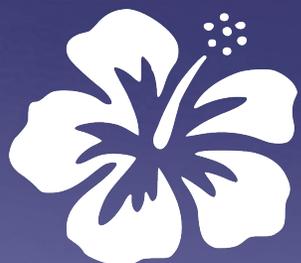


CTAO



NectarCAM

LPNHE
PARIS

cnrs

Exploring the Very-High-Energy Gamma-Ray Sky with CTAO

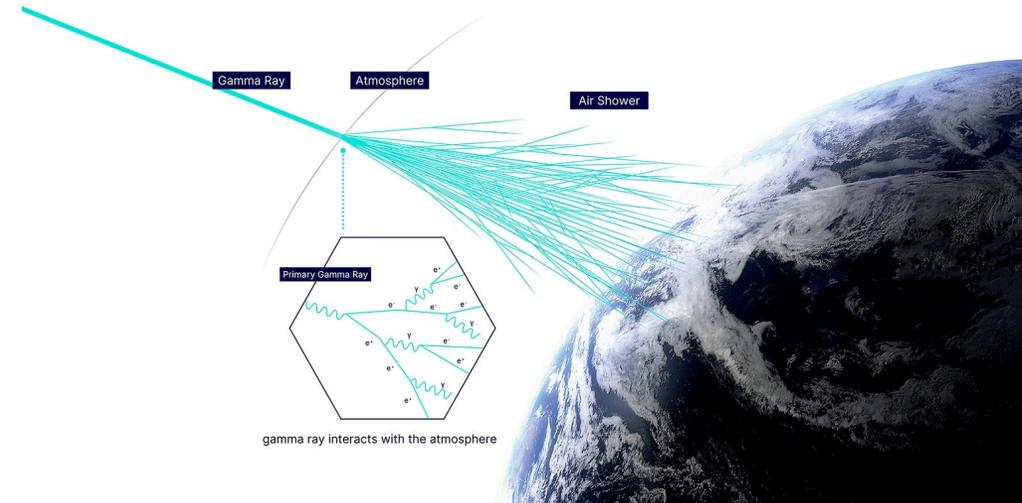


HEP@VUB seminar
5 March 2026

Pablo Correa
pcorrea@lpnhe.in2p3.fr

Contents

1. Introduction to TeV Gamma-Ray Astronomy
2. The Cherenkov Telescope Array Observatory
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The High-Energy Universe

- ▶ **Violent processes** in the Universe accelerate particles up to high energies
- ▶ **High-energy cosmic messengers** allow us to study these processes

Galactic sources



Supernova remnants

Pulsar wind nebulae



and more

Extragalactic sources



Active galactic nuclei

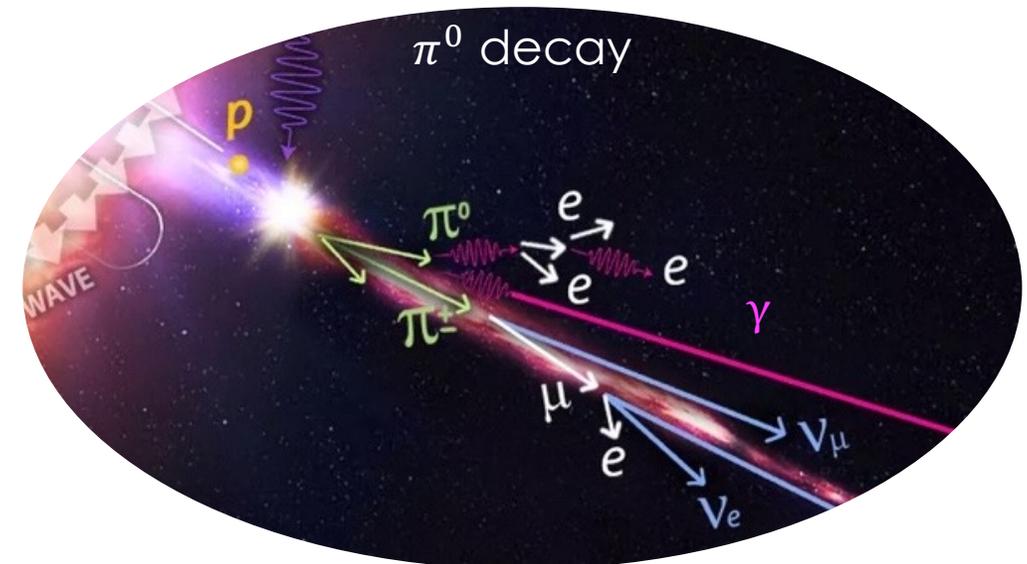
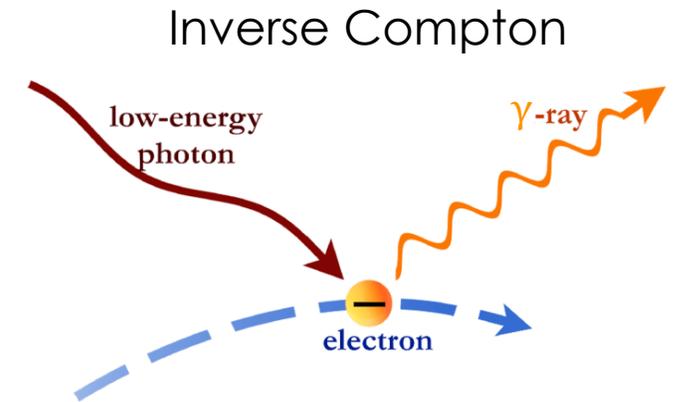
Starburst galaxies



and more

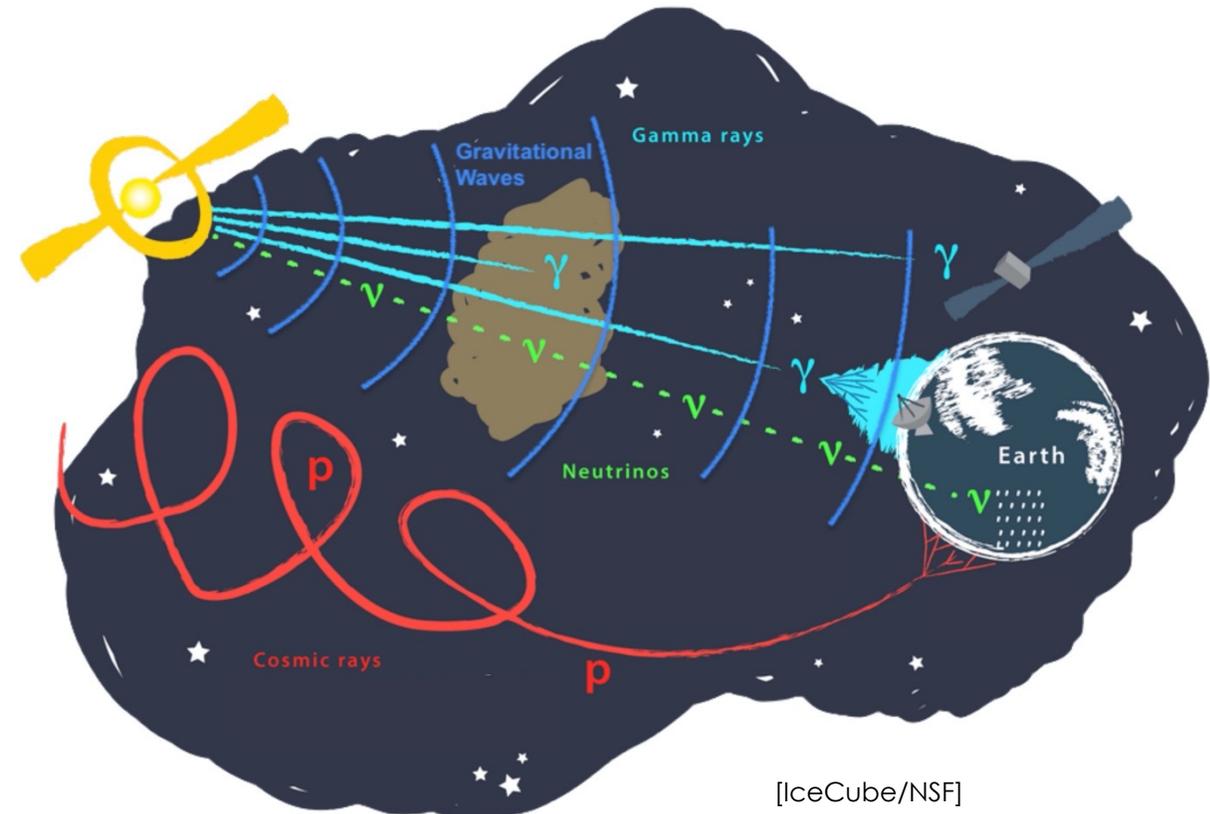
Gamma-Ray Production

- ▶ **Gamma rays** are tracers of particle acceleration
- ▶ **Leptonic** processes
 - ▶ Acceleration of **electrons & positrons**
 - ▶ Gamma rays from **inverse-Compton scattering**
 - ▶ Also Bremsstrahlung and synchrotron radiation
- ▶ **Hadronic** processes
 - ▶ Acceleration of **cosmic rays** (atomic nuclei)
 - ▶ Gamma rays from **neutral-pion decay**

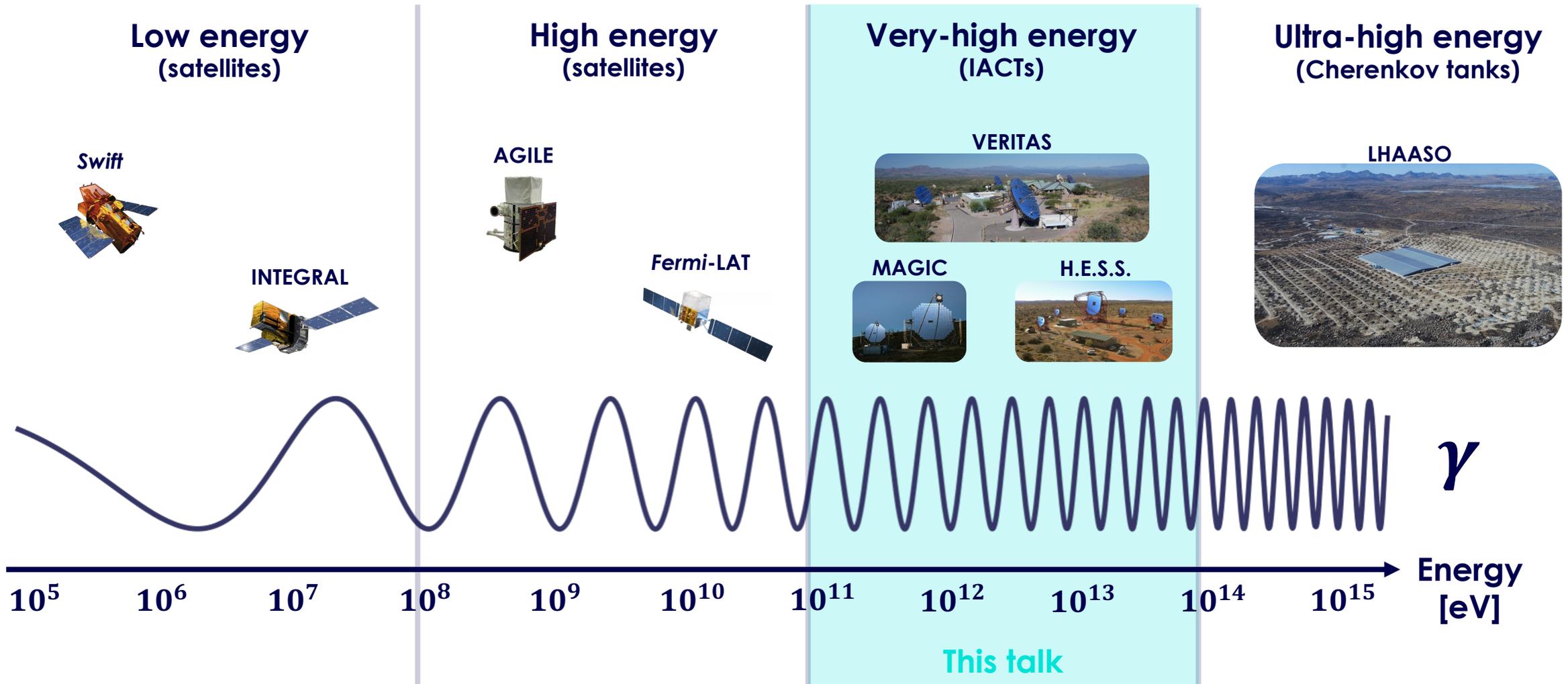


The Multimessenger Connection

- ▶ **Cosmic rays** (p)
 - ▶ **Energies** up to 3×10^{20} eV \approx 48 J
 - ▶ **Deflected** by $\vec{B} \rightarrow$ **origin unknown!**
- ▶ **Gamma rays** (γ)
 - ▶ Produced in **leptonic & hadronic** processes
 - ▶ **Easy to detect but easily attenuated**
- ▶ **Neutrinos** (ν)
 - ▶ Smoking gun of **hadronic** interactions
 - ▶ **Not attenuated but hard to detect**
- ▶ **Gravitational waves**
 - ▶ Can be coupled to acceleration processes

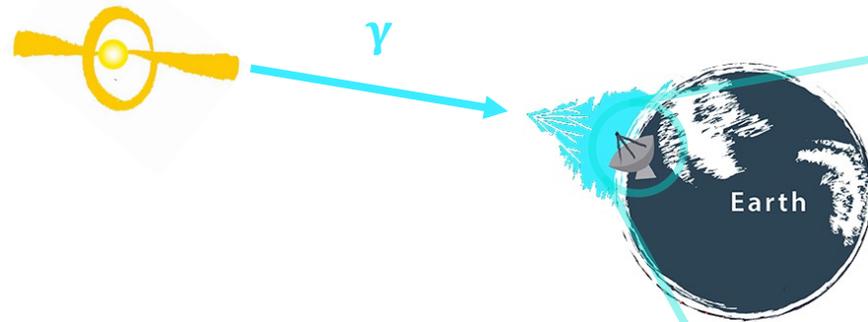


Observing the Gamma-Ray Sky

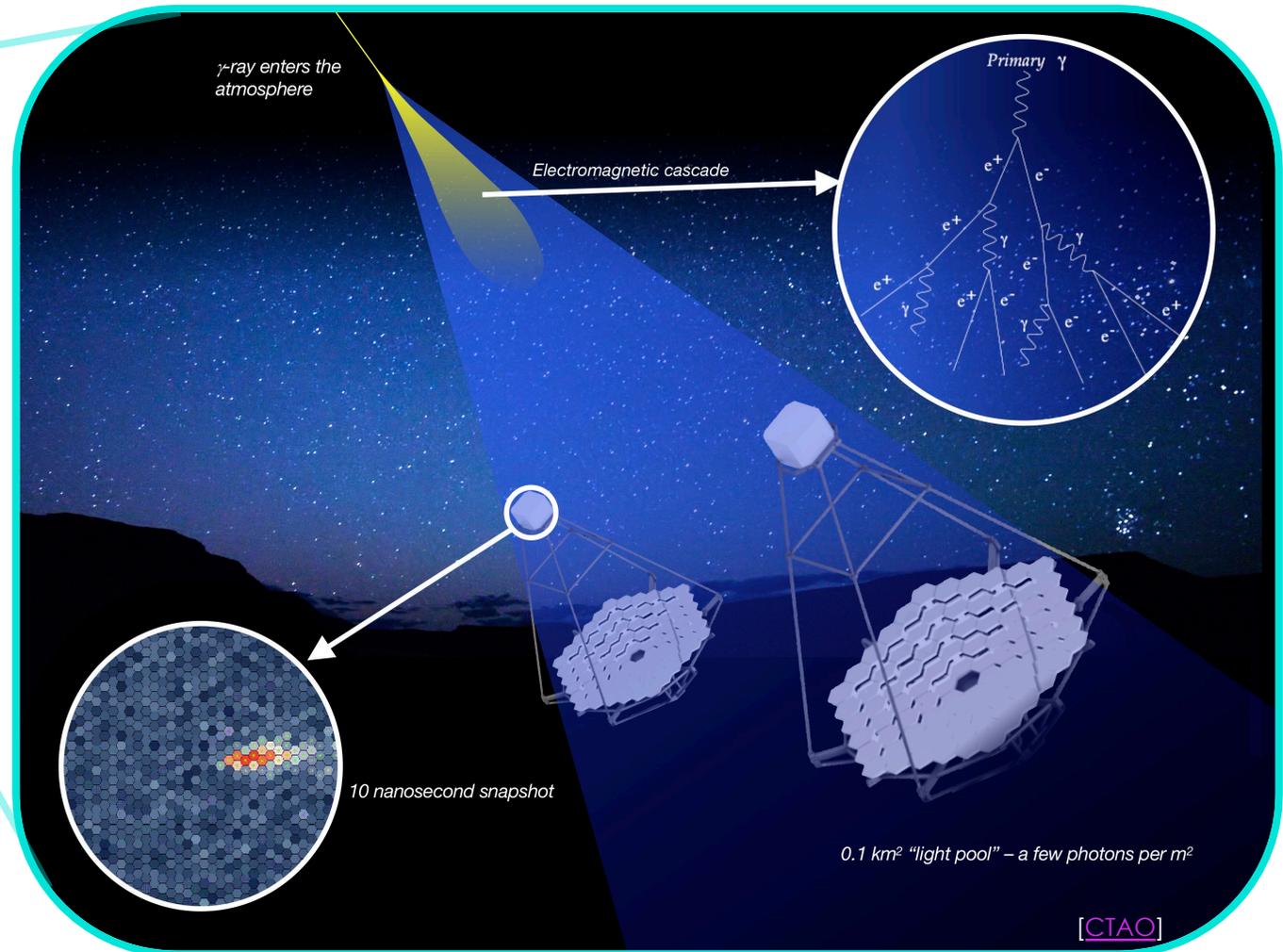


Imaging Air-Cherenkov Telescopes

[Link to video](#)



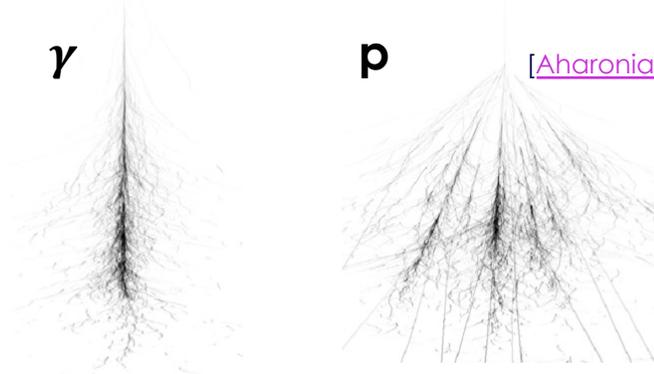
- ▶ **Gamma rays** induce **EM showers** in atmosphere
- ▶ Telescopes collect resulting **Cherenkov emission**
- ▶ **Stereoscopy**
 - ▶ Multiple telescopes
 - ▶ Reconstruct arrival direction, energy,...



[CTAO]

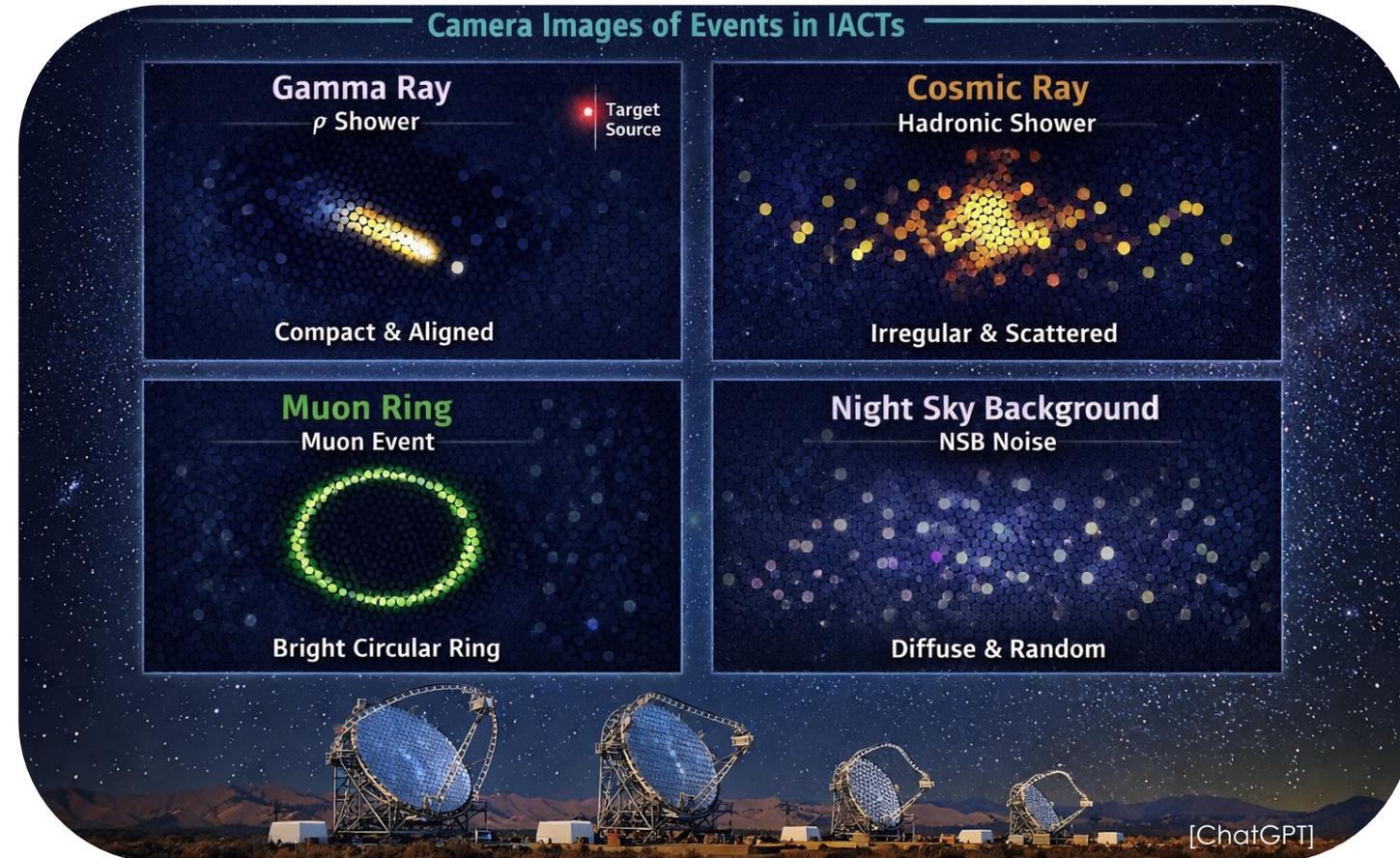
Image Types in IACTs

- ▶ **Stereoscopy** is key for NSB rejection at trigger level
- ▶ **Cosmic rays** (atomic nuclei) are main **background**
 - ▶ Hadronic showers
 - ▶ Messy images
- ▶ **Image reconstruction** is key for cosmic-ray rejection
 - ▶ **Muon rings** can also be exploited at highest energies



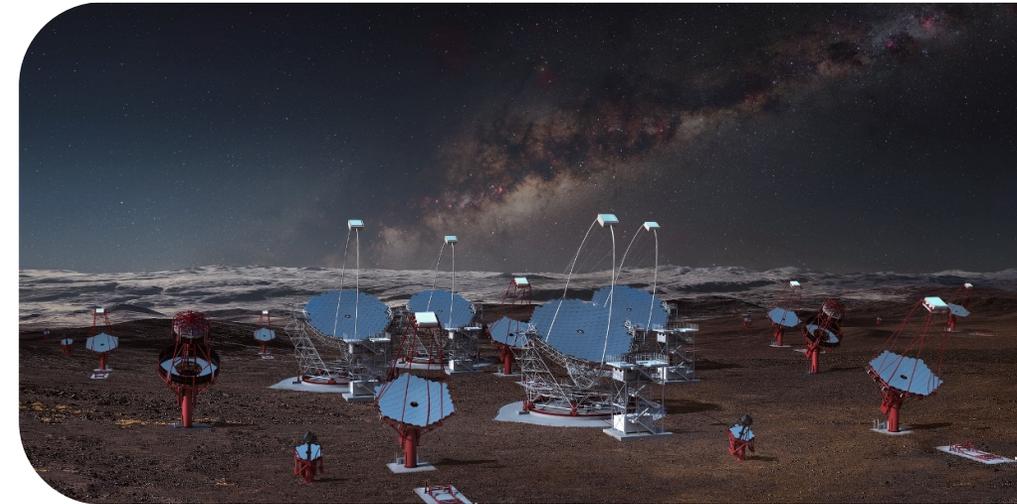
[Aharonian+ (2008) Rep. Prog. Phys. 71 096901]

CTAO



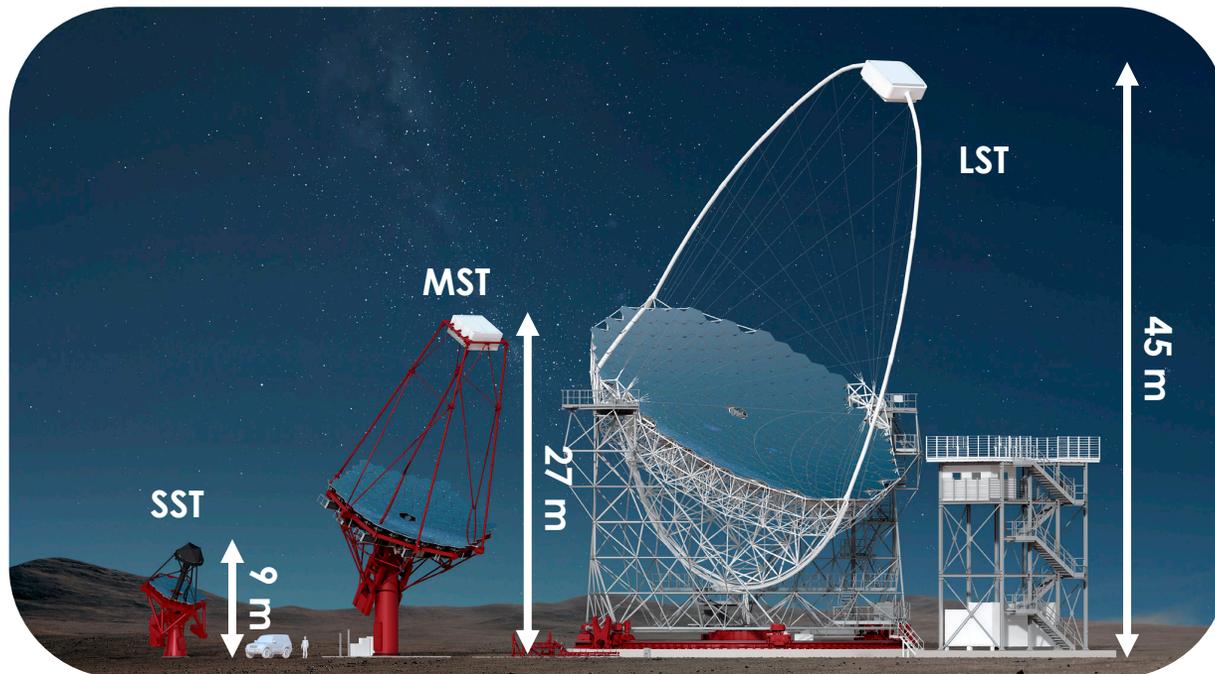
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Cherenkov Telescope Array Observatory **CTAO**

- ▶ **Three IACT types** distributed over **two arrays**
 - ▶ **Wide energy range:** 20 GeV – 300 TeV
 - ▶ **Complete sky coverage**



CTAO-North, La Palma, Canary Islands, Spain

[CTAO]



CTAO-South, Paranal, Atacama Desert, Chile



Large-Sized Telescope (LST)

► Low energies: 20 GeV – 3 TeV

Optical design	Parabolic
Primary reflector diameter	23.0 m
Effective mirror area (including shadowing)	370 m ²
Focal length	28 m
Total weight	103 t
Field of view	4.3 deg
Number of pixels	1855
Pixel size (imaging)	0.1 deg
Photodetector type	PMT
Telescope readout event rate after array trigger	>7.0 kHz
Telescope data rates (readout of all pixels; before array trigger)	24 Gb/s
Positioning time to any point in the sky (>30° elevation)	30 s
Pointing precision	<14 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees



[CTAO]

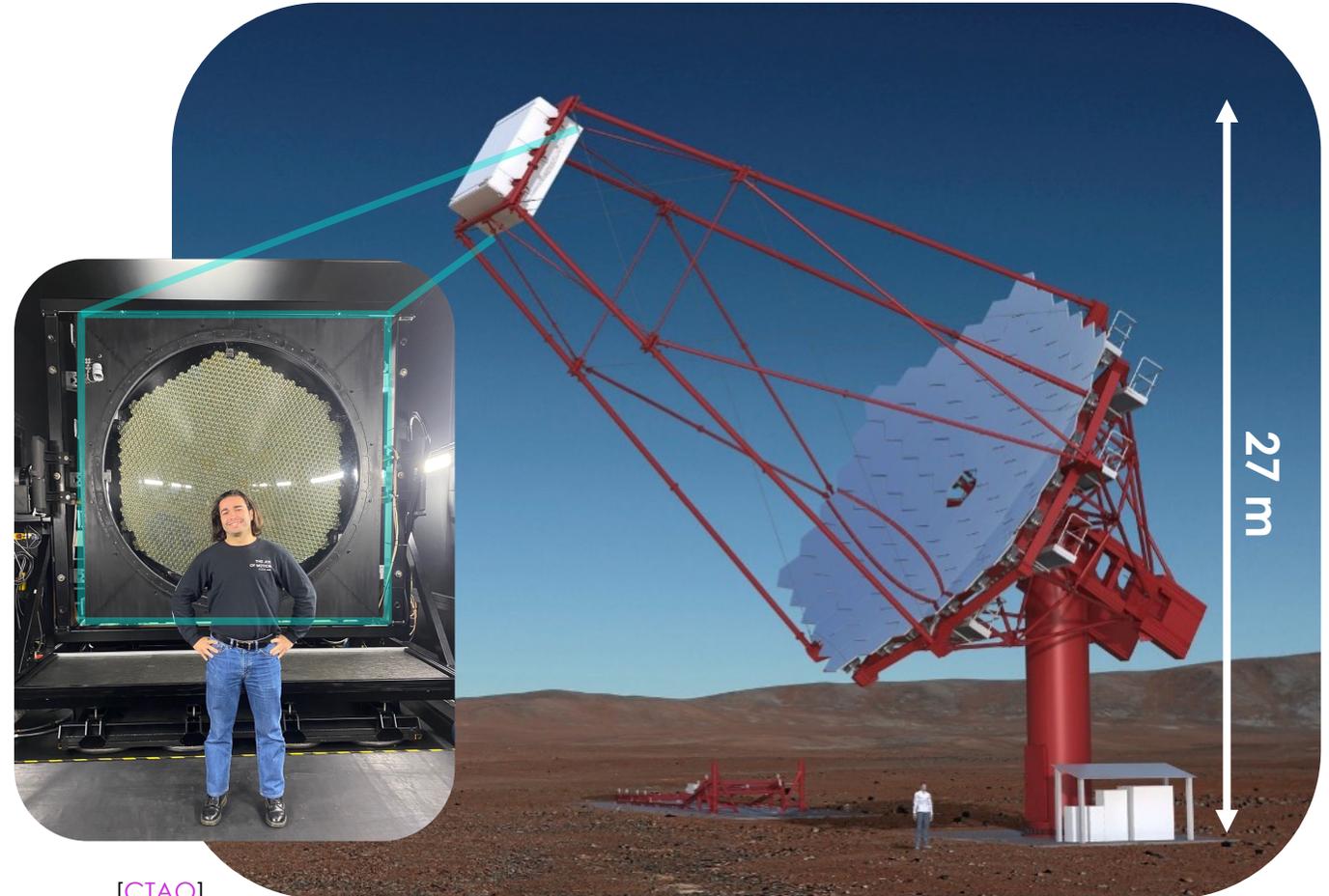
Medium-Sized Telescope (MST)



CTAO

► Intermediate energies: 80 GeV – 50 TeV

Optical design	Modified Davies-Cotton
Reflector diameter	11.5 m
Effective mirror area (including shadowing)	88 m ²
Focal length	16 m
Total weight	89 t
Field of view (FlashCam / NectarCAM)	7.5 deg / 7.7 deg
Number of pixels (FlashCam / NectarCAM)	1764 / 1855
Pixel size (imaging)	0.17 deg
Photodetector type	PMT
Telescope readout event rate before array trigger (FlashCam / NectarCAM)	>6 kHz / >7.0 kHz
Telescope data rates (readout of all pixels; before array trigger)	12 Gb/s
Positioning time to any point in the sky (>30° elevation)	90 s
Pointing precision	<7 arcseconds
Observable sky	Any astrophysical object with elevation > 20 degrees



Small-Sized Telescope (SST)

► High energies: 2 TeV – 300 TeV

Optical design	Modified Schwarzschild-Couder
Primary reflector diameter	4.3 m
Secondary reflector diameter	1.8 m
Effective mirror area (including shadowing)	>5 m ²
Focal length	2.15 m
Total weight	17.5 t
Field of view	8.8 deg
Number of pixels	2048
Pixel size (imaging)	0.16 deg
Photodetector type	SiPM
Telescope readout event rate (before array trigger)	600 Hz
Telescope data rates (readout of all pixels; before array trigger)	2.55 Gb/s
Positioning time to any point in the sky (>30° elevation)	70 s
Pointing precision	<7 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees



[CTAO]

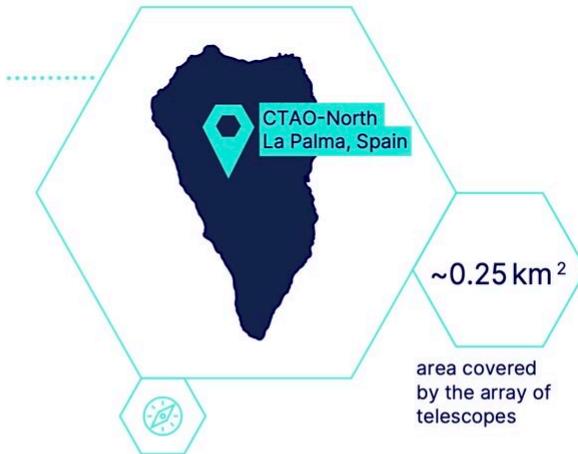
CTAO-North: Alpha Configuration

This talk



► Completion in ~6 years

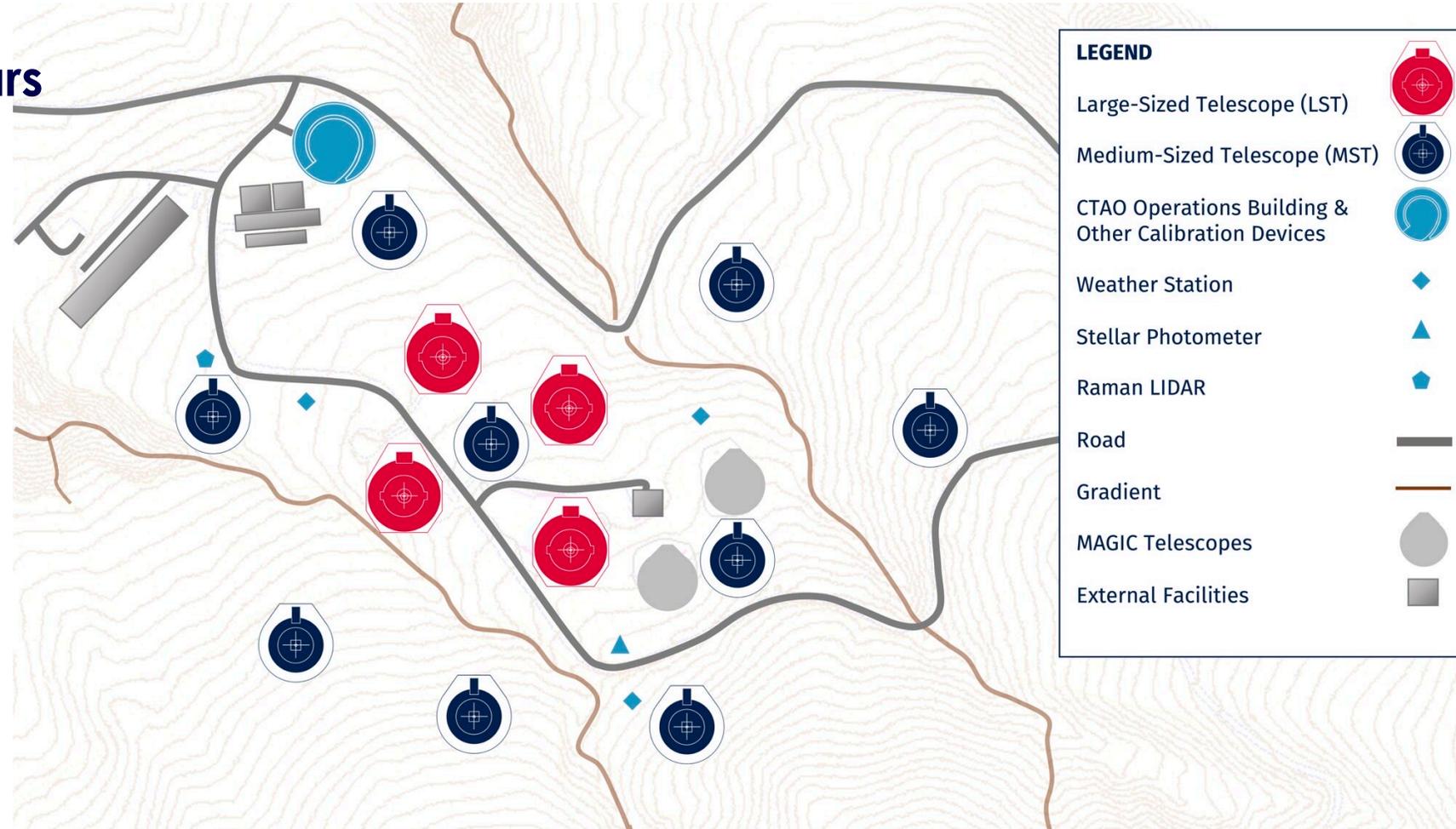
- 9 MSTs
- 4 LSTs



Array Coordinates

Latitude: 28° 45' 43.7904" North
Longitude: 17° 53' 31.218" West

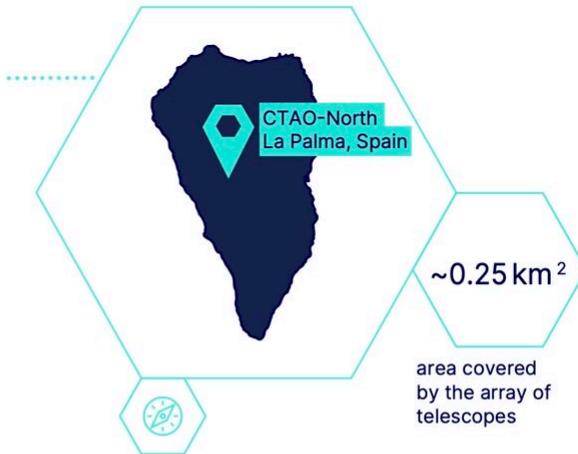
[CTAO]



CTAO-North: First Intermediate Array

► By ~2028

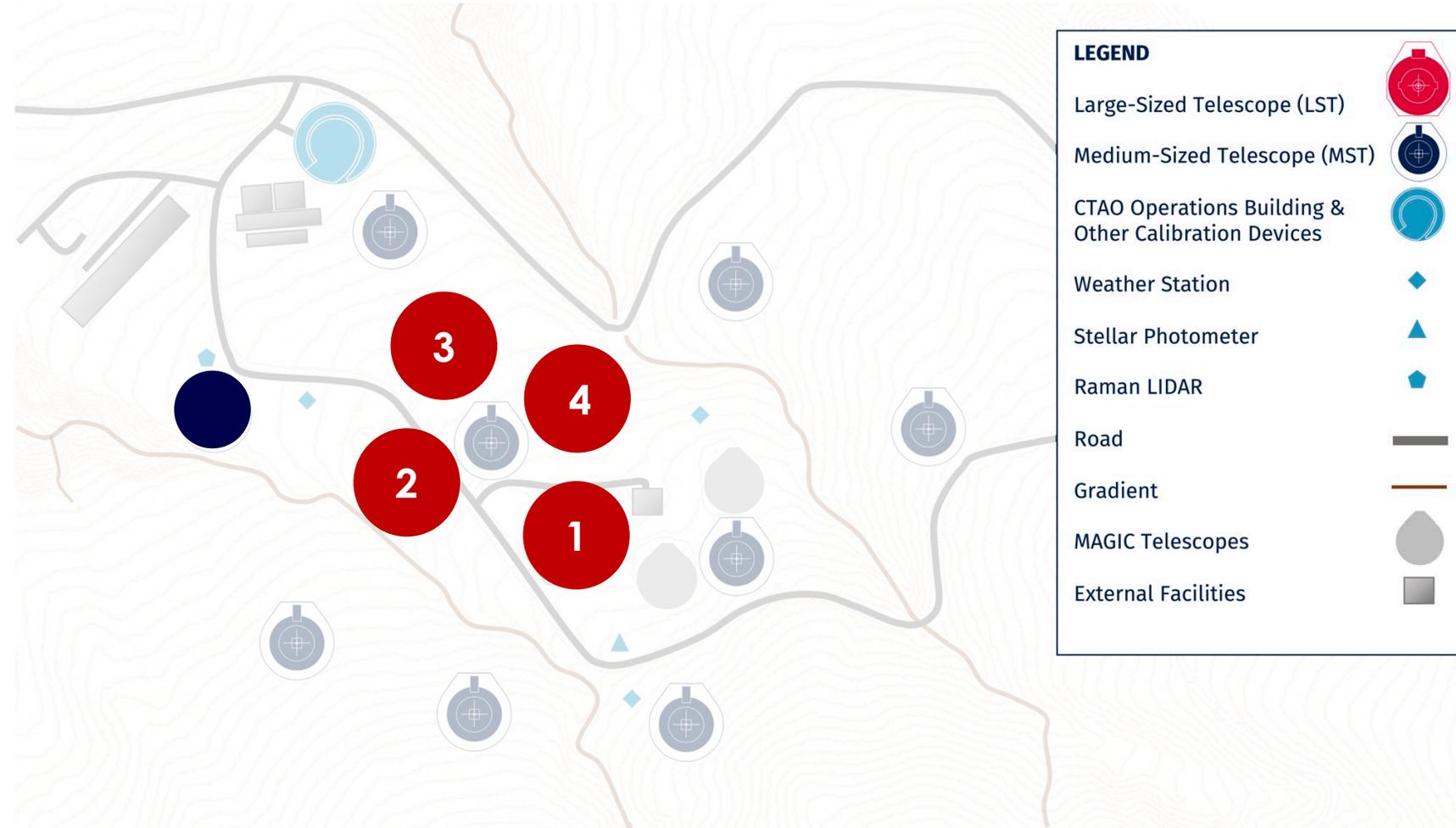
- 1 MST
- 4 LSTs



Array Coordinates

Latitude: 28° 45' 43.7904" North
Longitude: 17° 53' 31.218" West

[CTAO]



CTAO-North: Current Status

[Link to virtual tour](#)

- ▶ **LST-1** taking data since 2018
- ▶ **LST-4** in commissioning phase
 - ▶ Finished construction in 2025
- ▶ **LST-2** & **LST-3** under construction
 - ▶ To be completed in 2026



[Credit: M. Nieves Rosillo]

CTAO-South: Alpha Configuration

This talk

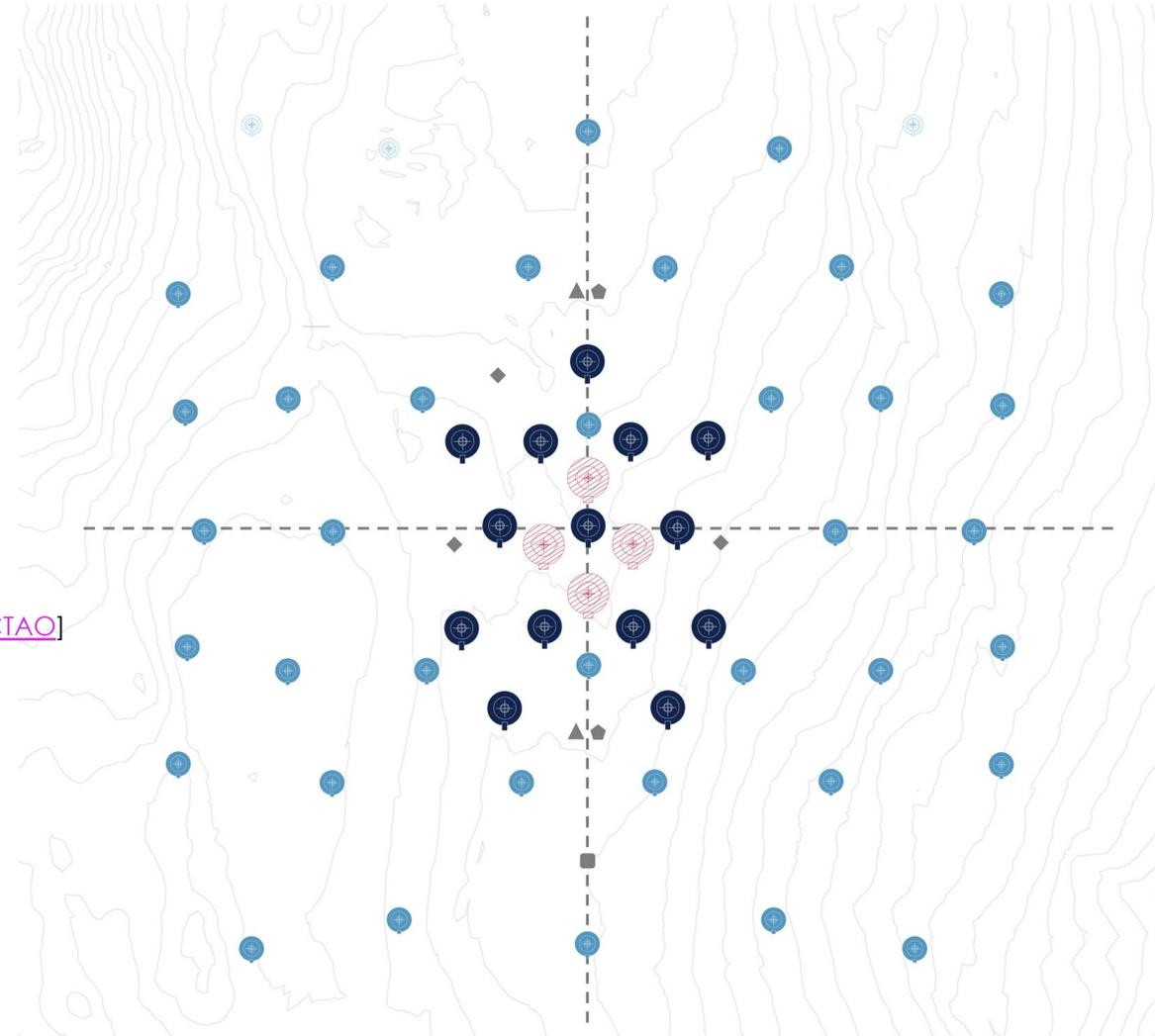


► Completion in ~6 years

- 37 SSTs
- 14 MSTs
- 4 LST foundations



[CTAO]



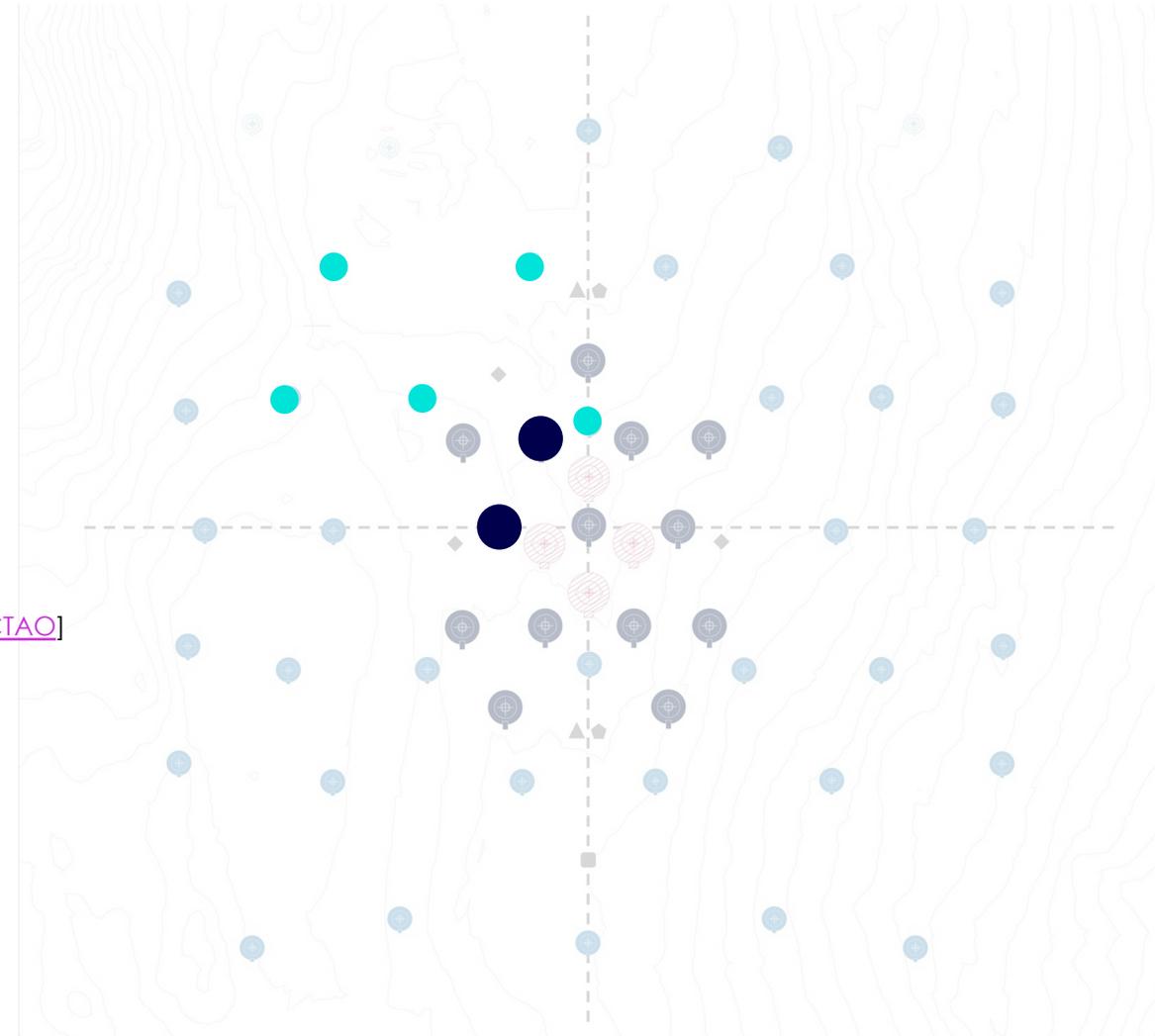
LEGEND			
Medium-Sized Telescope (MST)		Weather Station	
Small-Sized Telescope (SST)		Stellar Photometer	
Large-Sized Telescope (LST) Foundation		Raman LIDAR	
SST Foundation		Other Calibration Devices	

CTAO-South: First Intermediate Array

- ▶ **By ~2028**
- ▶ 5 SSTs
- ▶ 2 MSTs



[CTAO]

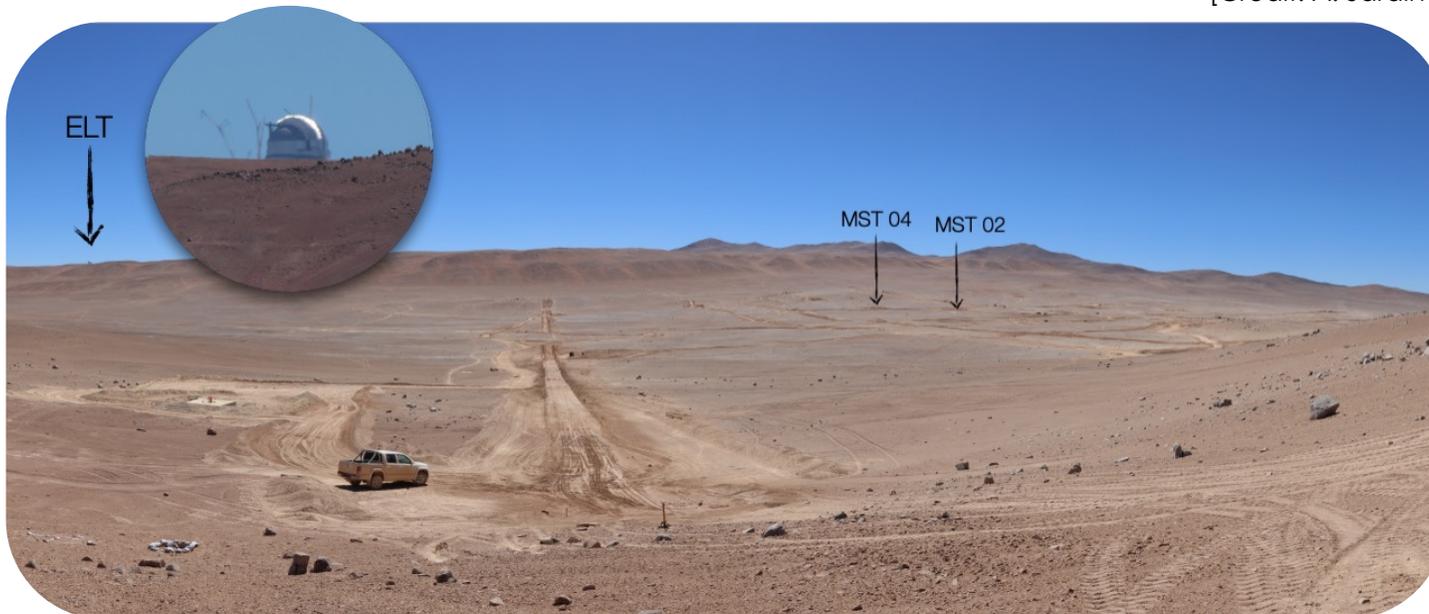


LEGEND	
Medium-Sized Telescope (MST)	
Small-Sized Telescope (SST)	
Large-Sized Telescope (LST) Foundation	
SST Foundation	
Weather Station	
Stellar Photometer	
Raman LIDAR	
Other Calibration Devices	

CTAO-South: Current Status

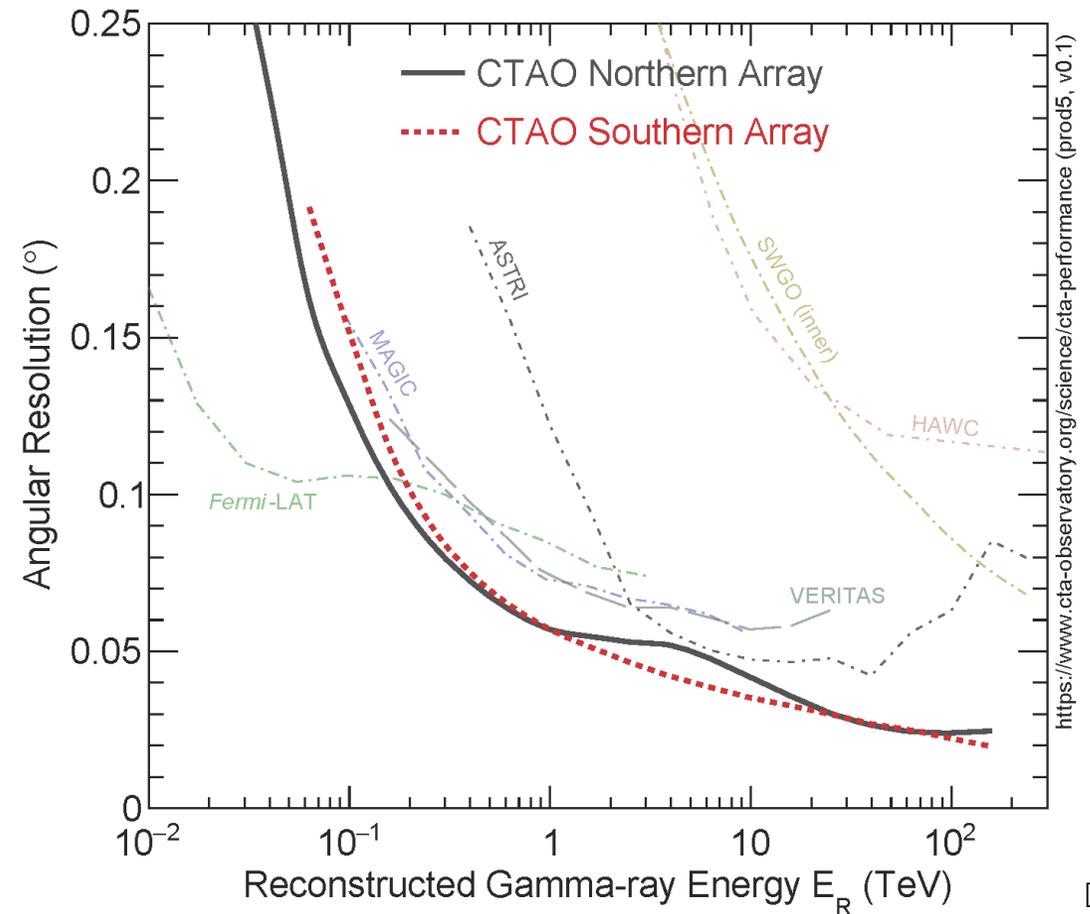
- ▶ **Foundations** for pathfinder array (2 MSTs + 5 SSTs) under construction
- ▶ Pictures from January 2026

[Credit: A. Jardin-Blicq]



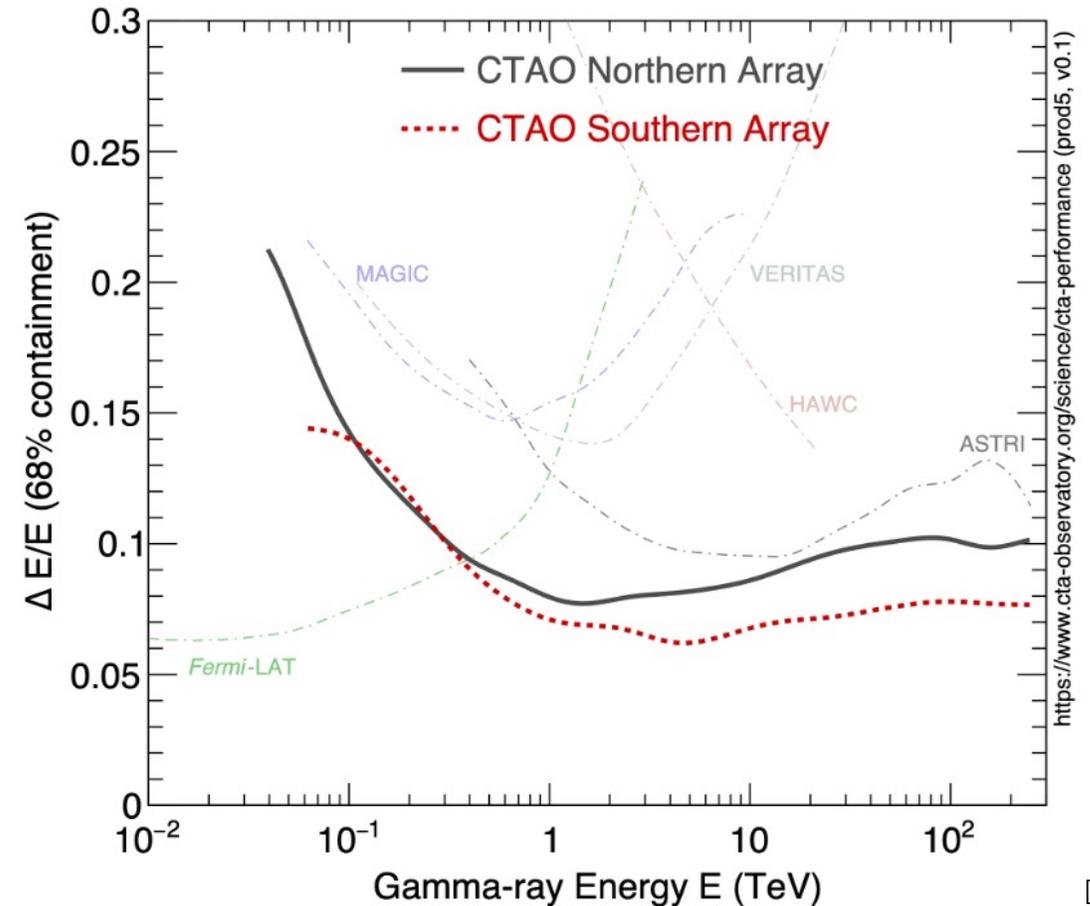
CTAO Performance

- ▶ **Angular resolution** $< 0.05^\circ$ above 1 TeV



CTAO Performance

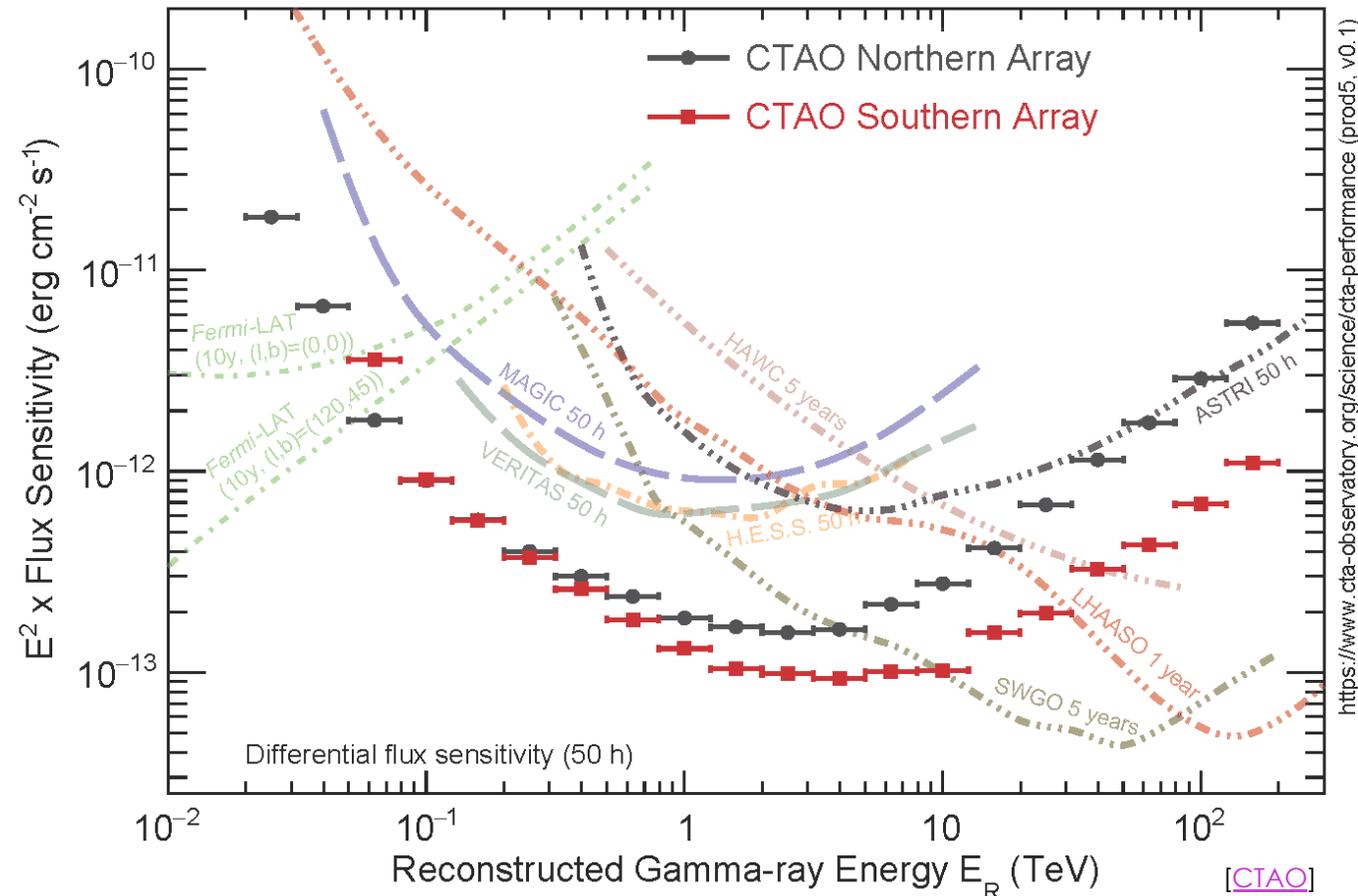
- ▶ **Angular resolution** $< 0.05^\circ$ above 1 TeV
- ▶ **Energy resolution** of 5–10% above 300 GeV



CTAO Performance

- ▶ **Angular resolution** $< 0.05^\circ$ above 1 TeV
- ▶ **Energy resolution** of 5–10% above 300 GeV

Integrated sensitivity improves by factor 5–10 compared to current VHE instruments

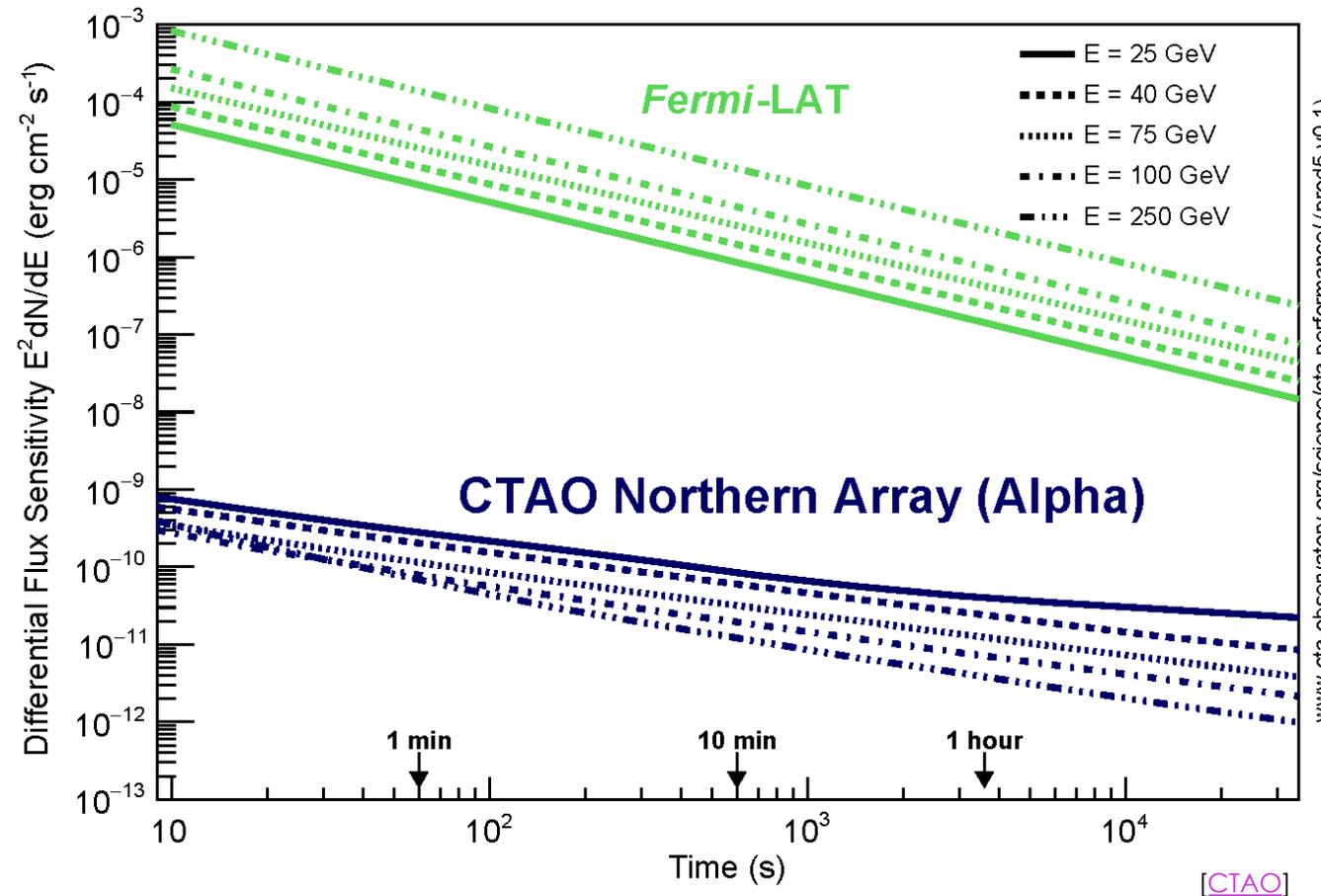


CTAO Performance



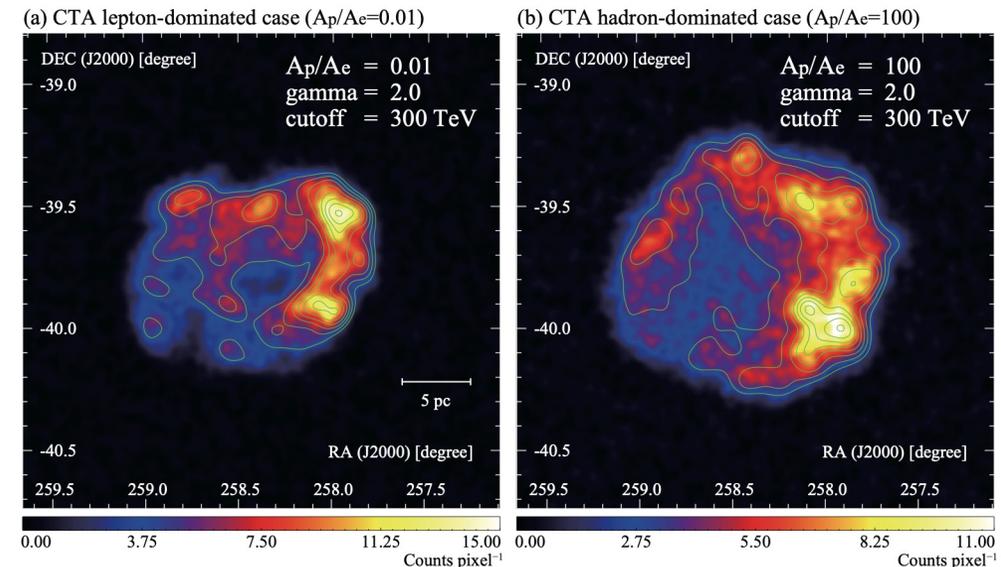
- ▶ **Angular resolution** $< 0.05^\circ$ above 1 TeV
- ▶ **Energy resolution** of 5–10% above 300 GeV

Transient sensitivity improves by factor 10^2 – 10^4 compared to *Fermi*-LAT



Contents

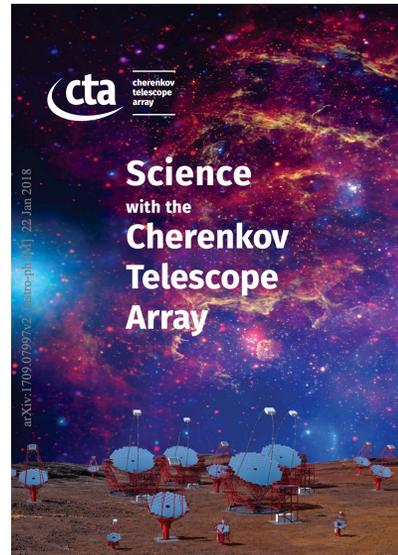
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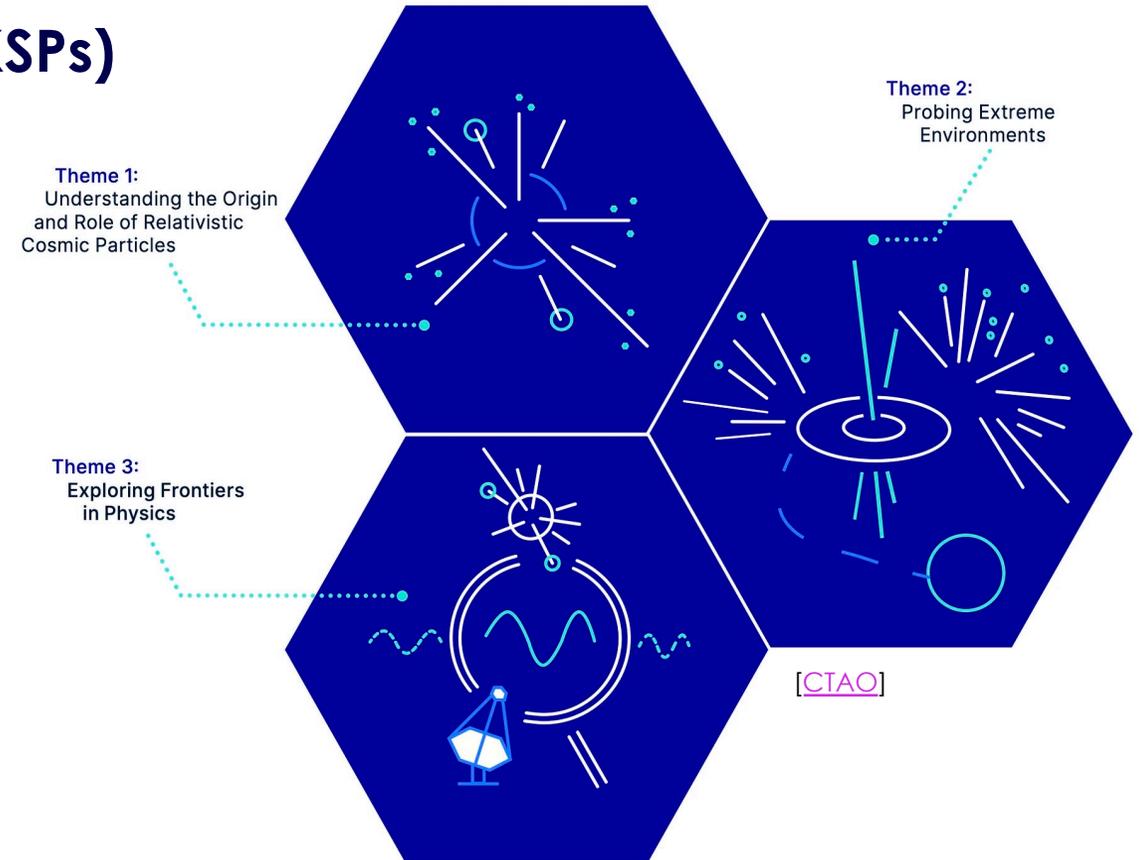
Science with CTAO



- ▶ **CTAO Consortium** leads scientific activities
 - ▶ Over 1500 members in ~200 institutes across 25 countries
- ▶ Identified various **key science projects (KSPs)**
 - ▶ All details in *Science with CTAO* book
 - ▶ **This talk: Very biased & incomplete overview**
 - ▶ With a focus on star-forming systems

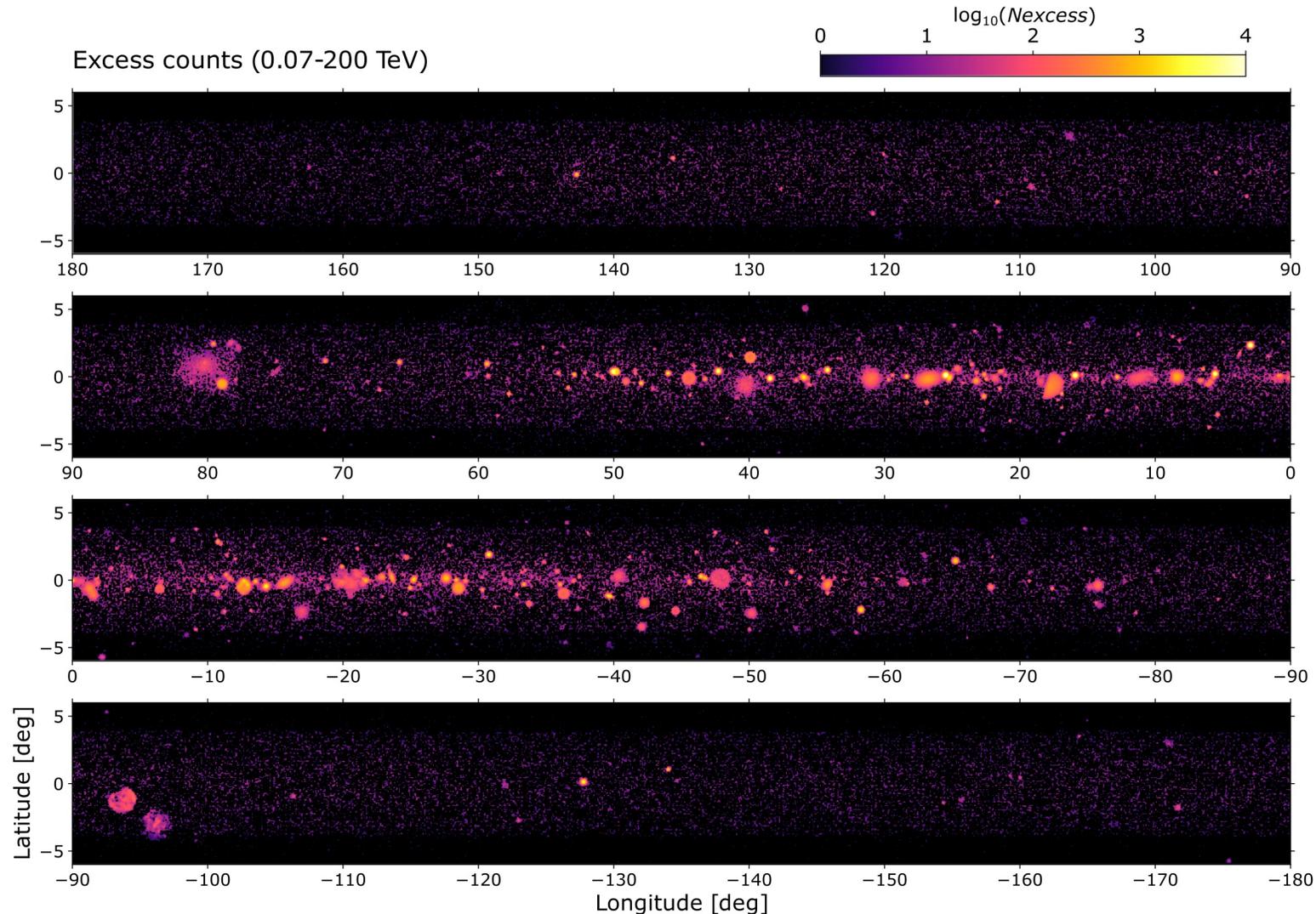
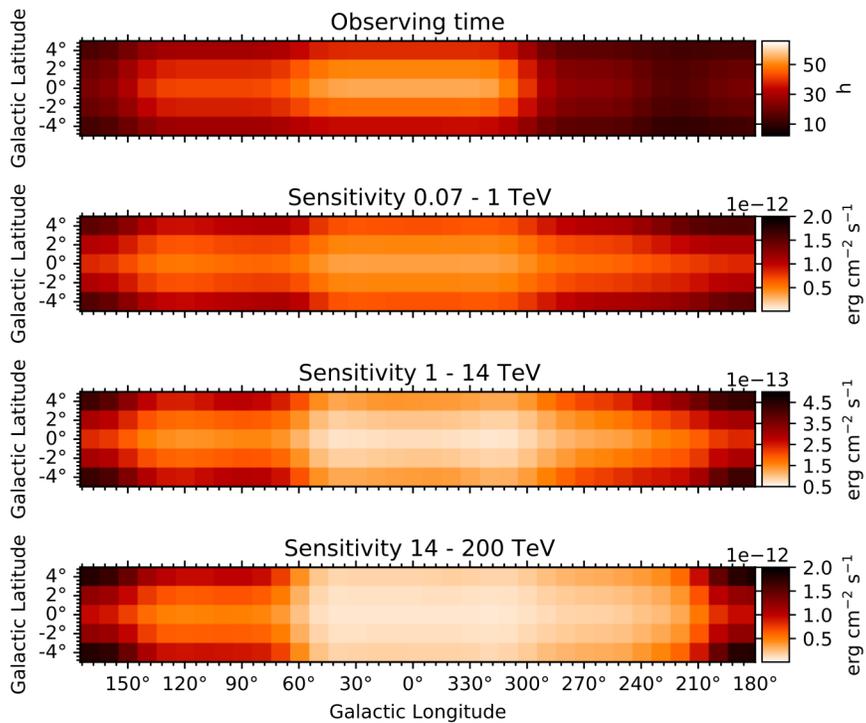


[CTAO (2019) World Scientific Publishing]



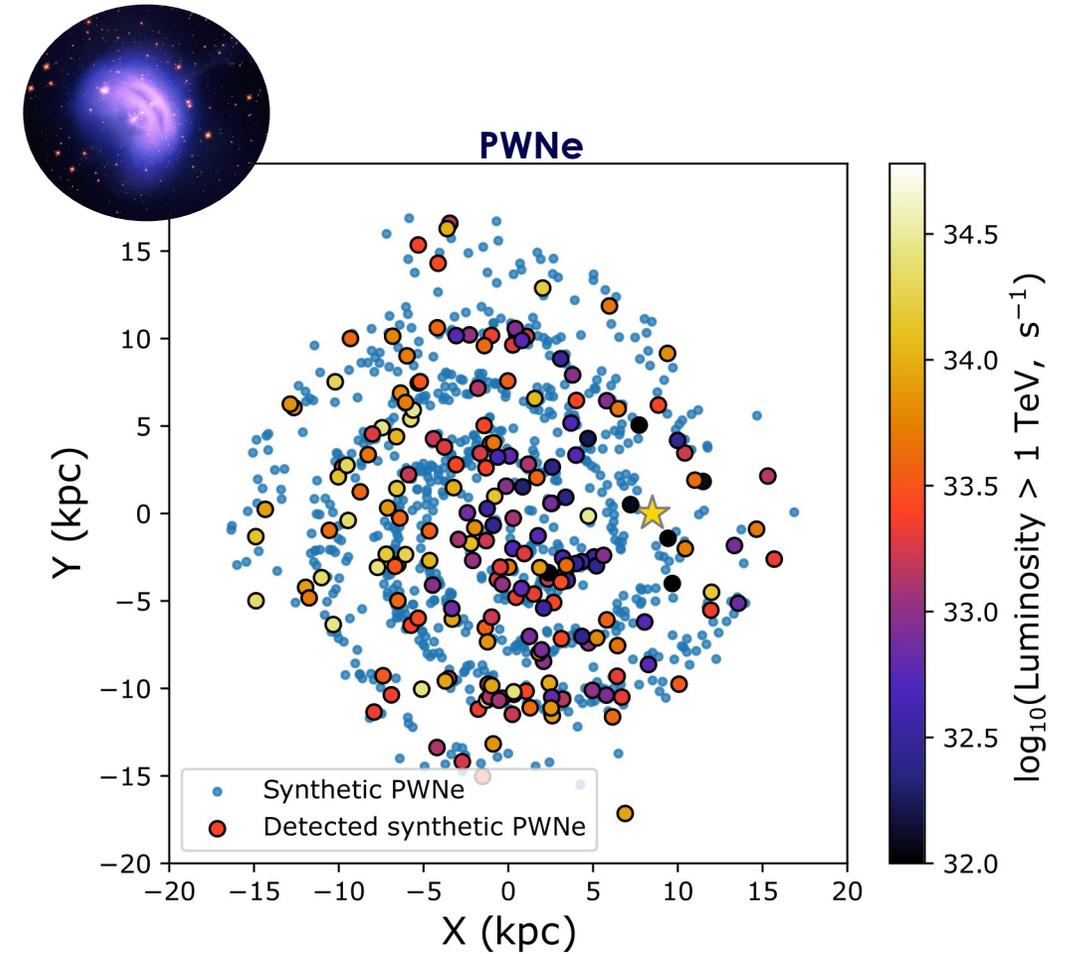
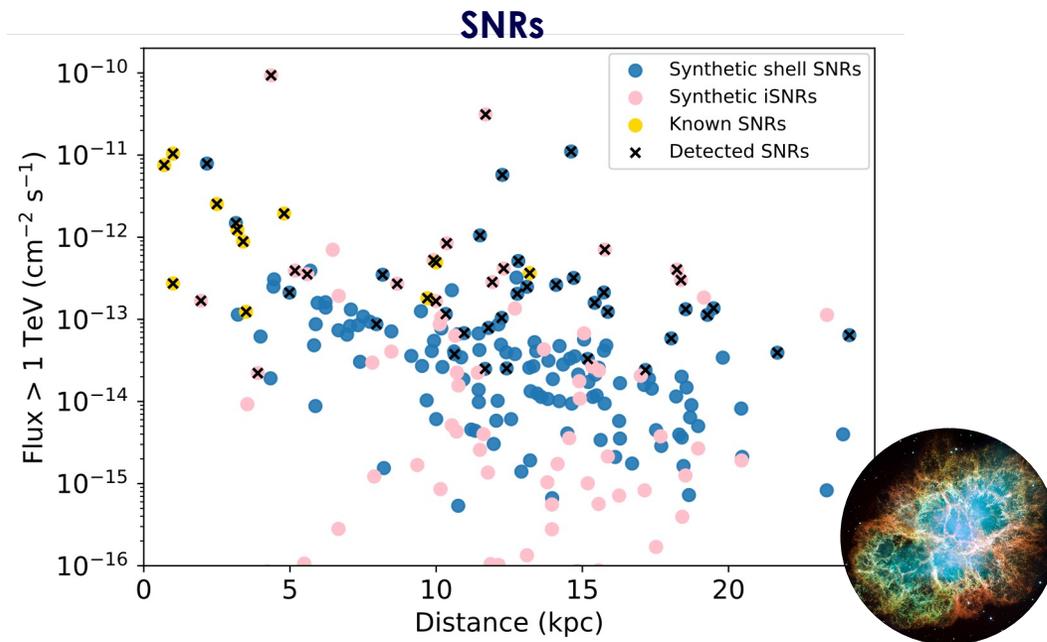
Galactic Plane Survey

- ▶ 1620 hr over 10 years
 - ▶ **1.8–4.2 mCrab sensitivity**
- ▶ Expect **~500 VHE sources**
 - ▶ Factor 5 improvement!



Galactic Plane Survey

- ▶ Perform **population studies**
 - ▶ Pulsar wind nebulae & supernova remnants
- ▶ Detect **rare VHE sources**
 - ▶ PeVatrons, gamma-ray pulsars, binary systems...

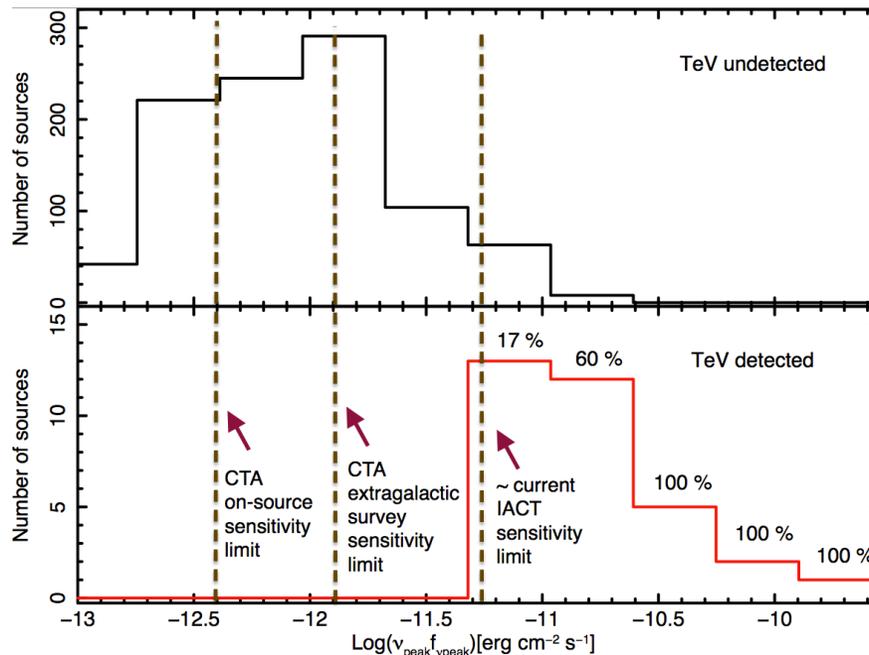
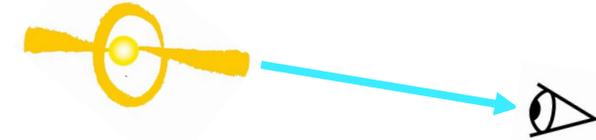


[CTAO (2024) JCAP 10 081]

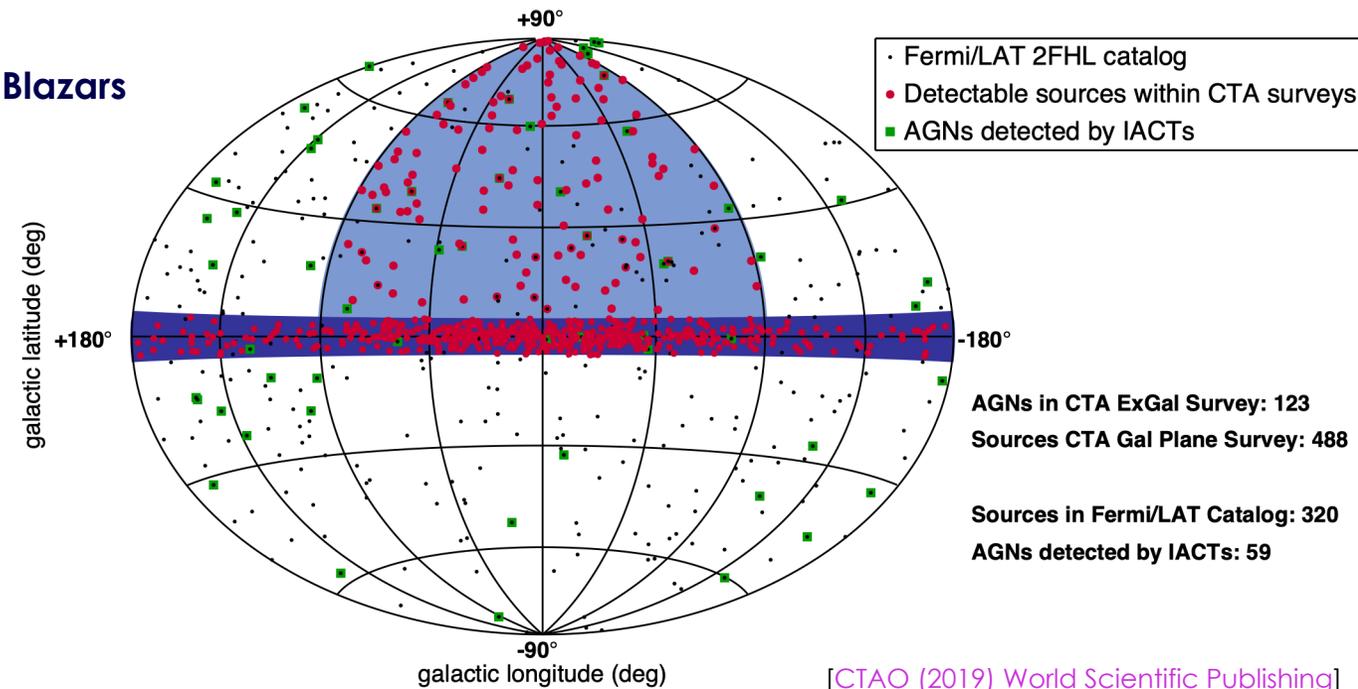
Extragalactic Survey

- ▶ Scan **25% of sky** with 1000 hr over ~3 years
 - ▶ **6.2 mCrab** sensitivity
- ▶ Expect **30–150 blazars** in survey (unbiased catalog)
- ▶ Expect **handful of other VHE sources**: starburst galaxies,...

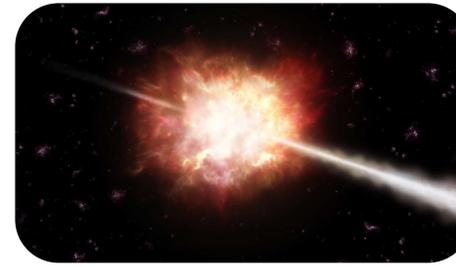
Blazars are AGN with jet pointed to observer



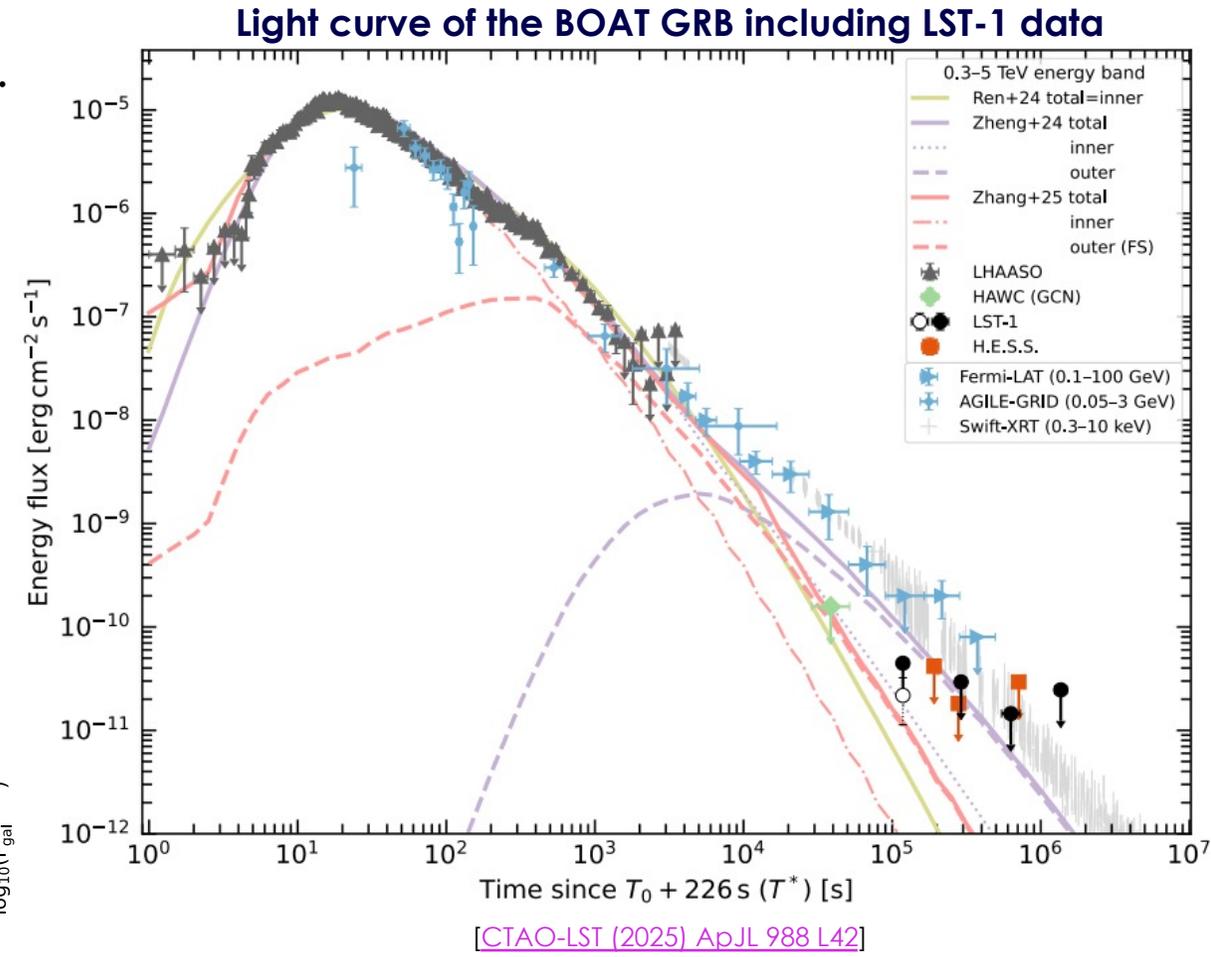
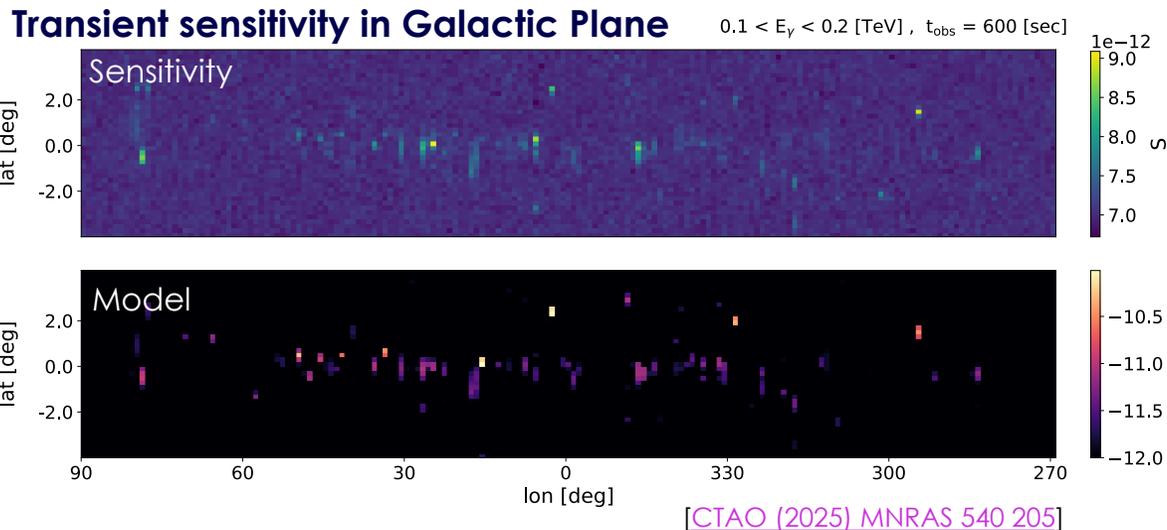
Blazars



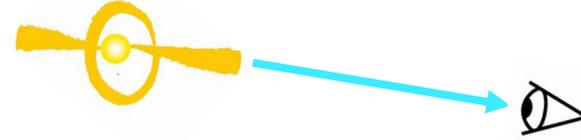
Transient Sources



- ▶ **Extragalactic transients**
 - ▶ Gamma-ray bursts, core-collapse supernovae,...
- ▶ **Galactic transients**
 - ▶ PWN flares, microquasars,...
- ▶ **Realtime analyses & alert follow-ups**
 - ▶ **Multimessenger & multiwavelength**



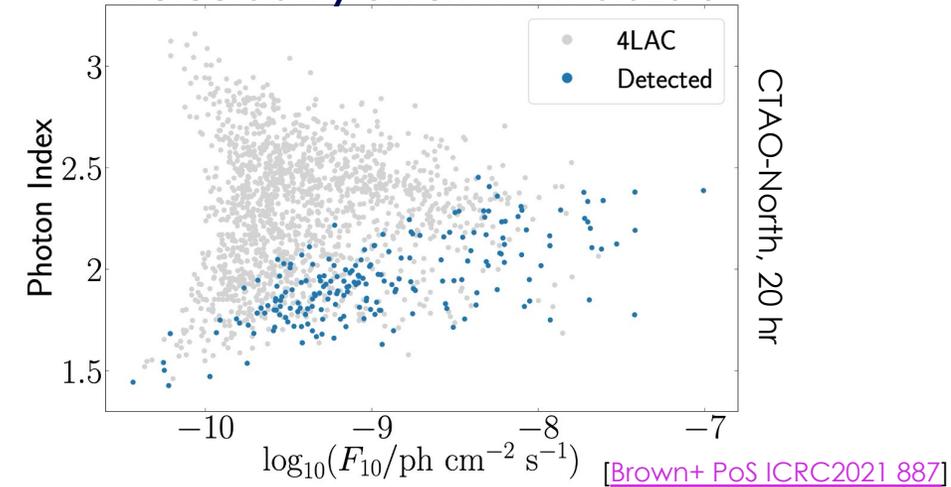
Blazars are AGN with jet pointed to observer



Active Galactic Nuclei

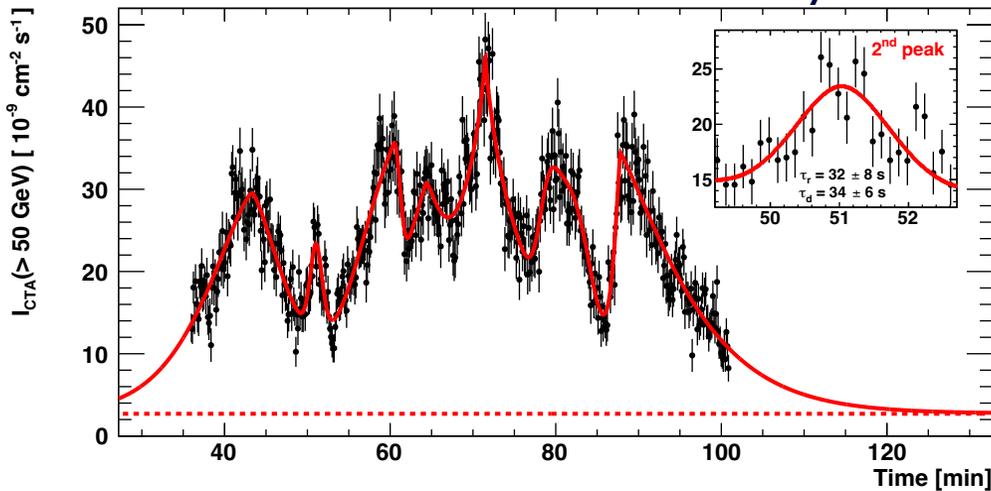
- ▶ CTAO will primarily observe **blazars**
 - ▶ **Population studies** of blazar subclasses up to $z \sim 2$
 - ▶ But also expect to detect **other AGN types**
- ▶ **Long-term monitoring** of selected sources
 - ▶ Distinguish **hadronic vs leptonic** scenarios
 - ▶ Study **spectral variability** from minutes to years

Detectability of *Fermi*-LAT blazars

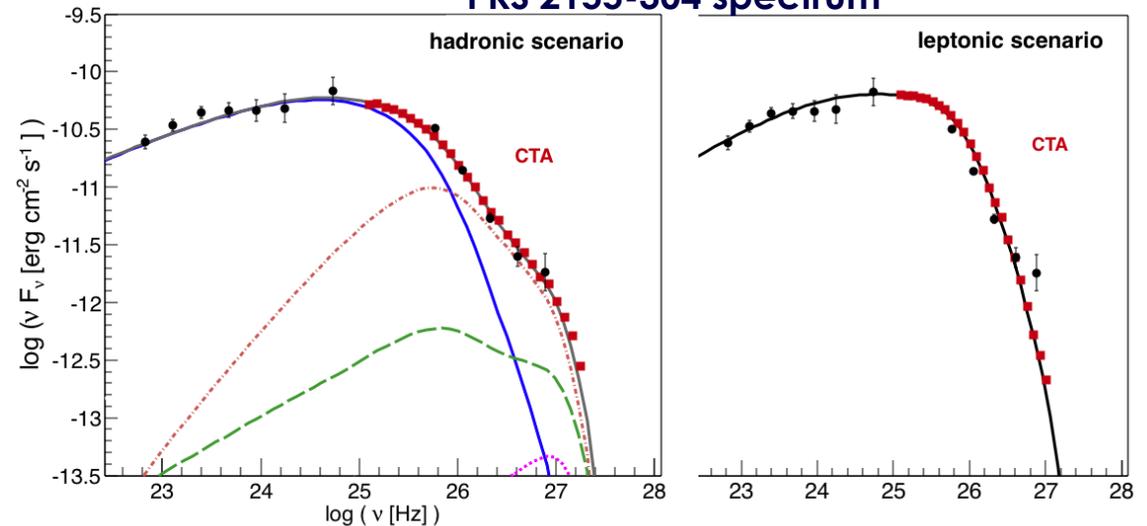


PKS 2155-304 time variability

[CTAO (2019) World Scientific Publishing]

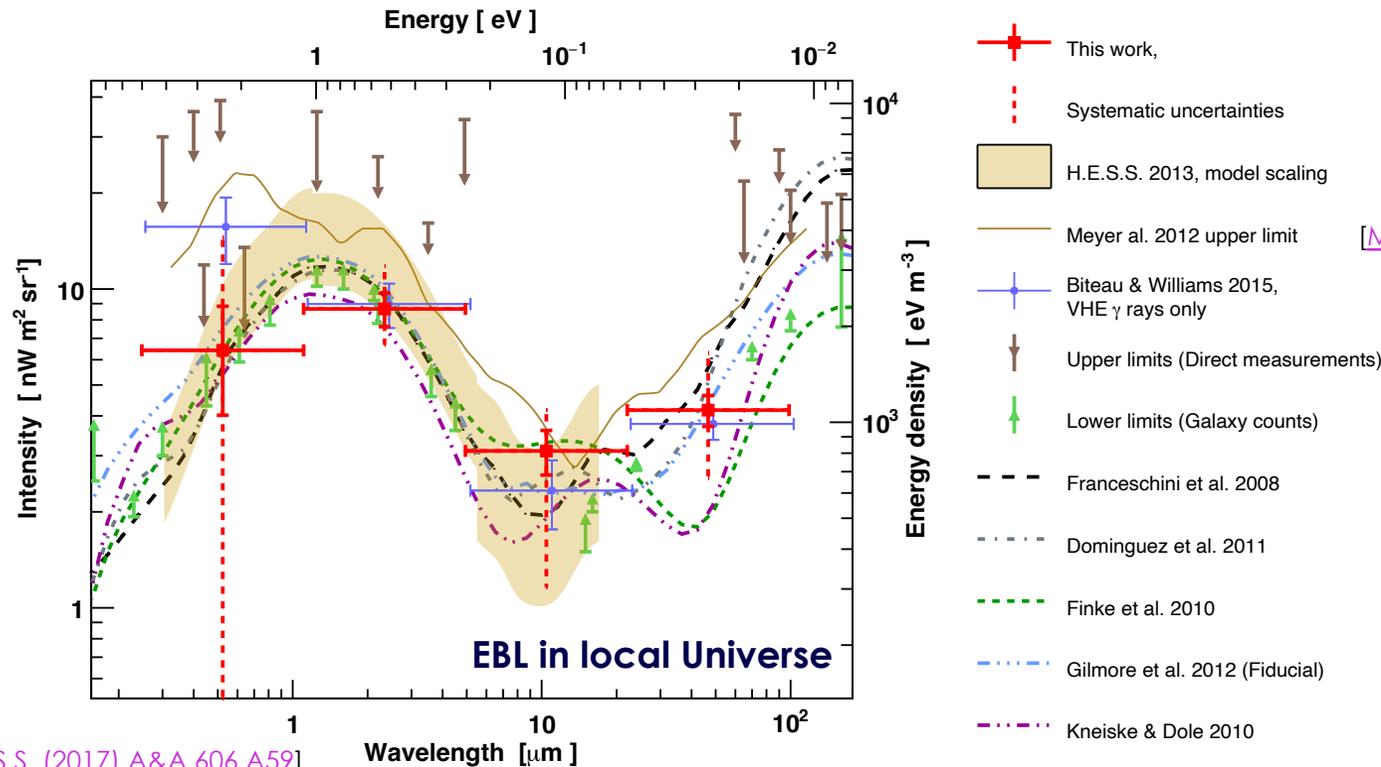


PKS 2155-304 spectrum

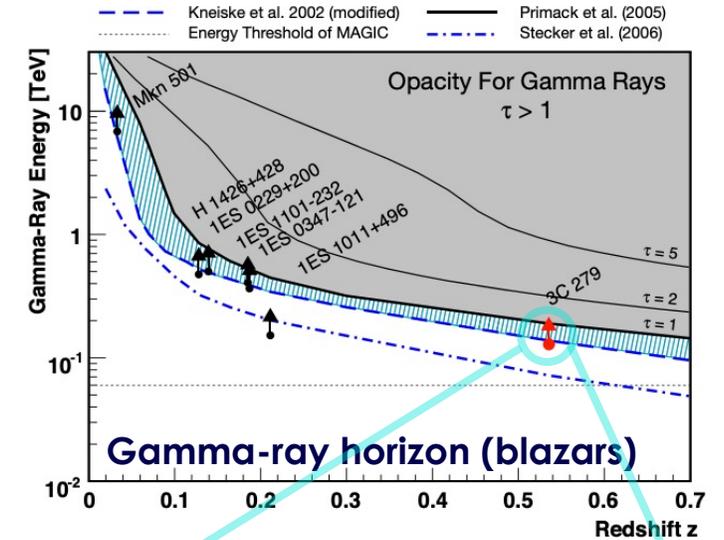


Extragalactic Background Light

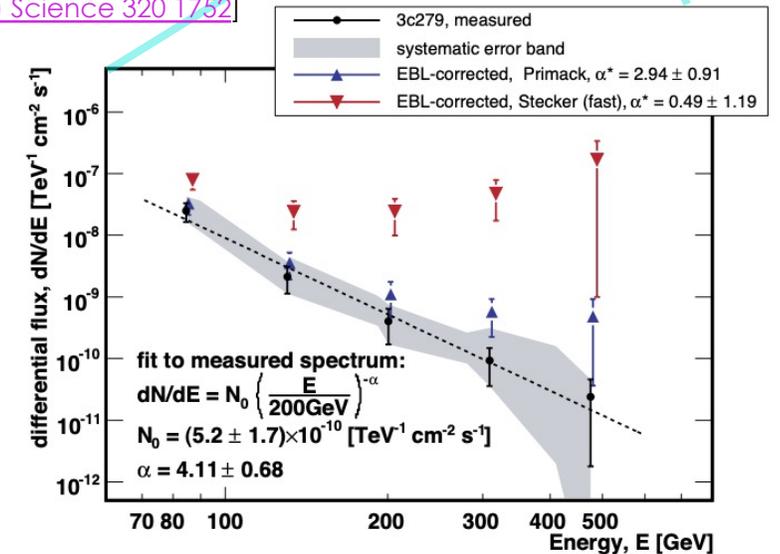
- ▶ Gamma rays get **absorbed by EBL**
- ▶ **Cumulative emission** from all galaxies in the Universe
- ▶ Optical+IR EBL leaves **imprint on VHE blazar spectra**



[H.E.S.S. (2017) A&A 606 A59]

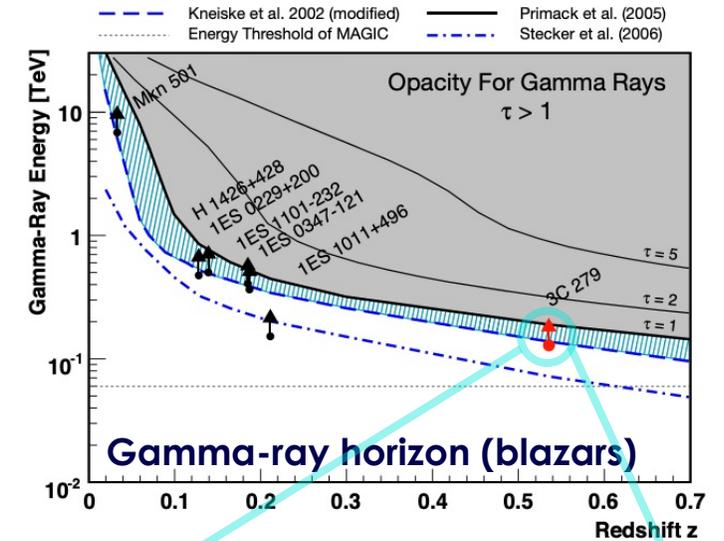
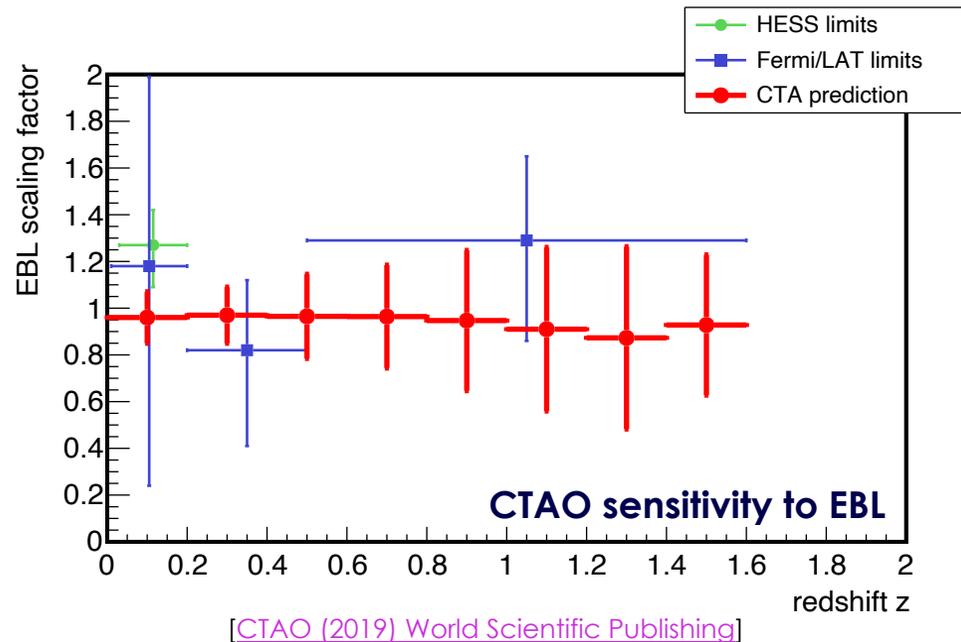


[MAGIC (2008) Science 320 1752]

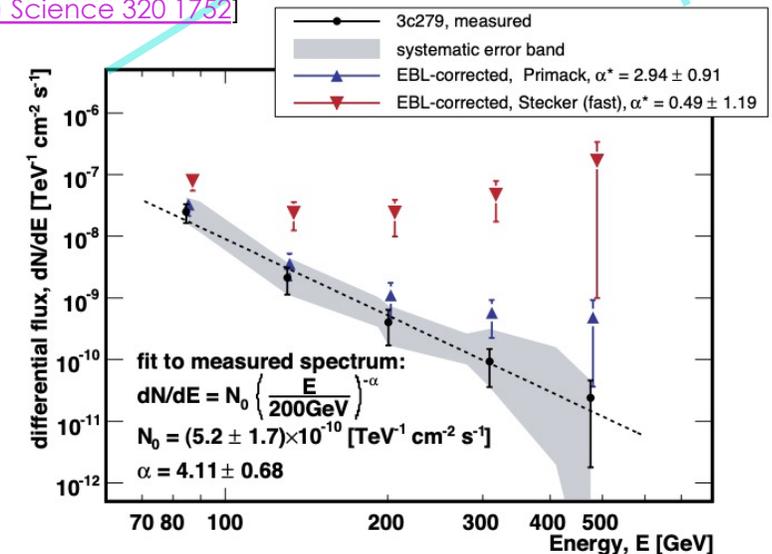


Extragalactic Background Light

- ▶ Gamma rays get **absorbed by EBL**
 - ▶ **Cumulative emission** from all galaxies in the Universe
 - ▶ Optical+IR EBL leaves **imprint on VHE blazar spectra**
- ▶ **Indirect measurement** of EBL up to $z \sim 2$



[MAGIC (2008) Science 320 1752]

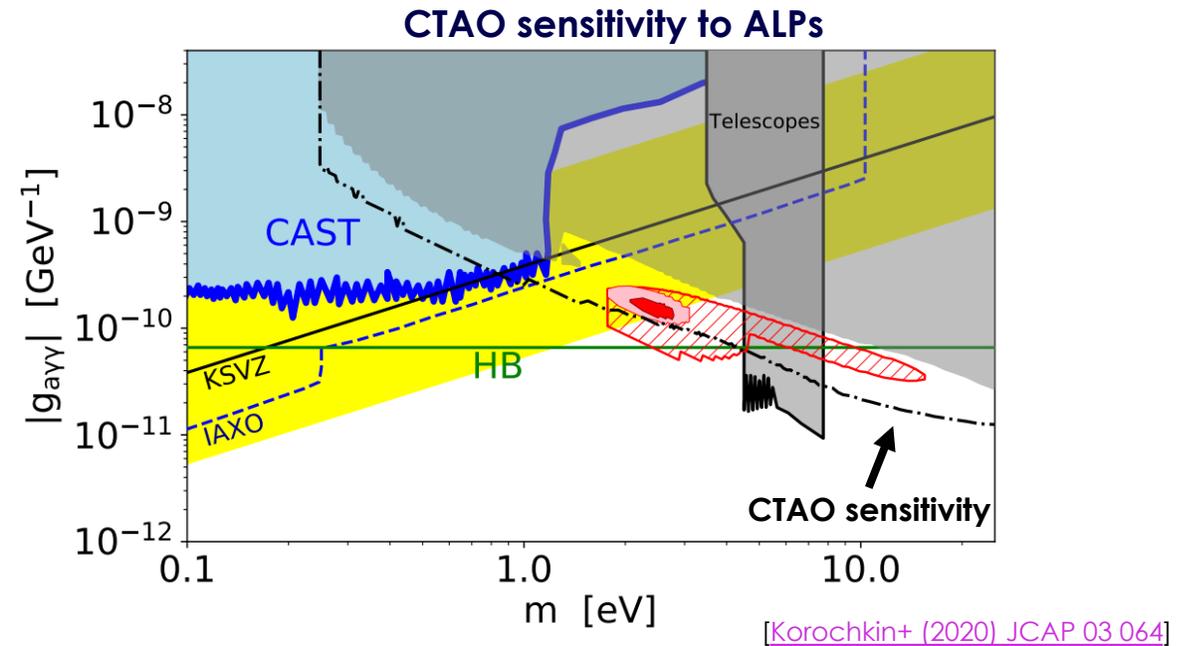
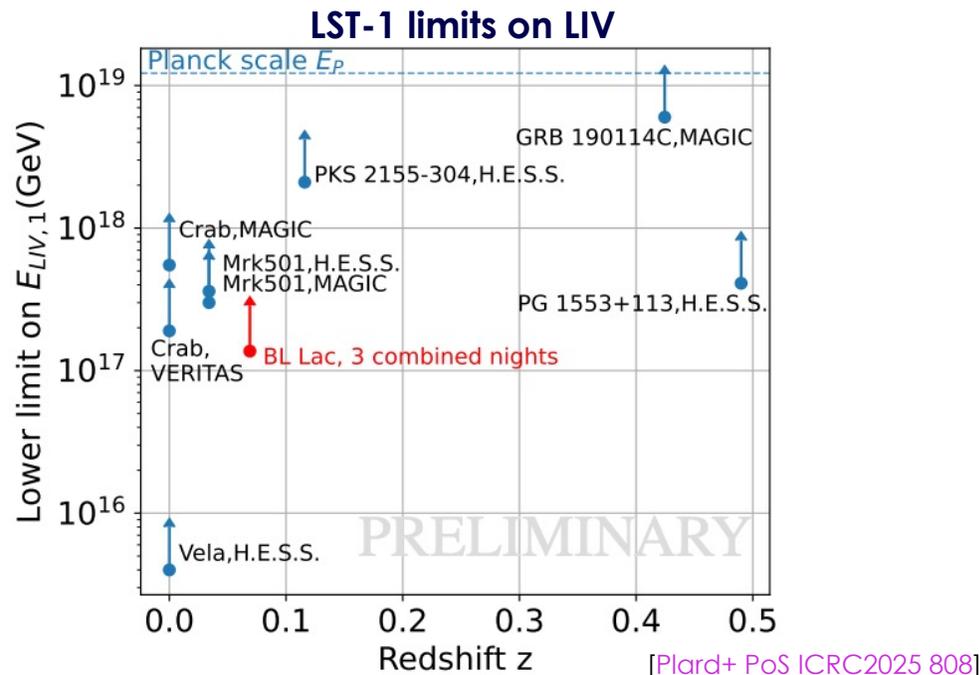


Physics Beyond the Standard Model

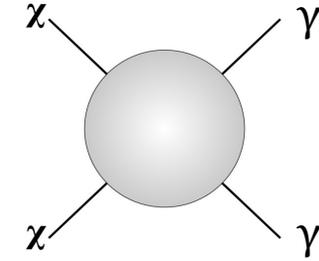
- ▶ **New physics** can be probed using deep observations of blazars & GRBs
- ▶ **Lorentz-invariance violation**
 - ▶ **Dispersion** in photon arrival times
- ▶ **Axion-like particles**
 - ▶ Photon-ALP oscillations in \vec{B} : $\gamma \uparrow$

$$E^2 = p^2 c^2 \times \left[1 \pm \sum_n \left(\frac{E}{E_{LIV,n}} \right)^n \right] \rightarrow v_\gamma(E) \neq c$$

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

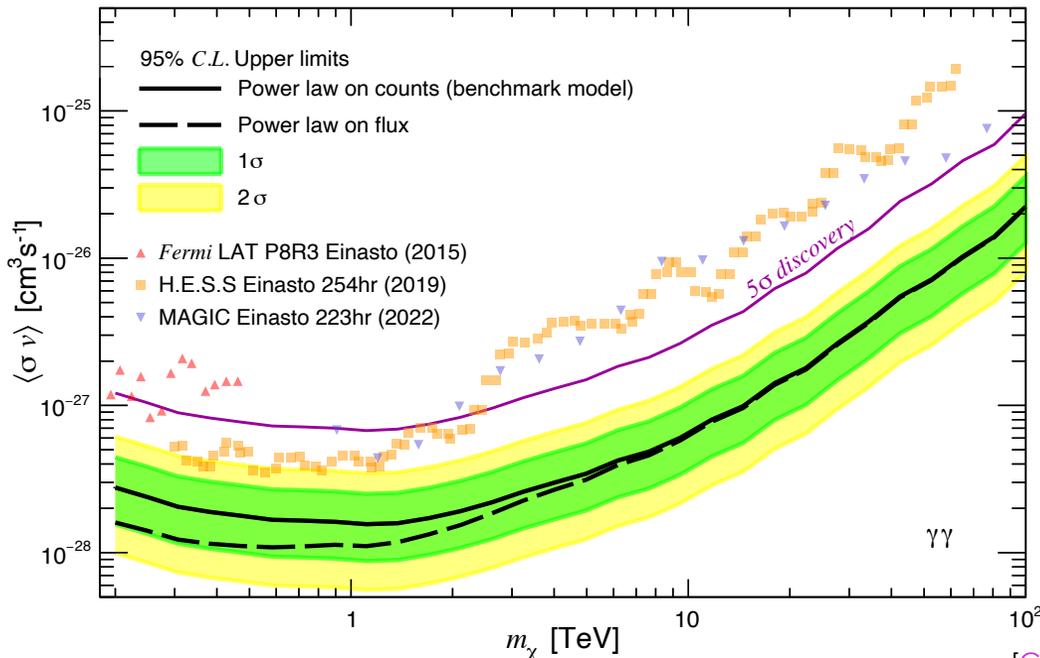


Dark Matter



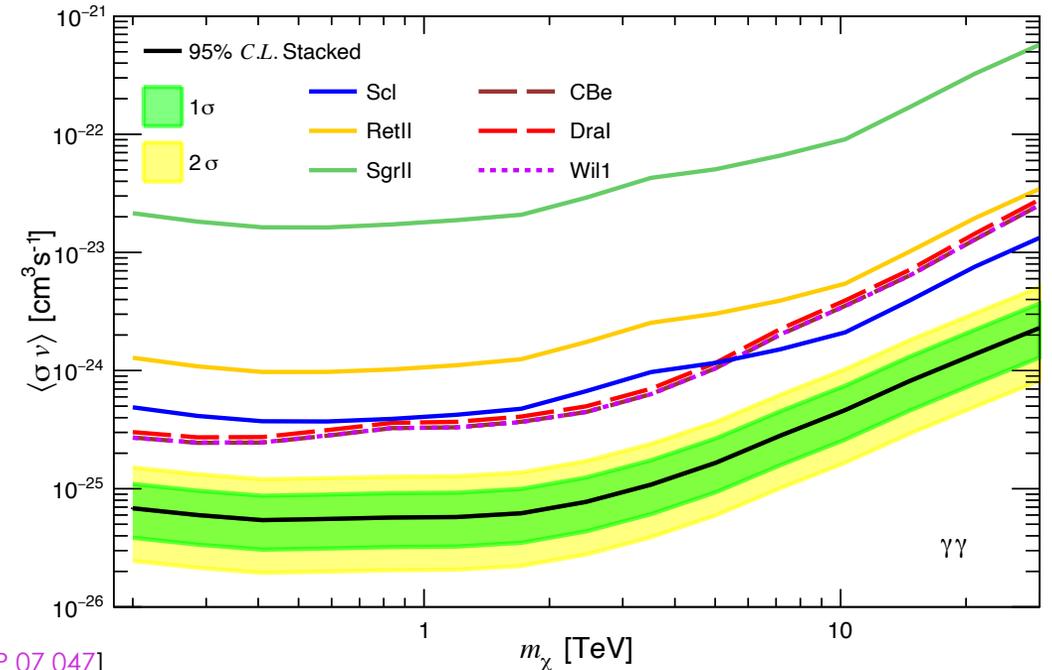
- ▶ **Indirect detection** of WIMP annihilation
- ▶ **Main targets:** Galactic Center & neighboring dwarf spheroidal galaxies

Galactic Center, 500h



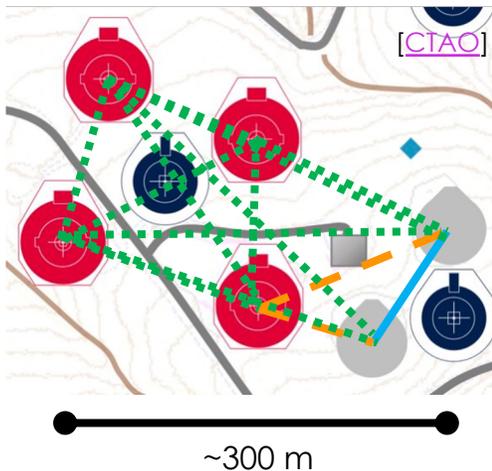
[CTAO (2024) JCAP 07 047]

dSphs, 100h per source

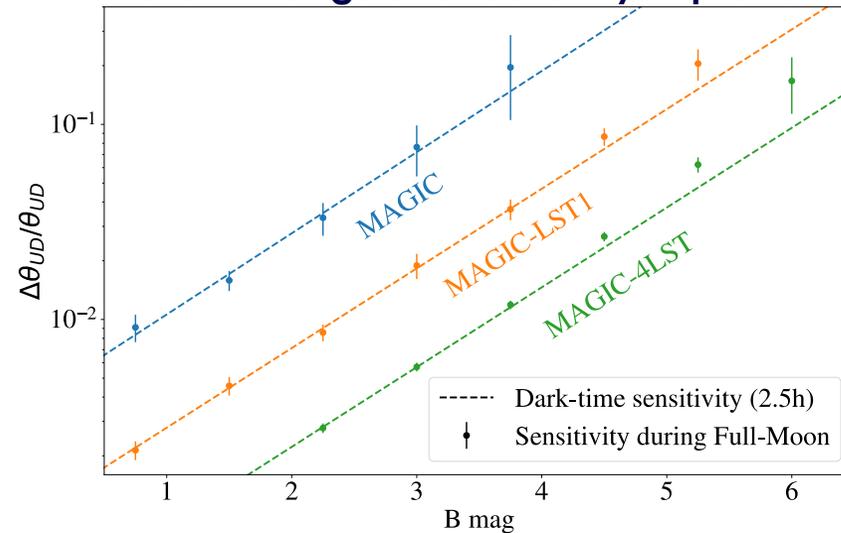


Stellar Intensity Interferometry

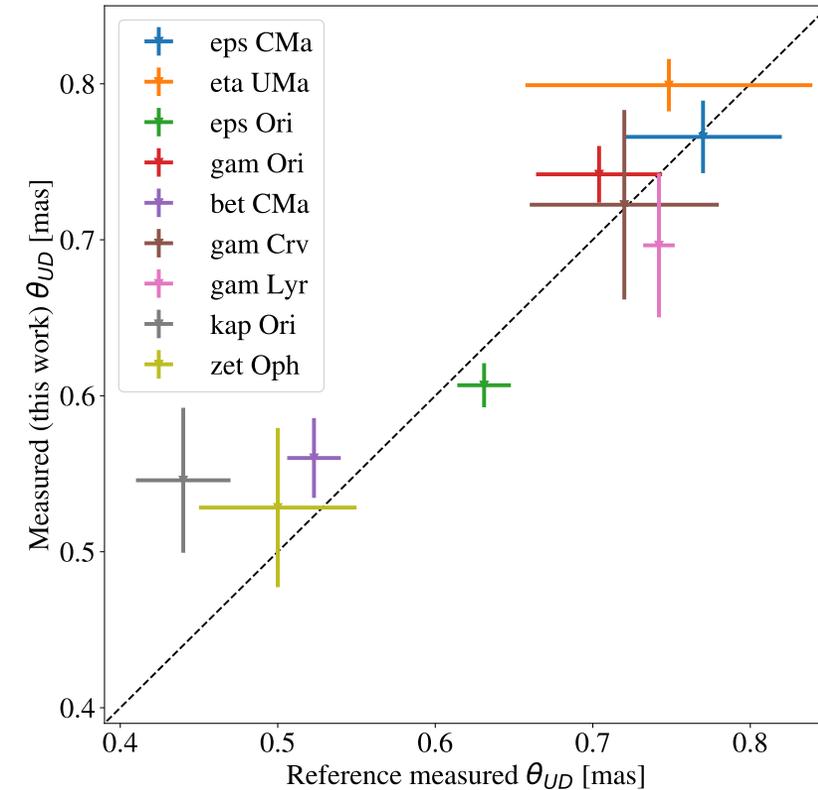
- ▶ CTAO can be used as an **interferometer**
 - ▶ **Correlate intensity measurements** from all telescope baselines
 - ▶ **Spatial resolution $< 100 \mu\text{as}$** for completed array
 - ▶ Observe **star diameters**, binaries, novae,...
- ▶ SII successfully applied on **previous IACTs**
 - ▶ **MAGIC+LST** studies ongoing at CTAO-North



MAGIC+LST angular uncertainty improvement



Stellar diameters observed with MAGIC



[MAGIC (2024) MNRAS 539 4387]

Contents

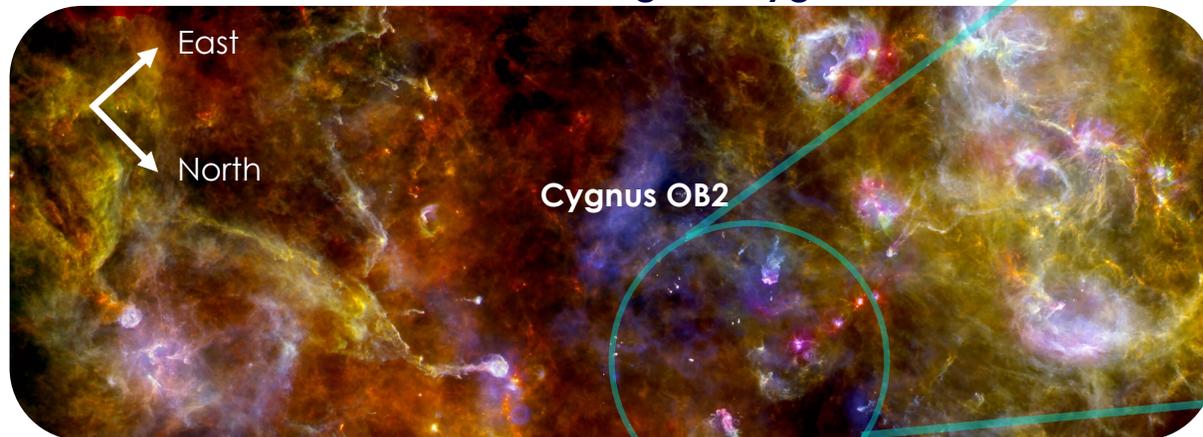
1. Introduction to TeV Gamma-Ray Astronomy
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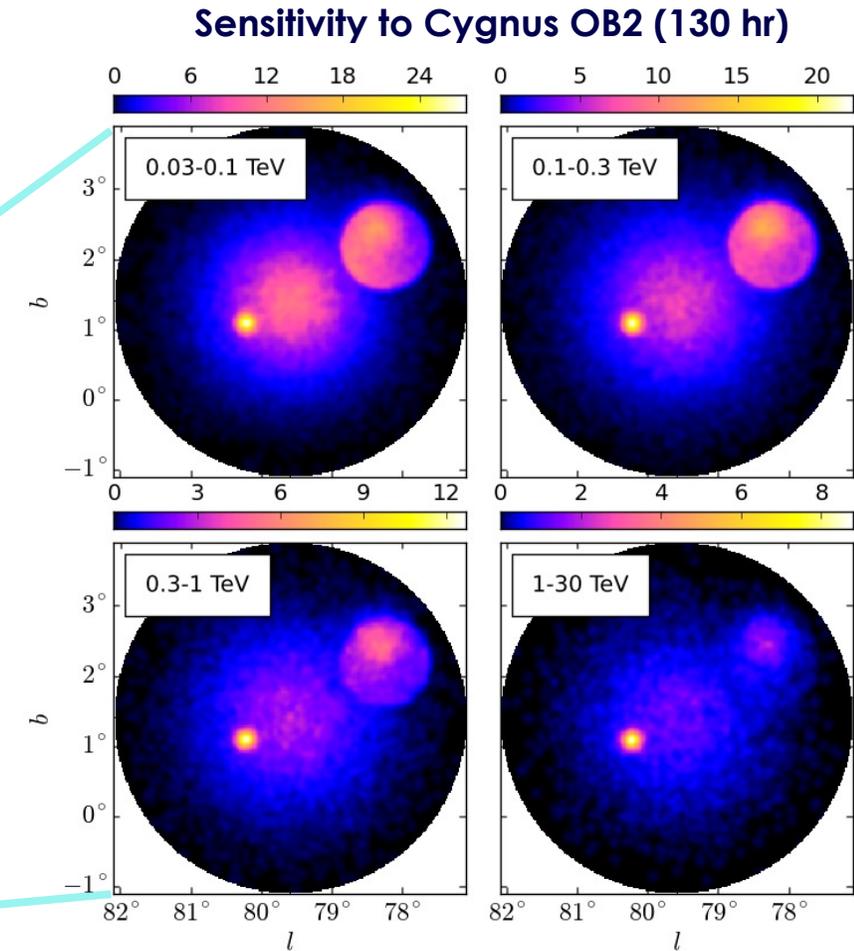
Galactic Star-Forming Systems

- ▶ **Stellar remnants** are VHE tracers of star formation
 - ▶ SNRs, PWNe, microquasars,...
- ▶ Resolve **star-forming regions** with many VHE sources
 - ▶ Cygnus region, Carina nebula, Westerlund 1 cluster
- ▶ Study **interplay of cosmic rays** and star formation
 - ▶ Acceleration, propagation, escape into ISM, feedback,...

Herschel IR image of Cygnus-X



[ESA]

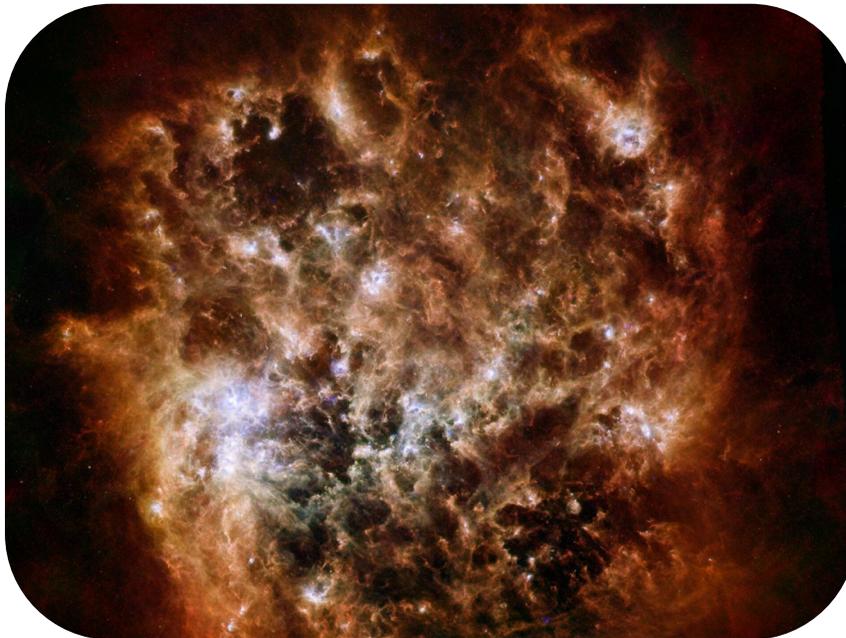


[CTAO (2019) World Scientific Publishing]

Neighboring Star-Forming Galaxies

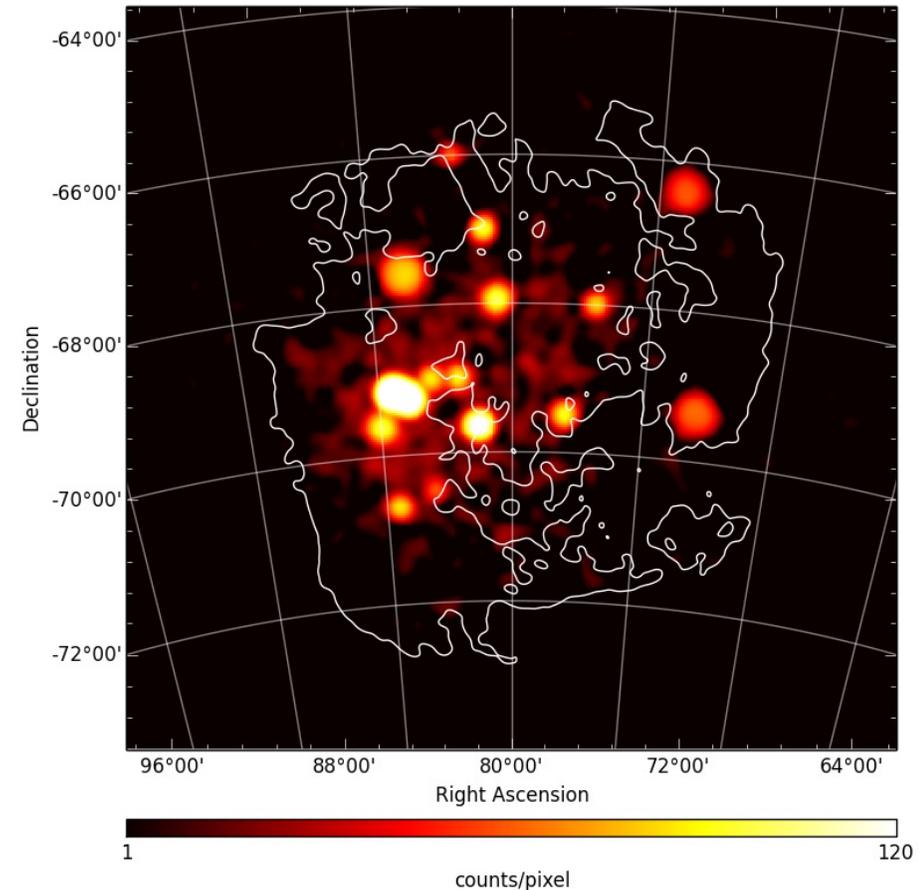
- ▶ Resolve local **star-forming galaxies**
 - ▶ Andromeda & Large Magellanic Cloud
- ▶ Probe **diffuse vs localized** VHE emission
 - ▶ Study cosmic-ray injection & diffusion across **entire galaxy**

Herschel + Spitzer IR image of LMC



[ESA/NASA]

LMC survey (340 hr; >200 GeV)



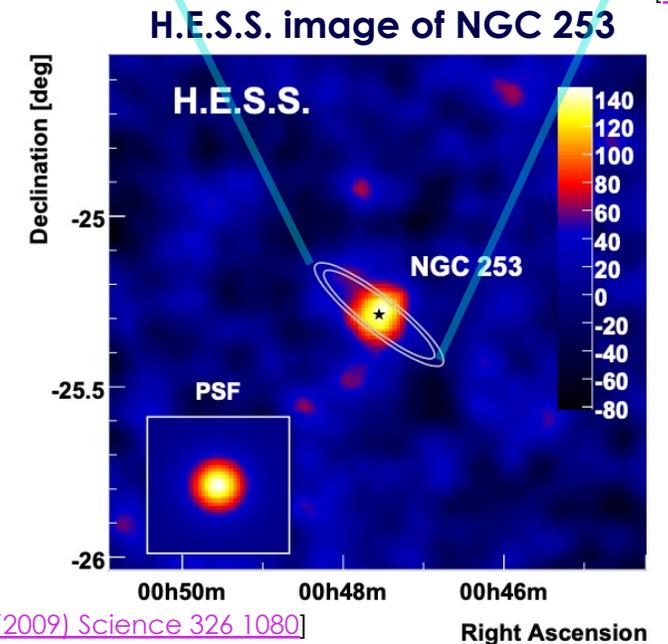
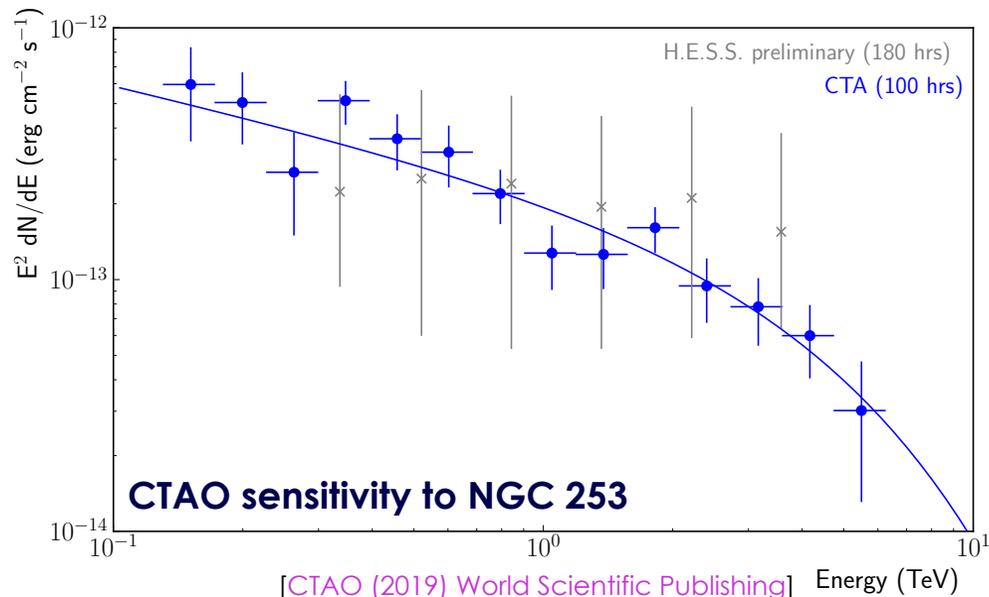
[CTAO (2019) World Scientific Publishing]

Starburst Galaxies

- ▶ **Starburst nuclei** in central ~ 100 pc
 - ▶ Typically triggered by **galaxy interactions & bar instabilities**
 - ▶ Enhanced star-formation rates $SFR \sim 10 M_{\odot} \text{ yr}^{-1}$ ($L_{IR} \sim 10^{10} L_{\odot}$)
- ▶ Study **equipartition of cosmic-ray reservoir**
 - ▶ **Energy balance** between cosmic rays, magnetic fields, radiation



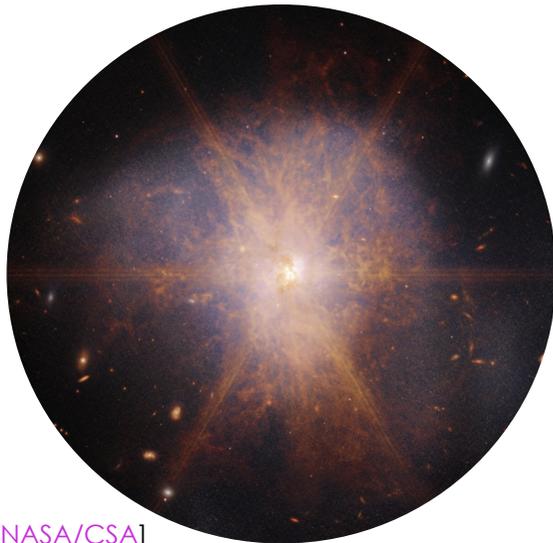
[NASA]



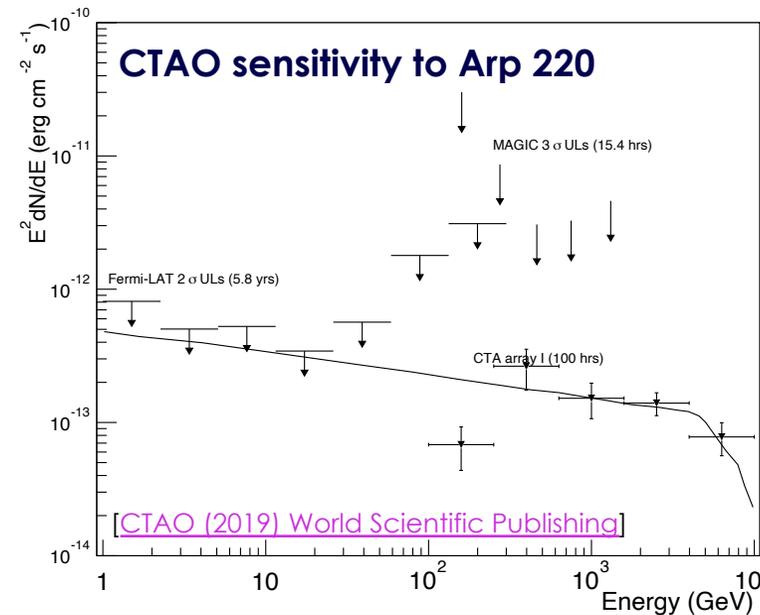
(Ultra)-Luminous Infrared Galaxies

- ▶ **Most extreme** starburst galaxies
 - ▶ LIRGs: $L_{IR} \geq 10^{11} L_{\odot}$; ULIRGs: $L_{IR} \geq 10^{12} L_{\odot}$
 - ▶ $SFR \gtrsim 10\text{--}100 M_{\odot} \text{ yr}^{-1}$
 - ▶ “Perfect” **calorimeters**
- ▶ Aim for **first U/LIRG observations** at VHE

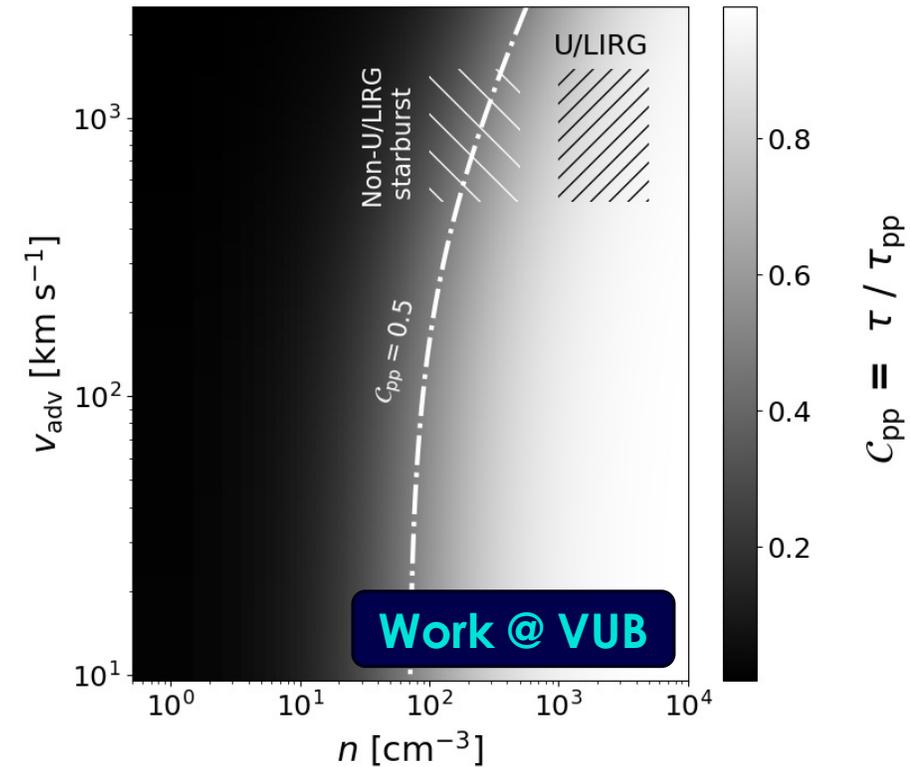
JWST IR image of Arp 220



[ESA/NASA/CSA]



Calorimetric conditions in U/LIRGs

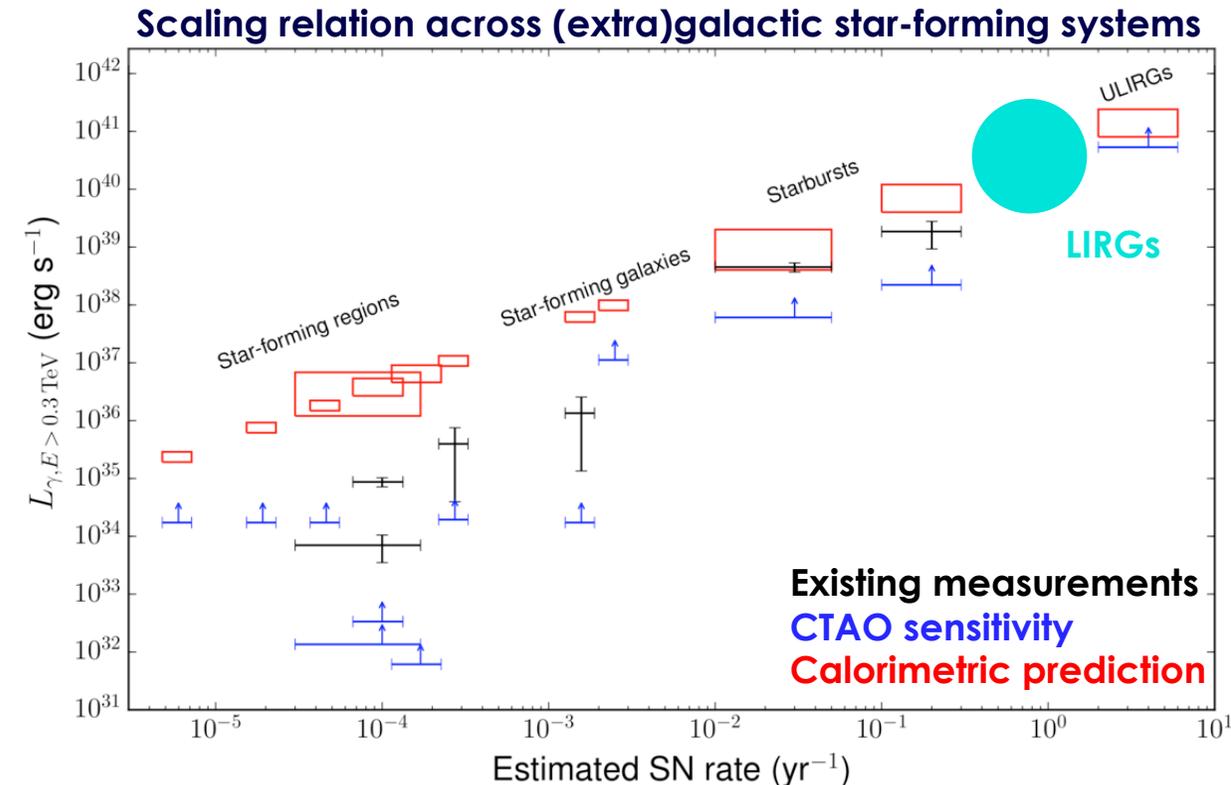


[Merckx+ (2023) PRD 108 023015]

The IR–VHE Connection

- ▶ **Scaling relation** between IR and VHE
 - ▶ Infrared traces star formation: $L_{IR} \propto \text{SFR}$
 - ▶ SFR yields supernova rate: $\text{SFR} \propto \text{SN rate}$
 - ▶ SNe drive cosmic-ray energy density: $\text{SN rate} \propto L_\gamma$
- ▶ **LIRGs** have not been explored yet
 - ▶ Build upon **starburst model** by Y. Merckx (VUB)
 - ▶ Target **GOALS galaxies** (nearest U/LIRGs)
 - ▶ Test **feasibility** of CTAO detection

Work to start soon by intern @LPNHE



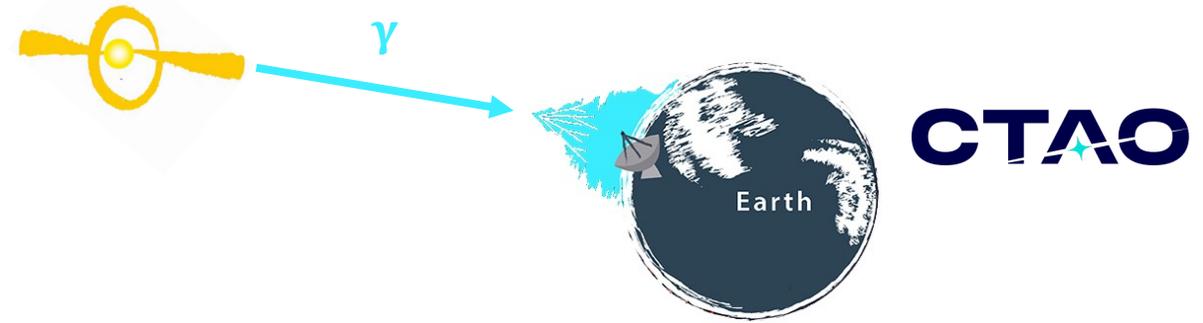
[CTAO (2019) World Scientific Publishing]

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Conclusions & Outlook



Summary

- ▶ CTAO is the **next-generation instrument** for VHE-gamma astronomy
- ▶ **CTAO science** covers high-energy astrophysics, BSM, stellar physics,...
- ▶ CTAO will probe **star formation** across all scales

Outlook

- ▶ First **intermediate CTAO arrays** will start taking data by 2028
- ▶ CTAO will be **completed in coming decade**
- ▶ Study feasibility of **observing LIRGs** with completed CTAO array