ASTRI SST-2M prototype and ASTRI mini-array data analysis and scientific prospects in the framework of the Cherenkov Telescope Array

S. Lombardi for the ASTRI Collaboration & the CTA Consortium
Outline of the talk

✧ The ASTRI Project in the framework of CTA
✧ The ASTRI SST-2M prototype and the ASTRI mini-array
✧ The ASTRI scientific data analysis
✧ Early science with the ASTRI mini-array
✧ Summary and outlook
The Cherenkov Telescope Array (CTA) Project

- Next generation ground based Gamma-ray Observatory
- Open observatory
- Two sites with total > 100 telescopes (LSTs+MSTs+SSTs)
  - Southern Site: Near Paranal in Chile (selected for negotiations)
  - Northern Site: La Palma, Canary Islands (selected for negotiations)
- 31 nations, ~300M€ project

Designed to operate for 30 years

See general talk on CTA by M. Daniel
The ASTRI Project (led by INAF) has two main goals:

✧ an end-to-end prototype of the CTA small-size telescope in a dual mirror configuration (ASTRI SST-2M), inaugurated on 2014 Sept. 24th and currently under testing at the INAF observing station on Mt. Etna (Sicily)

✧ an ASTRI mini-array composed of 9 SST-2M telescopes proposed to be installed at the chosen CTA Southern site in 2017
We aim at the production and deployment of about half (~35) of the CTA SST sub-array to explore the energy range above the TeV threshold.
ASTRI SST-2M innovative solutions:

- **Dual-mirror optical layout**
  - first time for VHE telescopes
  - reduces the plate-scale
  - optimal PSF across the entire FoV

- **SiPMs photo-detectors**
  - small pixel-size
  - can work during moonlight
  - fast front-end and control electronics

- **Wide field-of view**, excellent for:
  - extended sources
  - surveys
The ASTRI SST-2M prototype

✧ **Telescope characteristics:**
  - Optical design = Schwarzschild-Couder
  - Primary mirrors = 4.3m (segmented)
  - Secondary mirror = 1.8m (monolithic)
  - $F/D_1 = 0.5$; $F = 2.15m$
  - M1-M2 distance = 3m
  - Effective Area = $6.5m^2$

✧ **Camera properties:**
  - Sensor type = SiPMs
  - Number of logical pixels = 1984
  - Pixel size = 0.17° (plate scale = 37.5mm/°)
  - Field of View = 9.6°

✧ **Expected performance:**
  - Energy threshold ≥ 1TeV
  - Energy/Angular resolution ≤25% / ≤0.15°
  - Sensitivity ≈ 1 Crab @ 5σ in few hours

**End-to-end prototype**

mainly a technological (HW&SW) demonstrator, but foreseen a science and performance verification phase (early 2016)

(first Crab and blazars observations @1TeV with 2-mirrors, SiPM-equipped telescope!)

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The ASTRI SST-2M mini-array

Led by the Italian National Institute for Astrophysics in collaboration with:

Università de São Paulo & FAPESP, Brazil
North-West University, South Africa

Proposed to be installed at the final southern CTA site as one of the CTA precursors (implementation in 2017)
The ASTRI mini-array can verify some CTA-SST sub-array properties:

✧ Check of the trigger algorithms
  Preliminary MC simulations show that a typical event will trigger a number $O(5-7)$ of the whole CTA-SST sub-array

✧ Check of the wide field-of-view performance
  by detecting VHE showers with the core at a distance up to 500m

✧ Check the array control and **on/off-site data management systems** *(including scientific data analysis and archive)*

✧ Compare the mini-array performance with MC expectations
  by means of deep observations of Crab

✧ **Do the first CTA precursor science** *(first CTA scientific data)*
  by means of a few solid detections during the first year
ASTRI SST-2M E2E approach

End-to-end (E2E) prototype (including array control, data management and calibration subsystems) in a real astronomical site

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The ASTRI SST-2M prototype and mini-array Data Analysis:

- can handle both prototype and mini-array data
- follows the general CTA design and data model scheme defined in CTA Data Management
- is developed for on-line/on-site/off-site scientific analysis
- manages FITS data from DL0 to DL4 (CFITSIO/CCFITS libraries)
- is written in C++/Python/CUDA
- can run on x86/ARM CPUs & NVIDIA GPUs
- is developed in independent software modules linked by pipelines written in Python
- makes use of ad hoc and official CTA Science Tools
Single codebase, 3 hardware platforms (x86, ARM CPUs, GPUs)
Software modules automatically detect GPUs in the system (CPUs/GPUs execution switchable on user request)
MC-based preliminary performance on Jetson TK1:
- DL0 $\rightarrow$ DL1(c) $\geq$ 2000 evt/s $\approx$ 2 $\times$ max DAQ rate!
- Less than 10W!
Soon tests on real ASTRI SST-2M prototype data @ Mt. Etna (early 2016)
Preliminary performance
based on MC-CTA Prod2
and official CTA-MC pipelines

Sensitivity
slightly better than H.E.S.S.
above ~10 TeV for an array
composed of 9 telescopes

Angular resolution
a few (4–5) arcmin

Energy resolution
of the order of 10-15%

Wide field of view
~10°
**Preliminary performance**

- based on MC-CTA Prod2
- and official CTA-MC pipelines

**Sensitivity**

- slightly better than H.E.S.S.
- above ~10 TeV for an array composed of 9 telescopes

**Angular resolution**

- a few (4–5) arcmin

**Energy resolution**

- of the order of 10-15%

**Wide field of view**

- ~10°

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**PRELIMINARY ESTIMATES ACHIEVED WITH ASTRI PIPELINE IN REASONABLE AGREEMENT WITH PERFORMANCE ACHIEVED WITH CTA-MC PIPELINE**
ASTRI SST-2M mini-array targets

Supernova Remnants
- SNRs
- Pevatrons
- SNRs interacting with molecular clouds

PWNe

Gamma-ray Binaries

Extreme BL Lacs
- Synchrotron peak > 1 keV
- Inverse Compton peak > 1 TeV

Less beamed AGNs
- Radio galaxies

Starburst Galaxies

Dark Matter and exotic physics

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The aim is to **test both the SST-2M technological and scientific performance** at energies above a few TeV by means of **prolonged pointings**

- **Galactic science** ➔ choose sky regions containing multiple targets and fully exploit the wide field of view

- **Extra-galactic science** ➔ select a few promising targets

- **Fundamental physics** ➔ GC and new optimal dwarf targets

- **Synergies with MSTs and LSTs** precursors are of paramount importance
SNR RCW 86

Fairly young SNR (2000 yrs)

Seen in Radio, X, GeV (*Fermi*), TeV (H.E.S.S.)

Debated origin:
interacting source with molecular clouds or RX J1713-like source?

ASTRI mini-array (*blue points, simulated data*) can discriminate between hadronic and leptonic scenario and (if hadronic) look for VHE (~5x10^{14} eV) CRs

Giuliani et al., in prep.

Red points from Yuan et al., 2014
SNR W 28

Evolved SNR interacting with a giant MC, very bright @ TeV

H.E.S.S. resolved this source in almost 4 point-like sources near the MC

ASTRI mini-array can better resolve the source and study the diffusion of CR far from the SNR shell (blue circle)

ASTRI mini-array simulation

Giuliani et al., in prep.

H.E.S.S.

Aharonian et al., 2008

S. Lombardi, 28th Texas Symposium, 13-18 December 2015, Geneva, Switzerland
Gamma-ray unidentified: HESS J1641-463

Abramowski et al., 2014

Very hard source $\Gamma \sim 2.1$

ASTRI mini-array 200 hrs simulation

Romano, Vercellone, Giuliani et al., in prep.

S. Lombardi, 28th Texas Symposium, 13-18 December 2015, Geneva, Switzerland
Gamma-ray unidentified: HESS J1641-463

We can investigate:

✧ presence of a spectral cut-off (and its energy)

✧ nature of this source

Abramowski et al., 2014

ASTRI mini-array

200 hr

Romano, Vercellone, Giuliani et al., in prep.

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Mrk501: flares and spectral properties

Differential sensitivity for a mini-array composed of 9 ASTRI SST-2M telescopes in 10 h

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Mrk501: flares and spectral properties

Bonnoli, Tavecchio, Giuliani et al., in prep.

ASTRI mini-array, 2 hr

ASTRI mini-array, 20 hr

Observations up to 20 TeV, grazing the EBL “wall”

Need MWL triggers, fast reaction and (from CTA-S) observations at large ZA

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Extreme BL LACs: probe of extreme physics

**1ES 0229+200** E-HBL SED can be fit by both the $\gamma$-ray-induced cascade and proton-induced cascade emissions. Because of the uncertainty in EBL models, it is not easy to distinguish between the two possibilities at ~1-10 TeV energies.

- At higher energies, however, UHECR-induced cascade emission becomes harder than $\gamma$-ray-induced cascade emission.
- A detection of >25 TeV $\gamma$-rays from 1ES 0229+200 is consistent with an hadronic $\gamma$-ray emission (an alternative explanation in the next slide).
- Probe of gamma-ray absorption by the far-infrared EBL.
LIV and E-HBL

LIV effects studied for different values of the Lorentz-violating scales ($M_{LIV}$)

Fairbairn et al., 2014

MRK501

CTA

Fairbairn et al., 2014

MRK501

Bonnoli et al., proc. TAUP 2015, in press

1ES 0229+200

$M_{LIV} = 10^{19}$ GeV

$M_{LIV} = 3 \times 10^{19}$ GeV

$M_{LIV} = 10^{20}$ GeV

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Dark Matter searches

- Likely scenario for cold DM: weakly-interacting massive particles (WIMPs)
- WIMPs mass range: $O(10 \text{ GeV}) - O(100 \text{ TeV})$
- WIMPs annihilation $\rightarrow$ indirect detection (in $\gamma$-rays)

**TARGETS:**

- **Galactic center?**
  - Highest $J$-factor
  - Very high astroph. bkg
  - Uncertainties on inner DM distribution
  - Southern Hemisphere

- **Galactic halo?**
  - High $J$-factor
  - Not fully-free from astroph. bkg
  - Extended
  - Southern Hemisphere

- **Galaxy Clusters?**
  - Huge amount of DM
  - High astroph. bkg
  - Extended
  - High uncertainties on $J$-factors

- **DM Clumps?**
  - Free from astroph. bkg
  - Nearby and numerous
  - To be found!
  - Bright enough?

- **Dwarf Galaxies?**
  - DM dominated (high M/L ratios)
  - Free from astroph. bkg
  - Close ($<\sim 100 \text{ kpc}$)
  - Slightly extended at most
  - Less uncertainties on $J$-factors
  - $J$-factors $\sim 100$ lower than for GC
Dark Matter searches

- Preliminary prospects for indirect Dark Matter searches (>~5 TeVs) with ASTRI mini-array
- First comparative studies with known target (Segue1 dwarf, 160 hr exposure)
- ASTRI mini-array + 4MSTs \(\rightarrow\) very interesting scenarios
- Refined simulations/analysis + new targets (southern dwarfs and GC) in progress

Giammaria, Lombardi et al., in prep.

Preliminary searches

- ASTRI mini-array
- MAGIC

\[\tau^+ \tau^-\]

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The wide field of view and our galaxy

ASTRI mini-array 200 hr simulation for \( E > 10 \text{ TeV} \)

- This region can be monitored in the period [Feb. - Sept., \( \text{ZA} < 35° \)] for more than 400 hr
- Several sources can be investigated during a single pointing

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The ASTRI SST-2M prototype, inaugurated on September 24th 2014, will perform the first scientific observations with a Schwarzschild-Couder telescope equipped with SiPMs at the beginning of 2016.

The ASTRI scientific analysis software (on CPUs & ARM/GPUs) has been developed for both prototype and mini-array data analysis and will be soon tested/commissioned by means of real data from ASTRI SST-2M prototype and newest CTA-MCs (Prod3).
✧ The ASTRI mini-array is proposed to be a precursor for the whole CTA-S array, allowing us to investigate innovative technological solutions

✧ CTA precursor early science performed by means of ASTRI mini-array observations of a few selected targets (both Galactic and extra-Galactic) will allow us to obtain several solid detections during the first year and to pursue some fundamental physics searches

✧ Excellent synergies with the other CTA precursors (MSTs, LSTs) and with several observing facilities foreseen from 2017 and beyond
Thanks!

http://www.brera.inaf.it/astri/

Credit: R. Canestrari
Backup
The ASTRI Project in a nutshell

✧ **End-to-end SST-2M prototype:**
  - Validation and commissioning of the telescope via Cherenkov astronomical observation

✧ **End-to-end implementation of a mini-array (# ≥ 9) of SST-2M (pre-production) at the CTA southern site:**
  - Validation and commissioning of the array (including trigger and SW) via Cherenkov astronomical observations, first CTA scientific data

✧ **Aiming at the construction of 35 out of the 70 SST telescopes of the CTA southern array**
**ASTRI data levels**

ASTRI SST-2M prototype and ASTRI mini-array data levels are defined in compliance with the CTA data model.

<table>
<thead>
<tr>
<th>Data Level</th>
<th>Short Name</th>
<th>Description</th>
<th>Data reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 0 (DL0)</td>
<td>DAQ-RAW</td>
<td>Data from the Data Acquisition hardware/software.</td>
<td></td>
</tr>
<tr>
<td>Level 1 (DL1)</td>
<td>CALIBRATED</td>
<td>Physical quantities measured in each separate camera: photons, arrival times, etc., and per-telescope parameters derived from those quantities.</td>
<td>1-0.2</td>
</tr>
<tr>
<td>Level 2 (DL2)</td>
<td>RECONSTRUCTED</td>
<td>Reconstructed shower parameters (per event, no longer per-telescope) such as energy, direction, particle ID, and related signal discrimination parameters.</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Level 3 (DL3)</td>
<td>REDUCED</td>
<td>Sets of selected (e.g. gamma-ray-candidate) events, along with associated instrumental response characterizations and any technical data needed for science analysis.</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Level 4 (DL4)</td>
<td>SCIENCE</td>
<td>High Level binned data products like spectra, sky maps, or light curves.</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Level 5 (DL5)</td>
<td>OBSERVATORY</td>
<td>Legacy observatory data, such as CTA survey sky maps or the CTA source catalog.</td>
<td>$10^{-5}$ to $10^{-3}$</td>
</tr>
</tbody>
</table>
\begin{itemize}
\item Extraction of CAL1 from CAL0
\item Application of CAL1 to EVT0/MC0
\item NSB level extraction
\item Production of EVT1(a)/MC1(a) (TEL.-WISE CALIBRATED DATA)
\end{itemize}
Image Cleaning and Parameterization
- Telescope Pointing Reconstruction
- Production of EVT1(b)/MC1(b)
- Tel.-wise $\gamma$/h Separation
- Tel.-wise Energy Reconstruction
- Tel.-wise Arrival Direction Estimation
- Production of LUT1/EVT1(c)/MC1(c) (TEL.-WISE RECONSTRUCTED DATA)
ASTRI scientific data analysis

- Tel.-wise Data Merging
- Stereo Reconstruction
- Production of EVT2(a)/MC2(a)
- Array-wise $\gamma$/h Separation
- Array-wise Energy Reconstruction
- Array-wise Arrival Direction Estimation
- Production of LUT2/EVT2(b)/MC2(b)

(Array-wise reconstructed data)

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**Camera Calibration**
- EVT0 / MCO / CAL0 / SCI-TECH0 / CALDB
  - Tel. Camera Calibration & Quality Checks
  - astricalex / astrical

**Event Reconstruction**
- EVT1a / MC1a / CAL1 / SCI-TECH1a
  - Tel. Image Cleaning & Parameters & Pointing
  - astricleanpar

- EVT1b / MC1b / SCI-TECH1b
  - Tel. LUTs & Shower Reconstruction
  - astriluts / astrireco

- EVT1c / MC1c / LUT1 / SCI-TECH1c
  - Array Data Merging & Parameters
  - astrimer

- EVT2a / MC2a / SCI-TECH2a
  - Array LUTs & Shower Reconstruction
  - astriluts / astrireco

- EVT2b / MC2b / LUT2 / SCI-TECH2b
  - astriluts / astrireco

**Analysis**
- EVT3 / IRF3 / SCI-TECH3
  - Array Event-Lists & IRFs / GTI Generation
  - astriirf / astriana

**Science**
- Detection / Spectra / Skymaps / Light-Curves
  - ASTRl Science Tools / CT00LS

**Science Products**
- DL3

**Note:**
- Instrument Response Functions (Effective Area, Energy/Angular Resolution, Background Rate, Sensitivity)
- EVENT-LIST & GTI
- Production of IRF3/EVT3 (ARRAY-WISE REDUCED DATA)
Lombardi, Antonelli, Bastieri et al., in prep.

**ASTRI scientific data analysis**

<table>
<thead>
<tr>
<th>Calibration</th>
<th>RECONSTRUCTION</th>
<th>ANALYSIS</th>
<th>SCIENCE PRODUCTS</th>
</tr>
</thead>
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<tr>
<td>EVT0 / MCO / CAL0 / SCI-TECHO / CALDB</td>
<td>EVT1a / MC1a / CAL1 / SCI-TECH1a</td>
<td>EVT1c / MC1c / LUT1 / SCI-TECH1c</td>
<td>EVT3 / IRF3 / SCI-TECH3</td>
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<td>Tel. Camera Calibration &amp; Quality Checks</td>
<td>Tel. Image Cleaning &amp; Parameters &amp; Pointing</td>
<td>Array Data Merging &amp; Parameters</td>
<td>Detection / Spectra / Skymaps / Light-curves</td>
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<tr>
<td>SCIENTIFIC PRODUCTS (DL4)</td>
<td>Sky-maps, Spectra, Light-curves</td>
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</table>
Simulated data achieved by the ASTRI scientific simulator based on Instrument Response Functions (IRFs) for 9 SSTs from CTA prod2 for a Southern site. Reasonably conservative IRFs, since optimizations for ASTRI and for the analysis are not yet fully implemented.
LIV and E-HBL

LIV induces an effective mass for the photon

\[ \beta_\gamma = 1 - \left( \frac{E_\gamma}{M_{LVn}} \right)^n \quad ; \quad m_\gamma^2 = -\frac{E_\gamma^{2+n}}{M_{LVn}} \]

Modification of threshold for pair production at high E

LIV induces suppression of EBL-opacity

Figure 2. The arrival probability of a photon emitted from a hypothetical source at redshift z = 0.05 as a function of energy. The different curves represent different values of the Lorentz-violating scale $M_{LV1}$. VHE photons with energies $\geq 100$ TeV can travel through the CMB effectively unimpeded.

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The wide field of view and our galaxy

Eta Carinae region 270 hr

Crux Arm 200 hr

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The wide field of view

The ASTRI mini-array will have a larger field of view wrt the current IACT ones

Although the actual sensitivity will substantially drop for off-axis sources, a few targets can be monitored simultaneously

Close (angular distance < 3°) and bright (about $10^{-12}$ erg cm$^{-2}$ s$^{-1}$ above a few TeV) sources can be observed pointing in a “smart” direction:

- HESS J1825-137------- LS 5039
- Vela-X----------------- Vela Junior
- RX J1713.7-3946-------- HESS J1718-385.

Detections of serendipitous strong flares (a few Crab units) from hard spectrum sources will be possible as well
Adding a few of MST telescopes to the ASTRI mini-array could be useful in order to:

✧ **test trigger performance among different kinds of telescopes**
✧ decrease the energy threshold (crucial for e.g. Dark Matter searches)
✧ obtain a better energy coverage below 1 TeV
MWL facilities

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