Astrofisica con Specchi a Tecnologia Replicante Italiana

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Universidade de São Paulo Instituto de Astronomia, Geofisica e Ciencias Atmosferica

NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT

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

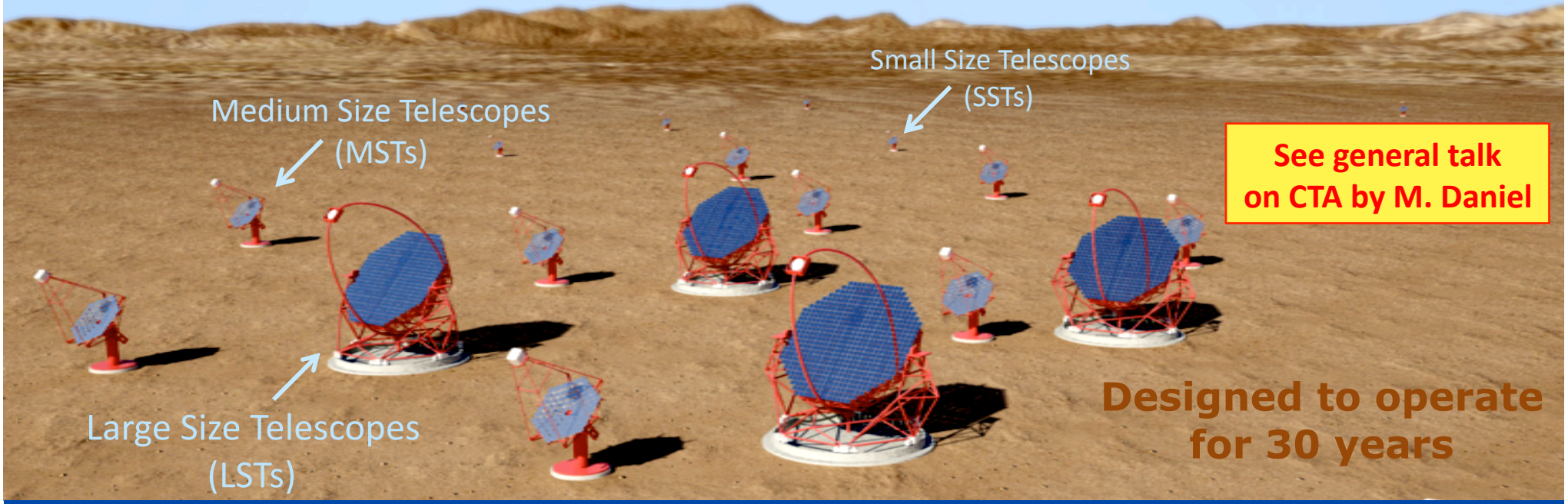
S. Lombardi for the ASTRI Collaboration & the CTA Consortium

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



See general talk on CTA by M. Daniel

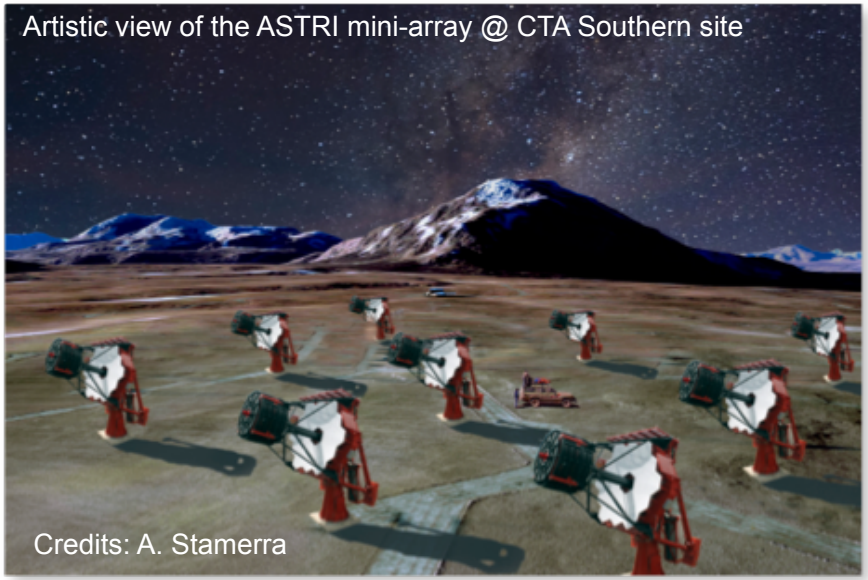
Designed to operate for 30 years

The ASTRI Project

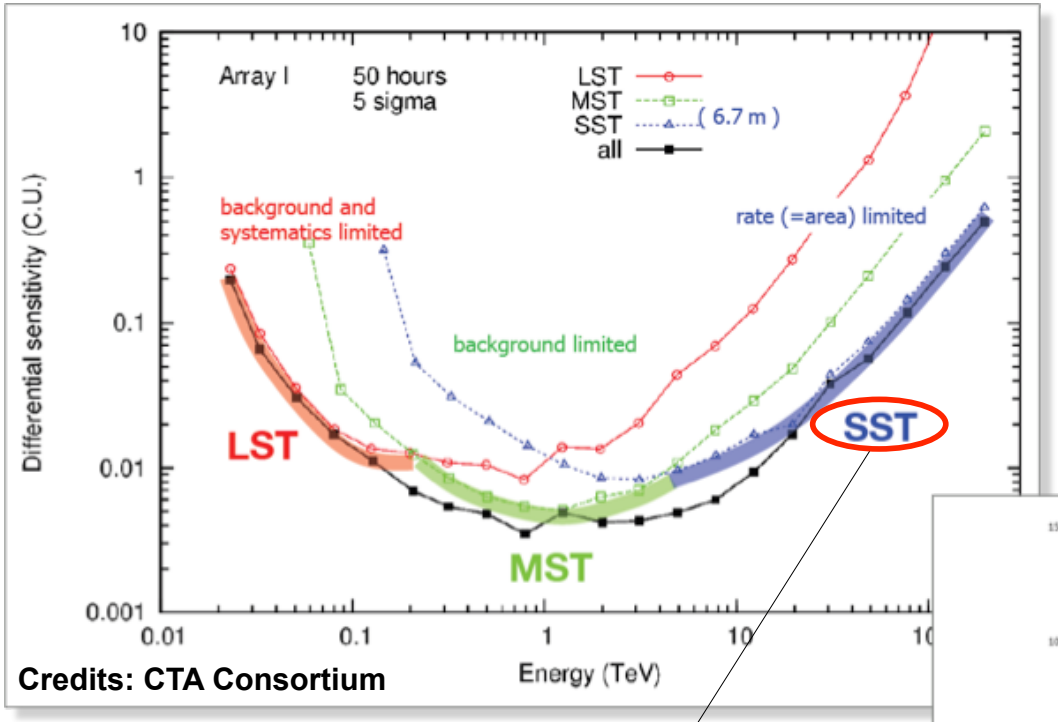
The **ASTRI Project** (led by INAF) has two main goals:

- 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


Inauguration @ Serra La Nave observing station (Mt. Etna, Sicily)
Credits: T. Abegg

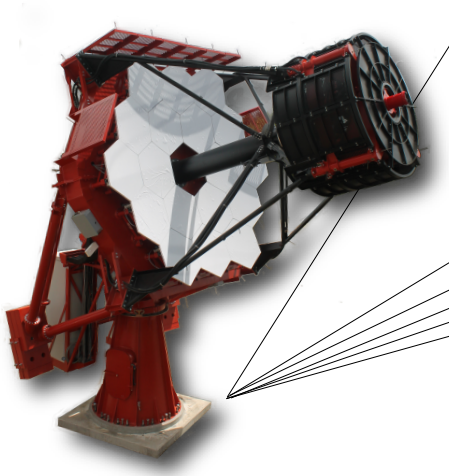

Artistic view of the ASTRI mini-array @ CTA Southern site
Credits: A. Stamerra

ASTRI in the framework of CTA

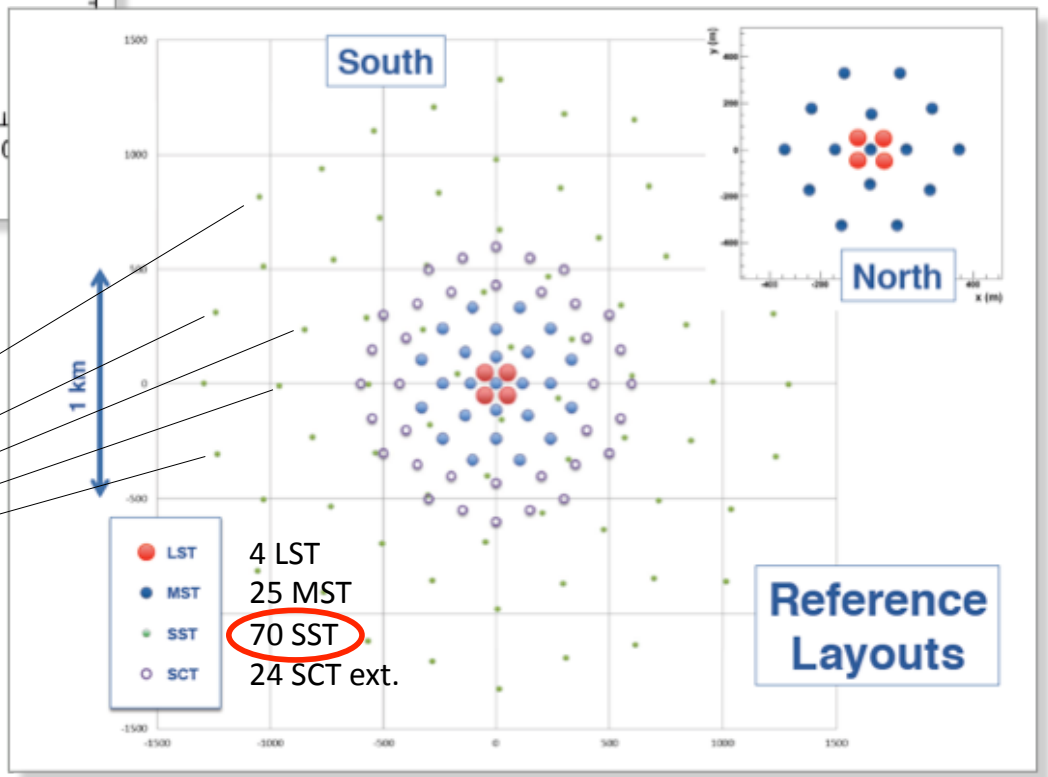


Credits: CTA Consortium

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

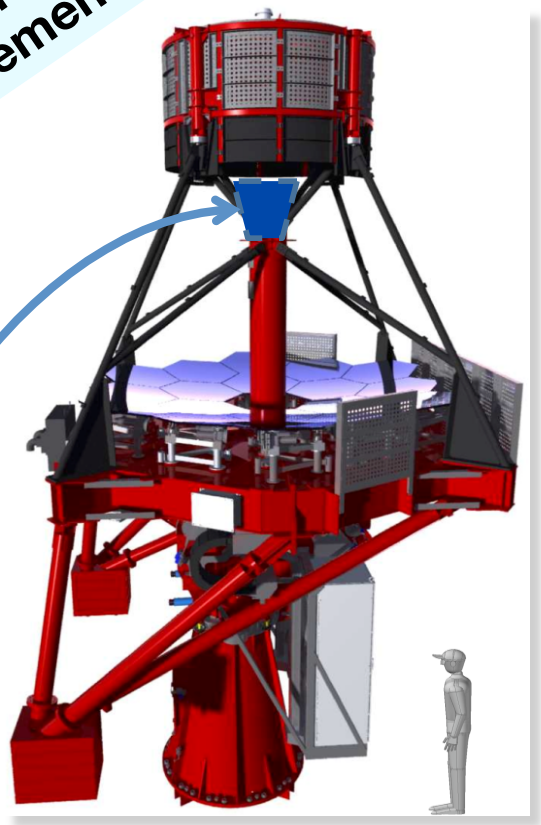


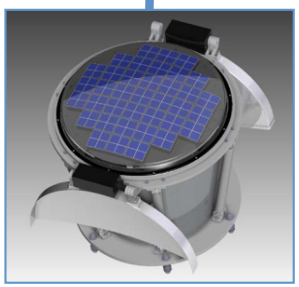
ASTRI SST-2M



ASTRI SST-2M telescope features

Design fully compliant with CTA requirements





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

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!)

✧ **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**

The ASTRI SST-2M mini-array

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

Universidade 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)

Credits: A. Stamerra

ASTRI SST-2M mini-array aims

The ASTRI mini-array can verify some CTA-SST sub-array properties:

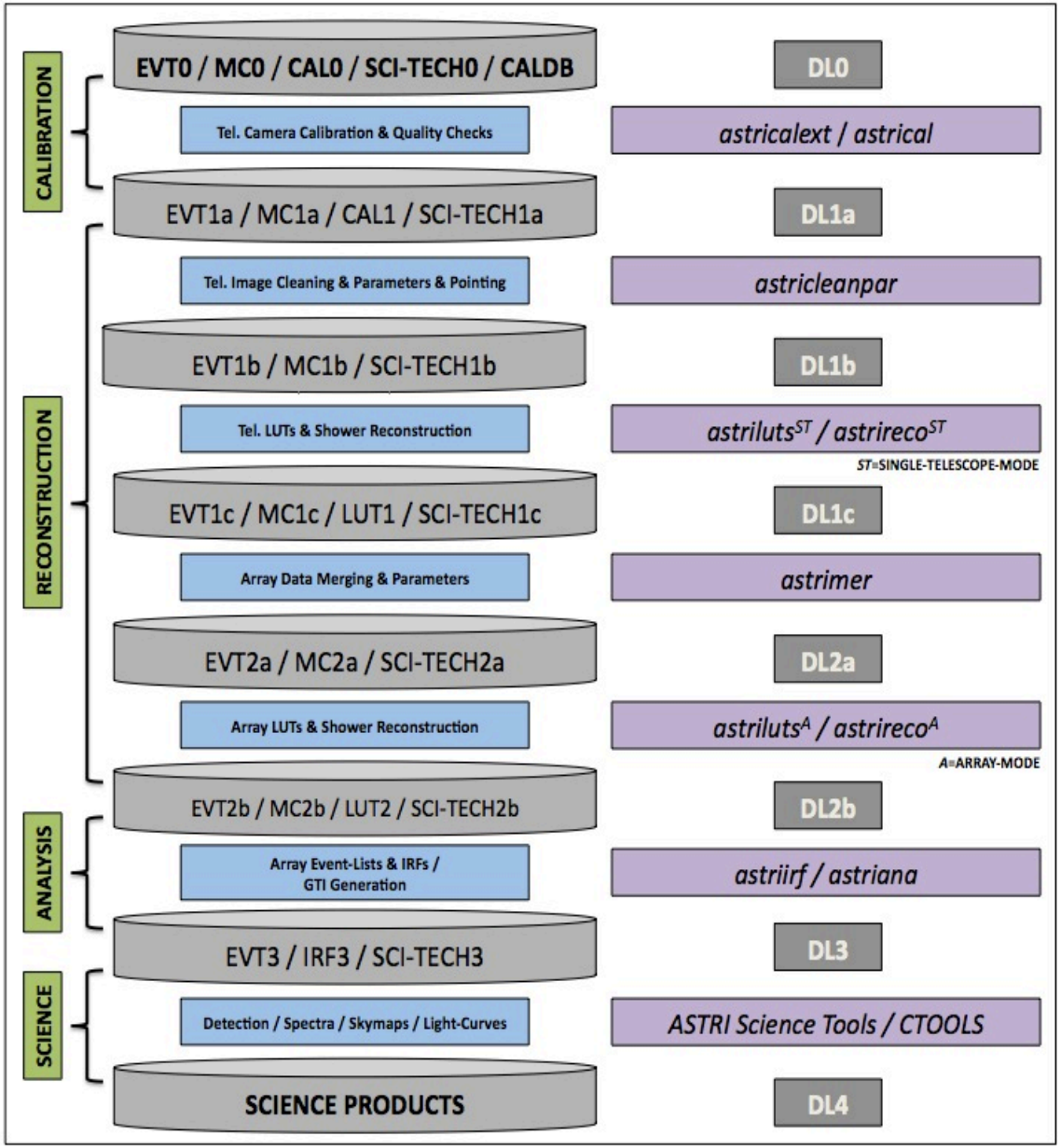
- ✧ Check of the trigger algorithms
  Preliminary MC simulations show that a typical event will trigger a number O(5-7) of the whole CTA-SST sub-array
- ✧ Check of the wide field-of-view performance
  by detecting VHE showers with the core at a distance up to 500m
- ✧ Check the array control and **on/off-site 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**

ASTRI scientific data analysis

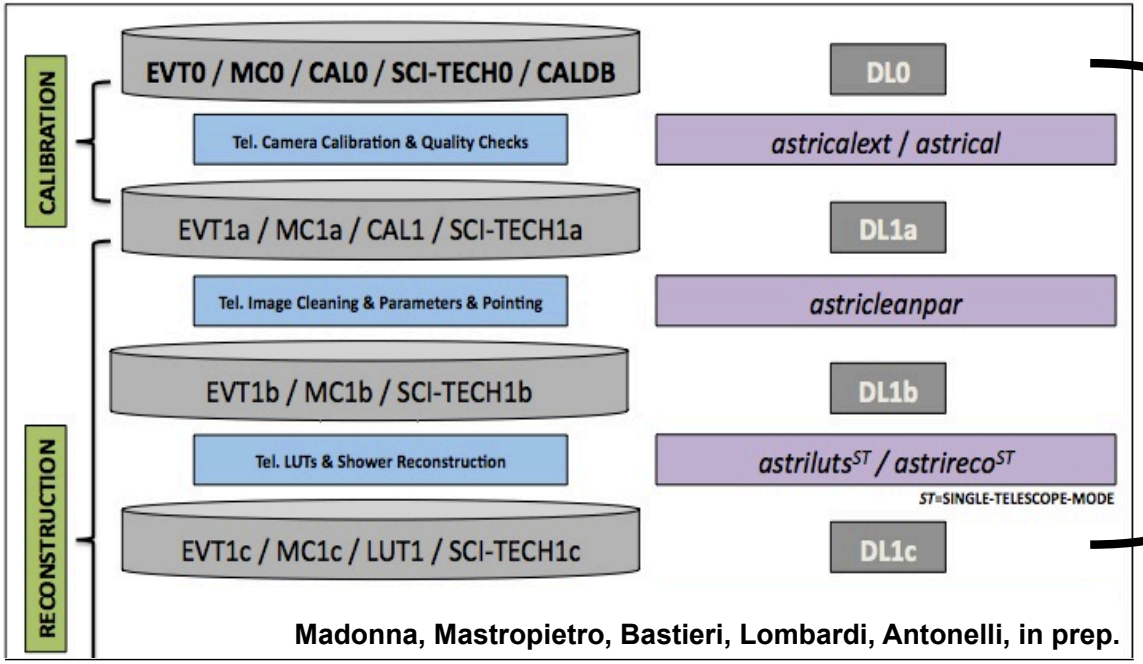
Lombardi, Antonelli, Bastieri, Madonna, Mastropietro et al., in prep.



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

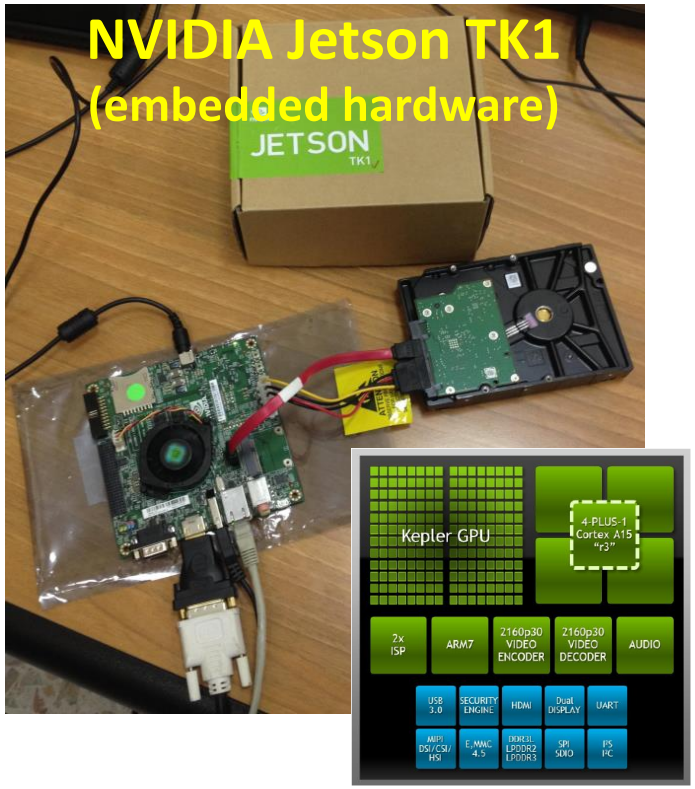
- can handle *both prototype and mini-array data*
- *follows the general CTA design* and data model scheme defined in CTA Data Management
- is developed for *on-line/on-site/ off-site* scientific analysis
- manages *FITS data* from DL0 to DL4 (CFITSIO/CCFITS libraries)
- is written in *C++/Python/CUDA*
- 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*

ASTRI scientific data analysis on ARM/GPUs



KEY ADVANTAGE FOR *ON-LINE/ON-SITE* ANALYSIS IN REMOTE OBS. SITES

SINGLE TELESCOPE RECONSTRUCTION ANALYIS PORTED ON ARM/GPUs (*NVIDIA Jetson TK1, C++/CUDA*)



- ✧ 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 ➔ DL1(c) @ >2000 evt/s ≈ 2 × max DAQ rate!**
  - **Less than 10W!**
- ✧ Soon tests on real ASTRI SST-2M prototype data @ Mt. Etna (early 2016)

ASTRI SST-2M mini-array performance

- **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

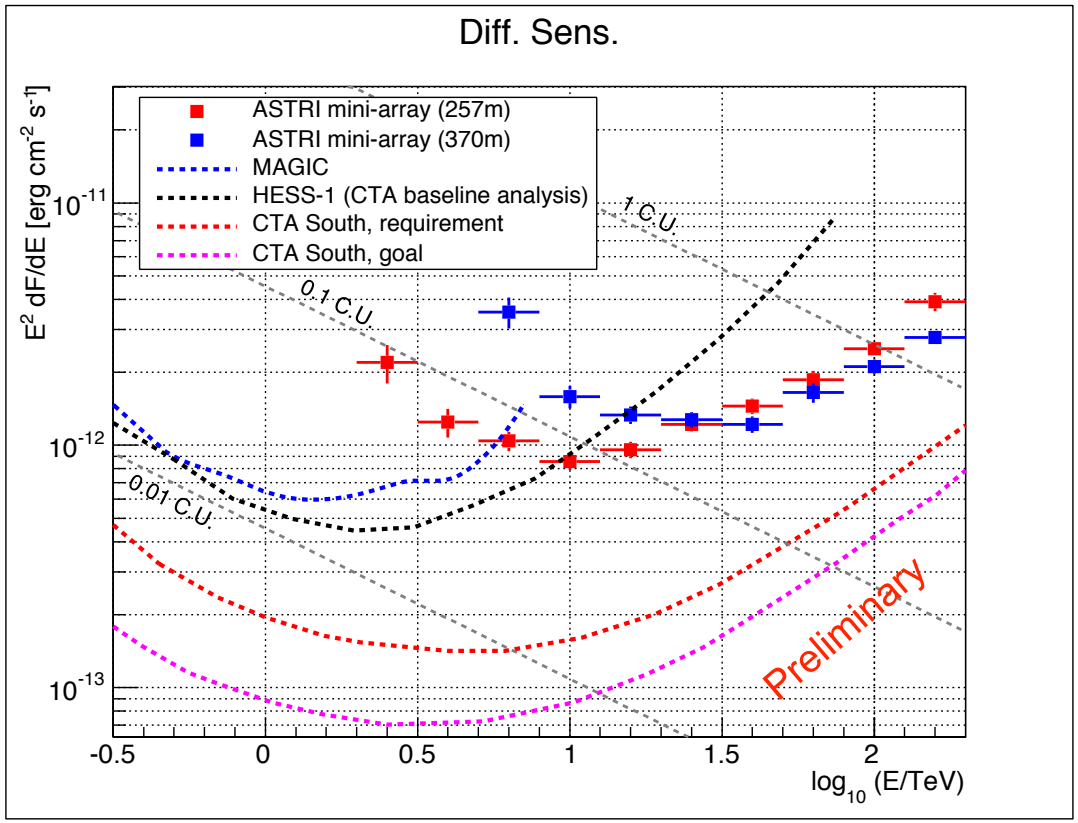
- **Energy resolution**

  of the order of 10-15%

- **Wide field of view**

  ~10°

Di Pierro et al., proc. TAUP 2015, in press



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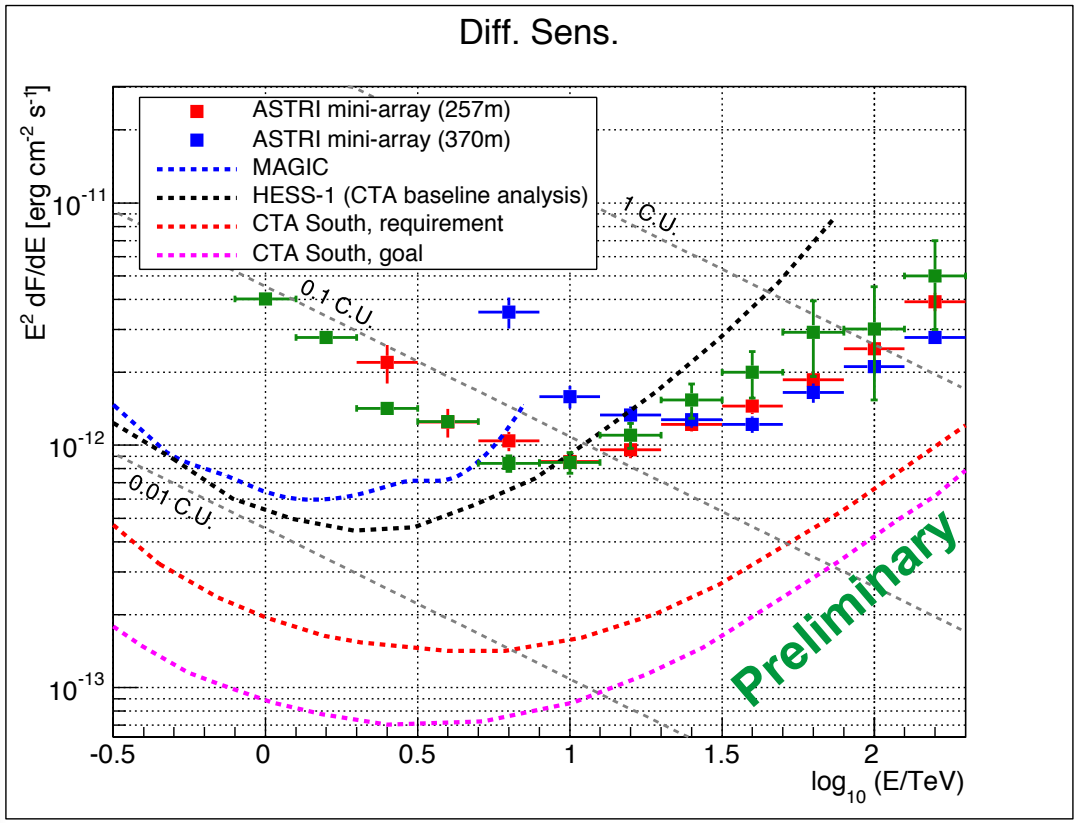
Lombardi et al., in prep.

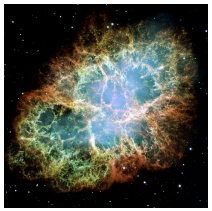


■ **ASTRI mini-array (~250m) – ASTRI DATA PIPELINE**

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

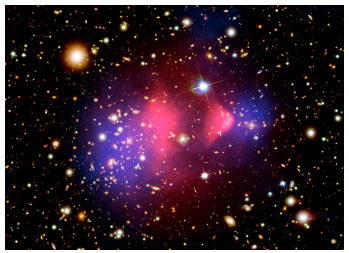
Synchrotron peak > 1 keV

Inverse Compton peak > 1 TeV

Less beamed AGNs

Radio galaxies

Starburst Galaxies



Dark Matter and exotic physics

ASTRI SST-2M mini-array scientific rationale

- 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 expolit 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

SNRs and PWNs

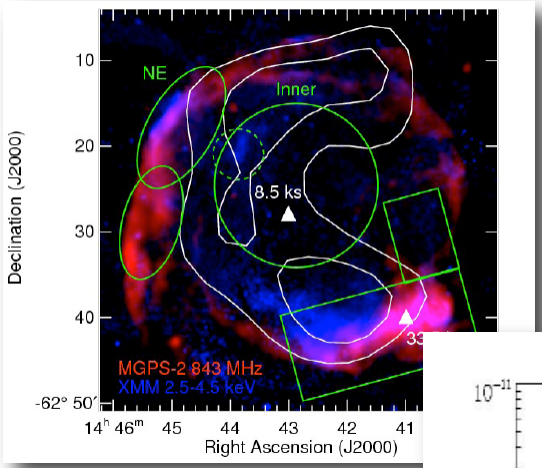
SNR RCW 86

Fairly young SNR (2000 yrs)

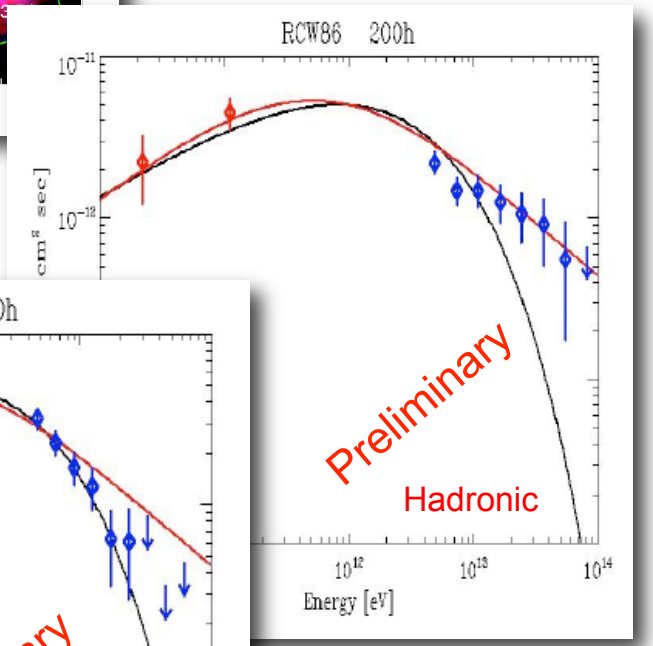
Seen in Radio, X, GeV (*Fermi*), TeV (H.E.S.S.)

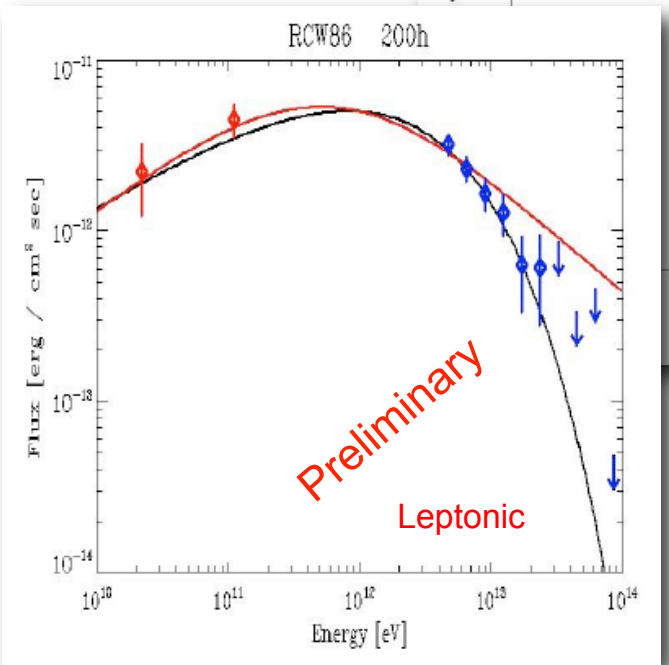
Debated origin:
- interacting source with molecular clouds or RX J1713-like source ?

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

SNRs and PWNs

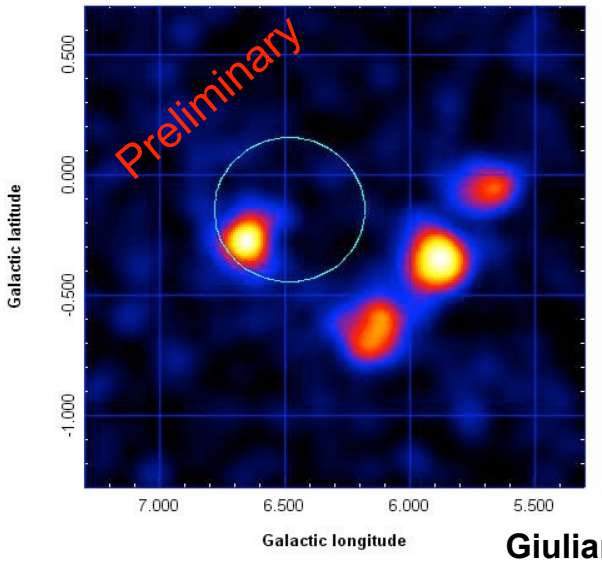
SNR W 28

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

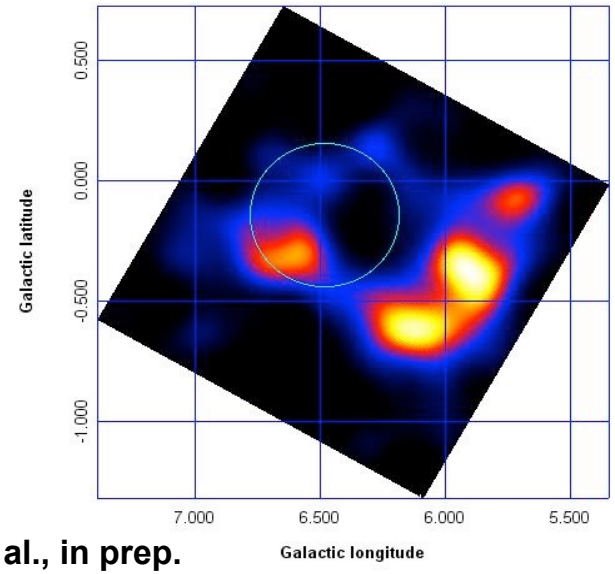
H.E.S.S. resolved this source in almost 4 point-like sources near the MC

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



H.E.S.S.

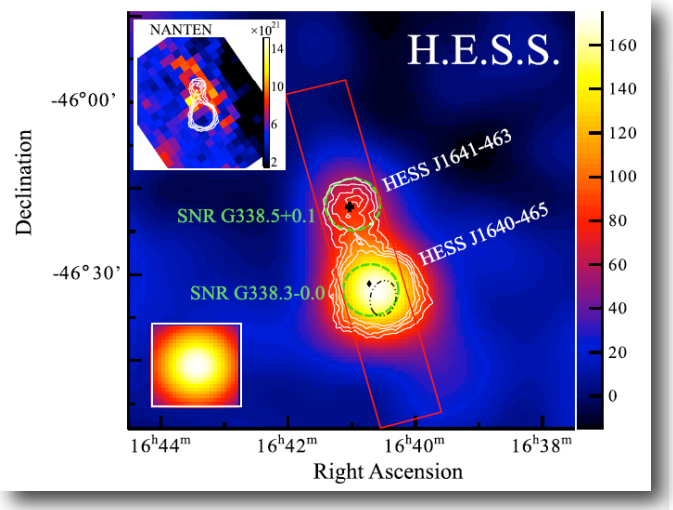


Aharonian et al., 2008

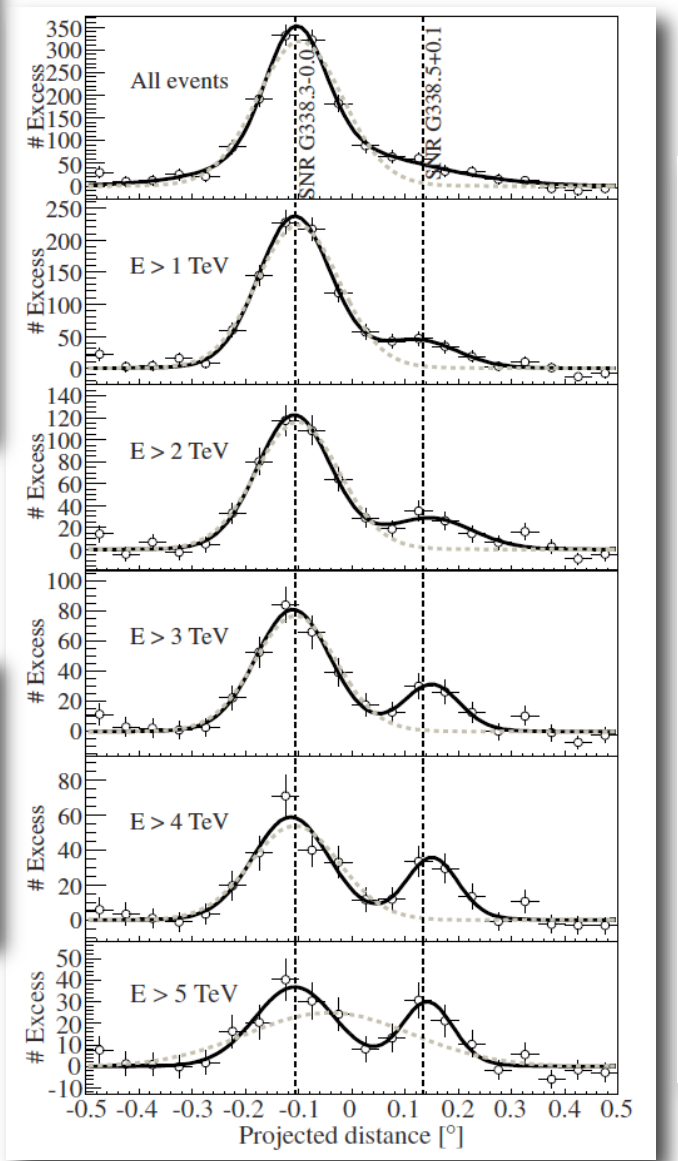
Giuliani et al., in prep.

Gamma-ray unidentified: HESS J1641-463

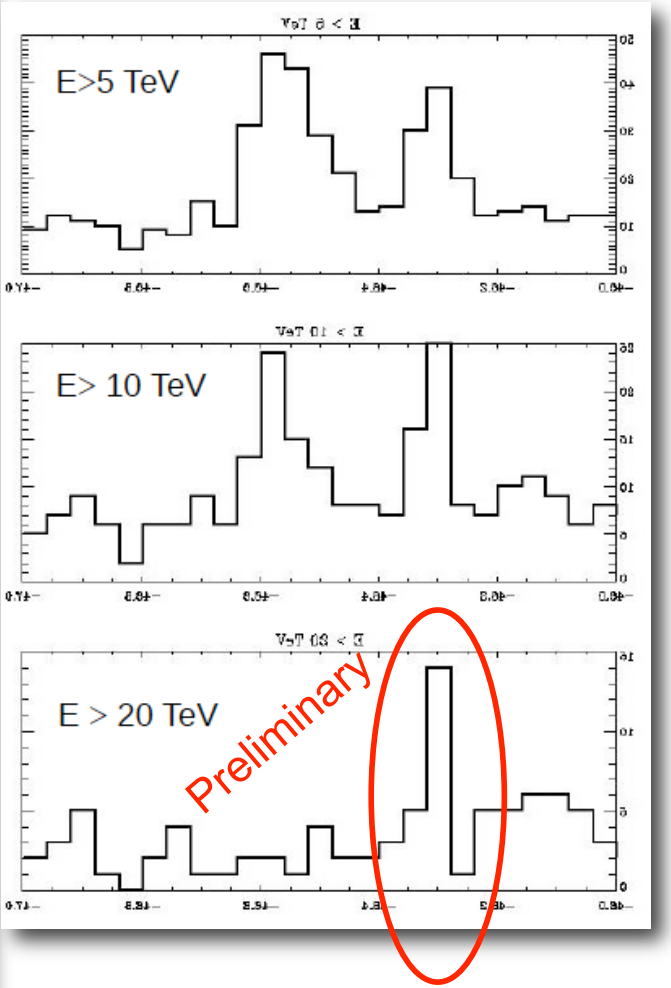
Abramowski et al., 2014



Abramowski et al., 2014



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

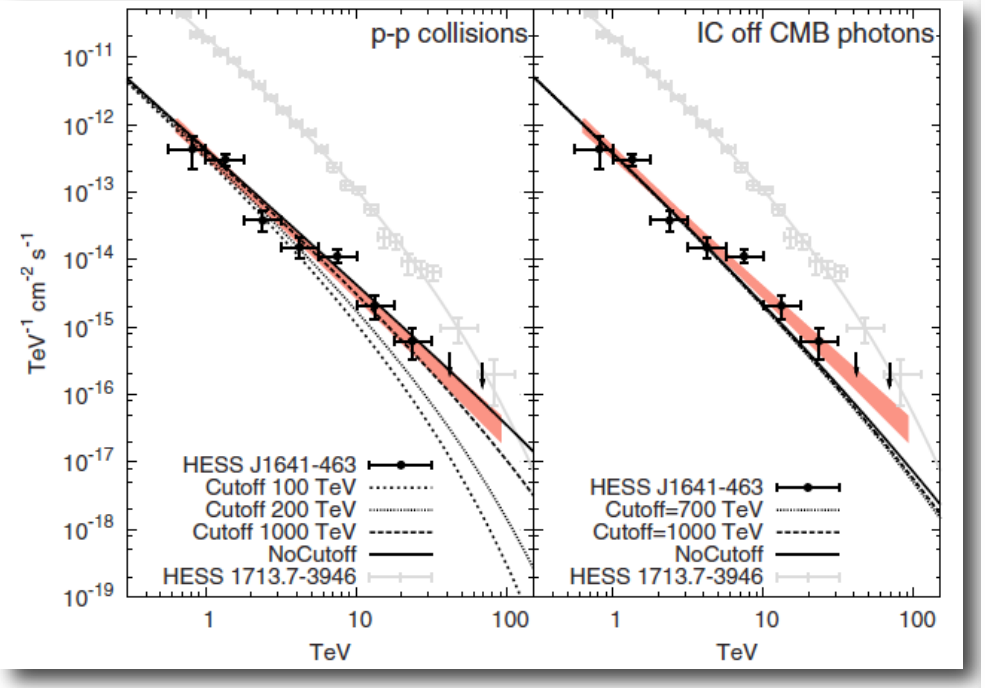


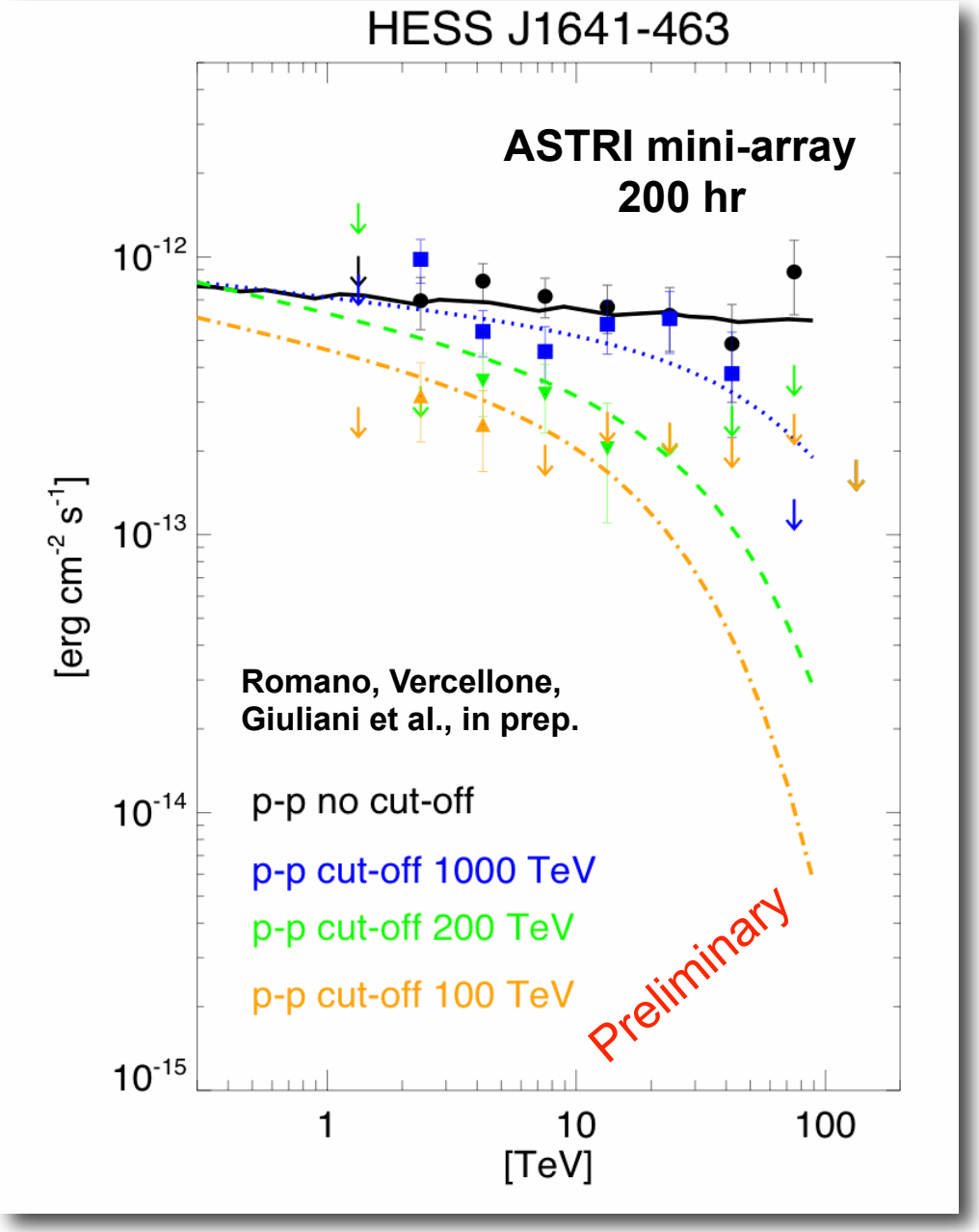
Very hard source $\Gamma \sim 2.1$

ASTRI mini-array 200 hrs simulation

Gamma-ray unidentified: HESS J1641-463

Abramowski et al., 2014

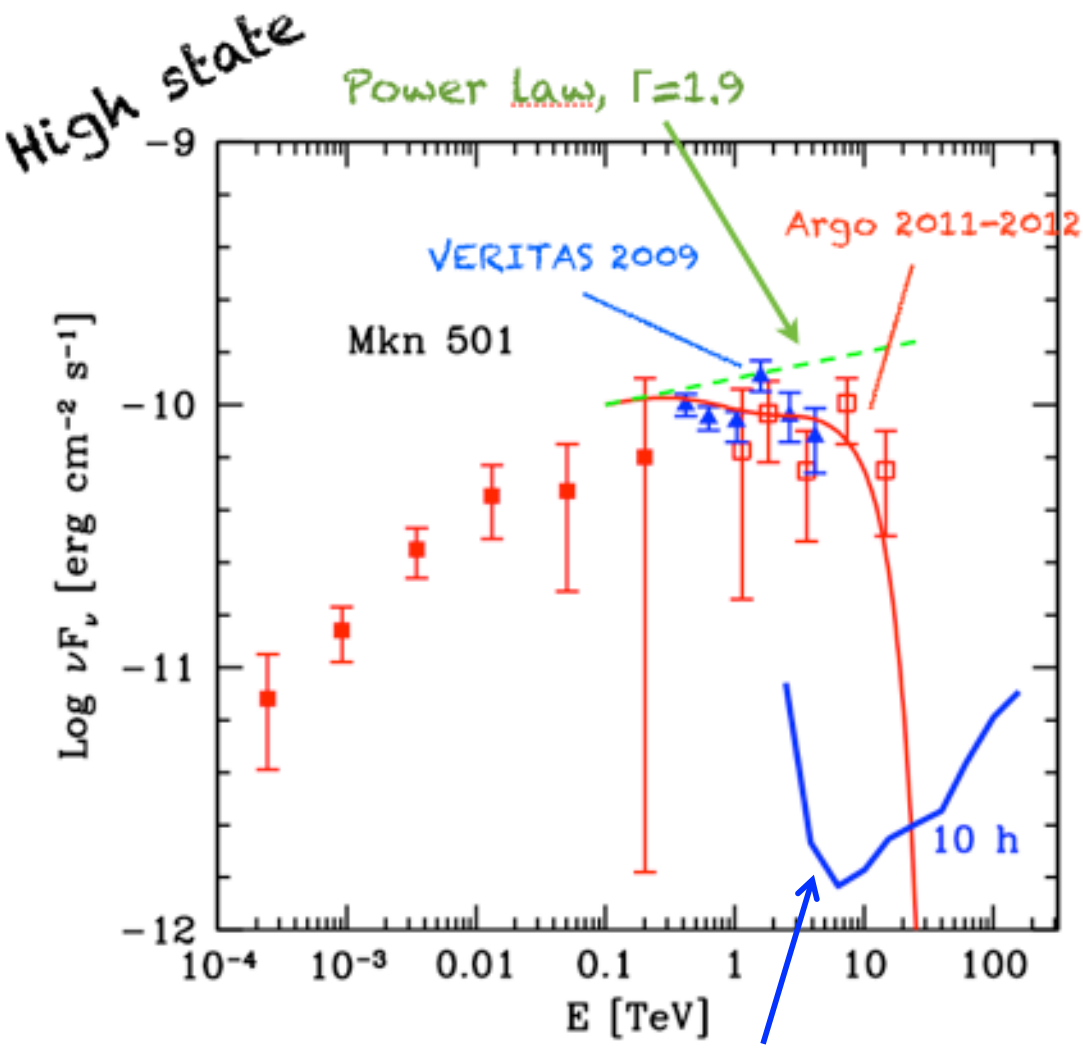




We can investigate:

- ✧ **presence of a spectral cut-off (and its energy)**
- ✧ **nature of this source**

Mrk501: flares and spectral properties



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

Mkn 501

Low quiescent flux

Relatively small duty cycle

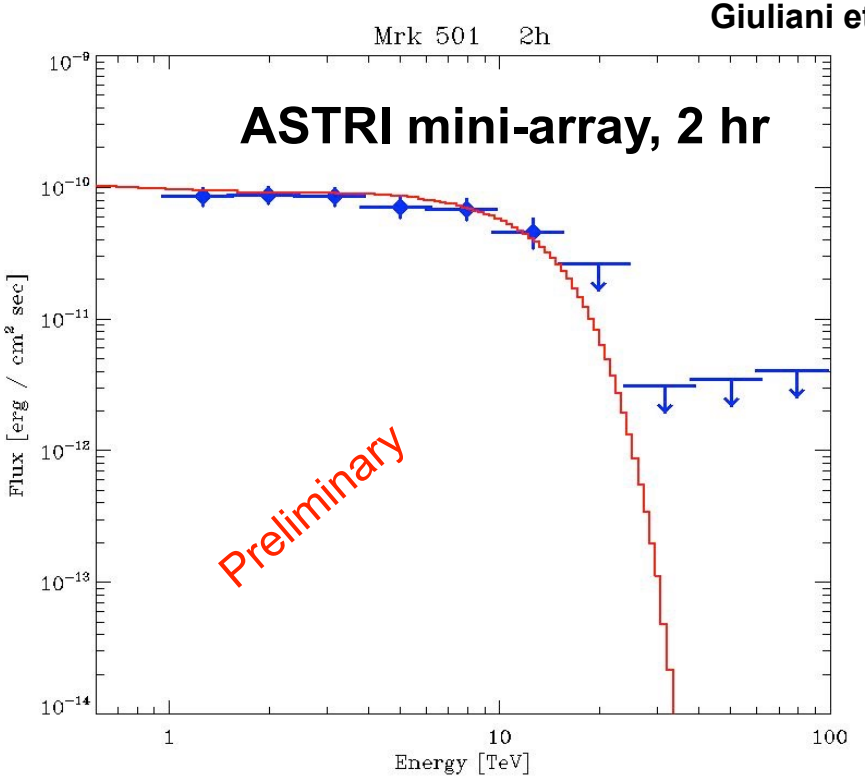
Large fluxes (~10 CU)

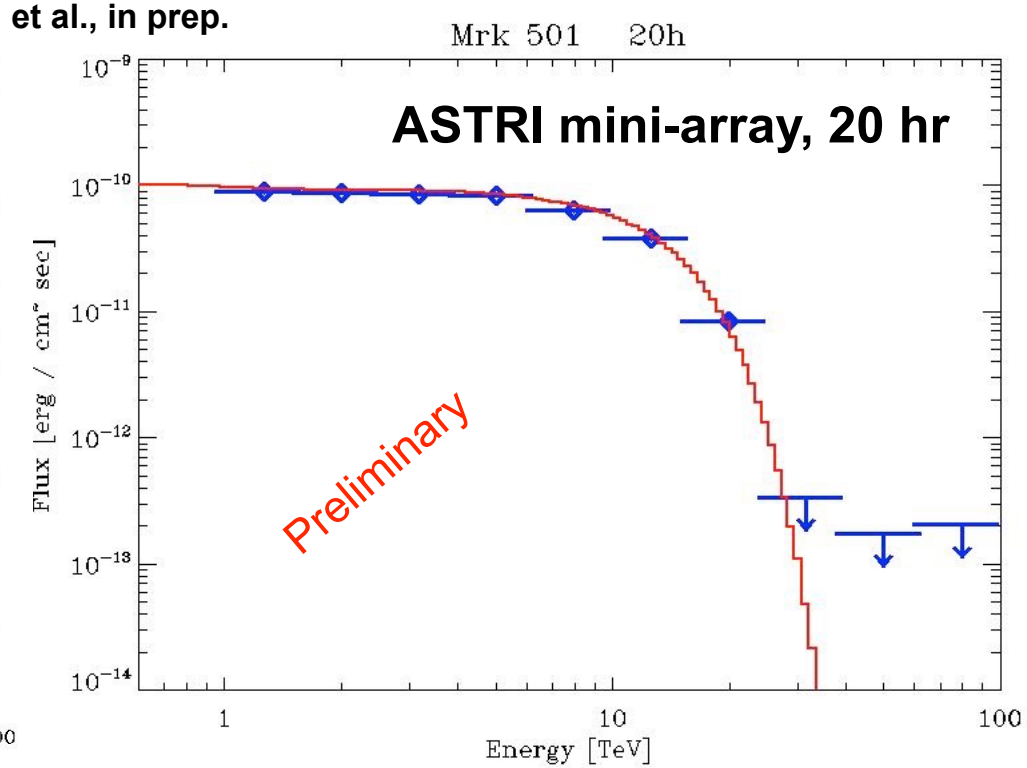
Prolonged (weeks) flares

Hard spectra

Mrk501: flares and spectral properties

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

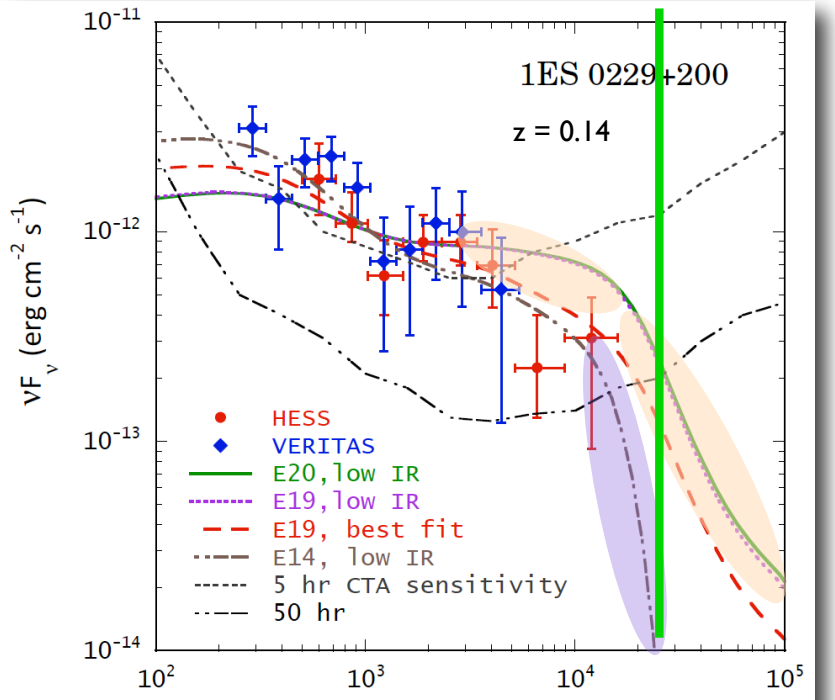




Observations up to 20 TeV, grazing the EBL "wall"

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

Extreme BL LACs: probe of extreme physics



Murase et al., 2012

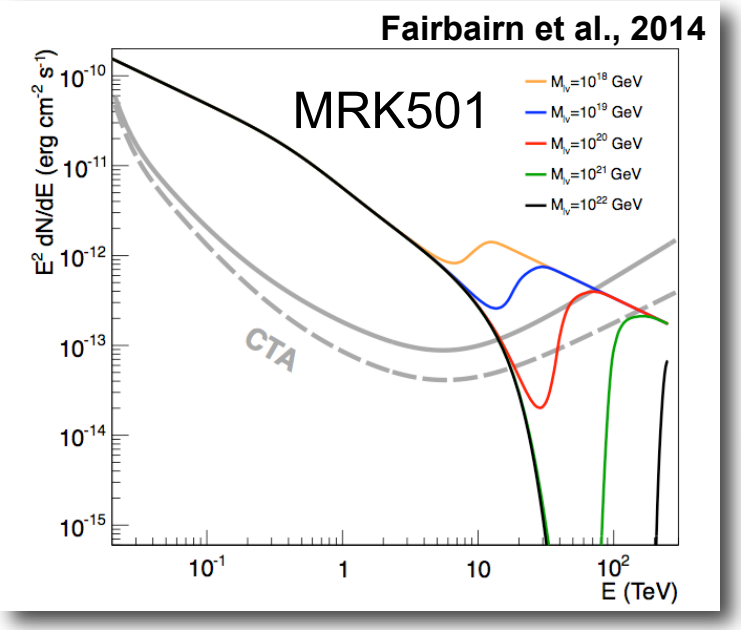
1ES 0229+200 E-HBL SED can be fit by both the **γ-ray-induced cascade** and **proton-induced cascade** emissions

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 γ-ray-induced cascade emission
- ✧A detection of >25 TeV γ-rays from 1ES 0229+200 is consistent with an hadronic γ-ray emission (an alternative explanation in the next slide)
- ✧Probe of gamma-ray absorption by the far-infrared EBL

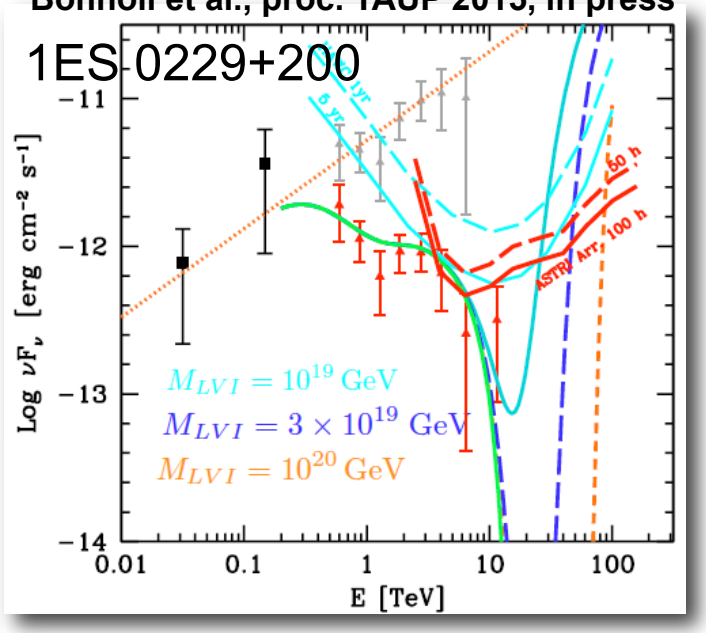
LIV and E-HBL

Fairbairn et al., 2014



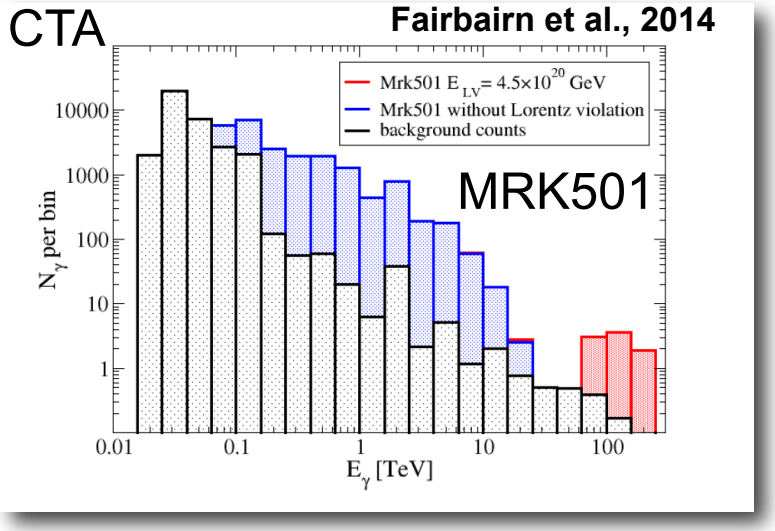
LIV effects studied for different values of the Lorentz-violating scales (M_{LIV})

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

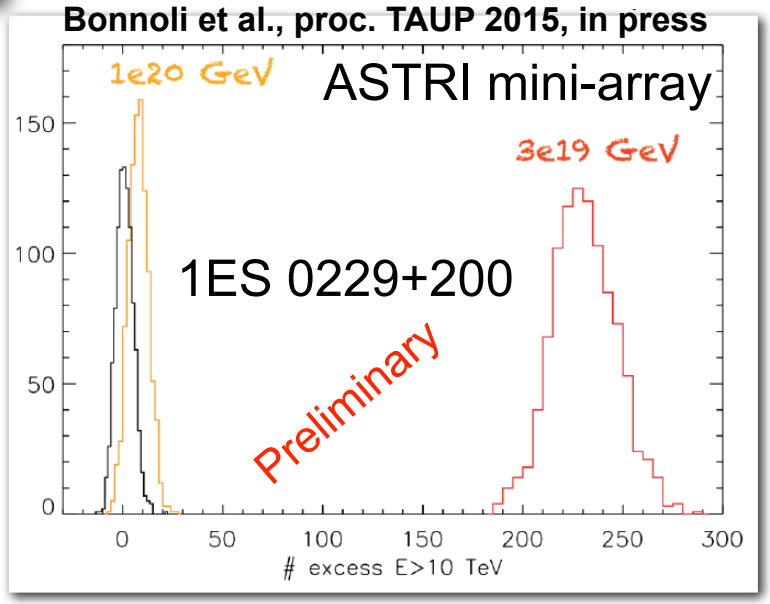


CTA

Fairbairn et al., 2014

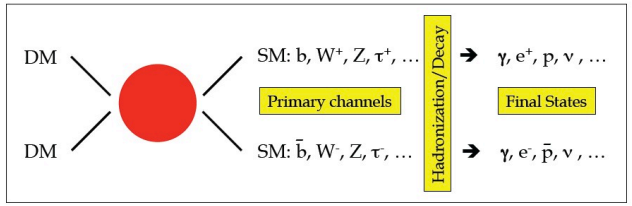


Bonnoli et al., proc. TAUP 2015, in press



Dark Matter searches

- Likely scenario for cold DM: weakly-interacting massive particles (WIMPs)
- WIMPs mass range: O(10 GeV) - O(100 TeV)
- WIMPs annihilation ➔ indirect detection (in γ-rays)



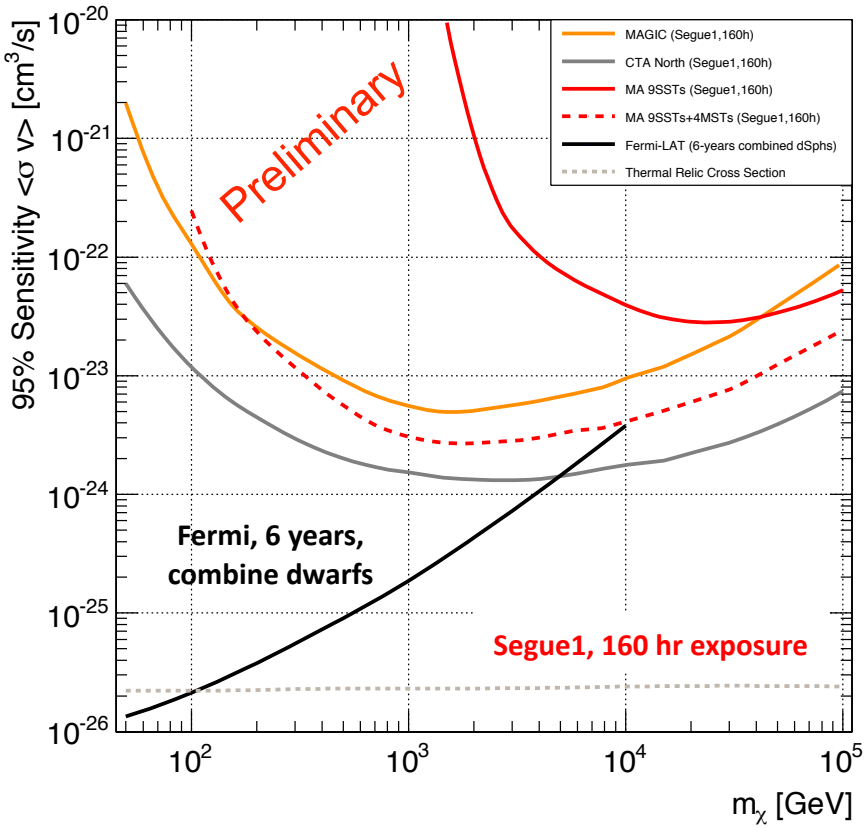
TARGETS:

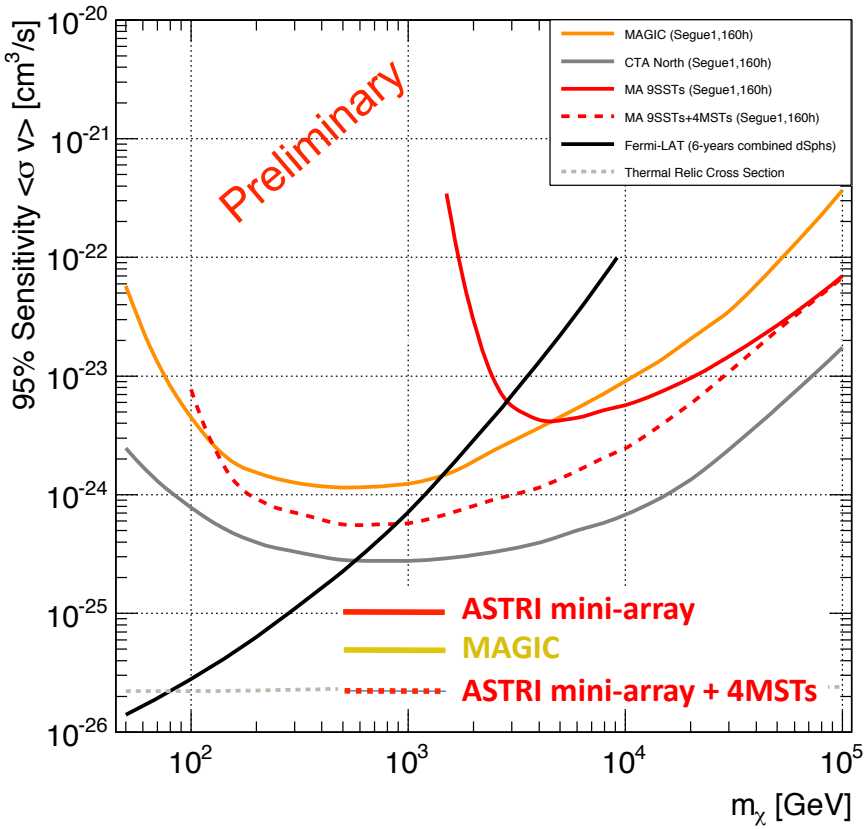
- *Galactic center?*
  - + Highest *J-factor*
  - − Very high astroph. bkg
  - − Uncertainties on inner DM distribution
  - − Southern Hemisphere
- *Galactic halo?*
  - + High *J-factor*
  - − Not fully-free from astroph. bkg
  - − Extended
  - − Southern Hemisphere
- *Galaxy Clusters?*
  - + Huge amount 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 (<~100 kpc)
  - + Slightly extended at most
  - + Less uncertainties on *J-factors*
  - − *J-factors* ~100 lower than for GC

Dark Matter searches

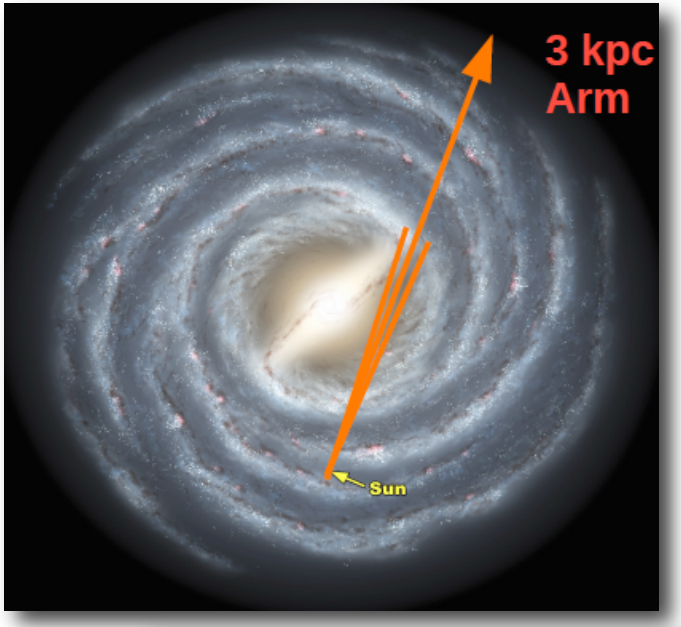
- Preliminary prospects for indirect Dark Matter searches (>~5 TeVs) with ASTRI mini-array
- First comparative studies with known target (Segue1 dwarf, 160 hr exposure)
- ASTRI mini-array + 4MSTs ➔ very interesting scenarios
- Refined simulations/analysis + new targets (southern dwarfs and GC) in progress

$b\,\bar{b}$ **Giammaria, Lombardi et al., in prep.** $\tau^+\,\tau^-$



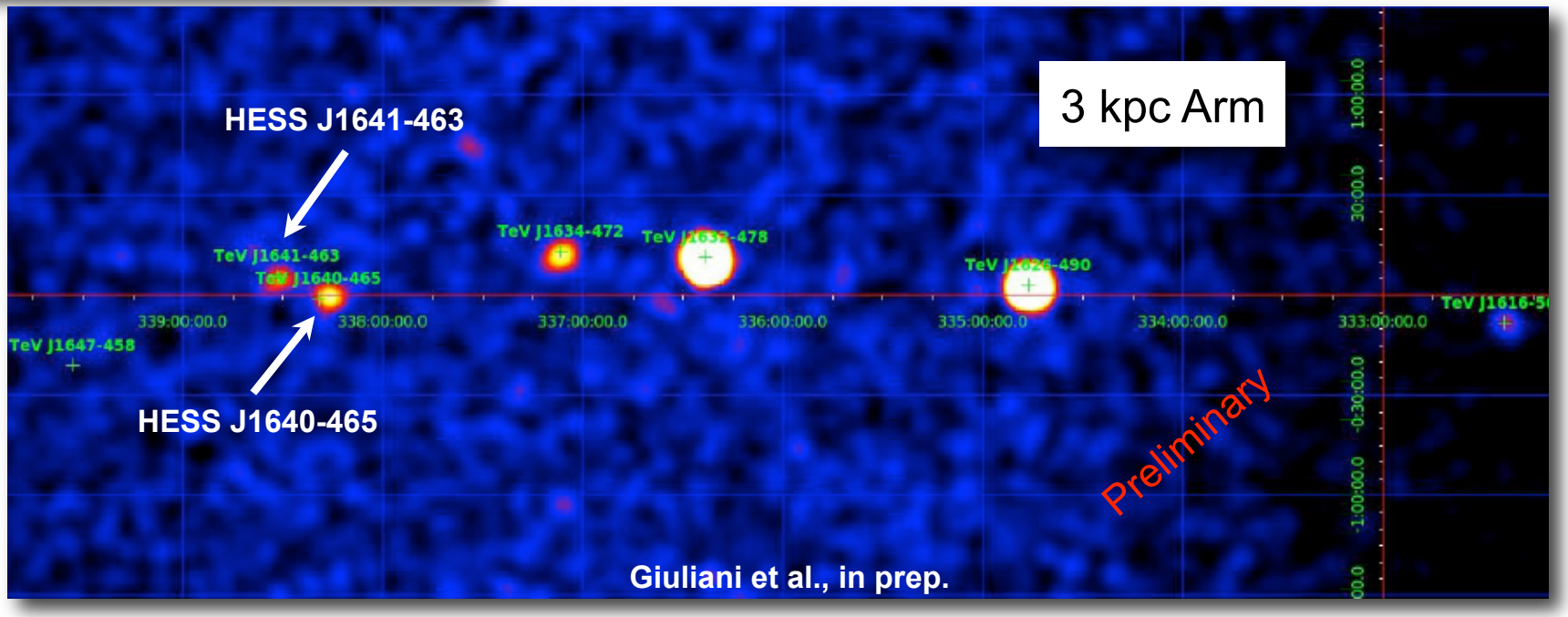


The wide field of view and our galaxy



ASTRI mini-array 200 hr simulation for E > 10 TeV

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



Summary and Outlook

- **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)

Summary and Outlook

- **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

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

Thanks!

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

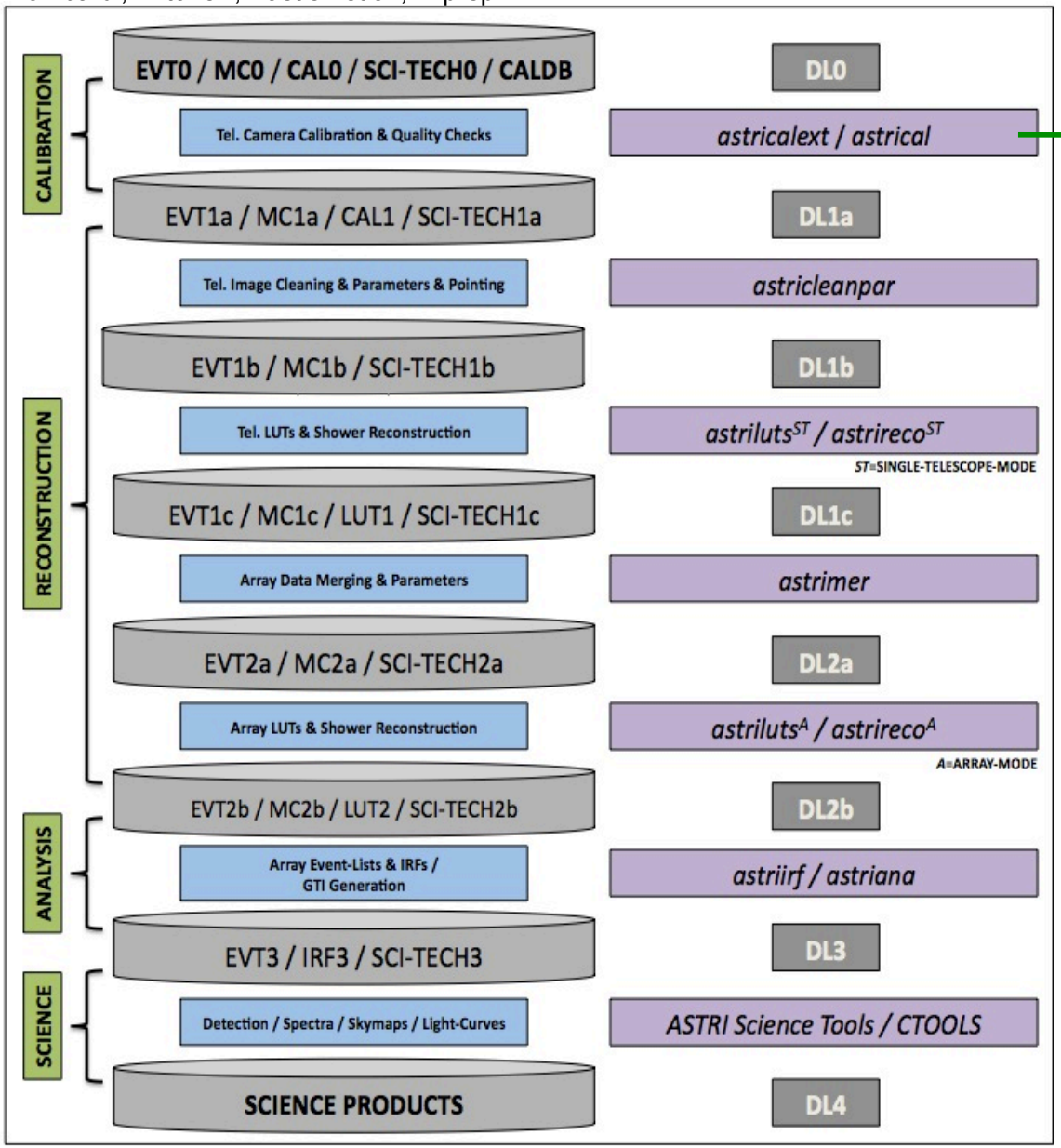
ASTRI SST-2M prototype and ASTRI mini-array data levels are defined in compliance with the CTA data model

Data Level	Short Name	Description	Data reduction factor
Level 0 (DL0)	DAQ-RAW	Data from the Data Acquisition hardware/software.	
Level 1 (DL1)	CALIBRATED	Physical quantities measured in each separate camera: photons, arrival times, etc., and per-telescope parameters derived from those quantities.	1-0.2
Level 2 (DL2)	RECONSTRUCTED	Reconstructed shower parameters (per event, no longer per-telescope) such as energy, direction, particle ID, and related signal discrimination parameters.	10^{-1}
Level 3 (DL3)	REDUCED	Sets of selected (e.g. gamma-ray-candidate) events, along with associated instrumental response characterizations and any technical data needed for science analysis.	10^{-2}
Level 4 (DL4)	SCIENCE	High Level binned data products like spectra, sky maps, or light curves.	10^{-3}
Level 5 (DL5)	OBSERVATORY	Legacy observatory data, such as CTA survey sky maps or the CTA source catalog.	10^{-5} - 10^{-3}

DATA-TDR document, CTA Consortium

ASTRI scientific data analysis

Lombardi, Antonelli, Bastieri et al., in prep.

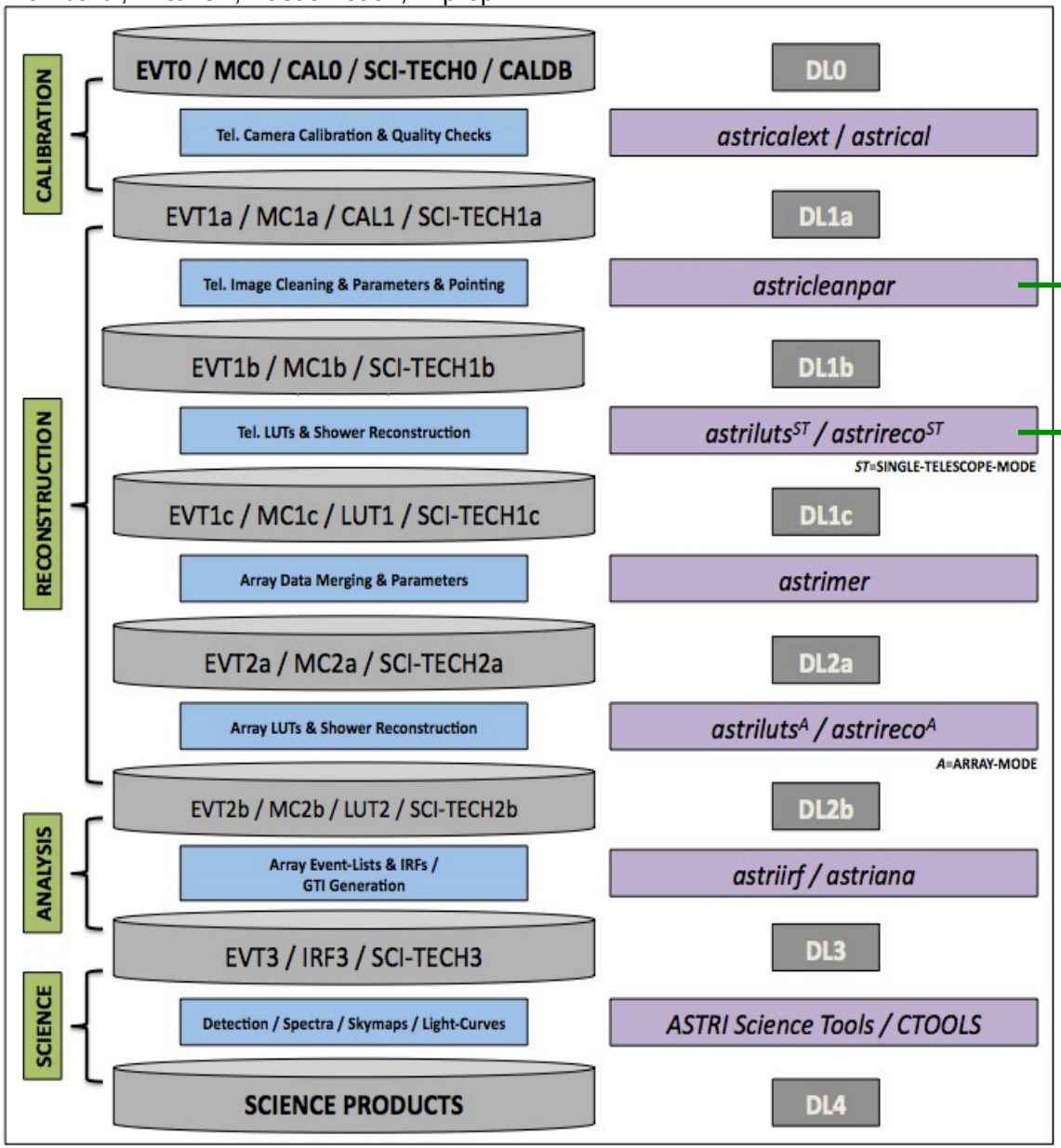


- ✧ Extraction of CAL1 from CAL0
- ✧ Application of CAL1 to EVT0/MC0
- ✧ NSB level extraction
- ✧ Production of EVT1(a)/MC1(a)

  (TEL.-WISE CALIBRATED DATA)

ASTRI scientific data analysis

Lombardi, Antonelli, Bastieri et al., in prep.



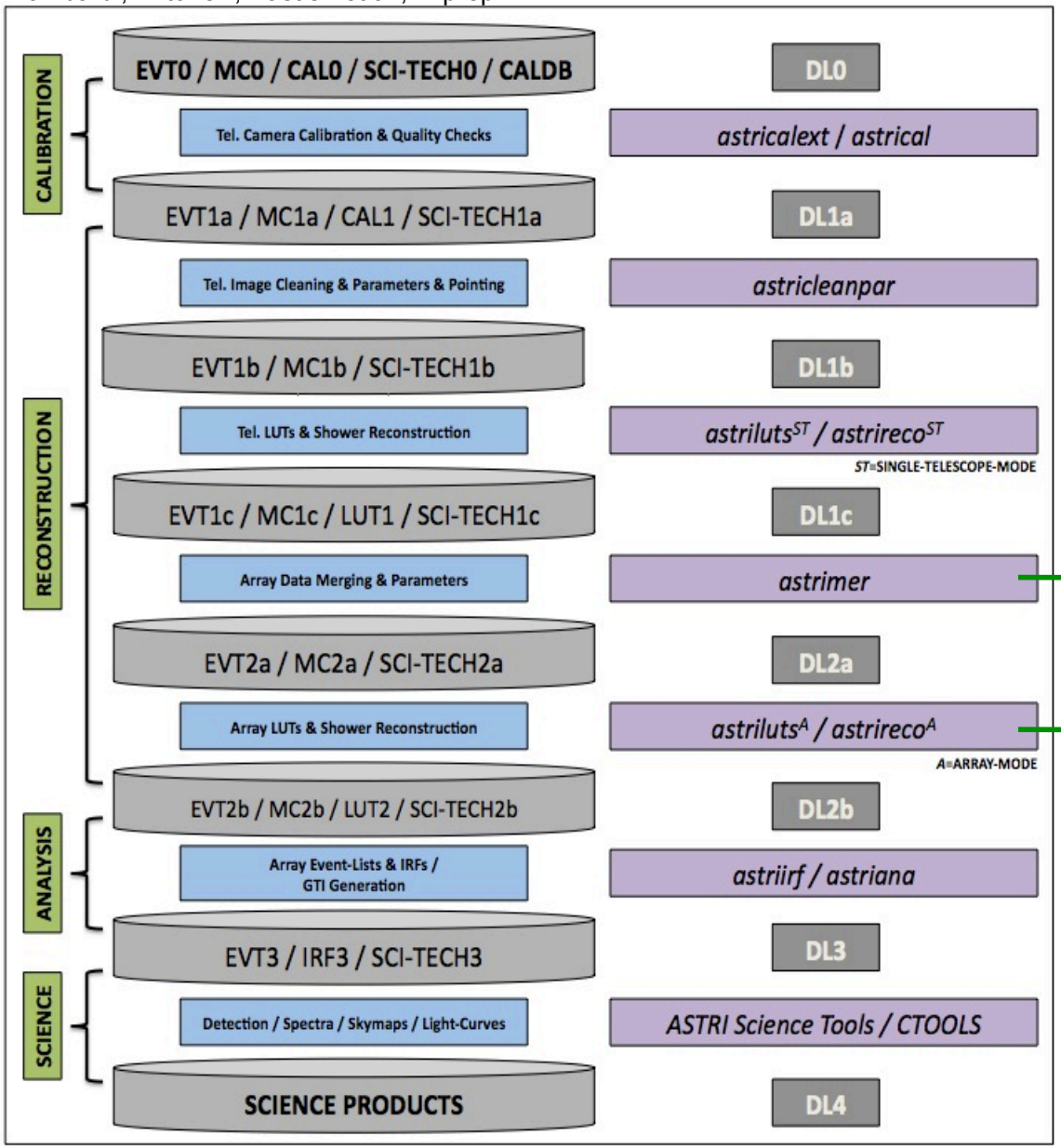
- ✧ Image Cleaning and Parameterization
- ✧ Telescope Pointing Reconstruction
- ✧ Production of EVT1(b)/MC1(b)

- ✧ Tel.-wise γ/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

Lombardi, Antonelli, Bastieri et al., in prep.



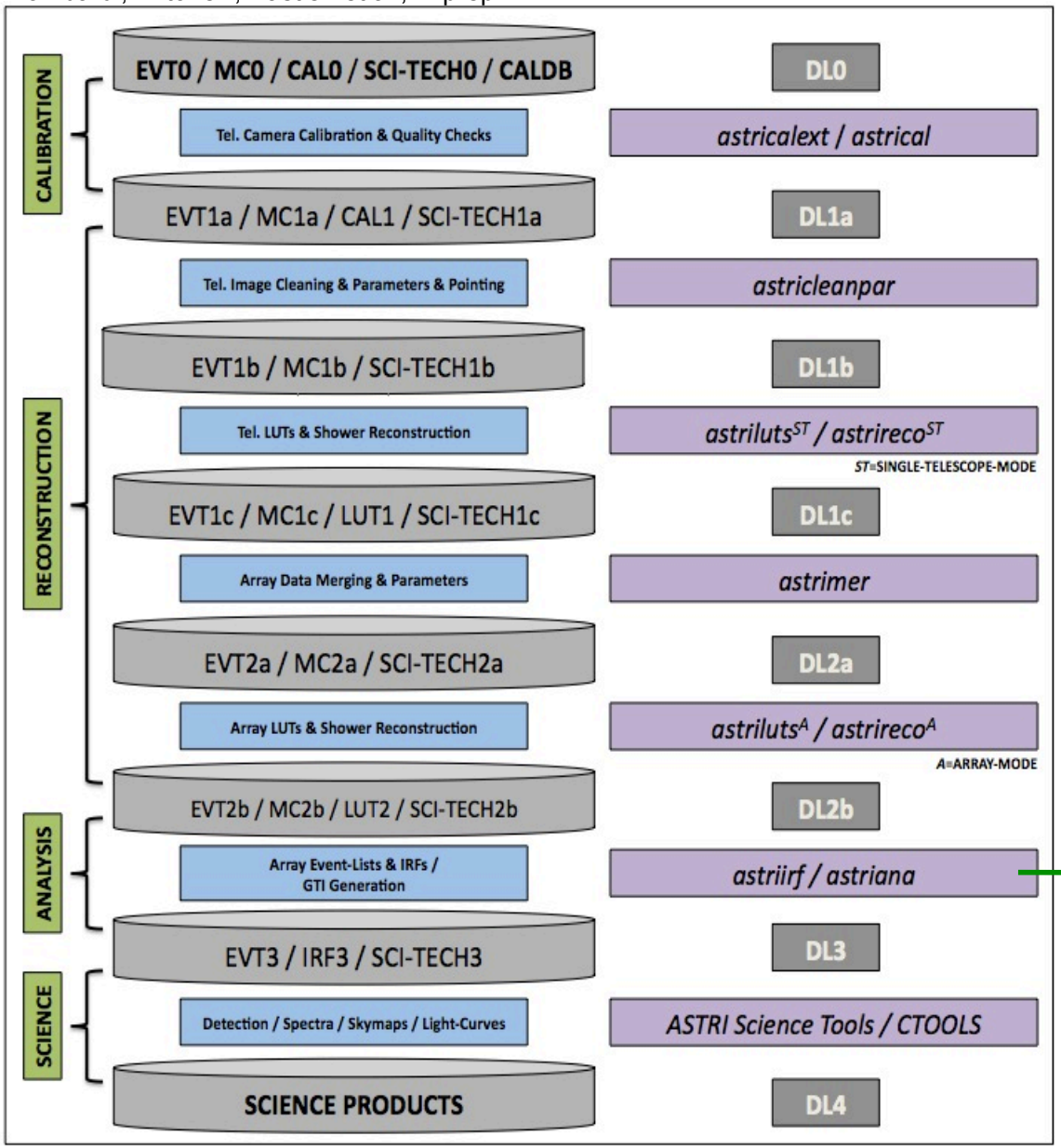
- ✧ Tel.-wise Data Merging
- ✧ Stereo Reconstruction
- ✧ Production of EVT2(a)/MC2(a)

- ✧ Array-wise γ/h Separation
- ✧ Array-wise Energy Reconstruction
- ✧ Array-wise Arrival Direction Estimation
- ✧ Production of LUT2/EVT2(b)/MC2(b)

(ARRAY-WISE RECONSTRUCTED DATA)

ASTRI scientific data analysis

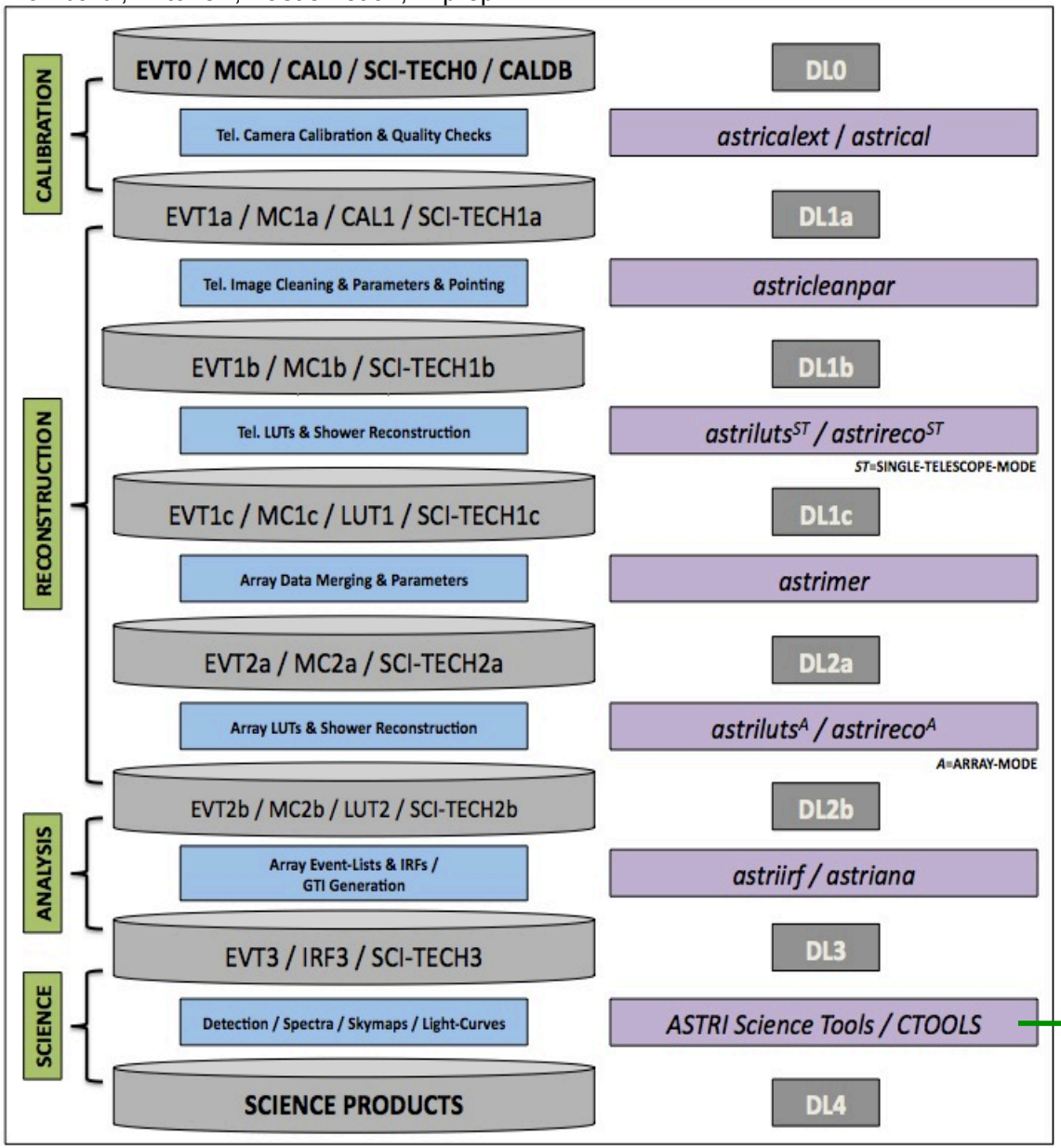
Lombardi, Antonelli, Bastieri et al., in prep.



- ✧ Instrument Response Functions
  (*Effective Area, Energy/Angular Resolution, Background Rate, Sensitivity*)
- ✧ EVENT-LIST & GTI
- ✧ Production of IRF3/EVT3
  (ARRAY-WISE REDUCED DATA)

ASTRI scientific data analysis

Lombardi, Antonelli, Bastieri et al., in prep.

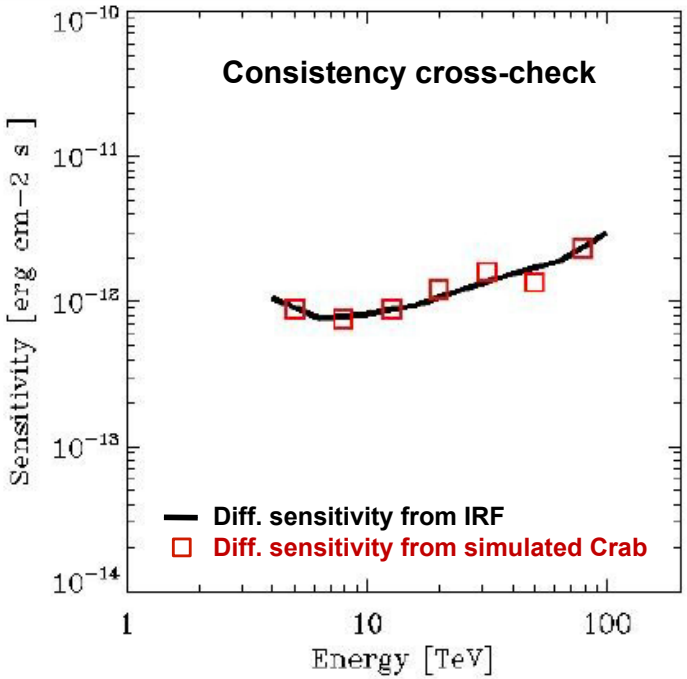


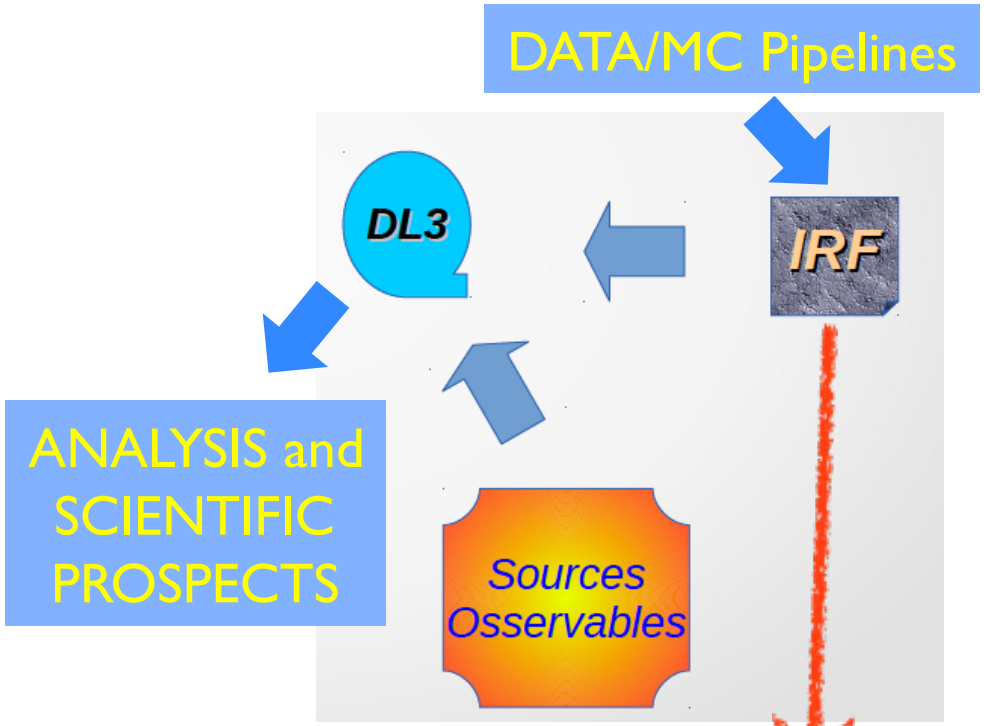
✧ **SCIENTIFIC PRODUCTS (DL4)**

Sky-maps, Spectra, Light-curves

ASTRI simulation tools

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.





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IRF for ON AXIS

log(E)	Area	r68	r80	ERes.	BG Rate	Diff Sens
-2.0	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-1.8	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-1.6	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-1.4	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-1.2	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-1.0	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-0.8	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-0.6	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-0.4	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-0.2	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
-0.0	0.0	0.0000	0.0000	0.0000	0.00000000	0.000000e+00
0.2	7045.3	0.1355	0.1764	0.1368	0.00000000	0.000000e+00
0.4	39824.7	0.1075	0.1518	0.1222	0.00000000	0.000000e+00
0.6	141911.7	0.0799	0.1064	0.1183	0.00001621	1.051026e-12
0.8	282517.1	0.0698	0.0907	0.1033	0.00001652	7.613567e-13
1.0	372093.3	0.0635	0.0827	0.1020	0.00001679	8.118874e-13
1.2	493827.6	0.0613	0.0808	0.1088	0.00001610	9.494925e-13
1.4	557620.2	0.0645	0.0914	0.1097	0.00001427	1.217832e-12
1.6	661707.3	0.0737	0.1131	0.1214	0.00001078	1.533251e-12
1.8	781255.9	0.0938	0.1428	0.1186	0.00000547	1.912365e-12
2.0	510052.9	0.1155	0.1809	0.1219	0.00000211	3.002351e-12

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LIV and E-HBL

LIV induces an effective mass for the photon

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

Delays

Modification of threshold for pair production at high E

LIV induces suppression of EBL-opacity

Fairbairn+ 2014

ASTRI mini-array

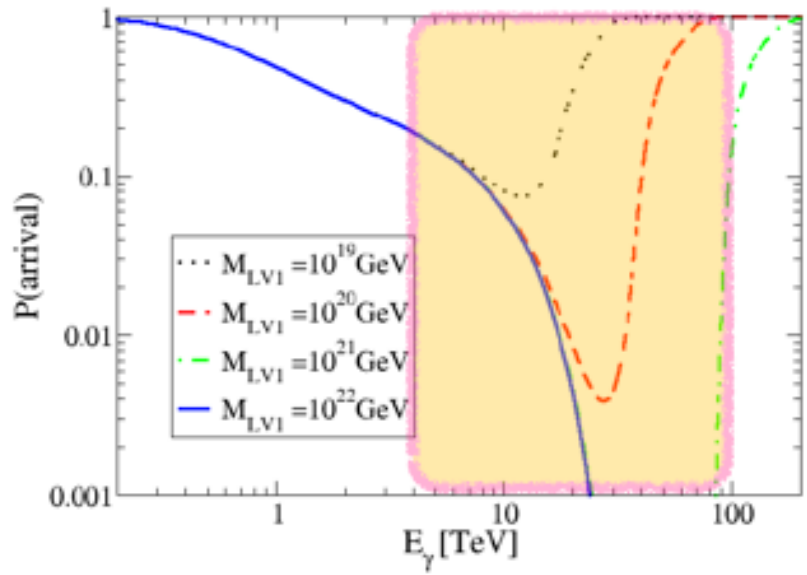
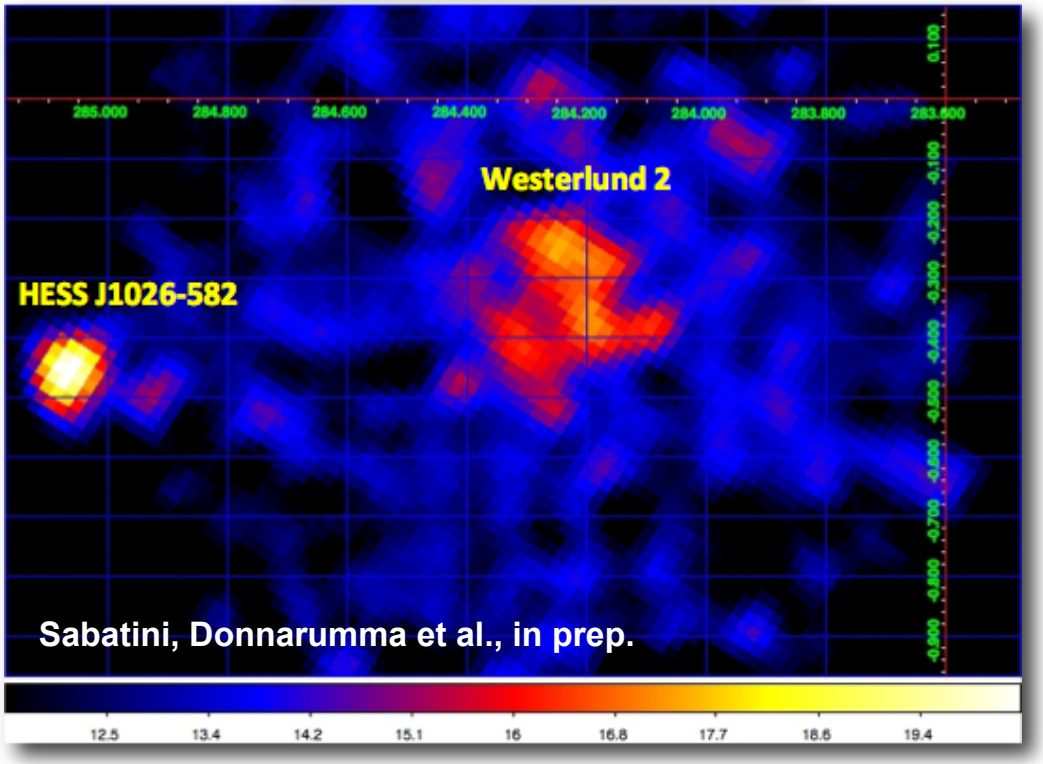


Figure 2. *The arrival probability of a photon emitted from a hypothetical source at redshift $z = 0.05$ as a function of energy. The different curves represent different values of the Lorentz-violating scale M_{LV1}. VHE photons with energies $\gtrsim 100$ TeV can travel through the CMB effectively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

The wide field of view and our galaxy

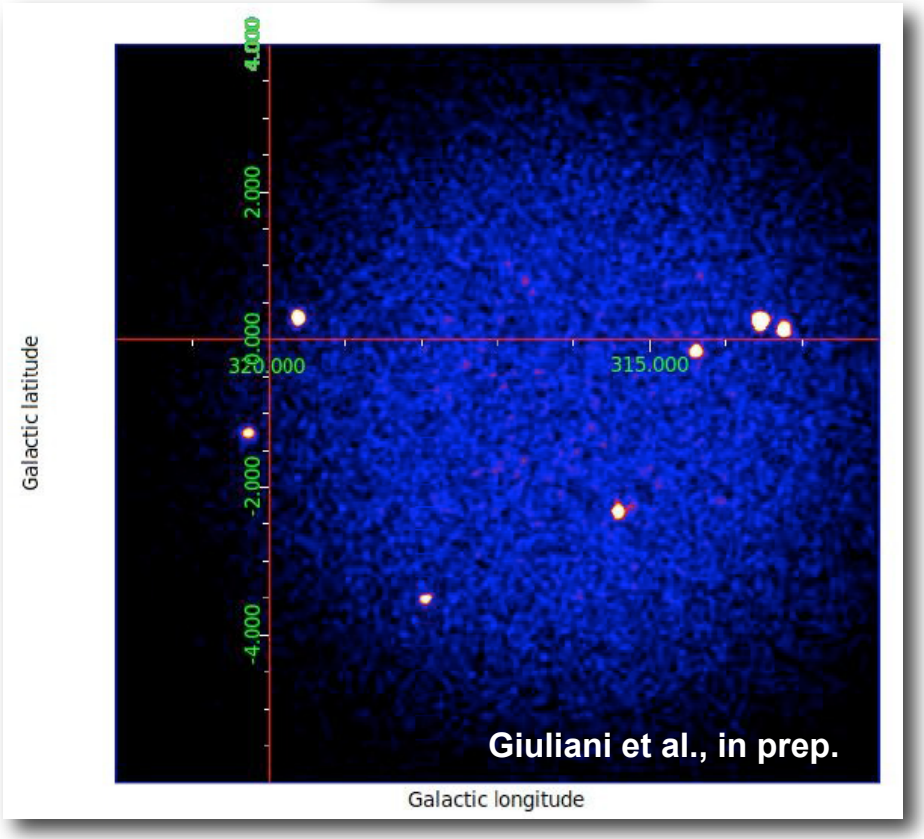
Eta Carinae region

270 hr

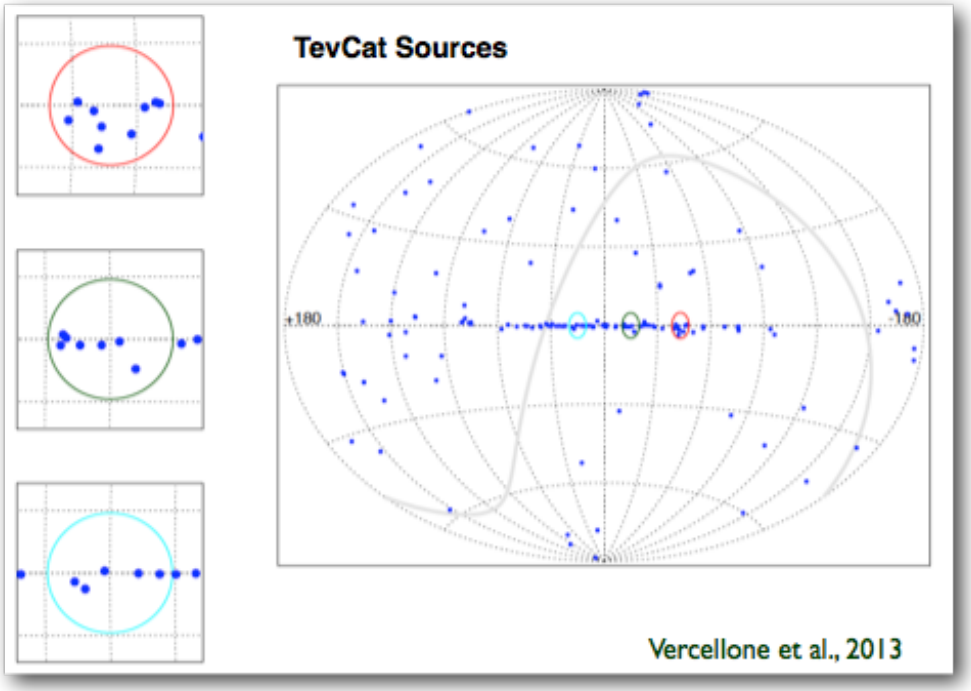


Crux Arm

200 hr



The wide field of view



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

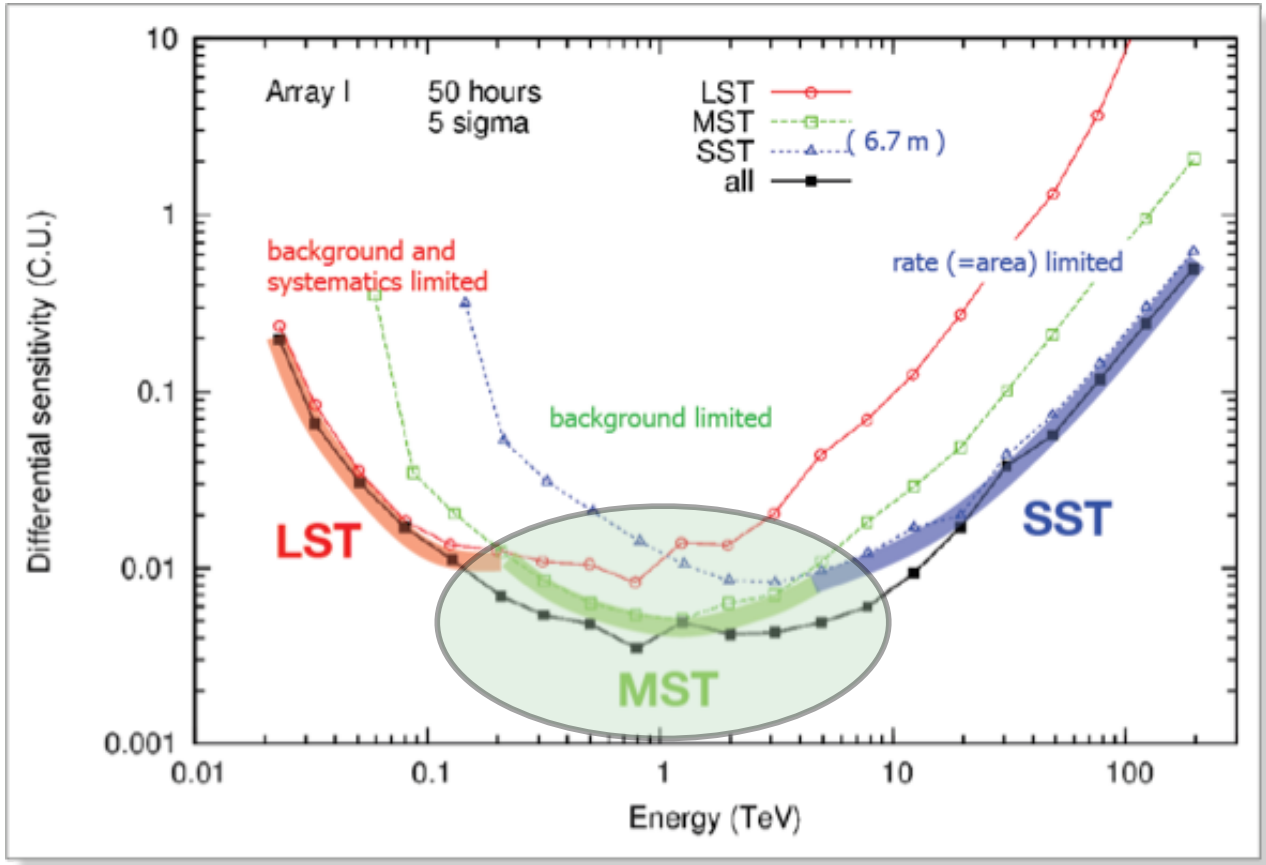
Although the actual sensitivity will substantially drop for off-axis sources, **a few targets can be monitored simultaneously**

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

Synergy with MSTs



Courtesy of the CTA Consortium

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