CTA & The Future of High-Energy Gamma-Ray Astronomy

- CTA Concept
- γ-Ray Science & ν Connections
- Status, Plans, & Schedule

Brian Humensky, for the CTA Consortium*
Columbia University
May 14, 2013

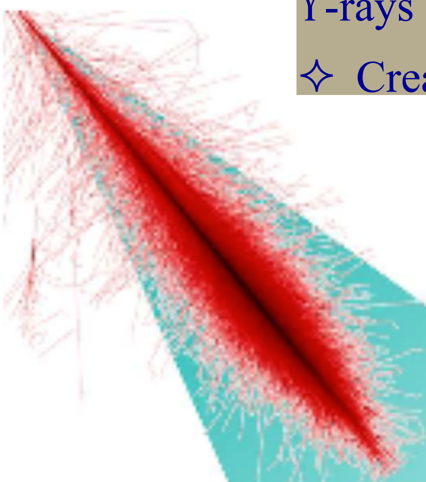
*http://www.cta-observatory.org/

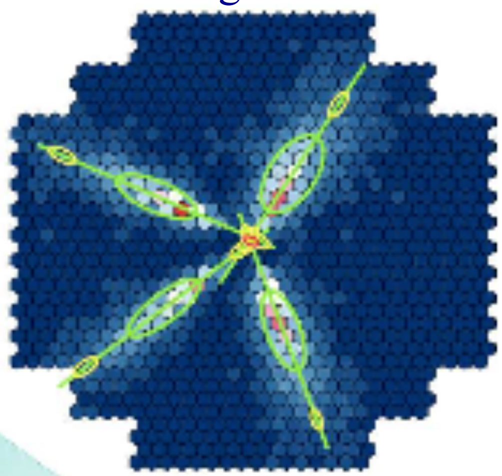
Detecting VHE (E > 30 GeV) ϒ-rays:

Imaging Atmospheric Cherenkov Technique

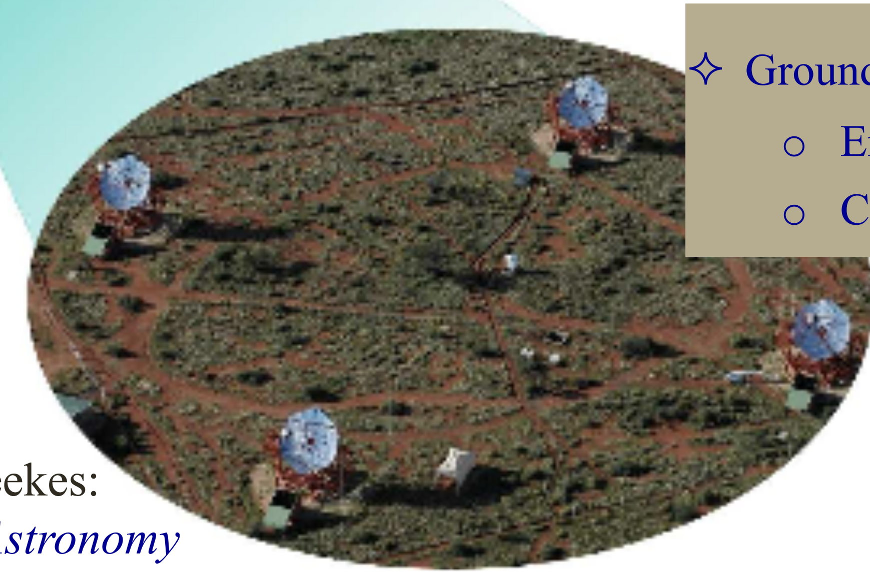
ϒ-rays interact with the atmosphere at a height of 15-30 km above ground

✧ Creates an air shower of cascading interactions over 10 km in length





✧ Image the air shower with multiple telescopes to determine the direction and energy of the ϒ-ray



✧ Ground-based detection

- Energy range ~30 GeV - 100 TeV
- Cherenkov light pool area of ~10^5 m^2

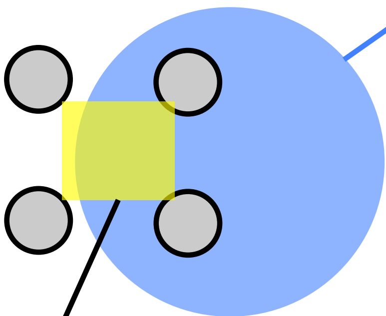
see also Trevor Weekes:
TeV Gamma-Ray Astronomy

Characteristics of current generation of IACTs

- Energy threshold ~ 25 to ~100 GeV.
- Point-source integral flux sensitivity: 0.7 to 1.0 % of the Crab Nebula flux in 50 h (~10^{-12} cm^{-2} s^{-1} above 300 GeV).
- Above 300 GeV, ~100 times more sensitive in 50 hours than Fermi-LAT in 1 year - for a given source.
- Gamma-ray FoV ~ 3º - 5º diameter.
- Angular resolution ~ 0.1º.
- Energy resolution ≈ 15%.

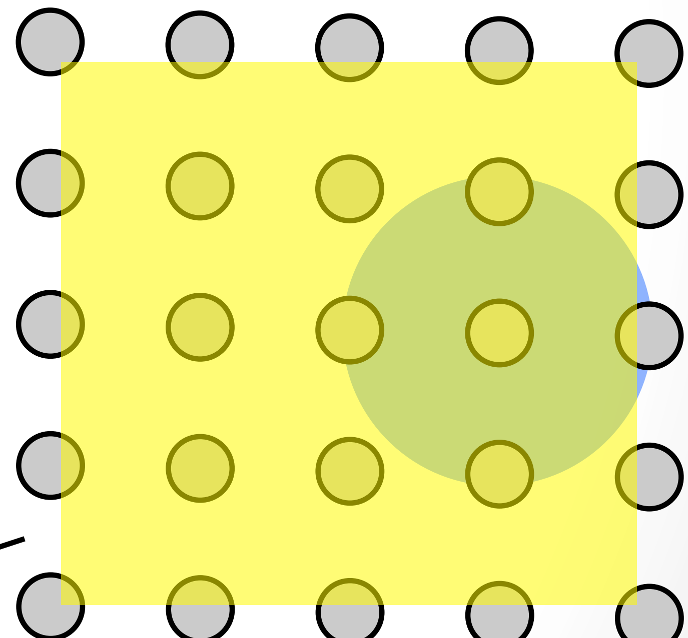
Water Cherenkov: see Jordan Goodman:
Results from Milagro and Status of HAWC

From current arrays to CTA

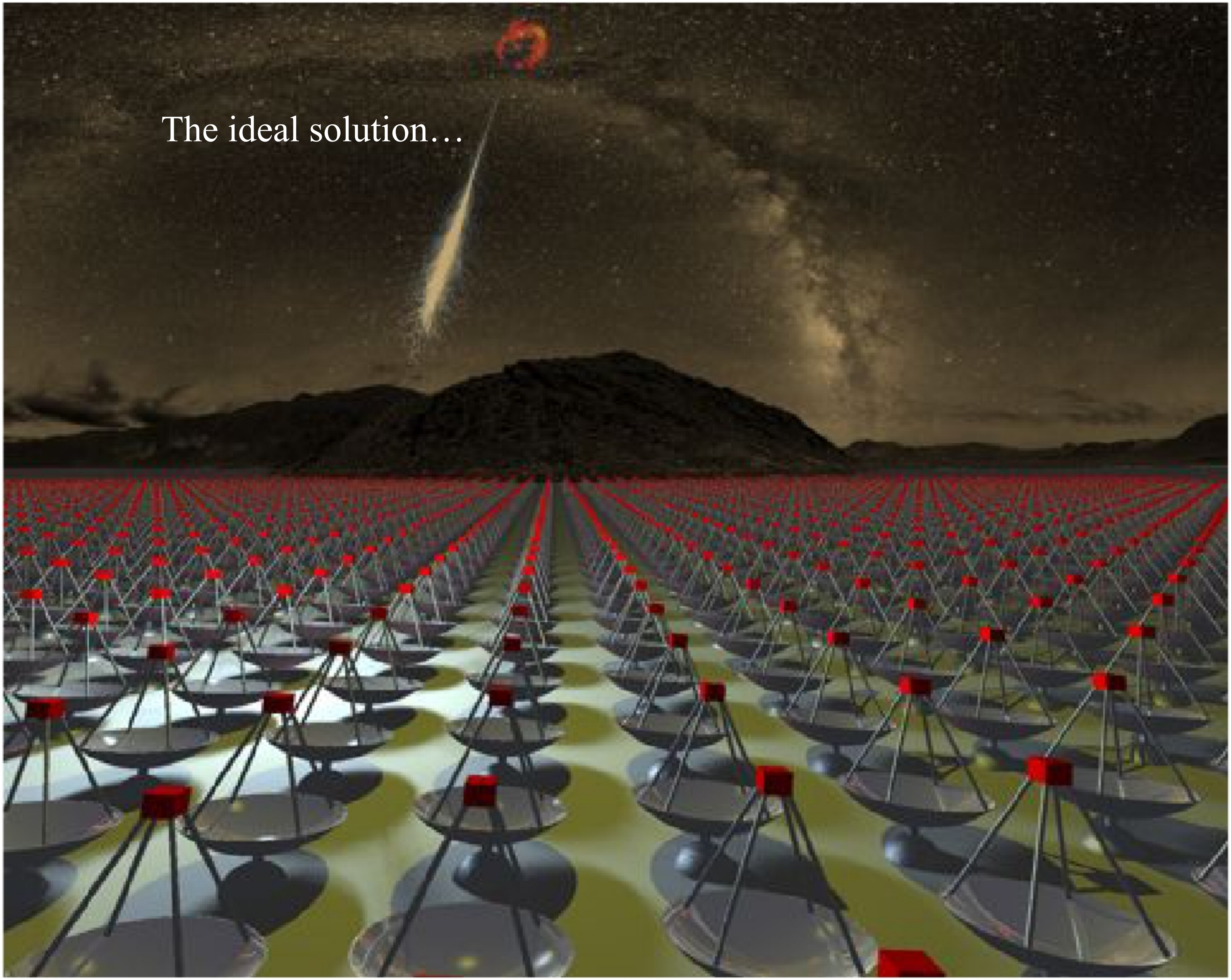


Light pool radius
R ≈100-150 m
≈ typical telescope spacing

Sweet spot for
best triggering
and reconstruction:
Most showers miss it!



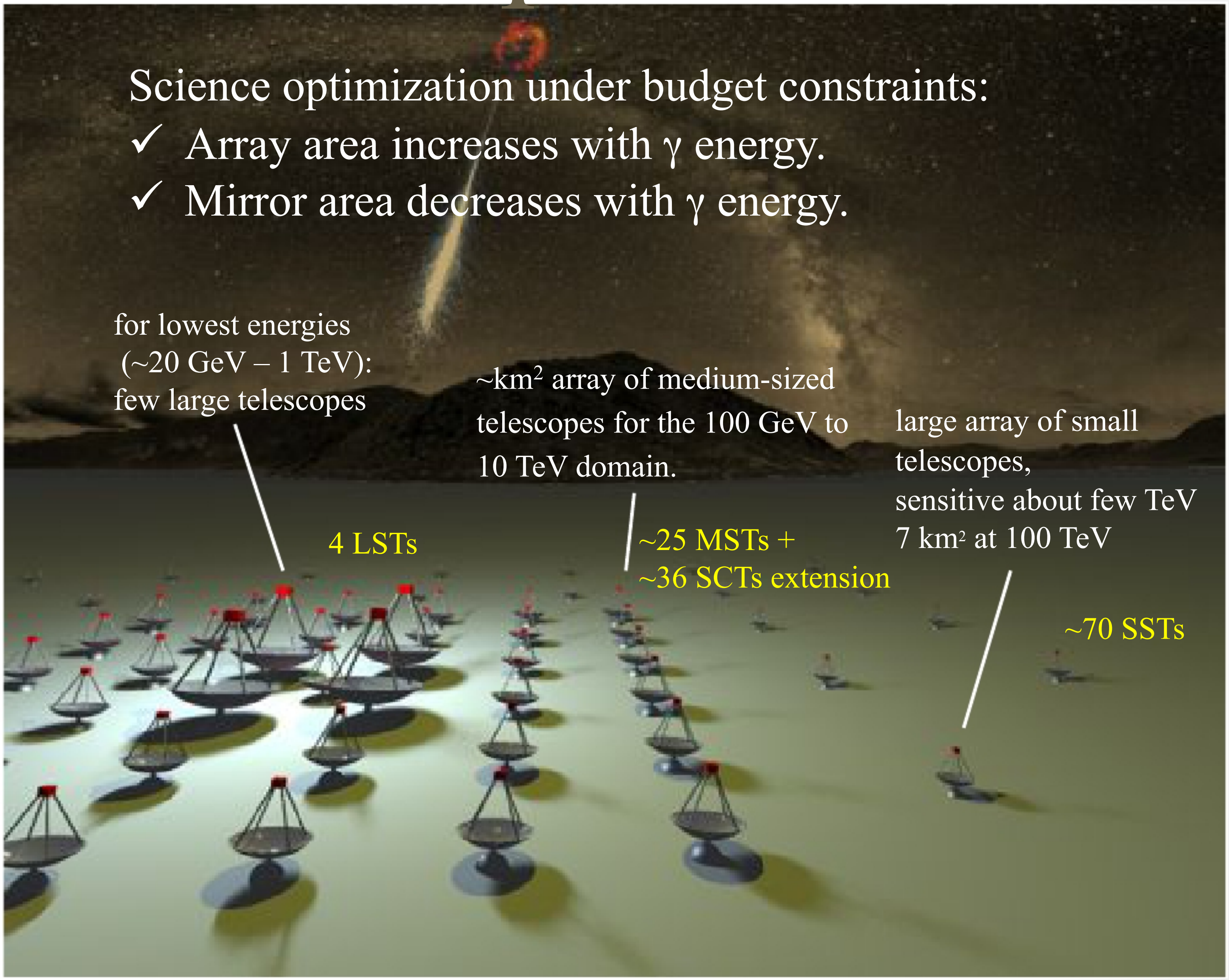
Large detection area
More images per shower
Lower trigger threshold


The ideal solution…

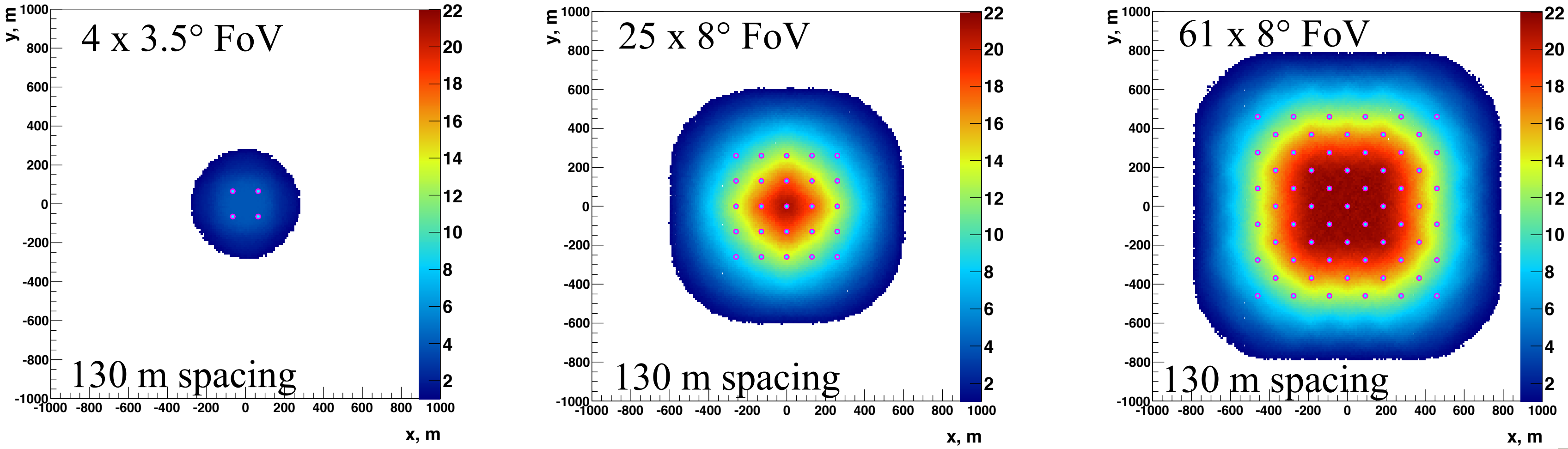
CTA Concept

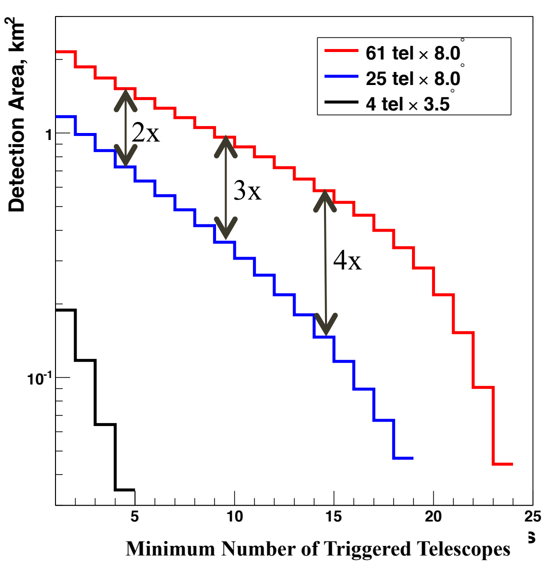
Science optimization under budget constraints:

- ✓ Array area increases with γ energy.
- ✓ Mirror area decreases with γ energy.



Extending the Mid-Size Array



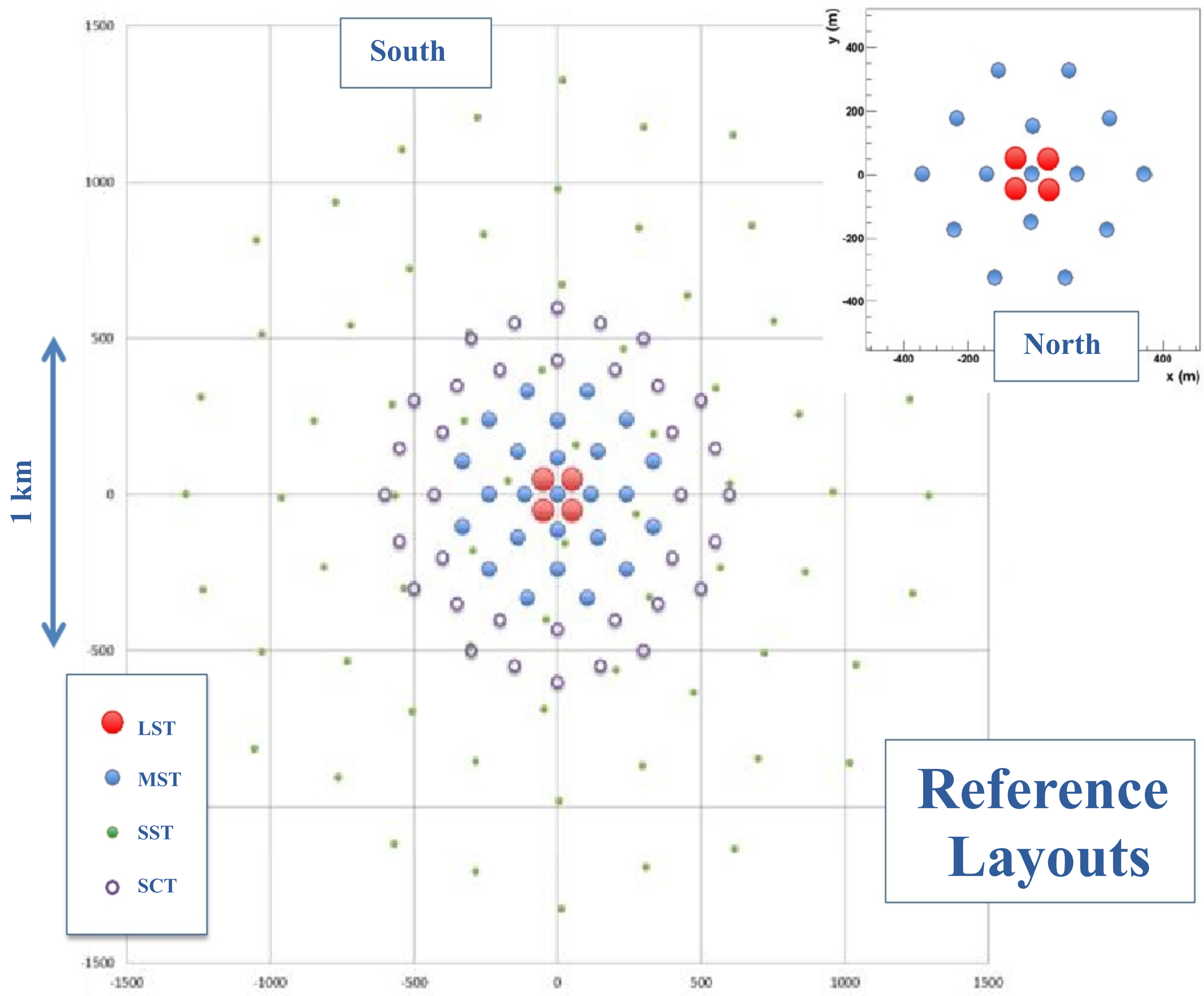


Figures: Slava Bugaev

Color scale: number of triggered telescopes for 500 GeV showers

US focus: maximizing performance in core energy range of IACT technique.

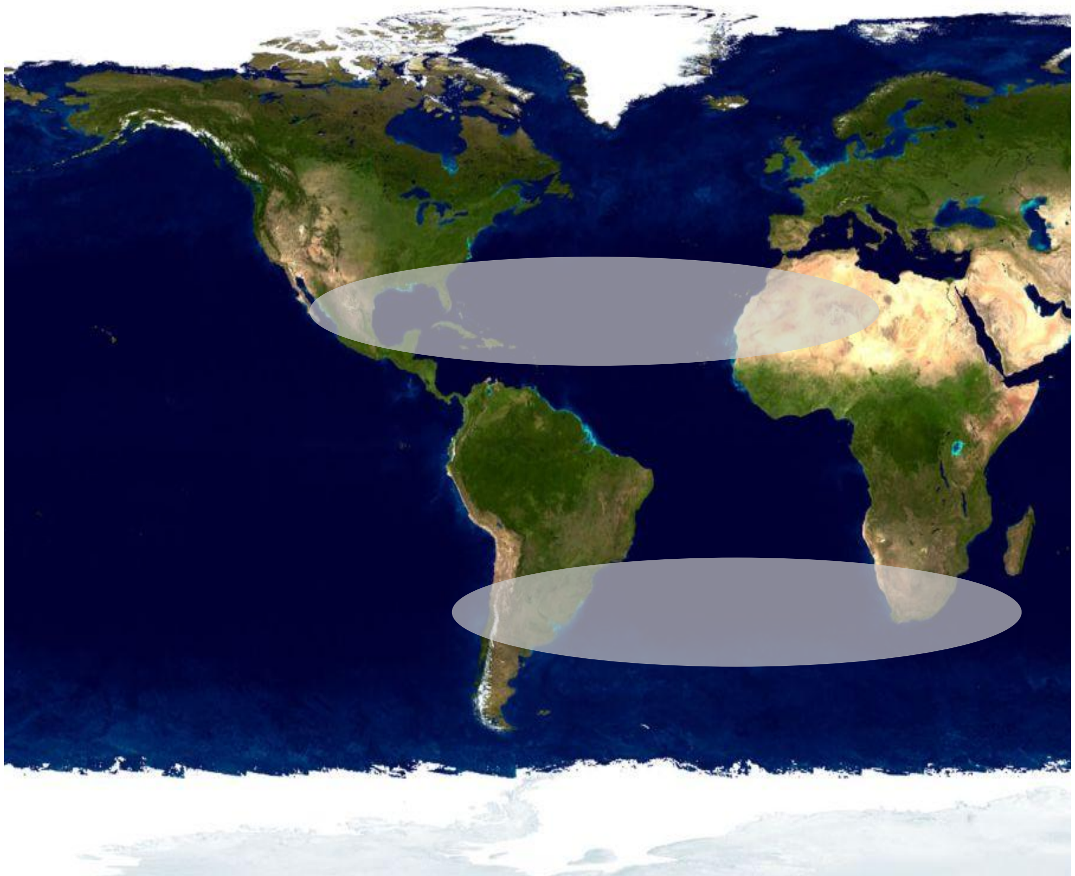
- Want:
  - Effective Area dominated by **contained** showers.
  - Increase **typical event multiplicity** & **image quality** to improve shower characterization.
- Implies:
  - Contribution of 36 additional telescopes.
  - Developing novel **Schwarzschild-Coude** design w/ secondary mirror & excellent angular resolution.



Reference Layouts

CTA: Cherenkov Telescope Array

One observatory with two (asymmetric) sites for all-sky coverage operated by one consortium.



Southern Array

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

Galactic + Extragalactic

Northern Array

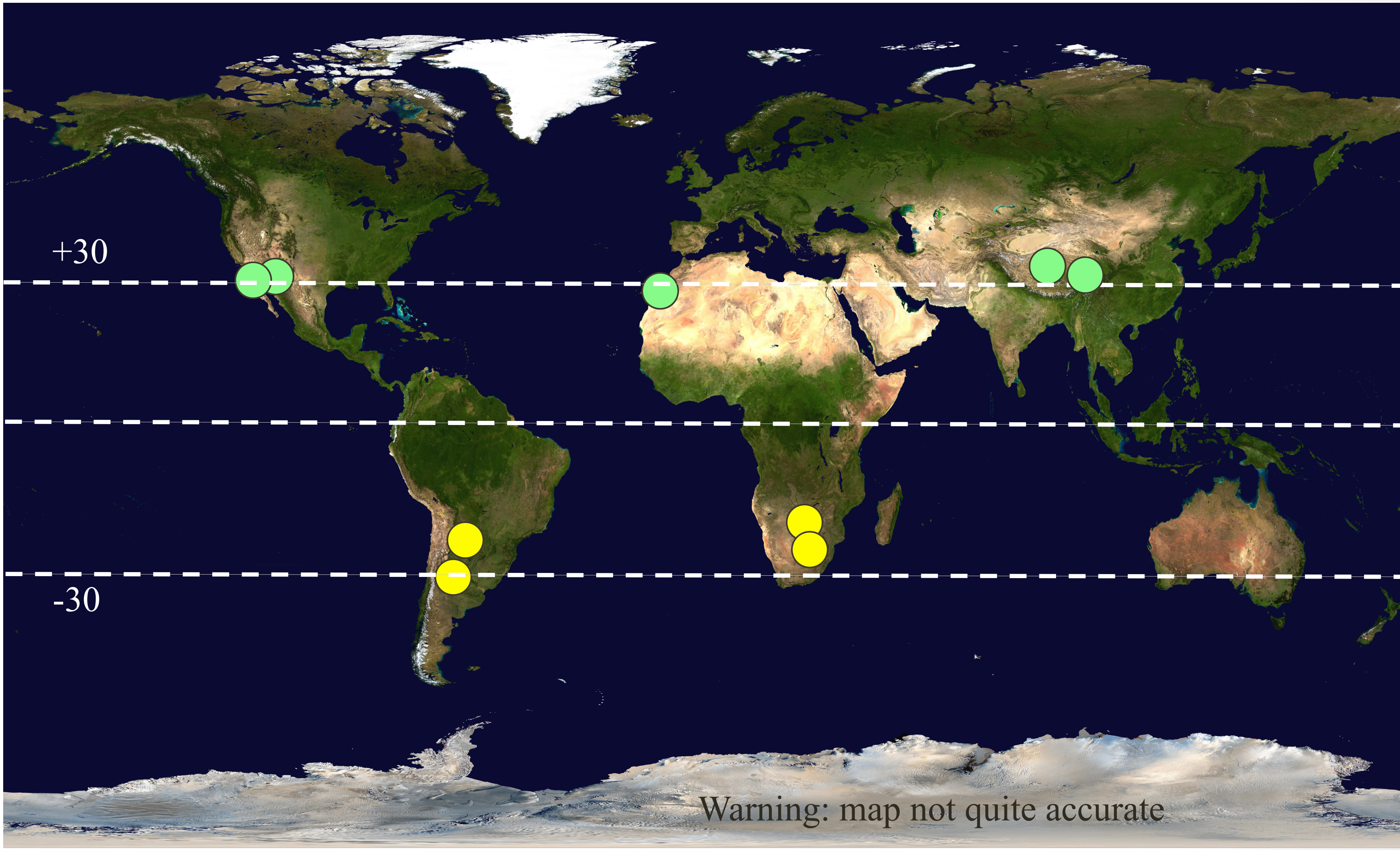
- Complementary to SA for full sky coverage.
- Energy range: some 10 GeV to few TeV.
- Limited field of view.

Mainly Extragalactic

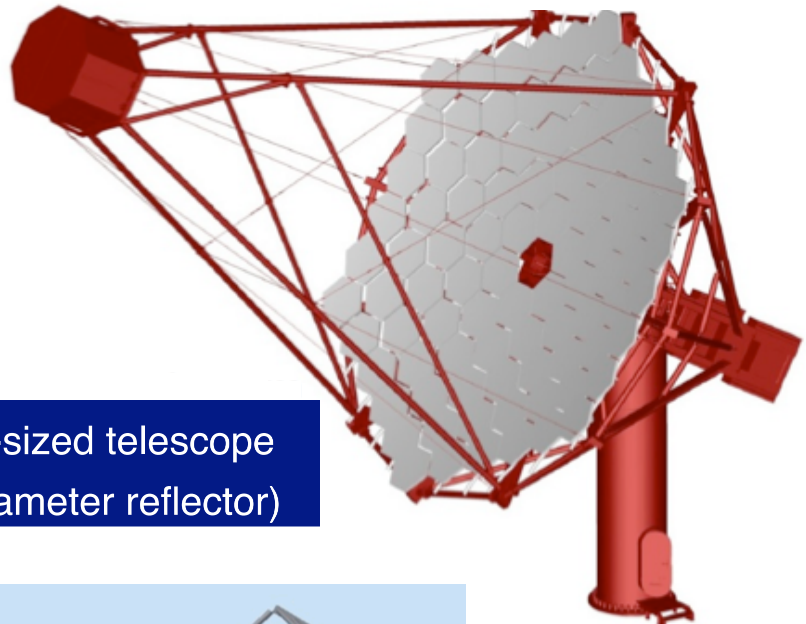
Site candidates

Two sites to cover full sky at 20º – 30º North, South.

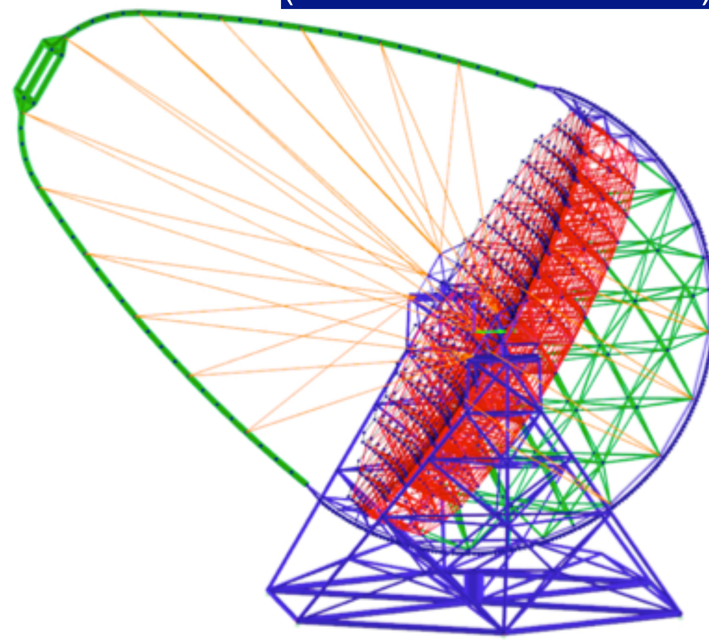
- To be selected in Fall 2013



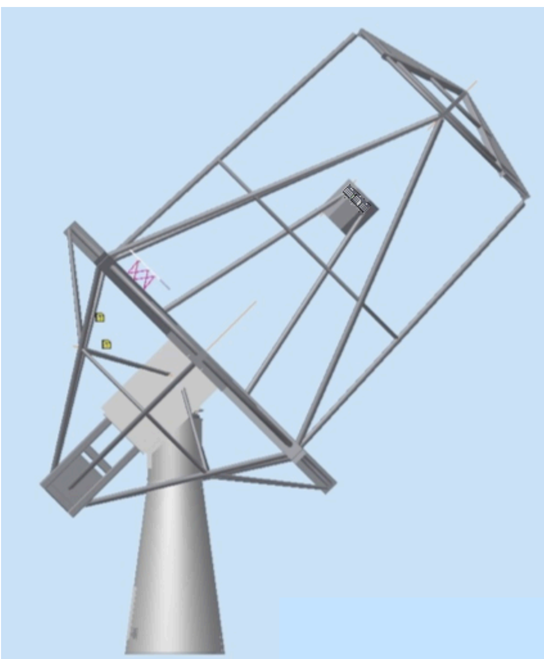
CTA Telescope Designs



medium-sized telescope
(12 m diameter reflector)

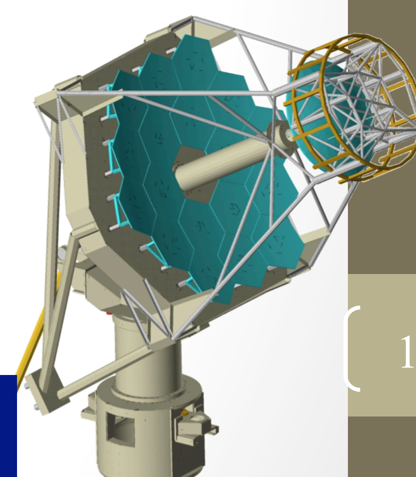


large-sized telescope
(28 m diameter reflector)



medium-sized telescope (SC)
(10 m primary, 5 m secondary)

- new design led by US groups
- provides wide field of view
- MRI funded prototype

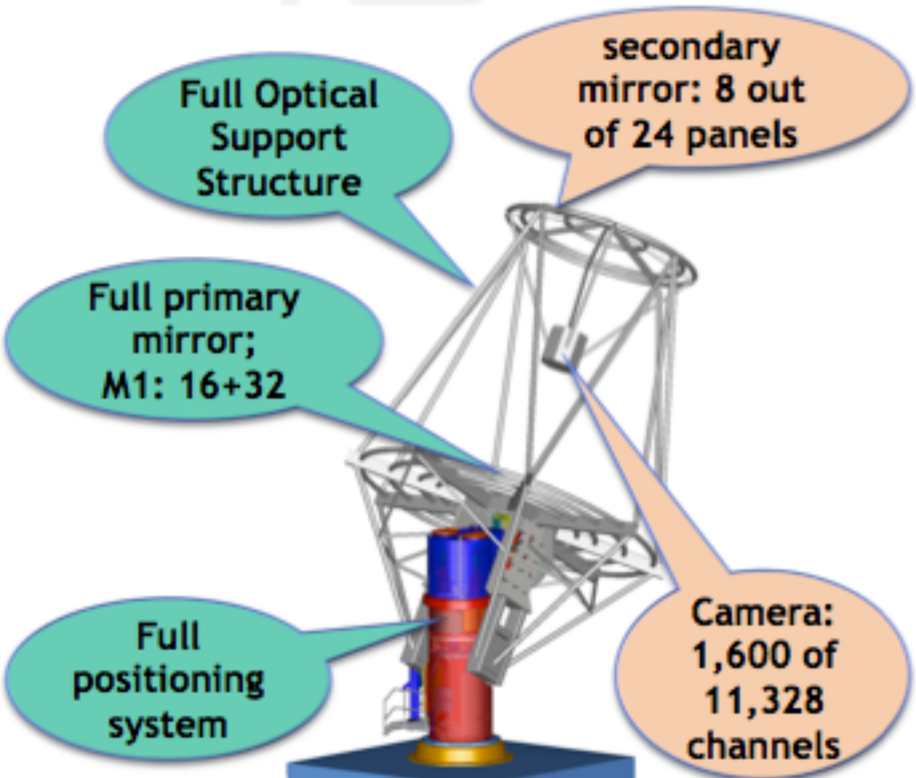


small-sized telescope
(4 m diameter primary)

Schwarzschild-Couder Telescopes

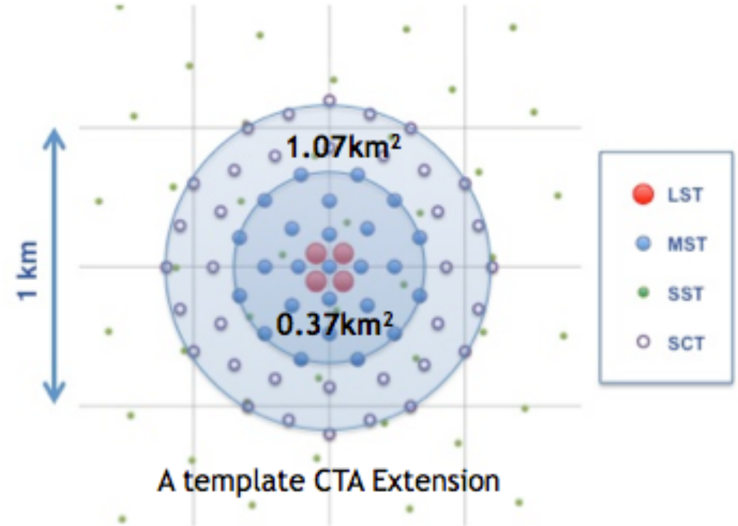
by design provides large field of view (8-9°)
and compact camera (SiPM detectors)
(0.07° x >11,000 pixels and high QE)

primary mirror: 9.7 m diameter
secondary mirror: 5.4 m diameter



SC prototype with reduced secondary mirror
and camera -> begin construction in 2014

propose: 36 SC telescopes at
Southern CTA site



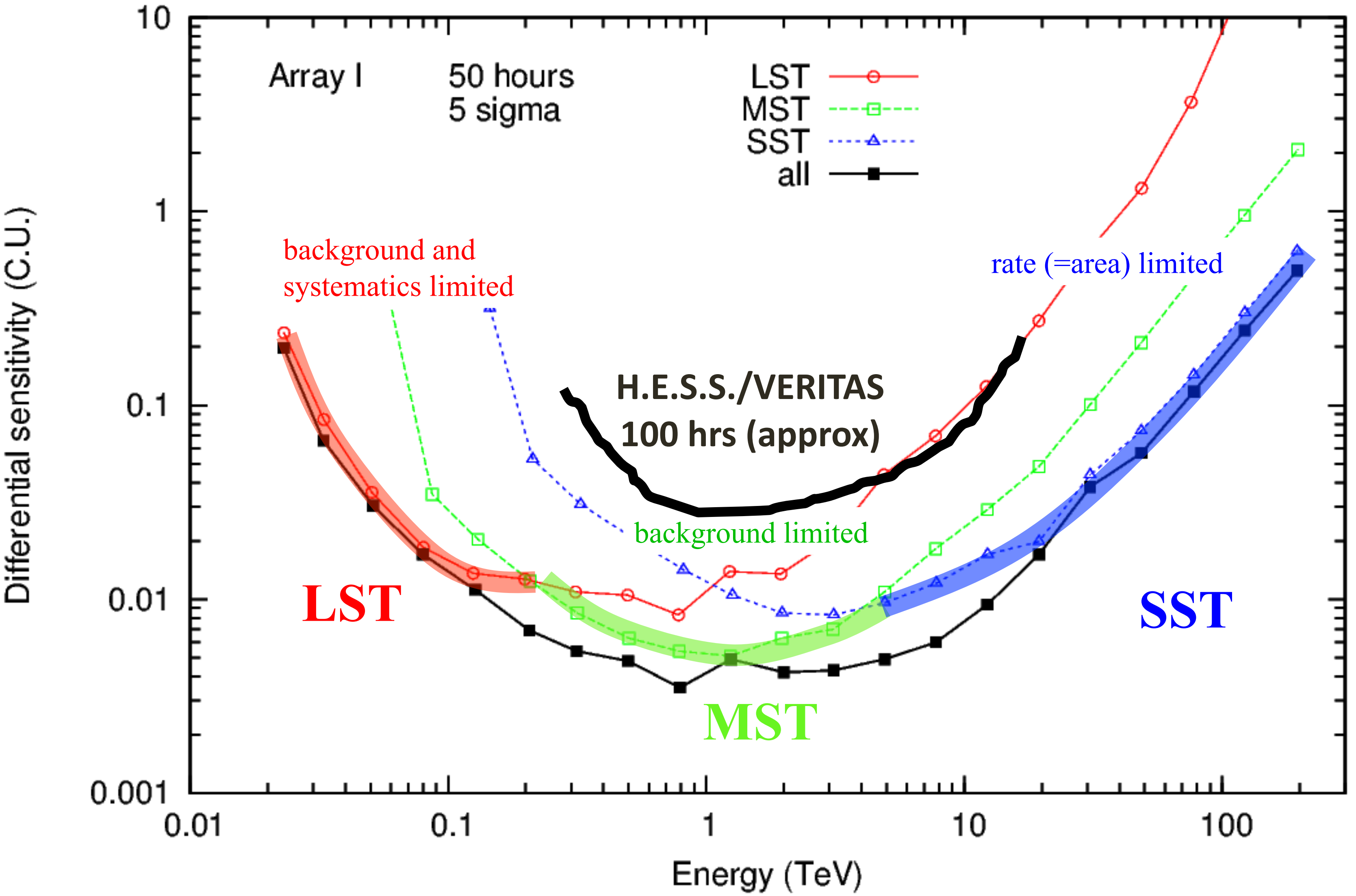
location of prototype SC telescope:
VERITAS site at Mt Hopkins, AZ

Telescope Parameters

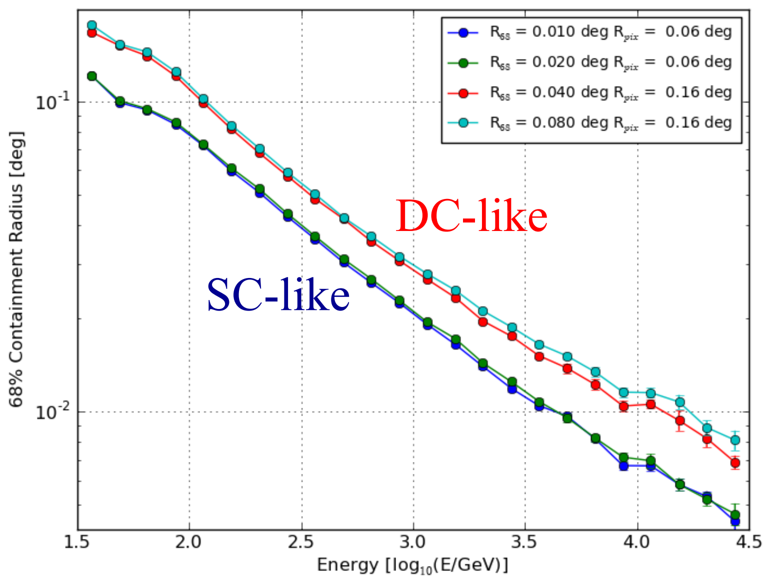
	SST "small"	MST "medium"	LST "large"	SCT "medium 2-M"
Number	70 (S)	25 (S) 15 (N)	4 (S) 4 (N)	36 (S)
Spec'd range	> few TeV	200 GeV to 10 TeV	20 GeV to 1 TeV	200 GeV to 10 TeV
Eff. mirror area	> 5 m^2	> 88 m^2	> 330 m^2	> 40 m^2
Field of view	> 8°	> 7°	> 4.4°	> 7°
Pixel size ~PSF θ_{80}	< 0.25°	< 0.18°	< 0.11°	< 0.075°
Positioning time	90 s, 60 s goal	90 s, 60 s goal	50 s, 20 s goal	90 s, 60 s goal
Availability	> 97% @ 3 h/week	>97% @ 6 h/week	>95% @ 9 h/week	>97% @ 6 h/week
Target capital cost	420 k€	1.6 M€	7.4 M€	2.0 M€

Differential Sensitivity (in units of Crab flux)

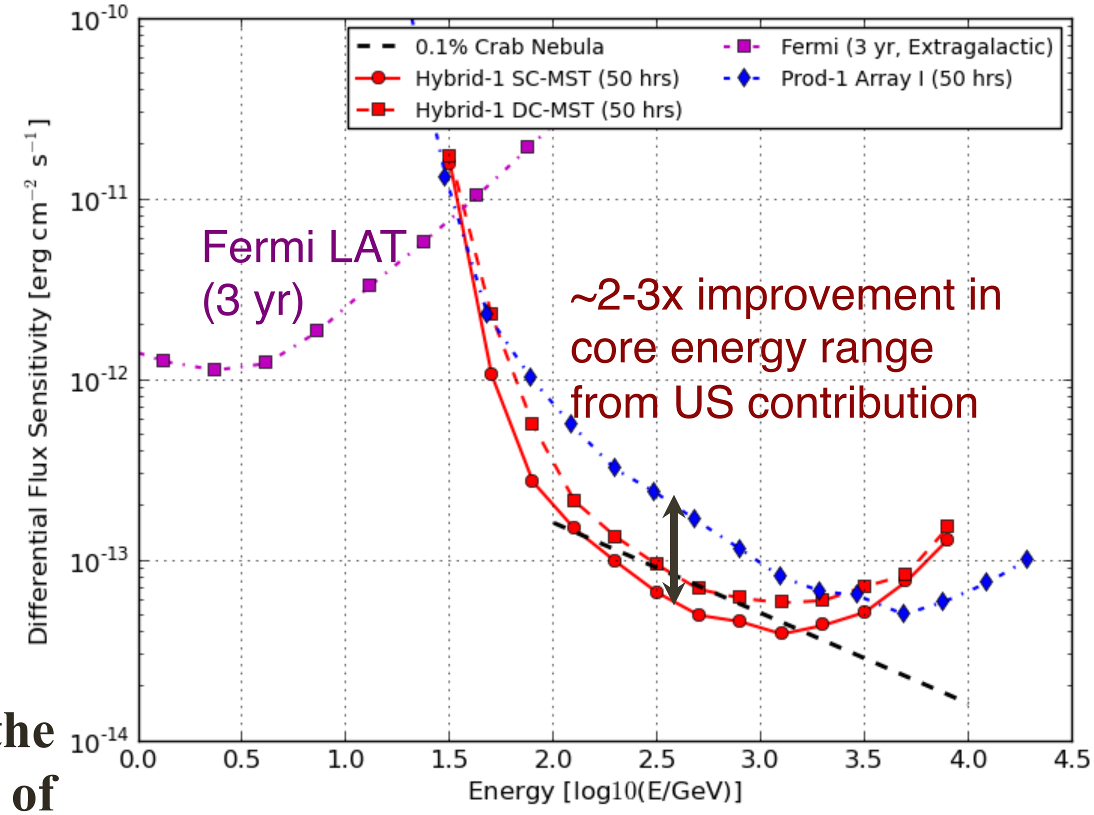
for detection in each 0.2-decade energy band



Sensitivity of CTA



68% Containment Radius of the gamma-ray PSF as a function of energy for SC- (green and blue lines) and DC-like (red and cyan lines) telescopes.



30-40% improvement in TeV PSF for SC telescopes & double contained effective area → 2-3 x improvement in core energy range.

T. Jogler et al. 2012, proceedings of Gamma2012, Heidelberg (arXiv: 1211.3181)

γ-Ray Science & ν Connections

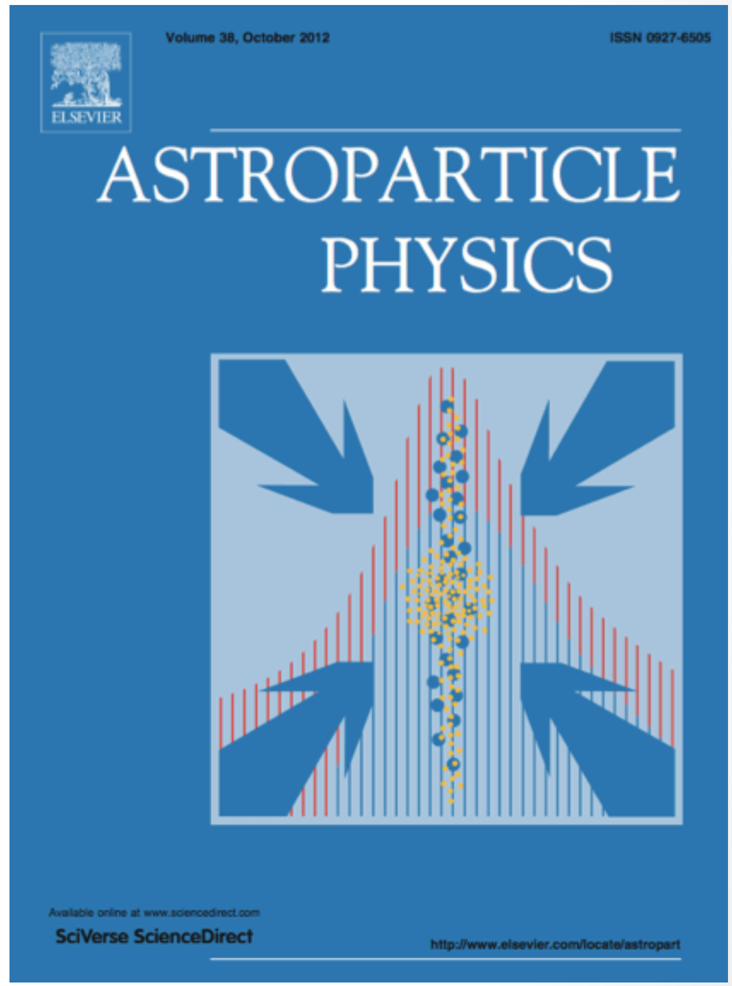
Seeing the High-Energy Universe with the Cherenkov Telescope Array – The Science Explored with the CTA

Special Issue:

ASTROPARTICLE PHYSICS Volume 43 (2013) 1-350

The CTA Consortium + O(20) scientists canvasing relevant fields

Overview articles + Case studies



Key Science Issues

- ✧ Where and how are particles accelerated in our Galaxy and beyond?
- ✧ What makes black holes of all sizes such efficient particle accelerators?
- ✧ The flaring sky: short-timescale phenomena at very high energies?

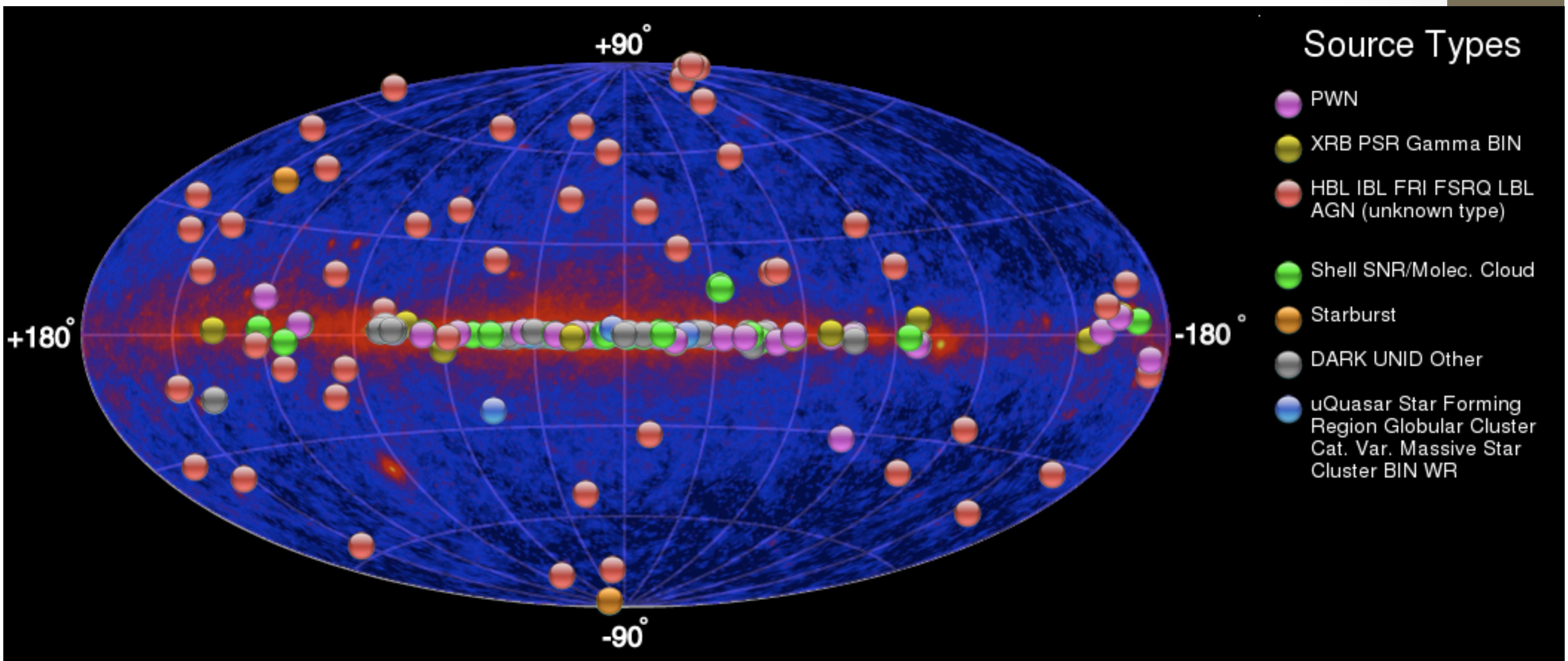
- ✧ What do high-energy gamma-rays tell us about the star formation history of the Universe and the fundamental laws of physics?
- ✧ What is the nature of dark matter?
- ✧ What surprises will we see?

Main Characteristics of CTA

- High sensitivity.
  - >4 orders of magnitude dynamic range in flux between strongest and faintest sources.
- Wide spectral range.
  - >4 orders of magnitude coverage in energy, up to 100s of TeV.
  - 10-15% energy resolution.
- Resolved source morphology.
  - Angular resolution as good as 0.02°.
  - Source localization to 10 – 20”.
- Well-resolved light curves.
  - Minute-scale variability of AGN.
- Large field of view.
  - Serendipitous discoveries.
- Surveying capabilities.
  - Full-sky survey at O(1%) Crab in about 1 year.
- Monitoring capabilities.
  - Use sub-arrays for AGN monitoring.

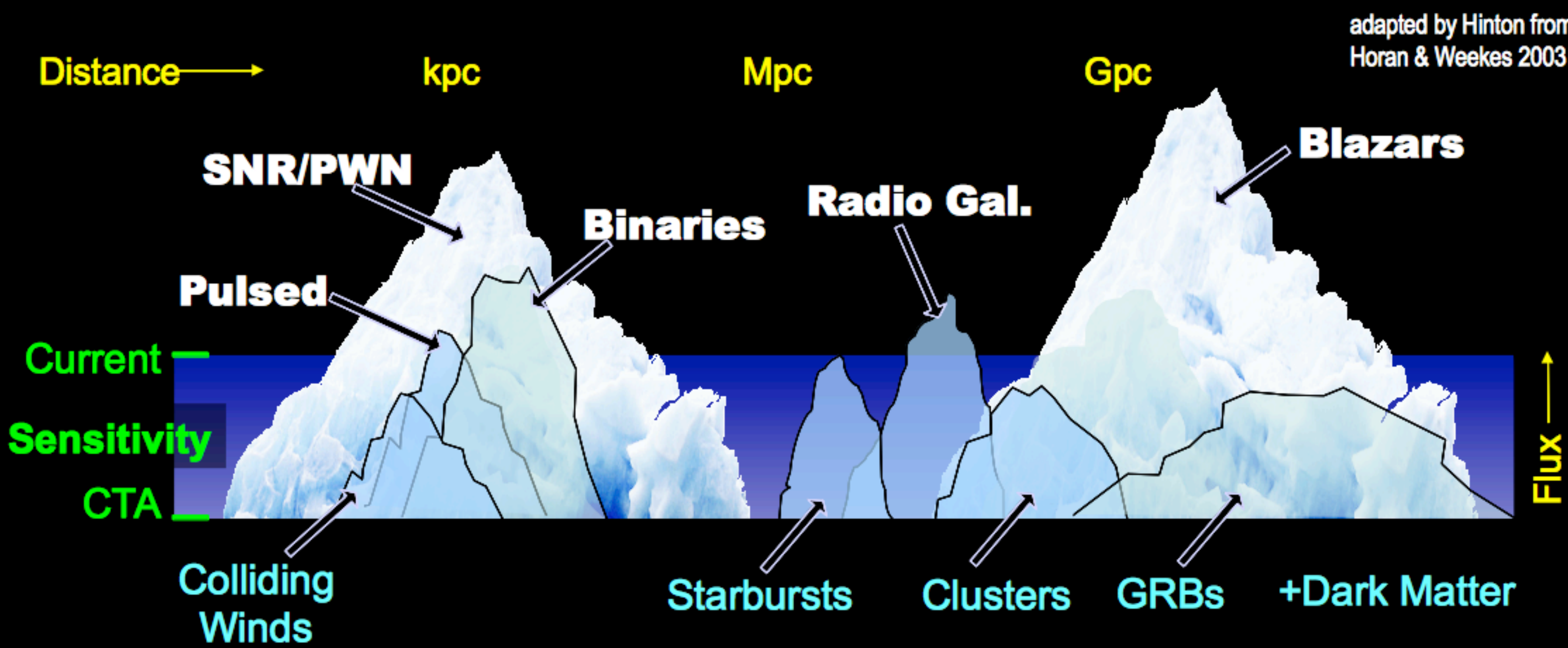
The VHE Gamma-ray Sky

© TeVcat (20/Sept/2012)



~150 Sources

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 ?**

Science with γ's and ν's

Gamma Rays and Neutrinos are both neutral messengers from the sites of cosmic-ray acceleration.

- Presence of VHE neutrino emission is an unambiguous signature of hadronic particle acceleration.

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p \quad \text{and } p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n.$$

$$\pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow \nu_\mu + (e^+ + \nu_e + \bar{\nu}_\mu)$$

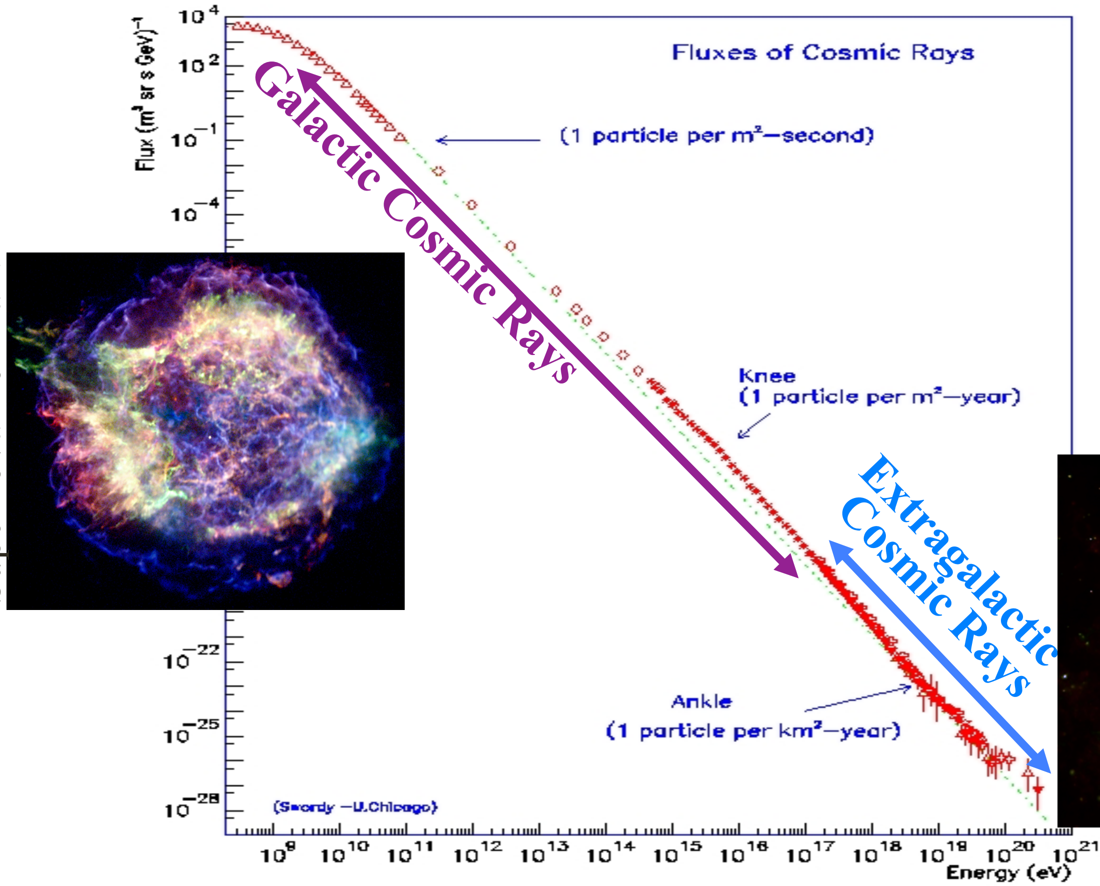
  - Breaks degeneracy between models of electromagnetic emission!

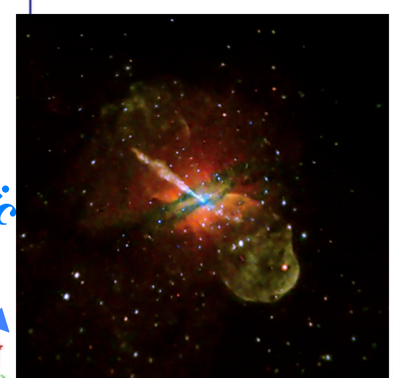
- IceCube is uniquely sensitive to the presence of very high energy charged particles in environments where the opacity for charged particles and gamma rays is high!

Understanding Nature's Particle Accelerators

- ✧ Growing indirect, direct evidence for acceleration of hadronic CRs in SNRs, but
  - ✧ Maximum energy?
  - ✧ SNR population responsible for bulk of Galactic CRs?
  - ✧ Injection, acceleration, confinement/escape, diffusion into ISM…
- ✧ Extragalactic CRs:
  - ✧ Acceleration sites – GRBs? AGNe?
  - ✧ Composition?
- ✧ Fermi, CTA, HAWC, IceCube will provide complementary information on all these questions.

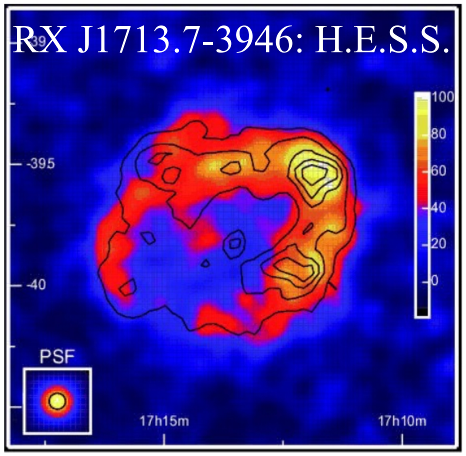
Cassiopeia A Supernova Remnant





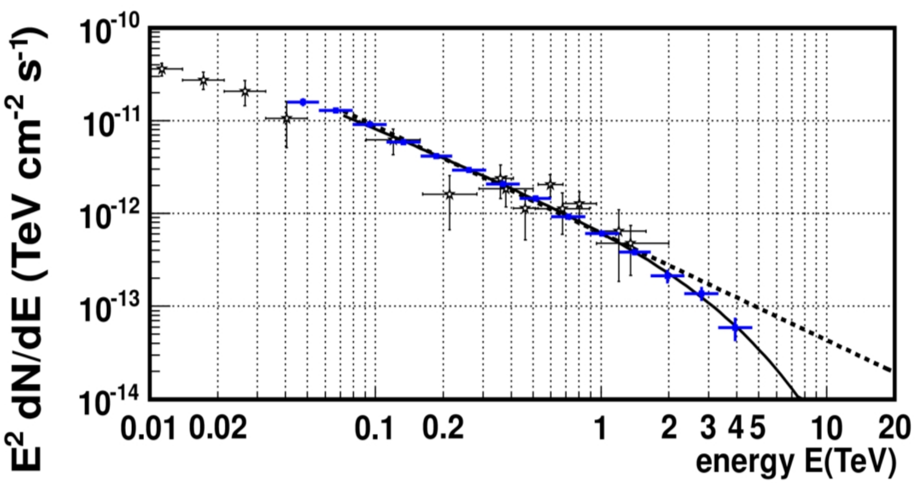
Centaurus A Radio Galaxy

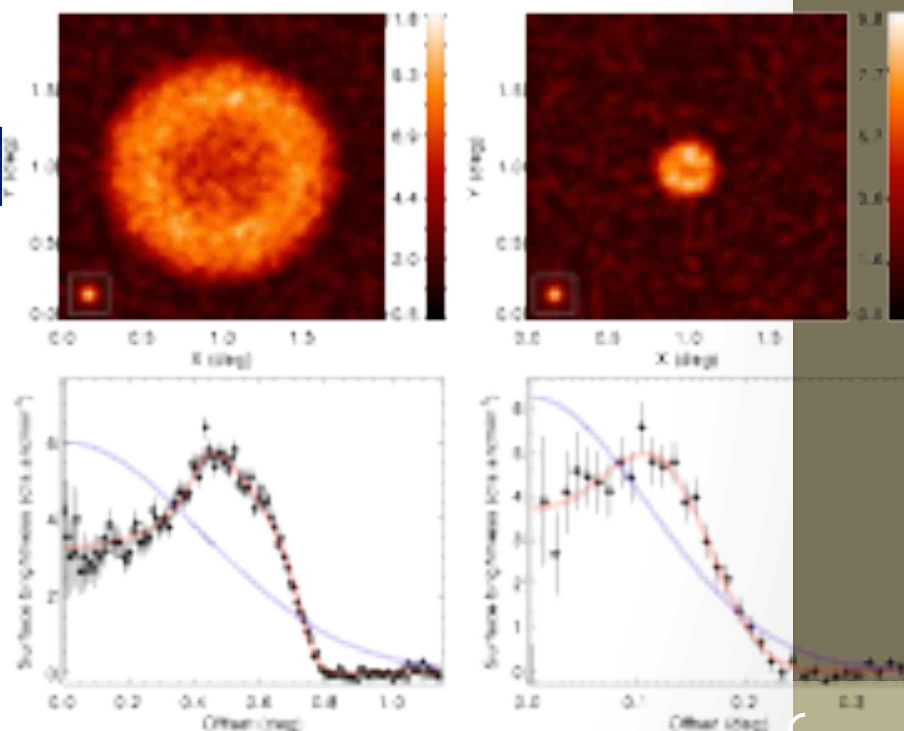
Supernova Remnant Studies with CTA



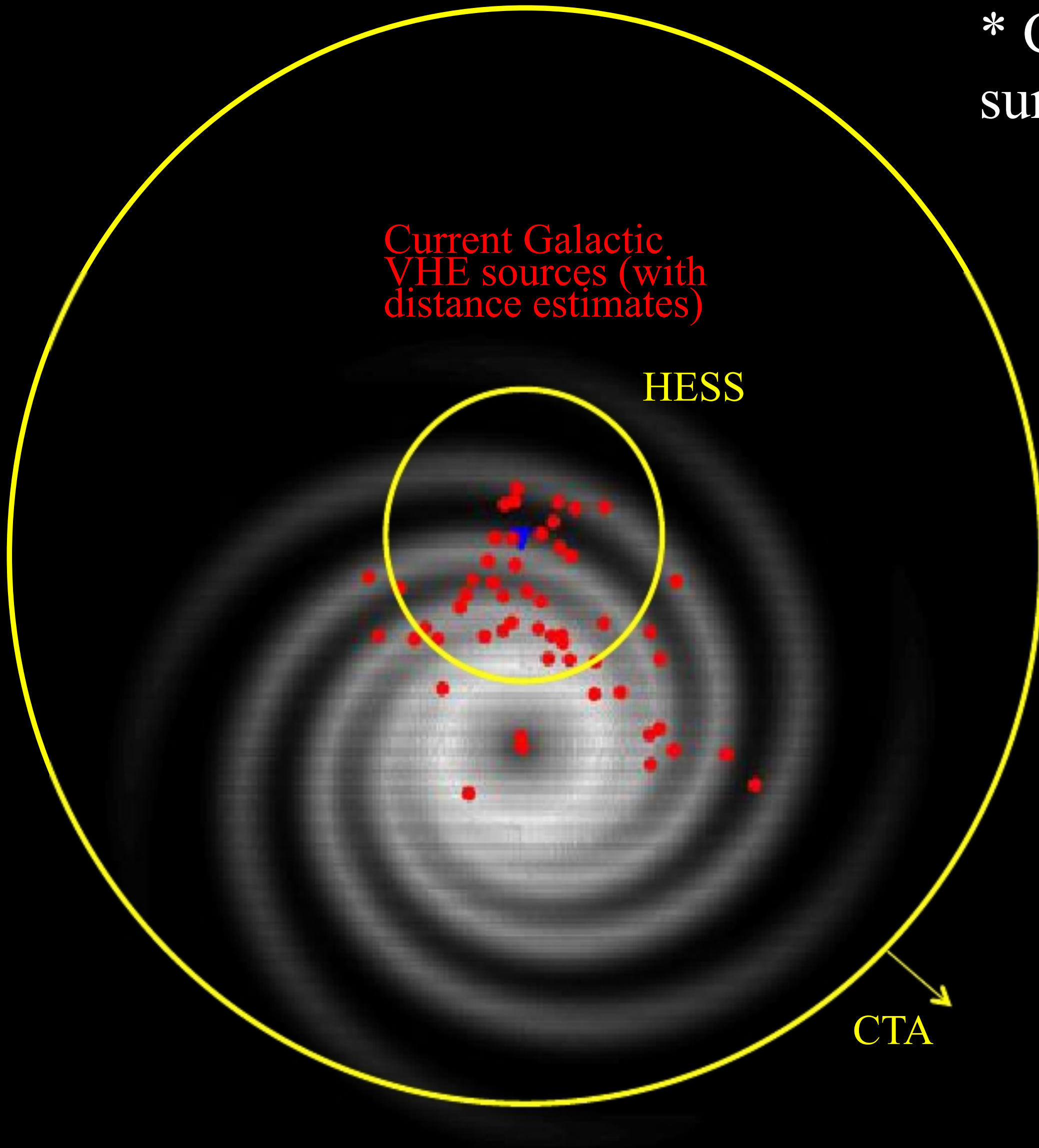
Morphology studies with CTA:
- (left) RX J1713.7-3946 from 50 hr data
  - using XMM image as template
- (below left) RX J1713 actual distance (1 kpc)
- (below right) RX J1713 at a distance of 4 kpc

IC 443: CTA simulated spectra (blue points), 50 hrs.





Supernova Remnants (& More): Population Studies



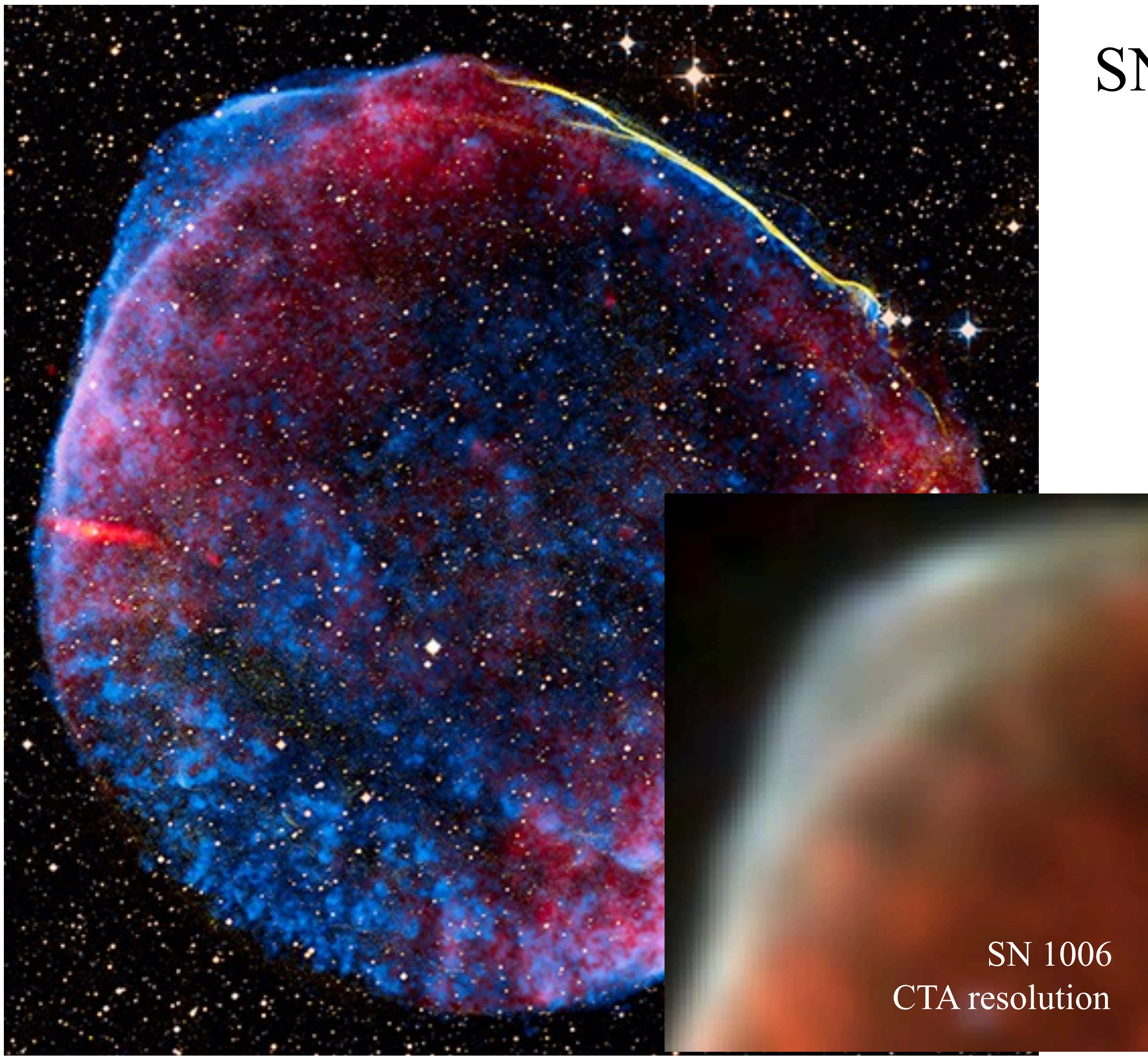
* CTA as ultimate survey machine

* CTA as ultimate flare machine

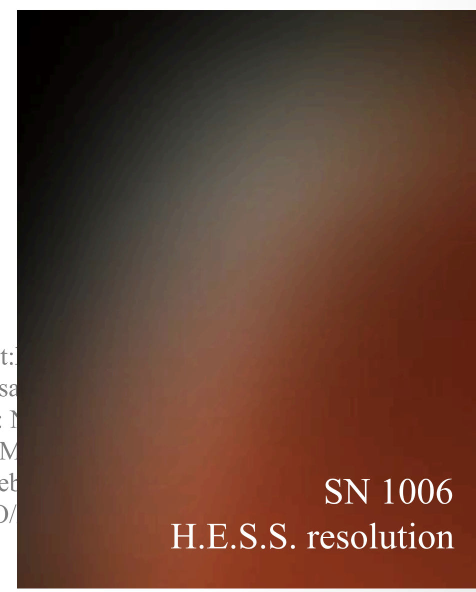
at 25 GeV, for flares 10000 times more sensitive than Fermi

* Coherent full-sky coverage from two sites

Supernova Remnants: Resolving Features



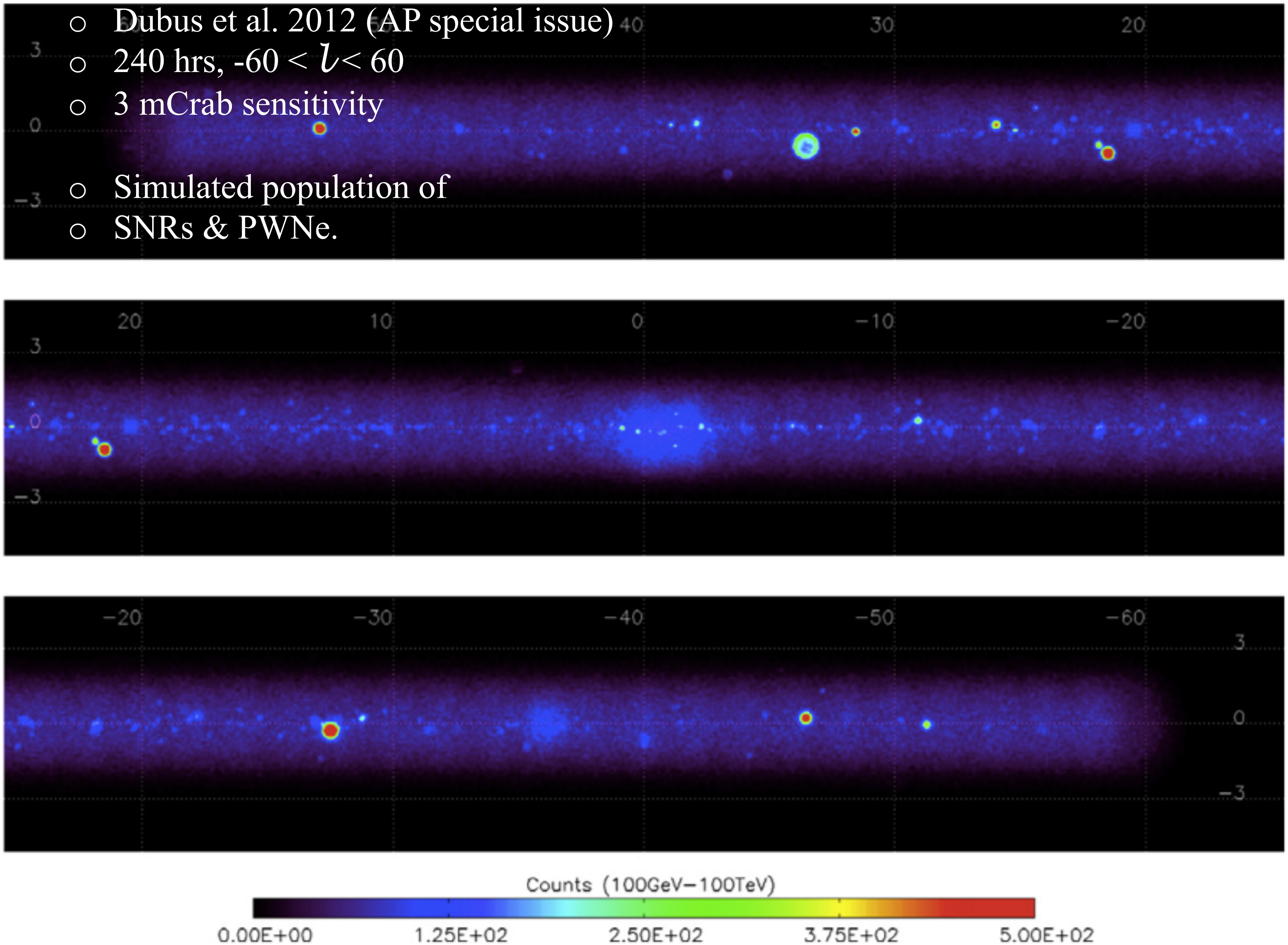
SN 1006



Quick Hits: Galactic Plane Survey

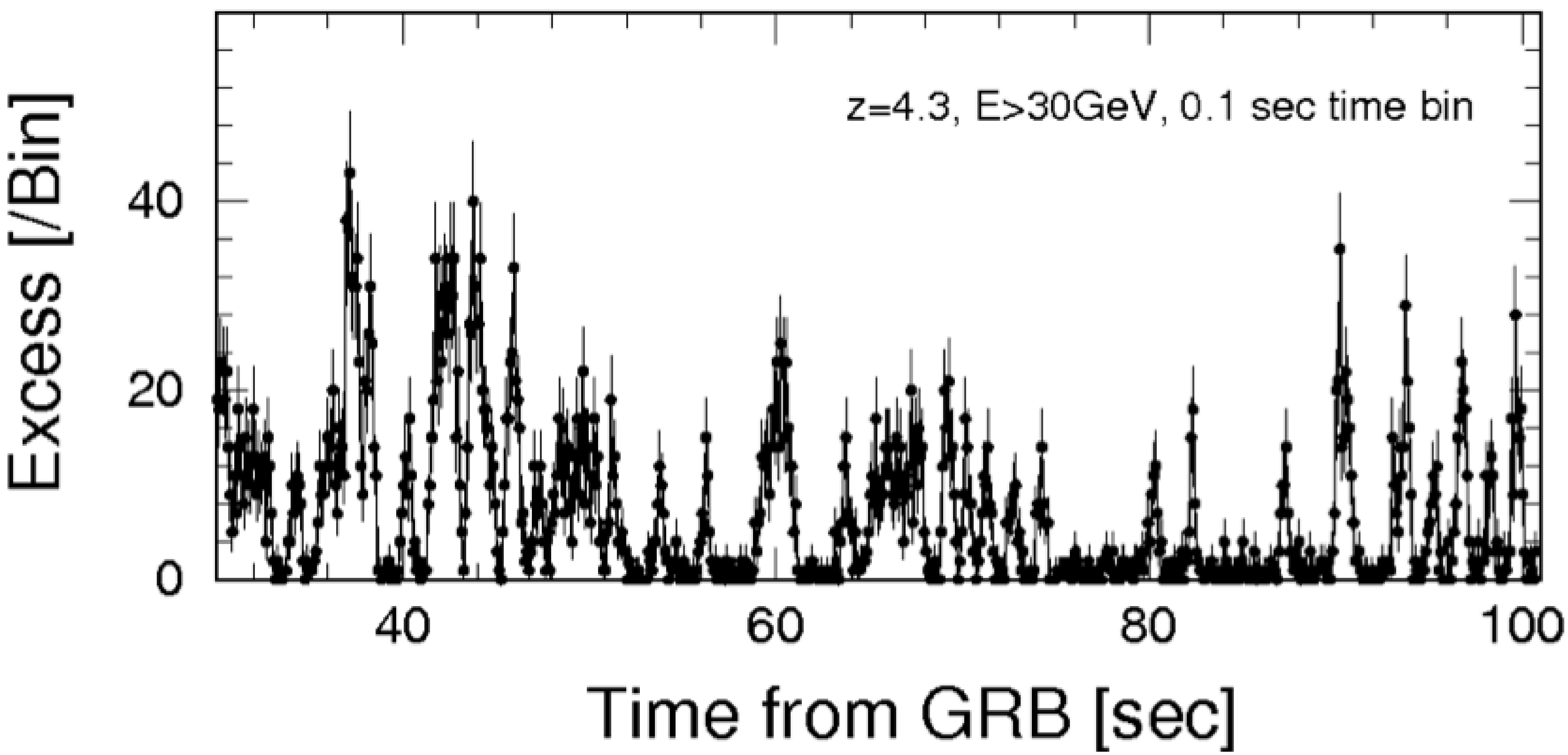
- Dubus et al. 2012 (AP special issue)
- 240 hrs, -60 < l < 60
- 3 mCrab sensitivity

- Simulated population of
- SNRs & PWNe.



Quick Hits: Simulated GRB (E > 30 GeV)

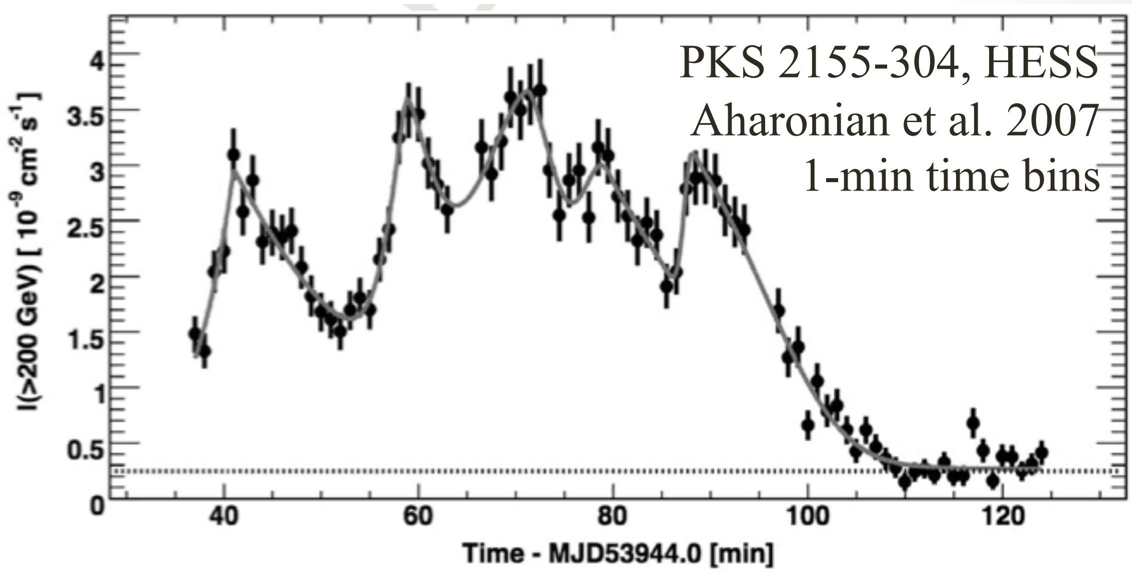
Simulation of GRB 080916C seen by GBM + LAT

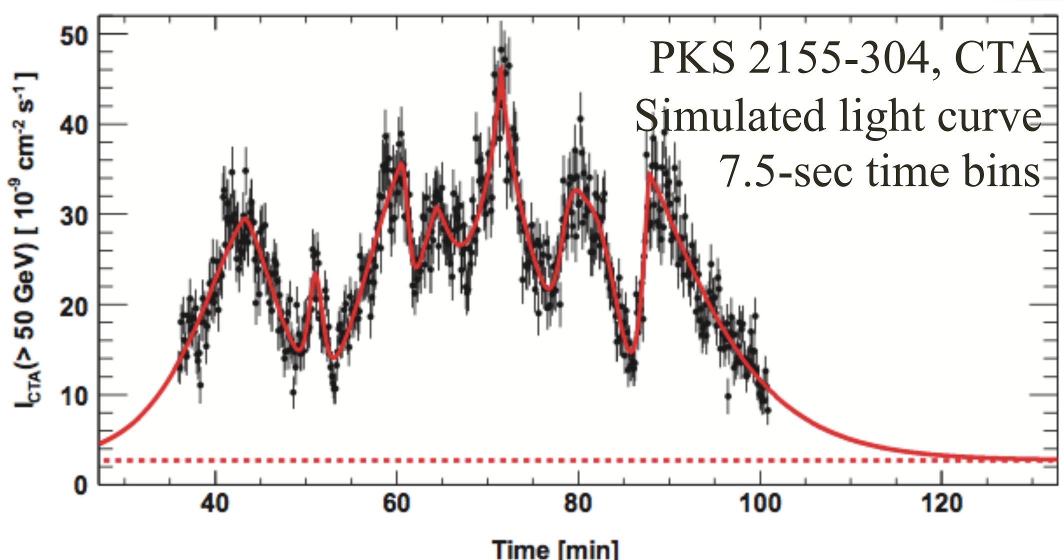


from
Gamma-Ray Burst Science in the Era of Cherenkov Telescope Array
(Astroparticle Physics special issue article)
Susumu Inoue et al.

Quick Hits: Flaring AGN / Radio Galaxies

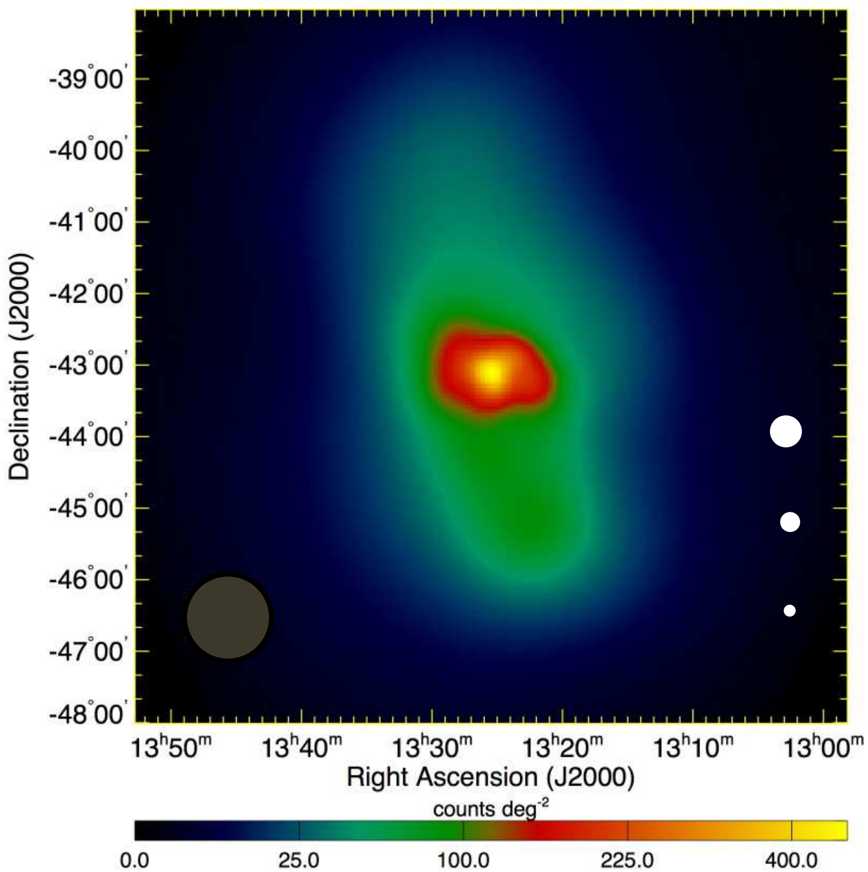
- Low threshold, high sensitivity → probe much shorter variability time scales than existing instruments.
- Ex: PKS 2155-304 flare seen by H.E.S.S. in 2006:
  - Shortest measured variability scale 173 ± 28 sec.
  - CTA can reach 25 ± 4 sec.
  - For Doppler factor of 20, implies spatial scale < 1 AU.
  - Can probe limits of jet formation, particle acceleration time scales!





H. Sol et al., Active Galactic Nuclei under the scrutiny of CTA, Astropart. Phys. (2012), http://dx.doi.org/10.1016/ j.astropartphys.2012.12.005

Quick Hits: Resolving Extragalactic Structures



Fermi LAT >200 GeV background-subtracted counts map of Cen A

Abdo et al. 2010, *Science* **328**, 725

- Fermi LAT PSF at 10 GeV
- CTA PSF at 100 GeV (≥2 images)
- CTA PSF at 300 GeV (≥10 images)

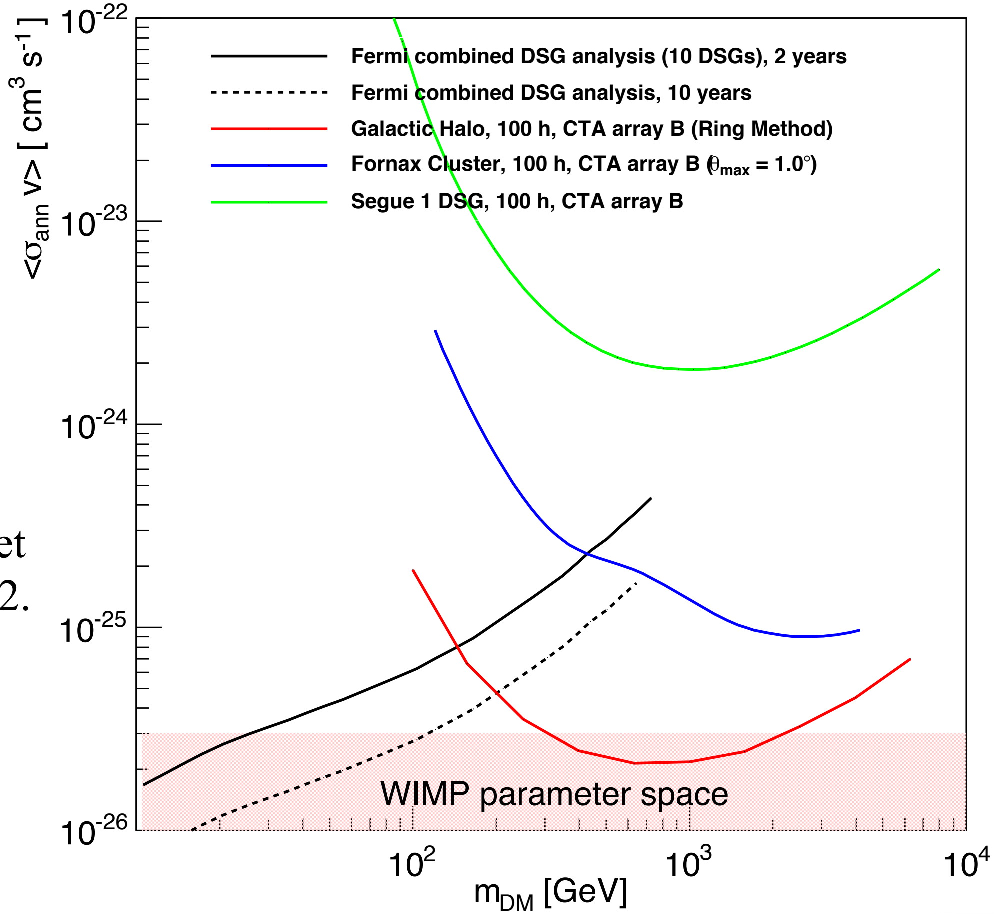
(68% containment)

Quick Hits: Indirect Dark Matter Searches

Fermi dwarf spheroidal and CTA Galactic Center searches are complementary in energy range.

Assuming b b-bar decay channel

LAT 2-year result from Ackermann et al. 2011, *Phys. Rev. Lett.* **107**, 241302.



Complements IceCube searches in the neutrino channel.

Status, Plans, & Schedule

COMMUNITY

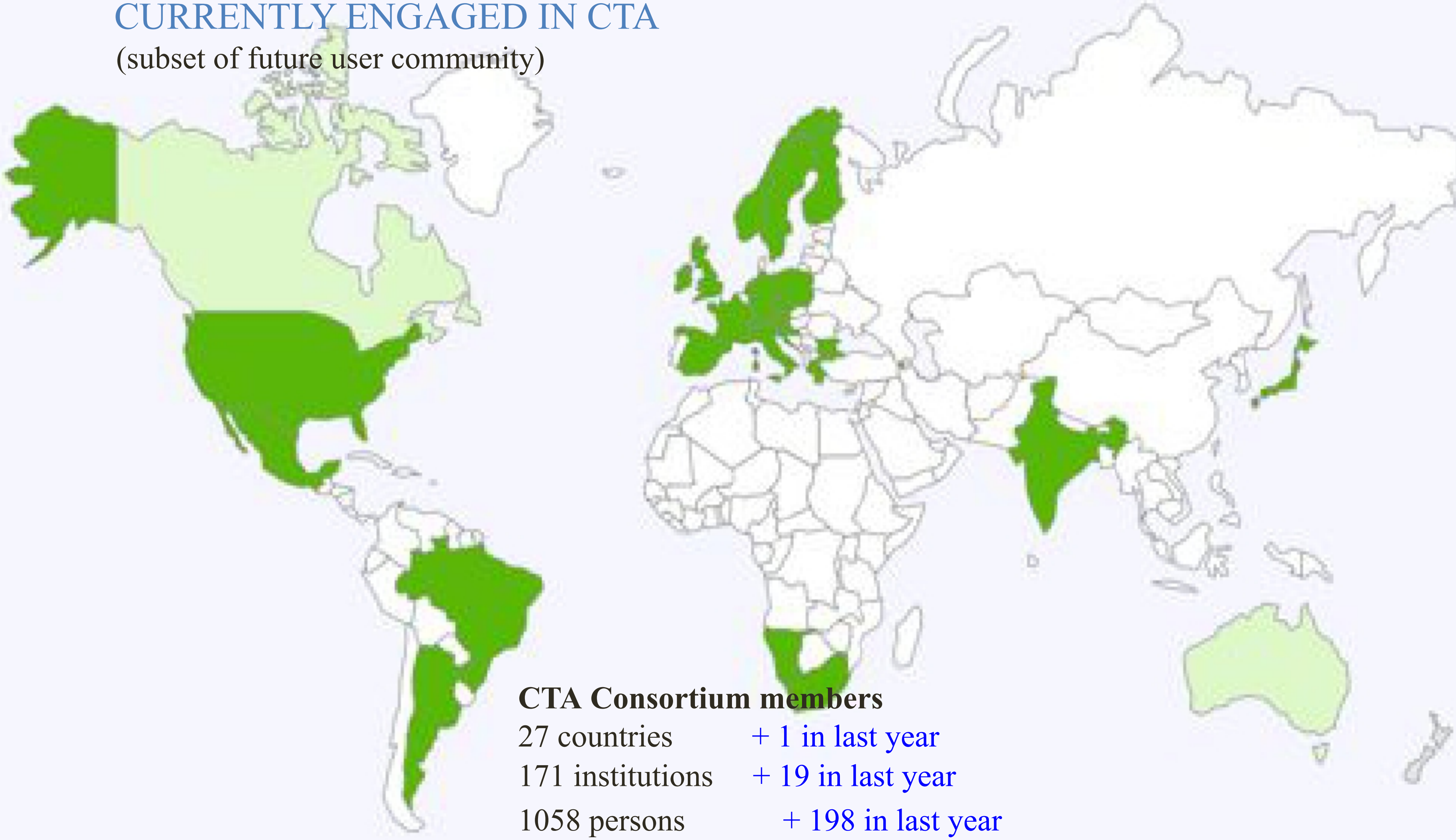
Members (27 countries)

Interested to join

Canada, Australia, Israel

CURRENTLY ENGAGED IN CTA

(subset of future user community)



CTA Consortium members

27 countries + 1 in last year

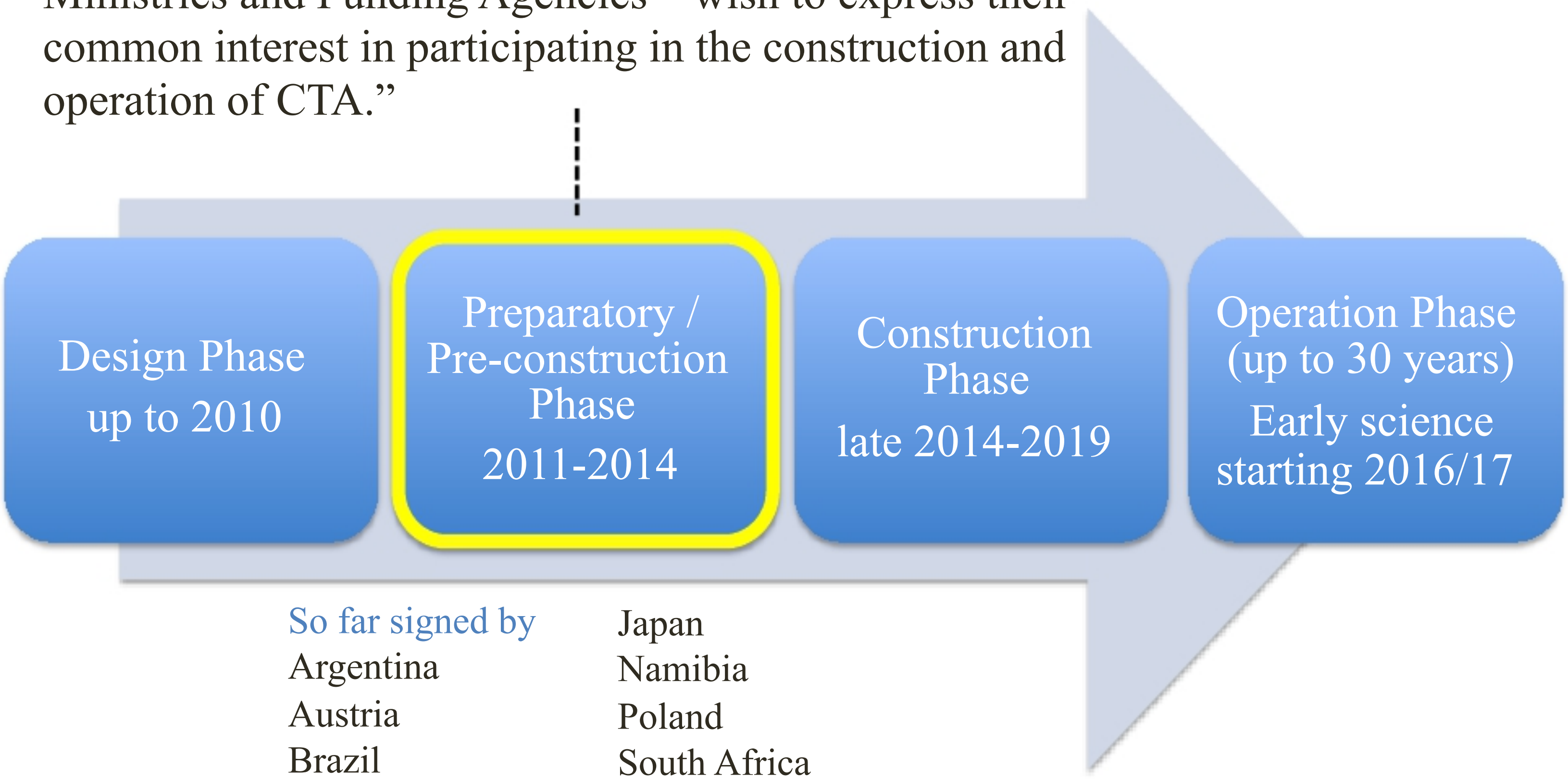
171 institutions + 19 in last year

1058 persons + 198 in last year

Recommended by Relevant Roadmaps …

Cherenkov Telescope Array: Global Timeline

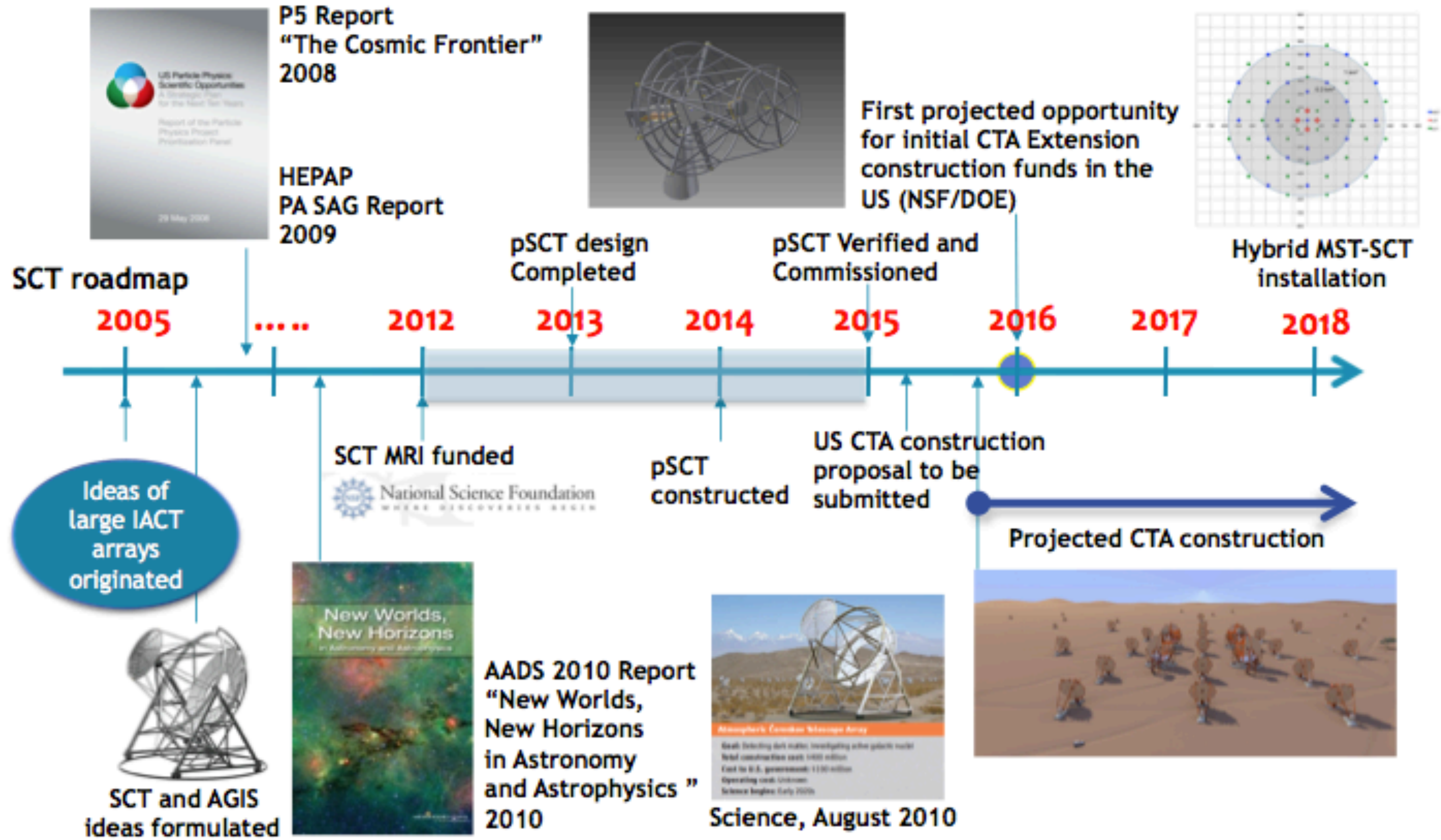
"By signing this Declaration of Intent, the signatories – Ministries and Funding Agencies – wish to express their common interest in participating in the construction and operation of CTA."



So far signed by

Argentina	Japan
Austria	Namibia
Brazil	Poland
France	South Africa
Germany	Spain
Italy	Switzerland
	UK

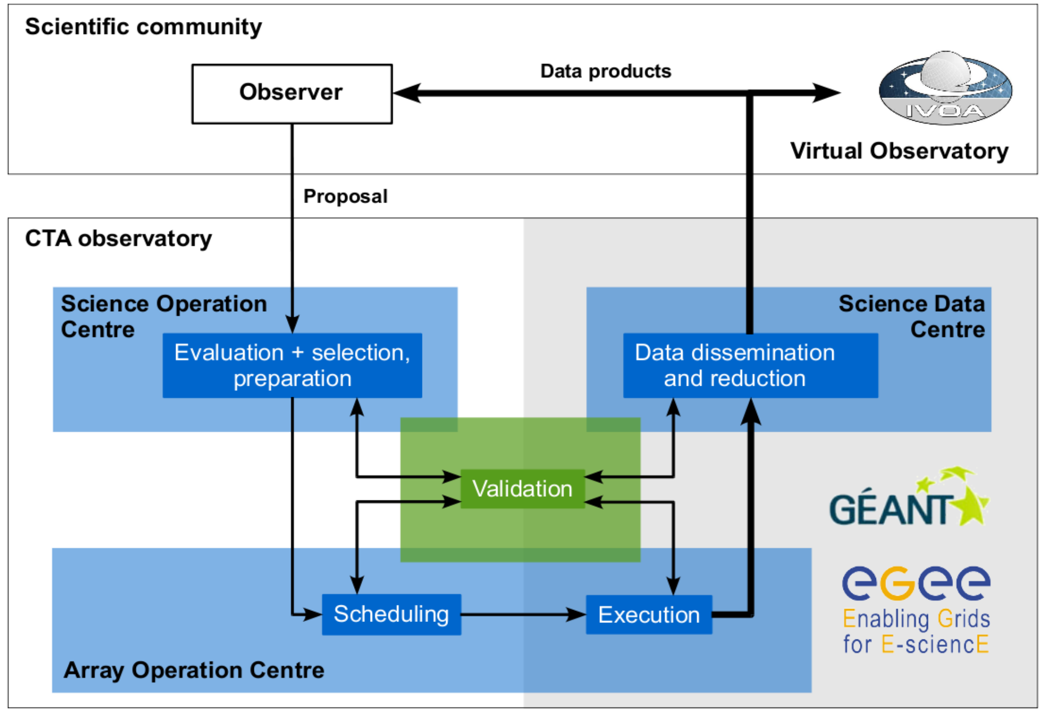
Cherenkov Telescope Array: US Timeline



CTA as an Open Observatory

Currently Envisioned:

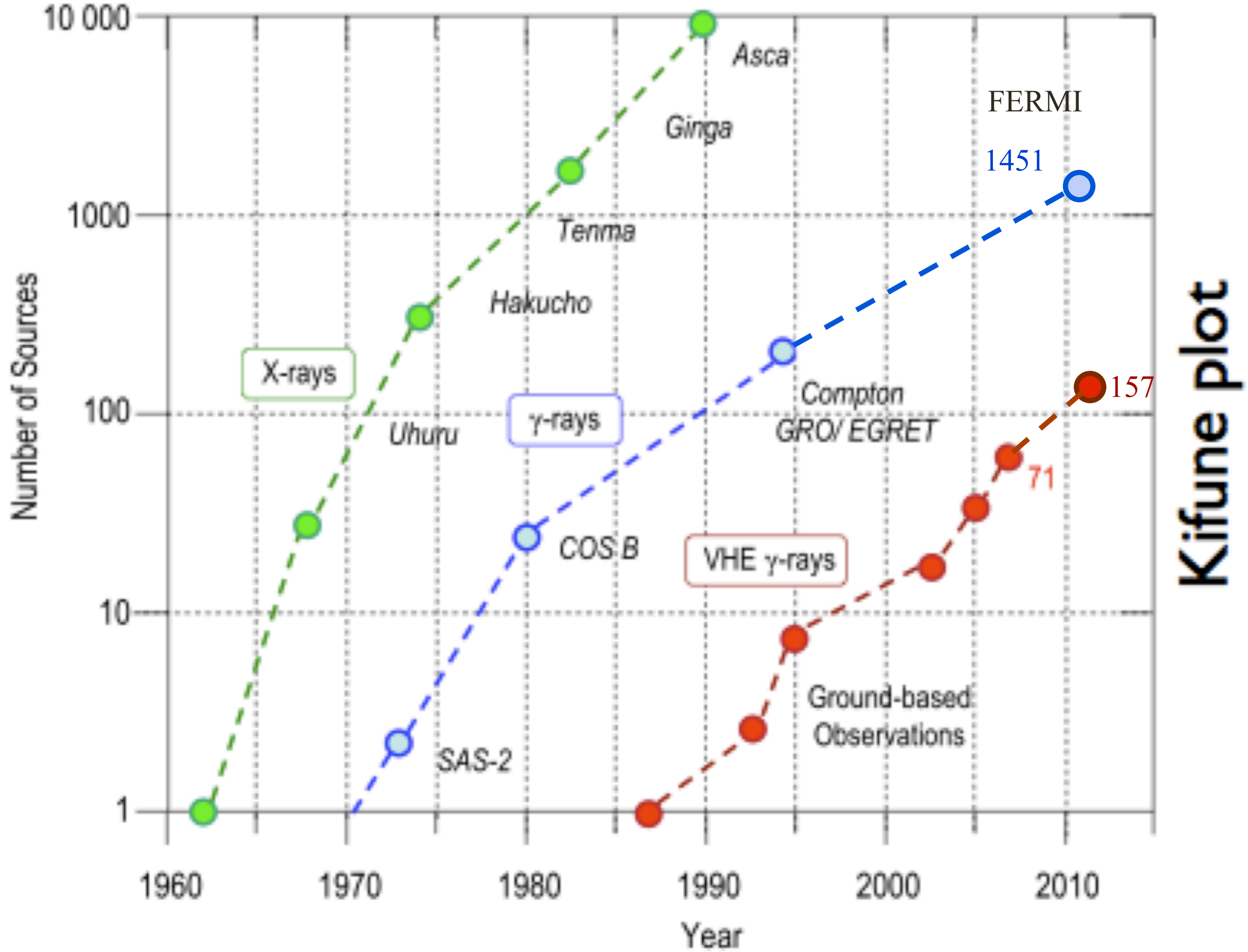
- Large Key Science Programs (surveys) use 1/3 to 1/2 of time.
- Bulk of time open for proposals from participating countries.
- Accessible for scientists worldwide.
- No access fees for individual proposals.
- All data available on the CTA Archive after a proprietary period.
- Fully open access for CTA Archive.



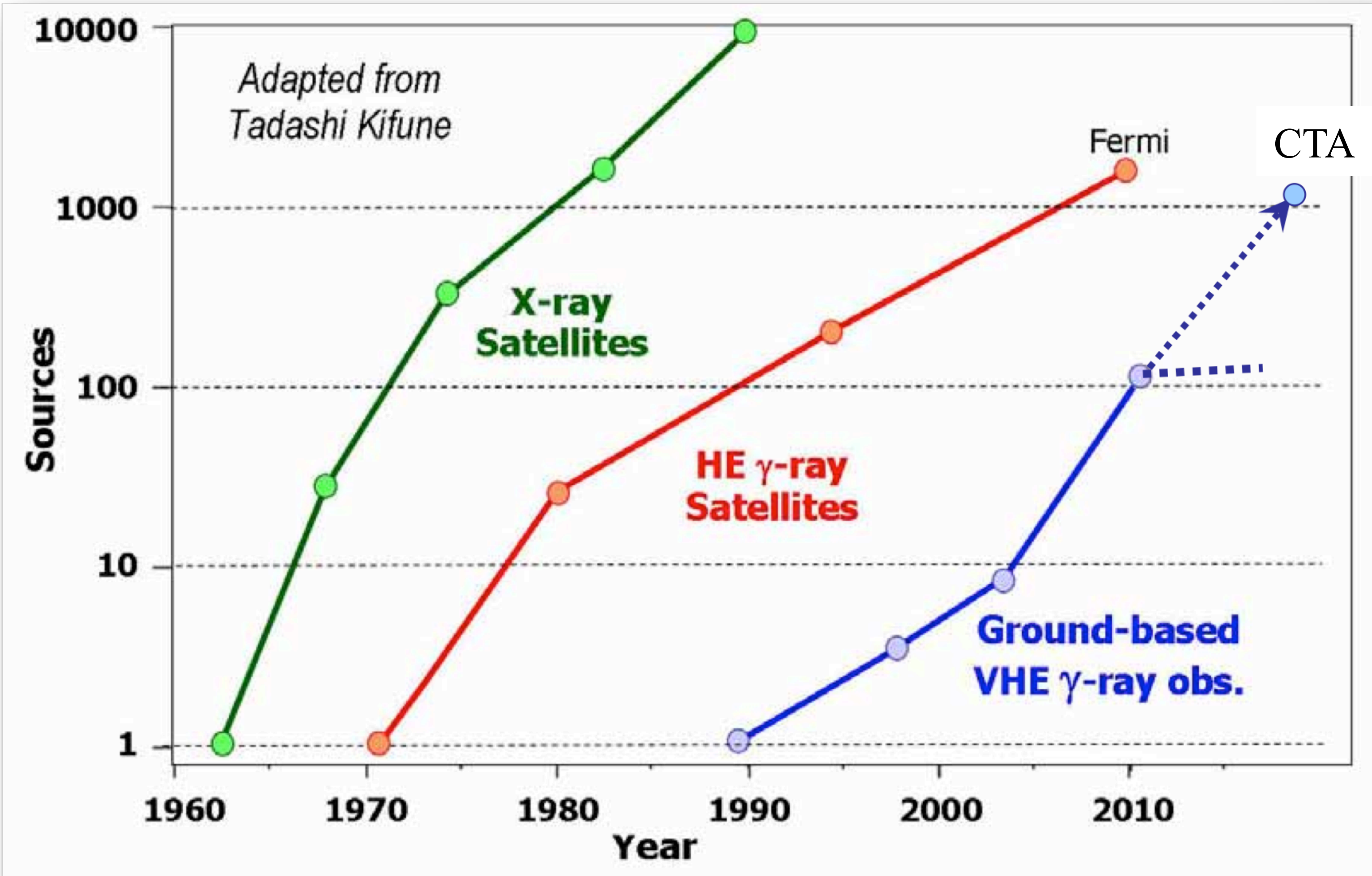
✧ Open formats and tools following astronomy standards (FITS) to represent and analyse data and instrument response functions (IRFs).

✧ User-oriented data center & Virtual Observatory interfaces.

VHE gamma astronomy is now well on-track…



… but needs CTA to continue.



Summary

- CTA will provide guaranteed science & discovery potential.
  - A natural way to extend Fermi and VERITAS/H.E.S.S./ MAGIC science.
- Proven technology combined with judicious innovation.
- On track for construction starting in next couple years, early science beginning ~2016.
- Will serve a large and diverse community.
  - Broad multi-wavelength, multi-messenger impact complementing IceCube, HAWC, Fermi.
- US contribution: Novel telescope design will make a major impact in 0.1- 10 TeV range.

Backup Slides

LARGE 23 M TELESCOPE

OPTIMIZED FOR THE RANGE BELOW 200 GEV

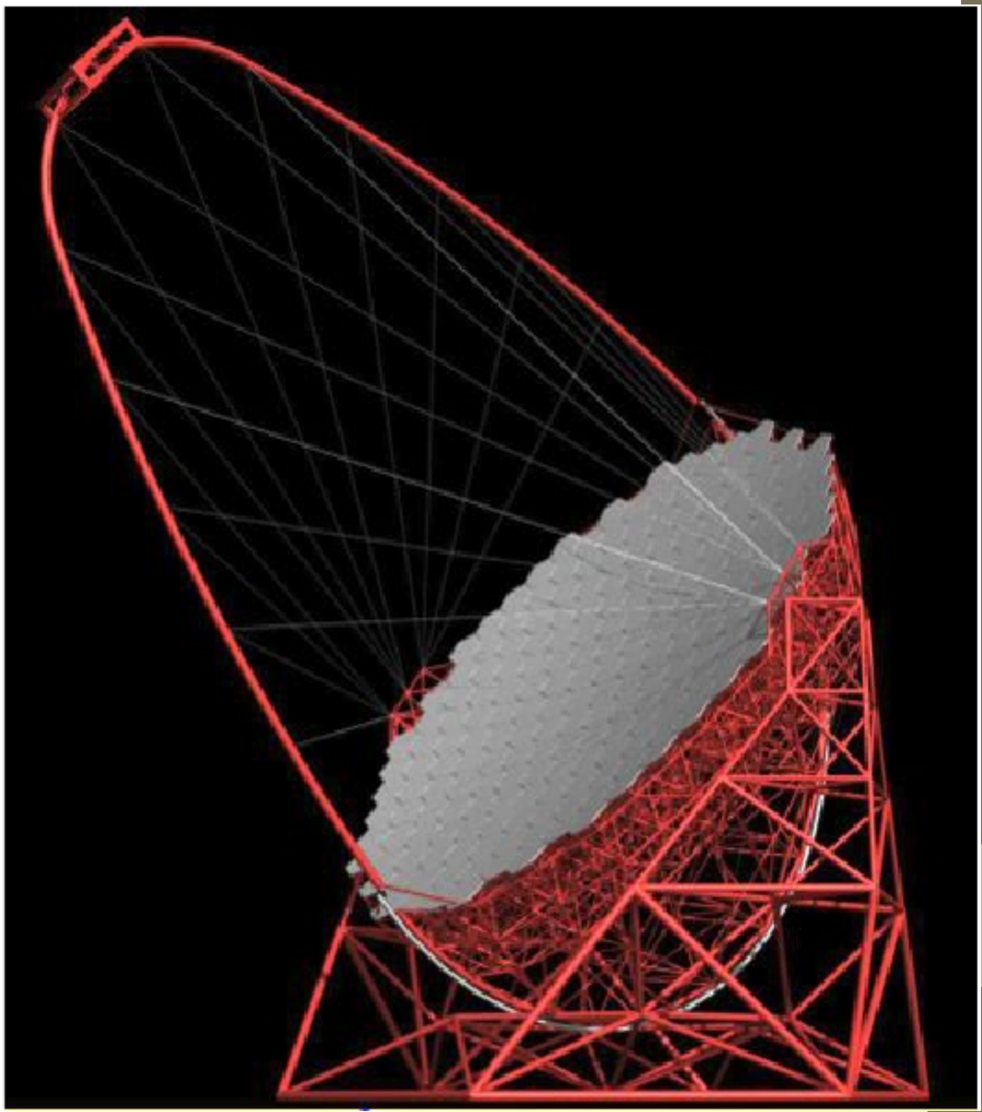
400 m^2 dish area
27.8 m focal length
1.5 m mirror facets

4.5 deg. field of view
0.1 deg. pixels
Camera diameter over 2 m

Carbon-fibre structure

Active mirror control

4 LSTs on each site



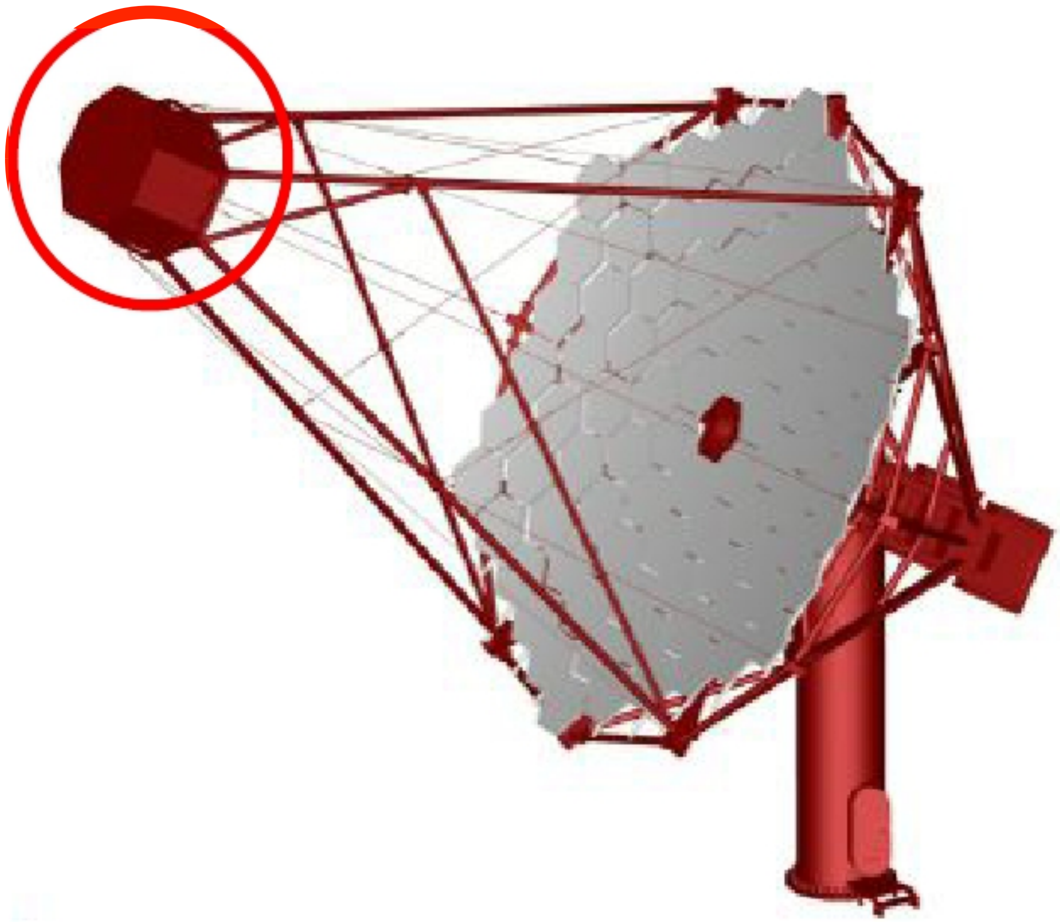
MEDIUM-SIZED 12 M TELESCOPE

OPTIMIZED FOR THE 100 GEV TO ~10 TEV RANGE

100 m^2 dish area
16 m focal length
1.2 m mirror facets

7-8 deg. field of view
~2000 x 0.18 deg. pixels

25 MSTs on South site
15 MSTs on North site



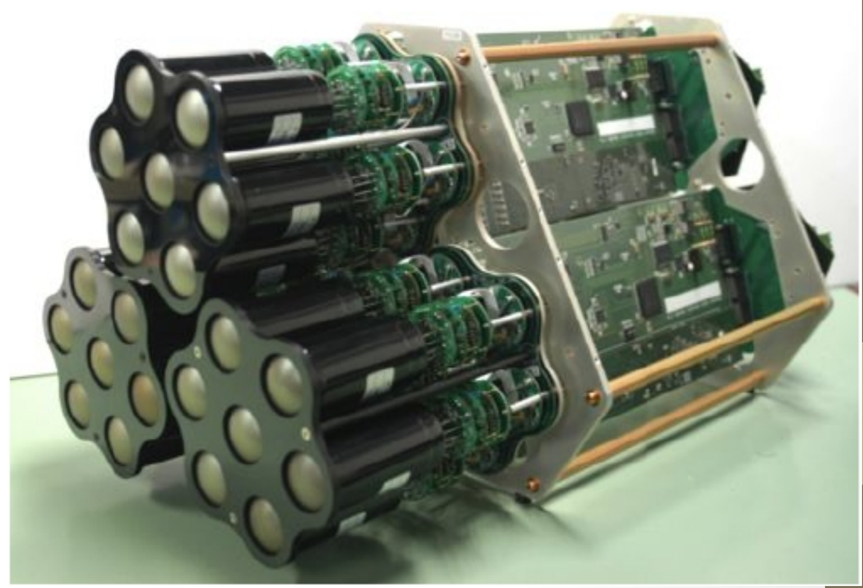

MST PROTOTYPE IN BERLIN

PHOTOMULTIPLIER CAMERAS

Recording signal waveform for "interesting" (triggered) images

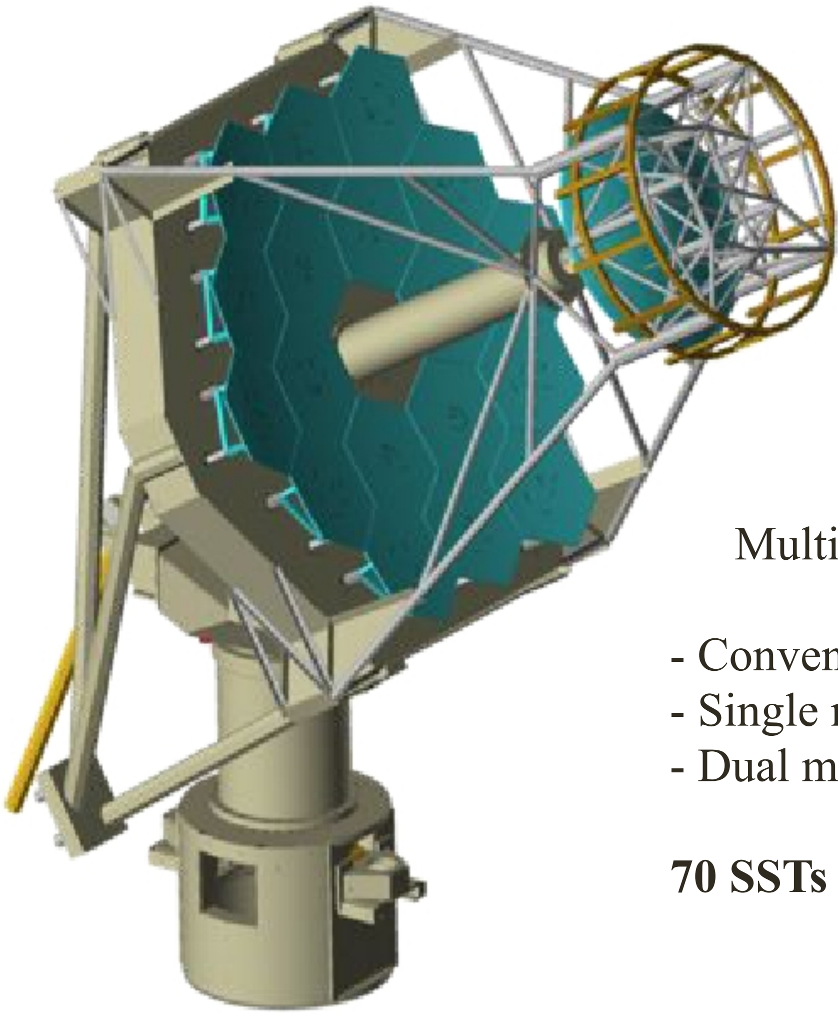
Options:

- Capacitor pipeline + analog trigger + (identical) "drawers"
    - **NectarCam**
    - **DragonCam**
- Flash-ADC + digital trigger + rack-based electronics
    - **Flashcam**



SMALL TELESCOPE

OPTIMIZED FOR THE RANGE ABOVE 10 TEV



ASTRI Design
4.3 m mirror
9.6 deg. foV
0.25 deg. pixels

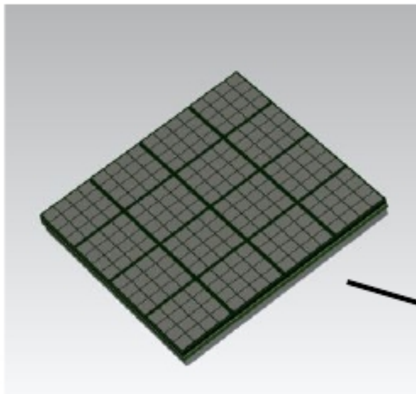
Multiple options under study:

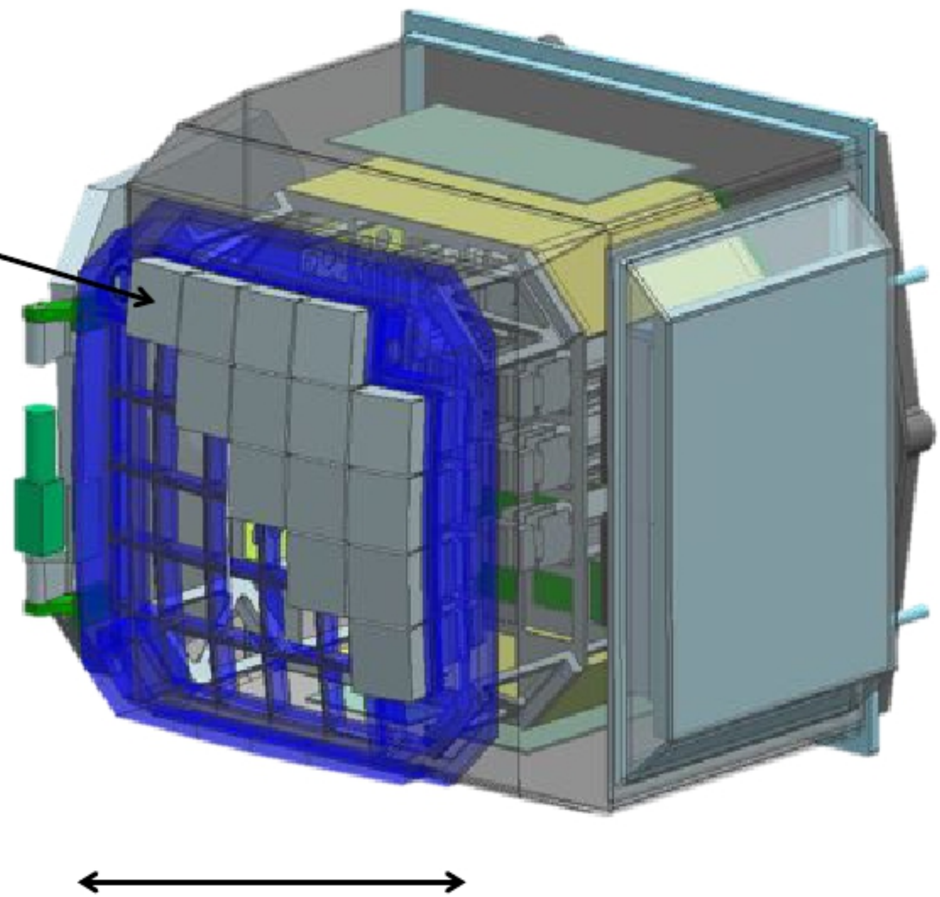
- Conventional single mirror, PMT camera
- Single mirror, silicon sensor camera
- Dual mirror optics, silicon & MAPMT camera

70 SSTs on Southern site

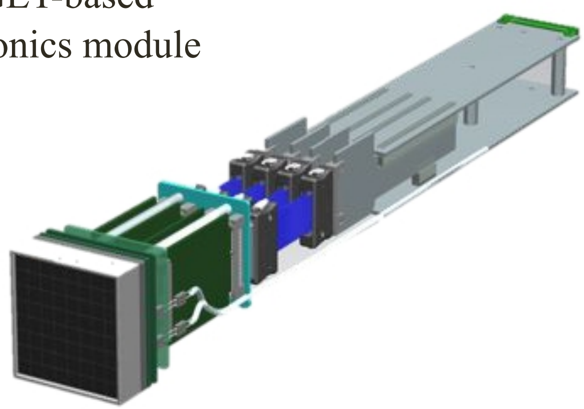
COMPACT SILICON CAMERAS

Hamamatsu
SiPM
50 x 50 mm^2
16 x 16 pixels
(grouped 2 x 2)



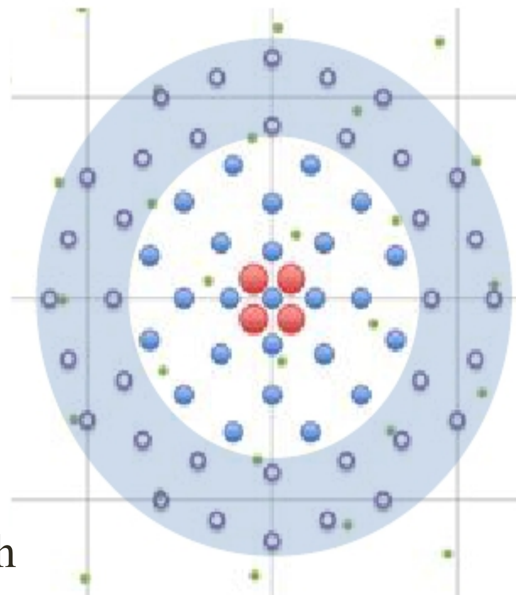


64 Channel
TARGET-based
electronics module



MEDIUM-SIZED DUAL MIRROR TEL.

EXTENDING THE MST ARRAY



9.7 m diameter
50 m^2 dish area
5.6 m focal length

8-9 deg. field of view
11000 x 0.07 deg. pixels

Extend South array
by adding 36 SCTs
contributed mostly by US