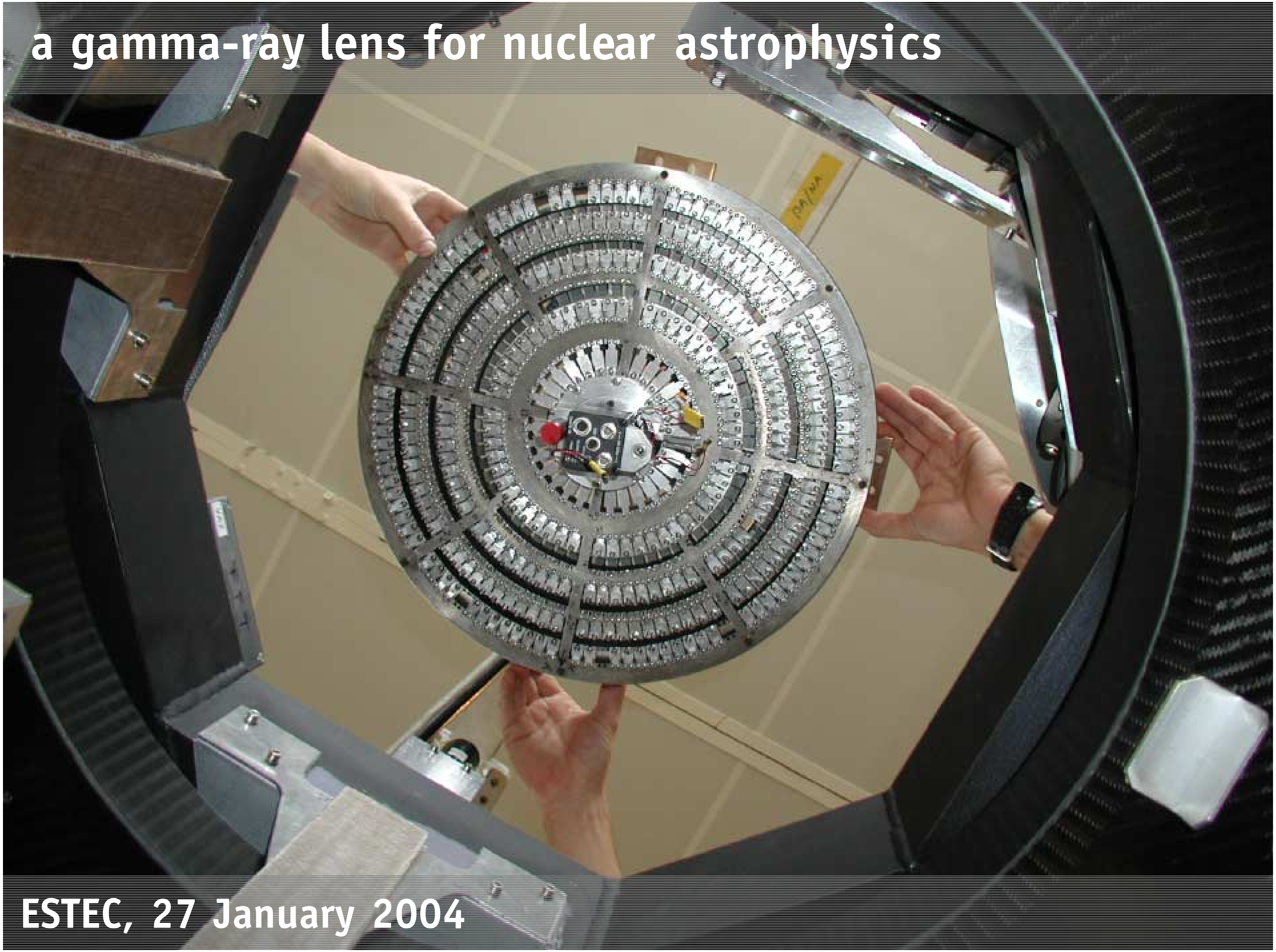
a gamma-ray lens for nuclear astrophysics



ESTEC, 27 January 2004

Peter von Ballmoos - CESR Toulouse for the CLAIRE and MAX collaborations

CESR Toulouse, CNES, IKZ Berlin, IEEC Barcelona, ANL Chicago, ILL Grenoble, CEA Saclay, IASF Roma and Bologna, Observatory of Geneva

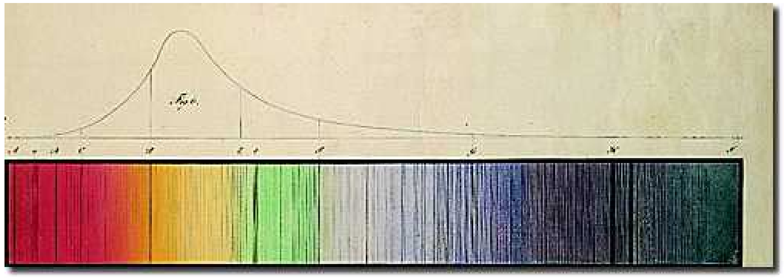
Focusing gamma-rays : why ? how ?

Gamma-ray lenses for nuclear astrophysics :

- **measuring the performance of a Laue lens**
- **CLAIRE TGD - confirming CLAIRE's first light**
- **CLAIRE's balloon flight of June 14, 2001**
- **from CLAIRE to MAX**

from Astronomy to Astrophysics ...

1814

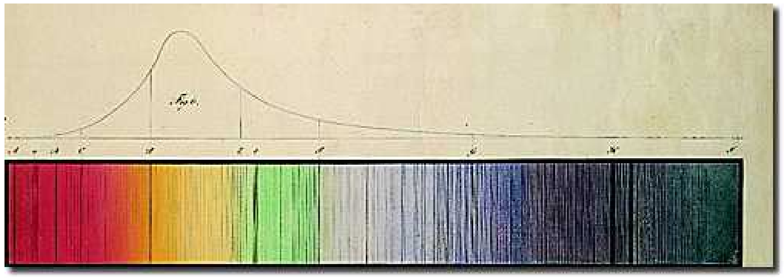


prism-spectrograph

Josef Fraunhofer
spectroscopy as a tool for studying chemical elements present in stars

and from gamma-ray astronomy to nuclear astrophysics

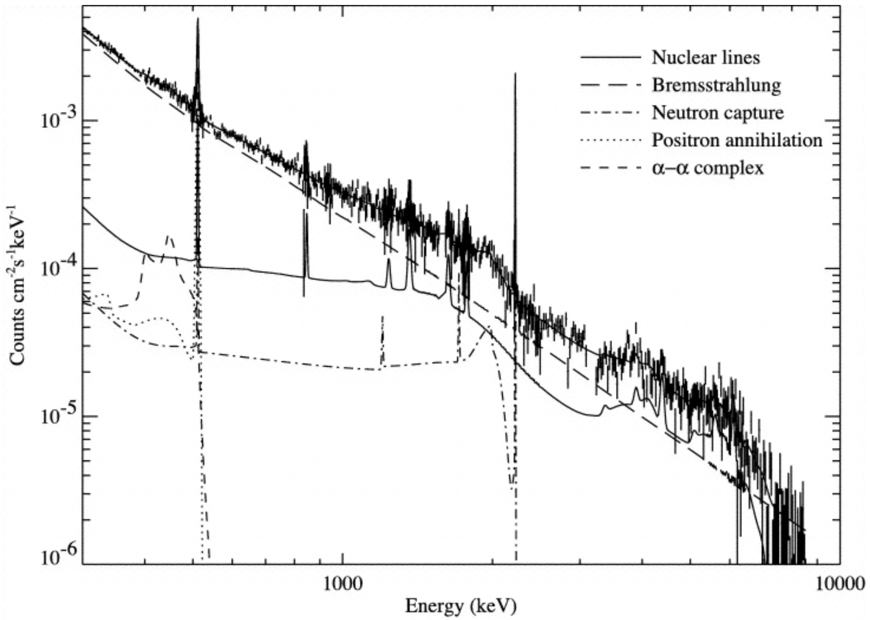
1814



prism-spectrograph

Josef Fraunhofer
spectroscopy as a tool for studying chemical elements present in stars

2003



gamma-ray telescope RHESSI

R. Lin et al. 2003

solar gamma-ray line flare
of 2002 July 23
prompt de-excitation lines of
Fe, Mg, Si, Ne, C, and O

the promise of nuclear astrophysics

radioactive decay {$^{26}Al(b^+,\gamma)^{26}Mg$, $^{56}Co(EC,\gamma)^{56}Fe$ ...}

nucleosynthesis in supernovae, novae, origin of chemical elements ...

nuclear desexcitation {$^{12}C(p,p',\gamma)$, }

physics of interstellar processes, energetic particles, cosmic rays ...

neutron capture {$^{1}H(n,\gamma)^{2}H$}

energetic particles

cyclotron emission and absorption

physics of magnetized neutron stars

annihilation {e^-e^+ }

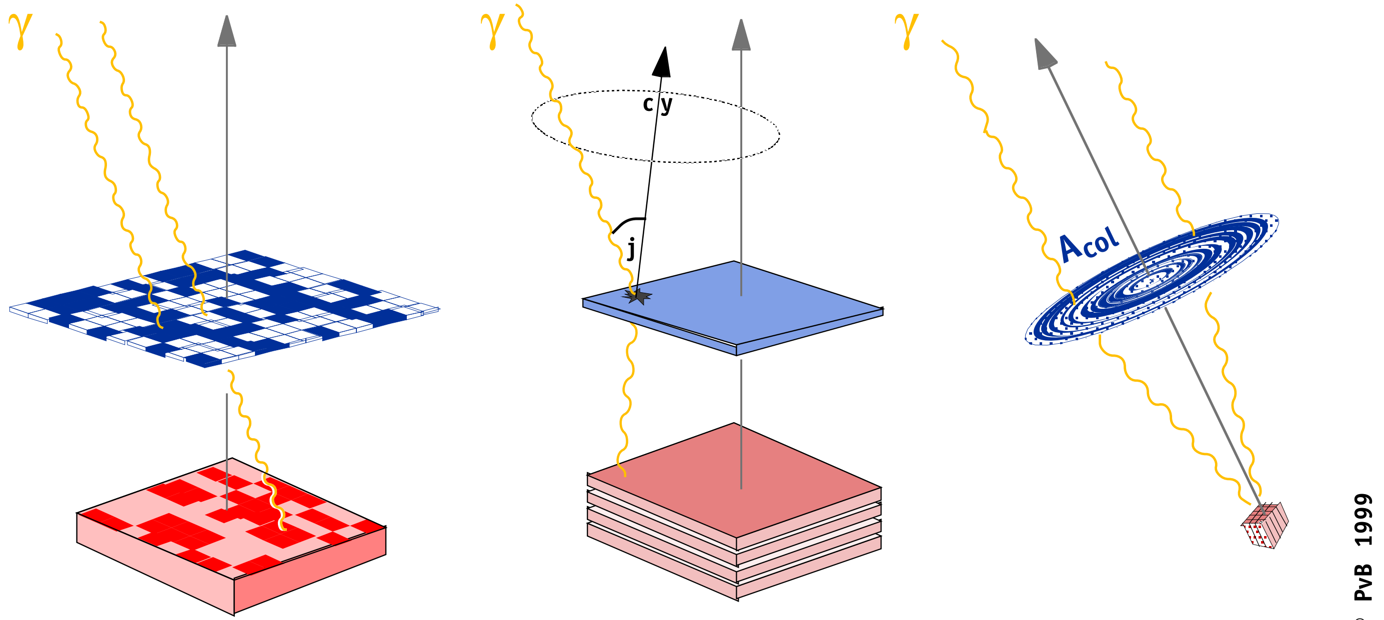
radioactivity, comapct objects (BH), hypernovae, light dark matter ...

Focusing Gamma-Rays - why ?

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

aperture system

detector



		$A_{det} = A_{col}$	$A_{det} = A_{col}$	A_{det}
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}

Focusing Gamma-Rays ?

... the inability to reflect or deflect individual photons makes the concentration of a gamma-ray beam impossible.

A. J. Dean, *Nuclear Instruments and Methods in Physics Research* **221**, 1984

Focusing gamma rays seems out of the question since their wavelengths (less than 0.01 angstrom) are smaller than the distance between atoms in solids.

Giovanni F. Bignami, *Sky & Telescope*, October 1985

Higher-energy X-ray photons can pas through a lens, but since they undergo no significant deflection, no focusing can take place.

Gerald K. Skinner, *Scientific American*, August 1988

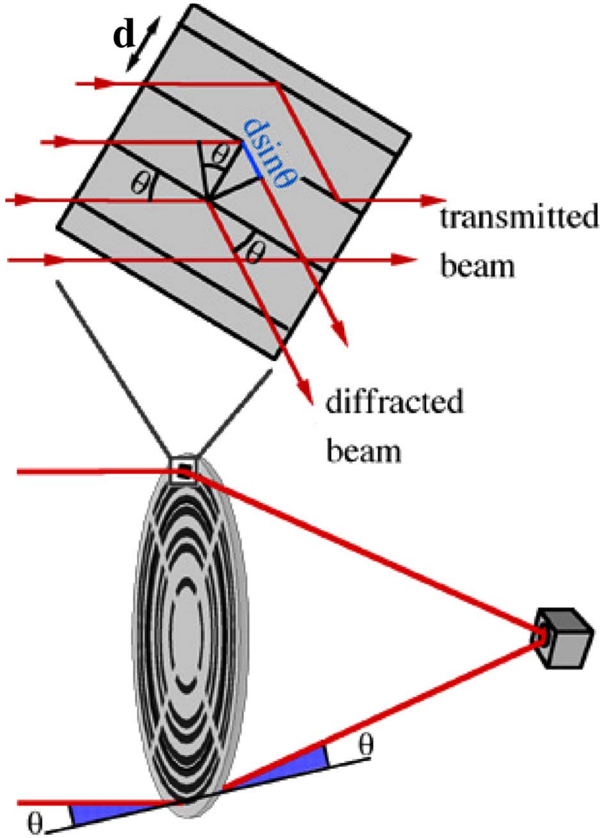
... gamma-rays can not be focused. They are scattered incoherently and the direction of the scattered electrons are lost.

von Ballmoos et al., *Astron. Astrophys.* **221**, 396, 1989

**"Tout le monde croyait que c'était impossible,
sauf un imbecile, qui ne le savait pas et qui l'a fait"**

***"Everybody believed that it was impossible,
except an idiot who didn't know that and who did it"***

Marcel Pagnol, 1895-1974.



λ(511 keV)	=	$2.42632 \cdot 10^{-2}$ Å

Bragg condition

$2d\sin\theta$	**=**	**$n\lambda$**

d[220]	=	2.0004Å
arcsin(λ/2d)	=	0.347°

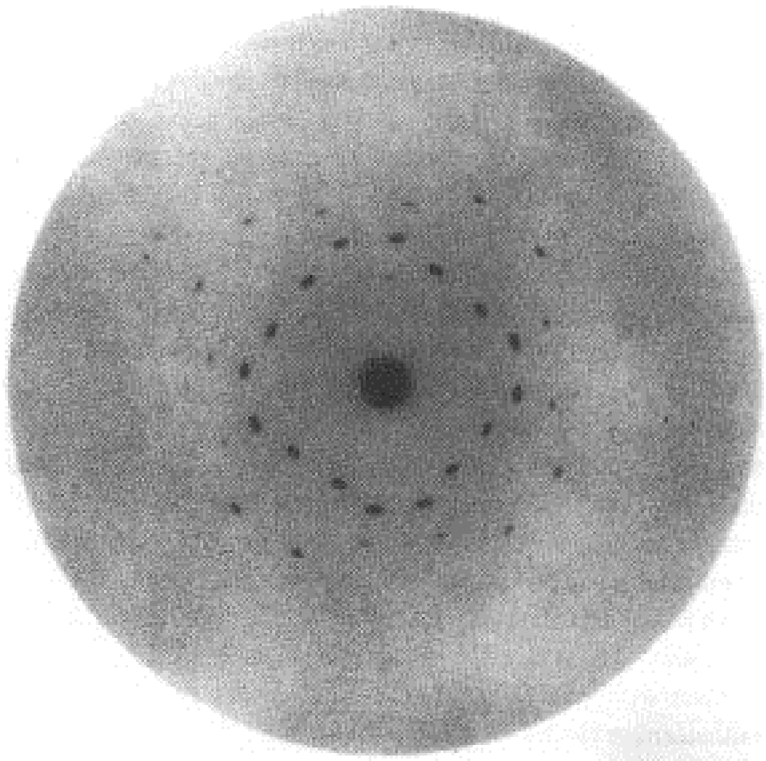
Laue-type Gamma-ray lens

2θ	=	0.695°
ex. radius [220]	=	10.1 cm
=> focal lenght	=	8.2 m

narrow band Laue lens :	higher orders at larger radia (CLAIRE)
broad band Laue lens :	most efficient order at all radia (MAX)

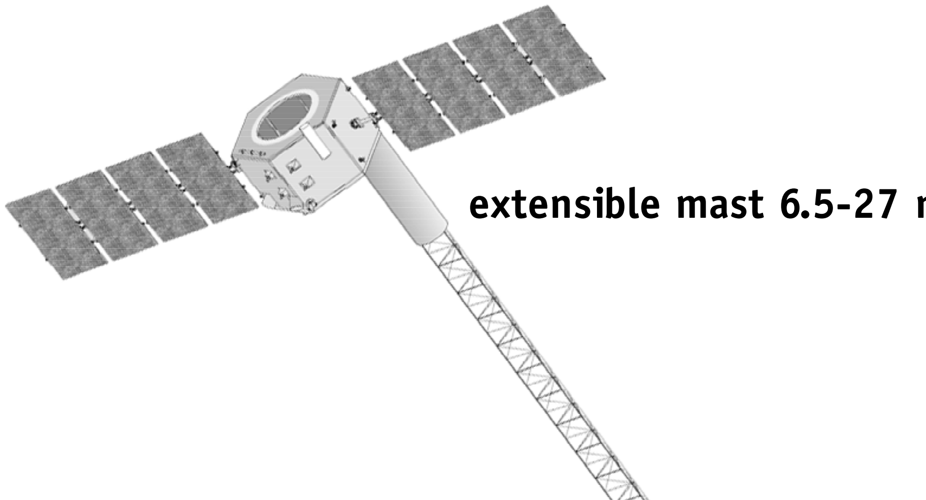
Focusing Gamma-Rays - how ?

Demonstrate the wave character of X-rays using very fine grids : crystals !

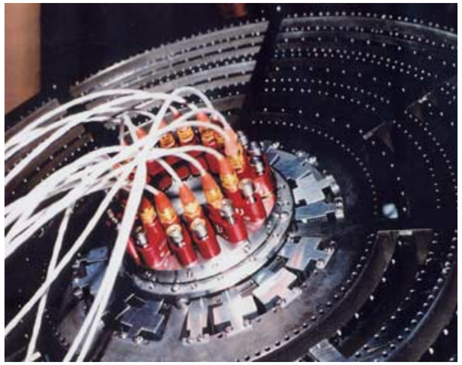


Laue, Friedrich and Knipping, 1912

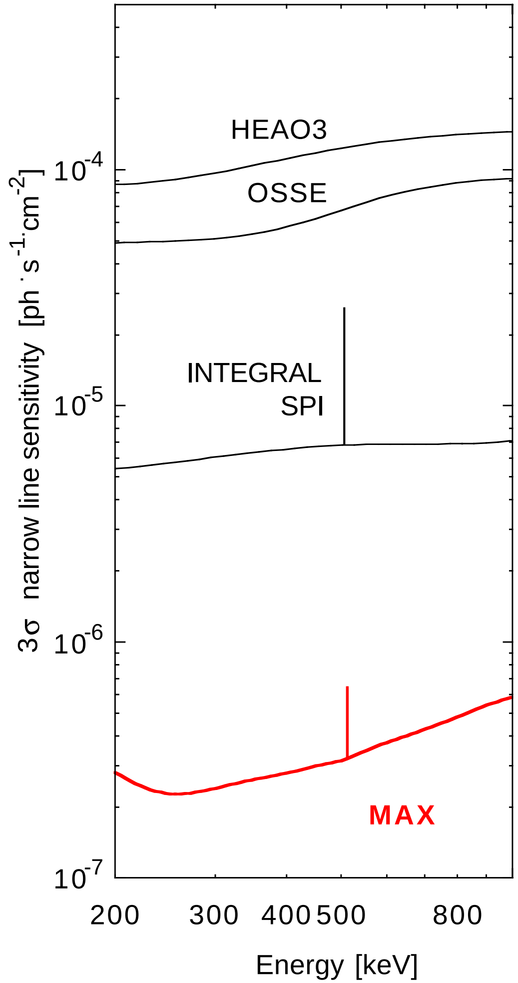
a tunable Laue lens observing one energy at the time



extensible mast 6.5-27 m



prototype tunable lens



March 2000 : AWG/SSAC assessment of MAX V1.0

Potential of MAX for nuclear astrophysics has been fully recognized :

- **innovative way of doing gamma-ray astronomy**
- **drammatic increase in performance - 2-3 magnitudes.**

yet : narrow bandpasss: few prime targets => narrow science community
complexity : moving parts (bender plates, mast - thermal distortions)

Reviewers bottom line :

- **Need for a precursor mission**

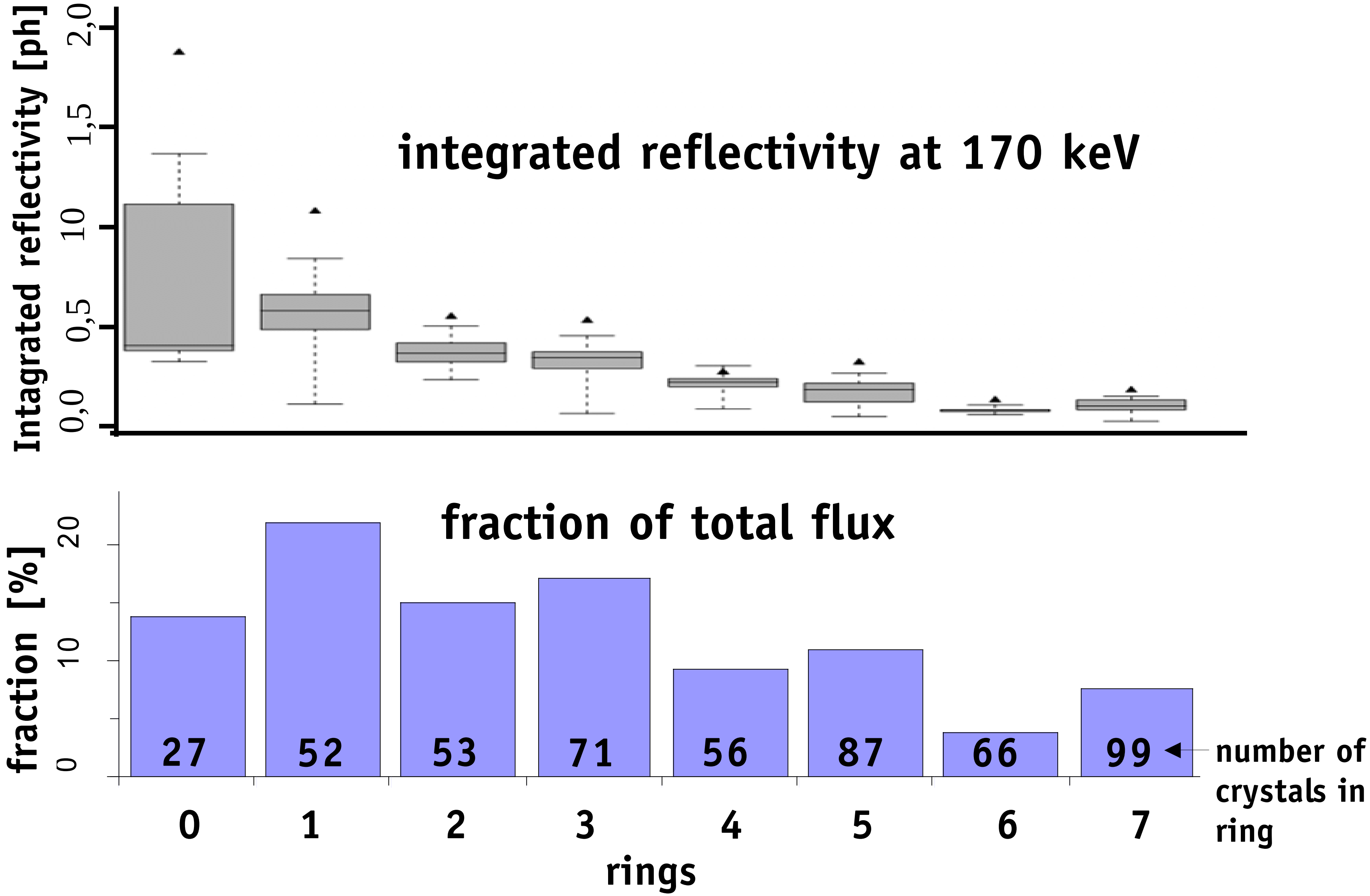
- **MAX *clearly* is the way to go in the future, but future has not arrived yet**

the messsage is *CLAIRE* ....

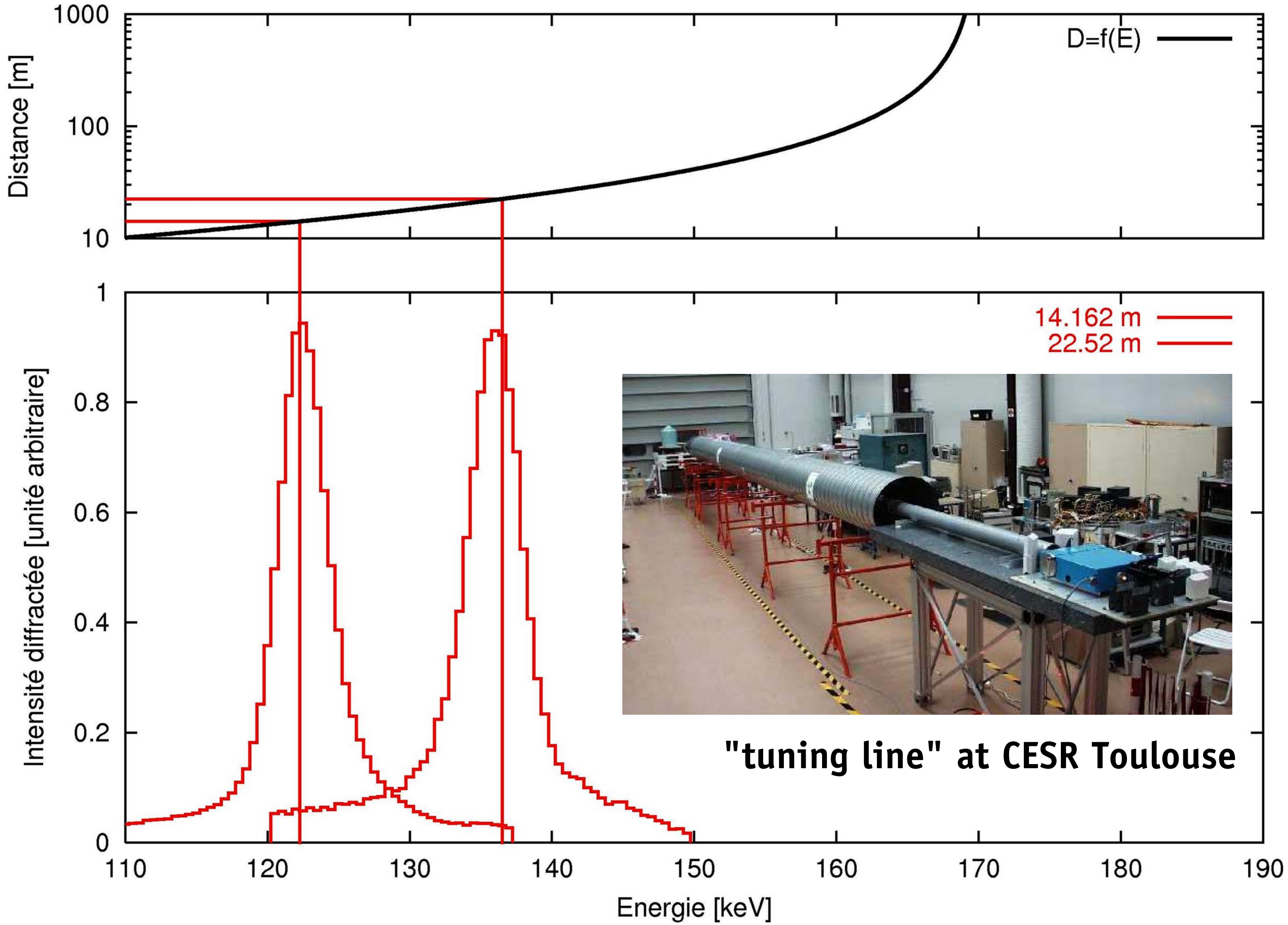
l'astronomie gamma
commence à voir

CLAIRE

CLAIRE : individual crystal quality mesured during tuning

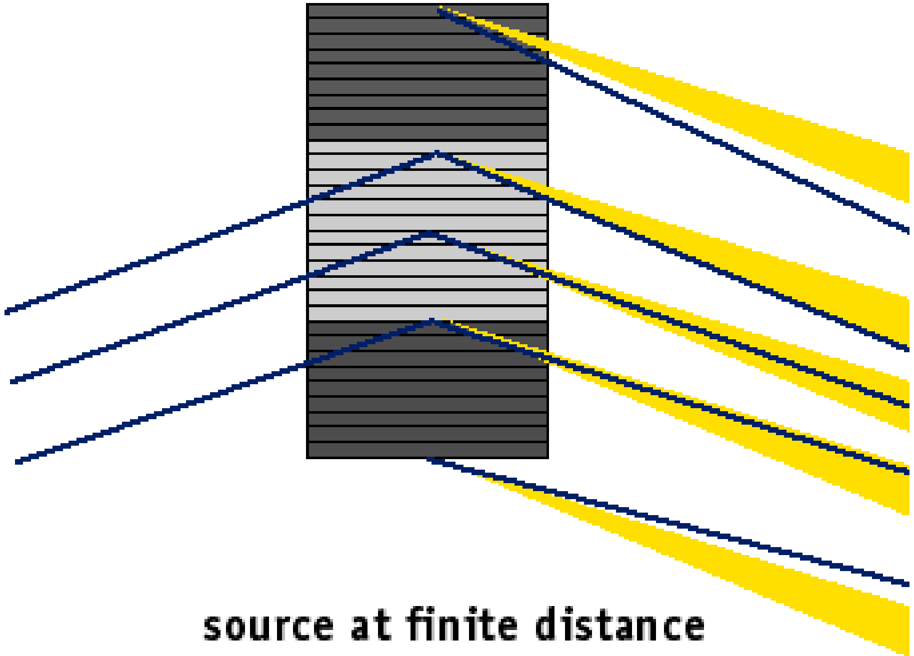


CLAIRE : testing the lens in the lab ... and beyond



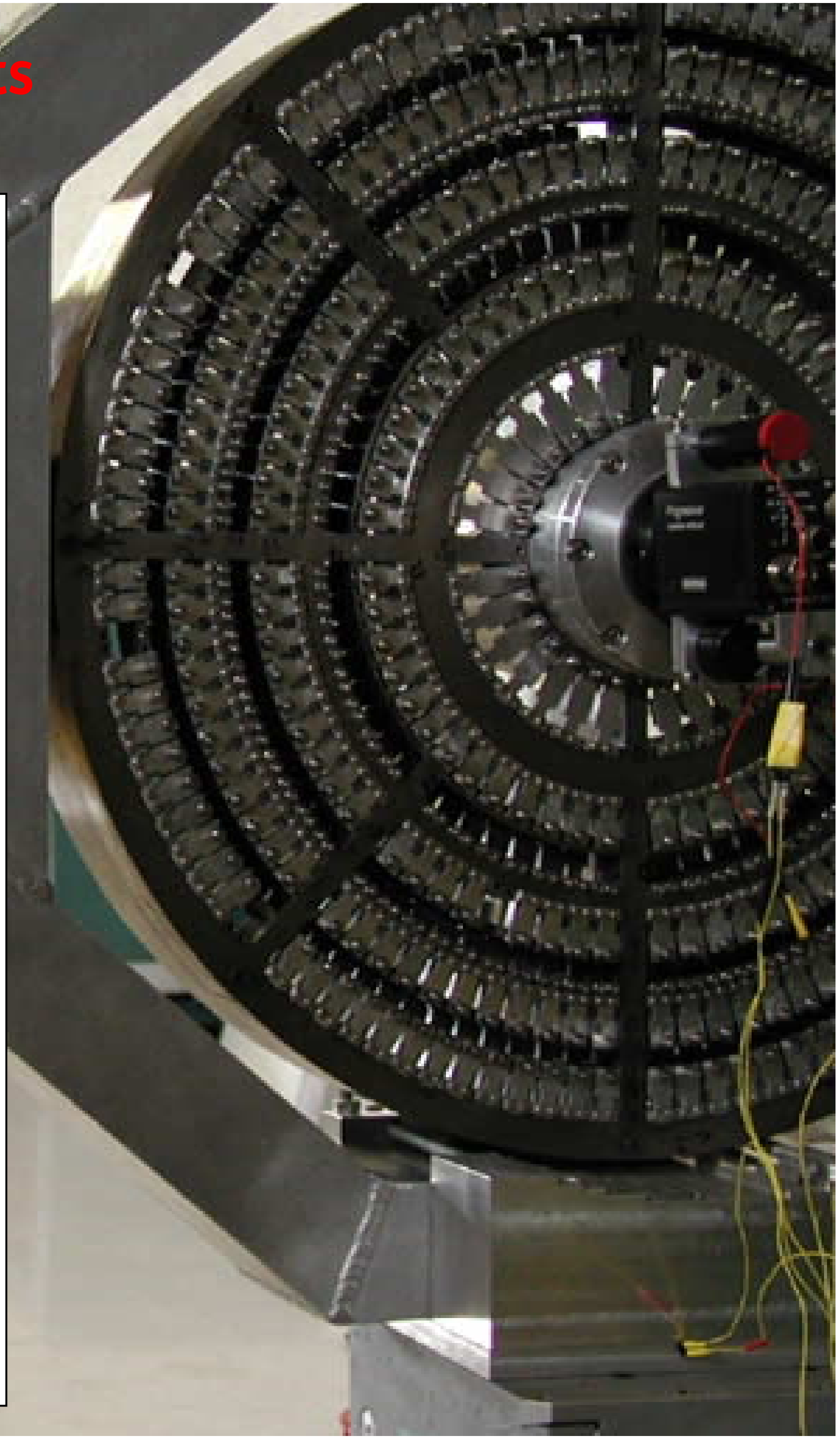
CLAIRE : laboratory measurements

a radioactive source ^{57}Co at 14 m
is seen with a efficiency of only ~ 3.2 %

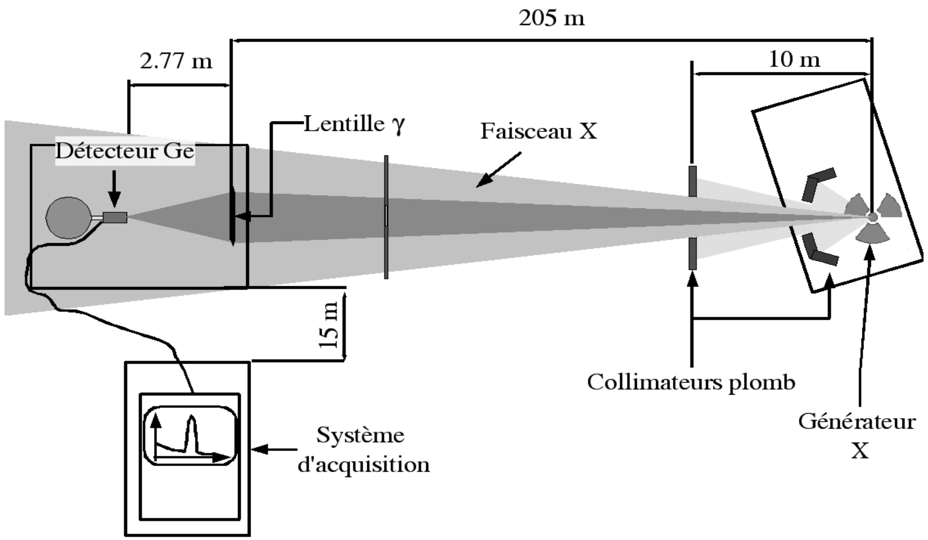


source at finite distance

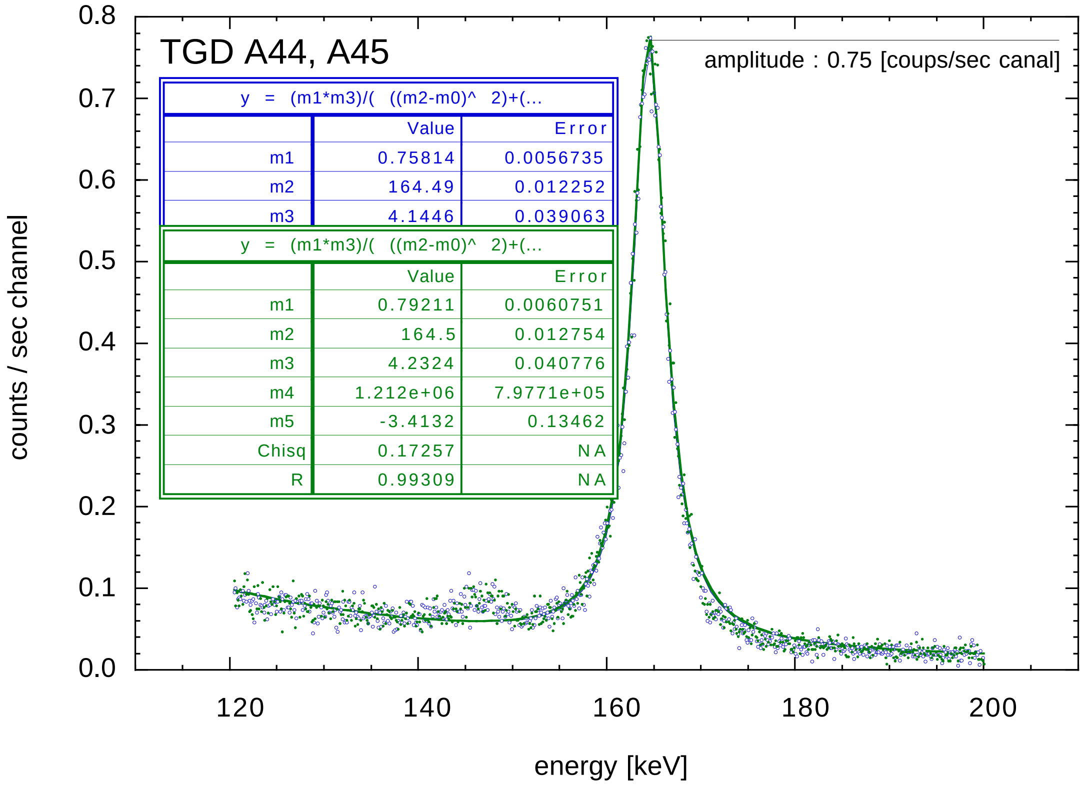
Extrapolation :
170 keV, continuum, ~ 1 $ph/cm^2/keV$
$\Rightarrow$ $Eff_{pic} = 12^{\pm 1}$ % (3 keV FWHM)



CLAIRE TGD : a source close to "inifinity" ...



CLAIRE TGD : diffraction efficiency

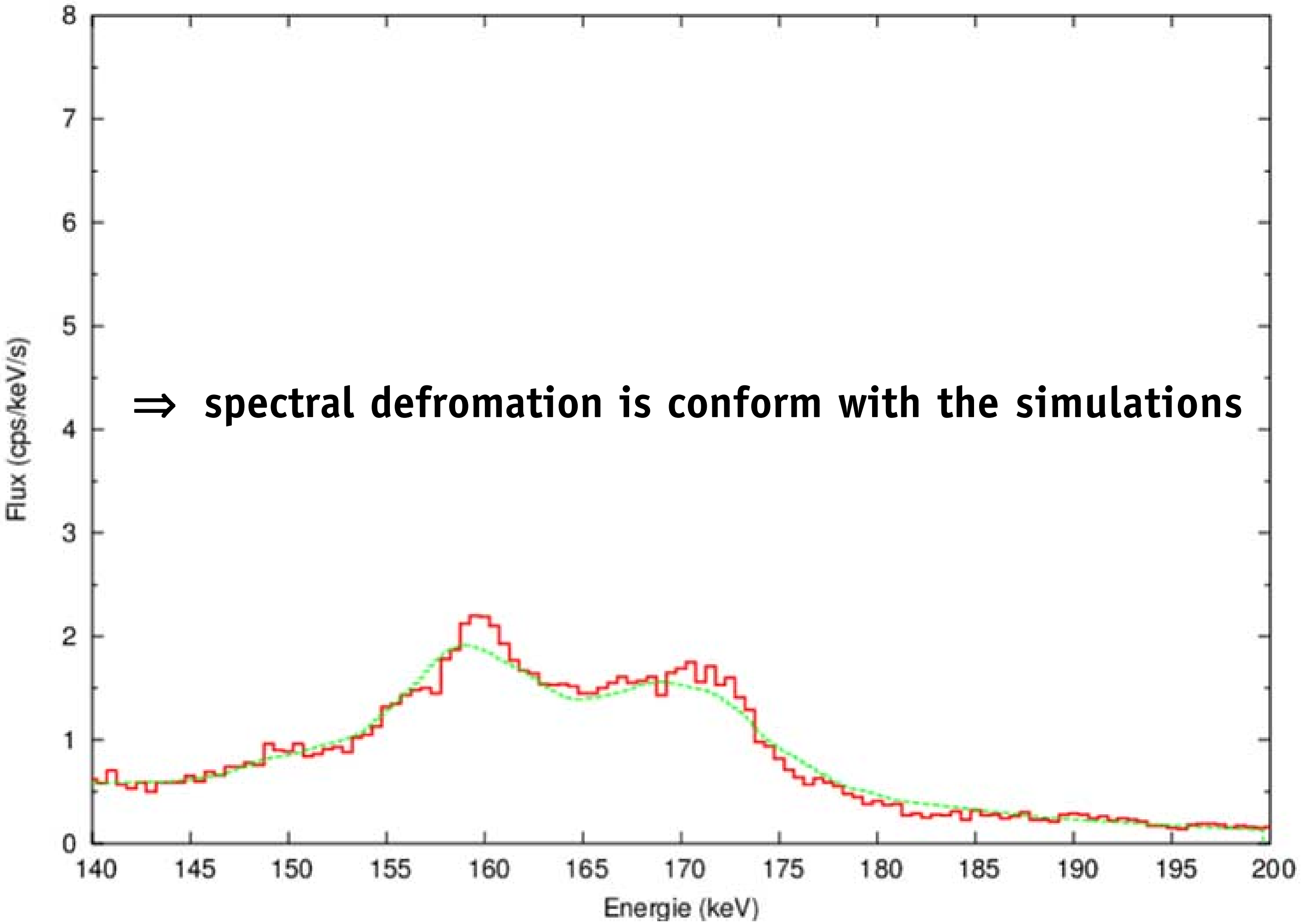


incident flux on the 511 cm^2 of CLAIRE : 83.7 c/s keV

peak amlitude (4.1 keV wide Lorentzian) : 5.99 c/s keV => ε_{peak} = 7.2%

efficiency for instrumental width (3 keV) : $\varepsilon_{peak} \approx 9.7$ %

CLAIRE TGD : off axis response



⇒ spectral defromation is conform with the simulations

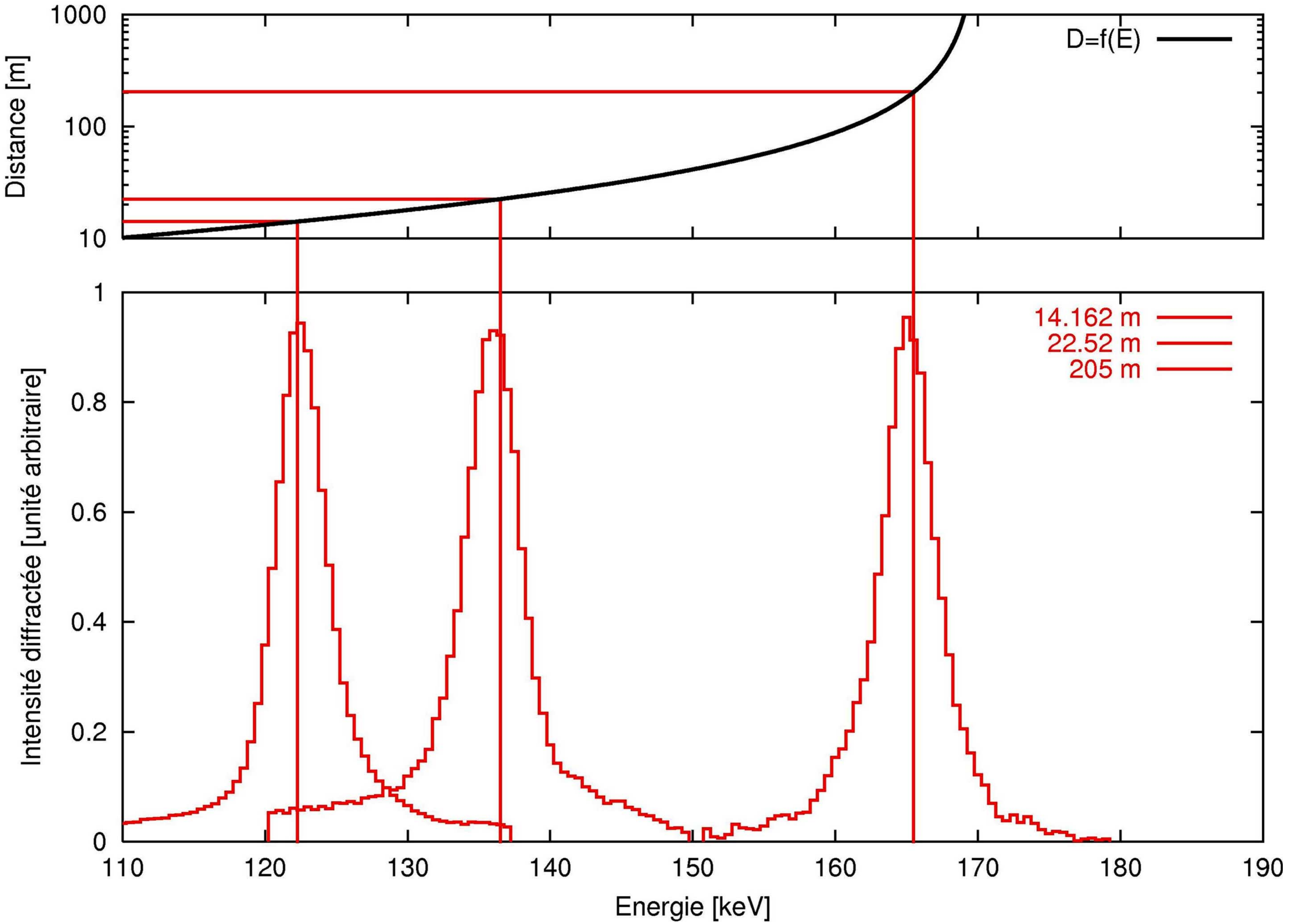
depointing

-270″

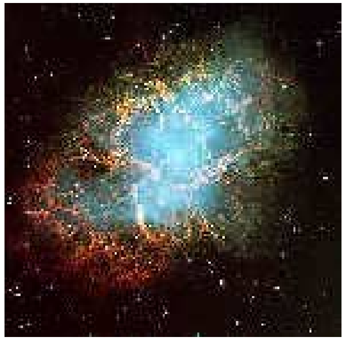
TGD

simulation

CLAIRE TGD : 14, 22.5 … and 205 m



CLAIRE 2001 : validating the γ-ray lens for astrophysics



The Crab Nebula ?

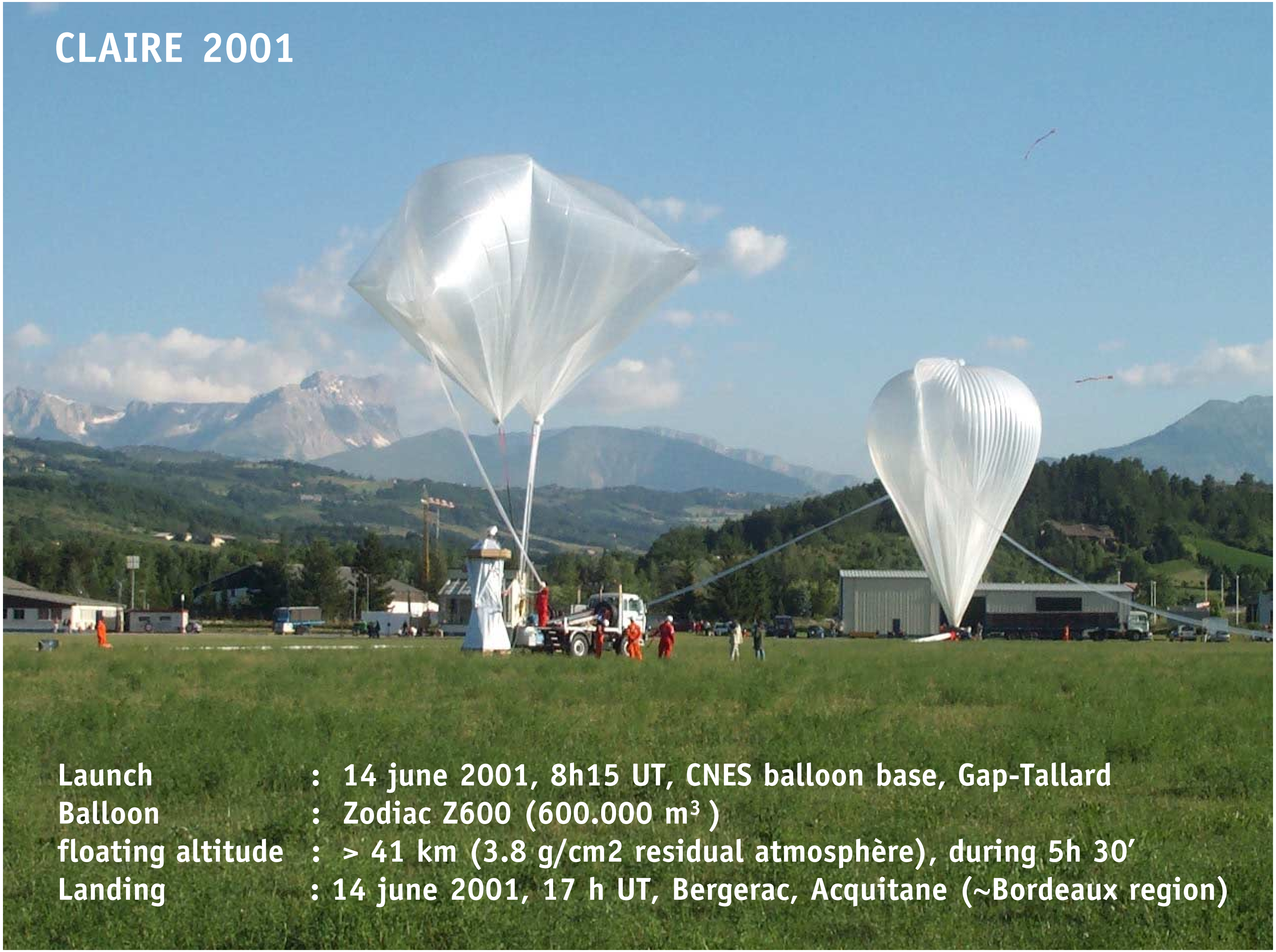
- well known continuum source
- close to the sun (~1° on June 15th)

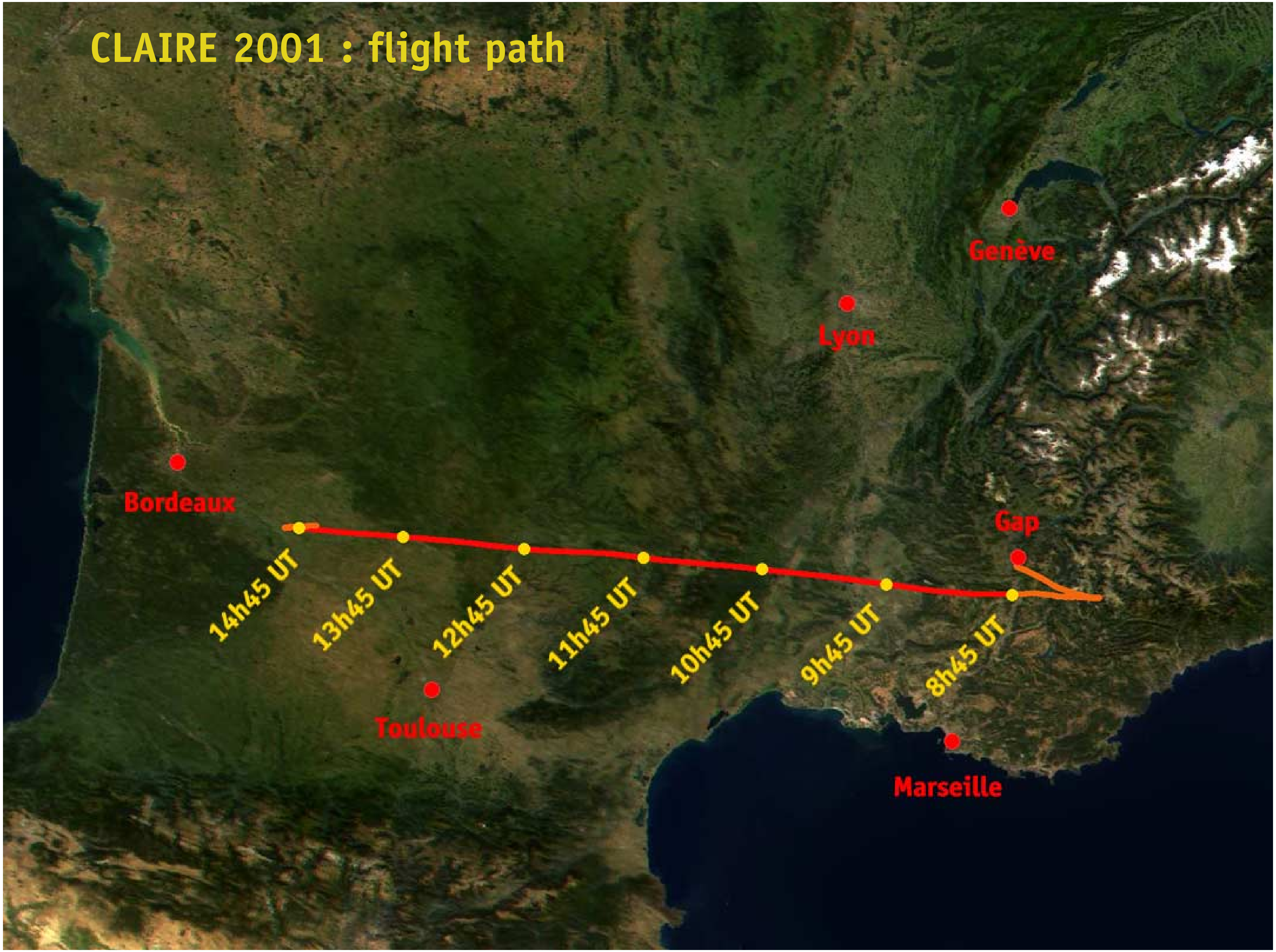
The Lens

- 576 Ge crystals on 8 rings
- optical axis materialized by invariant pixel of rotating CCD

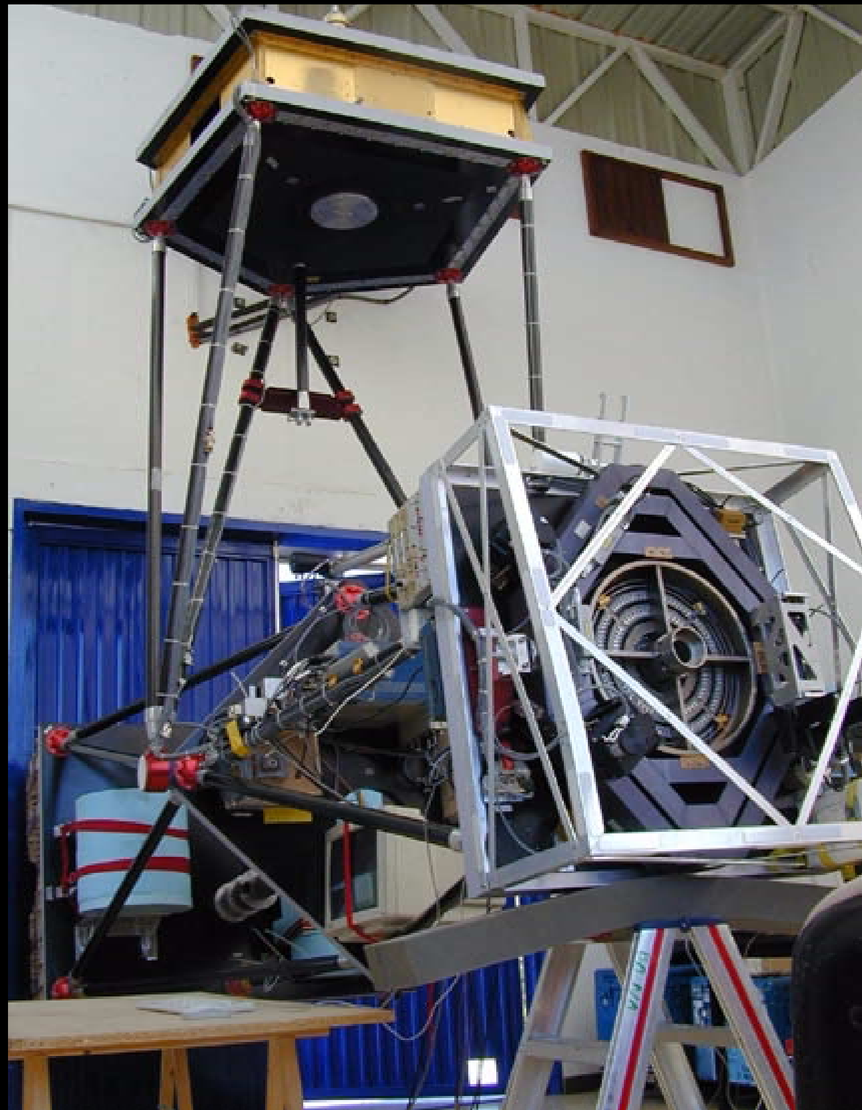
The Detector

- 3x3 Ge array, cooled by liquid nitrogen
- actively shielded (BgO, CsI)

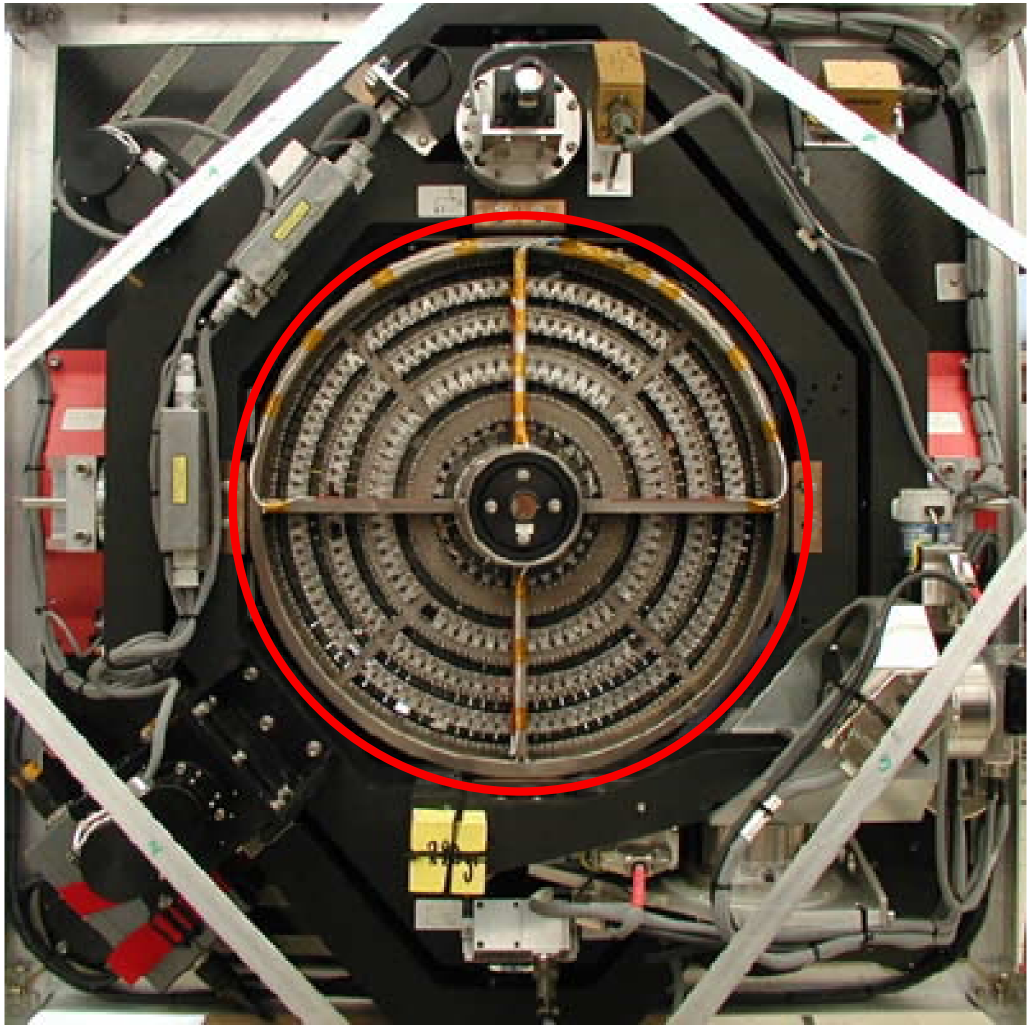

CLAIRE 2001
Launch : 14 june 2001, 8h15 UT, CNES balloon base, Gap-Tallard
Balloon : Zodiac Z600 (600.000 m^3)
floating altitude : > 41 km (3.8 g/cm2 residual atmosphère), during 5h 30′
Landing : 14 june 2001, 17 h UT, Bergerac, Acquitane (~Bordeaux region)



CLAIRE 2001 : flight path
Genève
Lyon
Bordeaux
Gap
Toulouse
Marseille
14h45 UT
13h45 UT
12h45 UT
11h45 UT
10h45 UT
9h45 UT
8h45 UT



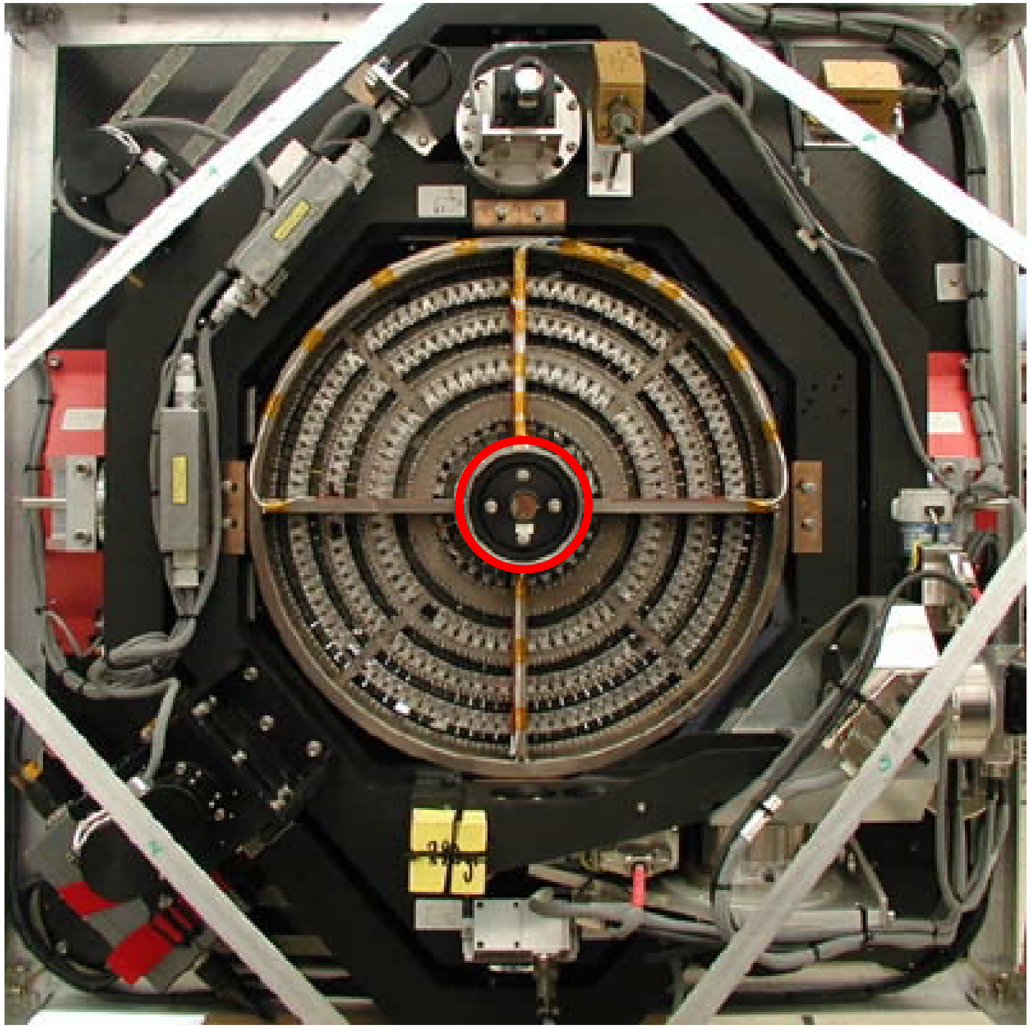
CLAIRE 2001 : Laue lens and fine pointing system



lens

- 576 Ge crystals
- A_{geo} = 511 cm^2
- E_{diff} = 170 keV, $\Delta E \approx 1.5$ keV
- FOV ≈ 45 arcsec

CLAIRE 2001 : Laue lens and fine pointing system



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- FOV ≈ 45 arcsec

optical axis

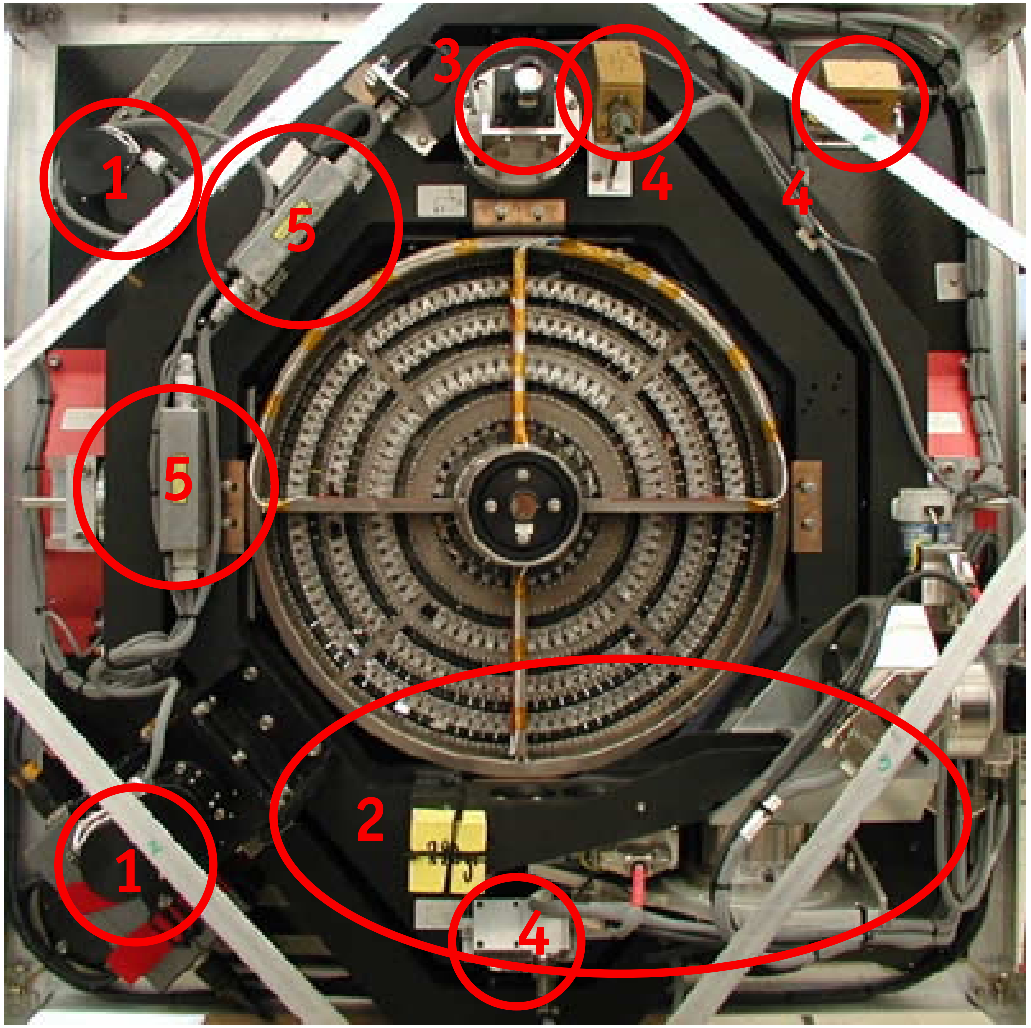
- invar. pixel of rotating CCD

fine pointing

- Geneva actuators 1
- precision sun sensor 2
- wide field CCD camera 3
- inclinometers 4
- mechanical & laser gyros 5

=> stability ≈ 3 arcsec

CLAIRE 2001 : Laue lens and fine pointing system



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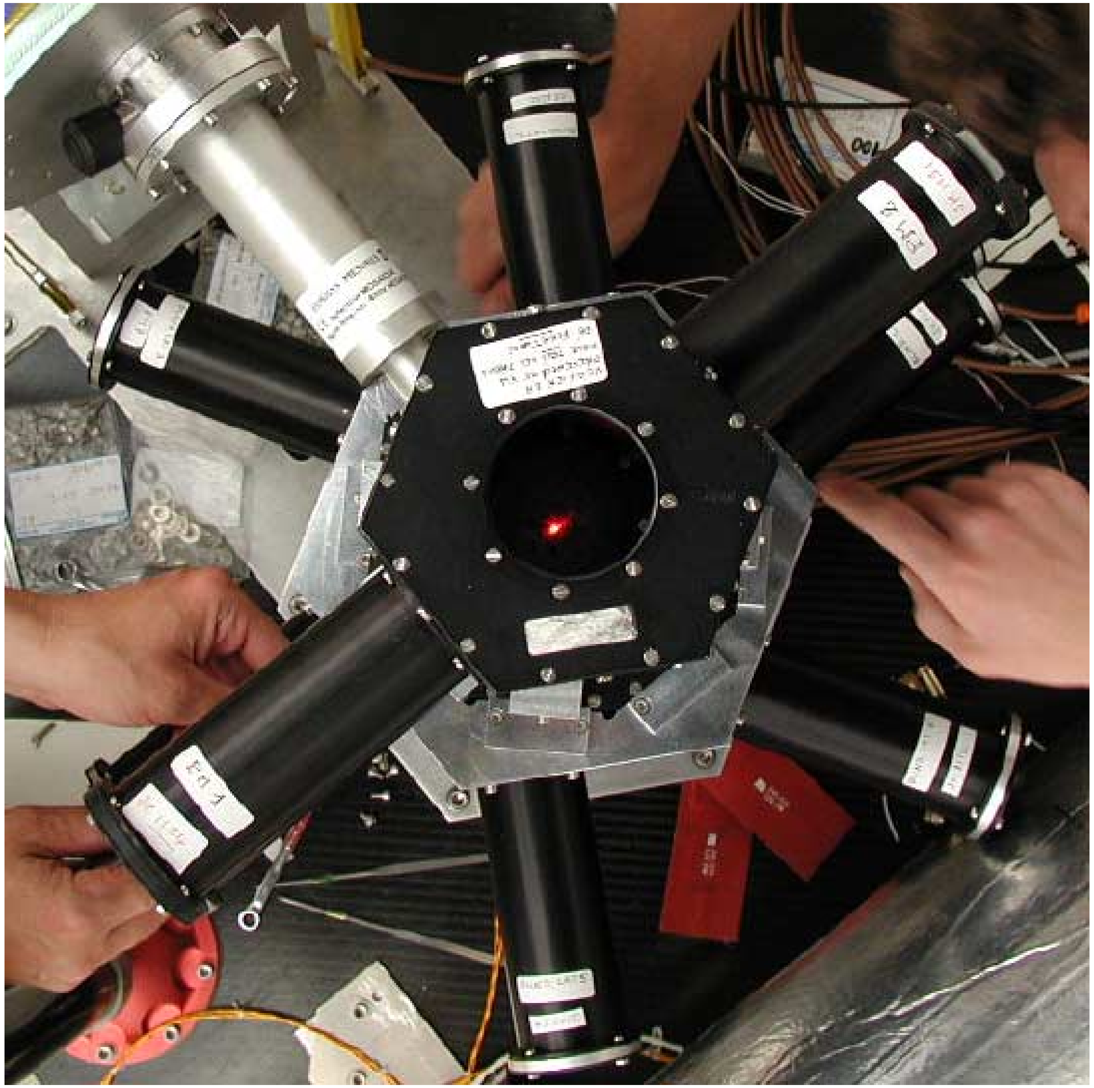
CLAIRE 2001 : Ge detector matrix and ACS



detector

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

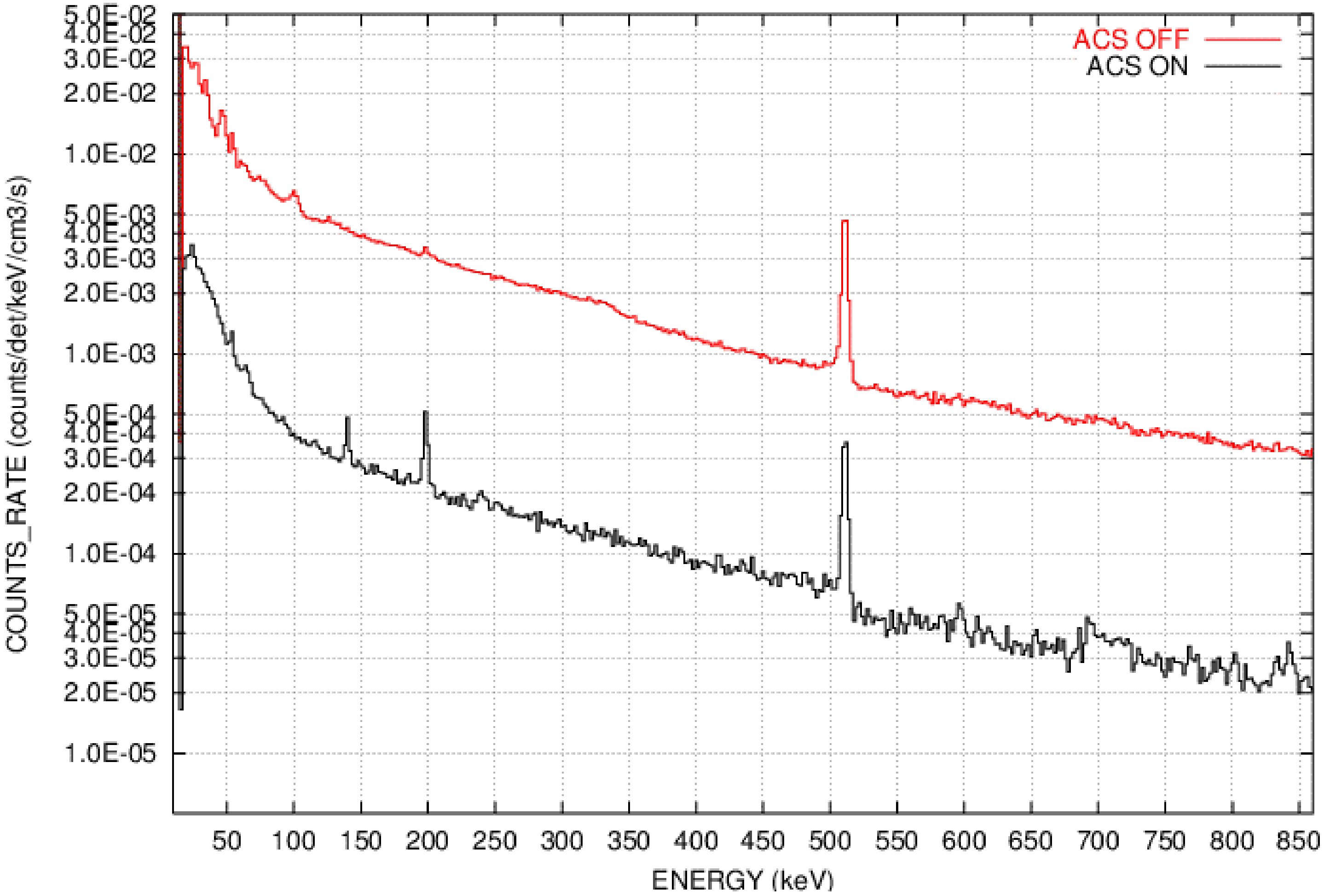
cooling

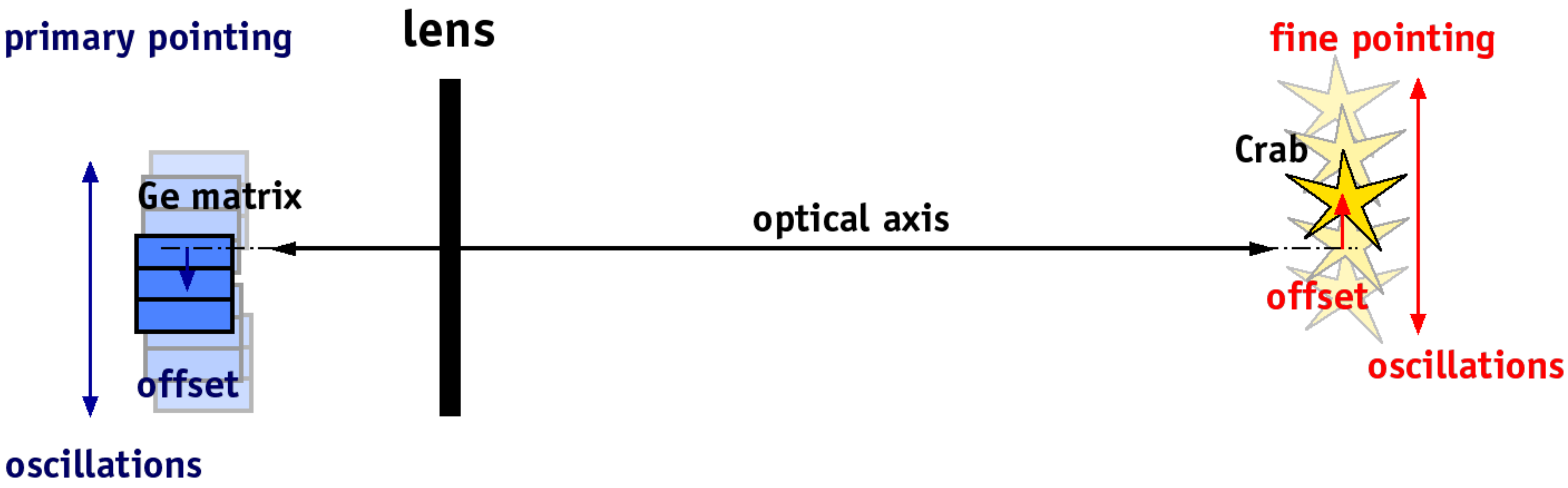
- pressurized N dewar

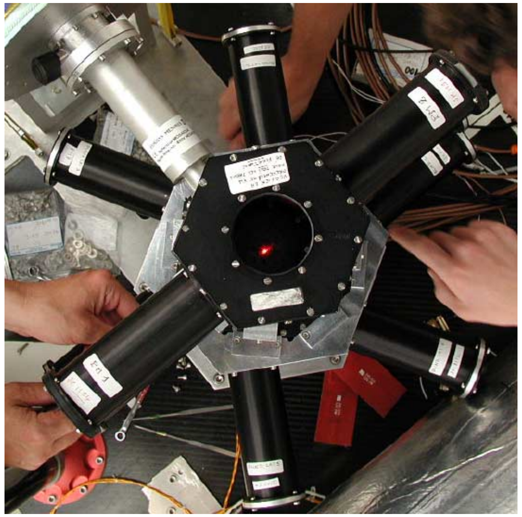
ACS system

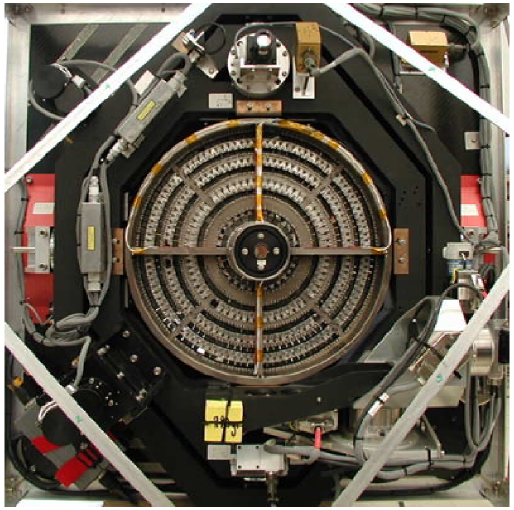
- CsI shield
- BGO collimator

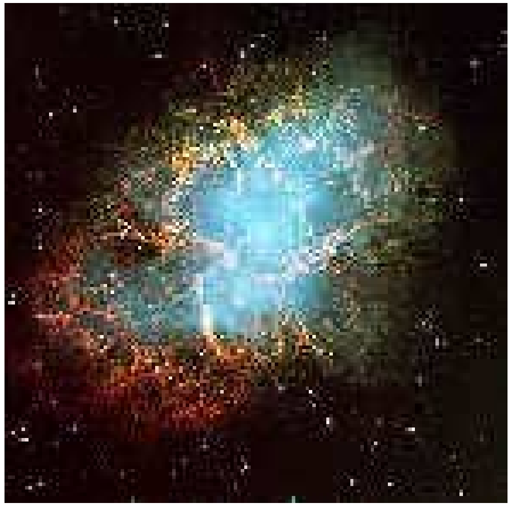
CLAIRE 2001 : flight spectra



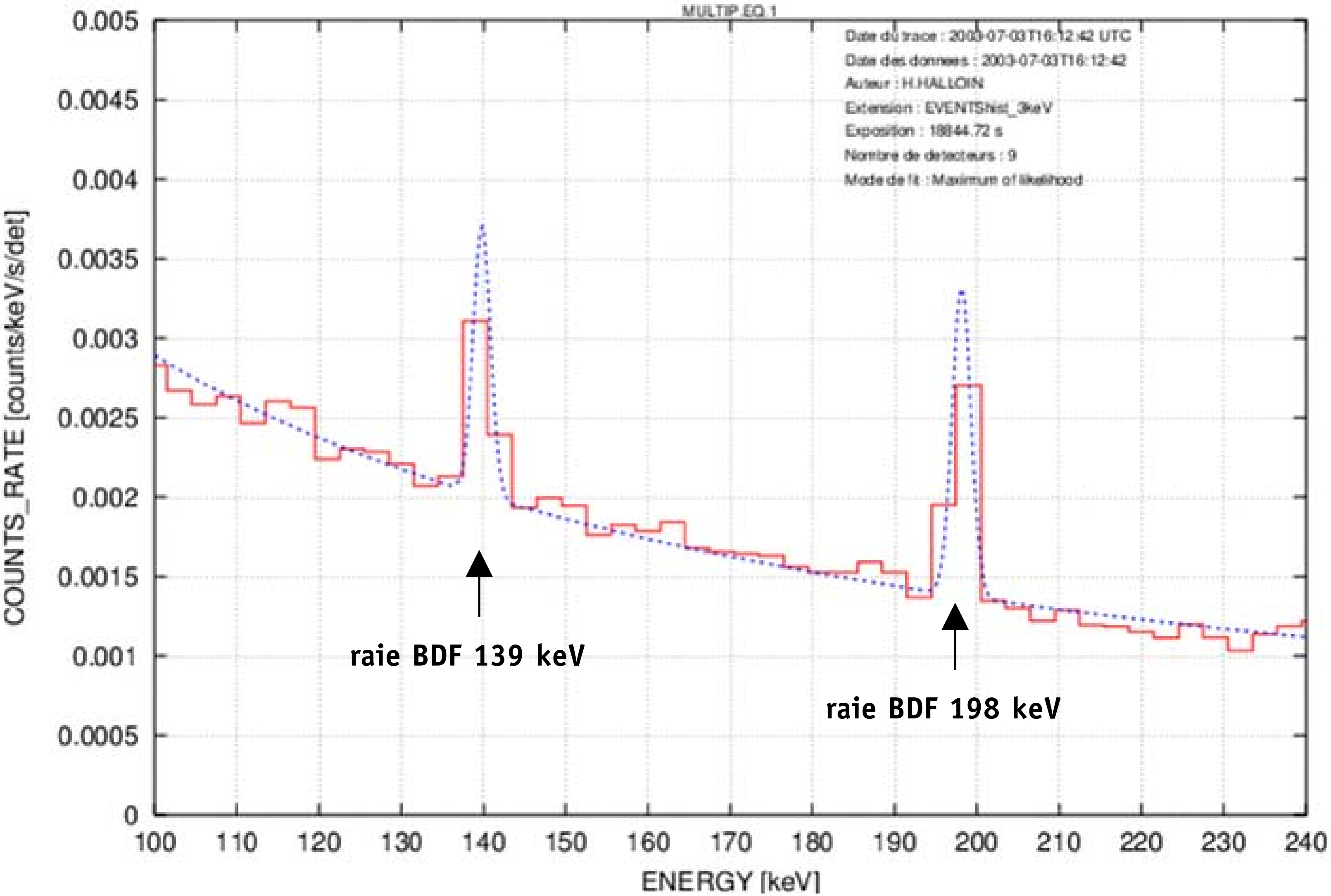

primary pointing
lens
fine pointing
Crab
Ge matrix
optical axis
offset
offset
oscillations
oscillations



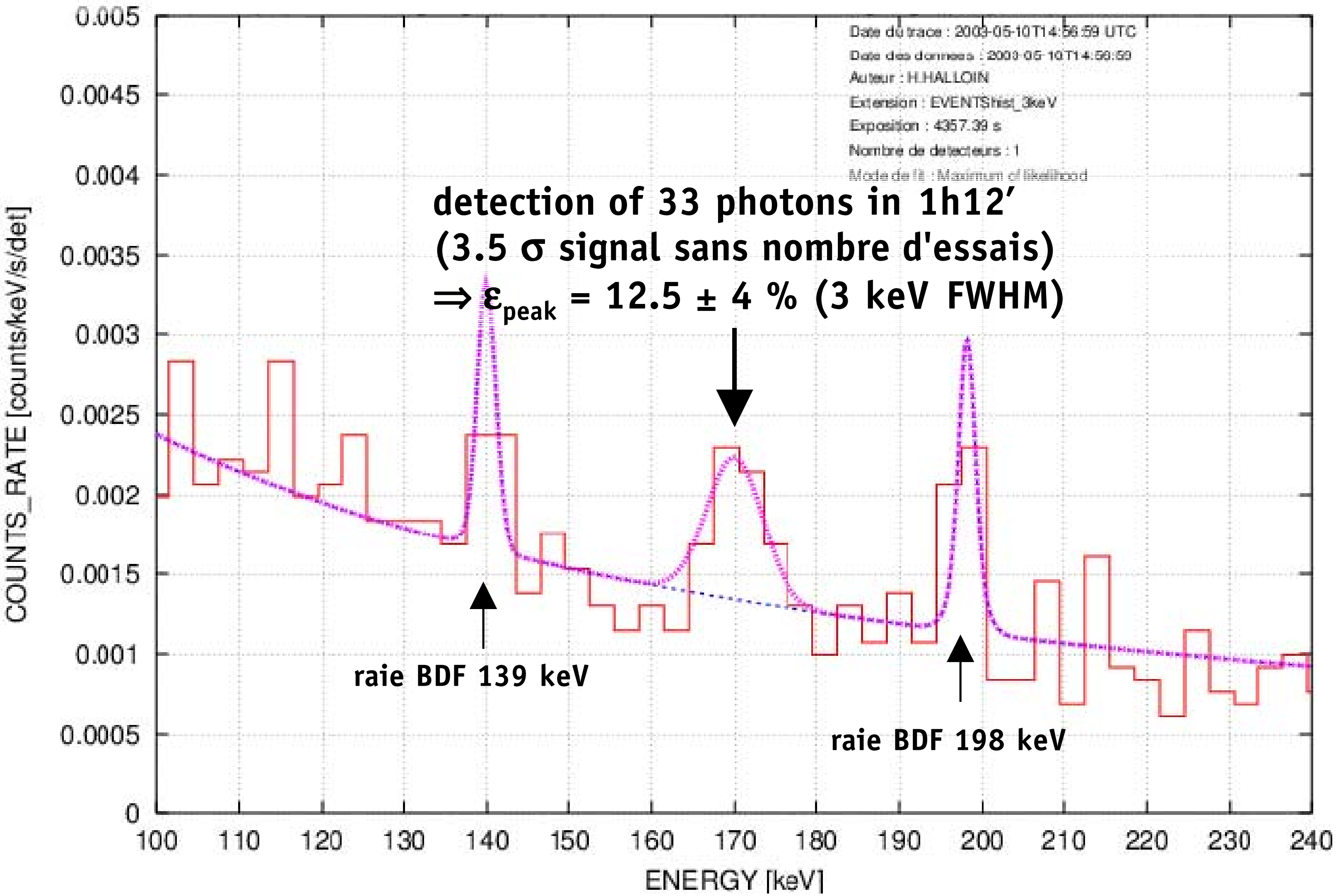




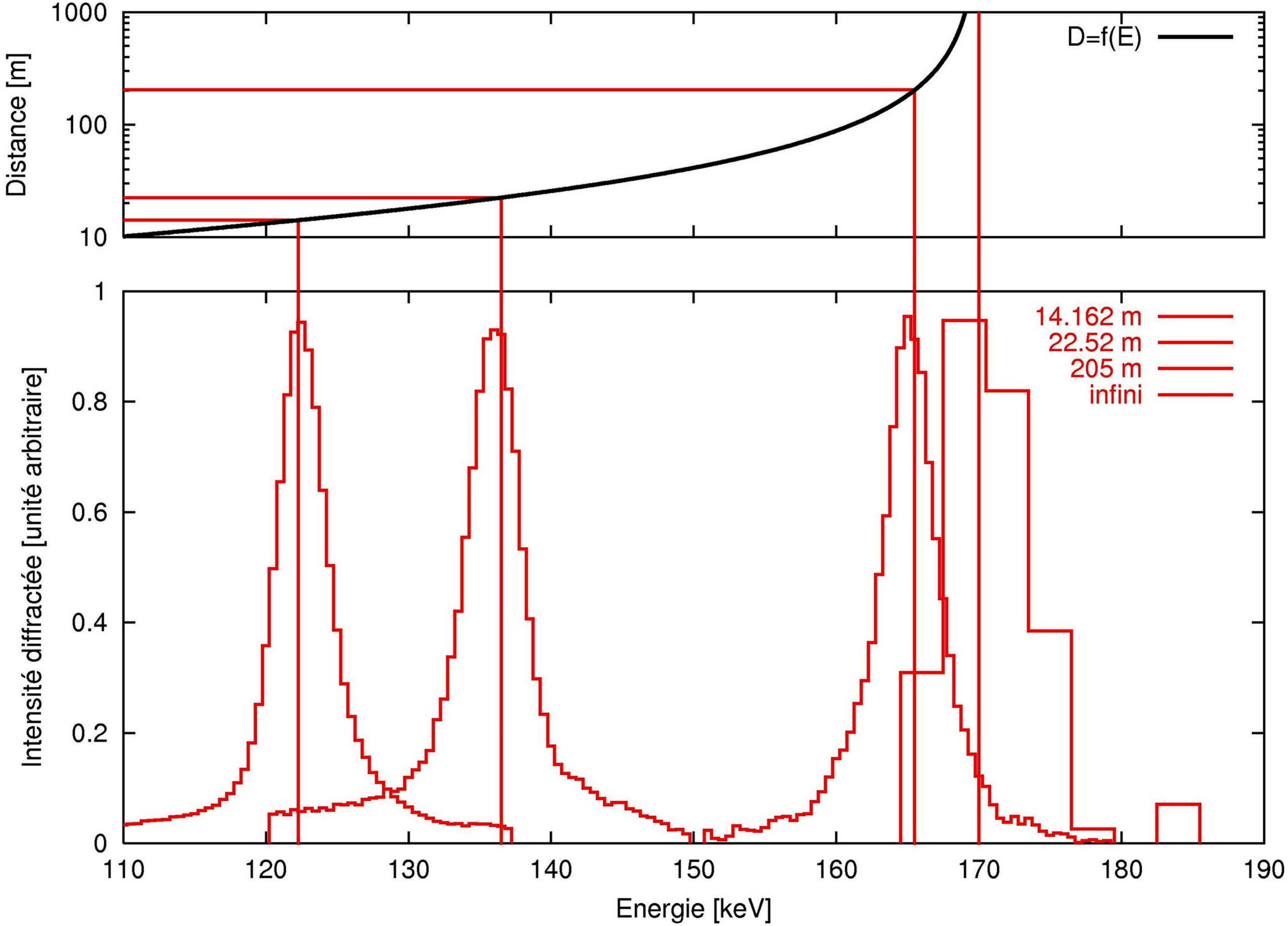
CLAIRE 2001 : single event background



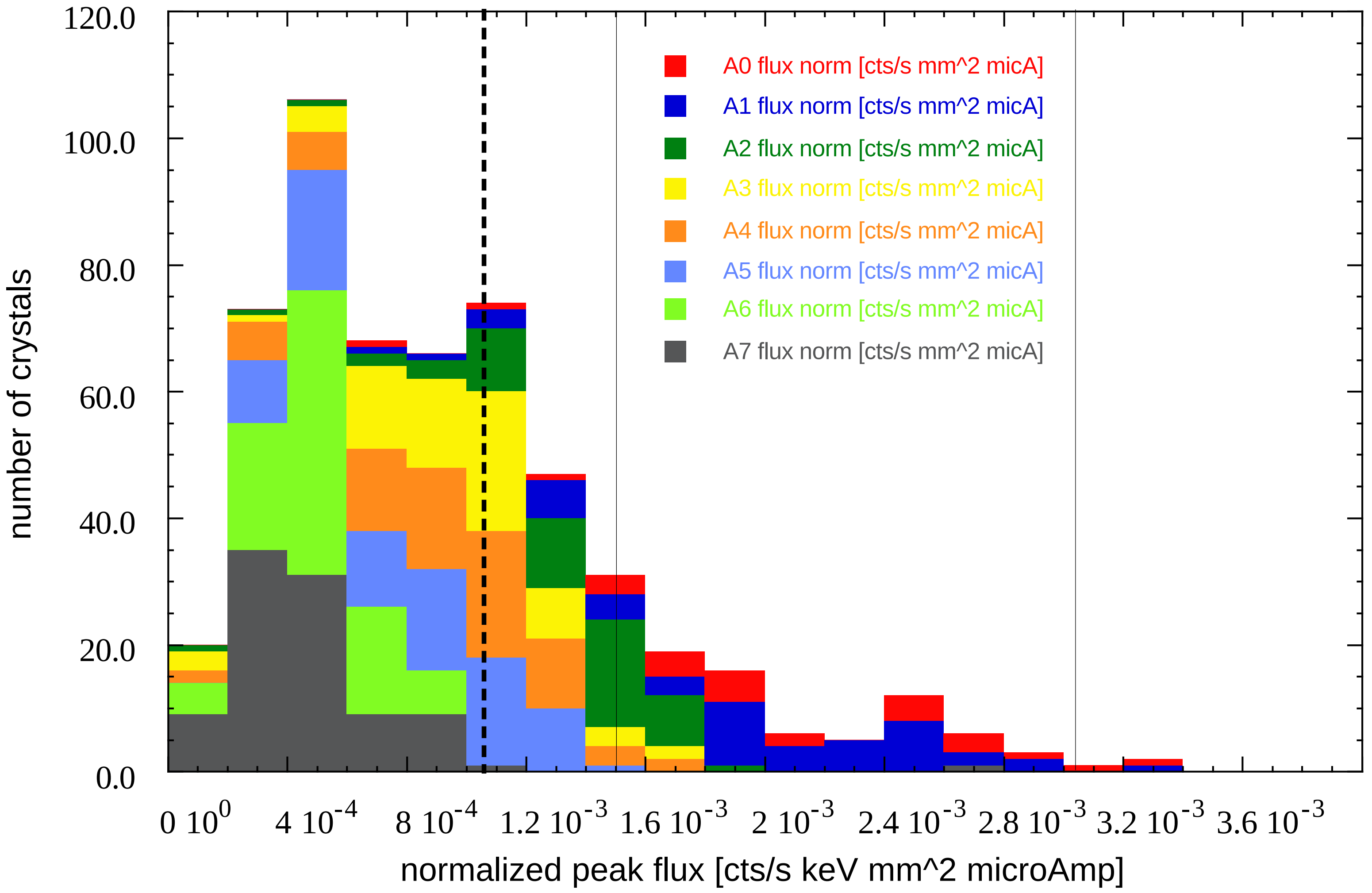
CLAIRE 2001 : detection of the Crab (I)

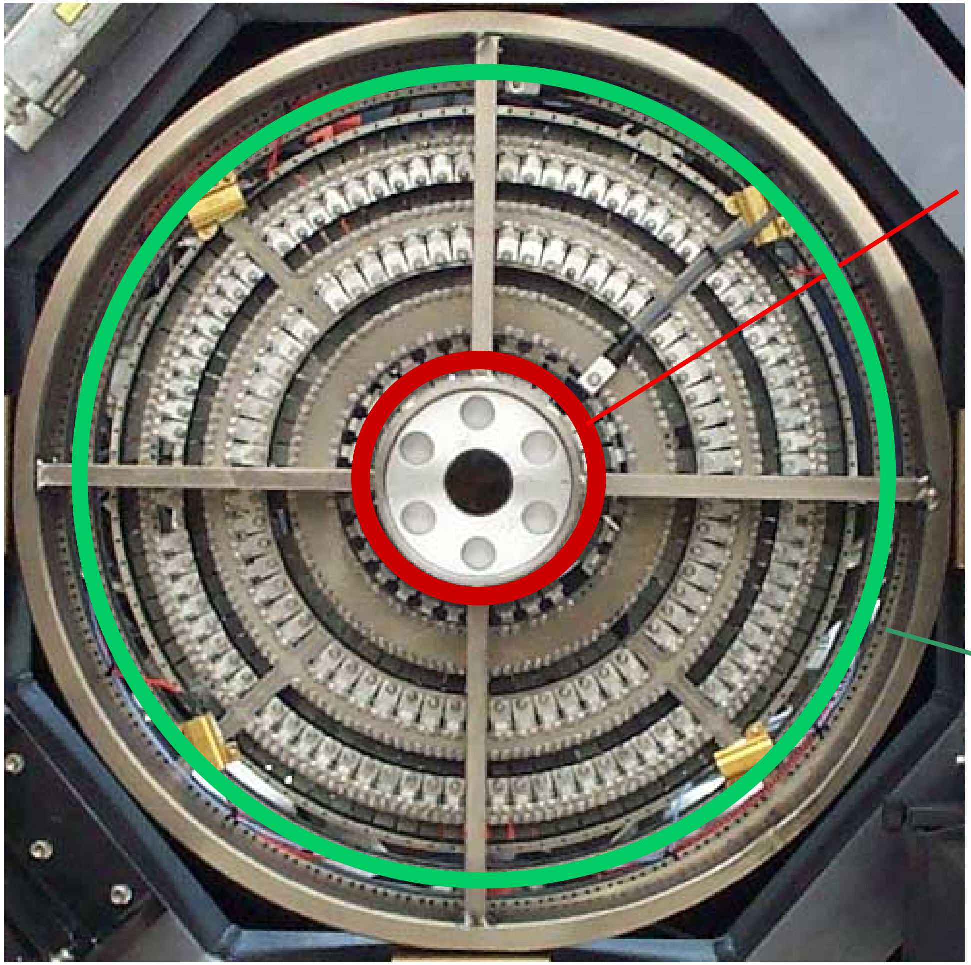


14 m, 22.5 m, 205 m ... infinity !



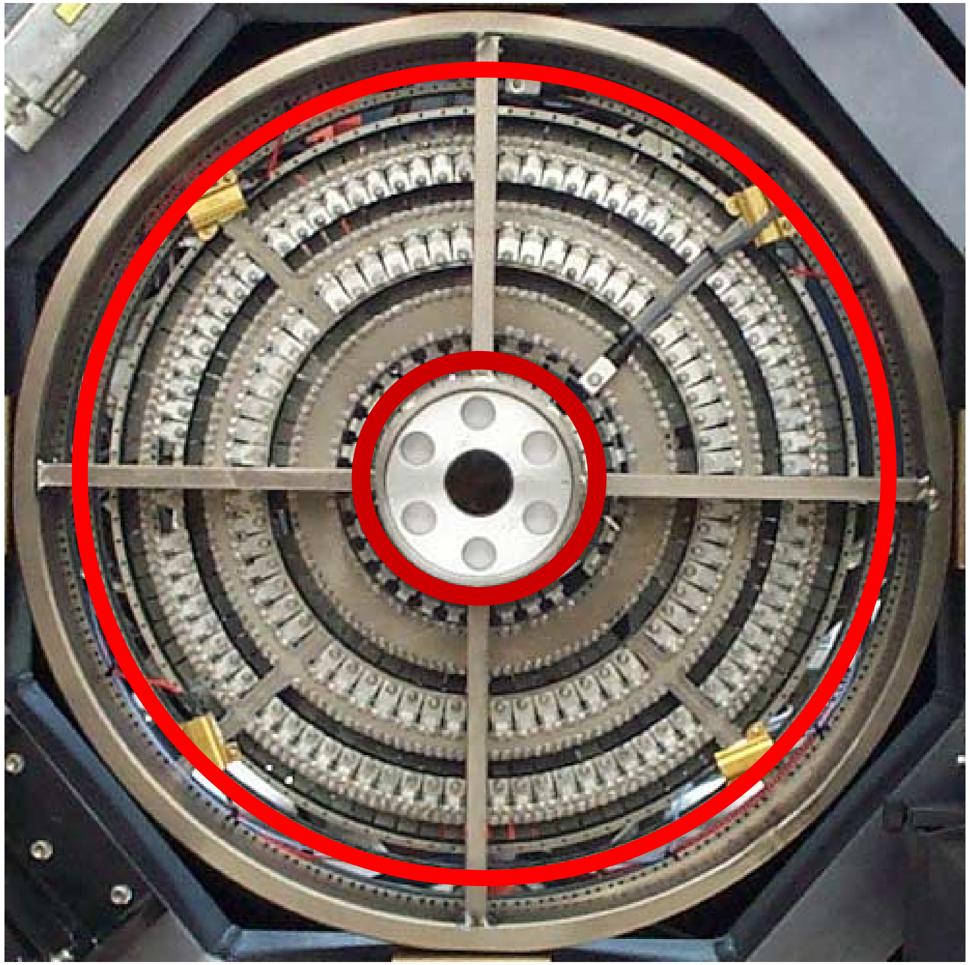
CLAIRE : diffracted flux of the 516 individual crystals of the lens



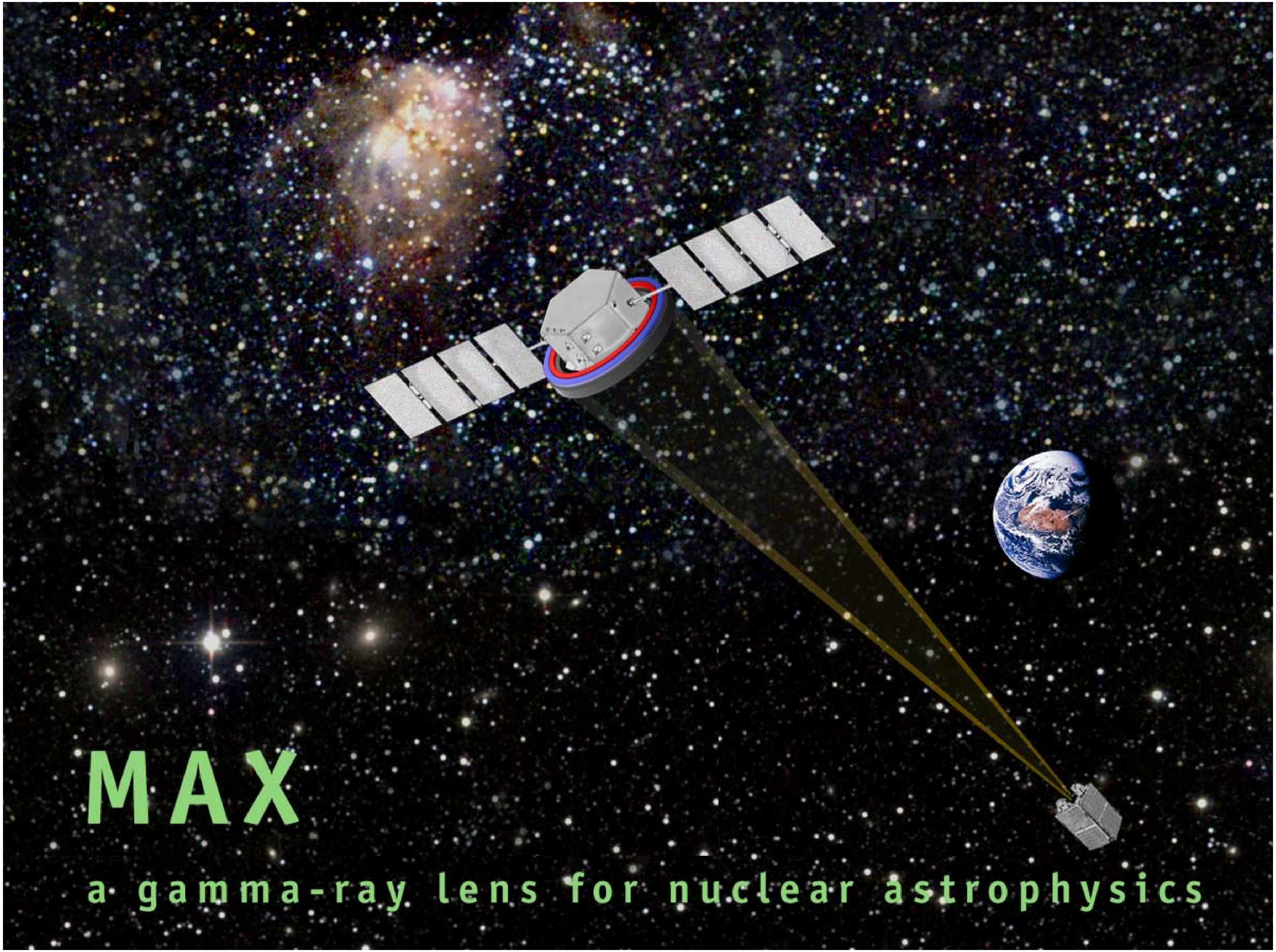


anneau [111]
$\varepsilon_{diff} \leq 25$ %

anneau [440]
$\varepsilon_{diff} \leq 7$ %



l'utilisation de cristaux [111] seuls demande une *longueur focale importante*

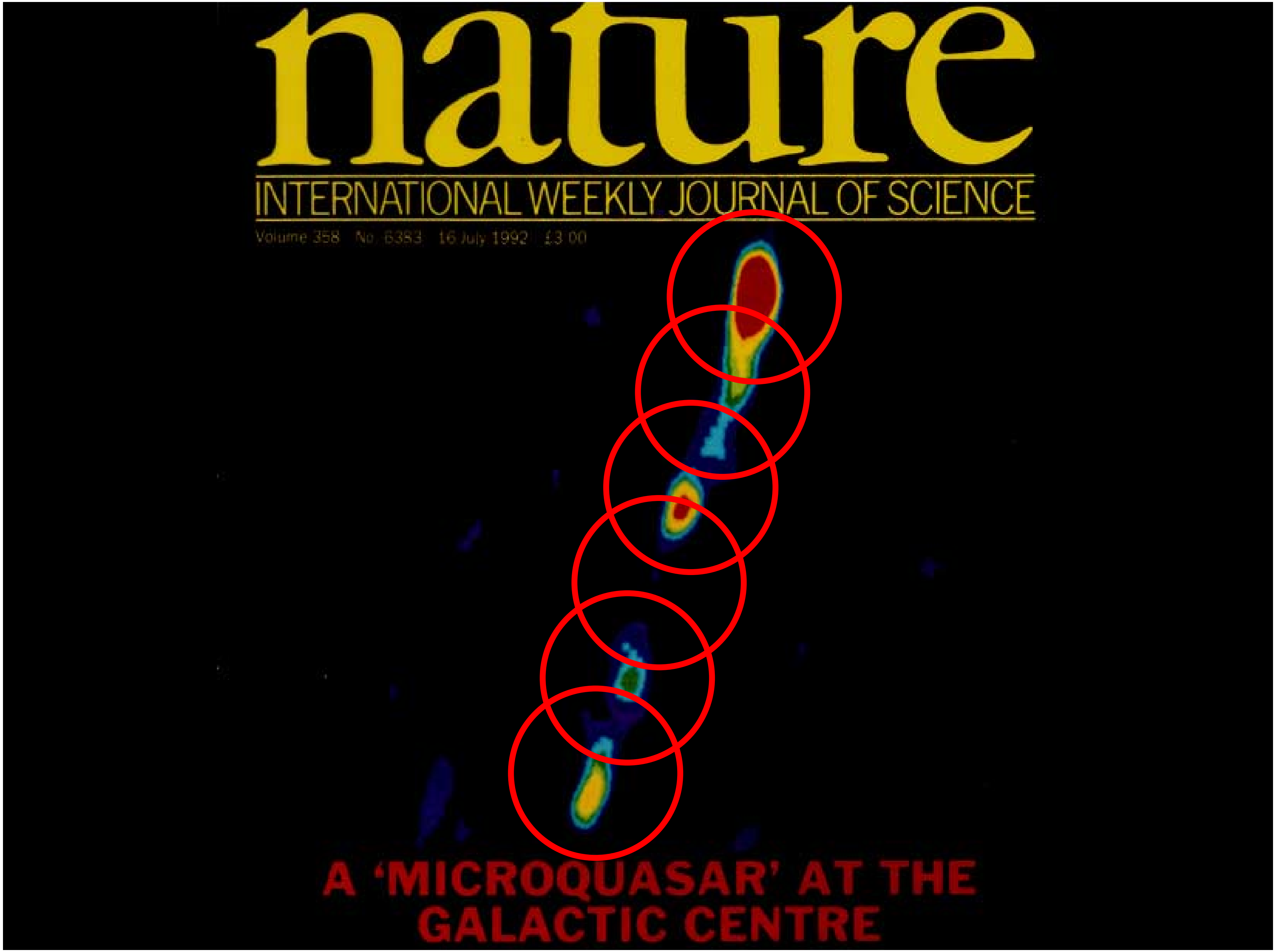

MAX
a gamma-ray lens for nuclear astrophysics

Primary scientific objective : Type Ia supernovae

A) signatures in SN Ia gamma-ray spectra are important for their own sake

- major contributors to the production of heavy elements
- understanding of life cycles of matter in the Universe
- chemical evolution of galaxies

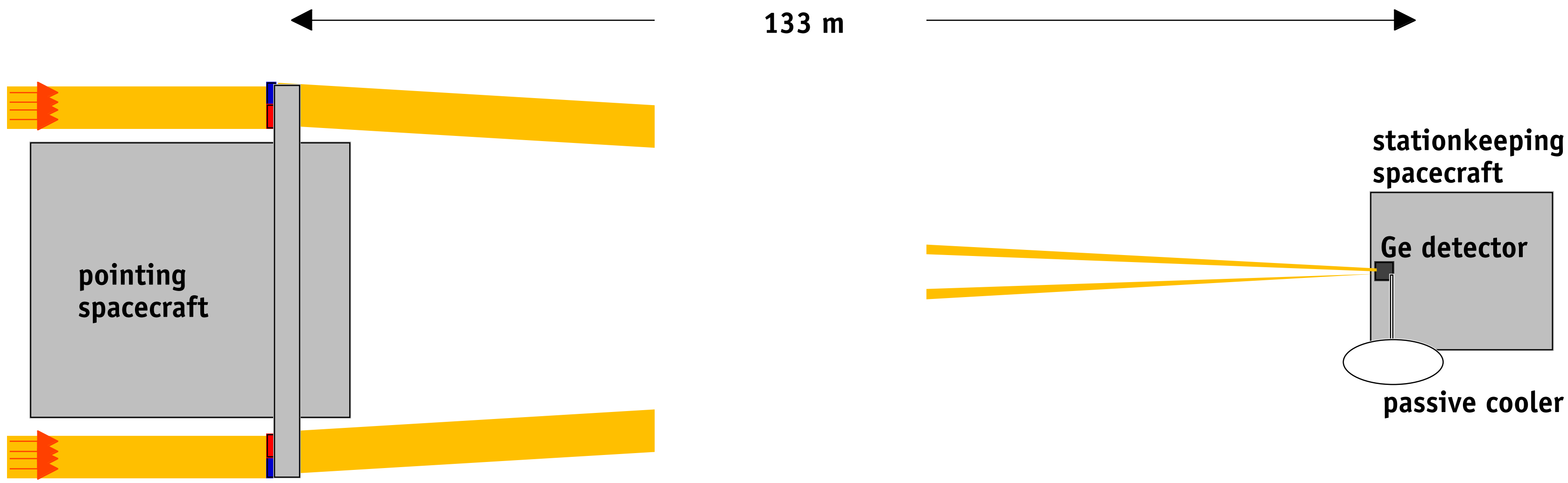
B) when finally understood and calibrated,
SN1a will be the ultimate tool for measuring
the size, shape, and age of the Universe.


nature
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
Volume 358 No. 6383 16 July 1992 £3.00
A 'MICROQUASAR' AT THE GALACTIC CENTRE

	band 1	band 2
principal gamma-ray lines	$^{56}Fe^*$	$e^+ e^-$ annihilation $^7Li^* (\alpha + \alpha)$
bandpass	800 à 900 keV	450 à 550 keV

sensitivity [photons cm^{-2} s^{-1}]	few 10^{-7} (10^{-6} à 511 keV)
spectral resolution E/ΔE	~ 500
angular resolution	1 arcmin
temporal resolution	< 1 microscec

formation flying lens- and detector-spacecraft



Laue lens: interior Ø 176 cm
exterior Ø 222 cm

MAX - a broad bandpass "ring lens"

crystals - Cu (847 keV)

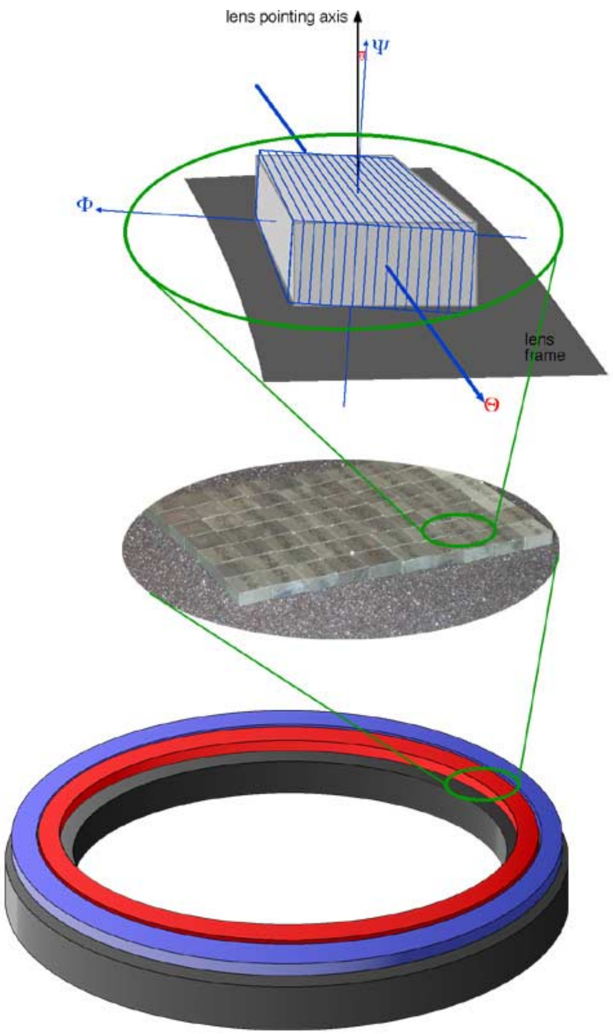
Ge (511 keV)

dense packing of the crystals

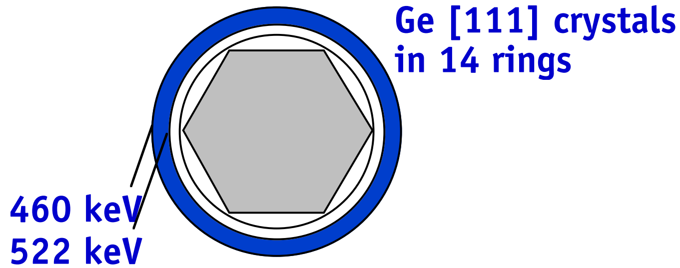
only most efficient orders

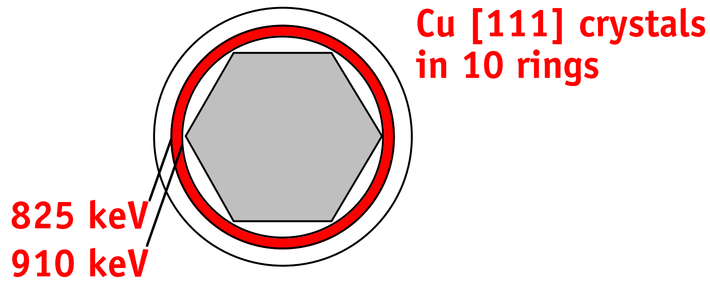
outer rings [111] Ge

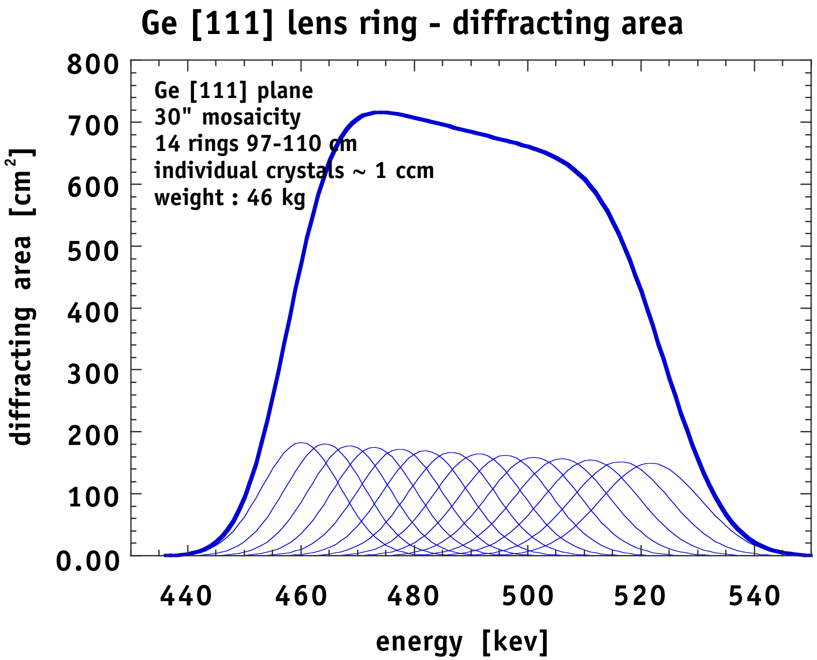
inner rings [111] Cu

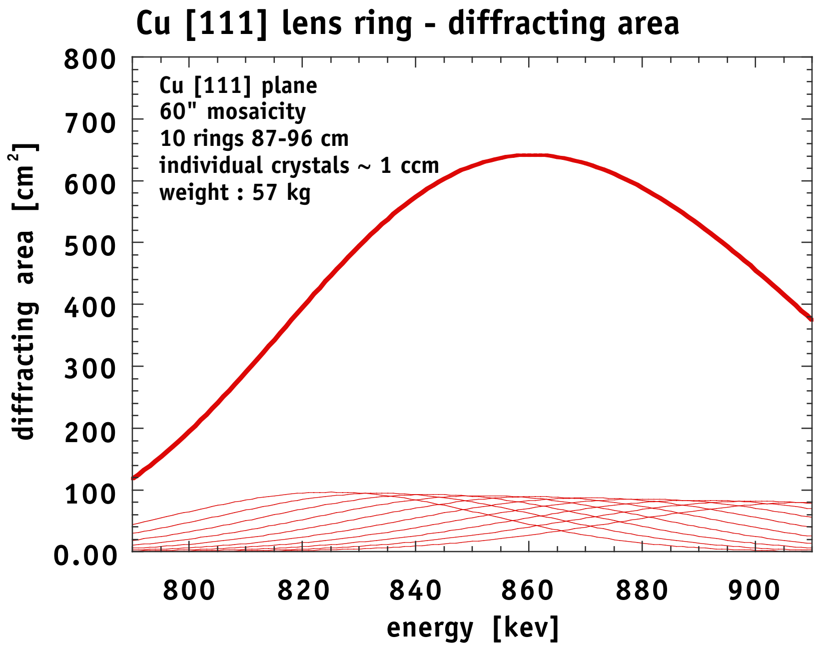


MAX - effective area









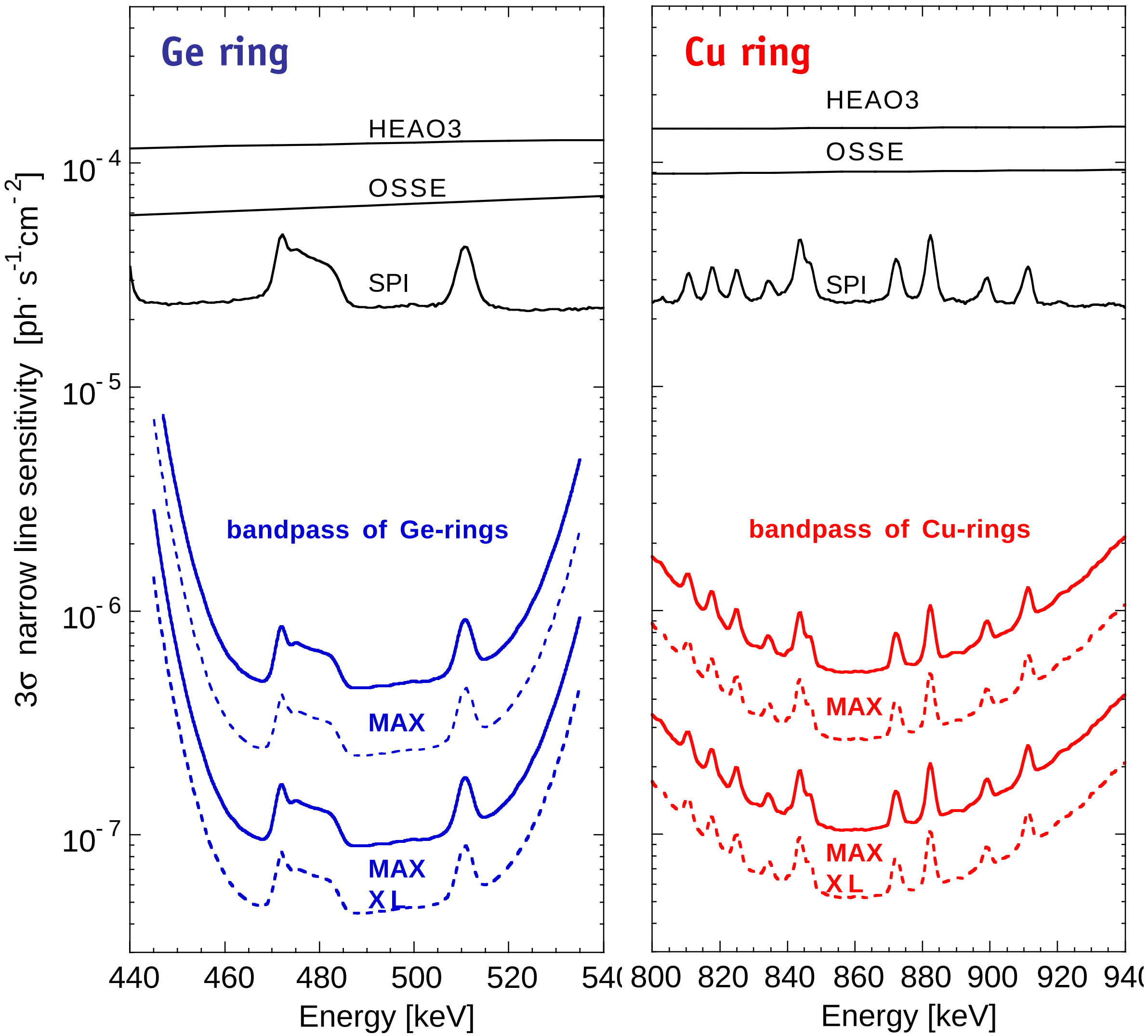
two 100 keV broad energy bands diffracting simultaneously

MAX

inner radius	86 cm
outer radius	111 cm
focal length	133 m

MAX XL

inner radius	193 cm
outer radius	250 cm
focal length	300 m



everything
CLAIRE ?