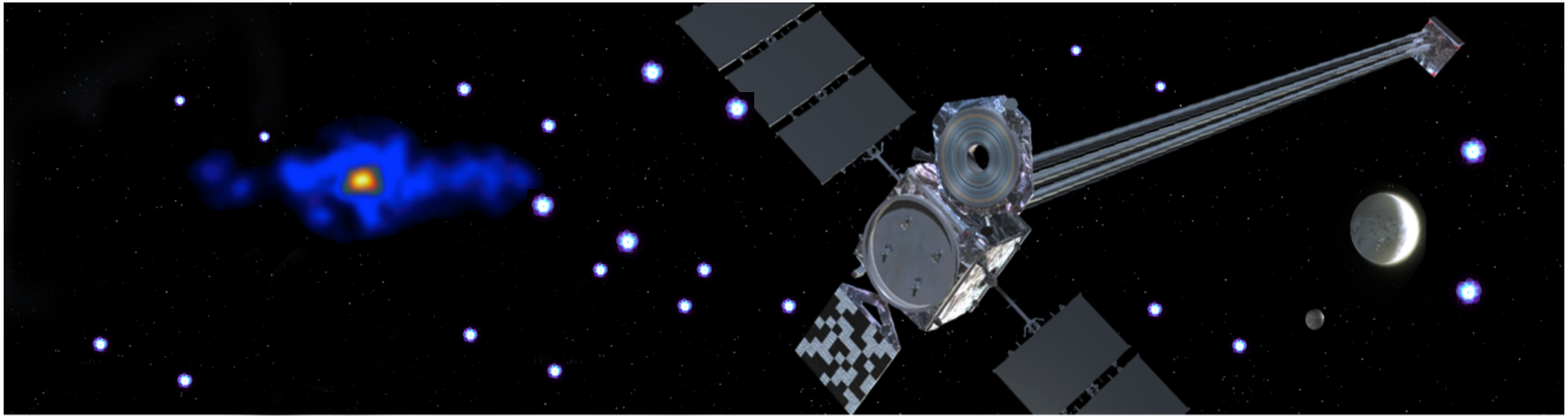


Nuclear Gamma-Ray Astronomy – the Next Step

Instrument Options in the MeV range

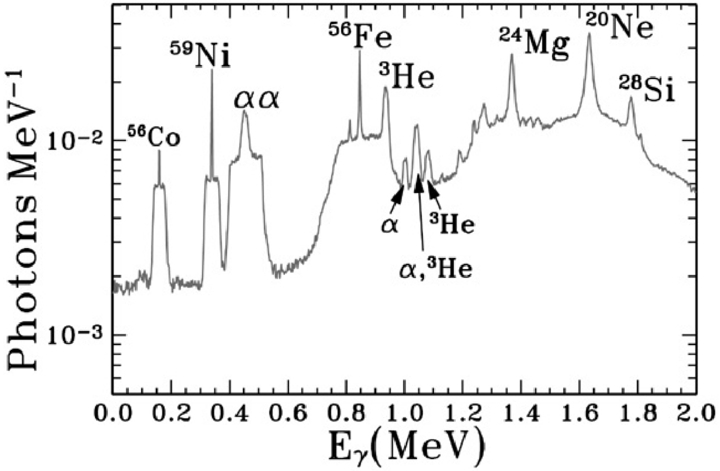
The roadmap of gamma-ray astronomy

A DUAL mission for Nuclear Astrophysics
and its relevance for GRB science

Peter von Ballmoos, IRAP(CESR) Toulouse

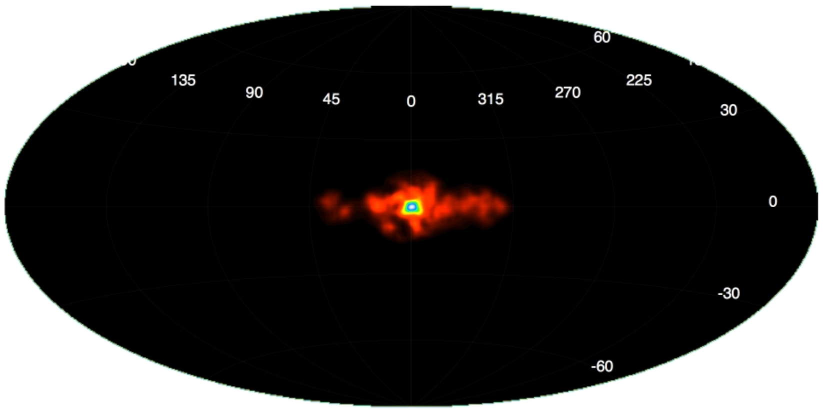
are there reasons to study MeV photons other than γ-ray bursts ?

Nuclear lines



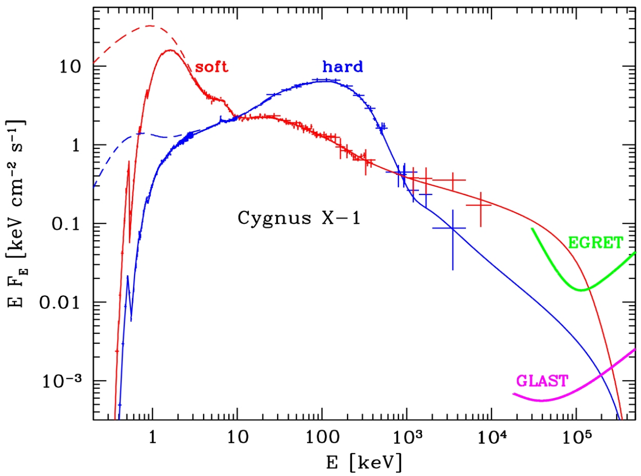
nuclear production and CR interaction sites, abundances, ISM phases, particle spectra, kinematics

Positron annihilation



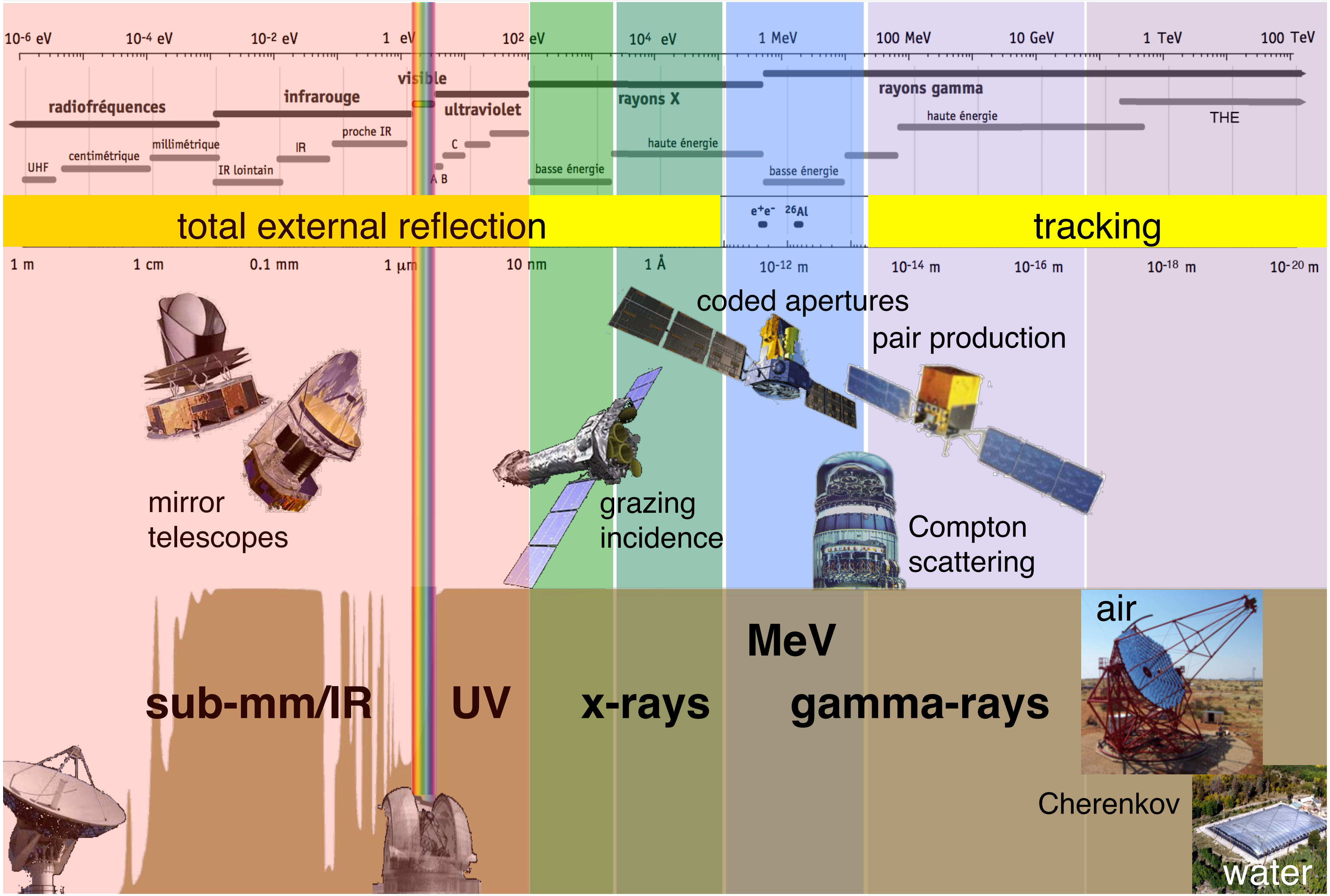
e+ production and annihilation site diagnostics

Thermal / non-thermal transition

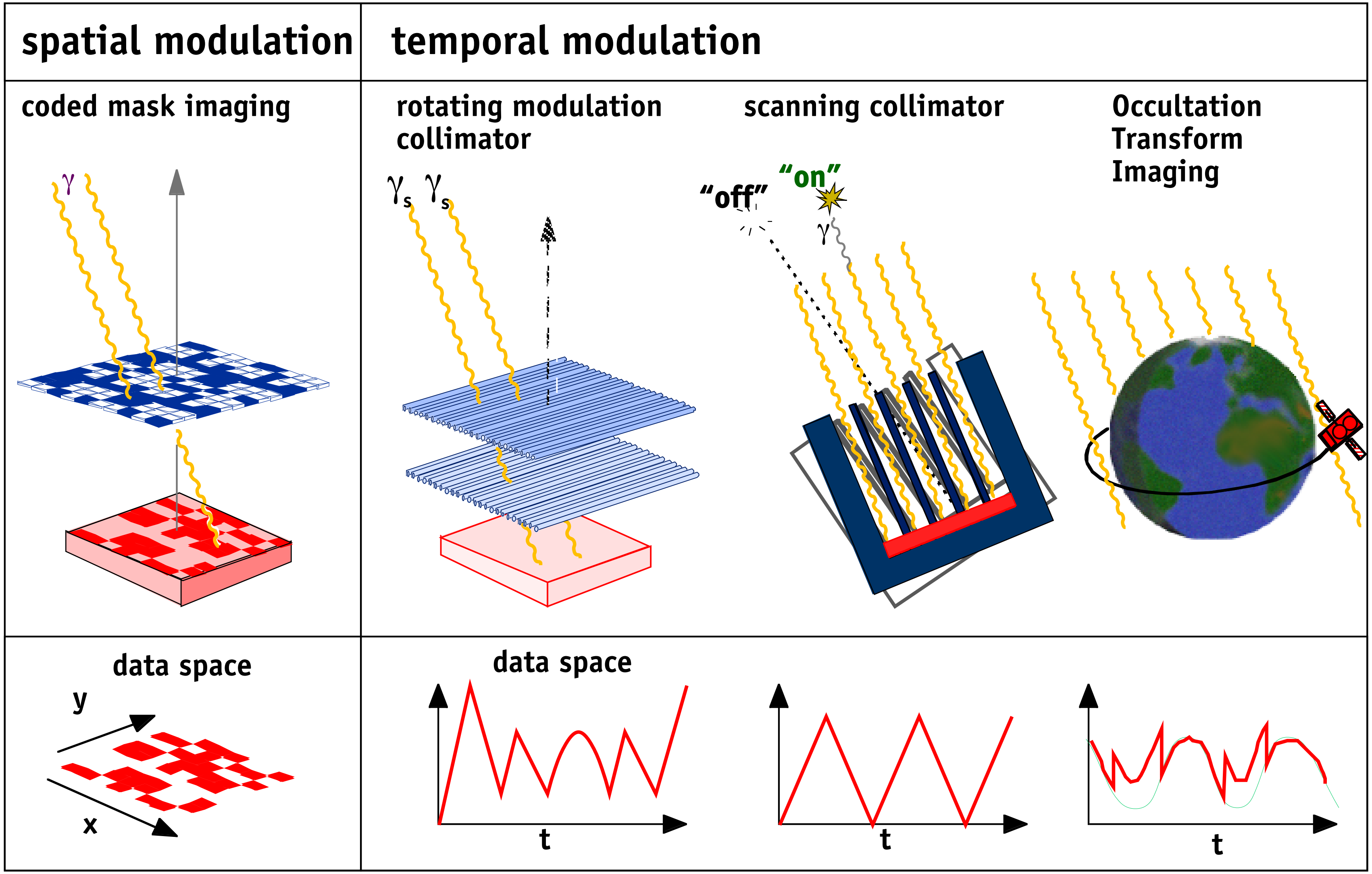


Cosmic accelerators : link between accretion (thermal) and ejection (non-thermal)

astronomy in the transition region : the "impossible" MeV range

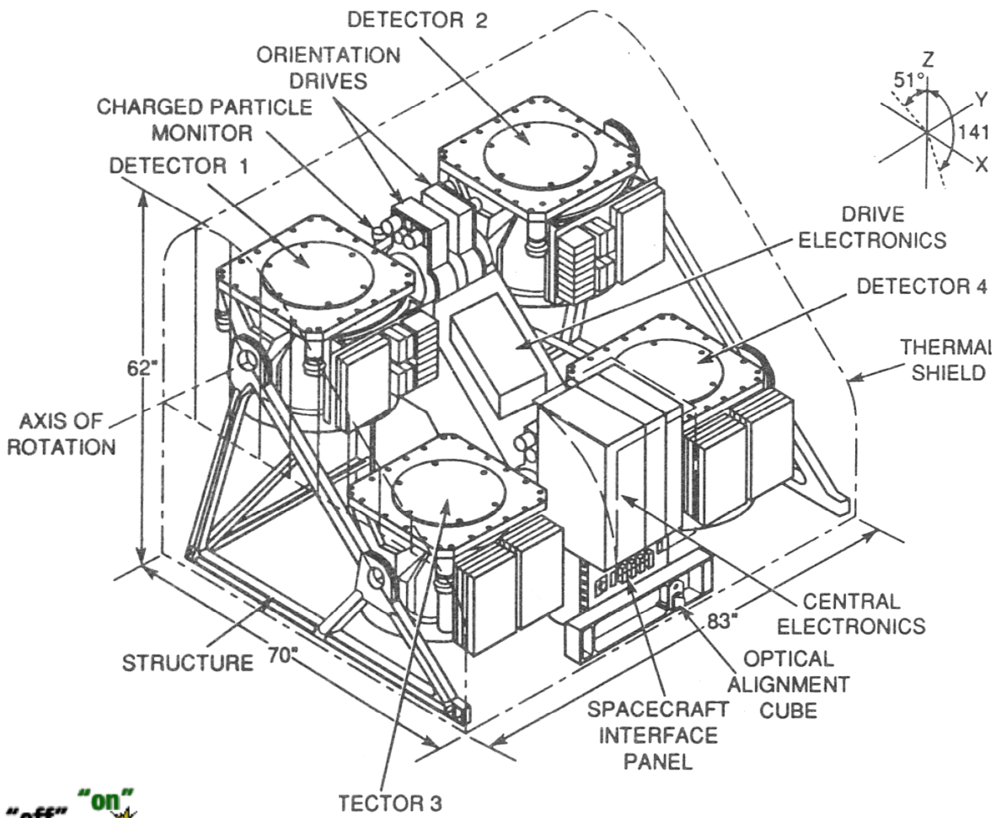


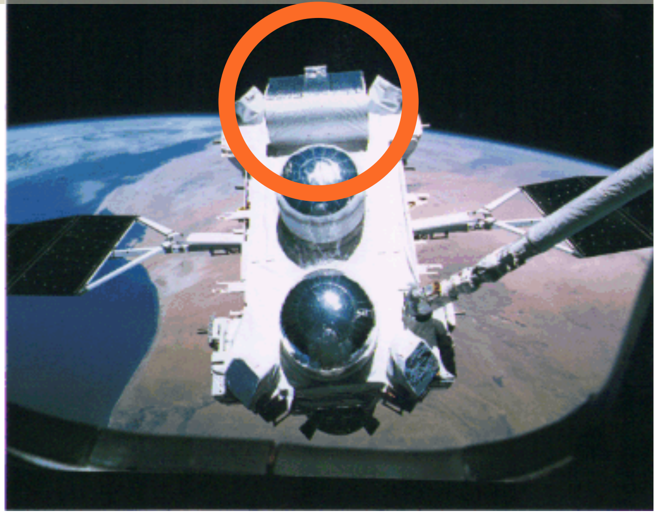
Geometric Optics : Modulating Aperture Systems

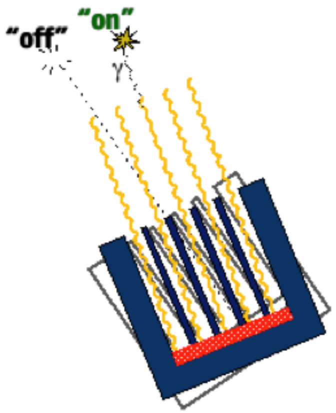


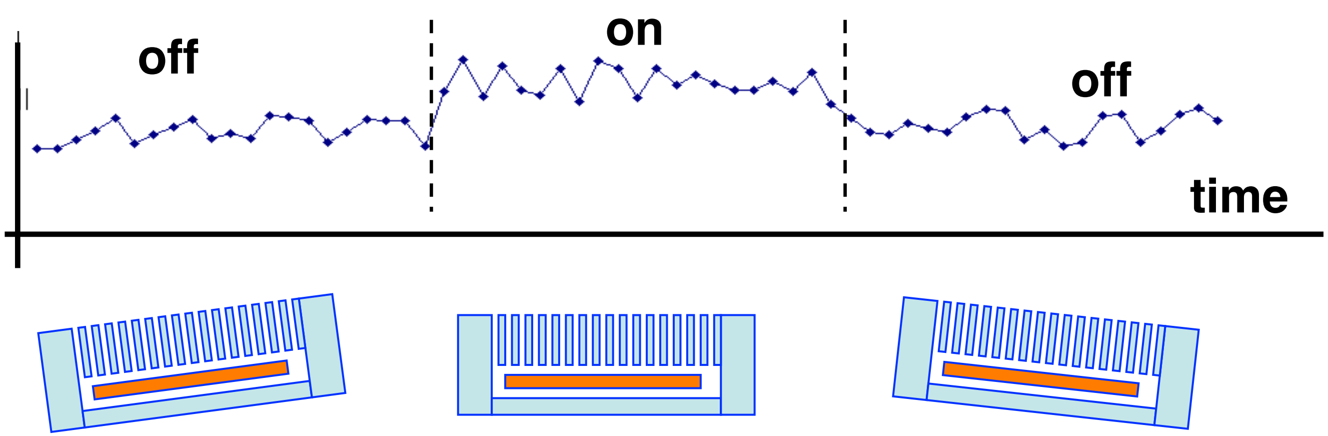
Collimator "on" - "off" telescope

GRO - OSSE





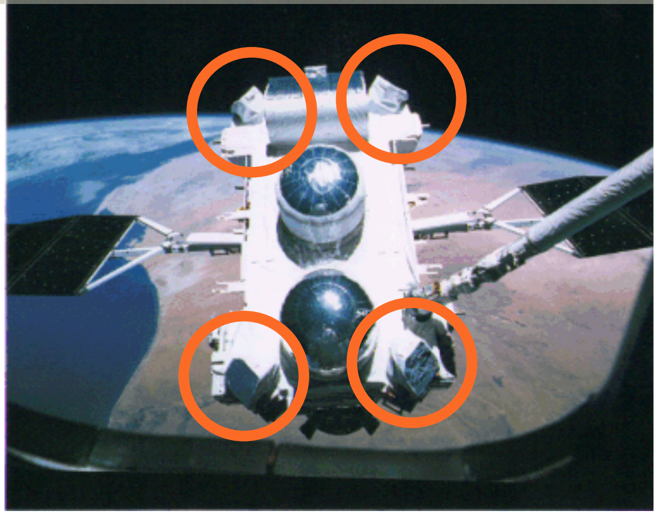


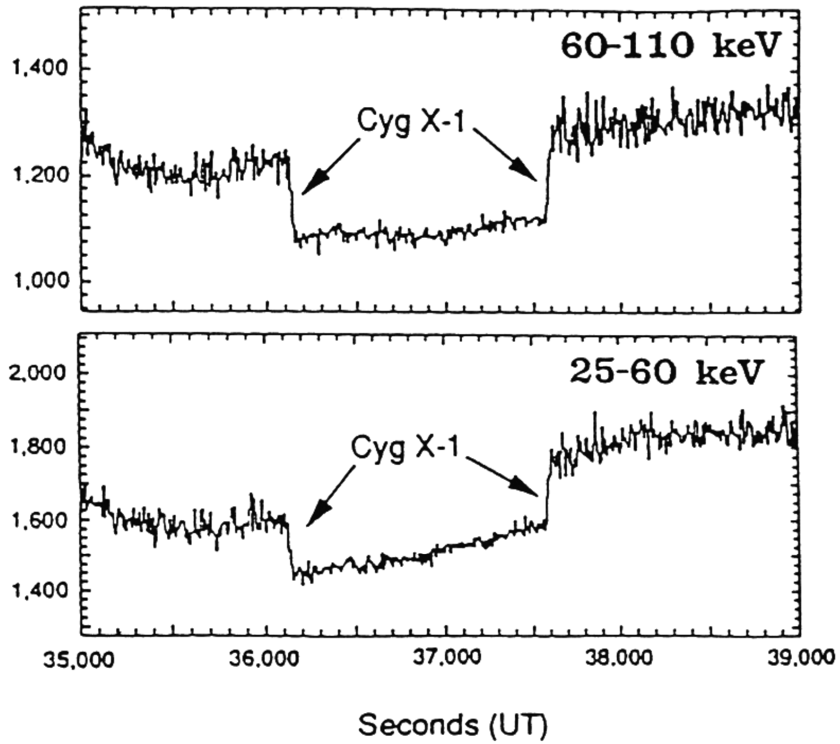


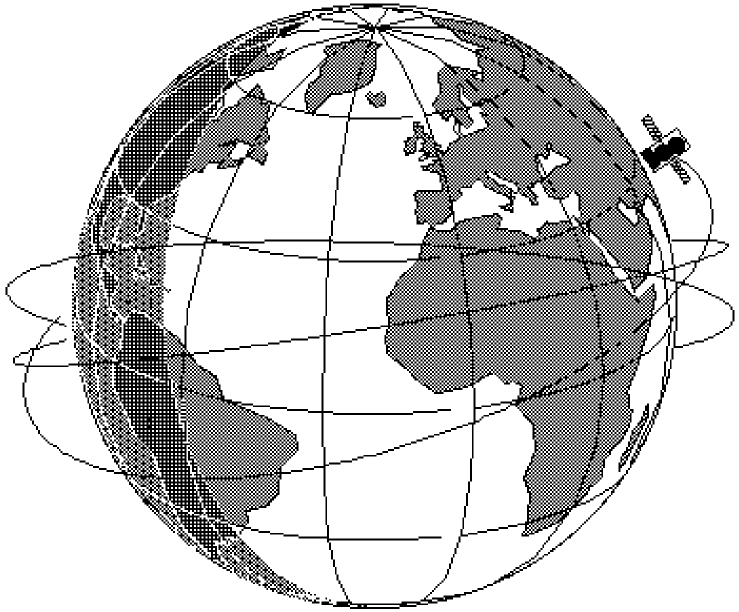
Occultation Transform Imaging

GRO - BATSE

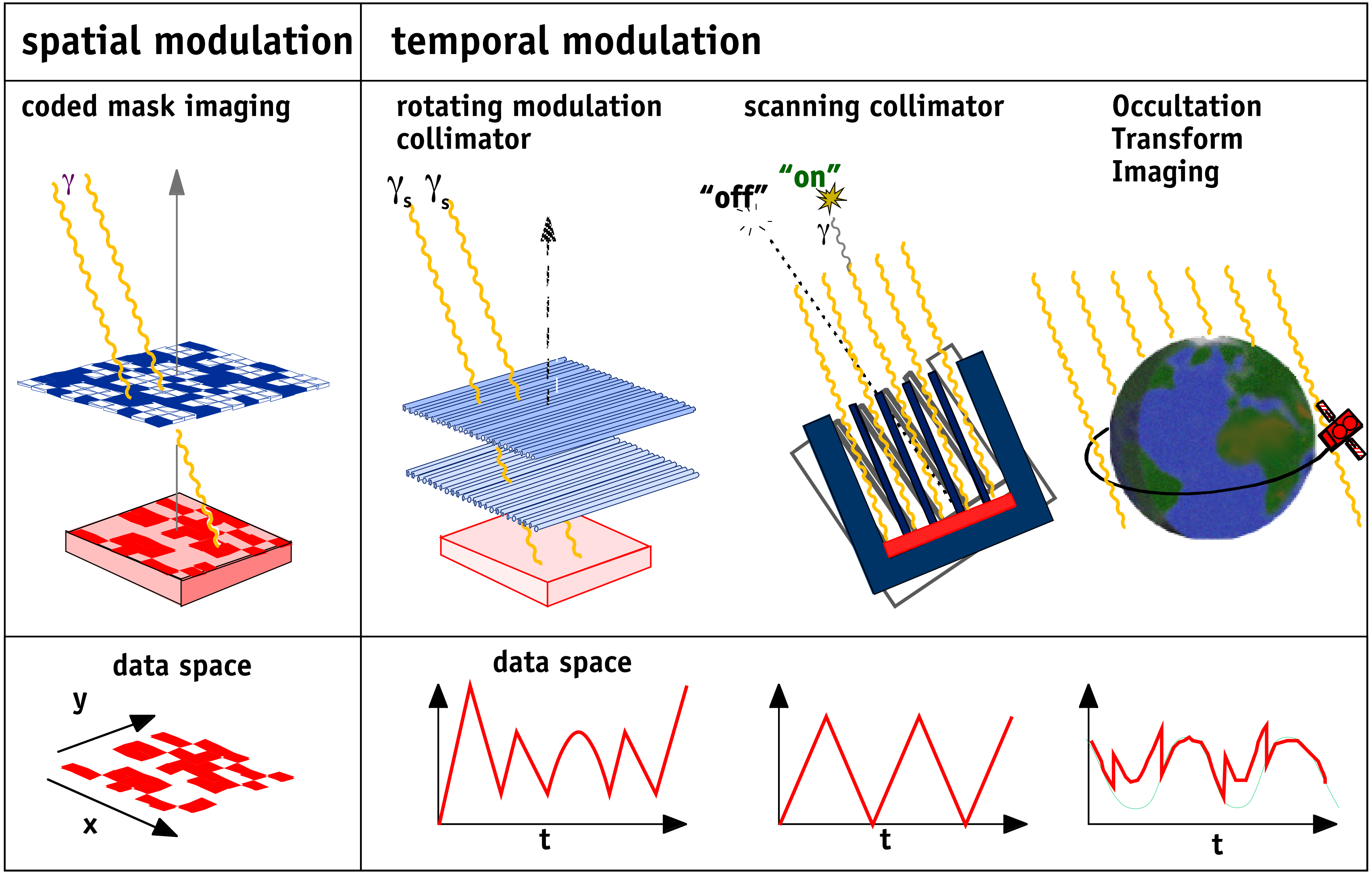
with the planet earth as
'rotation' modulation collimator
(or scanning anti-collimator)



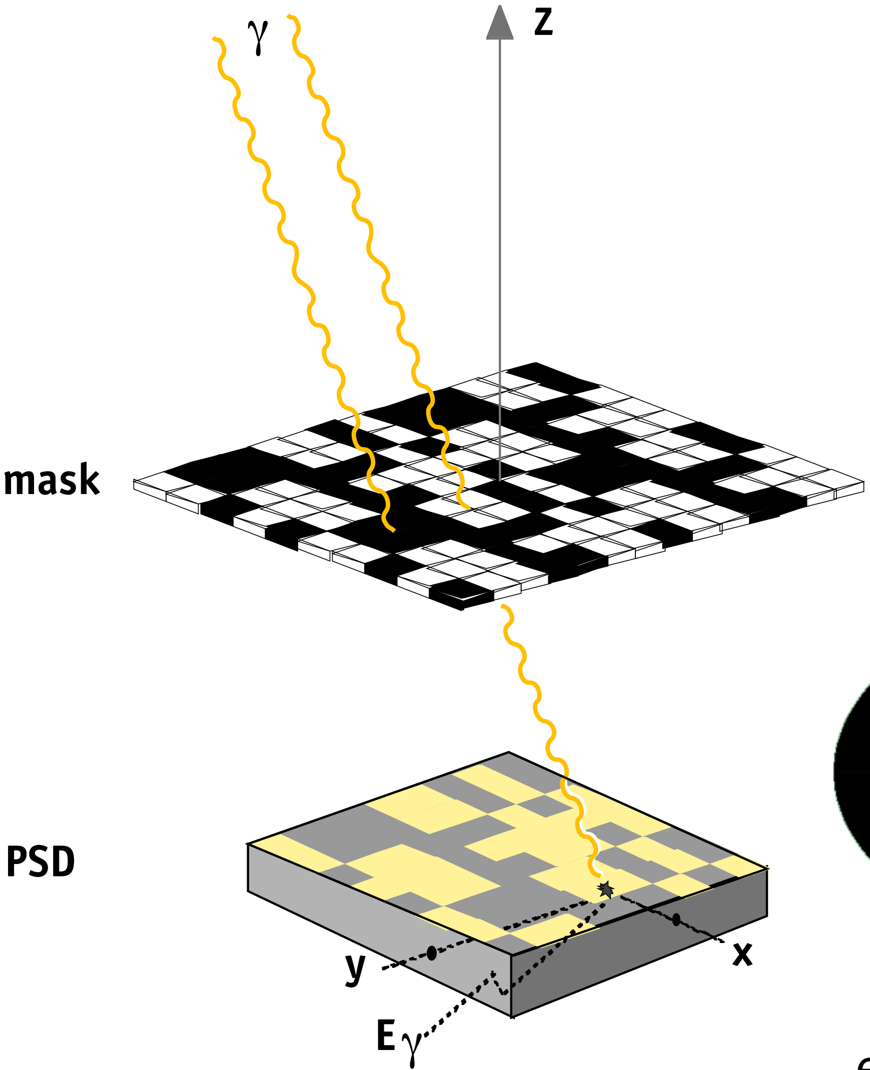




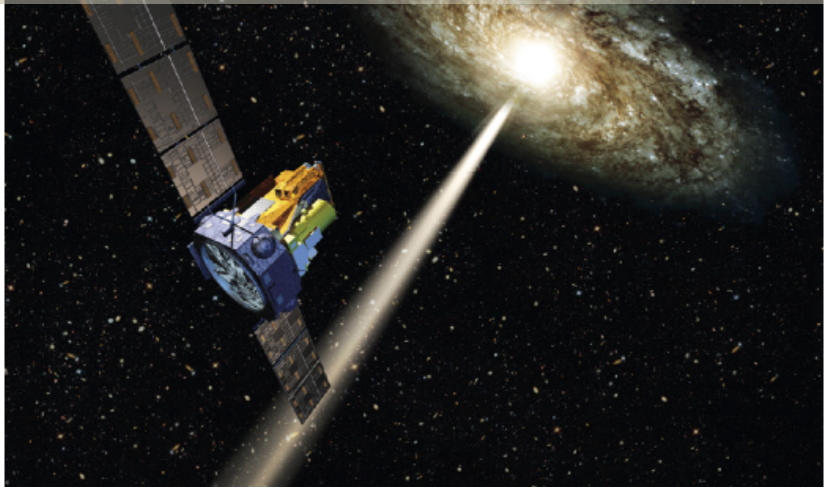
Geometric Optics : Modulating Aperture Systems

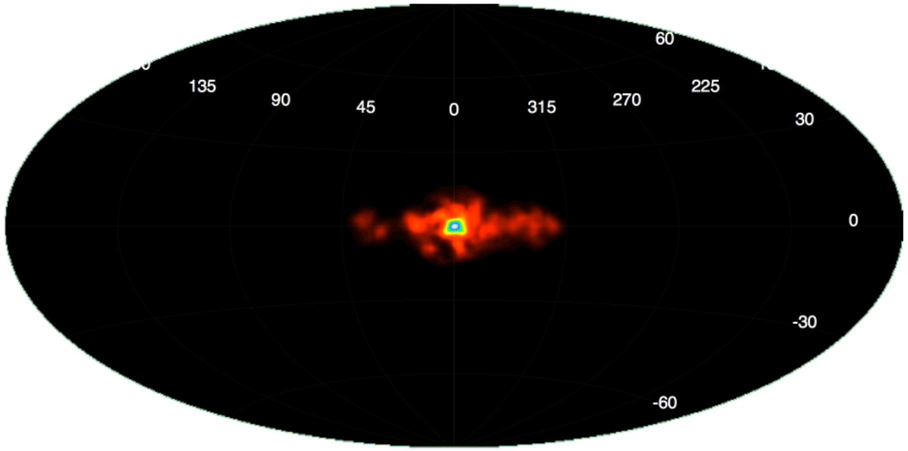


coded mask imaging



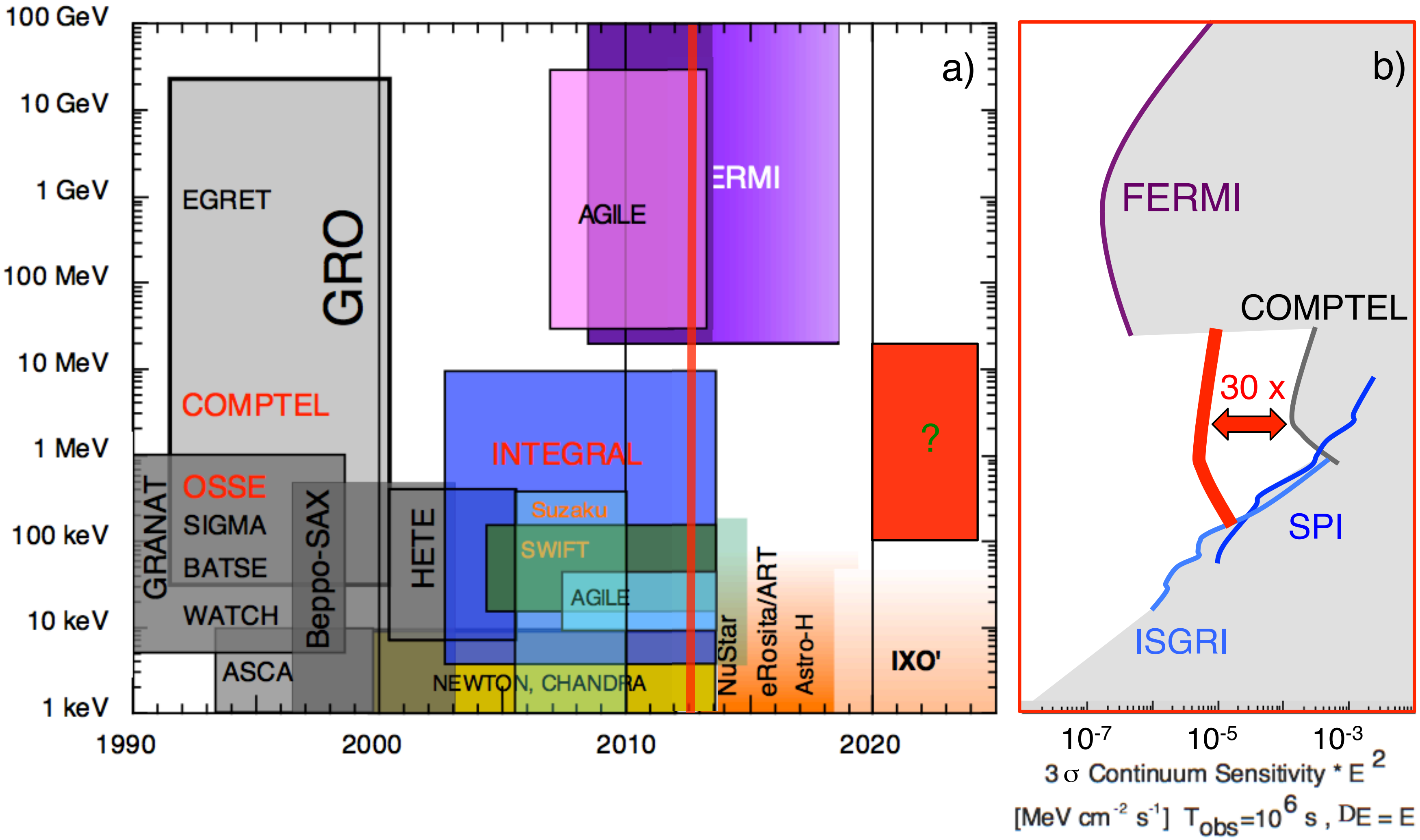
INTEGRAL/SPI





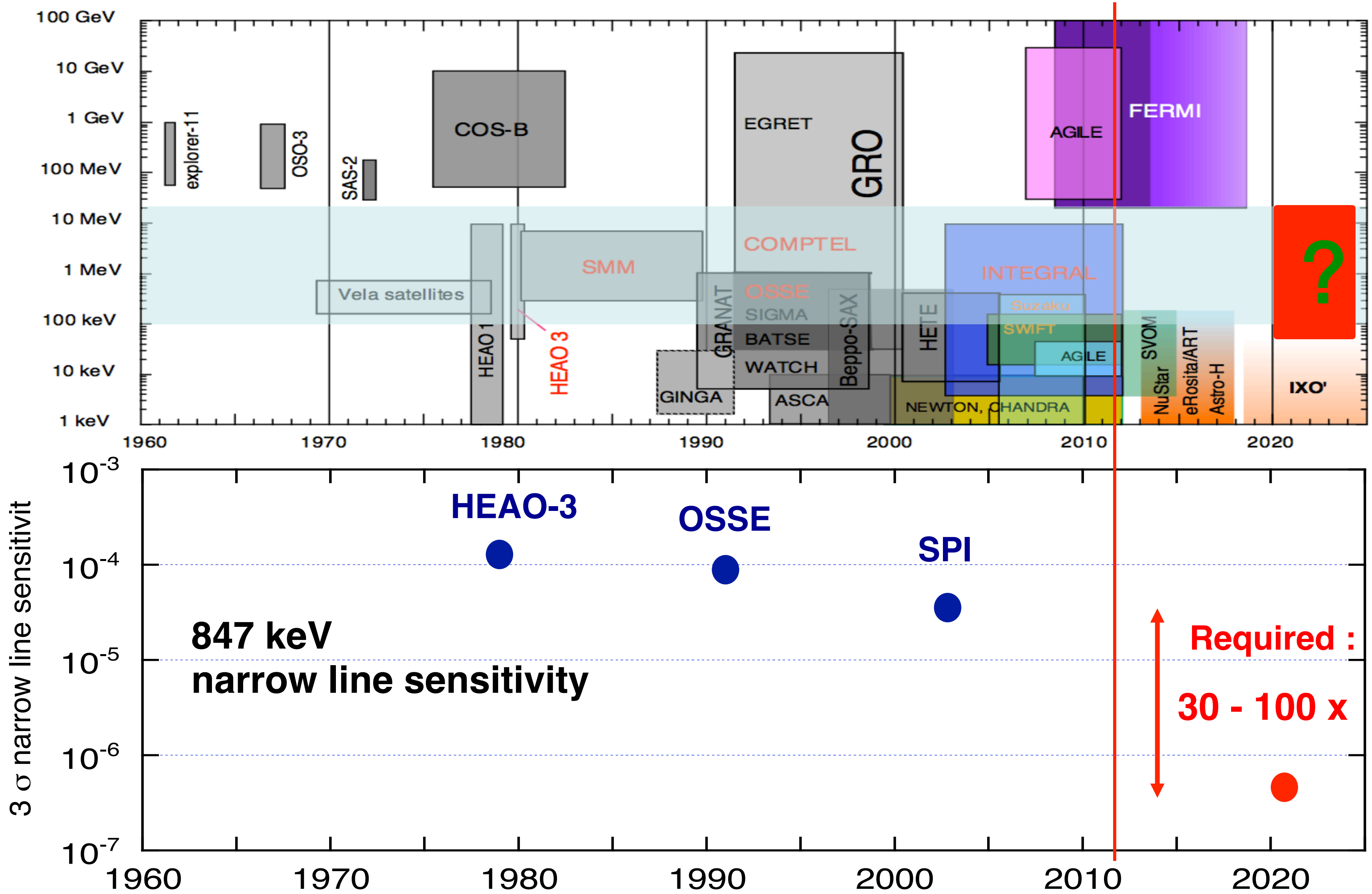
e+e- annihilation map

roadmap of space-borne high-energy astrophysics

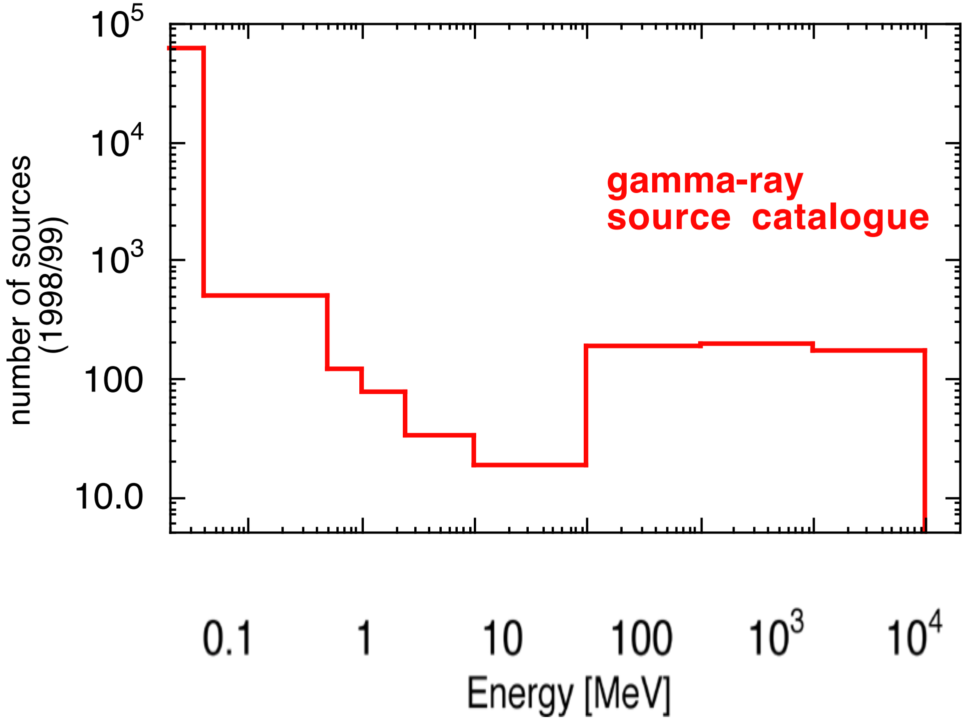


Post-INTEGRAL aera : a white spot on the high-energy astrophysics roadmap

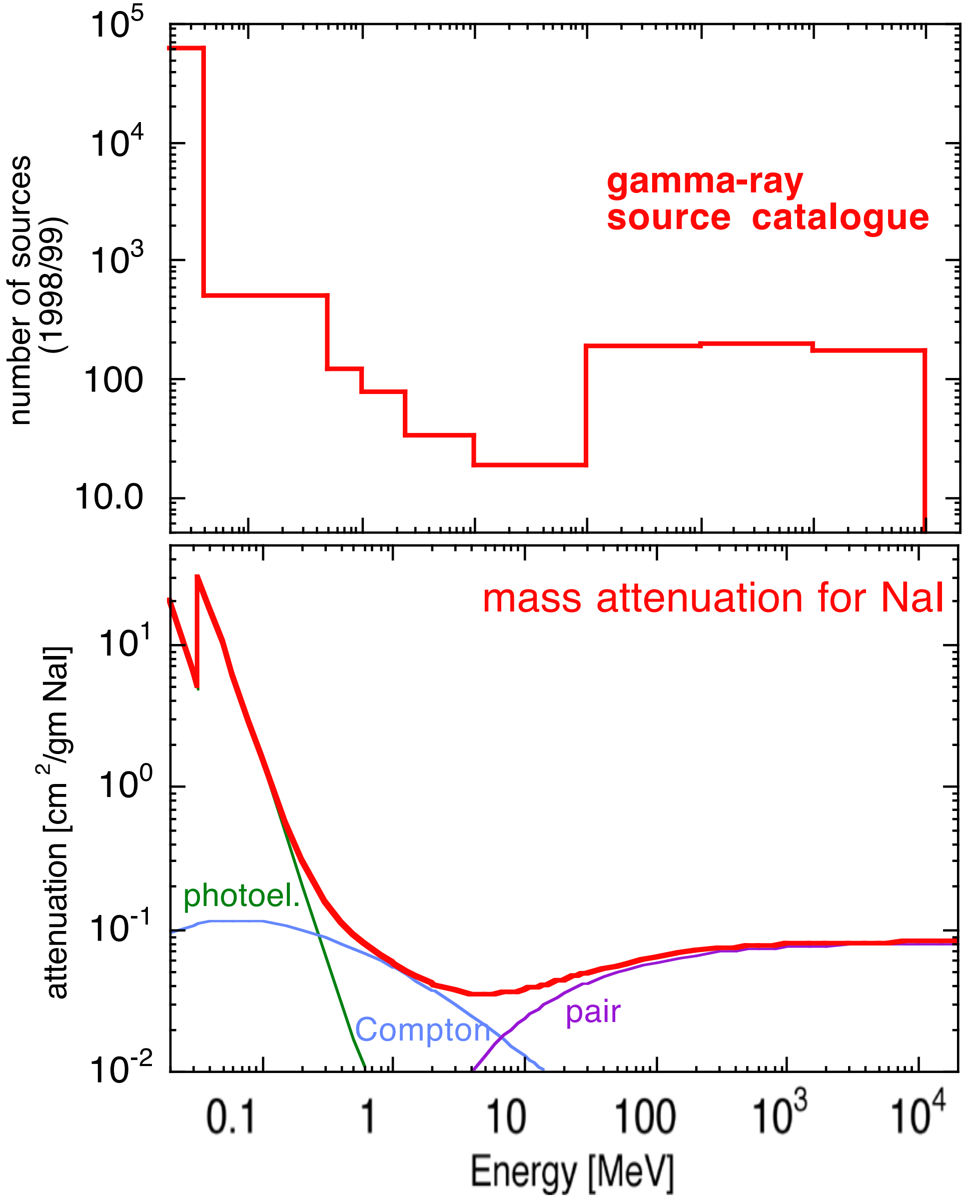
requirements for a future gamma-ray mission



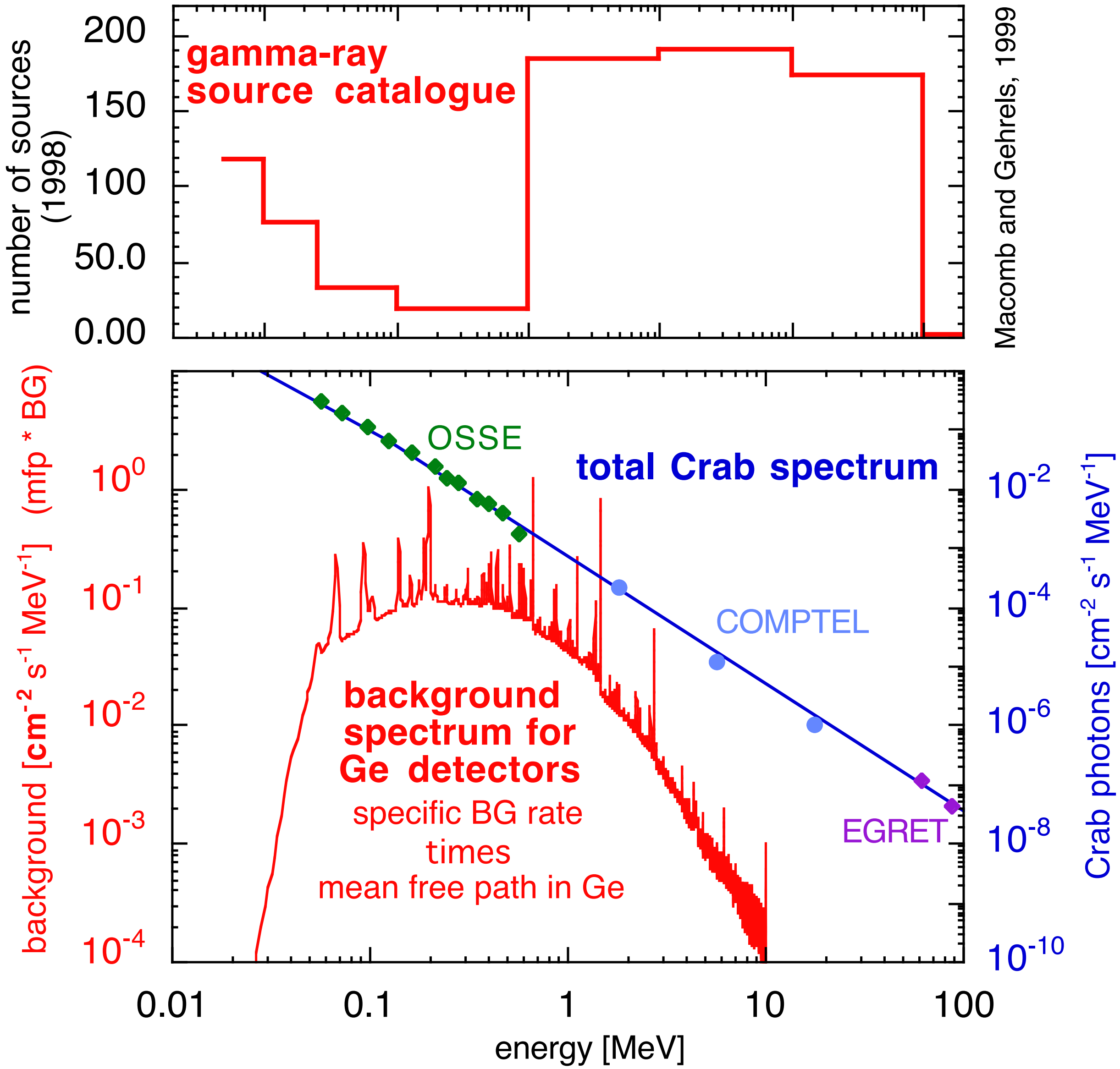
Gamma-ray source statistics



Gamma-ray source statistics



Gamma-ray source statistics



Requirements for a future gamma-ray mission

$f_{3\sigma} < 5 \cdot 10^{-7}\ s^{-1} \cdot cm^{-2}$

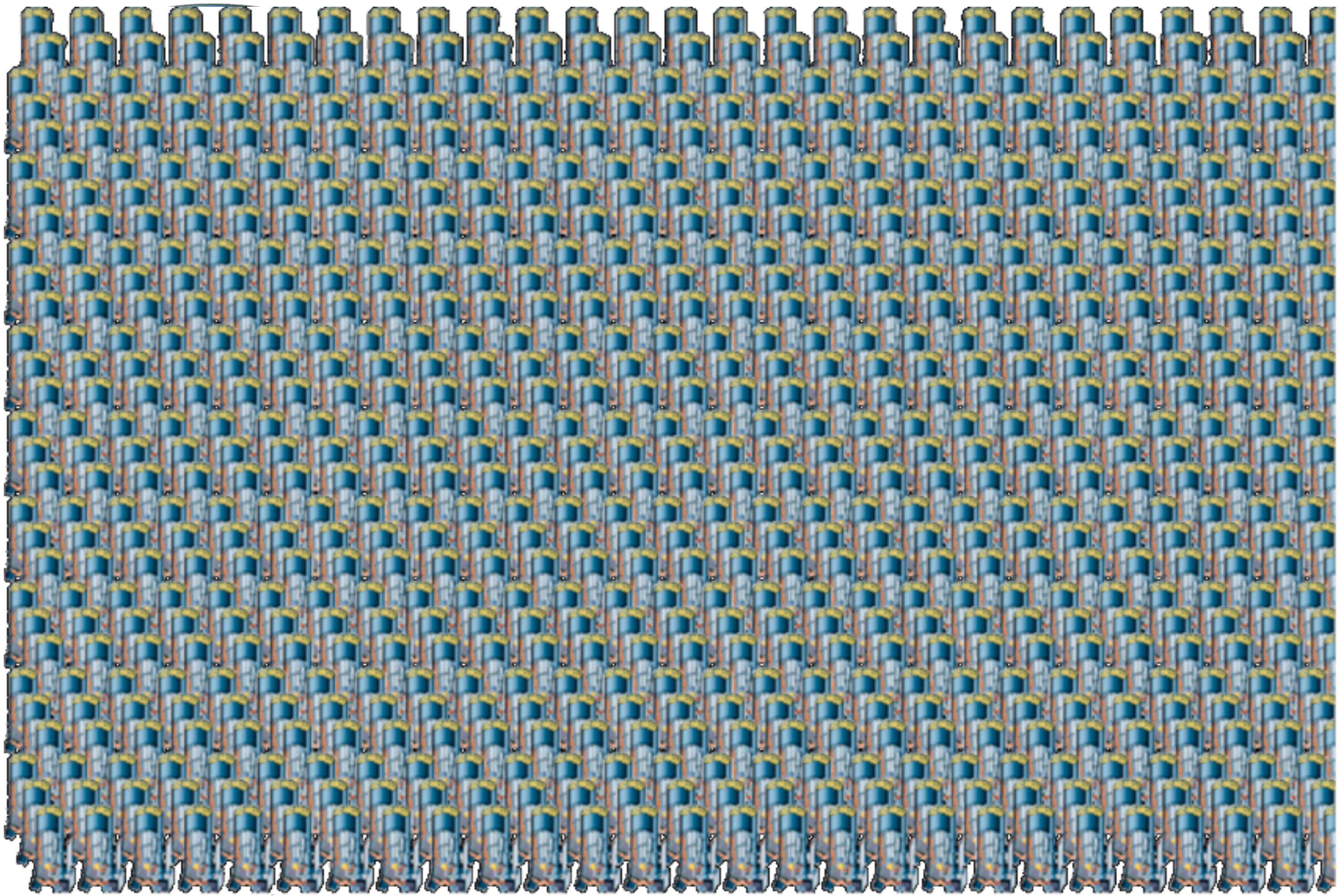
$$f_{3\sigma} < 5 \cdot 10^{-7}\ s^{-1} \cdot cm^{-2}\ !$$

You must be kidding

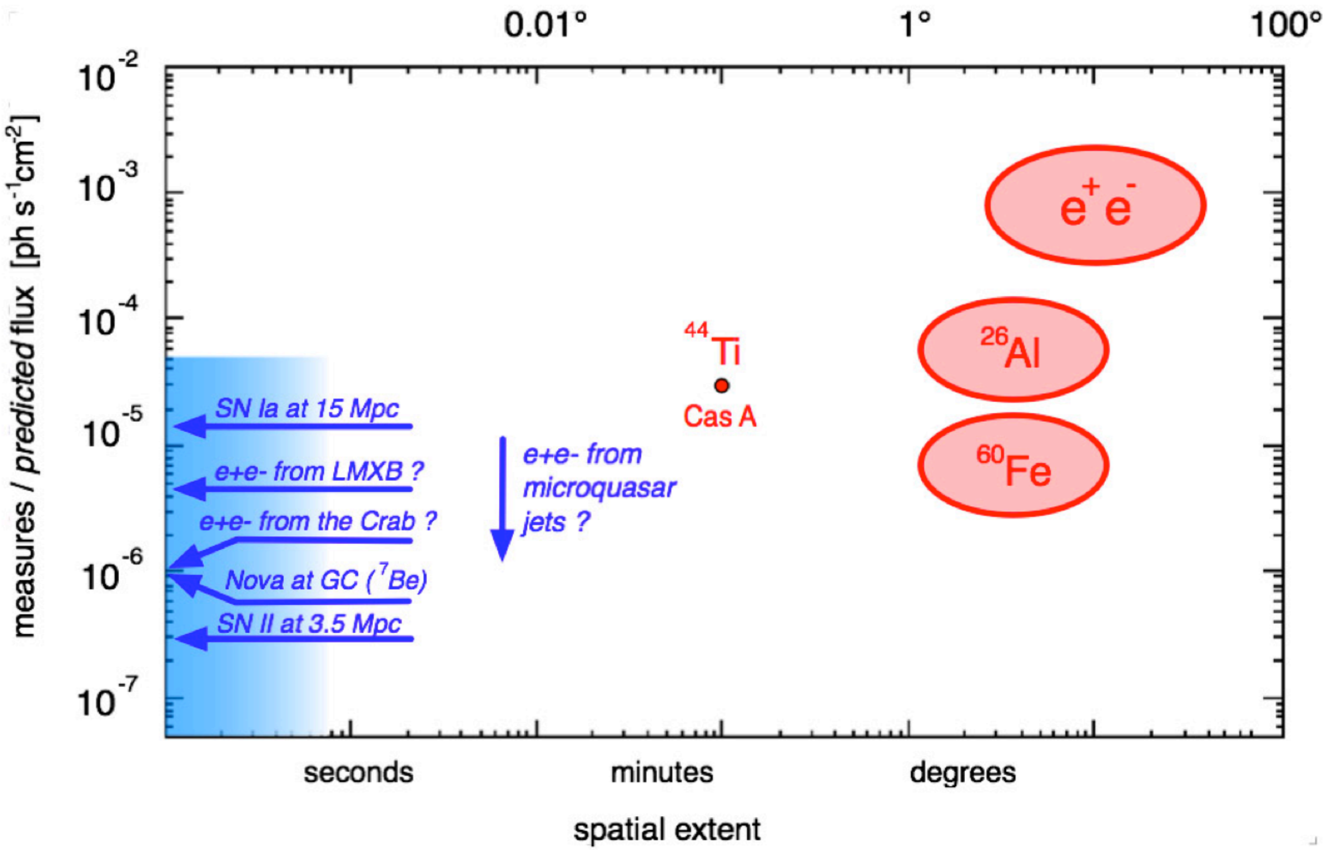
This means detecting one photon per cm^2 and month

with a BG of one CR particle per cm^2 and second
producing about one 511 keV BG event per cm^3 every minute in a Ge detector

Requirements for a future gamma-ray mission



DUAL requirements for a future gamma-ray mission

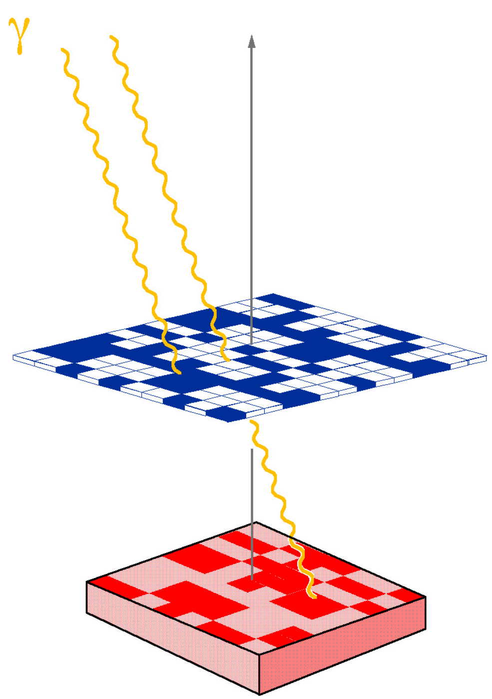
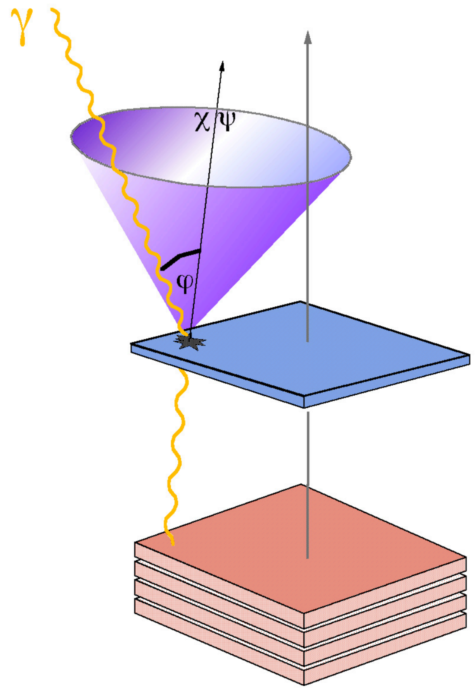
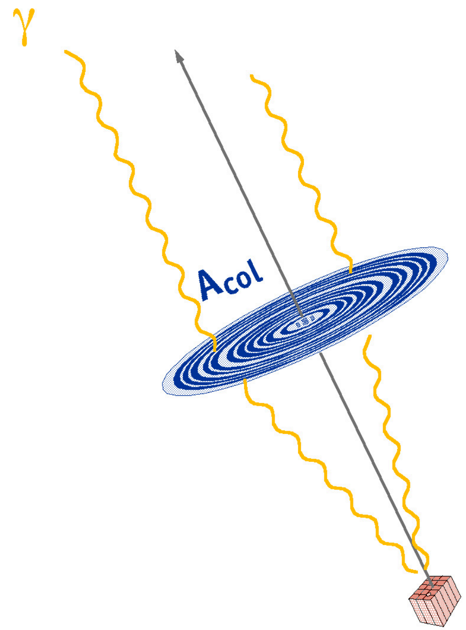


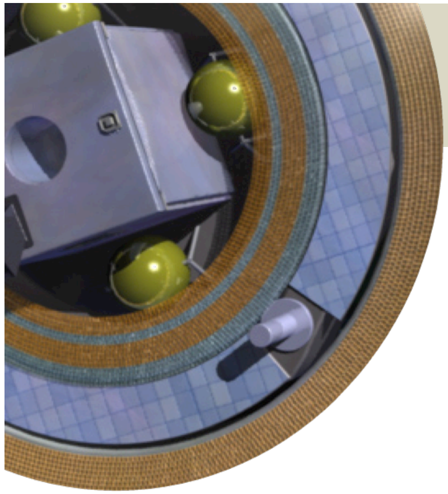
wide range of angular extent, intensities different by several orders of magnitude => two subsets of requirements :

- very deep pointed observations
- medium-sensitivity large-scale exposure (multiplexing advantage)

Instrument concepts in nuclear gamma-ray astronomy

The instrumental categories in nuclear astrophysics reflect our current perception of *light* itself.

	geometric optics absorption	**quantum optics** incoherent scattering	**wave optics** coherent scattering
detector aperture			
	Signal ~ A_{col} BG ~V_{det} ~ A_{det} = A_{col}	Signal ~ A_{col} BG ~V_{det} ~ A_{det} = A_{col}	Signal ~ A_{col} BG ~V_{det} ~ $\mathbf{A_{det}}$ **<<** $\mathbf{A_{col}}$

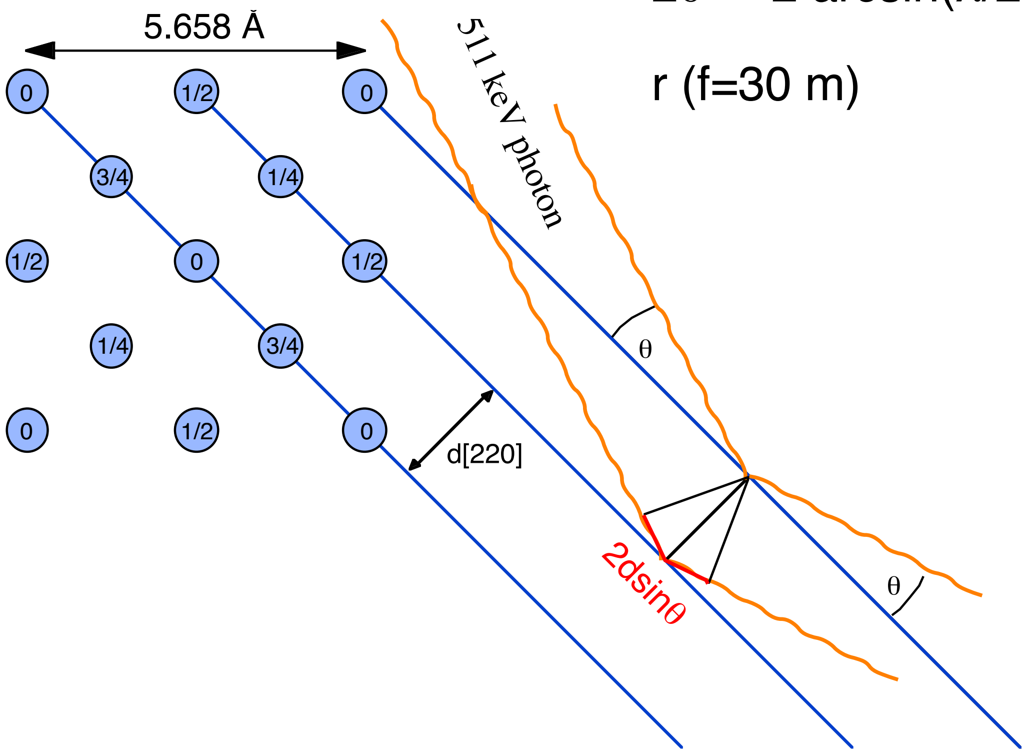


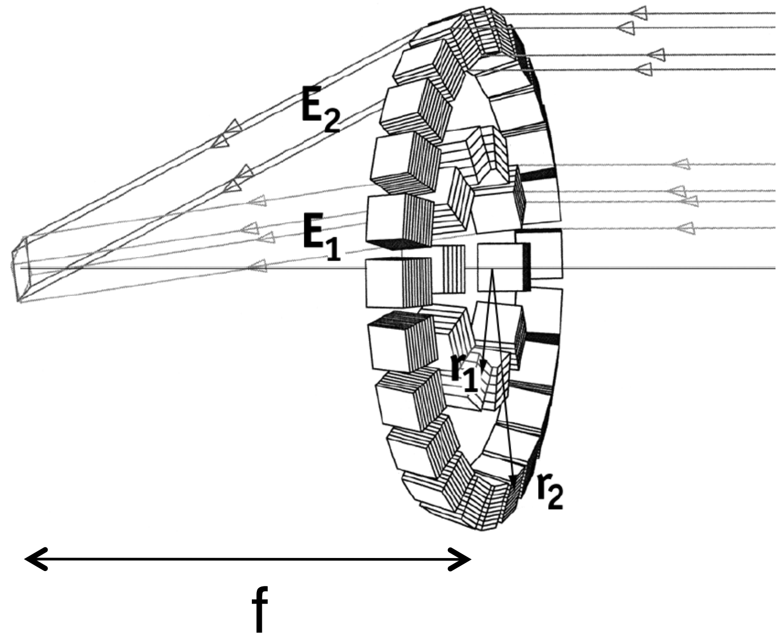
How to focus Gamma-rays : Laue lenses

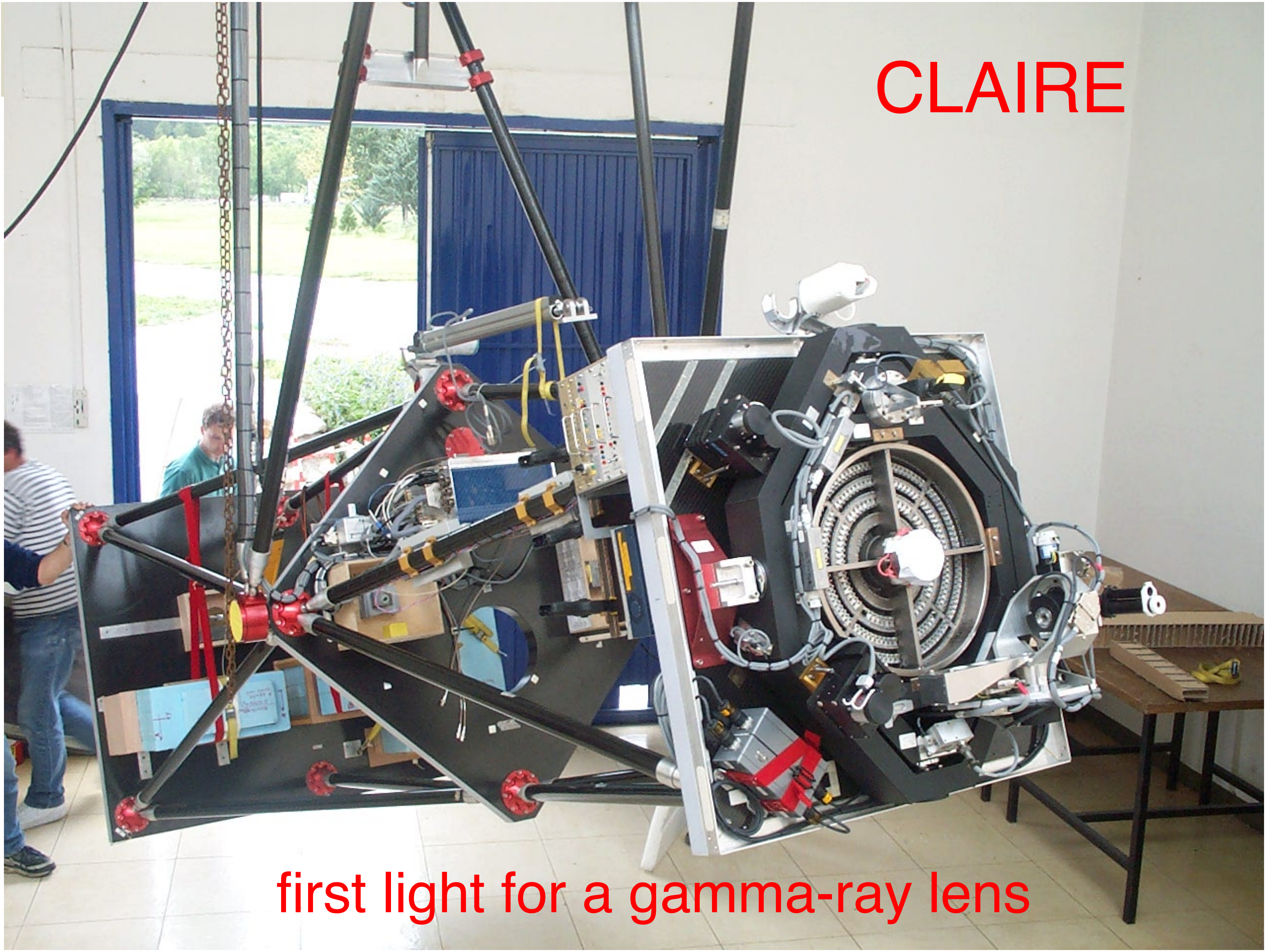
Bragg condition for Cu [111] planes

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

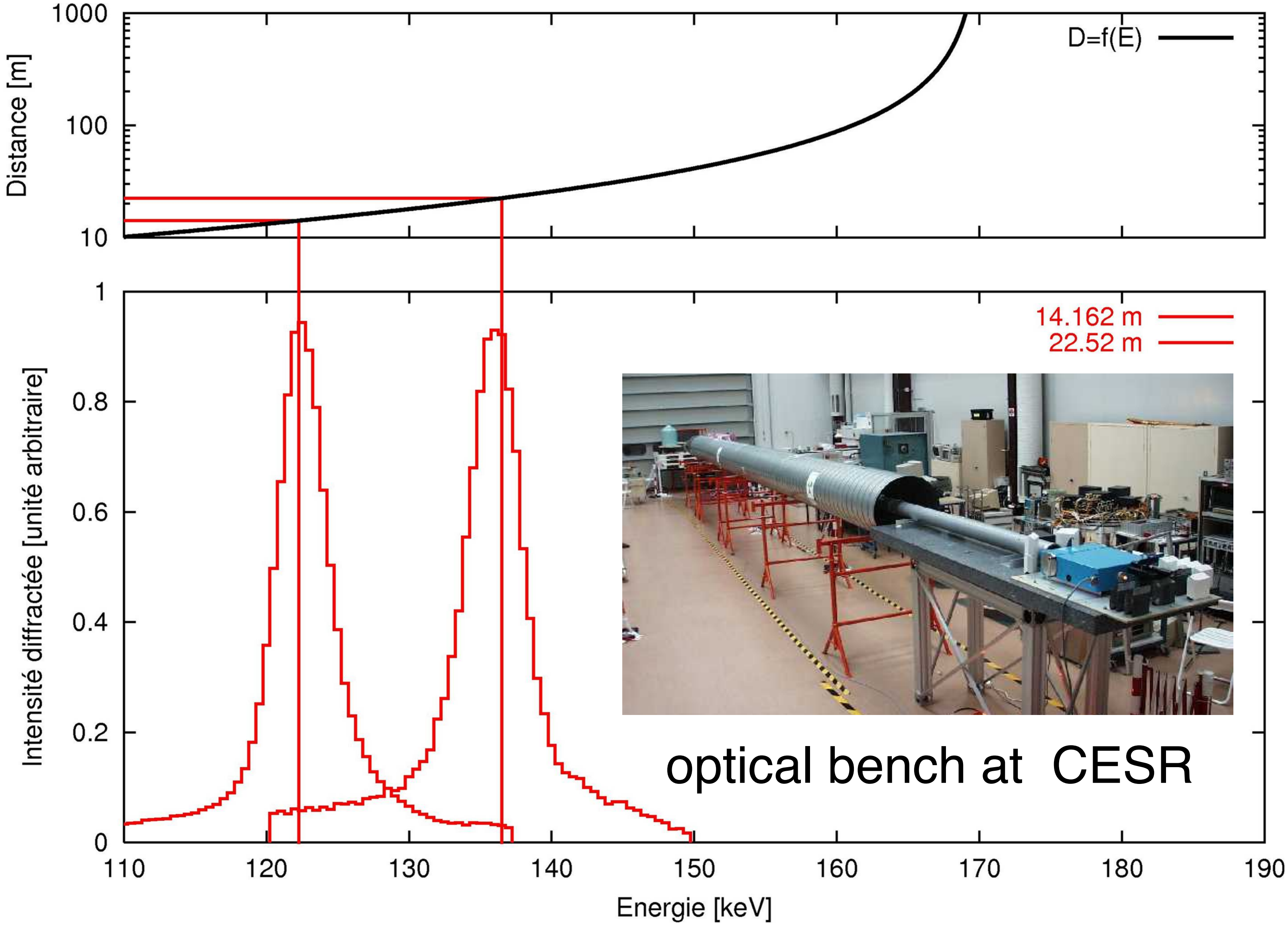
d [111]	=	2.08 Å
λ (847 keV)	=	$1.46 \cdot 10^{-2}$ Å
$2\theta = 2\arcsin(\lambda/2d)$	=	0.40°
r (f=30 m)	=	21 cm






CLAIRE
first light for a gamma-ray lens

CLAIRE : tests in the lab ... and beyond

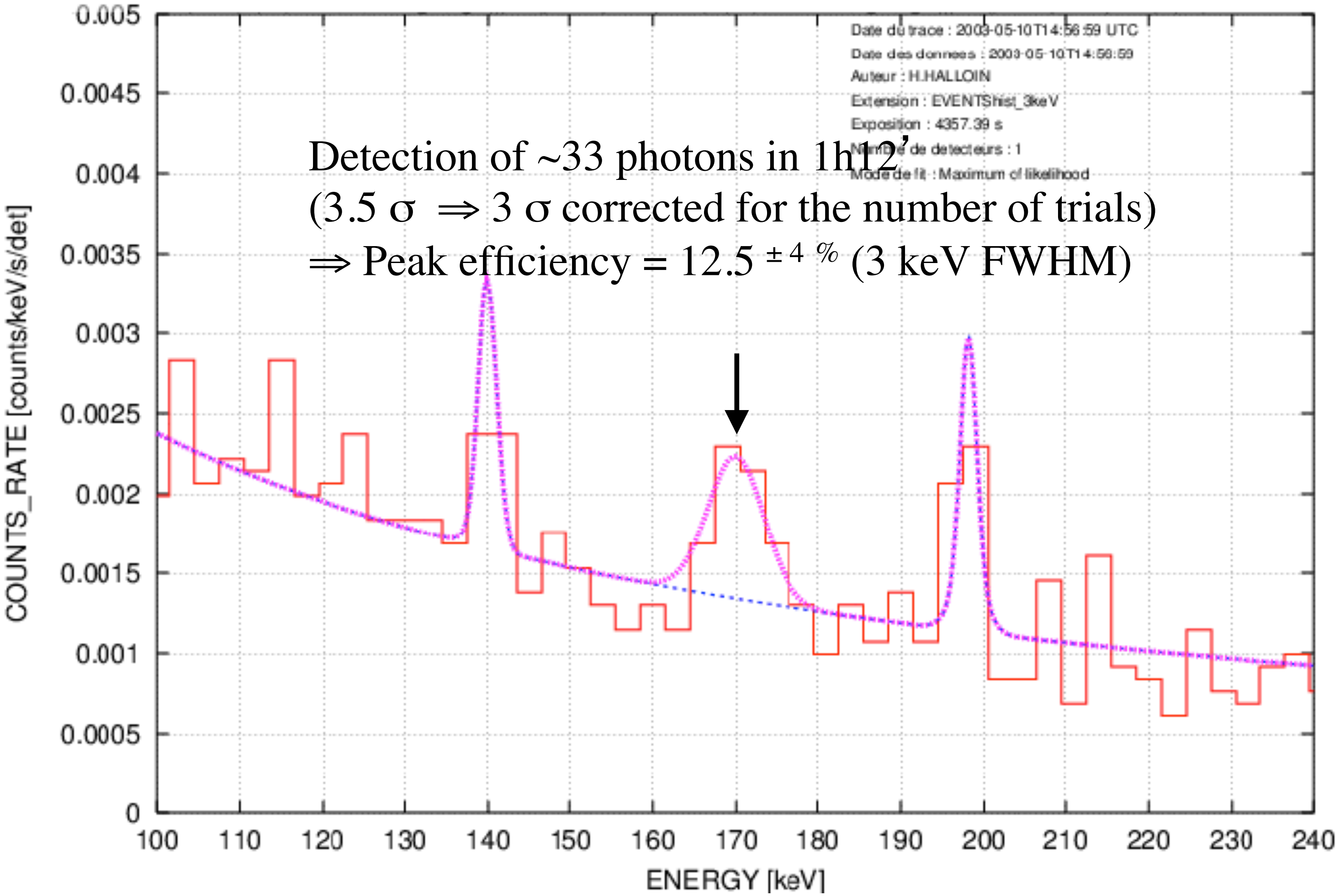


CLAIRE 2001

demonstrate the principle of a γ-ray lens on an astrophysical target

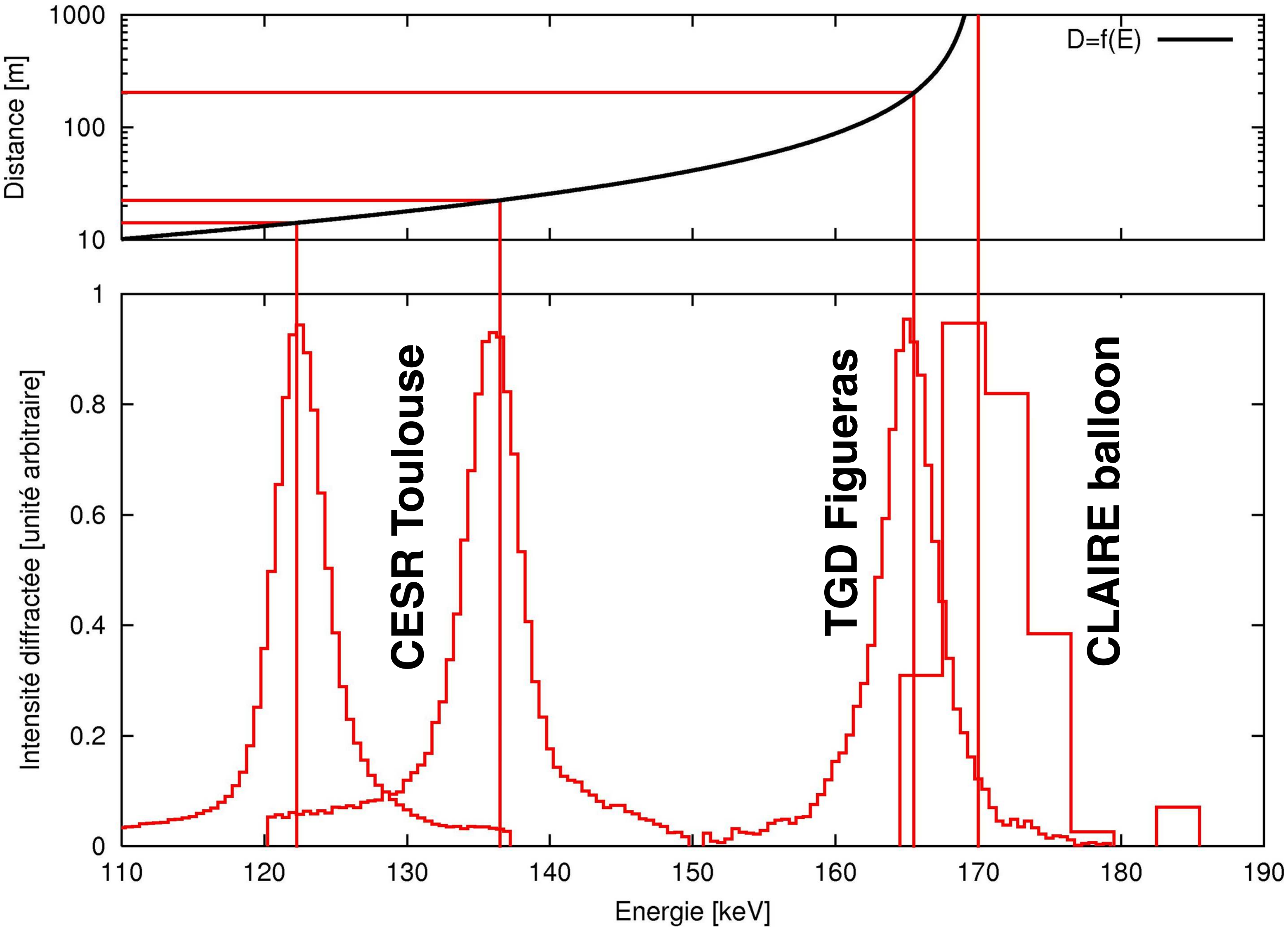
Launch	: 14 june 2001, 8h15 UT, CNES balloon base, Gap-Tallard
Balloon	: Zodiac Z600 (600.000 m^3)
floating altitude	: > 41 km (3.8 g/cm2 residual atmosphère), during 5h 30’
Landing	: 14 june 2001, 17 h UT, Bergerac, Acquitane (~Bordeaux region)

CLAIRE 2001 : first light for an astrophysical source



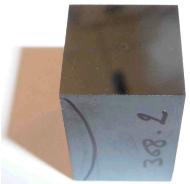
Detection of ~33 photons in 1h12'
(3.5 σ ⇒ 3 σ corrected for the number of trials)
⇒ Peak efficiency = 12.5 $^{\pm 4}$ % (3 keV FWHM)

CLAIRE : 14 m, 22.5 m, 205 m ... infinity ! $\varepsilon_{peak,3\ keV} \approx 10\ \%$



Technological Readiness Level (TRL) of the Laue lens

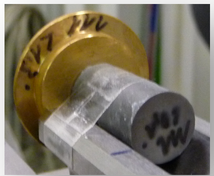
ESA pre-industrial serie / TRL study of crystal production



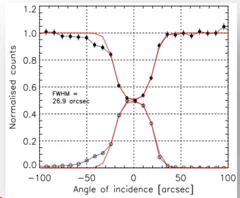
SiGe : mosaicity 20 and 40 arcsec, good homogeneity
Reflectivities : 20-30% at 284 keV.10-20% at 517 keV

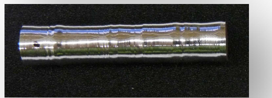
Cu : mosicity between 20 and 40 arcsec
Reflectivities : 15-20% at 511 keV, 12-23% at 816 keV

"Crystal Prospective"

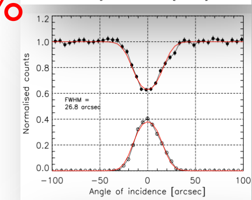


Pb (111) T_0=12mm, E=700 keV
Mosaicity = 27 arcsec; Quality fact : 100%

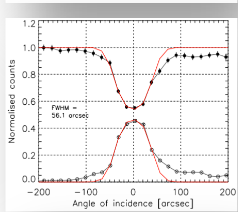




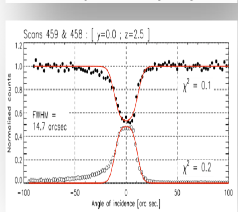
Rh (220) T_0=10mm, E=500 keV
Mosaicity = 27 arcsec; Quality fact : 82%



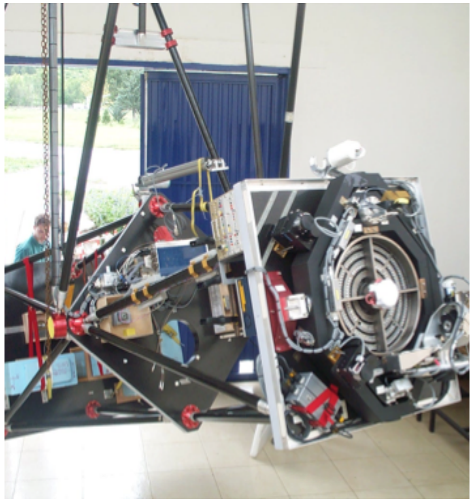
Ag (111) T_0=10mm, E=500 keV
Mosaicity = 56 arcsec; Quality fact : 92%



Au (111) T_0=2mm, E=500 keV
Mosaicity = 26 arcsec; Quality fact : 90%



The development of gamma-ray lenses

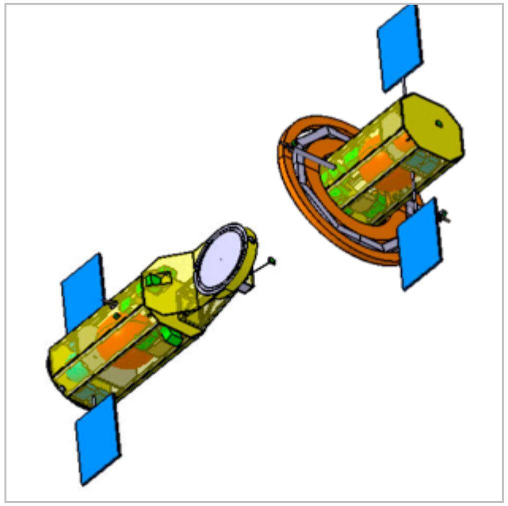


CLAIRE 2003

CNES balloon & TGD

Crab detection :

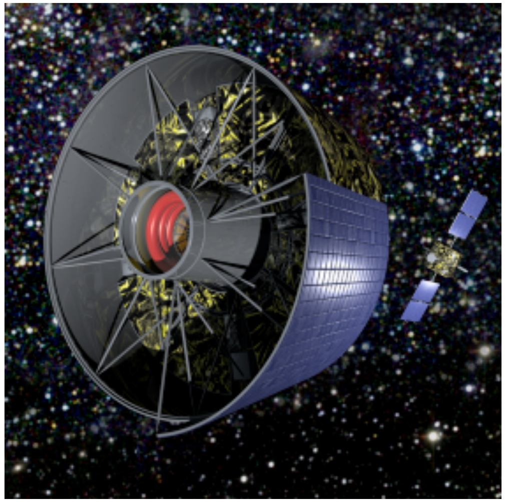
First light for a gamma-ray lens



Max 2005

CNES/PASO prephase A

Demonstrating the feasiblity of a spaceborne Laue Lens



GRI 2007

Cosmic Vision proposal

Community adopts the Laue lens for the next gamma-ray mission

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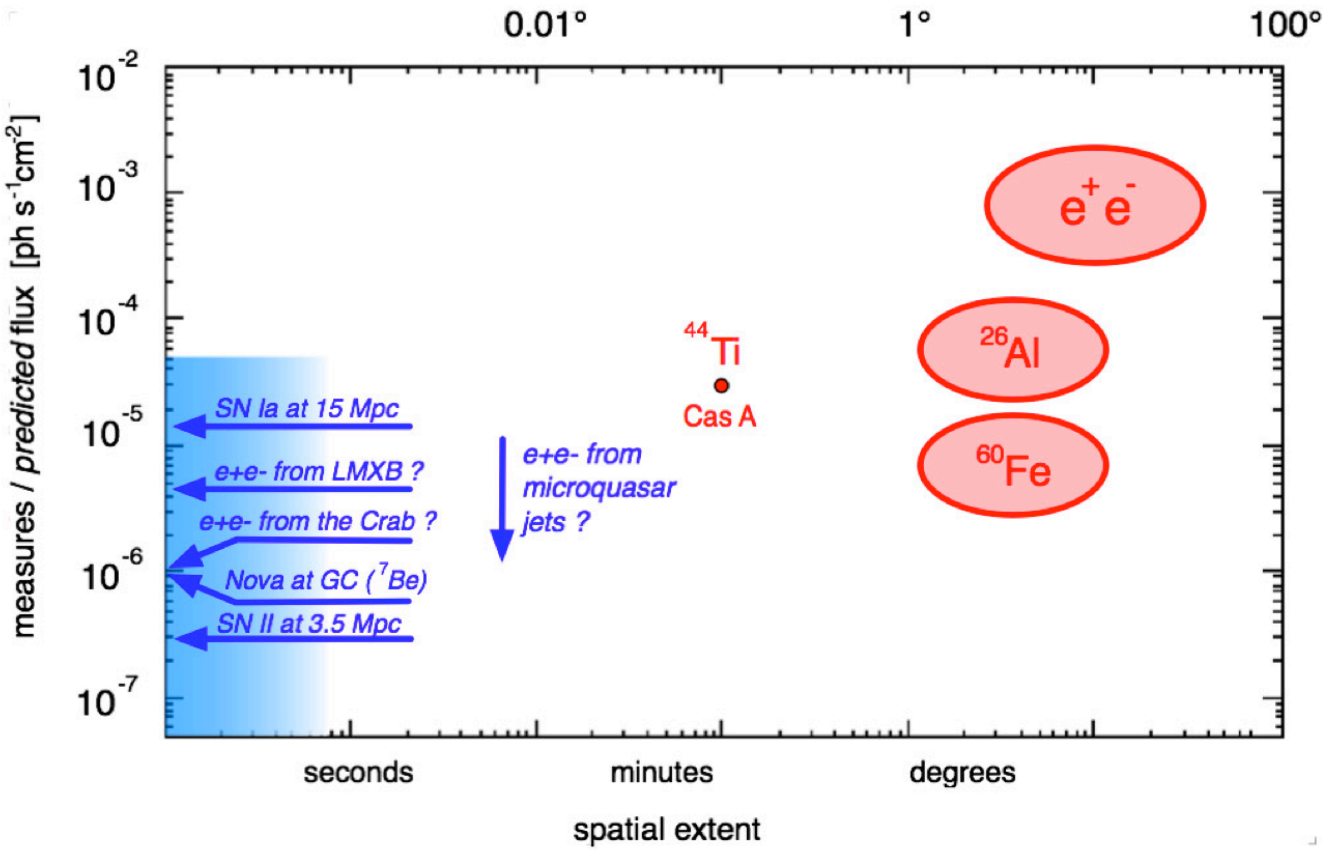
crystal R&D : gold, silver crystals; curved Si/Ge crystals; ESA pre-serie

lens R&D : lens prototype TAS Cannes, vibration, qualification

DUAL requirements for a future gamma-ray mission



wide range of angular extent, intensities different by several orders of magnitude => two subsets of requirements :

- very deep pointed observations
- medium-sensitivity large-scale exposure (multiplexing advantage)

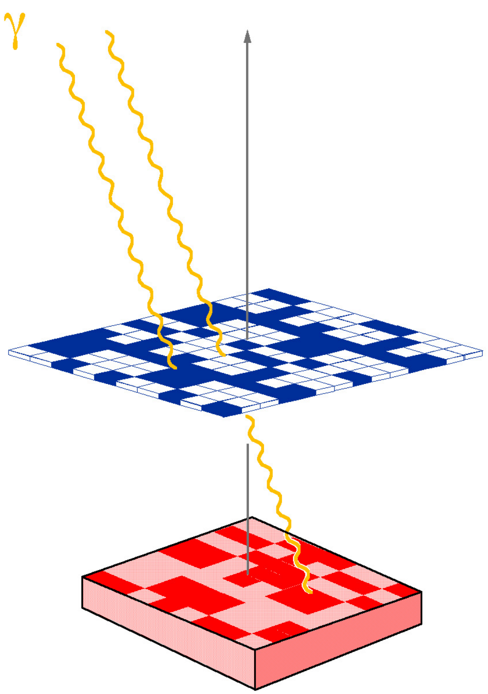
and what about gamma-ray bursts ?

Instrument concepts in gamma-ray astronomy

The instrumental categories in nuclear astrophysics reflect our current perception of *light* itself.

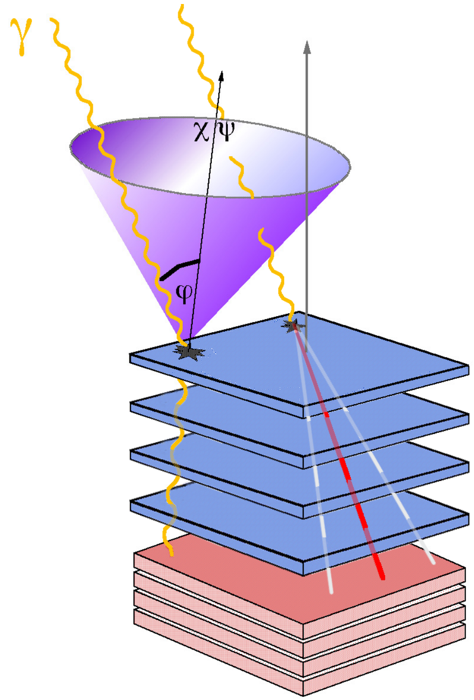
aperture
detector

geometric optics
absorption



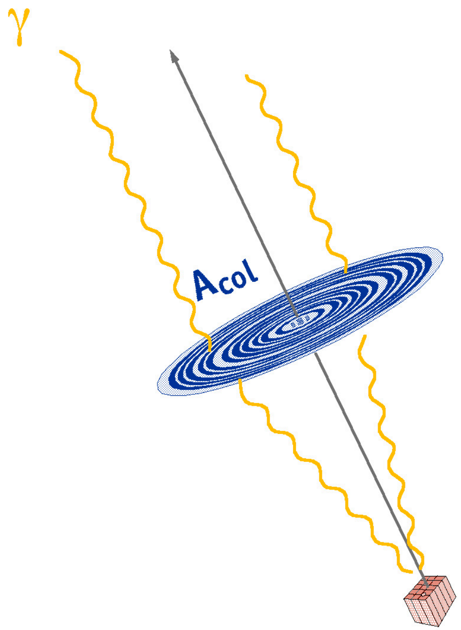
ex. coded masks
"on-off" collimators

quantum optics
incoherent scattering



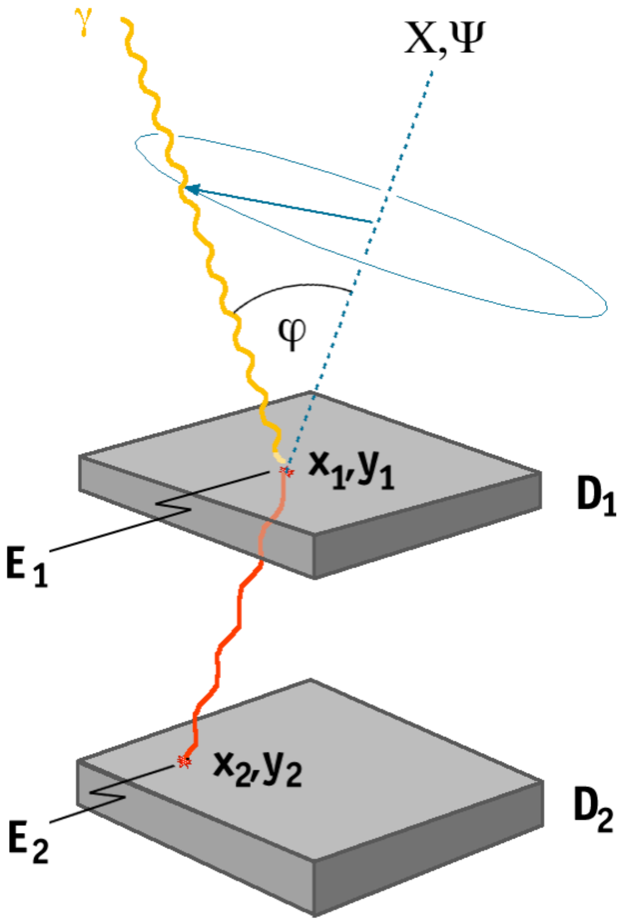
ex. Compton telescopes
tracking chambers

wave optics
coherent scattering



ex. Laue lenses
Fresnel lenses

the principle of Compton Telescopes



measured parameters :

x_1,y_1	:	interaction location in D_1
E_1	:	energy deposit in D_1
x_2,y_2	:	interaction location in D_2
E_2	:	energy deposit in D_2
t, Δt	:	arrival time, TOF D_1-D_2

derived parameters :

x_1,y_1,x_2,y_2 => χ, ψ

E_1,E_2 => $\bar{\varphi}$

$$\cos \bar{\varphi} = 1 - m_e c^2/E_2 + m_e c^2/E_1+E_2$$

encoding of the two dimensional source distribution into a 3-D dataspace ($\mathbf{X}, \mathbf{\Psi}, \varphi$)

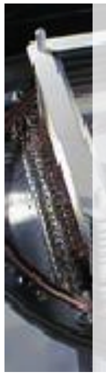
Balloon flights of new generation Compton telescopes

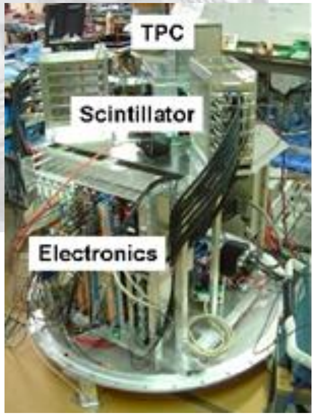
LXeGRIT
1997, 1999, 2000

Kyoto Univ.
2006

liquid Xe TPC

Xe 80%, Ar, C_2H_6 @1atm



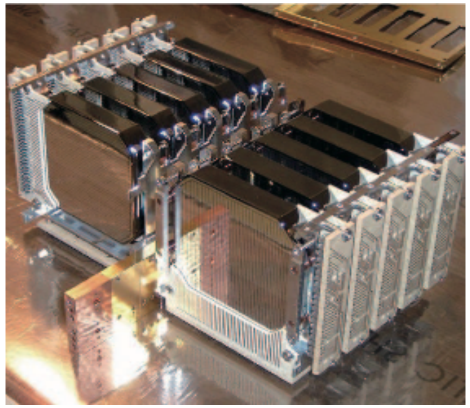


TIGRE
2007, 2010

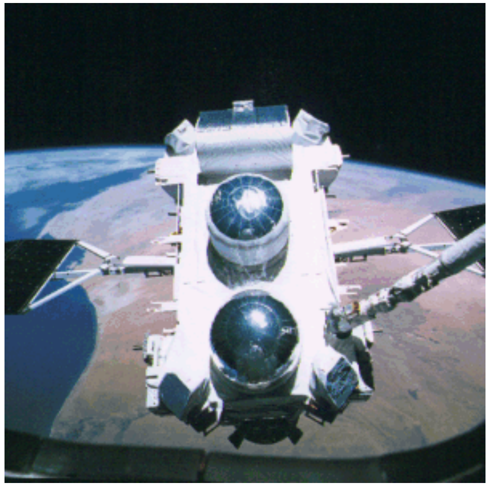
D1 : DSSD
D2 : NaI(Tl) &CsI(Tl)

NCT
2005, 2009

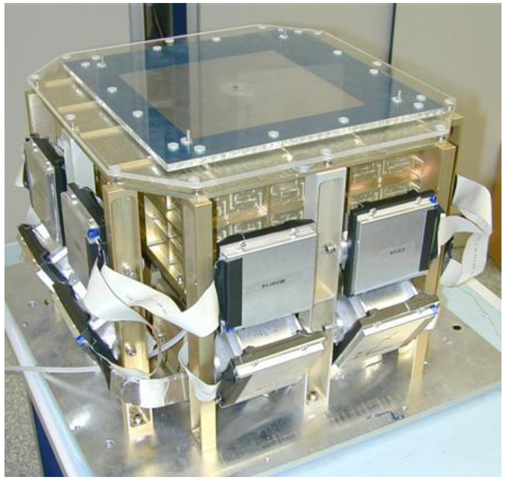
Ge strip detectors



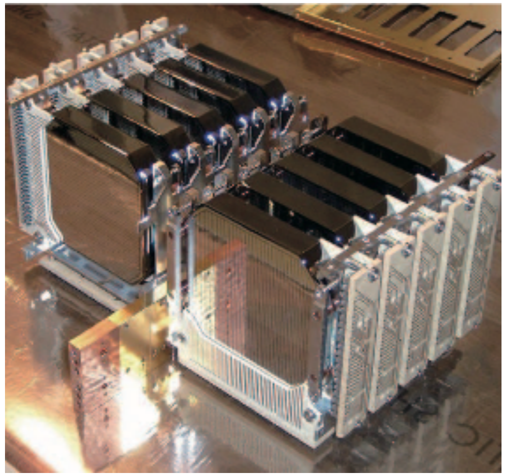
The development of Compton Telescopes



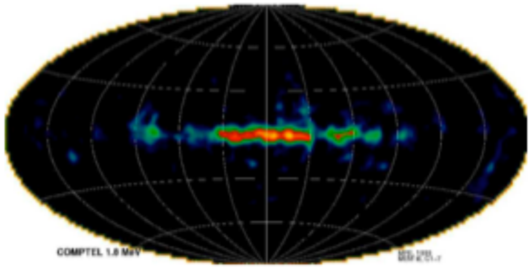
COMPTEL 1991-1999
large scintillator CT



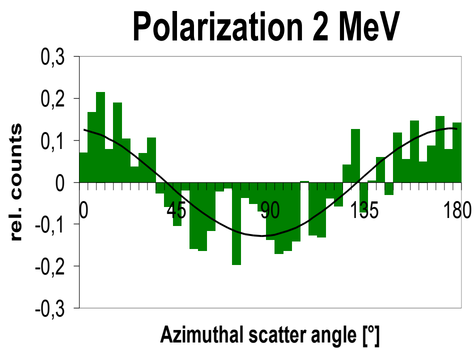
MEGA/MEGA balloon
Si tracker / CT



NCT balloon flights
Ge DSSD, 3D loc (mm^3)



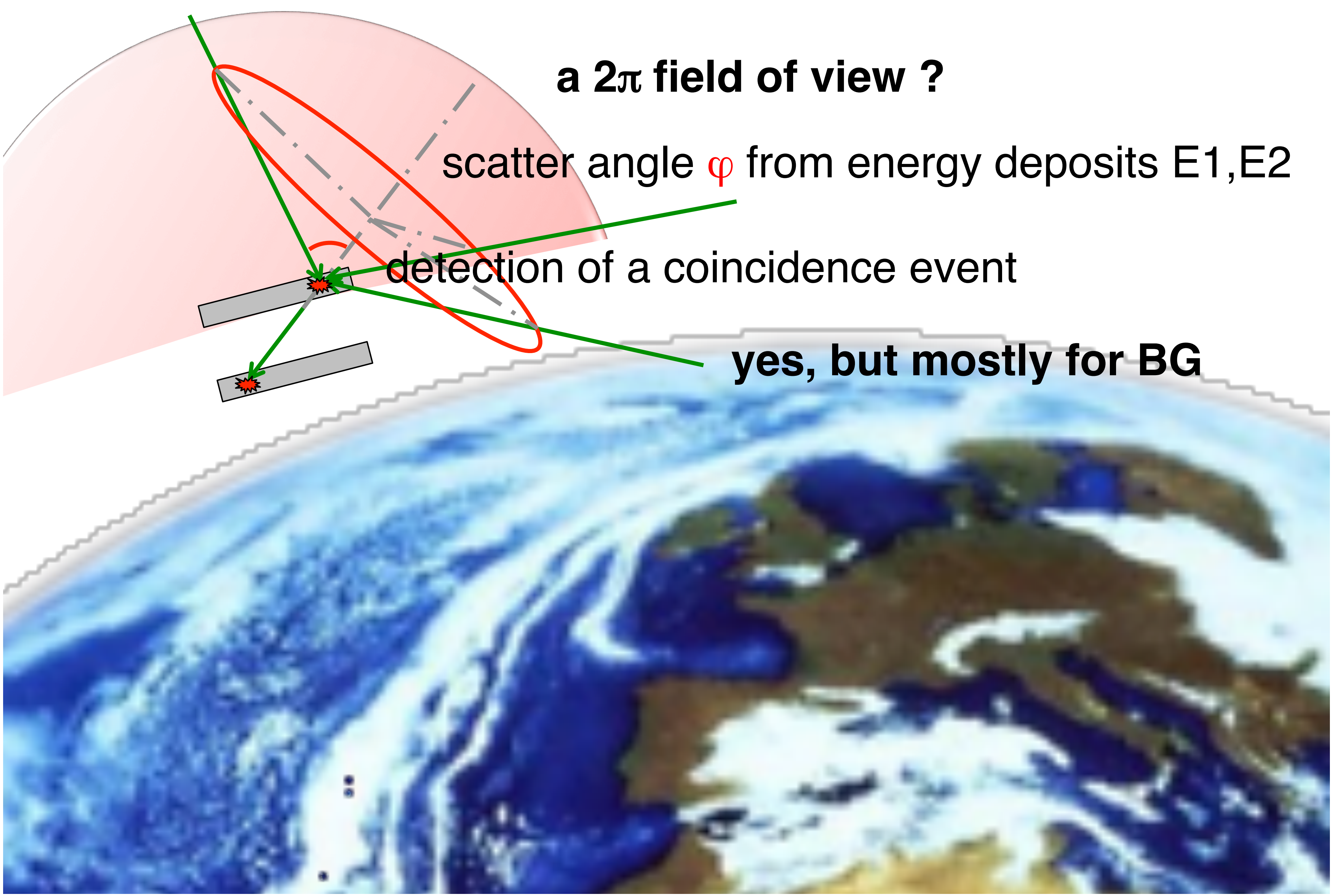
first ^{26}Al all-sky map



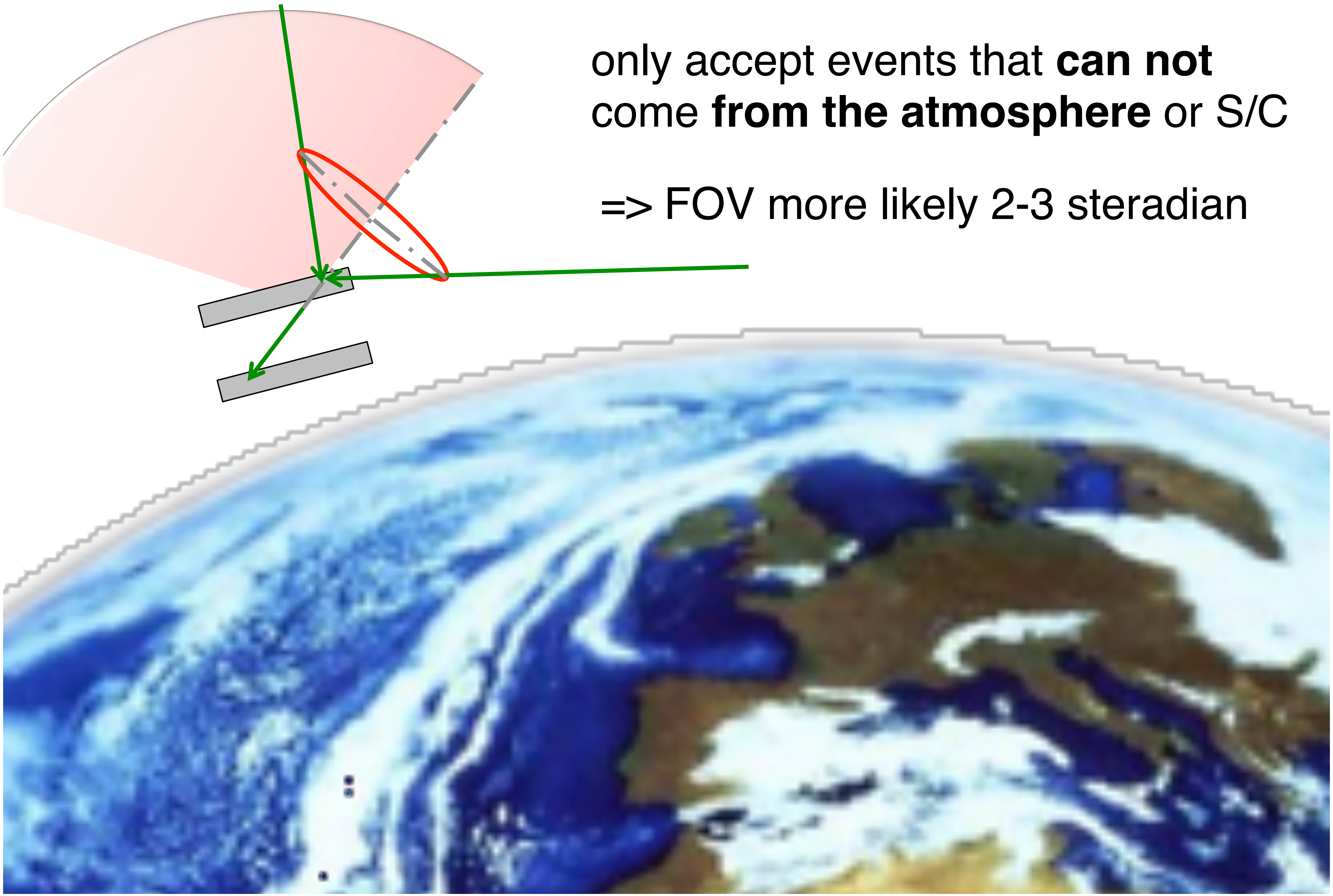
demonstrated polarization

Crab detection 2009

Compton telescopes have wide fields



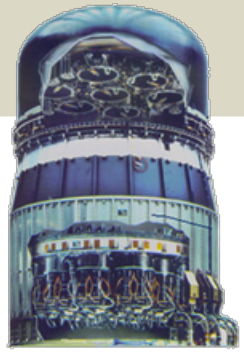
Compton telescopes have wide fields

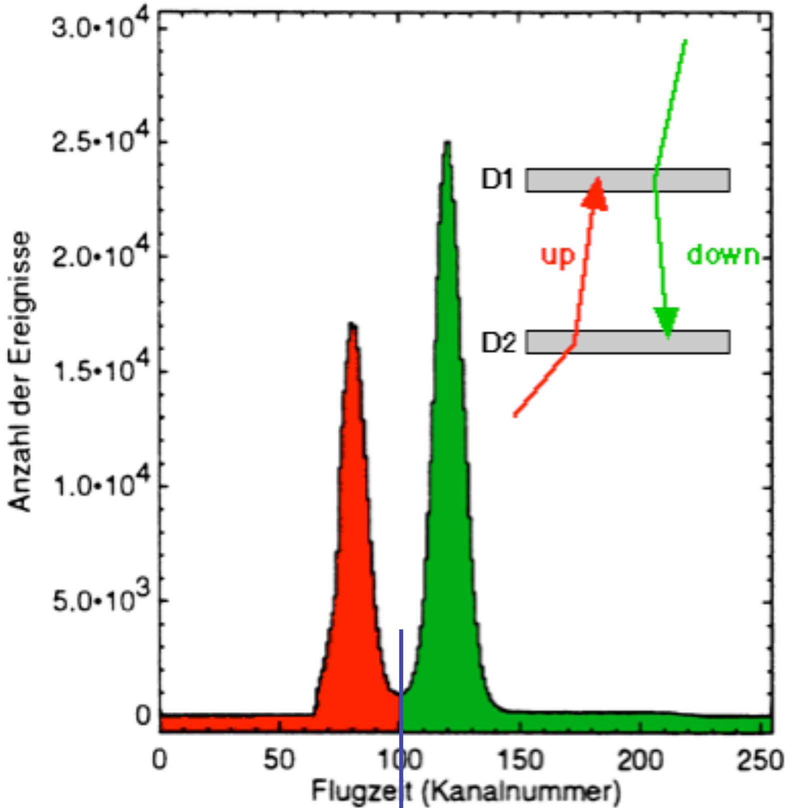


only accept events that **can not** come **from the atmosphere** or S/C

=> FOV more likely 2-3 steradian

Time of Flight coincidence (TOF) COMPTEL data

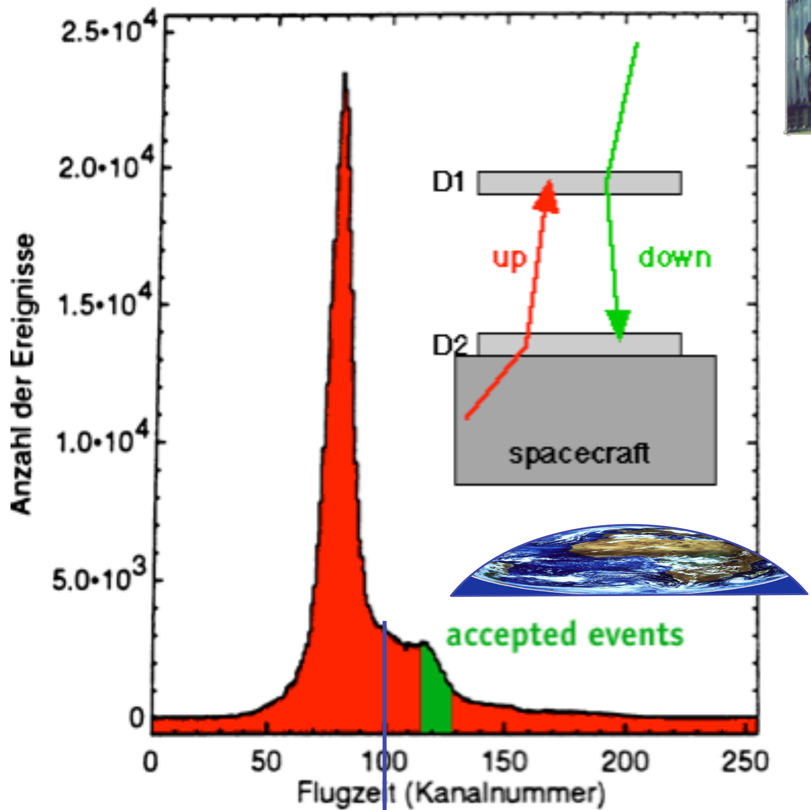




<- upward | downward ->

COMPTEL calibration data

channel width : 0.25 ns
distance D1-D2 : 1.5 m ≈> 5 ns)

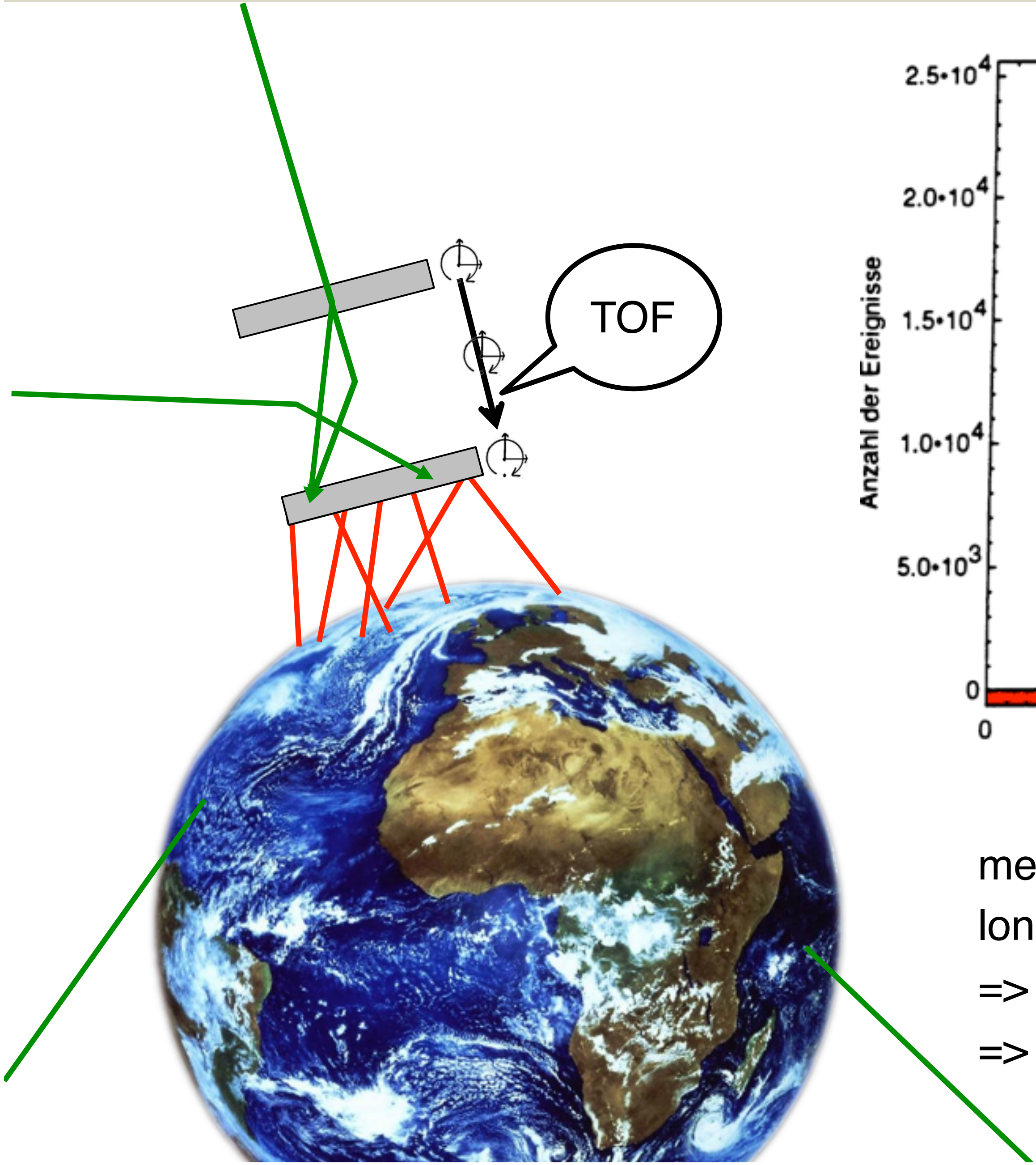


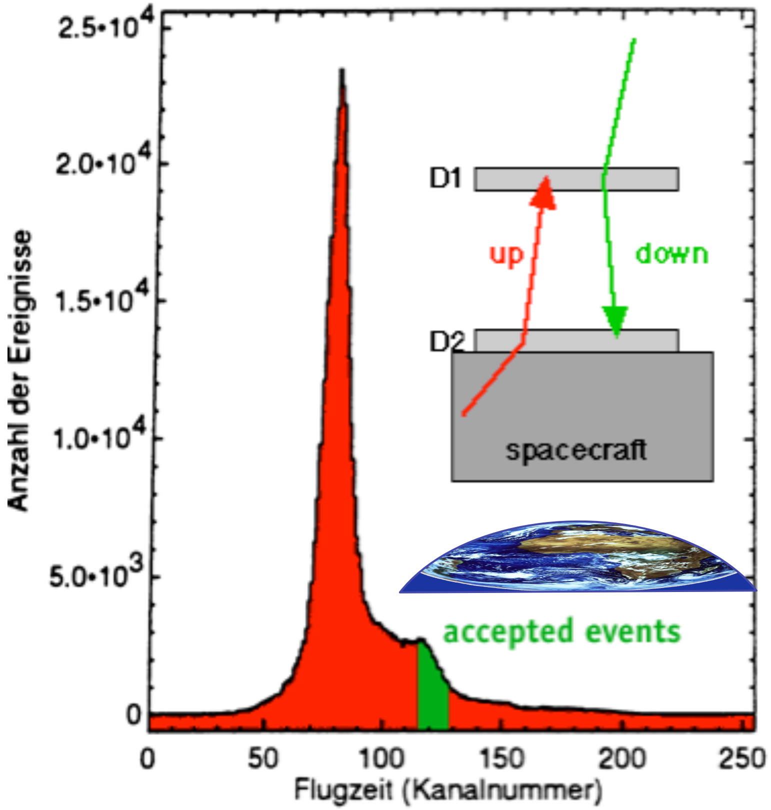
<- upward | downward ->

COMPTEL flight data

channel width : 0.25 ns
"upward BG" from spacecraft and the Earth

option A : time-of-flight electronics





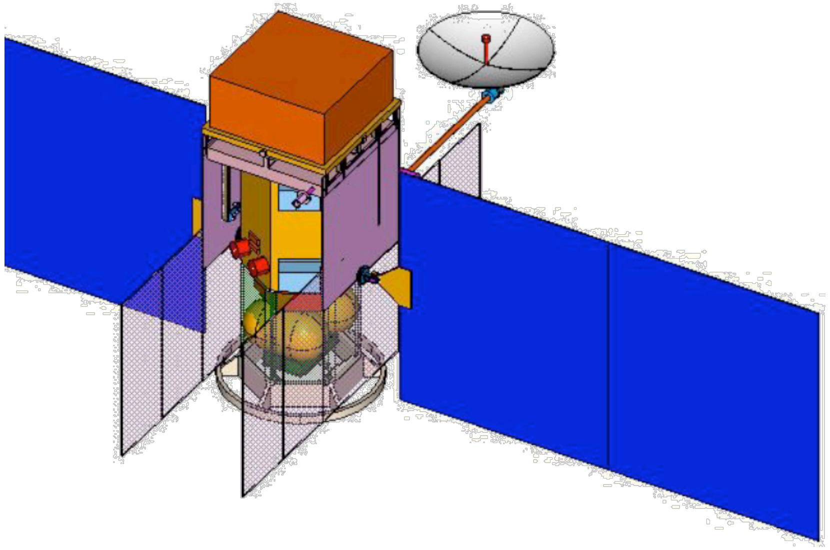
measuring TOFs requires
long baselines between D1 and D2
=> low probability for coincidence
=> **low efficiencies** (few % at most)

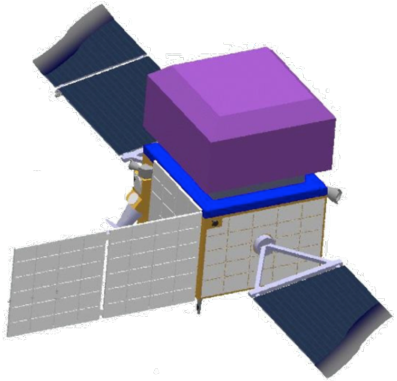
Compton Telescope Mission concepts

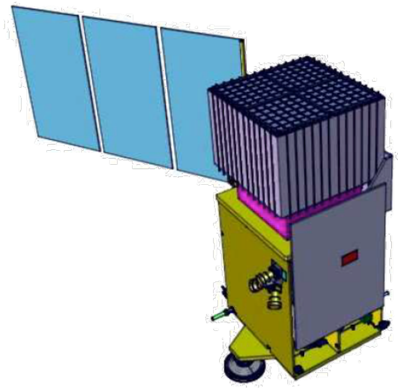
ACT
Nasa Mission
Concept study
Boggs et al. 2006

GRIPS/GRM
ESA cosmic vision 2011
Greiner et al. 2007/11

CAPSiTT
ESA cosmic vision 2011
Lebrun et al. 2011







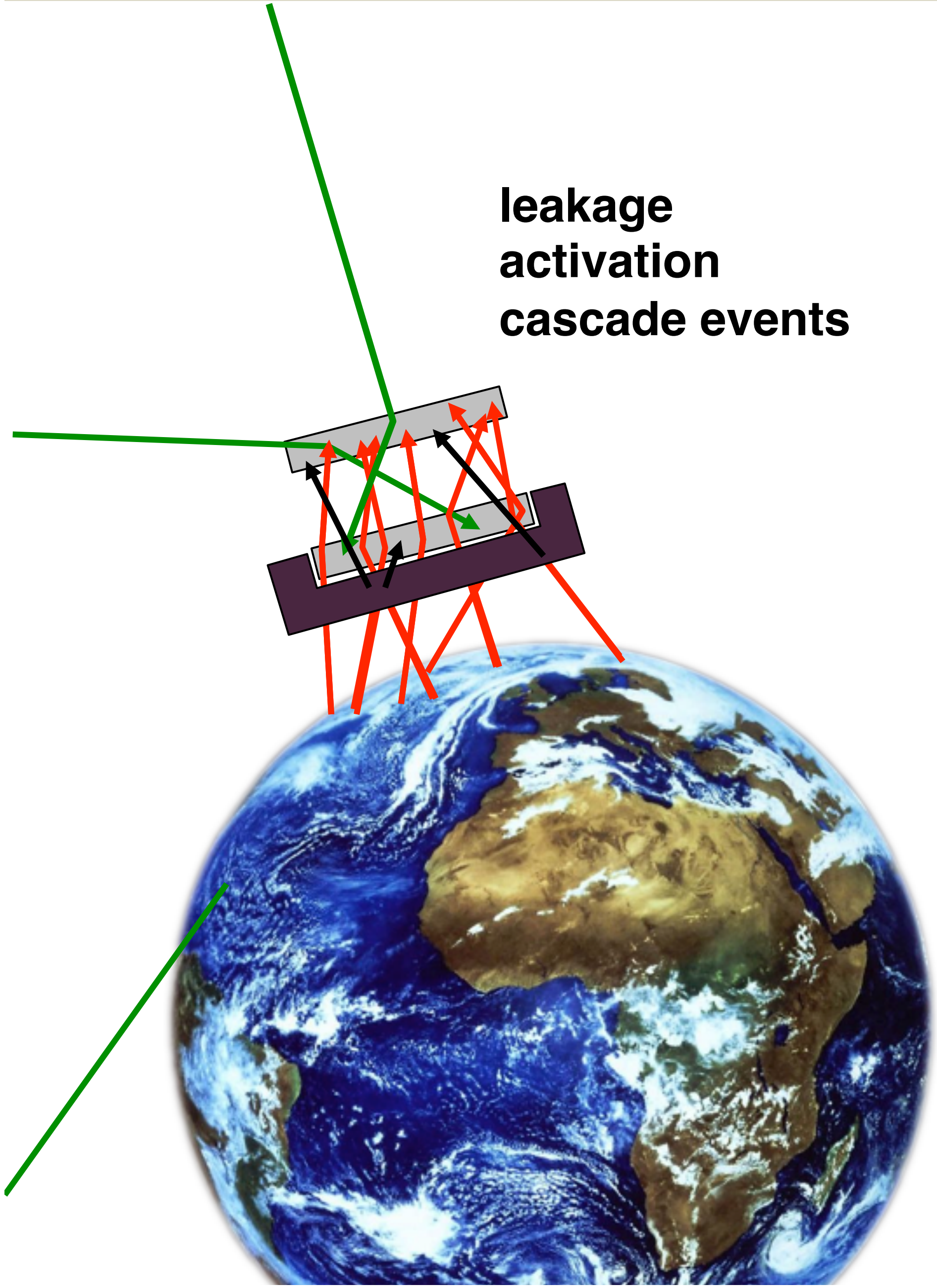
Ge strip detectors
mass (inst) : 2100 kg
$f_{3s} \approx 1.7 \cdot 10^{-6}$ ph s^{-1} cm^{-2}

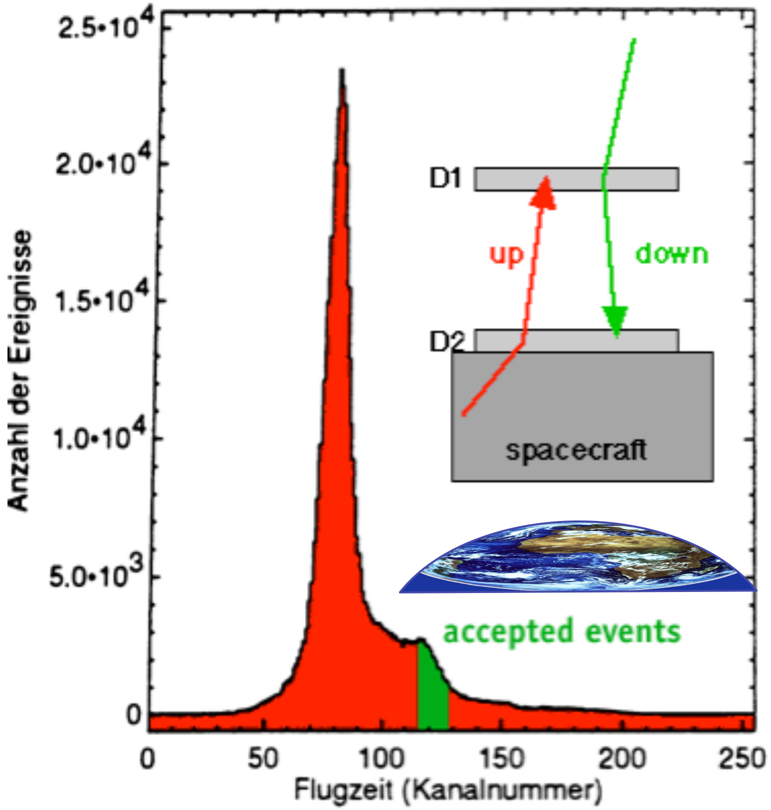
D1 Si-strip, D2 LaBr3
mass (inst) : 1578 kg
$f_{3s} \approx 3.4 \cdot 10^{-6}$ ph s^{-1} cm^{-2}

Si-strip detectors
mass (inst) : 970 kg
$f_{3s} \approx 5 \cdot 10^{-6}$ ph s^{-1} cm^{-2}

all telescopes have a wide FoV (1-2 ster) and modest angular resolution (≥2°)

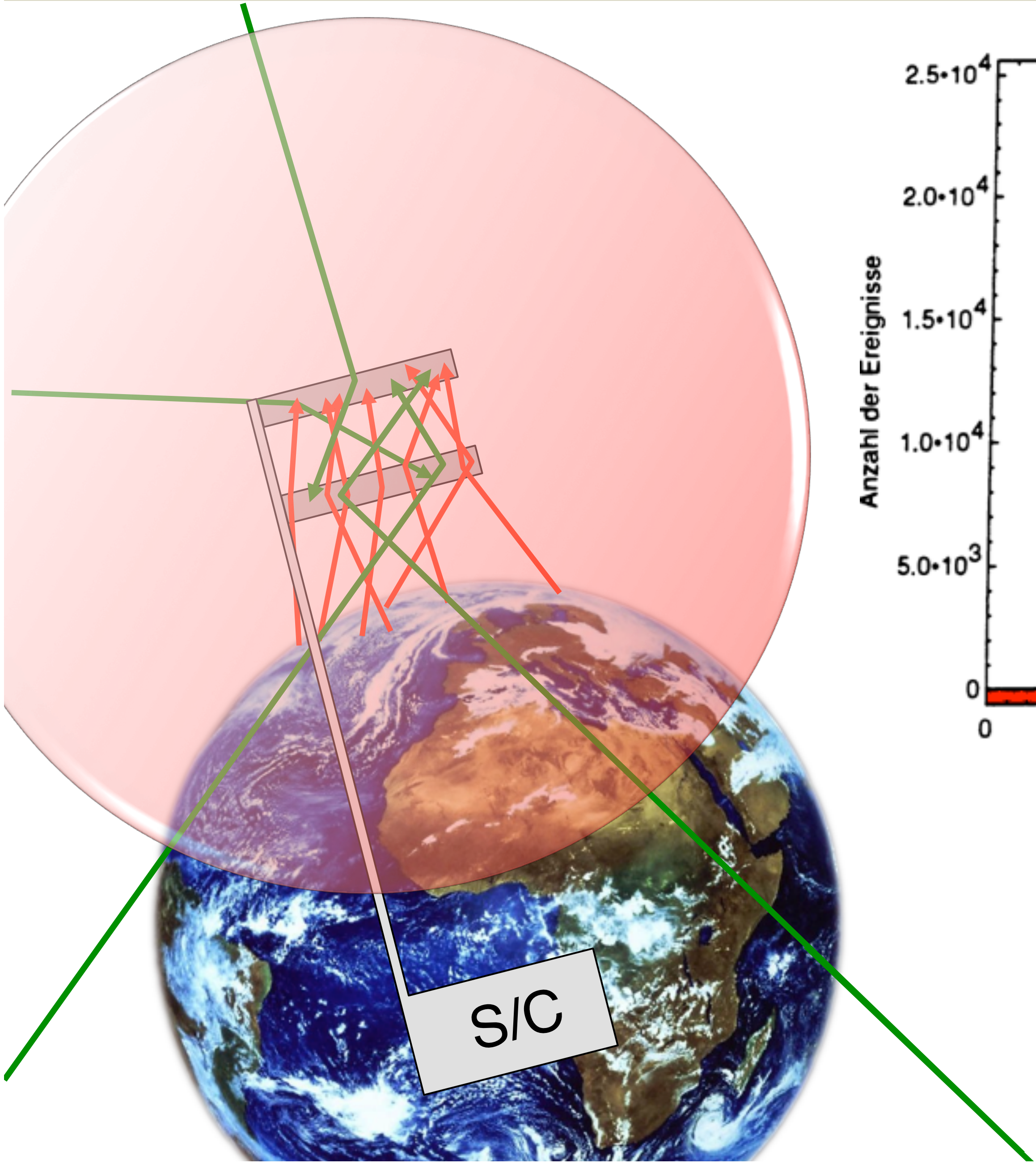
option B : anticoincidence shield

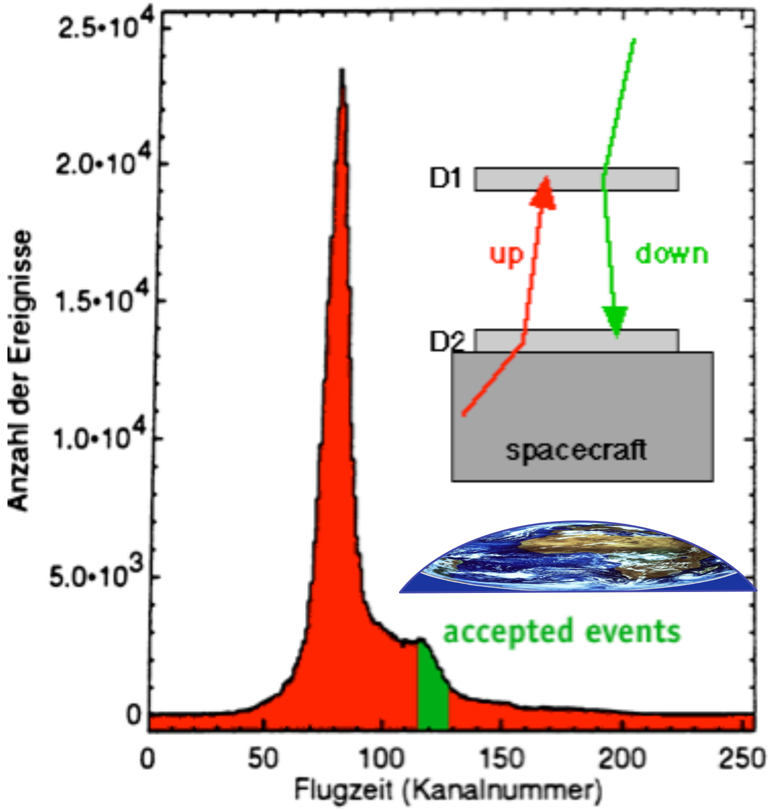


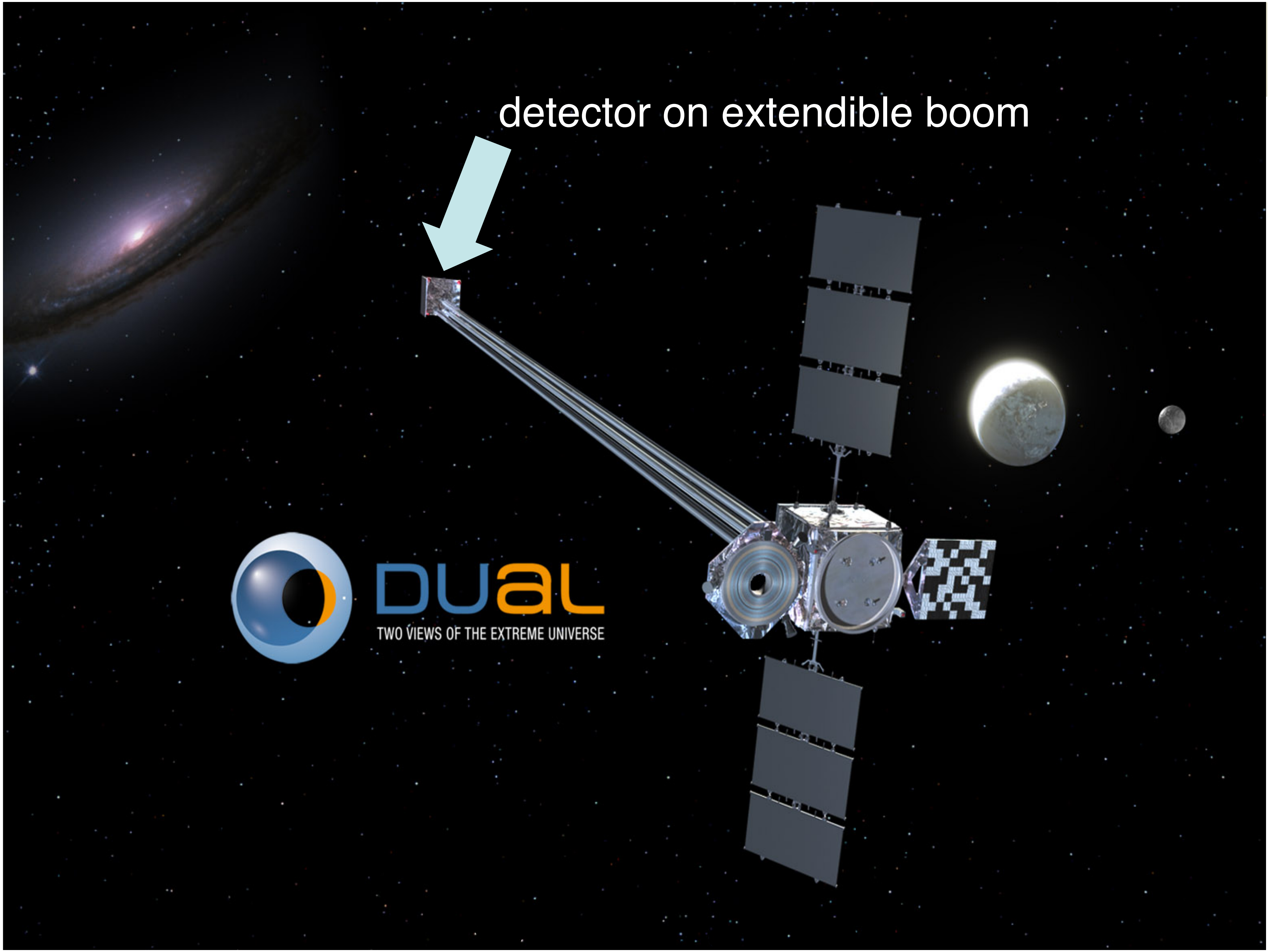


compact solid state CTs
can not measure the TOF
they require **AC shields** often **more massive than the instrument** itself

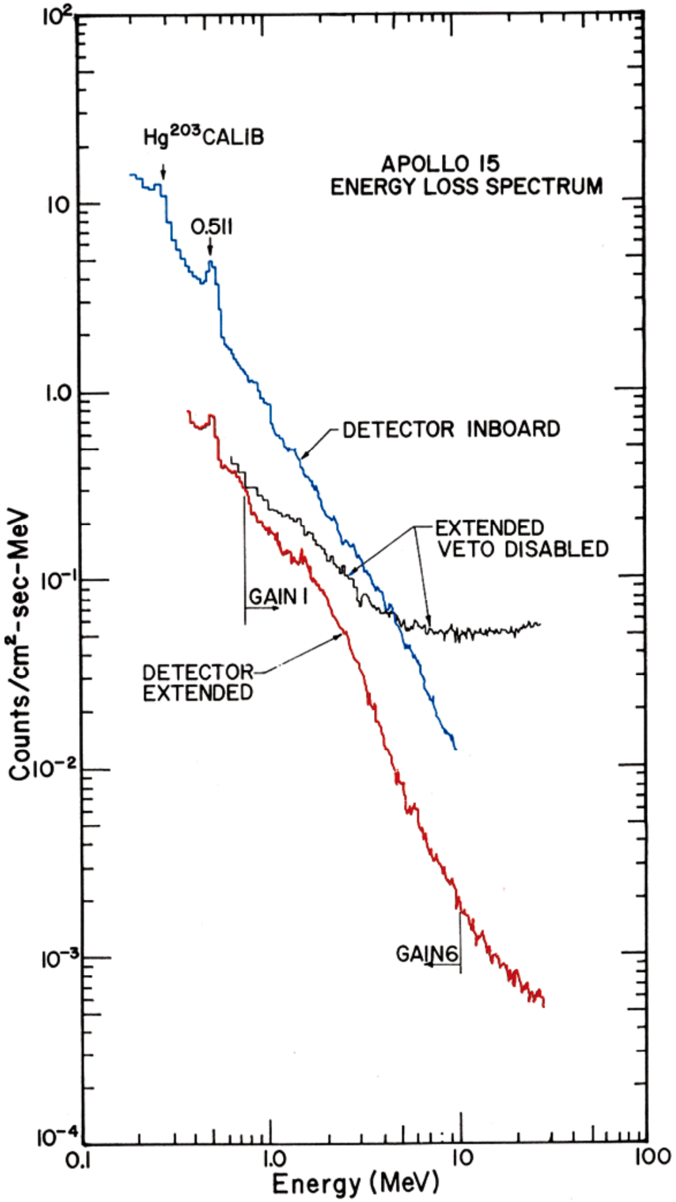
option C : no BG from external passive mass

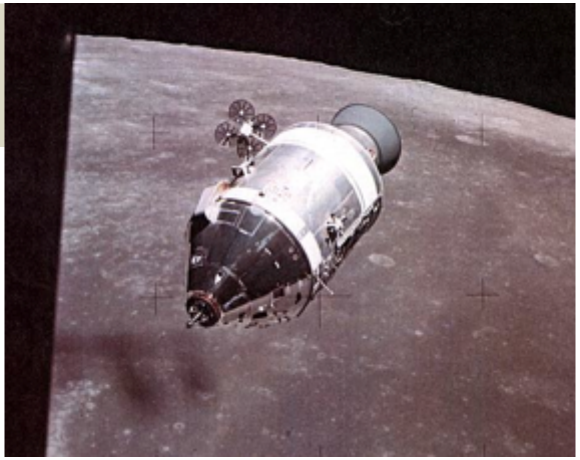





detector on extendible boom
DUAL
TWO VIEWS OF THE EXTREME UNIVERSE

Apollo 15 BG spectrum

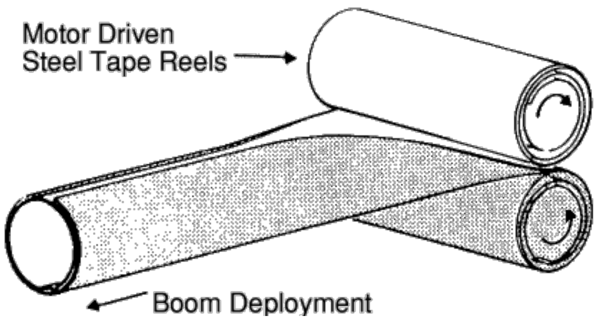




trans-Earth coast

detector :
NaI - 7 cm, 7 cm Ø
plastic veto

inboard : *on* spacecraft (W_{sc} = 2π)
extended position (boom, 7.6 m)



solid angle ratio W_{sc}/W_b
s/c seen in extended position (W_b~0.28 sr)

=> $W_{sc}/W_b \approx 20$

onboard BG $(b_{sc} + b_r)/5 = (b_{sc}/20) + b_r$

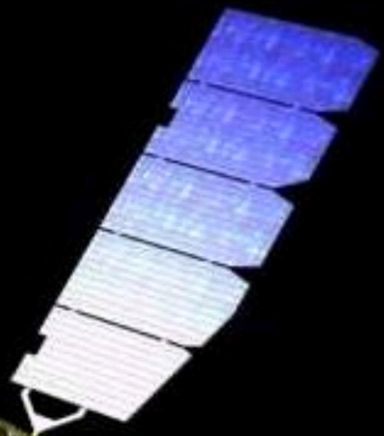
=> $b_r/b_{sc} \approx 0.2$!!

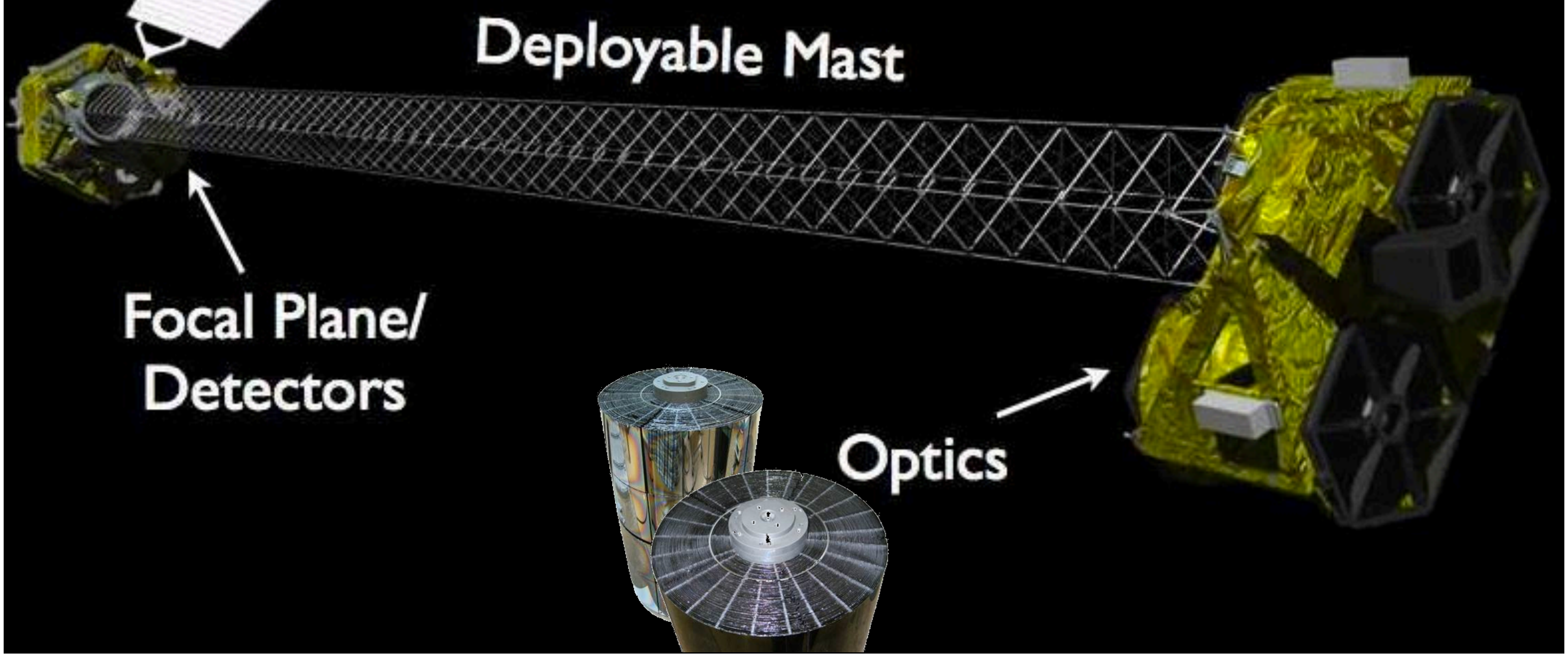
NuSTAR – Pegasus XL launch by the end of this session

13.6.2012 at 16h30 life broadcast

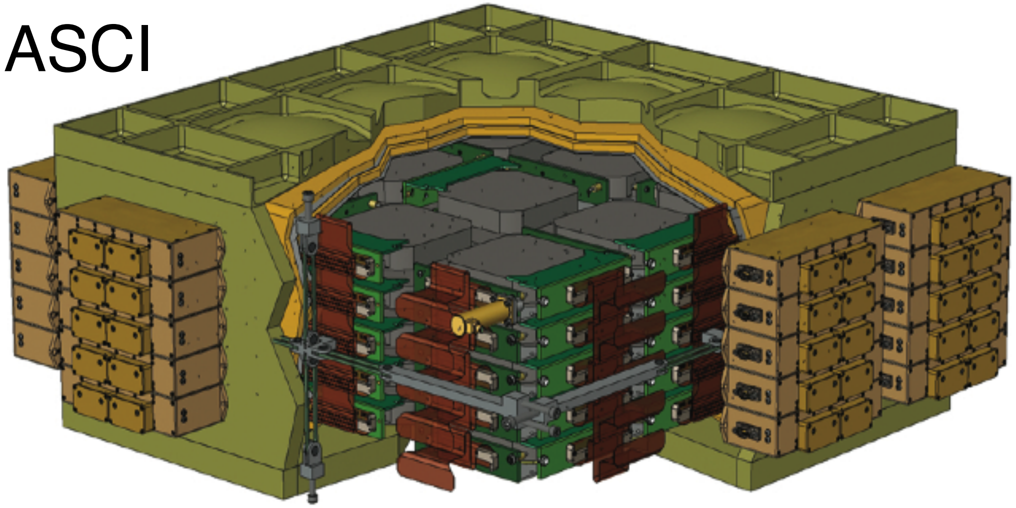
http://www.nasa.gov/nustar

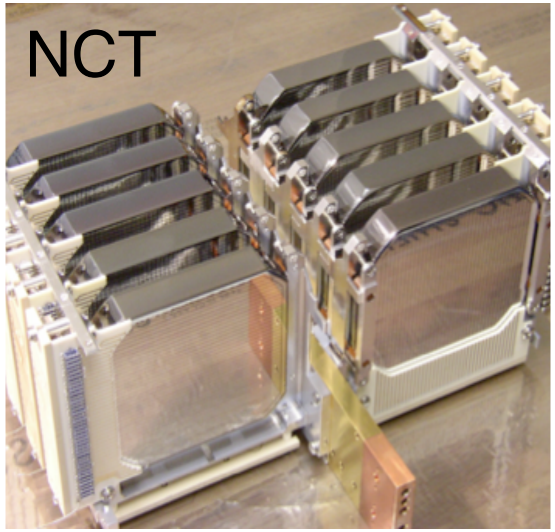
mast : 10 m focal length
payload mass : 360 kg
mission lifetime : 3 years
coverage : full sky





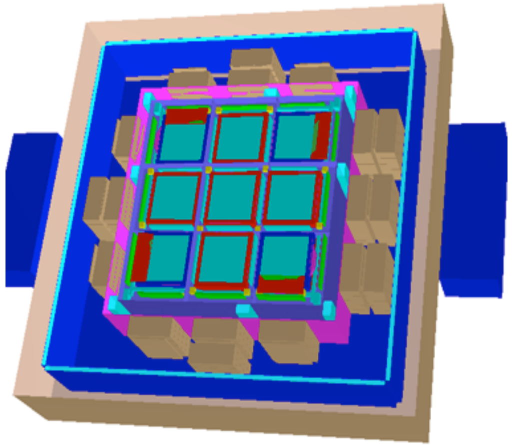
All Sky Compton Imager (ASCI)

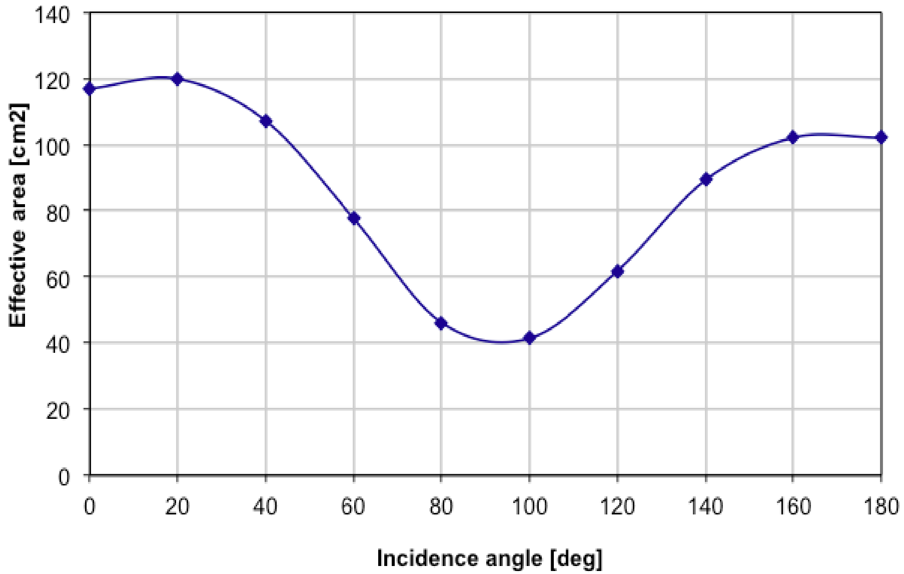




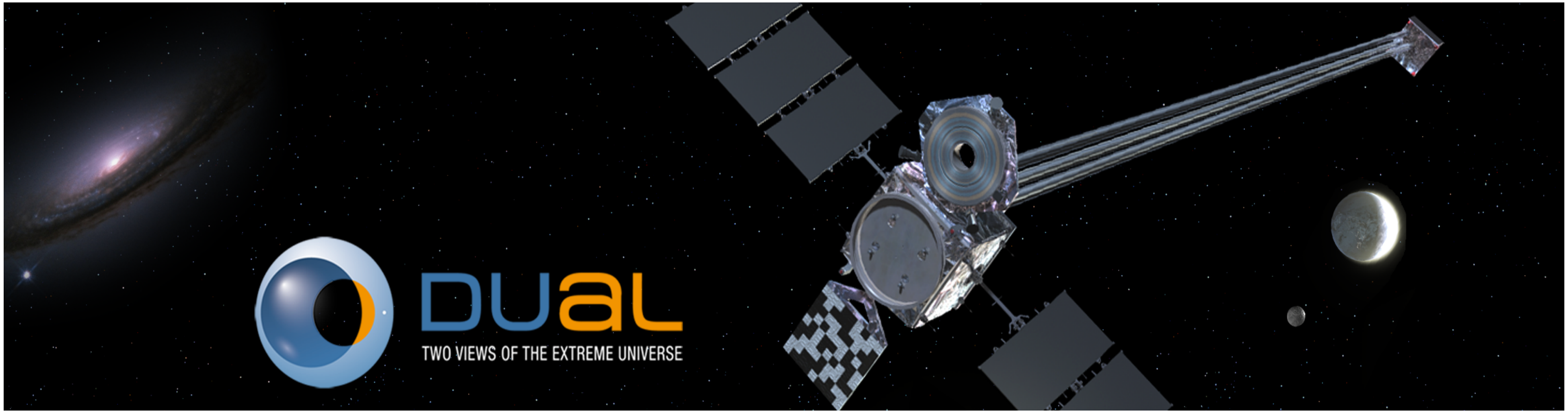
GeD/ parameter	ASCI	NCT
Strip pitch	2.00 mm	2.00 mm
Individual detector dimensions	100x100 mm^2	74x74 mm^2
	15 mm	15 mm
Spectral resolution (FWHM)@662 keV	1.6 keV	1.6 keV
Spectroscopy threshold	10 keV	12 keV
total # strip channels	4500	912
Instrument volume	6750 cm^3	972 mm^3

DUAL All Sky Compton Imager (ASCI)



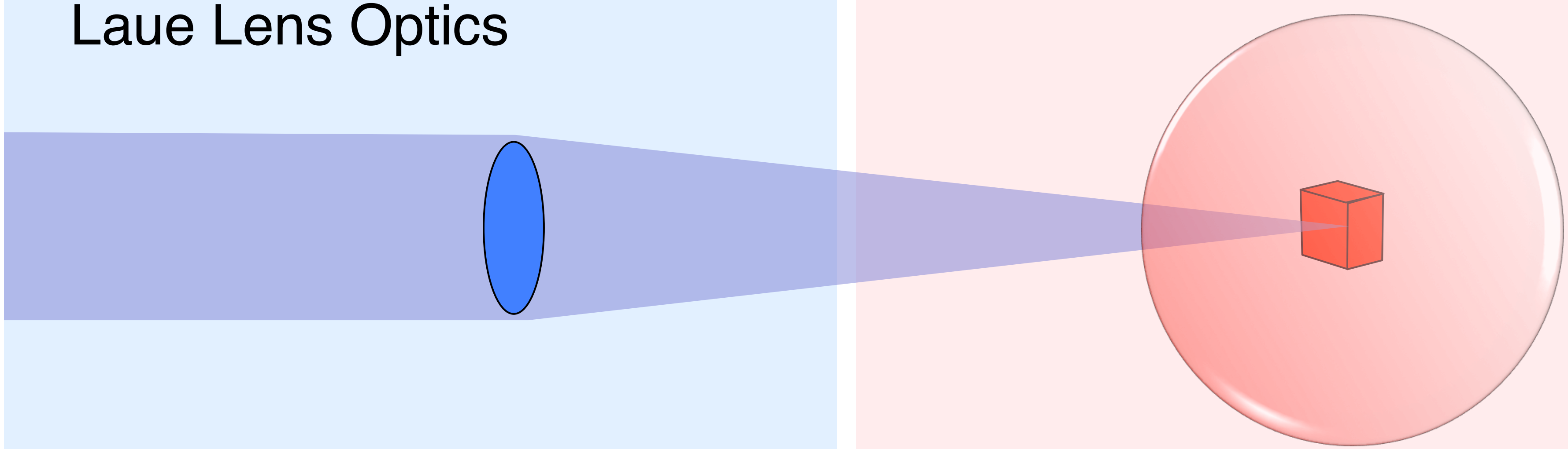


Energy range		0.1 – 10 MeV
Spectral resolution (10 MeV - 0.1 MeV)		0.2 – 1 % FWHM
Field of view		4 π at all times
Angular resolution	511 keV 847 keV 1809 keV	2.7° (4.5° at sensitivity limit) 2.1° (3.5° at sensitivity limit) 1.6° (2.7° at sensitivity limit)
Narrow line sensitivity (any DC source after T_{obs}= 3 year)	511 keV 847 keV 1809 keV	$2.6 \cdot 10^{-6}$ $ph \cdot cm^{-2} \cdot s^{-1}$ $1.1 \cdot 10^{-6}$ $ph \cdot cm^{-2} \cdot s^{-1}$ $7.2 \cdot 10^{-7}$ $ph \cdot cm^{-2} \cdot s^{-1}$
Continuum sensitivity (any DC source, T_{obs}= 3 year)	500 keV 5 MeV	$4.2 \cdot 10^{-5}$ $ph \cdot cm^{-2} \cdot s^{-1} MeV^{-1}$ $1.5 \cdot 10^{-6}$ $ph \cdot cm^{-2} \cdot s^{-1} MeV^{-1}$
Polarization sensitivity (MDP) 3 σ, any DC source, 200-500 keV T_{obs}=3 year	1 Crab 0.1 Crab 0.01 Crab	0.2% (statistical limit only) 2.4% 23.6%
GRB sensitivity (5 s)		~ 10^{-6} erg/cm^2
Timing		1 msec relative, 1 ms absolute



Coded Mask Optics
Laue Lens Optics

All Sky Compton Imager



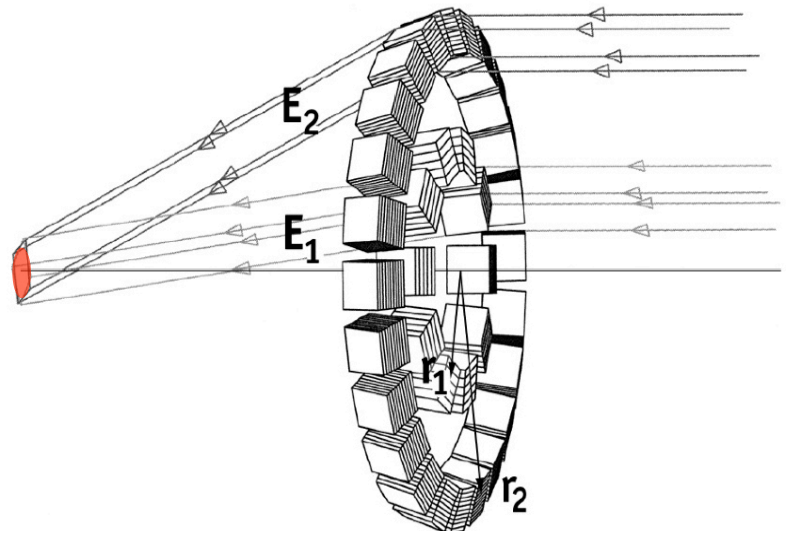
Deep dedicated pointing to GC

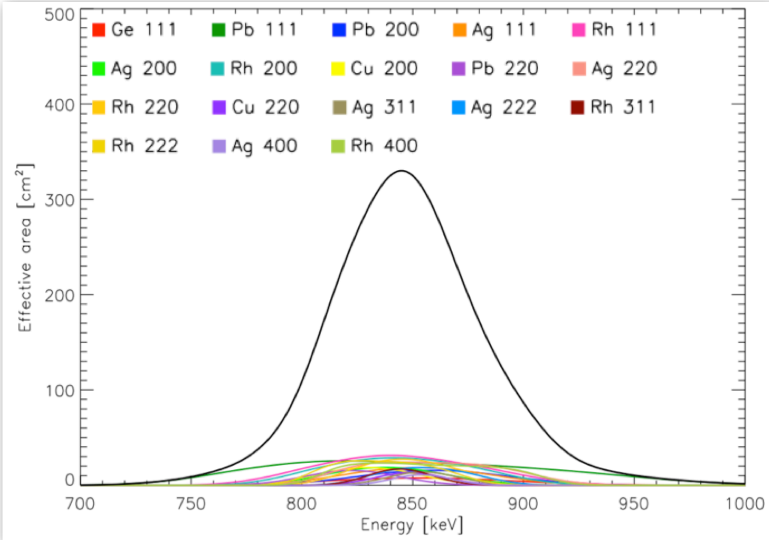
fine imaging of the 511 keV bulge

LLO : SN1a up to 40 Mpc

- All the sky (4π !) – all the time
- "Time has no mass !"
- Polarimetry

Laue-Lens Optic (LLO)





5800 crystals ona CeSiC monolithic substrate
diameter : 98 cm, m_{total}=80 kg, focal length : 30 m

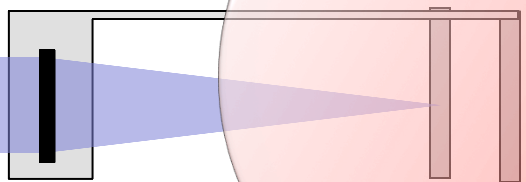
collect photons on ~ 300 cm², detect them on 1.5 cm² => S/N !

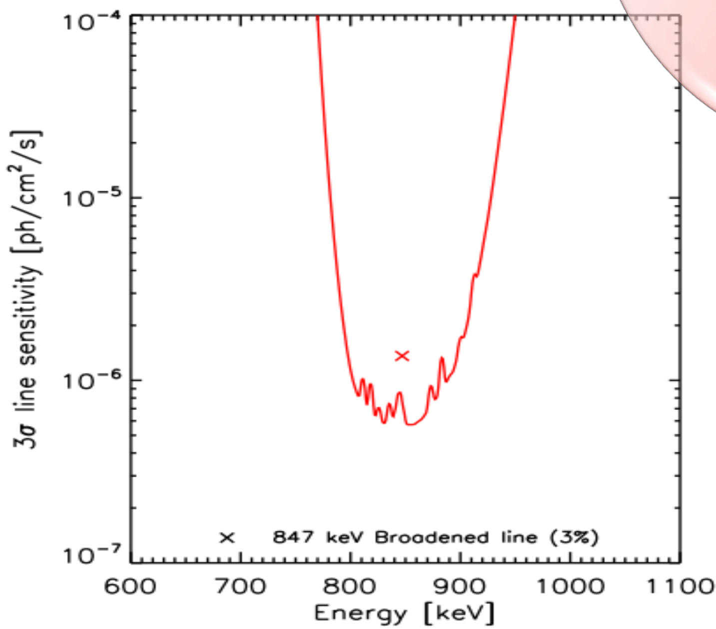
Energy range	800-900 keV
Spectral Resolution	0.2 – 1 % FWHM
Field of view / Angular resolution	5 arcmin / 1 arcmin
narrow Line Sensitivity (dE = 3%, $T_{obs}=10^6$ sec) broad Line Sensitivity (dE = 0.5%, $T_{obs}=10^6$ sec)	$1.0\cdot10^{-6}$ ph·cm^{-2}·s^{-1} 1.8 $1.0\cdot10^{-6}$ ph·cm^{-2}·s^{-1}

SN1a science – the priority for DUAL's Laue lens

which systems explode? why they explode? how they explode?"

Sn1a ^{56}Co ➔ ^{56}Ni : 847 keV gammas





Energy range	800-900 keV
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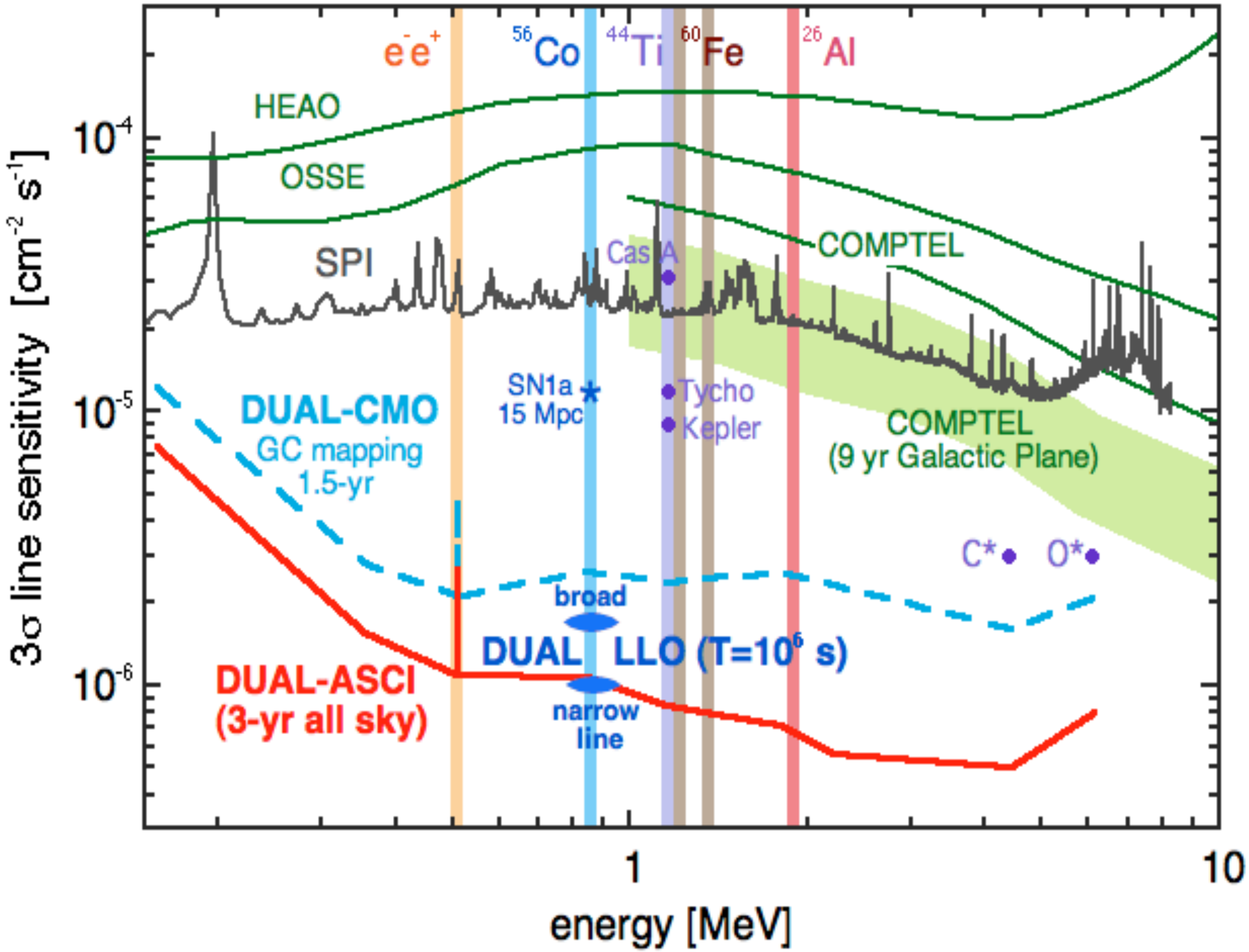
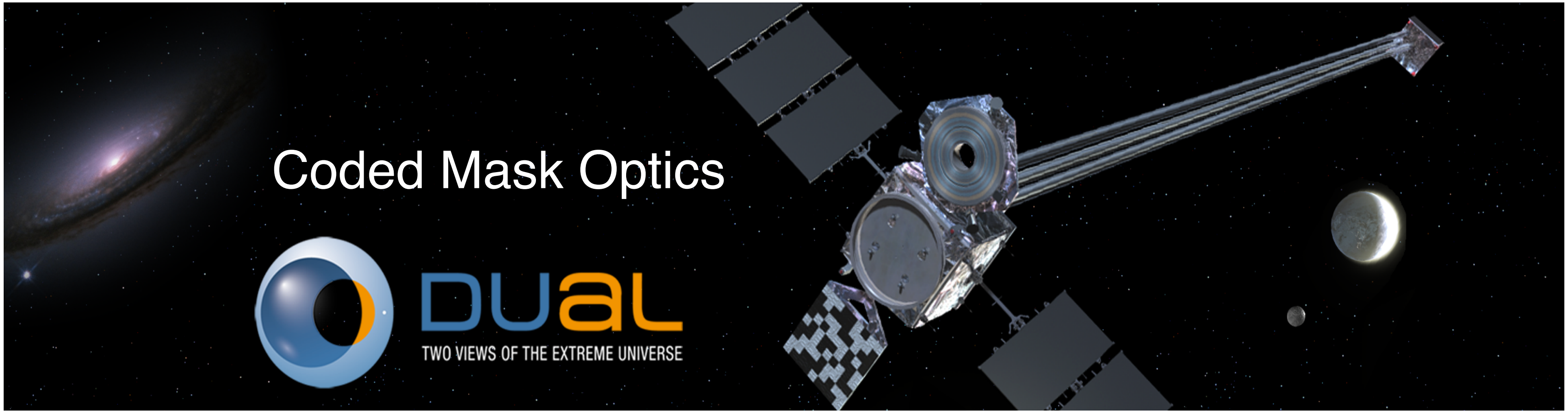
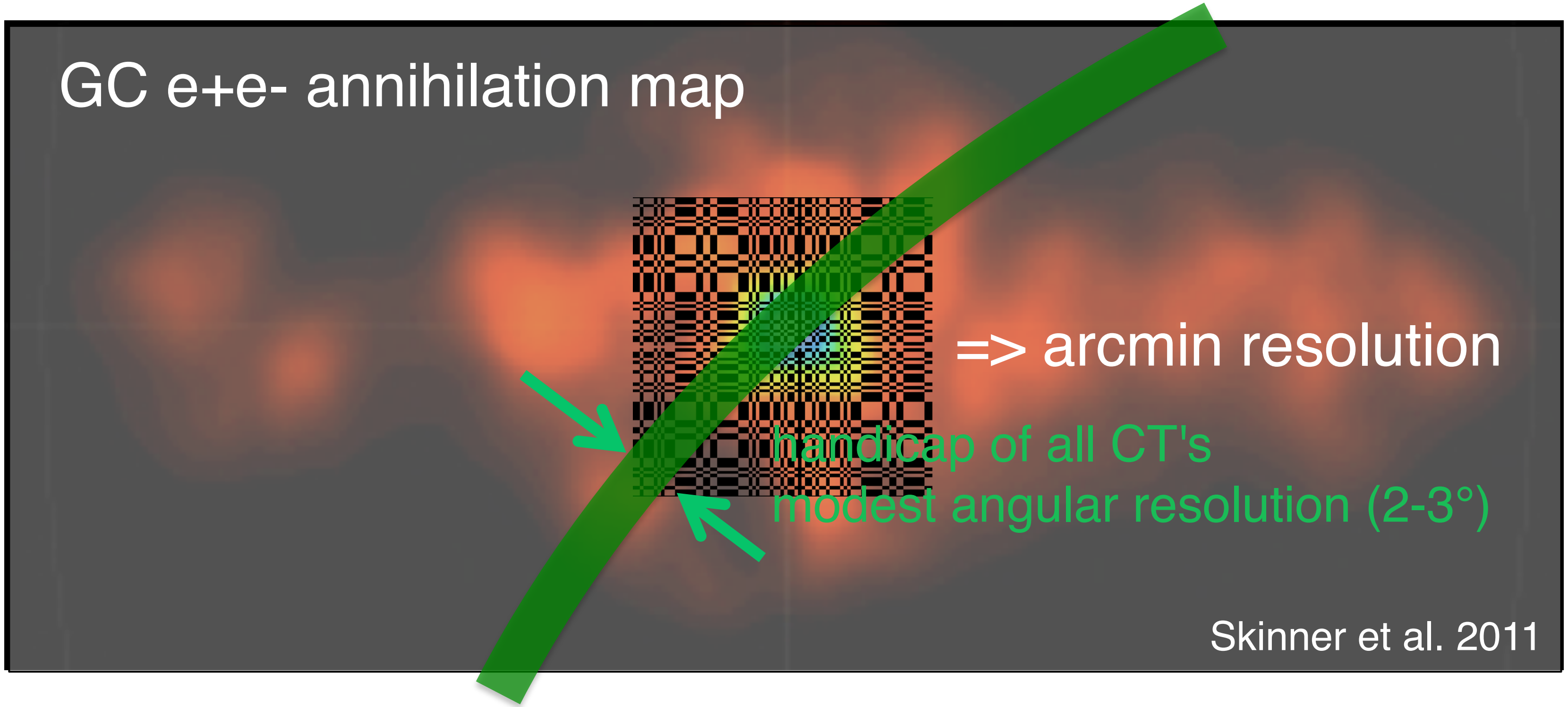
line sensitivity





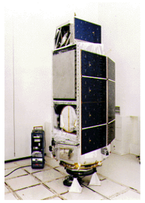


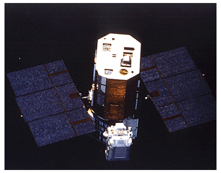
- very high exposure ($T \cdot (1 - f_{SN})$ of mission lifetime T)
- low BG due to "Compton-Collimator"

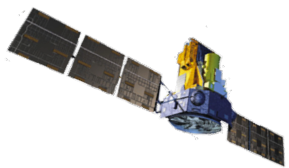
sensitivity in the 511 keV line

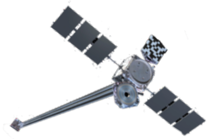
total galactic 511 keV flux

sensitivity $[ph/cm^2s^1]$









DUAL and GRB's

Compton mode (direct localization, spectroscopy, polarization)

6σ fluence (100 keV – 10 MeV) ~ 1.5×10^{-6} erg/cm^2 for long GRBs
~ 4×10^{-7} erg/cm^2 for short GRBs,

(≈ BATSE and Swift-BAT, albeit in lower energy bands than DUAL)

Burst mode (single interactions

energy threshold at ~20 keV => effective area ~300 cm^2 per Ge layer !

detection of 600 GRBs/yr !

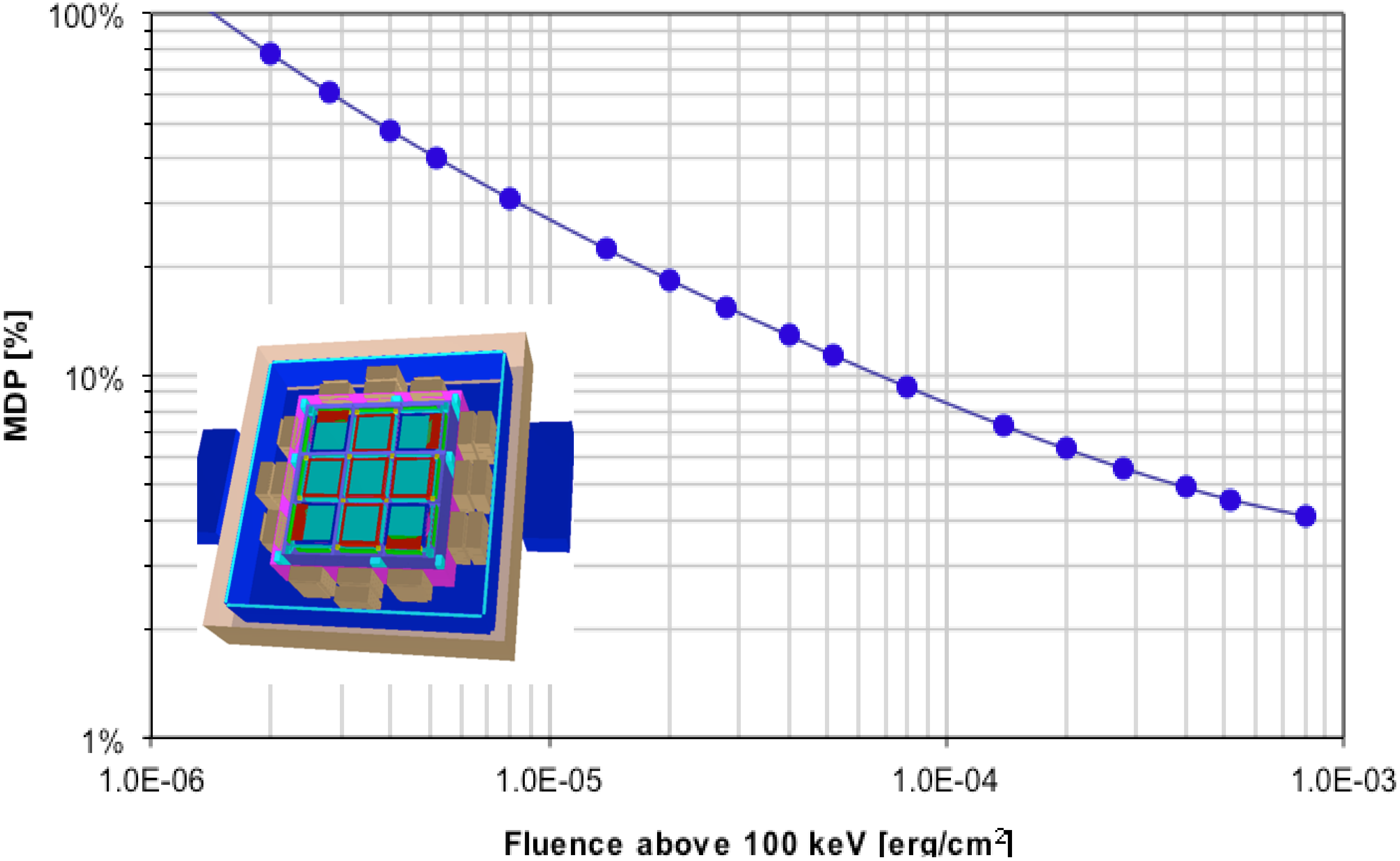
polarisation sensitivity :

50% polarisation for ~ 60 GRBs per year

10% polarisation for ~ 20 GRBs per year

A level of 10% is very constraining for models and is the level of optical polarisation which has been observed in a very few early afterglows

ASCI Minimum detectable polarisation for GRB's

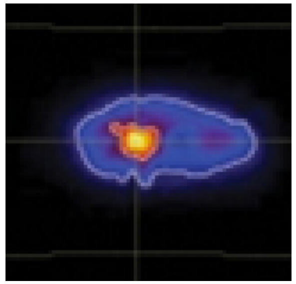


for a gamma-ray burst characterized by broken power-law spectrum with a single break (a=-1.0, b=-2.5, break : 150 keV)

SN1a !

Resolving the e^-e^+ emission

in the Galactic bulge



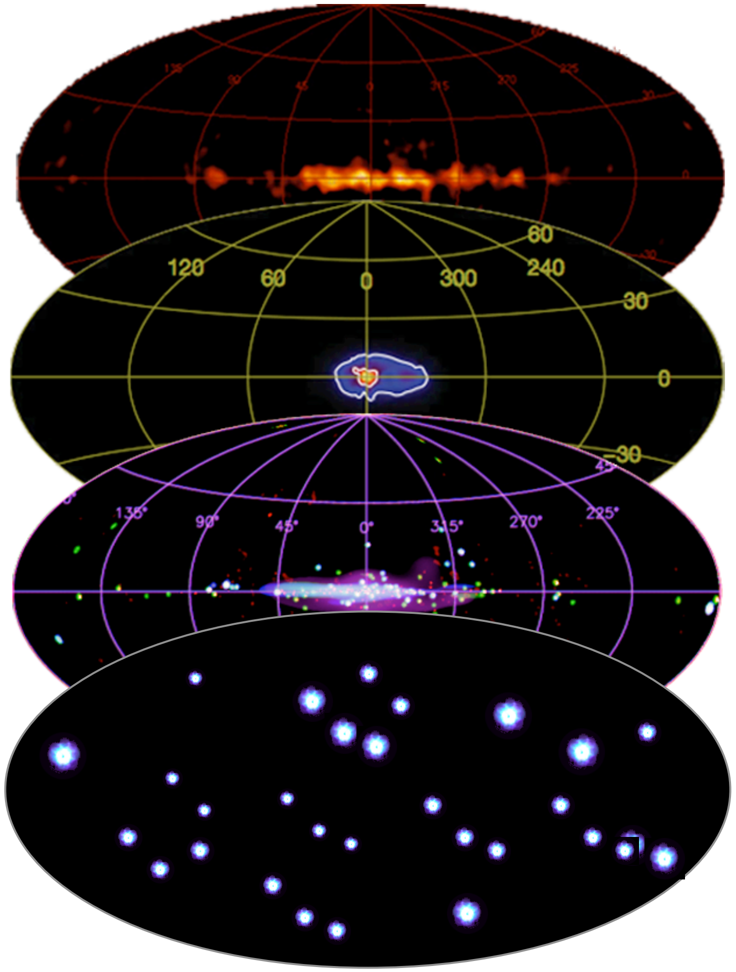
High angular resolution
imaging of the Galactic Center
Sources

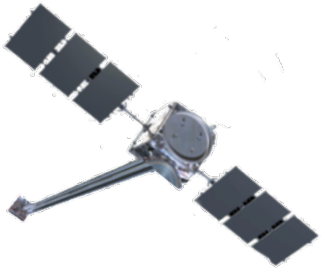
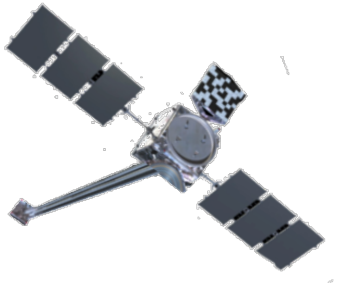
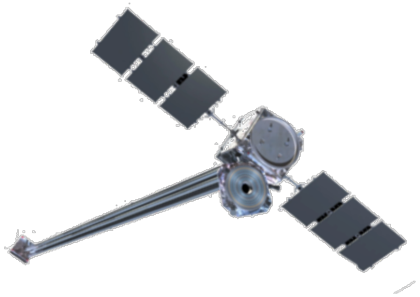
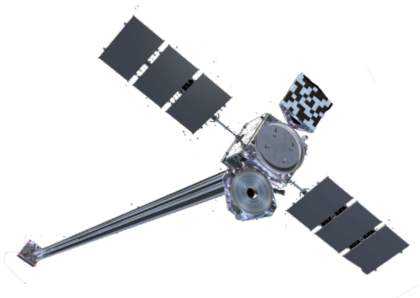
Galactic Radioactivities
(^{26}Al, ^{60}Fe, ^{44}Ti …)

e^-e^+ Annihilation Radiation

Compact Sources
(LMXB, magnetars, AGN …)

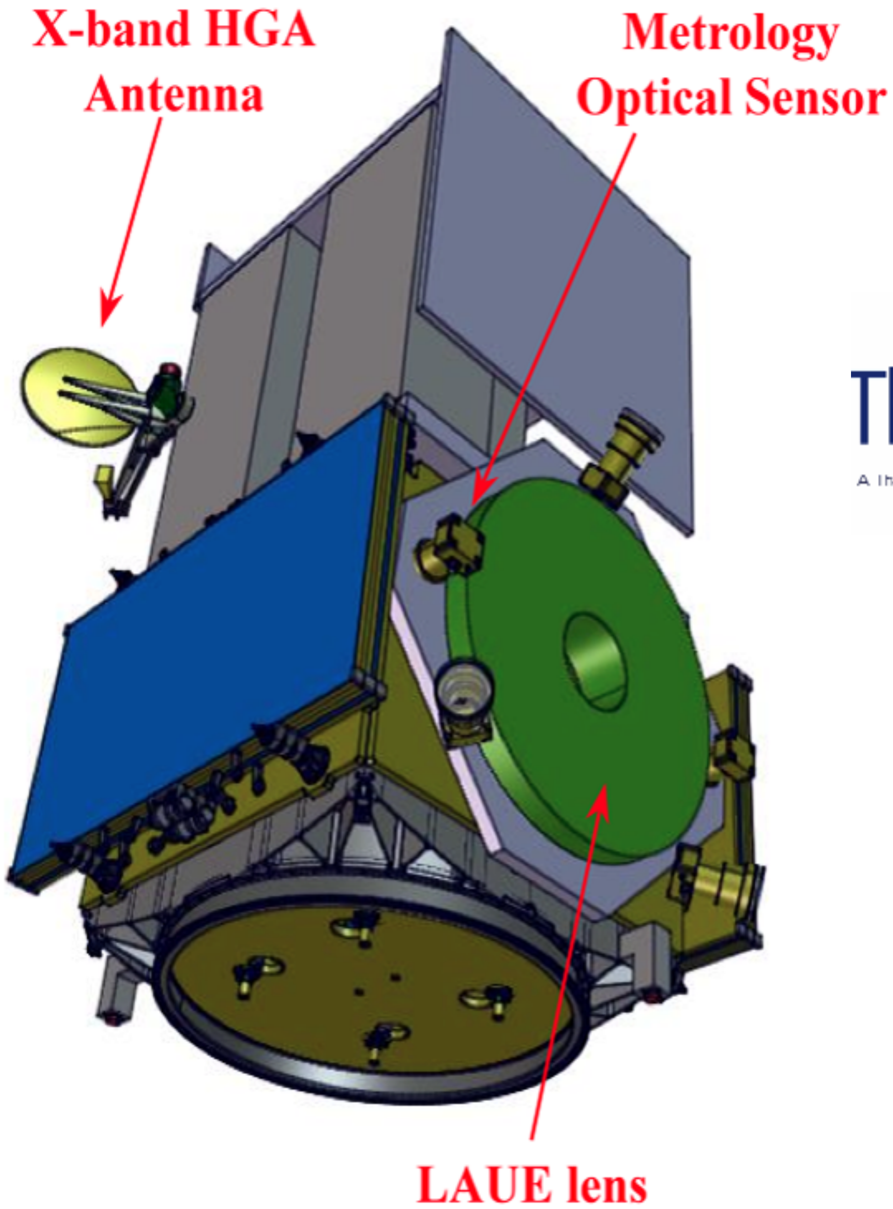
Gamma-ray bursts
- localization (direct imaging)
- spectroscopy (E/ΔE ≈ 0.2 % !)
- **polarisation !**

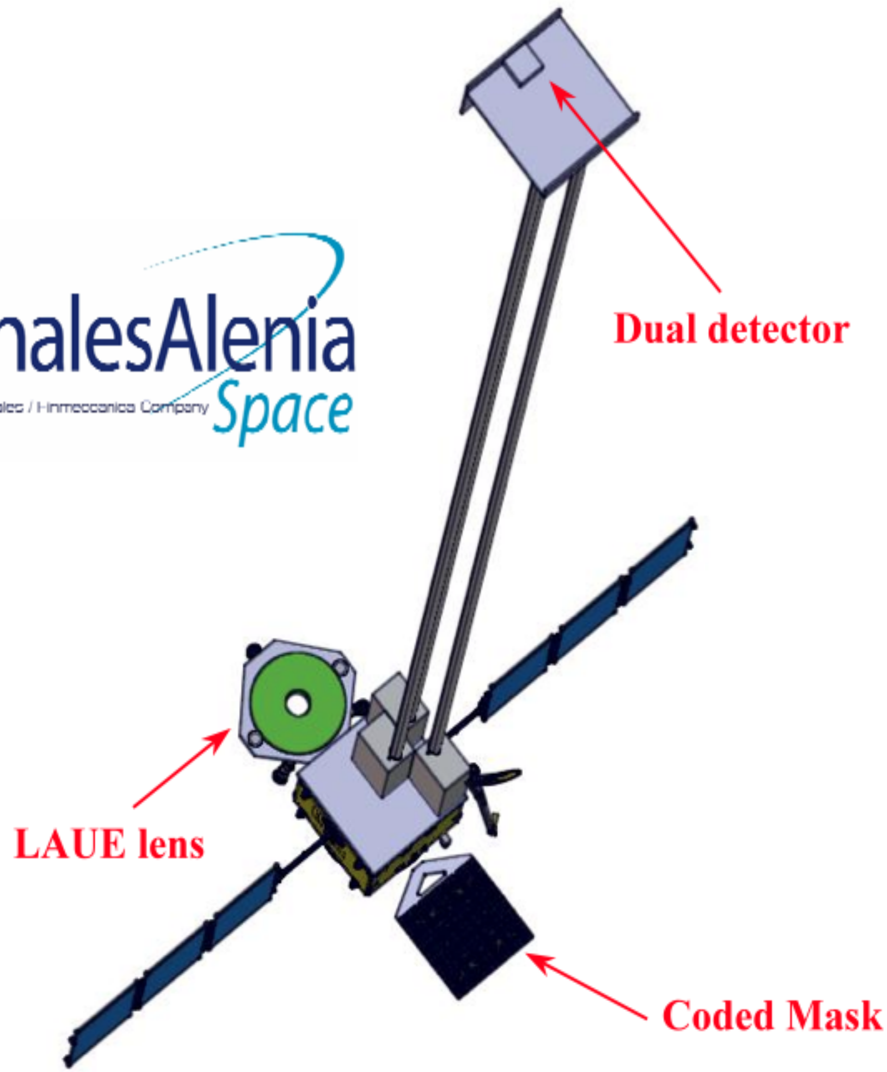


configuration	payload mass	science
	10-m mast : 30 kg ASCI : 90 kg	GRB's, all sky surveys
	10-m mast : 30 kg ASCI : 90 kg mask : 50-100 kg	GRB's all sky surveys high res mapping in GC
	30-m mast : 60 kg ASCI : 90 kg Laue lens : 80 kg	GRB's all sky surveys SN1a radioactivity
	30-m mast : 60 kg ASCI : 90 kg mask : 50-100 kg Laue lens : 80 kg	GRB's all sky surveys high res mapping in GC SN1a radioactivity

DUAL mission

TWO VIEWS OF THE EXTREME UNIVERSE





ThalesAlenia Space
A Thales / Finmeccanica Company