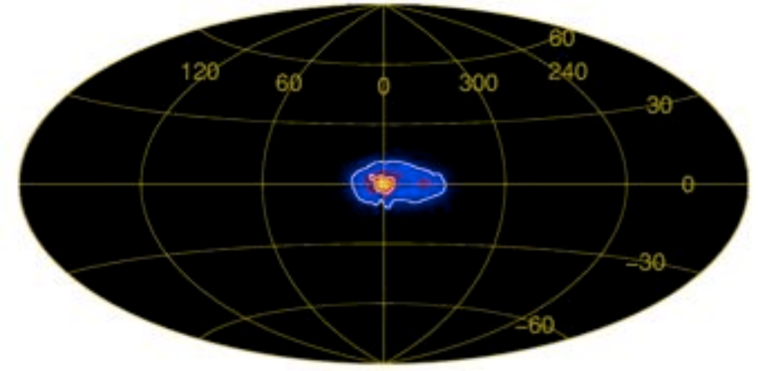
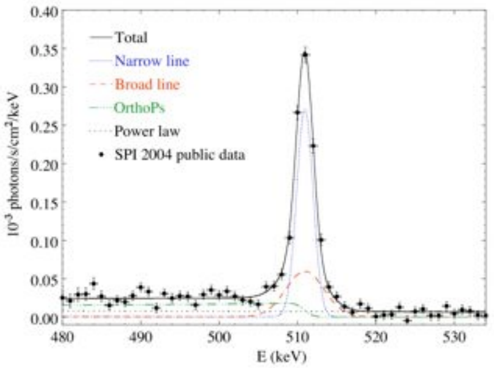
Soft Gamma Ray optics

Scientific goal, example

Origin of Galactic positrons?



[Weidenspointner et al., Nat 2008]



[Jean et al., A&A 2006]

Morphological analysis by model fitting :

- Bulge : 2 Gaussians : 3º& 11º FWHM, Flux ~ 10^{-3} ph/s/cm^2

⇒ No point sources

⇒ B/D ~ 1 : old star population favored if e+ annihilate close to their sources

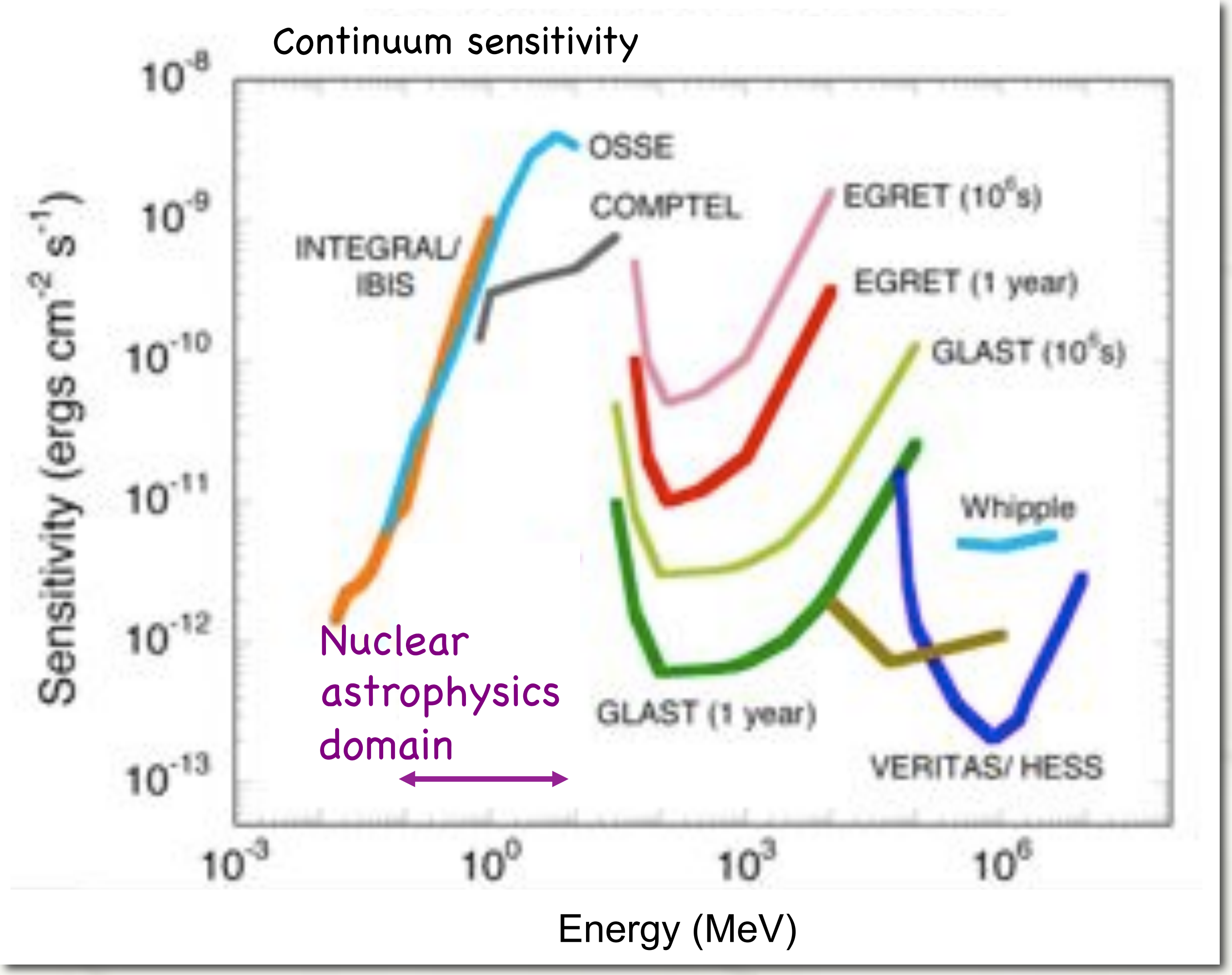
⇒ Similar asymmetry in the distribution of Low mass X-ray Binaries emitting at high energy

Spectroscopy of emission coming from the bulge:

⇒ Positrons annihilates in the warm and partially ionized phase

⇒ Emission from molecular clouds < 8% and hot gas < 0.5 %

Sensitivity of gamma-ray telescopes



Courtesy: S. Boggs

Hard X-ray Focusing by mosaic crystals

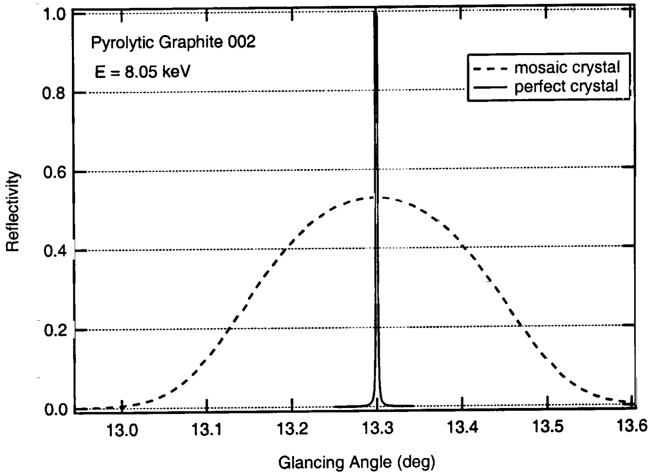
- Bragg diffraction from a crystal lattice ➔ reflectivity peaks at:

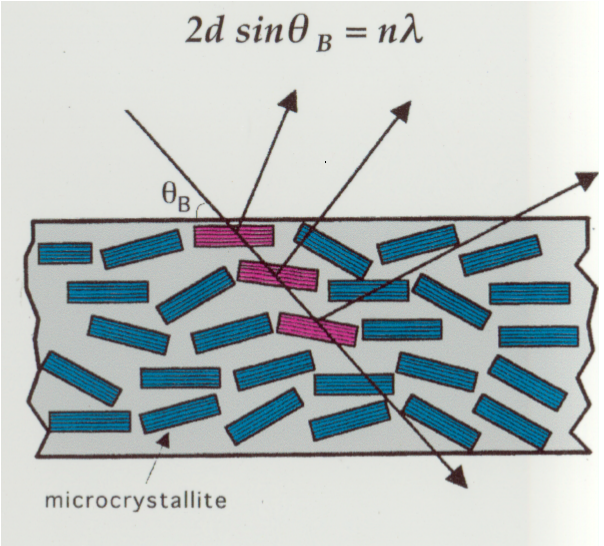
  $2\,d \sin \theta = n\,\lambda$

d typical value of a few Angstroms

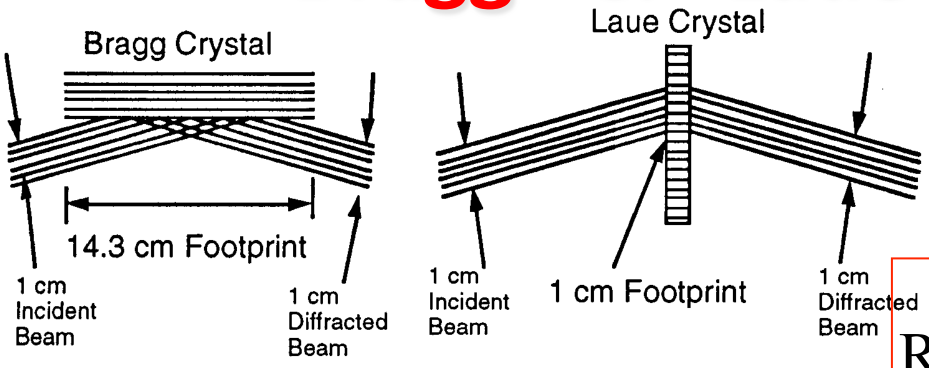
- mosaic crystals: at microscopic level a structure of microcrystals almost-parallel to the external crystal surface. The distribution of the crystallites normals is described by a Gaussian law

- each crystallite reflects in an independent way (without any interferometric coupling with the beams reflected from the other crystallites) ➔ the integrated reflectivity results to be much larger (>100) than for a perfect crystal case





“Bragg” & “Laue” Configurations

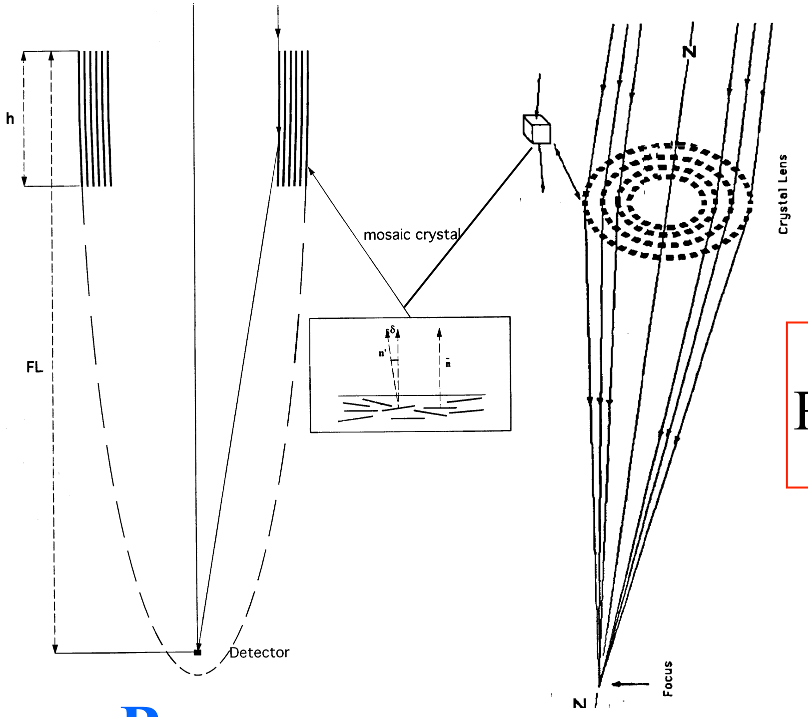


Bragg

$$\mathrm{Re}f_{\mathrm{int}\,eg} \propto \left(\frac{F}{V}\right)^2 \lambda^3 \frac{1}{\mu} \times FWHM_{Gauss}$$

Laue

$$\mathrm{Re}f_{\mathrm{int}\,eg} \propto \left(\frac{F}{V}\right)^2 \lambda^3 \frac{T}{\sin\theta} \times FWHM_{Gauss} \times e^{-\mu\frac{T}{\sin\theta}}$$



Bragg

Laue

F = Structure Factor

V = Volume of the lattice element

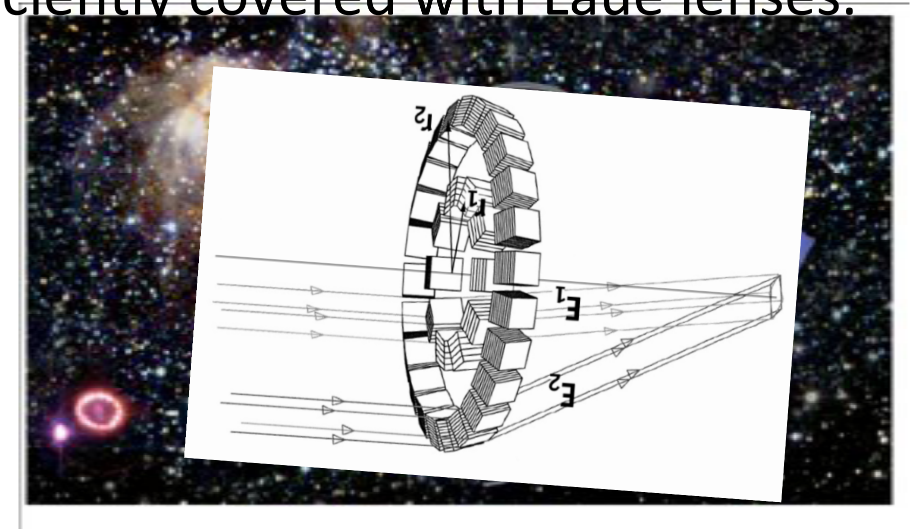
μ = lin. absorb. coeff

Why crystal diffraction for high energy telescopes?

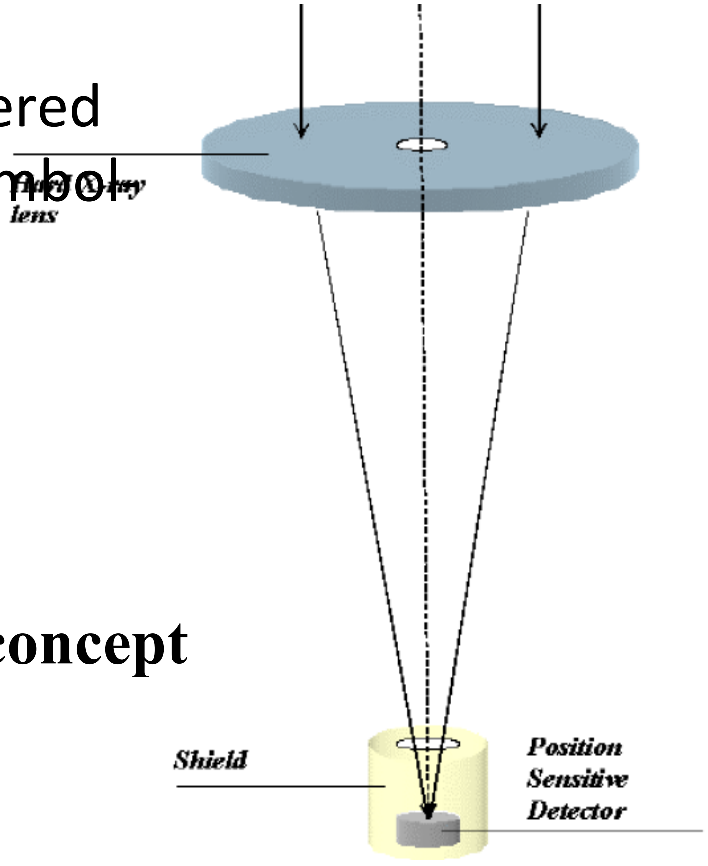
- Focusing optics in the hard X-/soft gamma-ray band is crucial for a significant leap

- The hard X-ray band (E<80 keV) can be covered with multilayer mirrors (NuStar, ASTRO-H, Simbol-X) .

- The higher energy band (>80 keV) can be efficiently covered with Laue lenses.

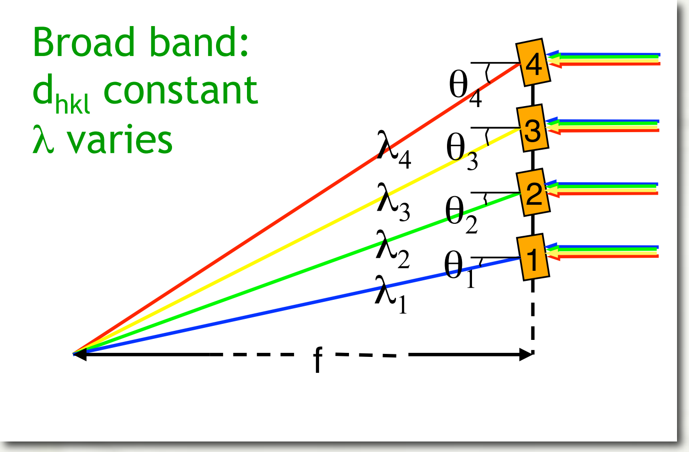


GRI concept

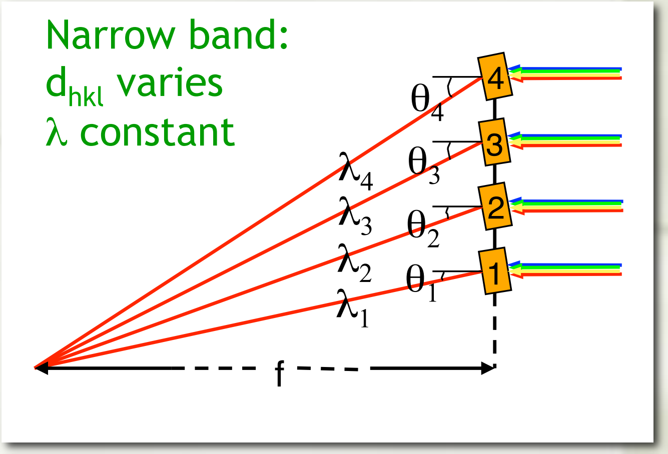


Two kinds of Laue lenses

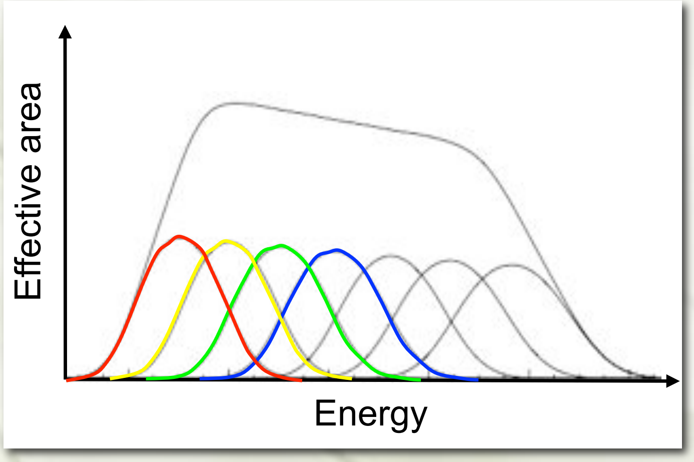
$$2\, d_{hkl} \sin\theta_B = n\, \lambda$$

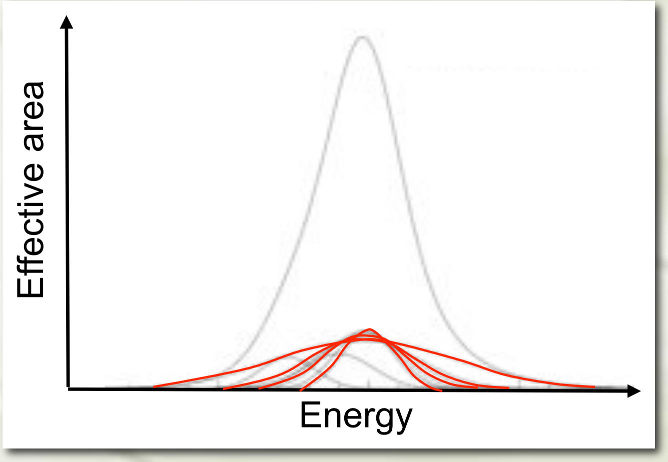


Broad band:
d_{hkl} constant
λ varies



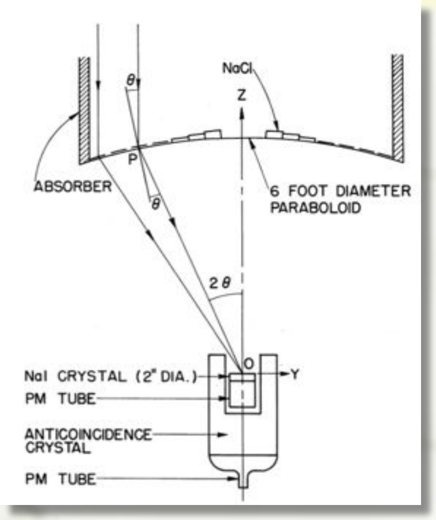
Narrow band:
d_{hkl} varies
λ constant

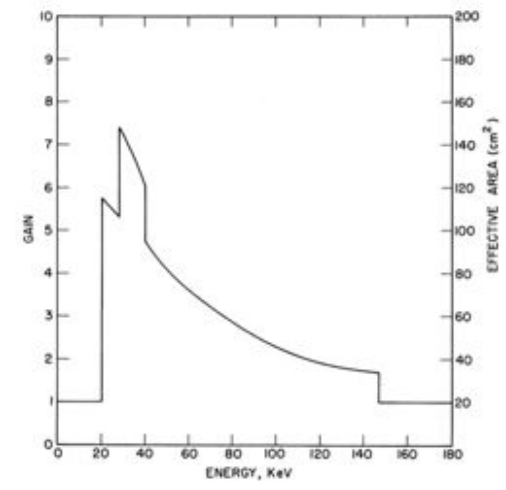




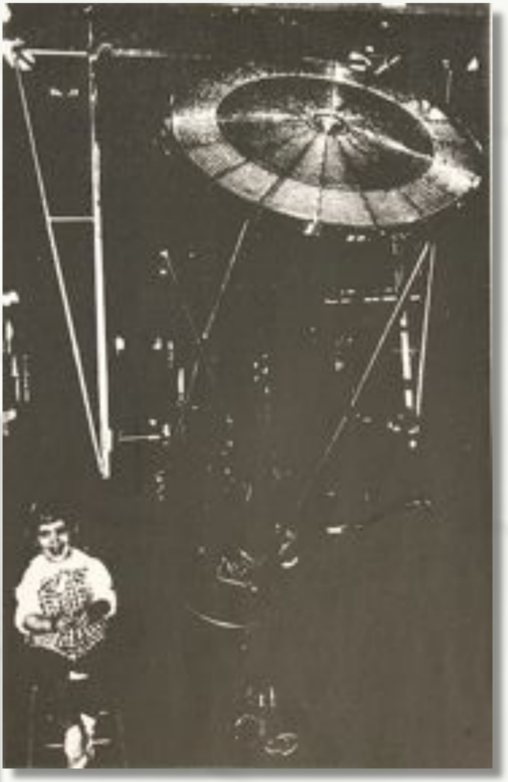
Credits. Barriere

An old concept





1967: 20 – 140 keV Hard X-ray lens



- 4000 rock salt crystals
- 3ft in diameter paraboloidal substrate
- F=0.91 m
- 11h balloon flight in 1968
  ⇒ Crab nebula detection

T. R. Lindquist & R. Webber, University of Minnesota

[Lindquist & Webber, Canadian J. of Physics, 1968]

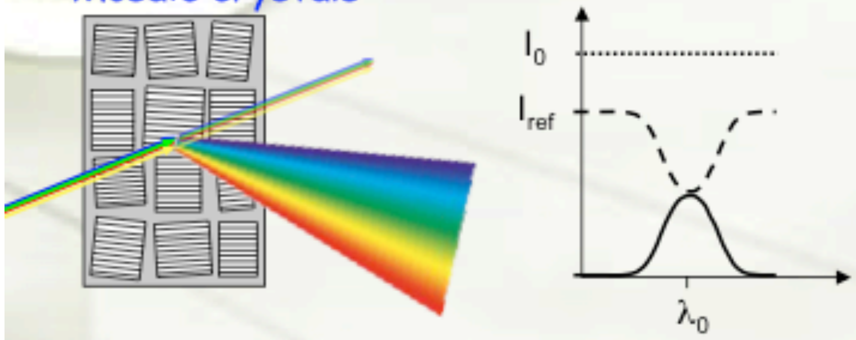
Crystals

Bargg's law: $2\,d_{hkl}\,\sin\theta_B = n\,\lambda$

A perfect crystal is a monochromator

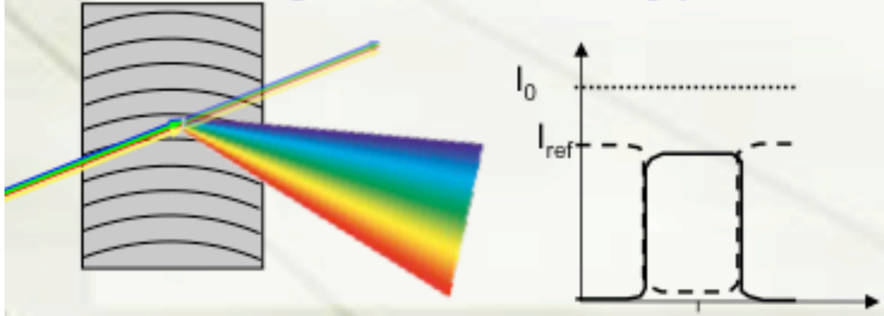
We need crystals having diffraction planes spanning across a range of orientations => each crystal (= each ring) diffracts an energy band

Mosaic crystals



- Major part of crystals grow 'naturally' with mosaic structure
- Gaussian bandpass
- Diffraction efficiency limited to 50% due to back-diffraction (equilibrium)

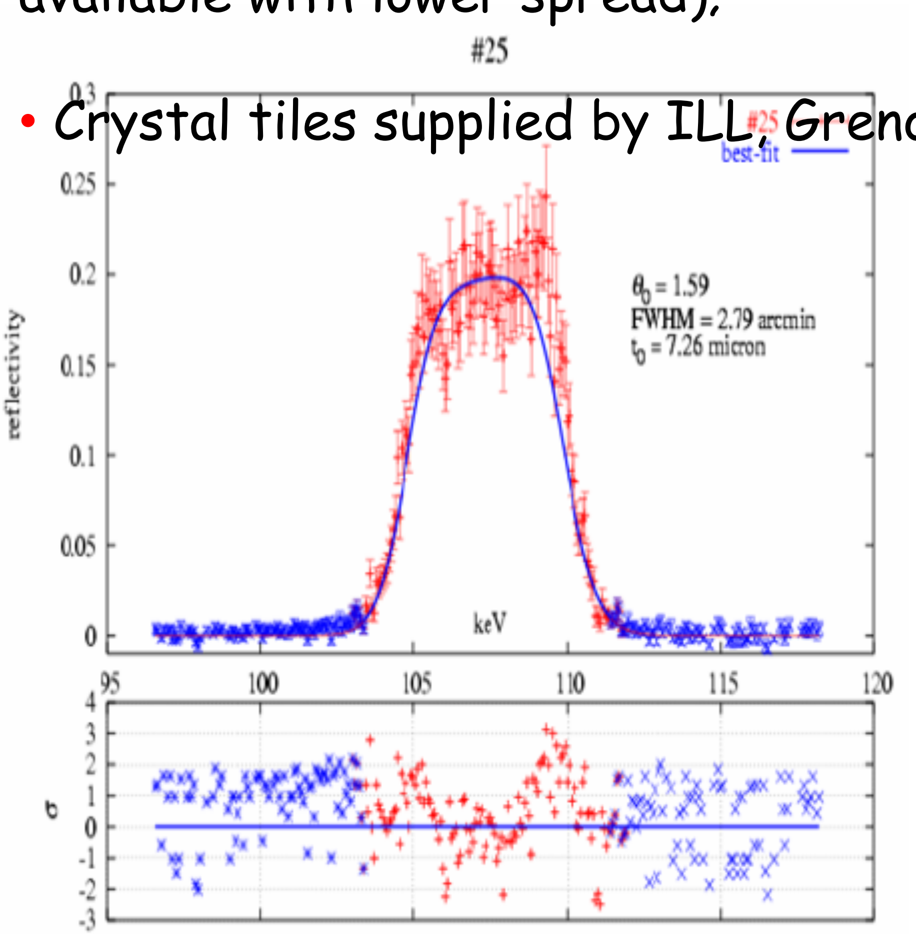
Crystals having curved diffracting planes (CDP crystals)



- Difficult to obtain without bending external device
- Rectangular shaped bandpass
- Diffraction efficiency can reach 100%

Mosaic crystals

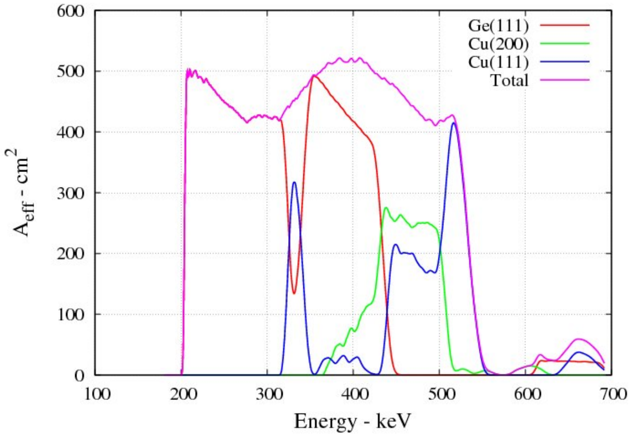
- Crystal material: Cu(111)
- Available mosaic spread: 3-4 arcmin(now also available with lower spread);
- Crystal tiles supplied by ILL, Grenoble.

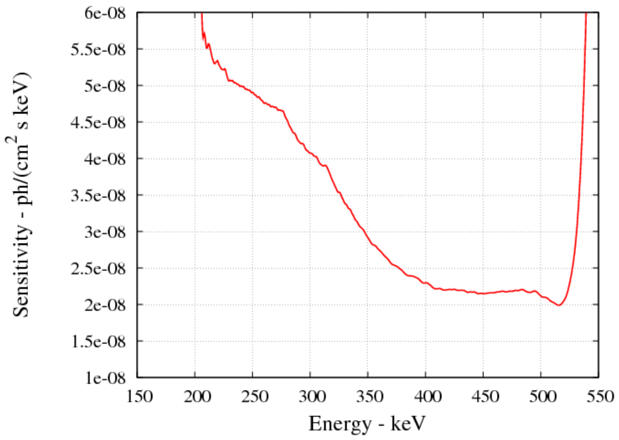


Credits;: F. Frontera – University of Ferrara

Example of configuration suitable for GRI low energy lens (200-550 keV)

Parameter	
Focal length (m)	100
Nominal passband (keV)	200–530
Inner radius (cm)	88
Outer radius (cm)	185
Crystal material	Ge[111], Cu[111], Cu[200]
Mosaic spread (arcmin)	0.5
Tile cross section (mm^2)	15 × 15
Tile thickness (mm)	optimized
Number of crystal rings	61
No. of tiles	17661 (Ge[111]), 3254 (Cu[200]), 3386 (Cu[111])
Crystal weight (kg)	155
Effective area (cm^2) @ 200 keV	500
Effective area (cm^2) @ 400 keV	530
Effective area (cm^2) @ 511 keV	430
Half power radius(mm)	12





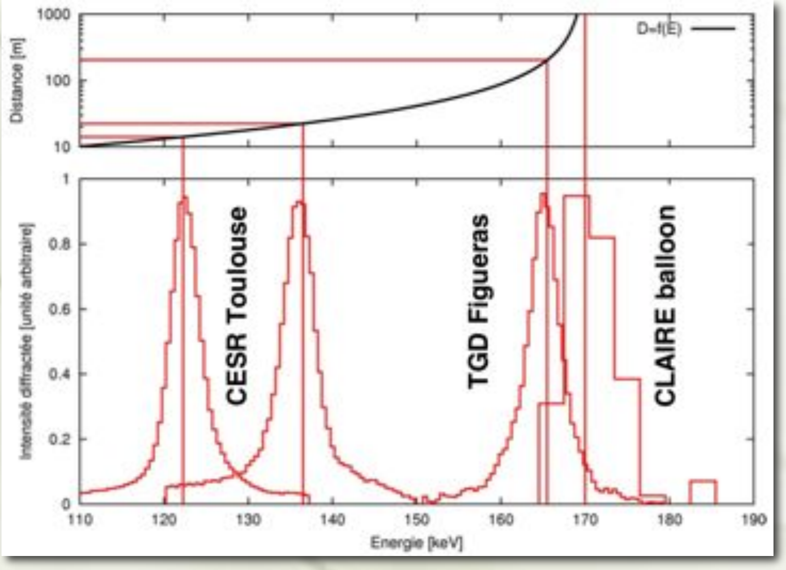
3 sigma sensitivity, $\Delta T = 10^6$ s

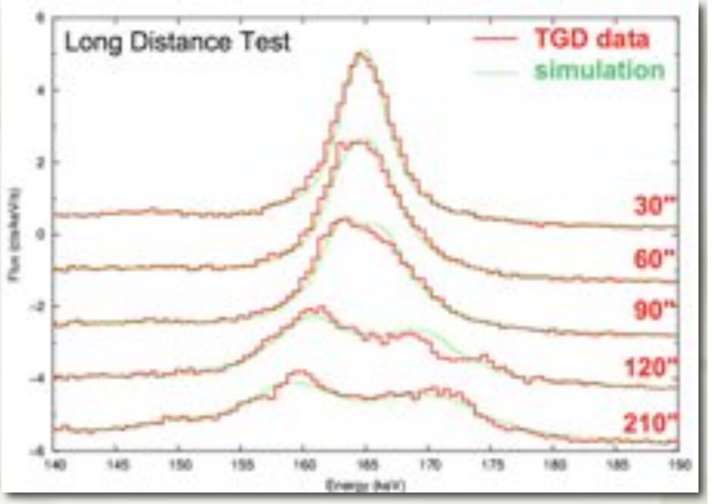
The most recent flown experiment: CLAIRE

2001: 170 keV (5 keV wide)

- 556 Ge mosaic crystals
- Gain ≈ 45
- Ground tests, 2 balloons flights
  ⇒ Crab nebula detection

CESR (univ of Toulouse) / French Space Agency

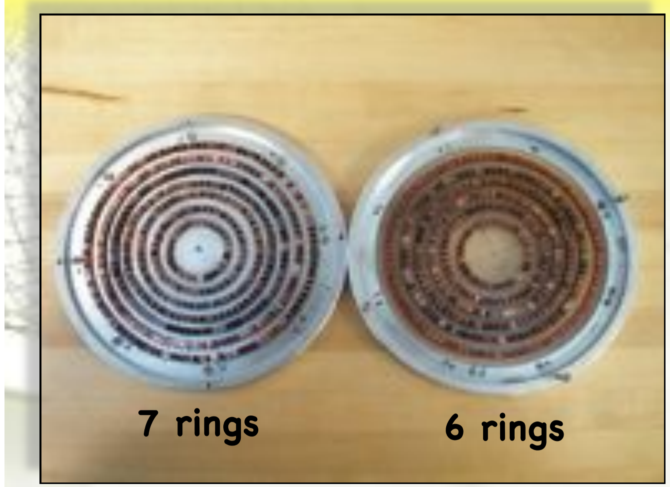




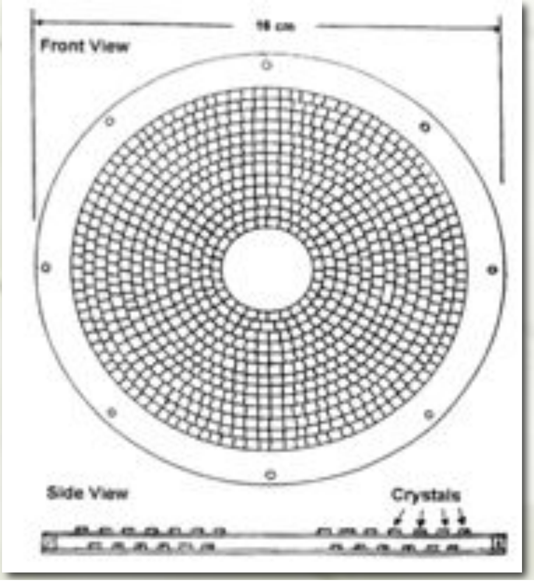
[von Ballmoos et al., ExpA 2005]

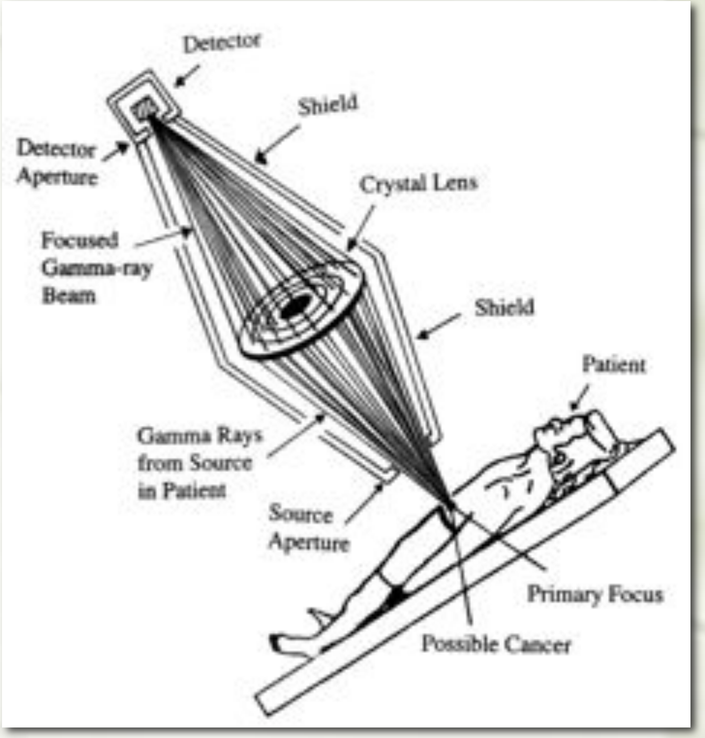
Spin-off: medical imaging

Medical imaging (APS, Argonne National Lab)



828 Cu crystals (4x4x3mm^3),
9 reflections to focus at 140.6 keV





[Smither & Roa, SPIE 2001]

Wide Band Laue Lens under development at the Univ. of Ferrara

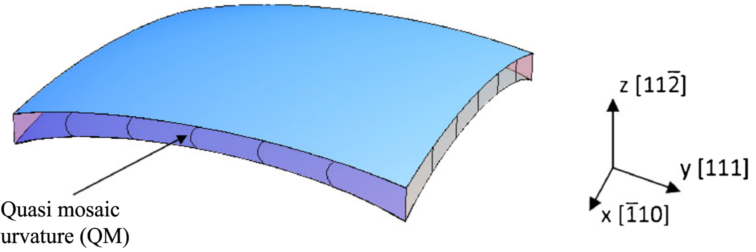
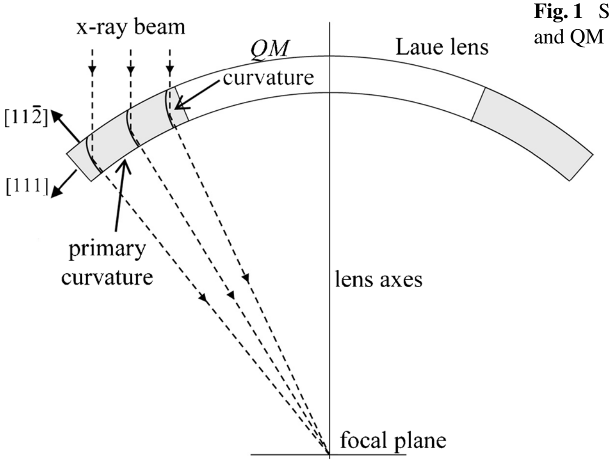


Fig. 1 Schematic representation of a crystal plate with the coordinate system. Crystallographic orientation and QM curvature are highlighted

Fig. 2 Schematic representation of a cross section of a Laue lens based on *QM* crystals. Primary curvature of $(11\bar{2})$ planes leads to a secondary curvature of (111) planes owing to quasi-mosaicity. In this configuration the (111) diffracting planes are perpendicular to the main surface of the plate. It can also be seen the capability of primary curvature to focalize diffracted radiation while *QM* curvature establishes an increase in diffraction efficiency



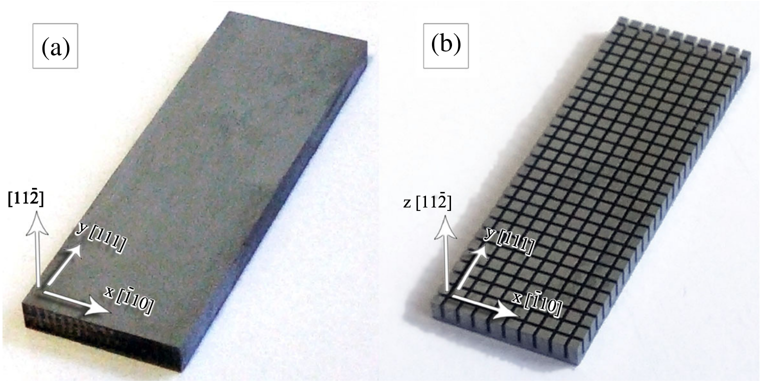
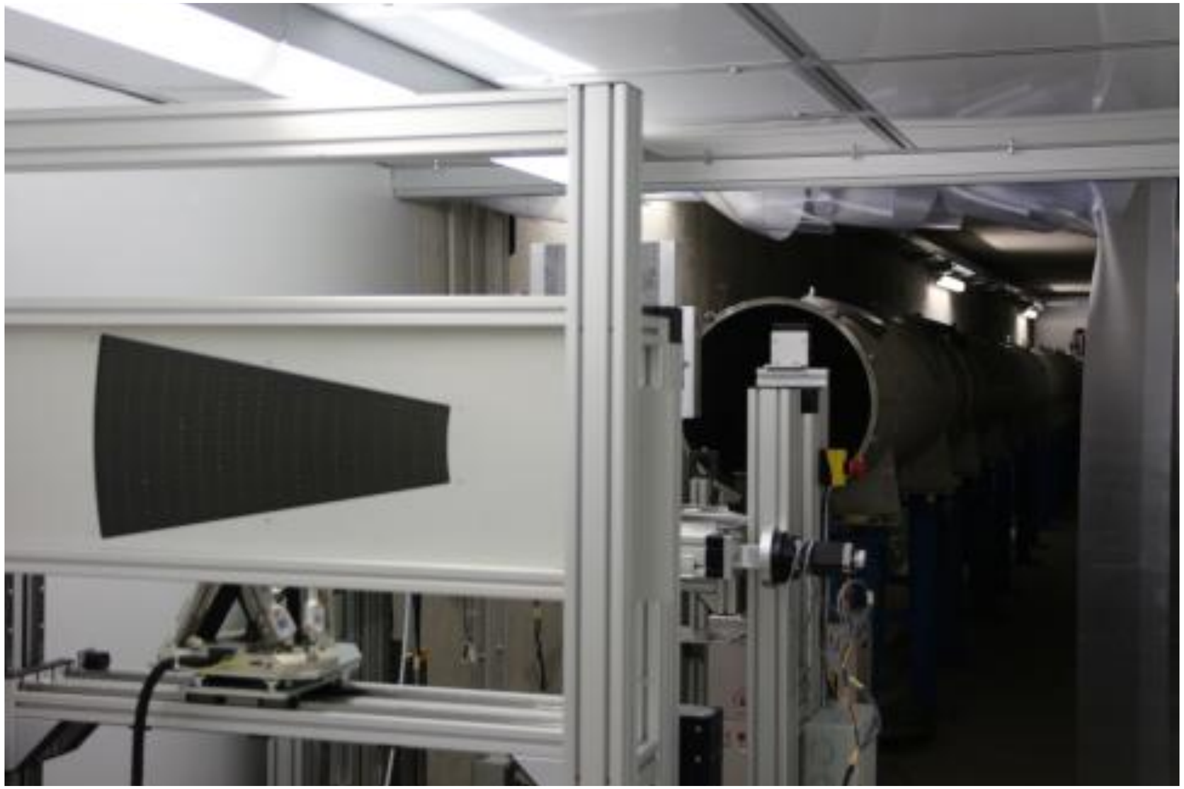


Fig. 3 Photo of the a Ge sample before (**a**) and after (**b**) the manufacture. Crystallographic orientation are highlighted

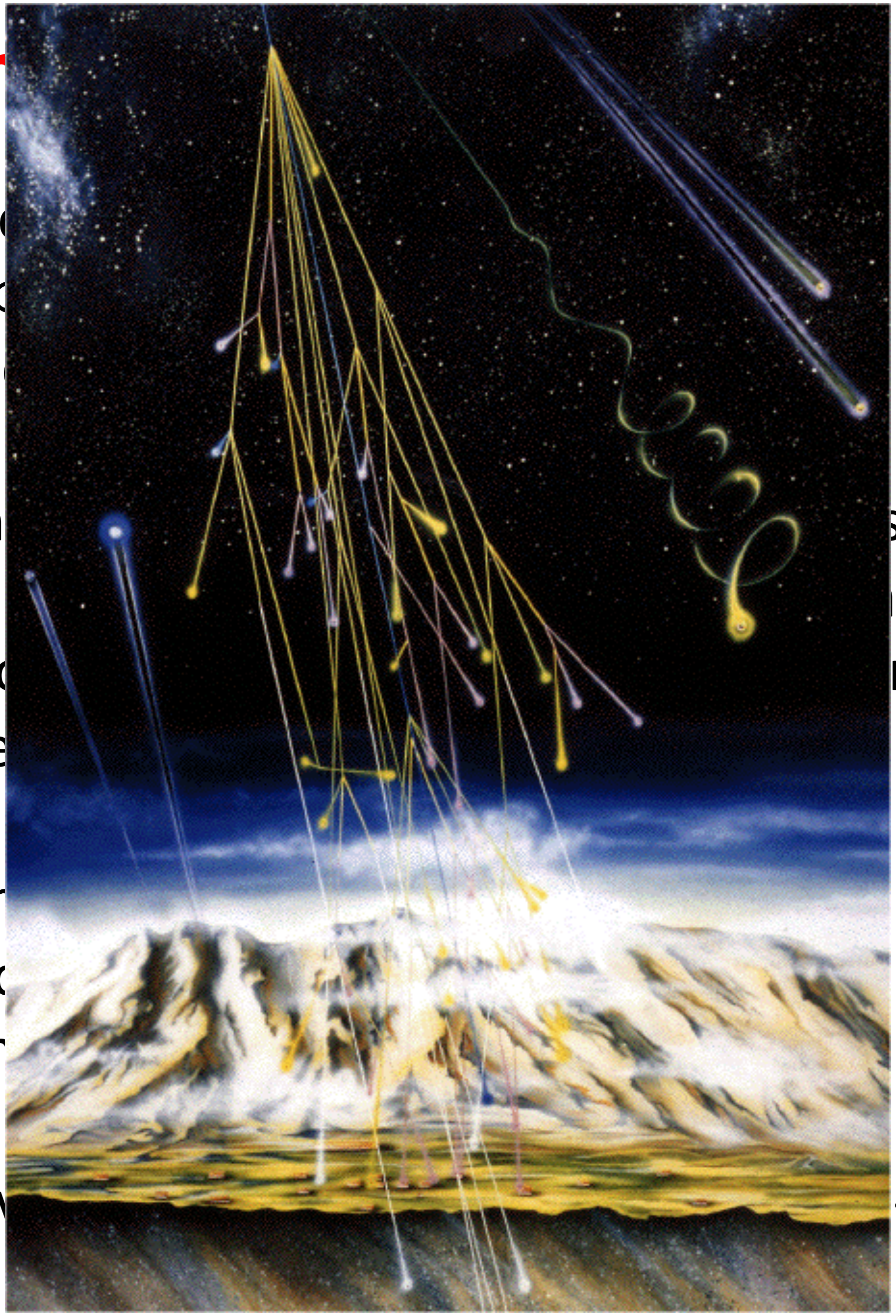
Credits: Camattari et al.

Laue lens under integration @ Univ. of Ferrara



Cherenkov Telescopes

Chrenkov Atm

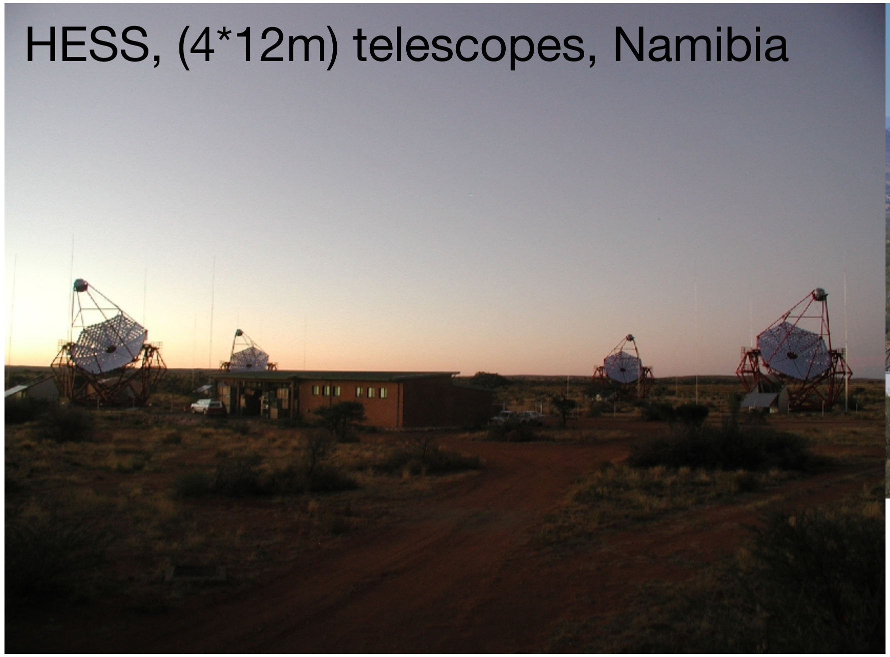


- Atmospheric Cherenkov Teles
observations of astronomical ob
energies from 50 GeV up to sev

- The showers extend over man s
to hundreds of meters in width t
around 8-12 km altitude. Electr re,
moves with ultra-relativistic spe

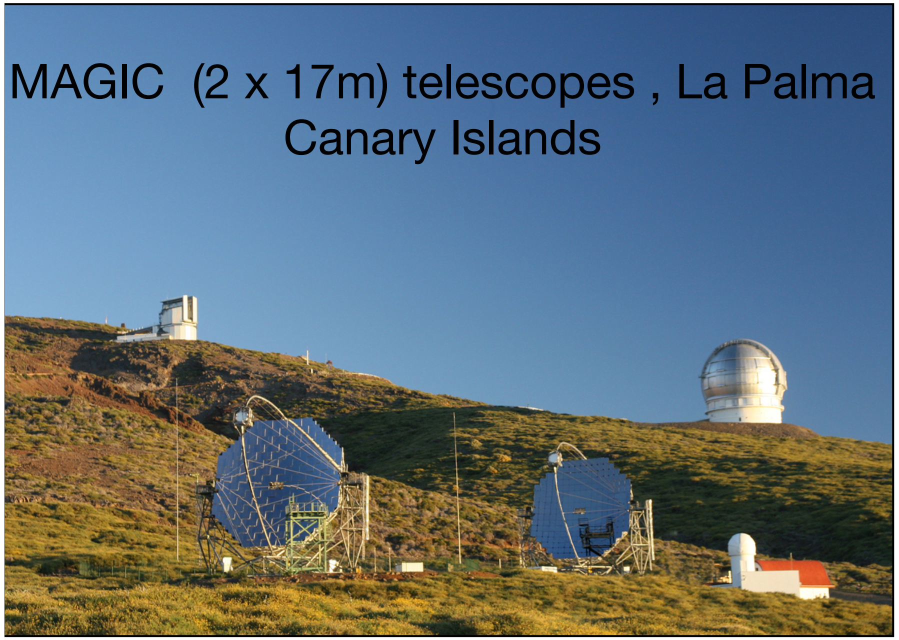
- This radiation is mainly concer
band and can therefore pass mo
detected by appropriate instru

- Light flashes from showers hav -3
ns in case of a g shower.



HESS, (4*12m) telescopes, Namibia

VERITAS, Arizona

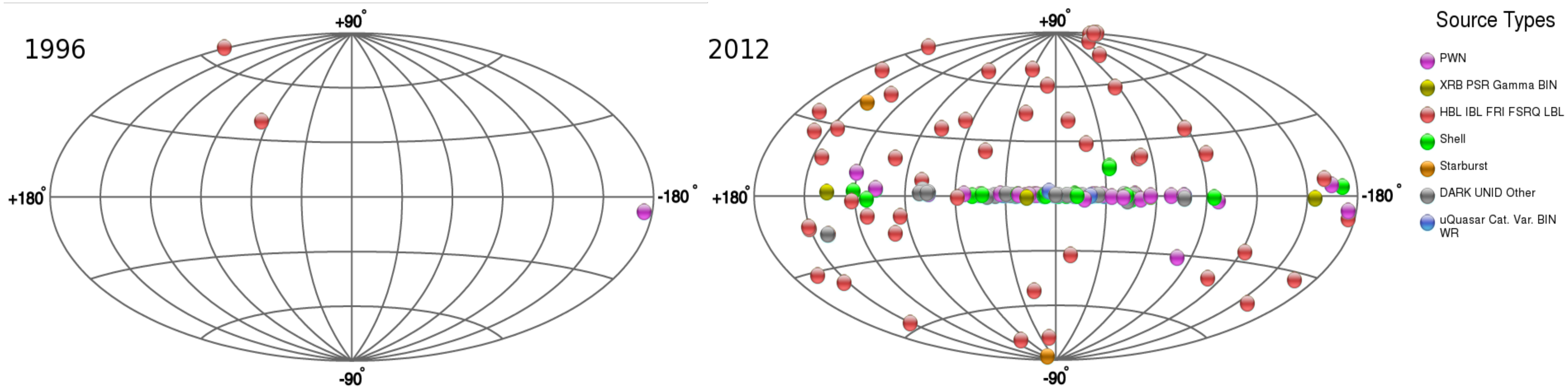


MAGIC (2 x 17m) telescopes , La Palma
Canary Islands

	WIPPLE	HESS	MAGIC	VERITAS
Site	Arizona	Namibia	Canary Island	Arizona
Lat (°)	32	-25	29	32
Alt (km)	1.3	1.8	2.2	1.3
Tel. Ǿ (m)	10	12	17	12
N. Tel.	1	4	2	4
FoV Ǿ (°)	2.3	5	3	3.5
Thresh. (GeV)	300	100	50	100
Sensitivity (mCrab)	150	7	20	10

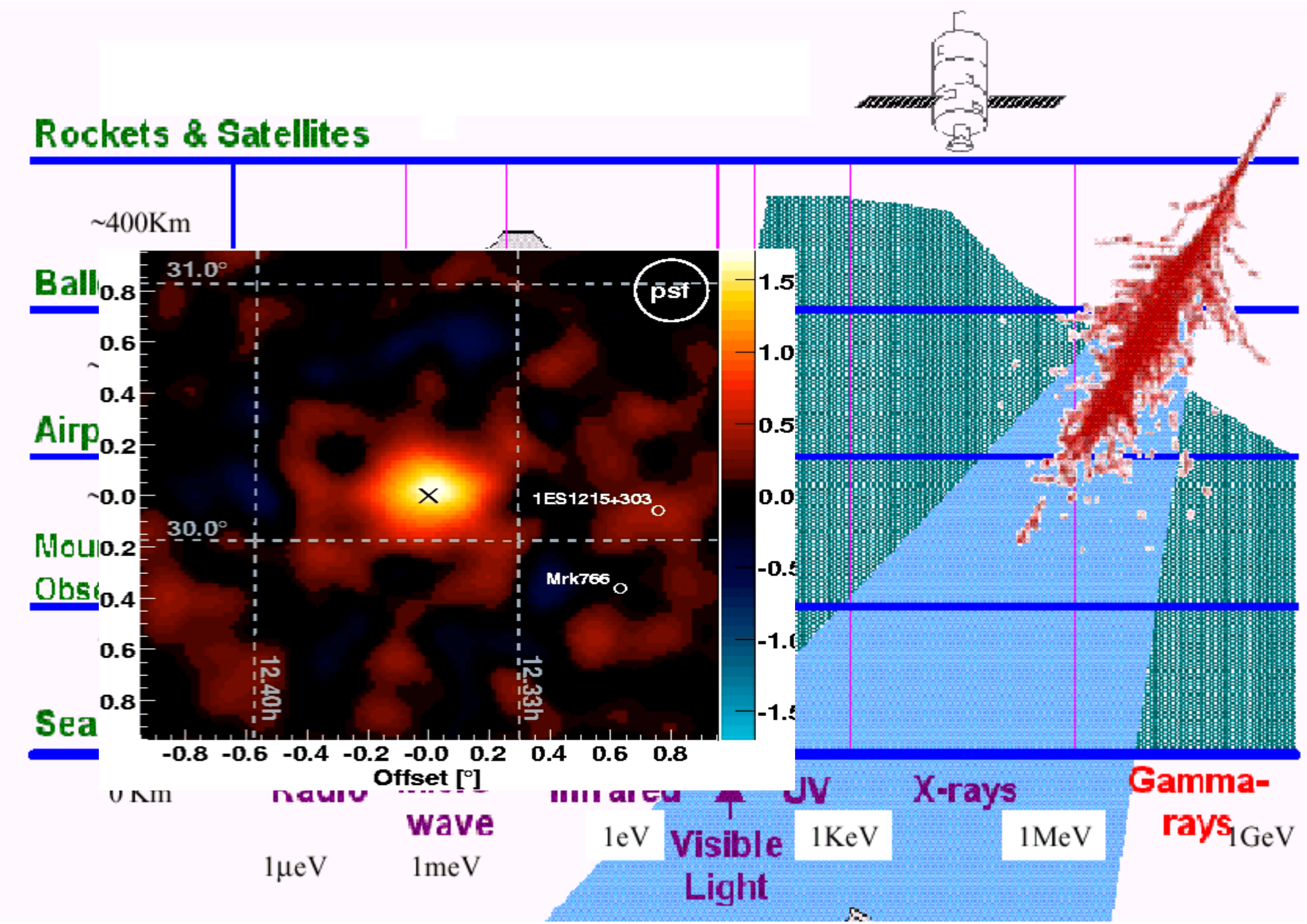
The VHE gamma ray sky

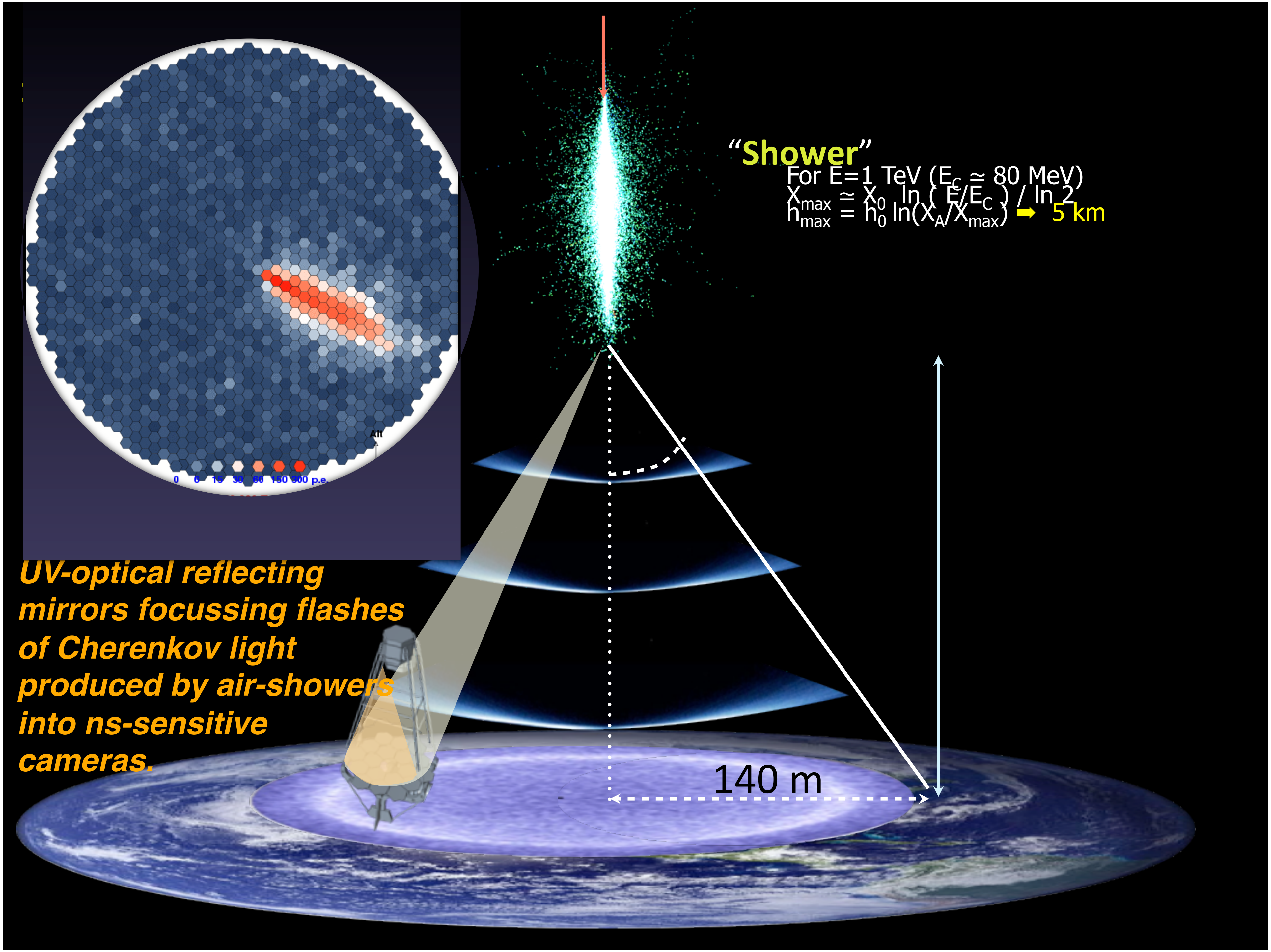
© TeVcat (May/2012)



156 Sources: 48 Extragalactic:

29 HBL + 4 IBL + 3 FRI + 3 FSRQ + 4 LBL + 2 AGN (unknown type) + 3 Starburst


Rockets & Satellites
~400Km
Ball
Airp
Mou
Obs
Sea
0 Km
31.0°
30.0°
psf
1ES1215+303
Mrk766
12.40h
12.33h
0.8
0.6
0.4
0.2
-0.0
0.2
0.4
0.6
0.8
-0.8
-0.6
-0.4
-0.2
-0.0
0.2
0.4
0.6
0.8
Offset [°]
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Radio
Micro
wave
Infrared
Visible
Light
UV
X-rays
Gamma-
rays
1μeV
1meV
1eV
1KeV
1MeV
1GeV



"Shower"

For E=1 TeV ($E_C \simeq 80$ MeV)
$X_{max} \cong X_0 \ln (E/E_C) / \ln 2$
$h_{max} = h_0 \ln(X_A/X_{max})$ ➡ 5 km

UV-optical reflecting mirrors focussing flashes of Cherenkov light produced by air-showers into ns-sensitive cameras.

Intensity of the Image

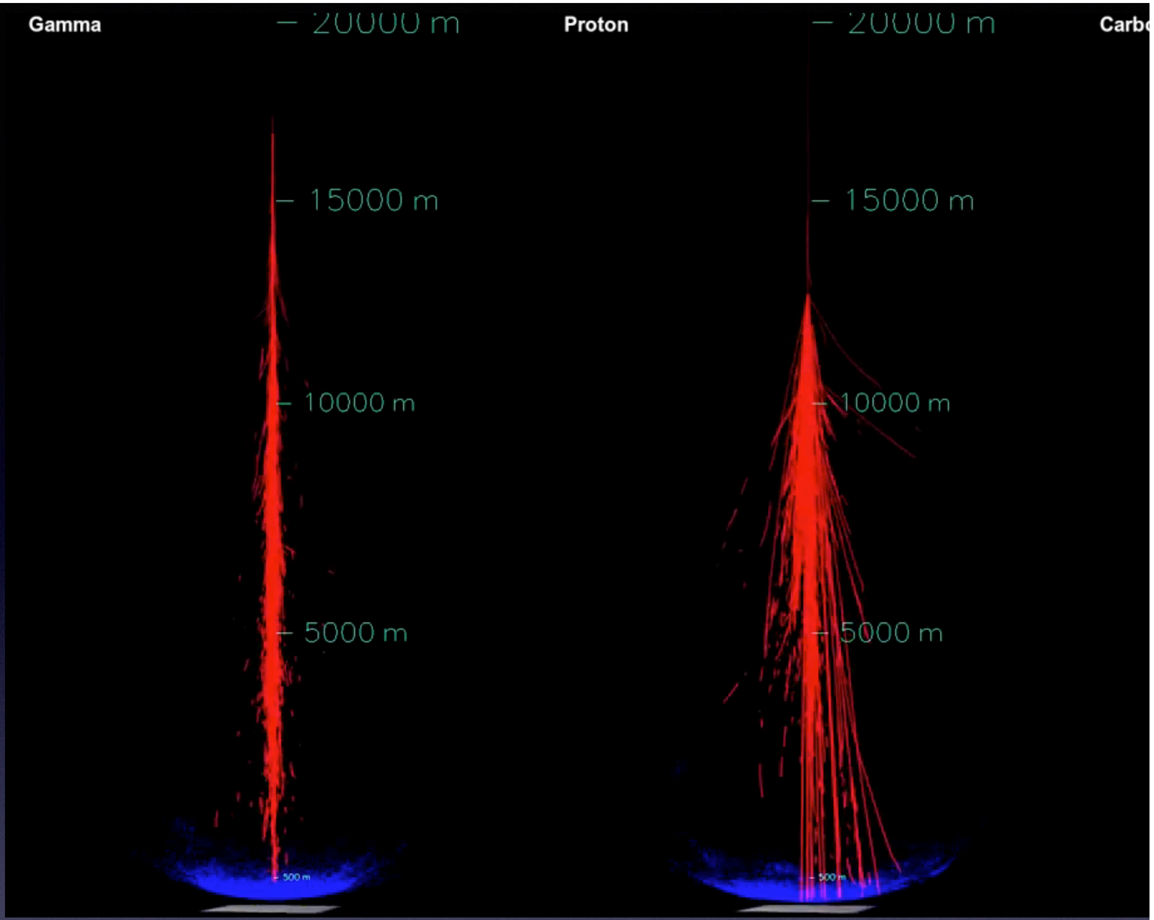
↳ Shower Energy

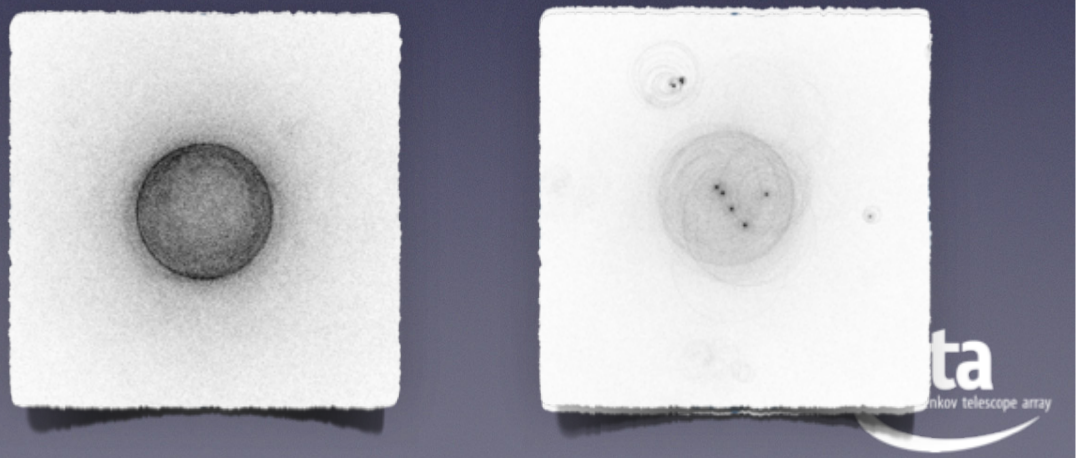
Orientation of the image

↳ Shower Direction

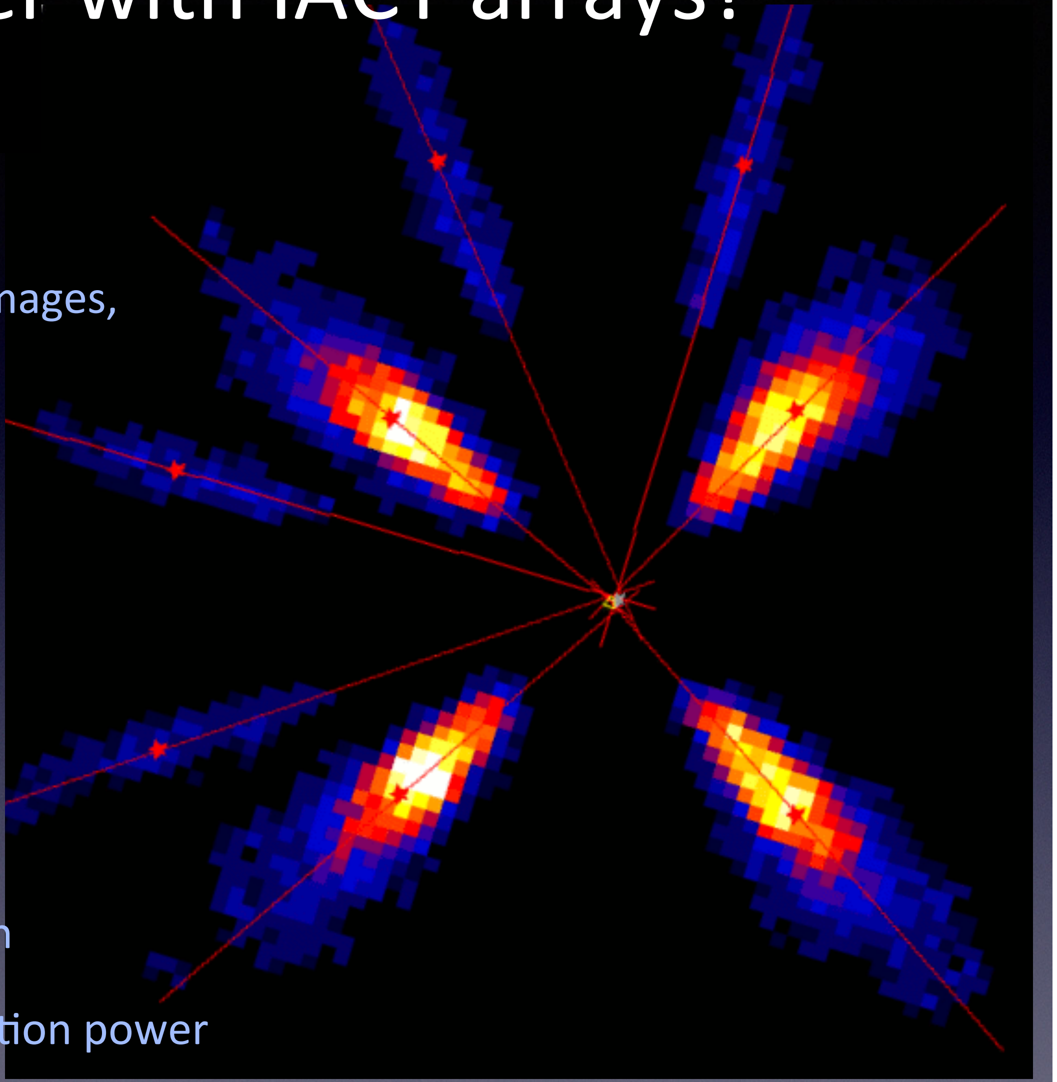
Image Shape

↳Particle type





How to do better with IACT arrays?



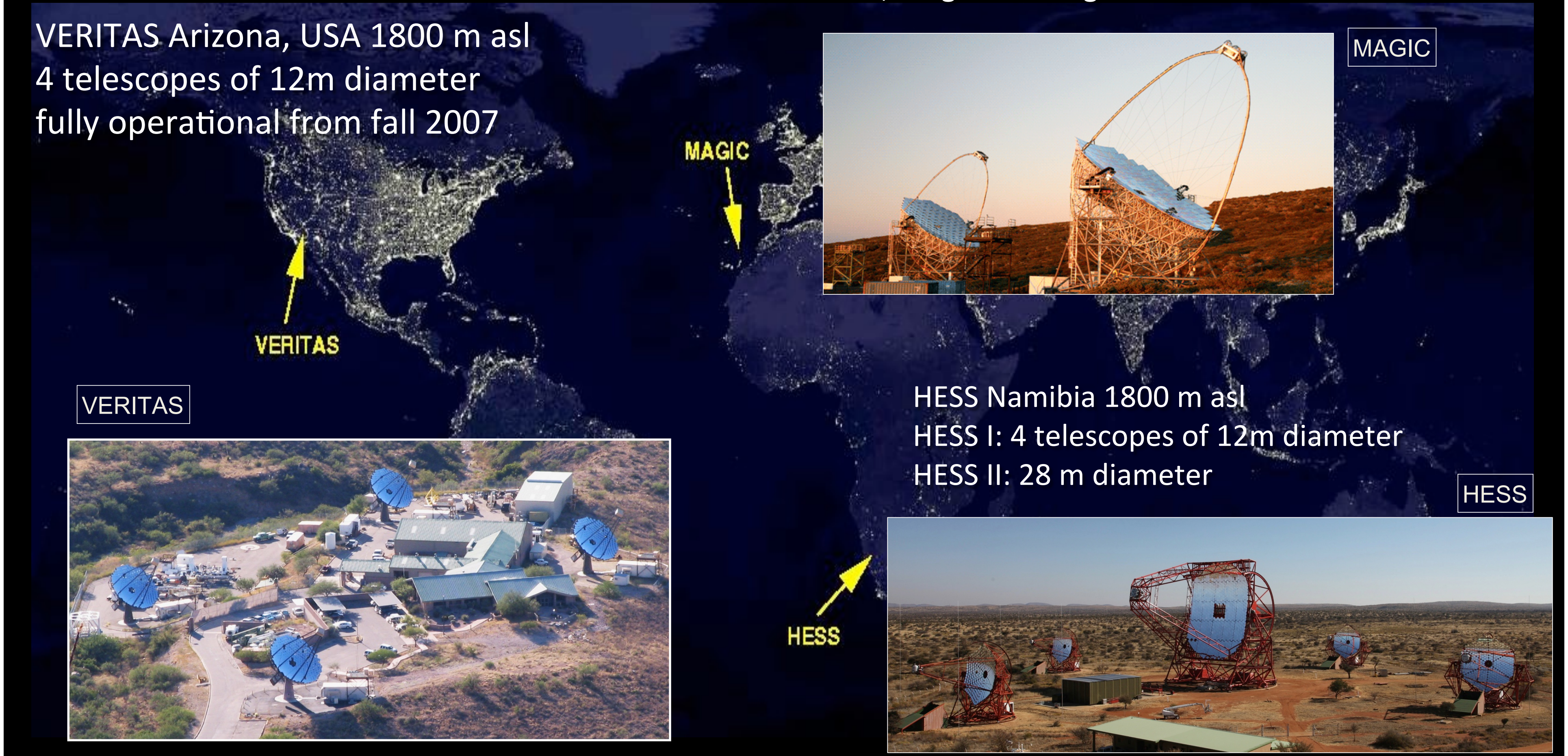
- More events
  - More photons = better spectra, images, fainter sources
    - ✓ Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - ✓ Improved angular resolution
    - ✓ Improved background rejection power

➡ More telescopes!

Simulation:
Superimposed images from
8 cameras

Major IACT Instruments

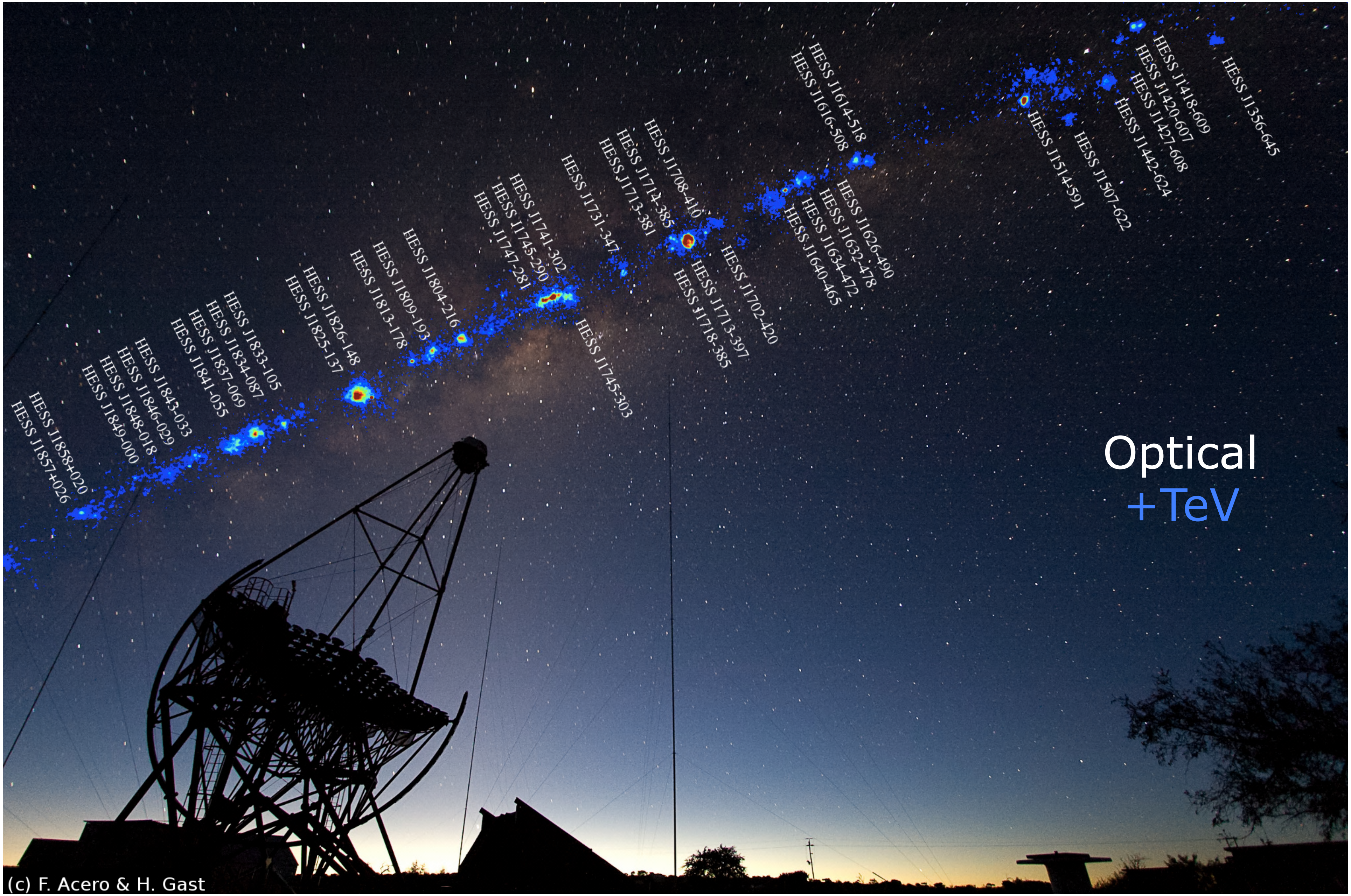
MAGIC Canary Islands 2200 m asl
2 x 17m telescopes. Magic I in operation since Oct 2003, Magic II first light shown at ICRC09



VERITAS Arizona, USA 1800 m asl
4 telescopes of 12m diameter
fully operational from fall 2007

HESS Namibia 1800 m asl
HESS I: 4 telescopes of 12m diameter
HESS II: 28 m diameter

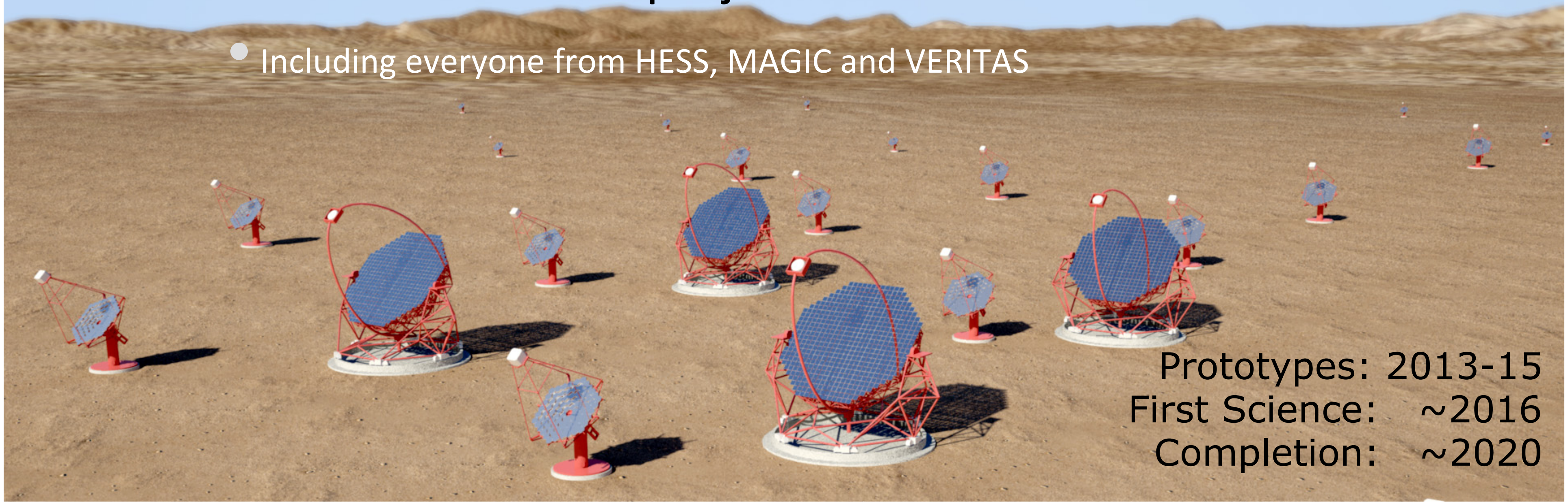
Dec 2003: 4 telescope commissioned
Dec 2014: HESS II commissioning?



(c) F. Acero & H. Gast

The Cherenkov Telescope Array

- A huge improvement in all aspects of performance
  - A factor ~10 in sensitivity, much wider energy coverage, much better resolution, field-of-view, full sky, …
- A user facility / proposal-driven observatory
  - With two sites with a total of >100 telescopes
- A 27 nation ~€200M project
  - Including everyone from HESS, MAGIC and VERITAS



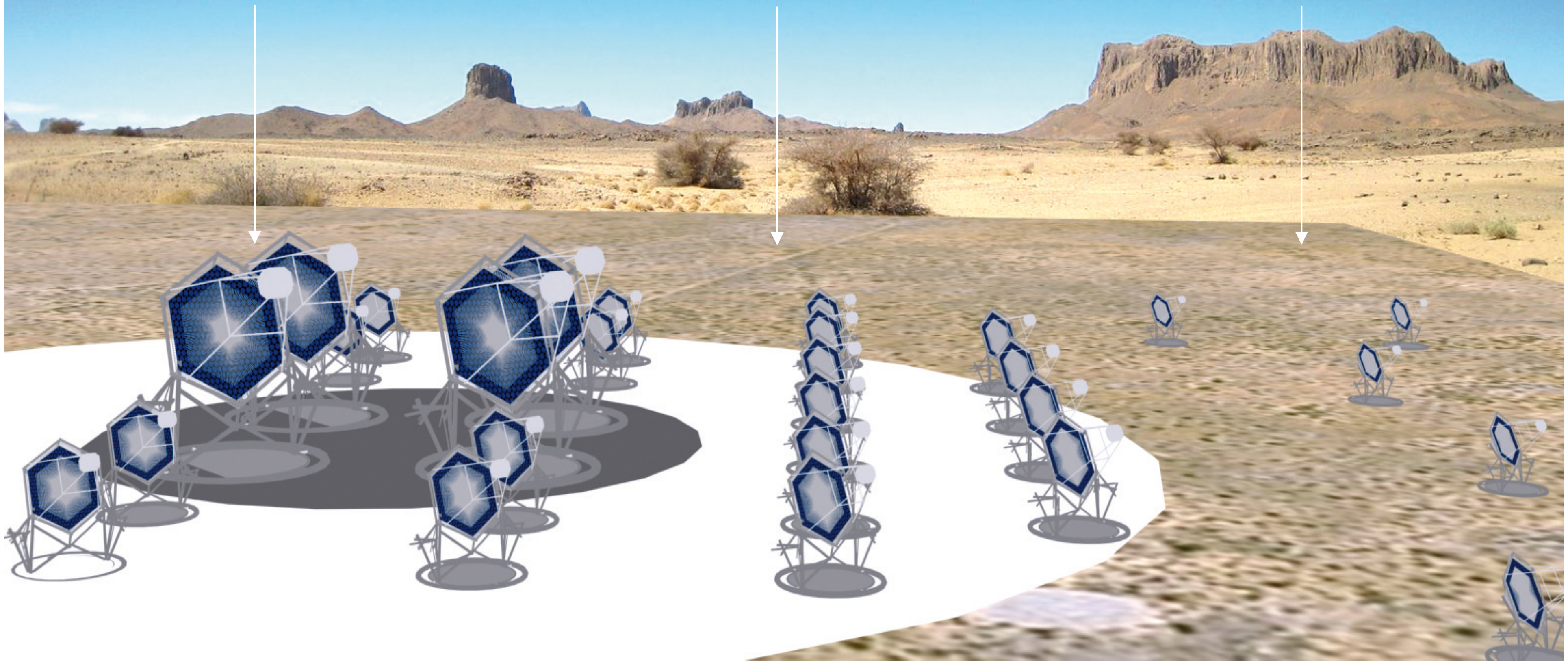
Prototypes: 2013-15
First Science: ~2016
Completion: ~2020

The Cherenkov Telescope Array concept

Low energy
Few 24 m telescopes
4.5° FoV
2000 pixels
~ 0.1°

Medium energy
About twenty 12 m telescopes
7° FoV
2000 pixels
~ 0.18°

High energy
Fifty + 4…7 m telescopes
10° FoV
2000 pixels
~ 0.2°…0.3°

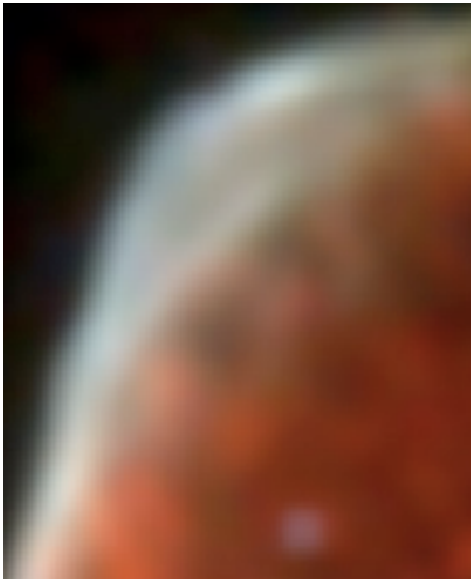


CTA behaviour

CTA performance goals

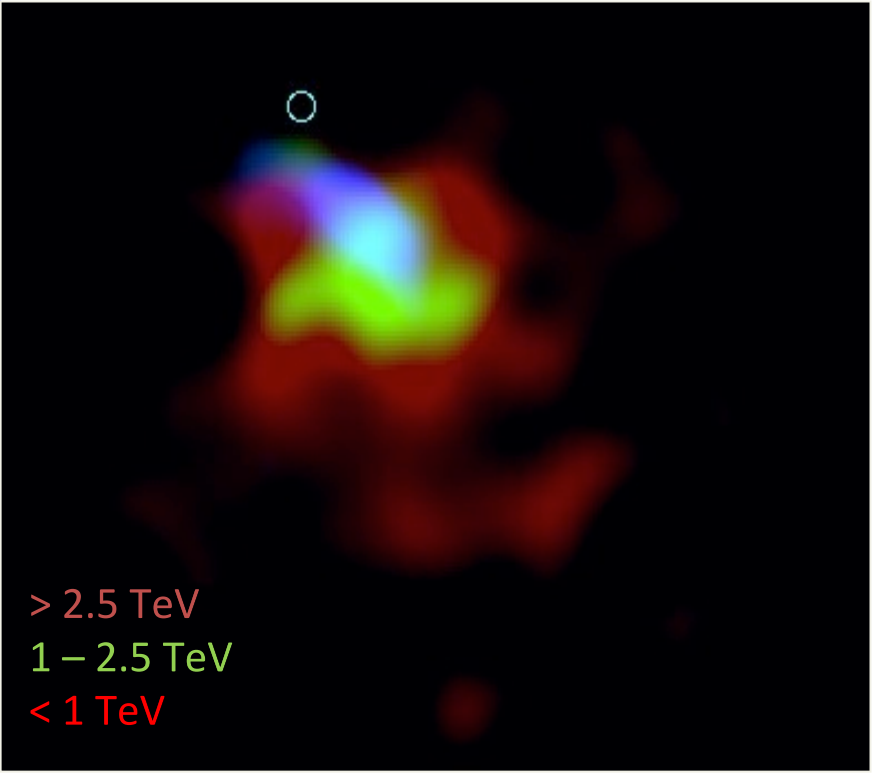
- Improve angular resolution by factor ~ 5.
- Substructure of SNR shock fronts can then be resolved

Resolution 0.1°

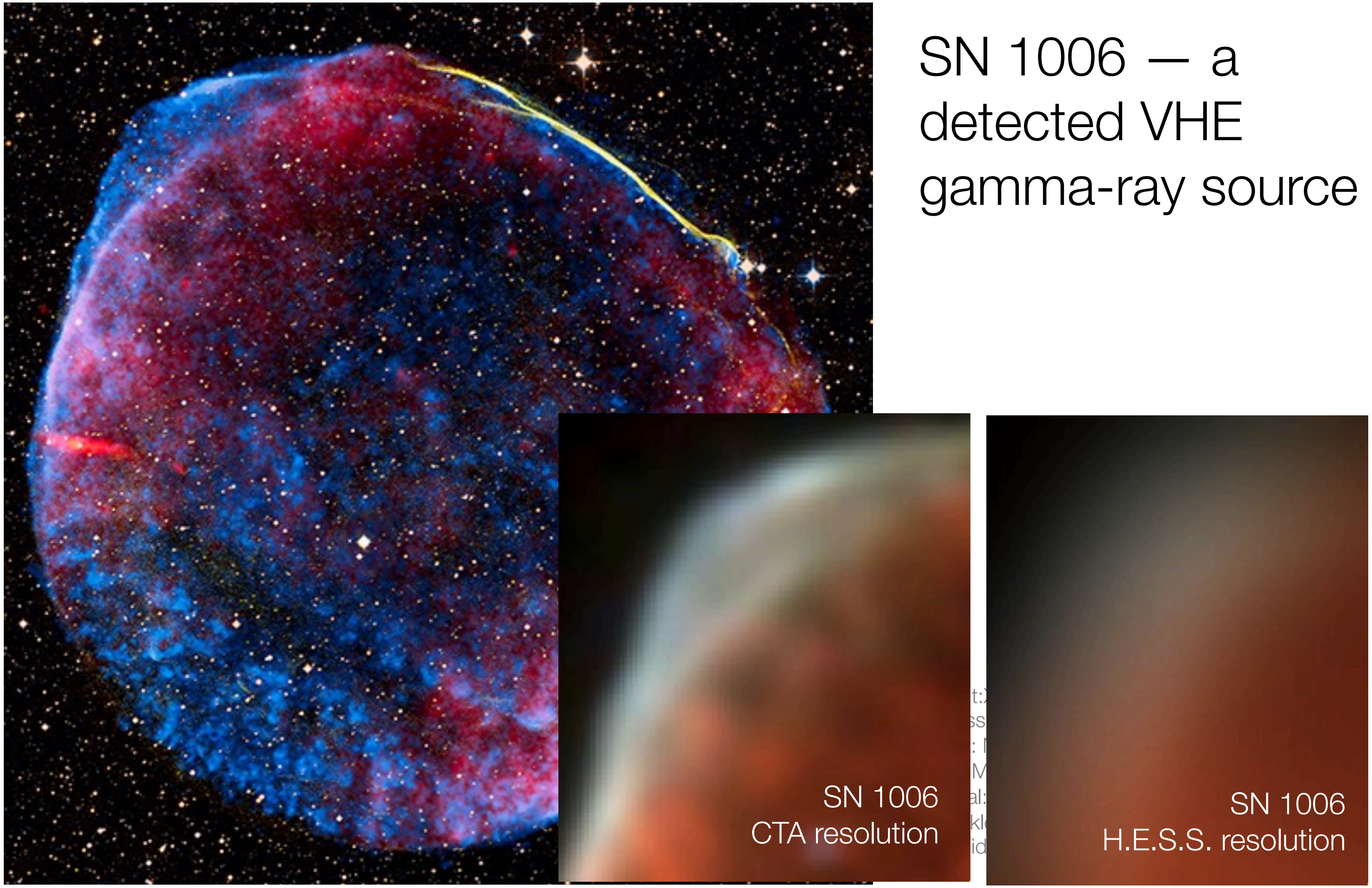


- Better understand energy dependent morphology of pulsar wind nebulae.
-
  s
  e

Resolution 0.02 °



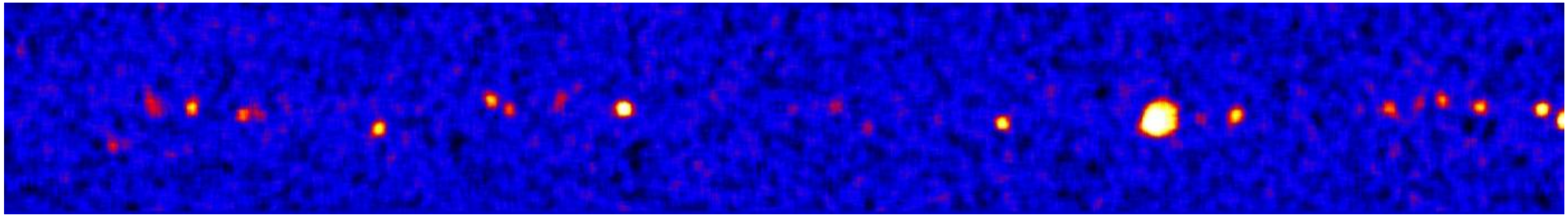
Resolving complex sources



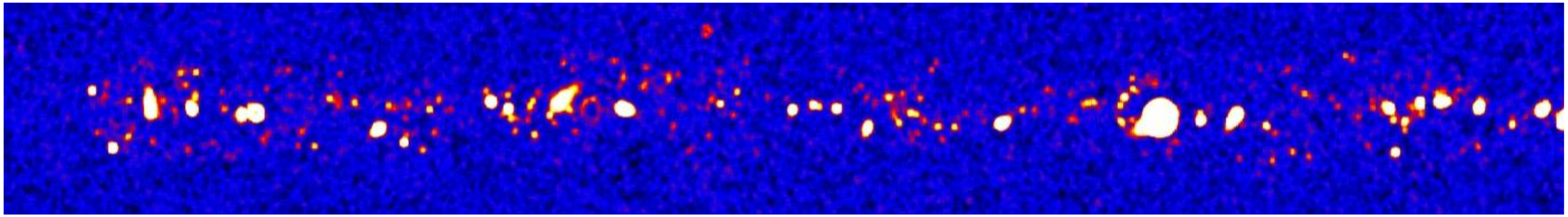
SN 1006 — a detected VHE gamma-ray source

CTA performance goals

- Aim for factor of 10 improvement in sensitivity.
- Compare simulated HESS ~ 500 hour image of galactic plane...

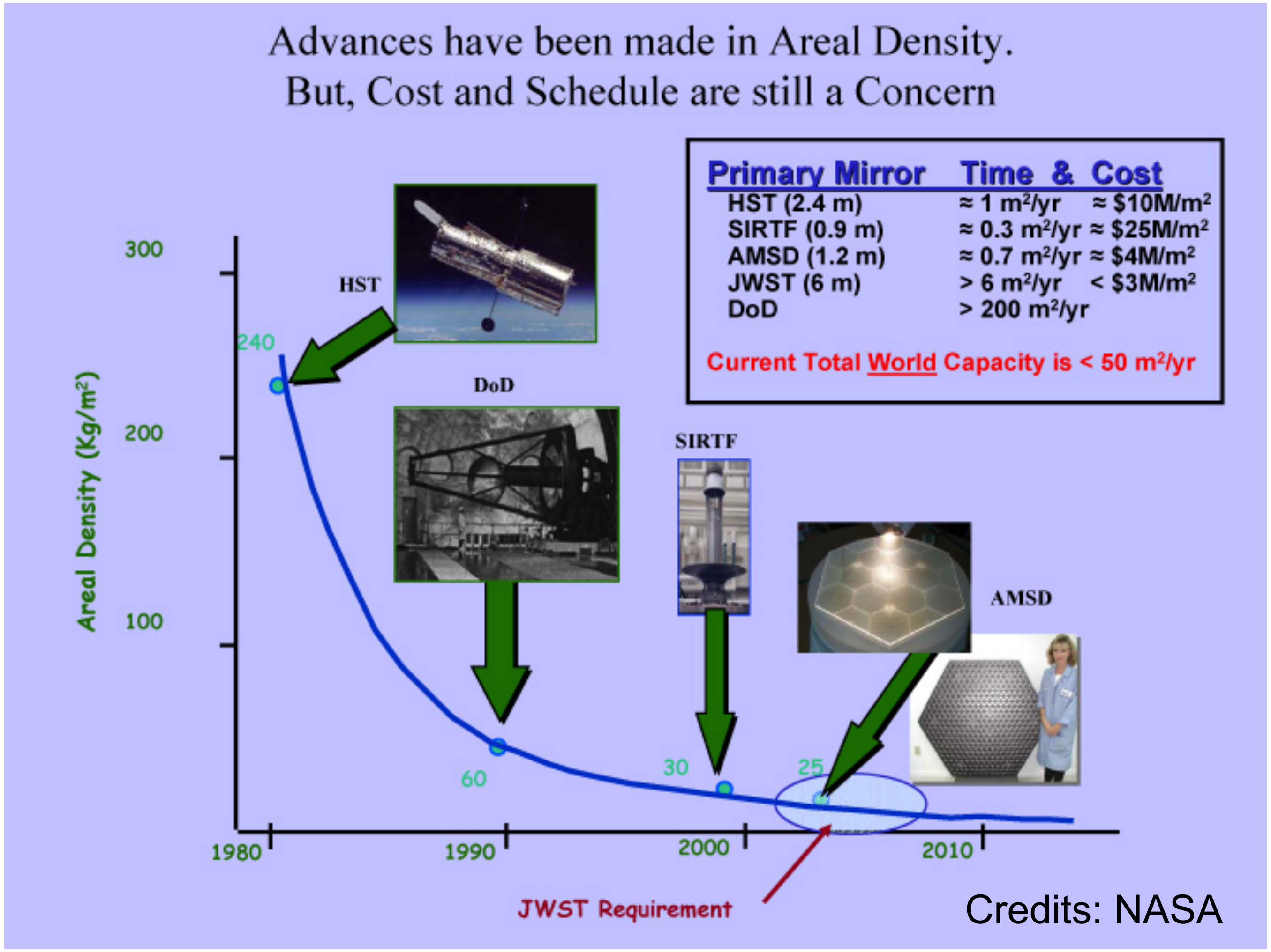


- ...with expectation with increased sensitivity, same exposure



- Expect to observe around 1000 sources (galactic and extra-galactic).

NASA trend study for optics to be used in scientific missions



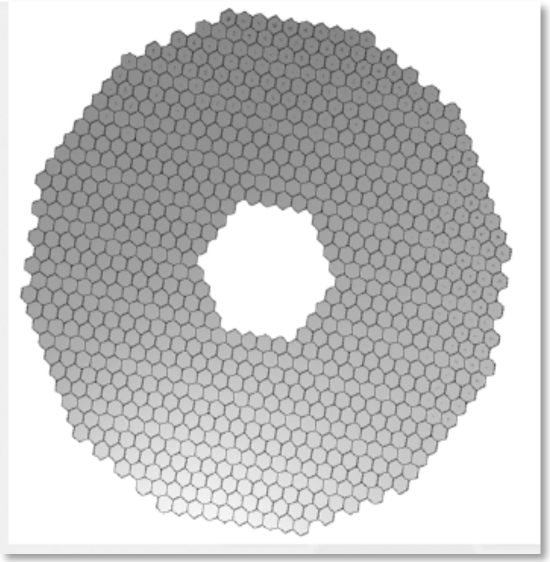
Advances have been made in Areal Density.
But, Cost and Schedule are still a Concern

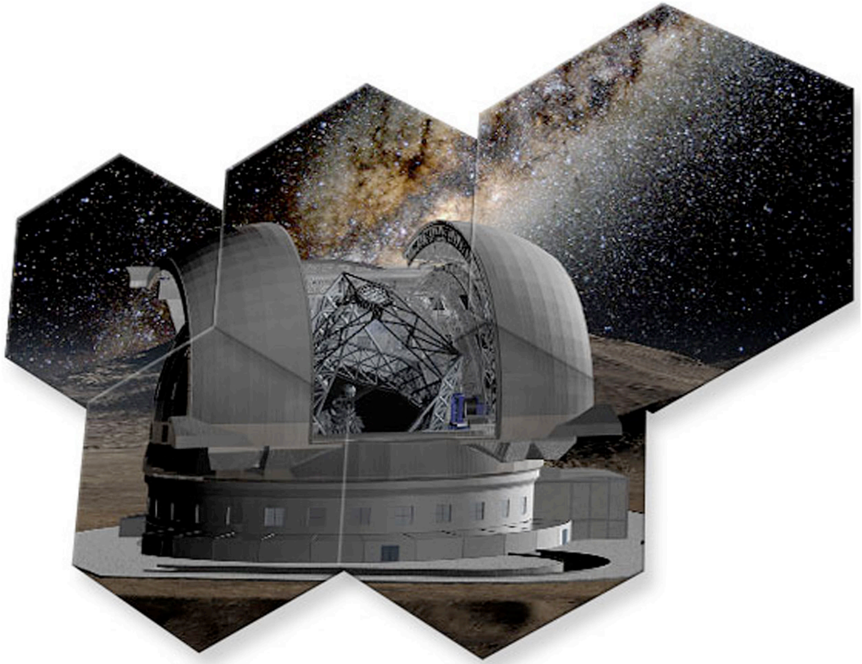
Primary Mirror	Time & Cost	
HST (2.4 m)	≈ 1 m^2/yr	≈ \$10M/m^2
SIRTF (0.9 m)	≈ 0.3 m^2/yr	≈ \$25M/m^2
AMSD (1.2 m)	≈ 0.7 m^2/yr	≈ \$4M/m^2
JWST (6 m)	> 6 m^2/yr	< \$3M/m^2
DoD	> 200 m^2/yr	

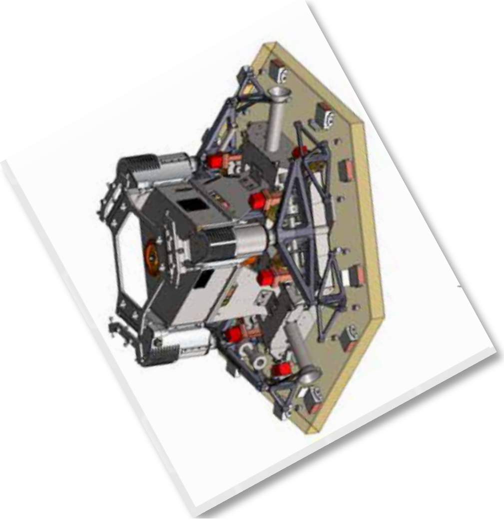
Current Total World Capacity is < 50 m^2/yr

Credits: NASA

ESO ELT Project







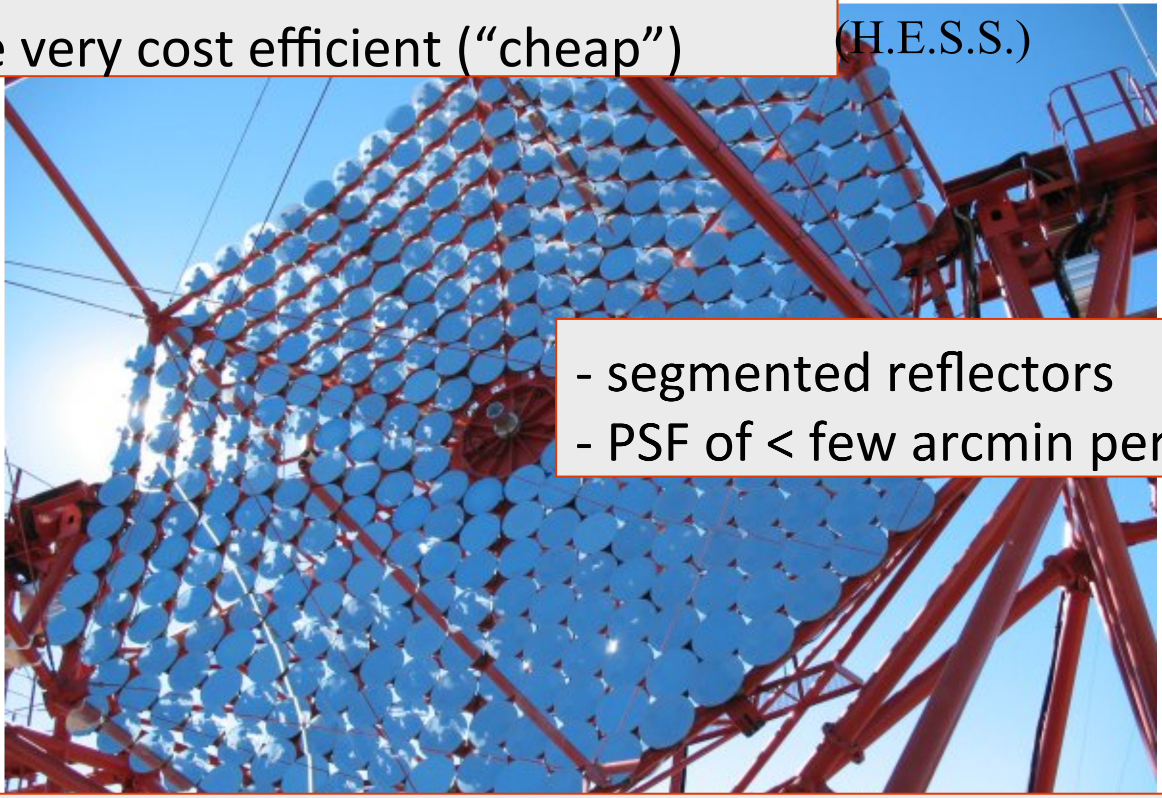
- Primary Diameter: 39 m
- 900 panels (max dimension 1.4 m)
- Mass-to-Area 100 kg / m^2
- Cost/m^2~ 100-300 KEuros
- Panel Angular resolution: 0.1 arcsec
- Time: 90 m^2/year

Mirrors for Cherenkov Telescopes

- high collecting area is needed;
- the angular resolution is not an issue (better than a few arcmin)
- a high volume production for mirrors is needed
- the areal cost must be maintained at a very low level (1000-3000 Euros / m^2)

Mirrors for CTA

- in total ~ 10 000 m^2 mirror area needed
- should be very cost efficient ("cheap")



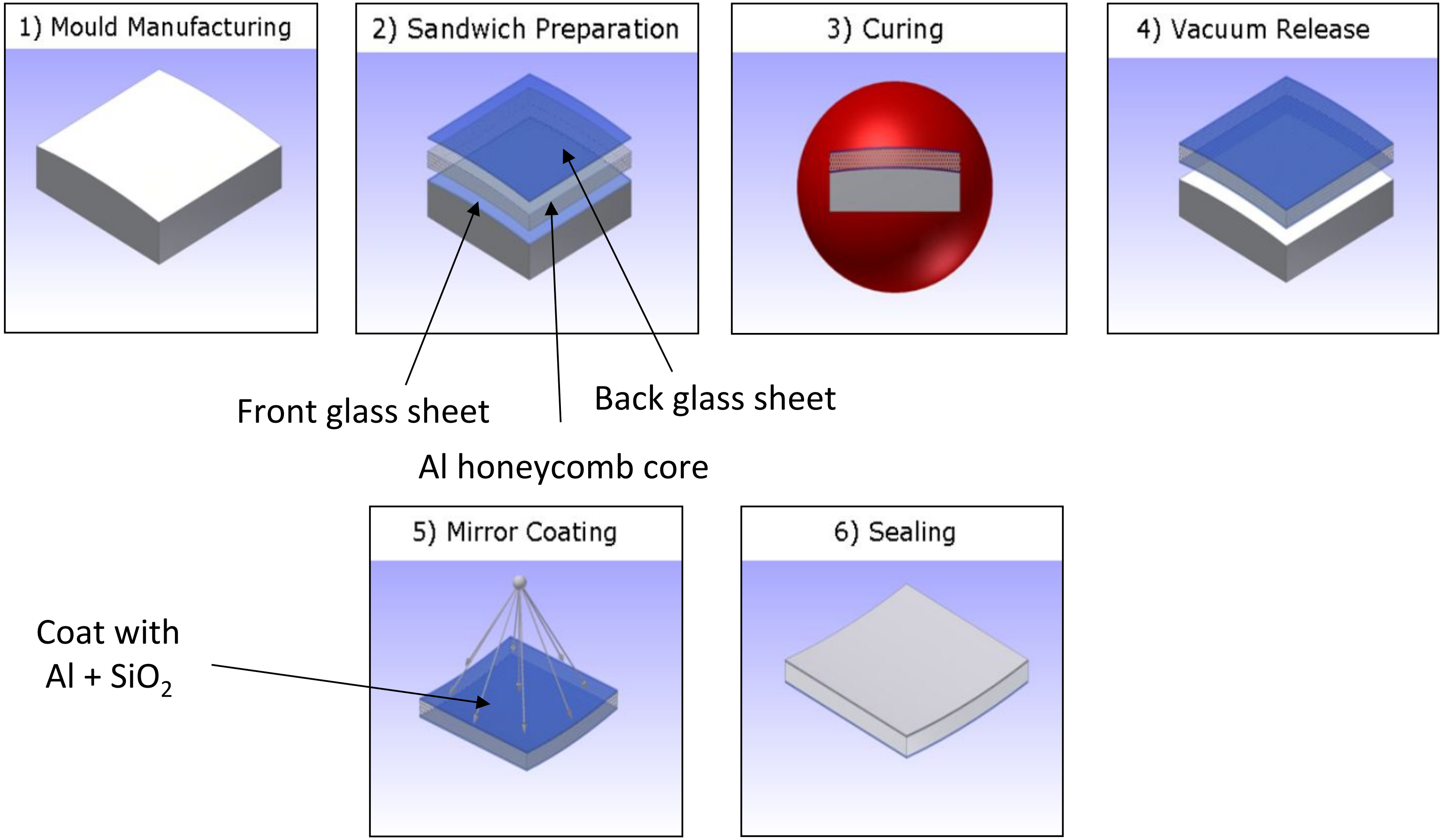
(H.E.S.S.)

- segmented reflectors
- PSF of < few arcmin per mirror okay

- good reflectance between 300 and 550 nm
- as lightweight as possible
- exposed to environment but lifetime should be ~10 years

Mirrors

- Cold slumping:



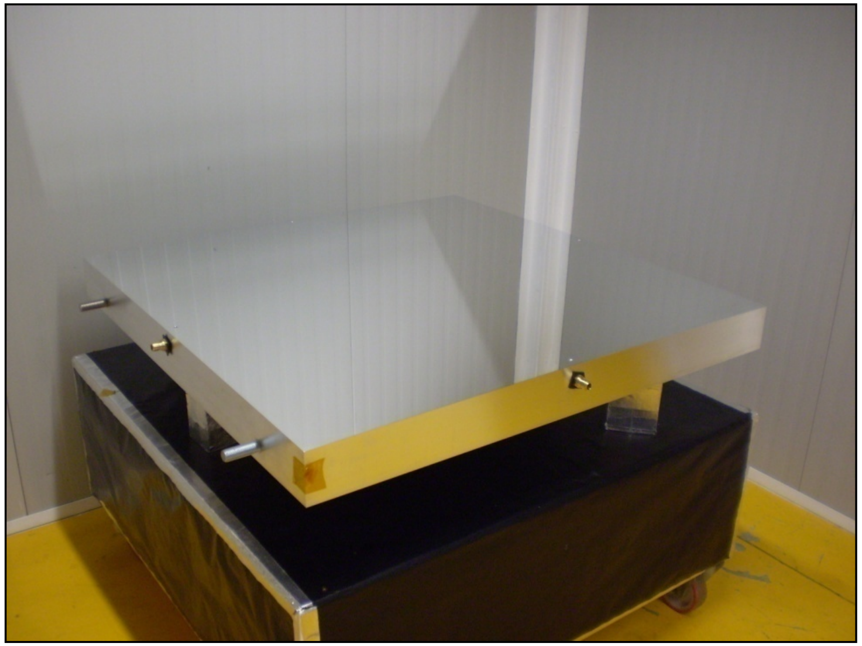
Front glass sheet

Back glass sheet

Al honeycomb core

Coat with $Al + SiO_2$

MAGIC II glass mirror panels production (Media Lario, Italy)



Aluminum master 1040 x 1040 mm

Front and rear of a produced segment

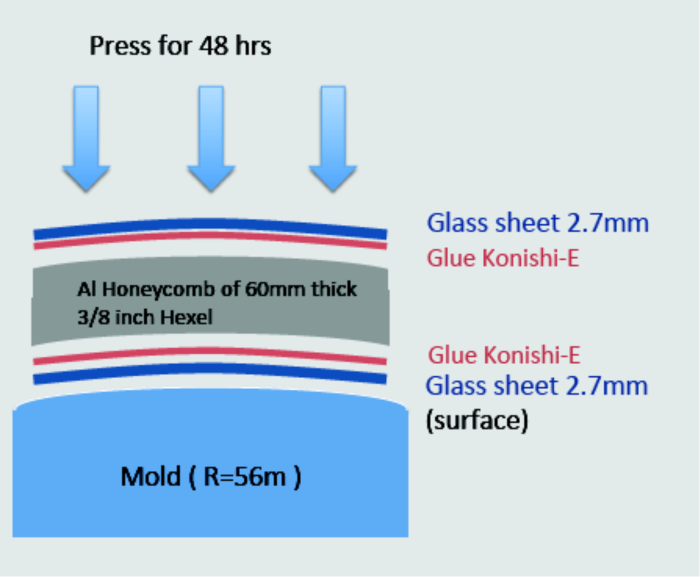
Size = 985 x 985 mm Weight = 9.5 Kg.

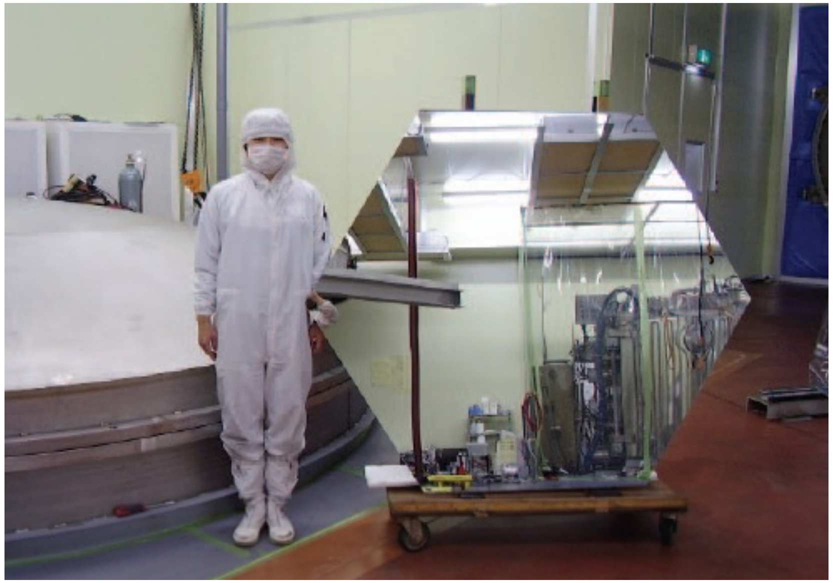
Nominal radius= 35 m

Vernani et al. – SPIE Proc. 7018-0V
Pareschi et al. – SPIE Proc. 7018-0W

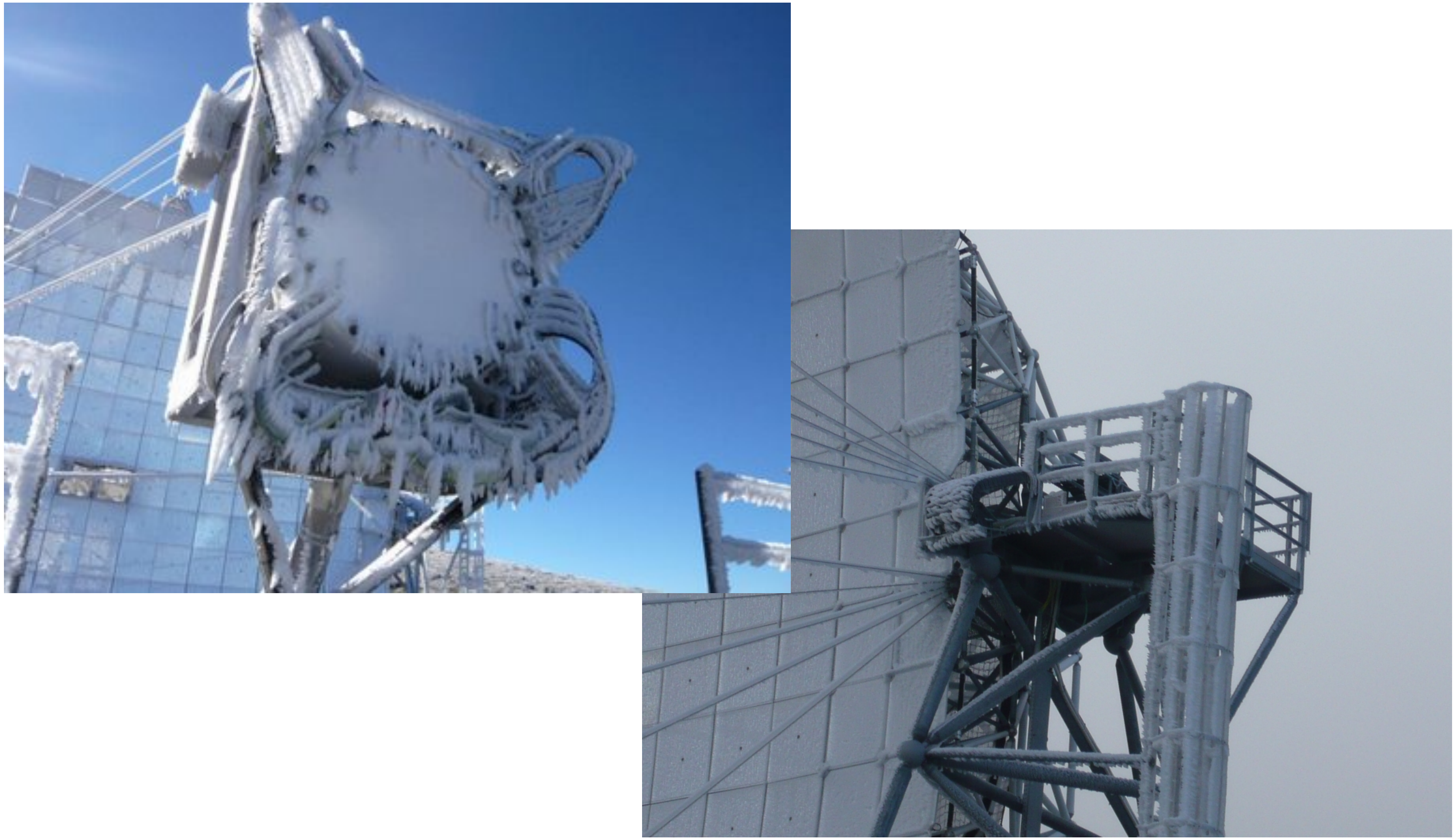
ICRR Japan

- cold-slumping technology as well
- focus on LST mirrors (hexagonal, 1.5 m flat-to-flat)
- 40 prototypes produced, extensive testing ongoing



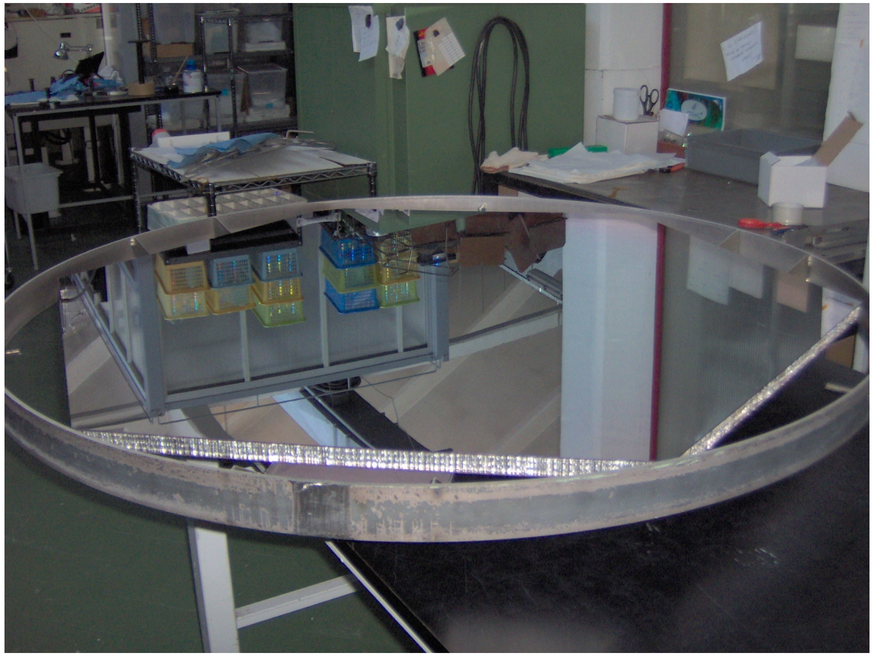


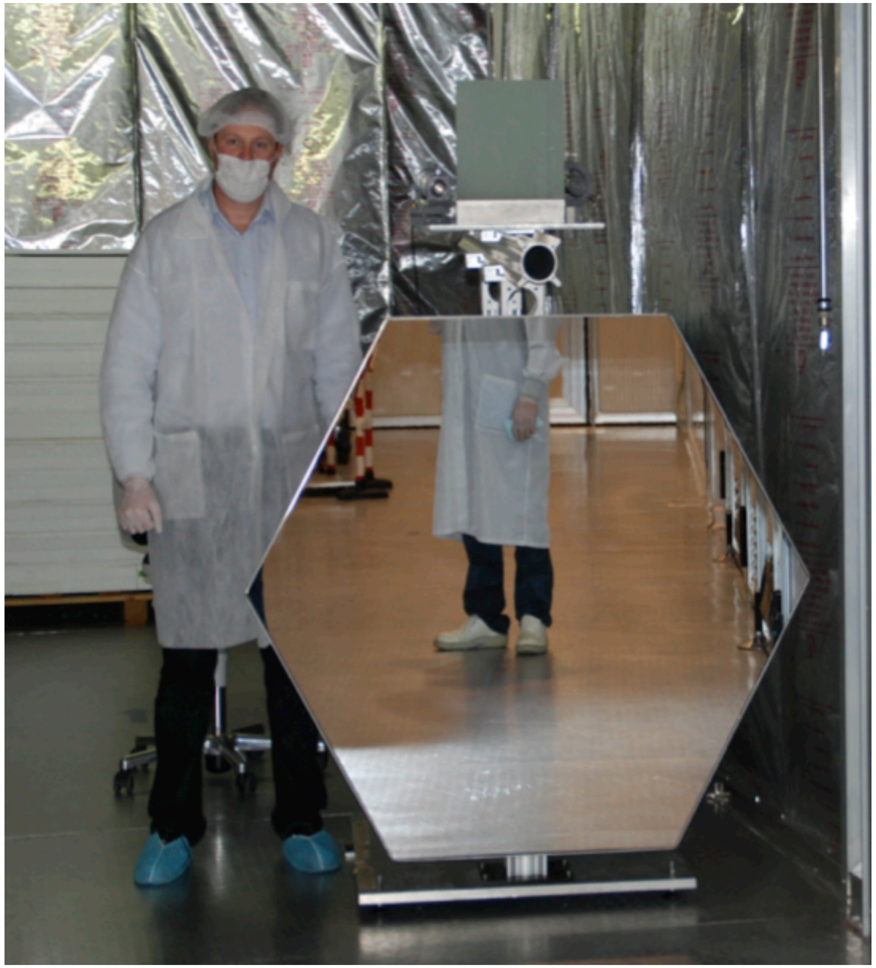
Severe environmental conditions!



Mirrors for the MST prototype

20 mirrors already produced and delivered for MST!





The Schwarzschild-Couder optical design

- Aspherical optical surfaces.
- De-magnifying telescope.
- Possibility to push the angular resolution.
- Very good optical performances for strong off-axis rays

F#: 0.5

f: 2.15 m

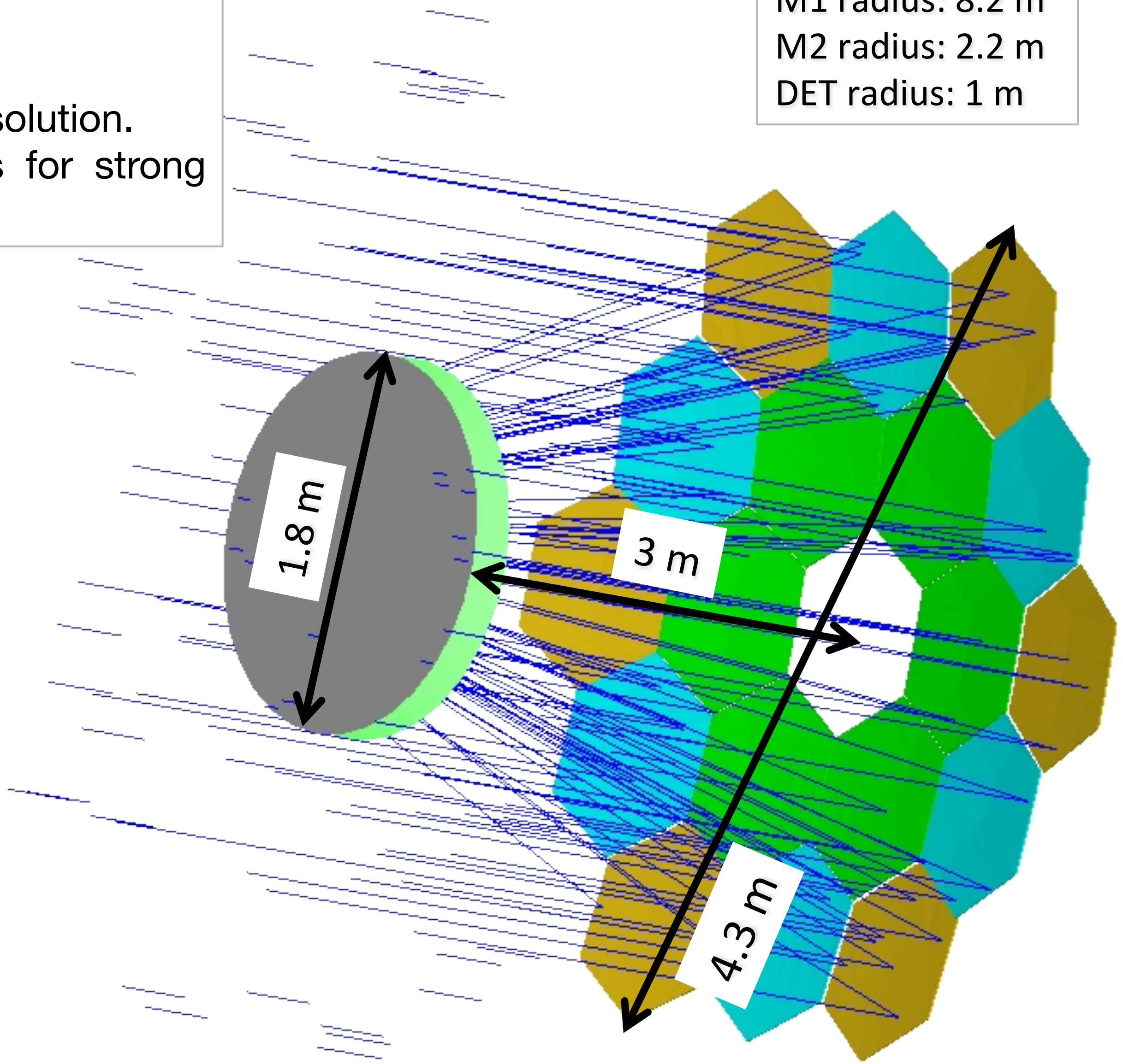
Pixel: 0.16°

FoV: 9.6°

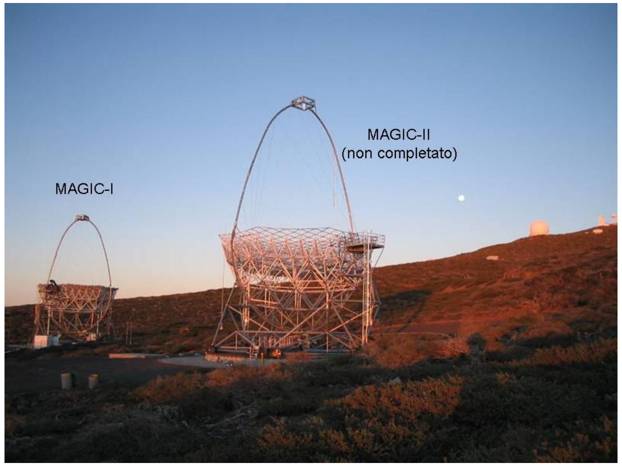
Plate-scale: 37.5 mm/°

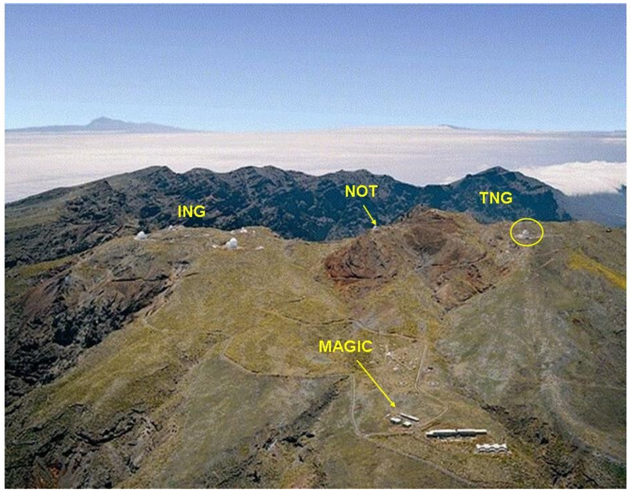
PSF: EE80% < 6 mm
Effective area: 6.5 m^2

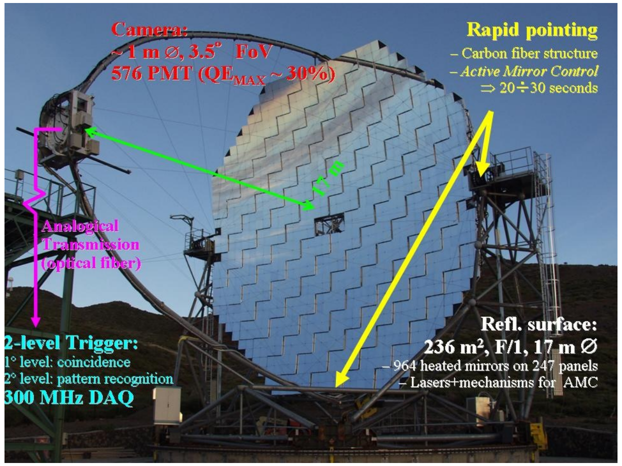
M1 radius: 8.2 m
M2 radius: 2.2 m
DET radius: 1 m



MAGIC Telescope System

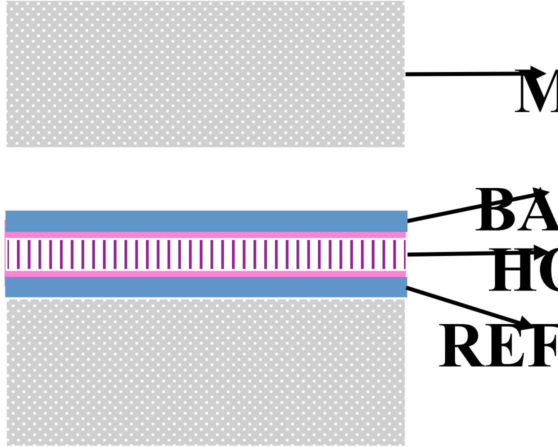






- Geometry: Parabolic
- Diameter: 17m
- Collecting Area: 240 m^2
- F-number (f/D): 1
- FOV: 3.8 deg
- Slew time: 20 s
- Angular resolution: < 3 arcmin
- Energy Resolution: 30%
- Operating Band: 50 GeV – 50 TeV
- Sensitivity (@1 TeV): 30 mCrab (1 single telescope)
  20mCrab (2 telescopes)
- Sensitivity @ 50 GeV: 0.1 Crab (1 single telescope)
  0.05 Crab (2 telescopes)

Glass Panel Manufacturing flow

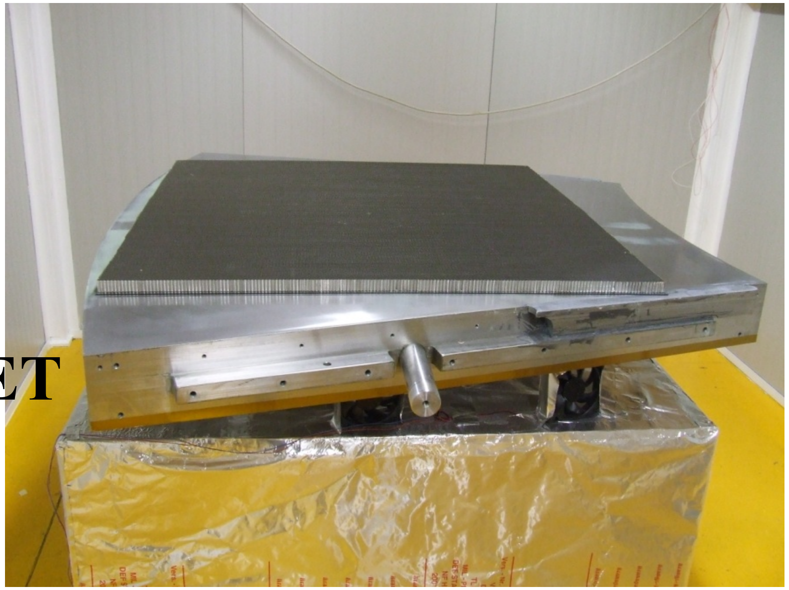


MASTER

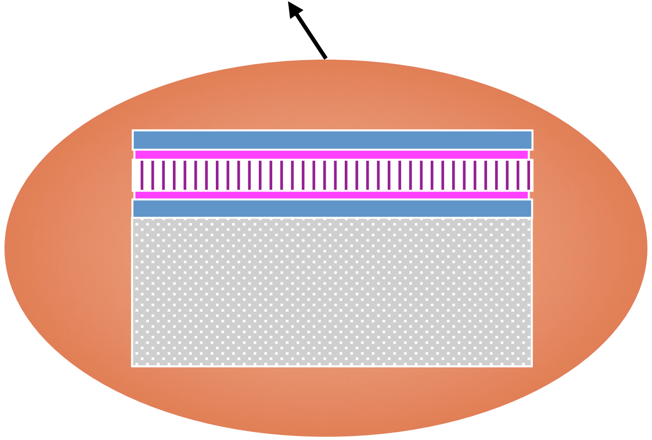
BACKING SHEET

HONEYCOMB

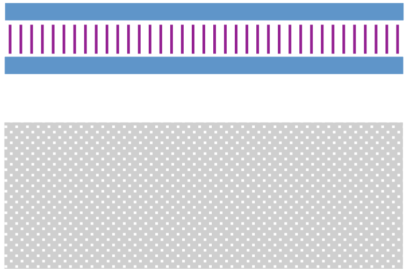
REFLECTING SHEET

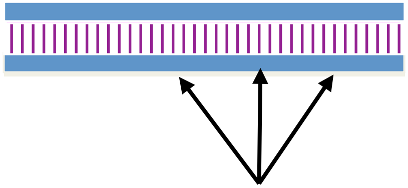


CURING CHAMBER



RELEASE

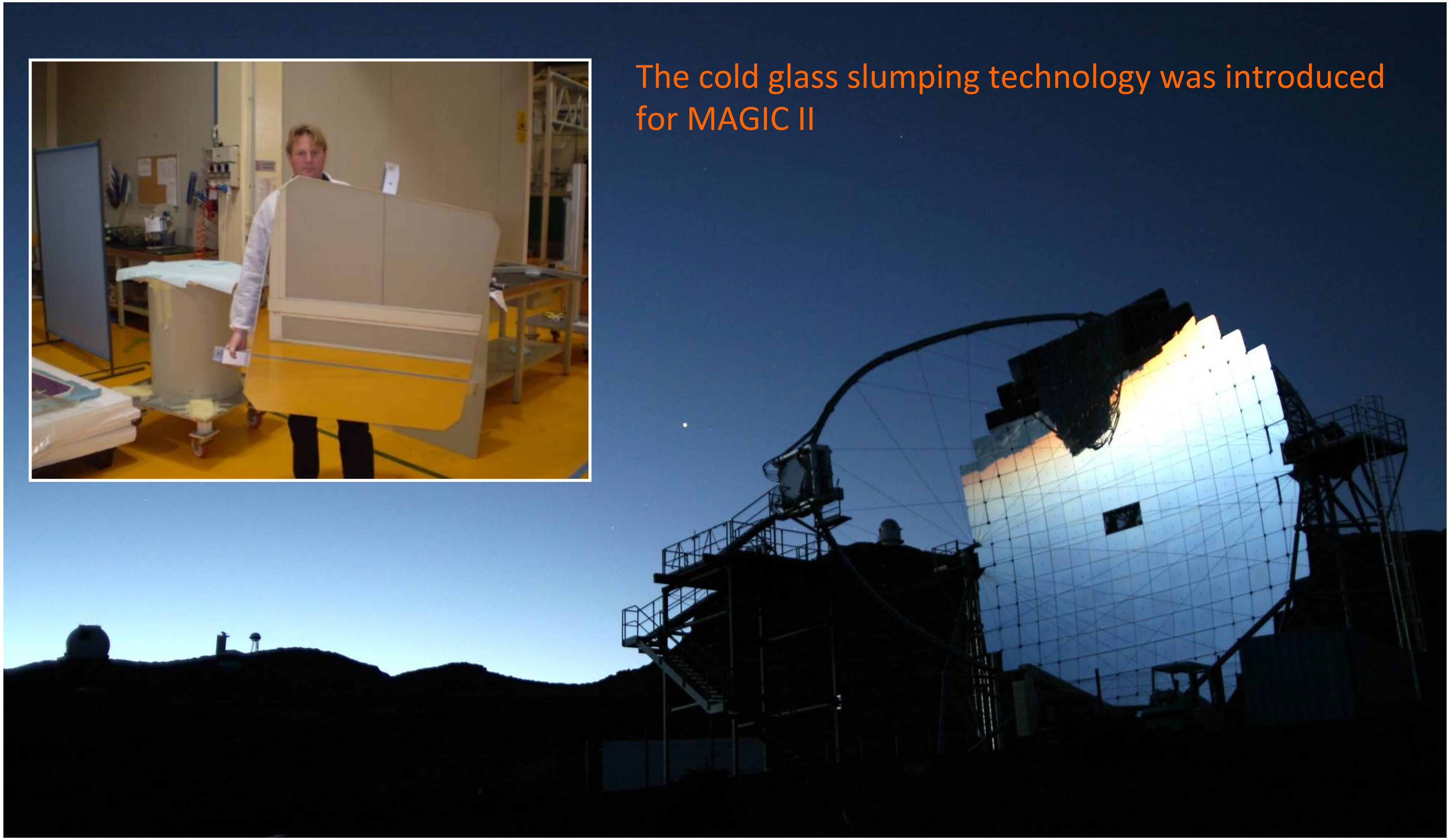




PVD COATING

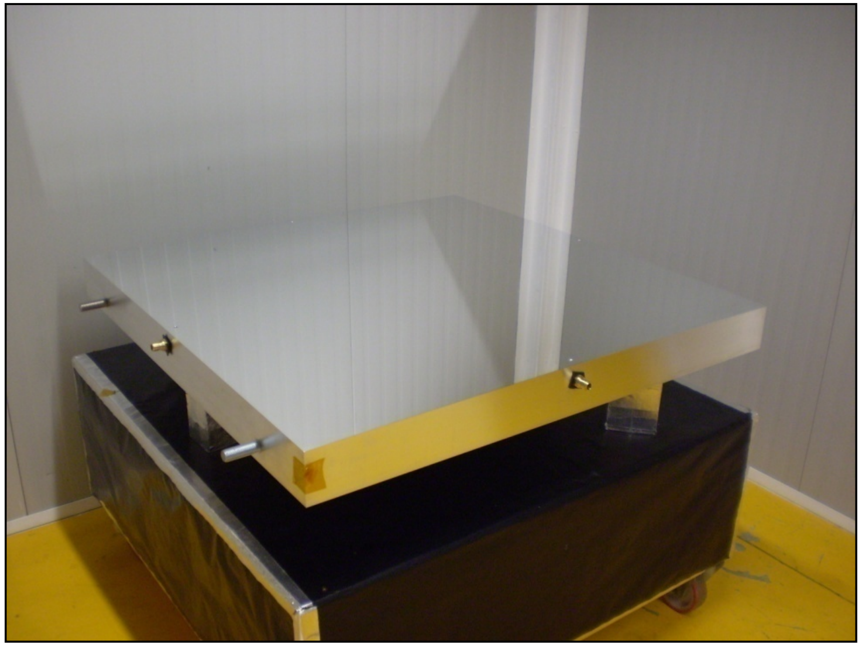
AL + SiO_2

MAGIC II



The cold glass slumping technology was introduced for MAGIC II

Master and panel in the making

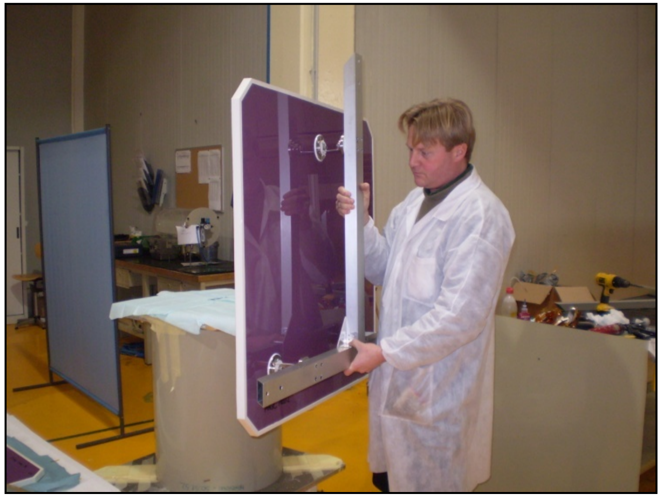


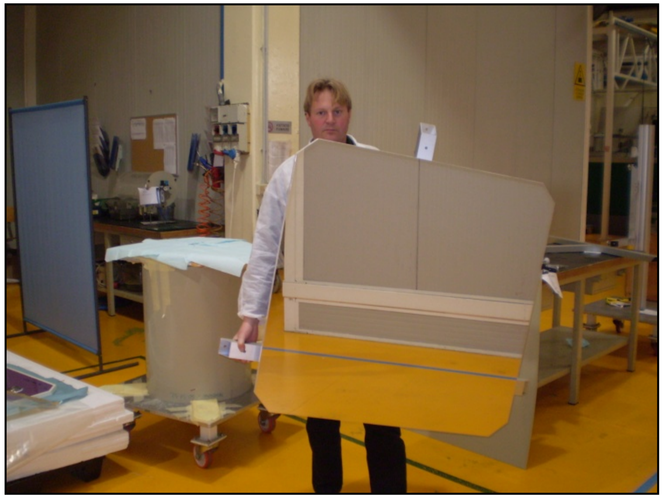
Aluminum master 1040 x 1040 mm

Front and rear of a segment

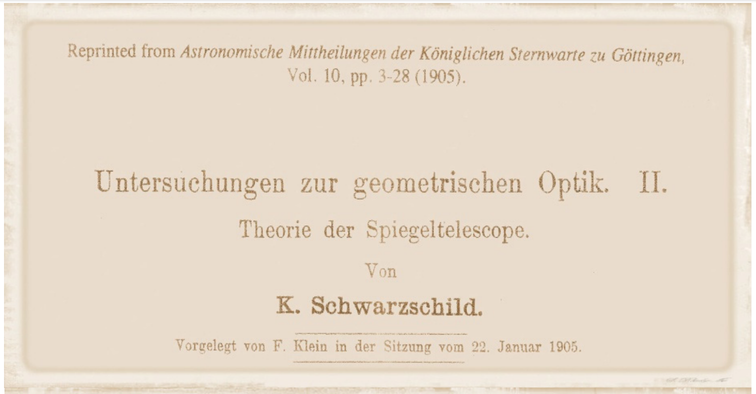
Size = 985 x 985 mm Weight = 9.5 Kg.

Nominal curvature radius= 35 m





Schwarzschild Telescope (1905)



Reprinted from *Astronomische Mittheilungen der Königlichen Sternwarte zu Göttingen*, Vol. 10, pp. 3-28 (1905).

Untersuchungen zur geometrischen Optik. II.

Theorie der Spiegeltelescope.

Von

K. Schwarzschild.

Vorgelegt von F. Klein in der Sitzung vom 22. Januar 1905.

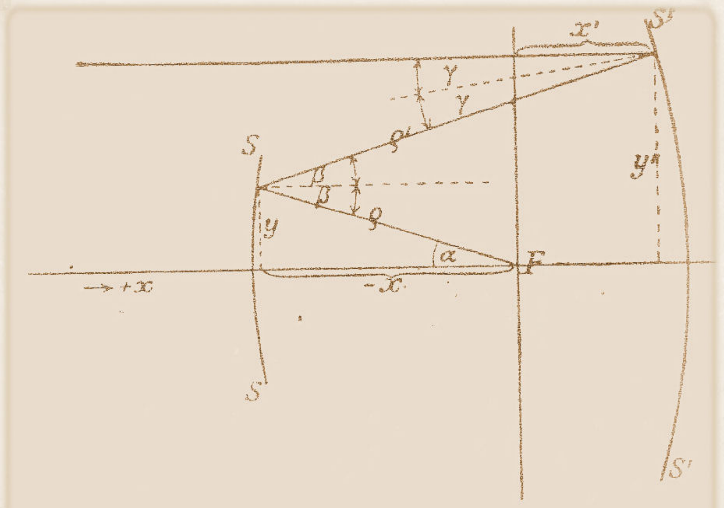


Fig. 8.

Telescope has never been built !

Karl Schwarzschild (1873 -1916)

Found exact solution for figures of two aspheric mirrors which correct spherical aberrations and coma

In 1926 Andre Couder optimized design (3rd order) by introducing curved focal plane

THIN FILM COATINGS


Al+SiO$_2$ coating

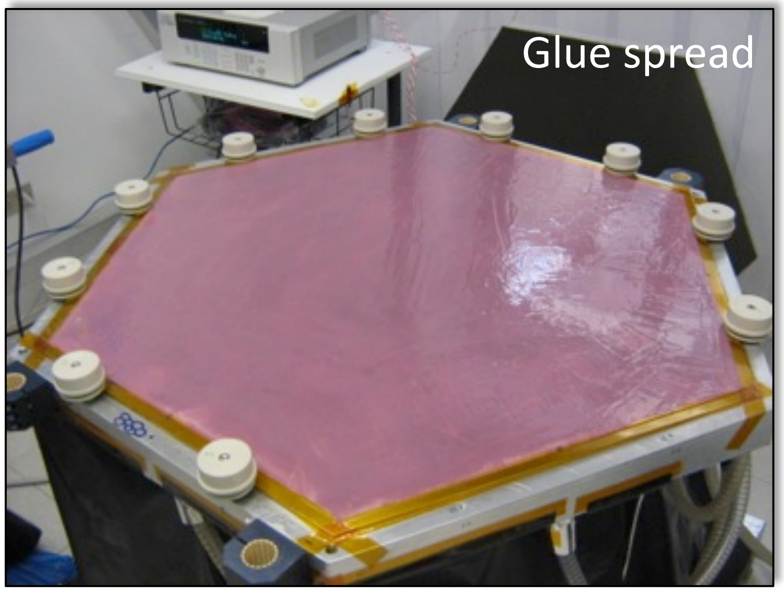

Dielectric coating

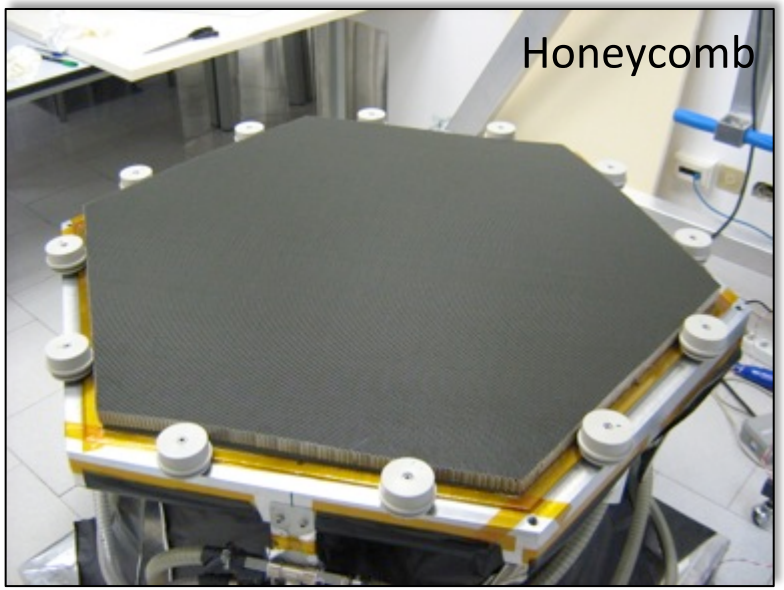

Mirrors finishing


Shipping box

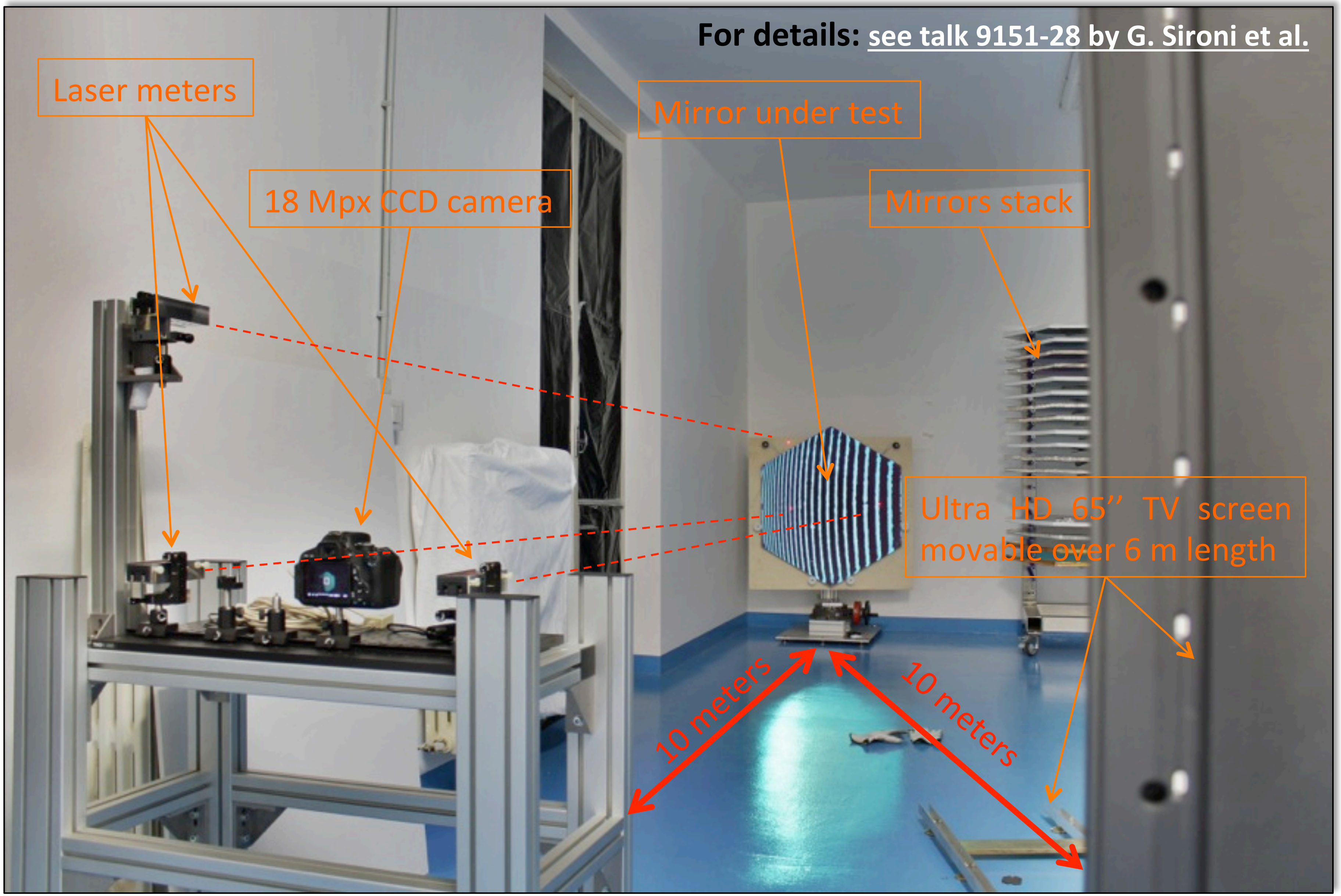

Operators


CS molds


Glue spread


Honeycomb

For details: see talk 9151-28 by G. Sironi et al.



Laser meters

18 Mpx CCD camera

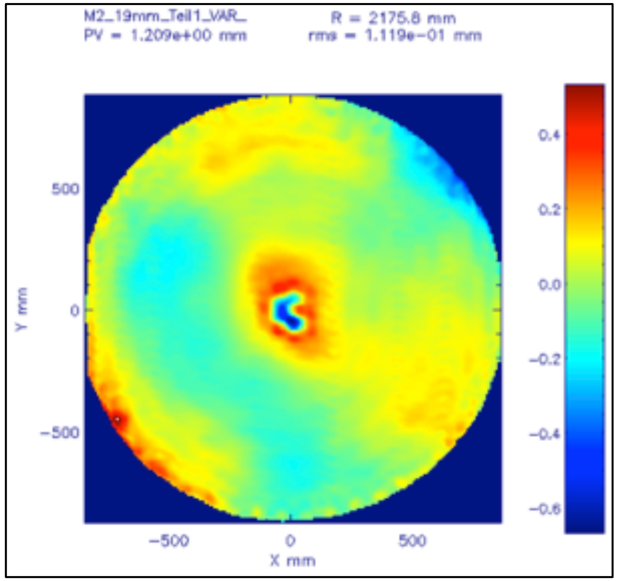
Mirror under test

Mirrors stack

Ultra HD 65'' TV screen movable over 6 m length

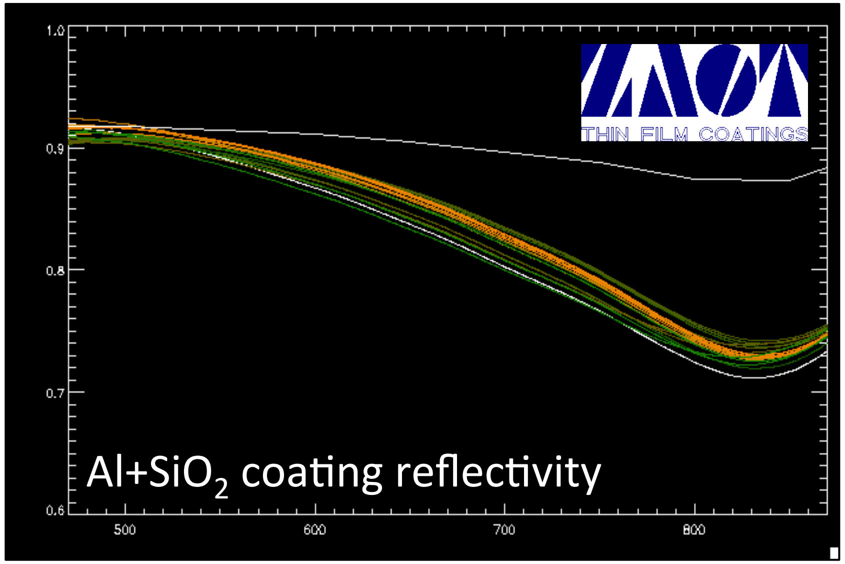
10 meters

10 meters

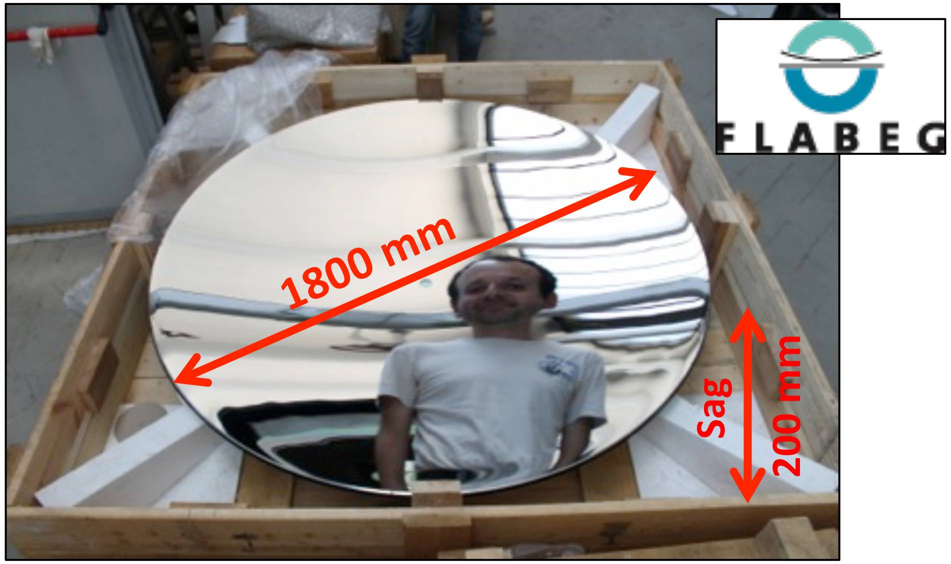


- ✧ Monolithic glass plate 19 mm thick
- ✧ Bended to desired profile with ad-hoc thermal process in FLABEG (Germany)
- ✧ Coating with ad hoc facility in ZAOT (Italy)

For details: <u>see poster 9151-135 by E. Giro et al.</u>



Al+SiO$_2$ coating reflectivity

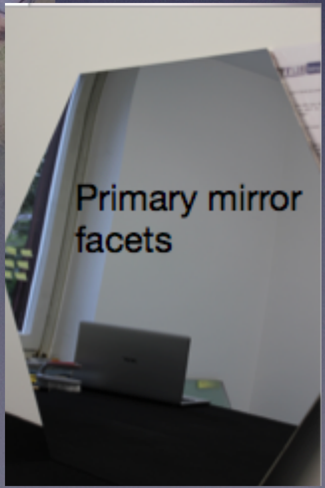


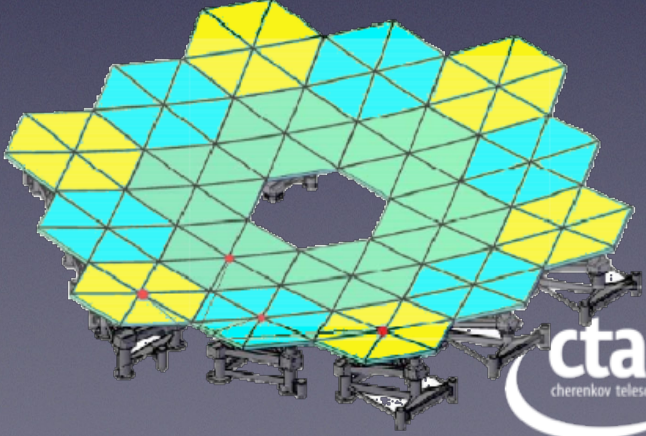

CANNETI OTTICA
OFFICINA MECCANICA
LA.LA. MILANO

ASTRI - Dual Mirror SST

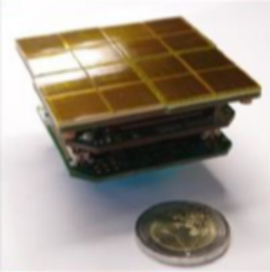
SST-2M Prototype in Serra La Nave (CT Italy)

- 4m diameter dual mirror
  - Segmented primary
  - Monolithic Secondary
- Effective area: 6 m^2
- Focal length: 2.2m
- FoV: 9.6°
- Pixel angular size 0.17°





SiPM Based camera



cta
cherenkov telescope array

ASTRI telescope prototype after scientific calibrtaion are accomplished

Can we predict volcanic eruptions ?

1) **By muons "tomography"**

Pointing ASTRI toward Etna we could get muons going through less dense material as lava; will they get less scatter than those going through the surrounding rocky regions ?

2) By sky monitoring

Observing the sky toward Etna in the 300-900 nm region, could we detect an increase or decrease of the sky flux at some wavelengths just before an eruption ?