Next-generation CTA observatory: status, first results and future exploration of the VHE sky

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Outline

- **What is CTAO?**
  - why? where? what telescopes?
  - how does it compare to the current generation?

- **CTAO science**
  - extragalactic (AGN population studies, long & short time scale variability, EBL, IGMF)
  - galactic (PeVatron search, star forming systems, Galactic Center, LMC)

- **CTAO status**
  - construction status
  - CTAO / LST prototype scientific results

Next-generation Cherenkov Telescope Array project

Next-generation Cherenkov Telescope Array observatory

The Cherenkov Telescope Array Observatory:

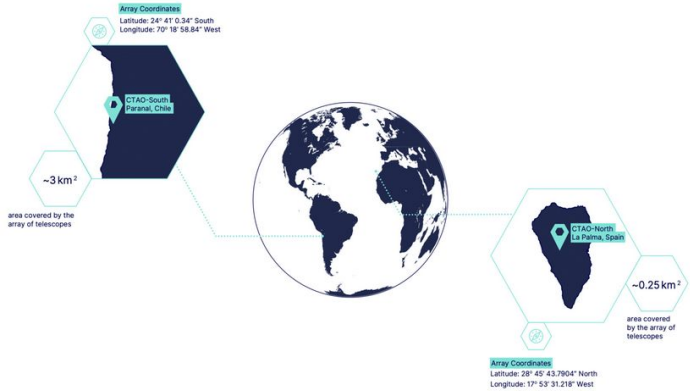
- wide energy range (20 GeV – 300 TeV), excellent angular resolution (0.05 deg) and sensitivity
- two sites to cover the North & South sky

The first observatory of its kind to operate as an open, proposal-driven observatory providing public access to its high-level science data and software products.

The CTAO will transform our understanding of the high-energy Universe by seeking to address a wide range of questions in astrophysics and fundamental physics.

1. Understanding the Origin and Role of Relativistic Cosmic Particles
2. Probing Extreme Environments
3. Exploring Frontiers in Physics

https://www.ctao.org/for-scientists/



Next-generation Cherenkov Telescope Array observatory

https://www.ctao.org

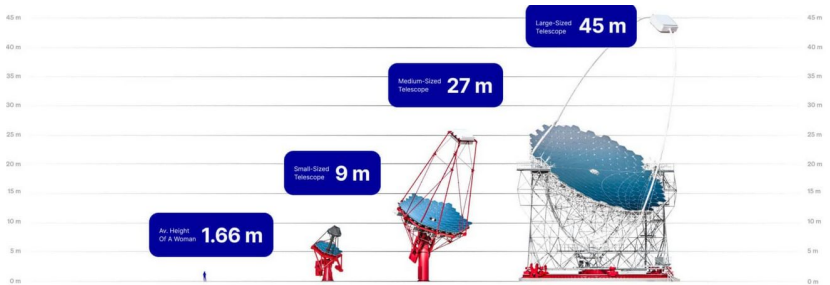
CTAO will use 3 different telescopes

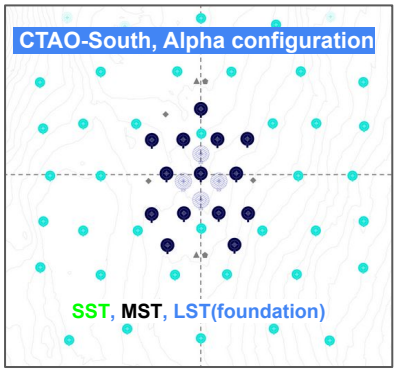
- small-sized **SST**s (D ~ 4m, E = 5 – 300 TeV)
- medium-sized **MST**s (D ~ 12m, E = 150 GeV – 5 TeV)
- large-sized **LST**s (D ~ 23m, E = 20 – 150 GeV)

Each telescope type is geared towards the specific energy range

More smaller telescopes to counter the falling with energy gamma-ray event rate

North and South arrays will comprise different combinations of SSTs, MSTs and LSTs





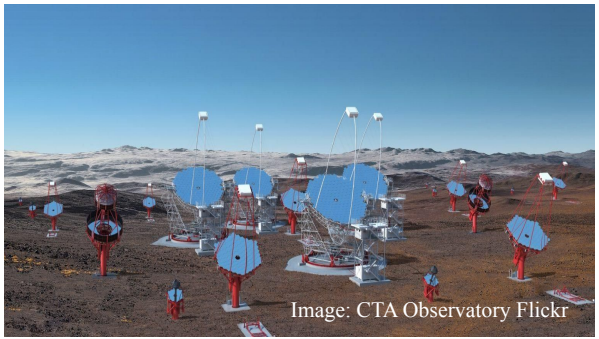
Next-generation Cherenkov Telescope Array observatory

The largest Cherenkov observatory every built

~1500 scientists and engineers
~200 institutes
31 countries

→ Large international effort

Southern site (Chile)



Layout*: 14 medium-sized telescopes
37 small-sized telescopes

Northern site (Canary Islands)

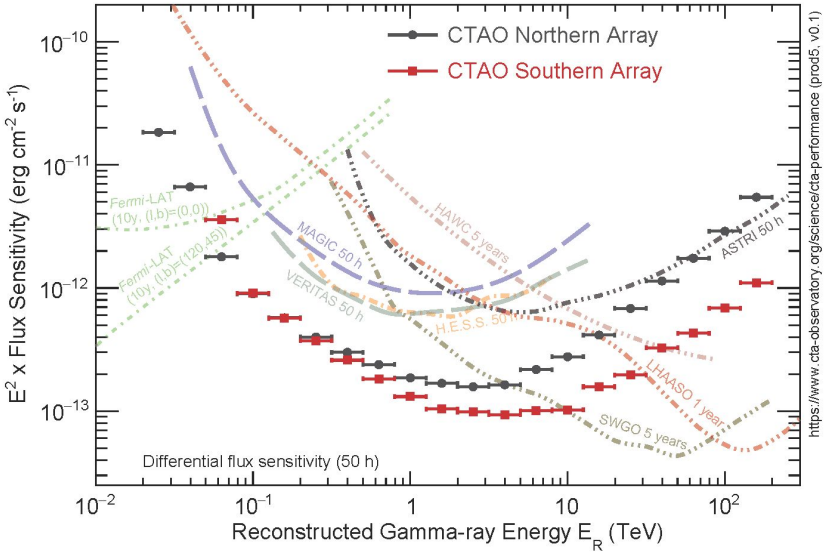
Layout: 4 large-sized telescopes
9 medium-sized telescopes

* Italian CTA+ program may bring LSTs CTAO-South too!

Extremely rich scientific outcome is expected

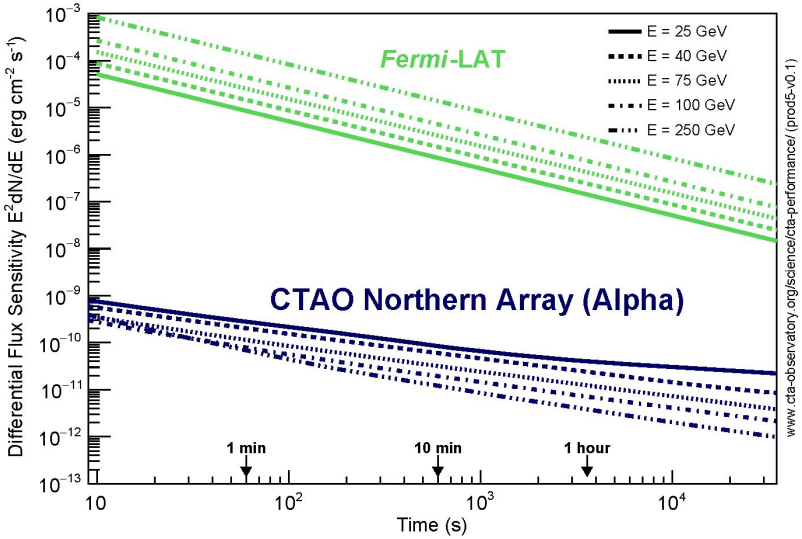
CTAO performance compared

CTAO website



Unprecedented sensitivity below few TeV

pulsar and high-z AGN observations, galactic sources study between the LAT and LHAASO bands

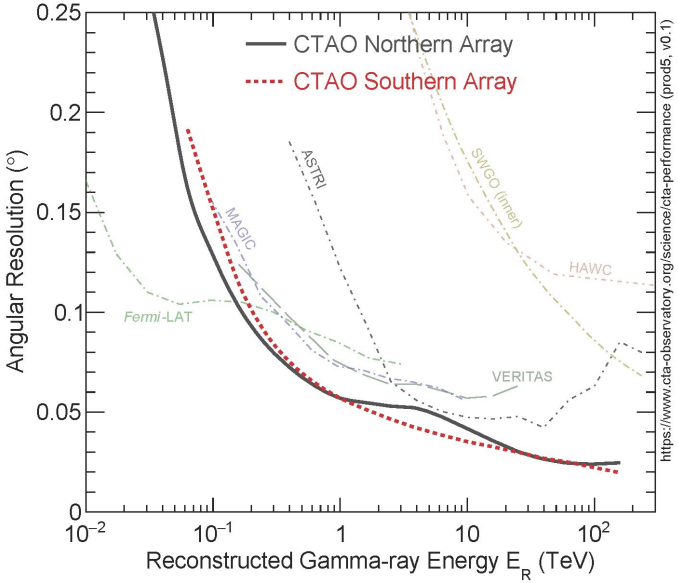


Superior short time scale sensitivity

highly-sensitive transients follow-up (AGN flares, variable galactic sources, GRBs, GW & ν alerts)

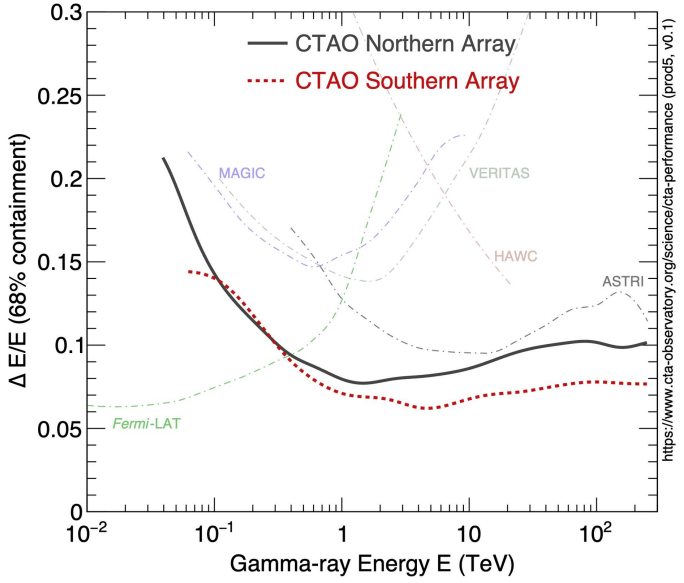
CTAO performance compared

CTAO website



Superior angular resolution

high-resolution studies of extended galactic and extragalactic VHE emitters



Superior energy resolution

high sensitivity to spectral features (breaks, absorption lines, new components, dark matter)

CTAO science themes

Understanding the Origin and Role of Relativistic Cosmic Particles

Provide the first high angular resolution measurements of cosmic-ray protons and nuclei in astrophysical systems

- census and precision measurements of cosmic accelerators
- propagation and influence of accelerated particles

Probing Extreme Environments

Probe extreme environments of particle acceleration at time and distance scales in acceleration sites inaccessible otherwise

- black holes and jets
- neutron stars and relativistic outflows
- cosmic voids

Exploring Frontiers in Physics

Probe several areas of fundamental physics

- dark matter
- quantum gravity and axion-like particle search

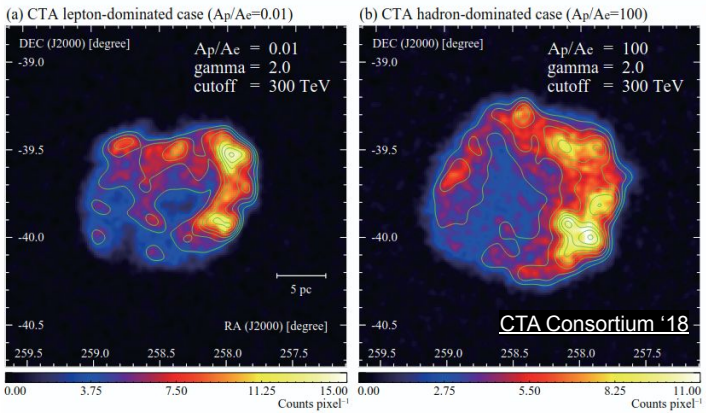
CTAO science themes

Understanding the Origin and Role of Relativistic Cosmic Particles

Key questions to answer:

- Where in our galaxy are particles accelerated up to PeV energies?
- What are the sources of high-energy cosmic electrons?
- What are the sources of the ultra-high energy cosmic rays?

simulated CTAO images of RX J1713−3946 SNR



CTAO will look for energy dependent morphology associated with diffusion & cooling in the extended emission around gamma-ray sources

→ Cosmic ray escape and impact on their environments (dynamical, magnetic fields, ionization)

Important synergies with radio observations capable of mapping molecular material / deriving the physical conditions in the TeV-emitting region

CTAO science themes

Probing Extreme Environments

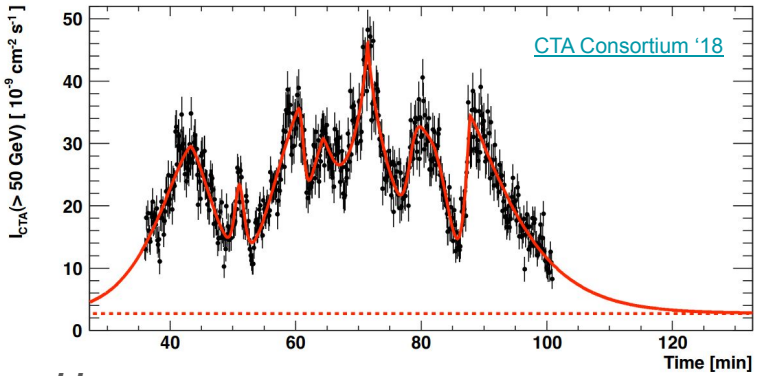
CTAO: key role in simultaneous broad-band jet studies

- establish the presence of VHE particles
- identify the presence of hadrons
- study extremely short-timescale variability

Neutron stars and relativistic outflows

- study the neutron stars environment and ultra-relativistic outflows
- relativistic outflow evolution across the orbit in binary systems
- rapidly respond to GRB, GW or ν triggers

simulated CTAO ight curve for the 2006 flare of PKS 2155-304



Cosmic voids

- extragalactic background light evolution beyong z~1
- constrain wide range of IGMF via pair echo observations
- test hypothesis of IGM heating by TeV electrons from electromagnetic cascades

CTAO science themes

Exploring Frontiers in Physics

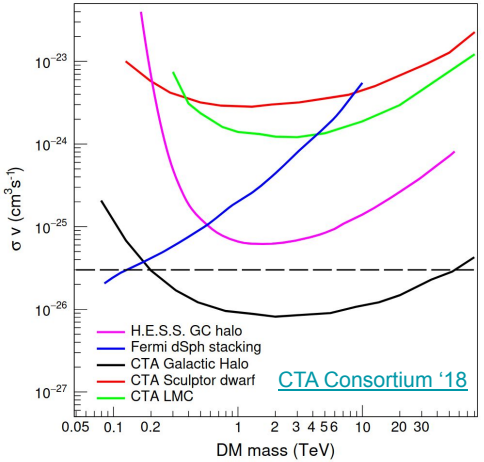
Dark matter search

- reach the thermal relic cross-section in TeV band
- measure dark matter annihilation cross-section (in case of detection)

Quantum gravity and axion-like particle search

- Lorentz invariance violation tests with blazars and GRBs
- search for APL-induced features in the TeV spectra of distant AGNs

Expected CTAO sensitivity to a WIMP annihilation signature



Newer predictions for DSphs: Abe+ '25

Synergy with a number of other experiments and indirect tests

CTAO science projects
(incomplete list)

CTAO: cosmic ray PeVatrons search

Cosmic ray origin is uncertain

Cosmic ray composition is a characteristic feature of the accelerating source which may help to constrain the CR origin

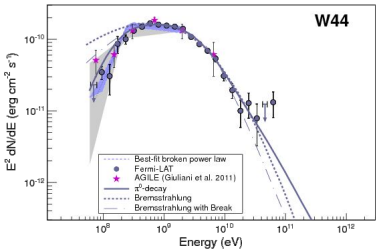
Commonly adopted that it is related to star formation activity.

- SNRs (e.g Ginzburg & Syrovatskii ‘64, Aharonian+ ‘12, Hillas 2005)
- pulsars & PWN (e.g. Neronov & Semikoz ‘12)
- stellar clusters (e.g. Bykov & Fleishman ‘92)

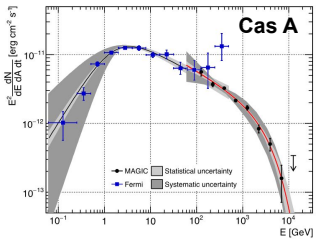
While alternatives exists (e.g. GC SMBH, HESS Collaboration 2016), indications for accelerated protons and electrons indeed found for a number of SNRs and stellar clusters.

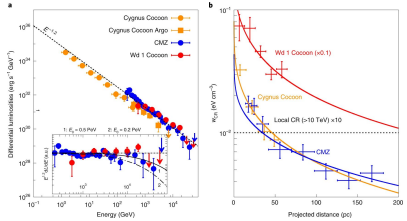
Proton dominance in the Galactic diffuse gamma-ray emission is believed to be consistent with star-formation origin (e.g. SN or stellar wind shocks)

Ackermann+ ‘13



Ahnen+ ‘17





Aharonian+ ‘19

Most recently LHAASO detected >40 UHE sources (Cao+ ‘24)

Which of those are hardonic accelerators?

CTAO: cosmic ray PeVatrons search

Majority of the detected PeVatrons (LHAASO, HAWC, Tibet ASγ, H.E.S.S.) are not associated with SNRs

Hadronic emitters among them yet to be identified

Key questions for CTAO:

- ~~Where~~ and how in the Galaxy are cosmic rays accelerated up to PeV energies?
- Are we sitting in a particular location of the Galaxy, or do the cosmic rays form a uniform sea within the whole Galaxy?
- What is the distribution of PeVatrons in the Galaxy?
- Do young shell-type SNRs accelerate hadronic cosmic rays up to PeV energies?
- If so, up to which energies and how effective is this acceleration?

Pragmatic tasks for CTAO:

- clarify the nature of the detected PeVatrons
- provide a spectral link from the VHE to the UHE range
- energy-dependent source morphology
- search for multi-wavelength counterparts
- search for PeVatrons in the southern hemisphere
- synergy with SWGO and ALPACA

CTAO: cosmic ray PeVatrons search

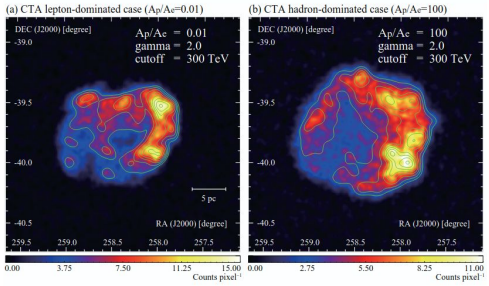
CTAO will be able to search for PeVatron SNRs

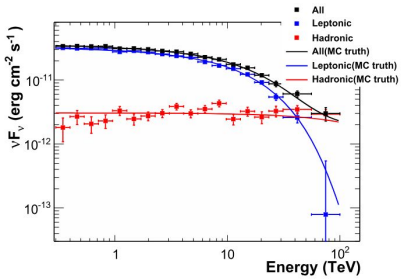
Individual sources:

- high-resolution morphology to identify the emission origin
- possible detection of hard (hadronic) components
- molecular clouds illuminated by nearby SNRs
- spectral cutoff energy variations over ~10 yrs

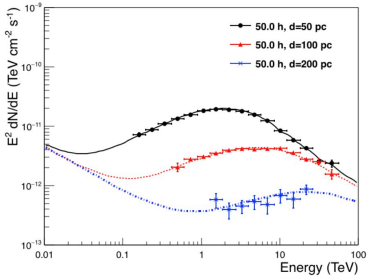
Sample studies:

- southern hemisphere observations are the key
- several detections expected within CTAO GPS
- deep exposure (250 hr) may be required to confirm soft-spectrum SNR PeVatrons





RX J1713.7-3946, CTA Consortium ‘17



Acero+ ‘13, CTA Consortium ‘18

Total observation time	$\Gamma_p = 2.0$	$\Gamma_p = 2.1$	$\Gamma_p = 2.2$	$\Gamma_p = 2.3$
50 h nominal	$80\%^{+5}_{-6}$	$(62\pm7)\%$	$(46\pm7)\%$	$24\%^{+7}_{-6}$
100 h nominal	$92\%^{+3}_{-5}$	$82\%^{+5}_{-6}$	$64\%^{+6}_{-7}$	$(47\pm7)\%$
250 h nominal	$100\%^{+0}_{-2}$	$96\%^{+2}_{-4}$	$92\%^{+3}_{-5}$	$86\%^{+4}_{-6}$
50 h (10 h nominal NSB + 40 h HNSB)	$68\%^{+6}_{-7}$	$(44\pm7)\%$	$34\%^{+7}_{-6}$	$20\%^{+6}_{-5}$
100 h (10 h nominal NSB + 90 h HNSB)	$88\%^{+4}_{-5}$	$64\%^{+6}_{-7}$	$(50\pm7)\%$	$31\%^{+7}_{-6}$

CTA Consortium ‘23

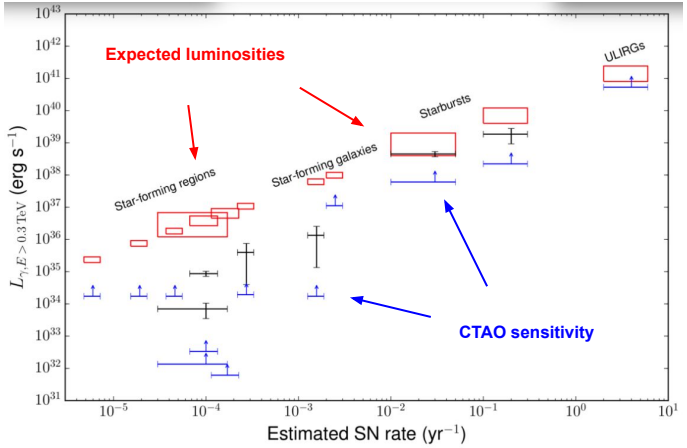
➔ New details on the particle acceleration and confinement at SNR shocks

CTAO: star forming systems observations

CTAO will study the relationship between high-energy particles and the star-formation process in our Galaxy and beyond

Key questions for CTAO:

- What is the relationship between star-formation and particle acceleration in systems on all scales? Does a universal far-infrared/TeV luminosity relationship exist?
- How does the calorimetric fraction change as a function of the SFR and does equipartition hold in star forming systems?
- What is the contribution of different source classes to the cosmic-ray population in star forming systems? Where and when are particles accelerated, how do they leave and what is their impact on the surrounding ISM?



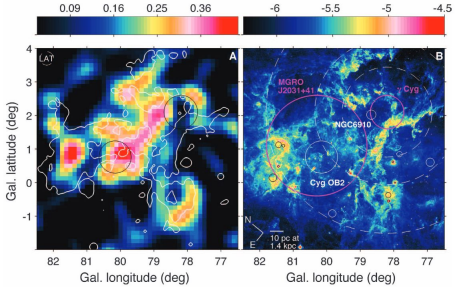
CTA Consortium '18

CTAO: star forming systems observations

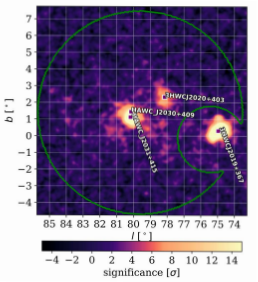
The Cygnus region – one of the key targets for CTAO – is a potential PeVatron

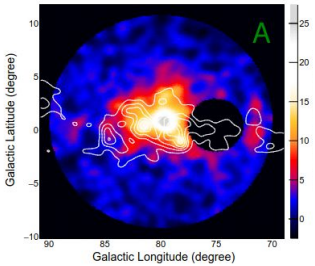
- Extended source with r_{68} ≃ 3º (Astiasarain+ ‘23)
- Radial profile consistent with a constant cosmic ray injection rate over a few million years (Aharonian+ ‘19)
- Only a few sources identified within at GeV & TeV enegies (Astiasarain+ ‘23, LHAASO Collaboration ’24)
- Emission extends > 1 PeV in photon energy making the region a very likely host for a galactic PeVatron (LHAASO Collaboration ’24).

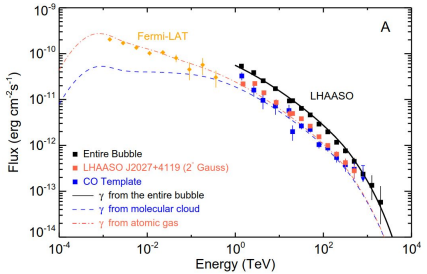
Ackermann+ ‘11



Alfaro+ ‘24







LHAASO Collaboration ‘24

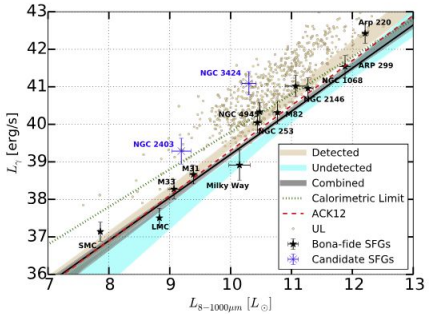
High-resolution CTAO observations are crucial to reveal the region structure at sub-degree scales

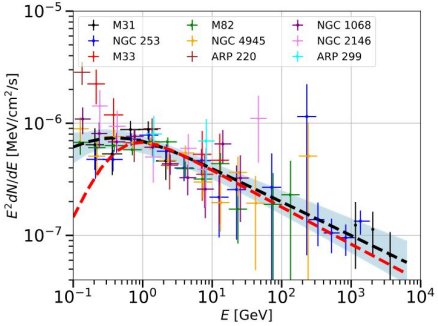
CTAO: star forming systems observations

CTAO will also observe the star-forming galaxies (SFG), expected to contain large number of cosmic rays.

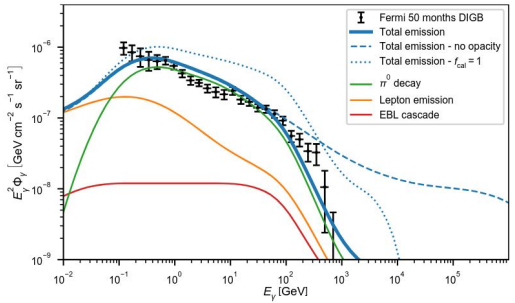
A dozen of them has already been detected in gamma-ray with Fermi/LAT and IACTs directly and others, potentially collectively as a part of the diffuse gamma-ray background.

(e.g. Acciari+ ‘09, Acero+ ‘09, Ajello+ ‘20, Roth+ ‘21)





Ajello+ ‘20



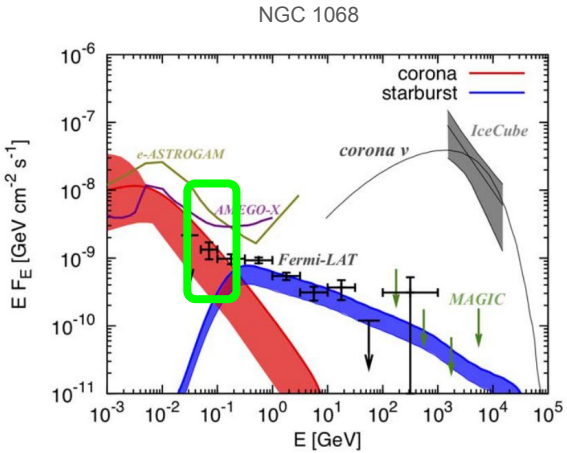
Roth+ ‘21

CTAO will shed light on SFGs calorimetry, equipartition and cosmic rays mixing with the ambient gas

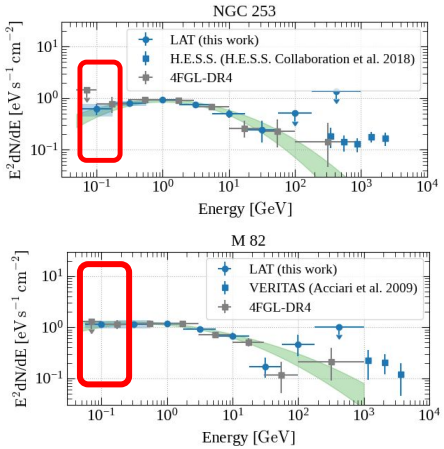
The list of CTAO observable SFGs (CTA Consortium ‘18) may be extended based on recent detections (e.g. Ajello+ ‘20) and new predictions (e.g. Shimono+ ‘21)

CTAO: star forming systems observations

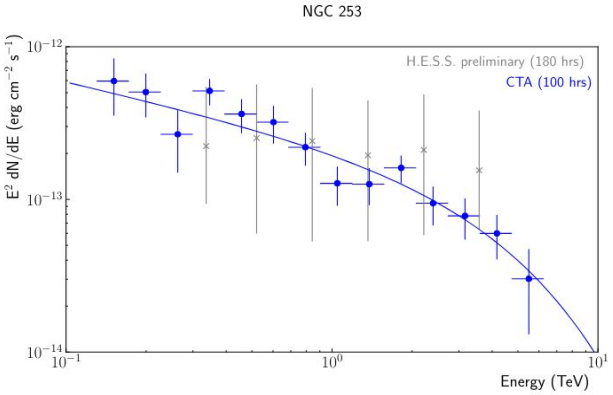
Possible “MeV excess” in star-forming galaxies testable with future MeV missions



Ajello+ ‘23



Vovk+ (in prep)



CTA Consortium ‘18

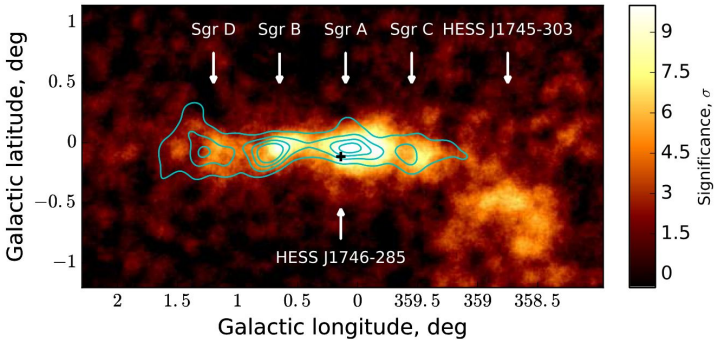
Origin of high-energy emission is testable with CTAO

(Klein-Nishina cutoff above ~10 TeV in case of leptonic emission)

CTAO: Galactic Center observations

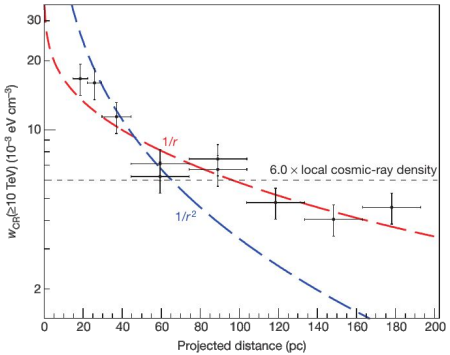
Arguably one of the most studied regions of the sky at nearly every wavelength

Large-scale diffuse γ-ray emission



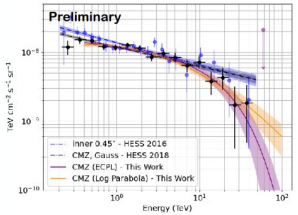
H.E.S.S. Collaboration '18

Centrally-peaked cosmic ray density profile

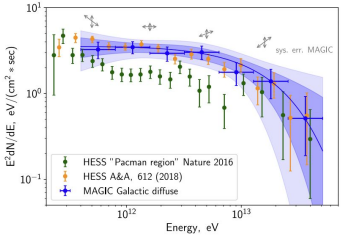


H.E.S.S. Collaboration '16

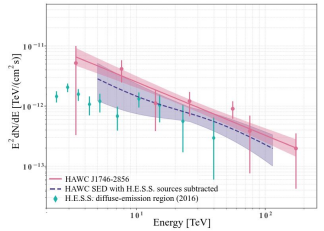
Probable PeVatron
(despite the indications for spectral transition ~20 TeV)



H.E.S.S. '24



MAGIC '20



HAWC (Albert+ '24)

Galactic Center observations is closely connected to other CTAO science programs: dark matter, galactic plane survey and extragalactic survey

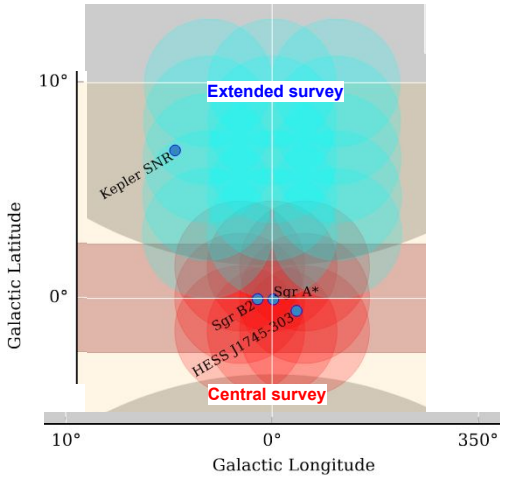
CTAO: Galactic Center observations

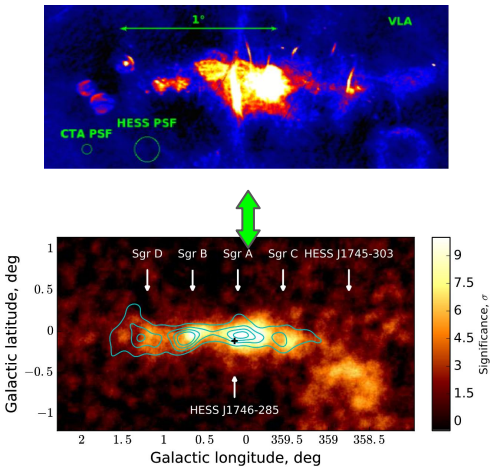
Arguably one of the most studied regions of the sky at nearly every wavelength

Key tasks for CTAO:

- reveal the nature of the central gamma-ray source
  (resolve source confusion and test possible variability)
- study diffuse VHE emission and particle acceleration in the region
  (distinguishing clouds from individual sources seen at other wavelengths)
- explore large-scale outflows
  (connection between central activity and large-scale Fermi Bubbles)
- study yet not VHE-detected SNRs, PWNs and molecular clouds
  (inc. possibly the galactic youngest SNR G1.9+0.3 and possibly interacting H.E.S.S. J1745−303)

CTA Consortium '18





H.E.S.S. Collaboration' 18

Galactic Center observations is closely connected to other CTAO science programs: dark matter, galactic plane survey and extragalactic survey

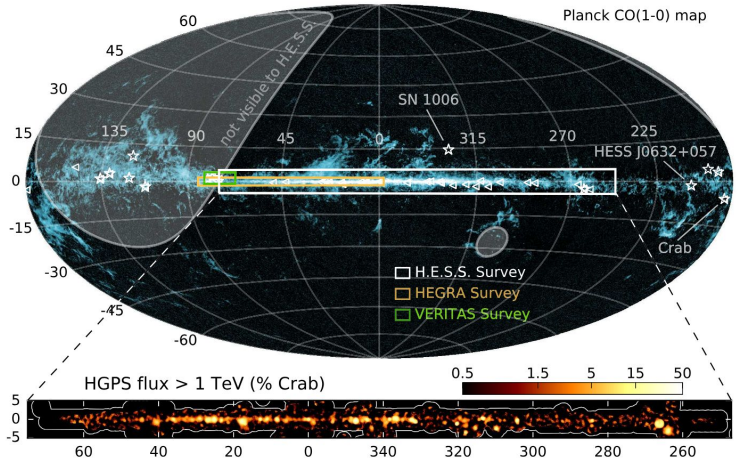
CTAO: Galactic plane survey

Critical study of different γ-ray source populations via systematic view of the Galaxy

Key goals Galactic plane survey:

- census of Galactic VHE gamma-ray source populations (SNRs, PWNe, binaries)
- identification of the promising targets for follow-up observations (PeVatron candidates, new γ-ray binaries)
- properties of the Galactic Plane diffuse emission
- discovery of the new and unexpected phenomena
- a multi-purpose legacy data set

Current state-of-the-art: H.E.S.S. Galactic plane survey



H.E.S.S. Collaboration' 18

Synergies with other CTAO programs (e.g. PeVatrons, GalCenter, star-forming systems) and other γ-ray and MWL / multi-messanger observatories

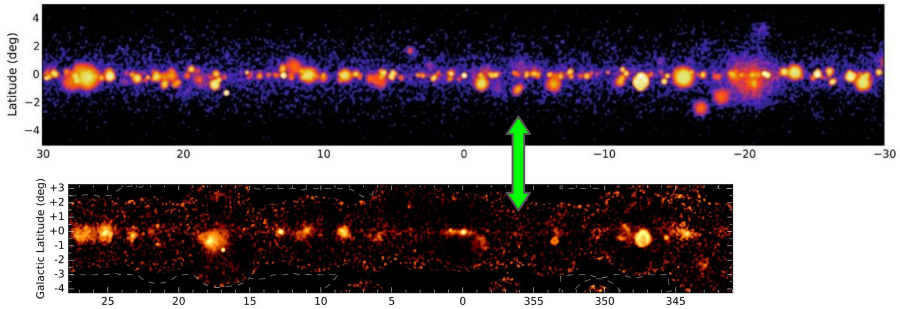
CTAO: Galactic plane survey

CTAO will survey the -90 < l < 90 deg GP stripe with sensitivity down to 3 mCrab

Key questions for CTAO:

- How and where are protons and nuclei accelerated to PeV energies?
- How are particles accelerated in relativistic shocks?
- What is the impact of cosmic rays on the interstellar medium (ISM), and how do they propagate?
- What is the role of external photon fields, jet content, and geometry in distinguishing jet sources, such as pulsars and microquasars?
- Where and how do pulsar complexes accelerate high-energy particles?

CTA Consortium '18



H.E.S.S. Collaboration' 18

- new and unexpected phenomena in the Galaxy
- PeVatron candidates and ~300 new VHE Galactic sources
- large-scale diffuse VHE gamma-ray emission

Multi-purpose, long-lasting value data set (sky images, catalogues) of the complete Galactic plane in VHE band

CTAO: Large Magellanic Cloud survey

LMC – nearby, resolved star-forming (dwarf) galaxy

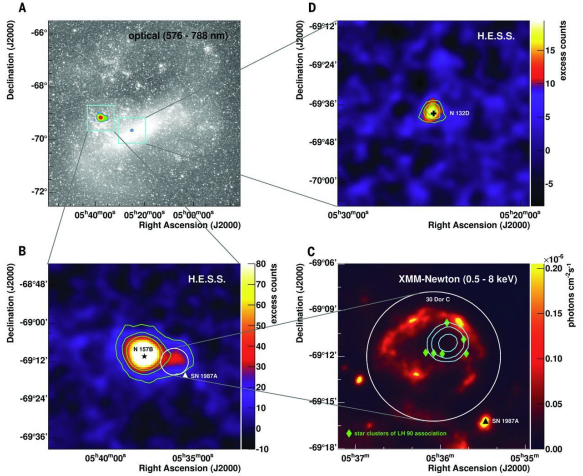
extraordinary bridge between detailed studies of the MW and surveys of far more distant galaxies

LMC in γ-rays – complement to Milky Way studies: particle accelerators (SNRs, pulsar, PWN etc), diffuse interstellar emission, indirect searches for dark matter, etc.

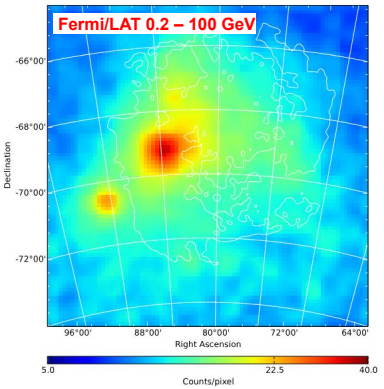
GeV–TeV detections (Abdo+ ‘10, H.E.S.S. Collaboration ‘15, Ackermann+ ‘16):

- dominant extended emission of uncertain origin
- several point sources (pulsars, PWN, SNR)

H.E.S.S. Collaboration ‘15



Ackermann+ ‘16



Several interesting sources not detected yet
(e.g. SN 1987A – youngest SNR – and 30 Doradus C – superbubble with non-thermal emission)

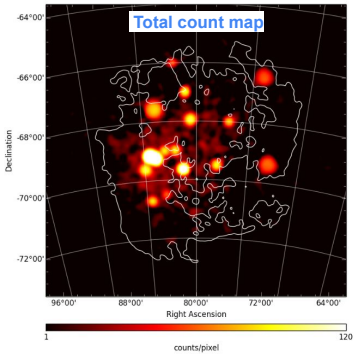
CTAO: Large Magellanic Cloud survey

Deep LMC observation with CTAO is planned

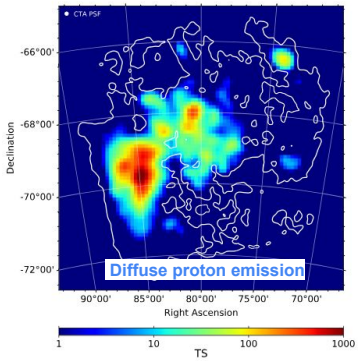
Key questions for CTAO:

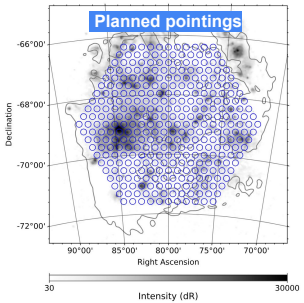
- What are the properties of CRs in the LMC at the galaxy scale, as revealed by their gamma-ray interstellar emission?
- What is the population of particle accelerators in the LMC, and does it differ in any way from the different gamma-ray source classes we know of today?
- What information can the CTAO survey of the LMC bring on the nature of DM?

CTA Consortium '19



Acharyya+ '23





→ Accurate measurements of known & new point sources, interstellar emission constraints, VHE emission from SN 1987A and 30 Doradus and more

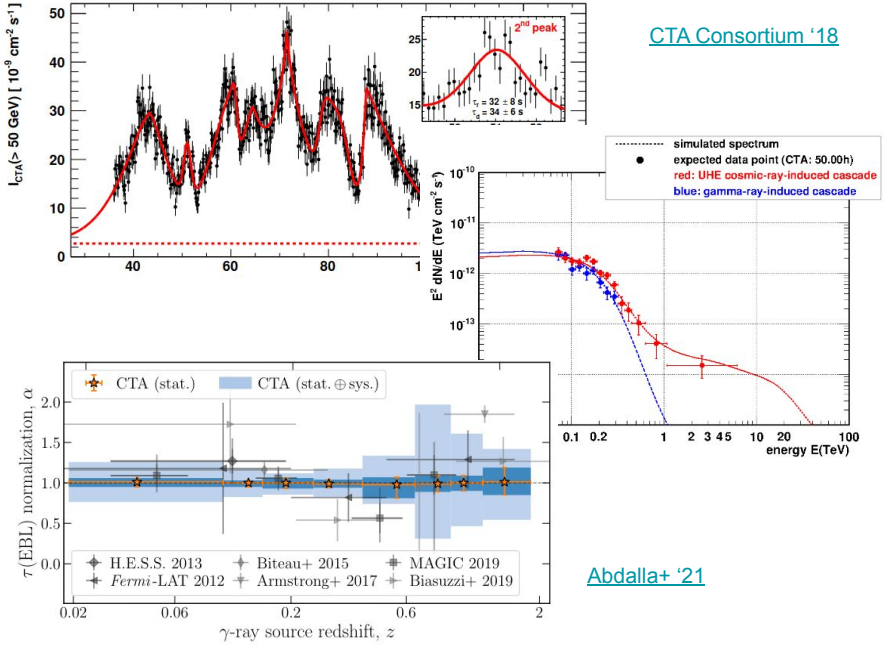
CTAO: active galactic nuclei

CTAO will make high-quality measurements of ~200 AGNs at least up to z~2

Scientific program to cover AGN physics, IGM, UHECRs and fundamental physics

Key questions for CTAO:

- What are the relevant particle acceleration and emission processes in VHE blazars?
- What causes the observed variability in AGN from time scales of a few years down to a few minutes?
- From where does the VHE emission of radio galaxies originate?
- Do AGNs accelerate UHECRs?
- What is the spectrum of the EBL at redshift z~0 and how does it evolve at higher redshifts ?
- What is the strength of the IGMF ?



CTA Consortium '18

Abdalla+ '21

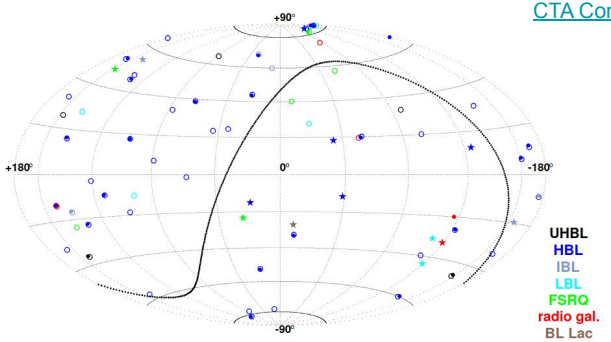
CTAO: active galactic nuclei

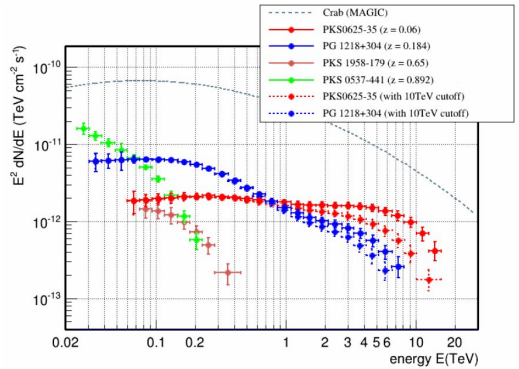
Versatile observation program to maximize the discovery potential

Key objectives for CTAO:

- Long-term monitoring of a few prominent AGN up to >10 yr
  long-term light curves and time resolved spectra for all studies involving AGN variability on medium and long time scales, addressing quiescent states, duty cycles, and spectral variability
- search and follow-up of short-term AGN flares
  effective sampling of the high states of AGN and high-statistics, high-temporal resolution spectra for studies of short-term variability; EBL / IGMF measurements at z >0.5
- High-quality spectra for a systematic coverage of redshifts and AGN typology
  a comprehensive data set, obtained under uniform conditions, for AGN classification and evolution studies; high-precision spectra for a precise measurement of the EBL, studies of emission scenarios for VHE blazars and of the IGMF.

CTA Consortium '18





CTAO: active galactic nuclei

MeV data would be crucial for some of the key questions of the AGN program

Hadronic emission:

- hadronic components appearing in MeV band
- polarized synchrotron emission from pγ interaction decay products

Putative corona emission

- hidden (absorbed) gamma-ray component

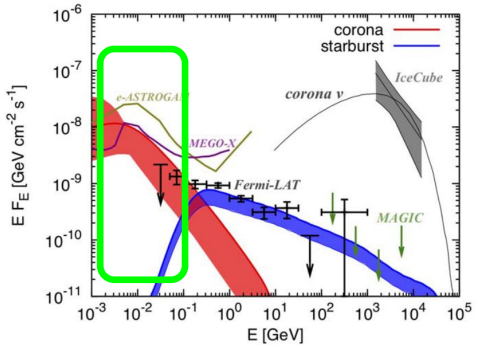
IGMF evolution at high redshifts:

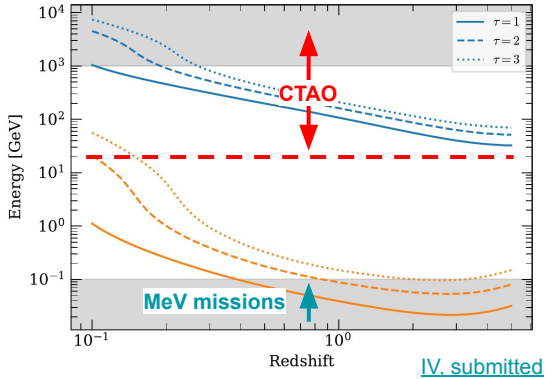
- critical to identify IGMF origin
- “pair echo” emission from high-z sources falls into MeV band

↓

Synergy with future MeV missions is crucial

Ajello+ ‘23





IV. submitted

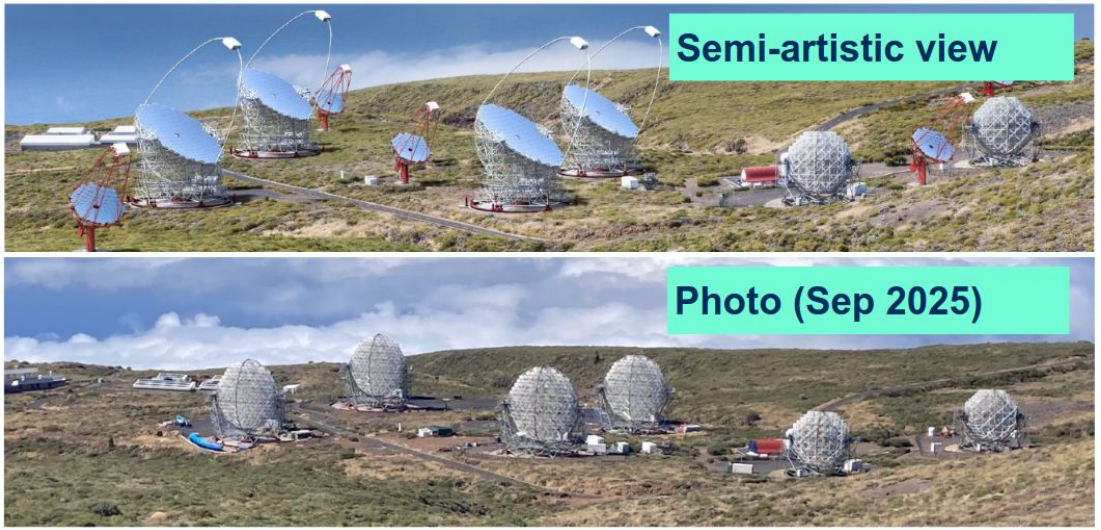
CTAO status
(and first early science results)

CTAO is already next door

CTAO-North is becoming the reality!

(Rough) CTAO-North timeline thus far

2006	CTAO idea inception
2015	LSTs construction start
2018	LST1 inauguration
2019	LST1 commissioning and first scientific observations
2023	LST2-4 construction start



Courtesy of Koji Noda

LSTs and CTAO-N array should be complete within a couple of years

CTAO first scientific results: CTAO/LST observartions

LST-1 is the first operational telescope of CTAO-North

23m LST-1 – the largest IACT in the northern hemisphere

- in commissioning since 2019
- test scientific operations since 2023
  (inc. stereo with nearby MAGIC telescopes)
- new call for obs. proposals in 2026-2027
- learn more at https://www.lst1.iac.es/

CTAO/LST prototype inauguration in 2018

https://www.lst1.iac.es (Akira Okumura)

Already several results announced / published

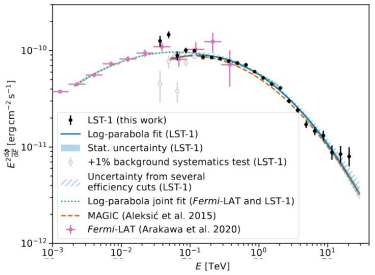
- Crab pulsar measurements down to 20 GeV (Abe+ ‘24)
- Galactic center diffuse emission detection (Abe+, ICRC 2025)
- GRB 221009A afterglow observations (Aguasca-Cabot+, ICRC 2025)
- Discovery of VHE emission from z~1 blazar OP 313 (Cortina+ ‘23, Di Pierro+ ‘25)
- LHAASO PeVatron candidate LHAASO J2108+5157 observations (Abe+ ‘23)
- Large zenith angle observation of the PeVatron candidate SNR G106.3+2.7 (Carrasco+, ICRC 2025)
- Stellar intensity interferometry observations (Raiola+, ICRC 2025)

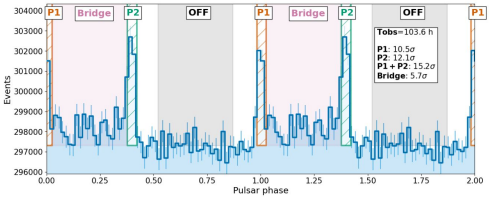
CTAO/LST results: Crab pulsar VHE emission

Crab pulsar & nebula – one of the first observational targets for CTAO/LST1

- Crab Nebula – VHE “standard candle”
- detailed study of GeV-TeV pulsed emission
- good agreement with prior measurements
- pulsar measurements down to 20 GeV

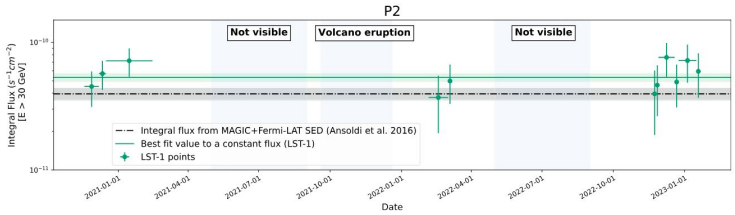
Abe+ ‘23

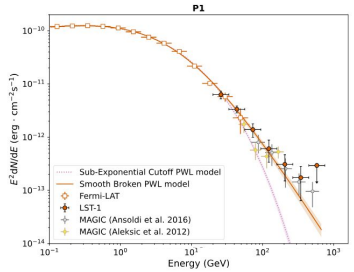


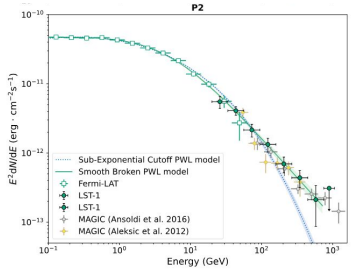


Abe+ ‘24

Telescope performance maintained even post nearby volcano eruption







Even on “mono” mode, CTAO/LST1 demonstrates excellent performance and low energy threshold

CTAO/LST results: Galactic Center diffuse emission

CTAO/LST-1 has observed Galactic Center in the “mono” mode for ~40 hr only

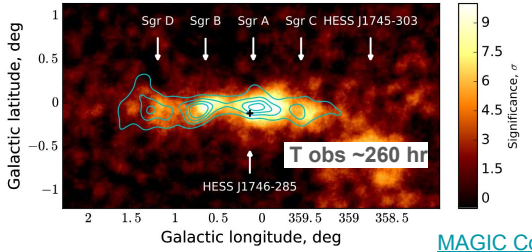
- Large zenith angles observations: lower energy threshold, but boost in the collection area
- Very extended source: profit from the large FoV
- CTAO-like analysis with a focus on background modelling

↓

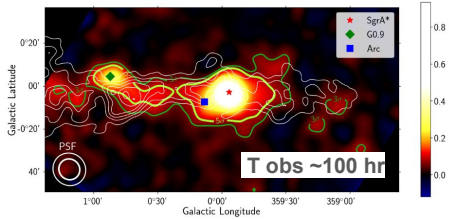
- comparable detection significance in much shorter time
- significant detection of the known sources (Sgr A* and G0.9+0.1, “Arc”)
- diffuse emission spectrum and cosmic ray density profile compatible with H.E.S.S. and MAGIC results

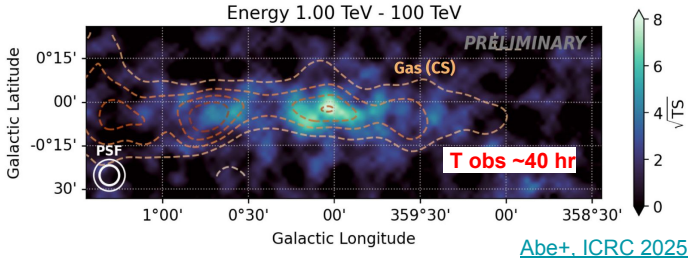
Excellent CTAO/LST-1 performance for extended sources

H.E.S.S. Collaboration ’18



MAGIC Collaboration ’20





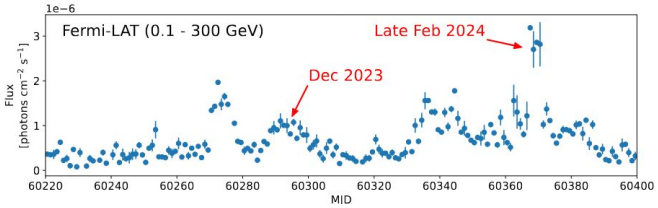
Abe+, ICRC 2025

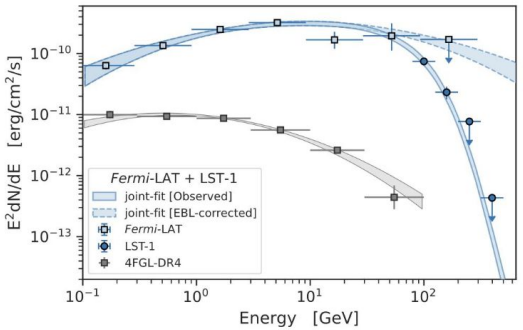
CTAO/LST results: blazar detection at z~1

Third the furthest VHE source detected thus far

- FSRQ at redshift z=0.997
- detected during the GeV flaring episode in Dec 2023
- very soft VHE spectrum – low energy threshold is a key
- collaboration with many other instruments – MAGIC, Fermi/LAT, Swift, optical and radio observatories
- detailed MWL modelling performed
- limits on EBL at z ~ 1

Di Pierro+ '25





The first LST-1 VHE source discovery!

Nievas Rosillo+ '25

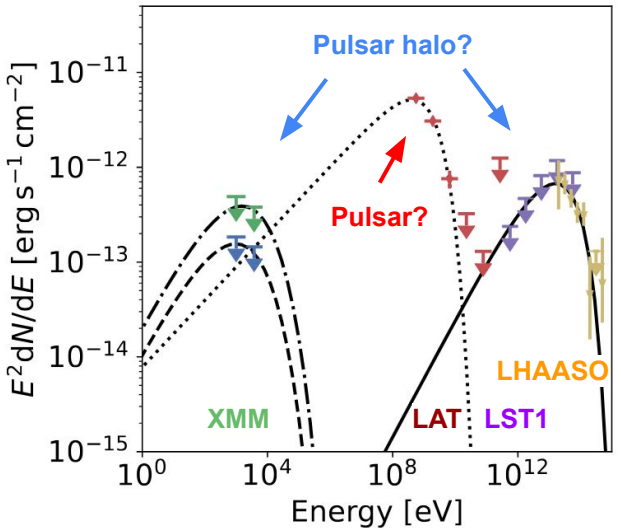
Examplary outcome of the LST-1 Target-of-Opportunity program

CTAO/LST results: LHAASO PeVatron candidates follow-up

Unidentified LHAASO J2108+5157 – one of the few UHE sources with no VHE counterpart

- the first γ-ray source directly discovered in the UHE band
- possible interaction with molecular clouds
- no known pulsars within 1 deg

- strong upper limits on the possible VHE emission
- spatially coincident LAT source consistent with a pulsar
- derived magnetic field B < 1 μG is compatible with the Geminga pulsar halo
- VHE-UHE emission still compatible with escaped cosmic rays interracting with molecular clouds; HE emission should then have a different origin



Abe+ ‘23

Good example of the LST-1 early observations program

Final words

CTAO – major international effort to advance observations in the wide 20 GeV – 300 TeV band

Large community: rich observational program, new unifying tools
(ctools, gammapy, data formats)

Number of scientific programs not covered in this talk
dark matter (Acharyya+ ‘21, Coronado-Blázquez+ 21, Rinchiuso+ ‘21, Abe+ ‘25), fundamental physics (Abdalla+ ‘21), neutrino and GW follow-up (Patricelli+ ‘18, Brown+ ‘24, Green ‘24), Galactic transients (Abe+ ‘25), gamma-ray binaries (Chernyakova+ ‘19), Crab nebula variability (Mestre+ ‘21)

CTAO is growing rapidly
(ERIC, CTAO-South construction start, new hirings)

CTAO-North is becoming reality
(LST-1 prototype operational, LST2-4 under construction)

First scientific results from CTAO/LST prototype are becoming available
highlighting the excellent telescope performance

CTAO era is around the corner