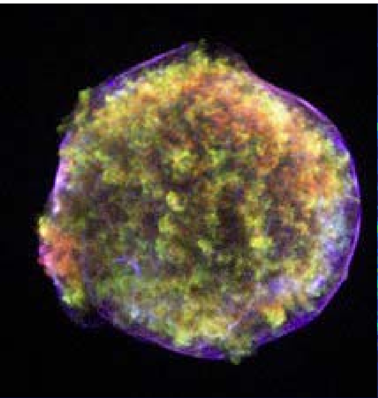
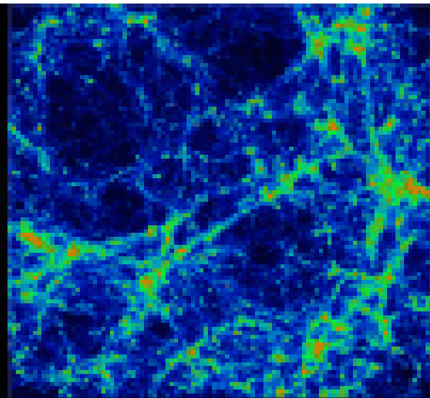
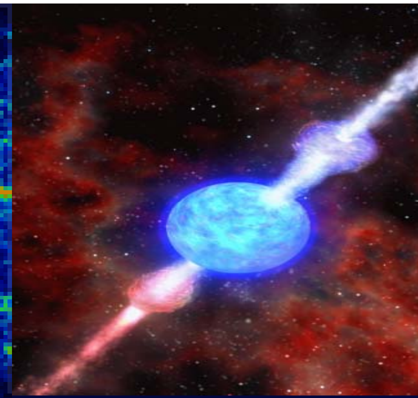
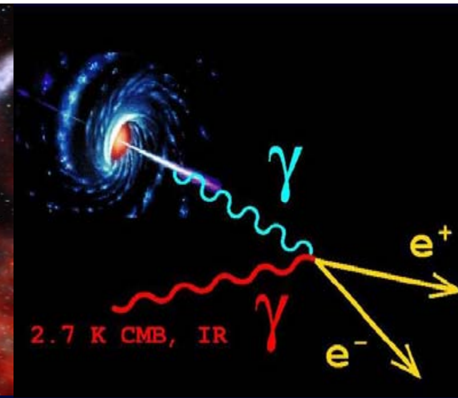
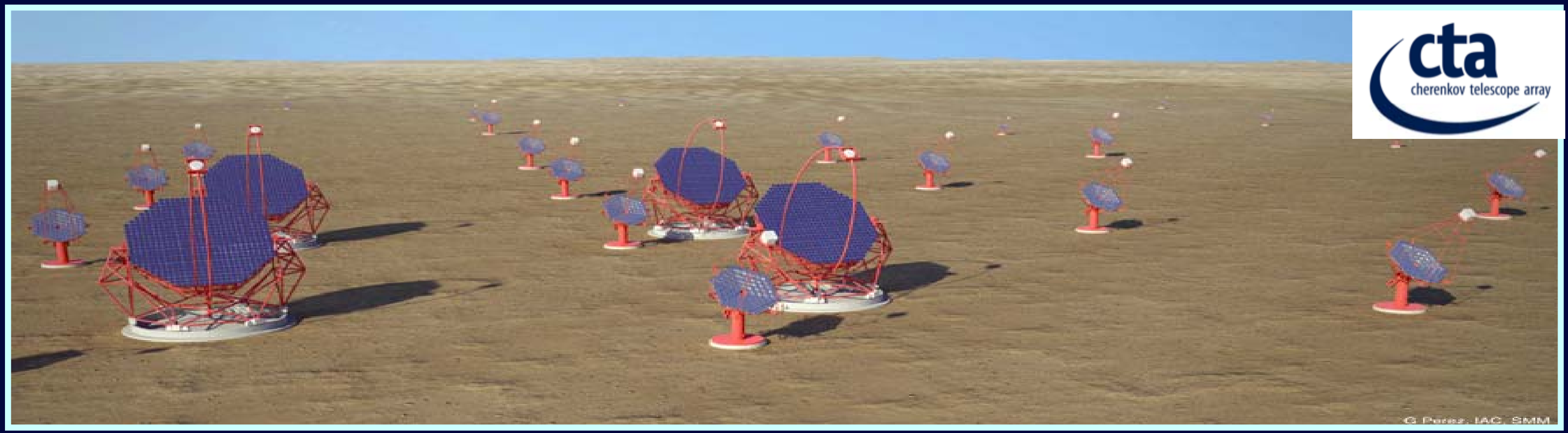





Very High-Energy Astrophysics
&
The Cherenkov Telescope Array

Rene A. Ong (UCLA)

SESE Colloquium, ASU, 6 Sept 2017



Outline

- **Scientific & Technical Motivation**

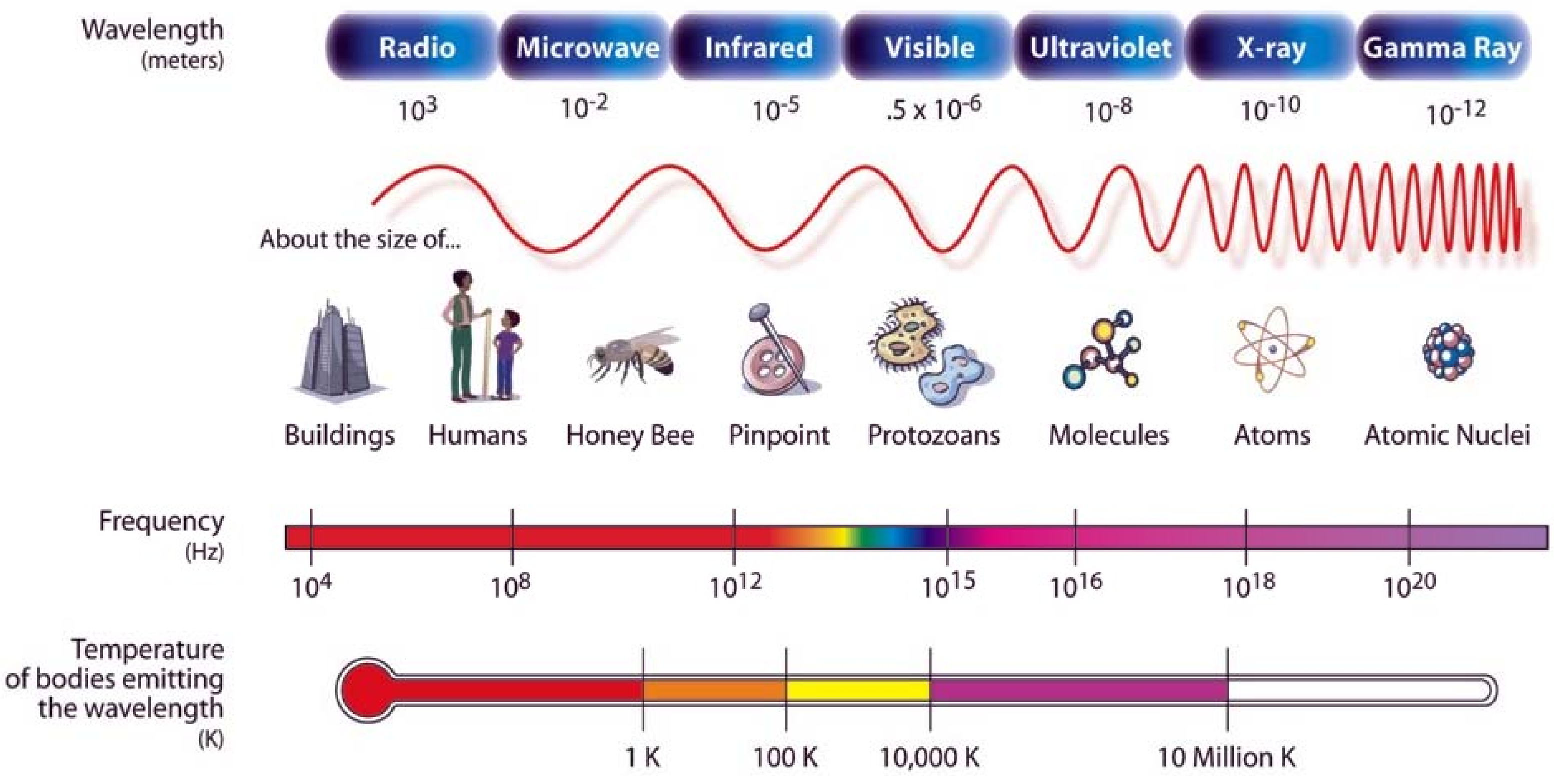
  Gamma rays – high energy light → a new astronomy
  Three selected science topics in brief
  Experimental Technique
  Planning for the Future → CTA

- **Cherenkov Telescope Array (CTA)**

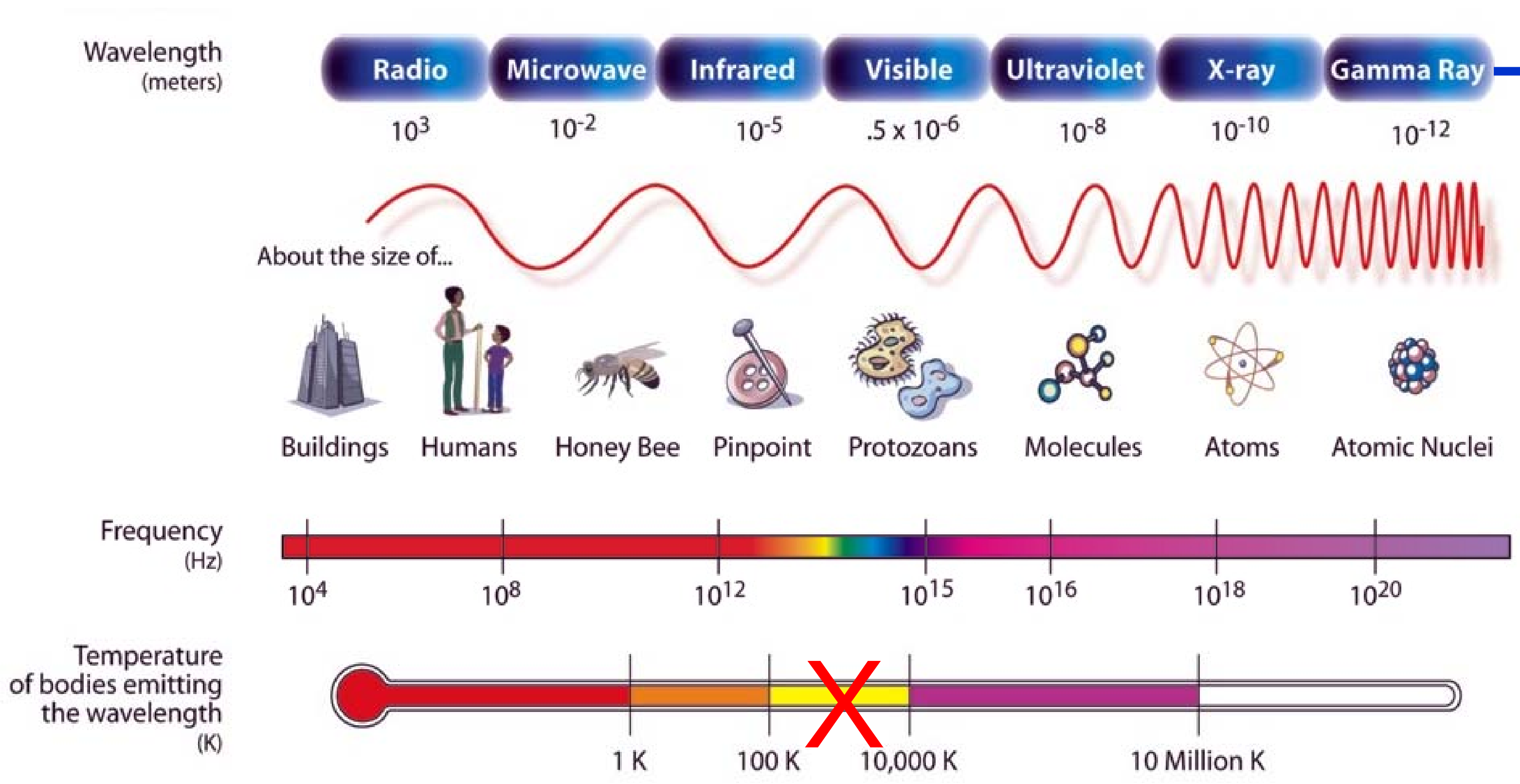
  Science Drivers → Requirements → Implementation
  CTA Design & Performance → Scientific Capabilities
  Present status (2017): sites, timeline, etc.

- **Summary**

Spectrum of Light



High Energy Light

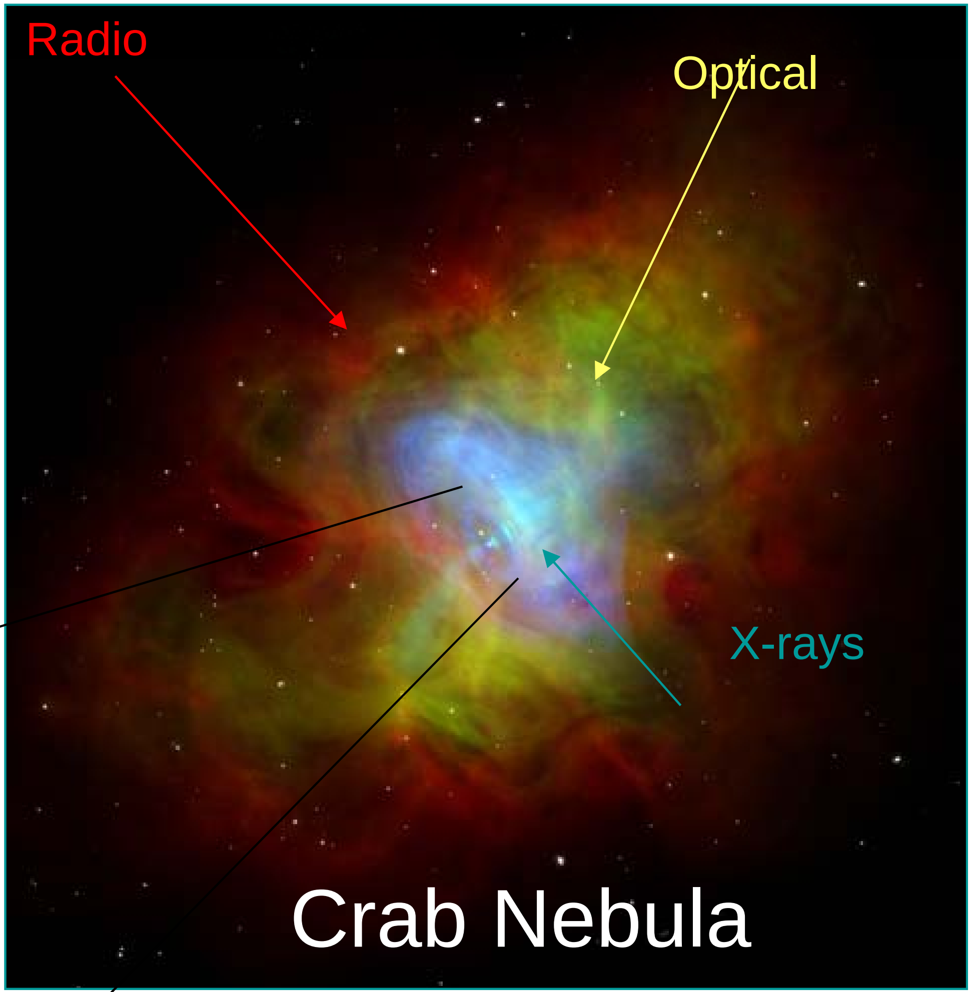


Very High Energy (VHE)

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

A New Astronomy

- Before 1930's – Astronomy only used visible light.
- New wavebands (radio, IR, X-ray, γ-ray) change our picture of the universe.
- Other messengers:
  neutrinos & grav. waves.

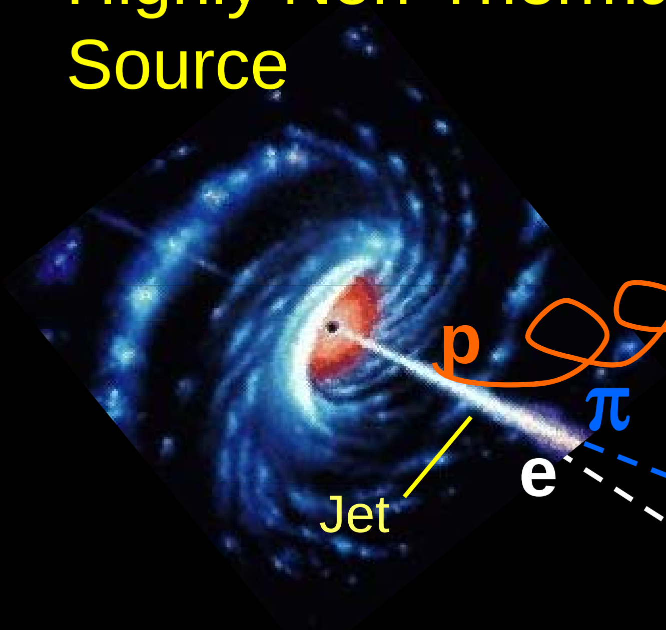


Crab Pulsar (X-rays)

Also a source of VHE γ-rays !

Very High Energy (VHE) Astrophysics

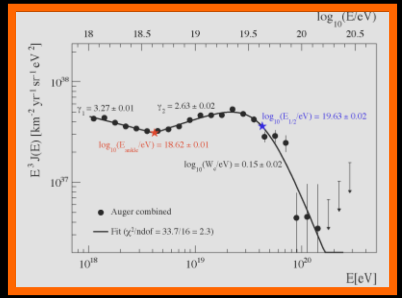
Highly Non-Thermal Source



Active Galactic Nucleus (AGN)

p

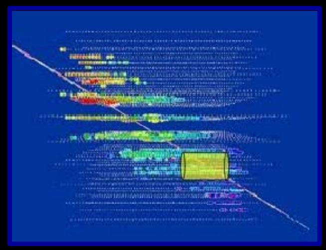
EeV Cosmic Rays



ν

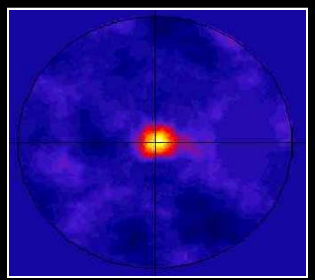
γ

PeV Neutrinos



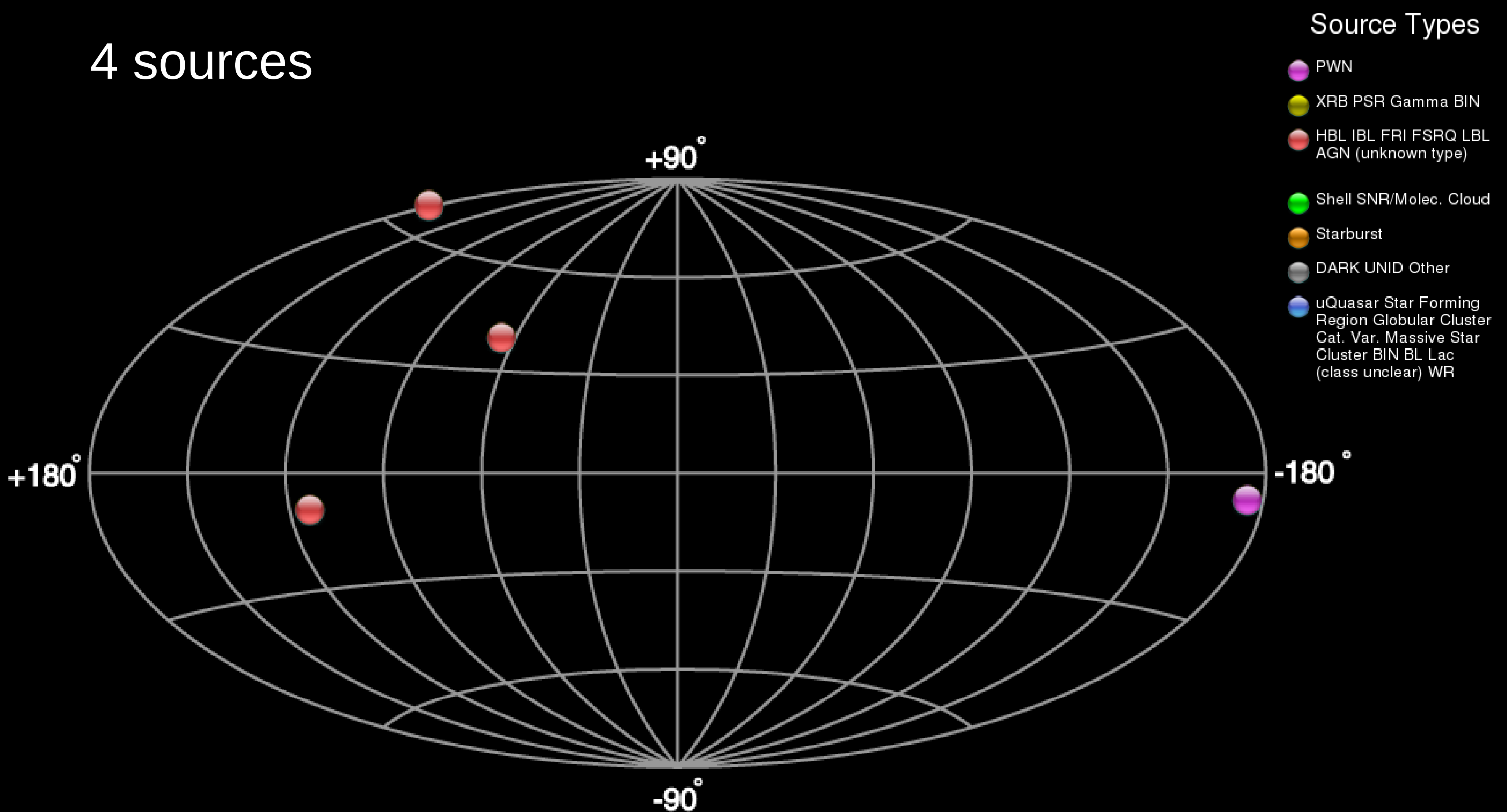
γ-rays provide, by far, the most direct information

GeV/TeV γ–rays



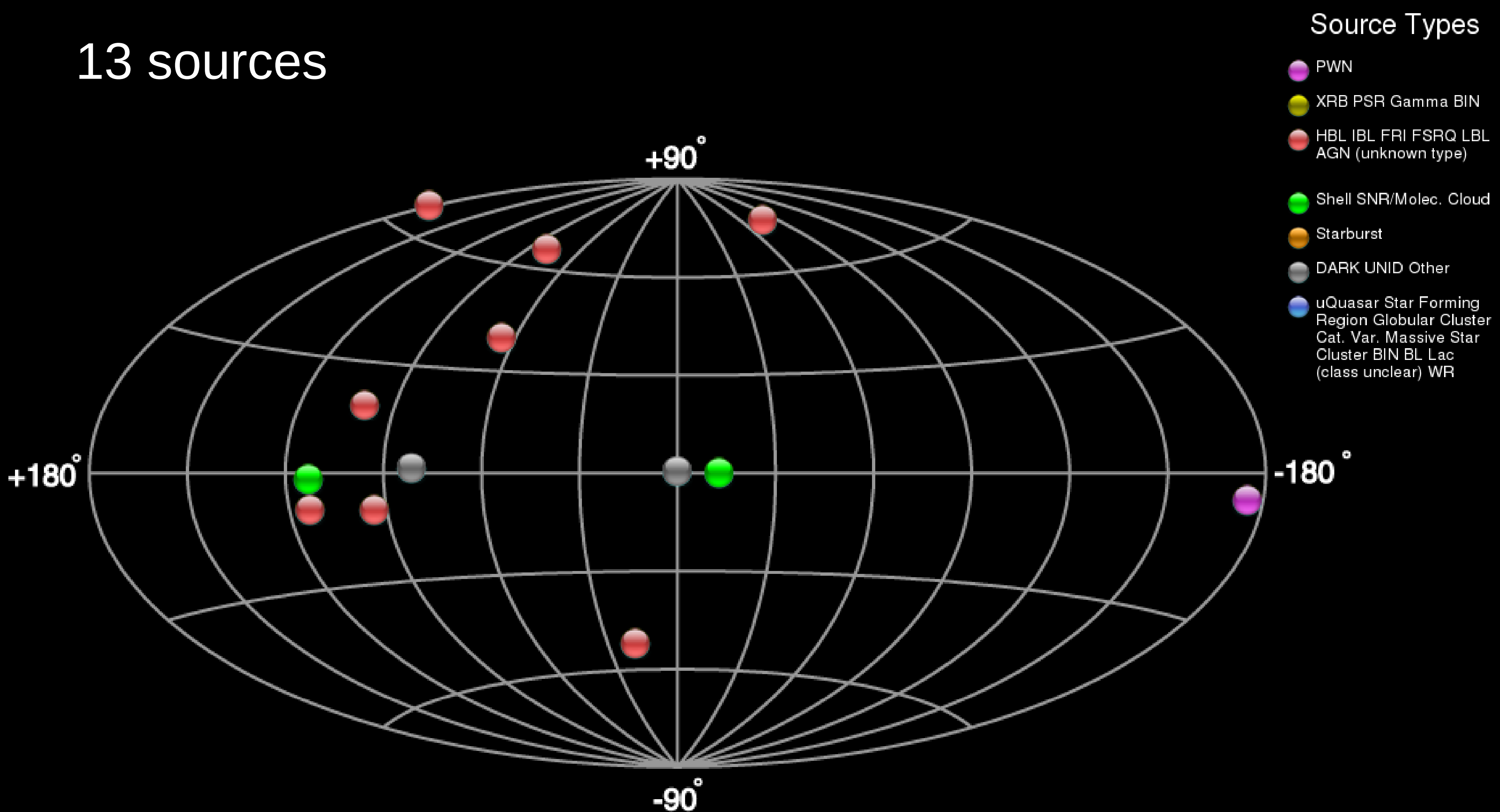
VHE γ-ray Sky c1997

4 sources



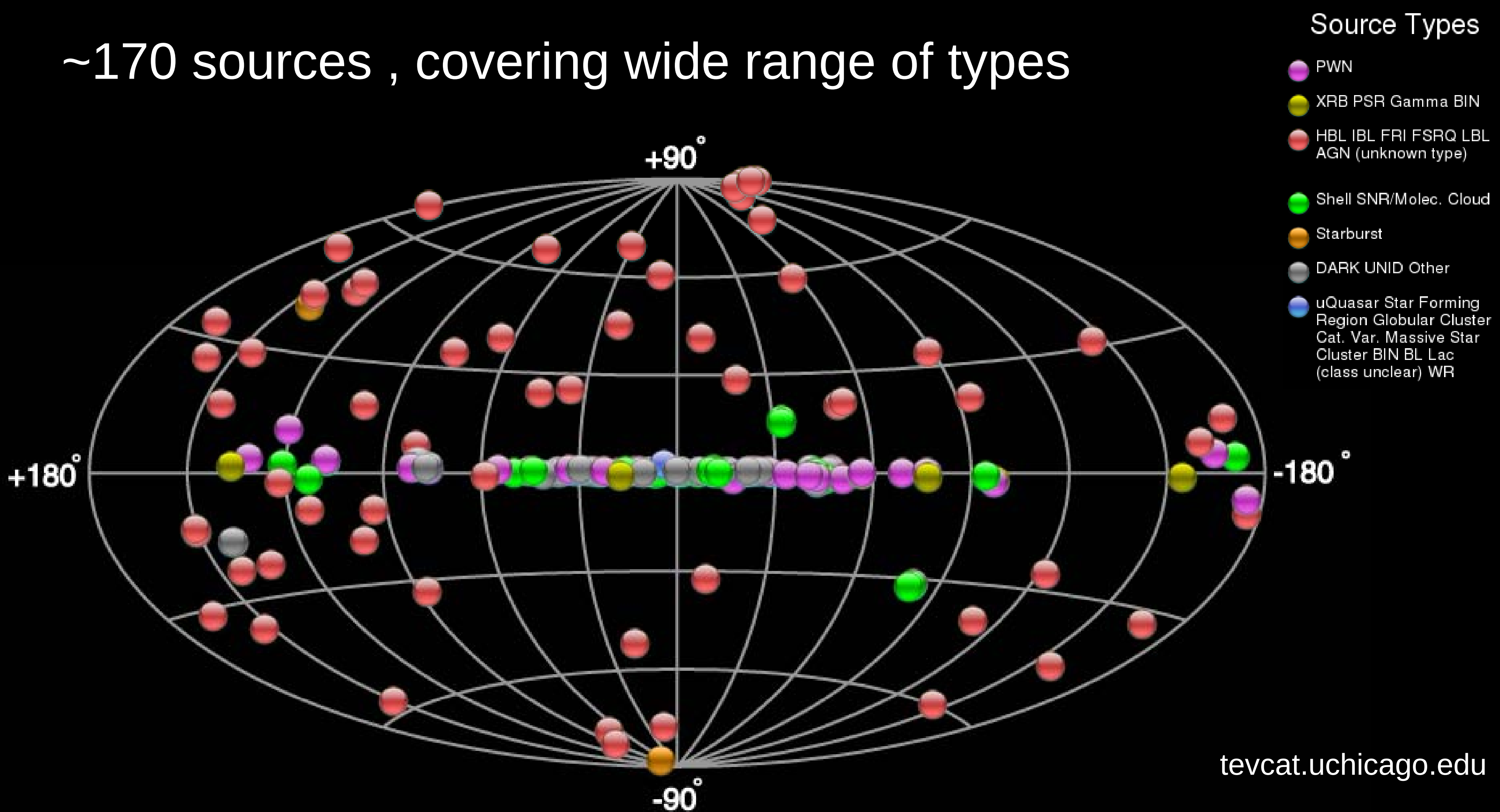
VHE γ-ray Sky c2006

13 sources



VHE γ-ray Sky c2017

~170 sources , covering wide range of types

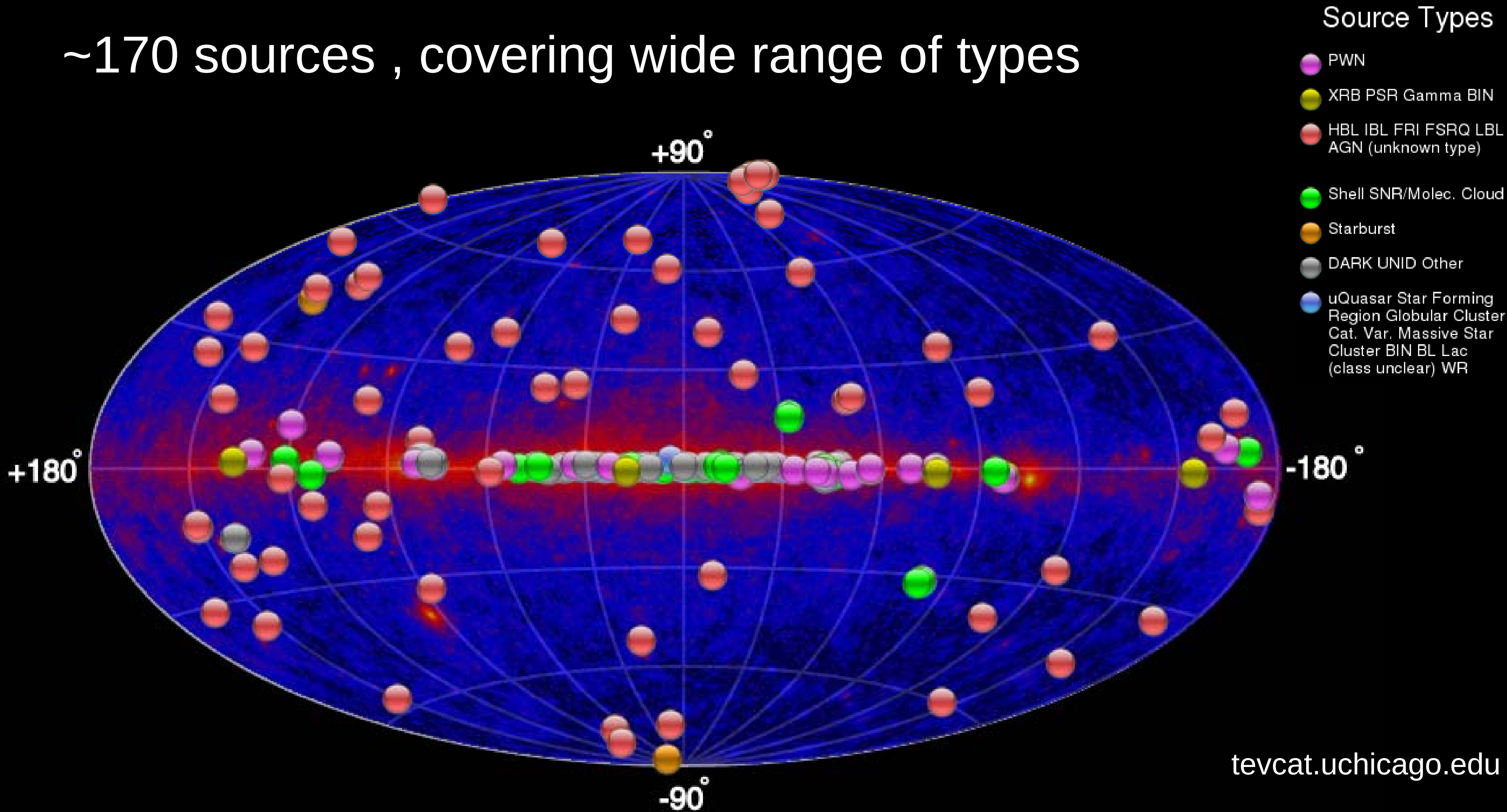


tevcat.uchicago.edu

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

HE + VHE γ-ray Sky c2017

~170 sources , covering wide range of types



- Wide variety of HE/VHE sources in our Galaxy and outside
- Many sources not clearly identified with known objects

Three Selected Science Topics

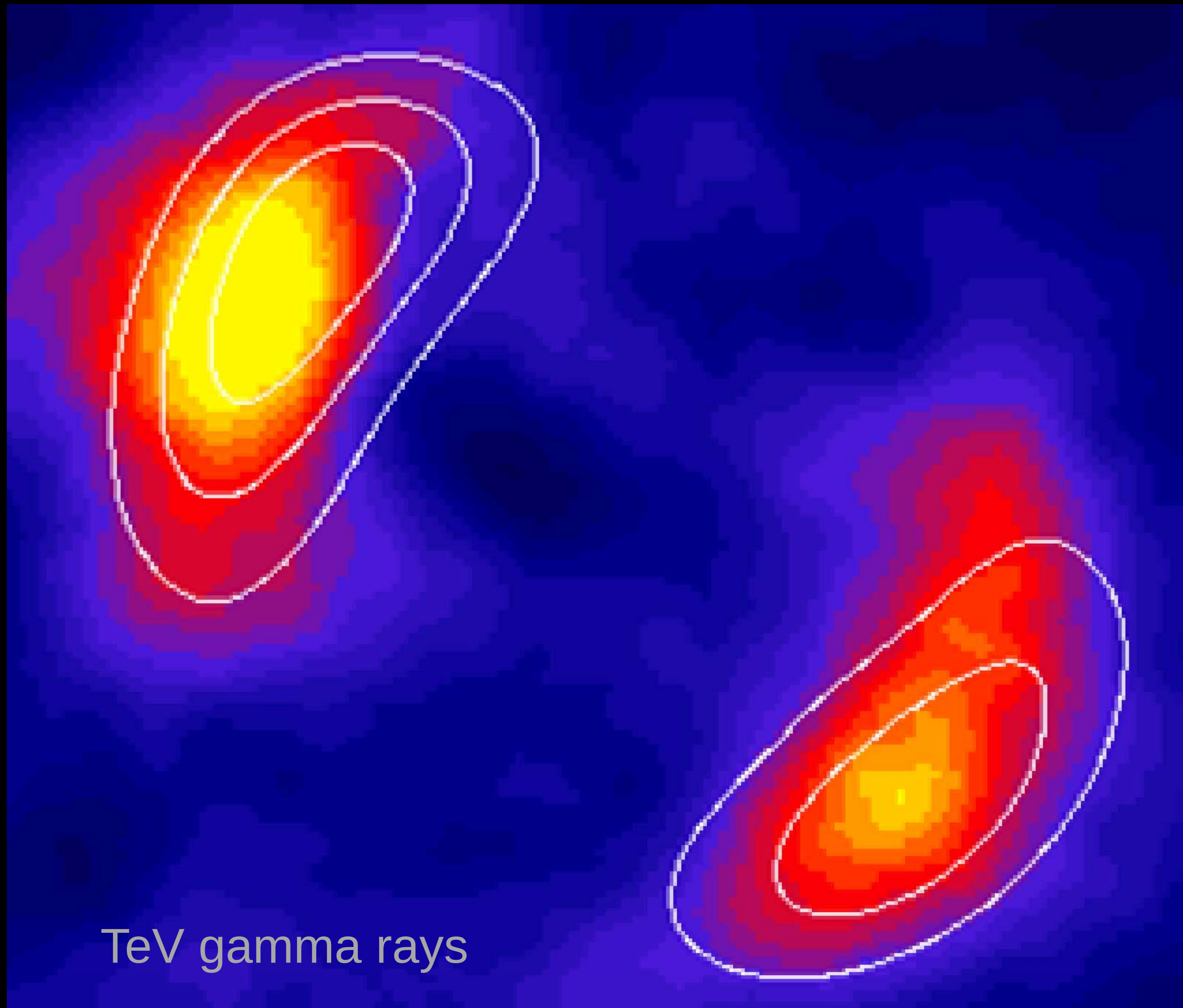
- Supernova remnants & origin of cosmic rays
- Active Galactic Nuclei (AGN)
- Galactic Center & Dark Matter

Supernova Remnants

SN 1006

Blue: X-ray
Yellow: Optical
Red: Radio

(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)



← 0.4° →

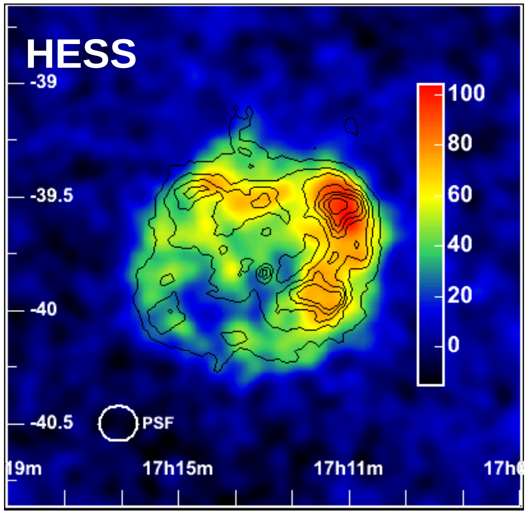
Supernova Remnants (SNRs)

“Standard Model” for the origin of the cosmic rays:

- Expanding shell of SNR & shock front sweeps up ISM material.
- Acceleration of particles via diffusive shock acceleration.
- Can supply and replenish CR’s if $\varepsilon \sim$ 5-10%.

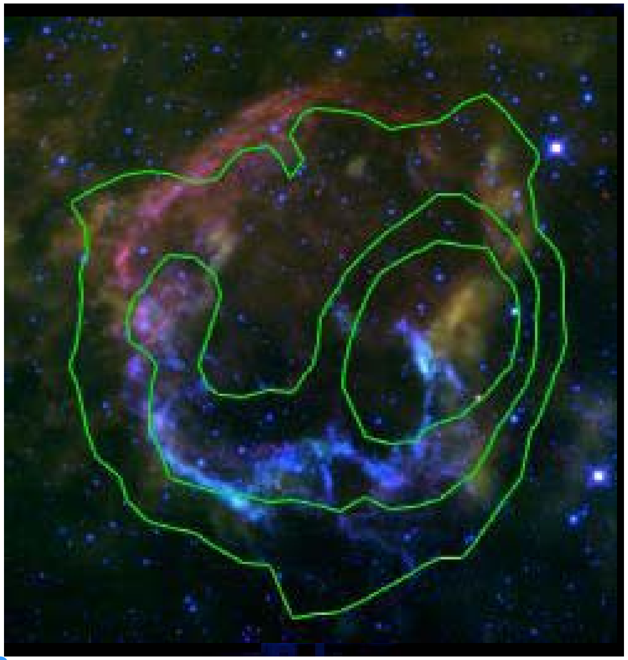
Good model … is it right ?

We don’t yet know if the model is right or not, but there has been considerable progress in the last few years.



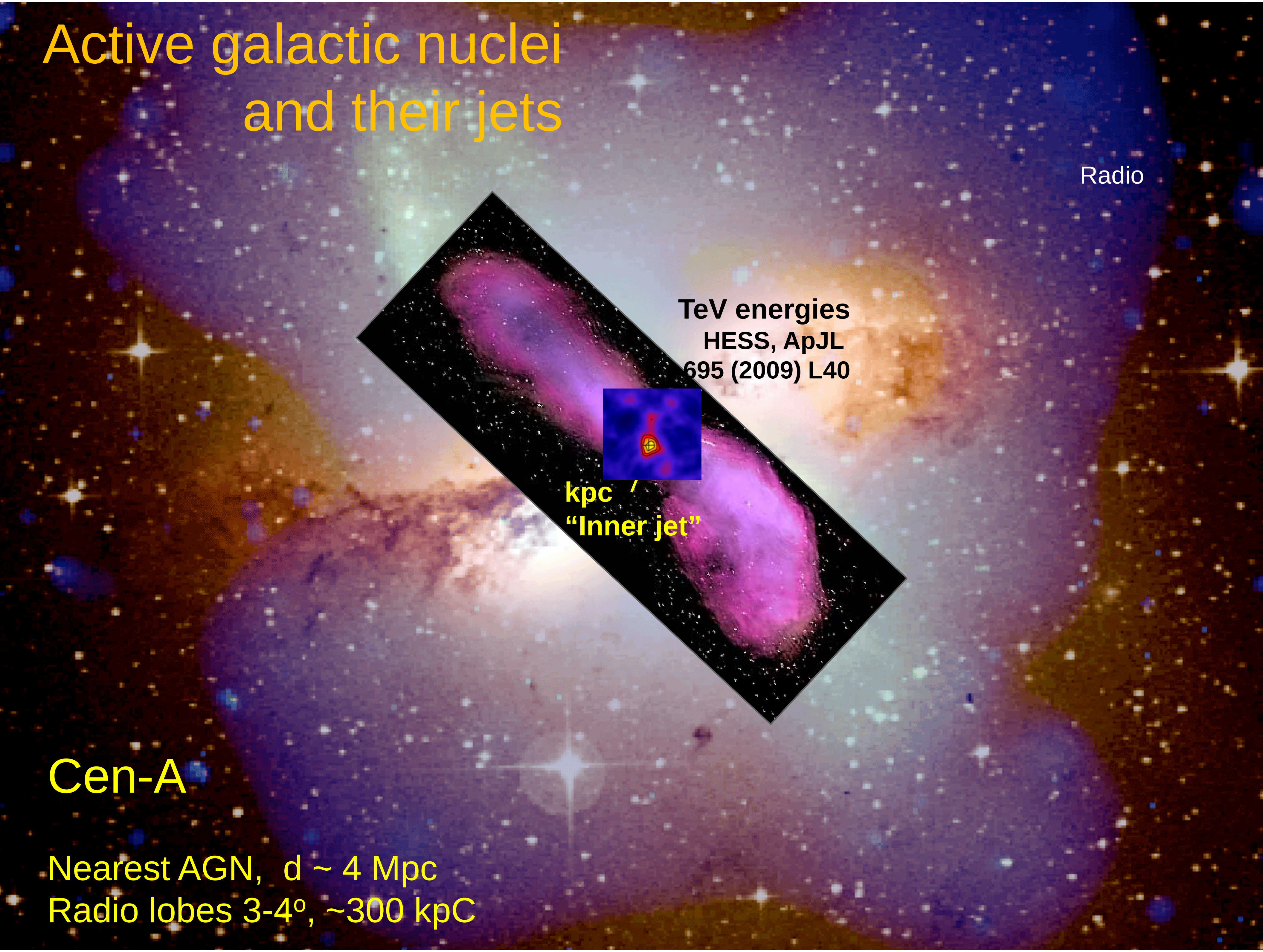
RXJ 1713-3946
Age = 1600 y
D = ~1 kpc

IC 443
Age ~ 30 ky
D ~ 0.8kpc



***WISE* – 22, 12, 4.6 μm**

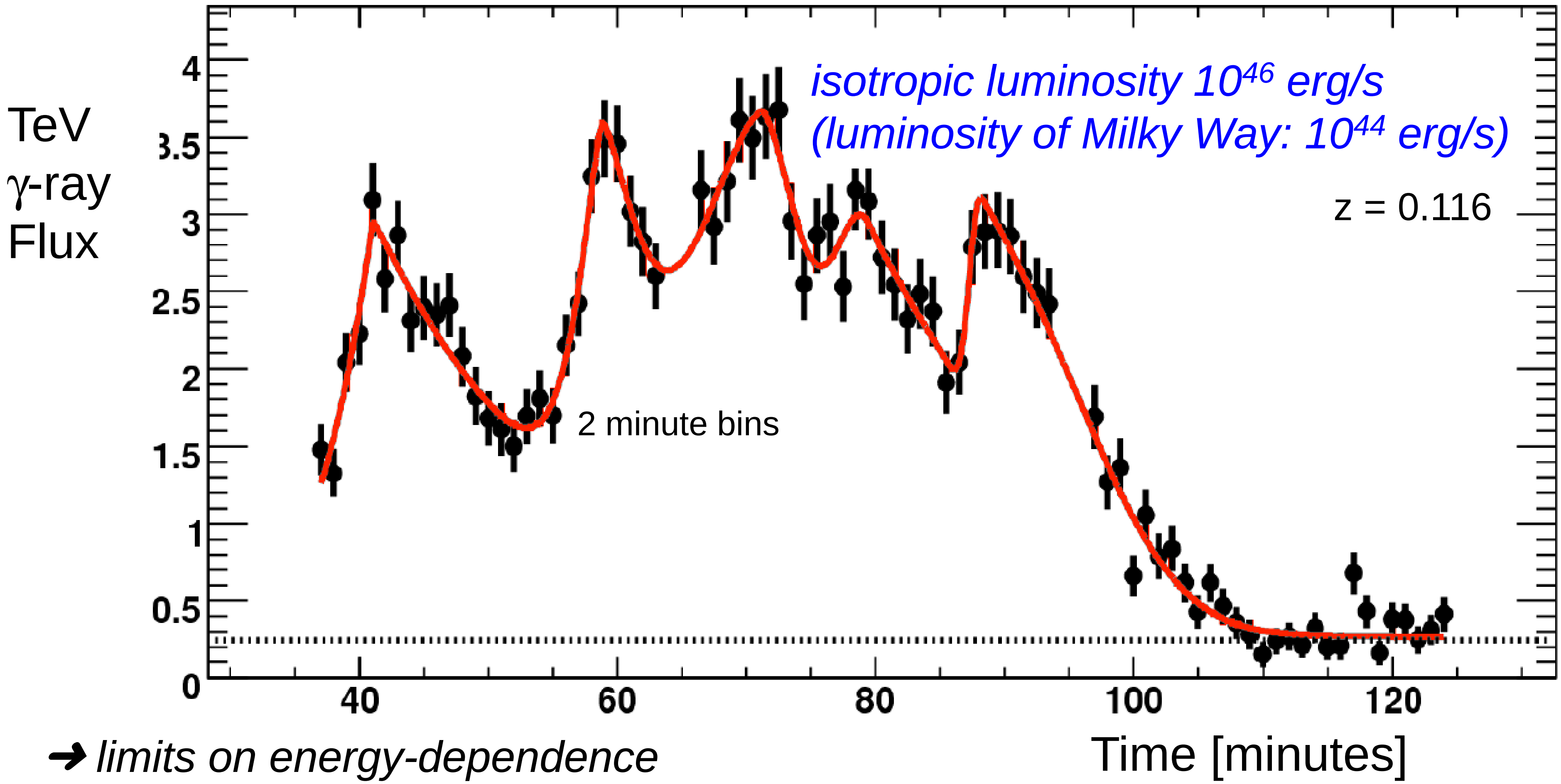
Active galactic nuclei and their jets



AGN that Point to Us

"Blazars": AGN with jets pointed to us
Remarkable variability !

PKS 2155-304 flare
in TeV γ-rays

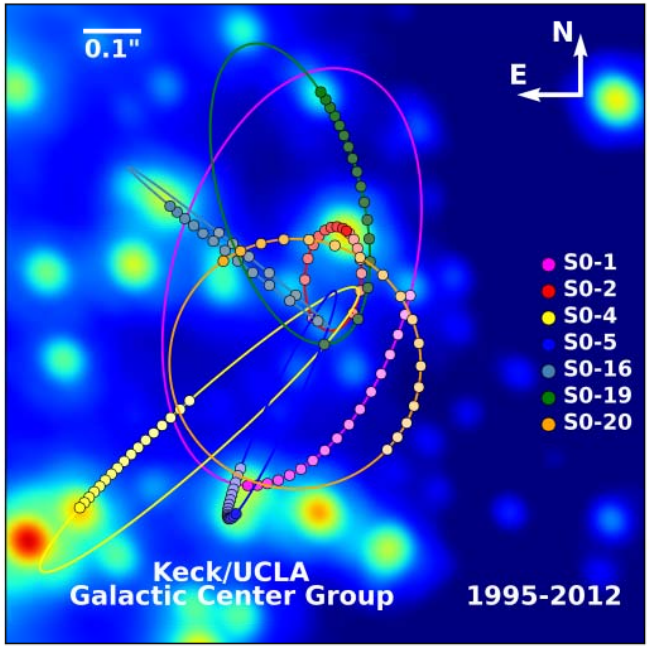


➜ *limits on energy-dependence of speed of light*

→ *Study transparency of universe (EBL)*

Galactic Center – A Mystery

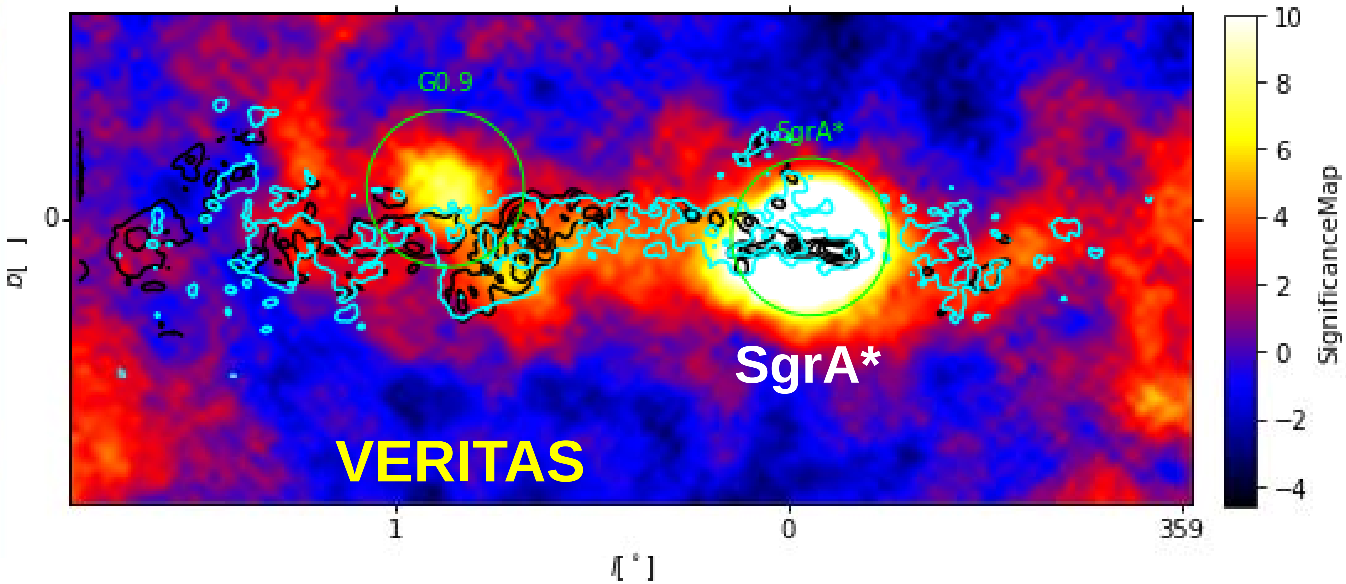
Infrared



Ghez et al., 2012
1″ x 1″

TeV γ-rays

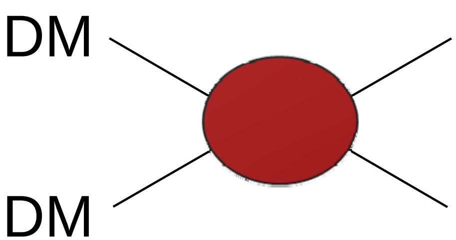
A, Archer et al.
VERITAS Coll.
(2015)
1^o x 2^o



TeV Emission is:

- **Intense and highly non-thermal**
- **completely unexpected**
- **not understood !**

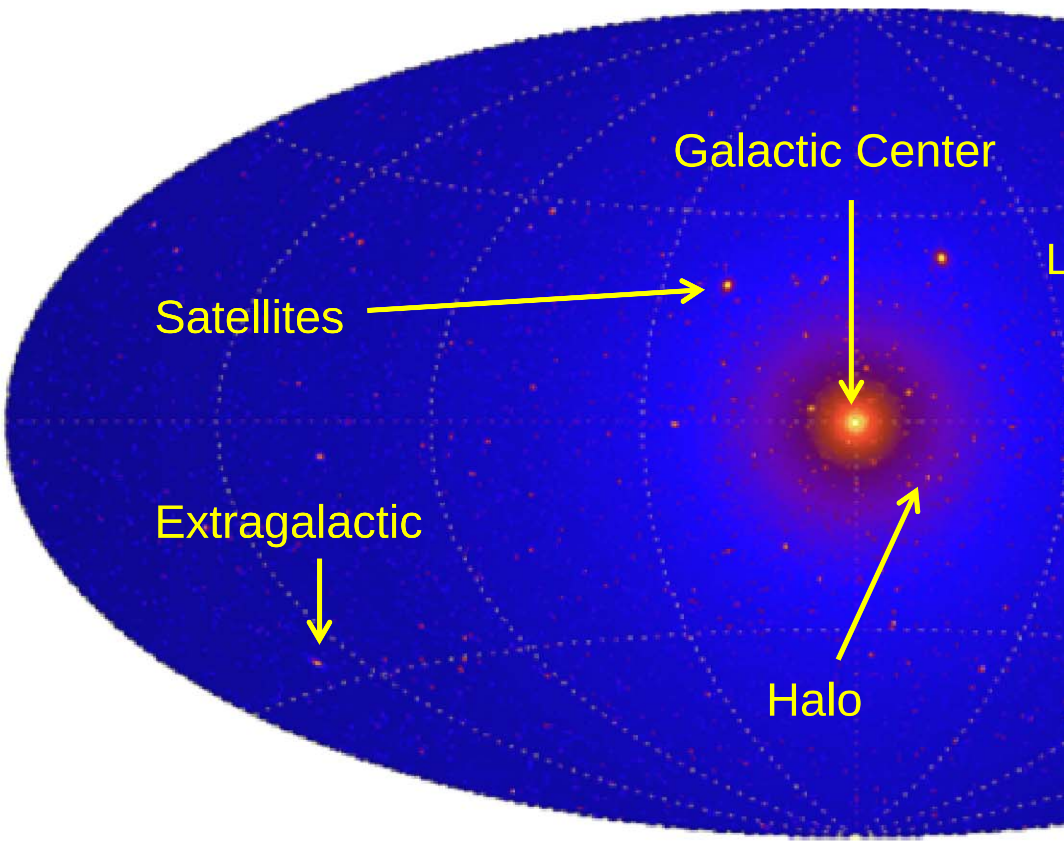
(Indirect) Dark Matter Detection



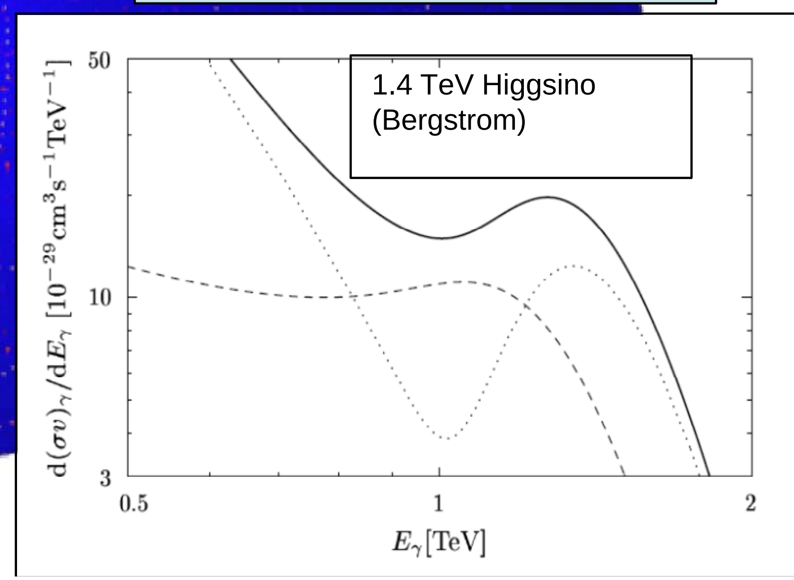
SM: b, W^+, Z, τ^+, …
Primary channels
SM: $\bar{b}$, W^-, Z, τ^-, …

Hadronisation and/or decay

➡ γ, e^+, $\bar{p}$, $\bar{\nu}$, …
Final states
➡ γ, e^-, p, ν, …

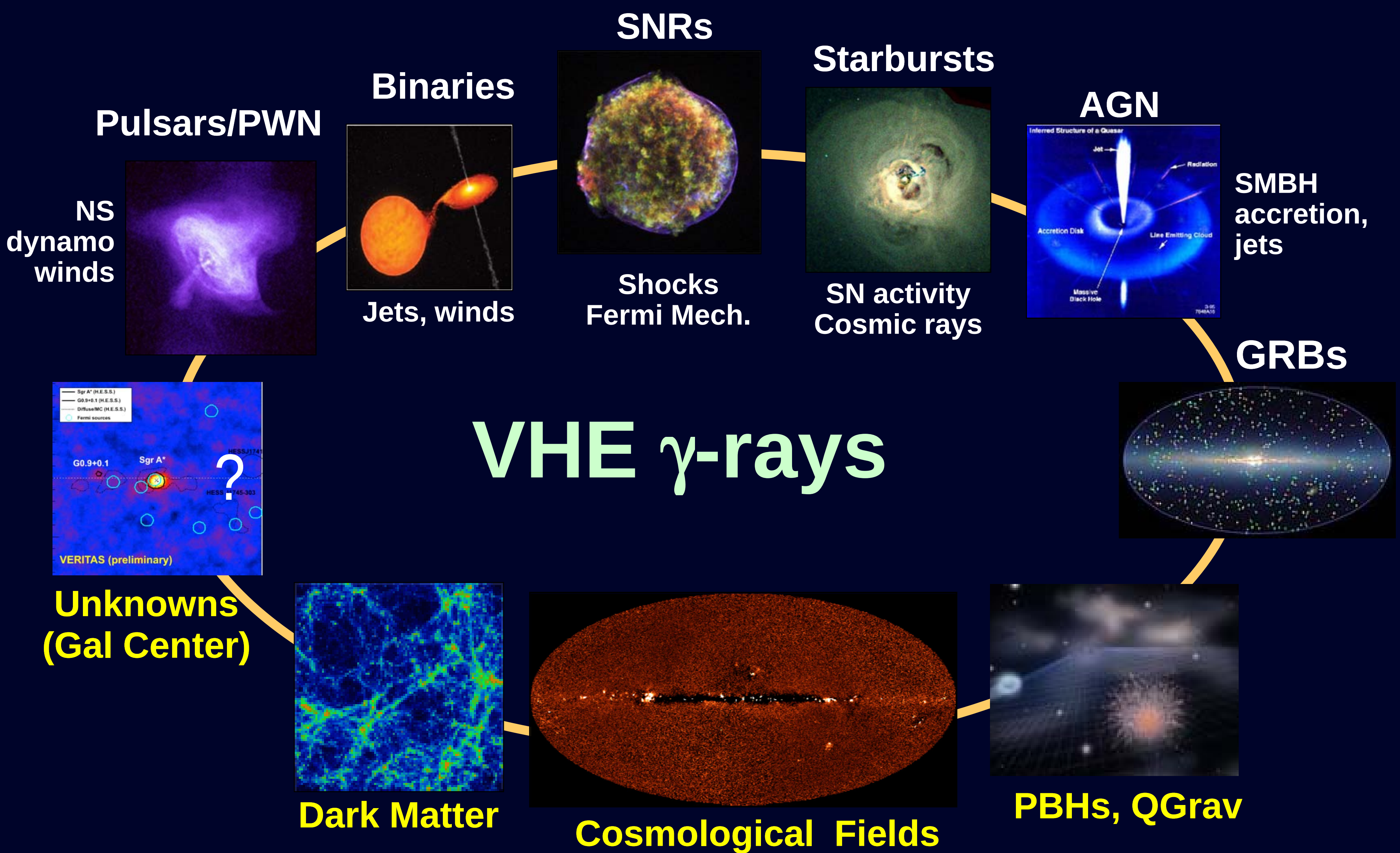


"Universal" Spectrum



Ultimate goal: Dark Matter Astronomy

Exploring the non-thermal Universe “ASTRO”

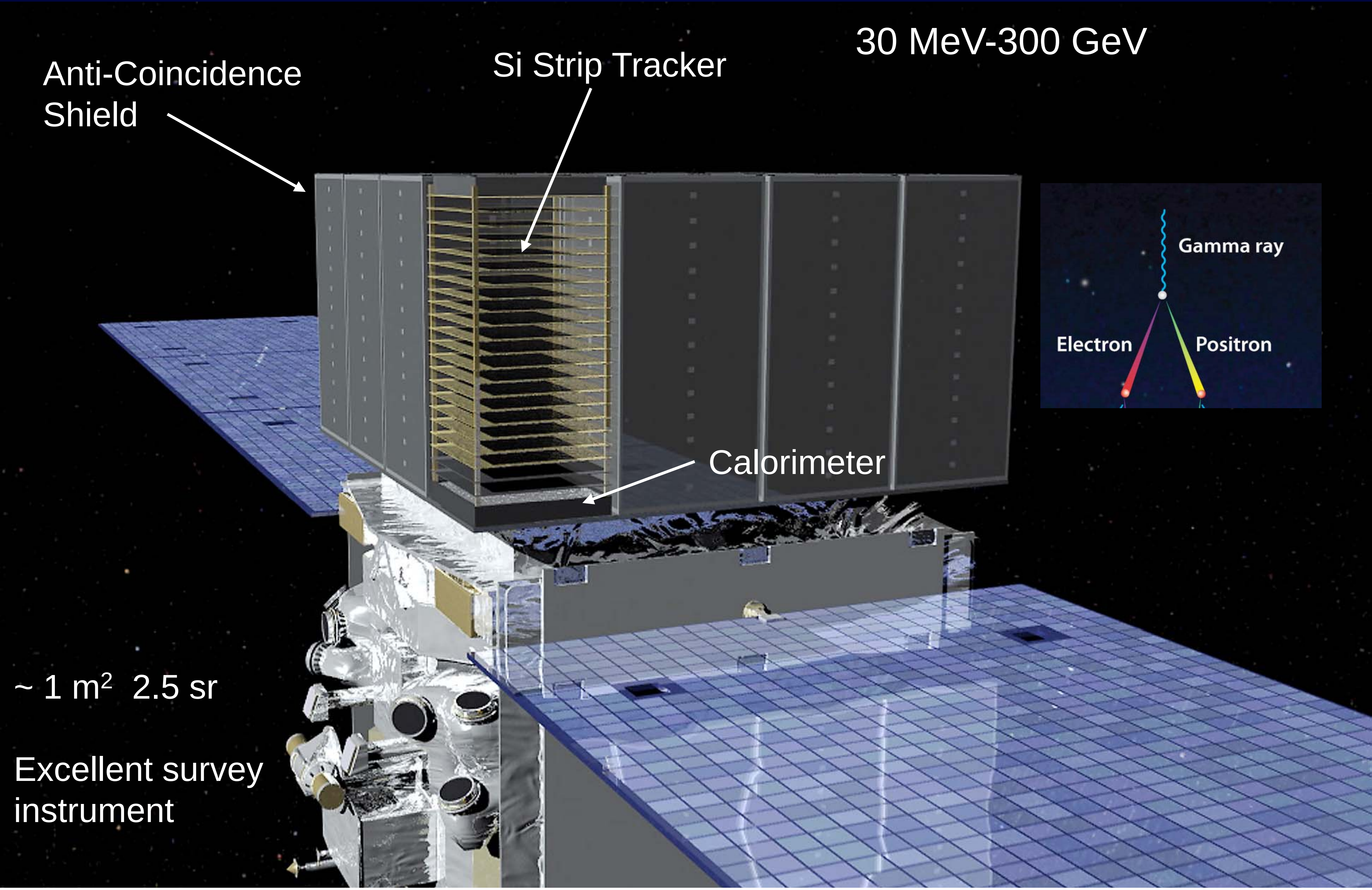


Probing New Physics at GeV/TeV scale “PARTICLE”

Experimental Technique
&
Planning for the Future

Fermi Large Area Telescope (LAT)

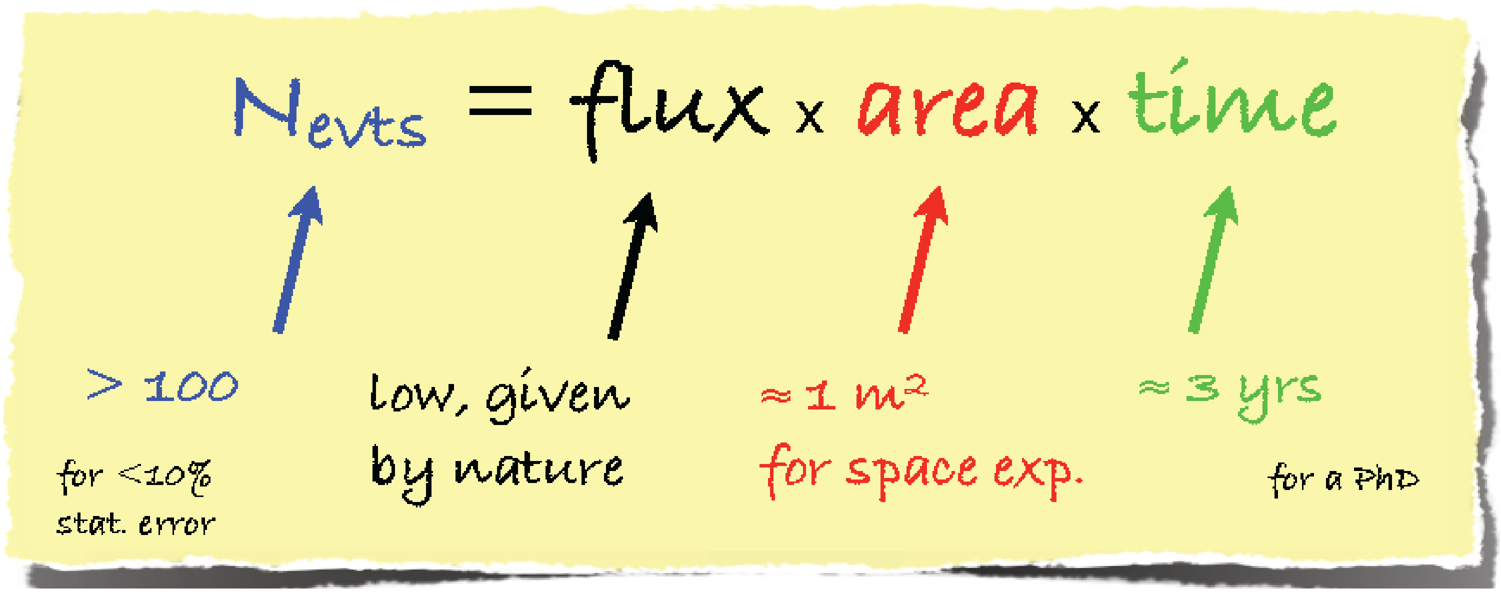
30 MeV-300 GeV



~ 1 m^2 2.5 sr

Excellent survey instrument

Beyond 100 GeV



Steeply falling spectrum:

x10 in Energy → divide by 100-500 in flux

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

Imaging atmospheric Cherenkov technique

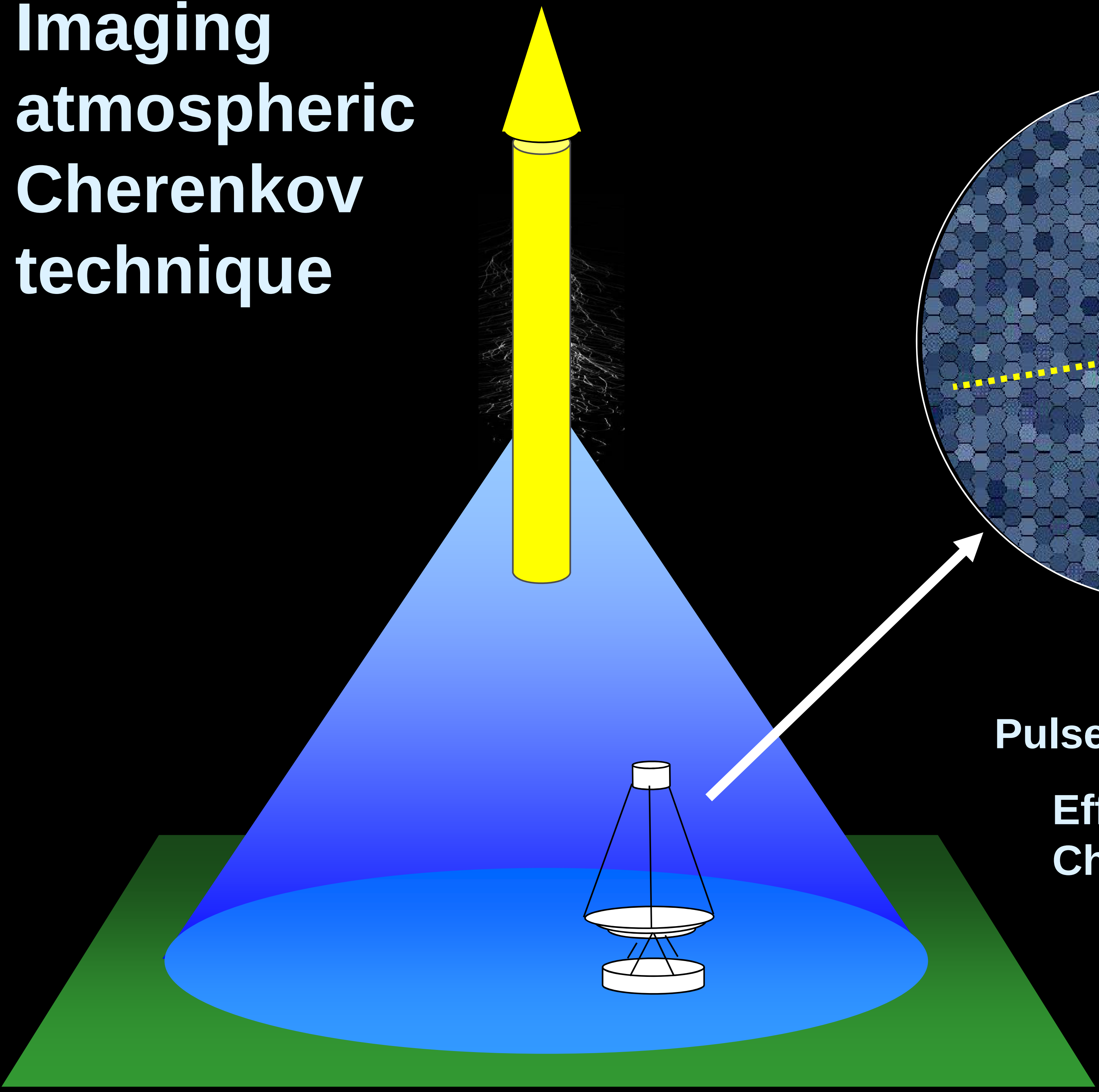
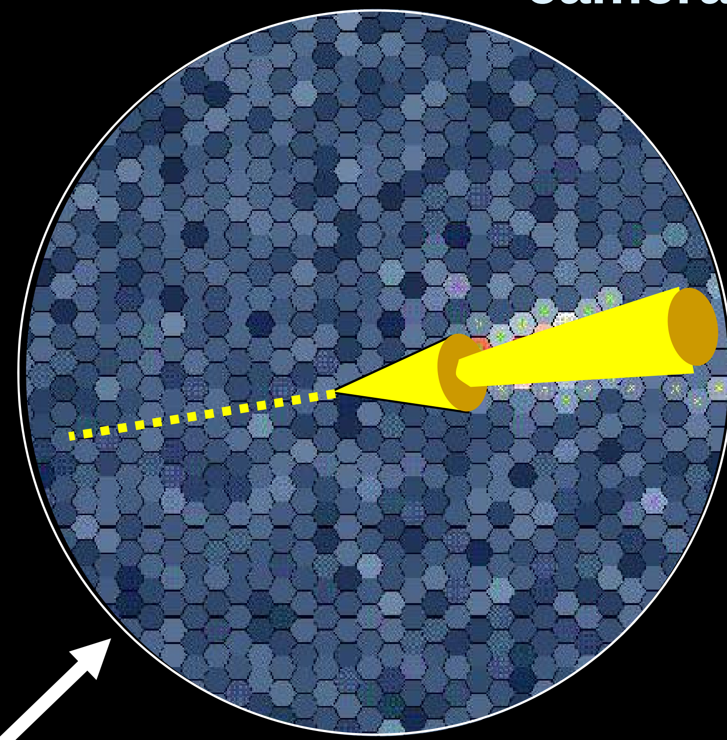


Image in camera



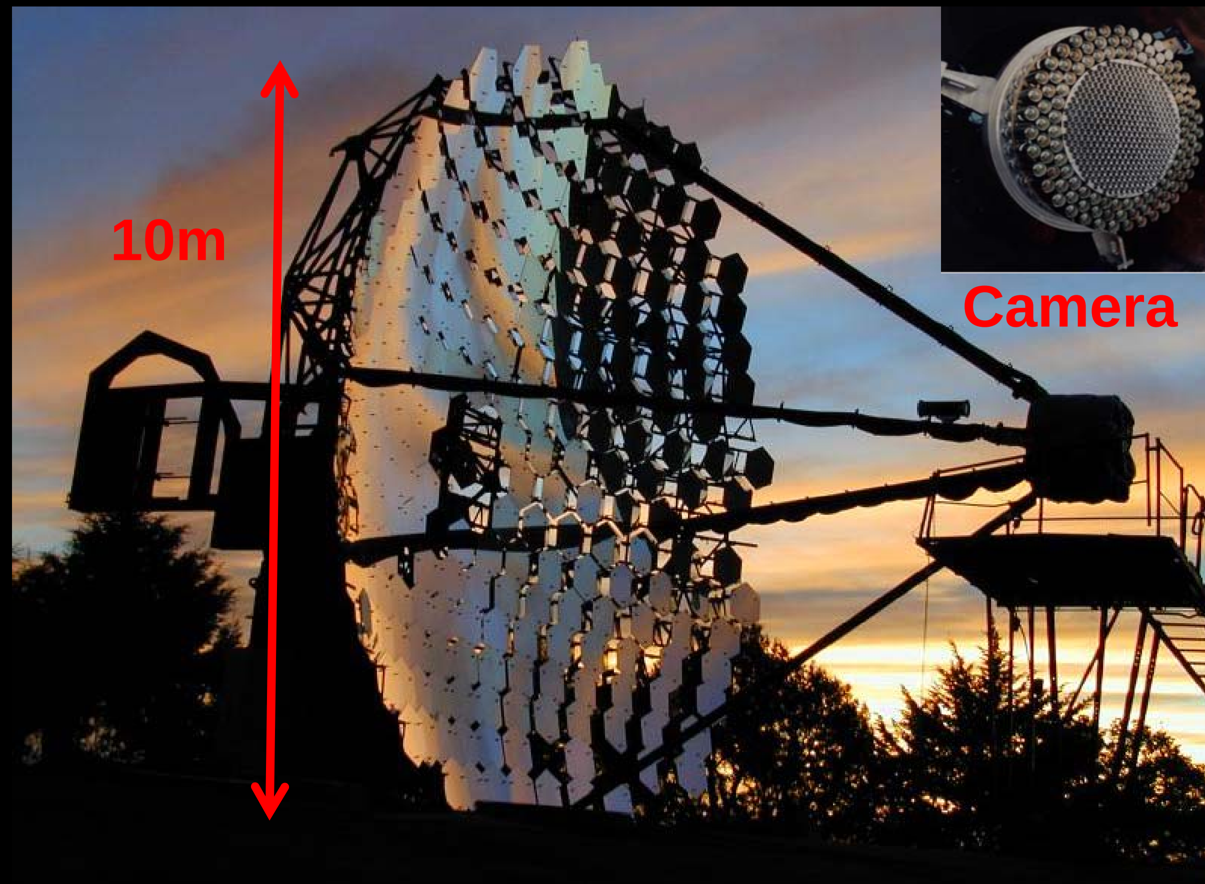
Pulse is ~few ns duration

Effective area = Cherenkov light pool $\sim 10^5\ m^2$!

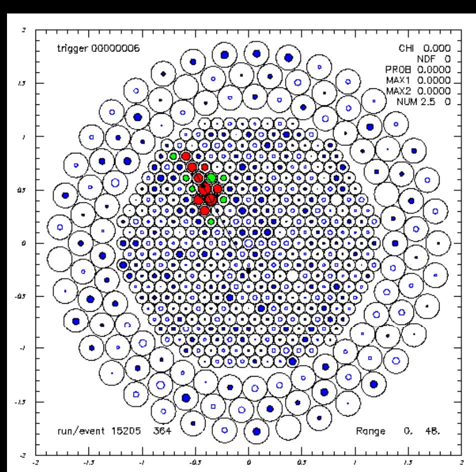
Whipple 10m γ-ray Telescope (1968-2011)

Mt. Hopkins, AZ USA

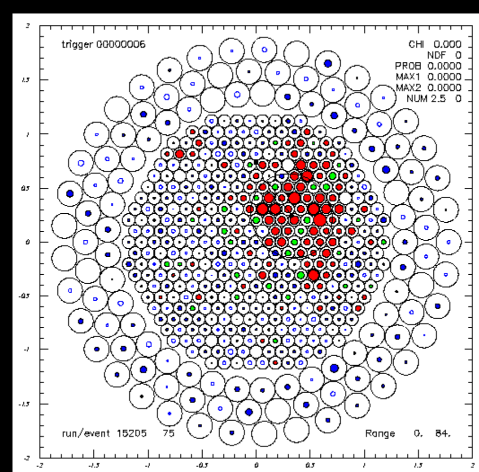
- Pioneered use of Imaging
- Made first source detection. (Crab Nebula in ~90 hours)



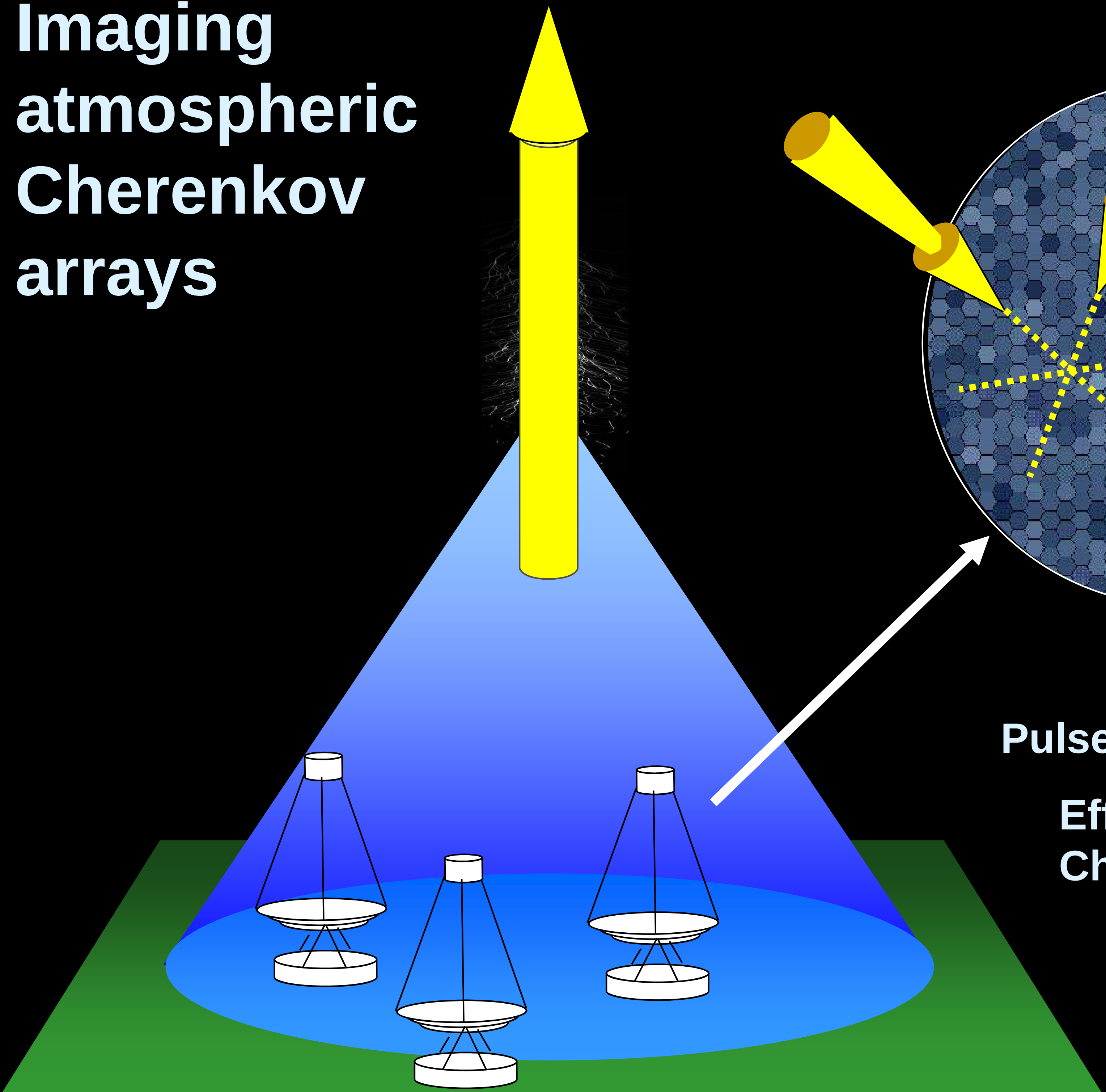
γ-ray

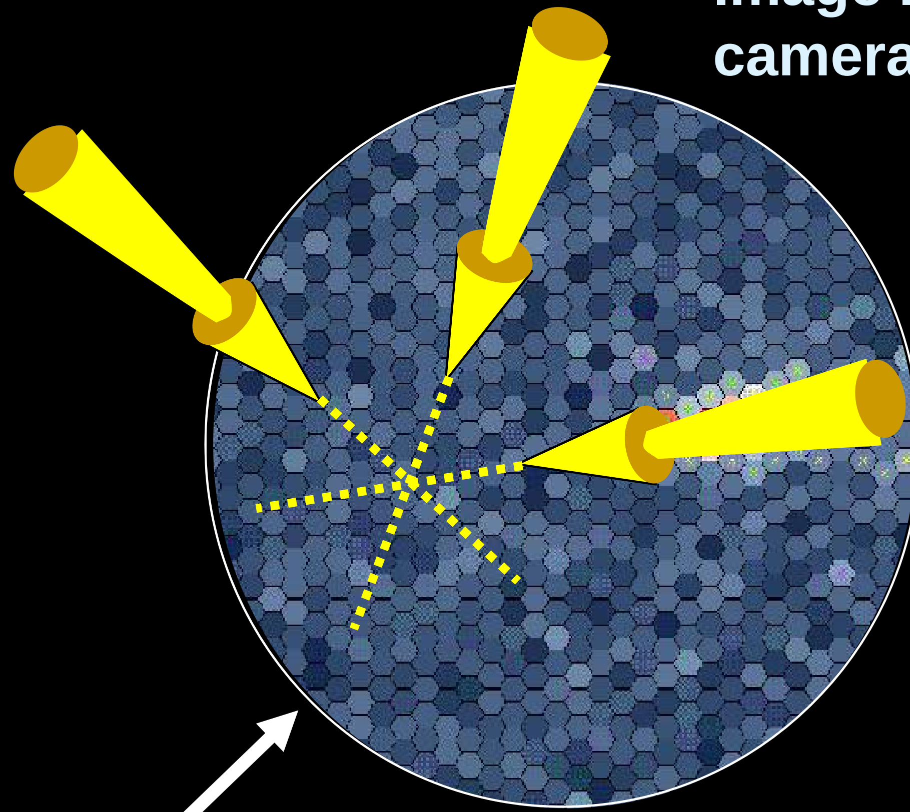


cosmic ray



Imaging atmospheric Cherenkov arrays

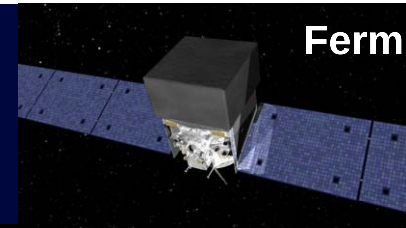


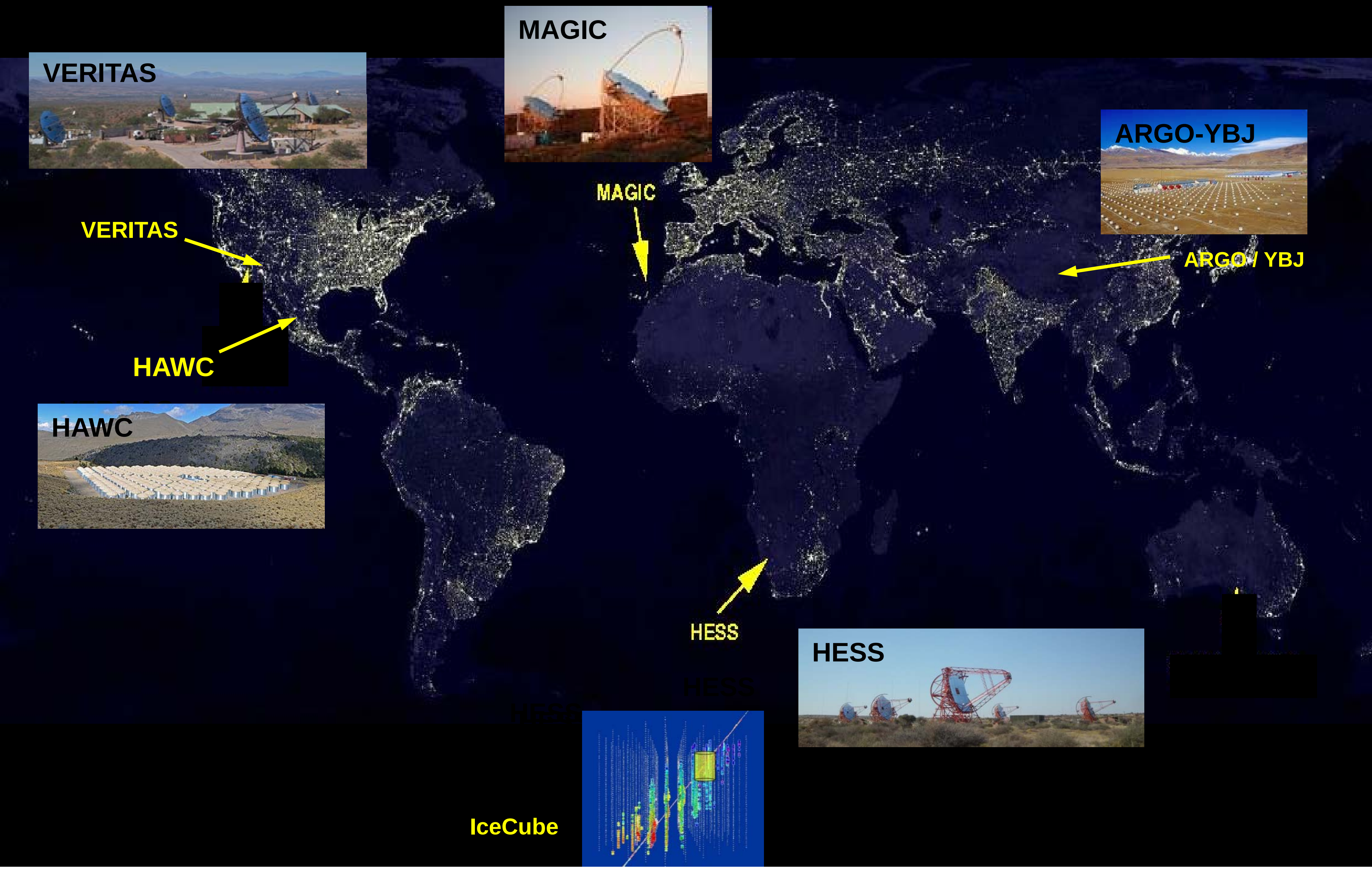


Pulse is ~few ns duration

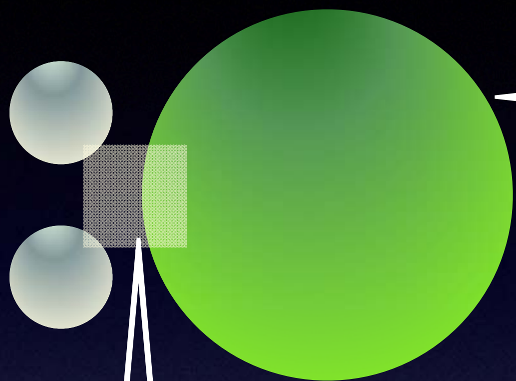
Effective area = Cherenkov light pool $\sim 10^5$ m^2 !

VHE Telescopes (2017)



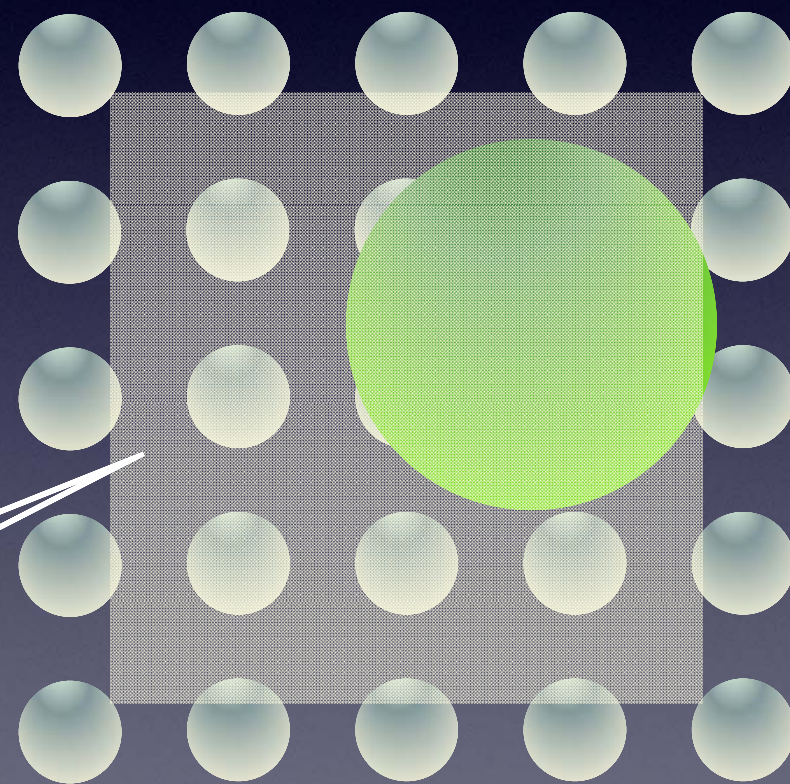


From current arrays to CTA



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

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



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

Planning for the Future

What we know, based on currents instruments:

Great scientific potential exists in the VHE domain

- *Expect many more sources & deeper probes for new physics*

IACT Technique is very powerful

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

Exciting science in both Hemispheres

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

Open Observatory → Substantial reward

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

International Partnerships required by scale/scope

- *Project must develop the instrument and the observatory*

Requirements & Drivers

cherenkov telescope array

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)

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?

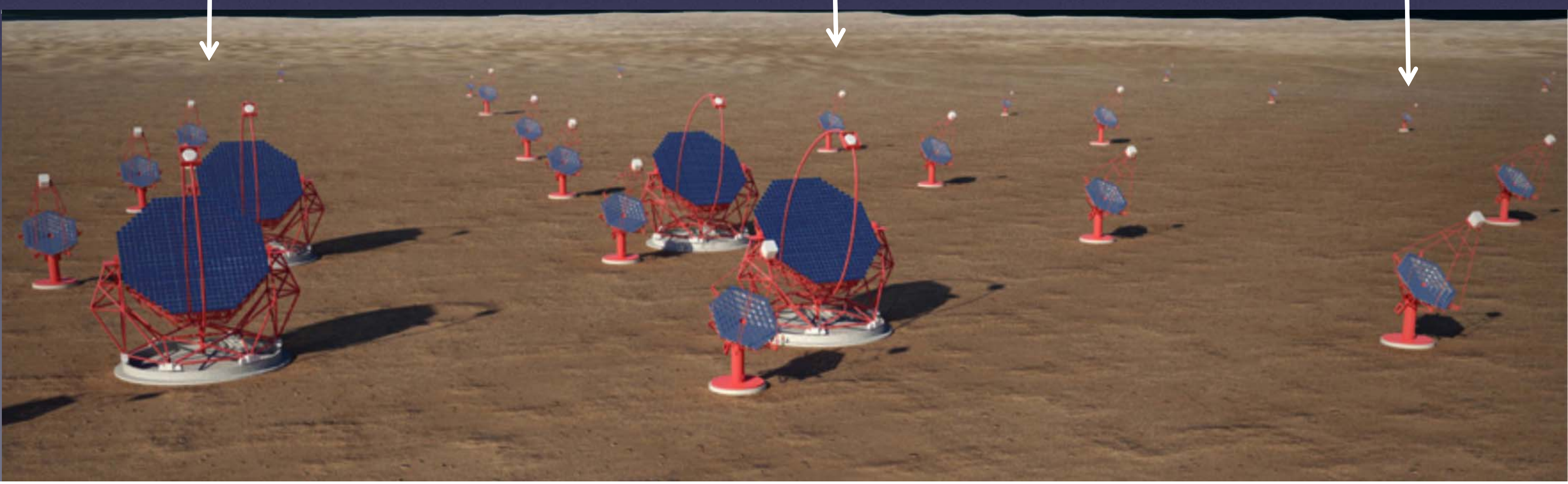
CTA Design (S array)

Science Optimization under budget constraints

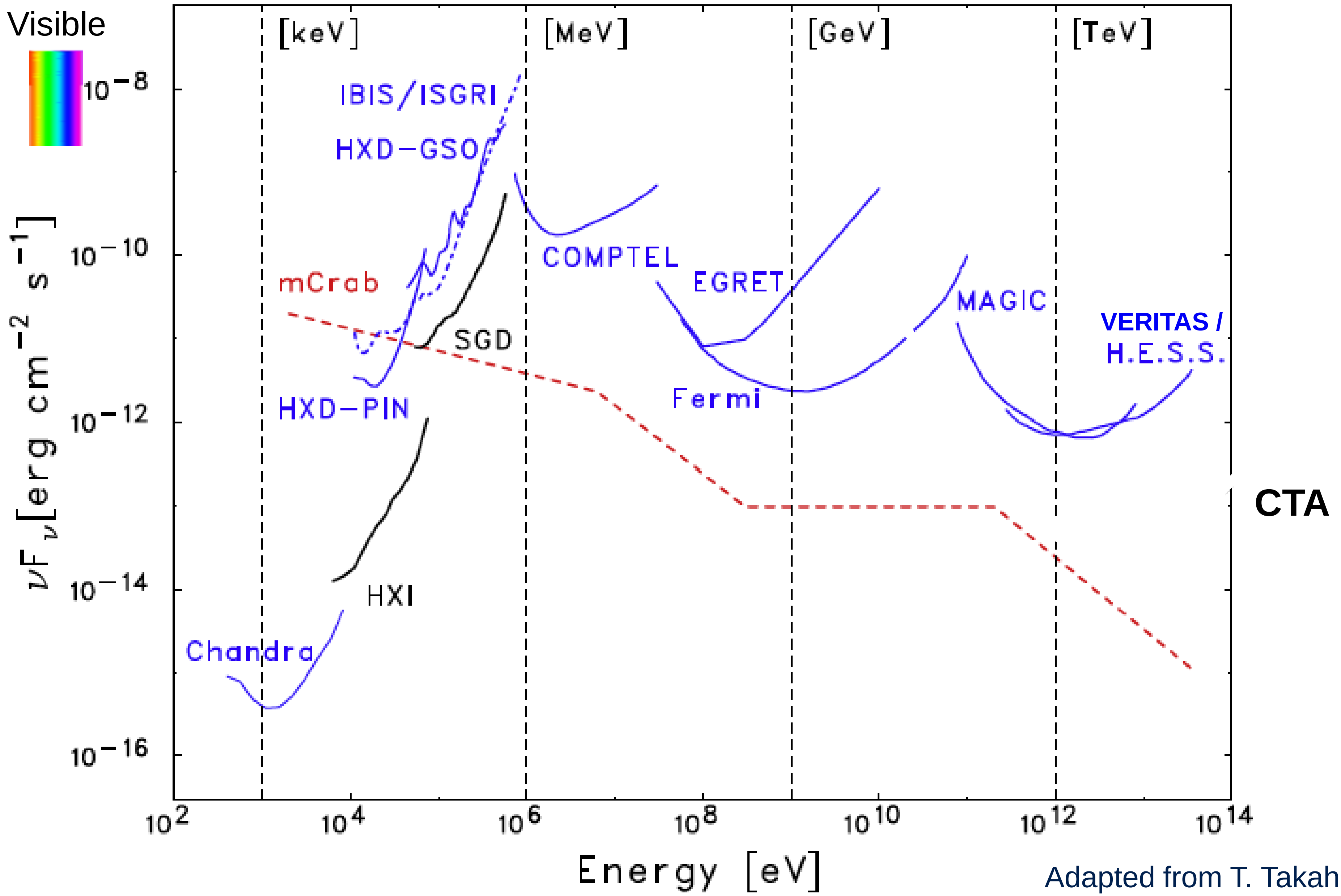
Low energies
Energy threshold 20-30 GeV
23 m diameter
4 telescopes
(LST's)

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

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

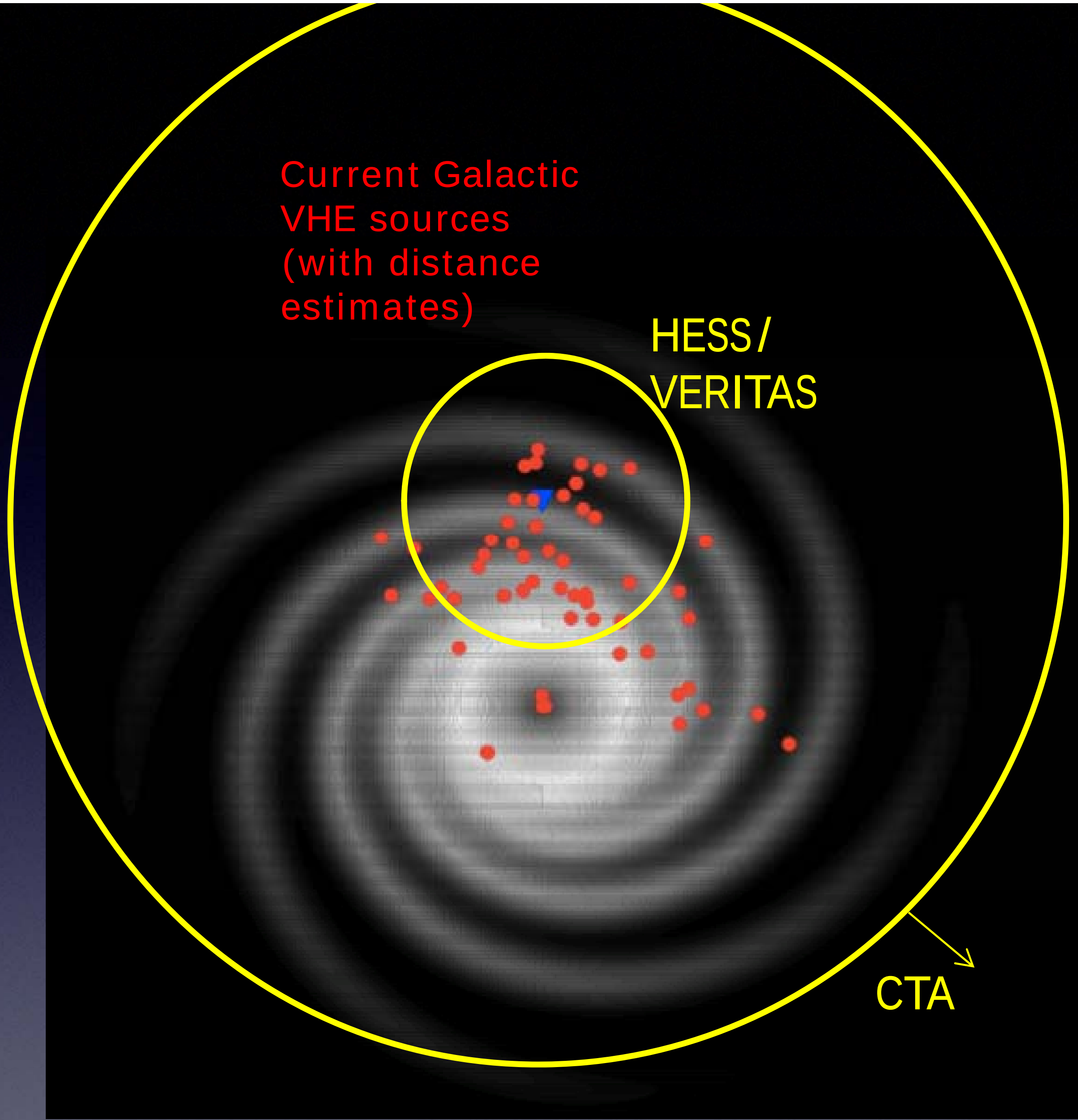


CTA Sensitivity in Context

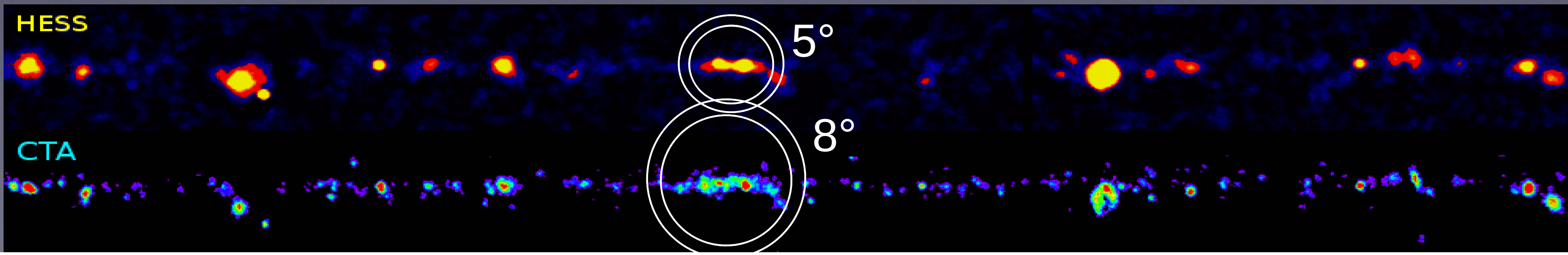


Adapted from T. Takahashi

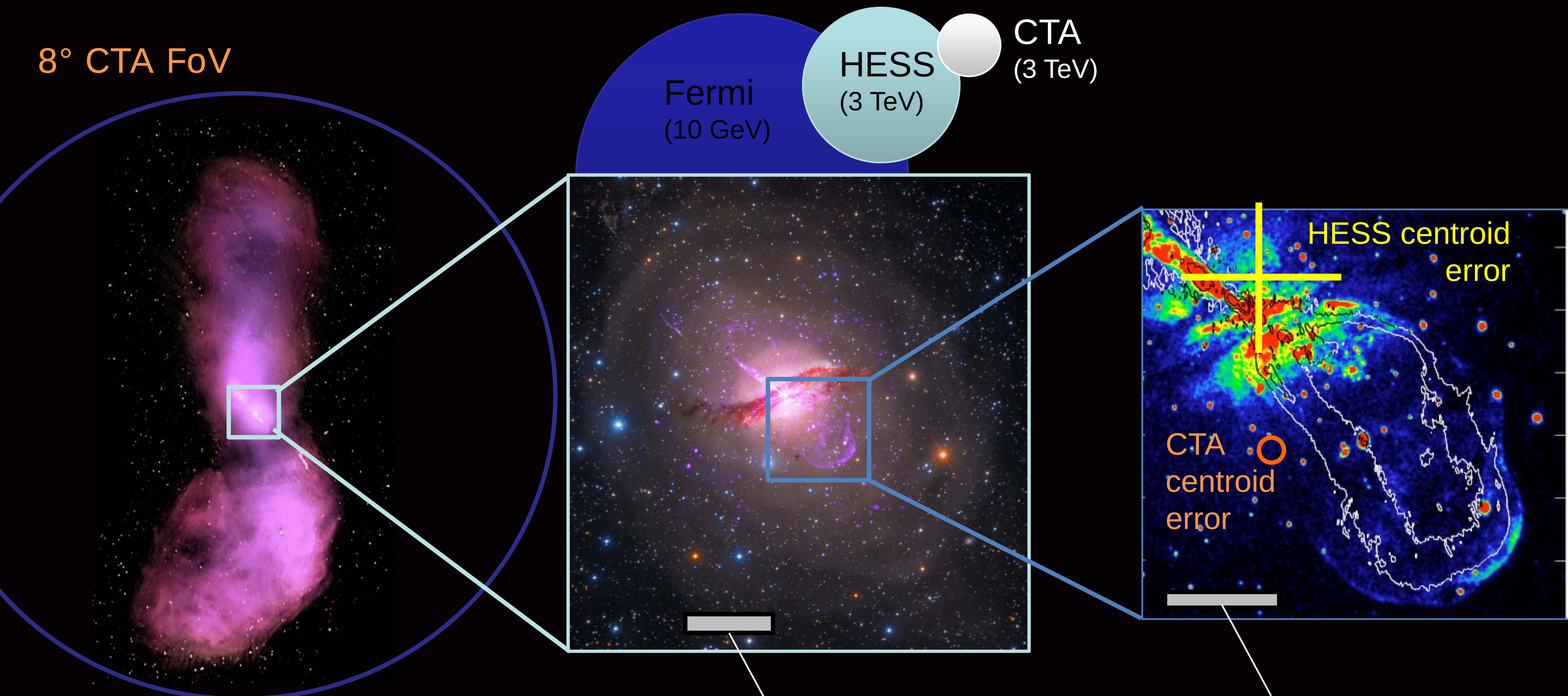
Galactic Discovery Reach



Survey speed:
x300 faster than HESS



Angular Resolution



0.1°
Typical HESS
Resolution

2 ′
CTA > 1 TeV

Example: Cen A

CTA Implementation & Status

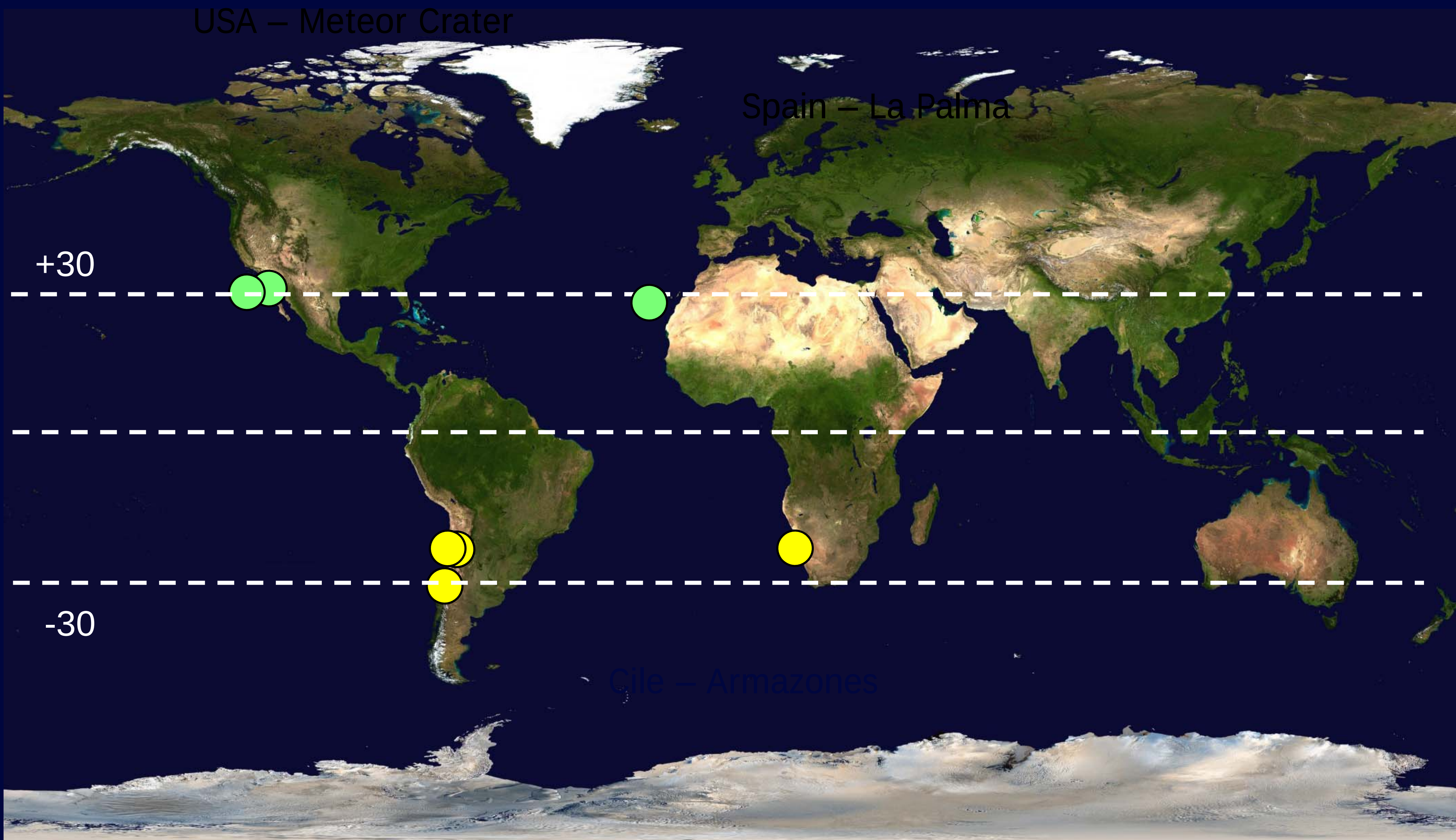
CTA Consortium

CTA is being developed by the CTA Consortium:

32 countries, ~1300 scientists, ~200 institutes, ~440 FTE

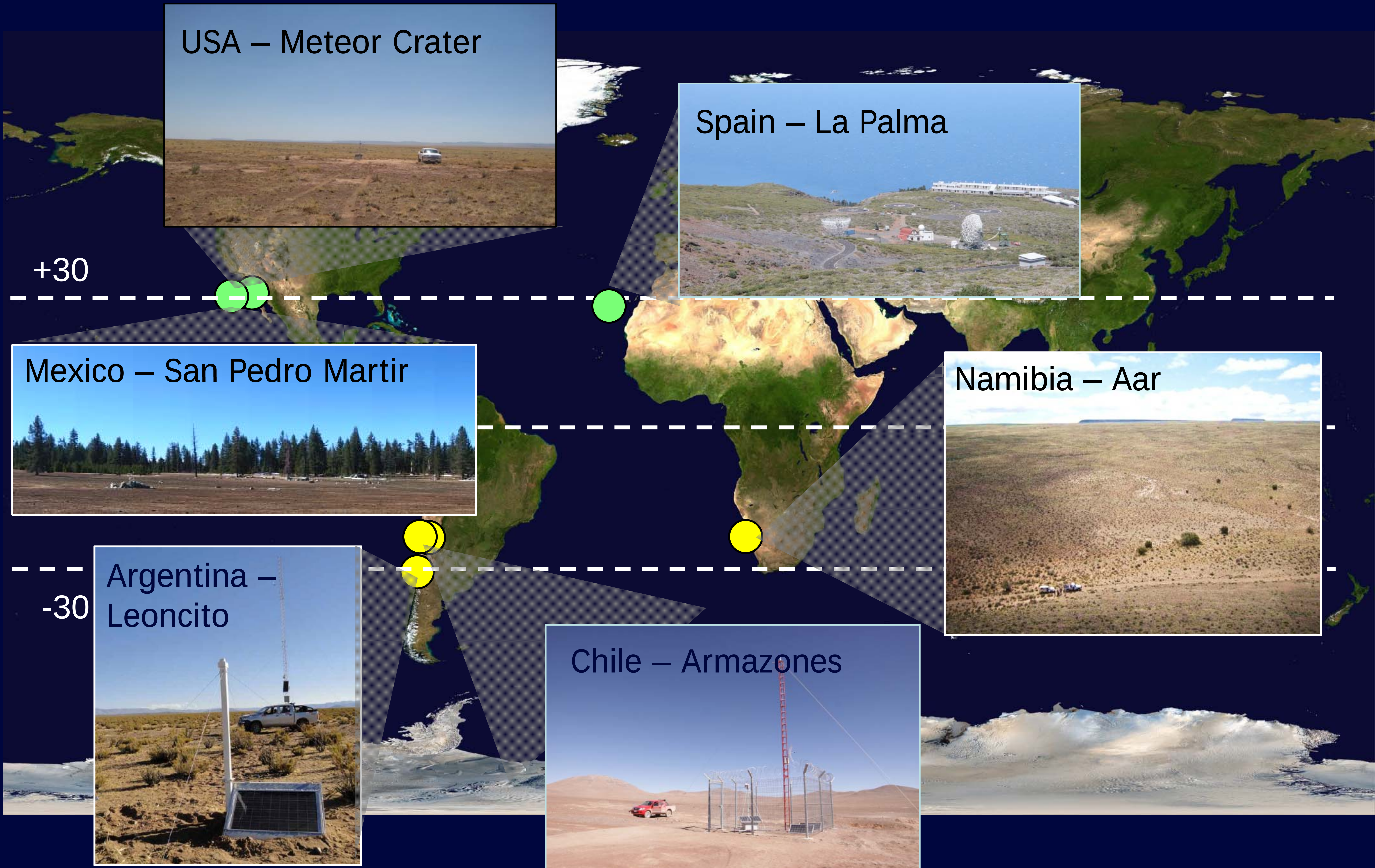
Site Selection

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

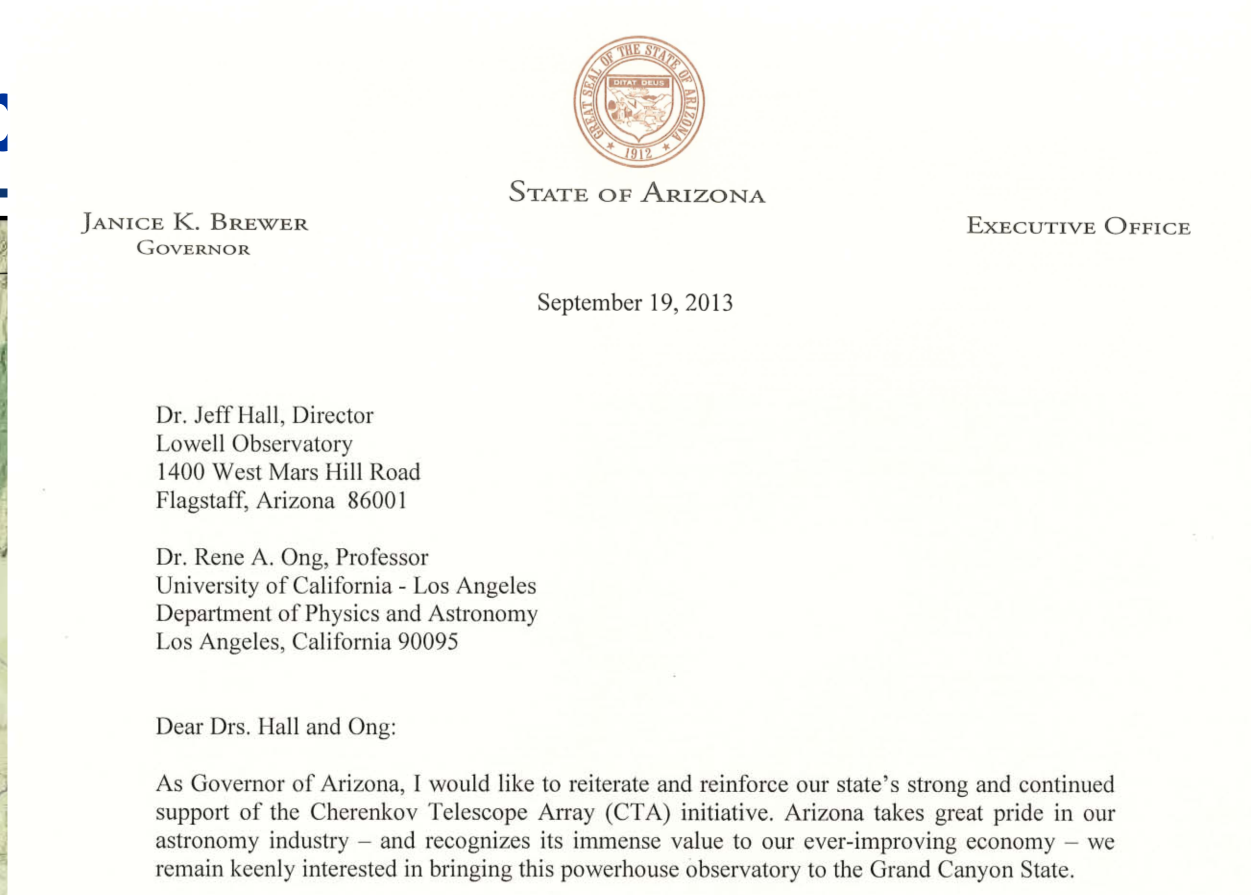


Site Selection

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



Prop



STATE OF ARIZONA

JANICE K. BREWER
GOVERNOR

EXECUTIVE OFFICE

September 19, 2013

Dr. Jeff Hall, Director
Lowell Observatory
1400 West Mars Hill Road
Flagstaff, Arizona 86001

Dr. Rene A. Ong, Professor
University of California - Los Angeles
Department of Physics and Astronomy
Los Angeles, California 90095

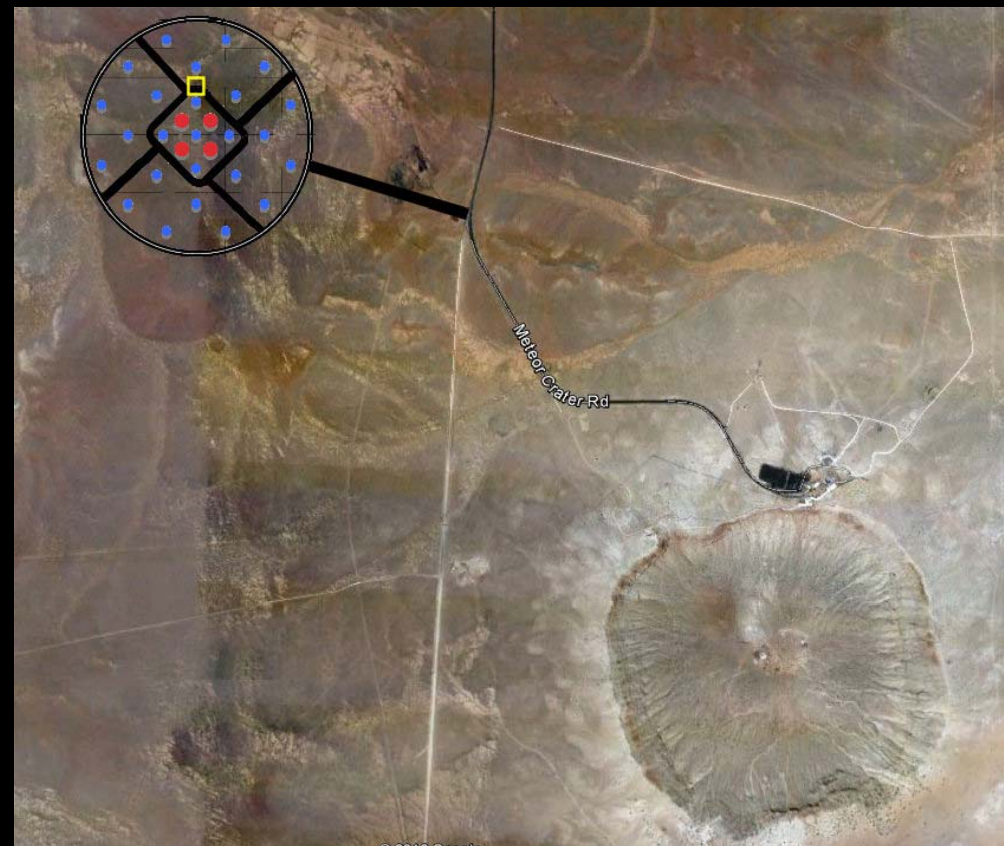
Dear Drs. Hall and Ong:

As Governor of Arizona, I would like to reiterate and reinforce our state's strong and continued support of the Cherenkov Telescope Array (CTA) initiative. Arizona takes great pride in our astronomy industry – and recognizes its immense value to our ever-improving economy – we remain keenly interested in bringing this powerhouse observatory to the Grand Canyon State.

Map of a portion of Arizona near Flagstaff, AZ. The access routes from the East Site (A) and the West Site (B) to Flagstaff (C) are shown in blue. The Grand Canyon starts at the top of the figure.

Meteor Crater Site

CTA Reference Site superimposed on local satellite imagery to show approximate scale and road configuration.

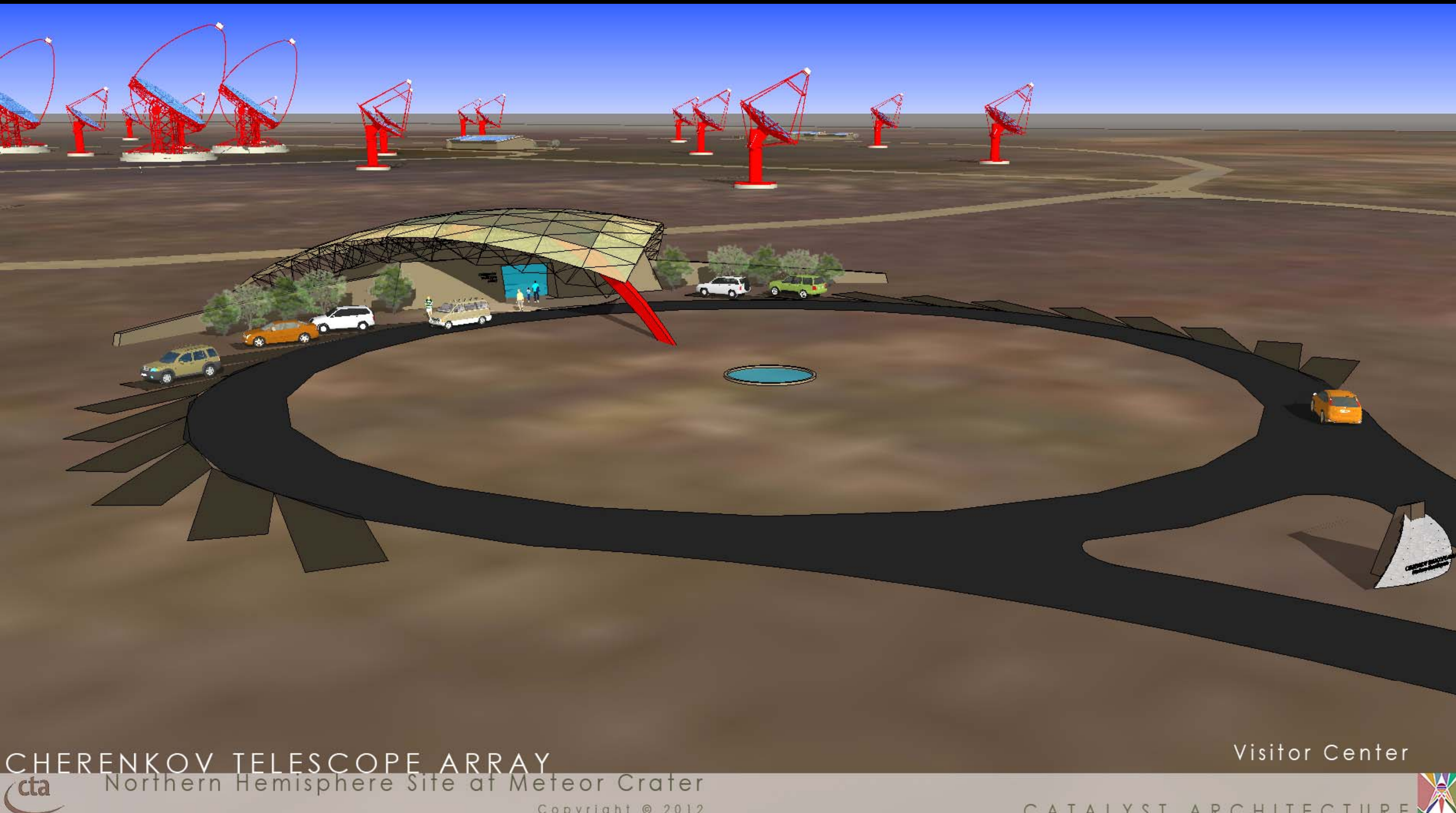


Wide view showing highway I-40 and the nearby railroad siding (9 km from site along paved road).

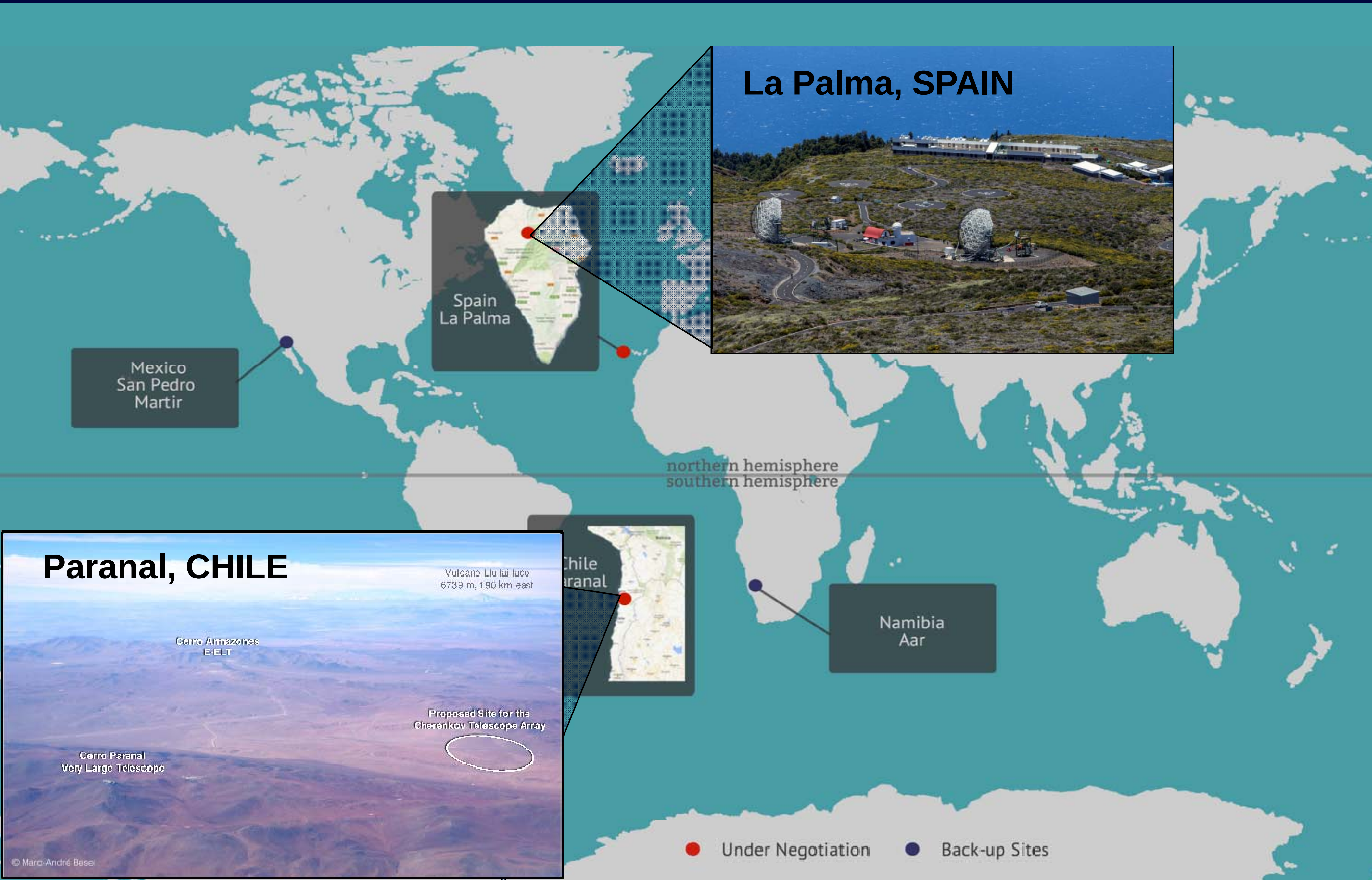
Zoom showing shortest route for access road (thick black line) and Atmoscope (yellow square).

CTA at Meteor Crater Site

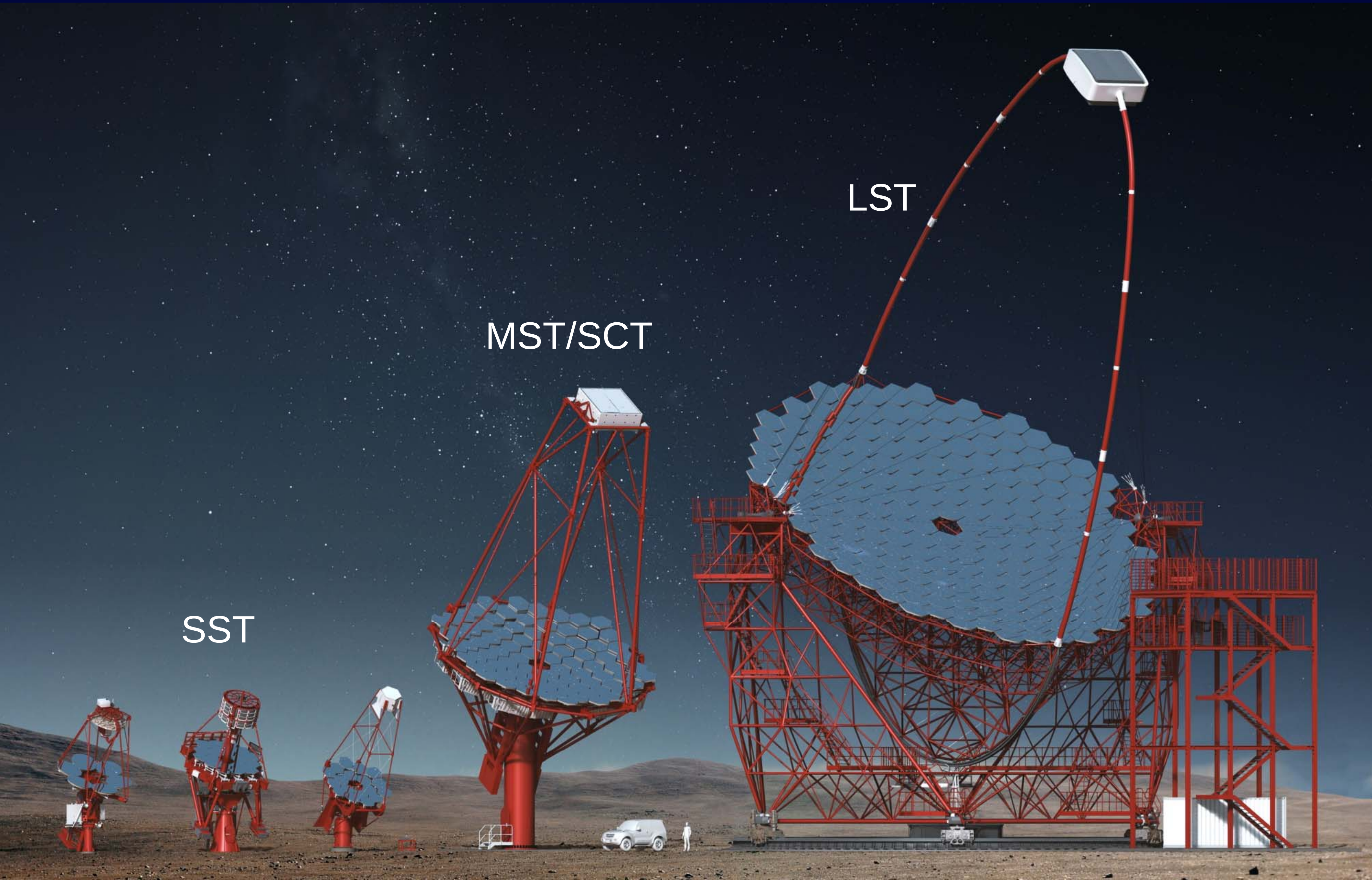
CTA at Meteor Crater Site

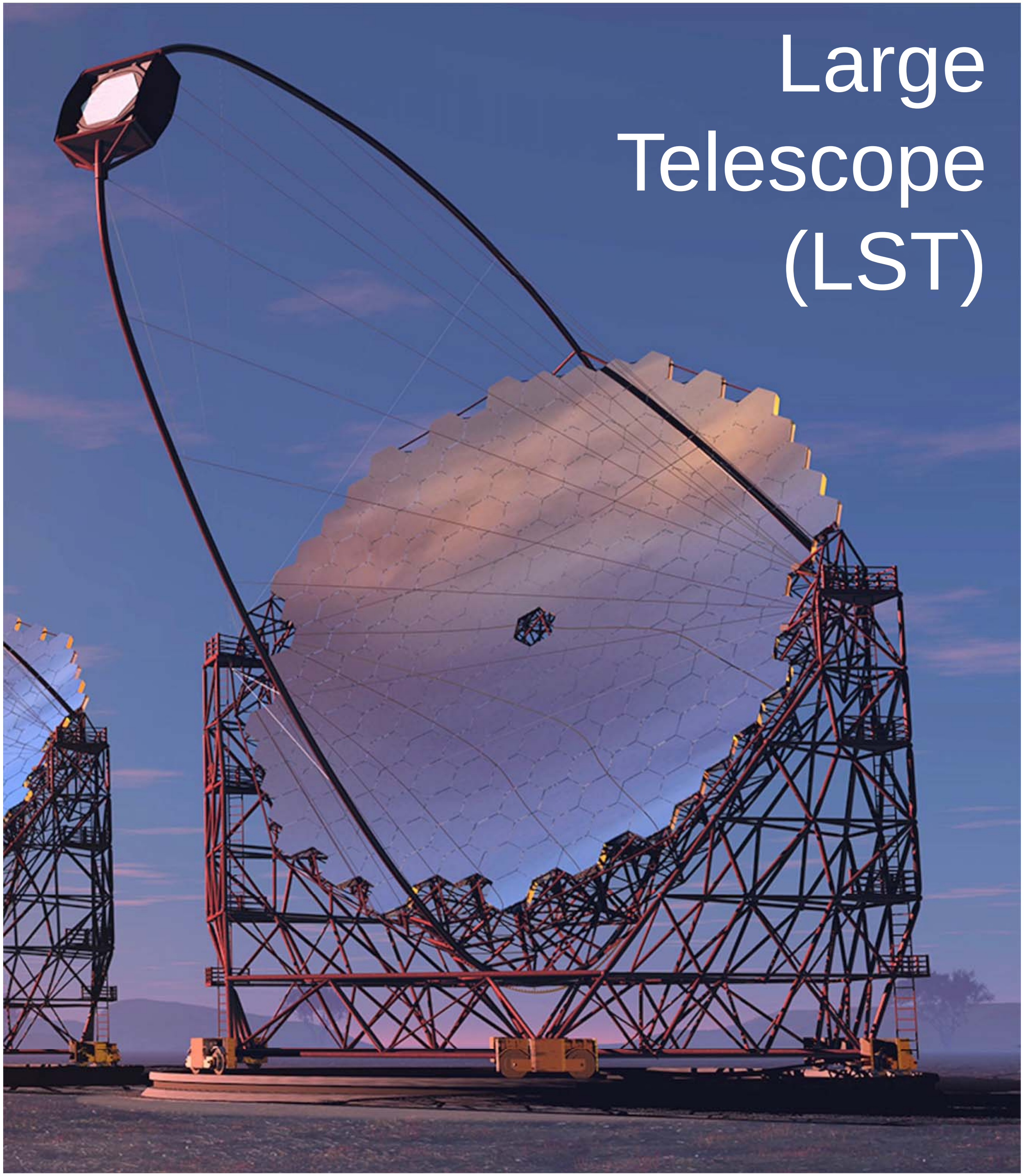


Selected Sites for CTA



CTA Telescope Types





23 m diameter / f = 28m
390 m^2 dish area
1.5 m mirror facets

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

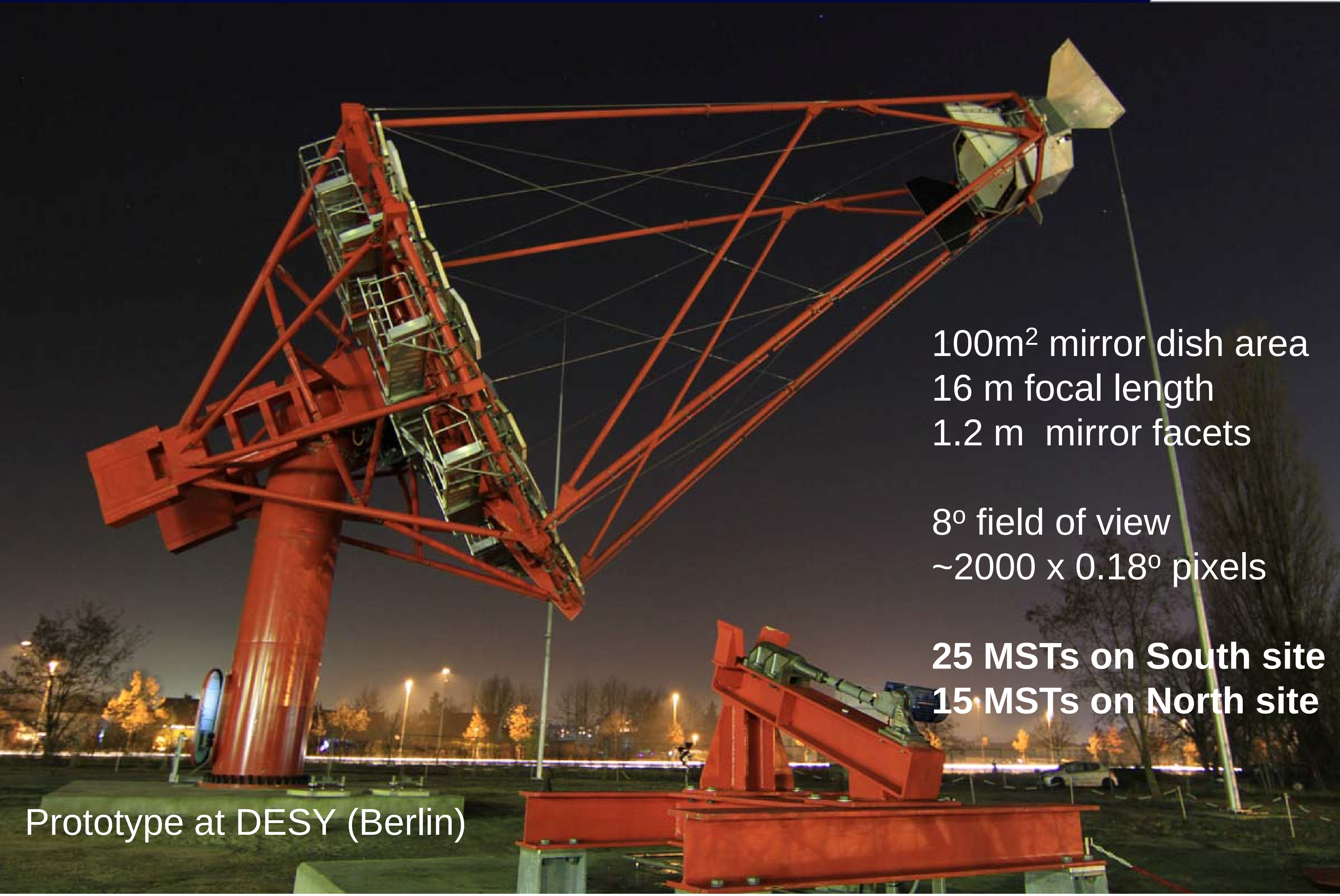
Carbon-fiber structure
for 20 s positioning

Active mirror control

4 LSTs on South site
4 LSTs on North site

First LST construction
underway (La Palma)

Medium Telescope (MST)



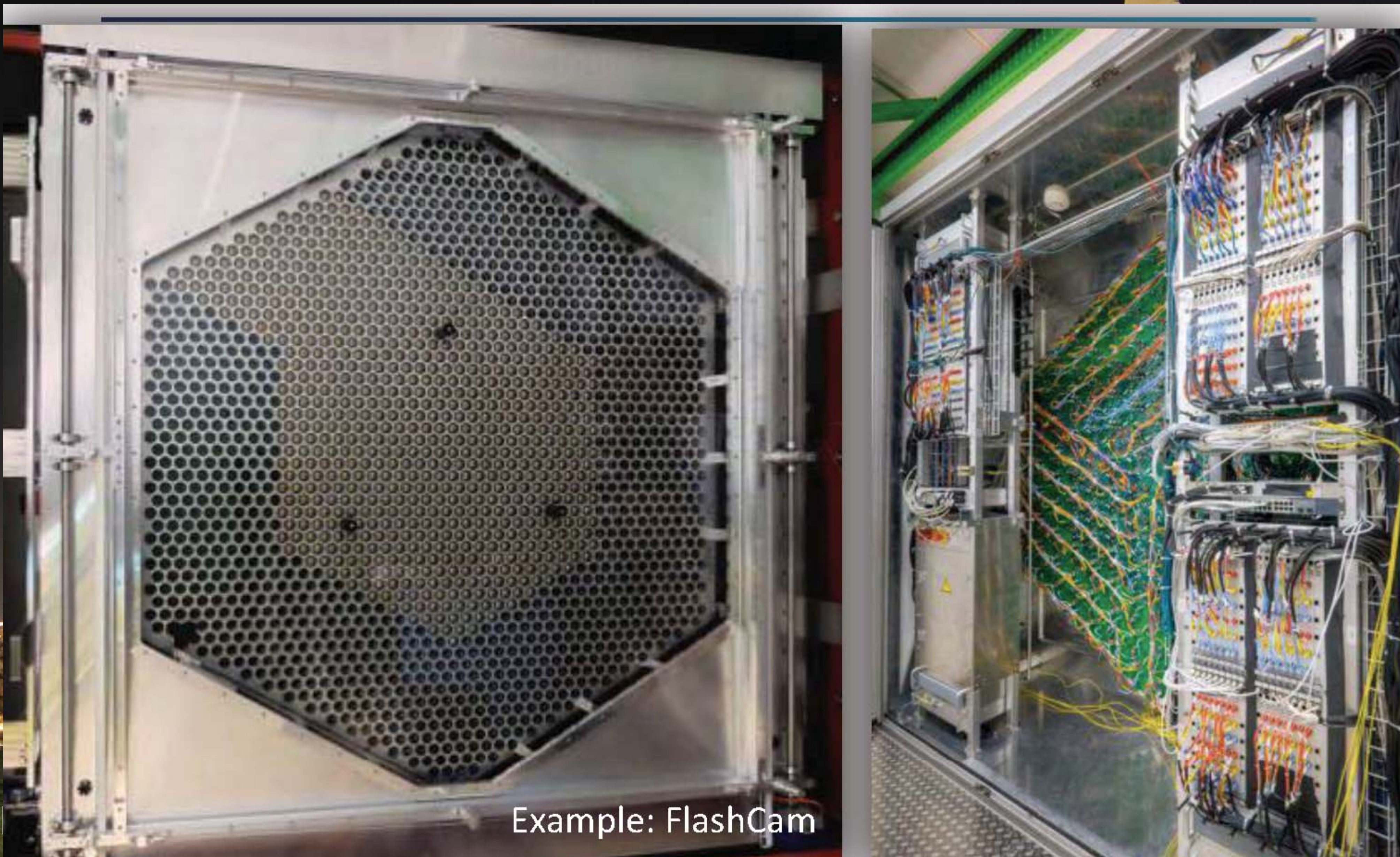
100m^2 mirror dish area
16 m focal length
1.2 m mirror facets

8^o field of view
~2000 x 0.18^o pixels

25 MSTs on South site
15 MSTs on North site

Prototype at DESY (Berlin)

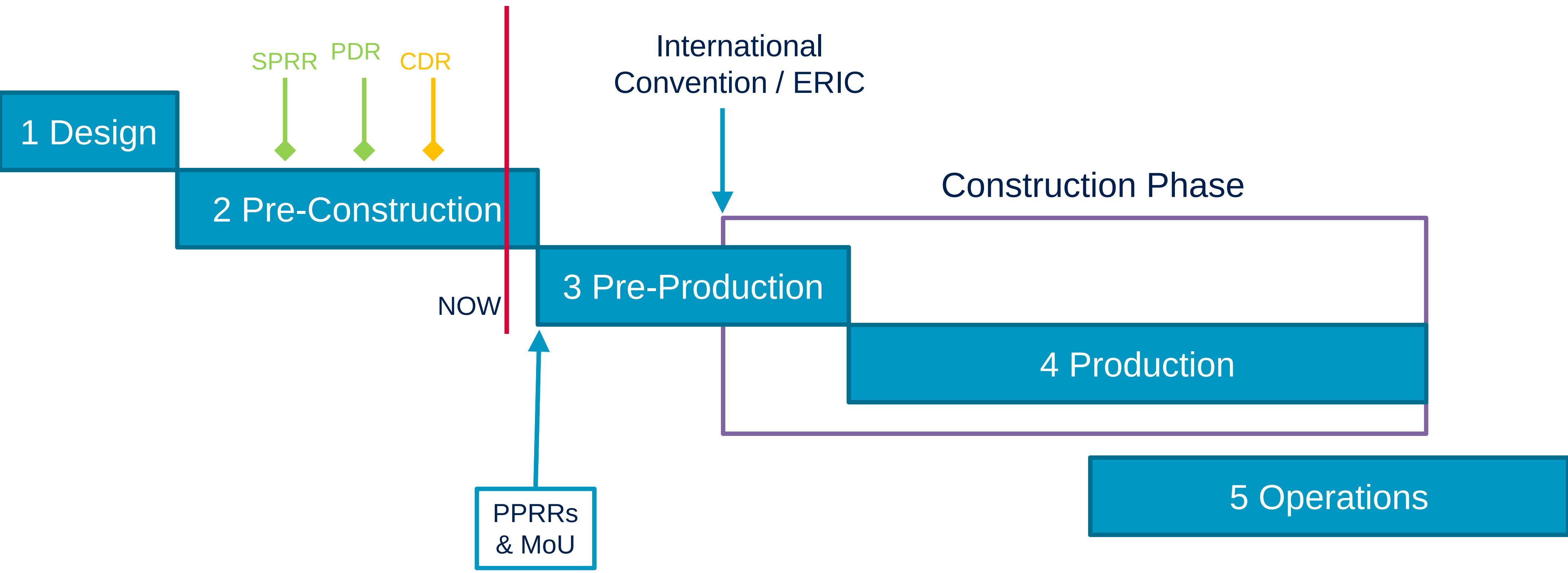
MST Integrated Camera



US Contribution: Dual-Mirror MST

- Schwarzschild-Couder design (V. Vassiliev et al.)
- 9.7m primary, 5.4m secondary
- 11328 x 0.07^{o} Si-PMT pixels
- 8^{o} field-of-view
- Prototype under construction: Whipple Obs. (Arizona, USA)

CTA Phases & Timeline



- 2016-7: Hosting agreements, site preparations start
- 2018: Start of construction
- Funding level at ~65% of required for baseline implementation
  → start with *threshold implementation*
  → additional funding & telescopes needed to complete baseline CTA
- Construction period of ~6 years
- Initial science with partial arrays possible before construction end

CONCLUSIONS

- With many discoveries, VHE γ-rays are now a well-recognized astrophysical discipline & part of growing multi-messenger science.
- VHE photons explore the very non-thermal universe and key questions in fundamental physics
- Outstanding science potential & power of atmospheric Cherenkov technique → CTA
- **Cherenkov Telescope Array (CTA)**

  Outstanding sensitivity & resolution over wide energy range
  Far-reaching key science program
  Open observatory with data released to public
  CTA requires a broad partnership of countries and communities – including, hopefully, the US