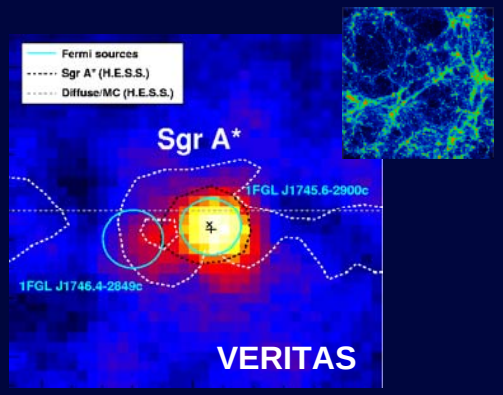
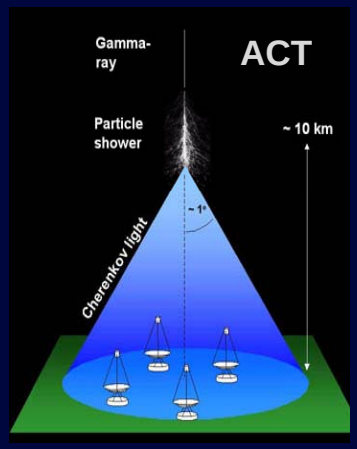
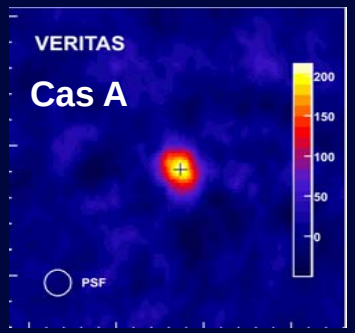
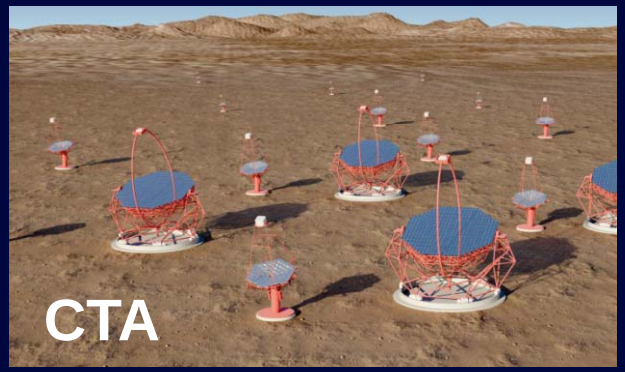
Very High Energy Astronomy and Prospects for CTA









Rene A. Ong (UCLA)

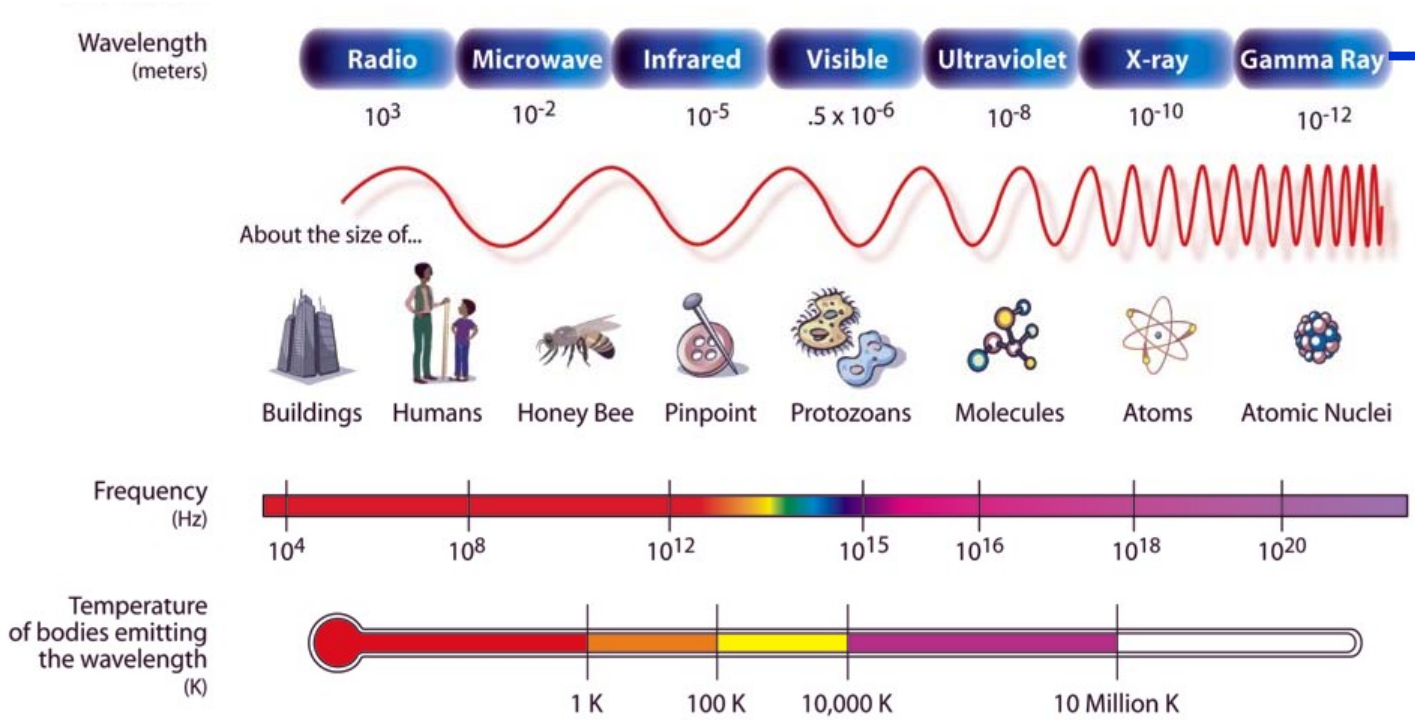
Lowell Observatory Colloquium

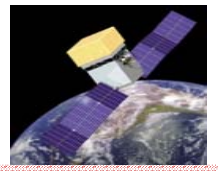
02 May 2013

OUTLINE

- HE and VHE Astronomy
- Selected Scientific Highlights
  - Galactic sources: SNRs, Crab
  - Extragalactic sources: AGN and cosmic radiation fields
  - Unidentified sources and Dark Matter
- Experimental Techniques
- Motivating the Cherenkov Telescope Array (CTA)
- Implementing CTA
- Summary

High-Energy Astronomy





HE (Space)

VHE (Ground)

Non-Thermal

Energy (eV)	1	10^{3}	10^{6}	10^{9}	10^{12}	10^{15}
	eV	keV	MeV	GeV	TeV	PeV

Scientific Motivations

Broad motivations for VHE γ-ray Astronomy:

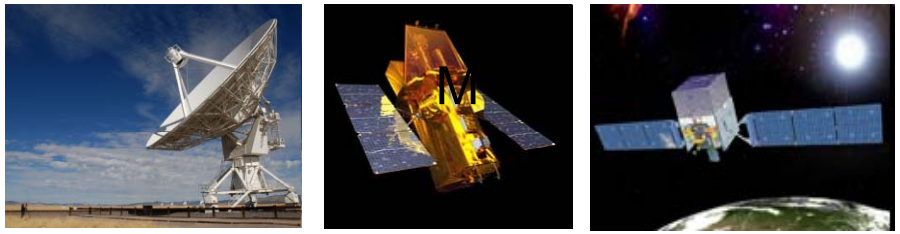
PHYSICS Motivations

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

ASTRONOMICAL Motivations

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

Multiwavelength Observations

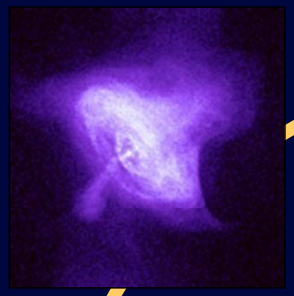


Radio X-rays Fermi LAT

Exploring the non-thermal Universe

Pulsars/PWN

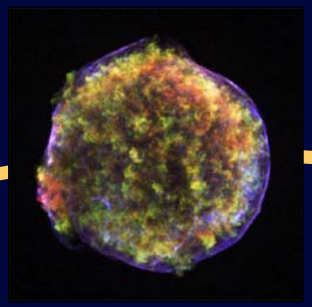
NS dynamo winds



Binaries

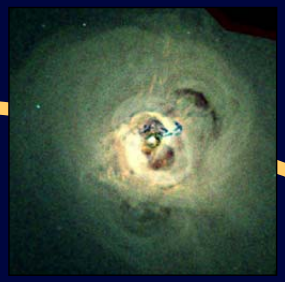
Jets, winds

SNRs



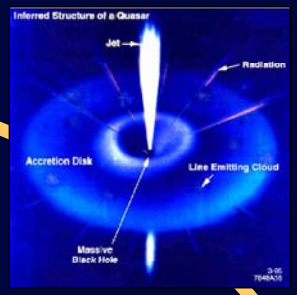
Shocks
Fermi Mech.

Starbursts



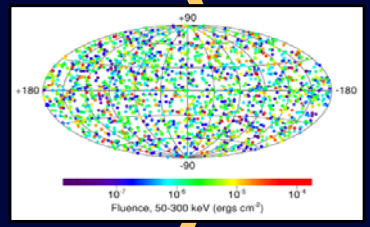
SN activity
Cosmic rays

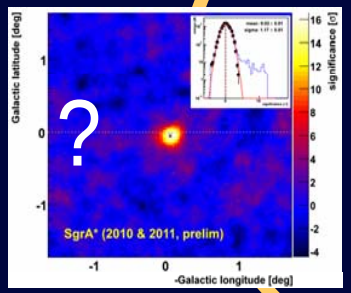
AGN



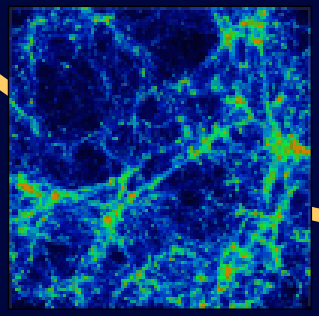
SMBH accretion, jets

GRBs

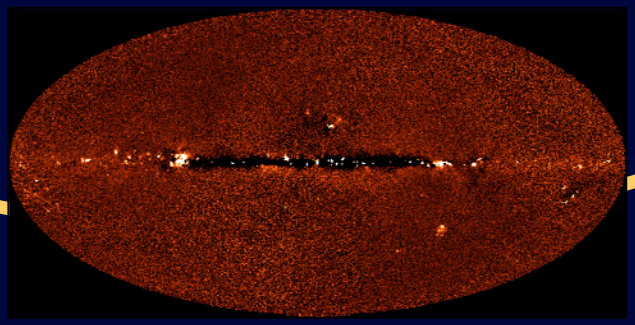




Unknowns
(Gal Center)



Dark Matter

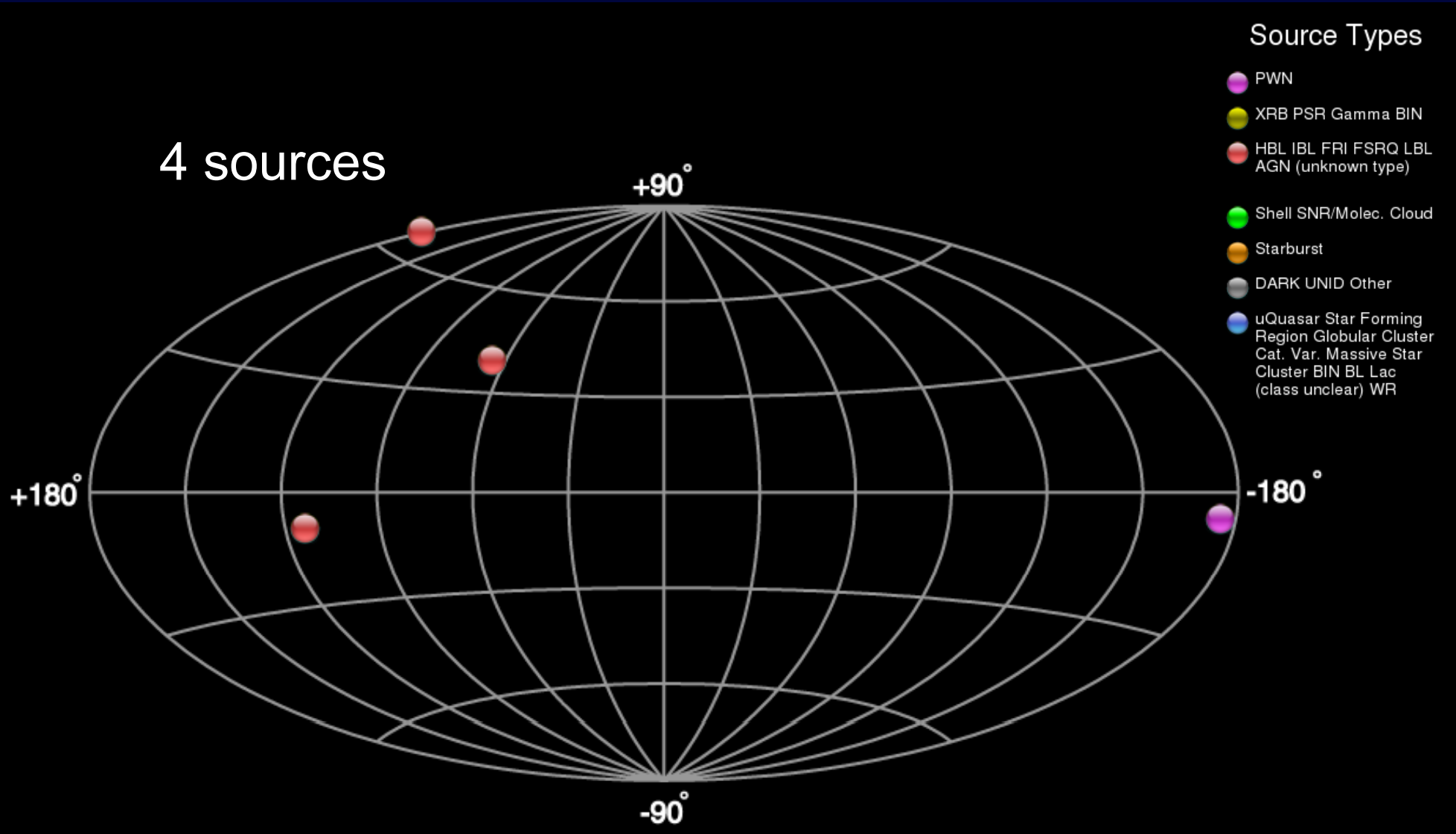


Cosmological Fields

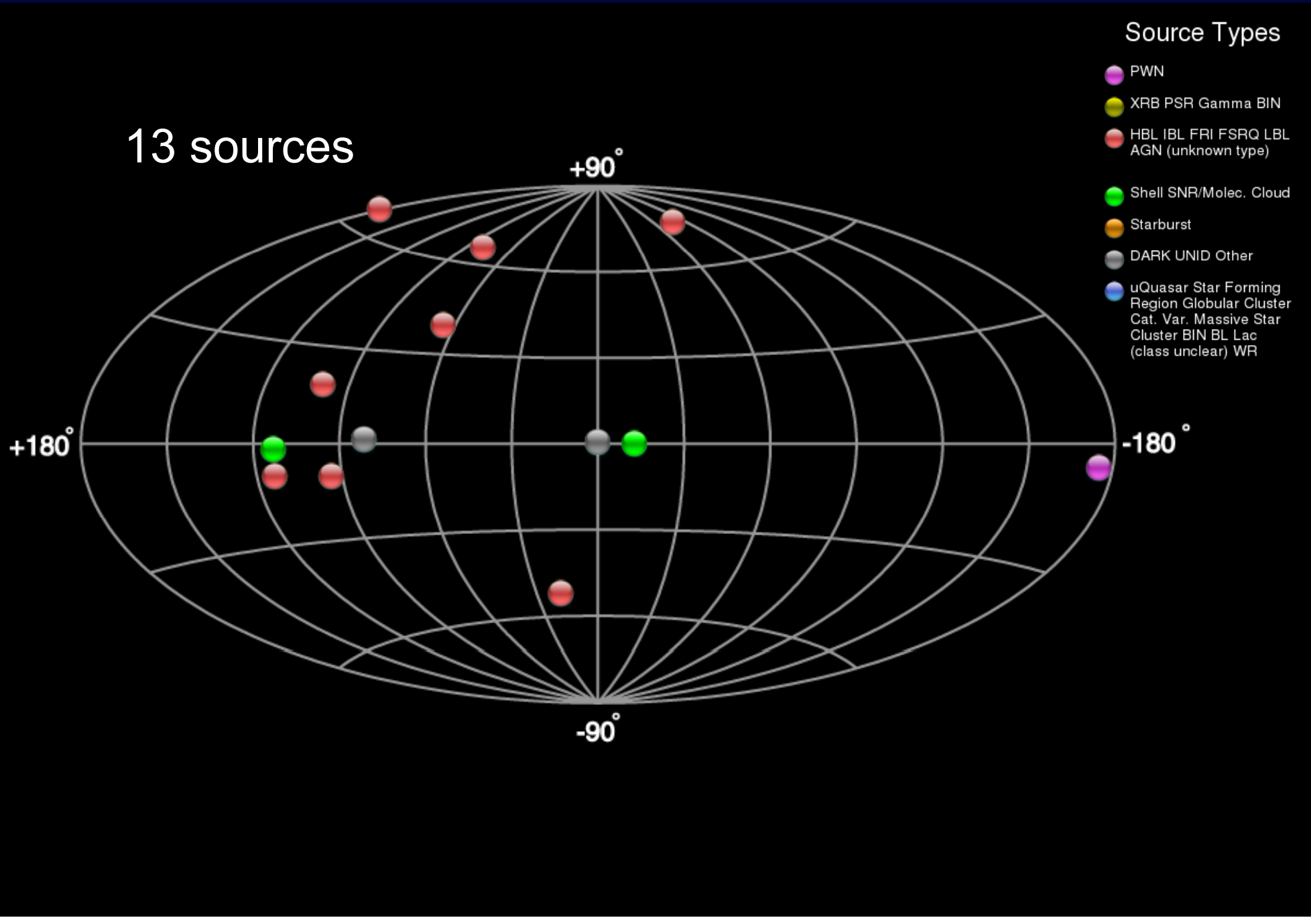
PBHs, QGR

Probing New Physics at GeV/TeV scale

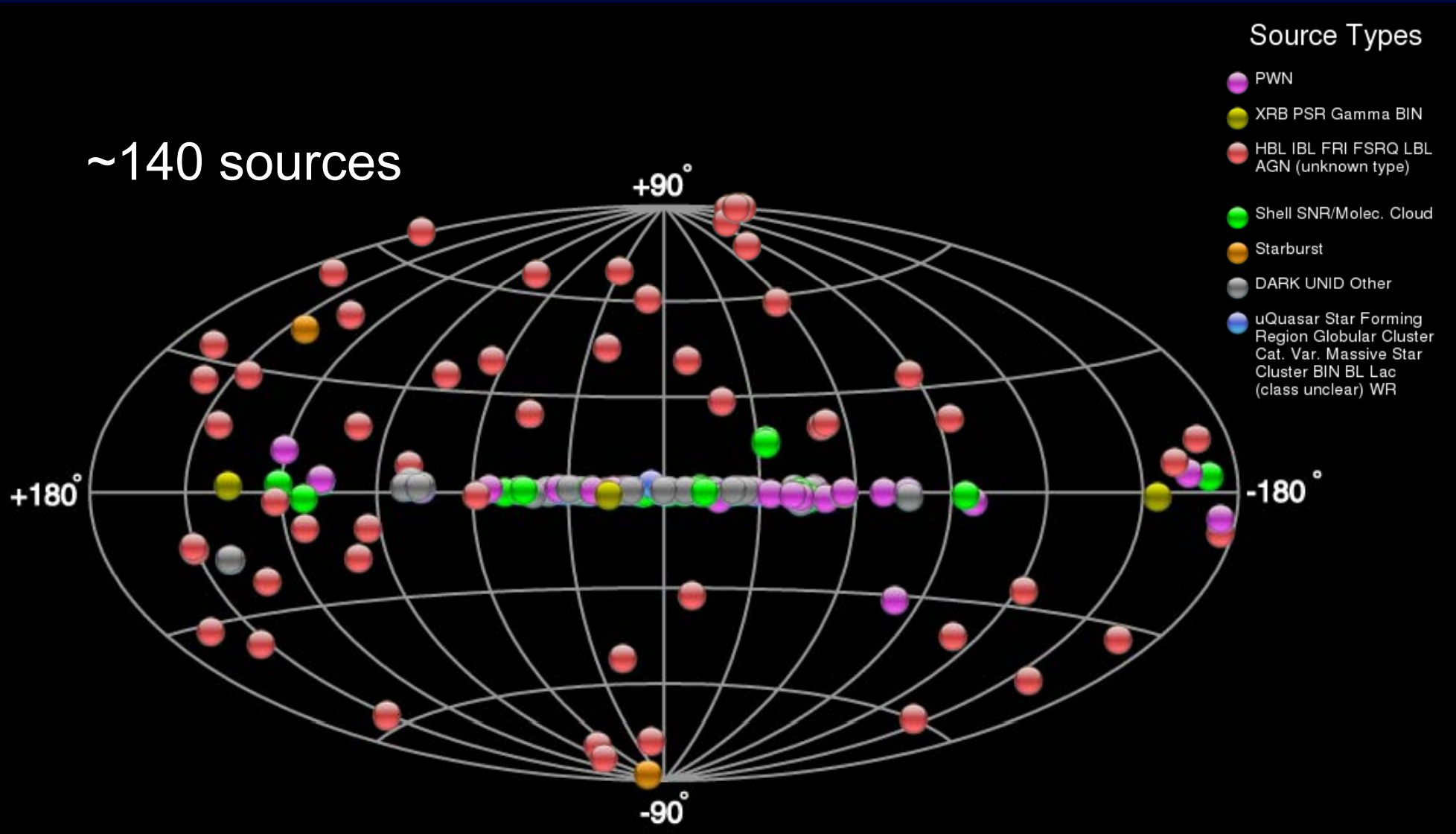
VHE γ-ray Sky c1997



VHE γ-ray Sky c2005

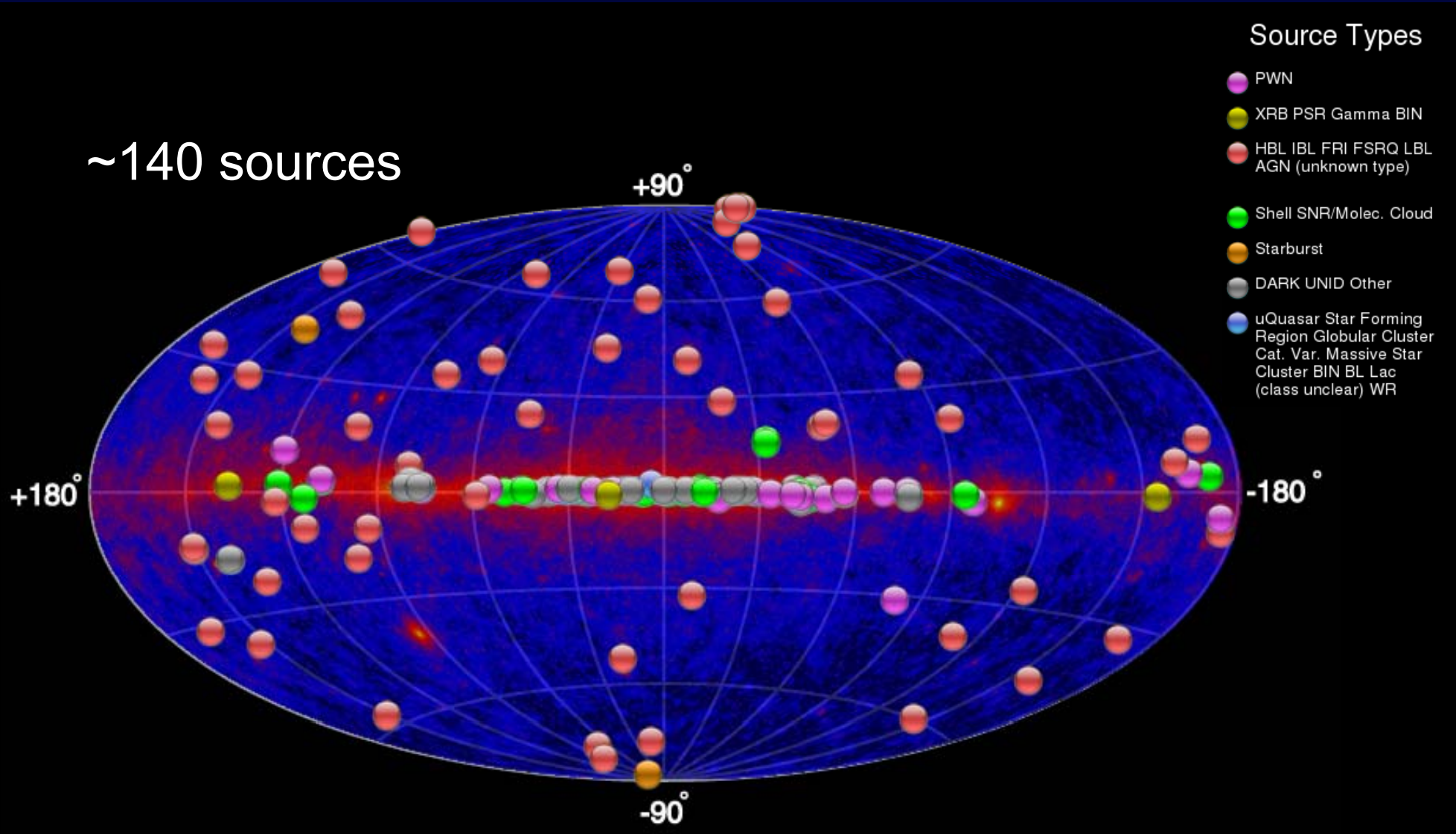


VHE γ-ray Sky c2013



- Almost all discoveries made by atm. Cherenkov telescopes
- Much more information: spectra, images, variability, MWL …

VHE γ-ray Sky c2013 + HE γ-ray Sky

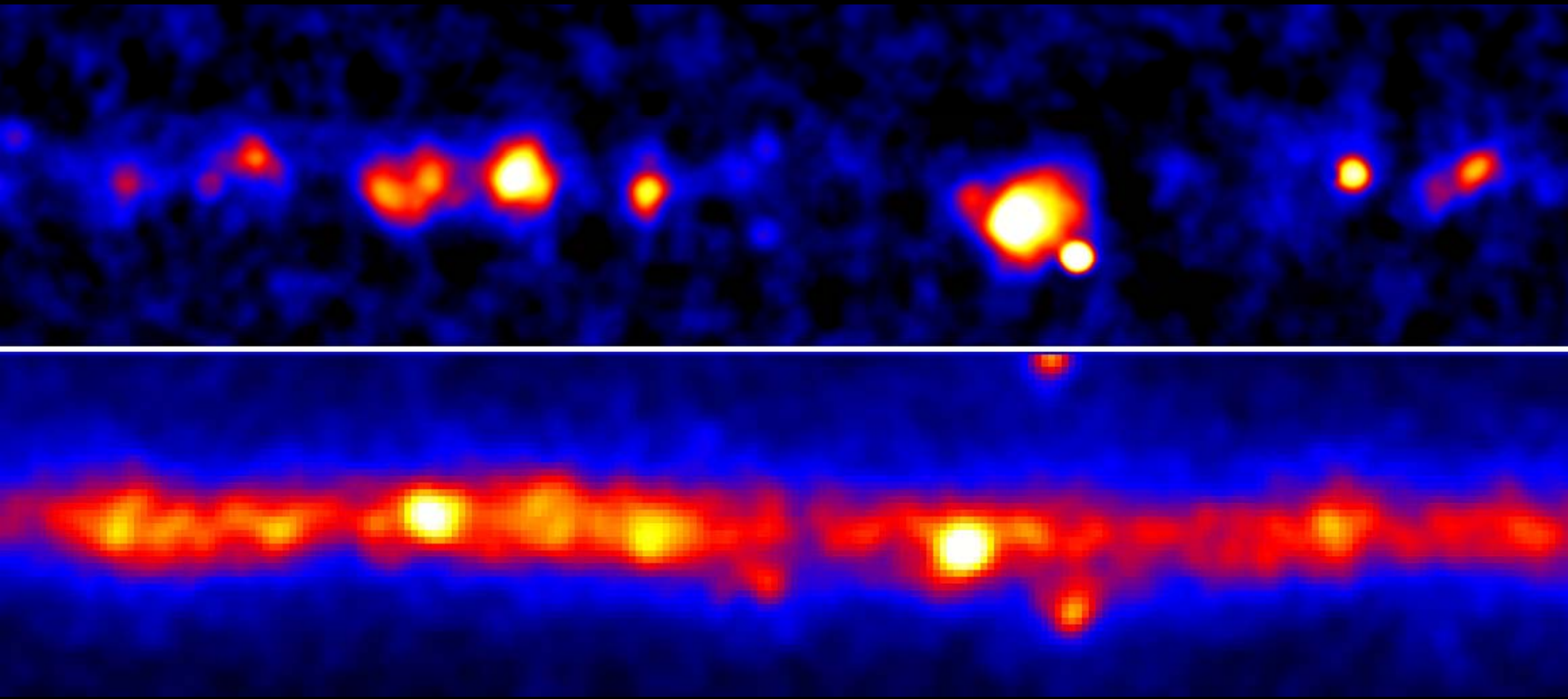


- Almost all discoveries made by atm. Cherenkov telescopes
- Much more information: spectra, images, variability, MWL …

The High Energy Milky Way

Extended sources, size typically few 0.1^{o}
few 10 pc

H.E.S.S. (TeV)



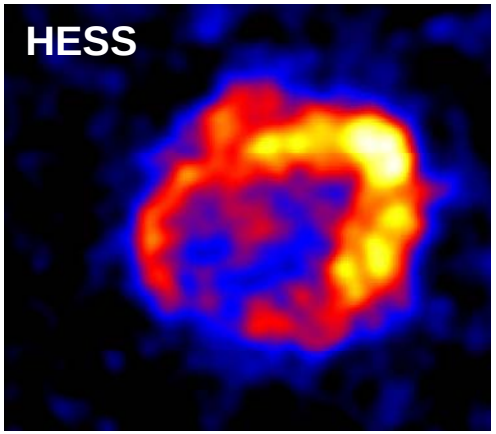
Fermi-LAT (GeV)

Selected Scientific Highlights

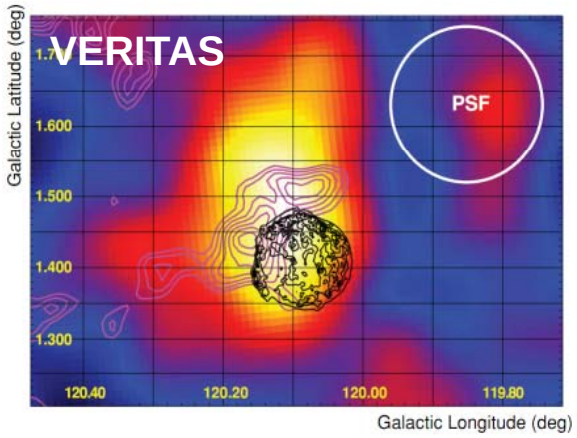
- Supernova Remnants: origin of cosmic rays
- The Crab nebula and pulsar
- AGN and intergalactic radiation fields (EBL and EGMF)
- Un-Identified sources & Dark Matter

Supernova Remnants (SNRs)

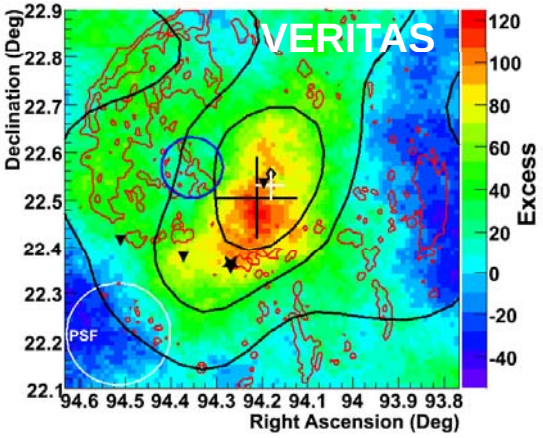
- Collapse of massive star or detonation of white dwarf.
- Outer layers ejected with $v \sim 3 \times 10^3$ km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.
- Acceleration of particles via "canonical" Fermi process – or diffusive shock acceleration.
- In ~ 10^4 yrs, blast wave deccelerates and dissipates.
- Can supply and replenish CR's if ε ~ 5-10%.



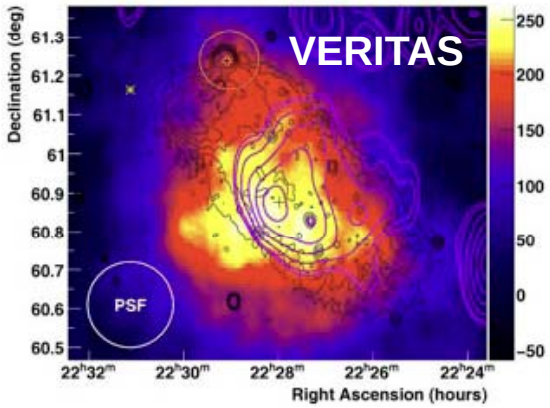
RXJ 1713-3946
Age = 1600y
D = ~1 kpc



Tycho
Age = 440y
D = 2-5 kpc

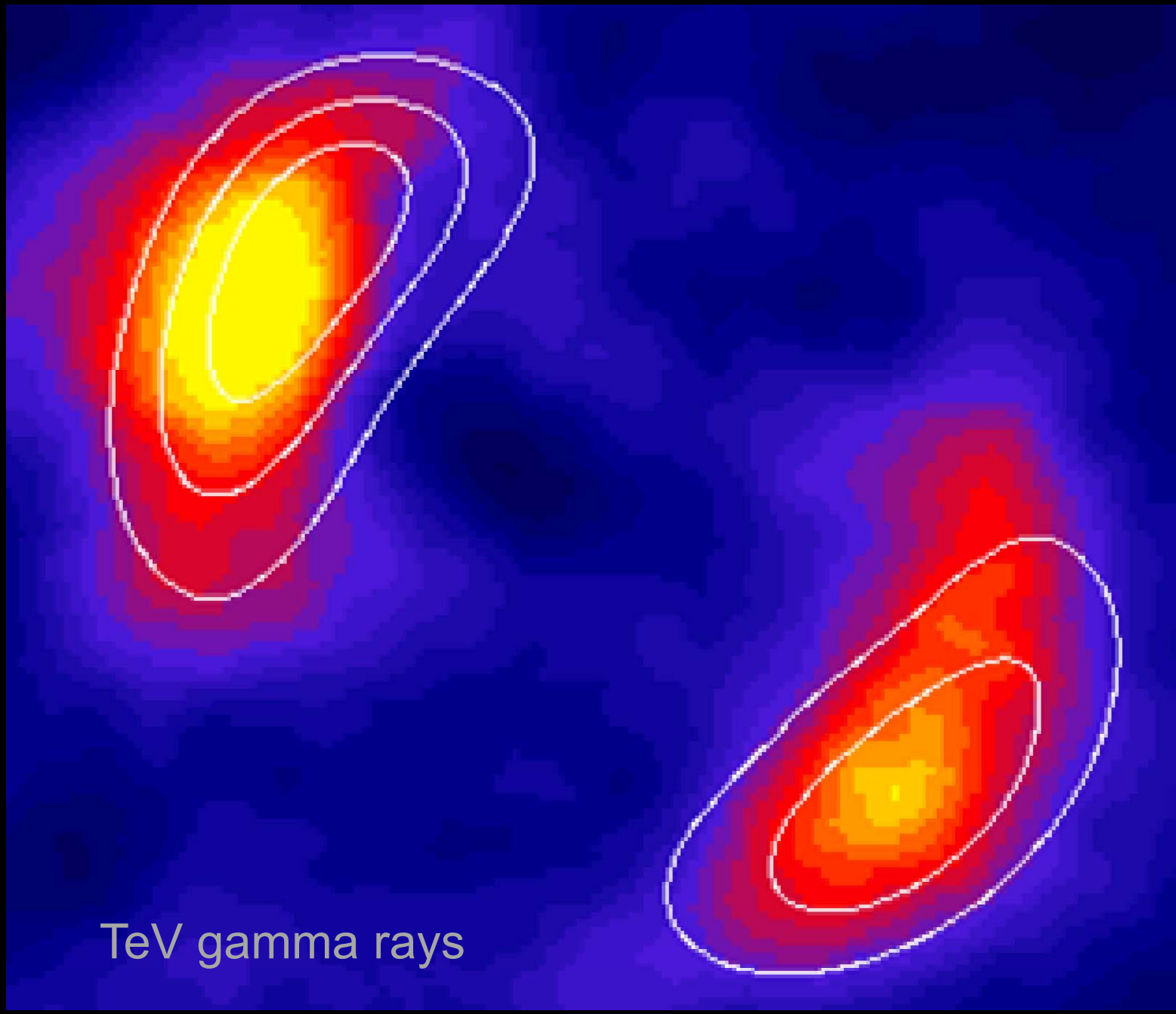


IC 443
Age ~ 30ky
D ~ 0.8kpc



G106.3+2.7
Age ~ 10ky
D ~ 0.8 kpc

SN 1006



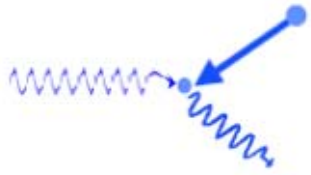
(Credit:X-ray: NASA/CXC/Rutgers/G.Cassam-Chenai, J.Hughes et al.; Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS)

SNR Questions

Supernova remnants accelerate particles to ~PeV energies!

Electrons → TeV γ-rays

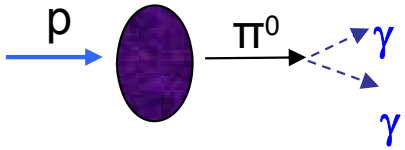
Up-scattering of soft photons



inverse-Compton scattering

Protons → TeV γ-rays

Target interaction, π^0 decay



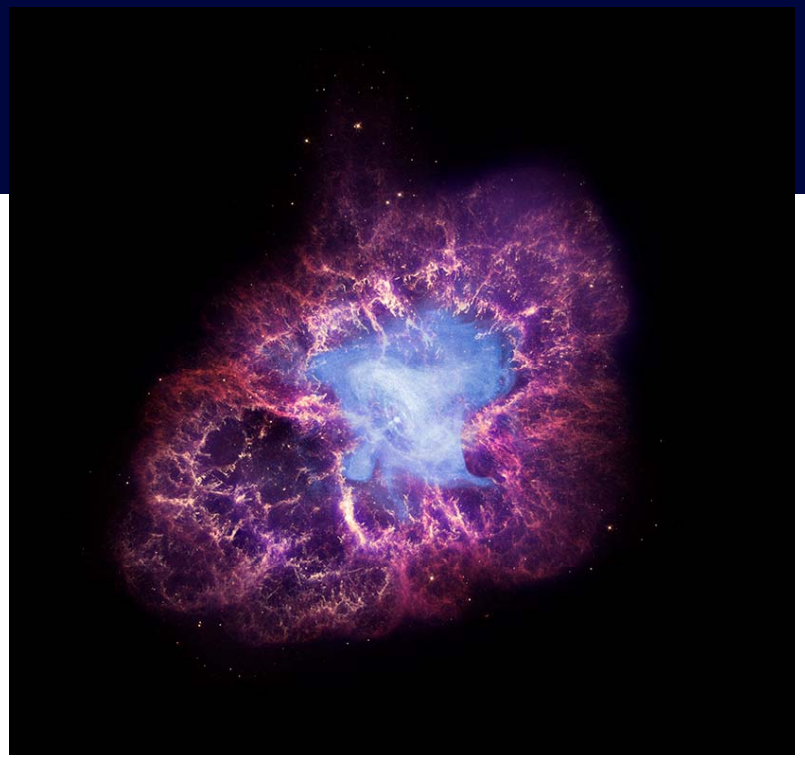
π^o and target material

but …

- Which particles are accelerated?
- Can we quantitatively account for the CR spectrum and yield?
- How and when are the particles released from the accelerator ?
- How do they propagate away from accelerator?

There is now good evidence for SNR acceleration of CRs, but there is still a lot to understand.

Crab



Crab Nebula and Pulsar

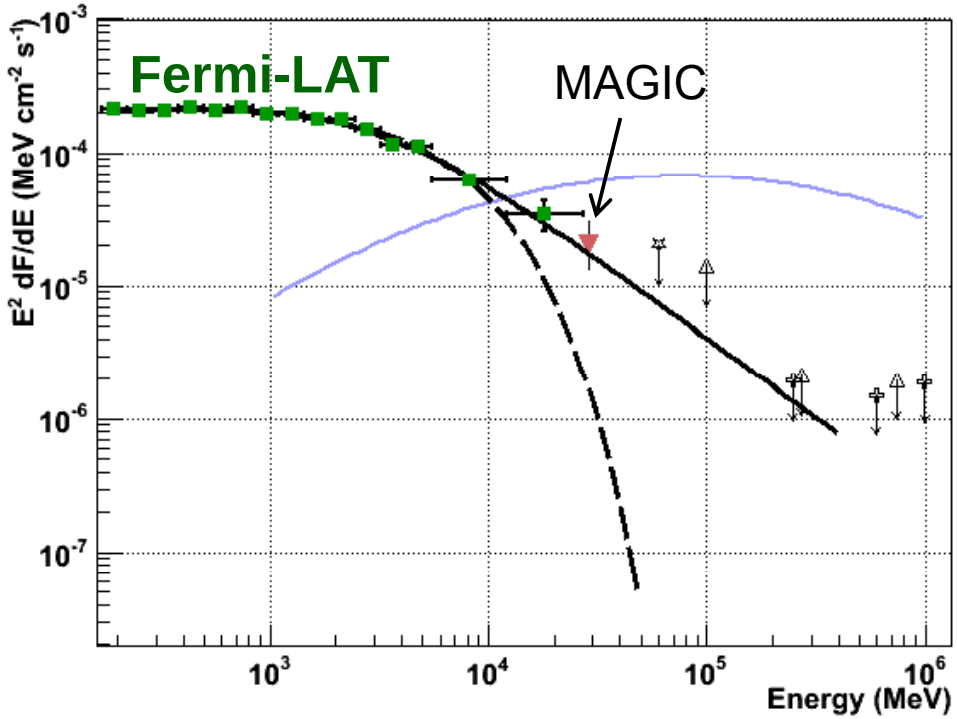
- Remnant from historical SN in 1054.
- One of the most energetic pulsars and brightest γ–ray pulsars.
- Nebula is the brightest, “steady" VHE γ-ray source. “Standard candle”.

γ-ray Observations of the Pulsar:

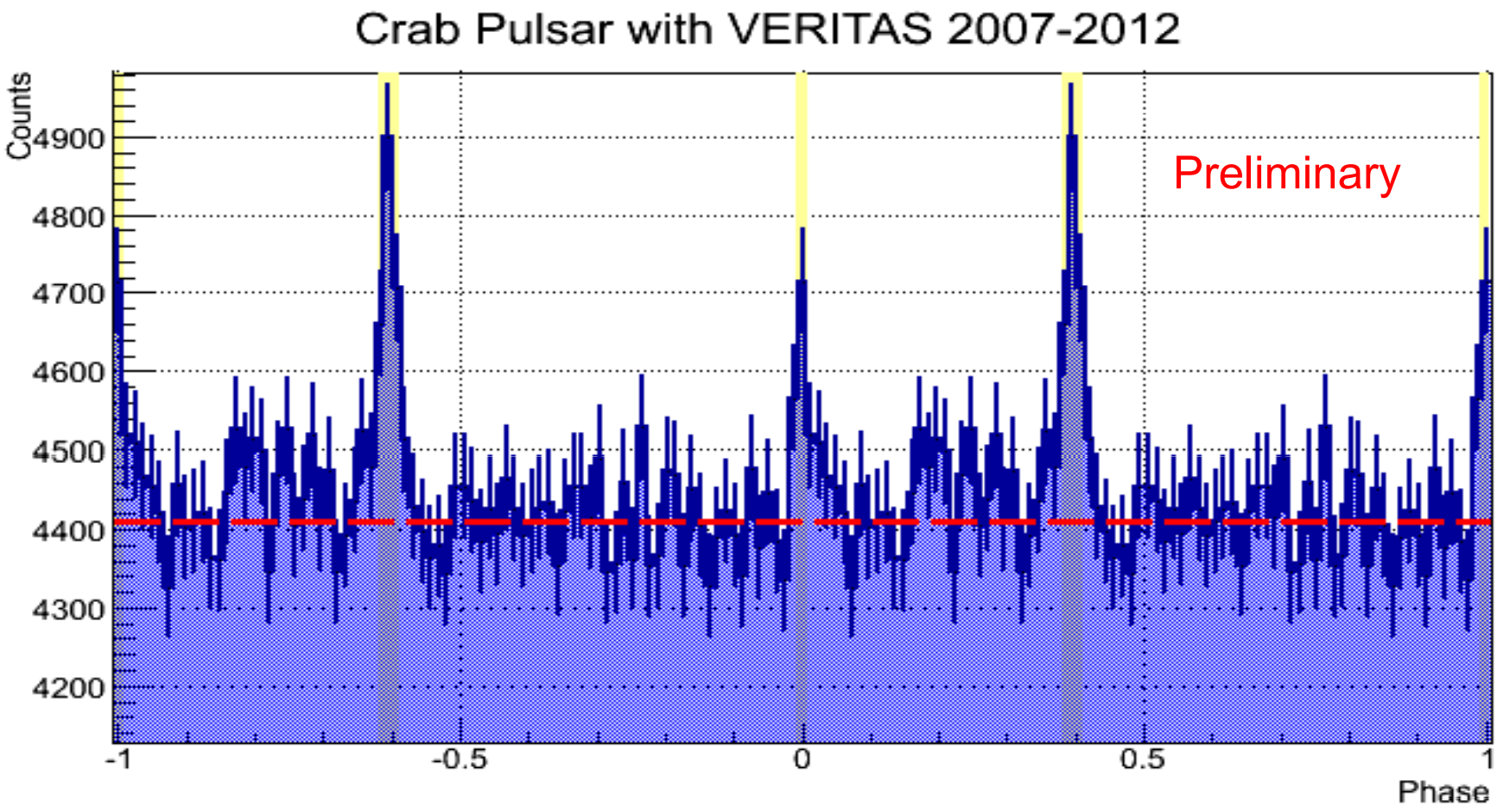
- **Fermi-LAT & MAGIC**
  Detections E<25 GeV, spectral break?
- **Limits from numerous Expts.**
  30-year effort to detect at VHE.

Conventional View:

- Single component with exponential cut-off.
- Production by curvature radiation.
- Emission from outer regions > 6 stellar radii.



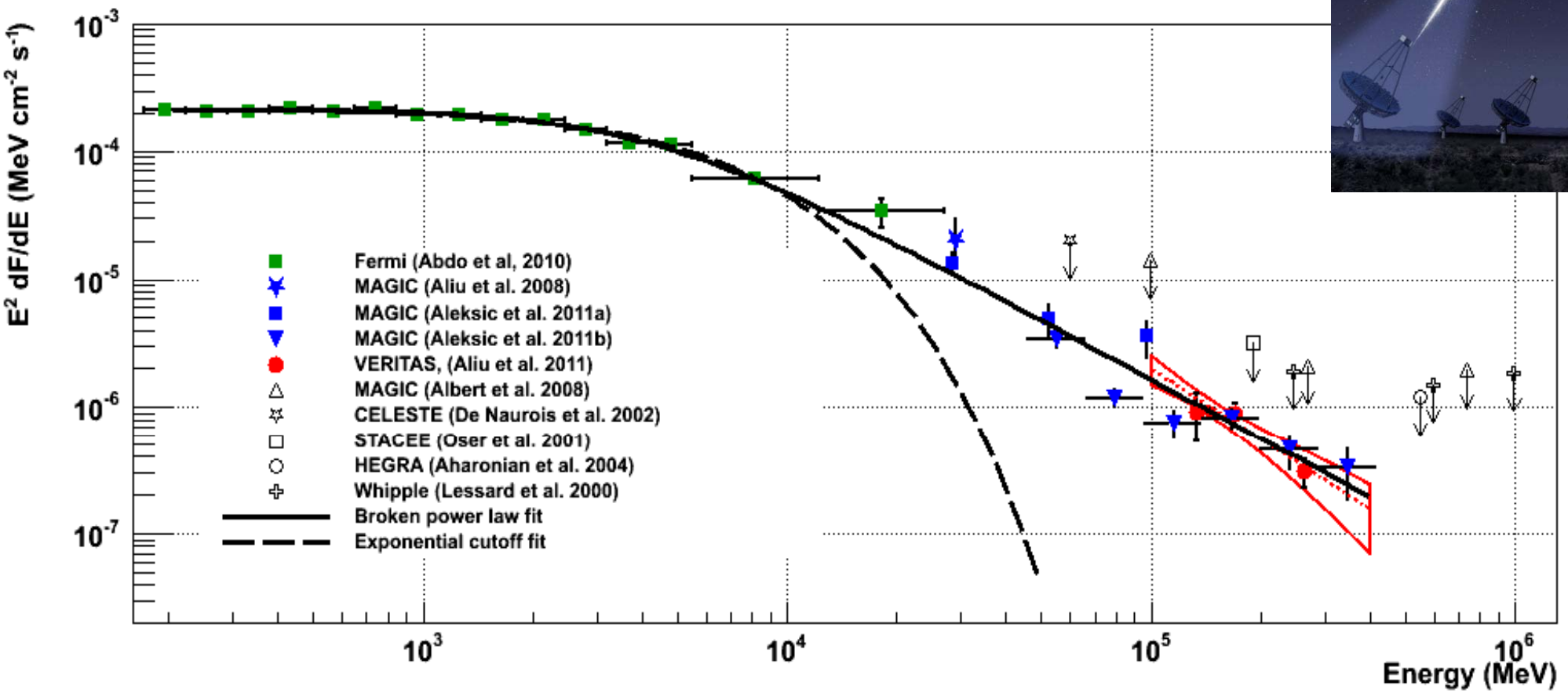
VERITAS Detection of Crab Pulsar



- 2007-09: 107h → clear two-peak pulsed signal.
- 2007-12, combined data: 130h, 10.7σ.
- 1514 ±145 total pulsed excess events.

E. Aliu et al.,
Science 334, 69 (2011)

The First VHE Pulsar

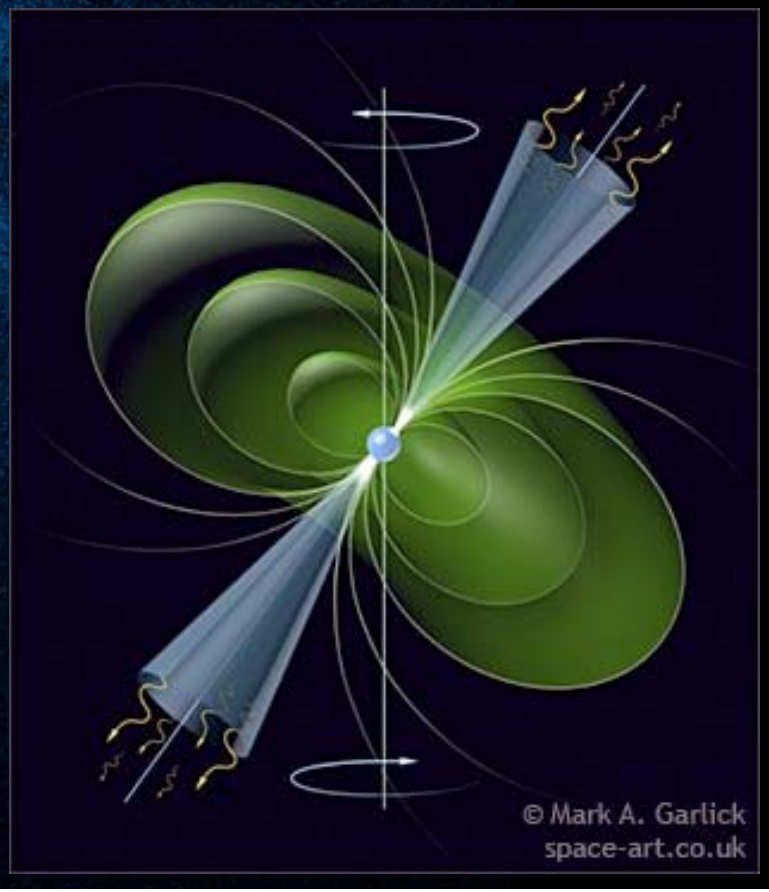


- VERITAS detection @ 280 GeV → emission region > 10 stellar radii.
- Detection above 100 GeV → new mechanism for γ-ray emission.
- Narrowing of pulses → tapered acceleration region ?
- Interesting limits on Lorentz invariance violation.
- VERITAS discovery now confirmed by MAGIC.

Crab Nebula Chandra X-ray

F. D. Seward, W. H. Tucker, R. A. Fesen

Alternatives to shock acceleration: Unipolar inductor mechanism



- Pulsed emission from pulsar magnetosphere
- Steady emission from extended electron nebula

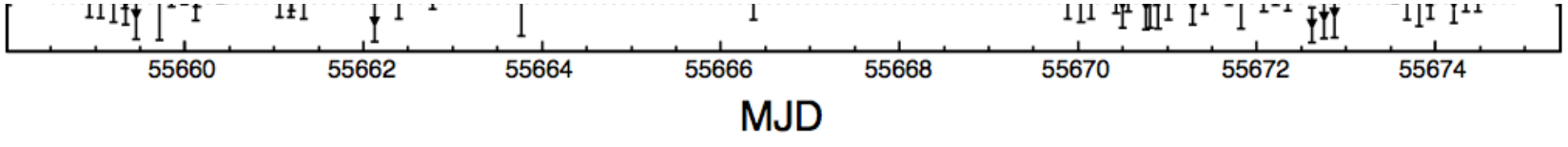
GeV Flaring

Normal

Crab Nebula

Flare State

April 2011



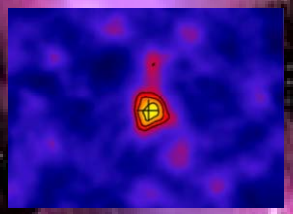
Active galactic nuclei and their jets

Active galactic nuclei and their jets

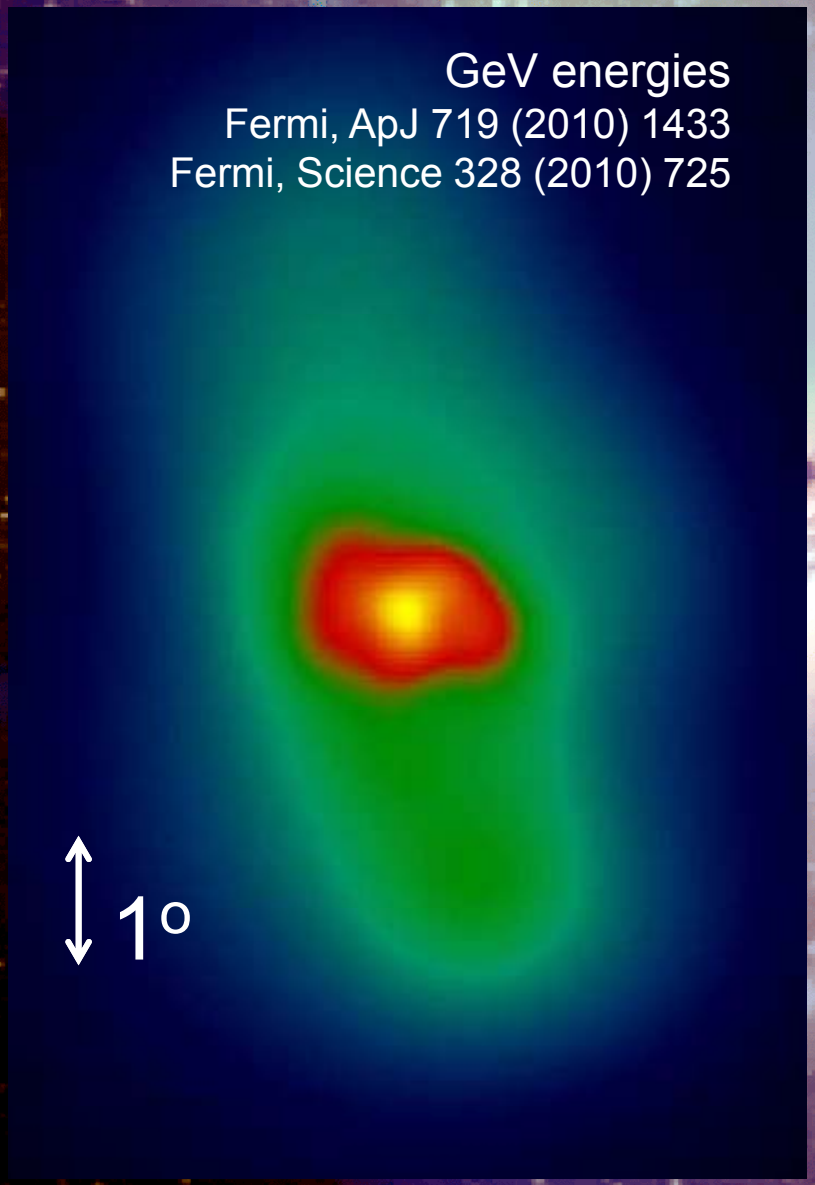
Radio

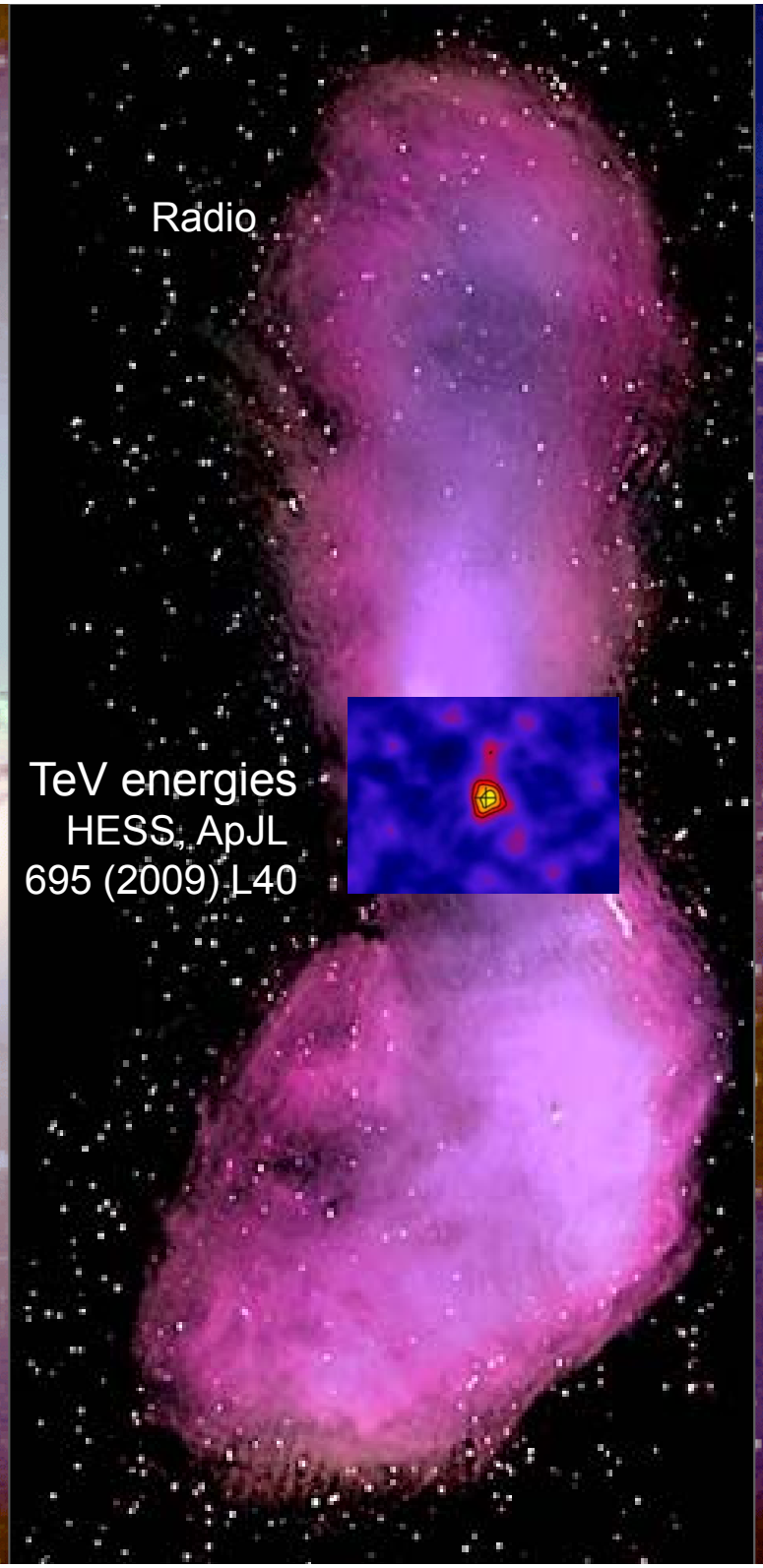
TeV energies

HESS, ApJL 695 (2009) L40



Active galactic nuclei and their jets

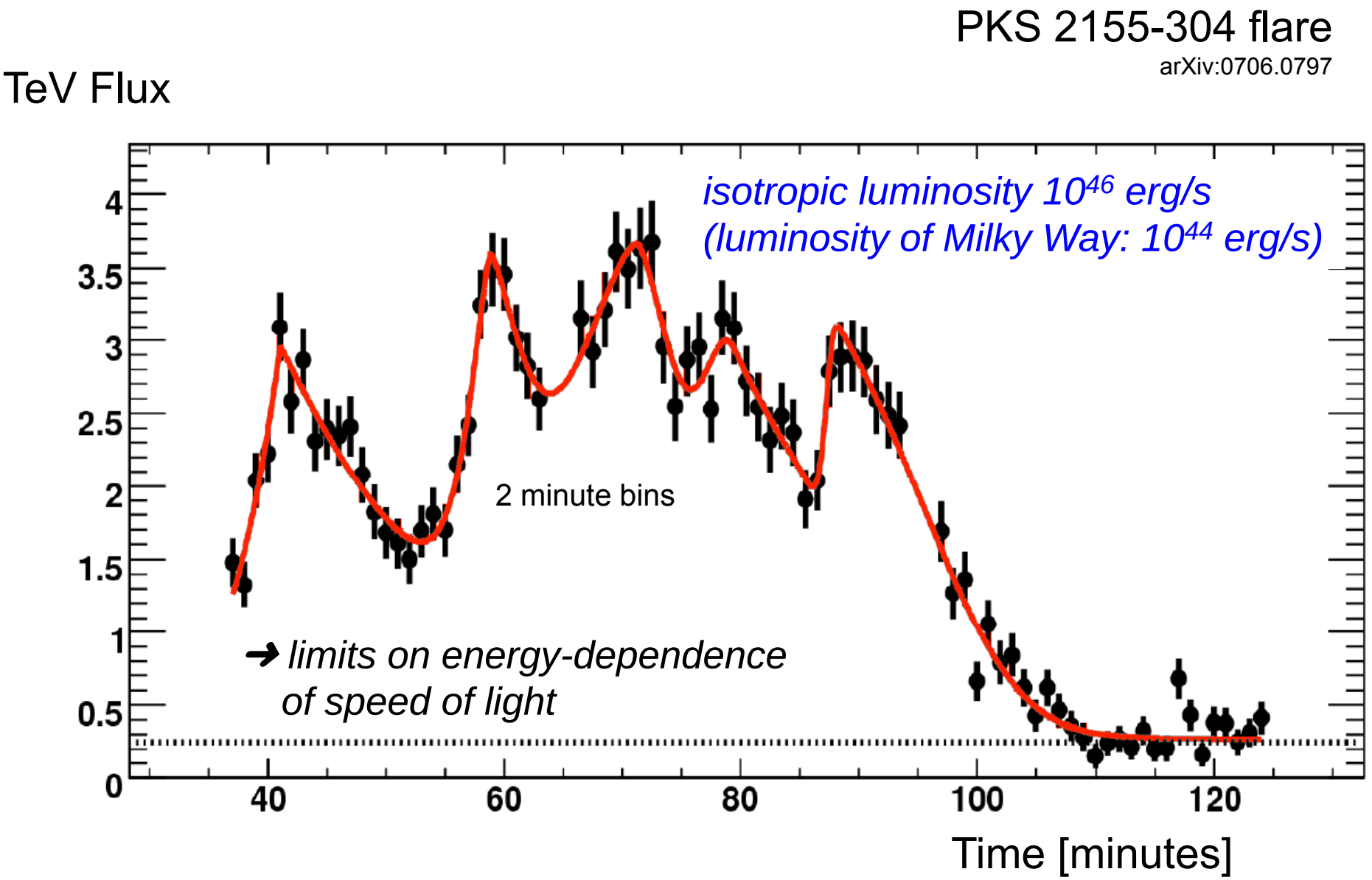




AGN: Extreme Blazar Variability

PKS 2155-304 flare

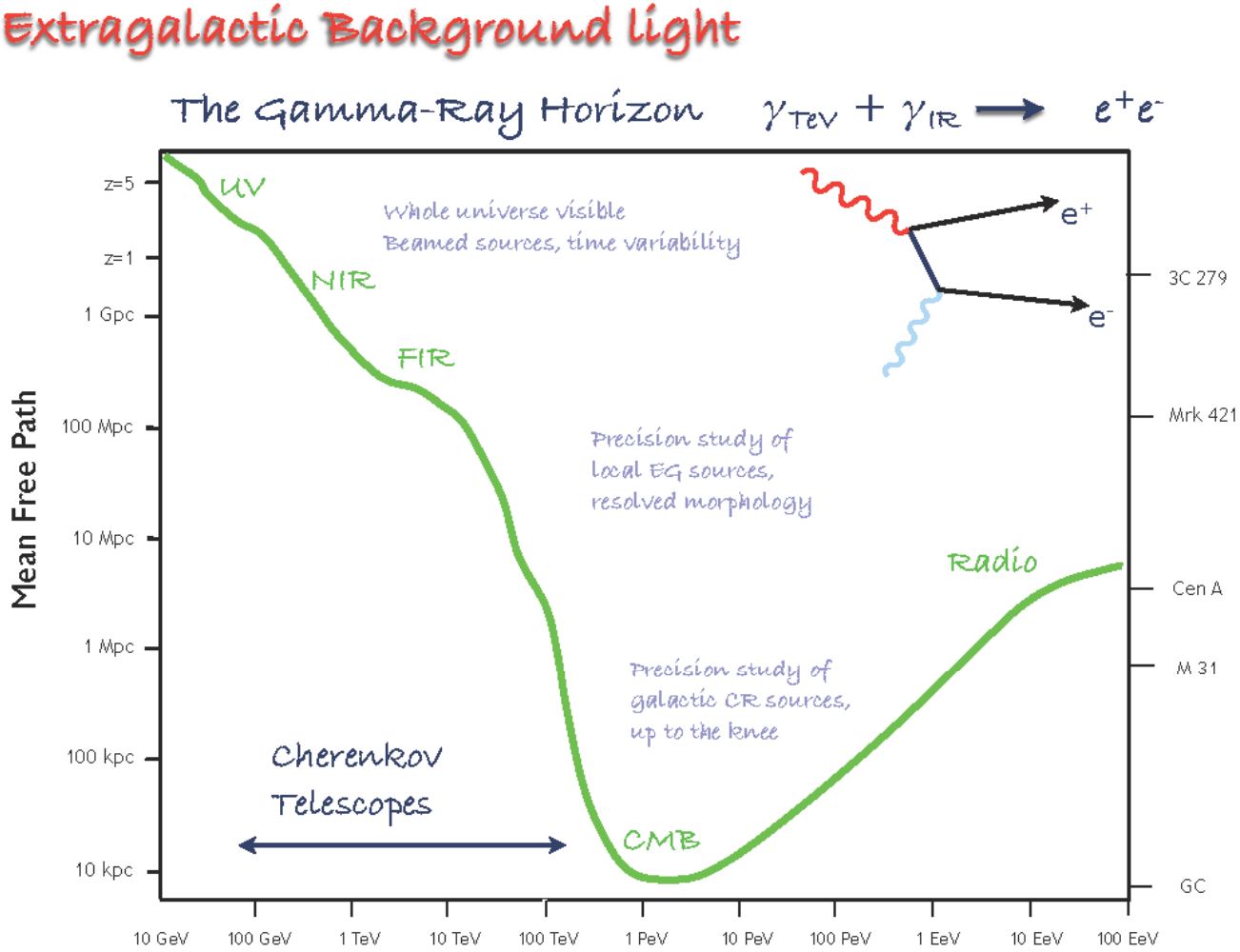
arXiv:0706.0797



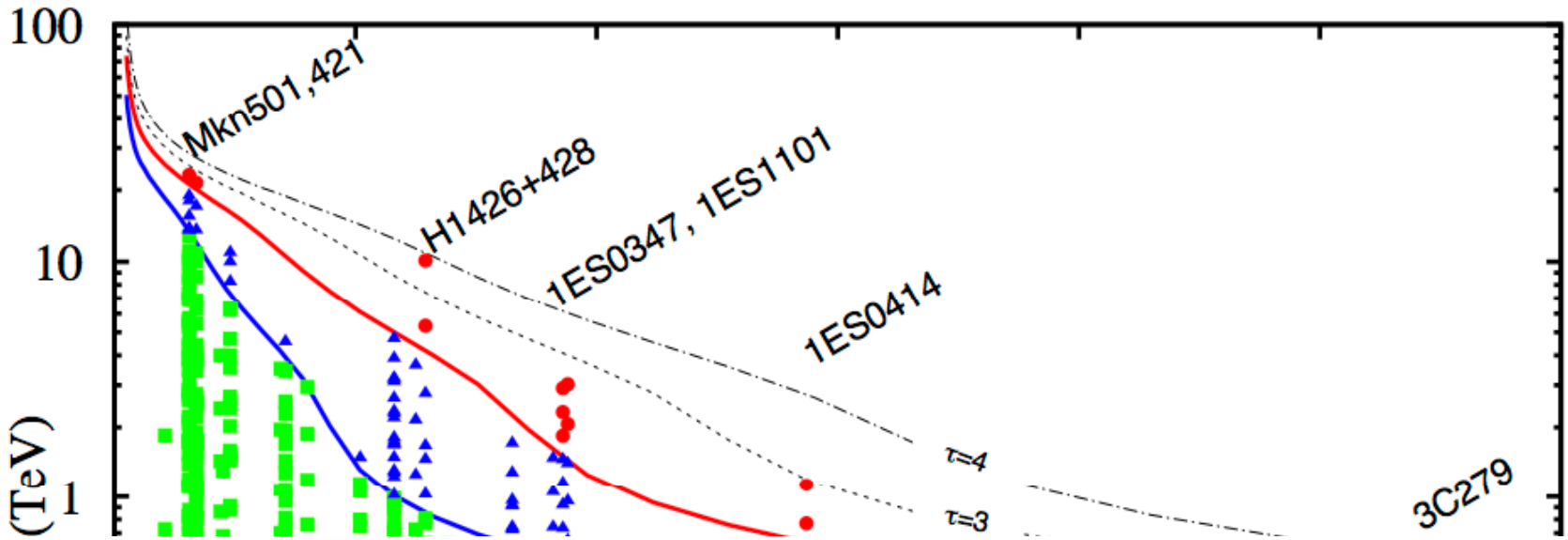
AGN as Cosmological Probes

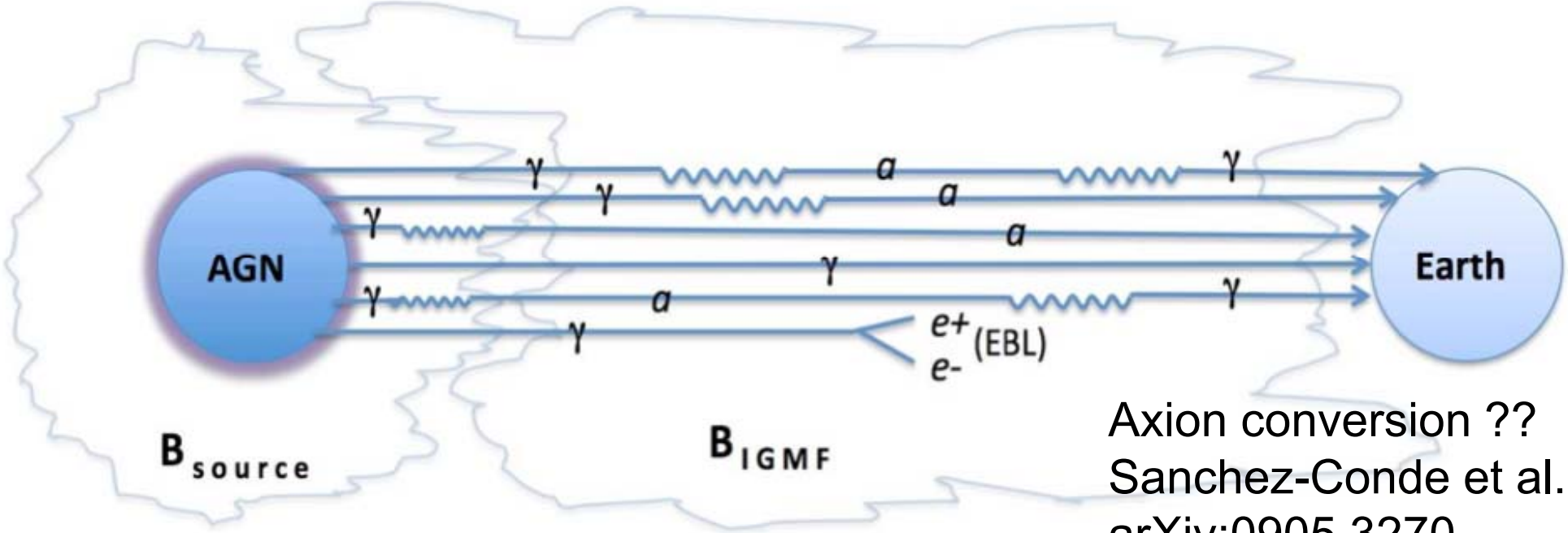
Extragalactic Background Light (EBL): rich subject with lots of science:

- EBL carries imprint of star formation history & evolution.
- $\gamma\gamma$ interaction probes EBL density & uniformity.
- Potential way to measure tiny extragalactic magnetic field (EGMF).
  B ~ 10^{-9} - 10^{-18} G



AGN: Is the Universe too Transparent ?

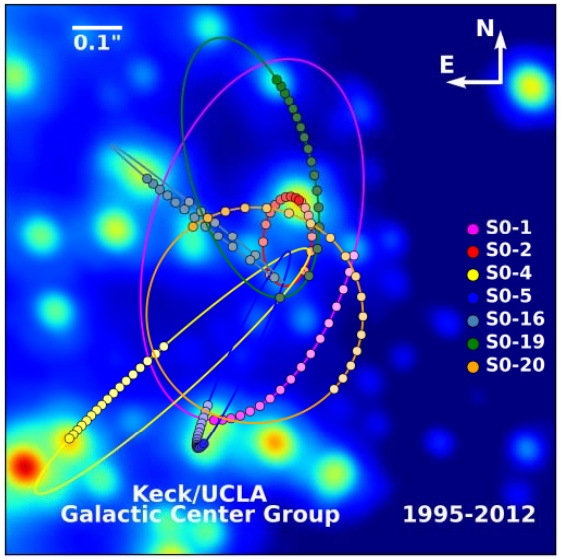




Axion conversion ??
Sanchez-Conde et al.,
arXiv:0905.3270

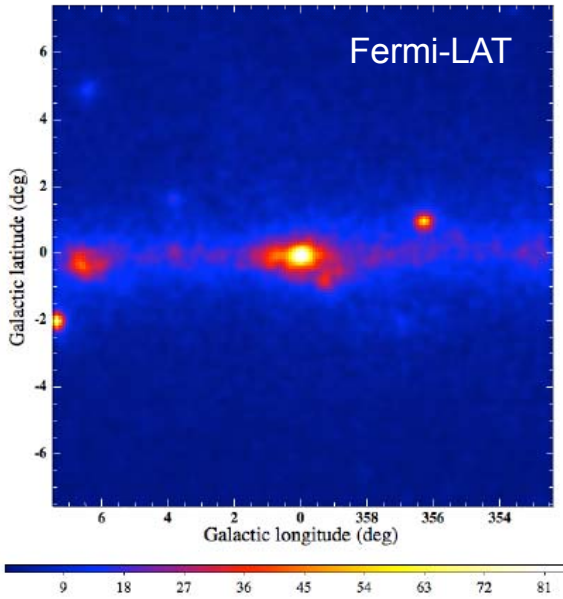
UnID Sources: Galactic Center

Infrared



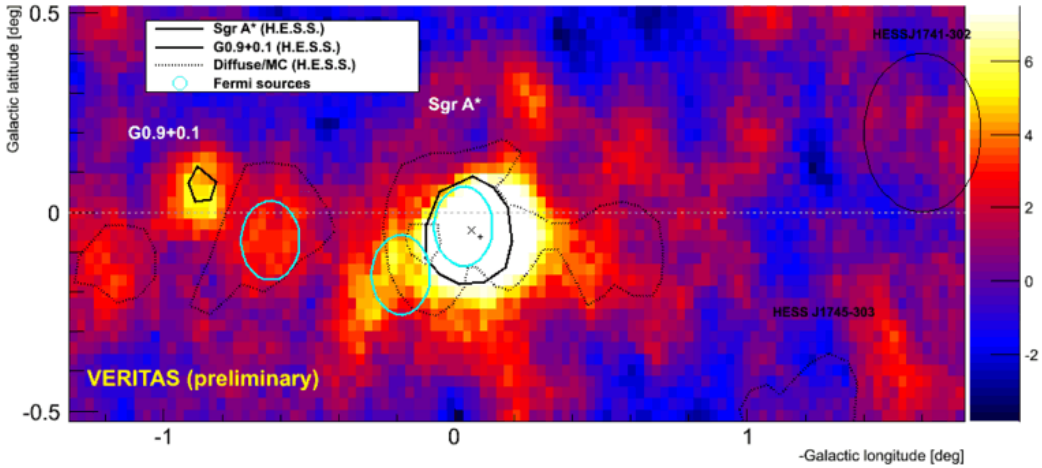
Ghez et al., 2012
1″ x 1″

GeV γ-rays



S. Murgia,
"Dark Attack 2012"
15° x 15°

TeV γ-rays



M. Beilicke et al.
"Gamma 2012"
1° x 3°

GeV & TeV emission is:

- **Intense & non-thermal**
- **totally unexpected**
- **not understood !**

Dark Matter ??

Dark Matter Detection

$\chi\chi \rightarrow qq, \gamma\gamma \ldots$

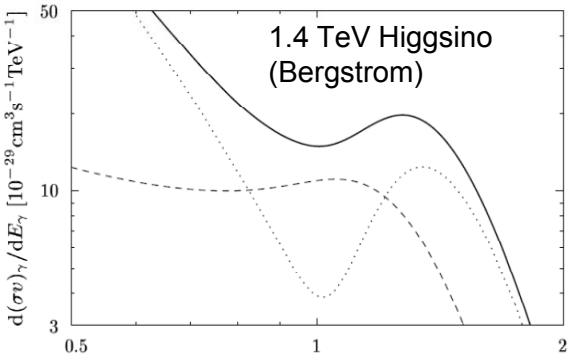
Gamma rays from DM annihilation:

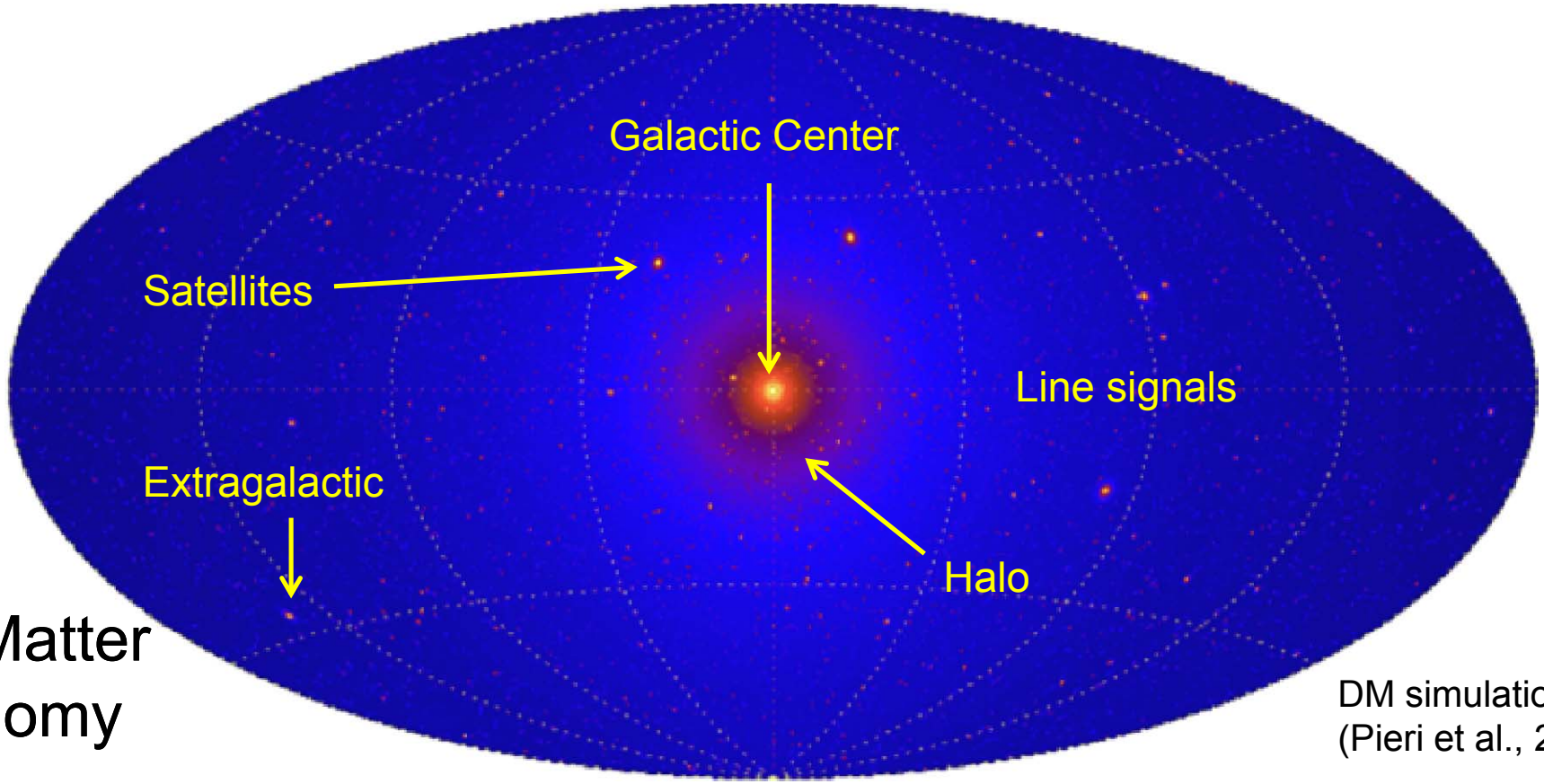
particle physics

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

DM distribution

"Universal" Spectrum



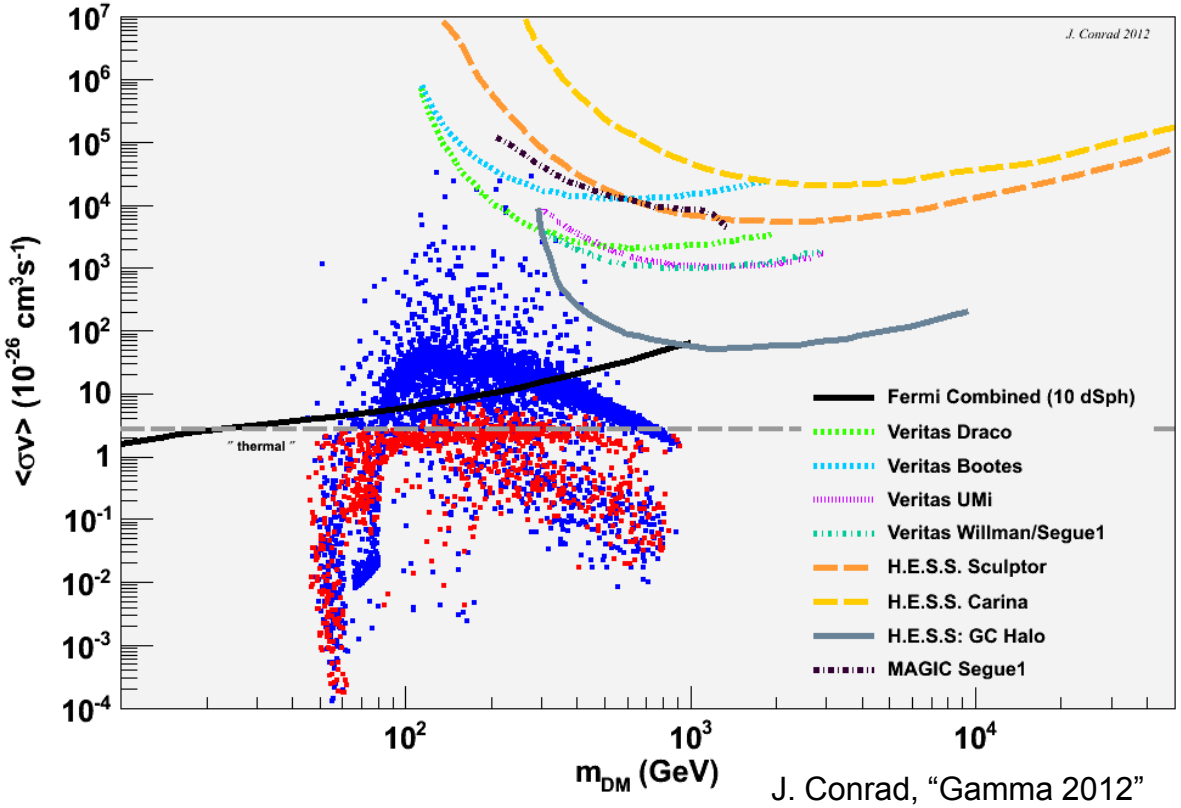


Dark Matter Astronomy

DM simulation (Pieri et al., 2011)

Dark Matter Results

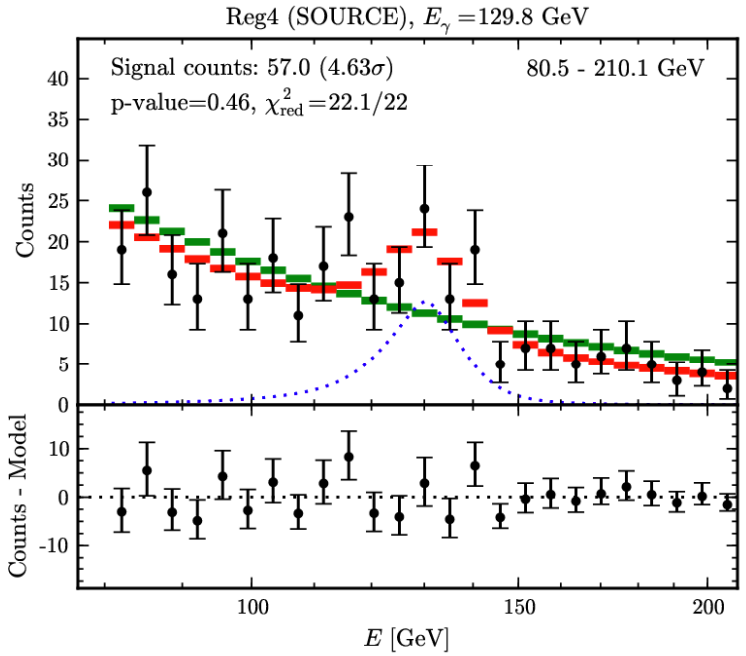
γ-ray DM limits



J. Conrad, "Gamma 2012"

But ...

C. Weniger, "Gamma 2012"



No signal (yet)

- Limits at or approaching thermal relic cross section.
- VHE instruments probe high mass region not easily accessible.

Evidence for line at ~130 GeV

- ~4σ (post trials).
- seen by several authors.
- close to Galactic center.
- systematic effect ?
- can be confirmed or refuted.

Summary of Key Science Topics

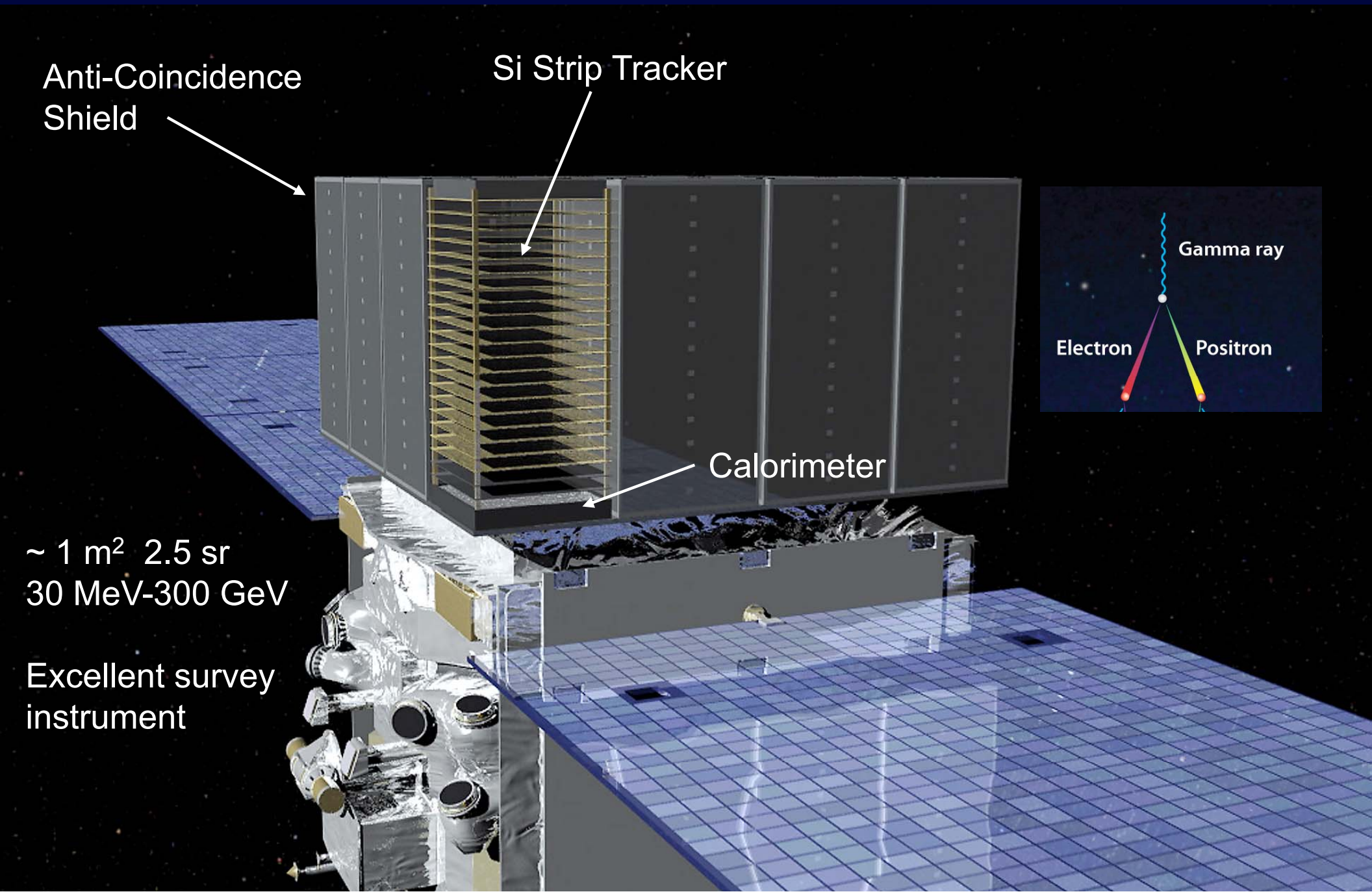
Bottom line: GeV and TeV gamma-ray sources are ubiquitous in the universe and probe extreme particle acceleration and particle interactions and propagation.

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?

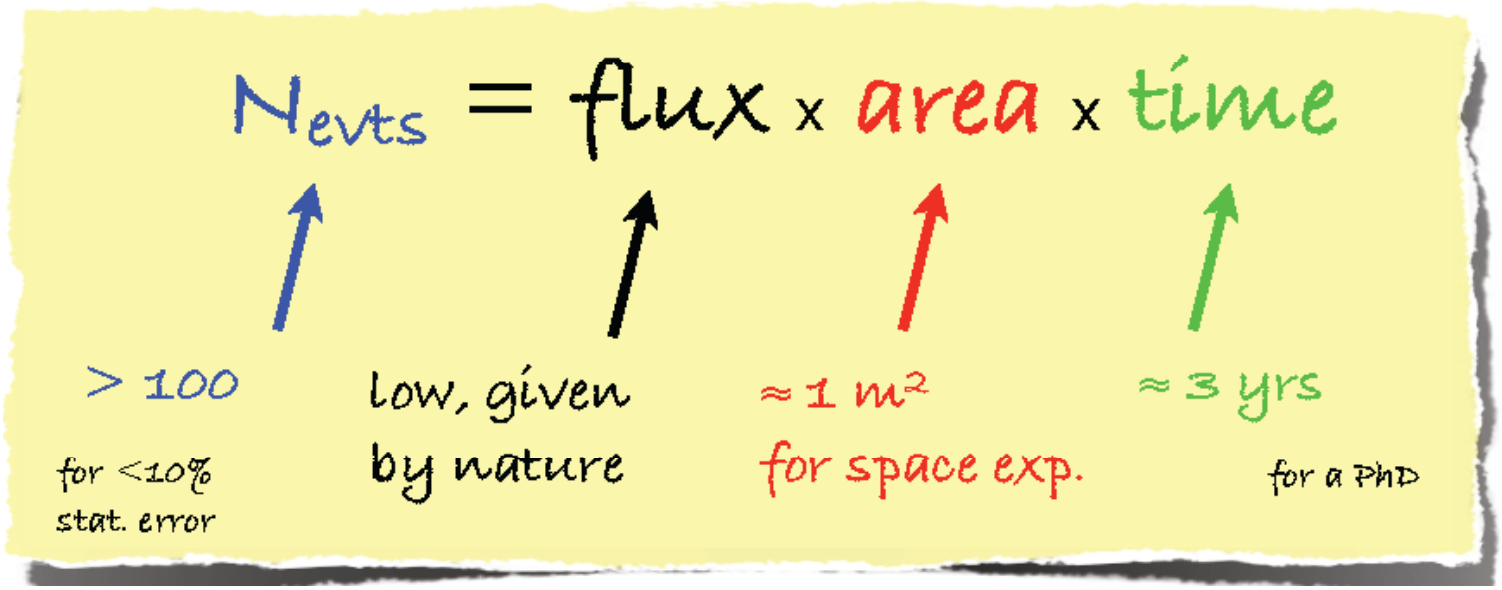
Bonus: Non-VHE science: e.g. optical interferometry, OSETI, etc.

Experimental Techniques

Fermi Large Area Telescope (LAT)



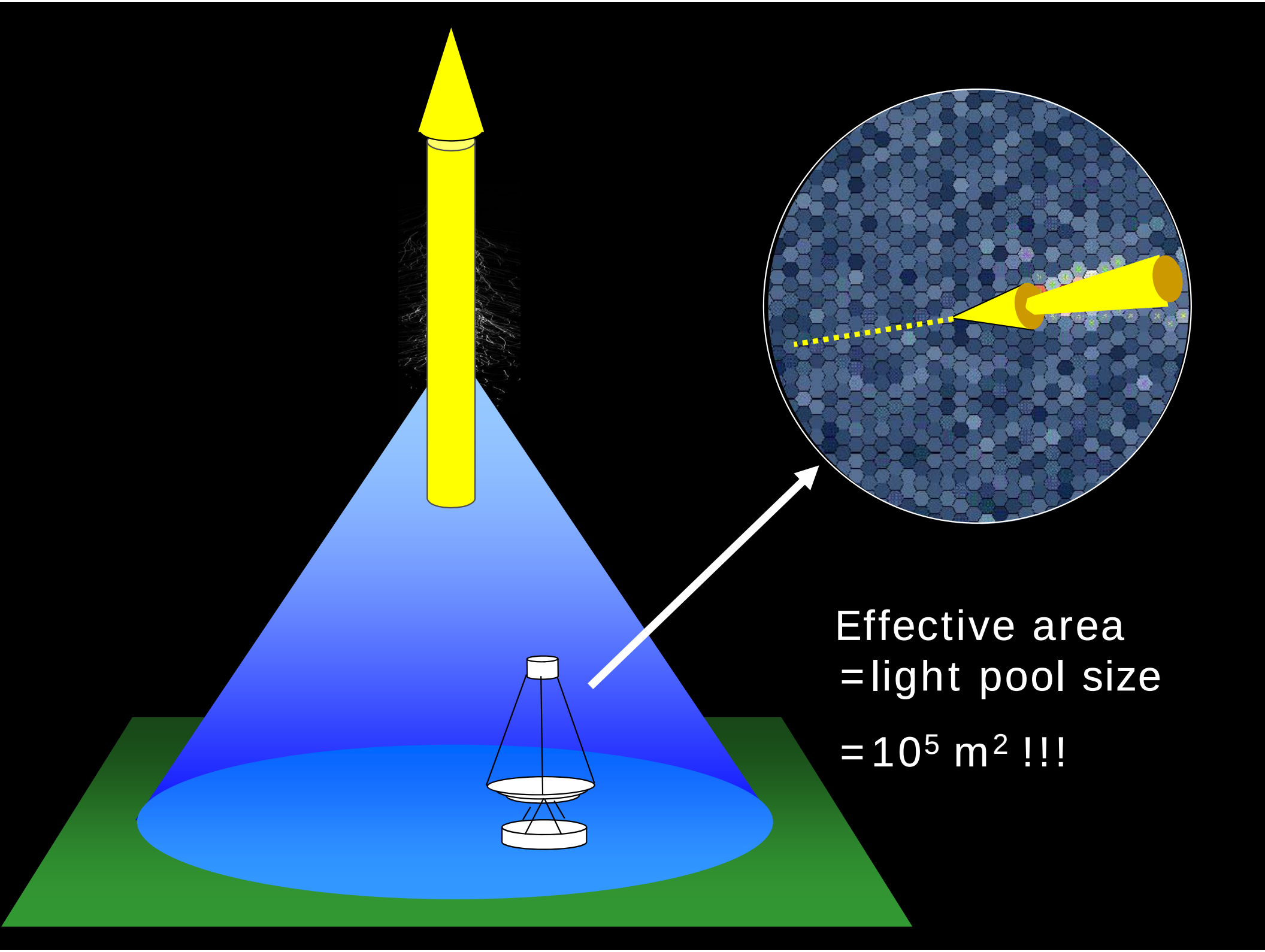
Beyond 100 GeV



Steeply falling spectrum:

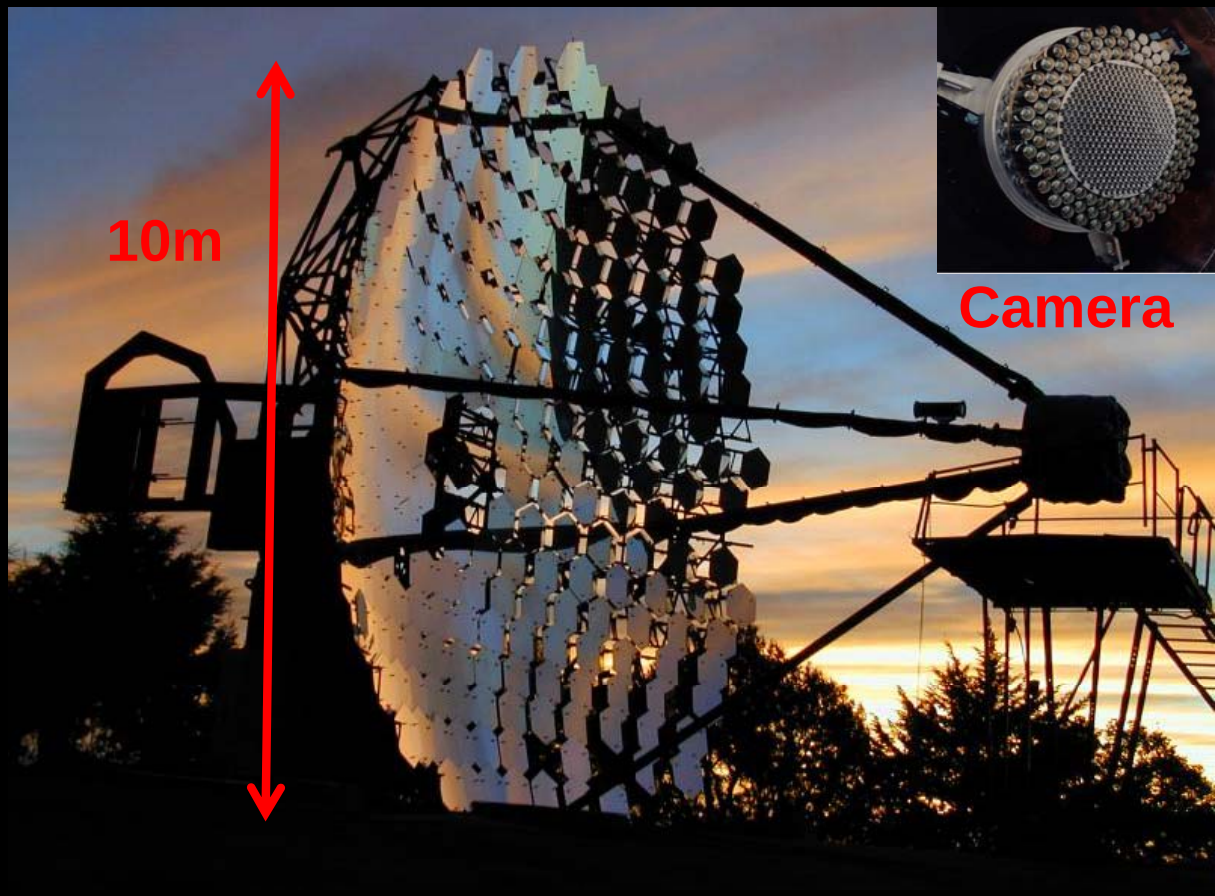
10x in Energy → / 100-500 in flux

- Large effective area needed to get detectable signals at VHE
- Natural detector: *the atmosphere*

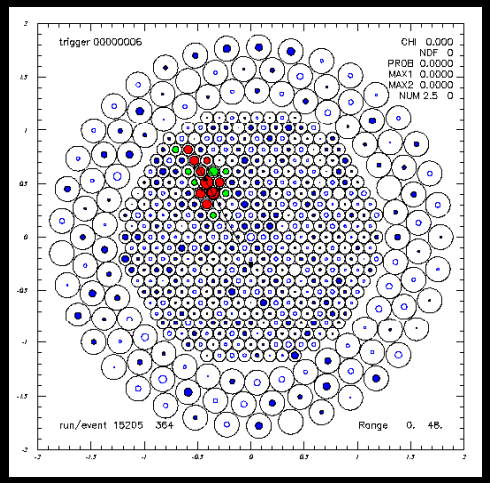

Effective area
=light pool size
=10^5 m^2 !!!

Whipple 10m γ-ray Telescope (1968-2011)

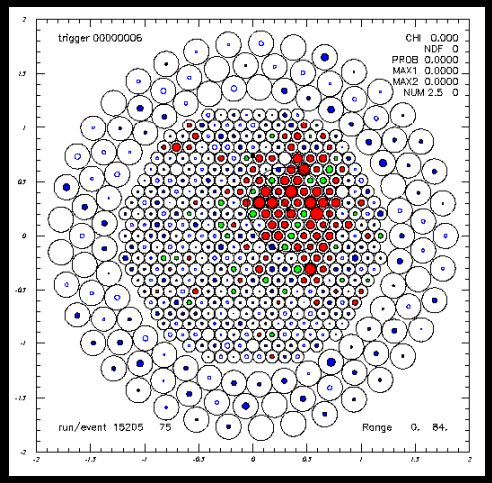
- Mt Hopkins, AZ
- Pioneered use of Imaging (T. Weekes et al.)
- Made first source detection. (Crab Nebula in ~90 hours)



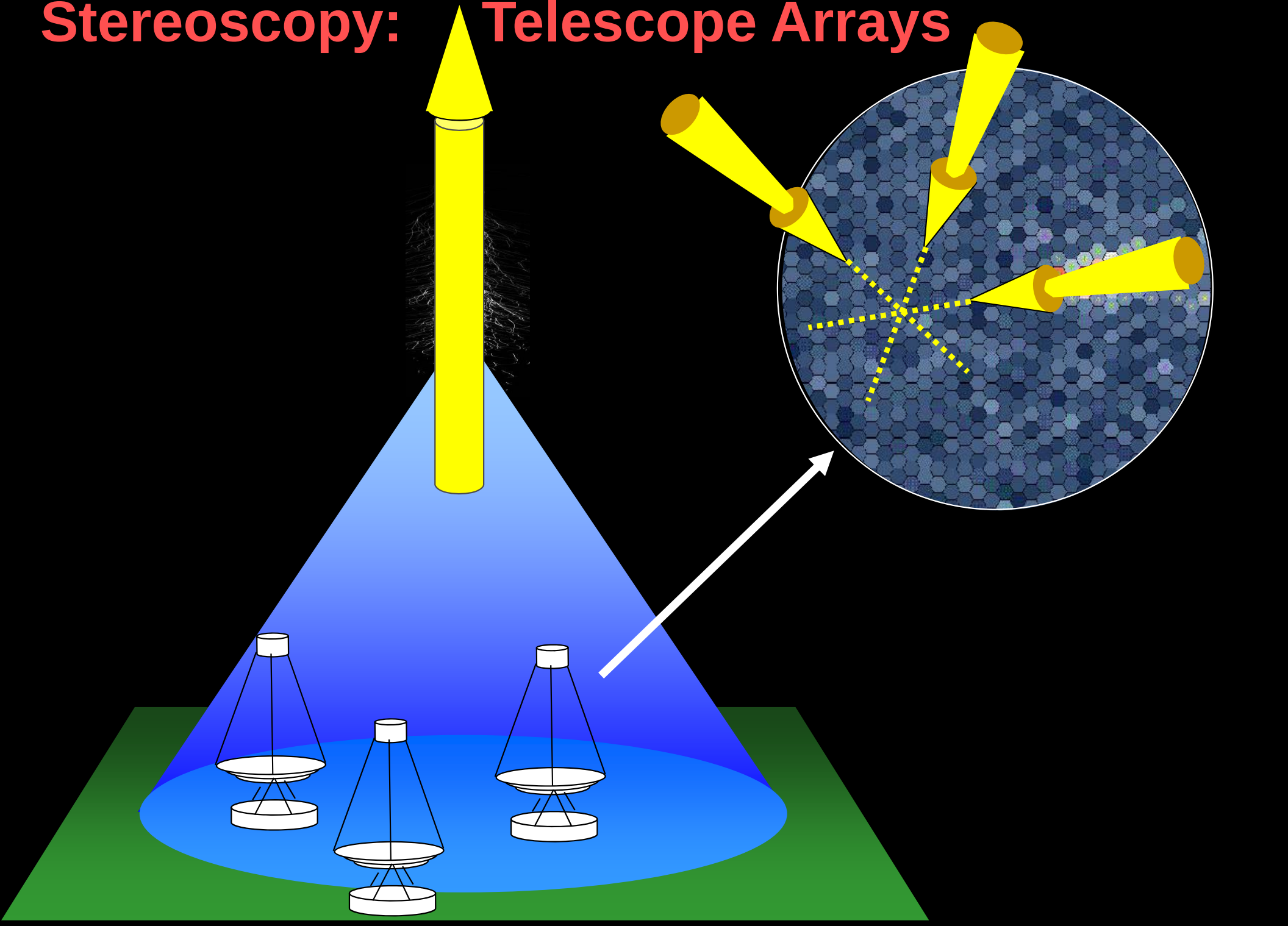
γ-ray



cosmic ray



Stereoscopy: Telescope Arrays



VHE Telescopes World-Wide

MAGIC

ARGO / YBJ

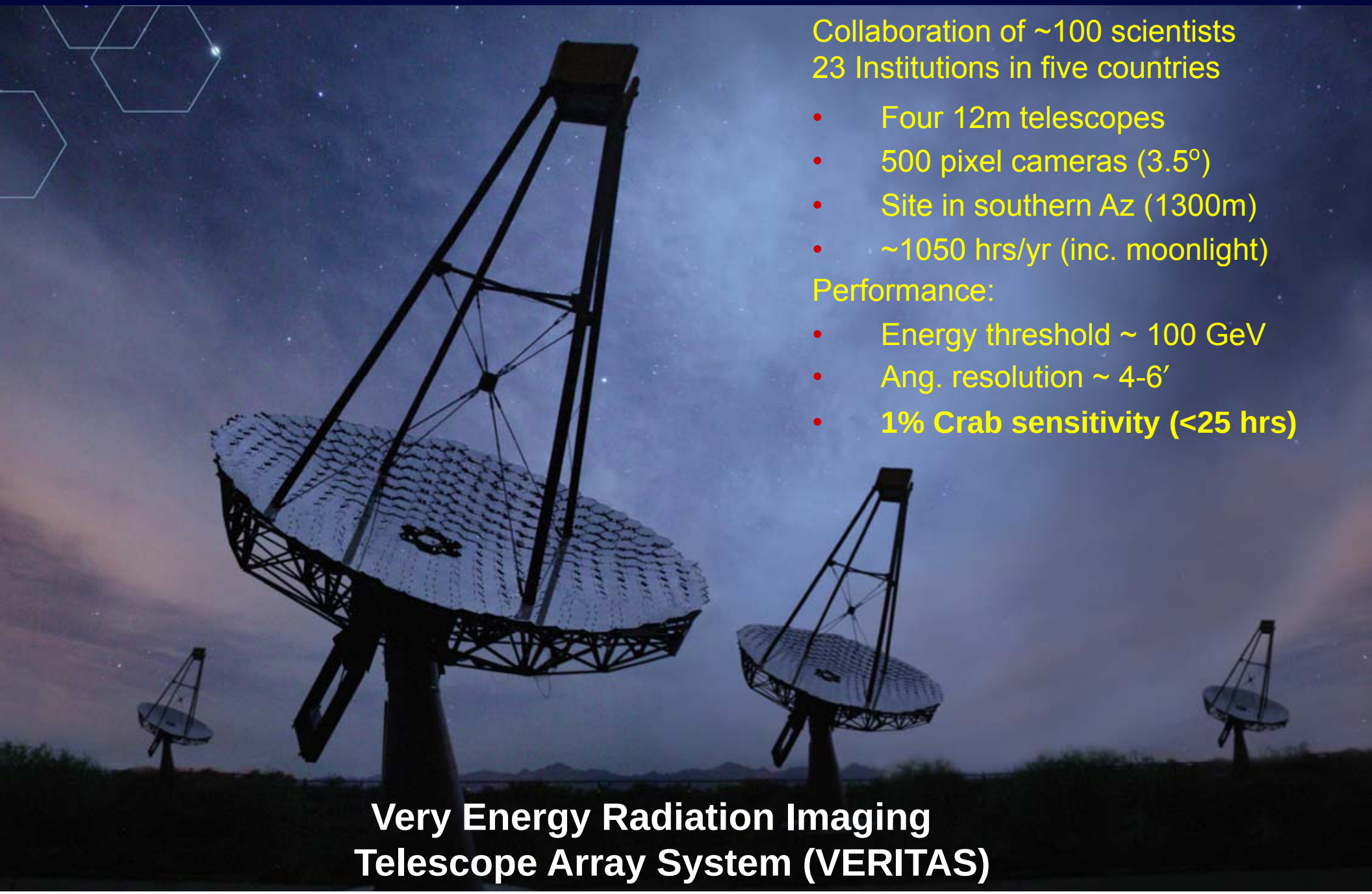
VERITAS

ARGO/YBJ

HESS

CANGAROO III

VERITAS



Collaboration of ~100 scientists
23 Institutions in five countries

- Four 12m telescopes
- 500 pixel cameras (3.5º)
- Site in southern Az (1300m)
- ~1050 hrs/yr (inc. moonlight)

Performance:

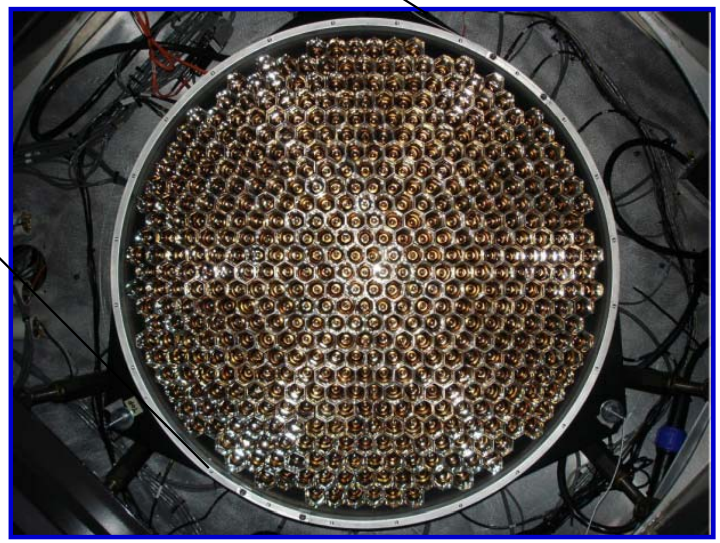
- Energy threshold ~ 100 GeV
- Ang. resolution ~ 4-6′
- **1% Crab sensitivity (<25 hrs)**

Very Energy Radiation Imaging Telescope Array System (VERITAS)

A VERITAS Telescope

12m reflector, f1.0 optics

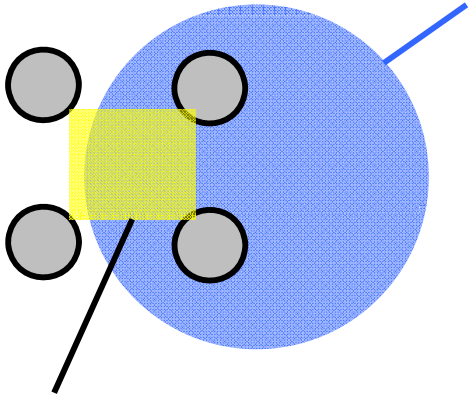
350 Mirror Facets



500 pixel Camera

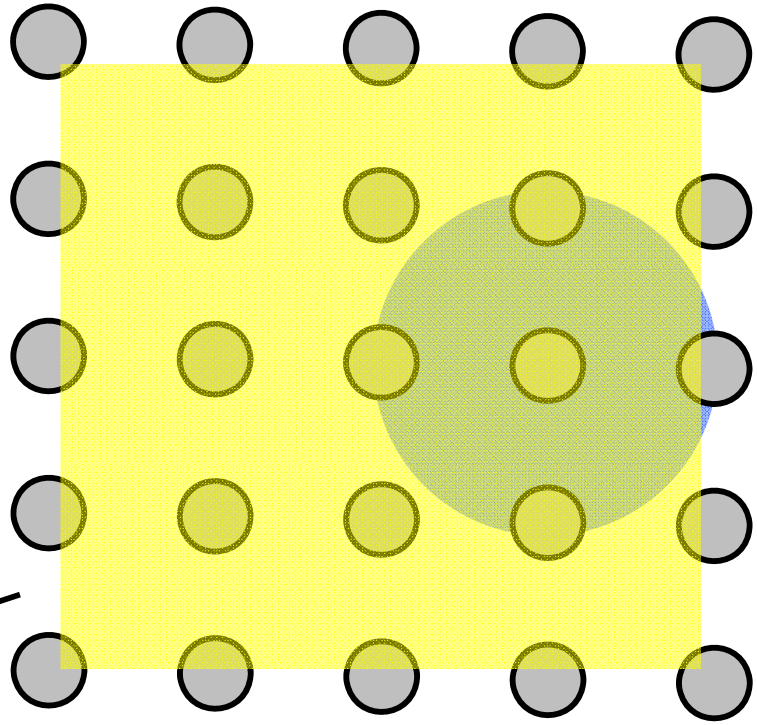
Motivating CTA

From current arrays to CTA



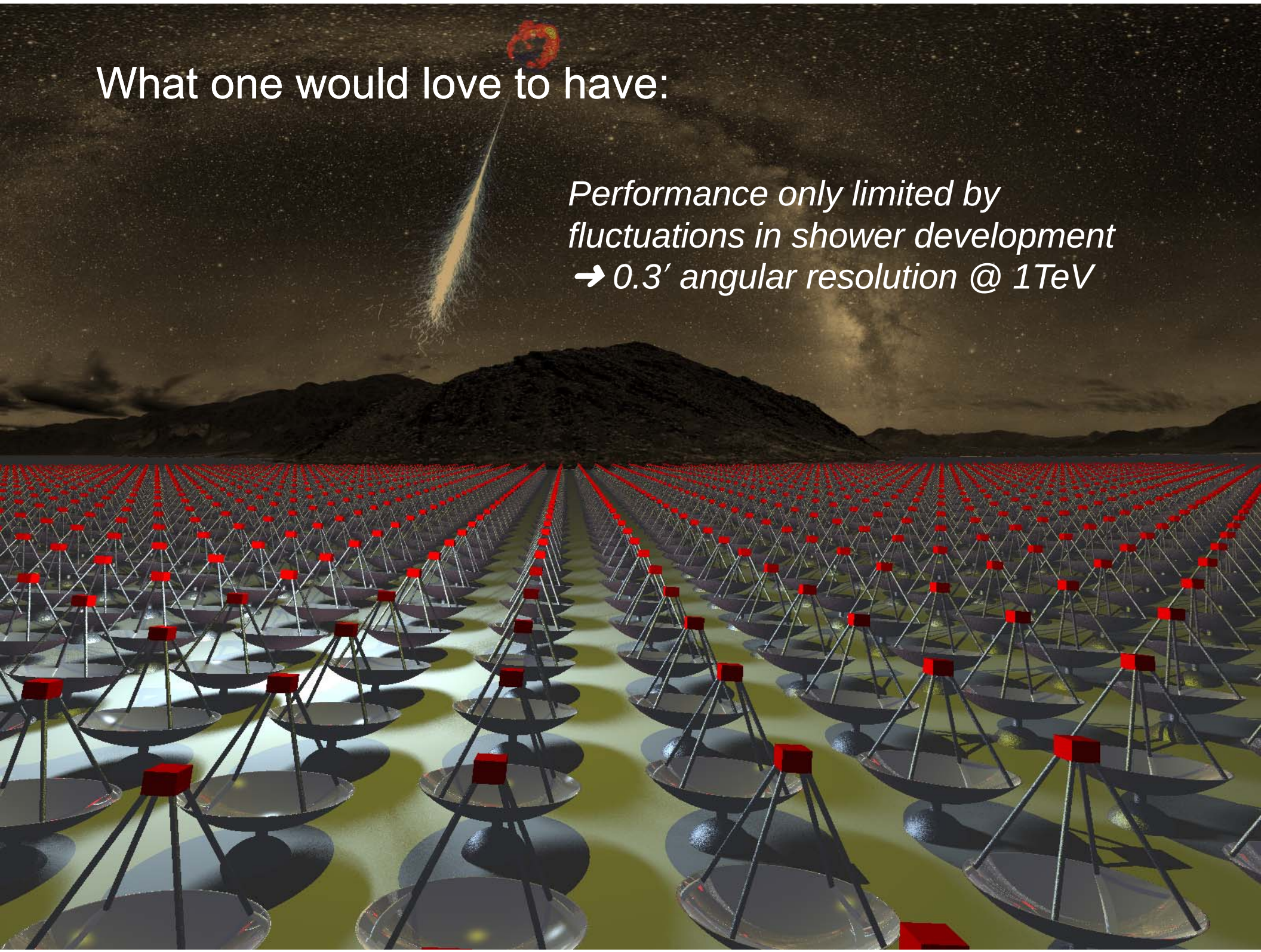
light pool radius
R ≈100-150 m
≈ typical telescope spacing

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



Large detection area
more images per shower
lower trigger threshold

What one would love to have:

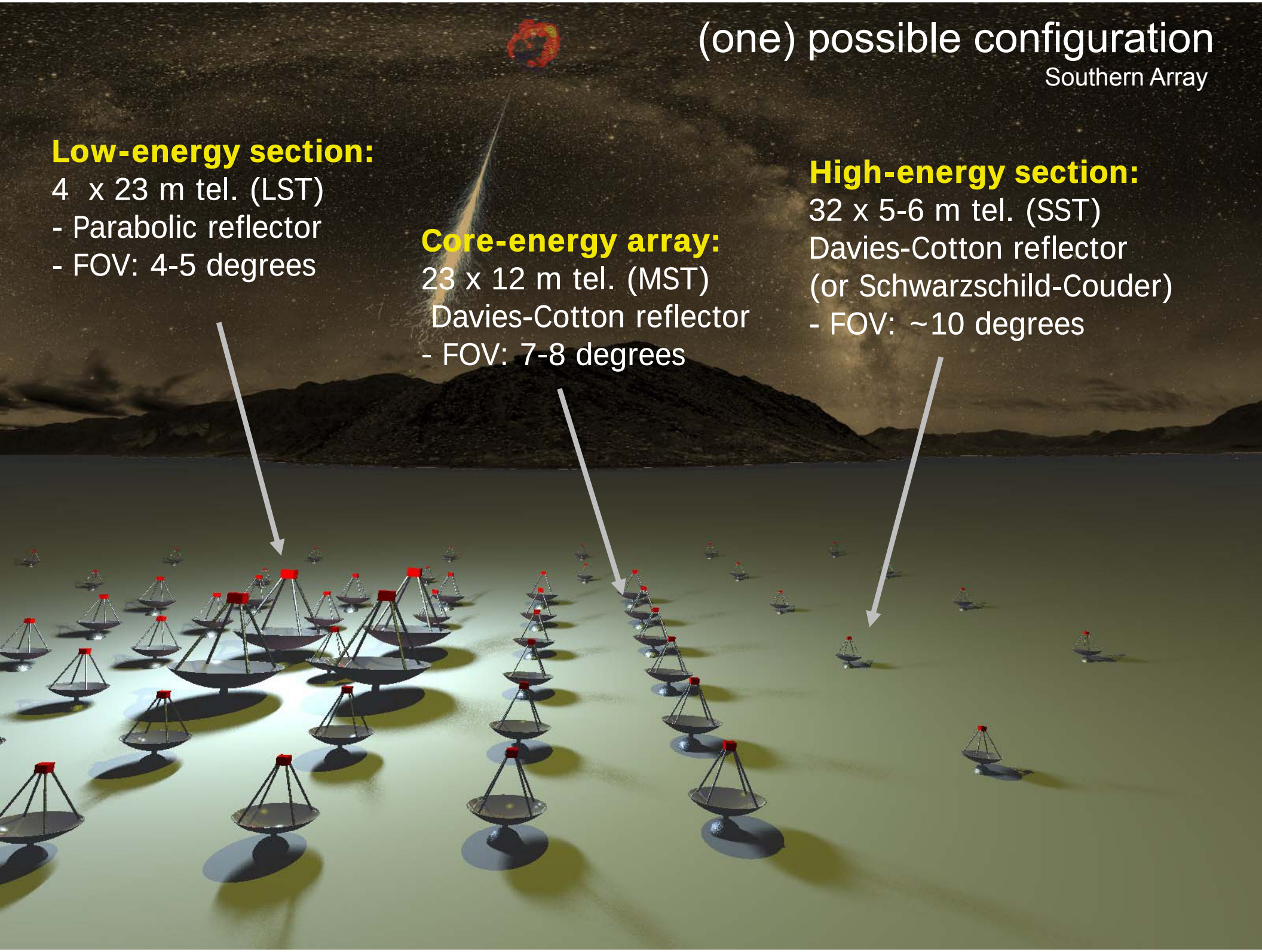


Performance only limited by fluctuations in shower development
➜ 0.3′ angular resolution @ 1TeV

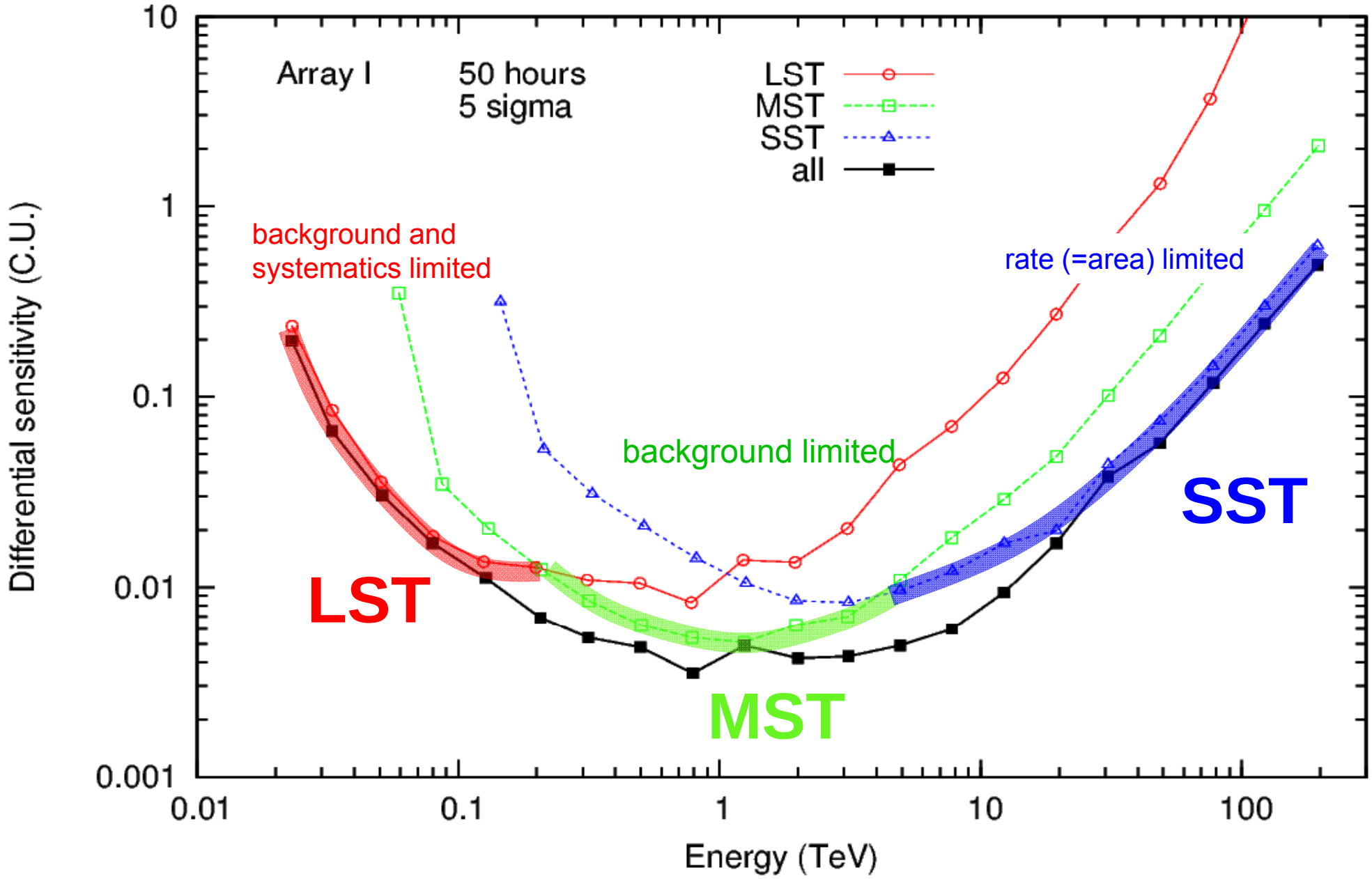
What one can (hopefully) afford:

Key design goals:

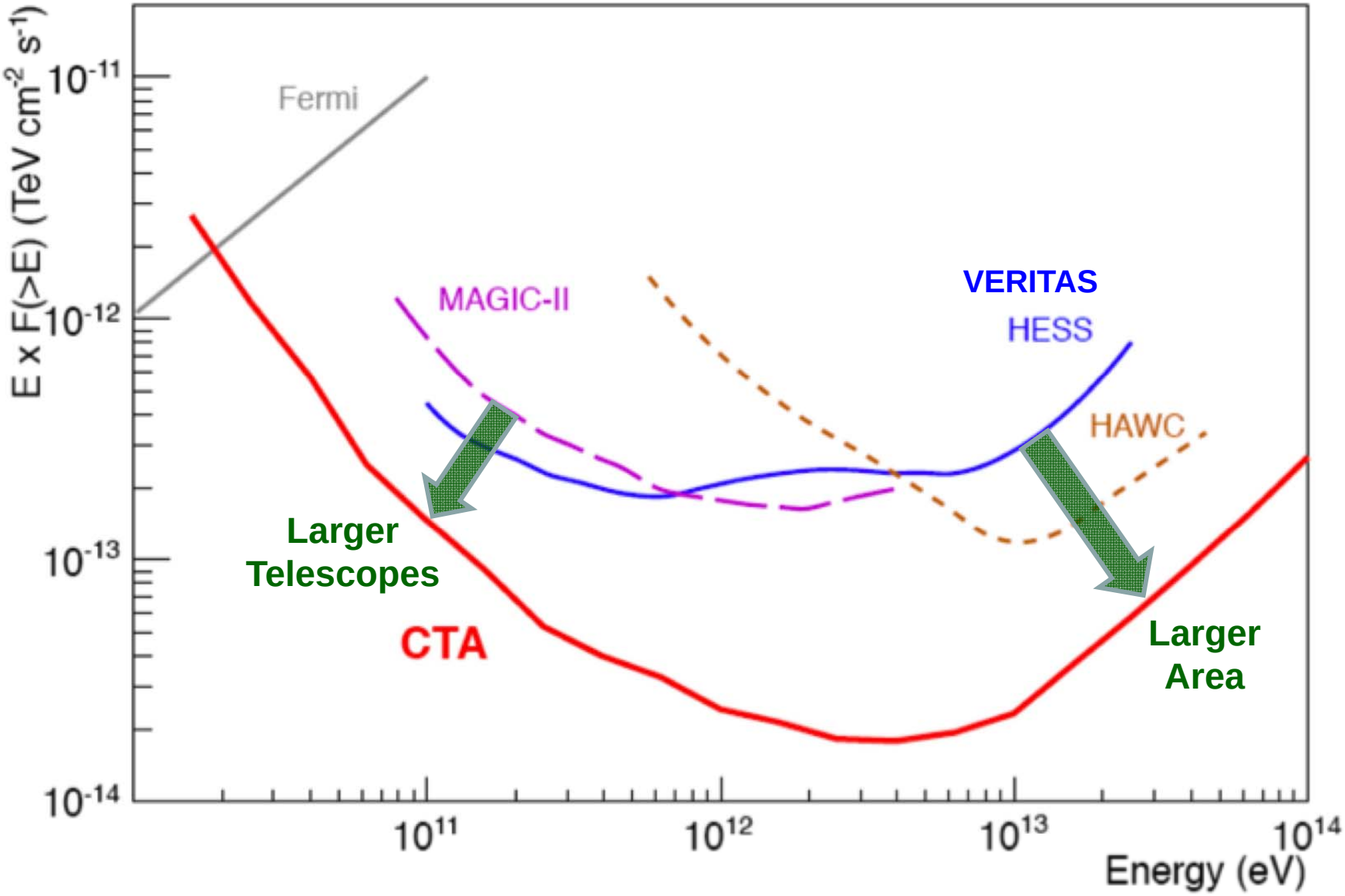
- 10-fold increased sensitivity at TeV energies
- 10-fold increased effective energy coverage
- Larger field of view for surveys
- Improved angular resolution
- Full sky coverage: an array in each hemisphere


(one) possible configuration
Southern Array
Low-energy section:
4 x 23 m tel. (LST)
- Parabolic reflector
- FOV: 4-5 degrees
Core-energy array:
23 x 12 m tel. (MST)
Davies-Cotton reflector
- FOV: 7-8 degrees
High-energy section:
32 x 5-6 m tel. (SST)
Davies-Cotton reflector
(or Schwarzschild-Couder)
- FOV: ~10 degrees

Sensitivity (units of Crab flux)

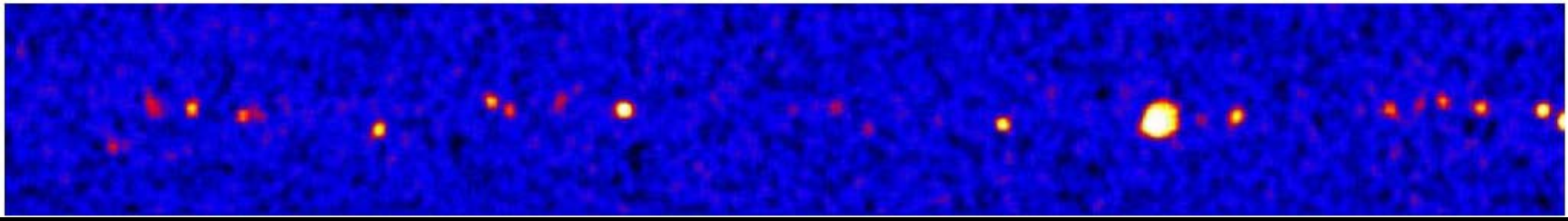


Sensitivity (differential)

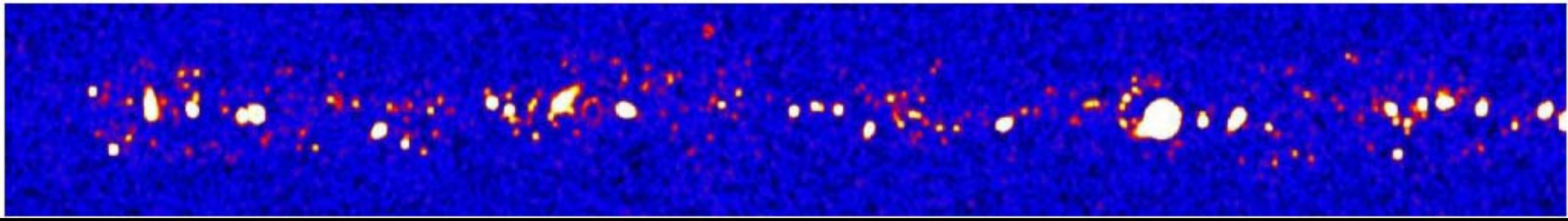


Galactic Plane Survey

HESS

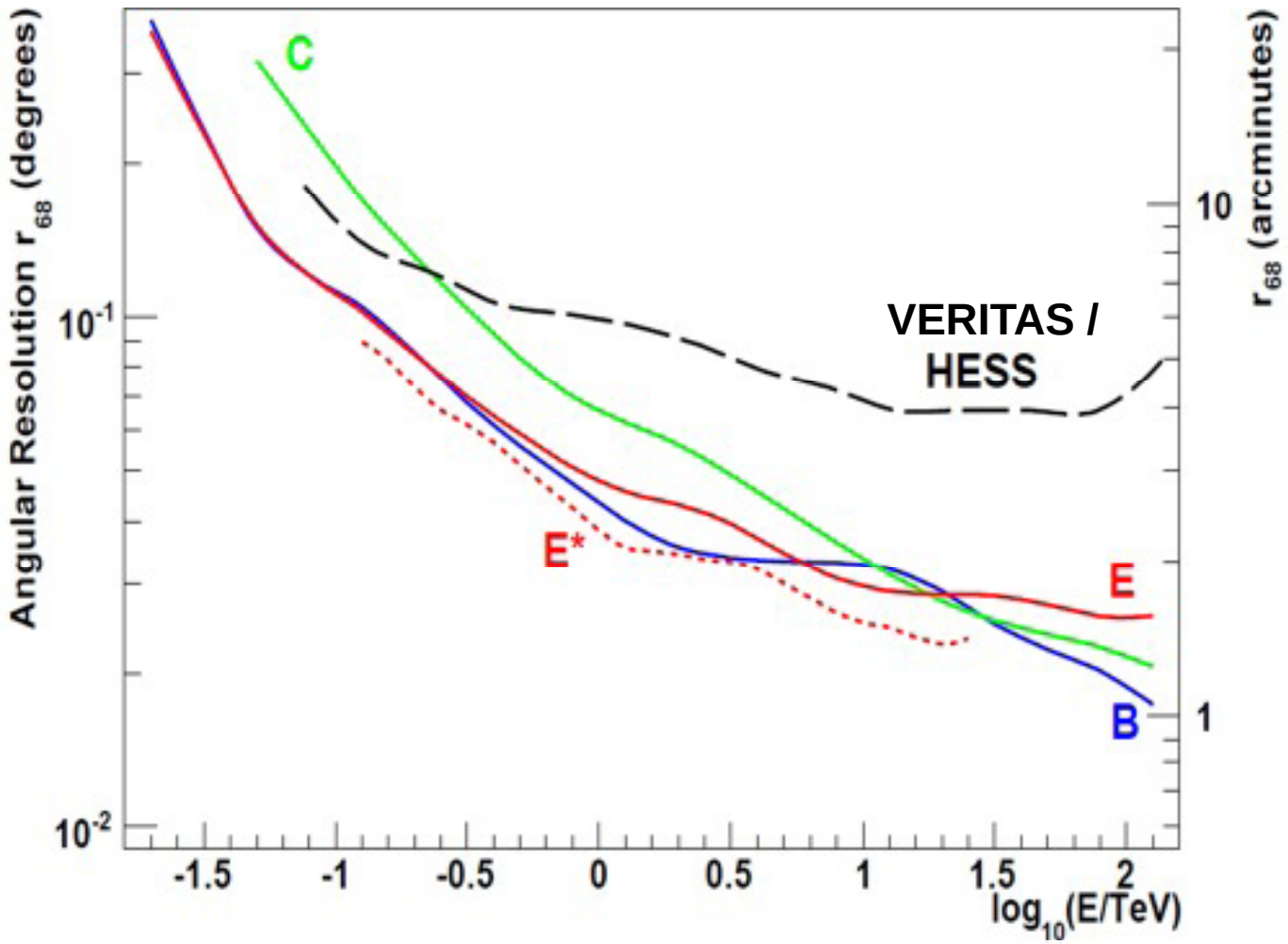


CTA (same exposure)



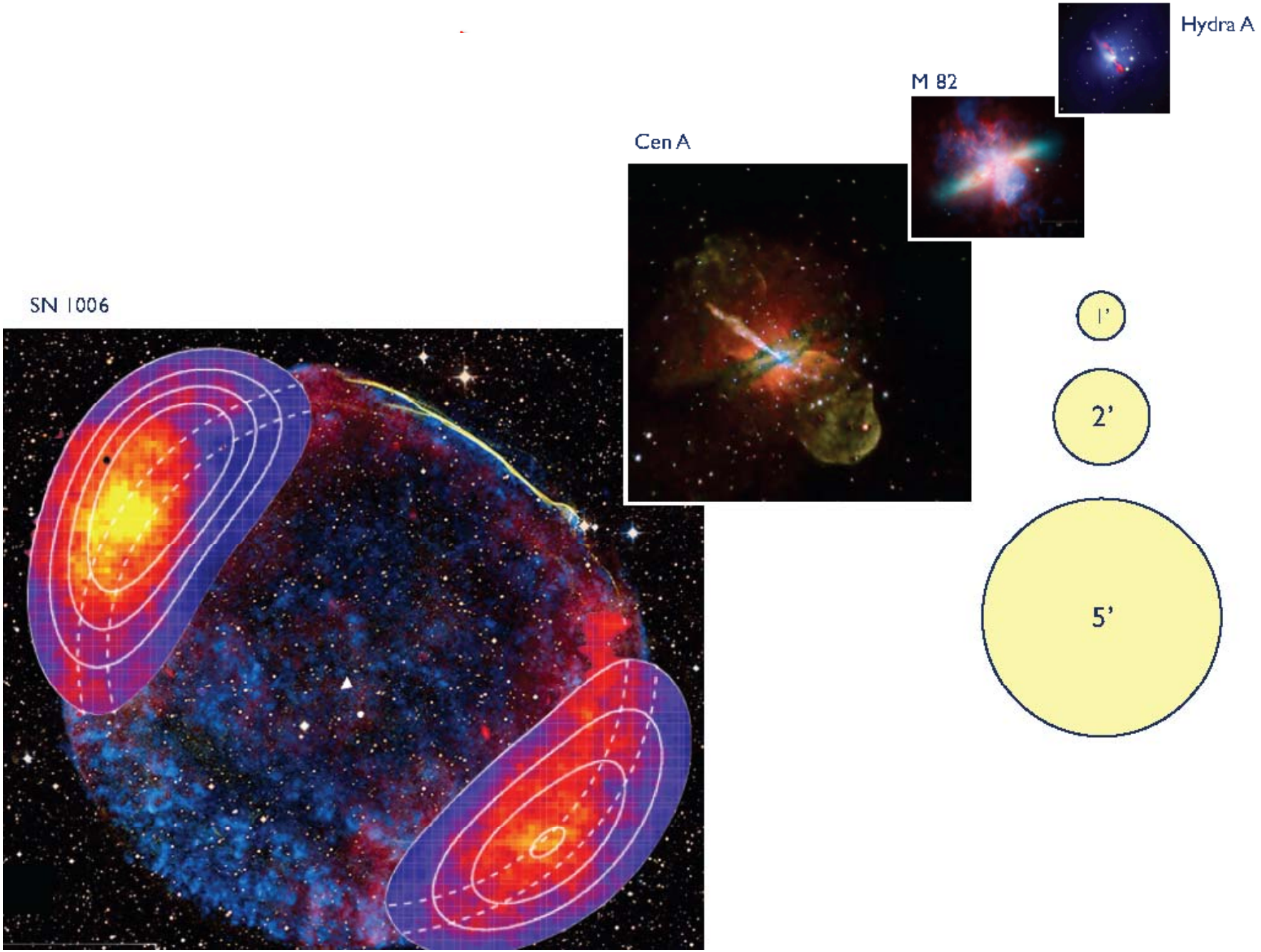
Expect ~1000 sources

Angular Resolution



1-2′ above 1 TeV

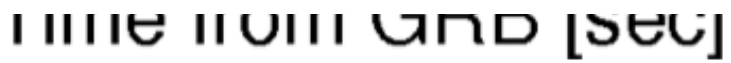
Angular Resolution



Comparison to Fermi

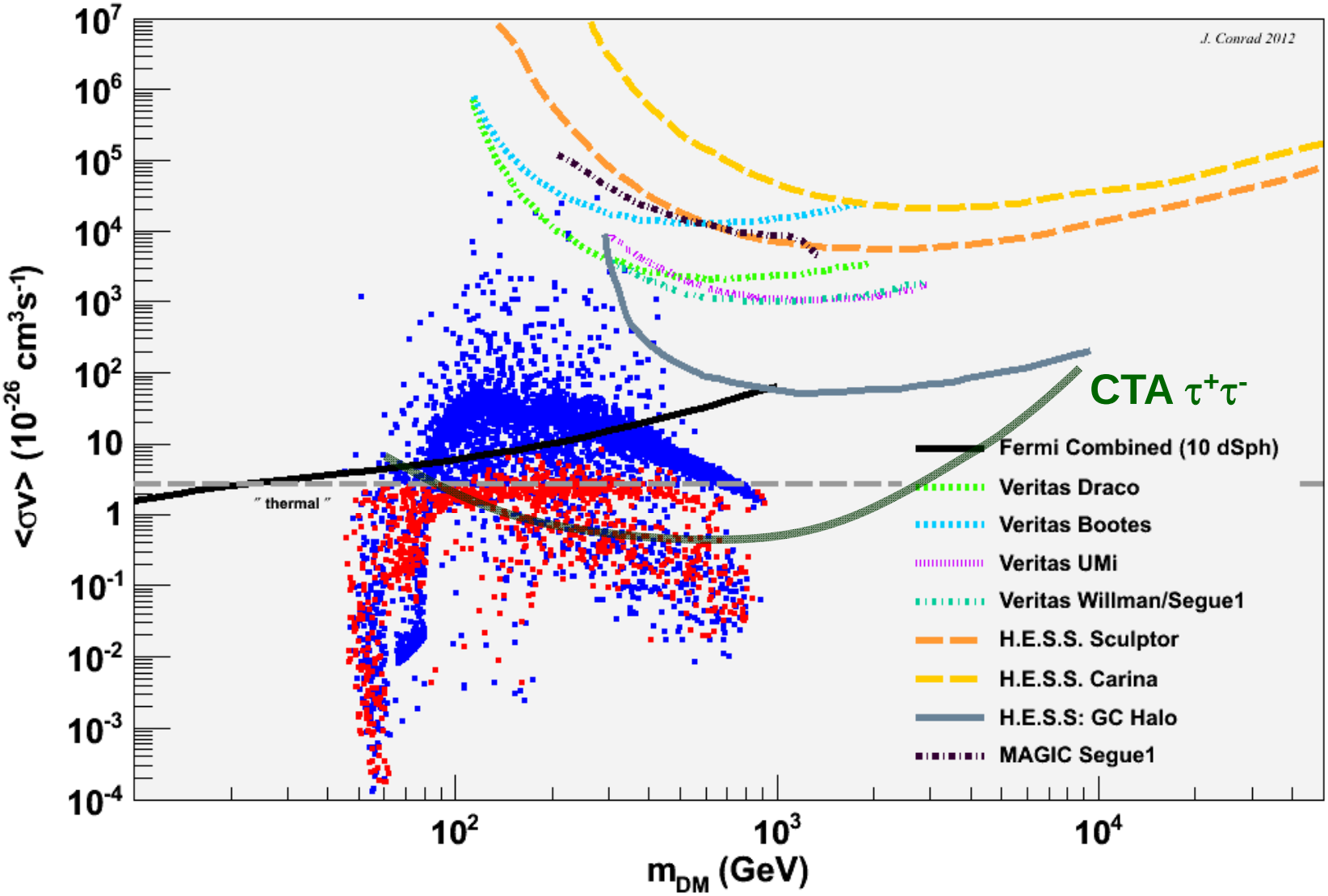
CTA more sensitive on all time scales below ~few years

Simulated GRB (z=4.3)



Rich structure, with unparalleled statistics

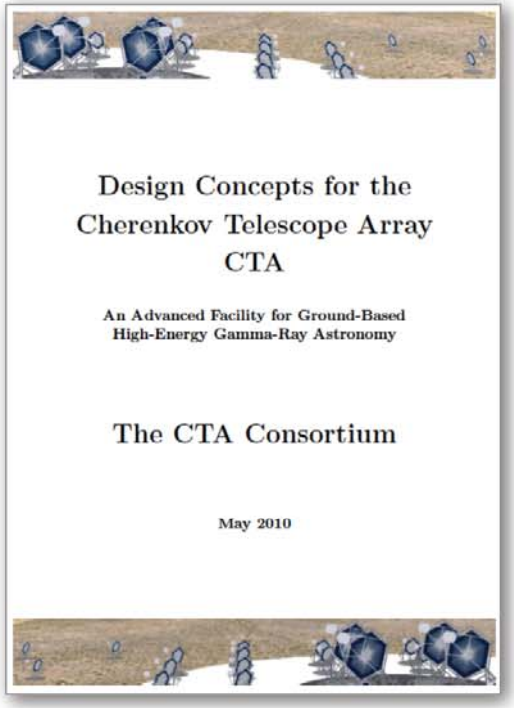
Dark Matter


J. Conrad 2012
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$<\sigma v>$ (10^{-26} $cm^3 s^{-1}$)
" thermal "
10^2
10^3
10^4
m_{DM} (GeV)
CTA $\tau^+\tau^-$
Fermi Combined (10 dSph)
Veritas Draco
Veritas Bootes
Veritas UMi
Veritas Willman/Segue1
H.E.S.S. Sculptor
H.E.S.S. Carina
H.E.S.S: GC Halo
MAGIC Segue1

Design and Science Case

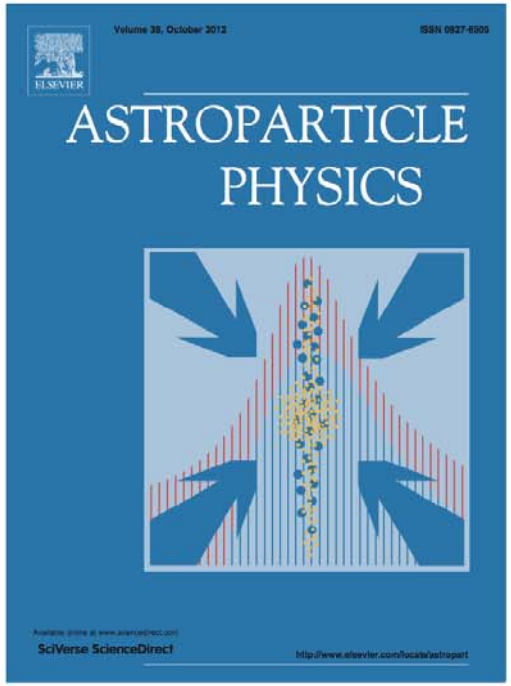
More Details:

general info: www.cta-observatory.org



"Design Concepts for the Cherenkov Telescope Array"

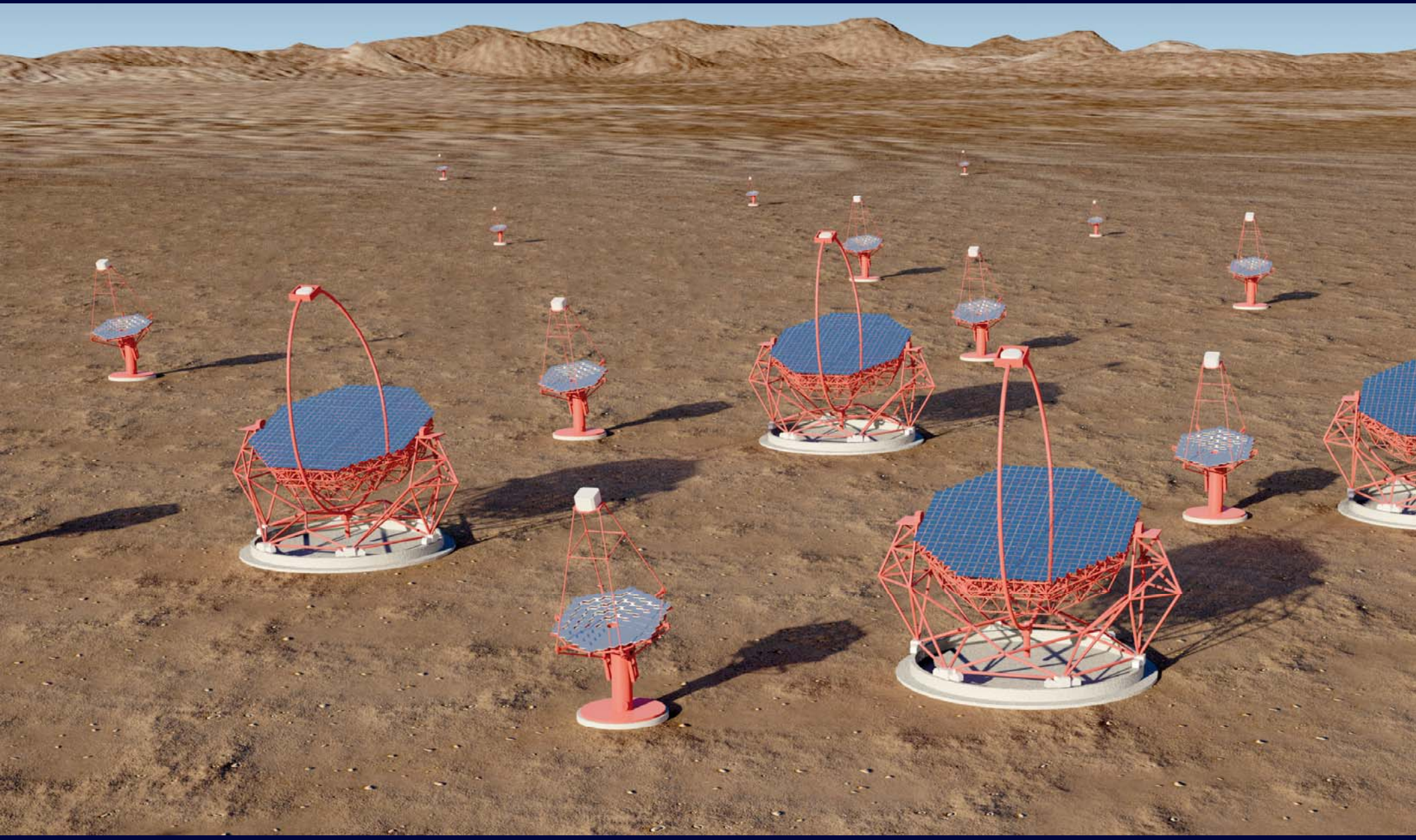
120 pages
arXiv:1008.3703
Exp. Astronomy 32 (2011) 193-316



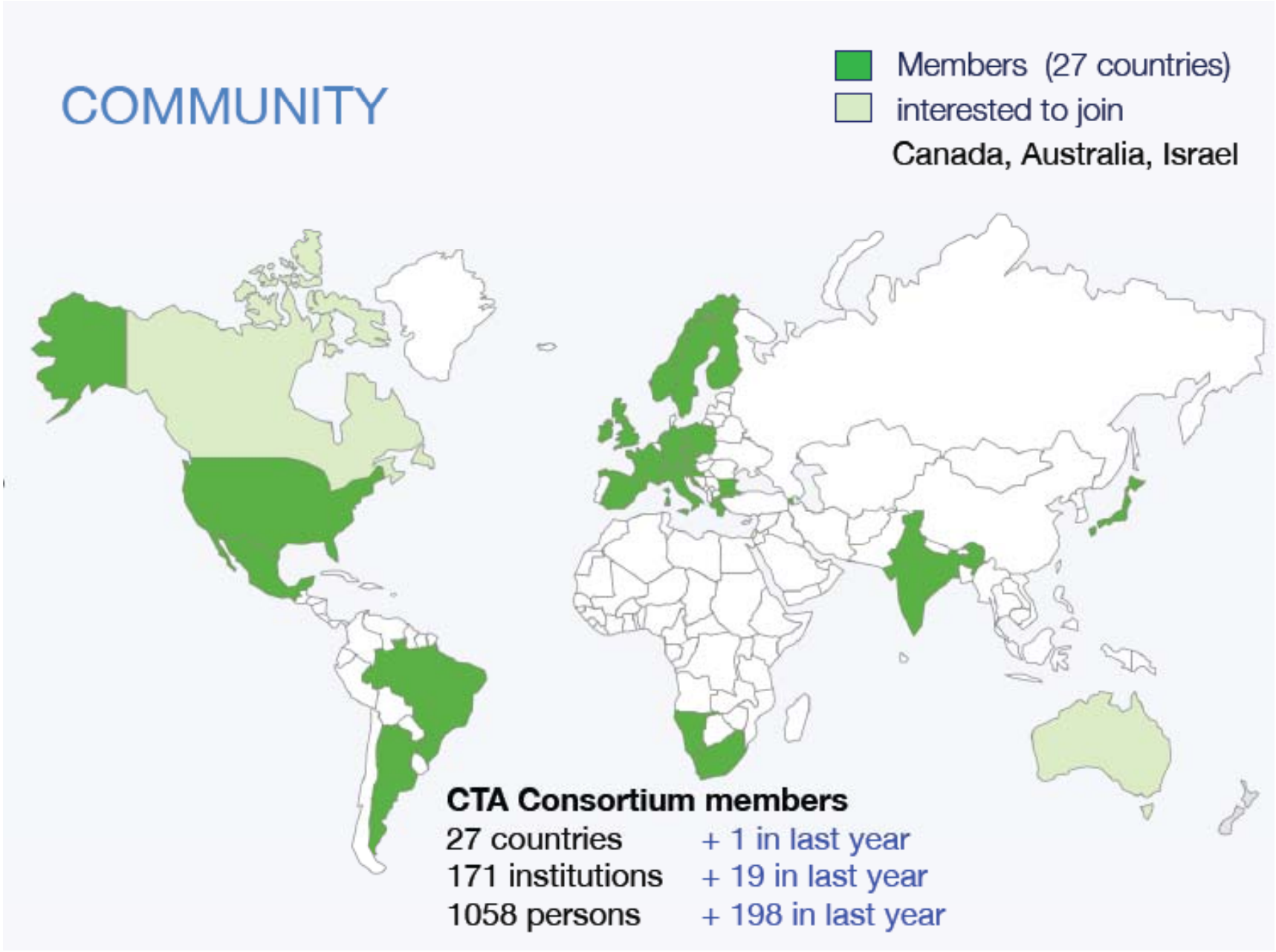
"Seeing the High-Energy Universe with the Cherenkov Telescope Array"

368 pages
in press, December 2012

Implementing CTA



A World-wide Effort



Telescopes Options

LST

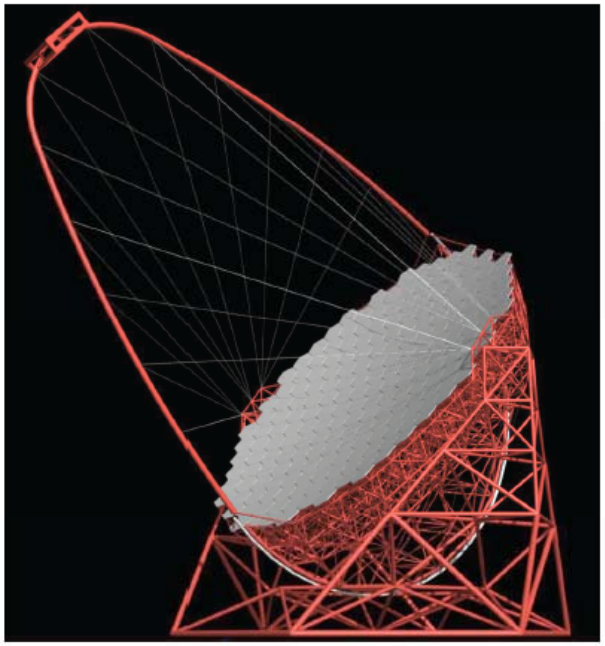
400 m² dish area
27.8 m focal length
1.5 m mirror facets

4.5° field of view
0.1° pixels
Camera ∅ over 2 m

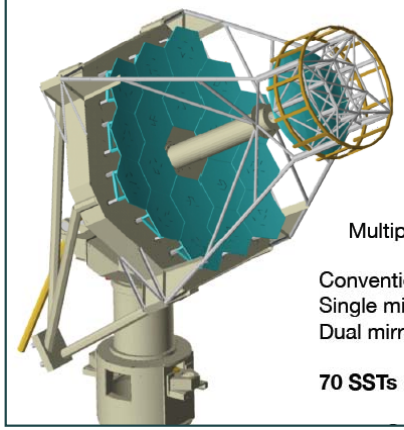
Carbon-fibre structure

Active damping
of oscillations,
active mirror control

4 LSTs on each site



SST



ASTRI Design
4.3 m mirror
9.6° foV
0.25° pixels

Multiple options under study:

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

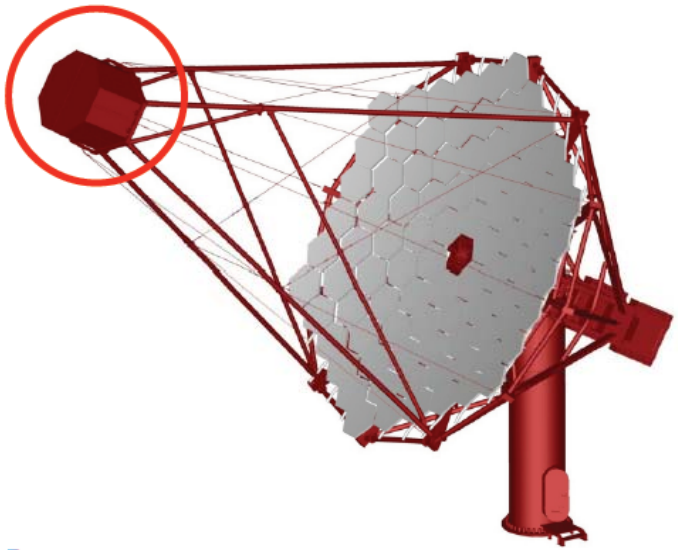
70 SSTs on Southern site

MST-1

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

7-8° field of view
~2000 x 0.18° pixels

25 MSTs on South site
15 MSTs on North site



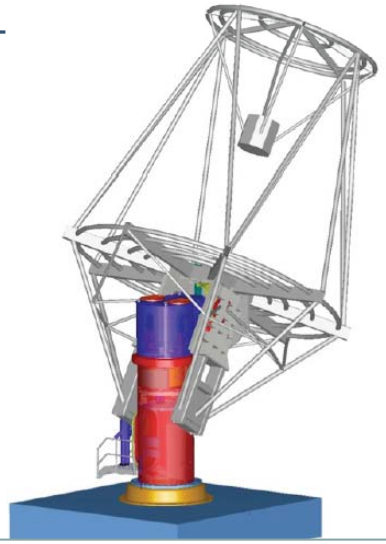
MST-2

MEDIUM-SIZED DUAL MIRROR TEL.
EXTENDING THE MST ARRAY

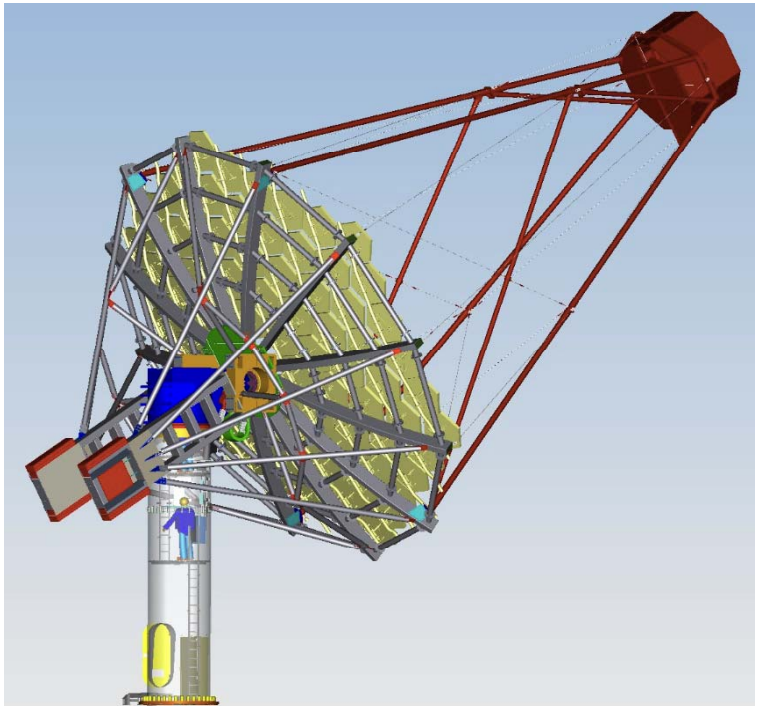
9.7 m diameter
50 m² dish area
5.6 m focal length

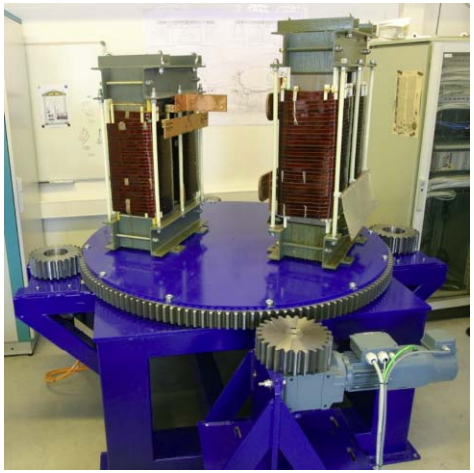
8-9° field of view
11000 x 0.07° pixels

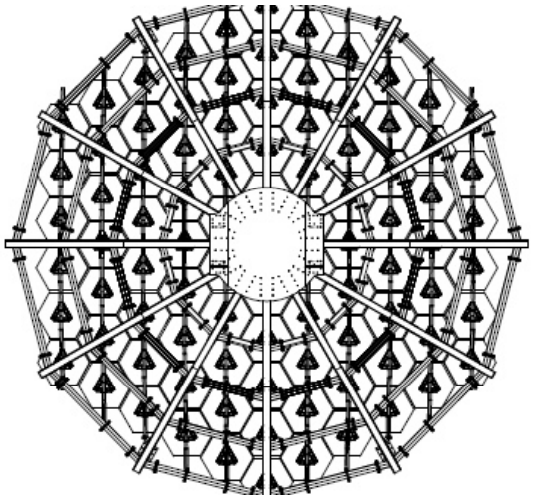
Extend South array
by adding 36 SCTs
contributed mostly by US

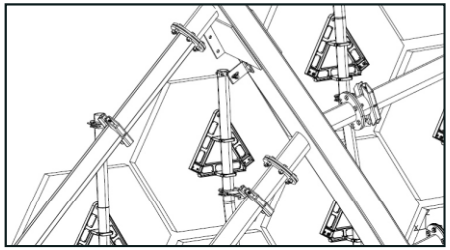


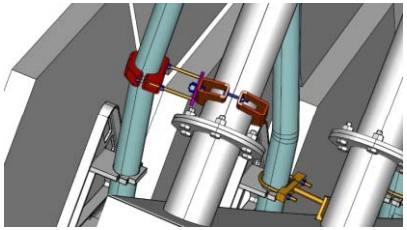
MST Development (DESY, Germany)









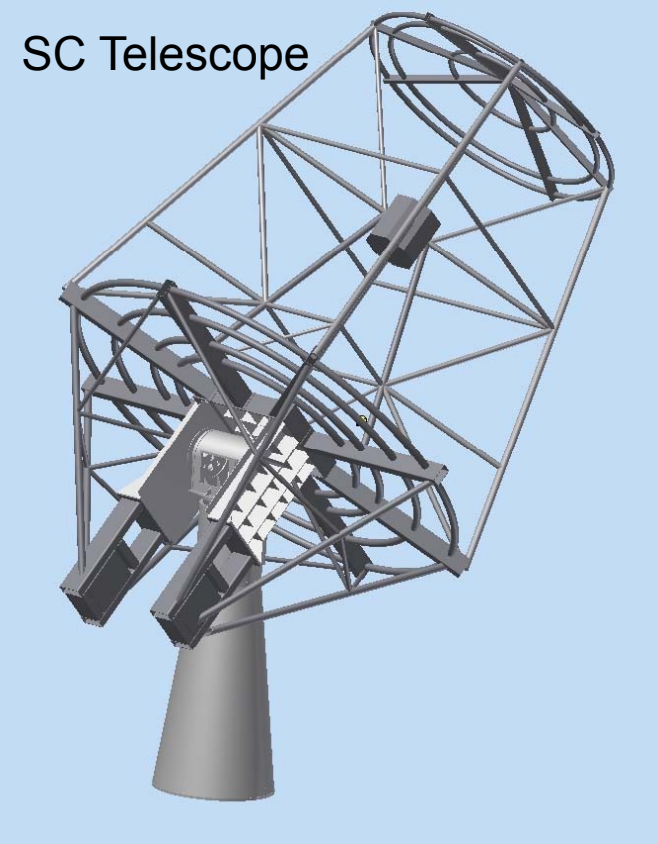


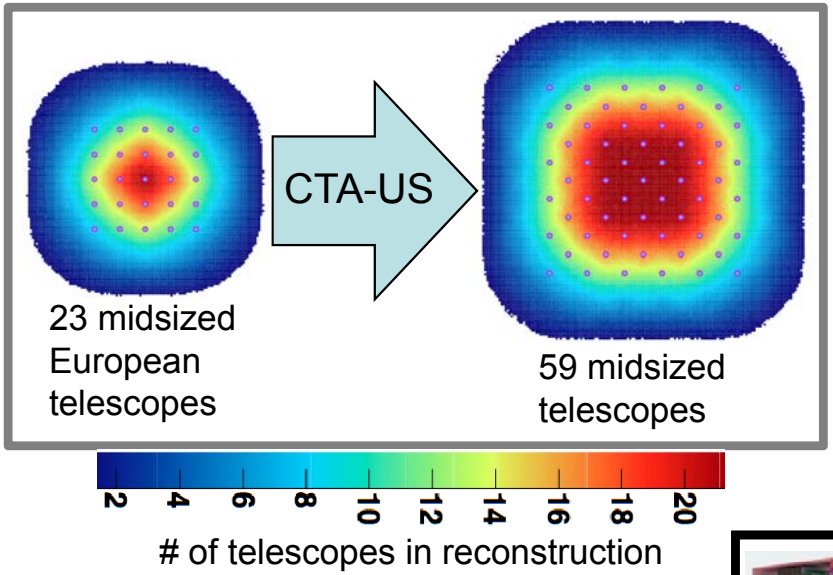
Proposed US Contributions

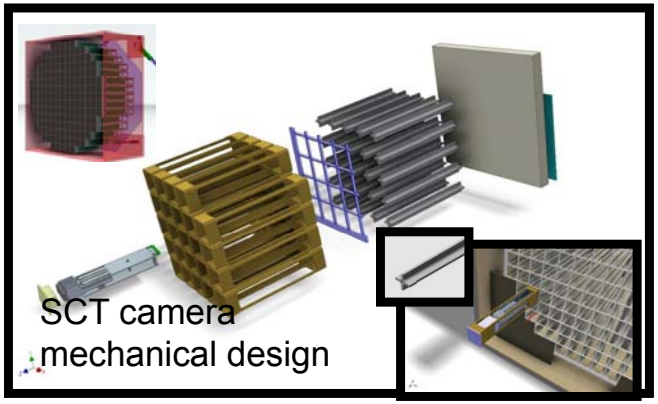
US Group is comprised of 24 Institutions and 2 National Labs

Proposing to contribute broadly to CTA:

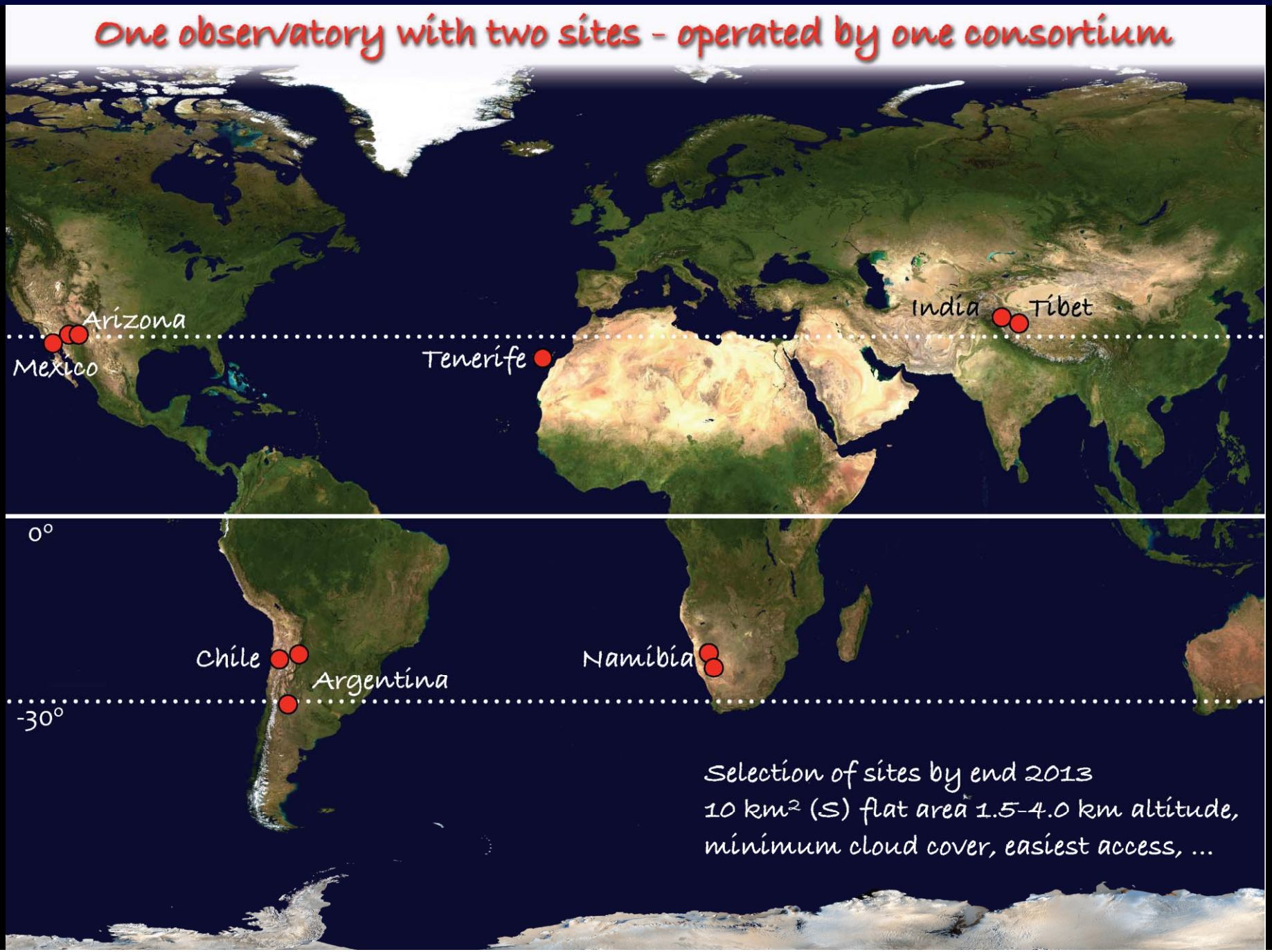
- Extending the MST array with two-mirror SC telescopes
- Novel camera technology, trigger, and readout
- Data processing, archiving, science tools
- **Northern Site**







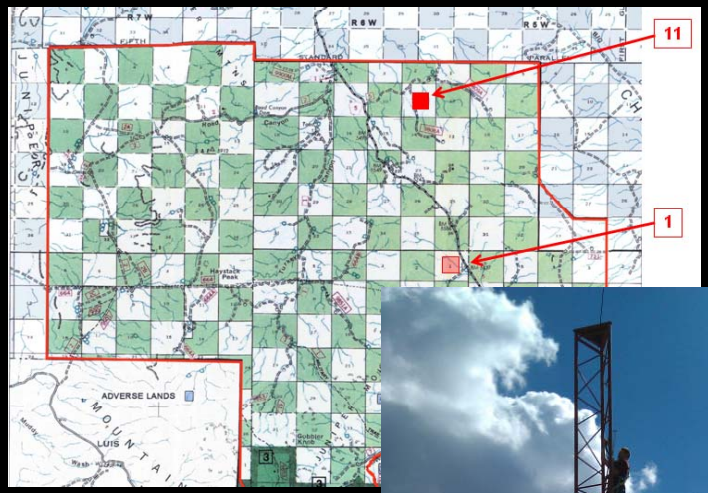
Candidate Sites



Proposed Sites in Arizona

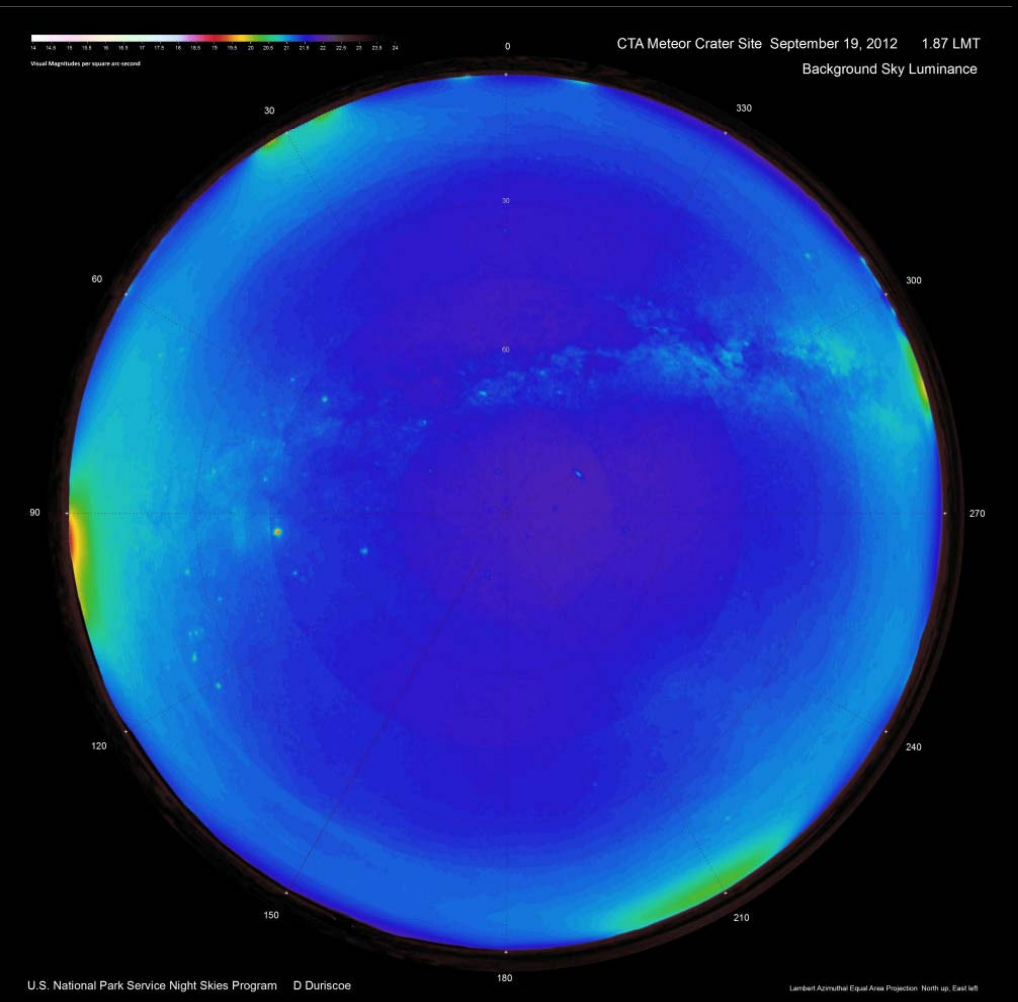
Proposed Sites in Arizona

Yavapai Ranch



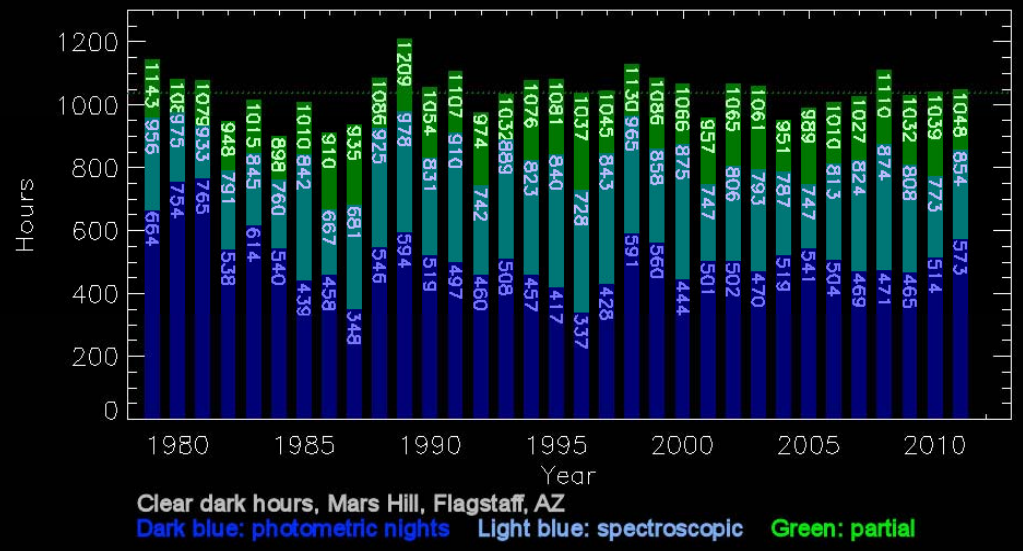
Meteor Crater

Night Sky & Cloud Cover



NSB Measurements @ Meteor Crater
Dan Duriscoe (NPS)

Both sites are excellent.



Mars Hill 30-yr Cloud Record
Brian Skiff, Jeff Hall (Lowell)

~1045 clear hrs/year

Architectural Drawings (Meteor Crater)

CHERENKOV TELESCOPE ARRAY

Northern Hemisphere Site at Meteor Crater

Site Plan

Copyright © 2012

CATALYST ARCHITECTURE

CHERENKOV TELESCOPE ARRAY

Northern Hemisphere Site at Meteor Crater

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BirdsEye from East

CATALYST ARCHITECTURE

CHERENKOV TELESCOPE ARRAY

Northern Hemisphere Site at Meteor Crater

Visitor Center

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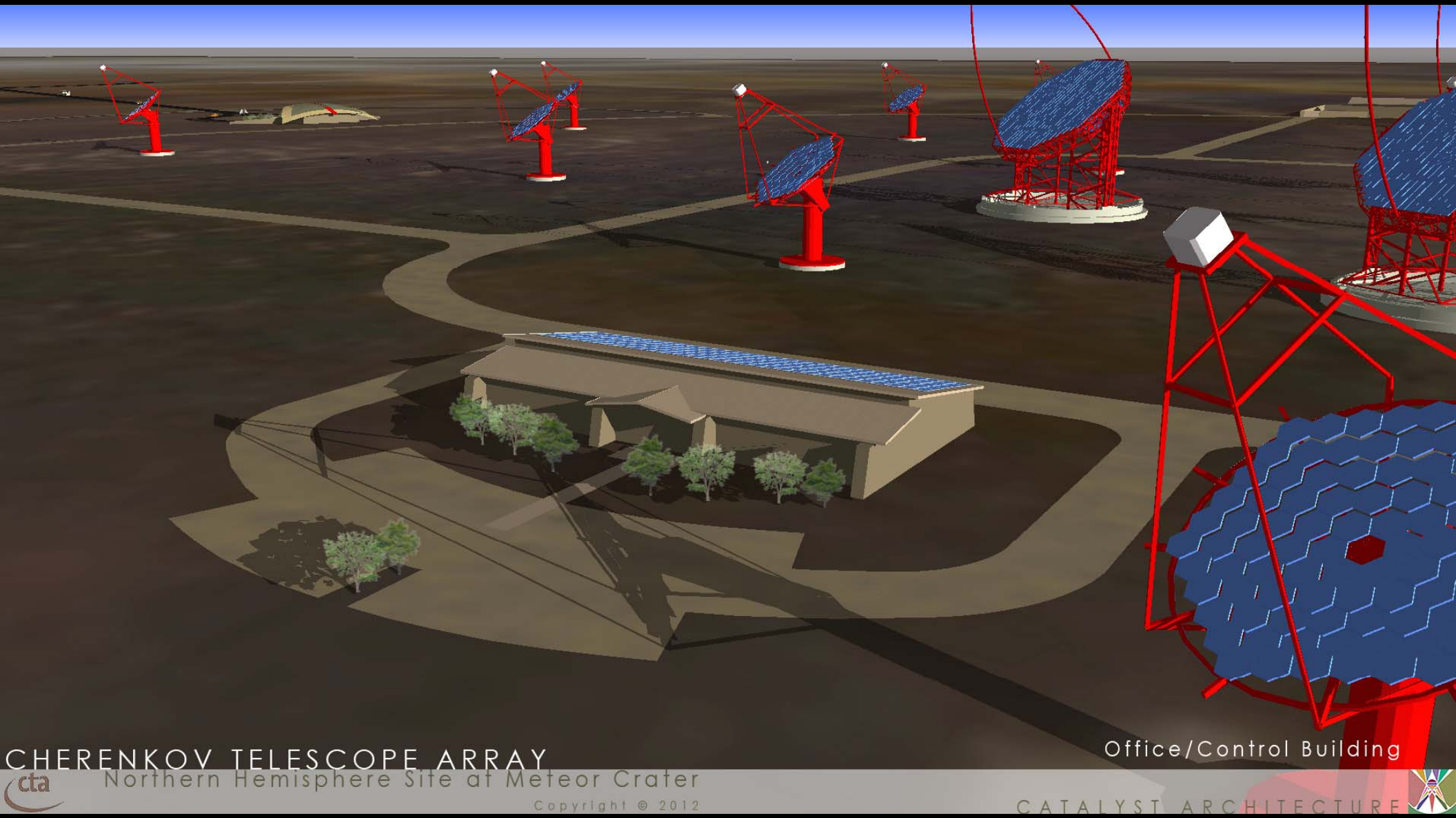
CATALYST ARCHITECTURE



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CATALYST ARCHITECTURE

CHERENKOV TELESCOPE ARRAY

Northern Hemisphere Site at Meteor Crater

Dormitory Building

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CATALYST ARCHITECTURE

Recommended by Key Roadmaps

Summary

- VHE γ-rays probe astrophysics of GeV/TeV particle acceleration in the cosmos and search for new physics beyond the standard model.
- Among the many scientific questions being attacked are the origin of **cosmic rays** and the nature of **dark matter**.
- The imaging **atmospheric Cherenkov technique** allows for sensitive telescopes with excellent angular & energy resolution.
- **CTA** is a proposed major observatory that would greatly expand our understanding of the VHE Universe, detecting many more sources and providing exquisite measurements of the source characteristics.
- The **Lowell Observatory** is already playing a very positive role in CTA and can certainly find a way to reap scientific benefit from the project.

"The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes."

Marcel Proust (1871-1922)

Easy to picture CTA in Arizona !