Laue Lenses for extending the focusing band beyond 100 keV

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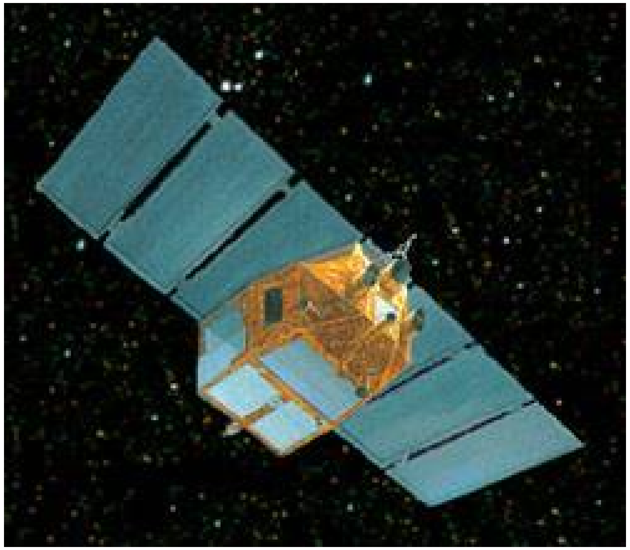
on behalf of the “LAUE” Collaboration

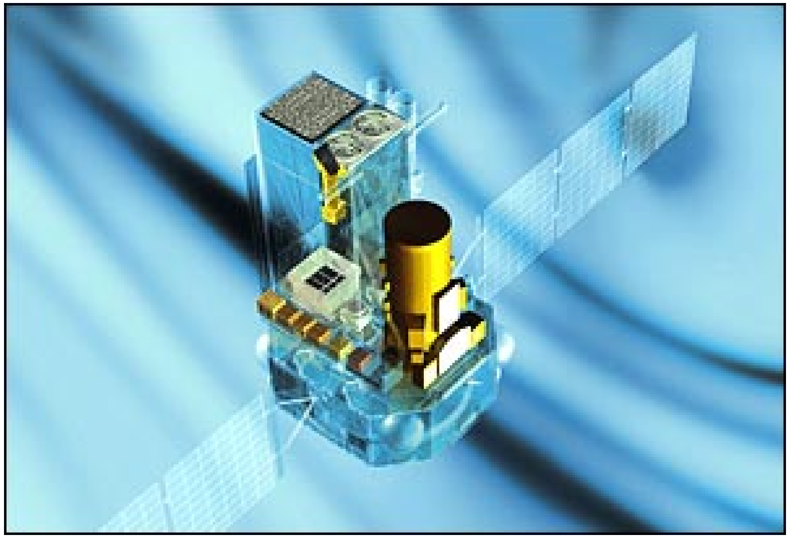
Workshop Nazionale su “ Astronomia X”

Roma, 16 Novembre 2012

Introduction 1/2

- Two main reqs. for spectral studies of many classes of galactic and extragalactic sources:
  - Broad energy band (from fraction of keV to hundreds of keV)
  - High flux sensitivity on source variability time scales.





Introduction 2/2

- The only viable way: focusing telescopes that cover the broadest energy band:
  - Low energy telescopes: (0.1-10 keV) well tested in space;
  - Medium energy telescopes (up to 70/100 keV): already mature (NuStar, ASTRO-H)
  - High energy telescopes (>70/100 keV): under development.

- **Soft Gamma-Ray telescope Requirements**:

  - **Continuum sensitivity about two orders of magnitude better than INTEGRAL at the same energies (goal: a few $x10^{-8}$ ph/(cm^2 s keV in 10^5 s, $\Delta E = 0.5\ E$).**
  - **a much better imaging capability (better than 1 arcmin)**

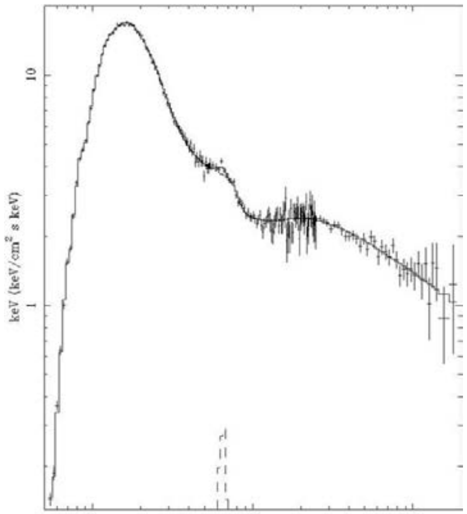
Why to extend the energy passband beyond 70/100 keV?

See, e.g., FF&von Ballmoos 2011

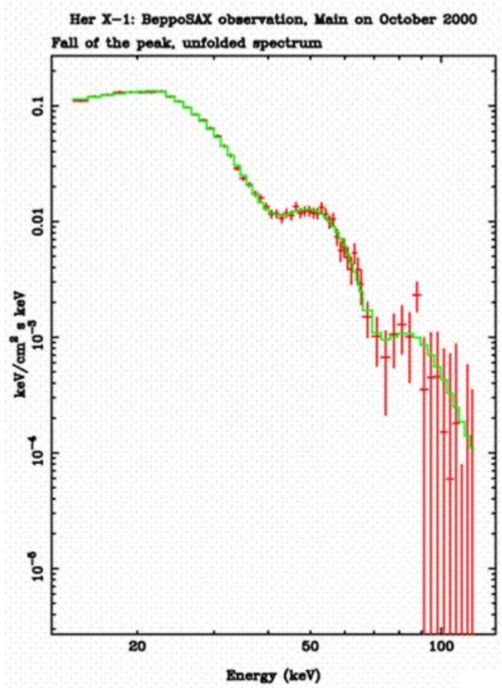
Examples of issues that can be faced with soft γ-ray observations (80/100-600 keV)

- High energy emission physics in the presence of super-strong magnetic fields (magnetars);
- Non thermal processes in cosmic sources (e.g., AGN);
- Origin and distribution of high energy cut-offs in AGNs spectra;
- Origin of Cosmic Hard X-ray background (CHXB).
- Precise role of non-thermal mechanisms in extended objects (e.g., Galaxy Clusters);
- Determination of the antimatter production processes and its origin.
- Gamma-ray source polarization.
- Dark matter probe??

Current spectral status: some examples

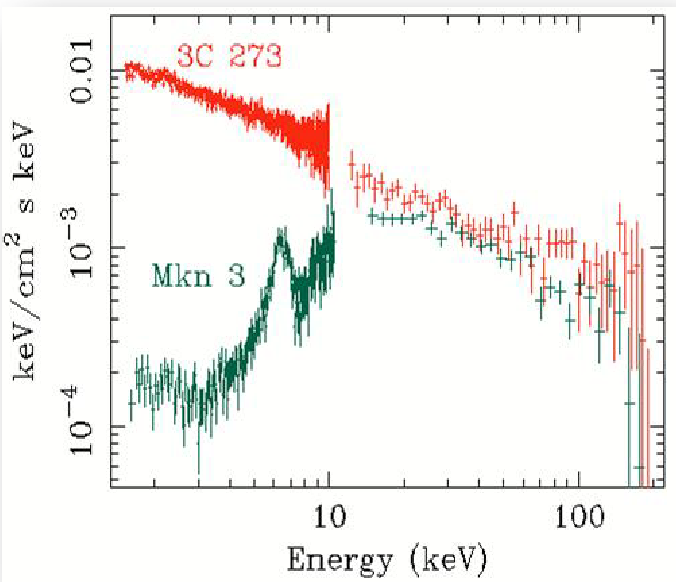


Cyg X-1 soft state

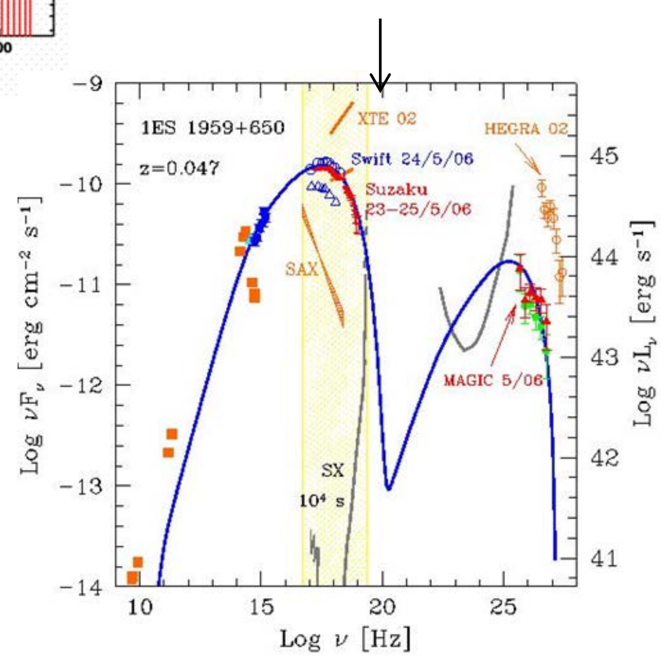


Her X-1 low ON

400 keV

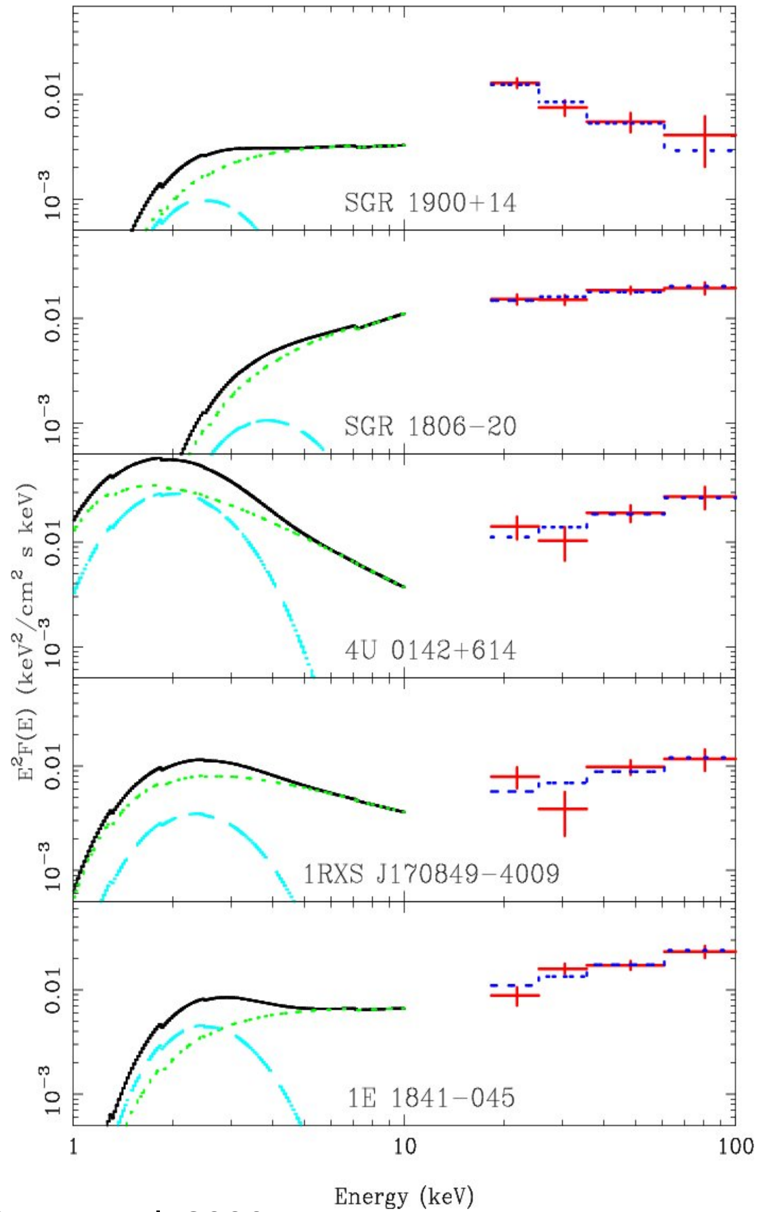


Seyfert 2 vs. QSO



Blazar

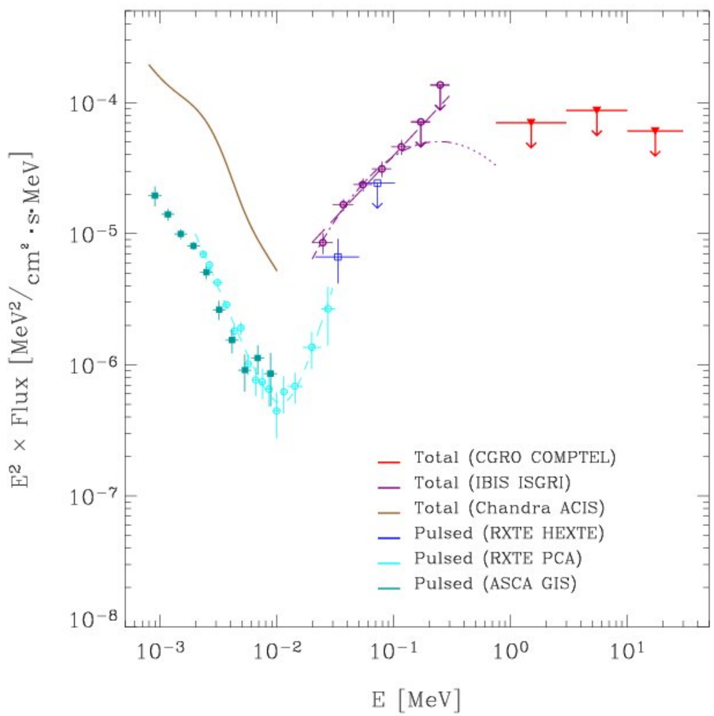
High-energy spectra of magnetars



Goetz et al. 2006

- **Which is the origin of the high energy component?**
- **E.g., Thompson & Beloborodov (2005) model: synchrotron originated by pair production.**

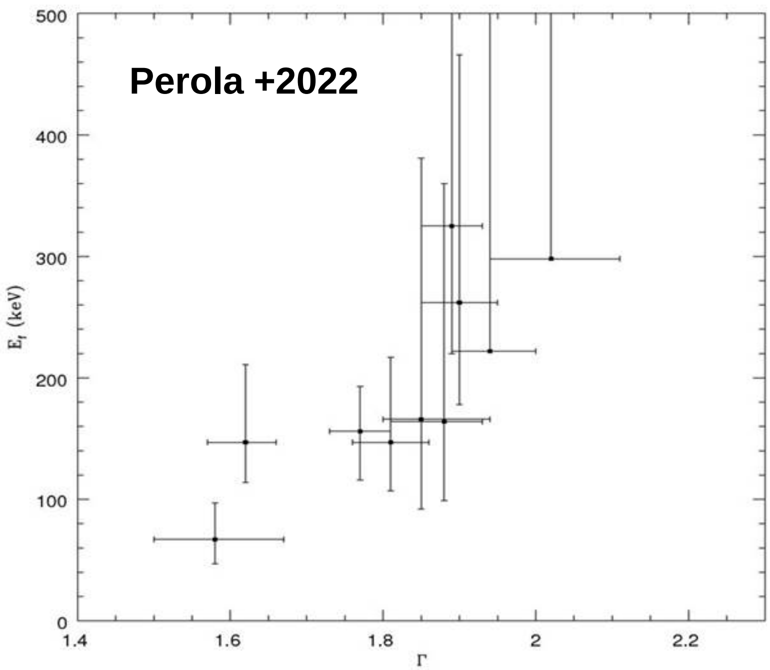
- Crucial to know the cutoff of the high energy spectrum.



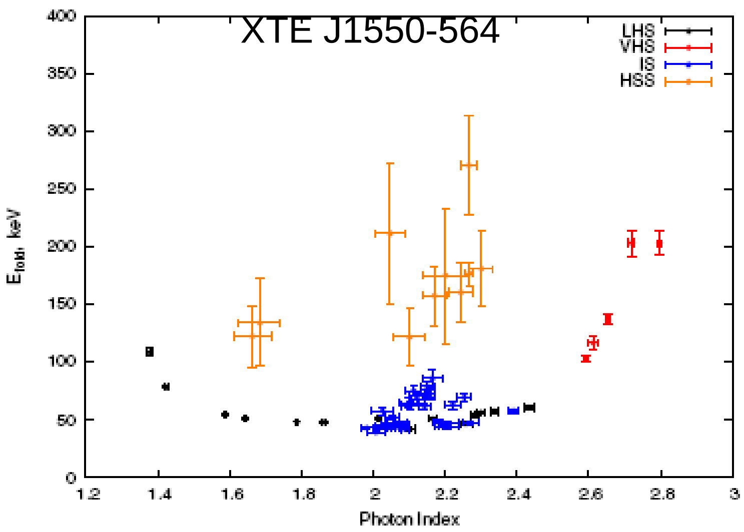
4U 0142+61 (Kuiper et al. 2006)

Emission physics of RQ AGNs

- Basic emission scheme is known: Compton up-scattering of seed photons
- But:
  – Which is the electron temperature?
  – Is there a non-thermal component?

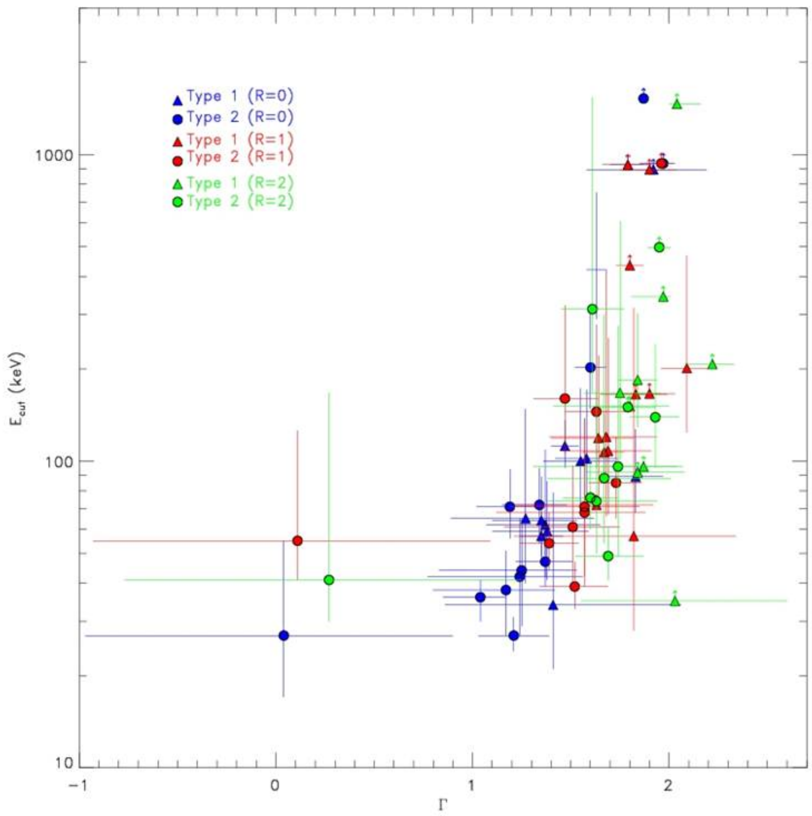


- Photon index and high energy cut-off measurements are crucial.
- E_{cut} vs. Γ could give info about the bulk motion role in the Comptonization process (Titarchuk et al. 2010).

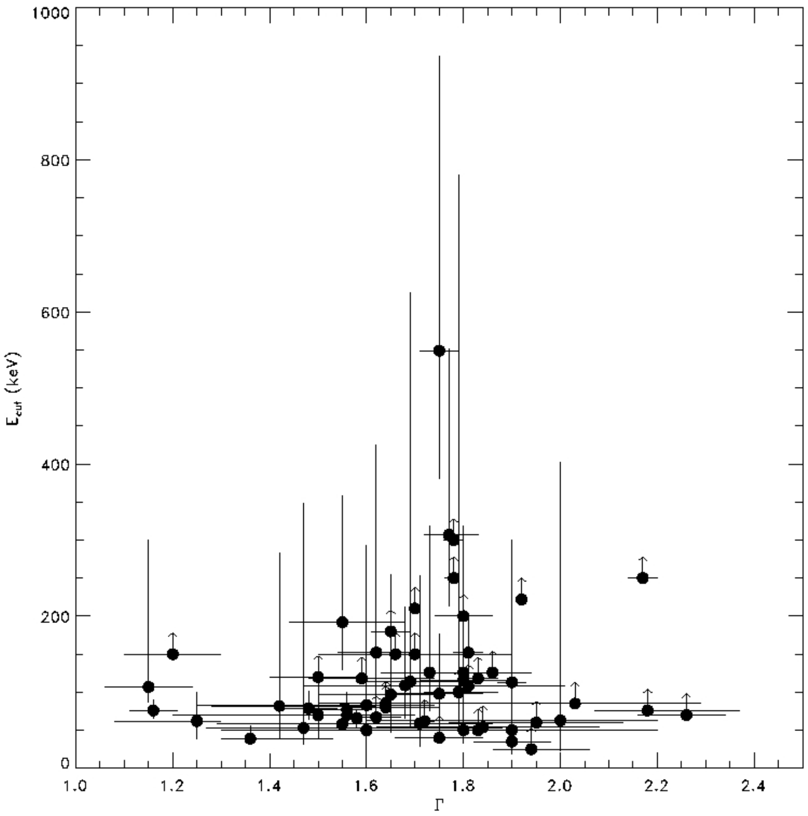


Current status of E_{cut} vs. Γ

Only INTEGRAL >15 keV



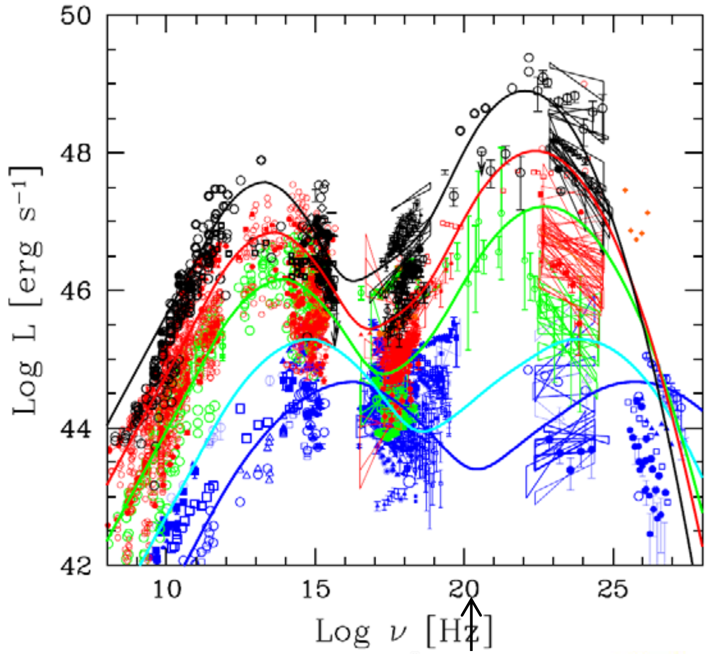
Broad band



Bassani+2012

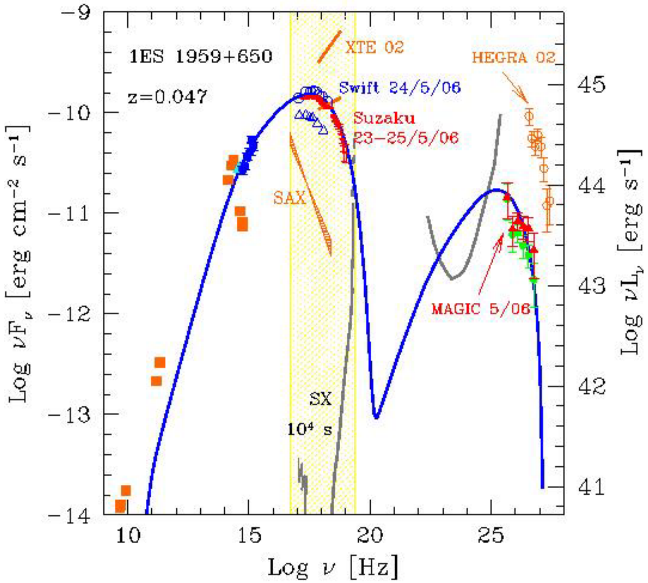
Emission physics of RL AGN (Blazars)

- **Two humps in the SED:**
  - **one interpreted as synchrotron emission,**
  - **the other as IC (SSC and/or EC).**



Ghisellini 2011

- **Low L: BL-Lac; High L: FSRQ**
- **To model SED, soft gamma-ray band (>100 keV) is crucial.**

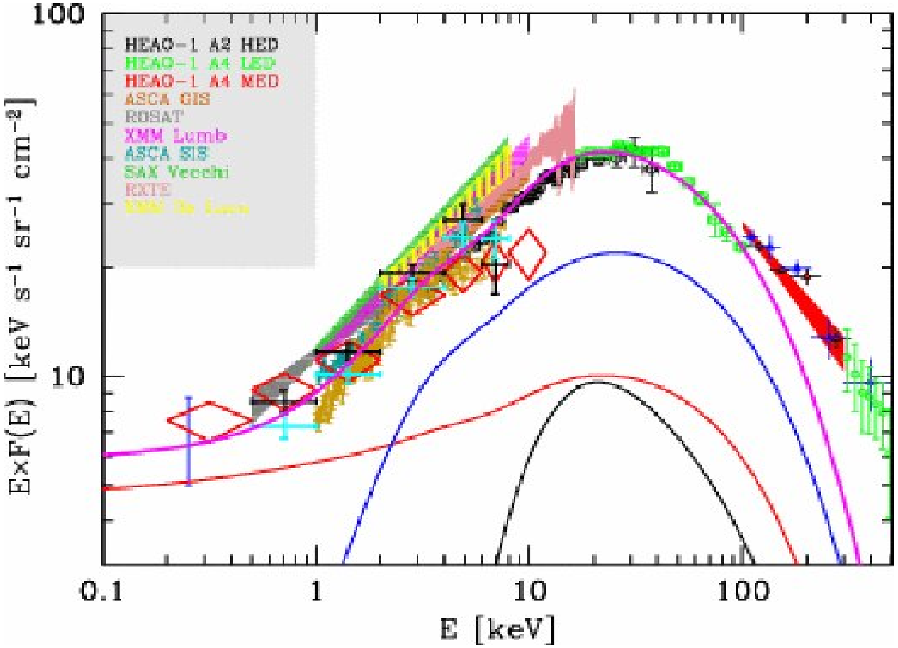


Ghisellini 2009

CXB (<100 keV)

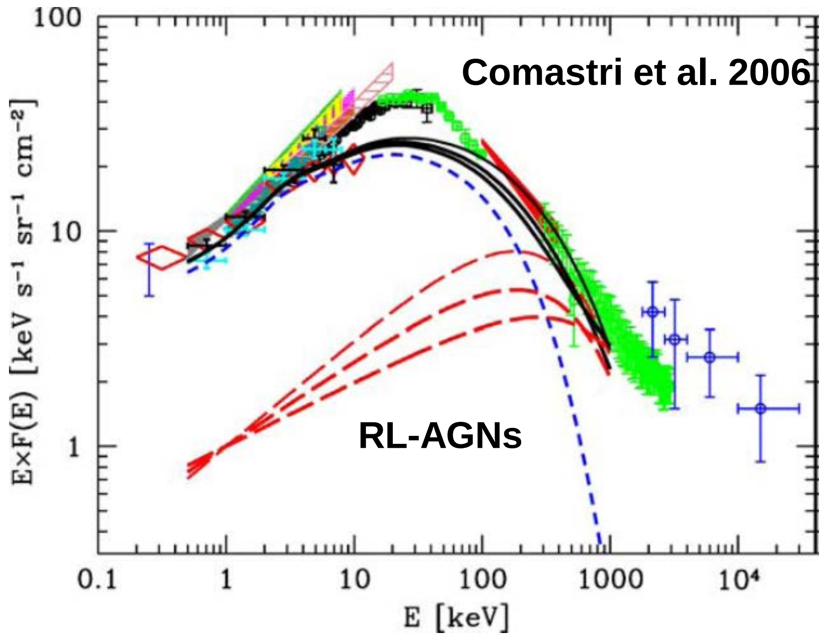
- In current synthesis models of CXB, assumption of RQ-AGN populations with
    - a distribution of photon indices,
    - fixed E_{cut} (=200 keV)
- Is it right to assume a fixed EF ?

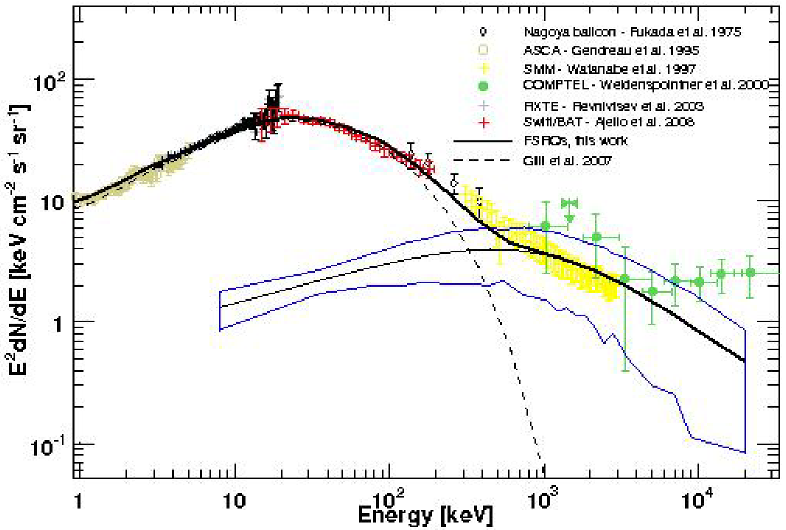
Gilli et al. 2007



CXB (>100 keV)

- **Likely due to Blazars.**
- **But:**
  - **The most recent results on Blazars are in 15-55 keV (Ajello+2009).**
- **Only assumptions about high energy spectrum**
- **Gamma–ray observations are crucial**





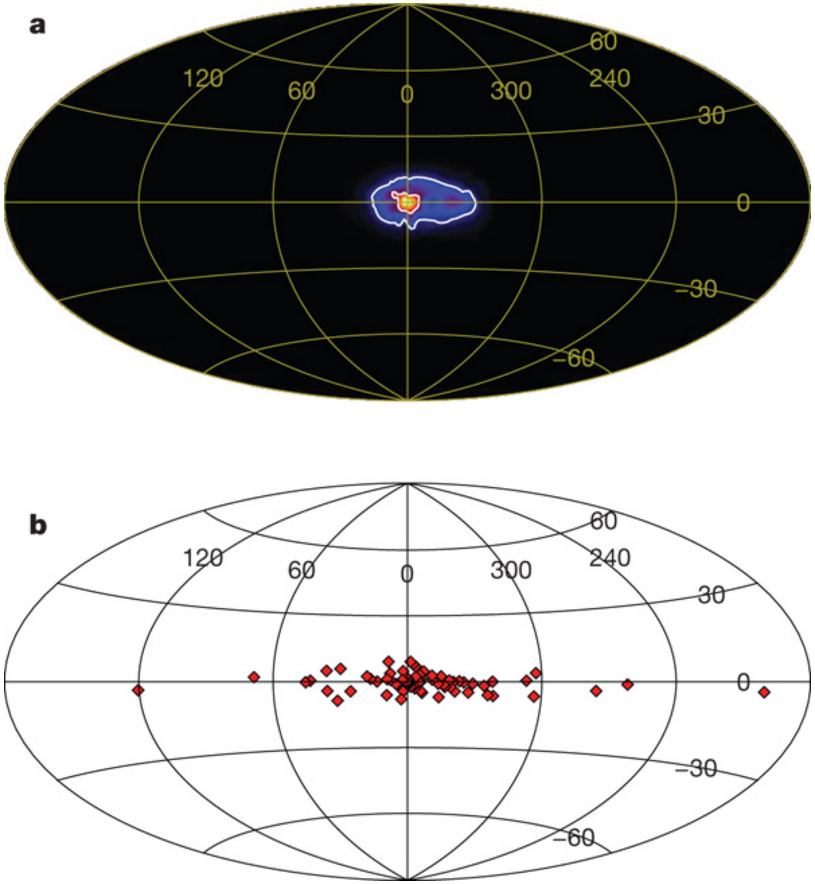
Ajello et al. 2009

Positron annihilation from GC

- Diffuse annihilation line emission with INTEGRAL (integrated flux: $1.7x10^{-3}$ 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

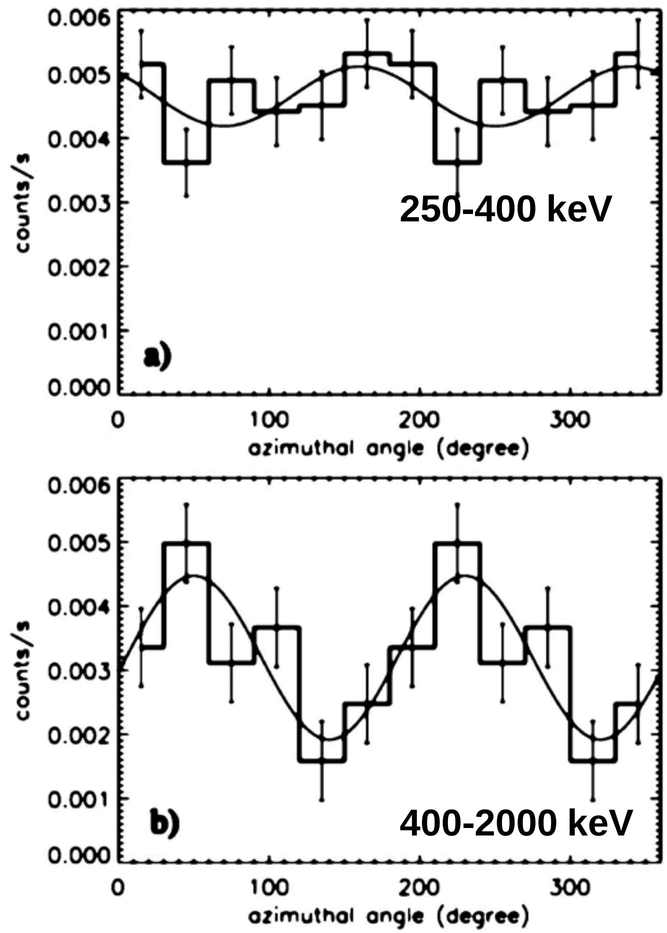


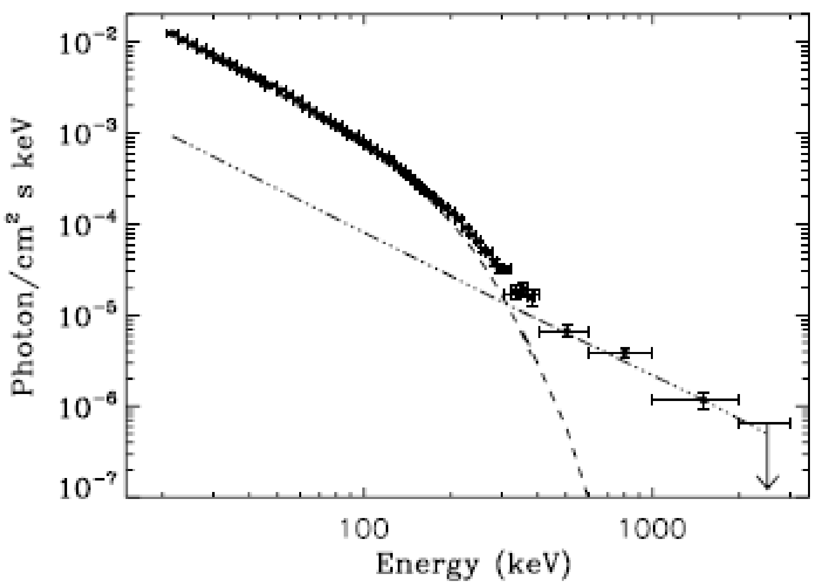
Weidenspointner+2008

Gamma-ray polarization

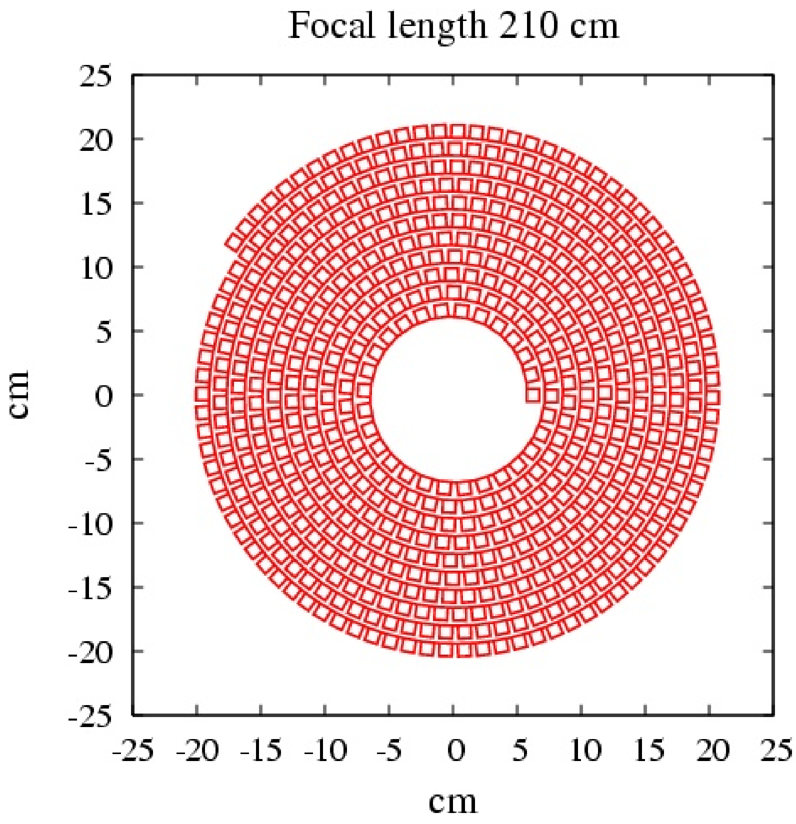
- **A very strong polarization signal found from Cygnus X-1 with INTEGRAL above 400 keV;**
- **Much more sensitivity is requested to extend this search to weaker sources.**

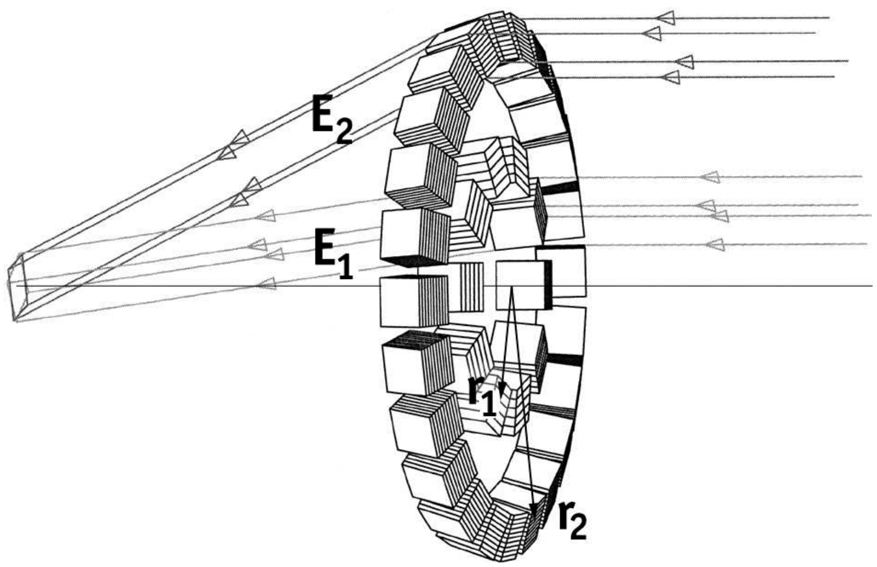
Laurent at al. 2011





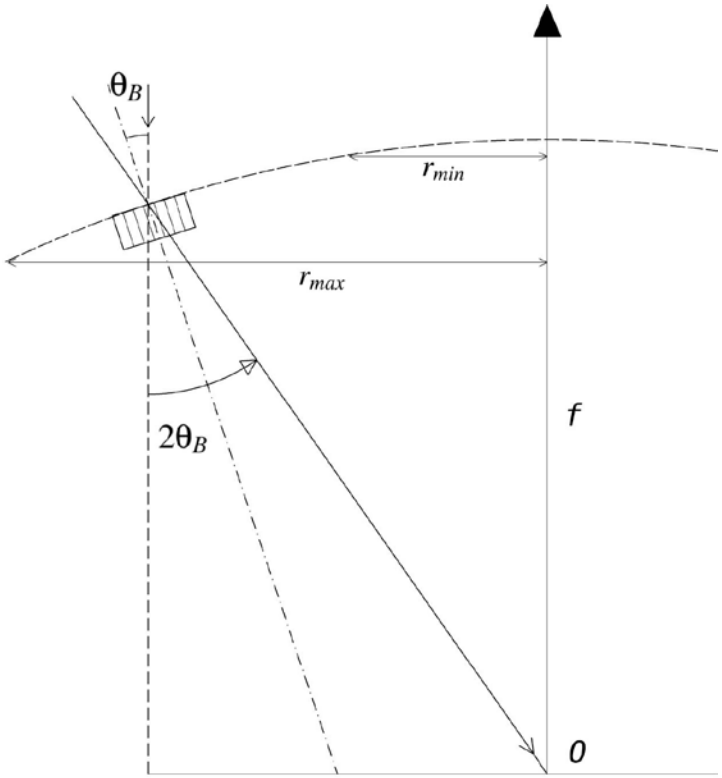
High energy (>70/100 keV) telescopes: Laue lenses

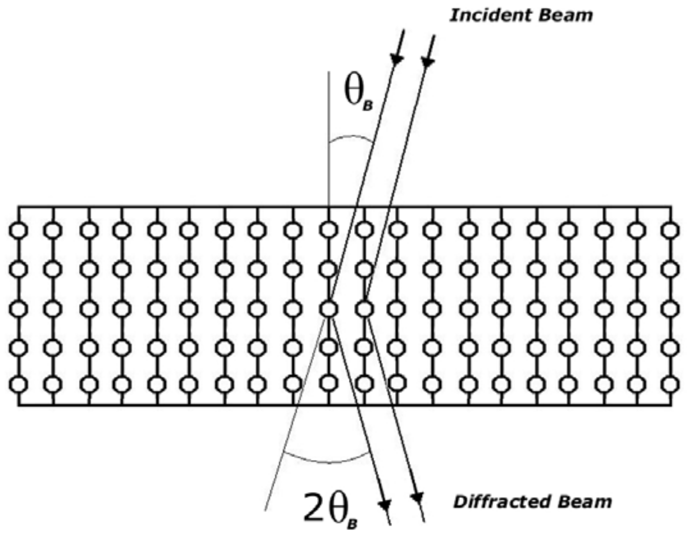




For a recent review: Frontera & Von Ballmoos 2011

Laue lens principle





- Bragg diffraction in transmission configuration
- Mosaic/bent crystals to extend the passband and get a smooth dependence of the lens effective area with energy;
- Material and lattice planes properly chosen to maximize reflectivity.

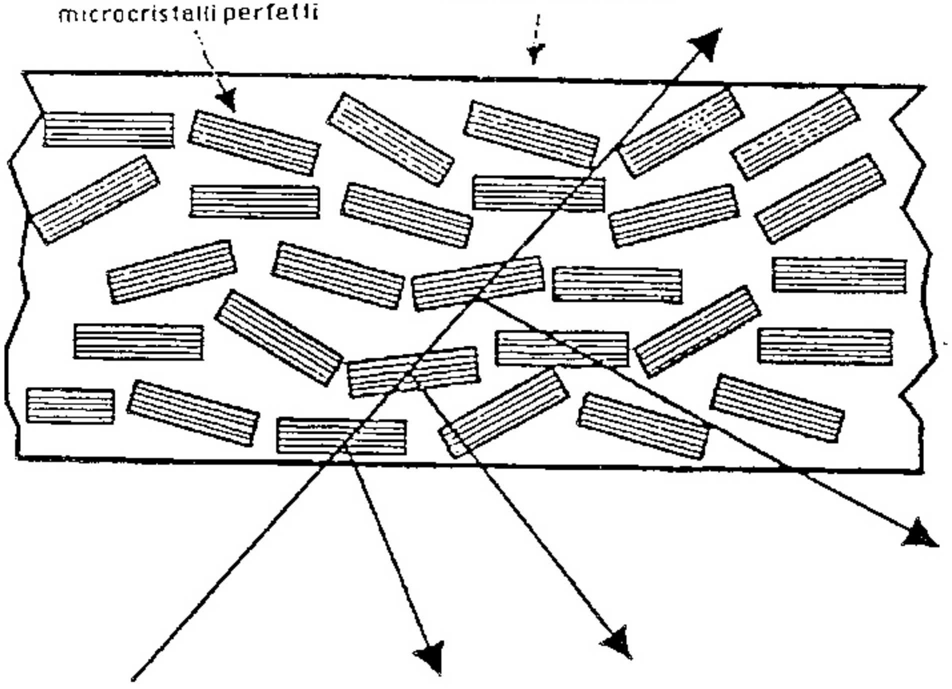
Flat **mosaic crystals**

- **Made of misaligned perfect microcrystals:**

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

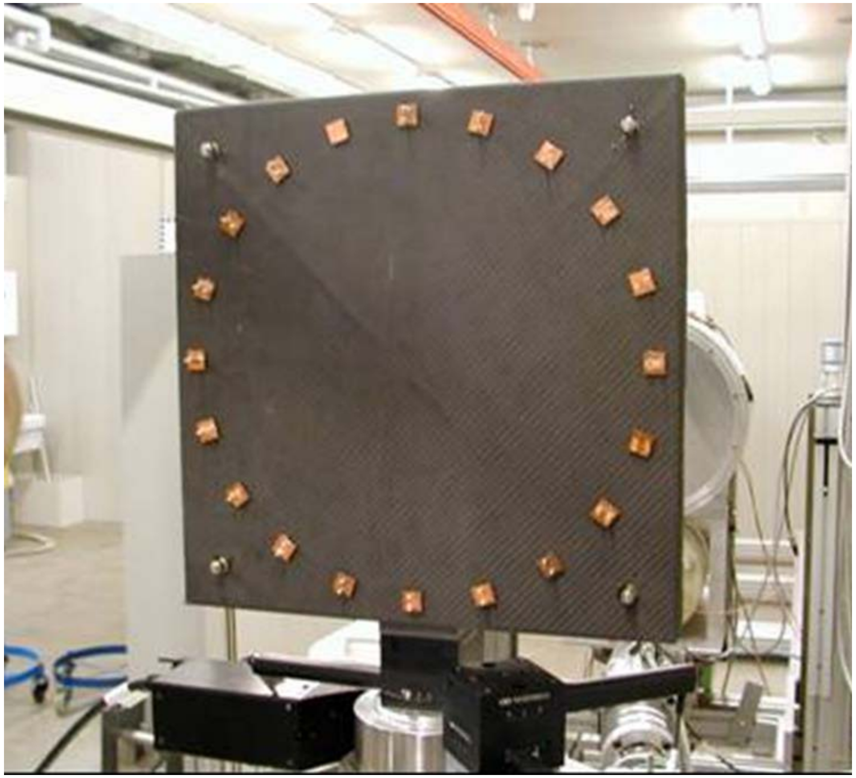
- **The energy passband of a mosaic crystal is given by:**

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

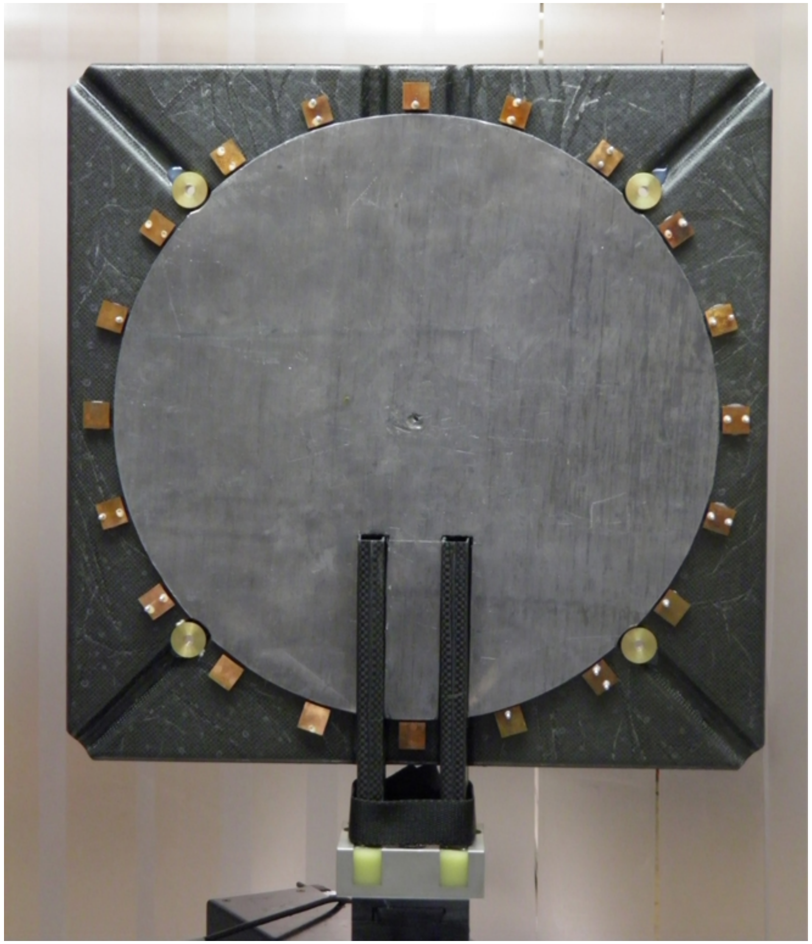


where β (mosaicity) = 2.35 η

Activity UNIFE on Laue lenses with flat mosaic crystals



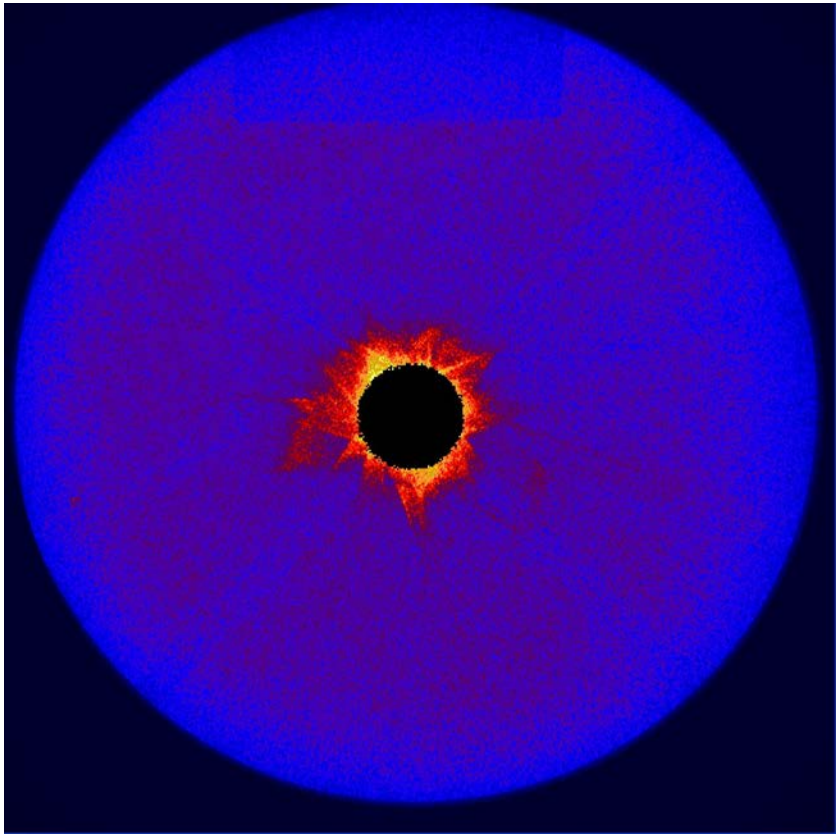
Frontera et al. 2008



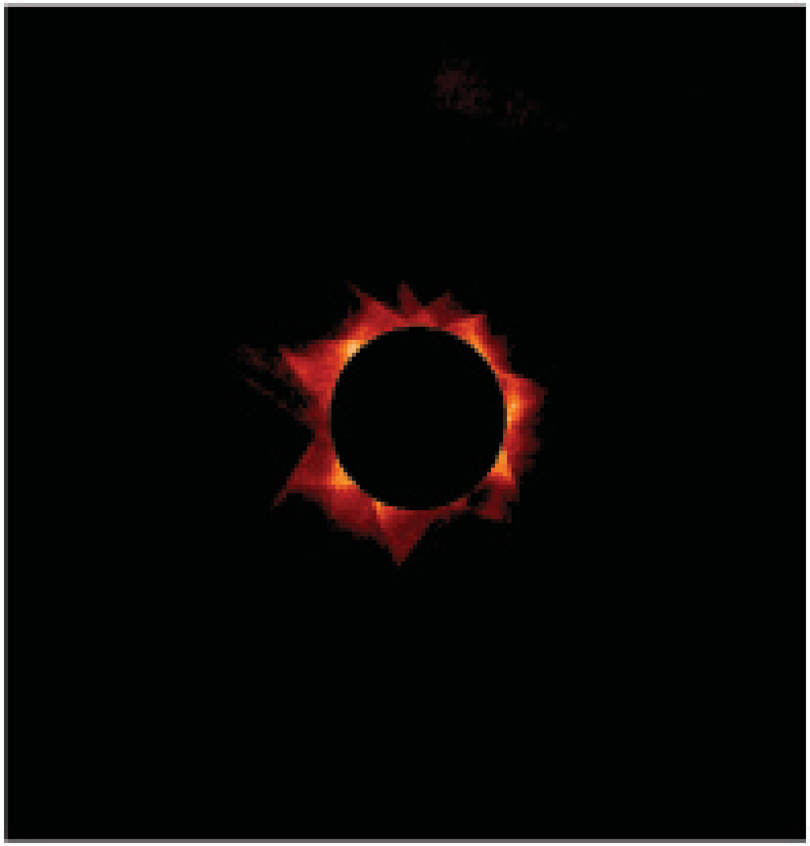
Virgilli et al. 2011

Prototype test results

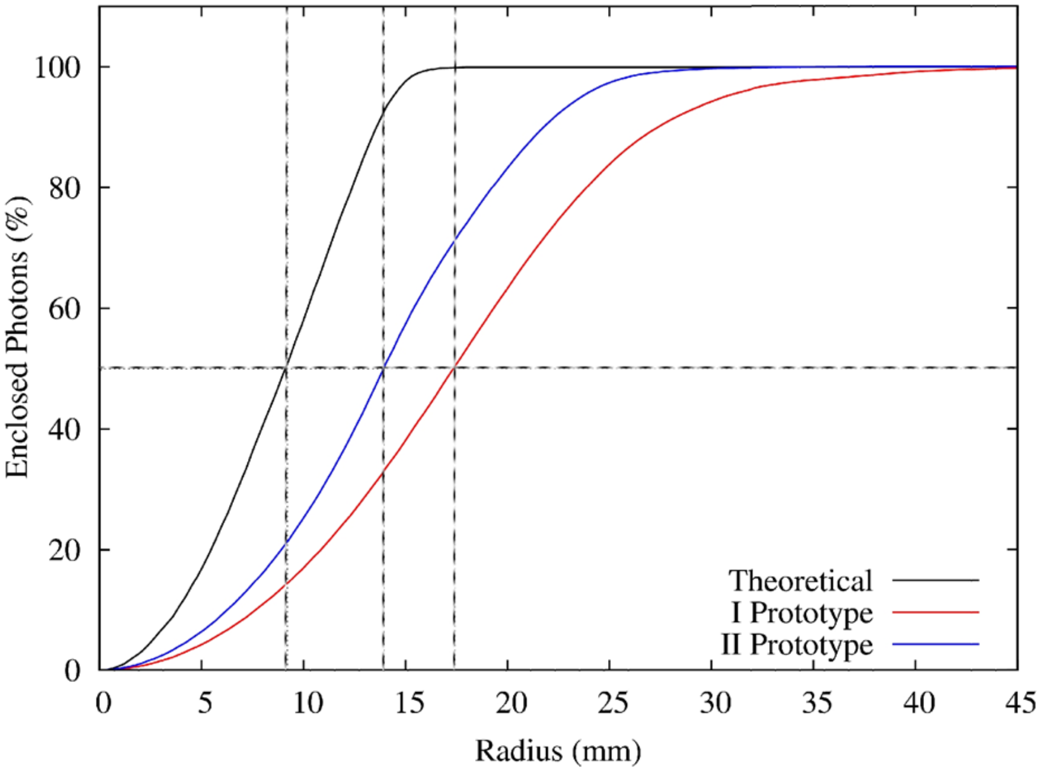
1st prototype



2nd prototype



1st prototype vs. 2nd prototype



A PSF improvement obtained, but not sufficient.

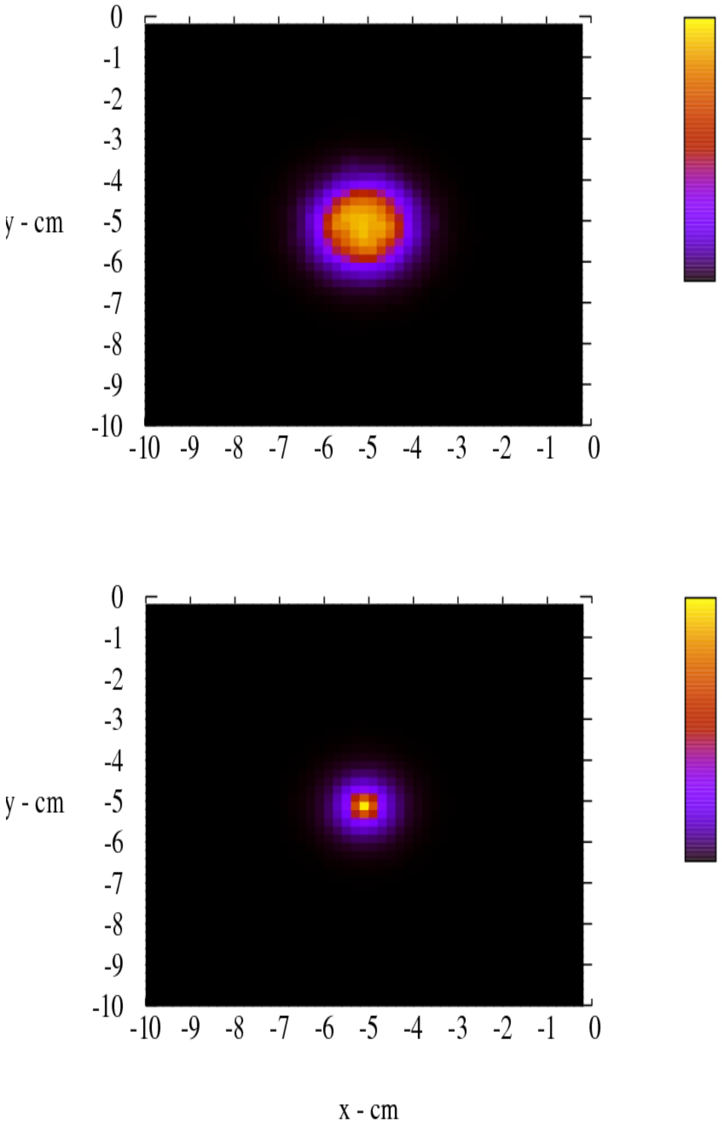
A new assembling technology is needed.

Curved crystals vs. flat crystals

- **For the same focal length, angular resolution improves by a factor ~10, moving from 15x15 mm^2 flat crystals to curved crystals;**

- **For 20 m FL, angular resolution from 3 arcmin to 20 arcsec;**

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



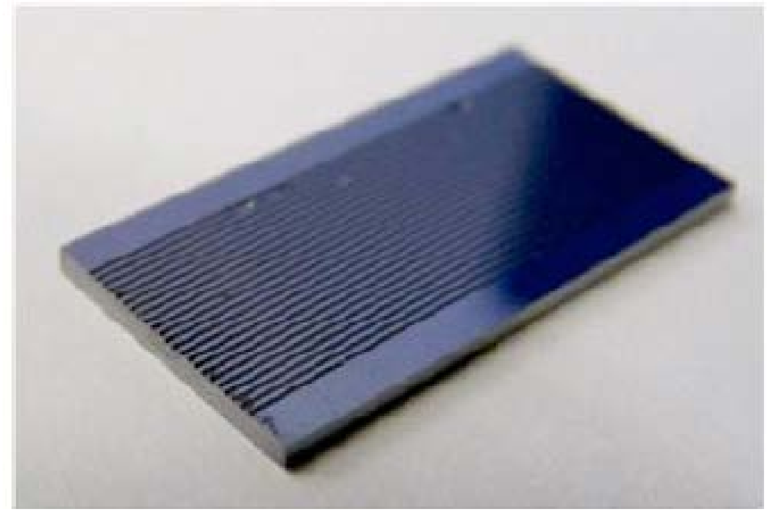
Laue Project

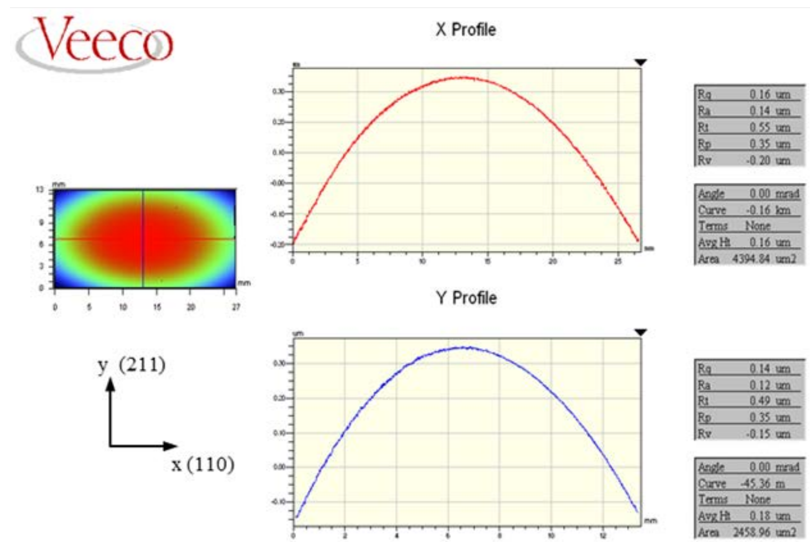
- **Main goals:**
  - **accurate assembly technology for long focal lengths;**
  - **Technology development for bending crystals;**
  - **Production of a 20 m FL lens petal made of bent crystals;**
  - **Feasibility and accommodation study of a space lens.**
- **Laue Consortium:**
  - **Scientific Institutions:**
    - **UNIFE, INAF/IASF-Bologna, CNR/IMEM-Parma;**
  - **and Industry:**
    - **DTM-Modena, TAS I-Milan and Turin.**

Bent crystal development

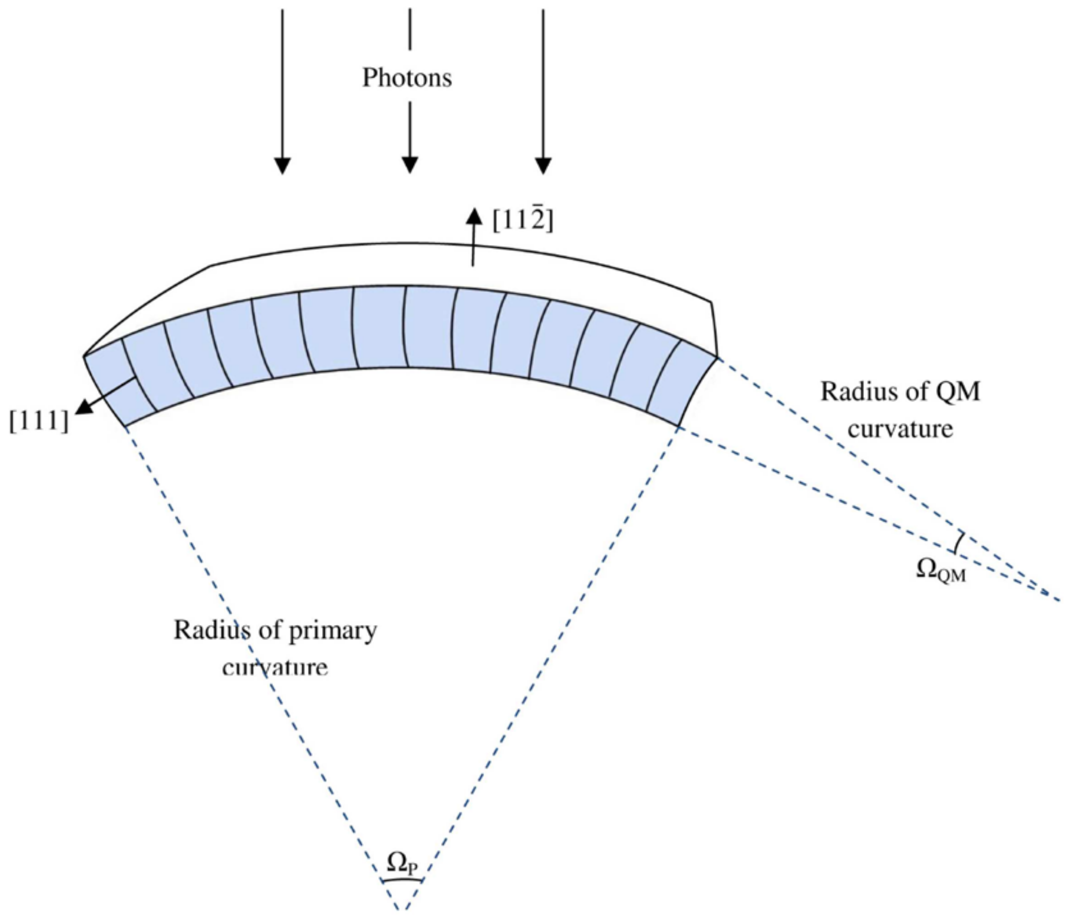
- **Bending technology through surface grooving (indentation), developed at University of Ferrara;**

- **Crystal growing and bending technology through lapping process, developed at CNR-IMEM.**





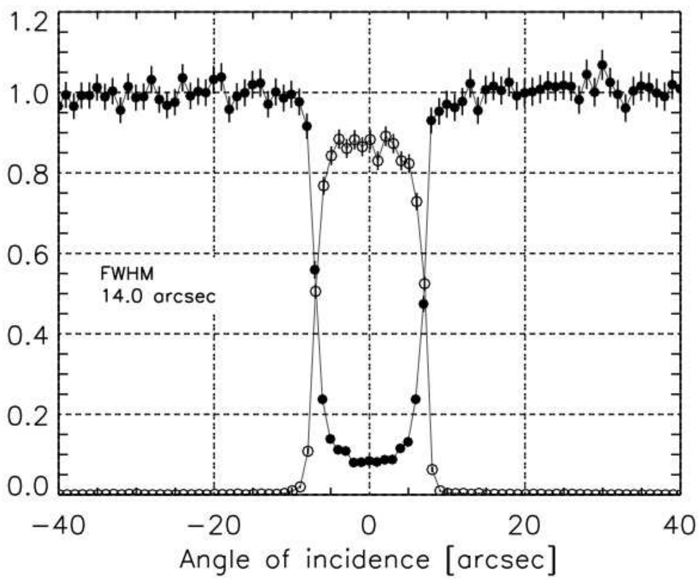
Internal structure of a bent crystal



Keitel + 1999
Malgrange 2002

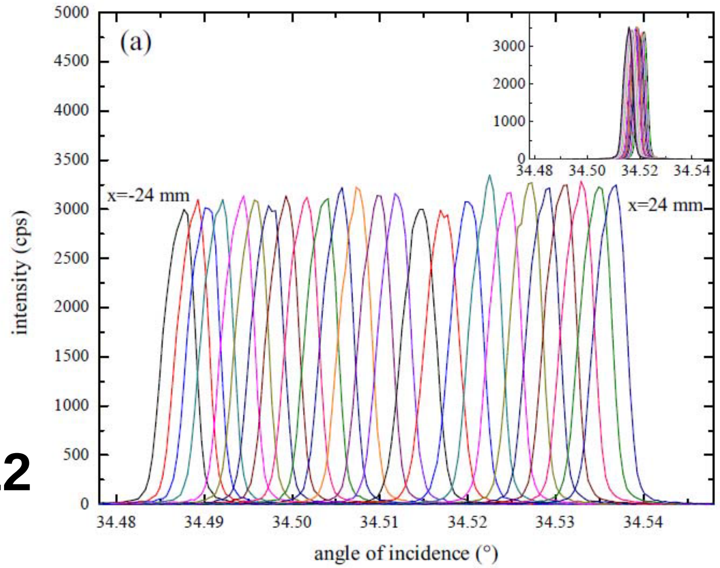
Bent crystals developed for LAUE

Barriere+2010



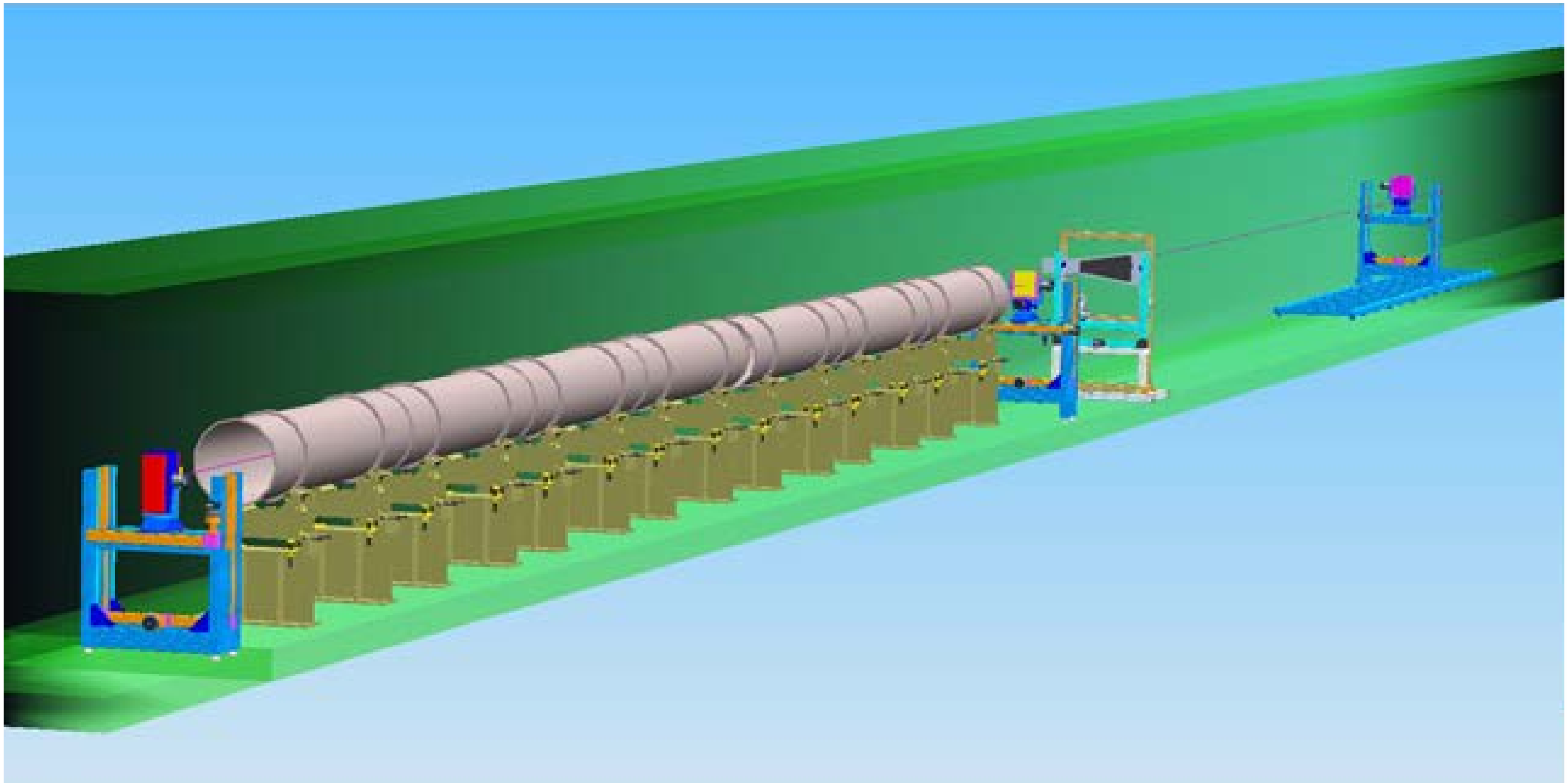
- Bent samples of perfect Si(111) and Ge(111) developed at UNIFE;
- Bent samples of mosaic GaAs (220) 25 arcsec spread, developed at IMEM- Parma
- Massive production of Ge (111) and GaAs (220) bent crystals 2 mm thick is starting.

Buffagni+ 2012

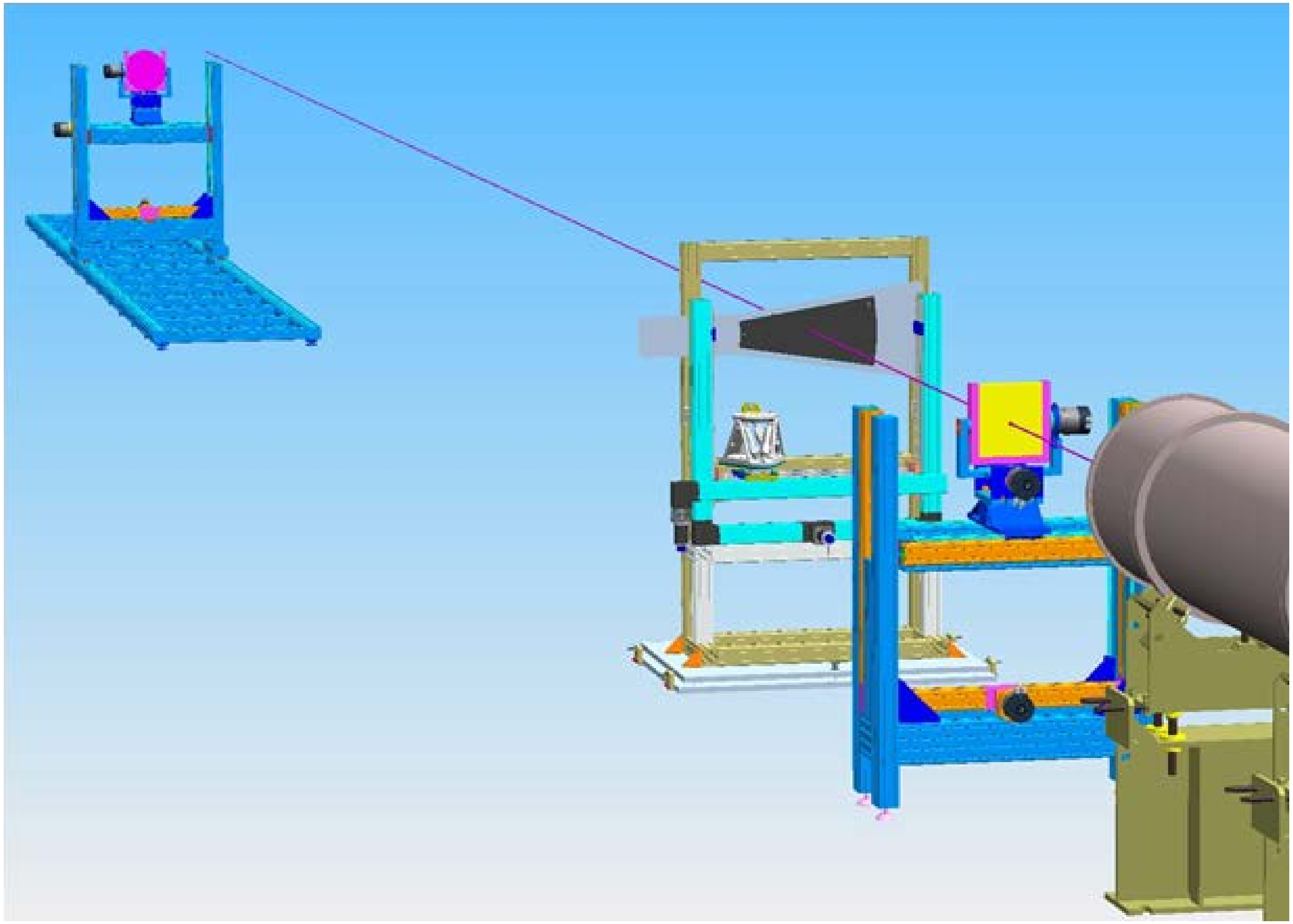


Feasibility study of a space lens

Apparatus for lens petal assembling and testing 1/2



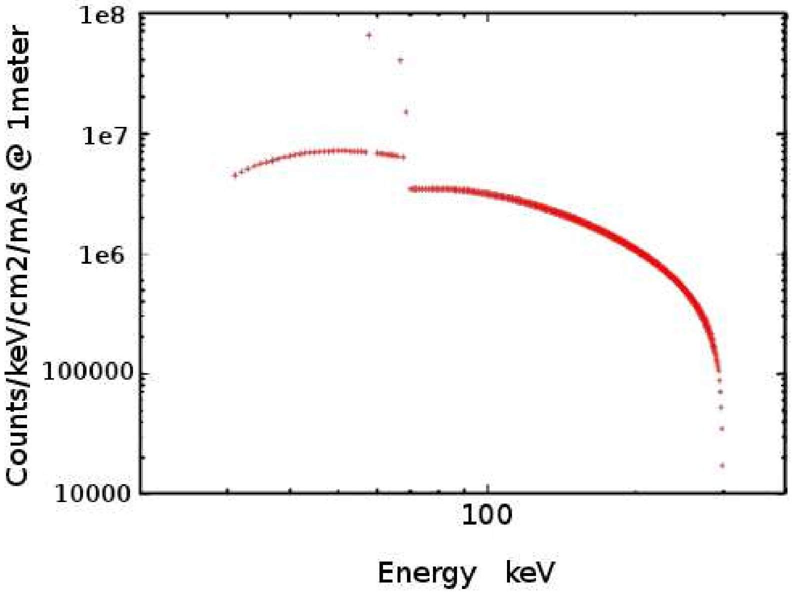
Apparatus for lens petal assembling and testing 2/2



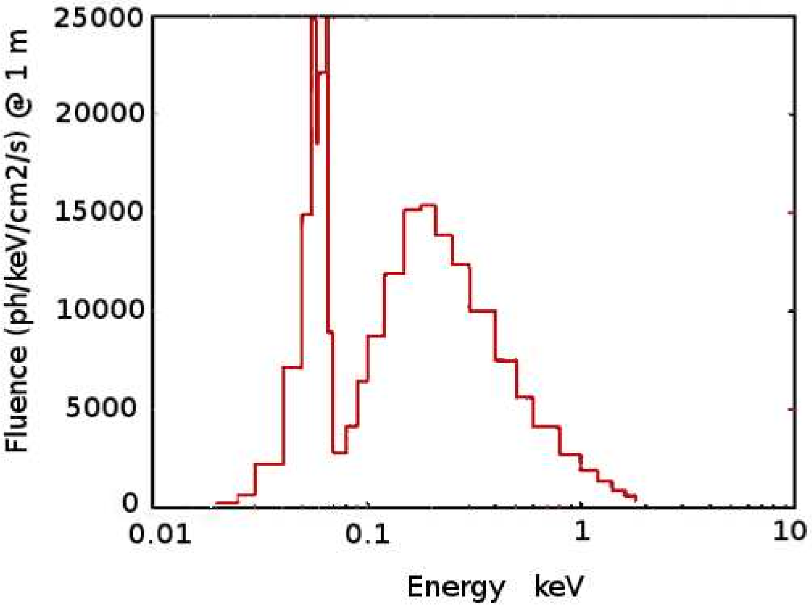
Gamma-Ray sources

- Portable betatron (max 2.5 MeV)
- X-ray generator ((320 kV max) with small source focus (0.3 mm)

Gamma-Ray source spectra



X-ray generator
320 kV (max)

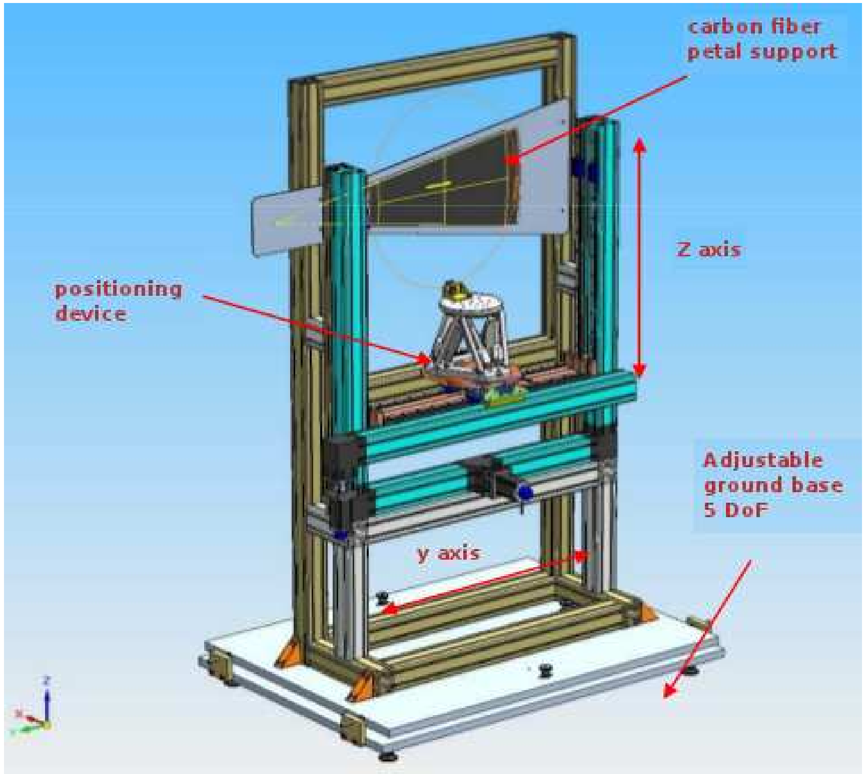


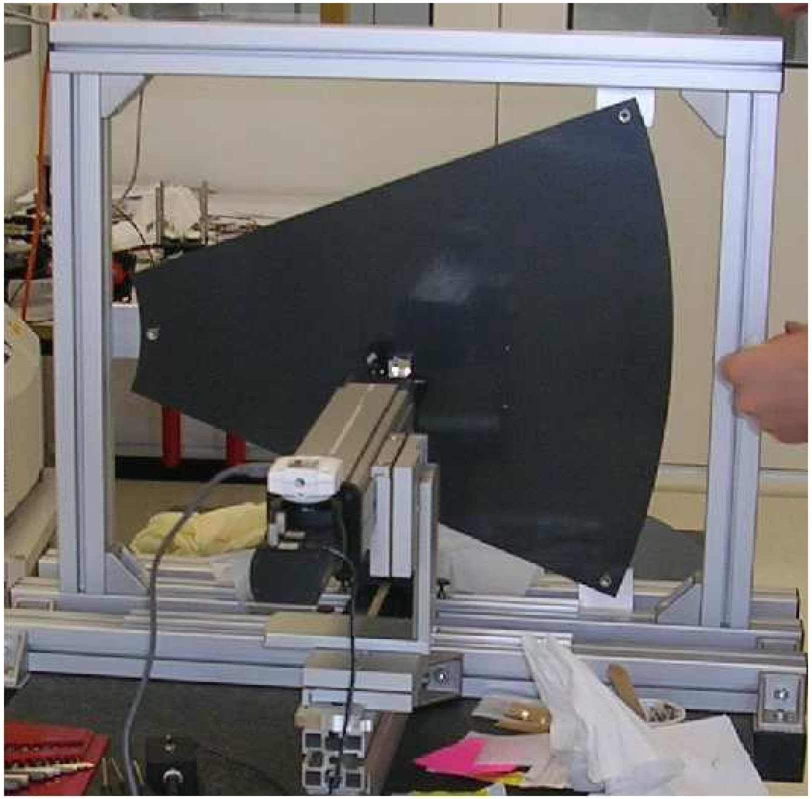
Portable Betatron
Emax:2.5 MeV

Apparatus development status: beam-line

Apparatus development status: clean-room

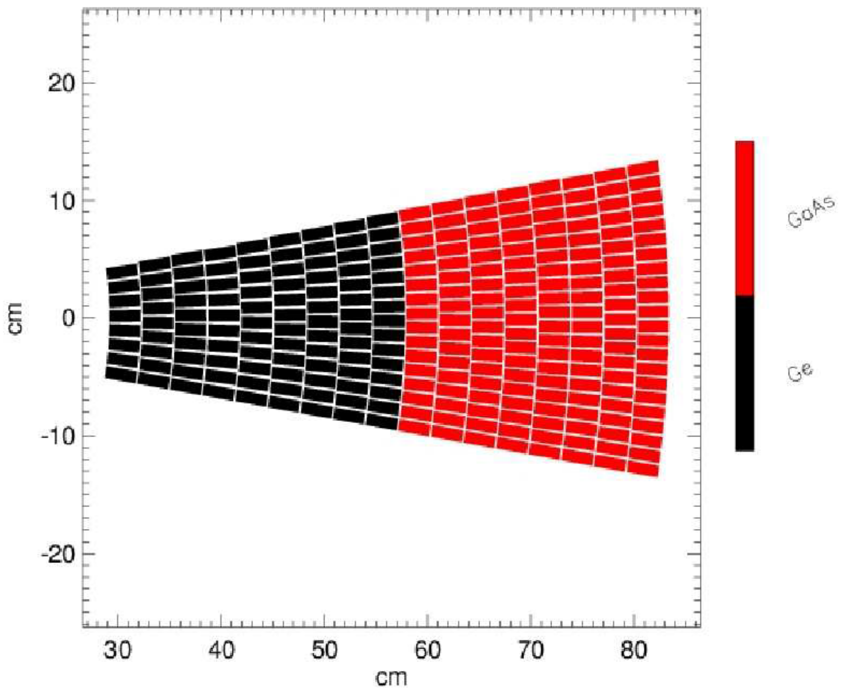
Apparatus development status: petal development model

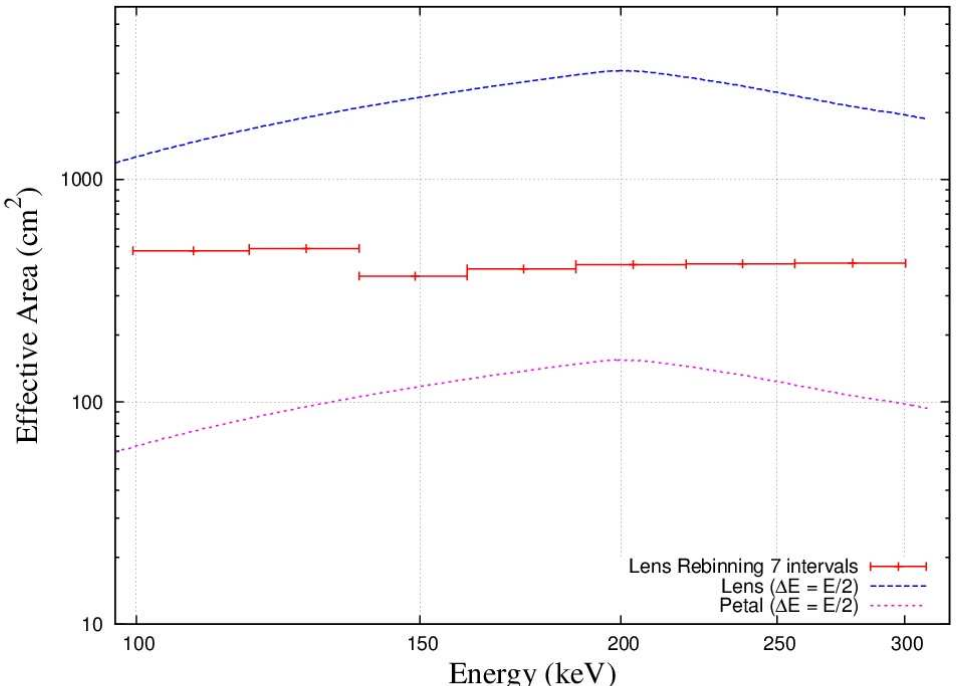




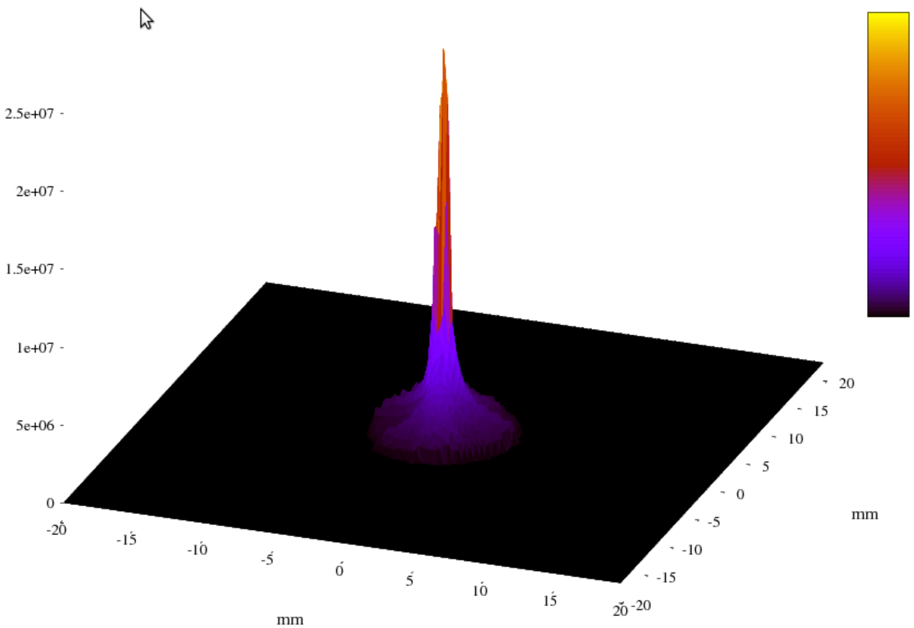
Apparatus development status: focal length

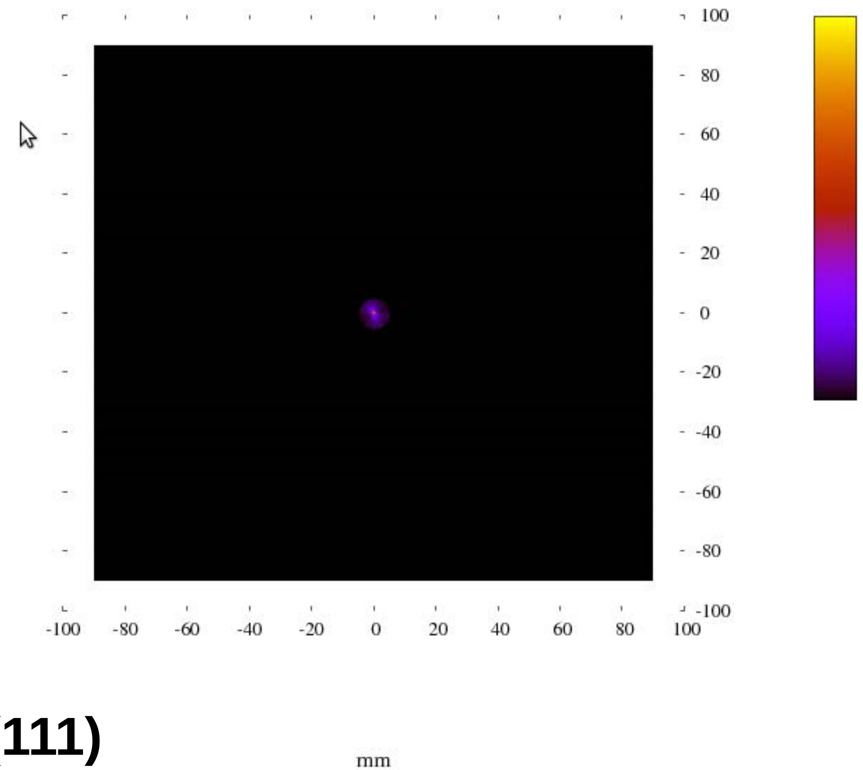
Expected effective area





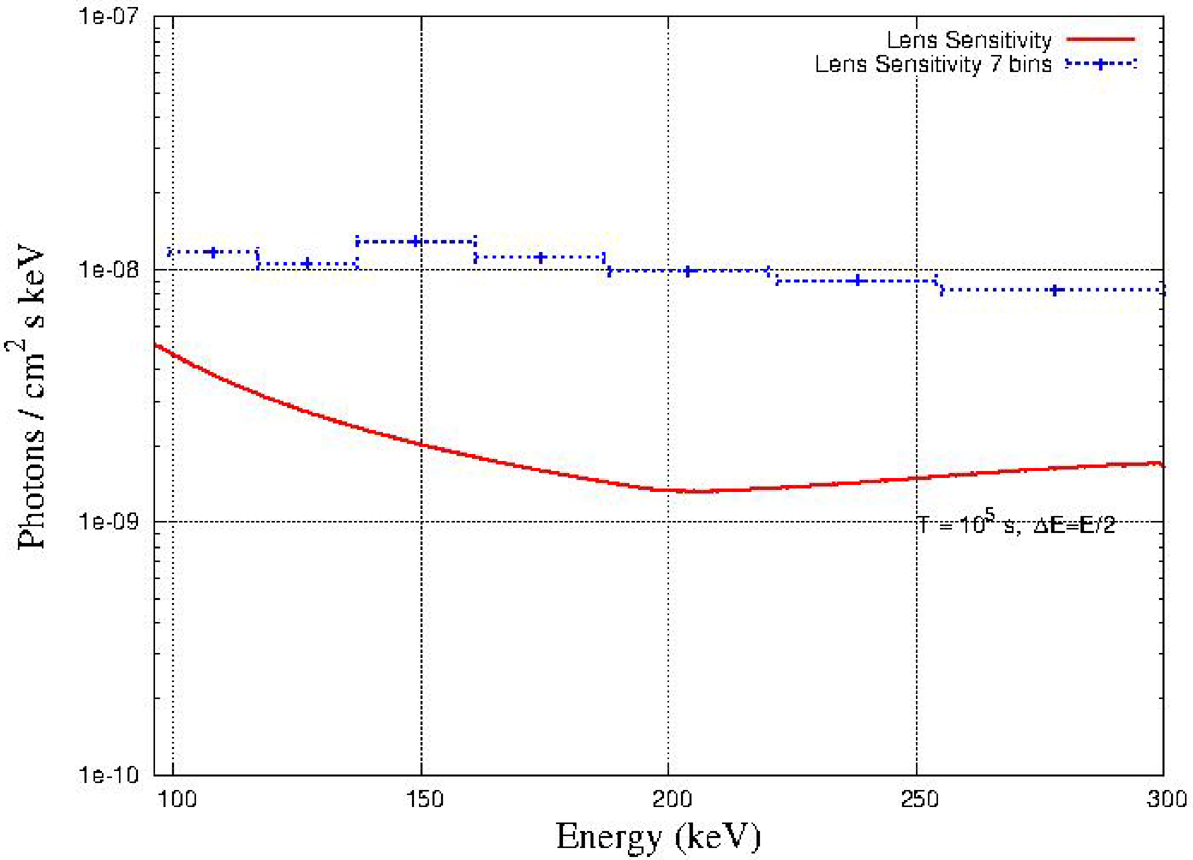
PSF of cylindrically bent crystals





Strips of Ge(111)
30x10 mm^2

Expected sensitivity



B=1.5x10^{-4} cts/cm^{2} s keV @ 200 keV

η_d = 0.9

J(@200 keV) = 3.2x10^{-15} erg/(cm^{2} s keV)

Conclusions

- **The energy band beyond 100 keV is crucial for settling many key-importance open issues;**

- **A big effort is in progress for the development of focusing Laue lenses;**

- **For the first time focusing crystals in a lens, thanks to the "LAUE“ project.**

- **Concrete prospects for proposing a broad band (e.g., 1-600 keV) satellite mission based on Laue lenses and multilayer optics.**