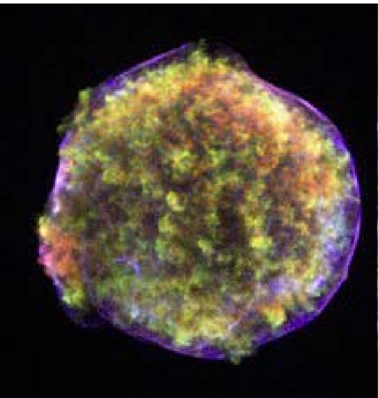
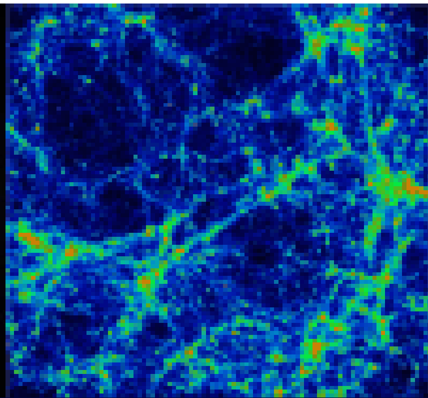
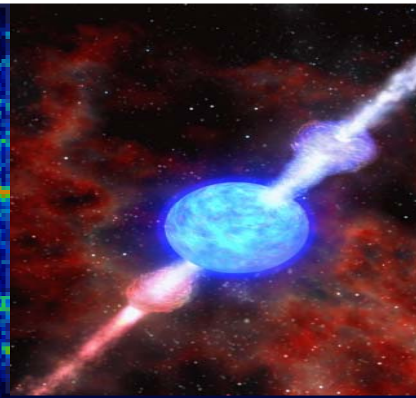
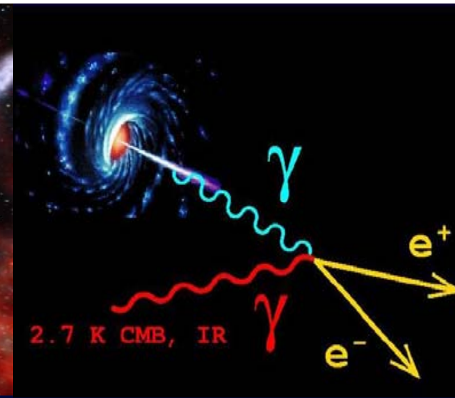
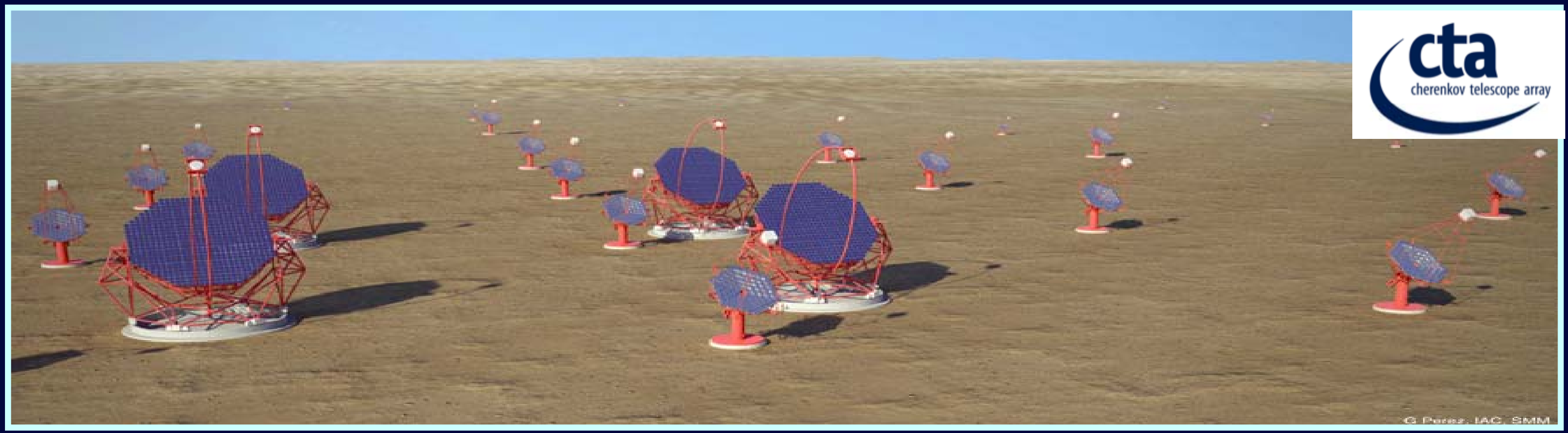





The Future of Very High-Energy Astrophysics

Rene A. Ong (UCLA and ICRR)

University of Kyoto, 04 October 2016



Outline

- **Scientific & Technical Motivation**

  Science Overview – VHE gamma-ray sky
  Three selected science topics in brief
  Experimental Technique
  Planning for the Future → CTA

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

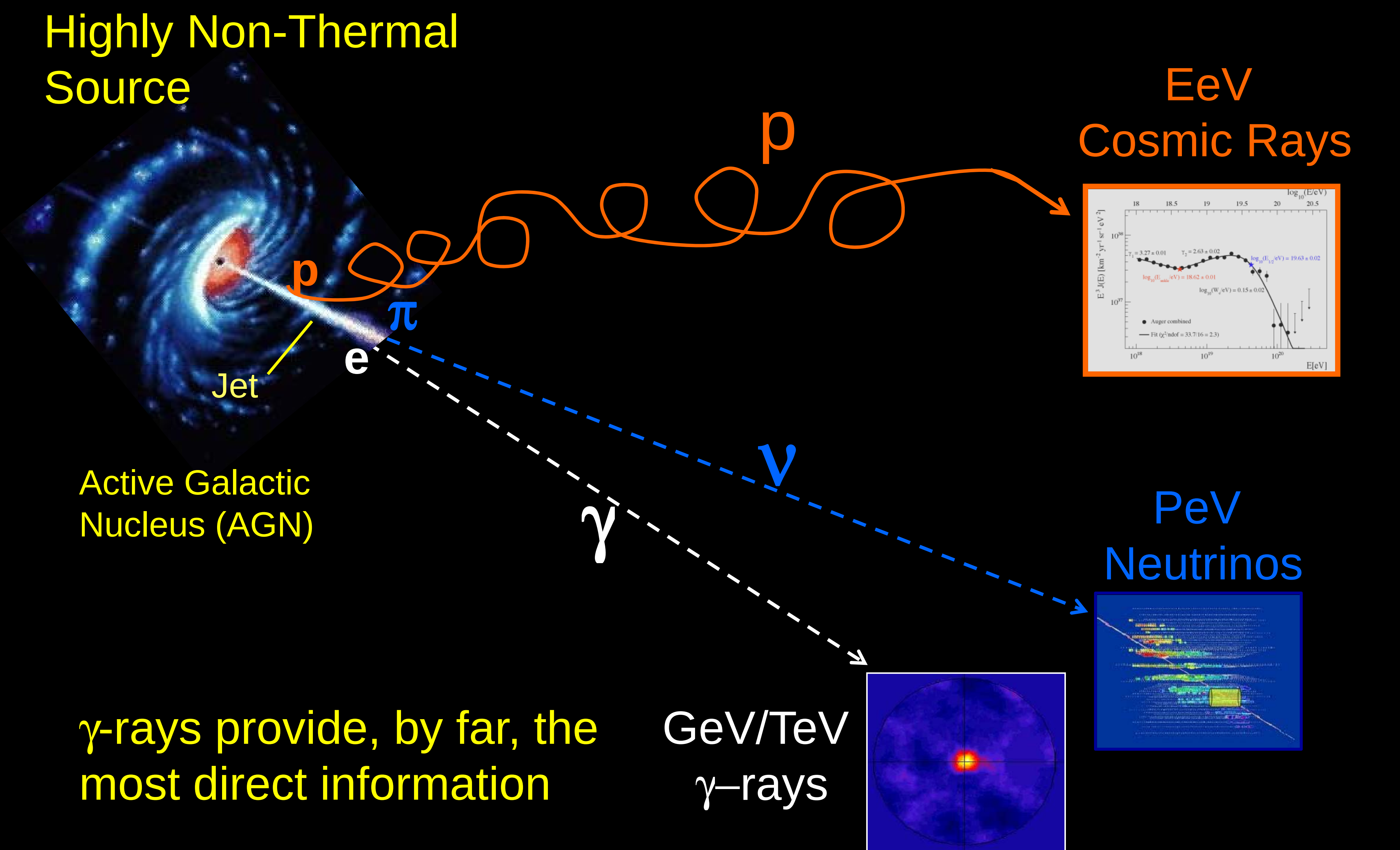
  Science Drivers → requirements
  CTA Design & Performance → **Scientific Capabilities**

- **CTA Implementation & Status**

  Implementation: design and prototype telescopes
  Present status (2016): status of sites, timeline, etc.
  Key Science Projects (KSPs) – Core science – a few examples

- **Summary**

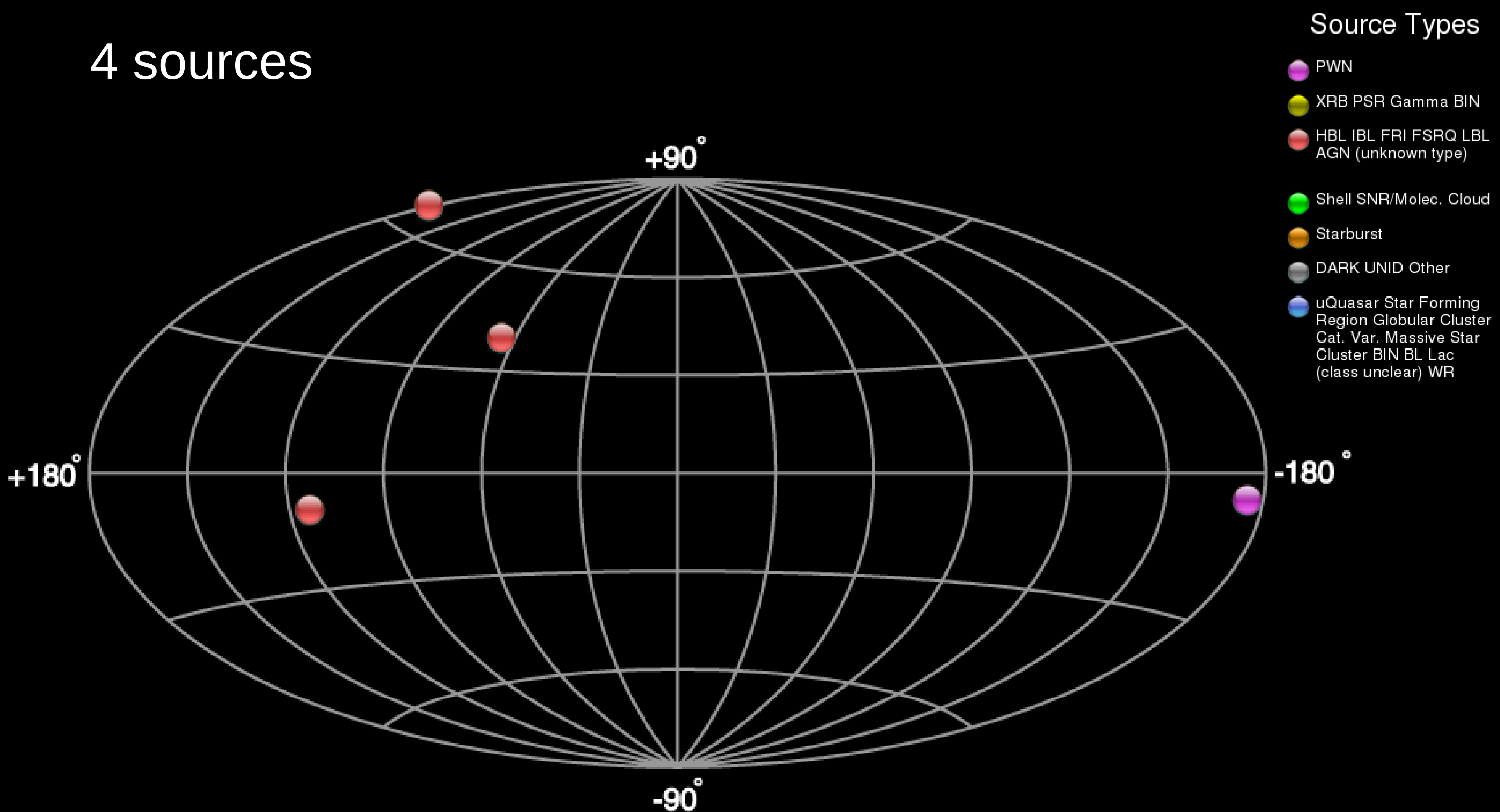
Very High Energy (VHE) Astrophysics



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

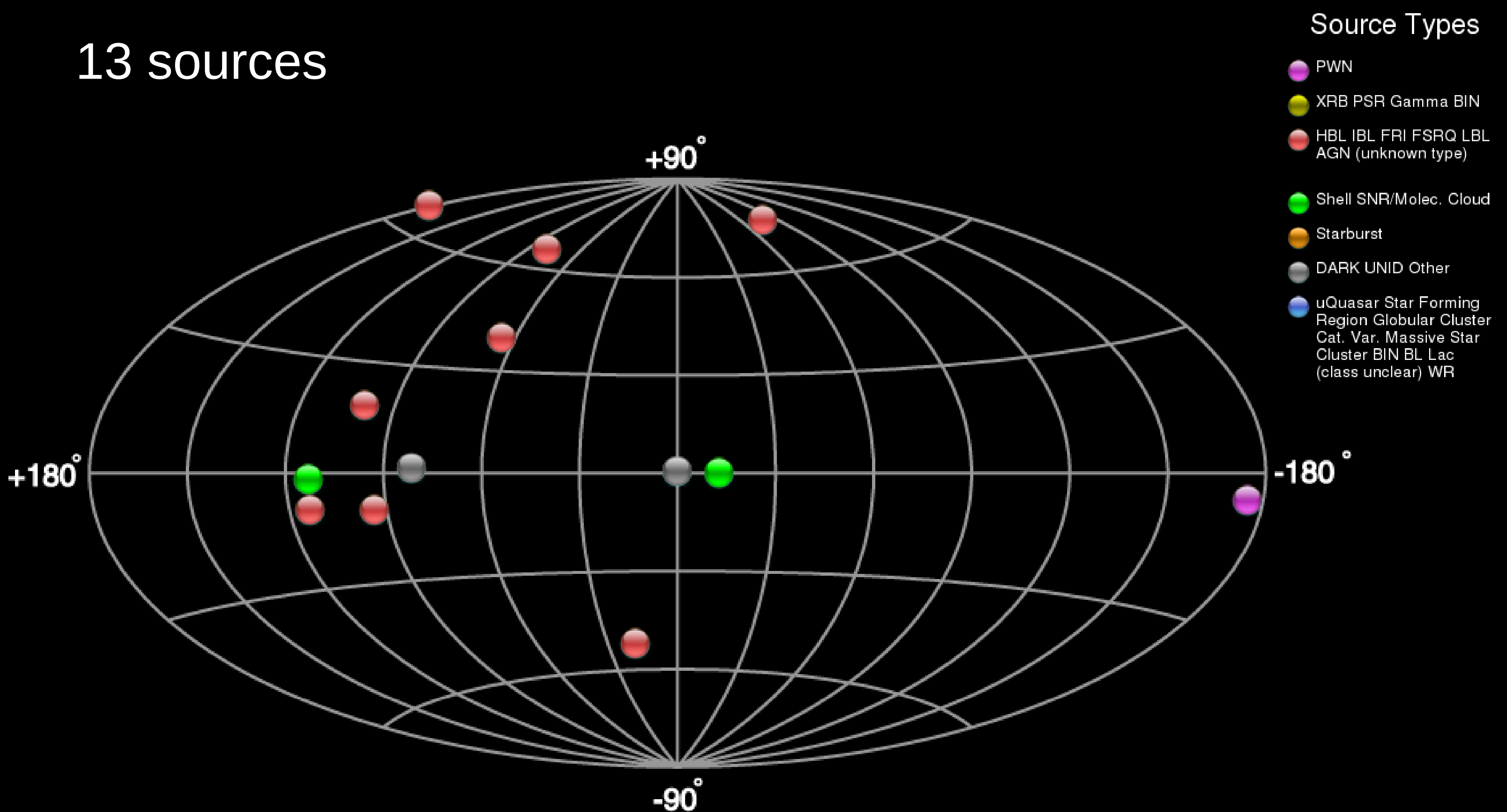
VHE γ-ray Sky c1997

4 sources



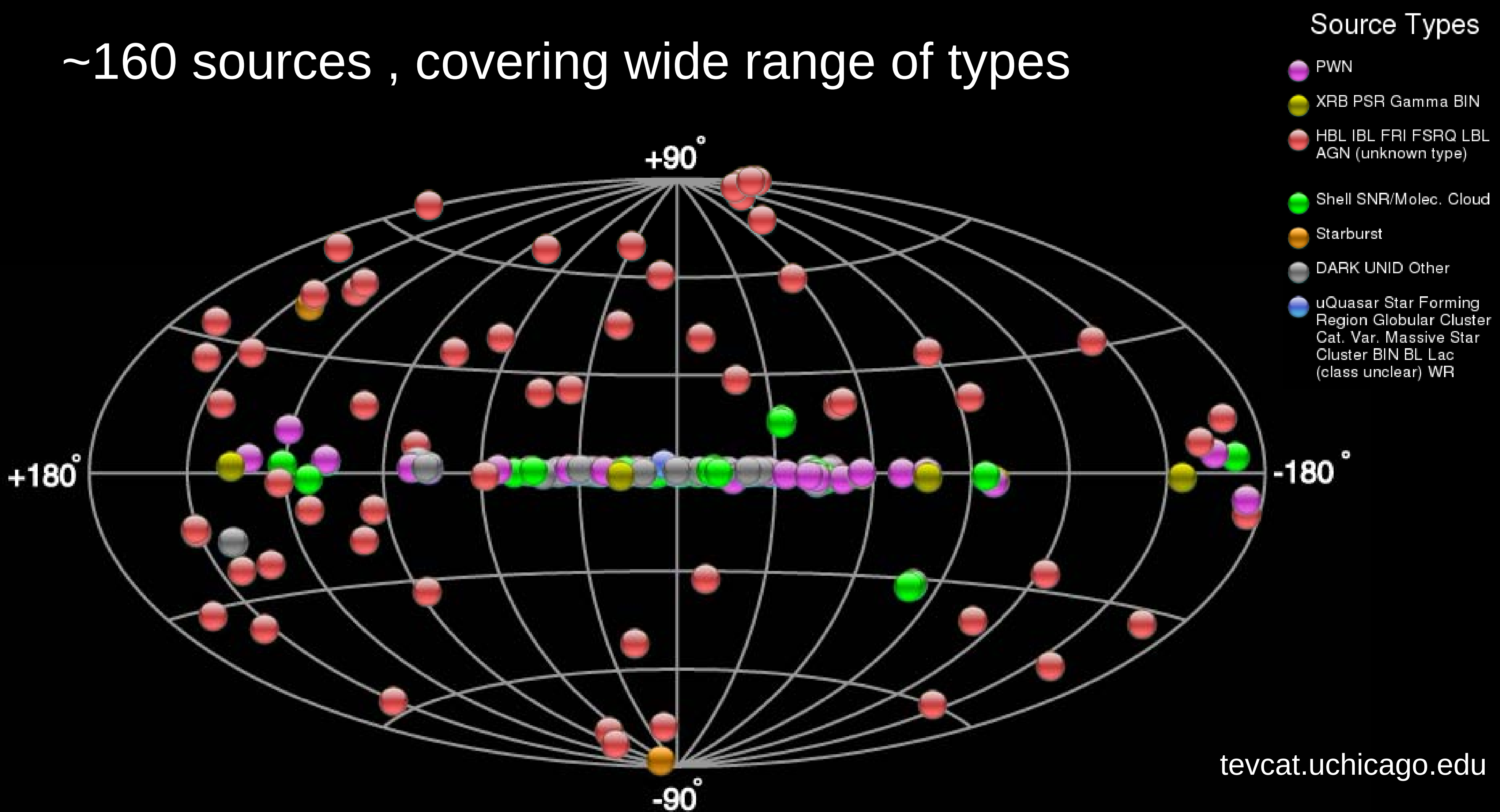
VHE γ-ray Sky c2005

13 sources



VHE γ-ray Sky c2016

~160 sources , covering wide range of types

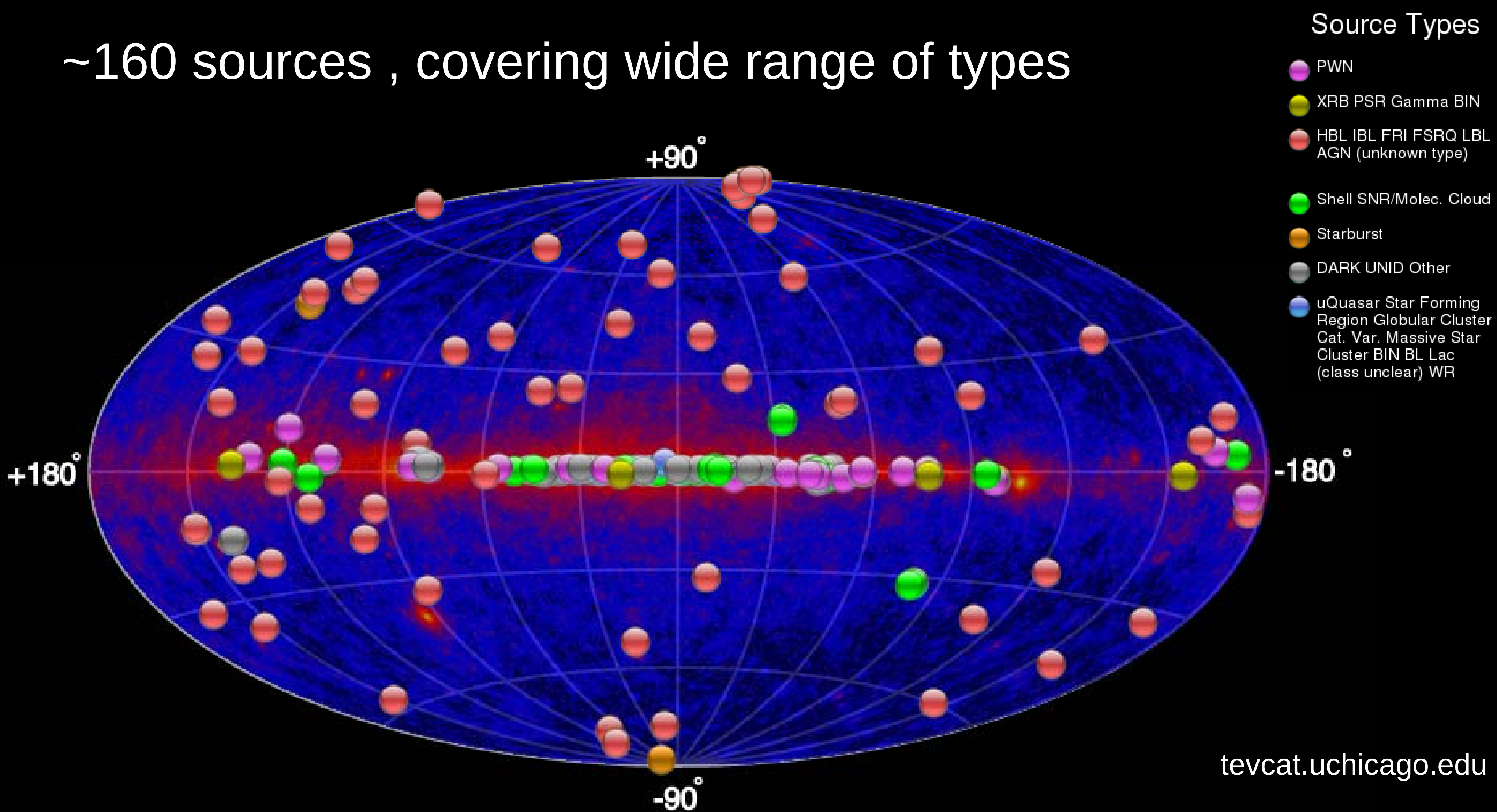


tevcat.uchicago.edu

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

TeV + GeV γ-ray Sky c2015

~160 sources , covering wide range of types

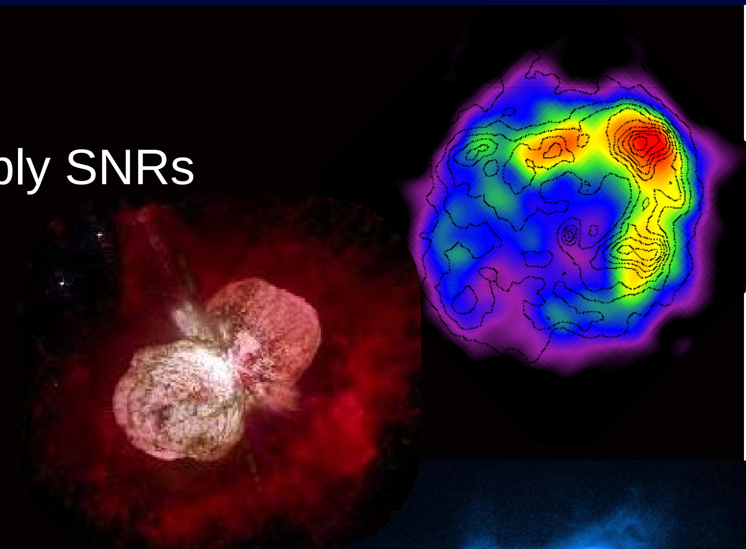


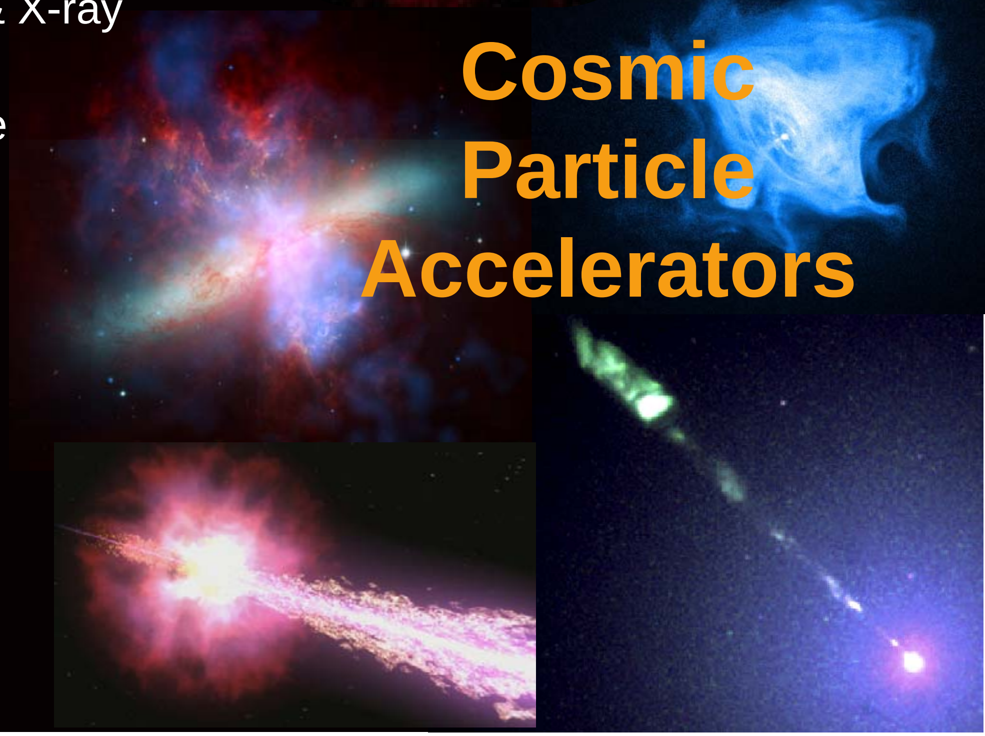
tevcat.uchicago.edu

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

VHE Astronomy Comes of Age

- Dominant expectation (pre-1990)
  - Will find the "cosmic ray" accelerators – probably SNRs
- Reality (~2016)
  - 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





*0.05-50 TeV

Three Selected Science Topics

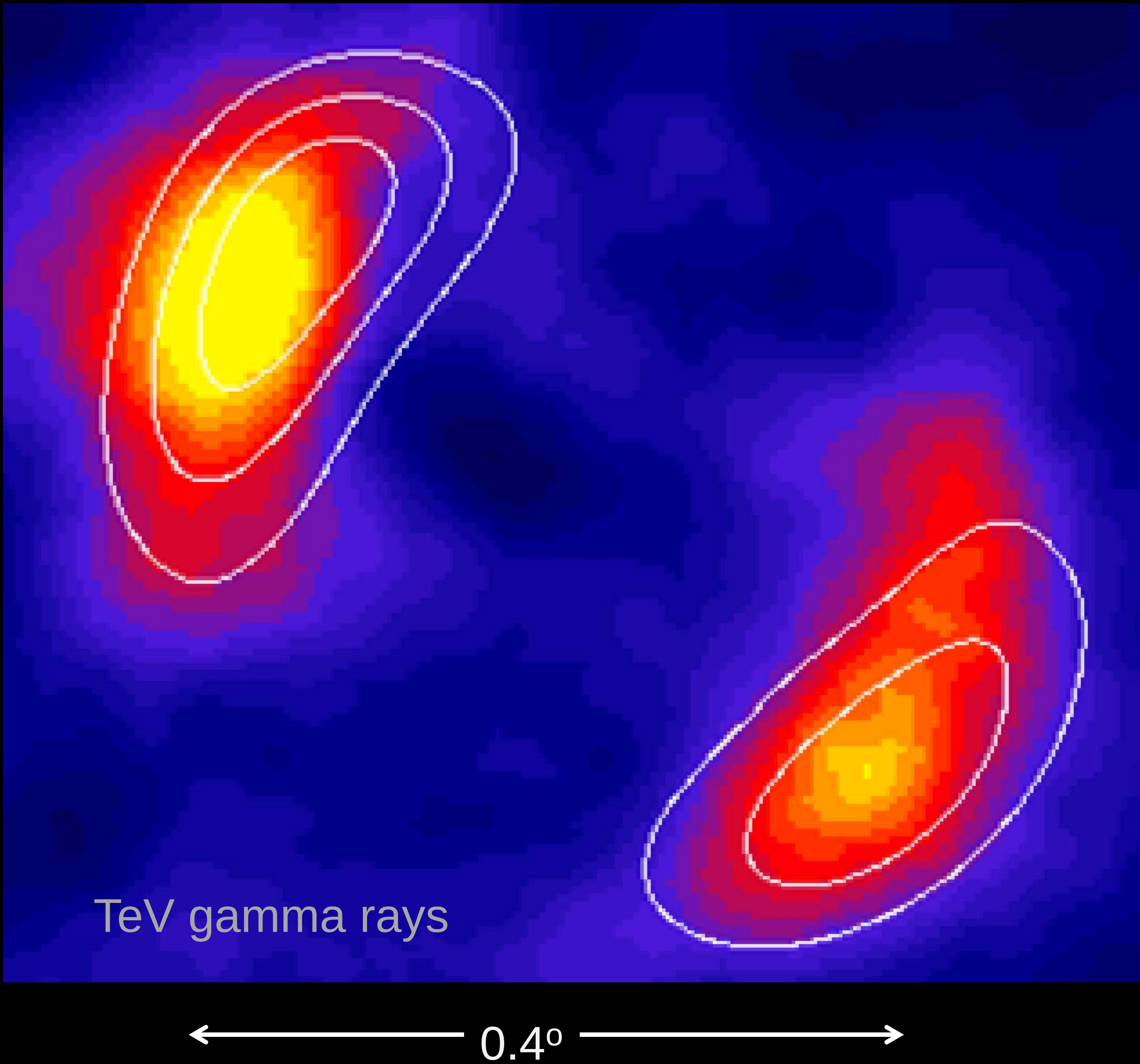
- Supernova remnants & origin of cosmic rays
- AGN and intergalactic radiation fields
- Galactic Center & Dark Matter

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)



Supernova Remnants (SNRs)

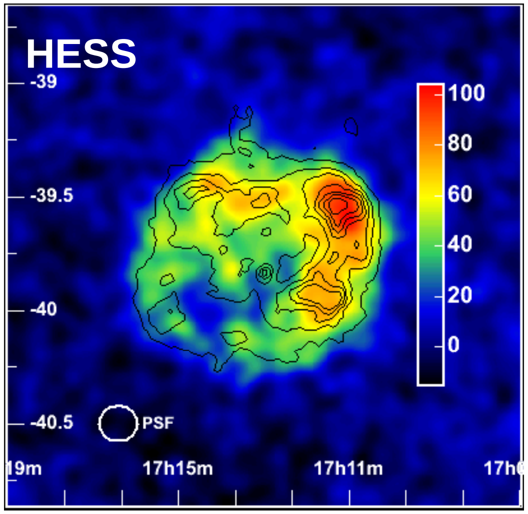
"Standard Model" for high-energy cosmic rays

- 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%.

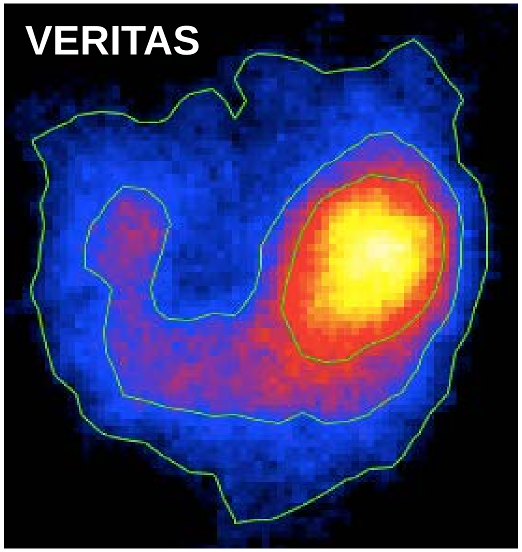
Good model … is it right ?

CTA will:

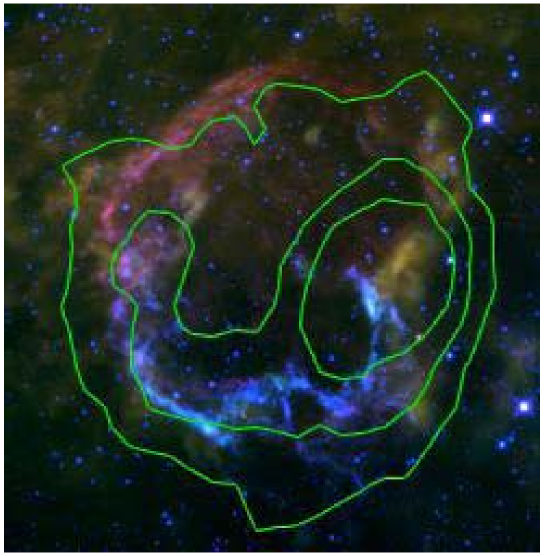
- discover many SNRs, including perhaps a few PeVatrons, and
- characterize them (morphology, SED, etc.) much better than present-day instruments.



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

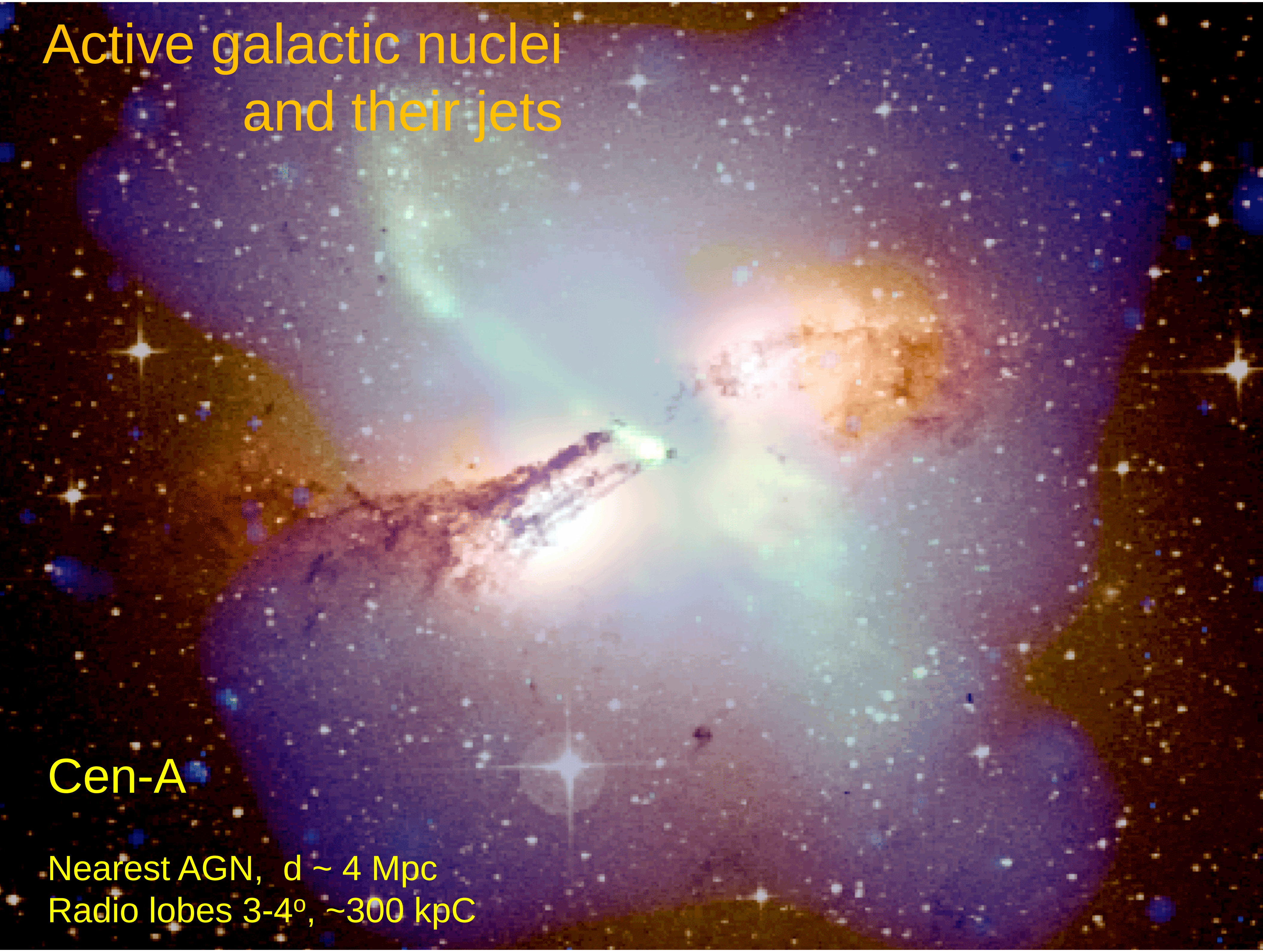


IC 443
Age ~ 30ky
D ~ 0.8kpc



IC 443
***WISE* – 22, 12, 4.6 μm**

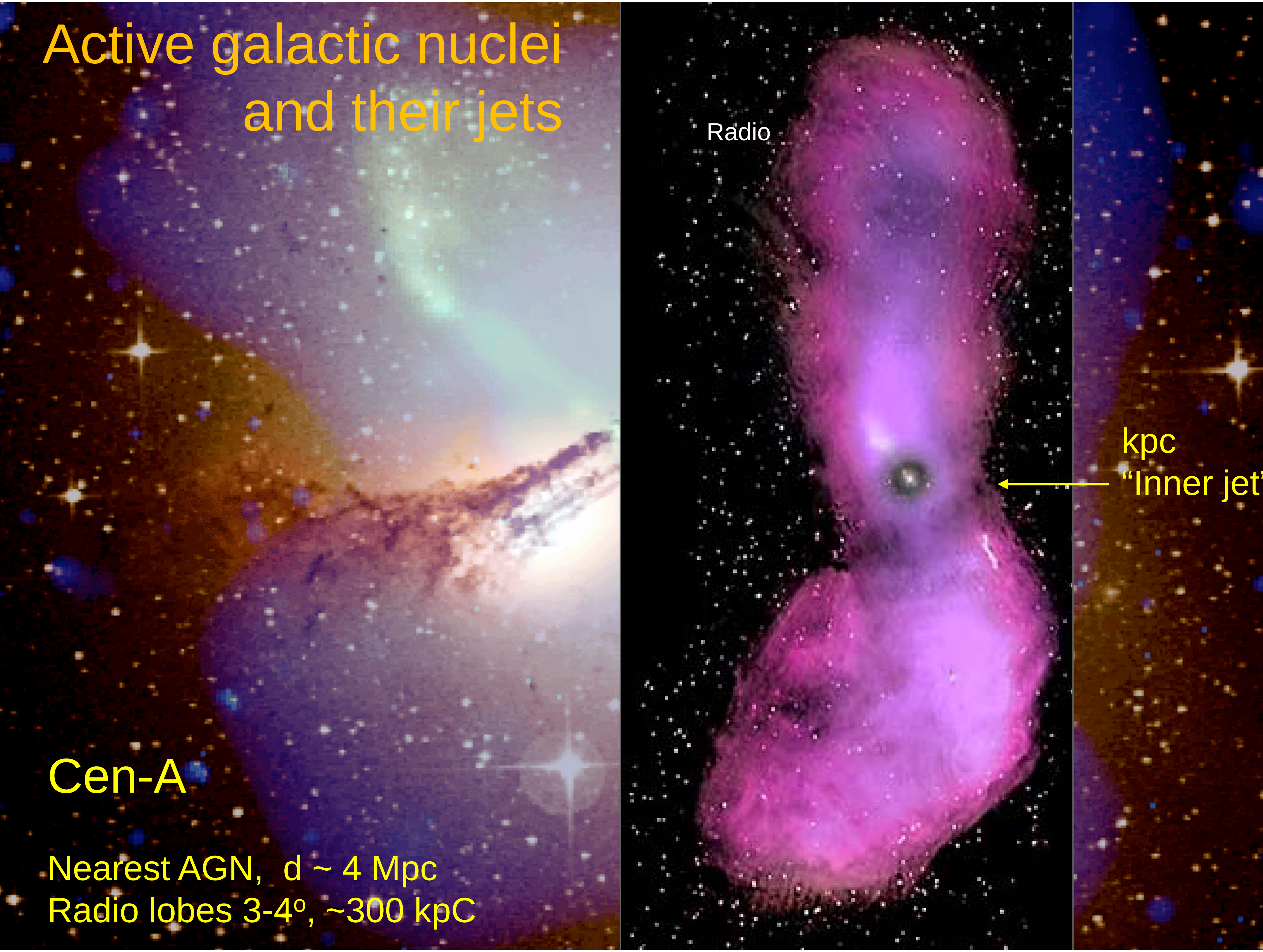
Active galactic nuclei and their jets



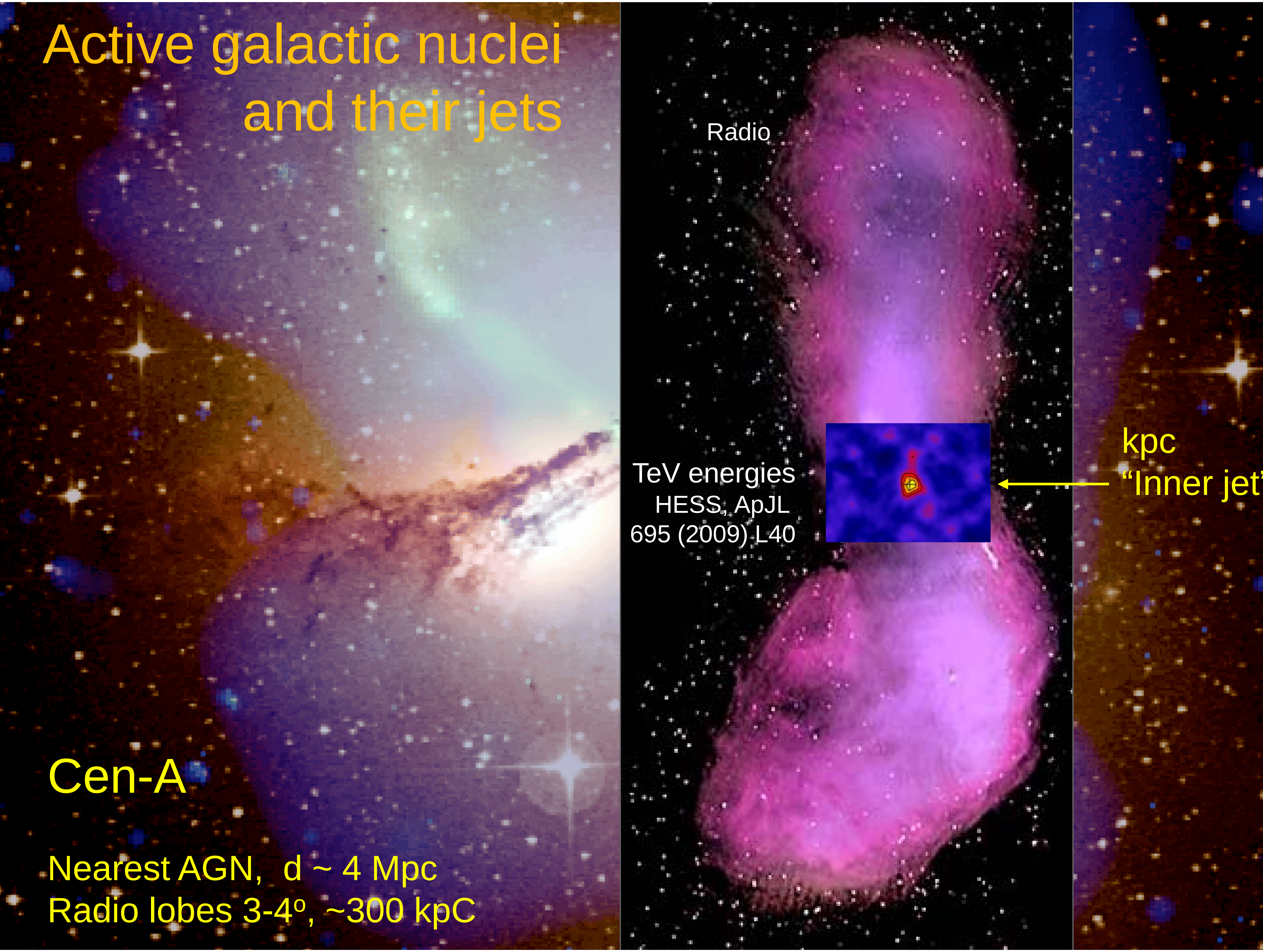
Cen-A

Nearest AGN, d ~ 4 Mpc
Radio lobes 3-4^{o}, ~300 kpC

Active galactic nuclei and their jets



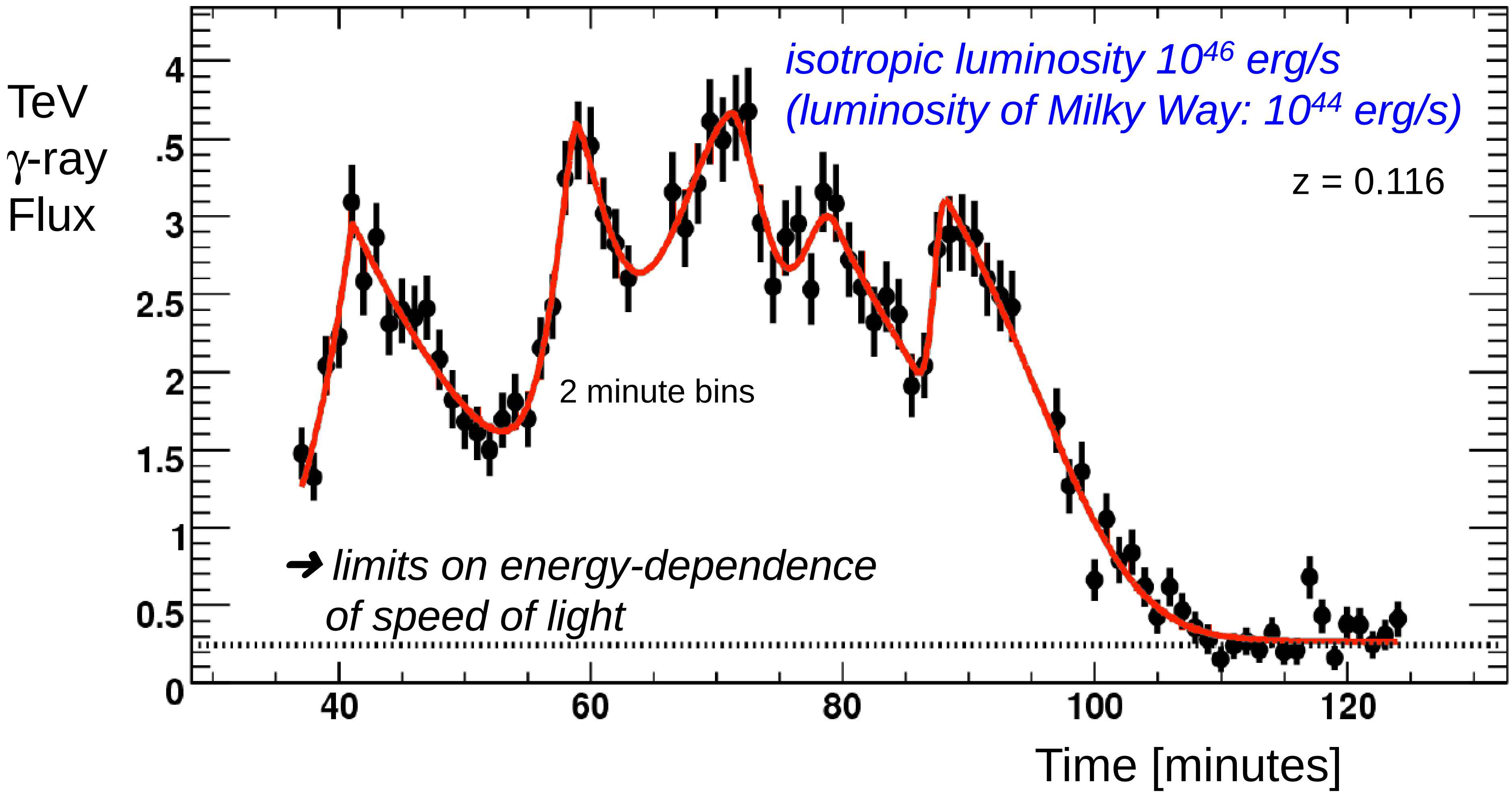
Active galactic nuclei and their jets



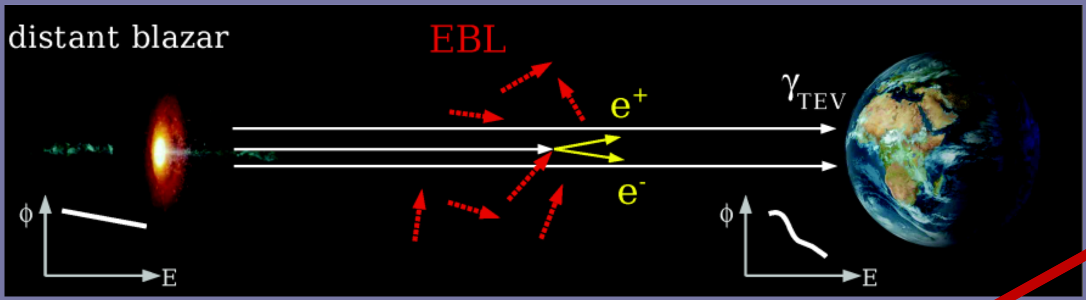
AGN: Extreme Variability

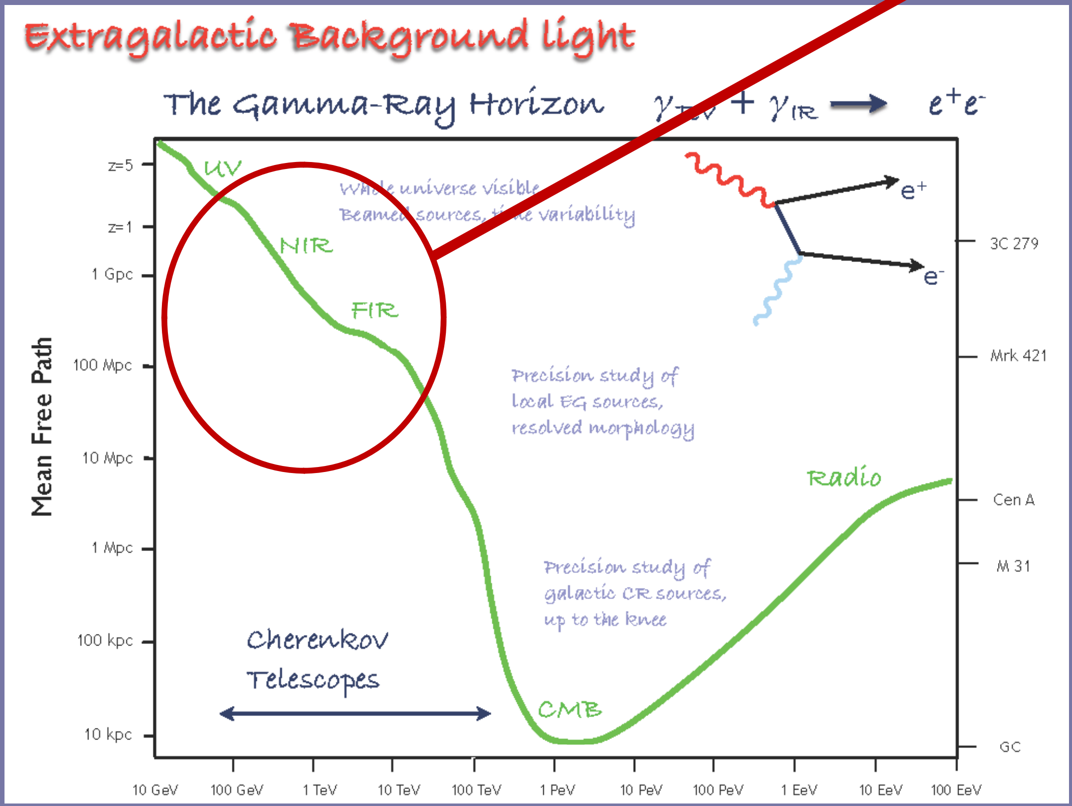
"Blazars": AGN with jets pointed towards us
strong VHE emitters

PKS 2155-304 flare
arXiv:0706.0797



VHE γ-rays as Cosmological Probes





1 TeV **1 PeV** Energy

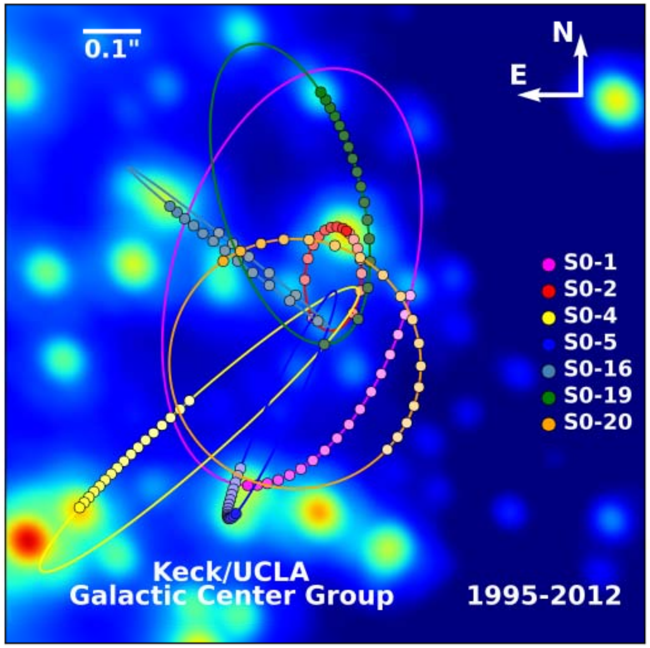
Extragalactic Background Light (EBL):

- OIR diffuse background produced by star-formation throughout history of universe.
- γγ interaction probes EBL density, uniformity, evolution.
- A way to measure/constrain tiny intergalactic magnetic field (IGMF):

$B \sim 10^{-10} - 10^{-18}$ G

Galactic Center

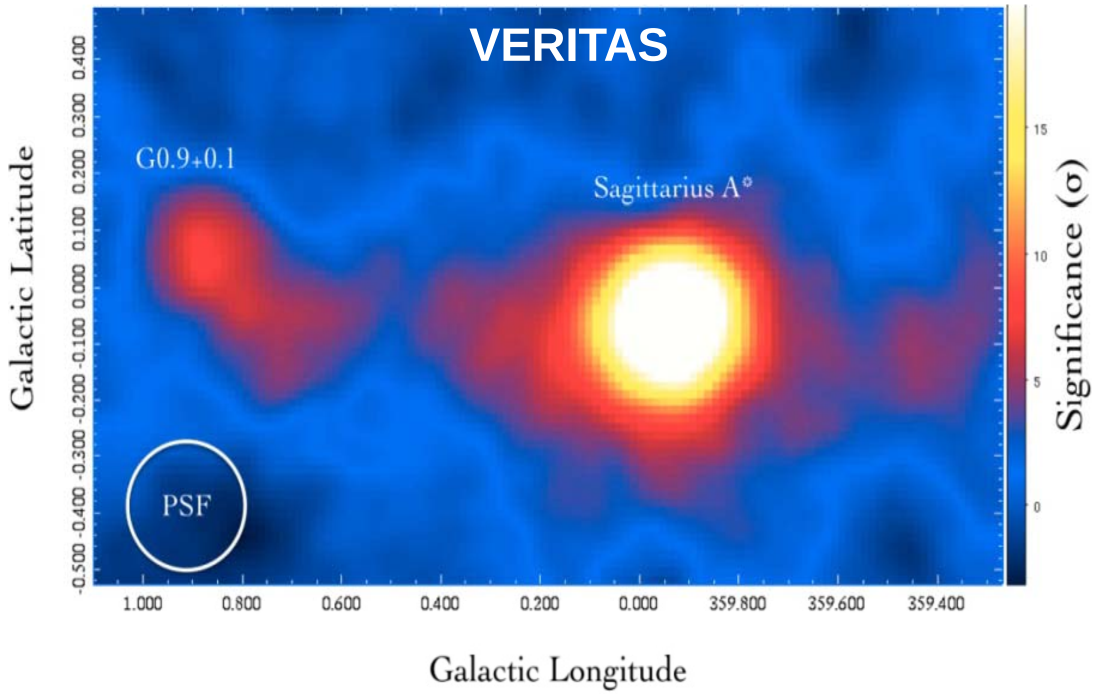
Infrared



Ghez et al., 2012
1″ x 1″

TeV γ-rays

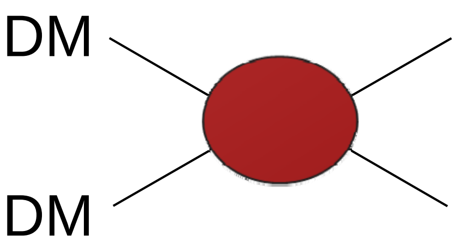
A, Archer et al.
VERITAS Coll.
(2015)



GeV & TeV emission is:

- intense & non-thermal
- totally unexpected
- not understood !

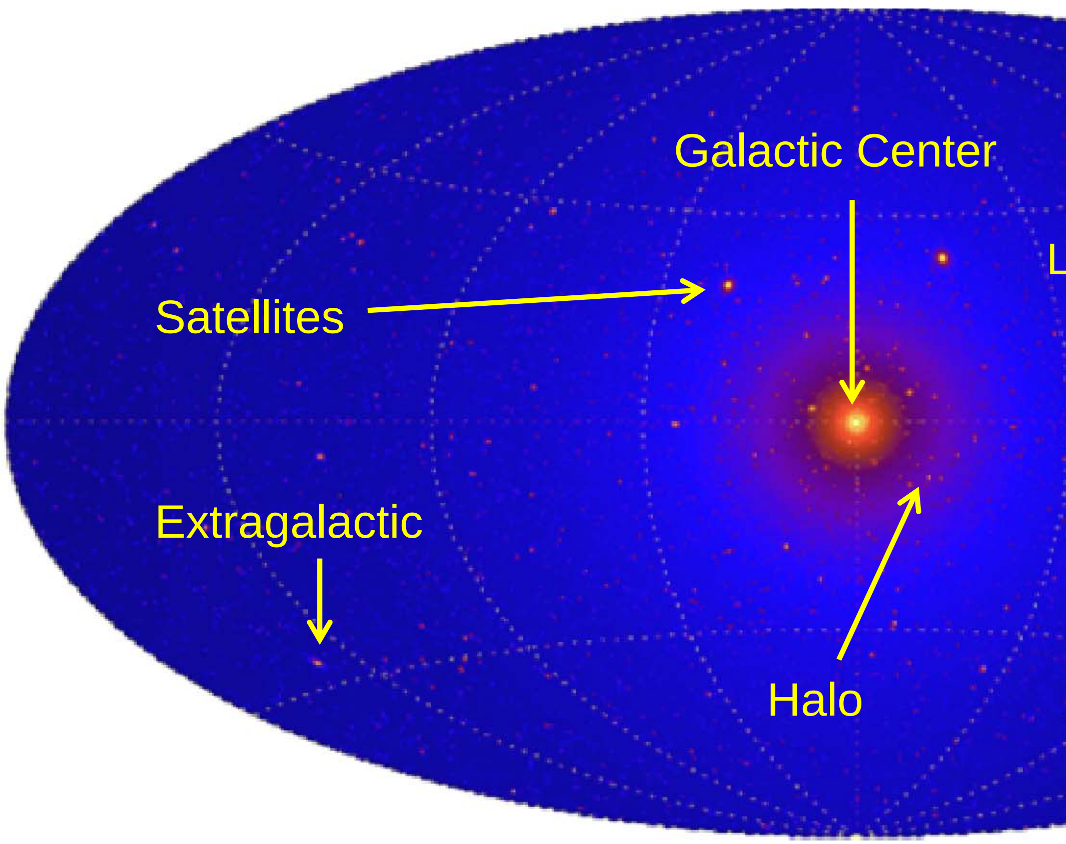
Dark Matter Detection



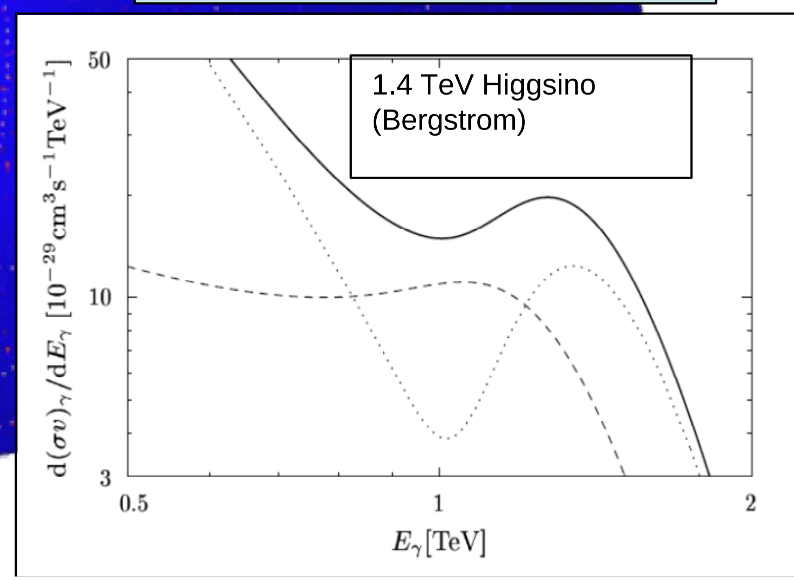
SM: b, W^+, Z, τ^+, …
Primary channels
SM: $\bar{b}$, W^-, Z, τ^-, …

Hadronisation and/or decay

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



"Universal" Spectrum

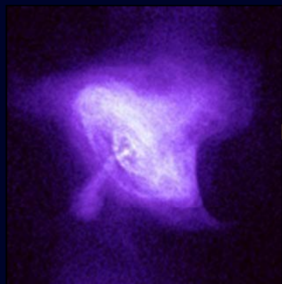


Ultimate goal: Dark Matter Astronomy

Exploring the non-thermal Universe "ASTRO"

Pulsars/PWN

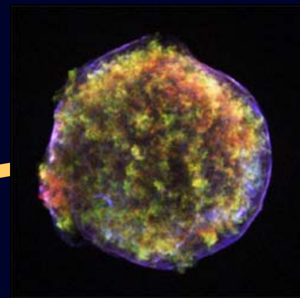
NS dynamo winds



Binaries

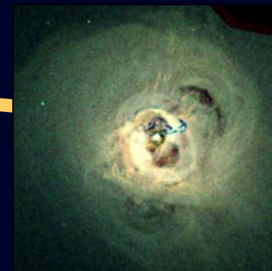
Jets, winds

SNRs



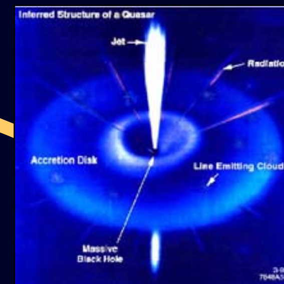
Shocks
Fermi Mech.

Starbursts



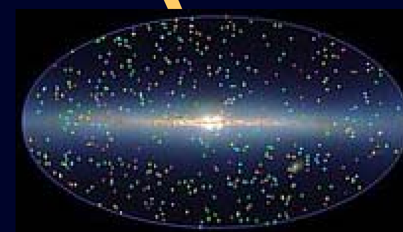
SN activity
Cosmic rays

AGN

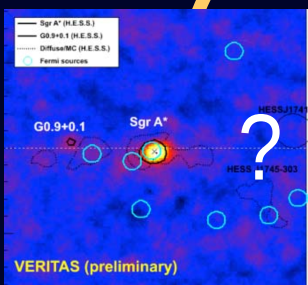


SMBH accretion, jets

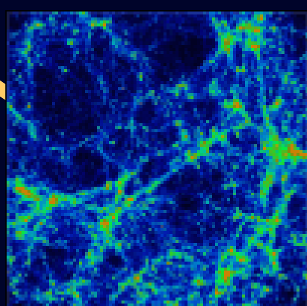
GRBs



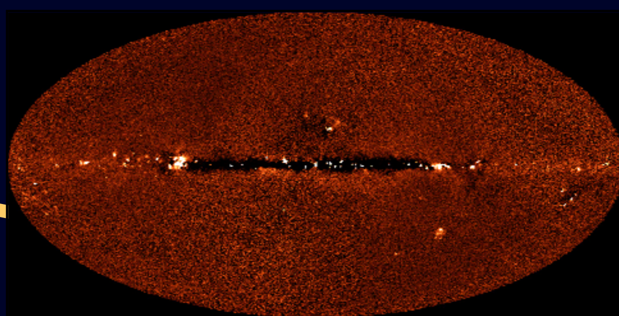
VHE γ-rays



Unknowns
(Gal Center)



Dark Matter



Cosmological Fields

PBHs, QGrav

Probing New Physics at GeV/TeV scale "PARTICLE"

Summary of Key Science Questions

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

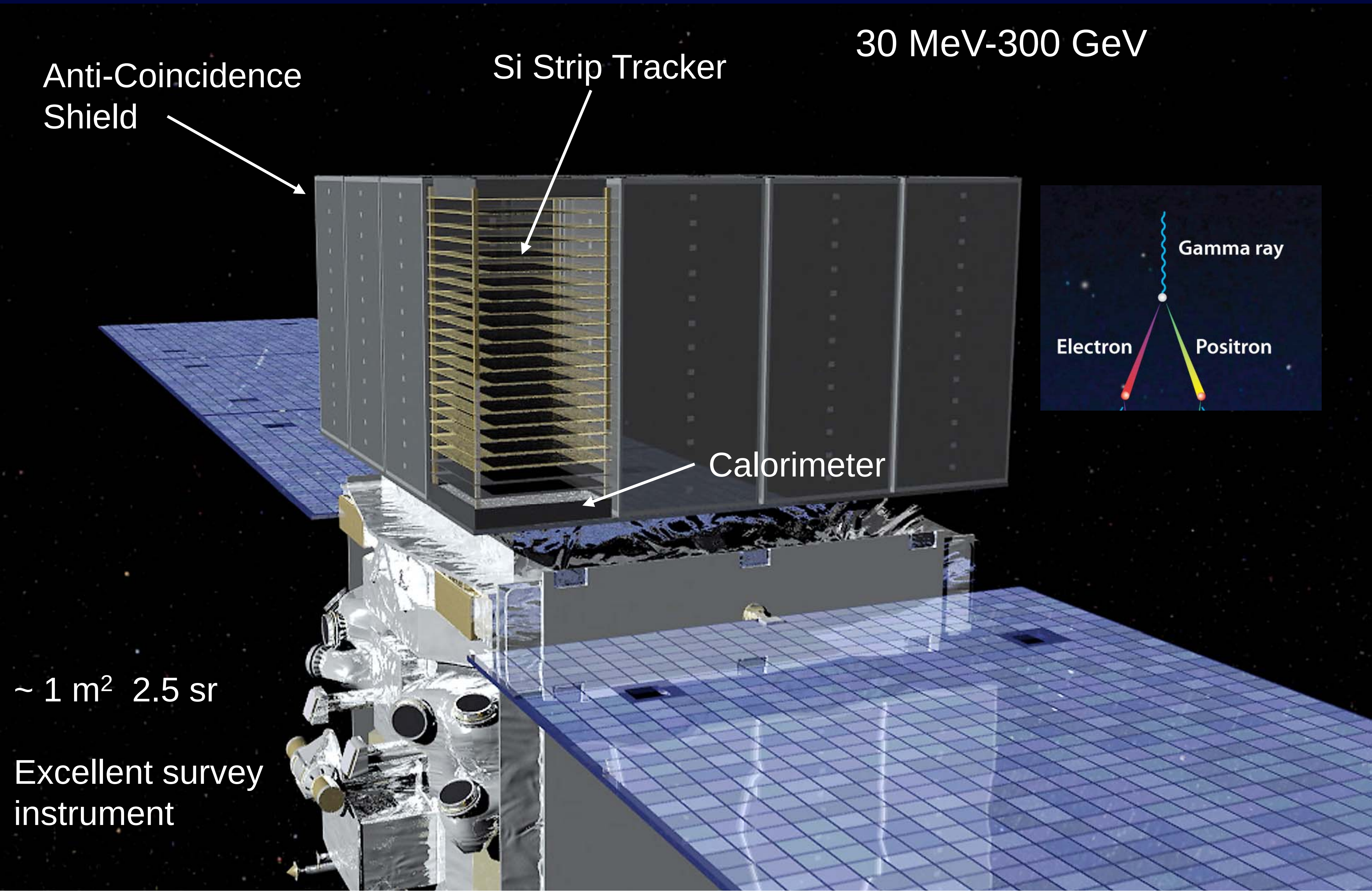
1. How are the bulk of cosmic ray particles accelerated in our Galaxy and beyond? (one of the oldest surviving questions of astrophysics)
2. Can we understand the physics of jets, shocks & winds in the variety of sources we see, including pulsars, binaries, AGN, starbursts, and GRBs?
3. How do black 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 unexpected phenomena will be revealed by exploring the non-thermal Universe?

Bonus science: optical interferometry, cosmic-ray physics, OSETI, etc.

Experimental Technique
&
Planning for the Future

Fermi Large Area Telescope (LAT)

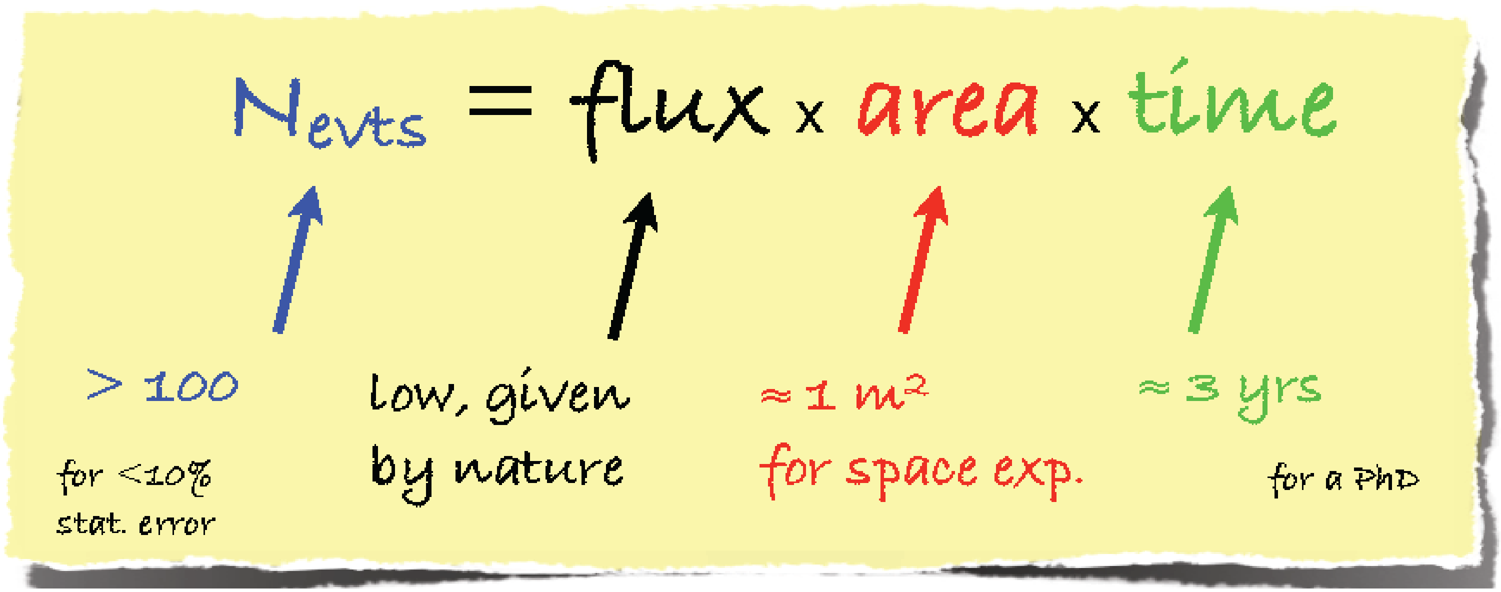
30 MeV-300 GeV



~ 1 m^2 2.5 sr

Excellent survey instrument

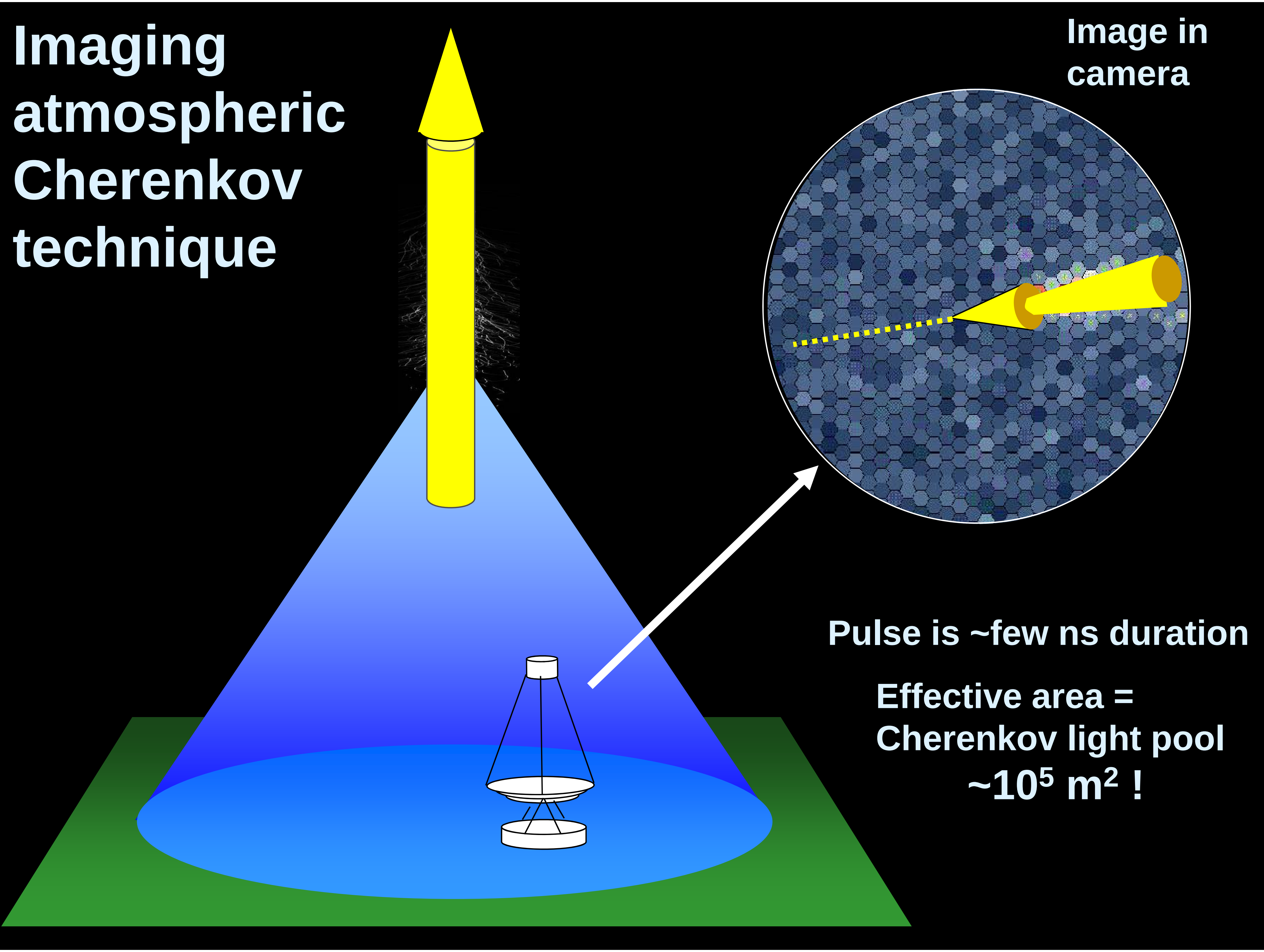
Beyond 100 GeV



Steeply falling spectrum:

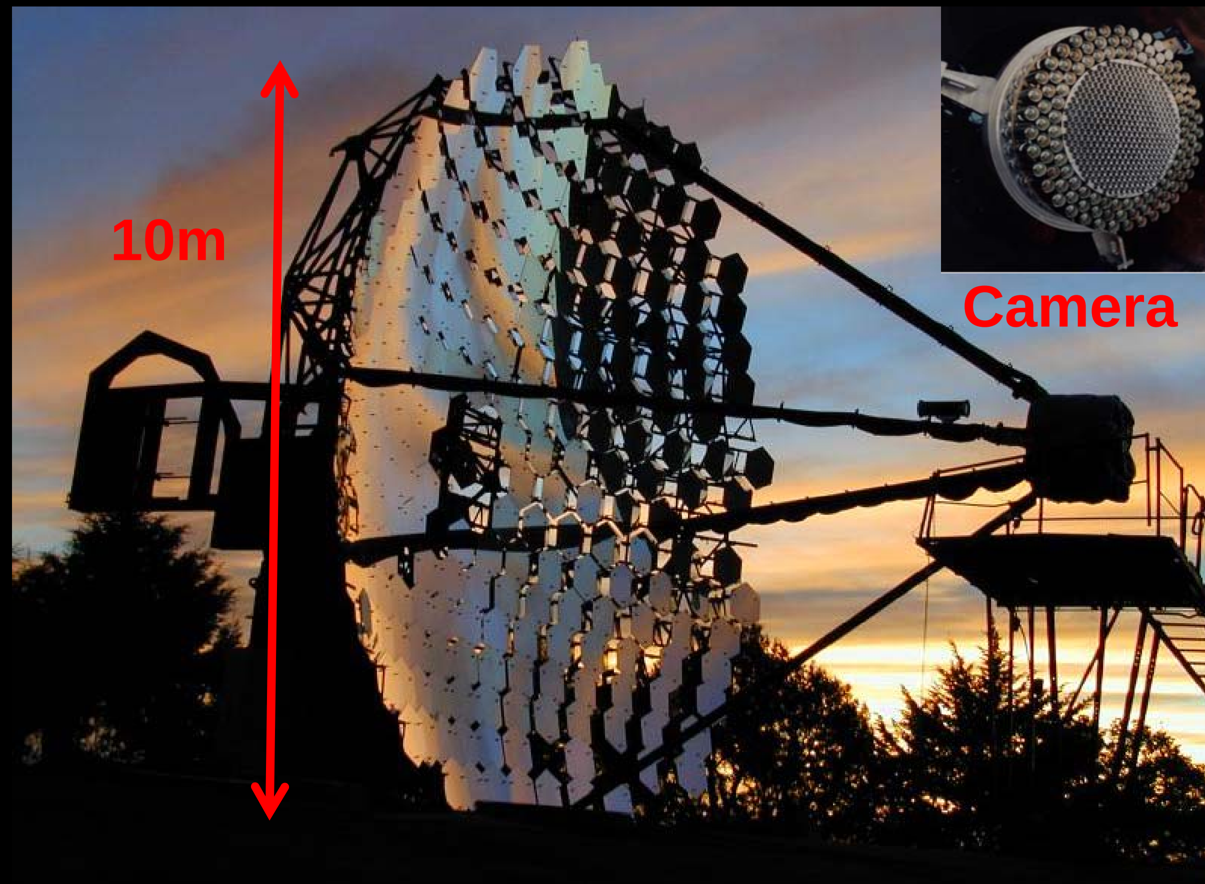
x10 in Energy → divide by 100-500 in flux

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

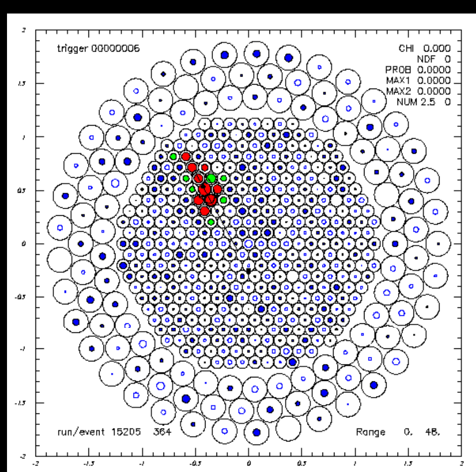

Imaging atmospheric Cherenkov technique
Image in camera
Pulse is ~few ns duration
Effective area = Cherenkov light pool
~10^5 m^2 !

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

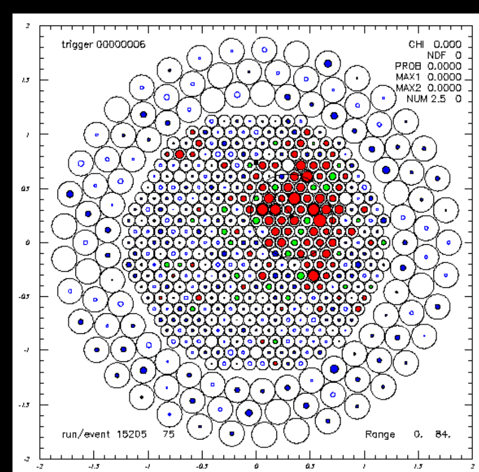
- Pioneered use of Imaging
- Made first source detection.
  (Crab Nebula in ~90 hours)



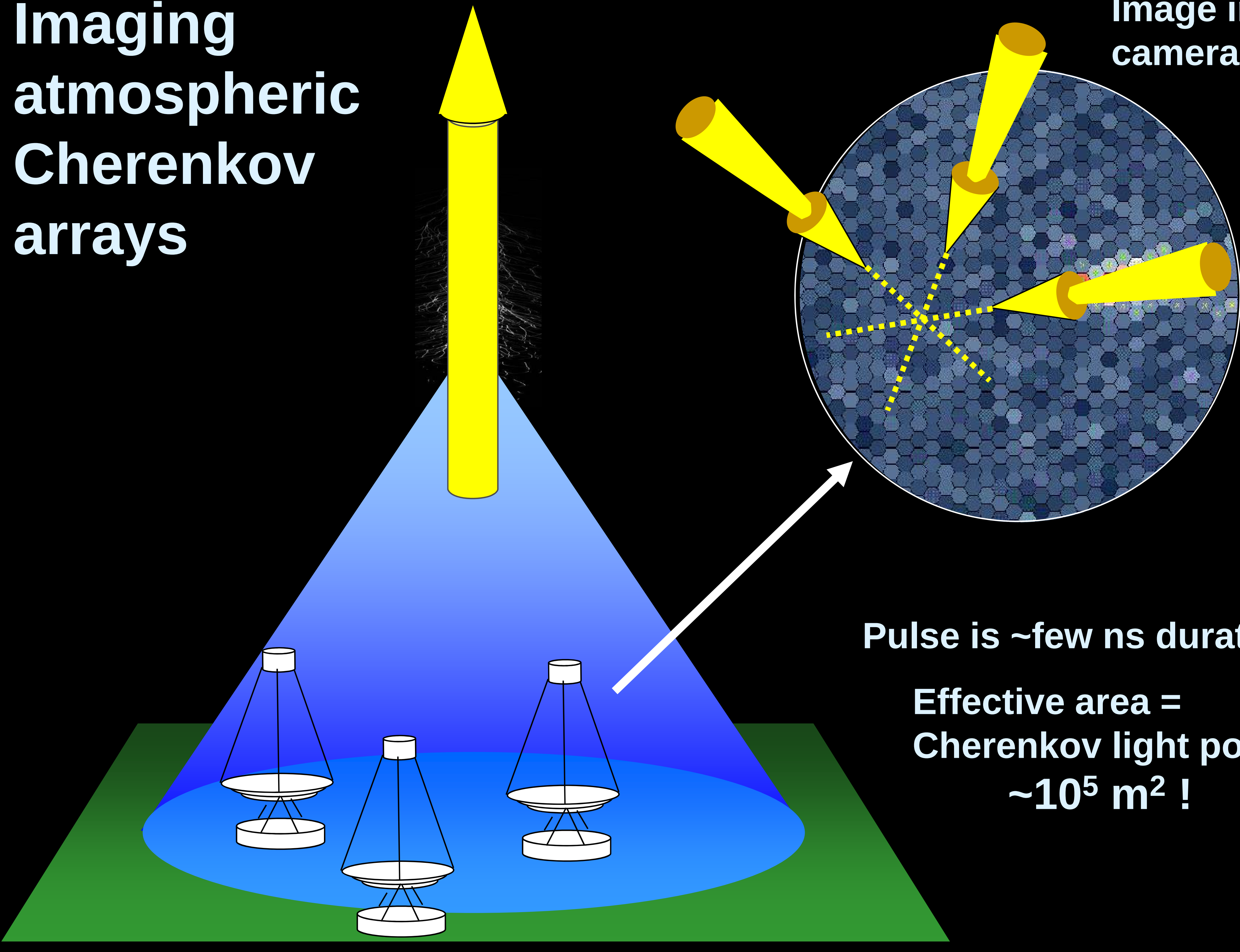
γ-ray



cosmic ray



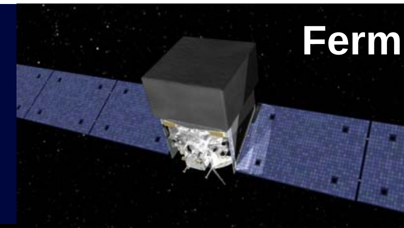
Imaging atmospheric Cherenkov arrays

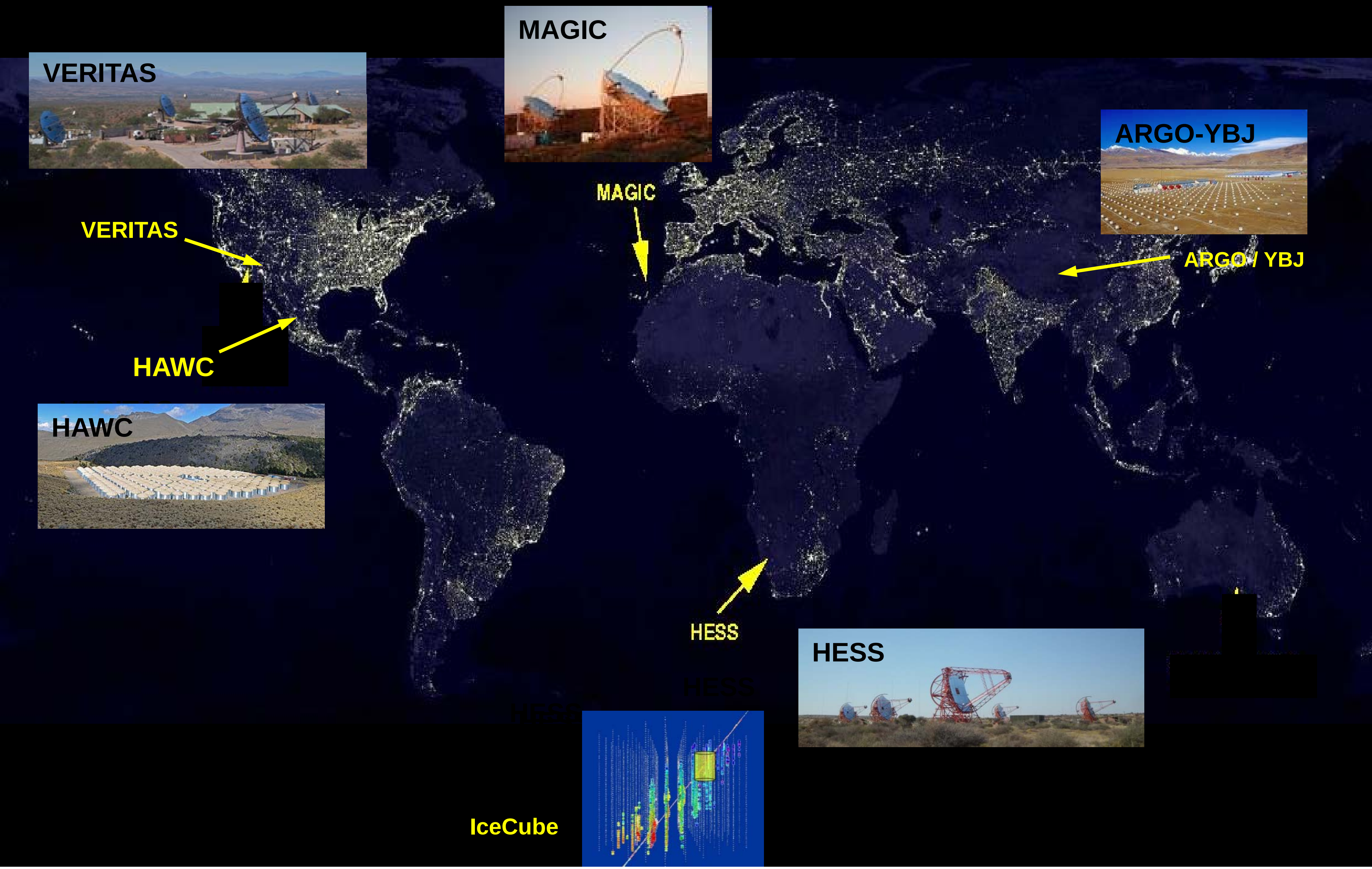


Pulse is ~few ns duration

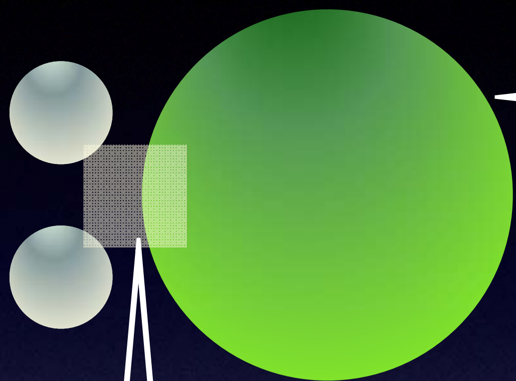
Effective area = Cherenkov light pool $\sim 10^5$ m^2 !

VHE Telescopes (2016)



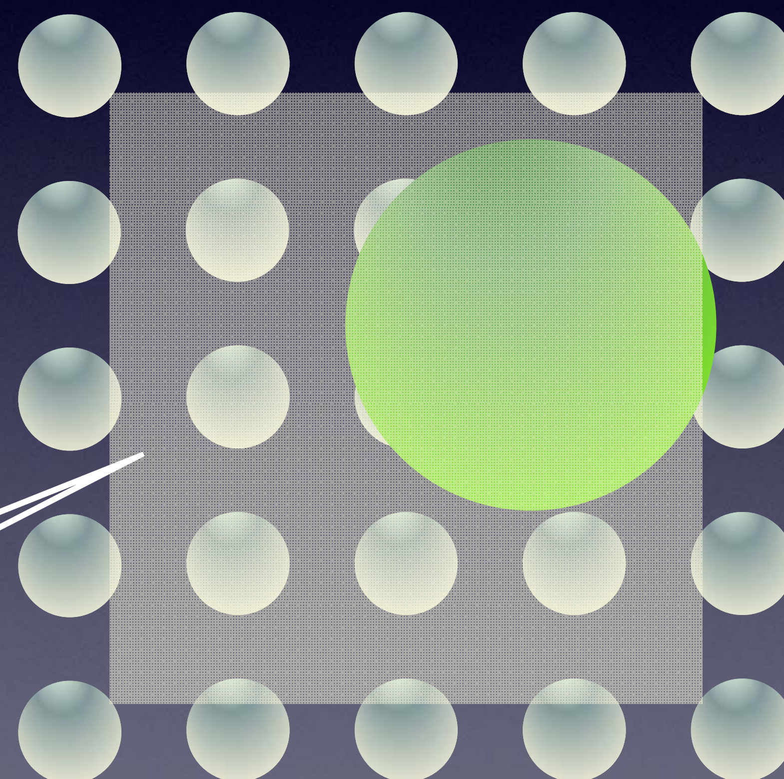


From current arrays to CTA



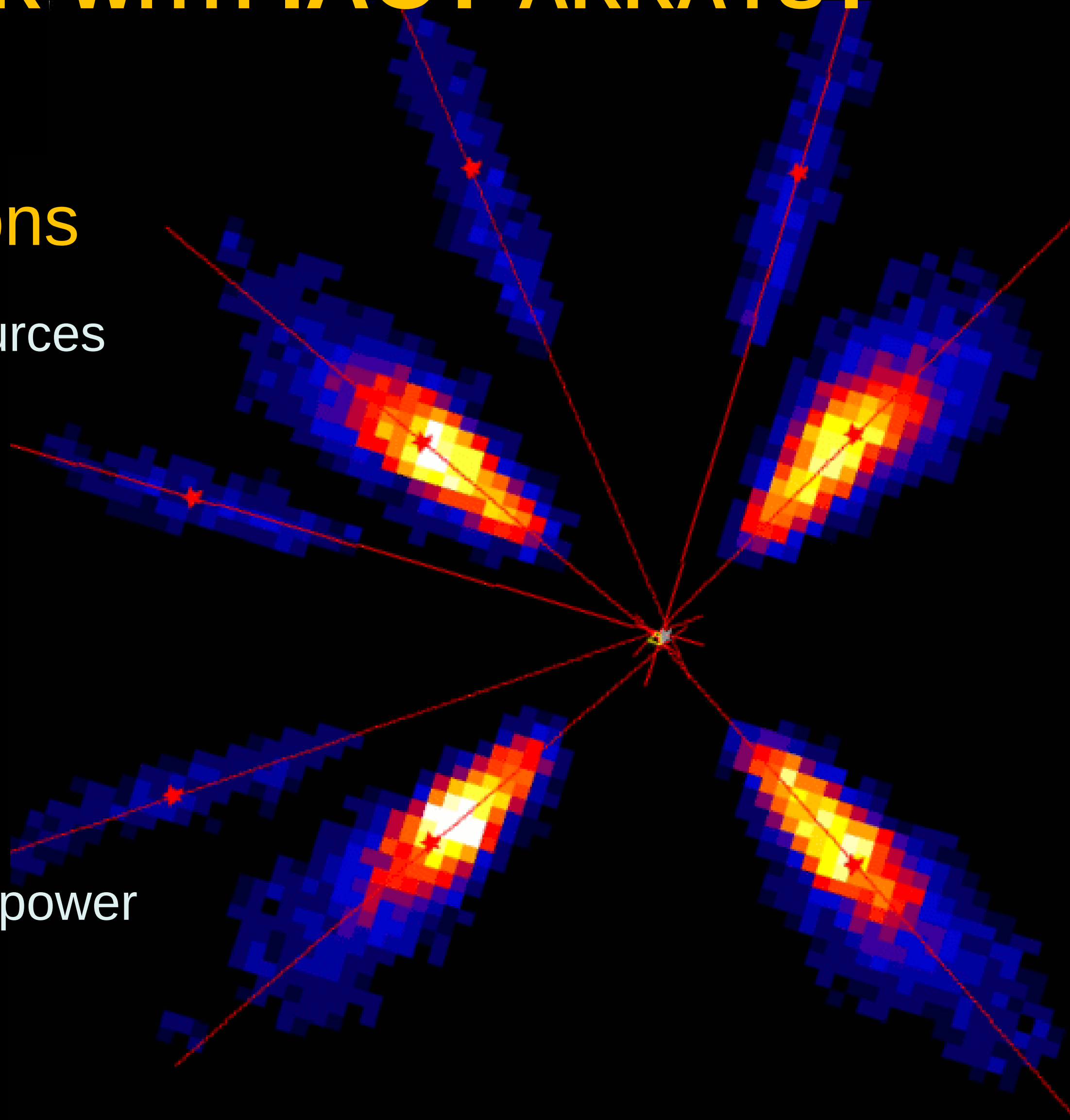
Light pool radius
R ≈ 100-150m
≈ typical telescope Spacing

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



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

How to do better with IACT arrays?



- ➡ More events, more photons
  - Better spectra, images, fainter sources
    - ✓Larger light collecting area
    - ✓Better reconstructed events
  - Better measurement of air shower and hence primary gammas
    - ✓Improved angular resolution
    - ✓Improved background rejection power
- ➡ More telescopes!

Simulation:
Superimposed images from 8 cameras

Planning for the Future

What we know, based on H.E.S.S., MAGIC, VERITAS:

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

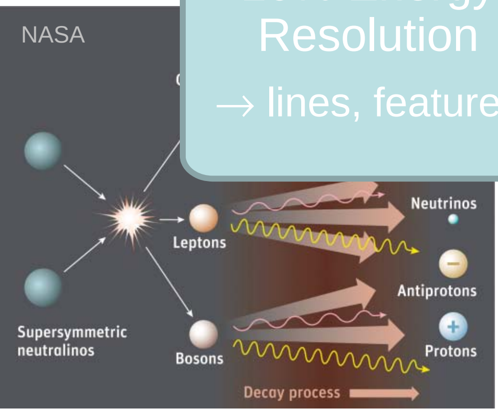
- *Open data/access, MWL connections to get the best science*

International Partnerships required by scale/scope

- *Project must develop the instrument and the observatory*


cta
cherenkov telescope array

Science Drivers

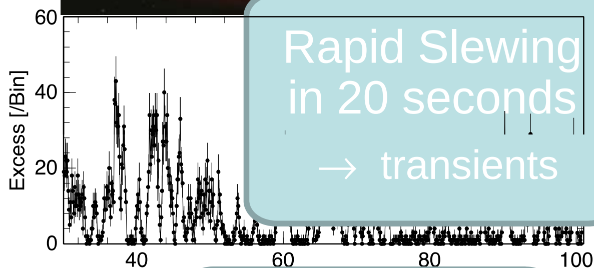


10% Energy Resolution

→ lines, features

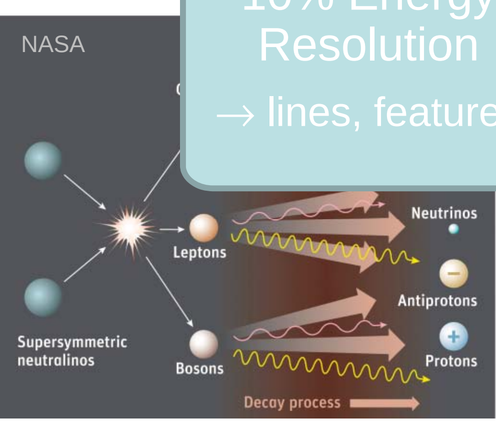
Science Drivers

Science Drivers



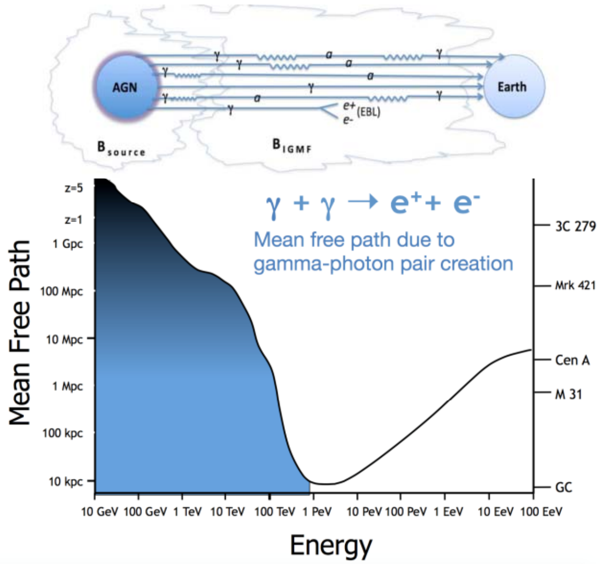
Rapid Slewing in 20 seconds

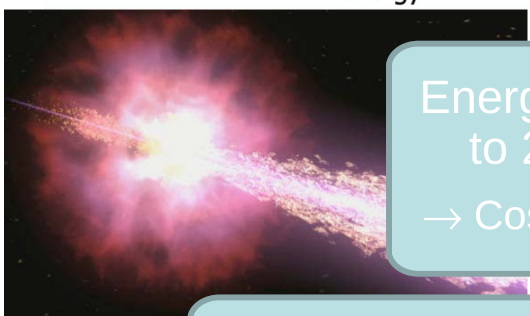
→ transients

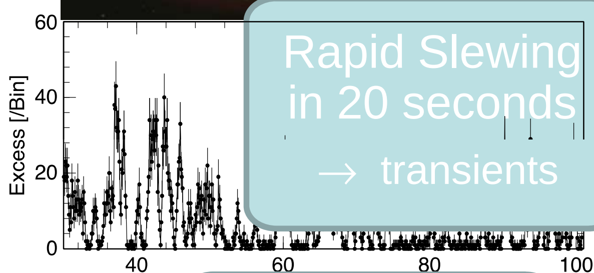


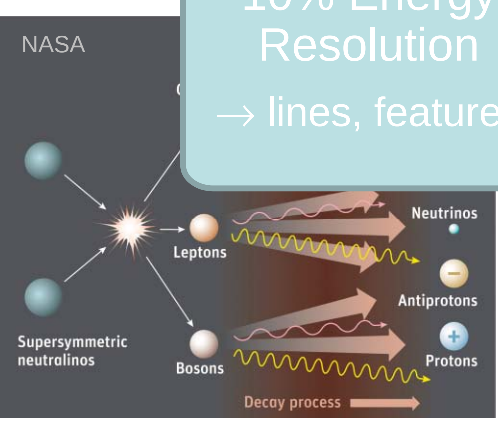
10% Energy Resolution

→ lines, features









Energies down to 20 GeV

→ Cosmology++

Rapid Slewing in 20 seconds

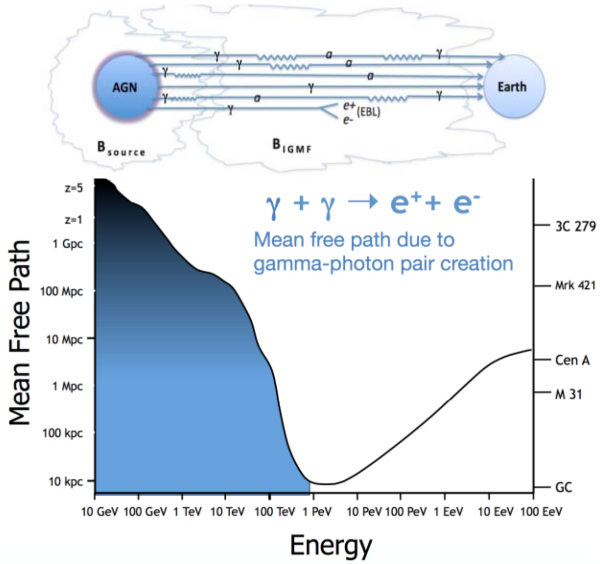
→ transients

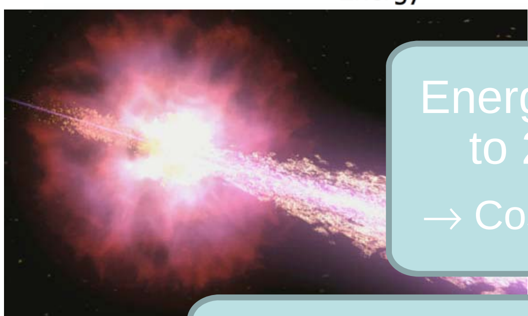
10% Energy Resolution

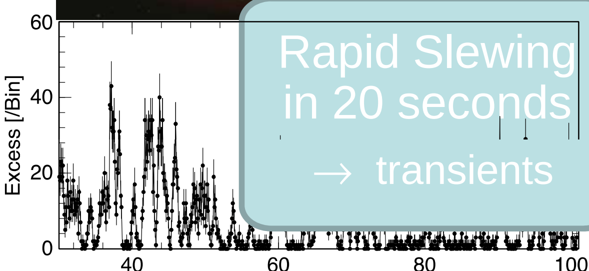
→ lines, features

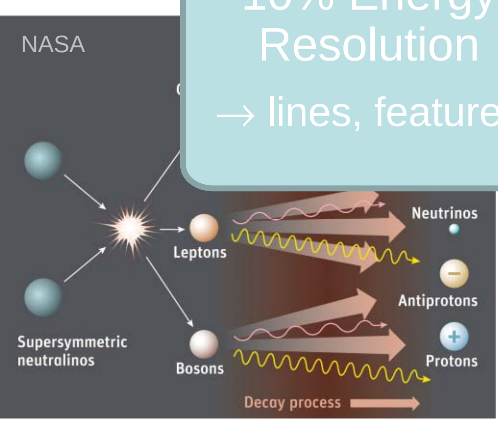
Science Drivers

Science Drivers









Energies down to 20 GeV

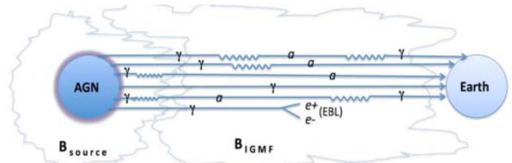
→ Cosmology++

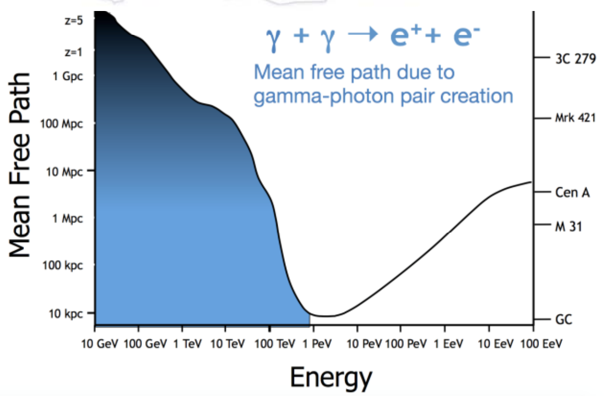
Rapid Slewing in 20 seconds

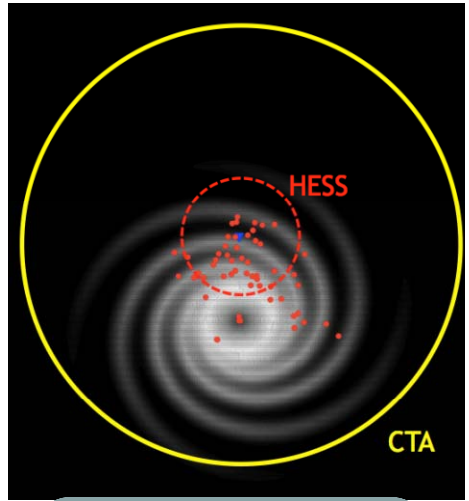
→ transients

10% Energy Resolution

→ lines, features

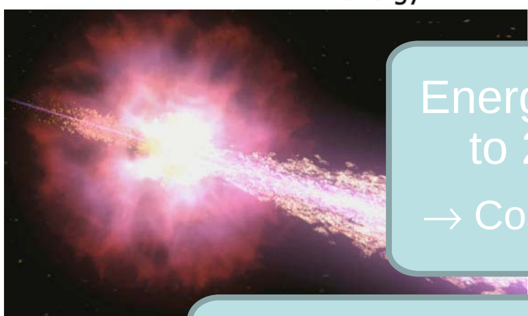






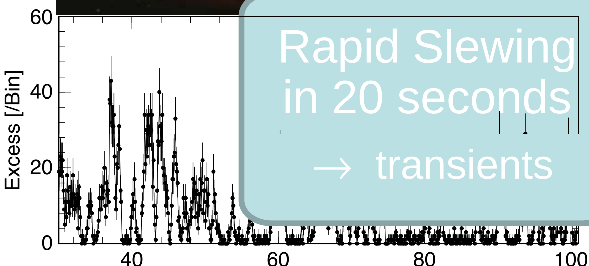
10 x Sensitivity, Large Collection Area

→ all topics



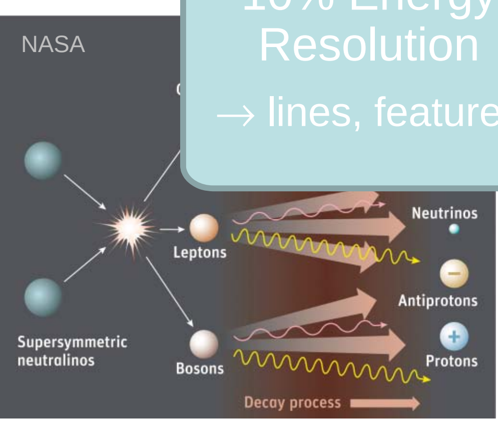
Energies down to 20 GeV

→ Cosmology++



Rapid Slewing in 20 seconds

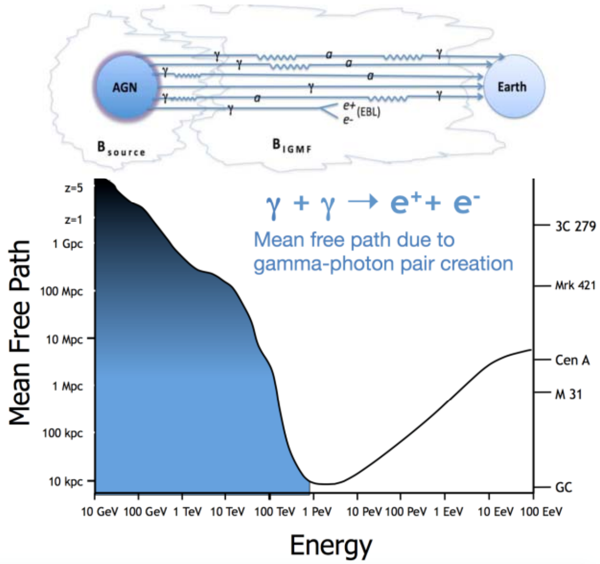
→ transients

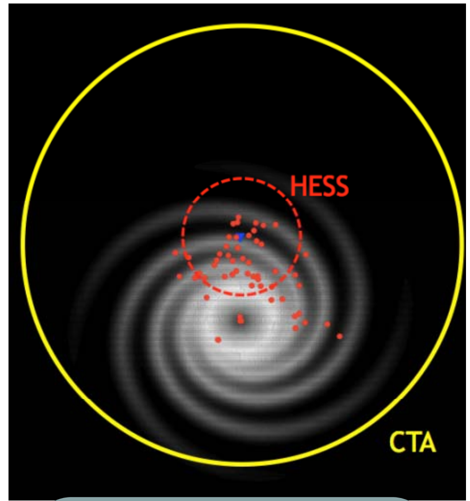


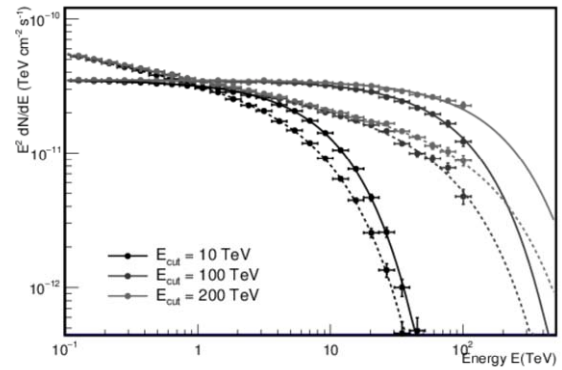
10% Energy Resolution

→ lines, features

Science Drivers







10 x Sensitivity, Large Collection Area

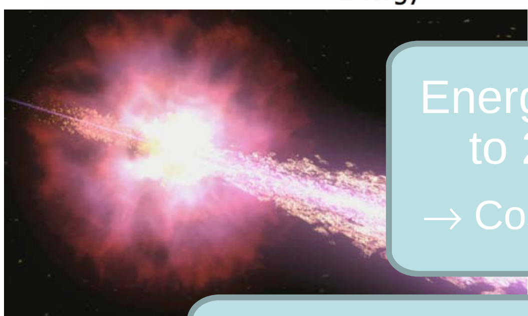
→ all topics

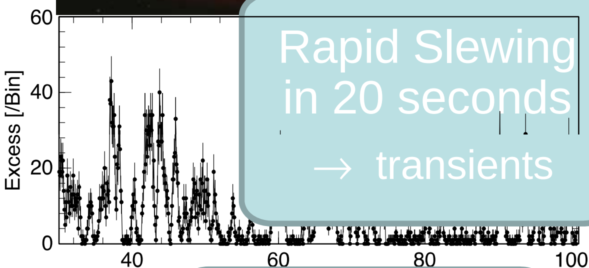
Energies down to 20 GeV

→ Cosmology++

Energies up to 300 TeV

→ Pevatrons



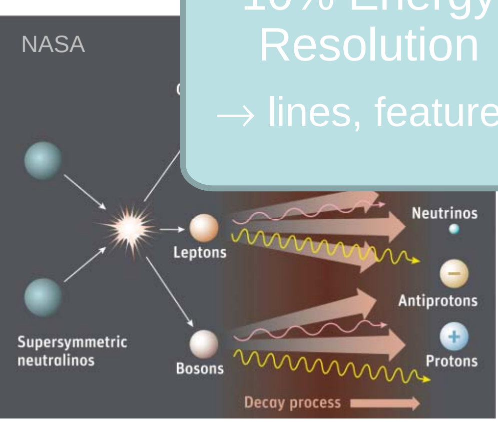


Rapid Slewing in 20 seconds

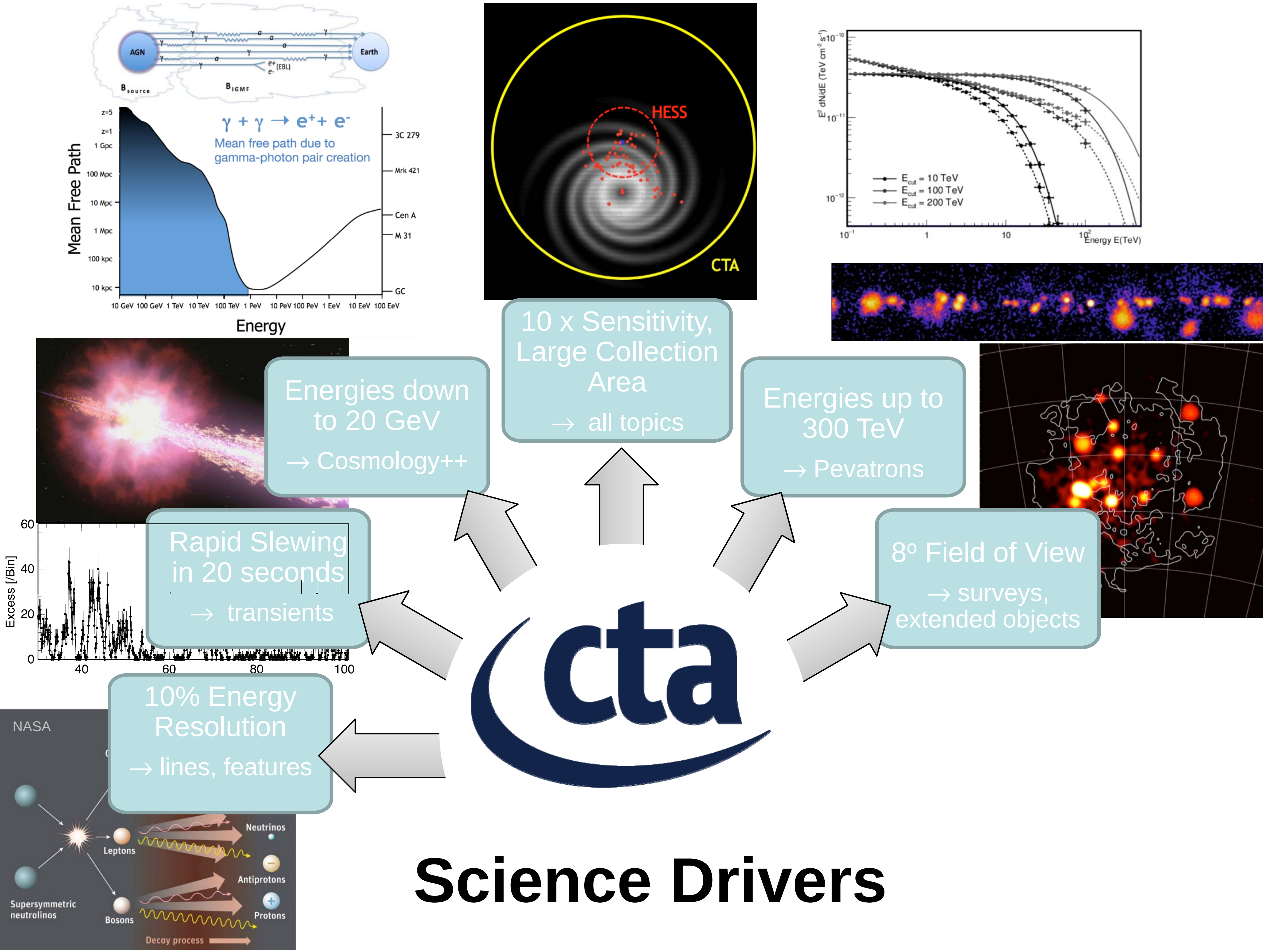
→ transients

10% Energy Resolution

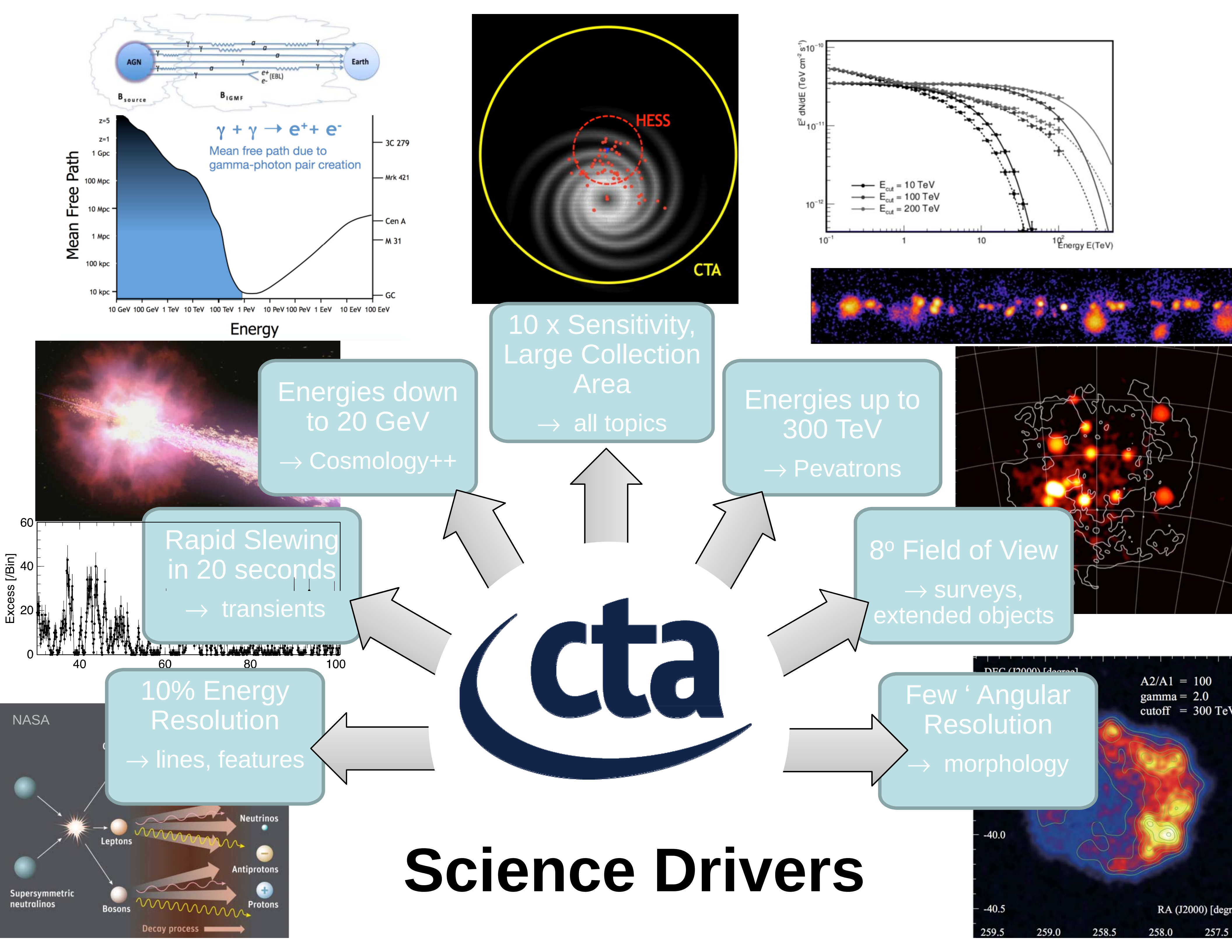
→ lines, features



Science Drivers



AGN
Earth
B source
B IGMF
e+ (EBL)
e-
γ + γ → e⁺+ e⁻
Mean free path due to gamma-photon pair creation
Mean Free Path
Energy
z=5
z=1
1 Gpc
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
10 GeV 100 GeV 1 TeV 10 TeV 100 TeV 1 PeV 10 PeV 100 PeV 1 EeV 10 EeV 100 EeV
3C 279
Mrk 421
Cen A
M 31
GC
HESS
CTA
E_cut = 10 TeV
E_cut = 100 TeV
E_cut = 200 TeV
Energy E(TeV)
10 x Sensitivity, Large Collection Area
→ all topics
Energies down to 20 GeV
→ Cosmology++
Energies up to 300 TeV
→ Pevatrons
Rapid Slewing in 20 seconds
→ transients
Excess [/Bin]
8º Field of View
→ surveys, extended objects
10% Energy Resolution
→ lines, features
NASA
Supersymmetric neutralinos
Leptons
Bosons
Neutrinos
Antiprotons
Protons
Decay process
cta
Science Drivers


Science Drivers
10 x Sensitivity, Large Collection Area
→ all topics
Energies down to 20 GeV
→ Cosmology++
Energies up to 300 TeV
→ Pevatrons
Rapid Slewing in 20 seconds
→ transients
8º Field of View
→ surveys, extended objects
10% Energy Resolution
→ lines, features
Few ' Angular Resolution
→ morphology
cta
AGN
Earth
γ + γ → e⁺+ e⁻
Mean free path due to gamma-photon pair creation
Mean Free Path
Energy
3C 279
Mrk 421
Cen A
M 31
GC
HESS
CTA
Energy E(TeV)
Excess [/Bin]
NASA
Neutrinos
Leptons
Antiprotons
Supersymmetric neutralinos
Bosons
Protons
Decay process
A2/A1 = 100
gamma = 2.0
RA (J2000) [degr

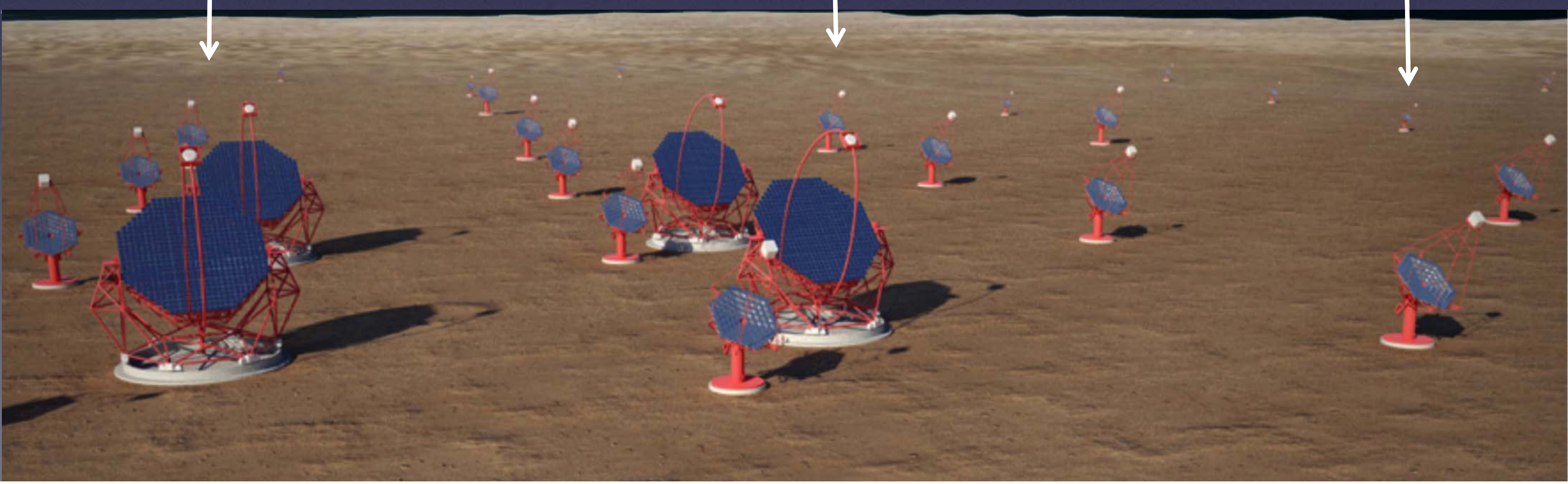
CTA Design (S array)

Science Optimization under budget constraints

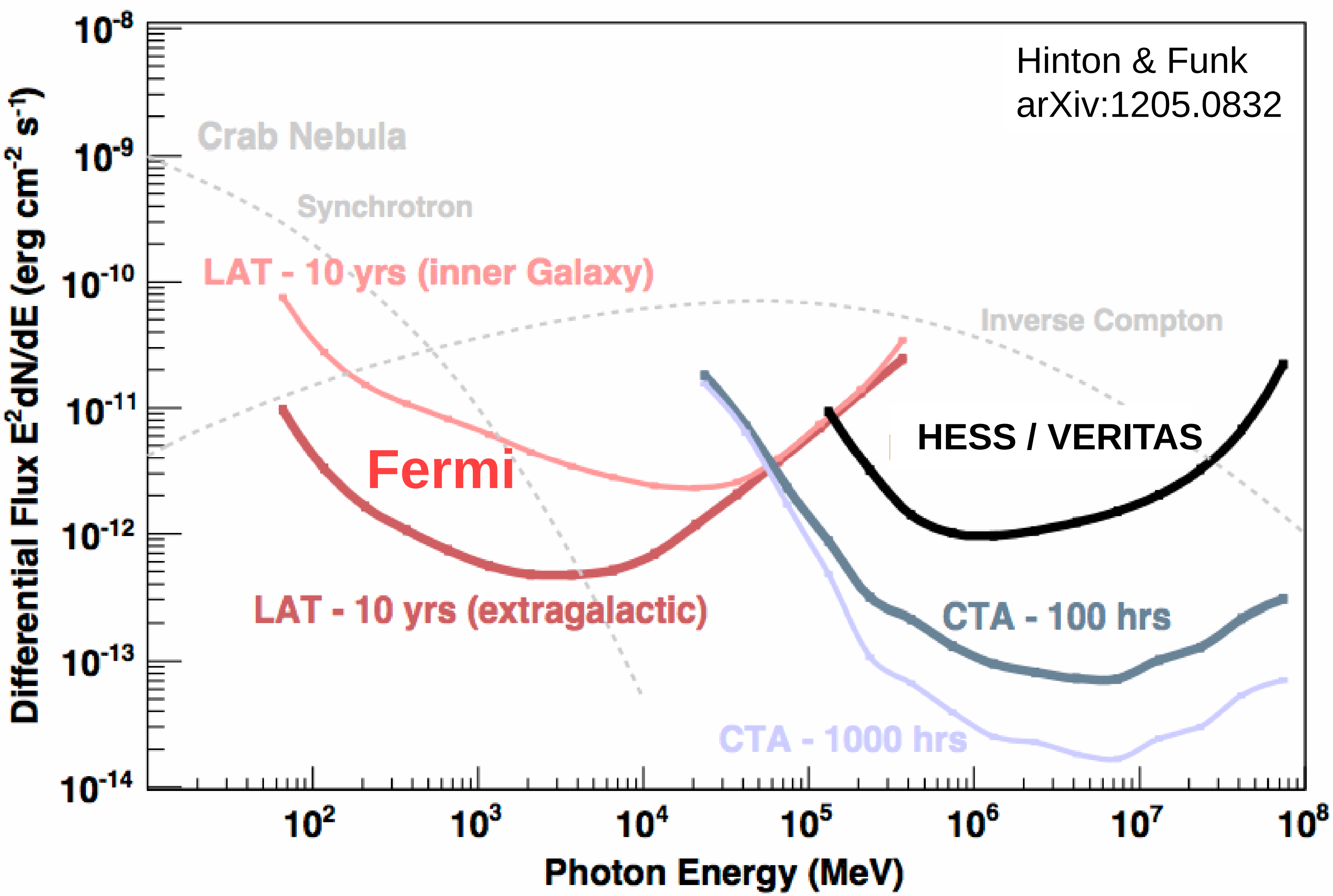
Low energies
Energy threshold 20-30 GeV
23 m diameter
4 telescopes
(LST's)

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)



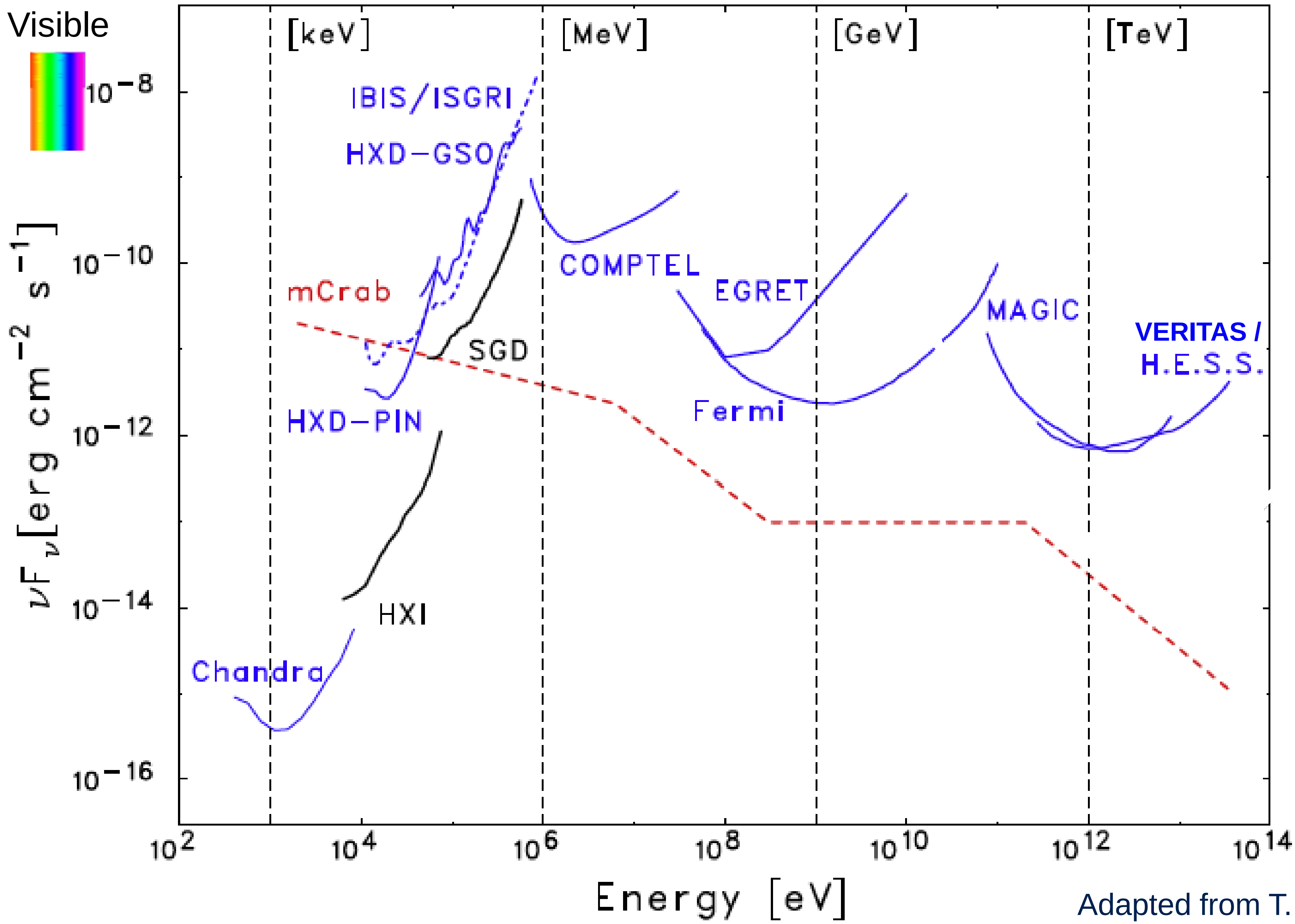
Differential Flux Sensitivity



Major **sensitivity improvement &** ***wider*** **energy range**

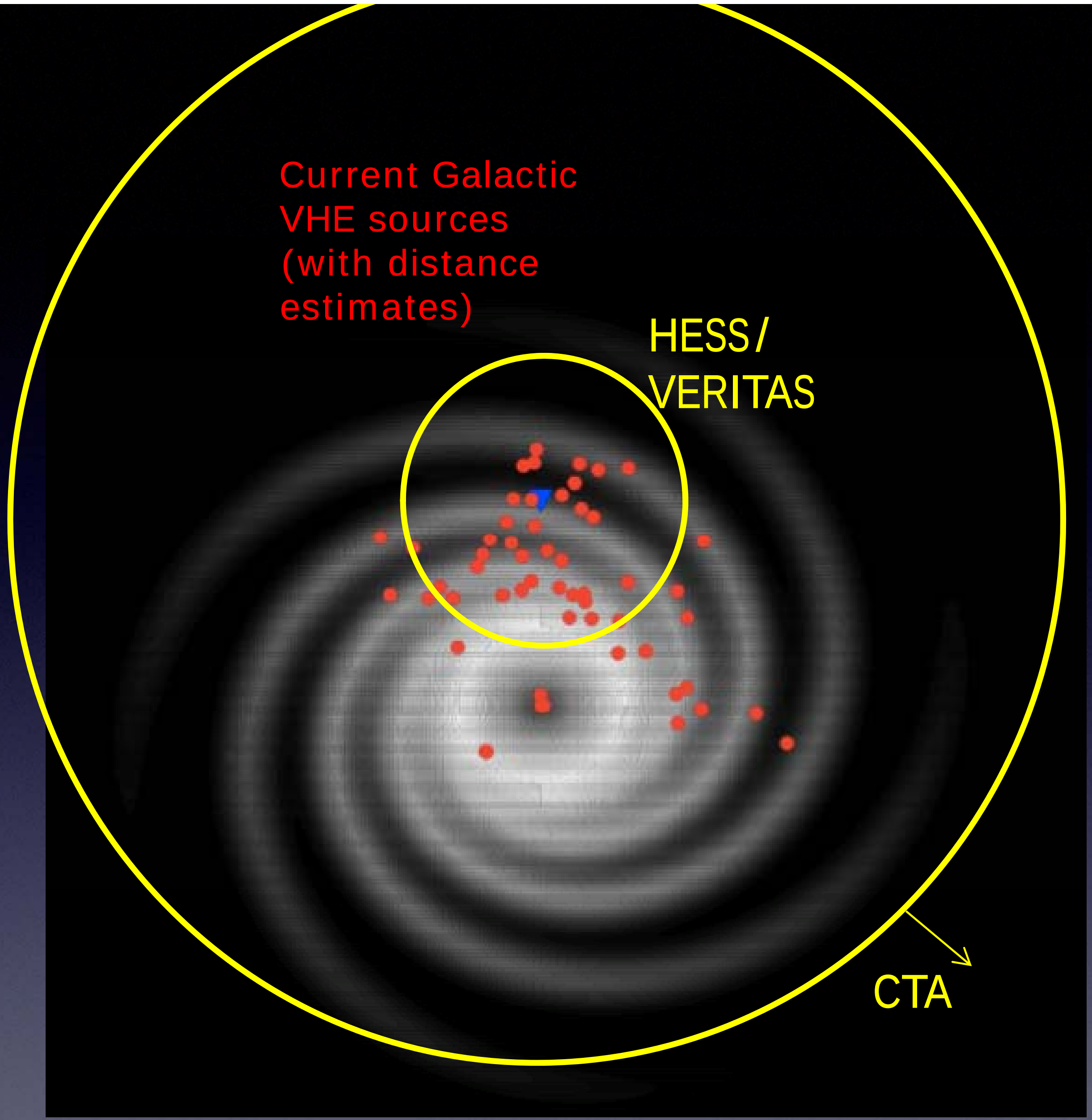
→ Factor of ~x10 increase in source population

CTA in Context

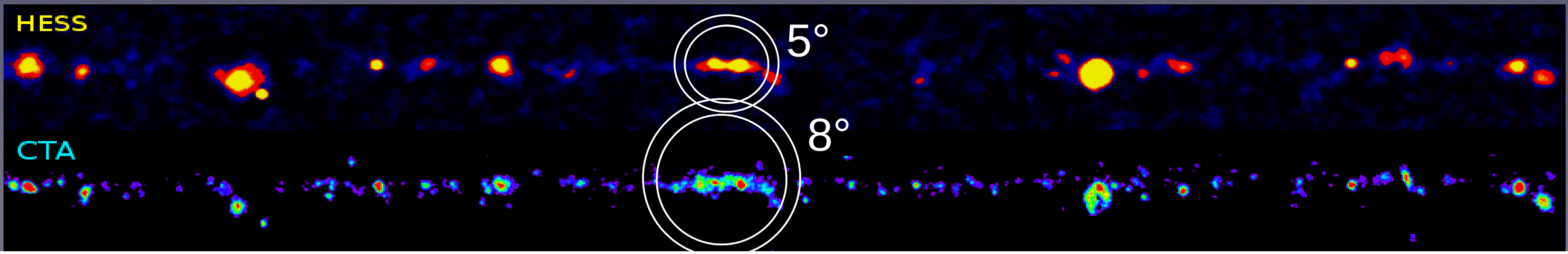


Adapted from T. Takahashi

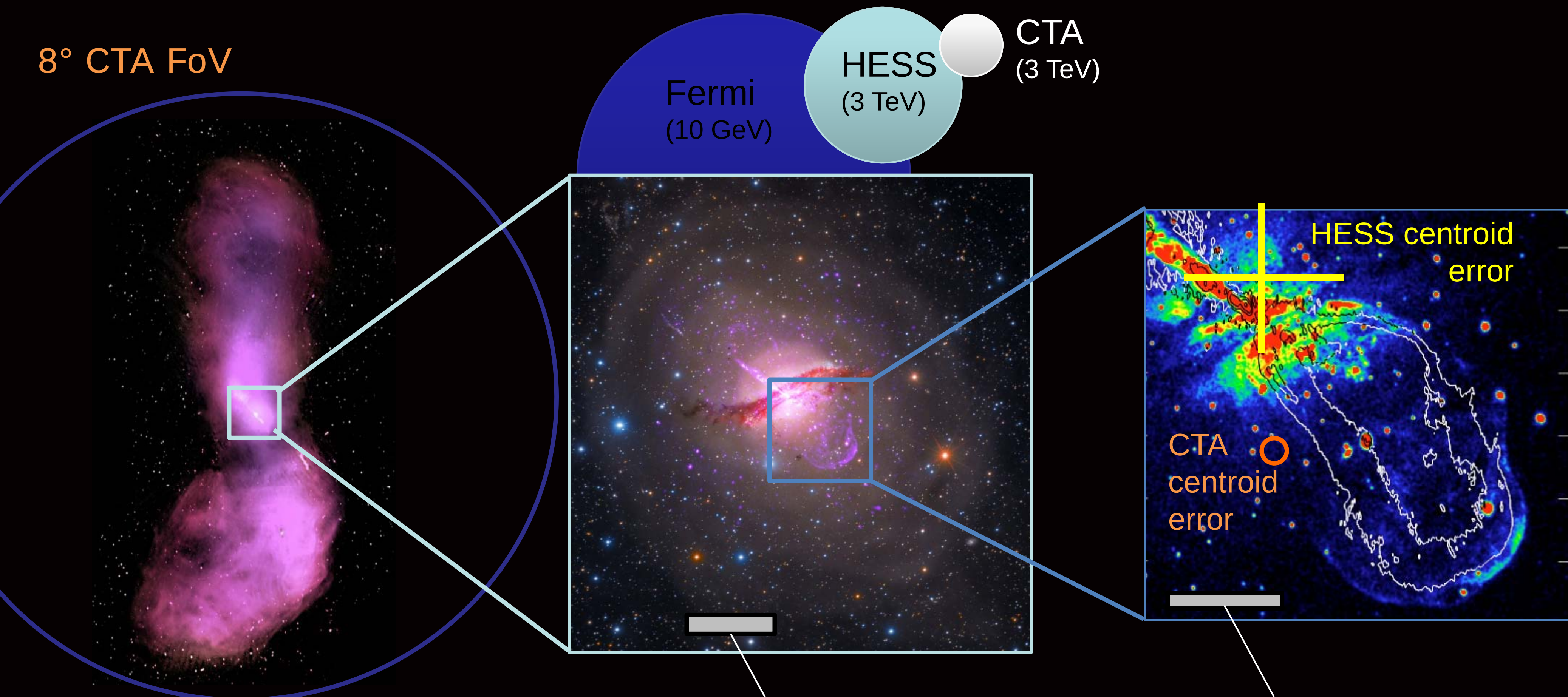
Galactic Discovery Reach



Survey speed:
x300 faster than HESS



Angular Resolution



0.1°
Typical HESS
Resolution

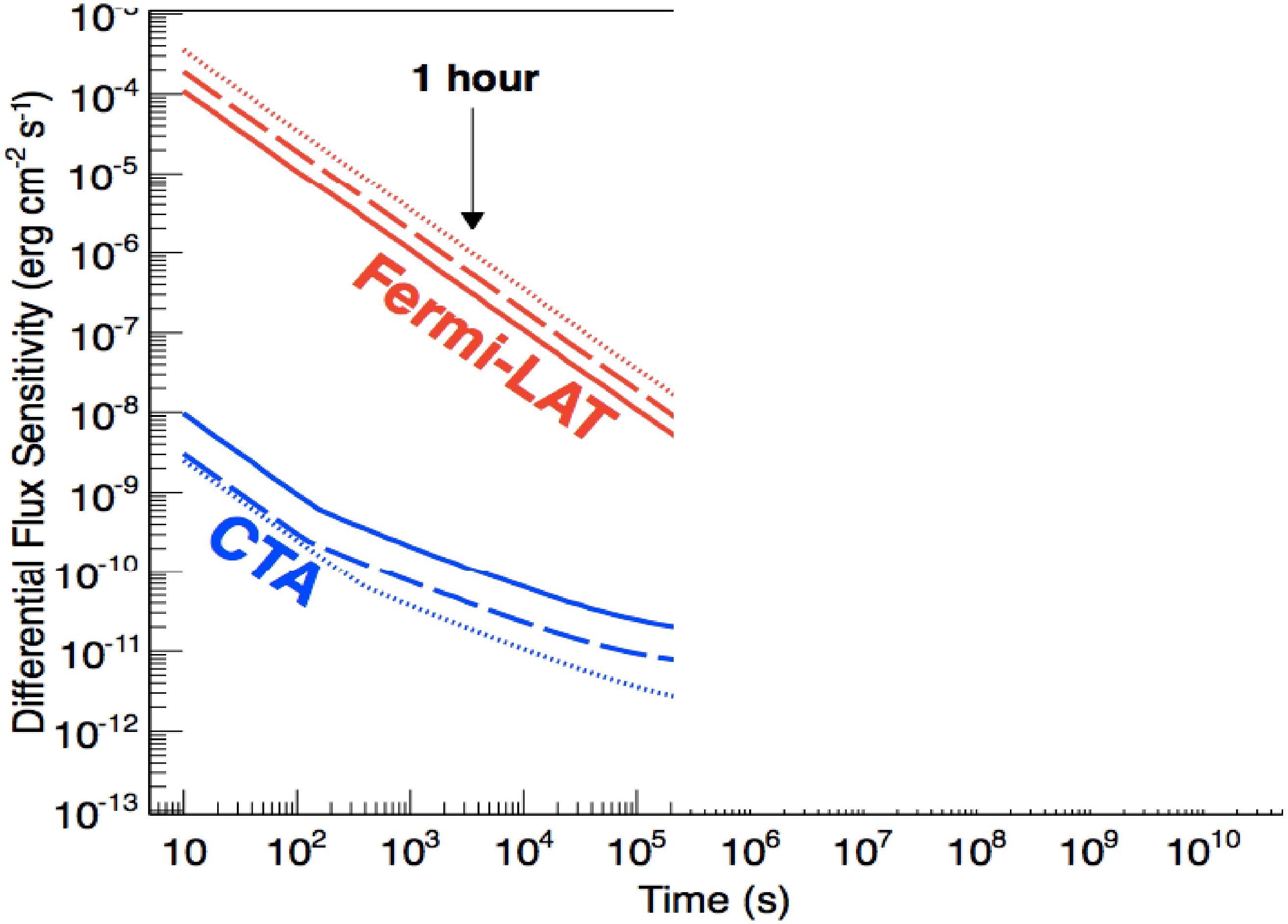
2 ′
CTA > 1 TeV

Example: Cen A

Transient Capability (< 100 GeV)

S. Inoue et al.,
arXiv:1301.3014

Hinton & Funk
arXiv:1205.0832



GRB (z=4.3) Light curve

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

CTA Implementation & Status

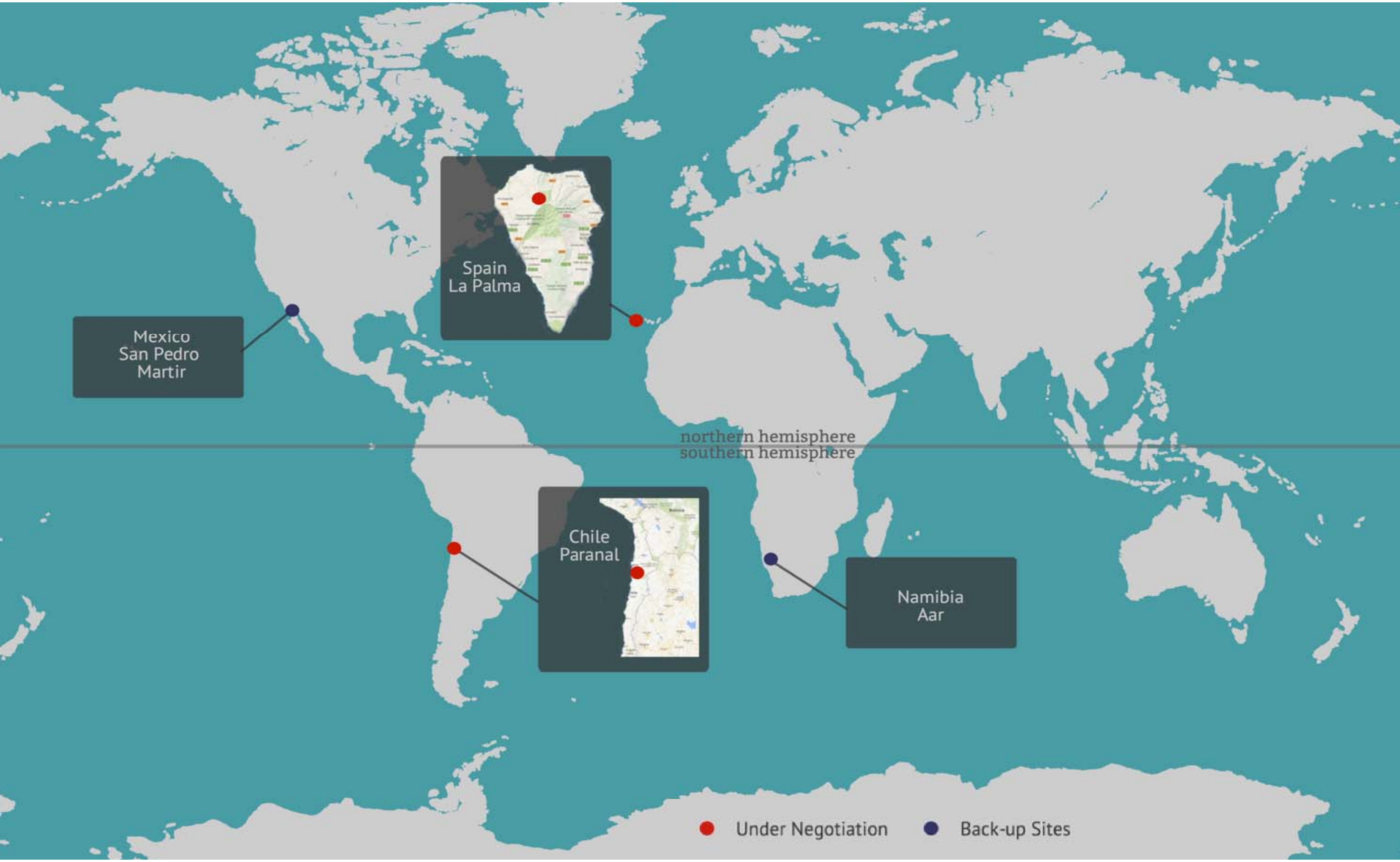
CTA Consortium

CTA is being developed by the CTA Consortium:

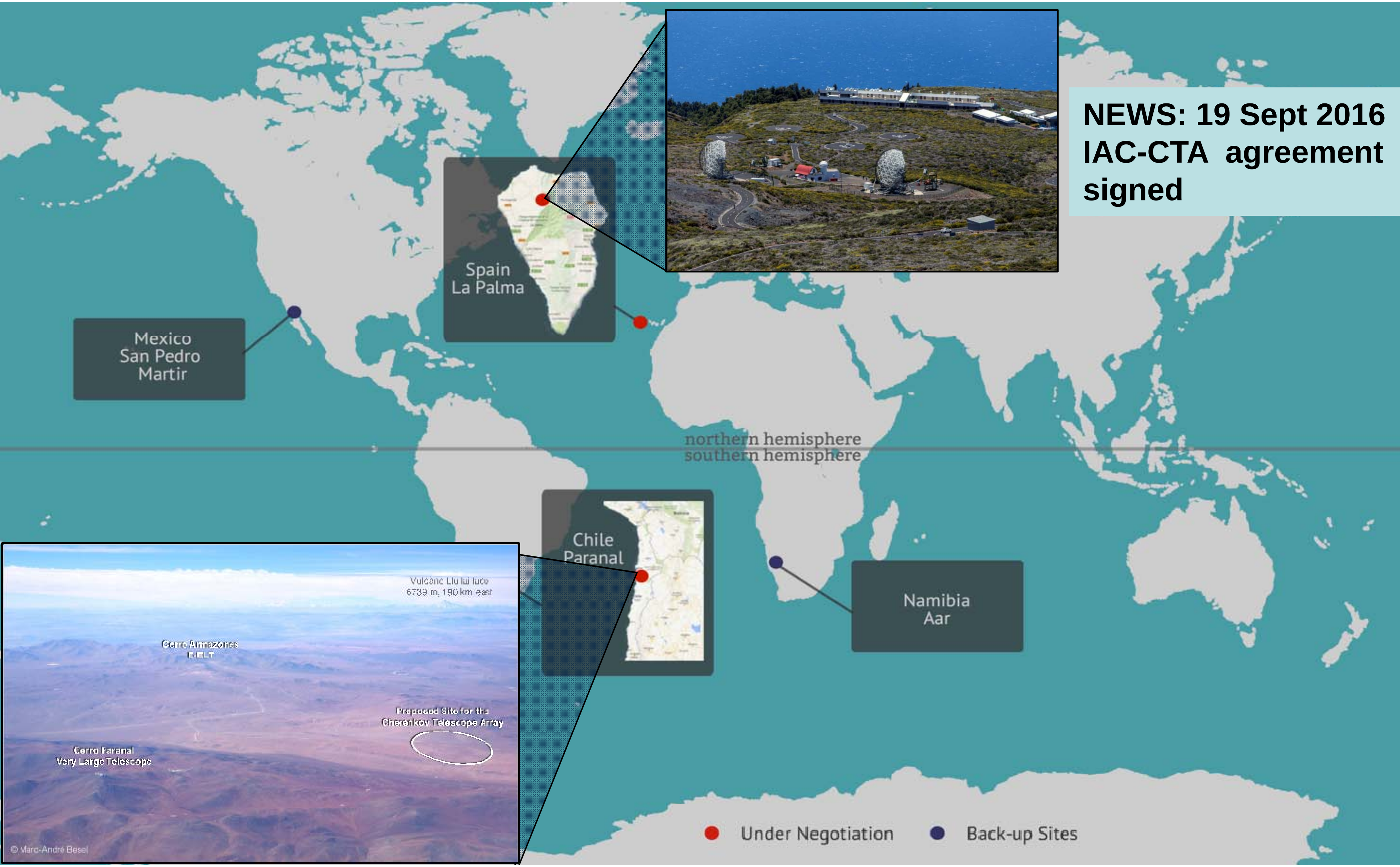
(full version shows pie chart with Japan FTE highlighted)

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

Status of Sites

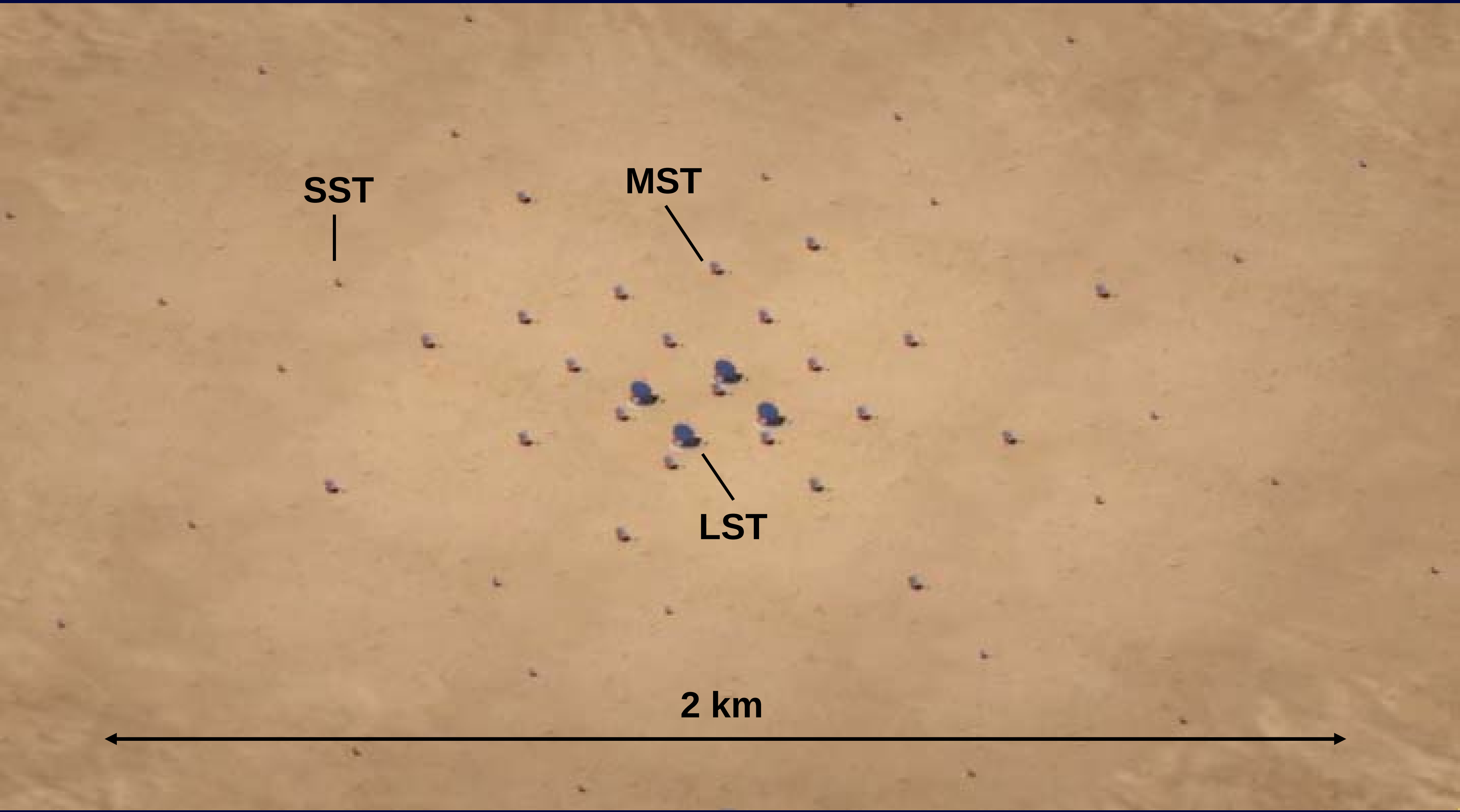


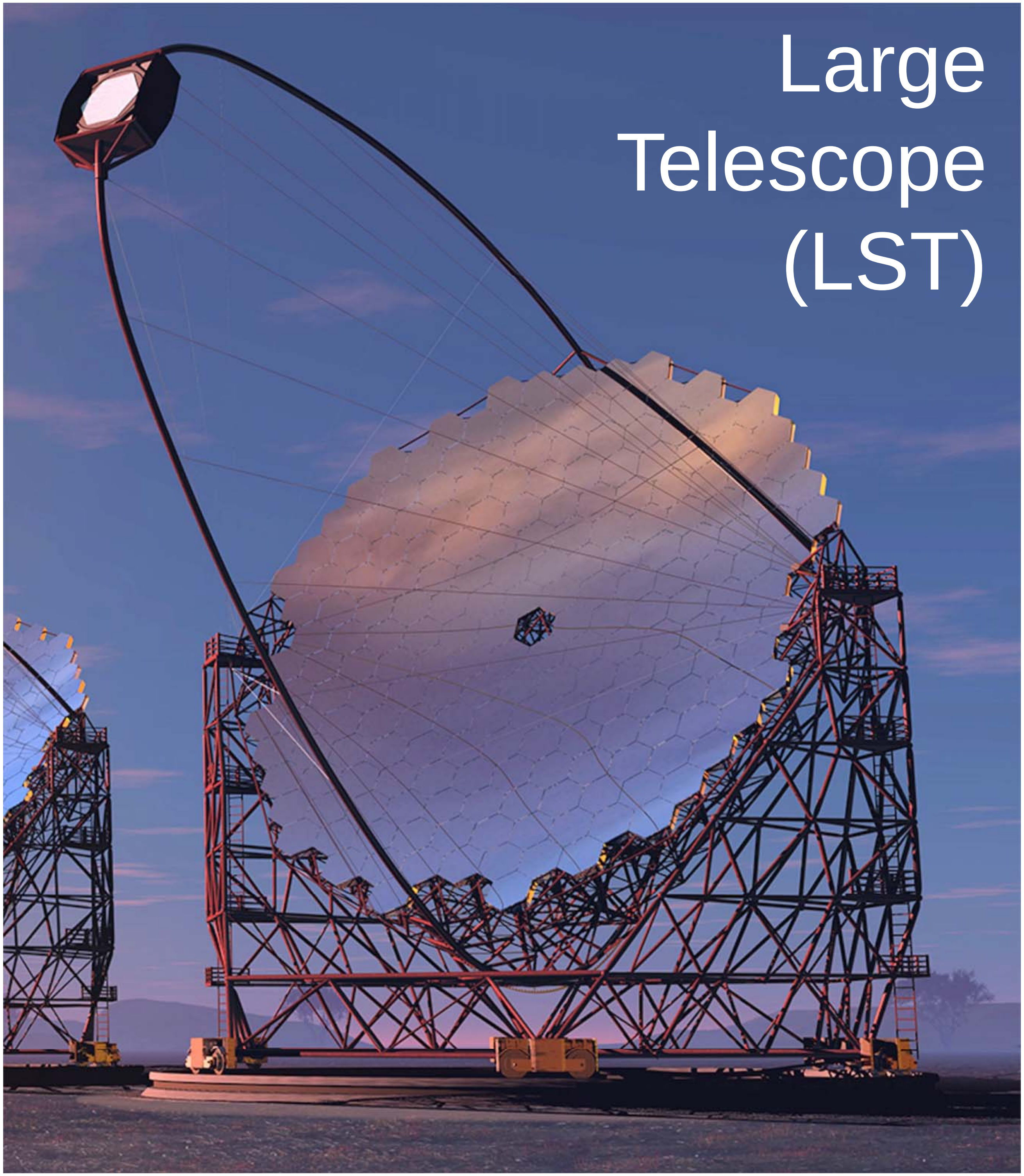
Status of Sites



NEWS: 19 Sept 2016
IAC-CTA agreement signed

CTA South Array
4 LSTs, 25 MSTs, 70 SSTs





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

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

Carbon-fiber structure
for 20 s positioning

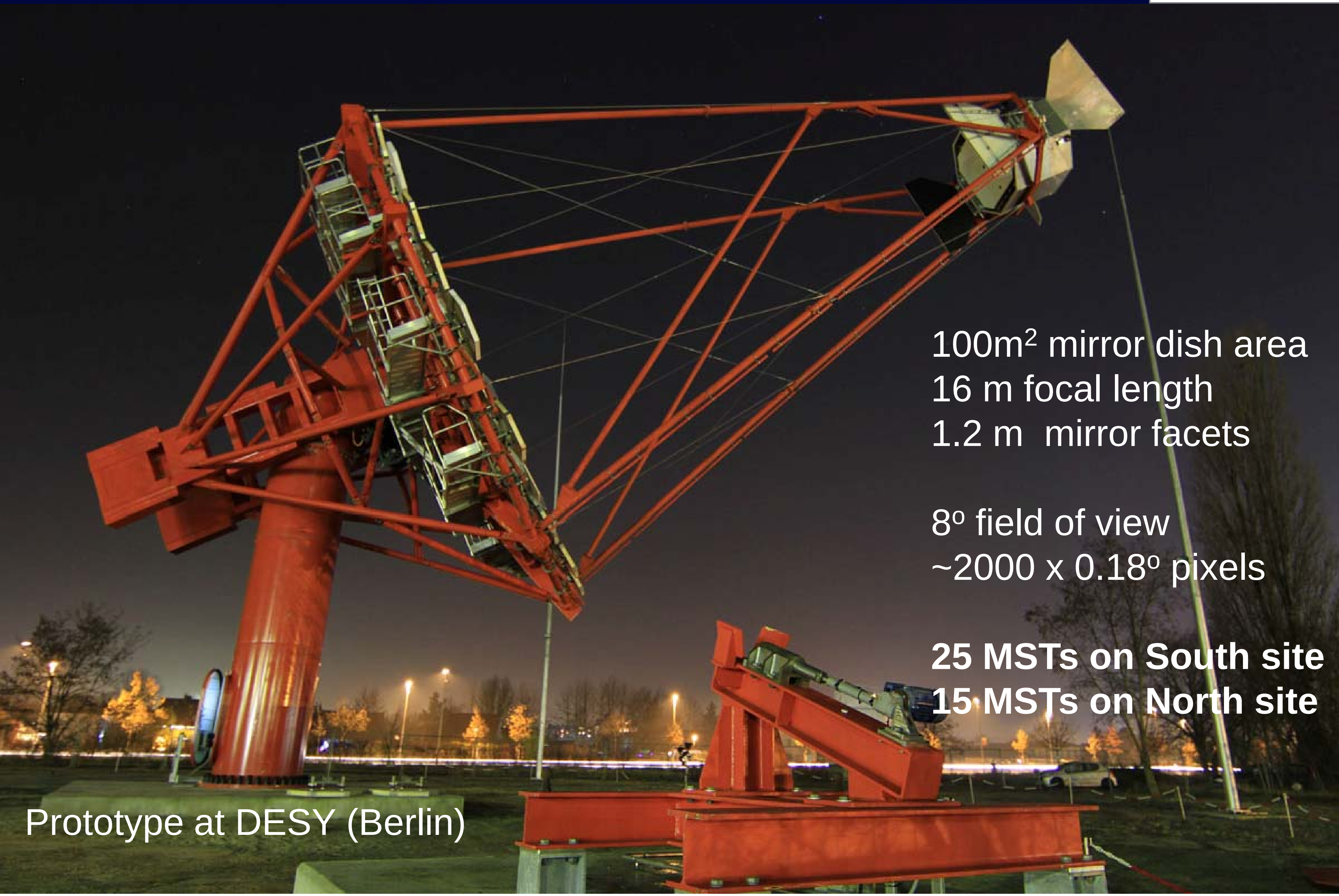
Active mirror control

4 LSTs on South site
4 LSTs on North site

Prototype construction
Underway (La Palma)

Major contribution
from JAPAN

Medium Telescope (MST)



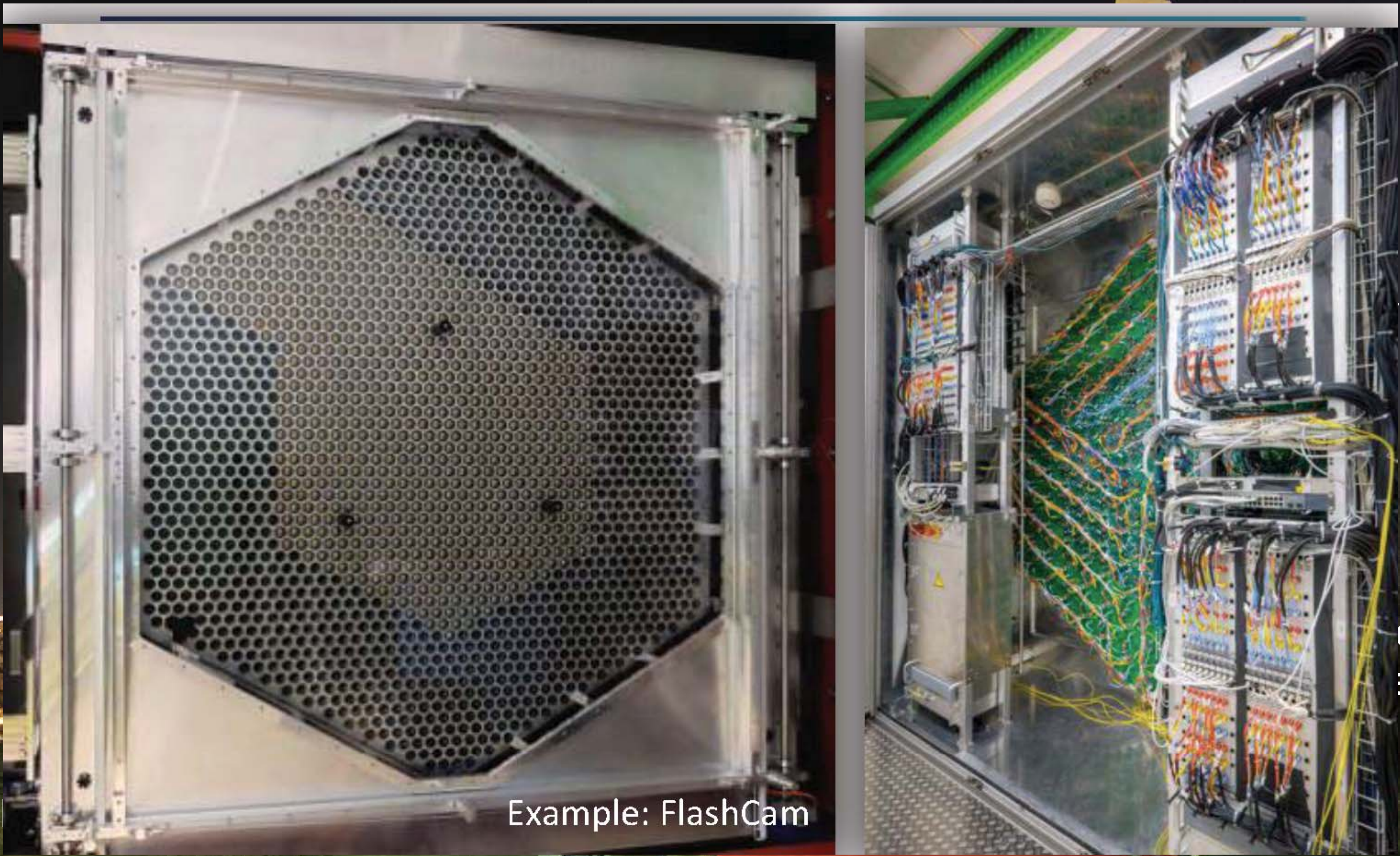
100m^2 mirror dish area
16 m focal length
1.2 m mirror facets

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

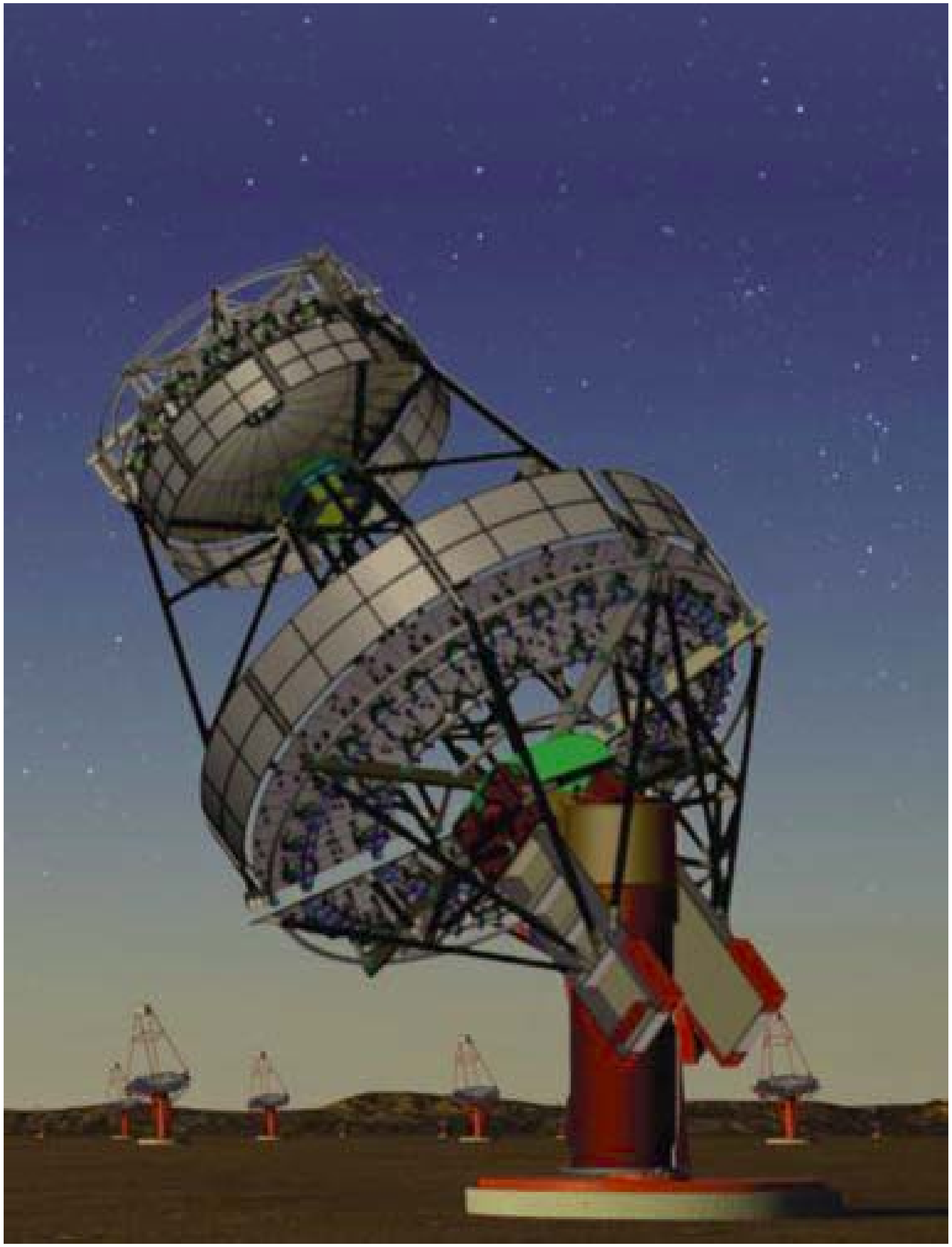
25 MSTs on South site
15 MSTs on North site

Prototype at DESY (Berlin)

MST Integrated Camera



Dual-Mirror MST



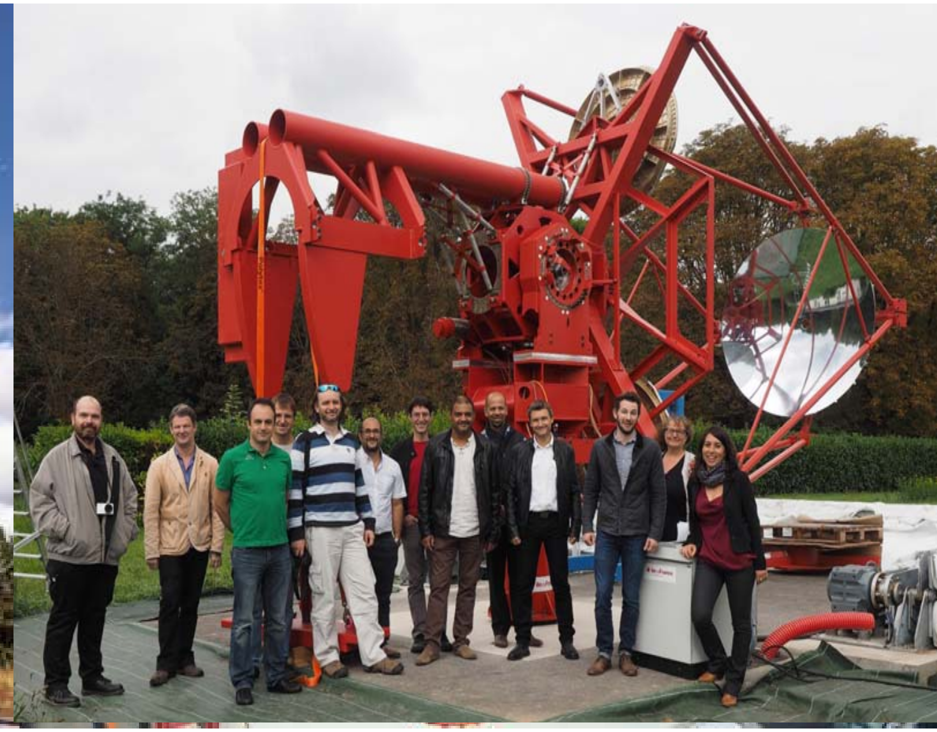
- Schwarzschild-Couder design (V. Vassiliev et al.)
- 9.7m primary, 5.4m secondary
- 11328 x 0.07^{o} Si-PMT pixels
- 8^{o} field-of-view
- Prototype under construction: Whipple Obs. (Arizona, USA)

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

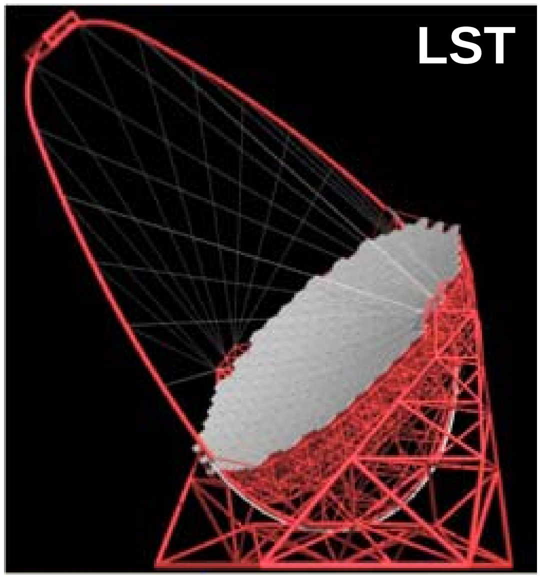
SST-1M
Krakow, Poland

SST-2M ASTRI
Mt. Etna, Italy



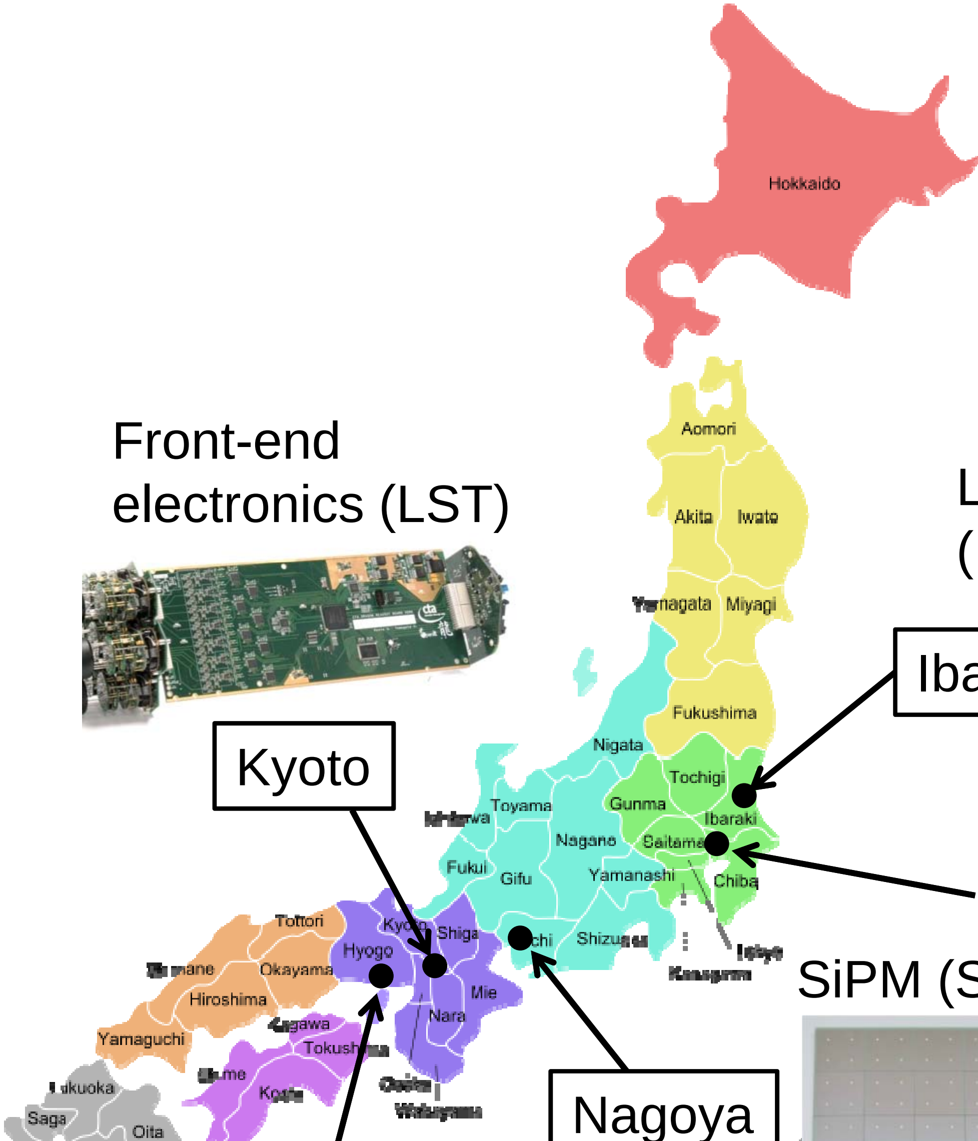
SST-2M GCT
Meudon, France
Contribution from Japan

Japanese Contributions to CTA



SST-GCT

Front-end electronics (LST)



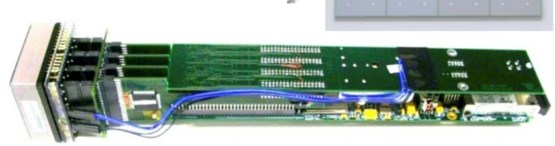
Major Contributions

\+

Software
Simulations
Science …

Light concentrator (LST)

SiPM (SST)

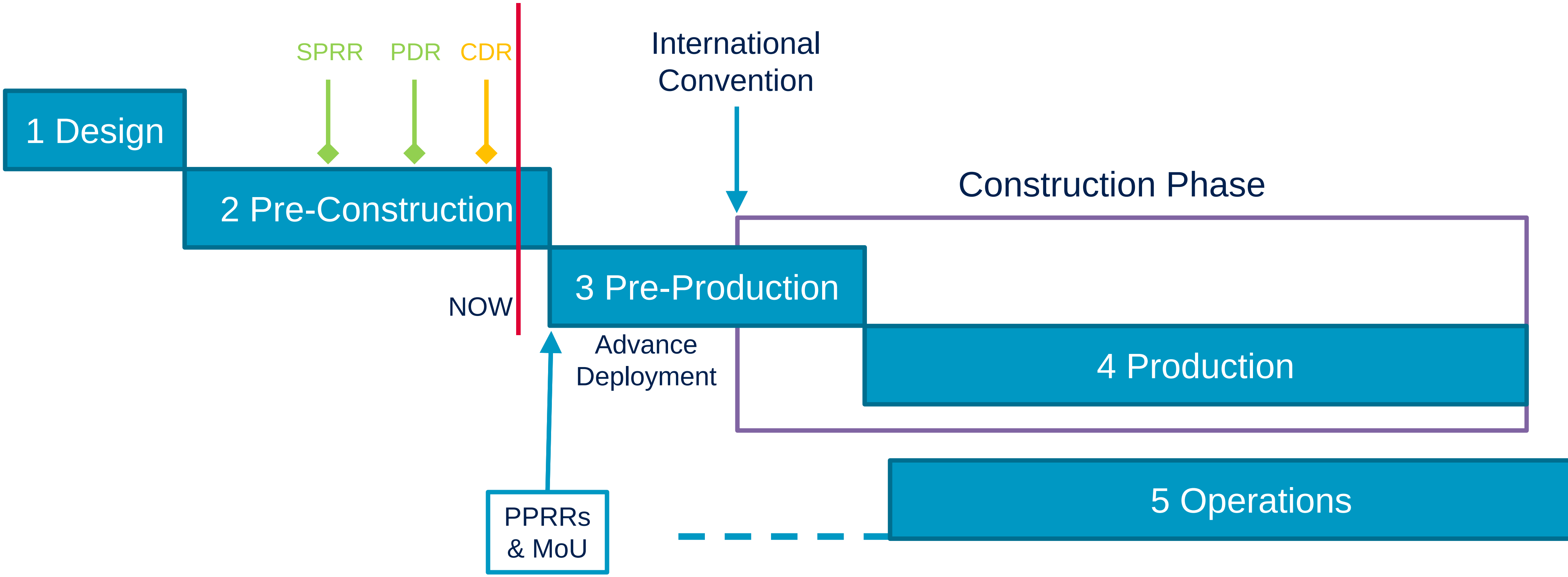


Front-end electronics (SST/ SCT)

PMT (LST)

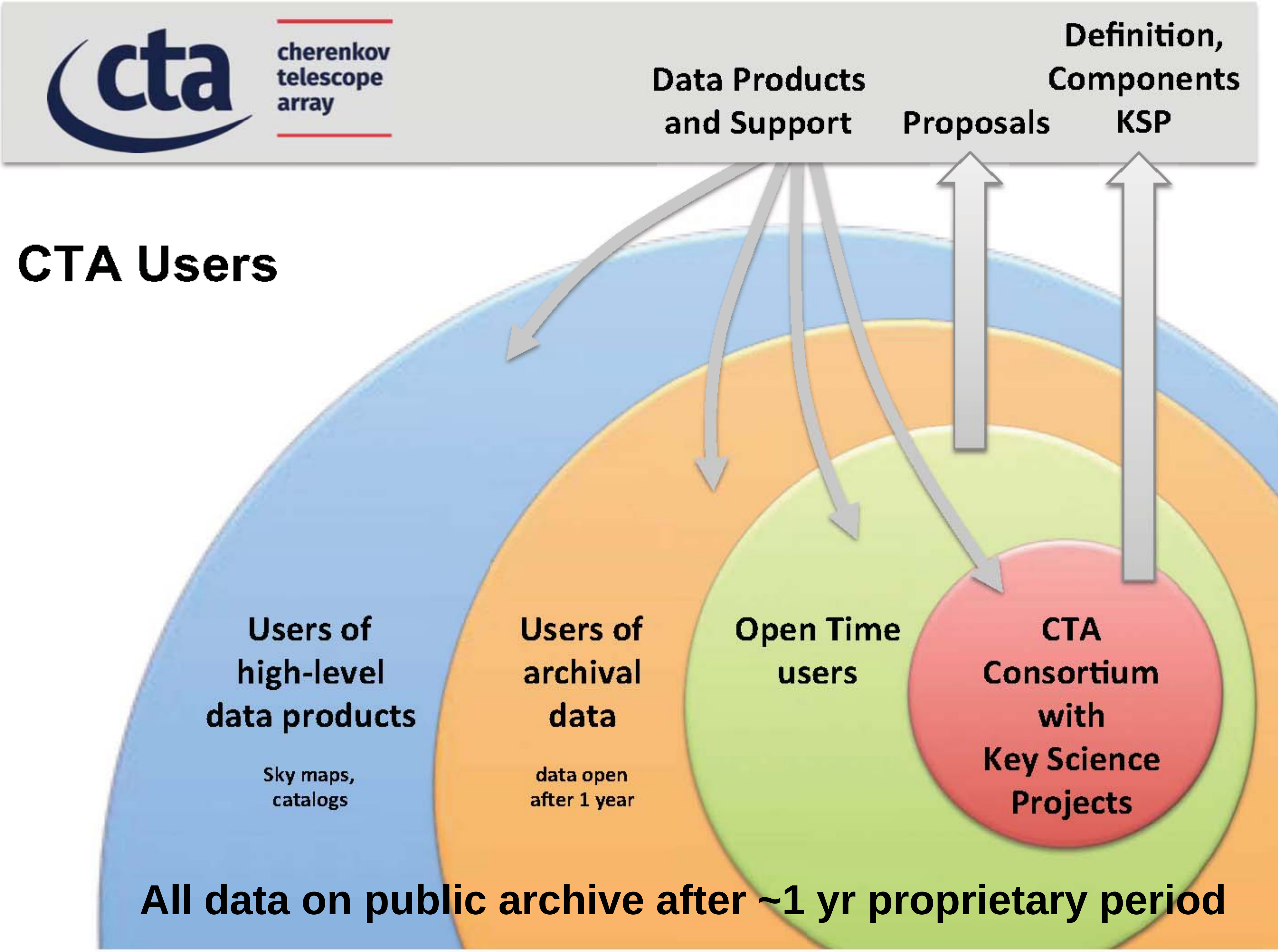
H. Tajima

CTA Phases



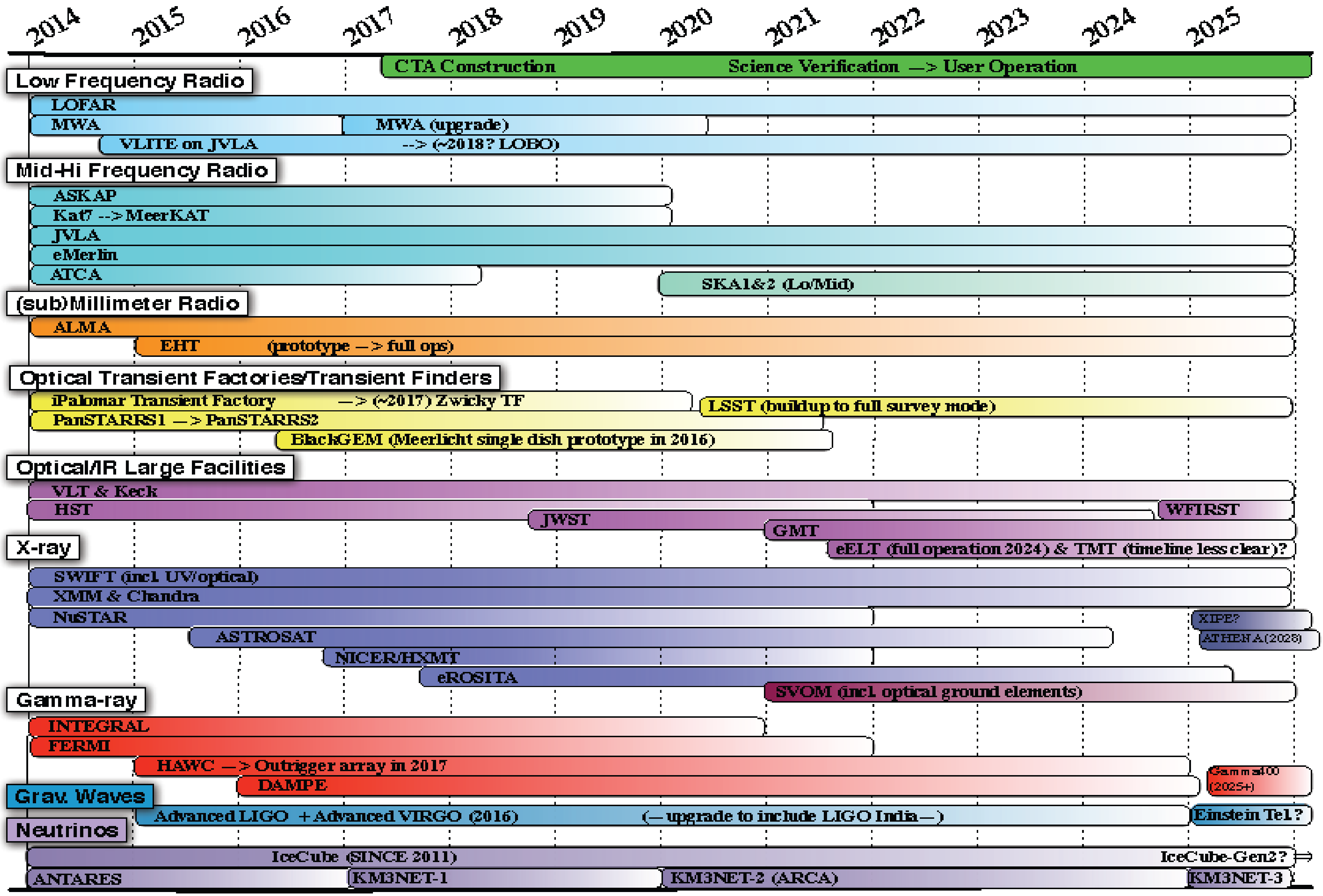
- Signed MoU for construction and site agreements in 2016
- Site preparations start in 2016 (N) and 2017 (S)
- Construction period of 4-5 years
- Initial science with partial arrays possible from 2018 (N) and 2019 (S)
- Note: LSTs in N completed on earlier time scale

CTA: An Open Observatory



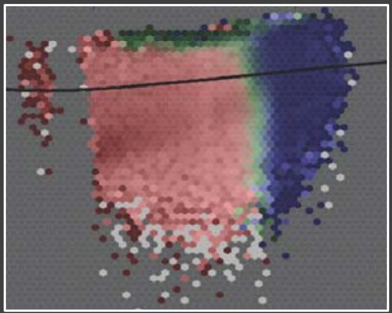
All data on public archive after ~1 yr proprietary period

Important MWL Synergies

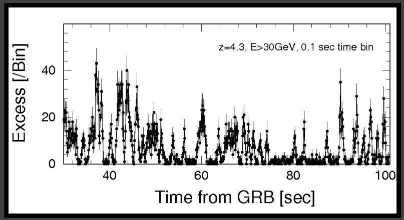


Caveat: Observatory timelines are very uncertain; this represents a notional picture based on available information

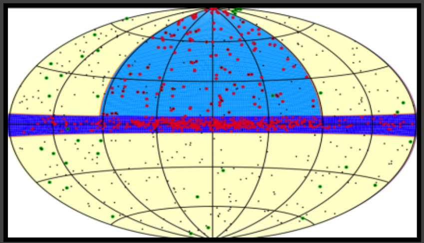
Key Science Projects (KSPs)



Dark Matter Programme

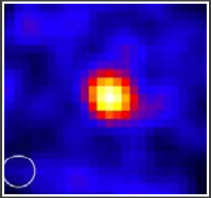


Transients



ExGal Survey

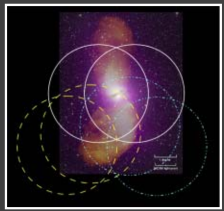
Galaxy Clusters

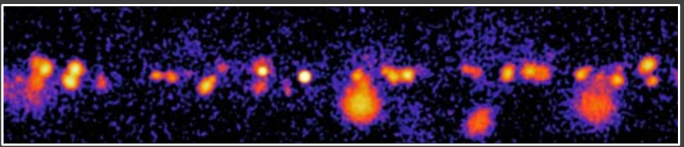


Extragalactic

Star Forming Systems

AGN

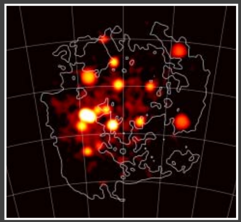




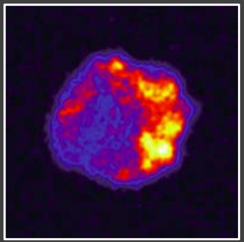
Galactic Plane Survey

Galactic

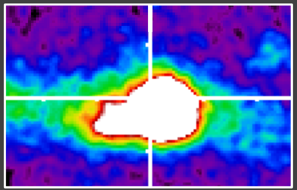
LMC Survey



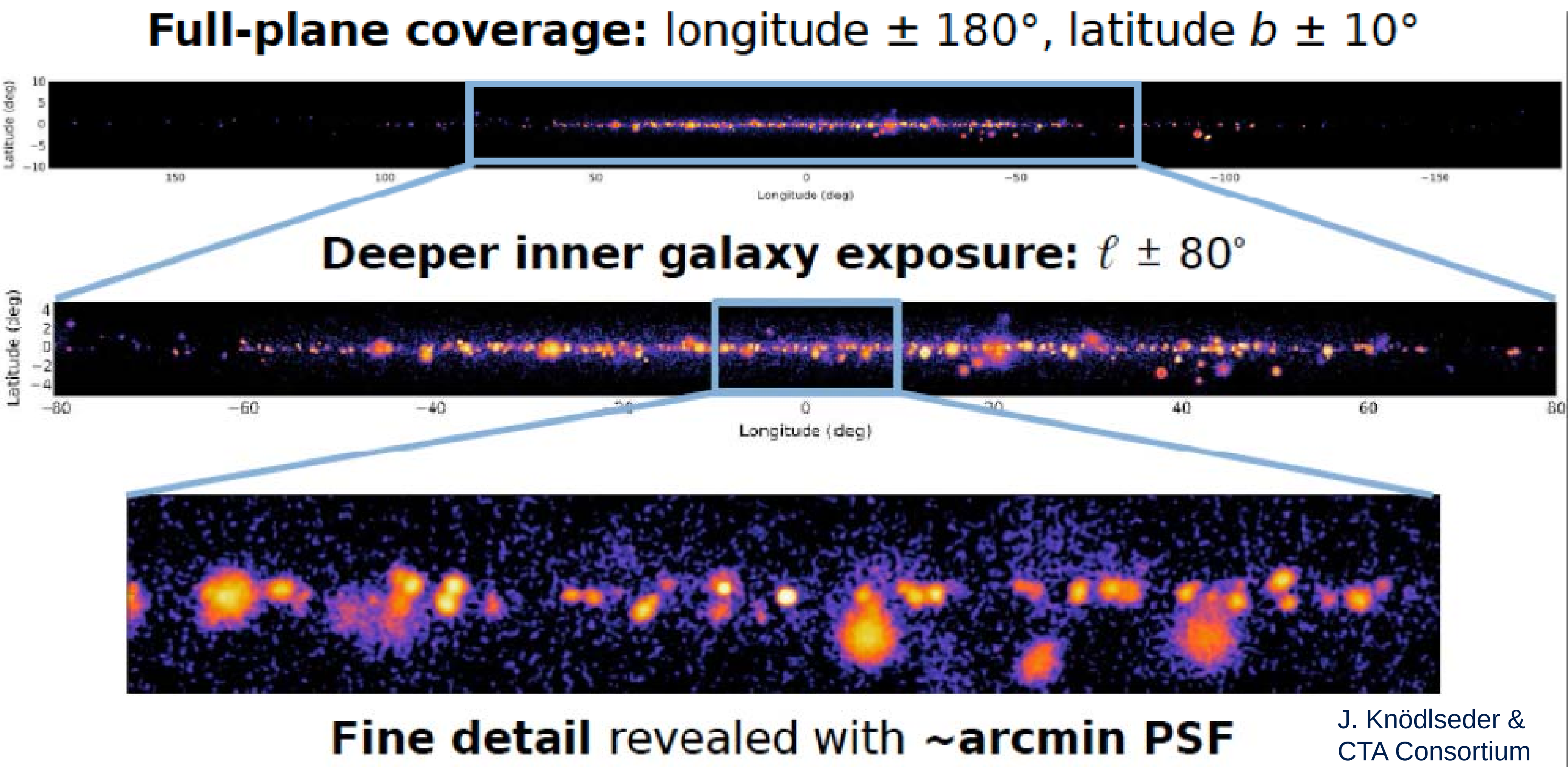
PeVatrons



Galactic Centre



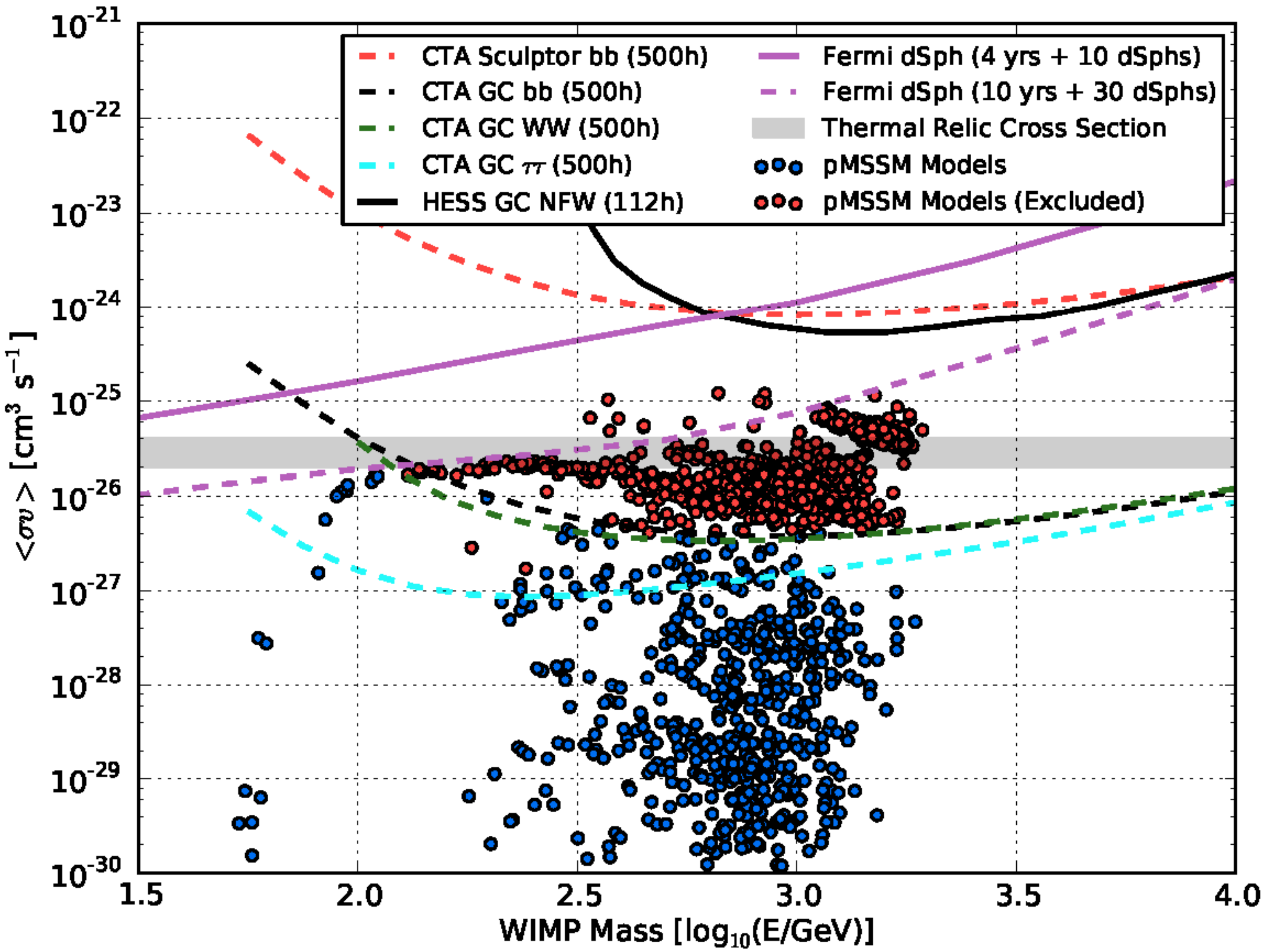
Galactic Plane Survey (GPS)



J. Knödlseder & CTA Consortium

SNRs / PeVatrons: Discovered in GPS → deep follow-up observations

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*

CONCLUSIONS

- With many discoveries, VHE γ-rays are now a well-recognized astrophysical discipline & part of growing multi-messenger science.
- VHE photons explore non-thermal universe and aspects of 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 – with a major contribution from Japan