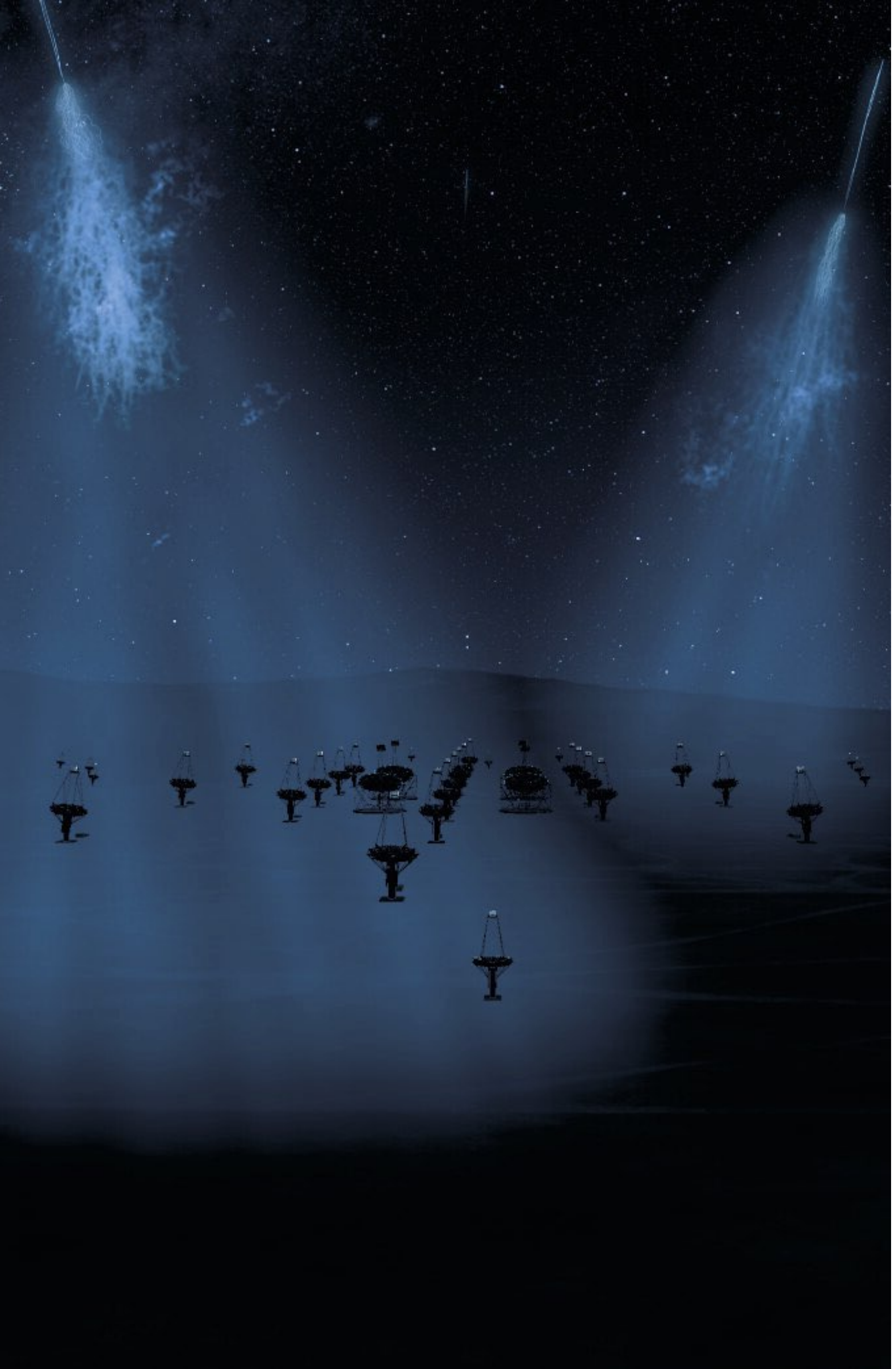


Credit of “CTA at night” images: DESY/Milde Science Comm./Exozet

The Cherenkov Telescope Array

Unveiling the Very-High-Energy Gamma-Ray Sky

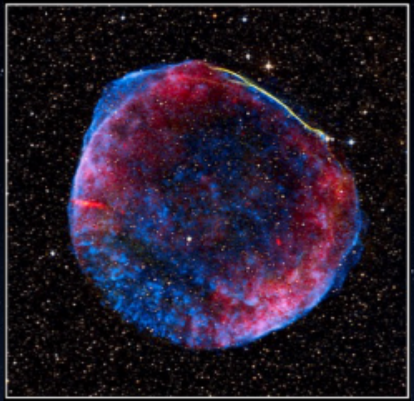
Sabrina Einecke
for the CTA Consortium

THE UNIVERSITY of ADELAIDE

19th Rencontres du Vietnam
Theory meeting Experiment: Particle Astrophysics and Cosmology
January 9th, 2023

cta cherenkov telescope array — the observatory for ground-based gamma-ray astronomy

CTA's Themes

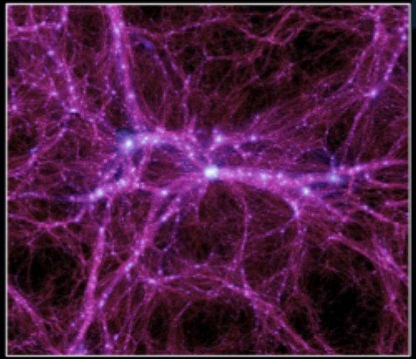


Understanding the Origin and Role of Relativistic Cosmic Particles

- What are the sites of high-energy particle acceleration in the Universe?
- What are the mechanisms for cosmic particle acceleration?
- What role do accelerated particles play in feedback on star formation and galaxy evolution?

Probing Extreme Environments

- What physical processes are at work close to neutron stars and black holes?
- What are the characteristics of relativistic jets, winds and explosions?
- How intense are radiation fields and magnetic fields in cosmic voids?



Physics Frontiers

- What is the nature of dark matter?
- Are there quantum gravitational effect on photon propagation?
- Do axion-like particles exist?

Imaging Atmospheric Cherenkov Telescopes

CTA's Telescopes

Large-Sized Telescopes (LSTs)

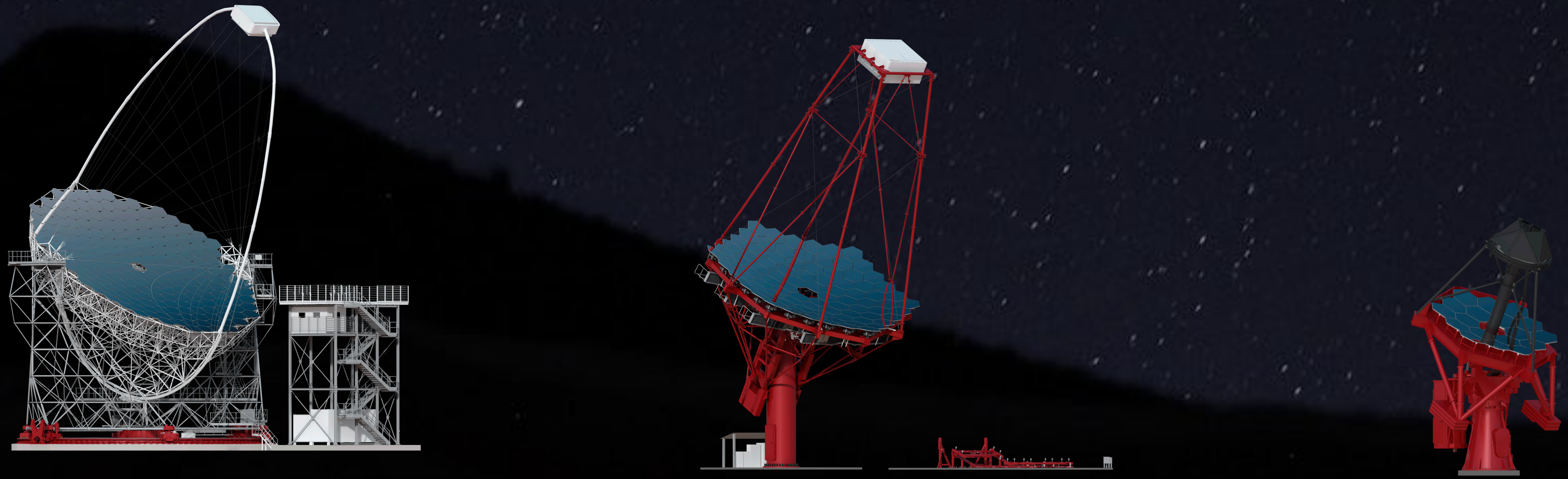
- Low-energy range: 20GeV - 3TeV
- Mirror of 23m diameter
- Camera with 1855 pixels (PMTs)
- 4.3° field of view
- Re-positioning within 20s

Medium-Sized Telescopes (MSTs)

- Mid-energy range: 80GeV - 50TeV
- Mirror of 11.5m diameter
- Camera with ~1800 pixels (PMTs)
- ~7.6° field of view
- Re-positioning within 90s

Small-Sized Telescopes (SSTs)

- High-energy range: 1TeV - 300TeV
- Mirror of 4.3m diameter
- Camera with 2368 pixels (SiPMs)
- ~10.5° field of view
- Re-positioning within 60s



CTA's Telescopes

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- Low-energy range: 20GeV - 3TeV
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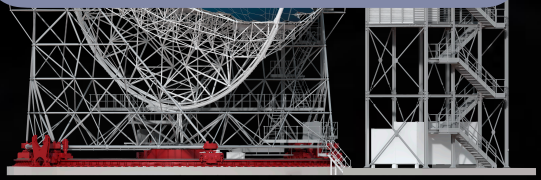
Essential for short-timescale phenomena, which are largely unexplored



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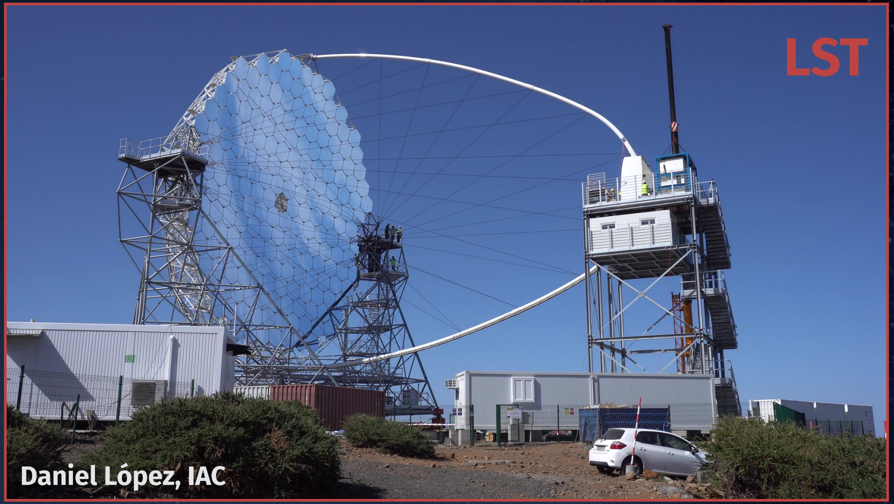
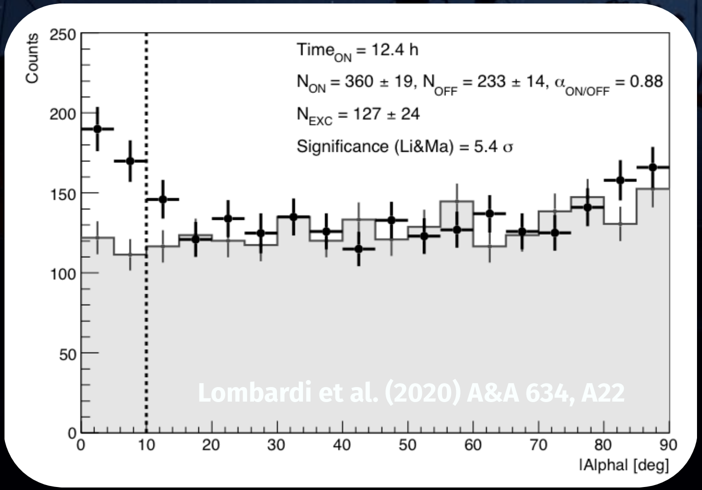
- High-energy range: 1TeV - 300TeV
- Mirror of 4.3m diameter
- Camera with 2368 pixels (SiPMs)
- ~10.5° field of view
- Re-positioning within 60s

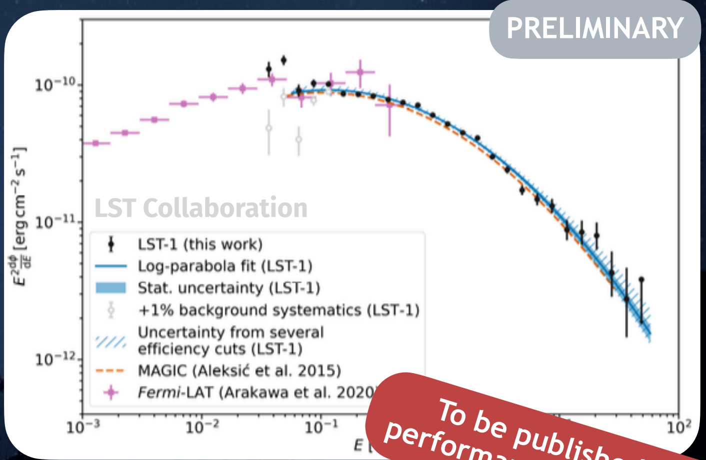
Essential for highest-energy phenomena, which are largely unexplored

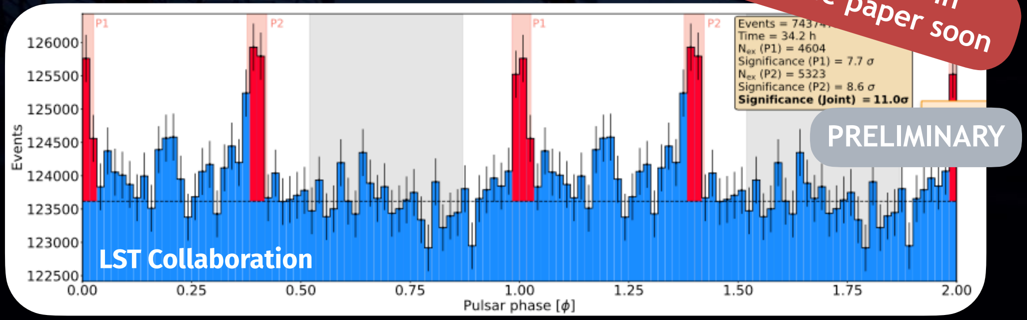
Prototype Telescopes

- Prototypes of all telescope types exist
- Engineering data leading to expected results
- LST-1 taking scientific data

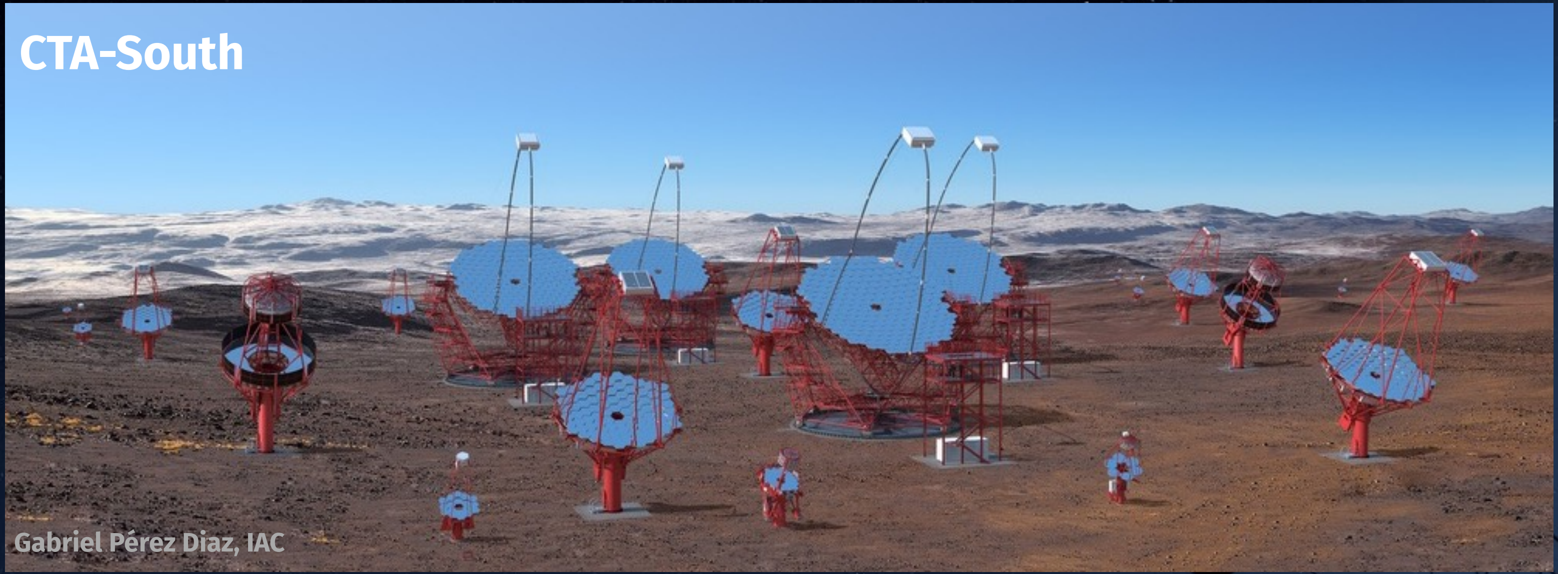








CTA's Sites



Southern Hemisphere

- European Southern Observatory (ESO) Paranal, Chile
- 14 Medium-Sized Telescopes
- 37 Small-Sized Telescopes

First Construction Phase: "Alpha Configuration"

Northern Hemisphere

- Observatorio del Roque de los Muchachos La Palma, Spain
- 4 Large-Sized Telescopes
- 9 Medium-Sized Telescopes

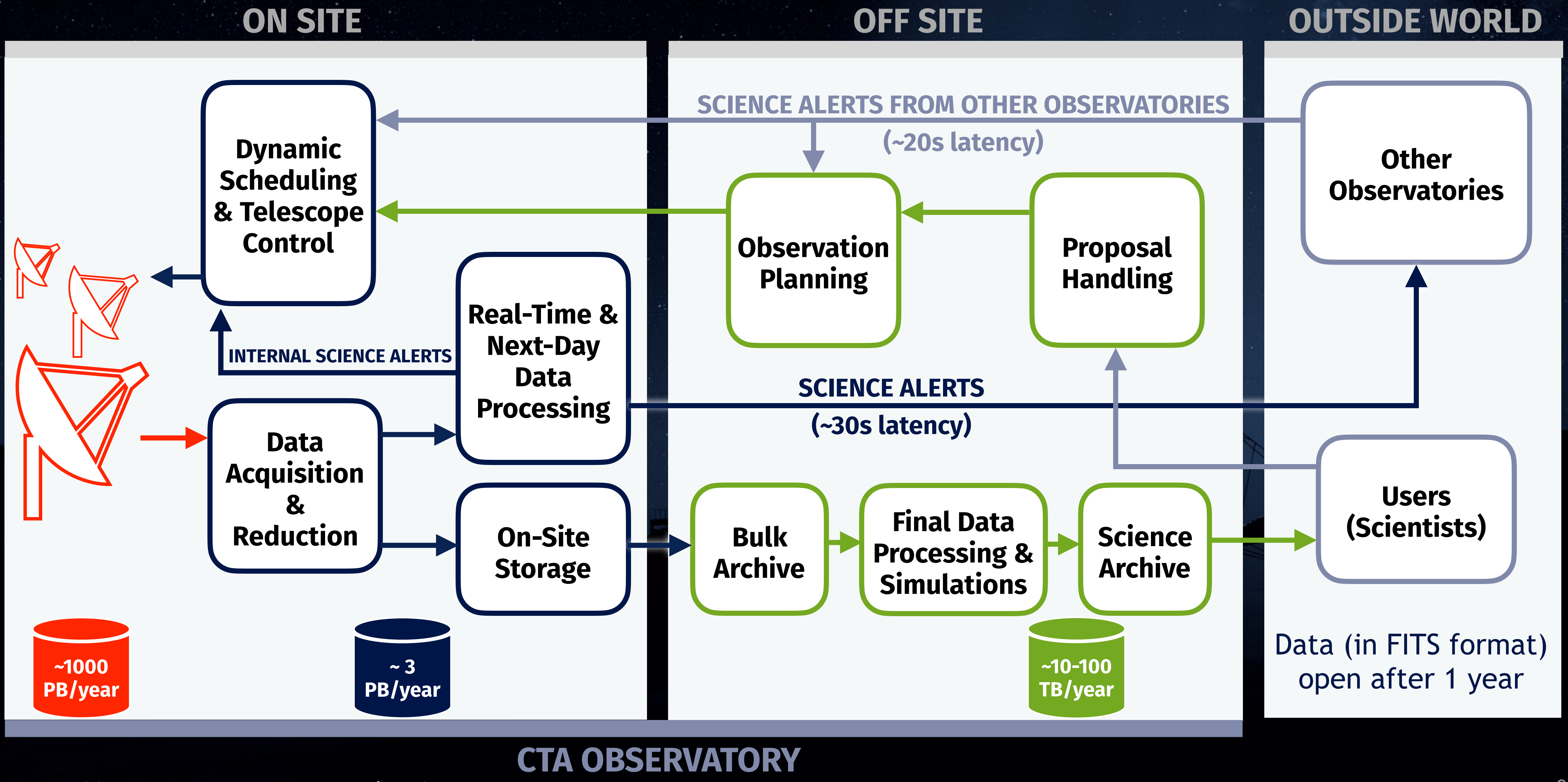
CTA Observatory

- First *open access* observatory for ground-based gamma-ray astronomy
- Data accessible via virtual observatory, together with analysis and visualisation tools
- CTA Observatory (CTAO) governed by Council,
  composed of shareholders from 11 countries and ESO, plus associate members from 2 countries

Highlights 2022

- Board of Governmental Representatives submitted formal European Research Infrastructure Consortium (ERIC) request to European Commission
  - Establishment of ERIC (expected in early 2023) will mark offical start of construction phase
- Release of layout of Alpha Configuration for first construction phase
- CTA-South:
  - Access road built
  - Inauguration Photovoltaic Plant providing electric power of 9MW (for ESO, ELT, CTAO)

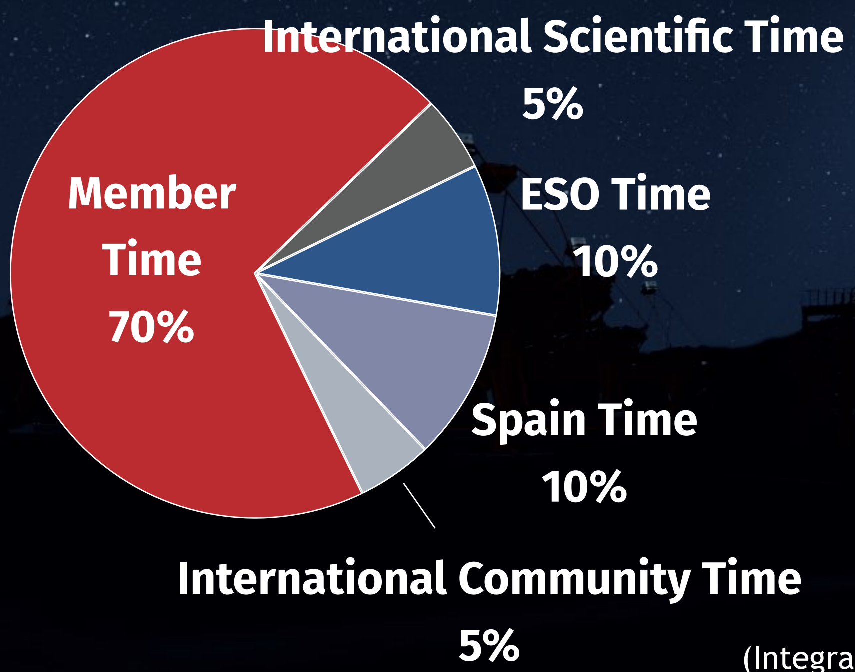
Design of Observatory



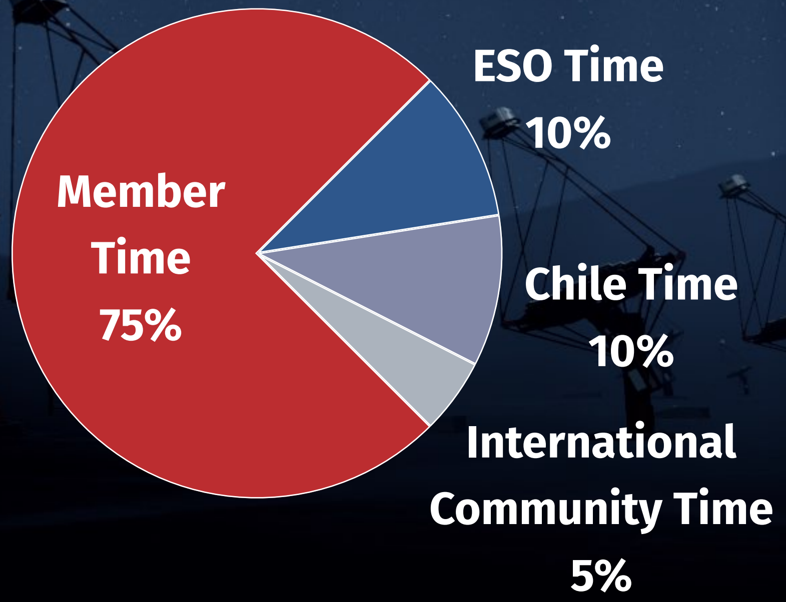
Observing Time Allocation

- Allocation through scientific proposals reviewed by a committee and selected for maximal science return
- Each observation period (~1 year) announced in call issued by CTAO
- International Community Observing Time (ICOT): Small fraction of observing time available for meritorious proposals by researchers of non-contributing countries (to be approved by CTAO ERIC Council incl. stated 5%)

CTAO Northern Array



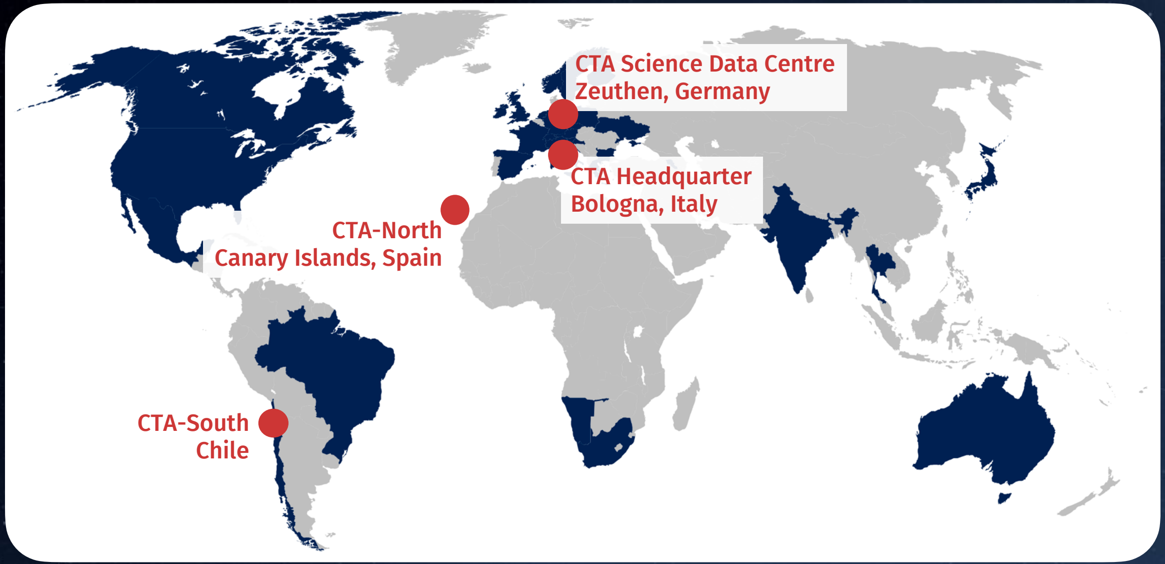
CTAO Southern Array



(Integrated over first 10 observation periods / 10 years)

CTA Consortium

- 25 countries
- About 150 institutes
- Over 1,500 members



- Close collaboration with CTA Observatory (CTAO)
- Involved in array design
- Supplying components (as in-kind contributions)
- Developed and detailed key science goals of CTAO

Science with CTA

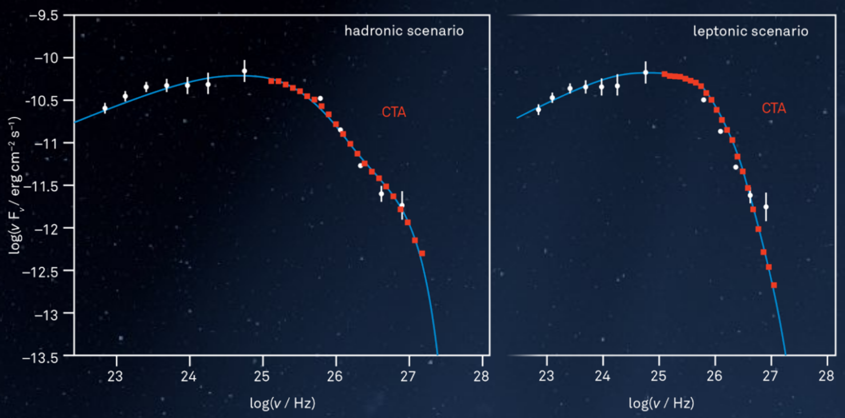
Key Science Projects

- Dark Matter Programme
- Galactic Centre
- Galactic Plane Survey
- Large Magellanic Cloud Survey
- Extragalactic Survey
- Transients
- Cosmic-Ray PeVatrons
- Star-forming Systems
- Active Galactic Nuclei
- Cluster of Galaxies
- Beyond Gamma Rays

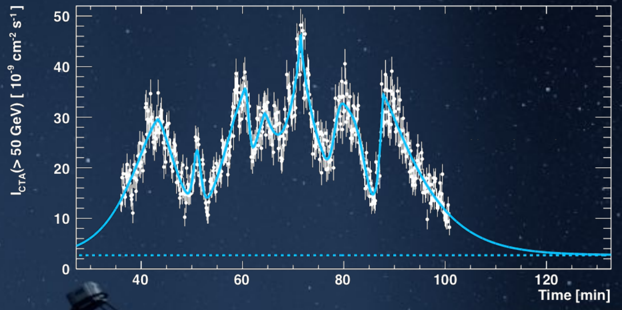
Observation Types

- Sky surveys
- Deep targeted observations
- Follow-up of transient and multi-messenger events
- Monitoring of variability

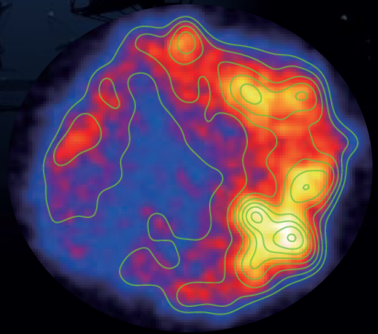
Design Drivers



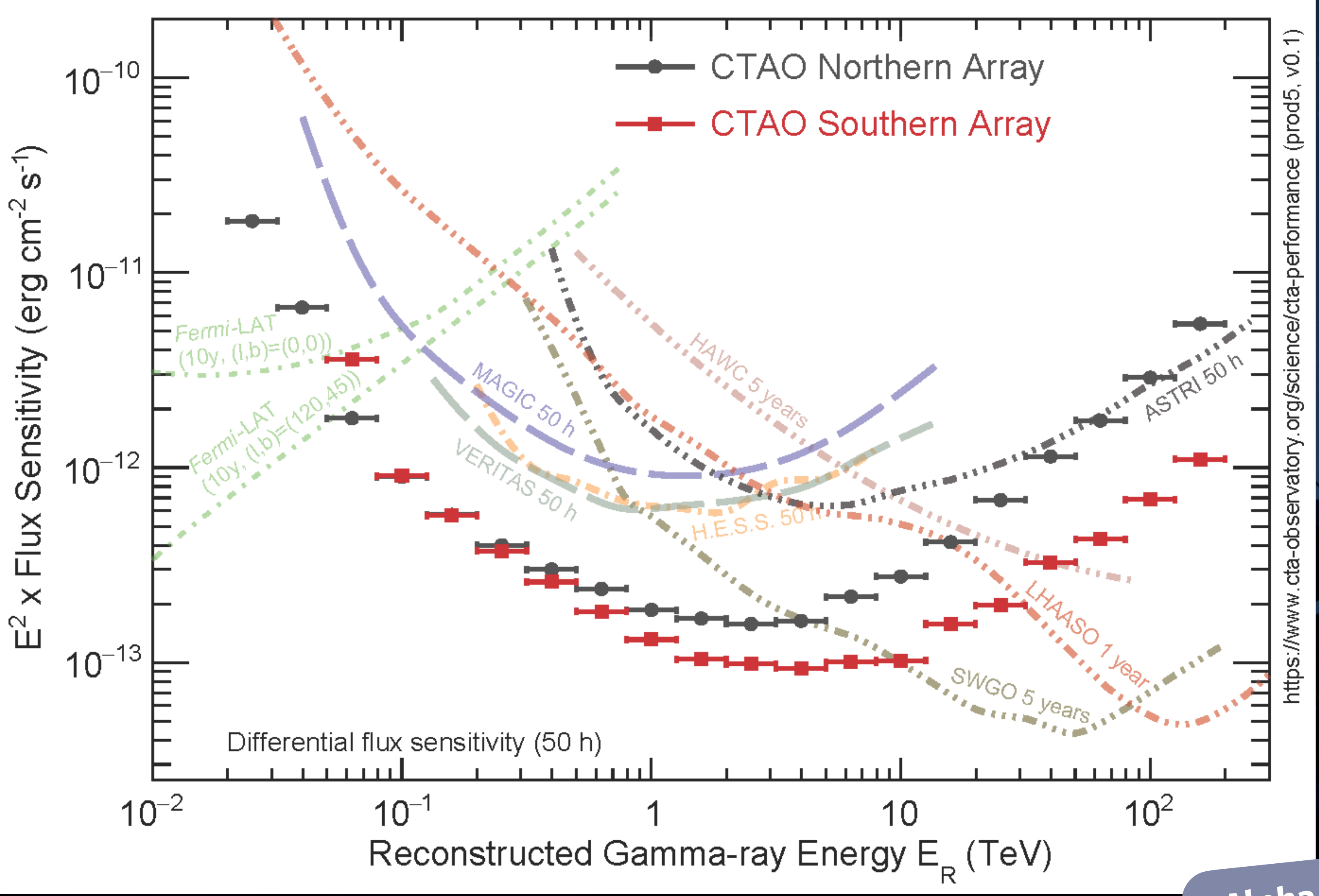
- Rapid slewing of ~20 seconds
  (transients: rapid follow ups of short-lived events)
- Full-sky coverage
  (Galactic and extragalactic surveys; transients)
- Energies down to 20 GeV
  (transients / AGNs: high-energy emission absorbed for high-redshift sources)
- Energies up to 300 TeV
  (PeVatrons)
- 10% energy resolution
  (AGNs / SNRs / PWNe: high-resolution spectra to distinguish between different models)



- 10 x sensitivity
  (Galactic plane survey: see entire galaxy, transients: shorter observation times and higher time resolution; AGNs: detect higher-redshift sources; dark matter: stronger constraints)
- 10 deg field of view
  (surveys: cover large areas in short times; transients: encompass events despite positions with large uncertainties and catch more serendipitous events)
- Arcminute angular resolution
  (Galactic sources / SNRs / PWNe: morphological studies and correlation with multi-wavelength observations)



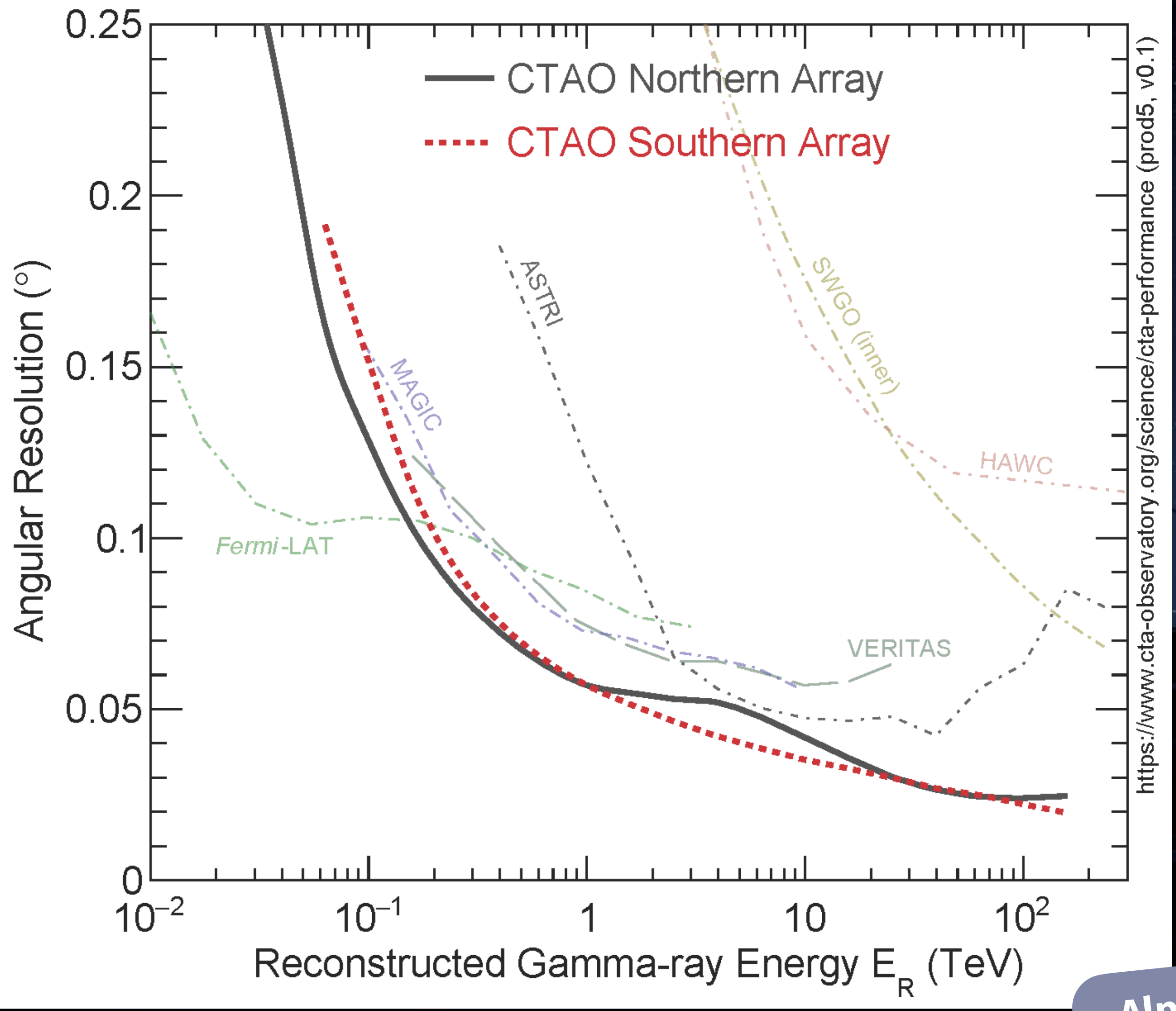
Performance: Sensitivity



CTAO ~5-10 times more sensitive than current Imaging Atmospheric Cherenkov Telescopes (MAGIC, H.E.S.S., VERITAS)

Alpha Configuration

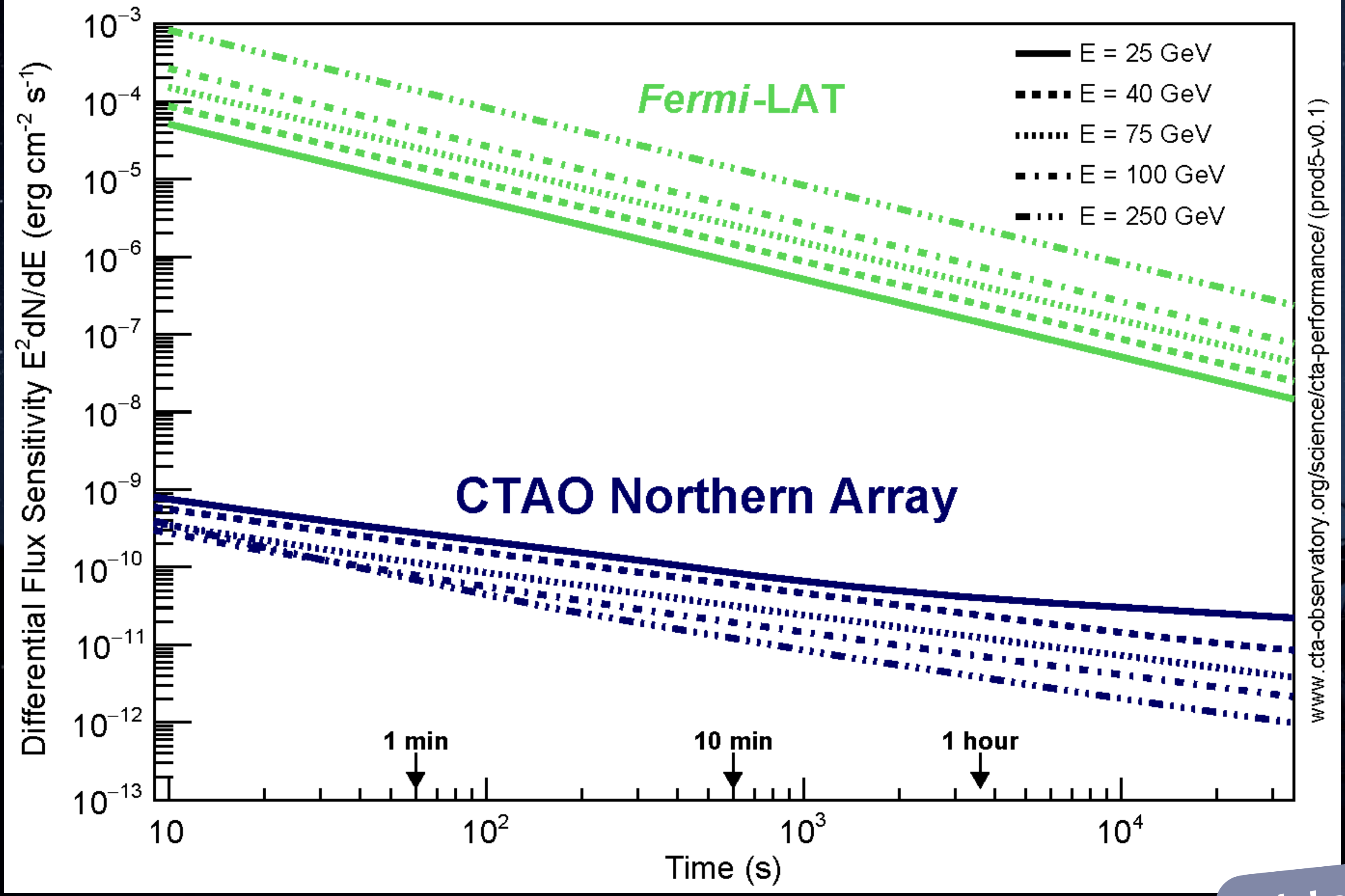
Performance: Angular Resolution



CTAO's angular resolution < 2 arcmin in multi-TeV range

Alpha Configuration

Performance: Sensitivity vs Observation Time



CTAO > 10,000 times more sensitive than *Fermi*-LAT in multi-GeV range

Alpha Configuration

Transients

Transient Classes

- Gamma-ray bursts
  - Probe physical mechanisms of most luminous explosions in universe
  - Probe cosmology and fundamental physics
- Galactic transients,
  e.g. PWN & magnetar flares
- X-ray / optical / radio transients
- High-energy neutrino events
  - Detect neutrino-emitting AGNs or other sources
  - Study production mechanisms of gamma rays and neutrinos
- Gravitational wave events
  - Investigate link between progenitor event and emerging gamma-ray burst
- Serendipitous VHE transients
- VHE transient survey
  (large FoV pointing mode)

LATENCIES

~30s to send alerts to other instruments

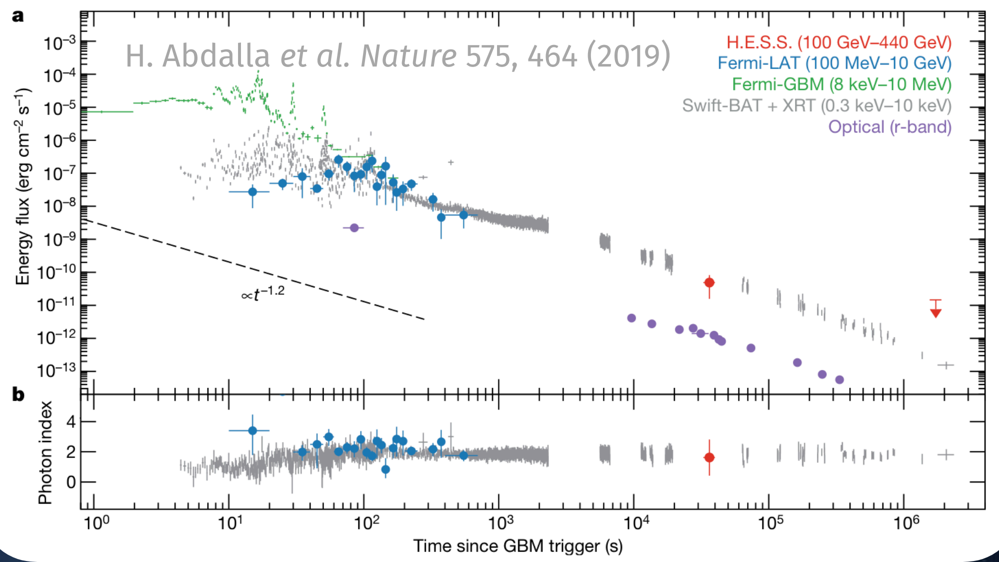
~20s to follow alerts from other instruments

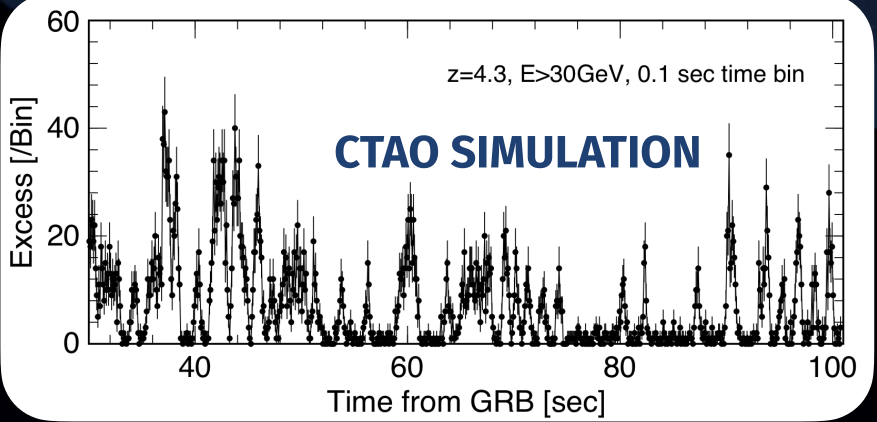
Transients

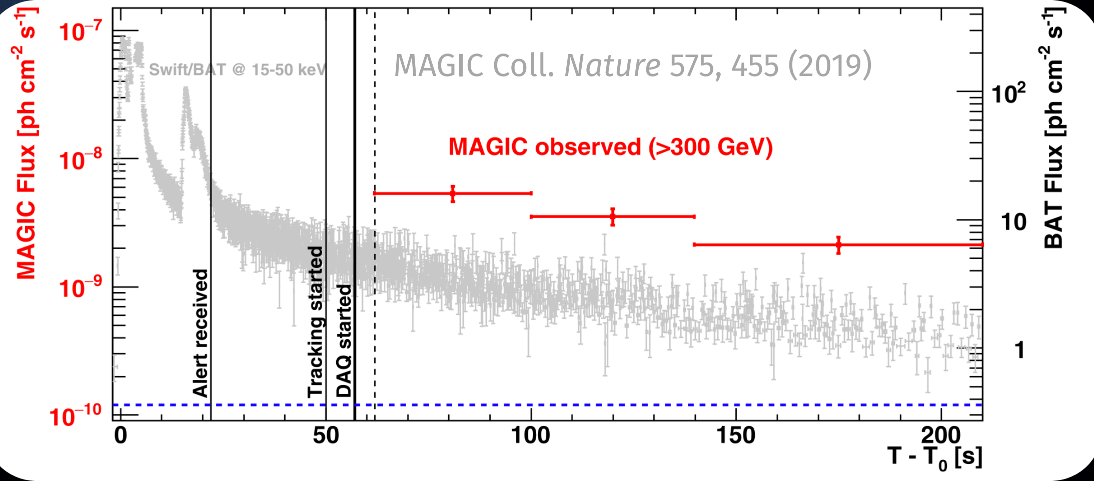
Gamma-Ray Bursts

- TeV GRBs finally detected in 2019
- 5 long GRBs & 1 short GRB (z = 0.08 - 1.1)

- **CTA will see GRBs up to z ~ 4**
- LSTs will increase detection probability by factor 10
- Light curves at seconds resolution
- Spectra at minute resolution







Active Galactic Nuclei

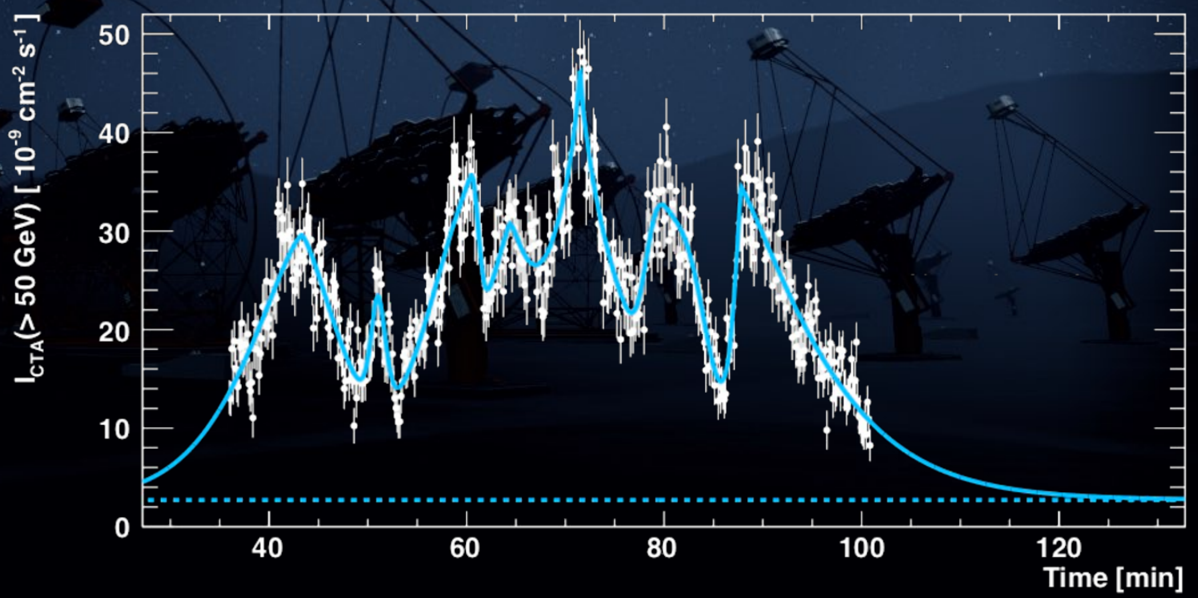
AGN Flare Programme

- Follow-up of external alerts
- Follow-up of internal alerts from long-term monitoring targets
- Follow-up of alerts from snapshot observations with full array

Snapshot observations

- Very short exposure of ~80 targets

- Rapid variability (timescales of hours, minutes)
  - Constraints on Doppler factor, particle acceleration, cooling processes
  - Constraints on emission region and light-crossing time
- Detection of FSRQs in flaring states
  - Link between FSRQ and other blazars
  - Particle acceleration and emission within blazar jets
  - Extragalactic Background Light



Active Galactic Nuclei

Long-Term Monitoring over 10 years

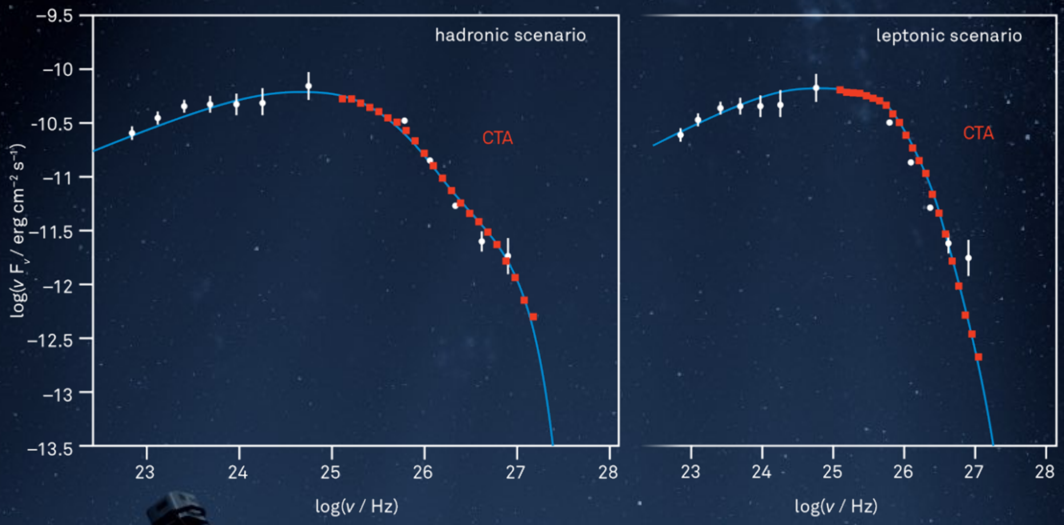
- Coverage of all known types of VHE AGN: EHBL, HBL, IBL, LBL, FSRQ, radio galaxies
- Spectra on weekly or monthly basis for bright sources
- Long-term VHE light curves
- Slow variability (annual timescales)
  - Duty cycle of source
  - Binary black holes, jet precession, accretion disk processes
- Intermediate variability (timescales of days, weeks, months)
  - Emission region in AGN jet
  - Acceleration and emission processes

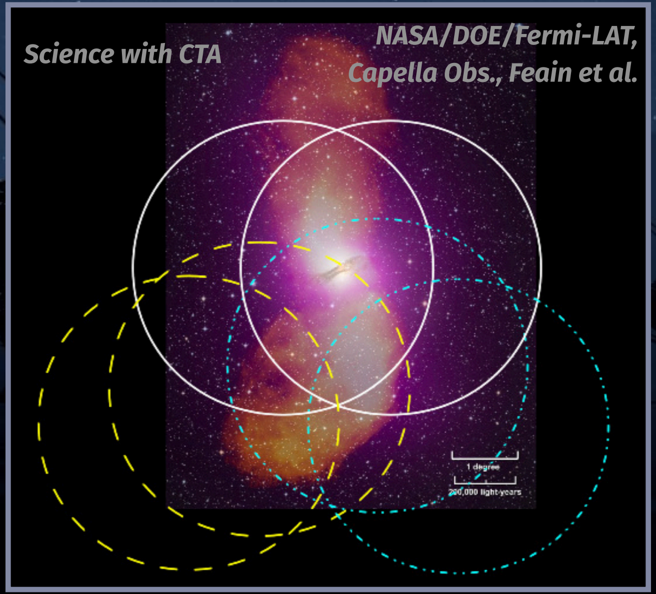
Source Class	Potential Targets
EHBLs	1ES 0229+200, 1ES 1426+428, 1ES 1101-232
HBLs	Mrk 421, Mrk 501, PKS 2155-304
IBLs	1ES 1011+496, 3C 66A, W Comae
LBLs	AP Librae, BL Lacertae
FSRQs	PKS 1510-089, PKS1222+216
Radio Galaxies	M87, NGC 1275

Active Galactic Nuclei

High-Quality Spectra

- Systematic coverage of redshifts and AGN classes
  - Leptonic / hadronic emission scenarios
  - Evolution of blazars with redshift
  - Precision measurement of Extragalactic Background Light
- Deep exposures of 2 radio galaxies (Cen A & M87)
  - Extended emission from radio lobes or kpc jet
  - Unification of blazars and radio galaxies
  - VHE emission region of radio galaxies
  - Leptonic / hadronic emission scenarios

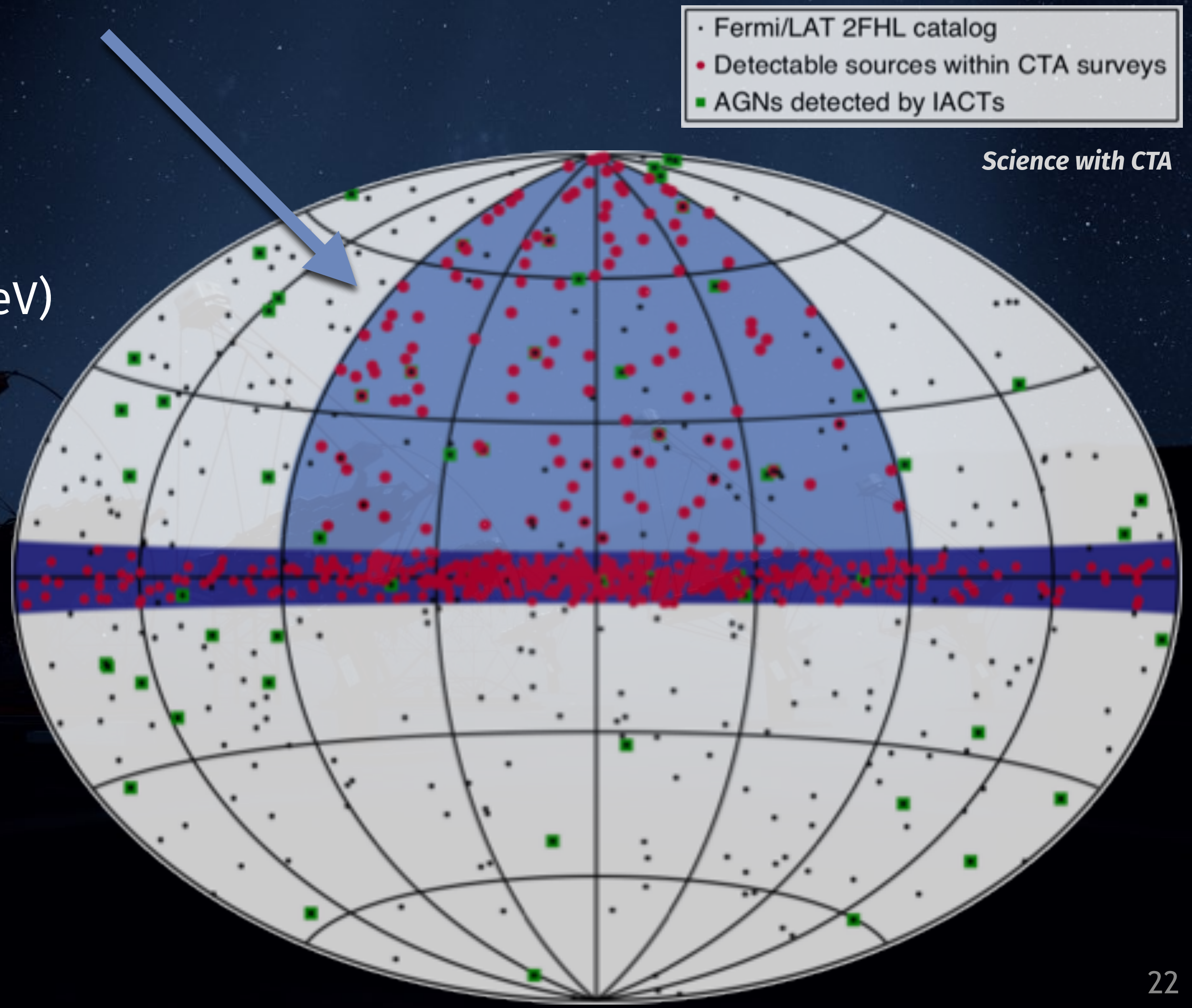




Extragalactic Survey

Blind Survey of 25% of Sky

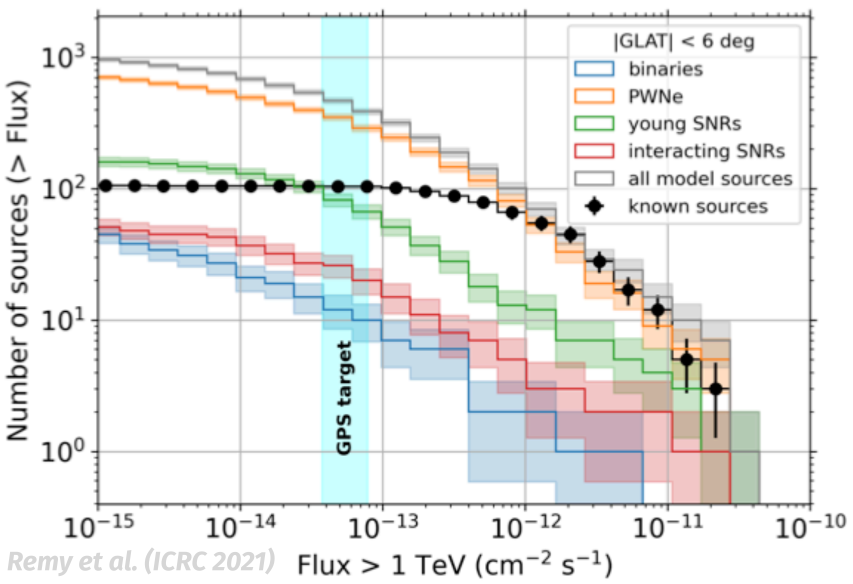
- Unbiased VHE catalogue at ~6 mCrab
  - Luminosity distribution and redshift dependence
  - Population studies
  - Detection of new VHE source classes (e.g. Seyfert galaxies, ULIRGs)
- High-resolution map of extragalactic sky (50 GeV - 10 TeV)
  - Discovery of dark sources / dark matter annihilation
  - Large-scale electron anisotropy
- Search for serendipitous VHE phenomena
  - GRBs in prompt phase



Science with CTA

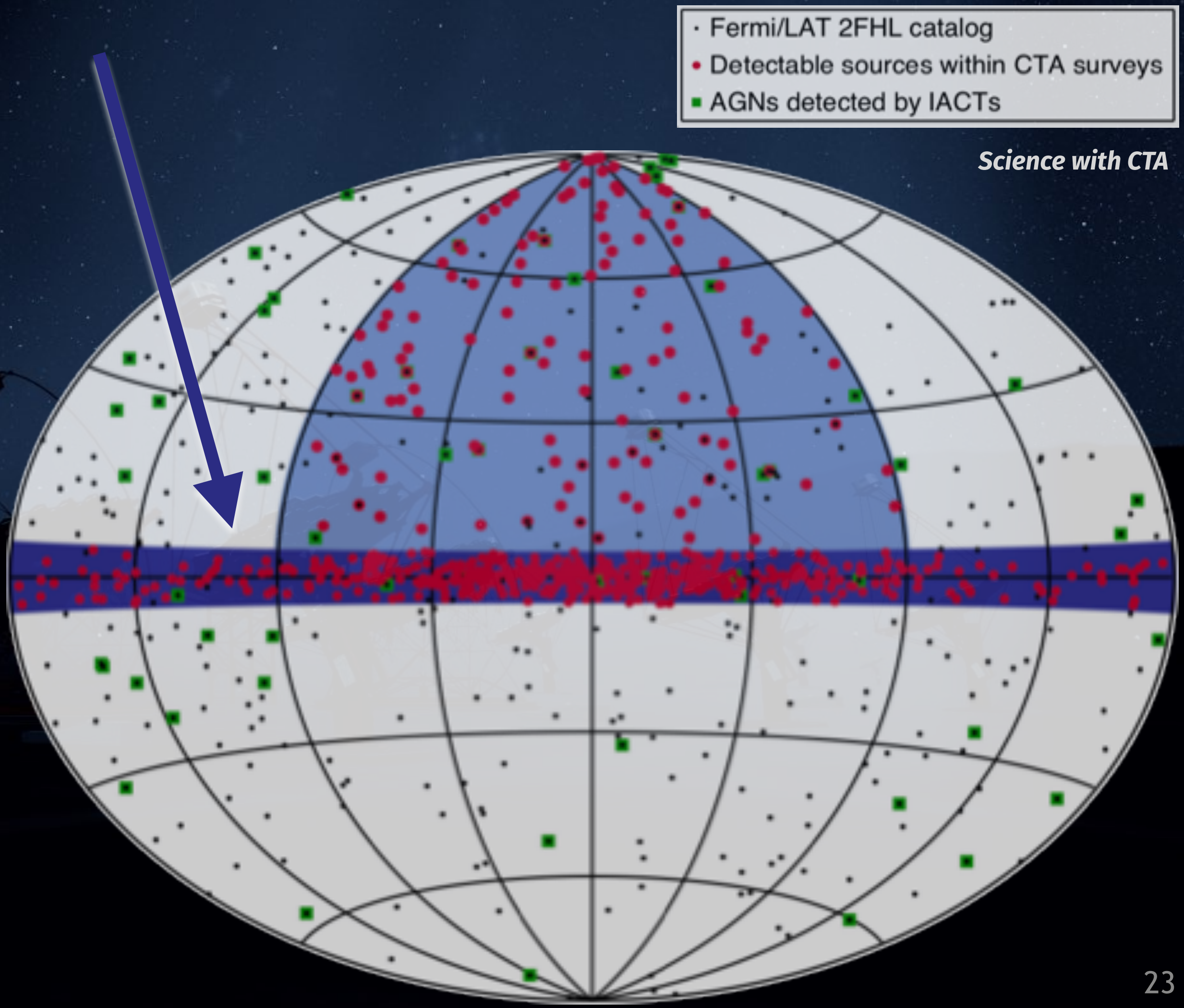
Galactic Plane Survey

- Unprecedented census of VHE sources in Galactic plane
  - Discover PeVatrons
  - Population studies (SNRs, PWNe, pulsars ++)
  - Discover new binary systems
- High-resolution sky maps
  - Study acceleration and propagation mechanisms
  - Measure large-scale diffuse emission



Remy et al. (ICRC 2021)

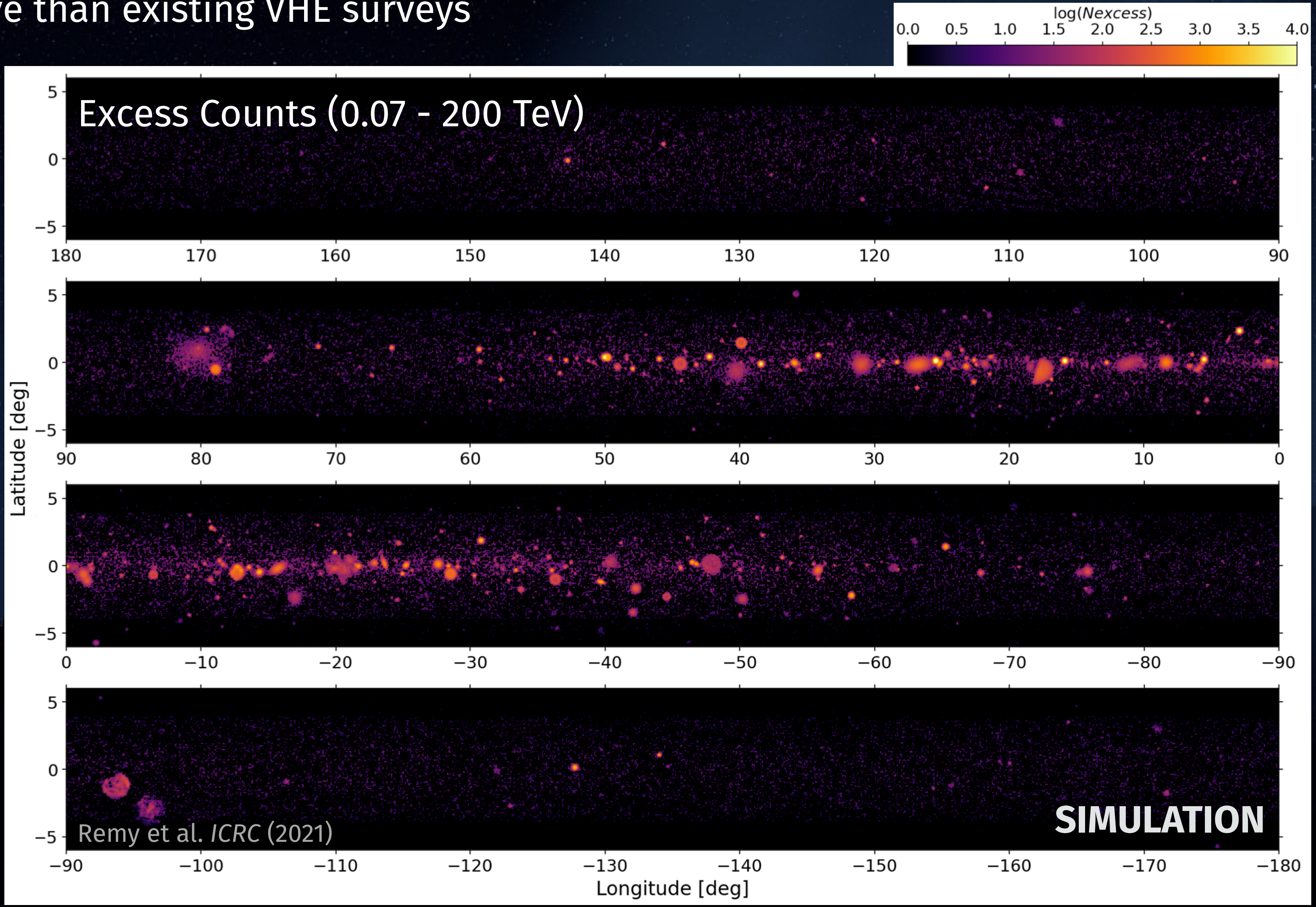
Increase HESS GPS / HAWC catalogue by factor ~5



Science with CTA

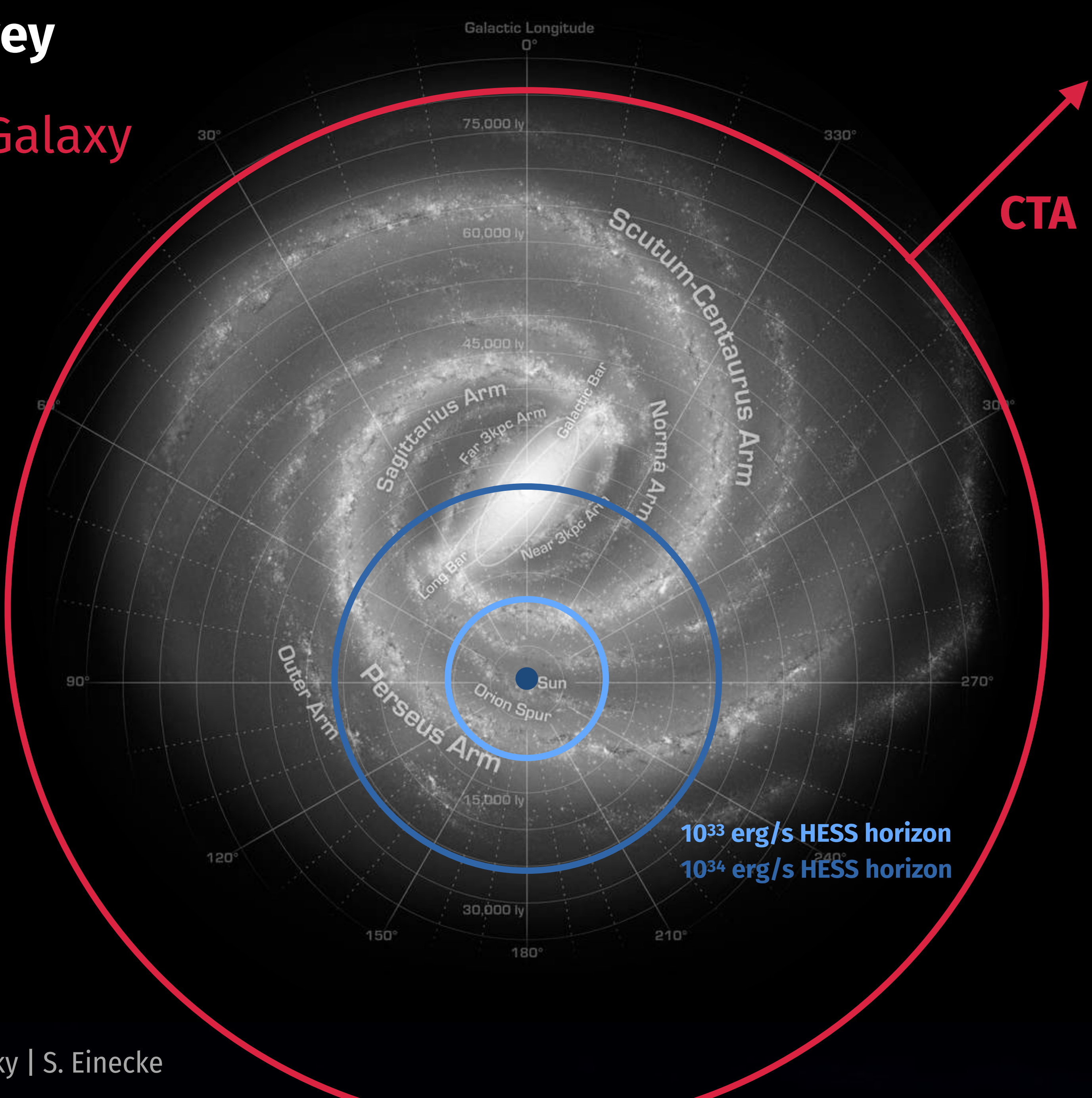
Galactic Plane Survey

- 5 to 20 times more sensitive than existing VHE surveys
- ~300 times faster survey
- Better angular resolution



Galactic Plane Survey

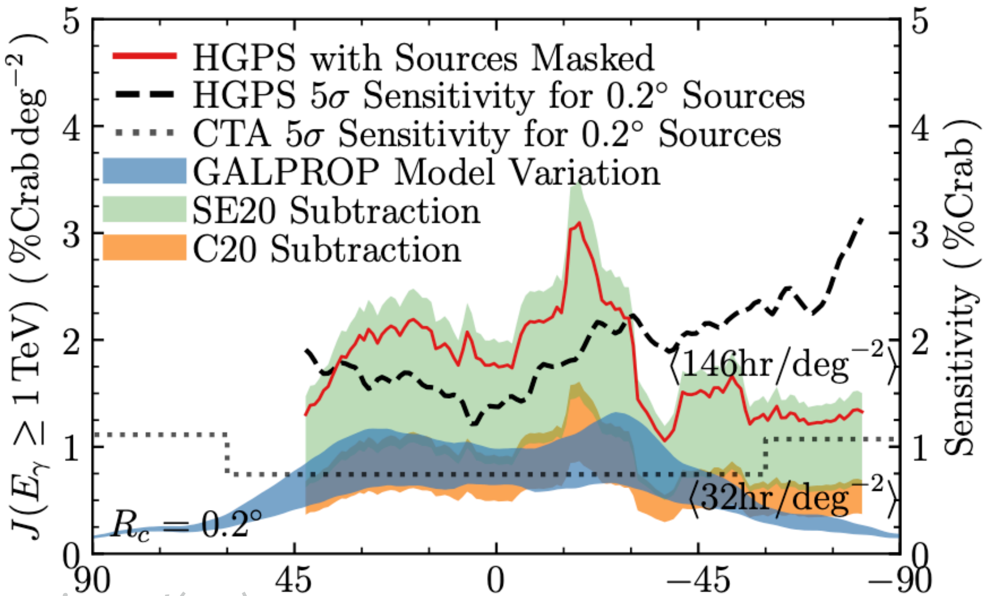
CTA will see **whole** Galaxy



Galactic Plane Survey

Challenges

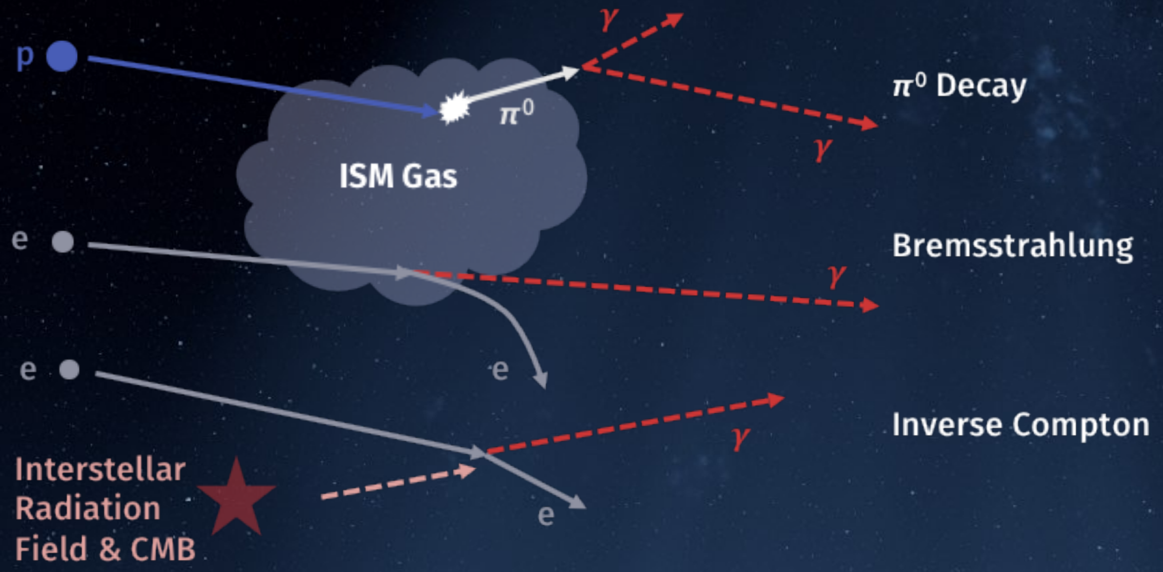
- Diffuse emission
  - To extract source properties, subtraction of diffuse emission required
  - Modelling diffuse emission much more complicated in VHE than in HE range
- Extended sources (faint emission extending to tens to hundreds pc around sources)
- Sources with complex morphology (uncertainties in cosmic-ray spectrum, gas density, ...)
- Source confusion
- Catalogue cross-matching and accelerator associations

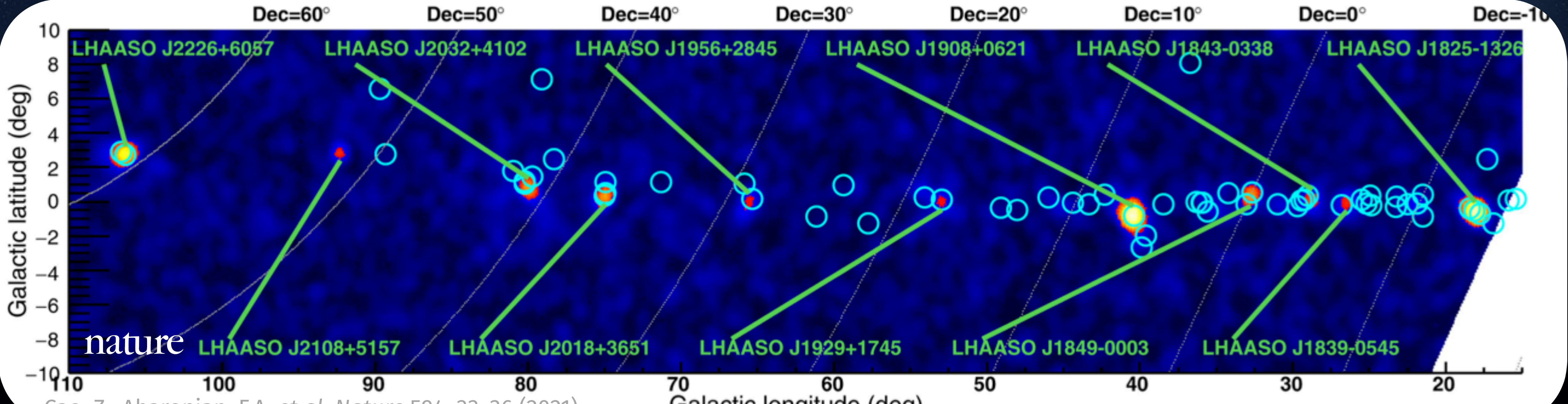


Marinos et al (2022), accepted in MNRAS

PeVatrons

- LHAASO revealed gamma-ray sources above 100 TeV (➔ ~ 1 PeV protons / electrons)
- What are the particle accelerators? SNRs? PWNs? Stellar clusters?
- What is the gamma-ray production mechanism? Leptonic? Hadronic?





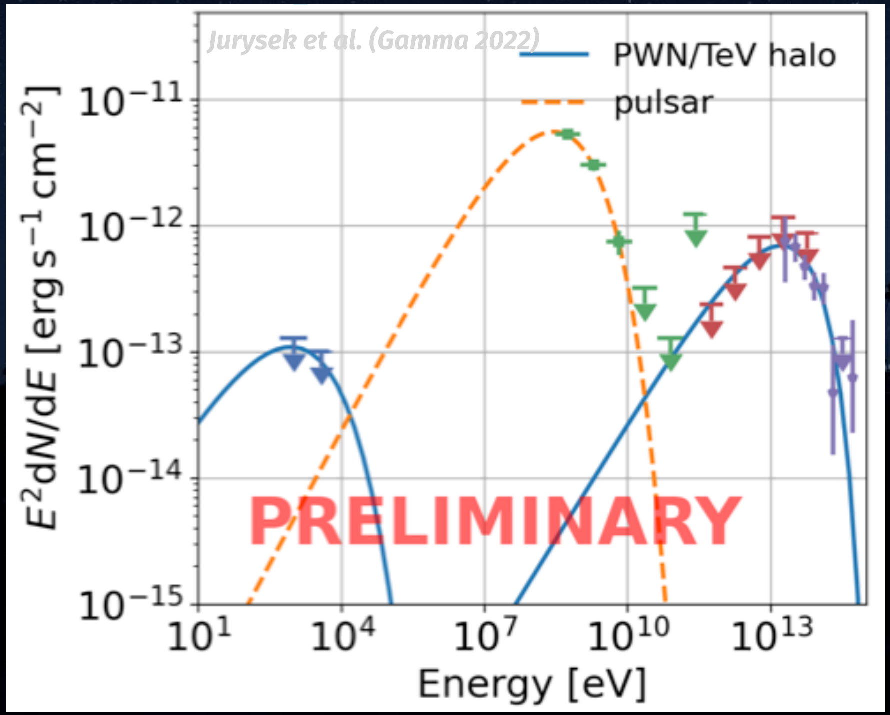
Cao, Z., Aharonian, F.A. *et al.* *Nature* 594, 33–36 (2021)

PeVatrons

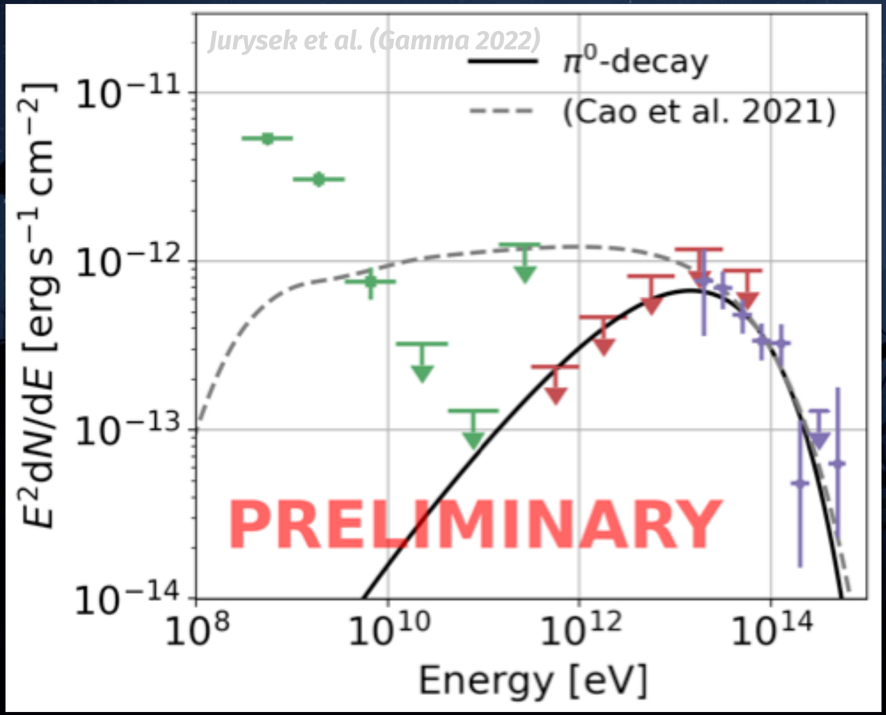
LHAASO J2108+5157

- 91h observations with LST-1
- Below models assume simple (single-component) proton / electron / gas distributions

Leptonic Scenario



Hadronic Scenario

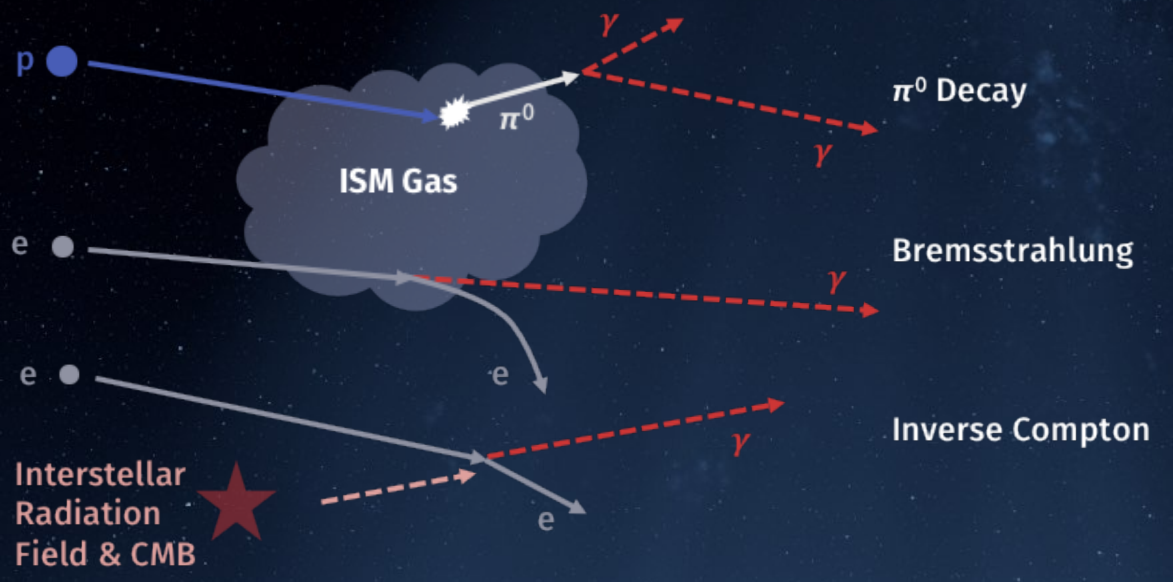


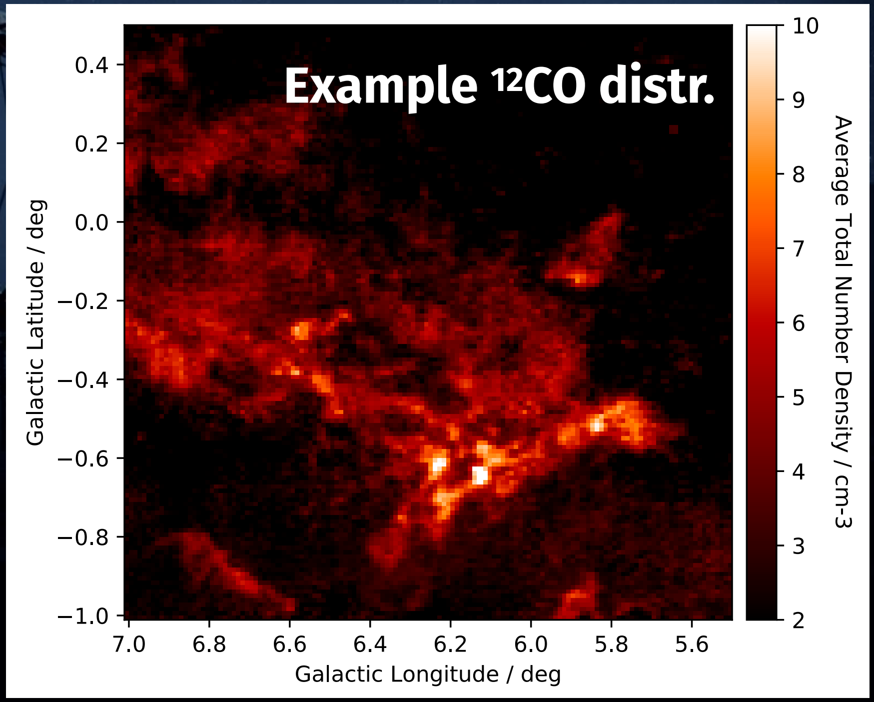
XMM-Newton
Fermi-LAT
LST-1
LHAASO-KM2A

PeVatrons

Detailed Modelling: What do we need?

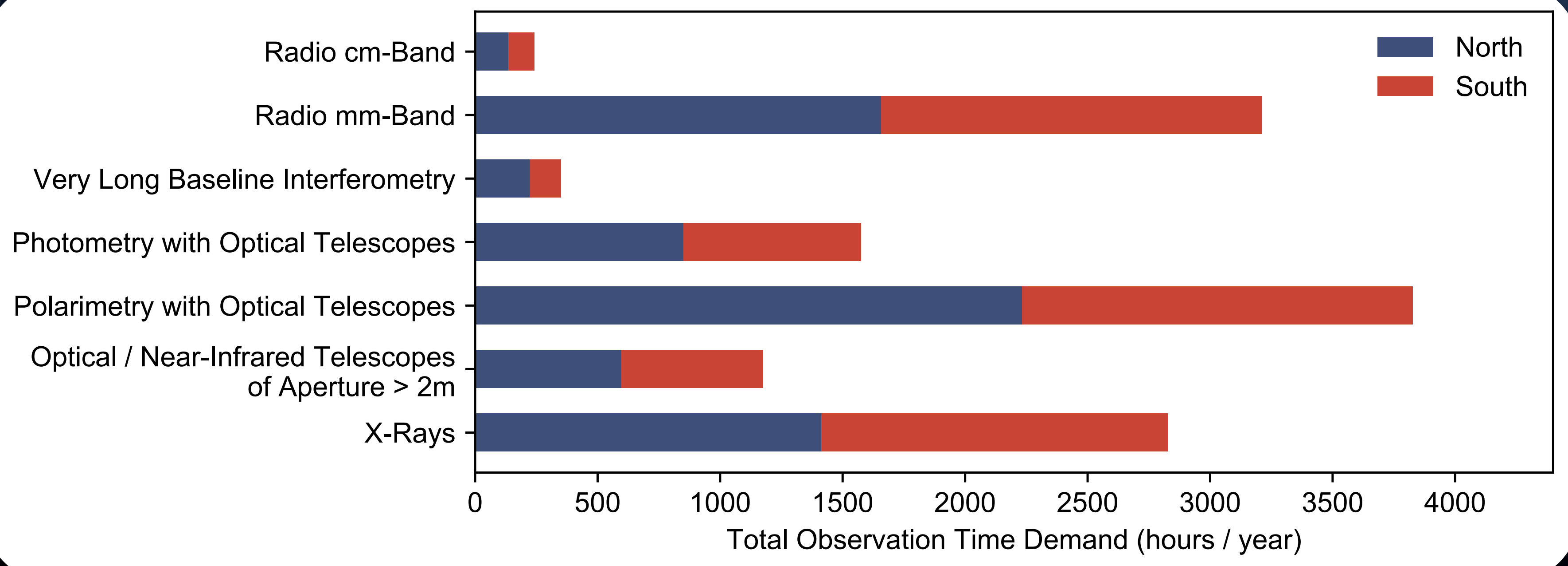
- 3D ISM gas distribution
  - ^{12}CO, ^{13}CO: Mopra (~35 arcsec res.)
  - HI, OH: GASKAP (~30 arcsec res.)
  - Physical distance (large uncertainties due to Galactic rotation model and local gas motions)
- 3D proton / electron distribution
  - Source parameters (energy budget, injection spectrum, …)
  - Local environment parameters (diffusion, advection, magnetic field, …)
- Multi-wavelength observations
- 3D modelling software





CTA's Multi-Wavelength Needs

- Radio: Particle and magnetic field density. Transients. Pulsar timing.
- Millimetre: Interstellar gas mapping. Matter ionisation levels. High-resolution interferometry.
- IR / Optical: Thermal emission. Variable non-thermal emission. Polarisation.
- X-rays: Accretion and outflows. Particle acceleration. Plasma properties.
- HE Gamma Rays: Transients. Pion decay signature. Inverse Compton process.



Plus: Alerts from transient factories, neutrino and gravitational wave alerts

The 1st CTAO Science Data Challenge

- Science Data: Simulated science-ready (DL3) data products of a complex and realistic gamma-ray sky
- Blind Challenge: Recover the science!

Objectives

- Enable broad scientific community to become familiar with CTAO data products and scientific analysis tools
- Test bed for driving forward new algorithms (for example for detection of large-scale structures)
- Step in verification of software packages (e.g. science analysis tools)

Process

- Release of 7 years of (simulated) observations (mid 2023)
- Community can download and explore data and submit their results
- Closing, evaluation of results and nomination of winners (early 2024)
- Write up closing-put document

Conclusion

- CTAO will be the first ground-based gamma-ray observatory with open access (proprietary period ~1 year)
- Major performance improvements compared to current instruments
- Funding (~300MEuro) for first construction phase secured (4 LSTs, 23 MSTs, 37 SSTs)

- CTAO will perform sky surveys, deep observations, follow ups, monitoring
- Extensive science programme to answer key questions and unveil the VHE gamma-ray sky
- Important multi-wavelength and multi-messenger synergies
- First Science Data Challenge coming soon

from emission to discovery

More information at www.cta-observatory.org

We gratefully acknowledge financial support from the agencies and organisations listed here: www.cta-observatory.org/consortium_acknowledgments/