Broad band Laue lenses for deep studies of celestial positron sources

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on behalf of a Large Collaboration

“Positrons in Astrophysics”

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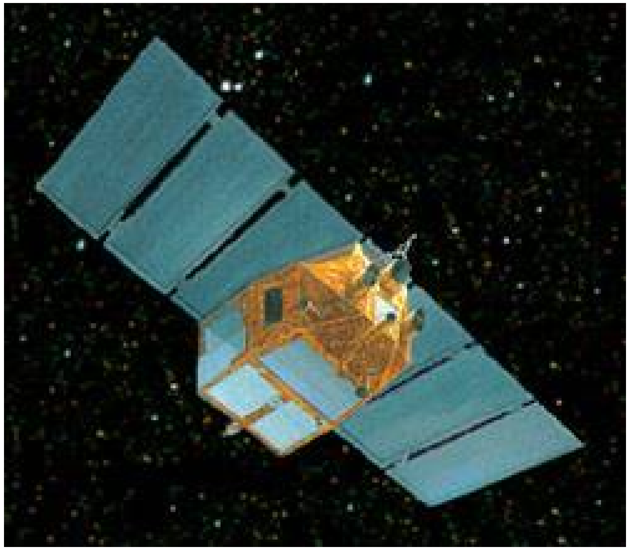
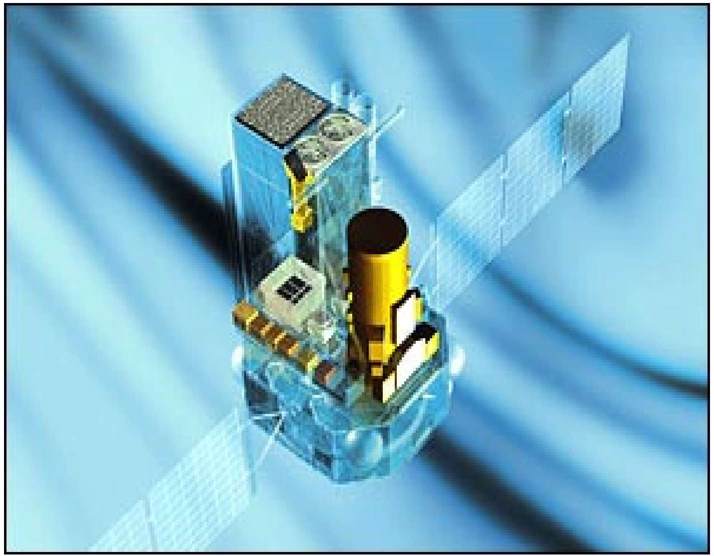
Introduction 1/2

- To understand the emission physics of many classes of celestial X-ray sources, three main requirements:
  - Broad energy band (from fraction of keV to many hundreds of keV)
  - High flux sensitivity on time scales shorter than the main source spectral variability time scale.
  - Imaging





Introduction 2/2

- The only viable way to meet these reqs is to join together different focusing telescopes with complementary passbands:
  – Low energy (0.1-10 keV) telescopes: well tested in space;
  – Medium X-ray energy (up to 70/100 keV) telescopes: soon in space (NuStar, ASTRO-H)
  – Soft gamma-ray (>70/100 keV) telescopes, still under development.

- **Requirements for soft gamma-ray telescopes (>70/100 keV):**
  - **Continuum sensitivity two orders of magnitude better than that of INTEGRAL at the same energies:**
    - **Goal: a few x10^{-8} ph/(cm^2 s keV) in 10^5 s,**
    - ⇨ **10^{-15} erg/(cm^2 s keV);**
  - **Much higher line sensitivity (Goal: 10^{-5} ph/cm^2 s in 10^6 s in the case of a narrow line);**
  - **much better (< 1 arcmin) imaging capability.**

⇩

Deep studies of positron candidate sources

Positron probes in X-/gamma-rays

- **Direct probe:**
  - **Detection of the positron annihilation line and associated continuum from Ps decay;**

- **Indirect probes**
  - **X-/gamma-rays from e^+ non thermal bremsstrahlung;**
  - **X-/gamma-rays from e^+ synchrotron in strong magnetic fields;**
  - **X-/gamma-rays from IC of low energy photons by positrons.**

Positron candidate sources

- **Supernovae explosions through their radioactive products (β^+ decay of radioactive nuclei: ^{56}Co, ^{44}Ti);**
- **Galactic BH binaries;**
- **Massive BHs (GC, AGNs)**;
- **Magnetized NSs (X-ray pulsars, magnetars);**
- **Dark matter sources (e.g., Galaxy Clusters).**

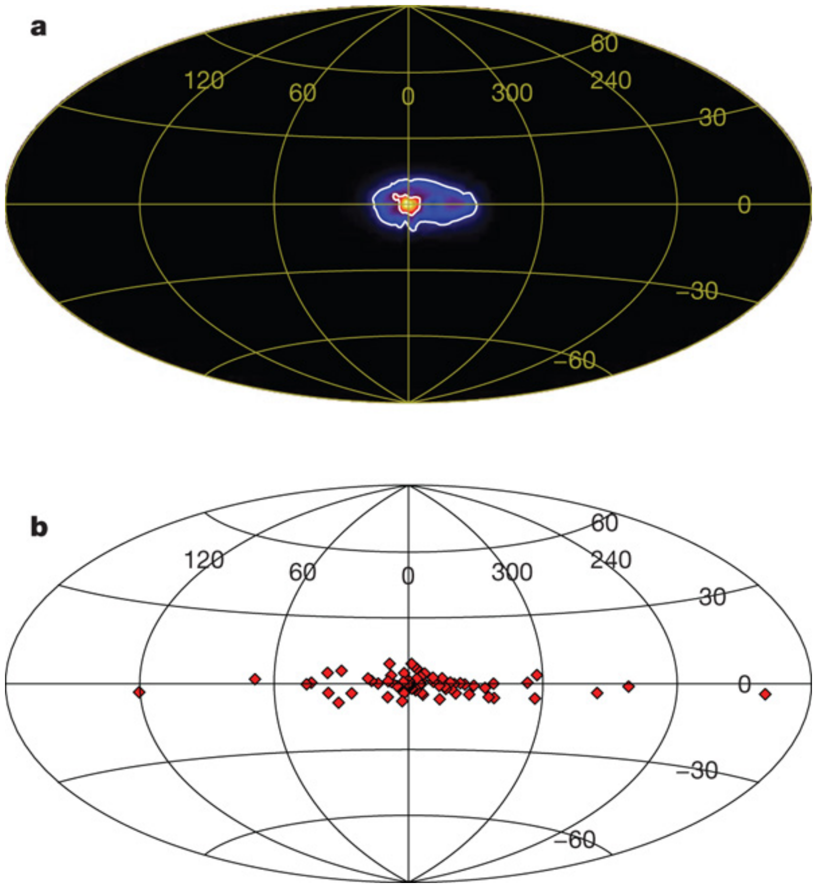
Strong constraints on plasma density in the production sites to avoid positron escape.

Positron annihilation from GC

- Diffuse annihilation line emission with INTEGRAL (integrated flux: $1.7\text{x}10^{-3}$ ph/cm^2 s).

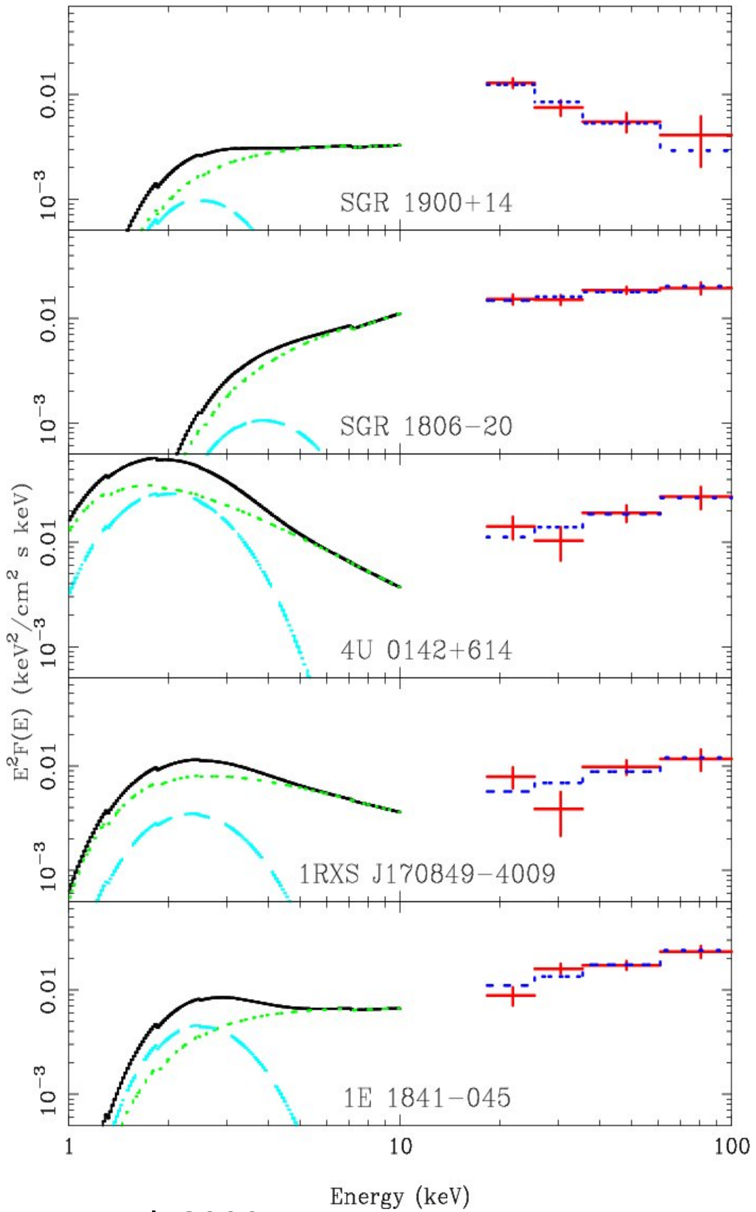
- Origin still unknown.
- Several models proposed:
  - Dark matter;
  - Antimatter
  - Source of radioactive elements like ^{26}Al, ^{56}Co, ^{44}Ti
  - Gamma Source (e.g., Pulsar)
  - BH Binaries

- More sensitivity and imaging capability required.



Weidenspointner+2008

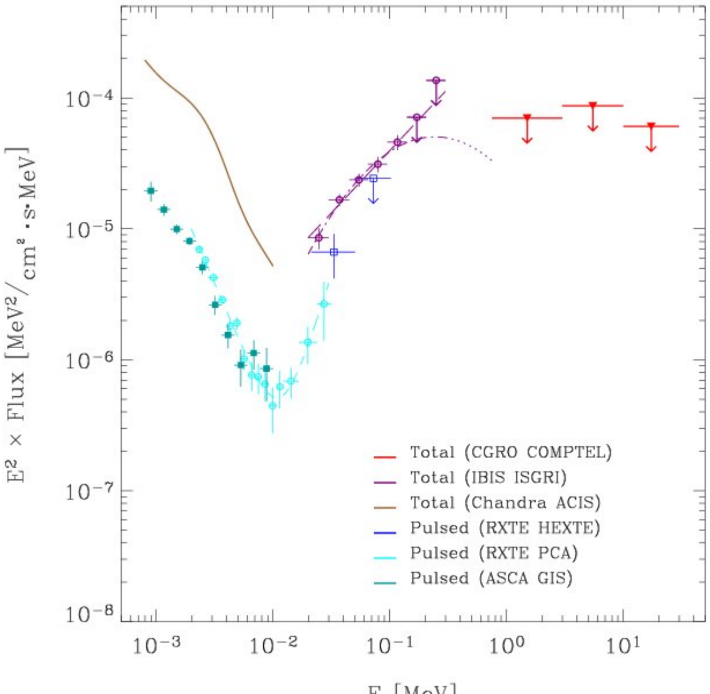
High-energy spectra of magnetars



Goetz et al. 2006

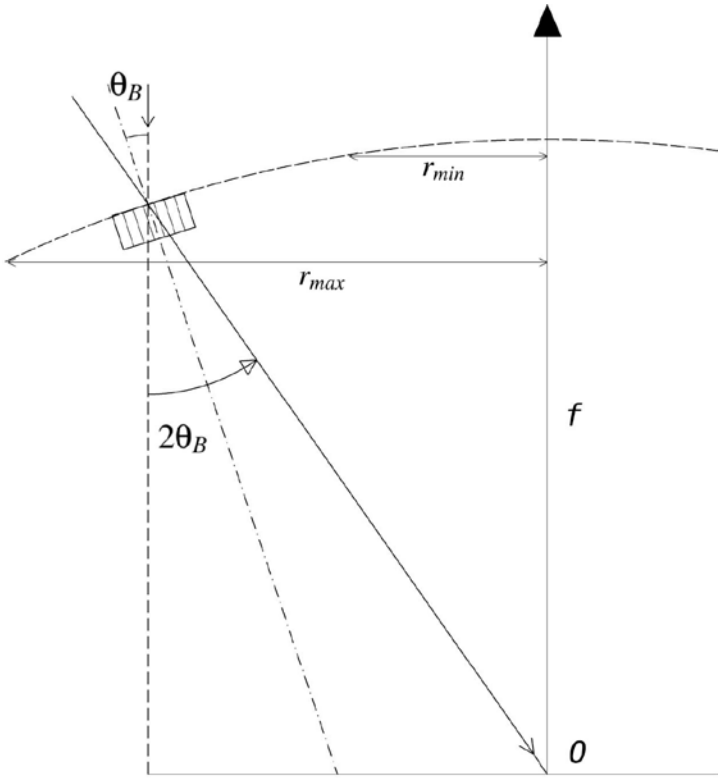
- Which is the origin of the high energy component?
- Crucial to know the cutoff of the high energy spectrum.

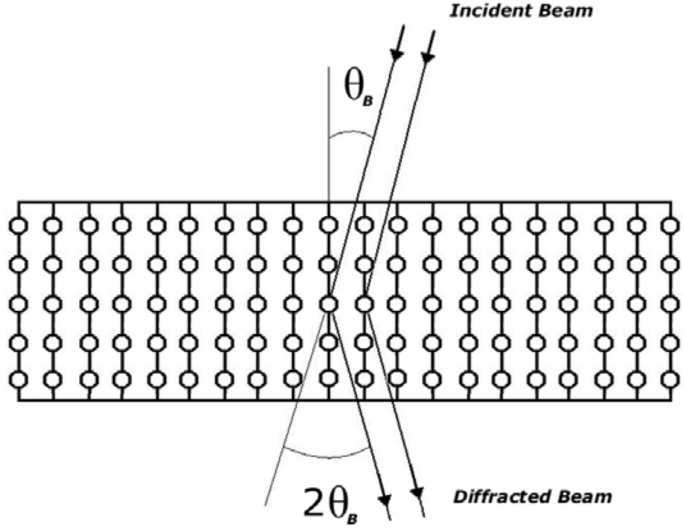
- Thompson & Beloborodov (2005) model:
  - positron flux required;
  - synchrotron spectrum.



4U 0142+61 (Kuiper et al. 2006)

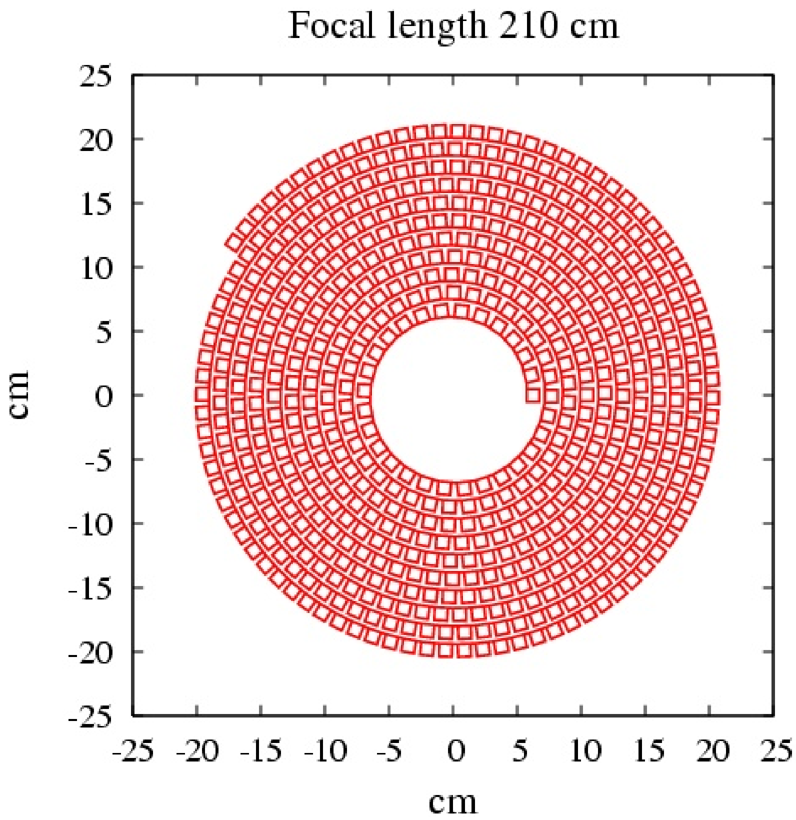
Laue lens principle

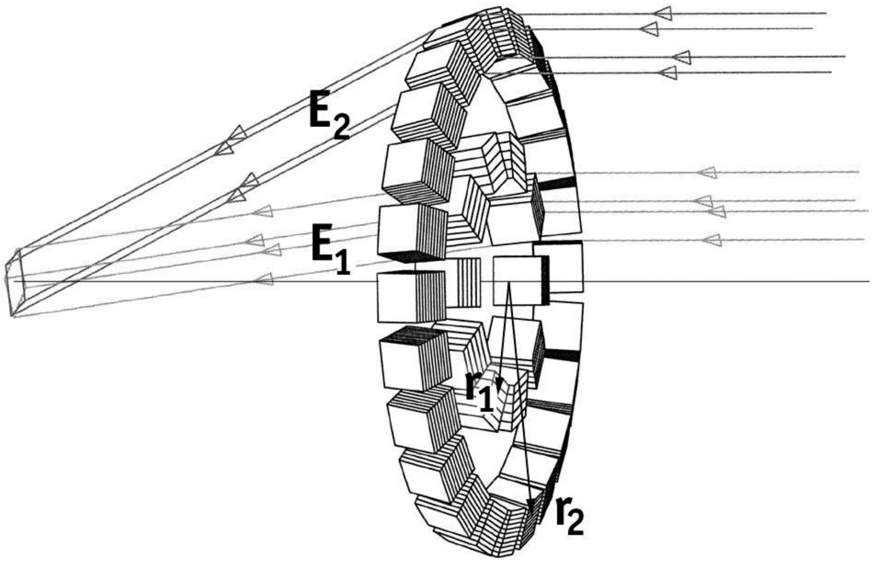




- **Bragg diffraction from suitable crystals in transmission configuration**

Laue lenses





For a recent review: FF & Von Ballmoos 2011

Mosaic crystals

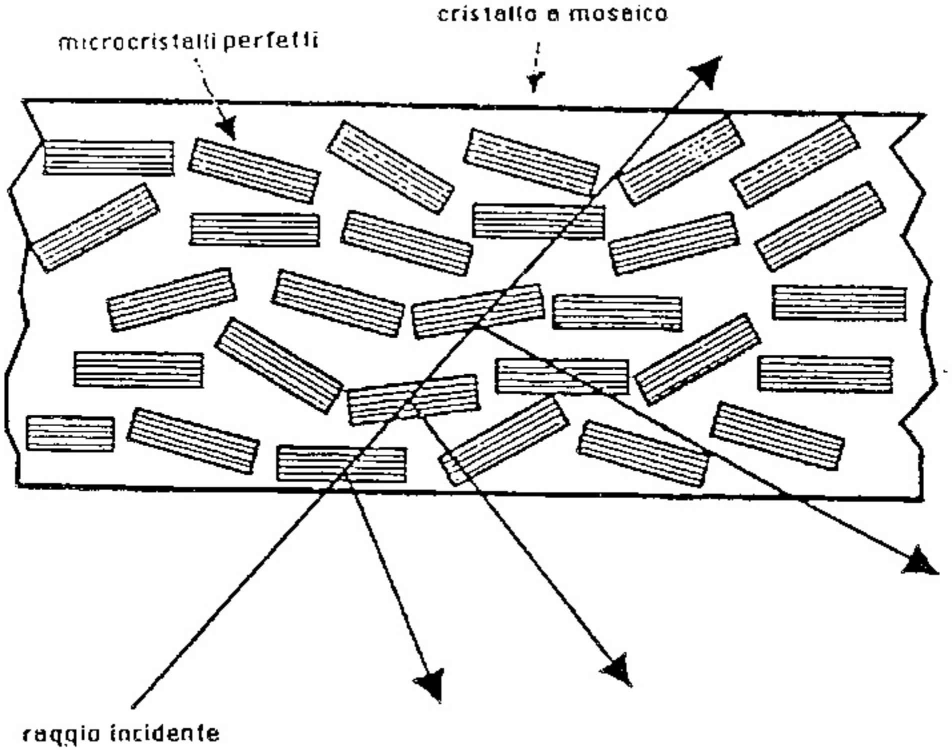
- **Made of slightly misaligned perfect microcrystals:**

$$W(\delta) = \frac{1}{\sqrt{2\pi\eta}} \exp\left(-\frac{\delta^2}{2\eta^2}\right)$$

- **Energy passband of a single mosaic crystal:**

$$\Delta E_{fwhm} = \frac{E\beta}{\tan\theta}$$

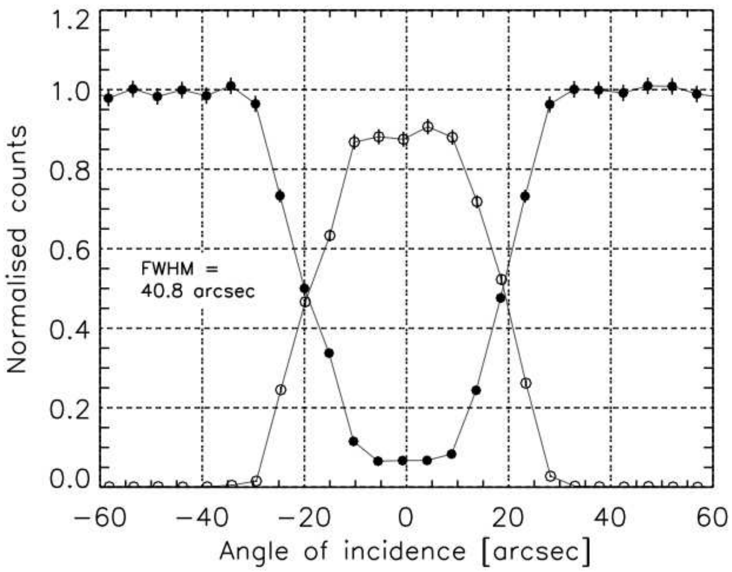
where β (mosaicity) = 2.35 η



Curved vs. mosaic crystals

- **Advantages of curved crystals:**
  - **Diffraction efficiency up to 1 (0.5 for mosaic crystals);**
  - **Better lens focusing**

SiGe(111) @ 150 keV developed by IKZ, Berlin



UNIFE on Laue lenses

2 lens prototypes already developed.

- 1^{st} Prototype:

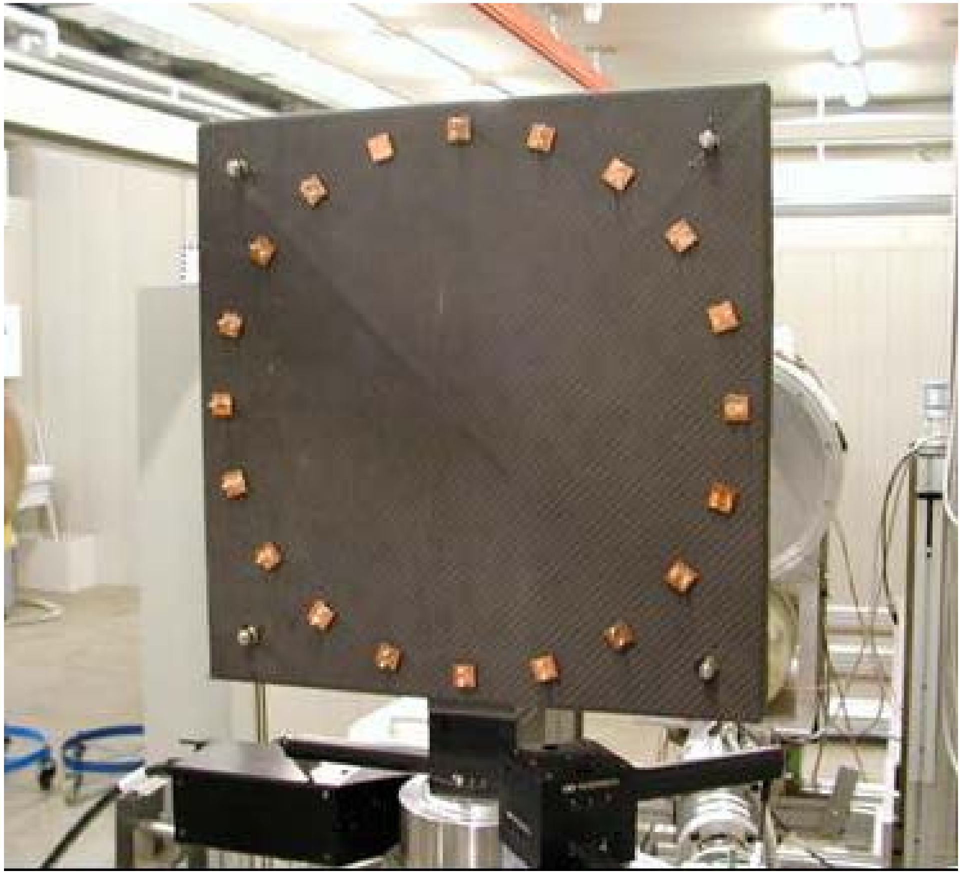
❖ **Flat mosaic crystals of Cu(111)**

❖ **Tile size: 15x15x2 mm^3**

❖ **Mosaic spread: 3-4 arcmin**

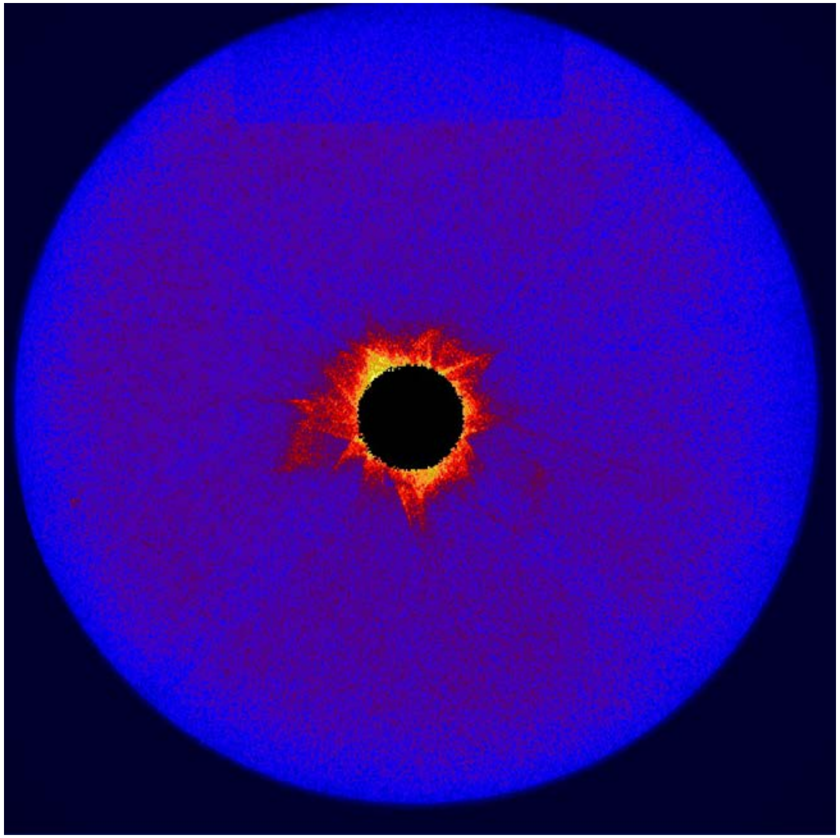
❖ **Lens support: carbon fiber**

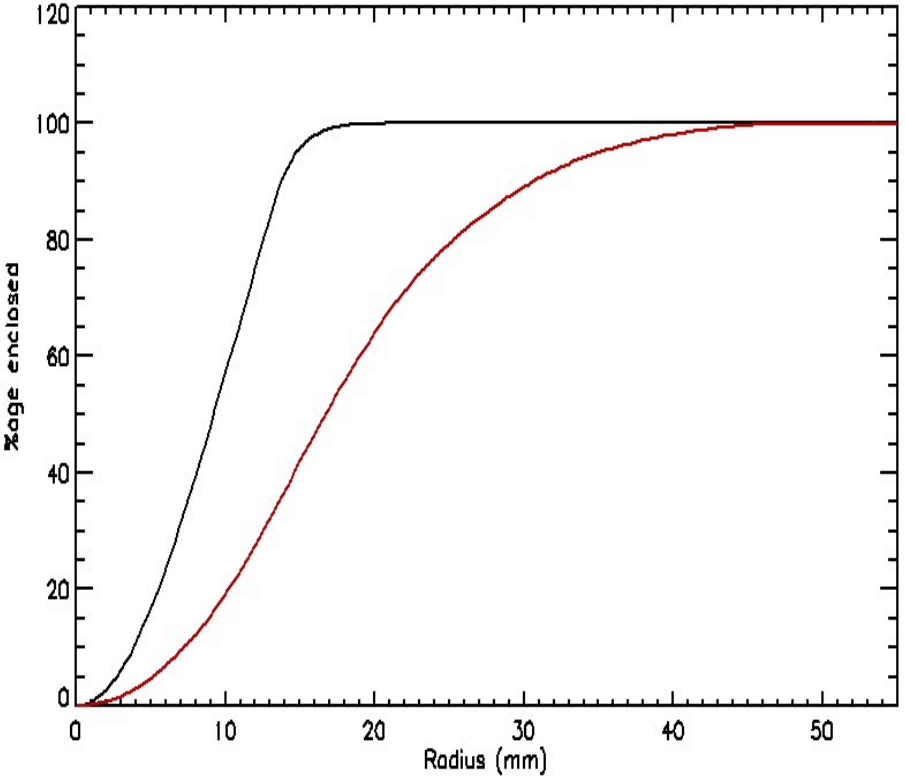
❖ **6 m focal length**



Frontera et al. 2008

First light from a Laue lens in 2008





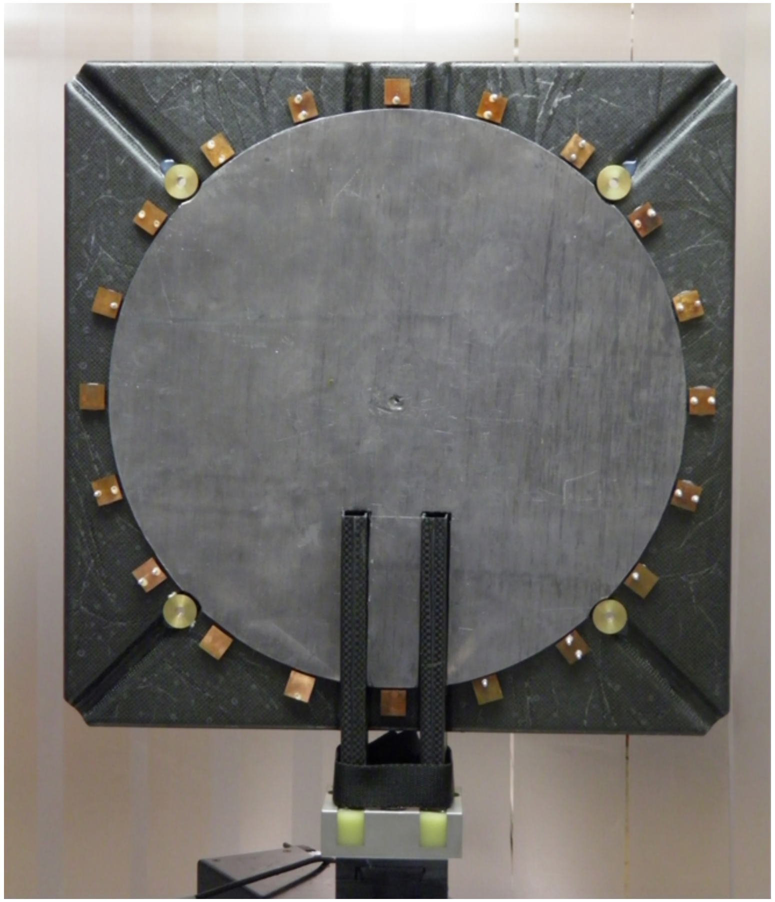
Encircled energy as a function of radius:

- Measured
- Expected (perfect assembling of the crystals in the lens)

UNIFE on Laue lenses 2/4

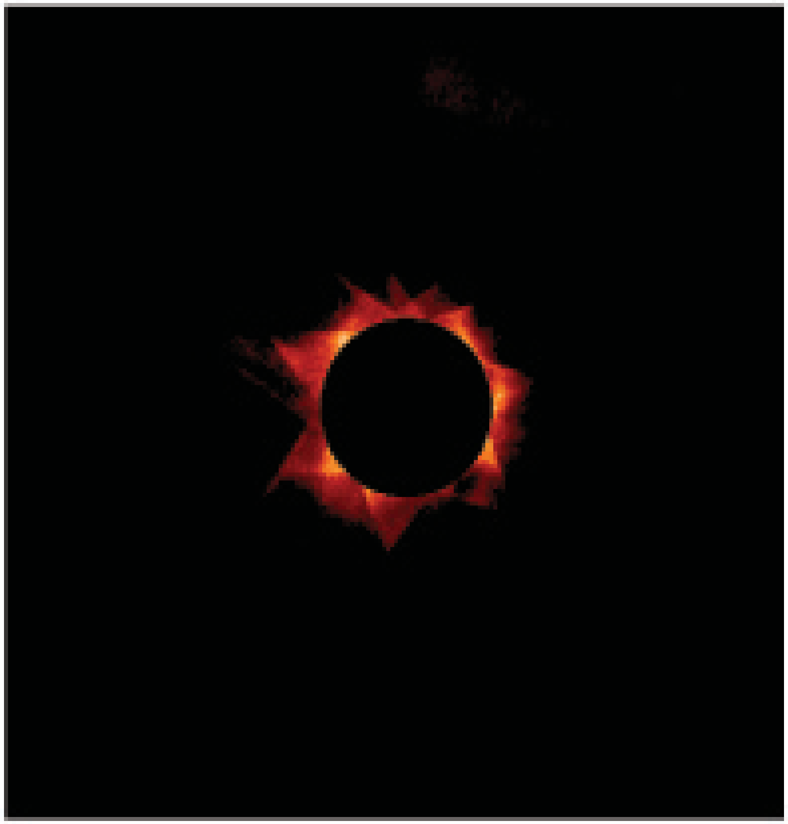
2nd lens prototype:

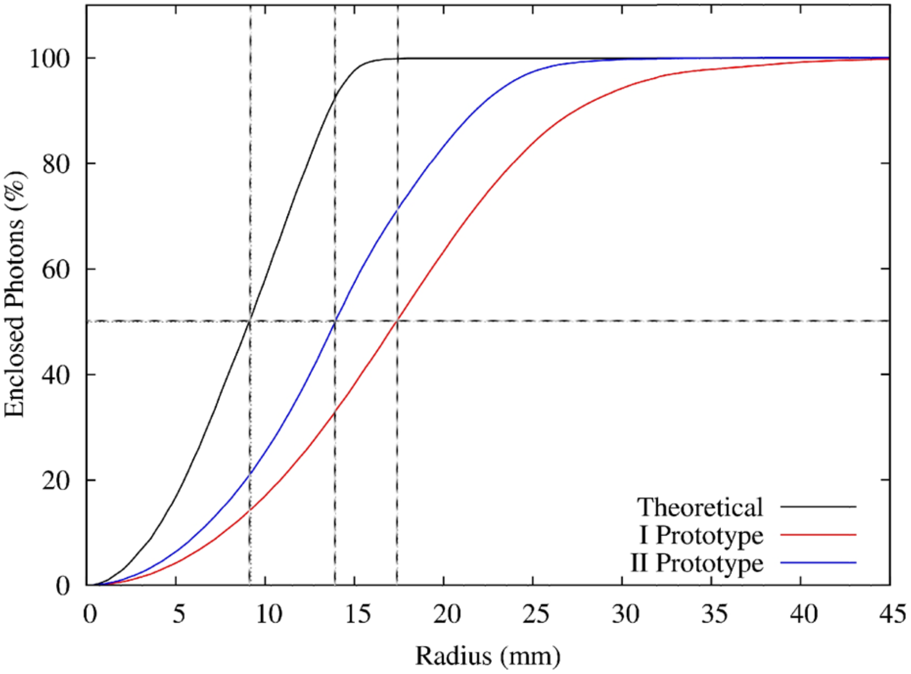
- ❖ Flat mosaic crystals of Cu(111)
- ❖ Tile size: 15x15x2 mm^3
- ❖ Mosaic spread: 2-3 arcmin
- ❖ Lens support: carbon fiber
- ❖ 6 m focal length



Virgilli et al. 2011

2^{nd} lens prototype focusing capability





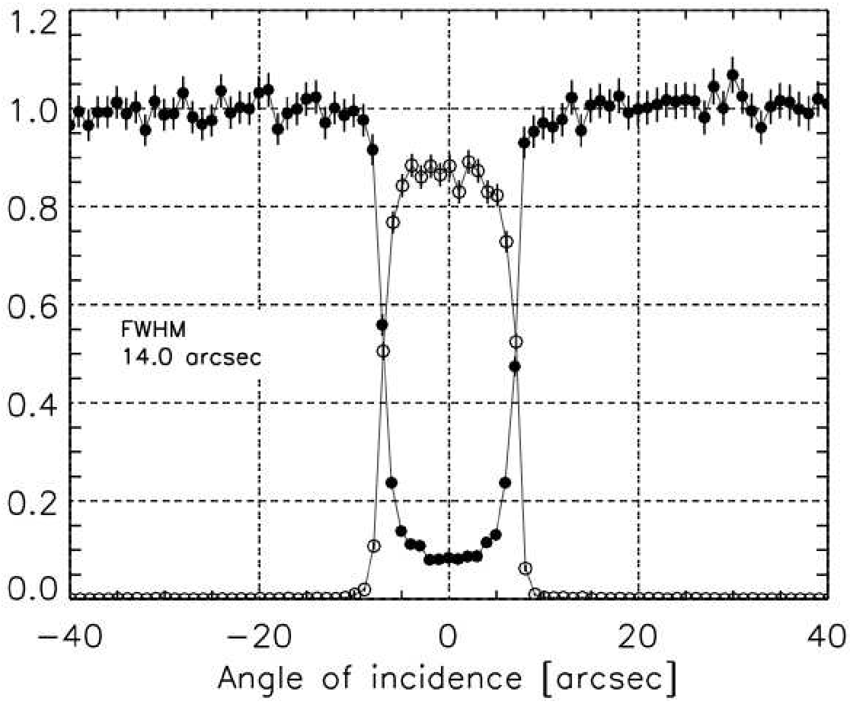
- Better encircled energy, but still not the expected.
- In order to get the theoretical expectation a new assembling technology (LAUE project) is now being developed.

Laue Project

- **A project "LAUE", supported by ASI, is on going, with the following goals:**
  - **new assembly technology for long focal lengths;**
  - **massive production of proper crystals;**
  - **development of lens petal made of curved crystals, 20 mFL;**
  - **Accommodation study of a space lens made of petals.**
- **Large Collaboration of**
  - **Scientific Institutions:**
    - **UNIFE, INAF/IASF-Bologna, CNR, IMEM-Parma;**
  - **and Industry:**
    - **DTM-Modena, TAS I-Milan and Turin.**

Current crystal development

- Indentation technology has been developed by LSS, University of Ferrara to produce curved crystals;
- Crystals of Si and Ge are currently curved (talk by V. Guidi).
- A bending technology is also developed for Si and GaAs by IMEM, CNR, Parma.

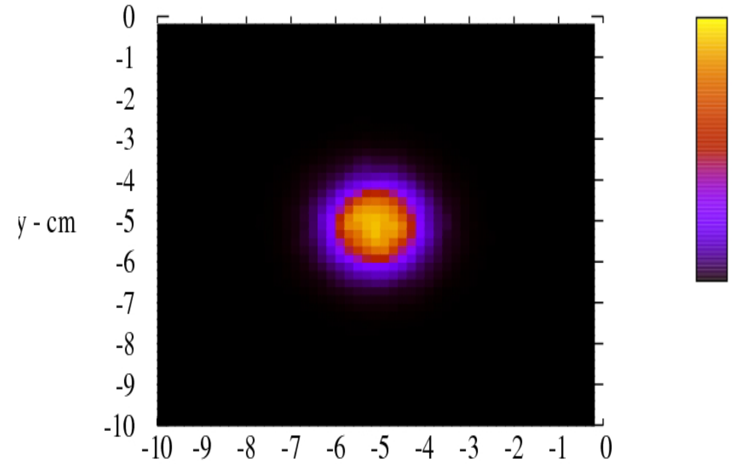


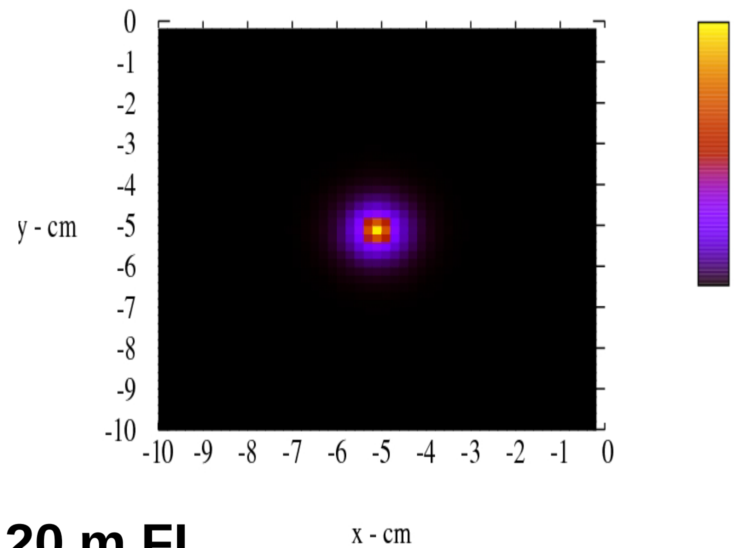
Measured reflectivity of a curved Si(111) @ 150 keV

Curved crystals vs. flat crystals

- **For 20 m FL, an angular resolution of 20 arcsec vs. 3.5 arcmin;**

- **Source image area reduced by a factor ~100.**





Crystal size 15x15 mm^2, 20 m FL

Conclusions

- A focusing telescope beyond 70/100 keV is crucial for a breakthrough in soft gamma-ray astronomy;
- Deeper searches of positron sources will be possible;
- A big effort is in progress for the development of focusing Laue lenses (P. von Ballmoos talk);
- In Ferrara: the project "LAUE", supported by ASI, is ongoing (resulta expected at the end of 2012);
- The Laue lens assembling technology is expected to become mature in the next future;
- Concrete prospects for proposing a broad band (e.g., 1-600/700 keV) satellite mission with both multilayer mirrors and Laue lenses.