ASTENA, a new mission concept for an Advanced Surveyor of Transient Events and Nuclear Astrophysics

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on behalf of
an International Collaboration

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ASTENA Collaboration

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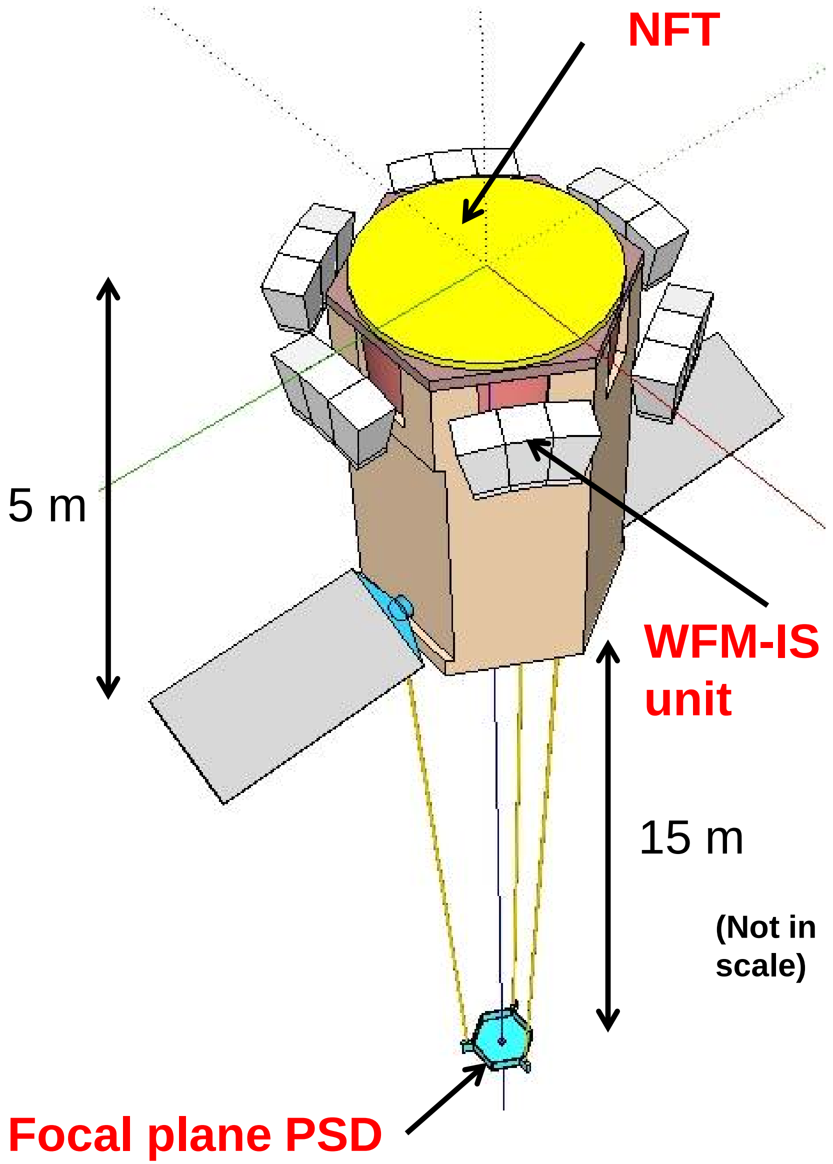
Context

- **In the framework of AHEAD WP9 devoted to Gamma-ray Astronomy, a Scientific Advisory Group was established to suggest top-priority themes. They resulted to be:**
  - **Gamma-Ray Bursts and**
  - **Nuclear Astrophysics.**
- **An AHEAD call for instrument/mission concepts was issued.**
- **ASTENA is one of the three accepted mission concepts for which a feasibility study has been supported.**

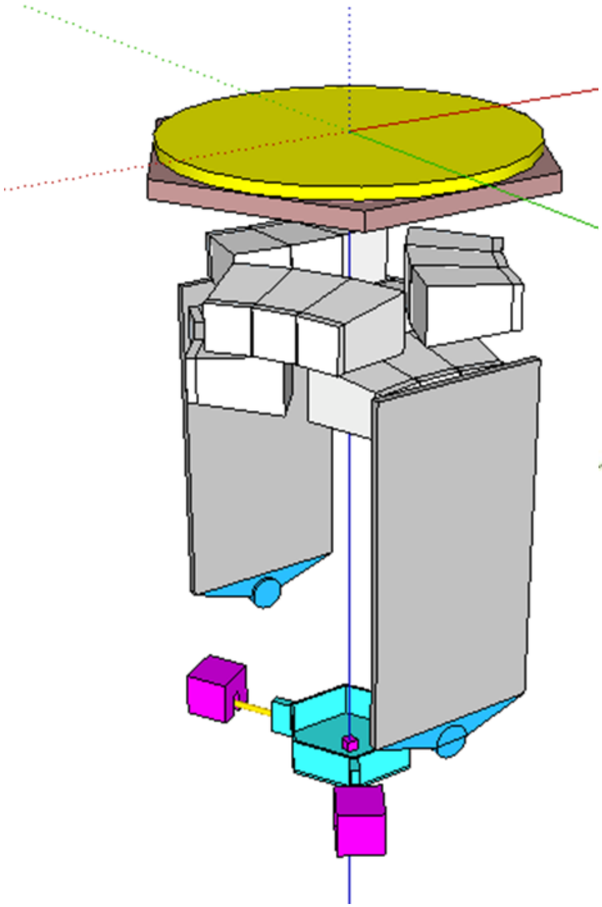
- The others two are **ASCI (All-Sky Compton Imager),** and **PACT (Pair and Compton Telescope).**

ASTENA in flight configuration

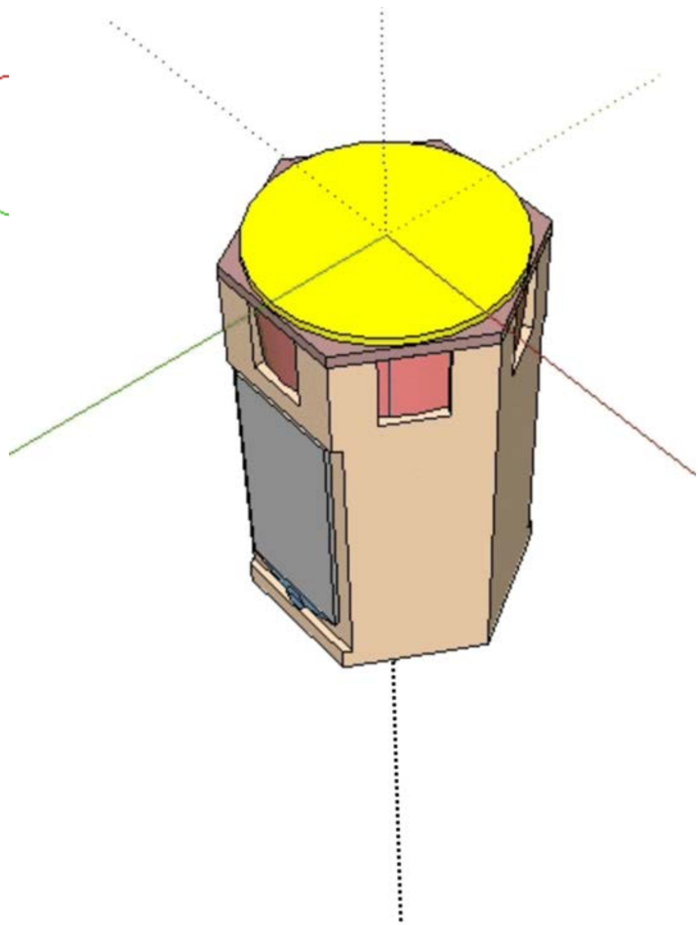
- Wide Field Monitor-Imaging Spectrometer (WFM-IS) (18 units).
- Narrow Field Telescope (NFT)
- Focal plane PSD on a deployable boom

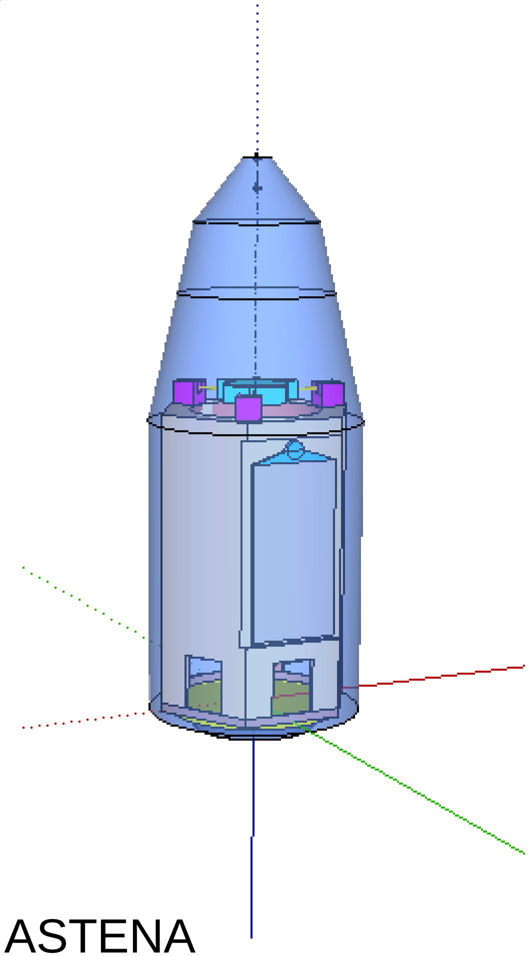


ASTENA folded configuration (before the launch)



Exploded view

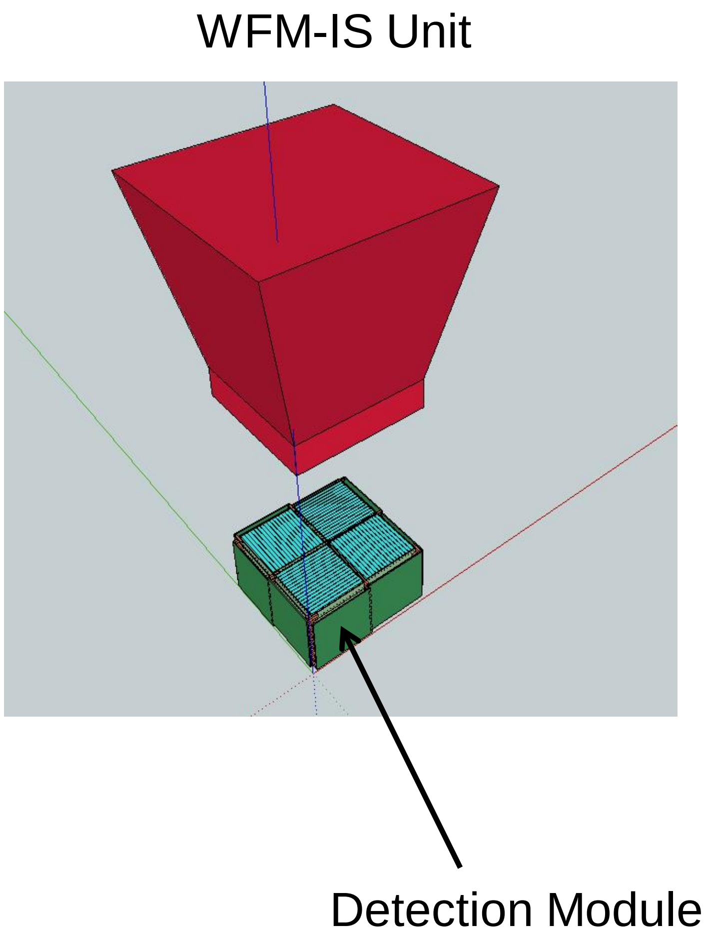




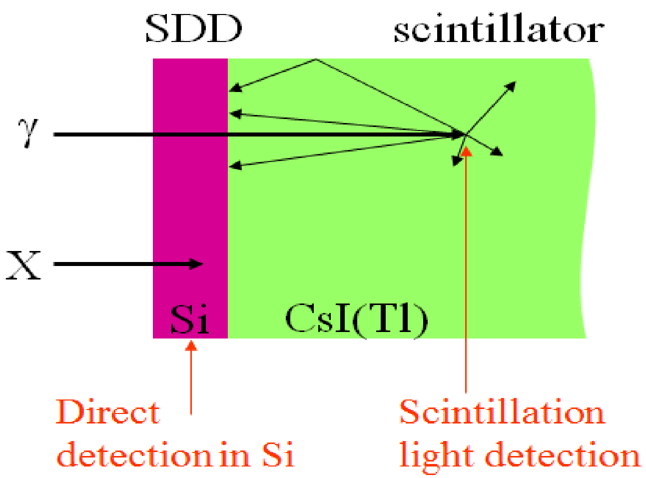
ASTENA accommodation within the **Soyuz** fairing

WFM-IS general features

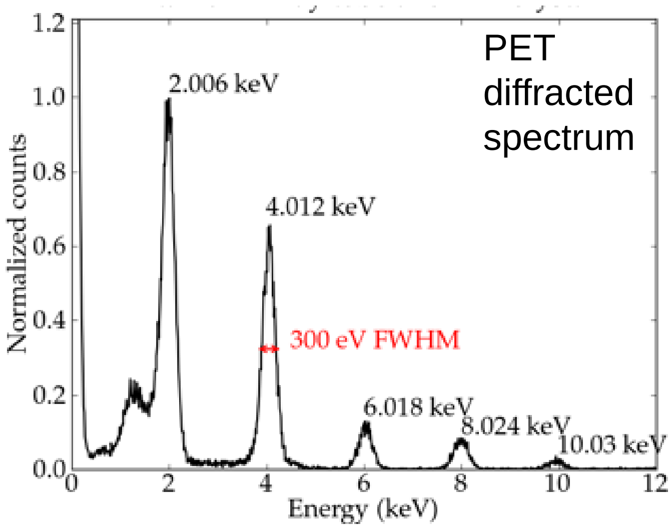
- **Energy band**: 2 keV-20 MeV
- **Total effective area**: ~ 2 m^2
- **Three-dimensional PSD** (~1 mm resolution)
- **At low energies (<100 keV),** imaging capabilities by means of a dual scale coded mask (FOV > 1 sr):
  - 1 arcmin PSLA up to 30 keV (crucial for NFT follow-up);
  - 5 arcmin PSLA 30-100 keV.
- **At high energies (>200 keV):**
  - Compton kinematics for crude direction determination
- **Polarimetric capabilities**

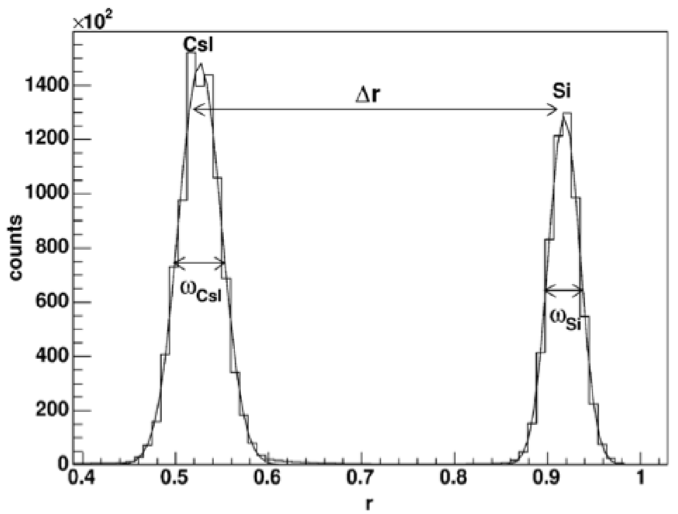


WFM-IS concept (similar to THESEUS XGIS)



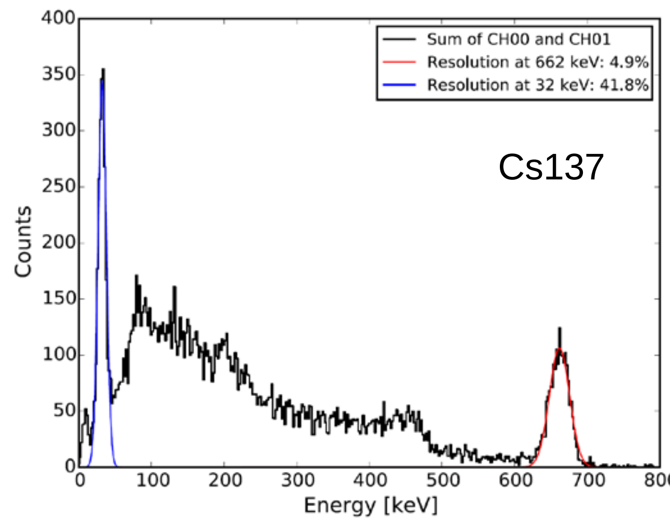
SDD Pulse height spectrum



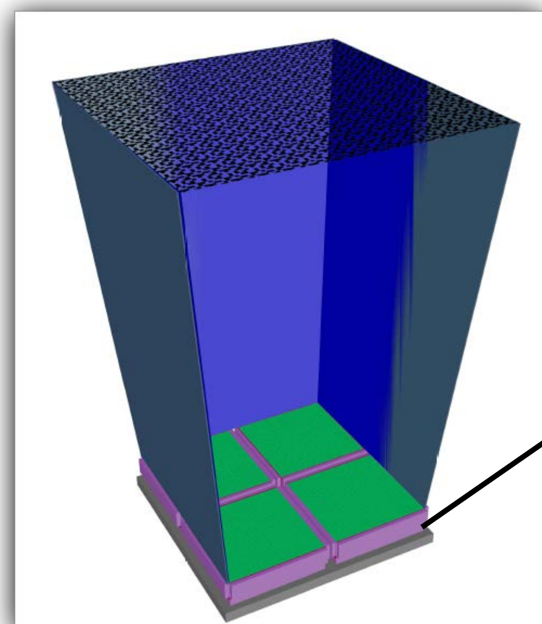


Pulse shape spectrum

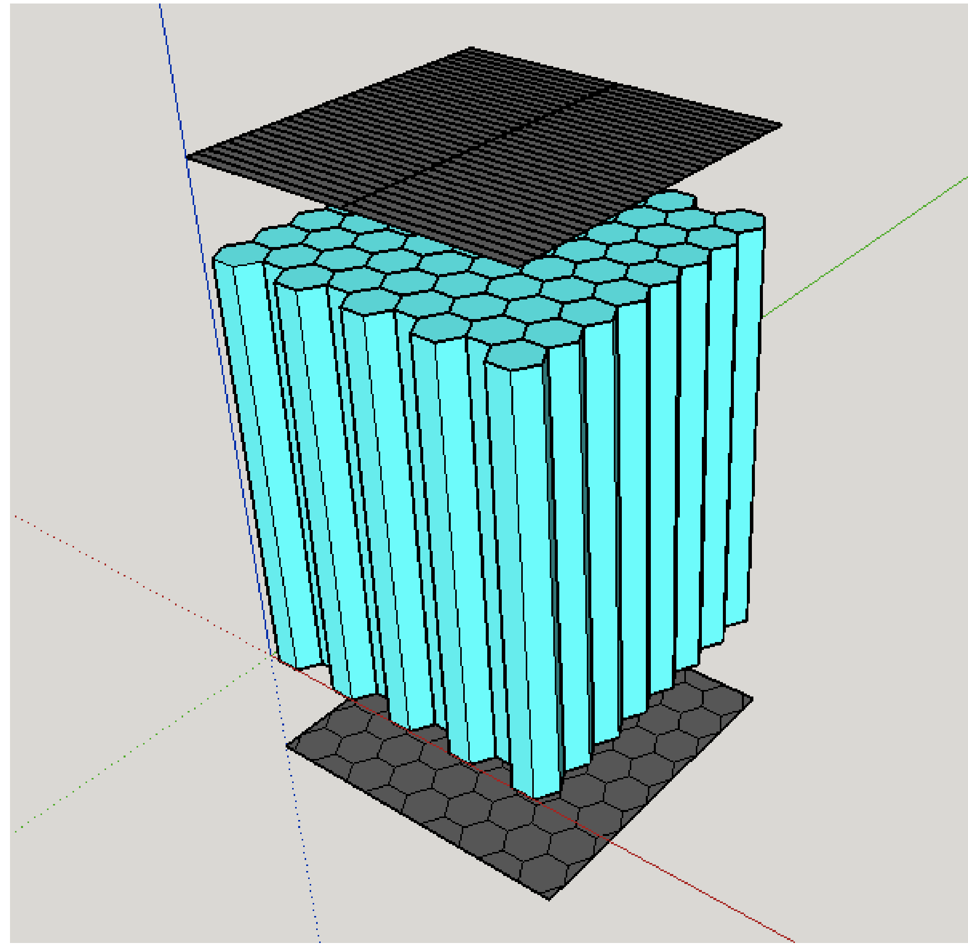
CsI Pulse height spectrum



WFM-IS detection configuration



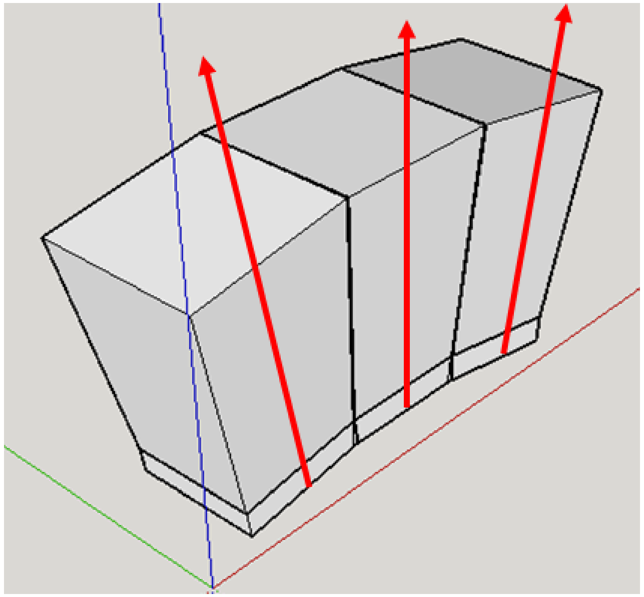
WFM-IS Unit



Detection module

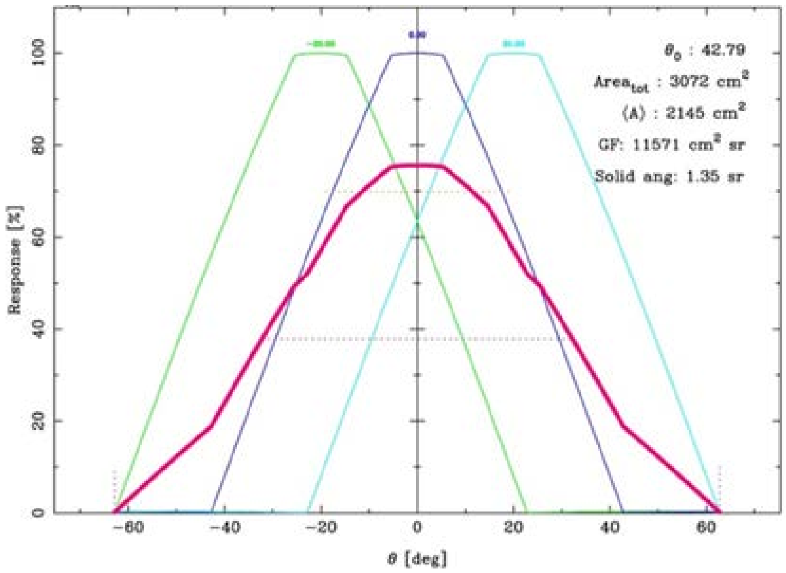
Angular response of a single WFM-IS unit and of a group of 3 units

Orientation of the block units

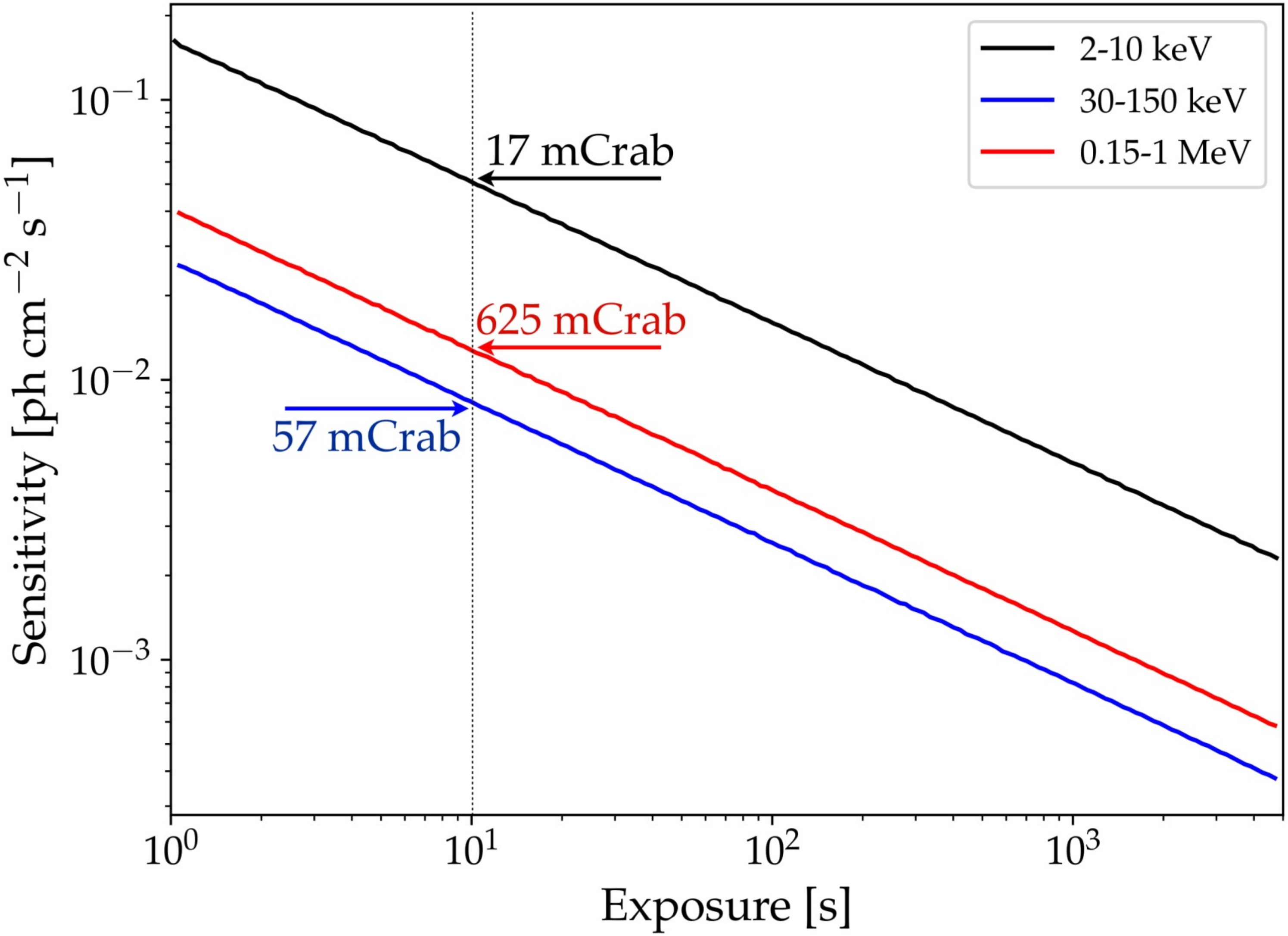


± 20° offset wrt the optical axis

Angular response up to 100 keV

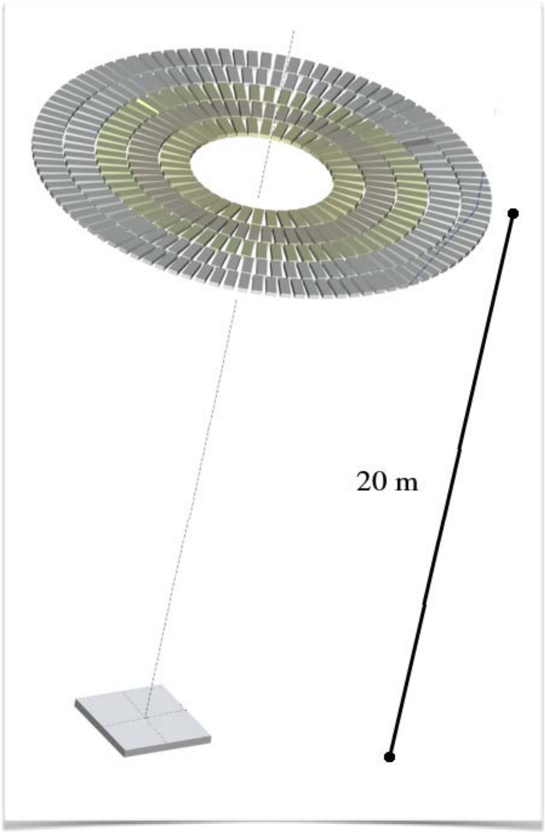


WFM-IS expected continuum sensitivity



Narrow Field Telscope (NFT)

- Based on **Laue lens with** bent crystals of Ge(111) and Si(111)
  - Crystal tiles: 2 mm thick, 10x30 mm^2 cross section
  - 3 m Diameter
  - Focal length: 20 m (extendable boom)
  - Energy band: 50-600/700 keV
  - Projected geometric area: ≈7 m^2



Virgilli+2017, JATIS 3(4), 044001

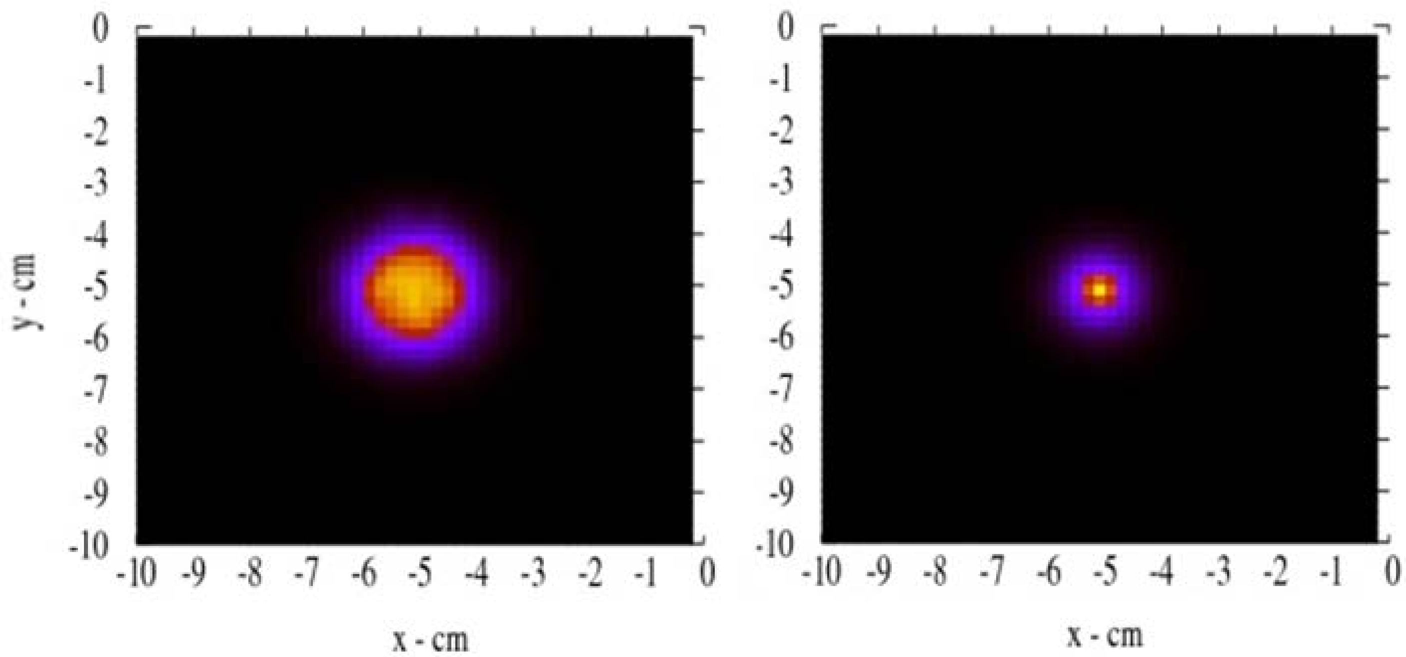
- **Focal plane detector** with:
  - High detection efficiency (>80%)
  - 3D PSD (spatial resolution of 300 µm in (x,y,z).
  - Energy resolution: 1% @511 keV

Khalil+2015, NIM A 786, 59

Lens development status

See Talk by Virgilli

On axis PSF

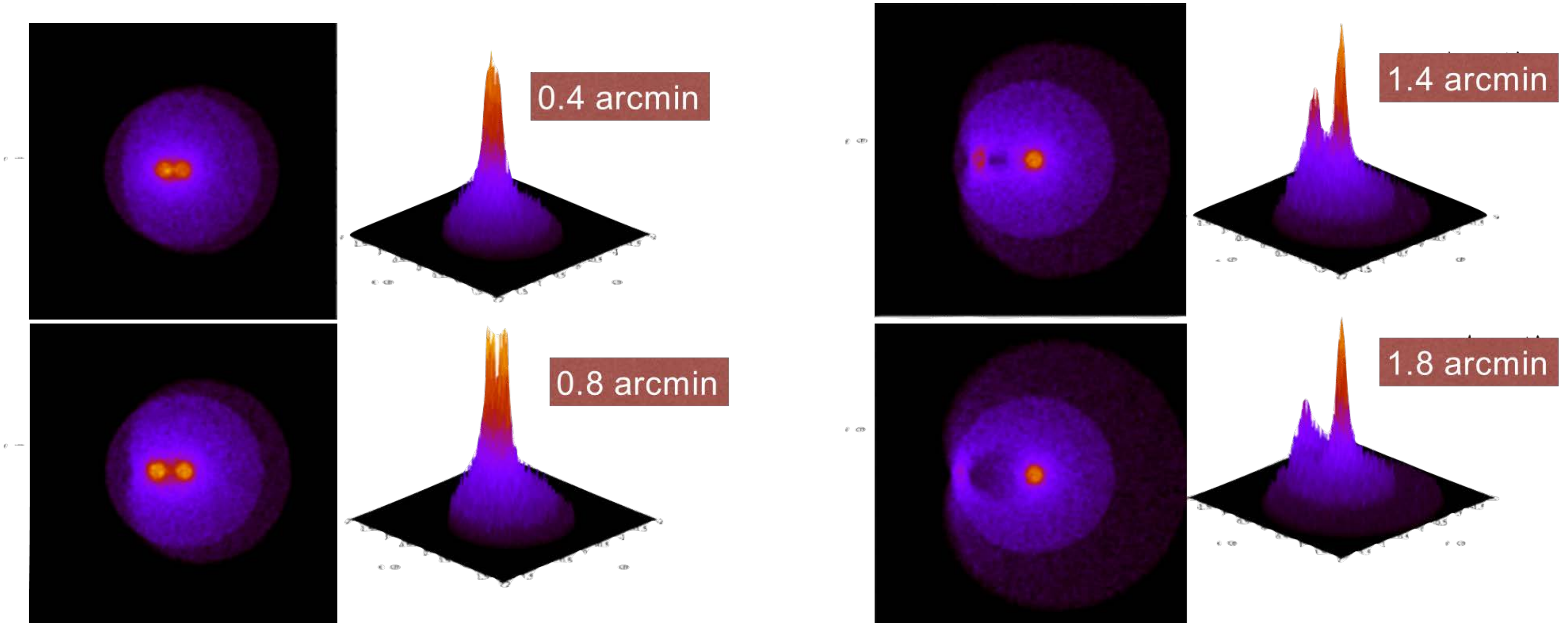


Flat crystals

Bent crystals with curvature radius equal to lens radius

Angular resolution = 30”

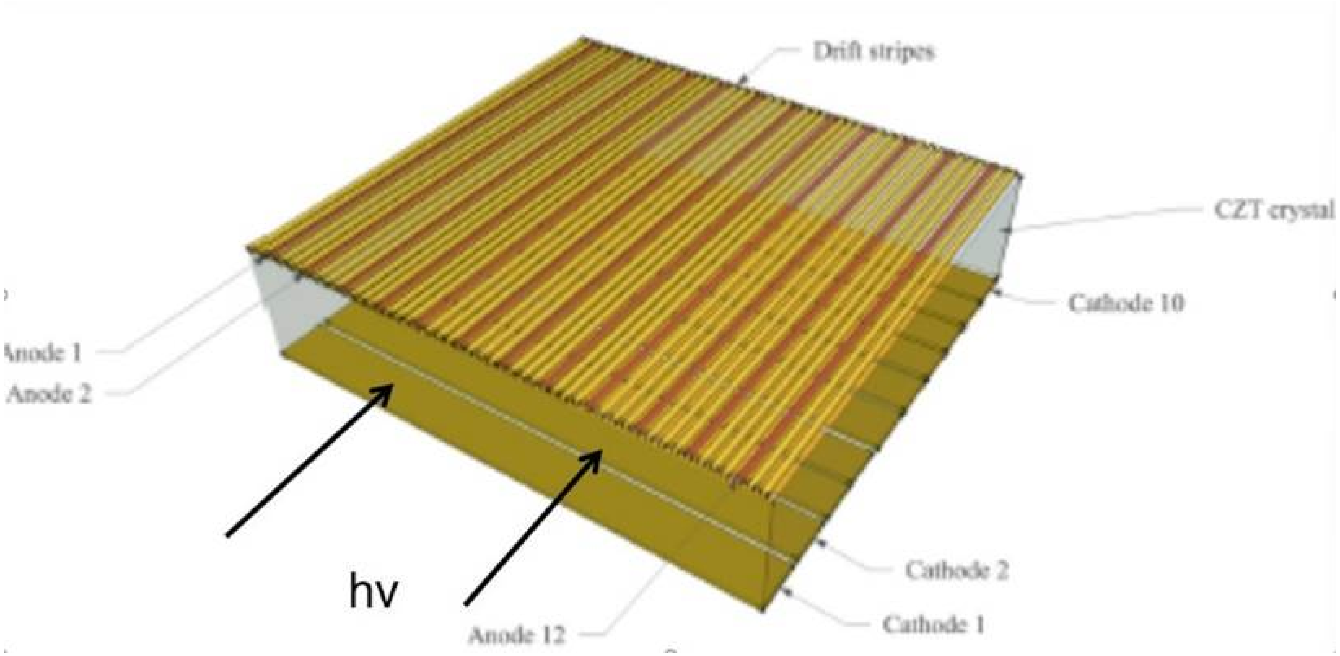
NFT field of view



FOV = 3.6 arcmin

Focal plane PSD

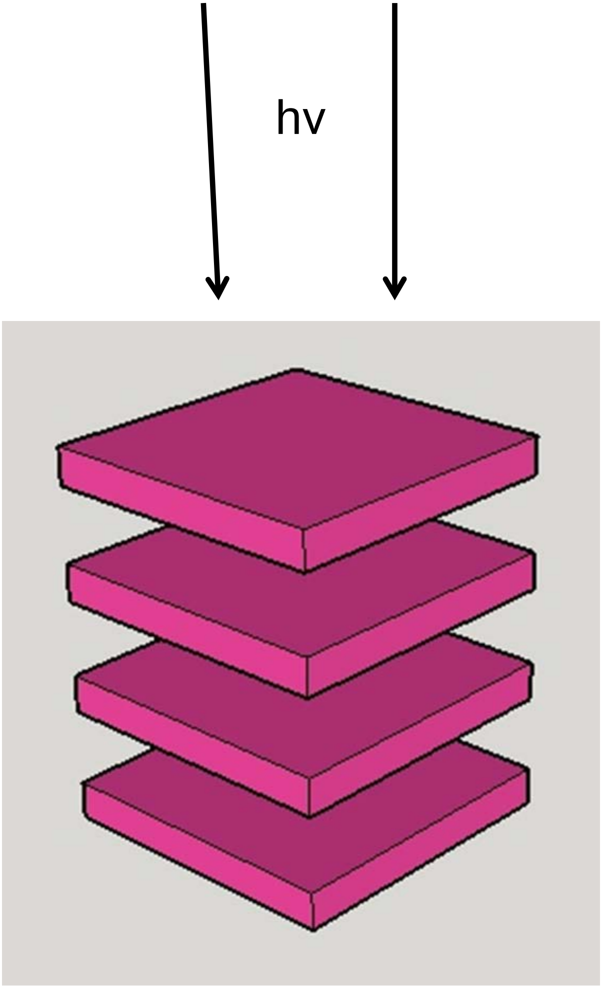
- Proposed solution:
- 4 layers of an array of 4x16 CZT elements:
  - 0.5x2 cm^2 cross section
  - 2 cm thick
- Drift strip configuration for the anodes and orthogonally segmented cathodes in Parallel Transverse Field (PTF) (Kuvvetli+2014)



CZT focal plane detector

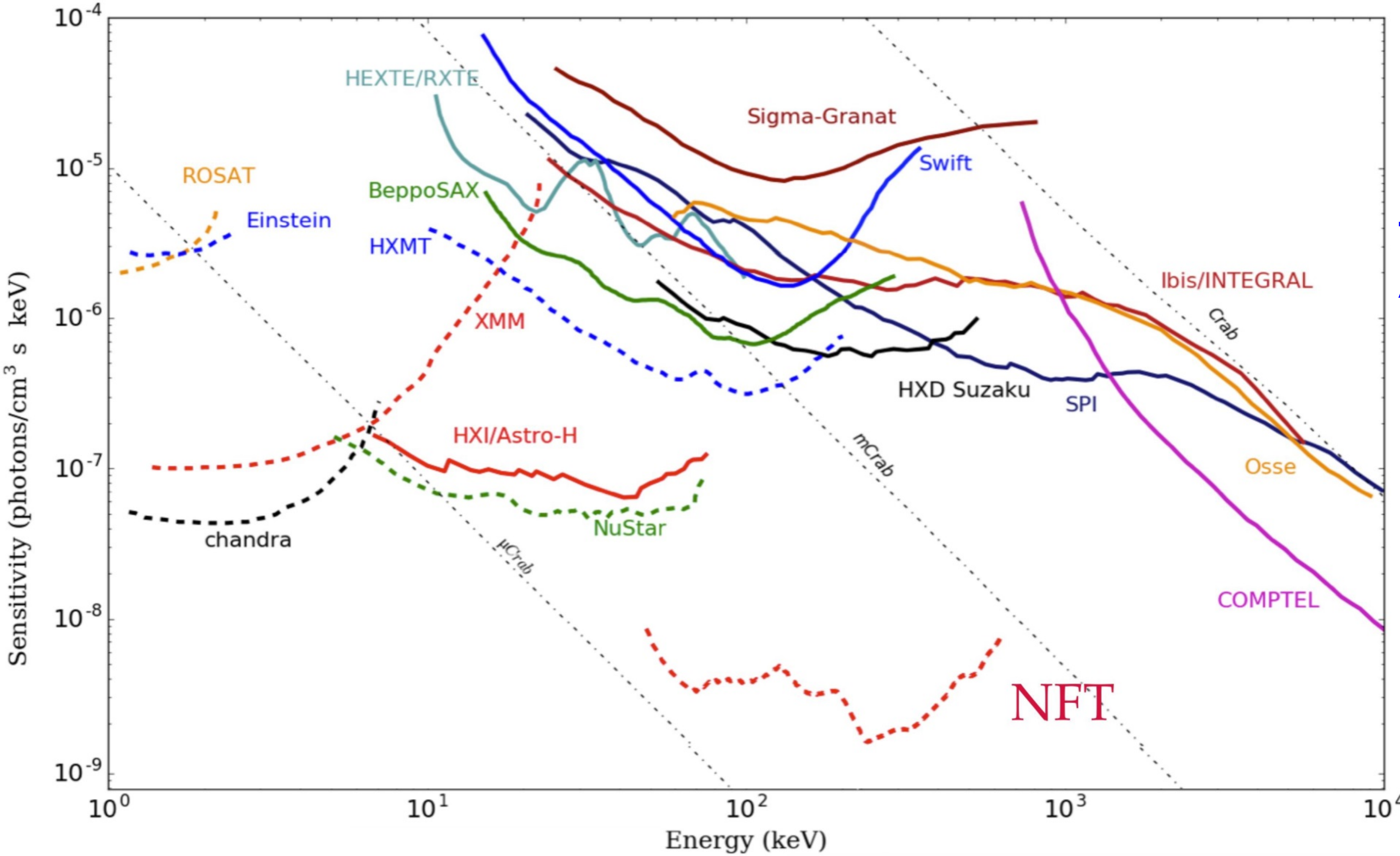
- **PSD size:**
  - **Cross section: 8x8 cm^2**
  - **Sensitive thickness: 8 cm**

- **Status: prototype under development and testing**



Exploded view

ASTENA/NFT expected sensitivity



T=10⁵ s,
ΔE=E/2

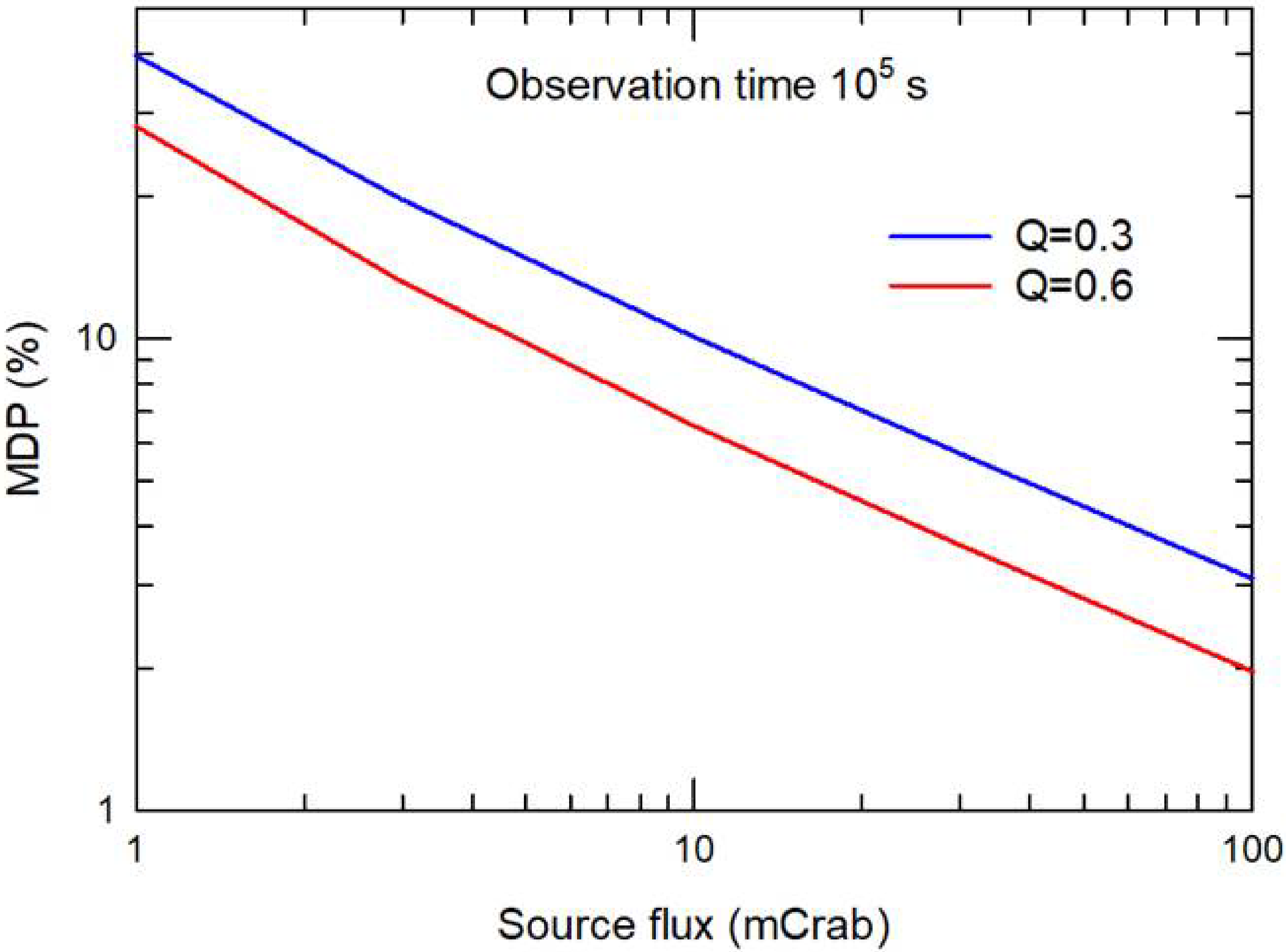
Sensitivity to lines (3σ, 10^5 s) (ph/cm^2 s)

Energy (keV)	Conf (a)	Conf(b)
100	3.7×10^{-7}	$7.4\ 10^{-7}$
200	2.3×10^{-6}	4.6×10^{-6}
300	4.6×10^{-6}	9.3×10^{-6}
400	1.2×10^{-5}	2.3×10^{-5}
500	2.3×10^{-5}	4.9×10^{-5}

Virgilli+2017, JATIS

ASTENA/NFT polarization sensitivity

(90-600 keV, 3D PSD 10x10 cm^2 cross section, 10 cm thickness)



Polarization modulation factor Q:

$$Q = \frac{C_{\max}^{100} - C_{\min}^{100}}{C_{\max}^{100} + C_{\min}^{100}}$$

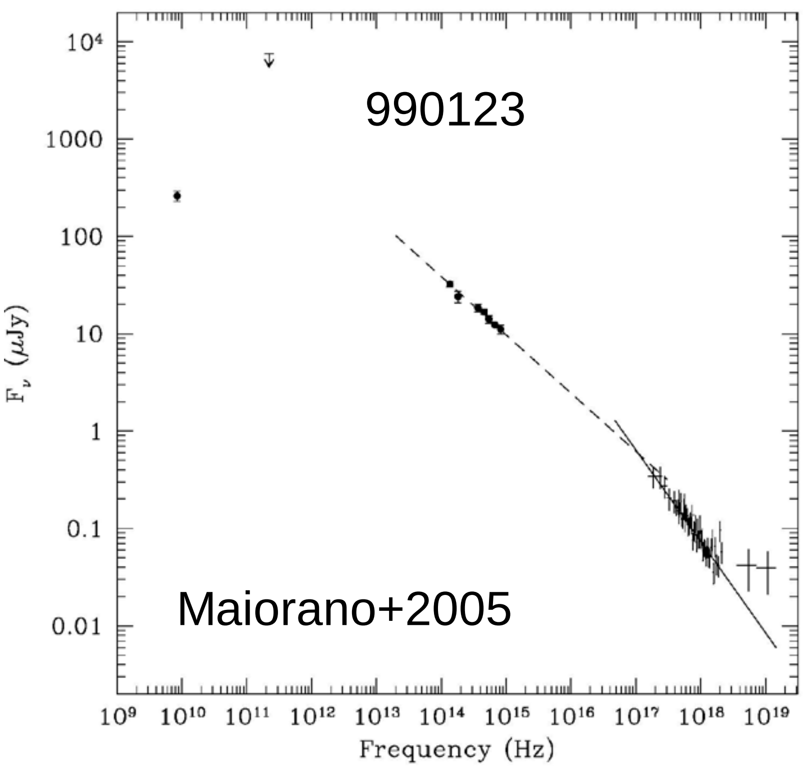
Polarization level:

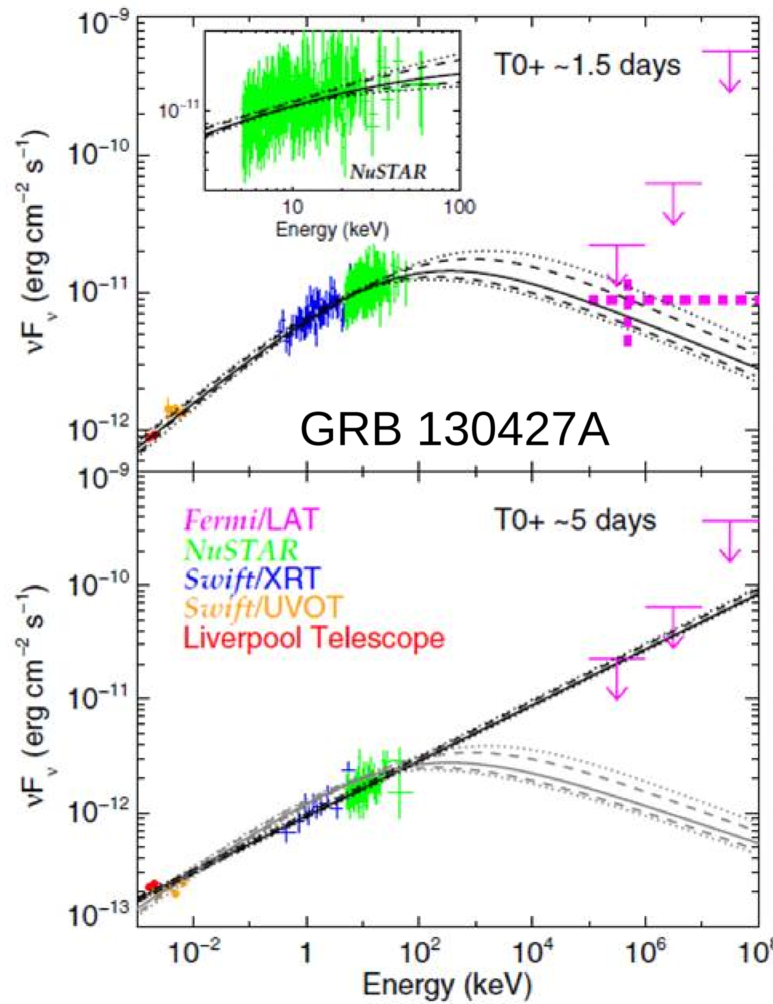
$$P = \frac{Q_p}{Q_{100}}$$

Key science cases
(paper in preparation)

- **Transient events:**
  - **High energy spectrum and polarization of the GRB afterglow emission;**
  - **Hard X-ray polarization of the GRB prompt emission**
  - **Deep search of very Low Luminosity GRBs (llGRBs)**
  - **Search of prompt emission, if any, from Fast Blue Optical Transients (FBOTs)**
  - **Deep search of Electromagnetic Counterparts of Gravitational Wave Events**
  - **Deep search of gamma-ray counterparts of Fast Radio Bursts (FRBs)**

GRB afterglow high energy spectrum



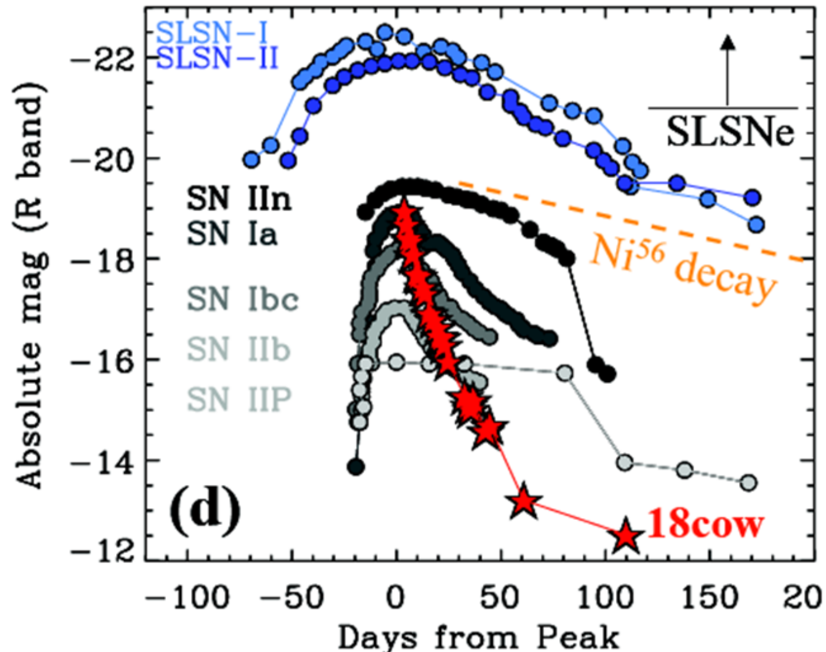


Kouveliotou+2013

In the case of 990123, only synchrotron was insufficient (Corsi+2005).
In the case of 130427A, synchrotron is sufficient at NuSTAR energies but NuSTAR is crucial to constrain the SED spectral shape (Kuoveliotou+2013).

Fast Blue Optical Transients (FBOT)

- FBOTs: **likely a new class of transient sources** due to the recent discovery of **AT2018cow** (ATel 11727, Margutti+2018)
- **AT2018cow is rapidly evolving, with luminosity rivalling Ibc-Sne.**



$L_{peak} \sim 4\times10^{44}$ erg/s

- **Hard X-ray counterpart consistent with an X-ray afterglow (power-law spectrum).**
- **No evidence of a prompt gamma-ray emission**
- **New class of low luminosity GRBs?**

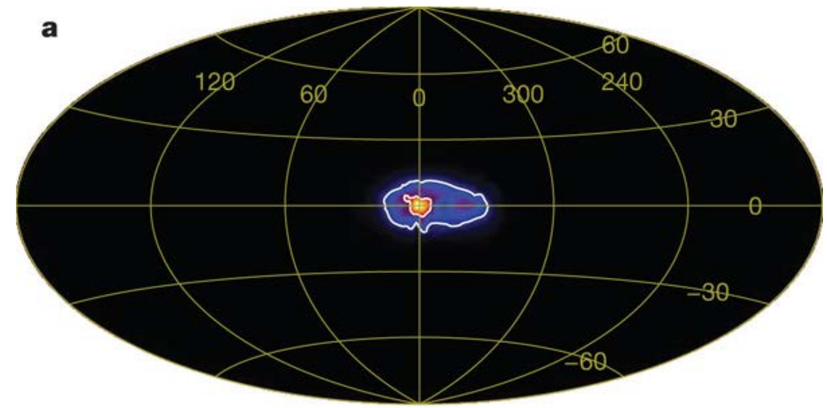
(Margutti+18)

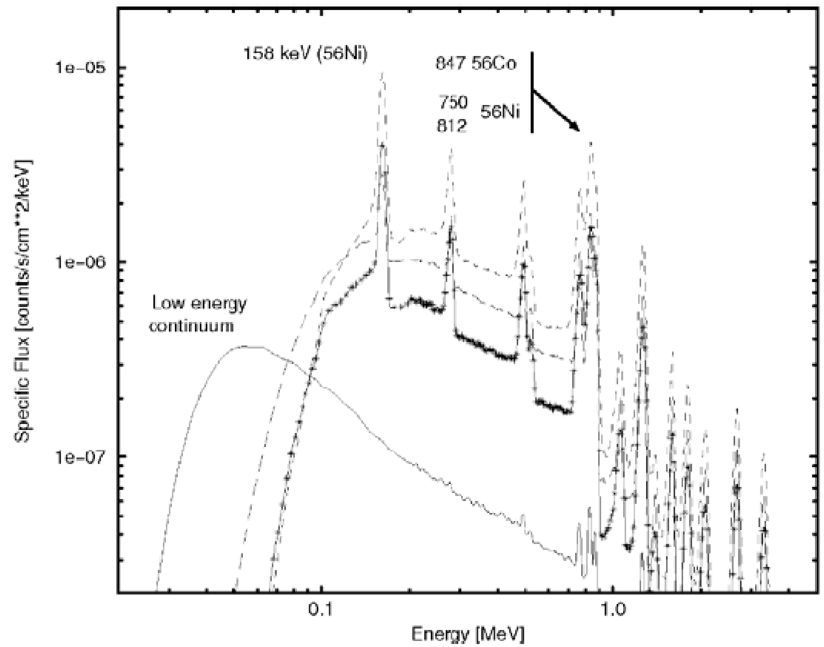
Nuclear Astrophysics

- **Determination of the origin of the 511 keV positron annihilation diffuse line** from Galactic Center region. Thanks to the NFT sensitivity and angular resolution (30”) test of:
  - Emission from point-like sources, eg, microquasars?
  - Truly diffuse emission? DM annihilation?

- **Study of intensity and time behavior of the 158 keV line (Ni^{56}→Co^{56}) emitted at early times ($\tau_{1/2}$=6.1 d) in Type 1a supernova explosions**.

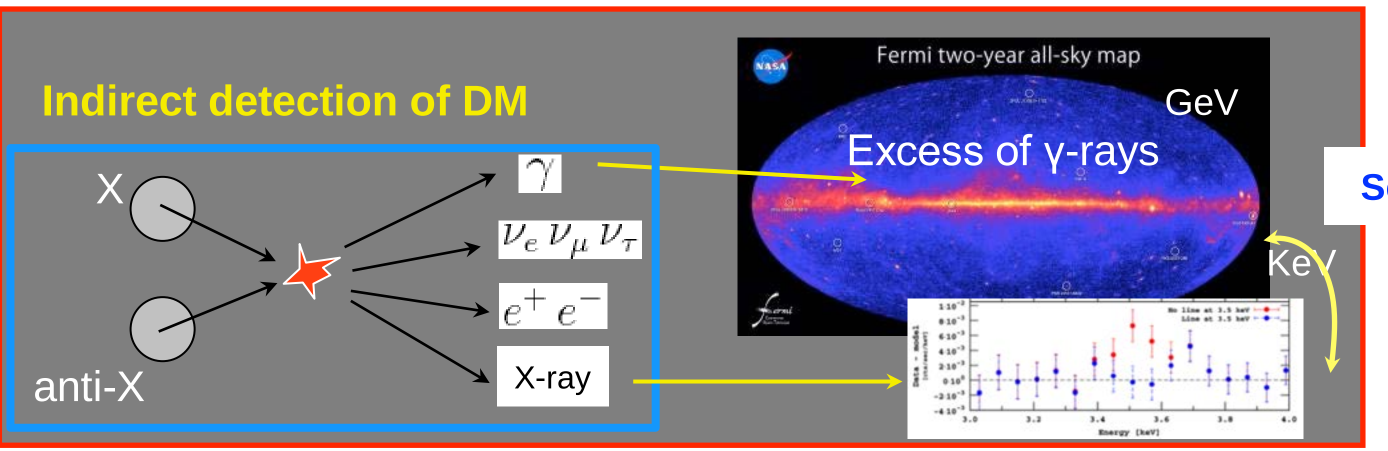
Weidenspointner+2008

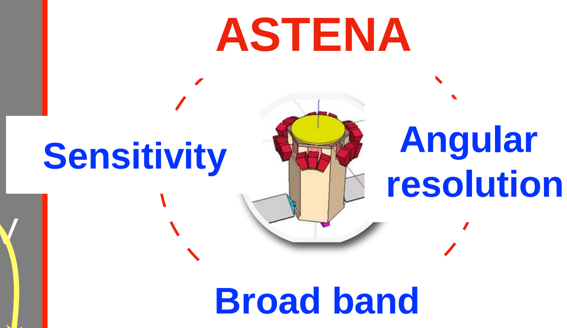




Gomez-Gomar+1998

Understanding the nature of Dark Matter with ASTENA



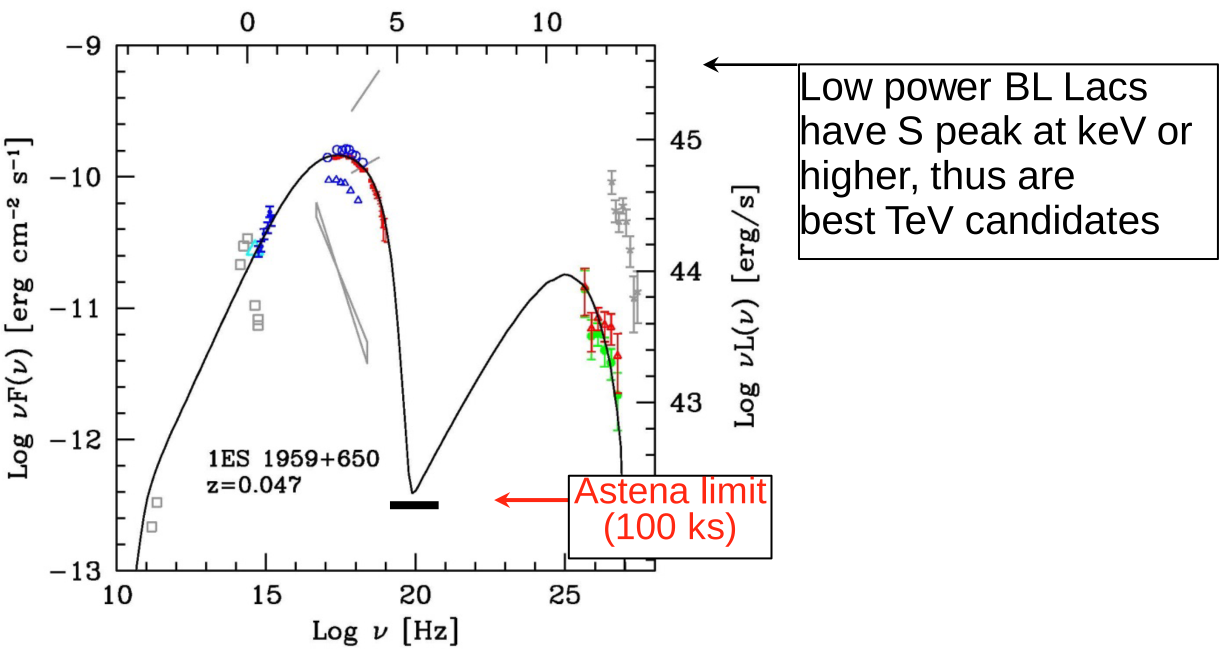


Some other science cases (Legacy science)

- **Origin of the high energy component of magnetars**
- **Hard X-/soft gamma-ray spectral properties of AGN**
    - **High energy cutoff of radio quiet AGN (Seyfert and QSO)**
    - **Blazar hard X-/soft gamma-ray spectrum (still unknown)**
    - **CXB at high energies (above the 30 keV CXB peak)**
- Ample space for the discovery of **new classes of source and new phenomena**

Emission physics and nature of Blazars

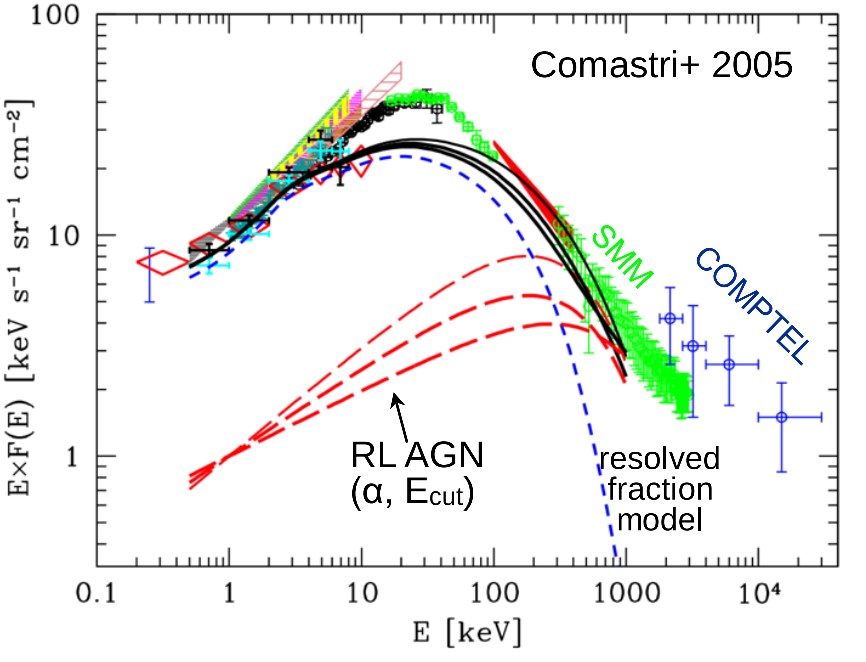
- Two humps in the SED:
  - mm-soft X-ray: synchrotron emission
  - 100 keV-TeV: IC (seed photons: disk, jet, BLRs)
- The variation of the overall SED at increasing L_{bol} is linked to M, $\dot{M}$, with $L_{jet} \sim \dot{M}c^2$
- Observations at 100-600 keV critical for:
  - physics of FSRQs vs BL Lacs
  - contribution of Blazars to XRB at ~>100 keV



Ghisellini 2009, 2011

CXB (E>50 keV)

- Spectral synthesis models are increasingly degenerate above the CXB peak: A single energy cutoff is assumed.
- Attempts to explain the CXB at E>30 keV with Blazars unsatisfactory: spectrum at hard X-rays still unknown
- Direct determinations of spectral shapes at 50-600 keV at different L_X (and z), essential to complete the cosmic history of accretion power
  ➔ feasible with ASTENA



Conclusions

- **ASTENA is the first mission concept based on a broad band hard X-/soft gamma-ray optics (50 keV-600/700 keV)**
- **It opens a new window in the high energy astrophysical research.**
- **It explores the high energy transient sky** (prompt and afterglow emission of classical short and long GRBs, llGRBs, FBOTs, TDEs …) and its properties (spectrum, light curve, polarization, etc) **with unprecedented sensitivity.**
- For the first time in the soft gamma-ray band it improves
  - the point source localization accuracy below 1 arcmin.
  - The continuum spectrum sensitivity orders of magnitudes better than the current instrumentation.
- Thanks to its angular resolution in gamma-rays, the **origin of the positron annihilation line from the GC region (a mystery 50 yrs old)** can be established