Science with the Cherenkov Telescope Array

A multi-wavelength and multi-messenger perspective

Ulisses Barres de Almeida
Brazilian Center for Physics Research — CBPF, Brazil
The Cherenkov Telescope Array

- CTA is the next generation ground-based gamma-ray astronomy observatory, operating in the range from **tens of GeV to 300 TeV**.
  - It will be the first facility in the field to function as an open observatory.

- It will consist of two arrays of Imaging Atmospheric Cherenkov Telescopes (IACTs)
  - **Northern Array**: in La Palma, Canary Islands, Spain, concentrating in the lower energy range, with a focus on the study of extragalactic objects.
  - **Southern Array**: near Cerro Paranal, in Chile, with full energy coverage and a view to the Galactic Plane and the Galactic Center

- Composed of three classes of telescopes
  - Large-, Medium-, and Small-Sized Telescopes (LST, MST, SST)

Schematic view of the planned northern (left) & southern (right) arrays
CTA Science & Capabilities

See “Science with the Cherenkov Telescope Array” book by World Scientific, also @ arXiv:1709.07997

**DESIGN DRIVERS**

- **10 x Sensitivity, Large Collection Area** → all topics
- **Energies down to 20 GeV** → Cosmology++
- **Energies up to 300 TeV** → Pevatrons
- **8° Field of View** → surveys, extended objects
- **Rapid Slewing in 20 seconds** → transients
- **10% Energy Resolution** → lines, features
- **Few Angular Resolution** → morphology

- **Mean Free Path**
  - $\gamma + \gamma \rightarrow e^+e^-$ Mean free path due to gamma-photon pair creation

- **Energies down to 20 GeV**
  - Cosmology++
  - Energy resolution 10%

- **Energies up to 300 TeV**
  - Pevatrons
  - Energy up to 300 TeV

- **Rapid Slewing**
  - In 20 seconds
  - Transients

- **8° Field of View**
  - Surveys, extended objects

- **10 x Sensitivity, Large Collection Area**
  - All topics

- **10% Energy Resolution**
  - Lines, features

- **Few Angular Resolution**
  - Morphology
CTA will function in two modes in the first decade

- **CTA: the first VHE observatory**
  - ~40% of observing time over first 10 years for Consortium Key Science Projects (KSPs)
  - rest of the time open to general observers (GO)
  - ultimately all data public (candidate photon lists with measured properties) + software tools to perform scientific analysis

**CTA Consortium/Key Science Projects**

- Users of high-level products (catalogs, skymaps ...)
- Users of archival data (available after proprietary period of ~1 year)

**General Observers**
CTA will function in two modes in the first decade

- **Consortium Key Science Projects**
  - 40% of the time for 10 years
  - legacy datasets for general observers
  - all data ultimately public

- **Galactic KSPs**
  - Galactic Plane Survey
    - Deep view of key topics: Galactic Center, PeVatrons, Star Forming Systems.

- **Extragalactic KSPs**
  - First Extragalactic Survey

- **Dark Matter Programme**
The Galactic Plane Survey

- Most primary goal of CTA Galactic Science: provide a census of Galactic VHE source populations
- To be performed down to ~ 2 mCrab in the inner Galaxy and Cygnus region, and ~ 4 mCrab elsewhere in the Galactic Plane.
- Detailed study of the diffuse emission
- Multi-purpose catalogue and legacy dataset
The Galactic Plane Survey

- Most primary goal of CTA Galactic Science: provide a census of Galactic VHE source populations
- To be performed down to ~ 2 mCrab in the inner Galaxy and Cygnus region, and ~ 4 mCrab elsewhere in the Galactic Plane.
- Detailed study of the diffuse emission
- Multi-purpose catalogue and legacy dataset
The Galactic Plane Survey

Catalogue cross-matching for source ID
21 cm atomic gas mapping
Recombination lines ionised gas census
Sub-mm imaging of molecular clouds
OH maps for Dark gas tracing

Optical catalogues of massive stars
Dust emission
Survey source counterpart ID
msec pulsars

Cross-matching of catalogues: source ID
PWN/SNR associations
Nebula properties
Microquasars

Spectral morphology studies
Source selection for further deep observations
Survey source counterpart ID
Microquasars
The Galactic Center

The inner Galaxy will be focus of a deeper survey within the GPS

- Extended Survey will cover unexplored regions in the VHE at higher latitudes
  - edge of the bulge emission
  - base of the Fermi bubbles
  - other sources e.g. Kepler SNR

- Goals include
  - diffuse emission
  - dark matter signals
  - cosmic-ray acceleration
  » PeVatrons
Galactic Transients

CTA counterpart time

External MWL time

250 hours

340 hours

60 hours

130 hours

180 hours

200 hours

180 hours

500 hours

RADIO

Optical

X-rays

Gamma-rays

ALMA

LSST

Athena,eROSITA

Fermi

SKA

Gamma-rays

RADIO

Optical

X-rays

Gamma-rays
The Extragalactic Survey

- Survey of 1/4 of the sky to limiting sensitivity of 5 mCrab.
- Unbiased determination of blazar luminosity function (LogN-LogS distribution)
- Probe of new source populations such as extreme blazars at the limit of current detectability
- Discovery potential – serendipity.

AGNs in CTA ExGal Survey: 123
Sources CTA Gal Plane Survey: 488
Sources in Fermi/LAT Catalog: 320
AGNs detected by IACTs: 59
**Experimental Facilities**

- **Light Detection**
  - Gamma rays
  - X rays
  - Visible light (400 nm)
  - Ultraviolet radiation
  - Microwave radiation
  - Infrared radiation

**Table of MWL & MM Links**

<table>
<thead>
<tr>
<th>Extragalactic MWL and MM links</th>
<th>Names:</th>
<th>Happy sorting Ulisses!</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGSO, M@TE, LHAASO, HAWC, FACT</td>
<td>J. Biteau &amp; J. Becerra</td>
<td>- Consortium meeting Lugano – 2019-06-04</td>
</tr>
<tr>
<td>KM3, GRAND, ARIANNA, ARA</td>
<td>F. Tavecchio</td>
<td>- Propagation (EBL, hadron beams)</td>
</tr>
<tr>
<td>AugerPrime TA x 4</td>
<td>T. Hovatta, F. d'Ammando, A. Zech</td>
<td>- Flares (T. Hovatta, E. Lindfors)</td>
</tr>
<tr>
<td>CenA &amp; M 87</td>
<td>T. Hovatta</td>
<td>- Redshift (J. Biteau)</td>
</tr>
<tr>
<td>Long-term monitoring (T. Hovatta)</td>
<td></td>
<td>- Optical support telescope, Liverpool, WEBT</td>
</tr>
<tr>
<td>Extragalactic survey (T. Hovatta)</td>
<td></td>
<td>- AGN targets (A. Zech)</td>
</tr>
<tr>
<td>AGN targets</td>
<td></td>
<td>- X-shooter/ESO, ESI/Lick</td>
</tr>
<tr>
<td>SAM/SOAR, SharCS/Lick</td>
<td></td>
<td>- X-shooter/ESO, ESI/Lick</td>
</tr>
<tr>
<td>X-shooter/ESO, ESI/Lick</td>
<td></td>
<td>- X-shooter/ESO, ESI/Lick</td>
</tr>
<tr>
<td>HAWC, FACT</td>
<td></td>
<td>- Chandra</td>
</tr>
<tr>
<td>Fermi-LAT</td>
<td></td>
<td>- HST, adaptive optics</td>
</tr>
<tr>
<td>NuStar, HXMT, AstroSAT</td>
<td></td>
<td>- Swift-UVOT/XRT, eROSITA, eXTP</td>
</tr>
<tr>
<td>Swift-UVOT/XRT, eROSITA, eXTP</td>
<td></td>
<td>- Chandra</td>
</tr>
<tr>
<td>Optical support telescope, Liverpool, WEBT</td>
<td></td>
<td>- Optical support telescope, Liverpool, WEBT</td>
</tr>
<tr>
<td>JWST, SPICA</td>
<td></td>
<td>- JWST, SPICA</td>
</tr>
<tr>
<td>ALMA</td>
<td></td>
<td>- ALMA</td>
</tr>
<tr>
<td>ATCA</td>
<td></td>
<td>- ATCA</td>
</tr>
<tr>
<td>Metsähovi</td>
<td></td>
<td>- Metsähovi</td>
</tr>
<tr>
<td>OVRO</td>
<td></td>
<td>- OVRO</td>
</tr>
<tr>
<td>VLBA</td>
<td></td>
<td>- VLBA</td>
</tr>
</tbody>
</table>

Adapted from slide by J. Biteau
MWL synergies will demand significant (and challenging amount) of external time, especially for transients;

Re-analysis of catalogued data or revisiting of survey fields is also envisaged.
CTA’s high sensitivity enables access to short timescales. Combined with a low energy threshold + rapid slewing capability & large field of view, this makes CTA an ideal high-energy transient telescope.

Transients with CTA

See poster by F. Schüssler on Transients
Long-term monitoring of 11 Northern + 4 Southern objects for a detailed understanding of the variability and nature of jet emission in blazars.
Follow-up of extreme extragalactic transient events, from external MWL / MM alerts, as well as CTA serendipitous discoveries (2-3 per year).

<table>
<thead>
<tr>
<th></th>
<th>Triggers</th>
<th>Radio</th>
<th>Optical</th>
<th>X-rays</th>
<th>GeVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN Flares</td>
<td>50-100</td>
<td>&lt; 800 hours</td>
<td>&lt; 300 hours</td>
<td>&lt; 500 hours</td>
<td>–</td>
</tr>
<tr>
<td>GRBs</td>
<td>O(20), 4 det</td>
<td>50 h/trigger</td>
<td>50 h/trigger</td>
<td>30 h/trigger</td>
<td>30 h/trigger</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>O(10), 2 det</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Gravitational waves</td>
<td>O(10), 1 det</td>
<td>&gt;50 h/trigger</td>
<td>50 h/trigger</td>
<td>25 h/trigger</td>
<td>20 h/trigger</td>
</tr>
<tr>
<td>FRBs</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
See poster by M. Seglar-Arroyo on GWs

1. Fast scan of large GW signal region, est. time of 2 hours/trigger + follow-up

2. Real time analysis for statistical identification of potential EM counterpart for follow-up

3. MWL campaigns and cross-matching of multiple catalogues for source ID
Recent IceCube neutrino & GW events, and the sub-TeV GRB detection by MAGIC sparked large MWL / MM follow-up campaigns. Over 150 instruments participate in follow-up campaigns of such events and related MoUs; dozens of alerts in past years. Follow-up & RTA searches covering entire EM.
## Multi-instrument coordination

### Instrument coordination and data access via GOP, MoUs or open data policies.

Mapping of availability at each band (and time) is fundamental for success.
MWL & Multi-messenger coordination within CTA:

1. CTA will demand significant amount of external data for achieving its KSP science goals.

2. Transients science is specially demanding, requiring also close coordination of ToO observations.

3. In optical support telescopes on site may be a solution for providing the dedicated coverage necessary.
BACK UP
## MWL Synergies

### Mapping matrix: Science Cases <-> MWL / Multi-messenger

<table>
<thead>
<tr>
<th>Band or Messenger</th>
<th>Astrophysical Probes</th>
<th>Galactic Plane Survey</th>
<th>LMC &amp; SFRs</th>
<th>CRs &amp; Diffuse Emission</th>
<th>Galactic Transients</th>
<th>Starburst &amp; Galaxy Clusters</th>
<th>GRBs</th>
<th>AGNs</th>
<th>Radio Galaxies</th>
<th>Redshifts</th>
<th>GWs &amp; Neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>Particle and magnetic-field density probe. Transients. Pulsar timing.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Sub)Millimetre</td>
<td>Interstellar gas mapping. Matter ionisation levels. High-res interferometry.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>IR/Optical</td>
<td>Thermal emission. Variable non-thermal emission. Polarisation.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Transient Factors</td>
<td>Wide-field monitoring &amp; transients detection. Multi-messenger follow-ups.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>X-rays</td>
<td>Accretion and outflows. Particle acceleration. Plasma properties.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MeV-GeV Gamma-rays</td>
<td>High-energy transients. Pion-decay signature. Inverse-Compton process</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Other VHE</td>
<td>Particle detectors for 100% duty cycle monitoring of TeV sky.</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Gravitational Waves</td>
<td>Mergers of compact objects (Neutron Stars), Gamma-ray Bursts.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>