The Schwarzschild–Couder Optical Design of ASTRI: Opportunities and Challenges

Giorgia Sironi

for the ASTRI Project

From 9 to 40: the SST Telescopes and Gamma-Ray Science with ASTRI and CTAO

- From scientific to design requirements
- From light concentrators to Schwarzschild-Couder
- From concept to implementation: nothing comes for free
- From 9 to 40

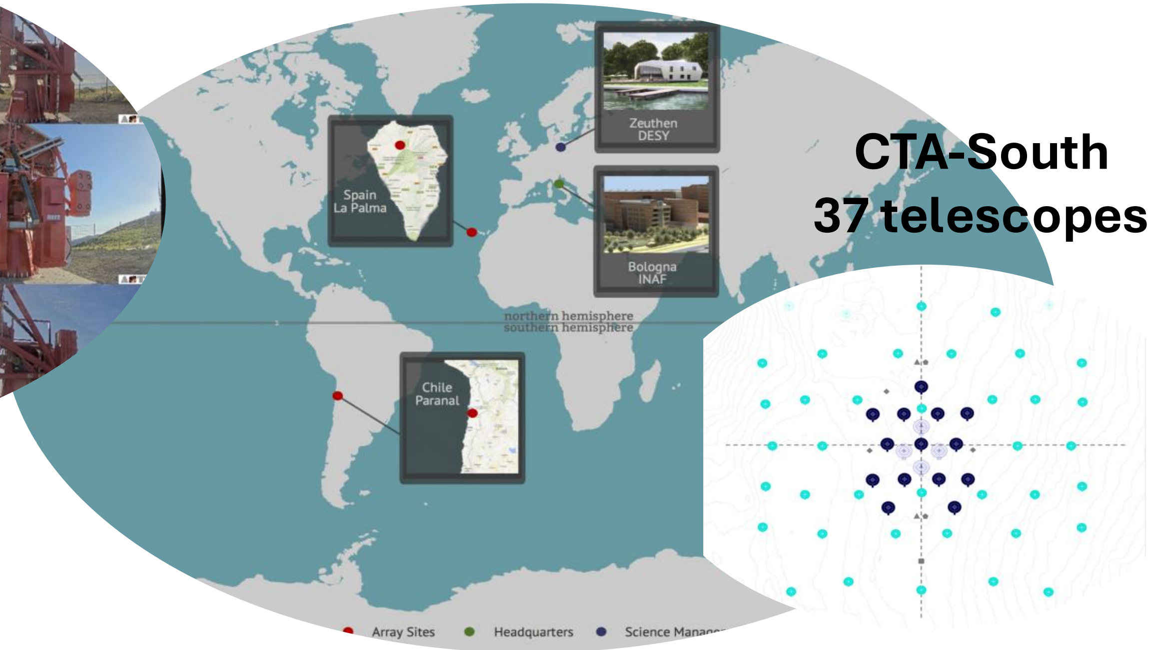
Summary

- From scientific to design requirements
- From light concentrators to Schwarzschild-Couder
- From concept to implementation: nothing comes for free
- From 9 to 40

Why has Schwarzschild–Couder become the baseline for TeV Cherenkov arrays?

ASTRI - Horn

ASTRI Mini-Array
9 telescopes



CTA-South
37 telescopes

- **From scientific to design requirements**
- From light concentrators to Schwarzschild-Couder
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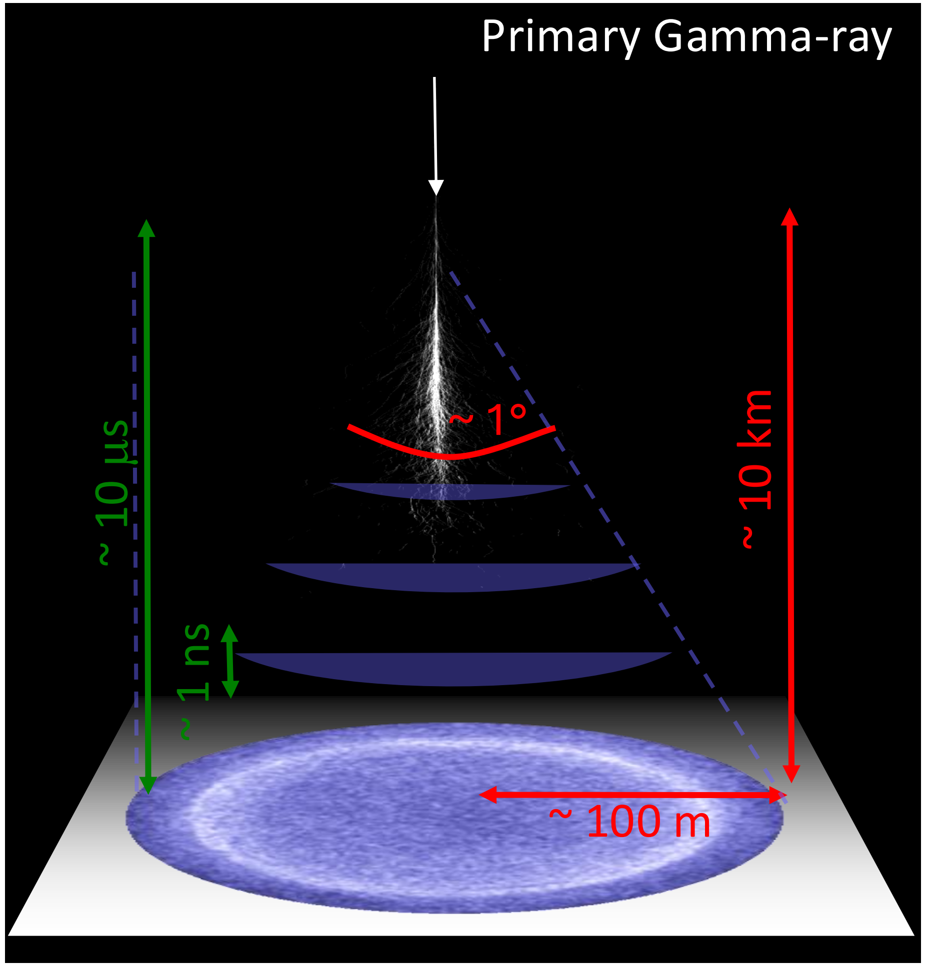
From scientific to design requirement

Very High Energy γ-rays (E > 20GeV) are generated by a variety of cosmic sources.

γ-rays interact with the atmosphere generating a particle cascade which produces detectable light by means of the Cherenkov effect:

- Origin at about 10 km
- Cone angle about 1°;
- Illuminating radius about 100 m;
- Light wave-front about 1 ns
- Light density about 10 ph/m^2
- (NSB about 10^8 $ph/m^2/s$)



Signal can be detected only in the flashes time frame: no exotic design → ns scale isocronicity

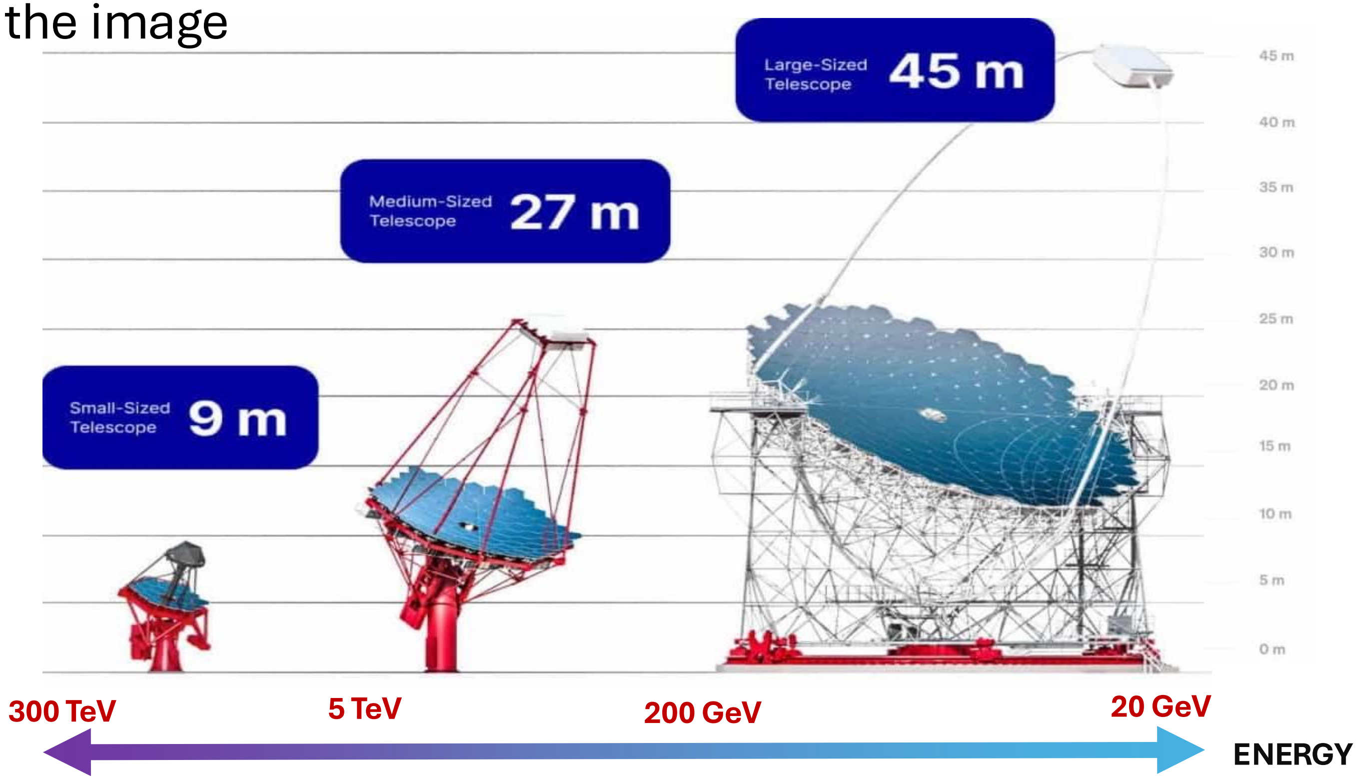
From scientific to design requirement

separate gamma signal by the cosmic background

A. Detect the **faint** nanoseconds scale Cherenkov signal drowned in in the continuous background ⇨ **Area (5.5-370 m^2)**

B. Be capable to image the cascade ⇨ Large FOV (4.3-10 deg)

C. Retrieve the signal image incoming direction by the geometry of the image ⇨ Moderate Resolution (0.1-0.25 deg)



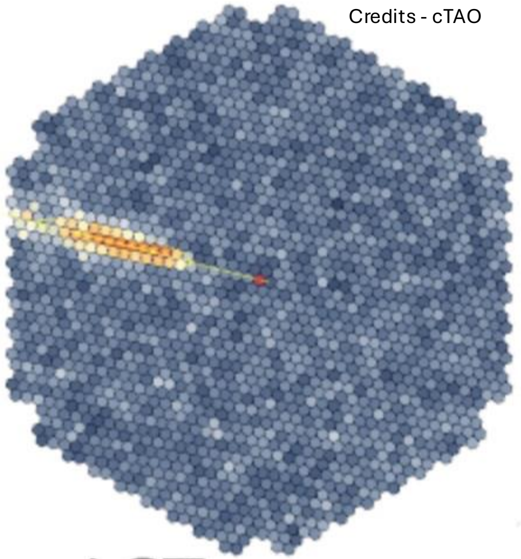
From scientific to design requirement

separate gamma signal by the cosmic background

A. Detect the **faint** nanoseconds scale Cherenkov signal drowned in in the continuous background ⇒ Area (5.5-370 m^2)

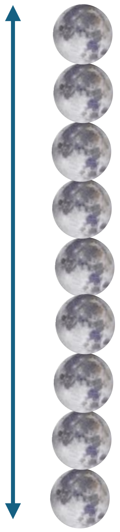
B. Be capable to image the **cascades extension** ⇒ **Large FOV (4-10 deg)**

C. Compute the signal image incoming direction by the geometry of the image ⇒ Moderate Resolution (0.1-0.25 deg)

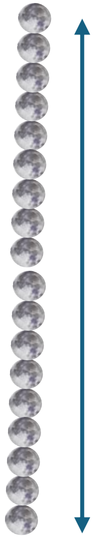


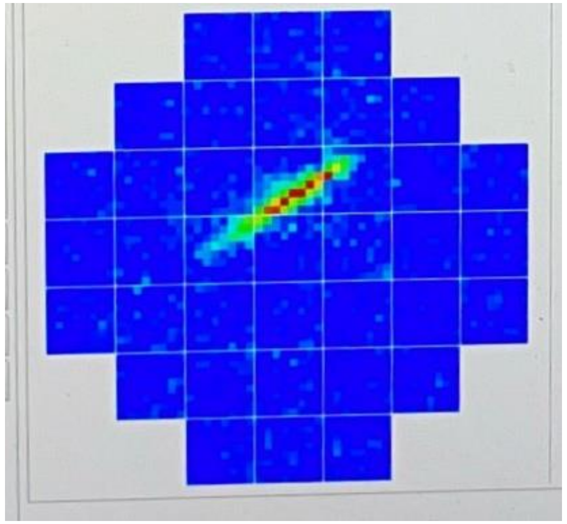
LST

4.3 deg



Moon 0.5 deg





~10 deg ASTRI/SST

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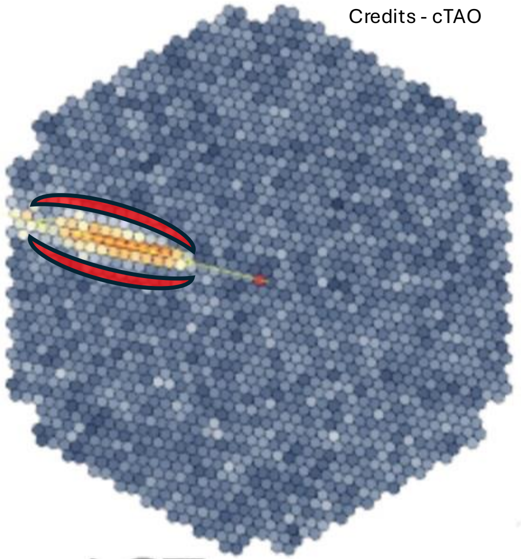

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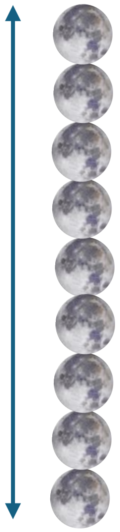

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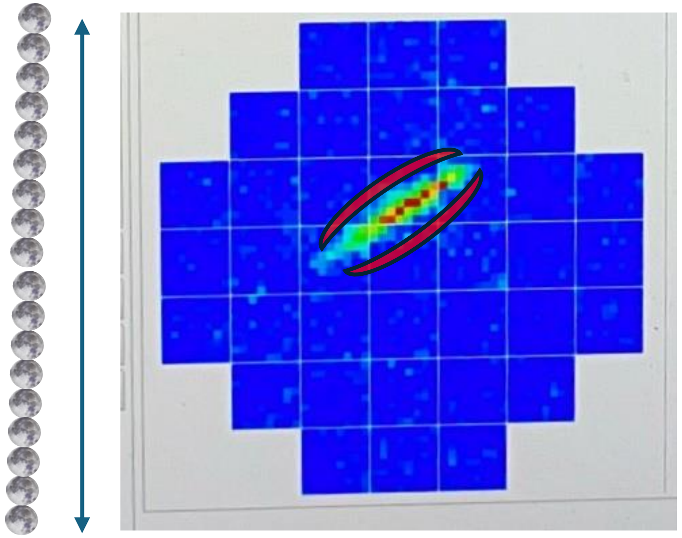
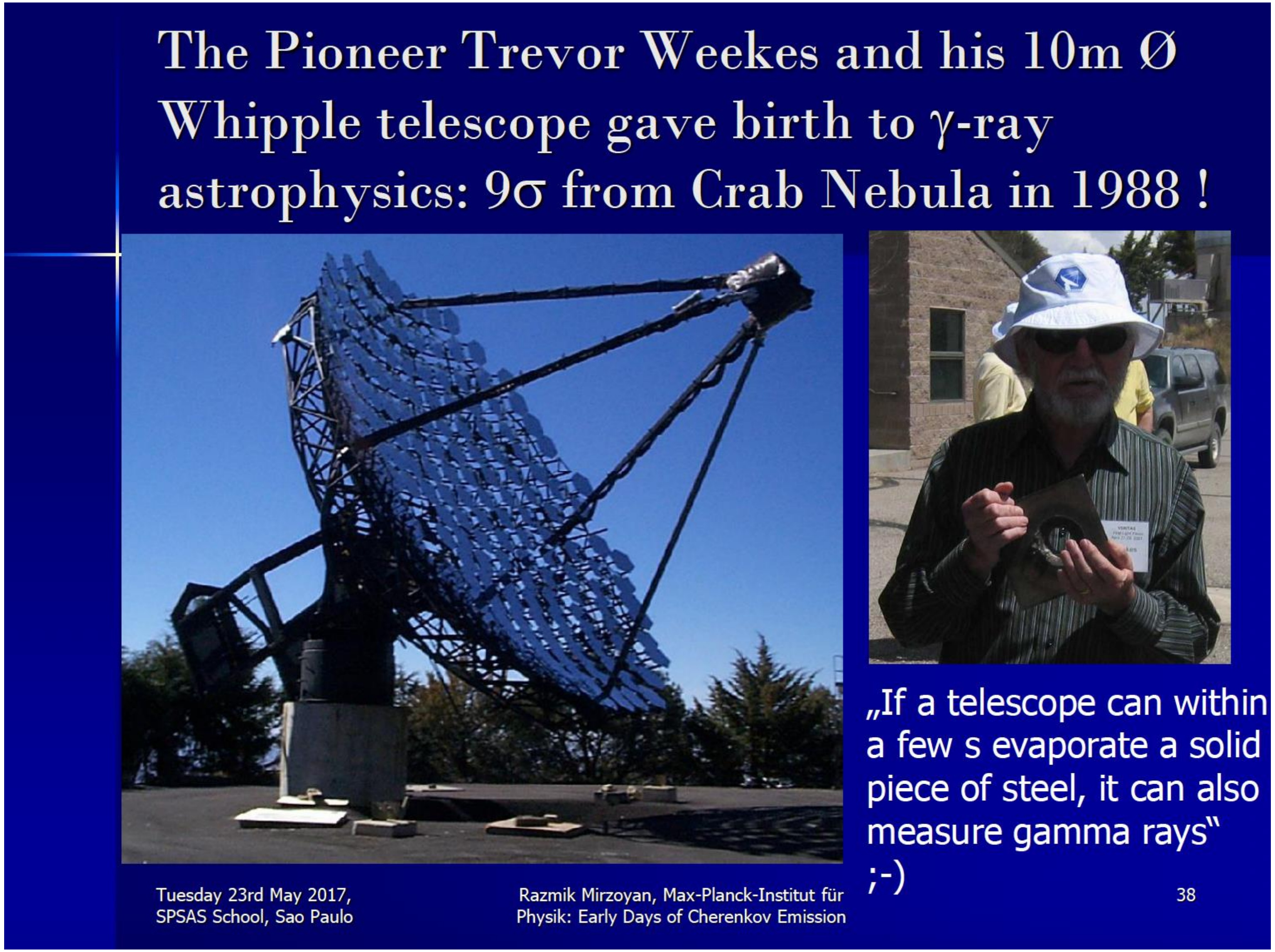


~10 deg ASTRI/SST

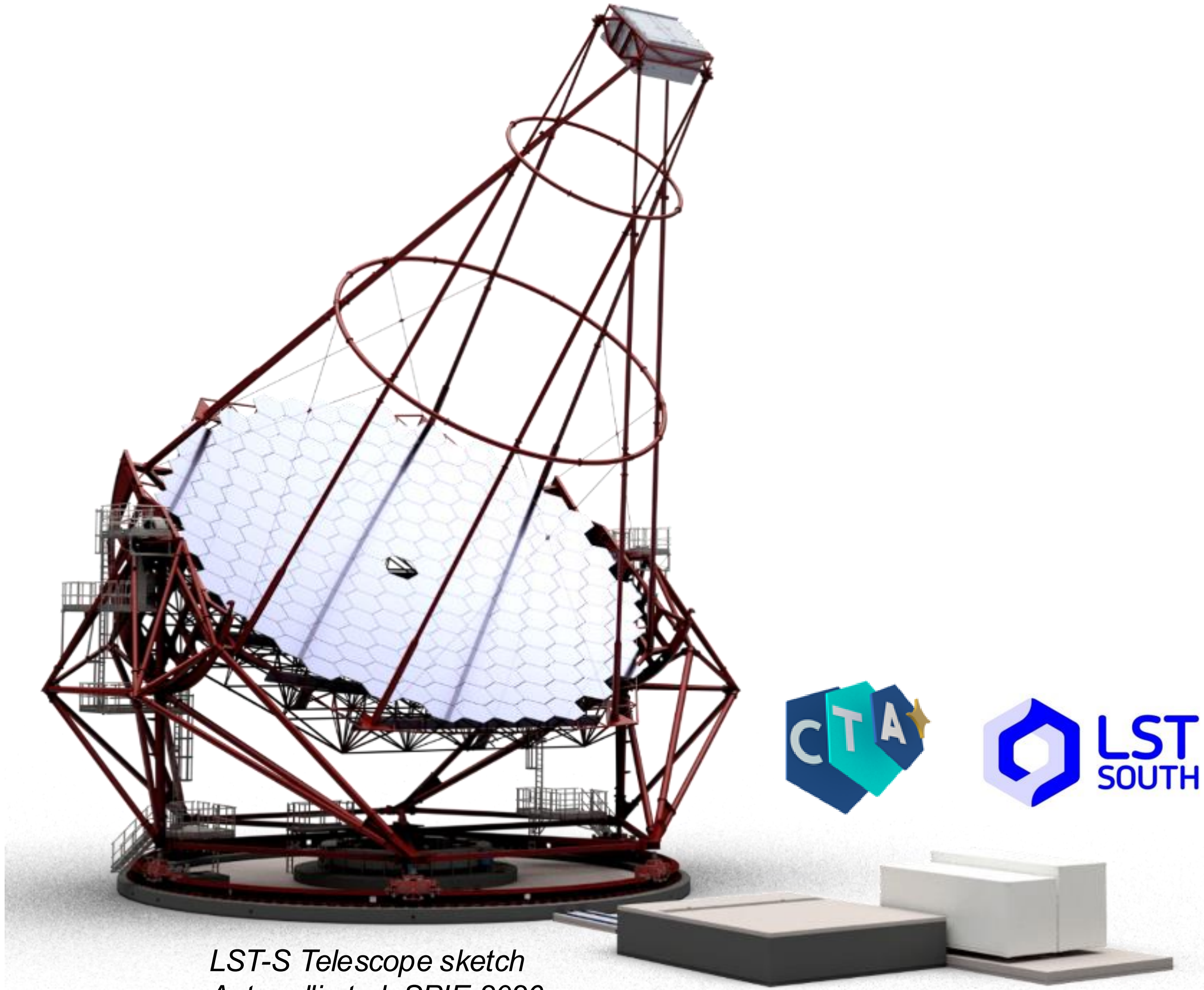
From light concentrators to Schwarzschild-Couder



From light concentrators to Schwarzschild-Couder

Spherical mirrors on a parabolic dish

- Parabolic dish, D=23 m
- Focal length 28 m, plate scale 488mm/deg
- 198 spherical mirrors, vertex-to-vertex=1.7 m
- FOV 4.2 deg populated with 0.1 deg PMT



LST-S Telescope sketch
Antonelli et al. SPIE 2026

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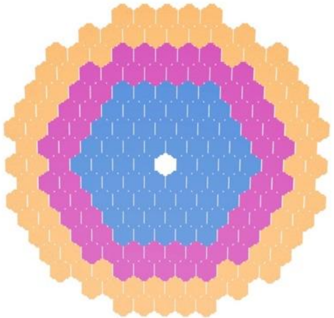

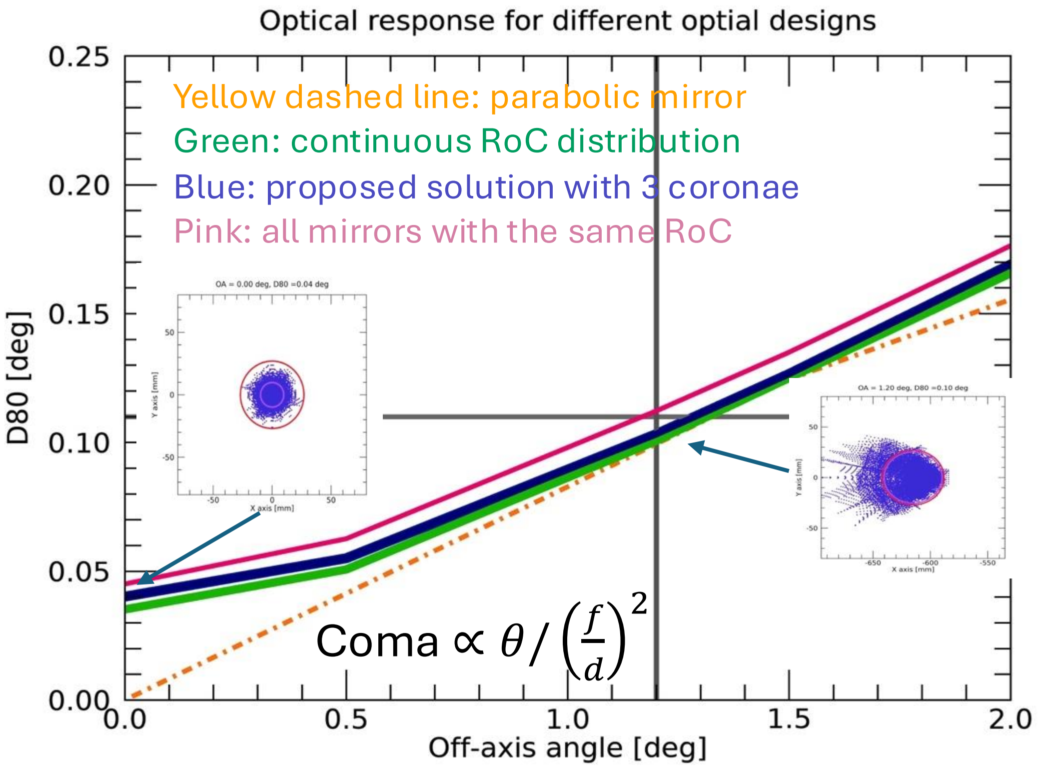

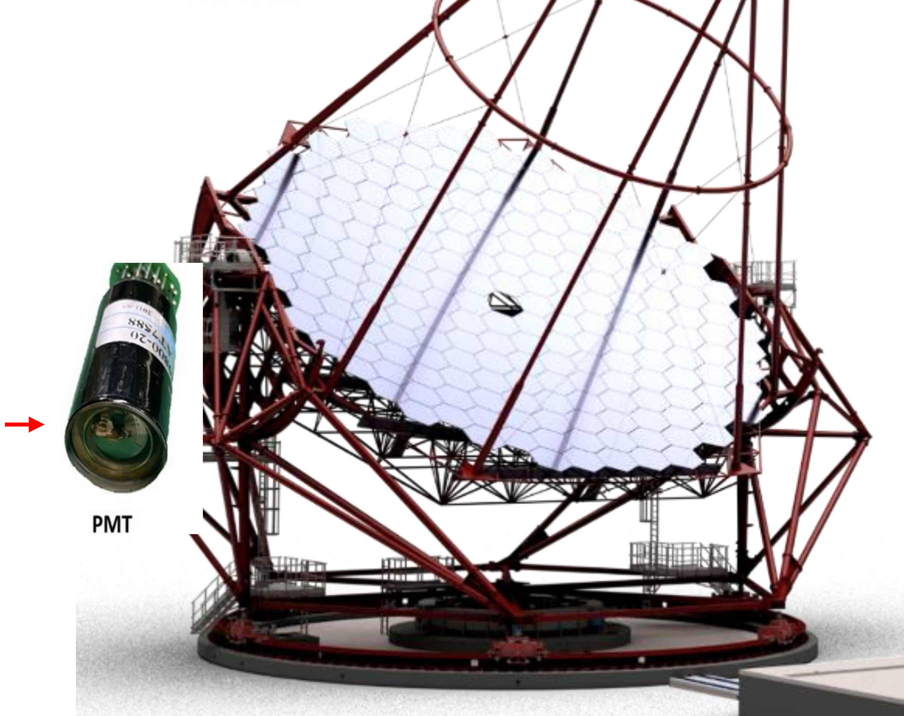

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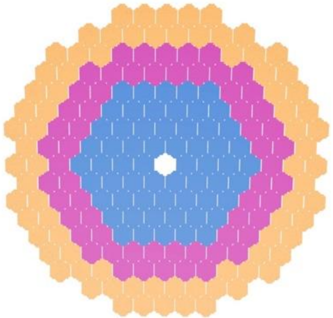

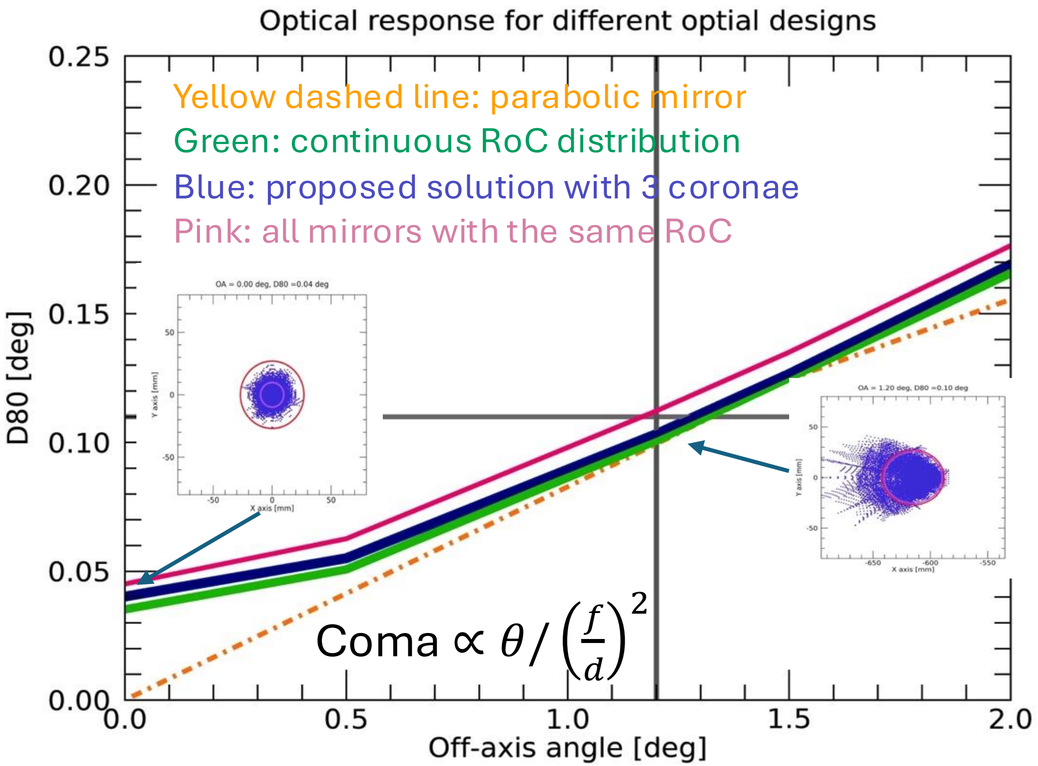

$$\text{Coma} \propto \theta / \left(\frac{f}{d}\right)^2$$

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Antonelli et al. SPIE 2026

Cherenkov Camera
2.8 m side
~2 tons
@28 m height

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From light concentrators to Schwarzschild-Couder

Karl Schwarzschild
(1873 – 1916)

- Solved Einstein's field equations of general relativity
- Formalized the Schwarzschild metric, defining the Schwarzschild radius for BH description.
- **Formalized optics theory defining conical functions**
- Photography, electromagnetism

From light concentrators to Schwarzschild-Couder

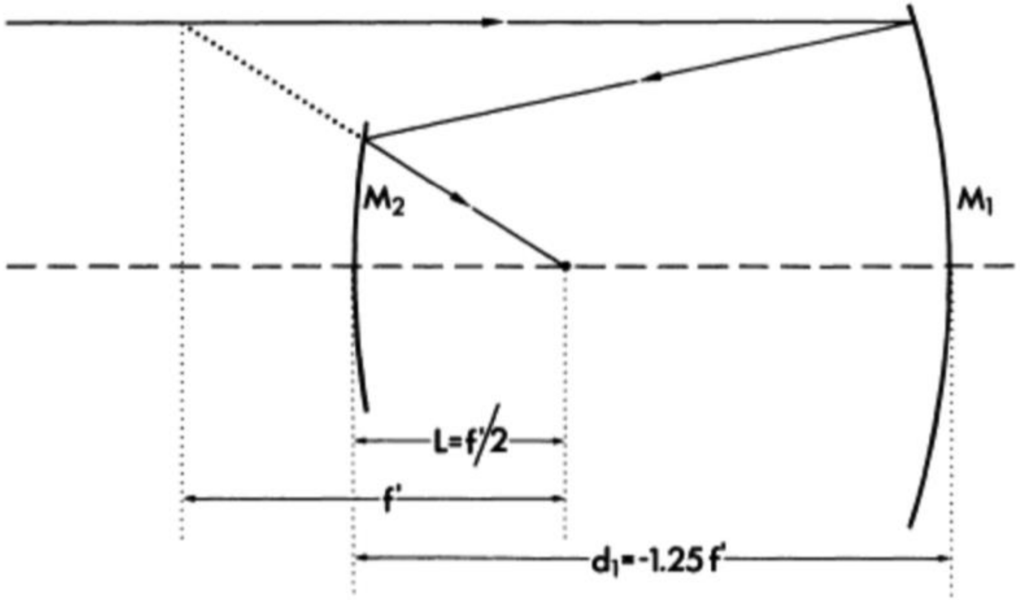
Karl Schwarzschild (1873 – 1916)

1905: Karl Schwarzschild solved the equations of Seidel describing the optical aberration in terms of *f/D* for **spherical** aberration and **coma** finding a relation between parameters capable to make a telescope **aplanatic**.

"For any geometry, 2 aspheric mirrors allow the correction of SI and SII to give an aplanatic telescope"

Schwarzschild telescope

b_{S1}= -13.5 (Hyperbola)
b_{S2}= 1.963 (Spheroid)
FoV: 2.8 deg
RMS_{edge}~12''



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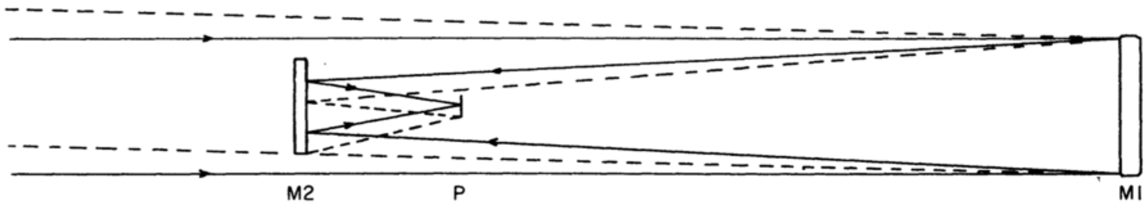
1926: Couder solved the third optics equation for SI, SII, SIII **removing the flat field** condition obtaining **aplanatic anastigmatic** telescope and a generalization of Schwarzschild theorem:

"N aspheric optics allow correcting N Seidel aberrations"

Andre' Couder
1897-1979

Couder telescope
b_{S1}= -14.203 (Hyperbola)
b_{S2}= -0.055 (Spheroid)
FoV: 3.0 deg
RMS_{edge}~1''



From light concentrators to Schwarzschild-Couder

Why did Schwarzschild fail for almost 100 years?

- no detectors requiring small plate scale
- aspheric mirrors impossible to manufacture
- alignment technology not available

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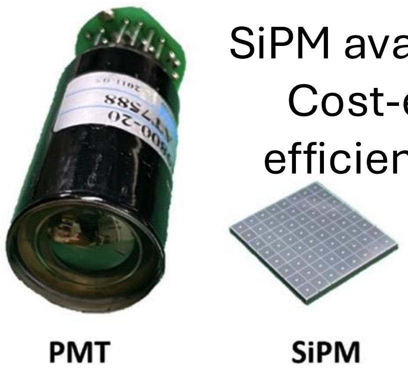

SiPM available since ’90
Cost-effective and
efficient since ~2010

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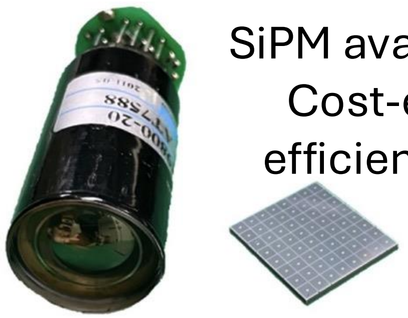

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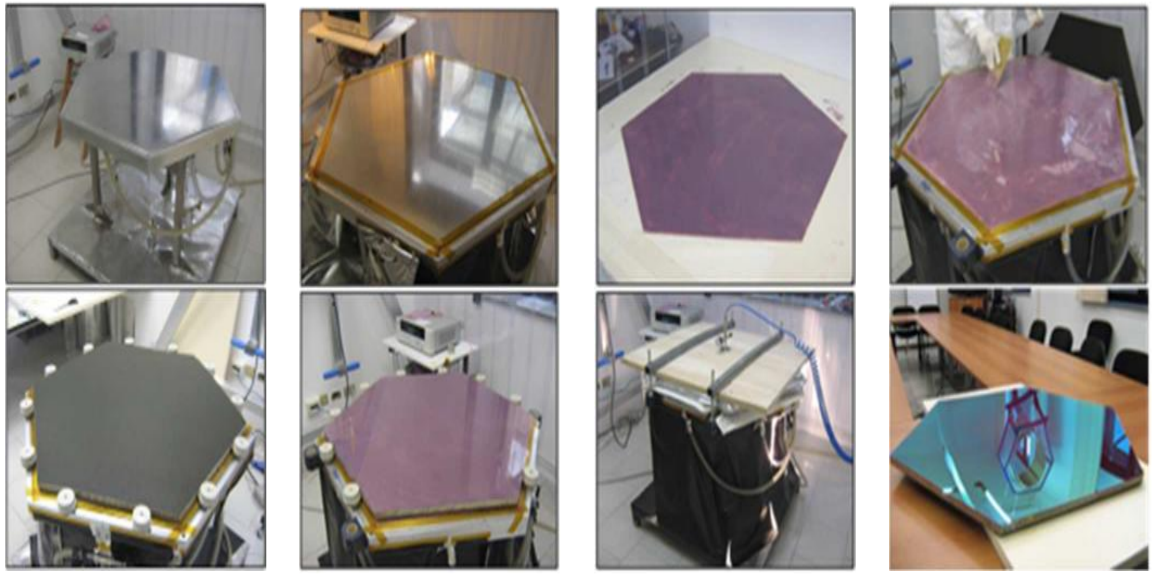

Glass Mirrors cold-replica approach (set-up since 2006)

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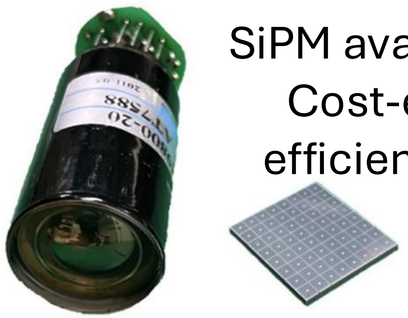

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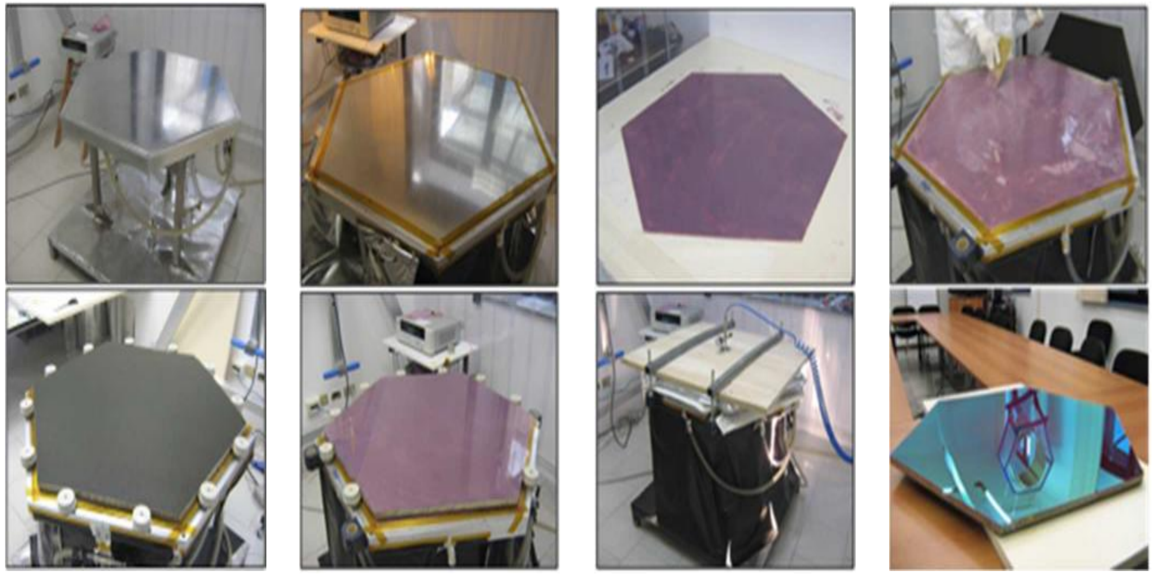
Mirror actuators are used in the majority of telescopes



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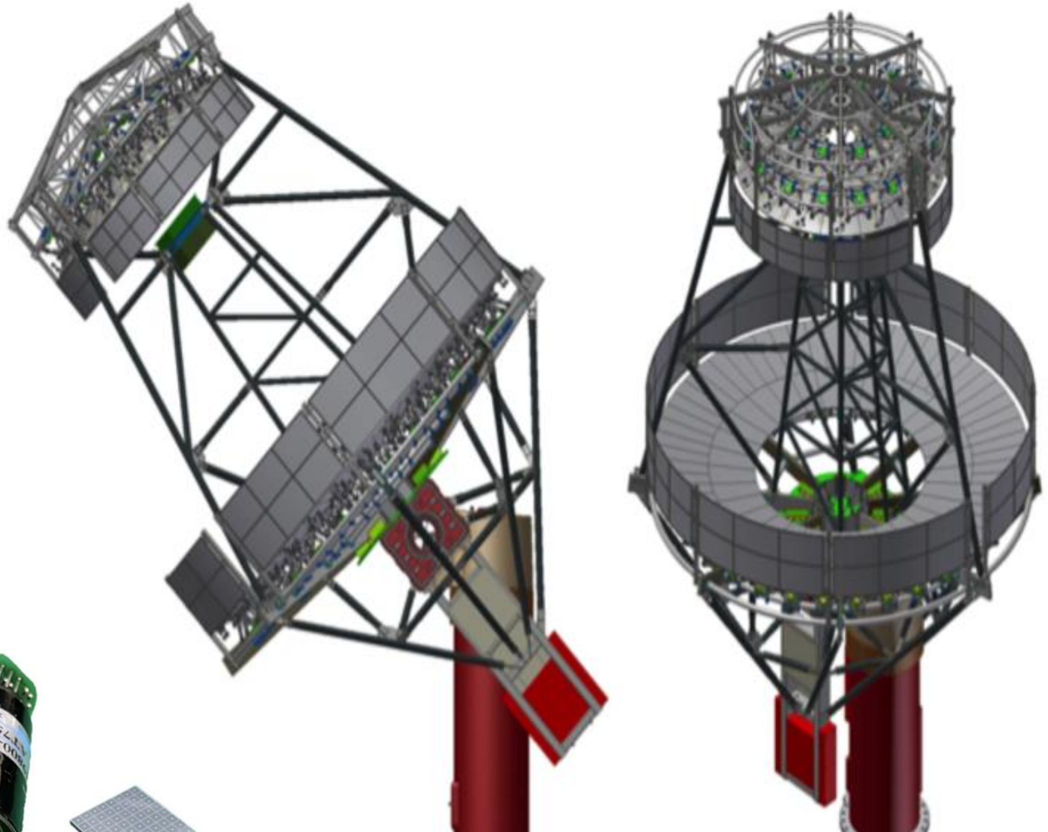
In **2007 V. Vassiliev** (UCLA) recovered the Schwarzschild-Couder solution and proposed to apply it to **Cherenkov telescopes**

Design	pSCT	MST
fl	5.58 m	16 m
D	~10 m	19.2 m
Area	40 m2	88 m2
F/#	~0.6	1.3
Design	SC	DC
FoV	8.3°	~8°
PSF	~0.06'	0.06°
Pixel [ang]	~0.06'	0.14°
Pixel	6.2 mm	4 cm
Pixel #	11328	



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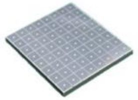
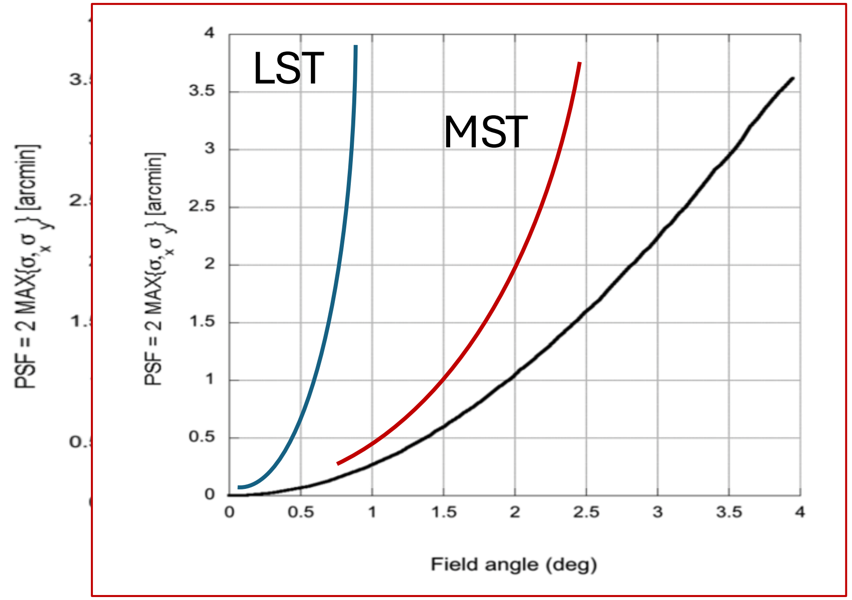


SiPM

Design for CTA-pSCT, V. Vassiliev



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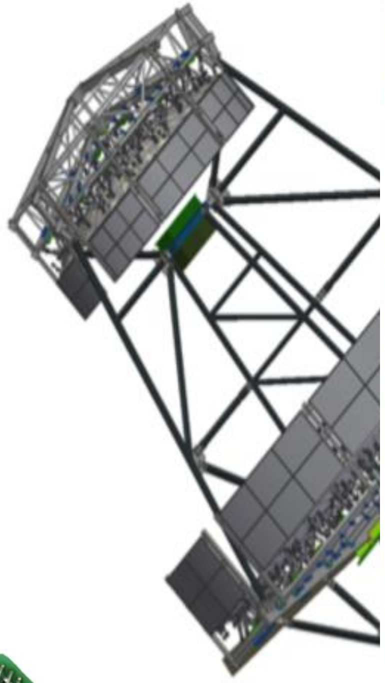
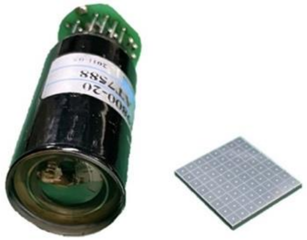
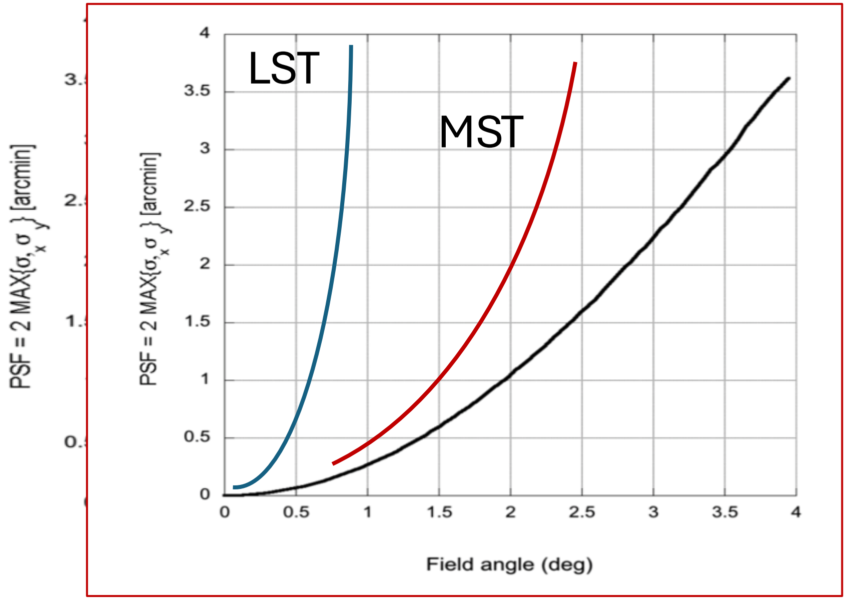




PMT SiPM

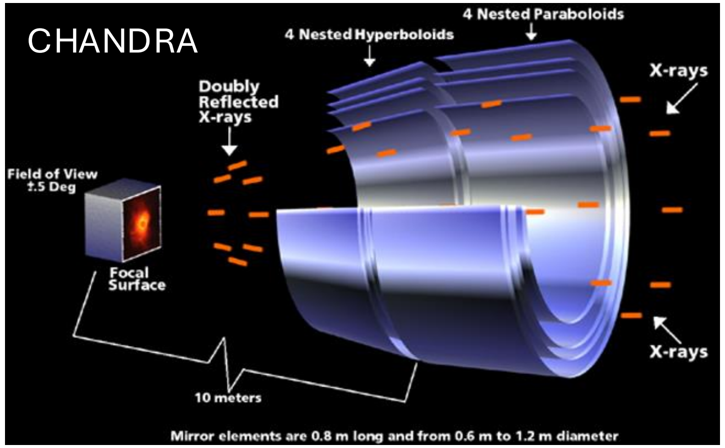
pSCT2019 inauguration



From light concentrators to Schwarzschild-Couder

2007: V. Vassiliev (UCLA) recovered the Schwarzschild-Couder solution and proposed to apply it to **Cherenkov telescopes**

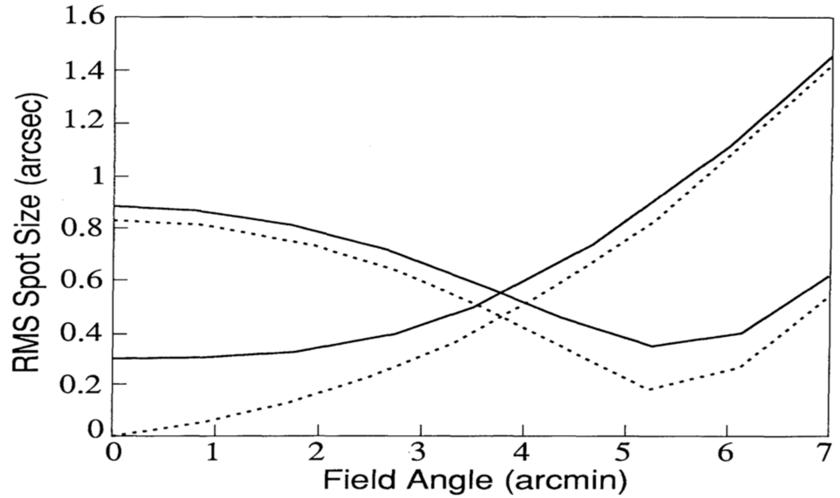
2020: P. Conconi applied Burrow, Burgs, Giacconi solution to modify the CHANDRA X-ray satellite design with **polynomial solution**



- Defines the surface profile allowing higher order polynomials admitted
- Optimization of the imagery quality is on the FoV

$$\frac{\rho_1^2}{\rho_0^2} = \sum_{i=1}^{n1} a_i \left(\frac{z_1}{\rho_0} \right)^i \qquad M = \sqrt{\frac{\int \theta \sigma^2 \, d\theta}{\int \theta \sigma \, d\theta}}$$

Burrows, C. J., Burg, R., & Giacconi, R. 1992, ApJ, 392, 760



Solving Seidel conditions On axis → Ray-tracing optimization On the FoV

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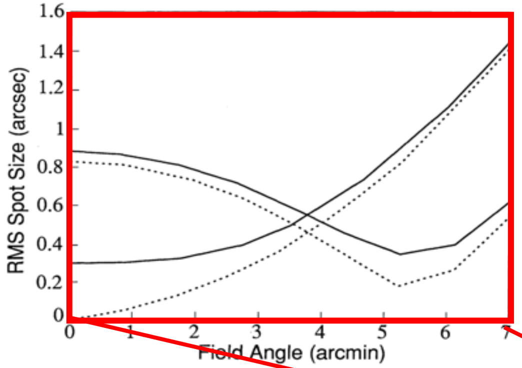
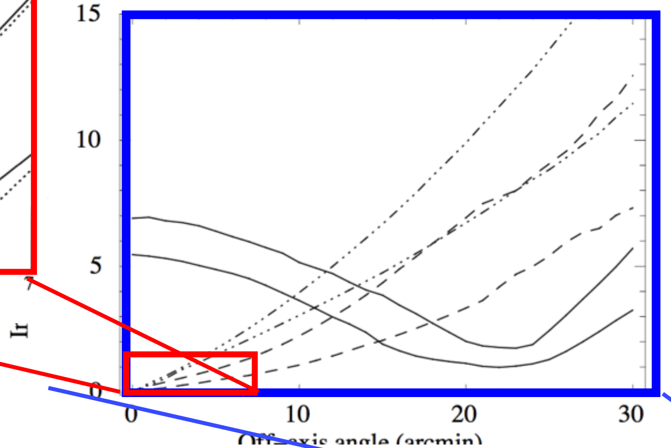
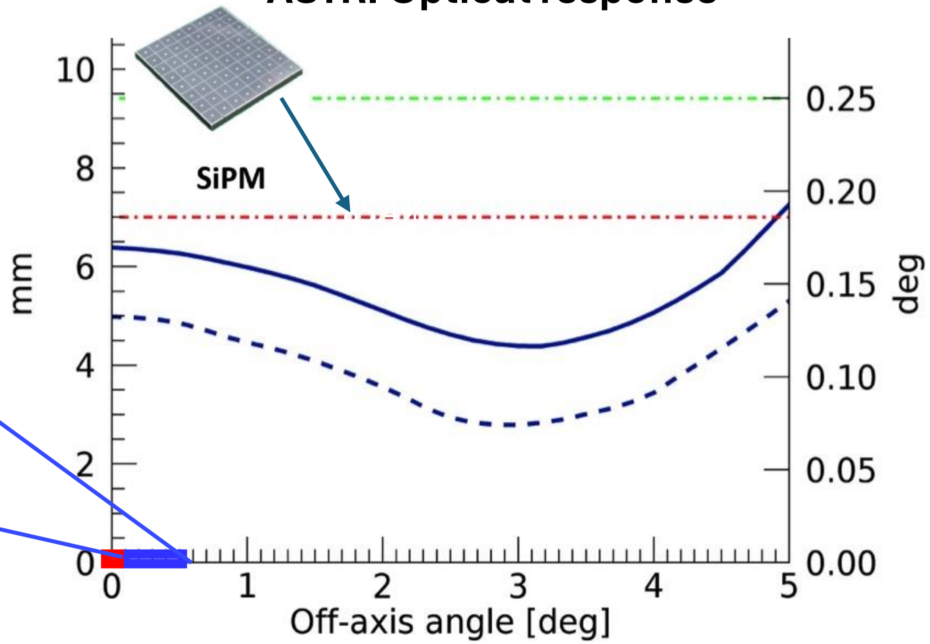
CHANDRA upgrade, Burrows et al. 1992



WFXT, Conconi et al. 2010



ASTRI Optical response



Real angular resolution is never perfect!!
On-axis value can be set at the expected manufacturing and alignment errors

From light concentrators to Schwarzschild-Couder

2011 INAF funded the development of an end-to-end Cherenkov telescope

ASTRI Astrofisica con Specchi a Tecnologia Replicante Italiana

MIUR

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE

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ASTRI Astrofisica con Specchi a Tecnologia Replicante Italiana

ASTRI-HORN

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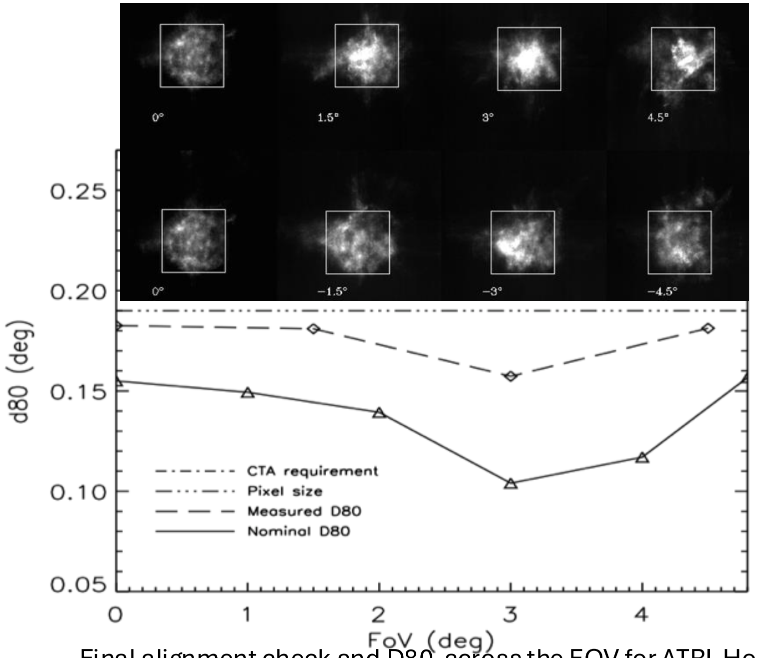
ASTRI-HORN



Final alignment check and D80 across the FOV for ATRI-Horn telescope (E. Giro, R. Canestrari, G. Sironi et al, A&A Volume 608, December 2017 https://doi.org/10.1051/0004-6361/201731602)

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2020 First Crab detection at Tev energies with a dual-mirror IACT

Astrofisica con Specchi a Tecnologia Replicante Italiana

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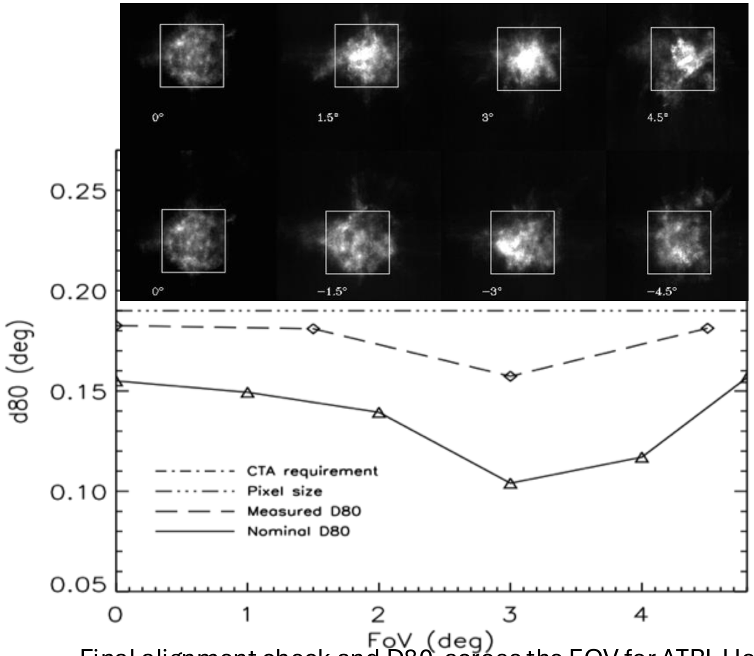
ASTRI-HORN



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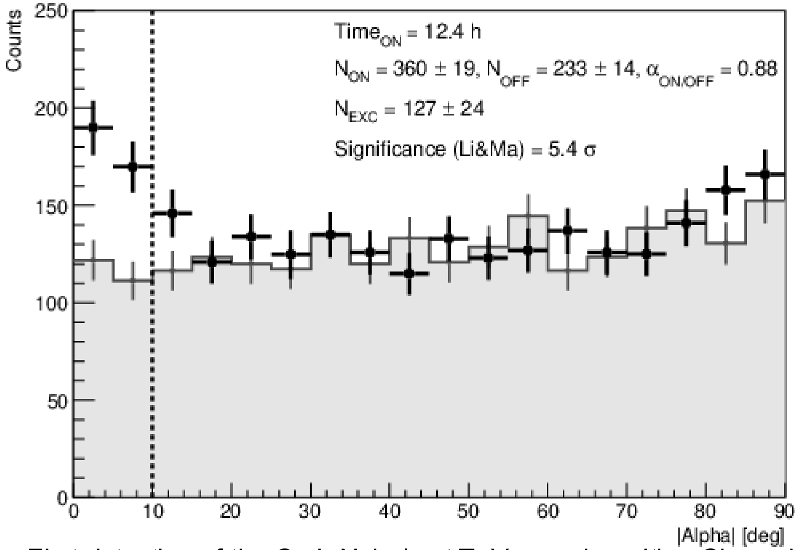

First detection of the Crab Nebula at TeV energies with a Cherenkov telescope in dual-mirror Schwarzschild-Couder configuration: the ASTRI-Horn telescope - Lombardi, S. et al - arXiv:1909.12149

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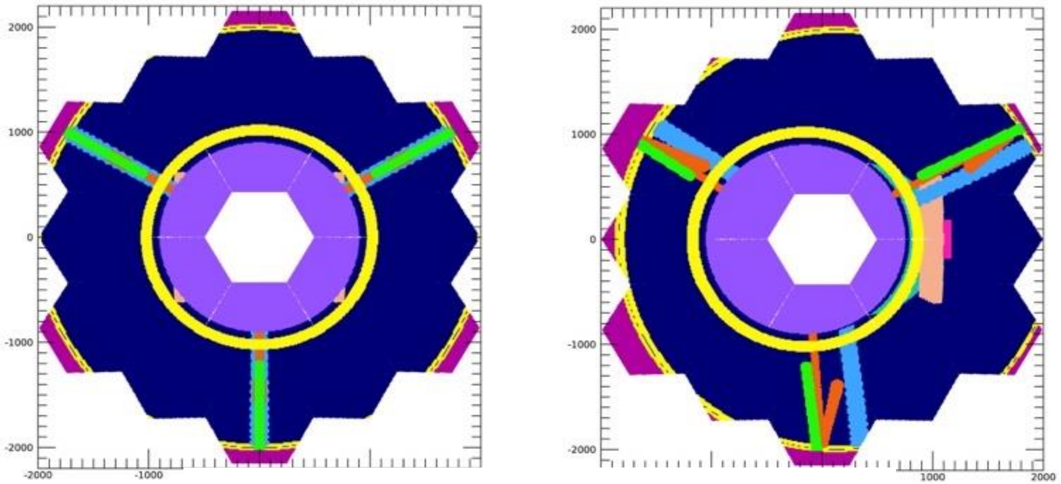
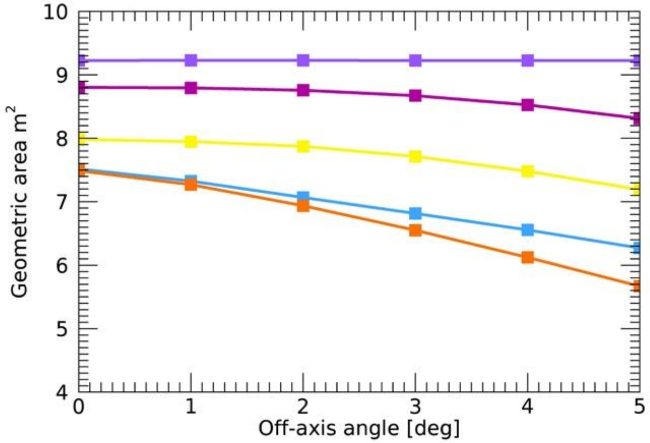
Drawbacks of dual mirrors

1. **Vignetting/blind camera**
   - M2 shadowing
   - No visibility of the sky from the focal plane
   - Auxiliary camera for pointing





ASTRI design fulfill area req (5.5 m) even at 5 deg off-axis

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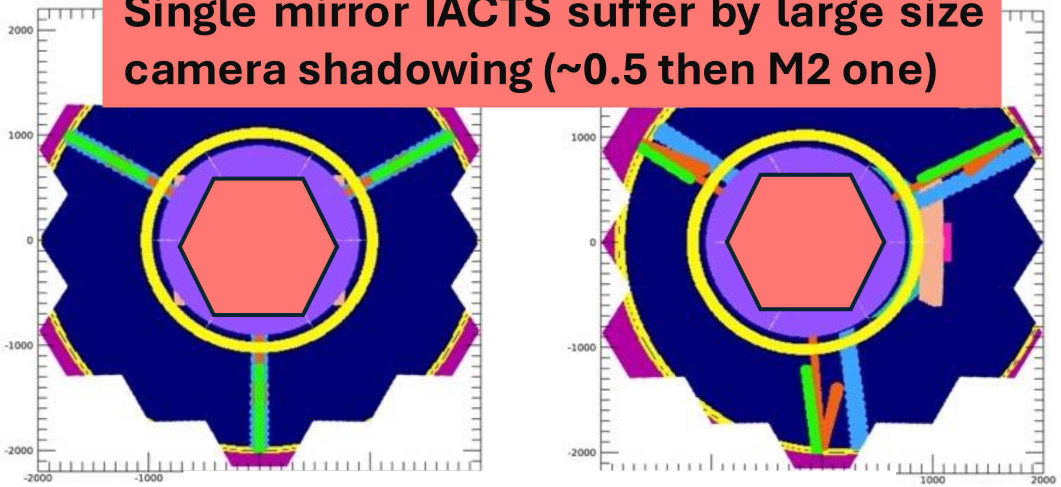
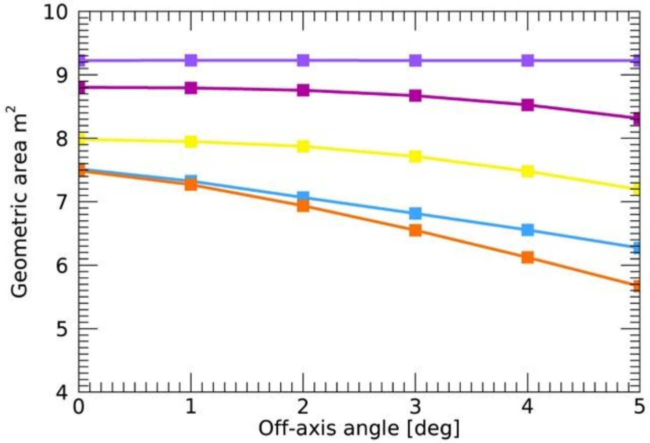
Single mirror IACTS suffer by large size camera shadowing (~0.5 then M2 one)





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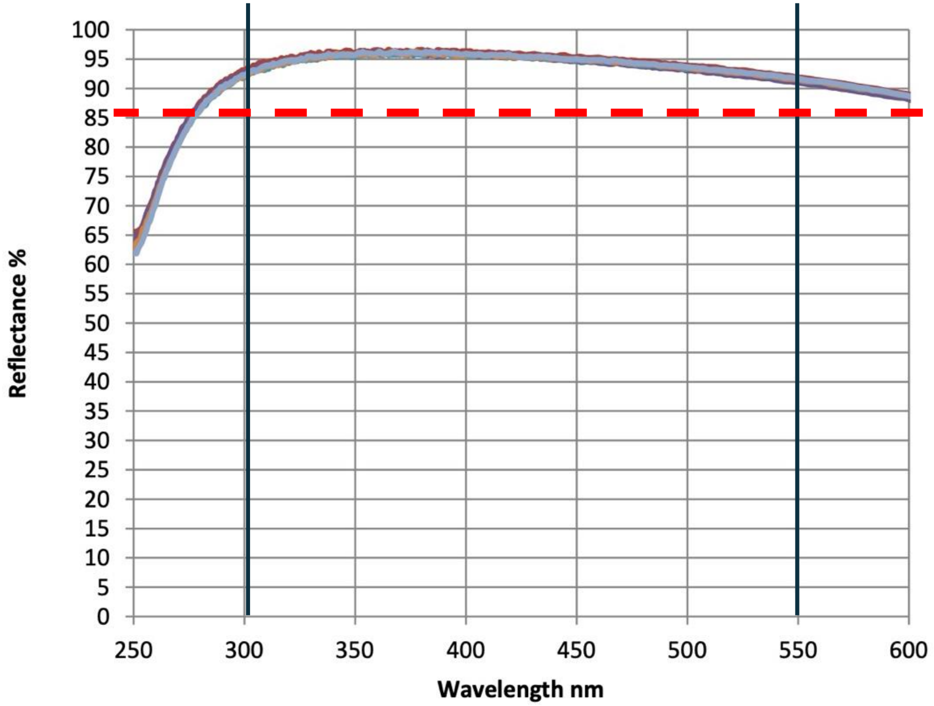
1. Vignetting/blind camera
2. **Double reflection – reflectivity accounts twice**

Requirement for CTA reflectivity

- R > 85% in wave-range 300-550 nm
- R disuniformity < 8%
- Environmental conditions

The developed Al+protective coating is well above requirement and resists to environmental exposure



Media Lario

ZAOT THIN FILM COATINGS

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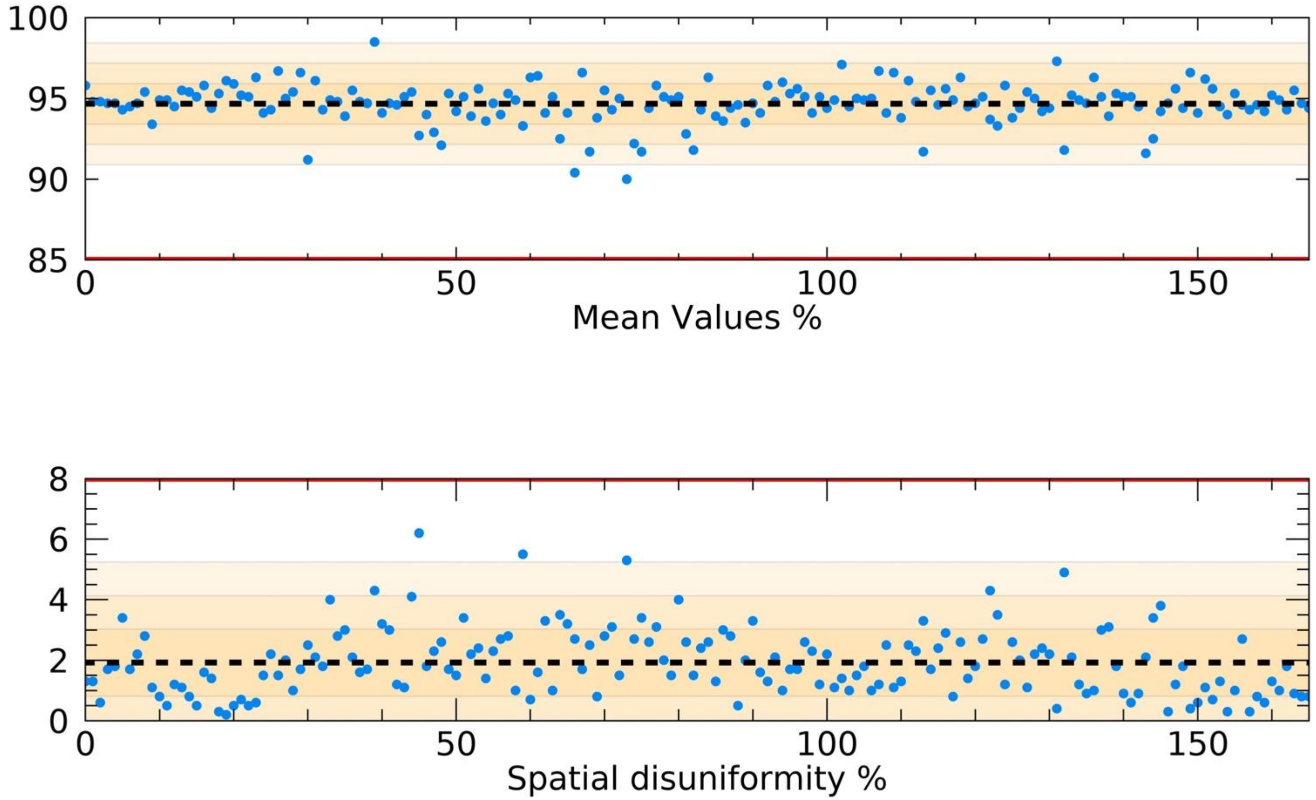
Requirement for CTA reflectivity

- R > 85% in wave-range 300-550 nm
- R disuniformity < 8%
- Environmental conditions



The developed Al+protective coating is well above requirement and resists to environmental exposure

From concept to implementation: nothing comes for free

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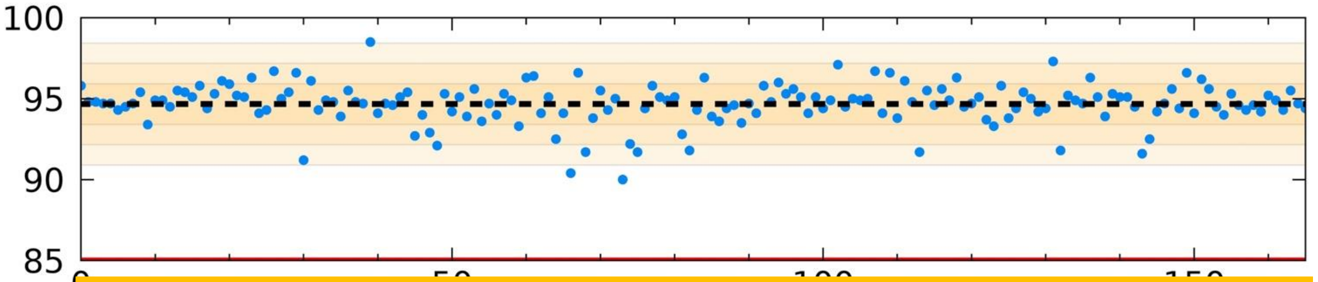
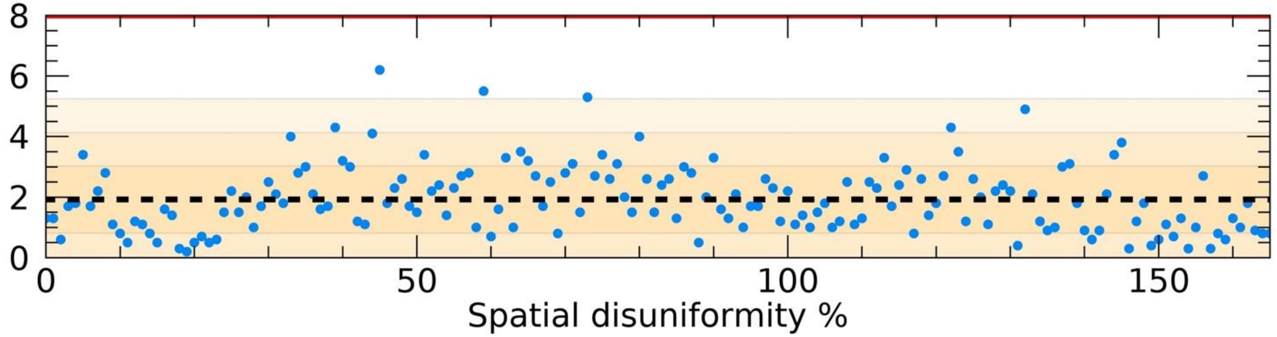


Media Lario latest mirror production batch

Mean R=94%   **Double reflection R = 88%**



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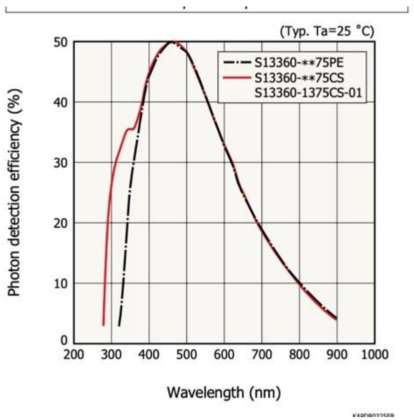
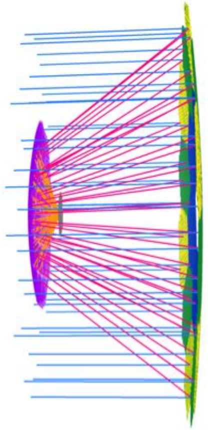
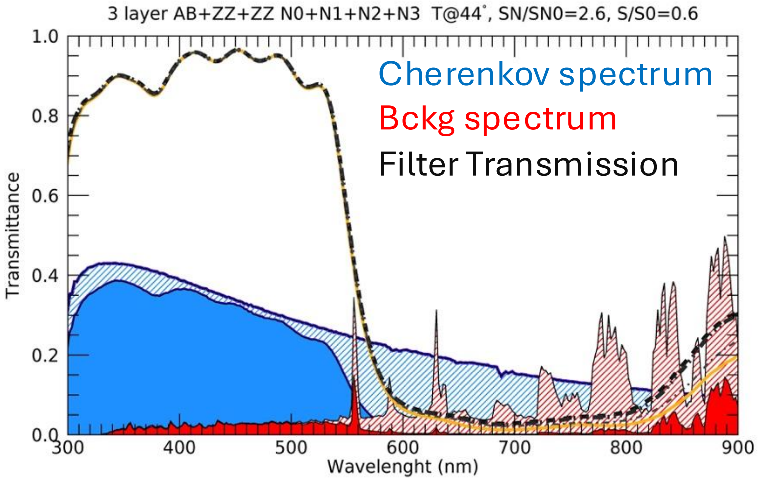
3. **Filtering window complexity**

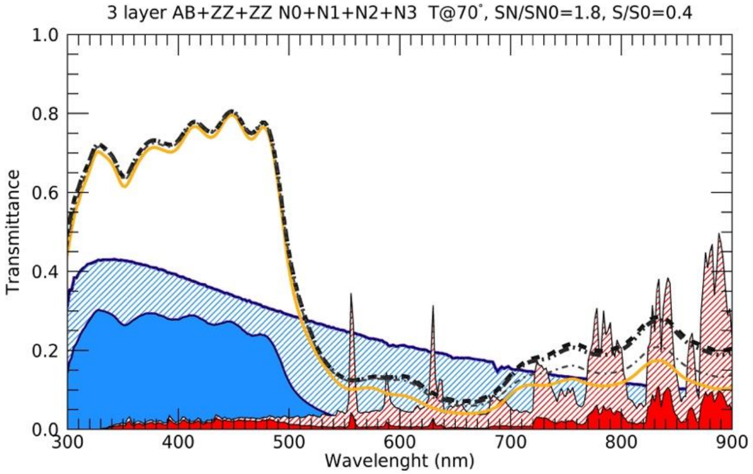
- SiPM are sensitive from 300 to 900nn
- A filter is required to cut the red background
- Energy cut-off depends on incidence angle
- ASTRI incidence angle at focal plane range 10-70 deg





Study for ASTRI Mini-Array filter





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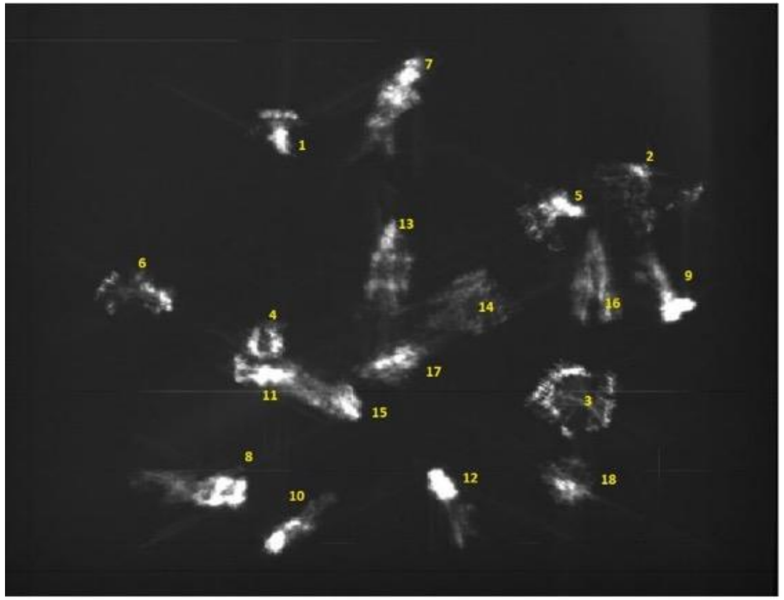
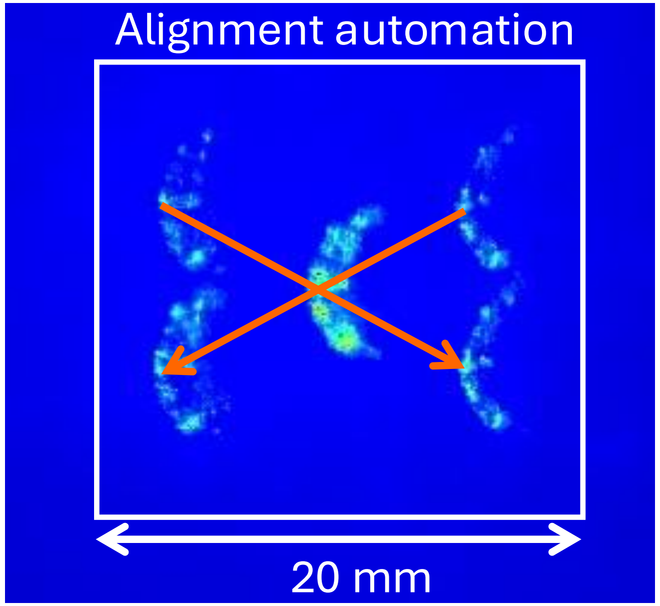
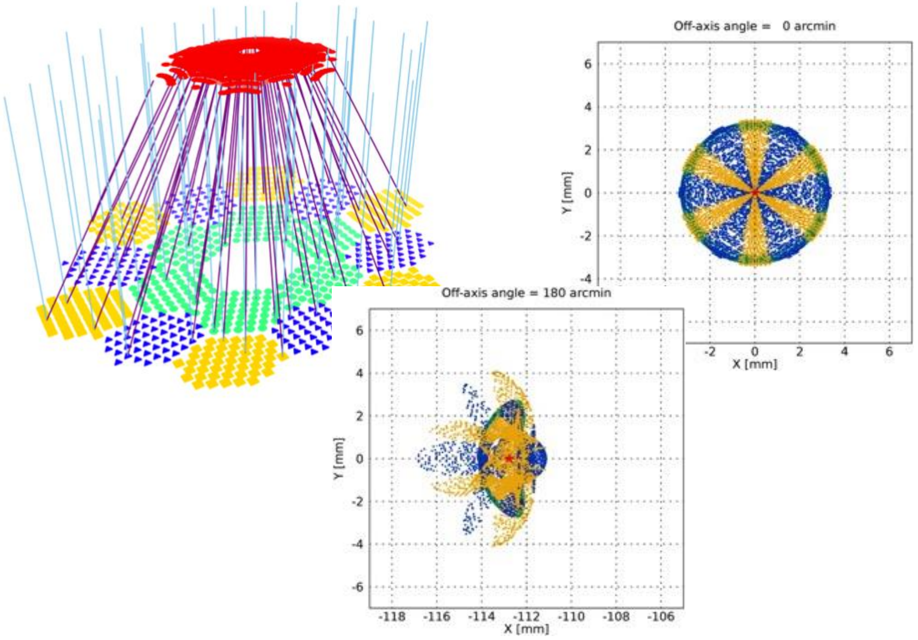
4. **Alignment complexity**

Auxialiry camera required for alignment







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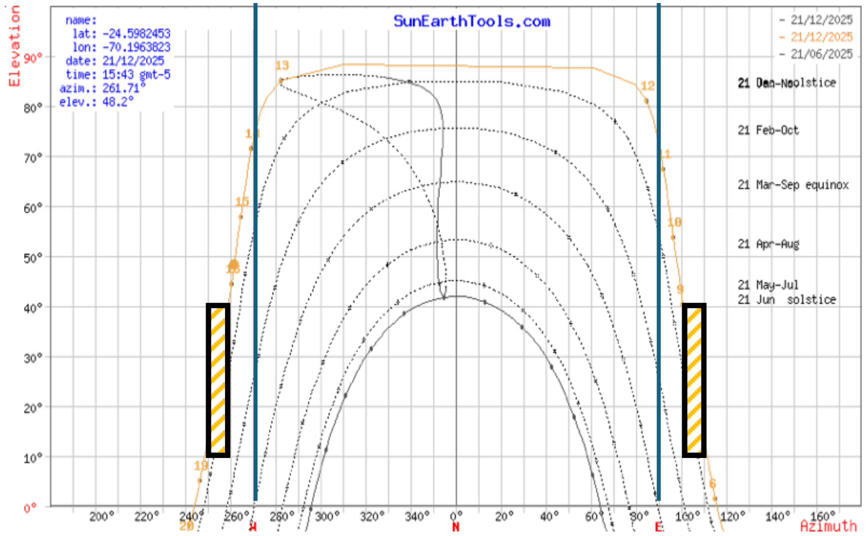
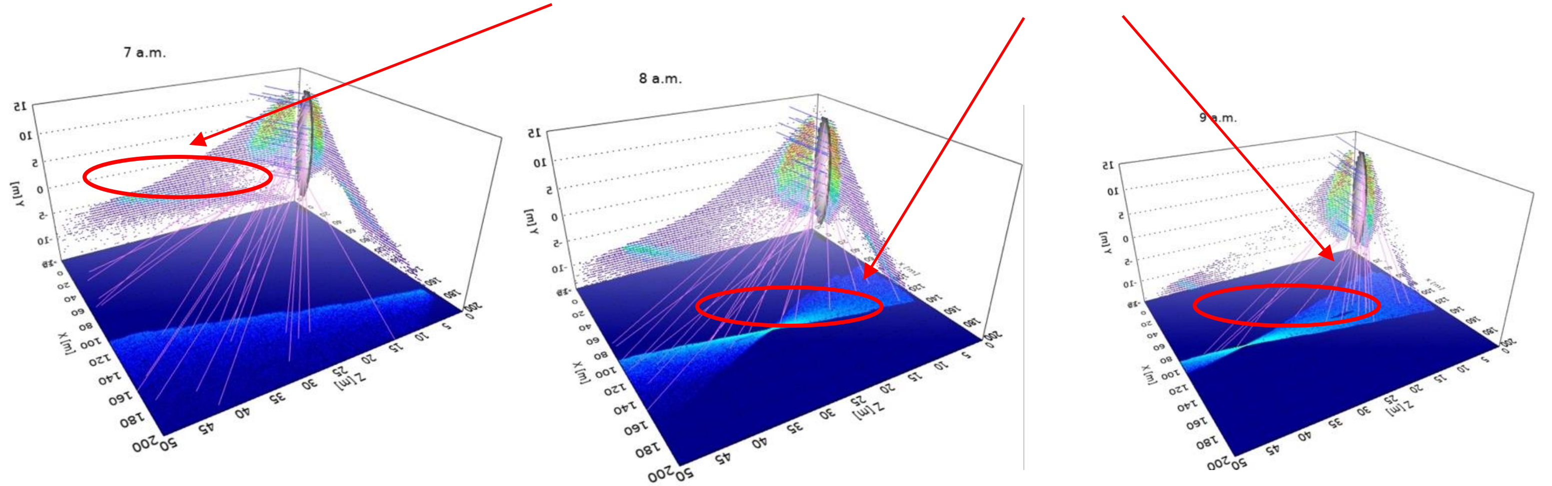
   - For all IACTS solar concentration shall be studied
   - Parking position is chosen to avoid solar reflection



Hot spots on air

Concentration area on the ground



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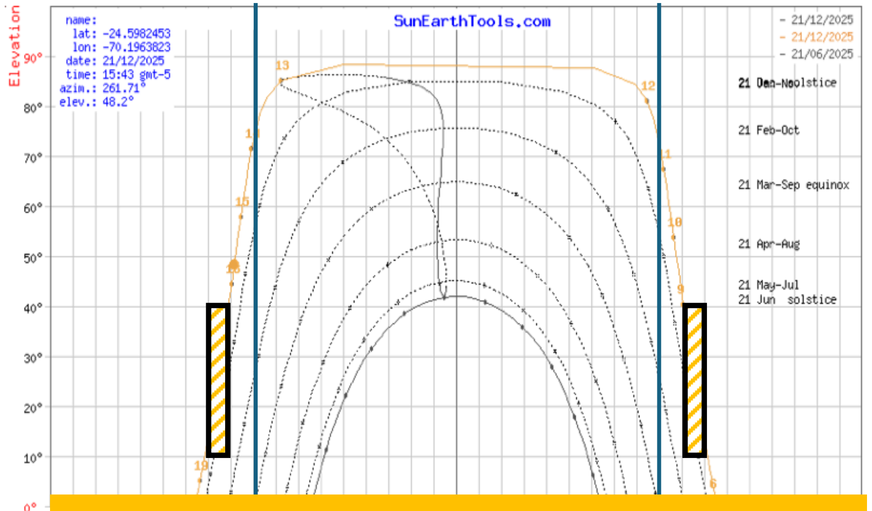
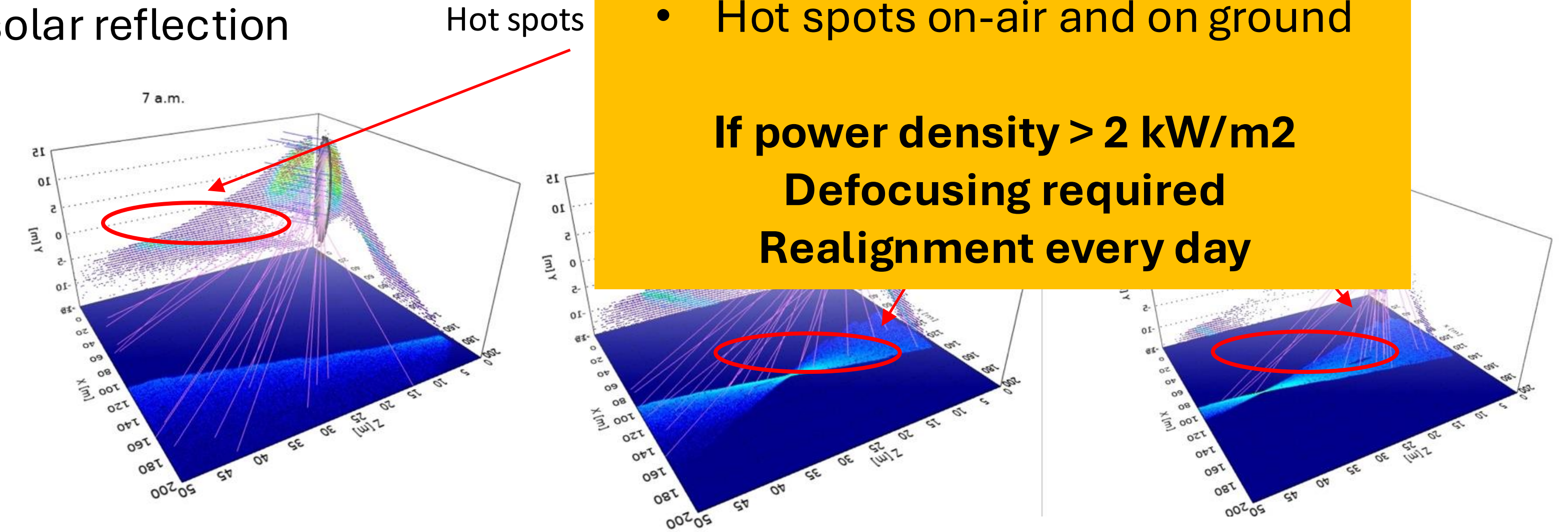


Single mirror case
- Hot spots at down/sunset
- Hot spots on-air and on ground

If power density > 2 kW/m2
Defocusing required
Realignment every day



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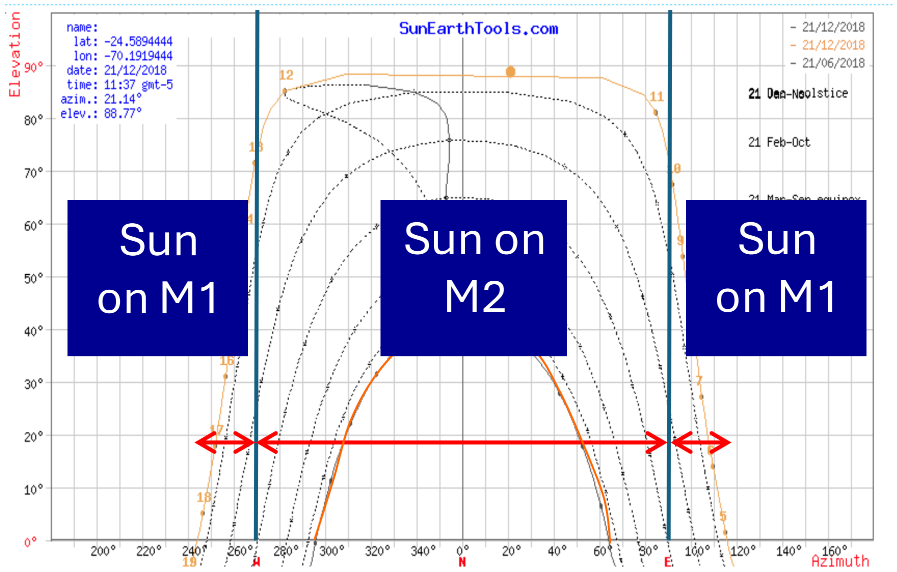

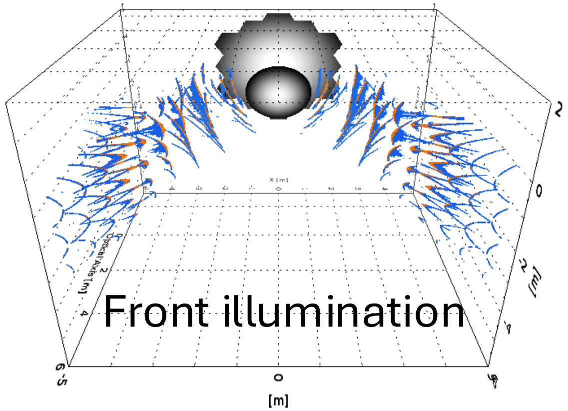

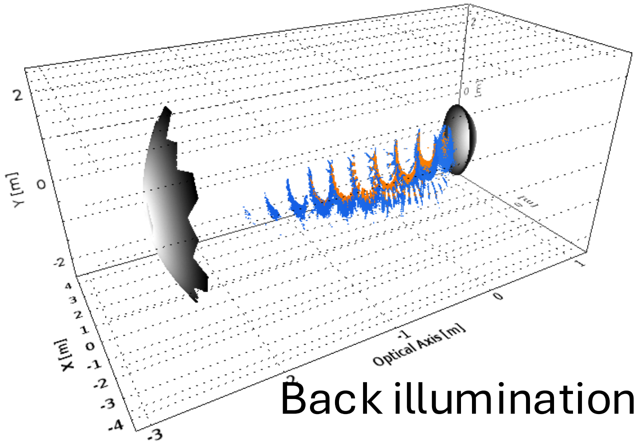

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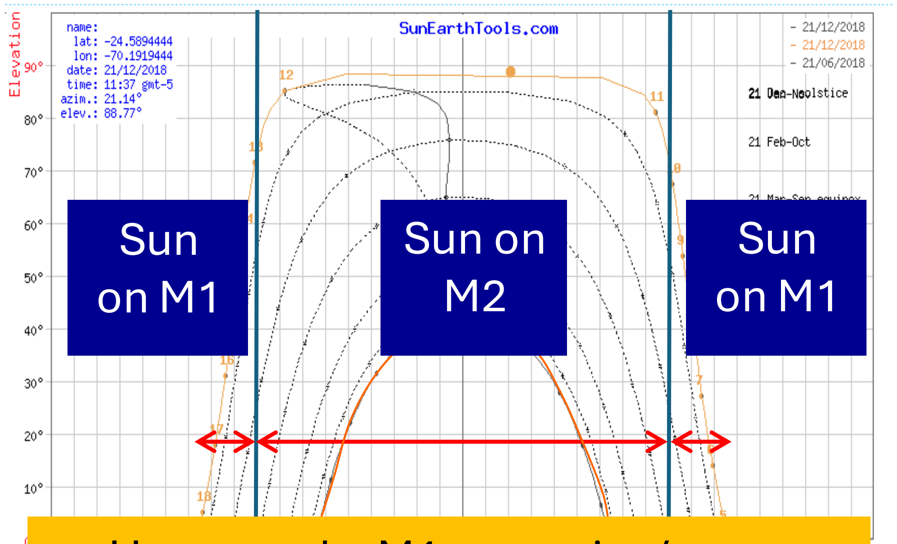
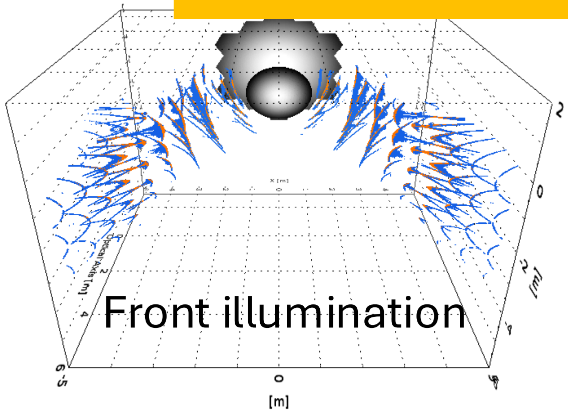
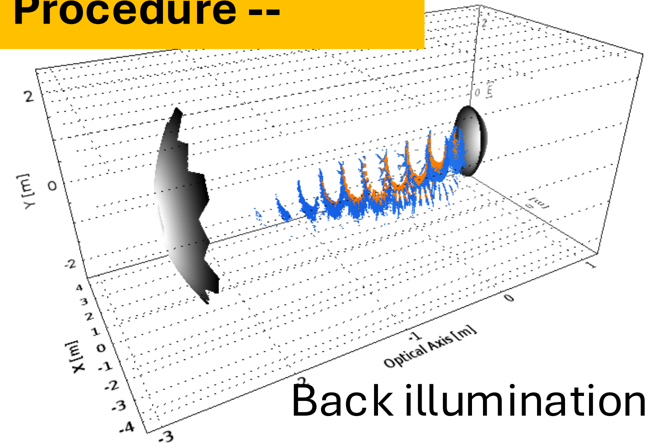


- Hot spots by M1 at sunrise/sunset
- Hot spots by M2 at noon
- Hot spots only on-air

-- Maintence Procedure --



Front illumination



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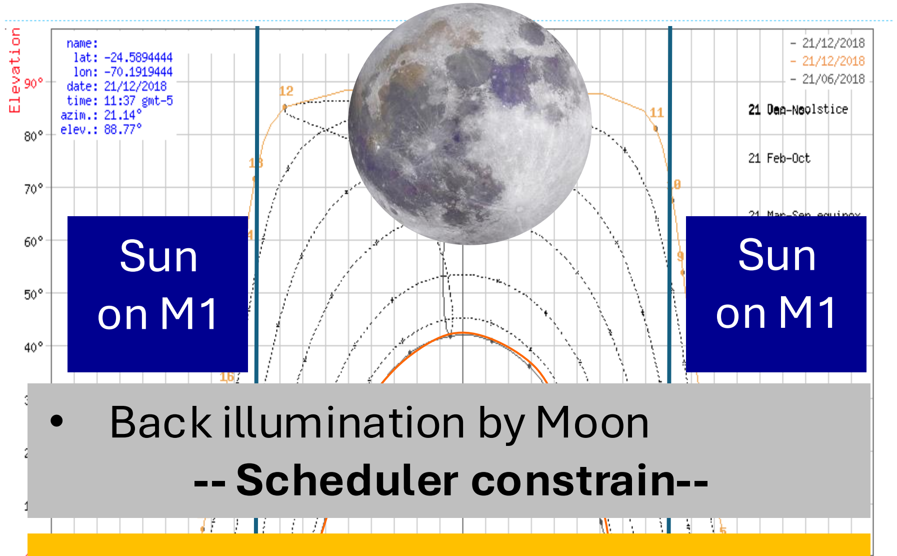

Sun on M1

Sun on M1

- Back illumination by Moon

-- Scheduler constrain--

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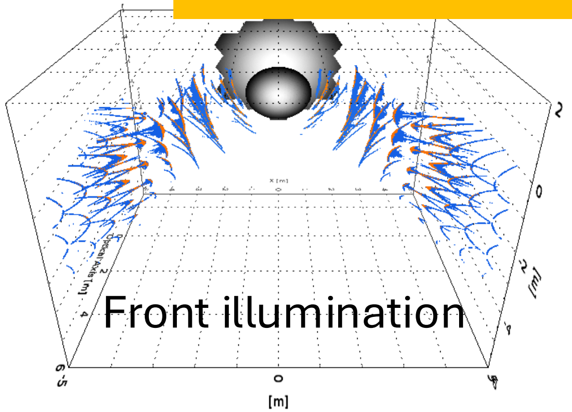

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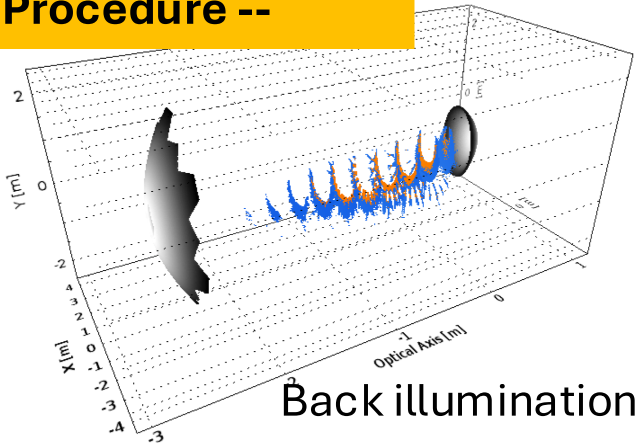

Back illumination

- From scientific to design requirements
- From light concentrators to Schwarzschild-Couder
- From concept to implementation: nothing comes for free
- **From 9 to 40**

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Advantages of dual mirrors

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Diameter M1	4 m	4 m
Focal lenght	2.15 m	5.6 m
Plate scale	**37.5 mm/°**	**98 mm/°**
D80 across FoV	**Comatic**	**Flat**

- Flat response across FoV
- Factor 2.5 in focal length
- Factor **2.5** plate scale
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From 9 to 40

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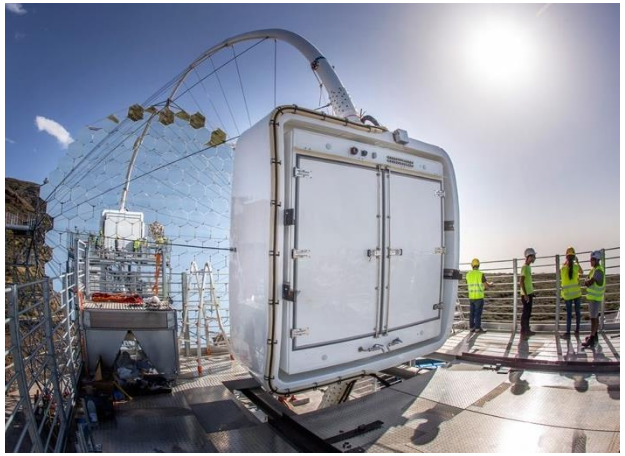

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- Realization (# sensors)
- Operation (weight, power consumption)
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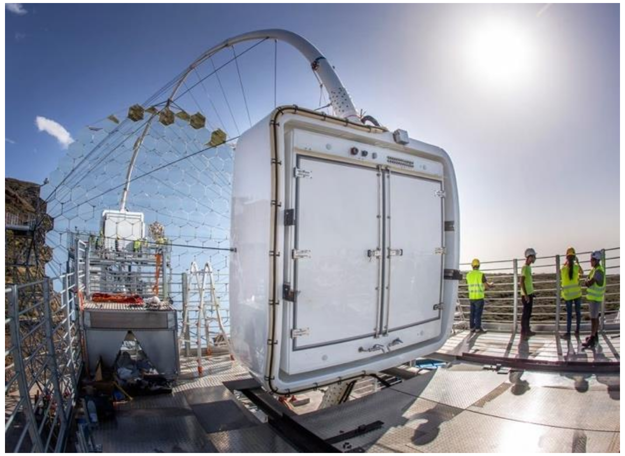

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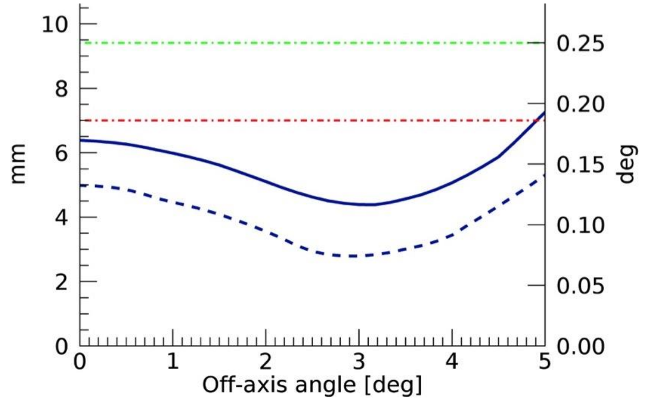
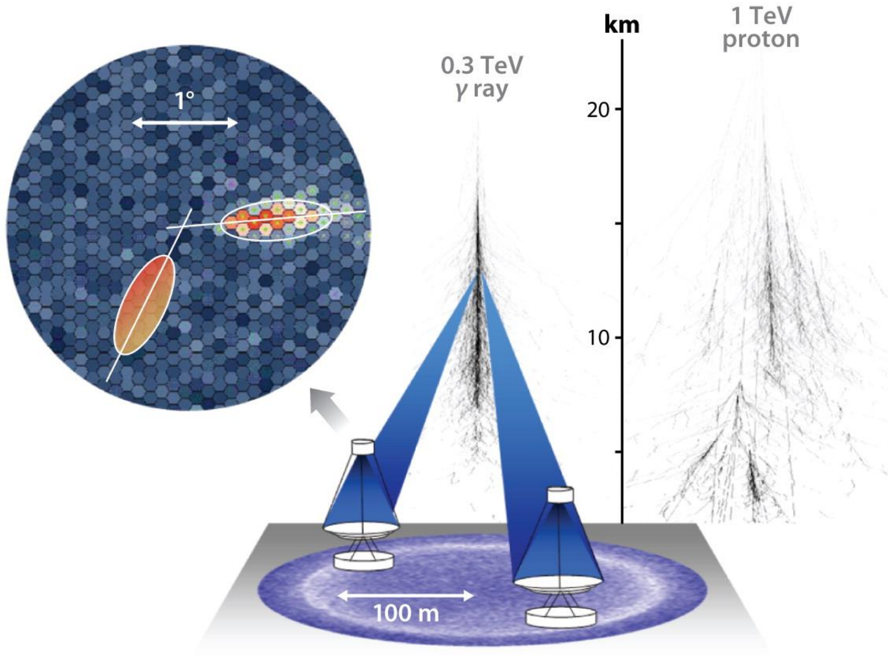
Array Concept

- **Distance between telescopes** is optimized by Monte Carlo simulation fine-tuning on the basis of the energy of the target sources
- Telescopes FOV and PSF across FOV are crucial elements for this evaluation
- ASTRI telescopes guarantee PSF within a physical pixel on a field of ~10 deg
- **ASTRI telescope can stand separation up to 250-300m!**

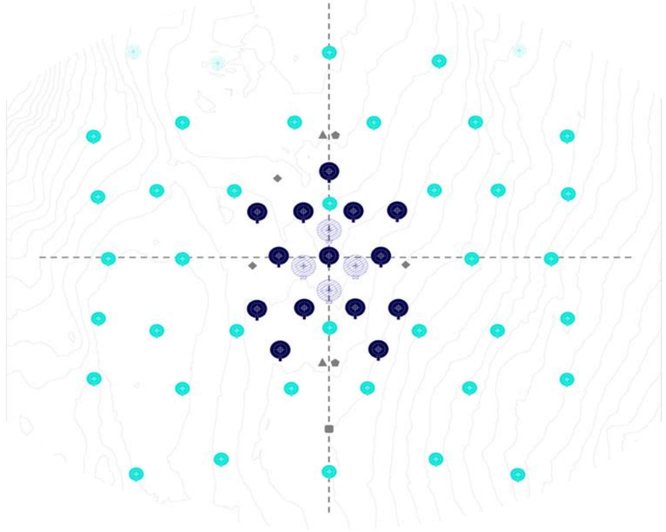




Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

ASTRI Mini-Array 9 telescopes
Ground area ~0.2 km2

CTA-S 37 SST telescopes
Ground area ~ 3 km2



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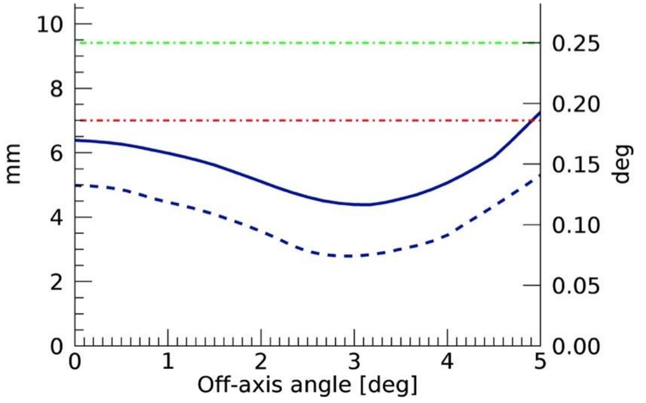

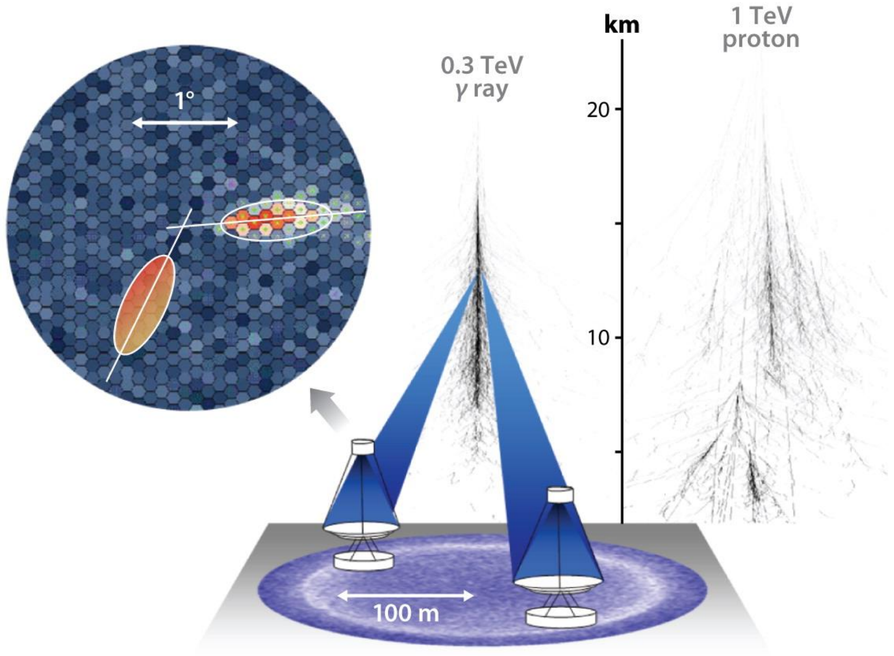

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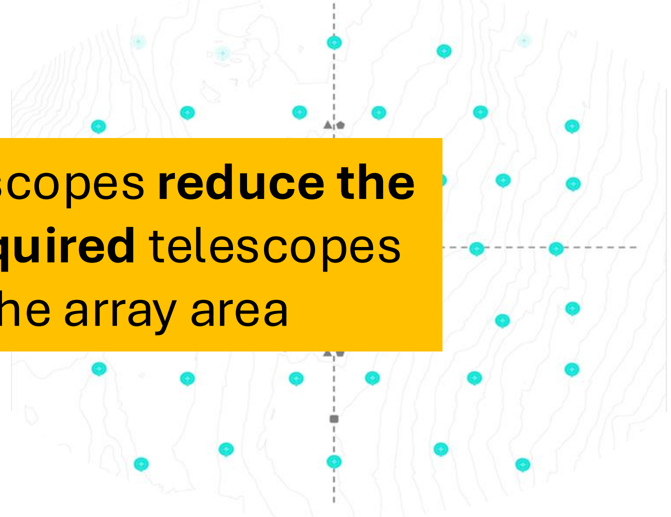
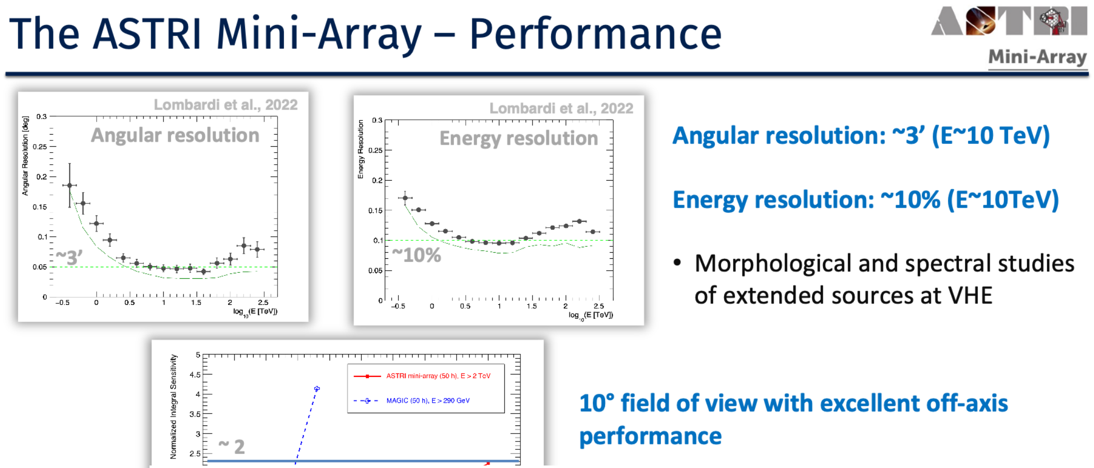
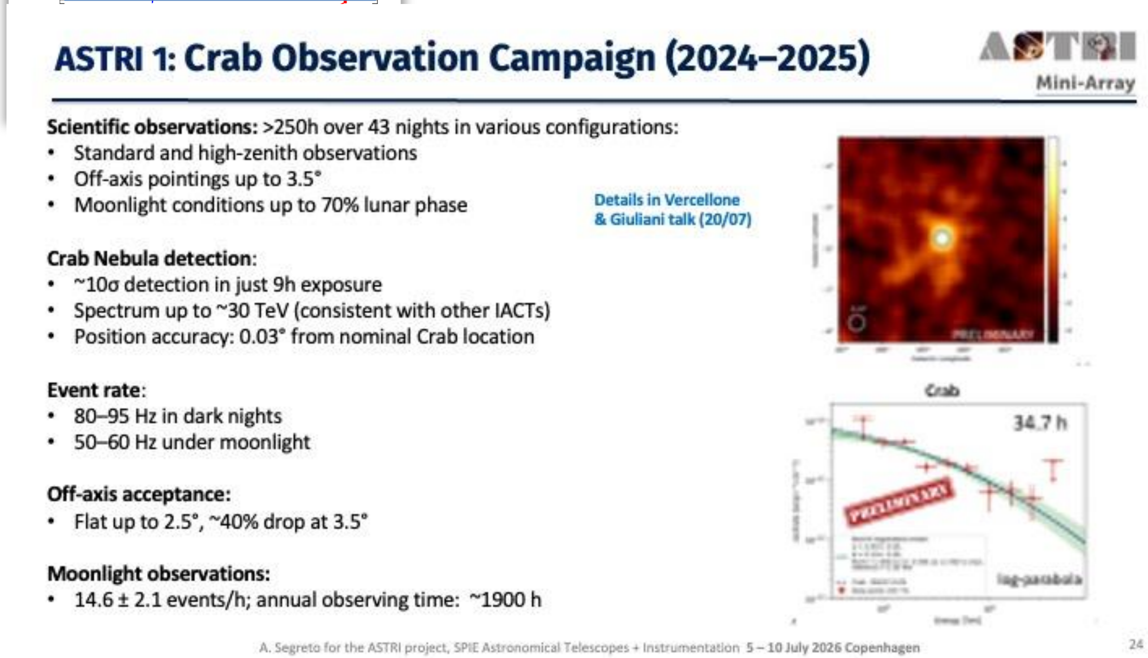


ASTRI like telescopes **reduce the number of required** telescopes to cover the array area

From 9 to 40

Mini-Array





See talks by S. Scuderi and G. Tosti for project updates
See talks by S. Vercellone, A. Giuliani for early results
See all the ASTRI Mini Array project talks and publication for details!!

From 9 to 40

2022: ASTRI-1

2026: 9 ASTRI telescope at ASTRI Mini-Array

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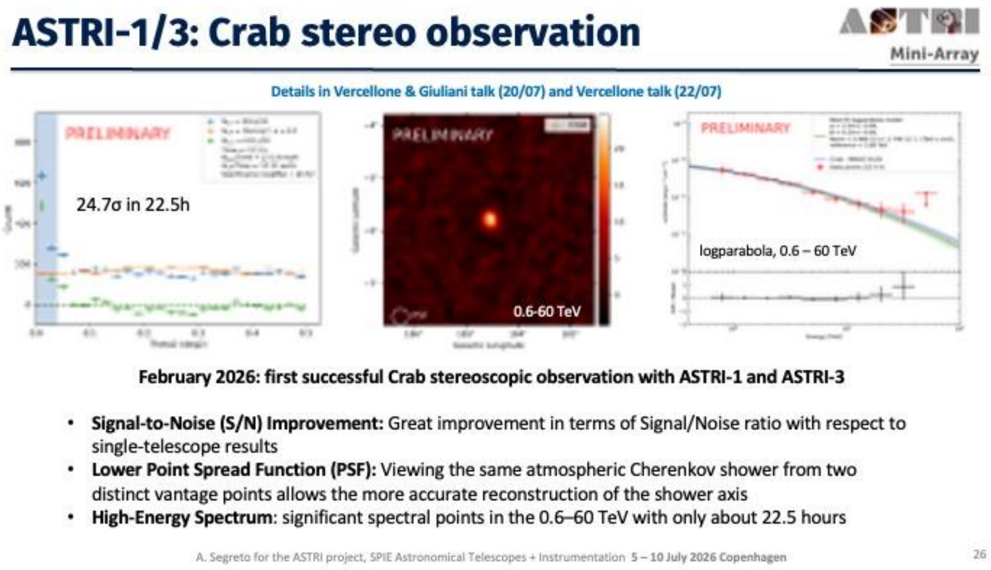
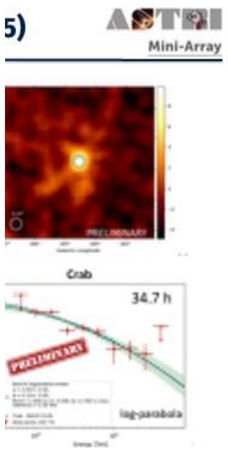
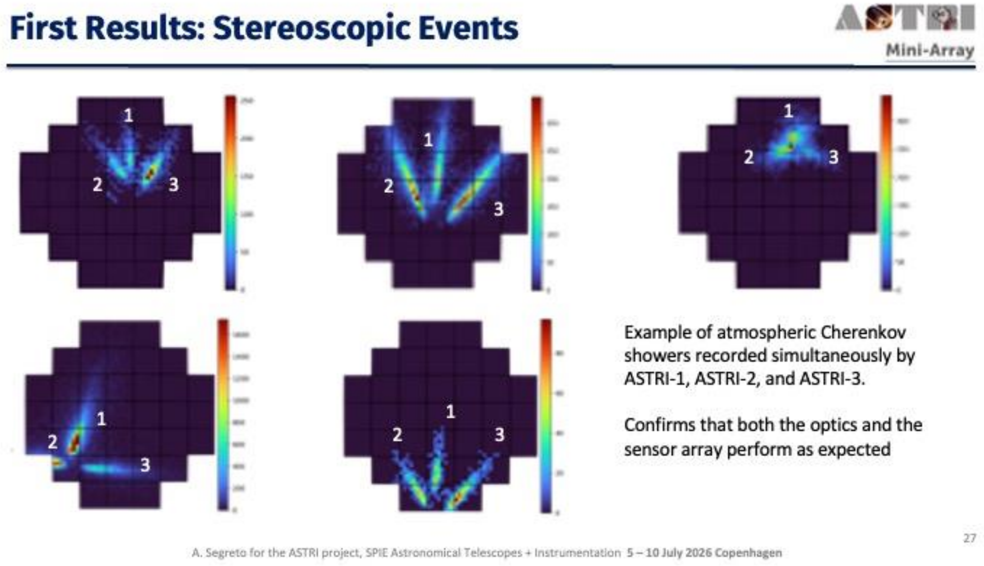
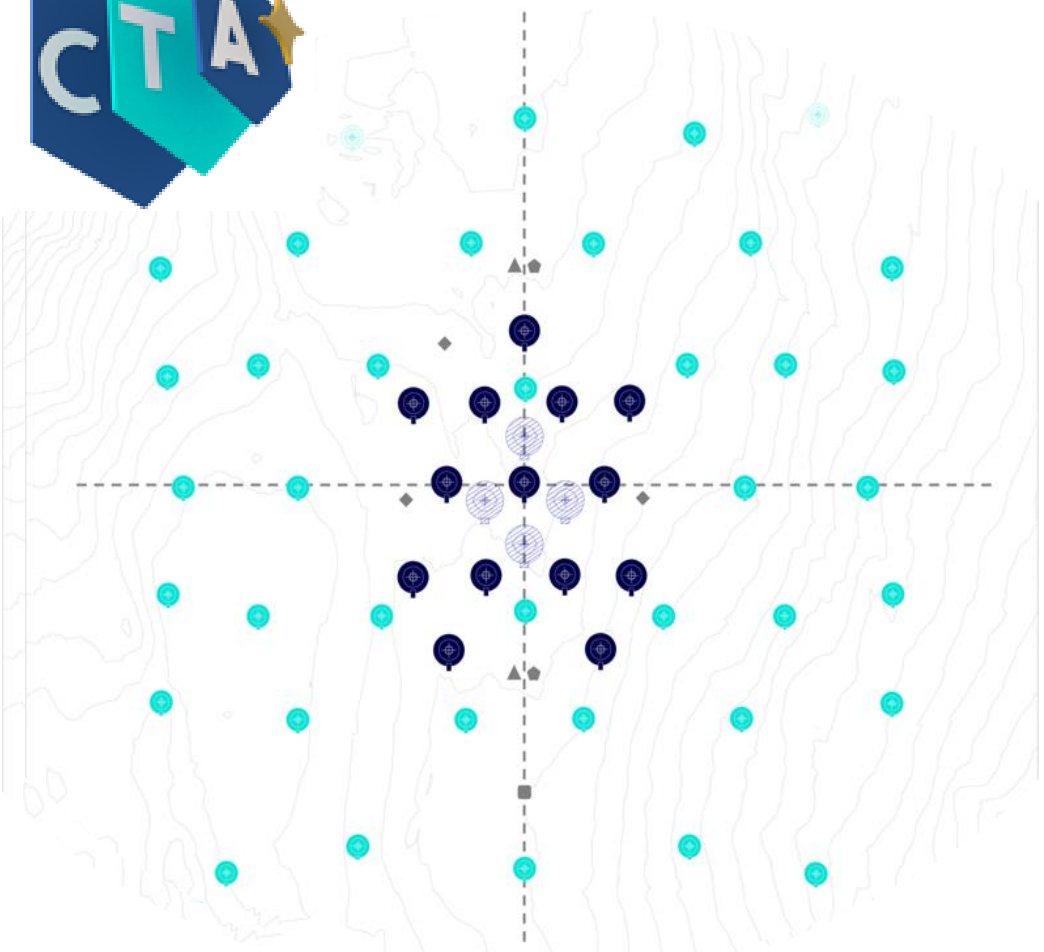




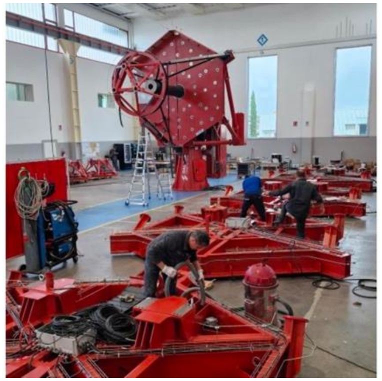


From 9 to 40

2027: CTA-SST installation will start at CTAO South site



- 10 CTA-SST telescopes completed in PNRR framework



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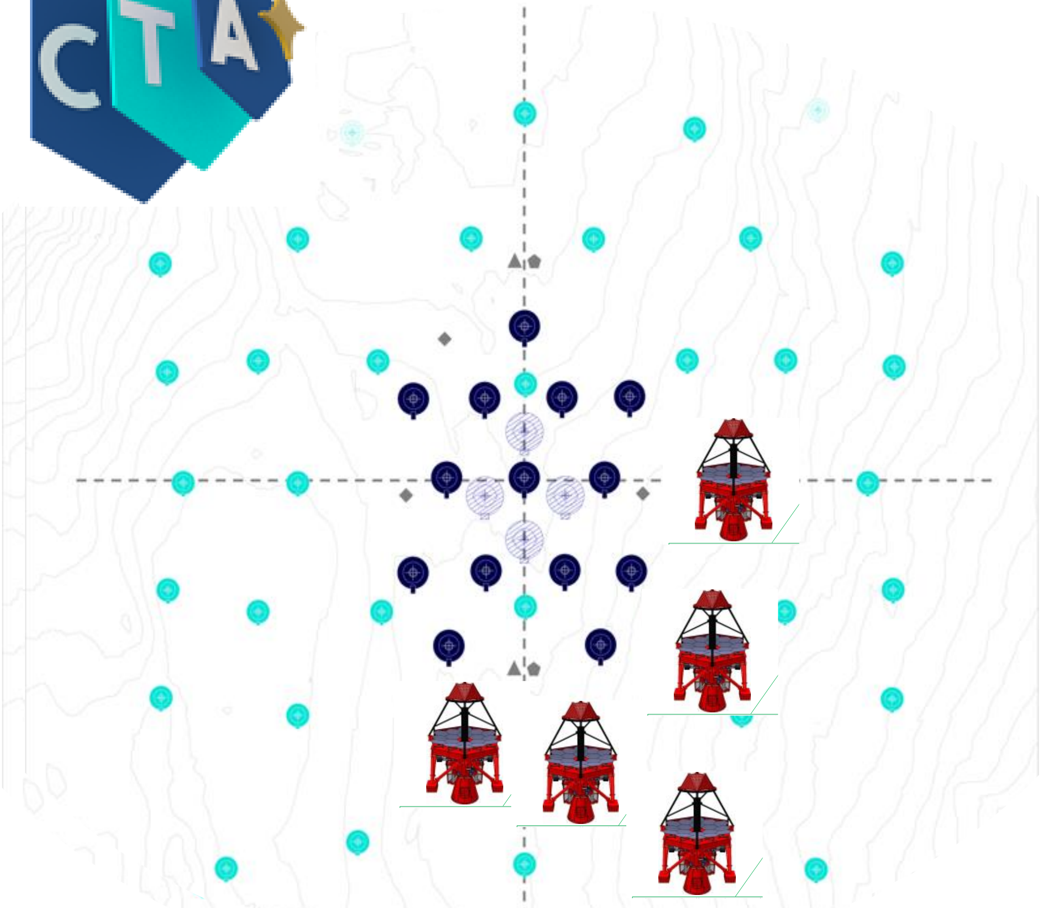

…we will start to join the dots

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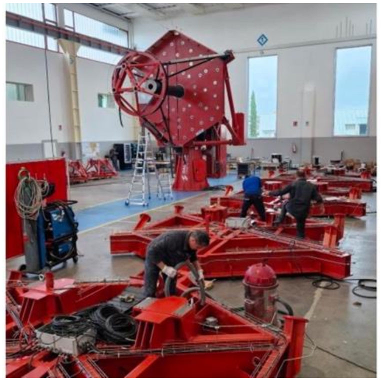

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From 9 to 40

20 years ago Schwarzschild–Couder design was proposed for IACT

It is no longer a promising concept. It is now an operational technology