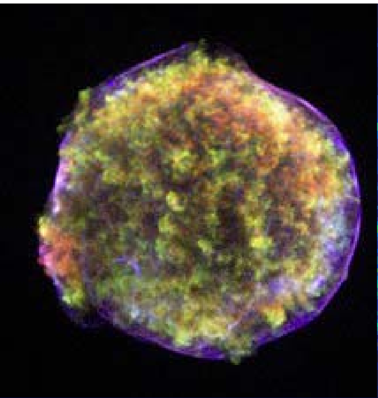
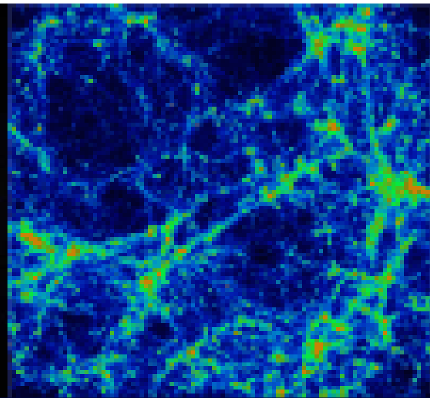
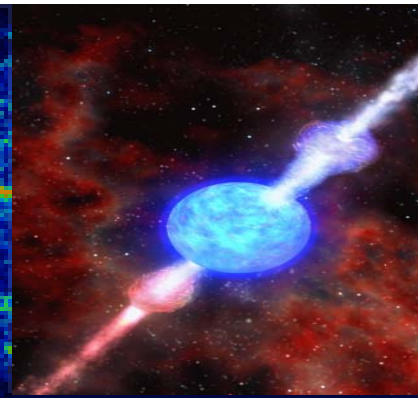
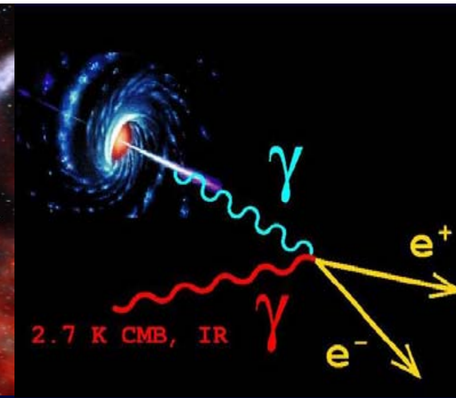




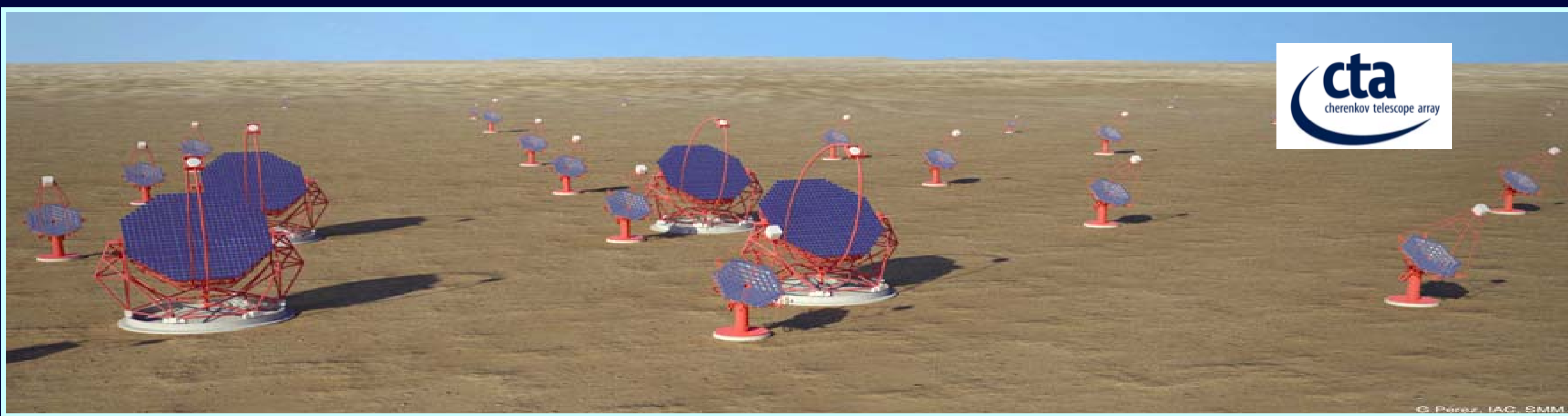




Very High-Energy Astrophysics with the Cherenkov Telescope Array

Rene A. Ong (UCLA)

Astrophysics Seminar, UCSD, 2 May 2018



Outline

- **Scientific & Technical Motivation**

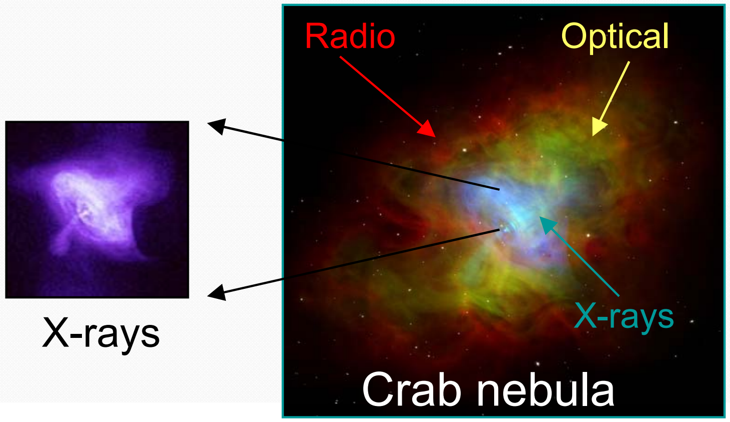
  The highest energy photons
  Three science topics in brief
  Experimental Technique
  Planning for the Future → CTA

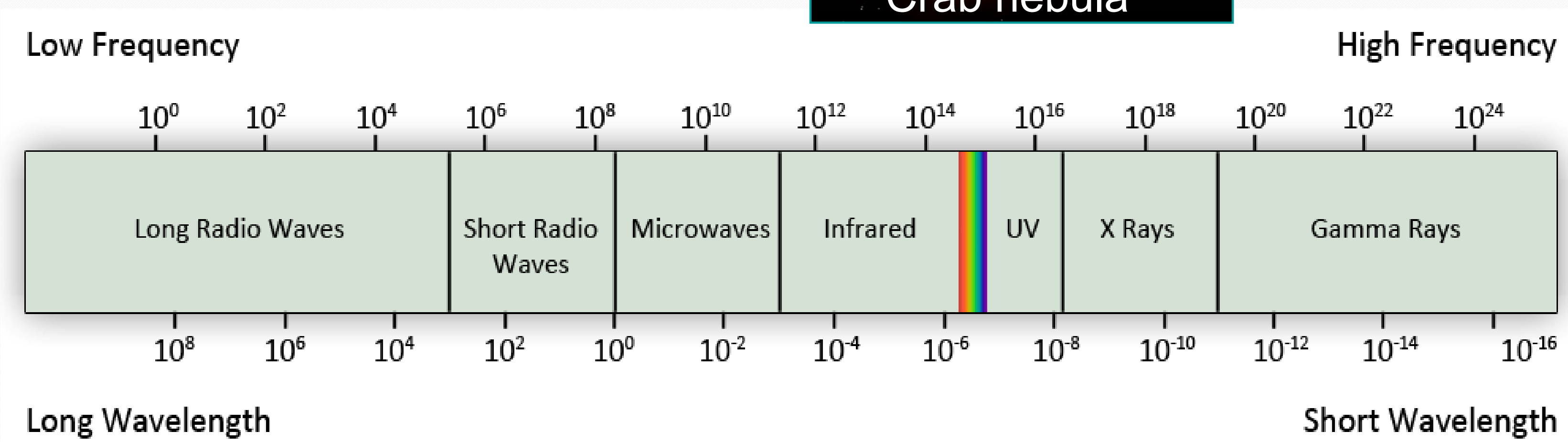
- **Cherenkov Telescope Array (CTA)**

  CTA Design & Performance → Scientific Capabilities
  Present status (2018): sites, timeline, etc.
  (Extra: Detecting optical photons with CTA)

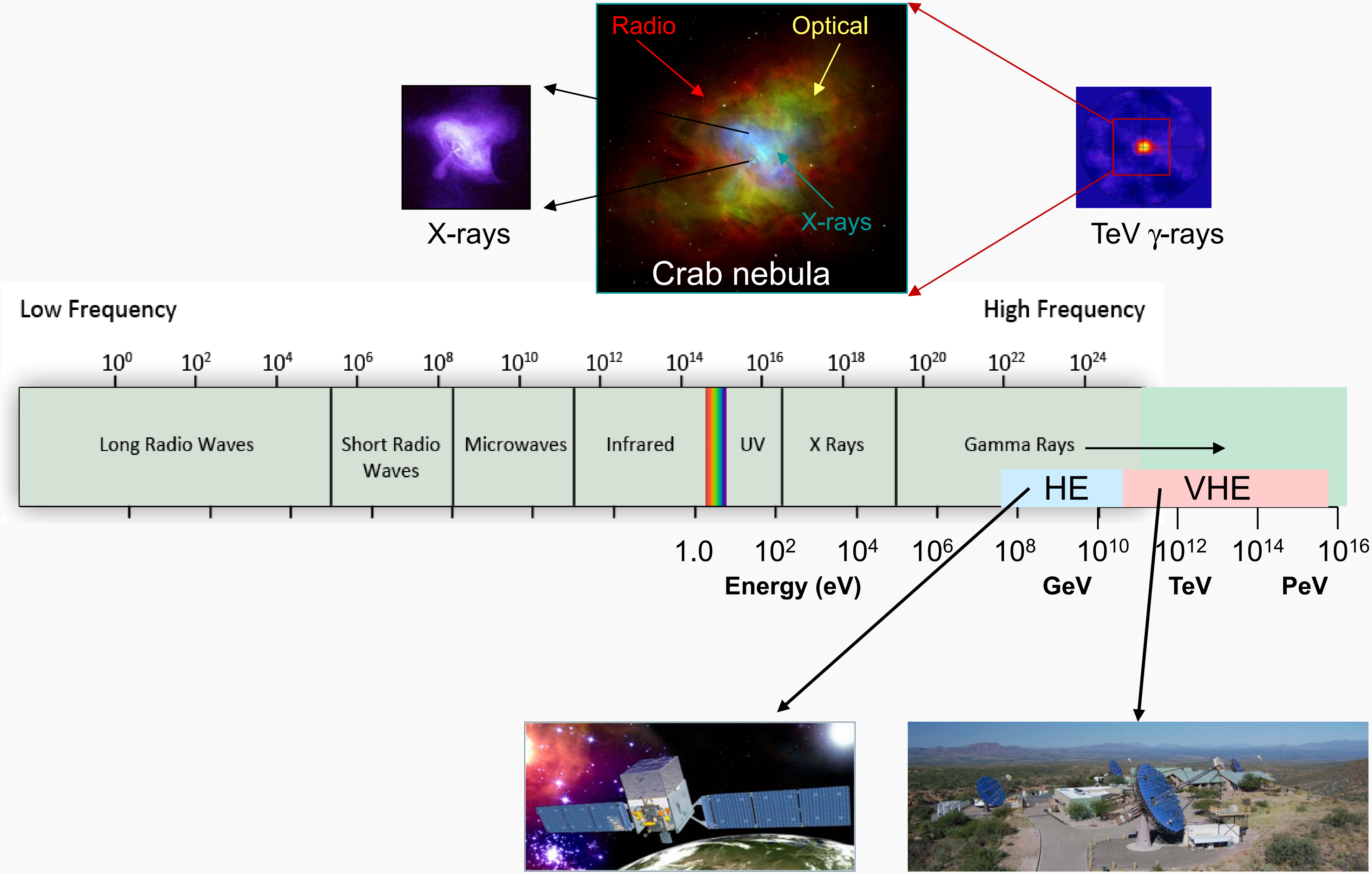
- **Summary**

Photons of all wavelengths





The Highest Energy Photons

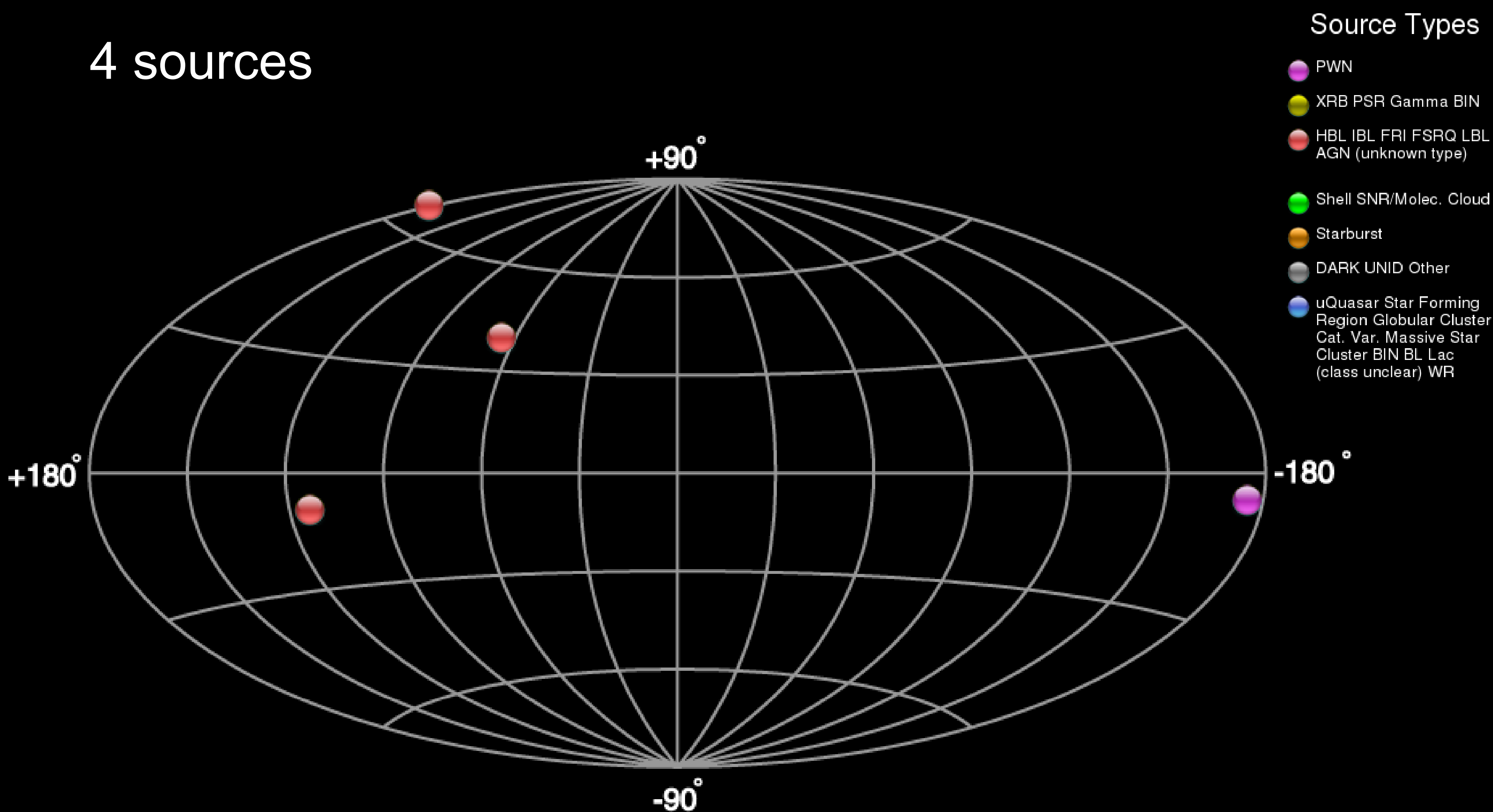


Fermi telescope

VERITAS telescope

VHE γ-ray Sky c1995

4 sources



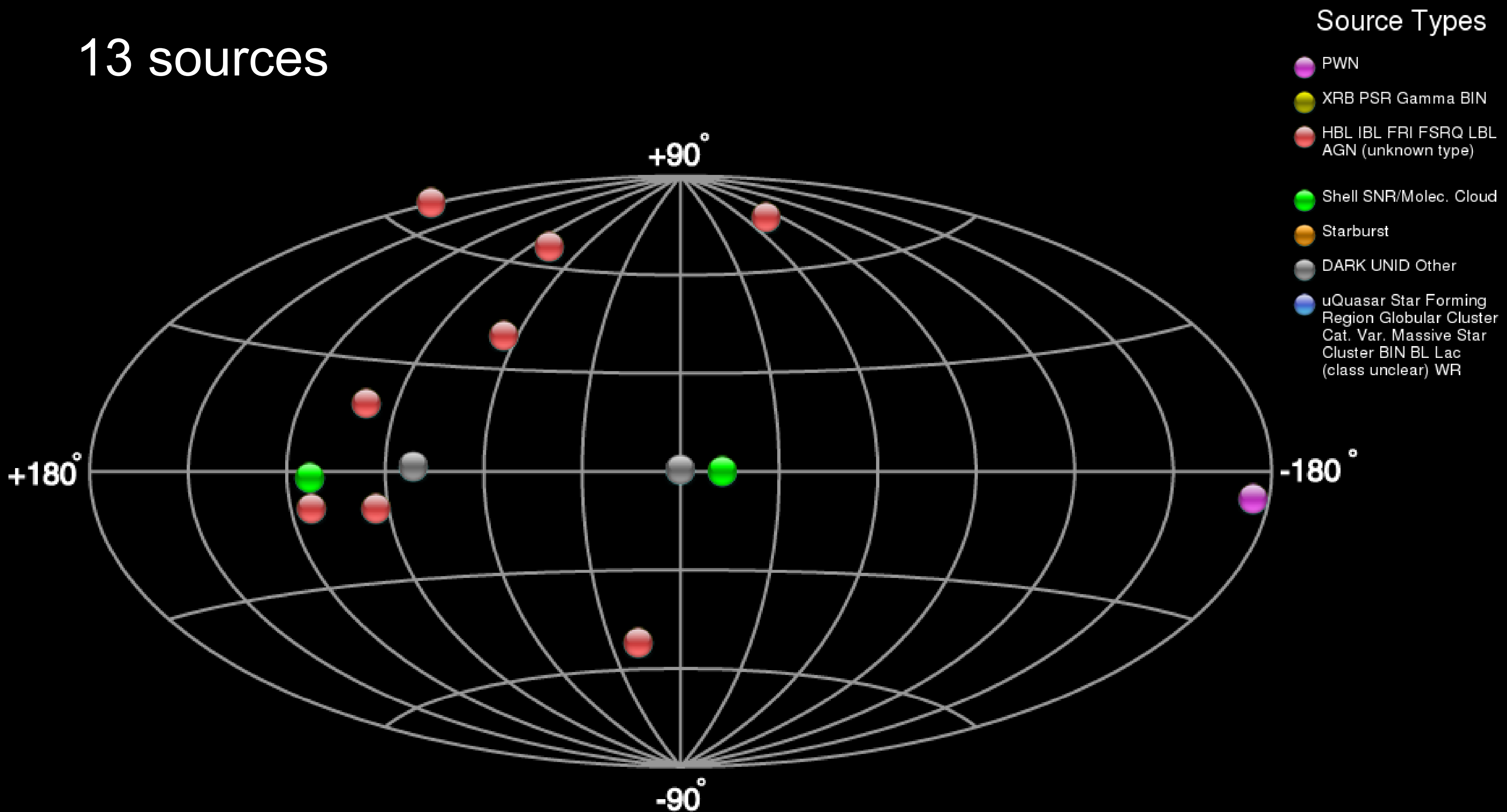
FROM UCSD SEMINAR IN 2003

Detected AGN (5)

Source	Type	Z	Confirmed?	Comments
Mrk 421	BL Lac	0.031	Yes	flaring, X-ray, IR abs.? spectral variability
Mrk 501	BL Lac	0.034	Yes	flaring, X-ray, IR abs.?
1ES 1959+650	BL Lac	0.048	Yes	flaring, IR abs.?
PKS 2155-304	BL Lac	0.116	Yes	
1ES 1426+428	BL Lac	0.129	Yes	weak source

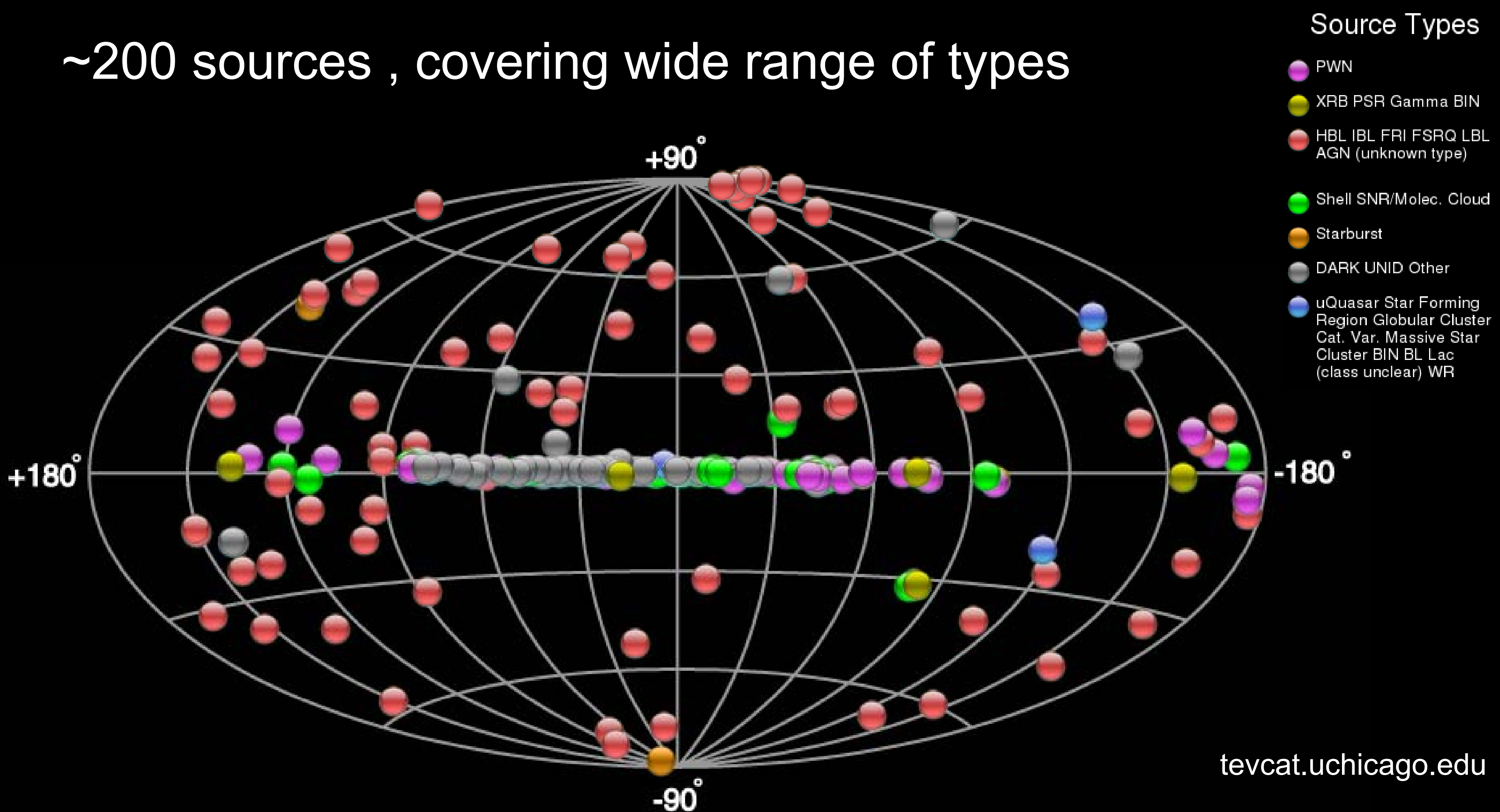
VHE γ-ray Sky c2005

13 sources



VHE γ-ray Sky c2018

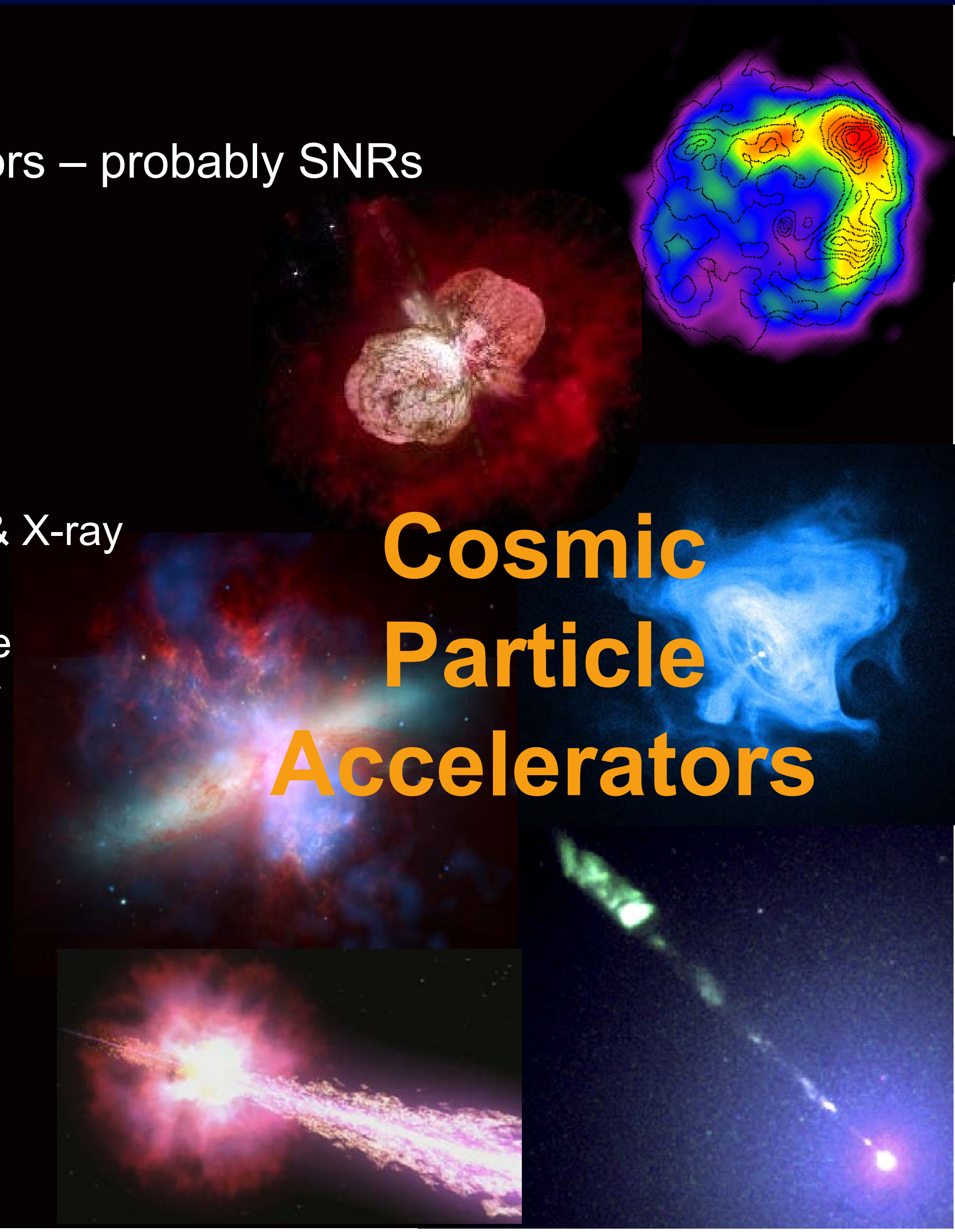
~200 sources , covering wide range of types



Detailed source information: spectra, images, variability, MWL …

VHE Astronomy Comes of Age

- Dominant expectation (pre-1990)
  - Will find the “cosmic ray” accelerators – probably SNRs
- Reality (present day)
  - Astonishing variety of TeV emitters
    - Within the Milky Way
      - Supernova remnants
      - Bombarded molecular clouds
      - Stellar binaries - colliding wind & X-ray
      - Massive stellar clusters
      - Pulsars and pulsar wind nebulae
      - Supermassive black hole Sgr A*
    - Extragalactic
      - Starburst galaxies
      - MW satellites
      - Radio galaxies
      - Flat-spectrum radio quasars
      - ‘BL Lac’ objects
      - Gamma-ray Bursts

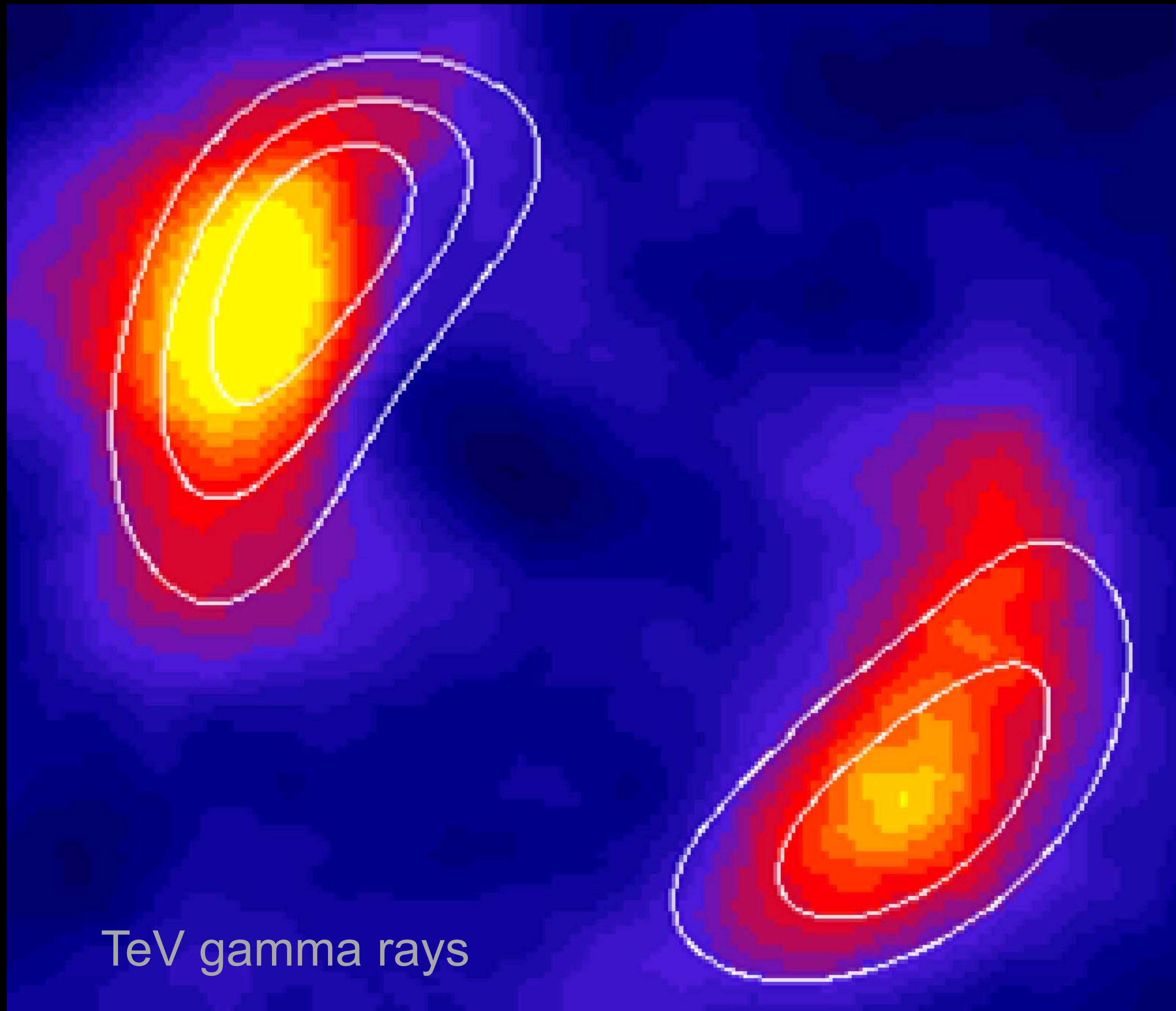


Three Science Topics (in brief)

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

Supernova Remnants

SN 1006



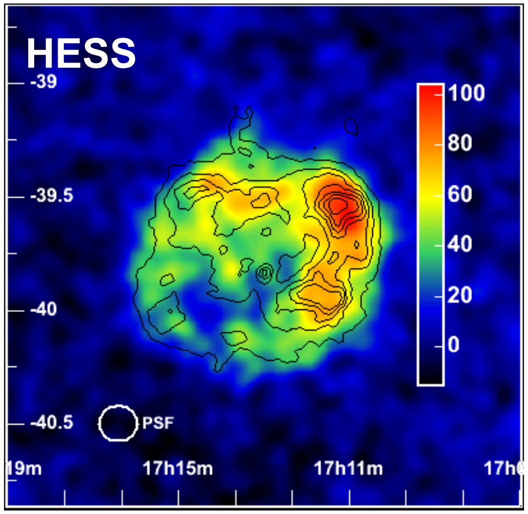
0.4°

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

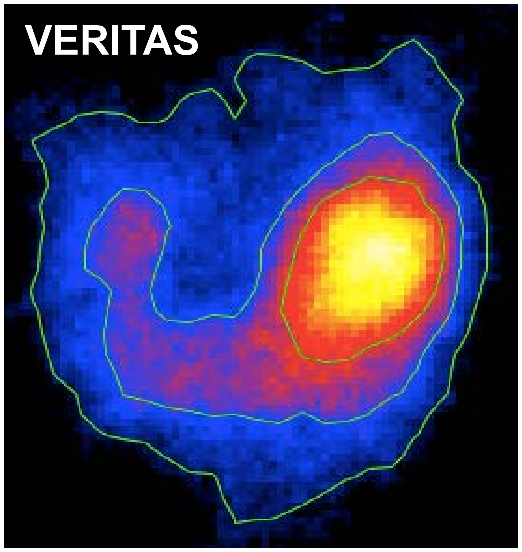
Supernova Remnants (SNRs)

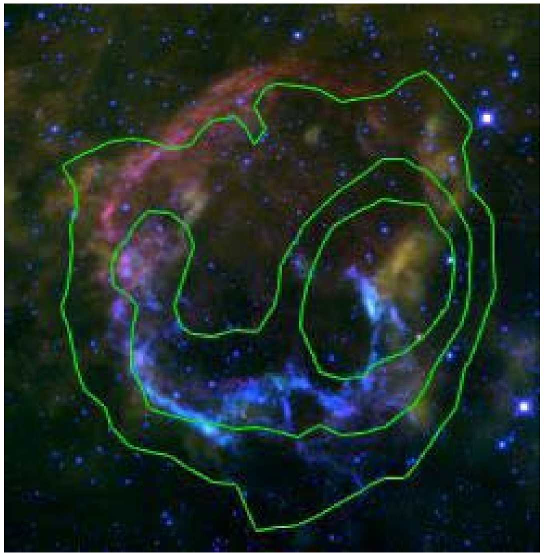
"Standard Model" for high-energy cosmic rays

- SNR, outer layers ejected with v ~ several x10^3 km/s.
- Expanding shell & shock front sweeps up material from ISM.
- Acceleration of particles via 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



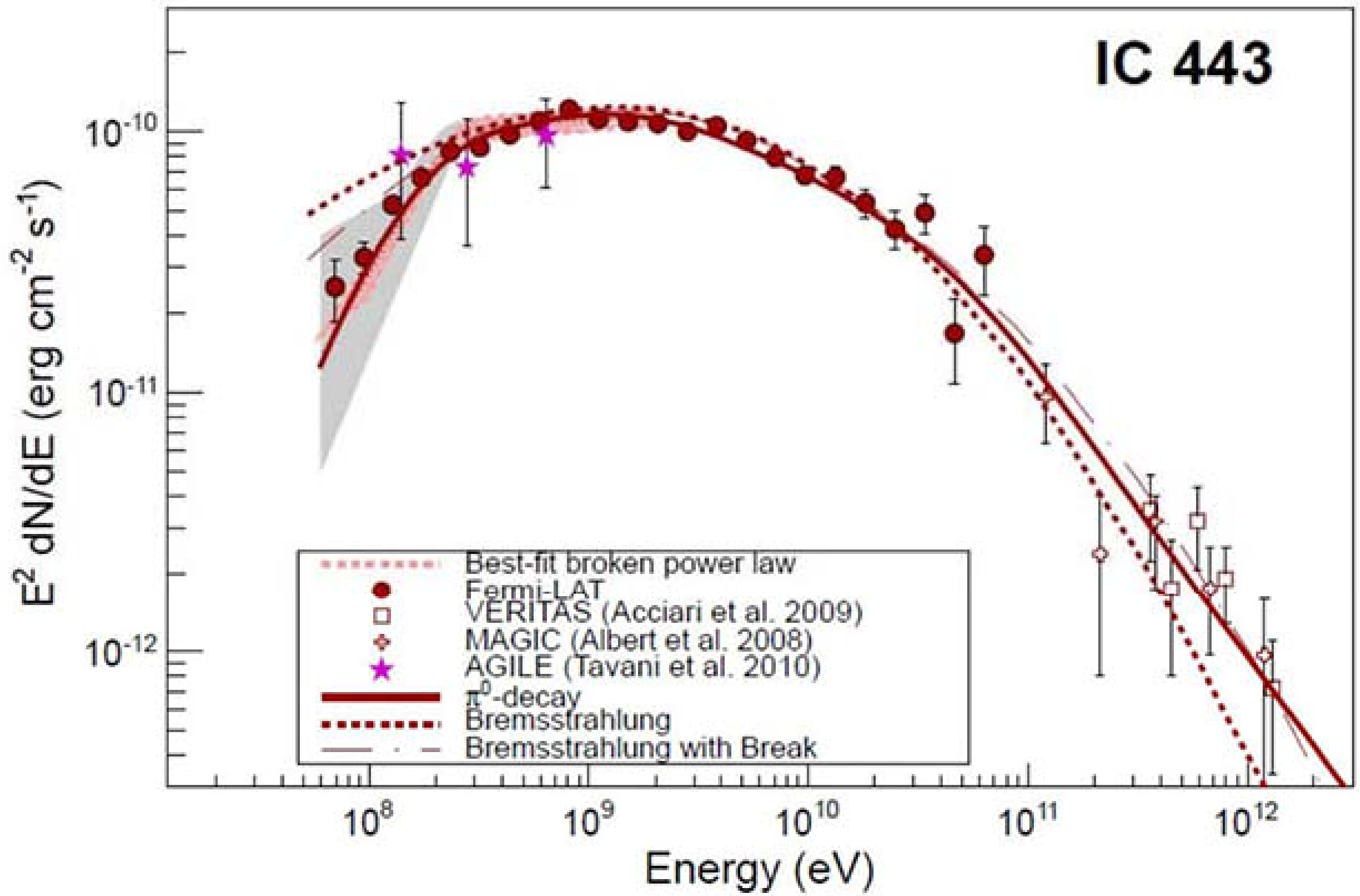


IC 443
Age ~ 30ky
D ~ 0.8 kpc

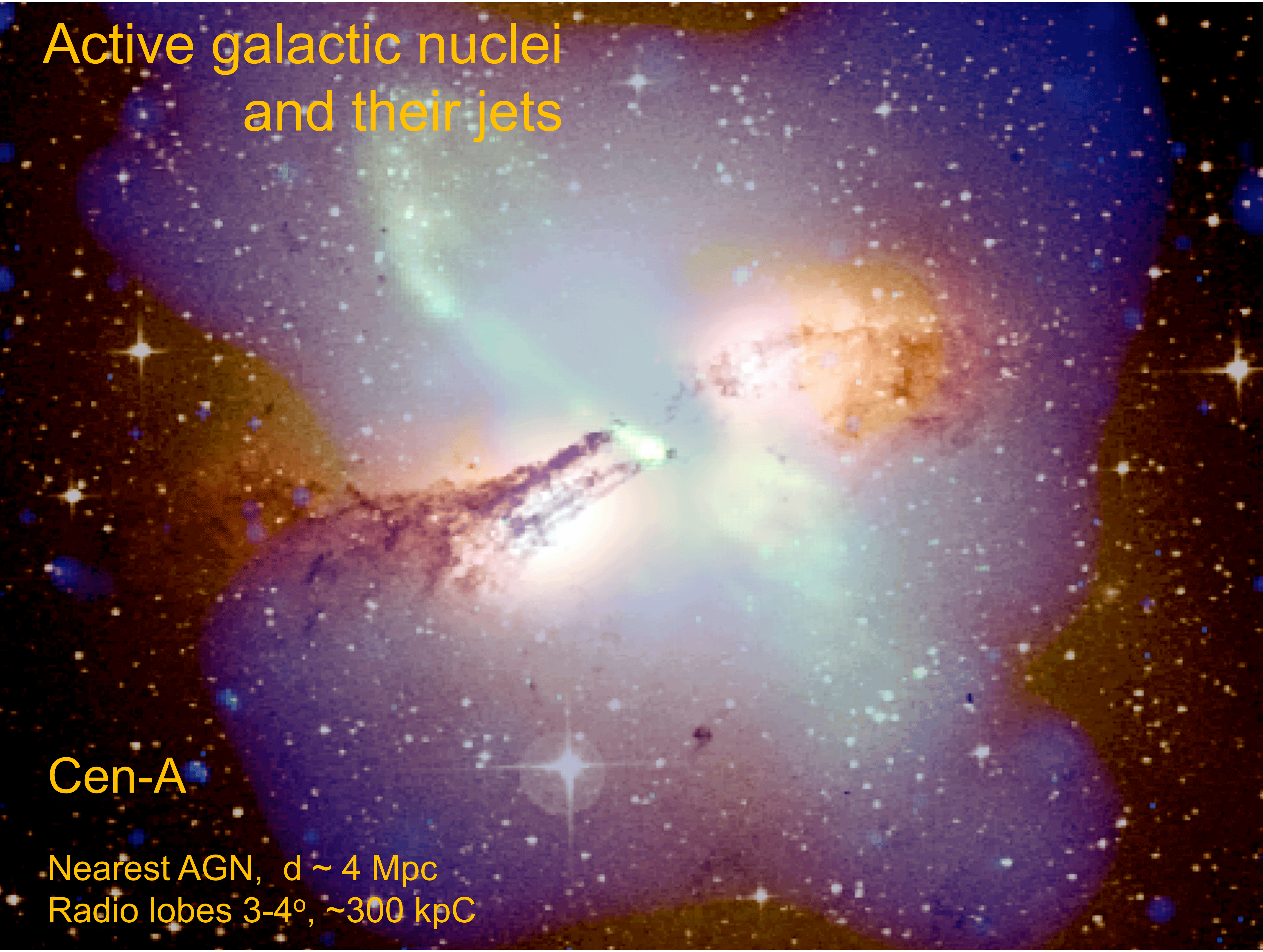
IC 443
WISE* – *22, 12, 4.6 μm

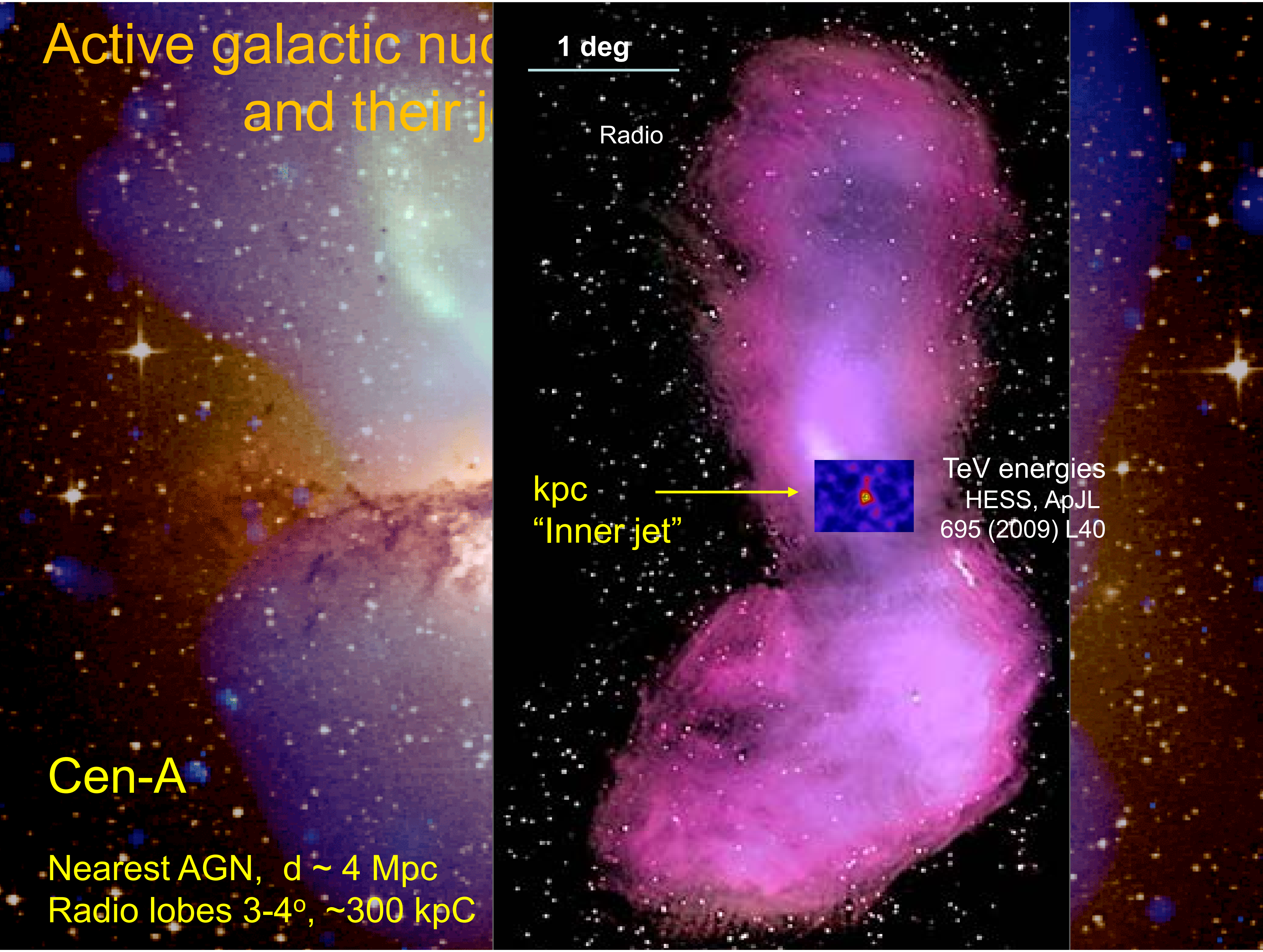
Good model … is it right ?

SNR IC 443 – a proton accelerator ?



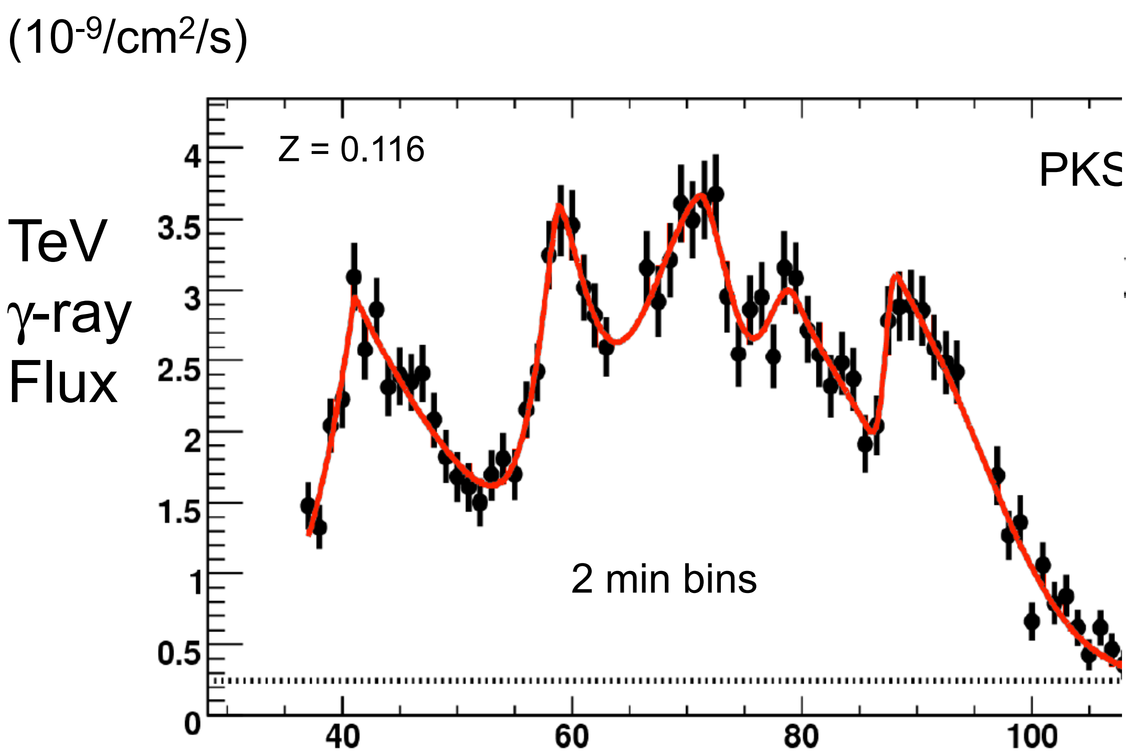
Supports the idea for proton acceleration.
But more sources and better data (spectra, morphology) are needed !


Active galactic nuclei
and their jets
Cen-A
Nearest AGN, d ~ 4 Mpc
Radio lobes 3-4°, ~300 kpC

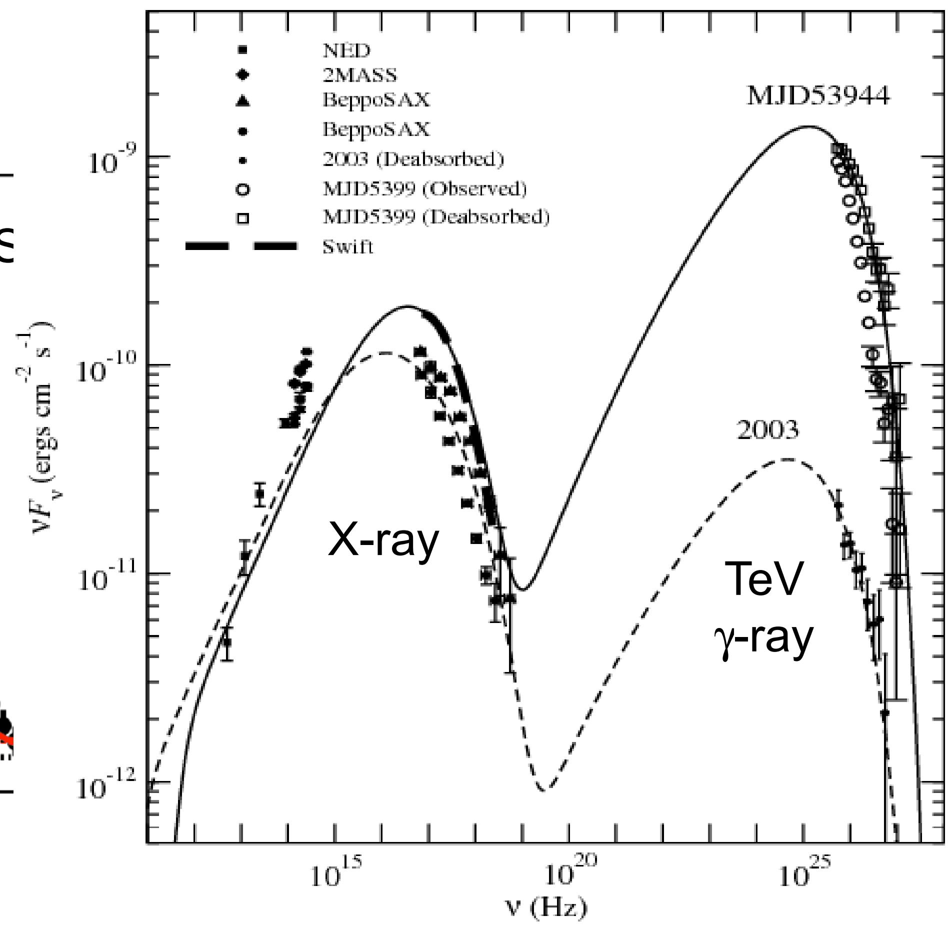

Active galactic nuc
and their j
1 deg
Radio
kpc
“Inner jet”
TeV energies
HESS, ApJL
695 (2009) L40
Cen-A
Nearest AGN, d ~ 4 Mpc
Radio lobes 3-4°, ~300 kpC

Blazars: AGN with jets pointed at us

Strong & highly variable TeV sources



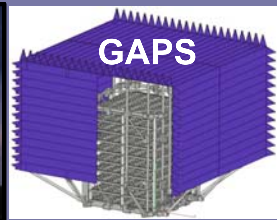
TeV γ-ray
isotropic luminosity 10^{46} erg/s
(luminosity of Milky Way: 10^{44} erg/s)

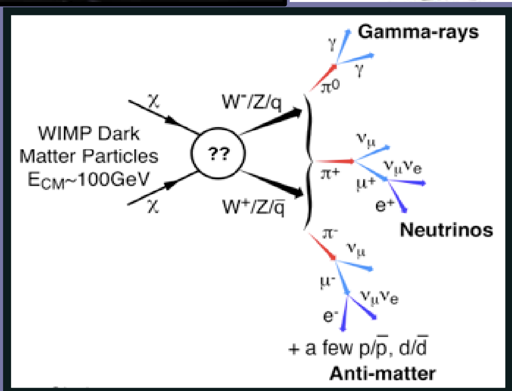


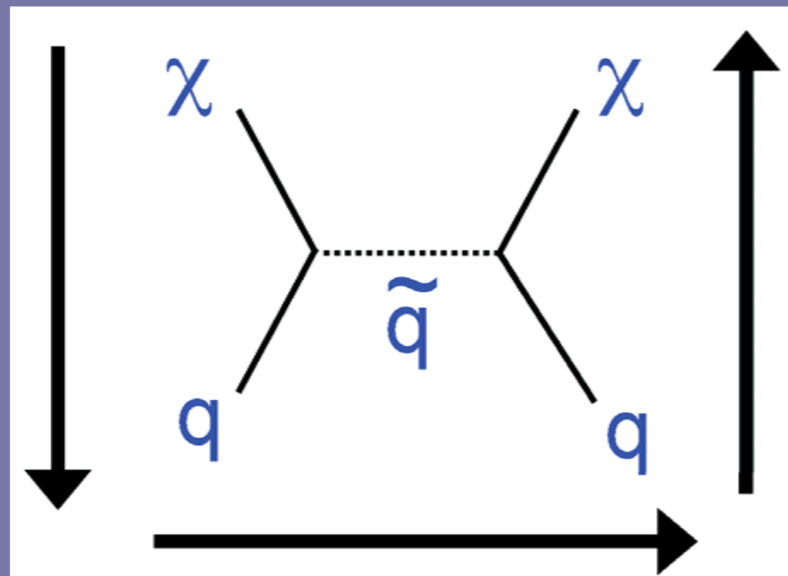
Broad-band SED fits
Multiple jet components & zones

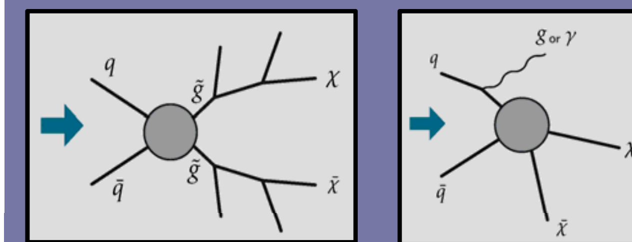
Many important aspects not understood: energetics, particle type, emission zones …
Need for detecting sources at all flux levels, unbiased sample of luminosity function.

Dark Matter: Complementary Approaches







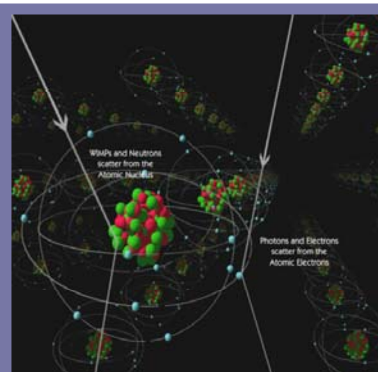


WIMP annihilation
In the cosmos

Indirect Detection

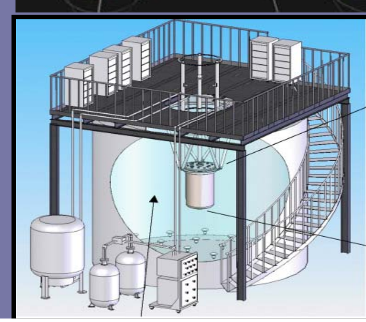
Heavy particle prod.
MET + jets

LHC Production

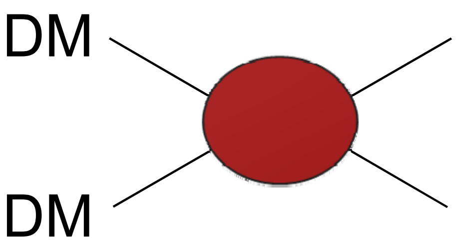


WIMP-Nucleon
Elastic scattering

Direct Detection



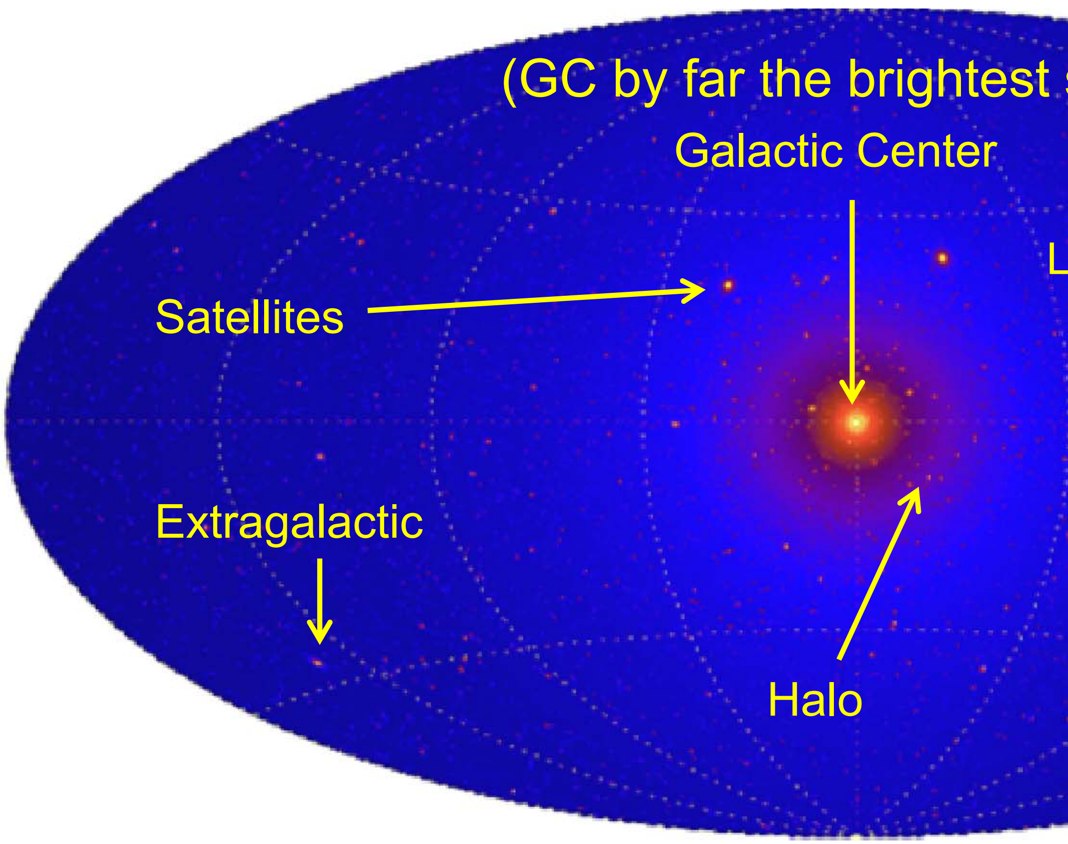
Indirect Detection of DM



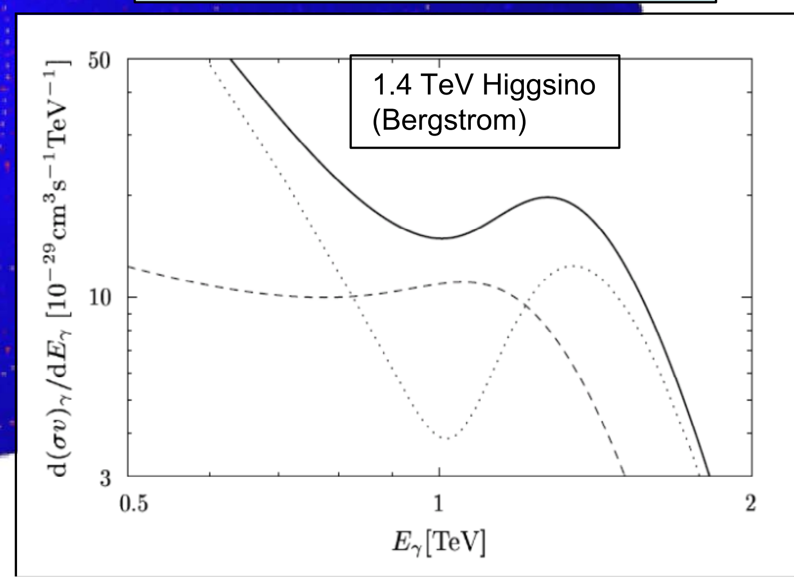
SM: b, W^+, Z, τ^+, …
Primary channels
SM: $\bar{b}$, W^-, Z, τ^-, …

Hadronization

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



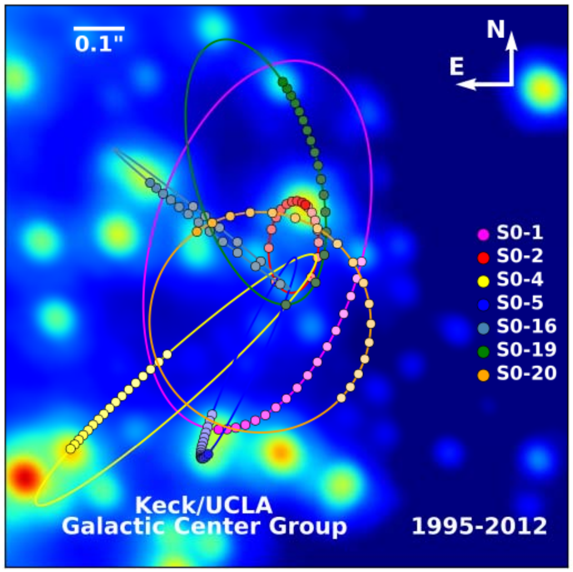
"Universal" Spectrum



Ultimate goal: Dark Matter Astronomy

Galactic Center – A High-Energy Mystery

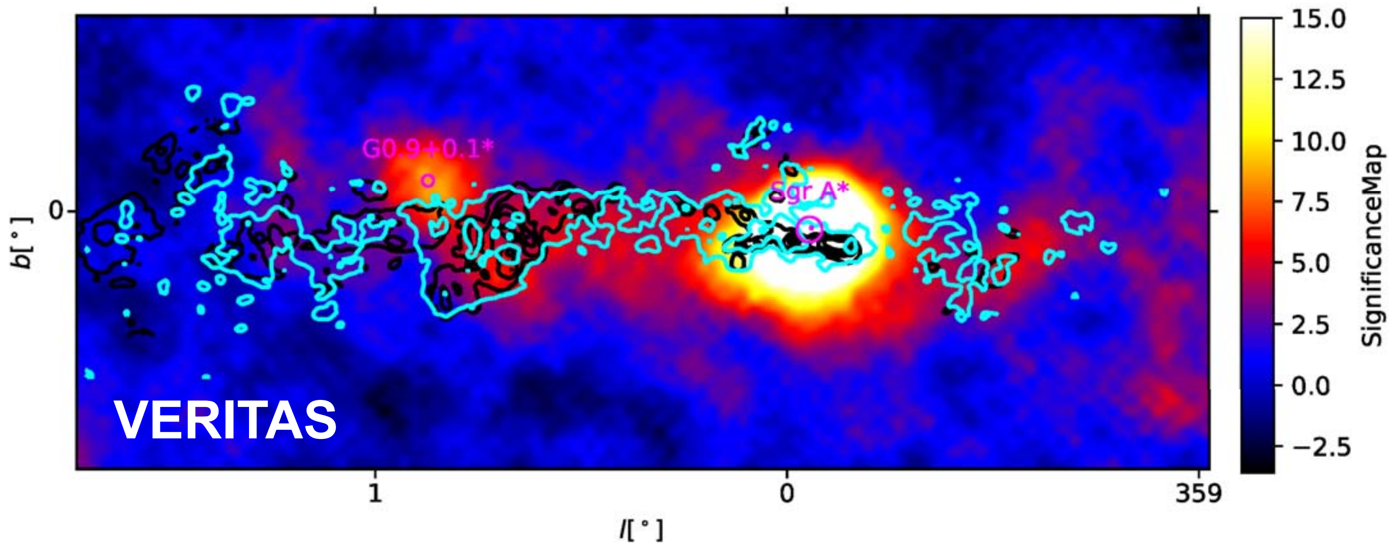
Infrared



Ghez et al., 2012
1" x 1"

TeV γ-rays

A, Archer et al. (2016), 1º x 3º



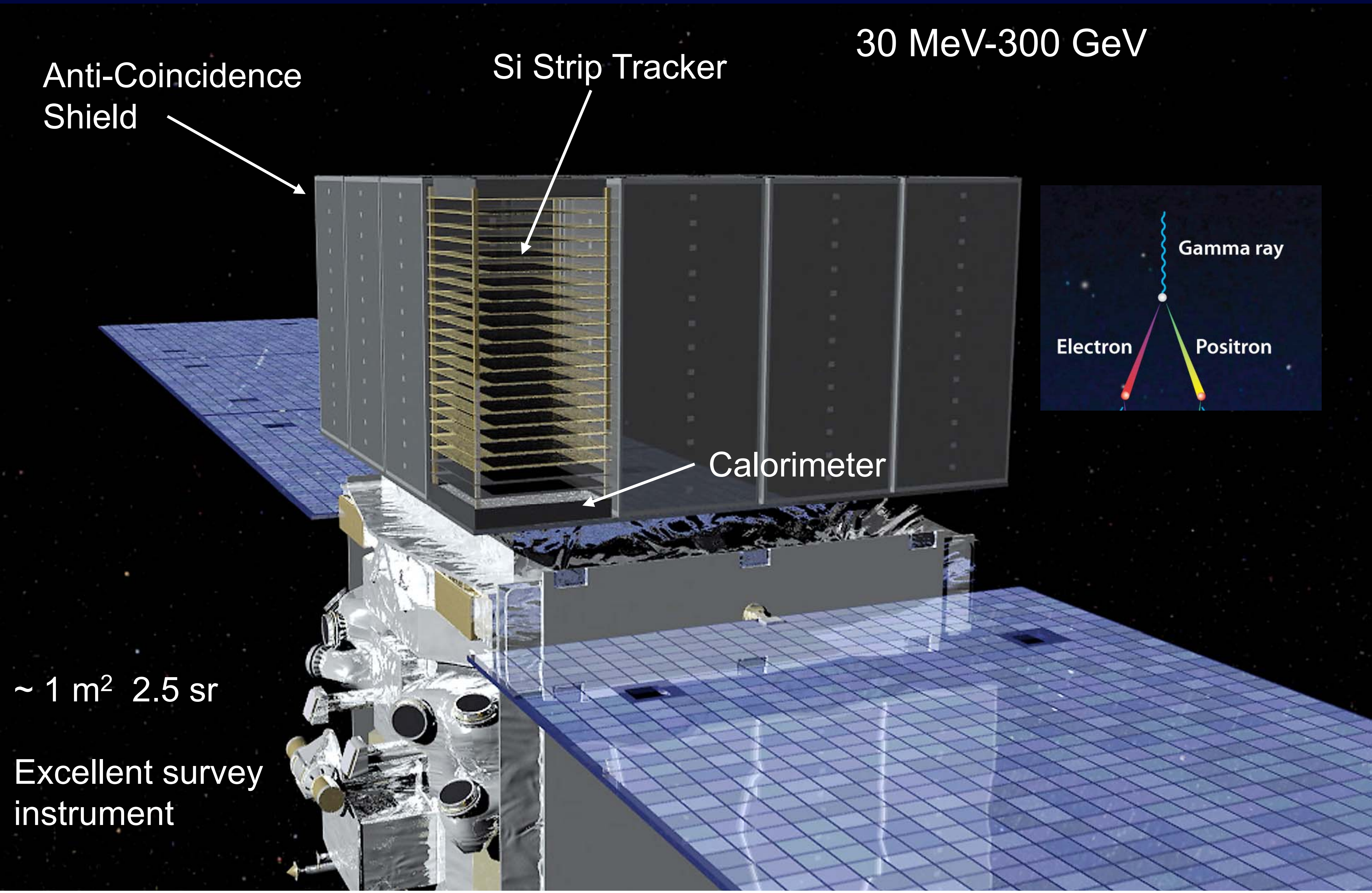
TeV γ-ray emission from SGR A*:

- intense & highly non-thermal
- completely unexpected
- not understood !

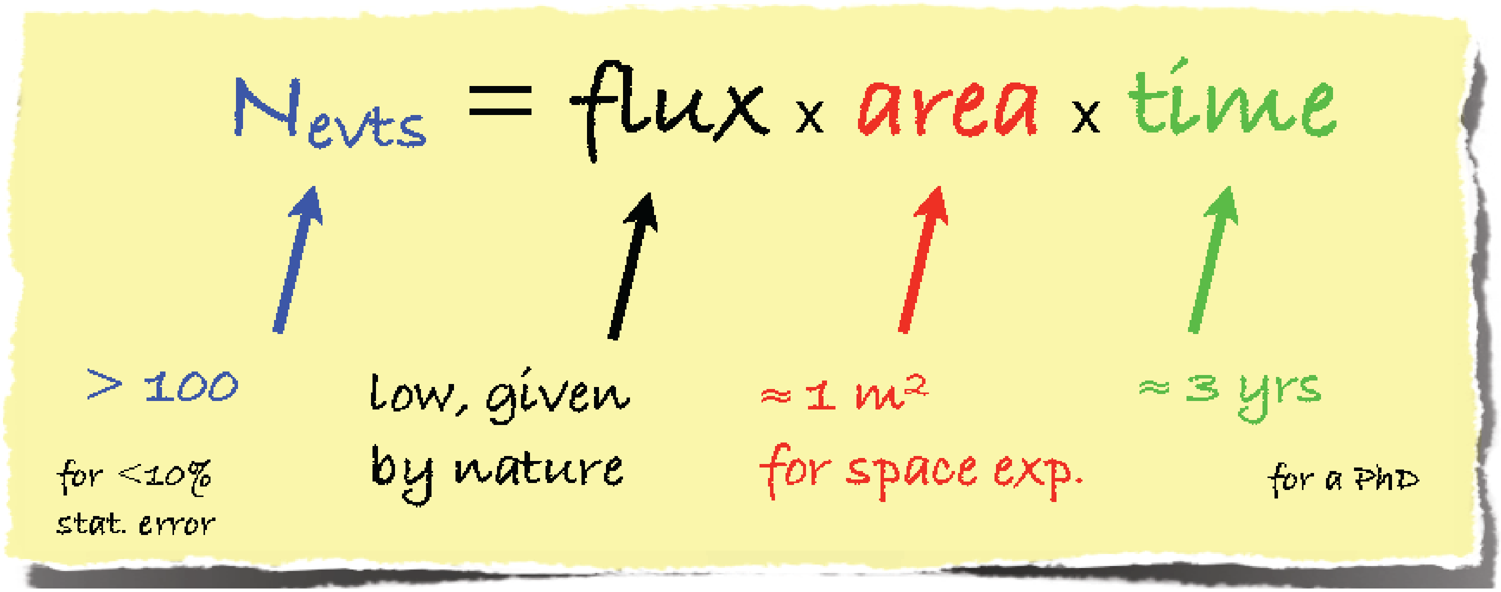
DM search is still very promising, but must be carried out *away* from central Galactic ridge.

Experimental Technique
&
Planning for the Future

Fermi Large Area Telescope (LAT)



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

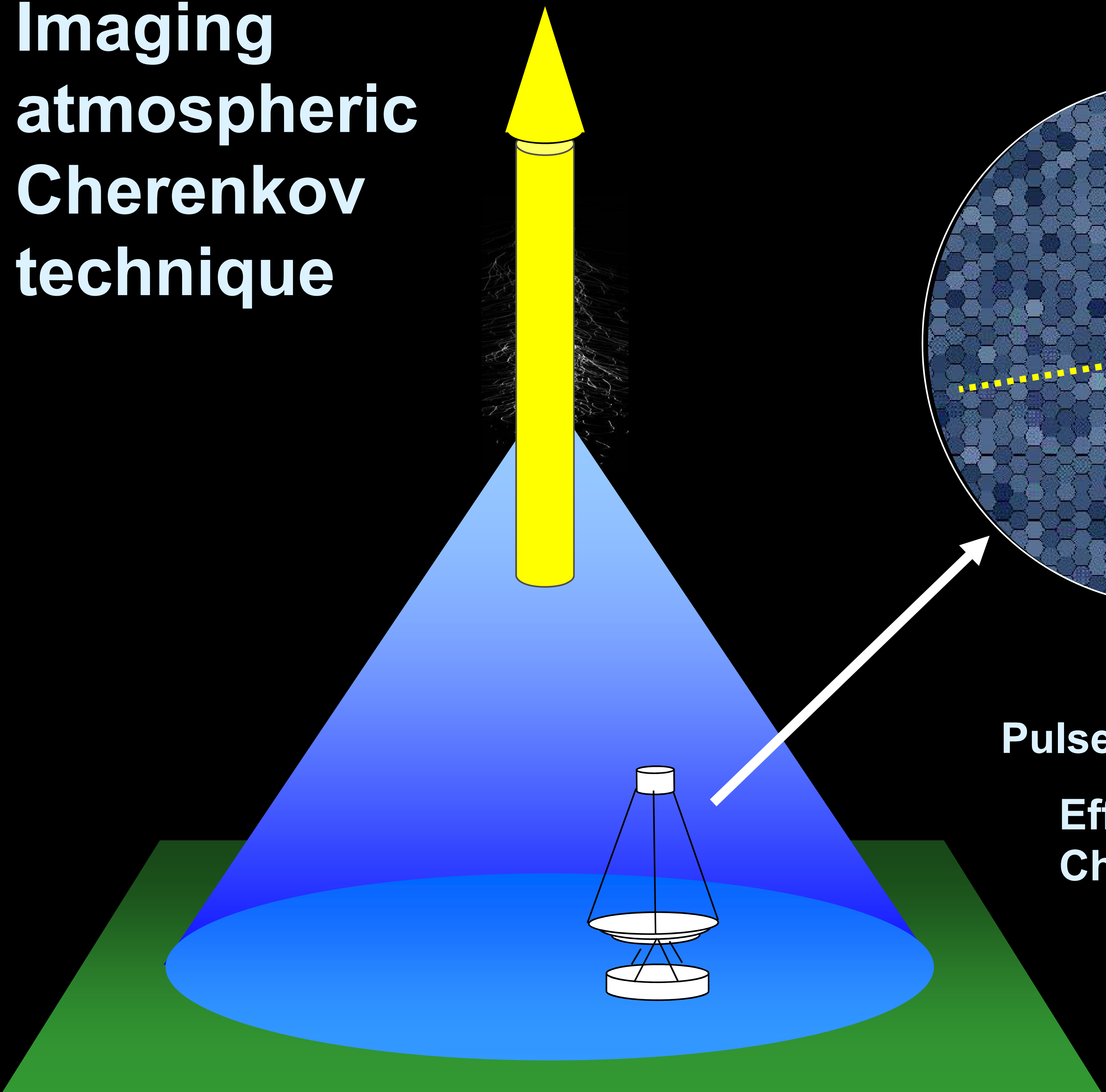
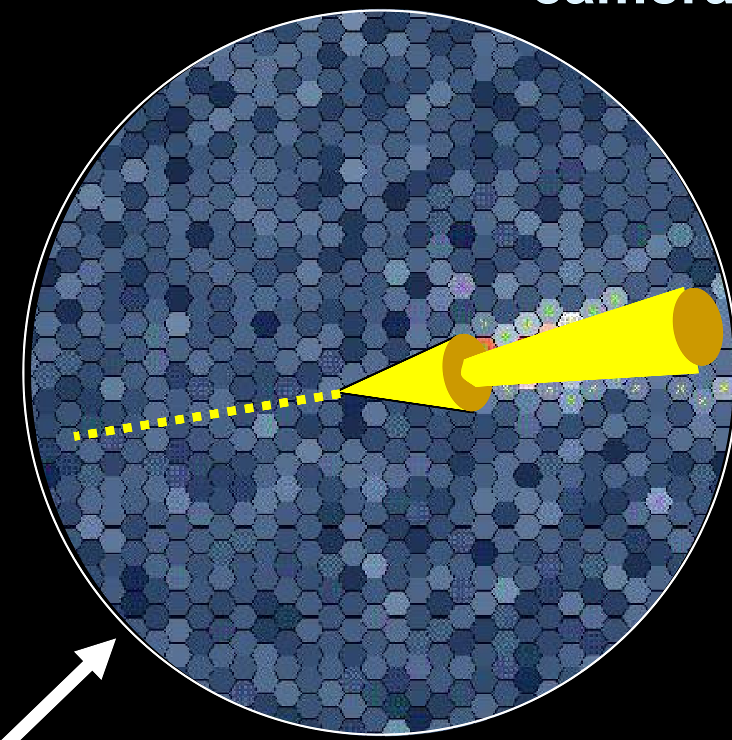


Image in camera



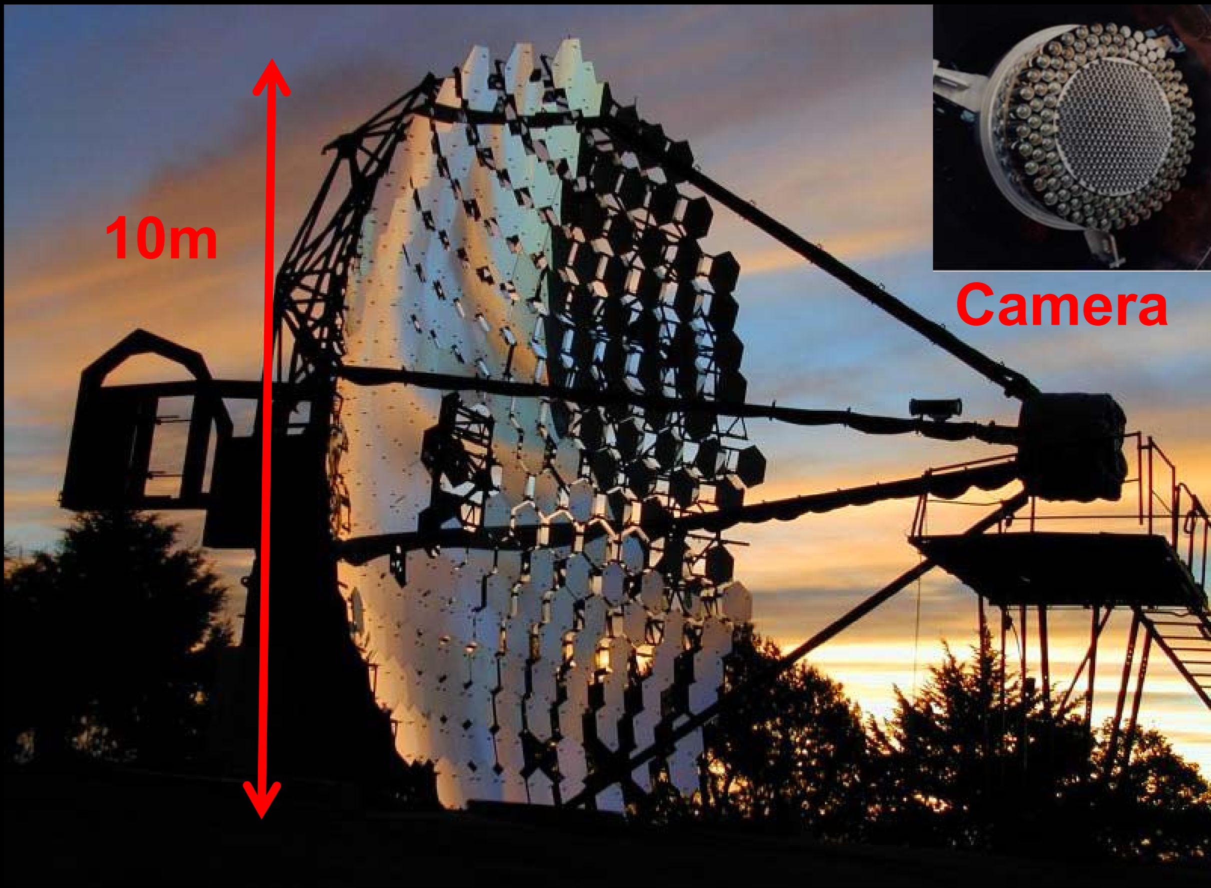
Pulse is ~few ns duration

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

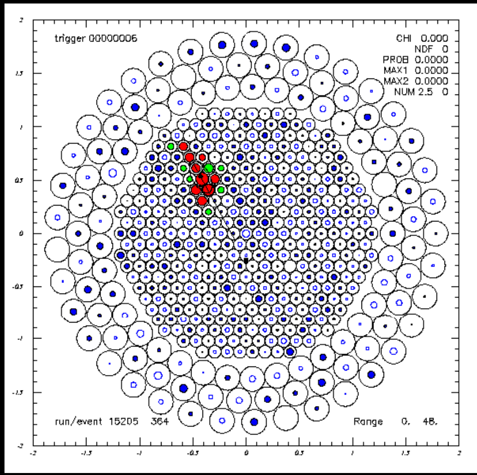
Whipple 10m
γ-ray Telescope
(1968-2011)

Mt. Hopkins, AZ USA

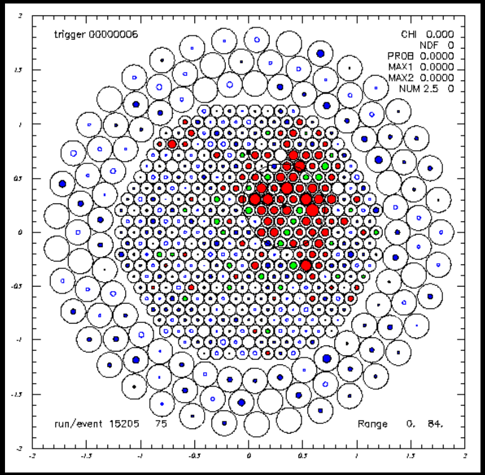
- Pioneered use of Imaging
- Made first source detection.
  (Crab nebula in ~90 hours)



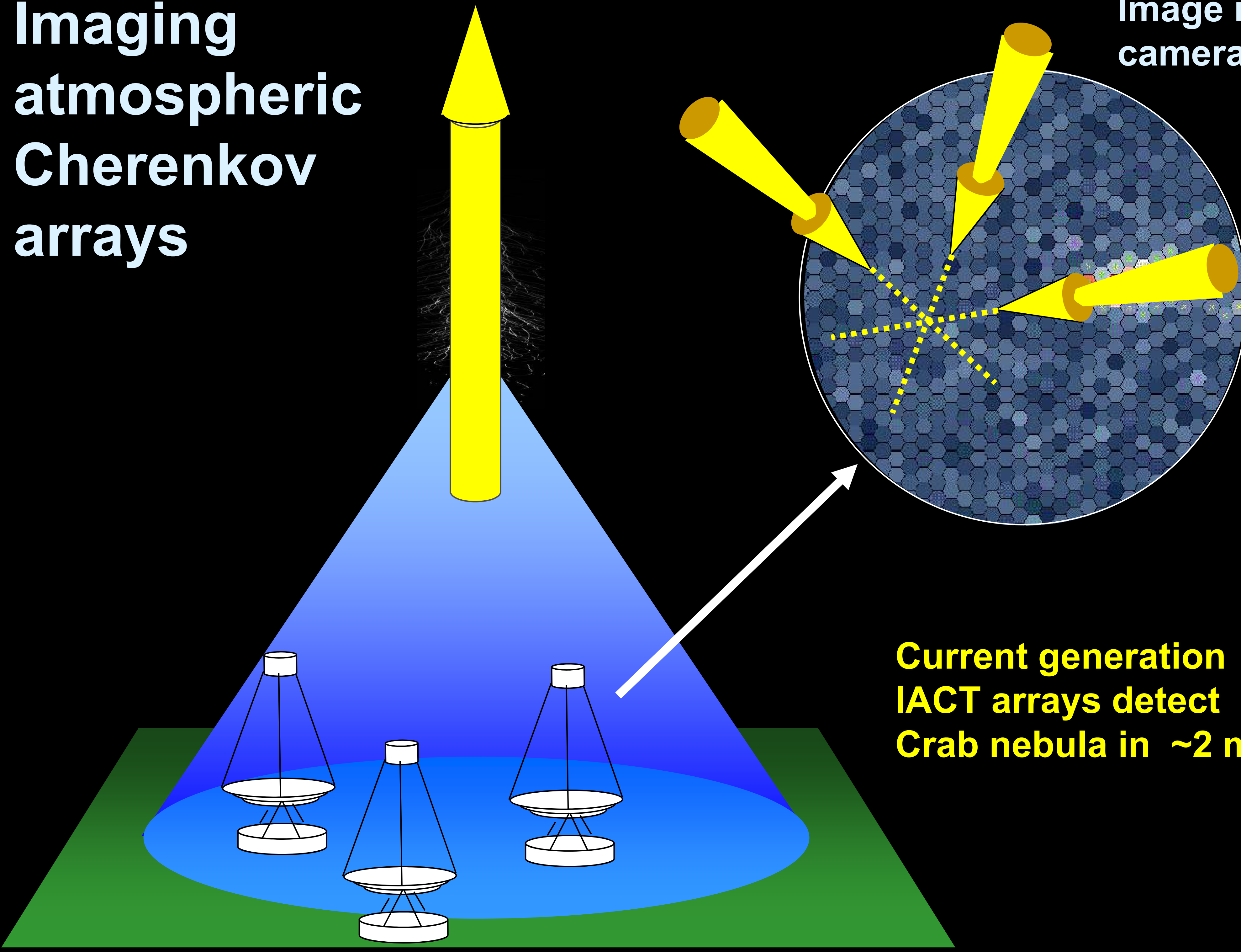
γ-ray



cosmic ray

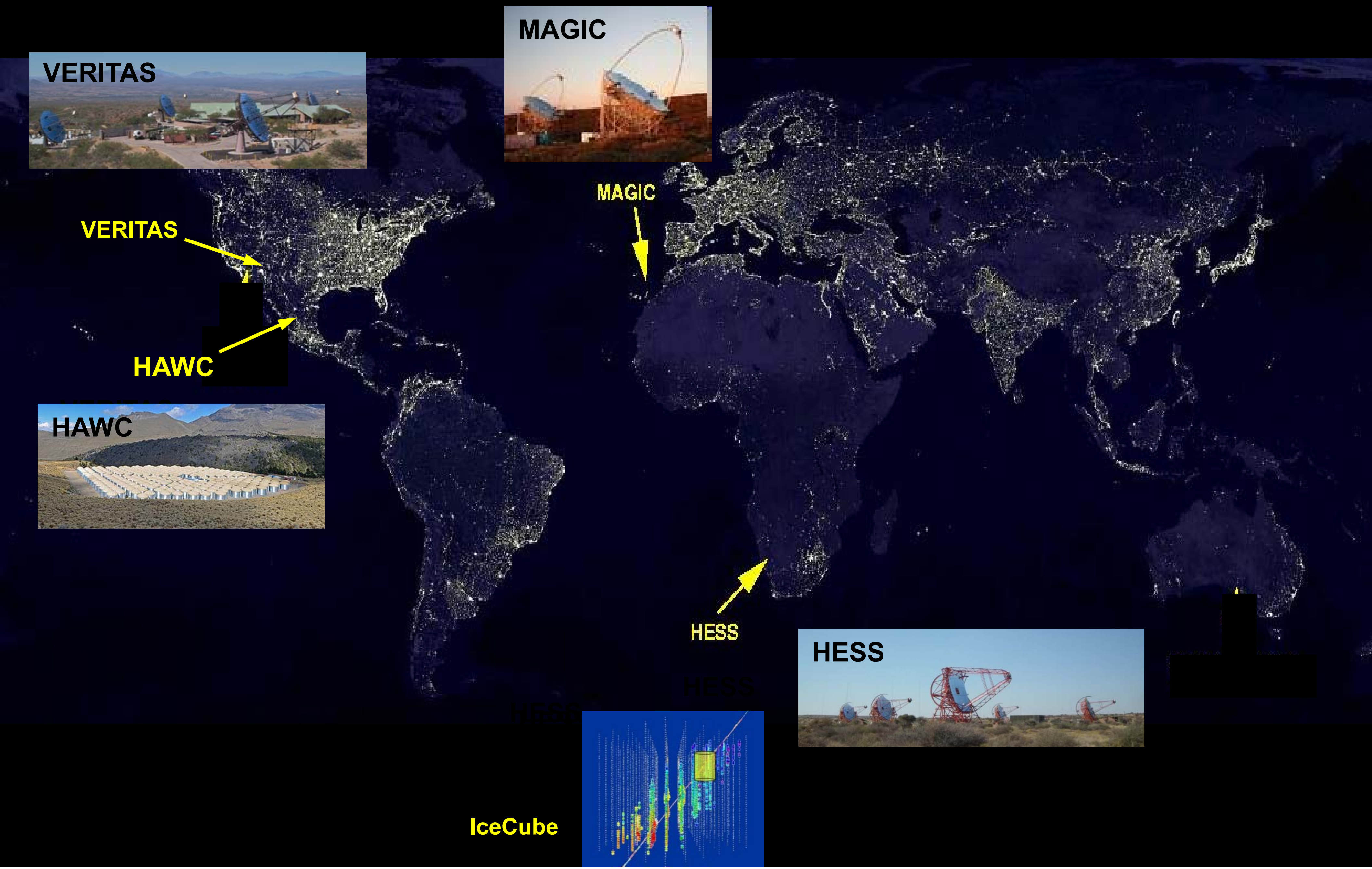


Imaging atmospheric Cherenkov arrays



Current generation IACT arrays detect Crab nebula in ~2 min

VHE Telescopes (2018)



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*


cta
cherenkov telescope array

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)

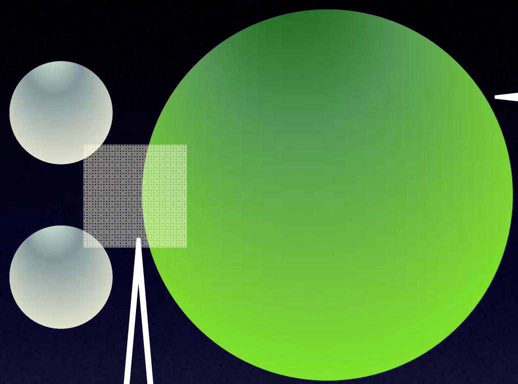
Large Field of view 8-10°
(Surveys, extended sources, flares)

Rapid Slew (20 s) to catch flares:
(Transients)

10x Sensitivity & Collection Area
(Nearly every topic)

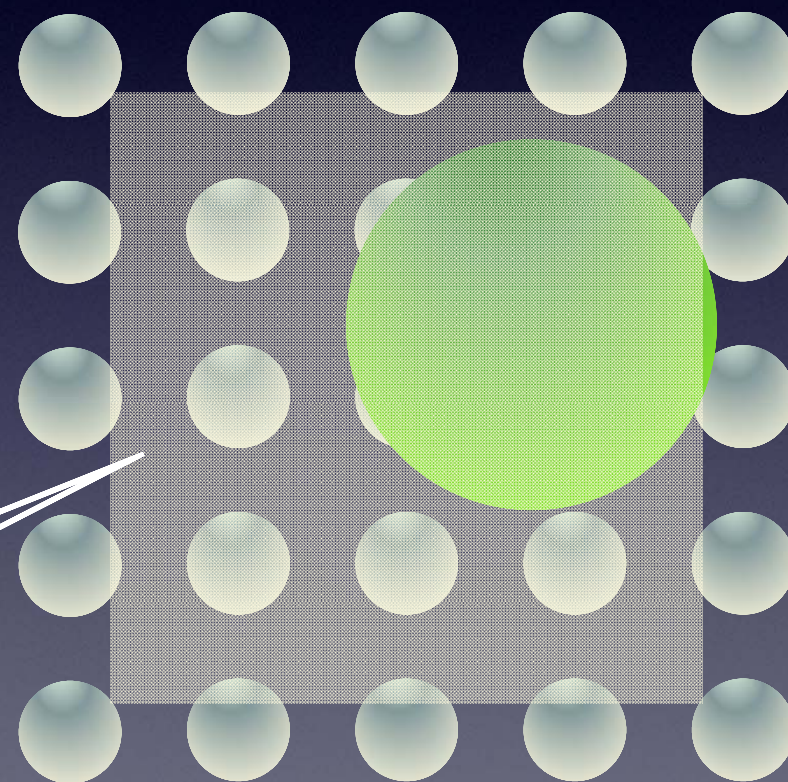
Angular resolution < 0.1° above most of E range
(Source morphology)

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*

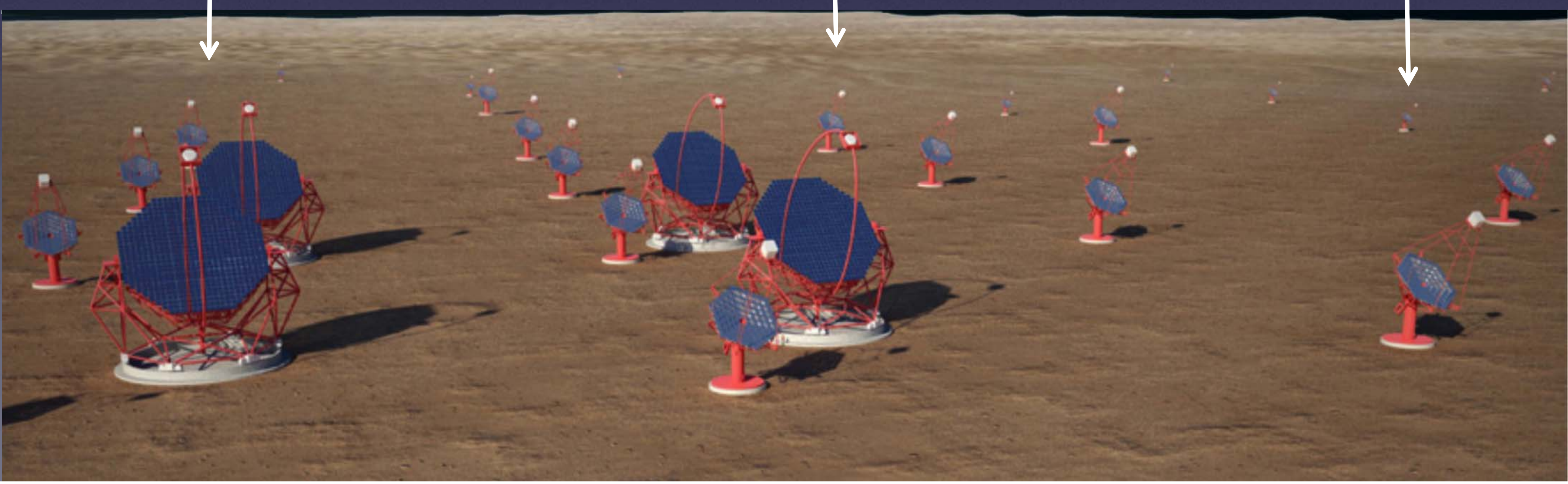
CTA Design (S array)

Science Optimization under budget constraints

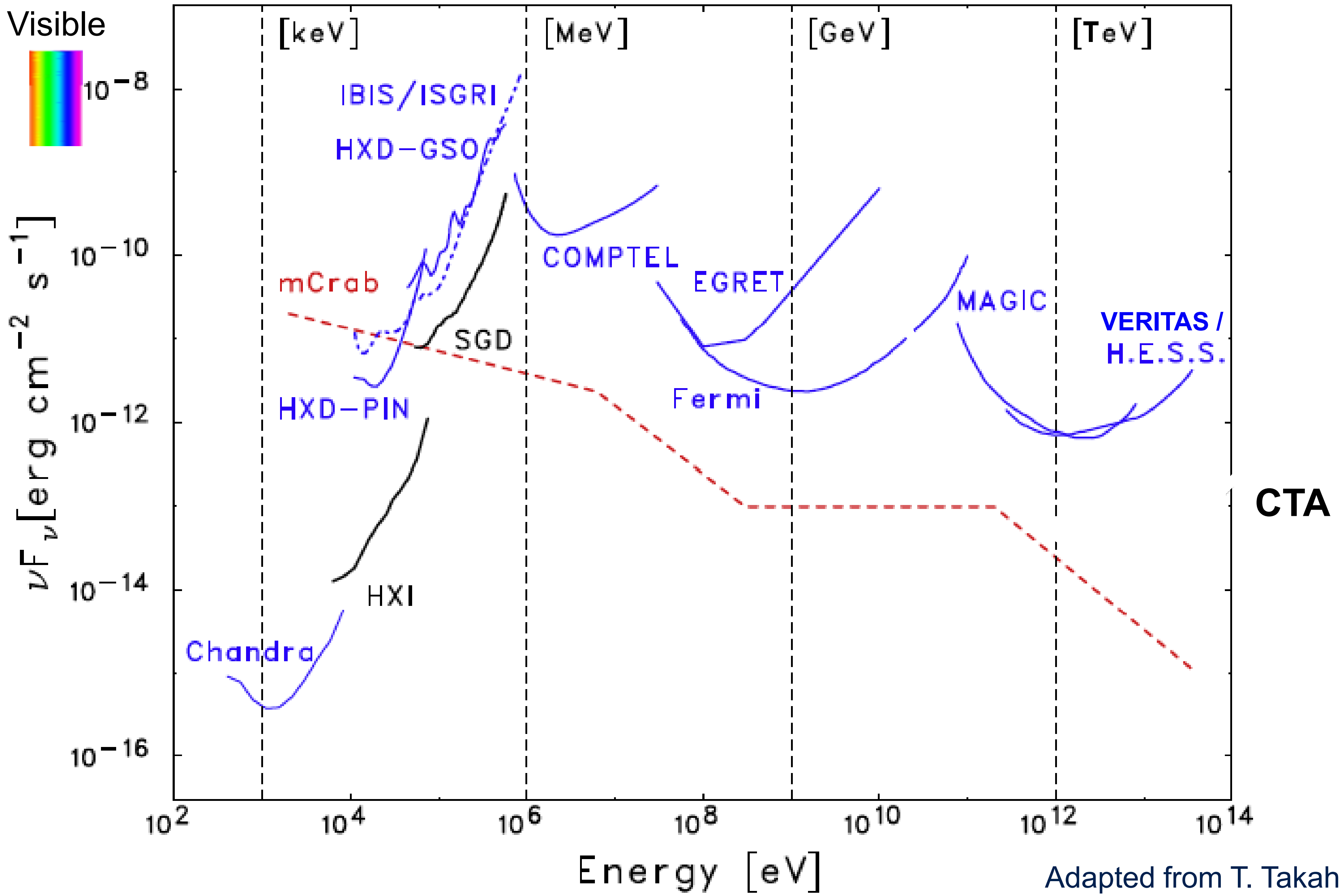
Low energies
Energy threshold 20-30 GeV
23 m diameter
4 telescopes
(LST's)

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)

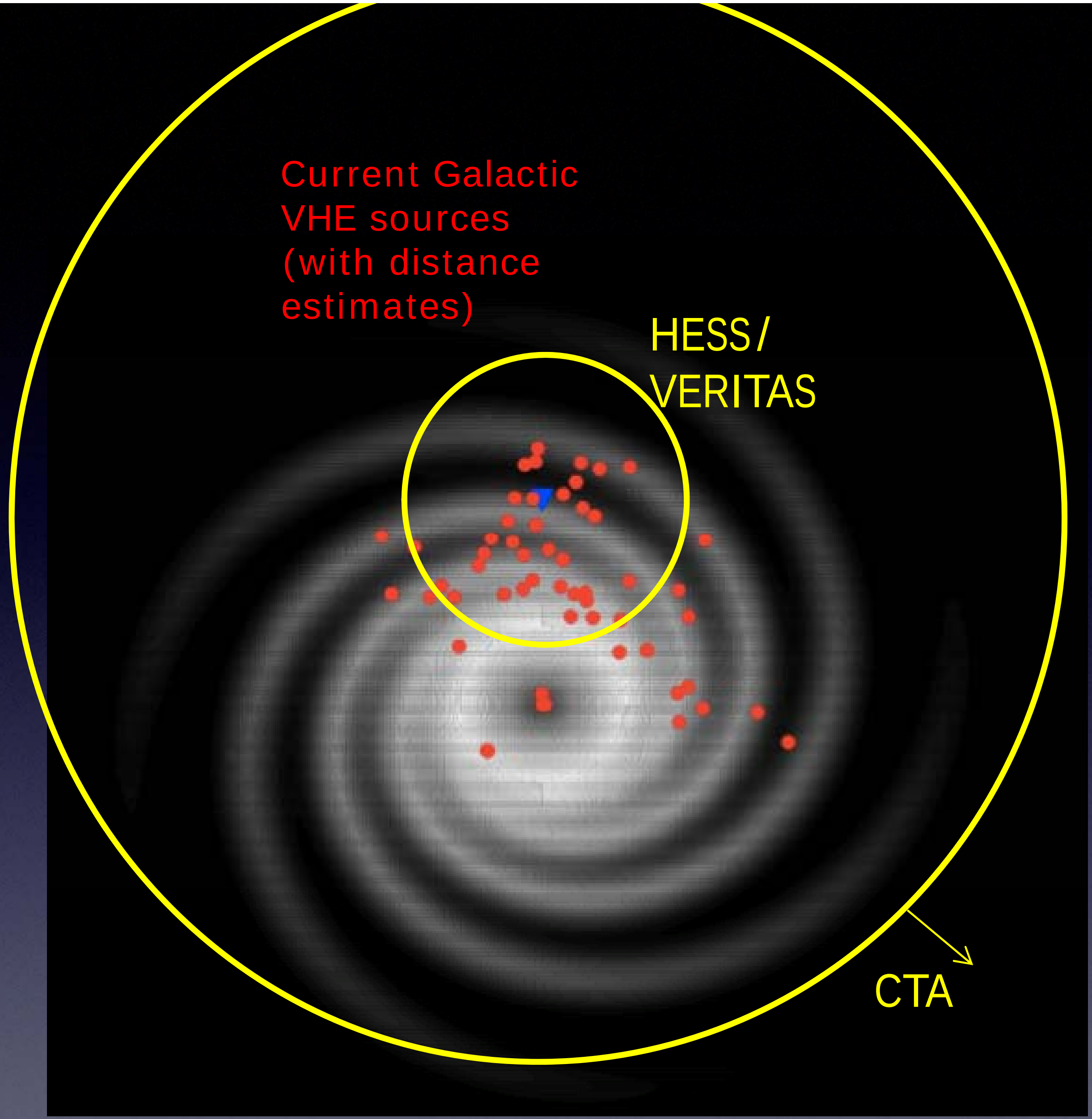


CTA Sensitivity in Context

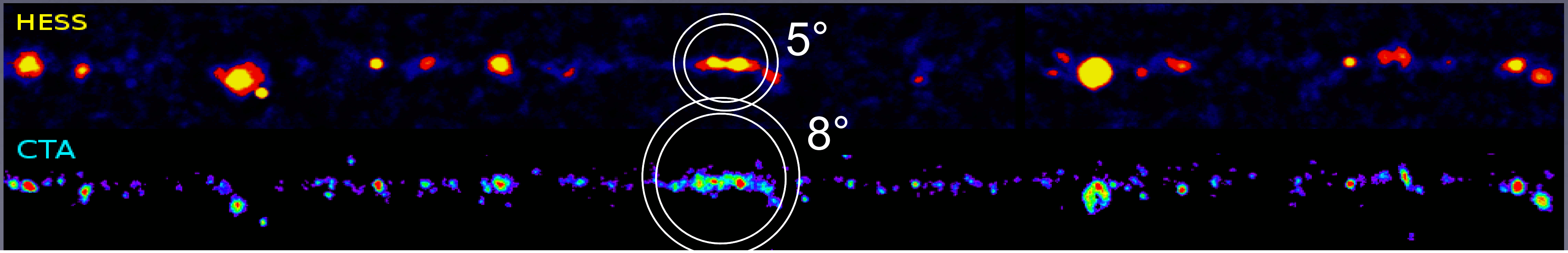


Adapted from T. Takahashi

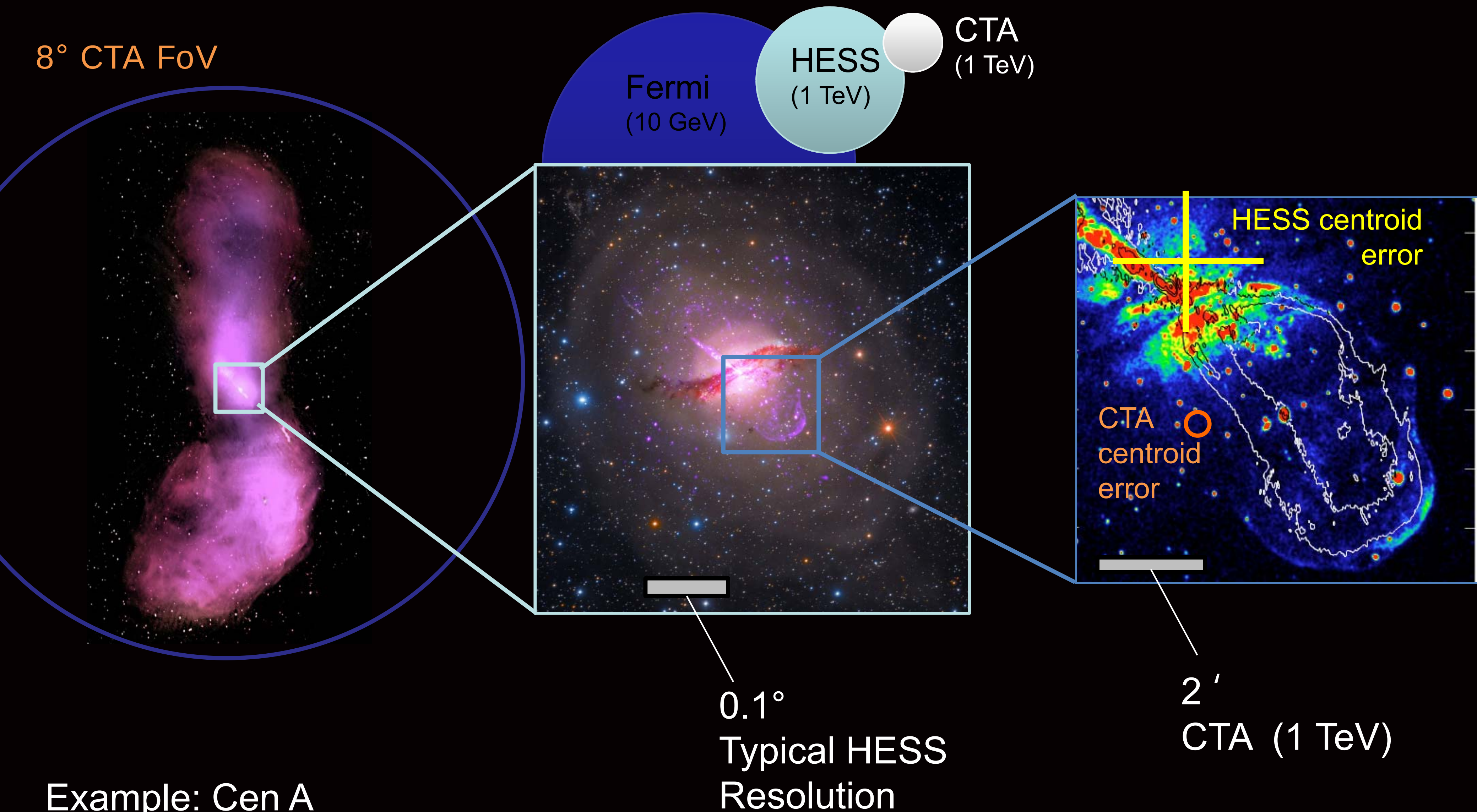
Galactic Discovery Reach



Survey speed:
x300 faster than HESS



Angular Resolution

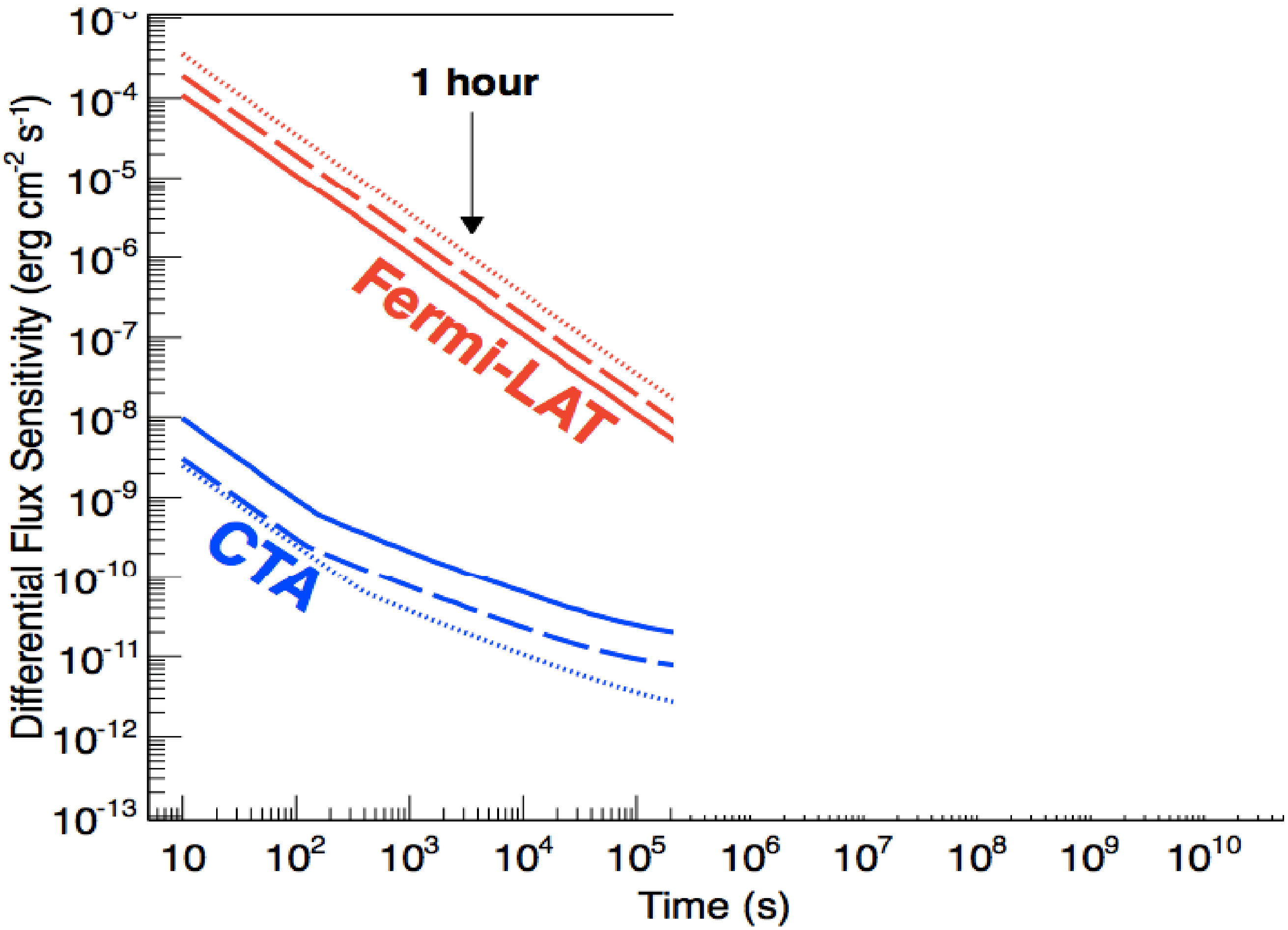


Example: Cen A

Transient Capability (< 100 GeV)

S. Inoue et al.,
arXiv:1301.3014

arXiv:1205.0832



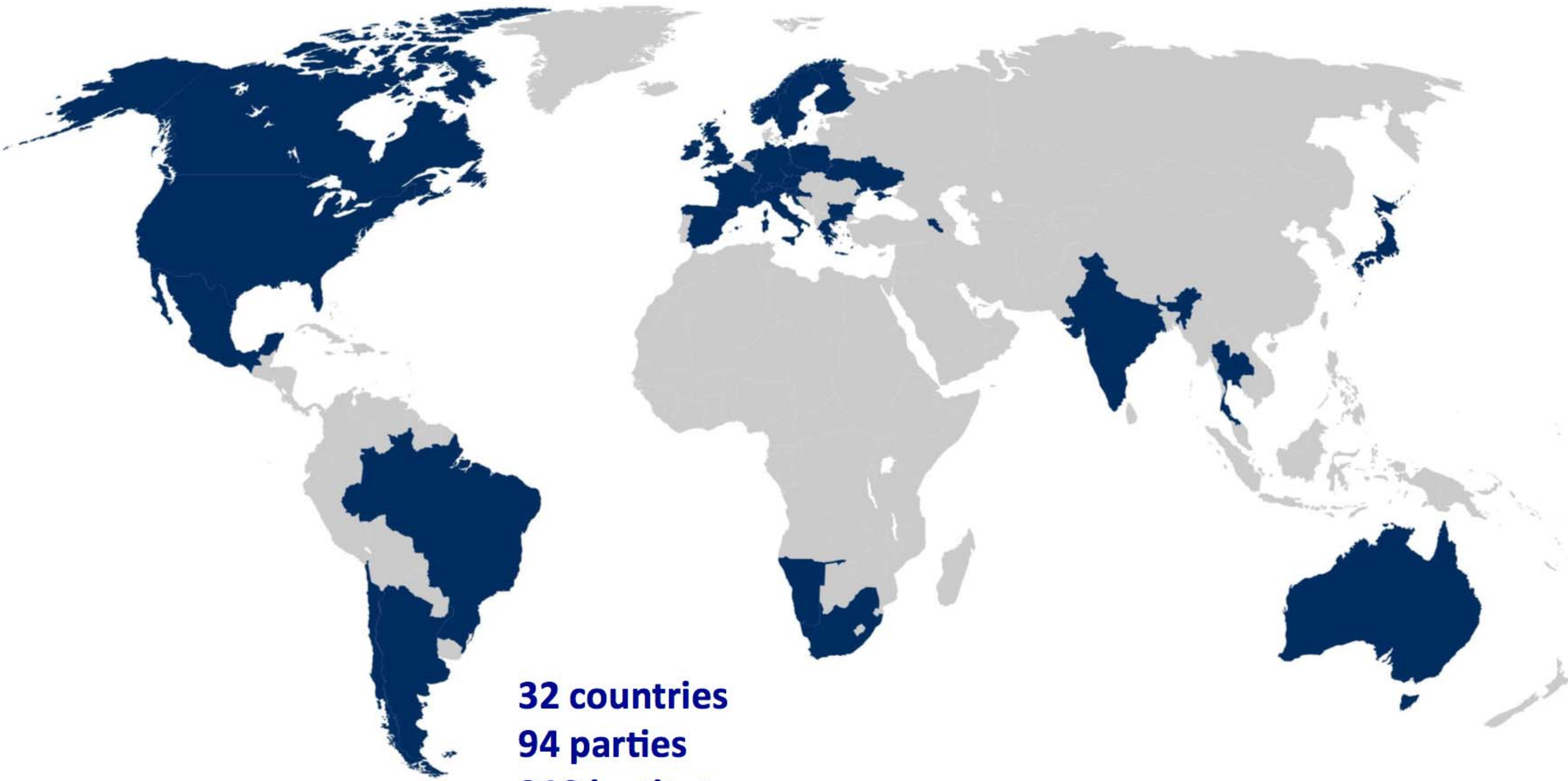
GRB (z=4.3) Light curve

Huge potential for short-timescale phenomena (GRB's, AGN, μquasars, alerts from neutrino and GW telescopes, etc.)

CTA Implementation & Status

CTA Consortium

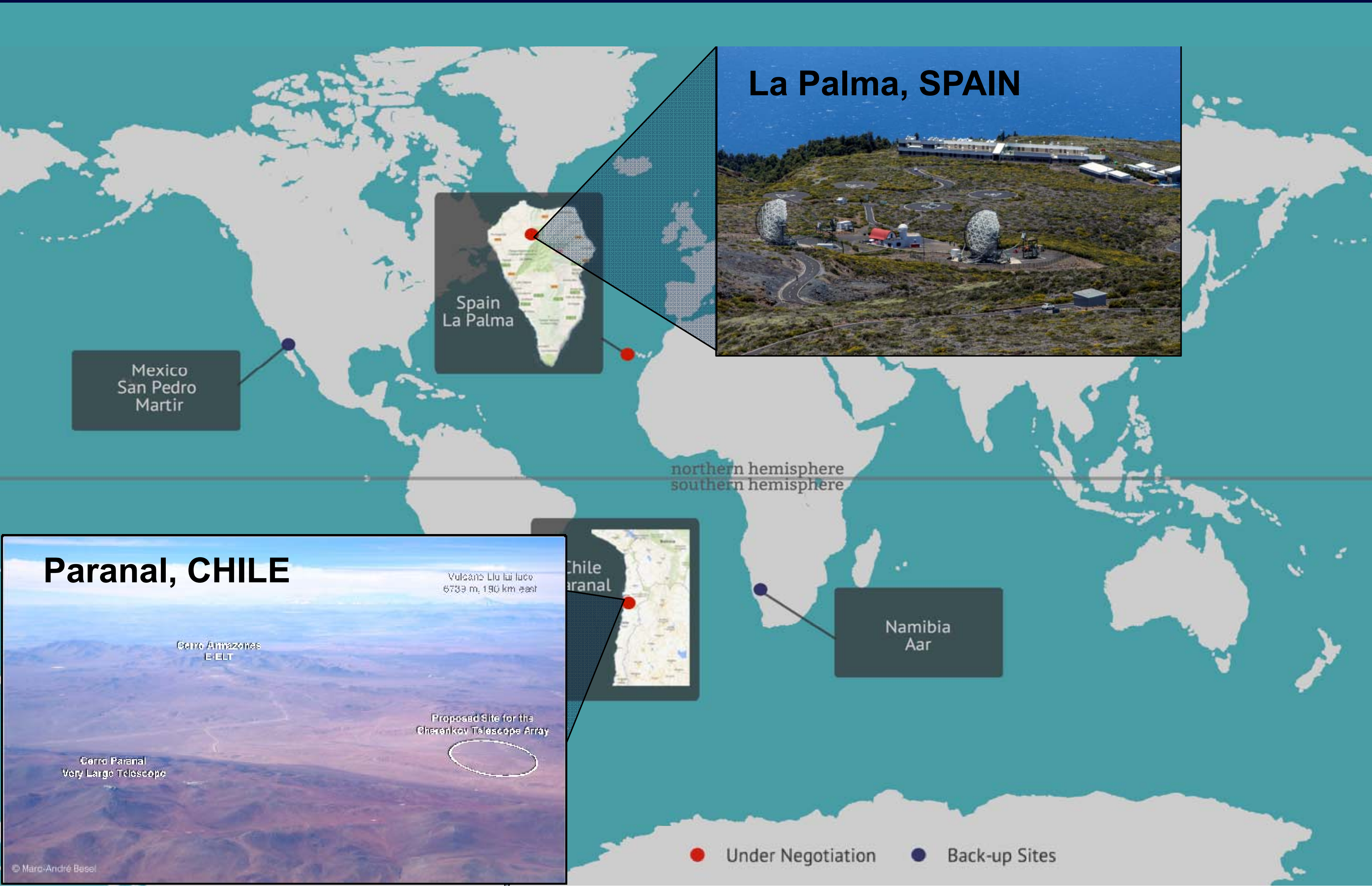
CTA is being developed by the CTA Consortium:



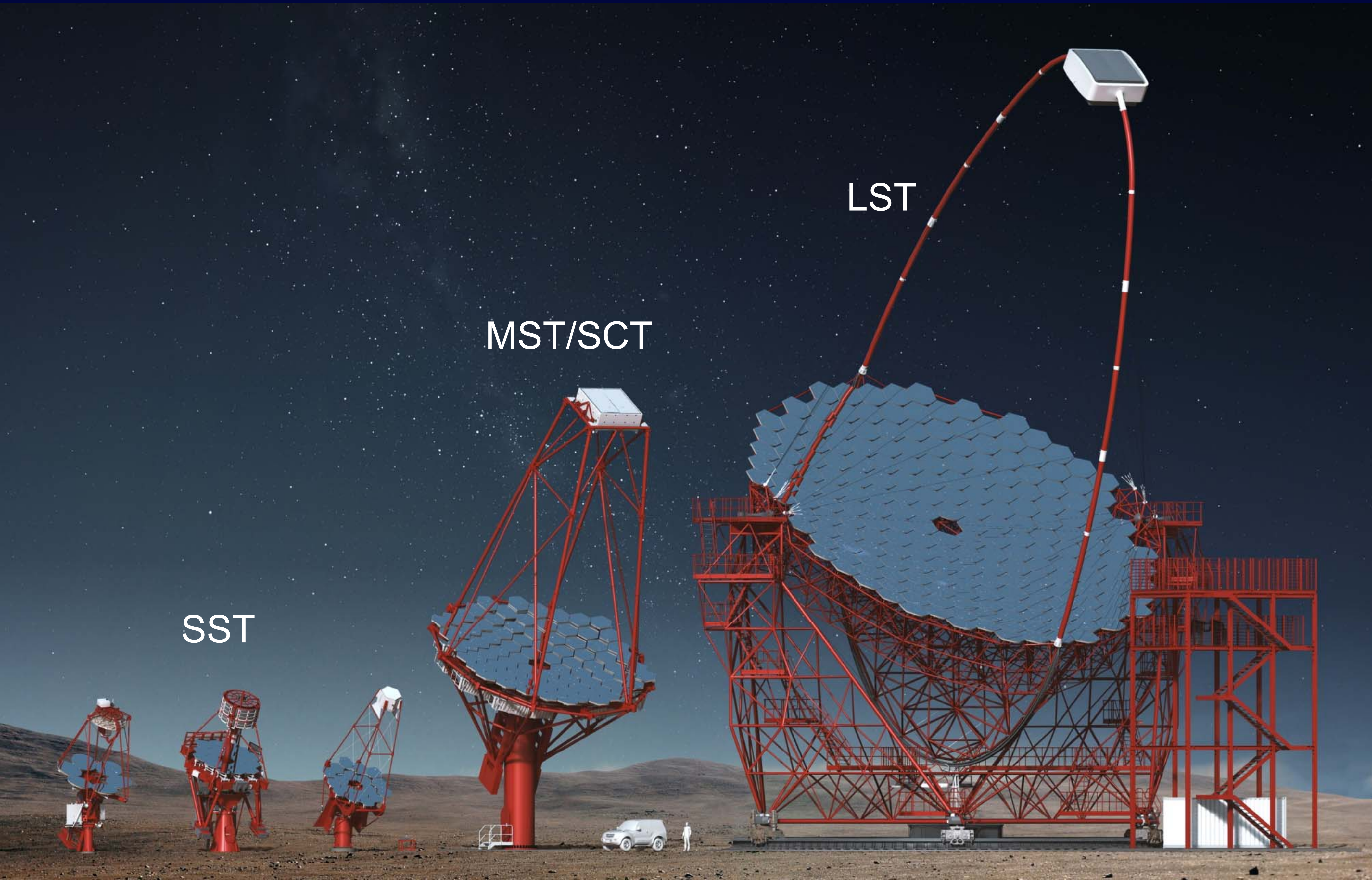
32 countries
94 parties
210 institutes
1420 members (484 FTE)

No single country has an FTE level > 25% total

Selected Sites for CTA



CTA Telescope Types



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

4.5^o field of view

Medium Telescope (MST)

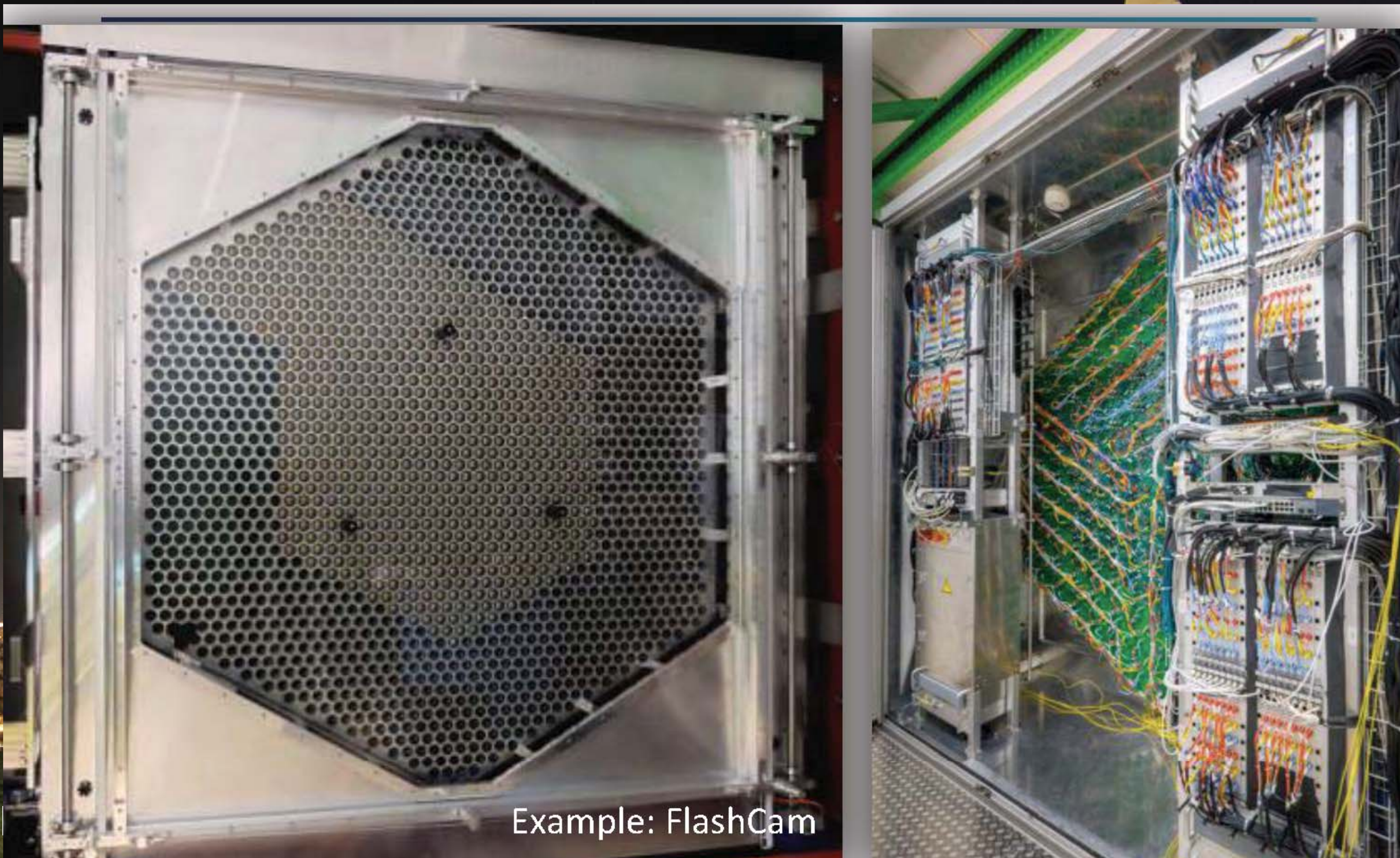
100m² mirror dish area
16 m focal length
1.2 m mirror facets

8° field of view
~2000 x 0.18° pixels

25 MSTs on South site
15 MSTs on North site

Prototype at DESY (Berlin)

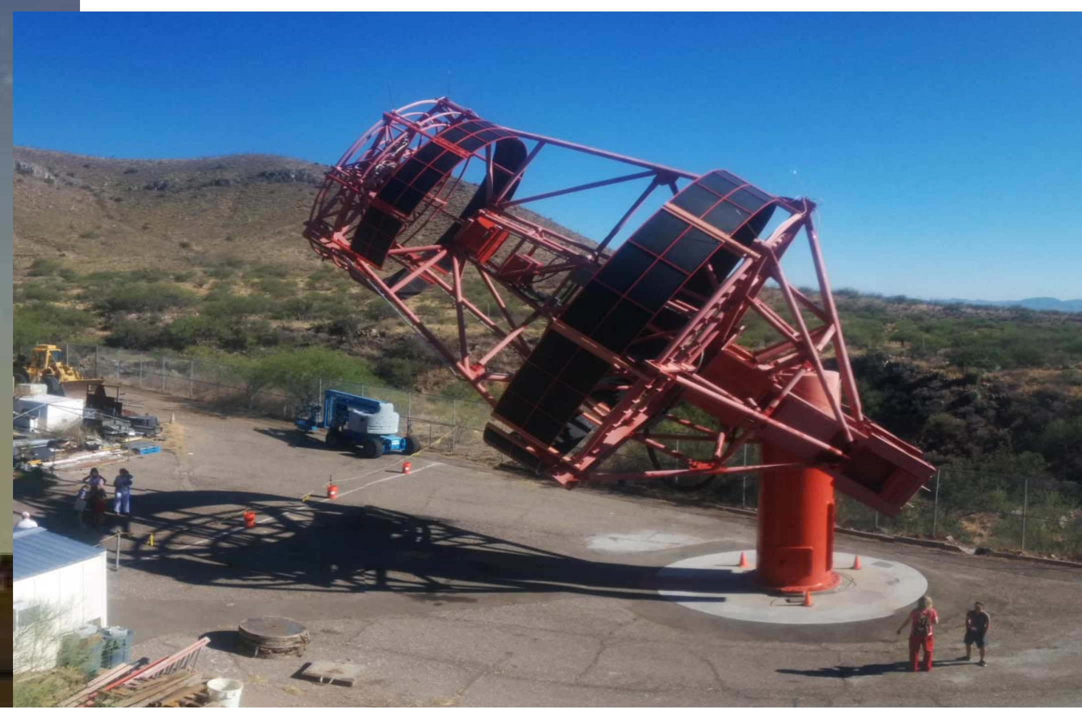
MST Integrated Camera



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)

US involvement prioritized in 2010 Decadal Survey



Small Sized Telescopes (SSTs)

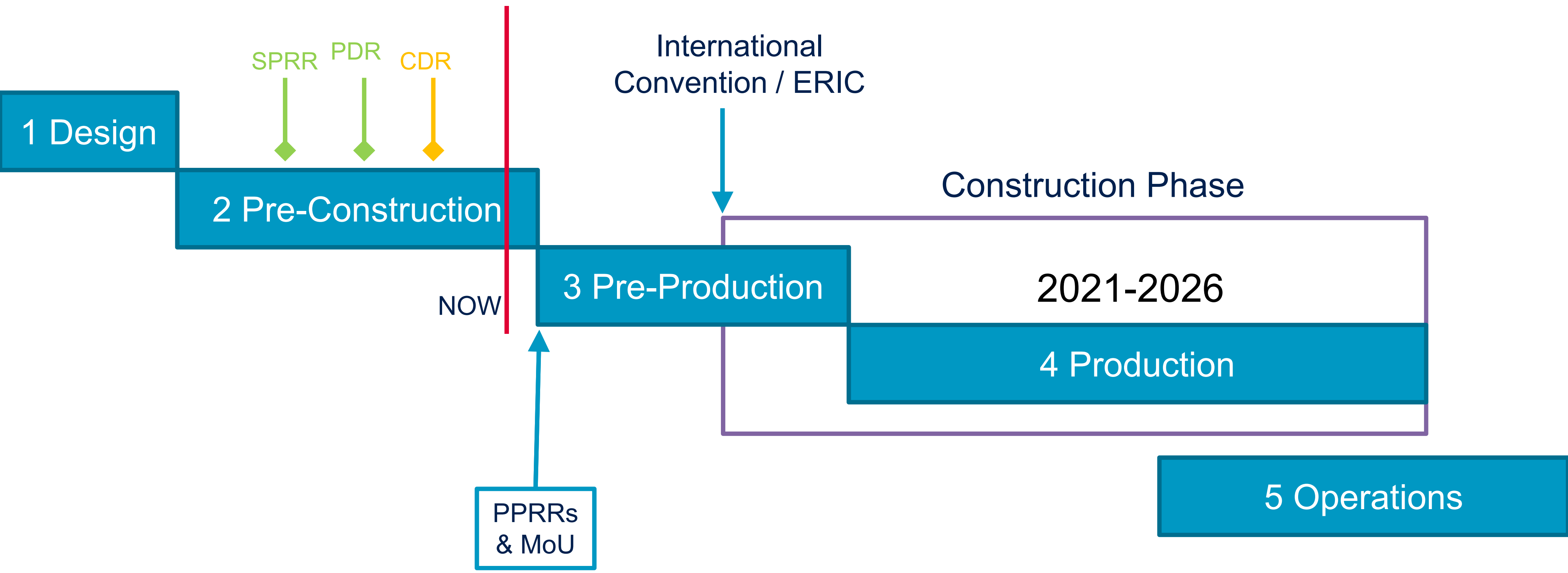
- 3 different prototype designs
- 2 designs use two-mirror approaches (Schwarzschild-Couder design)
- All use Si-PMT photosensors
- 7-9 m^2 mirror area, FOV of 9^o

SST-1M
Krakow, Poland

SST-2M ASTRI
Mt. Etna, Italy

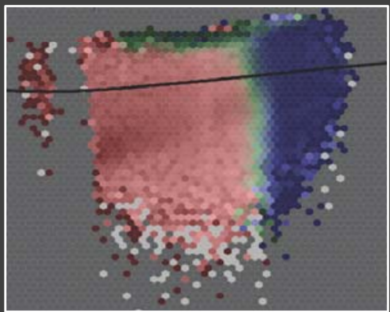
SST-2M GCT
Meudon, France

CTA Phases & Timeline

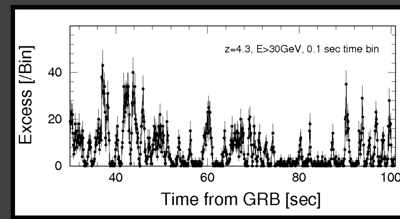


- 2017-8: Hosting agreements, site preparations start
- 2019: Start of construction ?
- Funding level at ~65% of required for baseline implementation
  → start with *threshold implementation*
  → additional funding & telescopes needed to complete baseline CTA
- Construction period of ~6 years (completion in 2026)
- Initial science with partial arrays possible before construction end

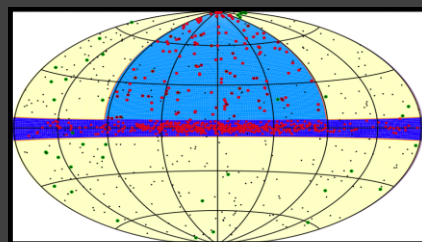
Key Science Projects (KSPs)



Dark Matter Programme

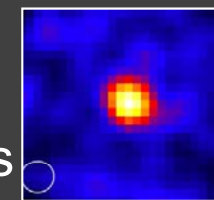


Transients



ExGal Survey

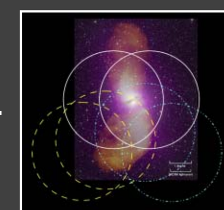
Galaxy Clusters

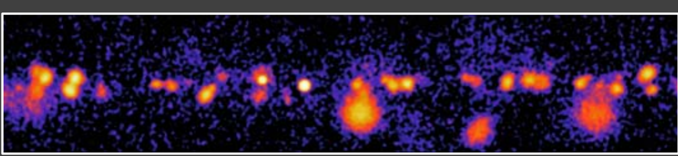


Extragalactic

Star Forming Systems

AGN

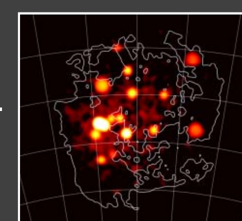




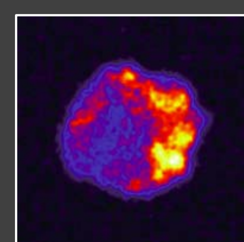
Galactic Plane Survey

Galactic

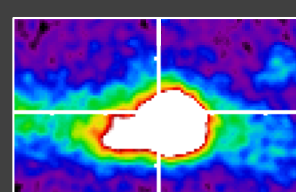
LMC Survey



PeVatrons



Galactic Centre



Science with CTA

200 page document describing core CTA science; placed on arXiv; to be published as book.

arXiv.org > astro-ph > arXiv:1709.07997

Search or Article

(Help | Advanced search

Astrophysics > Instrumentation and Methods for Astrophysics

Science with the Cherenkov Telescope Array

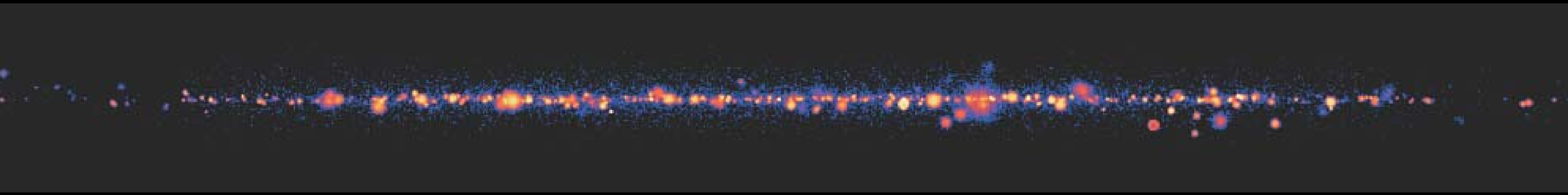
The Cherenkov Telescope Array Consortium: B.S. Acharya, I. Agudo, I. Al Samarai, R. Alfaro, J. Alfaro, C. Alispach, R. Alves Batista, J.-P. Amans, E. Amato, G. Ambrosi, E. Antolini, L.A. Antonelli, C. Aramo, M. Araya, T. Armstrong, F. Arqueros, L. Arrabito, K. Asano, M. Ashley, M. Backes, C. Balazs, M. Balbo, O. Ballester, J. Ballet, A. Bamba, M. Barkov, U. Barres de Almeida, J.A. Barrio, D. Bastieri, Y. Becherini, A. Belfiore, W. Benbow, D. Berge, E. Bernardini, M.G. Bernardini, M. Bernardos, K. Bernlöhr, B. Bertucci, B. Biasuzzi, C. Bigongiari, A. Biland, E. Bissaldi, J. Biteau, O. Blanch, J. Blazek, C. Boisson, J. Bolmont, G. Bonanno, A. Bonardi, C. Bonavolontà, G. Bonnoli, Z. Bosnjak, M. Böttcher, C. Braiding, J. Bregeon, A. Brill, A.M. Brown, P. Brun, G. Brunetti, T. Buanes, et al. (514 additional authors not shown)

(Submitted on 23 Sep 2017)

The Cherenkov Telescope Array, CTA, will be the major global observatory for very high energy gamma-ray astronomy over the next decade and beyond. The scientific potential of CTA is extremely broad: from understanding the role of relativistic cosmic

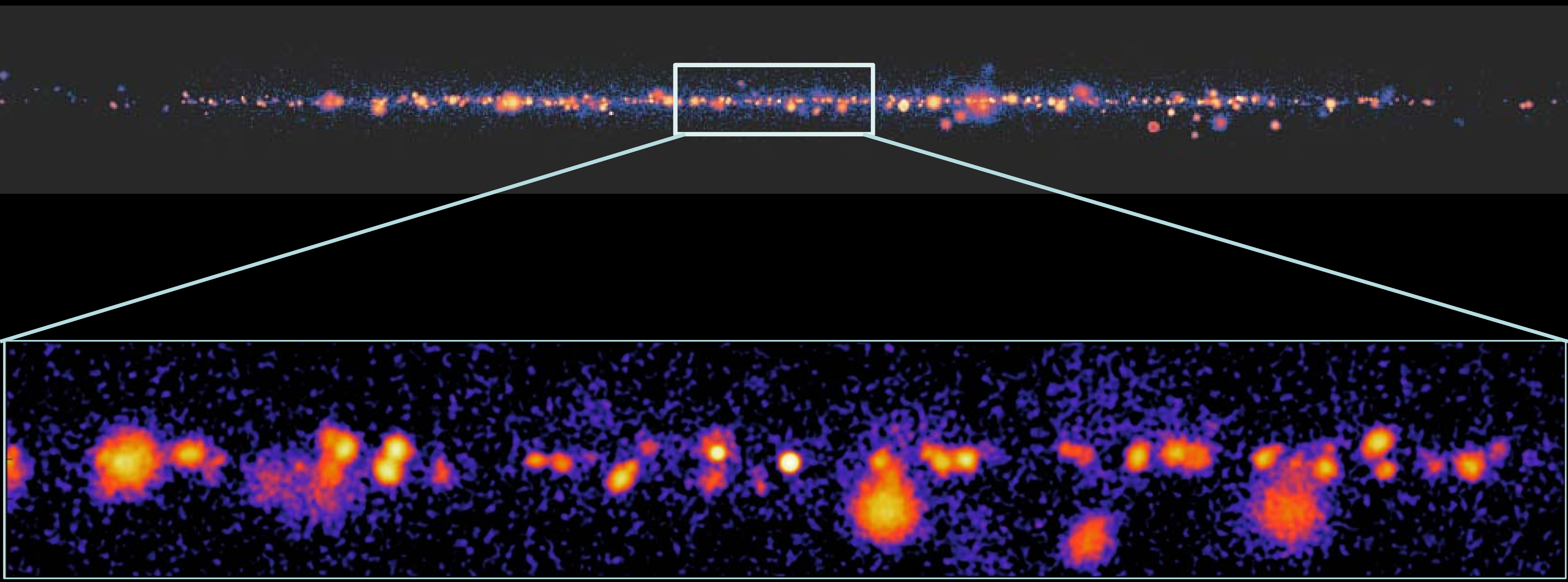
Galactic Plane Survey (GPS)

Full plane survey to depth of 1.5-2.5 mCrab



Galactic Plane Survey (GPS)

Full plane survey to depth of 1.5-2.5 mCrab



Expect 500-800 new sources: PWN, SNR, binaries, unknowns …

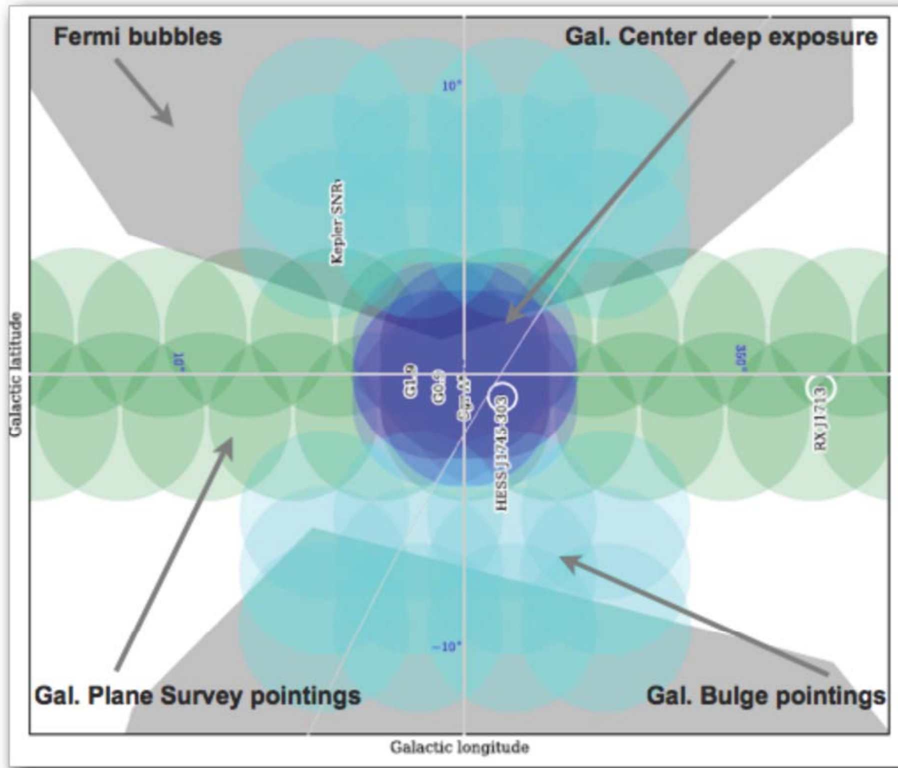
Also, Exgal actic Survey of ¼ sky to 6 mCrab

Galactic Center Survey

Multiple survey regions to encompass the entire GC region.

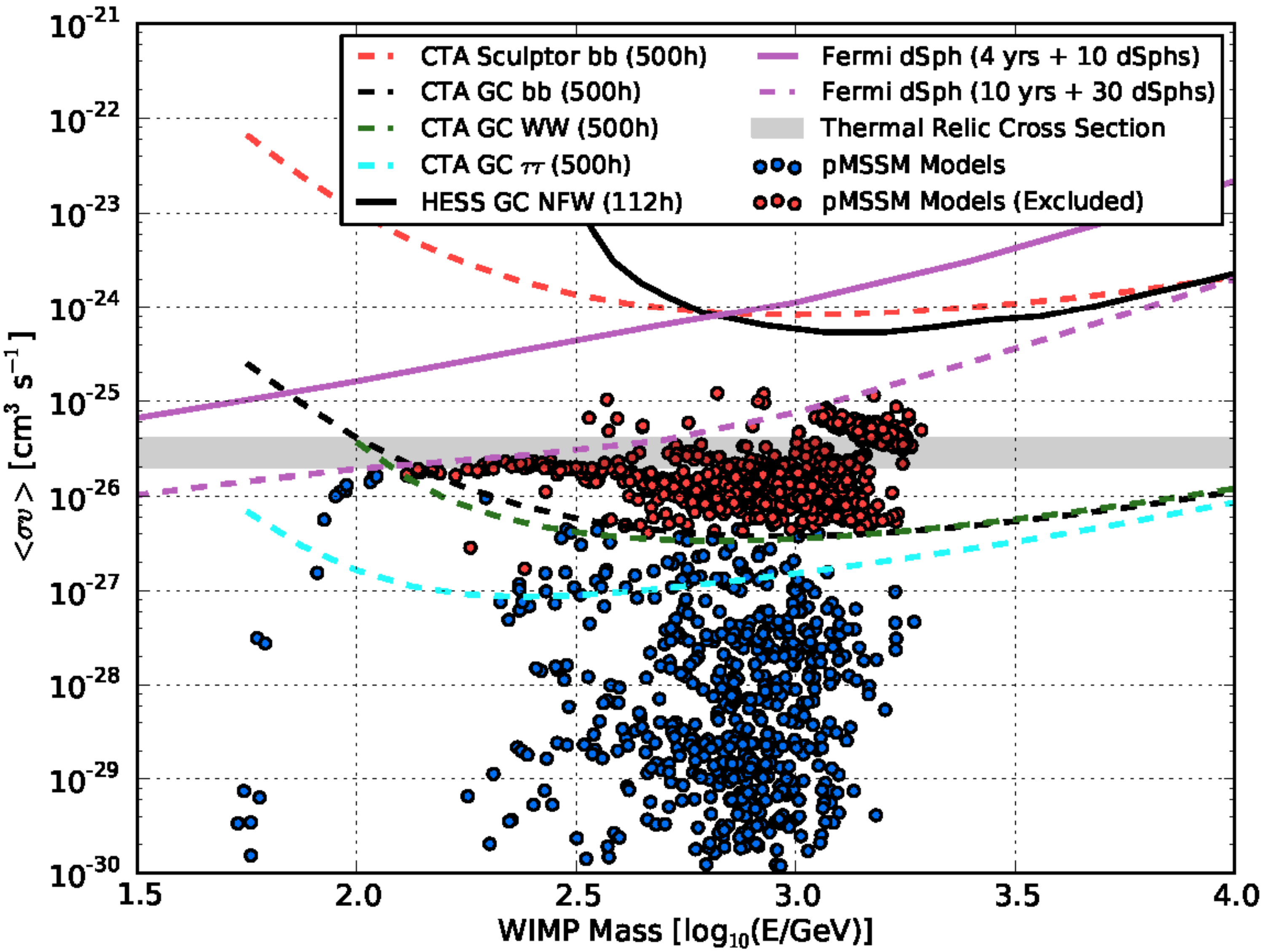
Astrophysical Goals:

- Determination of nature of central source, including a sensitive search for variability
- Detailed view of VHE diffuse emission and interaction of CR with clouds
- Resolving new, undiscovered point and
- extended sources
- Confirming the PeVatron hypothesis of SGR A*



Deep observation of GC Halo for indirect DM search

Dark Matter Reach



M. Wood et al.
arXiv:1305.0302

Sensitivity below thermal relic in TeV mass range

- *critical reach, not achieved by direct detectors or LHC*

Optical Science with CTA

Because of its very large photon collection area, CTA has great potential in the areas of:

- **Optical SETI (OSETI)**
- **Stellar intensity interferometry**

  mas angular scale measurements
- **Optical photometry**

  eclipsing binaries
  transiting exoplanets
  asteroid occultations
  fast radio bursts

(Slides from M. Daniel (SAO), J. Holder (Delaware), and T. Hassan (DESY))

Why optical rather than radio?

Idea first floated by R.N. Schwartz & C.H. Townes
'Interstellar and Interplanetary Communication by Optical Masers' *Nature* **190**, 205 (1961).

- **It is easier to deal with noise**
  - radio waves contend with interference from radio antennas, radio stations, the receiver itself adds noise (thus can require cooling), …
  - for optical the only significant source of terrestrial interference is lightning & Cherenkov radiation

- **Pulsed lasers can easily outshine the host star**
  - no known natural sources would have photons within a few ns of each other
    ➡ could easily be 1000x brighter in the receiving telescope

- **Much easier to form a narrow beam of light**
  - a radio transmitter 100 ly distant & projecting omni-directionally would require 5800 trillion watts to be detectable ~ 7000x the electricity-generating capacity of the USA!
  - width of beam ∝ wavelength of beam / diameter of the antenna used

    ➡ $\lambda_{optical} \ll \lambda_{radio}$

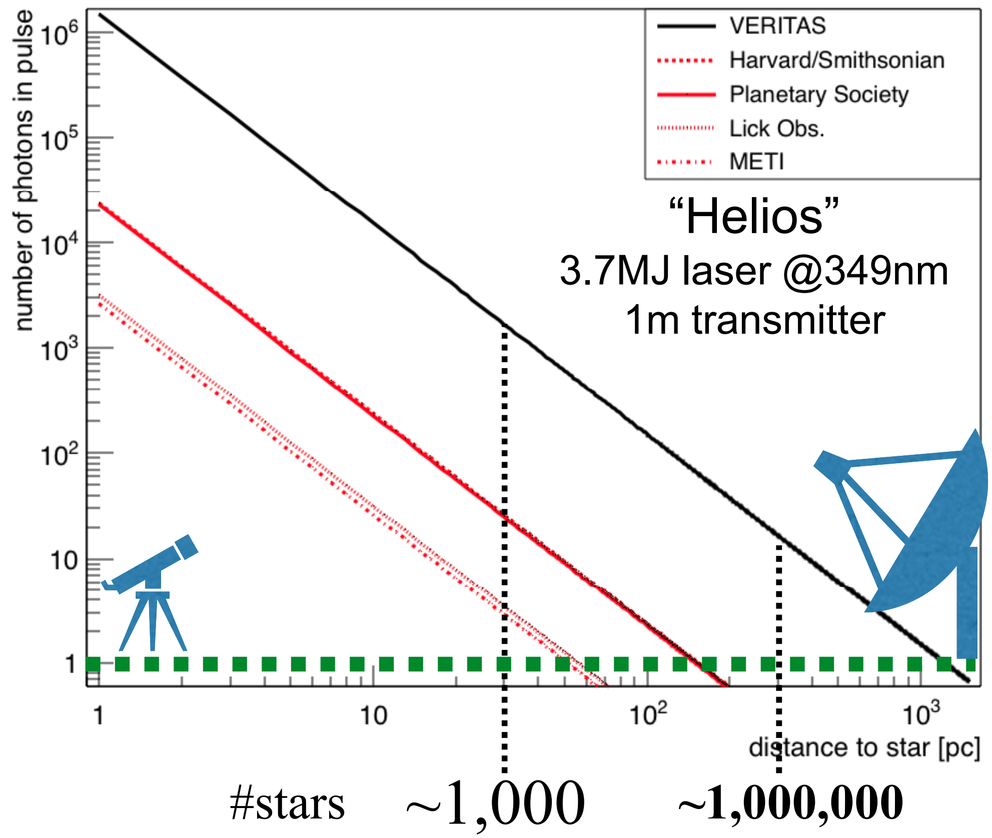
M. Ross *IEEE Spectrum* **7**, 32 (2006).

Just need a suitable optical light bucket as a receiver…

(Slides from M. Daniel (SAO), J. Holder (Delaware), and T. Hassan (DESY))

How do current IACTs compare ?

	Detector	λ [nm]	Sensitivity [ph m^{-2}]
VERITAS[1], 12m	3 pmts / <5ns	300-600	**1**
STACEE[2], heliostats	pmt ~12ns	300-600	10
Planetary Society[3], 1.8m	pmt / ~5ns	300-800	60
Harvard Oak Ridge[4], 1.5m	2 apd / 5ns	450-650	100
Lick Obs[5], 1m	2 apd / <1ns	950-1650	40
Princeton[6], 0.9m	2 apd / 5ns	450-650	80
Leuschner Obs[7], 0.8m	3 pmt / 5ns	300-700	41
METI / Boquete Obs[8], 0.5m	1pmt / 25ns	350-600	67



[1] Abeysekara et al. (2016)
[2] Hanna et al. (2009)
[3] Mead (2013)
[4] Howard et al. (2004)
[5] Maire et al. (2014)
[6] Howard et al. (2004)
[7] Korpela et al. (2011)
[8] Schuetz et al. (2016)

Large mirror area → Excellent photon sensitivity

(Slides from M. Daniel (SAO), J. Holder (Delaware), and T. Hassan (DESY))

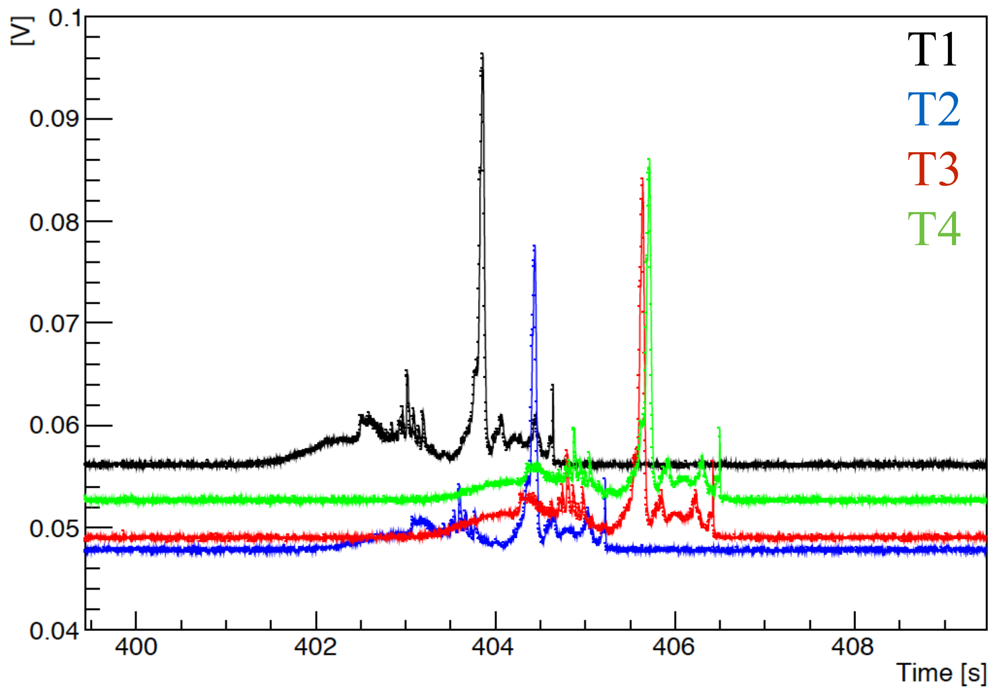
Additional Advantages of IACTs

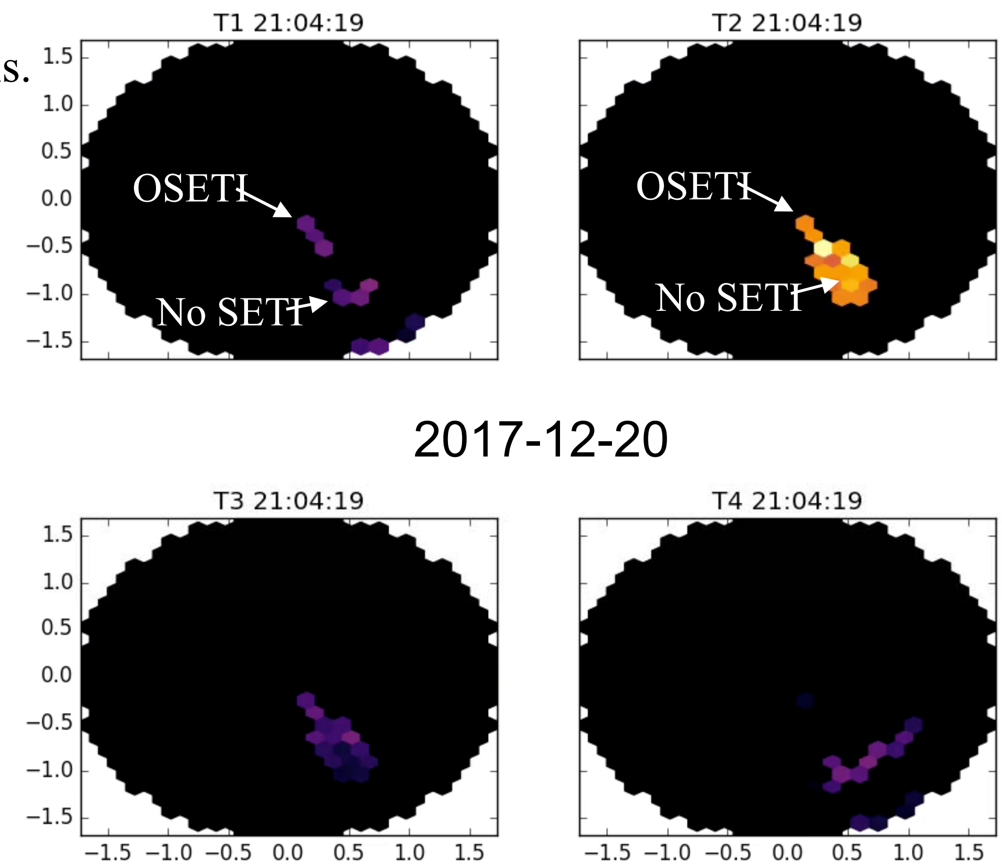
The large field of view of the cameras helps to

- remove background signals
- monitor multiple stars simultaneously

IACTS can monitor ~45-150 stars (V>12) in a single pointing

Lightning seen by VERITAS in current monitor pixels.

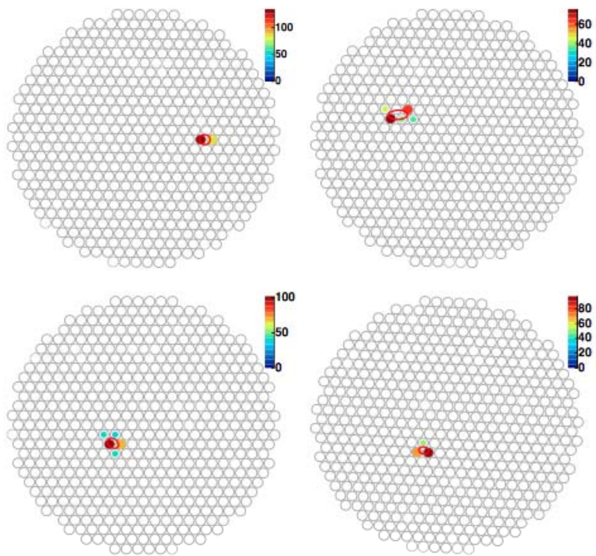




(Slides from M. Daniel (SAO), J. Holder (Delaware), and T. Hassan (DESY))

OSETI event selection criteria

- They appear in the same place in all four telescope cameras
- They have the same intensity in each telescope
- They are point-like (c.f. optical point-spread function)



Cosmic rays show parallax due to shower max. only being a few km in altitude

Shooting stars/satellites will move through the camera

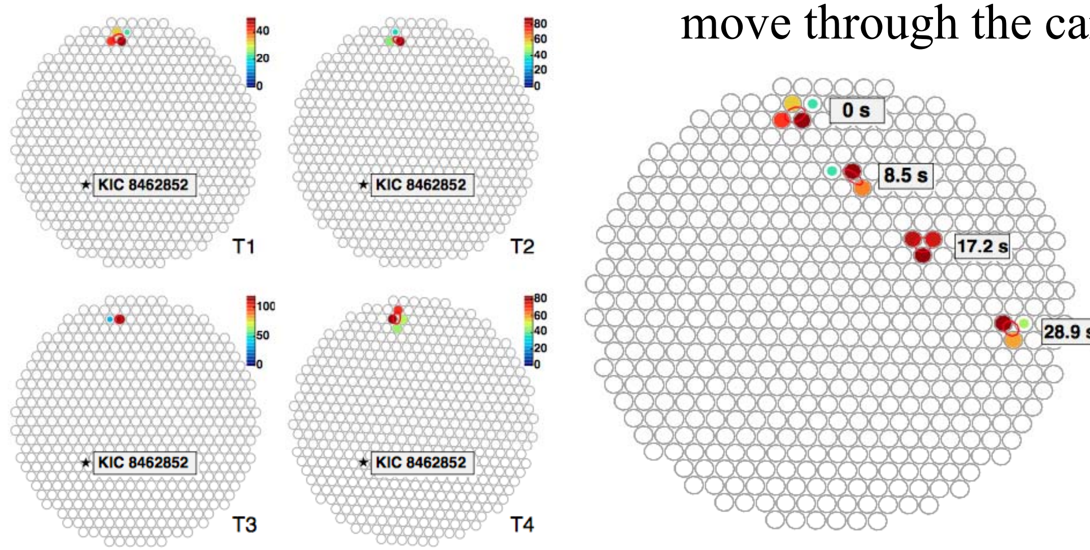


Fig. 3.— Point-like events generated by an object moving across the field-of-view of VERITAS over the course of 28.9 seconds on MJD 57283. **Left:** A single event viewed by all four telescopes. **Right:** A subset of the eight recorded events illustrating the motion of the image across the camera of a single telescope.

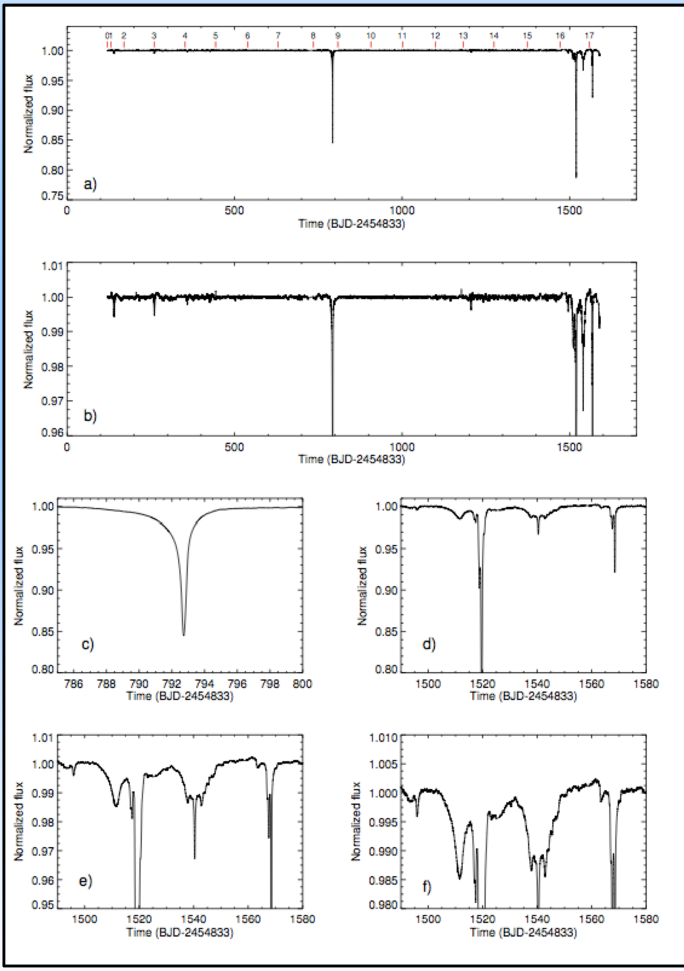
Abeysekara et al. *Ap.J* **818**, L33 (2016)

(Slides from M. Daniel (SAO), J. Holder (Delaware), and T. Hassan (DESY))

The VERITAS OSETI Publication : ApJ 818, L33 (2016)

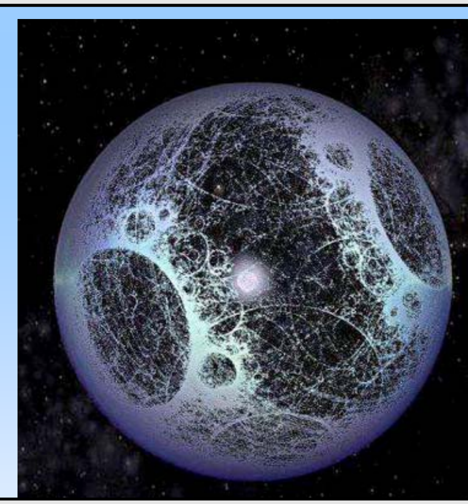
- The star KIC 8462852 has been identified as a SETI target, based on its unusual lightcurve.
- VERITAS had 10 hours of "free" data in its archive, taken over 6 years.

  ➡ no signal detected.



"Boyajian et al. 2015 recently announced KIC 8462852, an object with a bizarre light curve consistent with a "swarm" of megastructures. We suggest this is an outstanding SETI target."

J.T. Wright et al. *ApJ* **816**, 17 (2016).



Since the publication, 2-3 additional hours have been taken, mostly snapshots on 0FGL J2001.0+4352

(Slides from M. Daniel (SAO), J. Holder (Delaware), and T. Hassan (DESY))

OSETI with VERITAS: What Next?

BREAKTHROUGH
LISTEN

ABOUT BOARD ARE WE ALONE? NEWS EVENTS CONTACTS
LEADERS RESEARCH TELESCOPES OPEN DATA

Search

LISTEN

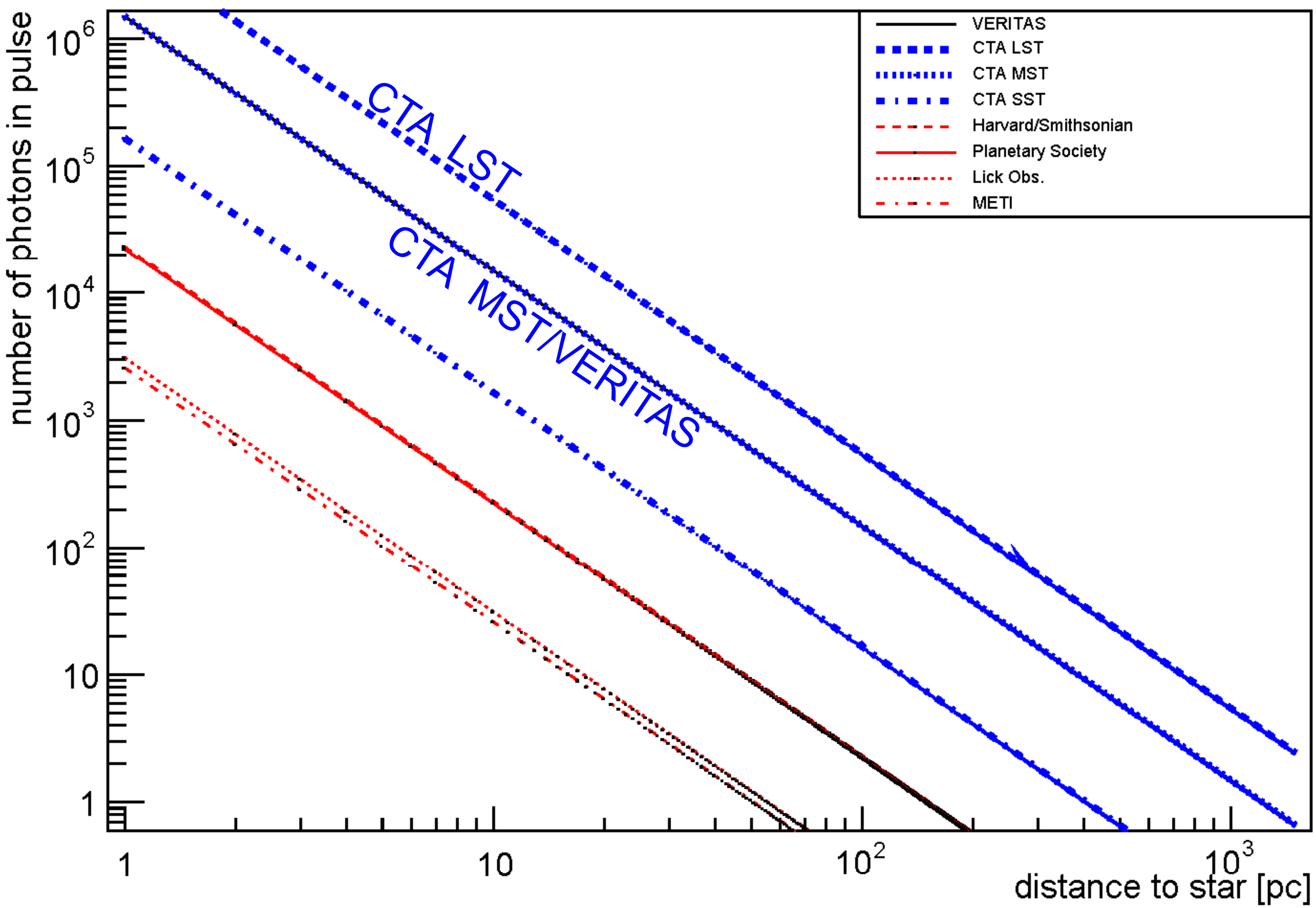
Breakthrough Listen is the largest ever scientific research program aimed at finding evidence of civilizations beyond Earth. The scope and power of the search are on an unprecedented scale:

The program includes a survey of the 1,000,000 closest stars to Earth. It scans the center of our galaxy and the entire galactic plane. Beyond the Milky Way, it listens for messages from the 100 closest galaxies to ours.

Test with 30 h of observations next season
- a list of ~1700 preferred stars
- archival search would also start here

(Slides from M. Daniel (SAO), J. Holder (Delaware), and T. Hassan (DESY))

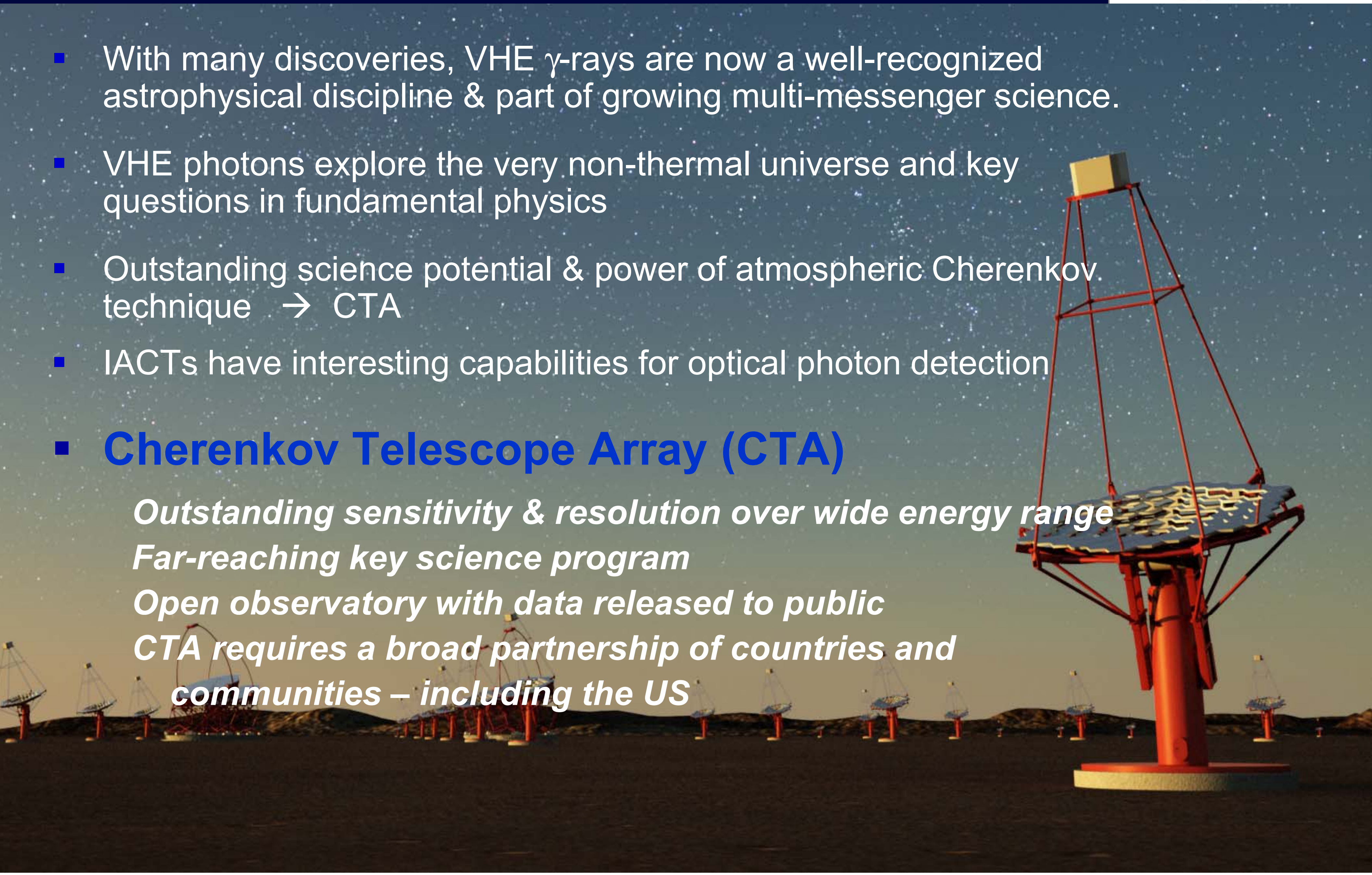
OSETI with CTA



With a large number of telescopes, many targets can be observed simultaneously

(Slides from M. Daniel (SAO), J. Holder (Delaware), and T. Hassan (DESY))

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
- IACTs have interesting capabilities for optical photon detection
- **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 the US