Synergies between SKA and the Cherenkov Telescope Array

Stefano Vercellone (INAF – OA Brera)  stefano.vercellone@brera.inaf.it
for the CTA Consortium

2nd National Workshop of SKA science and technology
Outline

Introduction

CTA

CTA Key Science Projects

Synergies

Summary
The sky above 50 GeV

Wakely & Horan http://tevcat.uchicago.edu/

~220 TeVCat sources

Source Types
- PWN
- Binary XRB PSR Gamma Bin
- HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
- Shell SNR/Molec. Cloud Composite SNR Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster Bin Bl Lac (class unclear) WRI

H.E.S.S.
MAGIC
VERITAS

UNID 20%
GAL 41%
EGAL 39%

360 Fermi-LAT sources E>50 GeV

EGAL 75%
GAL 11%
UNID 14%

Only ~25% of the 2FHL sources have been previously detected by Cherenkov telescopes. 2FHL provides a reservoir of candidates to be followed up at very high energies.
Outline

Introduction

CTA

CTA Key Science Projects

Synergies

Summary
Two sites (North and South) for a whole-sky coverage

Operated as an open Observatory

A factor of 5-20 more sensitive w.r.t. the current IACTs depending on the energy band

A few large size telescopes to cover the range 20 - 150 GeV

~km² array of medium size telescopes for the 0.15 - 5 TeV domain

~4km² array of small size telescopes, sensitive above 5 TeV up to 300 TeV

4 LSTs [N & S]

15 MSTs [N]
25 MSTs [S]
(24 SCTs [S])

70 SSTs [S]
CTA current prototypes
CTA locations

Artistic rendition, actual buildings and sites under design & construction

La Palma site contract signed

4 LSTs
15 MSTs

Spain
La Palma

Paranal site
ongoing discussion

4 LSTs
25 MSTs
70 SSTs

Chile
Paranal

1,451 scientists
202 institutes
31 countries

Heidelberg
MPIK

Zeuthen
DESY

Bologna
INAF

See details at https://www.cta-observatory.org/about/array-locations/
High-level timeline and proposed layout

Operational lifetime $\geq 30$ years
Effective area for gamma-ray detection

Adapted from W. Hofmann

Hofmann, 2016
**CTA Performance**

**Differential Sensitivity**

A factor of 5-20 improvement in sensitivity depending on energy, relative to current IACTs.

Extension of the accessible energy range from well below 100 GeV to above 100 TeV.

CTA as an *all-sky* Observatory

Sky Coverage

Credits: The CTA Consortium
CTA as a *transient factory*

**Huge advantage over Fermi** in energy range of overlap for \(~\text{minute} \to \text{~day}\) timescale phenomena

- Explosive transients
- AGN flares
- $\gamma$-ray binaries

*Real-time analysis SW is crucial*

**Disadvantage over Fermi**

- Limited FoV (compared to Fermi)
- Prompt reaction to external triggers is critical
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?
- Processes in relativistic jets, winds and explosions?
- Exploring cosmic voids

Theme 3: Physics Frontiers – beyond the SM
- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high energy photons?
- Do axion-like particles exist?
CTA Observing Programme

- **9 Key Science Projects (KSPs) and 1 DM Programme**
  - KSPs are a sets of observations addressing multiple science questions within CTA themes

- Focused on **major legacy projects**:
  - surveys & population studies (providing legacy data-sets)
  - large classes of sources
  - a few iconic objects

- Large potential for **guest observer proposals**
  - building on results from the KSP surveys
Science with the CTA

Publication describing the **CTA Science Goals**


**World Scientific:** [https://www.worldscientific.com/worldscibooks/10.1142/10986](https://www.worldscientific.com/worldscibooks/10.1142/10986)

An online version in open-access will be available too.
The Survey KSPs

**Extragalactic Survey:**
Unbiased survey of \( \frac{1}{4} \) sky to \( \sim 6 \) mCrab VHE population study, duty cycle
New, unknown sources; O(1000) h

**Galactic Plane Survey:**
Survey of entire plane to \( \sim 2 \) mCrab
Galactic source population: SNRs, PWNe, etc.
PeVatron candidates, early view of GC, O(1620) h

**Galactic Centre Survey:**
ID of the central source
Spectrum, morphology of diffuse emission
Deep DM search; base of the Fermi Bubbles
Central exposure: O(525) h, \( 10^\circ \times 10^\circ \) : O(300) h

**Large Magellanic Cloud Survey:**
Face-on satellite galaxy with high SFR
Extreme Gal. sources, diffuse emission (CRs)
DM search; O(340) h in six pointings
Outline

Introduction

CTA

CTA Key Science Projects

Synergies

Summary
Synergies during CTA operation

These are just a few of the future major multi-wavelength facilities available during the CTA era at lower energies.

We should add **LIGO + VIRGO + LISA**\(^*\) (gravitational waves), **IceCube + KM3NeT**\(^*\) (neutrinos) for the multi-messenger astrophysics.

\(^*\) Proposed and/or planned
Illustration of possible KSPs vs. GO time-budget

About 1350 hours/yr (South)
Galactic Plane Survey

- Discovery of PeVatron candidates ⏯ origin of cosmic rays
- Detection of many new VHE sources $O(300 – 500)$, particularly PWNe and SNRs
- Discovery of new VHE gamma-ray binaries
- Production of a multi-purpose legacy data set
- **Radio/mm and X-ray facilities** → PSR ephemerides, **PWNe/SNRs morphology**/SEDs, MWL phase-resolved studies in binaries, **cross-correlation of catalogs** and identification of new VHE sources, ...
- Non-thermal X-ray emission → a natural tracer of locations of extreme particle acceleration.
Simulated CTA image of the Galactic plane for the inner region $90^\circ < l < 90^\circ$, adopting the actual proposed GPS observation strategy, a source model incorporating both supernova remnant and pulsar wind nebula populations and diffuse emission.

SKA and its precursors can provide extremely useful information to be used as inputs.
Multi-wavelength view of the inner Galactic Centre region, showing the wide variety of diffuse emission.

The CTA point spread function is shown in comparison with that of the currently operating H.E.S.S. telescope to illustrate the possibility of resolving structures with CTA that are point-like with existing instruments.
Galactic Centre Survey

- Determination of the nature of the central source
- A detailed view of the VHE diffuse emission
- Search for variability in the VHE source near Sgr A*
- Studying the interaction of the central source with neighboring clouds
- Global VLBI array at mm/sub-mm frequencies, → direct imaging of the jet-launching regions of key sources such as Sgr A*.

MeerKAT image of the central regions of our Galaxy with a wealth of never before seen features, as well as a clearer view of previously known supernova remnants, star-forming regions, and radio filaments. (Credit: SARAO)
Cosmic-ray PeVatrons

What sources may accelerate hadrons to the knee?

SNRs are standard paradigm, but only a handful provide strong evidence for hadron acceleration so far, and only up to ~ 10 TeV

Use GPS as finder and follow-up 5 brightest sources with no cut-off.

MWL information critical for identification → SKA
The **SCORPIO Project** found several **SNRs** which could be used as a **reference for CTA simulations and future observations**.
Multi-messenger Astrophysics window is open!

Detection of a gravitational wave event following a GRB onset and its MWL follow-up.

Potential association of an extra-galactic source with an IceCube neutrino event.
**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.

**Transient Factories & SKA** will generate an overwhelming number of triggers, → 20 new FRBs discovered by ASKAP (Shannon et al, 2018).

The definition of appropriate response criteria is the key to understand the potential for VHE follow-up.
Outline

Introduction

CTA

CTA Key Science Projects

Synergies

Summary
1st CTA Science Symposium

Bologna, 6-9 May 2019

Exploring the High-Energy Universe with CTA

Pre-registration

#ctasympoisum2019

When:
6-9 May 2019

Where:
Teatro Duse
Via Cartoleria 42, Bologna

Regular registration opening soon!
CTA will be an **Observatory** open to the scientific community.

**Science** will focus on cosmic particle acceleration, extreme environments, and physics beyond the standard model.

Proprietary time (significant fraction in the first years) will be articulated in **Key Science Projects**.

Large potential for **Guest Observer proposals** – e.g., building on results from the KSP surveys.

CTA will have important **synergies** with both **SKA** and other astronomical and astro-particle facilities.

We gratefully acknowledge financial support from the agencies and organizations listed here: http://www.cta-observatory.org/consortium_acknowledgments
BACKUP SLIDES
A \(\gamma\)-ray impinges the atmosphere, producing a particle shower which, in turn, produces a flash of Cherenkov radiation lasting 5-20 ns in the range 300<\(\lambda\)<500 nm.
The Dark Matter Programme

- **Key target: Galactic Centre halo**
  - Deep observation $O(525 \, h)$ to reach canonical thermal cross-section for wide WIMP mass range

- **Complementary observations**
  - Dwarf Sph. Galaxies $O(100 \, h)$
  - LMC $O(340 \, h)$
  - Perseus Gal. Cluster $O(300 \, h)$
  - Expect strategy to evolve with new information
Galactic Plane Survey

### Current GPS surveys

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Hemisphere</th>
<th>Galactic Plane Coverage</th>
<th>Energy (GeV)</th>
<th>Sensitivity (mCrab)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermi-LAT 2FHL</td>
<td>(space)</td>
<td>full plane</td>
<td>&gt; 50</td>
<td>~30 – 40</td>
</tr>
<tr>
<td>H.E.S.S.-I</td>
<td>S</td>
<td>−95° &lt; l &lt; 60°,</td>
<td>b</td>
<td>≤ 2°</td>
</tr>
<tr>
<td>VERITAS</td>
<td>N</td>
<td>67° &lt; l &lt; 83°, −1° &lt; b &lt; 4°</td>
<td>≥ 300</td>
<td>20 – 30</td>
</tr>
<tr>
<td>ARGO-YBJ</td>
<td>N</td>
<td>northern sky</td>
<td>&gt; 300</td>
<td>240 – 1000</td>
</tr>
<tr>
<td>HEGRA</td>
<td>N</td>
<td>−2° &lt; l &lt; 85°,</td>
<td>b</td>
<td>&lt; 1°</td>
</tr>
<tr>
<td>Milagro</td>
<td>N</td>
<td>northern sky</td>
<td>&gt; 10,000</td>
<td>300 – 500</td>
</tr>
</tbody>
</table>

### CTA GPS survey

<table>
<thead>
<tr>
<th>Galactic Longitude</th>
<th>Hours</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOUTH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300° – 60°, Inner region</td>
<td>300</td>
<td>2.7 mCrab</td>
</tr>
<tr>
<td>240° – 300°, Vela, Carina</td>
<td>180</td>
<td>2.6 mCrab</td>
</tr>
<tr>
<td>210° – 240°</td>
<td>60</td>
<td>3.1 mCrab</td>
</tr>
<tr>
<td>NORTH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60° – 150°, Cygnus, Persus</td>
<td>180</td>
<td>4.2 mCrab</td>
</tr>
<tr>
<td>150° – 210°, anti-Centre, etc.</td>
<td>150</td>
<td>2.7 mCrab</td>
</tr>
</tbody>
</table>

### CTA/HAWC survey performance

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Hemisphere</th>
<th>Energy Threshold</th>
<th>Angular Resolution</th>
<th>Point Source Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTA</td>
<td>N, S</td>
<td>125 GeV</td>
<td>~ 0.07° at 1 TeV</td>
<td>2 – 4 mCrab</td>
</tr>
<tr>
<td>HAWC</td>
<td>N</td>
<td>2 TeV</td>
<td>0.30°</td>
<td>20 mCrab</td>
</tr>
</tbody>
</table>
**Central survey region:** a deep exposure of 525 h, centered on Sgr A*(l = ±1.0°, 0° and b = ±1.0°, 0°).

- **1st year** → updated analysis of the central source.
- **3rd year** → detailed study of the extended/diffuse emission will be possible + data for DM search.

**Extended survey region:** 300 h of exposure covering a large region to the south or north of the GPS region out to 10° in latitude.

These observations can be taken after the deep exposure, i.e. after the third year of operation.
The survey would connect with the Galactic Plane Survey ($|b| < 5^\circ$) over Galactic longitude $-90^\circ < l < 90^\circ$.

Several highly interesting regions such as the Virgo & Coma clusters, the Fermi Bubbles (North) and Cen A (South) will be covered by the proposed survey.

1/4 of the sky ($\sim 10^4 \text{ deg}^2$)
Limiting flux $\sim 5 \text{ mCrab}$
O(100) AGNs in $10^4 \text{ deg}^2$
The **Large Magellanic Cloud (LMC)** is one of the nearest star-forming galaxies, at a distance of 50 kpc ($\pm 2\% \rightarrow$ important for source energetics).

Its activity is attested by more than 60 supernova remnants, several HII regions, bubbles and shells observed at various wavelengths.

**It is a unique place to obtain a resolved, global view of a star-forming galaxy at TeV energies.**

Mapping of the interstellar gas over wide areas is absolutely essential to enable **identification of sources** within large scale surveys such as that of the LMC.

**(Sub)-millimeter wavelengths** $\rightarrow$ detailed **understanding of the environment** into which shock waves propagate and through which accelerated particles are transported and interact.
Cosmic-ray PeVatrons

Simulated reconstructed spectra for CTA for a PeVatron-like source with a flux equal to the Crab nebula, using two photon indices.

Three different exponential energy cutoff values are used, as indicated by the colors.

<table>
<thead>
<tr>
<th>Target</th>
<th>Type</th>
<th>Exposure (h)</th>
<th>Array</th>
<th>Year</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J1713.7–3946</td>
<td>SNR</td>
<td>50</td>
<td>S</td>
<td>1–3</td>
<td>Full array</td>
</tr>
<tr>
<td>PeVatrons</td>
<td>Unknown</td>
<td>5×50</td>
<td>S</td>
<td>&gt;3</td>
<td>MSTs + SSTs</td>
</tr>
</tbody>
</table>

Use GPS as finder and follow-up 5 brightest sources with no cut-off. MWL information critical for identification → SKA
AGNs are known to emit variable radiation across the entire electromagnetic spectrum up to multi-TeV energies, with fluctuations on time-scales from several years down to a few minutes.

VHE observations of active galaxies harbouring super-massive black holes and ejecting relativistic outflows represent a unique tool to probe the physics of extreme environments, to obtain precise measurement of the extragalactic background light (EBL) and to constrain the strength of the intergalactic magnetic field (IGMF).

AGNs will be useful to investigate fundamental physics phenomena such as the Lorentz invariance violation and signatures of the existence of axion-like particles.
Active Galactic Nuclei

A set of high-quality spectra from different blazar types and different redshifts is needed to unambiguously distinguish intrinsic spectral features, such as shown here, from external absorption.

Such measurements put strong constraints on the bulk Doppler factor, as well as on particle acceleration and cooling processes.