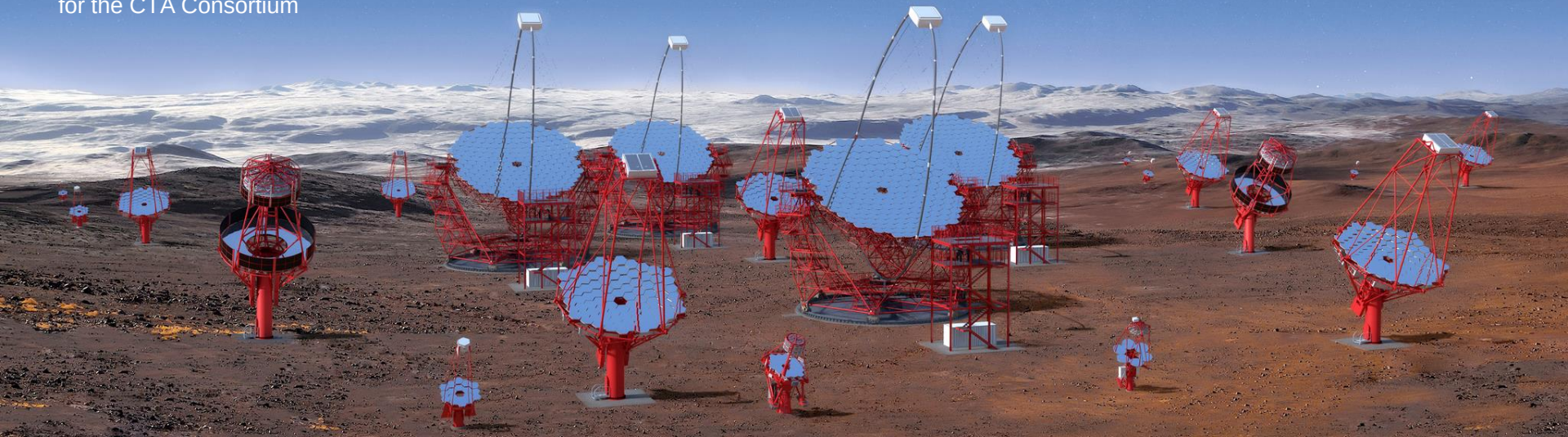
CTA – SETTING THE STAGE

Werner Hofmann
MPI for Nuclear Physics
Heidelberg

for the CTA Consortium



GROUND-BASED GAMMA RAY ASTRONOMY 1989

Whipple Telescope 1968

T. Weekes et al., ApJ 342 (1989) 379

"Observation of TeV Gamma Rays from the Crab Nebula using the Atmospheric Cerenkov Imaging Technique"

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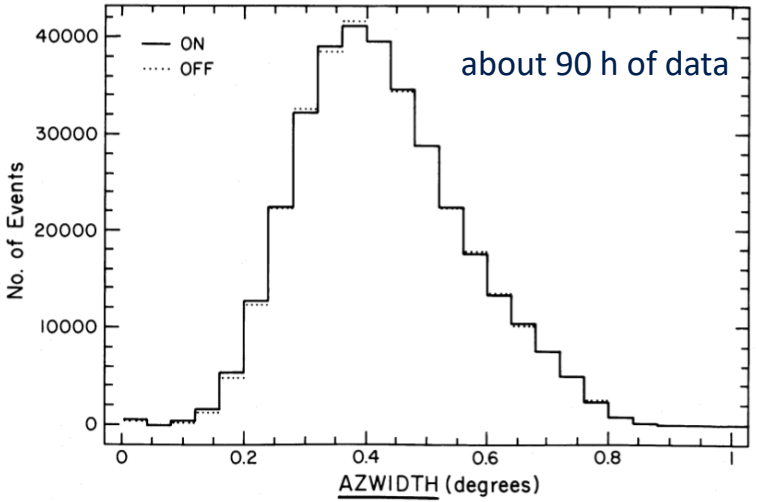

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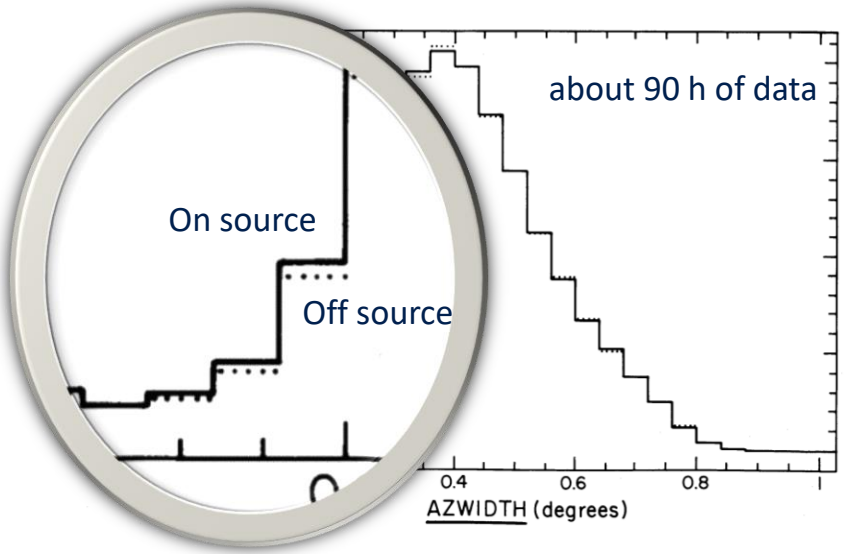
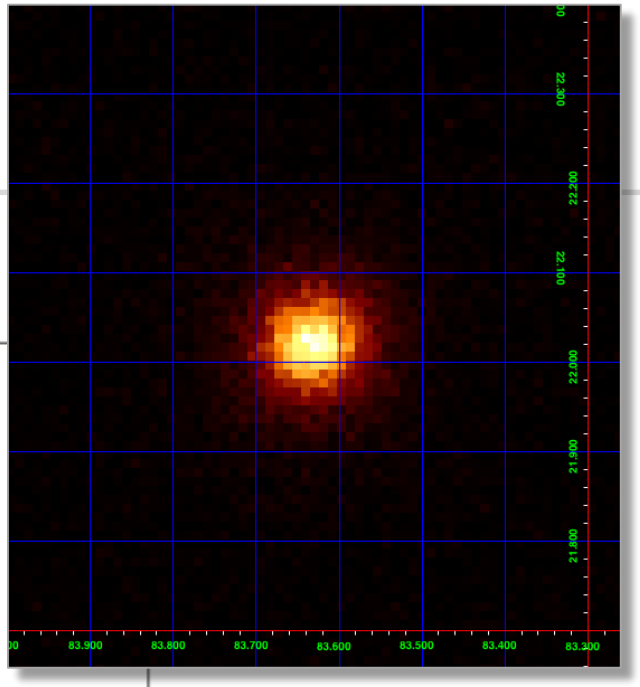
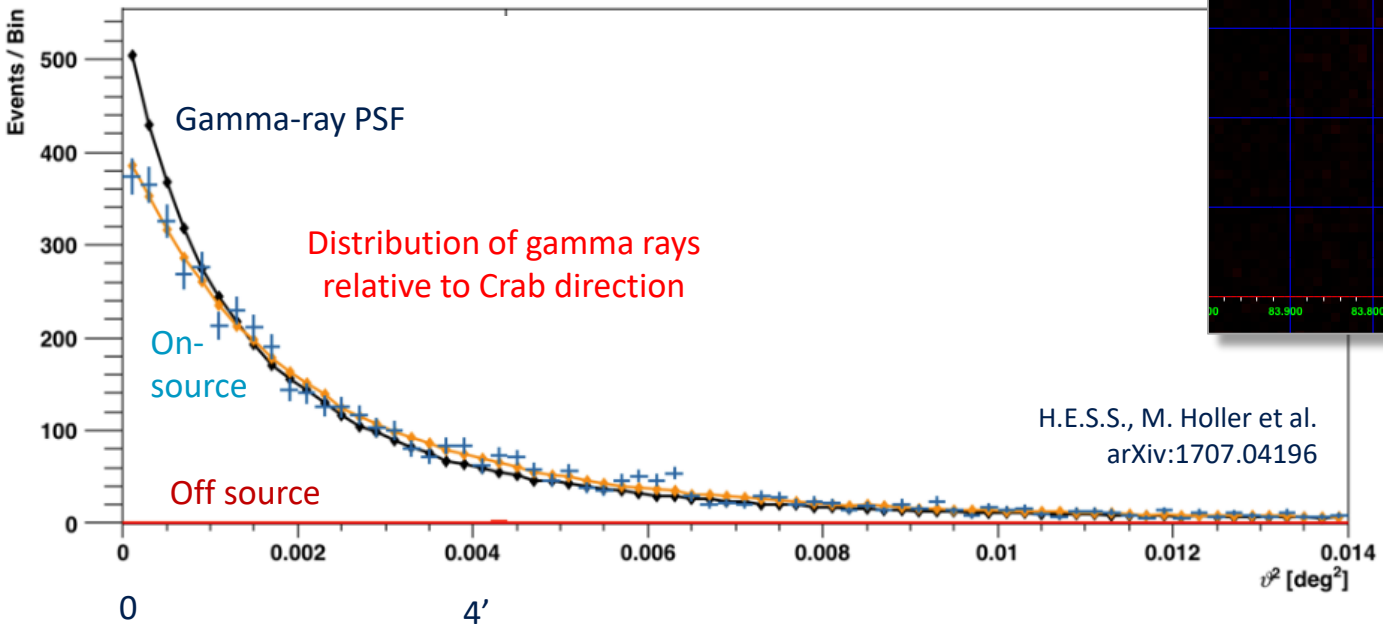


GROUND-BASED GAMMA RAY ASTRONOMY TODAY



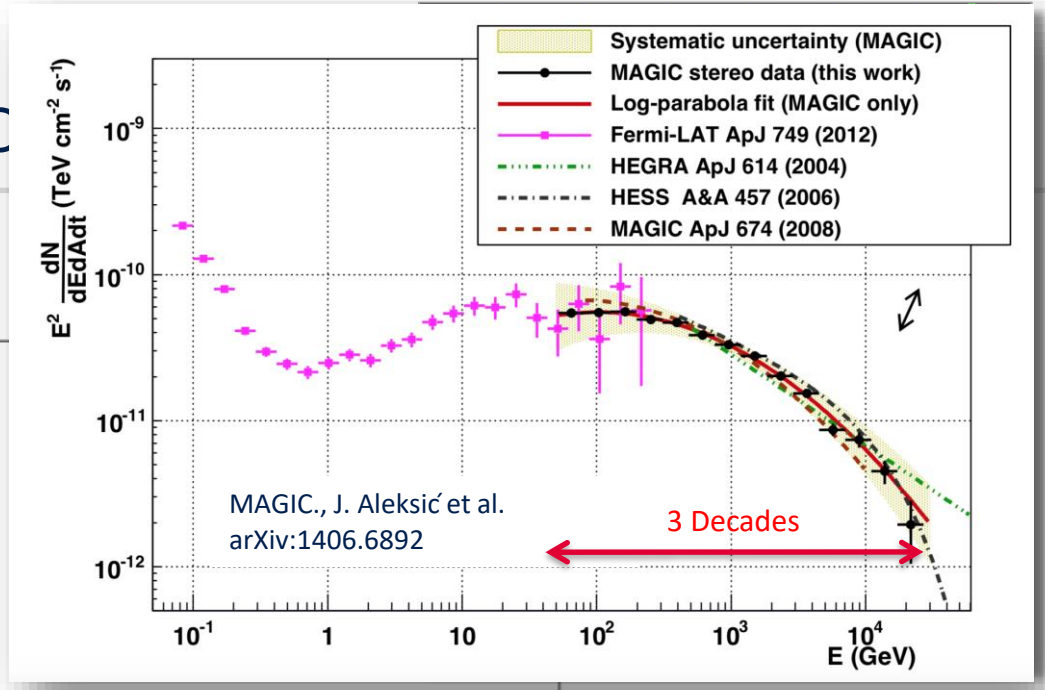


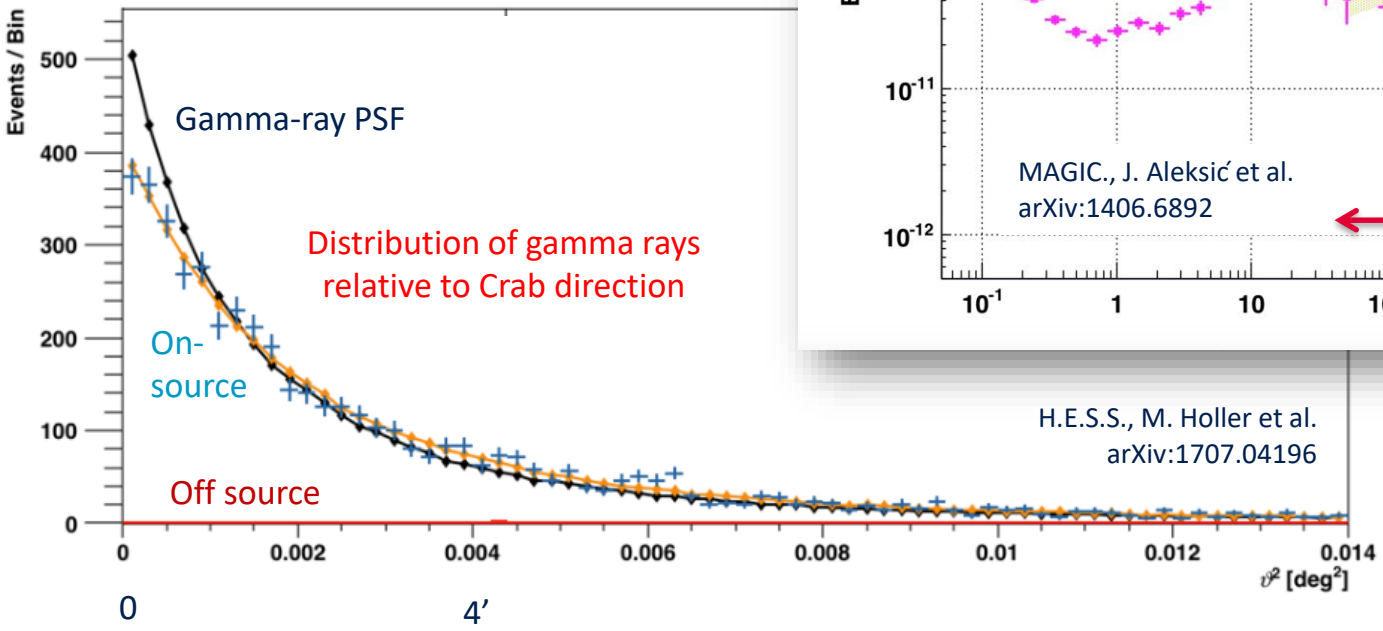
H.E.S.S., M. Holler et al.
arXiv:1707.04196

0 4’

Gamma-ray size of Crab Nebula: 52”±3”±8”

GROUND-BASED GAMMA RAY ASTRONC





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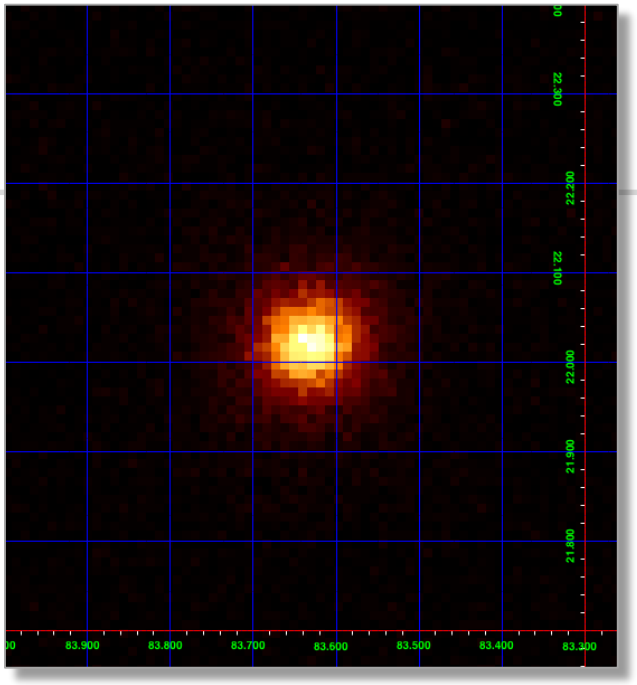
GROUND-BASED GAMMA RAY ASTRONOMY TODAY



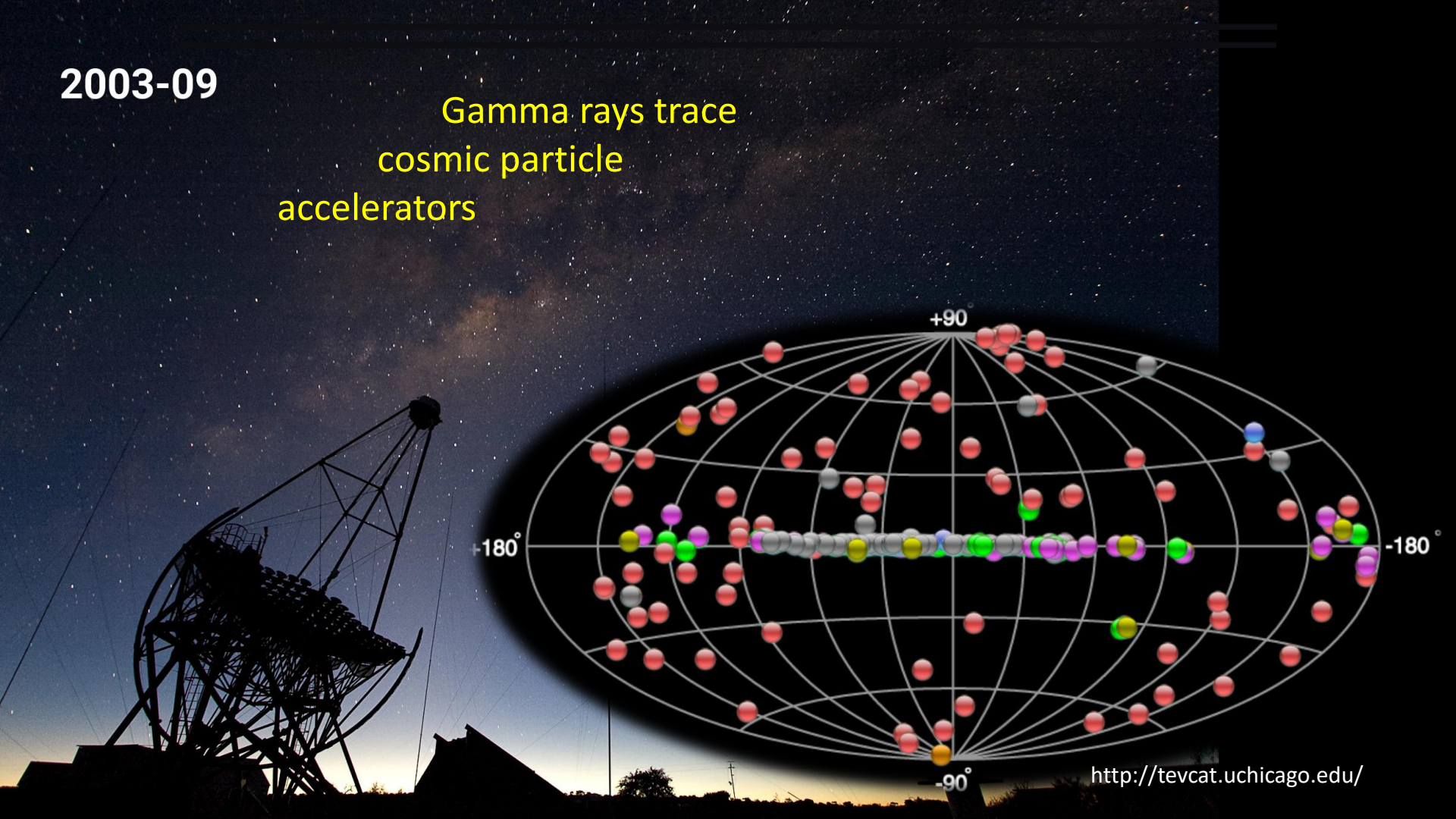
Real Astronomy!

showing a different sky

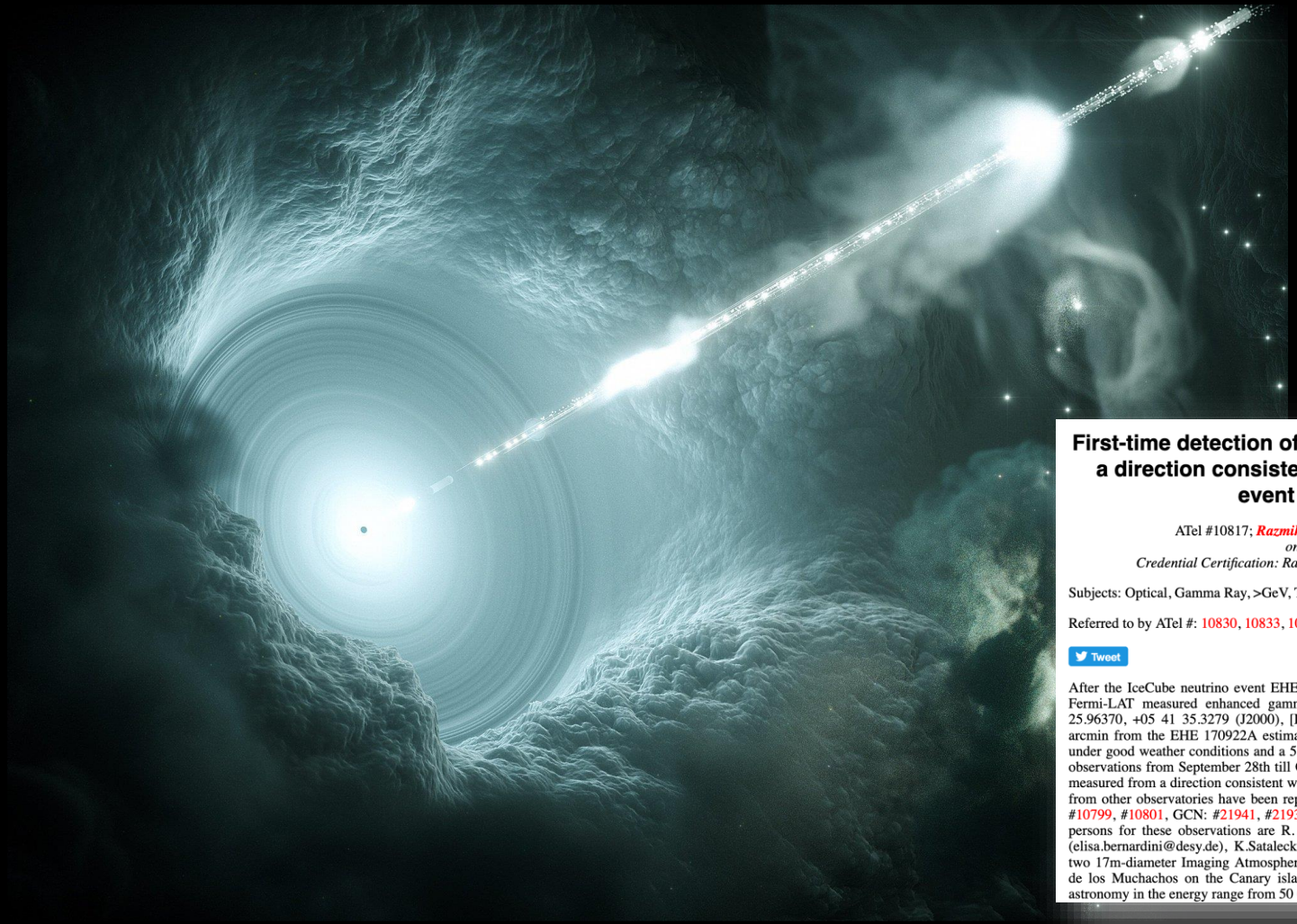
- 200+ sources of TeV gamma rays
- Sky images and sky maps
- Resolution approaches that of the human eye
- Sources like the Crab Nebula are virtually free of cosmic-ray background
- Dynamic range in gamma-ray flux: 3 orders of magnitude
- Dynamic range in energy: 3 decades
- Light curves on all scales from minutes to years

2003-09

Gamma rays trace cosmic particle accelerators



http://tevcat.uchicago.edu/



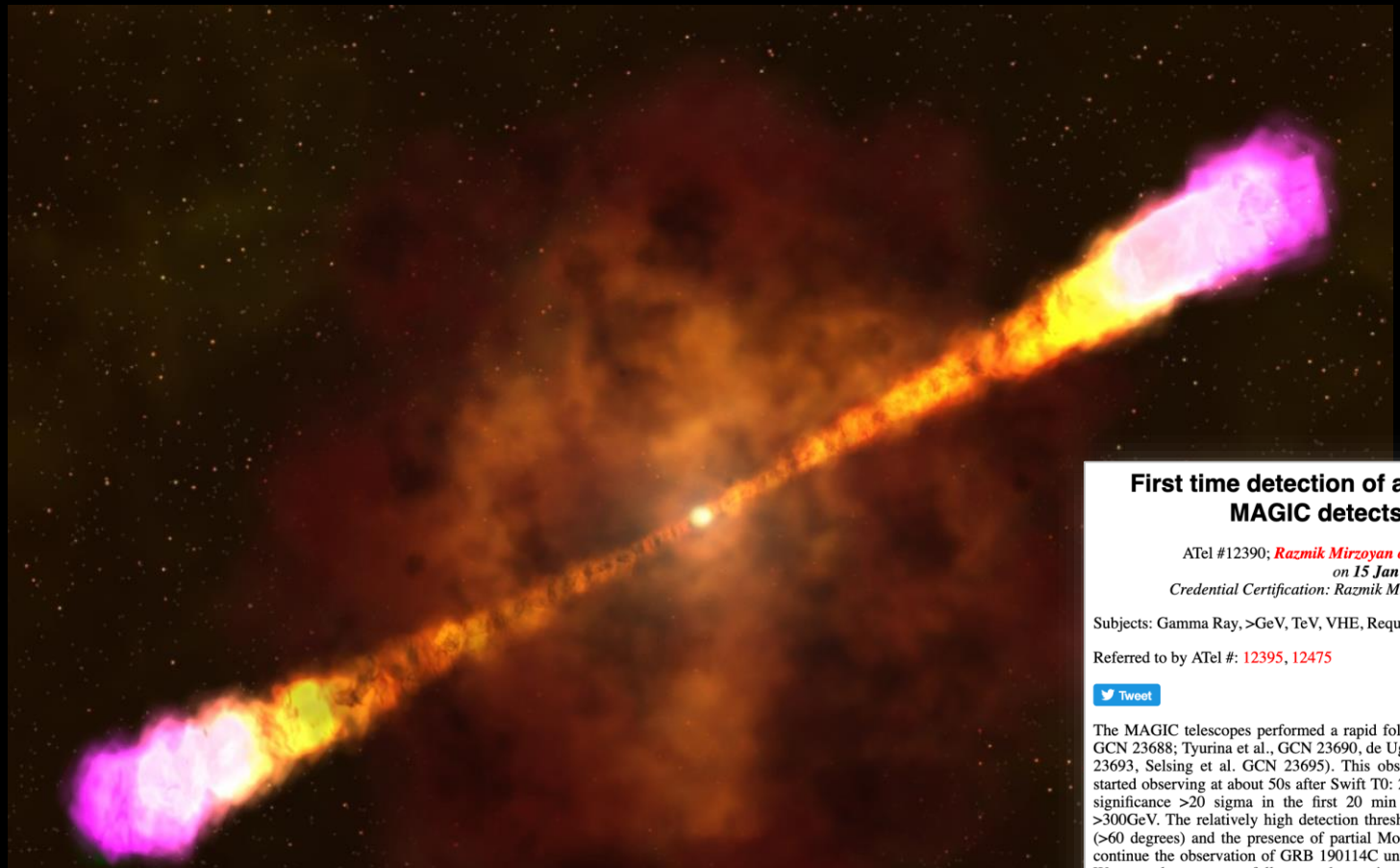
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
*on **4 Oct 2017; 17:17 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942, 12260

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.



NASA/GSFC

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

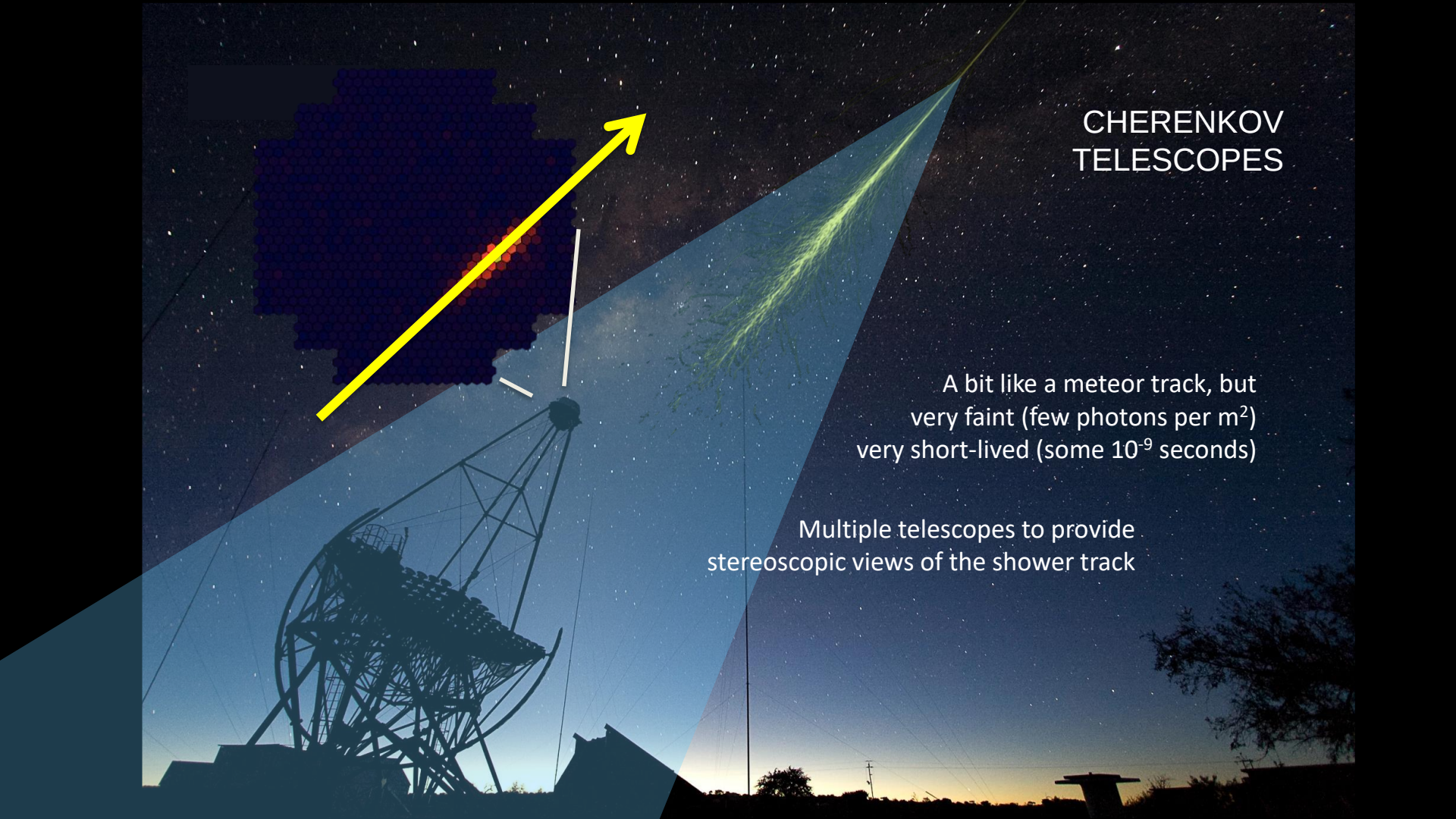
ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
*on **15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

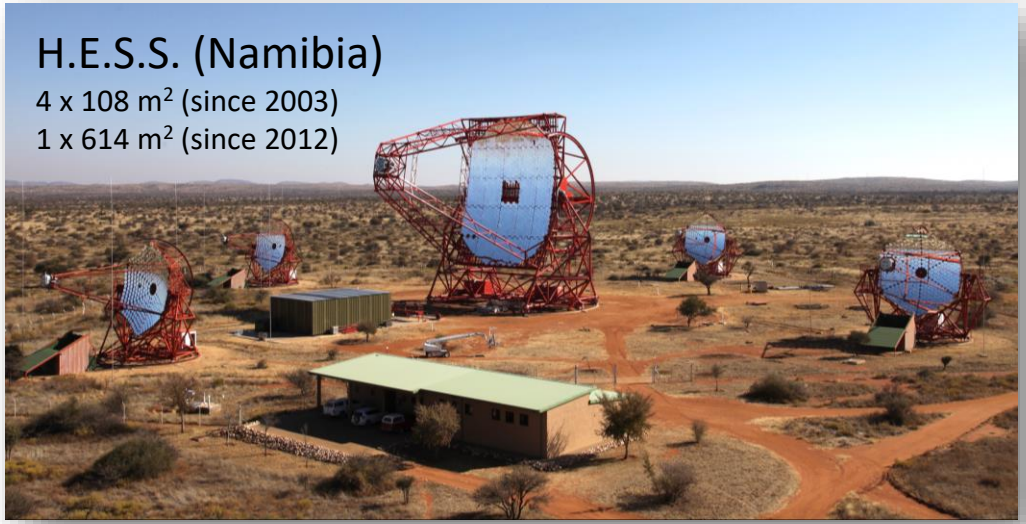
Tweet

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.


CHERENKOV
TELESCOPES
A bit like a meteor track, but
very faint (few photons per m^2)
very short-lived (some 10^{-9} seconds)
Multiple telescopes to provide
stereoscopic views of the shower track

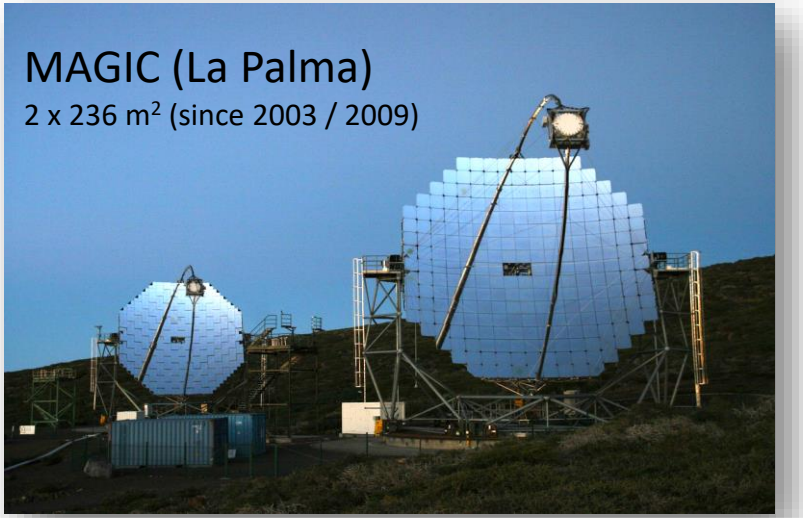
H.E.S.S. (Namibia)

4 x 108 m^2 (since 2003)
1 x 614 m^2 (since 2012)



MAGIC (La Palma)

2 x 236 m^2 (since 2003 / 2009)

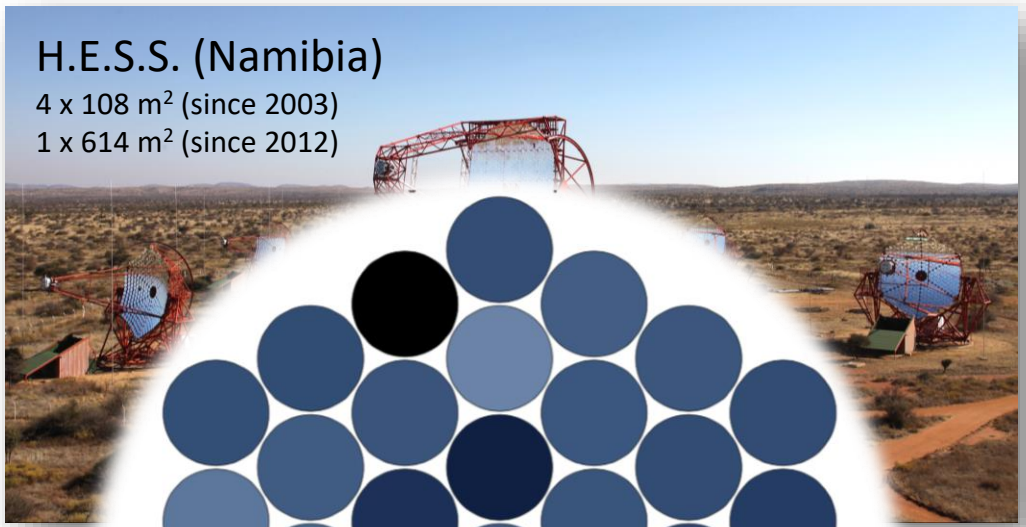


VERITAS (Arizona)

4 x 110 m^2 (since 2007)

H.E.S.S. (Namibia)

4 x 108 m^2 (since 2003)
1 x 614 m^2 (since 2012)



MAGIC (La Palma)

2 x 236 m^2 (since 2003 / 2009)

Whipple 1989 shower image

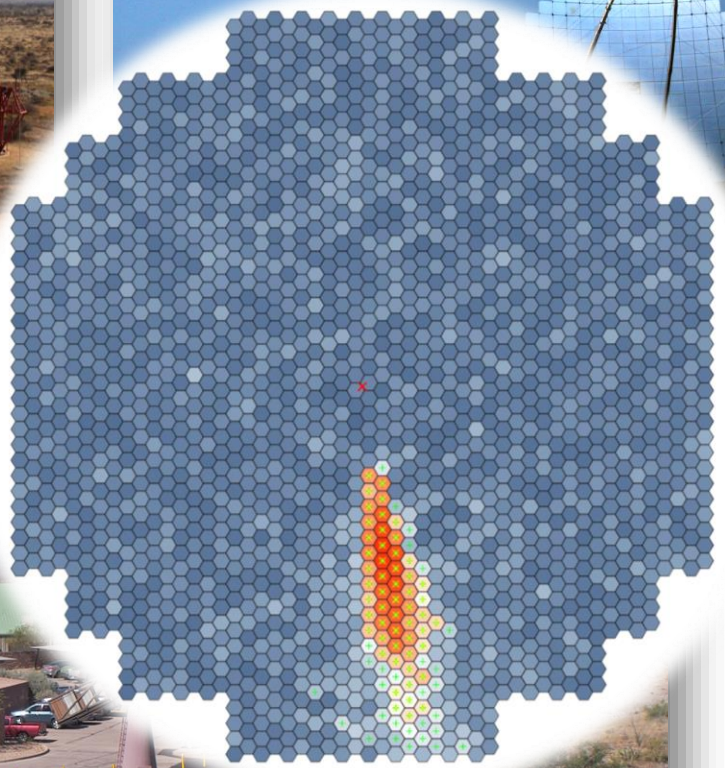
H.E.S.S. (Namibia)

4 x 108 m^2 (since 2003)
1 x 614 m^2 (since 2012)

MAGIC (La Palma)

2 x 236 m^2 (since 2003 / 2009)

Whipple 1989 shower image



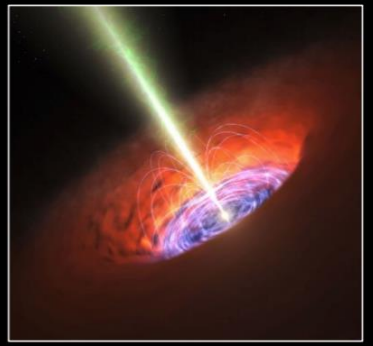
Modern camera

Theme 1: Cosmic Particle Acceleration

- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?

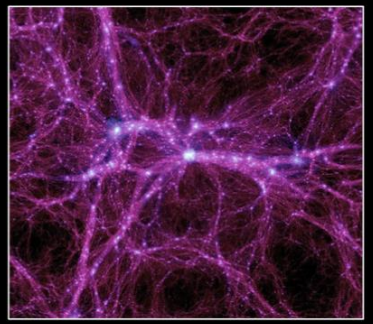
Theme 2: Probing Extreme Environments

- Close to neutron stars and black holes?
- Relativistic jets, winds and explosions?
- Cosmic voids

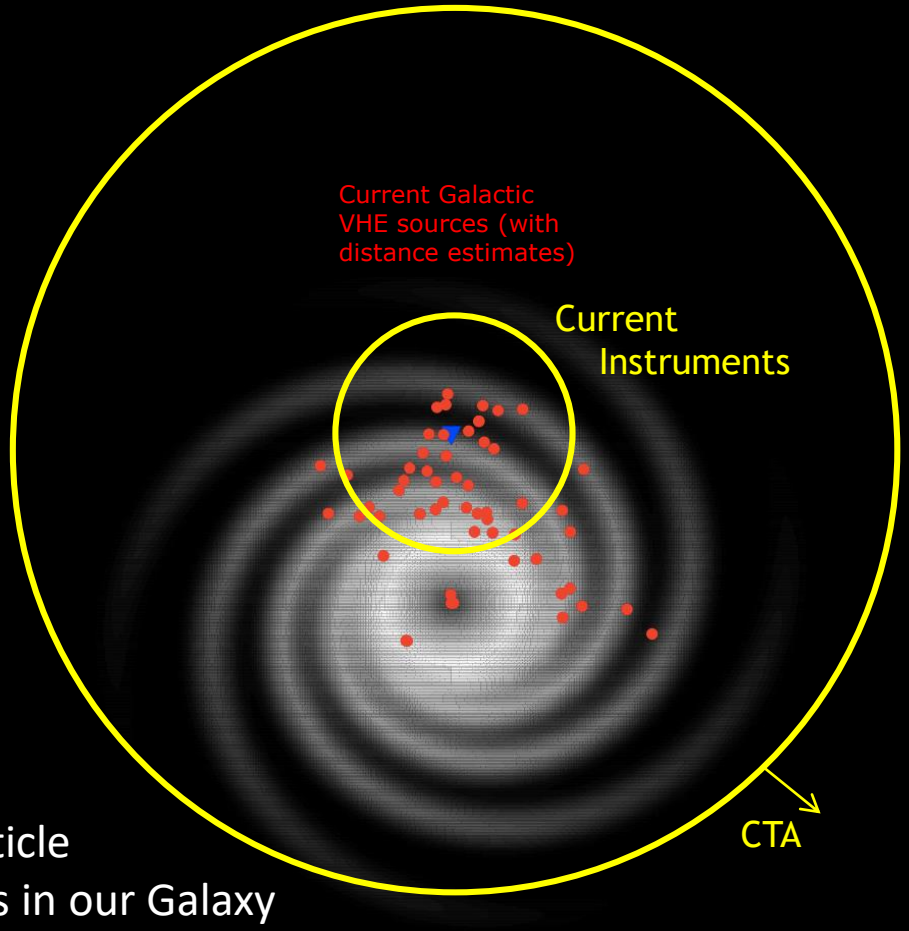


Theme 3: Physics Frontiers

- What is the nature of Dark Matter?
- Is the speed of light a constant?
- Do axion-like particles exist?



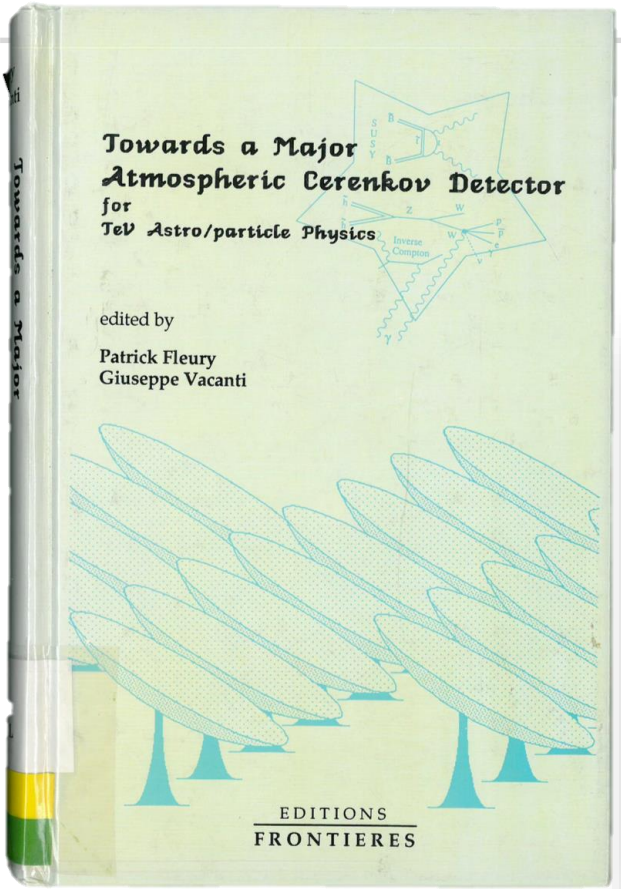
Current instruments provide exciting glimpses, but often fall short of providing the full answer



Cosmic particle accelerators in our Galaxy


GENESIS
OF CTA

THE 1992 PALAISEAU WORKSHOP



Following the observation of
TeV gamma ray emission from the Crab Nebula,
it seems desirable that a major program
be set forth by the international community
to develop TeV γ-Astronomy.

H.E.S.S. (Namibia)

4 x 108 m^2 (**since 2003**)
1 x 614 m^2 (since 2012)

MAGIC (La Palma)

2 x 236 m^2 (**since 2003** / 2009)

VERITAS (Arizona)

4 x 110 m^2 (**since 2007**)

IN THE UNITED STATES, 2005

Ground-based Gamma-ray Astronomy:
Towards the Future
October 20–22, 2005;
May's Landing & UCLA

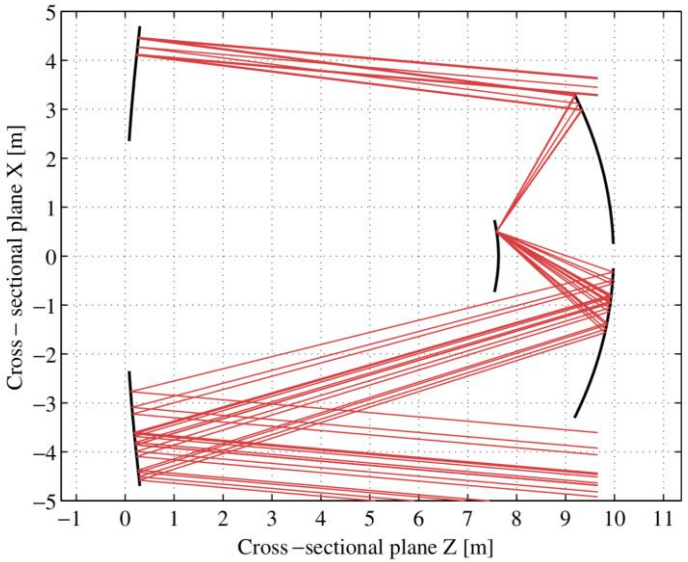
Wide field aplanatic two-mirror telescopes for ground-based γ-ray astronomy

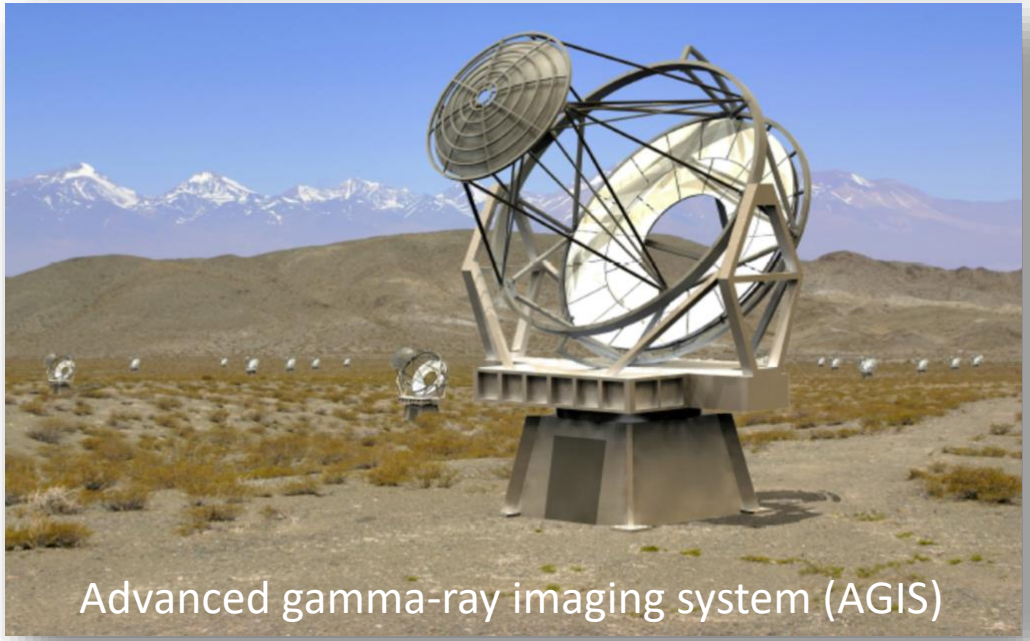
V. Vassiliev *, S. Fegan, P. Brousseau

Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095-1562, USA

Received 22 December 2006; received in revised form 13 March 2007; accepted 10 April 2007
Available online 18 April 2007

Astroparticle Physics
28 (2007) 10





National Research Council 2010 Decadal Report
New Worlds, New Horizons in Astronomy and Astrophysics


Advanced gamma-ray imaging system (AGIS)

New Worlds, New Horizons
in Astronomy and Astrophysics

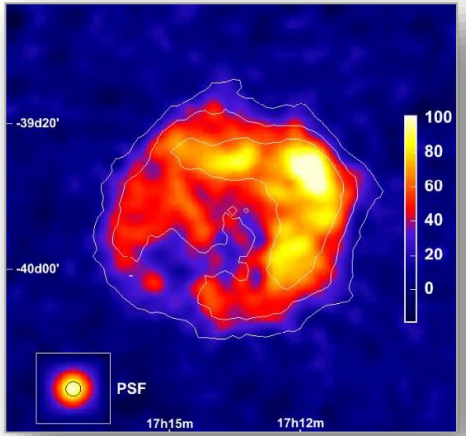
The committee recommends that the U.S. AGIS team collaborate ... with the European CTA team and that a U.S. budget for construction and operations of approximately $100 million ... be shared between DOE, NSF-Physics, and NSF-Astronomy.

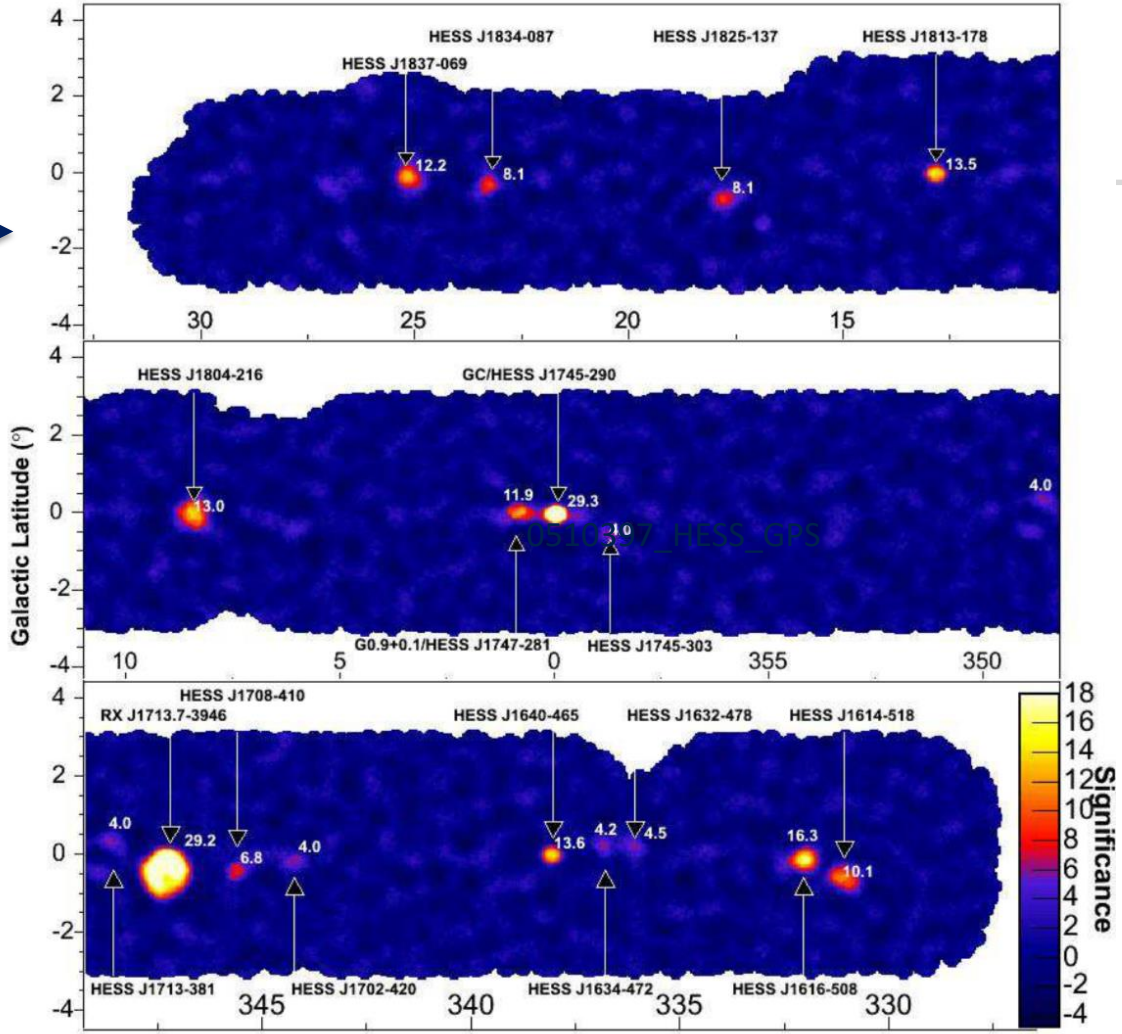
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

pSCT Inauguration
January 17, 2019
Whipple Observatory

2005

The VHE Milky Way
Galactic center VHE source
Galactic center ridge
First resolved VHE PWN
First resolved VHE SNR
VHE binaries
…





EUROPEAN ROADMAPPING

"The European Strategy Forum on Research Infrastructures (ESFRI) was established in 2002, with a mandate from the EU Council to support a coherent and strategy-led approach to policy-making on research infrastructures in Europe..."

2002:
ESFRI
established

".. in the second semester of 2004, ESFRI was asked to prepare a roadmap for new large-scale RIs needed by the EU scientific community. The ESFRI roadmap on RIs will be the first of this kind in Europe."

2004:
ESFRI prepares
for roadmapping
of RI's

OCTOBER 7, 2005

Dear Manel and Masahiro,

based on input from various sides, I got the impression that rapid input for the ESFRI roadmap committee is required to secure a slot for future Cherenkov instruments. I drafted a letter which could possibly be sent to the chairman of the committee, …. I attach the draft and was wondering if you would be prepared to join such an initiative? ...

The draft leaves open how exactly the telescope array should look like, and exactly where is should be built. … I personally would prefer to split the ~100 MEuro which such a system could reasonably cost, and use half of it to built a large number (20 ?) modest-sized (12 m?) telescopes with relatively low-cost, wide-field cameras (7 degr?), arranged on a ~100 m grid with some outrigger telescopes for even larger area at very high energy and LZA, and to spent the other half of the money for a few (3-4?) large telescopes …

Let me know what you think about some common action towards ESFRI.

Best wishes
Werner

NOVEMBER 2005: LETTER TO ESFRI

signed by over 60 group leaders from 15 countries

Letter of Intent for a Large Array of Imaging Atmospheric Cherenkov Telescopes for High-Energy Astrophysics

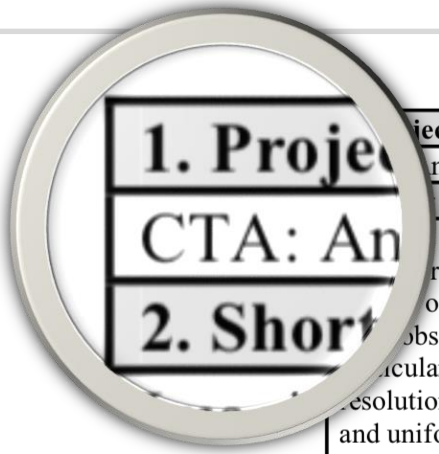
Interstellar space is filled with populations of high-energy particles. While the energy contained in this component is comparable to the energy density of starlight or galactic magnetic fields, knowledge about this "nonthermal Universe" and about the sources and propagation of the high-energy particles is rather limited. Particles are almost certainly accelerated in collective phenomena such as shock waves emitted by dying stars or are generated in the vicinity of supermassive black holes, but part of this nonthermal population may also result from the decay or annihilation of relic particles left over from the Big Bang, possibly forming the cosmic dark matter. An in-situ study of such particle populations is

… 2 pages …

This Letter of Intent is supported by the following senior scientists - mostly members of the H.E.S.S. and MAGIC collaborations and of the European part of the VERITAS collaboration - representing their research groups in Armenia, Bulgaria, the Czech Republic, Finland, France, Germany, Ireland, Italy, Namibia, Poland, South Africa, Spain, Switzerland, and the United Kingdom:

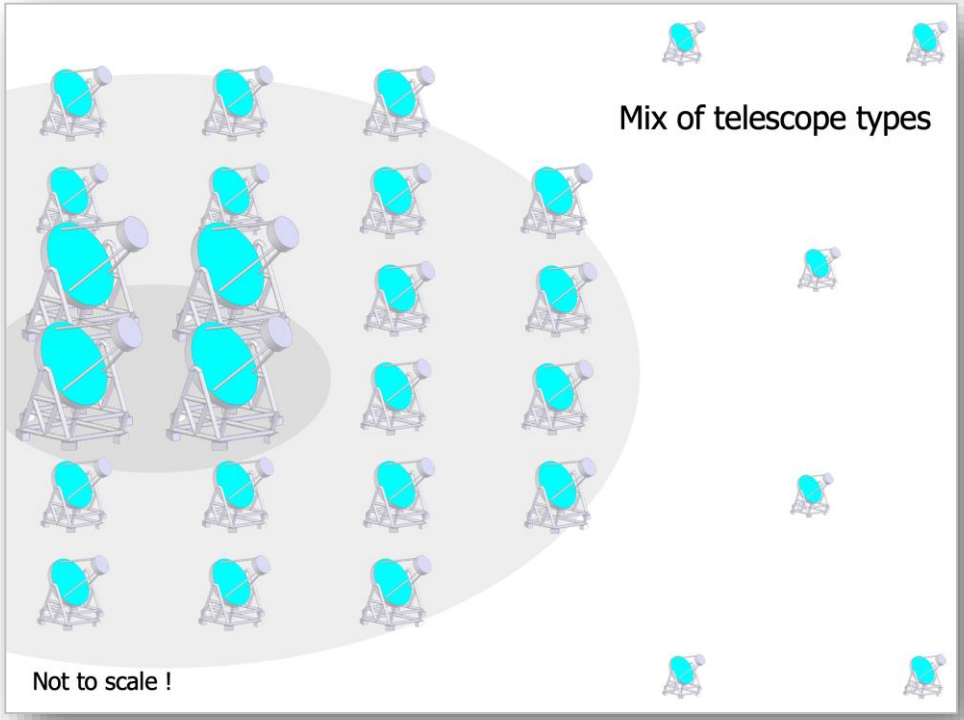
F. Aharonian, *Max -Planck-Institut für Physik für Kernphysik, Heidelberg*, ***Germany***
A. Akhperjanian, *Yerevan Physics Institute*, ***Armenia***
C.Baixeras, *Universitat Autonoma de Barcelona*, ***Spain***
A.R. Bazer-Bachi, *Centre d'Étude Spatiale des Rayonnements, Toulouse*, ***France***
A. Biland, *Institute for Particle Physics, Swiss Federal Institute of Technology (ETH) Zurich*, ***Switzerland***

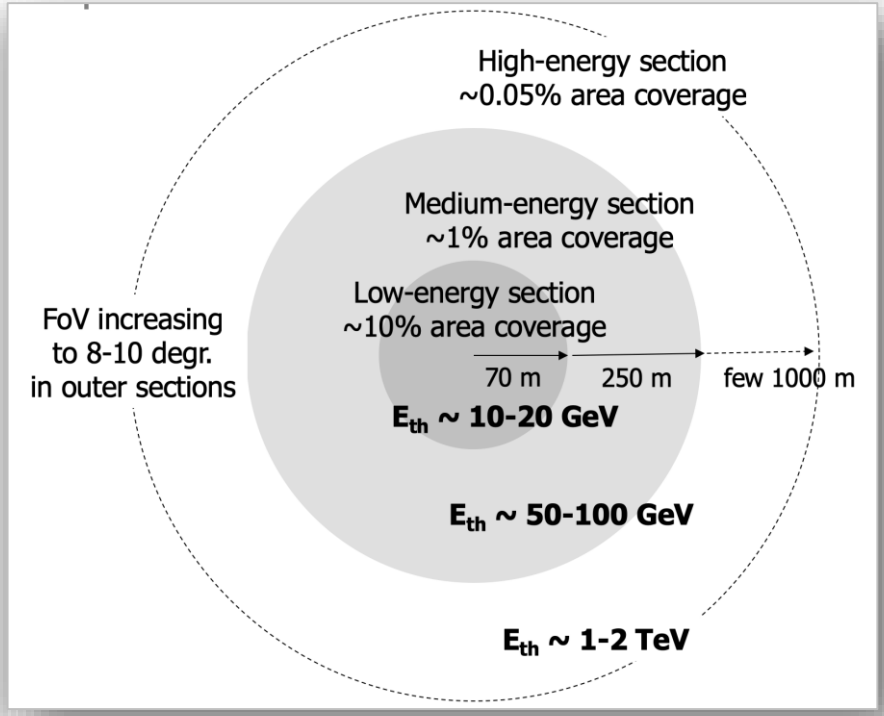
JANUARY 20, 2006
PROJECT DESCRIPTION TO ESFRI

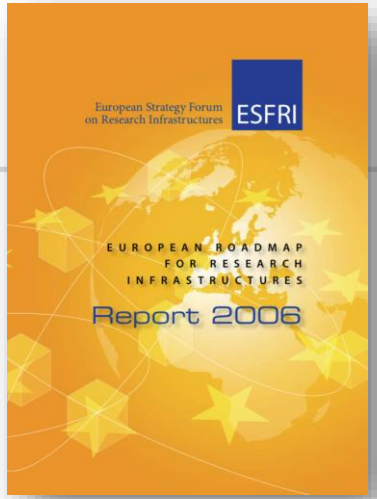


ject's name and descriptive title
n advanced facility for ground-based high-energy gamma ray astronomy
description of project and main characteristics
atmospheric Cherenkov telescopes have proven an extremely successful approach to ray astronomy in the energy range above a few tens of GeV. The proposed facility will of arrays of telescopes, aiming to (a) increase sensitivity by another order of magnitude for observations, (b) boost significantly the detection area and hence the detection rates, icularly important for transient phenomena and at the highest energies, (c) increase the angular esolution and hence the ability to resolve the morphology of extended sources, (d) provide wide and uniform energy coverage from some 10 GeV to beyond 100 TeV, and (e) enhance the all sky survey and monitoring capability. These features will allow the exploration of non-thermal processes in the Universe, in close cooperation with and complementing observatories in other wavelength ranges of electromagnetic radiation, and for other messenger types. Given the wealth of sources in the central region of our Galaxy and the richness of their morphological features, a site in the southern hemisphere is attractive. On the other hand, a complementary northern site has to be considered for the study of AGNs and the cosmological evolution of galaxies and star formation. The ensemble would provide full sky coverage and wider energy range coverage as demonstrated by H.E.S.S. - MAGIC large/small zenith angle simultaneous observations.
3. Science case (scientific justification, including new areas to be opened)
Data from Cherenkov telescopes of the latest generation have revealed a sky rich in features at TeV energies; in the last years, the number of sources has quadrupled. First sky maps show the band of the Milky Way lined with cosmic accelerators, with complex and resolved morphology. Their energy spectra extend beyond 10s of TeV; some of the objects emit most of their energy in the TeV range. Extragalactic sources at unprecedented distances of up to three billion light years have been

MARCH 8, 2006
PRESENTATION IN BRUSSELS

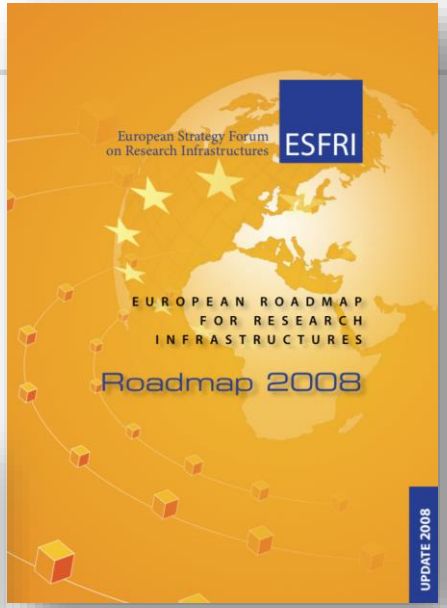






1st ESFRI Ro
CTA as Eme

Very strong support also by APPEC (Astroparticle European Coordination)



ESFRI 2008 Roadmap:
CTA as ESFRI Project

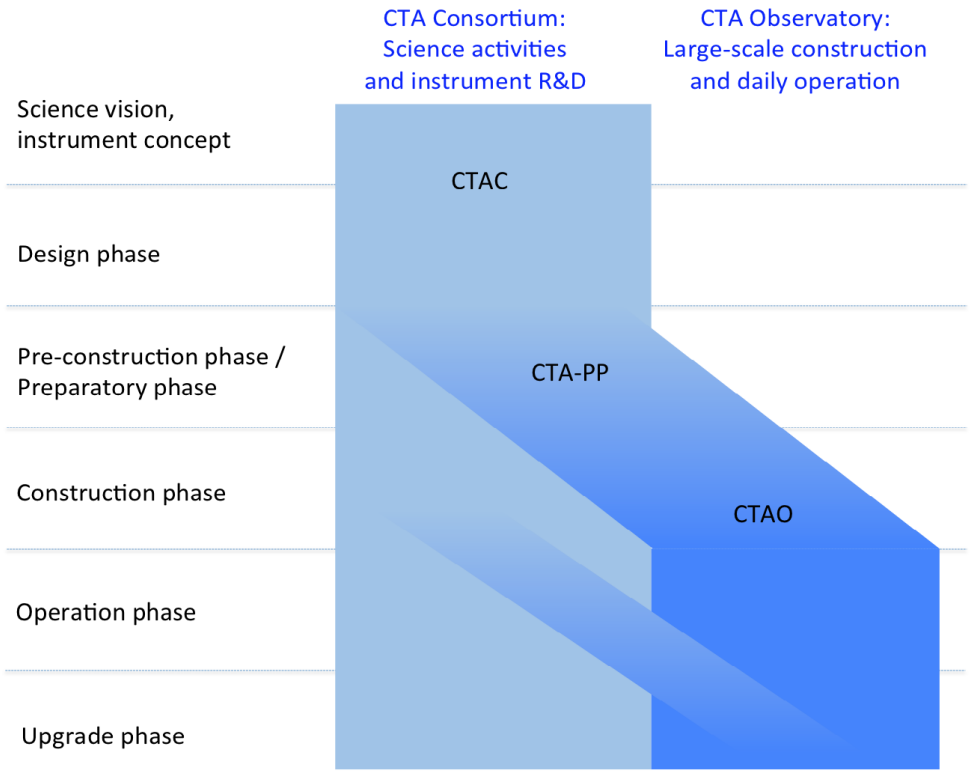
Supported under FP7 and H2020

ESFRI 2018 Roadmap:
CTA as ESFRI Landmark

THE CTA CONSORTIUM

31 Countries
over 200 Institutes
over 1400 Members

CTA CONSORTIUM AND CTA OBSERVATORY



- CTA as open observatory
- Regular AOs
- Proposals evaluated by TAC
- Observations carried out in queue mode
- Fully calibrated photon lists and analysis tools provided to observers
- Data open after proprietary period of 1 year

From:
Concept for CTA
construction and operation
WH 2011/12

CTA DECLARATION OF INTENT JULY 18, 2012

CTA Resource Board

"By signing this Declaration of Intent, the signatories – Ministries and Funding Agencies – wish to express their common interest in participating in the construction and operation of CTA. "

JULY 2014:
FOUNDING THE CTA OBSERVATORY GMBH

Interim legal entity,
based in Heidelberg

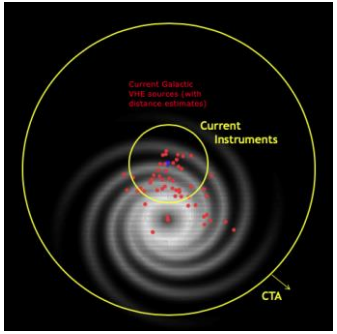
Initially 3 shareholders
representing
Germany, Italy, Switzerland

Now shareholders from
11 countries, plus ESO

Final legal entity:
ERIC, in preparation

DESIGNING CTA

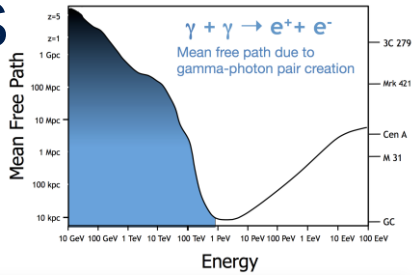
DESIGN DRIVERS

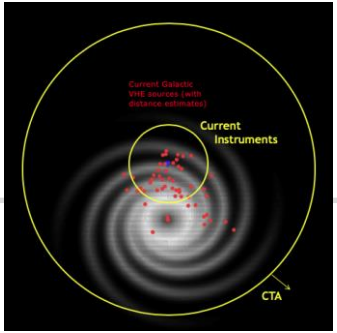


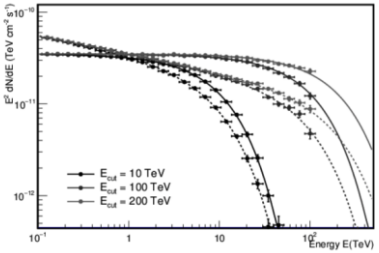
10 x Sensitivity, Large Collection Area

→ all topics

DESIGN DRIVERS





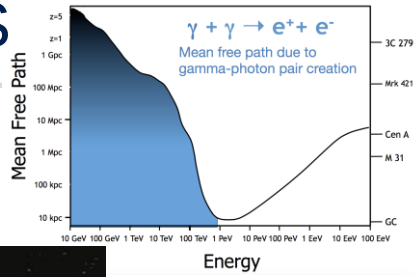


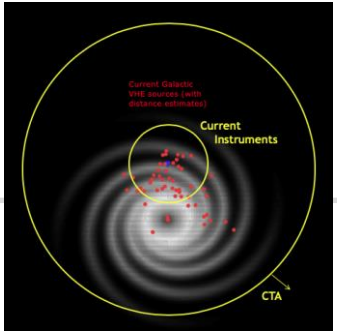
Energies down to 20 GeV
→ Cosmology++

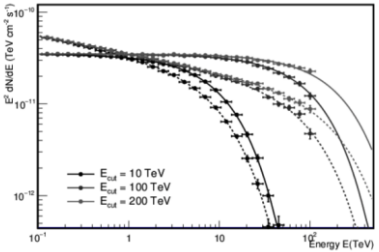
10 x Sensitivity, Large Collection Area
→ all topics

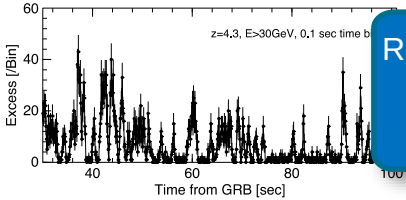
Energies up to 300 TeV
→ Pevatrons

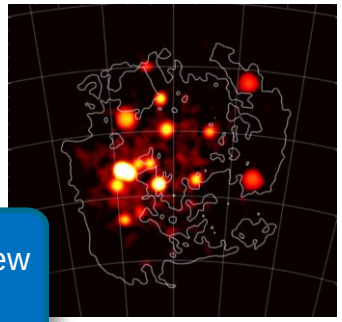
DESIGN DRIVERS











Energies down to 20 GeV
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10 x Sensitivity, Large Collection Area
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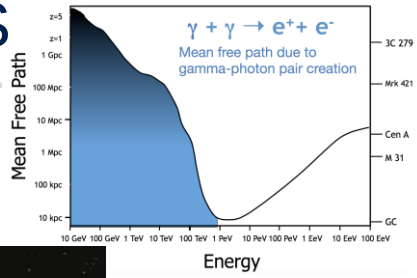
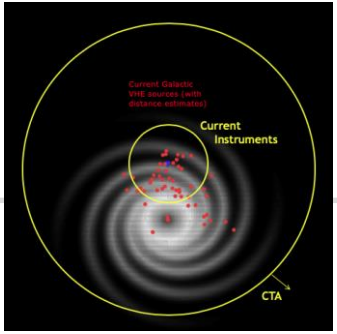
Energies up to 300 TeV
→ Pevatrons

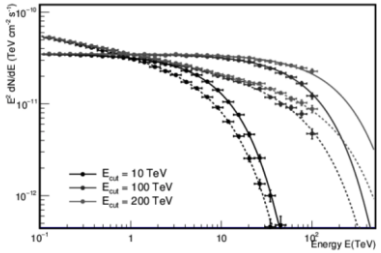
Rapid Slewing in 20 seconds
→ transients

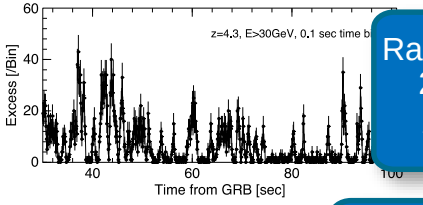
8º Field of View
→ surveys, extended objects

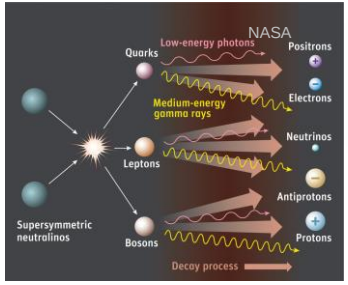
DESIGN DRIVERS

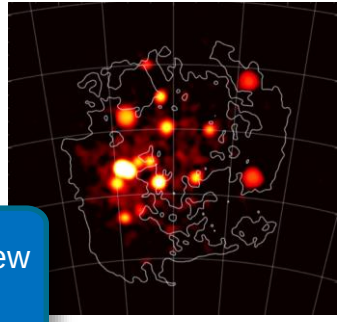


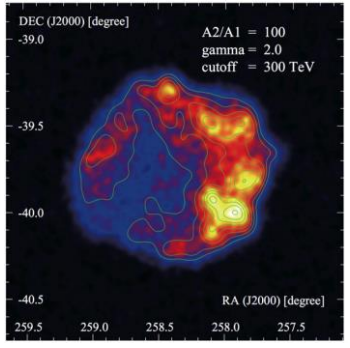












10 x Sensitivity, Large Collection Area
→ all topics

Energies down to 20 GeV
→ Cosmology++

Energies up to 300 TeV
→ Pevatrons

Rapid Slewing in 20 seconds
→ transients

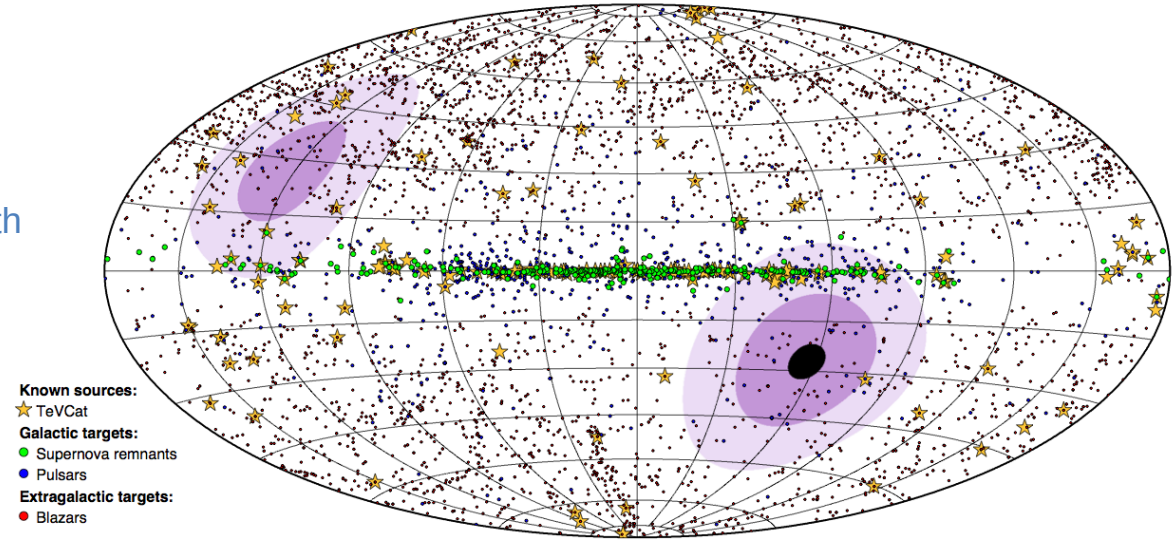
8º Field of View
→ surveys, extended objects

10% Energy Resolution
→ lines, features

Few ‘ Angular Resolution
→ morphology

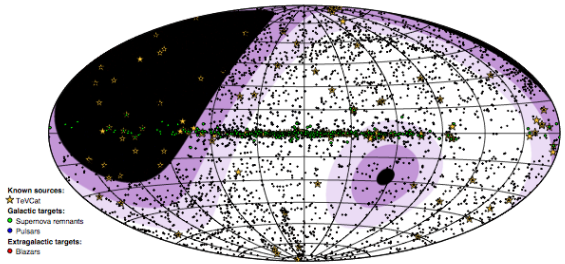
DESIGN DRIVER:
FULL-SKY COVERAGE

North+South

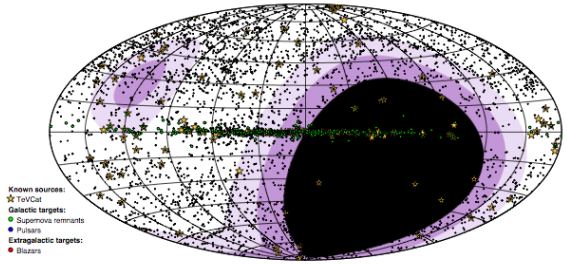


>60º zenith
45º-60º
30º-45º

South



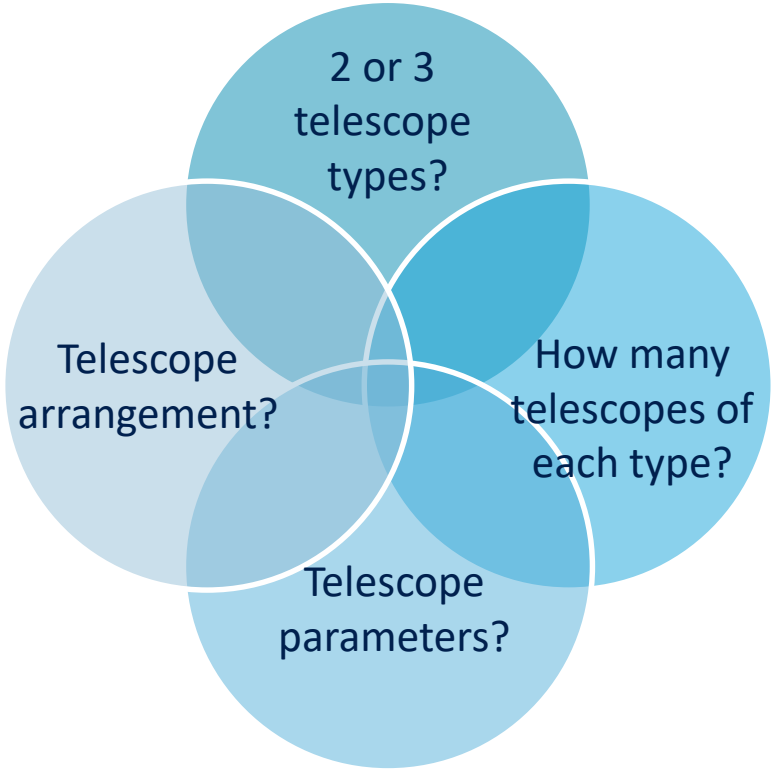
North



OPTIMIZING THE CTA ARRAYS

K. Bernlöhr et al., Astropart. Phys. 43 (2013) 171
T. Hassan et al., Astropart. Phys. 93 (2017) 76
A. Acharyya et al., arXiv 1904.01426 (2019)

Questions



Approach

Experience, analytical models & cost models

Square grids of telescopes

Plausible array layouts

Freeze telescope numbers and parameters

Optimize and fine-tune layout (at % level)

Simulations using tens of millions CPU-h

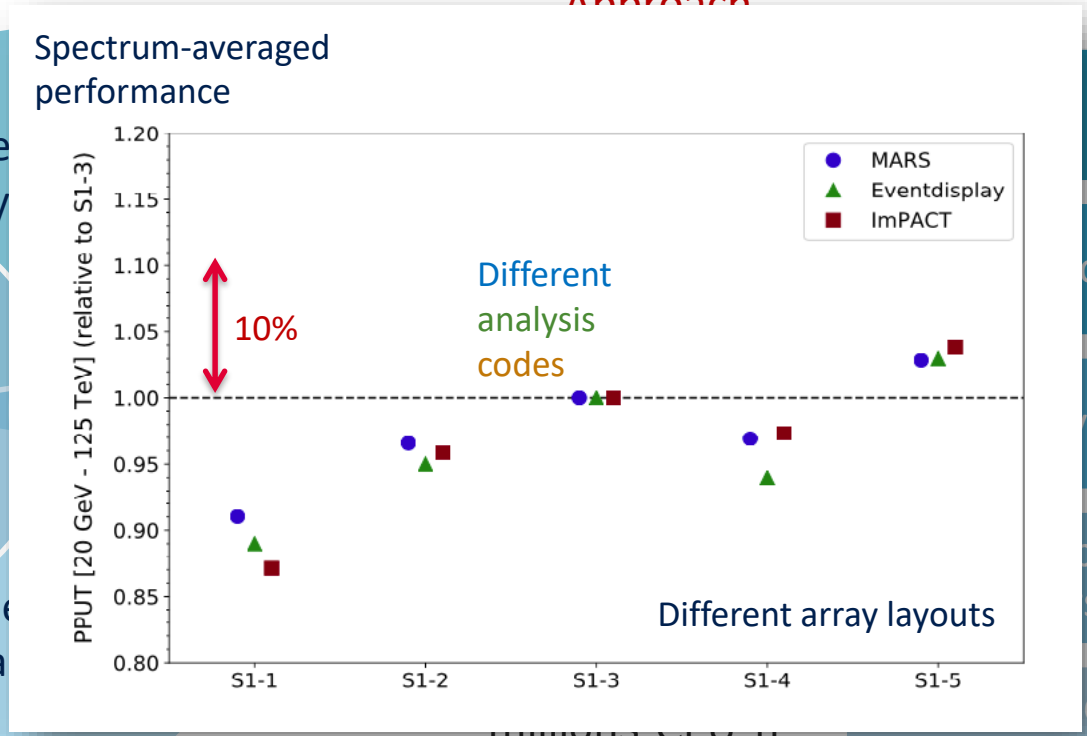
OPTIMIZING THE CTA ARRAYS

K. Bernlöhr et al., Astropart. Phys. 43 (2013) 171
T. Hassan et al., Astropart. Phys. 93 (2017) 76
A. Acharyya et al., arXiv 1904.01426 (2019)

Questions

Telescope arrangement?

Spectrum-averaged performance



Approach

copes

outs

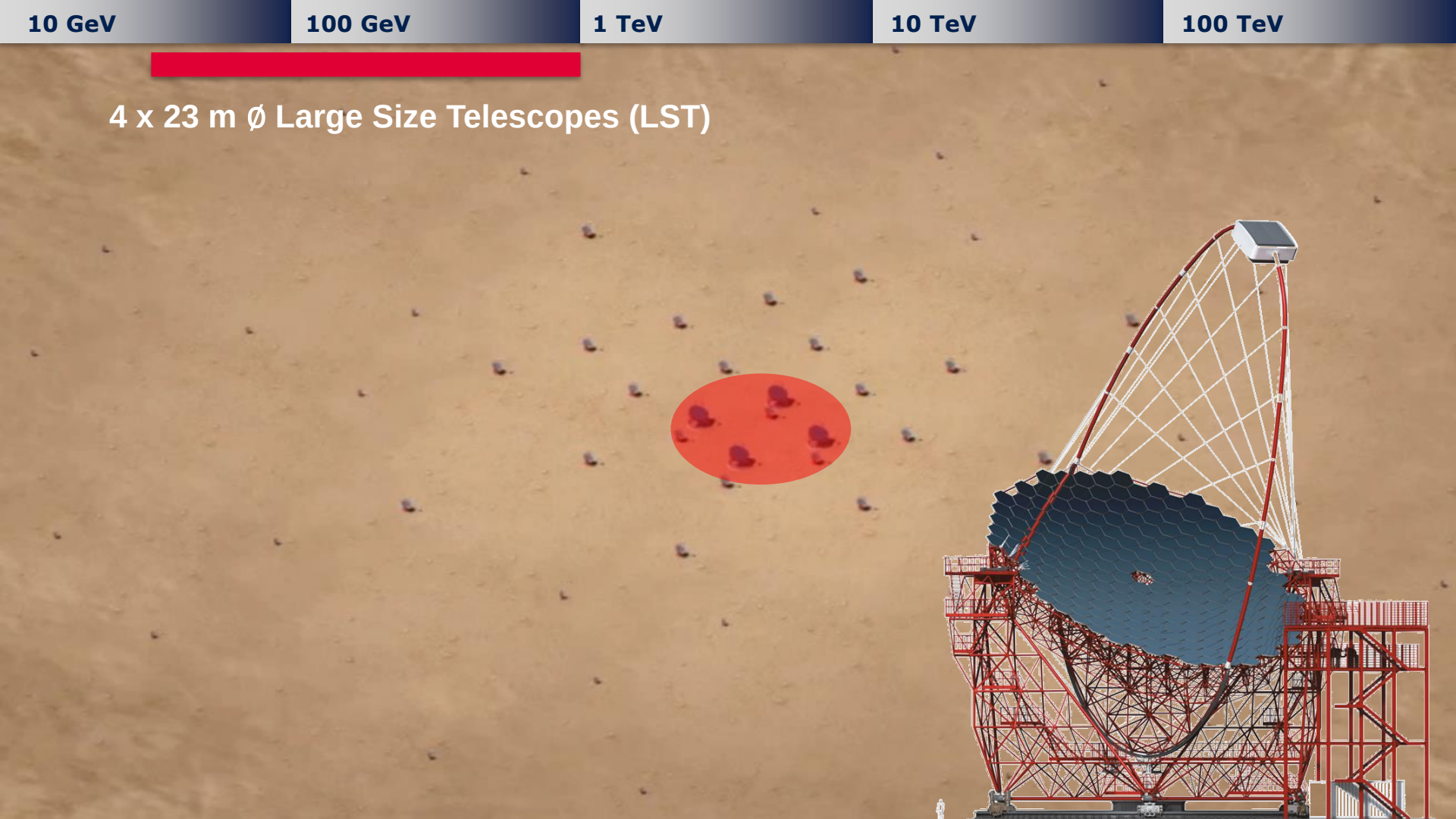
e numbers

d fine-tune layout (at % level)


10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1000 γ / h km²
10 γ / h km²
0.1 γ / h km²
Southern array
of Cherenkov telescopes
- about 3 km across

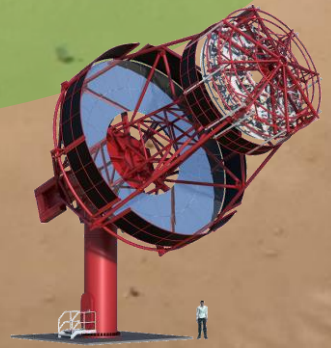
10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

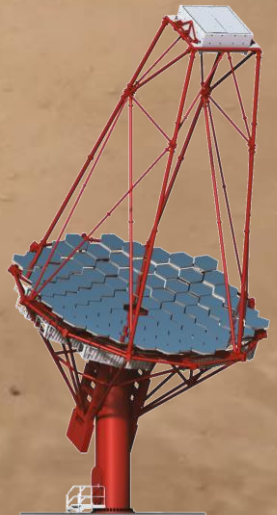
4 x 23 m ø Large Size Telescopes (LST)



10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

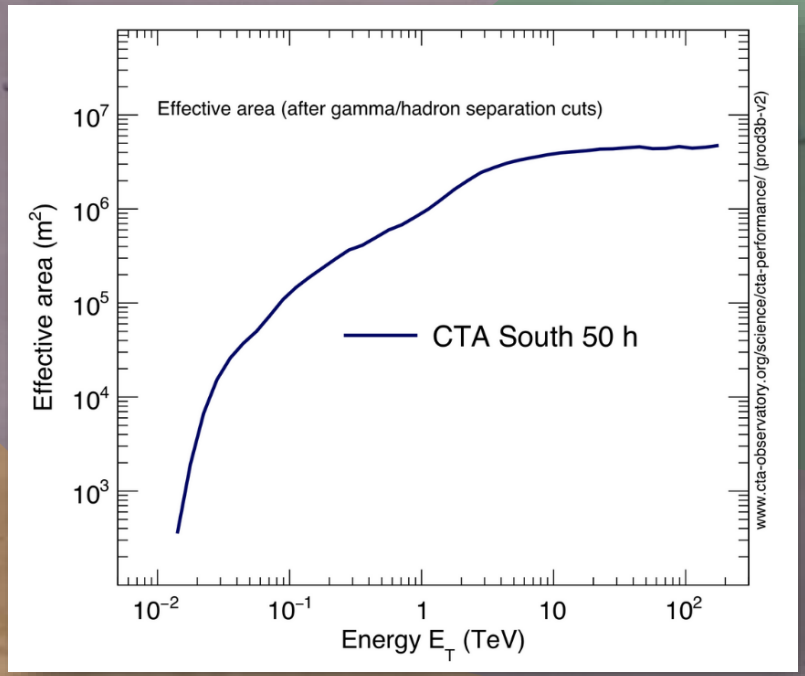
25 x 12 m ø Medium Size Telescopes (MST) (North: 15)

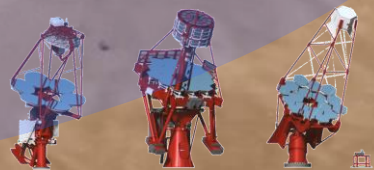




10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

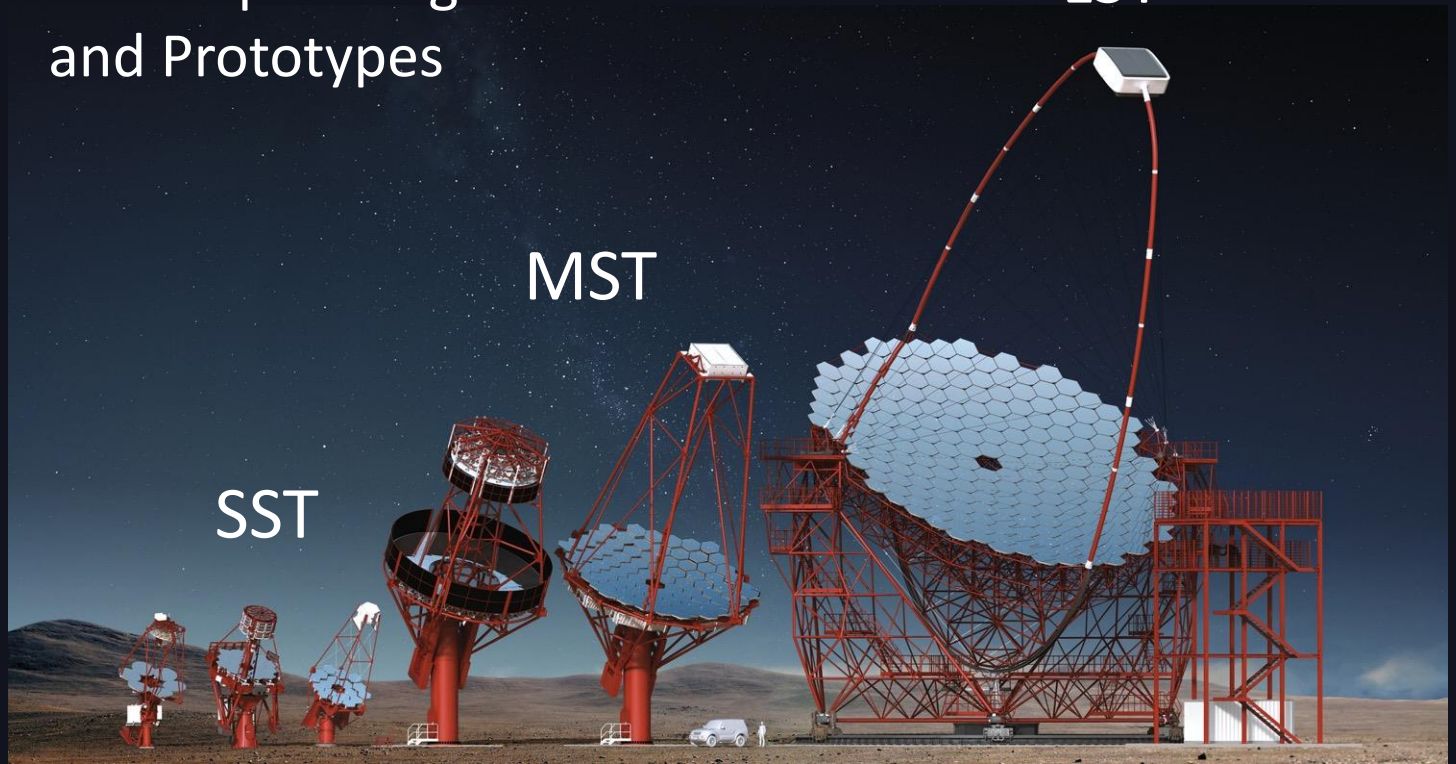
70 x 4 m ø Small Size Telescopes (SST) (South)





CTA TELESCOPES

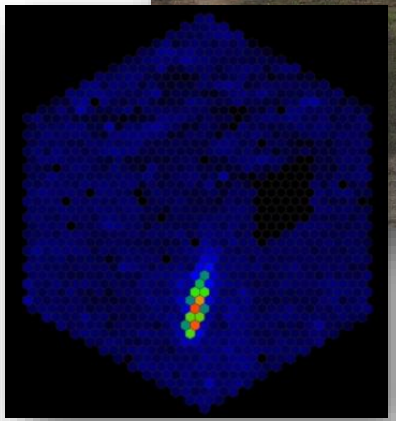
Telescope Designs
and Prototypes



SST-1M INAUGURATION

Warsaw

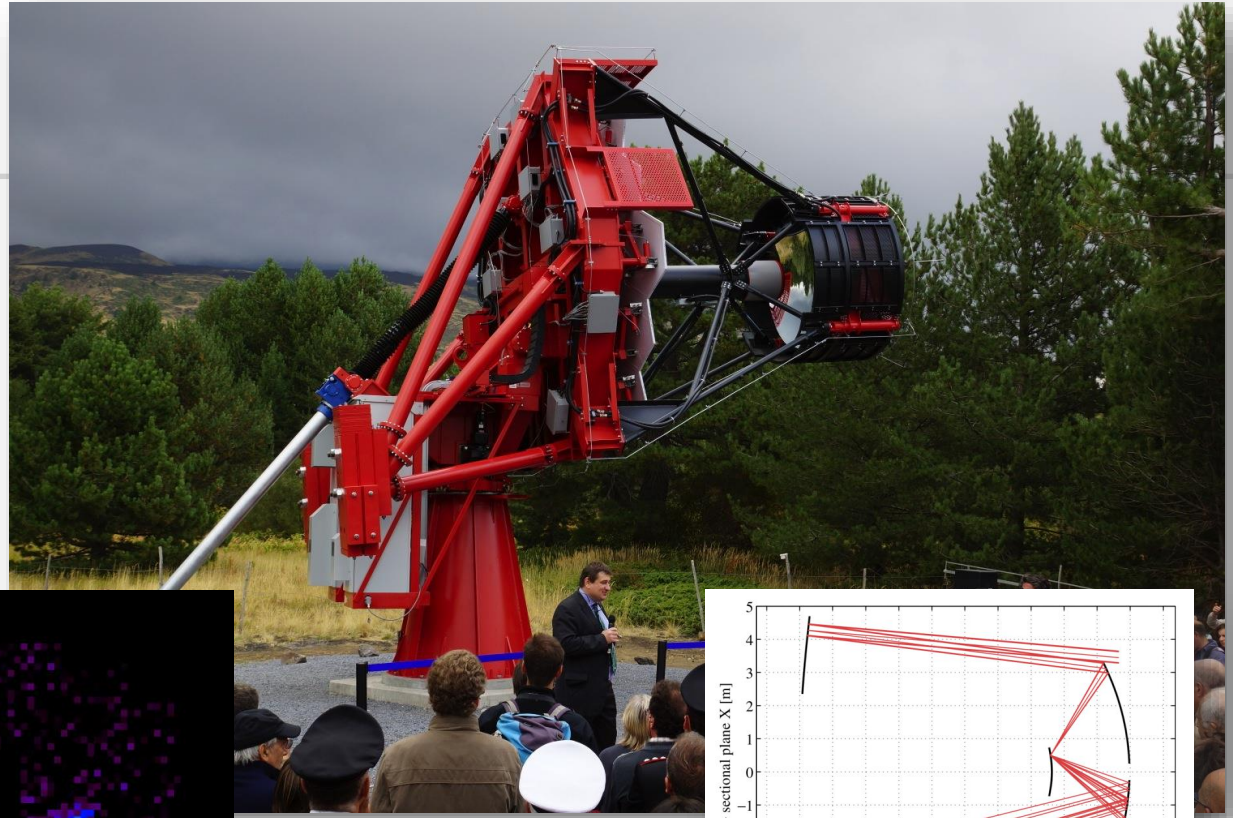
June 2, 2014

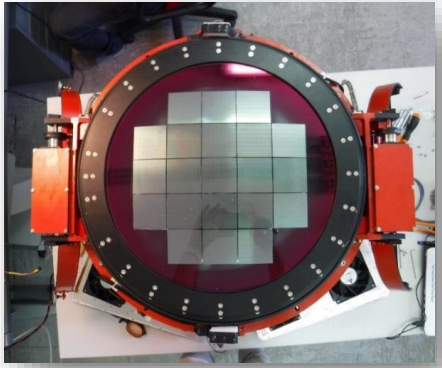


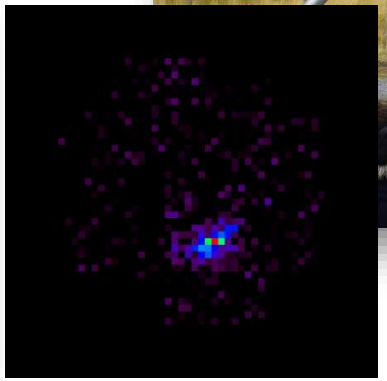
ASTRI-SST INAUGURATION

Serra La Nave Observatory
Sicily

Sept. 24, 2014



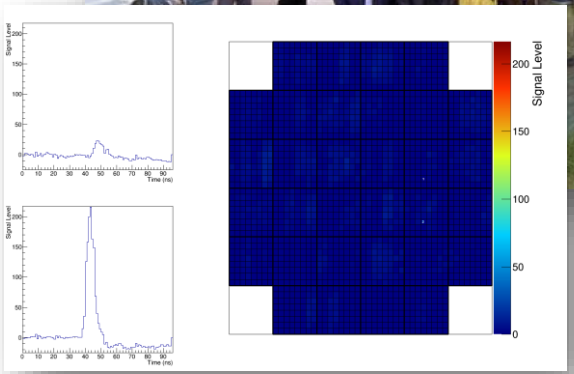




GCT SST INAUGURATION

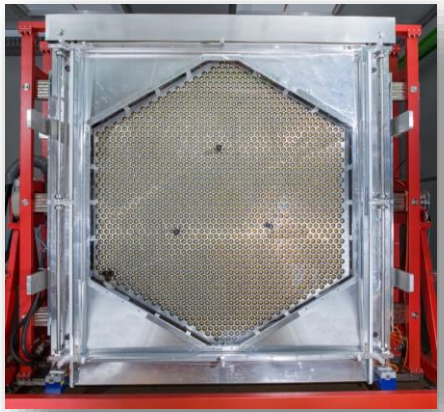
Paris-Meudon

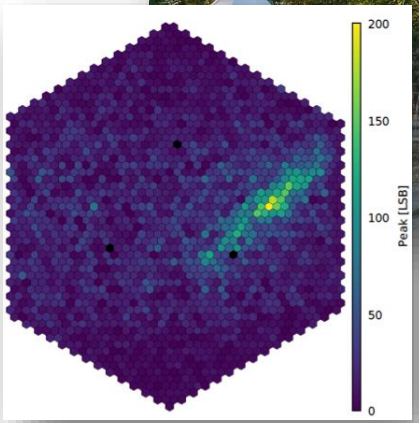
Dec. 1, 2015



MST TELESCOPE

Berlin-Adlershof

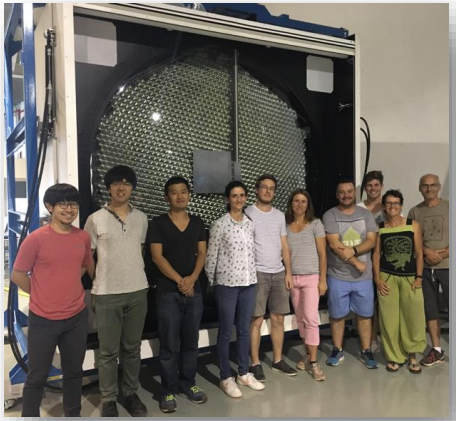


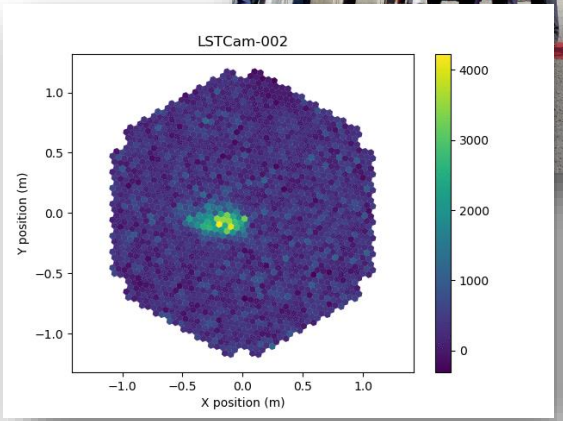


LST INAUGURATION

La Palma

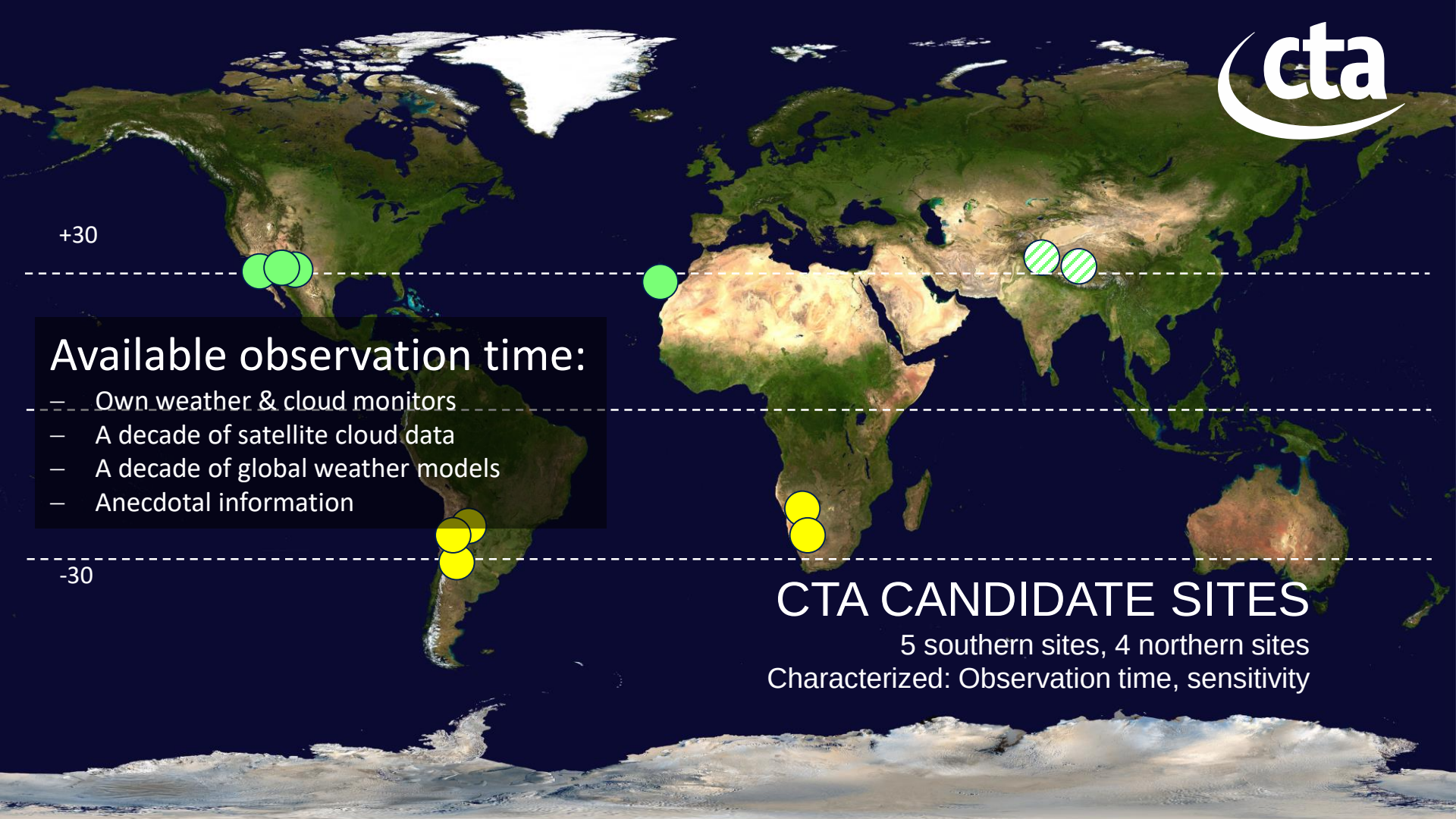
October 10, 2018





CTA Site Selection

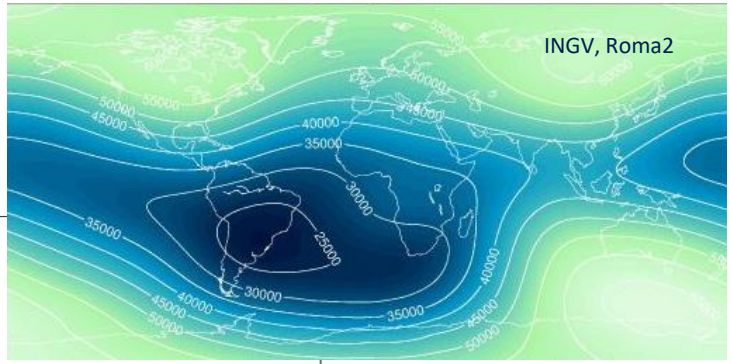
2008 - 2018

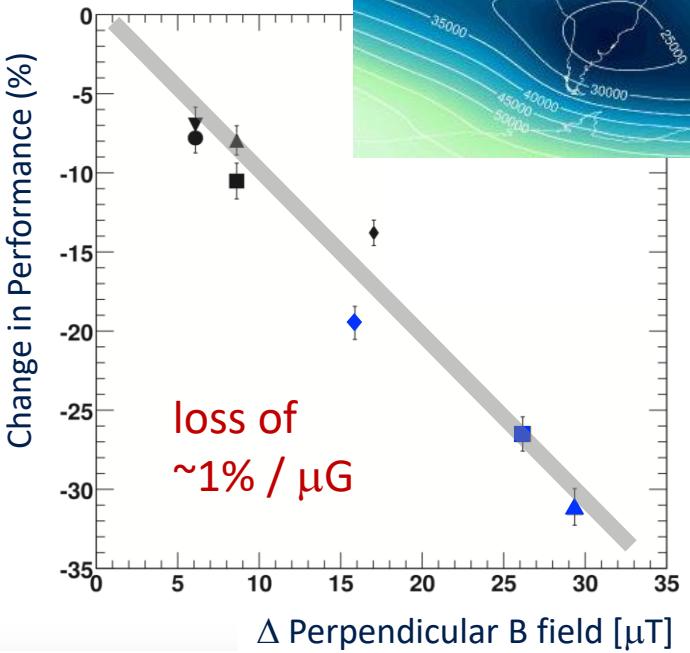

+30
-30
Available observation time:
– Own weather & cloud monitors
– A decade of satellite cloud data
– A decade of global weather models
– Anecdotal information
CTA CANDIDATE SITES
5 southern sites, 4 northern sites
Characterized: Observation time, sensitivity

INSTRUMENT SENSITIVITY: GEOMAGNETIC FIELD & ELEVATION

T. Hassan et al.
Astroparticle Physics
93 (2017) 76

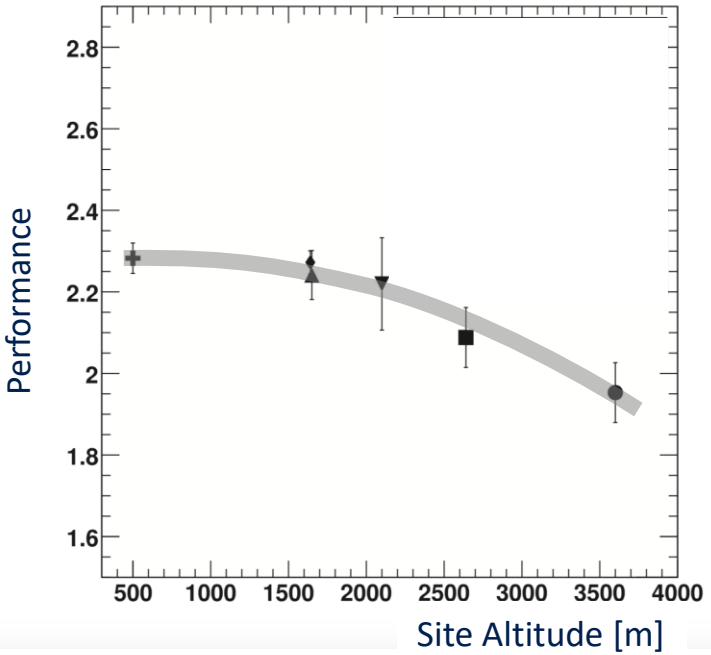
Impact of geomagnetic field



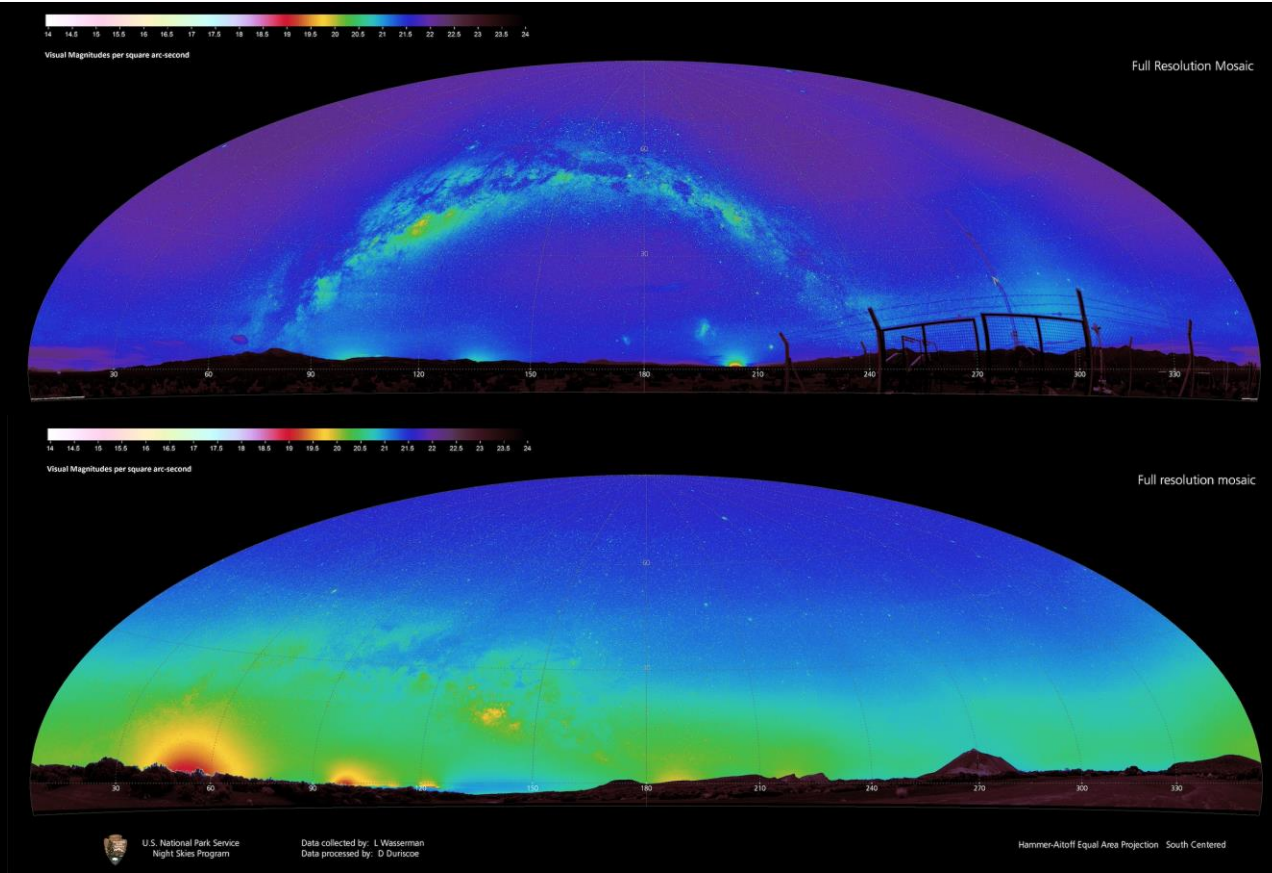


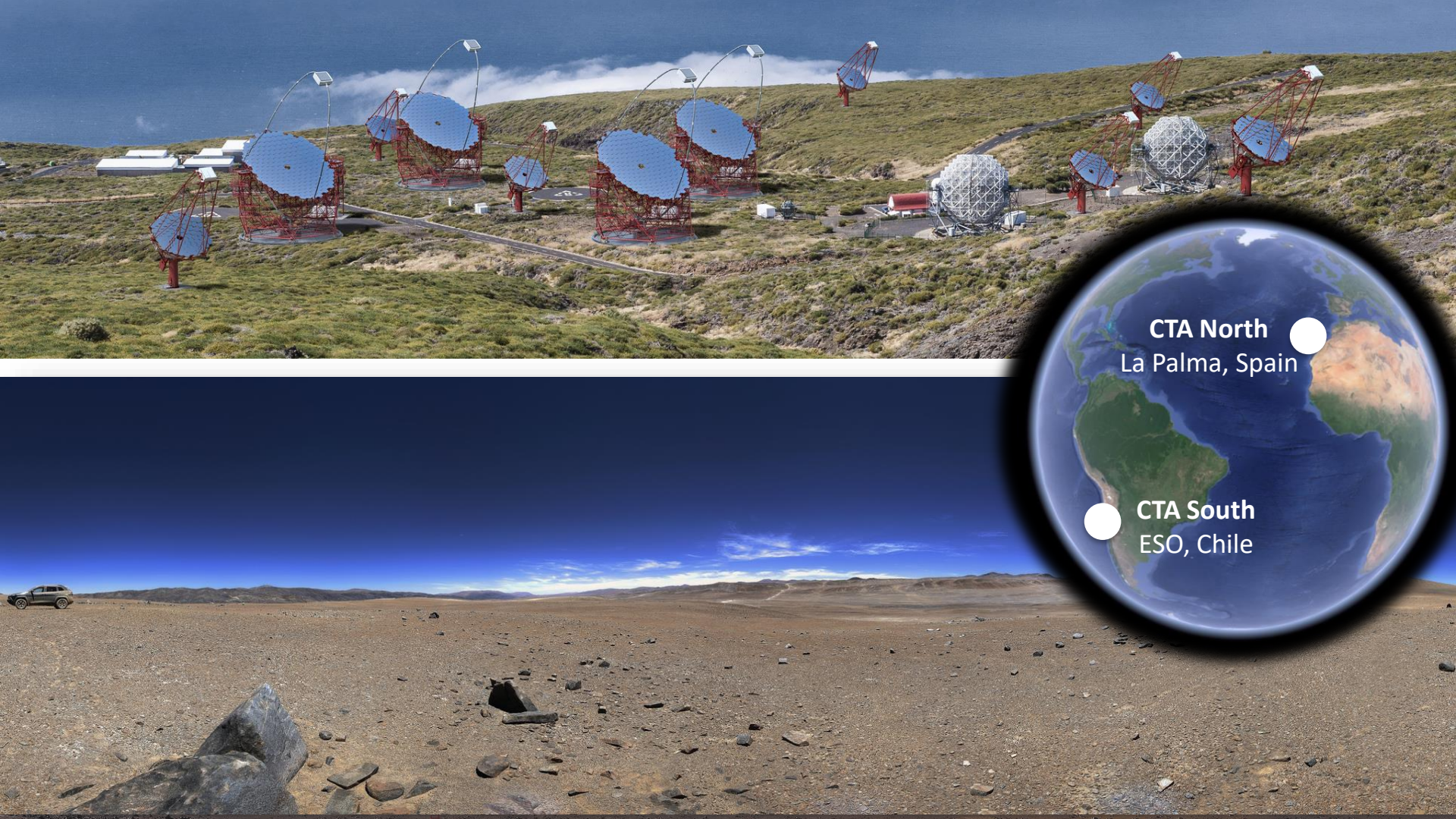
Spectrum-averaged sensivitity

Impact of site altitude

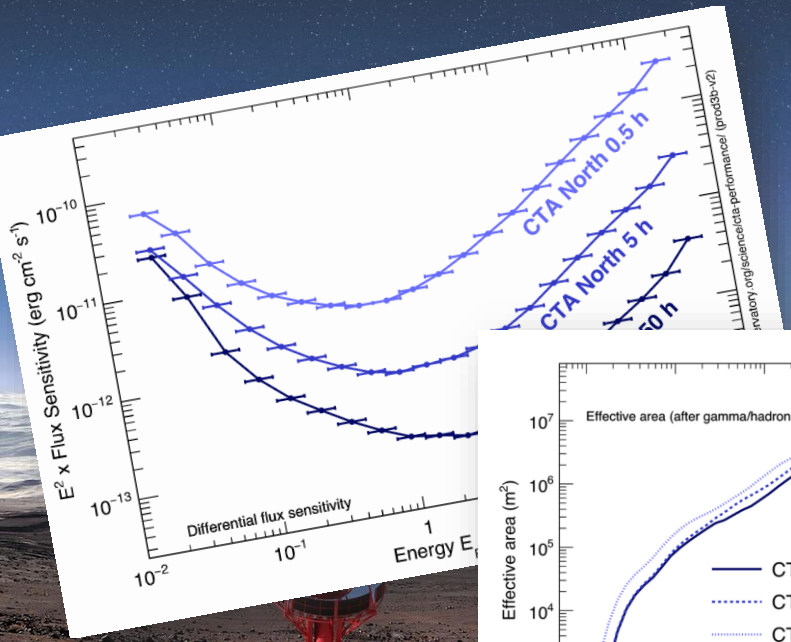


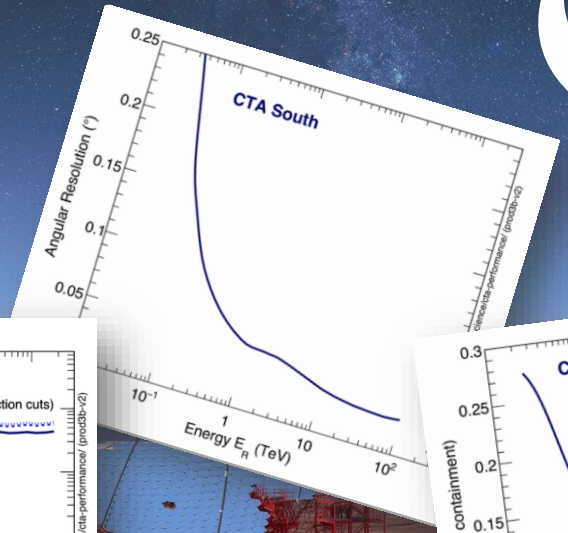
NIGHT SKY BRIGHTNESS

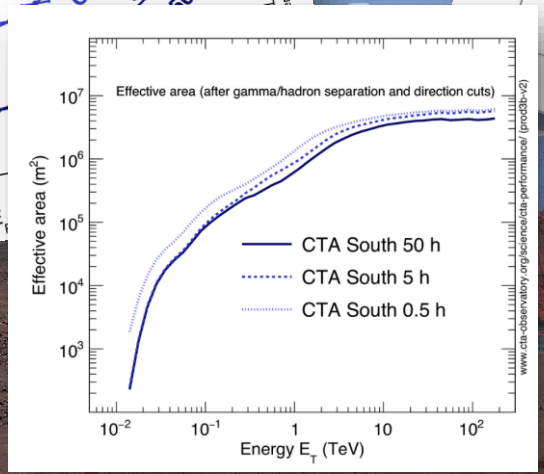


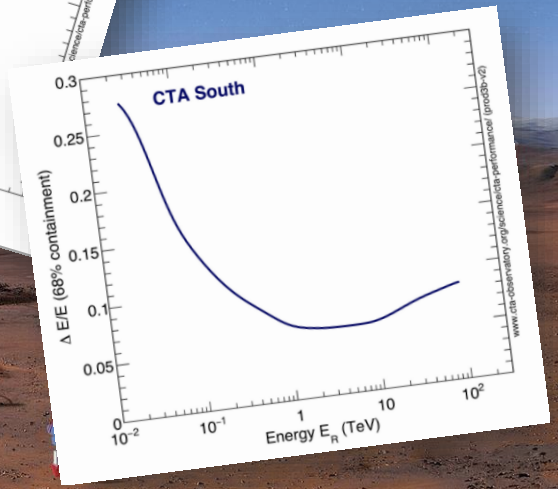

CTA North
La Palma, Spain
CTA South
ESO, Chile

CTA Performance

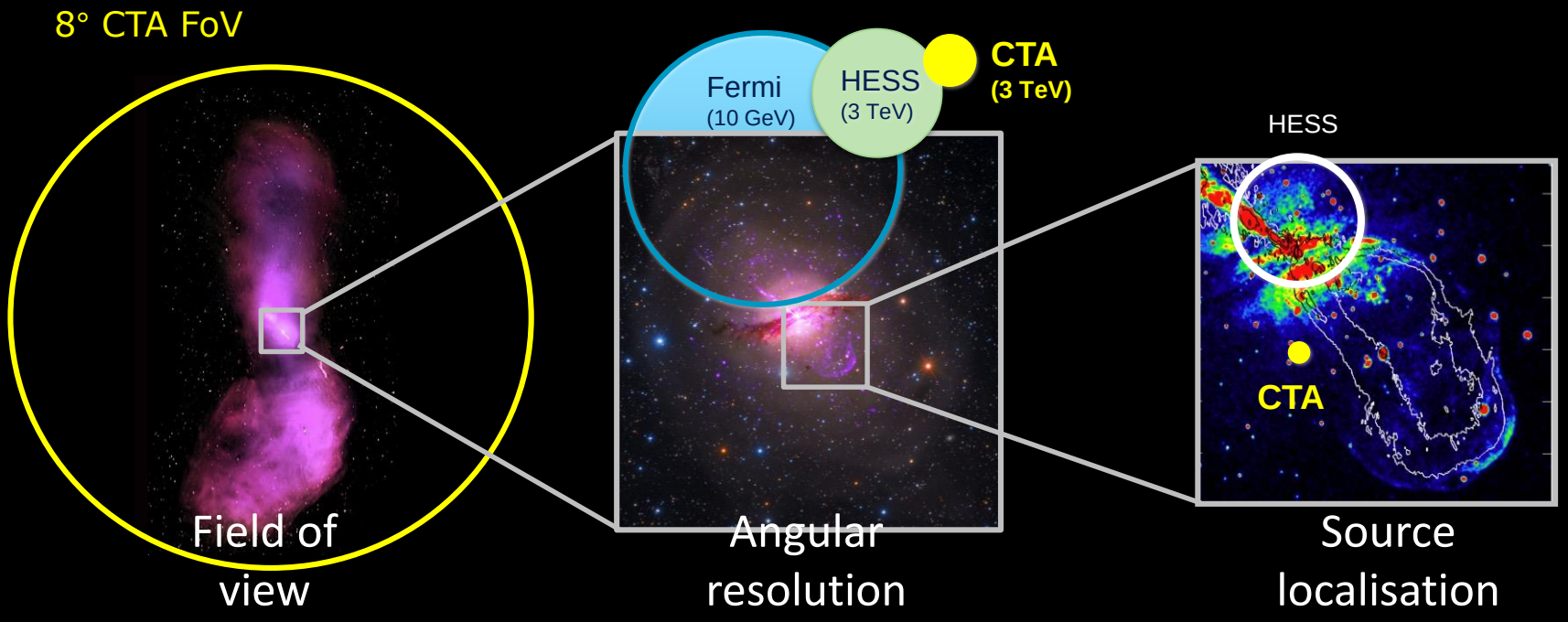






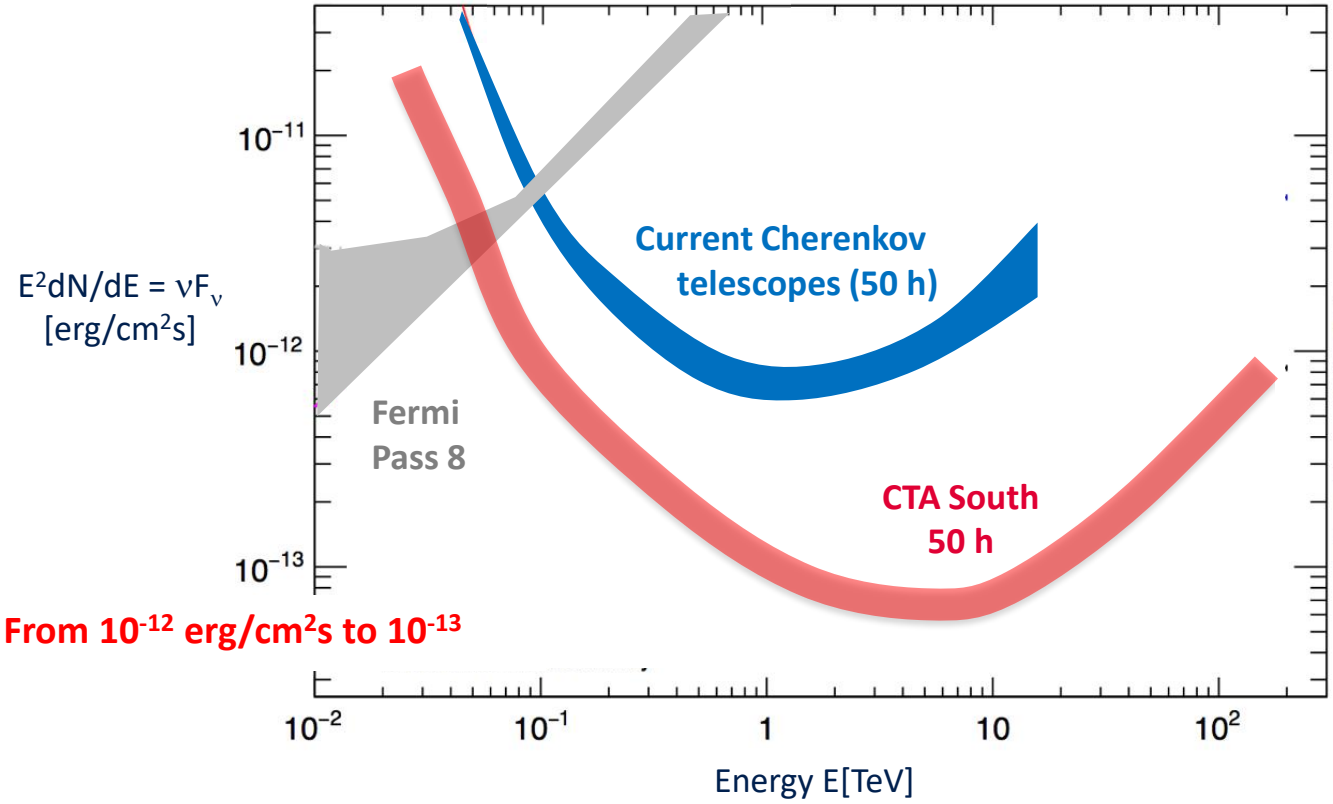


RESOLVING POWER



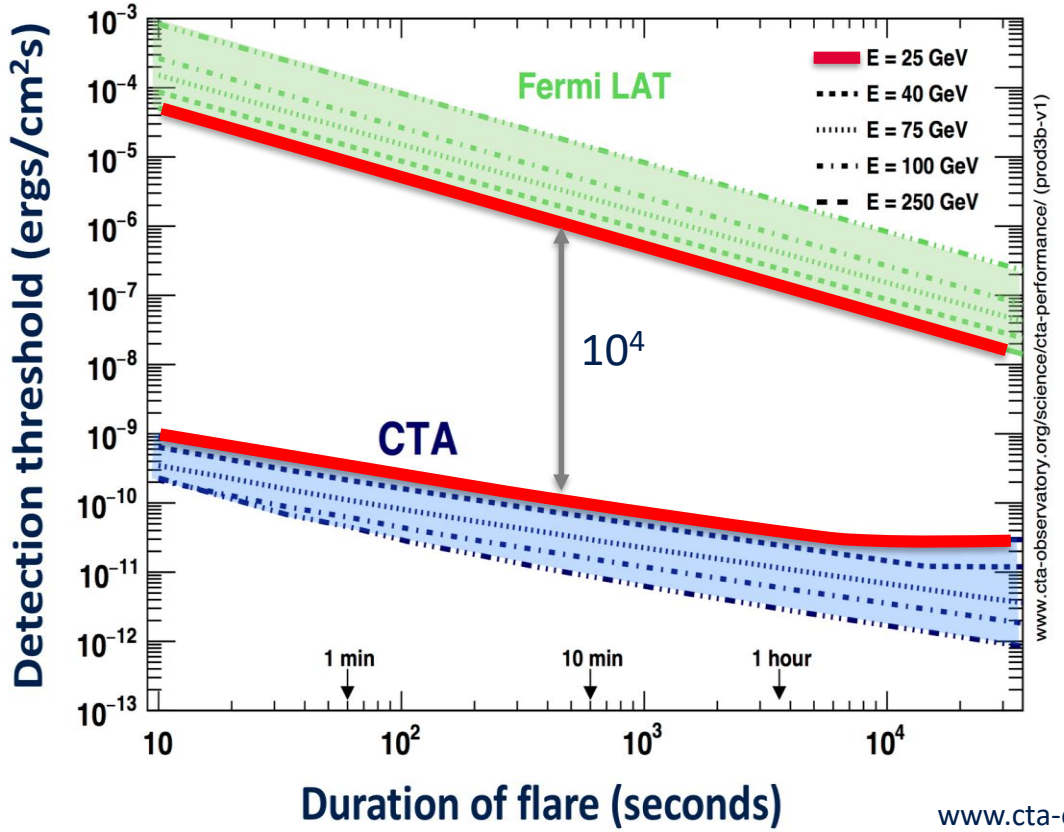
Example: nearby active galaxy Centaurus A

SENSITIVITY (STEADY SOURCES)

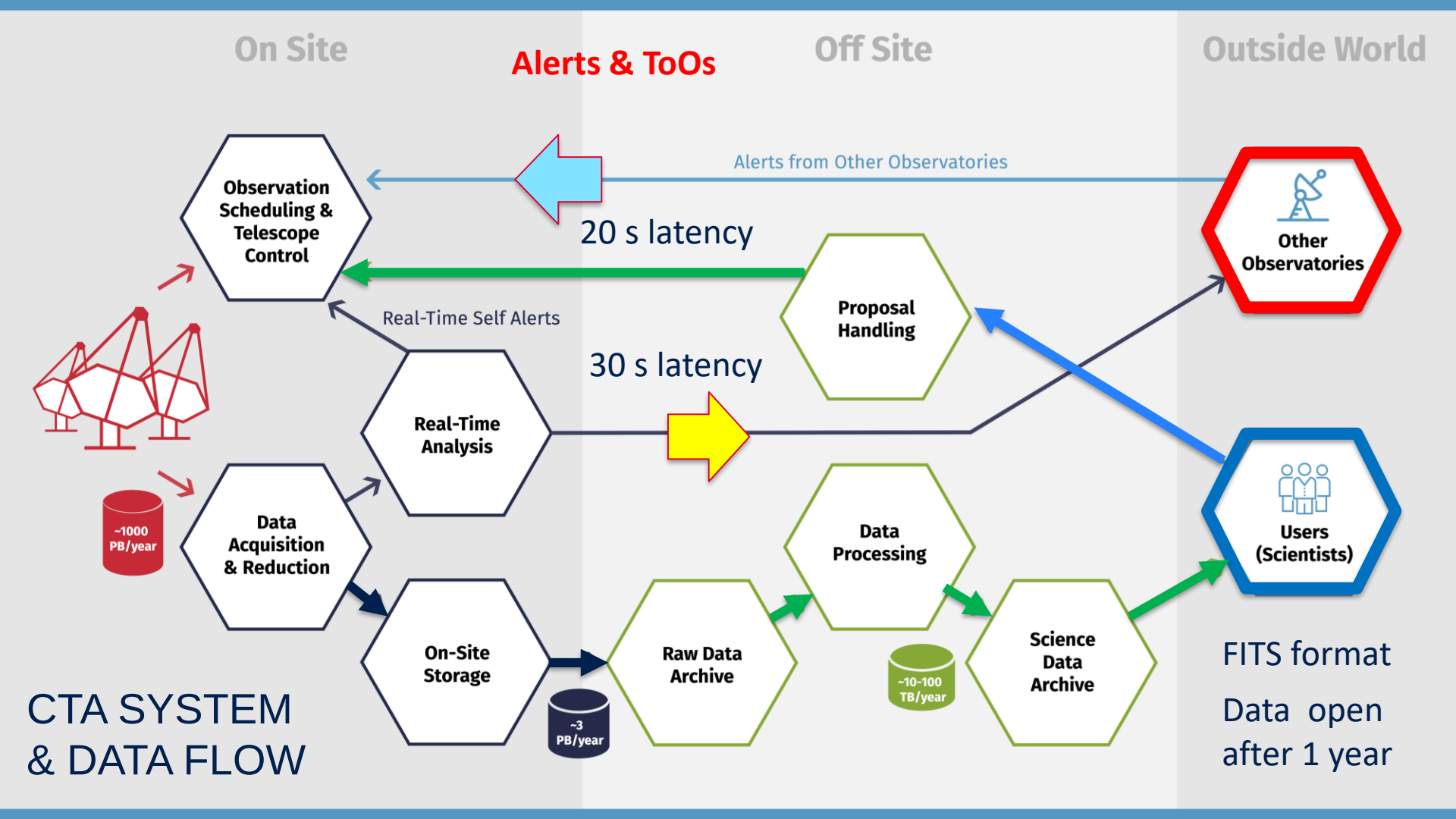


From 10^{-12} erg/cm^{2}s to 10^{-13}

FLARE SENSITIVITY (25 GEV)

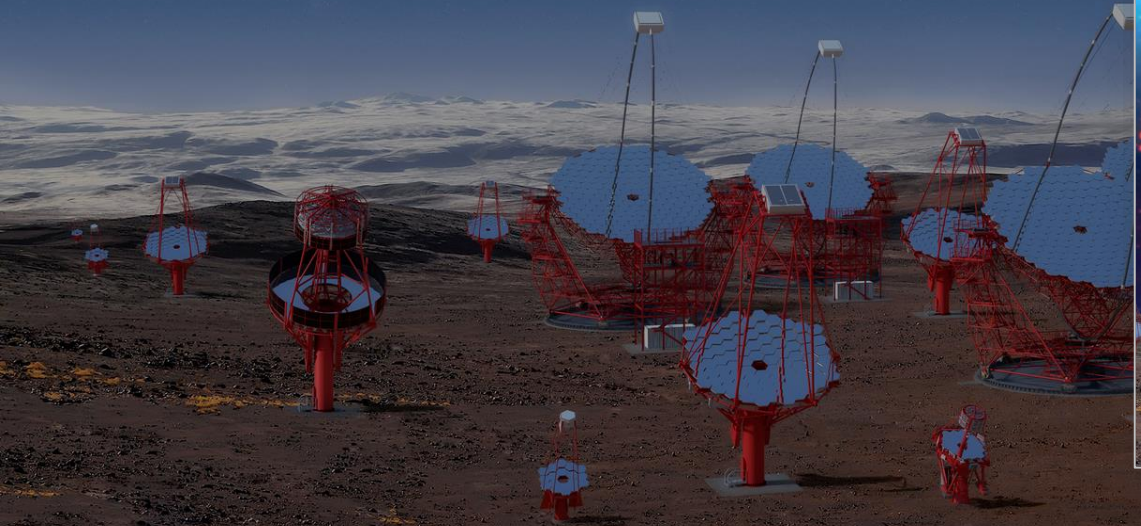


USING CTA


On Site
Alerts & ToOs
Off Site
Outside World
Observation Scheduling & Telescope Control
Alerts from Other Observatories
20 s latency
Other Observatories
Proposal Handling
Real-Time Self Alerts
30 s latency
Real-Time Analysis
~1000 PB/year
Data Acquisition & Reduction
Data Processing
Users (Scientists)
On-Site Storage
Raw Data Archive
~3 PB/year
~10-100 TB/year
Science Data Archive
CTA SYSTEM & DATA FLOW
FITS format
Data open after 1 year

CTA OBSERVATORY

During the first decade:
~40% Key Science Projects
(CTA Consortium)
~50% User time
~10% Host country time



www.worldscientific.com/worldscibooks/10.1142/10986

Key Science Projects

www.worldscientific.com/worldscibooks/10.1142/10986

KEY SCIENCE PROJECTS

provide legacy data sets and data products

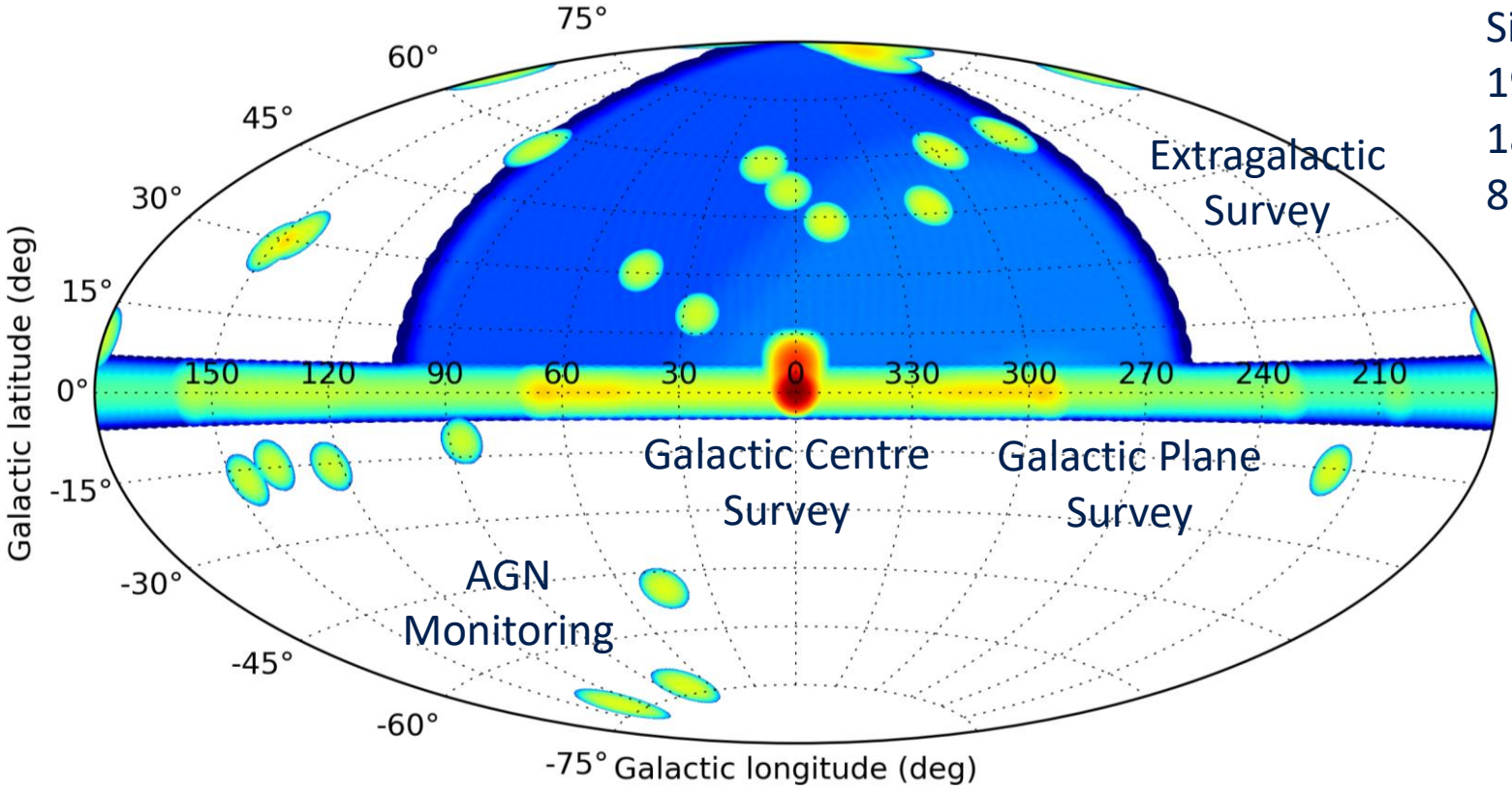
1. Dark Matter Programme
2. Galactic Centre
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Beyond Gamma Rays

Surveys

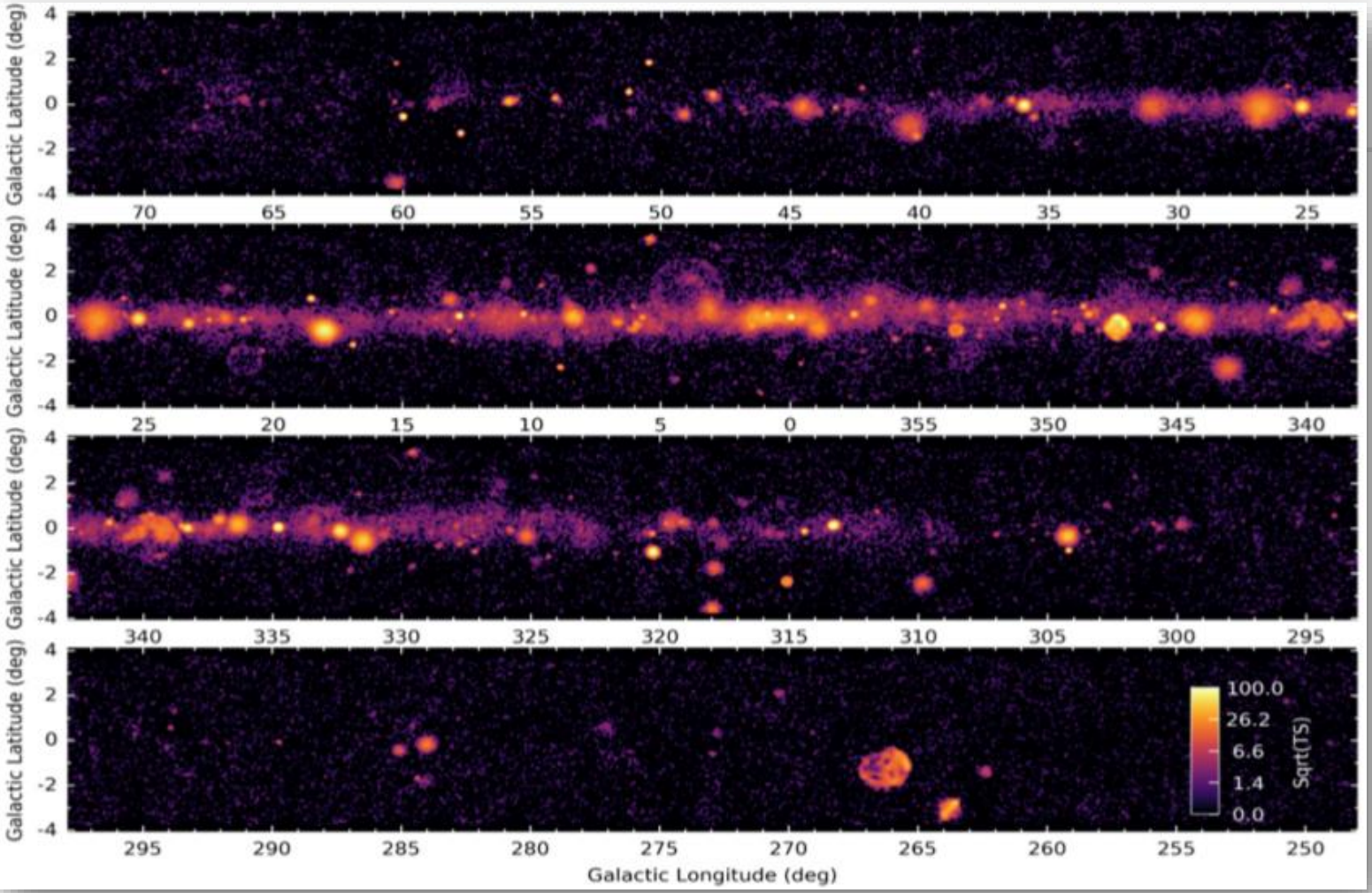
Key objects

www.worldscientific.com/worldscibooks/10.1142/10986

DATA CHALLENGE 1 EXPOSURE



Simulated:
1980 h South
1815 h North
8132 pointings

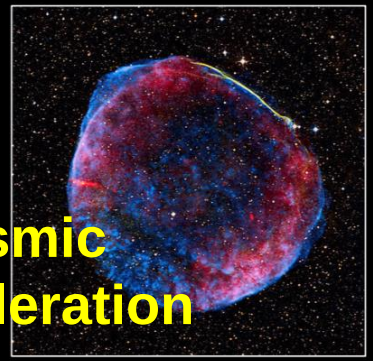


Simulated:
2445 h
4941 pointings

KEY SCIENCE PROJECTS

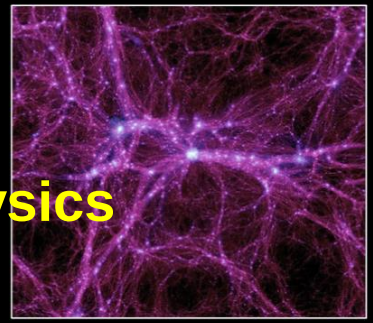
provide legacy data sets and data products

1. Dark Matter Programme
2. Galactic Centre
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Beyond Gamma Rays



Theme 1: Cosmic Particle Acceleration

Theme 2: Probing Extreme Environments



Theme 3: Physics Frontiers

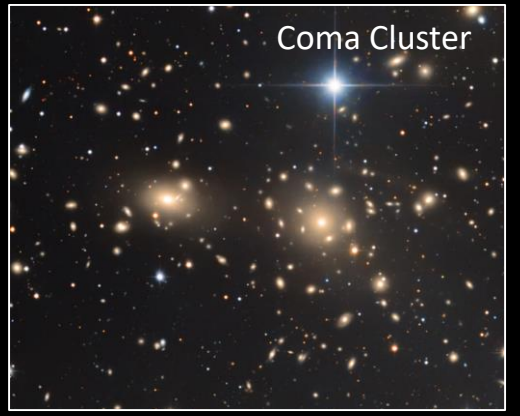
SCIENCE THEMES AND KEY SCIENCE PROJECTS

Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

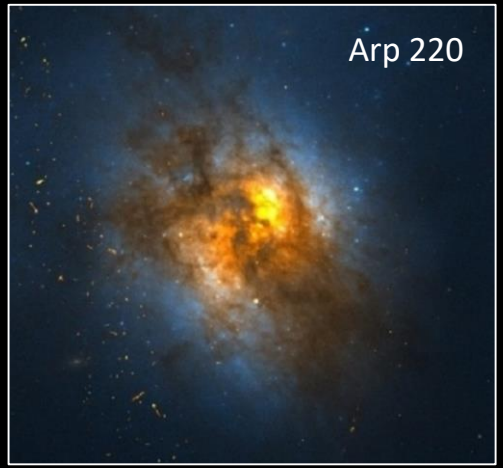
A CENSUS OF COSMIC PARTICLE ACCELERATORS

J.Fritz,
W. Pietsch,
R. Gendler

Hubble Heritage Team



R. Carroll,
R. Gendler
B. Franke

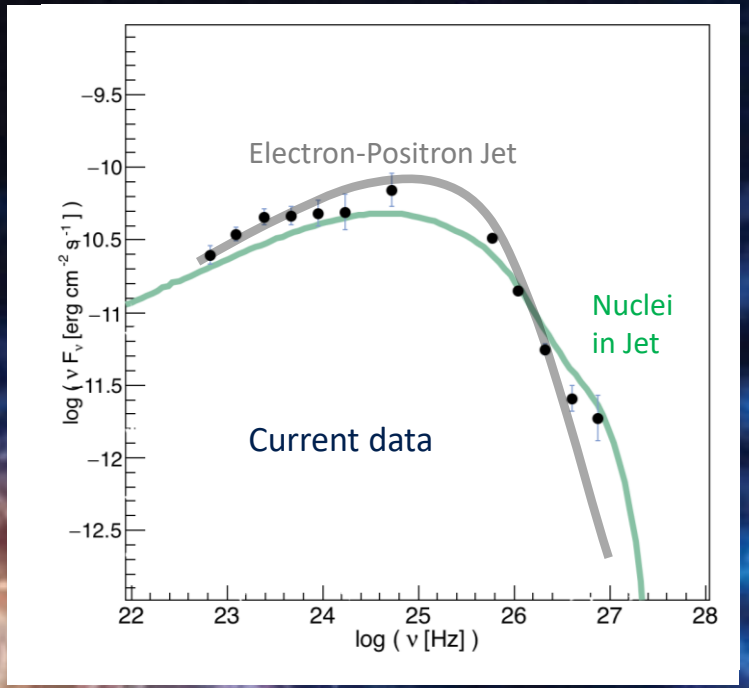


Univ. of Oklahoma
& NASA

ACROSS ALL COSMIC SCALES

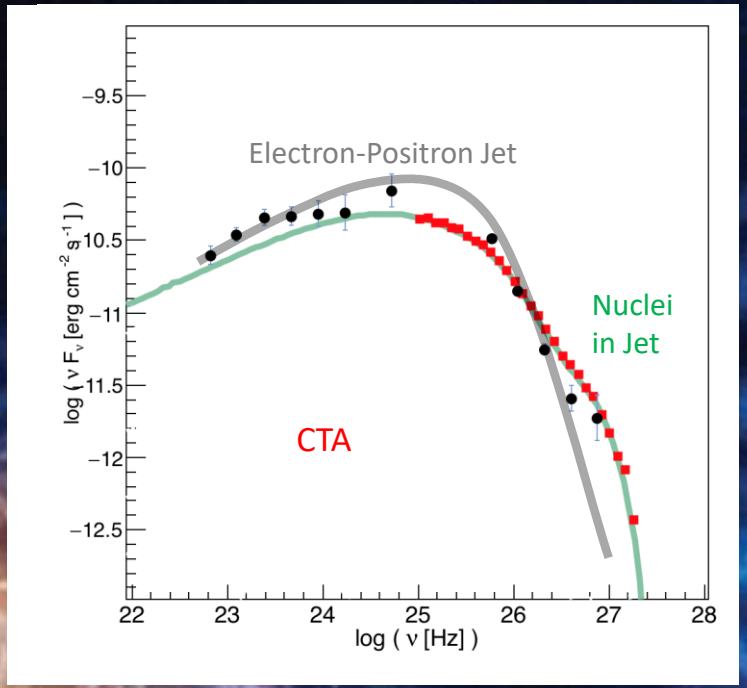
WHAT IS THE JET MADE OF?

Illustration: Scientific American



from: Science with CTA
www.worldscientific.com/worldscibooks/10.1142/10986

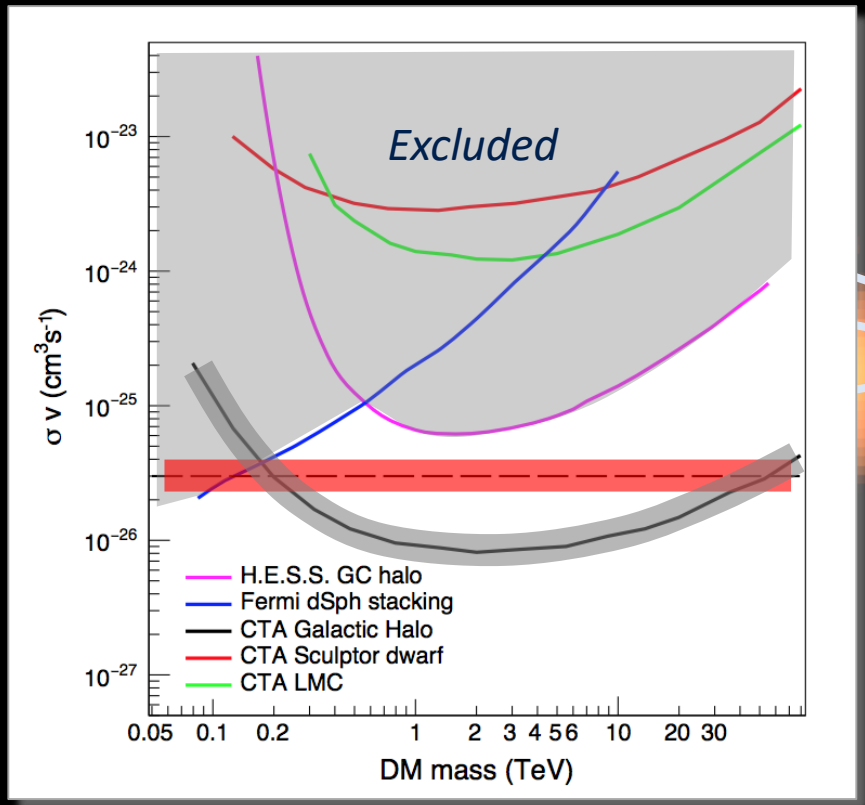
Illustration: Scientific American

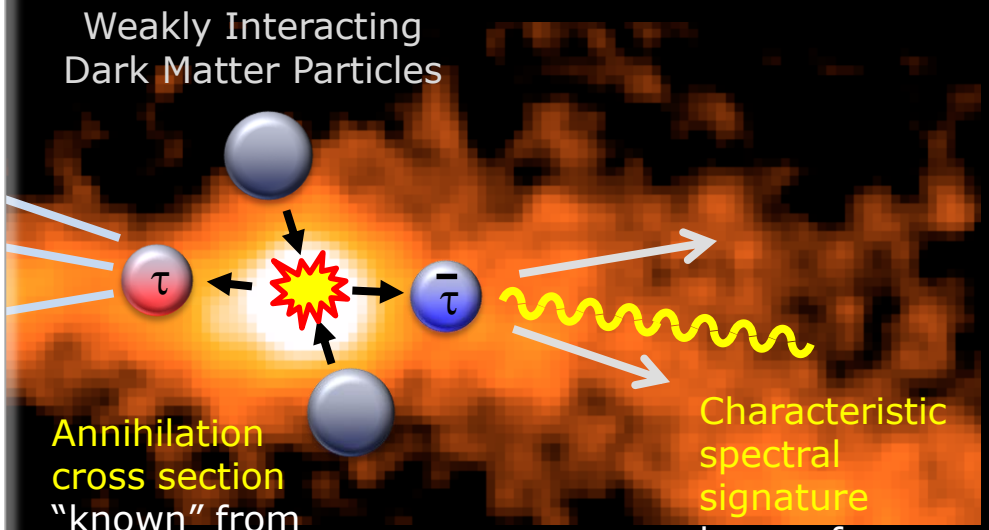


from: Science with CTA
www.worldscientific.com/worldscibooks/10.1142/10986

Illustration: Scientific American

GAMMA RAYS
TRACE ANNIHILATING OR DECAYING RELICS





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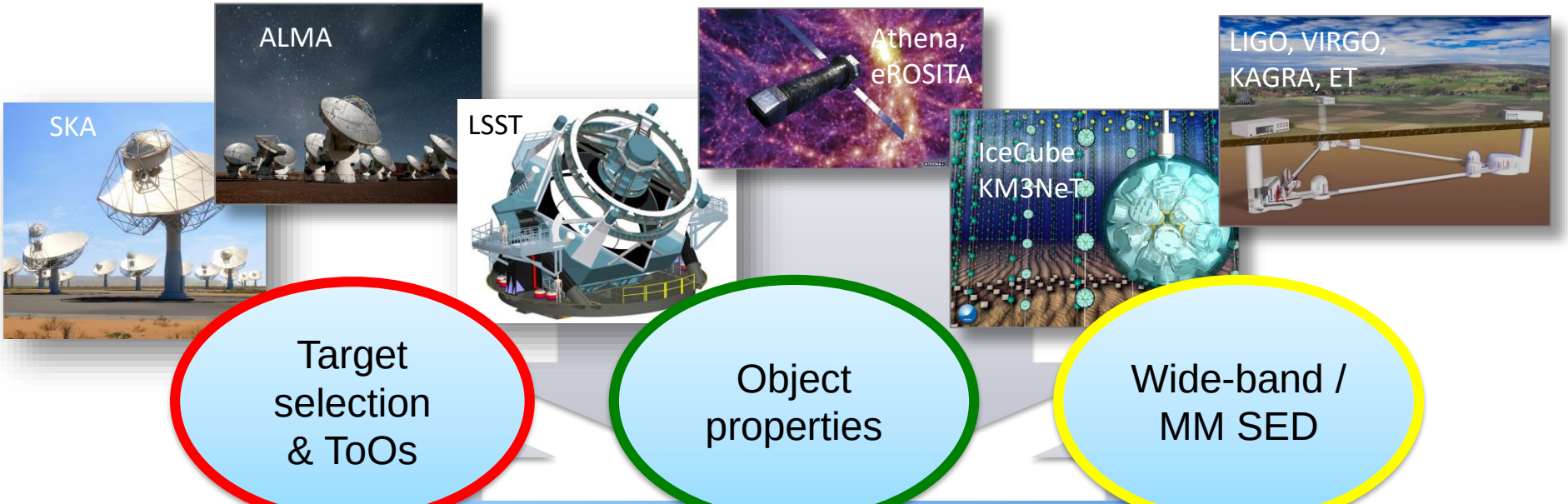
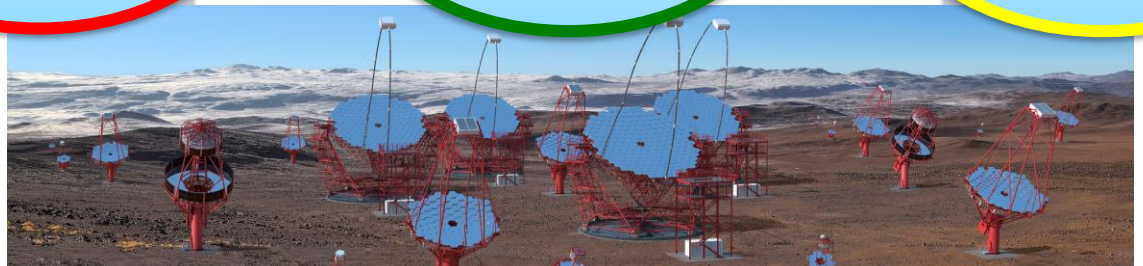
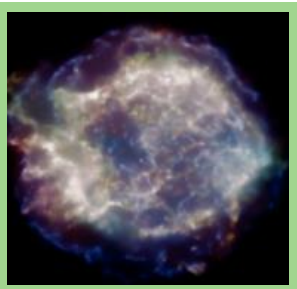
CRUCIAL: MULTIWAVELENGTH & MULTIMESSENGER LINKS



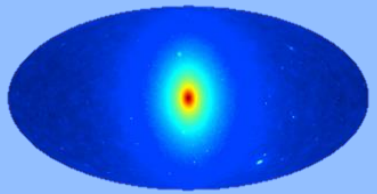


CTA SCIENCE

In-depth understanding
of known objects and
their mechanisms



Expected discoveries
of new object classes



The fun part:
Things we haven’t thought of

?