Calibration of gamma-ray instruments for Nuclear Astrophysics

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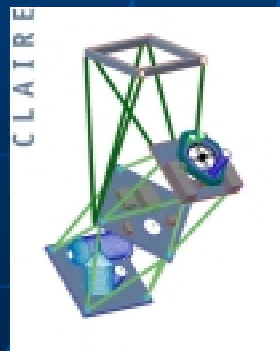


Outline

- Gamma-rays in astrophysics
- Detection of gamma-rays
- How to focus γ-rays?
- Steps towards a γ-rays lens for nuclear astrophysics
  - CLAIRE: a focusing γ-rays lens
  - The MAX mission
- Experimental proposals for the GRL

Radioactive isotopes relevant for γ-ray line astronomy

	Isotope	Decay chain	Lifetime	Line energy (keV)
Supernovae mainly	^{56}Ni	$^{56}Ni \rightarrow {}^{56}Co$	8.8 d	158, 812, 750, 480
	^{56}Co	$^{56}Co \rightarrow {}^{56}Fe$	111 d	847, 1238
	^{57}Ni	$^{57}Ni \rightarrow {}^{57}Co \rightarrow {}^{57}Fe$	(52 h) 390 d	122
	^{44}Ti	$^{44}Ti \rightarrow {}^{44}Sc \rightarrow {}^{44}Ca$	89 y (5.4 h)	78, 68, 1157
	^{26}Al	$^{26}Al \rightarrow {}^{26}Mg$	1.0×10^6 y	1809
	^{60}Fe	$^{60}Fe \rightarrow {}^{60}Co \rightarrow {}^{60}Ni$	2.0×10^6 y (7.6 y)	1173, 1332
Novae mainly	^{7}Be	$^{7}Be \rightarrow {}^{7}Li$	77d	478
	^{22}Na	$^{22}Na \rightarrow {}^{22}Ne$	3.8 y	1275

→ e^- capture → β^+ → β^-

γ-ray emission from galactic radioactivity

- Relevant radioactive nuclei for galactic γ-ray line emission:
  - how and where they are synthesized:
    - nucleosynthesis (hydrostatic and explosive), in stars
    - interaction with cosmic rays, in the interstellar medium

- Electron-positron annihilation emission (line and continuum):
  - e^+ from β^+- unstable nuclei
  - BUT other sources of e^+ ($\neq$ radioactivity) exist

Sites of explosive nucleosynthesis relevant for γ-ray line astronomy

- **SUPERNOVAE:**
  - ➢ Thermonuclear supernovae (SN Ia): exploding white dwarfs in binary systems (no remnant)
  - ➢ Core collapse supernovae (SN II, SN Ib/c): exploding massive stars ($M \geq 10\ M_\odot$) (neutron star or black hole remnant)

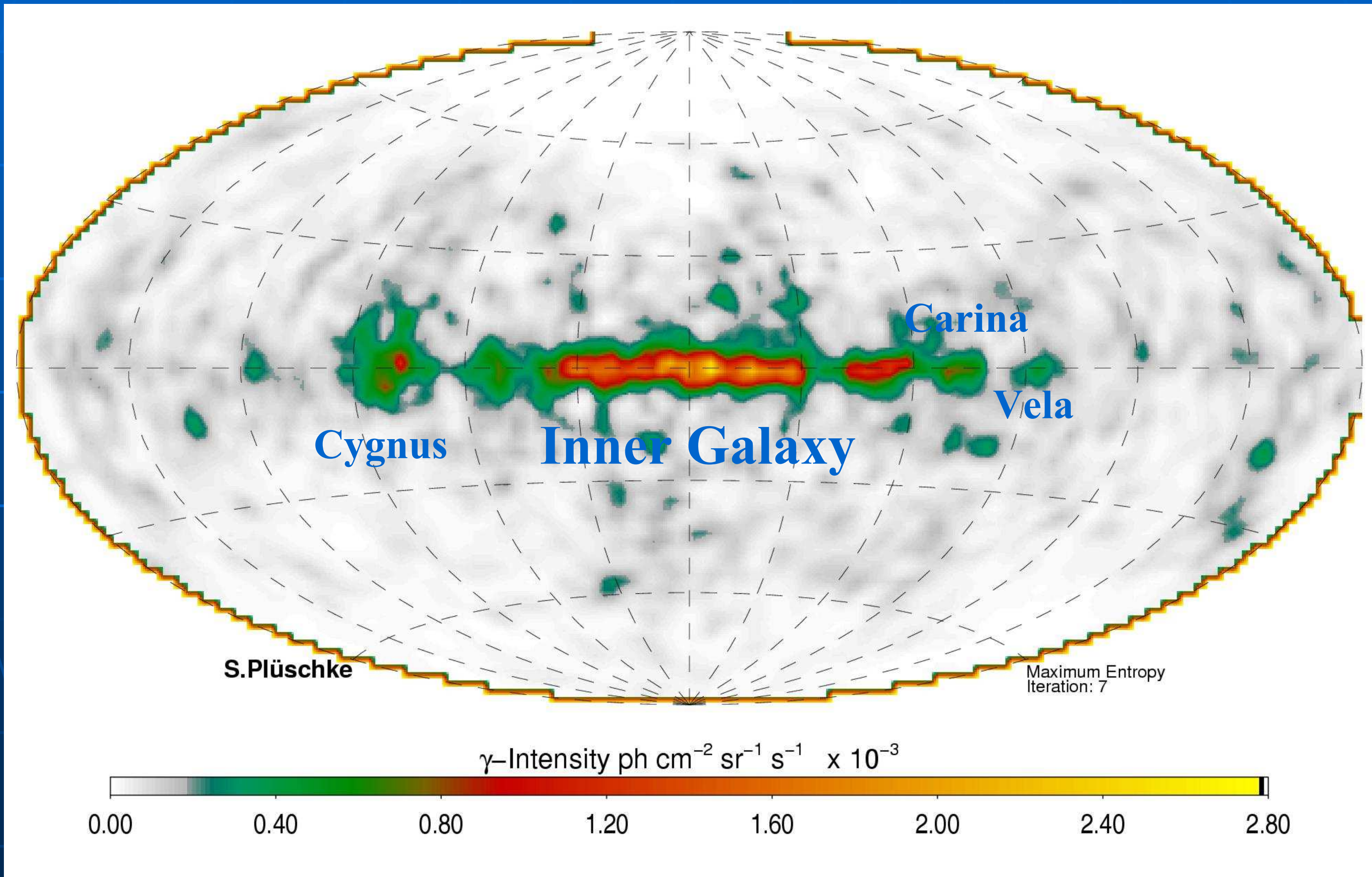
  $v \sim 10^4$ km/s, $E \sim 10^{51}$ erg, $M_{ej} \sim M_\odot$

- **CLASSICAL NOVAE:**

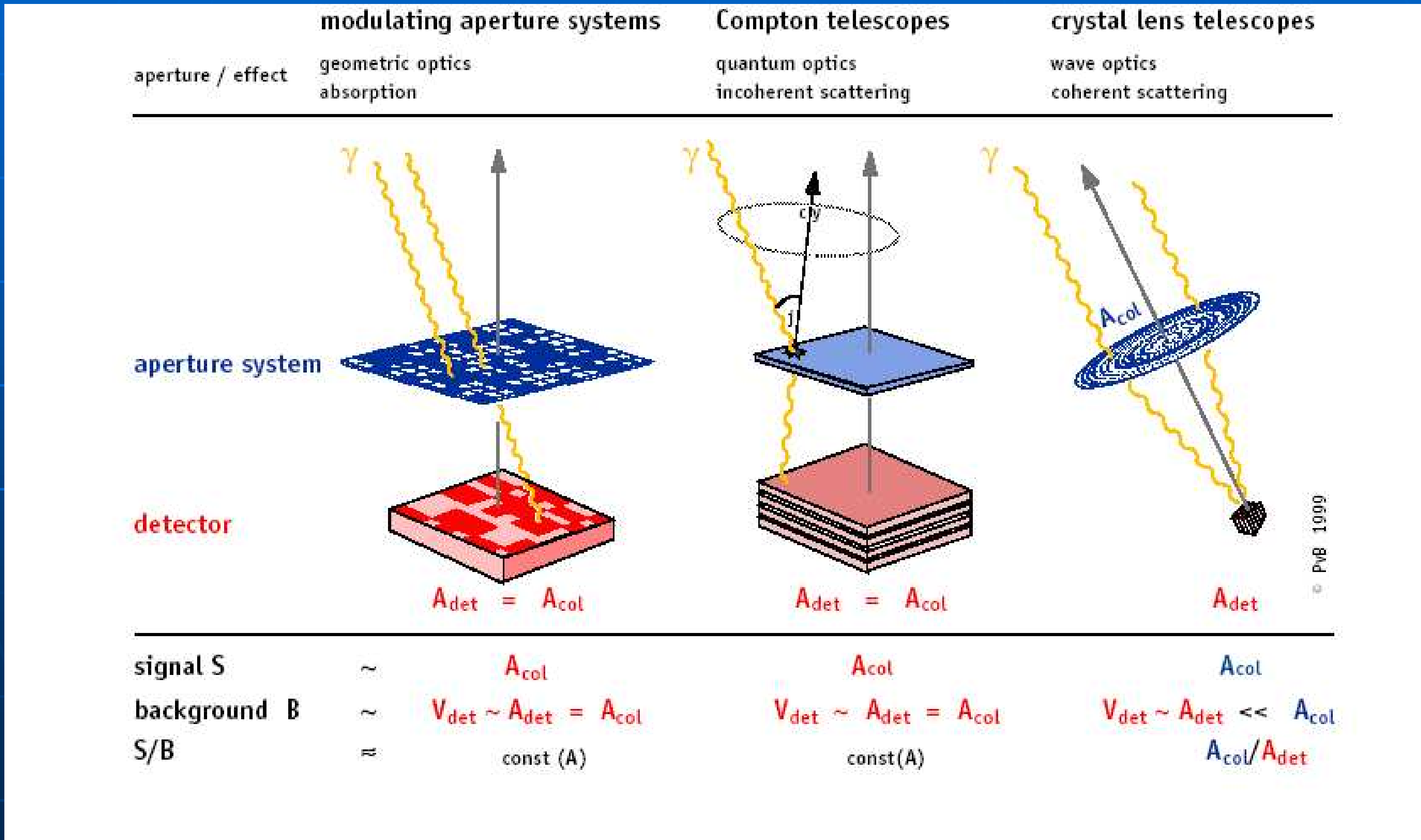
  Explosion of the external H-rich accreted shells of a white dwarf in a binary system

  $v \sim 10^2 - 10^3$ km/s, $E \sim 10^{45}$ erg, $M_{ej} \sim 10^{-4} - 10^{-5}\ M_\odot$

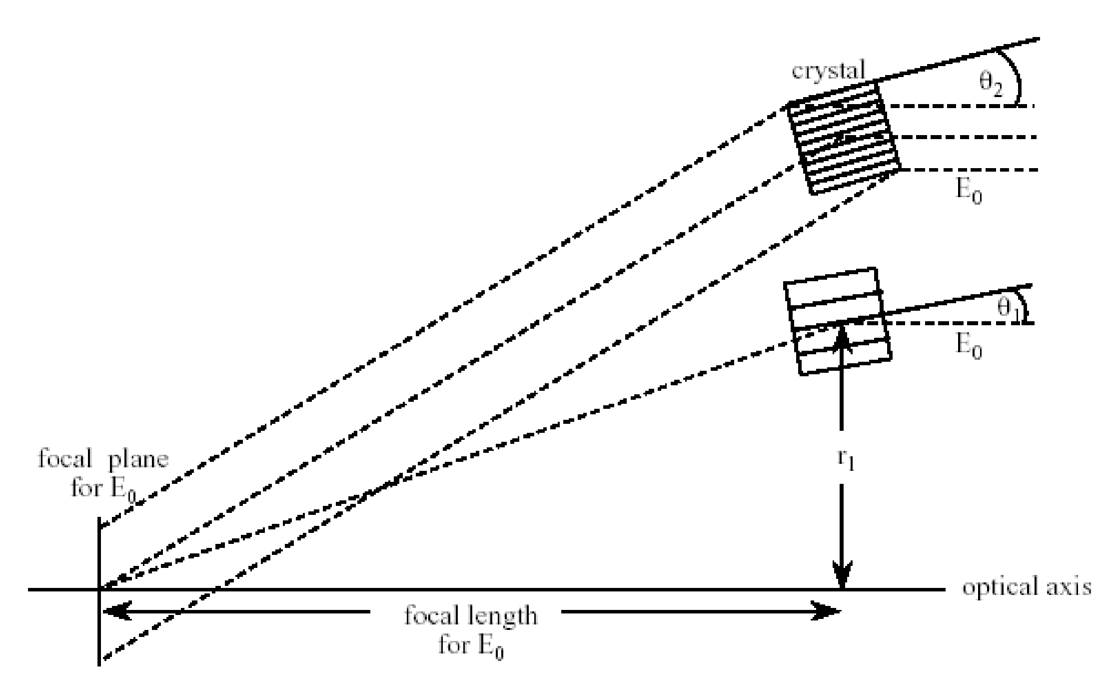
Compton Gamma-Ray Observatory: COMPTEL map of the 1.8 MeV line of ^{26}Al



γ-ray detection



How to focus γ-rays?



- Diffraction: Bragg condition

$$2d\sin\theta = n\lambda = n\frac{hc}{E}$$

- Crystal plane spacing:

$$d = \frac{a}{\sqrt{h^2+k^2+l^2}}$$

- (h,k,l: Miller indices of crystal planes)

$$r_i = f\tan(2\theta) \approx f\frac{n\lambda}{d_i}$$

- d smaller for outer rings

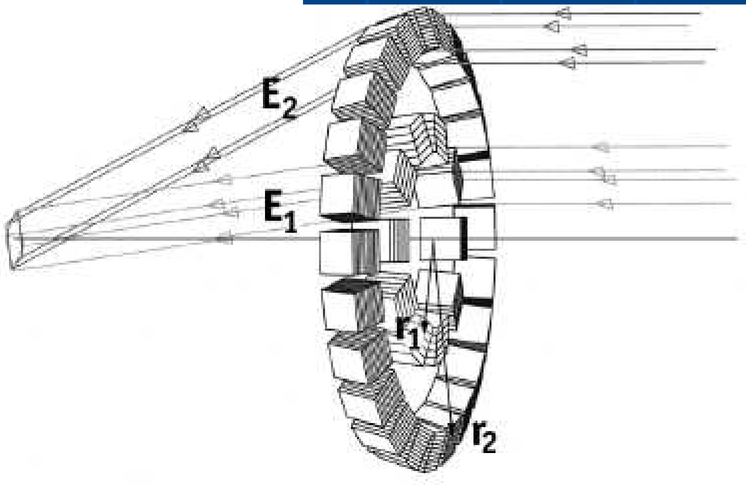
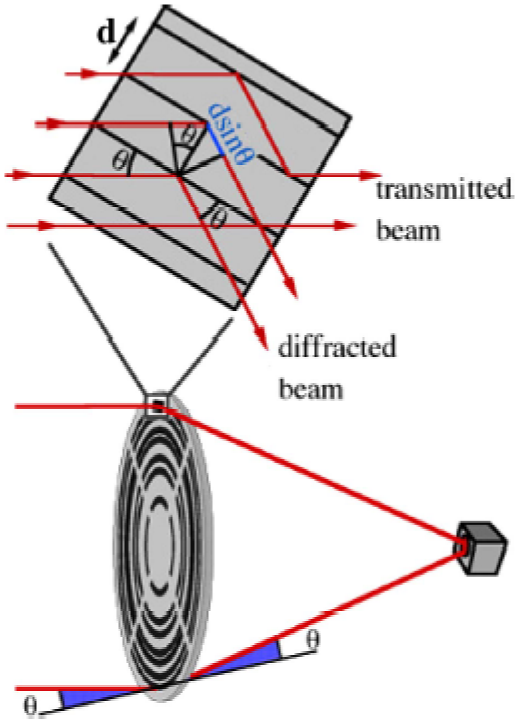


Figure 1 : The basic design of a crystal diffraction lens in Laue geometry

How to focus γ-rays?

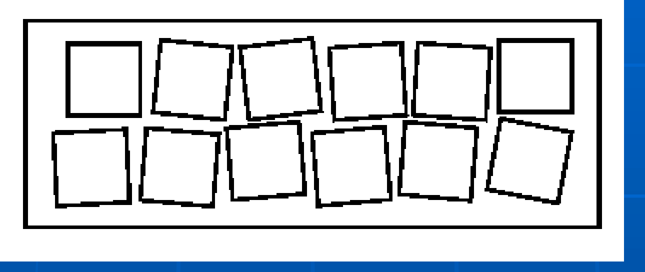


λ(511 keV)	=	$2.42632 \cdot 10^{-2}$ Å
condition de Bragg		
2dsinθ	=	nλ
d[220]	=	2.0004Å
arcsin(λ/2d)	=	0.347°
Lentille Gamma de type Laue		
2θ	=	0.695°
ex. radius [220]	=	10.1 cm
=> longueur focale	=	8.2 m

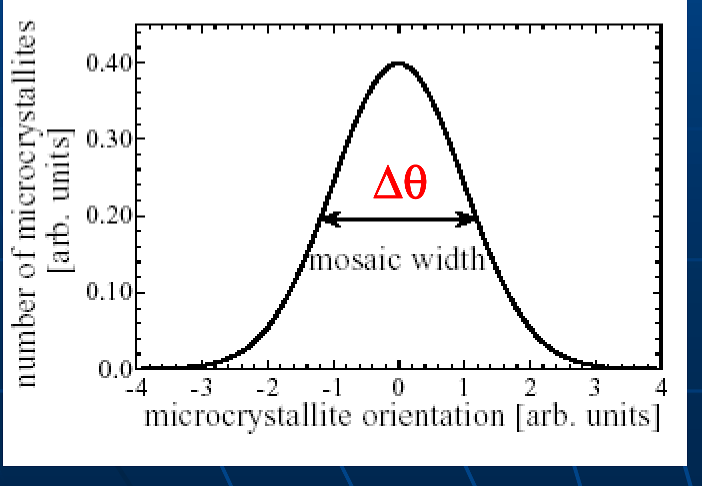
http://www.cesr.fr/~pvb/Claire/index.html

Mosaic crystals

Darwin model: the true defect structure of the crystal is replaced by an agglomerate of perfect crystal blocks typically of microscopic size, where each one is offset in inclination from the others.



The distribution of the inclination of the perfect crystal blocks is assumed to be Gaussian in the Darwin mosaic model, with a FWHM called the **Mosaic width**.



The Bragg condition is monochromatic:

$$2d \sin\theta = n\lambda = n\frac{hc}{E}$$

Energy bandpass:

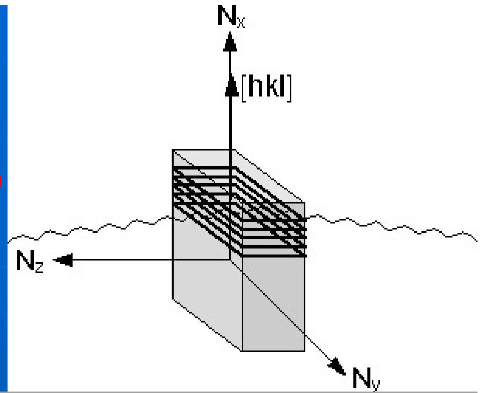
$$\Delta E = \frac{\Delta\theta}{\theta} E$$

Energy bandwidth ΔE of a Bragg reflection due to a mosaic width $\Delta\theta$, assuming incident photons with no angular divergence.

A gamma-ray lens for nuclear astrophysics

http://www.cesr.fr/~pvb/Claire/index.html

CLAIRE: a γ-ray lens prototype

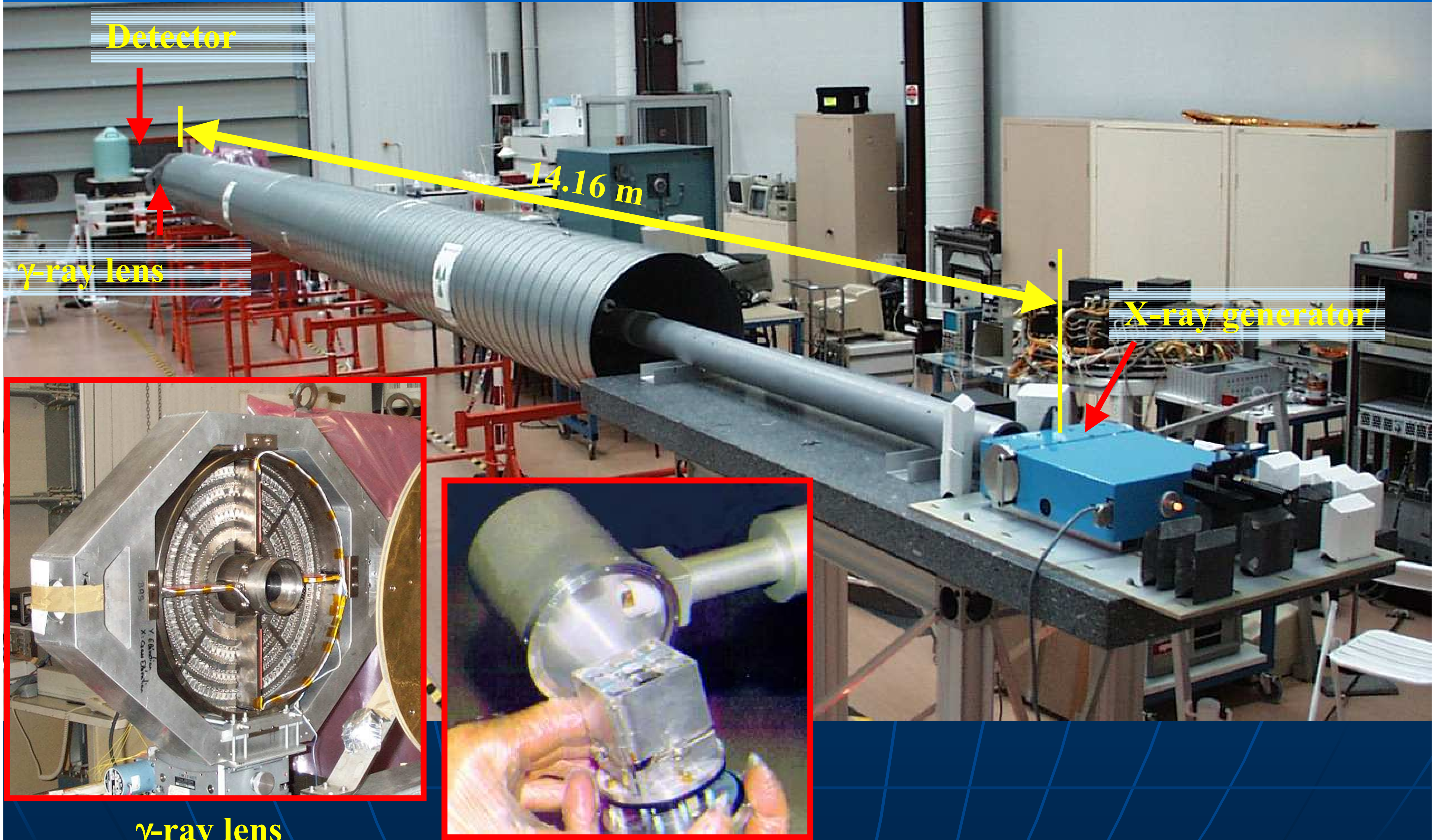


8 rings - 576 Ge crystals – 45 cm diameter – 511 cm^2 area

ring number	reflection plane [hkl]	number of crystals	crystal surface WxH [mm x mm]	crystal thickness T [mm]	Bragg angle @ 170 keV
1	111	28	10 x 10	3.0	0.66°
2	220	52	10 x 10	3.2	1.08°
3	311	56	10 x 10	4.6	1.27°
4	400	72	10 x 10	4.2	1.52°
5	331	80	10 x 7	5.1	1.67°
6	422	88	10 x 10	5.0	1.87°
7	333	96	10 x 7	6.2	1.99°
8	440	104	10 x 10	5.6	2.17°

http://www.cesr.fr/~pvb/Claire/index.html

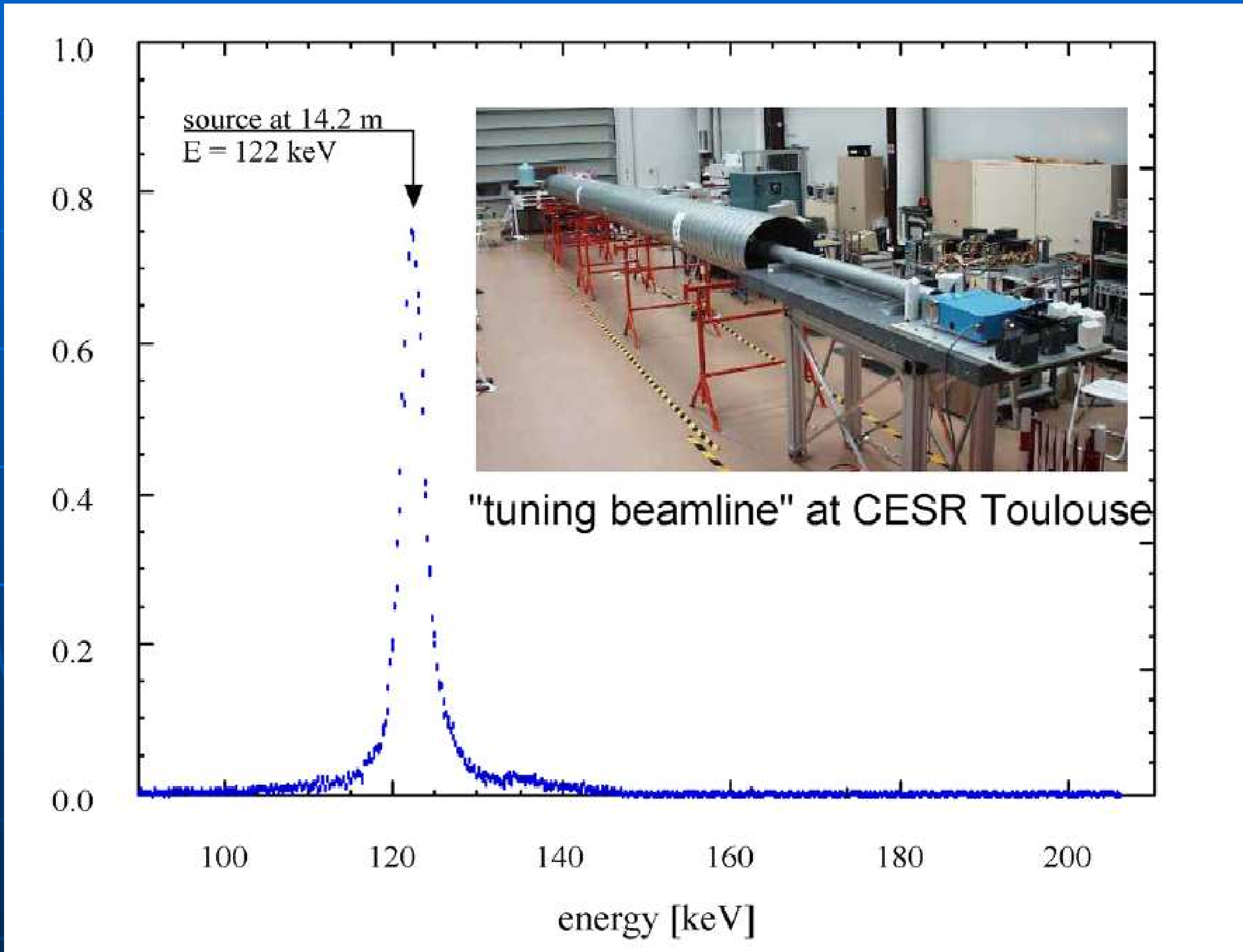
The gamma-ray bench at CESR



γ-ray lens

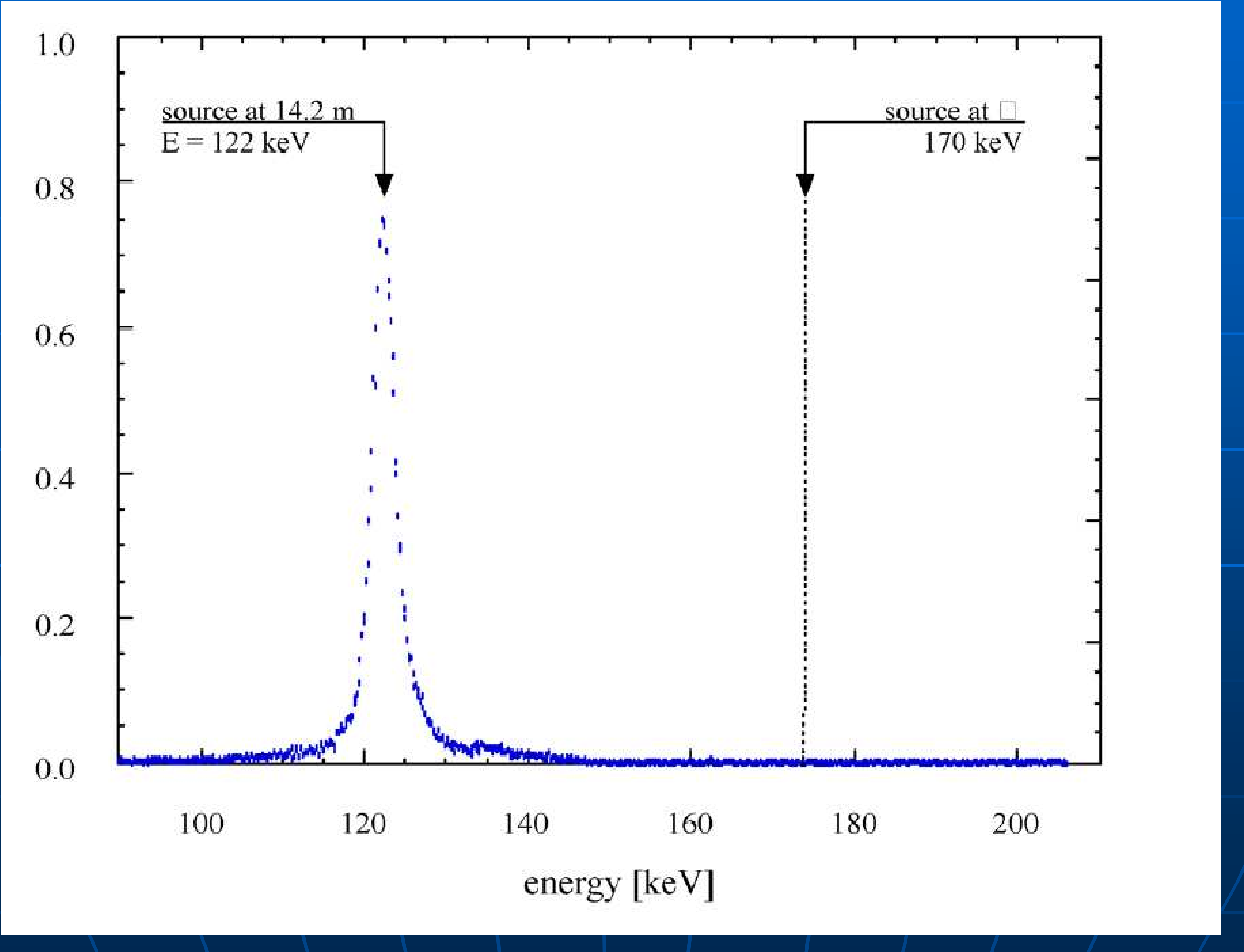
Detector

Does it work? Testing the lens in the lab



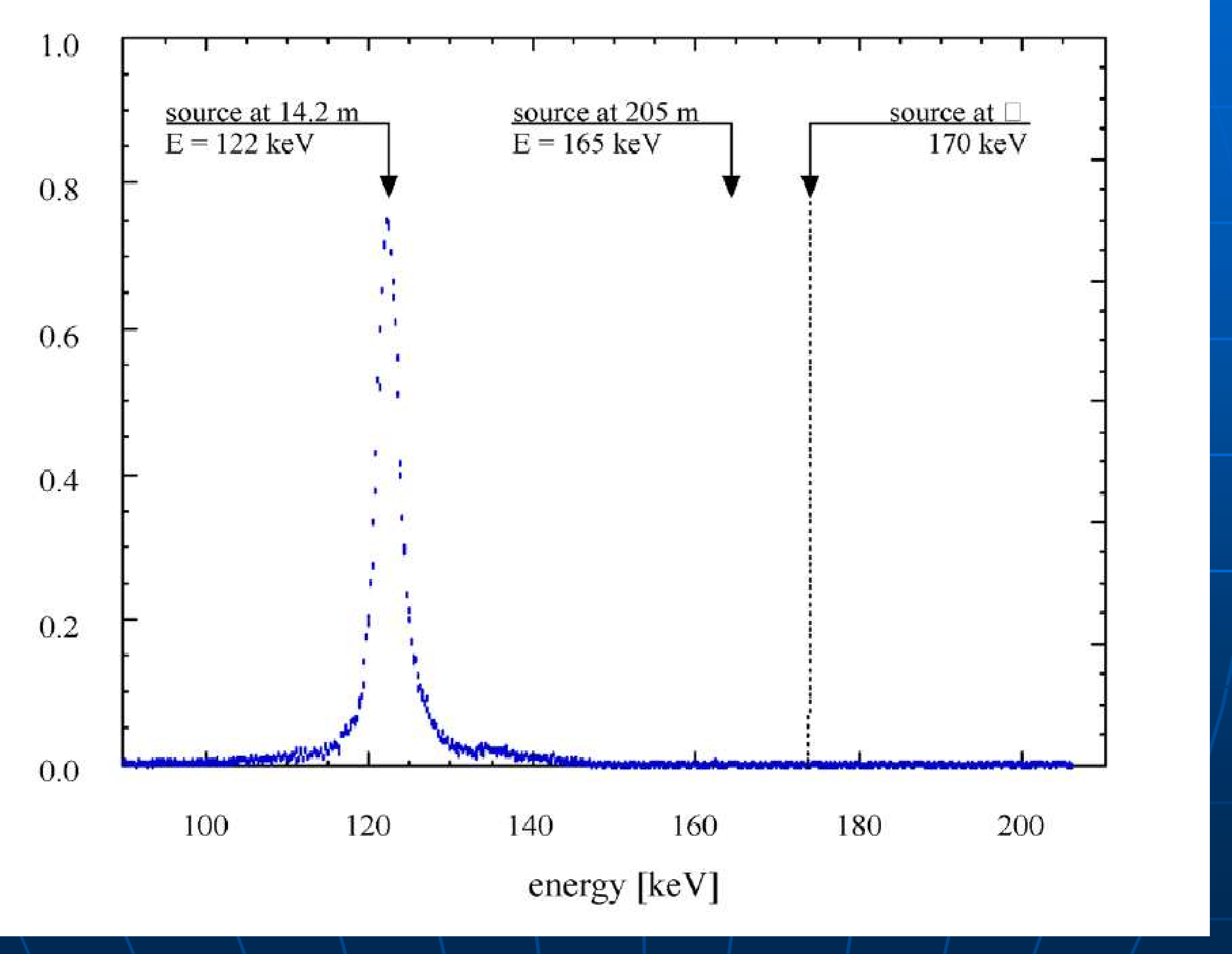
von Ballmoos et al. 2004.

Does it work? What's expected for sources at infinity?



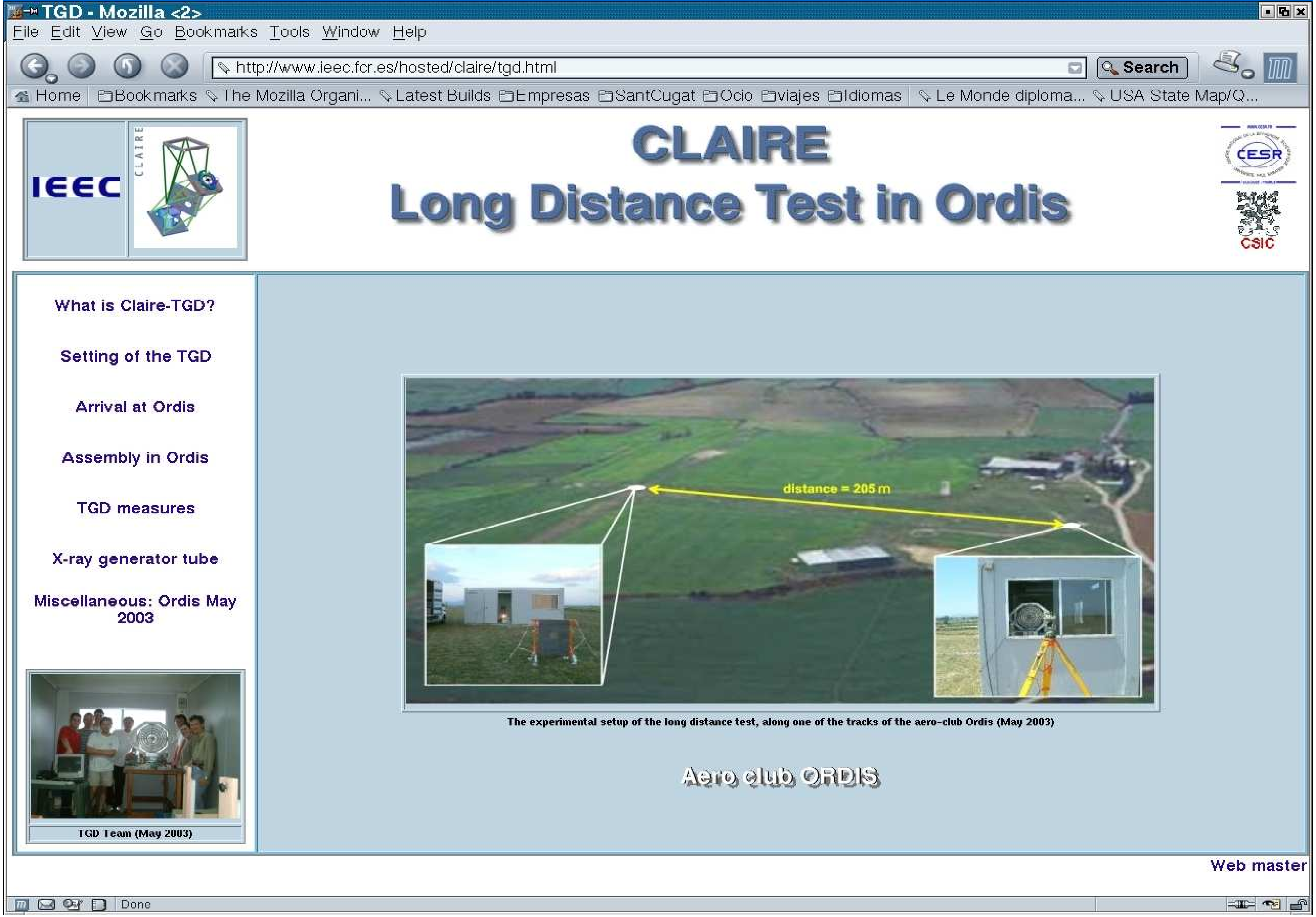
von Ballmoos et al. 2004.

Is the lens performing as expected for sources at quasi-infinity?

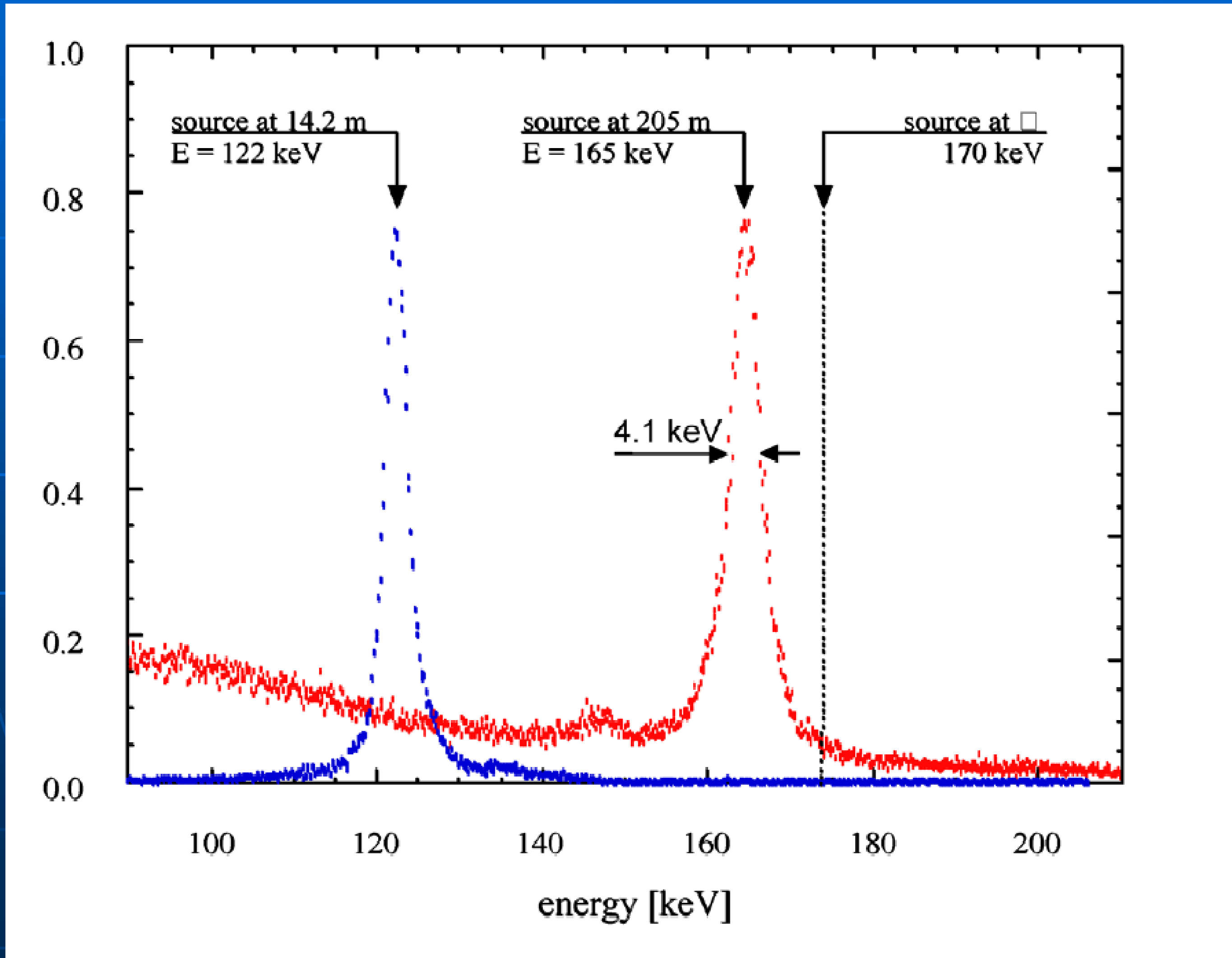


von Ballmoos et al. 2004.

CLAIRE TGD: at 200m



Is the lens performing as expected for sources at infinity?

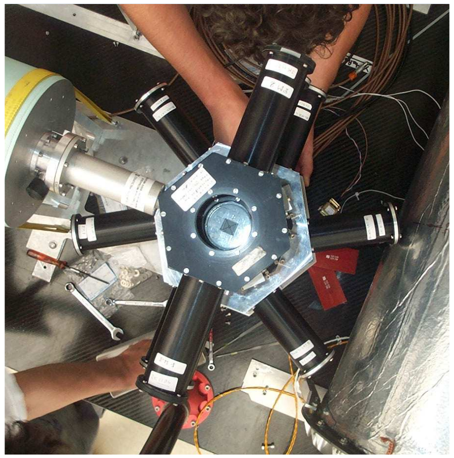


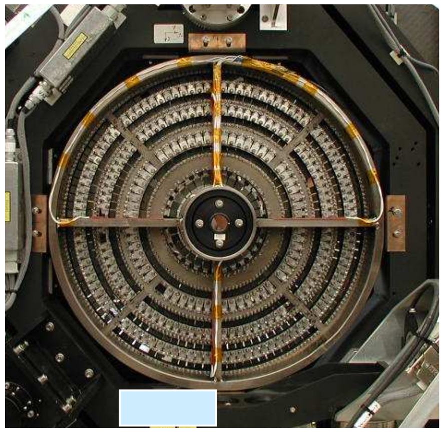
von Ballmoos et al. 2004.

CLAIRE:balloon-borne γ-rays lens telescope

Detector
- 3x3 matrix
- high purity Ge
  1.5*1.5*4 cm

AC shield
- CsI
- BGO

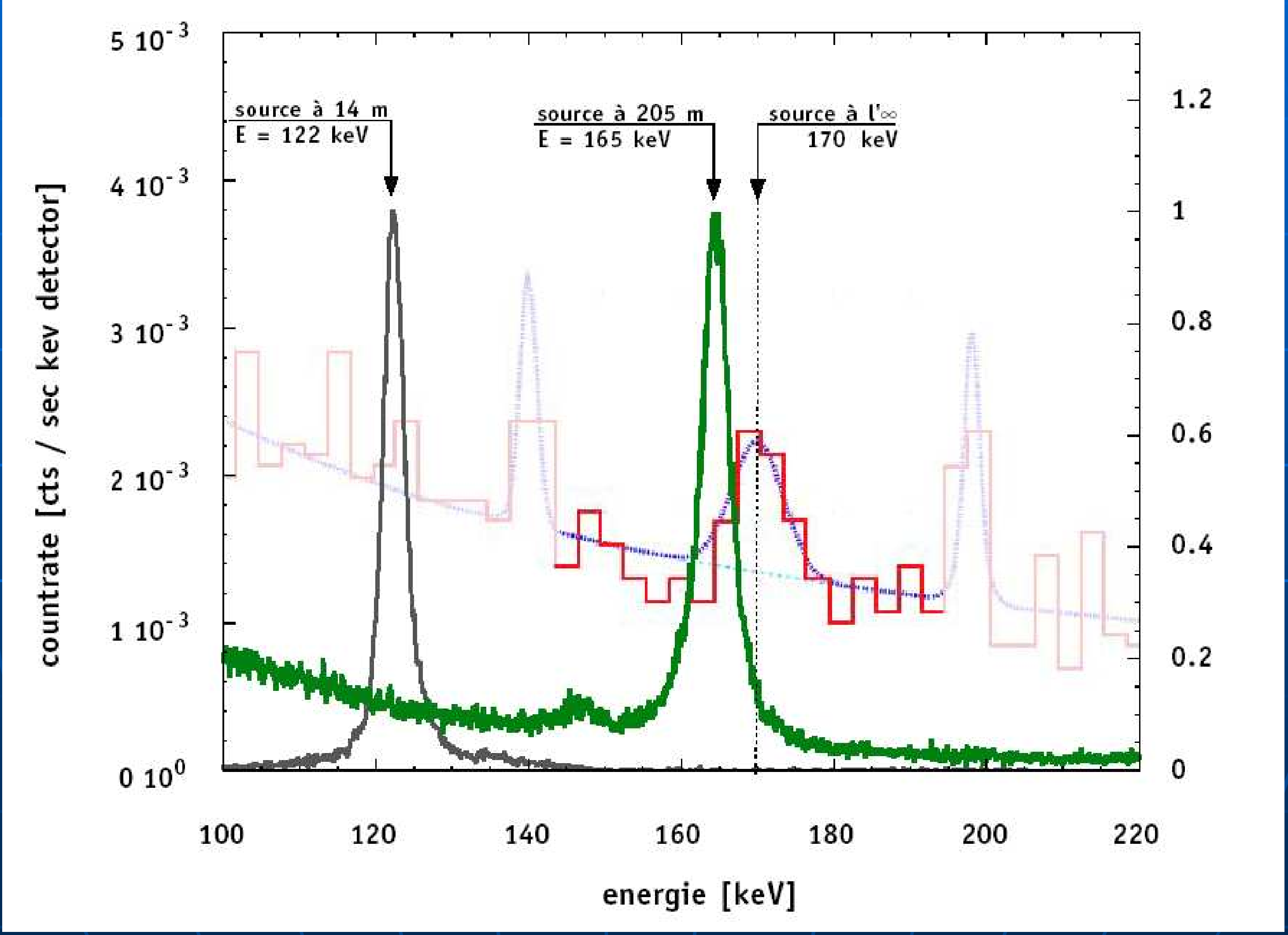




γ-ray lens
- 563 crystals
- E = 170 keV
- FWHM ~ 3 keV

http://www.cesr.fr/~pvb/Claire/index.html

Is the lens performing as expected for sources at infinity?



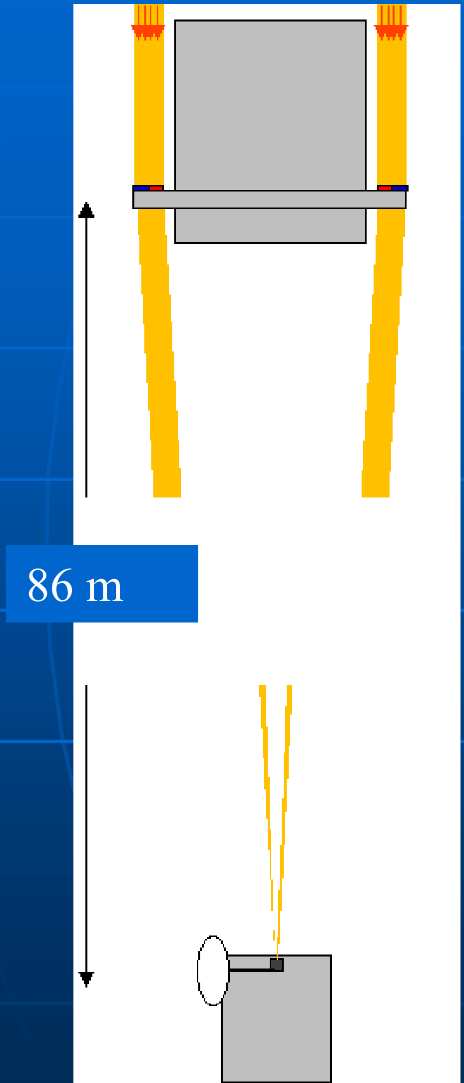
von Ballmoos et al. 2004.

From CLAIRE to MAX (space mission)

www.cesr.fr/~pvb/MAX/

MAX

V2.2 - baseline



Laue lens:

mosaic crystals	30" mosaicity
low E rings	
high E rings	
weight :	140 kg

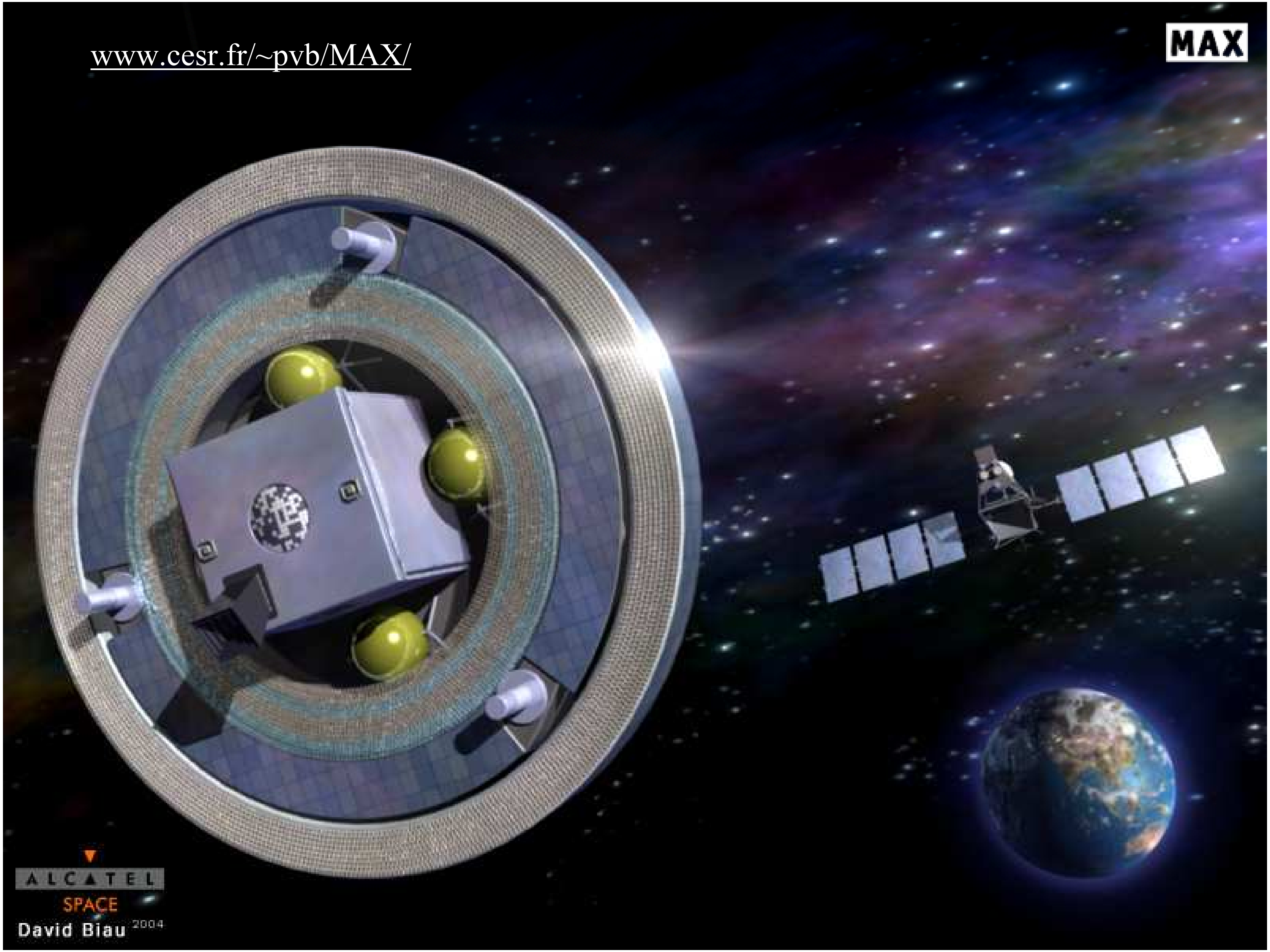
formation flying:

focal length	86 m
orbit	> 60'000 km, circular

detector

www.cesr.fr/~pvb/MAX/

www.cesr.fr/~pvb/MAX/



MAX 3σ narrow line sensitivity

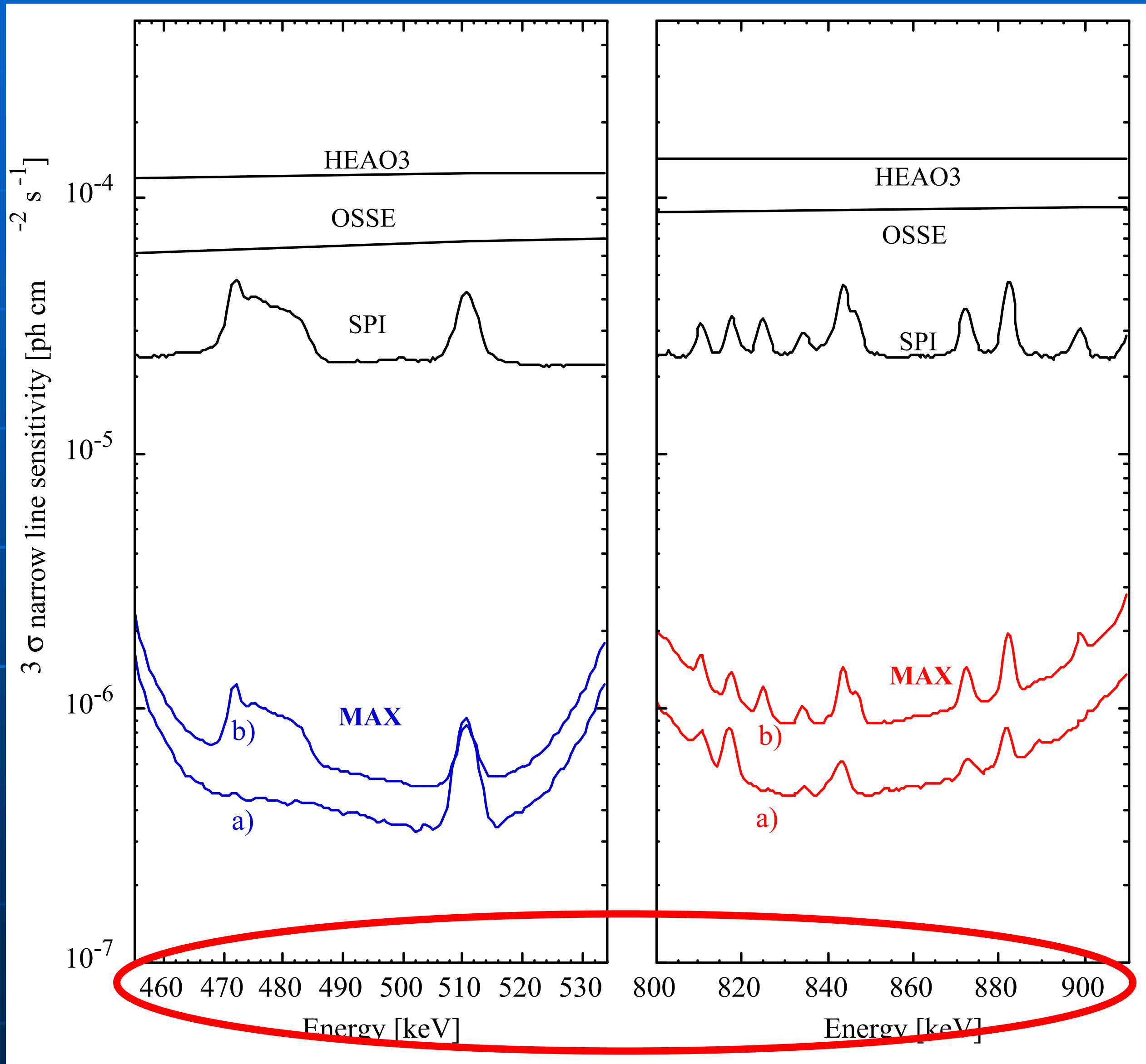
two broad energy bands diffracting simultaneously

- **E/ΔE ~ 500**
- **ang. res. ~ 1'**
- **timing**
- **polarization**

options

a) baseline detector Ge Compton stack

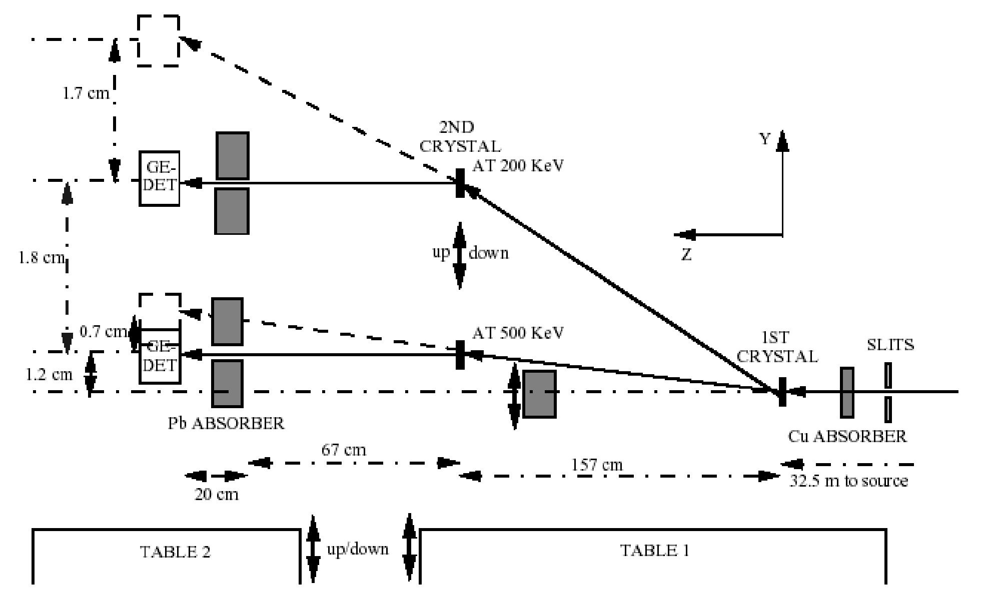
b) single detector SPI type GeD



www.cesr.fr/~pvb/MAX/

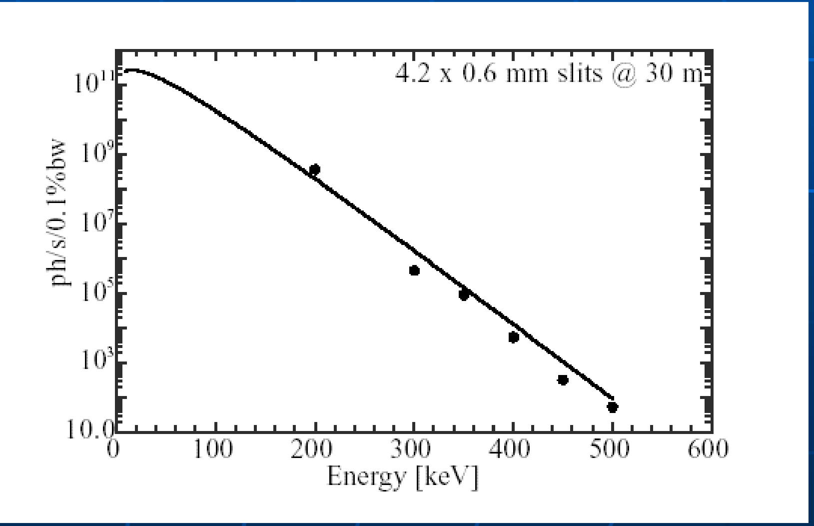
Diffraction efficiencies test with the APS at Argonne National Lab

- The Advanced Photon Source (APS) synchrotron at Argonne National Laboratory is a third generation synchrotron with 7GeV positrons energy. The critical energy is 19.5KeV.
- A bending magnet beam line was used for the test.



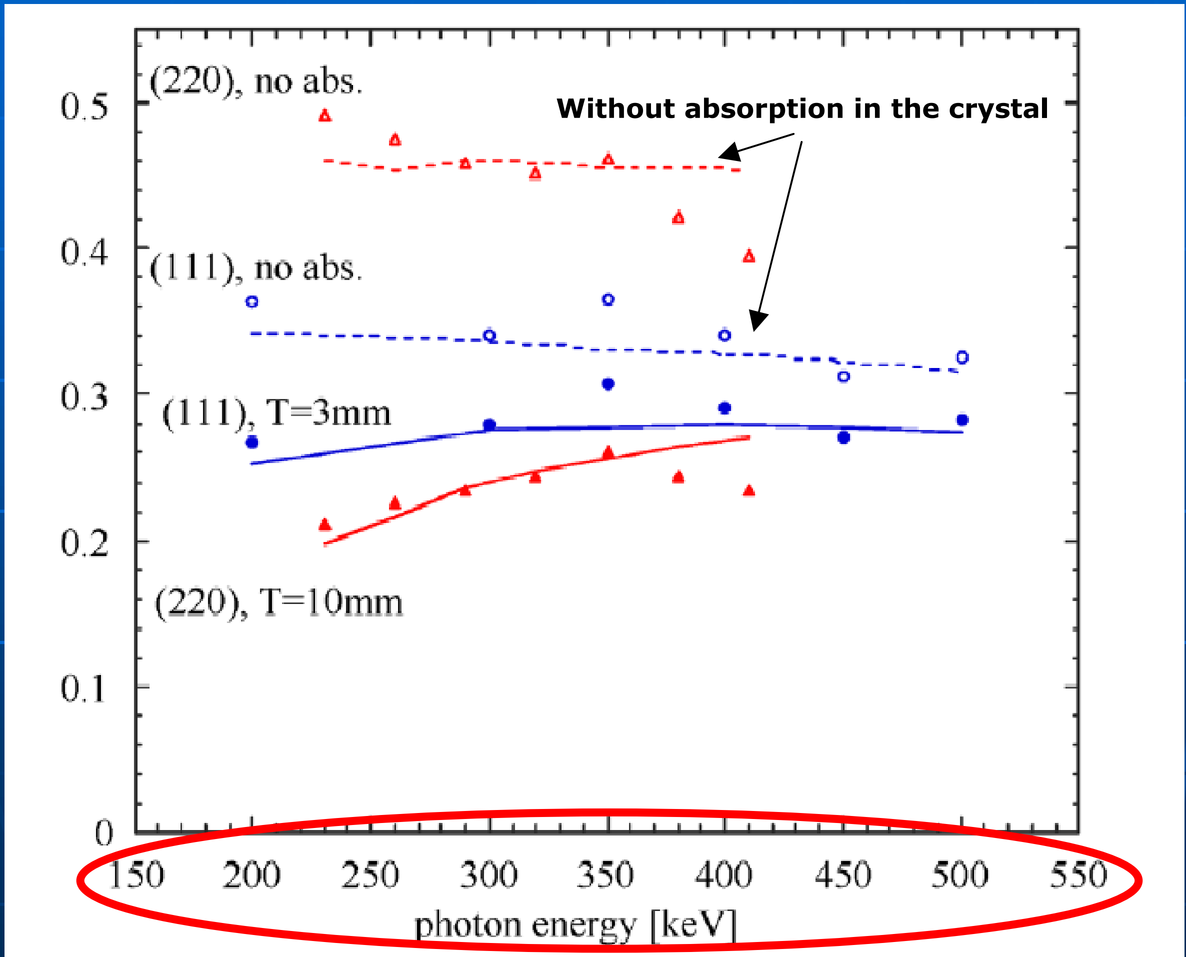
A. Kohnle et al.,NIM,1998

First and second crystals form a double-crystal monochromator



Calculated and measured bending magnet flux from the source.

APS beam test of a Ge crystal



Diffraction efficiency:

Ratio of doubly diffracted/ singly diffracted flux

A. Kohnle et al.,NIM,1998

These measurements served to verify the Darwin mosaic model used to calculate CLAIRE's performance

Experimental proposals for the gamma-ray line beam

Measurement of diffraction efficiencies in mosaic crystals

Crystals	Mosaicity	ΔE	Size	Energy	Miller indices
Ge	30 arcsec	20 KeV	1.5x1.5x1 cm^3	460-522 KeV	[111]
Cu	60 arcsec	70 KeV	1.5x1.5x1 cm^3	825-910 KeV	[111]

Diffraction efficiencies: larger E, various planes (i,j,k); Ge,Cu,Si,...

1. A small beam size makes possible to study the homogeneity of the crystal material, and to measure mosaic widths and efficiencies as a function of position over the crystal face.
2. Dependence of the diffraction efficiency on the mosaic width.
3. Effect of surface damage on the diffraction efficiency.

MAX project: what do we need from GRL?

Energy range	Beam size	Angular size (crystal, at 25m)	Flux	Polarization
0.2-2 MeV	~ $1cm^2$	~ 0.02 mrad	10^6-10^8 ph/s/0.1%bw	high rate of linear polarization desired

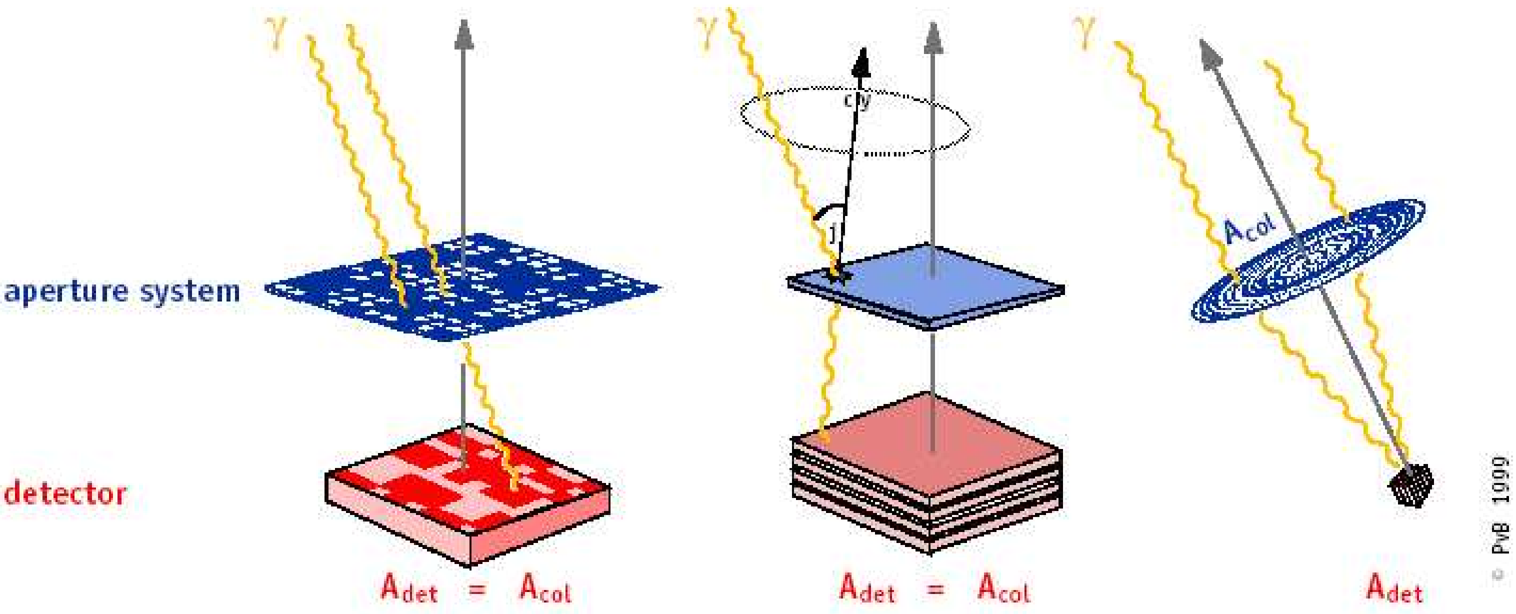
Options:

a) Tunable γ-ray energy in the range 0.2-2MeV ➡ FEL laser

b) Flat-spectrum in the energy range of 0.2-2MeV ➡ CO_2 laser
(select a narrow band of energies with crystal monochromator)

Other concepts for γ-ray telescopes

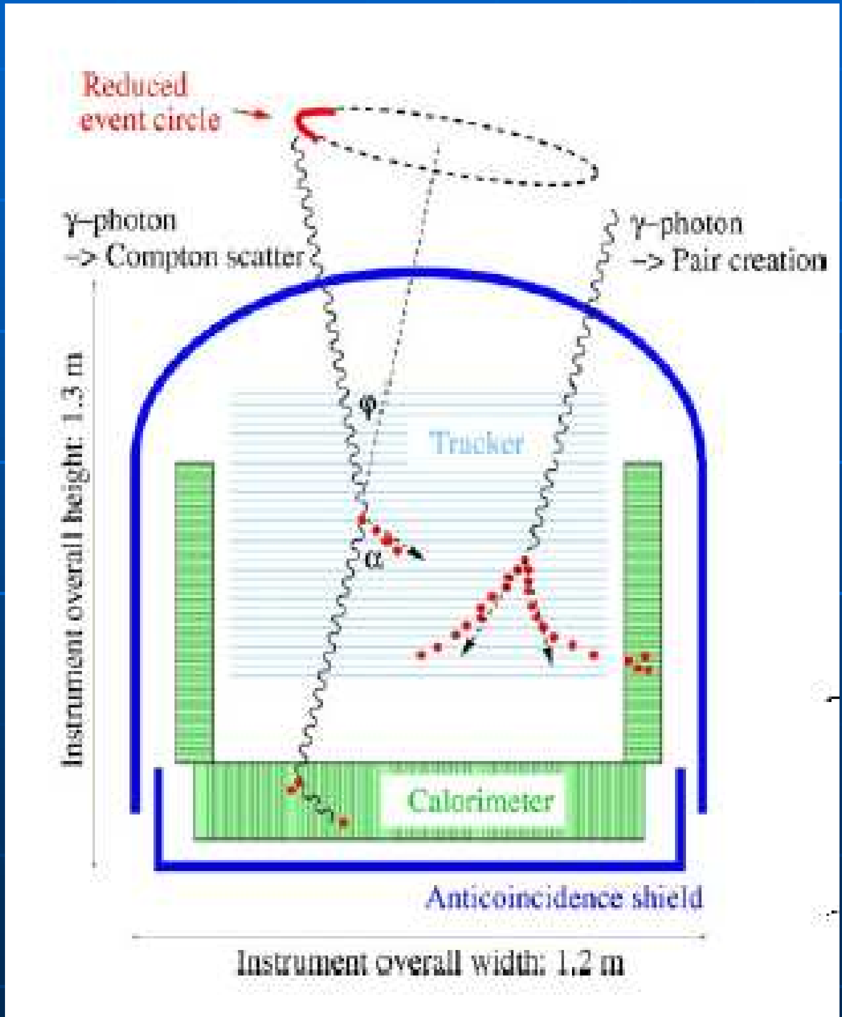
	modulating aperture systems	Compton telescopes	crystal lens telescopes
aperture / effect	geometric optics absorption	quantum optics incoherent scattering	wave optics coherent scattering



signal S	~	A_{col}	A_{col}	A_{col}
background B	~	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} << A_{col}$
S/B	≈	const (A)	const(A)	A_{col}/A_{det}

Mega γ-ray telescope

MEGA: Medium Energy Gamma-ray Astronomy (0.4-50MeV)



Detection Principle:

- Compton (< 10 MeV)
- Pair creation (> 10 MeV)
- Electron tracking
- Polarimeter

Telescope components :

- Tracker (layers of Si strip detectors)
- Calorimeter (CsI or CdTe)
- Shielding (plastic scintillator)

Parameters :

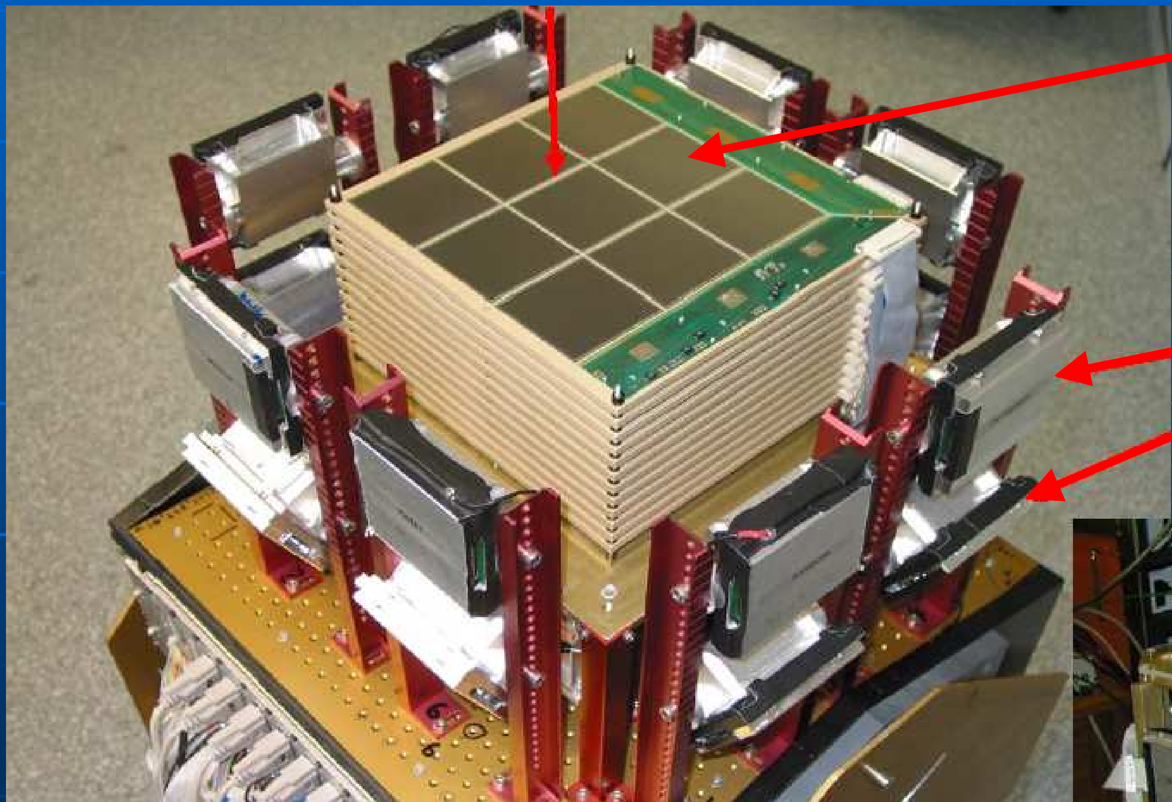
- energy range : 400 keV - 50 MeV
- spectral resolution : 3-4 % (FWHM)
- field of view : 120° (FWHM)
- angular resolution : 2-4° (FWHM)
- effective surface : 100 cm^2
- sensitivity : > 10 × COMPTEL
- new science: polarimetry

Kanbach, et al. NewAR(2004)

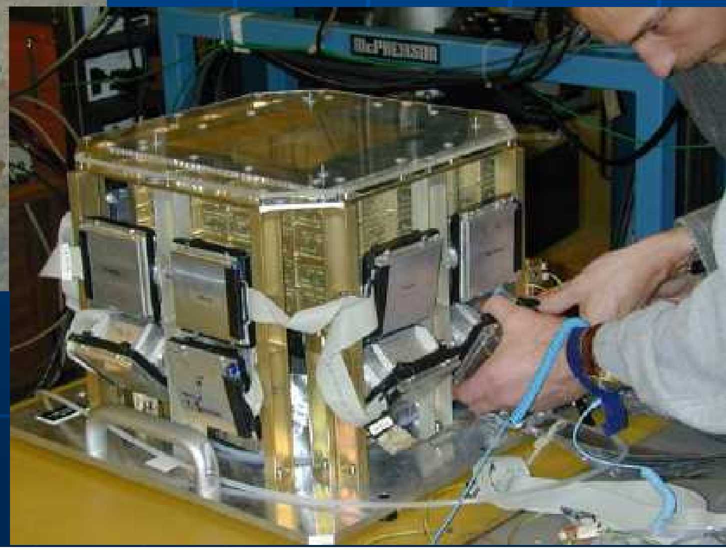
Mega prototype

10 layers of double sided silicon strip detectors 18x18 cm^2, 0.5 mm thick

Wafers 6x6 cm^2



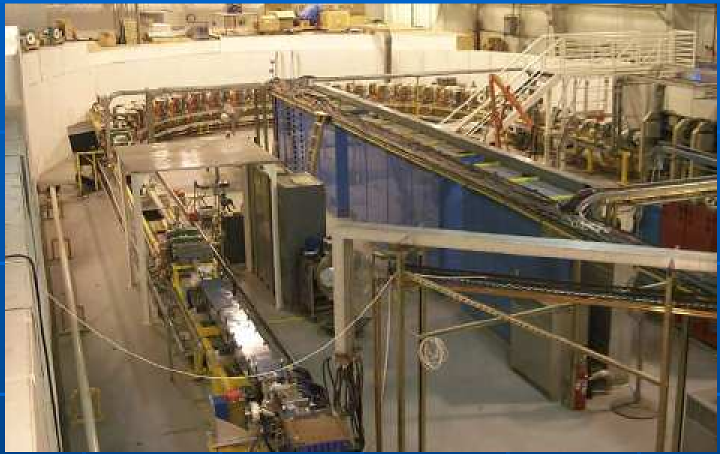
Calorimeter CsI

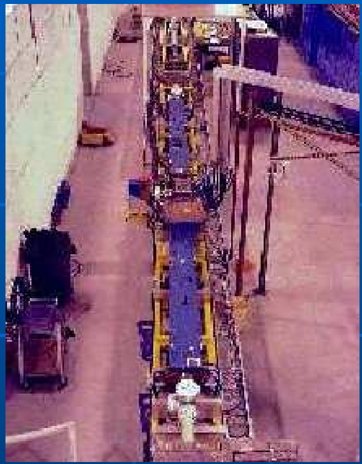


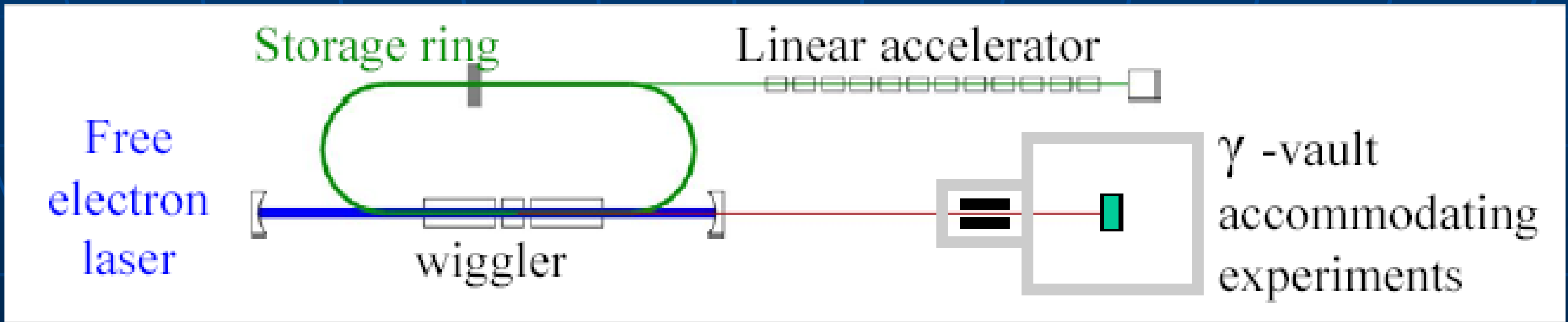
Kanbach et al. (2004)

Mega-Prototype measurements at HIGS

The High Intensity Gamma-ray Source (HIGS) at Duke University







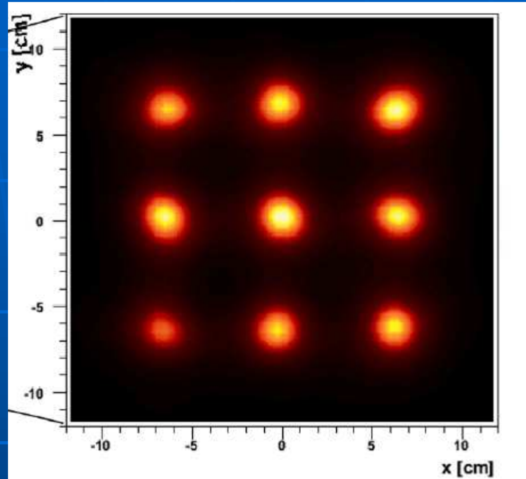
Andritschke.R, et al. (2003)

Mega-Prototype measurements at HIGS

Measured Energies and Angles (15.5 10^6 triggered events)

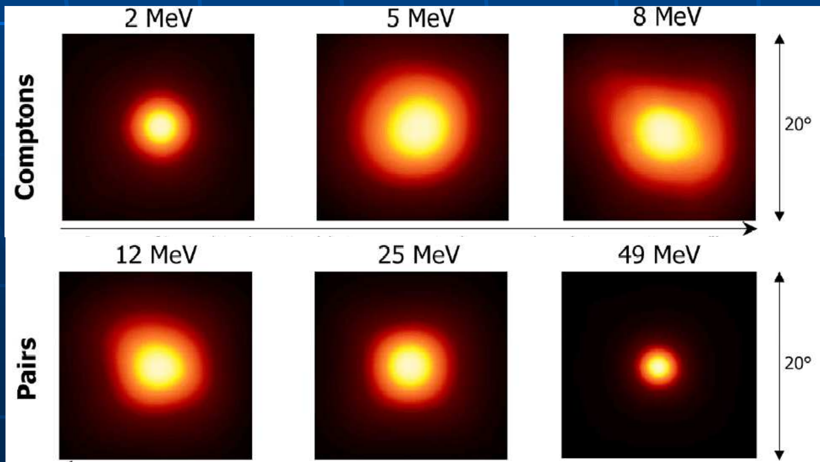
Energies [MeV], Angles ($\cdot 10^3$ events)

Angles	0.7	2	5	8	10	12	17	25	37	49
0°	300	400	345	255	435	435	435	345	435	1095
30°	246		345		525	525	525	390	480	390
60°			480		525	705	570	570	570	570
80°						480		570	480	480
120°			120			165		165	120	165
180°			120		165	120			220	240
Σ	546	400	1410	255	1650	2430	1530	2040	2305	2940

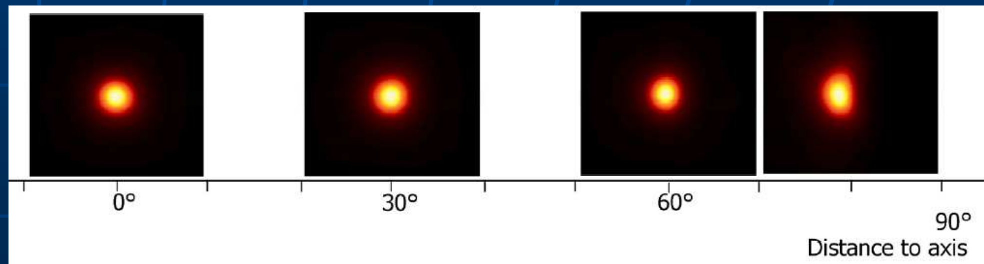


Deconvolved image of pair events (50MeV) for the 9 XY-positions incidenting on Si-strip detectors.

Beam images 0º incidence



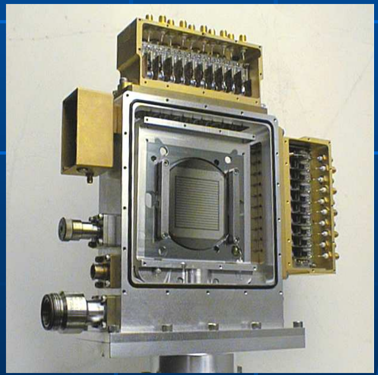
Beam images at 49 MeV



Andritschke.R, et al. NewAR 48 (2004)

ACT options

PROPERTY	CZT STRIP	Si STRIP	Ge STRIP	LIQUID Xe	Xe μWELL
ΔE/E (1 MeV)	1%	0.2-1%	0.2%	4.5%	1.7%
Spatial Resolution	<1mm^3	<1mm^3	<1mm^3	<1mm^3	0.2 mm^3
Stopping Power (Z, density)	48 8.3 g/cm^3	14 2.3 g/cm^3	32 5.3 g/cm^3	54 3.0 g/cm^3	54 0.02 g/cm^3 (3 atm)
Volume (achieved)	4 cm^3	60 cm^3	130 cm^3	3000 cm^3	50 cm^3
Operating T	10º C	-20º C	-190º C	-100º C	20º C
Application	calorimeter	scatterer	scat/cal	scat/cal	scatterer
Institutions	UNH, UCSD	NRL, UCR	Berkeley, NRL	Columbia, Rice	GSFC


- TIGRE MEGA Ge-ACT Liquid XE
- UC Riverside MPE, UNH UC Berkeley Columbia