DESY – 09/30/2011

Developing a Laue lens for soft gamma-ray astronomy: challenges and promises

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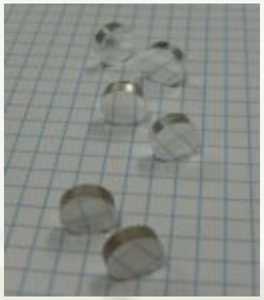
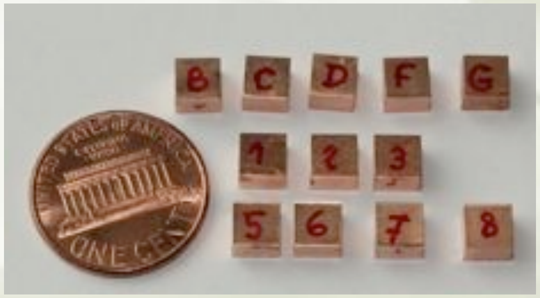




Outlines

- Introduction
  - Science drivers for Laue lens development
  - Laue lens principle
  - Existing Laue lenses
- Laue lens development status
  - Crystals
  - Assembly of crystals onto a substrate
  - Focal plane instrument
- Example of Laue lenses projects - performances
- Conclusions

Type 1a Supernova explosion mechanism?

Commonly accepted scenario, which allows the use of these objects as standard candles.

Standard candles used to constrain the Cosmic expansion over the Universe history
=> Accelerating Cosmic expansion

But we do observe some variety in the light curves (sub-super luminous) ...

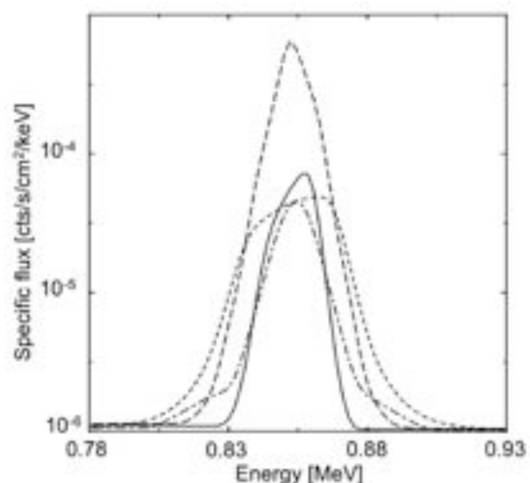
- Due to the physics of the explosion?
- Sub-Chandrasekhar explosions?

Constraining SNIa explosion model

Large amount of ^{56}Ni synthesized during explosion
Decay chain ^{56}Ni -> ^{56}Co -> ^{56}Fe give rise to a bright line at 847 keV

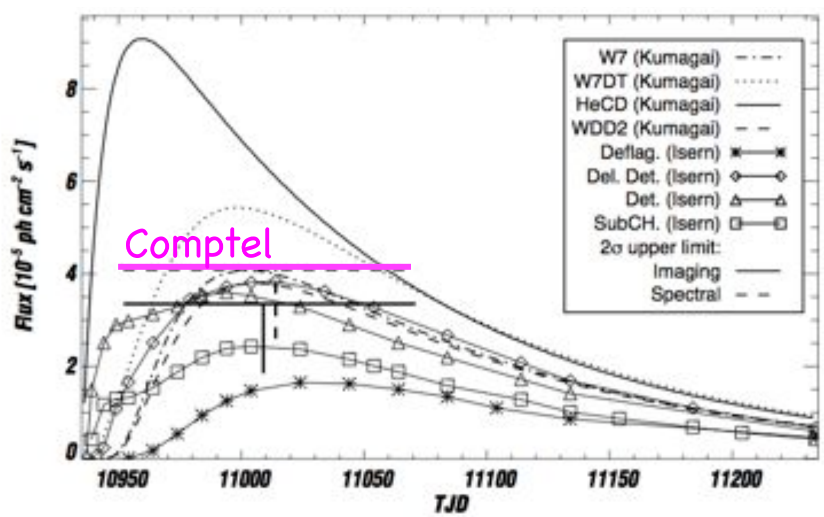
⇒ Observation of this line will put strong constraints on models

847 keV line profile
(1Mpc, 120 days after explosion)



[Gòmez-Gomar et al., RAS 1998]

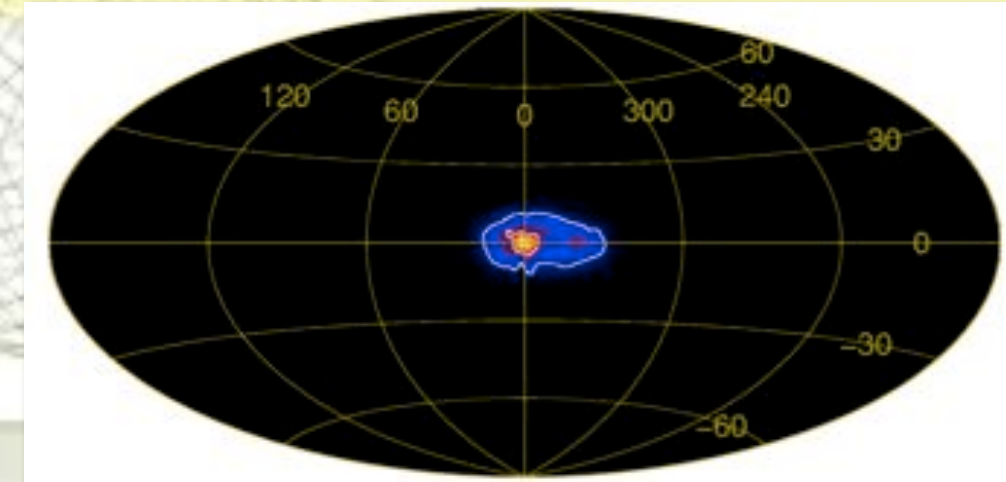
847 keV line light curve (11.3 Mpc)



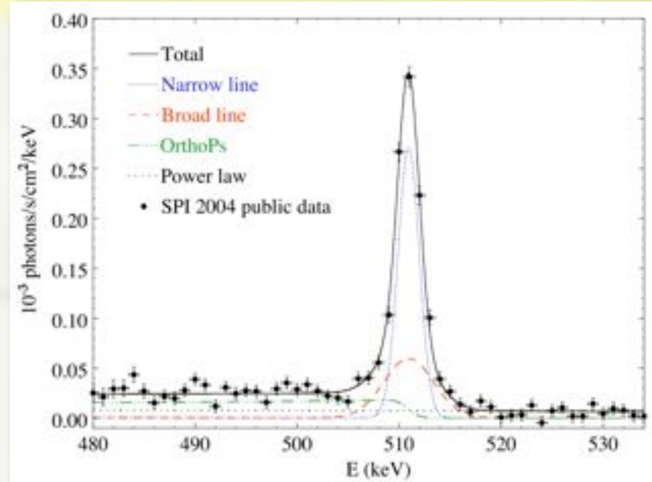
SN1998bu [Georgii et al., A&A 2002]

Sensitivity of $2x10^{-6}$ ph/cm^2/s required to detect SNeIa out to ~40 Mpc
(dozen detected per year including 1-2 with high significance)

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 %

Galactic positrons: possible sources and requirements

Bulge:
- Unresolved point sources? (LMXBs??, microquasar??)
- Central black hole (Sgr A*) + diffusion?

Disk:
- Combination of LMXBs + ^{26}Al & ^{44}Ti. Correlation with ^{26}Al??

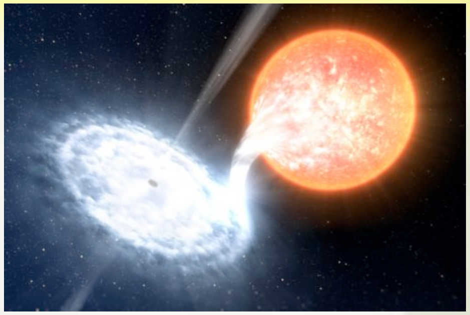
Disk + Bulge:
- Beta decay from ^{56}Co + large scale propagation?

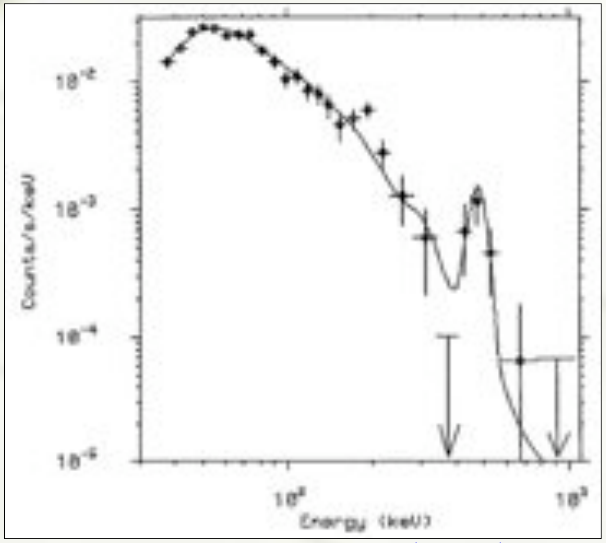
$\Rightarrow$ Need for better sensitivity and better angular resolution combined with fine spectroscopy

INTEGRAL/SPI 3σ sensitivity for 1Ms: 4.5×10^{-5} ph/s/cm^2

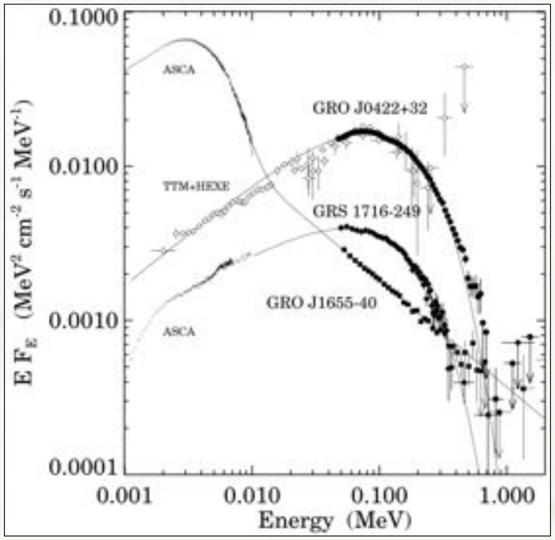
Galactic compact objects

- Measure the shape/amplitude of the high-energy emission tail as function of state
- Search for 511 keV annihilation features
- QPOs @ high-energy





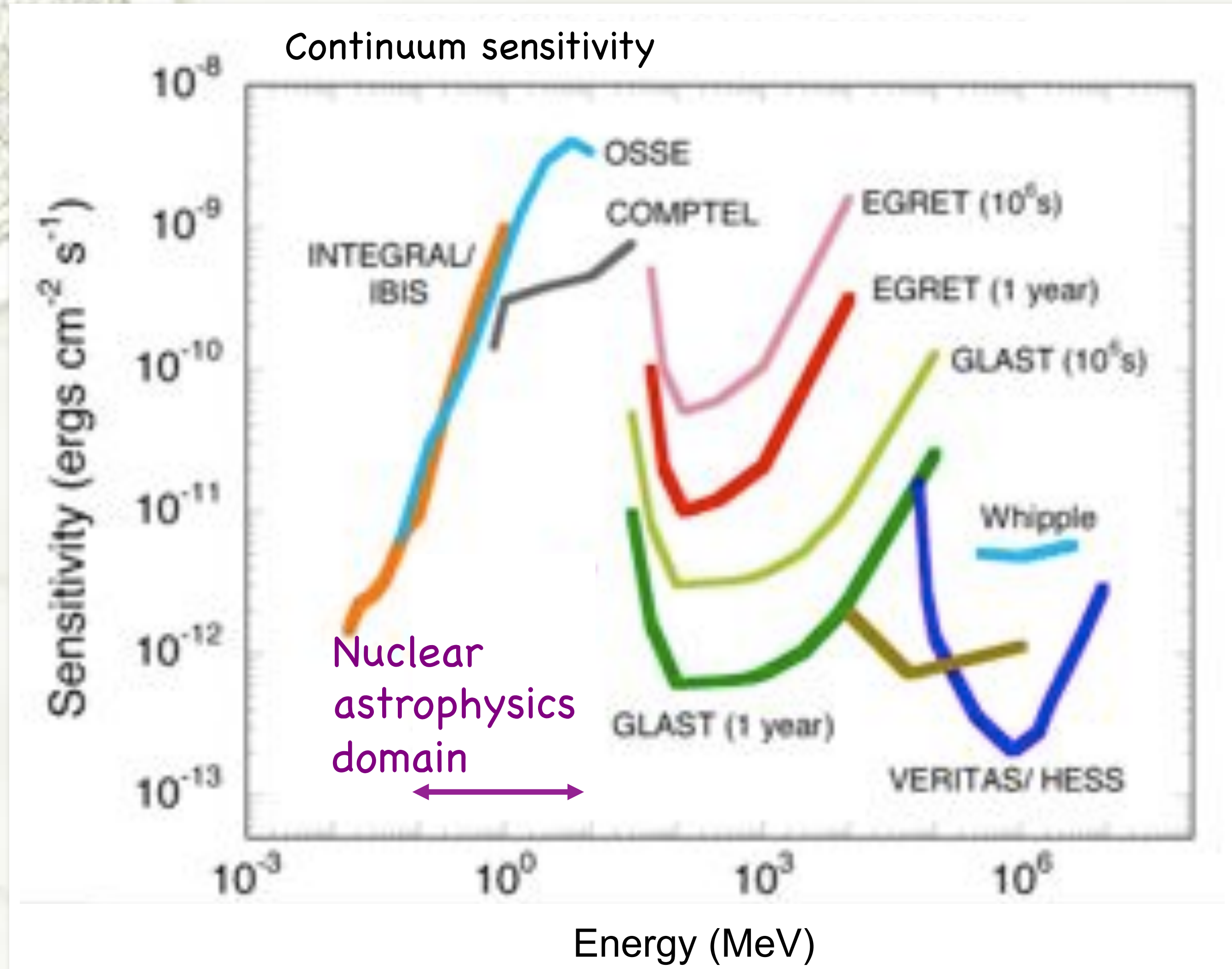
Goldwurm et al. (1992)



Grove et al. (1998)

- Physical nature of hard component - relation to relativistic jets
- Conditions for 511 keV line: sudden ejection events?
- Nature of jet?

Sensitivity of gamma-ray telescopes



Courtesy: S. Boggs

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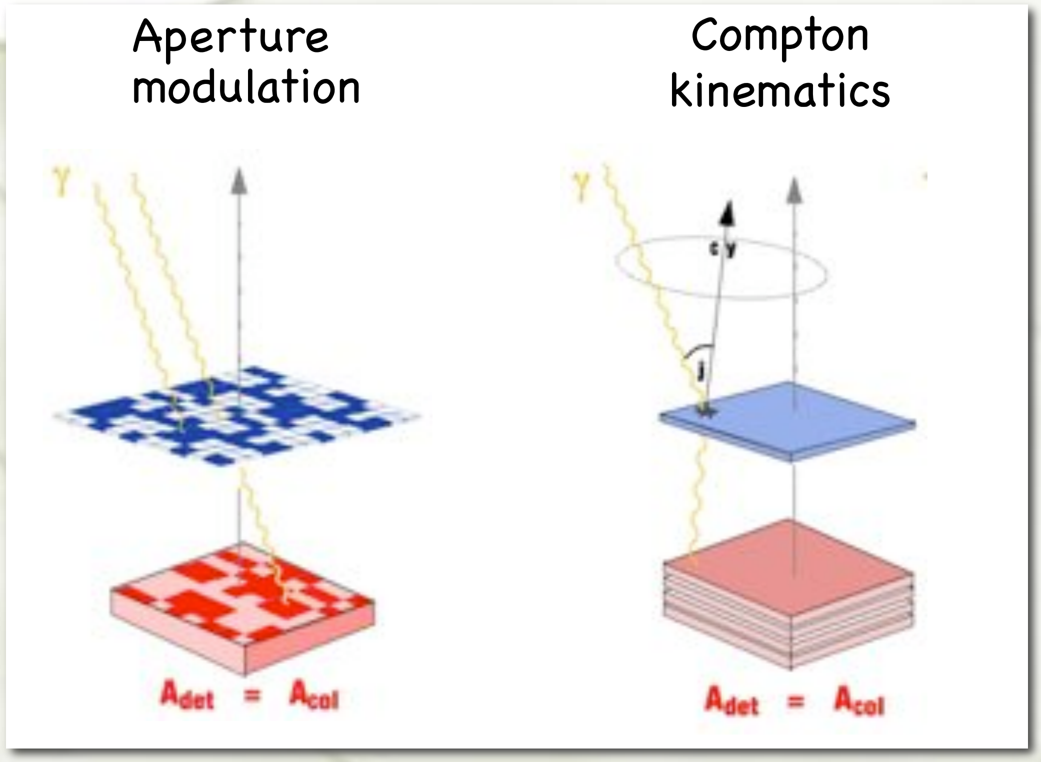
Principle of existing gamma-ray telescopes

- Aim:
  - Determine the original incidence direction
  - Spectroscopy
- Problem:
  - Very intense instrumental background
  - Sources fluxes are weak

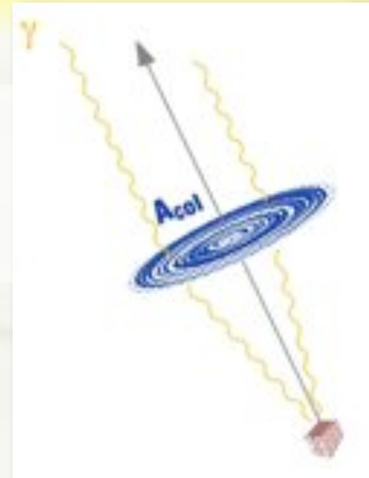


Detection significance:

$$n_\sigma = \frac{S}{\sqrt{S+N}} \approx \frac{S}{\sqrt{N}} \propto \frac{S}{\sqrt{V_{det}}}$$

⇒ Sensitivity only increases as the square root of the detector surface

Alternative solution



- How to make a sizeable sensitivity leap in the soft gamma ray domain?
  - ⇒ Decoupling the sensitive area from the collecting area

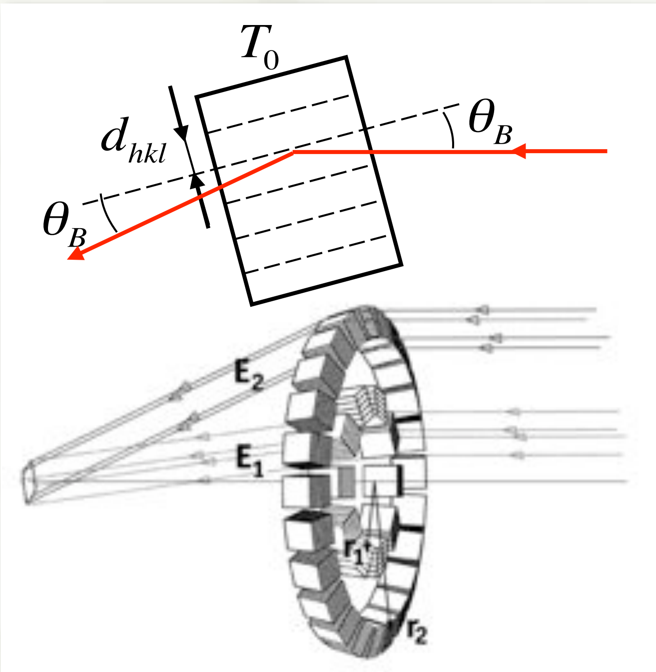
- Depth-graded multilayers mirrors [Jensen et al., SPIE 2007]
  - Outstanding imaging capabilities
  - E_{max} ≈150 keV (today E_{max} = 80 keV)
- Phase Fresnel lens [Skinner, Exp A. 2005]
  - Chromatic
  - Very long focal length 10^6 km (500 keV)
- Laue lens

Laue lens principle

- Based on Bragg diffraction in the volume of crystals: Laue Geometry

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

- Crystal slabs arranged on concentric rings: Photons are diffracted from every ring towards a common focal point
- Beam deviated of 2 $\theta_B \Rightarrow$ long focal length: - Formation flying
  - Extensible boom



Small angle of deviation
= conservation of the polarisation of incident radiation

Experimentally confirmed
[Curado da Silva et al., IEEE 2007]

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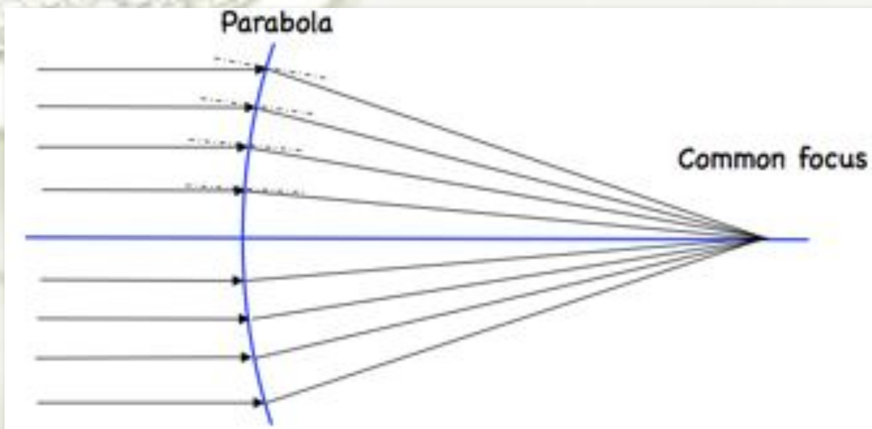
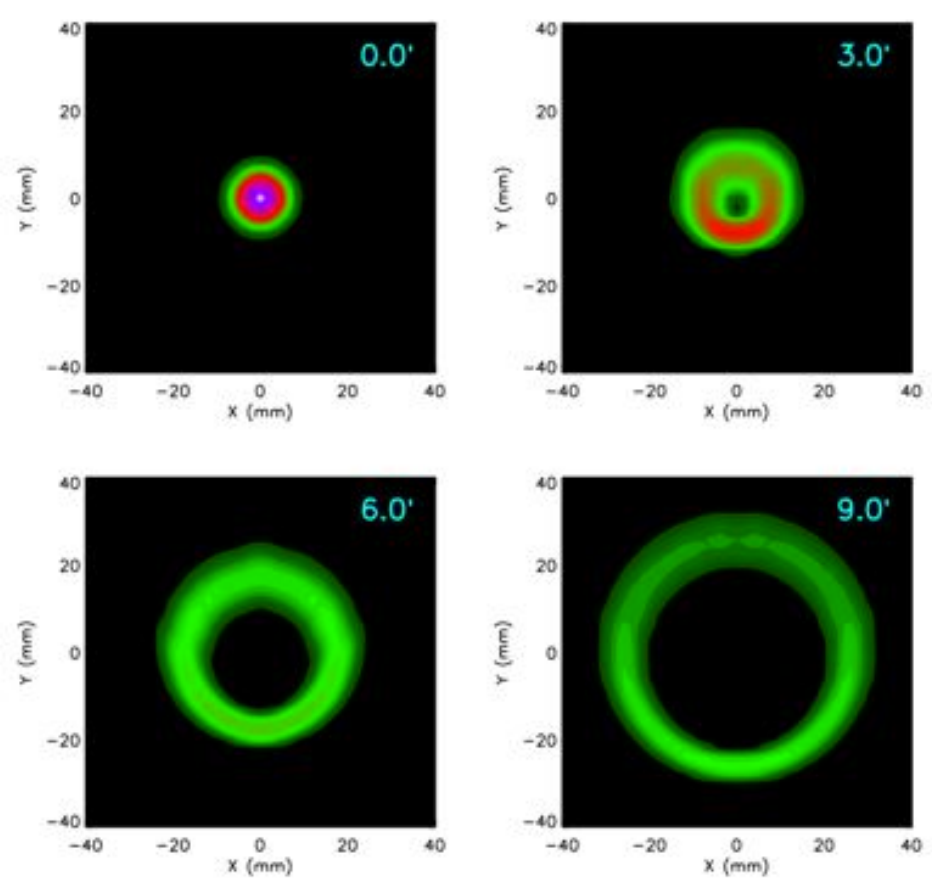
Laue lens optical system: concentrator





The incidence angle (Bragg angle) is determined by the focal distance and radius

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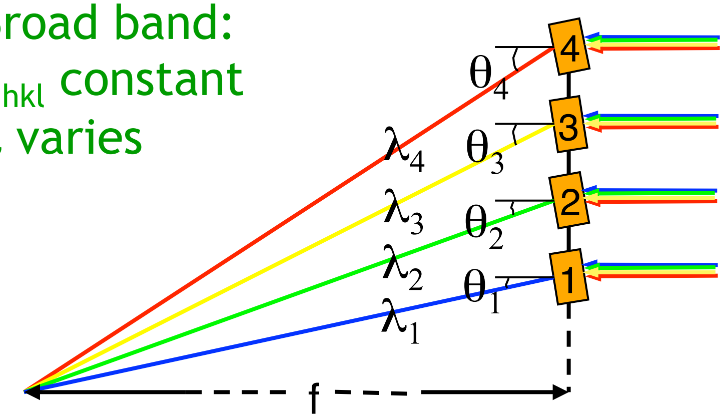
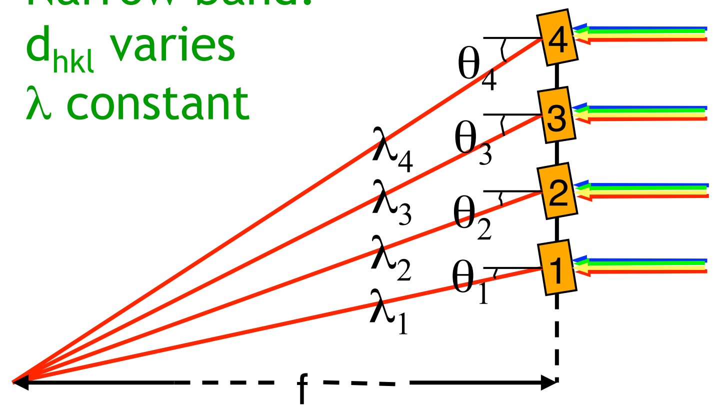
Two kinds of Laue lenses

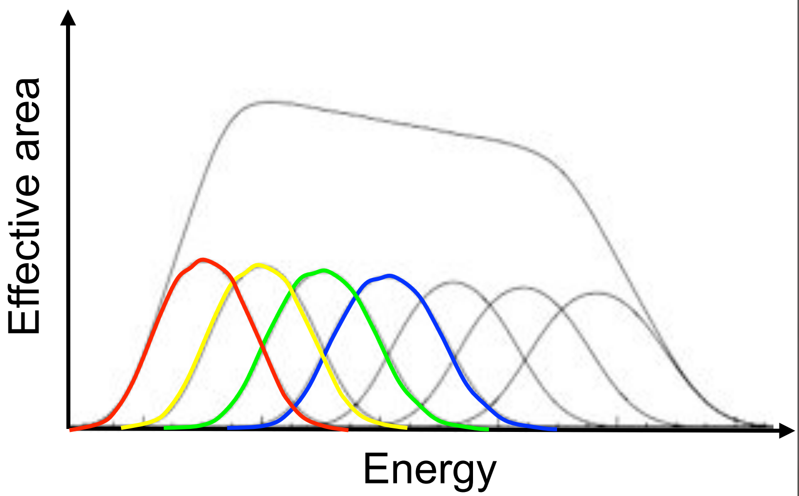
$$2\, d_{hkl} \sin\theta_B = n\, \lambda$$

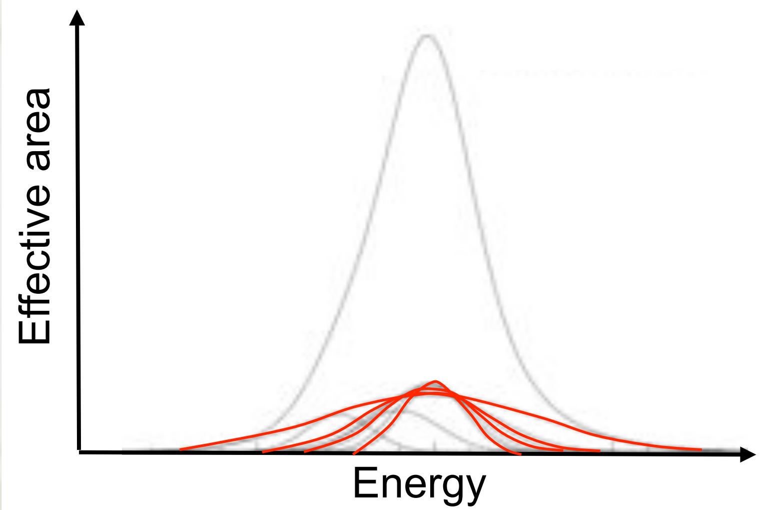
Broad band:
d_{hkl} constant
λ varies



Narrow band:
d_{hkl} varies
λ constant







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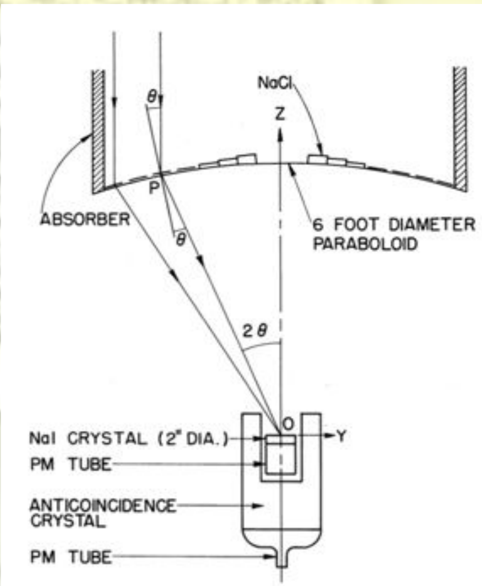
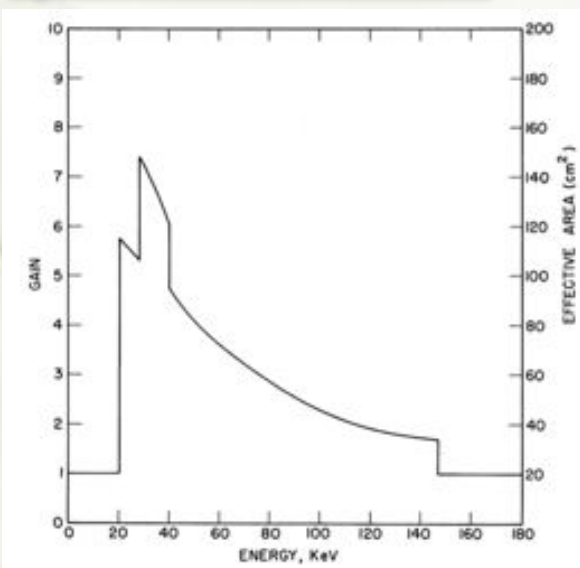
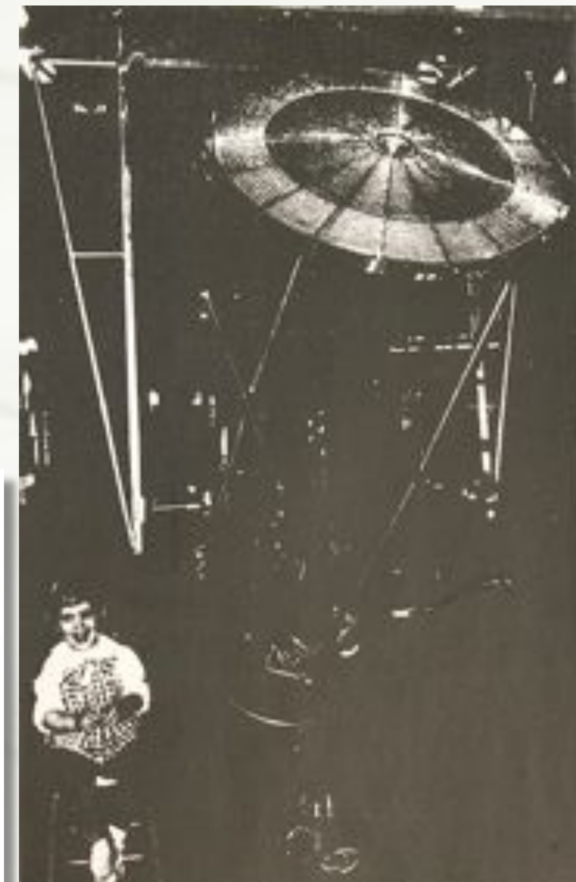
Astrophysical Laue lenses 1/2





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

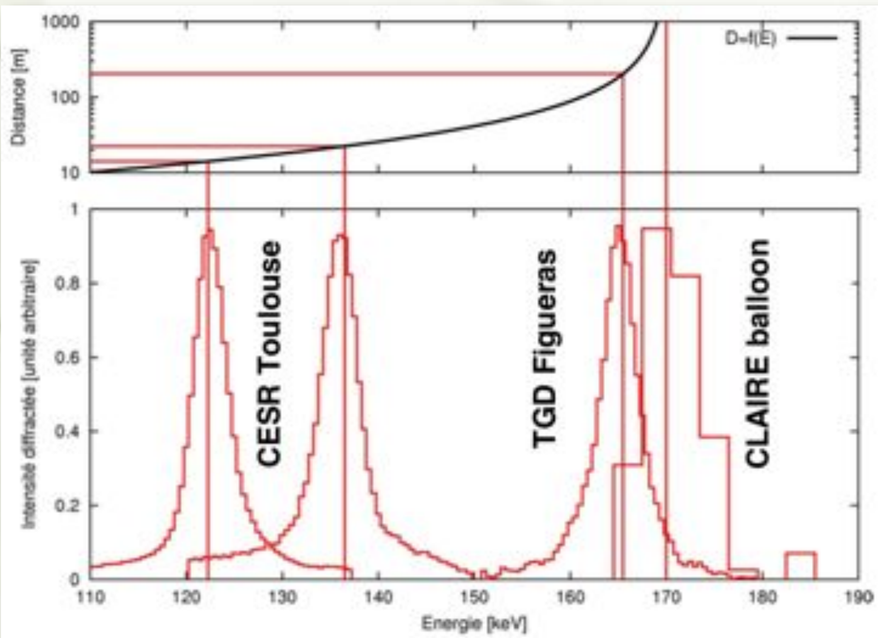
[Lindquist & Webber, Canadian J. of Physics, 1968]

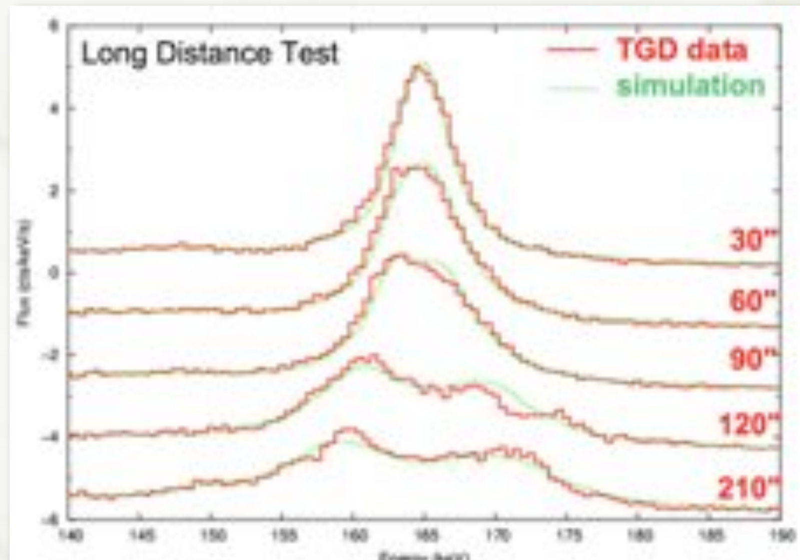
Astrophysical Laue lenses 2/2

2001: 170 keV (5 keV wide)

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

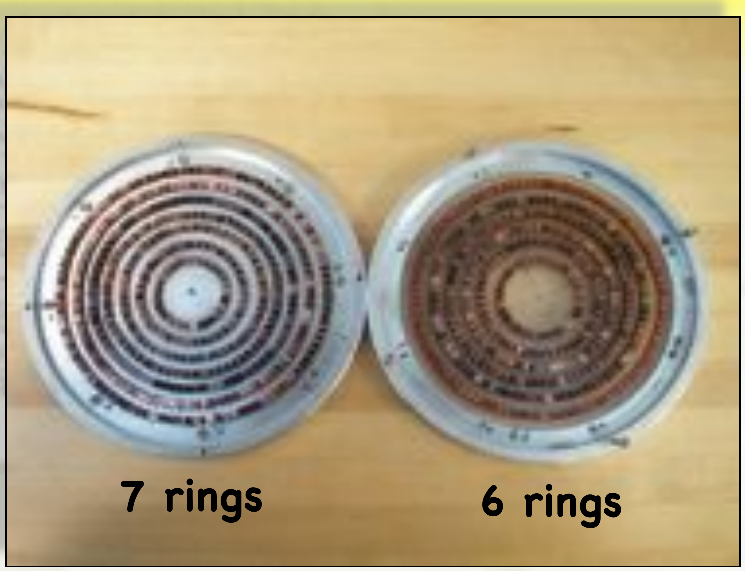
CESR (univ of Toulouse) / French Space Agency



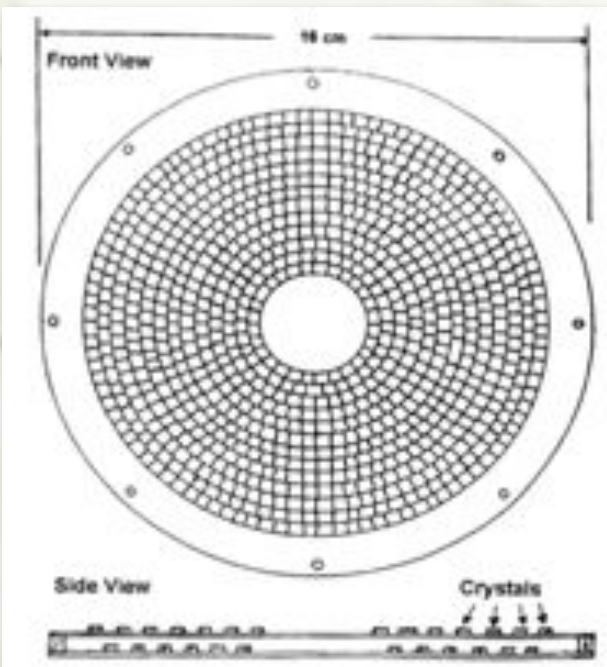


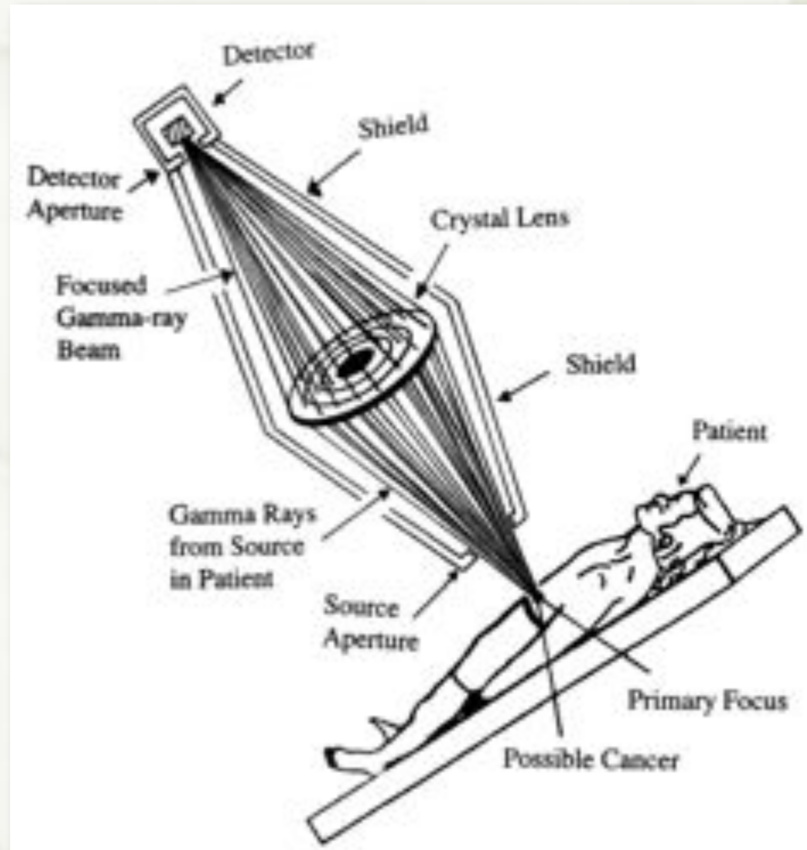
[von Ballmoos et al., ExpA 2005]

Medical imaging (APS, Argonne National Lab)



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





[Smither & Roa, SPIE 2001]

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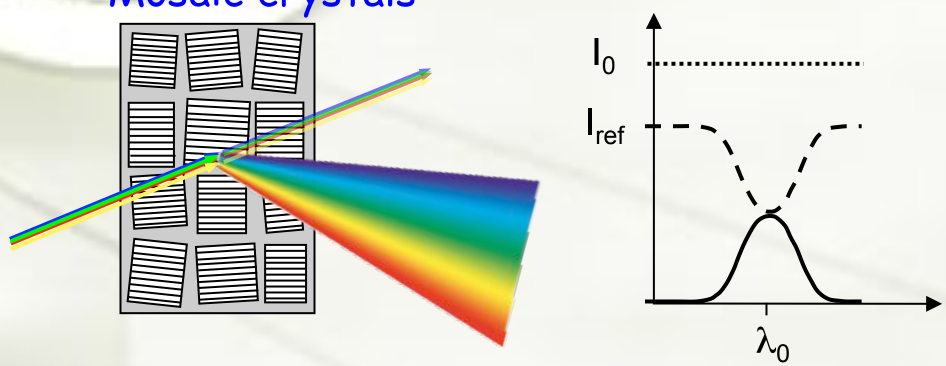
Required crystals type

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

A perfect crystal is a monochromator

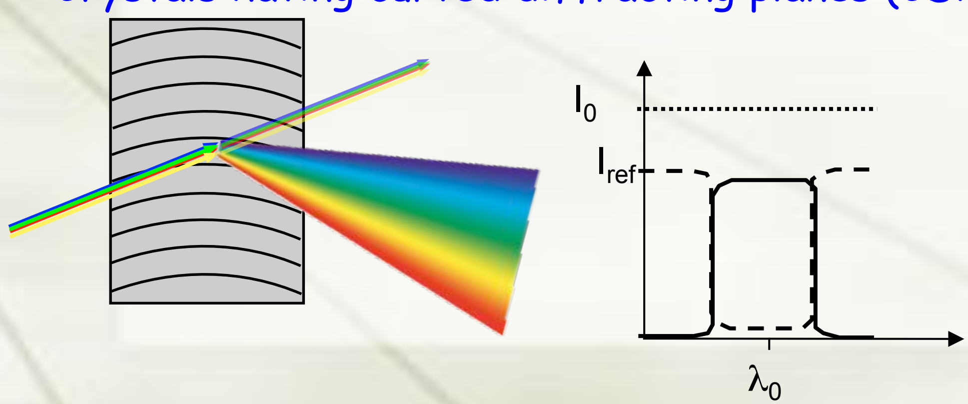
We need crystals having diffraction planes spanning across a range of orientations => each crystal (= each ring) diffracts an energy band

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%

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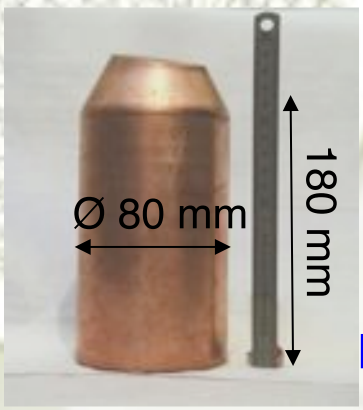
Mosaic crystals

Cu (ILL, Grenoble, France)



[Courtois et al., Exp A 2005]

Au (MaTecK GmbH)

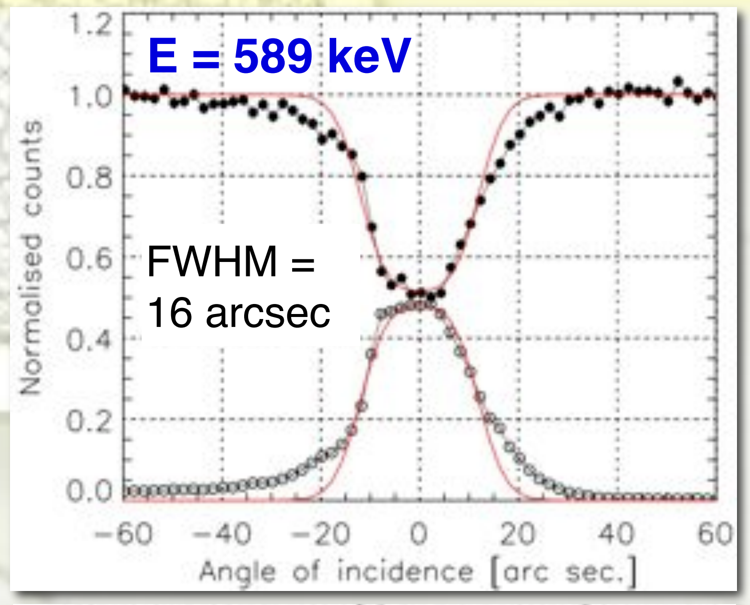
GaAs
(IMEM, Parme, Italy)

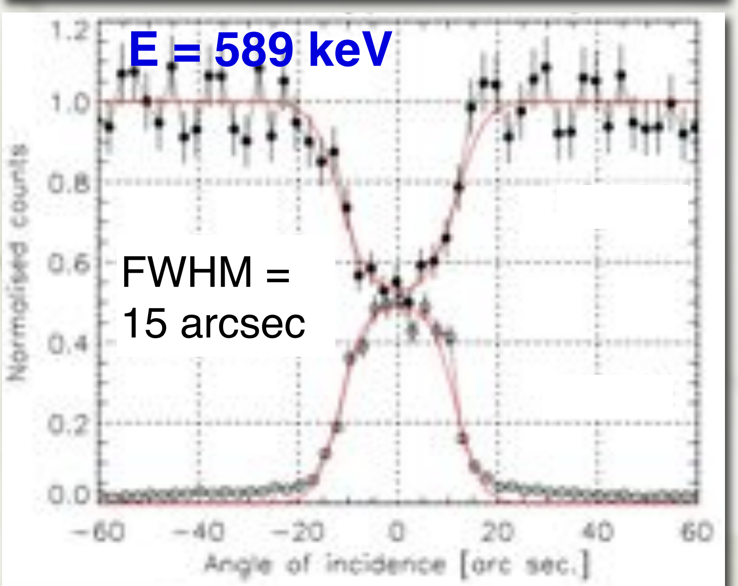
Rh & Ag (MaTecK GmbH)

Cellular structure as revealed by DSL etching in GaAs

[Ferrari et al, SPIE 2008]

Mosaic crystals





Gold mosaic crystal
(produced by Mateck, Germany)

2 mm thick => Reflectivity = 0.31

Copper mosaic crystal
(produced by ILL, Grenoble, France)

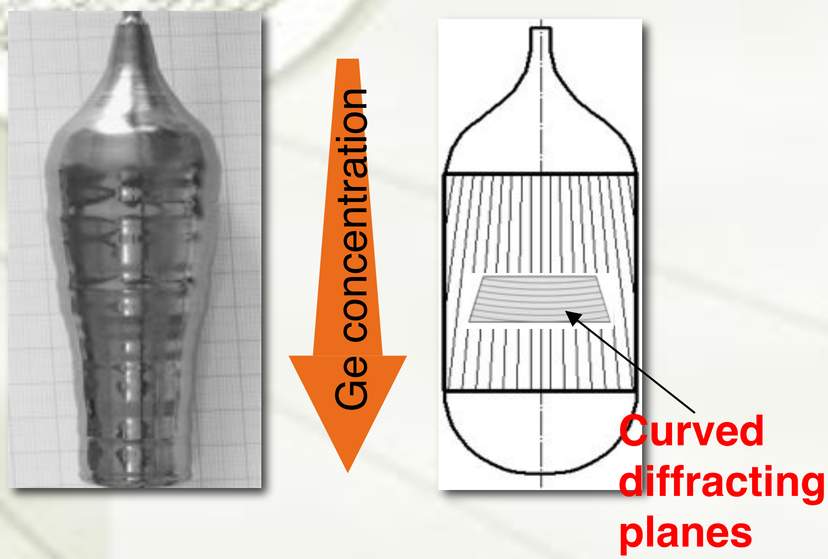
8.6 mm thick => Reflectivity = 0.24

[Barrière et al. SPIE 2007]

Crystals with curved diffracting plans

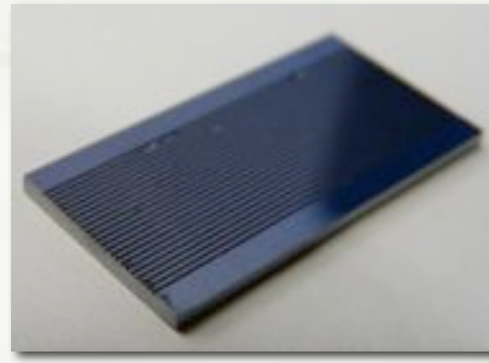
Composition gradient crystal

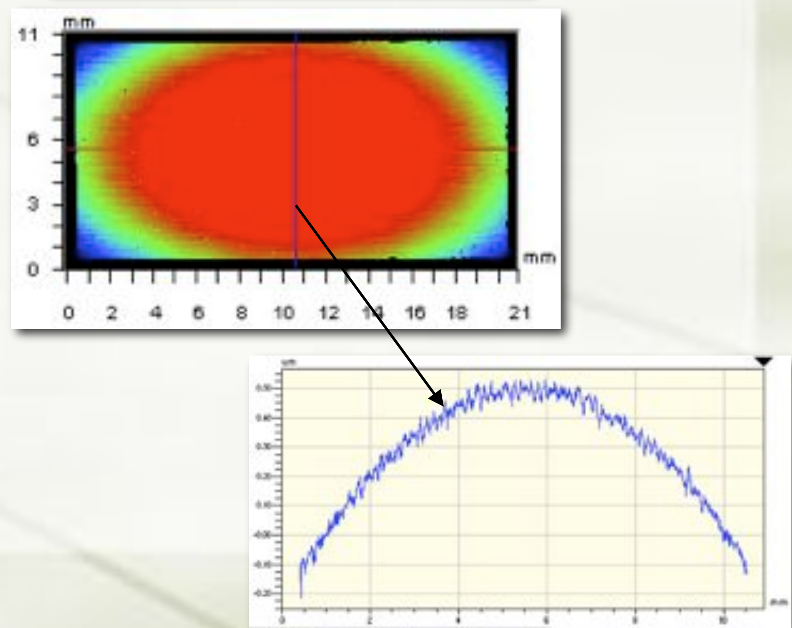
Example: $Si_{1-x}Ge_x$, x increasing along the growth axis



Elastic bending by surface treatment

Example: Si wafer curved by grooves





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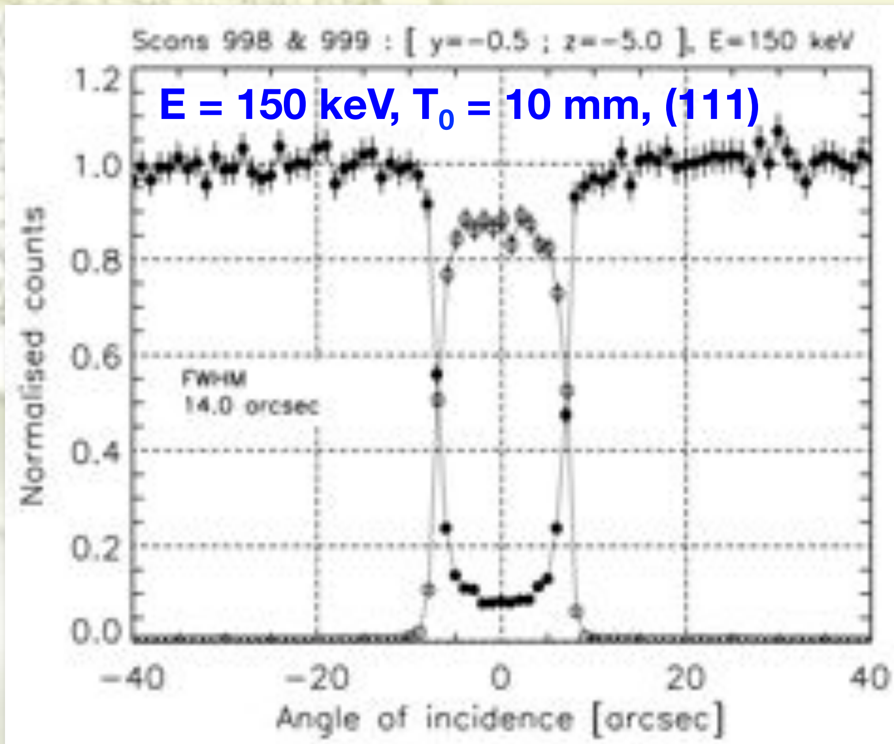
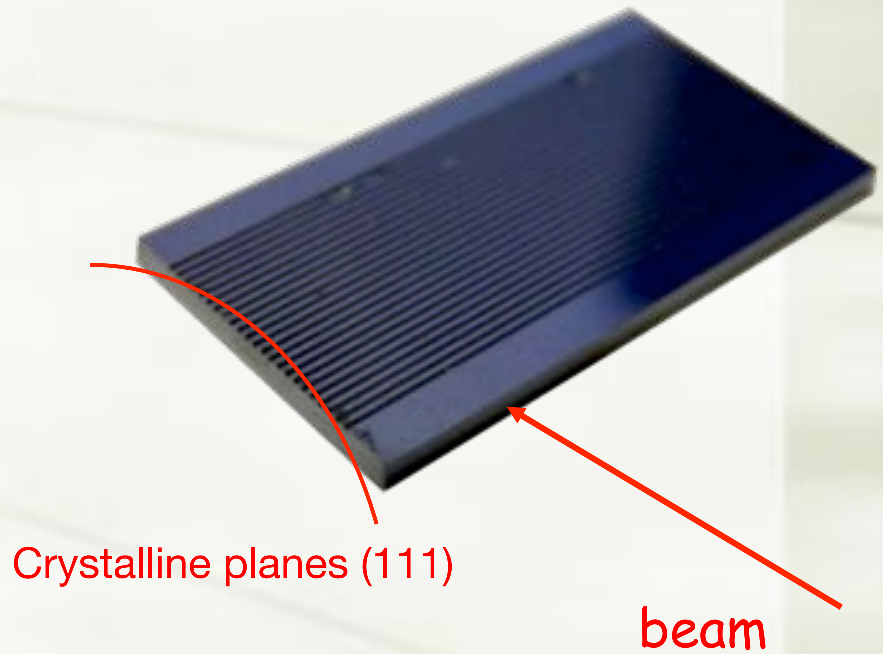
Crystals with curved diffraction planes: new approach



Grooved Si crystal: Very first sample



Diffraction efficiency: 0.92
Transmission coeff: 0.73
⇒ Reflectivity: 0.67

Theoretical value: 0.69
=> The curvature is very close to the ideal

Next steps:
- Is it possible to bend thicker crystals?
- Does it work on crystals with higher Z
  (Ge is a very good candidate)

[Barrière et al., Applied Cryst. 2010]

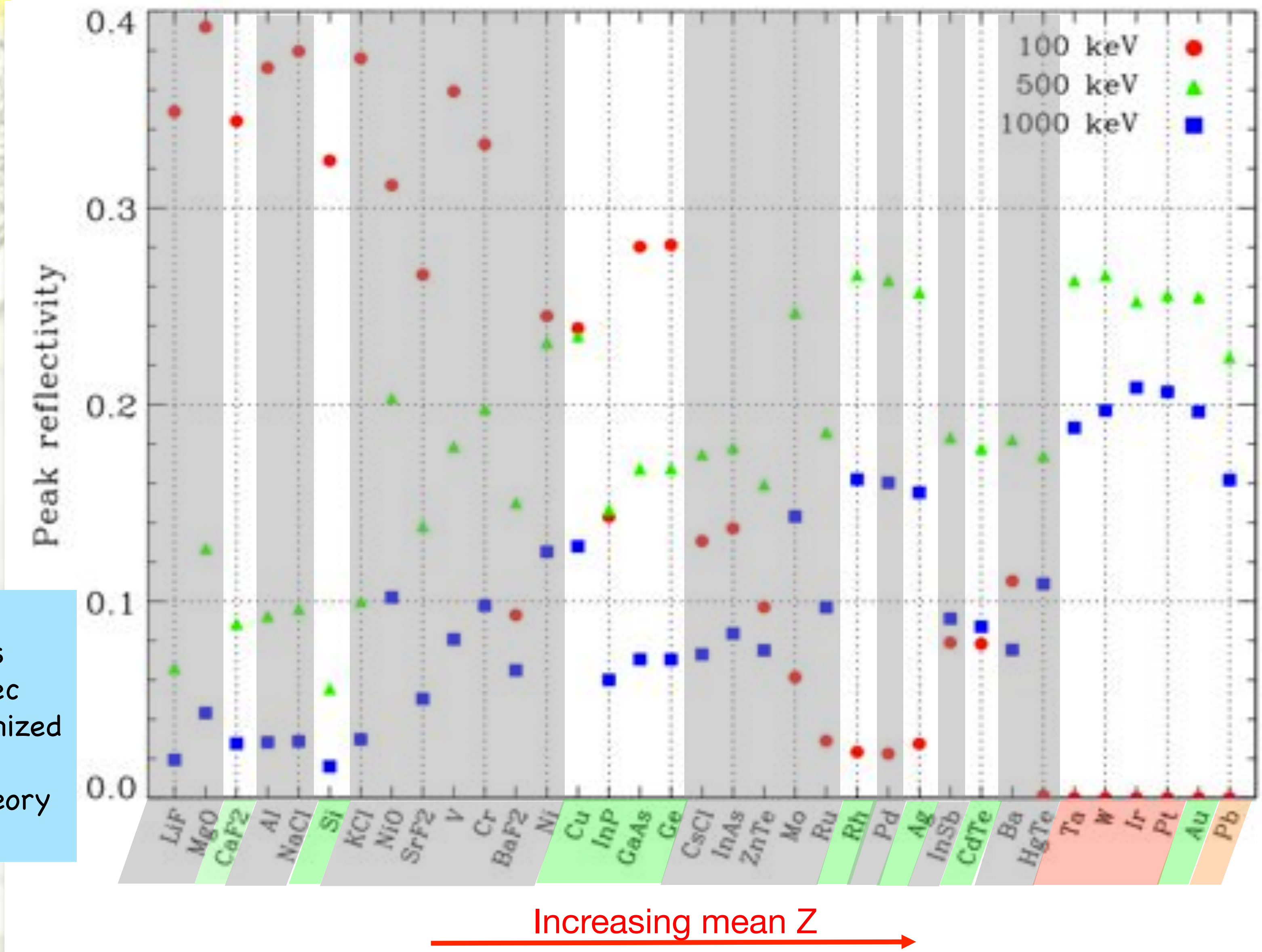
Search of efficient diffracting materials

1) Calculate the reflectivity of various *potentially interesting* materials
   - Available in large quantities,
   - not toxic, radioactive, too expensive
   - (melting point under 3000 K)
   - Relatively good crystal quality mosaicity around a few arcmin

2) Find crystal producers, and get some representative samples

3) X-ray diffraction:
   - Measure the actual mosaicity, check the homogeneity of the selected samples
   - Calculate reflectivity and check the accordance with theoretical predictions

Where do we stand in the search of efficient crystals?



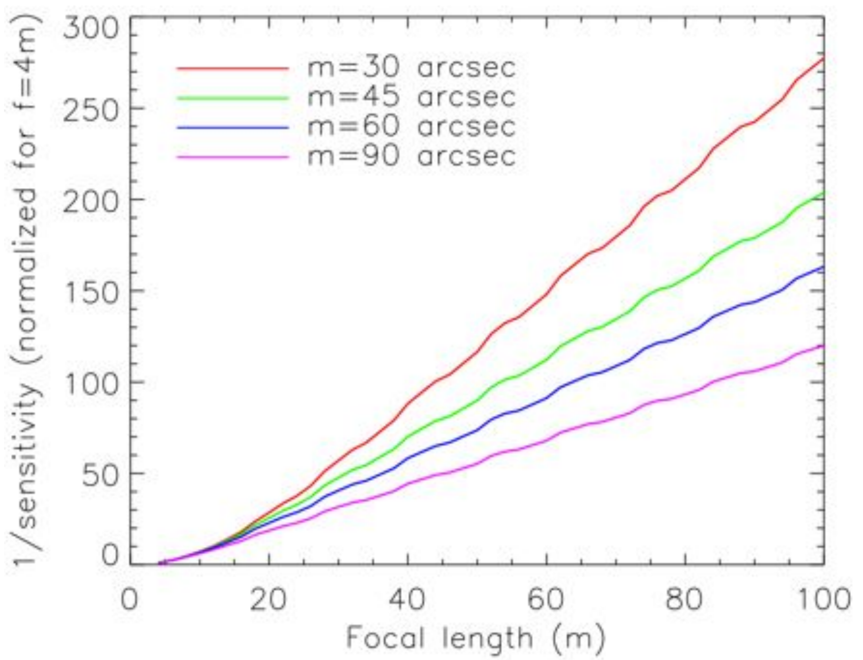
<u>Hypothesis:</u>
- Mosaic crystals
- Mos = 60 arcsec
- Thickness optimized but ≥ 2 mm
- Kinematical theory of diffraction

[Barriere et al., Applied Cryst. 2009]

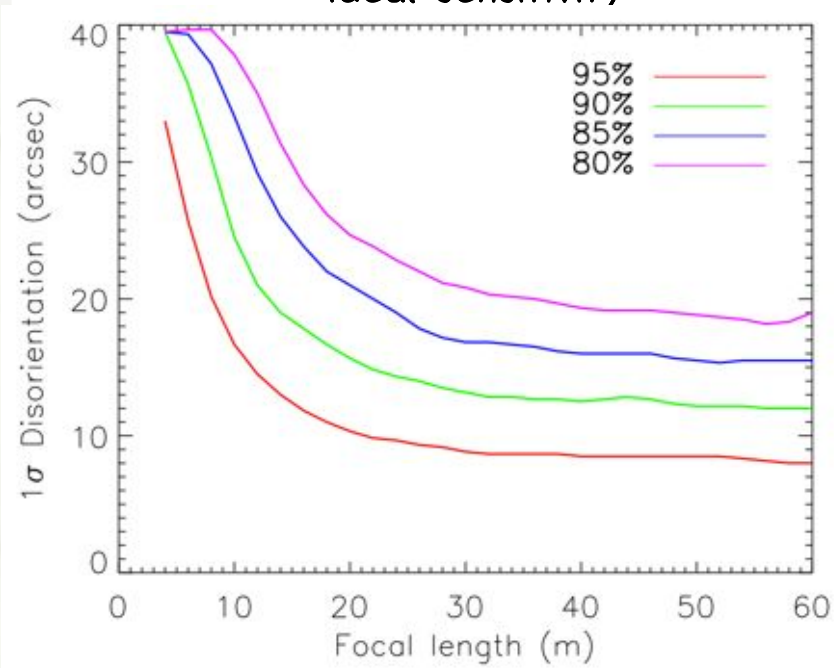
Crystal orientation requirements

Telescope sensitivity VS focal distance

For a given energy band, crystals ideally oriented



Crystal disorientation to get 90% of ideal sensitivity



A bigger lens (= the longer focal length) yields a higher telescope sensitivity

The longer the focal length, the tighter the constraint on the crystal orientation

=> High energy Laue lenses need VERY accurately oriented crystals

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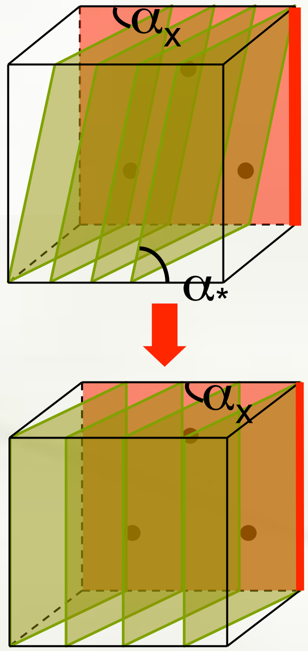
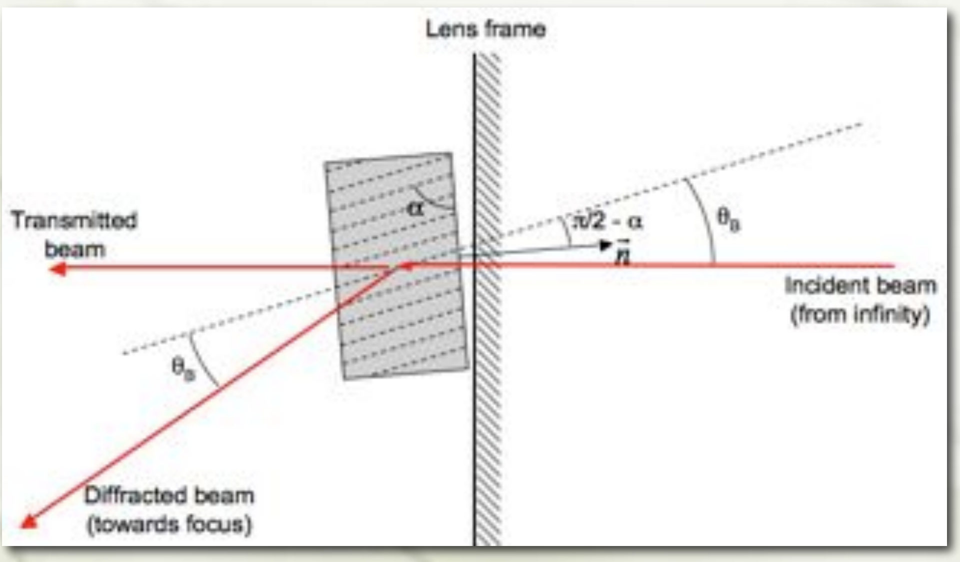
Main issue: orientation precision

- Problems:
  - most of crystals does not cleave (split along diffracting plans)
  - Some of them are too smooth to be polished => not possible to make a plan of reference)
- Crystals cutting precision is about 2 arcmin
  - Good enough for two angles but not for Bragg's Angle
  - no external reference for Bragg's angle
- Crystals have to be oriented in an X-ray beam





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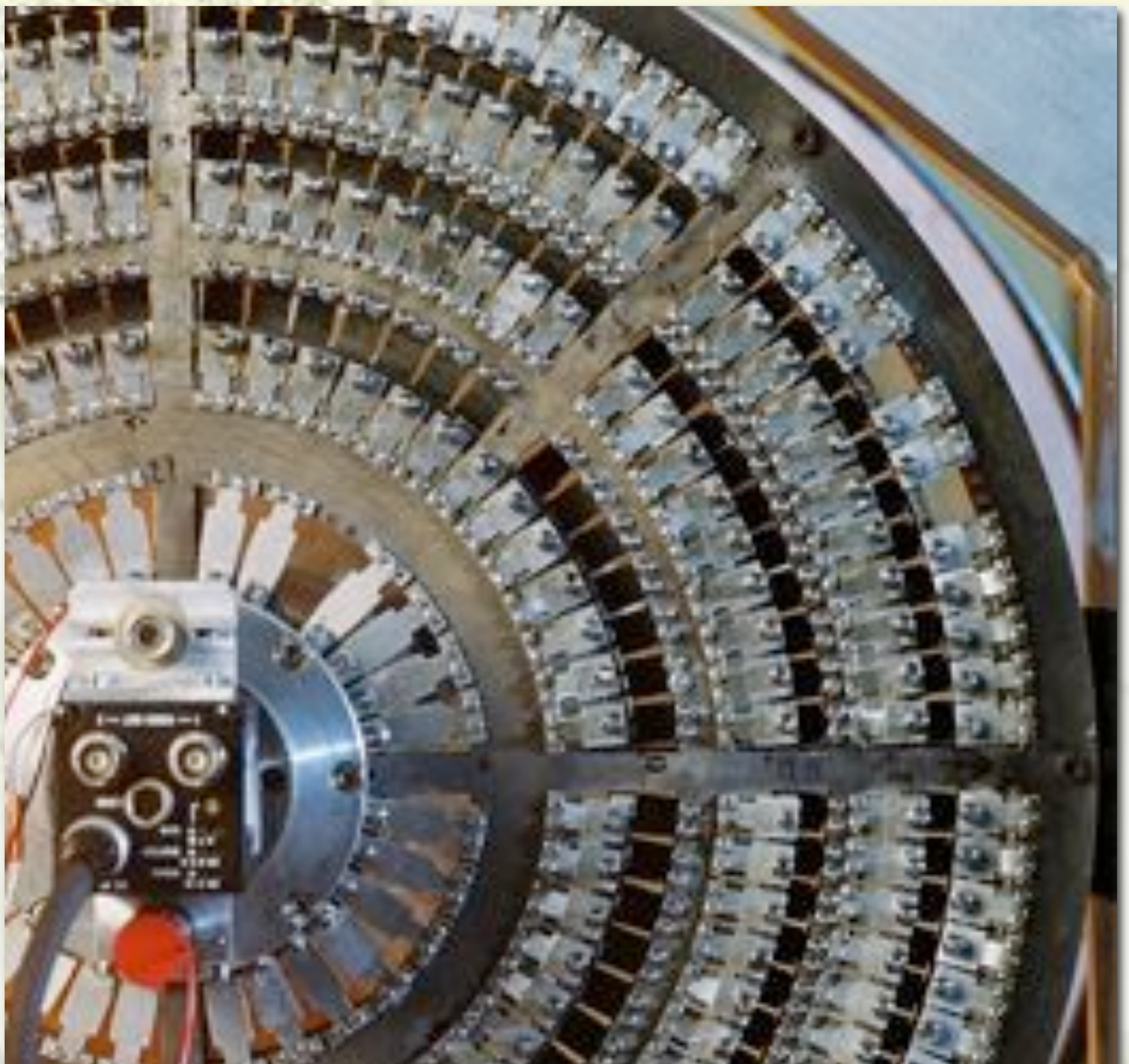
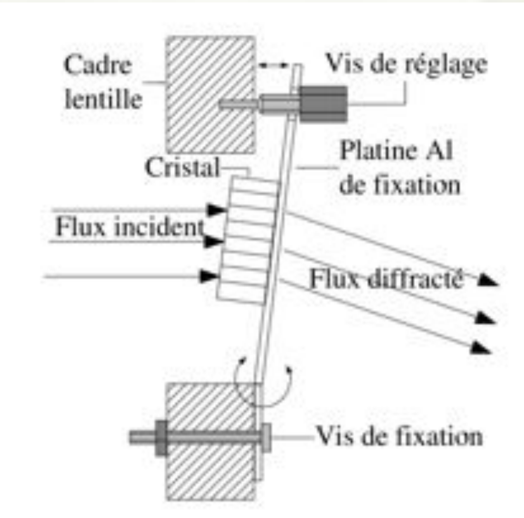
Crystals orientation: CLAIRE's method



Laue lens built in 2000
By CESR/CNES (France)

Made of 556 Ge crystals
Using 8 different
orientations to focus at
170 keV (source at infinity)



[von Ballmoos et al., ExpA 2005]

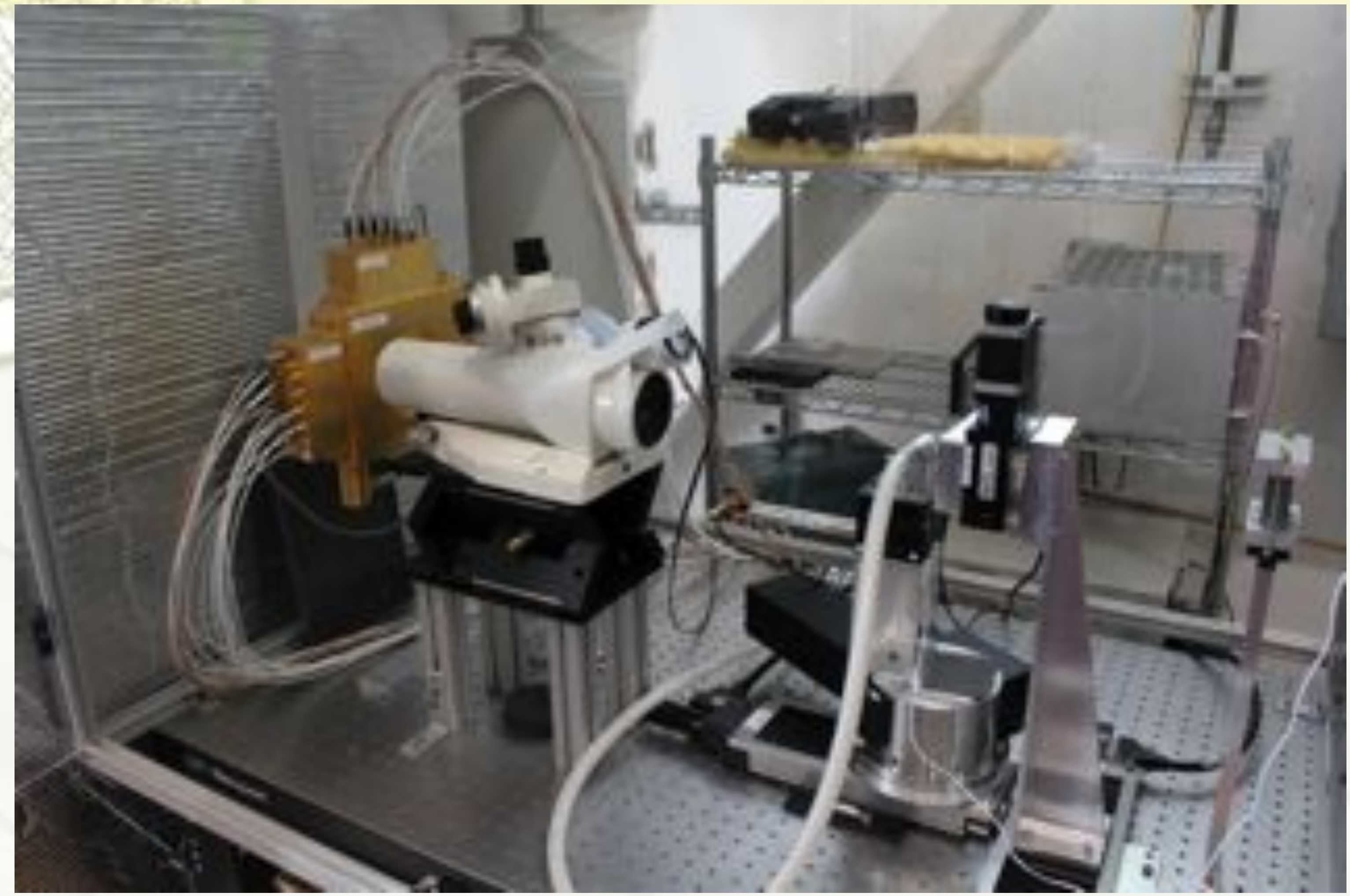
[Halloin et al., NIM A 2003]

X-ray beamline at SSL

Beamline features:

- 13 m long (minimum beam divergence = 20 arcsec)
- X-ray generator: continuum 50 - 150 keV, maximum flux around 100 keV

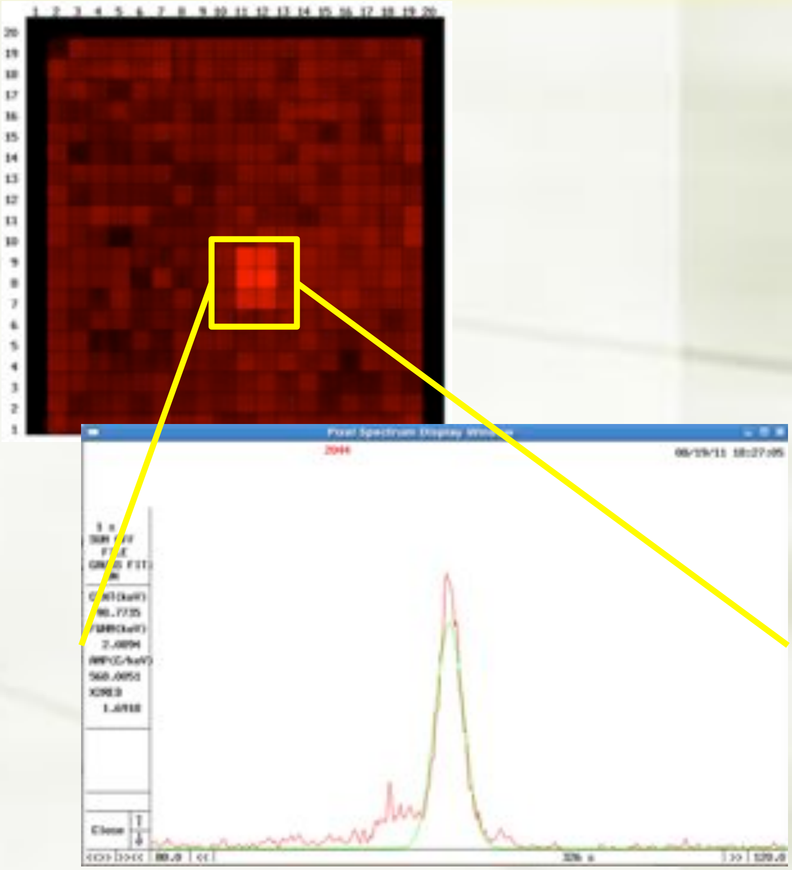
Gluing station



Determination of crystal orientation within ~ 1″

Substrate orientation monitored with autocollimator (~ 1″ accuracy)

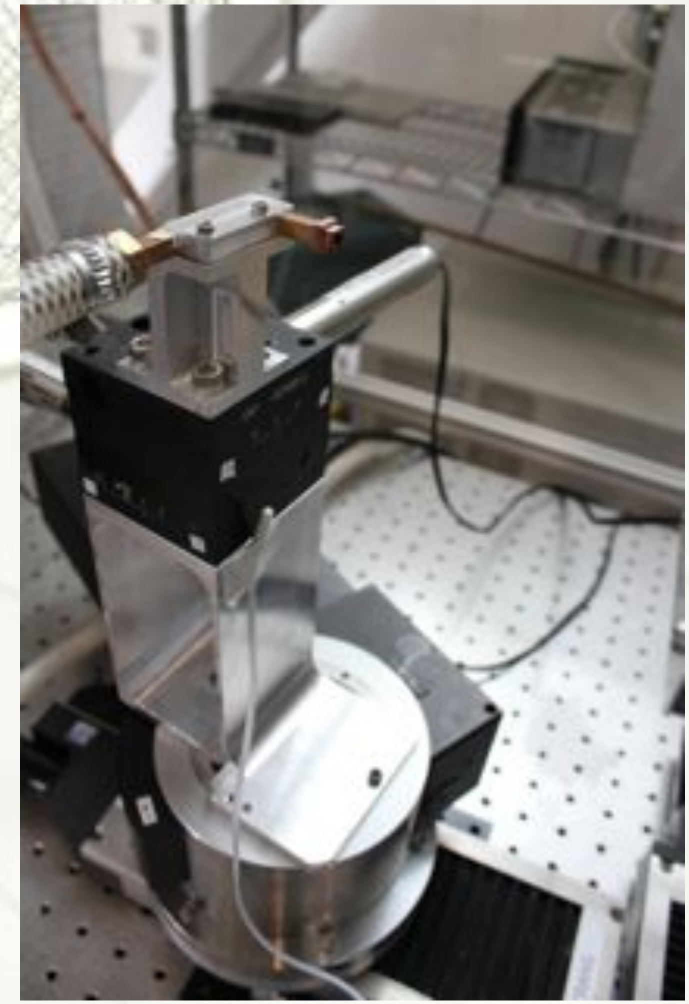
Detector 'Homer'

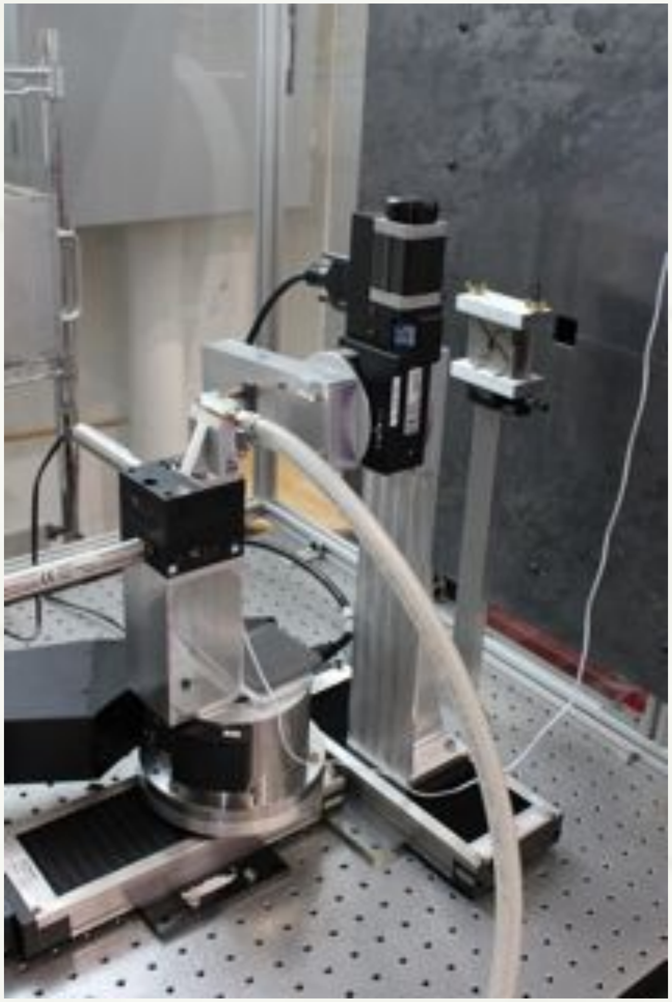


Ge cross-strip detector (19x19 strips, 2 mm pitch): 1st prototype of NCT

Relative calibration: ± 0.04 keV
Absolute calibration: ± 0.03 keV

Crystal and substrate holder





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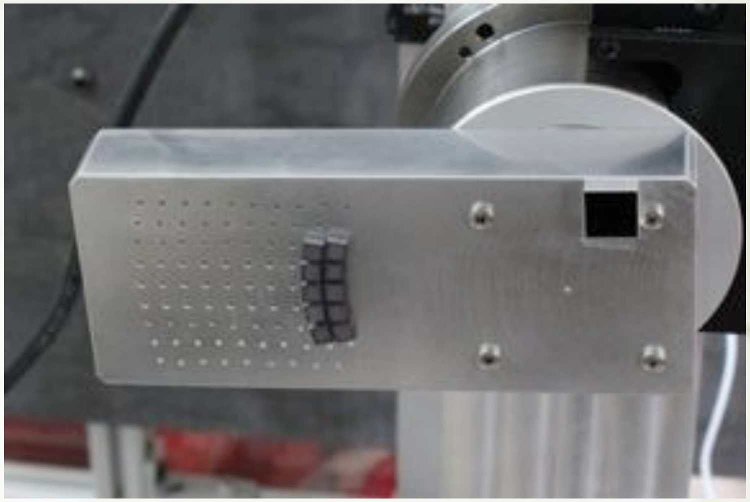
Laue lens assembly: First trial

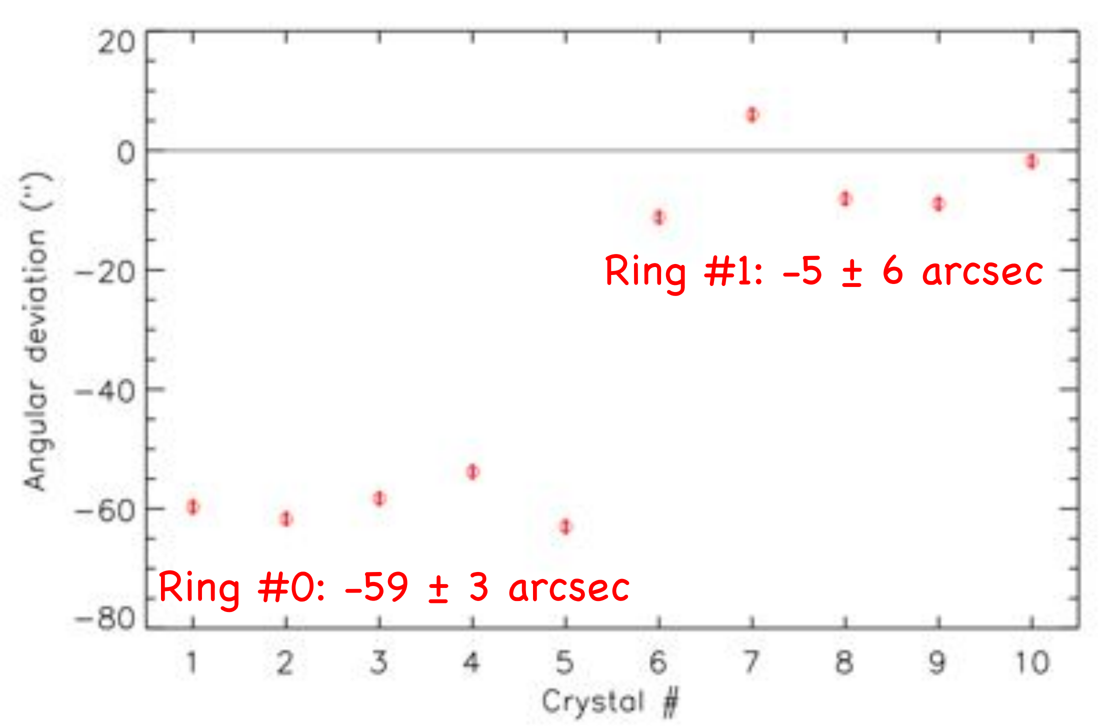
1) Setup crystal at tip of vacuum chuck
2) Position crystal in front of substrate hole
3) Check substrate orientation (autocollimator)
4) Orient crystal with X rays
5) Inject glue through substrate
6) Let glue cure for 6+ hours
7) Check orientation of substrate and crystal

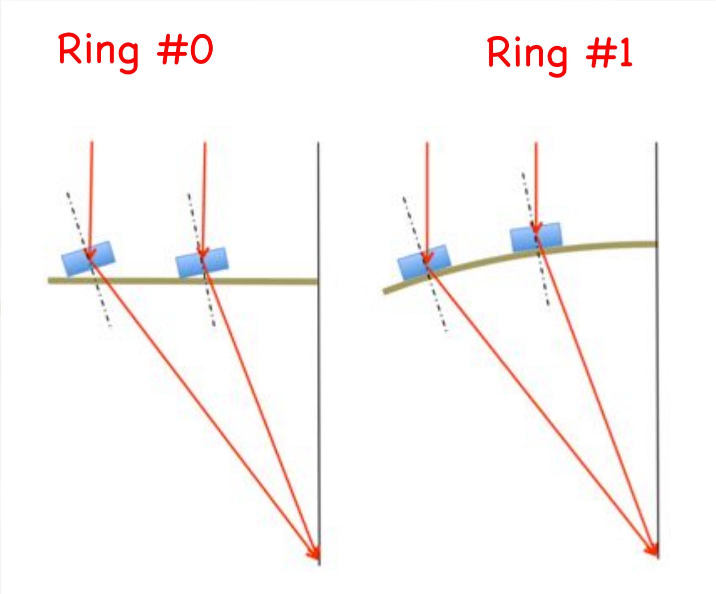


- Glue MasterBond EPO30-2: Very low shrinkage upon cure (3×10^{-4})
- $5 \times 5 \times 3$ mm^3 Si 111 crystals provided by N. Abrosimov (IKZ, Berlin)
- Aluminum 'training' substrate

Results

- 1st ring: substrate perpendicular to beam
- 2nd ring: substrate tilted of 1.133°: no glue wedge





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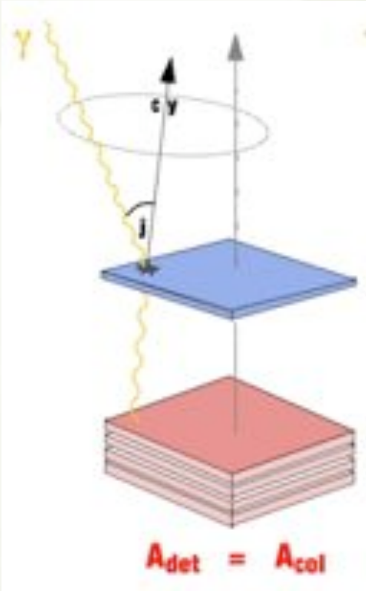
First trial: Conclusions

- 10 Si crystals (5x5x3 mm^3) were glued onto a substrate at a pace of 2-3 per day (6h curing time).
- Despite the lack of thermal control, accuracy of 5 ± 6 arcsec was achieved
- The method allows for dense packing of crystals
- Future development at SSL
  - New substrate with parabolic shape (thin parallel bond line)
  - Thermal control
  - Tool to position the crystal on the vacuum chuck
  - Orientation of substrate with respect to beam
  - Control of the amount of glue injected
  - Faster glue

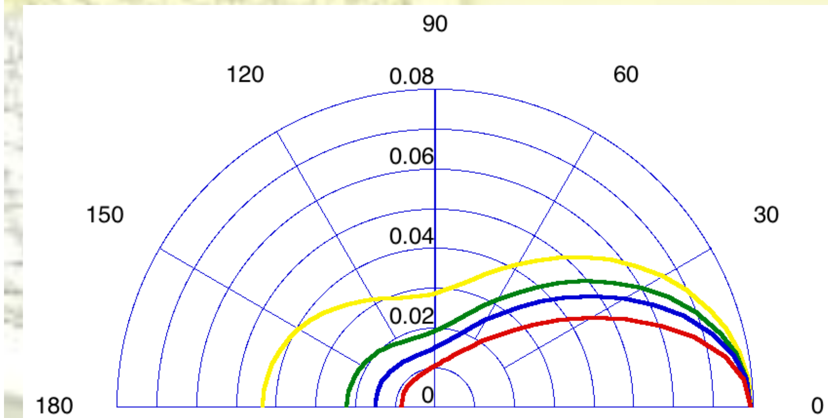
Detector requirements

Compton detectors gather all the suitable features:

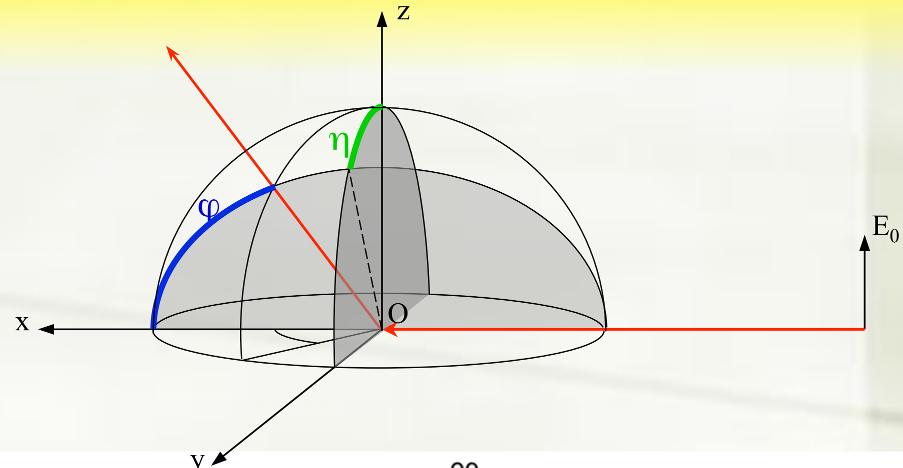
Finely pixelated	Reconstruct focal spot shape => decrease background and imaging
Good spectroscopy	Spectroscopy, background reduction
Good timing	Source pulsation
Size	Field of view (25′ @ 10m with 8x8cm), background monitoring



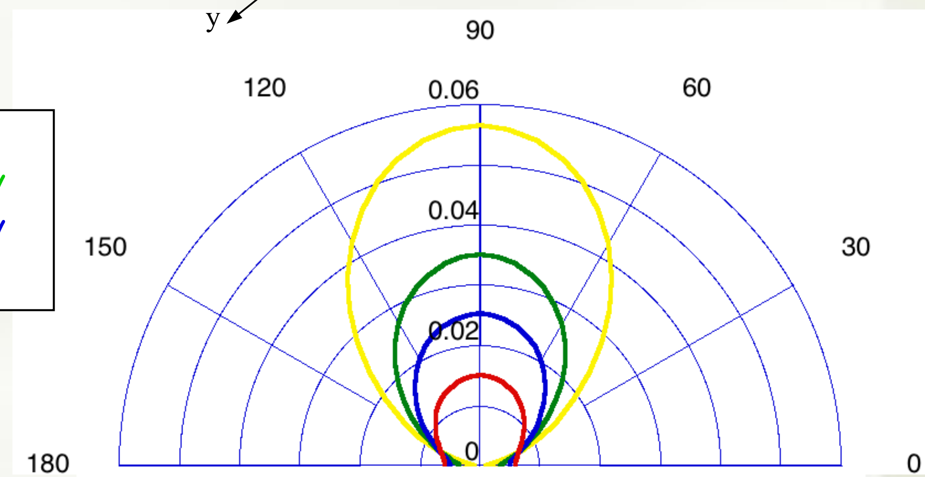
Polarisation detection: Compton diffusion



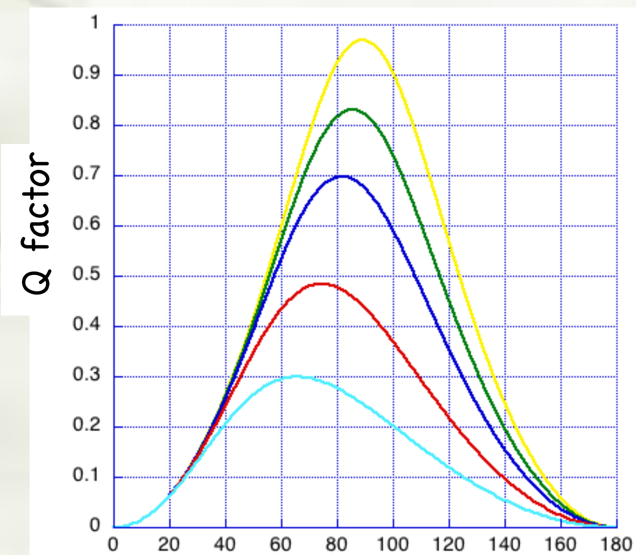
Differential cross section as function of diffusion angle φ (averaged on η)



100 keV
300 keV
500 keV
1 MeV



Differential cross section as function of azimutal angle η (φ = 90°)



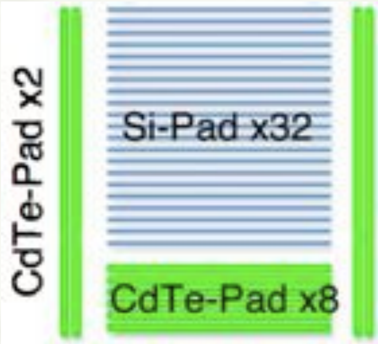
Diffusion angle φ (deg)

⇒ Planar detector finely pixelated is optimal

[Lei et al., SSR 1997]

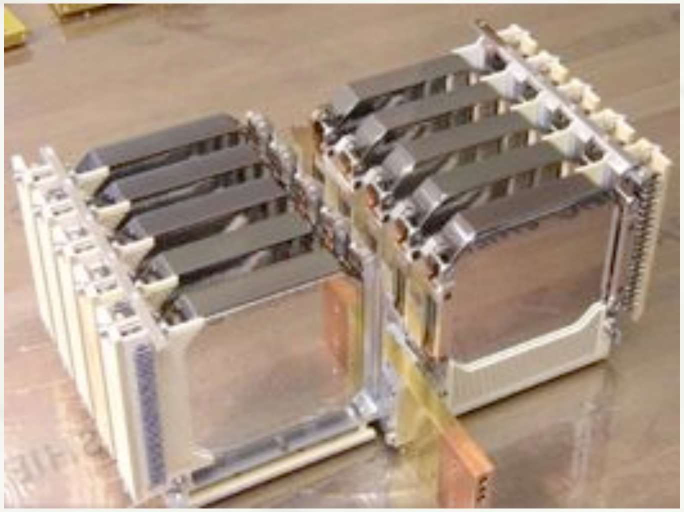
R&D for compact Compton telescopes (examples!)

Developed at ISAS / JAXA
(Tokyo, Japan)



[Aono et al., SPIE 2007]

Nuclear Compton Telescope
developed at SSL (Berkeley, USA)



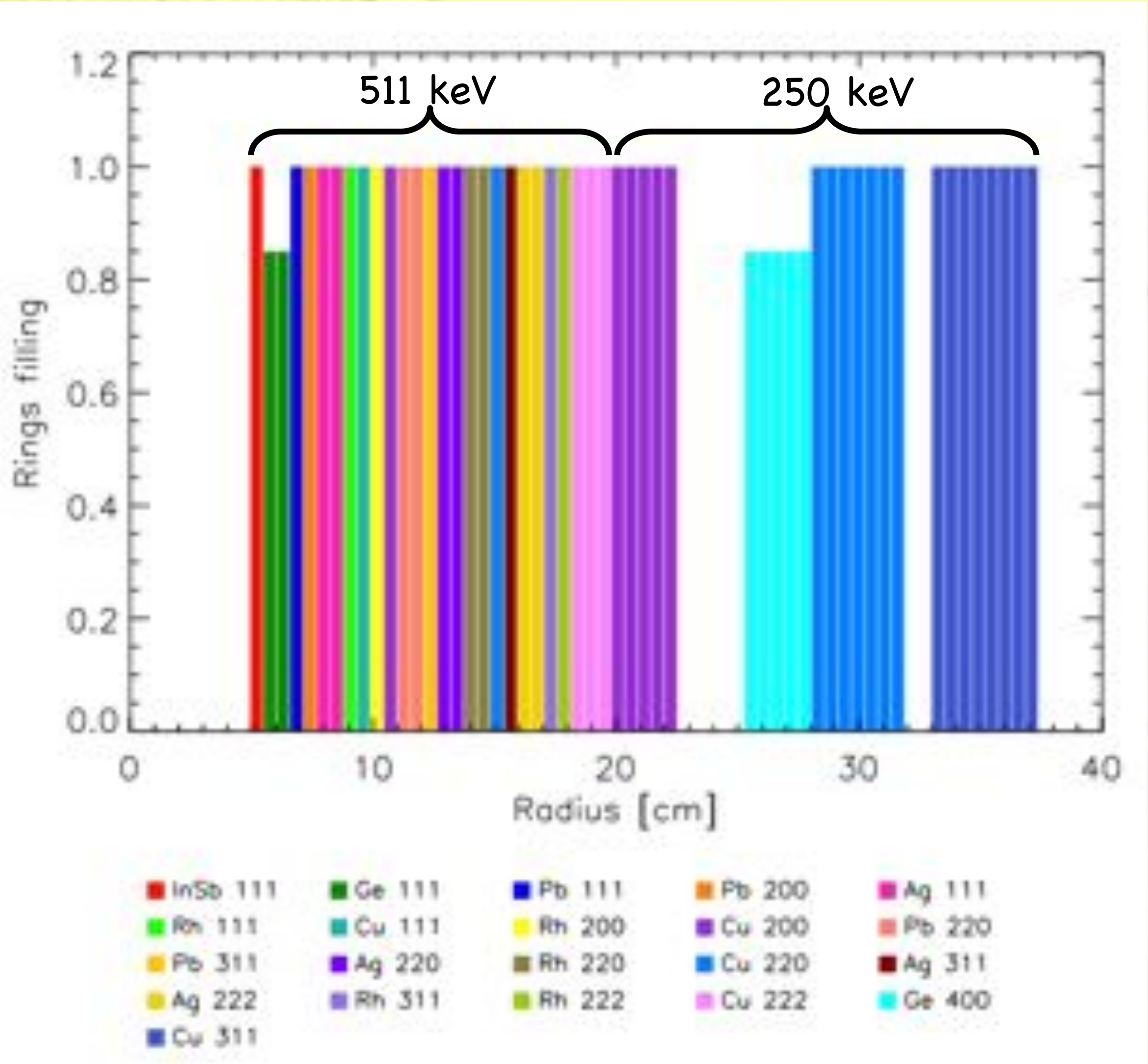
HPGe stripped planar detectors

[Boggs et al., ASR 2007]

Outlines

- Introduction
  - Science drivers for Laue lens development
  - Laue lens principle
  - Existing Laue lenses
- Laue lens development status
  - Crystals
  - Assembly of crystals onto a substrate
  - Focal plane instrument
- Example of Laue lenses projects - performances
- Conclusions

Crystal distribution



<u>511 keV band:</u>
3697 crystals
5x5 mm2
Mosaicity: 70 arcsec
Crystallite size: 60μm

<u>250 keV band:</u>
4200 crystals
10x5 mm2
Mosaicity: 70 arcsec
Crystallite size: 40μm

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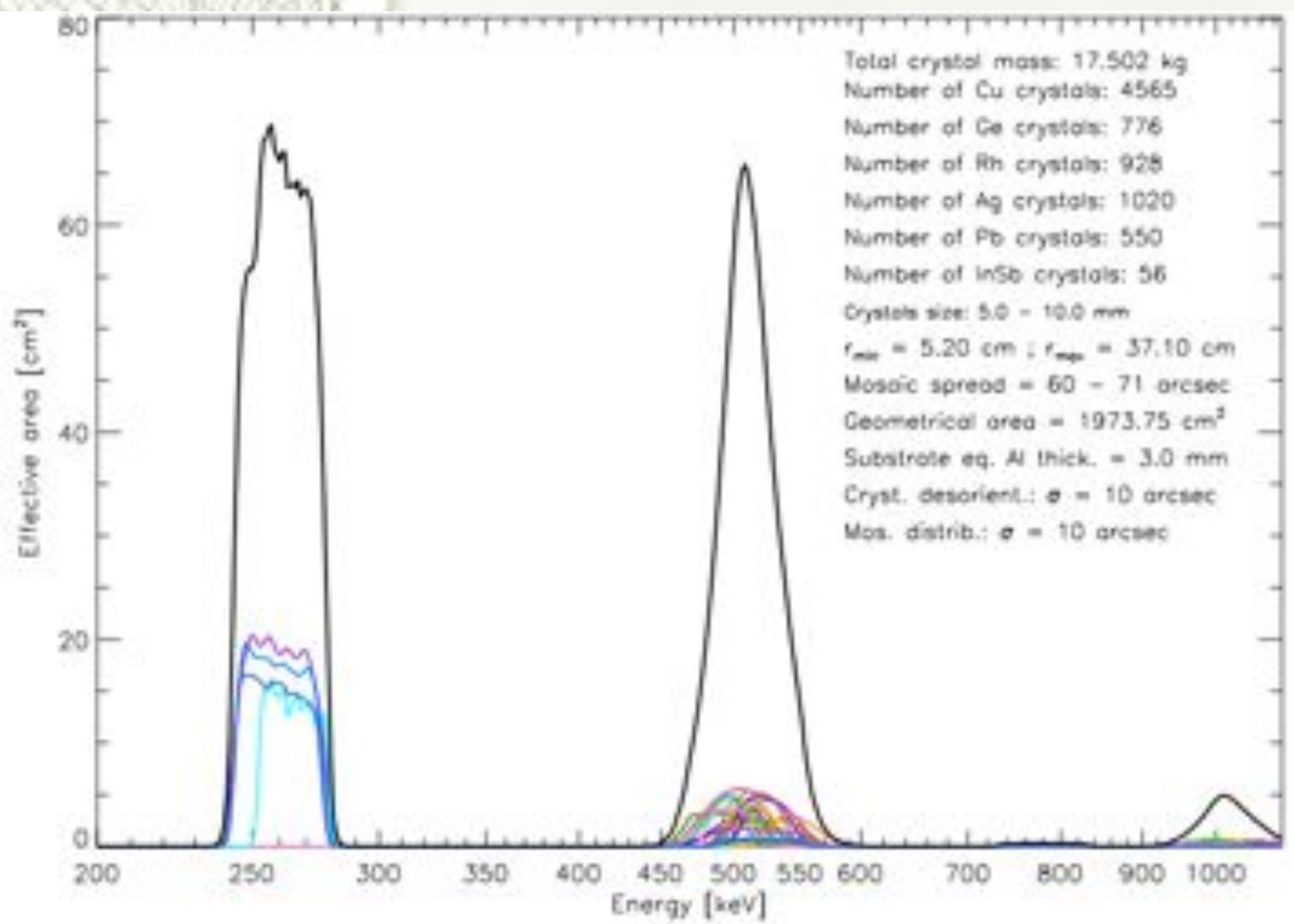
Effective area for a point source on axis



Effective area calculation includes:

- Absorption through the substrate: 3 mm of aluminum
- Crystals non-ideally oriented: Gaussian distrib with σ=10 arcsec
- Crystal mosaicity following a Gaussian distrib with σ=10 arcsec

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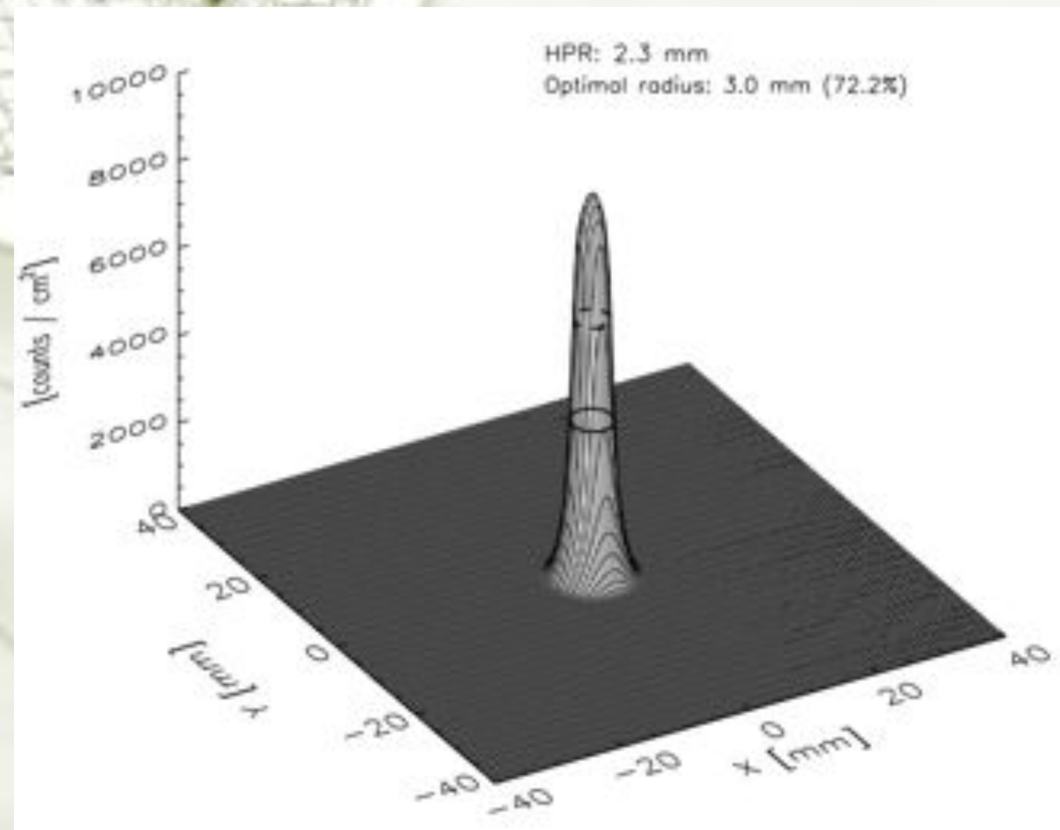
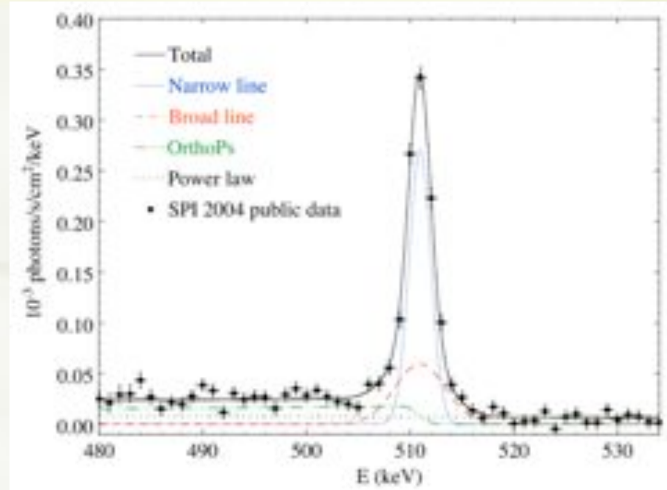
Point Spread Function for a narrow line at 511 keV





Input spectrum: sum of 2 Gaussians as described in Jean et al., A&A, 2006

Concentration factor: 165

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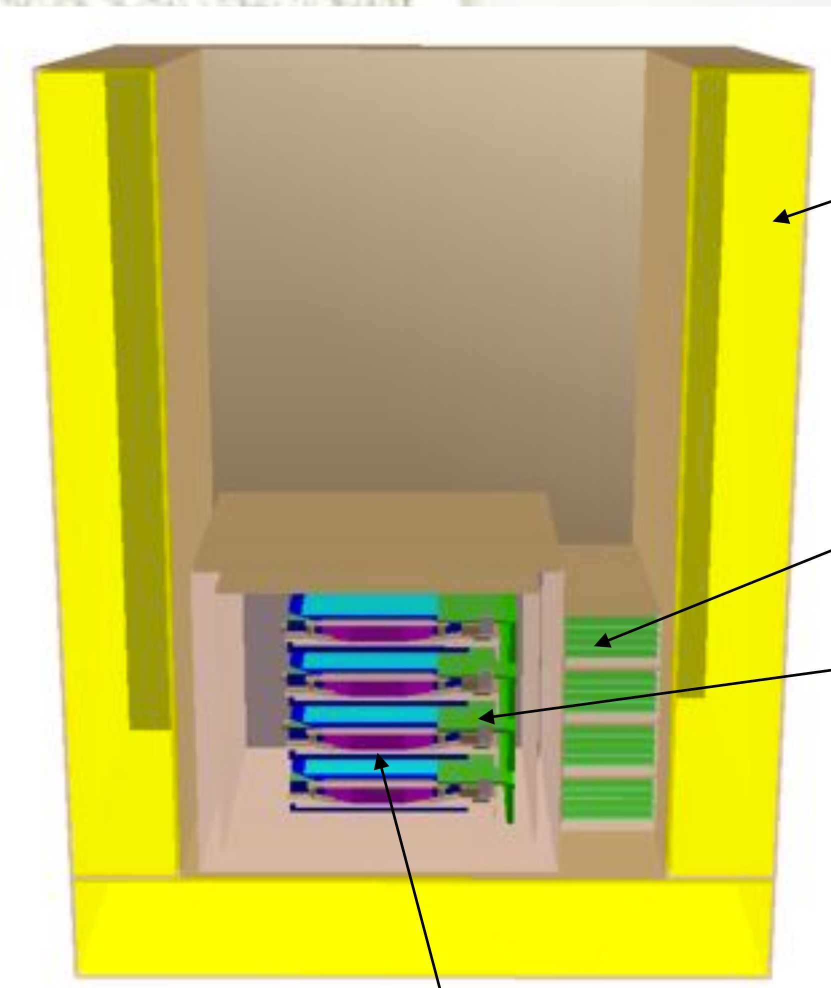
Detector for a balloon flight



BGO active shield

Electronics cards

Preamplifiers

Stack of 4 NCT elements: High purity cross strip Ge detectors

<u>Cross strip 3D GeDs</u> developped at Lawrence Berkeley National Laboratory for the Nuclear Compton Telescope (NCT):

- 37 + 37 strips
- 2-mm pitch
- 15-mm thickness
- 81000 mm^3 volume
- 1.6 mm^3 event localization

Point source sensitivity

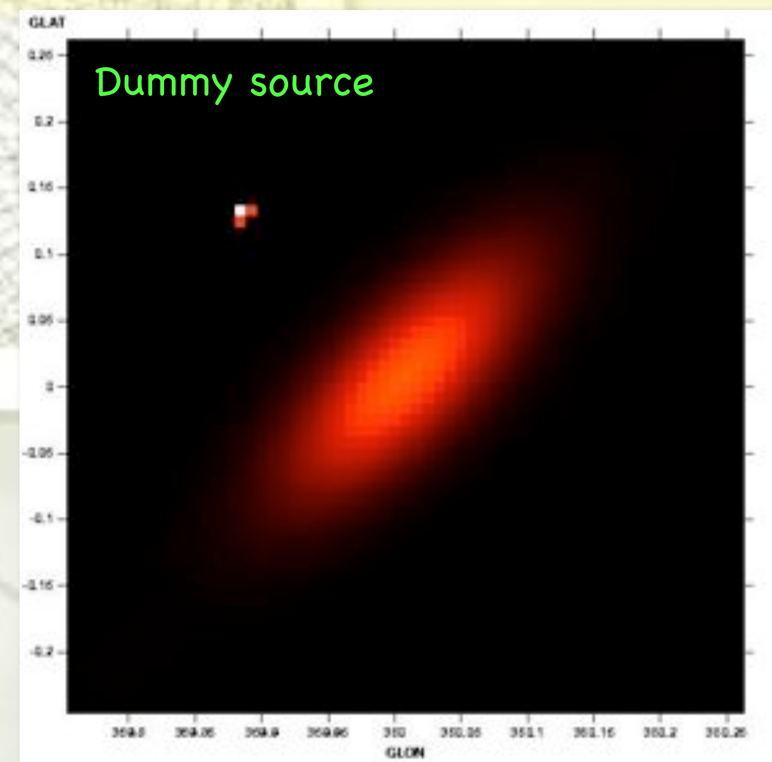
3σ sensitivity, 10ks integration time

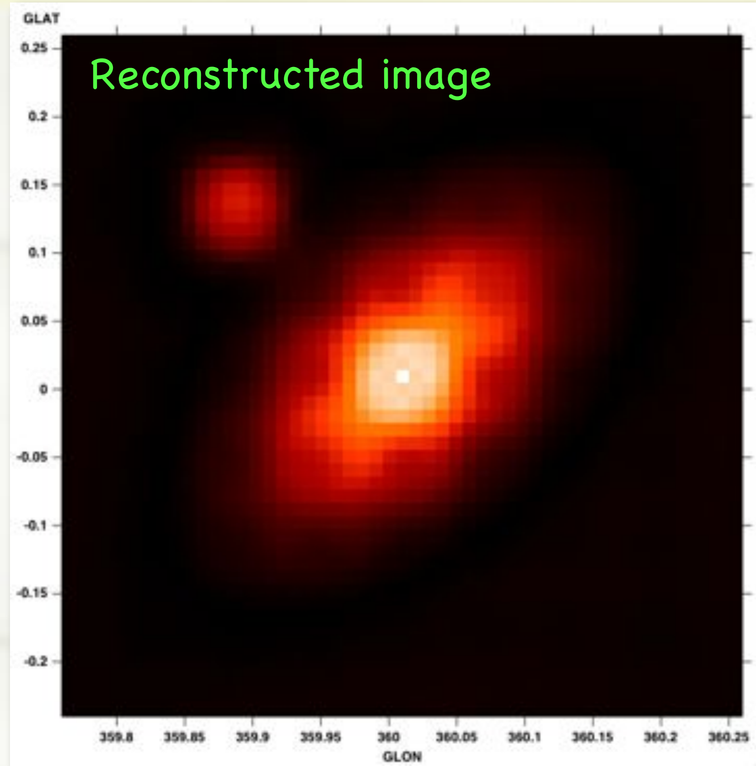
	250 - 275 keV (photo-electric)	500 - 520 keV (Compton reconstruction)
Mean effective area (cm^2)	63	61
Narrow line ($ph/s/cm^2$)	8.8×10^{-5}	1.5×10^{-4}
Continuum ($ph/s/cm^2/keV$)	4.8×10^{-6} (ΔE=25 keV)	8×10^{-6} (ΔE=20 keV)
Minimum detectable polarization (assuming a source having a Crab-like spectrum)	1 Crab: 57% 0.36 Crab: 100%	5.4 Crab: 100%

Calculated using end-to-end GEANT4 simulations

3 times more sensitive than INTEGRAL / SPI (for comparable exposure time)

Imaging: Dithering observation pattern + maximum likelihood image reconstruction





<u>Simulation parameters:</u>

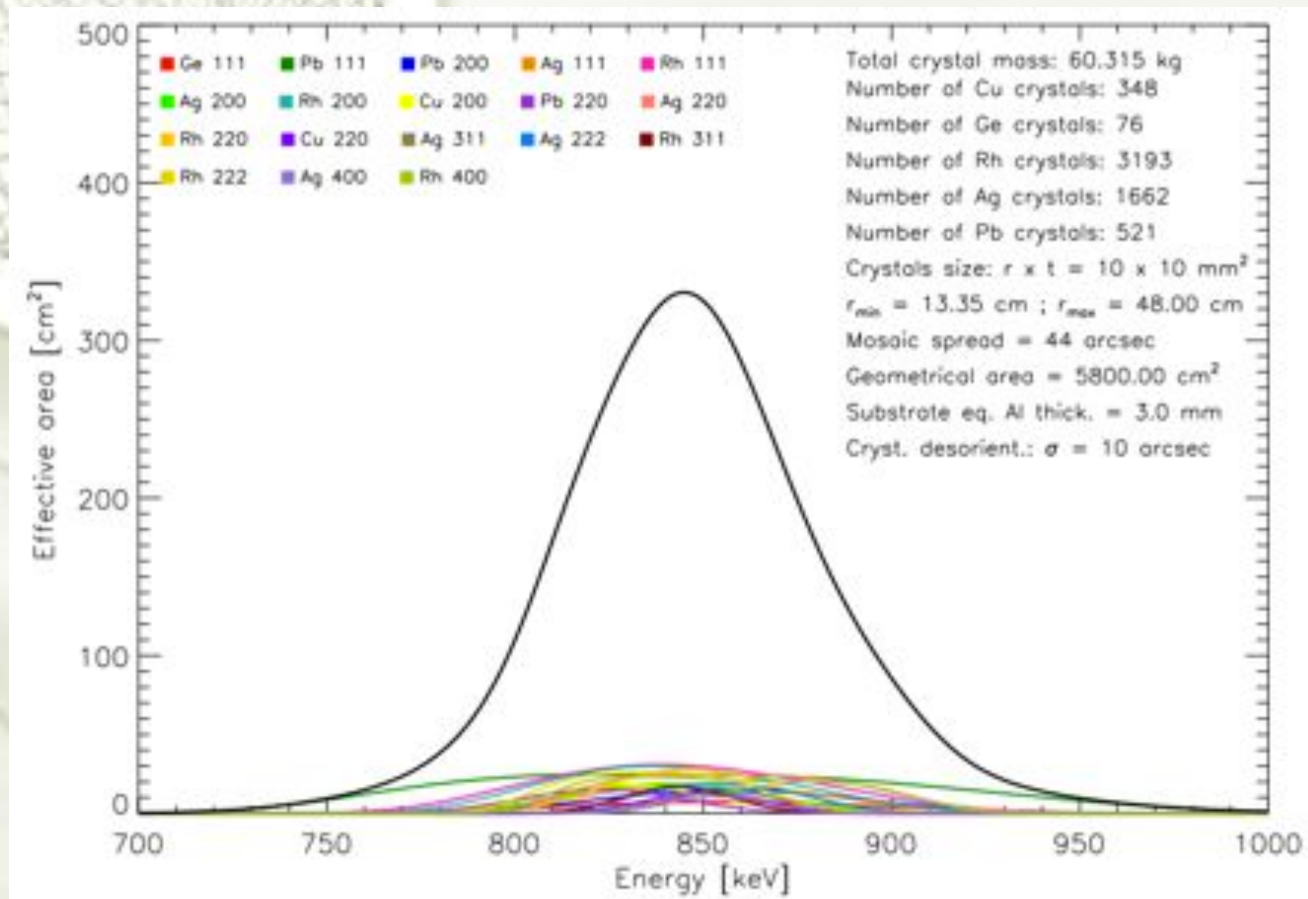
- Extended source, Gaussian profile: σ = 2 x 5 arcmin
- e^+ – e^- annihilation line (as measured by SPI)
- Total flux: 1x 10^{-4} ph/s/cm^2
- Detector energy resolution: 2 keV (0.4%)
- Observation duration: 100 ks
- Background from CLAIRE balloon flight

Observation patern:
grid of 7 x 7 pointings

⇒ Center detected at 7σ, point source at 3σ

⇒ No proper background subtraction!!!

Laue lens for SNIa science



Focal length = 30 m

5800 crystals, 1x1cm^2:
Rh, Ag, Ge, Cu, Pb

Lens diameter = 1 m
Crystal mass = 60 kg
Total lens mass = 80 kg
(CeSiC substrate)

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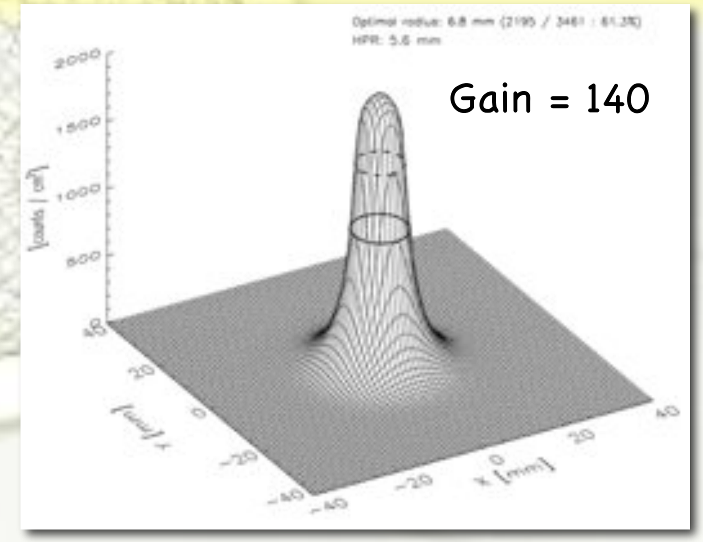
Laue lens for SNIa science



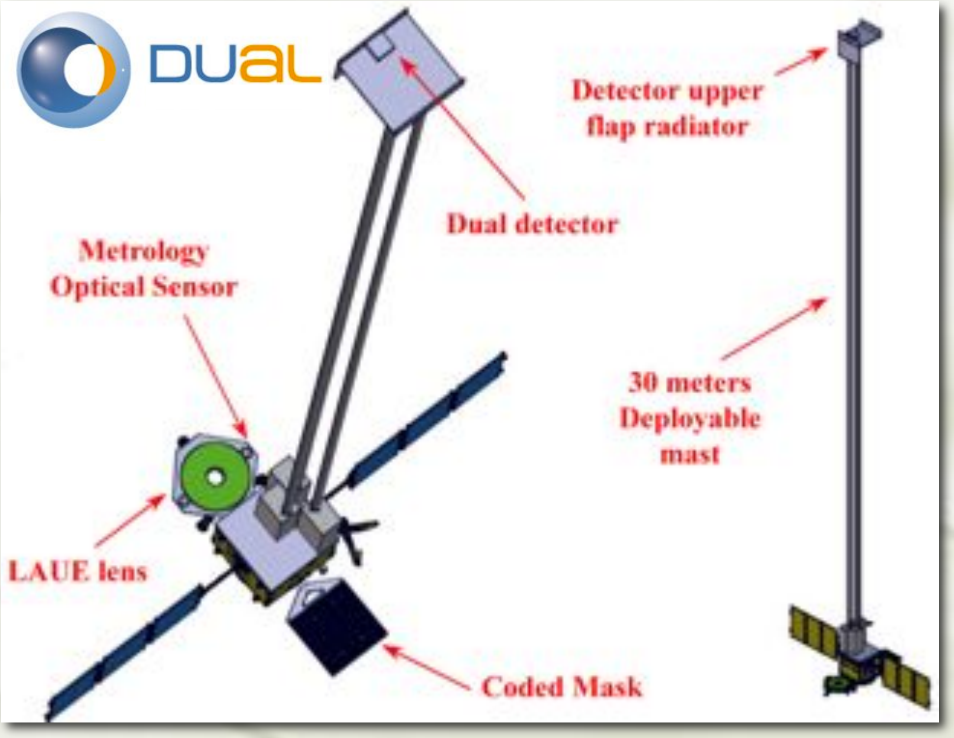
Sensitivity at 847 keV: (3σ, 1 Ms):

- 3% broadened line: 2×10^{-6} ph/s/cm^2
- Narrow line: 1×10^{-6} ph/s/cm^2

Proposed as part of the DUAL mission lead by P. von Ballmoos (Cosmic vision AO for 3rd Medium class mission)

[von Ballmoos, Boggs]

Baseline deployable mast (30 m) built by SENER (Spain). "Tape meter type", 70 kg



Conclusions

- Laue lens are not a new technology, but so far the crystal quality / assembling precision / focal length limitations have prevented making them really efficient.

- Crystals are the center piece of Laue lenses
  - ⇒ Search for more efficient crystals:
    - CDP crystals (grooved crystals) : Si, Ge
    - High-Z mosaic crystals for high energy: Ag, Rh, Pb
    - Mosaic crystals: Cu

- Very accurate mounting required for long focal distance (astrophysics)
  - Work in progress at SSL
  - Challenge: large number of crystals to orient

- Laue lenses have limitations (pretty chromatic, FoV ~< 0.5deg) that can be turned into advantage for very specific applications
  - SNeIa telescope (2×10^{-6} ph/s/cm^2 achievable in 1 Ms)
  - Source focusing / monochromatization
  - Line observation
  - …