

**VERITAS**  
Ten-Year Celebration

<http://veritas.aao.artizona.edu/10Years/>

A celebration and conference to mark ten years of VERITAS operations.

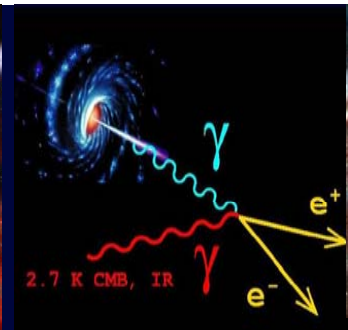
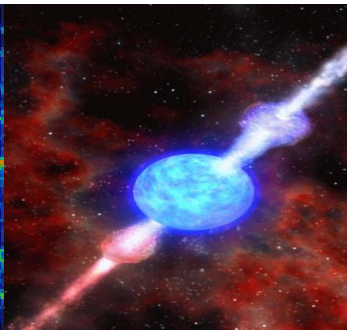
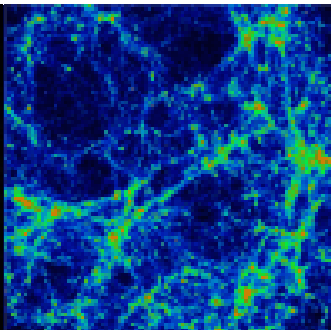
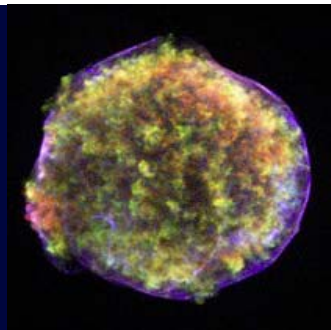
**JUNE 28-29, 2017**  
Tucson, AZ

BARNARD  
Smithsonian

UCLA

PURDUE

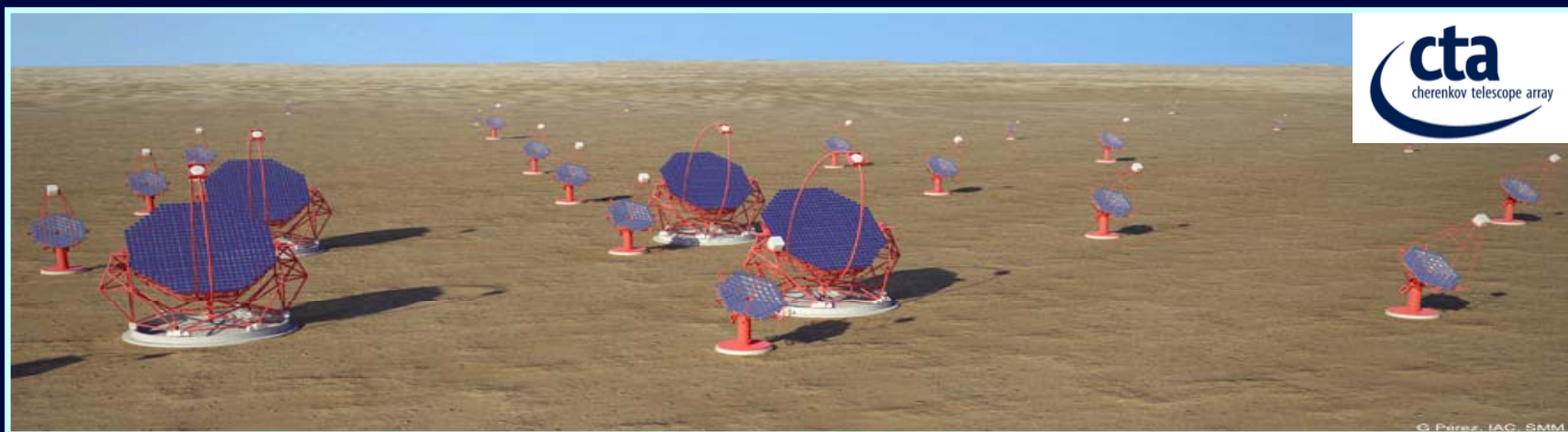
McGill  
Washington



## VERITAS 10yr Celebration

# The Cherenkov Telescope Array

Rene A. Ong (UCLA),  
for the CTA Consortium



# Outline

- **Motivation & History**

This Marvelous (Cherenkov) Technique

Early Cherenkov telescope arrays – The promise of the 90's

→ Motivation for CTA

- **Cherenkov Telescope Array**

Science Drivers → requirements

CTA Design & Performance → Scientific Capabilities

Key Science Projects

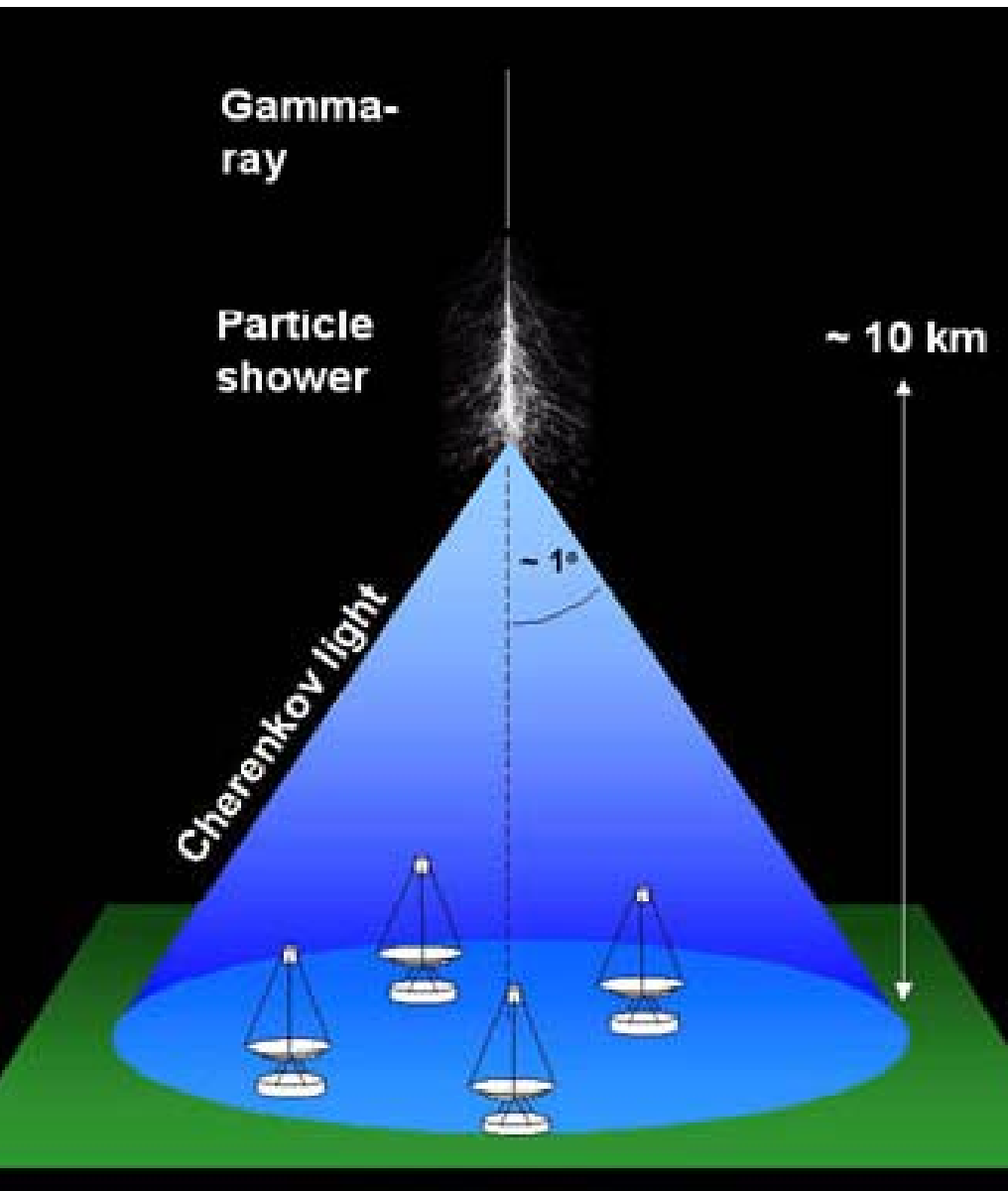
- **CTA Implementation & Status**

Prototype telescopes, sites

Present status (2017)

- **Summary – how we got to CTA**

# This Marvelous Technique



## Atm. Cherenkov showers:

- V. large light pool  $\sim 250\text{m}$  diameter
- Rapid time structure  $\sim 5\text{ ns}$
- Very calorimetric

## Imaging technique:

- Excellent shower reconstruction
- Large background rejection
- Improved by:
  - More views of shower
  - Higher resolution images

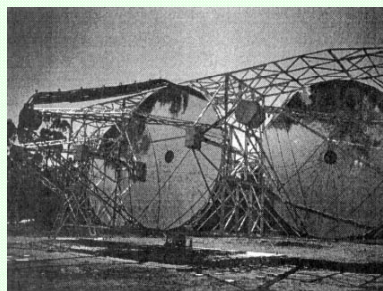
Granularity of Cherenkov emission is remarkably small ( $< 1\text{ arc-min}$ ) !

# Early Cherenkov telescope arrays

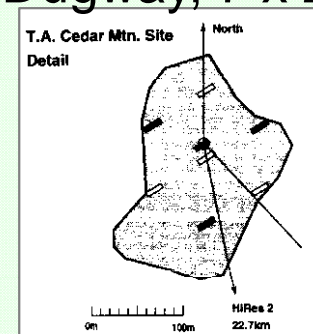
Crimean Obs  
12 x 2.5m



Durham V, VI.  
Narrabri, 3 x 7m



Tel Array,  
Dugway, 7 x 2m



1970

1980

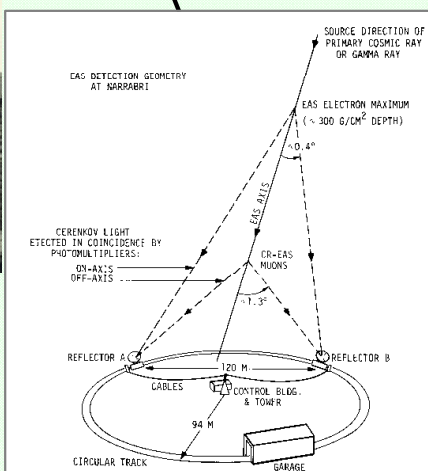
1990

2000

Imaging



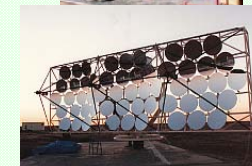
Harwell  
1962



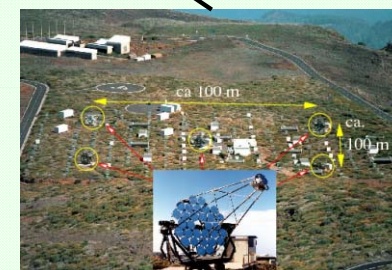
Grindlay et al.  
Narrabri  
2 x 7m



GRANITE  
Whipple  
10m + 11m



CANGAROO  
- BIGRAT  
Woomera  
2 x 4m



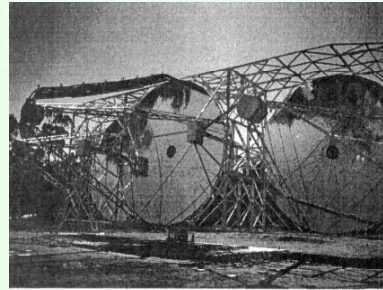
HEGRA IACT  
La Palma  
6 x 3.4m

# Early Cherenkov telescope arrays

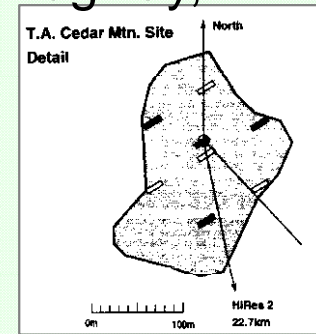
Crimean Obs  
12 x 2.5m



Durham V, VI.  
Narrabri, 3 x 7m



Tel Array,  
Dugway, 7 x 2m



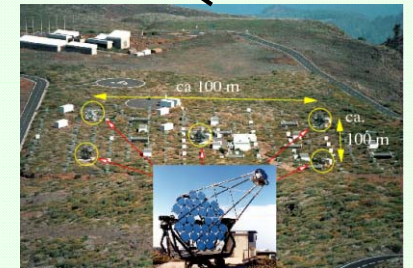
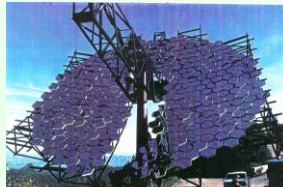
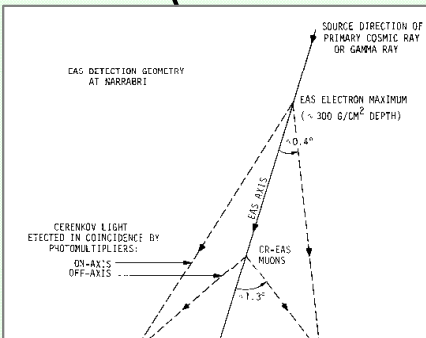
Imaging

1970

1980

1990

2000



HEGRA IACT

Harwell  
1962

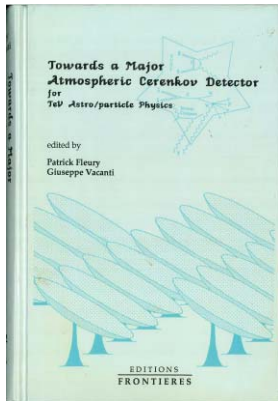
The promise of arrays of Cherenkov telescopes has been well appreciated for many years

Narrabri  
2 x 7m

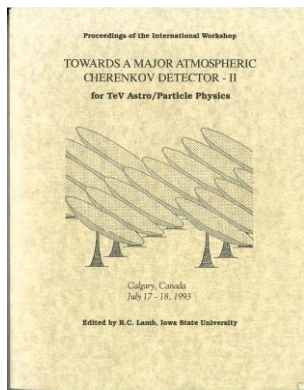
Narrabri  
2 x 4m

# The Promise of the 1990's

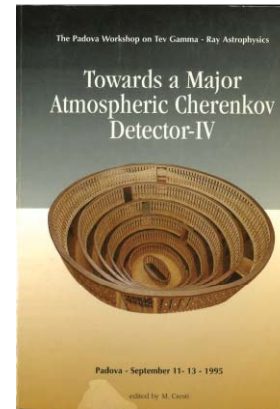
## Towards a Major Atmospheric Cherenkov Detector



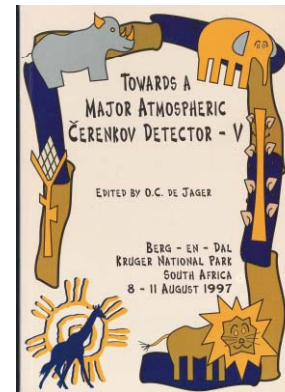
### I. 1992 PALAISEAU



### II. 1993 CALGARY



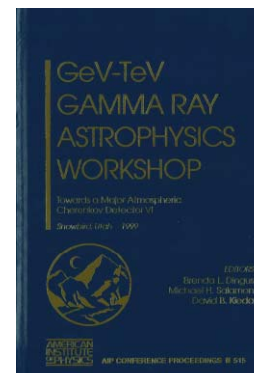
### IV. 1995 PADOVA



### V. 1997 KRUGER PARK



### III. 1994 TOKYO

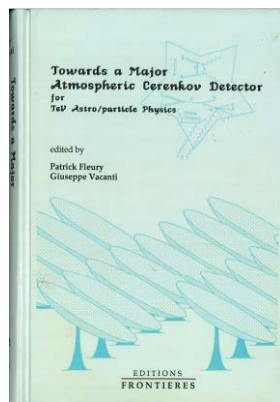


### VI.. 1999 SNOWBIRD

(and then the meeting got hijacked!)

# The Promise of the 1990's

## I. 1992 PALAISEAU

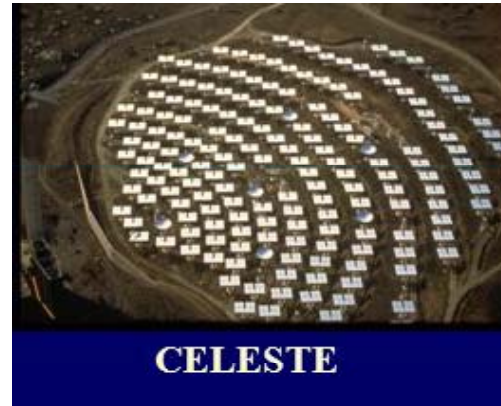
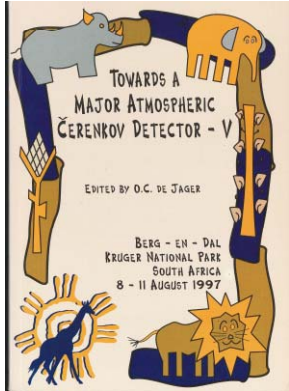


### T. Weekes Summary Talk “Quo Vadis”

The scale of the Large Array Project is far beyond that normally considered for atmospheric Cherenkov telescopes. Given the climate for funding these days it will probably be only accomplished if it is undertaken as an international collaboration. It should not be undertaken prematurely; there must be a clear scientific justification for it, the design must be carefully optimized and its individual components must be thoroughly tested. The design should carefully consider all the science (other than gamma-ray astronomy) that might be done with this unique instrument; funding may well be dependent on the inclusion of some of these aspects in the design. It was the almost general consensus the time was not yet ripe for this ambitious project but we should be laying the groundwork for this undertaking over the next 1-2 years.

# The Promise of the 1990's → Solar Cherenkov Arrays, Stereo Imaging

## V. 1997 Kruger Park



**CELESTE**



**STACEE**

### Solar Arrays

228

CELESTE: A status report

*Paré, E. for the CELESTE Collaboration . . . . .* 228

Description of the initial phase of the CELESTE experiment

*Québert, J. for the CELESTE Collaboration . . . . .* 234

The Mini-GRAAL Project

*Arqueros, F., et al. . . . .* 240

The STACEE Project

*Ong, R.A. and Covault, C.E. for the STACEE Collaboration . . . . .* 247

The STACEE Telescope : On-site Tests and Observations

*Covault, C.E. for the STACEE Collaboration . . . . .* 257

### Stereo Imaging

263

Stereo Imaging of VHE Gamma-Ray Sources

*Aharonian, F.A. and Konopelko, A.K. . . . .* 263

Precision Determination of Source Location with the HEGRA IACT System

*Panter, M. and Pühlhofer . . . . .* 278

Measuring  $\gamma$ -Ray Energy Spectra with the HEGRA IACT System

*Hofmann, W. for the HEGRA Collaboration . . . . .* 284

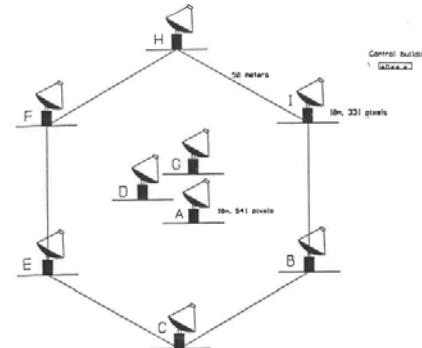
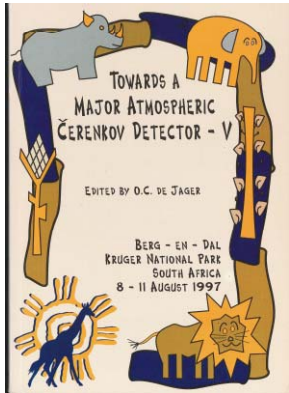
Stereoscopic Observations of the Crab Nebula at the Whipple Observatory

*Bussóns-Gordo, J., et al. . . . .* 293

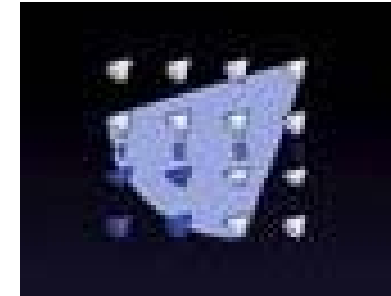


# The Promise of the 1990's → “Big 4”

## V. 1997 Kruger Park



VERITAS-9



H.E.S.S.-16

### Large Telescopes under Development

392

The Deep Universe  $\gamma$ -ray Observatory

*Magnussen, N. and Meyer, H.* . . . . . 392

GRACE - A Major, new Gamma-Ray Astronomy Facility in India

*Bhat, C.L.* . . . . . 398

HESS - an Array of Imaging Atmospheric Čerenkov Telescopes for Stereoscopic Observations of Air Showers in the 100 GeV Energy Range

*Hofmann, W.* . . . . . 405

The MAGIC Telescope Project

*Lorenz, E.* . . . . . 415

Monte-Carlo Studies for The MAGIC Telescope Project

*González, J.C., et al.* . . . . . 422

VERITAS: the Very Energetic Radiation Imaging Telescope Array System

*Weekes, T.C. et al.* . . . . . 433

The 7/10m Woomera Telescope

*Matsubara, Y. for the CANGAROO Collaboration* . . . . . 447

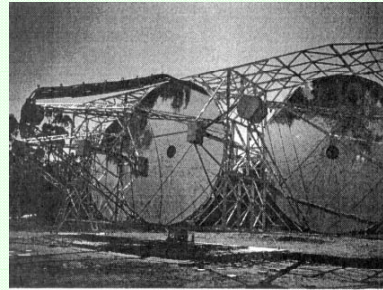
“The Big 4”

# Early Cherenkov telescope arrays

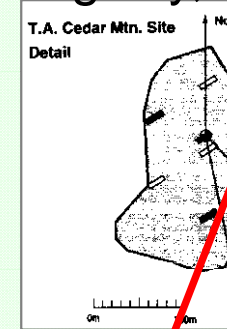
Crimean Obs  
12 x 2.5m



Durham V, VI.  
Narrabri, 3 x 7m



Tel Array,  
Dugway, 7



**3<sup>rd</sup> Generation  
Imaging Arrays**  
**CANGAROO**  
**HESS**  
**MAGIC**  
**VERITAS**

1970

1980

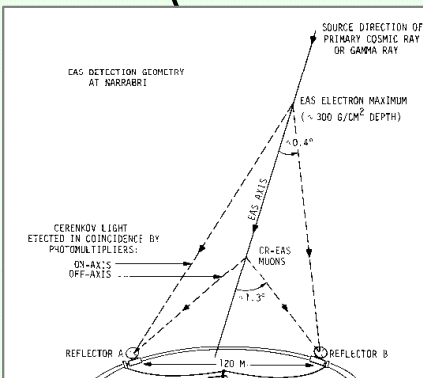
Imaging

1990

2000



Harwell  
1962



HEGRA IACT

The promise of arrays of Cherenkov telescopes  
In the 1990's → **Big Four**

2 x 7m

2 x 4m

# The Return to Palaiseau 2005

## VII. 2005 Palaiseau



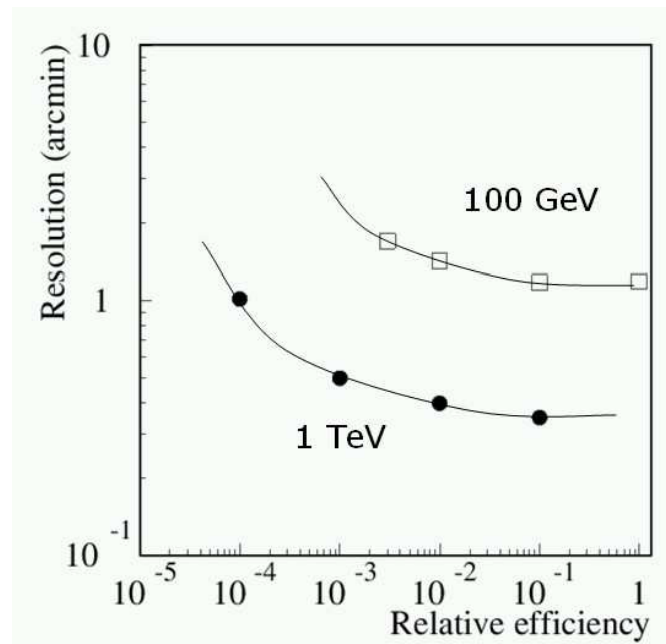
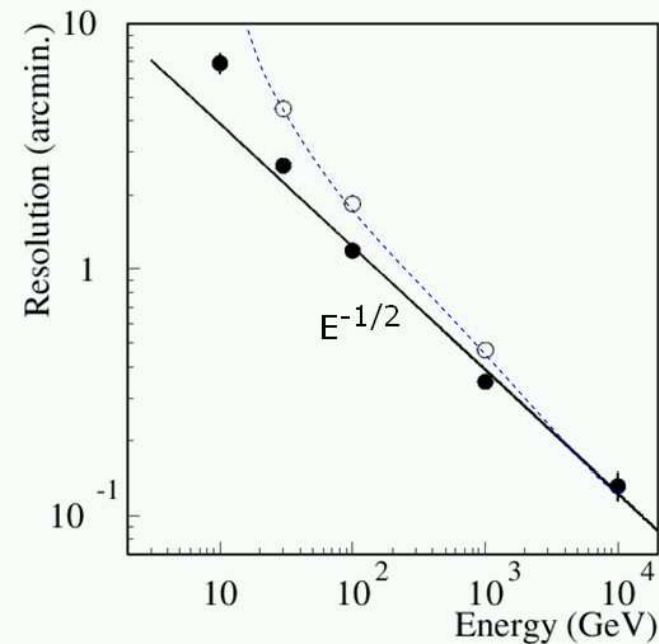
### Session 4: The future of ground-based VHE astronomy

Next generation of IACT arrays: scientific objectives versus energy domains . . . . .	331
<i>Felix Aharonian</i>	
Beyond VERITAS . . . . .	347
<i>Simon Swordy</i>	
VHE Gamma-Ray Future Project: Beyond CANGAROO . . . . .	359
<i>Takanori Yoshikoshi</i>	
MAGIC-II . . . . .	373
<i>Masahiro Teshima</i>	
H.E.S.S.-II: Expansion of H.E.S.S. for higher sensitivity and lower energy . . . . .	379
<i>Michael Punch for the HESS Collaboration</i>	
Performance Limits for Cherenkov Instruments . . . . .	393
<i>Werner Hofmann</i>	
GLAST and Very High Energy astrophysics . . . . .	401
<i>Berrie Giebels</i>	
The high altitude MACE $\gamma$ -ray telescope . . . . .	415
<i>Ramesh Koul</i>	
Extending the High-Energy Sensitivity of Air Čerenkov Telescopes . . . . .	421
<i>I. de la Calle Pérez and S. D. Biller</i>	
HAWC/miniHAWC: High Altitude Water Cherenkov Experiment . . . . .	429
<i>Andrew Smith</i>	
Point Source and Diffuse Source Sensitivities in GeV/TeV Observatories . . . . .	437
<i>D. B. Kieda</i>	
High Energy All Sky Transient Radiation Observatory . . . . .	445
<i>V. Vassiliev and S. Fegan</i>	
Performance of a prototype system of Cherenkov telescopes at high altitude . . . . .	457
<i>Dieter Horns, Felix Aharonian, and Andrea Santangelo</i>	
STAR a next generation Cherenkov telescope . . . . .	463
<i>Ira Jung, Henric Krawczynski, Jim Buckley and Abe Falcone</i>	



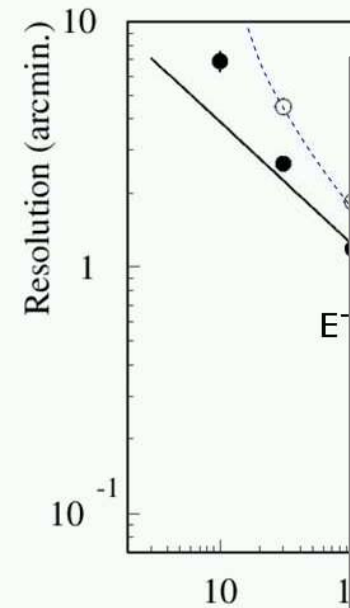
# The Return to Palaiseau 2005

W. Hofmann, *Performance Limits for Cherenkov Telescopes*



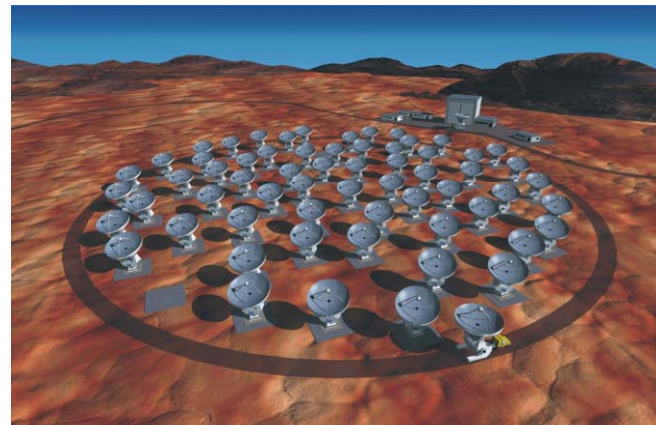
# The Return to Palaiseau 2005

W. Hofmann, *Performance Limits for Cherenkov Telescopes*



## 4 The bottom line

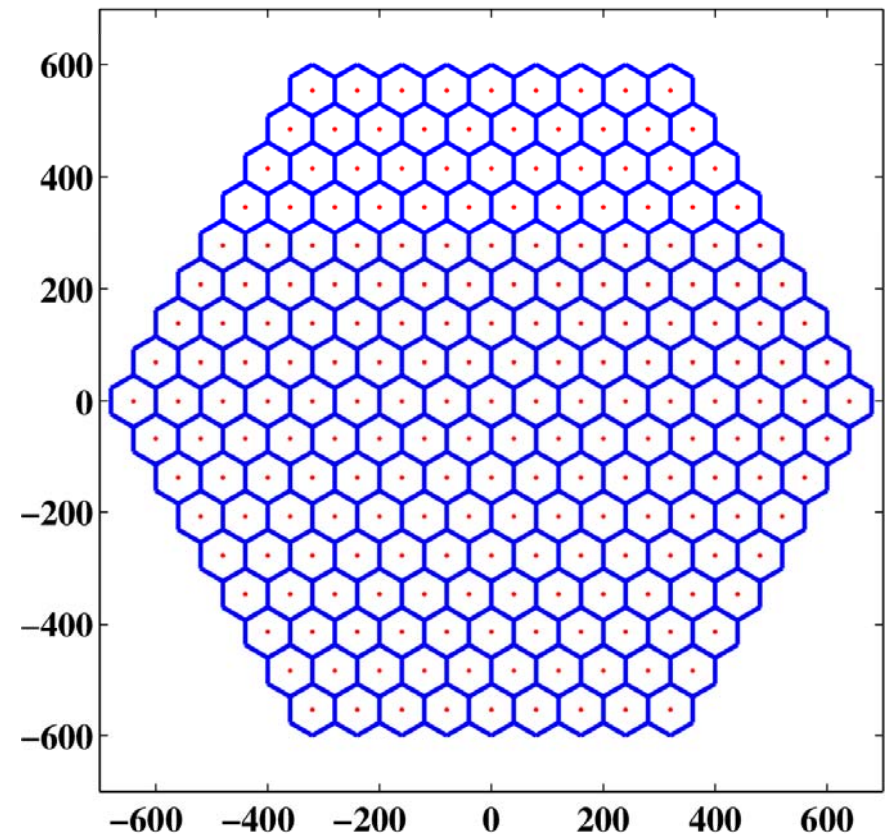
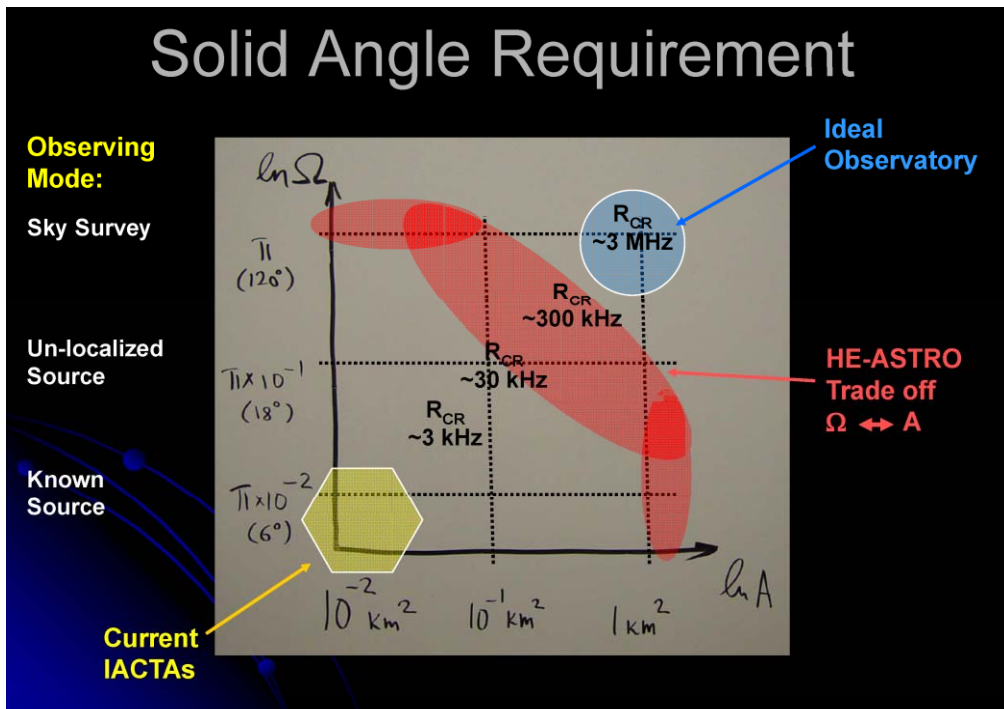
Financial considerations aside, shower physics seems to allow further improvement of the performance of Cherenkov instruments in particular in the domain around a TeV and above. An ideal detector, covering a large fraction of the ground with 10 m class Cherenkov telescopes equipped with very fine pixels could provide a gain of up to an order of magnitude in angular resolution and in proton rejection, and non-negligible electron rejection, corresponding to a Q-factor of about 3-5. At lower energies, shower fluctuations become more and more important and gains are reduced to factors of a few at 100 GeV, and may be negligible at even lower energies.



“... a dense array of (high resolution) medium-size telescopes “

# The Return to Palaiseau 2005

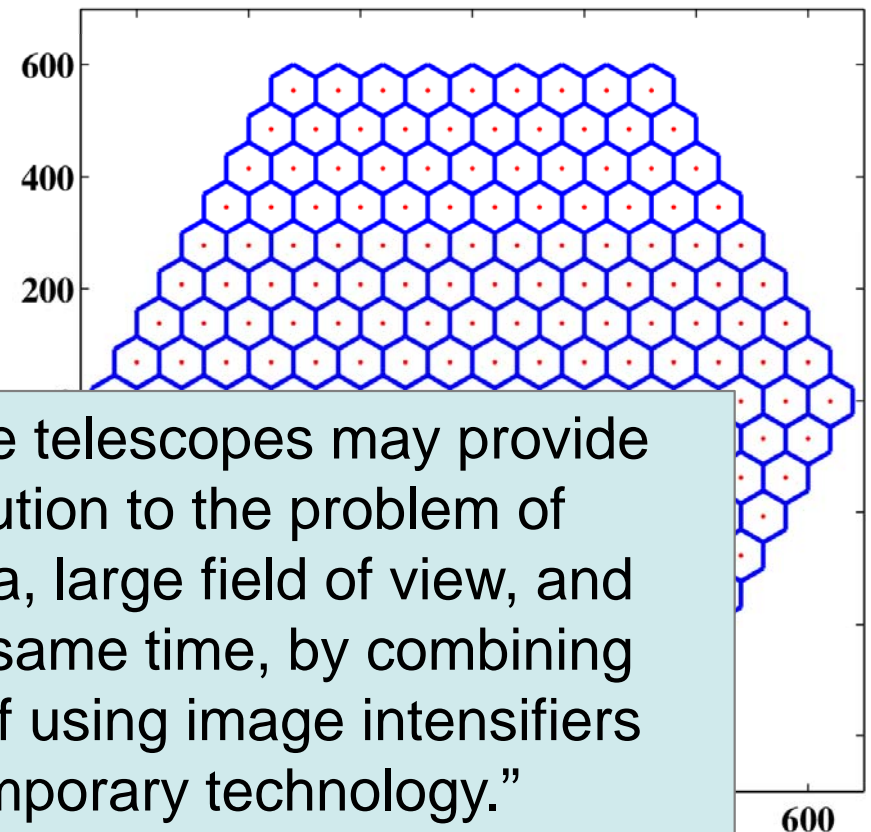
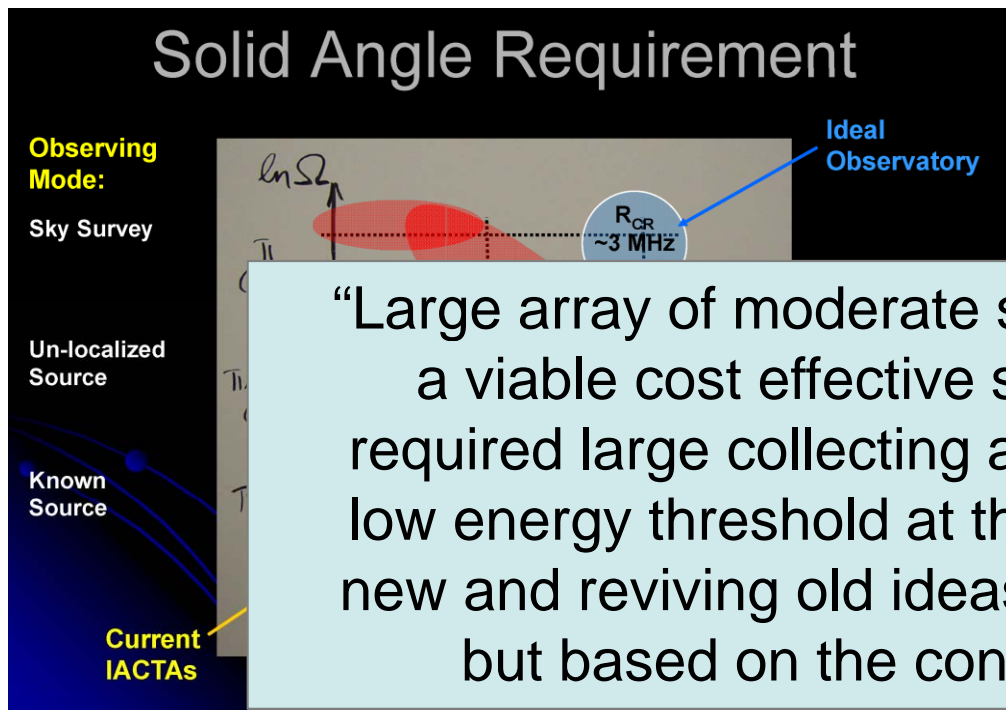
S. Fegan & V. Vassiliev, *High Energy All Sky Transient Radiation Obs.*



HE-ASTRO:  
217 Telescopes ( $\varnothing 10\text{m}$ ), 80m separation.  
1.1 km<sup>2</sup> collection area & 12° FOV.  
Challenging !

# The Return to Palaiseau 2005

S. Fegan & V. Vassiliev, *High Energy All Sky Transient Radiation Obs.*



“Large array of moderate size telescopes may provide a viable cost effective solution to the problem of required large collecting area, large field of view, and low energy threshold at the same time, by combining new and reviving old ideas of using image intensifiers but based on the contemporary technology.”

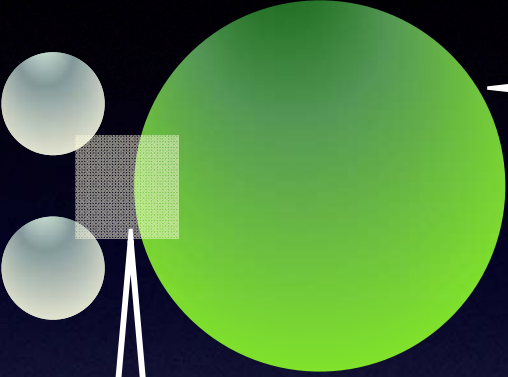
HE-ASTRO:

217 Telescopes ( $\emptyset 10\text{m}$ ), 80m separation.

1.1 km<sup>2</sup> collection area & 12° FOV.

Challenging !

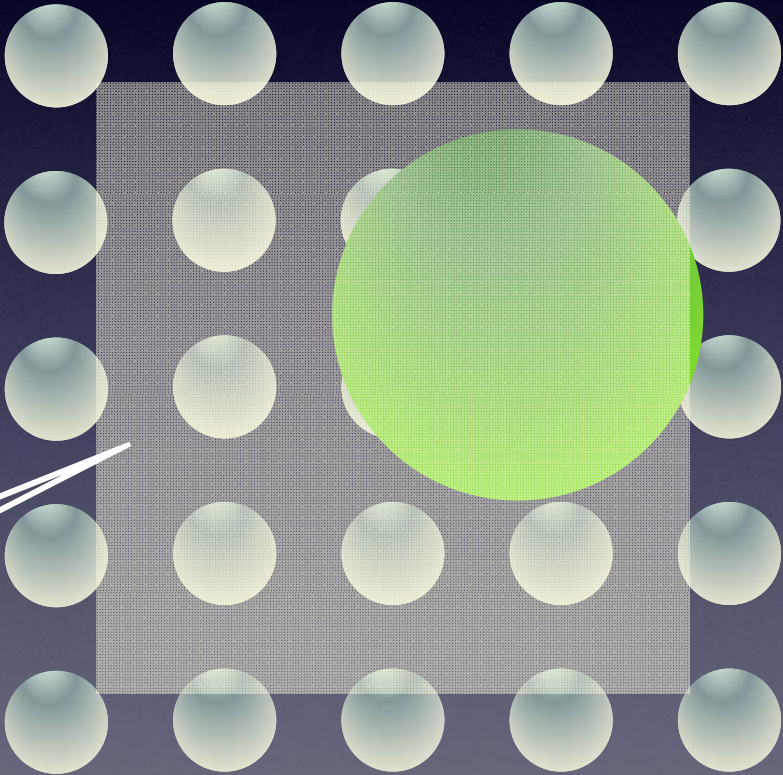
# The Power of Contained Events



*Light pool radius  
 $R \approx 100-150\text{m}$   
 $\approx$  typical telescope Spacing*



*Sweet spot for best triggering & reconstruction...  
**most showers miss it!***

- 
- ✓ *Large detection Area*
  - ✓ *More Images per shower*
  - ✓ *Lower trigger threshold*

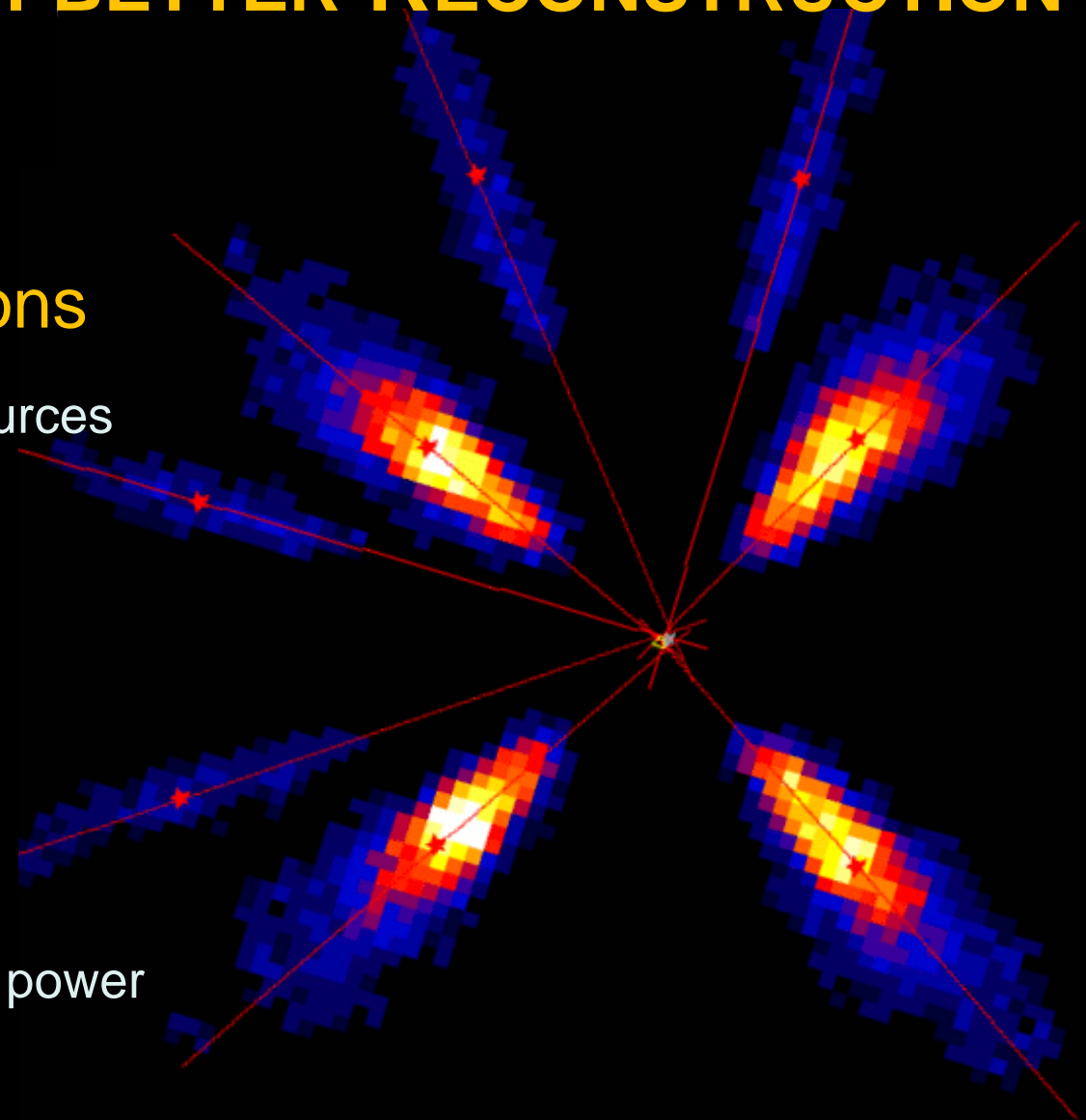


# MANY VIEWS → MUCH BETTER RECONSTRUCTION

## → More events, more photons

- Better spectra, images, fainter sources
  - ✓ Larger light collecting area
  - ✓ Better reconstructed events
- Better measurement of air shower and hence primary gammas
  - ✓ Improved angular resolution
  - ✓ Improved background rejection power

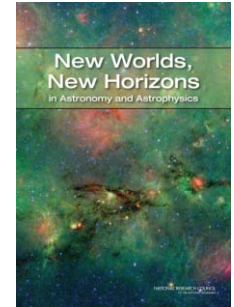
## → More telescopes!



**Simulation:**  
Superimposed images from  
8 cameras

# Parallel Paths

## AGIS



Astro2010

2006: Sante Fe (LANL)  
2007: Chicago  
2007: SLAC  
2008: UCLA  
2009: ANL

2005: May's Landing (UCLA)

2010  
Zeuthen

2010

2009: Zurich

2009: Krakow

2008: Barcelona  
2008: Padova

2006: Berlin

2007: Paris



ESFRI  
2008

## CTA



2005

# Planning for the Future

**What do we know, based on current instruments?**

**Great scientific potential exists in the VHE domain**

- *Frontier astrophysics & important connections to particle physics*

**IACT Technique is very powerful**

- *Have not yet reached its full potential → large Cherenkov array*

**Exciting science in both Hemispheres**

- *Argues for an array in both S and N*

**Open Observatory → Substantial reward**

- *Open data/access, MWL connections to get the best science*

**International Partnerships required by scale/scope**

- *Numerous funding streams → a challenge to coordinate*



# cta

cherenkov telescope array

# Science Themes

## 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

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

## Theme 3: Physics Frontiers – beyond the SM

- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high energy photons?
- Do axion-like particles exist?

# Summary of Key Science Questions

**Bottom line: GeV and TeV gamma-ray sources are ubiquitous in the universe and probe extreme particle acceleration, and the subsequent particle interactions and propagation.**

1. Where and how are the bulk of CR particles accelerated in our Galaxy and beyond? (one of the oldest surviving questions of astrophysics)
2. Can we understand the physics of jets, shocks & winds in the variety of sources we see, including pulsars, binaries, AGN, starbursts, and GRBs?
3. How do black holes of all sizes efficiently particles? How are the structures (e.g. jets) formed and how is the accretion energy harnessed?
4. What do high-energy gamma rays tell us about the star formation history of the Universe, intergalactic radiation fields, and the fundamental laws of physics?
5. What is the nature of dark matter and can we map its distribution through its particle interactions?
6. What new, and unexpected, phenomena will be revealed by exploring the non-thermal Universe?

**Bonus science: optical interferometry, cosmic-ray physics, OSETI, etc.**

# 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 Design (S array)

## Science Optimization under budget constraints

### Low energies

Energy threshold 20-30 GeV

23 m diameter

4 telescopes

**(LST's)**

### Medium energies

100 GeV – 10 TeV

9.5 to 12 m diameter

25 telescopes

**(MST's/SCTs)**

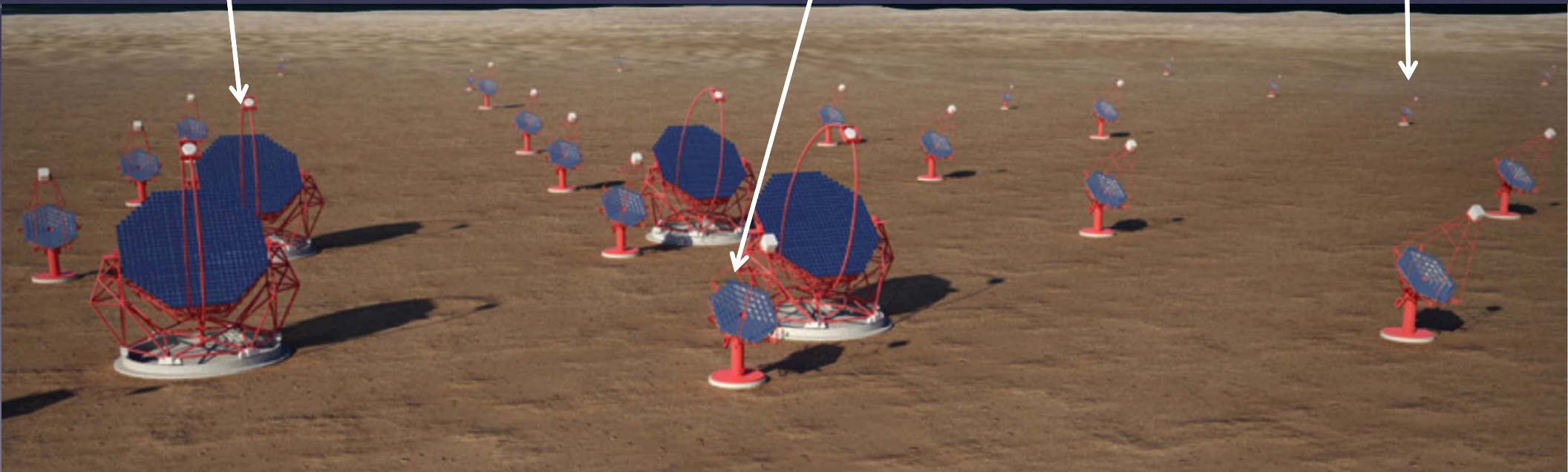
### High energies

10 km<sup>2</sup> area at few TeV

3 to 4m diameter

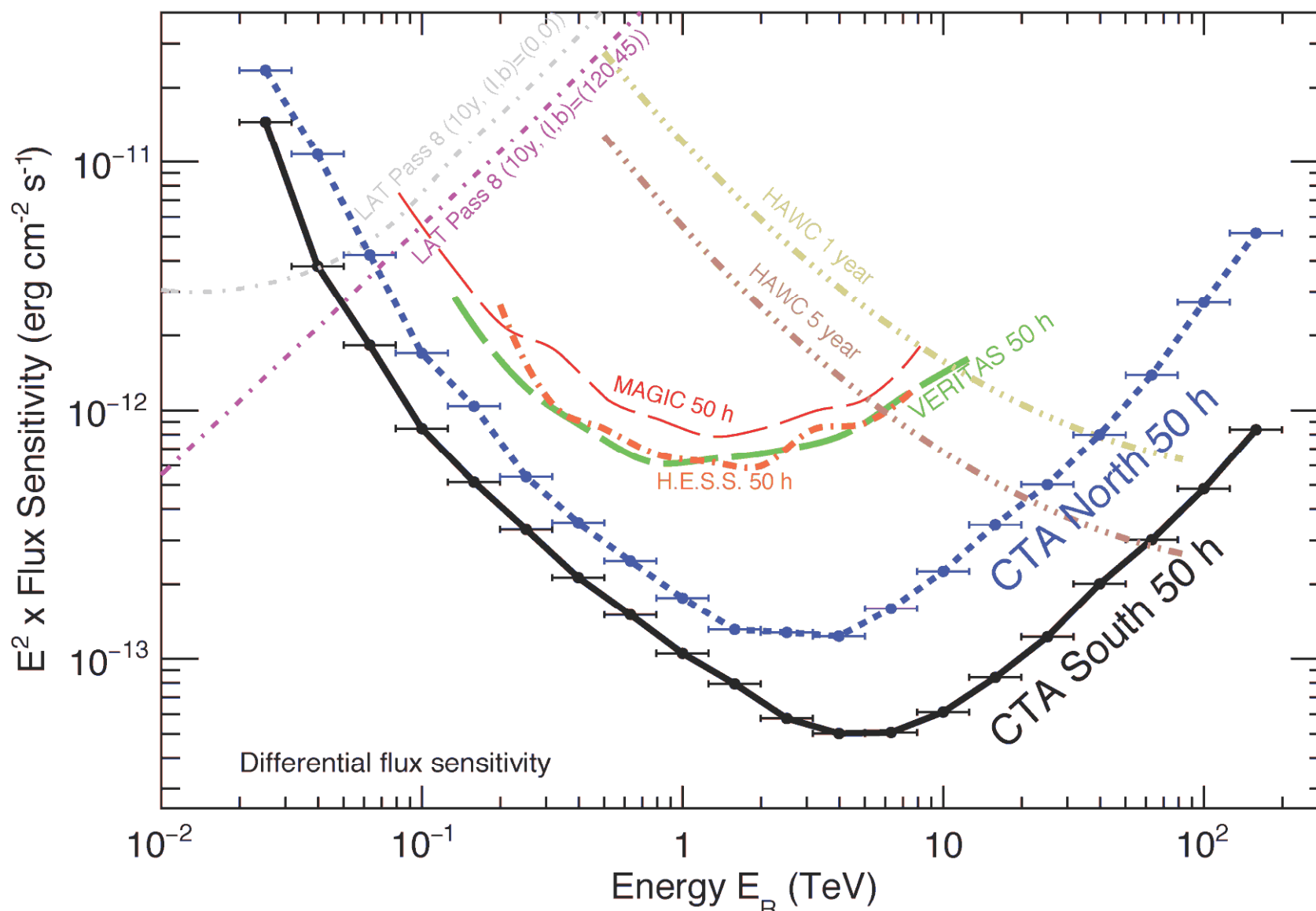
70 telescopes

**(SST's)**





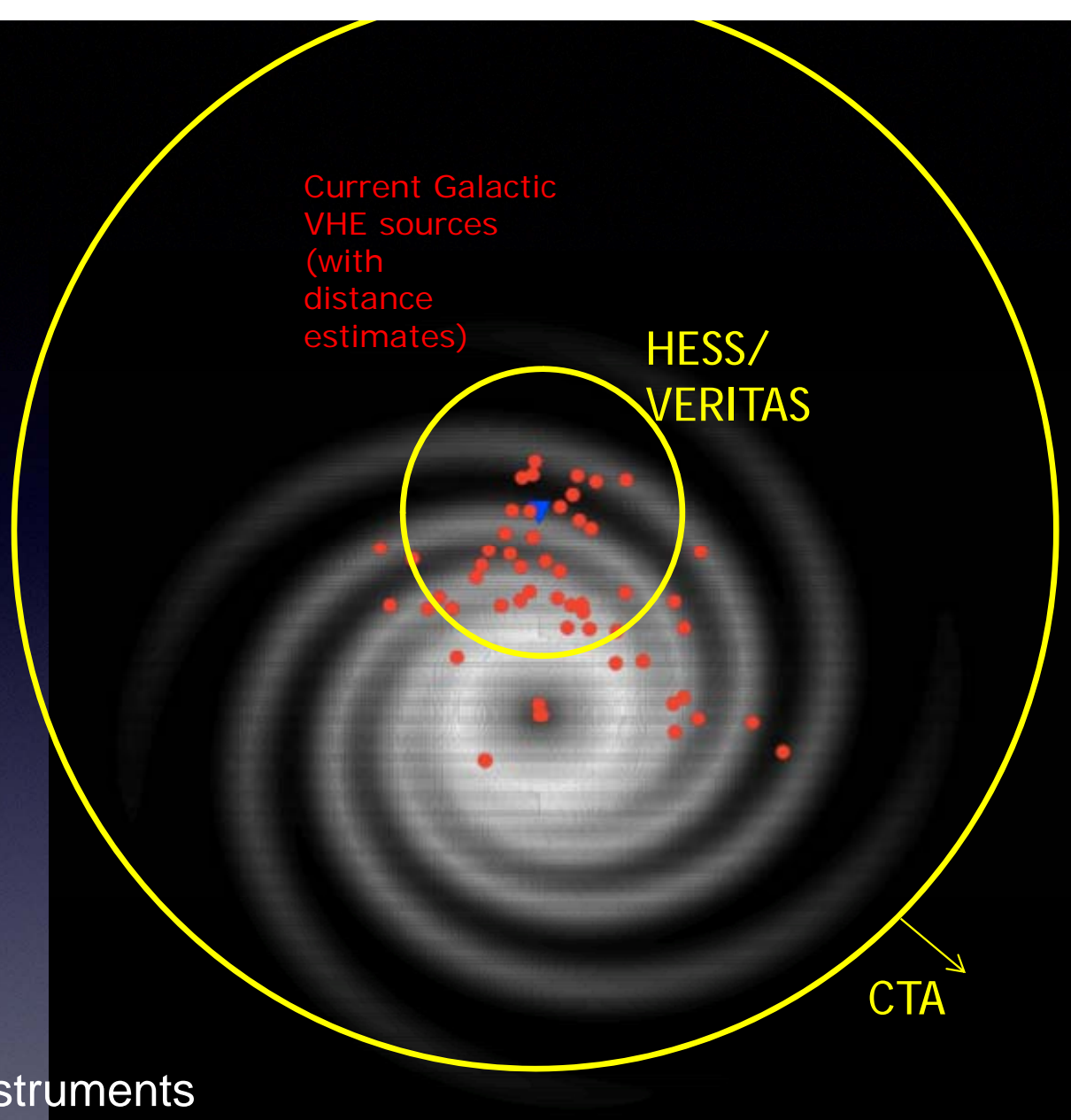
# Flux Sensitivity



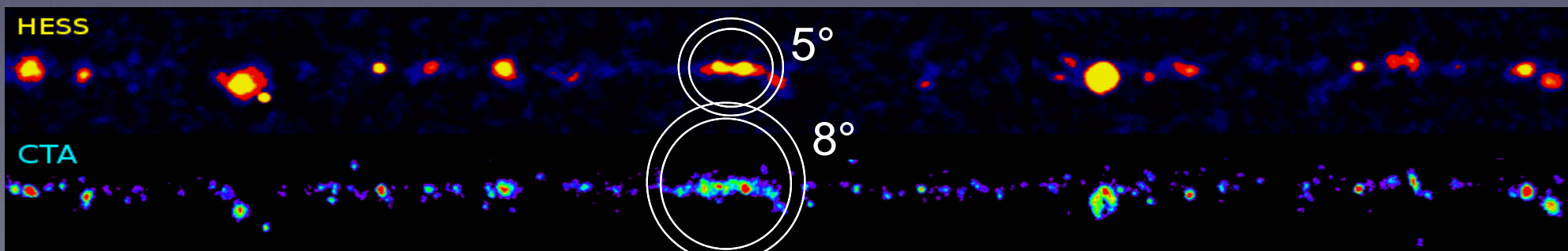
**Major sensitivity improvement & wider energy range**

**→ Factor of >10 increase in source population**

# Galactic Discovery Reach

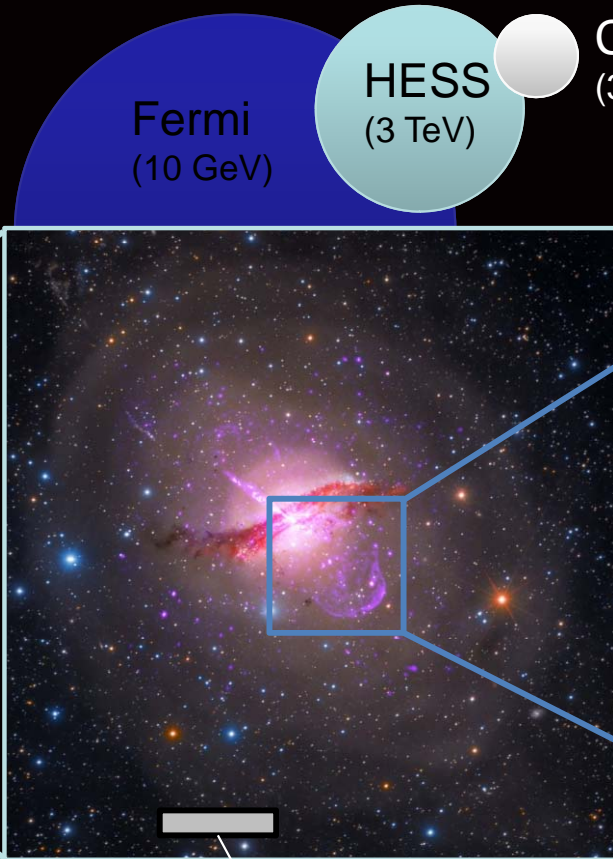
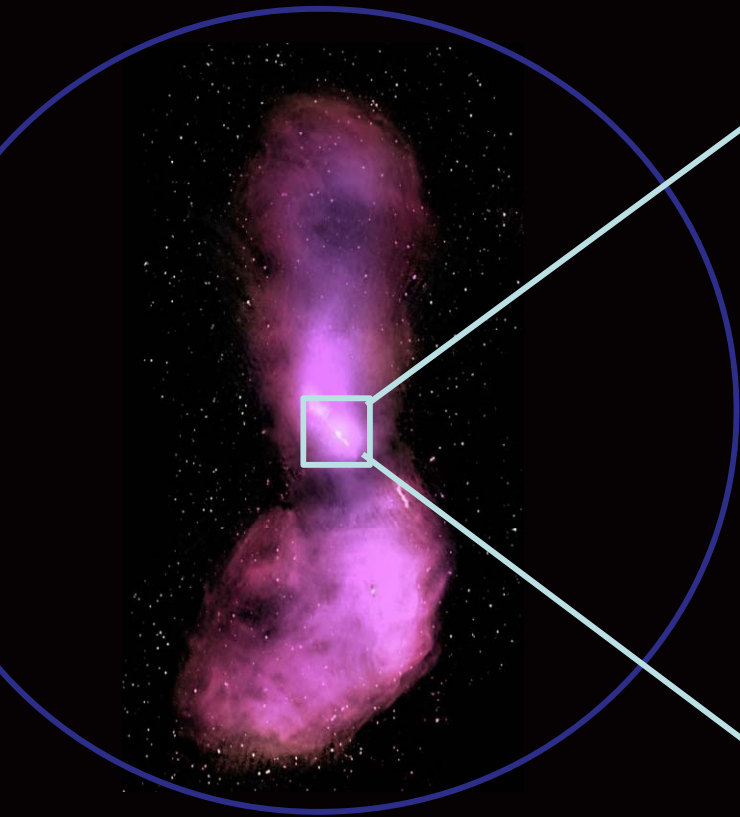


Survey speed:  
x300 faster than current instruments



# Angular Resolution

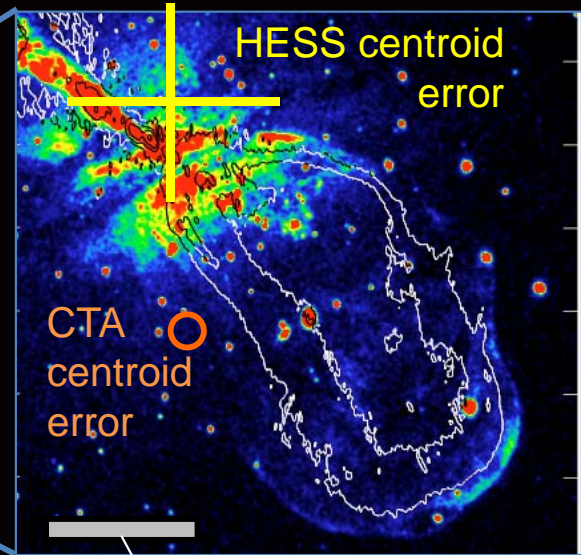
8° CTA FoV



CTA  
(3 TeV)

HESS  
(3 TeV)

Fermi  
(10 GeV)



HESS centroid error

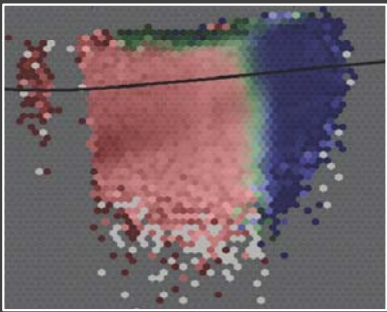
CTA centroid error

0.1°  
Typical  
HESS/MAGIC/VERITAS  
Resolution

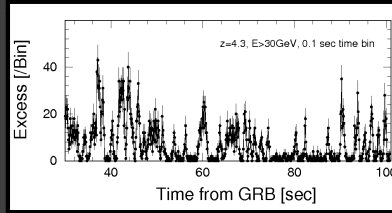
2'  
CTA > 1 TeV

Example: Cen A

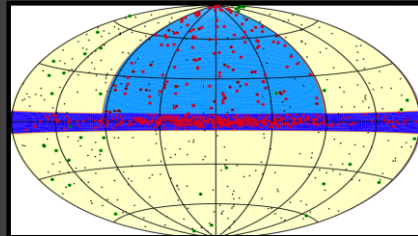
# Key Science Projects (KSPs)



Dark Matter Programme

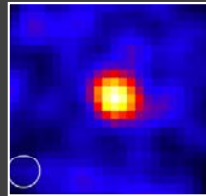


Transients



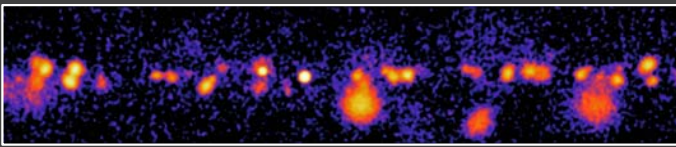
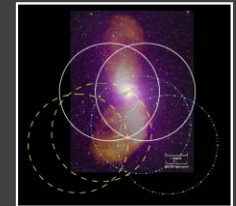
ExGal Survey

Galaxy Clusters



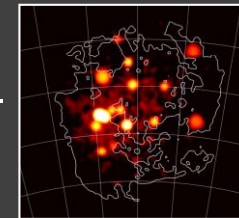
Star Forming Systems

AGN



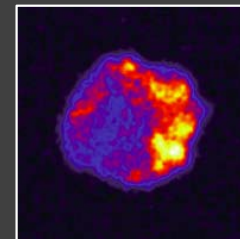
Galactic Plane Survey

LMC Survey

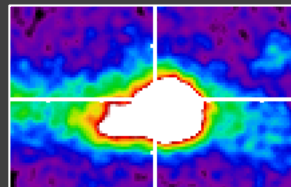


Galactic

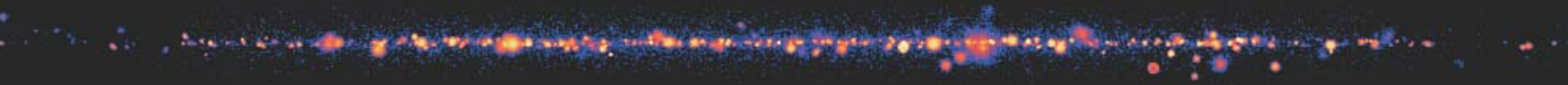
PeVatrons



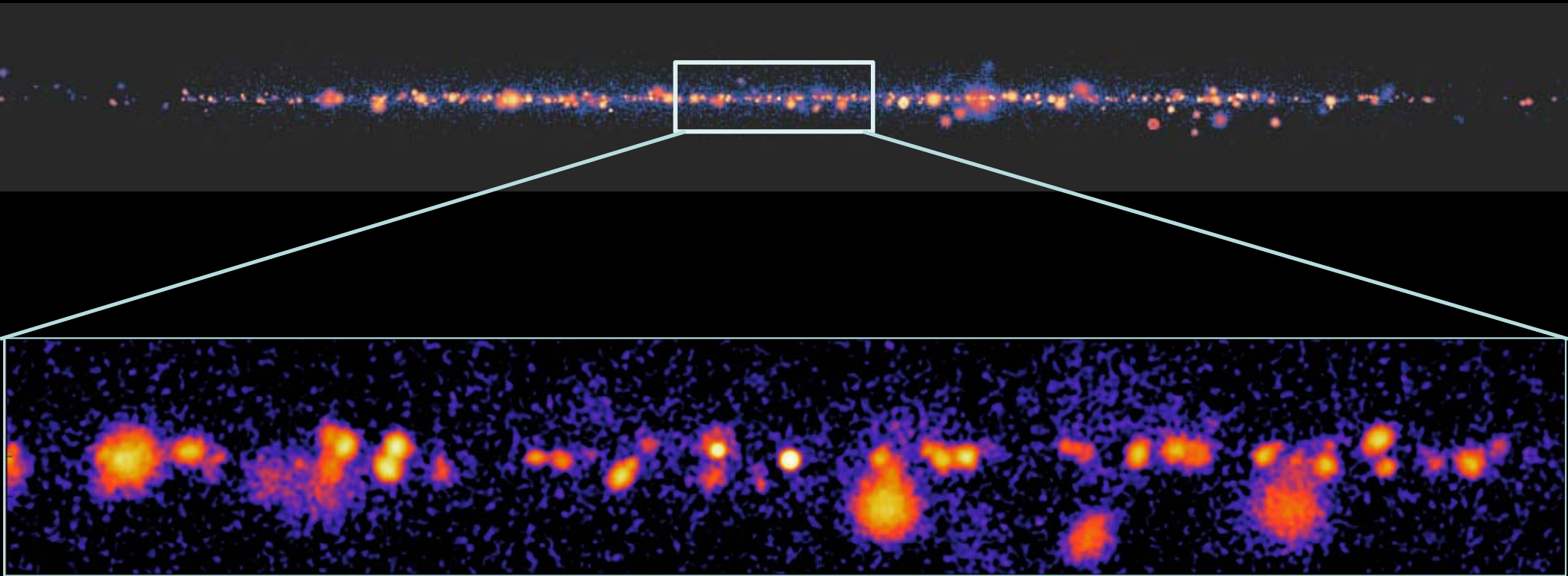
Galactic Centre



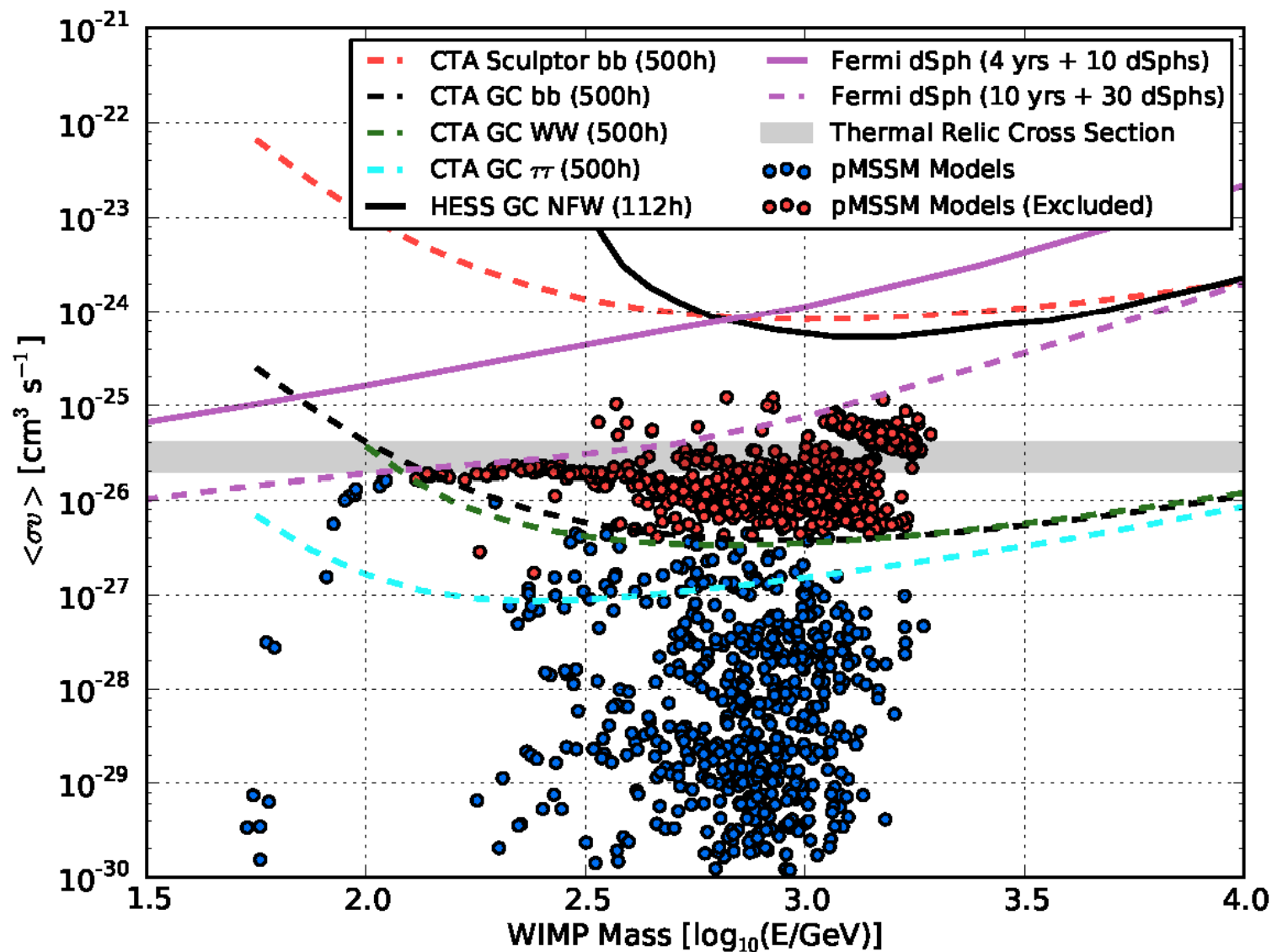
# Galactic Plane Survey (GPS)



# Galactic Plane Survey (GPS)



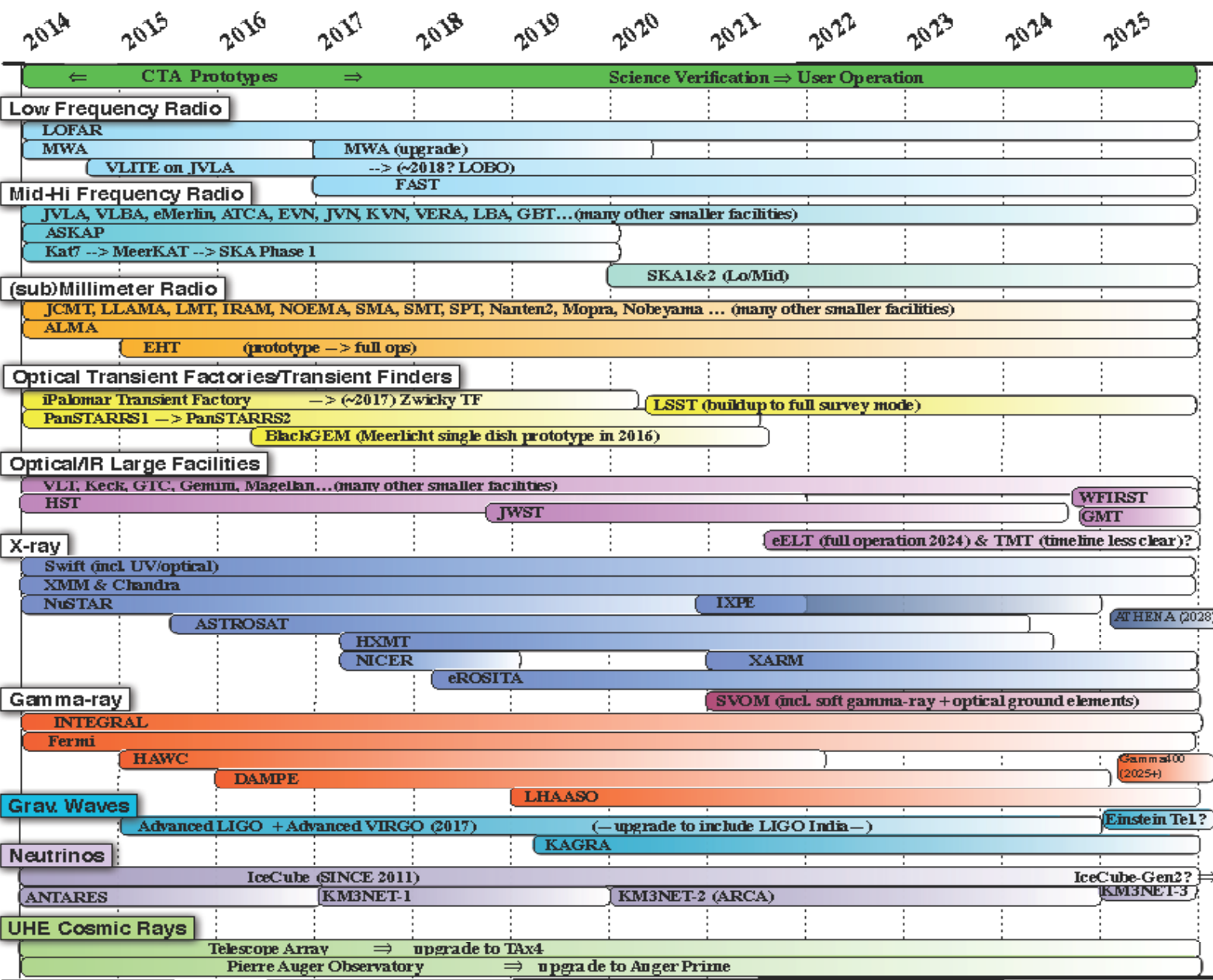
# Dark Matter Reach



M. Wood et al.  
arXiv:1305.0302

Sensitivity below thermal relic in TeV mass range  
- *critical reach, not achieved by direct detectors or LHC*

# Important MWL/MM Synergies



Caveat: Observatory timelines are very uncertain; this represents a notional picture based on available information





# Science with the Cherenkov Telescope Array

## Science with CTA

200 page document describing  
core CTA science

Will soon be put on arXiv and  
become a regular book

# CTA Implementation & Status

# CTA Consortium



**CTA is being developed by the CTA Consortium:**



32 countries, ~1402 scientists, ~208 institutes, ~480 FTE



# Large Telescope (LST)

23 m diameter  
390 m<sup>2</sup> dish area  
28 m focal length  
1.5 m mirror facets

4.5° field of view  
0.1° pixels  
Camera  $\varnothing$  over 2 m

*Carbon-fiber structure  
for 20 s positioning*

Active mirror control

**4 LSTs on South site  
4 LSTs on North site**

**Prototype construction  
Underway (La Palma)**

# LST 1 Foundation



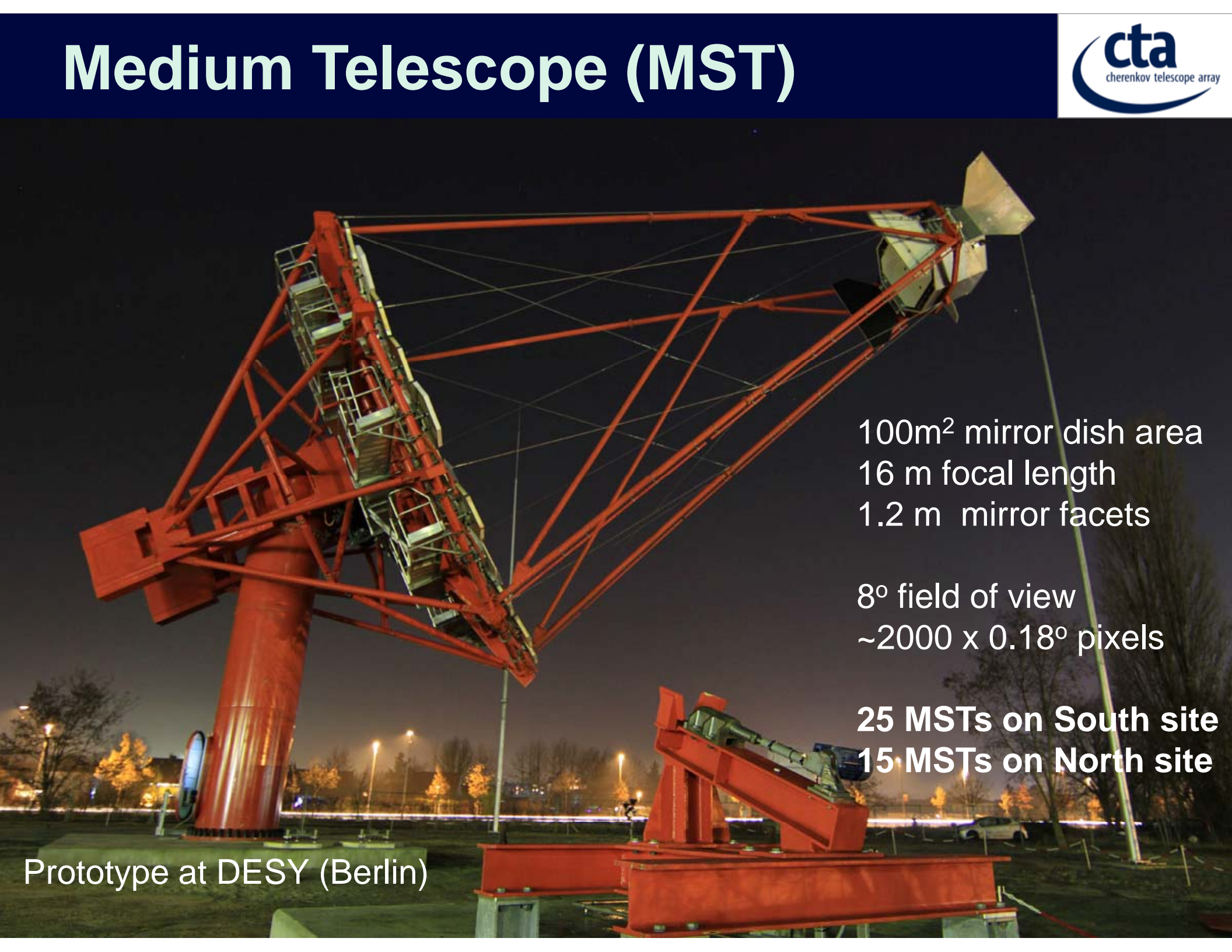
# LST 1 Foundation Completed



# LST: Structure & Mirrors



# Medium Telescope (MST)



100m<sup>2</sup> mirror dish area  
16 m focal length  
1.2 m mirror facets

8° field of view  
~2000 x 0.18° pixels

25 MSTs on South site  
15 MSTs on North site

Prototype at DESY (Berlin)

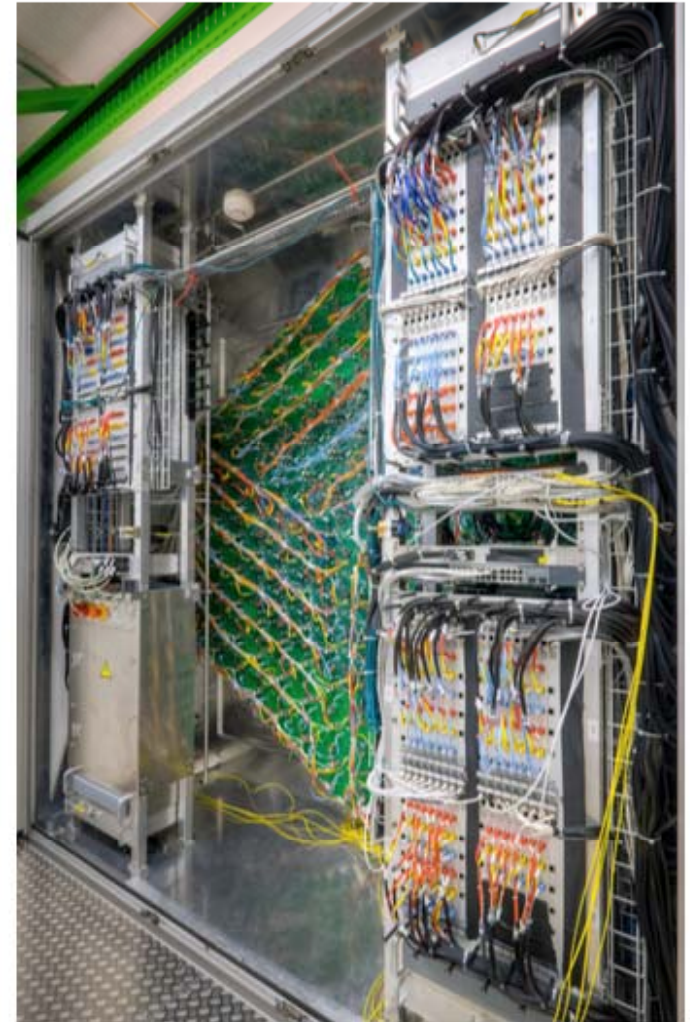
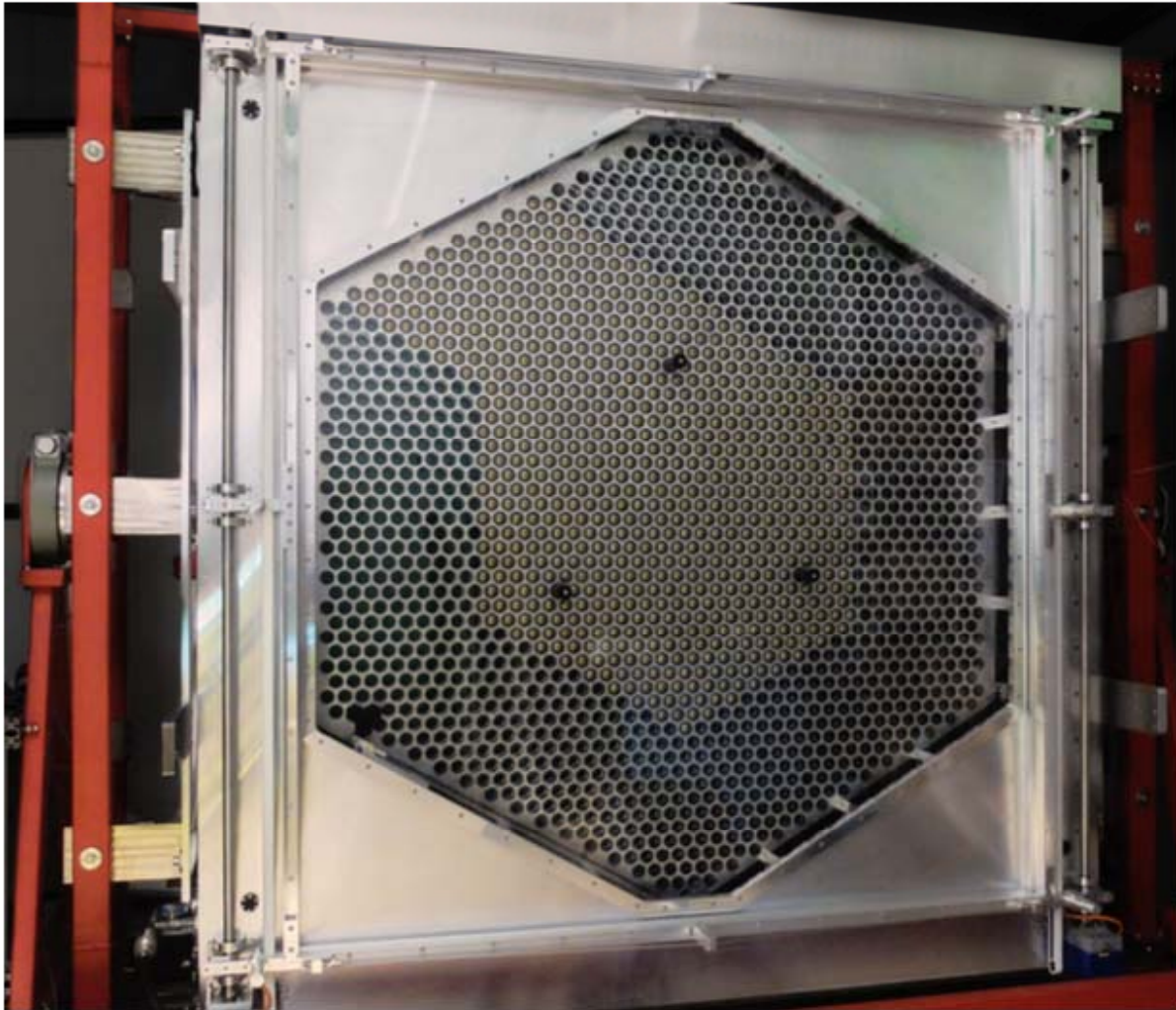


# MST: Structure

Updated structure to improve rigidity



# MST: FlashCam

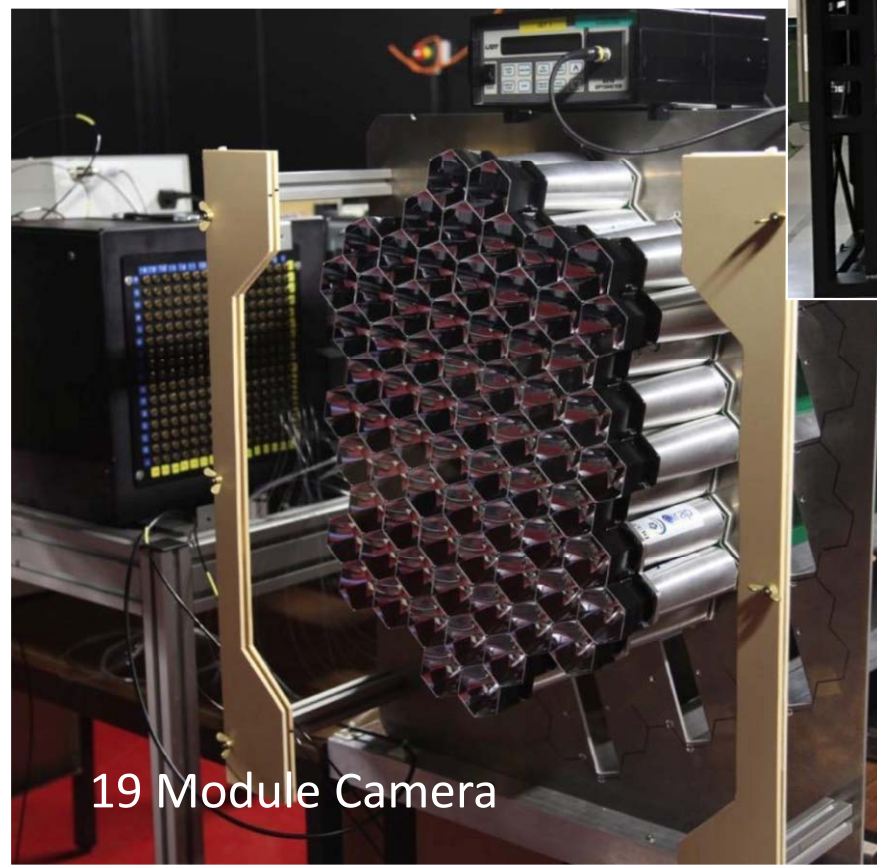
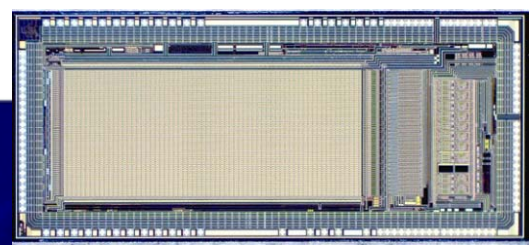
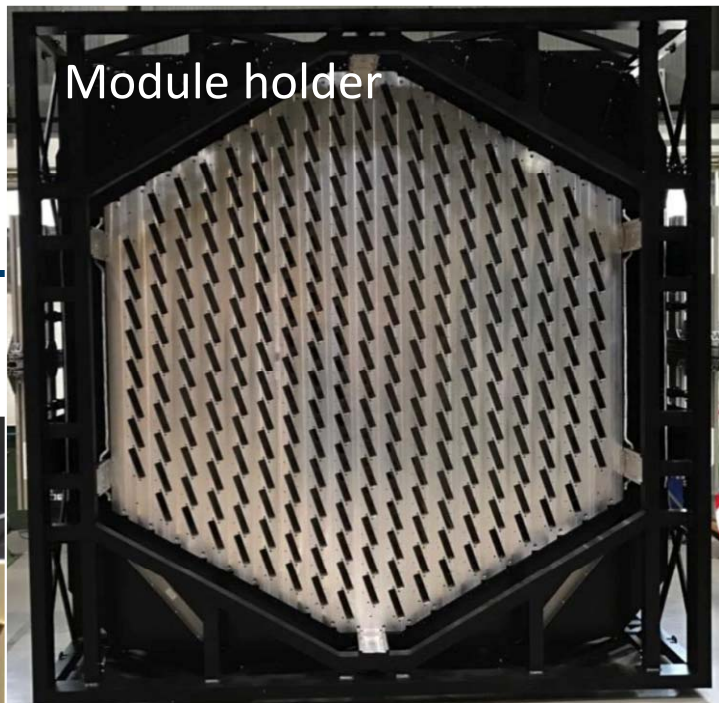


250 MHz sampler, digital pipeline

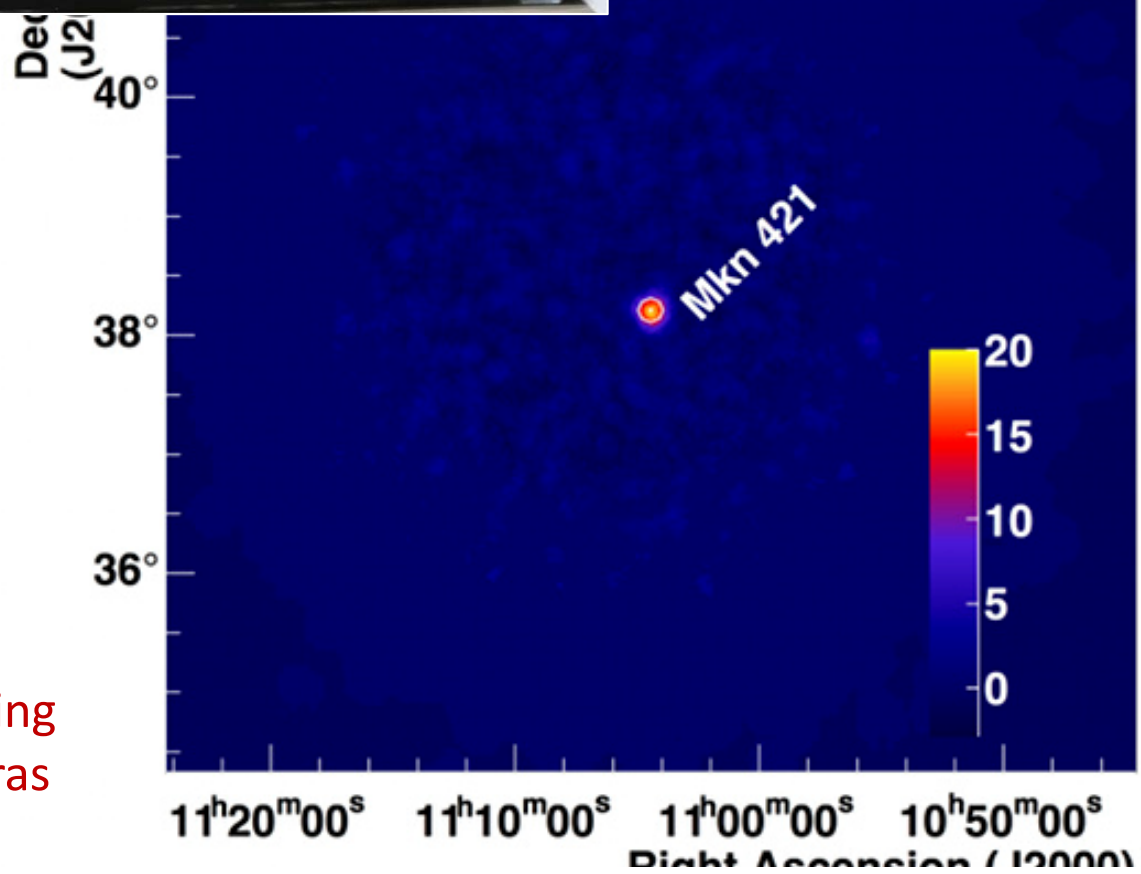
# MST: NectarCam



Module holder

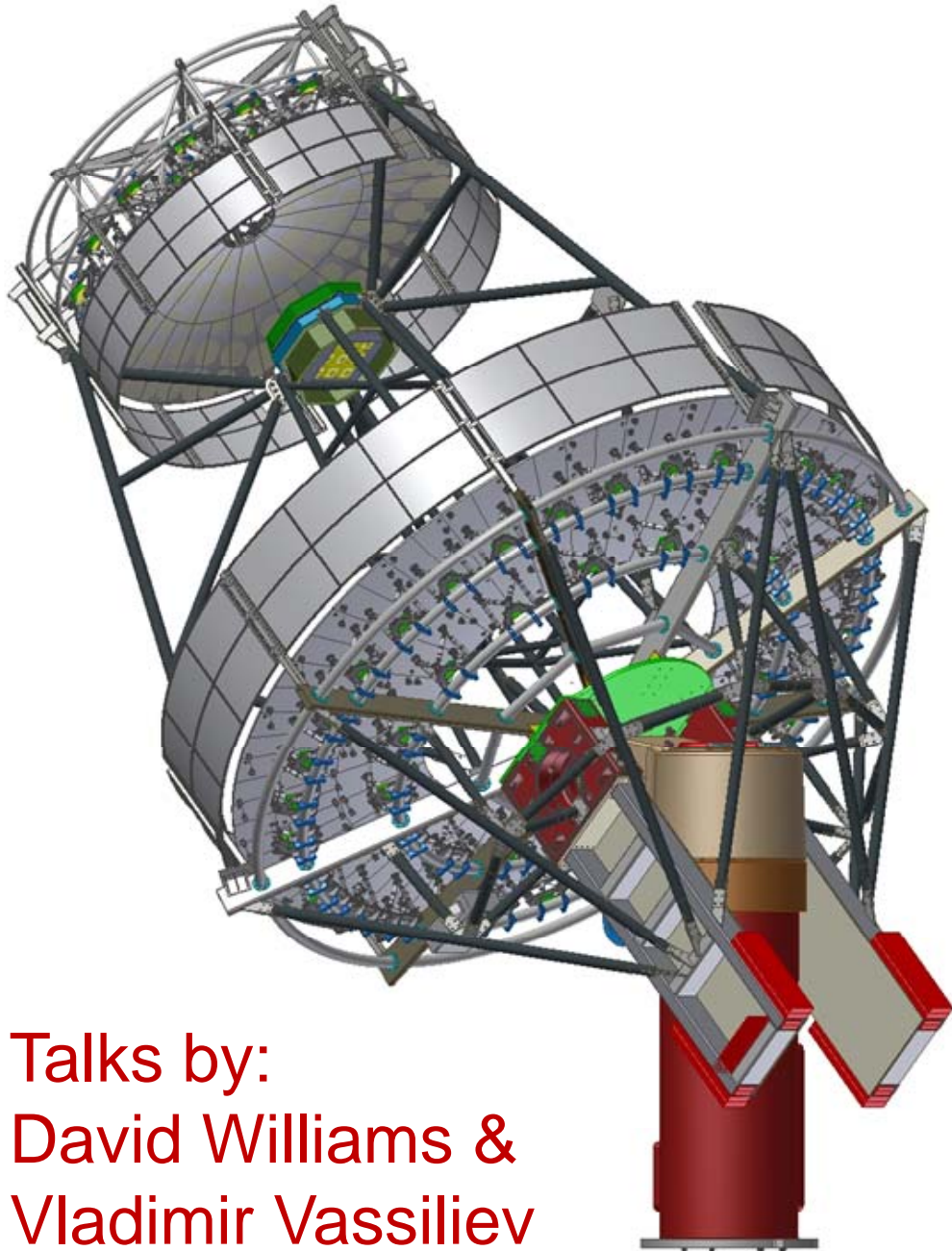


19 Module Camera



H.E.S.S. Mrk 421 using new (Nectar) cameras

# Medium Telescope 2-mirror (SCT)



Talks by:  
David Williams &  
Vladimir Vassiliev

9.7 m primary  
5.4 m secondary  
5.6 m focal length,  $f/0.58$   
50 m<sup>2</sup> mirror dish area  
PSF better than 4.5'  
across 8° FOV

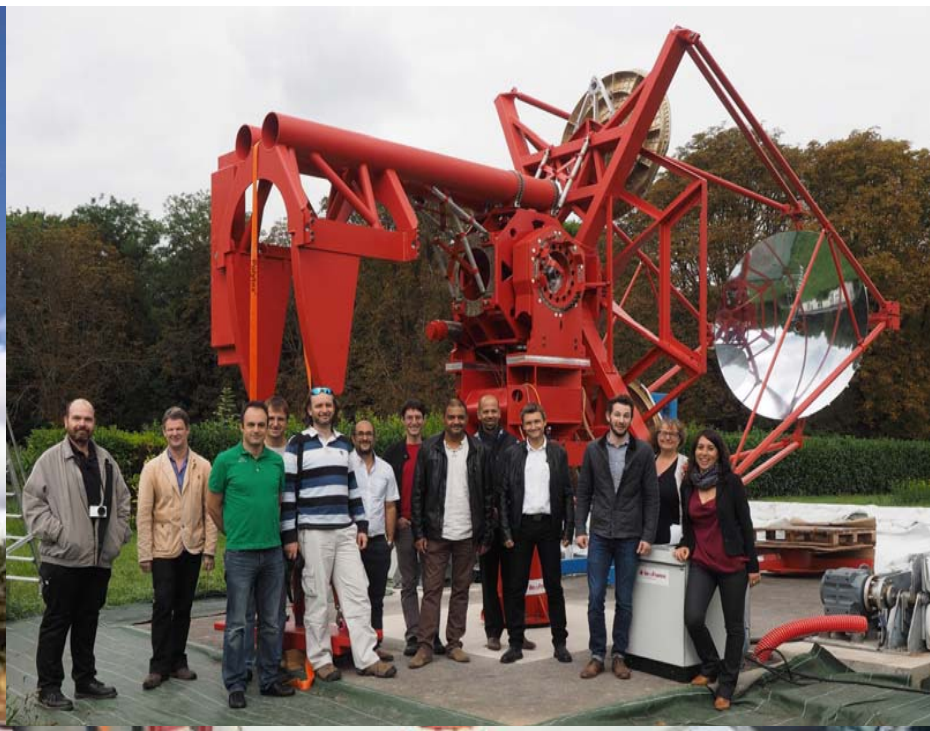
8° field of view  
11328 x 0.07° SiPMT pixels  
TARGET readout ASIC

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

→ Increased  $\gamma$ -ray collection area  
→ Improved  $\gamma$ -ray ang. resolution  
→ Improved DM sensitivity

# Small Sized Telescopes (SSTs)

- 3 different prototype designs
- 2 designs use two-mirror approaches (Schwarzschild-Couder design)
- All use Si-PM photosensors
- 7-9 m<sup>2</sup> mirror area, FOV of 9°

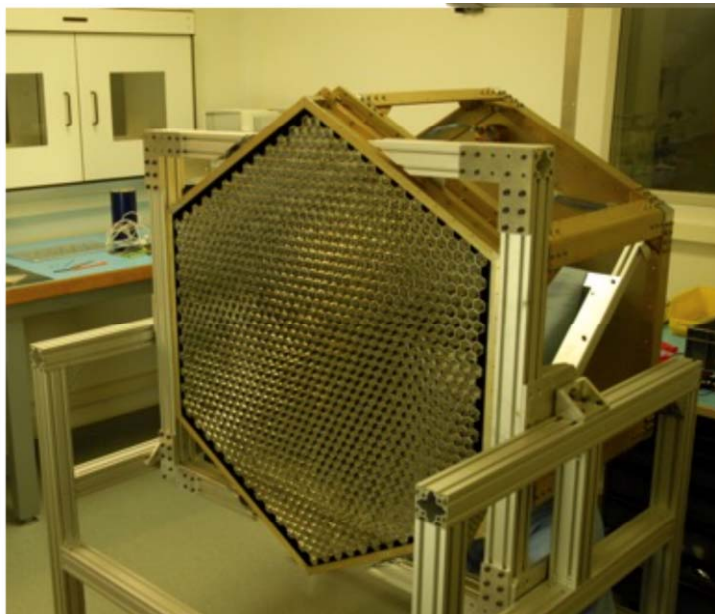


SST-1M  
Krakow, Poland

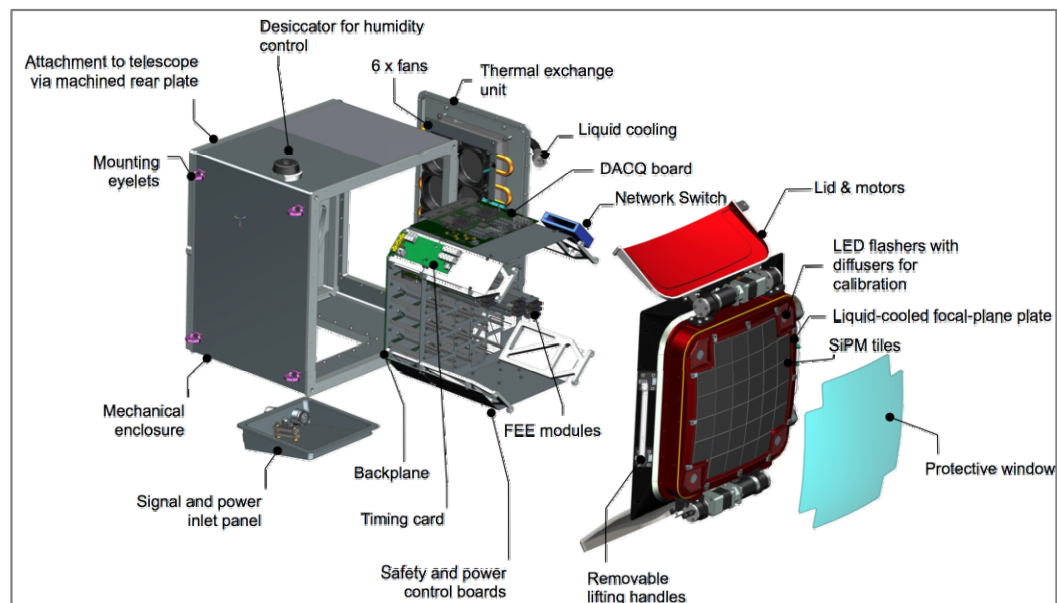
SST-2M ASTRI  
Mt. Etna, Italy

SST-2M GCT  
Meudon, France

# Small Sized Telescopes (SSTs)



SST-1M  
Digicam – close to  
being installed on  
telescope

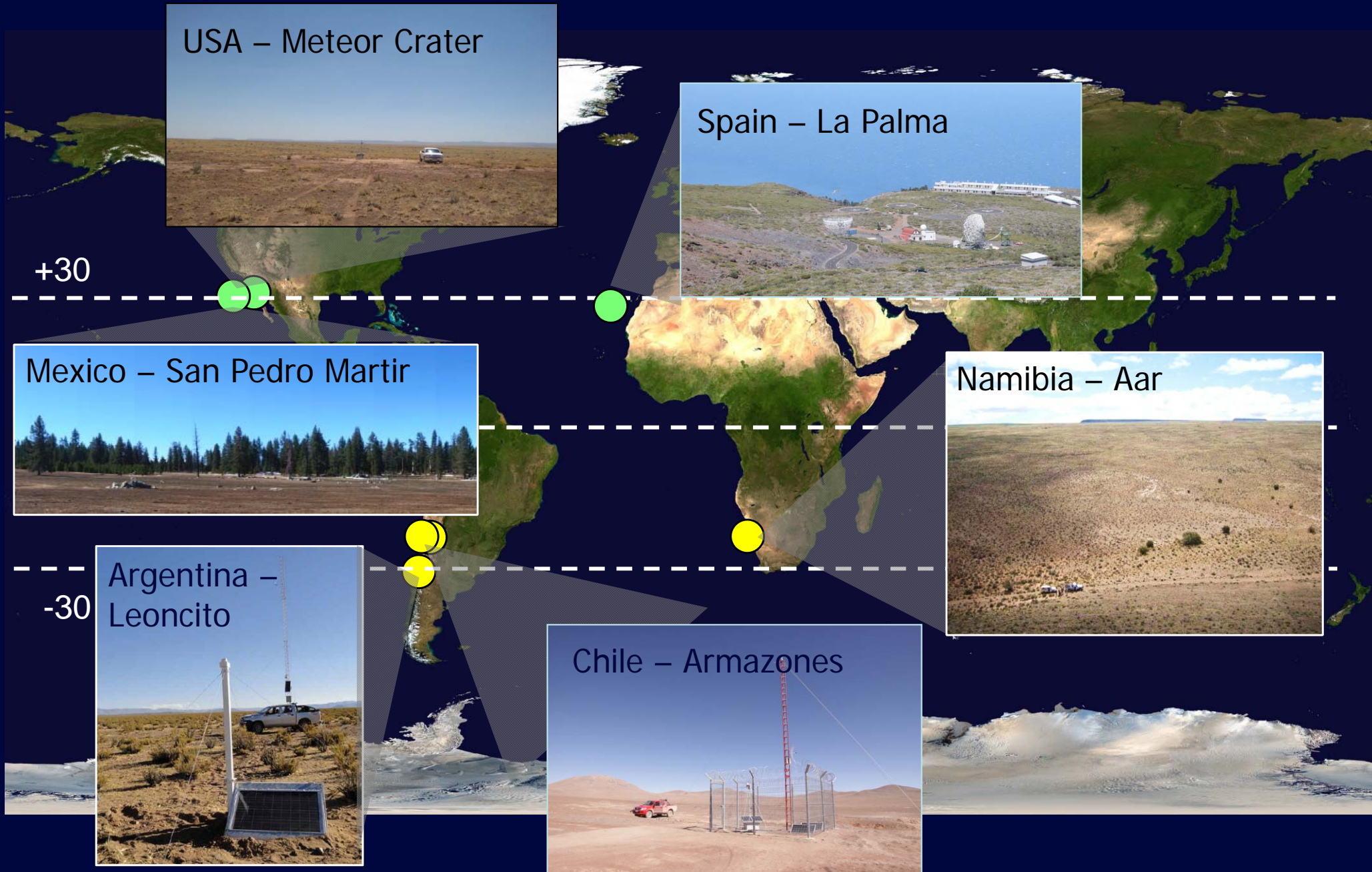


SST-2M-GCT  
Si-PM camera 75% complete  
(similar readout to SCT)

SST-2M-ASTRO  
Camera now installed  
Undergoing tests/initial data

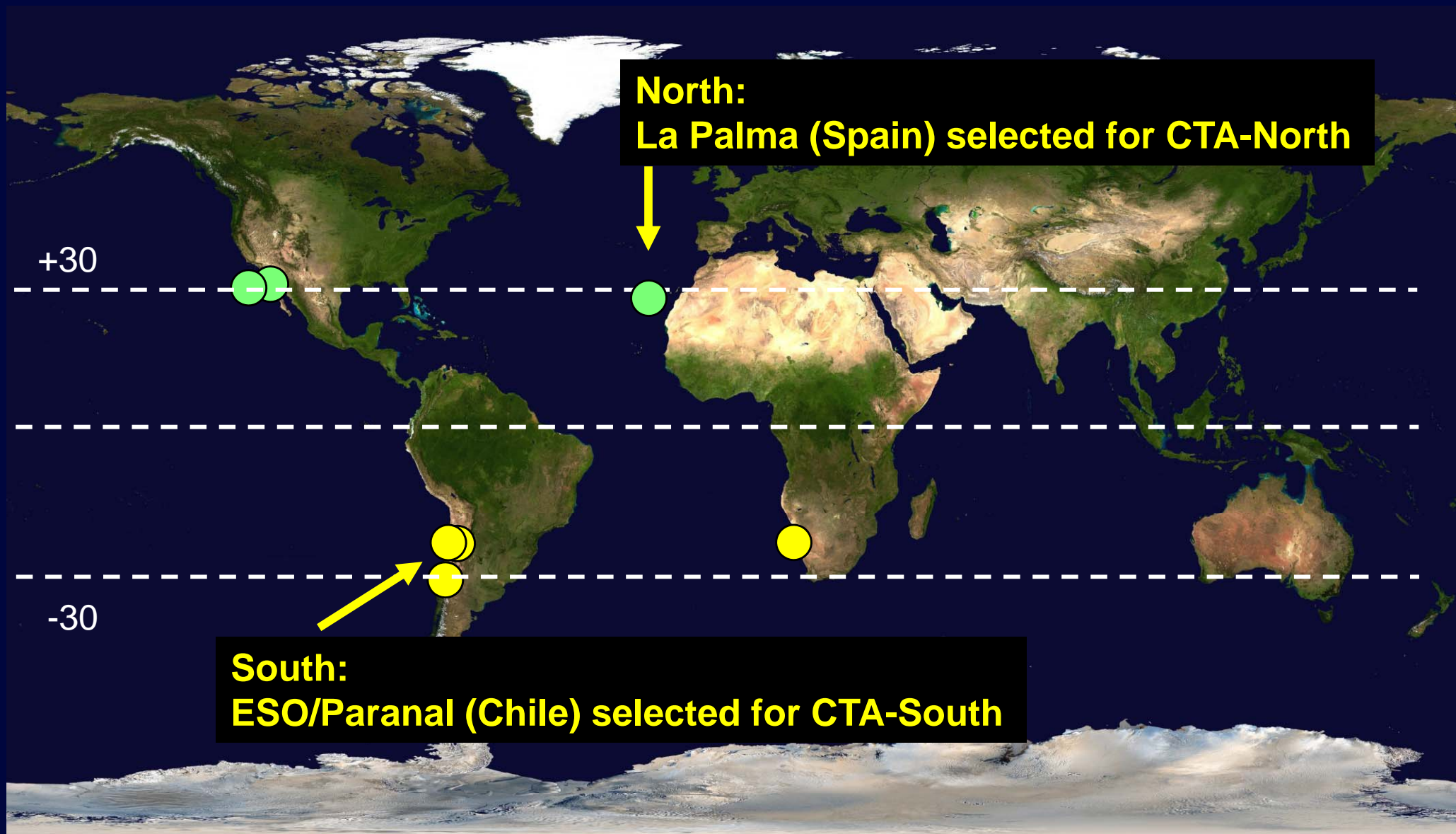
# Site Selection

Two sites to cover full sky,  
latitude  $20^{\circ}$ - $35^{\circ}$  in N, S



# Site Selection

Two sites to cover full sky  
at  $20^{\circ}$ - $35^{\circ}$  N, S





# LA PALMA

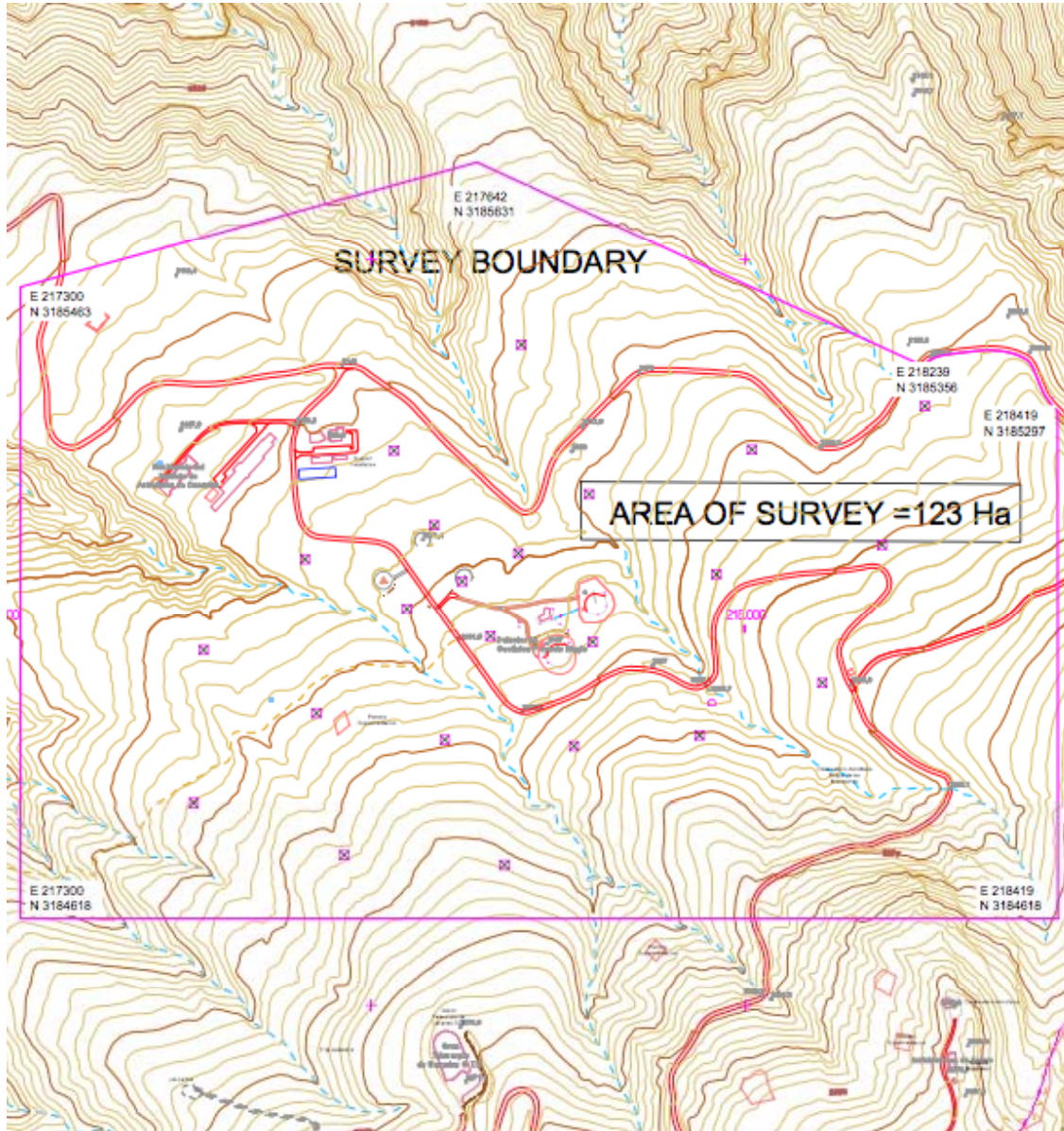
---



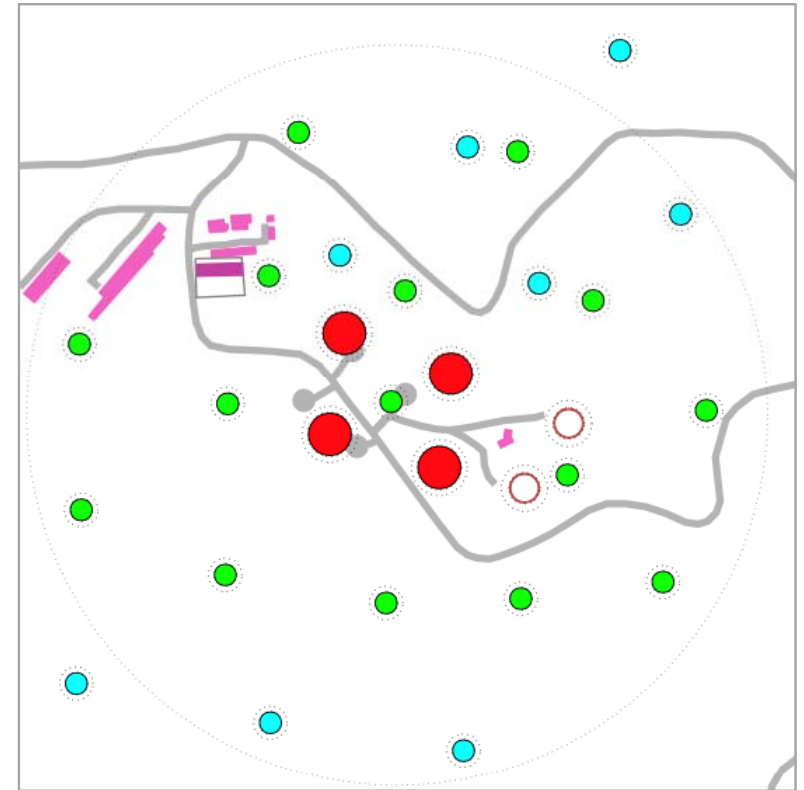
- Canary Islands, Spain
- Observatorio del Roque de los Muchachos
- Existing observatory, under management by Instituto de Astrofísica de Canarias (IAC)
- Site of LST 1 & existing MAGIC telescopes

# North Layout

4 LSTs  
15 MSTs



Possible layout – still in progress



Current work:  
topographical study  
building concepts  
tender for geotechnical, RIBA  
design contracts soon

# ESO/PARANAL



- Atacama Desert, Chile
- Below Cerro Paranal
- Existing observatory, under management by European Southern Observatory (ESO)
- Near a set of existing (VLT) and future (ELT) telescopes

Vulcano Lullailaco  
6739 m, 190 km east

Cerro Armazones

ELT

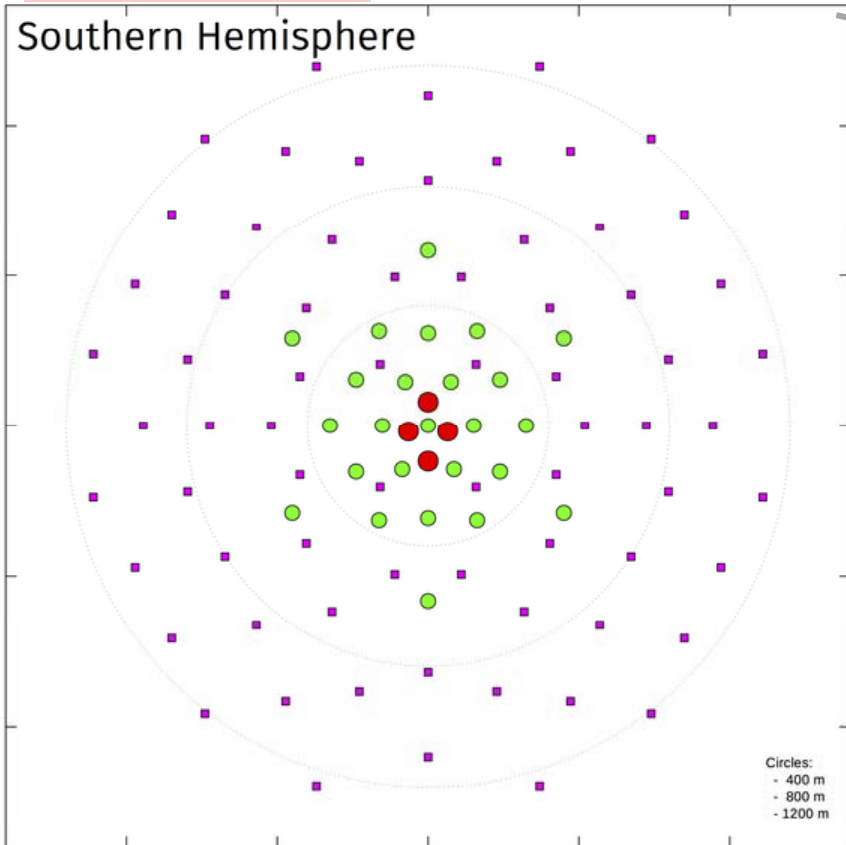
Proposed Site for the  
Cherenkov Telescope Array



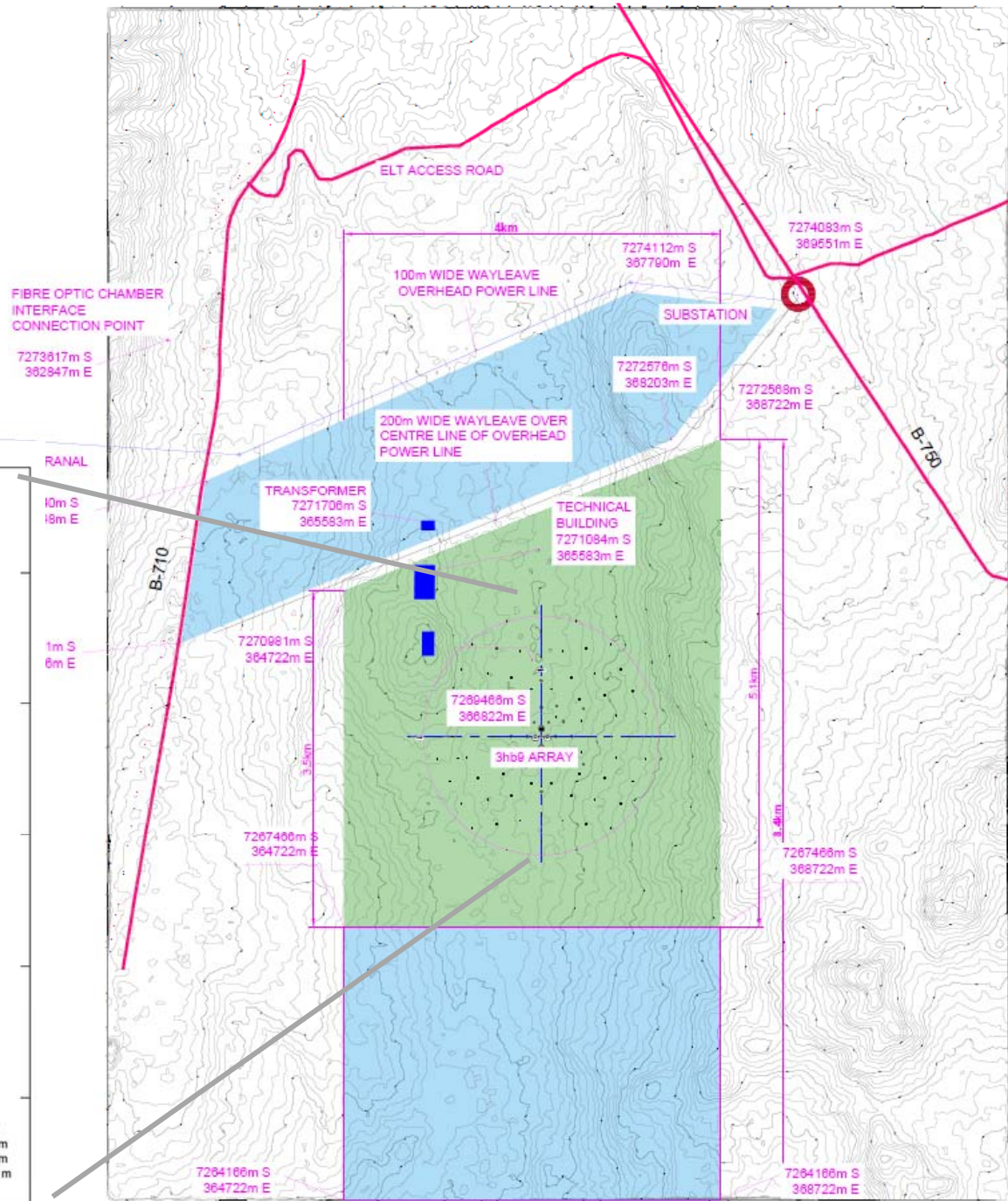
Cerro Paranal  
Very Large Telescope

# CTA South

4 LSTs  
25 MSTs  
70 SSTs



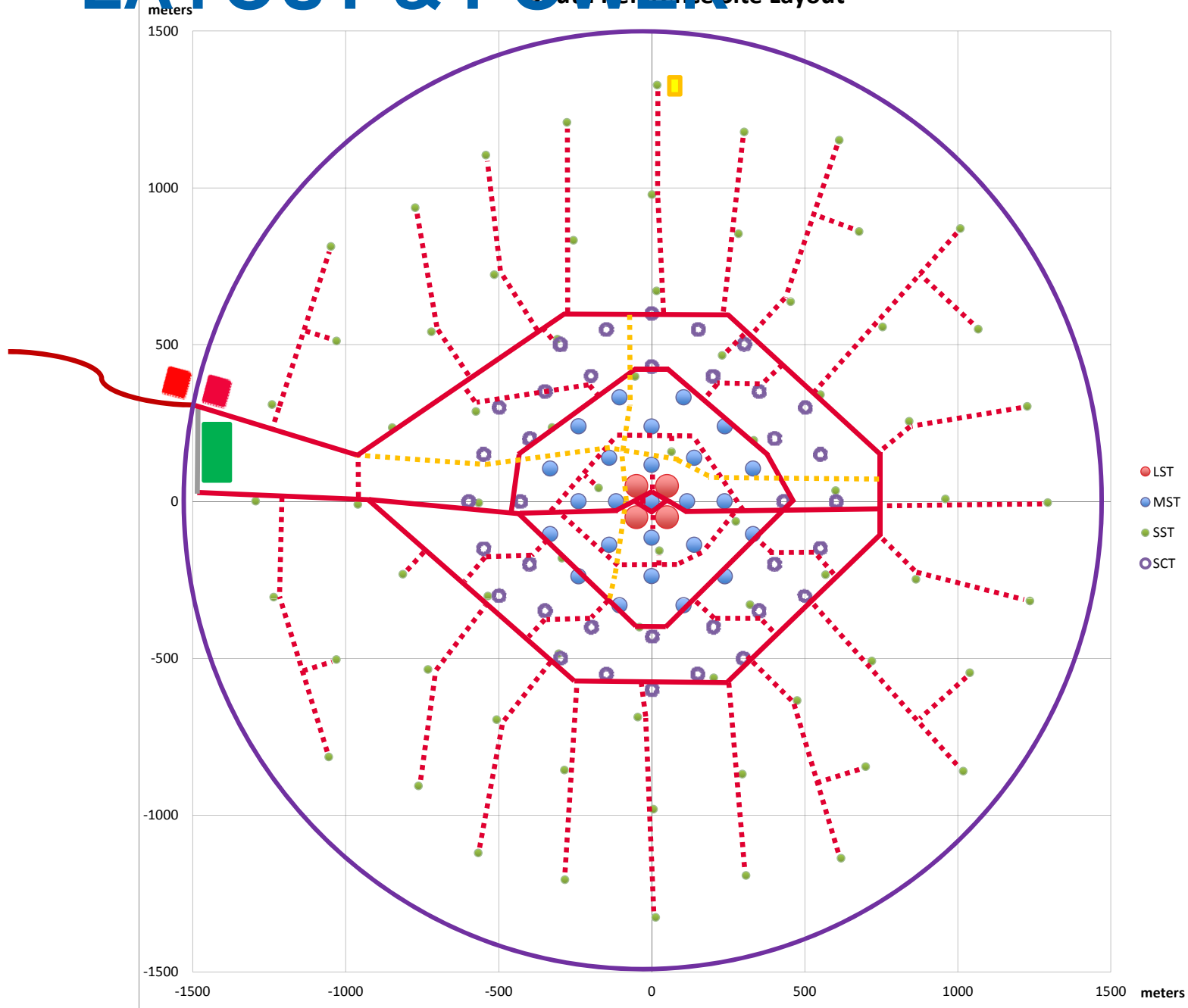
4 LSTs, 25 MSTs, 70 SSTs



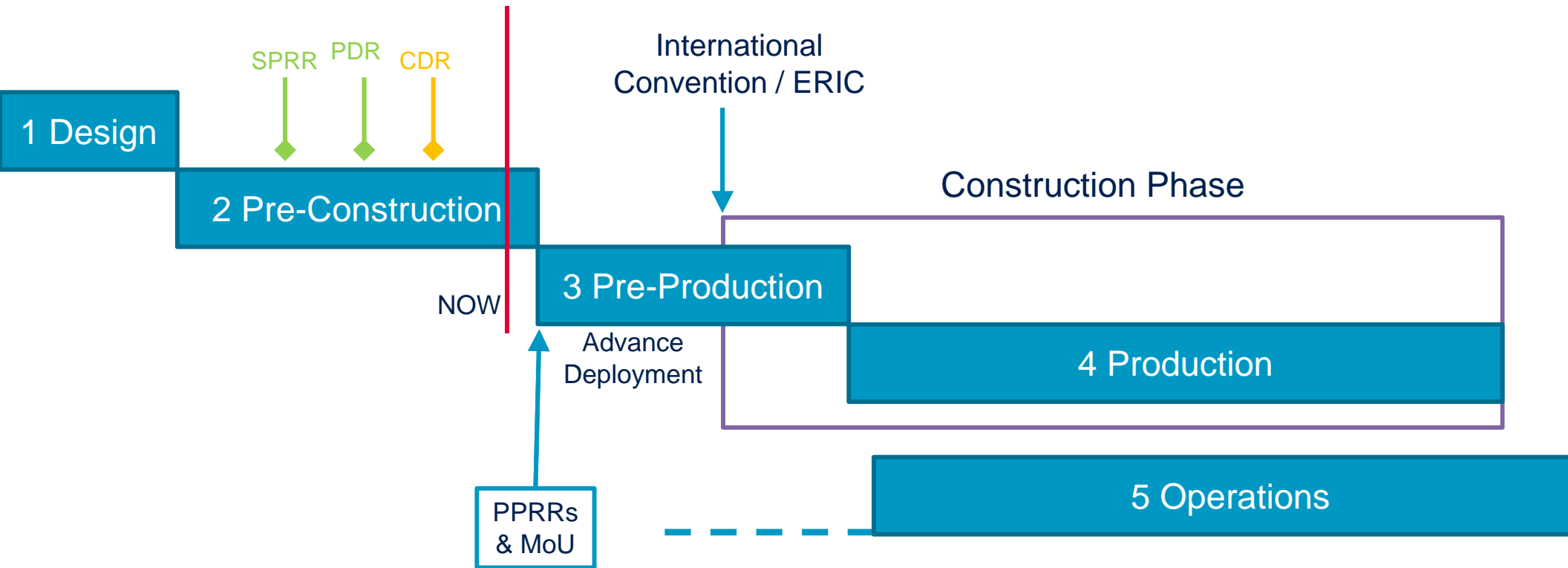
Current work: geotechnical studies (boreholes, etc.), topographical survey, RIBA-3,4 (roads, power, ducting, buildings)

# ESO/PARANAL – POSSIBLE LAYOUT & POWER

South Reference Site Layout



# CTA Phases & Timeline



- 2016: Hosting agreement, site preparations start (N)
- 2017: Hosting agreement, site preparations start (S)
- Funding level at ~65% of required for *baseline implementation*
  - start with *threshold implementation*
  - additional funding, telescopes needed to complete CTA
- Construction period of 5-6 years
- Initial science with partial arrays possible before construction end

- **3<sup>rd</sup> Generation instruments (e.g. VERITAS) Critical**

With many discoveries, VHE  $\gamma$ -rays are now well-recognized and exciting area of research

Outstanding science potential & the power of the atmospheric Cherenkov technique → CTA

- **Cherenkov Telescope Array (CTA)**

*Excellent sensitivity & resolution over wide energy range*

*Far-reaching science program*

*Open observatory with all data released to public*

*CTA requires a broad partnership of countries and communities*

- In next decade, CTA will start to provide high-quality data, of a quality not yet seen with any gamma-ray technique
- However, all of this rests squarely on the foundation of earlier work that developed the technique and the science over period of 30 years – a great deal of that foundation came in the US or people working in US.

# Acknowledgements

Thanks to all my VERITAS and CTA colleagues!

Special thanks to:

Roger Blandford, Corbin Covault,  
Frank Krennrich, **Reshmi Mukherjee**,  
David Williams



Smithsonian

U.S. DEPARTMENT OF  
**ENERGY**

Office of Science



**NSERC**  
**CRSNG**

