Cherenkov Telescope Array Astrophysics & the ASTRI Mini-Array

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Contents

- CTA concept
- CTA performance
- CTA science: astrophysics and beyond
- ASTRI Mini-Array – CTA Precursor
The High-Energy Gamma Ray Sky (1989)

E > 100 GeV

(Galactic coordinates)

Background colours indicating northern / southern sky
The TeV sky

Today: >250 sources

13 Shell-type SNR (~half resolved)
10 SNR/molec. cloud
34 Pulsar wind nebulae
6 X-ray binaries
4 Massive star clusters
1 Globular cluster
...

33 HBL
4 IBL
4 LBL
3 FSRQ
2 Starburst Galaxies
...

http://tevcat.uchicago.edu/
Major TeV observatories

VERITAS
4 Medium-Sized Tel. (‘MSTs’)  
2007: Full operation  
2009: Relocation of T1  
2012: PMT upgrade

HAWC
Particle-detector water tanks (2015)

MAGIC
2 Large-Sized Tel. (‘LSTs’)  
2003: MAGIC-I  
2009: MAGIC-II  
2012: PMT upgrade

H.E.S.S.
4 MSTs (2003)  
+ 1 LST (2012)

LHAASO
Particle-detector water tanks  
+ 18 Small-Sized Tels (‘SSTs’)  
since 2018
Why to build CTA?

Full Sky Coverage

CTA North
ORM La Palma, Spain

CTA South
ESO, Chile
Why to build CTA? Key Capabilities

- Full sky coverage
- CTA North: ORM La Palma, Spain
- CTA South: ESO, Chile
- Energy Threshold ~ 80 GeV for CTA North
- Energy Threshold ~ 20 GeV for CTA South

- SENSITIVITY x 10
- ARCMINUTE ANGULAR RESOLUTION
- 10% ENERGY RESOLUTION
- WIDE ENERGY RANGE: 20 GeV – 300 TeV
- FoV x 2
- FULL SKY COVERAGE
- 30 s RESPONSE TO EXTERNAL ALERTS
Theme 1: Cosmic Particle Acceleration
- How and where 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?
- Characteristics of relativistic jets, winds and explosions?
- Cosmic voids: their radiation fields and magnetic fields

Theme 3: Physics Frontiers
- What is the nature of Dark Matter?
- Is the speed of light a constant?
- Do axion-like particles (ALPs) exist?
Initial CTA Array: $\alpha$-configuration

**Science-based optimization**
North: extragalactic oriented (high-$E/z$ absorption)

- LST-1 inauguration (‘18)
- MST camera agreement (‘20)
- Single SST design (‘18-19)

**Shower-based optimization**
LSTs ~20-200 GeV, MSTs 0.2-2 TeV, SSTs >2 TeV

- CTA-North
- CTA-South
CTA Science and Design

© R. Zanin

- **sub-TeV**
  - Parabolic optical design
  - 23 m mirror diameter
  - PMT camera
  - ~4 deg FoV
  - 4 LSTs at the array center

- **TeV**
  - Davies-Cotton optical design
  - 12 m mirror diameter
  - PMT camera
  - ~7 deg FoV
  - MSTs are workhorse
  - ~1km² area covered

- **multi-TeV**
  - Schwarzschild-Couder optical design
  - 4 m dual mirror
  - SiPM camera
  - ~8 deg FoV
  - >50 SSTs
  - ~4km² area coverage
CTA Science and Design

Sub-TeV
- GRBs
- Transient sources
- AGNs
- Cosmological sources
- Pulsars
- Grav. waves

TeV
- EBL
- Surveys
- Morphological studies
- Dark matter
- UHE neutrinos
- Extreme blazars

multi-TeV
- PeVatrons
- Star-forming regions
- Galactic plane survey
- Nearby galaxies

From the science case to the design multi-TeV PeVatrons Star-forming regions Galactic plane survey Nearby galaxies

20 GeV 500 GeV 1 TeV 10 TeV 300 TeV

LST MST SST

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CTA Science and Design: Brazil @

© R. Zanin

CTA Telescopes

- sub-TeV
  - CBPF contributed to optical alignment system of LST-1

- TeV
  - IFSC contributes to the development and building of camera support structure

- multi-TeV
  - IAG-USP contributing to end-to-end construction of the ASTRI precursor telescopes

Credits
- M. Leone
CTA comparative performance

$\alpha$-configuration

From $10^{-12}$ to $10^{-13}$ erg/cm$^2$s

Differential flux sensitivity (50 h)
CTA comparative performance

On time scales <1 h
CTAO is $10^3$ times (@25 GeV)
to $10^6$ times (@250 GeV) more
sensitive than Fermi-LAT

From $10^{-12}$ to $10^{-13}$ erg/cm$^2$s
Differential flux sensitivity (50 h)
CTA comparative performance

\(\alpha\)-configuration

From \(10^{-12}\) to \(10^{-13}\) erg/cm\(^2\)s

Differential flux sensitivity (50 h)
CTA Angular Resolution

![Diagram showing angular resolution vs reconstructed gamma-ray energy. The graph compares CTAO Northern Array and CTAO Southern Array performance, with other instruments like MAGIC, SWGO (inner), Formi-LAT, and HAWC also plotted.](https://www.cta-observatory.org/science/cta-performance/prod5-v0.1)
CTA Performance: FOV & Resolution

CTA FoV

CENTAURUS A
Distance: 165,000 Light Years

COLOUR COMPOSITE IMAGE OF CENTAURUS A JET ON GALACTIC SCALES
Distance: 4,000 Light Years

TANAMI IMAGE OF THE INNER JET
Distance: 1 Light Year

EHT IMAGE OF THE JET LAUNCHING REGION
Distance: 1 Light Day

LAT @10 GeV

LHAASO @100 TeV

CTA @3 TeV
CTA Science Questions *in and beyond Astrophysics*

**Theme 1: Cosmic Particle Acceleration**
- How and where 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?
- Characteristics of relativistic jets, winds and explosions?
- Cosmic voids: their radiation fields and magnetic fields

**Theme 3: Physics Frontiers**
- What is the nature of Dark Matter?
- Is the speed of light a constant?
- Do axion-like particles exist?
Key Science projects

1. Galactic Centre
2. Galactic Plane Survey
3. Cosmic Ray PeVatrons
4. Star Forming Systems
5. LMC Survey
6. Extragalactic Survey
7. Active Galactic Nuclei
8. Transients
9. Clusters of Galaxies
+ Dark Matter Programme
CTA Key Science Projects

See “Science with the Cherenkov Telescope Array” book by World Scientific, also @ arXiv:1709.07997
Particle acceleration to very high energies is associated with extreme environments:
- SN explosions, neutron stars, black holes, relativistic outflows

Major Questions:
- Are SNR the main CR accelerators in our Galaxy?
- Where in our Galaxy are particles accelerated to PeV ($10^{15}$ eV) energies?
- What are the sources of UHECRs ($E>10^{18}$ eV): AGNs?

To answer:
- Galactic and Extragalactic Surveys
- Deep Observations of nearby sources, galaxies and clusters
- Precision measurements of bright targets to probe physical processes
a census of cosmic particle accelerators

ACROSS ALL COSMIC SCALES
Galactic Plane Survey

H.E.S.S.

CTA, for same exposure

expect \(~500\) detected sources

Distance reach \(~20\ \text{kpc}\)
1.1 Key Characteristics & Capabilities

Extragalactic Survey

Galactic Plane Survey (GPS) – covering 1/4 of the sky to a depth of kpc, detecting essentially the entire population of mCrab. No extragalactic survey has ever been performed using IACTs, and the existing VHE surveys using ground-level particle detectors are limited to a few tens of per cent of the sky.


diffuse emission associated with accelerated hadrons or dark matter annihilation.

CTA GPS will provide a distance reach of \( \sim 10 \) kpc, the excellent angular resolution of CTA is critical here to avoid being limited by source confusion from a technical standpoint due to the complexity and confusion of the gamma-ray and optical emission.

The search for an annihilation signature of dark matter, throwing light on the nature of the dark matter which is expected to explain the missing matter in the universe, is a high priority science area. The CTA will provide the first fully deep and high-precision survey of the Galactic Centre region. This will be a 5 kpc by 5 kpc survey to be compared with the 1 kpc by 1 kpc H.E.S.S. survey.

The realisation of an extremely deep and high-precision survey of the Galactic Centre region is non-trivial due to the high background and the need to handle very low fluxes. The use of an active Galactic centre is envisaged (see Chapter 213 – A simulated view of the Galactic Centre region as seen by CTA (excess events above 800 GeV after background subtraction). The central source is clipped to show the details of the diffuse emission (thus the point-like central source which is an order of magnitude brighter is washed out).


event; the same background model is used in all cases.

Figure 5.3 – A simulated view of the Galactic Centre region as seen by CTA (excess events above 800 GeV after background subtraction).

The excellent angular resolution of CTA is critical here to avoid being limited by source confusion due to the complexity and confusion of the gamma-ray and optical emission (see Figure 5.3).

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Some other KSPs are also effectively surveys due to the wide field of view. For example, a deep survey of the inner region of the Local Group will be valuable for studies of diffuse gamma-ray emission and for the search for dark matter annihilation. Some KSPs have relatively small fields of view but are still surveys in the sense that large enough samples of objects to understand source evolution and/or duty cycle can be obtained.

Data products from the survey KSPs include catalogues and flux maps which will serve as valuable long term resources for the CTA community. The data will be made available to the scientific community in the form of products. The products will contain information on relativistic particle transport which is expected to provide new insights into the nature of the diffuse gamma-ray emission in the Galactic plane. The products will also contain information on the diffuse gamma-ray emission in the Galactic plane.
Search for PeVatrons in the Galaxy

- **CR able to produce 100 TeV photons should have** $E_{\text{CR}} \sim \text{PeV}:

  **PeVatrons**

  - **Photons with $E \sim 100$ TeV**: produced preferentially by *hadronic process* (proton-photon, proton-proton interactions)
  
  - Cross-section for *IC interactions electron-photon* decreases very quickly for $E > 10$ TeV (Klein-Nishina effect)
Cosmic Ray Interactions (cascading)

- **photo-hadronic processes** $p + \gamma_b \rightarrow \begin{cases} 
\pi^0 + p \rightarrow 2\gamma, \\
\pi^\pm + n \rightarrow e^\pm + \nu_s,
\end{cases}$

- **proton-proton interactions** $p + p_b \rightarrow \begin{cases} 
p + p + \pi^0 \rightarrow 2\gamma, \\
p + n + \pi^+ \rightarrow e^+ + \nu_s,
\end{cases}$

- **pair creation** $\gamma + \gamma_b \rightarrow e^\pm,$

- **synchrotron cooling** $e^\pm + \vec{B} \rightarrow \gamma_{synchron} \rightarrow \gamma_b,$

- **inverse Compton scattering** $e^\pm + \gamma_b \rightarrow \gamma,$
LHAASO discovered PeVatrons @ Galaxy

Cao et al., 2021, Nature

<table>
<thead>
<tr>
<th>Source name</th>
<th>RA (°)</th>
<th>Dec. (°)</th>
<th>Significance above 100 TeV ((\times\sigma))</th>
<th>(E_{\text{max}}) (PeV)</th>
<th>Flux at 100 TeV (CU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHAASO J0534+2202</td>
<td>83.55</td>
<td>22.05</td>
<td>17.8</td>
<td>0.88 ± 0.11</td>
<td>1.00(0.14)</td>
</tr>
<tr>
<td>LHAASO J1825-1326</td>
<td>276.45</td>
<td>-13.45</td>
<td>16.4</td>
<td>0.42 ± 0.16</td>
<td>3.57(0.52)</td>
</tr>
<tr>
<td>LHAASO J1839-0545</td>
<td>279.95</td>
<td>-5.75</td>
<td>7.7</td>
<td>0.21 ± 0.05</td>
<td>0.70(0.18)</td>
</tr>
<tr>
<td>LHAASO J1843-0338</td>
<td>280.75</td>
<td>-3.65</td>
<td>8.5</td>
<td>0.26 ± 0.16</td>
<td>0.73(0.17)</td>
</tr>
<tr>
<td>LHAASO J1849-0003</td>
<td>282.35</td>
<td>-0.05</td>
<td>10.4</td>
<td>0.35 ± 0.07</td>
<td>0.74(0.15)</td>
</tr>
<tr>
<td>LHAASO J1908+0621</td>
<td>287.05</td>
<td>6.35</td>
<td>17.2</td>
<td>0.44 ± 0.05</td>
<td>1.36(0.18)</td>
</tr>
<tr>
<td>LHAASO J1929+1745</td>
<td>292.25</td>
<td>17.75</td>
<td>7.4</td>
<td>0.71 ± 0.16</td>
<td>0.38(0.09)</td>
</tr>
<tr>
<td>LHAASO J1956+2845</td>
<td>299.05</td>
<td>28.75</td>
<td>7.4</td>
<td>0.42 ± 0.03</td>
<td>0.41(0.09)</td>
</tr>
<tr>
<td>LHAASO J2018+3651</td>
<td>304.75</td>
<td>36.85</td>
<td>10.4</td>
<td>0.27 ± 0.02</td>
<td>0.50(0.10)</td>
</tr>
<tr>
<td>LHAASO J2032+4102</td>
<td>308.05</td>
<td>41.05</td>
<td>10.5</td>
<td>1.42 ± 0.13</td>
<td>0.54(0.10)</td>
</tr>
<tr>
<td>LHAASO J2108+5157</td>
<td>317.15</td>
<td>51.95</td>
<td>8.3</td>
<td>0.43 ± 0.05</td>
<td>0.38(0.09)</td>
</tr>
<tr>
<td>LHAASO J2226+6057</td>
<td>336.75</td>
<td>60.95</td>
<td>13.6</td>
<td>0.57 ± 0.19</td>
<td>1.05(0.16)</td>
</tr>
</tbody>
</table>

Discovery of **12 sources emitting at several hundreds of TeV, up to 1.4 PeV**

Candidates: SNRs, galactic center, pulsar wind nebulae, young stellar clusters?

**CTA ->** can identify, probe morphology and spectra
Primary goals of CTA Galactic Science

• Provide a census of the VHE Galactic source populations (identify unknown and new sources)
  – Massive stars
  – Compact objects: galactic NSs and BHs
  – Pulsars and PWNe
  – Supernova remnants
  – Microquasars, binary systems
  – Young stellar clusters
• Identify PeVatrons among them
• To be performed down to ~ 2mCrab in the inner Galaxy and around the Cygnus region, and ~ 4mCrab elsewhere in the Galactic Plane
• Detailed Study of the diffuse emission
• Multi-purpose catalogue and legacy datasets
Galactic Particle Accelerators: ex. SNR

Simulated CTA TeV-bright supernova remnant RX J1713–3946 for 2 emission scenarios:

CTA will be able to differentiate between these scenarios.
Large Magellanic Cloud Survey

- Global view of a near star-forming galaxy at TeV energies
- More than 60 SNRs
- Resolving regions down to 20 pc size
- Diffuse emission view of particle transport

Observation time: about 300 hours

Current (H.E.S.S) vs. CTA
The extragalactic Survey

The first ever in the VHE band

- Unbiased survey of the sky
  - Coverage of 1/4 of full sky
  - Performed over 10 years
    - Complete to 5 mCrab
  - Blazar Luminosity Function
  - Probe new sources, e.g.:
    - Extreme blazars
    - Galaxy Clusters
- Serendipity transients discovery and follow-up potential, e.g. GRBs, TDEs, FRBs,…
- Monitoring (multi-band) and Follow-up of strong AGN flares
- Multi-messenger science: GW and neutrino triggers

Figure 8.3 – Proposed region of the extragalactic survey in Galactic coordinates:
CTA EXTRAGALACTIC TARGETS

Other galaxies

GRBs

Blazars

Radio galaxies

Star forming regions

Survey / deep field

Galaxy clusters

EBL / IGMF

Thanks to D. Mazin
CTA Differential Flux Sensitivity

CTA will be a high-energy transient monitor

Orders of magnitude advantage over Fermi-LAT in intra-day timescales: GRBs, AGN flares, binaries.

CTA -> ability to probe very short timescales in gamma-rays
**Transients & Variability Phenomena**

**Transients** are a diverse population of astrophysical objects. Some are known to be prominent *emitters of high-energy gamma-rays*, while others are sources of non-photonic, multi-messenger signals such as cosmic rays, *neutrinos and/or gravitational waves*.

Possible classes of targets

- Gamma-ray bursts
- Galactic transients
- High-energy neutrino transients
- Gravitational wave transients
- Radio, optical, and X-ray transients
- Serendipitous VHE transients
- AGNs, PWN, binaries, accretion & relativistic outflows
CTA ability to probe very short timescales in gamma-rays:
- explore connection between accretion and ejection phenomena in compact objects
- study phenomena in relativistic outflows: GRBs, AGN, PWN, binary systems
- In GRBs: high-statistics measurements for the first time $>10$ GeV; detect $\sim 2$ GRB/yr

CTA simulated light curve flare of PKS 2155–304 provides access to timescales $<<$ light-crossing time of the supermassive black hole

CTA Simulated light curve GRB 080916C, $z = 4.3$
AGN monitoring

What is the jet made of? How is it launched? What causes the variability? What is the acceleration mechanism?

- Long-term monitoring of selected AGN over 10 years
- Follow-up of flaring AGN
- High-quality measurement of selected AGN spectra

Total observation time: about 3000 hours
AGN monitoring

What is the jet made of? ✓
How is it launched?
What causes the variability?
What is the acceleration mechanism?

from: Science with CTA
www.worldscientific.com/worldscibooks/10.1142/10986
AGN Variability
Where is emission region? Jet launching? Acceleration Mechanism?

AGN Blazars: most frequent extragalactic gamma-ray emitters

Strong variability in time at TeV: \( t_v \approx 200 \) s
\( \rightarrow \) very compact and fast emitters \( \Gamma_{em} > 50 \)

Ex.: PKS2155-304 (Aharonian et al. 2007)

High flux strong Doppler boosting (jet bulk \( \Gamma \approx 5-10 \))
AGN Variability
Shock or Magnetic Reconnection Acceleration?

Strong variability in time at TeV:
\( t_v \approx 200 \text{ s} \)
very compact and fast emitters
\( G_{\text{em}} > 50 \) (e.g. Giannios et al. 2009)

Table 1 Temporal characteristics of Flares.

<table>
<thead>
<tr>
<th>Flare (MJD) Components</th>
<th>[Name]</th>
<th>( T_r ) (days)</th>
<th>( T_d ) (days)</th>
<th>Reduced-( \chi^2 ) (DOF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 (58133.0–58139.0)</td>
<td>Envelope [1]</td>
<td>1.62 ± 0.06</td>
<td>1.49 ± 0.05</td>
<td>1.77 (43)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fast/uniFB02 are [1]</td>
<td>0.06 ± 0.02</td>
<td>0.04 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>F2 (58222.0–58232.0)</td>
<td>Envelope [1]</td>
<td>1.61 ± 0.03</td>
<td>2.74 ± 0.05</td>
<td>1.52 (79)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fast/uniFB02 are [1]</td>
<td>0.05 ± 0.01</td>
<td>0.09 ± 0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fast/uniFB02 are [2]</td>
<td>0.09 ± 0.02</td>
<td>0.08 ± 0.01</td>
<td></td>
</tr>
</tbody>
</table>

Column (1) presents the name of the are and their duration, next row in column (1) presents number of fitted components for the same are, Column (2) presents the type of components used for fitting and their names, Column (3) presents the rise time of the are, Column (4) presents the decay time of the are, Column (5) presents the reduced-\( \chi^2 \) and degrees of freedom (DOF) of the overall for the are with all the components.

Ex.: PKS2155-304 (Aharonian et al. 2007)
Particles are accelerated stochastically - Fermi process

**Shock Acceleration**

1\textsuperscript{st}-order Fermi
(Bell 1978; Begelman & Eichler 1997):

\[
\langle \Delta E/E \rangle \sim \frac{v_{sh}}{c}
\]

**Reconnection Acceleration**

As in shocks: 1\textsuperscript{st}-order Fermi
(de Gouveia Dal Pino & Lazarian 2005;
del Valle, de Gouveia Dal Pino, Kowal 2016):

\[
\langle \Delta E/E \rangle \sim \frac{v_{rec}}{c}
\]
Magnetic Reconnection acceleration may prevail

Particels are accelerated by magnetic reconnection up to $10^{16-20}$ eV at inner magnetically dominated regions.

Medina-Torrejon, de Gouveia Dal Pino, Kowal 2023

(e.g. Giannios et al. 2009)
Gamma-ray absorption by extragalactic background light (EBL)

- Extragalactic Background Light (EBL): integrated IR and optical emission from stars and galaxies through evolution of the universe (very hard to measure)
- EBL interacts with gamma-rays: photon-photon -> pair production

CTA:
- measure EBL precisely @ z=0 for large number of objects
- large sample of blazars z=0-2: evolution of EBL
Gamma-ray absorption by extragalactic background light (EBL)

arXiv:2010.01349

Best at $z \sim 0.2$: $\pm 5\%_{(stat)} \pm 12\%_{(syst)}$

Up to $z \sim 2$ ($z \sim 1$ for current TeV observatories)

Constraints limited by instrument systematics
Pair production by TeV photons interacting in voids: allows to measure weak magnetic fields (IGMF)

- **Secondary gamma-rays produced by primary pairs via inverse-Compton** scattering on the EBL -> cascade from further pair and inverse-Compton interactions

- **Deflections of secondary pairs in the IGMF form:**
  - pair halo (around the primary source)
  - pair echoes: that arrive with time delay relative to primary emission

- **IGMF > 10^{-12} G:** full isotropisation of the emission: pair halo
- **IGMF < 10^{-12} G:** extended emission

**CTA will detect secondary pair emission for IGMF ~ 10^{-16} - 10^{-12} G** (for sources @ ~ 100Mpc)
Gamma-ray propagation & absorption: pair echo and halo & cosmic magnetic fields

Observables

1) **Time delays**
   \[ \Delta t \sim 3 \text{ yrs } (E/0.1 \text{TeV})^{-1}(B/10^{-16} \text{G})^2 \]
   Useful for low B-field, limited by variability pattern

2) **Spectrum & morphology**
   \[ E_2 \sim 80 \text{ GeV } (E_1/10 \text{ TeV})^2 \]
   Degree-scale extension scaling as B whose shape depends on jet parameters:

Credits: Ievgen Vovk

arXiv:2010.01349
Axions are a proposed solution to the strong-CP problem of quantum chromodynamics and also well-motivated candidates to constitute a part or all of CDM.

Gamma-ray propagation: photon-axion oscillations

- **Axion Like Particles (ALPs):** massless particles predicted by quantum chromodynamics (and also DM candidates)

- **ALPS:** convert into photons (and vice versa) when traverse ambient MF

- For very distant AGN: conversion of ALP into gamma-ray enhances the TeV photon flux (which competes with the absorption on the EBL)

- Clue: To probe ALPs we need distant AGN embedded in measurable MFs -> a distant AGN in the center of a galaxy cluster: e.g. **NGC1275 in Perseus cluster** (75 Mpc)
Gamma-ray propagation: photon-axion oscillations

CTA constraints on ALPs:

\[ m_a \text{ versus ALP-coupling to photons } g_{a\gamma} \]

- **Green regions:** exclusion in the ALP parameter space by CTA from flaring state of the radio galaxy NGC 1275
- **Purple and blue:** exclusion regions from current-generation instruments
- **Salmon:** hints for ALPs from additional cooling of white dwarfs (WD) and increased transparency of the Universe to TeV γ-rays
- **Green lines:** other projected sensitivities
- **Dark orange:** parameter space for QCD axion

arXiv:2010.01349
Searching for Dark Matter annihilation

Does dark matter annihilate producing gamma rays?
What is the (dark) matter content?

CTA prospects for CDM signatures:
- Around the Galactic center
- In dwarf galaxies
- In clusters of galaxies
Dark matter search in galactic center

Weakly Interacting Dark Matter Particles (WIMPs)

Annihilation cross section “known” from Dark Matter abundance

Characteristic spectral signature known from particle physics
Dark matter annihilation

Canonical cross section

arXiv:2010.01349
Gamma-Rays & DM in galaxy clusters

- Galaxy clusters able retain VHECR for Hubble time -> produce gamma-rays

**Diffuse Gamma-Ray emission from clusters z=0-5**  

**CTA will probe gamma-ray and DM: Perseus cluster (in prep.)**

[Figure 1. Trajectories of CRs through a cluster of mass ~ 10^{15} M_{\odot} selected from our background simulation. The thick line corresponds to a CR with energy of 10 PeV, and the thin line to a CR with energy 500 PeV.]
Quantum Gravity effects (at Planck scales): arrival time delays between photons of different energies travelling large distances (due to wavelength dependent refractive index of the vacuum) -> LIV - variation of light speed

\[ \Delta t \sim \left( \frac{\Delta E}{\xi_\alpha E_{Pl}} \right)^\alpha \frac{L}{c} \]

\[ E_{Pl} = \sqrt{hc/G_N} \approx 1.22 \times 10^{19} \text{ GeV} \]

\[ \alpha \sim 1-2 \quad \xi_\alpha \text{ - factor of Planck energy for QG} \]
A CTA Precursor @ Tenerife

9 SST-2M telescopes: INAF (Italy) + Brazil, South Africa, Spain, Switzerland

3 structures: Brasil - IAG-USP (FAPESP funding)

Currently in construction

Installation Teide Observatory (Tenerife, Canary Islands): 2022-2025
Expected performance:

- **Sensitivity:** better than current IACTs ($E > 10$ TeV):
  - Extend spectra of already detected sources and measure cut-offs
  - Characterize morphology of extended sources at the highest VHE

- **Energy/Angular resolution:** < ~10% / < ~ 0.05° ($E \sim 10$ TeV)
- **Wide FoV ($\geq 10^\circ$), with homogeneous off-axis acceptance**
  - Optimal for multi-target fields, surveys, and extended sources
  - Enhanced chance for serendipity discoveries
We extend current IACTs **differential sensitivity up to several tens of TeV and beyond**

Investigate possible spectral features at VHE, such as the presence of **spectral cut-offs** or the detection of emission at several tens of TeV expected from **Galactic PeV sources**
Sensitivity: better than current IACTs ($E \gtrsim 3$ TeV)
- Broad-band spectrum
- Spectral cut-off constraints

Energy/Angular resolution: $\sim 10\% / \sim 0.05^\circ$ ($E \sim 10$ TeV)
- Extended sources morphology

$10^\circ$ field of view with excellent off-axis performance
- Multi-target fields
- Serendipitous discoveries
Pillar 1
The origin of cosmic rays
- Quest for PeVatrons
- Particle propagation
- PWN HE emission
- UHECR from SB galaxies

Time-domain
- GRB, GW, ν

Pillar 2
Fundamental physics
- IR EBL constraints
- Probing IGMF
- Blazars & hadron beams
- Test on ALPs & LIV

Non γ-ray
- UHECR measure S1^3

Synergies
- MWL, Legacy
The **ASTRI Mini-Array** will investigate these and future UHE sources, providing both the opportunity for **their precise identification** and important **information on their morphology and spectra**

<table>
<thead>
<tr>
<th>Source name</th>
<th>RA (°)</th>
<th>dec. (°)</th>
<th>Significance above 100 TeV (σ)</th>
<th>$E_{\text{max}}$ (PeV)</th>
<th>Flux at 100 TeV (CU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHAASO J0534+2202</td>
<td>83.55</td>
<td>22.05</td>
<td>17.8</td>
<td>0.88 ± 0.11</td>
<td>1.00(0.14)</td>
</tr>
<tr>
<td>LHAASO J1825-1326</td>
<td>276.45</td>
<td>-13.45</td>
<td>16.4</td>
<td>0.42 ± 0.16</td>
<td>3.57(0.52)</td>
</tr>
<tr>
<td>LHAASO J1839-0545</td>
<td>279.95</td>
<td>-5.75</td>
<td>7.7</td>
<td>0.21 ± 0.05</td>
<td>0.70(0.18)</td>
</tr>
<tr>
<td>LHAASO J1843-0338</td>
<td>280.75</td>
<td>-3.65</td>
<td>8.5</td>
<td>0.26 ± 0.10</td>
<td>0.73(0.17)</td>
</tr>
<tr>
<td>LHAASO J1849-0003</td>
<td>282.35</td>
<td>-0.05</td>
<td>10.4</td>
<td>0.35 ± 0.07</td>
<td>0.74(0.15)</td>
</tr>
<tr>
<td>LHAASO J1908+0621</td>
<td>287.05</td>
<td>6.35</td>
<td>17.2</td>
<td>0.44 ± 0.05</td>
<td>1.36(0.18)</td>
</tr>
<tr>
<td>LHAASO J1929+1745</td>
<td>292.25</td>
<td>17.75</td>
<td>7.4</td>
<td>0.71 ± 0.07</td>
<td>0.38(0.09)</td>
</tr>
<tr>
<td>LHAASO J1956+2845</td>
<td>299.05</td>
<td>28.75</td>
<td>7.4</td>
<td>0.42 ± 0.03</td>
<td>0.41(0.09)</td>
</tr>
<tr>
<td>LHAASO J2018+3651</td>
<td>304.75</td>
<td>36.85</td>
<td>10.4</td>
<td>0.27 ± 0.02</td>
<td>0.50(0.10)</td>
</tr>
<tr>
<td>LHAASO J2032+4102</td>
<td>308.05</td>
<td>41.05</td>
<td>10.5</td>
<td>1.42 ± 0.13</td>
<td>0.54(0.10)</td>
</tr>
<tr>
<td>LHAASO J2108+5157</td>
<td>317.15</td>
<td>51.95</td>
<td>8.3</td>
<td>0.43 ± 0.05</td>
<td>0.38(0.09)</td>
</tr>
<tr>
<td>LHAASO J2226+6057</td>
<td>336.75</td>
<td>60.95</td>
<td>13.6</td>
<td>0.57 ± 0.19</td>
<td>1.05(0.16)</td>
</tr>
</tbody>
</table>

**Discovery of 12 sources emitting at several hundreds of TeV, up to 1.4 PeV**

Crab aside, the majority of remaining sources represent **diffuse γ-ray structures with angular extensions up to 1°**

The **actual sources** responsible for the ultra high-energy γ-rays have not yet been firmly localized and identified (except for the Crab Nebula), leaving the origin of these extreme accelerators open.
Gamma-Ray Bursts with Mini-Array

- GRBs confirmed as a new class of TeV emitters thanks to the MAGIC detection of GRB 190114C (z=0.42)
- SSC component extending into the TeV energy range
- LHAASO detection of GRB 221009A (z=0.15) well above 10 TeV challenges the standard physics model

The ASTRI Mini-Array
- might have detected emission from GRB 190114C
- is able to confirm afterglow emission at $E > 1$ TeV from close ($z < 0.4$) GRBs if observations start within the first tens of seconds up to few minutes from the onset of the burst
- can measure the spectral cut-off, either originated by the EBL absorption or intrinsic, if greater than 1 TeV

The expected number of follow-ups on observable GRBs is about 1 per month

Simulation of the emission from three GRB 190114C-like bursts, at three different redshifts ($z = 0.078$, $z = 0.25$ and $z = 0.42$)

Simulations of GRB 221009A will start very soon
The ASTRI Mini-Array will start **scientific observations in 2025** from the *Observatorio del Teide* with a 4 (core science) + 4 (observatory science) year programme.

Its **10° field of view** will allow us to investigate both extended sources (e.g., SNRs) and crowded/rich fields (e.g., the Galactic Center) with a single pointing.

Its **3’ angular resolution** at 10 TeV will allow us to perform detailed morphological studies of extended sources.

Its **sensitivity extending above 100 TeV** will make it the most sensitive IACT in the energy range 5-200 TeV in the Northern hemisphere before CTAO-N.
Brasil in the SST-CTA Program:

Currently: ~60 members in CTA-Br (~29 -> in SST–CTA from IAG-USP, EACH-USP, Mackenzie, UFABC, IFUSP, CBPF)

Aim: production in Brazil of optical support of the 40 (ASTRI based) SST structures of CTA-South array (α-configuration) (FAPESP)
CTA Observatory is coming

31 Countries
200+ institutes
1400+ members
One aim!
CTA Observatory is coming

31 Countries
200+ institutes
1400+ members
One aim!

Moving from prototype to construction:

• by Summer / September 2023
• last about 5 yr

Early science operations foreseen during the construction phase
...in the mean time
The TeV sky
Today: >250 sources

Thank you