Laboratorio di Astrofisica delle alte energie – Università di Bologna
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Technological development: Athena and CTA as case studies

Valentina Fioretti (valentina.fioretti@inaf.it)
Andrea Bulgarelli (andrea.bulgarelli@inaf.it)
INAF Osservatorio di Astrofisica e Scienza dello Spazio (OAS Bologna)

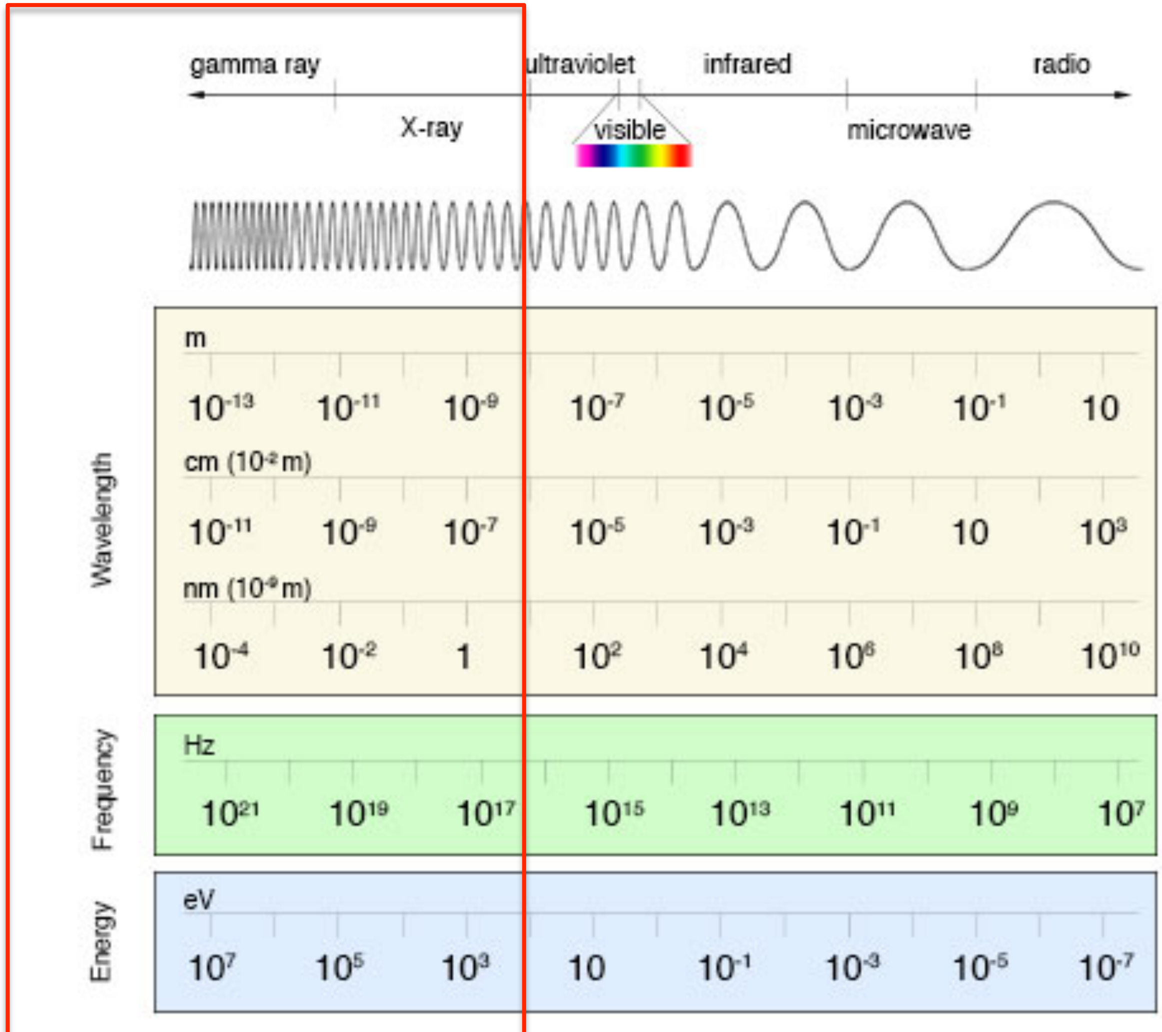
Outline

- review of two future projects in X-ray and Gamma-ray astrophysics:
  - ESA/Athena (Advanced Telescope for High ENergy Astrophysics)
  - CTA (Cherenkov Telescope Array)

- technological development activities in OAS: building the astronomy of the future

Observing the Universe at high (and very high) energies

high energies:
- X-rays and gamma-rays
- > keV energy



$$E(\mathrm{eV}) = hc/\lambda(\mu\mathrm{m}) \approx 1.24/\lambda(\mu\mathrm{m})$$

1 eV ≈ 11600 Kelvin deg.

1000 eV = 1 keV

1000 keV = 1 MeV

1000 MeV = 1 GeV

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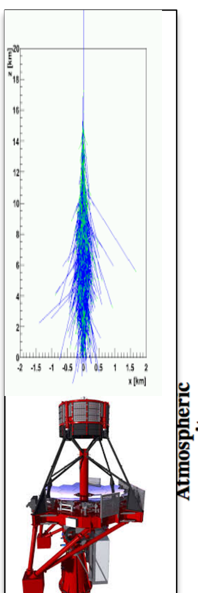
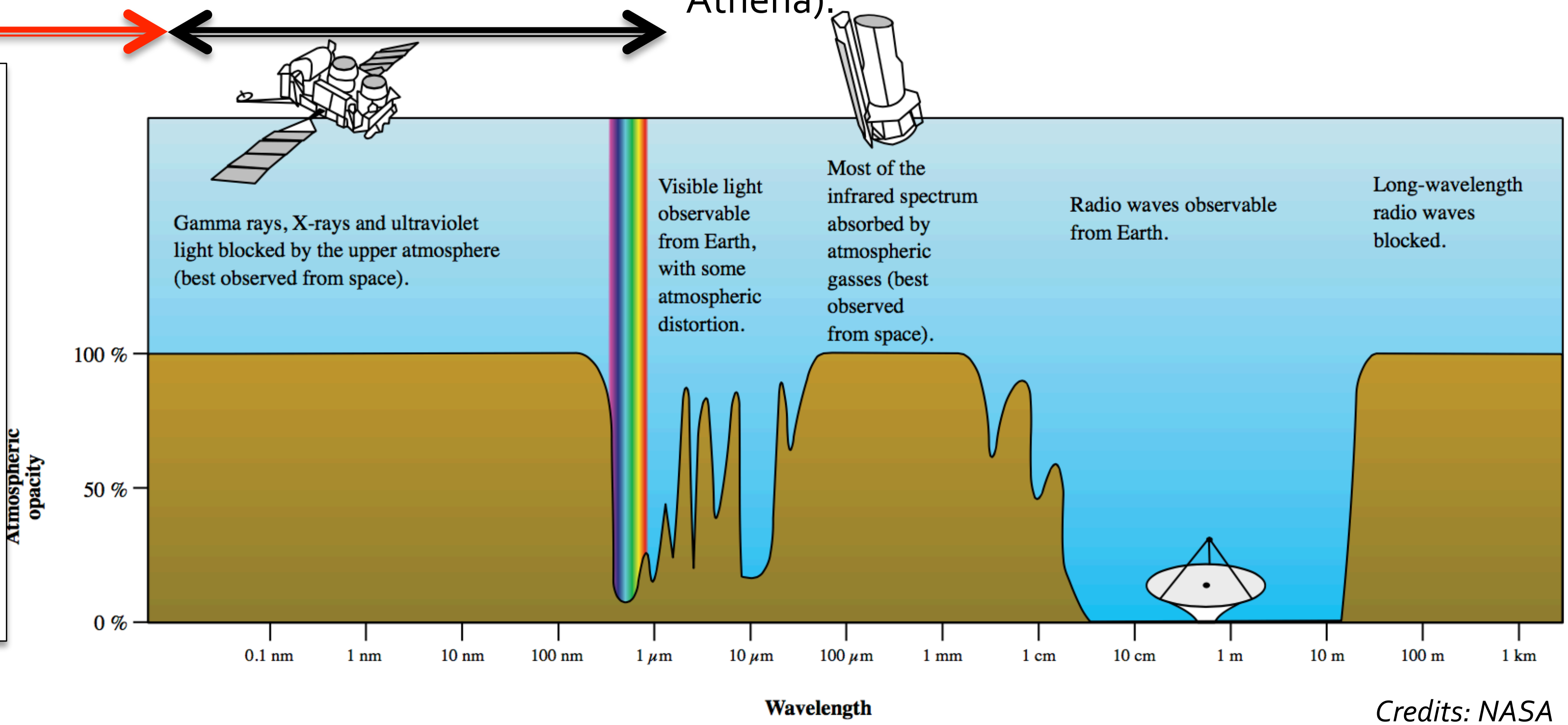
Observing the Universe at high (and very high) energies

Above E > 10 GeV (Very High Energy Gamma-rays) we can indirectly observe the gamma-ray sky by exploting their interaction with the atmosphere, collecting the secondaries with on-ground telescopes (e.g. CTA)

X-ray and Gamma-rays are absorbed by the atmosphere. Observations need telescopes orbiting in space (e.g. Athena).



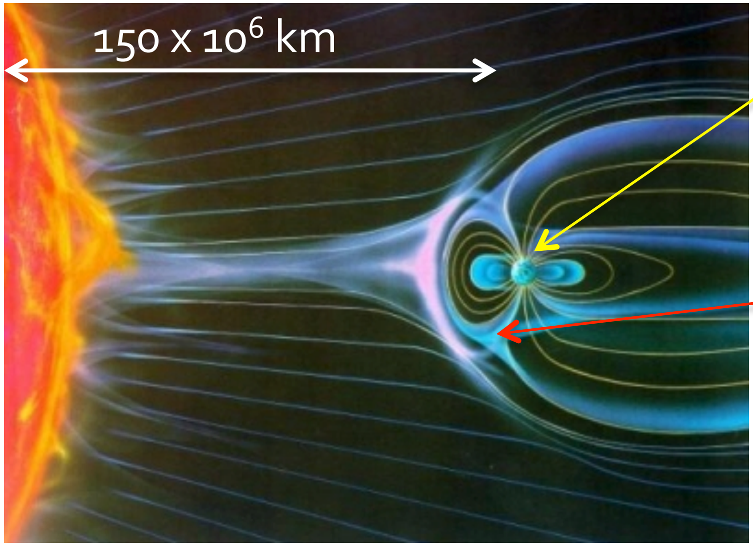


Credits: NASA

X-ray and gamma-ray space telescopes

- from keVs to hundreds of GeV, telescopes are placed on board space satellites and launched to space
- each space mission is the result of the collaboration of space agencies (NASA, ESA, ASI) with research institutes and universities
- Orbits and technologies depend on the scientific goals of the mission

Sun



Earth

magnetosphere: the region of space dominated by the Earth's magnetic field

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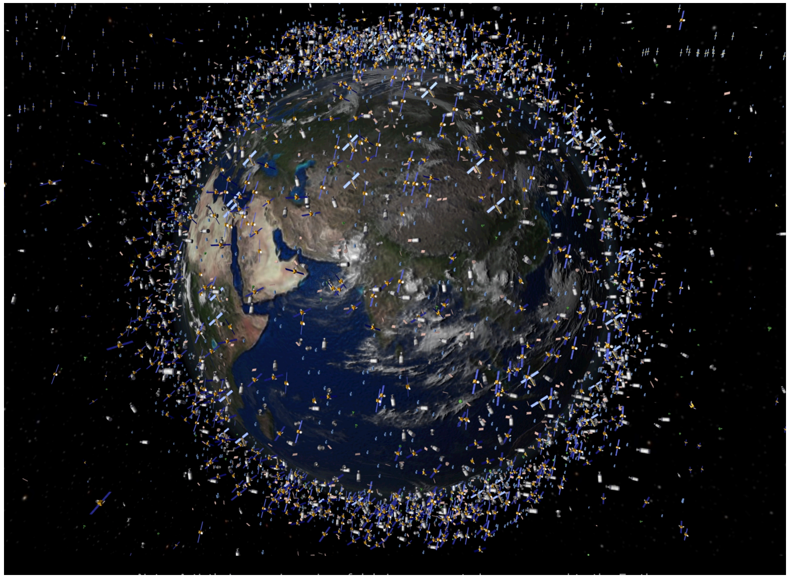
Current X-ray and gamma-ray telescopes

Current (main) X-ray and gamma-ray telescopes operating from space are:

- in **Low Earth Orbit** (the spacecraft operates below the radiation belts, < 1000 km of altitude, with circular orbits lasting periods of 90 minutes):
    - NASA Swift (X)
    - NASA NuSTAR (X)
    - JAXA/NASA Suzaku
    - NASA Fermi (Gamma-ray)
    - ASI AGILE (Gamma-ray)
    - … and the International Space Station!



PRO: good background shielding by the Earth's magnetic field

CONS: Earth covering 1/4 of the sky

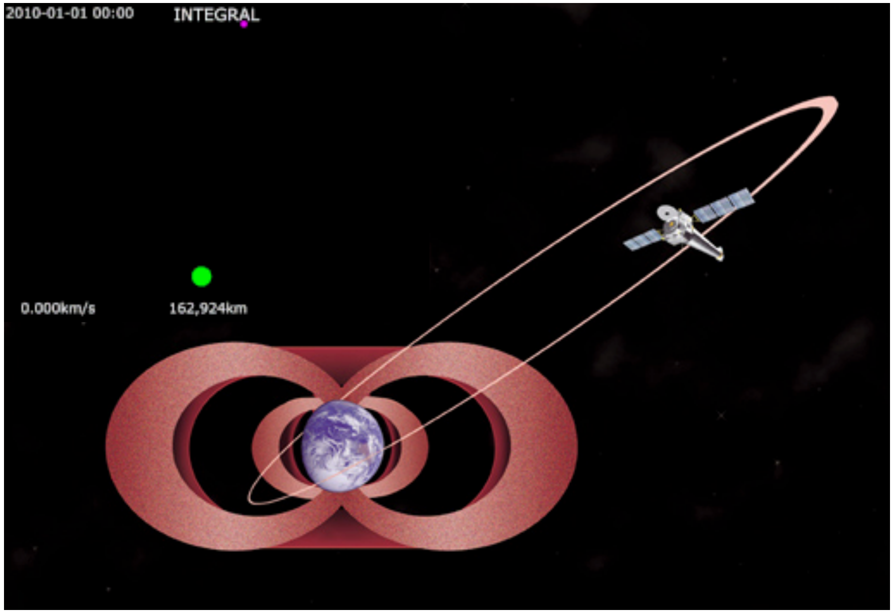
Current X-ray and gamma-ray telescopes

Current (main) X-ray and gamma-ray telescopes operating from space are:

- in **High Elliptical Orbit** (the spacecraft reaches extreme apogees (>10^5 km), with an orbital period of a few days, and spends most of the operating time beyond the radiation belts):
  - NASA Chandra (X)
  - ESA XMM-Newton (X)
  - ESA INTEGRAL (X and Gamma)

PRO: almost uninterrupted observations of the sky

CONS: high background



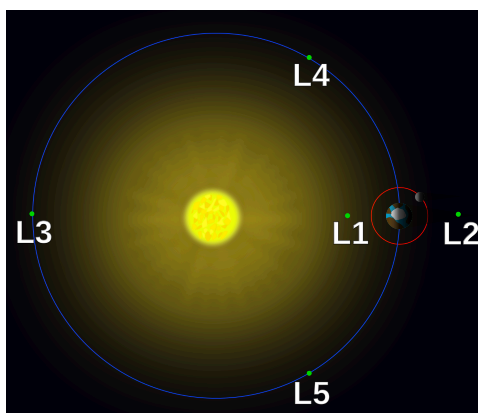
Current X-ray and gamma-ray telescopes

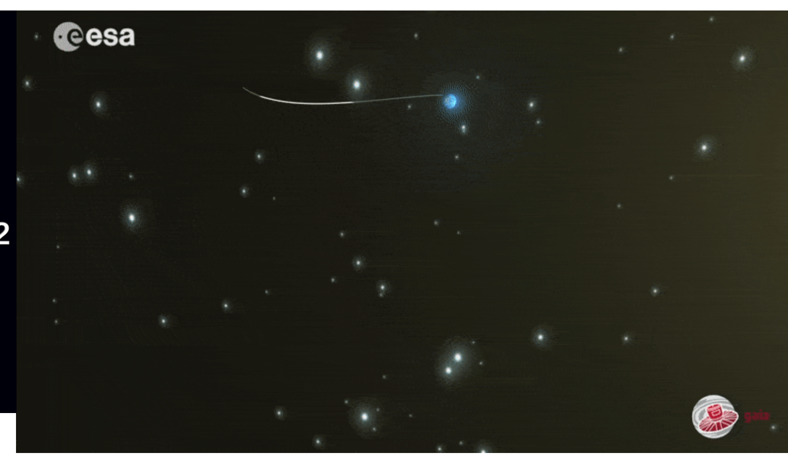
Current (main) X-ray and gamma-ray telescopes operating from space are:

- in **lagrangian L1 or L2 points** (regions of gravitational equilibrium at 1.5×10^6 km where the combined gravitational forces of the Earth and the Sun combined with the spacecraft centripetal force causes the latter to maintain an almost constant position relative to the two larger bodies):
  - MPE/eRosita on-board the Spektr-RG (X) – launched in 2019 in L2

PRO: uninterrupted observations of the sky, thermally stable

CONS: high background





credits: ESA/GAIA

X-ray focusing telescopes (e.g. Chandra, XMM-Newton, Athena)

An X-ray telescope is composed by two main system:

- the focusing system, to collect X-ray photons in a very small area
- the detection system, to register the energy and position of the photon in the sky

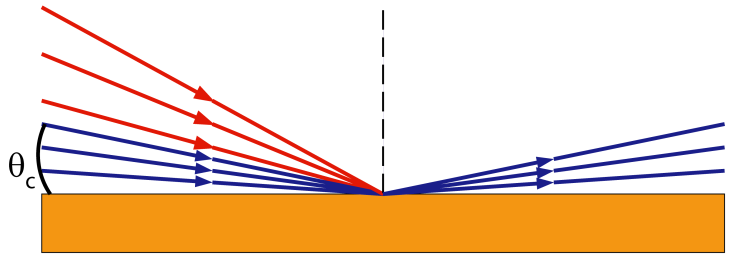
How to focus X-rays?

.... lens? Impossible! X-ray are much more energetic than the optical photons, and they would cross the lens without interacting*

... mirror? Yes, but only if the angle between the mirror and the X-ray is very small (grazing incidence)

**the use of special crystals and diffraction could solve the issue in the far future*

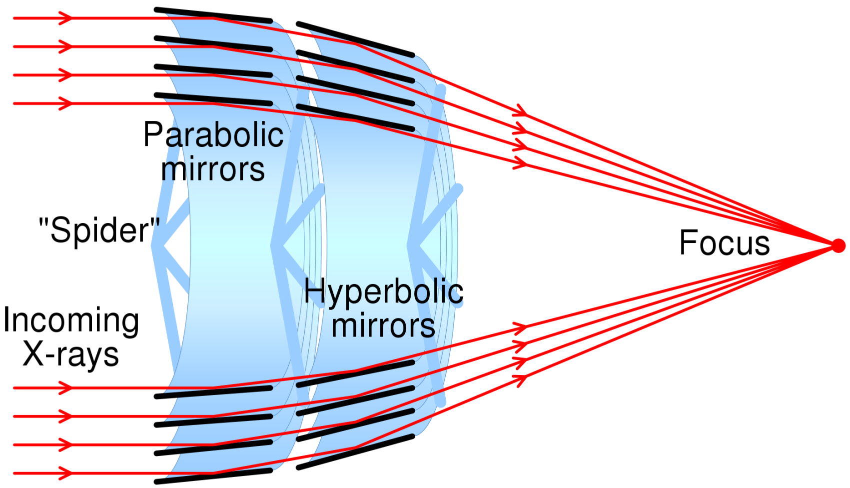
X-ray mirrors



$$\vartheta_{crit} \propto \frac{\sqrt{\rho}}{E}$$

The maximum incident angle that allows the reflection depends on the energy and the material density

- higher density -> higher θ_{crit}:
  - high-Z metals (Au, Ir, Pt) are used as coating layers for X-ray grazing mirrors on top of lighter supporting plates (e.g. glass, Ni)
- high energy -> lower θ_{crit}:
  - **maximum energy for X-ray mirrors is < 100 keV**



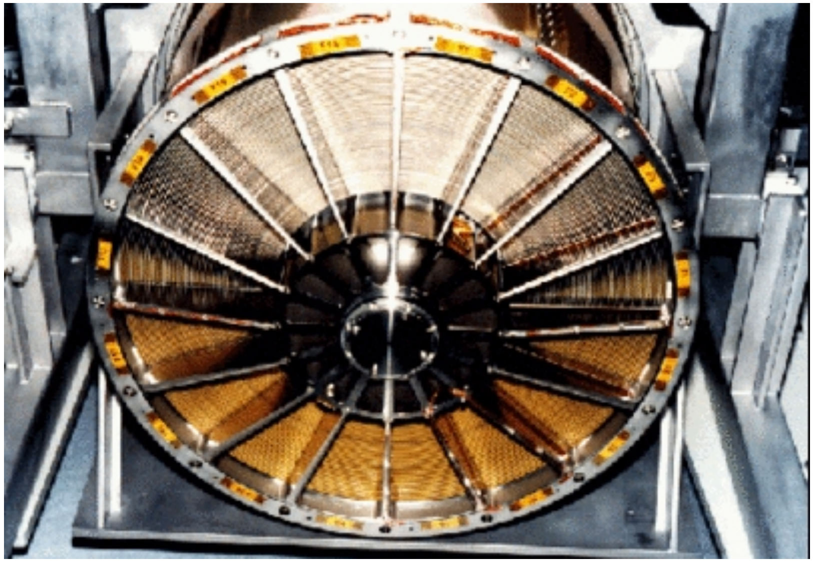
Solution: use of many confocal and coaxial mirror shells, usually with a parabolic and hyperbolic geometry (Wolter-I) kept together by special structures (spiders)

X-ray mirrors: XMM and Chandra

NASA Chandra X-ray mirror
- 4 shells (Glass + Ir)
- higher angular resolution

Credits: NASA

NASA XMM-Newton X-ray mirror
- 58 shells (Ni + Au)
- higher effective area

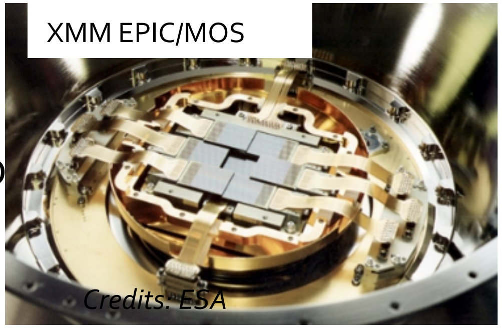


Credits: ESA

X-ray Detectors for focusing telescopes

The technology for X-ray detectors depends on the scientific goals of the mission (e.g. sky surveys, study of gas dynamics):

- Charge-Coupled Devices (CCDs):
    - Silicon-based
    - High dynamic range, high quantum efficiency and low noise make CCD suitable for X-ray imaging and spectroscopy
    - XMM-Newton EPIC and Chandra ACIS detectors are CCDs

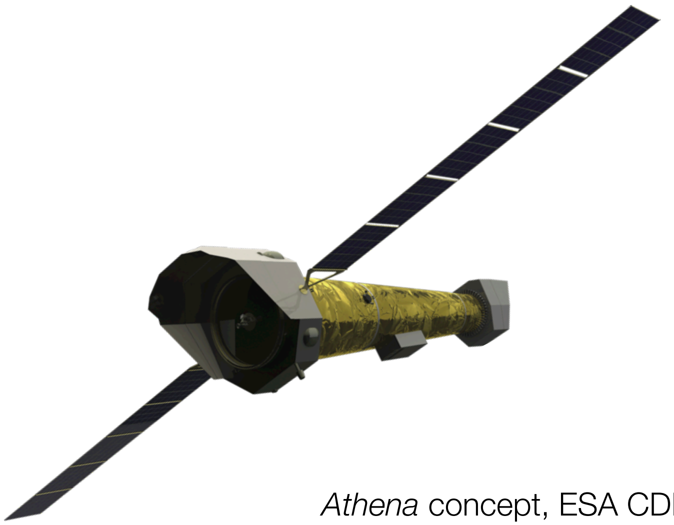


- Active Pixel Sensors (APS):
    - Silicon-based
    - the charge is collected within the pixel, thus increasing the energy resolution while allowing larger array sizes and higher frame rates than CCDs.
    - Athena Wide Field Imager will be made of APS

- X-Ray Micro-calorimeters
    - the photon energy is measured as the temperature rise of an absorber material at very low temperatures, then converted to an electrical pulse. They reach an energy resolution >50 times better than CCDs
    - Athena X-IFU will be an X-ray micro-calorimeter

The ESA Athena mission: the future of X-ray astronomy

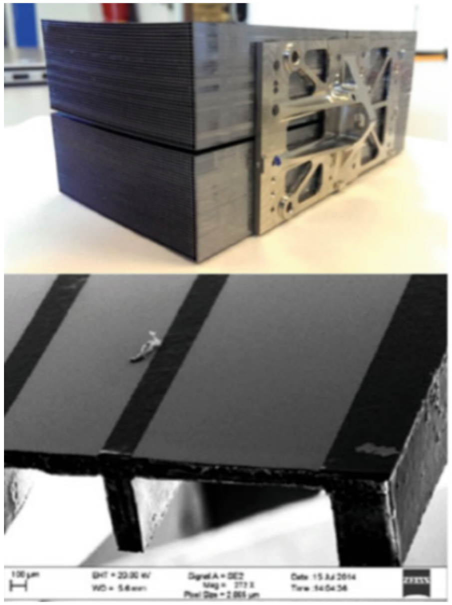
- ESA mission
- Launch 2031-2032 in L2 or L1 halo orbit
- Energy range: 0.2 – 12 keV
- X-ray mirror:
  - Silicon Pore Optics (SPO)
  - 12m focal length
- X-ray detectors
  - WFI sensitive imaging & timing
  - X-IFU spatially resolved high-resolution spectroscopy



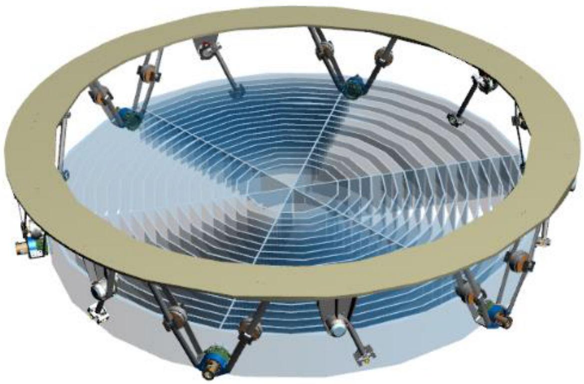
Athena concept, ESA CDF
Credit: IRAP, CNES, ESA & ACO

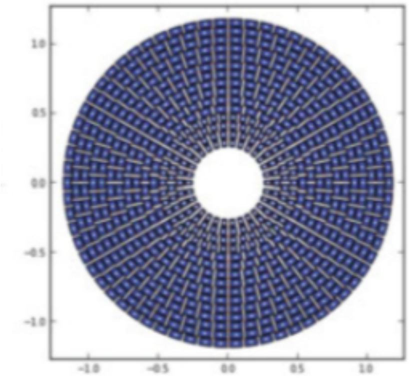
Athena X-ray optics

- Wolter-I design (paraboloid + hyperboloid)
- Millions of **Silicon pores** instead of metal shells
- > 2 m in diameter
- Expected Performance:
  - 5´´ HEW on-axis
  - ≥1.4 m^2 effective area @ 1 keV, 0.25 m^2 effective area @ 6 keV



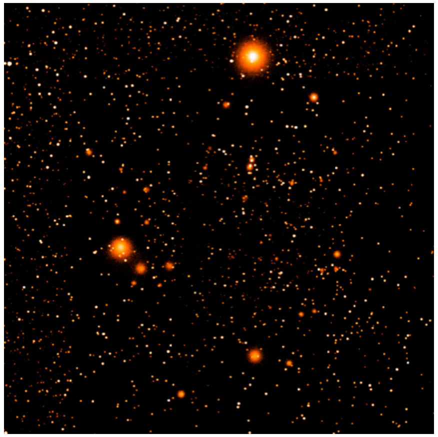
Credits: ESA



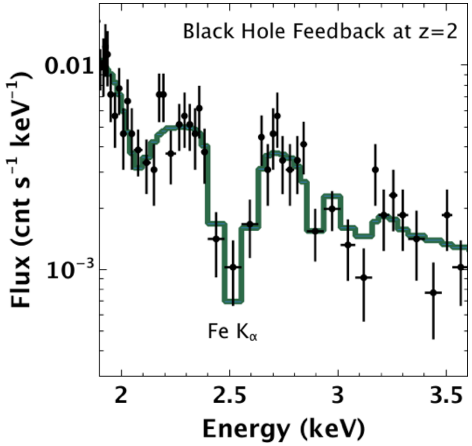


Athena X-ray detectors: Wide Field Imager

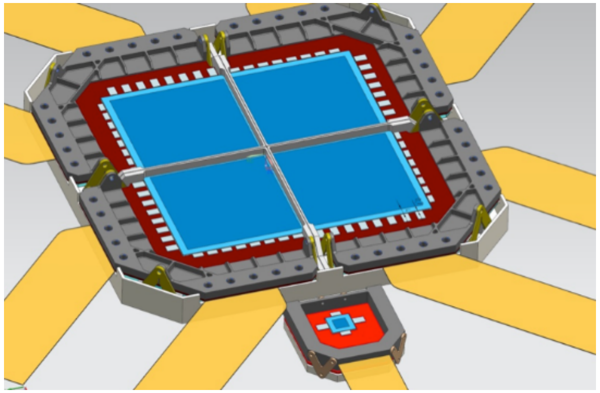
- Silicon Active Pixel Detector based on DEPFET technology
- Key performances:
  - <80 (<170) eV spectral resol. @ 1 (7) keV
  - 2.2′′ pixel size (PSF oversample)
  - Field of view: 40′×40′ square
- Consortium led by MPE, with other European partners (DE, AT, DK, FR, **IT**, PL, UK, CH, P & GR) and NASA
- Optimized for sensitive wide-field imaging and intermediate resolution spectroscopy, up to very bright sources



Credit: A.Rau/WFI team.



Credit: WFI team.



http://www.mpe.mpg.de/ATHENA-WFI/

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Athena X-ray detectors: X-ray Integral Field Unit (X-IFU)

- X-IFU is an X-ray micro-calorimeter, composed by:
  - an high-Z absorber (Mo-Au) thermalizes the X-ray photon (<10-15 keV), i.e. converts the energy in temperature
  - a thermometer (Transition-edge sensor, TES) that detects the termal signal
  - a cooling system (thermal sink) that keeps the temperature low (a cryogenic system at 50 mk or -273.1°C!)

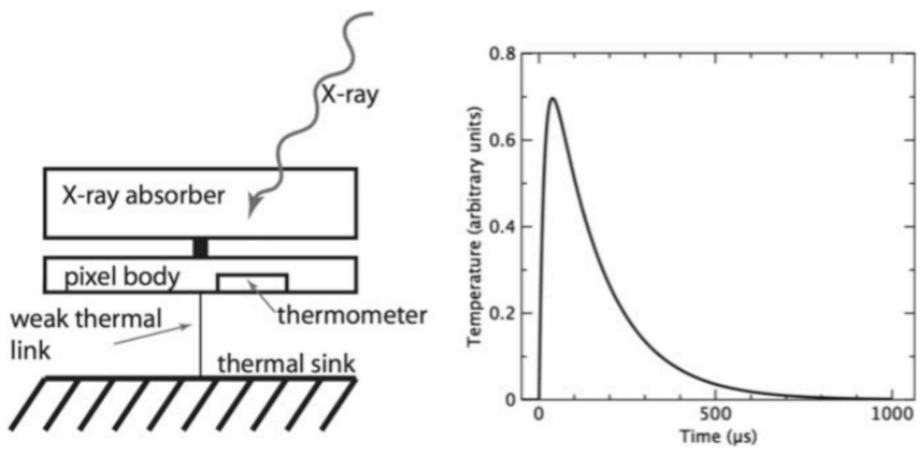


Fig. 3.25 *Left panel*: schematic view of an X-ray micro-calorimeter detector: the incoming X-ray photon is photo-absorbed in the absorber and a thermal signal is registered with a sensitive thermometer [68]. *Right panel*: the fast rise and slower decay of the temperature (or resistance) with time for the ATHENA X-IFU [5]

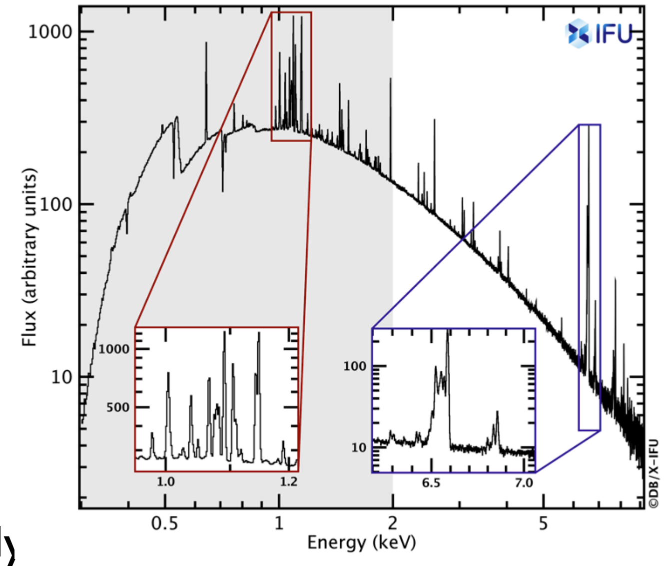
Athena X-ray detectors: X-IFU

- Cryogenic imaging spectrometer, based on Transition Edge Sensors, operated at 50 mK featuring an active cryogenic background rejection subsystem

- Key performance parameters:
  - 2.5 eV energy resolution <7 keV
  - FoV 5′ diameter
  - Pixel size <5′′

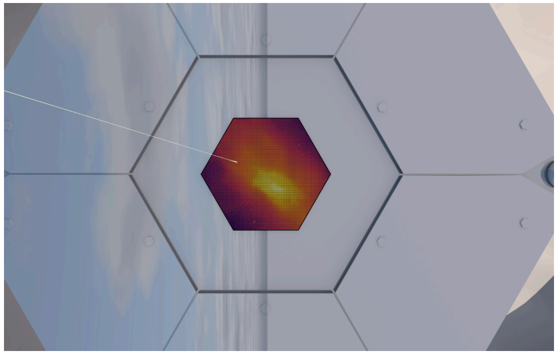
- Consortium led by IRAP/CNES-F, with Netherlands and **Italy** further ESA member state contributions from Belgium, Czech Republic, Finland, Germany, Ireland, Poland, Spain, Switzerland and contributions from Japan and the United States

- Providing both spatially-resolved high spectral resolution and high count rate capability



Credits: X-IFU Consortium

http://x-ifu.irap.omp.eu/



Athena X-ray detectors: X-IFU

https://www.youtube.com/watch?v=KU9djJsk-1k&t=0s&ab_channel=AthenaX-IFU

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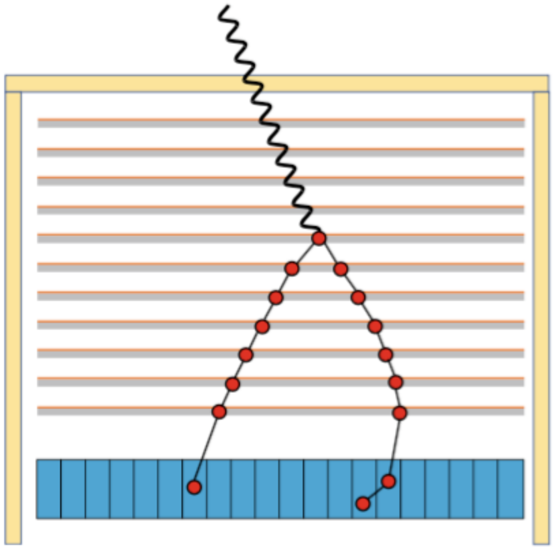
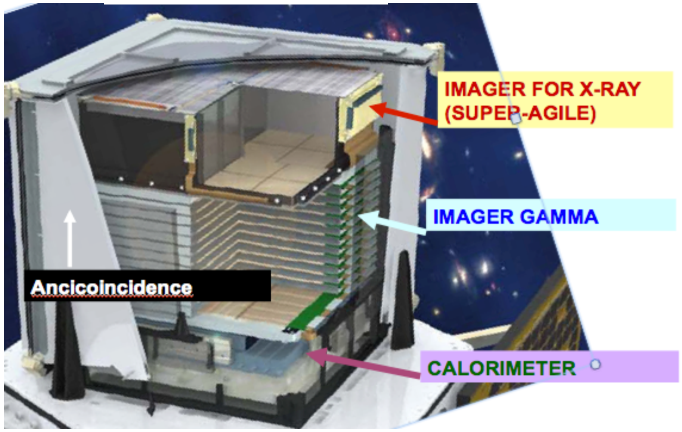
Gamma-ray space telescopes

- energy range: 30 MeV – 50 GeV (AGILE), 30 MeV – 300 GeV (Fermi)
- current operative missions: ASI/AGILE and NASA/ Fermi
- orbit: LEO

- indirect detection system:
  - a set of Tungsten and Silicon planes (tracker) convert the photon in electron-positron pairs and track their position and energy
  - a calorimeter at the bottom absorbs the electron and positron pair
  - the measurement of the energy and direction of the electron and positron pair allows to reconstruct the energy and position of the incident gamma-ray



AGILE/GRID

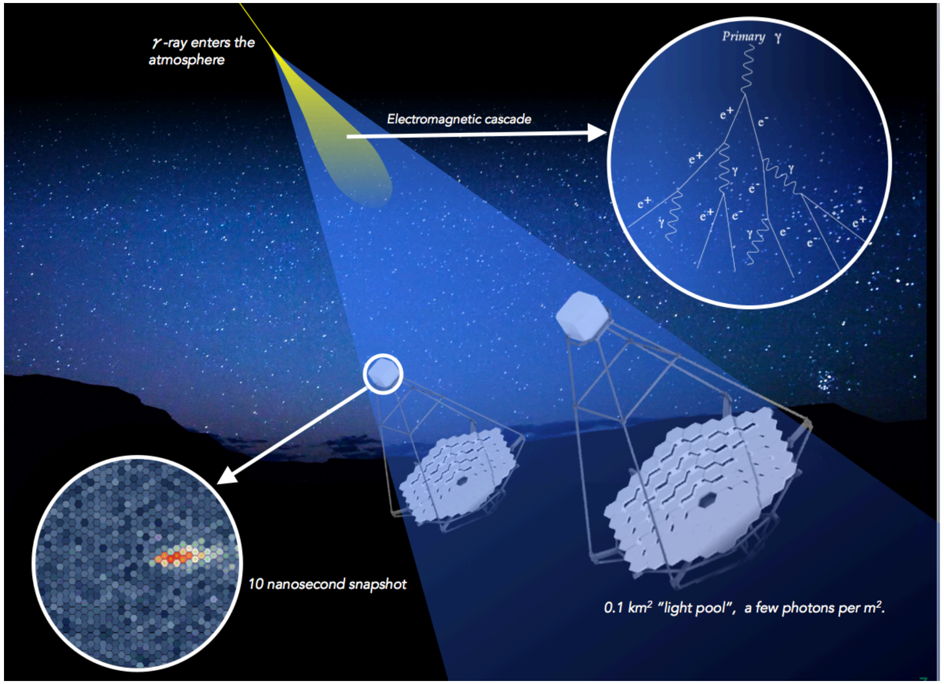


Credits: ASI

On-ground very high energy telescopes: the Cherenkov effect

When gamma rays reach the earth's atmosphere:

- they interact with it, producing cascades of subatomic particles, also known as air or particle showers.
- Nothing can travel faster than the speed of light in a vacuum, but light travels 0.03% slower in air.
- these ultra-high energy particles can travel faster than light in air, creating a blue flash of "Cherenkov light" at about 540 nm of wavelength.
- Although the light is spread over a large area (250 m in diameter), the cascade only lasts a few nanoseconds.
- It is too faint to be detected by the human eye but not too faint for IMAGING AIR CHERENKOV TELESCOPES (IACT).



Credits: CTA

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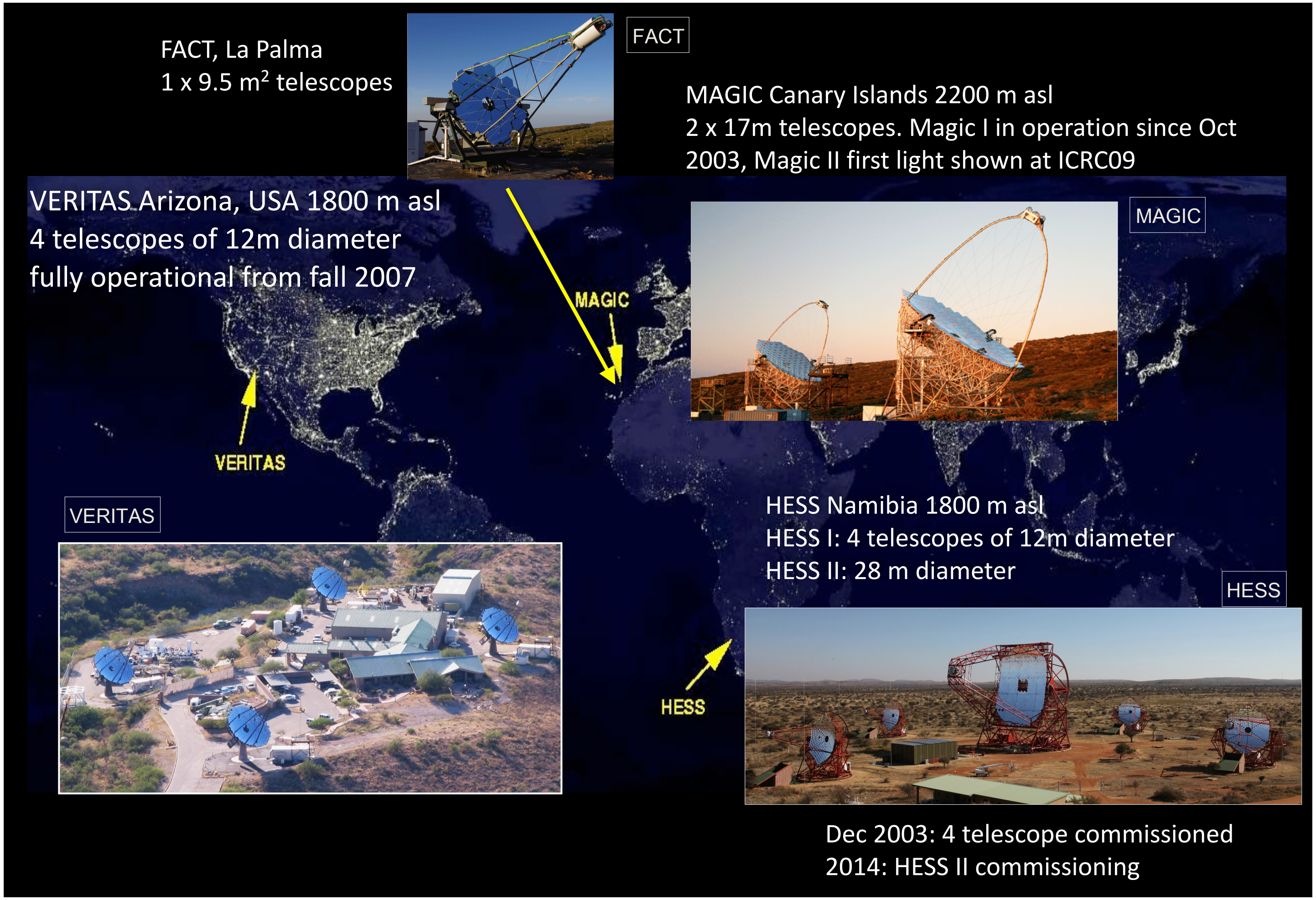
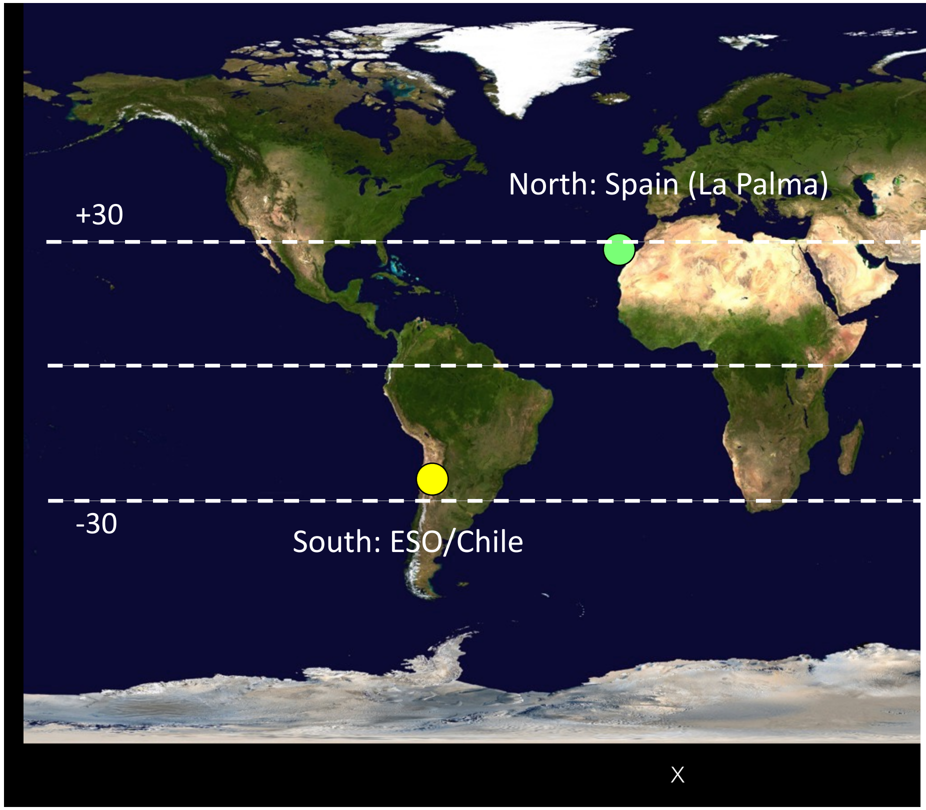
On-ground very high energy telescopes: current IACT experiments

IACTs are composed by UV-optical reflecting mirrors focussing flashes of Cherenkov light produced by air-showers into high-speed cameras



Cherenkov Telescope Array: a new window towards the very high energy universe

The Cherenkov Telescope Array (CTA) will be a next-generation ground-based observatory for very high energy gamma-ray astronomy. It will consist of two arrays of telescopes, a southern-hemisphere array at ESO's Paranal Observatory and a northern array on the island of La Palma, Spain.



Northern Array
- complementary to SA for full sky coverage
- Energy range: some 10 GeV to few TeV
- Limited field of view

Mainly Extragalactic Sources

Southern Array
- Full energy and sensitivity coverage: some 10 GeV to above 100 TeV
- Angular resolution: 0.02 to 0.2 deg
- Large field of view

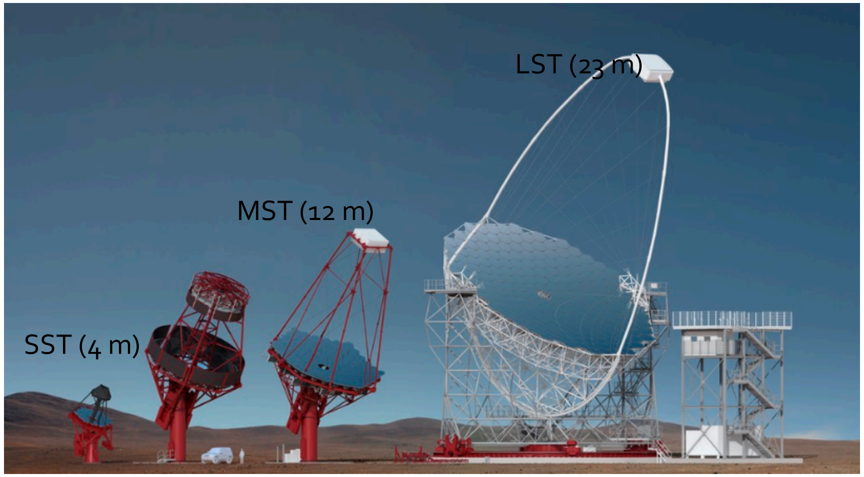
Galactic + Extragal. Sources

Credits: CTA

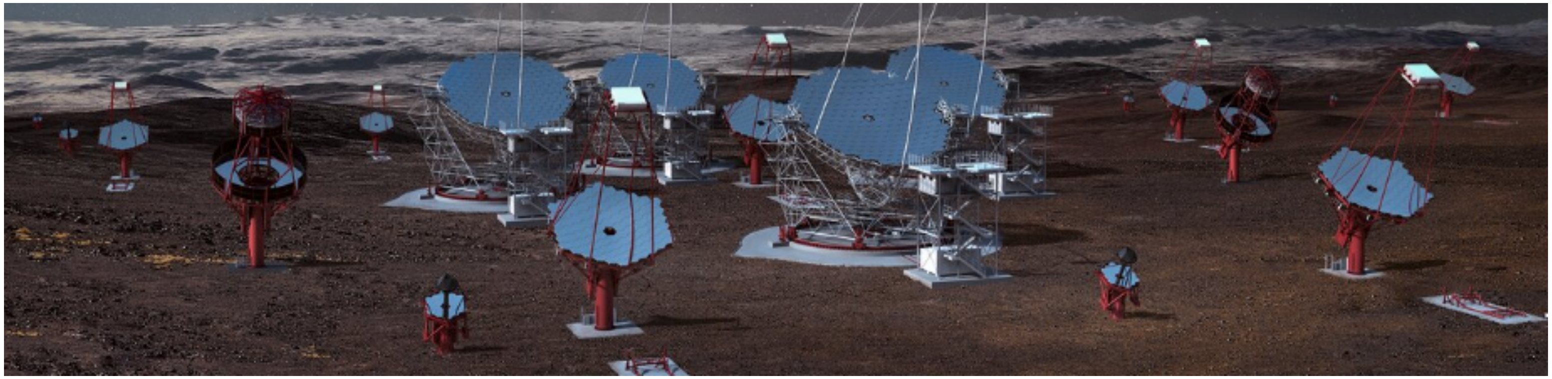
Cherenkov Telescope Array: a new window towards the very high energy universe

CTA in a nutshell:

- CTA will employ 8 Large-Sized, 40 Medium-Sized and 70 Small-Sized Telescopes, distributed over the two array sites
- energy range from 20 GeV to 300 TeV
- with its large collecting area and wide sky coverage, CTA will be the largest and most sensitive high-energy gamma-ray observatory in the world.
- 10 times more sensitive than existing instruments.
- more than 1500 members from 32 countries



Credits: CTA



Cherenkov Telescope Array: a new window towards the very high energy universe

https://youtu.be/5gRHFQP_SjU

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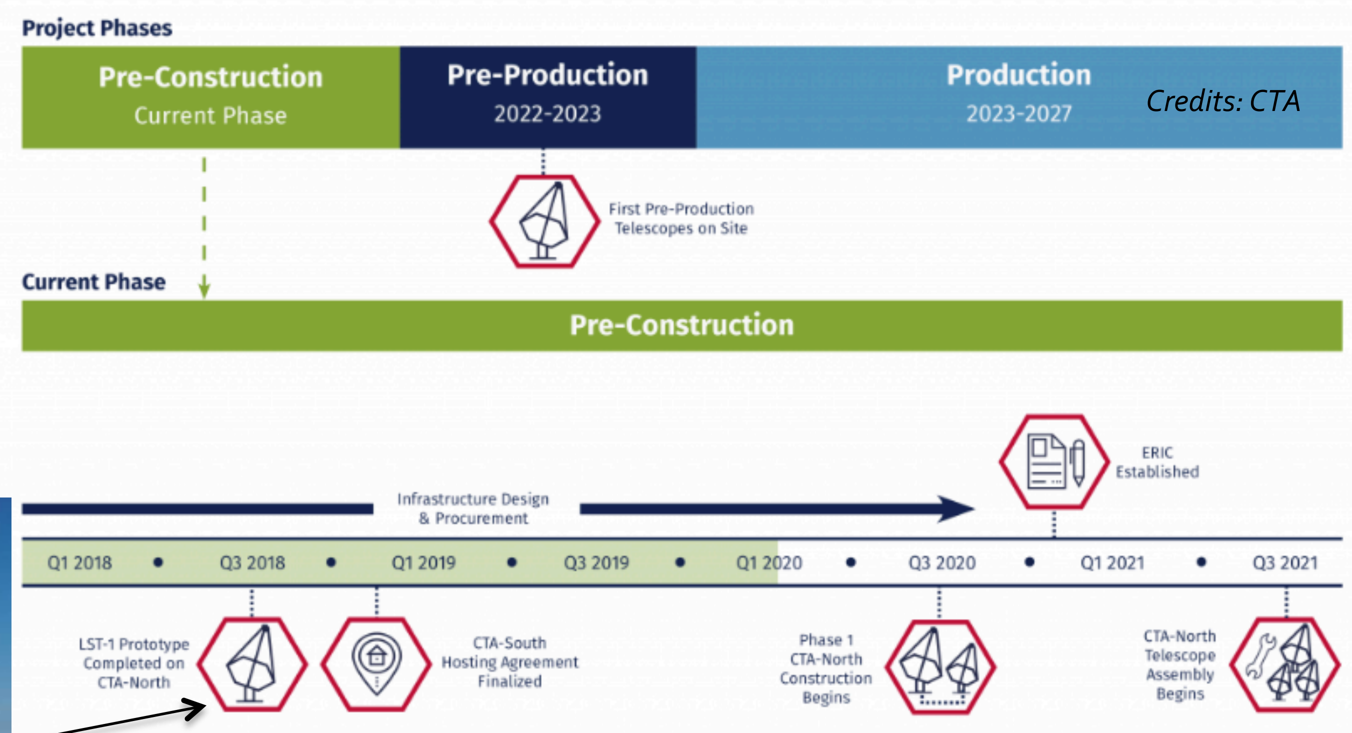
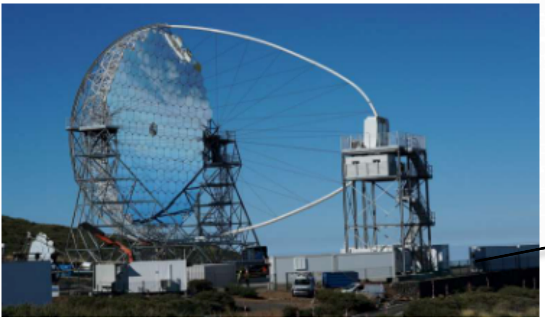
Cherenkov Telescope Array: project plan

ASTRI prototype @Etna





Technological development at OAS

Instrumentation development for both large, ground based, telescopes and space missions is an extremely important area of activity carried out at OAS, within national and international collaborations with the support of national (ASI) and international (ESA, NASA) space agencies, and the European Southern Observatory (ESO).

INAF, and OAS, is currently involved in the development of two future large projects for high and very high energy astrophysics: Athena and CTA

… but also THESEUS, HERMES, e-ASTROGAM, SWGO, COSI, IXPE, …

Main activities:

- software development, both in terms of simulations and data analysis pipelines
- hardware development of detectors, read-out systems and interface control units

Technological development at OAS

The development of a high energy space telescope requires:

Astronomers

- Scientific goals

↓

- Top scientific requirements
  (e.g. sensitivity, angular and spectral resolution)

↓

- Top technological requirements
  (e.g. background level, effective area, focal length)

Engineers

- Mass budget
- Payload design
- Feasibility study
  (e.g. materials, tolerances, thermal control)

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Technological development at OAS

The development of a high energy space telescope requires:

Instrument group
(astronomers, engineers,
computer scientists)

Astronomers

- Scientific goals
- Top scientific requirements
  (e.g. sensitivity, angular and spectral resolution)
- Top technological requirements
  (e.g. background level, effective area, focal length)

- ✓ Simulation of the telescope and its interaction with the environment to drive the design of the instruments
- ✓ Development of the software for data reconstruction and analysis
- ✓ Calibration and performance evaluation
- ✓ scientific simulation of the science target

Engineers

- Mass budget
- Payload design
- Feasibility study
  (e.g. materials, tolerances, thermal control)

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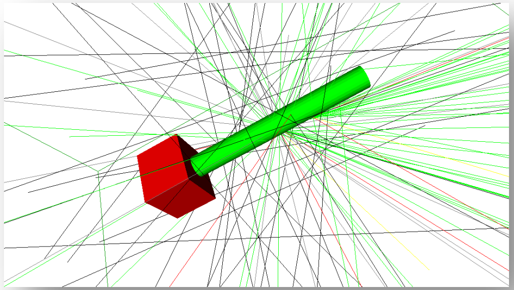
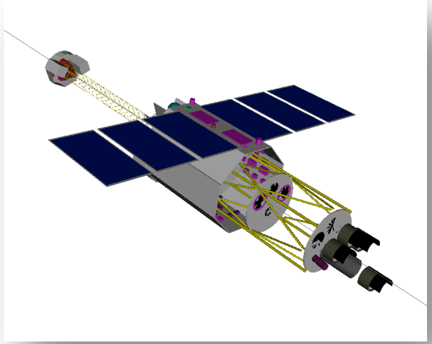
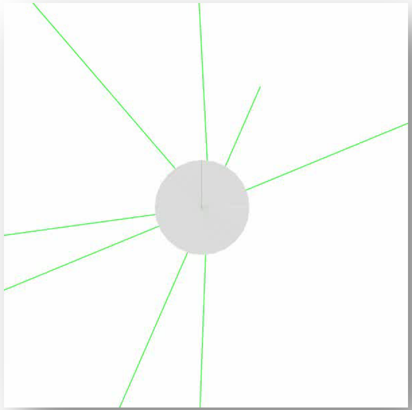
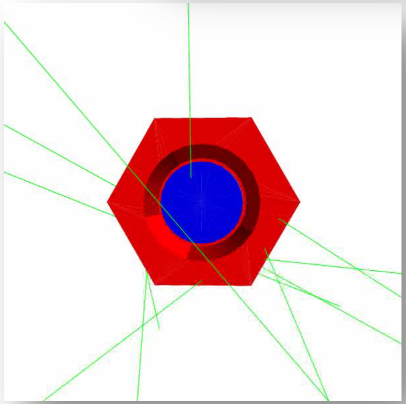
Technological development at OAS: Geant4 simulations for Athena

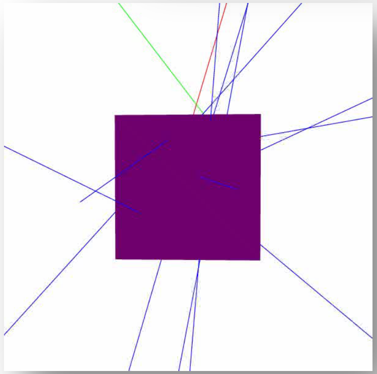
Geant4 (https://geant4.web.cern.ch/) is a C++ based toolkit (open source, from CERN) for the simulation of radiation and particle interaction with matter. Geant4 is the library of reference for the simulation of X-ray and Gamma-ray telescopes with the space radiation environment and the science target. We can build a 3d virtual model of the spacecraft and use it as a real observation in space.











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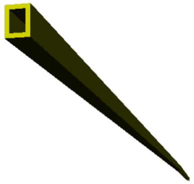
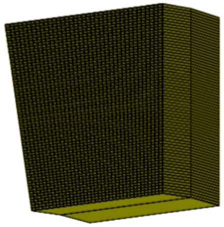
Technological development at OAS: Geant4 simulations for Athena

In Athena, we use Geant4 to evaluate the instrumental background generate by cosmic rays and diffuse photons interacting with the material of the spacecraft.
For example, we created a model of the Athena SPO mirror to evaluate the effect of protons entering the field of view and reaching the detectors.

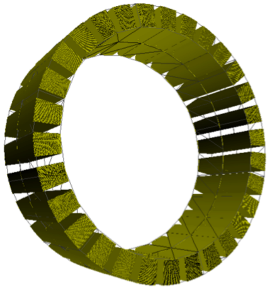
pore



Mirror Module



full Row



SPO

Technological development at OAS: Real-Time Analysis of CTA

CTA will be able to observe very short (tens of seconds) emission from flaring and transient sources (e.g. Gamma-ray Bursts) . At OAS we are developing (coordinator A. Bulgarelli) the **Real-Time Analysis** (RTA), a software system that will analyse CTA data during the observation.

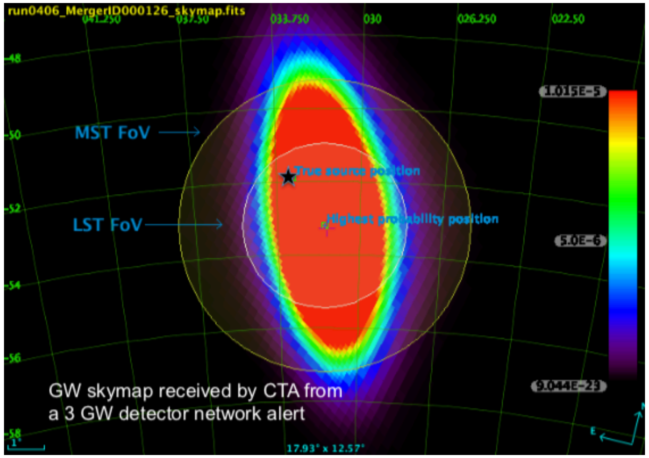
The RTA will have to face unprecedented challenges:

- processing in real time GBs of data to reconstruct the photons
- detecting science targets and issuing science alerts within 30 seconds

The CTA Real-Time Analysis is the key system in the context of multi-messenger and multi-wavelength astronomy (e.g. follow-up of gravitational waves).

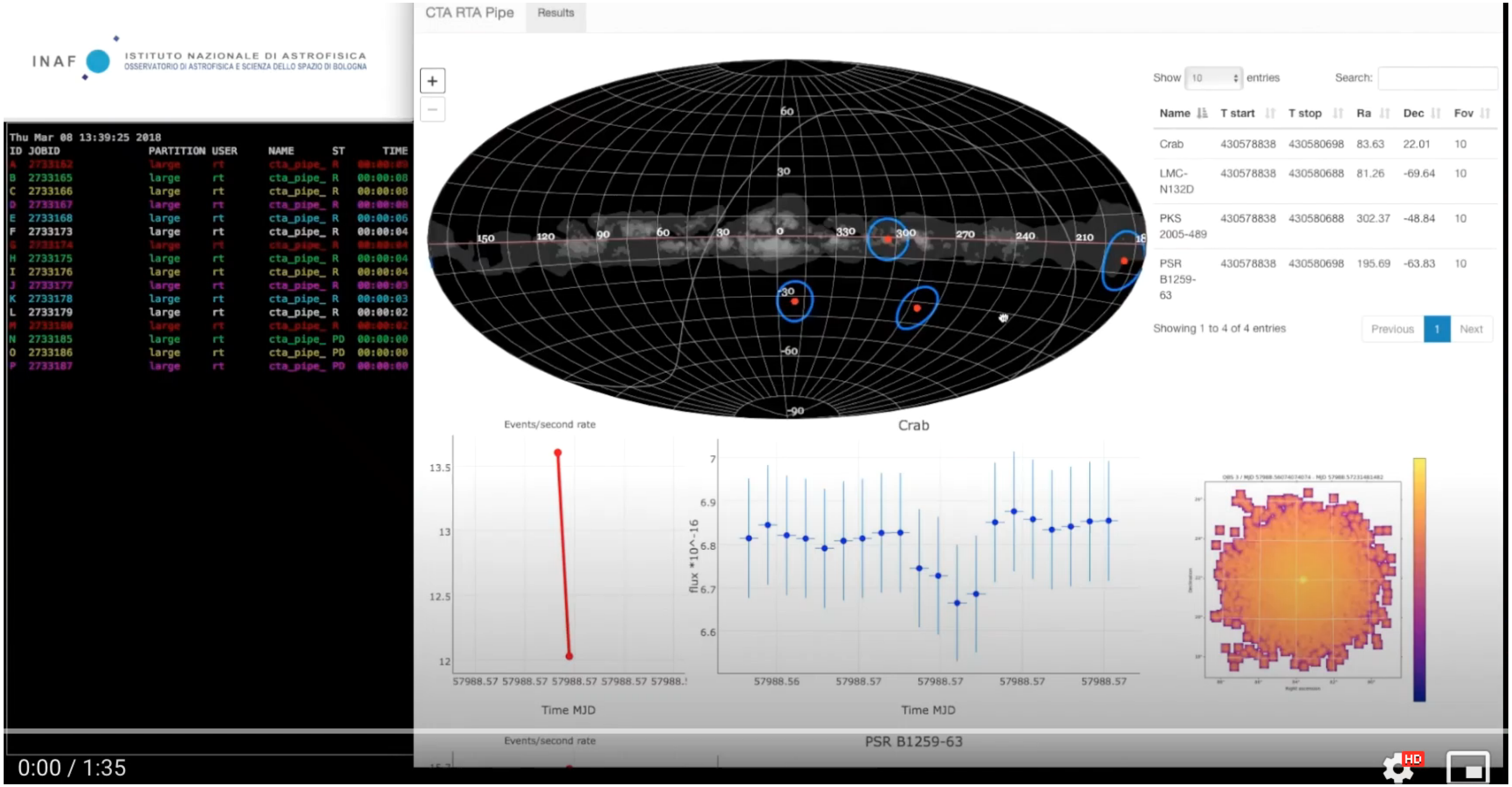
The activity includes:

- development of the analysis pipeline (e.g. data streaming, databases) and quick-look GUI
- exploring new algorithms for data analysis at very short exposures
- testing and contributing to the software for scientific analysis
- data mining and machine learning



Technological development at OAS: Real-Time Analysis of CTA – web GUI

For example, we are developing the RTA web GUI for alert monitoring (credits: N. Parmiggiani).



https://youtu.be/S3H67eqS9Dc

Summary

- Observing X-ray and Gamma-rays from space
- X-ray focusing telescopes
  - XMM, Chandra, Athena
- Gamma-ray space telescopes
  - AGILE, Fermi
- Very high energy on-ground telescopes
  - CTA
- Technological development at OAS

Questions? Contact us!