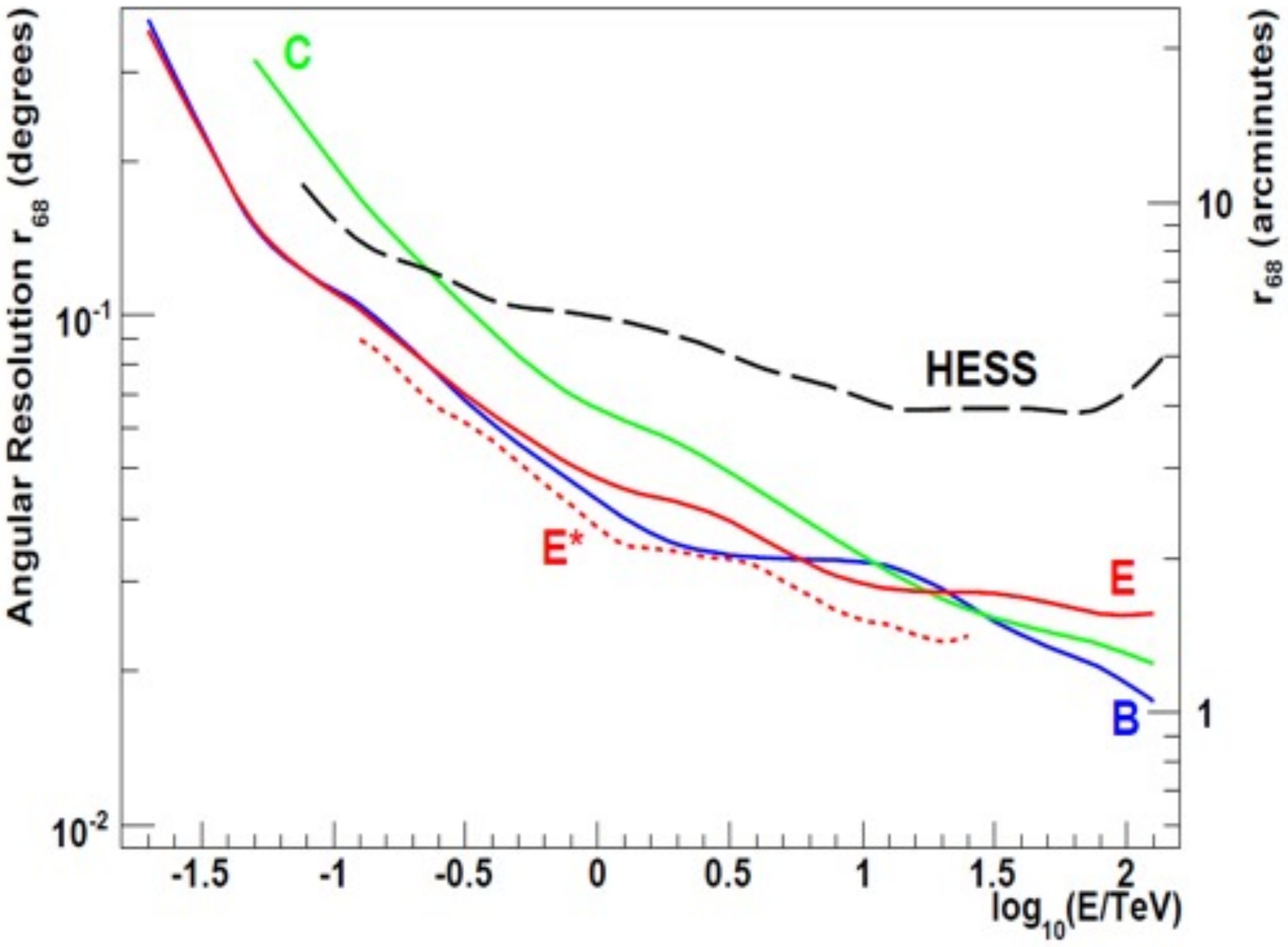
- better BG rejection,
- improved ang. resolution,
- better photon statistics

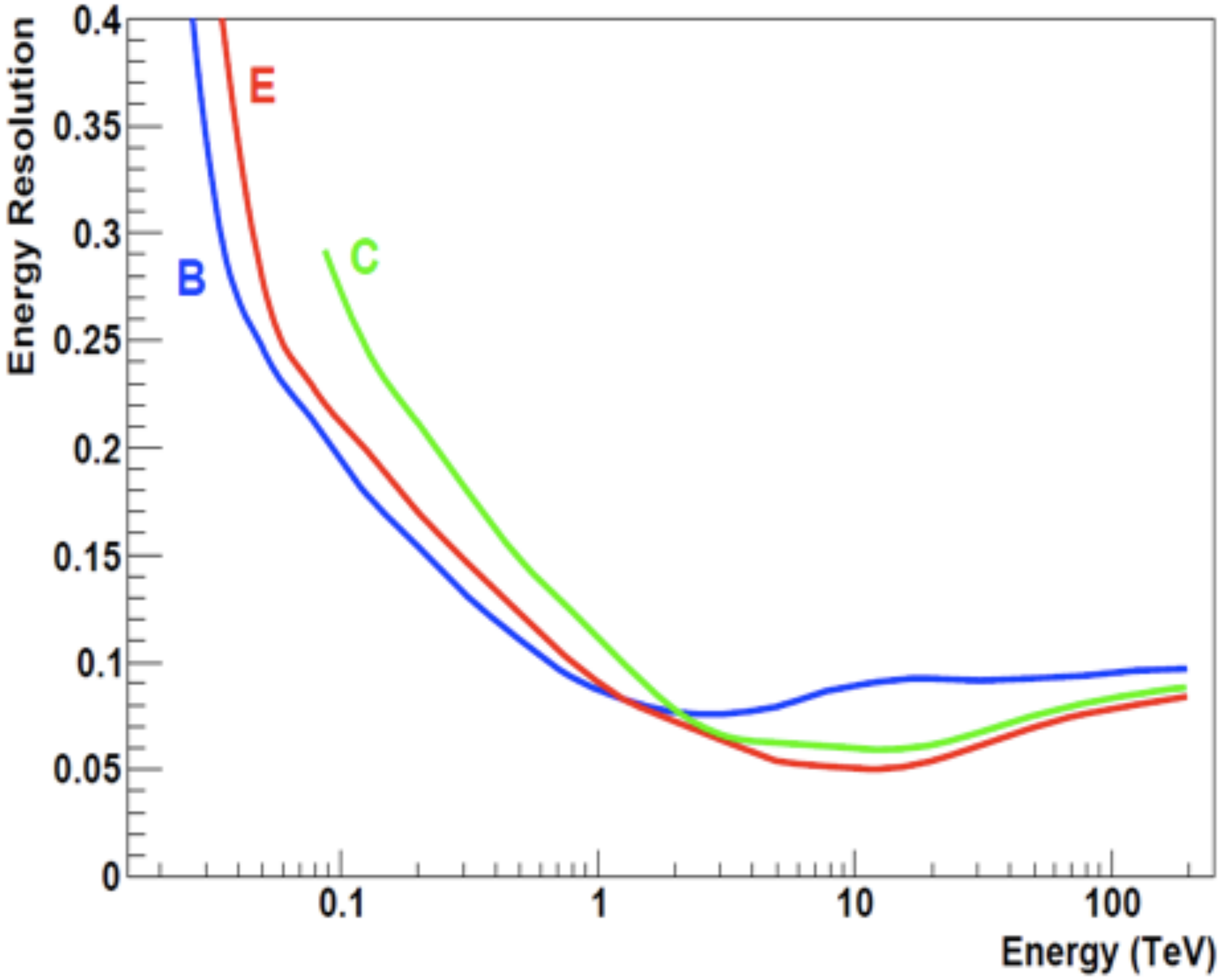
High energies:
limited by statistics

- large array

Performance: angular and energy resolution







1-2′ for E > 1 TeV

(fundamental limit: ~ 10″)

<10% for E > 1 TeV

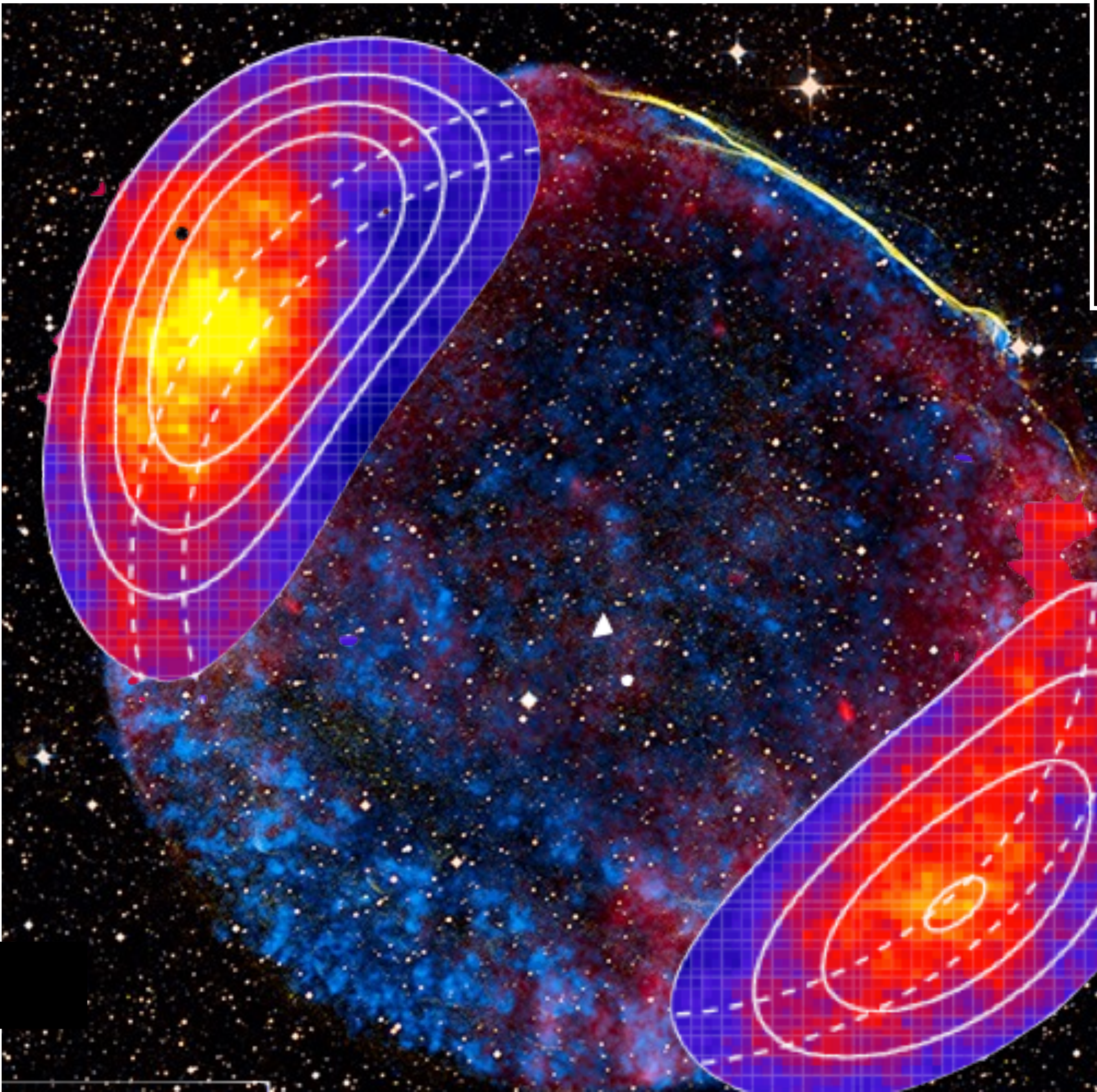
Angular Resolution

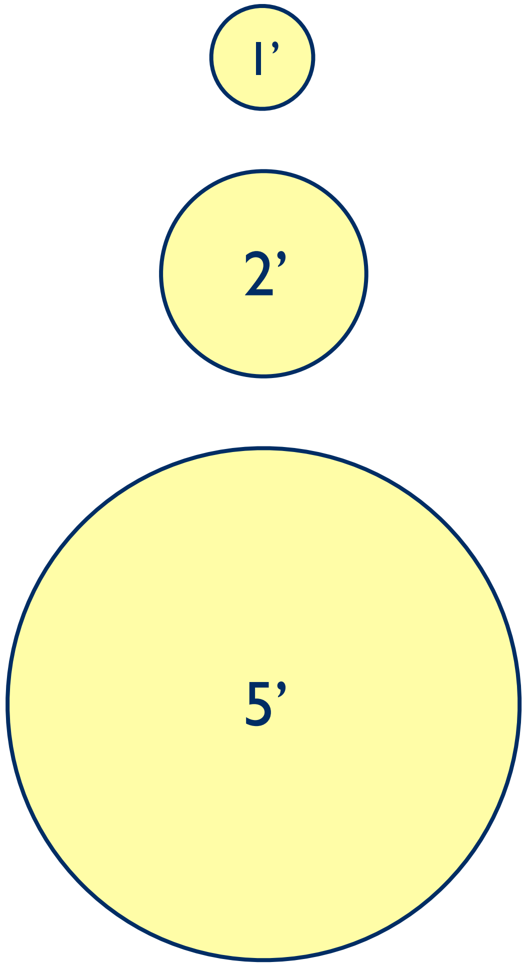
Hydra A

M 82

Cen A

SN 1006





Performance:

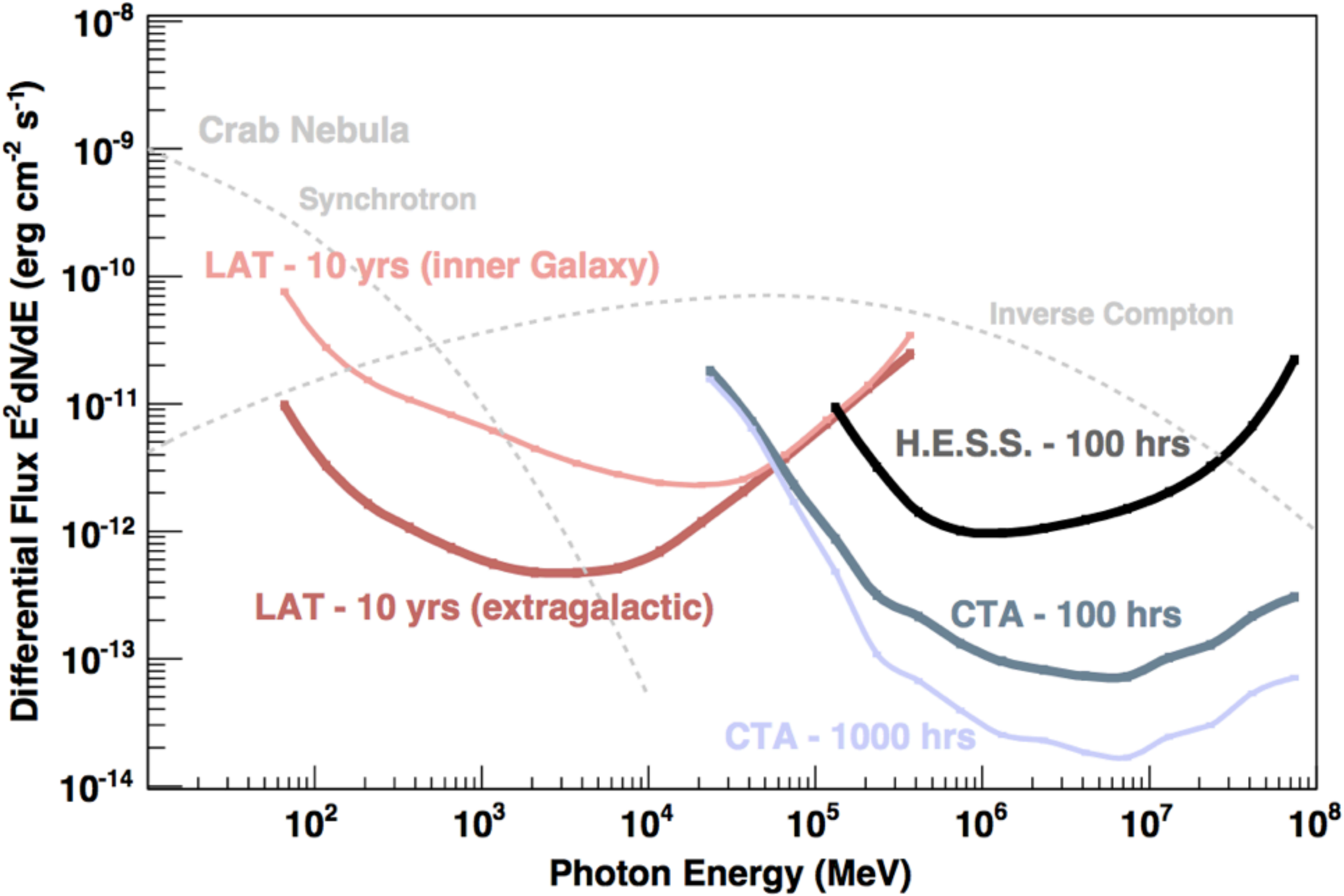
Energy TeV	Area km^2	Ang.Res arc min	E.Res %	FOV °
0.03	0.003	12	30	4-5
0.3	0.1	4	13	6-8
3	1	2	8	7-9
30	3	1.5	7	8-10

Improvement (relative to HESS) :

Diffuse continuum: ≈ x 5
Angular resolution for point sources: ≈ x 2
FoV for surveys: ≈ x 2
Energy resolution for lines: ≈ x 1.5

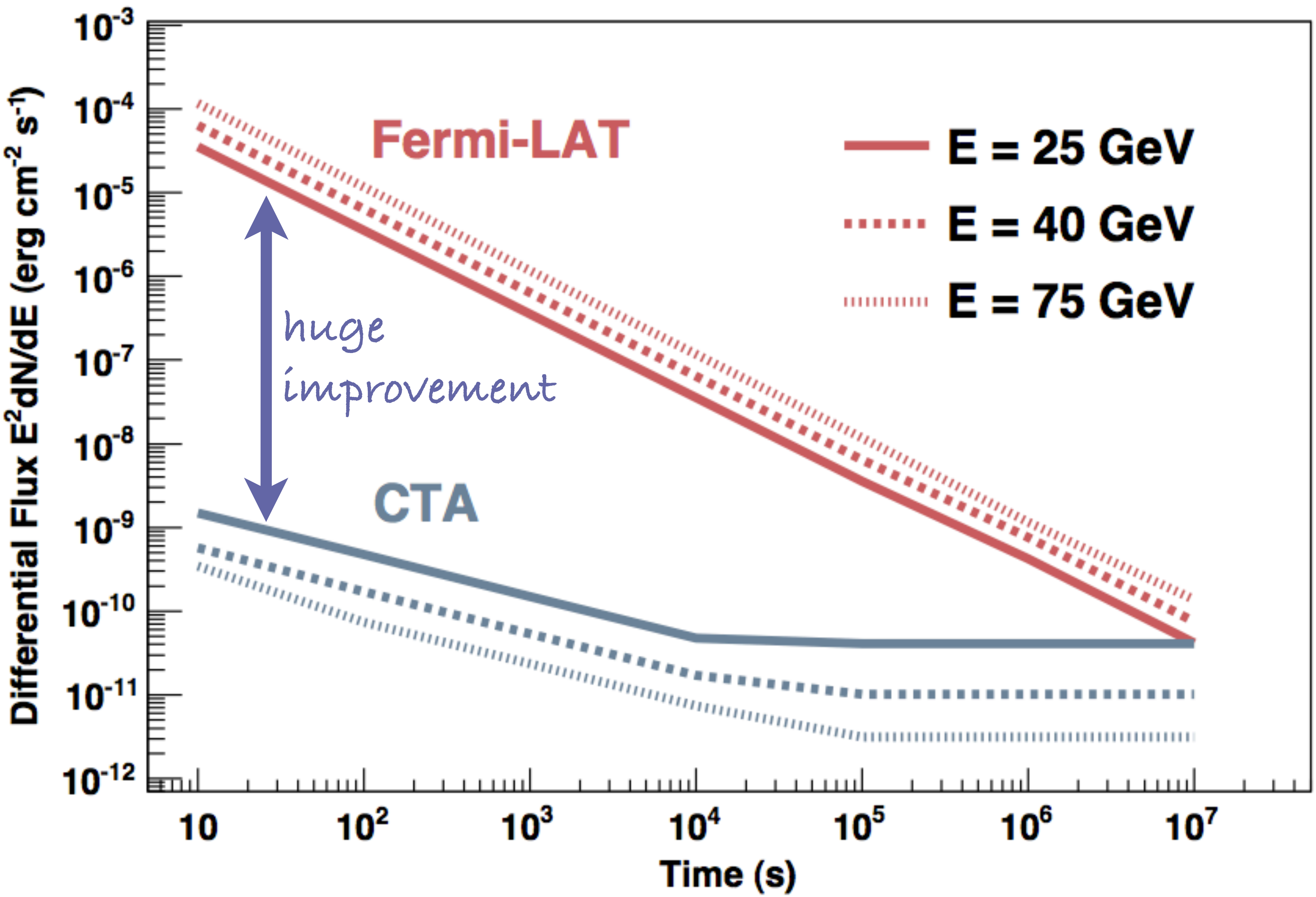
all-sky survey for point-like emission line sources: ≈ x 30
pointed observation of a 0.5° continuum source: ≈ x 5

CTA versus Fermi – steady sources



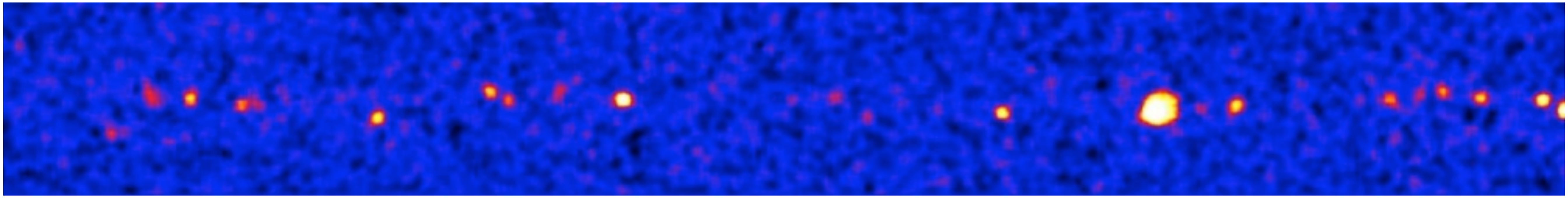
Variability and Short-Timescale Phenomena

(flares, GRBs, ...)

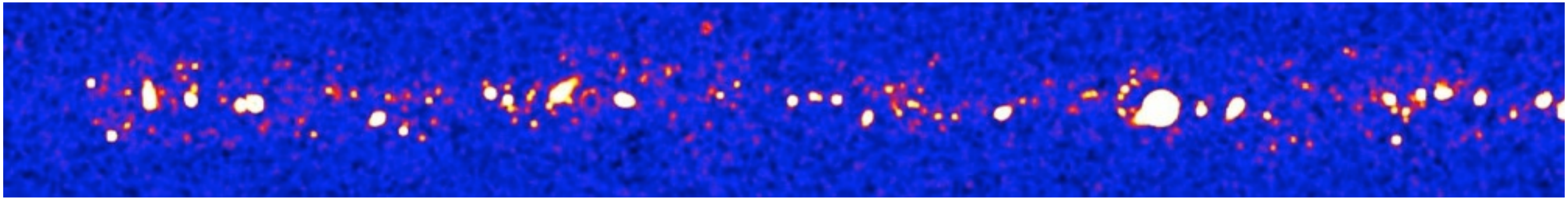


Funk, Hinton 2012

CTA expectation:



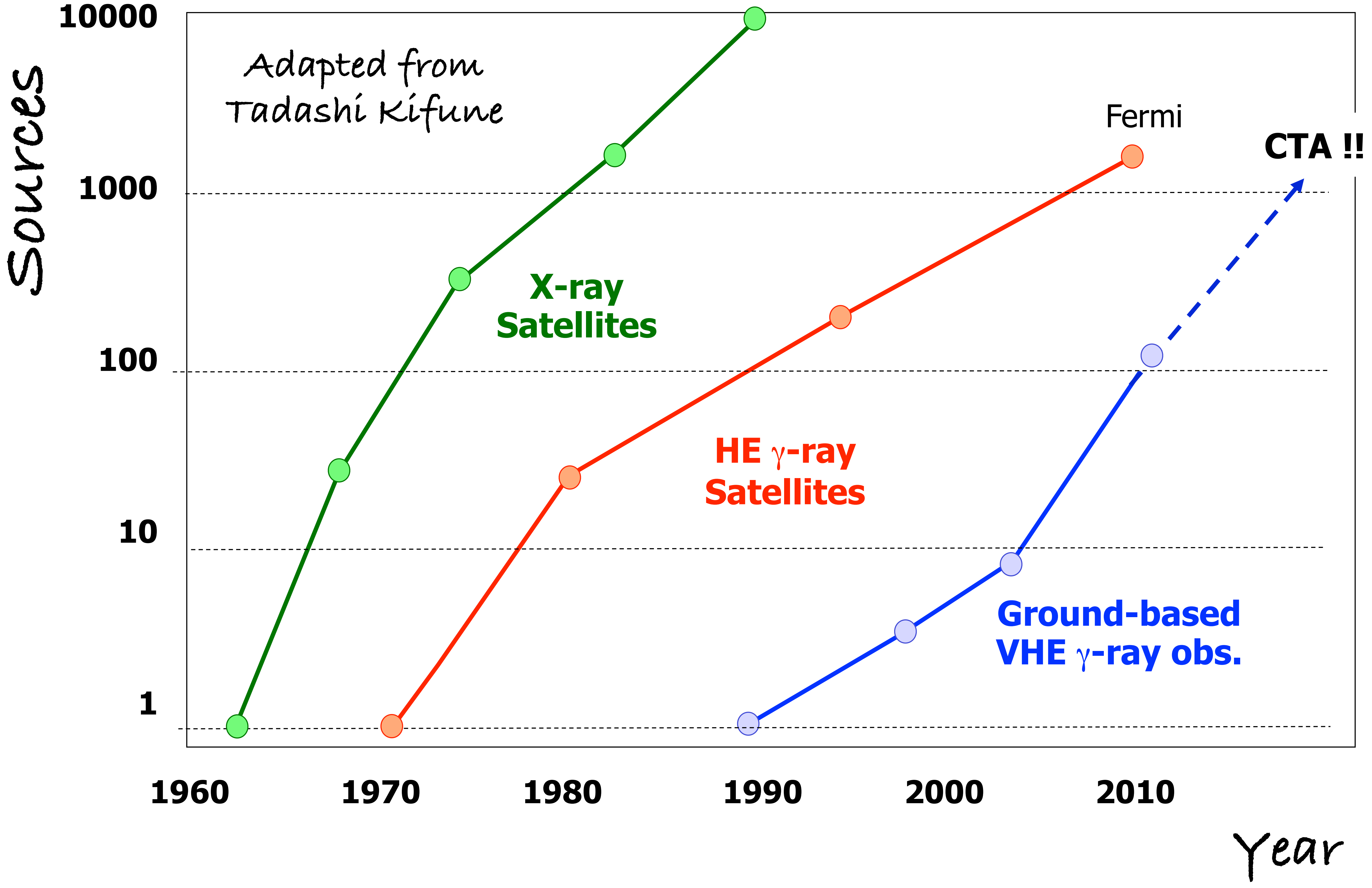
HESS ~500 h



CTA expectation: >1000 sources

Gamma-Ray Astronomy becomes "Mainstream"

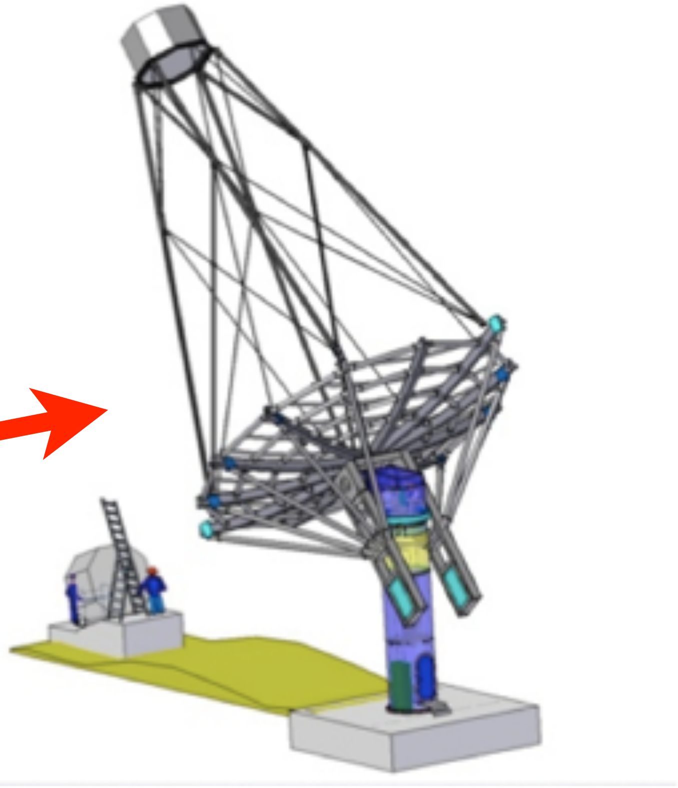
(with lots of sources and results...)

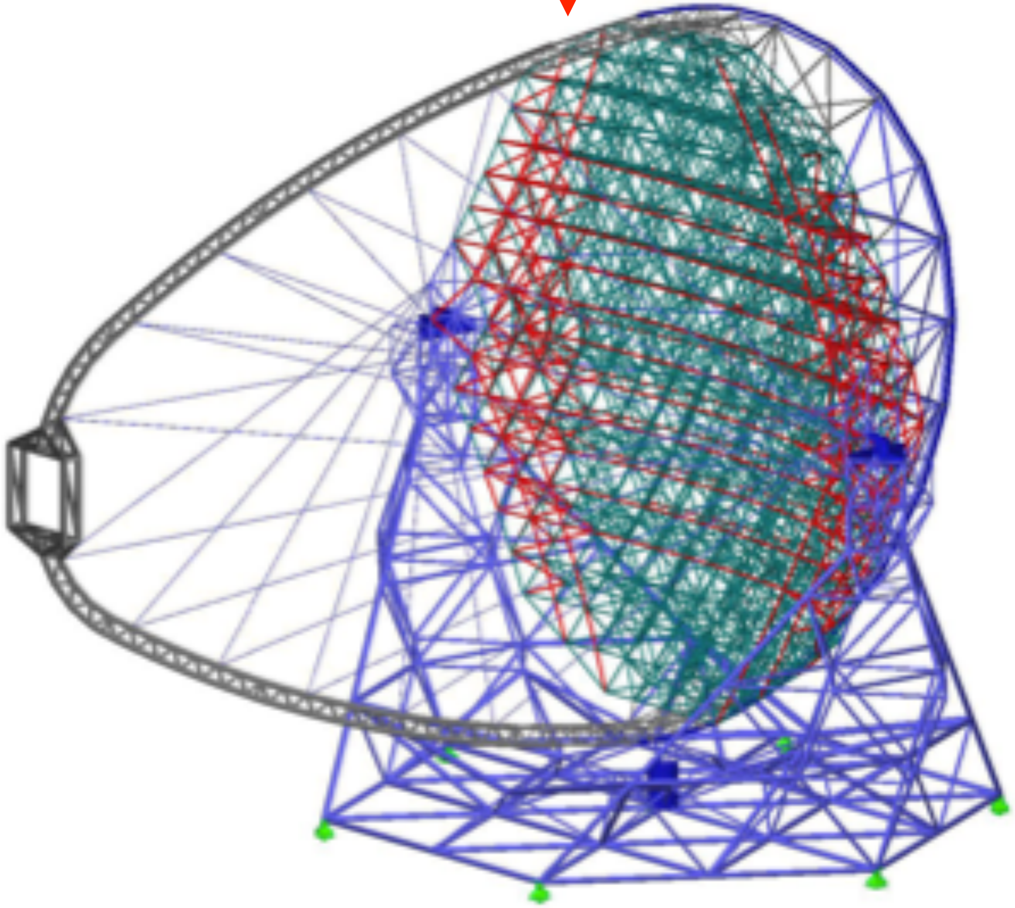


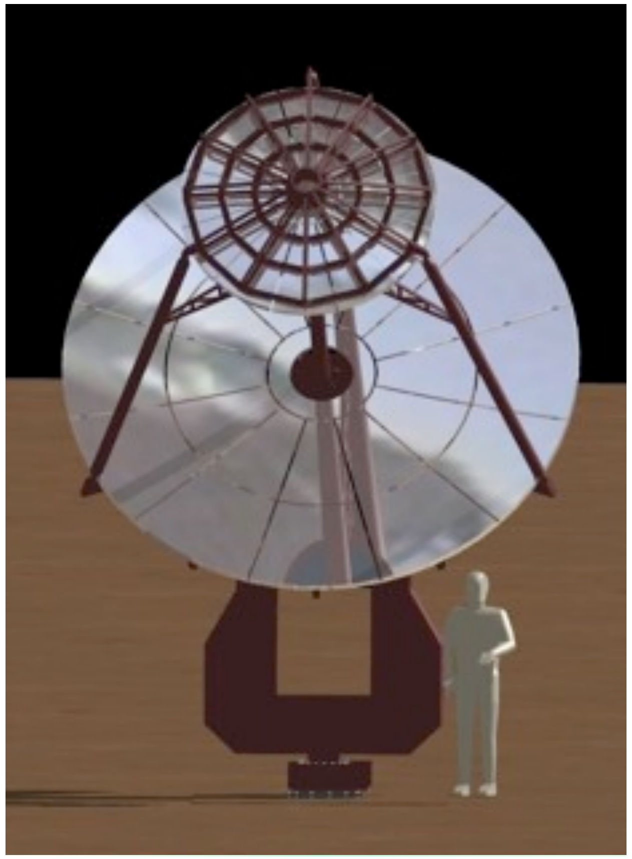
some existing telescopes of different sizes

Options for LST, MST

& SST

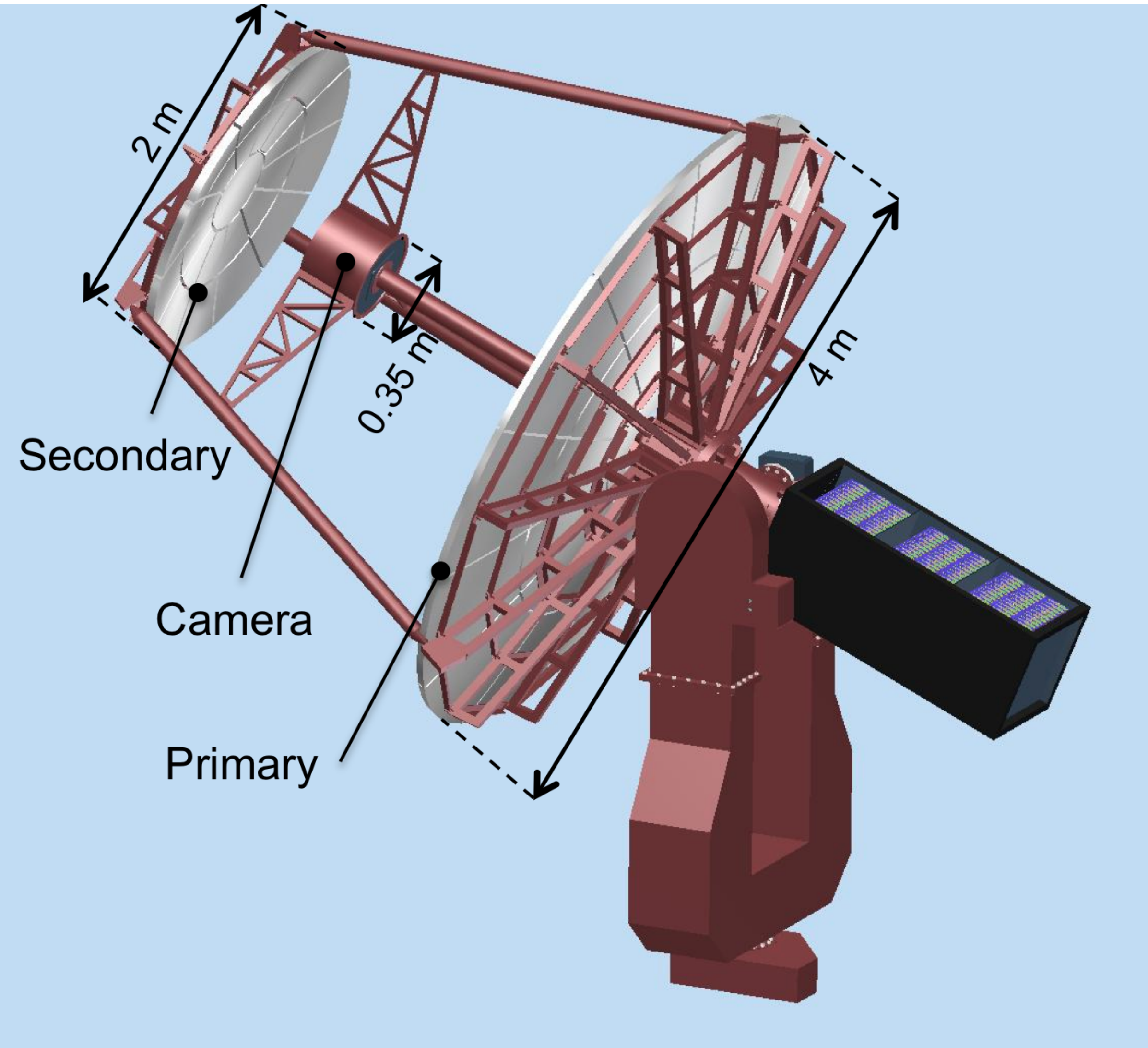


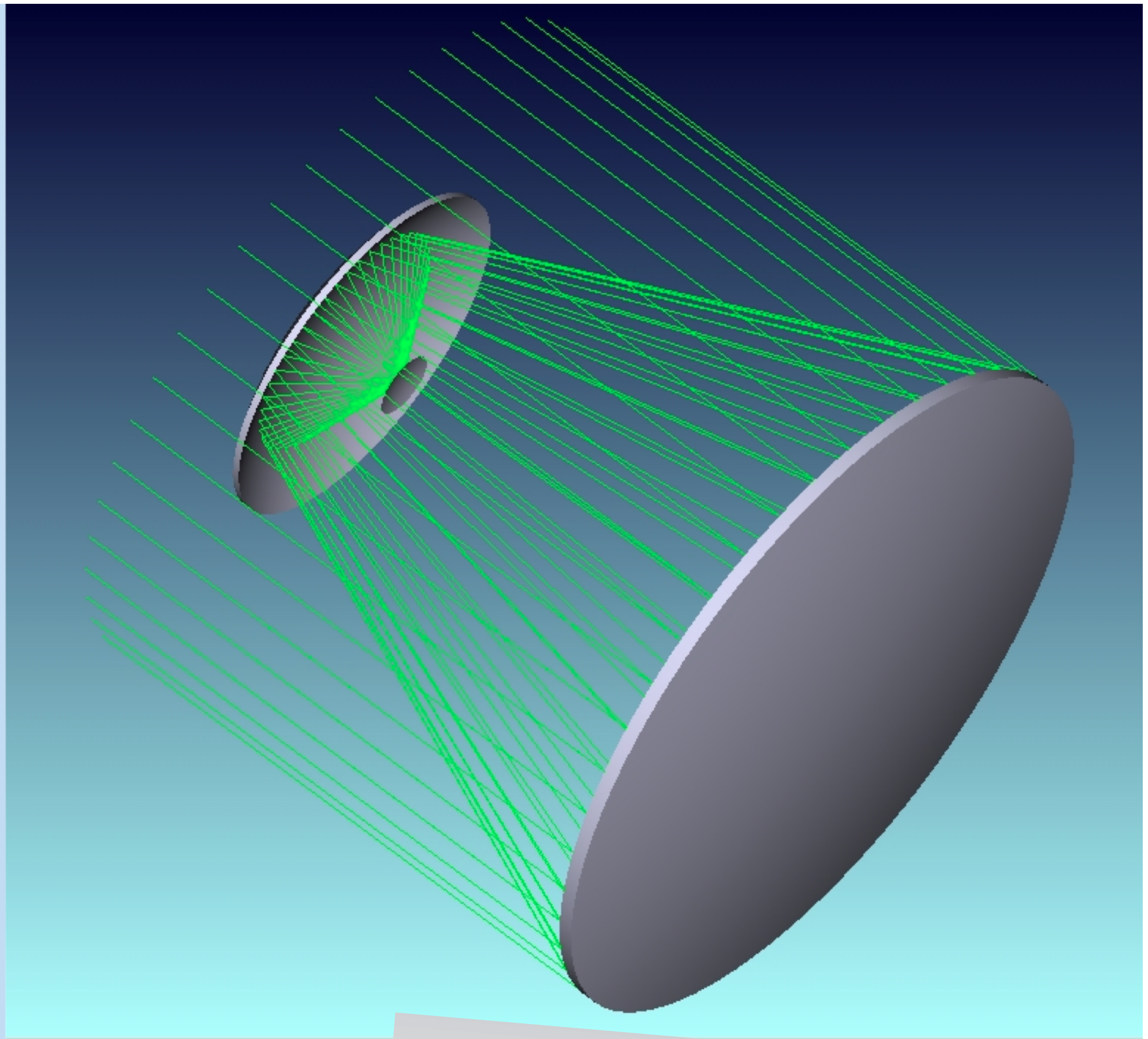




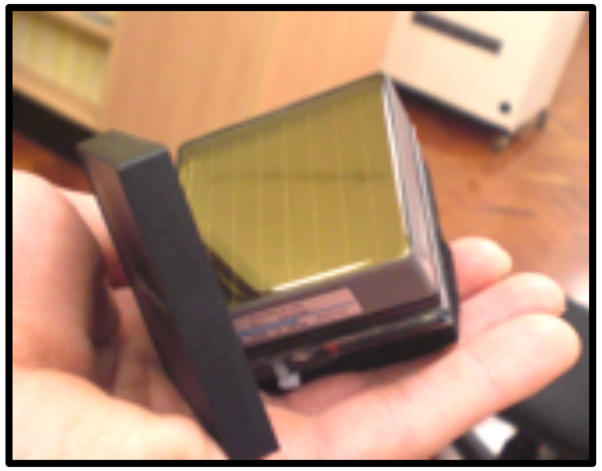
SST dual mirror design:

10° FOV, small plate scale, much cheaper camera

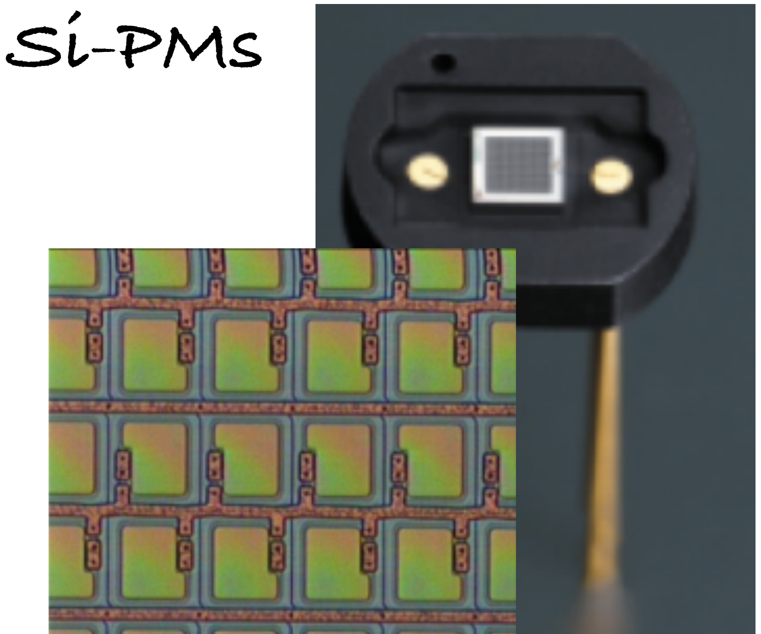




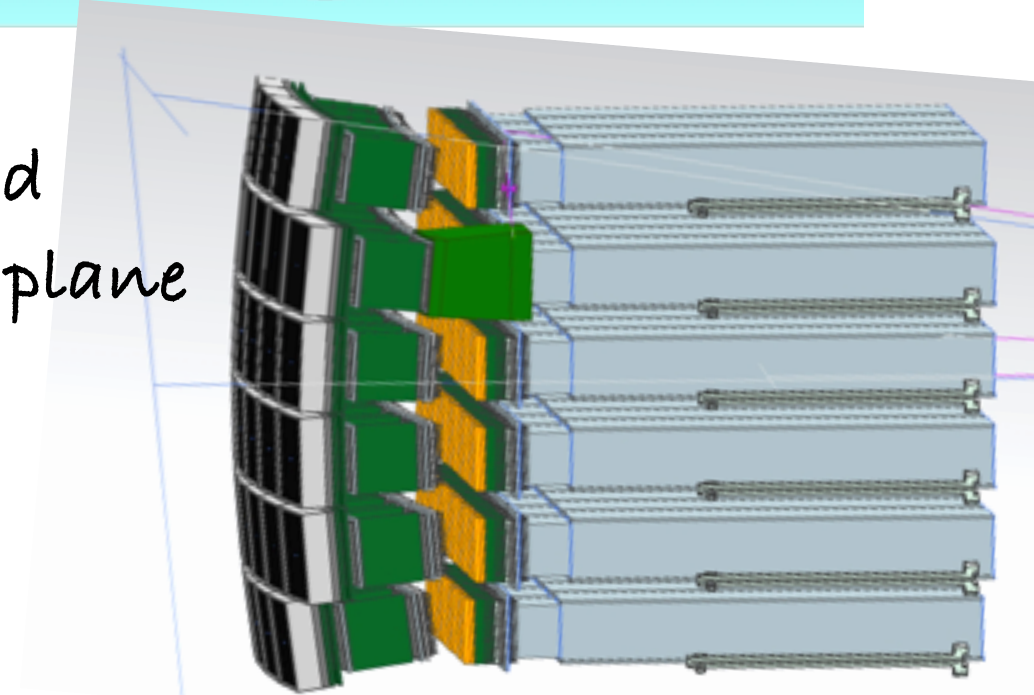
MA-PMs



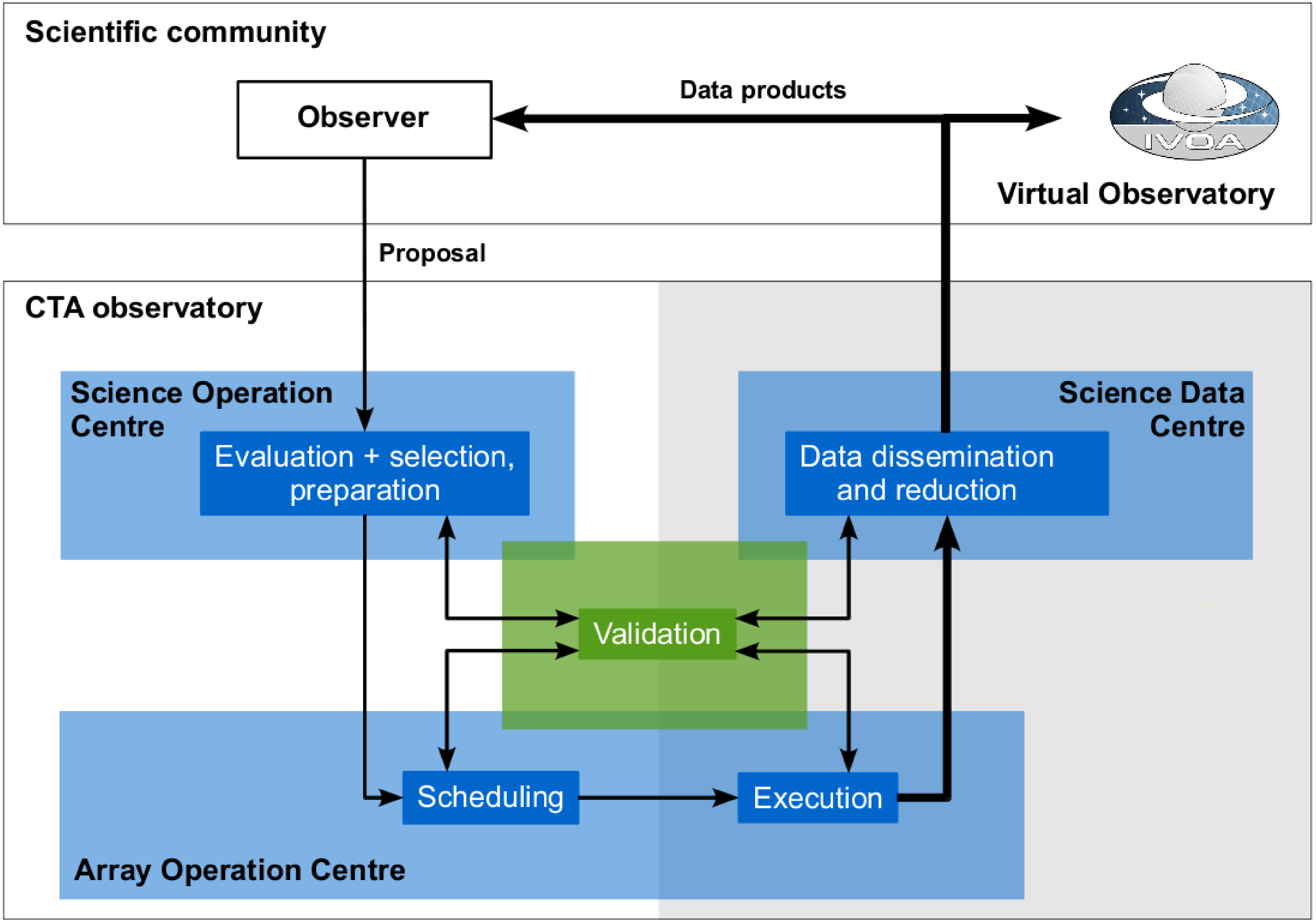
Si-PMs



curved
focal plane



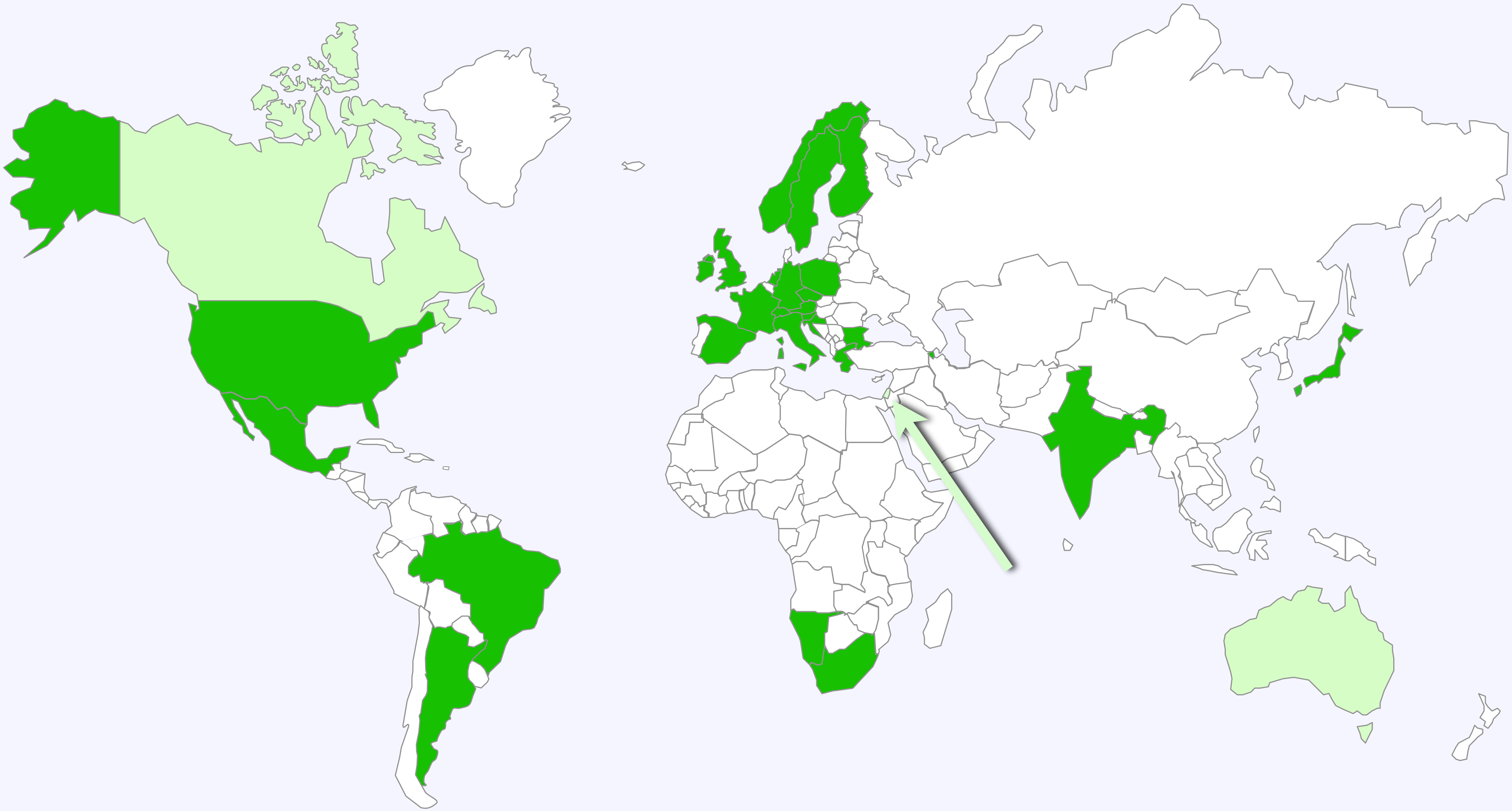
CTA as an open observatory



CTA Members: 27 Countries

>1000 scientists and engineers from
>170 institutions

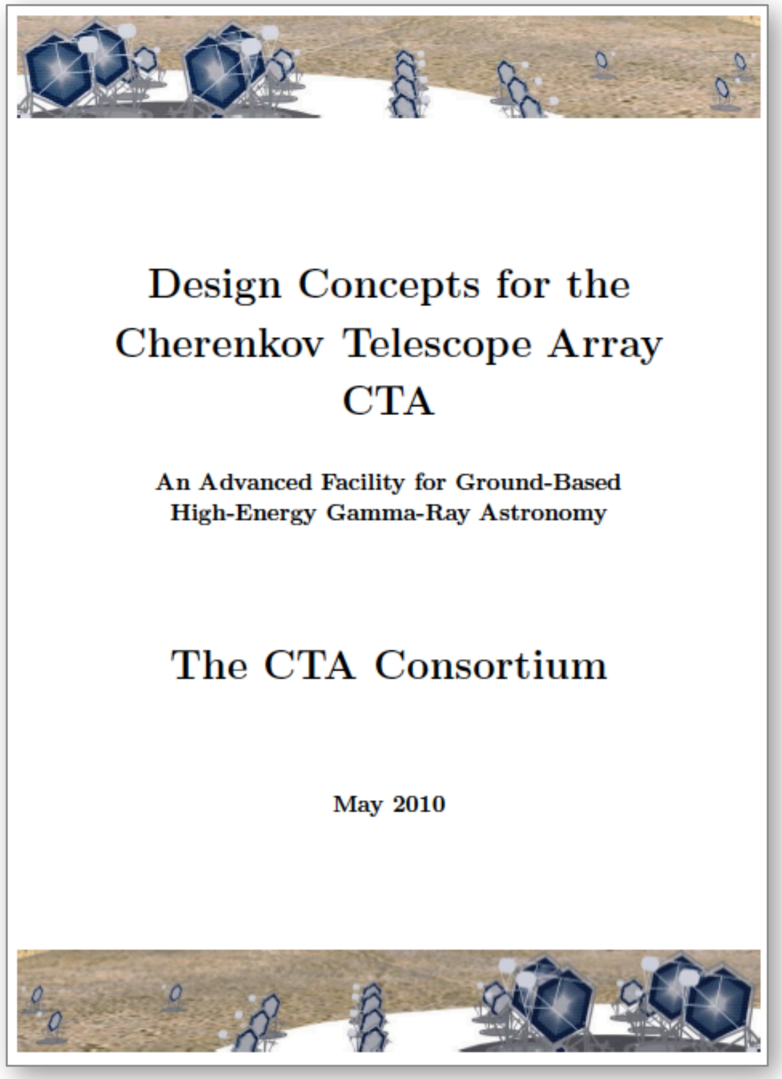
🟩 Members (27 countries)
▢ interested to join



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

More Details:

general info: www.cta-observatory.org



Design Concepts for the
Cherenkov Telescope Array
CTA

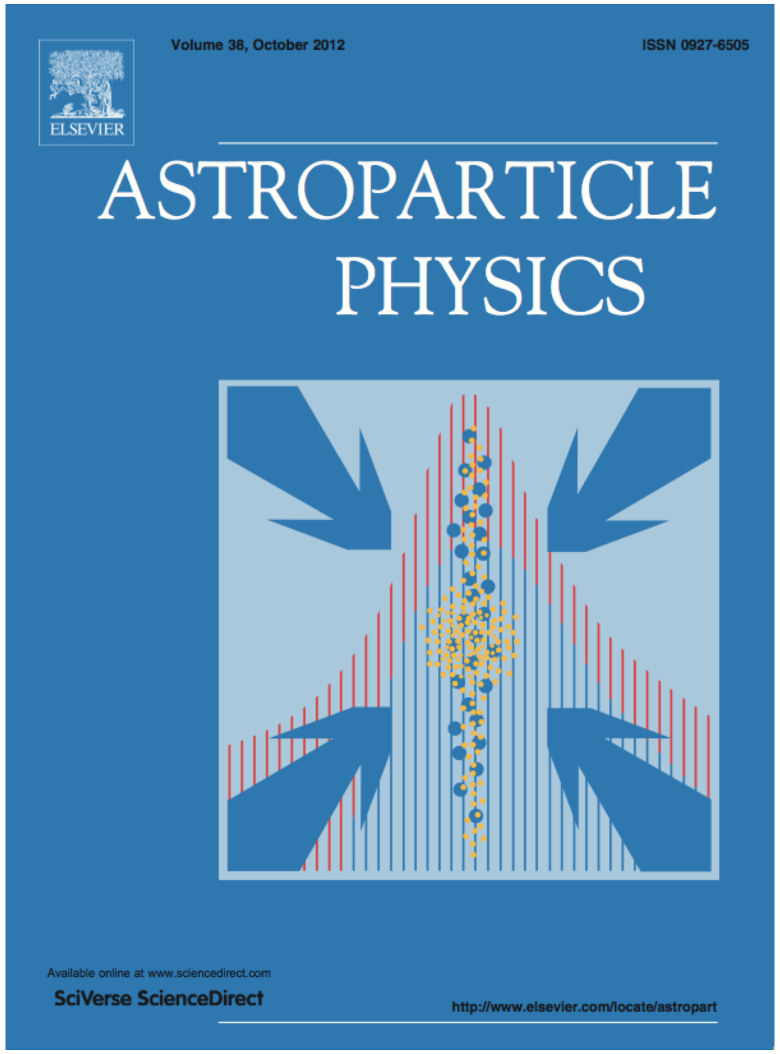
An Advanced Facility for Ground-Based
High-Energy Gamma-Ray Astronomy

The CTA Consortium

May 2010

“Design Concepts for the
Cherenkov Telescope Array”

120 pages
arXiv:1008.3703
Exp. Astronomy 32 (2011) 193-316



Volume 38, October 2012 ISSN 0927-6505

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ASTROPARTICLE
PHYSICS

Available online at www.sciencedirect.com
SciVerse ScienceDirect
http://www.elsevier.com/locate/astropart

“Seeing the High-Energy Universe
with the Cherenkov Telescope Array”

368 pages
in press, December 2012

… an artist's impression

Photons in Astroparticle Physics ...

- play many roles as
  probes, projectiles and targets
- range from 10^{-6} - $\approx 10^{20}$ eV
- pose many exciting questions for research in the near future
- Cherenkov Telescopes are the best means of
  studying γ-rays at energies 50 GeV ... 300 TeV
- the GeV ... >300 TeV range will see
  the largest progress in the next decade

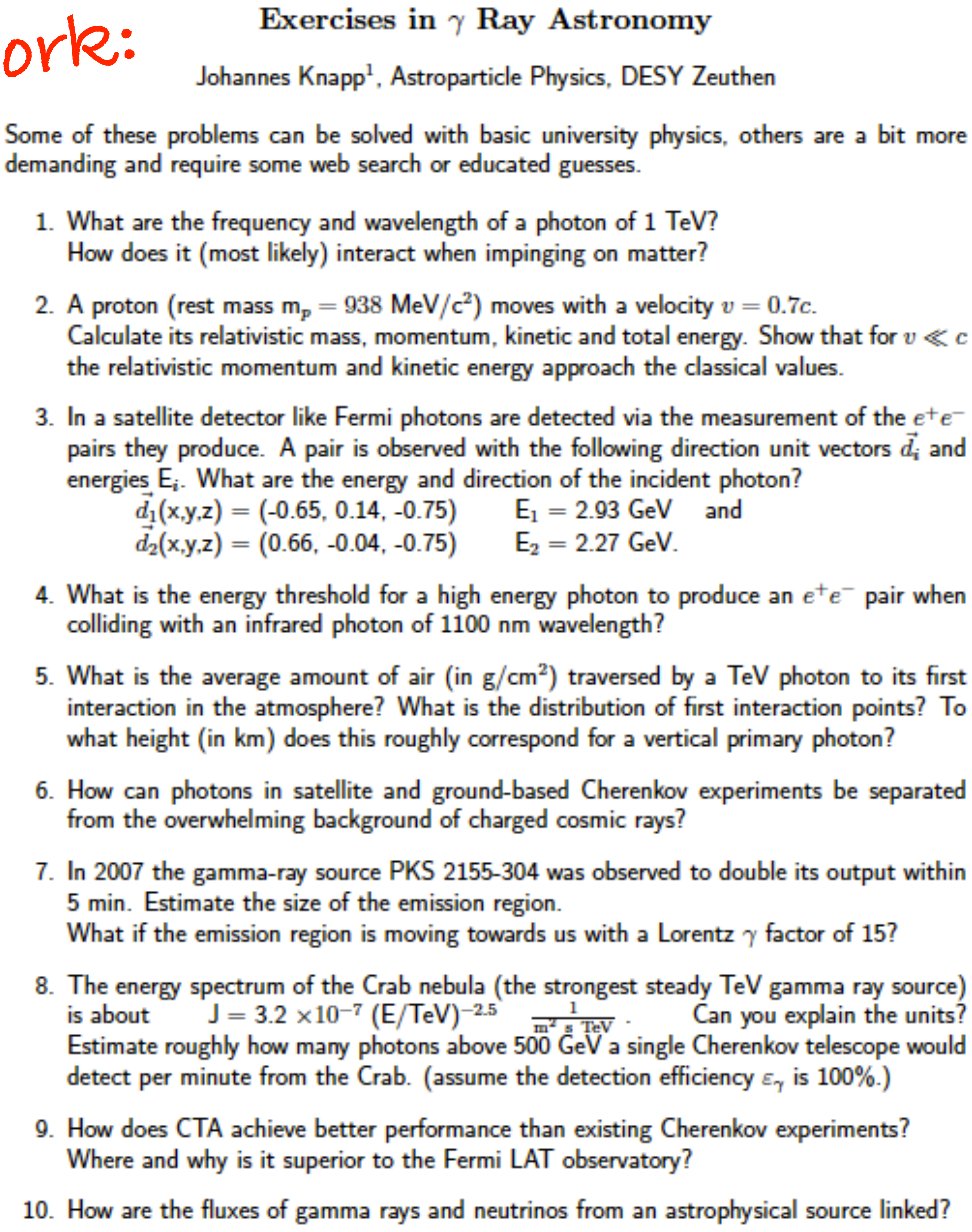
← with Fermi and CTA

CTA: … a new project in Astroparticle Physics

- has a huge science potential (for a moderate price)
- offers an attractive mix of discovery potential and a wealth of "guaranteed" good physics,
- is almost production ready,
- no major technical problems (main problems are political/sociological/organisational)
- strong international support (scientists & funding agencies)
- will be funded / built very soon …

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

Homework:



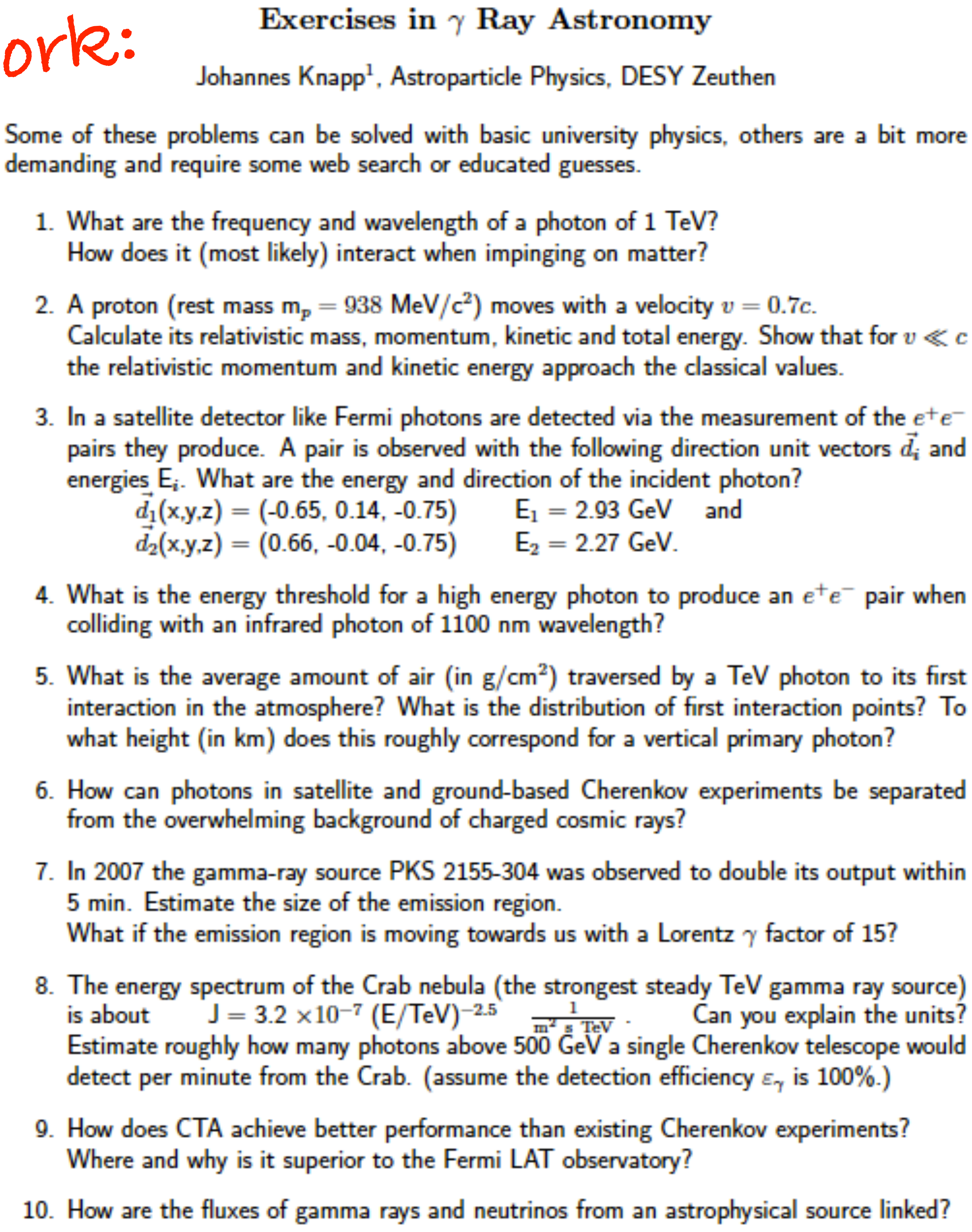
Exercises in γ Ray Astronomy

Johannes Knapp[1], Astroparticle Physics, DESY Zeuthen

Some of these problems can be solved with basic university physics, others are a bit more demanding and require some web search or educated guesses.

1. What are the frequency and wavelength of a photon of 1 TeV?
   How does it (most likely) interact when impinging on matter?
2. A proton (rest mass $m_p = 938$ MeV/c^2) moves with a velocity $v = 0.7c$.
   Calculate its relativistic mass, momentum, kinetic and total energy. Show that for $v \ll c$ the relativistic momentum and kinetic energy approach the classical values.
3. In a satellite detector like Fermi photons are detected via the measurement of the e^+e^- pairs they produce. A pair is observed with the following direction unit vectors $\vec{d_i}$ and energies E_i. What are the energy and direction of the incident photon?
   $\vec{d}_1$(x,y,z) = (-0.65, 0.14, -0.75) $E_1 = 2.93$ GeV and
   $\vec{d}_2$(x,y,z) = (0.66, -0.04, -0.75) $E_2 = 2.27$ GeV.
4. What is the energy threshold for a high energy photon to produce an e^+e^- pair when colliding with an infrared photon of 1100 nm wavelength?
5. What is the average amount of air (in g/cm^2) traversed by a TeV photon to its first interaction in the atmosphere? What is the distribution of first interaction points? To what height (in km) does this roughly correspond for a vertical primary photon?
6. How can photons in satellite and ground-based Cherenkov experiments be separated from the overwhelming background of charged cosmic rays?
7. In 2007 the gamma-ray source PKS 2155-304 was observed to double its output within 5 min. Estimate the size of the emission region.
   What if the emission region is moving towards us with a Lorentz γ factor of 15?
8. The energy spectrum of the Crab nebula (the strongest steady TeV gamma ray source) is about $J = 3.2 \times 10^{-7}\,(E/\mathrm{TeV})^{-2.5}\ \frac{1}{\mathrm{m^2\ s\ TeV}}$. Can you explain the units?
   Estimate roughly how many photons above 500 GeV a single Cherenkov telescope would detect per minute from the Crab. (assume the detection efficiency ε_γ is 100%.)
9. How does CTA achieve better performance than existing Cherenkov experiments?
   Where and why is it superior to the Fermi LAT observatory?
10. How are the fluxes of gamma rays and neutrinos from an astrophysical source linked?

Homework:



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I am sure the organisers will be happy to donate a valuable prize for the first correct and complete solution.