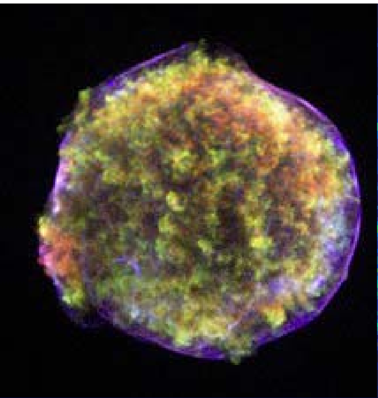
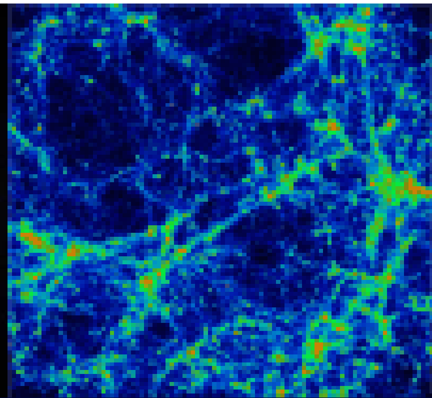
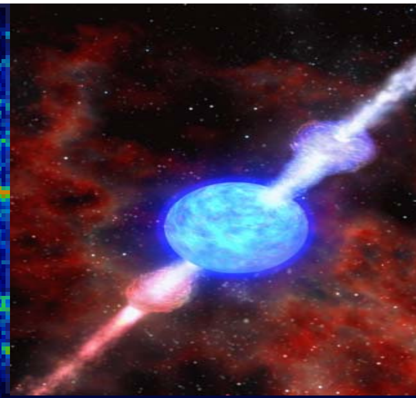
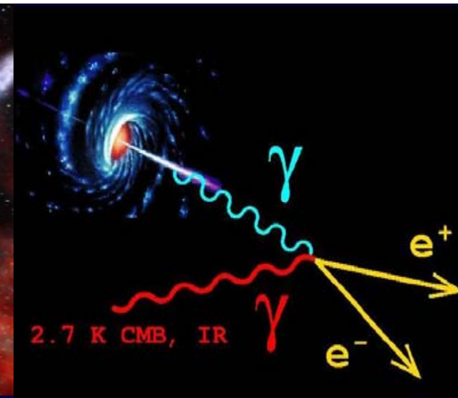
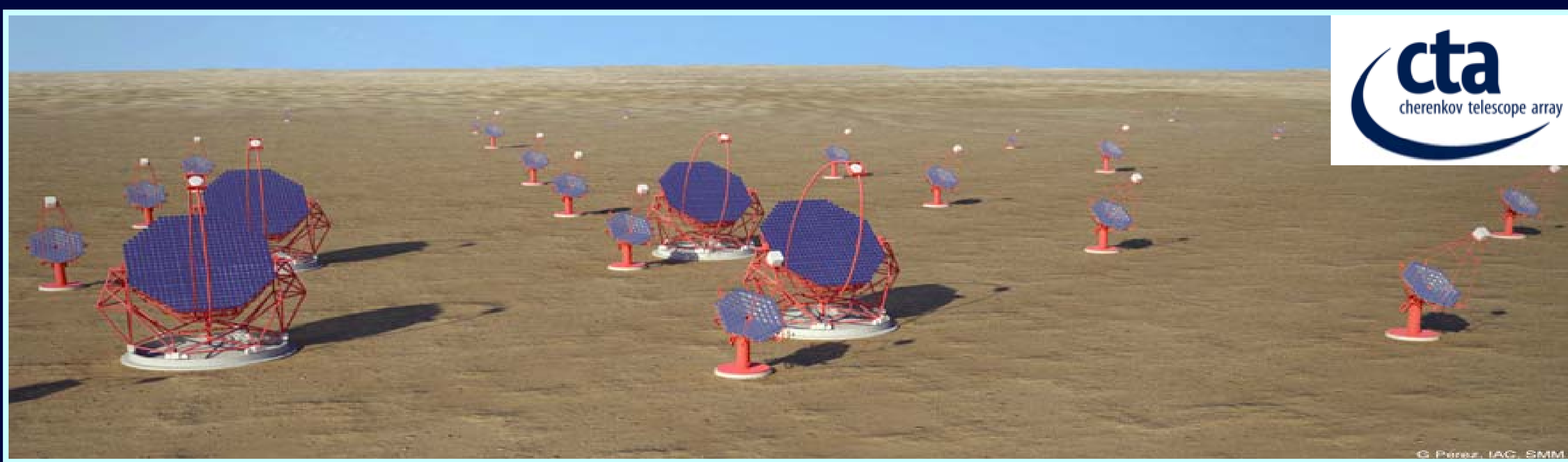





The Cherenkov Telescope Array for VHE Astrophysics

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

HAWC Science Symposium, 26 March 2015



Outline

- **Scientific & Technical Motivation**

  VHE sky and Existing Instruments
  Imaging Atmospheric Cherenkov technique
  Planning for the Future → CTA

- **Cherenkov Telescope Array (CTA) Concept**

  Requirements & Drivers
  CTA Design & Performance → Scientific Capabilities

- **CTA Implementation & Status**

  Implementation: Telescope and Array Design
  Present Status (2015): site selection, Critical Design Review (CDR), etc.

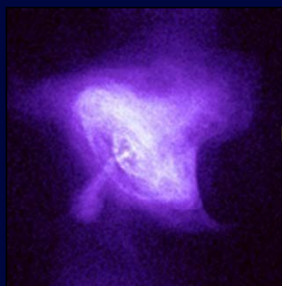
- **Synergies with HAWC (and other facilities)**

Scientific & Technical Motivation

Exploring the non-thermal Universe

Pulsars/PWN

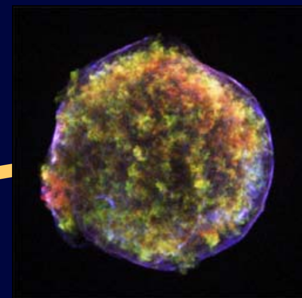
NS
dynamo
winds



Binaries

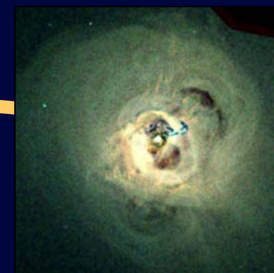
Jets, winds

SNRs



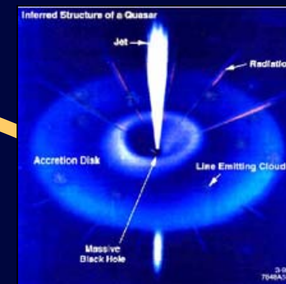
Shocks
Fermi Mech.

Starbursts



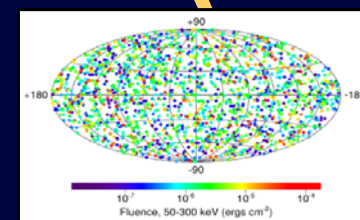
SN activity
Cosmic rays

AGN

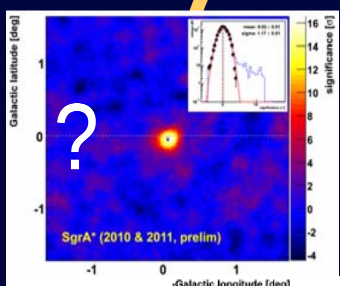


SMBH
accretion,
jets

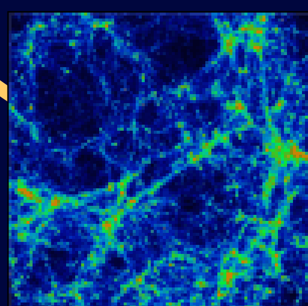
GRBs



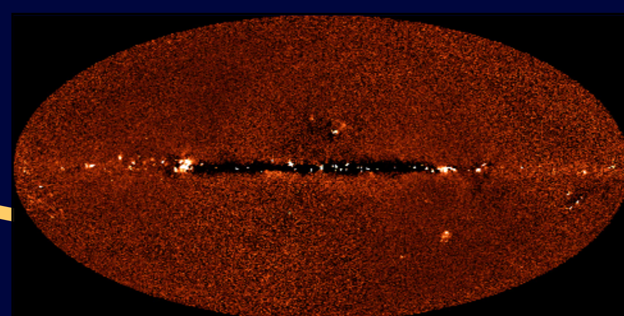
VHE γ-rays



Unknowns
(Gal Center)



Dark Matter



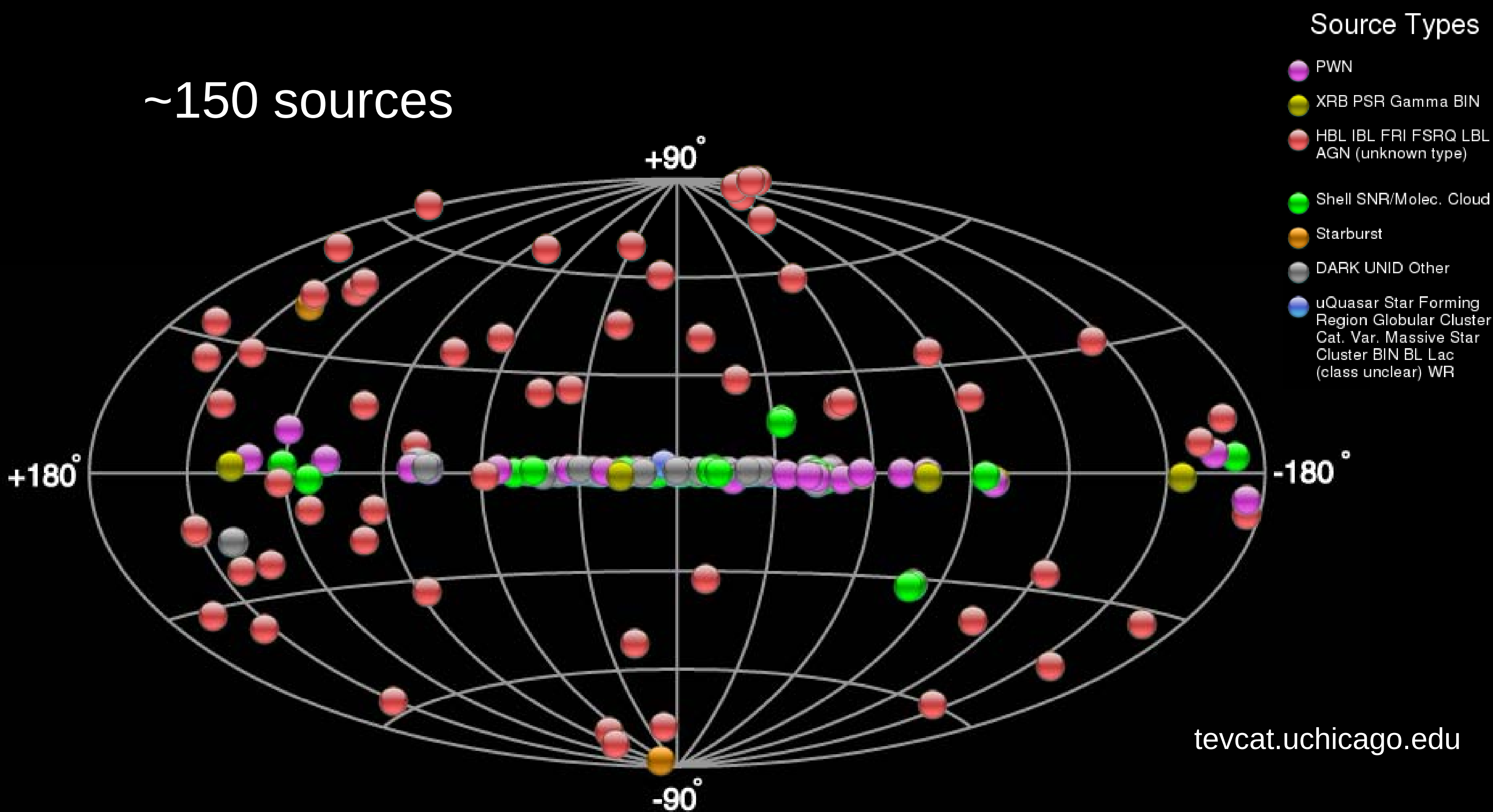
Cosmological Fields

PBHs, QGr

Probing New Physics at GeV/TeV scale

VHE γ-ray Sky c2014

~150 sources

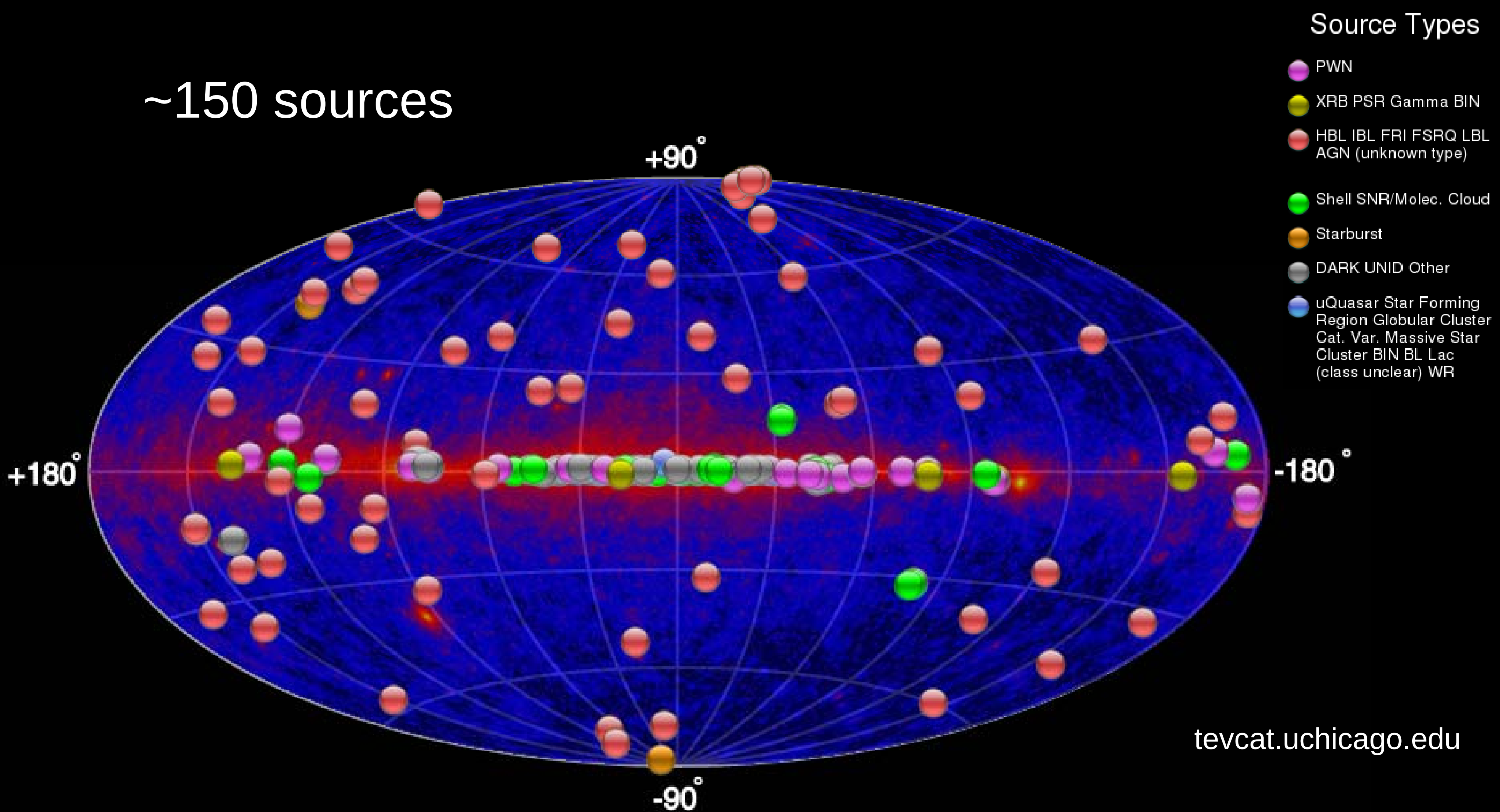


tevcat.uchicago.edu

Detailed source information: Spectra, Images, Variability, MWL …

VHE γ-ray Sky c2014

~150 sources



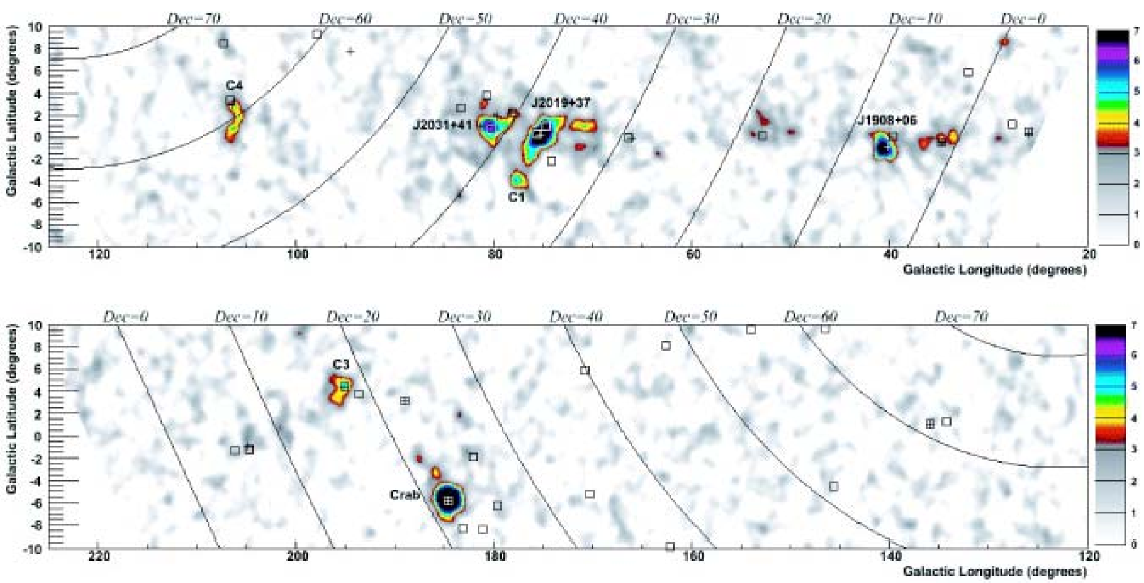
tevcat.uchicago.edu

Detailed source information: Spectra, Images, Variability, MWL …
+ FERMI-LAT map

Wide-Field View of VHE Sky

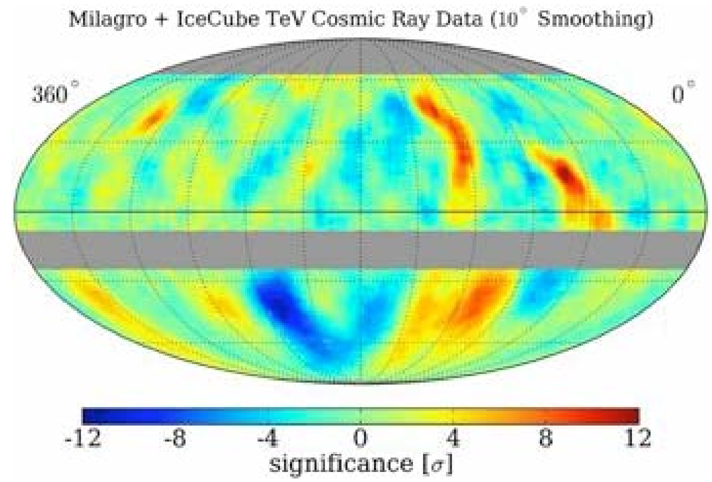
Complementary results from wide-field VHE telescopes:

e.g. Milagro, Tibet, ARGO-YBJ, IceCube

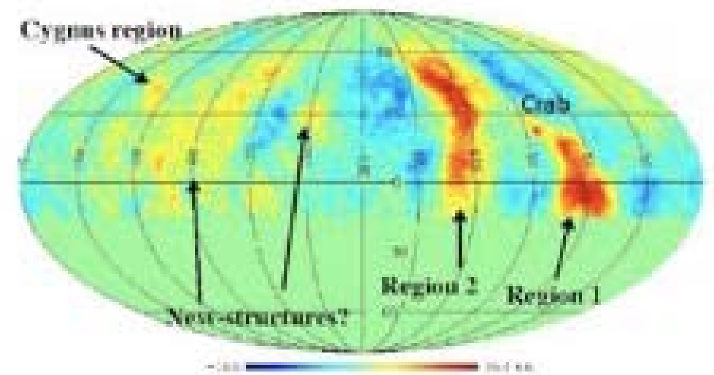


Portion of Milagro sky-survey near Galactic plane

Milagro/IceCube

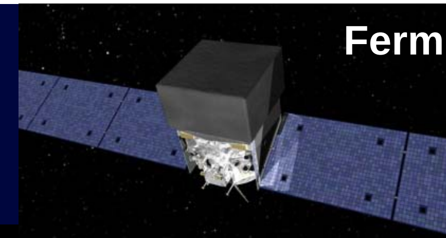


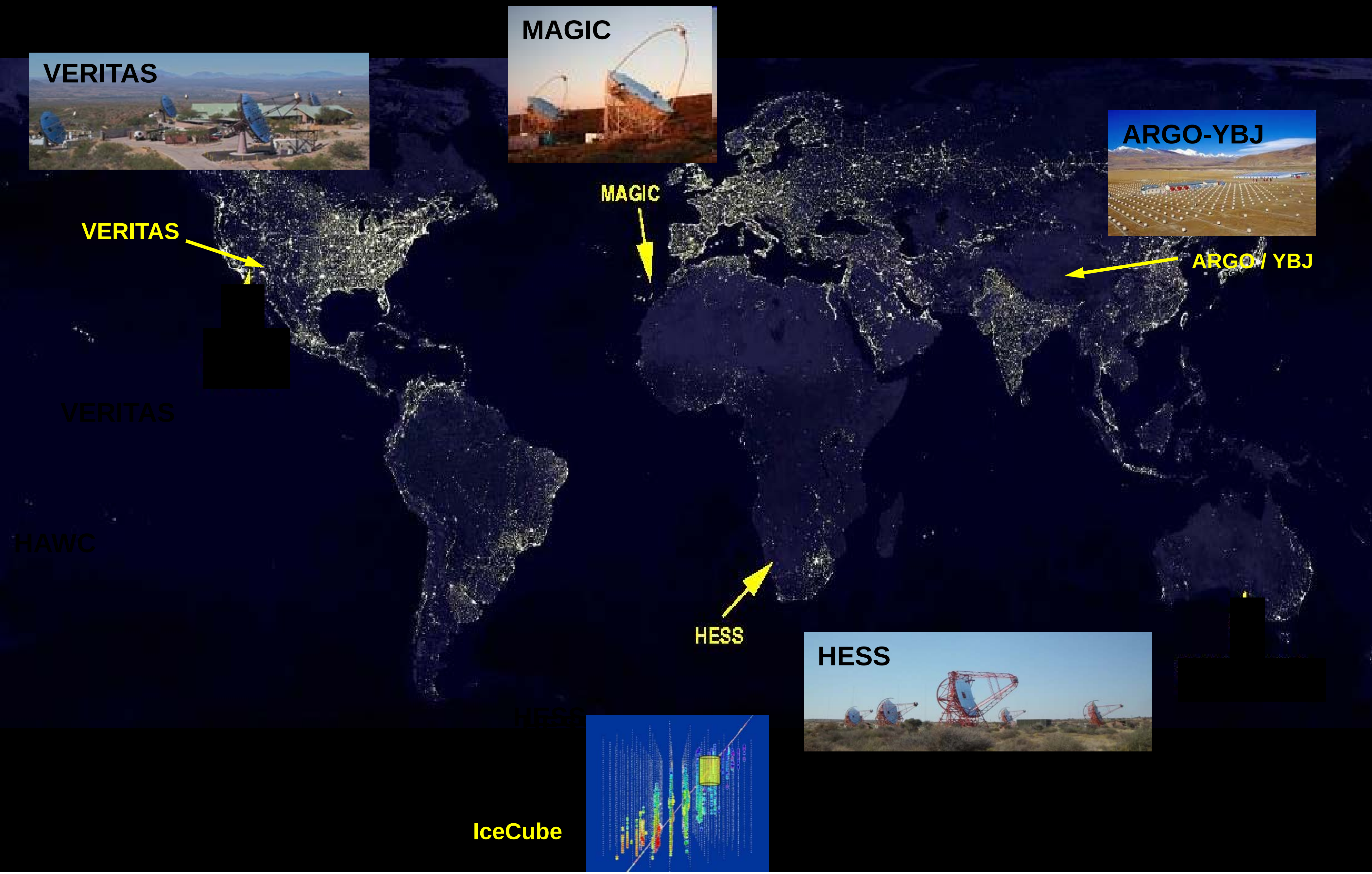
AGRO-YBJ



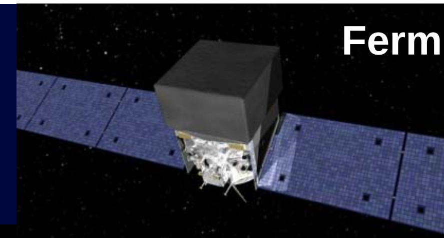
Cosmic ray anistropy – confirmed by 3 experiments

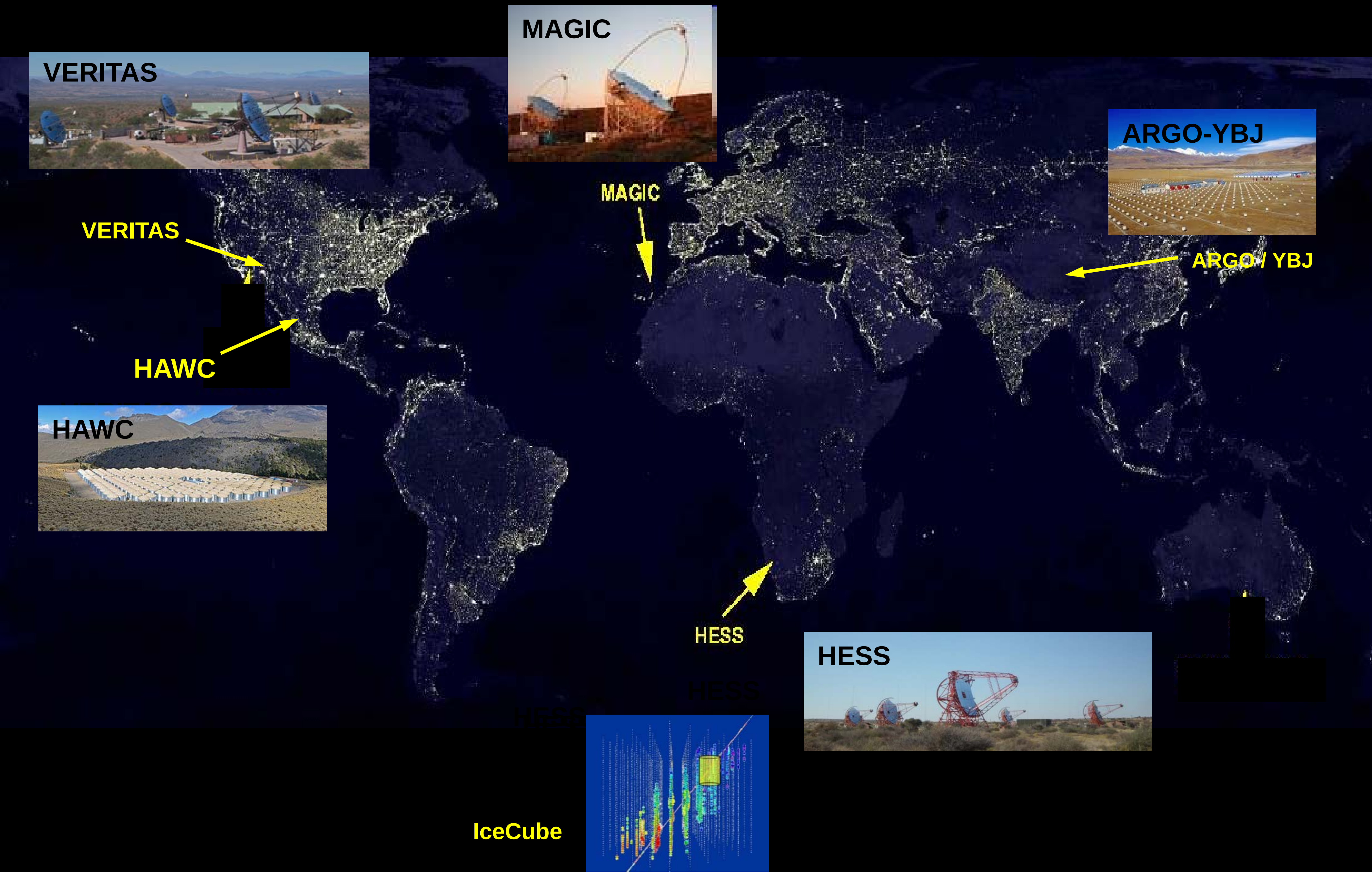
VHE Telescopes (2013)

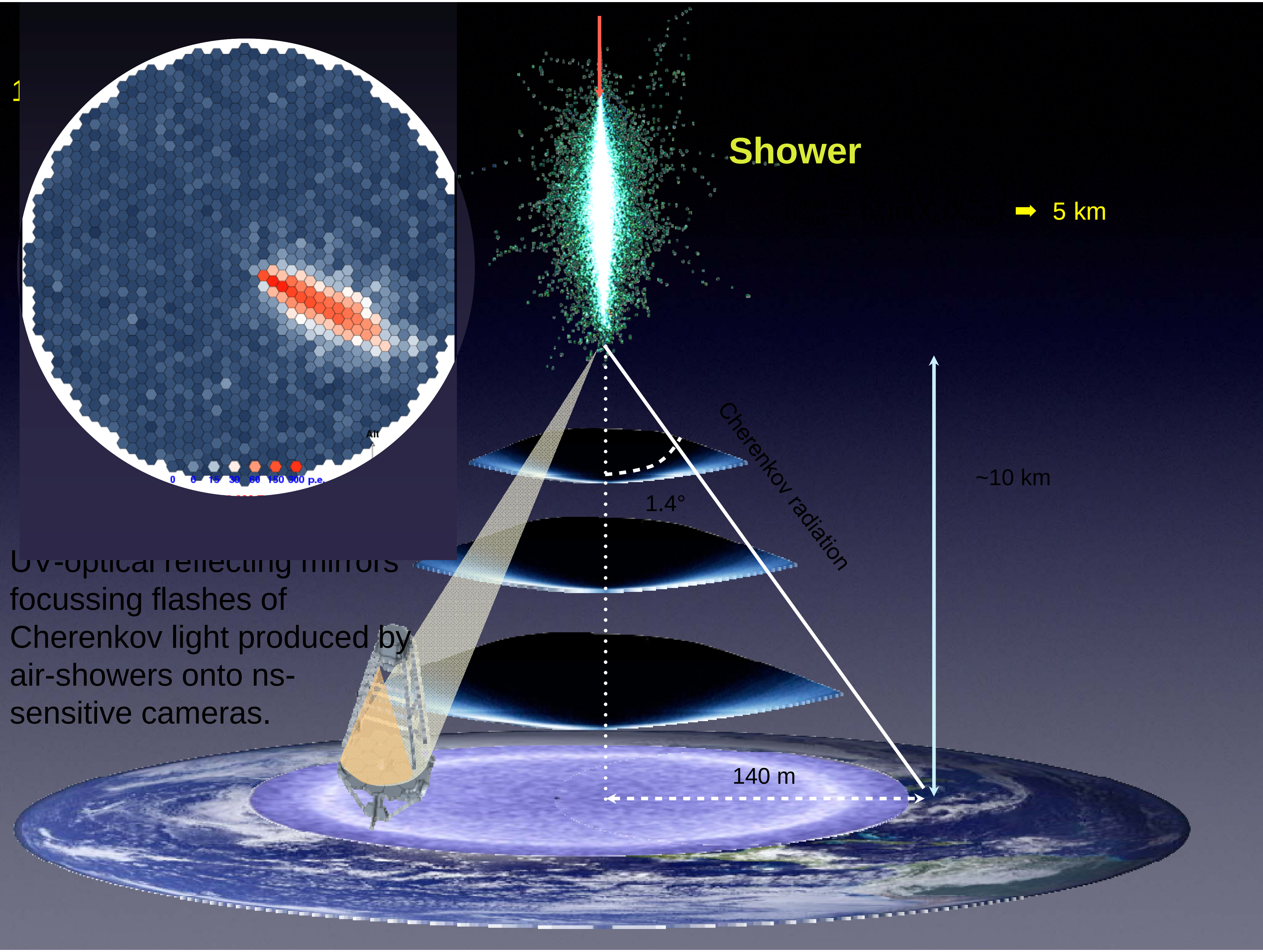




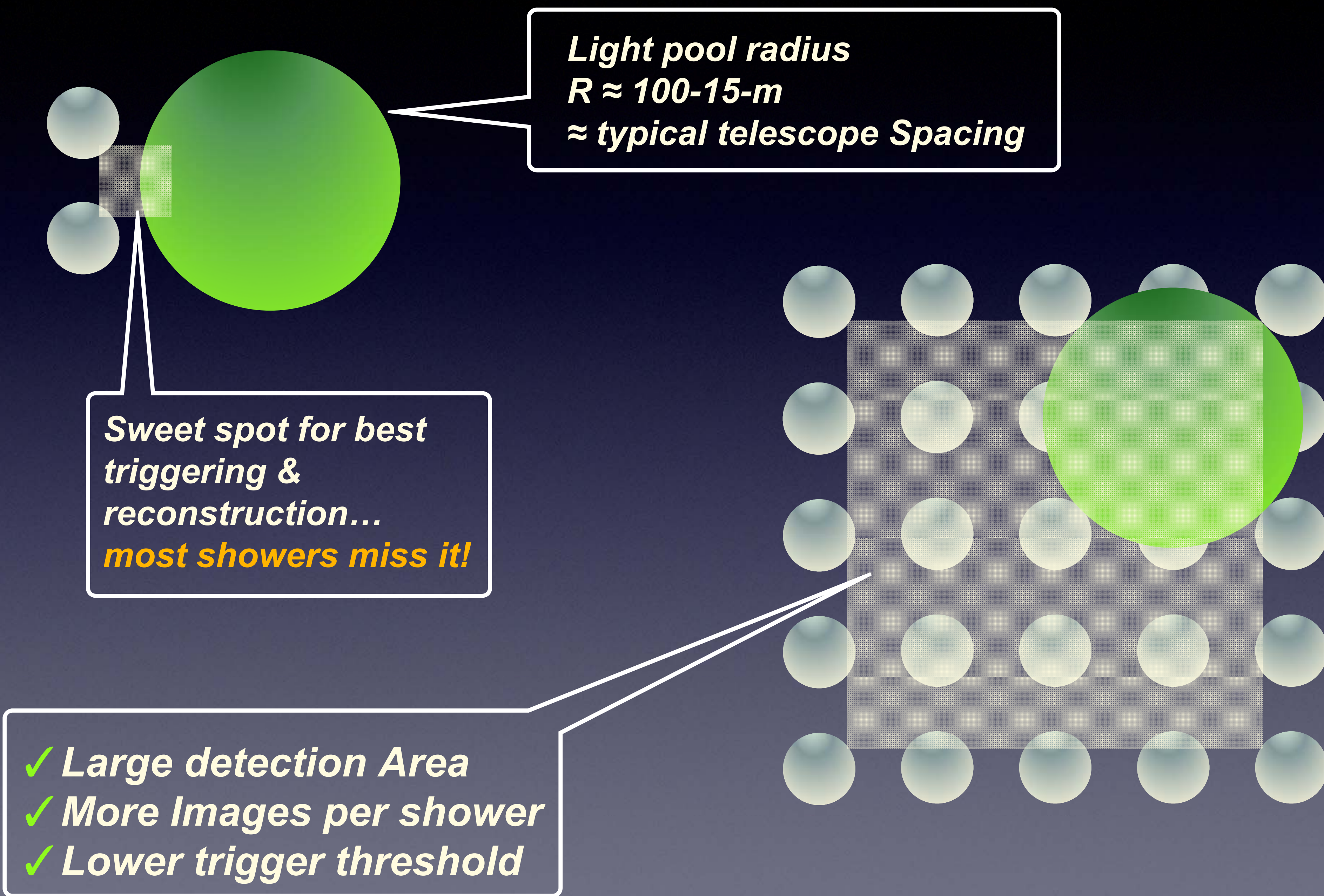
VHE Telescopes (2015)






Shower
5 km
Cherenkov radiation
~10 km
1.4°
140 m
0 6 15 30 60 150 300 p.e.
Alt
UV-optical reflecting mirrors
focussing flashes of
Cherenkov light produced by
air-showers onto ns-
sensitive cameras.

From current arrays to CTA

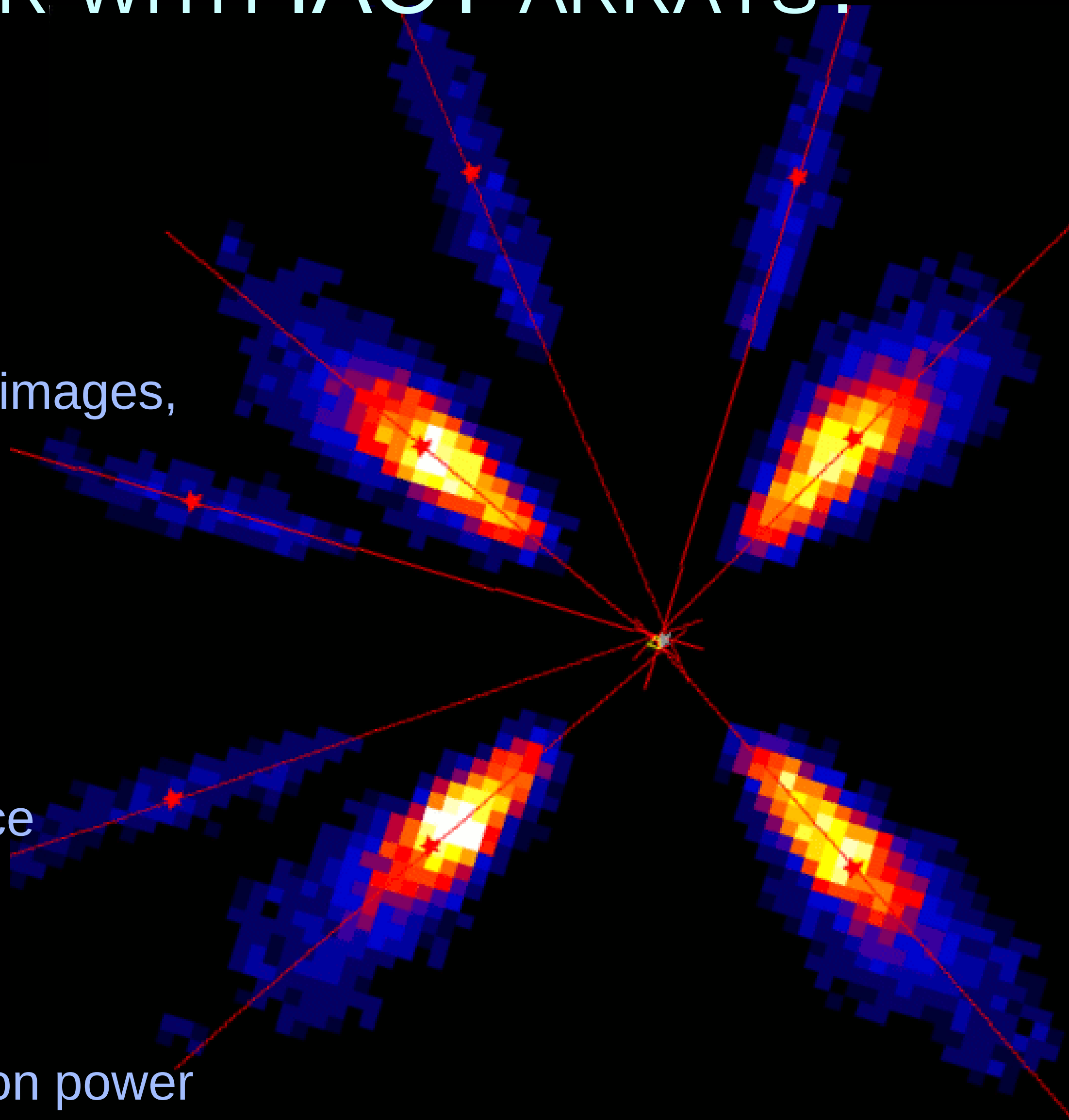


How to do better with IACT arrays?

➡ **More events**

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

➡ **More telescopes!**



Simulation:
Superimposed images from 8 cameras

Planning for the Future

What do we know, based on current results?

Great scientific potential exists in the VHE domain

- Many more sources, much better understanding possible
- Much deeper probes of new physics

IACT Technique is very powerful

- Have not yet reached its full potential

Exciting science in both Hemispheres

- Argues for new facilities in S and N

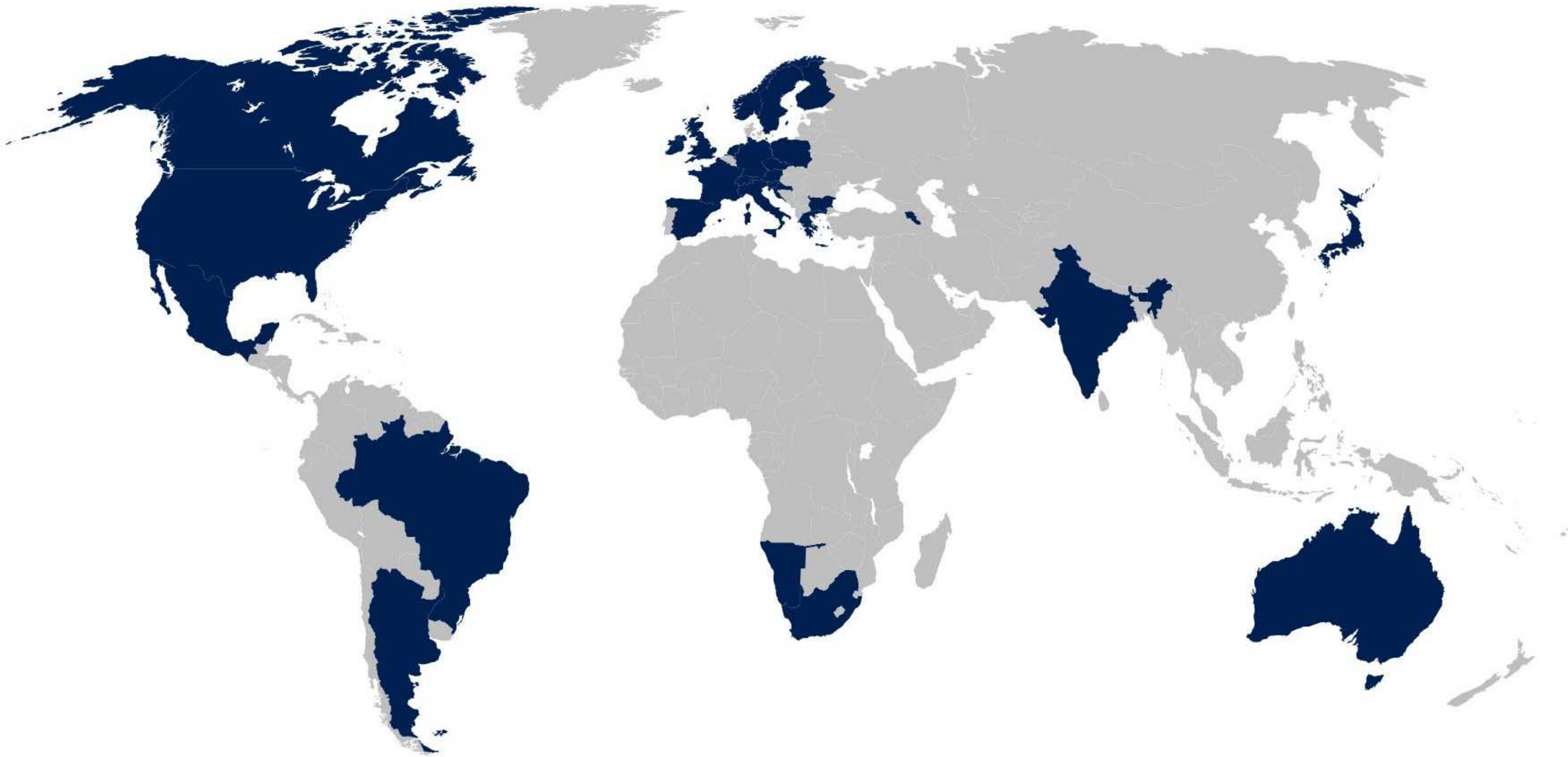
Truly Astronomical facility → Substantial reward

- Open Observatory needed to get the best science
- MWL/MM connections are of critical importance


cta
cherenkov telescope array

CTA Consortium

CTA is being developed by the CTA Consortium:



29 countries, ~1200 participants, ~180 institutes, ~400 FTE

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?

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)

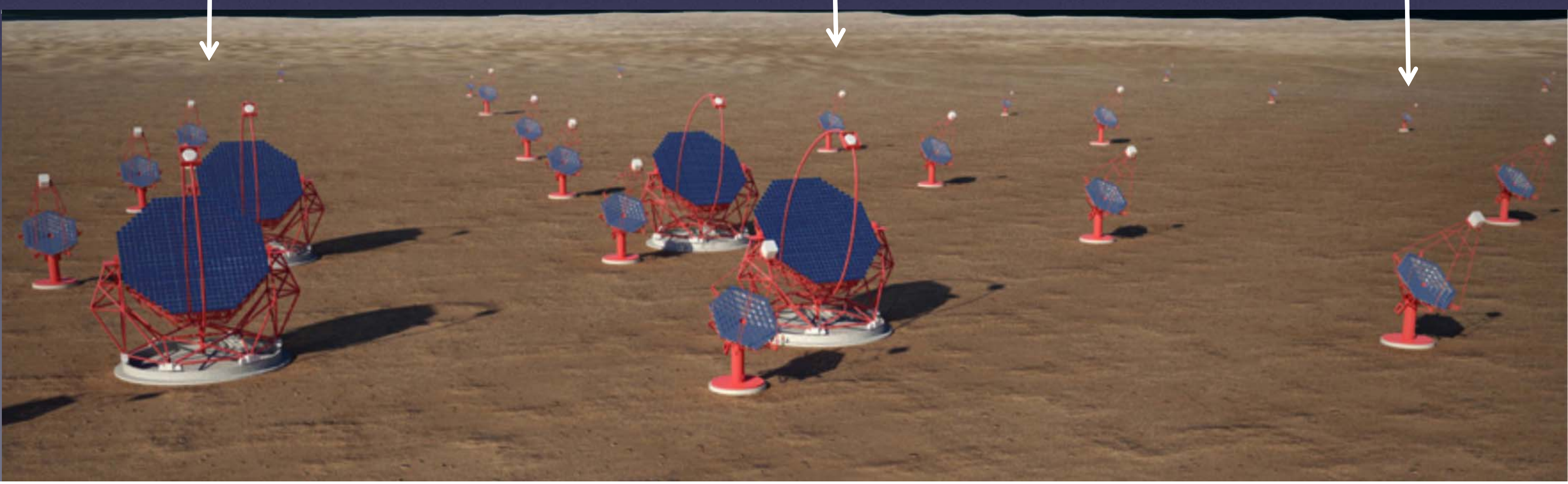
CTA Design (S array)

Science Optimization under budget constraints

Low energies
Energy threshold 20-30 GeV
23 m diameter
4 telescopes
(LST's)

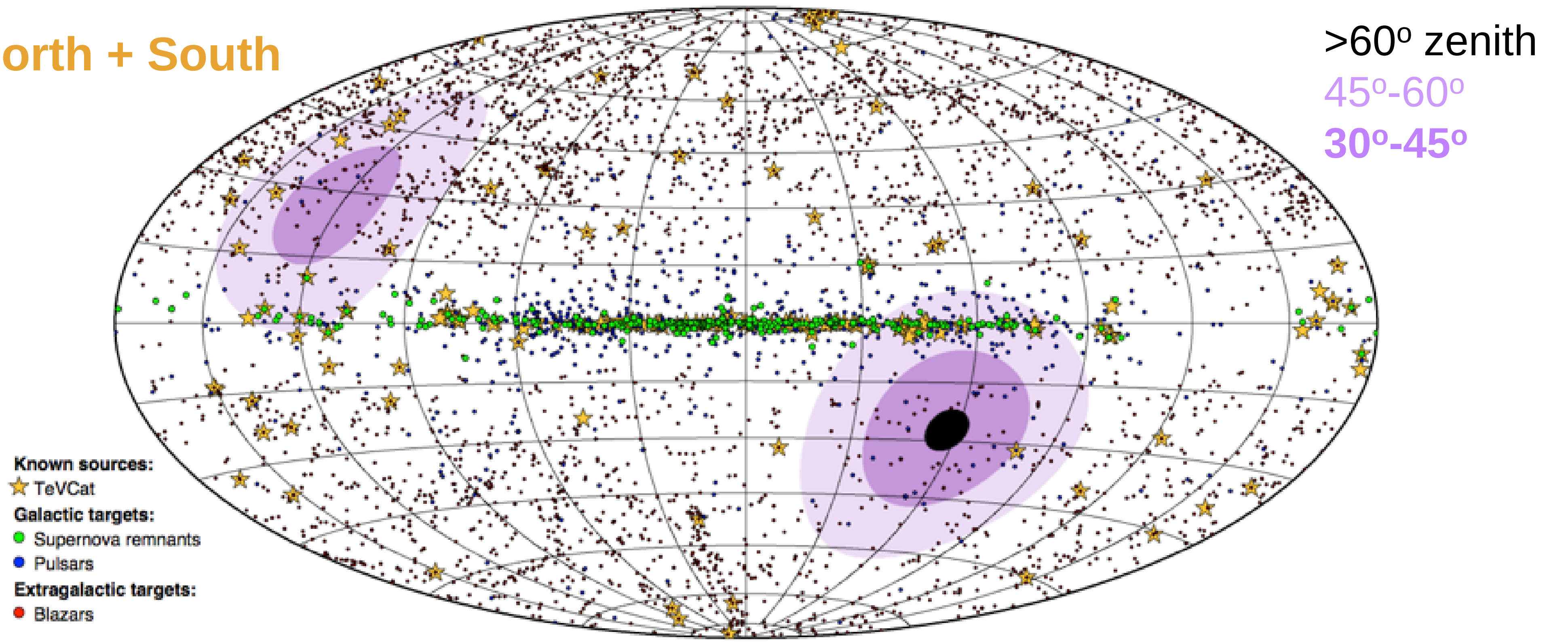
Medium energies
100 GeV – 10 TeV
9.5 to 12 m diameter
up to 25 single-mirror telescopes
up to 24 dual-mirror telescopes
(MST's)

High energies
10 km^2 area at few TeV
4 to 6 m diameter
up to 70 telescopes
(SST's)

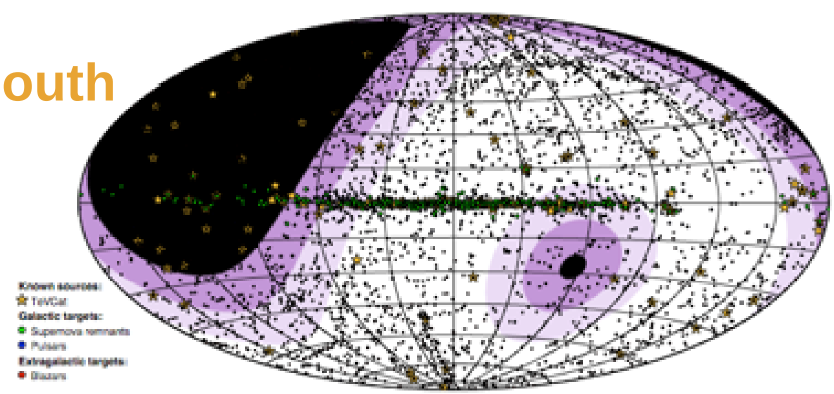


Full Sky Coverage

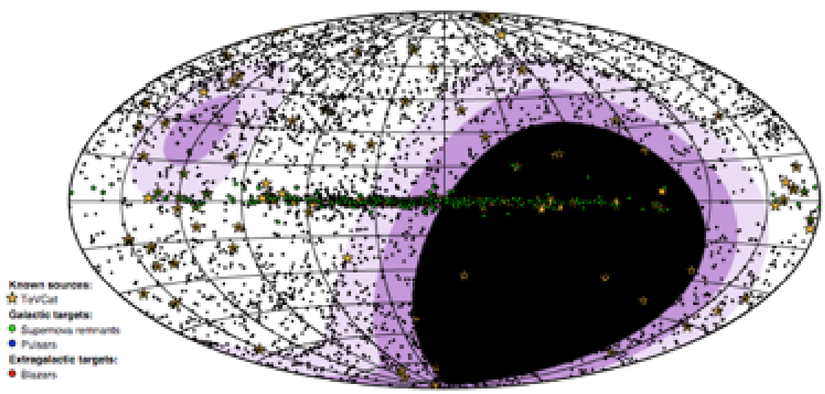
North + South



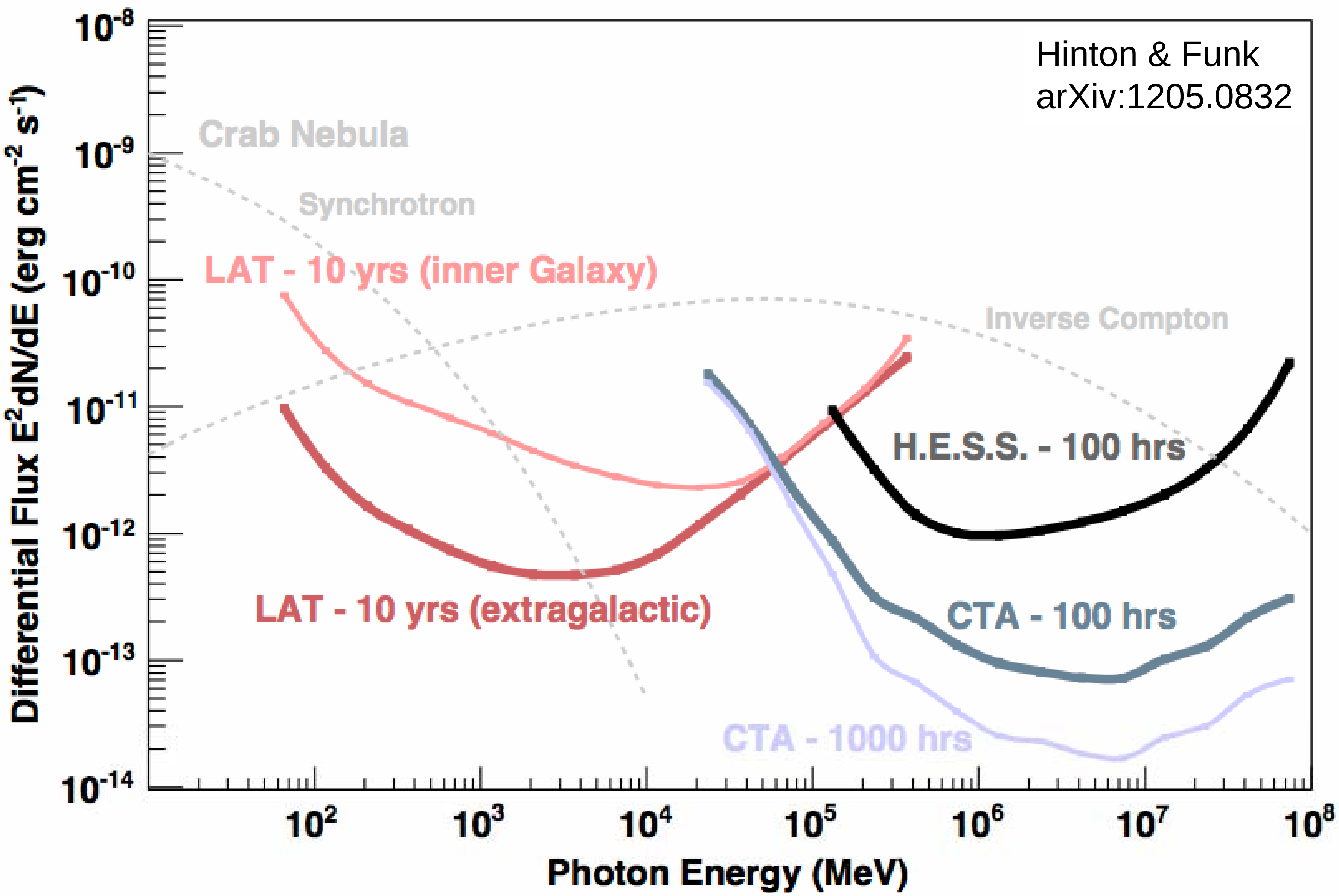
South



North



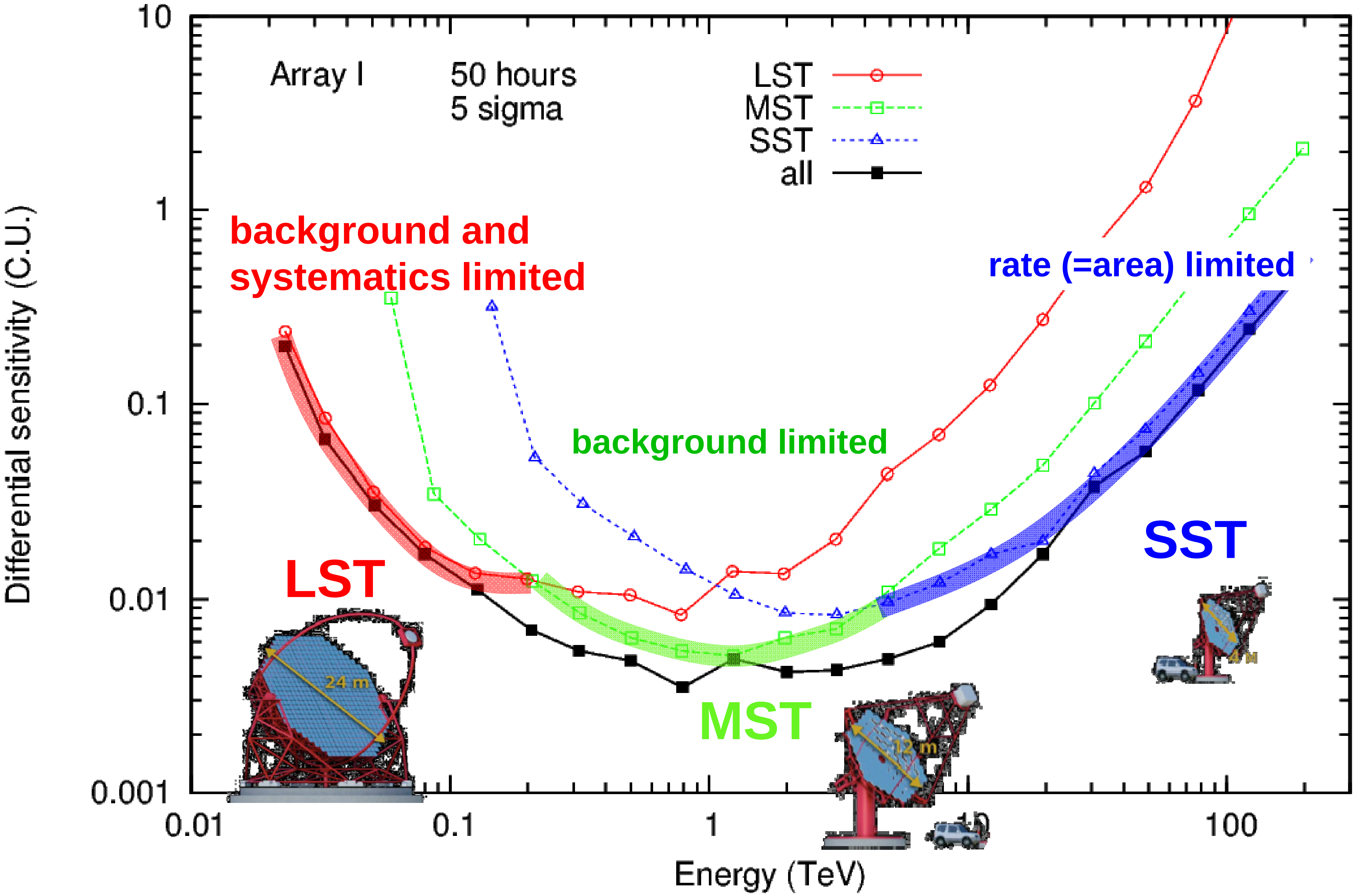
Differential Flux Sensitivity



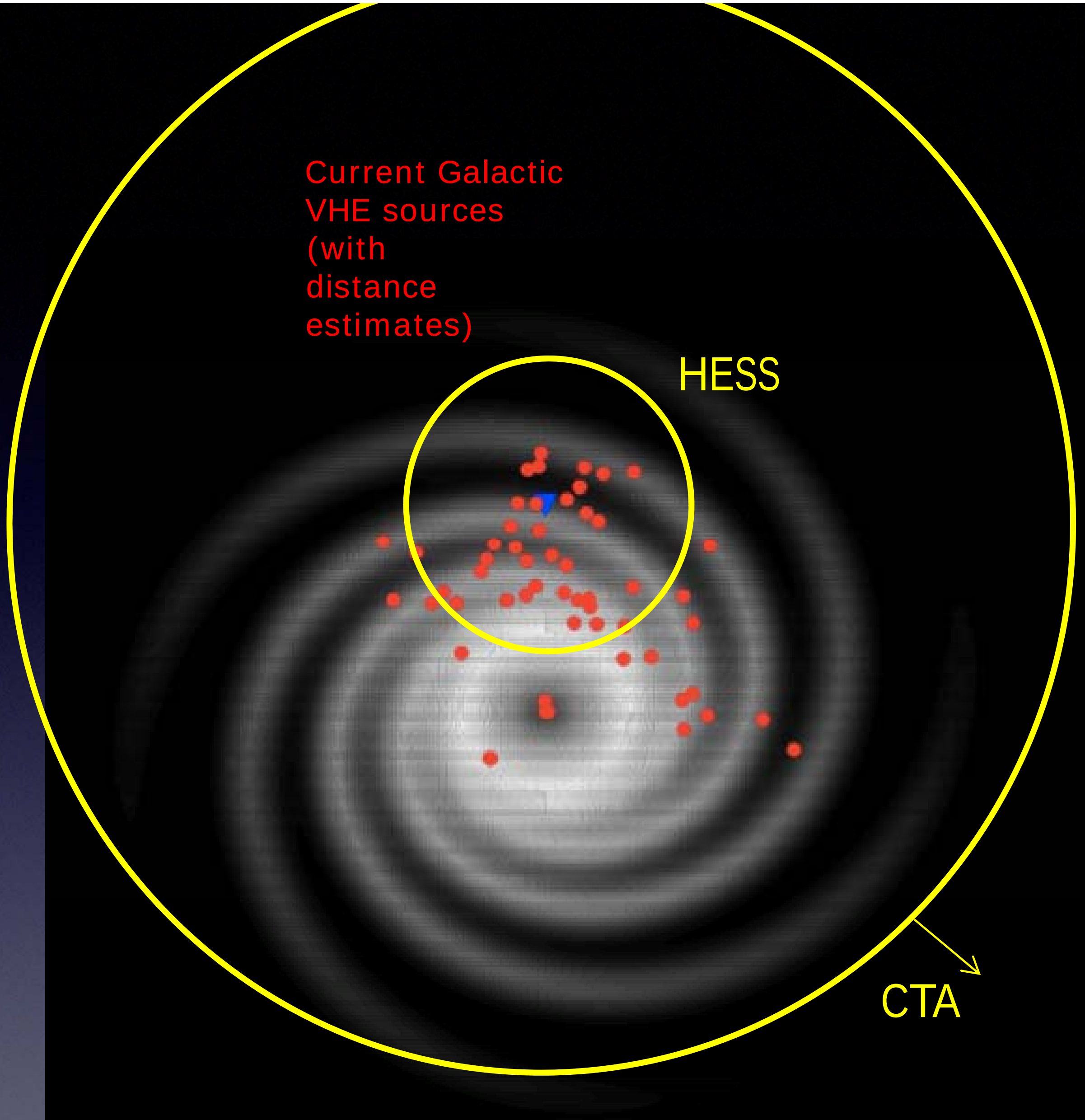
Major improvement over a wide energy range

Flux Sensitivity (Crab units)

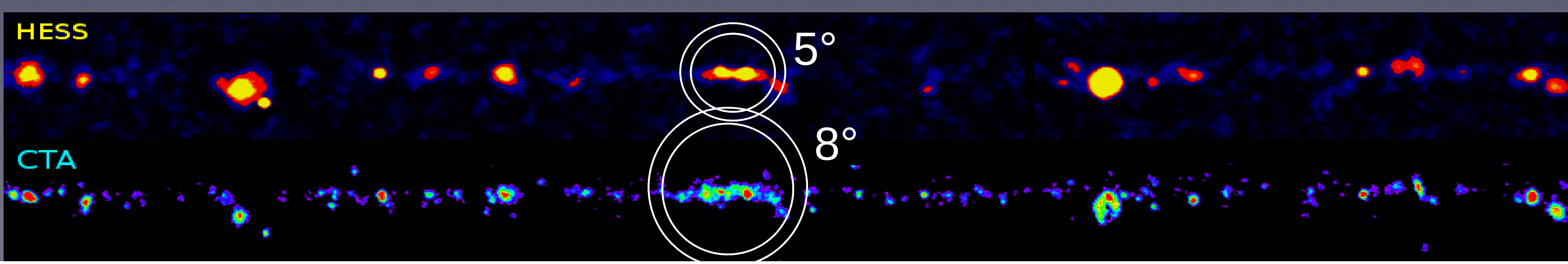
For detection in each 0.2-decade energy bin



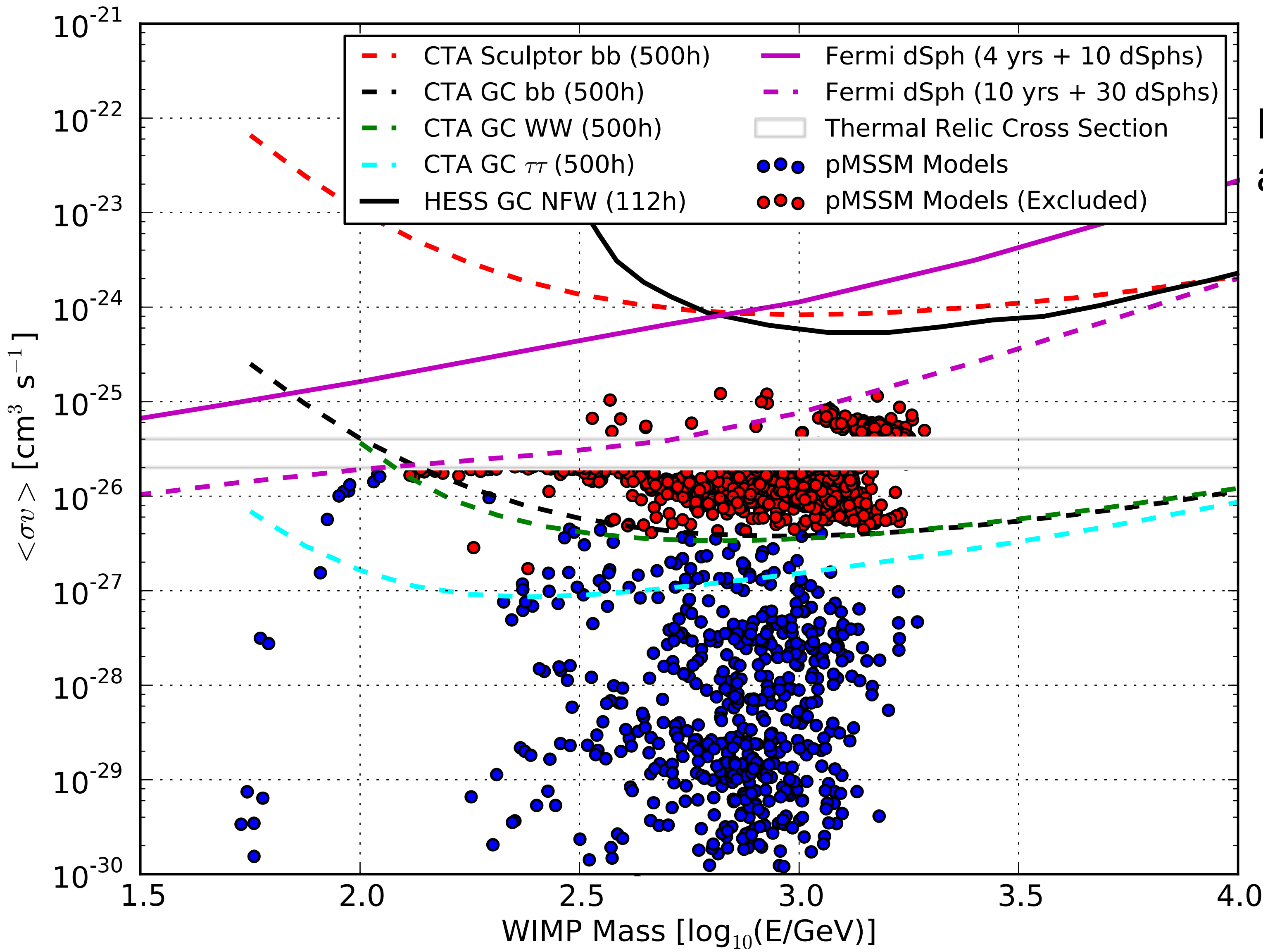
Galactic Discovery Reach



Survey speed:
x300 faster than HESS



Dark Matter Reach

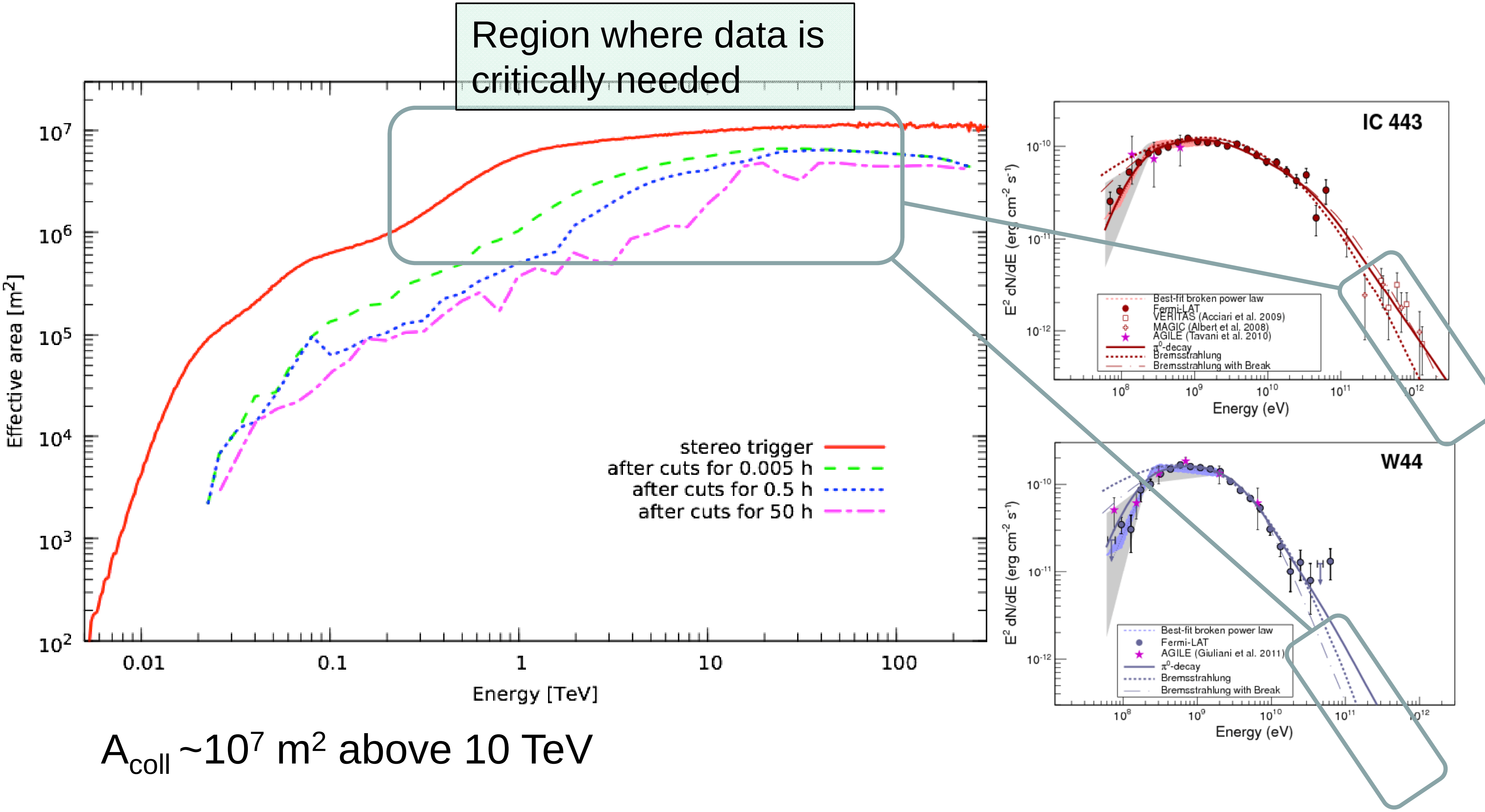


M. Wood et al. arXiv:1305.0302

Sensitivity below thermal relic in TeV mass range

- critical complementarity to direct detectors and LHC

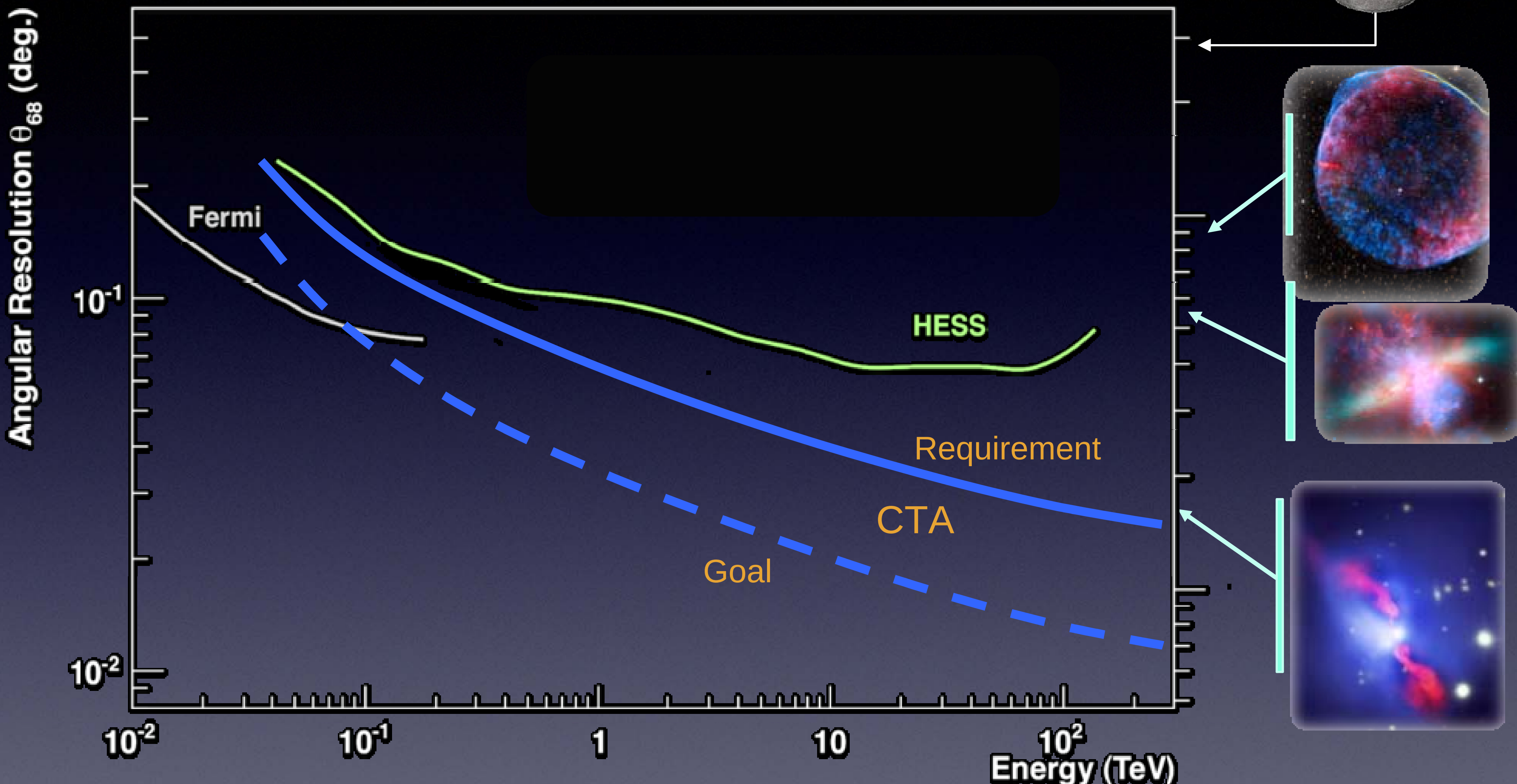
CTA Collection Area



A_{coll} ~10^7 m^2 above 10 TeV

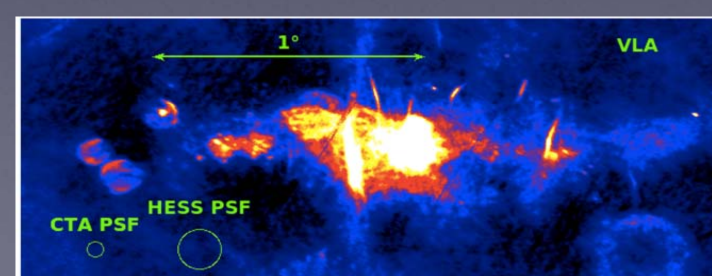
Crucial for:
High-energy spectra, discovery of Pevatrons → Origin of CRs

Angular Resolution



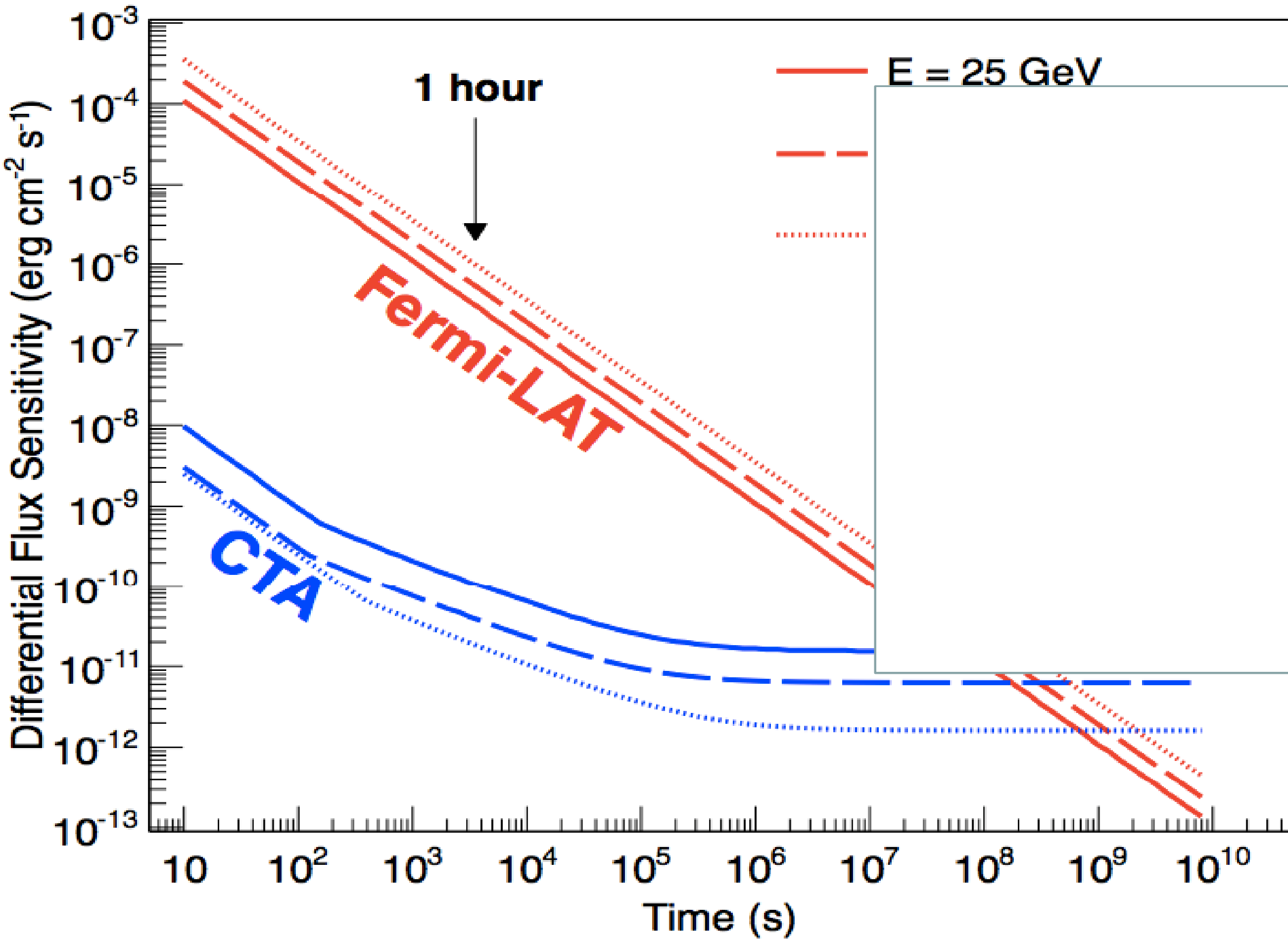
Angular resolution critical for
Source morphology and identification

Galactic-Center
region

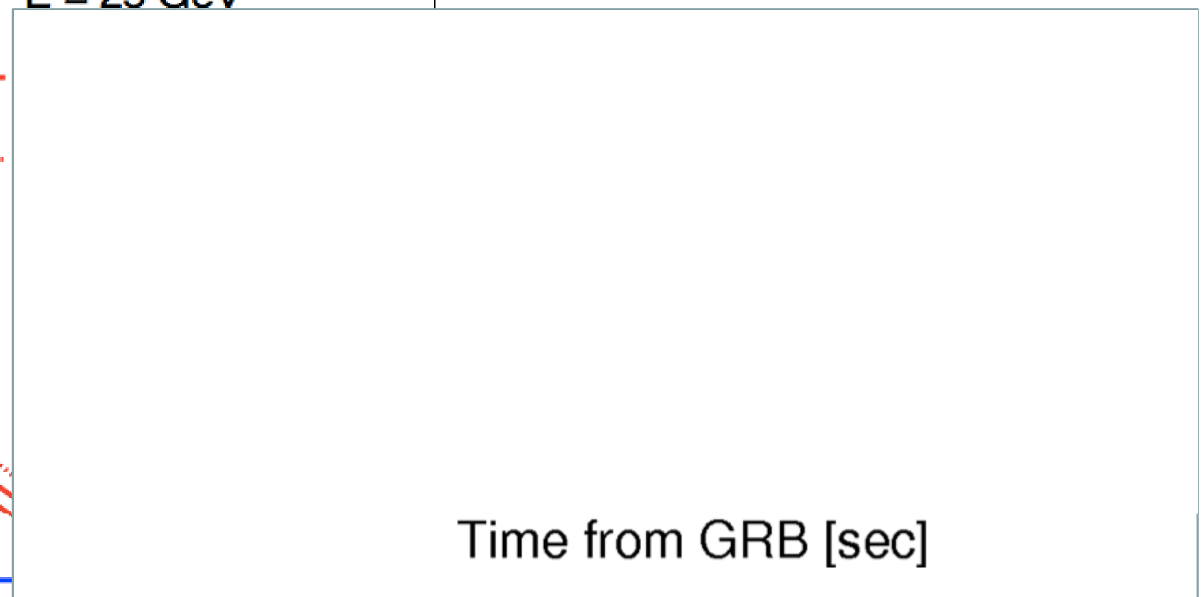


Transient Capability (< 100 GeV)

Hinton & Funk
arXiv:1205.0832



S. Inoue et al.,
arXiv:1301.3014



GRB (z=4.3) Light curve

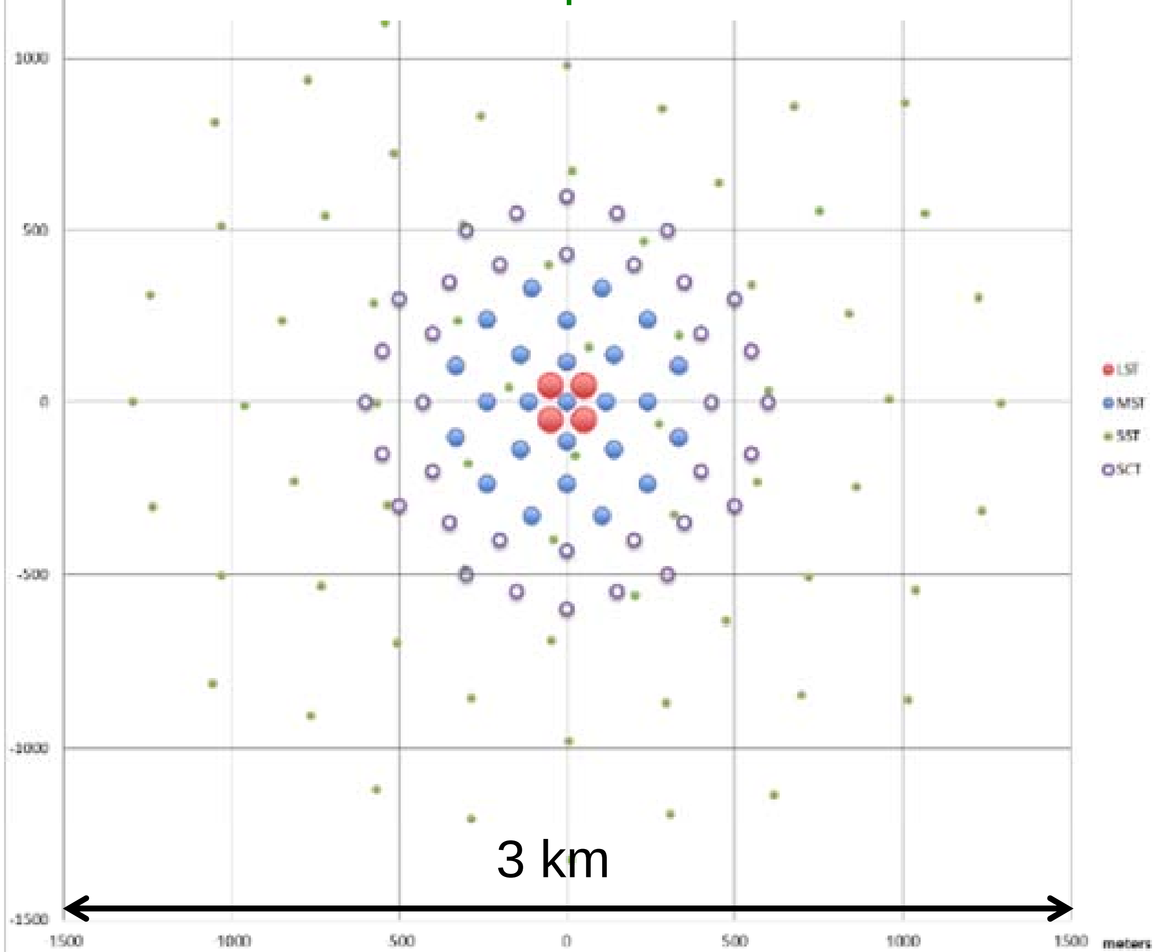
Huge potential for short-timescale phenomena
(GRB's, AGN, Micro-quasars, etc.)

CTA Implementation & Status

Southern & Northern Sites

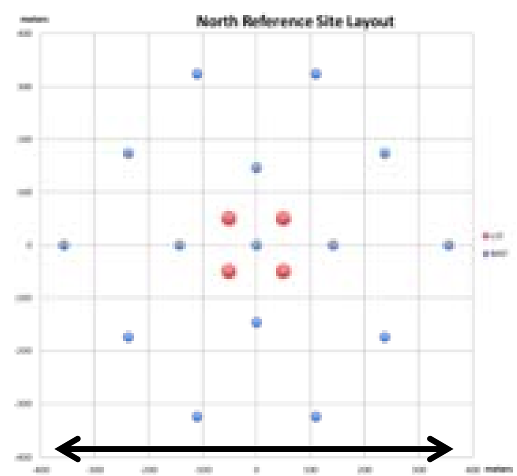
South site

4 large 23m telescopes: LST
25 medium12m telescopes: MST
24 medium 10m telescopes: SCT (US)
70 small 4m telescopes: SST



North site

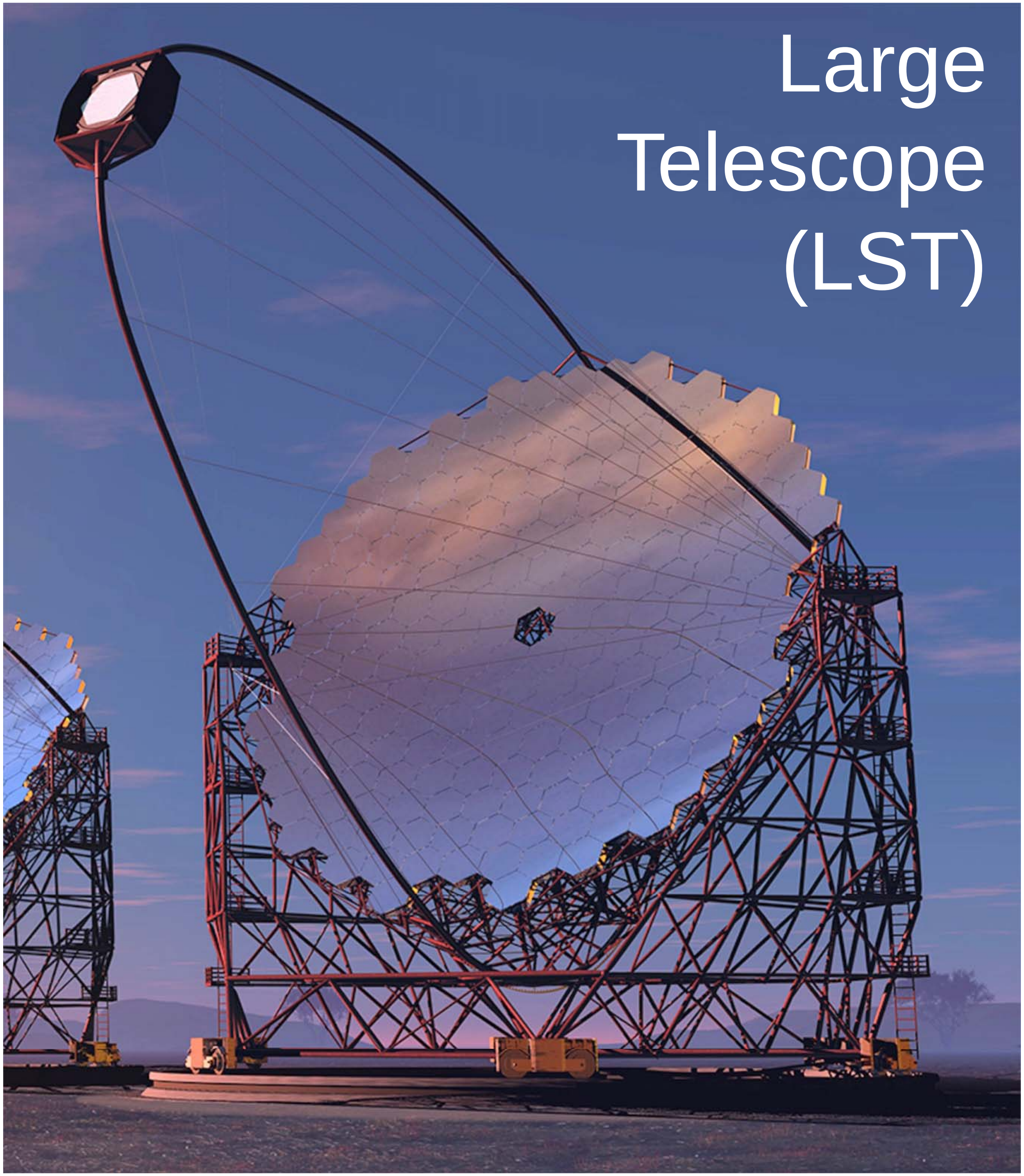
4 large LST
15 medium MST



800 m

Telescope Specifications

	LST "large"	MST "medium"	SCT "medium 2-M"	SST "small"
Number	**4 (S) 4 (N)**	**25 (S) 15 (N)**	**24 (S)**	**70 (S)**
Energy range	20 GeV to 1 TeV	200 GeV to 10 TeV	200 GeV to 10 TeV	> few TeV
Effective mirror area	> 330 m^2	> 90 m^2	> 40 m^2	> 5 m^2
Field of view	> 4.4^o	> 7^o	> 7^o	> 8^o
Pixel size ~PSF θ_{80}	< 0.11^o	< 0.18^o	< 0.075^o	< 0.25^o
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€	420 k€



23 m diameter
389 m^2 dish area
28 m focal length
1.5 m mirror facets

4.5^o field of view
0.1^o pixels
Camera Ø over 2 m

Carbon-fiber structure
for 20 s positioning

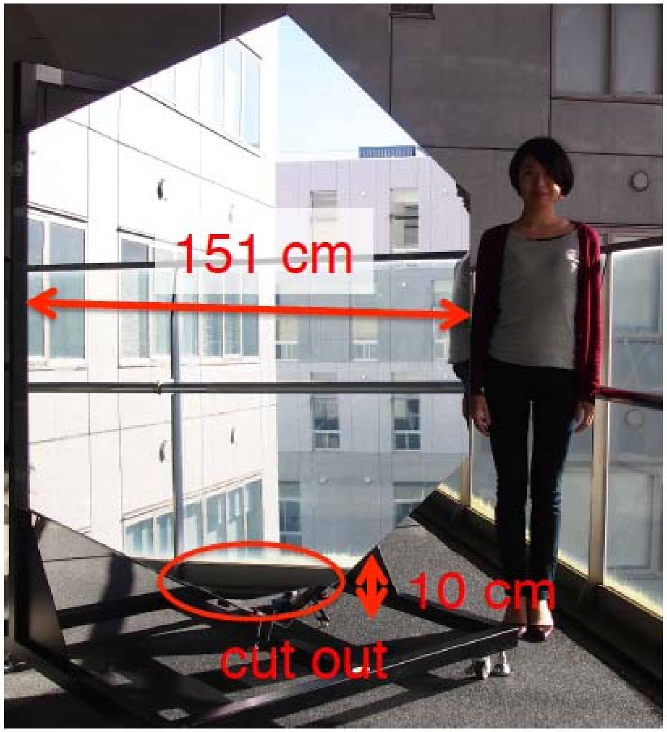
Active mirror control

4 LSTs on South site
4 LSTs on North site
Prototype = 1st telescope

LST Full Prototype

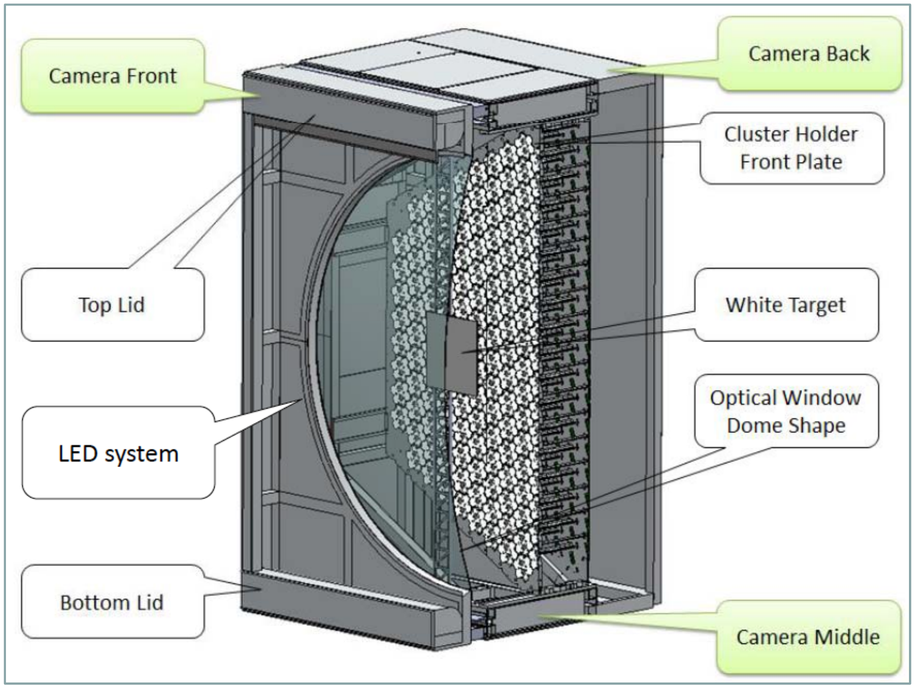
Elevation drive prototype

Mirror prototype
(cold-slump, Sanko)

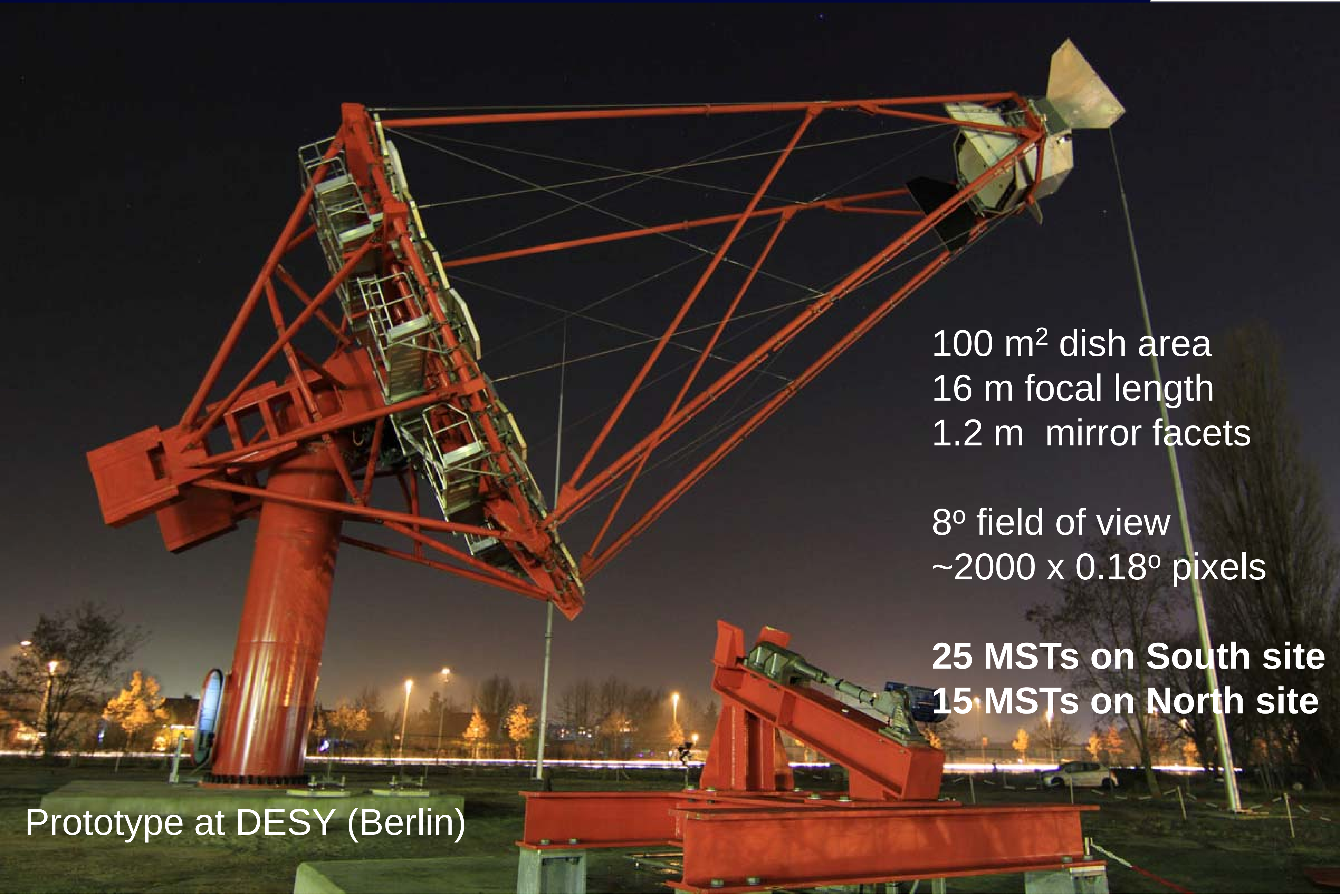


Area = 1.96 m^2
Mass = 47 kg

Prototype Camera design



Medium Telescope (MST)



100 m² dish area
16 m focal length
1.2 m mirror facets

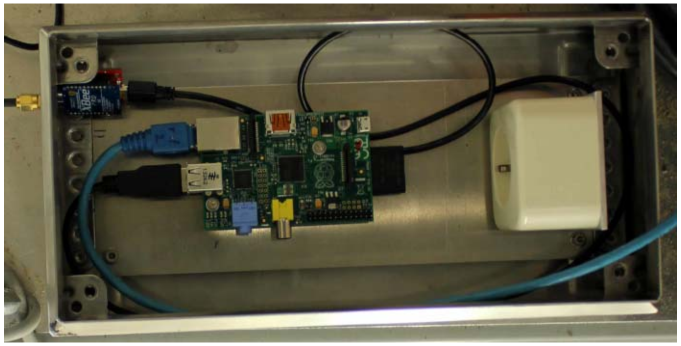
8º field of view
~2000 x 0.18º pixels

25 MSTs on South site
15 MSTs on North site

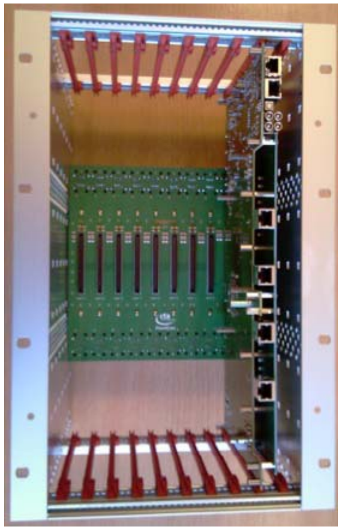
Prototype at DESY (Berlin)

MST Cameras and Mirror Control

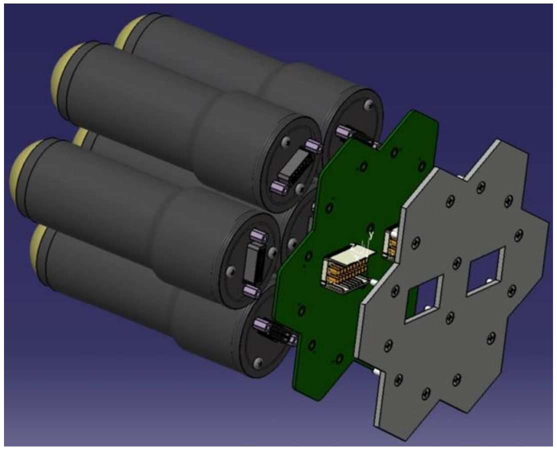
Prototype automatic mirror control (AMC)

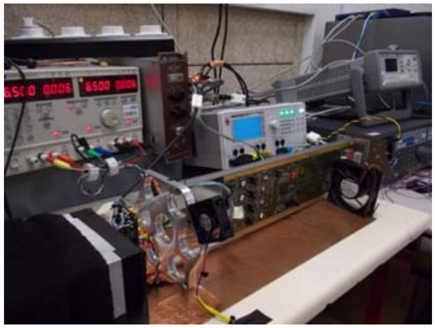


Flash-ADC + digital trigger + rack electronics (“FlashCAM”)



Capacitor pipeline + analog trigger + fully-contained “drawers” (“NectarCAM”)



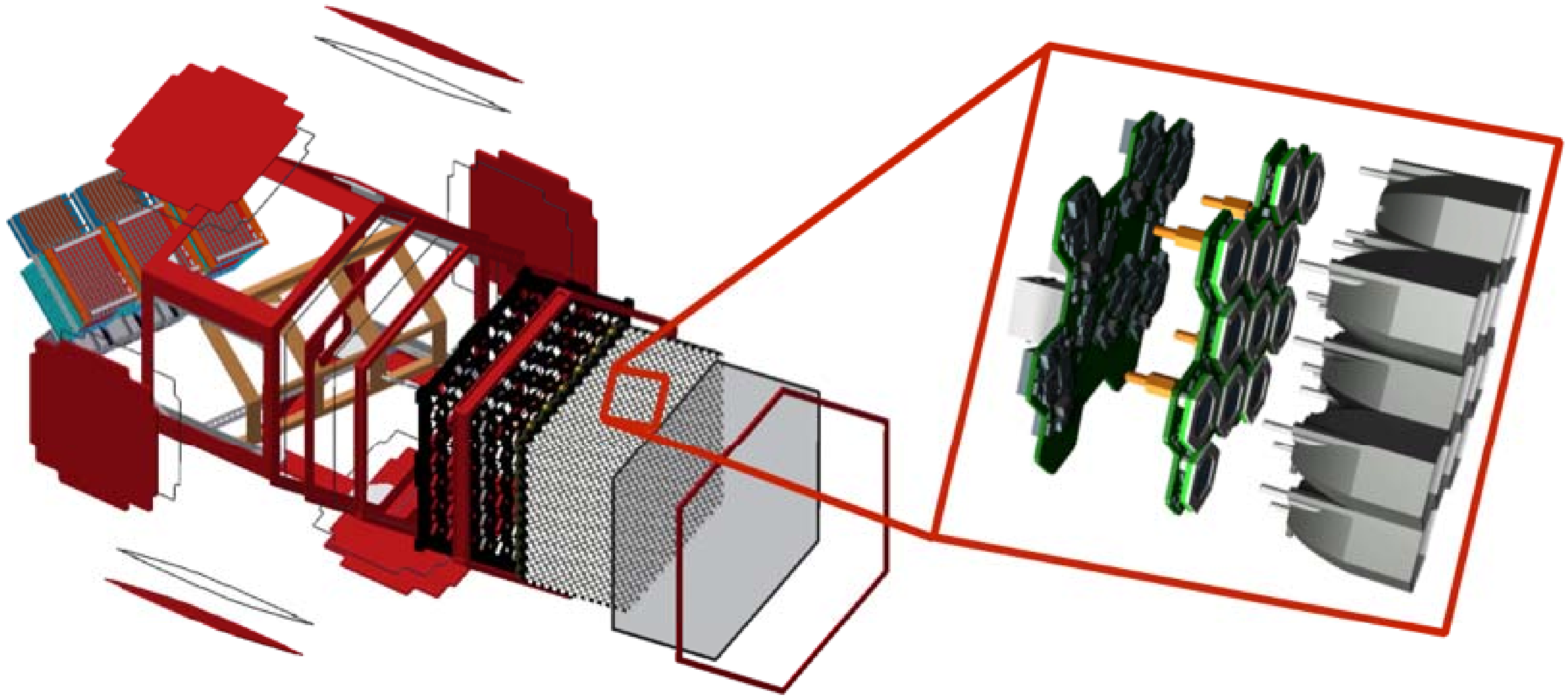


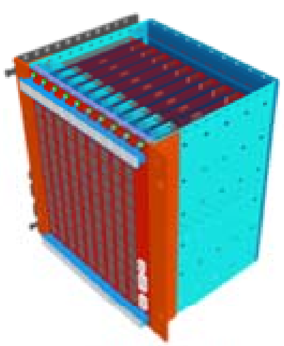
Nectar-board prototype

Small Telescope 1-mirror (SST-1M)

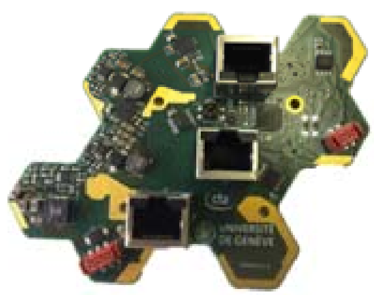
SST-1M Prototype Inauguration, 2 June 2014 (Krakow)

Silicon-PMT Camera

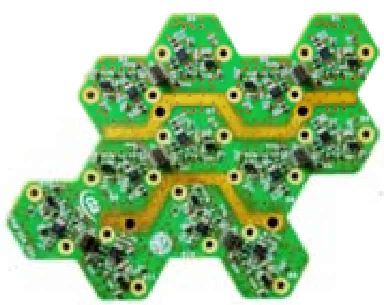




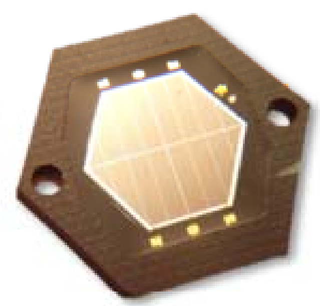
DigiCam



Slow Control Board



Preamplifier board



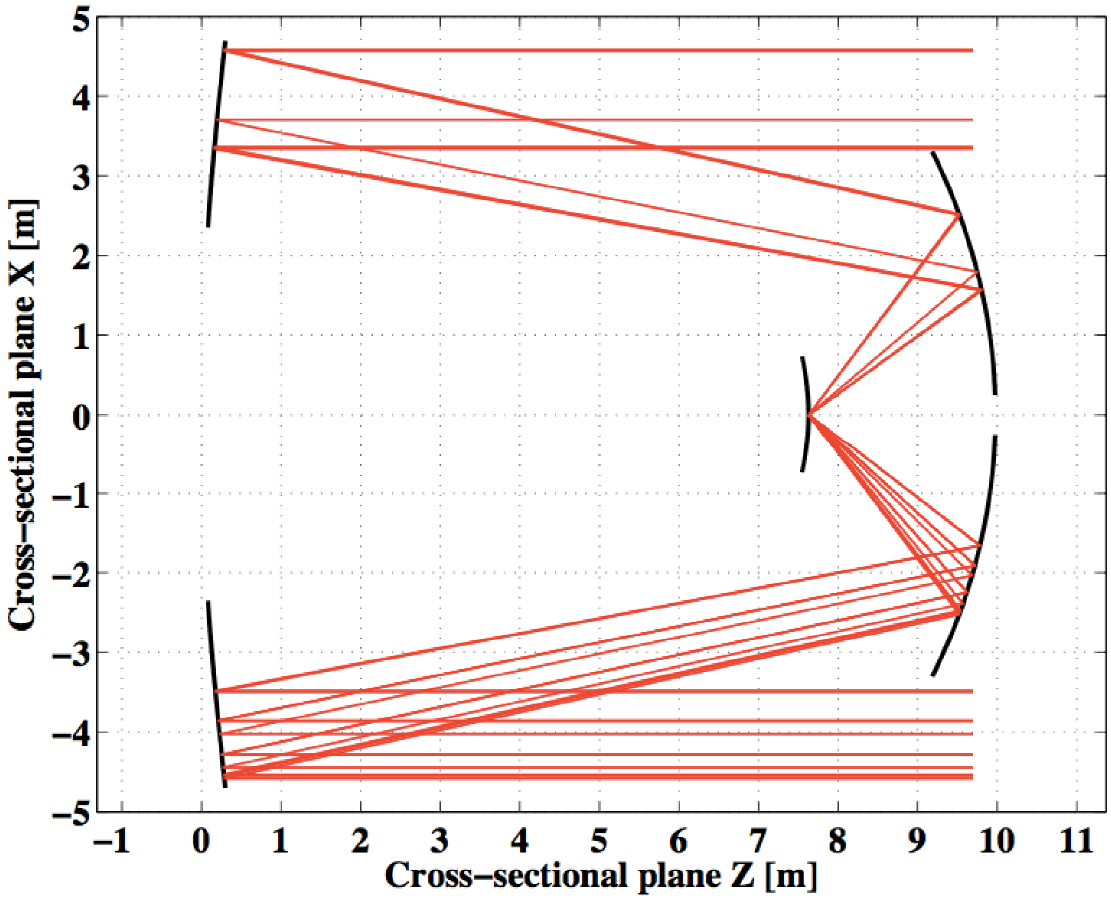
Hexagonal sensors

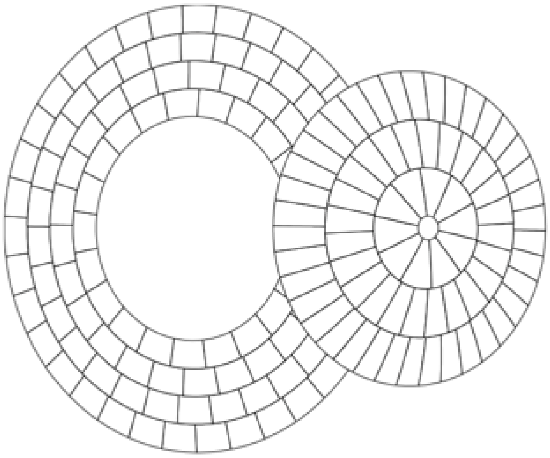
Light guides

Two-Mirror Telescopes

Schwarzschild-Couder (SC) Design

Vassiliev, Fegan, Brousseau
Astropart.Phys.28:10-27,2007





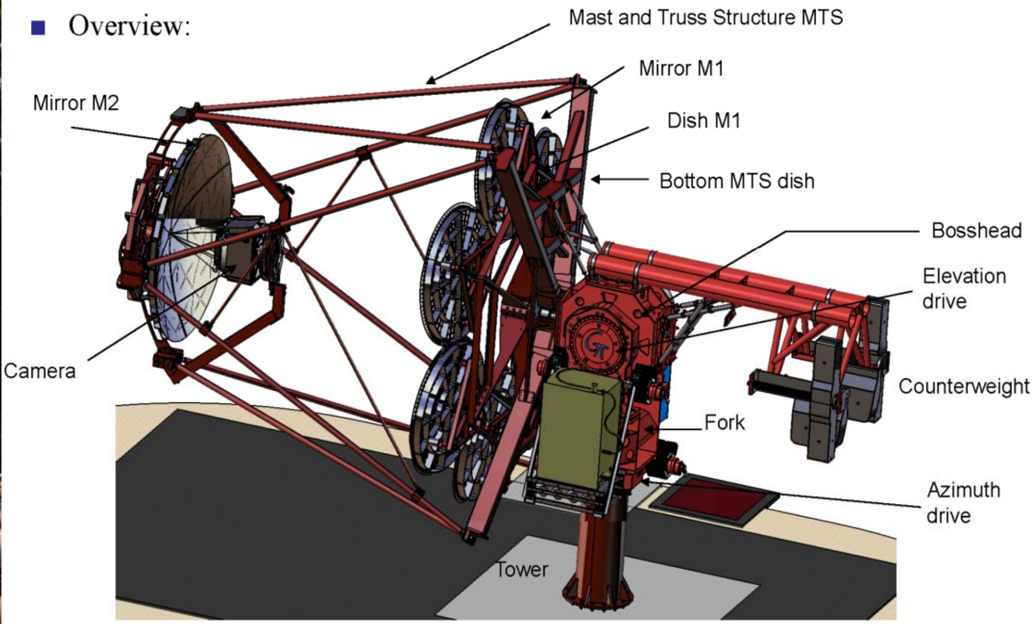
- Reduced plate scale
- Reduced PSF
- Uniform PSF across f.o.v.

➜ Cost-effective small telescopes with compact sensors (SST-2M)

➜ Higher-performance medium telescopes with small pixels (MST-SCT)

Small Telescope 2-mirror (SST-2M)

SST-2M –ASTRI Prototype
Inauguration, 24 Sept 2014
(Serra La Nave, Sicily)



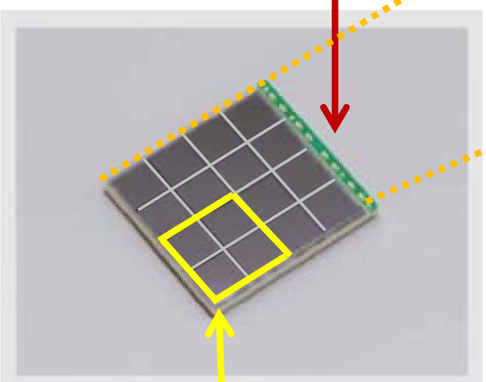
SST-2M-GCT (Gate-CHEC Telescope)

Both 2-Mirror SST Designs use compact, Silicon-PM Cameras

SST-2M -ASTRI Focal Plane

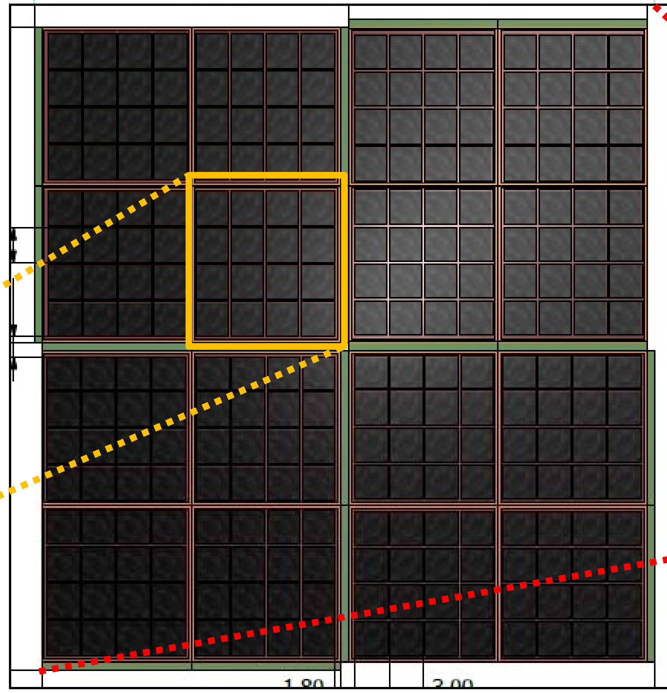
S11828-3344M1
the 'Unit'

geometrical dead area



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

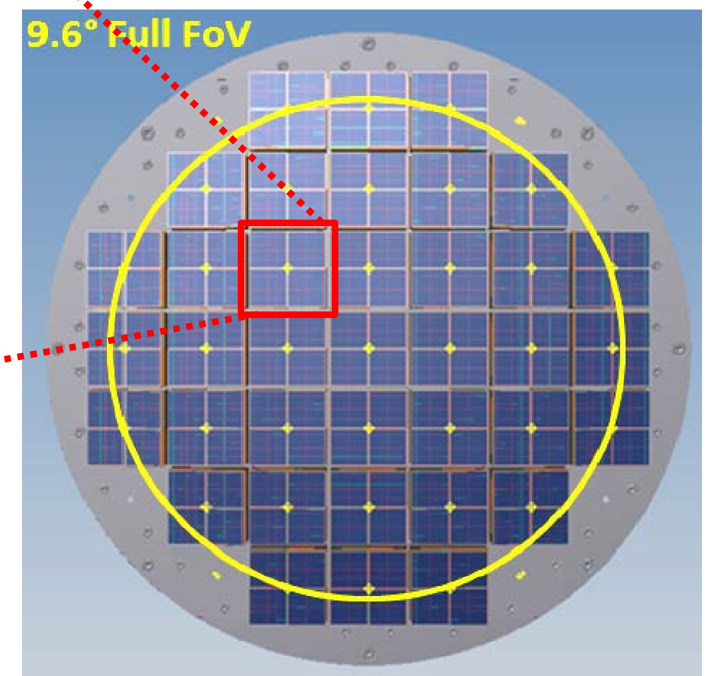
Photon Detection Module
PDM



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

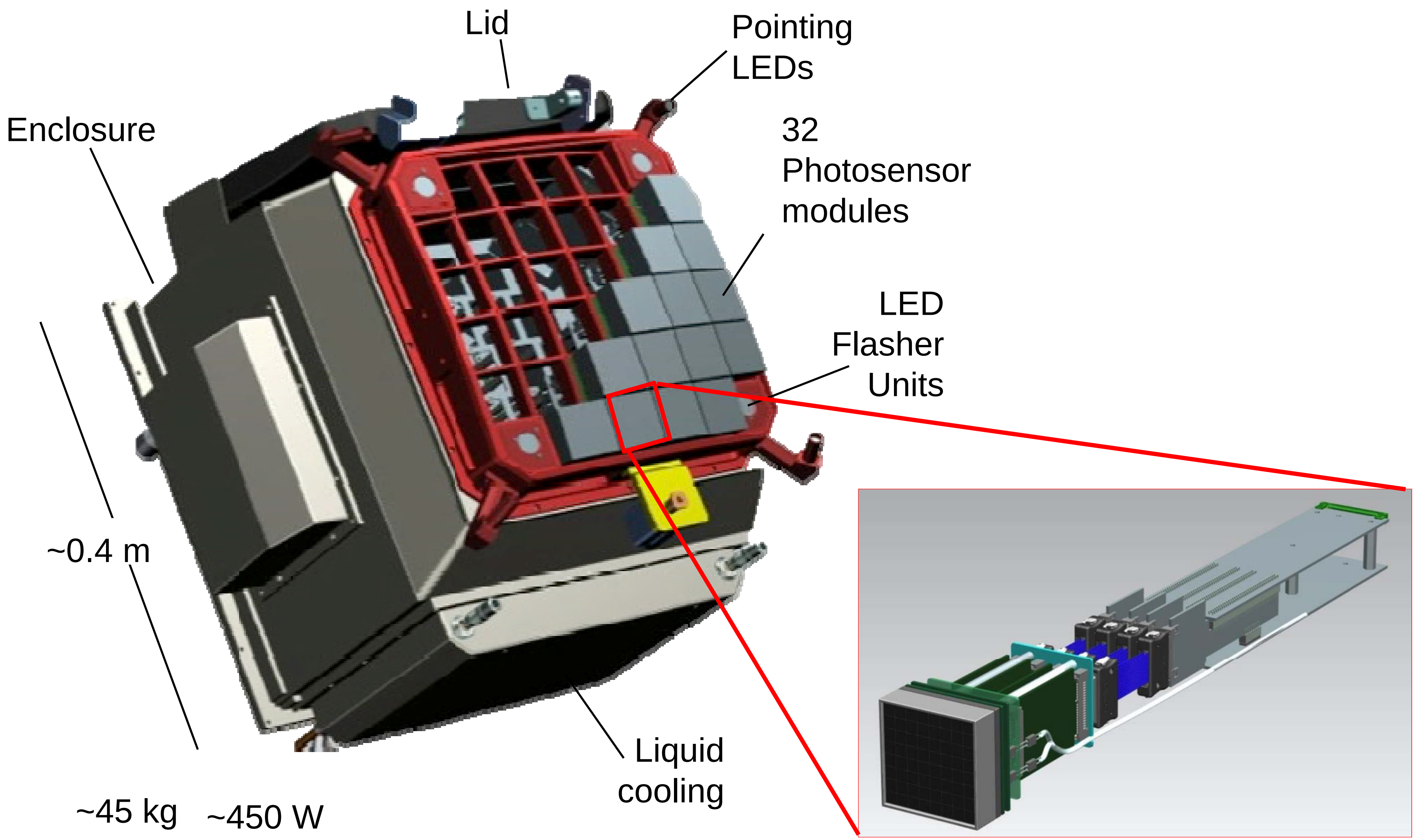
Each PDM works independently from the others

ASTRI Focal Plane



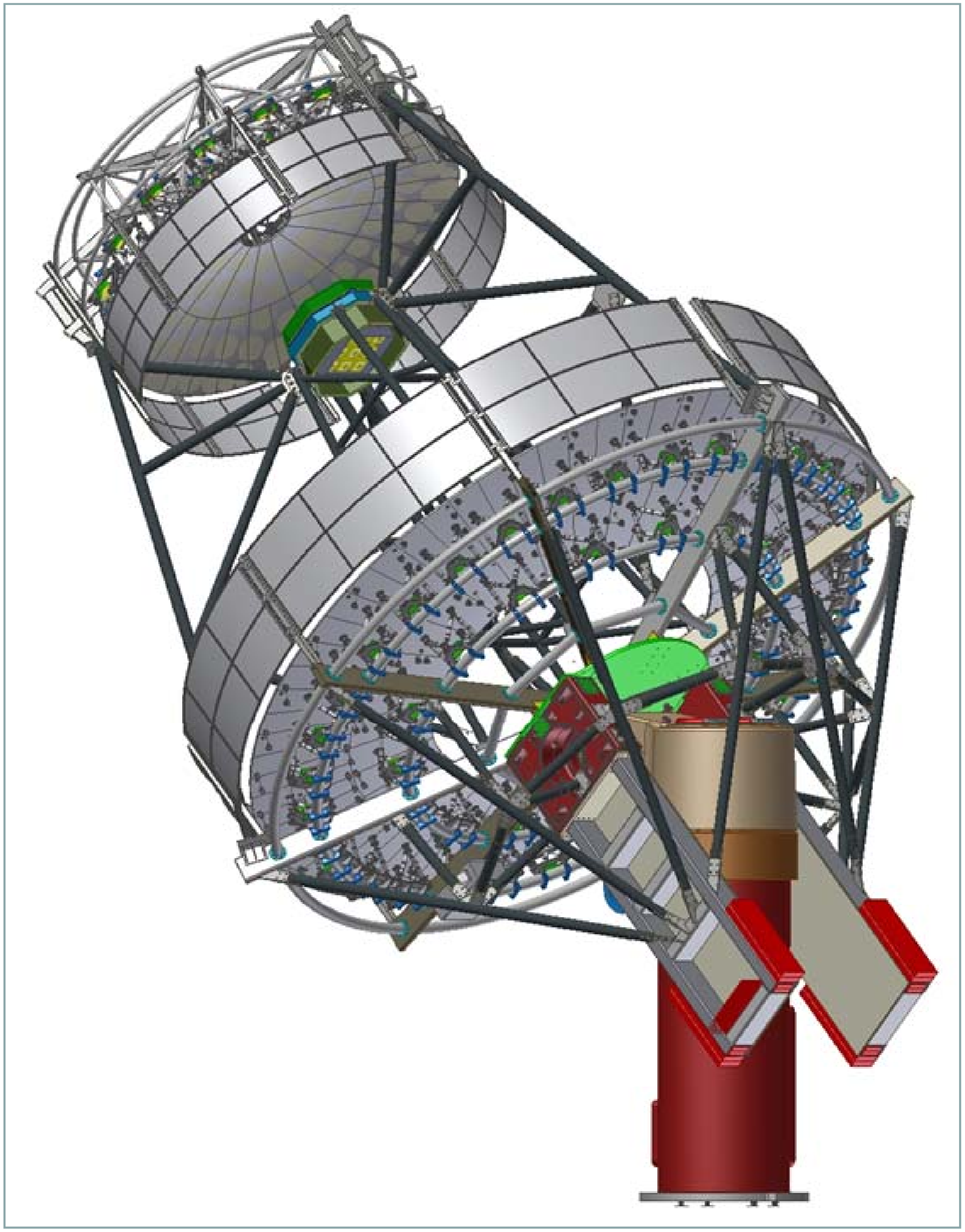
37 PDMs → Focal Plane
560×560mm
(1984 channels)

SST-2M-GCT Camera + Module



Photosensor module

Medium Telescope 2-mirror (SCT)



9.7 m primary
5.4 m secondary
5.6 m focal length, f/0.58
40 m^2 eff. coll. area
PSF better than 4.5’
across 8^o fov

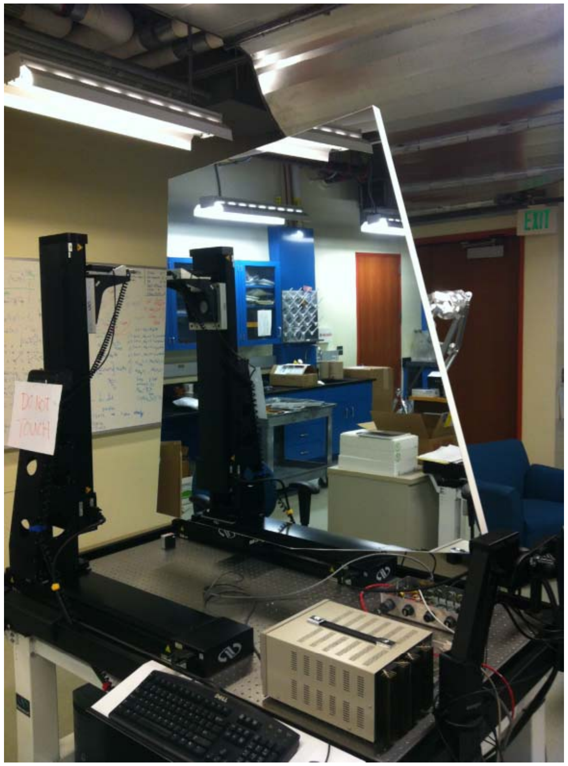
8^o field of view
11328 x 0.07^o SiPMT pixels
Target readout ASIC

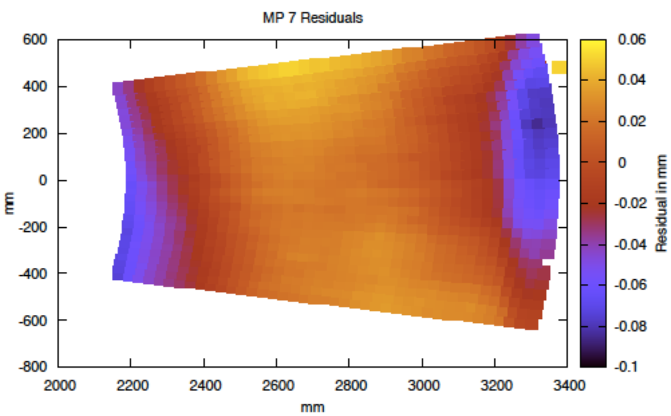
Extend South array
by adding 24 SCTs

➜ Increased γ-ray collection area
➜ Improved γ-ray angular resolution

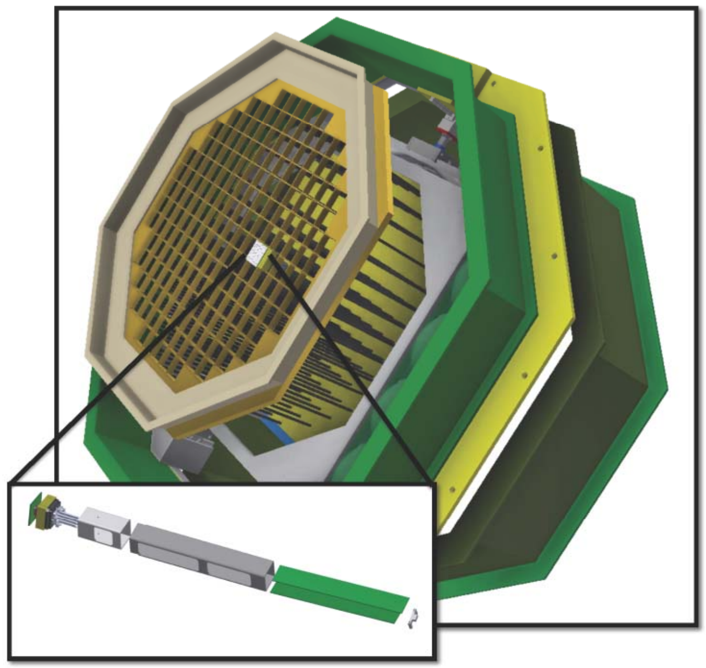
SCT Prototype Development

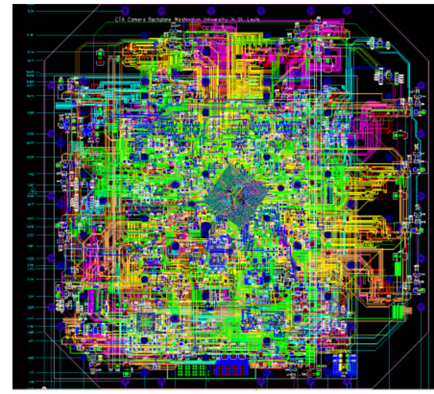
Prototype panels for
primary mirror (M1)



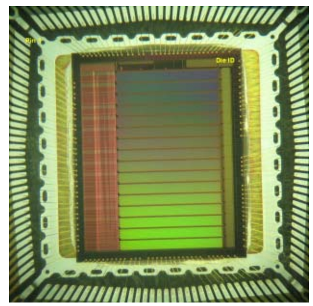


Camera design, backplane and elements





Individual (64-chan)
Camera module



Target-7
ASIC

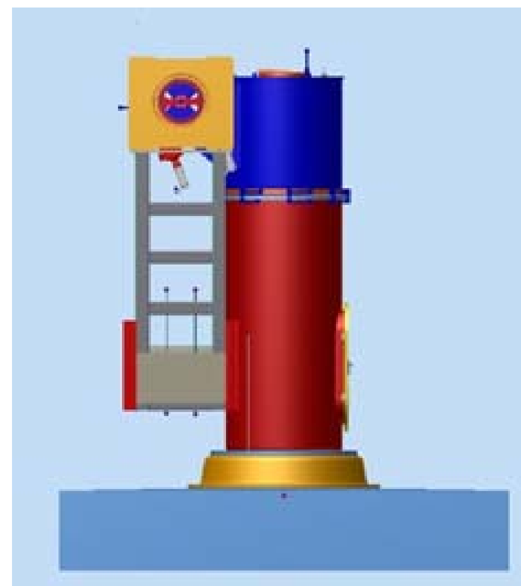
SCT Prototype @ Whipple Obs.

Prototype location at Whipple basecamp
(near VERITAS, Arizona USA)

Soon: Positioner installed

Summer: Camera delivered

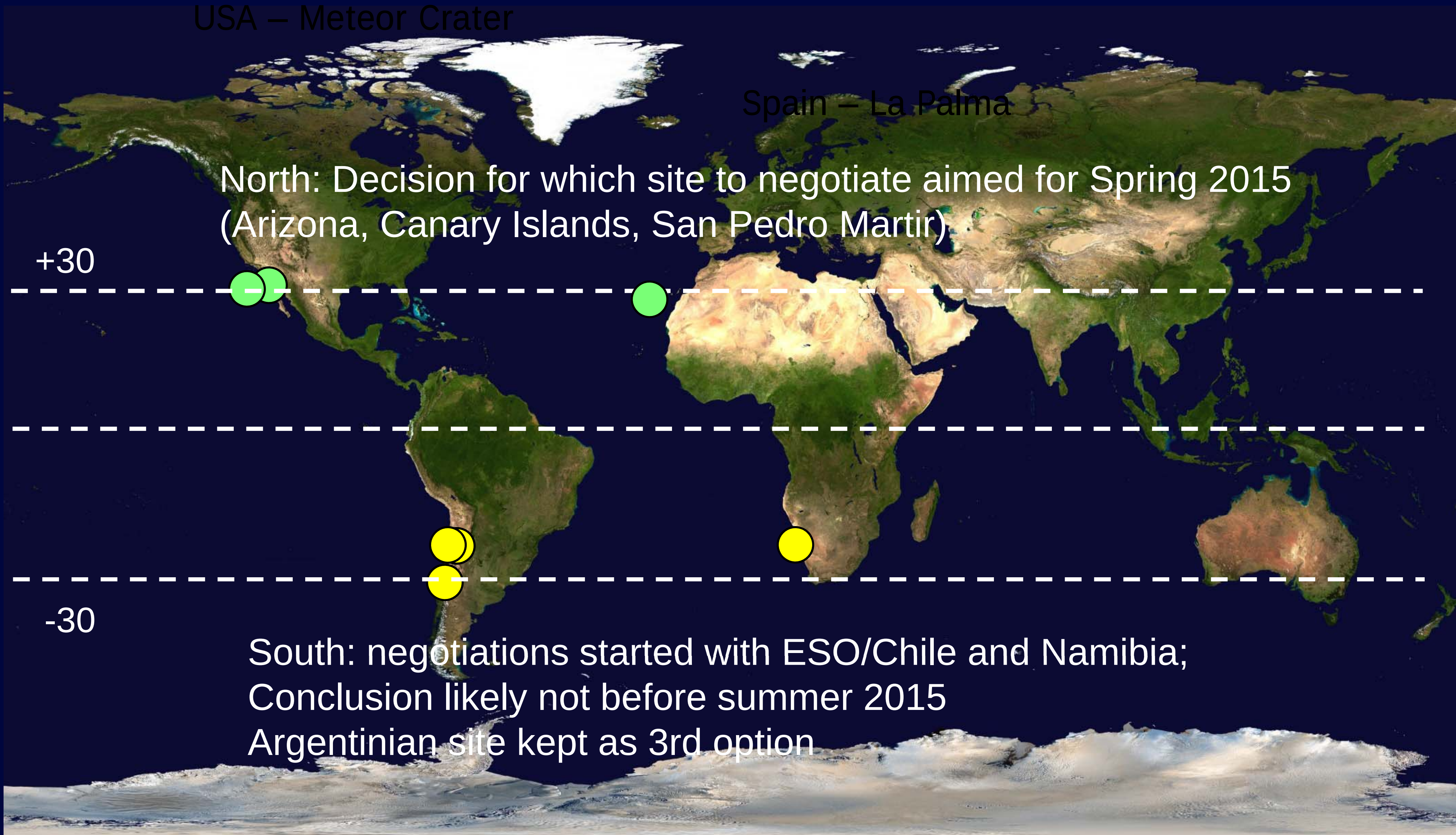
Fall: Start of commissioning



Positioner from DESY
(Same as MST)

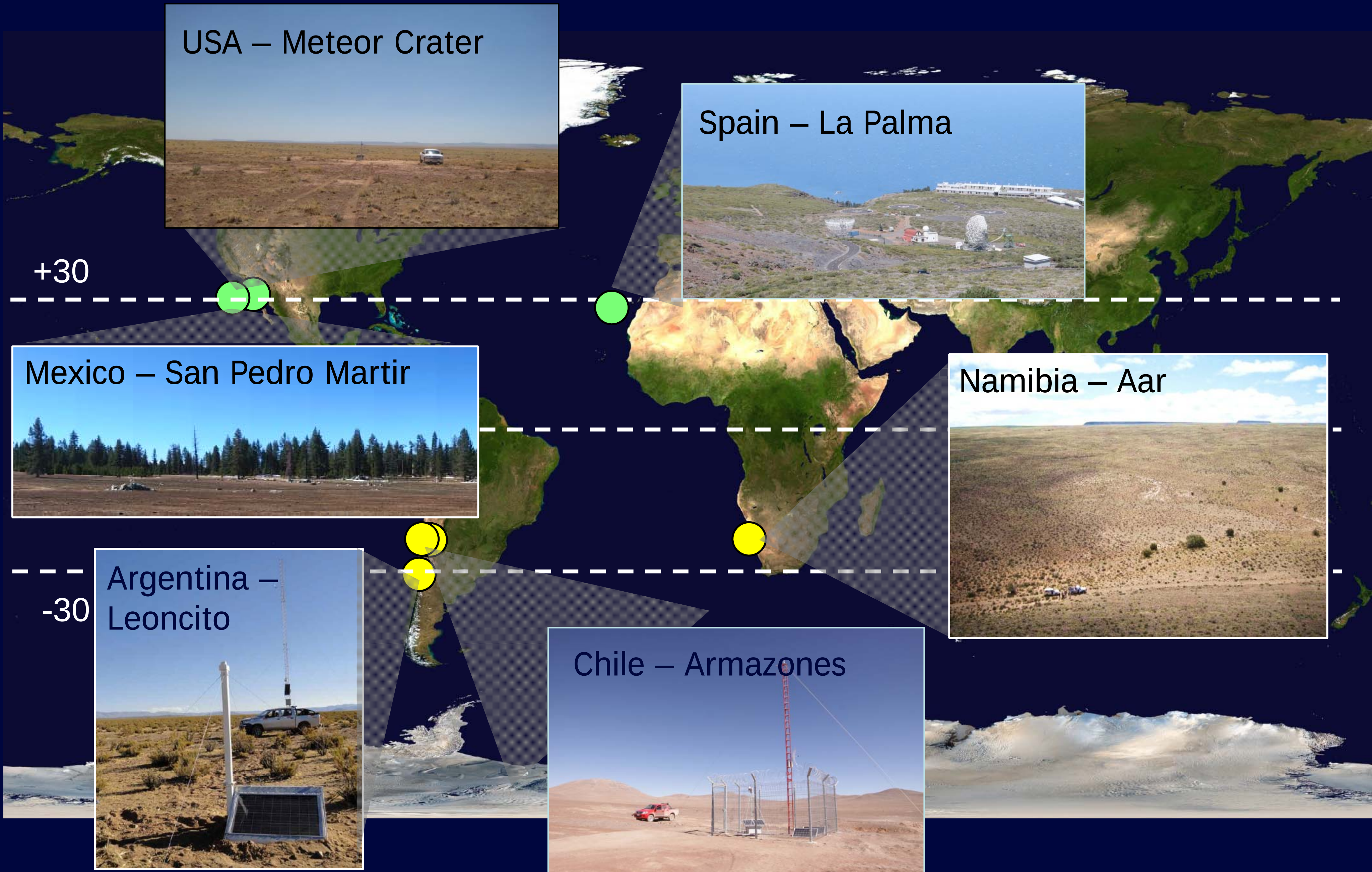
Site Selection

Two sites to cover full sky at 20º-35º N, S



Site Selection

Two sites to cover full sky at 20º-35º N, S



Steps Towards Approval

Science Performance and Preliminary Requirement Review → Preliminary Technical Design Report /Preliminary Design Review → Technical Design Report / Critical Design Review → Founding Agreement

Feb. 2013 ✔ Nov. 2013 ✔ June 2015

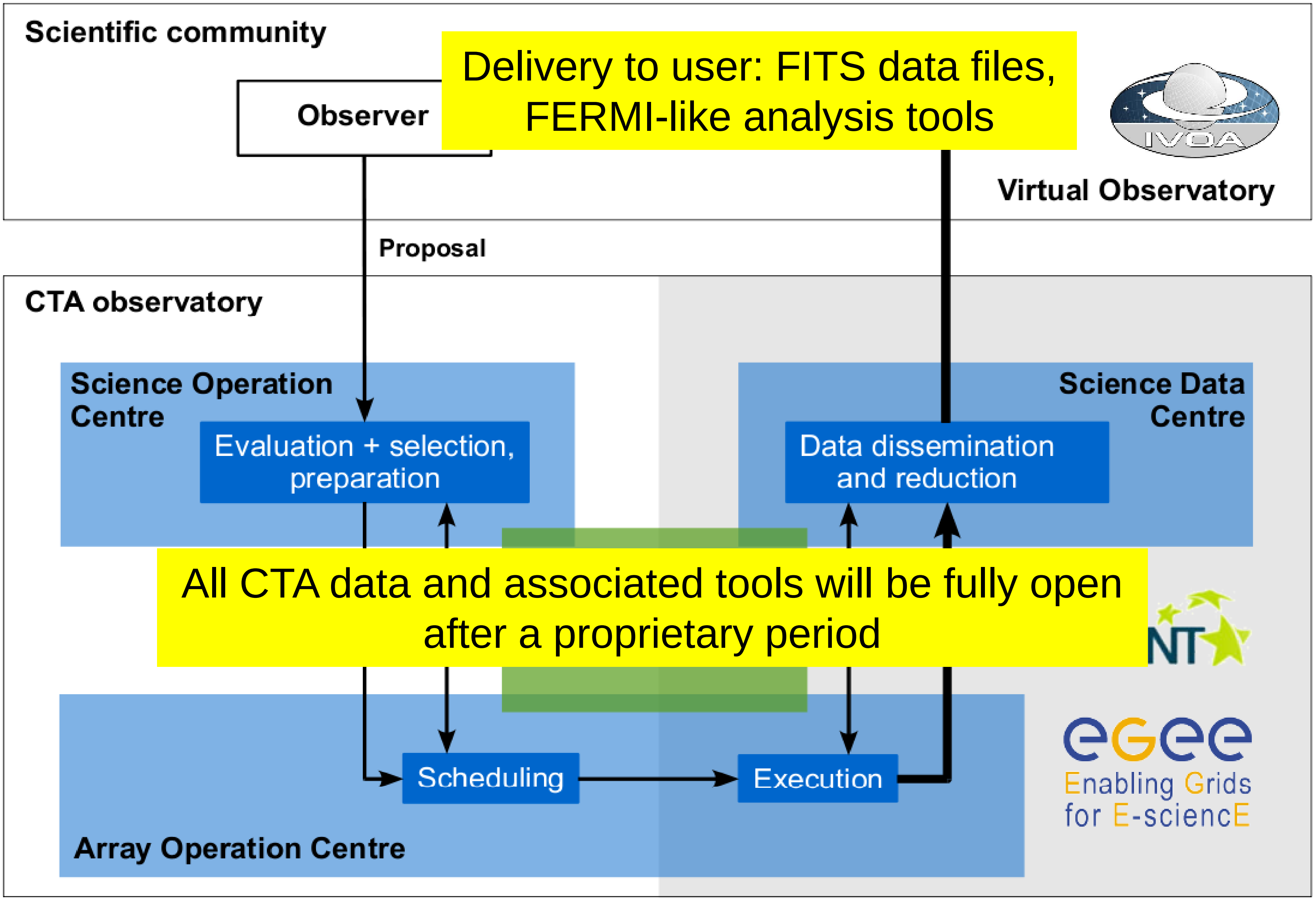
EC-supported Preparatory Phase, followed by CTA GbmH, for legal support

CDR scheduled for June 2015 by
Science and Technical Advisory Committee (STAC) – Chair. R. Blandford

After approval, assume 5-year construction phase

Open Access, Public Data

First Time in this field



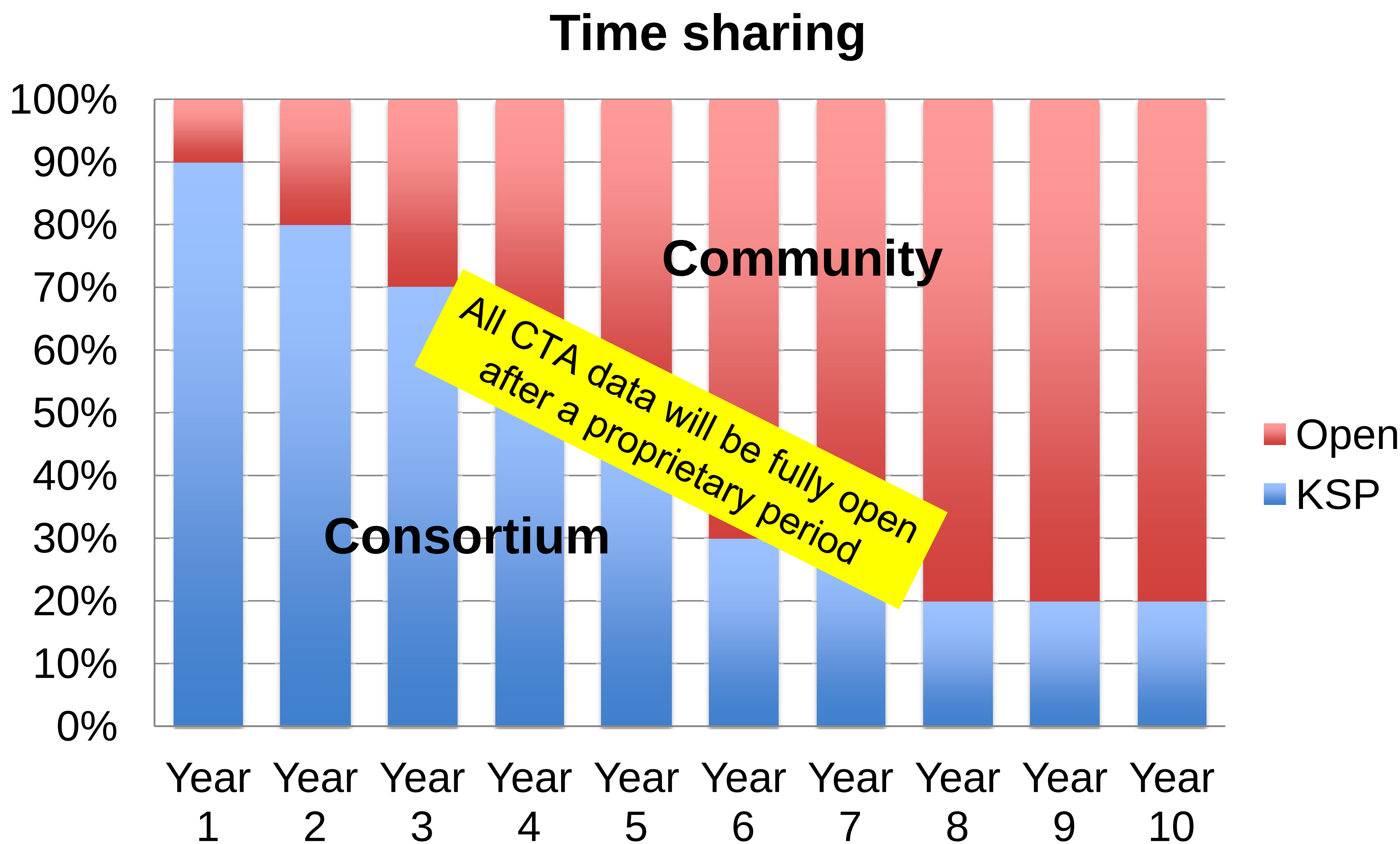
Key Science Projects (KSPs)

The KSPs are:

- aimed to ensure that some of the key science issues for CTA are addressed in a coherent fashion, with well-defined strategy
- typically hard to carry out within a Guest Observer program.
- planned, proposed, carried out by CTA Consortium under guaranteed time
- conceived to provide legacy data sets for use by the entire community

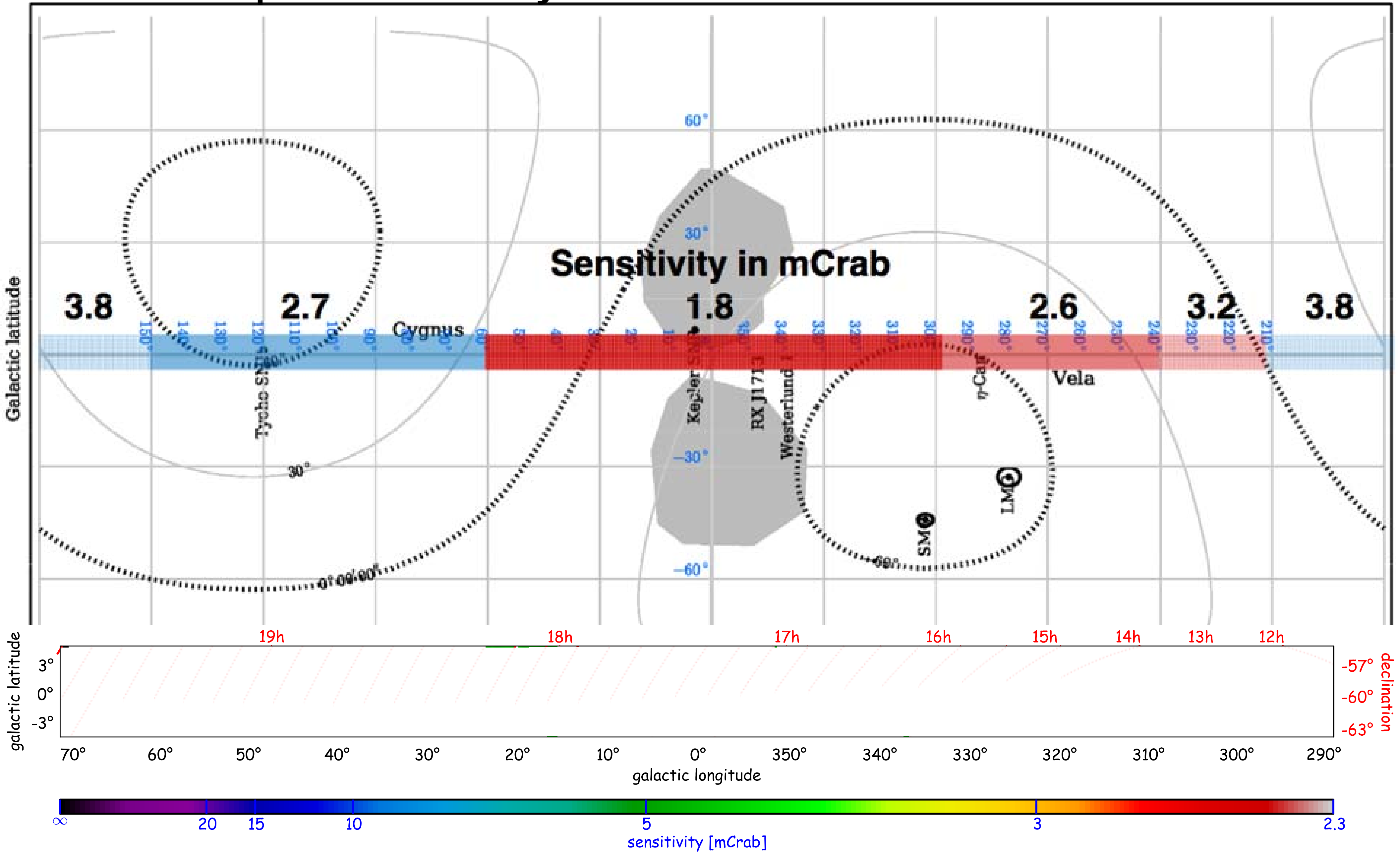
The KSPs will evolve over time!

KSP Scheduling

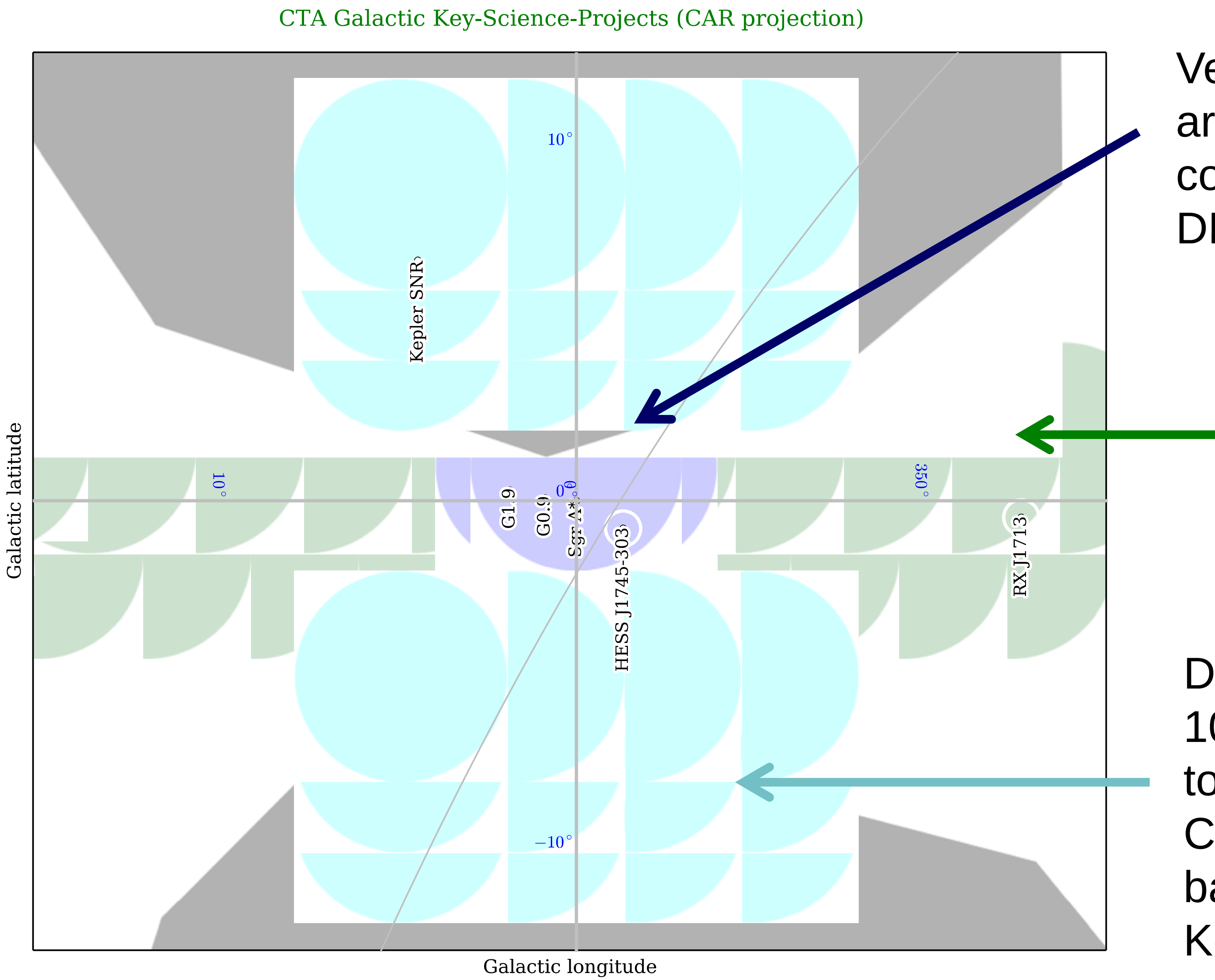


Galactic Plane Survey (GPS)

Entire plane surveyed to < 3.8 mCrab



Galactic Center



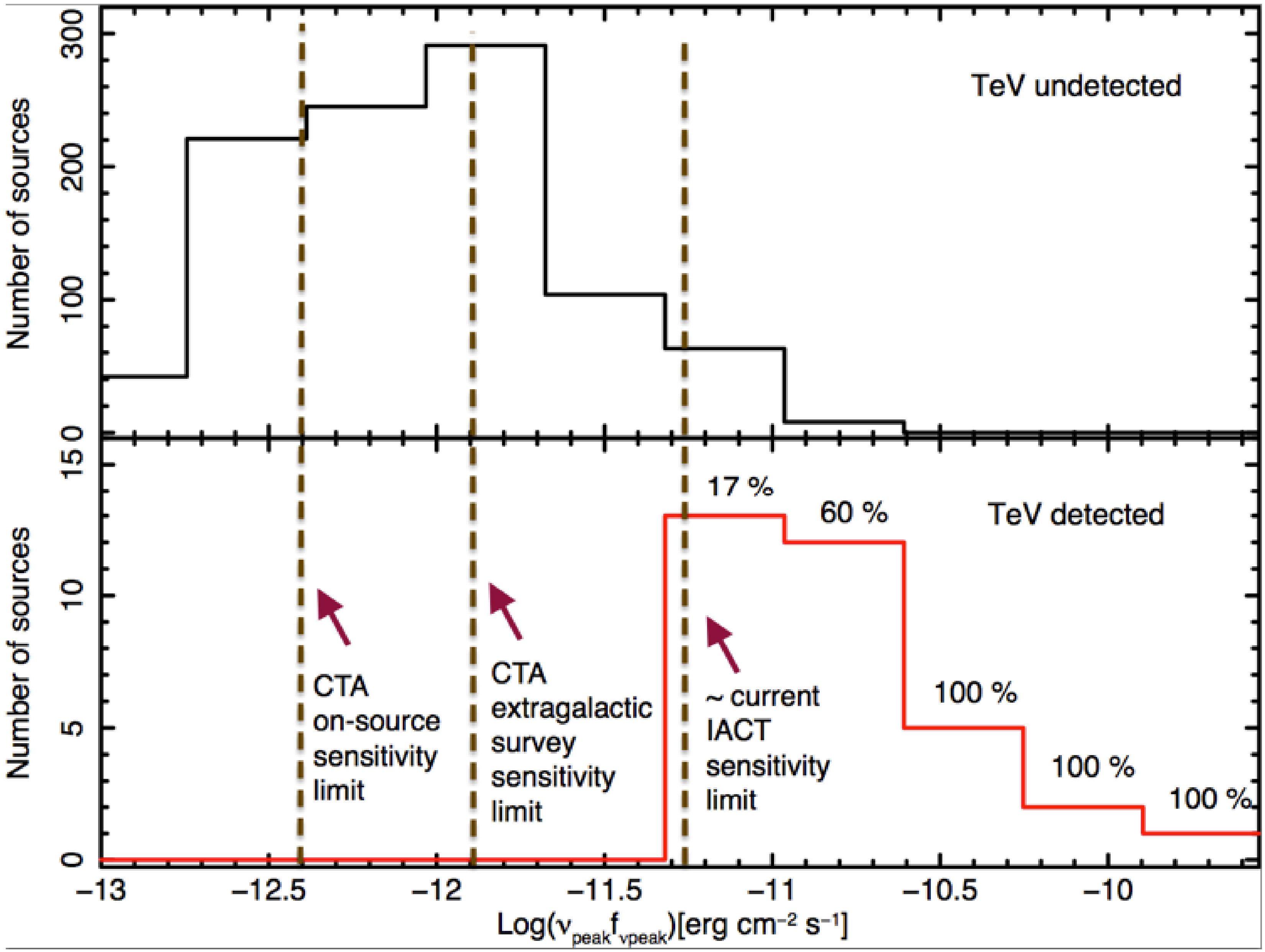
Very deep exposure around SGR A*, covering central source, DM halo, radio lobes

GPS pointings

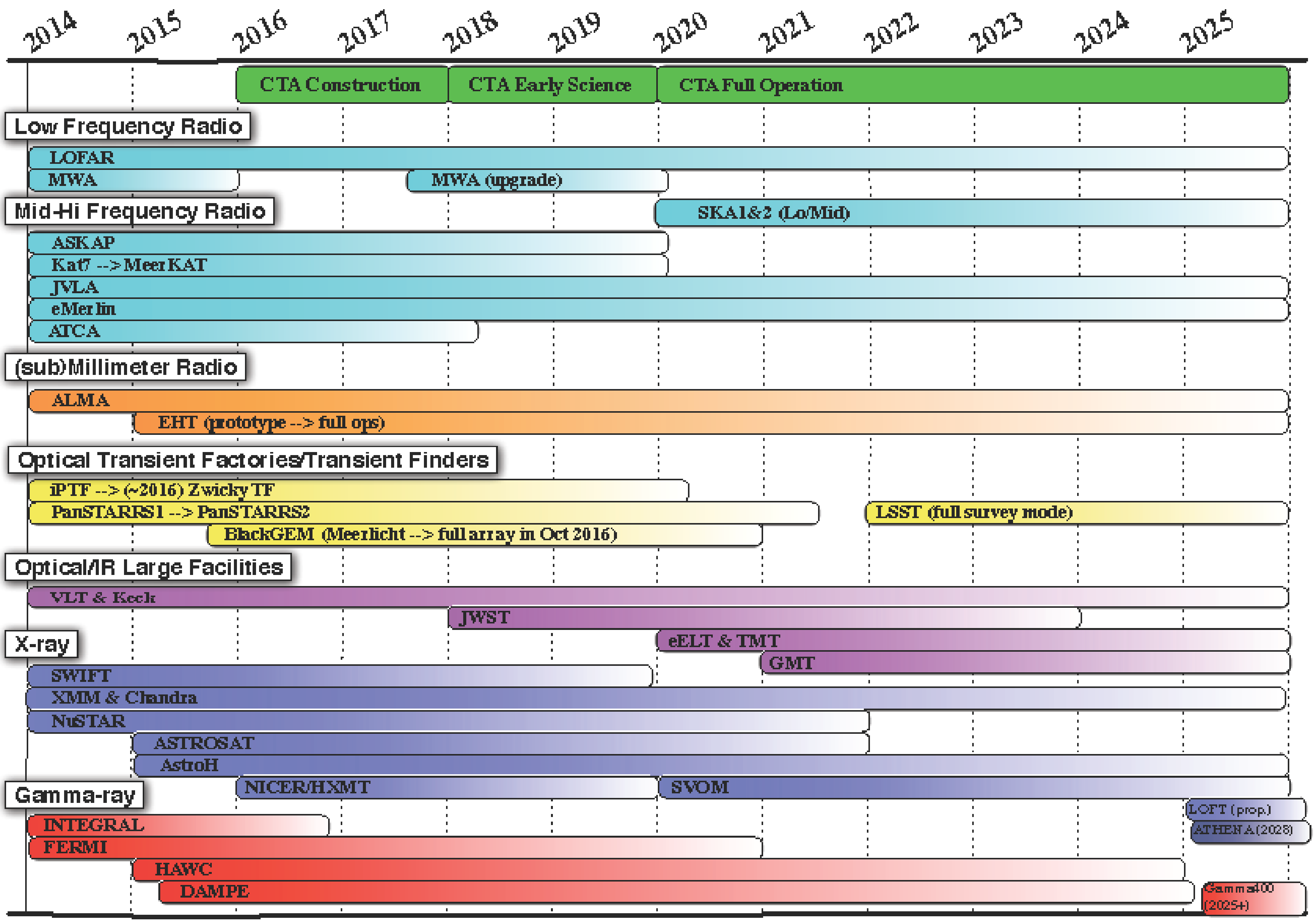
Deep exposure in 10º by 10º region, to edge of Gal. bulge, Covering radio spurs, base of Fermi bubbles, Kepler SNR

Extragalactic Survey

Survey ~1/4 of sky (overlapping with GPS)



Important Synergies



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

HAWC & CTA

HAWC	CTA
Wide FOV	Moderate FOV
100% duty cycle	15% duty cycle
N hemisphere	N & S Hemispheres
Moderate resolution	Excellent resolution

Complementary Capabilities !

We can envision many ways to collaborate effectively

Summary

- **We've learned a lot from previous/present experiments**

  Fruitful science & power of the atmospheric Cherenkov technique
  → new, much more powerful Observatory using IACTs

- **Cherenkov Telescope Array (CTA)**

  Science drivers → Design → Performance → Science Capabilities
  Design of the Arrays, Status of Prototype construction
  CTA Consortium and the Key Science Projects
  Open Observatory
  2015: Update on site and critical design review

- **HAWC: an important VHE instrument → great science**

  In few years, CTA will provide powerful data to complement HAWC
  We look forward to close cooperation between HAWC & CTA

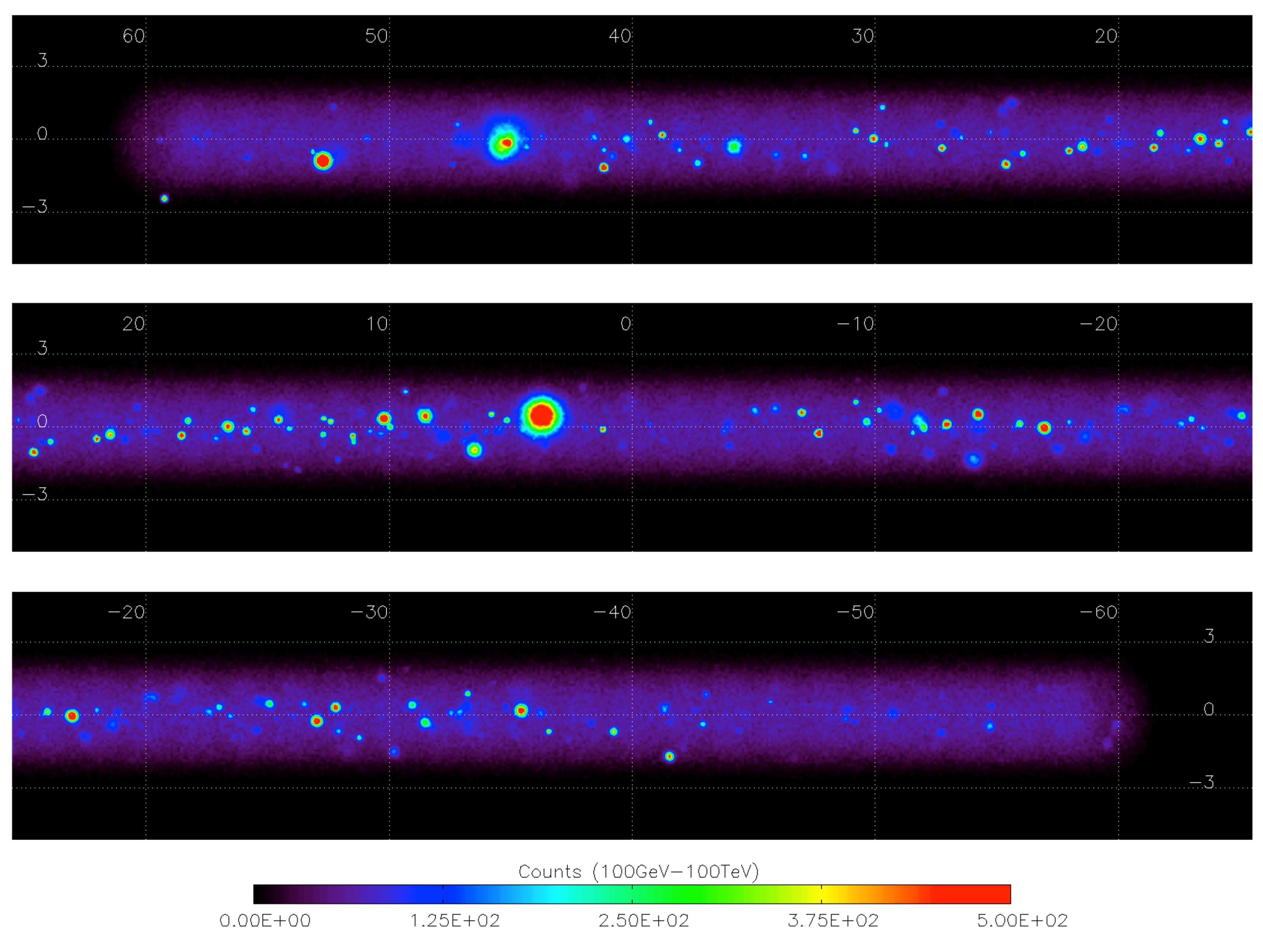
Congratulations HAWC !

On behalf of the CTA Consortium, congratulations to the HAWC collaboration on reaching this important milestone !

BACKUP

CTA South Array

CTA Galactic Plane Survey



Simulation for | l | < 60º

CTA Key Science Projects (KSPs)

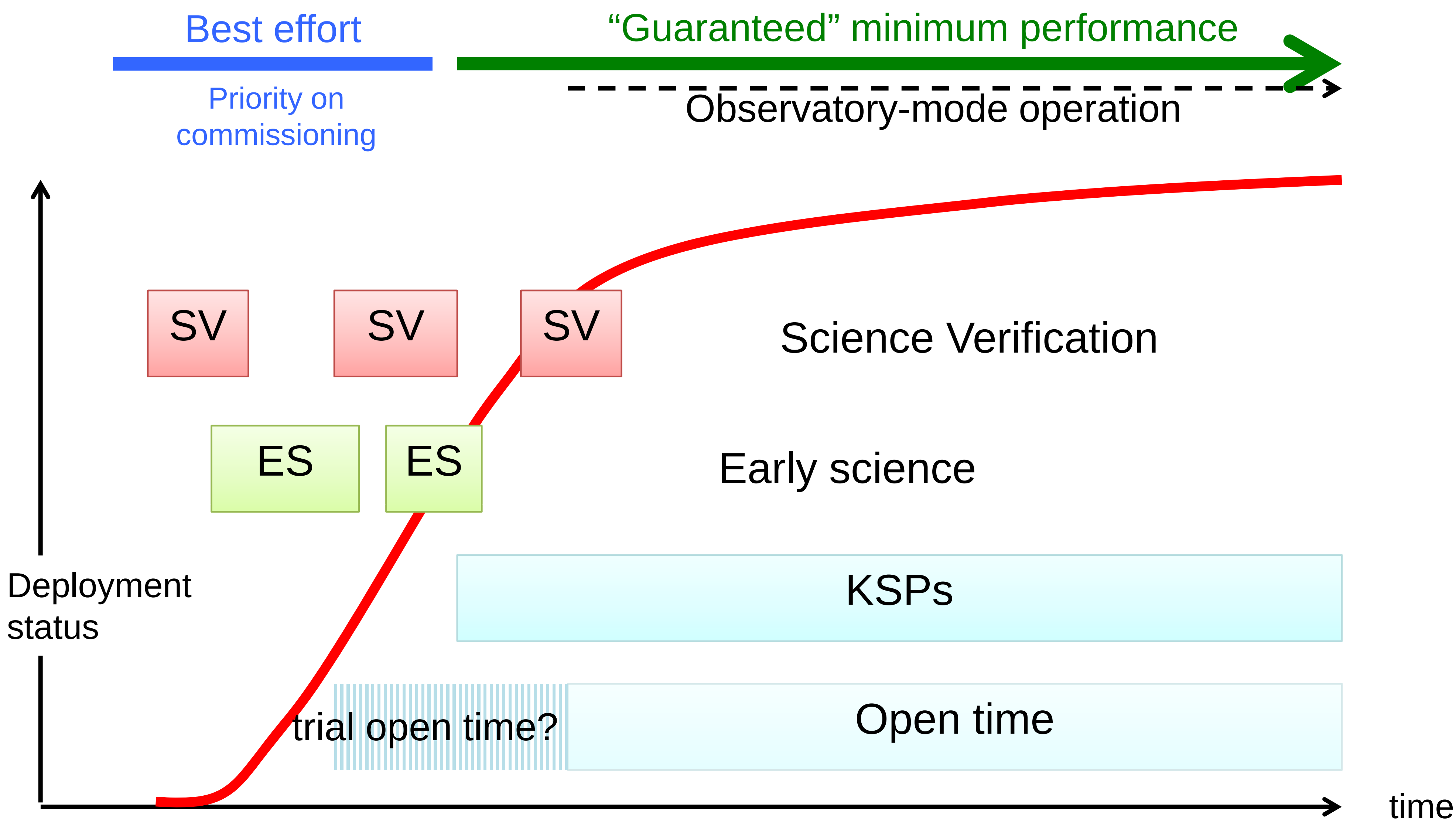
Ten KSPs to be proposed

KSPs

Theme		Question	Dark Matter Programme	Galactic Centre	Galaxy Clusters	LMC Survey	Active Galaxies	Star-forming Systems	Galactic Plane Survey	Extreme Accelerators	Transients	Extragalactic Survey	Cygnus Region
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?					✔✔				✔	✔	

Science Questions

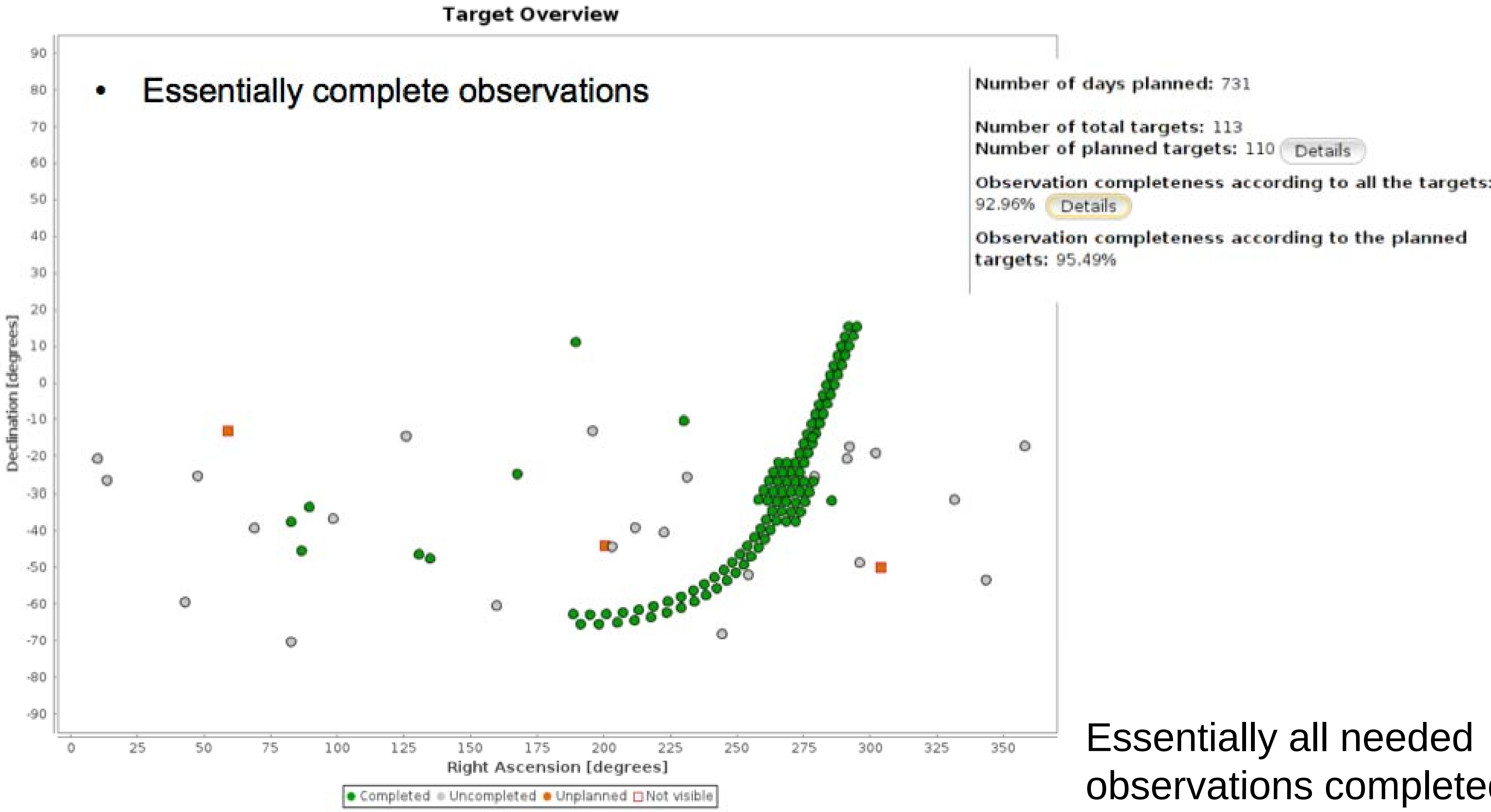
Science Verification, Early Science



This is a notional view !

Observing Schedule (S, Yrs 1-2)

- Essentially complete observations



Essentially all needed observations completed in the two years.

Scientific Motivation

Broad motivations for VHE γ-ray Astronomy:

PHYSICS Motivations

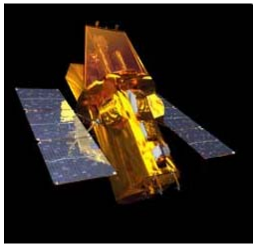
- Origin of Cosmic Rays
  - energy balance of Galaxy
- Physics of compact objects
- Physics Frontiers (e.g. DM)

ASTRONOMICAL Motivations

- New observational window into non-thermal Universe
- High energy particle (e,p) accel.
  - shocks, winds, jets, etc.

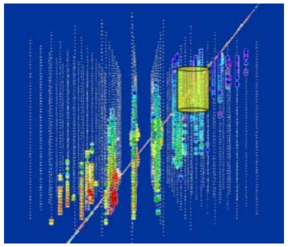
Multiwavelength/Multi-Messenger Observations

Radio



X-rays

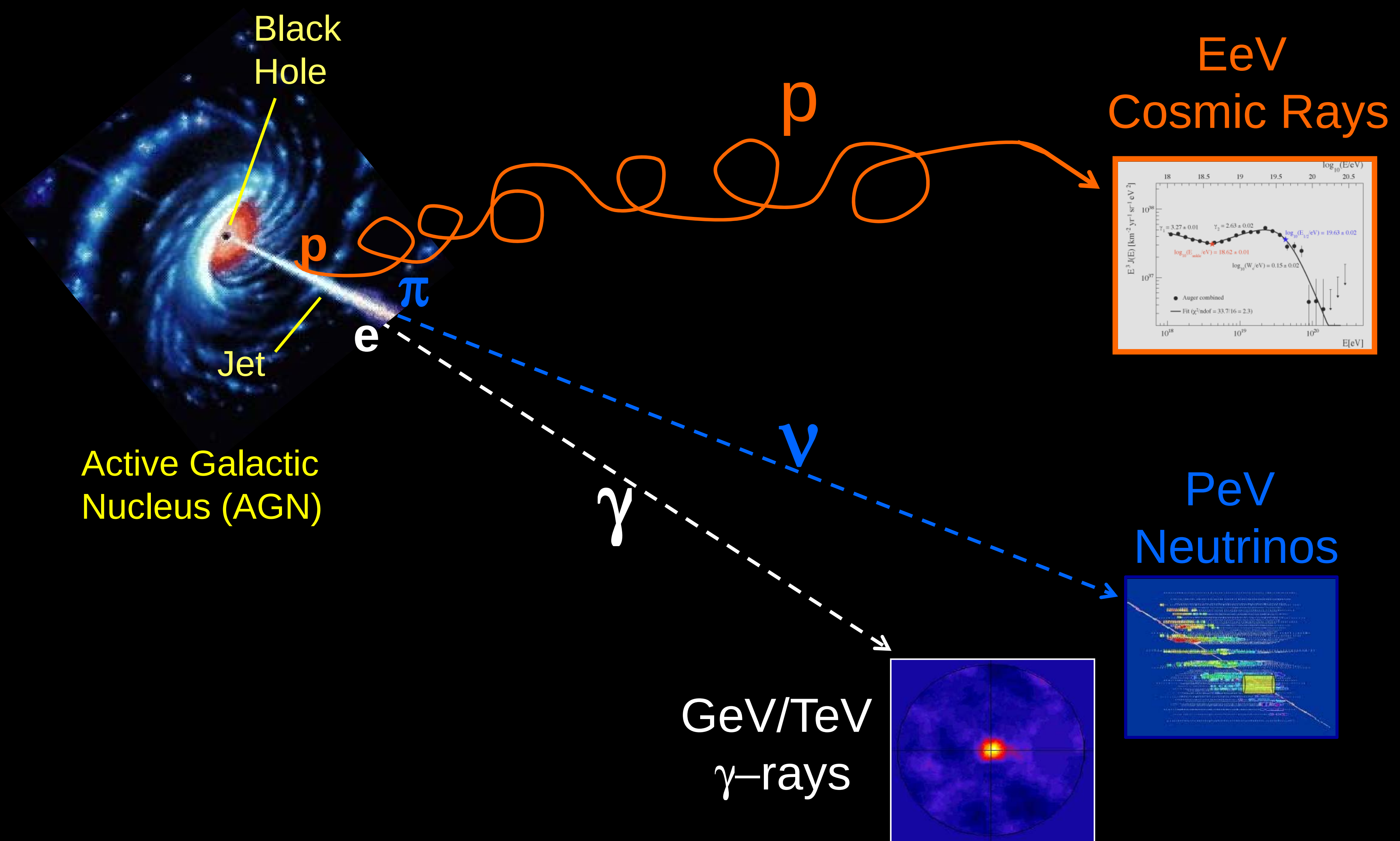
HE γ–rays



VHE neutrinos

Grav. waves

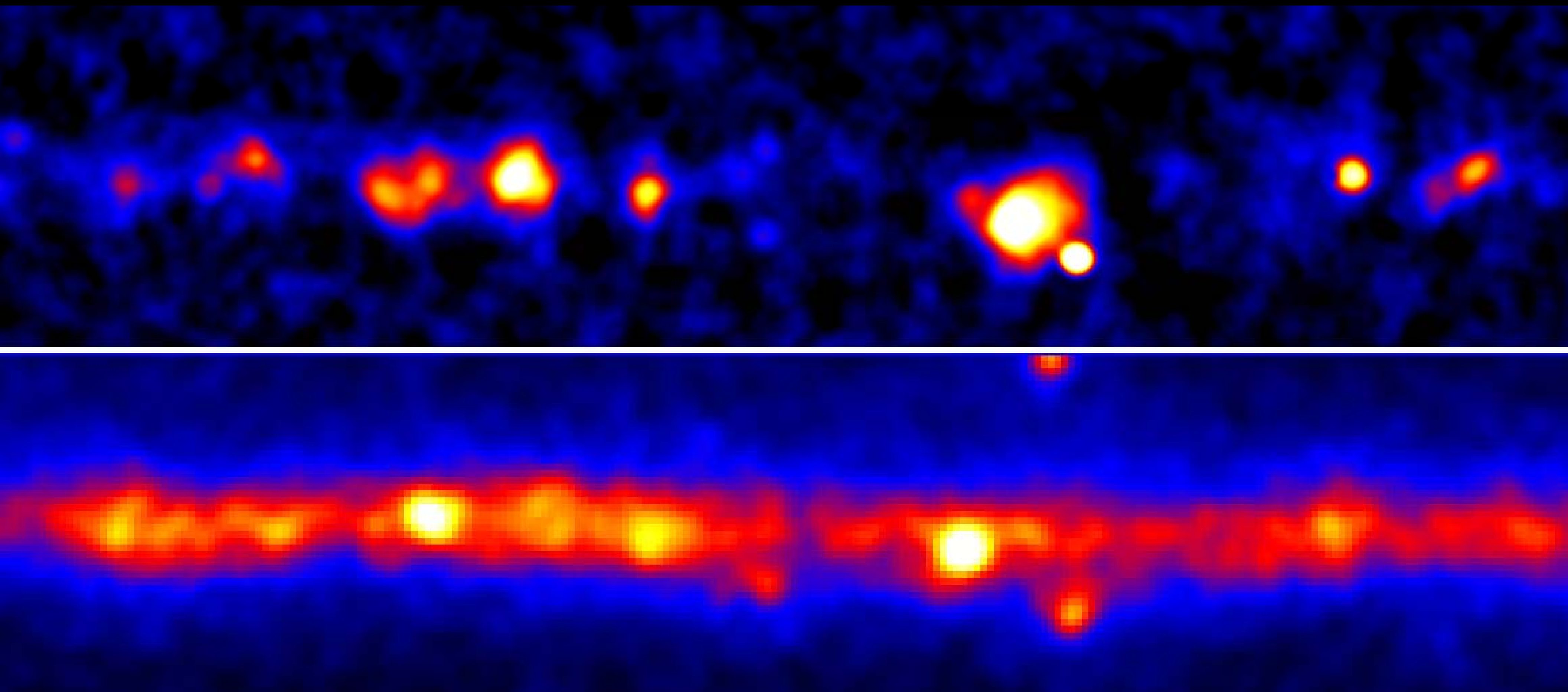
VHE Multi-Messenger Astrophysics



The High Energy Milky Way

Extended sources, size typically few 0.1°
few 10 pc

H.E.S.S. (TeV)



Fermi-LAT (GeV)

Courtesy of W. Hofmann

The Many Faces of TeV Particle Acceleration

Pulsars

NS dynamo

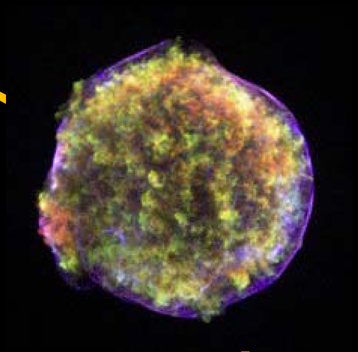
AGN

Jets powered by accretion or unipolar Induction. UHECR's ?

Star Forming Regions

SNRs, cosmic rays, molecular clouds.

Supernova Remnants

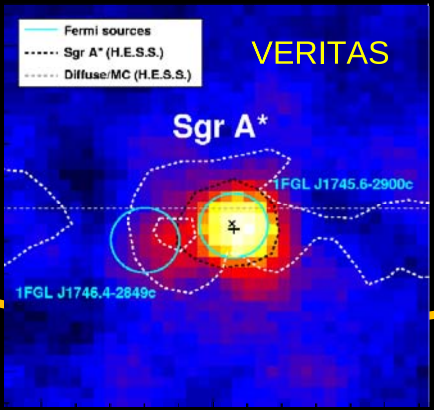


Fermi Acceleration

Gamma-Ray Bursts

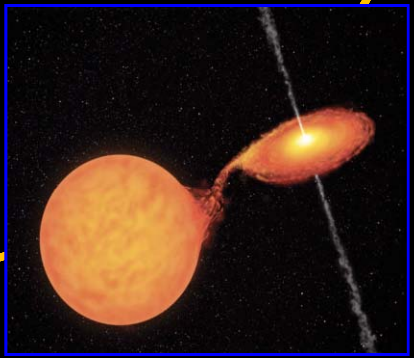
Star collapse→ relativistic jets

Unidentifieds



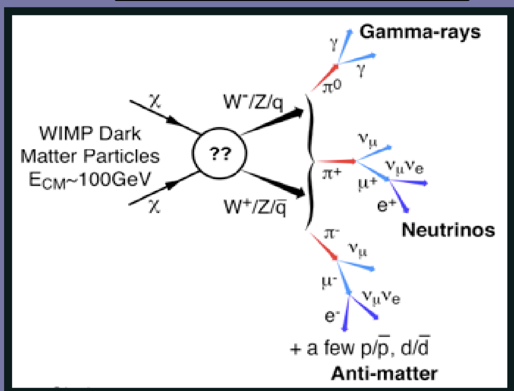
???

Binary Systems



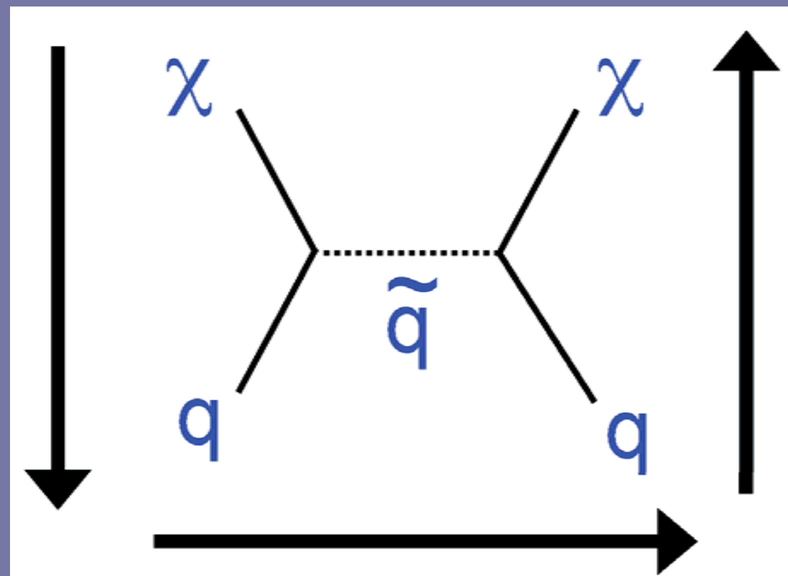
Accretion jets or stellar winds

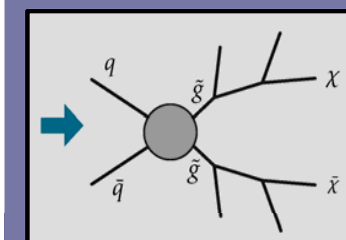
WIMP DM Complementary Approaches

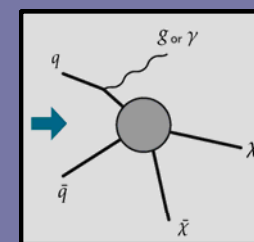


WIMP annihilation
In the cosmos

Indirect Detection

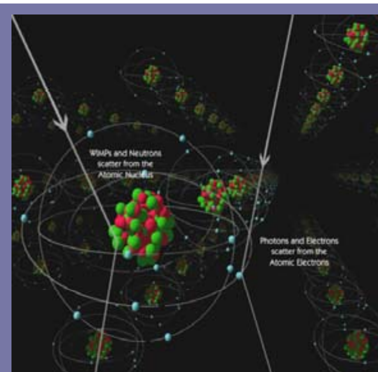






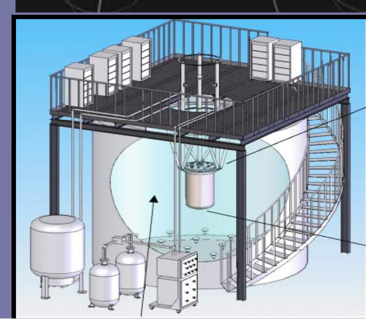
Heavy particle prod.
MET + jets
Weak pair prod.
MET + monojet

LHC Production



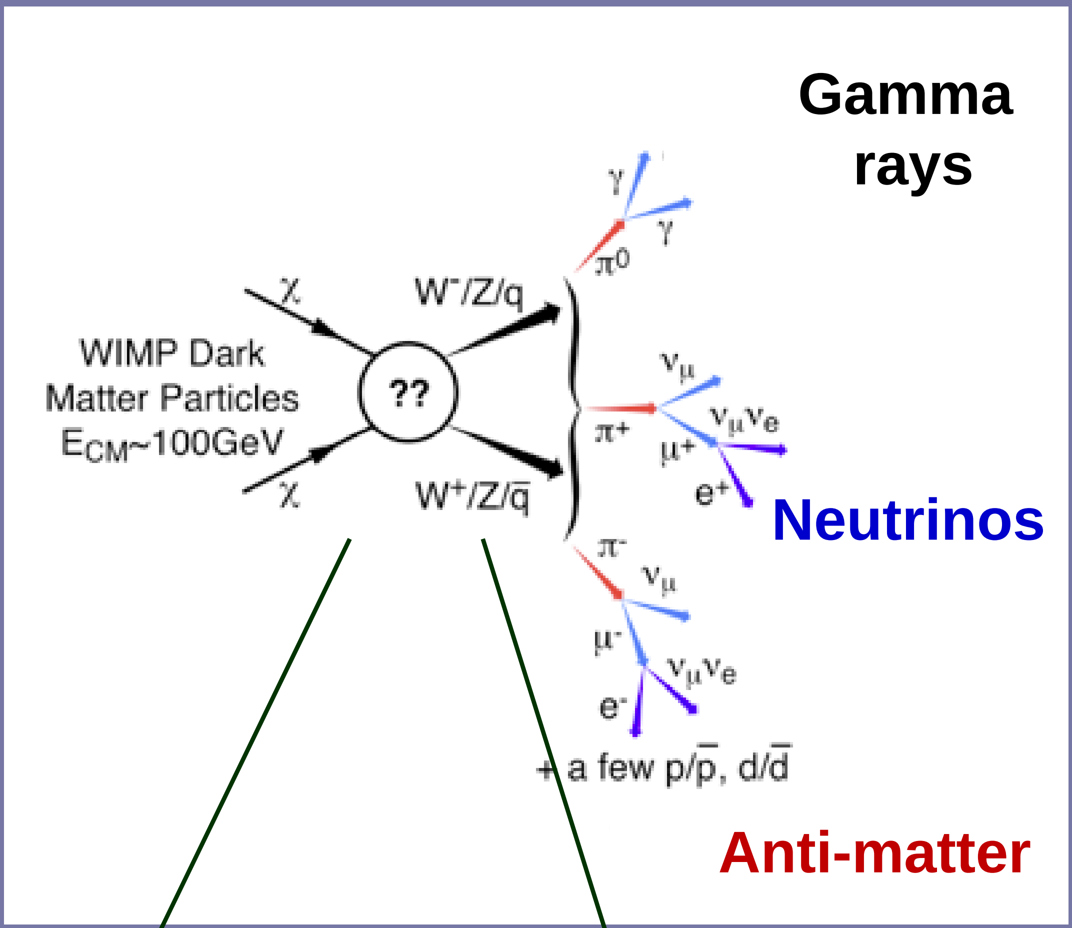
WIMP-Nucleon
Elastic scattering

Direct Detection



WIMP Indirect Detection

WIMP Annihilation



Particle Physics
(Uncertainty from m_χ, decay modes, etc.)

$\gamma\gamma$
$Z\gamma$
γ (cont.)

GeV	Fermi, AGILE (Satellite)
TeV	HESS, MAGIC VERITAS (Atm. Cherenkov)

ν from Sun

GeV-TeV
IceCube, Antares
Super-K
(Ice/Water Cherenkov)

$e^+, \bar{p}, \bar{d}$ in CR

GeV-TeV
PAMELA, Fermi, AMS
(Satellite)

WIMP Indirect Detection: γ-rays

- Gamma rays from DM annihilation:

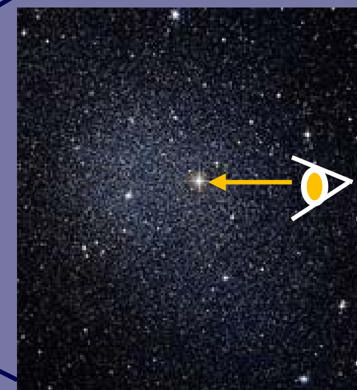
particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

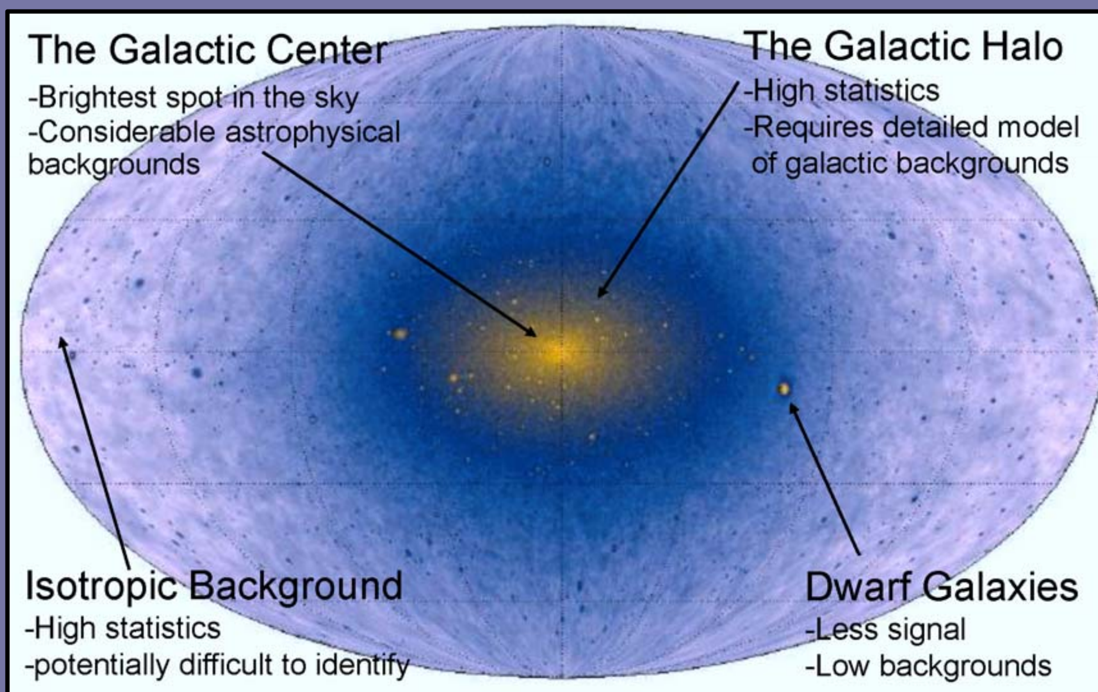
DM distribution

DM distribution

Line-of-sight Integral (Uncertainty from unknown DM profile)



Where to look:



D. Hooper, Aspen 2013

What to look for: