THE CHERENKOV TELESCOPE ARRAY (CTA) AND THE ASTRI MINI-ARRAY OF TELESCOPE PRECURSORS

A. BULGARELLI (INAF) ON BEHALF OF ASTRI COLLABORATION AND CTA CONSORTIUM

MANY SLIDES PROVIDED BY G. PARESCHI

CONTRIBUTIONS FROM V. FIORETTI, A. ZOLI, V. CONFORTI, M. TRIFOGLIO, F. GIANOTTI

Bologna, 5 November 2015

OUTLINE

- What is CTA?
  - CTA is an Observatory
  - CTA is a Consortium
  - CTA is a Big Science Project
    - Organisation, costs, management under budget constraint
- Cherenkov Telescope Array (CTA) Concept
  - Key Science Projects
  - Requirements & drivers
  - CTA design & performance
- ASTRI and CTA/ASTRI Mini-Array
- Data challenges

THE CTA CONSORTIUM

5 continents
28 countries
85 parties
176 institutes
1193 members (390 FTE)

Now also Chile jointed the CTA Consortium

THE CTA CONSORTIUM AND THE CTA OBSERVATORY

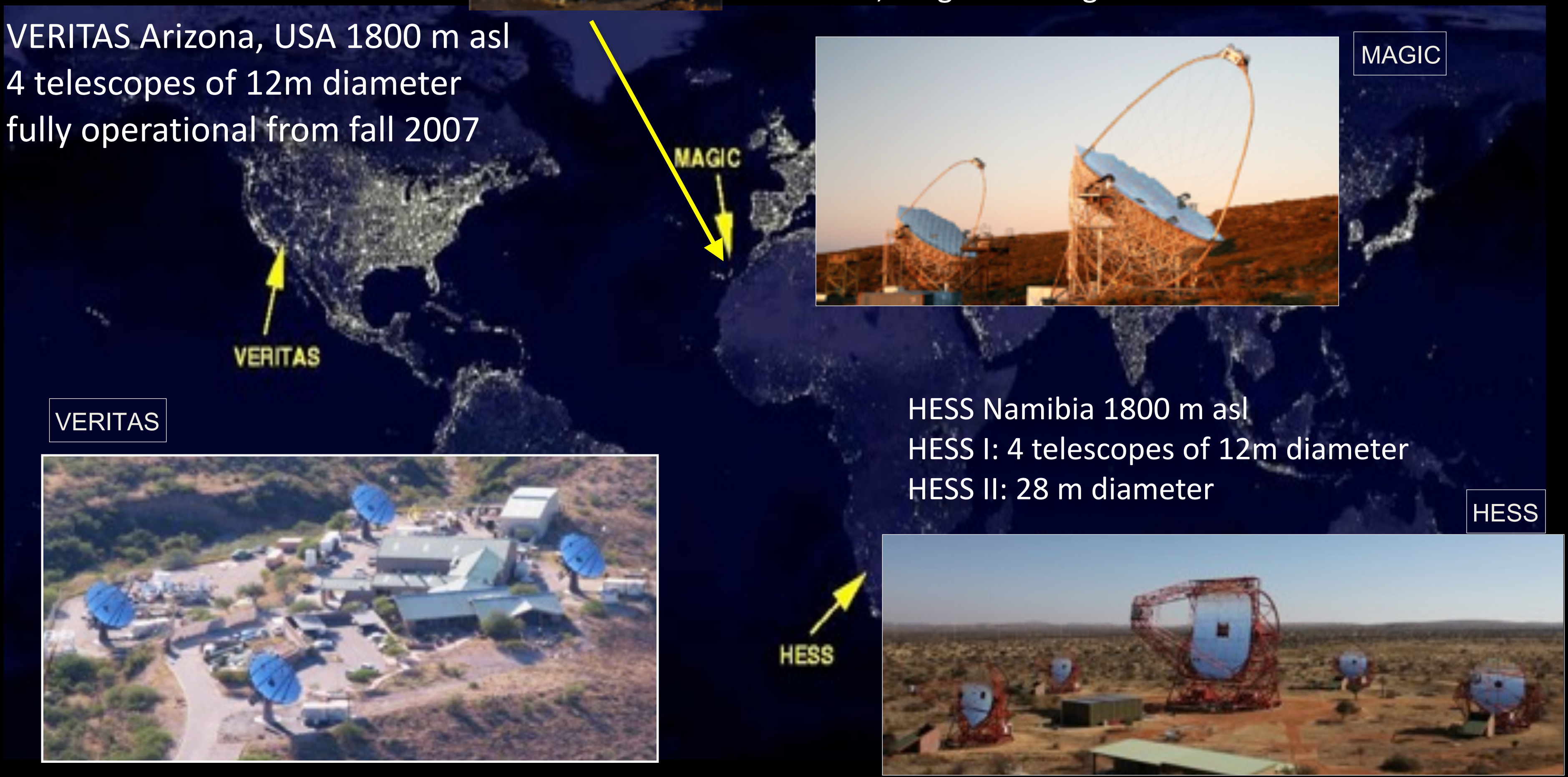
- **The CTA Consortium,**
  - which has **proposed, planned, designed and prototyped the CTA facility**,
  - contributes through its institutes to the **construction** and **aspects of operation**,
  - and which will carry out the **Key Science Projects (KSPs)**
- **The CTA Observatory,** a legal entity
  - **coordinating facility construction and operating the facility**,
    - for use both through the CTA Consortium's Key Science Projects,
    - and through the open program in which observation time is awarded on the basis of proposals responding to Announcements of Opportunity (AOs).
- **the Archive Access** under which all CTA gamma ray data will be openly available, after a proprietary period.

CURRENT IACT EXPERIMENTS

FACT, La Palma
1 x 9.5 m^2 telescopes

FACT

MAGIC Canary Islands 2200 m asl
2 x 17m telescopes. Magic I in operation since Oct 2003, Magic II first light shown at ICRC09



VERITAS Arizona, USA 1800 m asl
4 telescopes of 12m diameter
fully operational from fall 2007

MAGIC

VERITAS

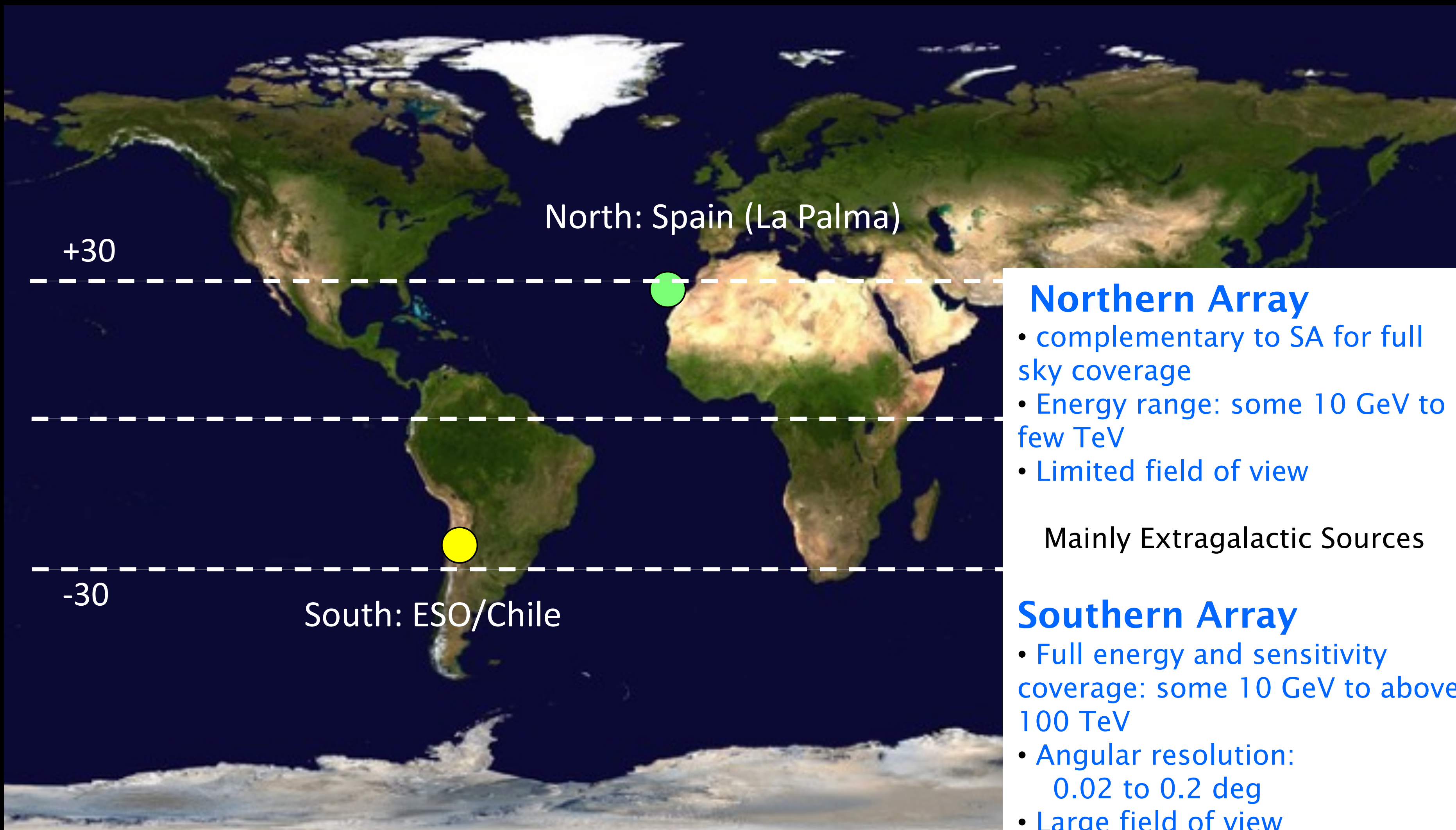
HESS Namibia 1800 m asl
HESS I: 4 telescopes of 12m diameter
HESS II: 28 m diameter

HESS

Dec 2003: 4 telescope commissioned
2014: HESS II commissioning

CTA SITES

One Observatory with two (asymmetric) sites for all-sky coverage



Northern Array

- complementary to SA for full sky coverage
- Energy range: some 10 GeV to few TeV
- Limited field of view

Mainly Extragalactic Sources

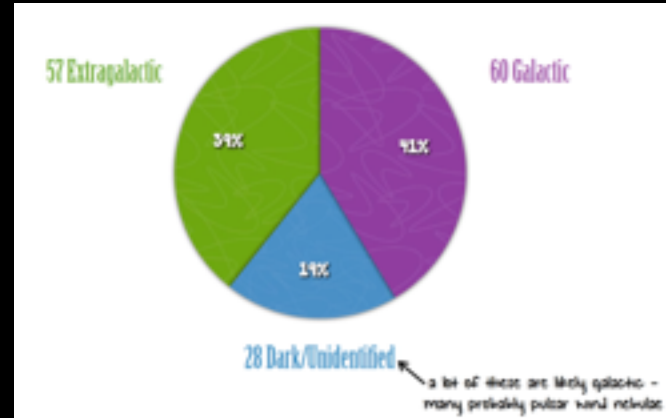
Southern Array

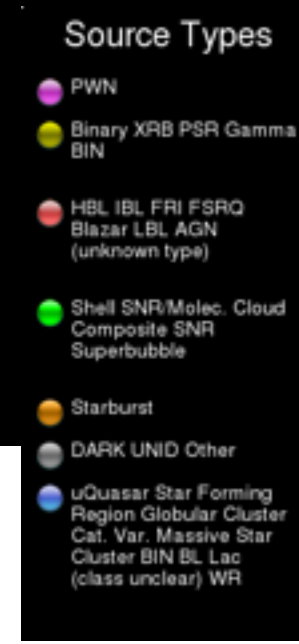
- Full energy and sensitivity coverage: some 10 GeV to above 100 TeV
- Angular resolution:
  0.02 to 0.2 deg
- Large field of view

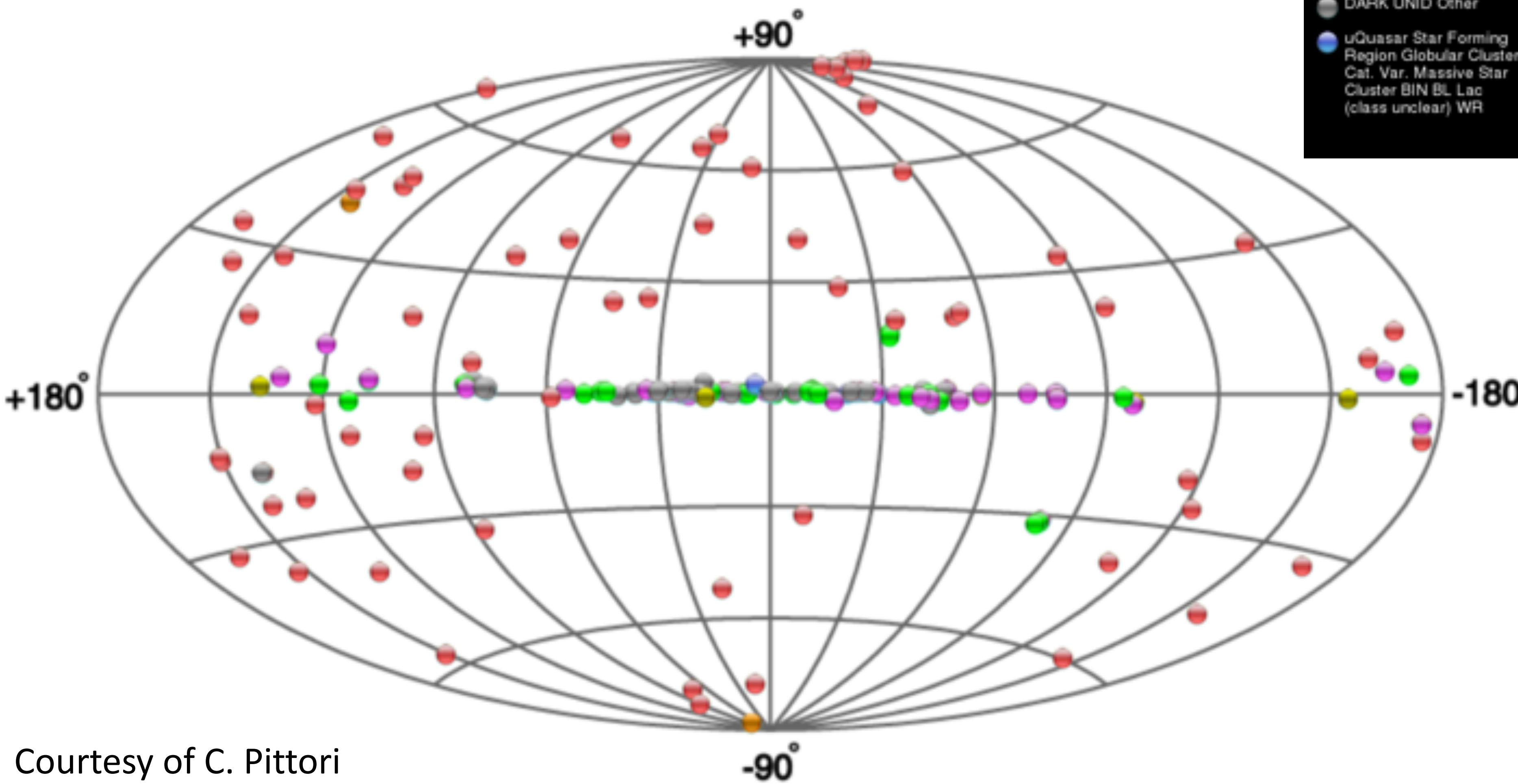
Galactic + Extragal. Sources

TEVCAT

November 2015: 175 sources (< 10 in 2003)

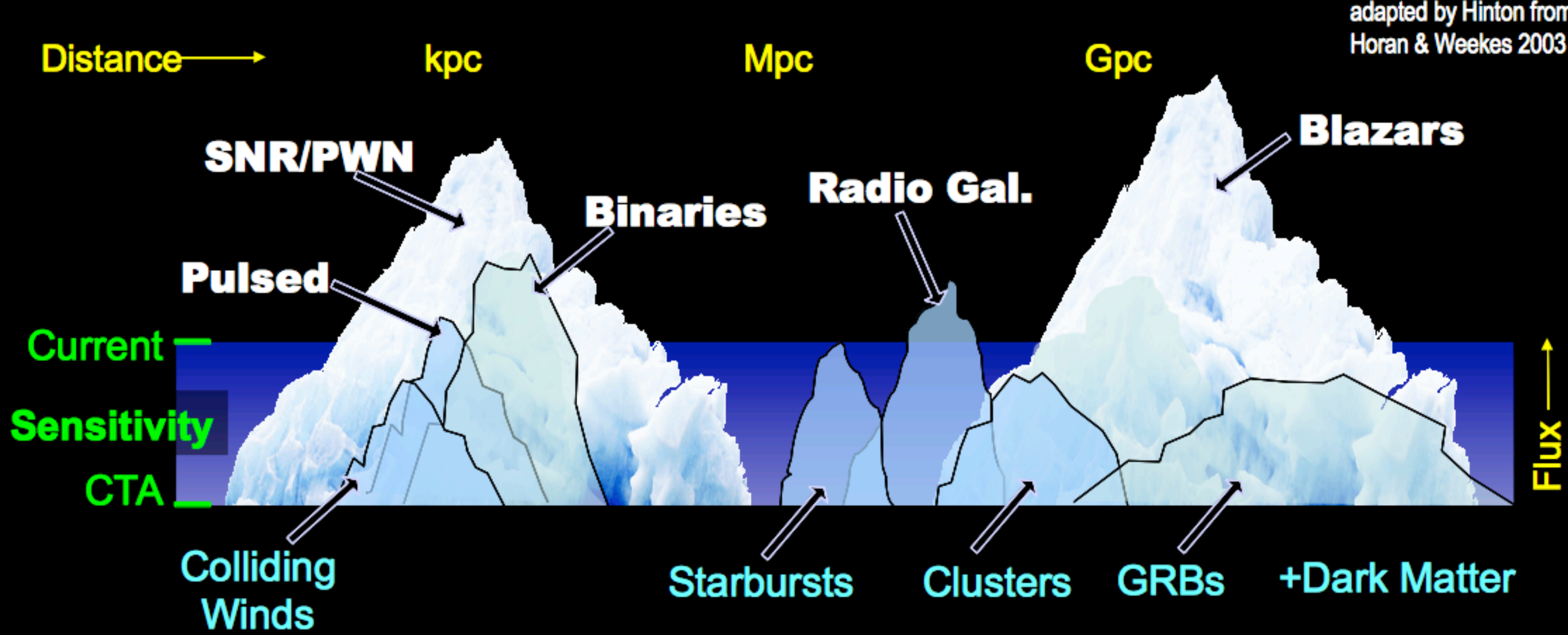






Courtesy of C. Pittori

Science Potential



- **Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg**
- **What big science questions remain ?**

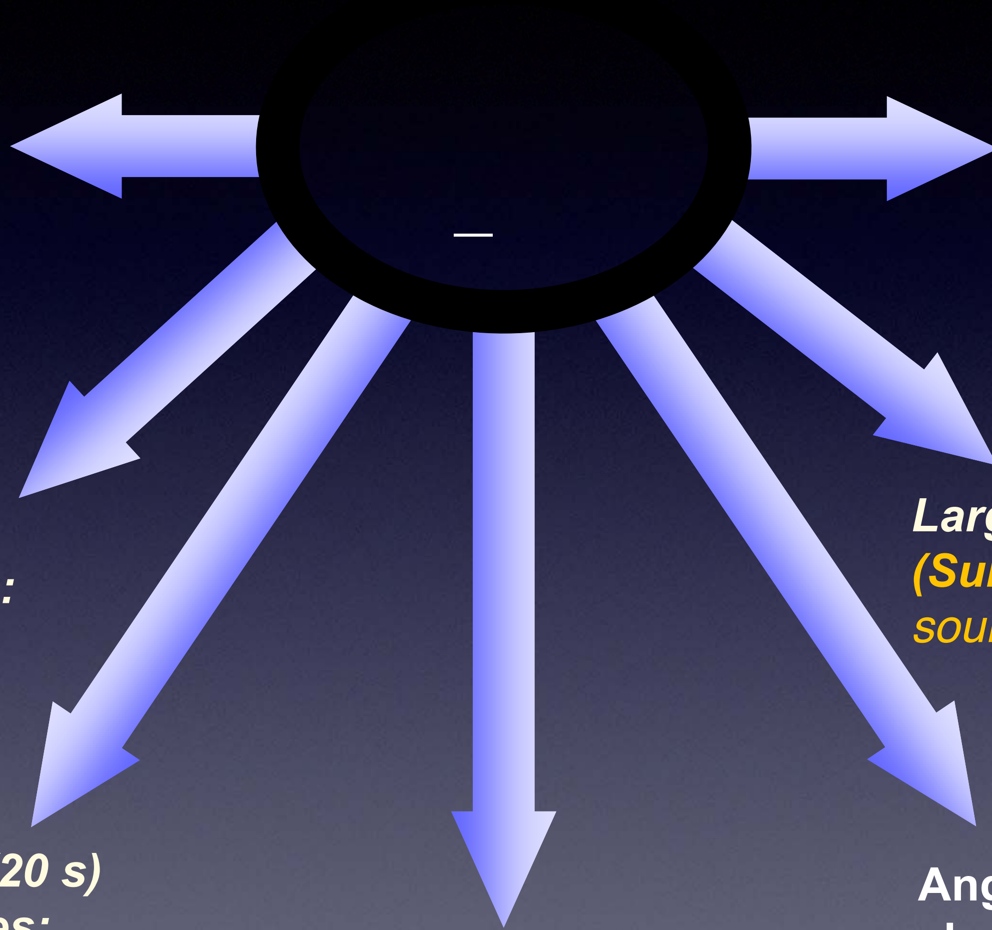
CTA KEY SCIENCE PROJECTS

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?					✔	✔			✔✔	

Figure 3.1 – Matrix of CTA science questions and proposed key science projects (KSPs). The KSPs are sets of observations addressing multiple science questions within the CTA themes. KSPs which contribute to the overall programme aimed at Dark Matter detection are indicated in green, with the exclusively dark-matter-oriented targets described entirely within the DM Programme Section (4). For KSPs simultaneously addressing DM and other physics/astrophysics, the motivation and context for the DM element is again described in Section 4. KSPs are ordered with dark matter due to its importance and transversal nature, followed by surveys and then more focused KSPs by increasing distance scale.

REQUIREMENTS

Requirements & Drivers



Energy coverage down to 20 GeV
(Discovery domain: GRBs, Dark Matter)

Energy coverage up to 300 TeV
(Pevatrons, hadron acceleration)

Good energy resolution, ~10-15%:
(Lines, cutoffs)

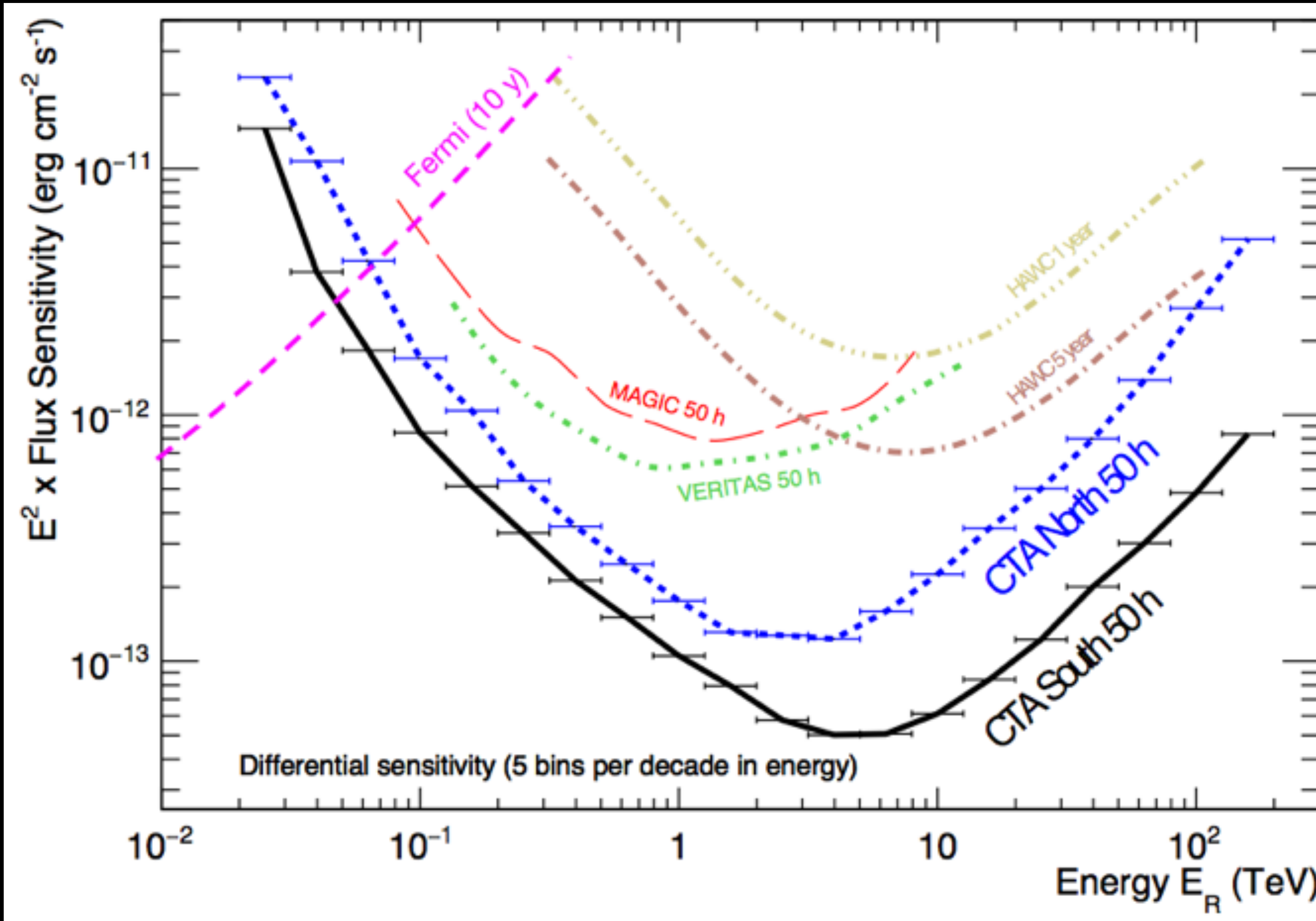
Large Field of view 8-10°
(Surveys, extended *sources, flares)*

Rapid Slew (20 s) to catch flares:
(Transients)

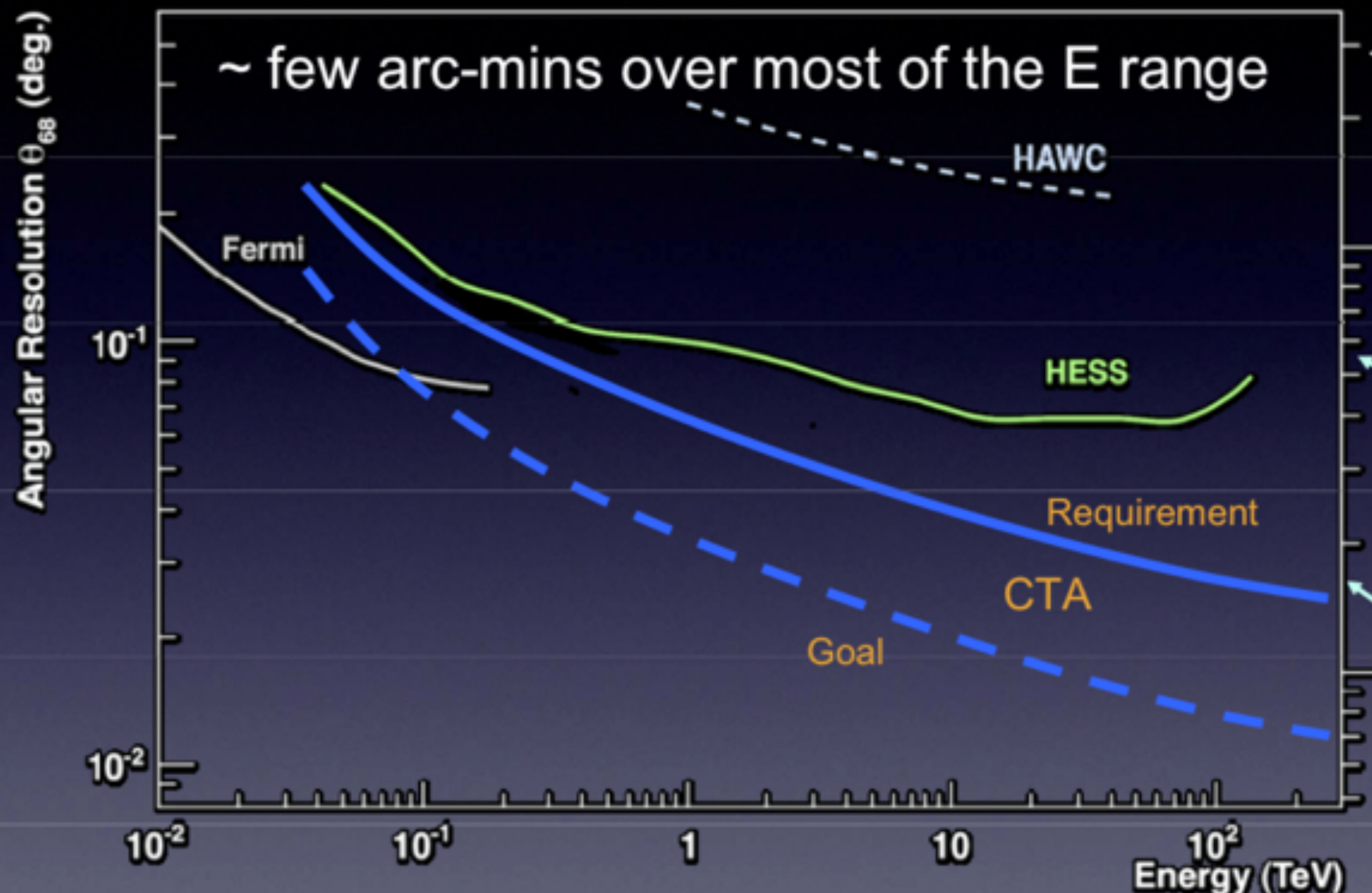
10x Sensitivity & Collection Area
(Nearly every topic)

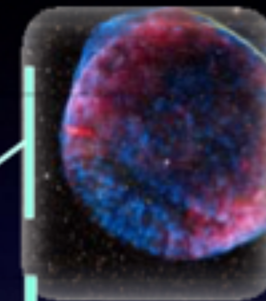
Angular resolution < 0.1° above most of E range
(Source morphology)

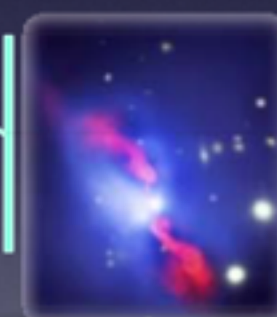
CTA SENSITIVITY



Angular Resolution

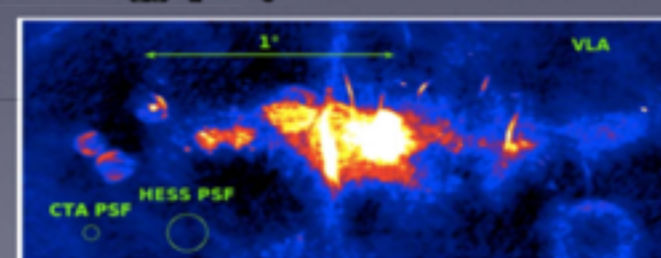




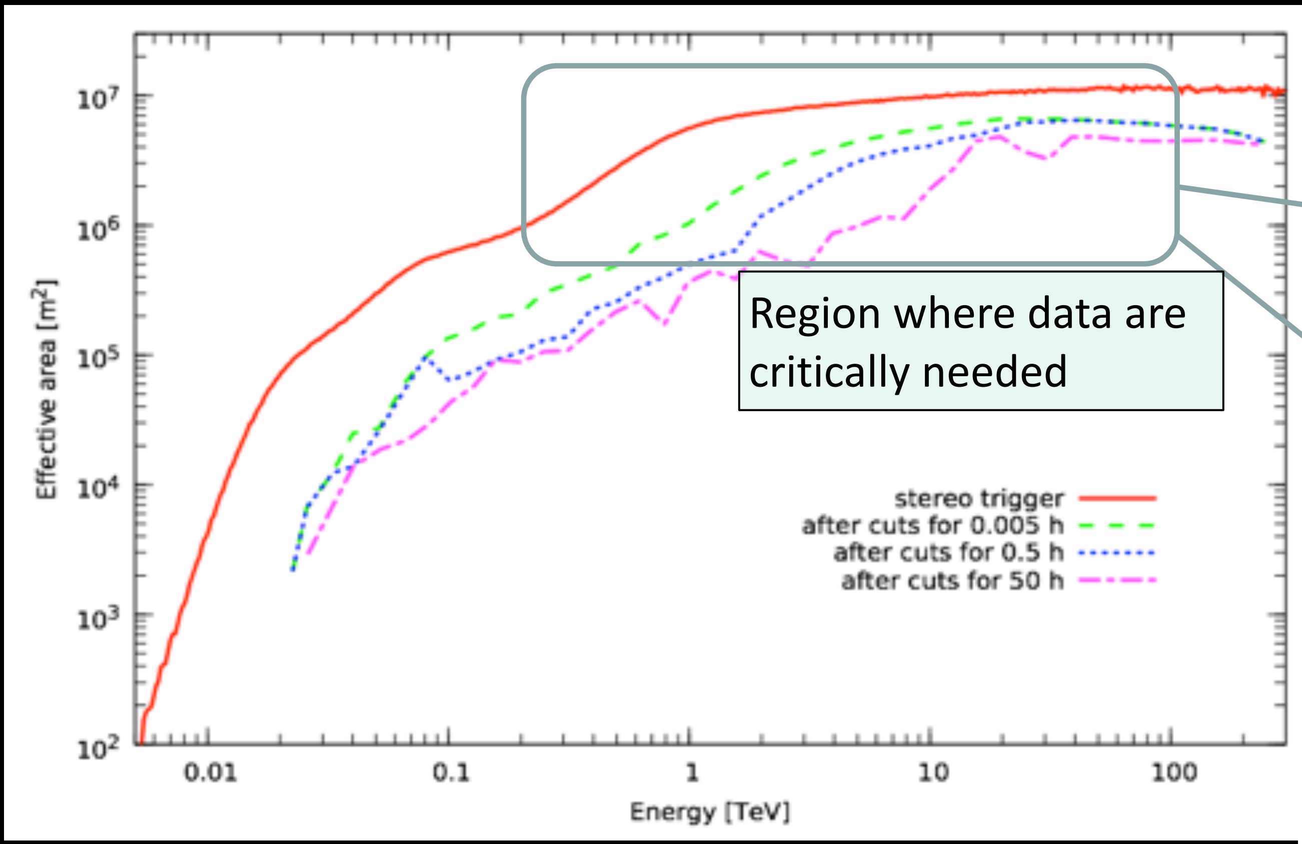


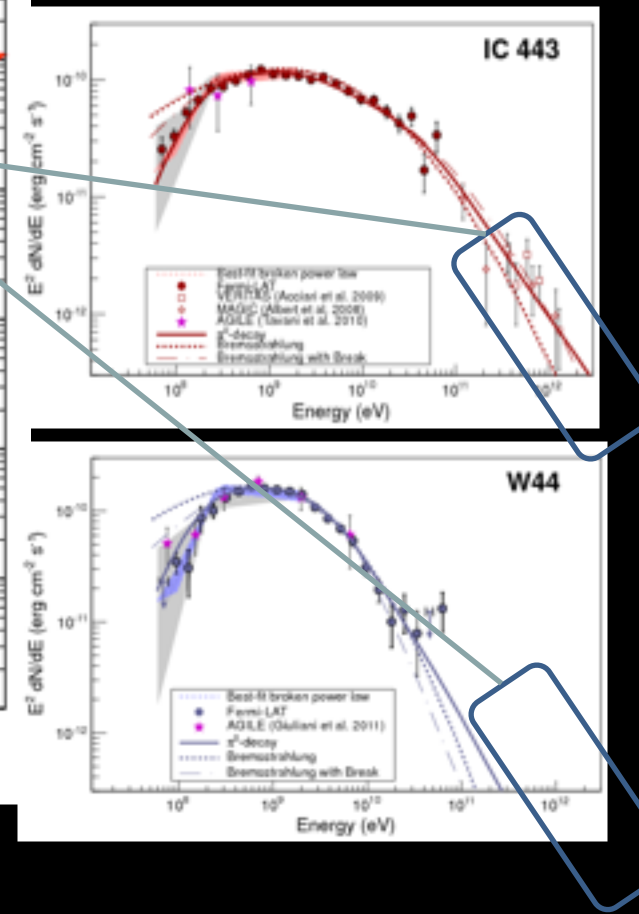
Angular resolution critical for
Source morphology and identification

Galactic-Center
region



CTA EFFECTIVE AREA





A_{coll} ~10^7 m^2 above 10 TeV (*importance of SSTs*)

Crucial for:

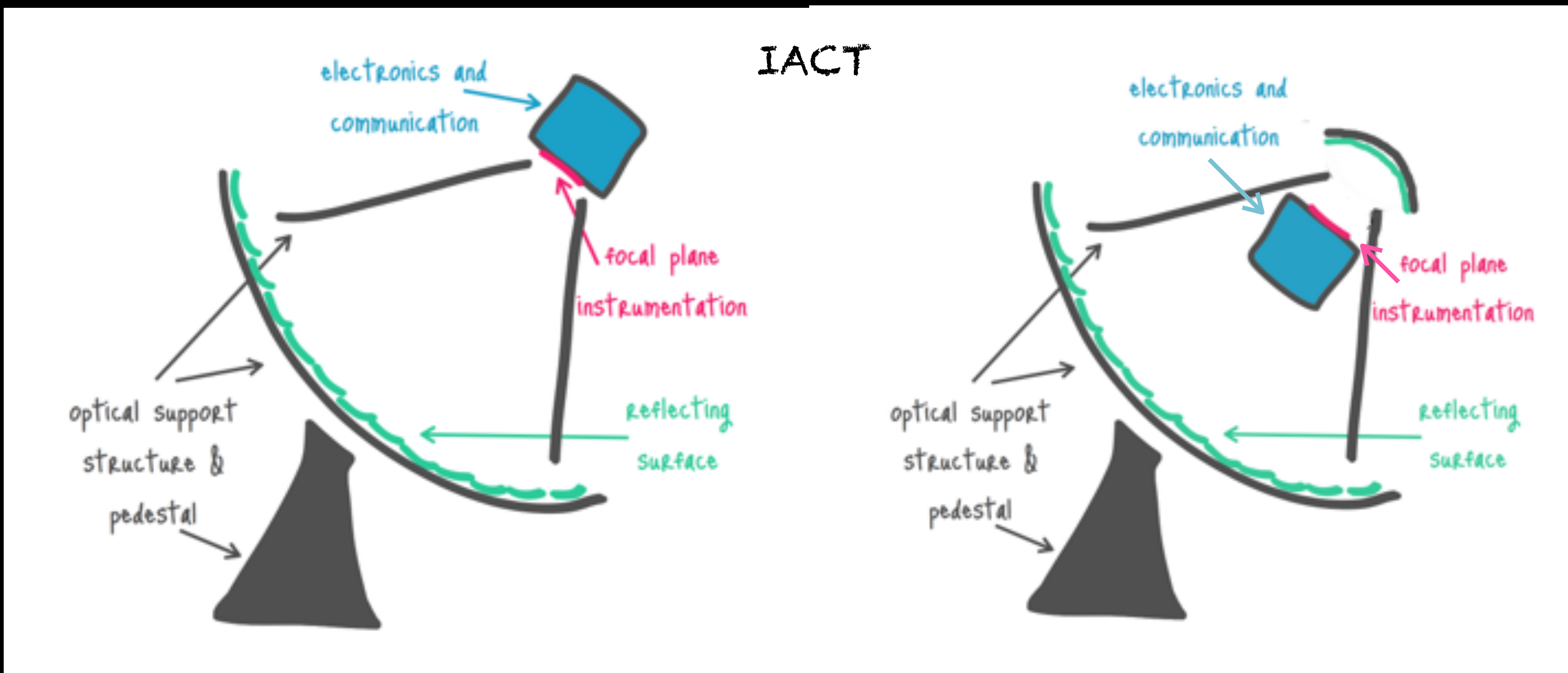
High-energy spectra, discovery of PeVatrons → Origin of CRs

DESIGN

THE TELESCOPES

Davies-Cotton configuration

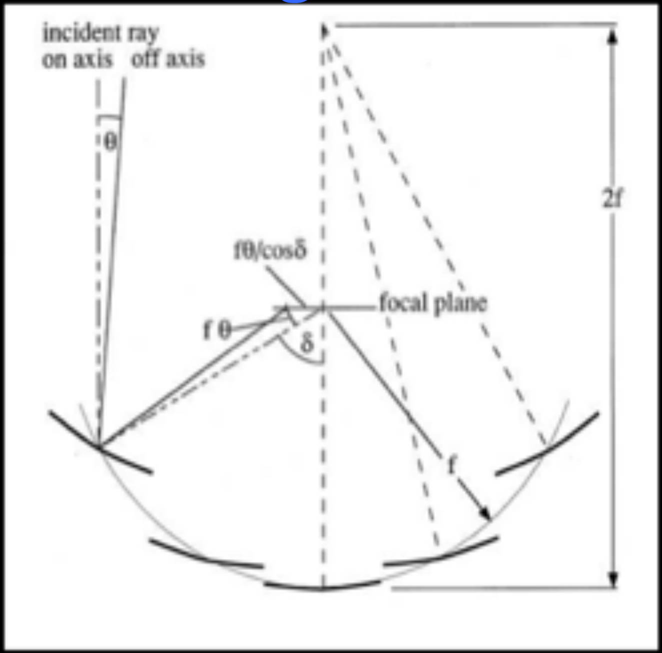
Schwarzschild-Couder configuration



THE MIRRORS

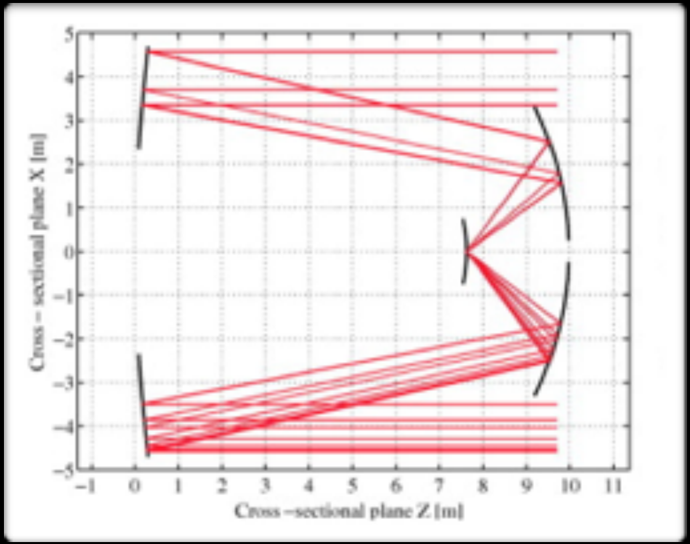
Segmented reflectors composed of many individual mirror facets

Davies-Cotton configuration



The **facets** are manufactured as <u>spherical mirrors</u> and arranged in a Davies-Cotton layout, in which all reflector facets have the same <u>focal length f</u>, which is identical to the focal length of the telescope as a whole. <u>The facets are arranged on a sphere with a radius of 2f</u>. Such an arrangement was chosen because of the cost and optical error reasons.

Schwarzschild-Couder configuration



V. Vassiliev, , S. Fegan, P. Brousseau
Astr. Phys. Volume 28 (1) ,2007, pp 10–27

two-mirror, **aplanatic optical systems** which are free from both coma and spherical aberrations.
S-C telescopes provide for wide FoV γ-ray observations, are isochronous, and can be optimized to have no vignetting across the field. They also allow for a significantly reduced plate scale, making them compatible with finely-pixelated cameras, which can be constructed from modern, cost-effective image sensors such as multi-anode PMTs, silicon PMTs (SiPMs).
The **primary mirror** could be segmented

THE MIRRORS/2

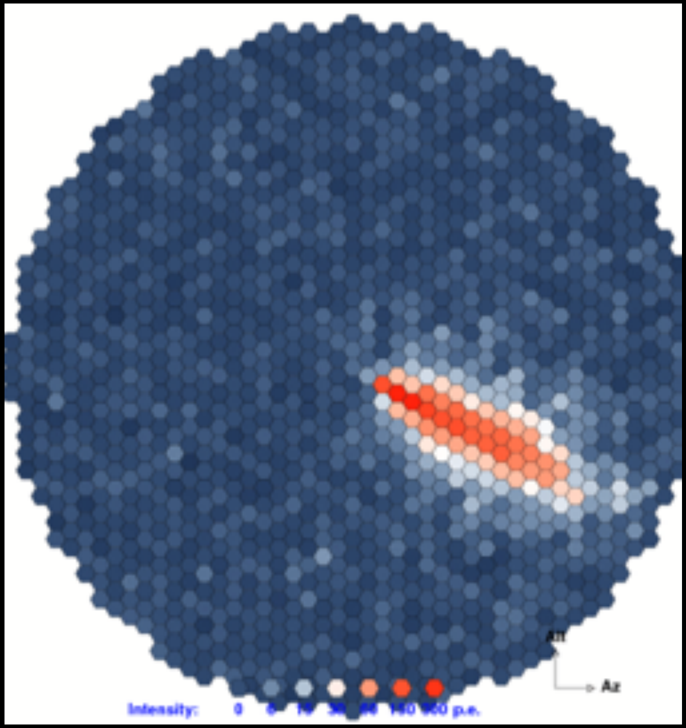
Segmented reflectors composed of many individual mirror facets

Davies-Cotton configuration

Schwarzschild-Couder configuration

THE CHERENKOV CAMERAS

- **UV-optical pixellated ns-sensitive cameras.**
- Current IAC telescopes use photomultiplier tubes as the detectors, except FACT (solid-state Geiger-mode Avalanche Photodiodes (G-APD))
- SiPM pixels will be used for some CTA cameras
  - e.g. ASTRI

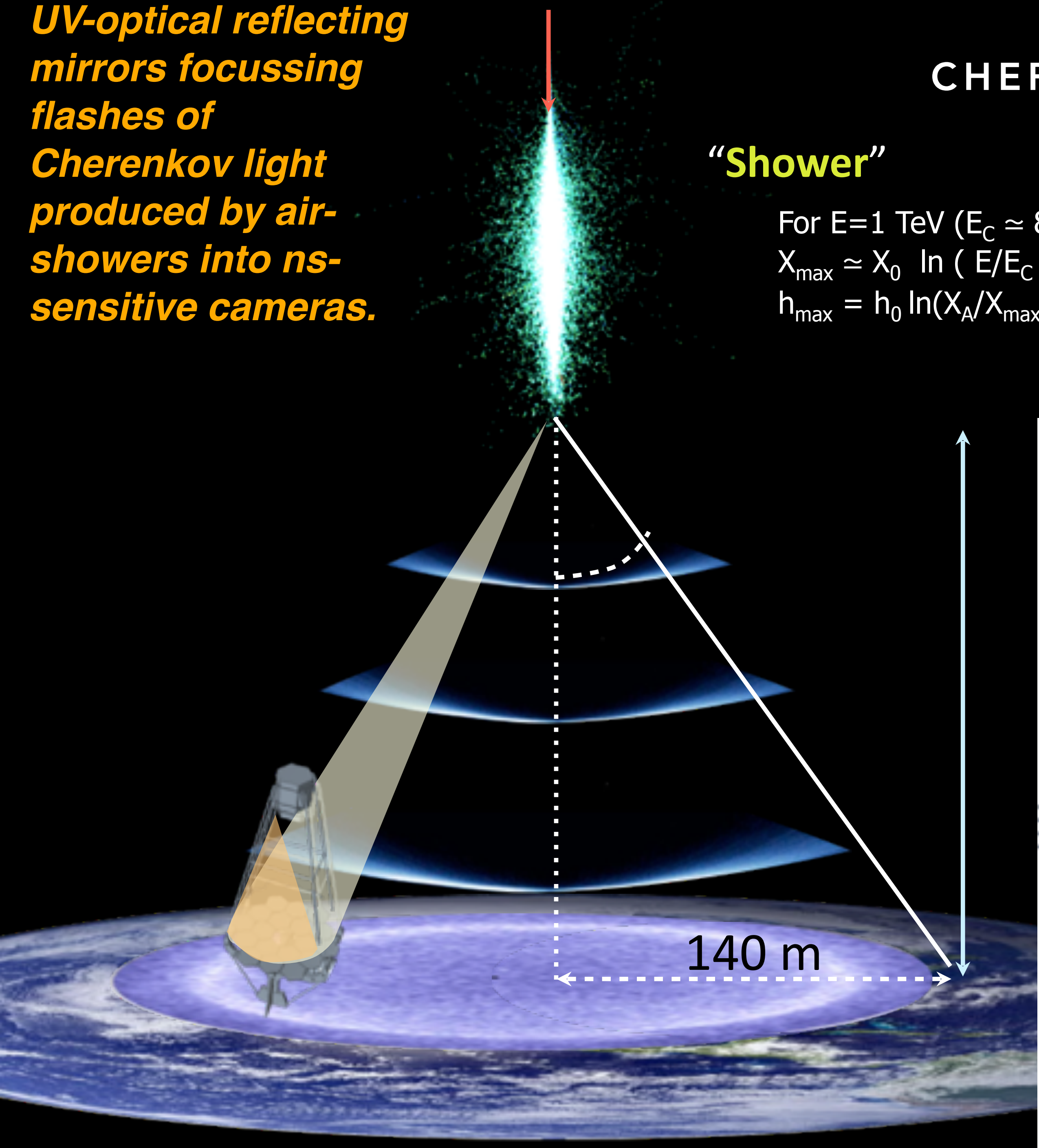


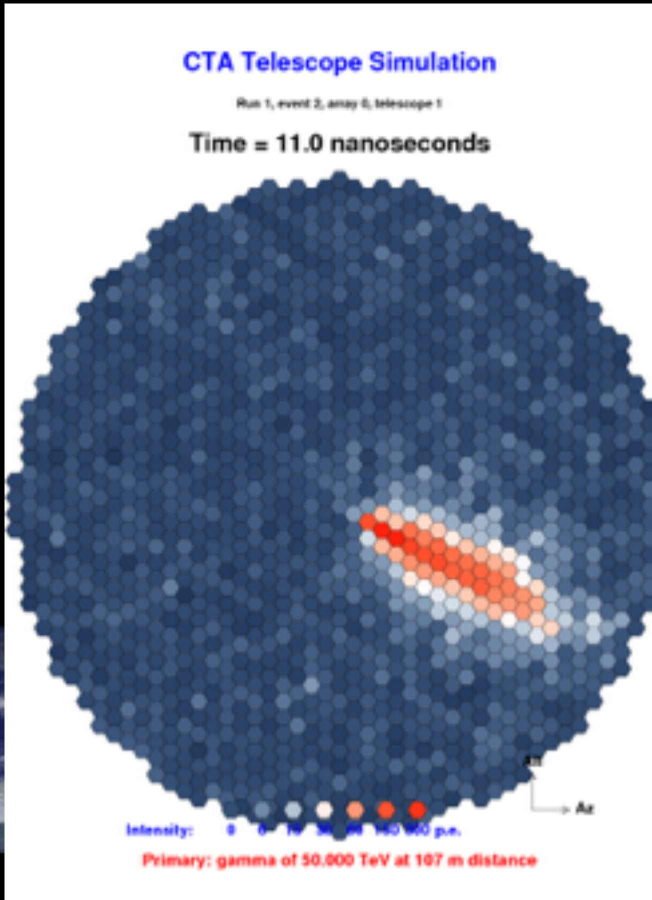
IACT = IMAGING AIR CHERENKOV TELESCOPES

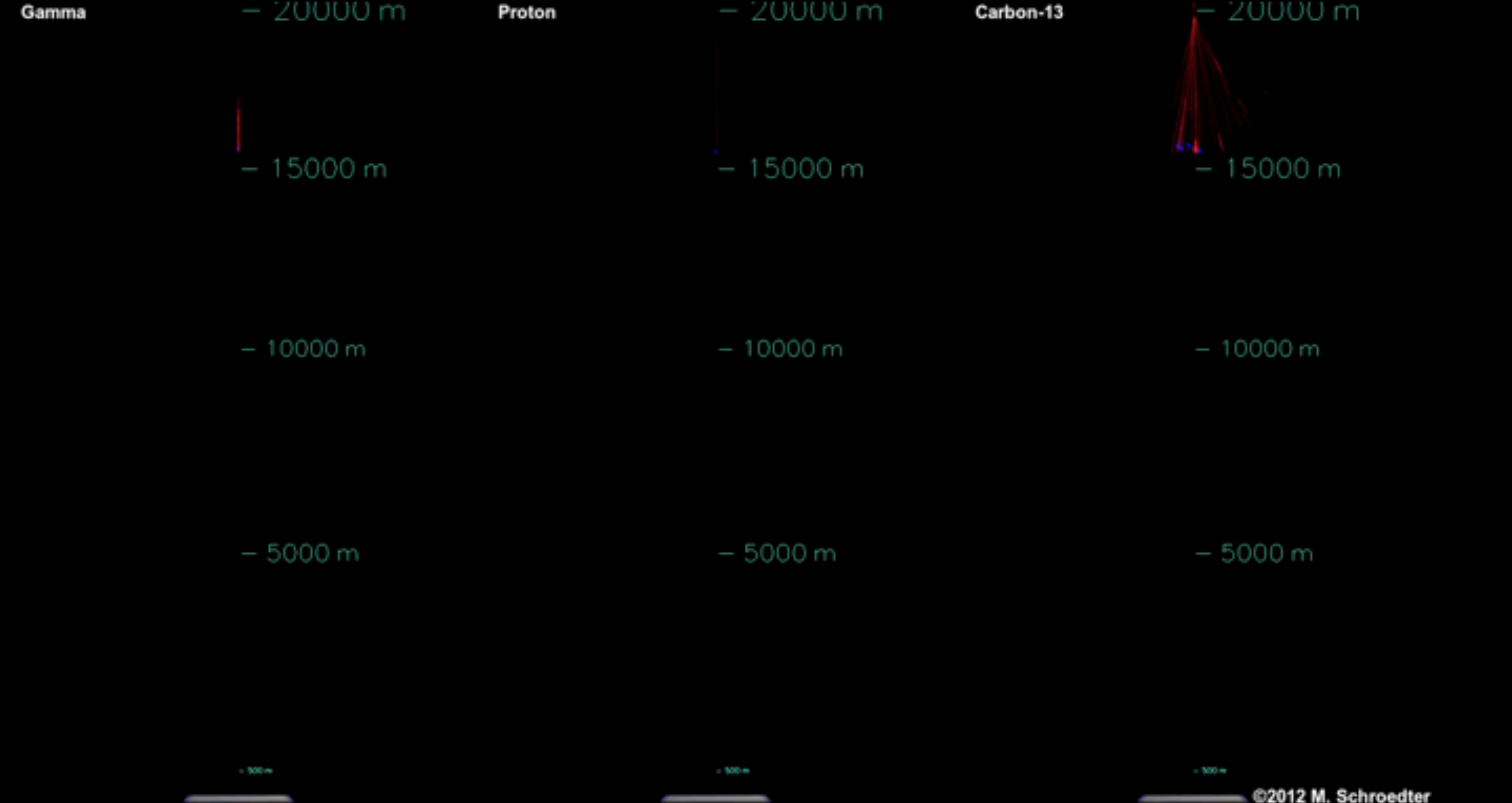
UV-optical reflecting mirrors focussing flashes of Cherenkov light produced by air-showers into ns-sensitive cameras.

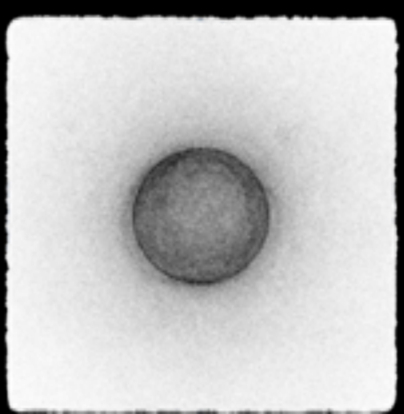
"Shower"

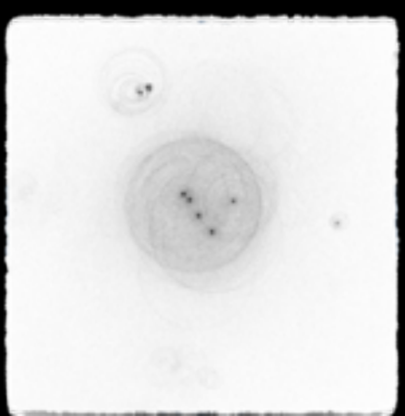
For E=1 TeV ($E_C \simeq$ 80 MeV)
$X_{max} \simeq X_0 \ \ln (E/E_C) / \ln 2$
$h_{max} = h_0 \ln(X_A/X_{max})$ ➡ 5 km











Intensity of the Image
↳ *Shower Energy*

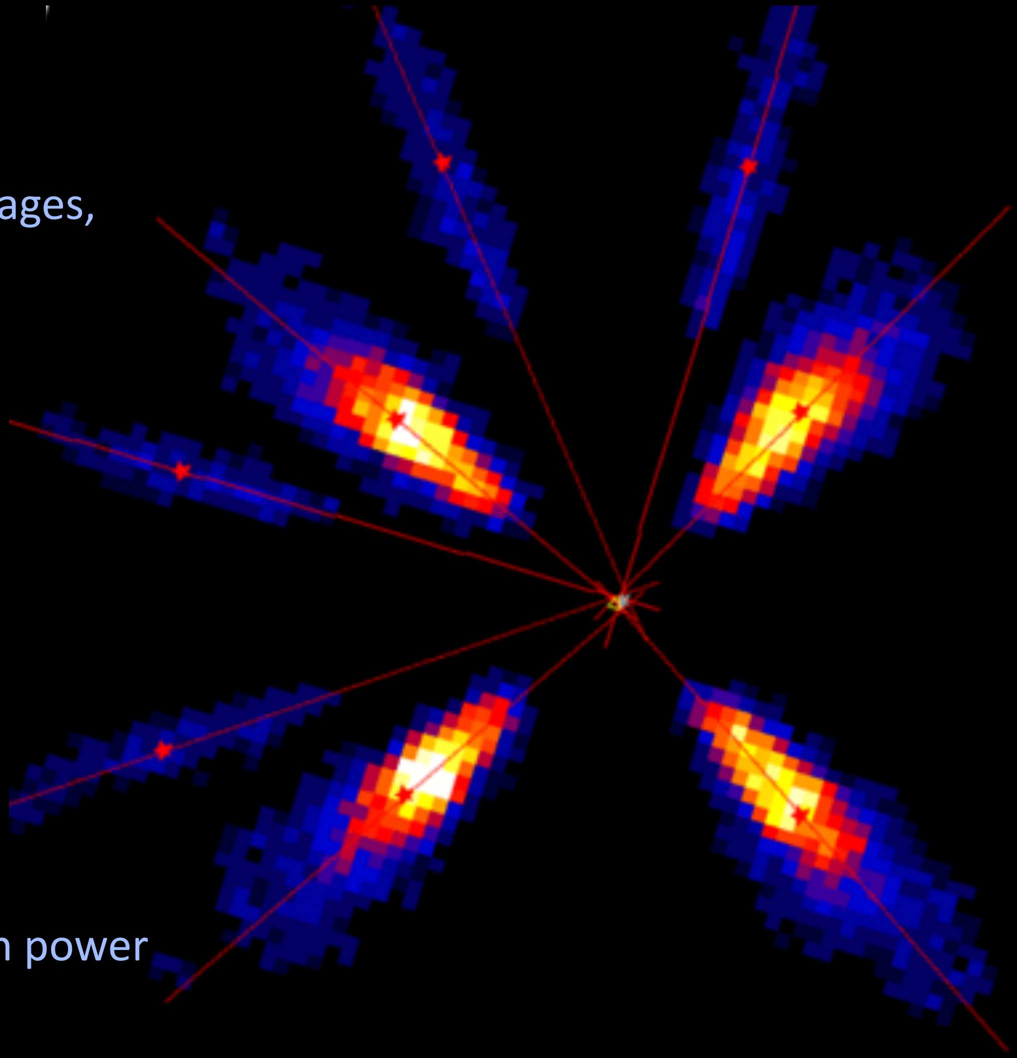
Orientation of the image
↳ *Shower Direction*

Image Shape
↳ *Particle type*

- More events
  - More photons = better spectra, images, fainter sources
    - ✓ Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - ✓ Improved angular resolution
    - ✓ Improved background rejection power

➡ More telescopes

➡ ARRAYS!



Simulation:
Superimposed images from 8 cameras

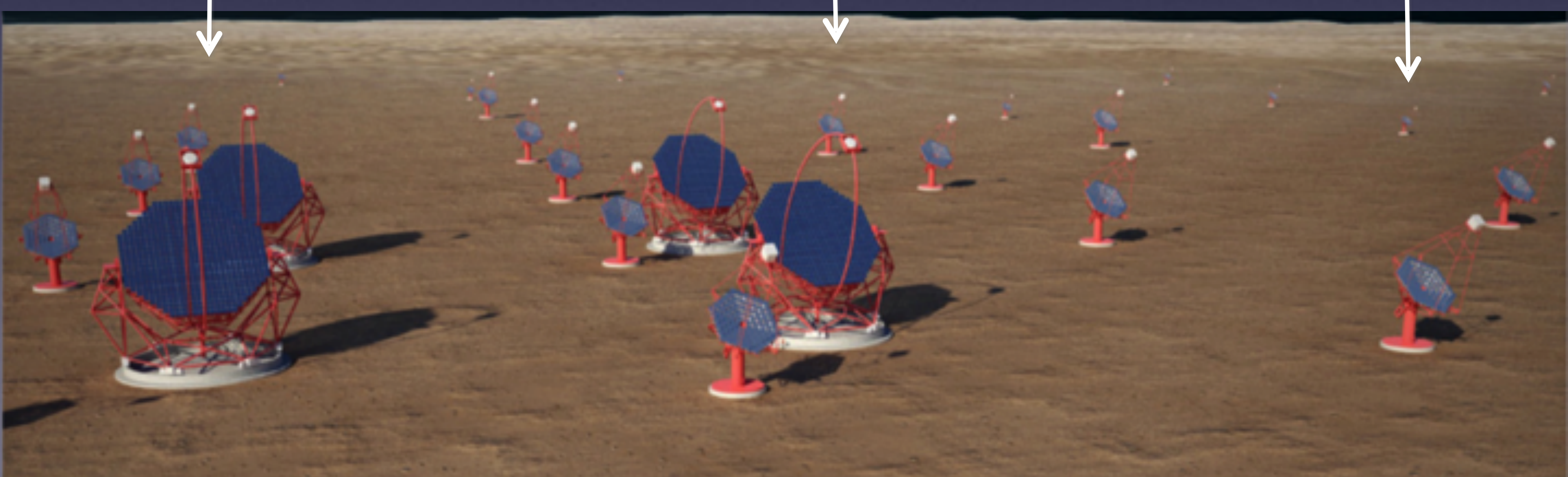
CTA Design (S array)

Science Optimization under budget constraints

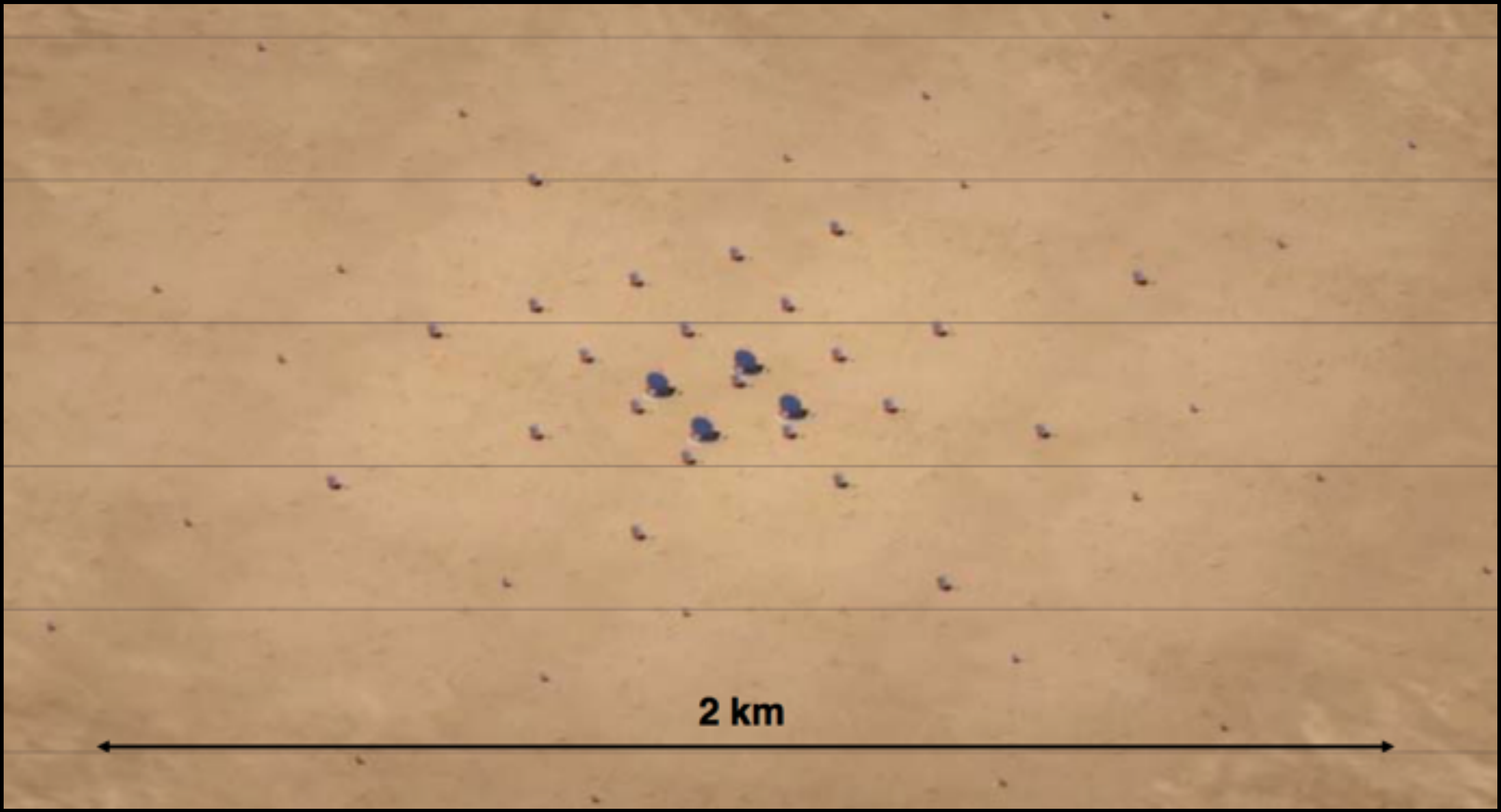
<u>Low energies</u>
Energy threshold 20-30 GeV
23 m diameter
4 telescopes
(LSTs)

<u>Medium energies</u>
100 GeV – 10 TeV
9.5 to 12 m diameter
25 single-mirror telescopes
> 24 (up to 36) dual-mirror telescopes
(MSTs/SCTs)

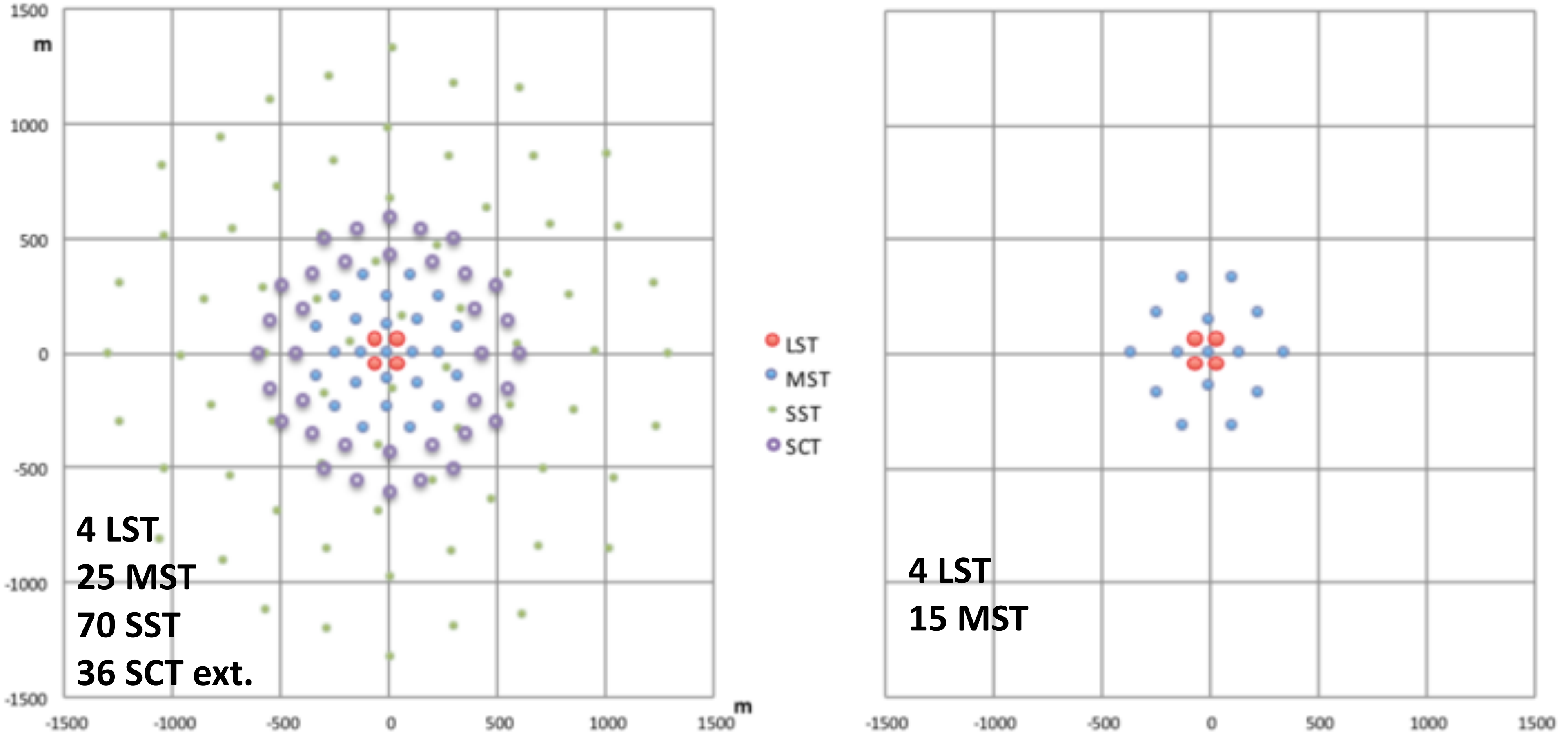
<u>High energies</u>
10 km^2 area at few TeV
4 to 6 m diameter
70 telescopes
(SSTs)

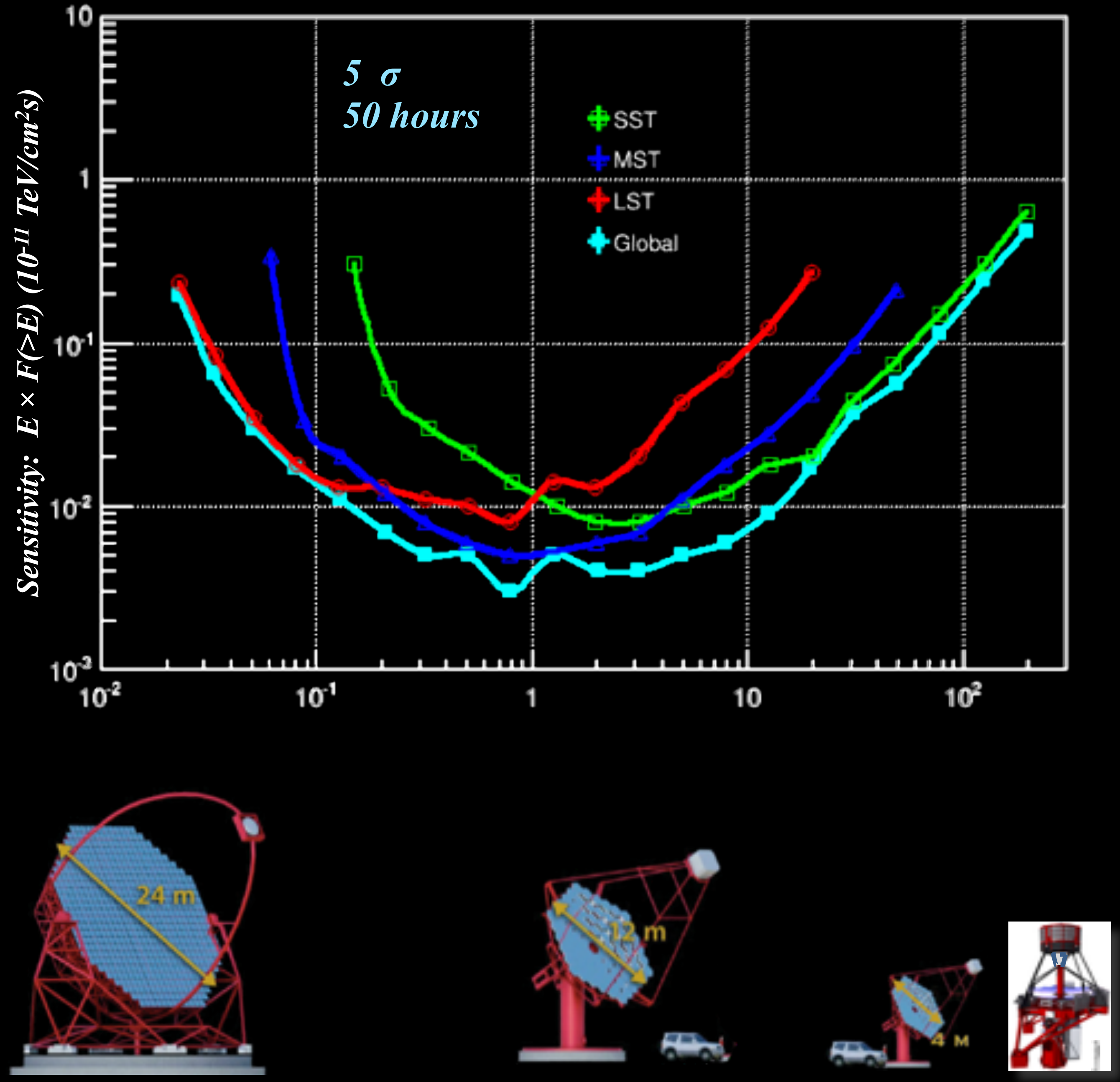


CTA SOUTH ARRAY



ARRAY LAYOUTS





5 σ
50 hours
SST
MST
LST
Global
Sensitivity: E × F(>E) (10^-11 TeV/cm^2s)
10
1
10^-1
10^-2
10^-3
10^-2
10^-1
1
10
10^2
24 m
12 m
4 m

TELESCOPE SPECIFICATIONS

3 SST types

SiPM Cameras

	LST "large"	MST "medium"	SCT "medium 2-M"	SST "small"
Number	**4 (S) 4 (N)**	**25 (S) 15 (N)**	**≤ 36 (S and N)**	**70 (S)**
Energy range	20 GeV to 200 GeV	100 GeV to 10 TeV	200 GeV to 10 TeV	5 TeV – 300 TeV
Effective mirror area	370 m^2	90 m^2	40 m^2	> 5 m^2
Field of view	> 4.5°	> 7°	> 8°	> 9°
Pixel size ~PSF θ_{80}	< 0.11°	< 0.18°	< 0.07°	< 0.25°
Positioning time	50 s, 20 s goal	90 s, 60 s goal	90 s, 60 s goal	90 s, 60 s goal
Target capital cost	7.4 M€	1.6 M€	< 2.0 M€	600 k€

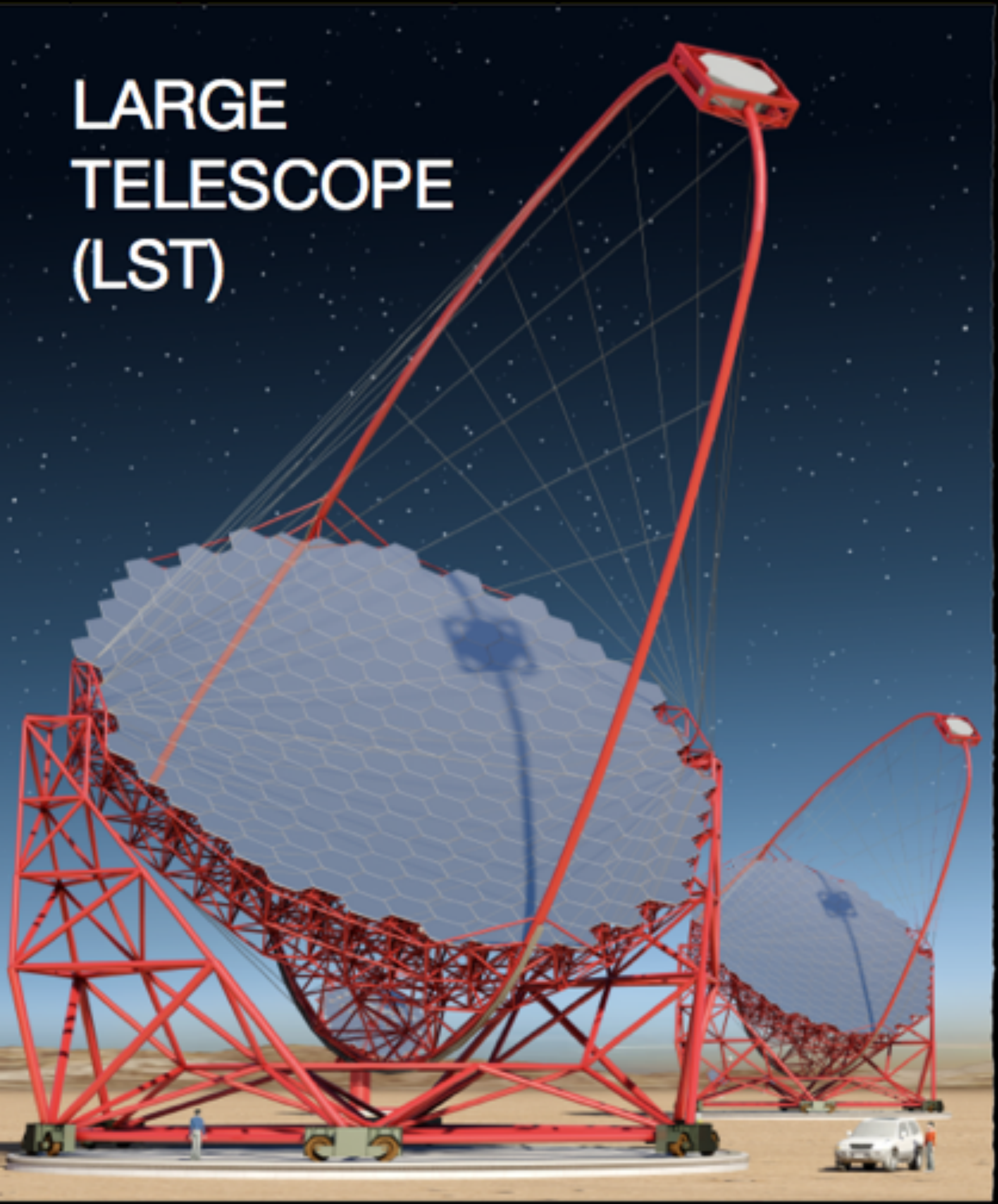
Davies-Cotton

Schwarzschild-Couder

SST TELESCOPES: THREE DIFFERENT KIND OF SST TELESCOPES BEING DEVELOPED

SST-1M, Krakow since Nov. 2013 | ASTRI, Serra la Nave, Mt. Etna, Sicily since Aug. 2014 | GCT, Observatoire Paris, Medoun, since Apr. 2015

- 3 designs with associated prototypes proposed for the CTA array:
  - A single mirror Davies-Cotton telescope: SST-1M
  - 2 dual-mirror Schwarzchild-Couder telescopes: SST-2M ASTRI and SST-2M GCT



Cover the low energy domain from 20 GeV to 200GeV

23 m diameter

389 m^2 dish area

28 m focal length

1.5 m mirror facets

4.5° field of view

0.1° pixels

Camera Ø over 2 m

Total weight of the LST: 103 tons

Carbon-fibre structure for 20 s positioning

Fast rotation 180° in 20 sec for the GRB follow up observations

Active mirror control

4 LST on South site
4 LST on North site
Prototype 1st telescope

MEDIUM SIZE TELESCOPE

Optimized for 100 GeV - 10 TeV Range

12 m diameter

100 m^2 dish area

16 m focal length

1.2 m mirror facets

8° field of view

0.18° pixels (~2000 pixels)

Camera Ø over 1.5 m

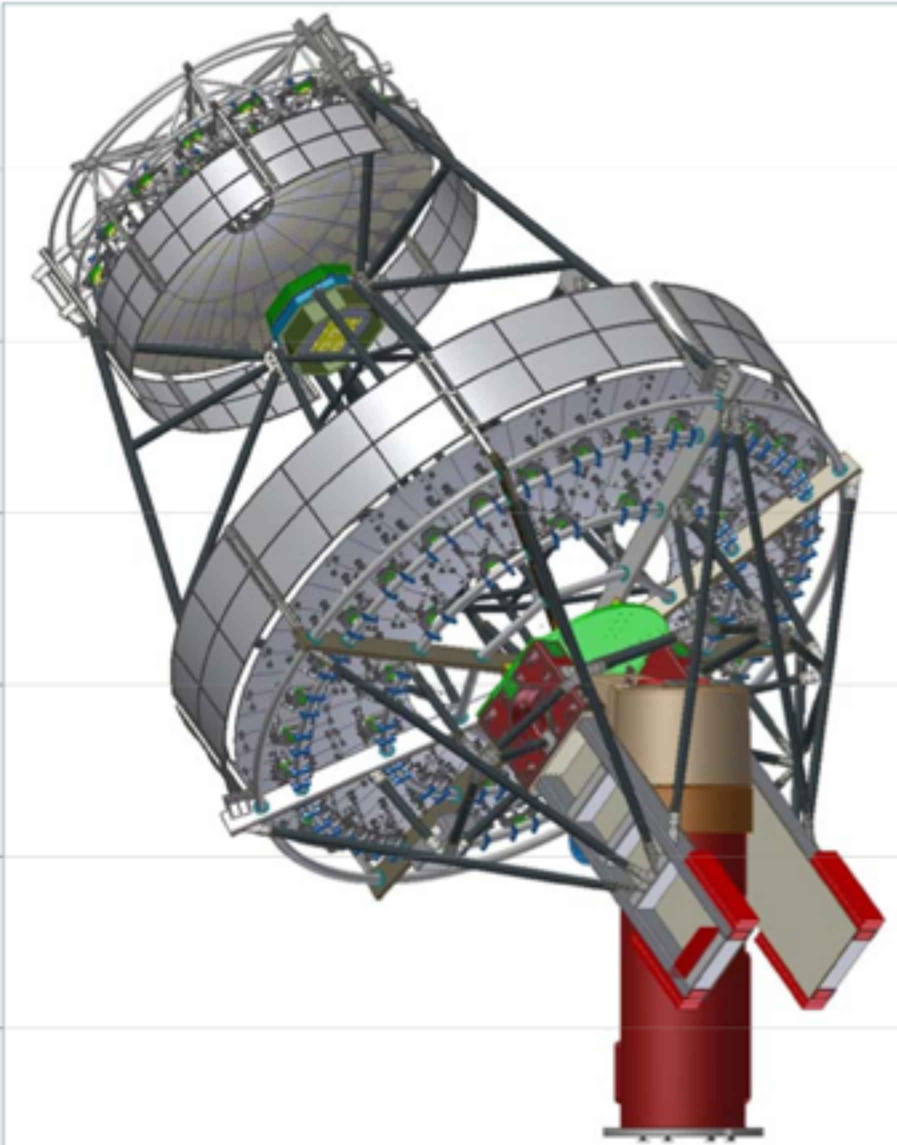
Active mirror control

25 MST on South site

15 MST on North site

MST Prototype in Berlin

MEDIUM TELESCOPE 2-MIRROR (SCT)



9.7 m primary
5.4 m secondary
5.6 m focal length, f/0.58
50 m^2 mirror dish area
PSF better than 4.5′
across 8^o FOV

8^o field of view
11328 x 0.07^o SiPMT pixels
TARGET readout ASIC

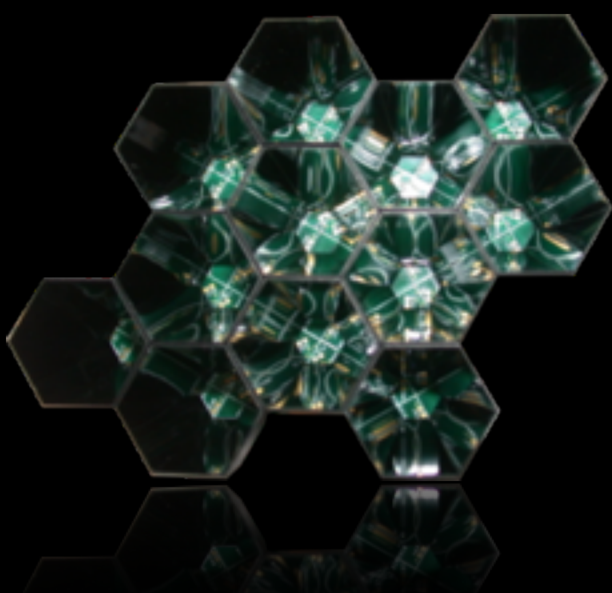
SCTs can augment / replace
MSTs in either S or N
→ proposed US contribution

→ Increased γ-ray collection area
→ Improved γ-ray ang. resolution
→ Improved sensitivity

SMALL SIZE TELESCOPE (SST-1M)

Optimised for Energy range above 10 TeV

- Spacing by 200-300 m
- Davies-Cotton Design
- 4m diameter single mirror
- f/D = 1.4
- SiPM camera with new hexagonal sensor



SST-1M Prototype in Krakow

ASTRI AND CTA/ASTRI MINI-ARRAY

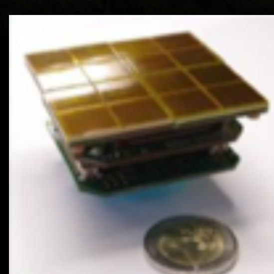
ASTRI SMALL SIZE TELESCOPE (ASTRI SST-2M)

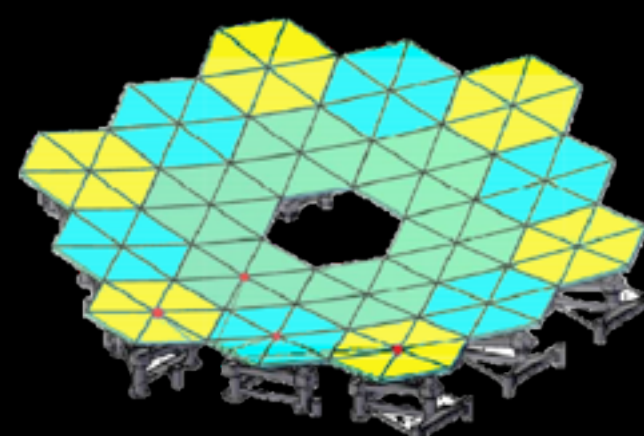
Optimised for Energy range above 10 TeV

SST-2M Prototype in Serra La Nave (CT Italy)

- 4m diameter dual mirror
  - Segmented primary
  - Monolithic Secondary
- Effective area: 6 m^2
- Focal length: 2.2m
- FoV: 9.6°
- Pixel angular size 0.17°

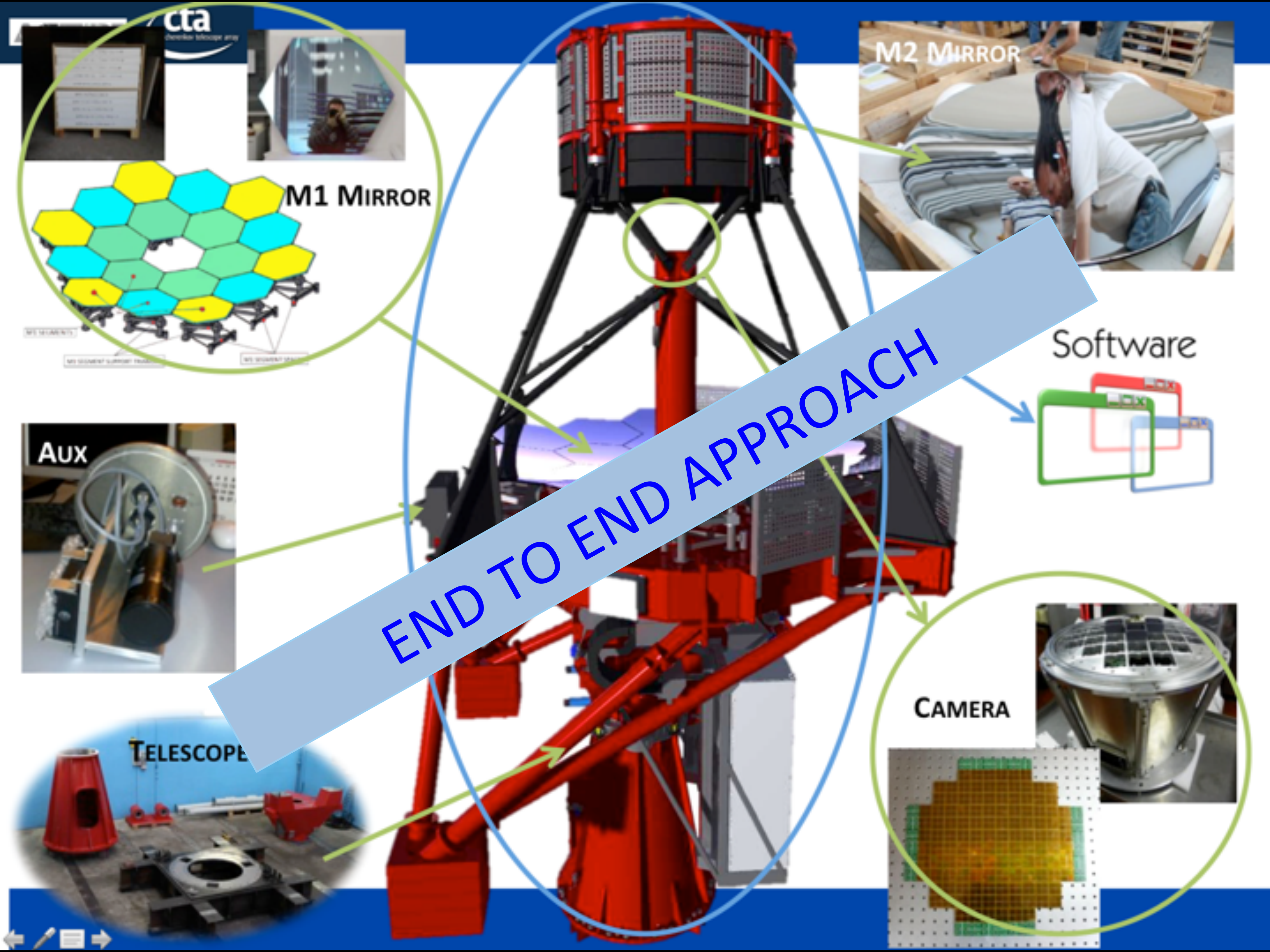
SiPM Based camera





ASTRI/CTA IN A NUTSHELL

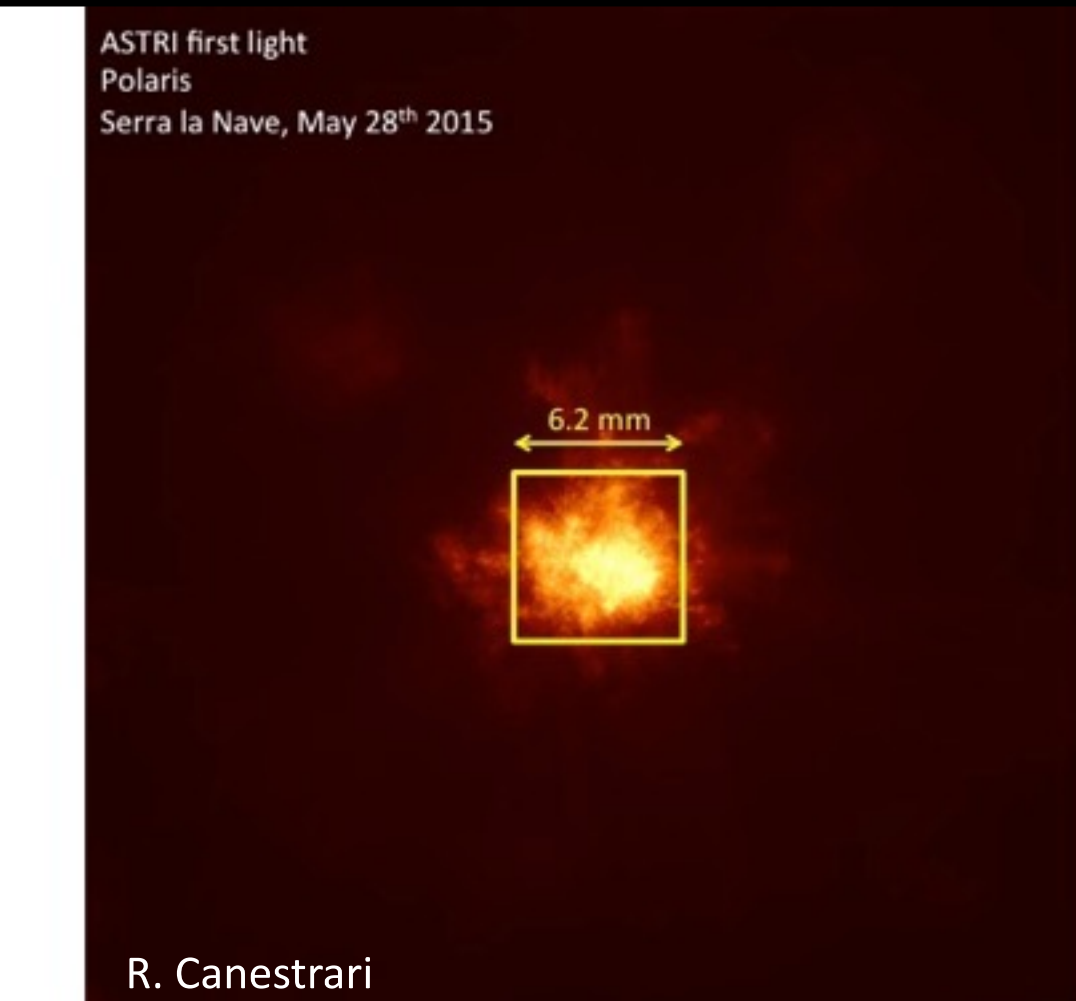
- INAF project funded in 2010-2014 by the Italian MIUR (> 40 FTE)
- Now the project continues with the support of MIUR and MEF ("Industrial Astronomy" program) with the participation of Institutes from South Africa and Brazil
- E2E implementation of an SST-2M prototype in Sicily (Mount Etna, astronomical site of Serra La Nave)
  ➔ Validation e commissioning of the telescope via Cherenkov astronomical observation
- E2E implementation of a mini-array (# ≥ 7) of SST-2M (pre-production) at the CTA site
  ➔ Validation e commissioning of the array (including trigger and software) via Cherenkov astronomical observations, first CTA scientific data
- Aiming at the realization of 35 out of the 70 SST telescopes of the CTA southern array
- Participation in the production of the MST mirrors 🡐

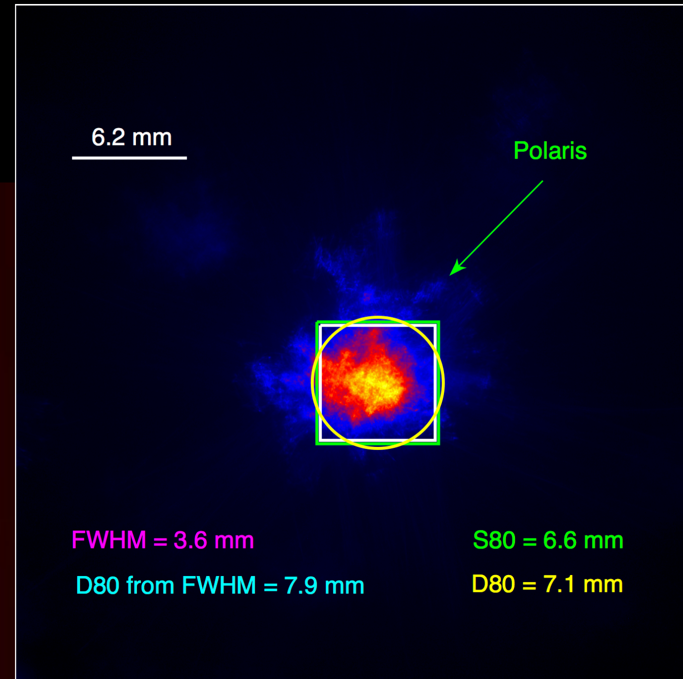

cta
M1 Mirror
M2 Mirror
Software
Aux
Camera
Telescope
END TO END APPROACH

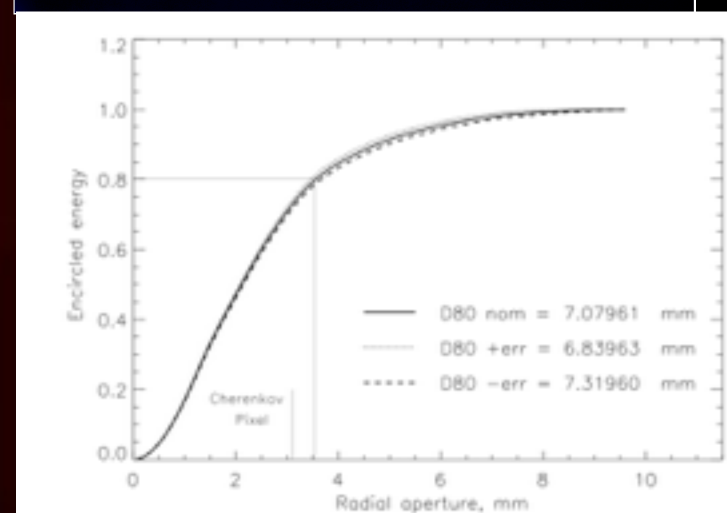
INAUGURATION: 24 SEPTEMBER 2014

SERRA LA NAVE, ETNA: AN ASTRONOMICAL SITE

ASTRI: FIRST LIGHT FOR A S-C TELESCOPE! (MAY 2015)







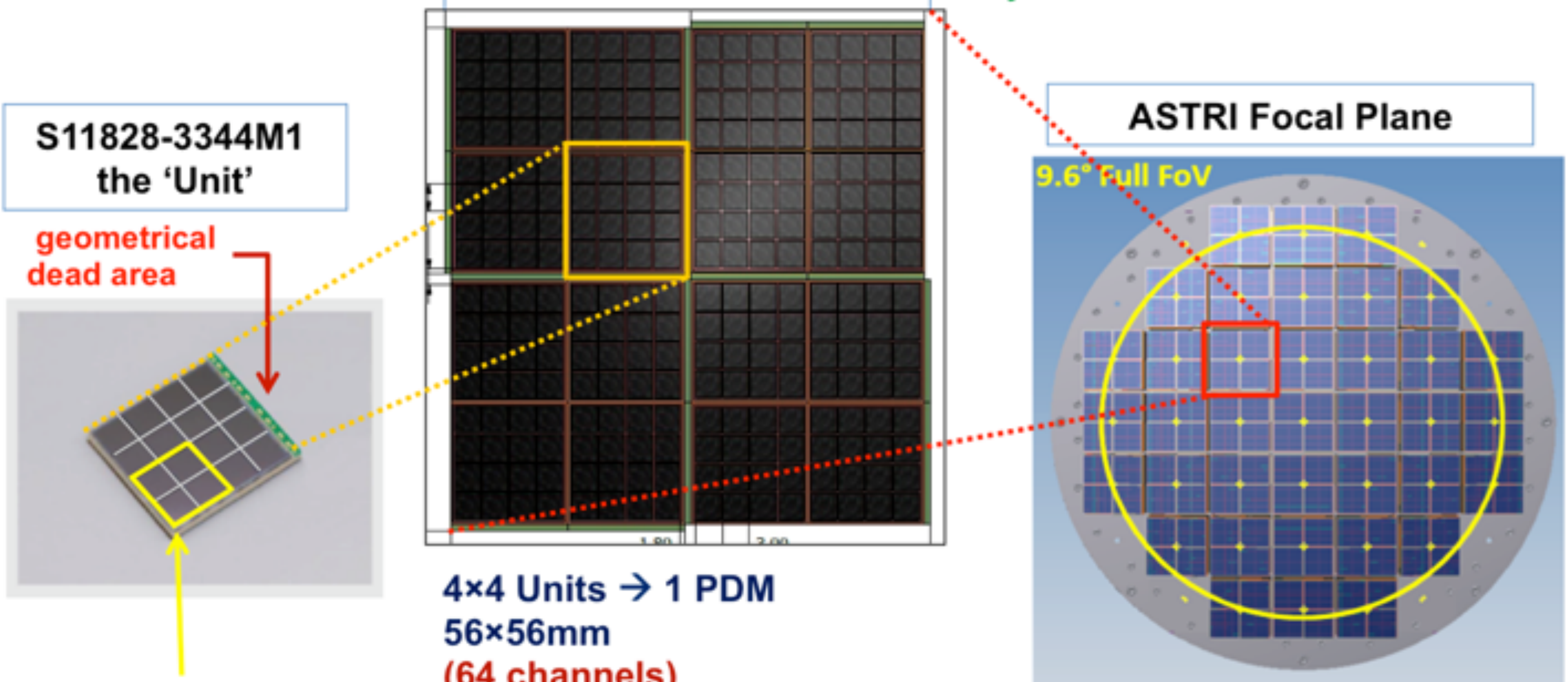
PSF: CTA REQUIREMENTS FULLY MET

ASTRI CAMERA

Modularity: Unit, PDM, Focal Plane

Photon Detection Module
PDM

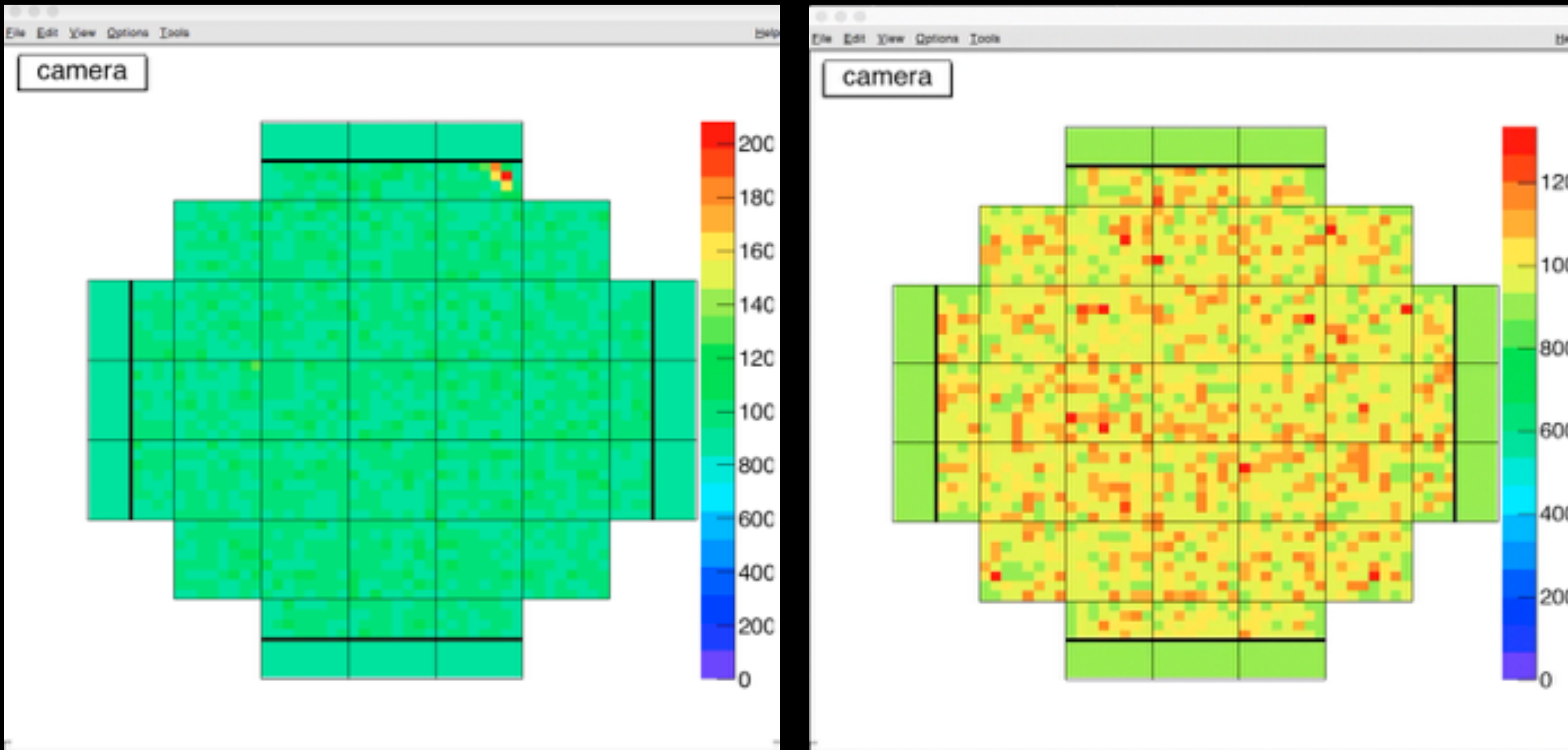
Each PDM works independently from the others



Logical pixel
6.2×6.2mm
≡ 0.17°
(4 channels)

4×4 Units → 1 PDM
56×56mm
(64 channels)

37 PDMs → Focal Plane
560×560mm
(1984 channels)



simulated data from ASTRI camera

THE ASTRI MINI-ARRAY OF PRECURSORS CONCEPT

- Our goal is the deployment and the operation of a mini-array composed of a few SST-2M telescopes at the final CTA southern site.

An ancient concept...

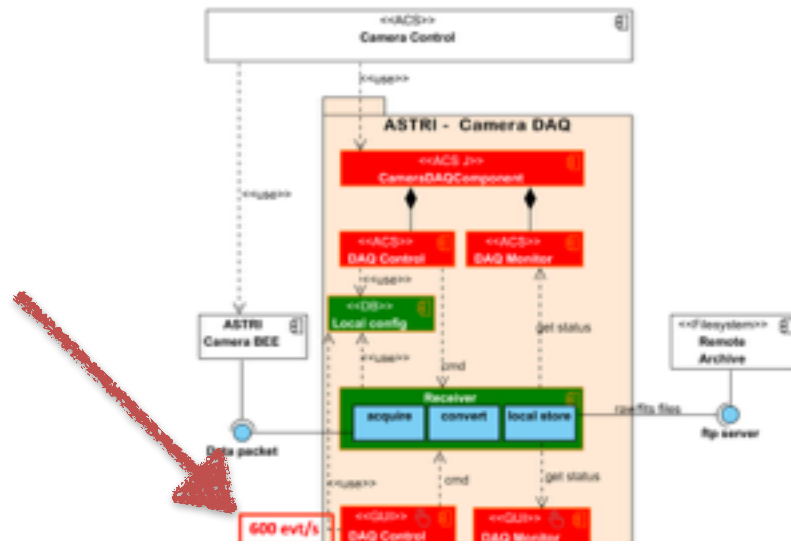
MINI-ARRAY OF PRECURSORS

The ASTRI/CTA SST-2M mini-array can verify some array properties:

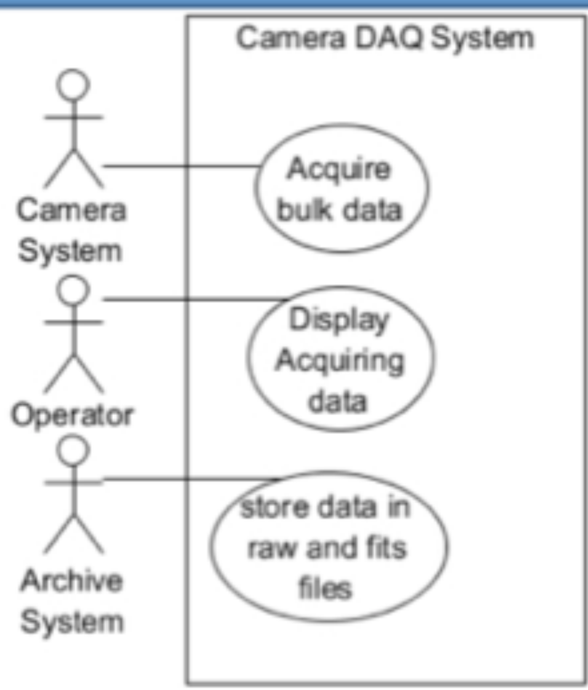
- **Check of the trigger algorithms**
  - Preliminary MC simulations show that a typical event will trigger a number O(5-7) of the whole CTA-SSTs sub-array.
- **Check of the wide field-of-view performance** by detecting VHE showers with the core at a distance up to 500m
- **Compare the mini-array performance with the Monte Carlo expectations** by means of deep observations

ASTRI CAMERA ACQUISITION SYSTEM AND ICT @ IASFBO

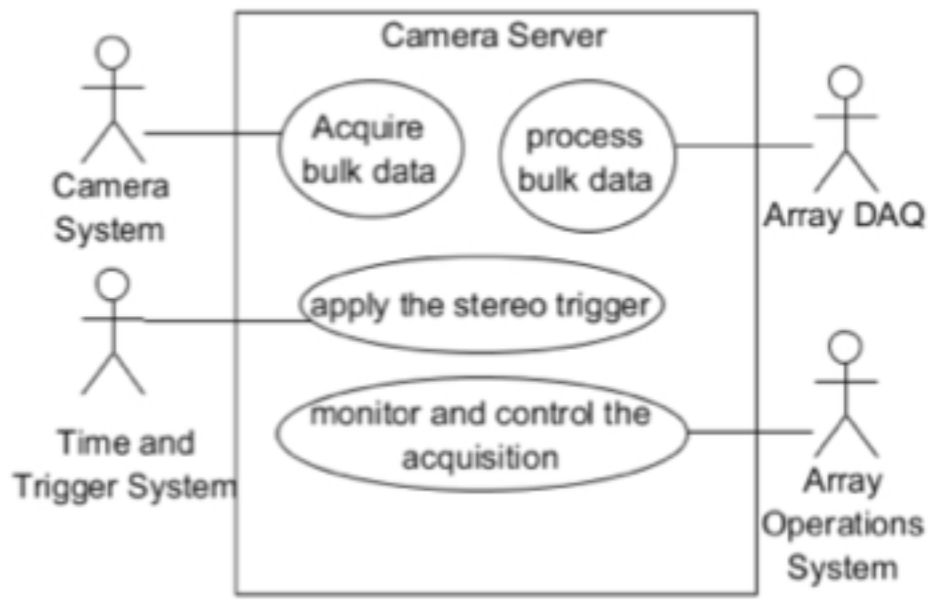
- The acquisition from ASTRI Camera system operates in 2 main contexts:
  - On the ASTRI SST-2M Prototype as Camera DAQ
  - On the ASTRI SST-2M telescopes within the ASTRI mini-array as Camera Server
- ICT responsibility for prototype and Mini-Array



Use Cases in prototype context

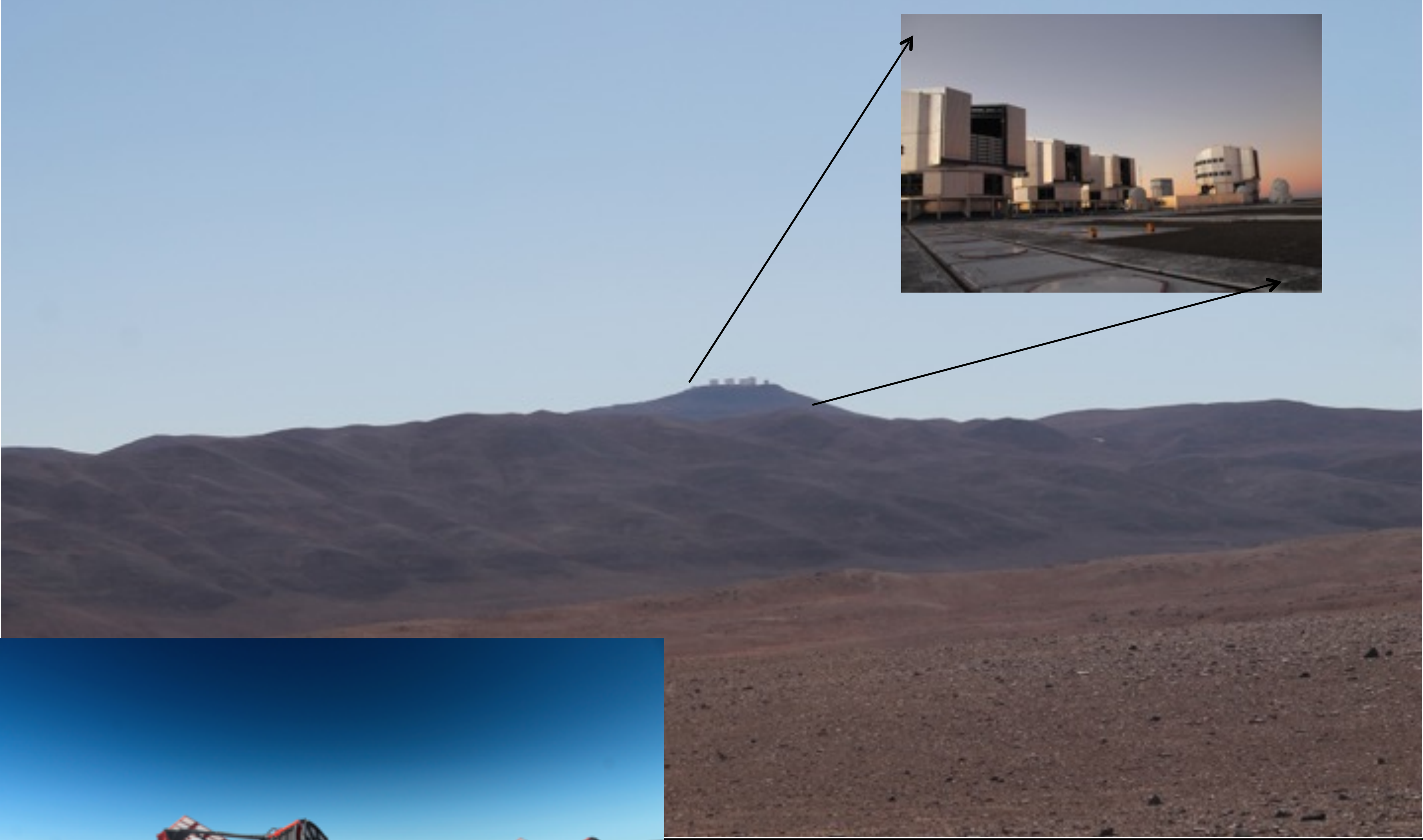


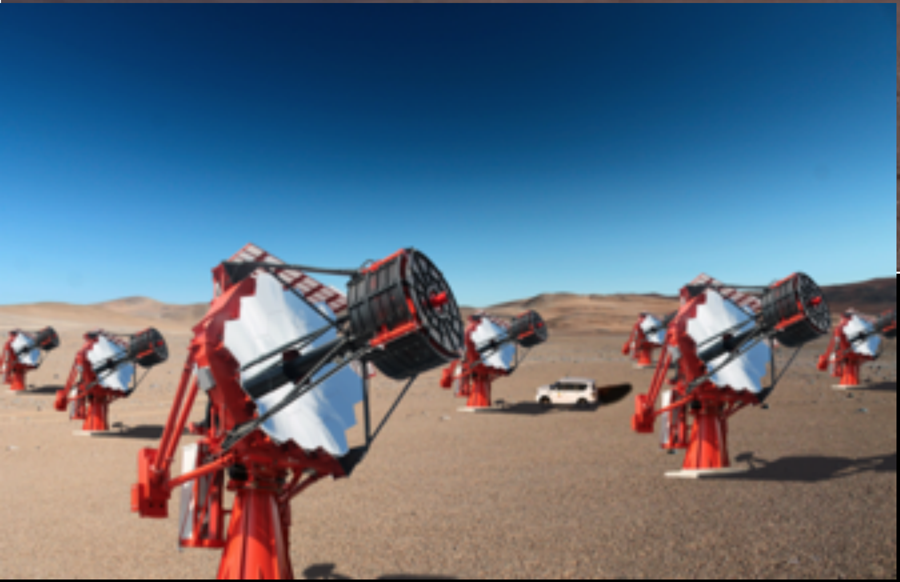
Use Cases in mini-array context

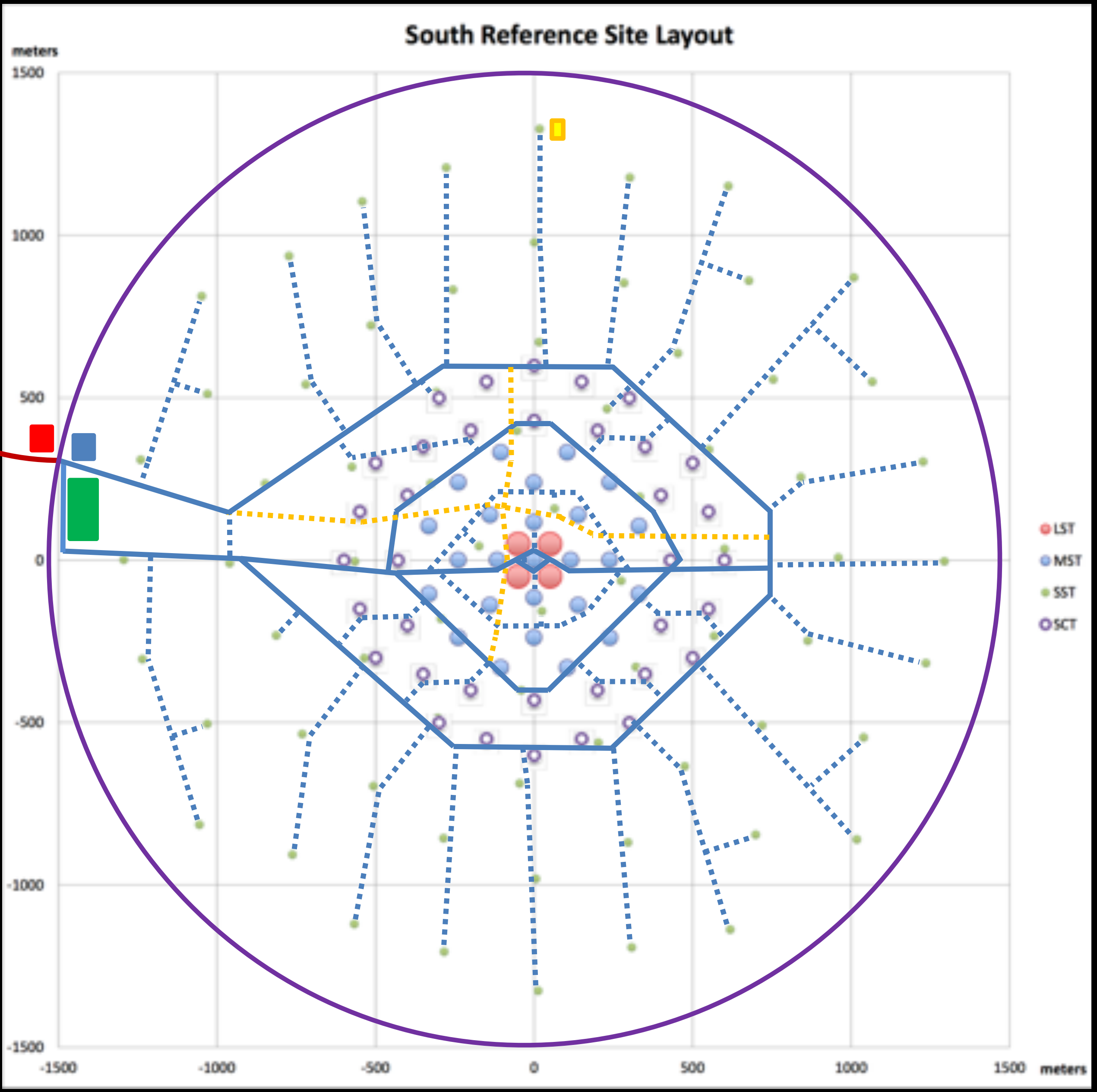


CHILE


Vulcano Llullaillaco
6739 m, 190 km east
Cerro Armazones
E-ELT
Proposed Site for the
Cherenkov Telescope Array
Cerro Paranal
Very Large Telescope
© Marc-André Besel







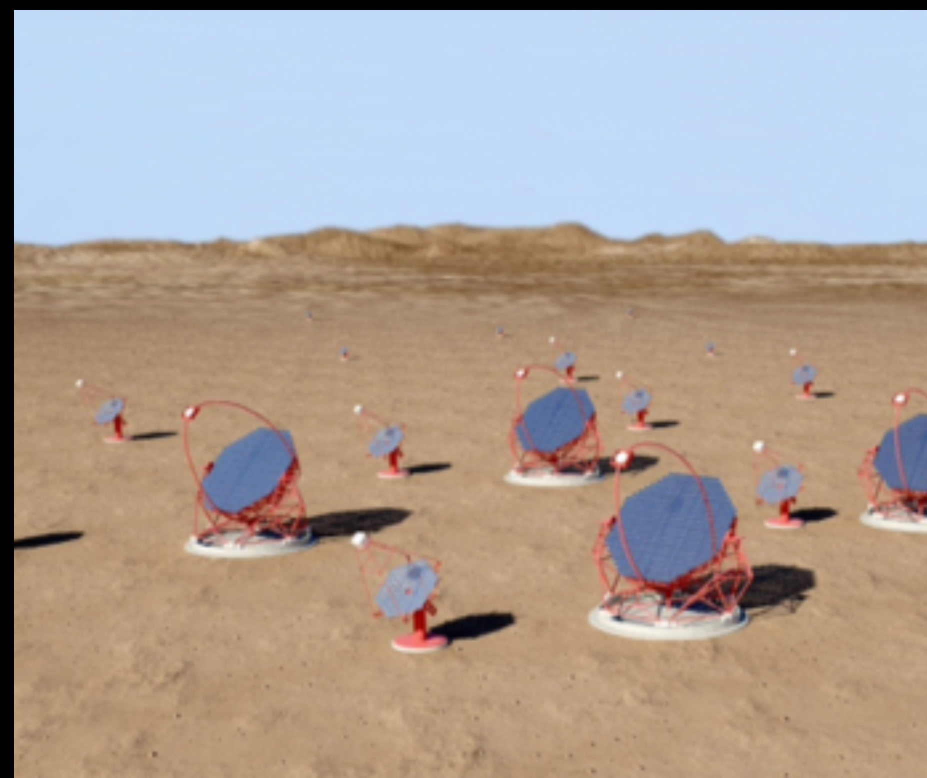
South Reference Site Layout
meters
1500
1000
500
0
-500
-1000
-1500
-1500
-1000
-500
0
500
1000
1500
meters
LST
MST
SST
SCT

CTA DATA CHALLENGES

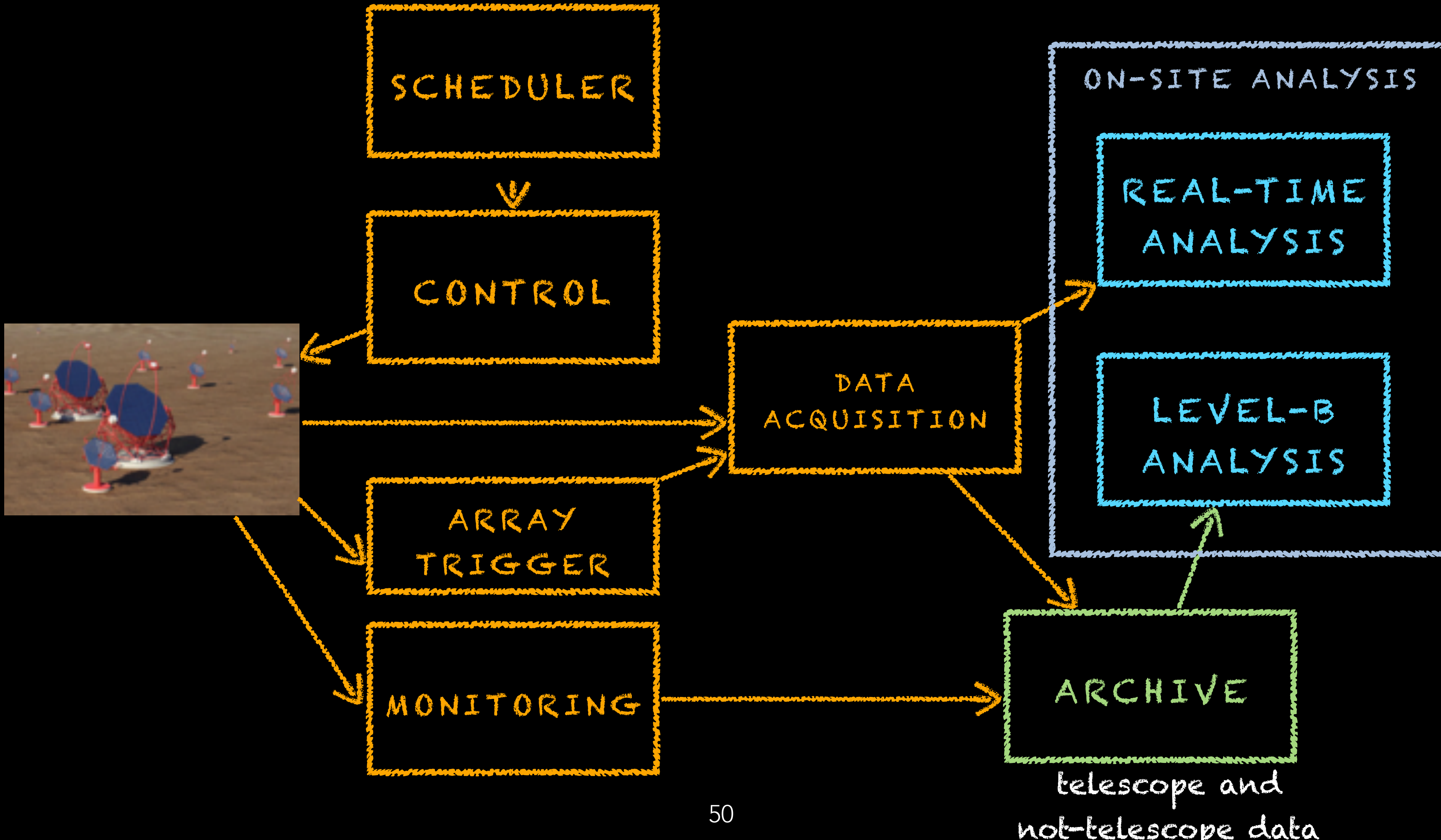
DATA RATE AND DATA VOLUME: FULL CTA ARRAY (AFTER TRIGGER)

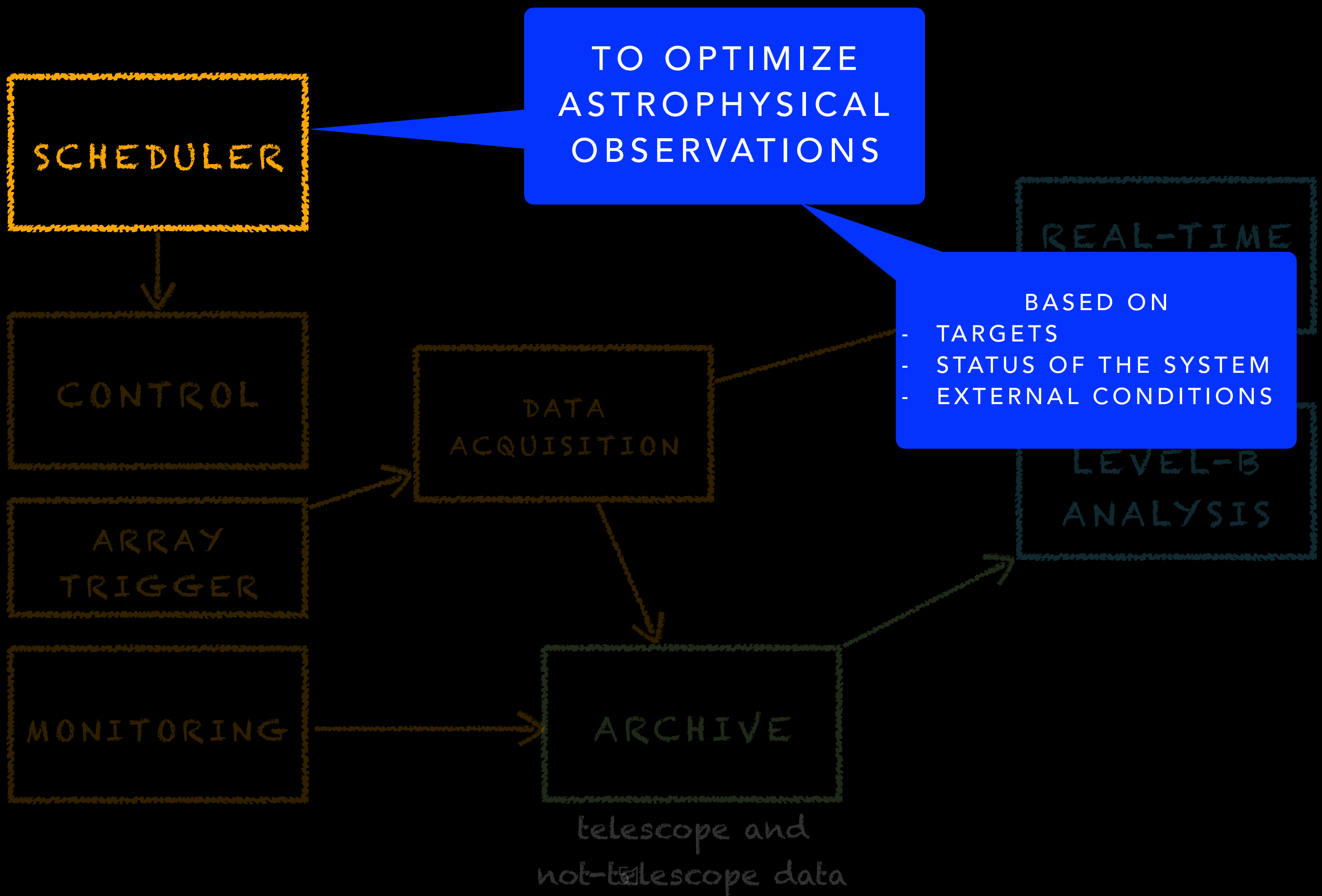
Site	Event data rate	Raw data rate(+20%)	Annual raw data volume	Reduction factor	Reduced raw data rate	Annual raw data volume	Max daily volume
South	4.28 GB/s	5.14 GB/s	24.3 PB	10	0.514 GB/s	2.43 PB	**22.2 TB**
North	2.15 GB/s	2.58 GB/s	12.2 PB	10	0.258 GB/s	1.22 PB	**11.15 TB**
Total	6.43 GB/s	7.72 GB/s	36.5 PB	10	**0.772 GB/s**	**3.65 PB**	33.3 TB

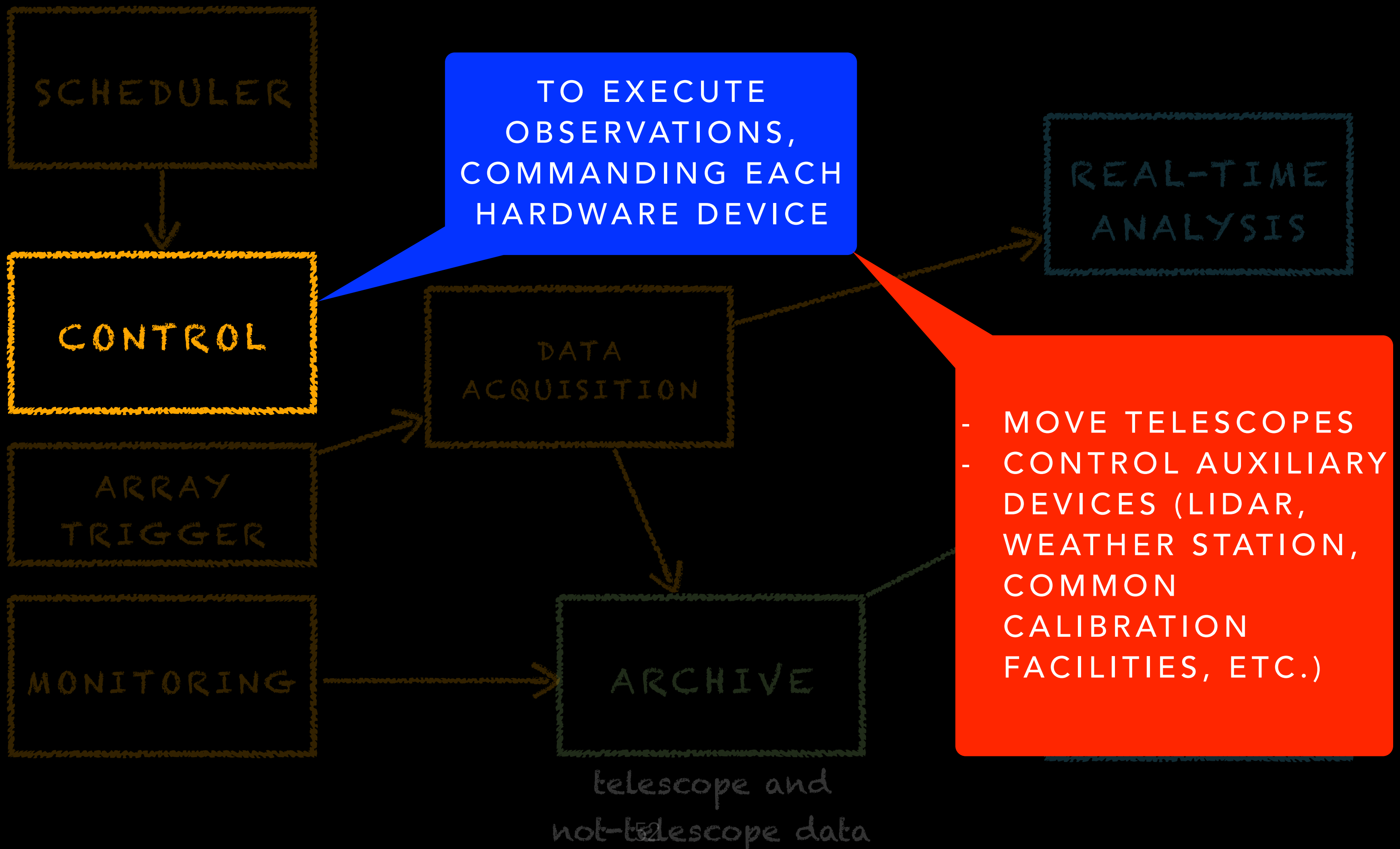
- **Assumptions:**
    - This is the data that should be transferred off-site and stored
    - Stable volume after 2023
    - On-site data storage for 2 months: 1 PB (South) taking into account all the data level produced

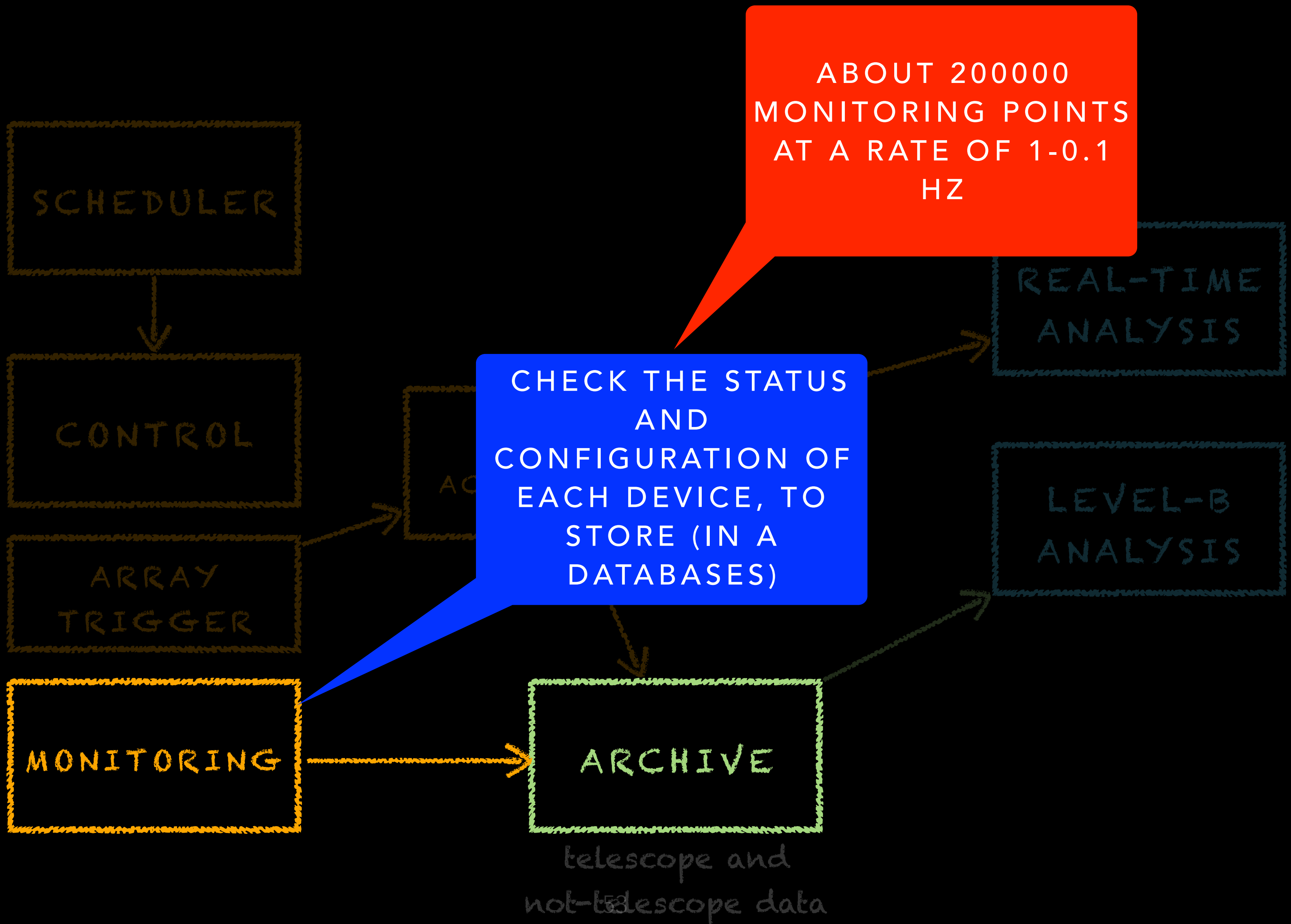


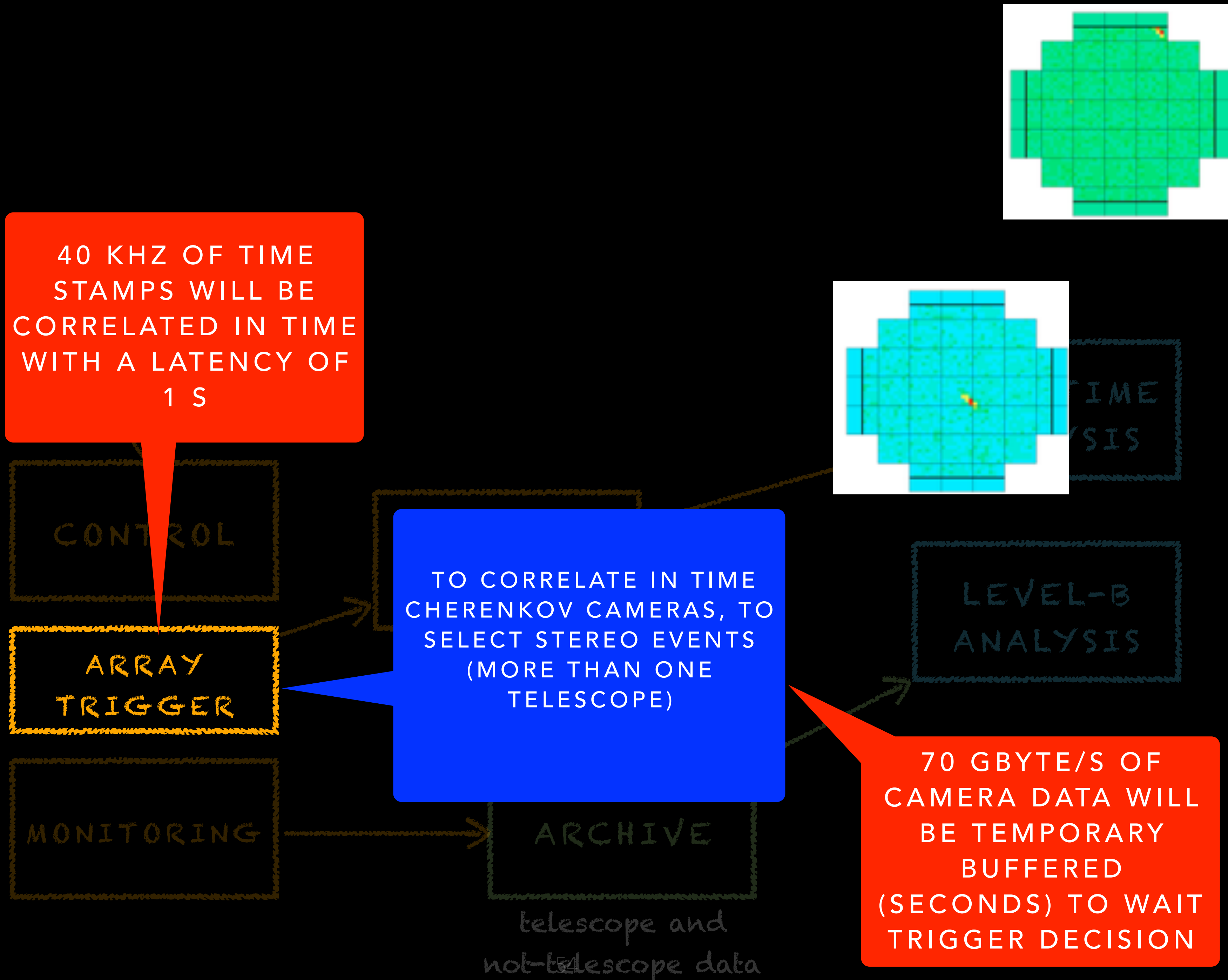
A SKETCH OF THE CTA ON-SITE SOFTWARE

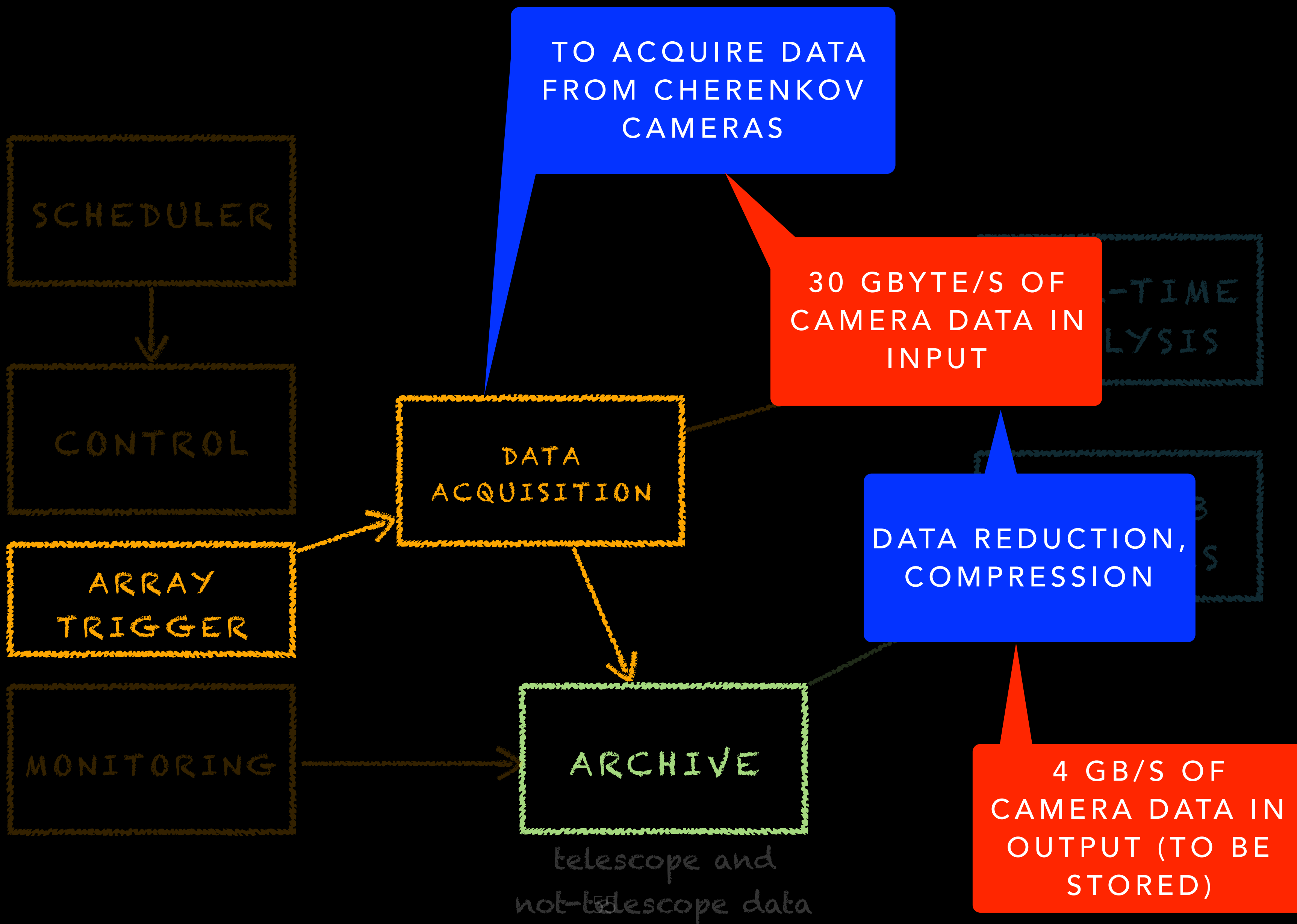



SCHEDULER
TO OPTIMIZE ASTROPHYSICAL OBSERVATIONS
BASED ON
- TARGETS
- STATUS OF THE SYSTEM
- EXTERNAL CONDITIONS
REAL-TIME
CONTROL
DATA ACQUISITION
ARRAY TRIGGER
LEVEL-B ANALYSIS
MONITORING
ARCHIVE
telescope and not-telescope data

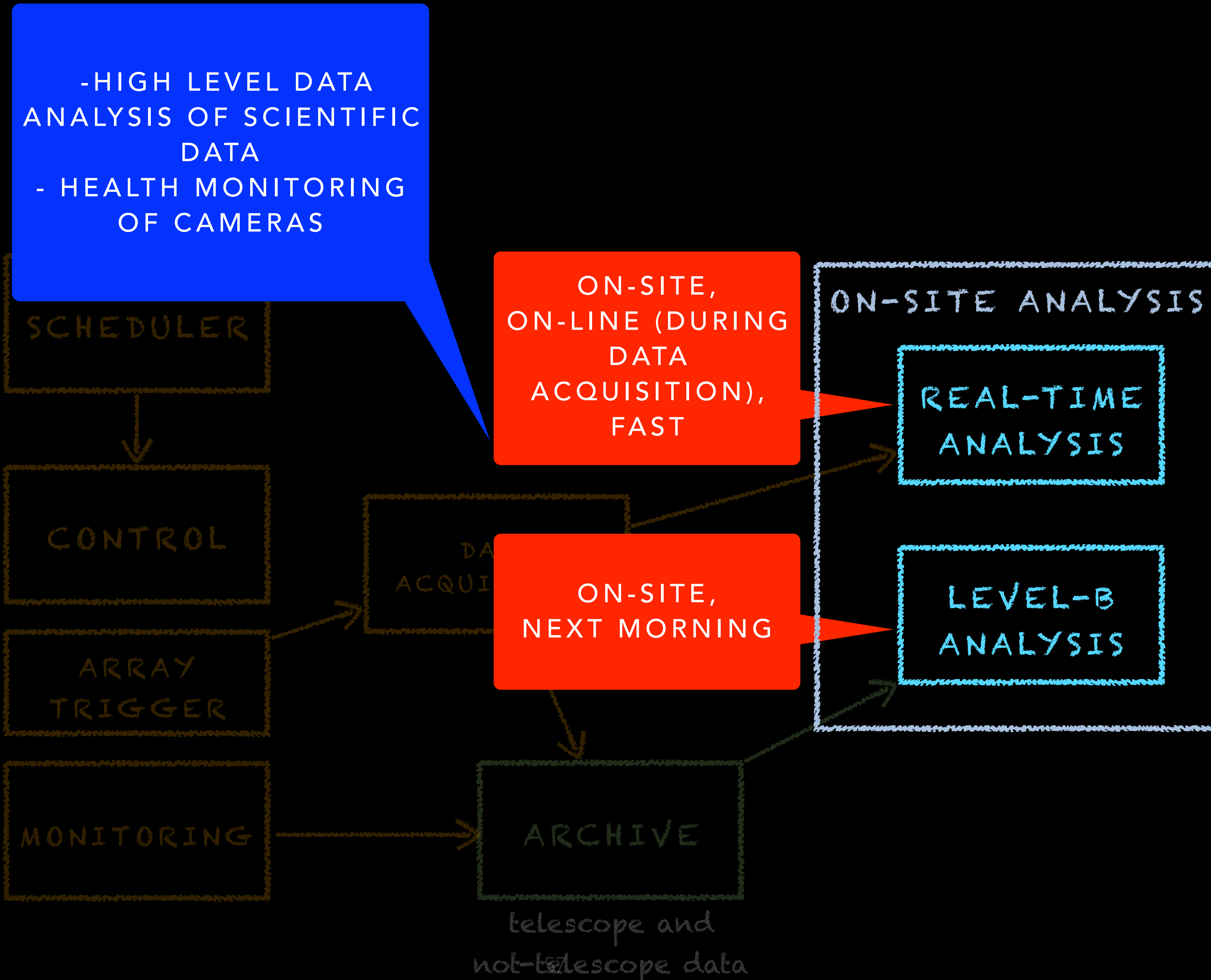

SCHEDULER
CONTROL
ARRAY TRIGGER
MONITORING
DATA ACQUISITION
ARCHIVE
REAL-TIME ANALYSIS
TO EXECUTE OBSERVATIONS, COMMANDING EACH HARDWARE DEVICE
- MOVE TELESCOPES
- CONTROL AUXILIARY DEVICES (LIDAR, WEATHER STATION, COMMON CALIBRATION FACILITIES, ETC.)
telescope and not-telescope data


ABOUT 200000 MONITORING POINTS AT A RATE OF 1-0.1 HZ
SCHEDULER
CONTROL
ARRAY TRIGGER
MONITORING
CHECK THE STATUS AND CONFIGURATION OF EACH DEVICE, TO STORE (IN A DATABASES)
REAL-TIME ANALYSIS
LEVEL-B ANALYSIS
ARCHIVE
telescope and not-telescope data

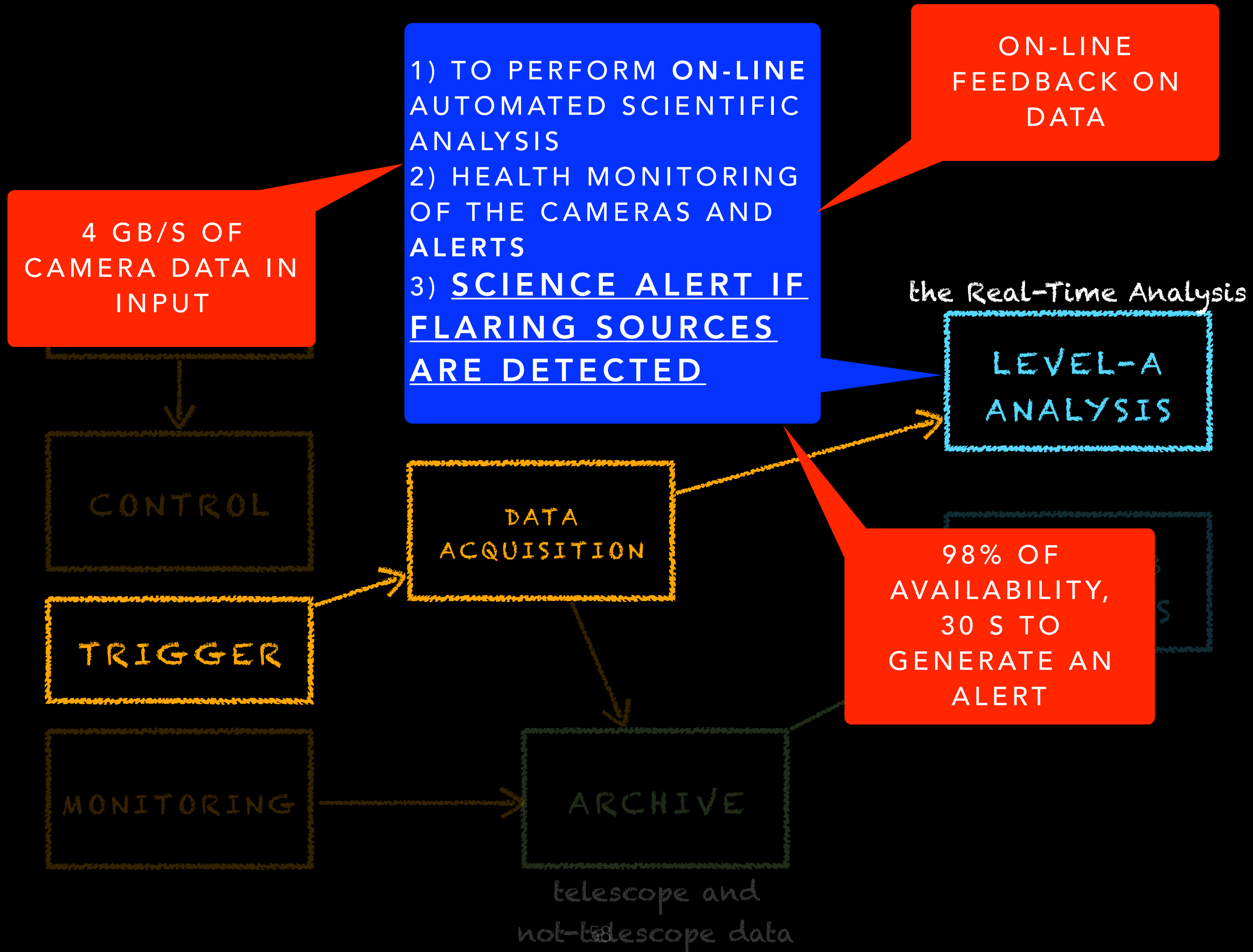

40 KHZ OF TIME STAMPS WILL BE CORRELATED IN TIME WITH A LATENCY OF 1 S
CONTROL
ARRAY TRIGGER
MONITORING
TO CORRELATE IN TIME CHERENKOV CAMERAS, TO SELECT STEREO EVENTS (MORE THAN ONE TELESCOPE)
LEVEL-B ANALYSIS
ARCHIVE
telescope and not-telescope data
70 GBYTE/S OF CAMERA DATA WILL BE TEMPORARY BUFFERED (SECONDS) TO WAIT TRIGGER DECISION

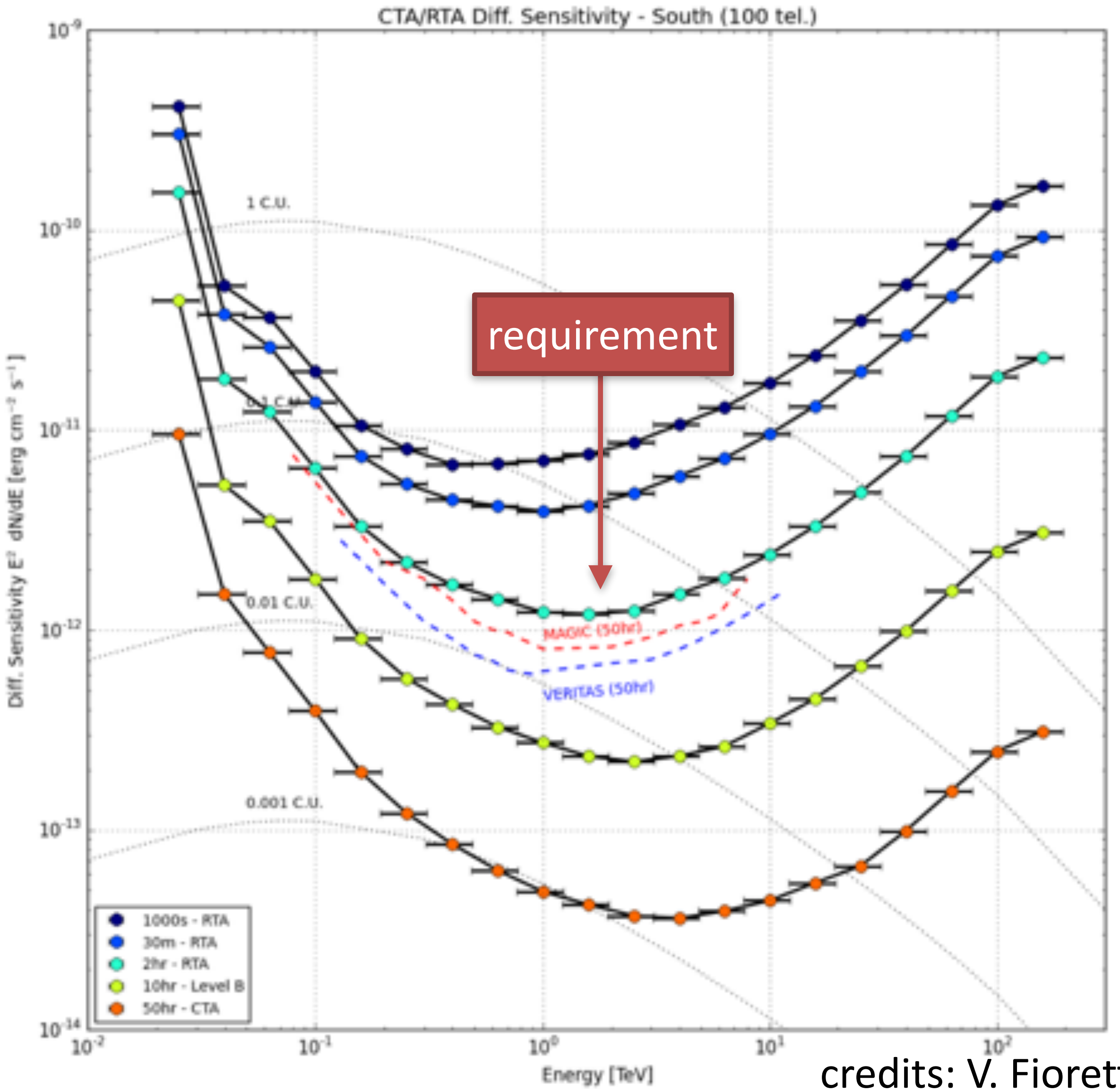

TO ACQUIRE DATA FROM CHERENKOV CAMERAS
SCHEDULER
CONTROL
ARRAY TRIGGER
DATA ACQUISITION
30 GBYTE/S OF CAMERA DATA IN INPUT
DATA REDUCTION, COMPRESSION
MONITORING
ARCHIVE
4 GB/S OF CAMERA DATA IN OUTPUT (TO BE STORED)
telescope and
not-telescope data

CTA DATA CHALLENGES/2: THE ON-SITE/REAL-TIME ANALYSIS @ IASFBO



-HIGH LEVEL DATA ANALYSIS OF SCIENTIFIC DATA
- HEALTH MONITORING OF CAMERAS
ON-SITE, ON-LINE (DURING DATA ACQUISITION), FAST
ON-SITE ANALYSIS
REAL-TIME ANALYSIS
SCHEDULER
CONTROL
ON-SITE, NEXT MORNING
LEVEL-B ANALYSIS
ARRAY TRIGGER
MONITORING
ARCHIVE
telescope and not-telescope data


1) TO PERFORM ON-LINE AUTOMATED SCIENTIFIC ANALYSIS
2) HEALTH MONITORING OF THE CAMERAS AND ALERTS
3) SCIENCE ALERT IF FLARING SOURCES ARE DETECTED
ON-LINE FEEDBACK ON DATA
4 GB/S OF CAMERA DATA IN INPUT
the Real-Time Analysis
LEVEL-A ANALYSIS
CONTROL
DATA ACQUISITION
TRIGGER
98% OF AVAILABILITY, 30 S TO GENERATE AN ALERT
MONITORING
ARCHIVE
telescope and not-telescope data



credits: V. Fioretti

- **RESULTS**
- Based on standard CTA IRFs
- CTA Southern array, composed by 4 large-sized telescopes, 24 medium-sized telescopes and 72 small-sized telescopes, for a total covered area of ~ 4 km^2

Differential sensitivity, in erg cm^{-2} s^{-1}, of the Real-Time and Level B analysis pipelines computed for t_{exp} = 1000s, 30m, and 2hr (RTA) and 10hr (Level B). The differential sensitivity is computed by requiring, for each energy bin, a statistical significance of 5 standard deviations (σ) of the gamma-ray excess above the background. The expected CTA sensitivity is also shown for t_{exp} = 50hr as reference. The dotted lines show the Crab flux in 0.001, 0.01, 0.1, 1, and 10 C.U., while the dashed lines show the MAGIC and VERITAS sensitivity for a t_{exp} = 50hr exposure.

CONCLUSIONS

- Development of prototypes
  - for many telescopes: in progress
  - ASTRI SST-2M prototype
- We are entering in the “pre-production” phase
  - Mini-Array

“Thank you”