Télescopes spatiaux pour l'astronomie gamma

Introduction / Contexte

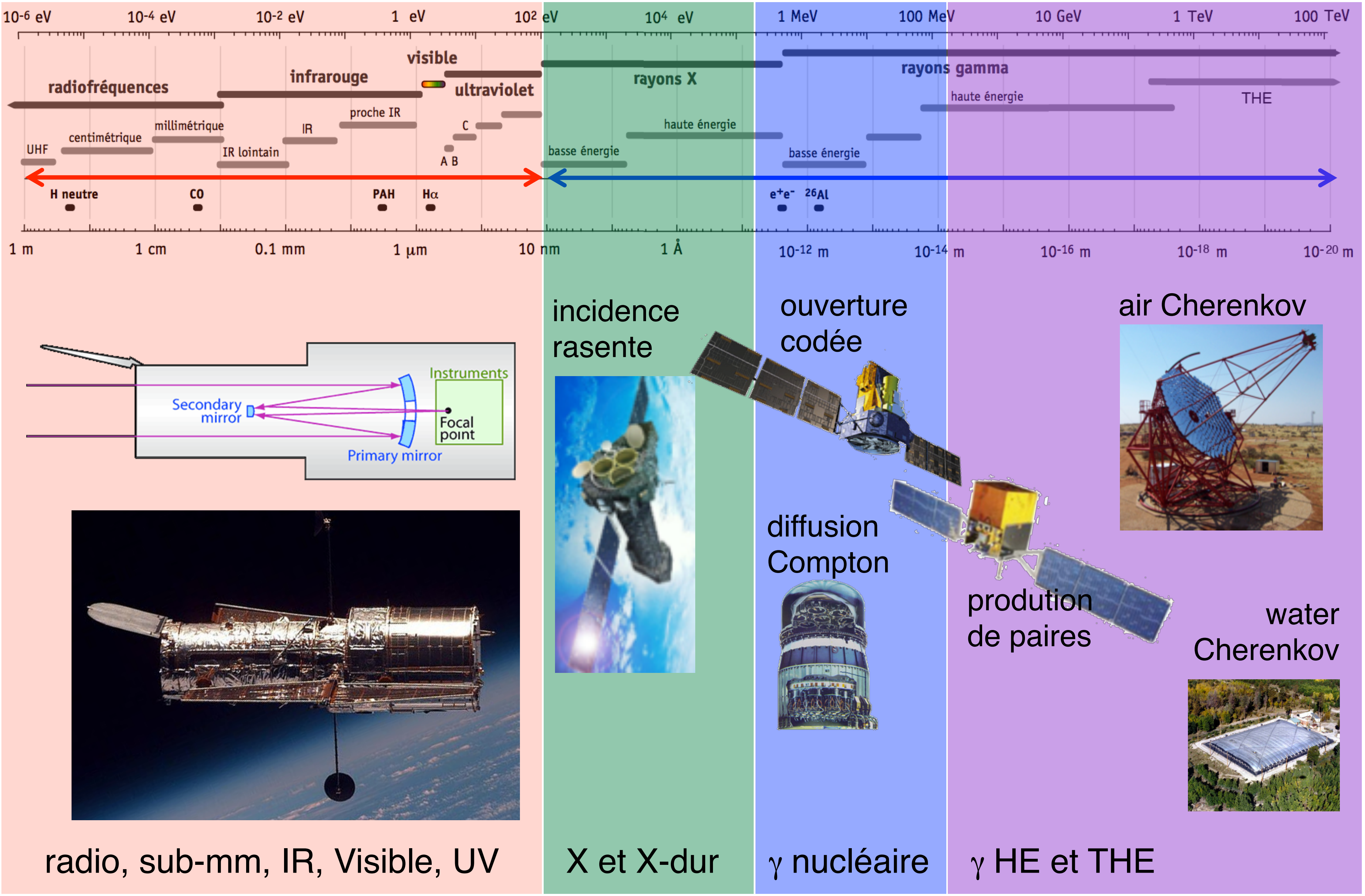
Interactions et détection des rayons γ

Les télescopes - Collimateurs, Masques, Conversion de paires, Compton, lentilles de Laue …

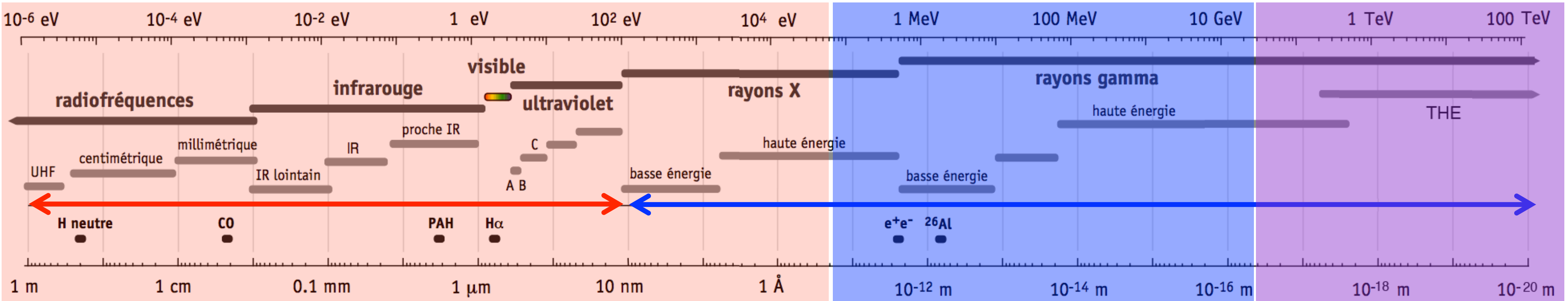
Perspectives pour l'astronomie gamma

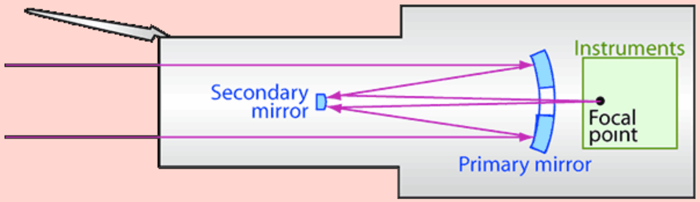
Peter von Ballmoos, IRAP Toulouse

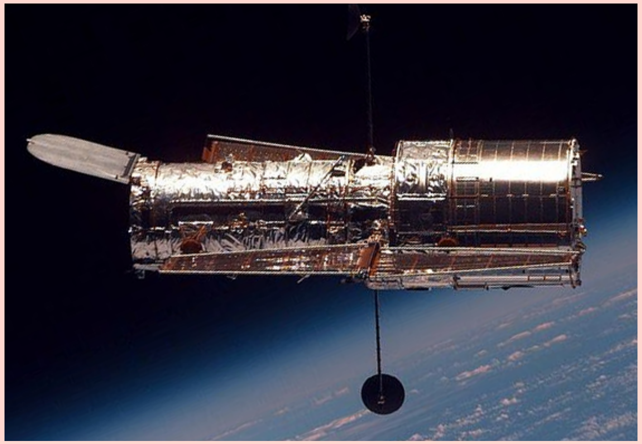
le télescope astronomique et les instruments des Hautes Energies



le télescope astronomique et les instruments des Hautes Energies



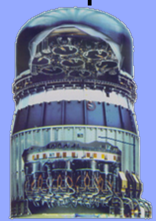




incidence rasente

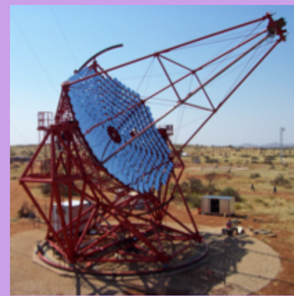
ouverture codée

diffusion Compton



prodution de paires

air Cherenkov



water Cherenkov

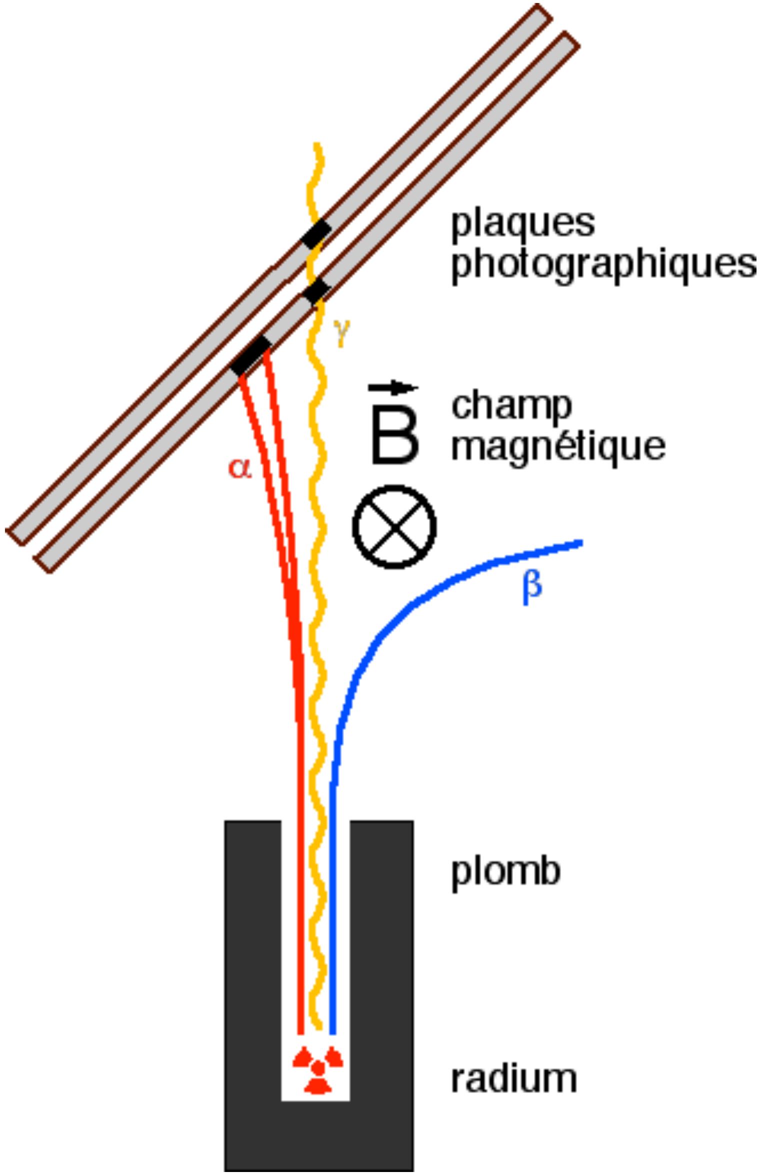
total external refelection

spacebased γ's

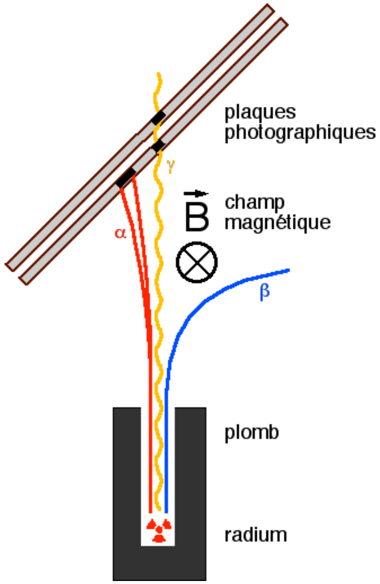
VHE γ's

discovery of spectral domains - who's missing ?

IR	Herschel	1800
UV	Ritter	1801
radio	Hertz	1886
X	Röntgen	1895
γ	Villard	1900



Session de l'Académie des Sciences du 9 avril 1900



PHYSIQUE. — *Sur la réflexion et la réfraction des rayons cathodiques et des rayons déviables du radium* (¹). Note de M. P. VILLARD.

» Les rayons émis par un petit tube de verre rempli de matière active passaient par une ouverture rectangulaire de 6^{mm} de largeur, pratiquée dans une barre de plomb, et traversaient un champ magnétique. Une plaque photographique 13 × 18, disposée sous une incidence presque rasante, enregistrait les trajectoires : dans ces conditions, on observe que les rayons admis dans le champ se divisent en deux groupes distincts, entièrement séparés après un trajet de quelques centimètres.

» L'un de ces groupes est dévié dans le sens prévu; l'autre, formé par les rayons non déviables, se propage rectilignement dans toute la longueur de la plaque. Ce faisceau non dévié est assez pénétrant pour impressionner, à 25^{cm} de distance, une plaque sensible protégée par plusieurs feuilles de papier noir et une lame d'aluminium; on peut même lui faire traverser une lame de plomb de 0^{mm},2 d'épaisseur.

» Les résultats complexes que j'avais observés s'expliquent donc sans difficulté : le faisceau qui, dans mes expériences, traversait sans se réfracter la lame d'aluminium inclinée, correspond aux rayons non déviables : l'expérience a en effet montré qu'il est insensible au champ magnétique. Les rayons déviables, au contraire, se comportent comme les rayons cathodiques et émergent normalement à la lame traversée (²).

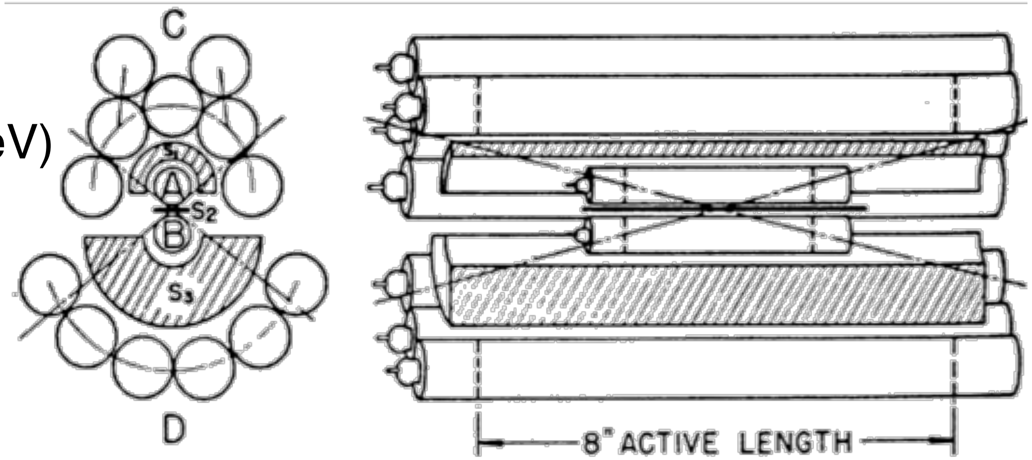
» Je me propose de reprendre ces expériences avec des rayons déviables purs.

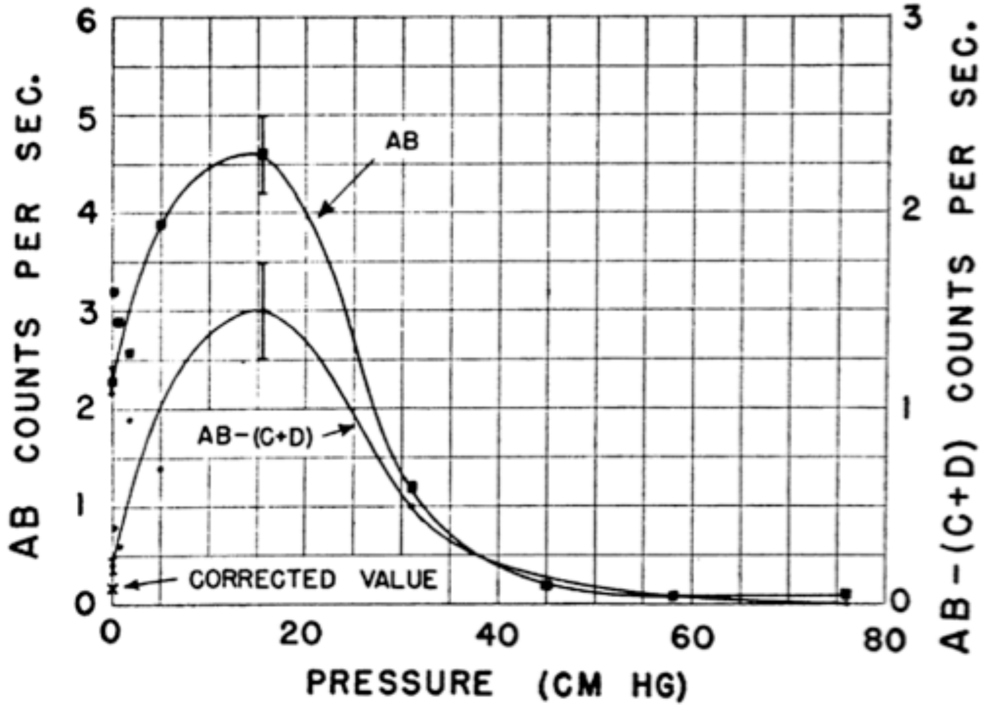
» Les faits précédents conduisent à admettre que la partie non déviable de l'émission du radium contient des radiations très pénétrantes, capables de traverser des lames métalliques, radiations que la méthode photographique permet de déceler. »

28.1.1948 First cosmic γ-rays ?

G. Perlow and C. Kissinger
Phys. Rev. 81, 4, 1951

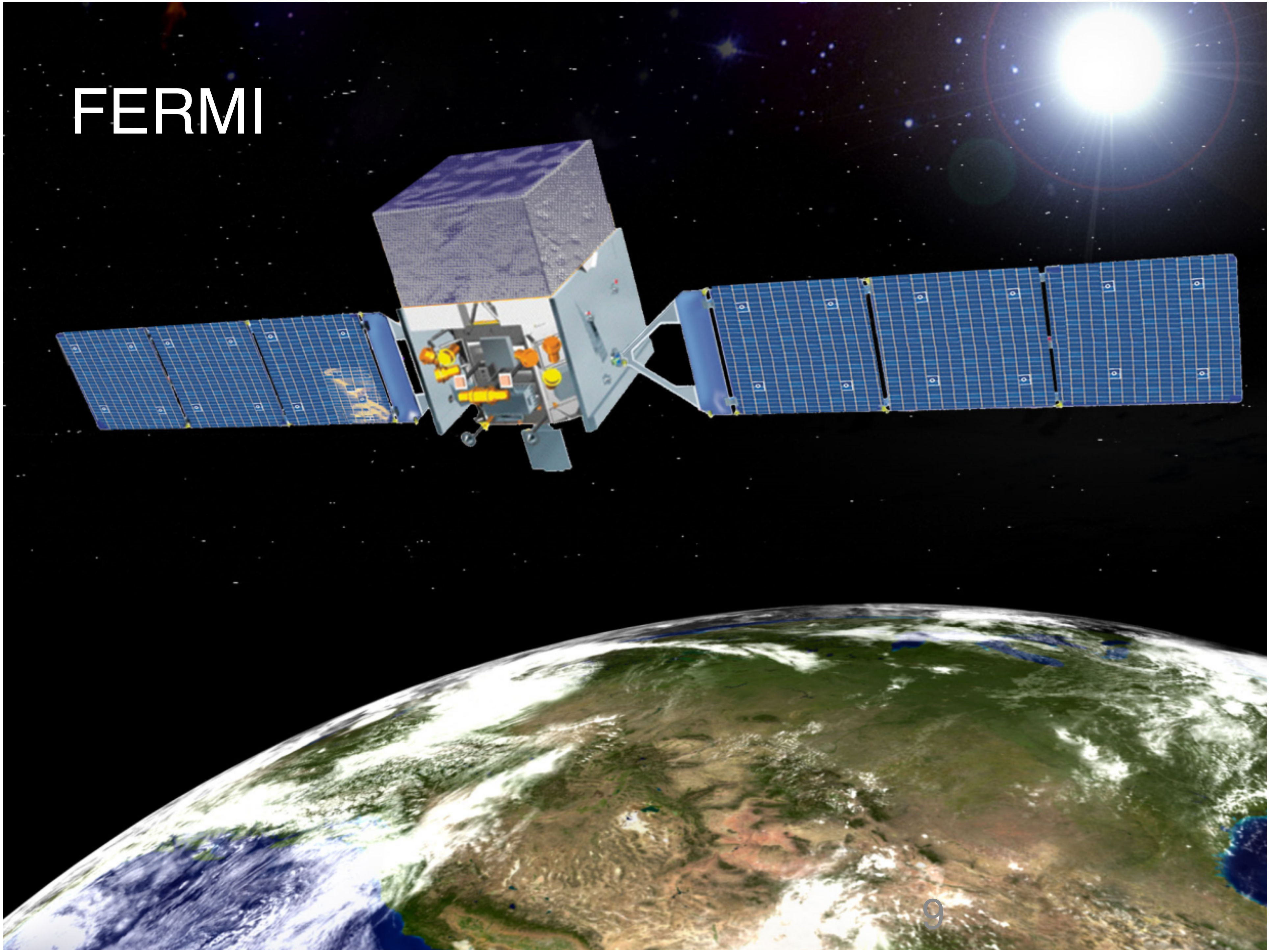
2π gamma-ray flux (3.4-90 MeV)
77 sec observing time
0.09±0.05 c/s above 3.4 MeV





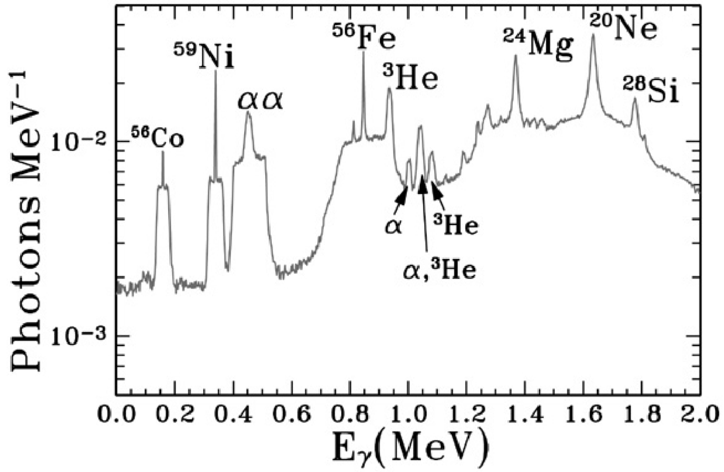
The history of gamma-ray astronomy

1900	P. Villard	discovery of gamma-rays
1911	V. Hess	discovery of Cosmic Rays (balloons, growth curves)
1932	C. Anderson	discovery of positrons (balloon borne Wilson-chamber)
1948	Hulsizer &Rossi	high energy γ's < 1% of CR (counters:balloon / B29)
1948	Perlow & Kissinger	marginal measurement of cosmic γ-rays (counters : V2)
1958	EXPLORER 1	discovery of radiation belts (J. Van Allen)
1958	Peterson & Winckler	first gamma-rays from solar flare (balloon, counters)
1958	Ph. Morrison	Vatican conference (nuovo cimento) : predictions ...
1960's	RANGER 3 & 5	cosmic diffuse flux : $dn(E) \sim E^{-2.2}$
1961	EXPLORER 11	22 cosmic HE g-rays detected, BG of 22000 CR events
1962	ASE-MIT rocket	first cosmic X-ray source : SCO X-1
1967/68	OSO-3	HE g-rays from the Galaxy
1967	VELA satellites	discovery of gamma-ray bursts (nuclear test ban treaty)
1970	UHURU	first X-ray sky survey
1972 ff	balloons	detection of cosmic 511 keV annihilation line
1972,75	SAS-2, COS-B	HE g-rays from galactic plane, Vela, Geminga
1979	HEAO-3	discovery of galactic ^{26}Al (Ge spectrometer)
1987	SMM, balloons	SN1987A : ^{56}Co line, SN n detection
1989-98	GRANAT/SIGMA	variable Galactic Center sources
1991-99	Compton-GRO	^{26}Al sky map, ^{44}Ti from Cas A, compact source spectra
1997	Beppo-SAX et al.	γ-ray burst afterglow / identification of hosts galaxies
2002 ...	INTEGRAL	history will tell
2008 ….	FERMI	history will tell


FERMI

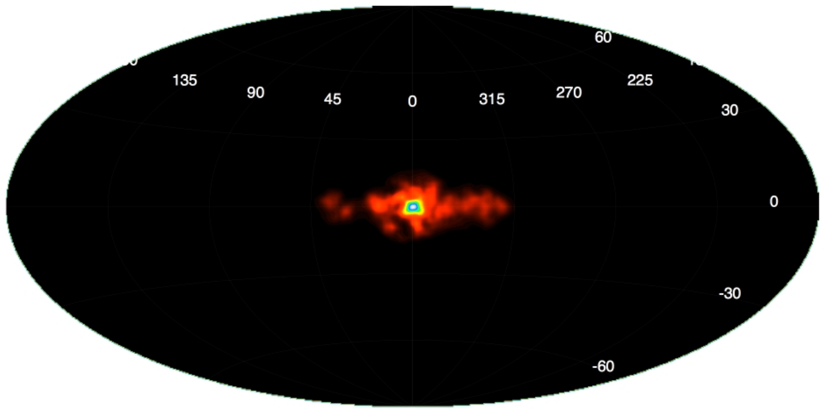
Why study soft gamma-rays ?

Nuclear lines



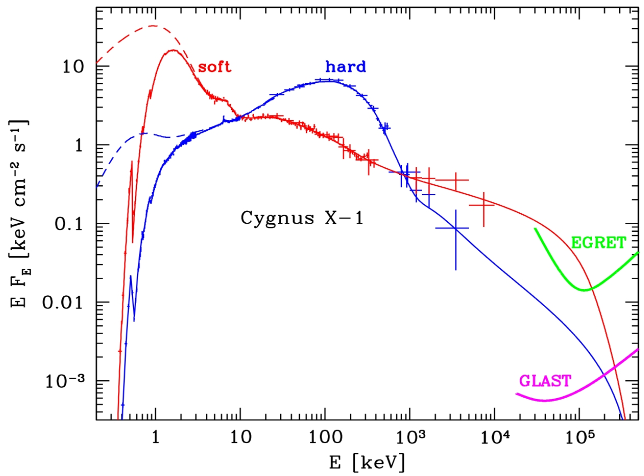
nuclear production and CR interaction sites, abundances, ISM phases, particle spectra, kinematics

Positron annihilation



e+ production and annihilation site diagnostics

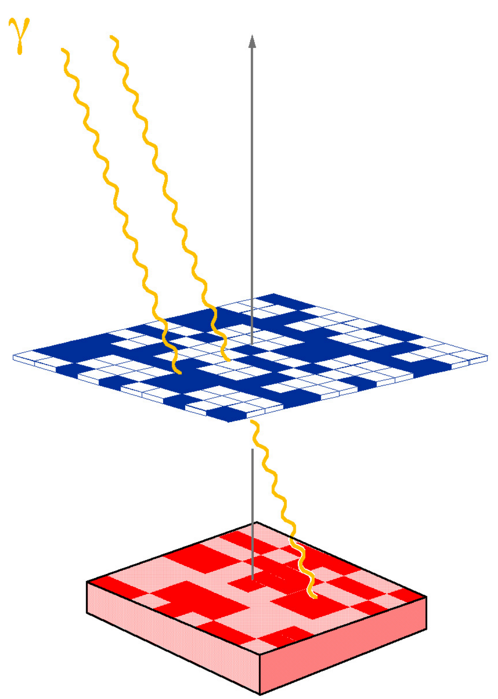
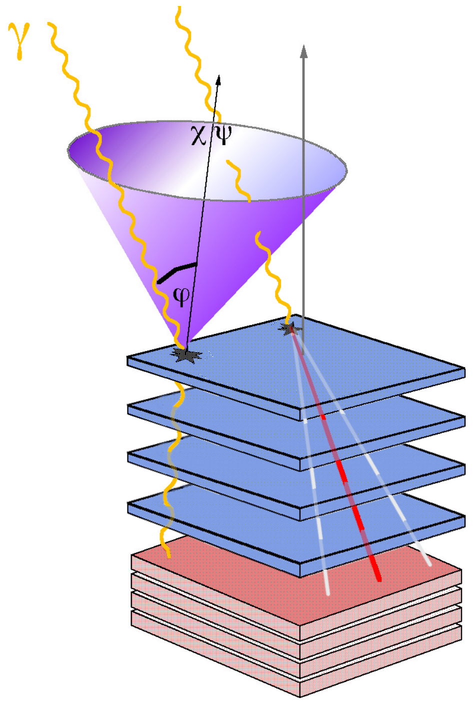
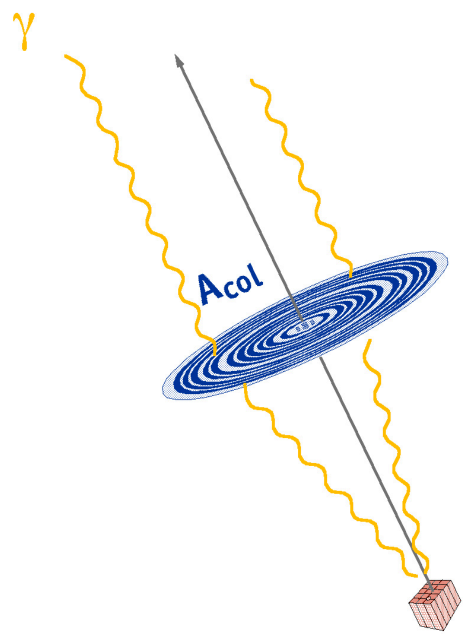
Thermal / non-thermal transition



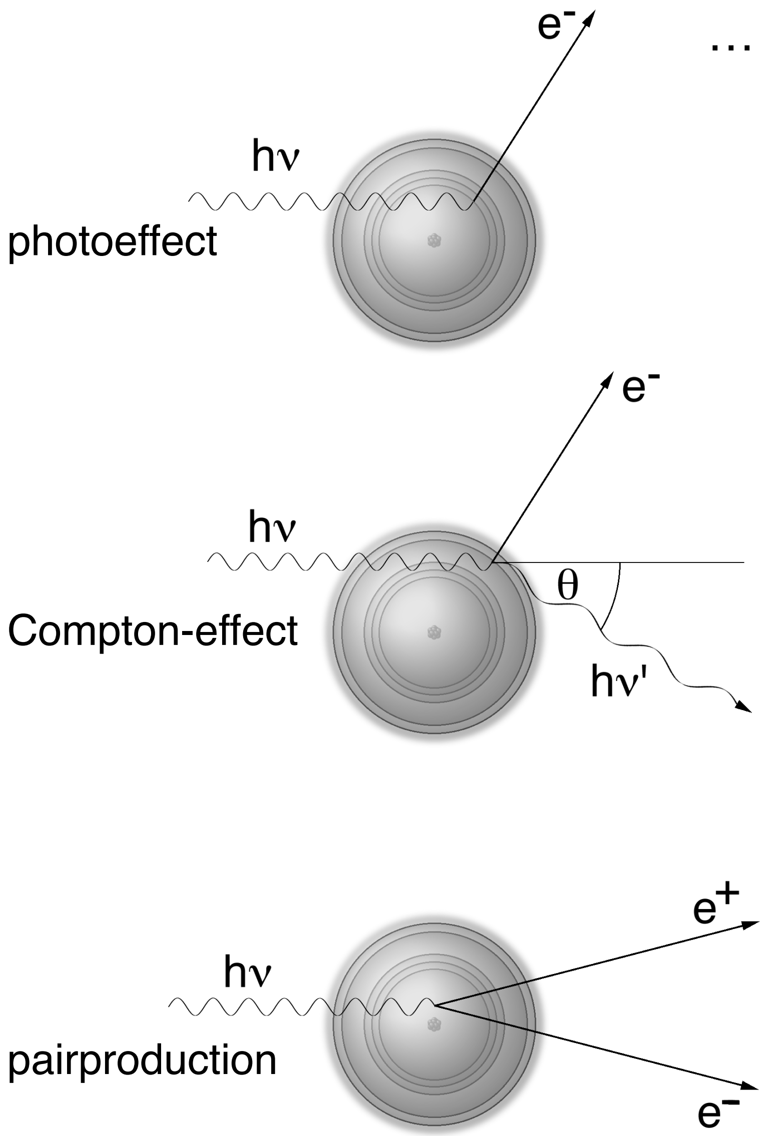
Cosmic accelerators : link between accretion (thermal) and ejection (non-thermal)

Instrument concepts in gamma-ray astronomy

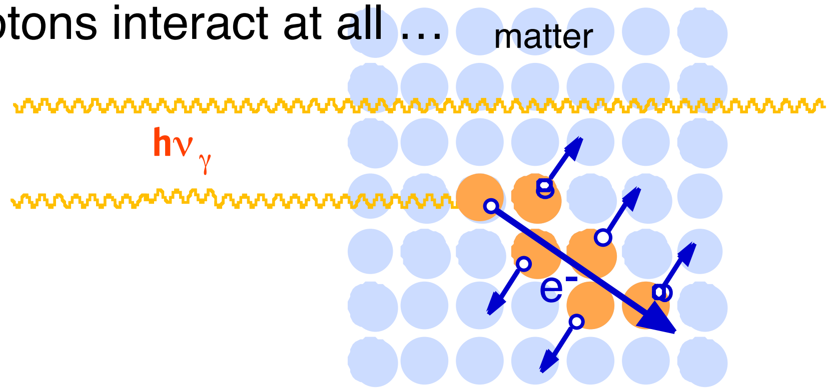
The instrumental categories in nuclear astrophysics reflect our current perception of *light* itself.

	geometric optics absorption	**quantum optics** incoherent scattering	**wave optics** coherent scattering
aperture detector			
	ex. coded masks "on-off" collimators	ex. Compton telescopes tracking chambers	ex. Laue lenses Fresnel lenses

three main interaction processes of gamma-rays with matter



… if photons interact at all …



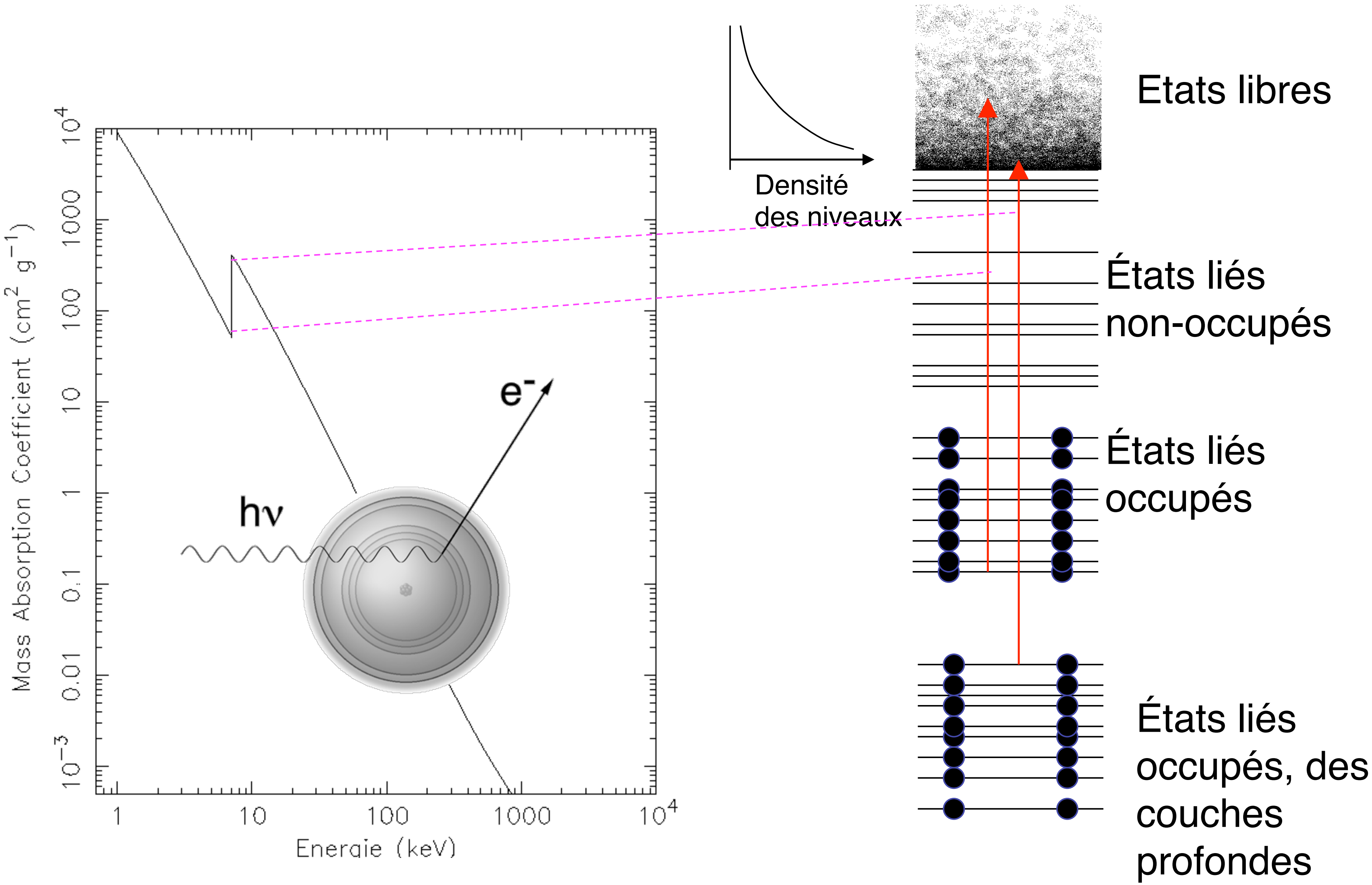
Détecter les rayons X et γ

I **conversion** : Dans la quasi-totalité des cas d'interet practique, les photons sont détectés par la production d'electrons secondaires :

II **ionisation** du materiau du detector par electron rapide -> creation d'un grand nombre de porteurs de charge

III **collection** (reconversion) du signal du détecteur, amplification du courent et convertsion par un CAD

L'effet photoélectrique



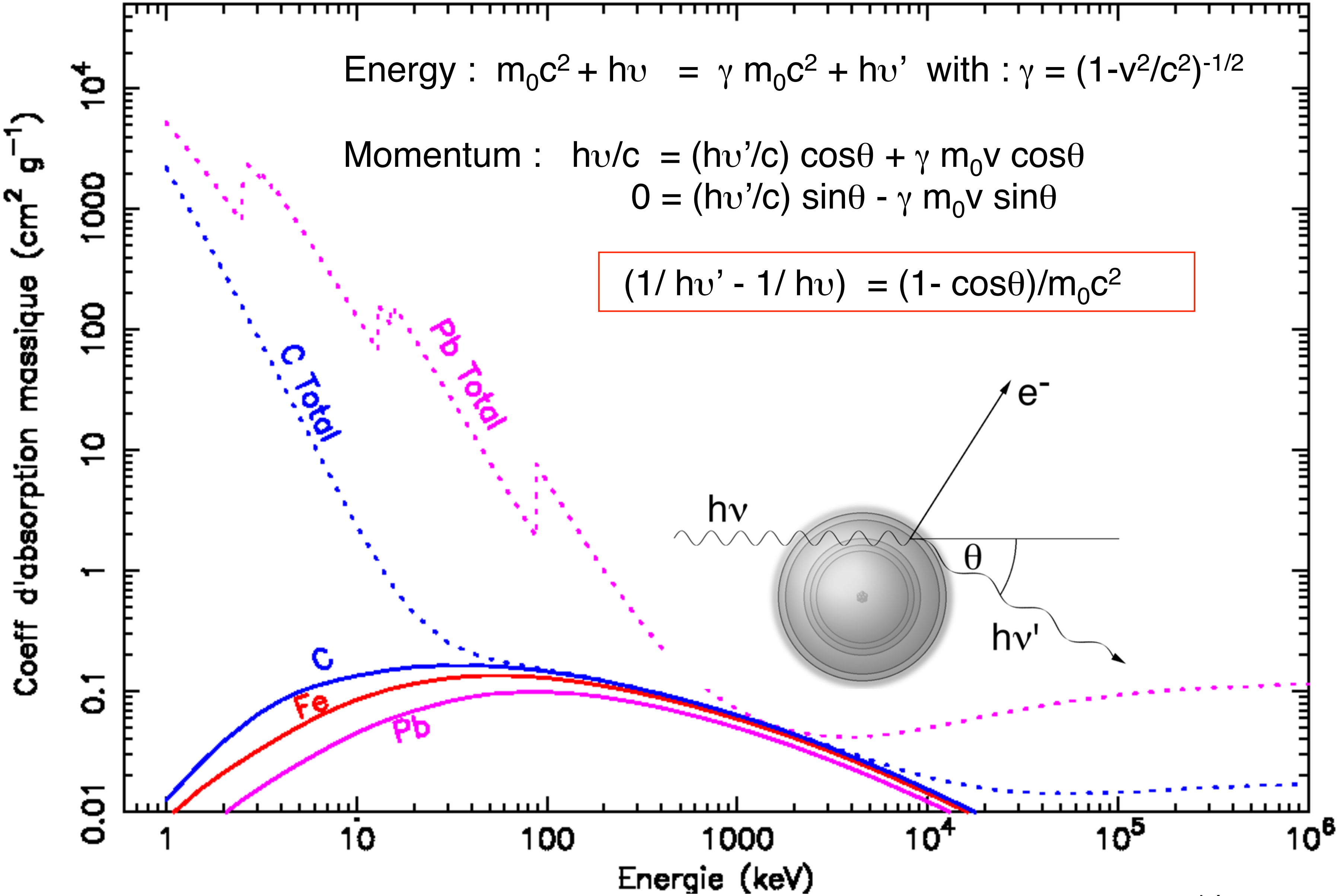
Compton Scattering

$$\text{Energy}: \quad m_0c^2 + h\upsilon = \gamma\, m_0c^2 + h\upsilon' \quad \text{with}: \gamma = (1 - v^2/c^2)^{-1/2}$$

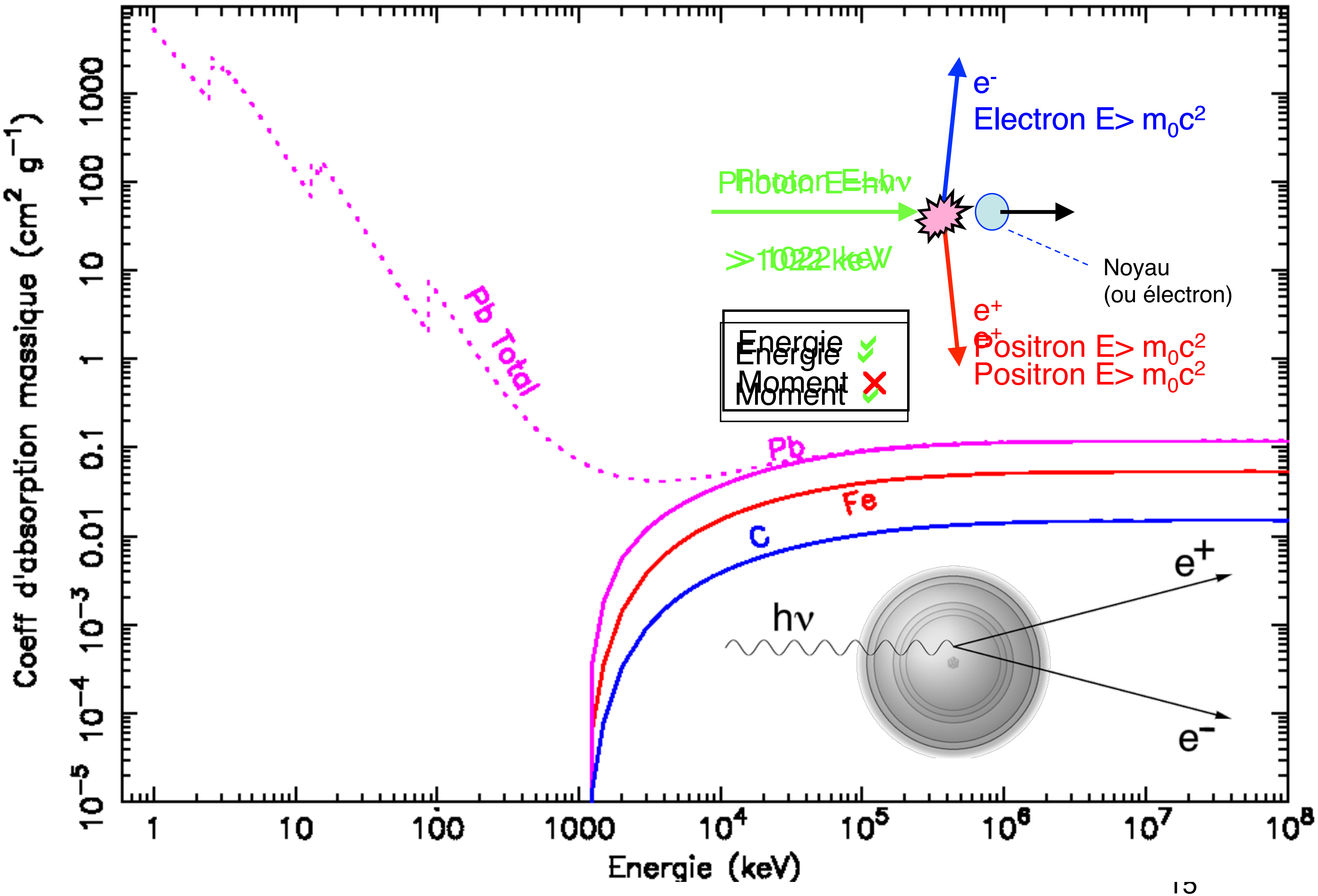
$$\text{Momentum}: \quad h\upsilon/c = (h\upsilon'/c)\cos\theta + \gamma\, m_0 v \cos\theta$$

$$0 = (h\upsilon'/c)\sin\theta - \gamma\, m_0 v \sin\theta$$

$$(1/h\upsilon' - 1/h\upsilon) = (1 - \cos\theta)/m_0c^2$$



Production de paires électron-positron



Détecteurs pour le domaine γ

Détecteurs à Gaz

Chambre d'ionisation

Compteurs Proportionnels

Compteurs Geiger

Scintillateurs

Scintillateurs - organiques, inorganiques

Photomultiplicateurs

Semiconducteurs

Semiconducteurs à bassse temperature - gap étroit

Semiconducteurs à haute temperature - gap large

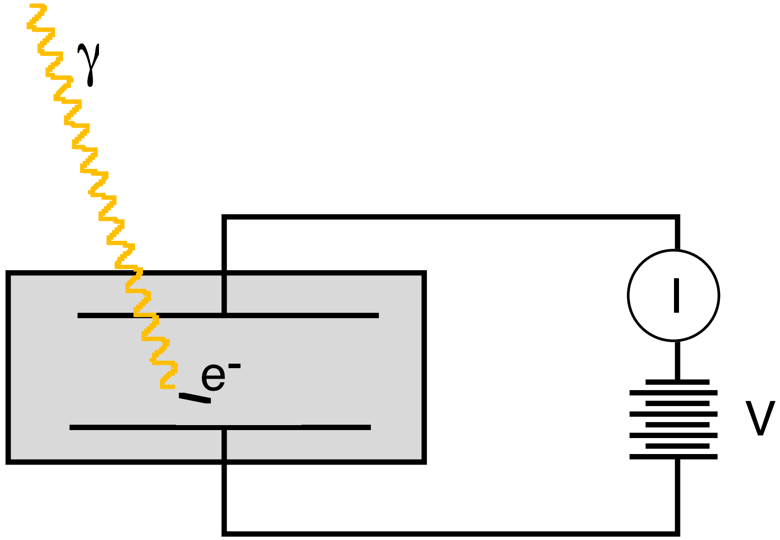
Détecteurs à temperature ultra-basse

Bolomètres

Détecteurs à Phonons

Détecteurs à Gaz

Ionization chambers, Proportional counters, Geiger counters



creation of n_o ion pairs (free electron and positive ion)

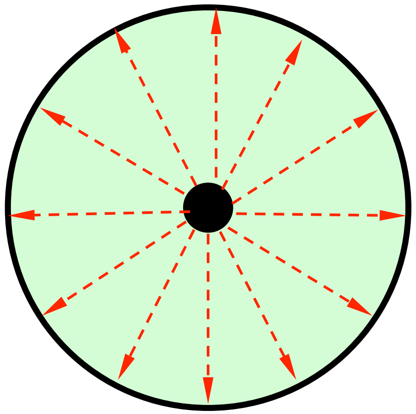
$n_o \approx E\gamma / W$ (e.g. N ≈ 30000 for a 1 MeV gamma-ray)

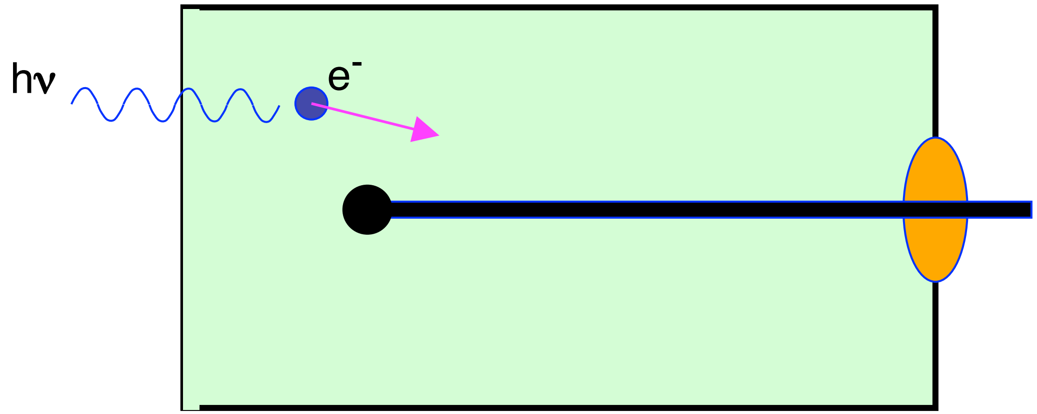
E_i ionization energy (least tightly bound e) ≈ 10 - 20 eV

W average energy required to produce ion pair ≈ 30-35 eV

Eg ~ n_o (for W independent of Eγ)

Détecteurs à Gaz - Chambre d'ionisation

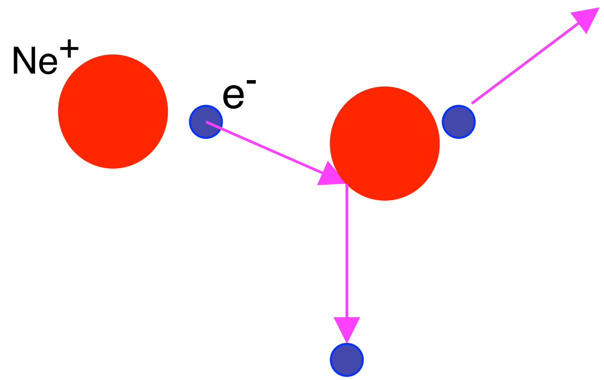




Energie d 'électron éjecté = hν - E_{ion} (où : E_{ion} = énergie d 'ionisation)

e.g. 1 keV-10 eV

Suffisant pour ioniser plusieurs autres atomes



$e^- + Ne \rightarrow Ne^+ + 2e^-$

Le nombre d électrons libérés n 'est pas

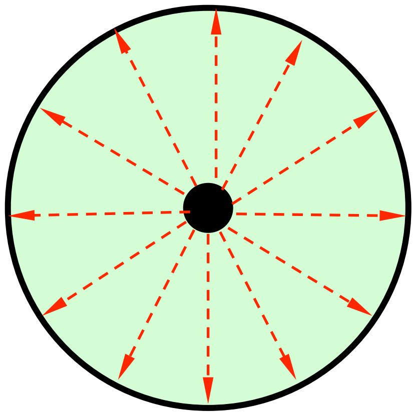
hν / E_{ion}

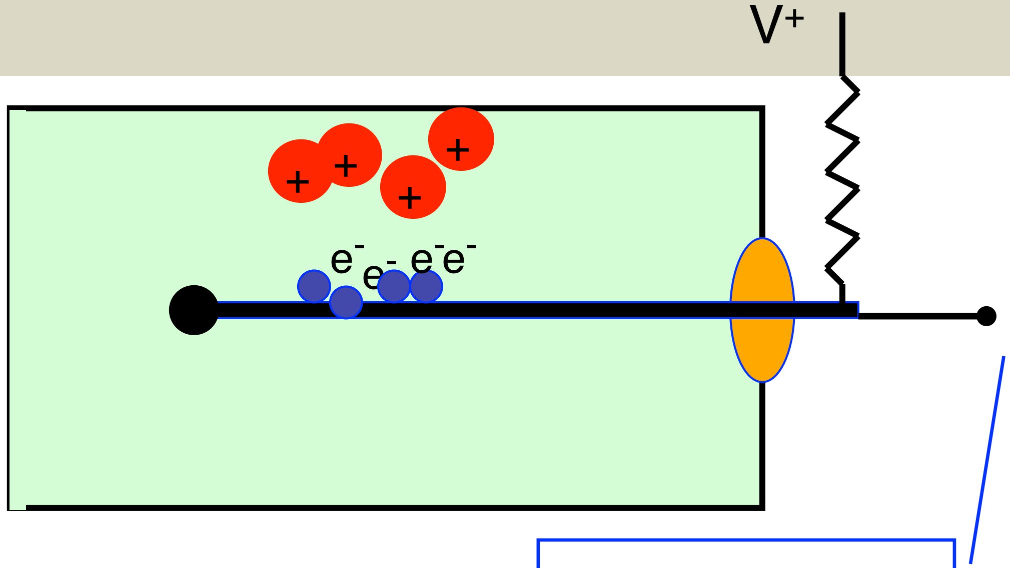
mais

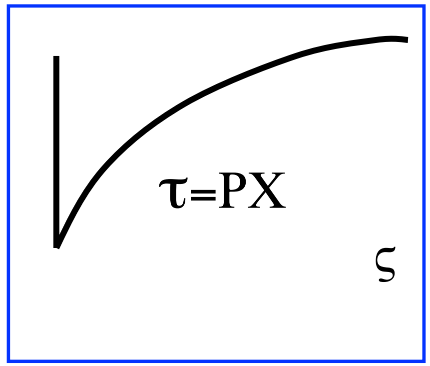
hν/W , où $W > E_{ion}$

parce que la plupart de l'énergie -> énergie cinétique (chaleur)

Chambre d 'ionisation







Les électrons vont vers l 'anode (assez vite)
Les ions positifs vont vers la cathode (moins vite)

Si plusieurs photons arrivent, un courant circule

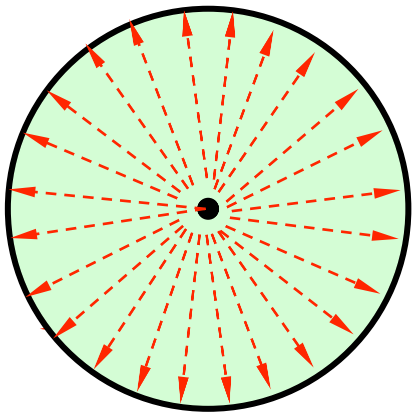
S'ils arrivent un par un, on verra une
série d'impulsions de charge électrique dq = ($h\nu$/W)

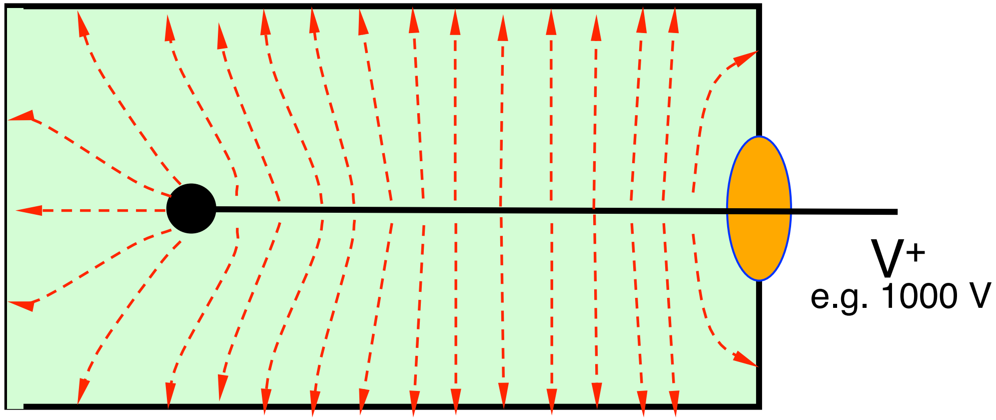
Si la capacité du détecteur est C, des impulsions d 'un
potentiel égal à dV=dq/C seront produites.
Après chaque impulsion il y a une récupération exponentielle, avec un temps
caractéristique RC, où R est la résistance en série avec l 'alimentation.

Compteurs proportionnels

En fait, on n'utilise rarement les chambres d 'ionisation

Mais on peut utiliser un compteur proportionnel





Très similaire, mais
- Anode plus fine
- Potentiel plus elevé

En conséquence
- champs électrique très fort près de l 'anod
- Quand les électrons sont près de l 'anode, ils peuvent gagner suffisamment d'énergie entre les collisions avec les atomes du gaz pour ioniser encore plus d'atomes. Résultat: une avalanche d 'électrons. E.g. Signal ~10^4 fois plus grand !

Compteurs proportionnels

At higher electric fields, free e^- will be accelerated to energies larger than the ionization energies => additional ion pairs

threshold for gas multiplication ~ 10^6 V/m (at 1 atm)

$dn_e/n_e = \alpha\, dx$ increase of number of e^- per unit pathlength

α Townsend coeff. ~ with field strength

$n(x) = n_e(0)e^{\alpha x}$ exponential growth : Townsend avalanche

in a proportional counter

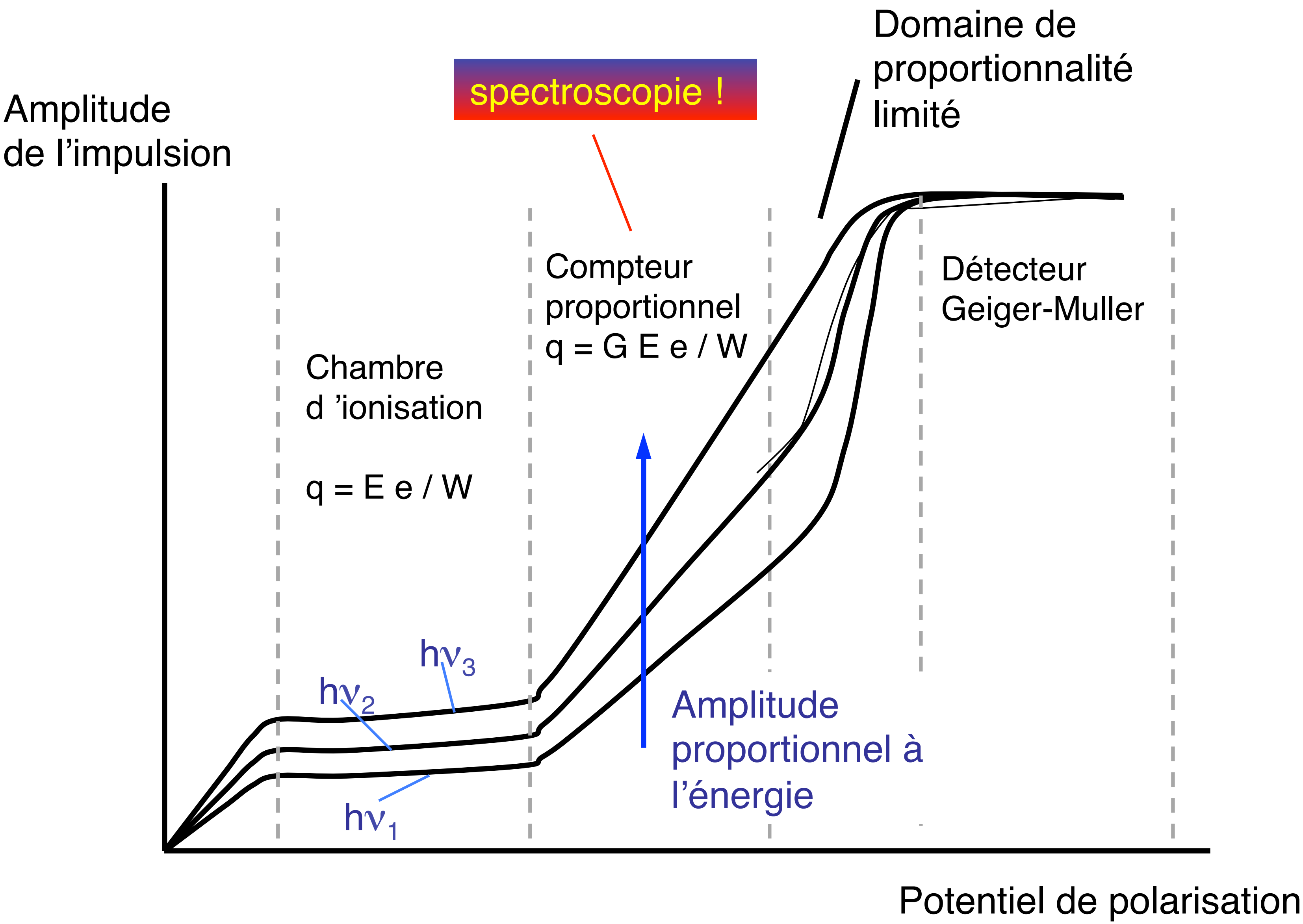
- the avalanche terminates when all e^- collected
- $n_{\text{secondary ion pairs}} \sim n_{\text{primary ion pairs}} \sim E\gamma$
- multiplication by > 10^3 (=> external amps.)
- improved S/N with resp. to ion chambers

fill gases : e.g. Ne, Ar, Xe

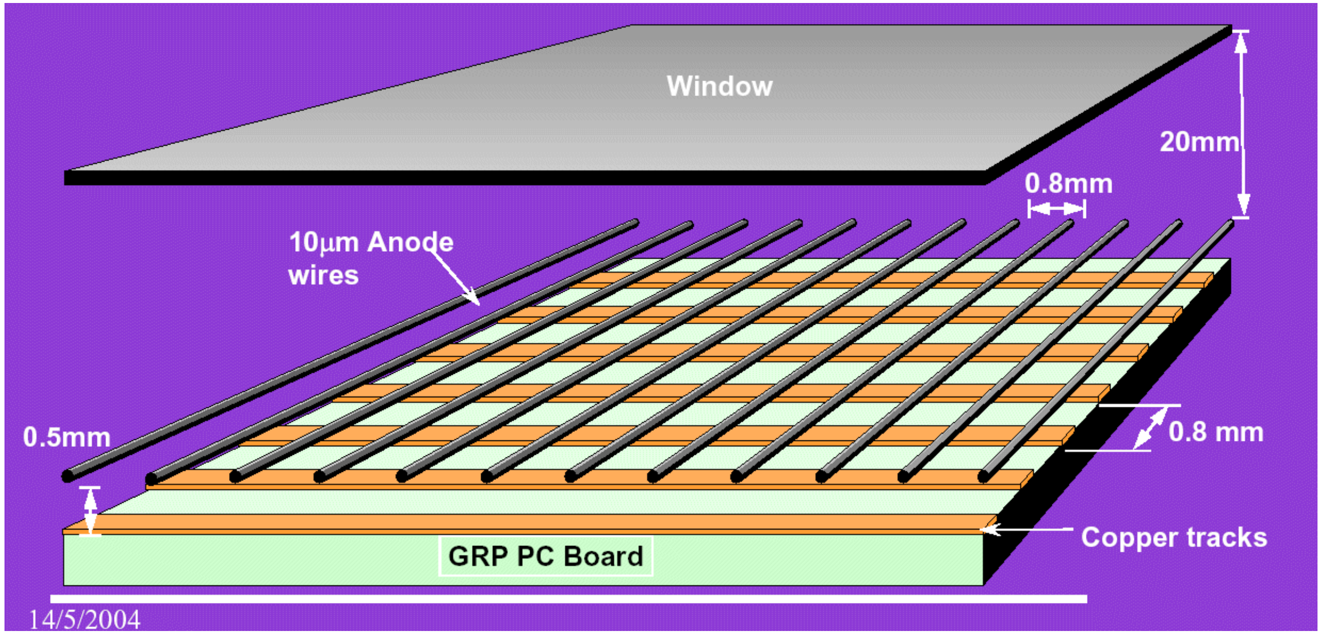
quench gas : absorbs undesired UV photons (e.g. CH_4)

energy resolution : 10% - 13% (12% for Ar + 0.5 % CH_4)

Les compteurs proportionnels



MWPCs



MWPC
(Multiwire Proportional Counter)

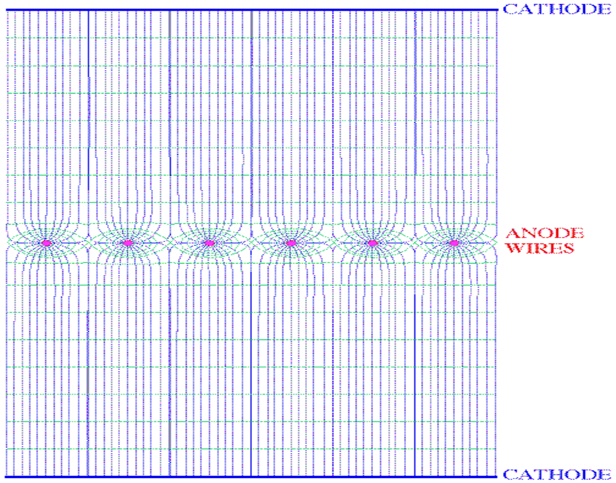


Fig. 1: The multiwire proportional chamber: thin, parallel anode wires are mounted symmetrically between two cathode meshes.

Scintillators

fluorescence

- instantaneous emission of visible light after excitation / ionization
- (>< phosphorescence - larger I - retarded fluorescence)

the ideal scintillator would have :

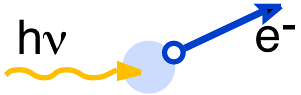
- converts fast electron energy into scintillation light with high efficiency
- linear conversion
- medium transparent to its own scintillation light
- fast decay time of induced luminescence (fast signals)
    - large size at constant quality
- refraction index ≈ 1.5 (close to glass <-> PMT's)

two main scintillator types

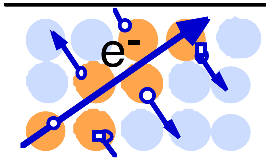
organic scintillators (liquid, plastic) <-> PSD/neutrons

inorganic scintillators : spectroscopy (<-density)

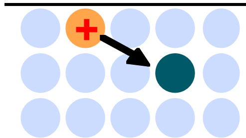
inorganic scintillators *Scenario of an interaction*



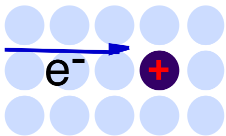
γ-ray interaction with matter produces a secondary e^-
photoeffect, Compton, pair-production



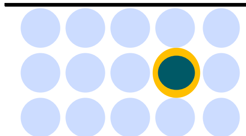
ionization : fast e^- traversing crystal gen. a large number of e^-/hole pairs
e^- are raised from the valence-band to the conduction-band



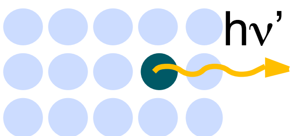
holes quickly drift to an activator site
$E_{ionization}$ of impurity < $E_{ionization}$ of typical lattice site



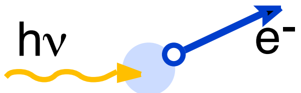
e^- are free (conduction)
until they encounter an ionize impurity ...



excitation : e^- fall into impurity => neutral, excited atom
(possibly with allowed transition to ground state)



deexcitation : transition in visible domain (for appropriate activators)
(excited states $t_{1/2}$ ~10^{-7}s)



visible photons interact with matter e.g on the photocathode of a PMT
(who transforms em-radiation back into electrons ...)

Properties of certain inorganic scintillators

	light yield ph/keV	scint. yield [%NaI]	ΔE/E at 662	decay time [ns]	after-glow	λ_{peak} [nm]	n refr.	hygro	ρ [g/cm^3]
NaI(Tl)*	38	100	7.5 %	250	5 %	415	1.85	yes	3.67
CsI(Na)*	41	85	9 %	630	5 %	420	1.84	yes	4.51
CsI(Tl)*	54	45	9 %	1005	5 %	550	1.79	low	4.51
CaF_2(Eu)*	19	50		940		435	1.47	no	3.18
BaF_2* fc	1.9	3	~10%	.6-.8	-	225	1.54	low	4.88
sc	10	16		630	-	310	1.50		4.88
BGO	8-10	20	13%	300	0.1 %	480	2.15	no	7.13
$CdWO_4$*	12-15	30-50		14000		475	~2.3	no	7.9
PWO †	~ 0.1	0.3-1.3		10,20, 500(3)	(3)	420 500	2.16	no	8.28

Détecteurs à gaz vs. à détecteurs semi-conducteur

~ ‘ Chambres d’ionisation à l’état solide’

Détecteurs à gaz		**Détecteurs à semi-conducteur**
- Ions, - Electrons libres		- Trous positifs en bande de valence, - Electrons libres en bande de cond.
- Densité ~ 0.01 g cm^{-3}		Densité ~ 1.5 - 5 g cm^{-3}
- Fenêtre nécessaire pour retenir gaz	⟺	Pas (toujours) de fenêtre
- W (énergie par paire électron-ion) quelques dizaines de eV		- W (énergie par paire électron-trou) quelques eV
- Énergie maximale ~ 50 keV (détecteurs Xe à haute pression)		- Énergie maximale utile ~ 10 MeV (Détecteurs Ge de grande taille)

Besoins : détecteur à semi-conducteur

L'efficacité de détection pour les rayons X est ~ $1 - exp(-\mu\rho x)$

L'épaisseur x, qui est importante est seulement la partie où le champ électrique peut séparer les électrons et trous libres et peut conduire ces porteurs vers l'anode et la cathode respectivement.

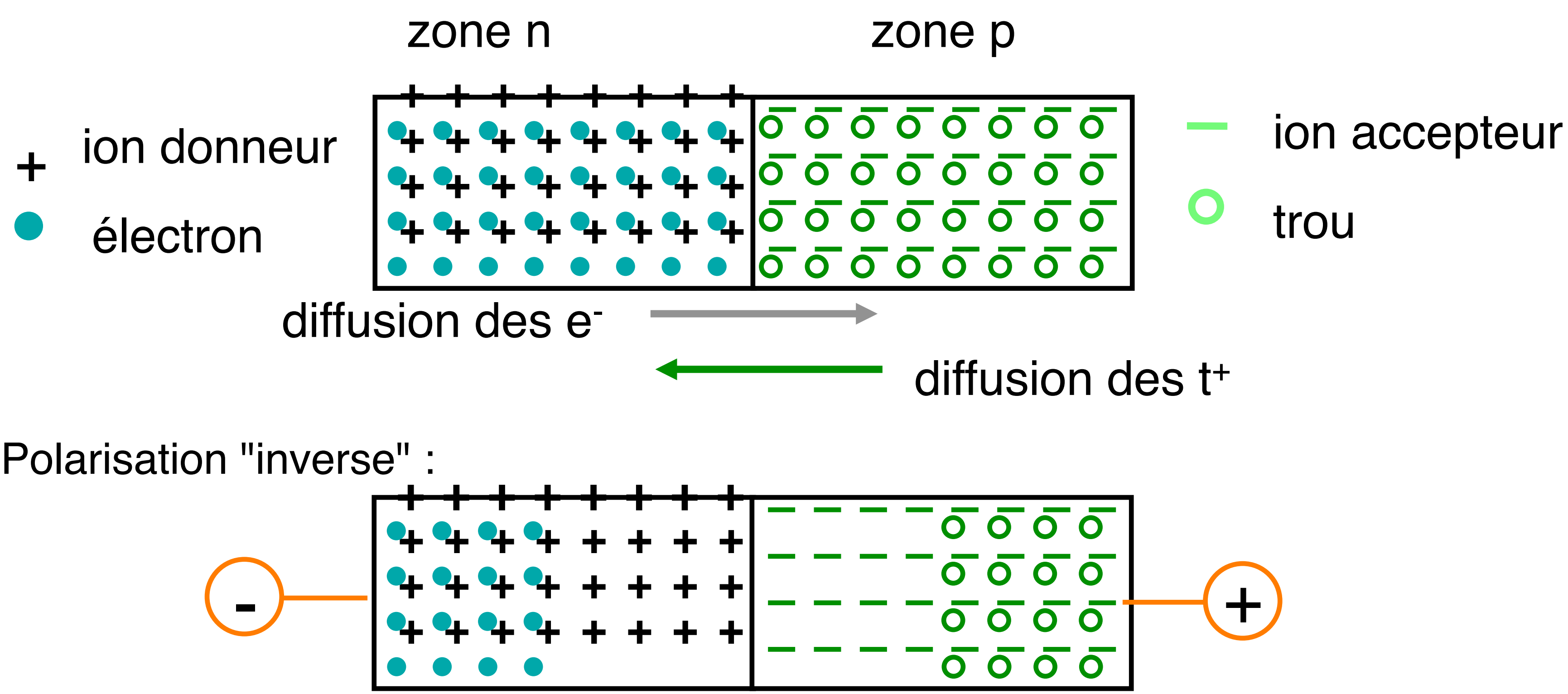
Pour avoir un champ suffisante sur un épaisseur important on utilise :

- des semi-conducteurs intrinsèques (très pur, résistivité très élevée et/ou 0
- structures P-N (comme une diode à biais inverse) avec une profondeur de déplétion élevé par un biais important.

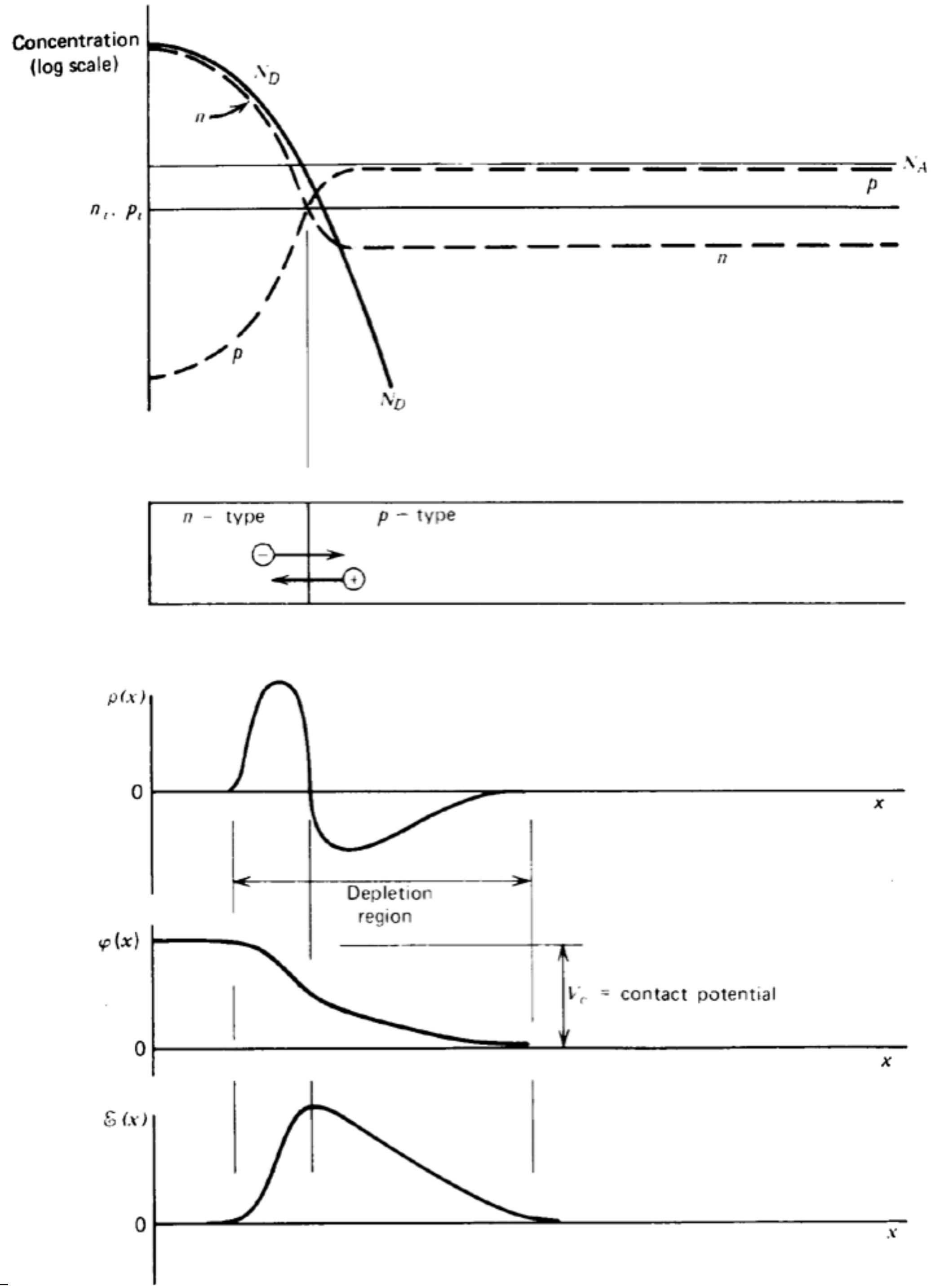
Pour ne pas avoir un courant de fuite trop important, il faut que $kT<<E_{gap}$

Pour avoir un grand nombre d'électrons libérés (pour une énergie de photon particulière) il faut que W soit petit.

Détecteurs semi-conducteurs : jonction pn



À l’équilibre : zone dépourvue de porteurs libres (déplétée) : haute résistivité

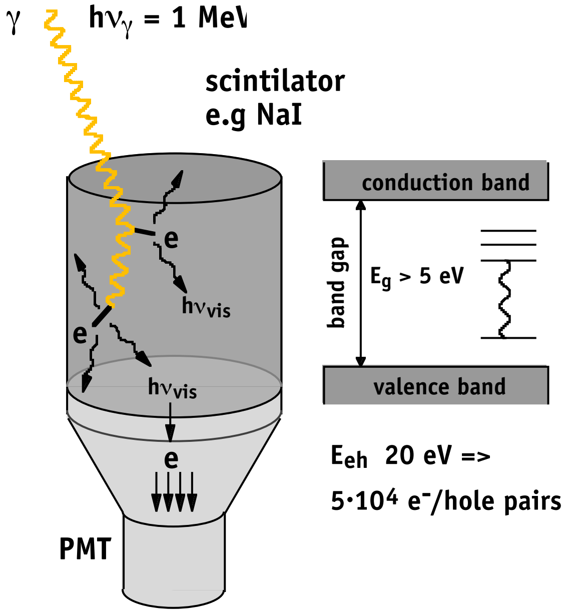


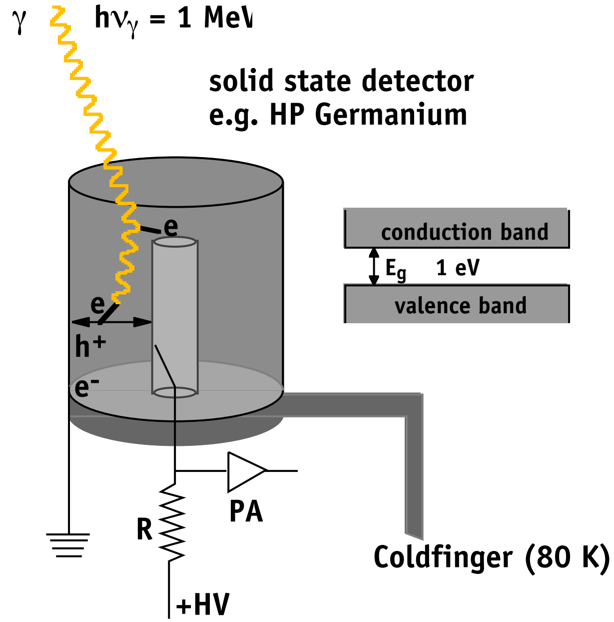
densité de charge

potentiel

champ electrique

scintillator vs. semiconductor





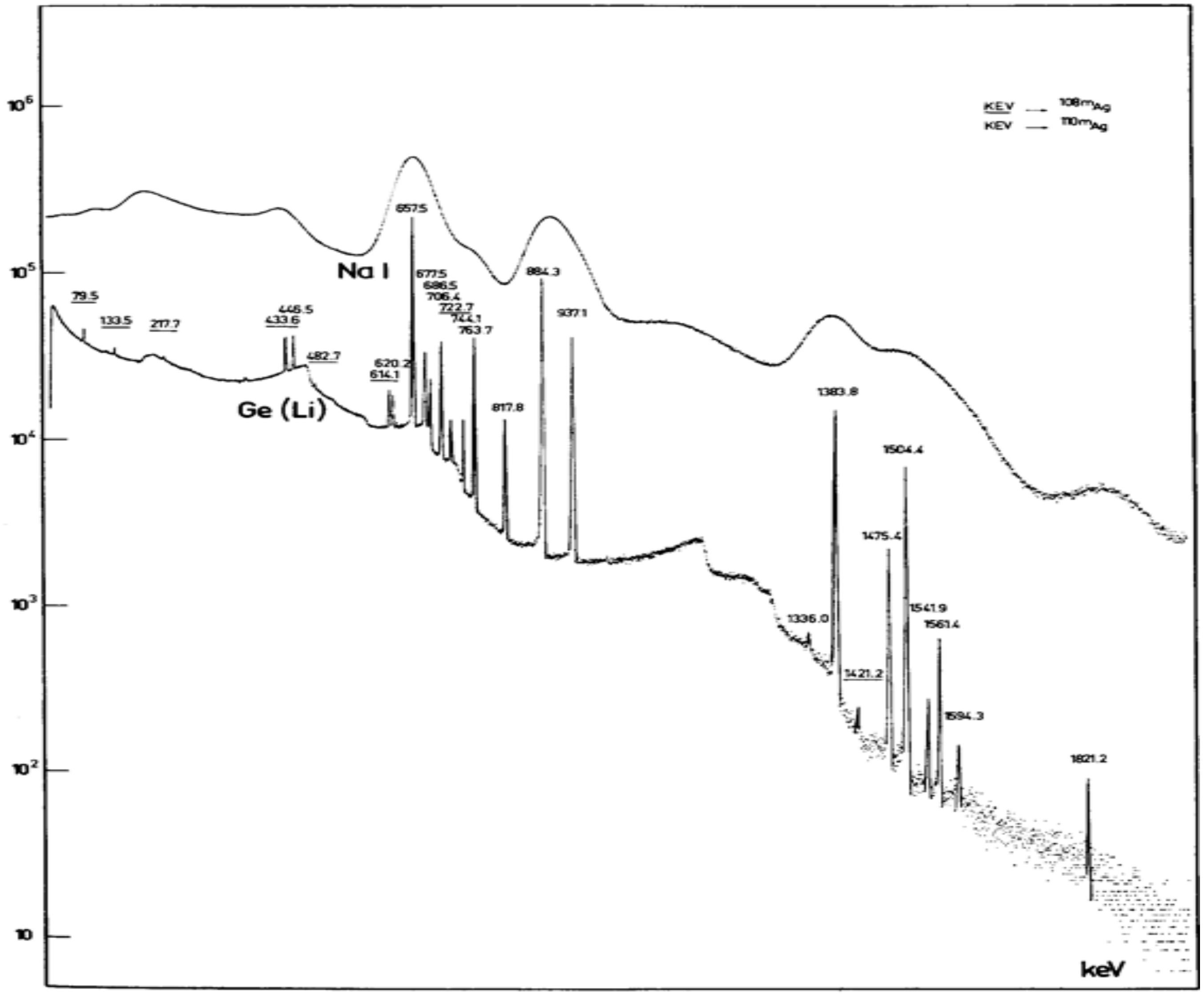
Scintillation eff. ~ 12% => 120 keV (V/UV)
Vis. photon energy ~ 3eV => 40'000 V/UV ph
on photocathode => 20'000 photons
quantum eff. QE ≈ 20% => 4'000 photo-e$^-$ (N_{sci})

Energy to form e-/hole pair : $E_{eh} \approx 3$ eV
$N_{sem} \approx 10^6/3\text{eV} \approx$ 300'000 charge carriers
$F_{sem} \approx$ 0.06-0.14 (Fano factor)

$R = 0.42\,(N_{sc}/F_{sci})^{1/2} \approx 25$

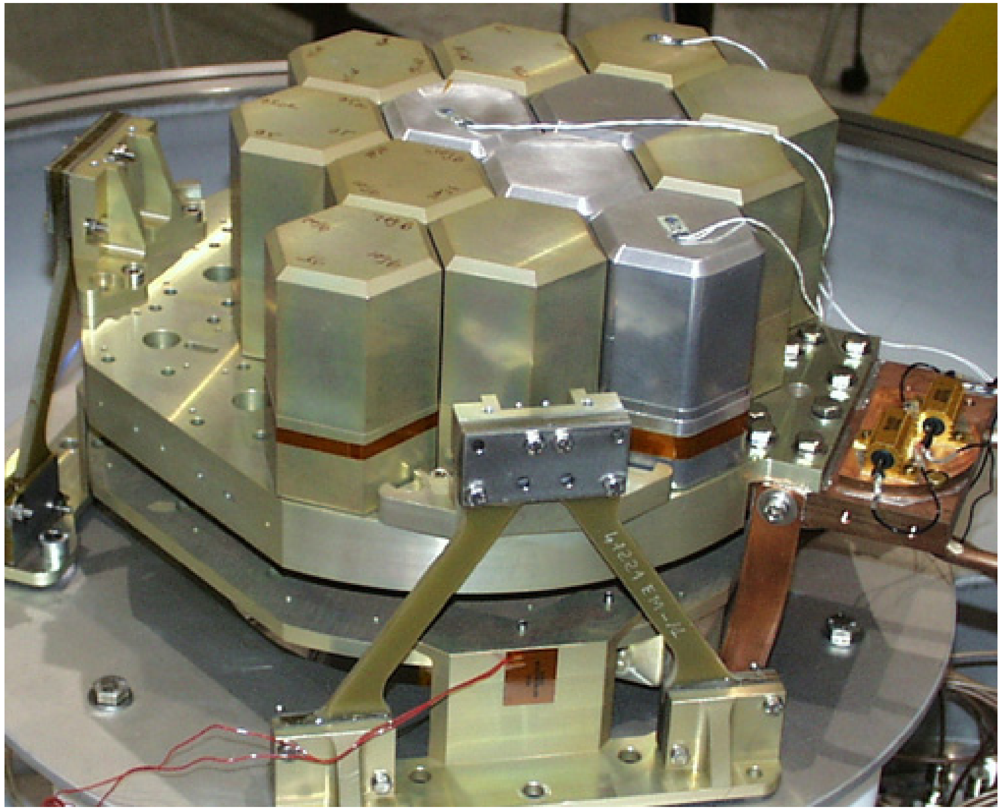
$R = 0.42\,(N_{sem}/F_{sem})^{1/2} \approx 500$

Comparison : scintillator / semiconductor spectra



Knoll, 1989

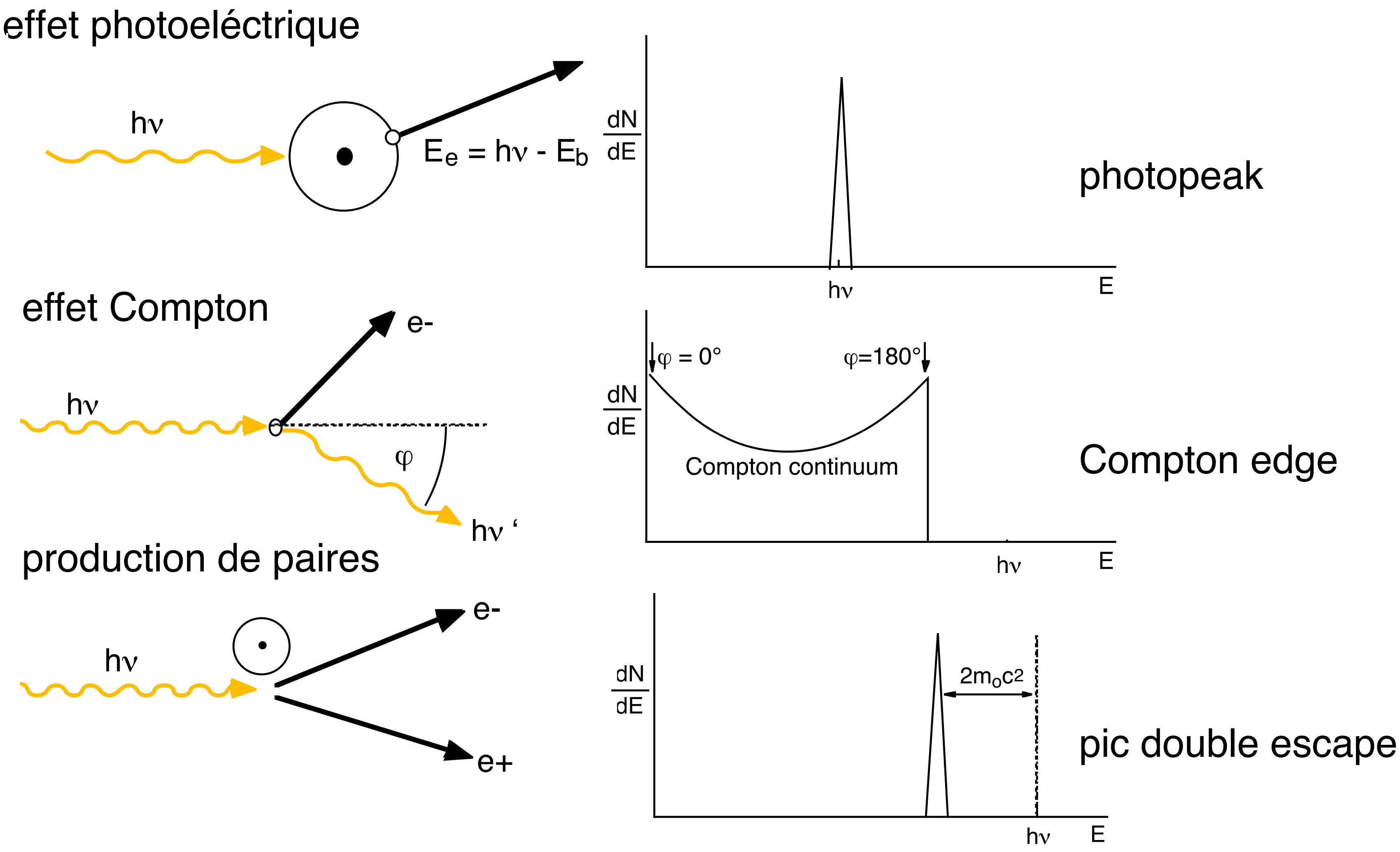
INTEGRAL SPI Ge detectors / lab cryostat



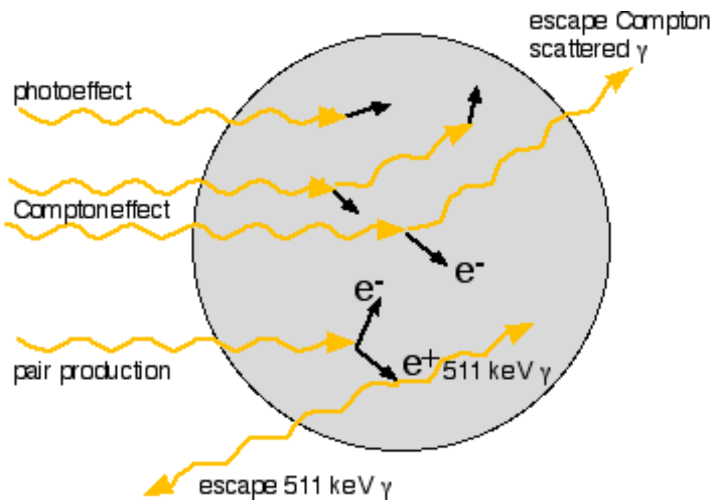
technical challenges

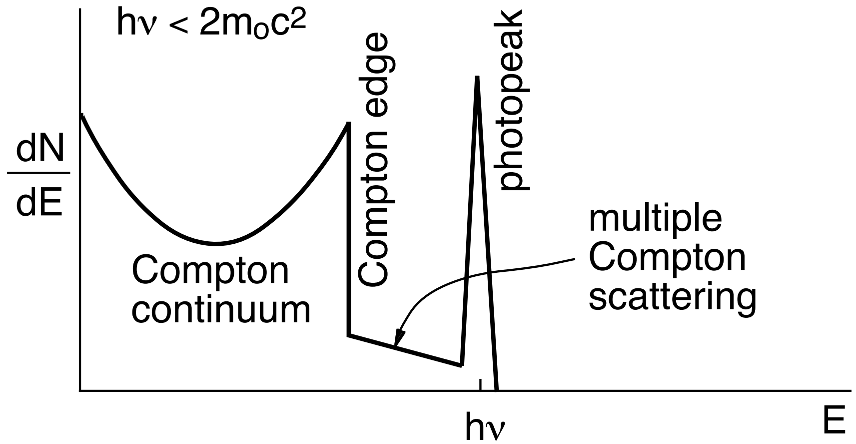
- Ge detectors have to be encapsulated for protection from surface contamination and abrasion
- Ge detectors have to be cooled to 85 - 100 K
- Cryostats have to under vacuum (condensation)

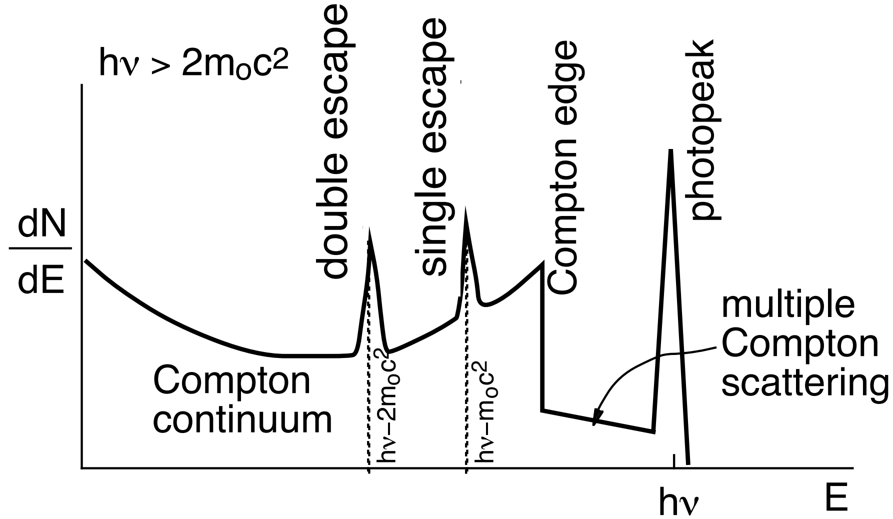
Interaction du rayonnemnt gamma avec la matière



Gamma-Ray Spectra







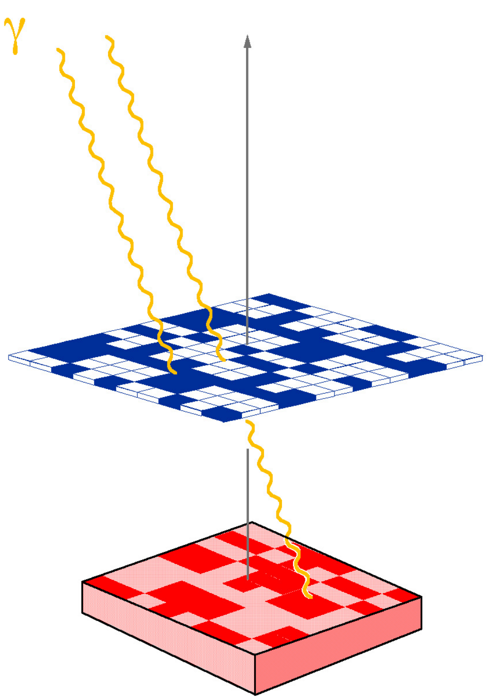
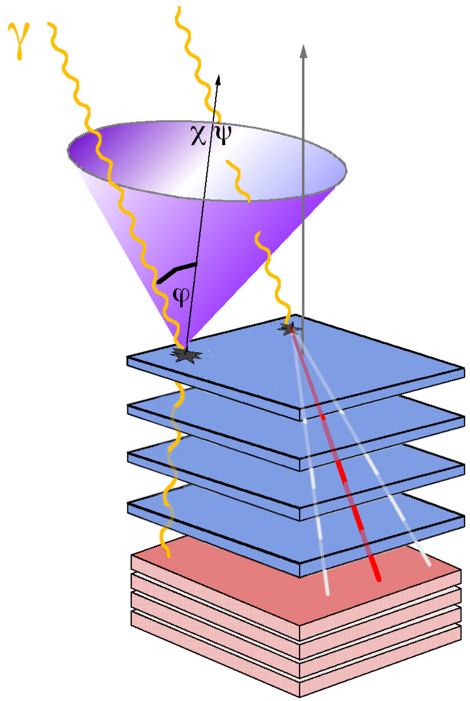
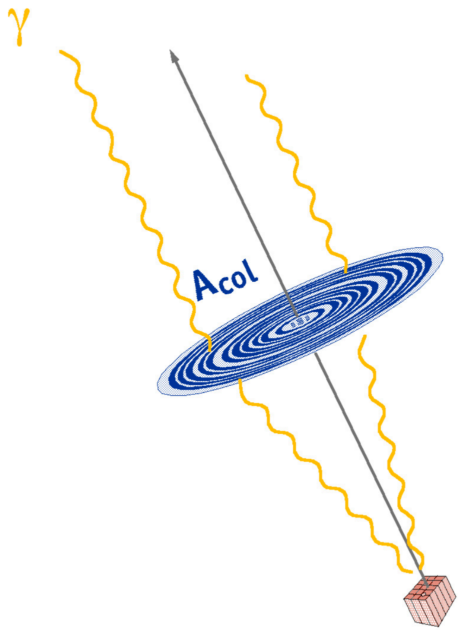
Compton edge

$$h\nu_c = h\nu - h\nu_b$$

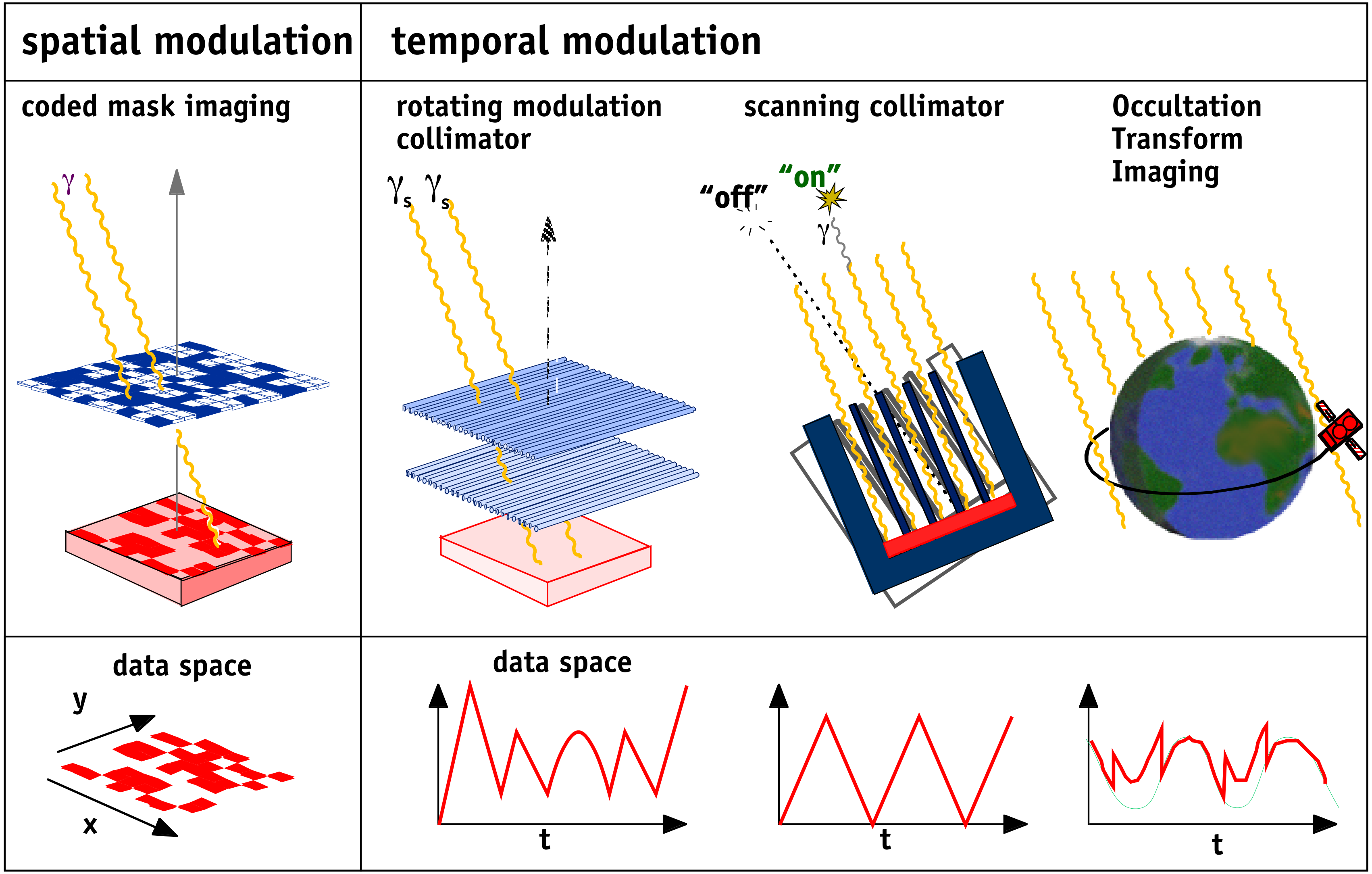
$$h\nu_b = \frac{h\nu}{1 + (2\,h\nu/m_oc^2)}$$

Instrument concepts in gamma-ray astronomy

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

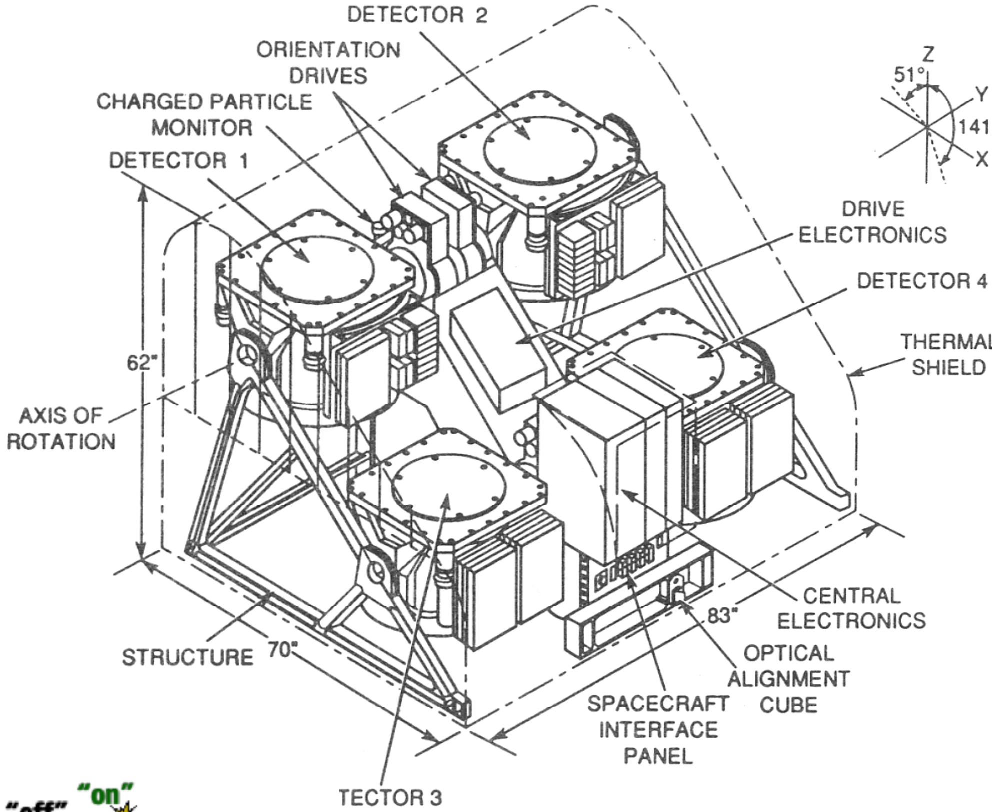
	geometric optics absorption	**quantum optics** incoherent scattering	**wave optics** coherent scattering
aperture detector			
	ex. coded masks "on-off" collimators	ex. Compton telescopes tracking chambers	ex. Laue lenses Fresnel lenses

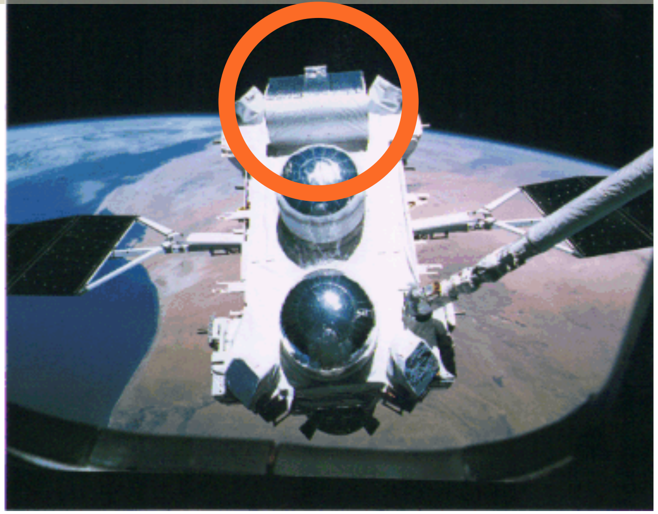
Geometric Optics : Modulating Aperture Systems

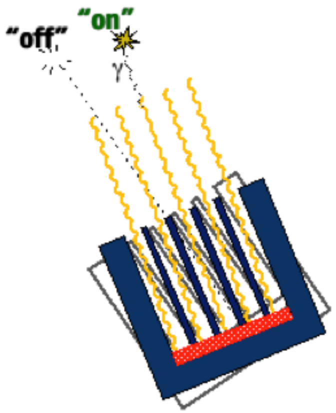


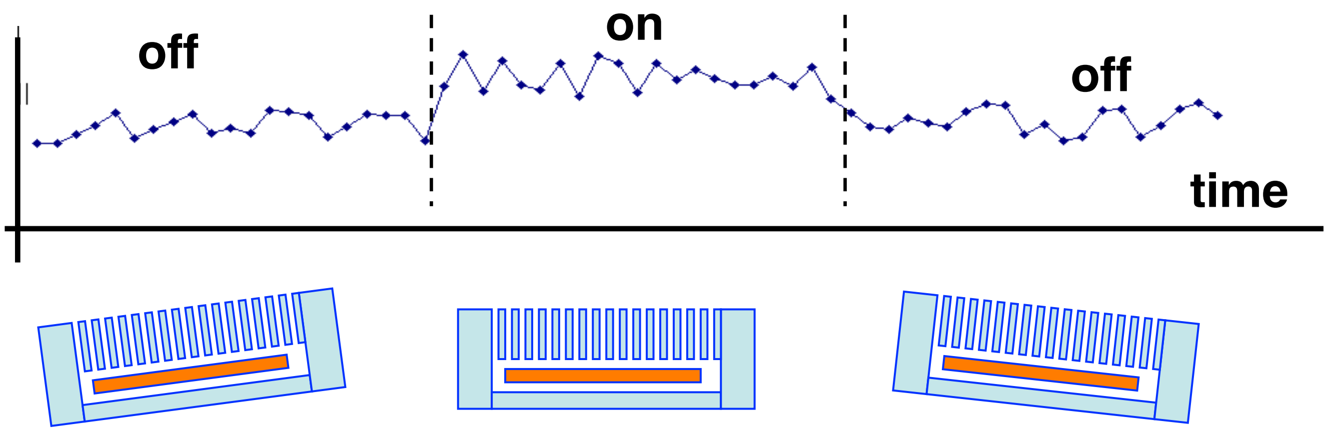
Collimator "on" - "off" telescope

GRO - OSSE

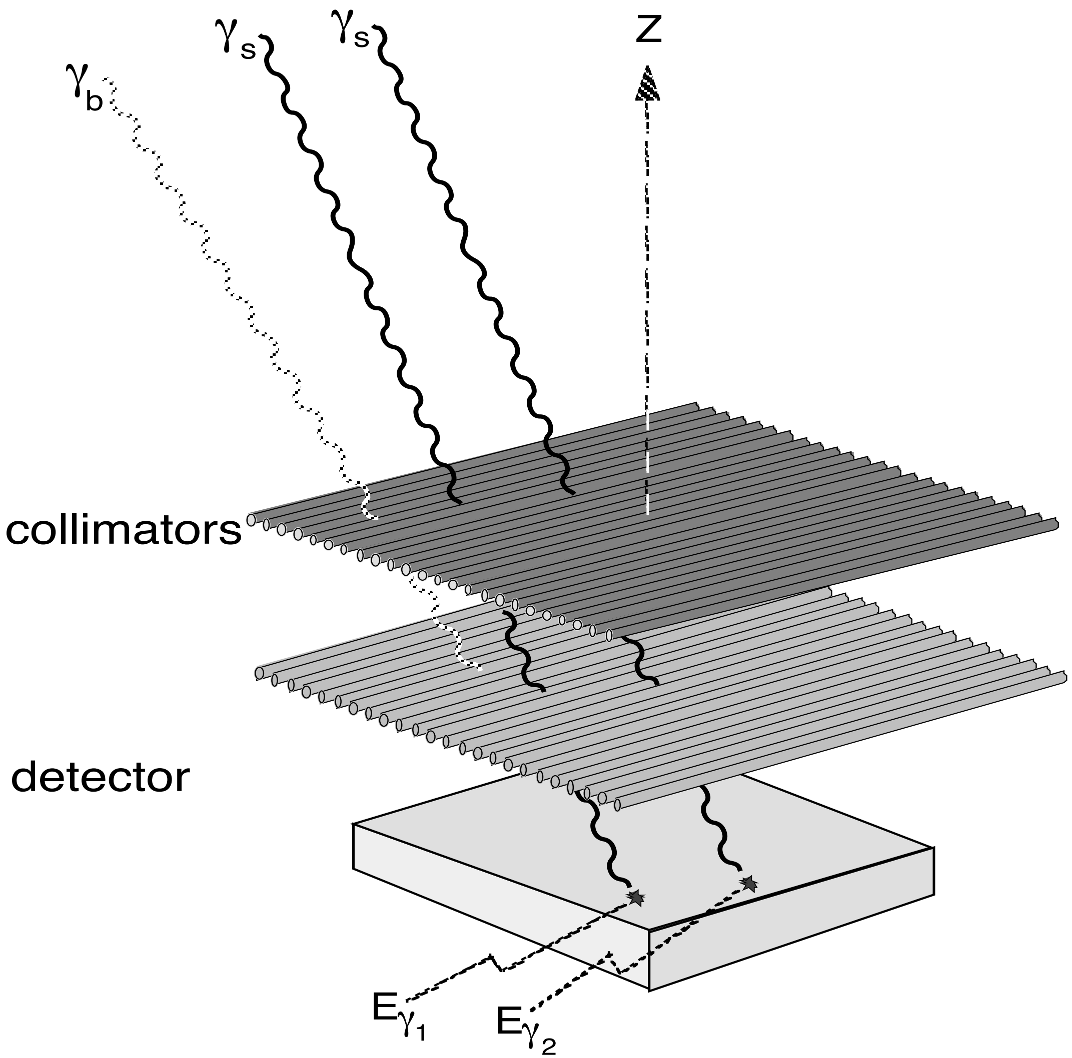








temporal modulation of a point source with a bigrid (Oda)-collimator



measured parameters :

Eγ : energy deposited

t : arrival time

expected count rate on detector :

$$N'(t) = \sum_i s_i \cdot \varepsilon \cdot f_i(t) + B$$

s_i : flux from the i*th* source

ε : detection efficiency

f_i : transmission function for source i at time t

B : background count rate.

temporal modulation of a point source with a bigrid (Oda)-collimator

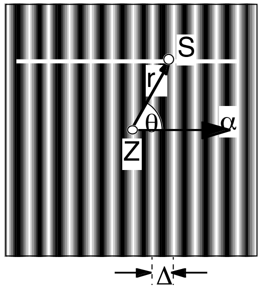
Transmission f_i for a point source located at the position r,θ from the instrument z-axis

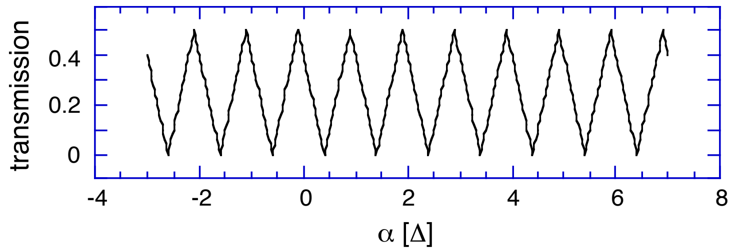
$$f_i \quad = \quad |\, 0.5 - (|\, g_i - \mathrm{int}(g_i)\, |)\, |$$

with g_i depending on the type of collimator movement and where $\mathrm{int}(g_i)$ is the integer part of g_i

scanning modulator

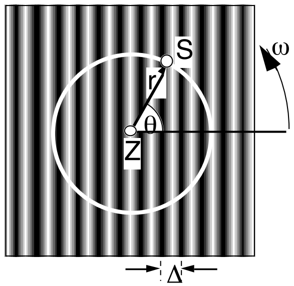
$$g_i(\alpha) = \frac{r \cdot \cos(\theta) - \alpha}{\Delta}$$

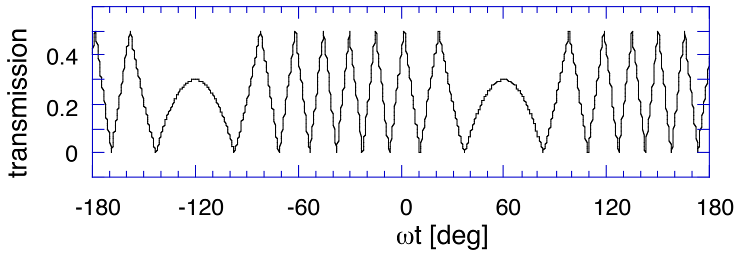




rotating modulator

$$g_i(\alpha) = \frac{r \cdot \cos(\theta - \omega t)}{\Delta}$$

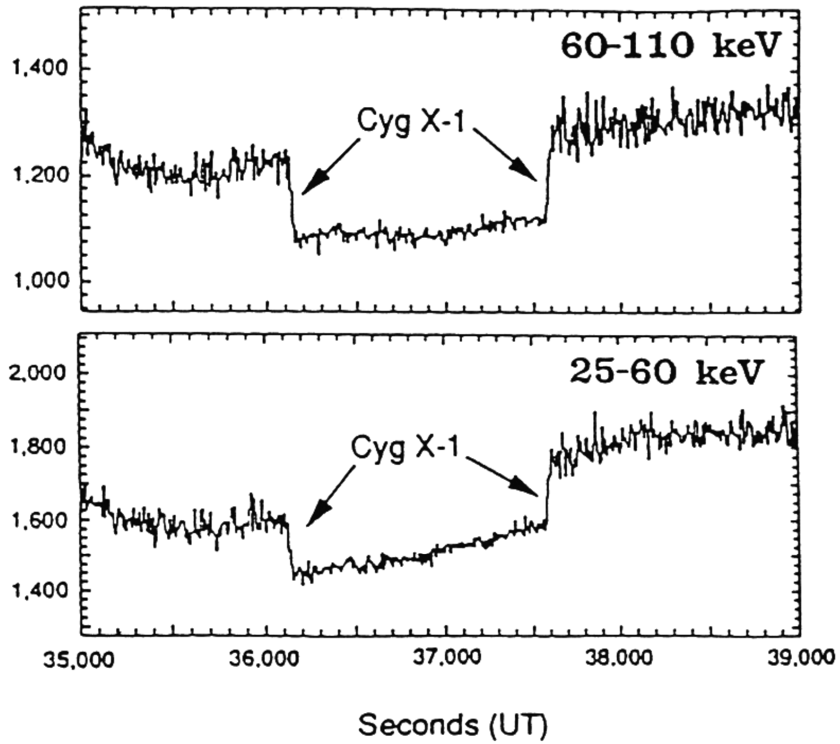


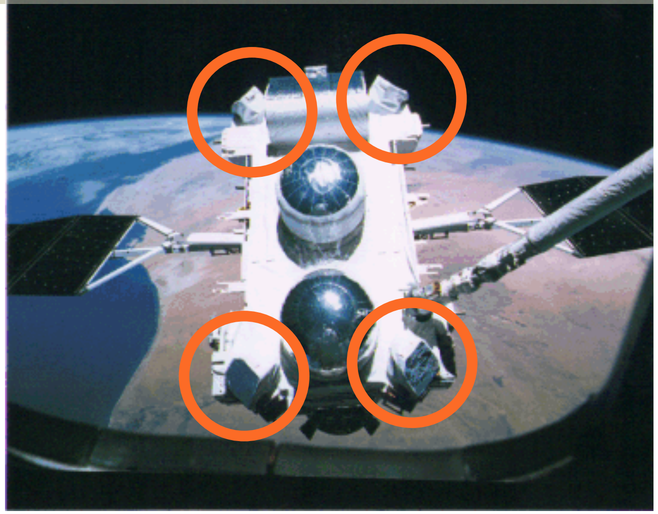


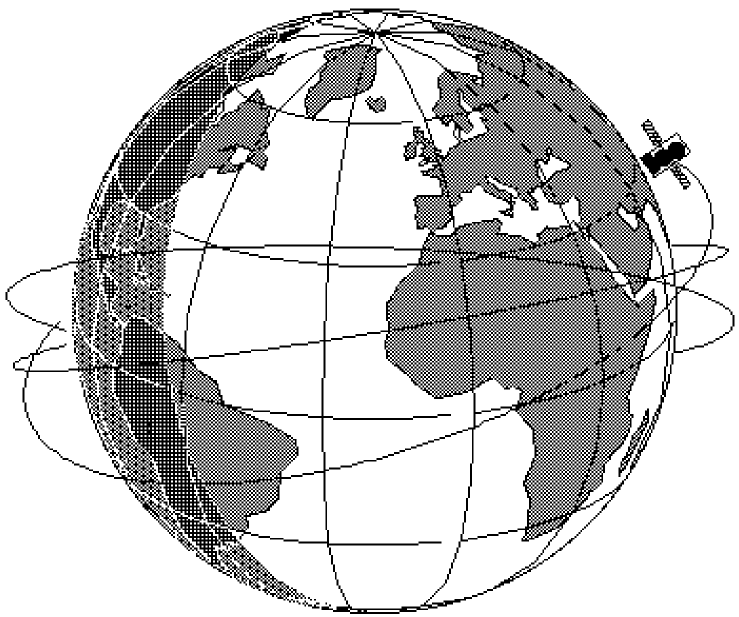
Occultation Transform Imaging

GRO - BATSE

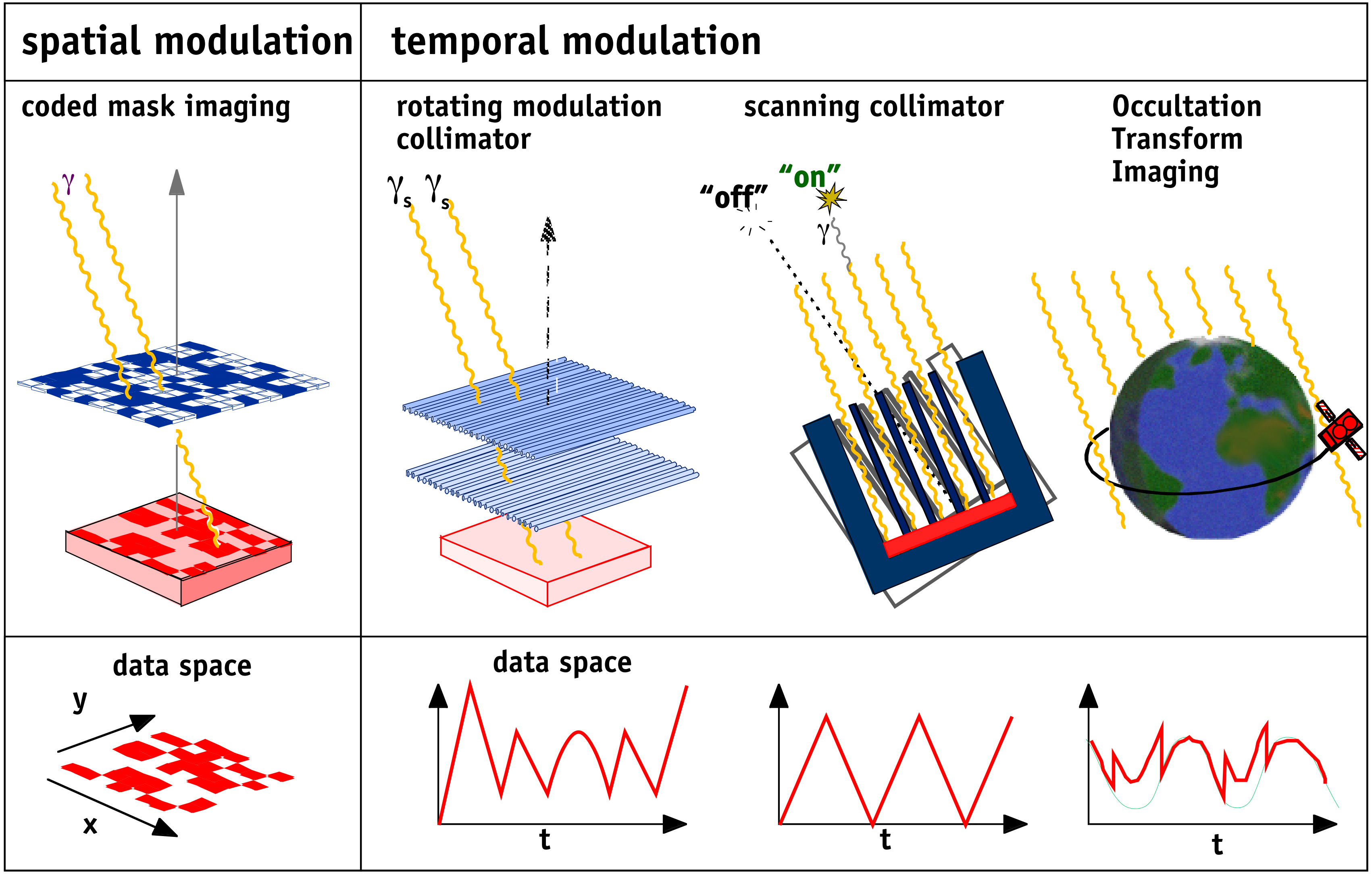
with the planet earth as
'rotation' modulation collimator
(or scanning anti-collimator)





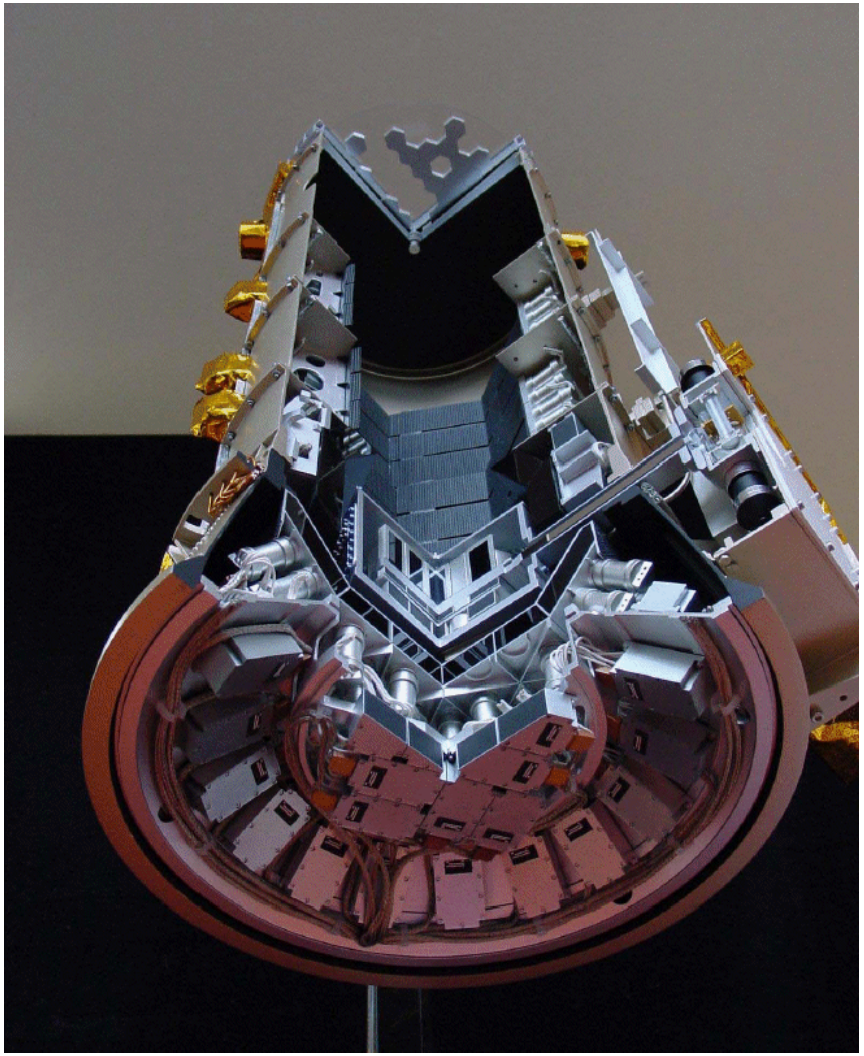


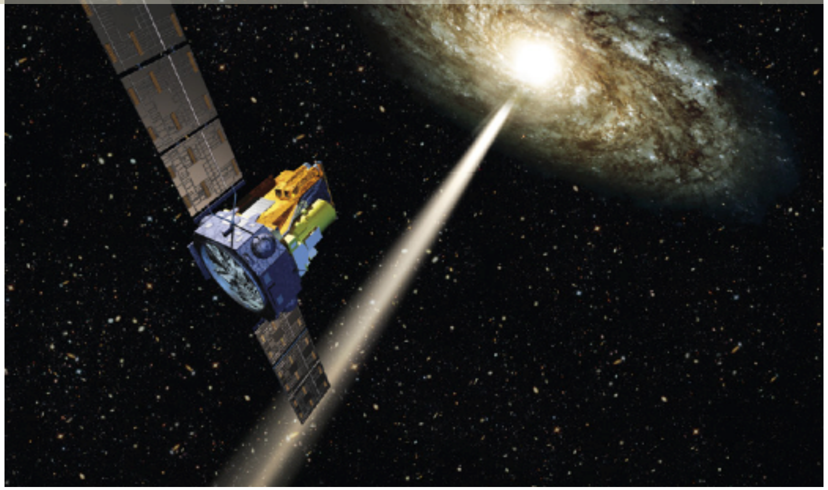
Geometric Optics : Modulating Aperture Systems

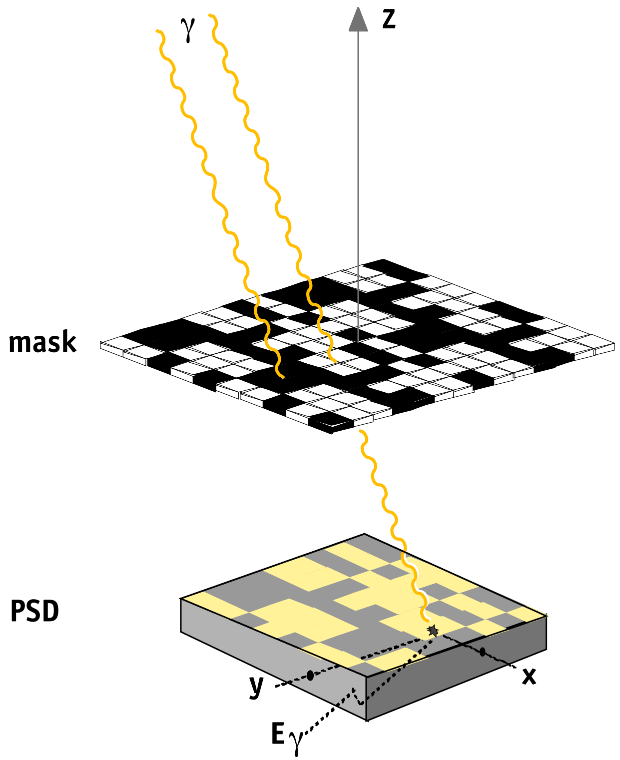


coded mask imaging

INTEGRAL/SPI







Why is it ...

Aristotle and the coded mask

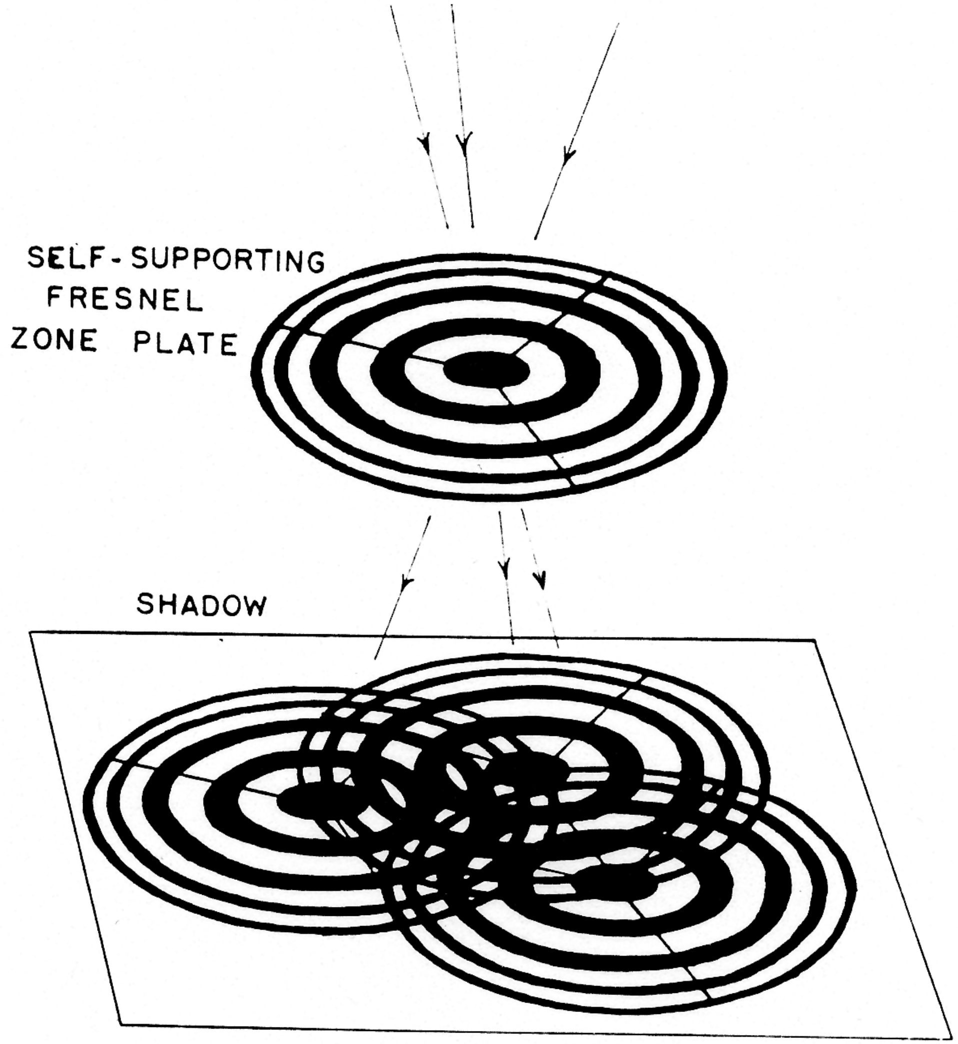
“Why is it that when the sun passes through quadilaterals, as for instance wickerwork, it does not produce a figure rectangular in shape but circular ?”

Aristotle,problemata physica - problem XV,6

“Why is it that in an eclipse of the sun, if one looks at it through a sieve or through leaves, such as a planetree or other broad leaved tree, or if one joins of one hand over the fingers of the other, the rays are crescent-shaped where they reach the earth ? Is it for the same reason as that when light shines through a rectangular peep-hole, it appears circular in the form of a cone ? The reason is that there are two cones, one from the sun to the peephole and the other from the peep-hole to the earth, and the vertices meet ..."

Aristotle, problemata physica - problem XV,11

“X-ray star camera”

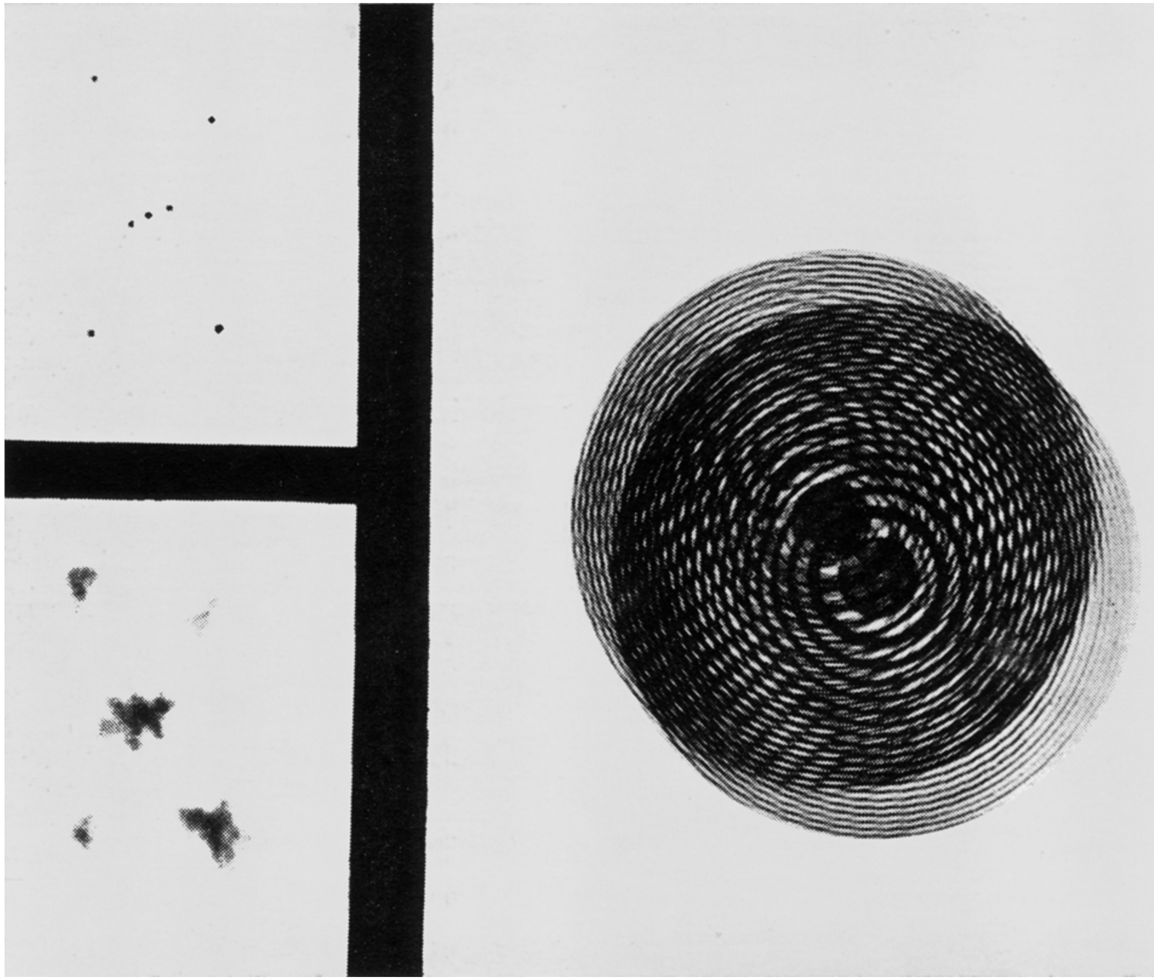


Fresnel Zone Plate = Mask

⇒ Shadowgram = Hologram

Mertz & Young, 1961

“Illustrative sample of optical Fresnel transformation”



Mertz and Young’s demo of the principle using visible light :

upper left : source

illuminated pinholes simulate the n stars

right : hologram

a Fresnel zone plate casts n distinct shadows

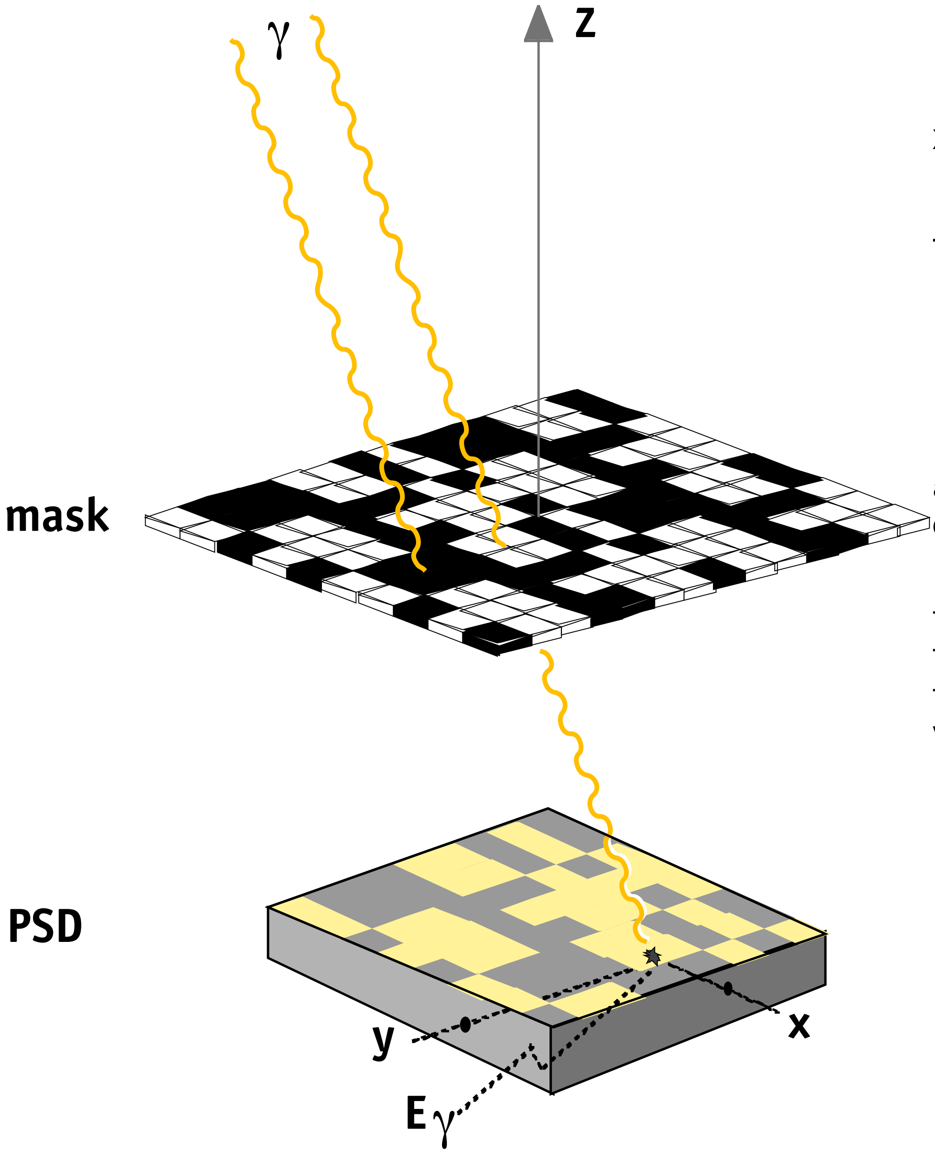
lower left : image

reconstructed by

diffraction from a reduced copy of hologram

Mertz & Young, 1961

coded mask imaging



measured parameters :

x,y : int. location on the detector
Eγ : energy deposited
t : arrival time

astronomy : encoding of a two dimensional source distribution (i,j) into a 2-D dataspace (k,l)

for sources at finite distance (nuclear medicine, tomography of X-ray emitting plasmas) coded mask techniques can be used to extract depth information for volumetric object reconstruction.

coded mask imaging : *Encoding*

The intensity measured by the PSD can be expressed as a two-dimensional matrix $D_{i,j}$ (the shadowgram) presenting the number of interactions registered in the detector element *i,j.*

$$D_{k,l} = \sum_{i,j} S_{i,j} \cdot A_{i+k,j+l} + B_{k,l}$$

$S_{i,j}$: matrix of the source distribution,

$A_{i,j}$: aperture transmission function
(1 for transparent mask elements,
0 for opaque elements)

$B_{i,j}$: background noise matrix
(all contributions not modulated by the aperture)

coded mask imaging : *Decoding*

direct deconvolution :

correlate the encoded matrix D with decoding array G (postprocessing array)

$$S'_{i,j} = \sum_{k,l} D_{k,l} \cdot G_{i+k,j+l}$$

Substituting the encoded matrix D results in

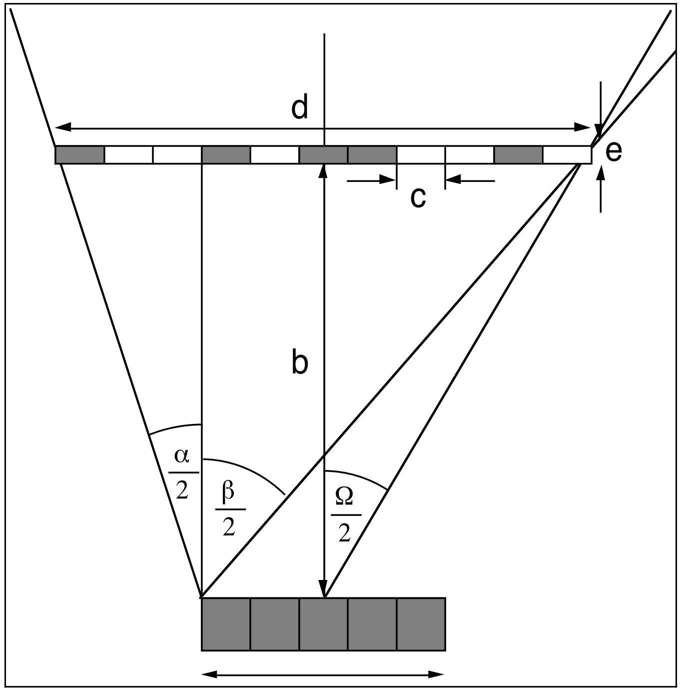
$$S' = (S * A) * G + B * G$$

A*G is the point spread function (PSF). Optimal mask patterns produce delta function $A*G \equiv \delta$

$$S' = S + B * G$$

=> source is perfectly reconstructedd with the exception of a background term.

Field of view characteristics of a coded mask instrument



FOV (FWHM) $\Omega = 2 \text{ arctg } \frac{d}{2b}$

fully coded FOV $\alpha = 2 \text{ arctg } \frac{d-a}{2b}$

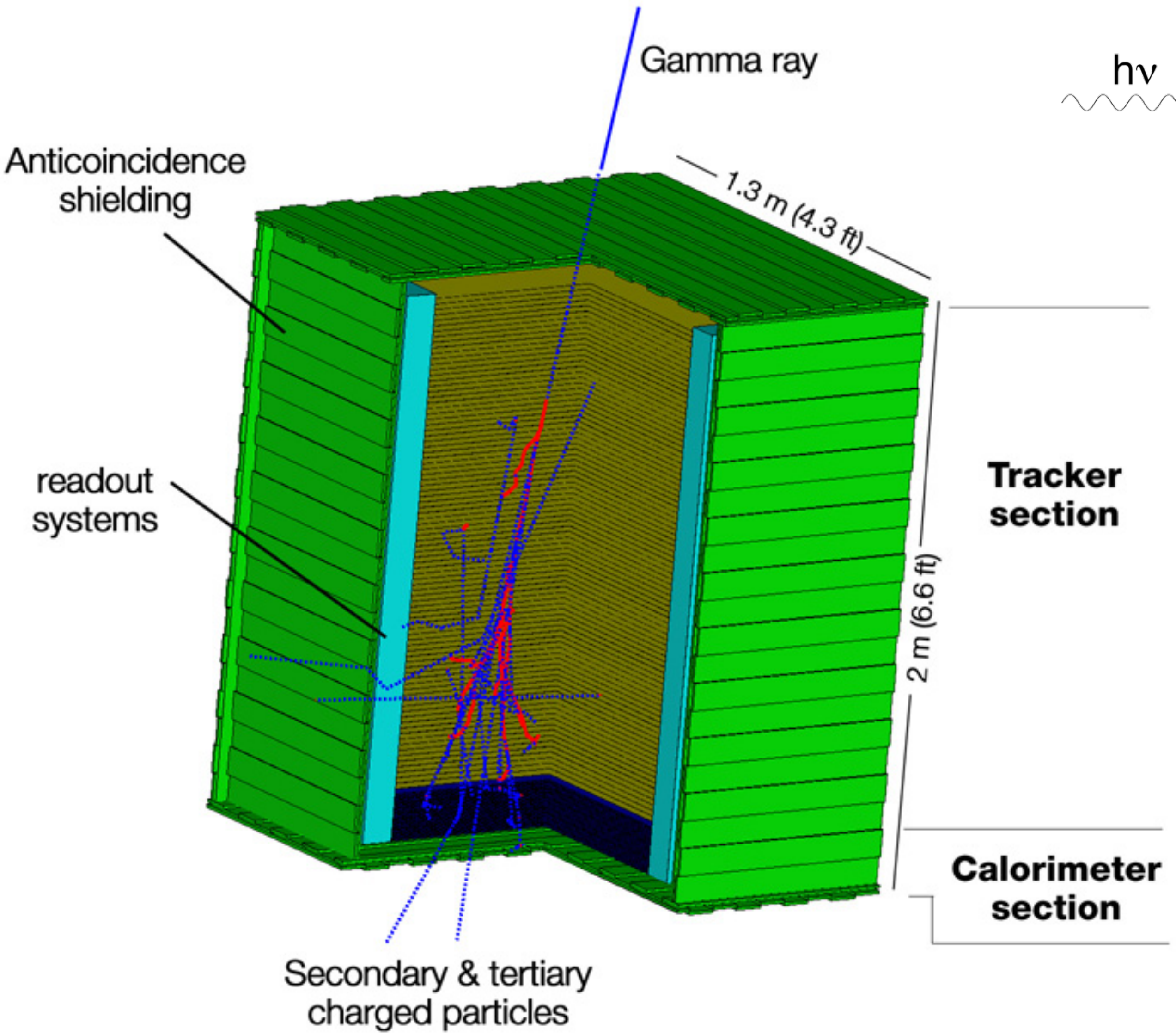
partially coded FOV $\beta = 2 \text{ arctg } \frac{a+d}{2b}$

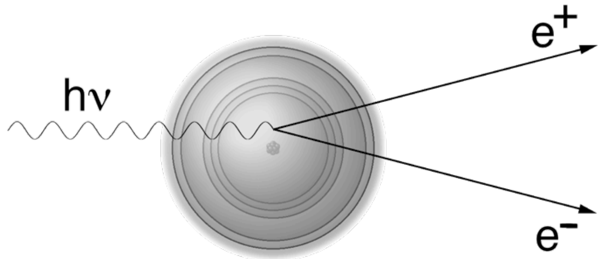
angular resolution $\Delta\theta = r \; \Delta\theta'$

$= r \text{ arctg } \frac{c}{b}$

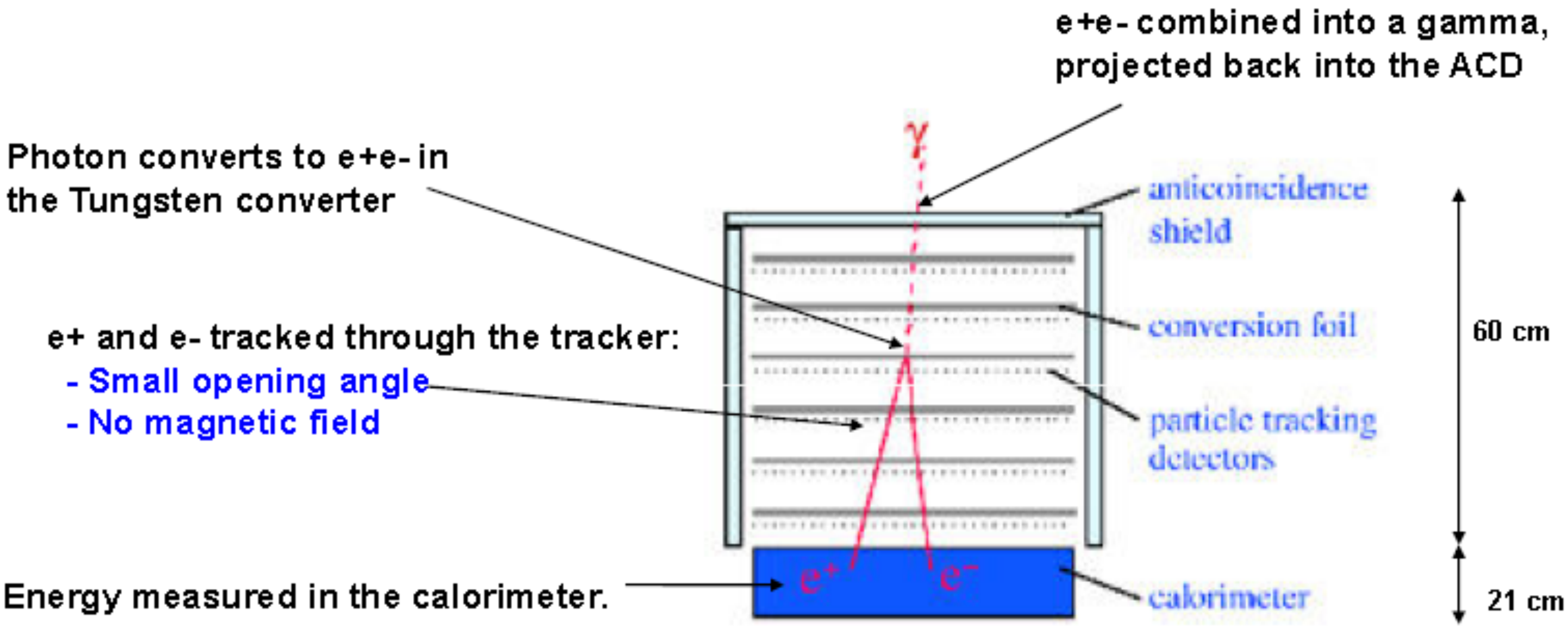
vignetting e,b, z from z axis

pair-conversion telescope (tracker and calorimeter)

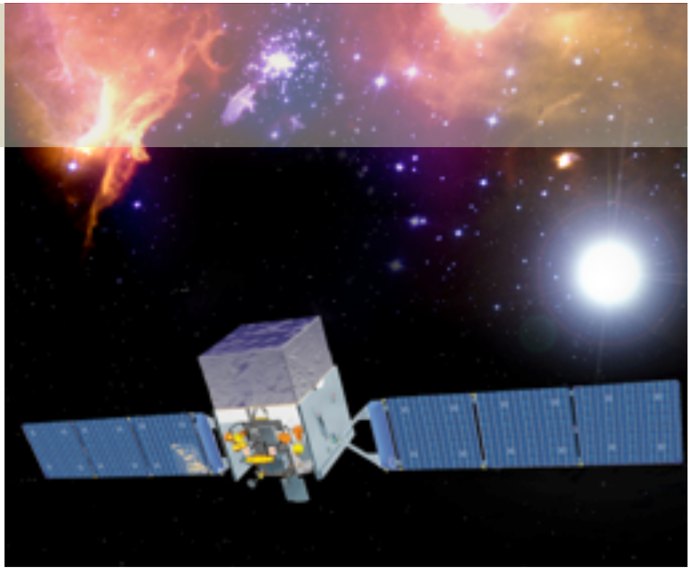


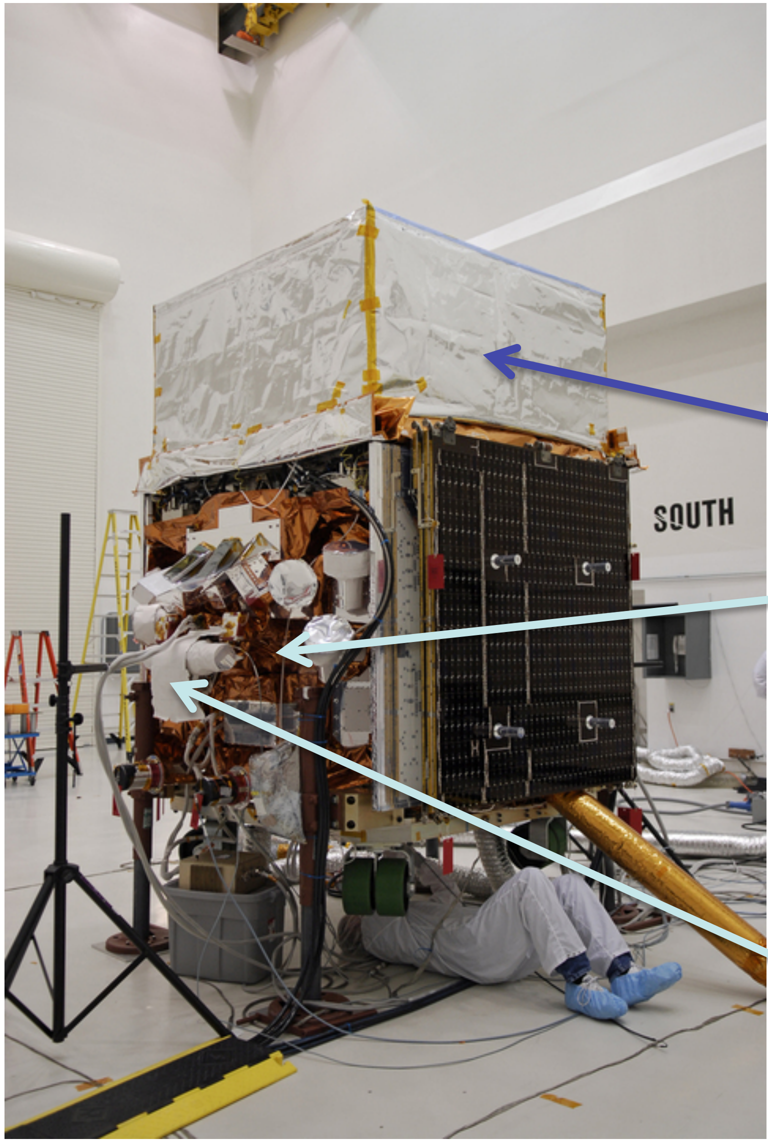


pair-conversion telescope (tracker and calorimeter)



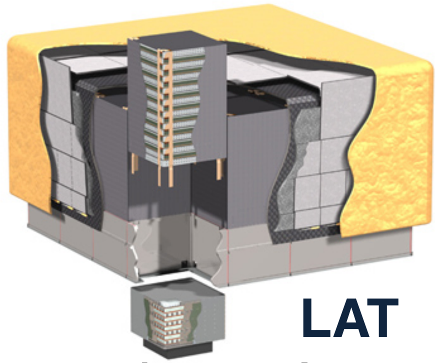
FERMI





GBM NaI (x12)
8 keV – 1 MeV
-Burst triggering
-Localization
-Spectroscopy

GBM BGO (x2)
150 keV – 30 MeV
- Spectroscopy

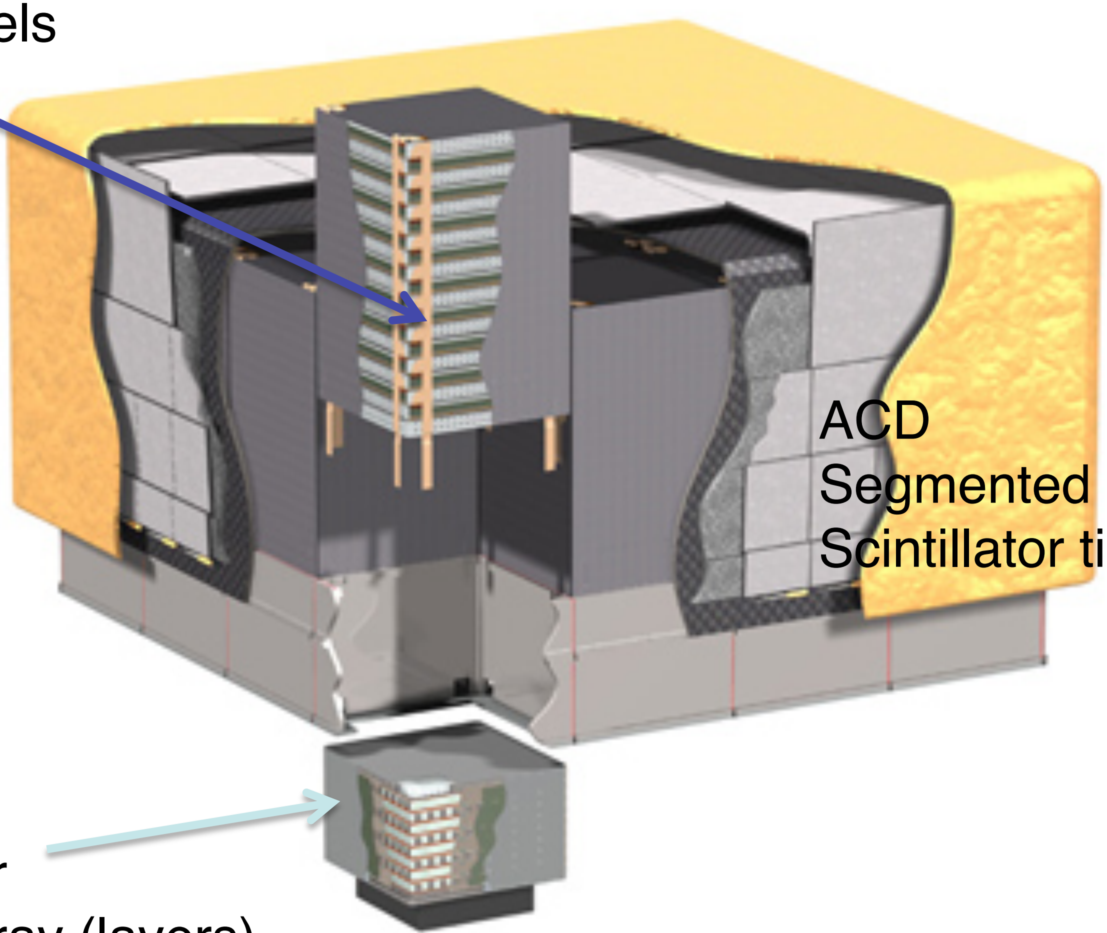


LAT
Large Area
Telescope
0.1– 300 GeV

LAT

LAT : 4 x 4 modular structures
3000 kg, 650 W, 20 MeV – 300 GeV

Si Tracker
pitch=228μm
8,8 10^5 channels
18 planes

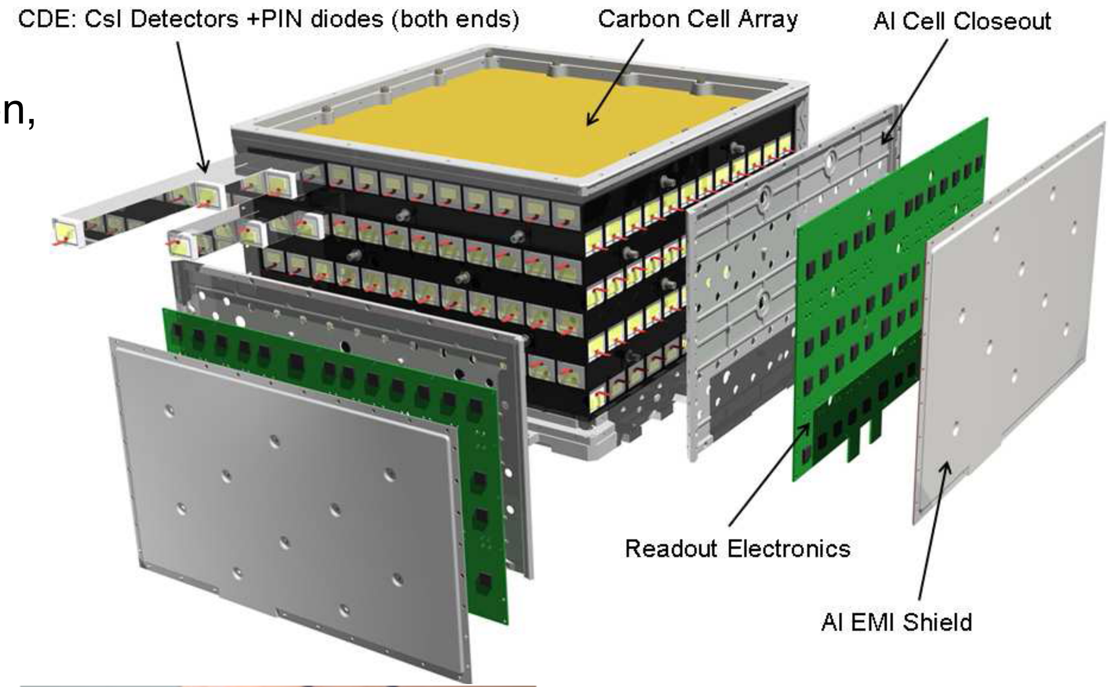


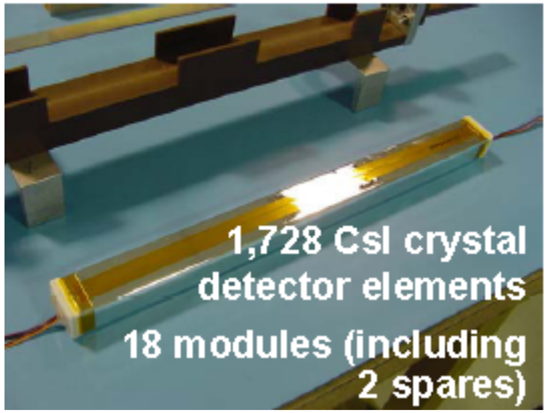
ACD
Segmented
Scintillator tiles

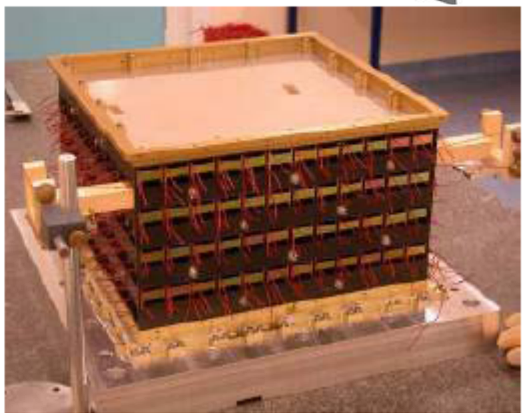
CsI calorimeter
Hodoscopic array (layers)
6,1 10^3 channels

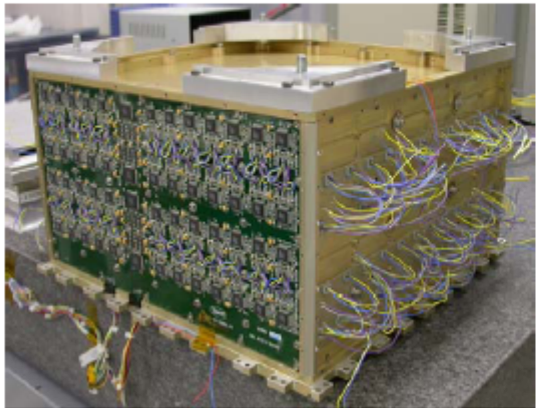
LAT-Calorimètre

Team effort involving the France (IN2P3 & CEA), Sweden, and the United States





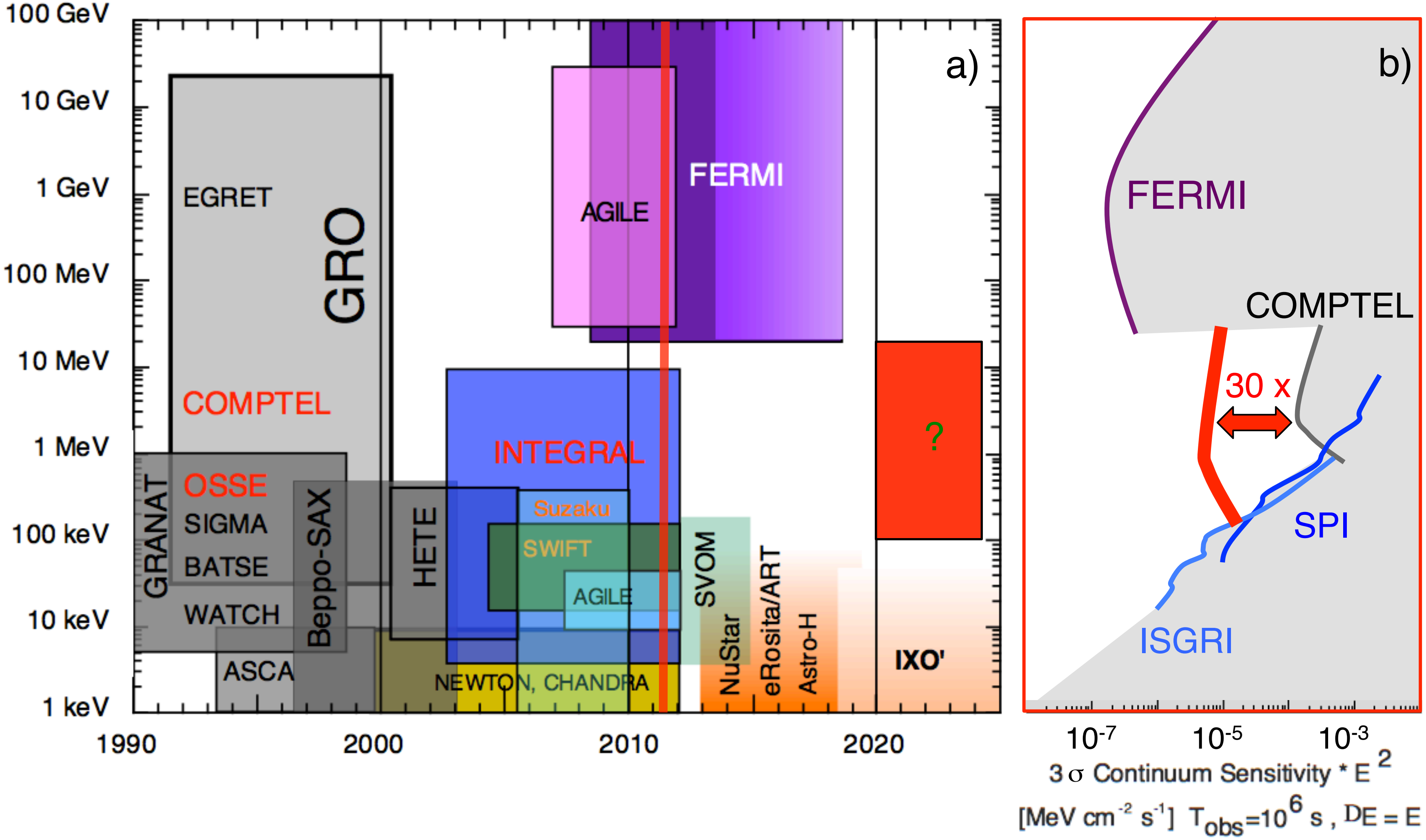




Les satellites gamma

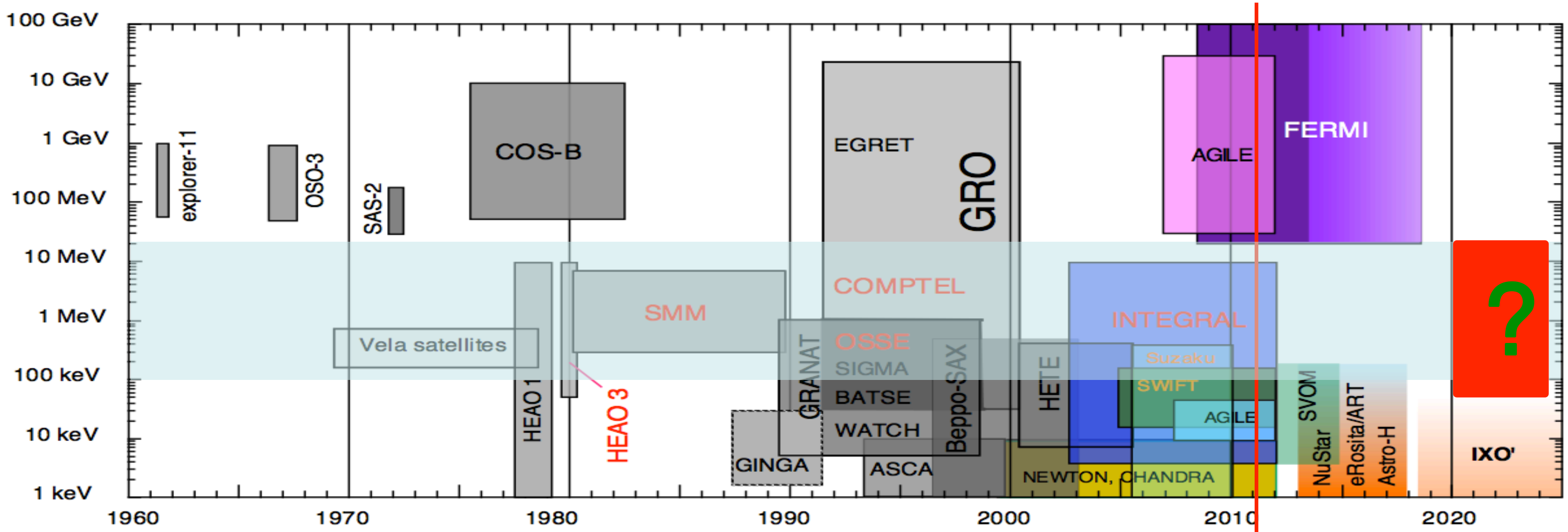
Instrument	EGRET	AGILE	GLAST
Lancement	1991	2006	2008
Domaine d'énergie	2 MeV-30 GeV	30 MeV-50 GeV	20 MeV-300 GeV
Trajectographe	Chambre à étincelles	Pistes de silicium + W (14 pl.)	Pistes de silicium + Pb (18 pl.)
Calorimètre	NaI (Tl) 8.5 X_0	CsI (Tl) 1.5 X_0	CsI (Tl) 8 X_0
Surface effective de détection	1200 cm^2 à 1 GeV	700 cm^2 à 1 GeV	10 000 cm^2 à 10 GeV
Domaine d'énergie	2 MeV-30 GeV	30 MeV-50 GeV	10 MeV-300 GeV
Champ de vue	0.20 stérad.	2 stérad.	2.4 stérad.
Résolution angulaire	1.5° à 1 GeV	0.6°	0.12° à 10 GeV 4° à 100 MeV
Localisation de la source	5' to 10 '	30 ' à 300 MeV	0.4 '
ΔE/E	10 %	100 %	10 %

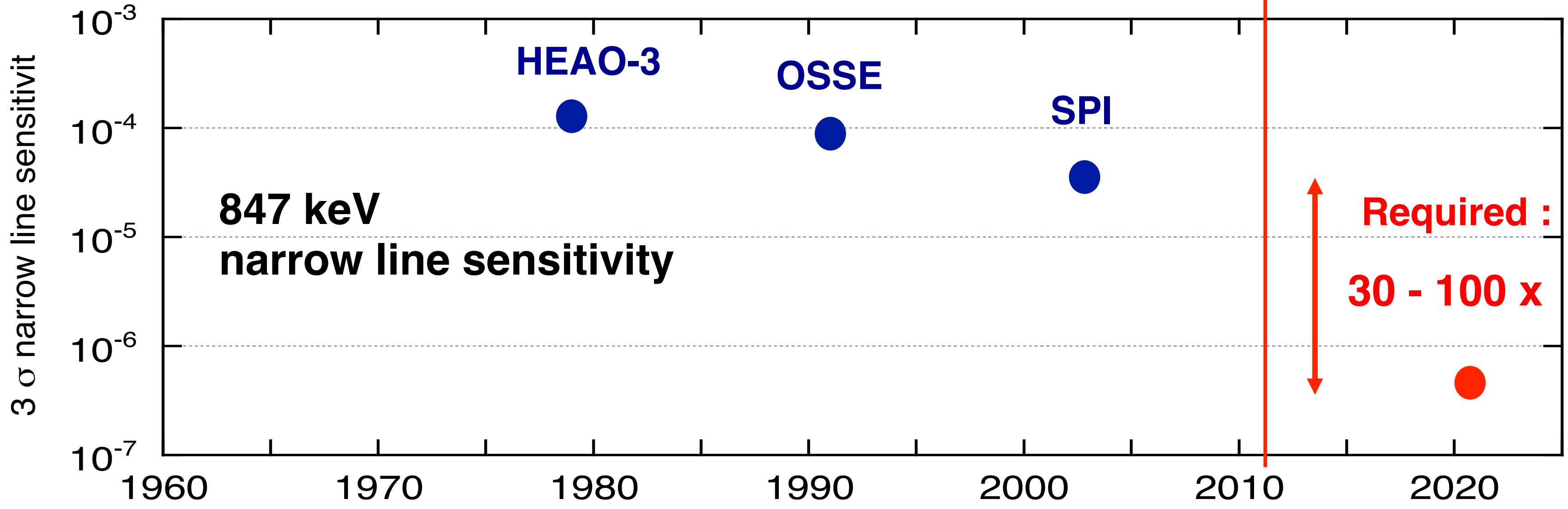
roadmap of space-borne high-energy astrophysics



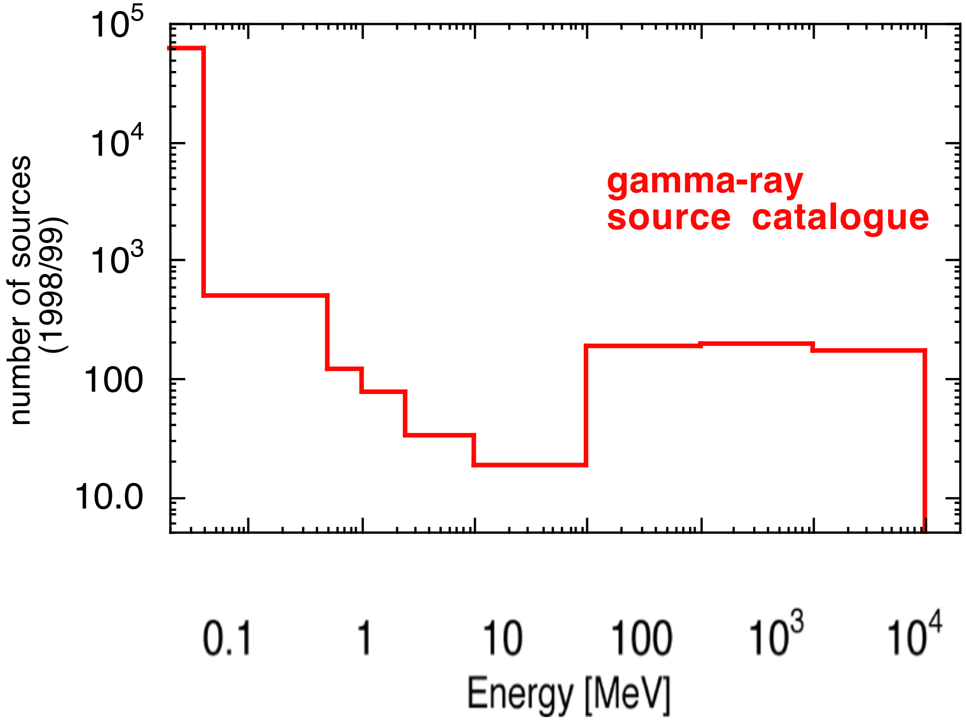
Post-INTEGRAL aera : a white spot on the high-energy astrophysics roadmap

requirements for a future gamma-ray mission

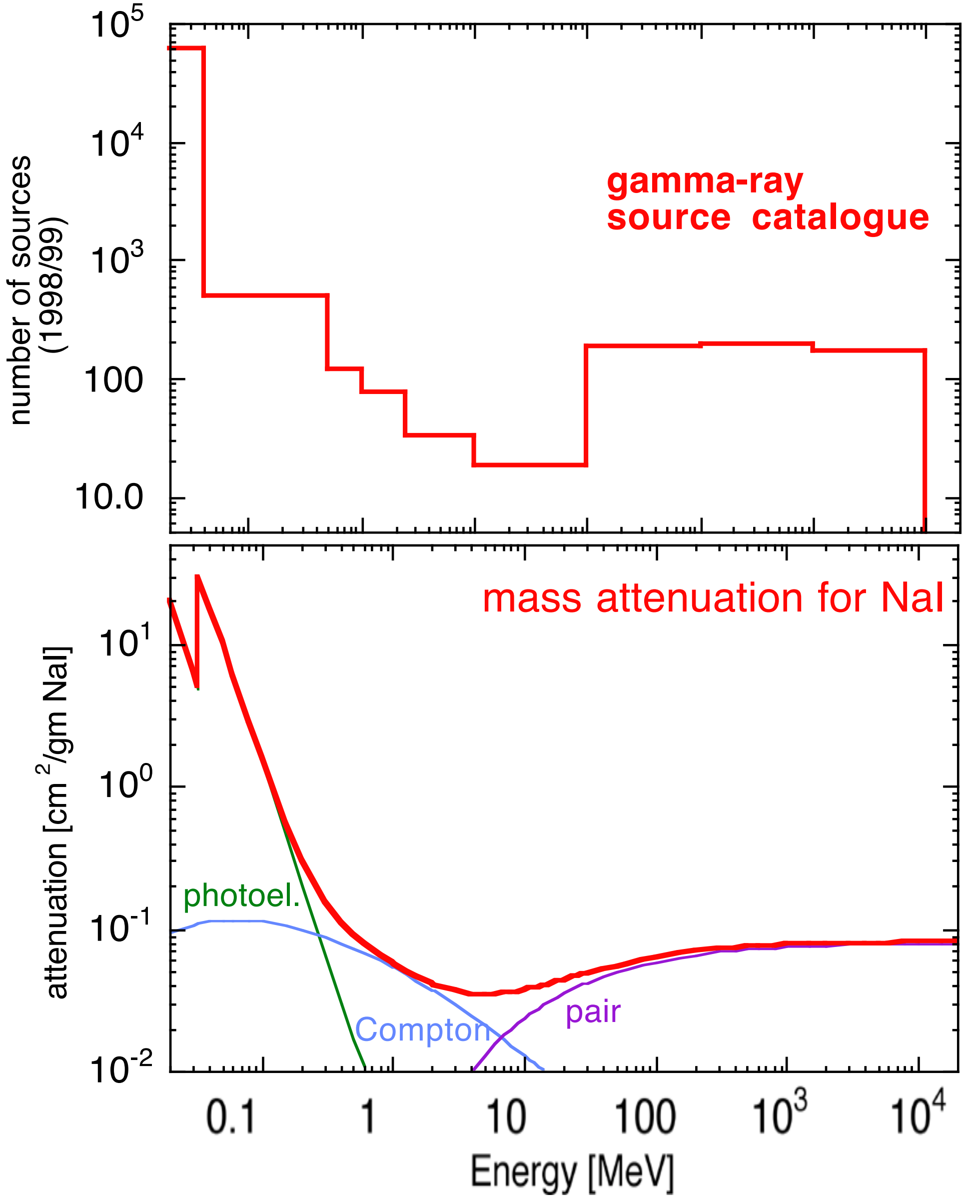




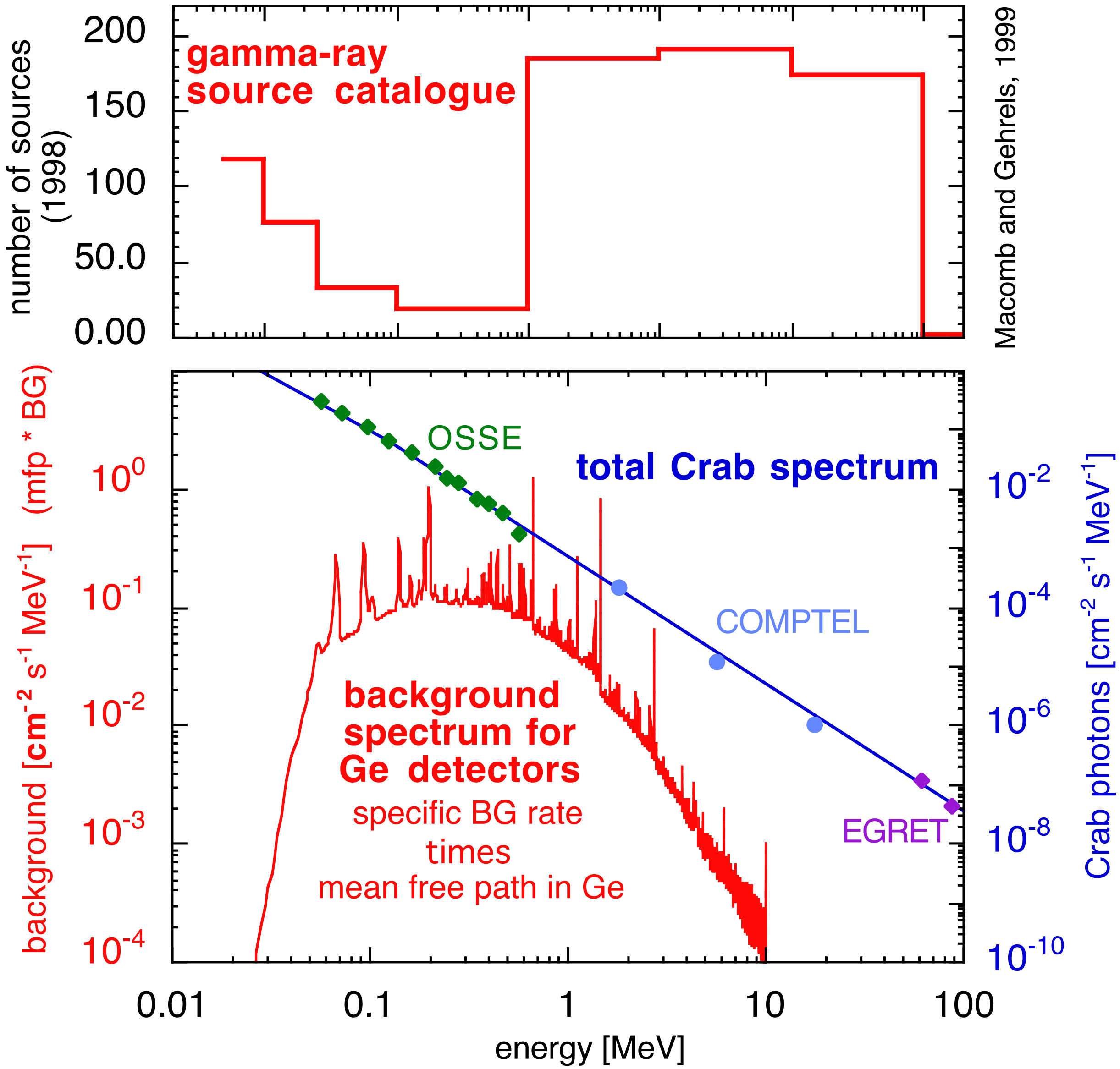
Gamma-ray source statistics



Gamma-ray source statistics



Gamma-ray source statistics



Requirements for a future gamma-ray mission

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

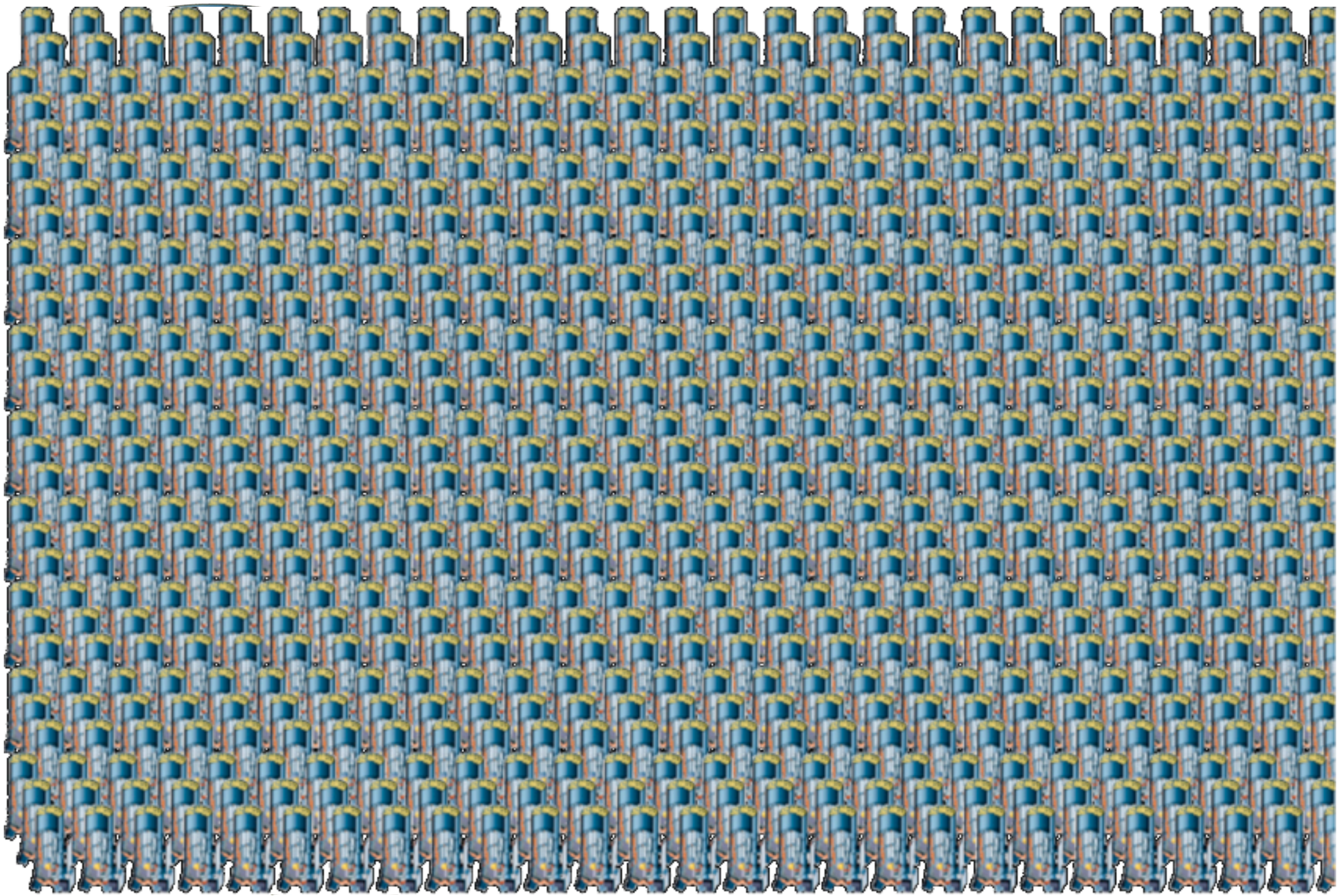
$f_{3\sigma} < 5 \cdot 10^{-7}\ s^{-1} \cdot cm^{-2}$!

You must be kidding

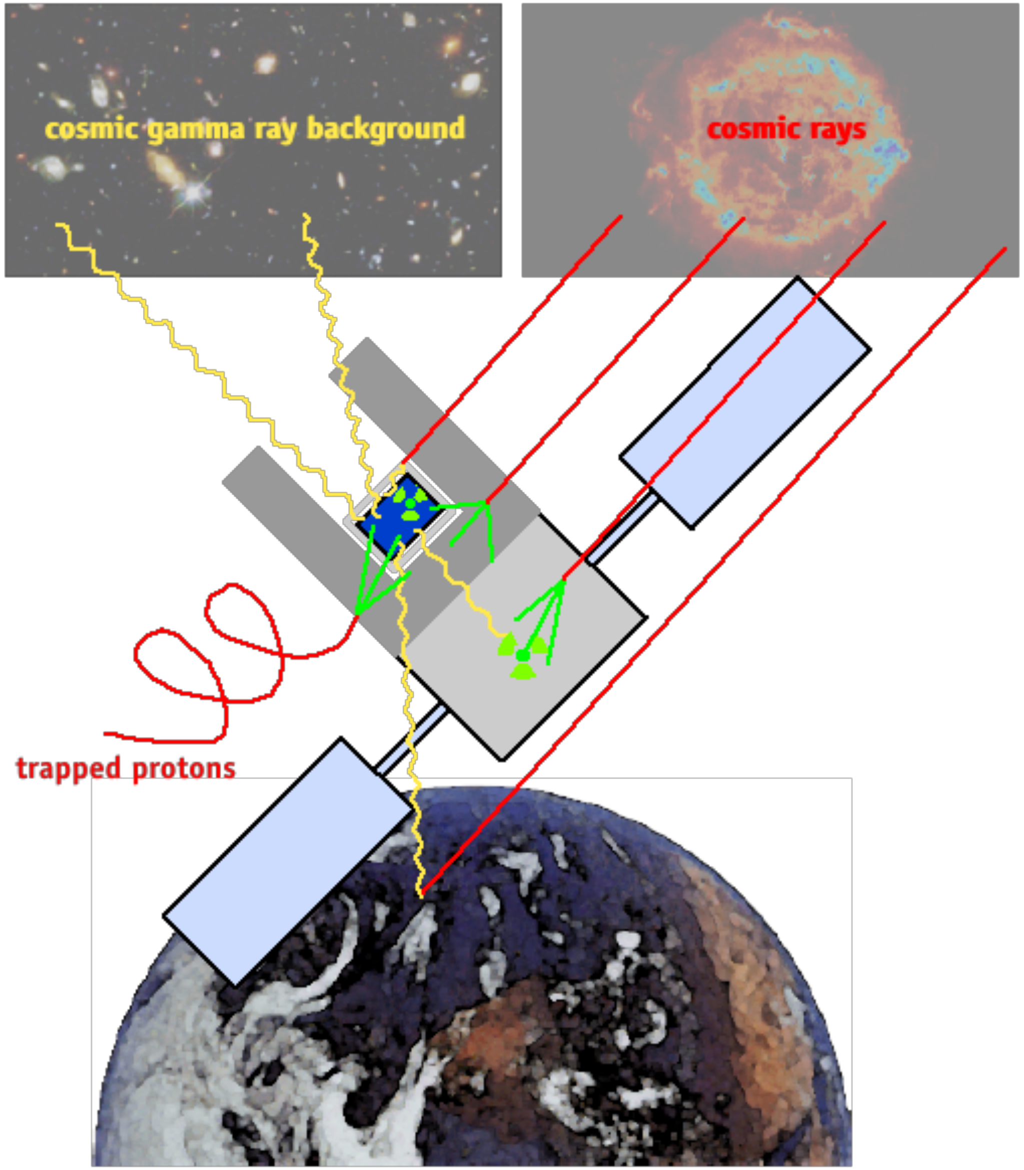
This means detecting one photon per cm^2 and month

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

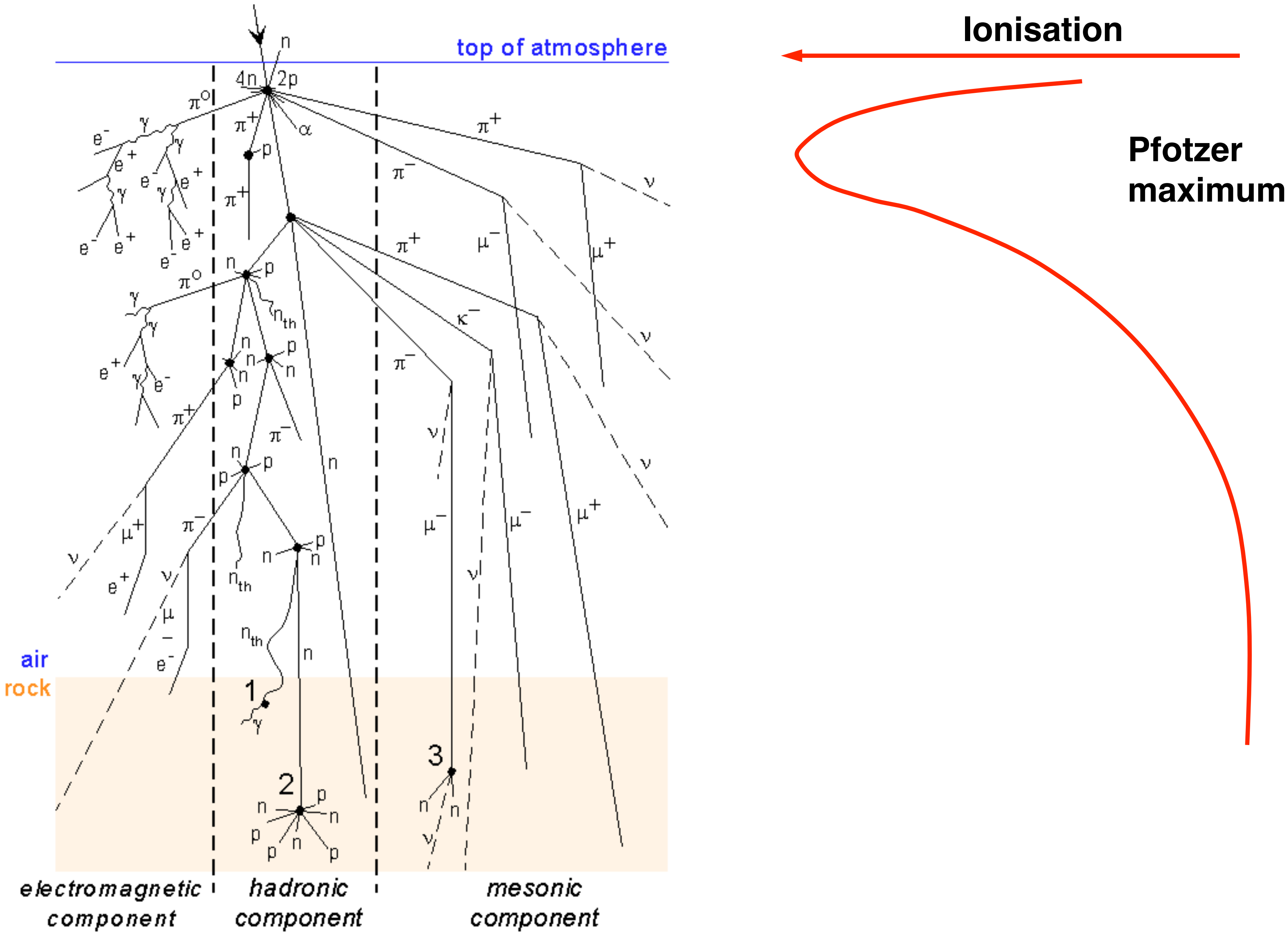
Requirements for a future gamma-ray mission



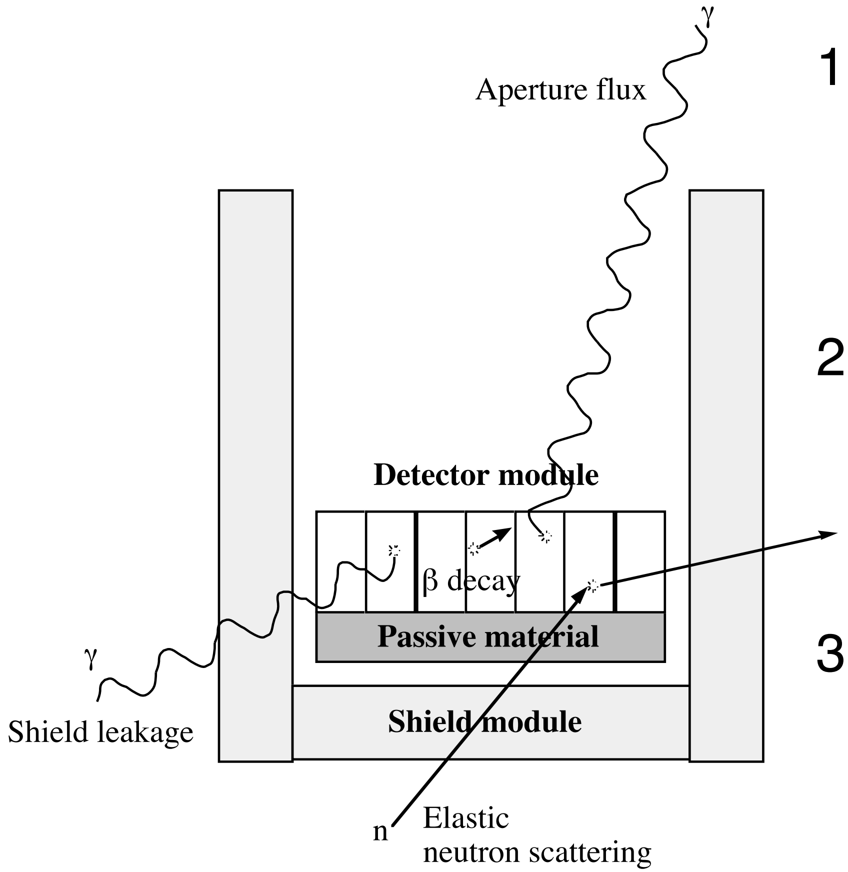
HE Background



Cosmic Ray interactions and γ-ray background



satellite and balloon background



1 *Aperture flux*

- atmospheric gamma rays
- diffuse cosmic gamma rays

2 *Elastic neutron scattering*

signal from recoil of the a detector nuclei (produced by nuclear interactions of CR...)

3 - *Shield leakage*

gamma rays penetrate the shield without triggering the shield anticoincidence

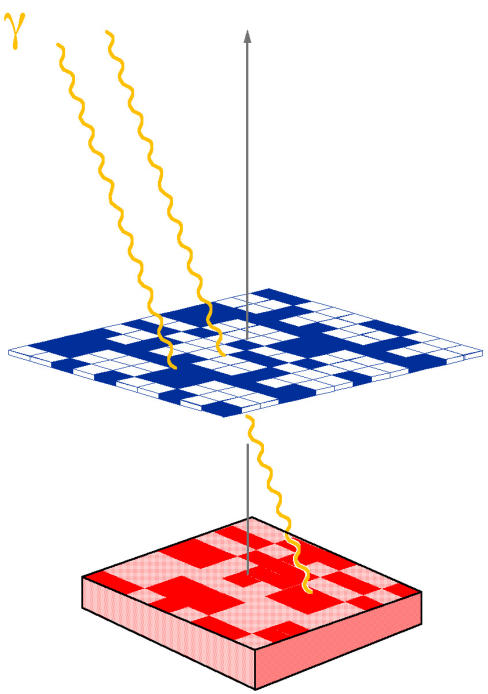
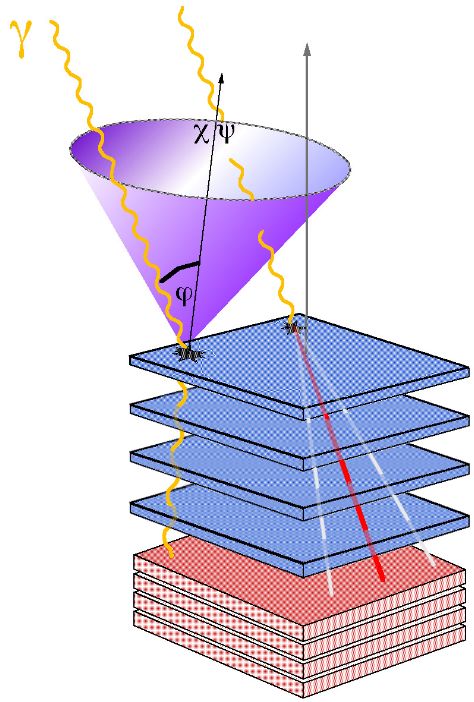
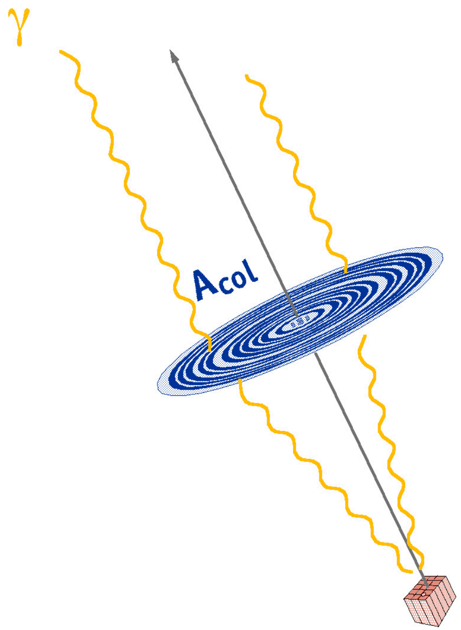
4 *Beta decays*

incident neutrons and protons interact with

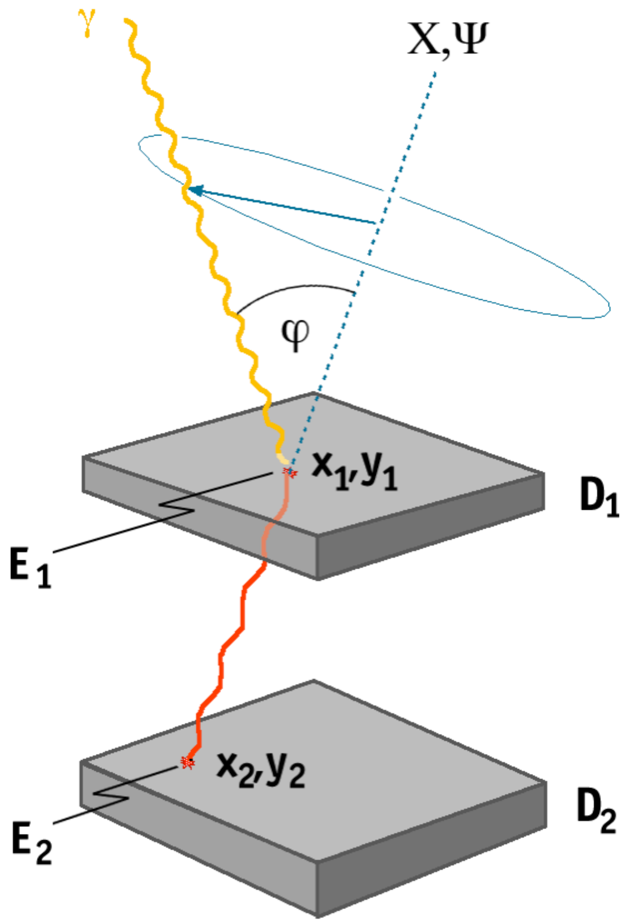
the detector nuclei to produce beta-unstable nuclides. not prompt

Instrument concepts in 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			
	ex. coded masks "on-off" collimators	ex. Compton telescopes tracking chambers	ex. Laue lenses Fresnel lenses

Quantum Optics : e.g. 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

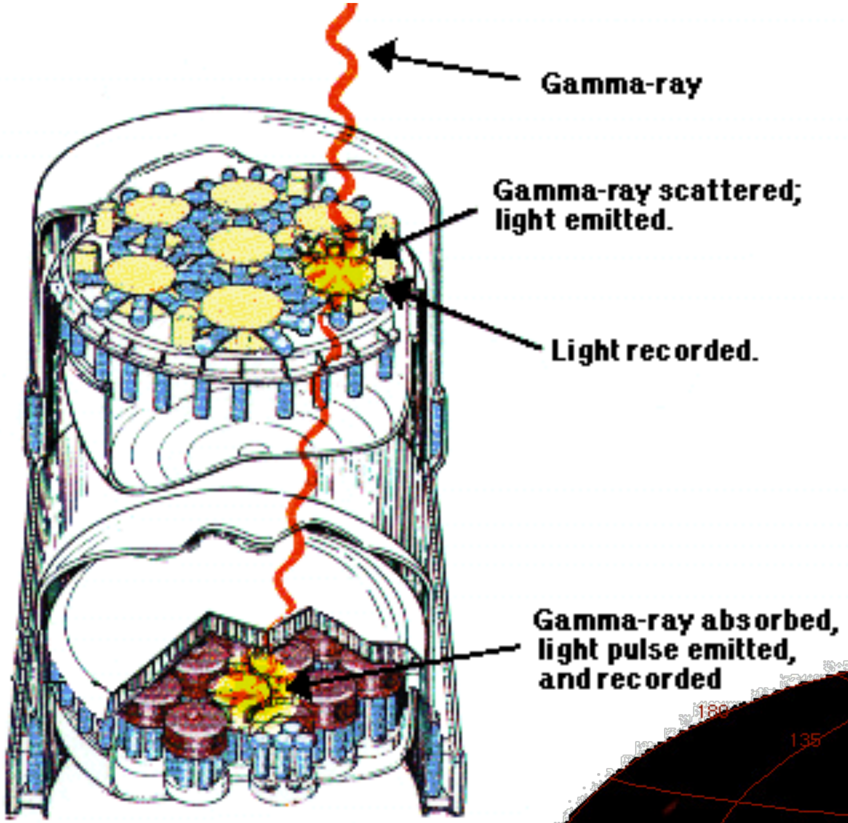
E_1,E_2 => $\bar{\varphi}$

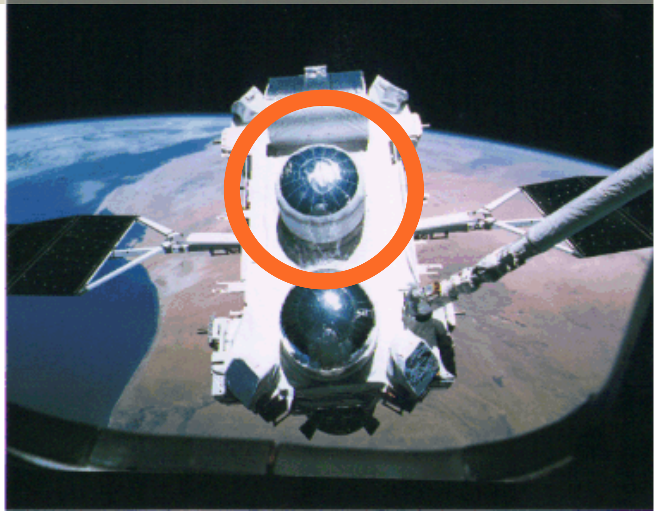
$\cos \bar{\varphi} = 1 - m_e c^2/E_2 + m_e c^2/E_1+E_2$

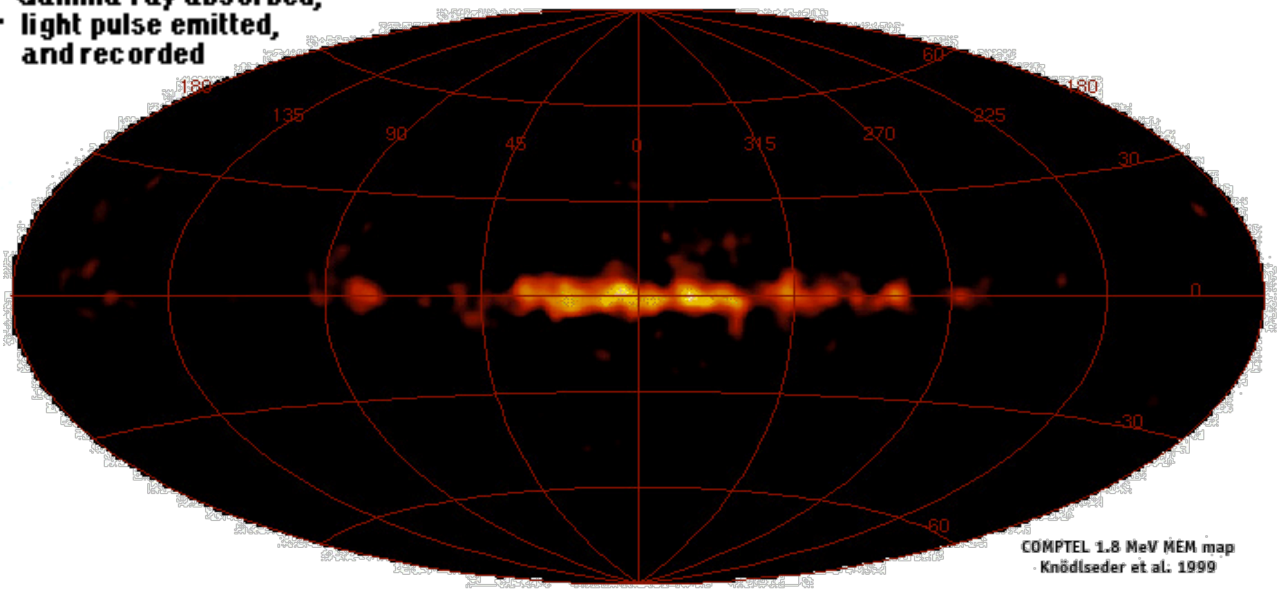
encoding of the two dimensional source distribution into a 3-D dataspace ($\mathbf{X}, \mathbf{\Psi}, \varphi$)

Compton telescope

GRO - COMPTEL







COMPTEL 1.8 MeV MEM map
Knödlseder et al. 1999

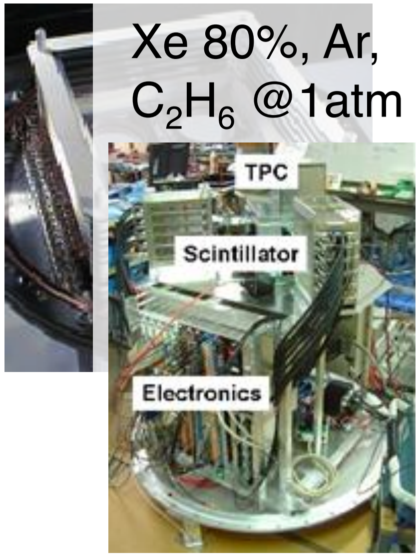
Balloon flights of new generation Compton telescopes

LXeGRIT
1997, 1999, 2000

liquid Xe TPC

Kyoto Univ.
2006

Xe 80%, Ar, C_2H_6 @1atm

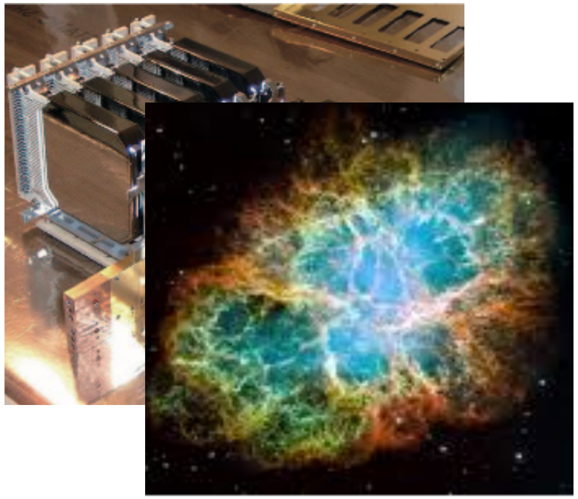


TIGRE
2007, 2010

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

NCT
2005, 2009

Ge strip detectors



2009 : Crab detection

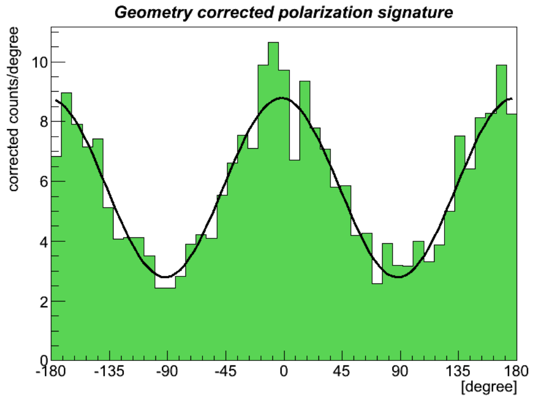
Development of a small balloon-borne telescope

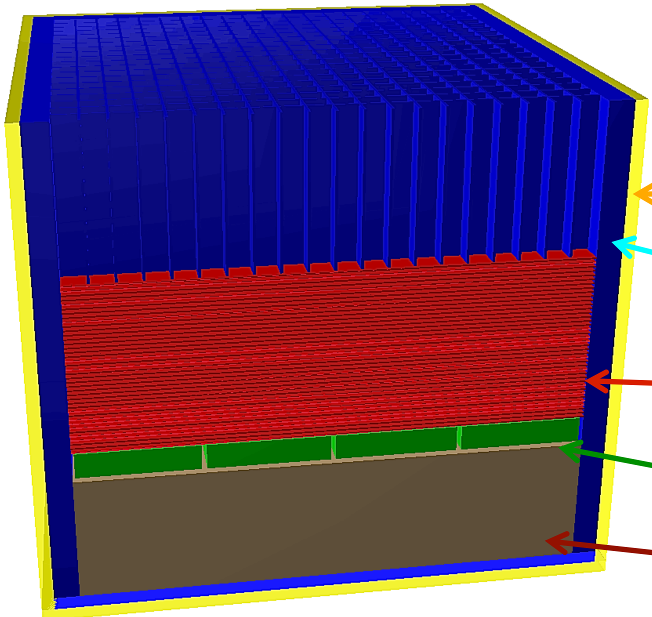
GEANT 4 LOI at 662 keV : 1.69 mm (Tatischeff et al. 2011)

•Midterm project (→ 2016)

• Goal #1: to reach a high technology readiness level for DSSDs (bonding, ASIC…) and $LaBr_3$ imaging modules

• Goal # 2: to measure the polarizati between ~100 and ~400 keV





←Plastic ACS ⇒ APC

Collimator in Ta

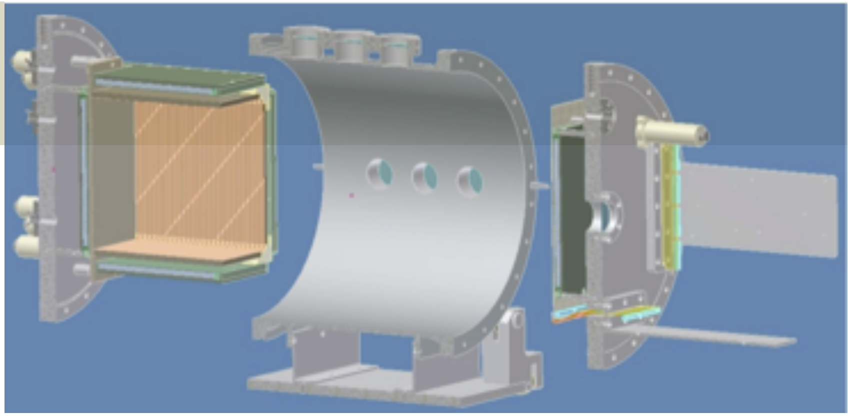
Si (DSSDs) tracker ⇒ APC + IPNO

$LaBr_3$ modules ⇒ CSNSM

Electronics ⇒ Irfu, CSNSM, APC

+ balloon overall system: IRAP (Toulouse), APC

HARPO



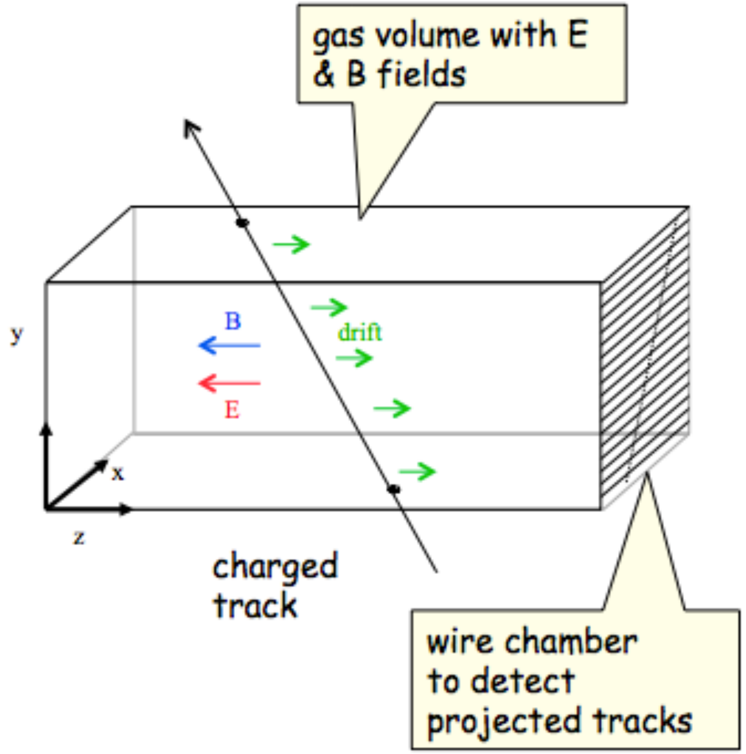
Laboratoire Leprince-Ringuet /
IN2P3 & CEA-DSM / IRFU

Novel concept for a γ-ray detector based on a TIME PROJECTION CHAMBER :

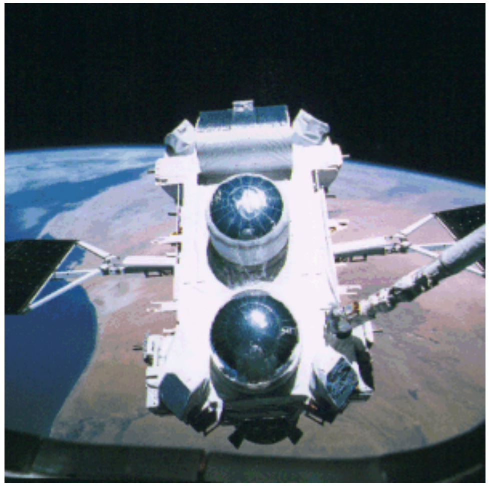
first polarimeter for cosmic γ rays in the MeV - GeV energy range
(angular properties of triplet conversion events reconstructed in the TPC)

Gas E.g.: Xe, Ar (+ % CH_4)
E-field **E** ~ 100 to 200 V/cm
B-field (big to measure momentum)
Wire chamber

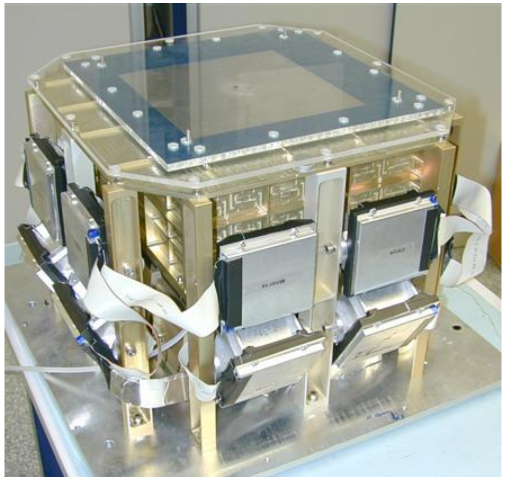
Track points recorded in 3-D
Particle Identification by dE/dx
Large track densities possible



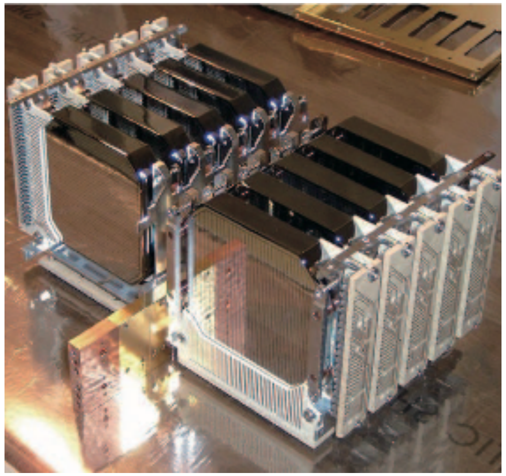
The development of Compton Telescopes



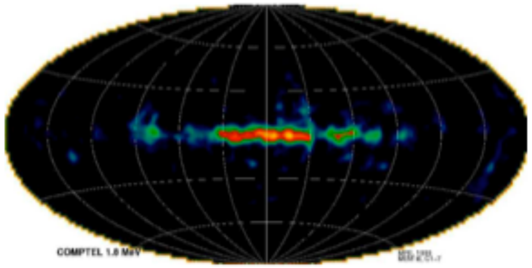
COMPTEL 1991-1999
first ^{26}Al all-sky map

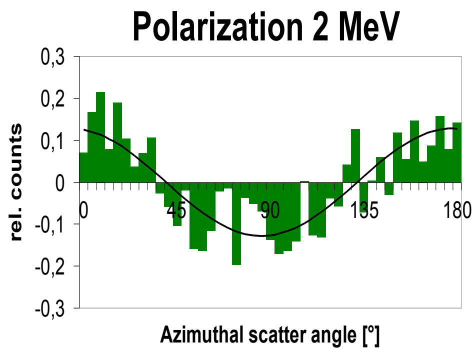


MEGA/MEGA balloon
Si tracker / CT



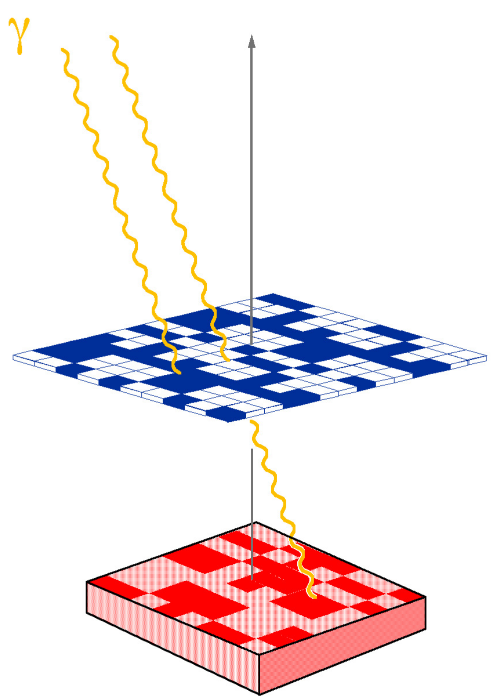
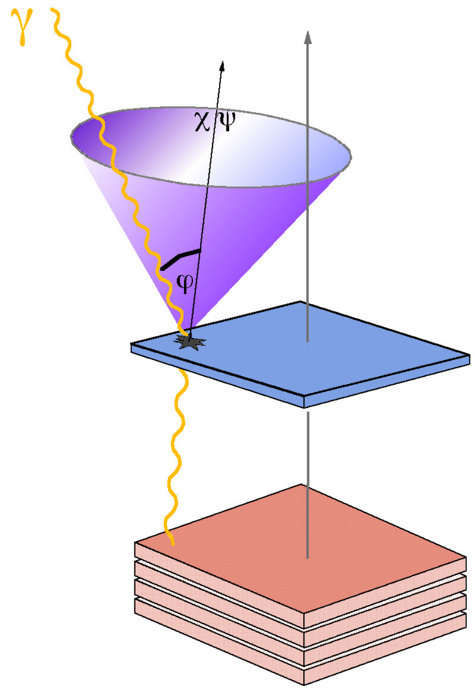
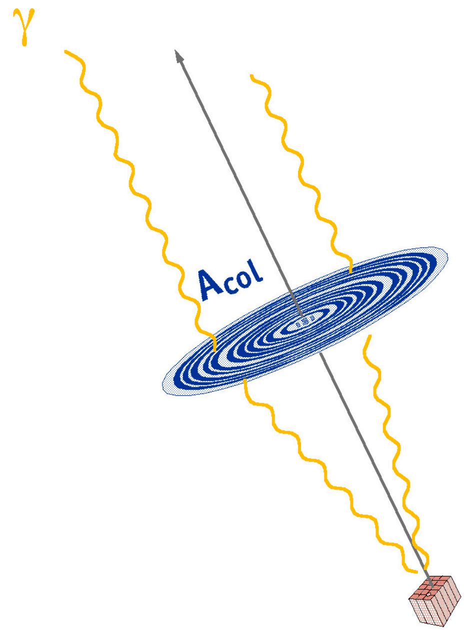
NCT Ge stack
balloon flight 2009



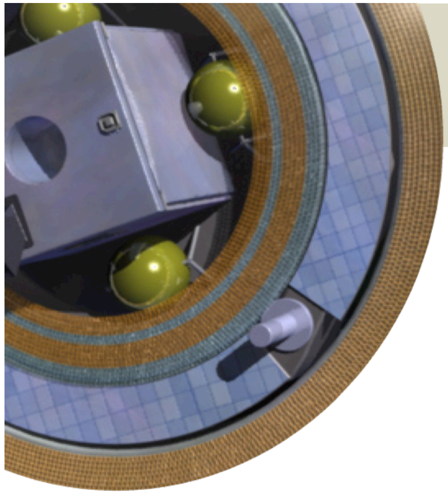


Instrument concepts in nuclear gamma-ray astronomy

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} ~ $\mathbf{A_{det}} \ll \mathbf{A_{col}}$


CLAIRE
first light for a gamma-ray lens



How to focus Gamma-rays : Laue lenses

Bragg condition for Cu [111] planes

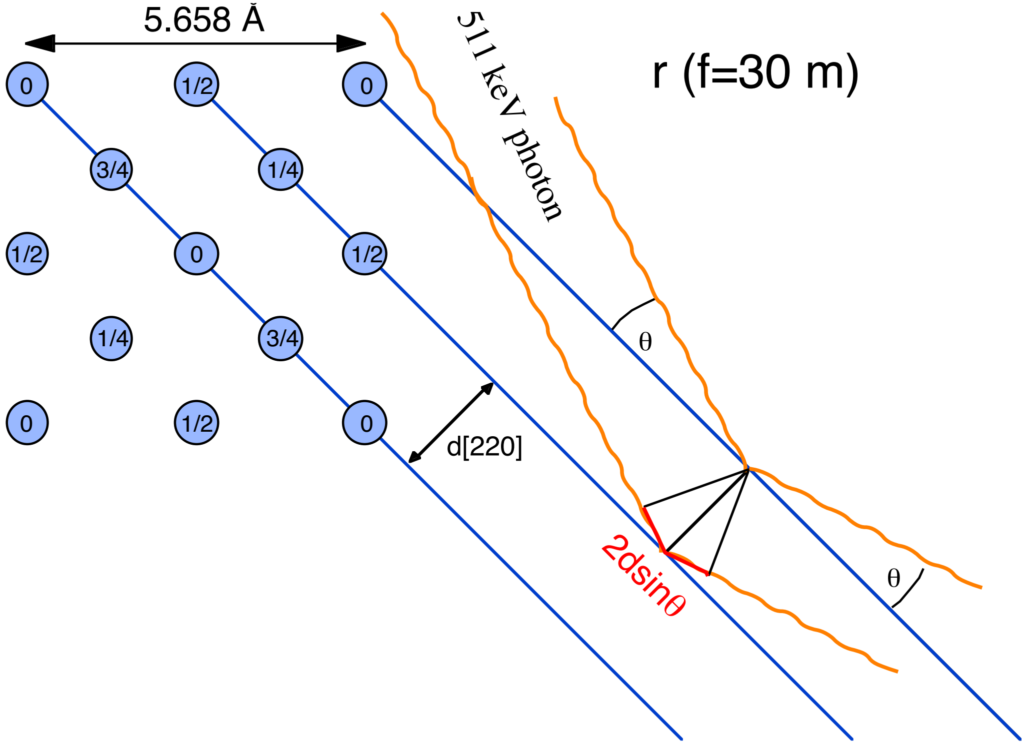
$2d\sin\theta = n\lambda$

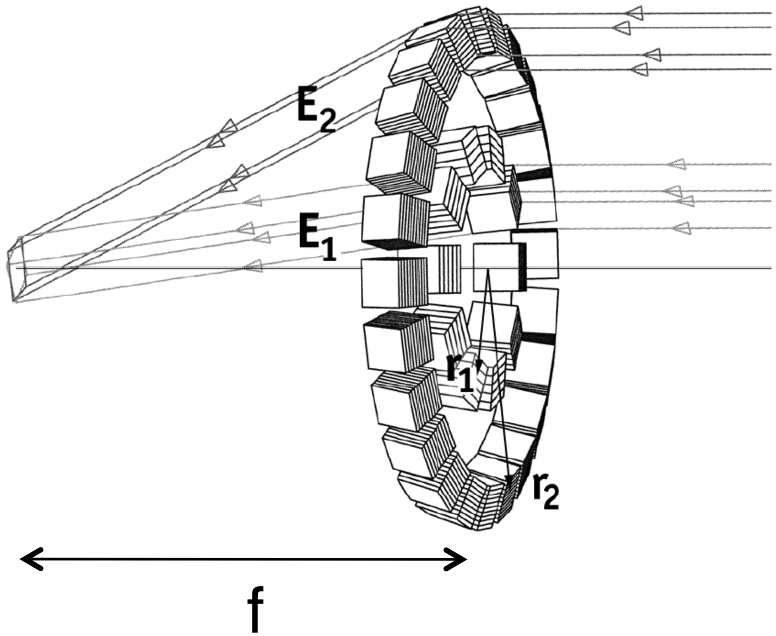
d [111] = 2.08 Å

λ (847 keV) = $1.46 \cdot 10^{-2}$ Å

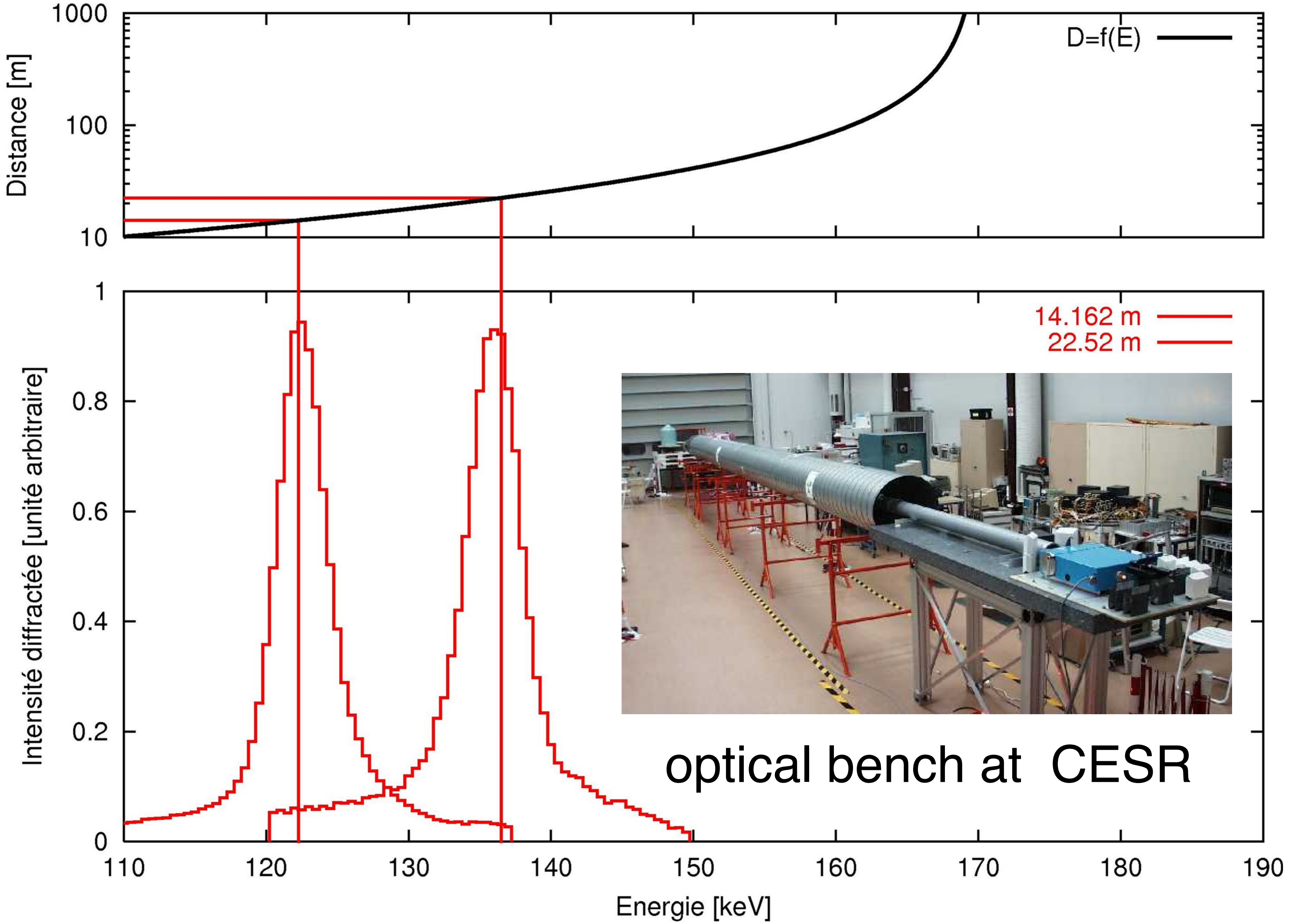
$2\theta = 2 \arcsin(\lambda/2d)$ = 0.40°

r (f=30 m) = 21 cm

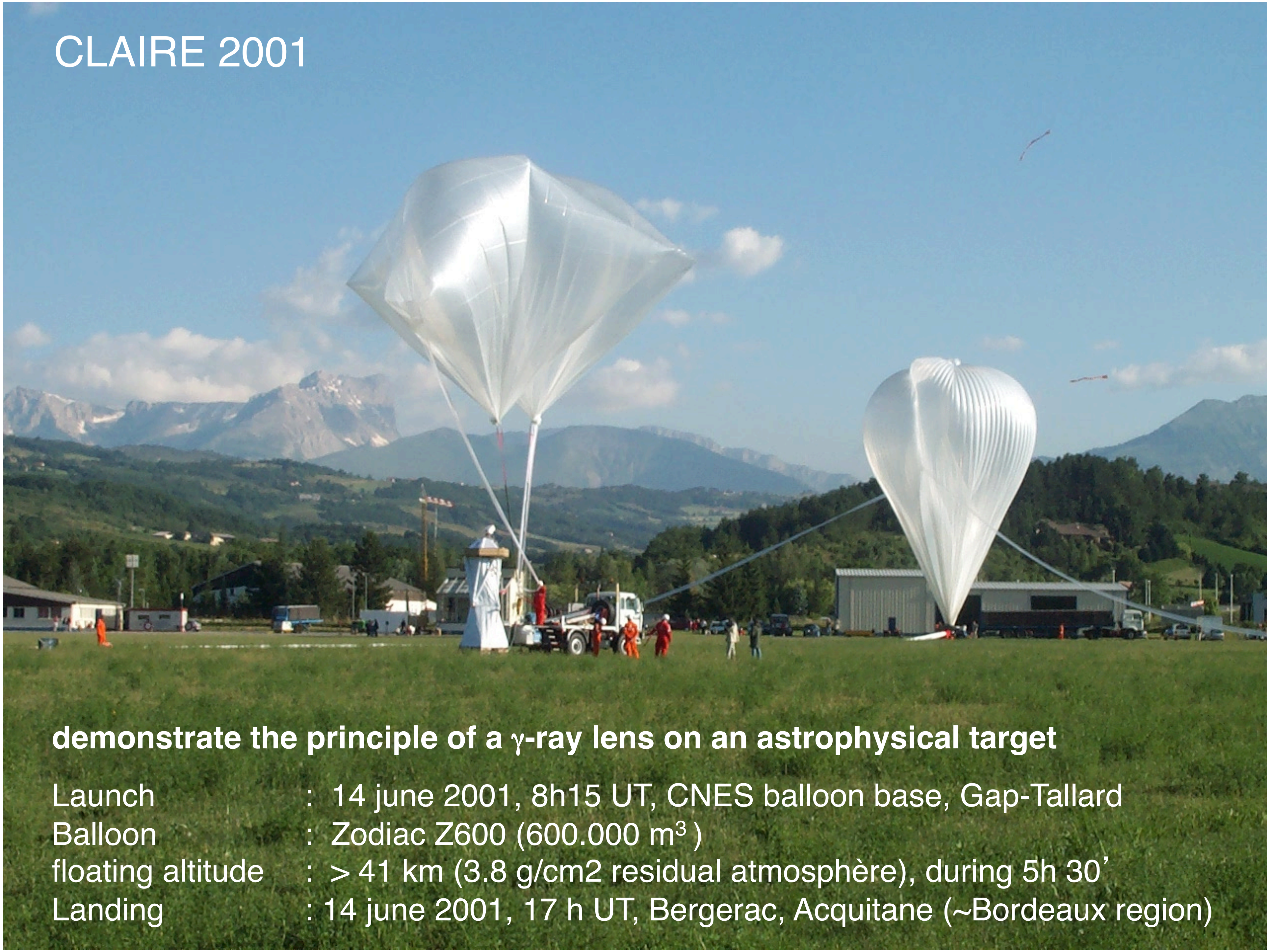




CLAIRE : tests in the lab ... and beyond



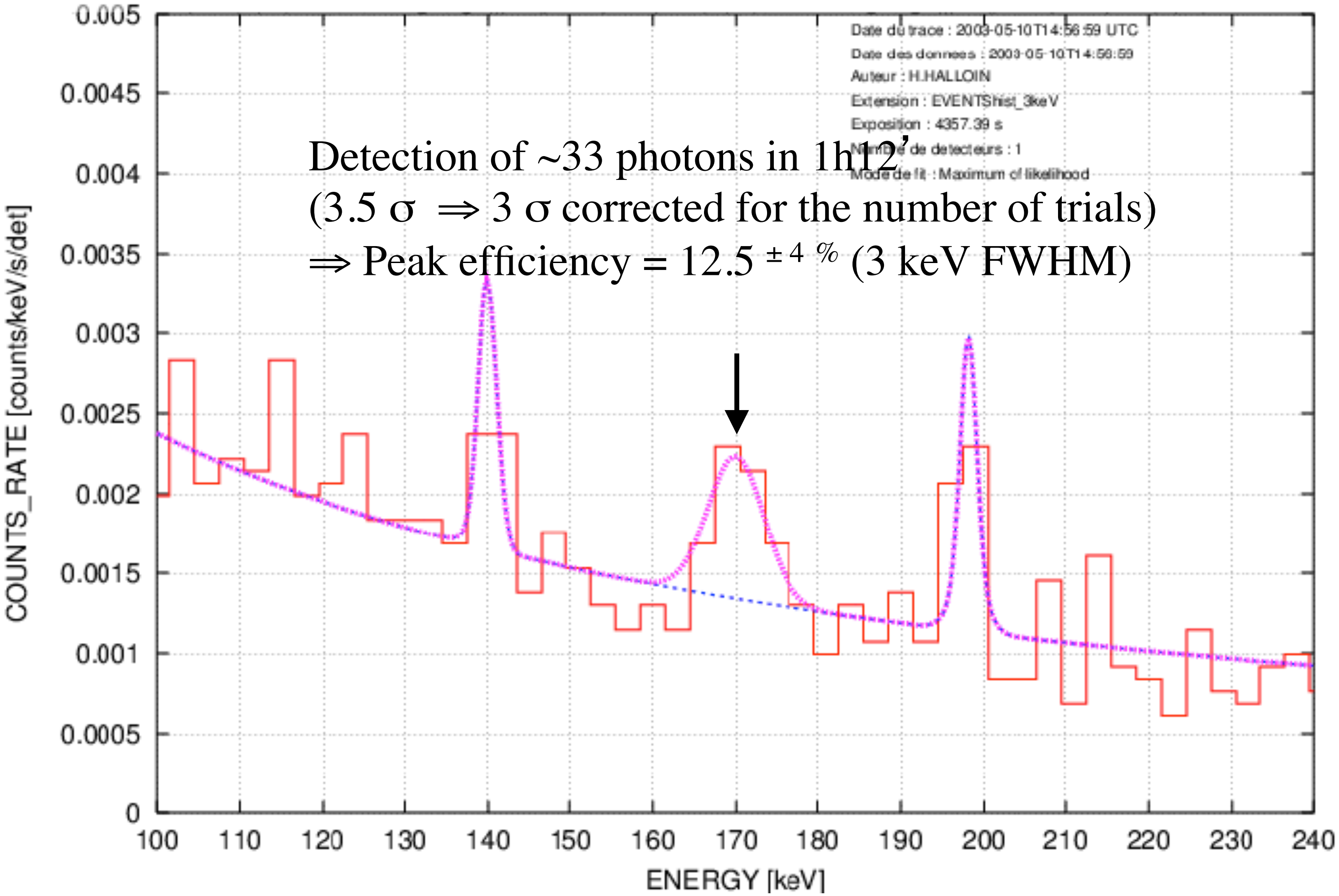
CLAIRE 2001



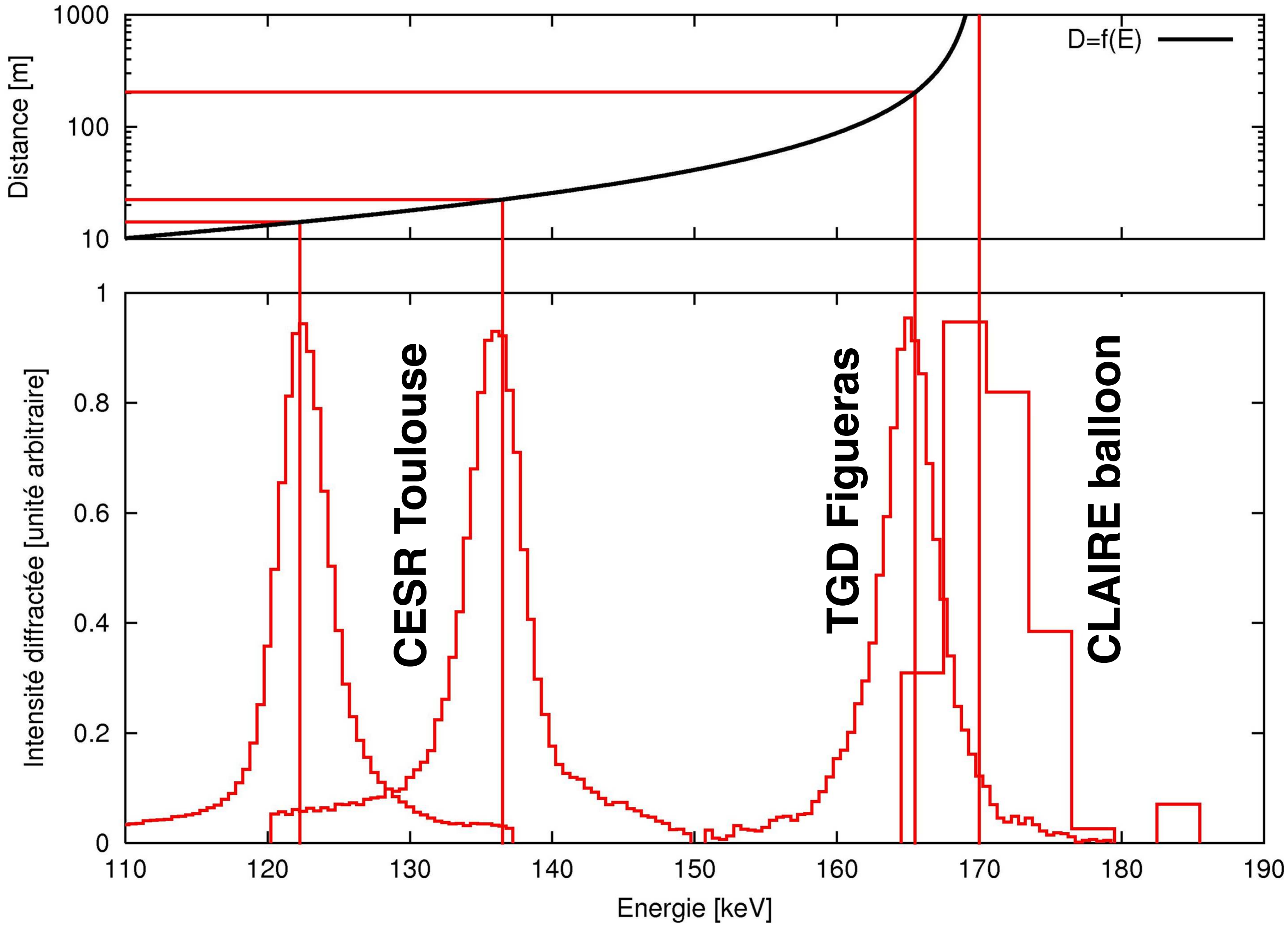
demonstrate the principle of a γ-ray lens on an astrophysical target

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)

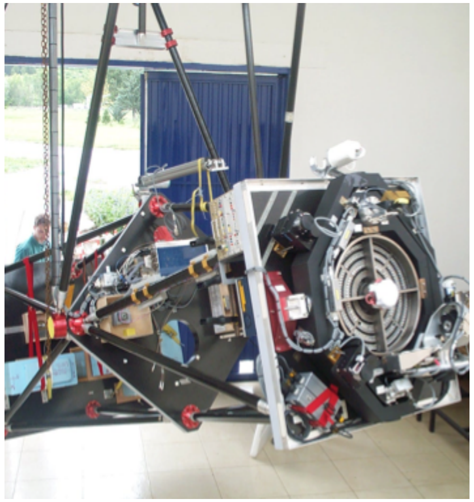
CLAIRE 2001 : first light for an astrophysical source



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



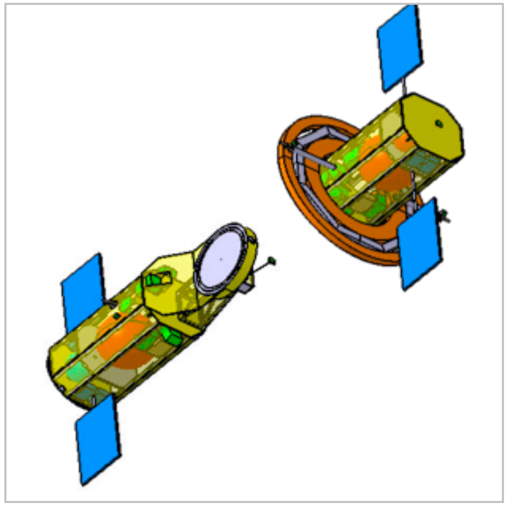
The development of gamma-ray lenses



CLAIRE 2003
CNES balloon & TGD

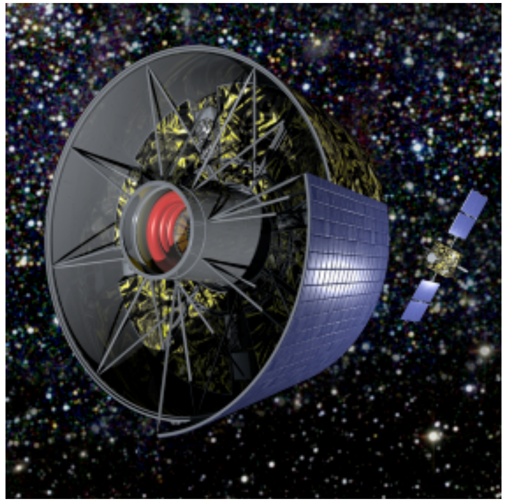
Crab detection :

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

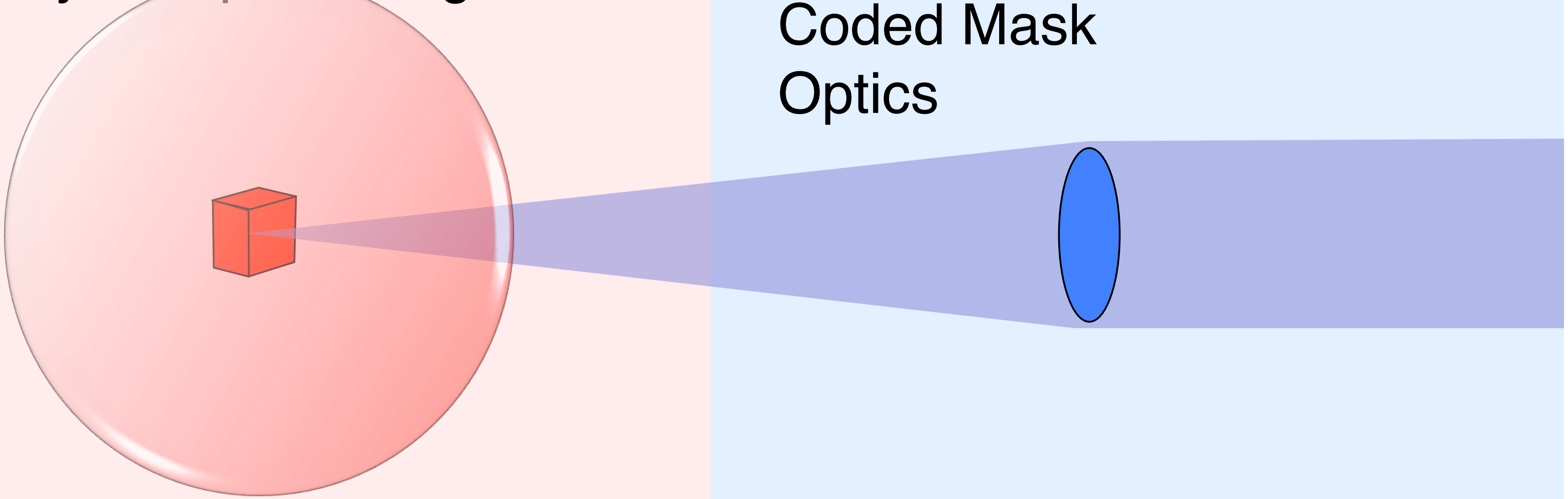
lens R&D : lens prototype TAS Cannes, vibration, qualification

DUAL mission concept

TWO VIEWS OF THE EXTREME UNIVERSE

All Sky Compton Imager

Laue Lens Optics
Coded Mask
Optics



All the sky (4π !) – all the time

Incoherent Compton scattering

Small low BG detector

Times has no mass !

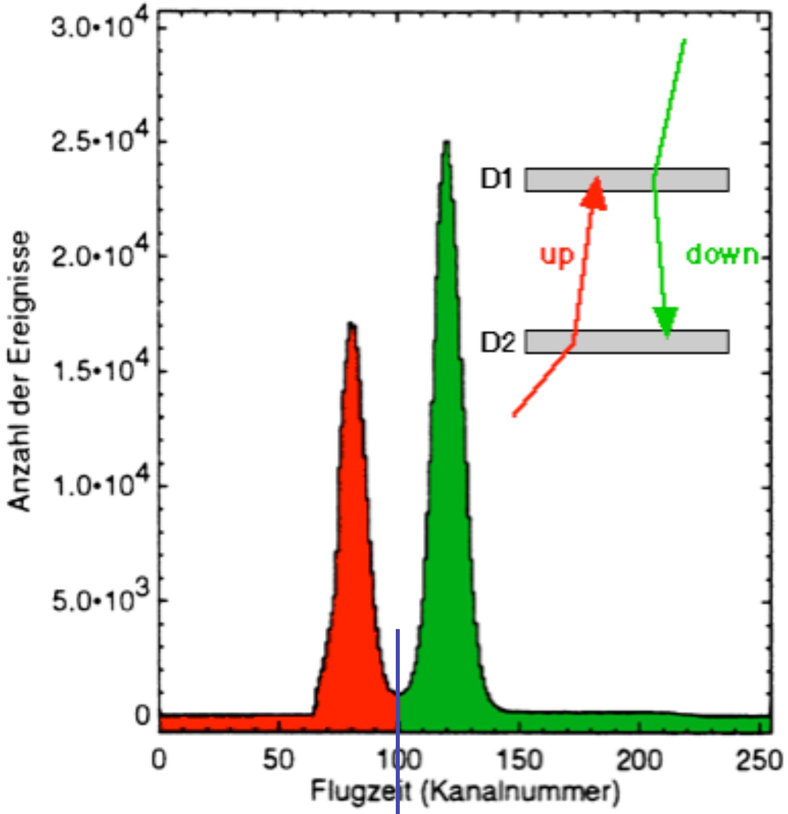
Polarimetry

Deep dedicated pointings

LLO : SN1a up to 40 Mpc
Coherent Bragg scattering

CMO : arcmin imaging in the GC Coded Mask Imaging at f=30m

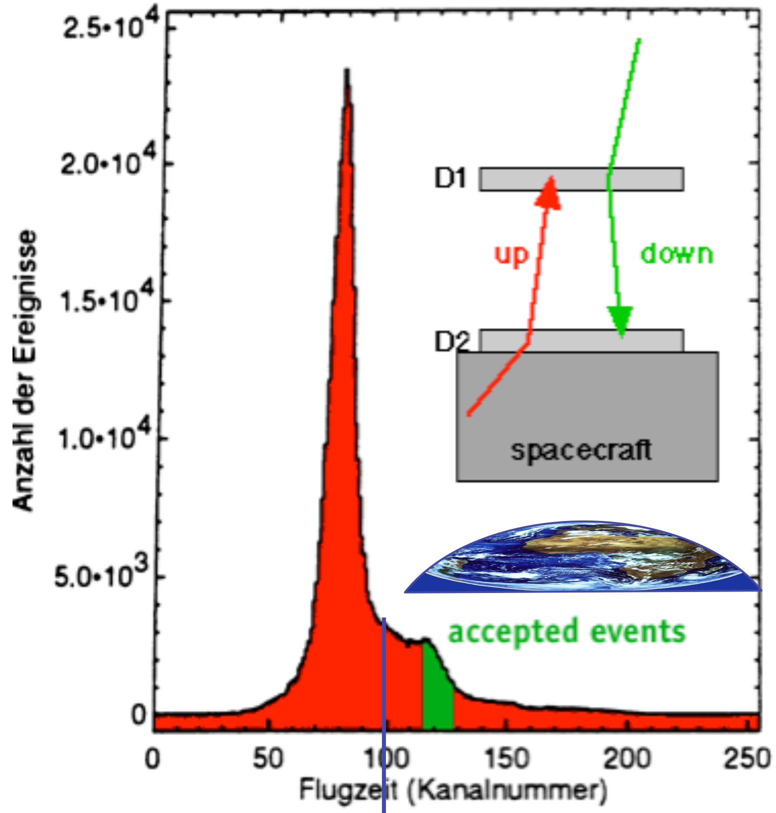
Time of Flight coincidence (TOF) COMPTEL data



<- upward | downward ->

COMPTEL calibration data

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

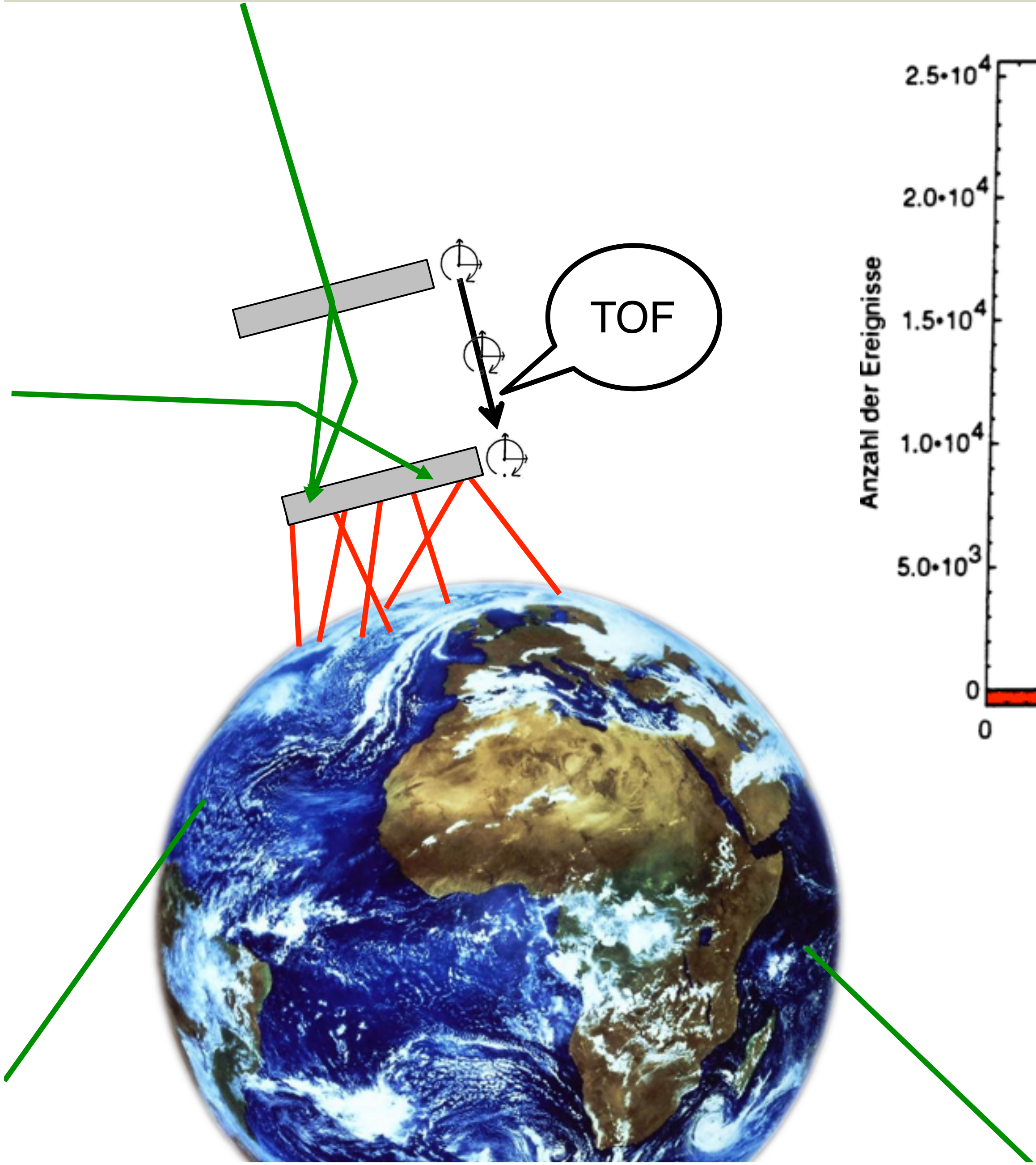


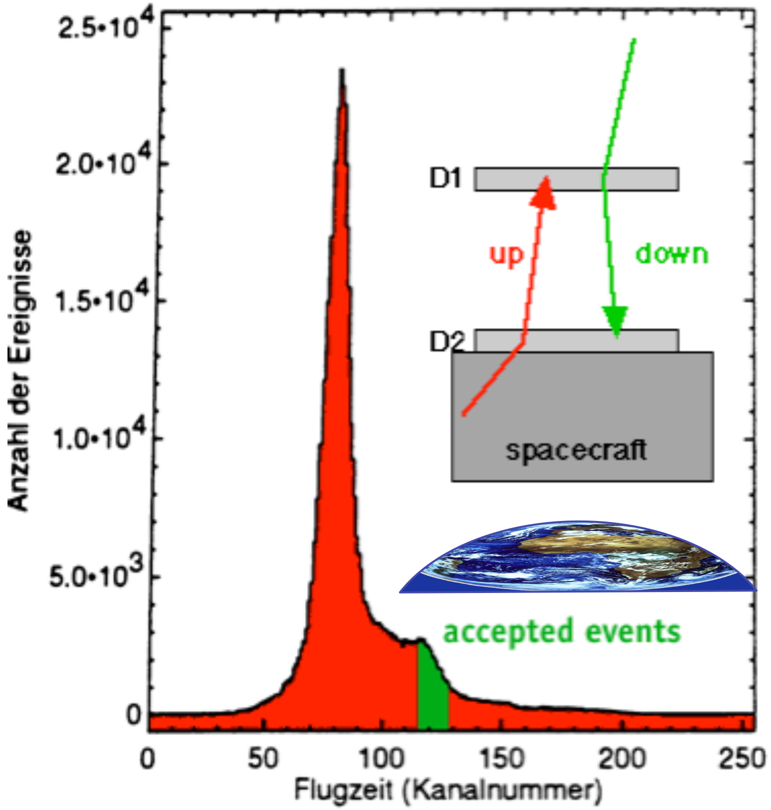
<- upward | downward ->

COMPTEL flight data

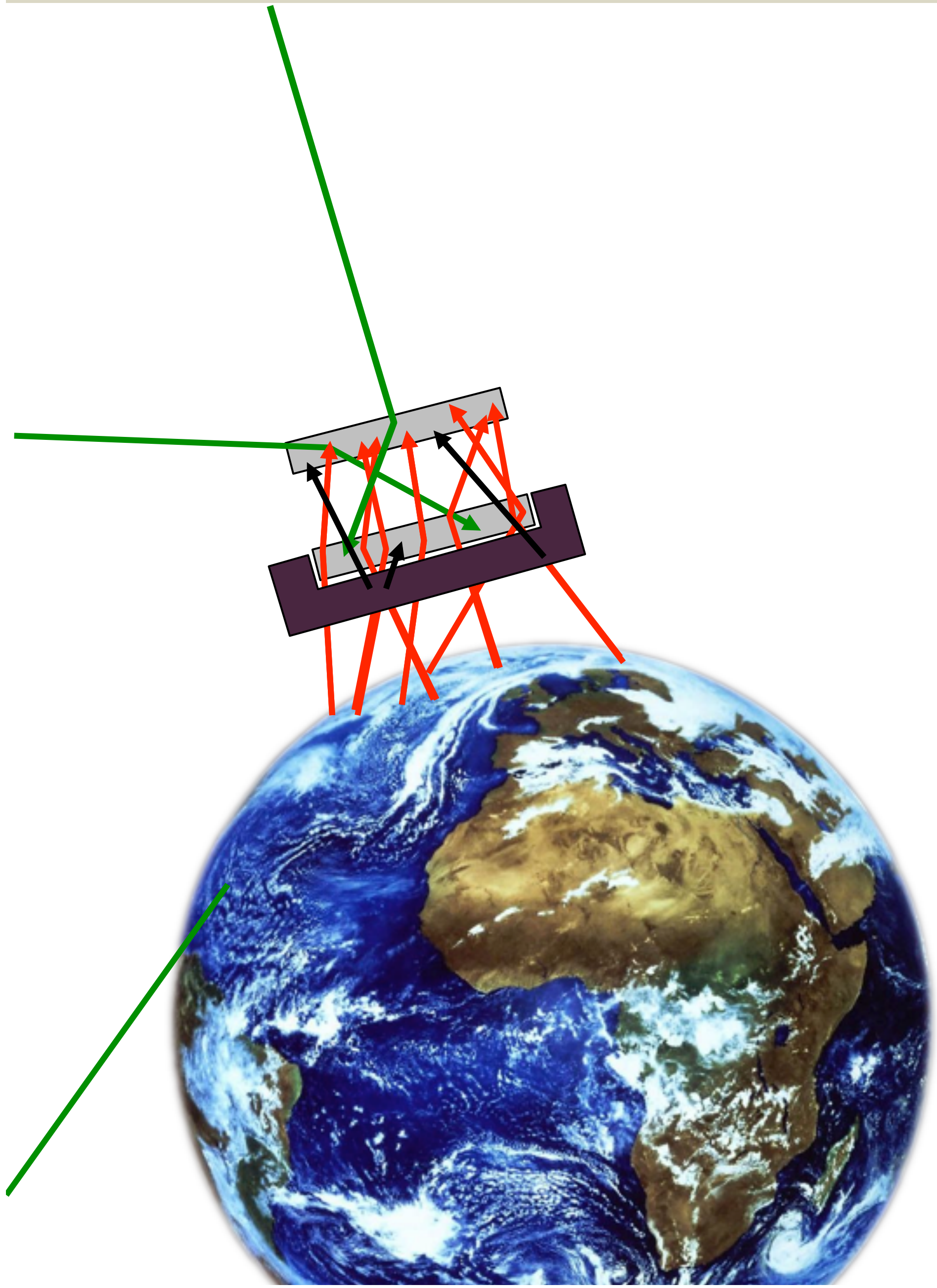
channel width : 0.25 ns
"upward BG" from spacecraft and the Earth

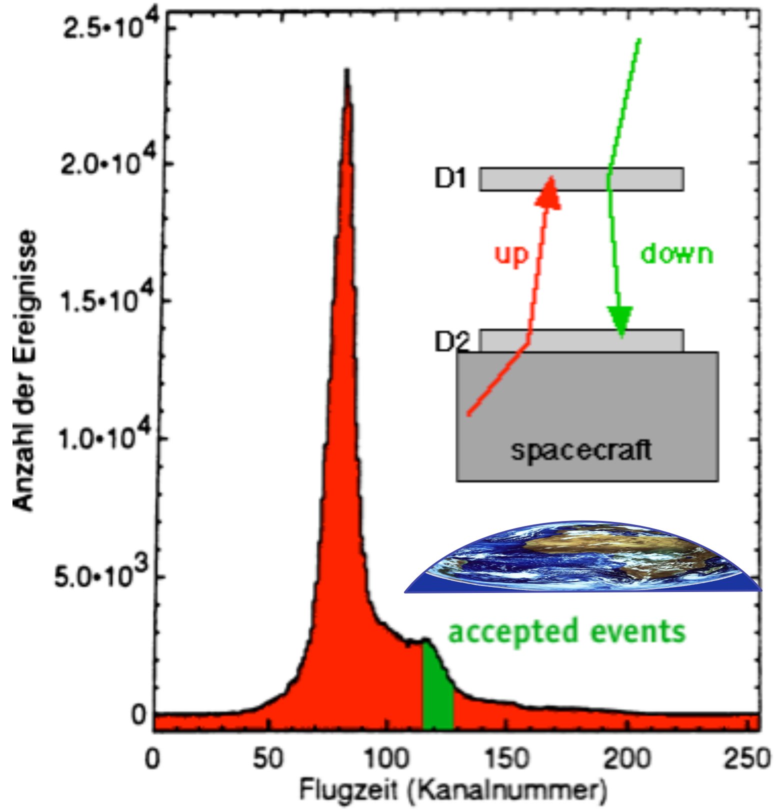
option A : time-of-flight electronics



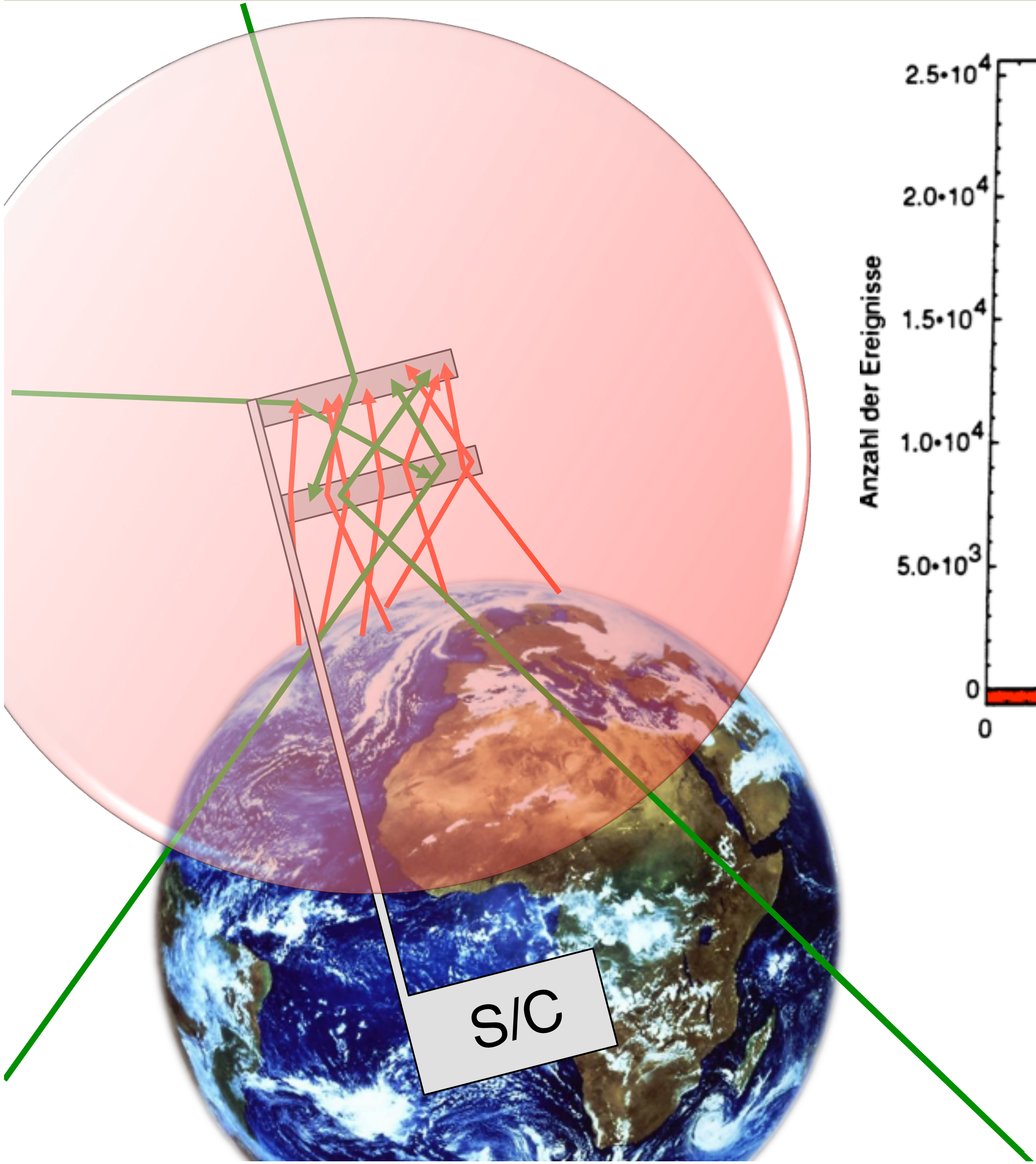


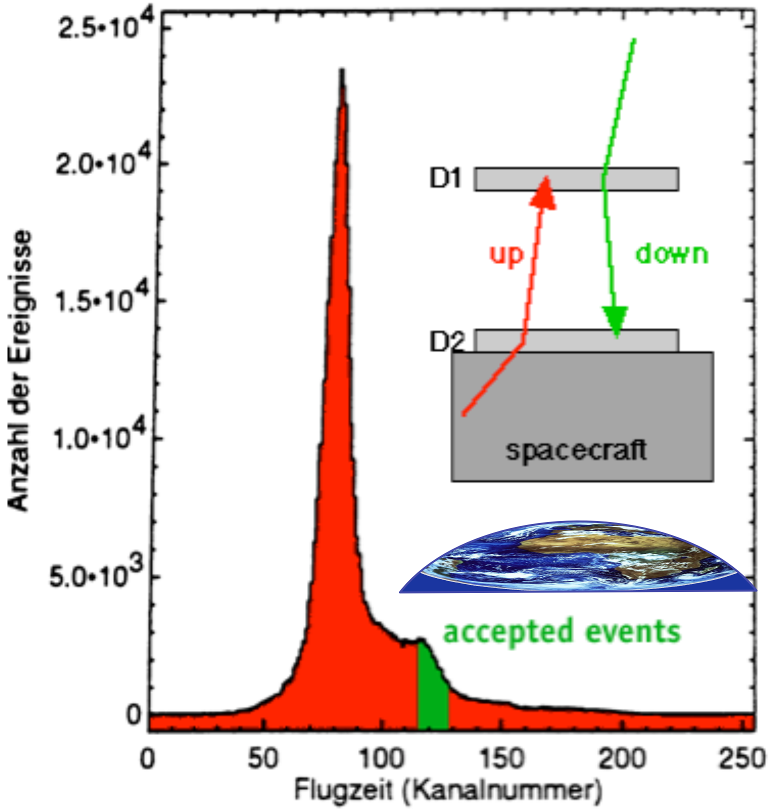
option B : anticoincidence shield





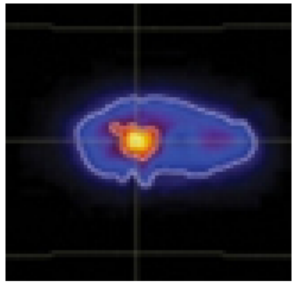
option C : no BG from external passive mass





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 …)

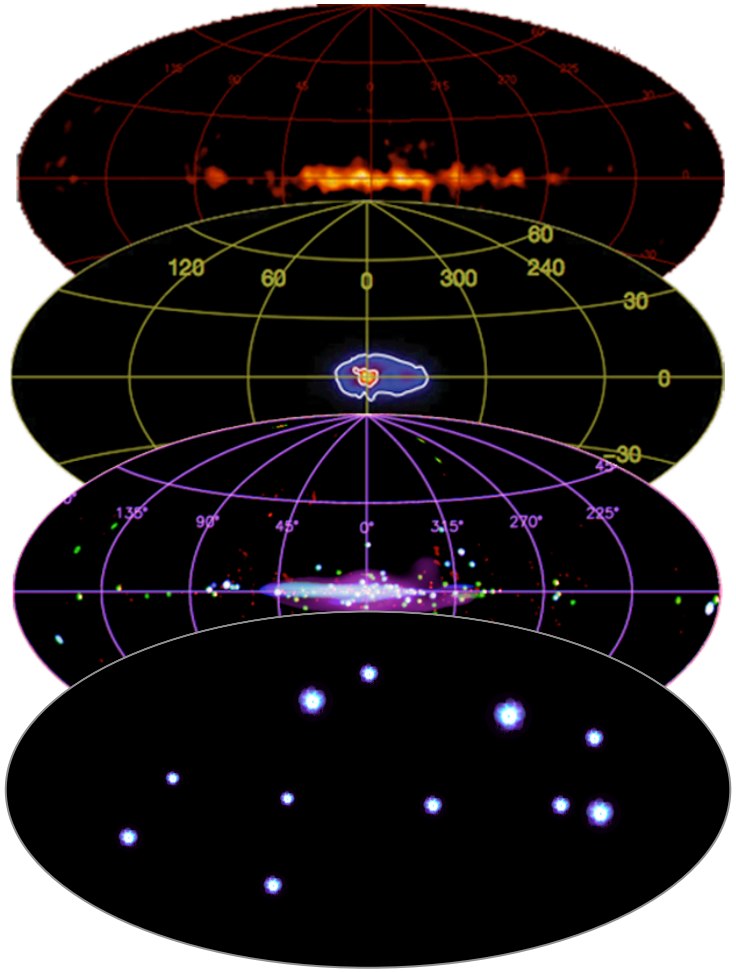
e$^-$e$^+$ Annihilation Radiation

Compact Sources

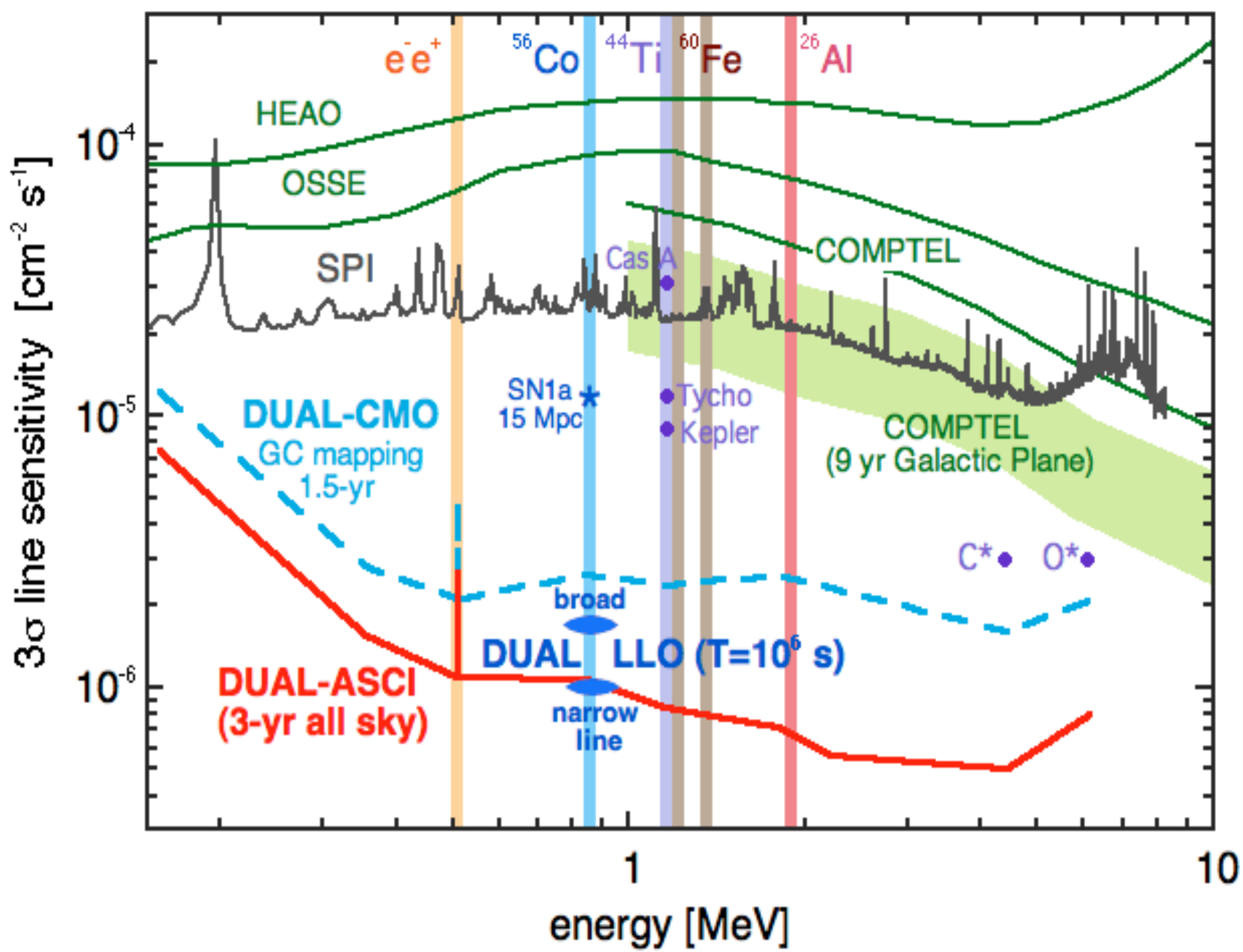
(LMXB, magnetars, AGN …)

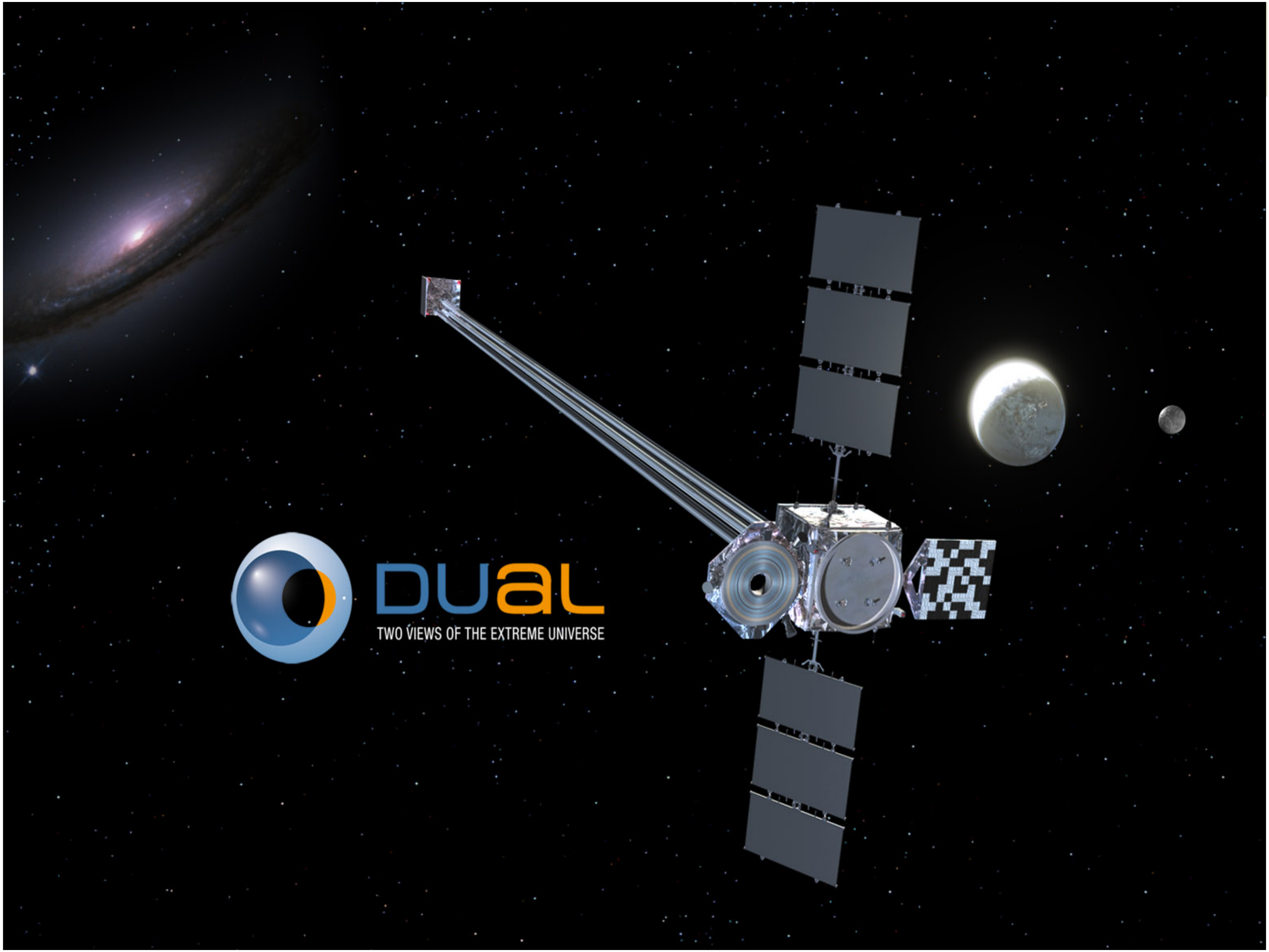
Gamma-ray bursts

(polarisation !)



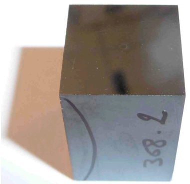
line sensitivity




DUAL
TWO VIEWS OF THE EXTREME UNIVERSE


All that Antimatters
in Positron Astrophysics
March 20-23, Mürren, Bernese Oberland, Switzerland
SOC : Felix Aharonian (DIAS Dublin), Roberto Battiston (INFN Perugia), Céline Boehm (IPPP Durham / LAPTH Annecy), Michael Charlton (Swansea University), Eugene Churazov (MPI Astrophysik Garching); Nidhal Guessoum (American Univ. of Sharjah), Jeffrey S. Hangst (Aarhus University), Pierre Jean (IRAP Toulouse), Mark Leising (Clemson University), Pierrick Martin (IPAG Grenoble), Piergiorgio Picozza (INFN Rome), Nikos Prantzos (IAP Paris), Gerry Skinner (GSFC Greenbelt), Clifford M. Surko (UCSD San Diego), Pietro Ubertini (IASF Rome), Tadayuki Takahashi (ISAS Tokyo), Peter von Ballmoos (IRAP Toulouse),

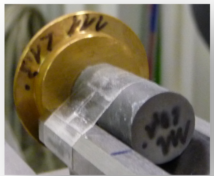
Crystal R&D : TRL of the diffraction media

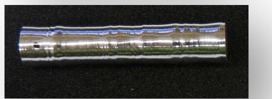


ESA pre-industrial serie / TRL study of crystal production

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

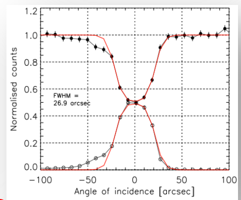
Cu : mosicity between 20 and 40 arcsec
Reflectivities : 15-20% at 511 keV, 12-23% at 816 keV



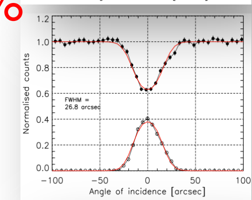


“Crystal Prospective”

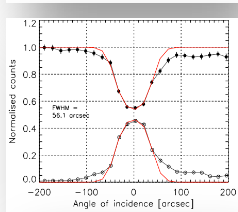
Pb (111) T_0=12mm, E=700 keV
Mosaicity = 27 arcsec; Quality fact : 100%



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%