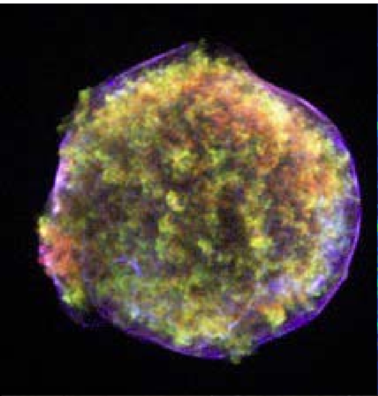
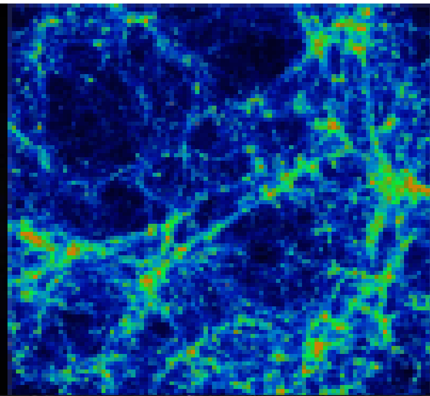
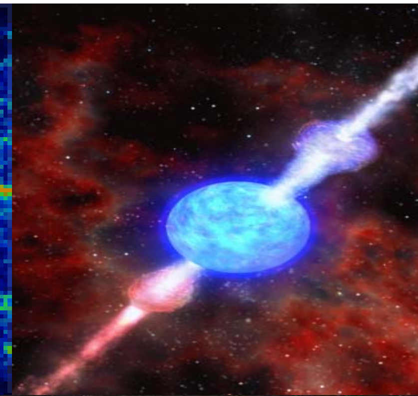
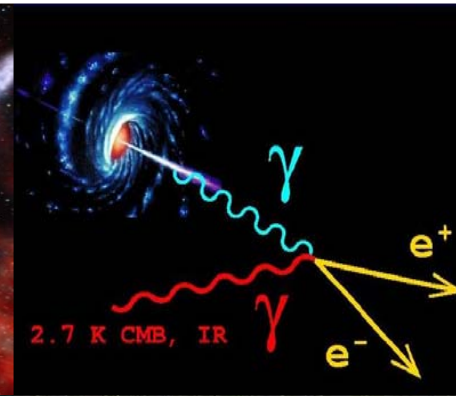
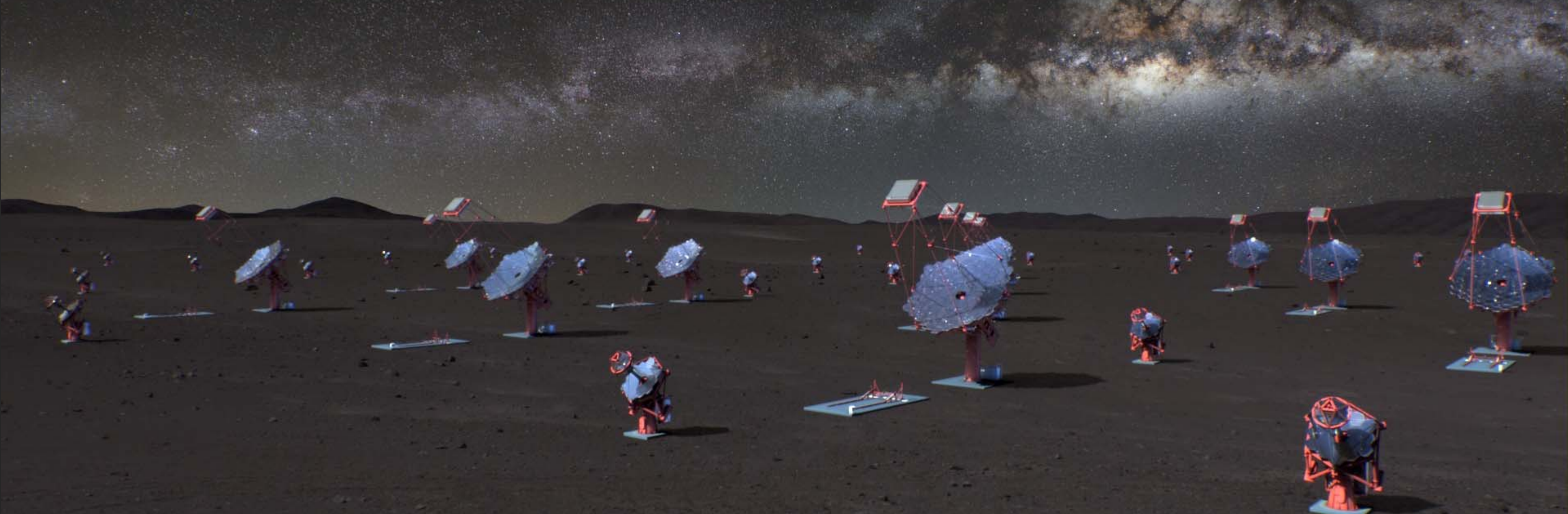








The Cherenkov Telescope Array Observatory: Science and Status



GSSI Colloquium, 8 May 2024

Rene A. Ong (UCLA, INFN)

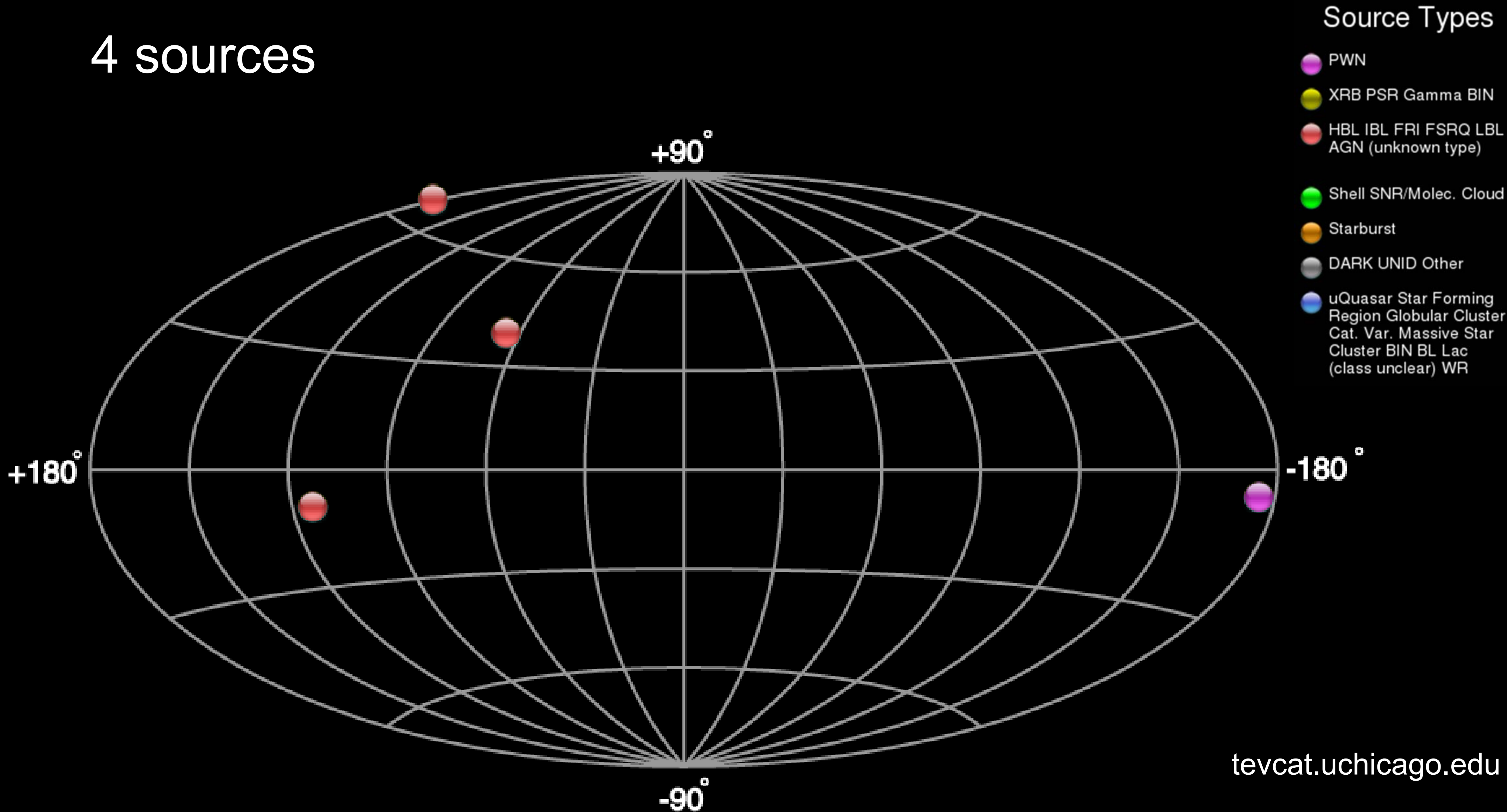
Outline

- **Scientific & Technical Motivation**
  - Astronomical perspective – the high-energy γ-ray universe
  - Physics perspective – multi-messenger approach, new physics
  - Atmospheric Cherenkov technique
  - Moving beyond the current instruments → CTAO
- **Cherenkov Telescope Array Observatory (CTAO)**
  - CTAO design → performance
  - Implementation & Status
  - CTAO Key Science
- **Summary**

(Note: the term “CTA” is being deprecated in favor of “CTAO”.)

TeV γ-ray Sky c1994

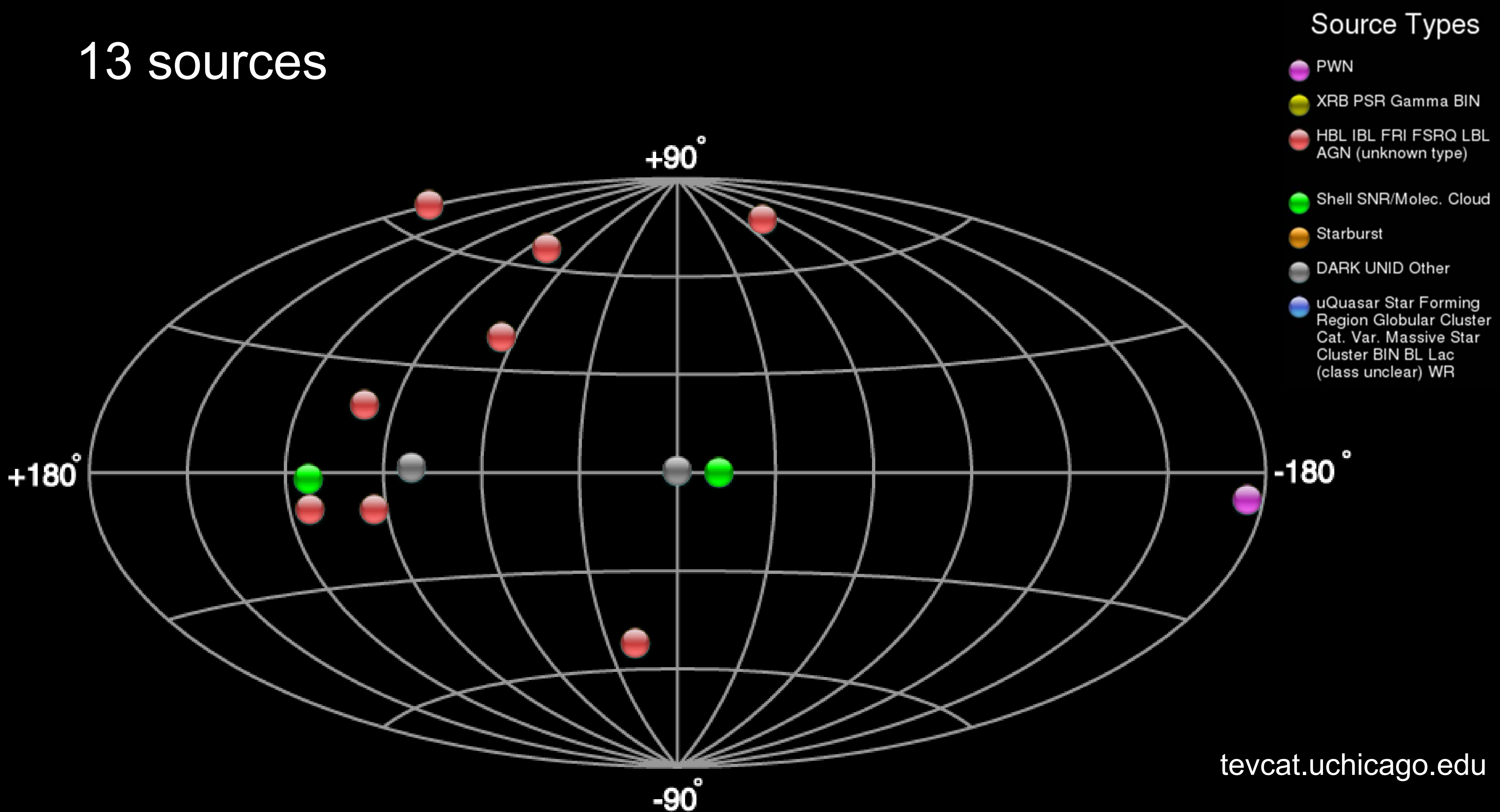
4 sources



tevcat.uchicago.edu

TeV γ-ray Sky c2004

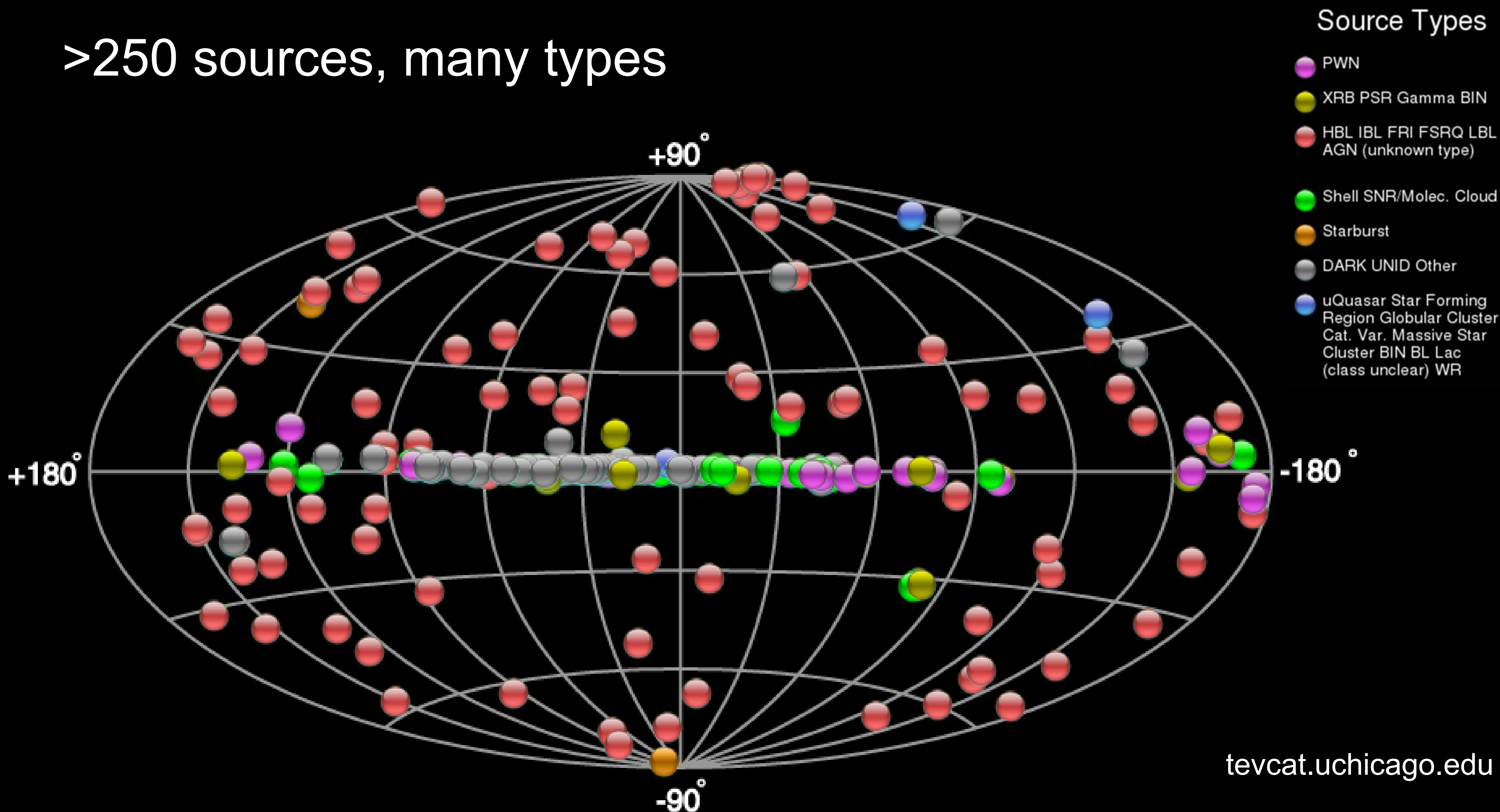
13 sources



tevcat.uchicago.edu

TeV γ-ray Sky c2024

>250 sources, many types



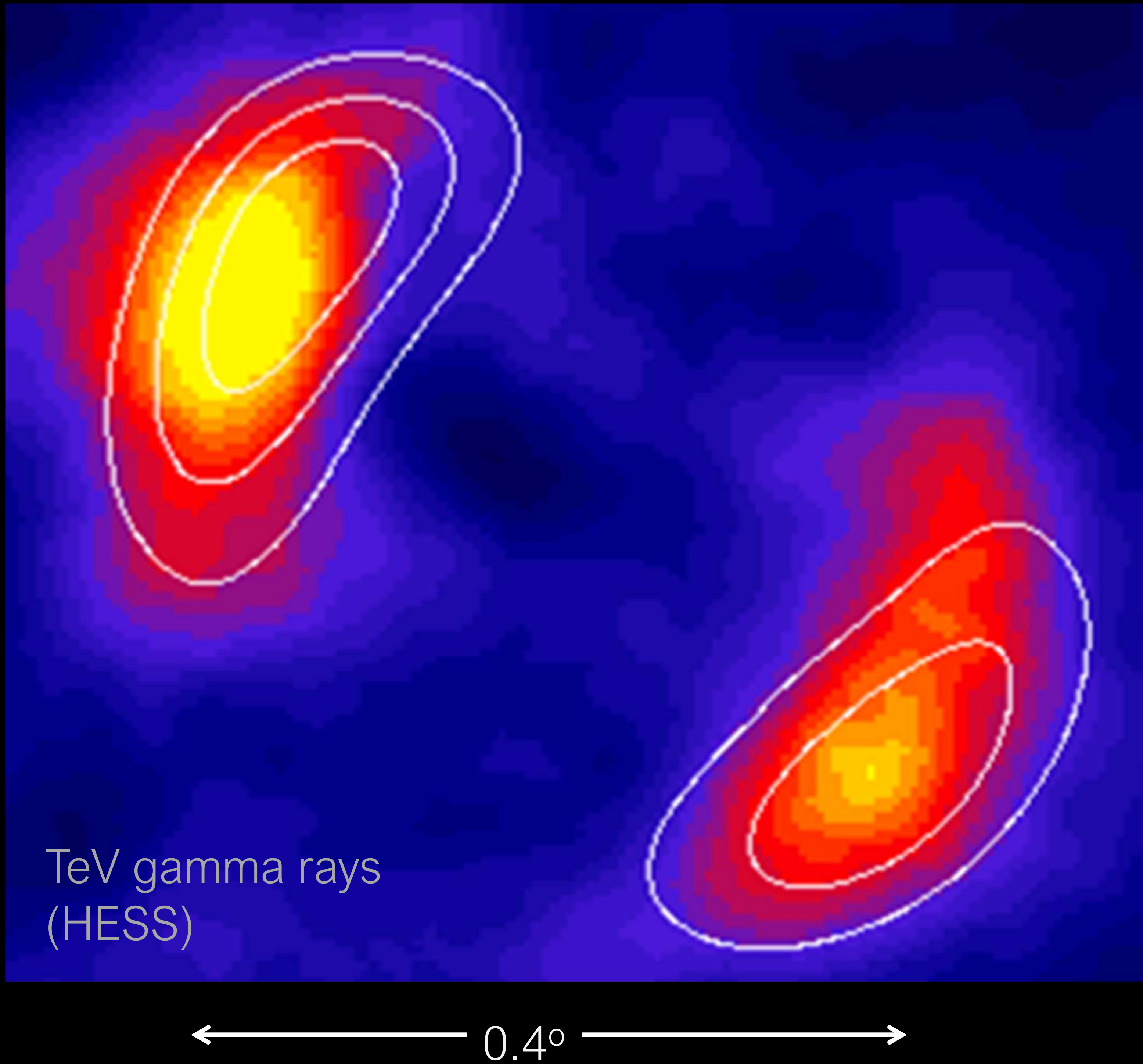
~75% discovered by the three major atm. Cherenkov telescopes

→ includes spectra, images, variability, MWL information and more!

Some Science Examples

Supernova Remnants

SN 1006

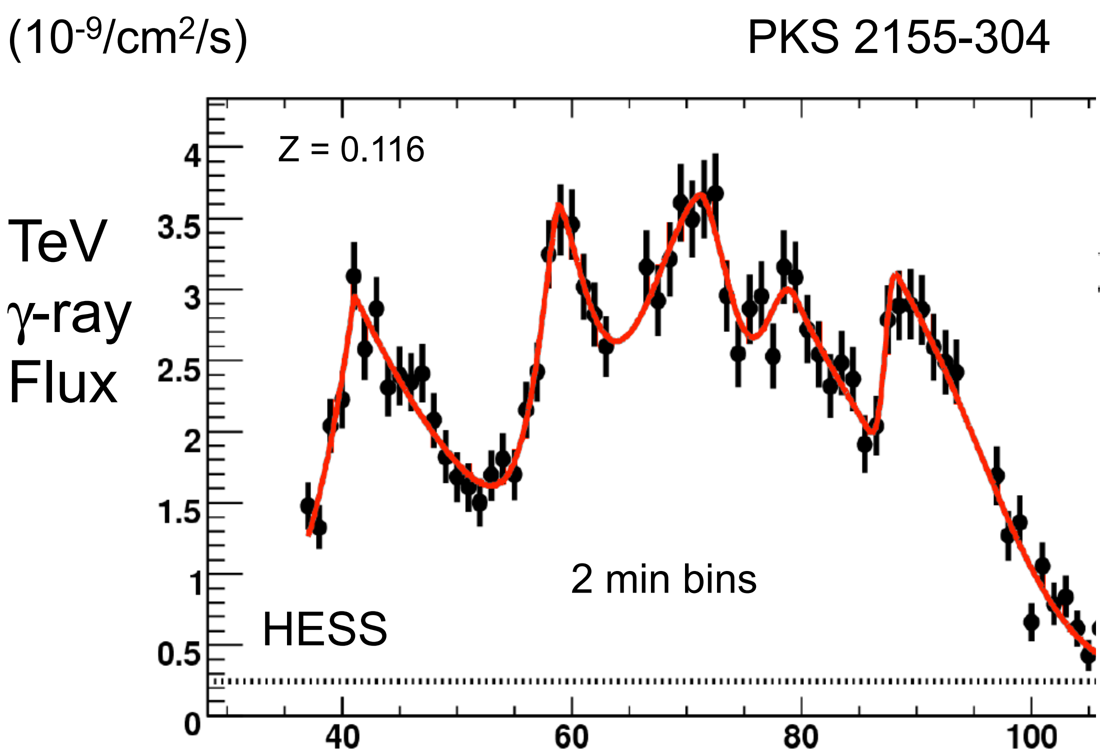


(Credits:
X-ray (blue): NASA/CXC/Rutgers/ G.Cassam-Chenai, J.Hughes et al.; Radio(red):NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: (yellow) Middlebury College/ F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS)

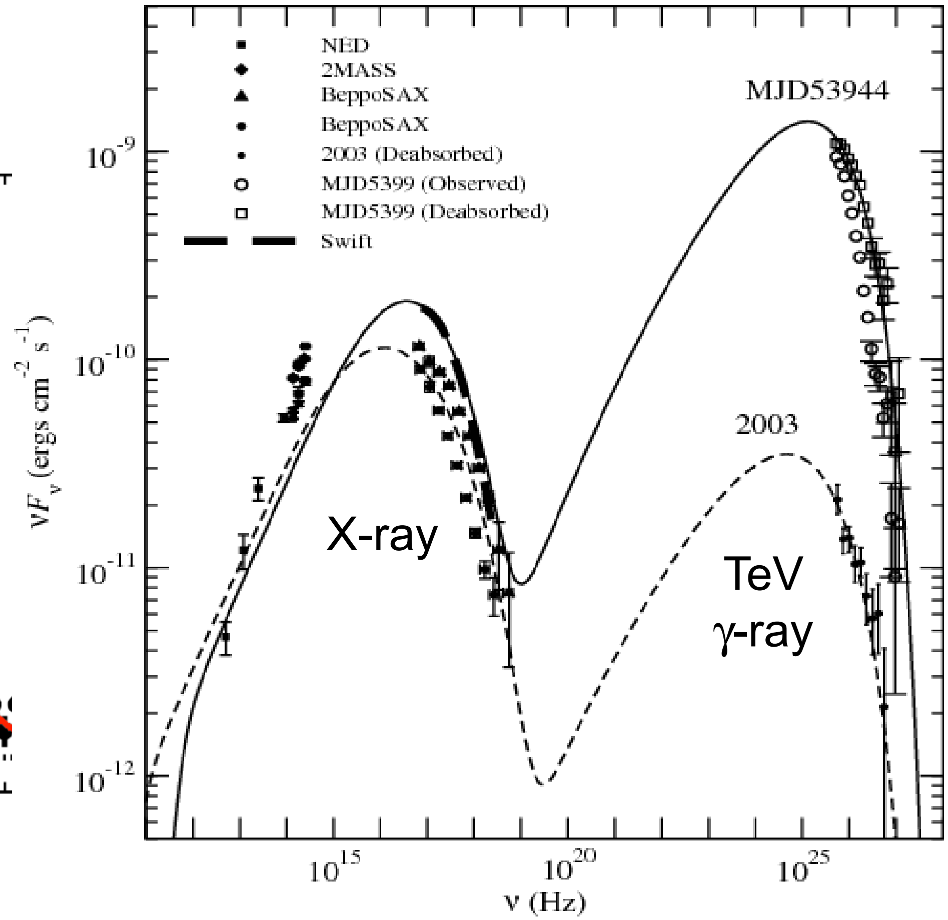
AGN – Active Galactic Nuclei

Blazars: Jets pointed towards Earth

Strong & highly variable TeV sources



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

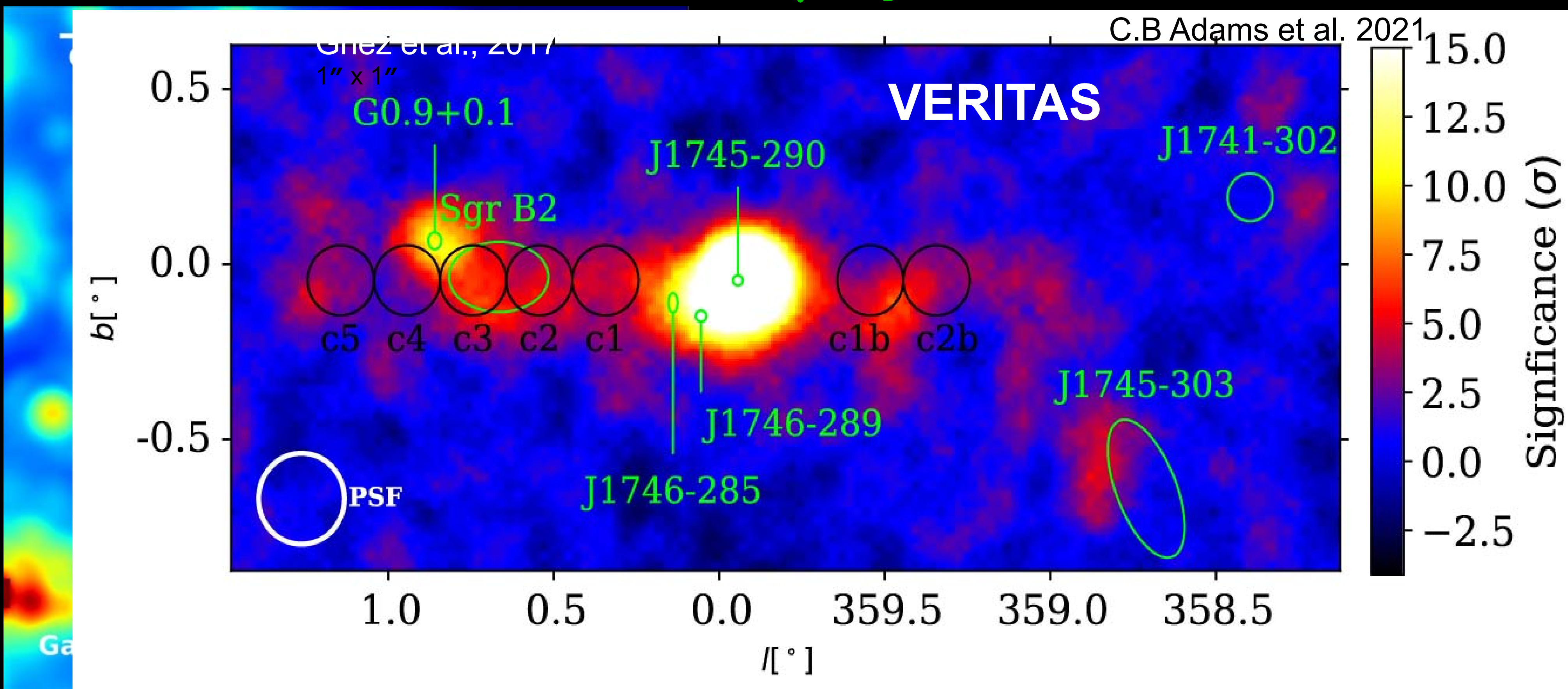


VHE emission dominates output

But many open questions: BH energetics, variability, beam composition, etc.

Galactic Center – A High-Energy Mystery

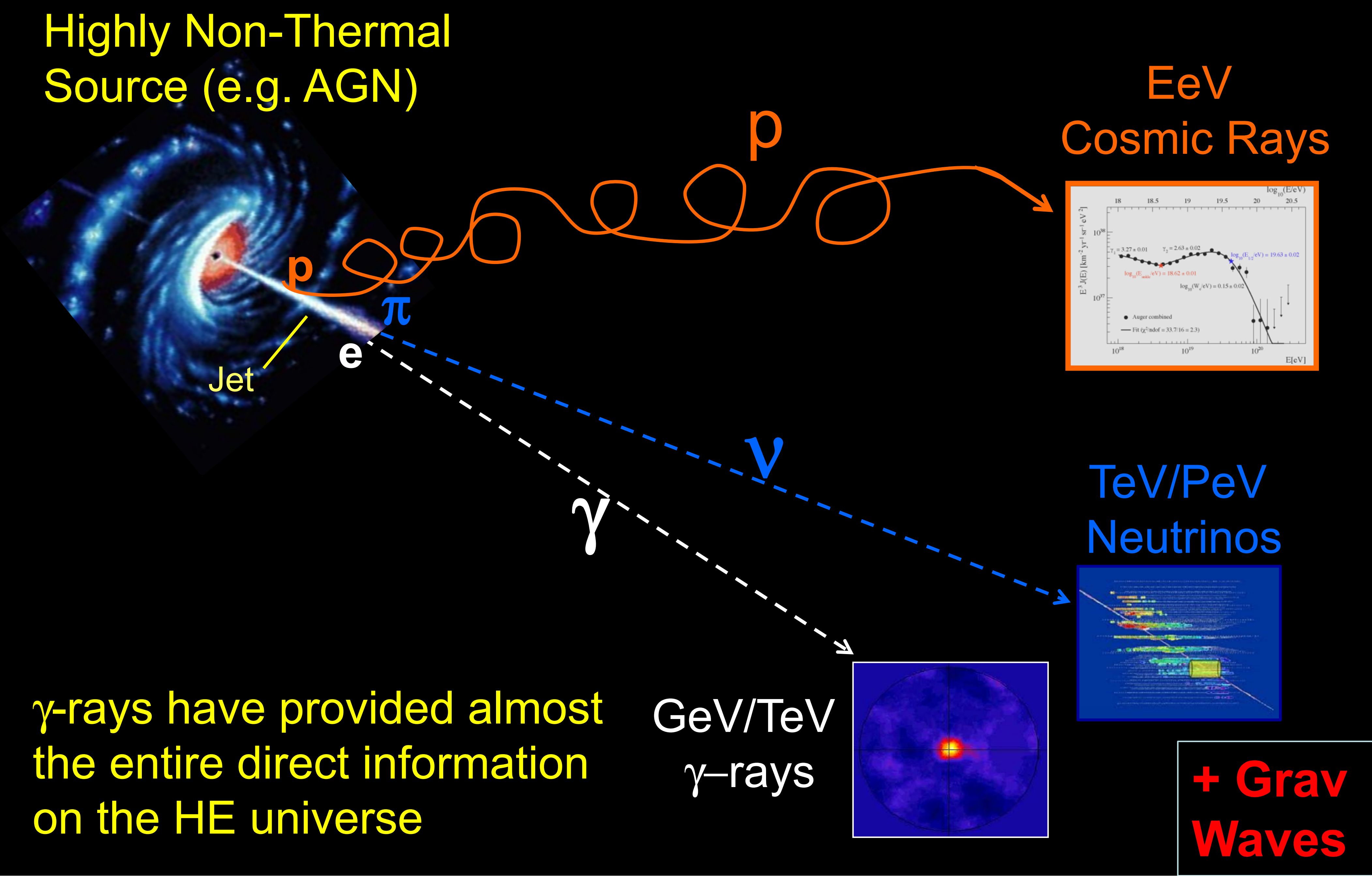
TeV γ-rays



TeV emission:

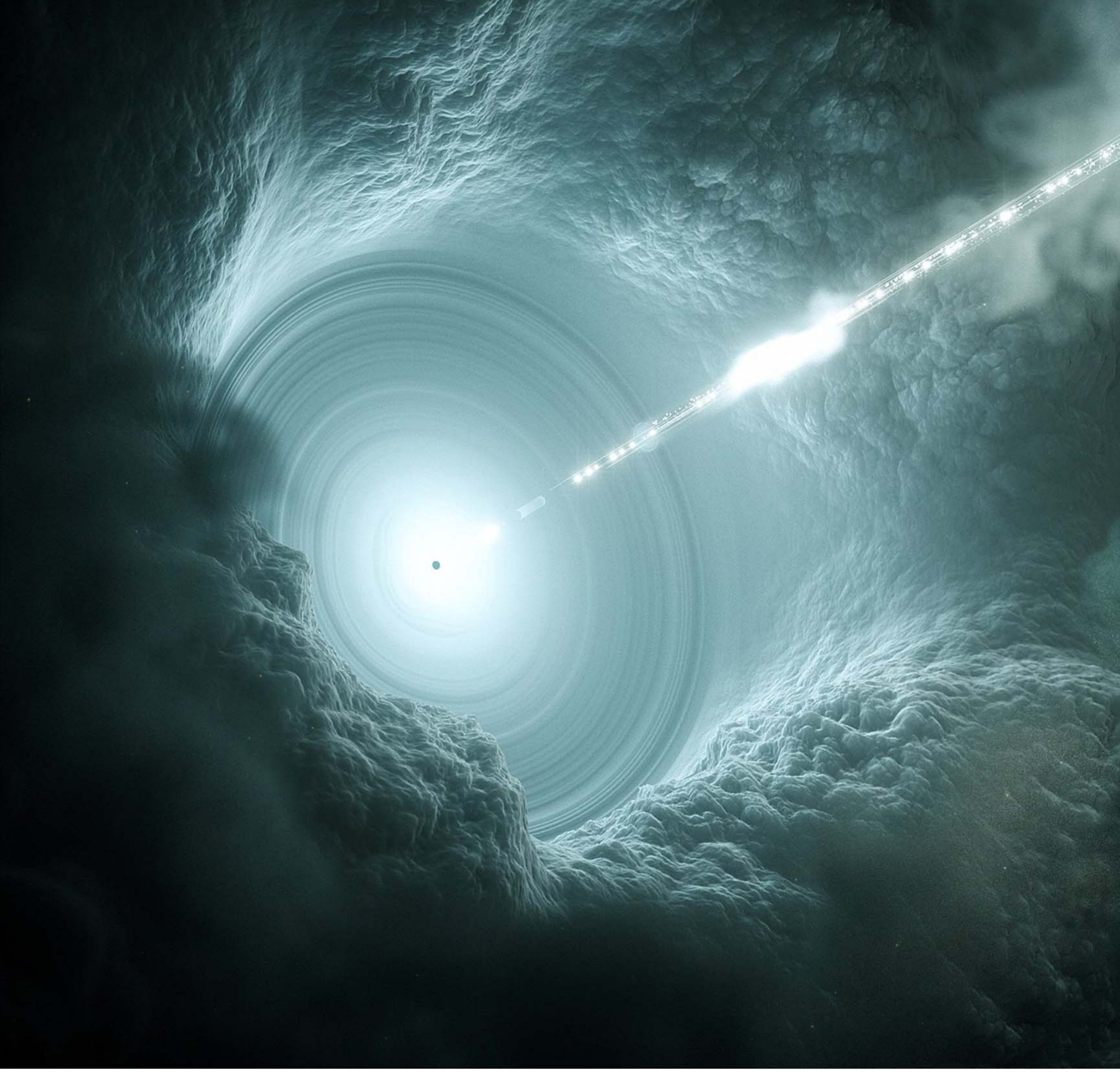
- A complete surprise!
- Central source: Sgr A*, intense and non-thermal
- Diffuse emission up to 40 TeV, likely PeVatron origin

Multi-Messenger Astronomy



γ-rays have provided almost the entire direct information on the HE universe

γ-rays and Neutrinos



First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
*on **4 Oct 2017; 17:17 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

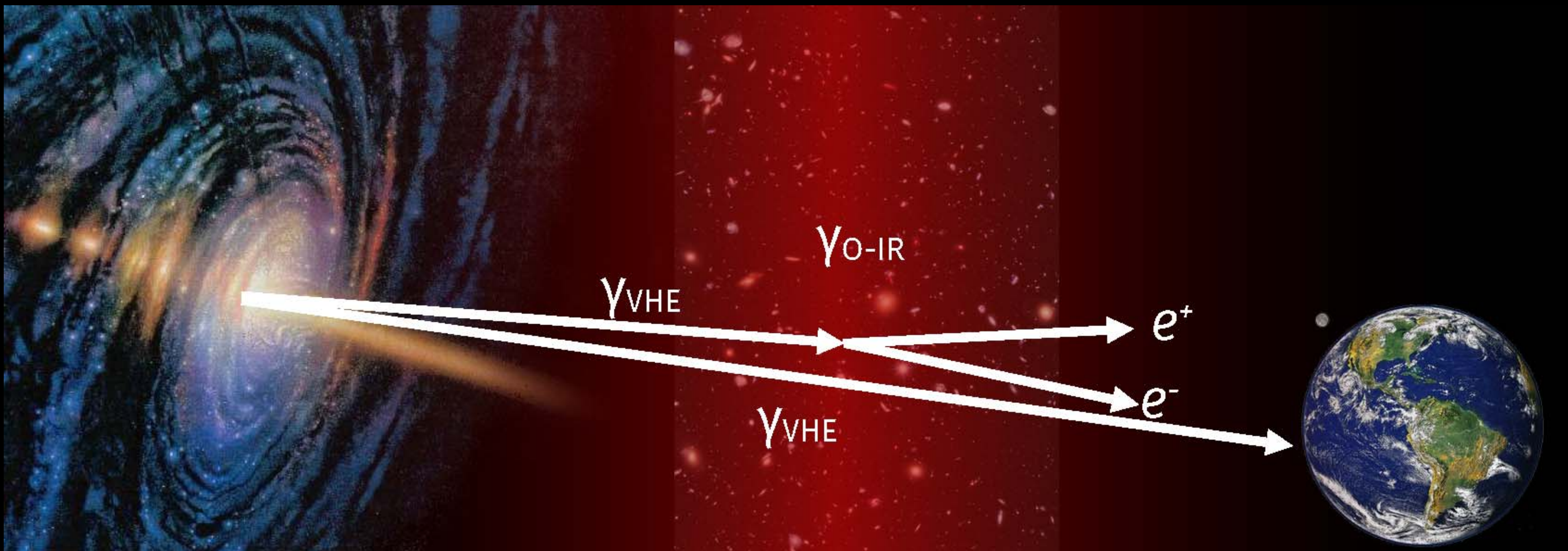
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942, 12260

Tweet

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

The universe illuminated by γ-rays

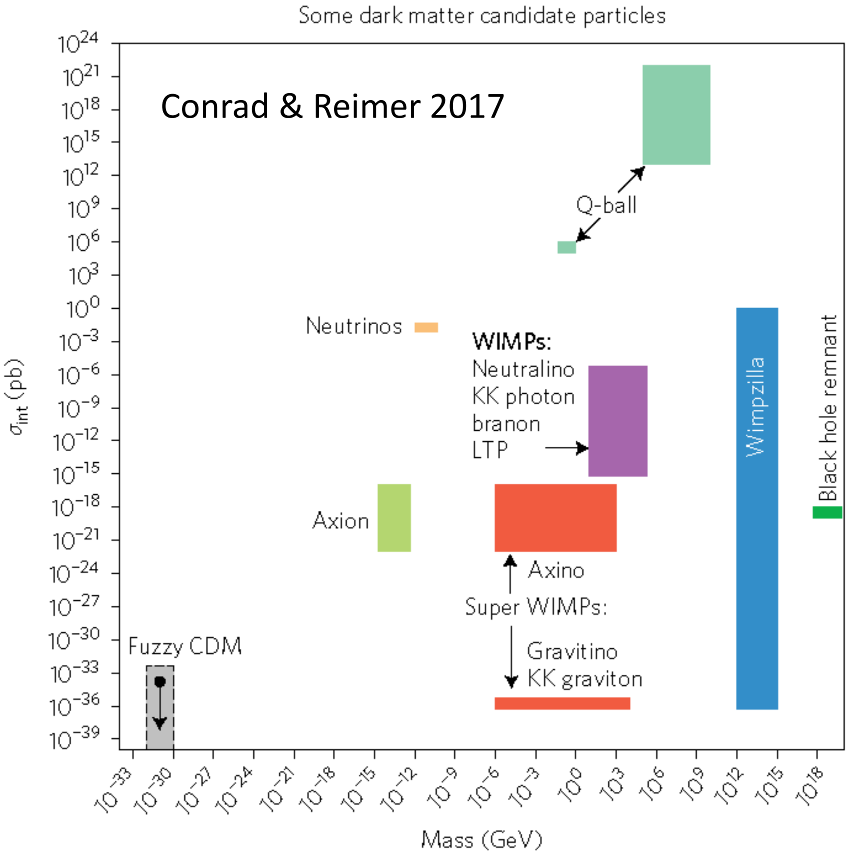


γ-rays from distant sources interact with cosmic photon fields

Signatures at Earth (spectral, temporal, angular) →

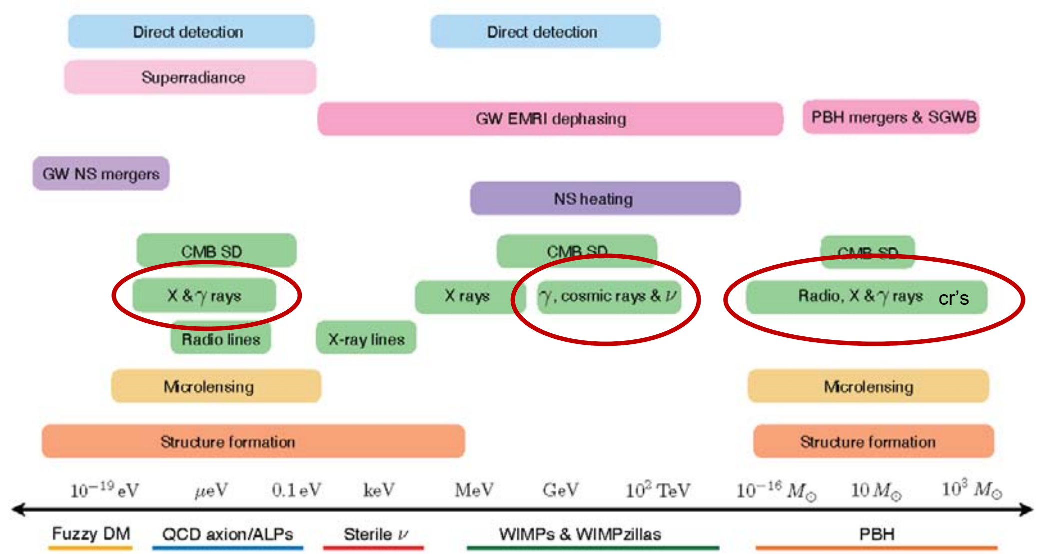
- Measurement of O/IR radiation from star formation
- Constraints on (tiny) intergalactic B field
- Search for ALP dark matter

Dark Matter Candidates & Probes



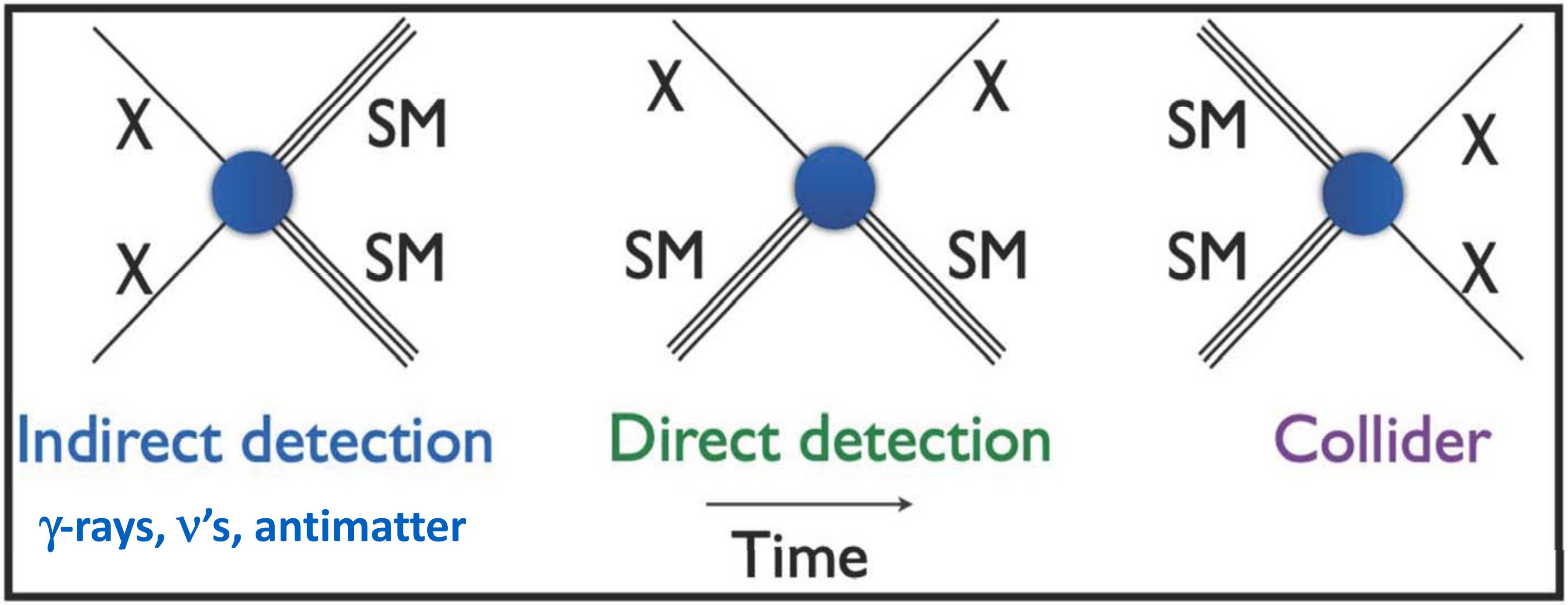
- Among the best motivated candidates are the WIMP and the axion.

EuCAPT White Paper
2110.10074



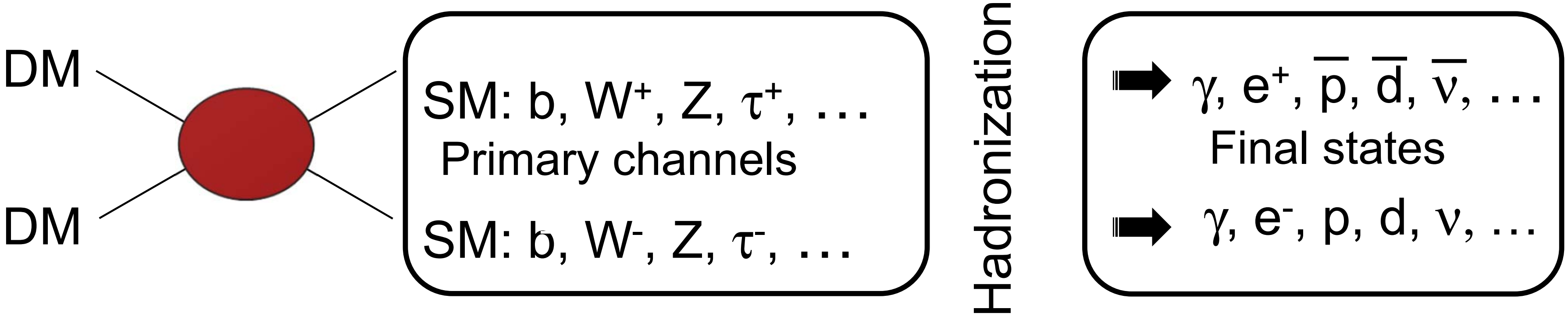
- WIMPs, PBHs, and ALPs are probed by γ-ray measurements.
- For this talk, I focus on WIMPs.

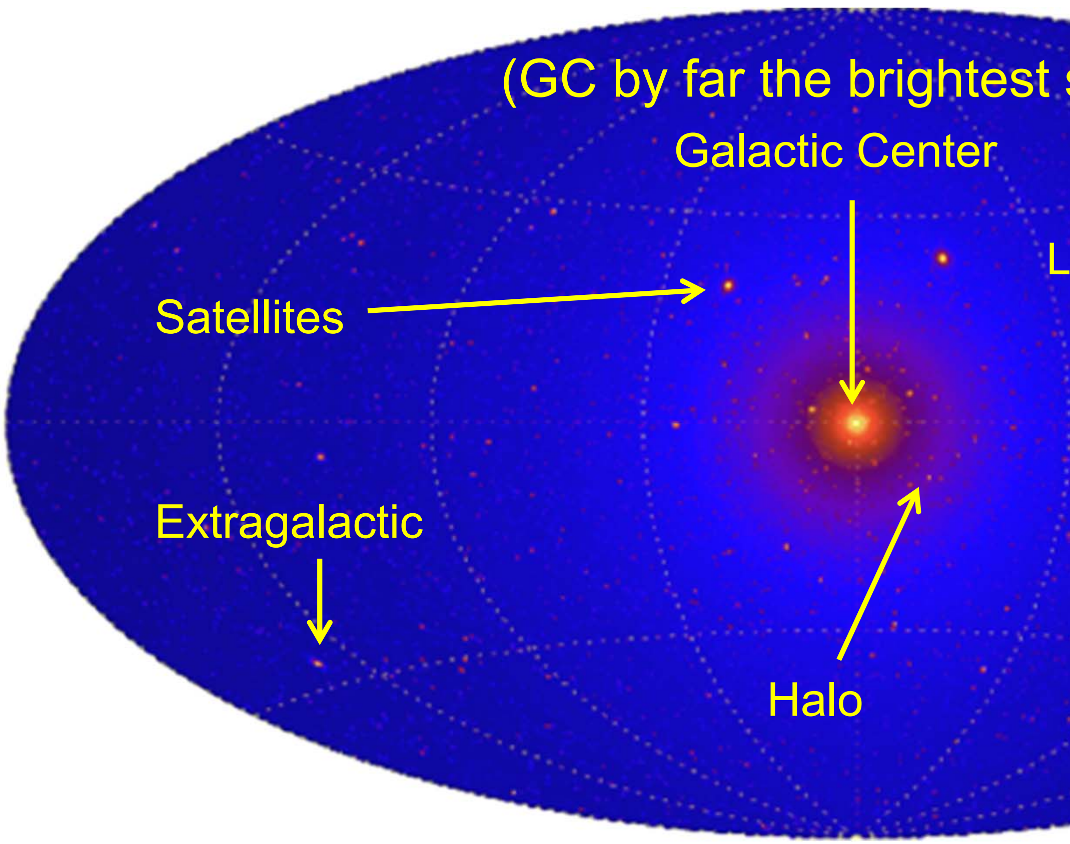
WIMP Complementary Approaches

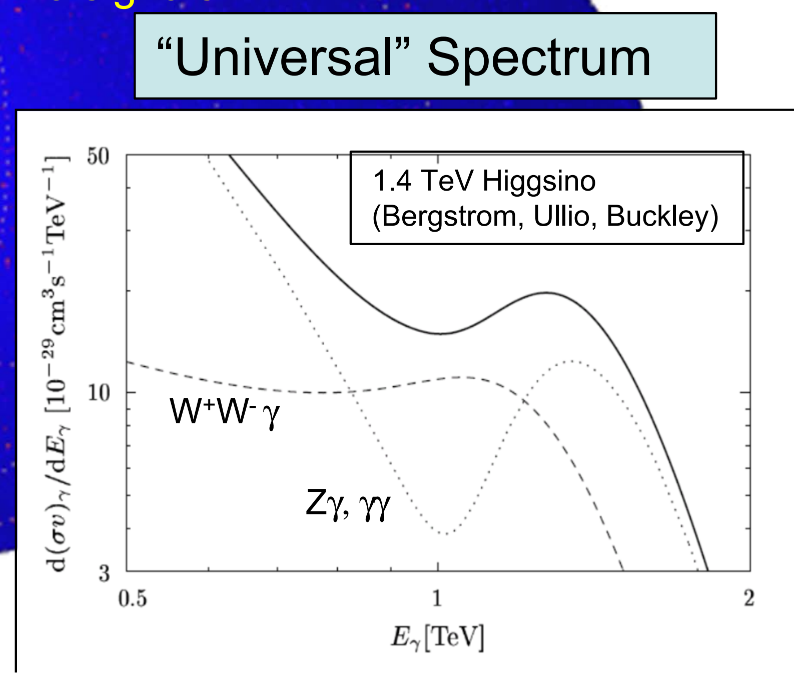


- ❑ Each approach has its own strengths and weaknesses.
- ❑ The BSM physics is unknown and there is a large amount of parameter space, so we need to take many different approaches.

Indirect Detection of DM



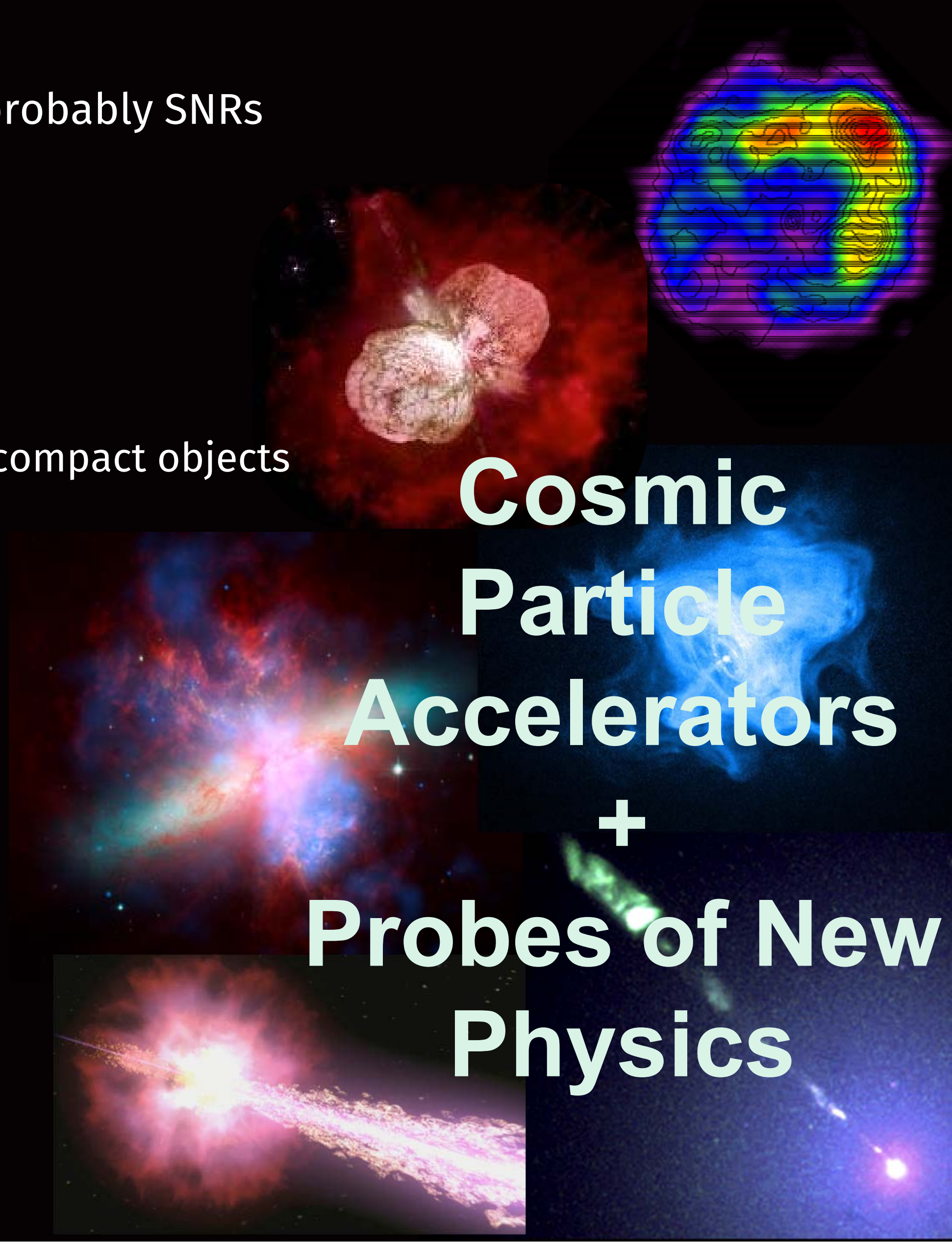


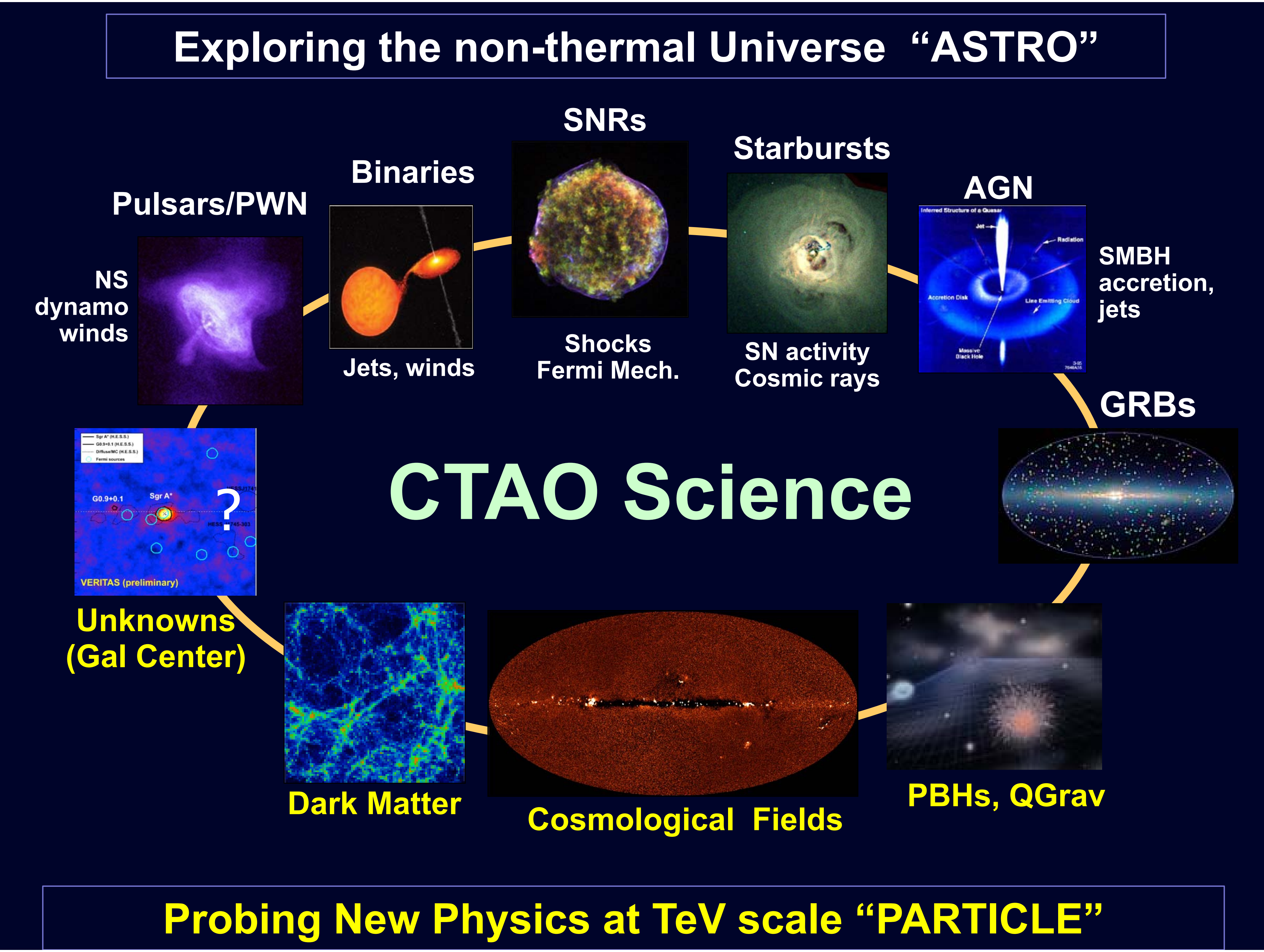


Ultimate goal: Dark Matter Astronomy

VHE Astronomy Comes of Age

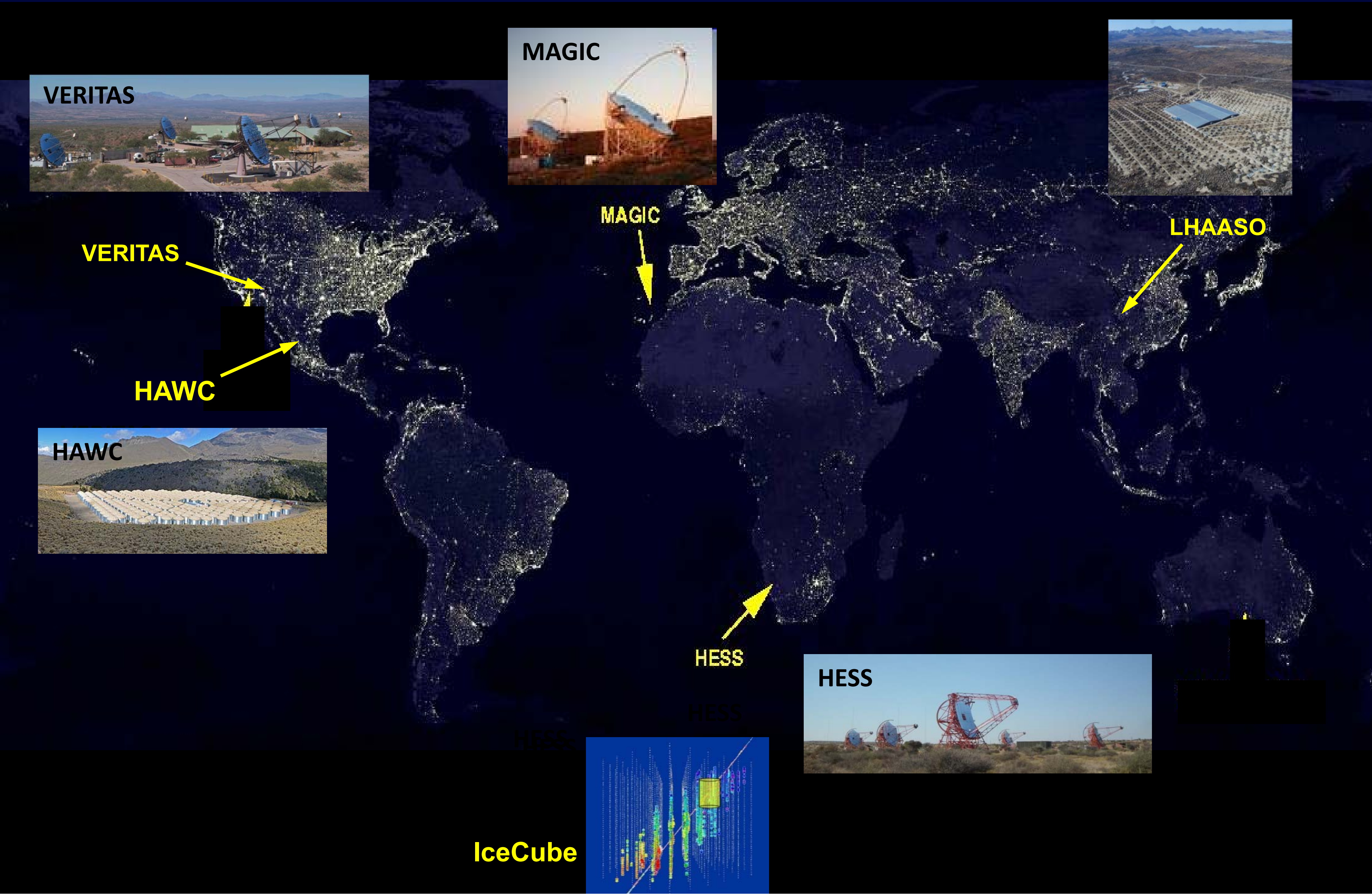
- Dominant expectation (pre-2000)
  - Will find the <u>cosmic ray accelerators</u> – probably SNRs
- Reality (present day)
  - Astonishing variety of TeV emitters
    - Within the Milky Way
      - Supernova remnants
      - Bombarded molecular clouds
      - Stellar binaries - colliding winds, compact objects
      - Massive stellar clusters
      - Pulsars and pulsar wind nebulae
      - Novae
      - Supermassive black hole Sgr A*
      - Sensitive searches for DM
    - Extragalactic
      - BL Lac objects
      - Flat-spectrum radio quasars
      - Radio galaxies
      - MW satellites
      - Starburst galaxies
      - EBL and IGMF constraints
      - Gamma-ray bursts
      - Neutrino counterparts
      - GW follow-up

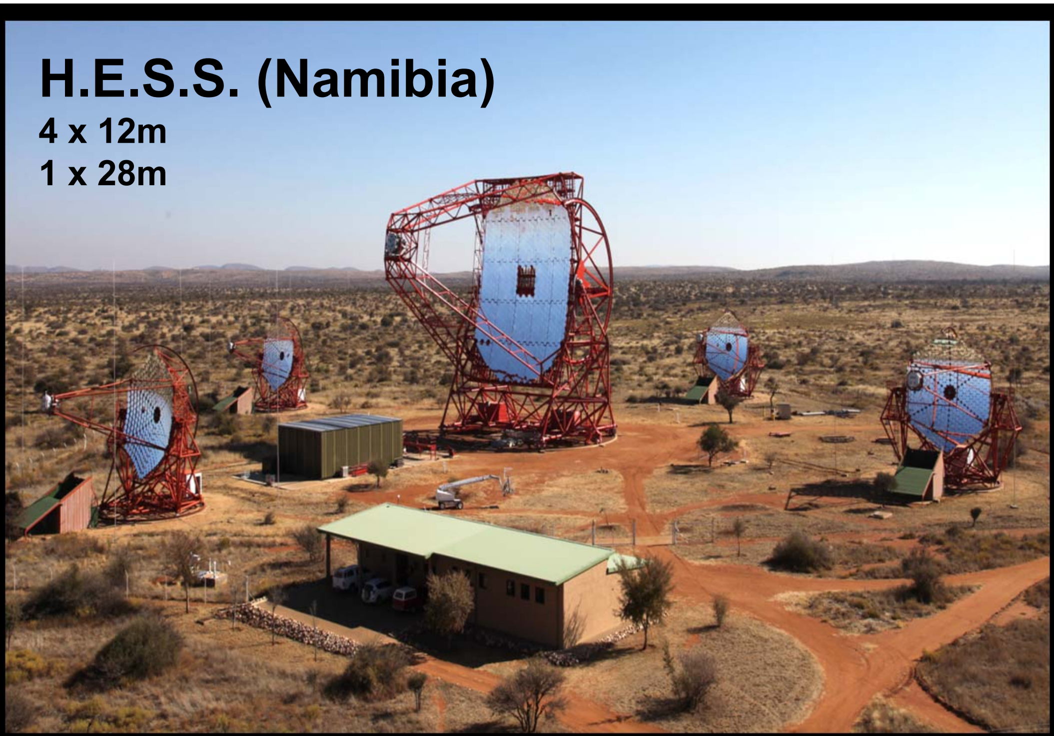



Exploring the non-thermal Universe "ASTRO"
SNRs
Starbursts
Binaries
AGN
Pulsars/PWN
SMBH
accretion,
jets
NS
dynamo
winds
Inferred Structure of a Quasar
Jet
Radiation
Accretion Disk
Line Emitting Cloud
Massive Black Hole
Shocks
Fermi Mech.
SN activity
Cosmic rays
Jets, winds
GRBs
Sgr A*
G0.9+0.1
?
VERITAS (preliminary)
CTAO Science
Unknowns
(Gal Center)
Dark Matter
Cosmological Fields
PBHs, QGrav
Probing New Physics at TeV scale "PARTICLE"

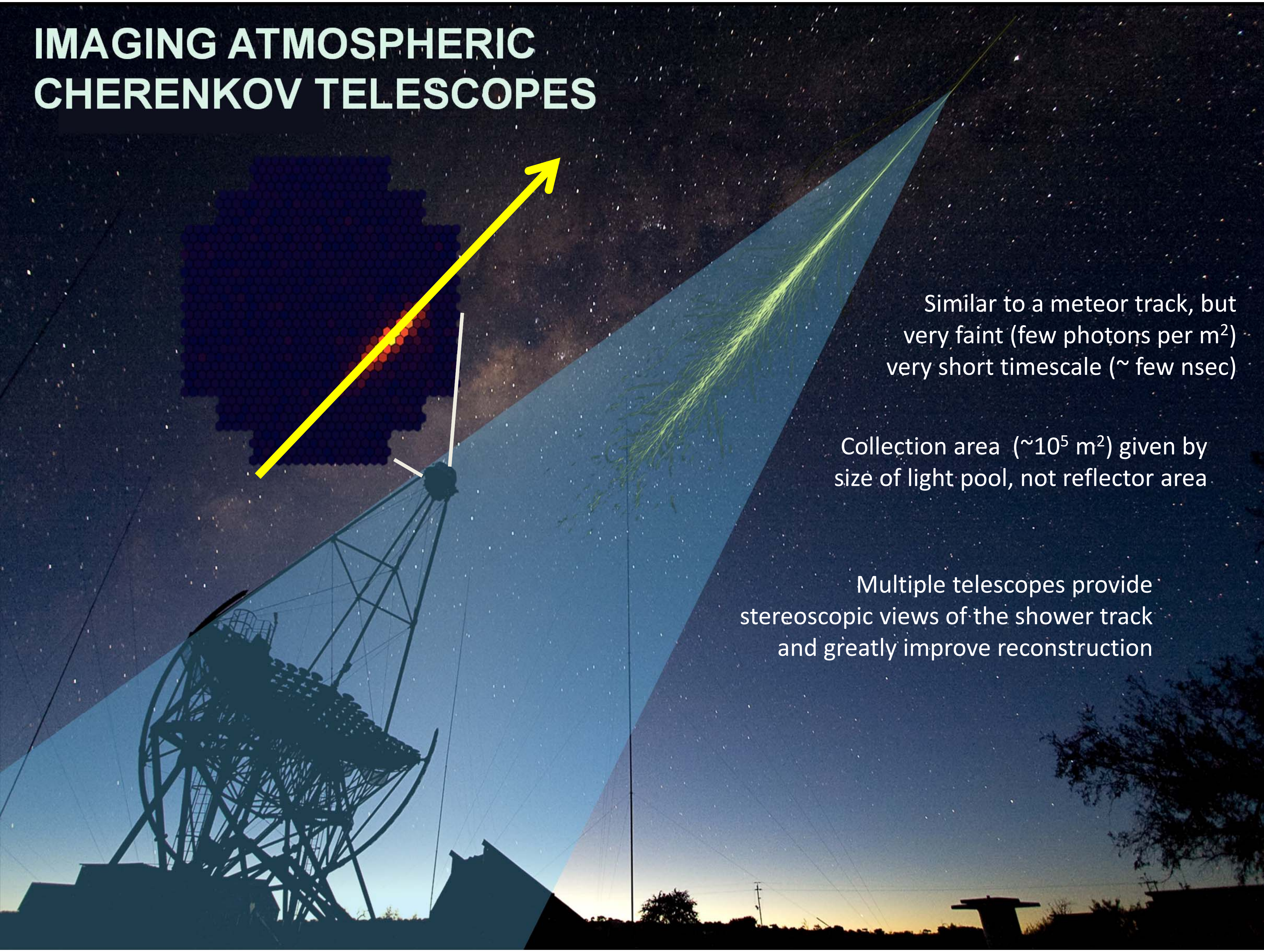
Experimental Technique
&
Planning for the Future

VHE Telescopes (2024)



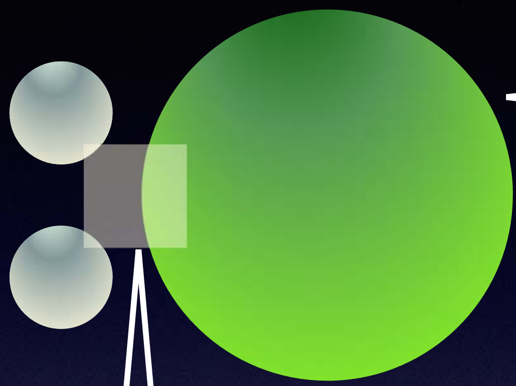


Current instruments – small # of telescopes covering a moderate area


IMAGING ATMOSPHERIC CHERENKOV TELESCOPES
Similar to a meteor track, but very faint (few photons per m²) very short timescale (~ few nsec)
Collection area (~10⁵ m²) given by size of light pool, not reflector area
Multiple telescopes provide stereoscopic views of the shower track and greatly improve reconstruction

CURRENT INSTRUMENTS VS CTAO

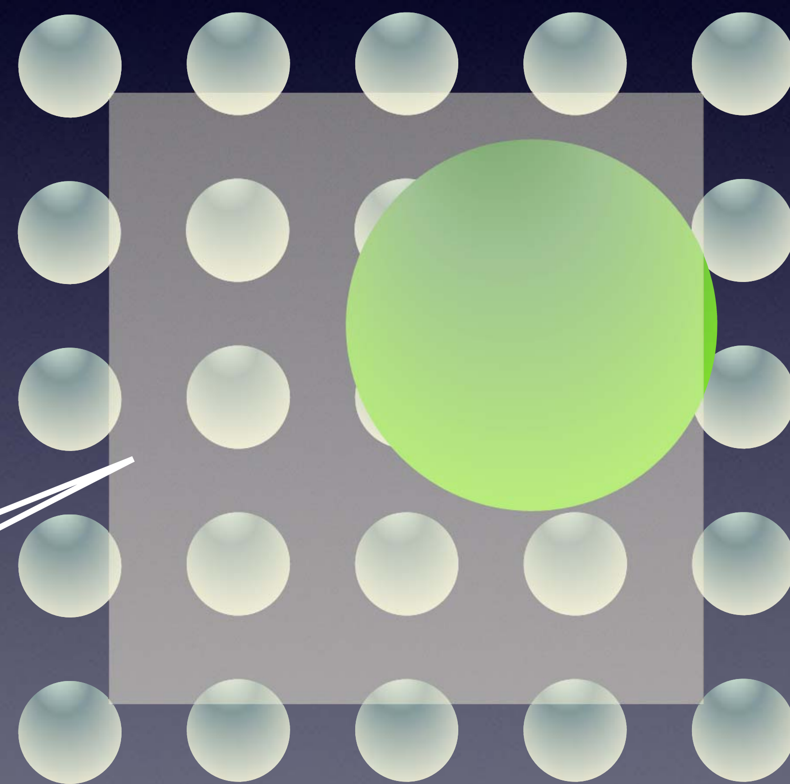
Current Instruments



Light pool radius
R ≈ 125m
≈ typical telescope Spacing

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

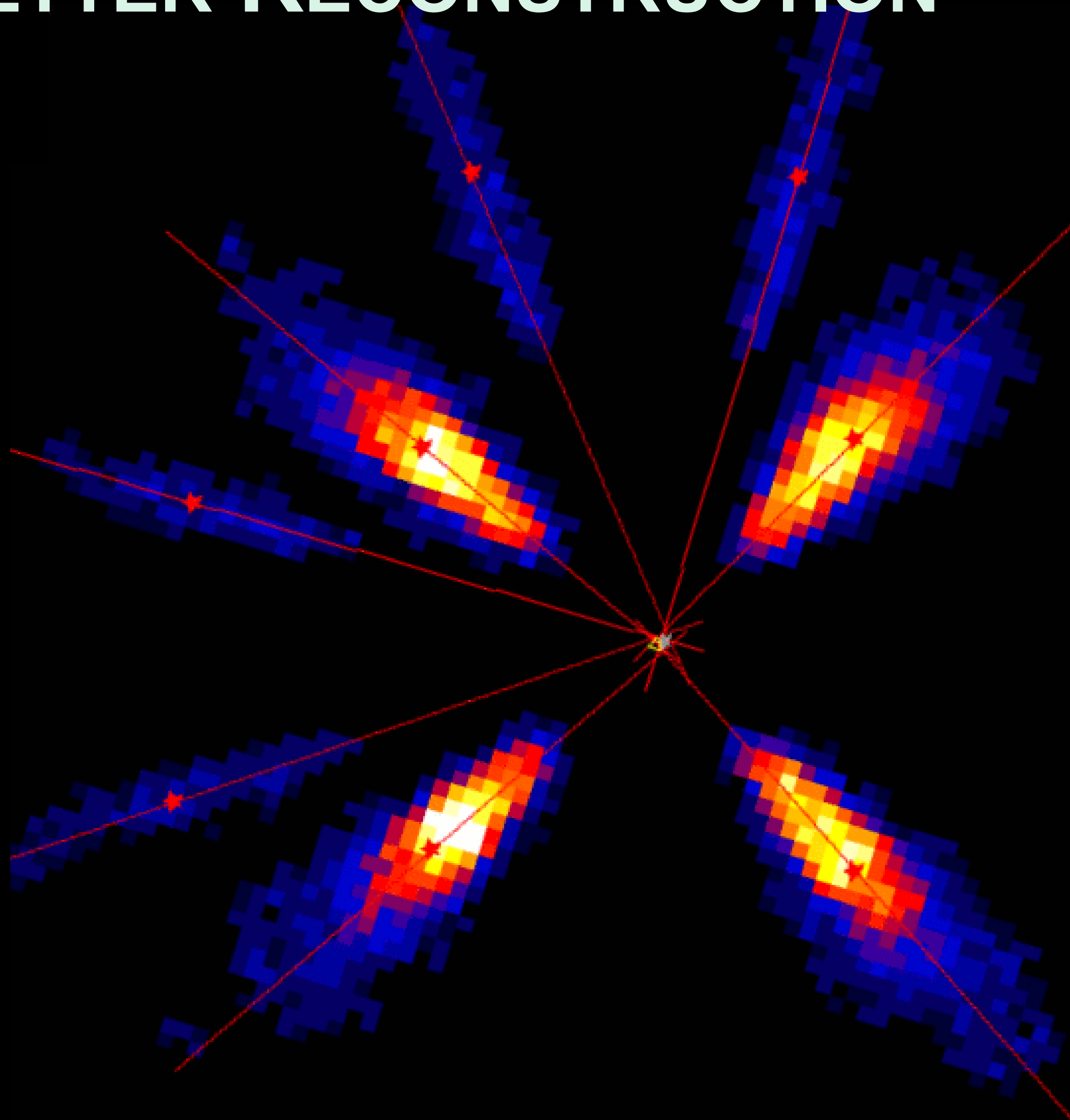
CTAO



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

More Images → Better Reconstruction

- → Multiple views of shower
  - ▸ Better measurement of air shower and hence primary gamma ray
    - ✓ Improved angular resolution
    - ✓ Improved background rejection
    - ✓ Better spectra, images
  - ▸ Collect more photons
    - ✓ Larger light collecting area
      → detect fainter sources
- → More telescopes!



Simulation:
Superimposed images from 8 cameras

Planning for the Future

What do we know, based on current instruments?

Great scientific potential exists in the VHE domain

- *Frontier astrophysics & important connections to particle 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 access/data, MWL/MM connections for the best science*

International Partnership required by the project scope

- *Many funding streams → **a challenge to coordinate***


ctao
cherenkov telescope array

CTAO Science Themes

Theme 1: Cosmic Particle Acceleration

- Where and how 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?
- What is the nature of 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?

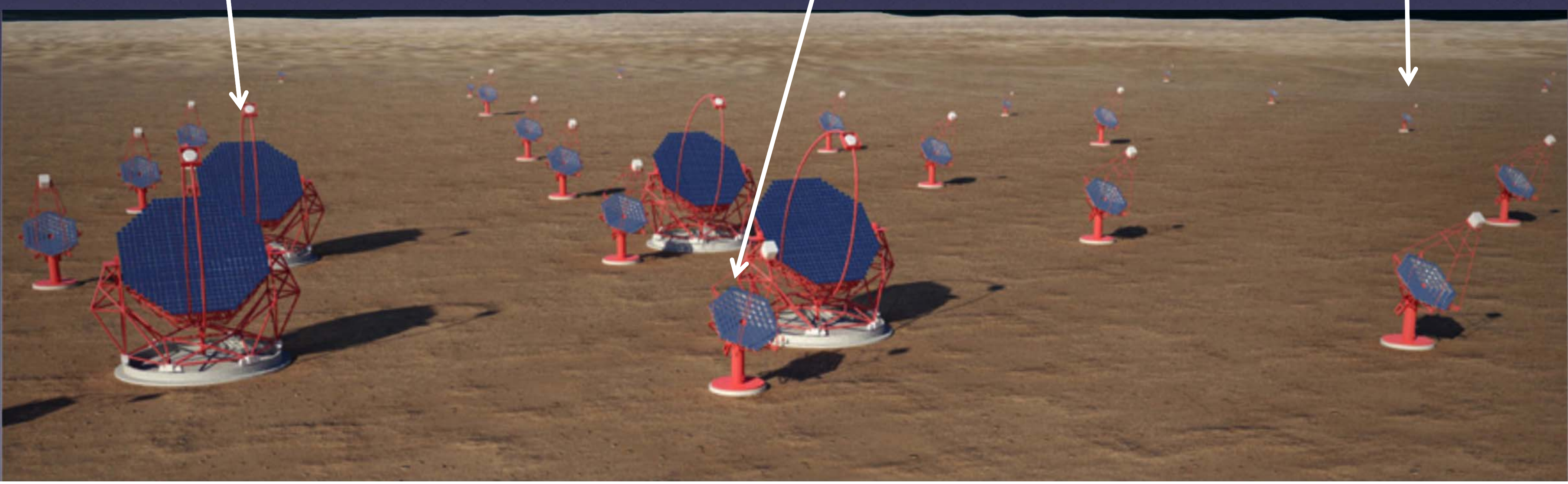
CTAO Design (S array)

Beta Configuration = Initial Arrays

Low energies
Energy threshold 20 GeV
23 m diameter
2-3 telescopes
(LST's)

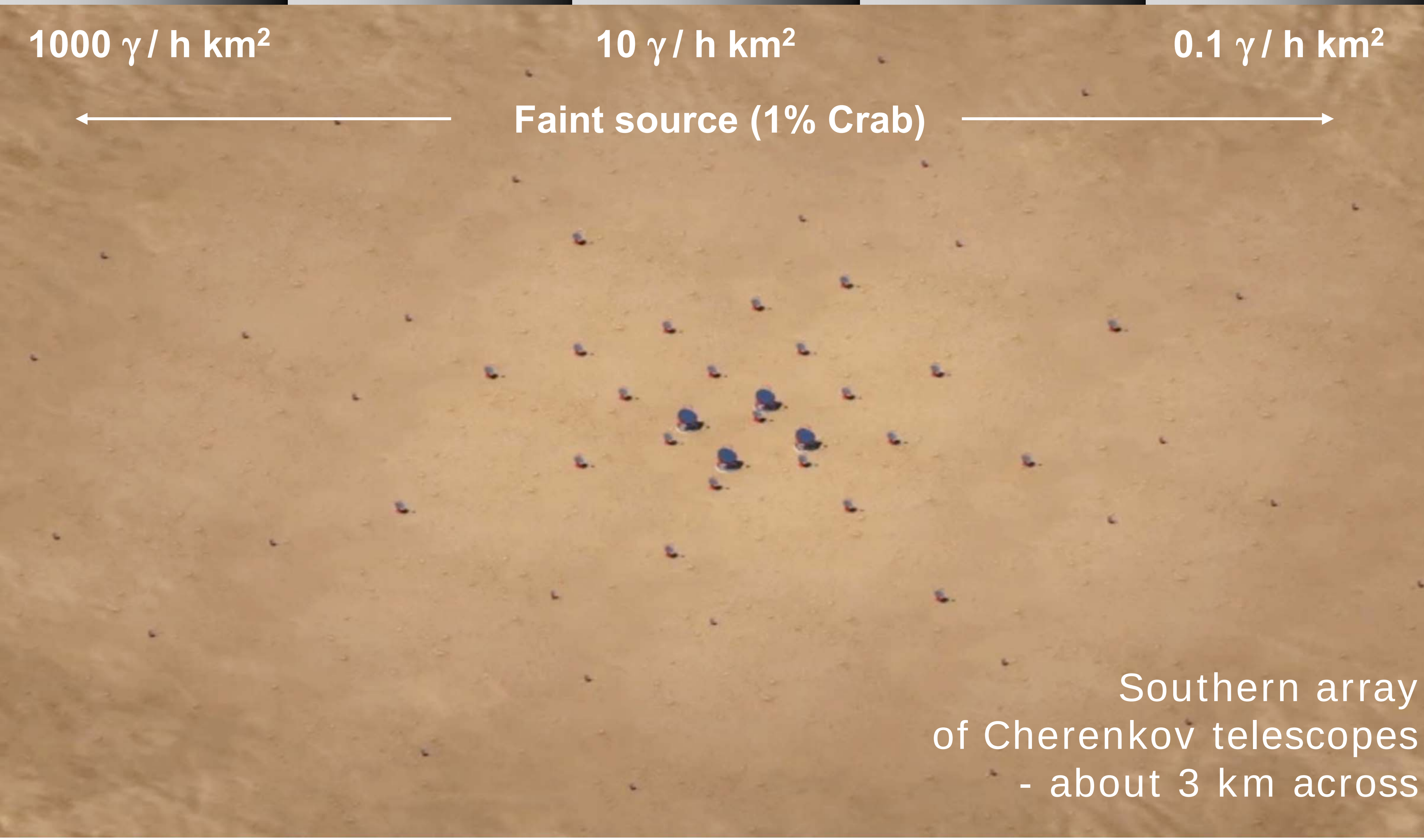
Medium energies
100 GeV – 10 TeV
12 m diameter
14 telescopes
(MST's)

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



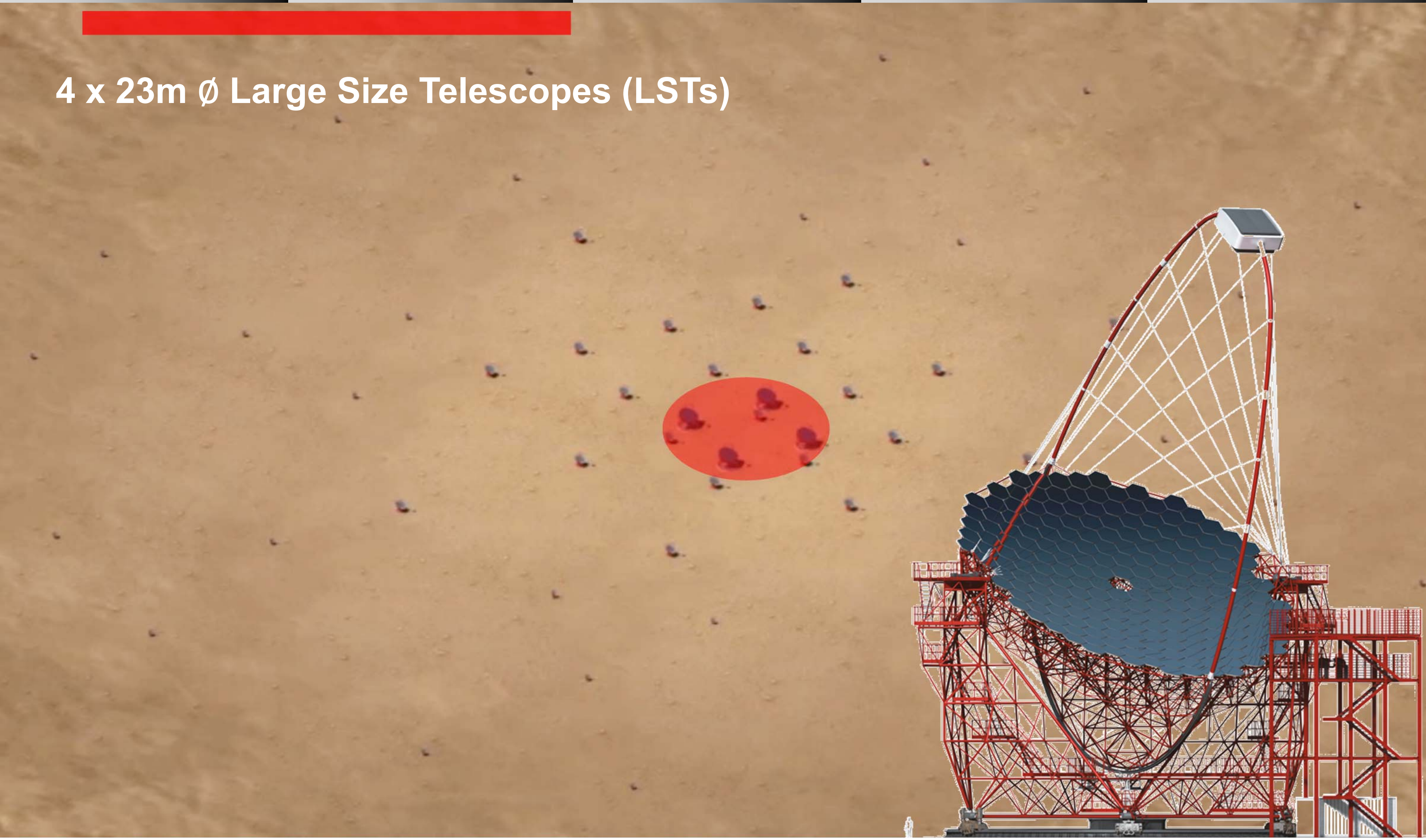
Cherenkov Telescope Array Observatory (CTAO)

10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV



Cherenkov Telescope Array Observatory (CTAO)

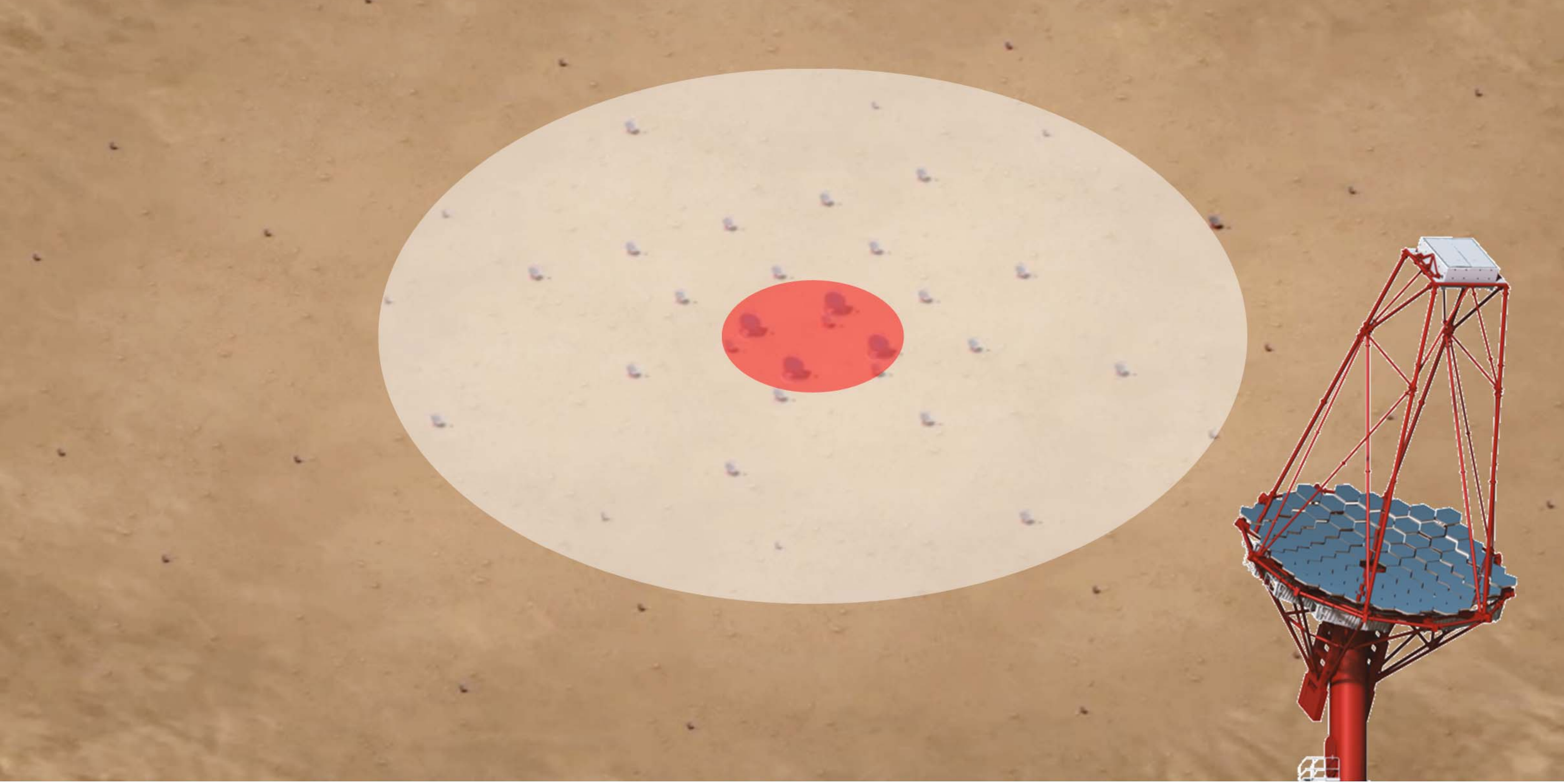
10 GeV	100 GeV	1 TeV	10 TeV	100 TeV



Cherenkov Telescope Array Observatory (CTAO)

10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

14 x 12m Ø Medium Size Telescopes (MSTs) (North: 9)



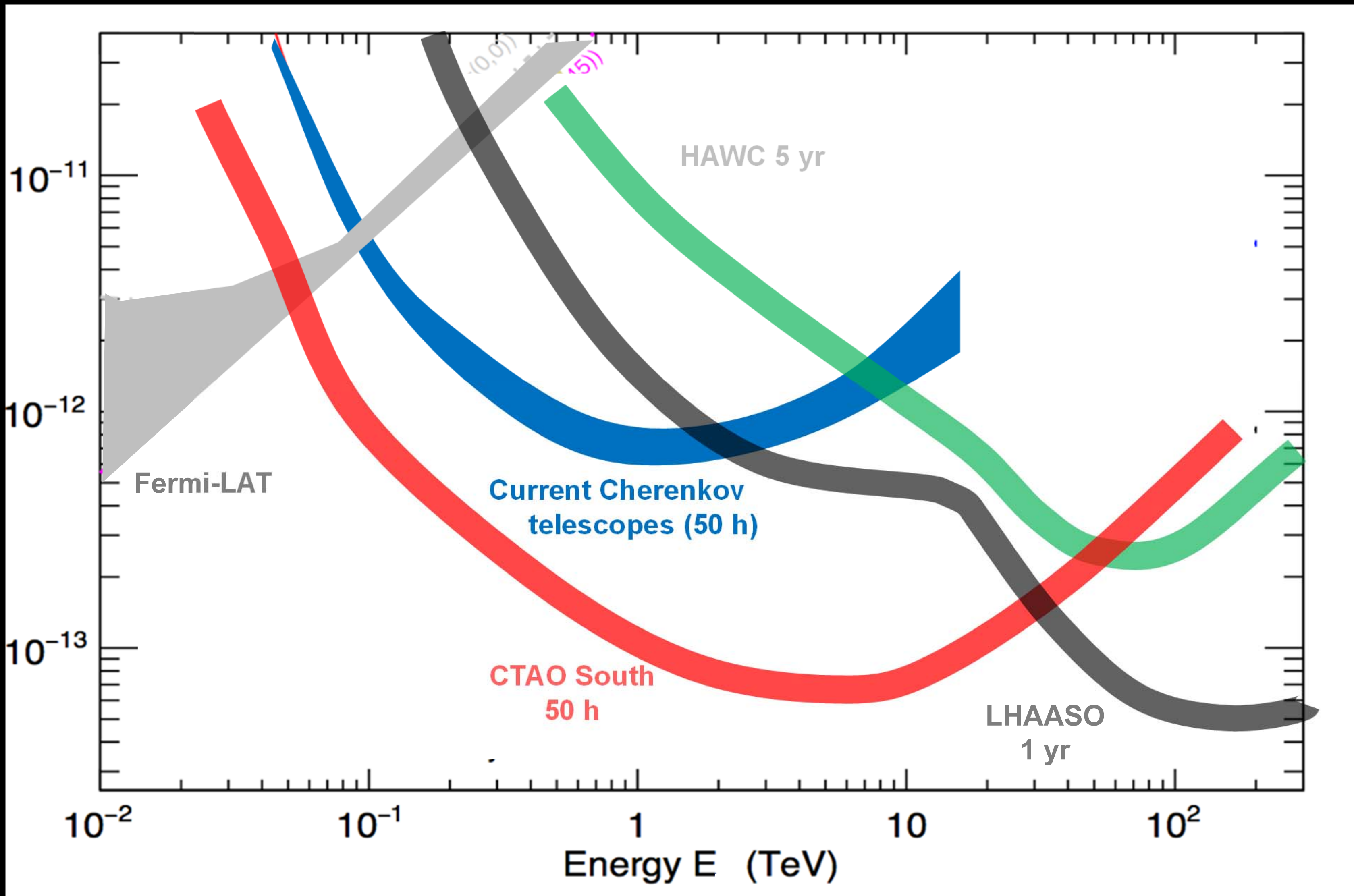
Cherenkov Telescope Array Observatory (CTAO)

10 GeV	100 GeV	1 TeV	10 TeV	100 TeV

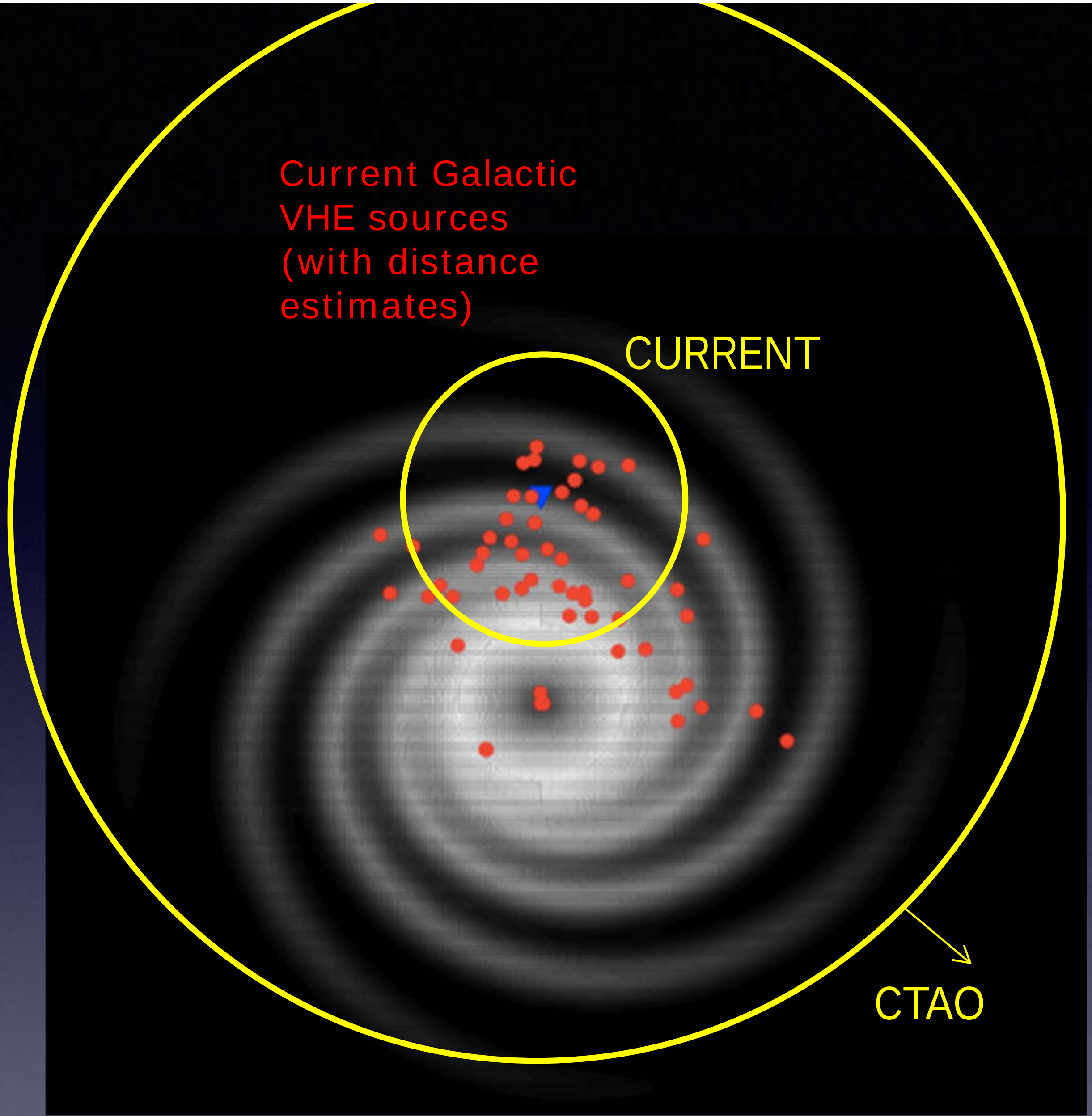
Sensitivity (steady sources)

CTAO
Cherenkov Telescope Array Observatory

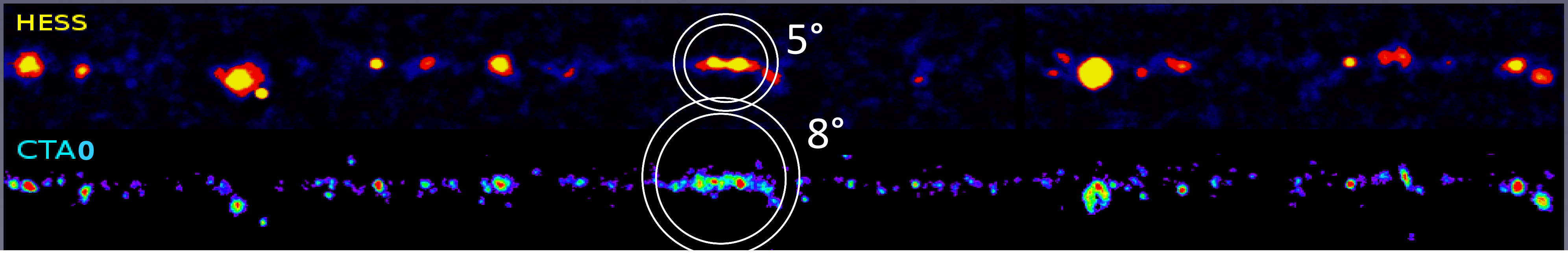
$E^2\,dN/dE$
$= \nu F_\nu$
($erg/cm^2/s$)



Galactic Discovery Reach



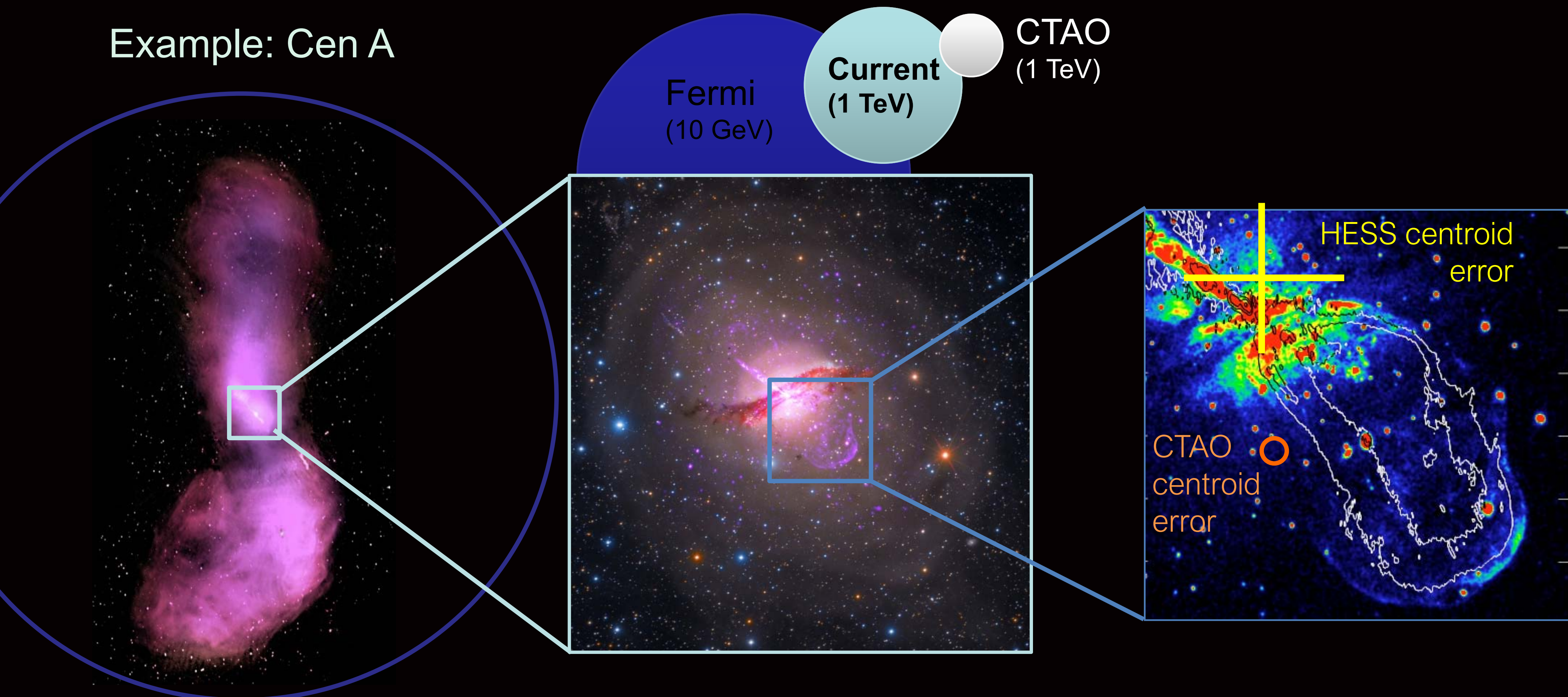
Survey speed:
x300 faster than current



Angular Reconstruction

CTAO
Cherenkov Telescope Array Observatory

Example: Cen A



Field of View (8°)

Angular resolution (2’)

Source Localization (5’’)

CTAO Implementation & Status

CTAO Timeline

CTAO
Cherenkov Telescope Array Observatory

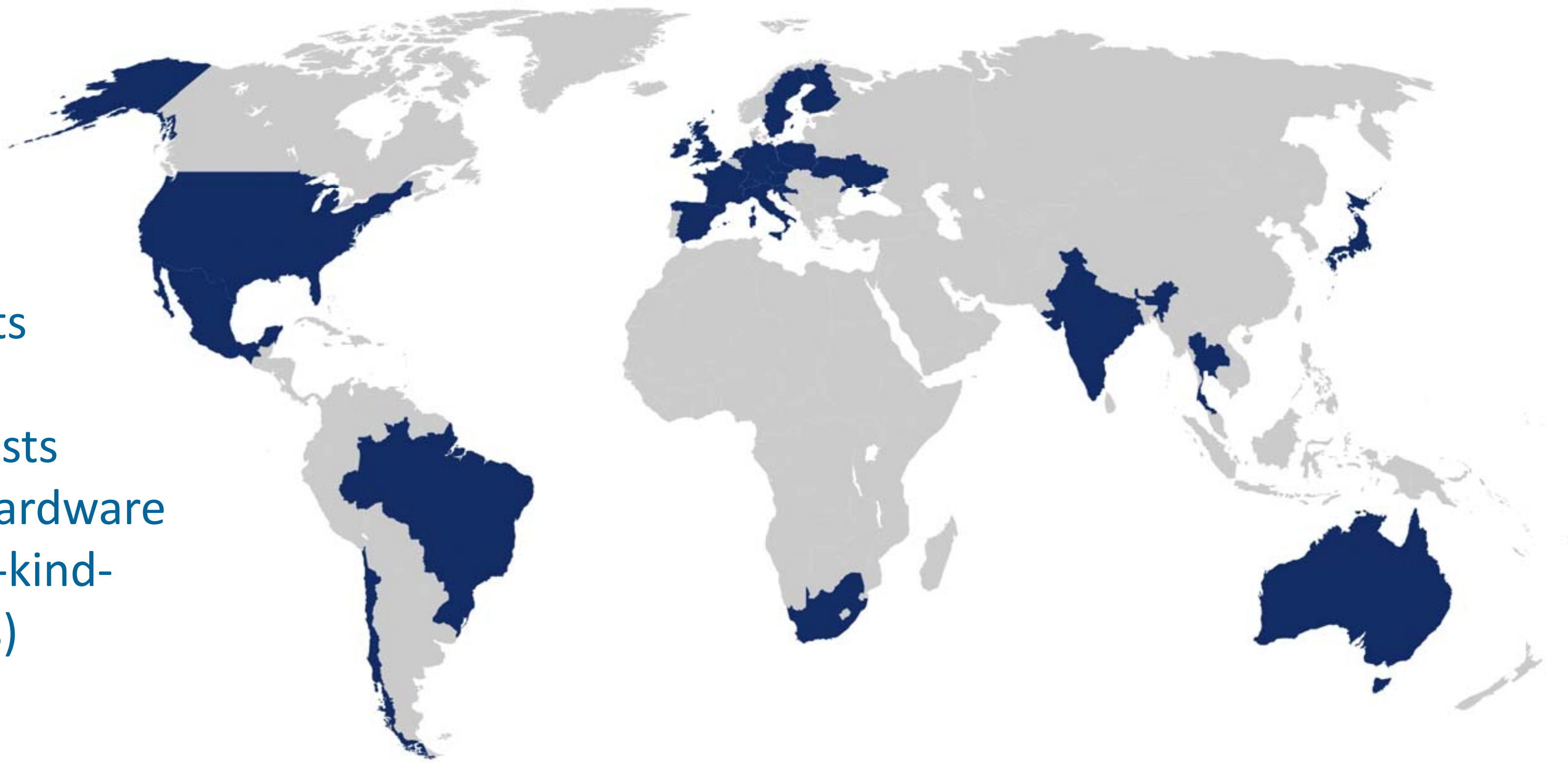
2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024

- 2005: Palaiseau γ-ray meeting
- 2006: CTA as "emerging proposal" on ESFRI Roadmap
- 2008: CTA Consortium formed, AGIS (US) Formed
- 2008: CTA on ESFRI Roadmap
- 2010: Project Office established, US Decadal Survey
- 2011: Agency Resource Board founded
- 2012: Declaration of Intent by agencies
- 2014: CTAO GmbH founded
- 2015: Design Report
- 2015: Site decisions
- 2016: Bologna as future HQ
- 2018: SST selection
- 2019: LST-1 (CTAO-N) starts operations
- 2022: Alpha config. funded
- 2023: CTAO-N construction ongoing
- 2024: CTAO-S construction start
- 2027-8: Interim arrays – initial data

→ Large projects take a long time.

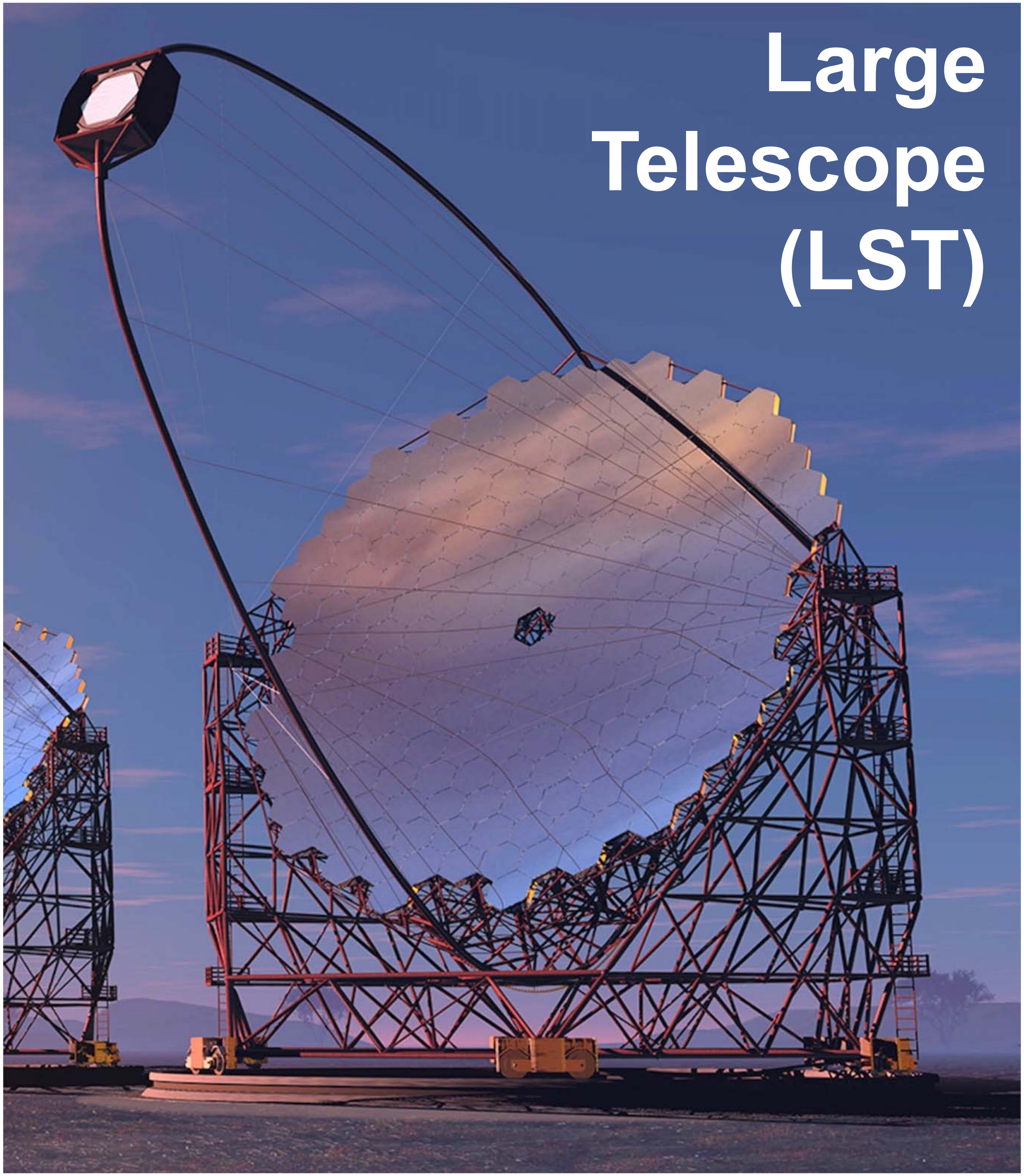
CTAO Consortium

CTAO
Cherenkov Telescope Array Observatory



25 Countries
over 150 Institutes
over 1000 Scientists

Consortium scientists will supply CTAO hardware and software as in-kind-contributions (IKCs)



23 m diameter
390 m^2 dish area
28 m focal length
1.5 m mirror facets

4.5^o field of view
0.1^o pixels (PMTs)
Camera Ø over 2 m

Carbon-fiber structure for 20s positioning

Active mirror control

2-3 LSTs on South site
4 LSTs on North site

LST-1 operational (La Palma), LST-2, LST-3, LST-4 in construction

Medium Telescope (MST)

CTAO
Cherenkov Telescope Array Observatory

12m diameter
100 m^2 mirror dish area
16 m focal length
1.2 m mirror facets

8^o field of view
~2000 x 0.18^o pixels
(PMTS)

14 MSTs on South site
9 MSTs on North site

Prototype near Berlin

Small Telescope (SST)

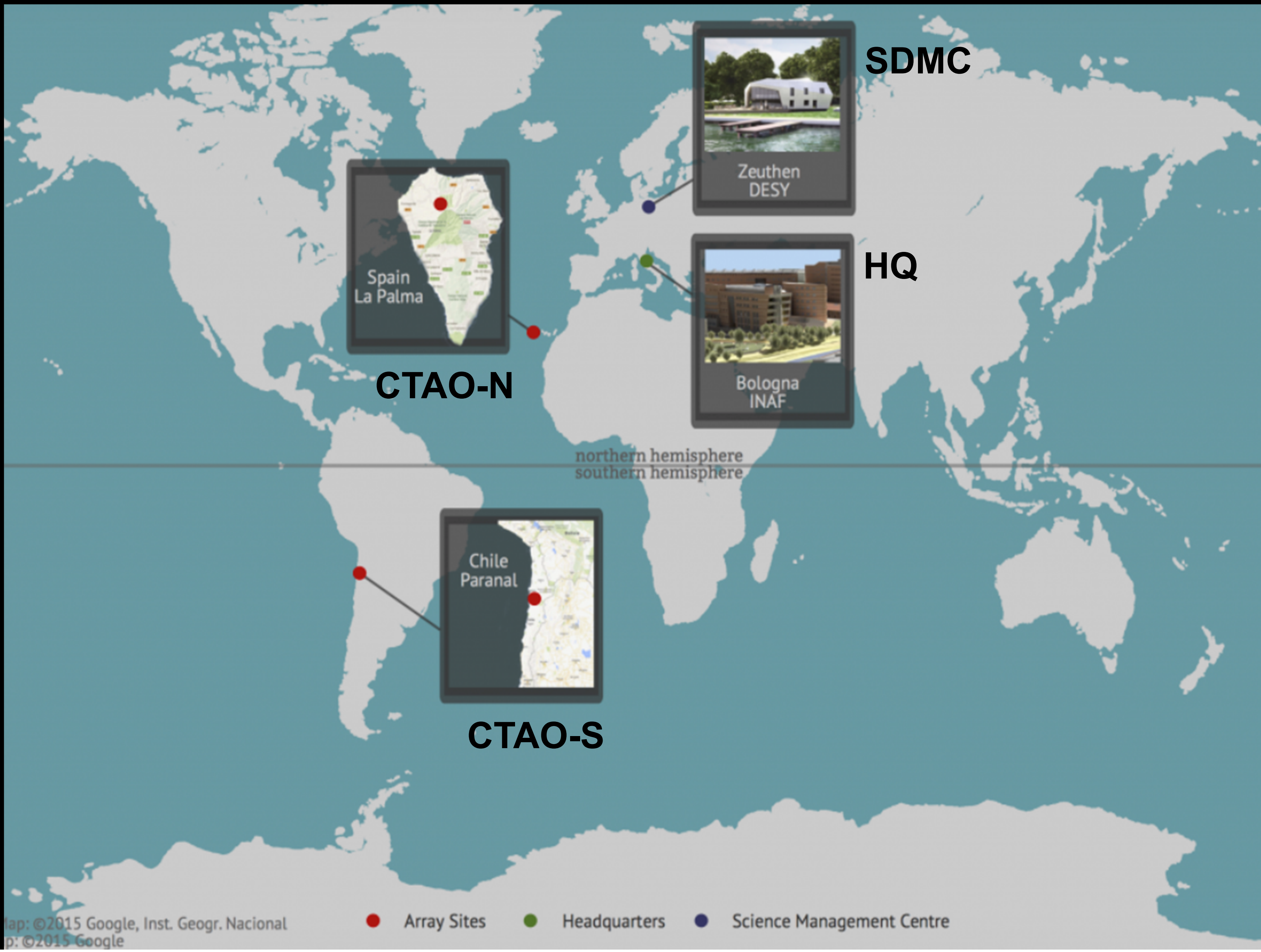
Schwarzschild-Couder design
5 m^2 dish area
4.3m primary mirror
1.8m secondary mirror

SiPM camera
8.8^o field of view
0.16^o pixels (SiPMs)

42 SSTs on South site

Major contribution of Italy

The CTAO Sites



CTAO-S

- Atacama Desert, Chile, below Cerro Paranal
- Existing observatory (ESO)
- Near existing (VLT) and future (ELT) telescopes
- Site agreement in place since 2018

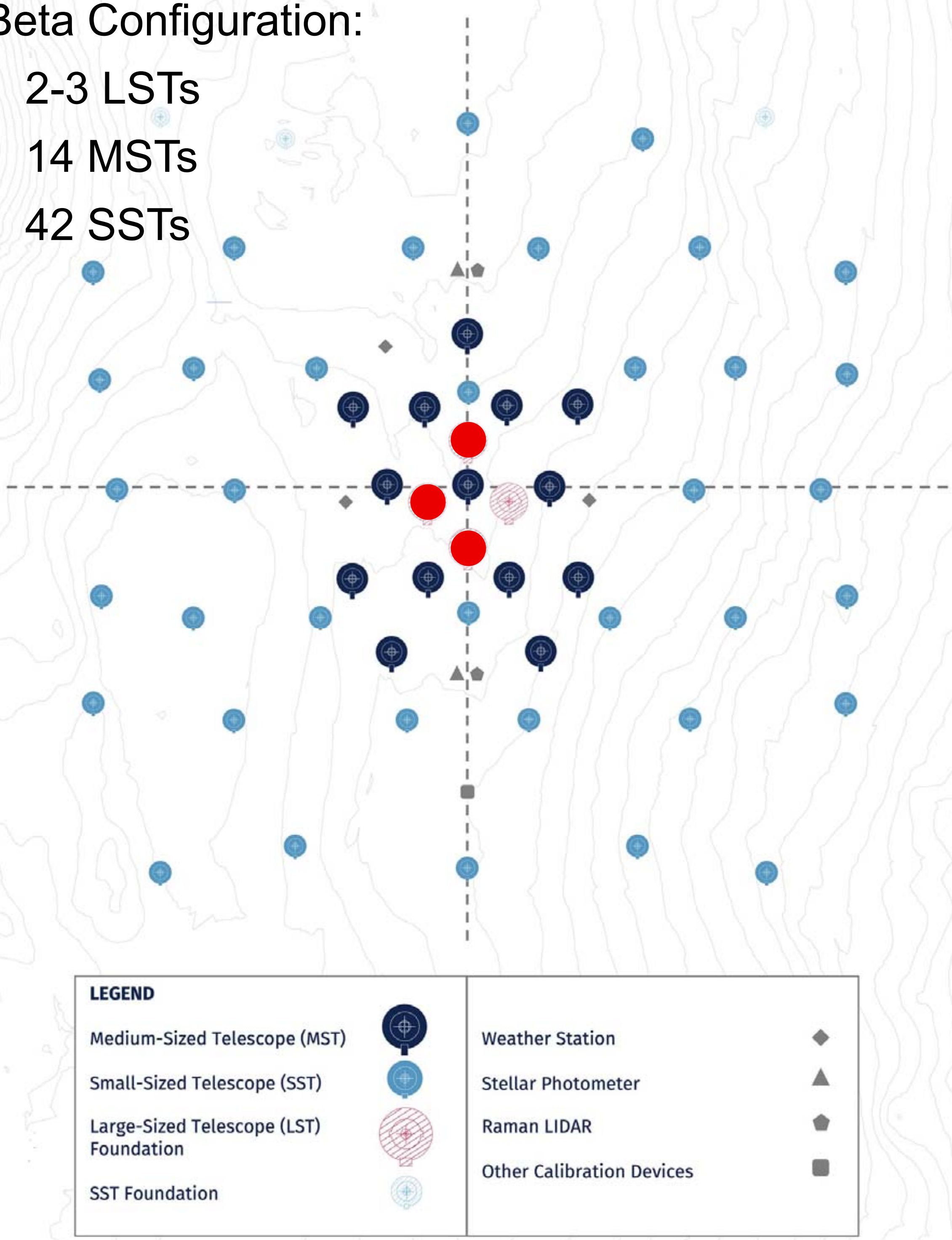
CTAO-S

Currently mostly empty desert, but significant construction (21M€) to start later in 2024:

- Power system, sub-station 1
- Road network, earthing grid
- Start of foundations

Beta Configuration:

- 2-3 LSTs
- 14 MSTs
- 42 SSTs



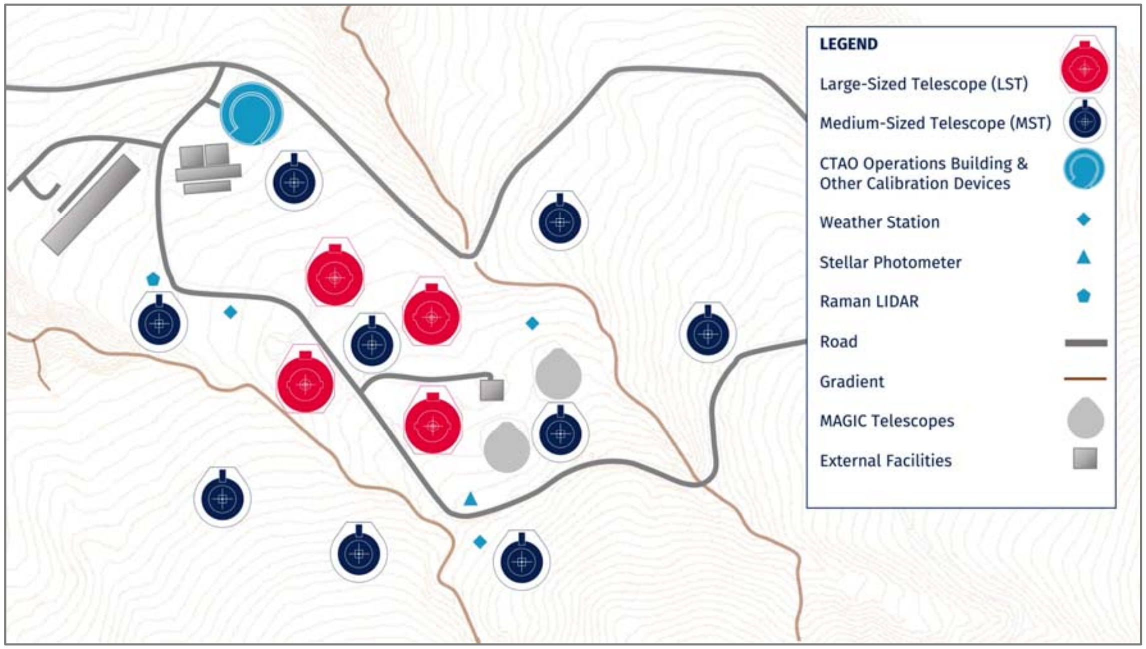
CTAO-N

- La Palma, Canary Islands, Spain
- Observatorio del Roque de los Muchachos
- Existing observatory (IAC)
- Site of LST-1 & existing MAGIC and optical telescopes
- Site agreement in place since 2017

CTAO-N

Beta Configuration:

- 4 LSTs
- 9 MSTs



LST-1:

- Commissioned in 2018; regular observations started in 2019, with a number of high profile results so far

Additional telescopes

- LST-2, LST-3, LST-4 currently under construction with planned completion at end of 2025
- MST-1 (pathfinder) scheduled for Q3 2025

LST Construction Feb 2024

Credit: D. Mazin


LST Construction
March 2024
Credit: D. Mazin

LST Construction
April 2024

Credit: IAC

CTAO Status c2024

CTAO has been in development since 2008, with many significant milestones achieved:

- Strong science case developed by the Consortium and well recognized within the community.
- Excellent progress made on the development of hardware – telescopes, cameras, readout electronics, atmospheric monitoring, computing, etc. – carried out by the IKC providers.
- Software development is progressing well – both back-end (pipeline, low-level data products, etc.) and front-end (scheduler, data portal, user tools, etc.). 2nd Science Data Challenge to take place this year (internal) and next year (open).
- Major funders have agreed to budget envelope for alpha (now beta) configuration. CTAO to hire ~30 additional people to ramp up the construction effort.
- CTAO-N development is well underway; CTAO-S development to start later in 2024. **New: interim arrays announced for both sites with plan to start initial data taking in 3-4 years**.

CTAO SCIENCE

During the first decade:
~40% **Key Science Projects**
(CTAO Consortium)
~60% User time, including Host time

All data made public after a nominal proprietary period

www.worldscientific.com/worldscibooks/10.1142/10986
arXiv:1709.07997

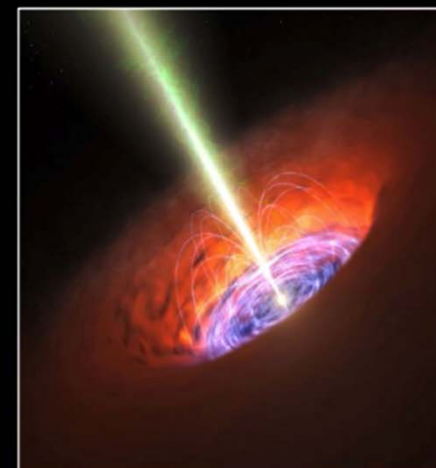
KEY SCIENCE PROJECTS

Provide legacy data sets and data products

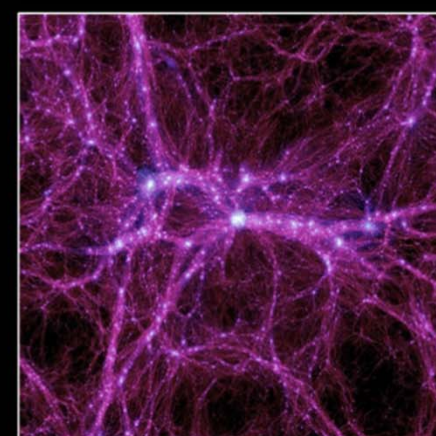
1. Dark Matter Programme
2. Galactic Centre
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Beyond Gamma Rays

Theme 1: Cosmic Particle Acceleration

Theme 2: Probing Extreme Environments



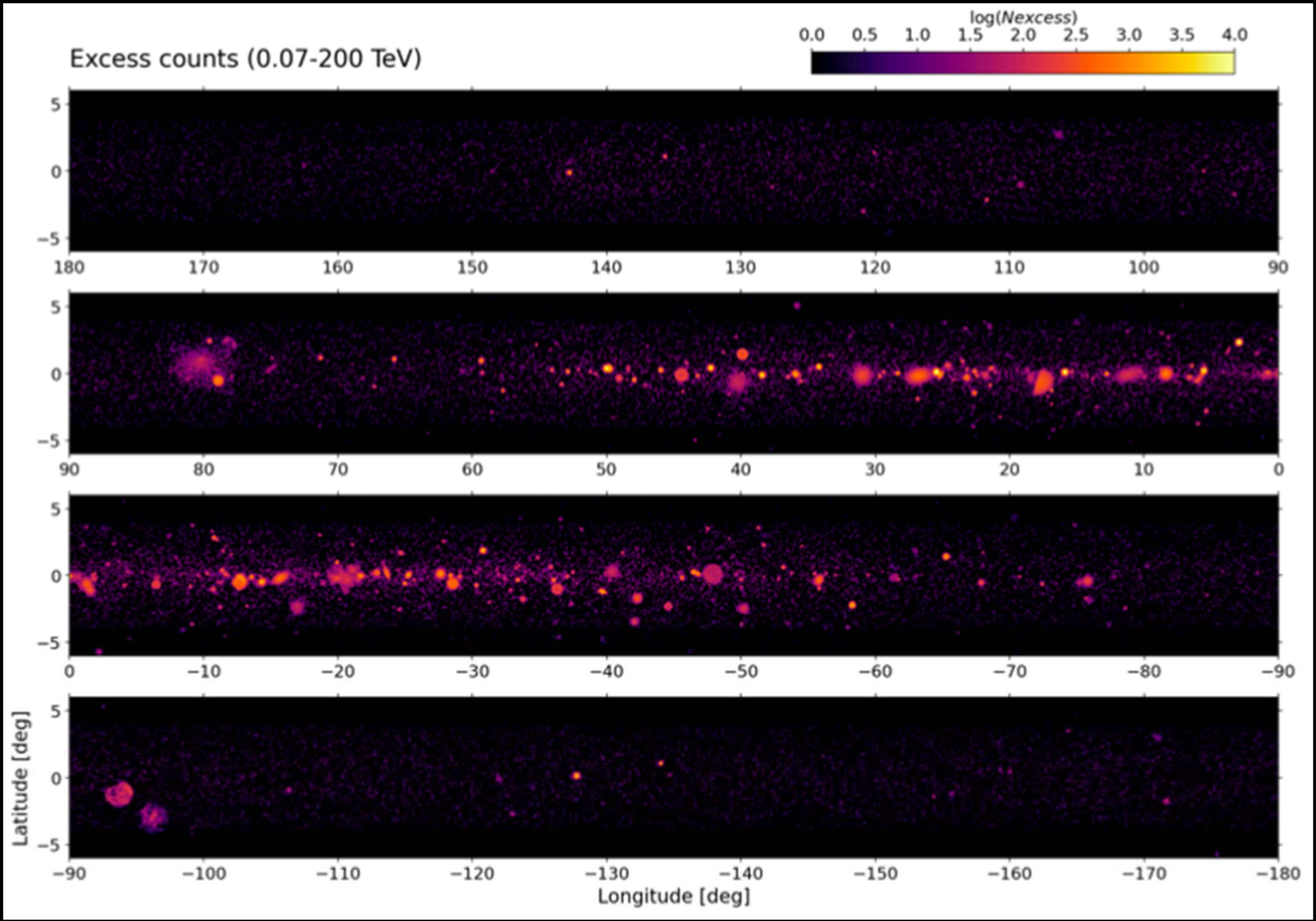
Theme 3: Physics Frontiers



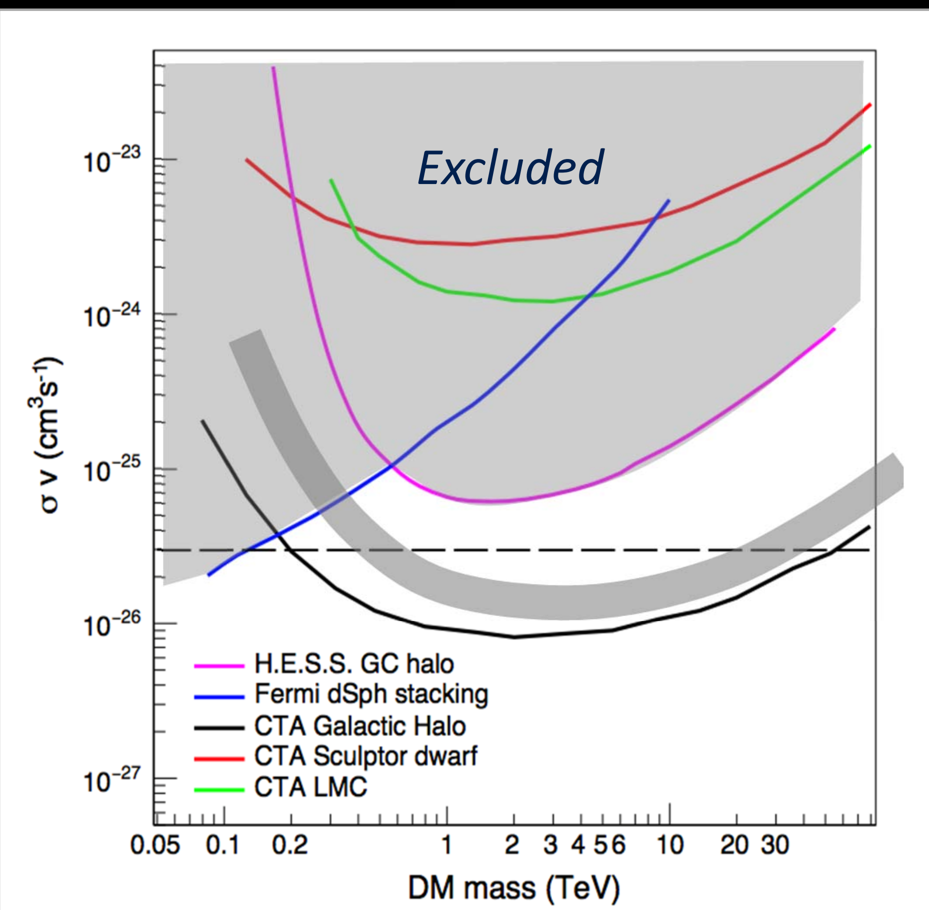
www.worldscientific.com/worldscibooks/10.1142/10986
arXiv:1709.07997

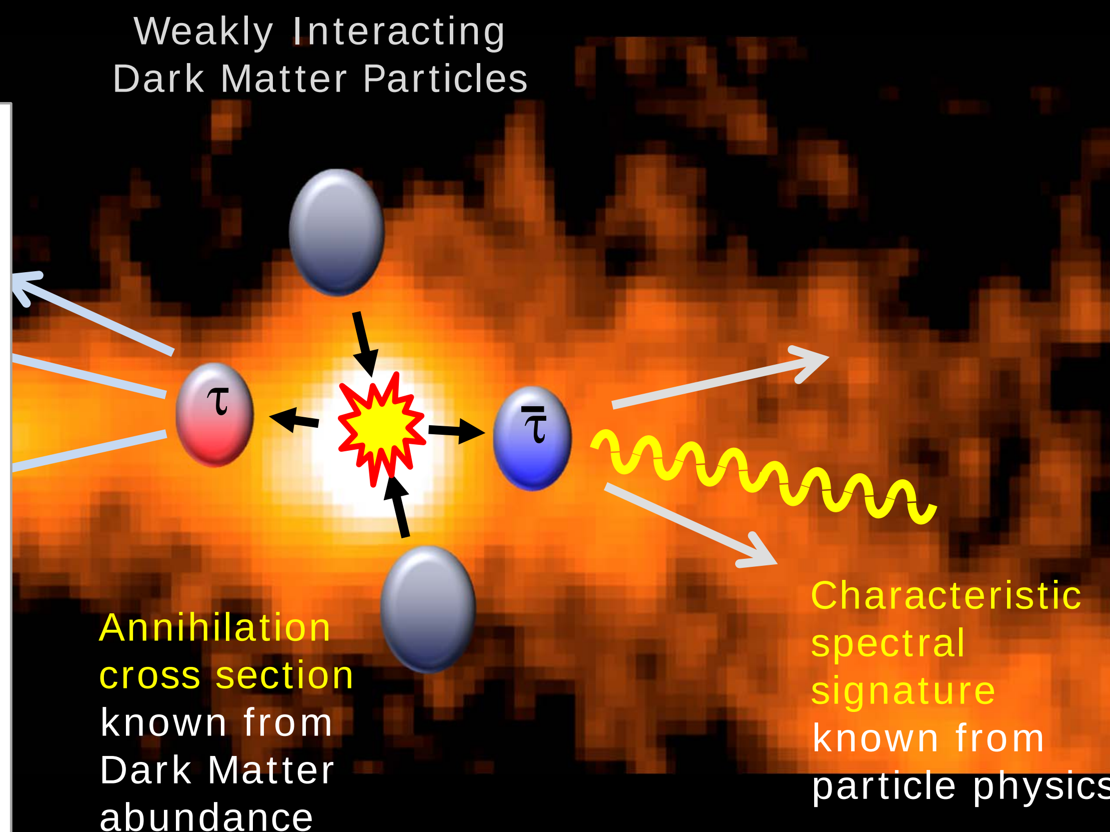
Galactic Plane Survey (GPS)

Full plane survey to depth of 1.5-2.5 mCrab



γ-rays trace DM annihilation or decay





"Sensitivity of the Cherenkov Telescope Array to a Dark Matter Signal from the Galactic Centre"
A. Acharyya et al. JCAP 01, 057 (2021)

2nd CTAO Science Symposium

https://www.ctao-symposium.org/

Focus: Broader science and synergies with CTAO

CONCLUSIONS

CTAO
Cherenkov Telescope Array Observatory

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

Outstanding sensitivity & resolution over wide energy range
Far-reaching science program
Open observatory with data released to public
Technical designs now mature and construction starting
Initial science data in 3-4 years

CTAO requires a broad partnership of countries and communities.

THANK YOU !

LST Movie

CTAO
Cherenkov Telescope Array Observatory