The Wide Field Imager for ESTREMO: architectural design for SDD/Scintillator detectors

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Constrains & Requirements

Technical constrain
- weight ~150 kg
- power ~120 W

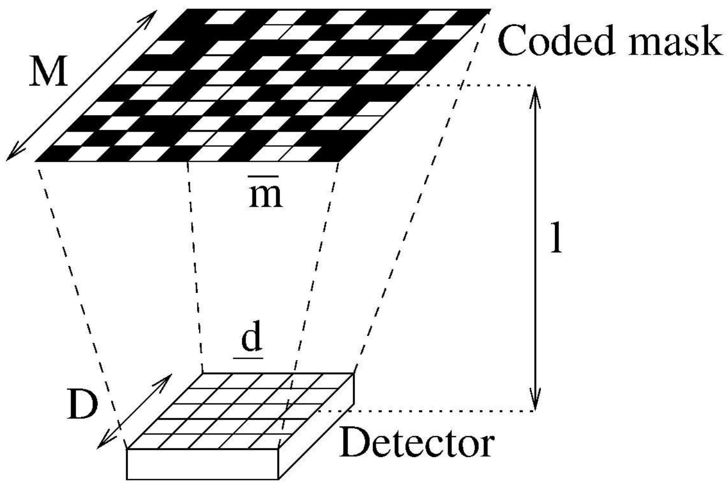
Performance requirements
- wide field of view ~3 sr
- PSLA ~1 arcmin
- good sensitivity to moderately strong GRB

Proposed approach

System architecture: coded mask instrument with pixelated detector

Detection plane: Silicon Drift Detectors (SDD) coupled to CsI(Tl) scintillator with Pulse Shape Discrimination (PSD) readout

System architecture: a constrain-driven parameterized approach



MURA-like mask pattern

$M \sim 2D$

$l = \alpha D$

↓

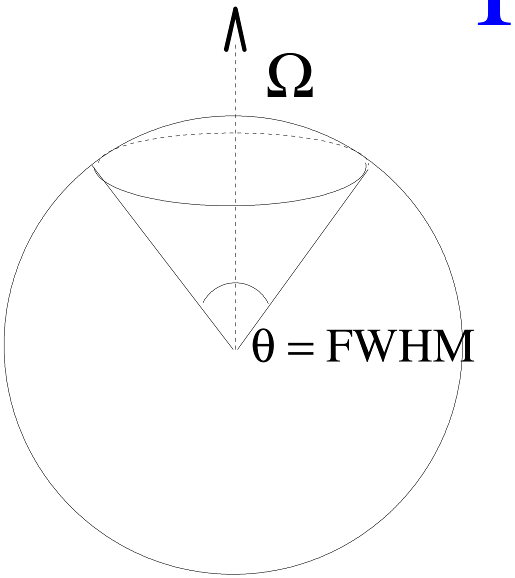
$\mathrm{FCFOV} = (M-D)/l = 1/\alpha$

$\mathrm{FWHM} = M/l = 2/\alpha$

$\mathrm{FWZR} = (M+D)/l = 3/\alpha$

- FOV constrains → can fix α → all instrument dimensions parameterized as a function of the detection plane size D
- Mass constrains → can fix the maximum D
- Power constrains → can fix the maximum number of channels i.e. the pixel size → define angular resolution and PSLA
- <u>How many detection units do we need to accomplish these constrains?</u>

FOV constrains



$\Omega = 3$ sr

$\Omega = 2\pi(1 - \cos\theta/2)$

$\theta = \mathrm{FWHM} = 2/\alpha$

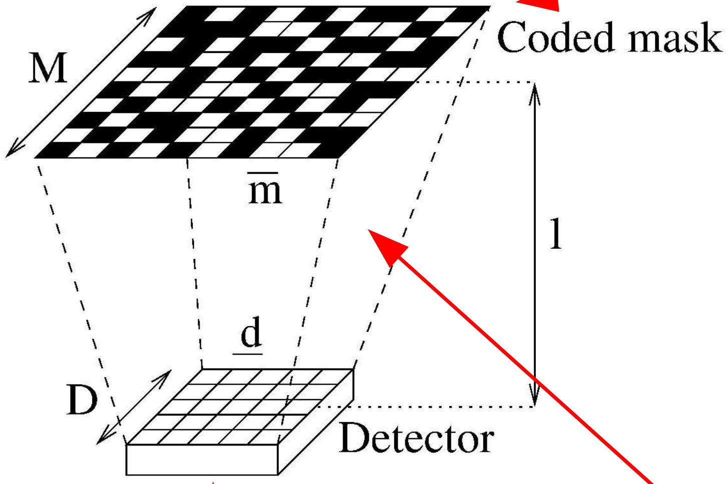
Let's consider the possibility to divide the FOV Ω into *N* different detection units each with non-overlapping FOV Ω_N

$$\Omega = N\,\Omega_N = 2\pi N\,(1 - \cos 1/\alpha)$$

N	α
1	0.98
2	1.42
3	1.75
4	2.03
6	2.49

This is for non-overlapping FOV if overlapping is required, then modules can be added, provided compatibility with mass budget

Mass constrain 1/2



Coded mask: tungsten $\rho_W = 19.25\ g/cm^3$

E (keV)	σ (cm²/g)	t_{90} (cm)
100	4.26	0.028
150	1.49	0.080
200	0.73	0.163

σ: absorption cross section without coherent scattering, from NIST XCOM database.

t_{90}: thickness needed to achieve 90% absorption

$$M_M = 4D^2 \rho_W (1 - f_{mask})\ h$$

mask total mass

open mask fraction ~0.5

mask thickness

Detection plane: SDD/CsI

mass dominated by CsI

$\rho_{CsI} = 4.51\ g/cm^3$

$$M_D = D^2\ (1.0 + \rho_{CsI} t)$$

detection plane total mass

to account for silicon and electronics mass

CsI thickness

Lateral shield / collimator: lead

(a graded shield should be used)

$\rho_{Pb} = 11.34\ g/cm^3$

E (keV)	σ (cm²/g)	t_{90} (cm)	t_{99} (cm)
100	5.34	0.038	0.076
150	1.91	0.106	0.213
200	0.94	0.217	0.434

$$M_S = 6D^2 \rho_{Pb} (\alpha^2 + 1/4)^{1/2} q$$

shield total mass

shield thickness

Mass constrain 2/2

$$M = N\,(M_D + M_M + M_S)$$

M ~ 150 kg

instrument total mass

number of detection units

detection plane mass

mask mass

shield mass

$$M = N\,D^2\,(1.0 + \rho_{CsI}\,t \;+\; 4\rho_W\,(1 - f_{mask})\,h \;+\; 6\rho_{Pb}\,(\alpha^2 + 1/4)^{1/2}\,q)$$

$$M = N\,D^2\,(1.0 + 4.51\,t \;+\; 38.5\,h \;+\; 68.0\,(\alpha^2 + 1/4)^{1/2}\,q)$$

CsI thickness ~1cm

mask thickness ~0.16 cm

depends on *N*

shield thickness ~0.2 cm

- Given the mass budget, the material thickness and the number of detection units, can solve for D to have the maximum allowed detection plane size!
- The shield mass dominates: careful shield tuning can “free” mass budget for the detection plane.

N	t (cm)	h (cm)	q (cm)	α	N M_D (kg)	N M_M (kg)	N M_S (kg)	D (cm)	A (cm^2)	total A (cm^2)
1	1.00	0.16	0.20	0.98	31.0	34.7	84.3	75.0	5632	5632
2				1.42	25.7	28.8	95.5	48.3	4670	4670
3				1.75	22.7	25.4	101.9	37.0	4119	4119
4				2.03	20.6	23.1	106.3	30.6	3744	3744
6				2.49	23.3	20.0	112.1	23.2	3245	3245

Power constrain

$P_{MAX} = 120\ W$

- <u>current</u> detector design and technology: $P_1 = 4$ mW/channel including electronics
- conservative estimate: expected to be reduced to ~2 mW/channel
- maximum number of channels with current design: $n_{ch} = P_{MAX} / P_1 \sim 3 \cdot 10^4$
- depending on the detection plane size D we can define the minimum pixel size d

$$N\, D^2/d^2 = P_{MAX} / P_1 \sim 3 \cdot 10^4$$

N	total A (cm^2)	d_{min} (mm)
1	5632	4.3
2	4670	3.9
3	4119	3.7
4	3744	3.5
6	3245	3.3

← all these pixel sizes are already available

Angular resolution and PSLA

$\theta \sim (m^2 + d^2)^{1/2} / l$

mask size pixel size mask-detector distance

$\mathrm{PSLA} \sim \theta / n_\sigma$

N	D (cm)	l (cm)	d_{min} (cm)	q (')
1	75	74	0.43	28.7
2	48	69	0.39	28.0
3	37	65	0.37	27.8
4	31	61	0.34	27.7
6	23	58	0.33	27.6

$1 - \cos 1/\alpha = \Omega/2\pi N \sim 1/2\alpha^2$ to first order: $\alpha \sim (\pi N/\Omega)^{1/2}$

$m \sim d$

$$\theta \sim (2\Omega / \pi n_{ch})^{1/2}$$

- The angular resolution depends mainly on the FOV and the number of pixels.
- To achieve a PSLA ~ 2' we need to detect the minimum target GRB with ~15σ significance → sensitivity calculations

Sensitivity calculations

Target GRB:

- Band parameters: α=-1, β=-2.5, E_p=200 keV, norm. 0.23, Δt=20s

E band (keV)	GRB flux (ph/cm2 s)	diffuse BKG (ph/cm2 s sr)	internal BKG (ph/cm2 s)
2 – 10	1.80	7.40	0.043
2 – 20	2.55	9.20	0.087
20 – 200	1.85	1.77	0.550

courtesy of
L. Amati

What is the minimum effective area required to detect the GRB at 15σ in 10s?

$$n_\sigma = N_{GRB} / (N_{GRB} + N_{BKG})^{1/2}$$

N	Ω (sr)	$A_{eff,\,min}$ (cm^2)	$A_{geom,\,min}$ (cm^2)	$A_{geom,\,MAX}$ (cm^2)
1	3	110	116	5632
2	1.5	74	78	2335
3	1	62	65	1373
4	0.75	56	59	936
6	0.5	51	54	541

mean efficiency in
20-200 keV ~95%

- The mass budget constrains allow to have an effective area up to 10 - 50 times higher than the minimum required to fulfill basic scientific requirements
- A trade-off between scientific performances and mass can be done

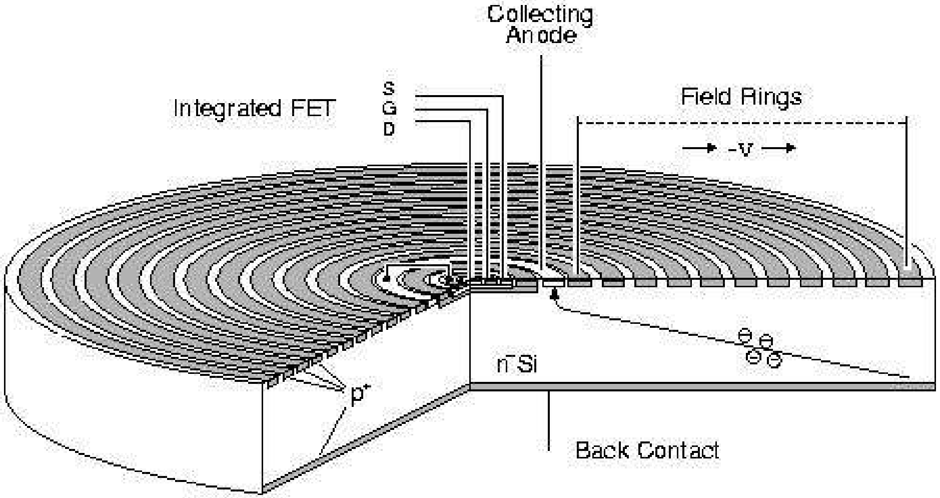
Architectural improvements

- From sensitivity calculations it seems that a single detection unit is better than more units BUT the segmented architecture may be required to fulfill symmetry and room allocation constrains
- Detection units FOV have been considered non-overlapping so far. FOV may be partially overlapped to increase the effective area at the price of a higher number of detection units (compatibility with mass budget).
- “Smart” design of adjacent detection units may result in weight reduction as the shield of one unit may be shared between two adjacent units.

Silicon Drift Detectors (SDD)

- SDDs are silicon devices first introduced by E. Gatti and P. Rehak in 1984 (Gatti & Rehak, NIM A225, 1984)

- electric field modulation inside the depletion region by means of suitably polarized electrodes



P. Lechner et al., NIM A377, 1996

- Small collecting anode -> low output capacitance -> low electronic noise -> higher energy resolution than an equivalent p-i-n PD

- Possibility to integrate first amplifying JFET directly on-chip: further signal-to-noise ratio improvement

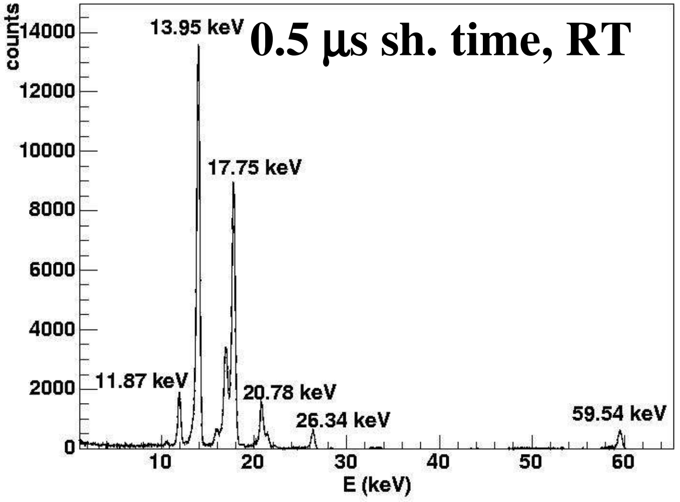
- Several dimensions available, possibility to measure drift time for position resolution (not considered here), single devices or integrated arrays available

SDD: low noise characteristics

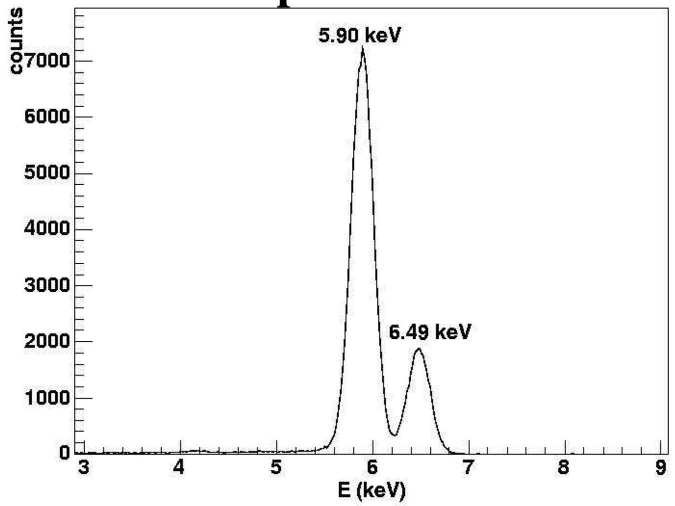
- electronic noise can be a factor 5 - 10 lower than that of p-i-n PDs of equivalent active area
- few mm^2 SDDs developed by MPI Halbleiterlabor (HLL, Munchen, Germany) for room temperature X-ray spectroscopy

Property	Value
active area	10 mm^2
Si thickness	300 µm
JFET	embedded
E threshold	0.6 keV
energy resolution	5% FWHM @5.9 keV 0.9% FWHM @ 60 keV at room temperature
ENC	44 e$^-$ rms @ 20°C

^{241}Am spectrum, 10 mm^2 SDD



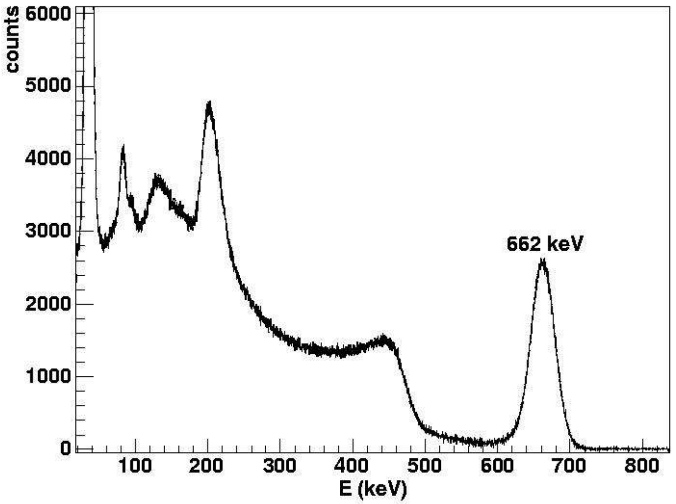
^{55}Fe spectrum



SDDs as photodetectors for scintillators readout

- SDDs tested as photodetectors for CsI(Tl) scintillating crystals readout (Fiorini et al., IEEE TNS, 44, 1997)

Property	**Value**
crystal type	CsI(Tl)
light yield	25 - 38 e$^-$/keV
E threshold	< 16 keV
efficiency	depending on thickness 80% @ 200 keV 25% @ 1 MeV with 1 cm crystal
energy resolution	4.8% FWHM @ 662 keV at room temperature

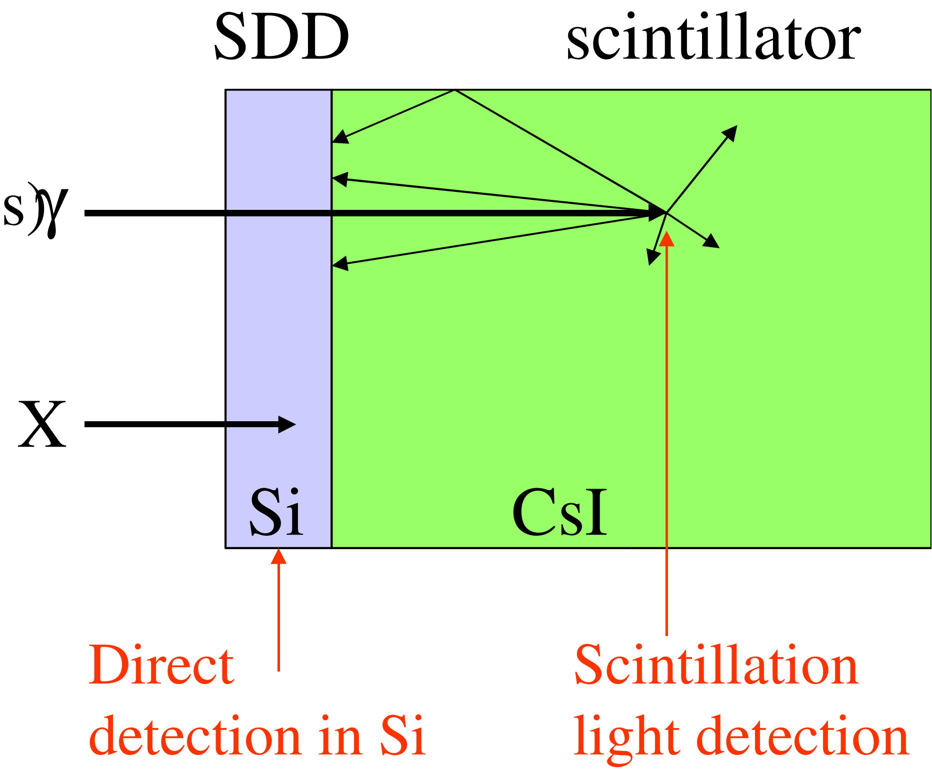


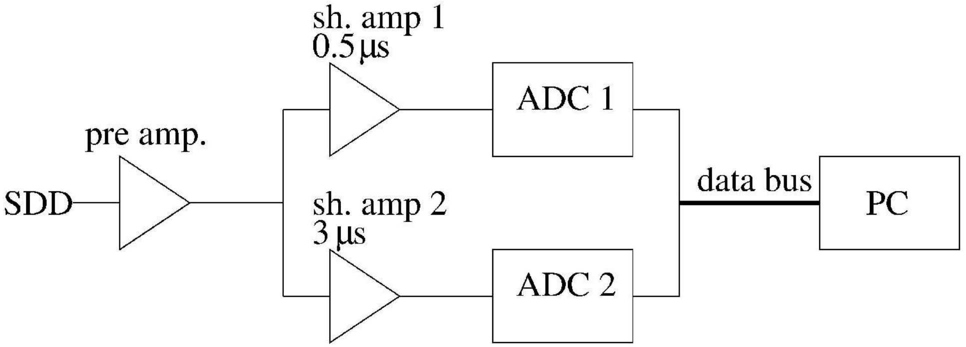
^{137}Cs spectrum, 10 mm^2 SDD
3 µs sh. time, RT

- ΔE/E dominated by crystal conditioning, wrapping and optical coupling

Detection Principle

- SDD coupled to CsI(Tl) crystal is still a direct X-ray detector
- X rays interacting in Si: fast pulse (< 10 ns)
- γ rays interacting in CsI: slow pulse (few μs)
- identification of the interaction by means of <u>pulse shape discrimination</u> (PSD)
- **Main features**:
  - low energy threshold (~2 keV)
  - extended energy range (~1 MeV, depending on crystal thickness)
  - excellent energy resolution



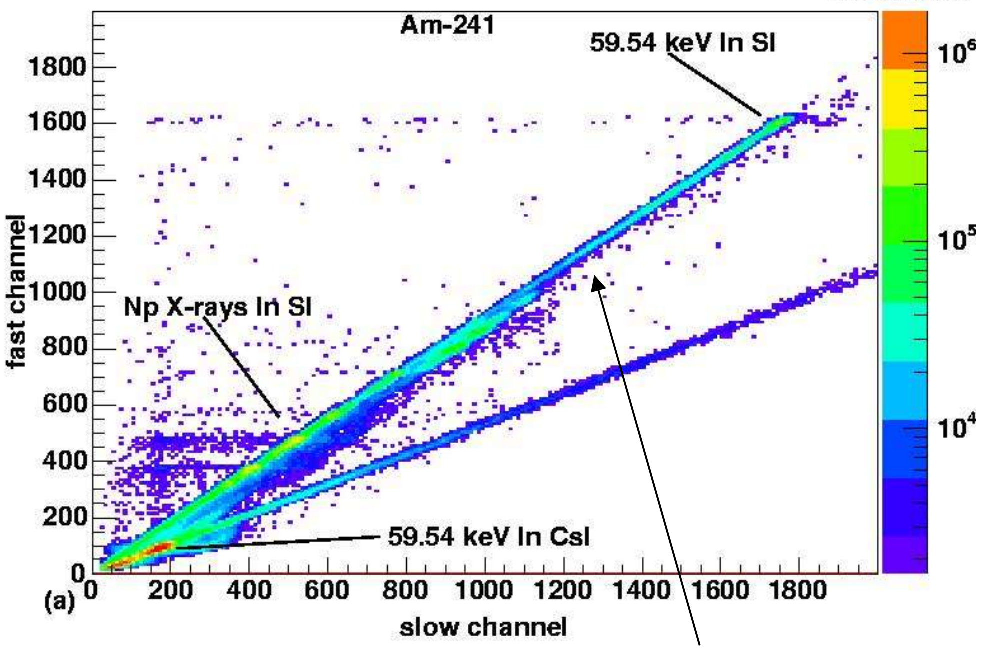


2D spectra: fast vs. slow component

- (ADC_{fast}, ADC_{slow}) points concentrate on two stright lines depending on the place of interaction (silicon or CsI)
- key parameter: $r = ADC_{fast} / ADC_{slow}$

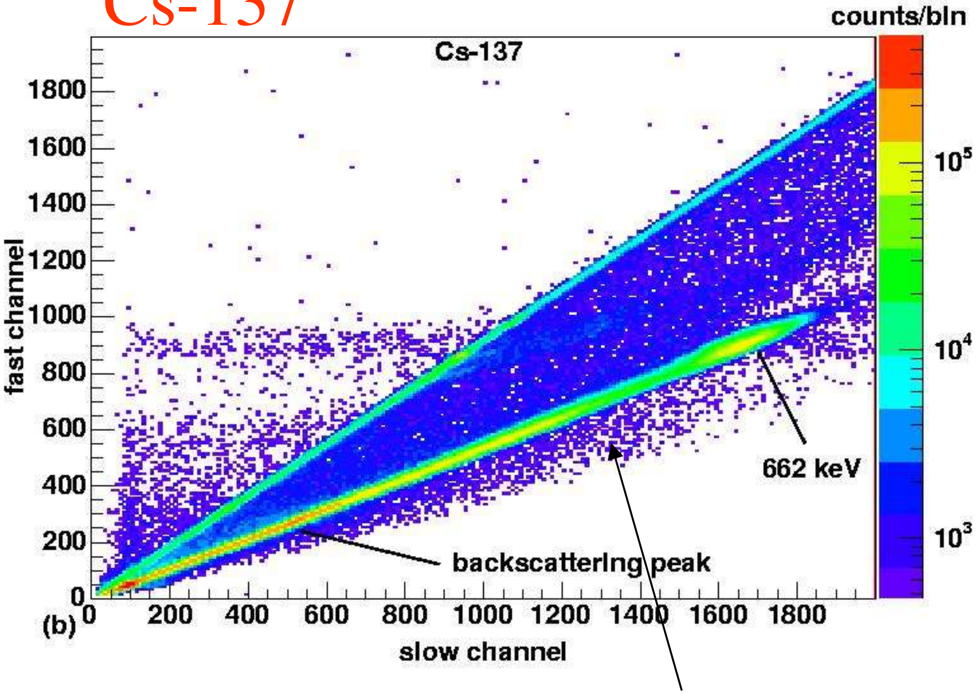
Marisaldi et al., (2004) IEEE TNS 51, 1916

Am-241



In silicon: r = 0.92

Cs-137

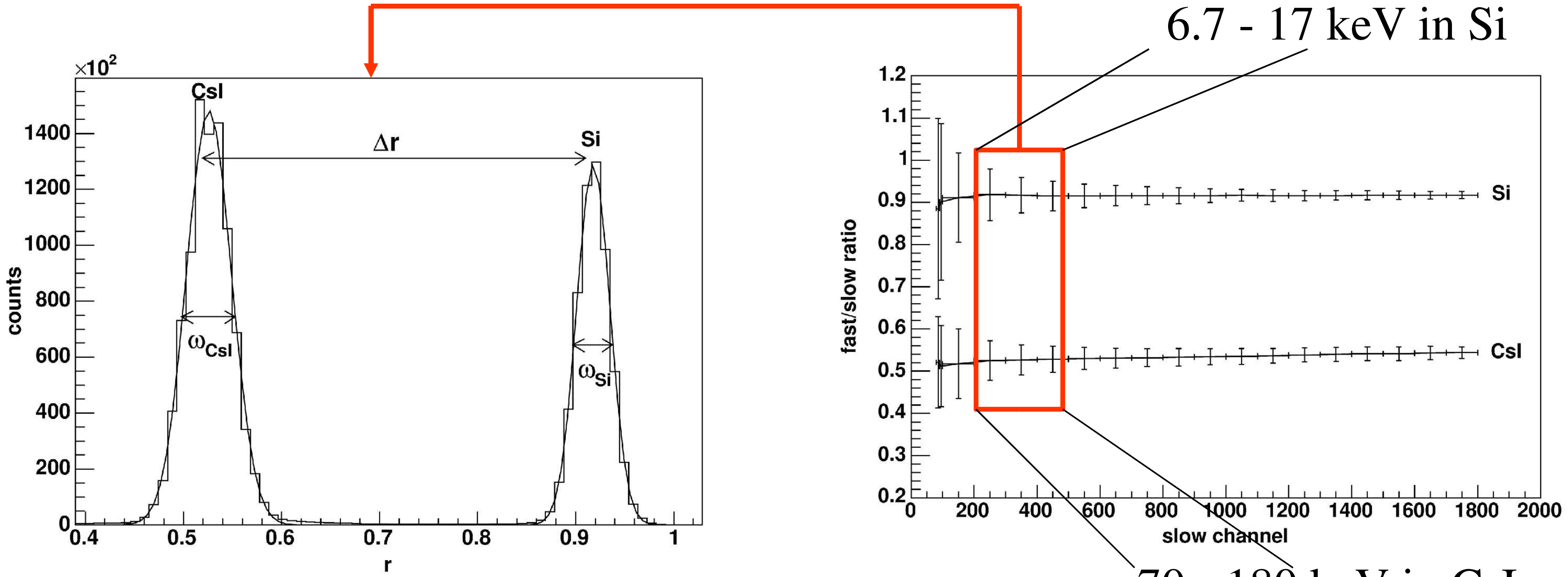


In CsI: r = 0.54

Pulse Shape Discrimination (PSD)

- Figure of merit M:
- 99.9% PSD possible if M>1.5

$$M = \frac{\Delta r}{\omega_{Si} + \omega_{CsI}}$$



6.7 - 17 keV in Si

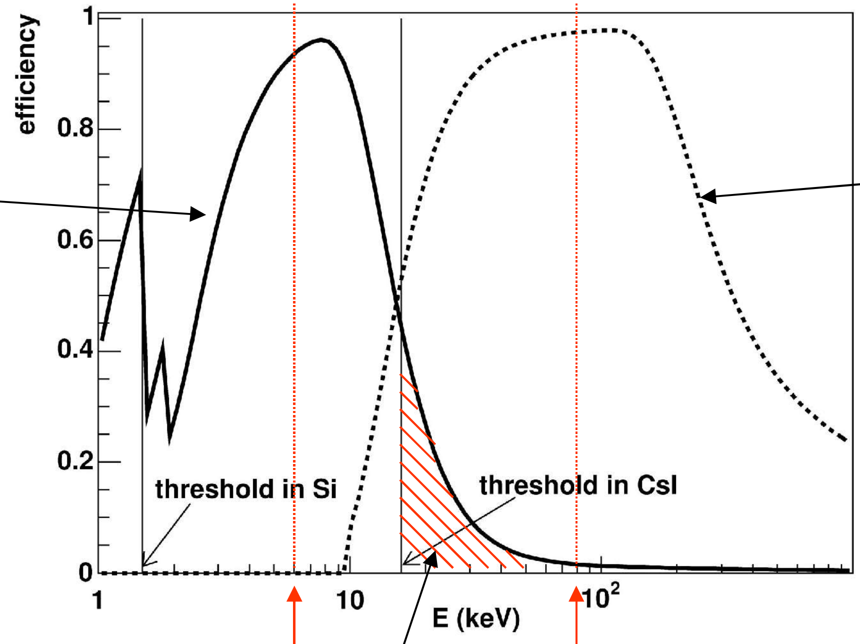
70 - 180 keV in CsI

- 100% PSD achieved for E>3.6 keV in Silicon and E>35 keV in CsI
- PSD still possible for E>1.5 keV in Silicon and E>16 keV in CsI
- lower noise and higher light yield ——> lower 99.9% PSD limit

Why SDD?

- SDDs' low electronic noise is <u>necessary</u> for:
  - lower energy threshold (1 keV in Si, 9 keV in CsI @ 10°C)
  - Si & CsI energy range overlapping
  - good spectroscopic capabilities in Si (4.5% @ 5.9 keV at RT)
  - good spectroscopic capabilities in CsI (< 6% @ 662 keV at RT)

SDD efficiency in Si

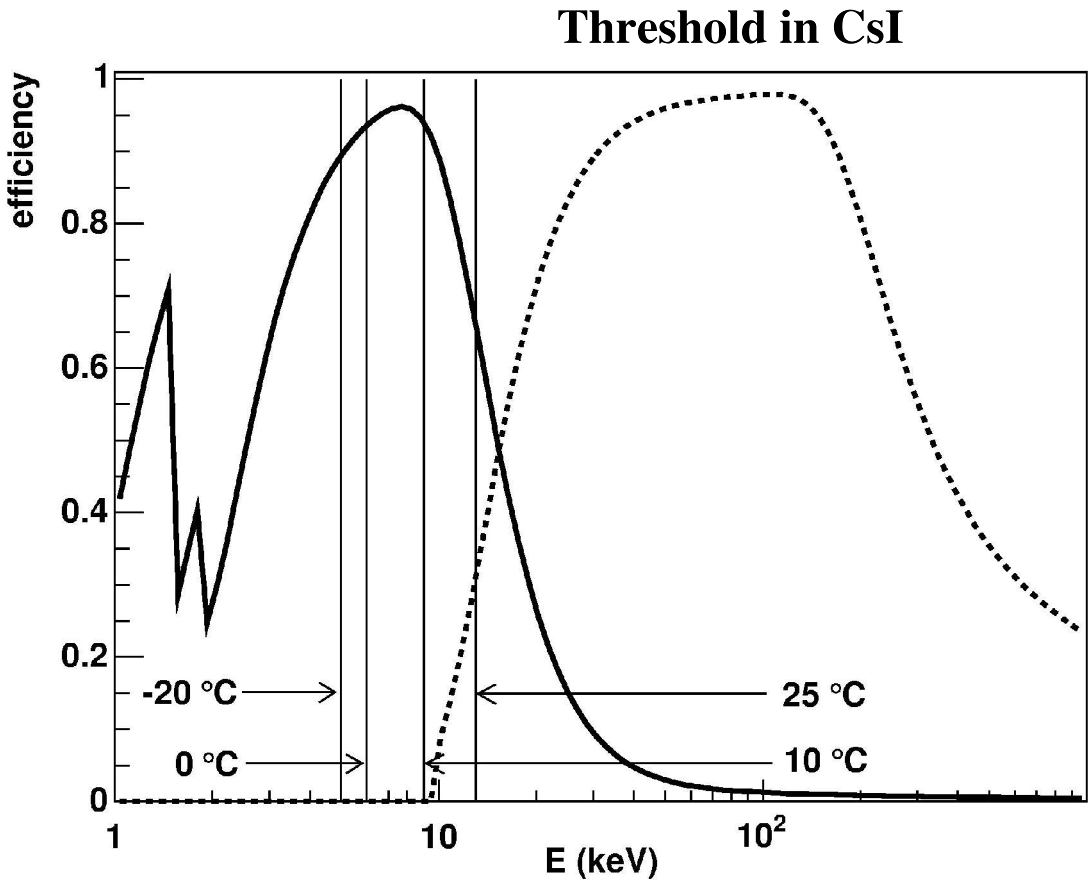


efficiency in CsI

Thresholds with PD readout

Energy range overlap: ~100% efficiency

How much should I cool?



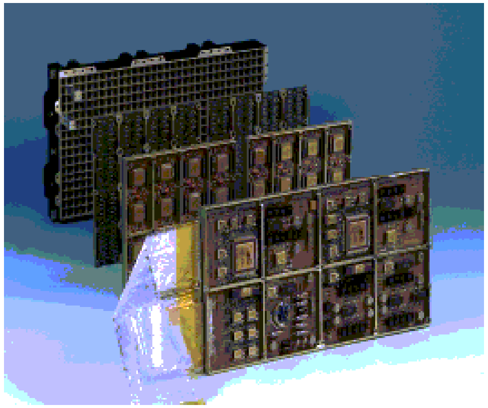
Average efficiency:

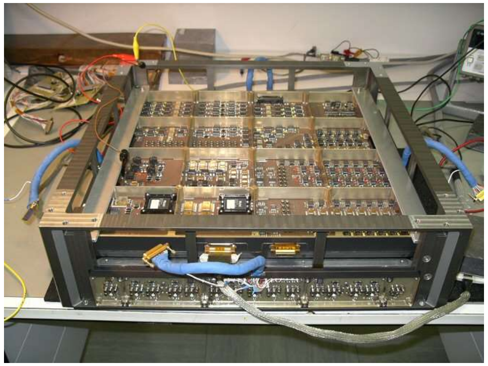
2-10 keV: SDD	84%
2-20 keV: SDD	67%
2-20 keV: SDD/CsI	92%
20-200 keV: SDD/CsI	96%
200-600 keV: SDD/CsI	47%

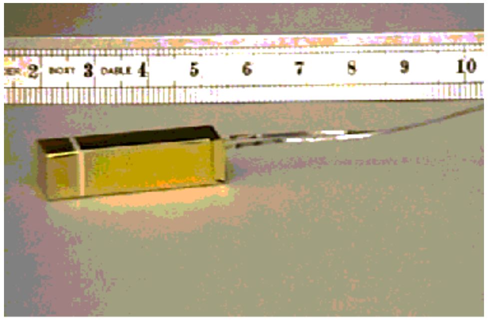
- cooling at 10 °C is enough to fill the efficiency gap between Silicon and CsI
- cooling below 0 °C allows 99.9% PSD over all the detector energy range

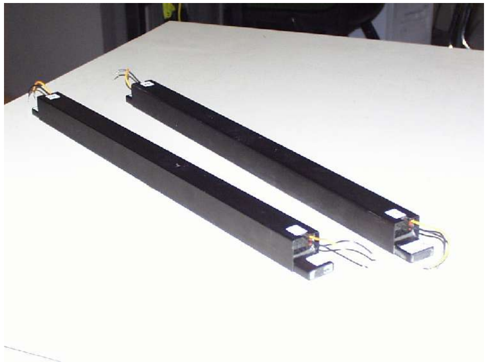
Technology heritage

Instrument design and realization





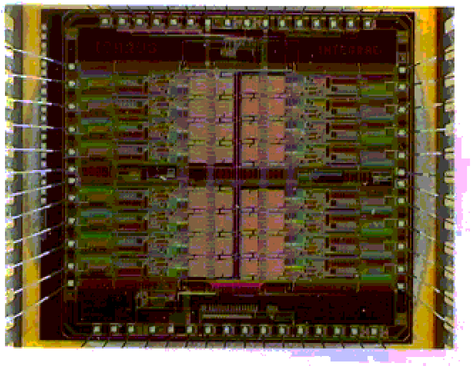




the IBIS/PICsIT detector onboard the INTEGRAL satellite

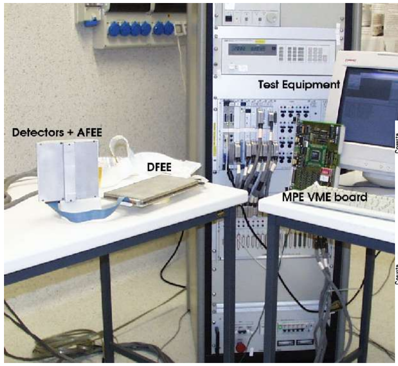
the mini-calorimeter of the AGILE satellite

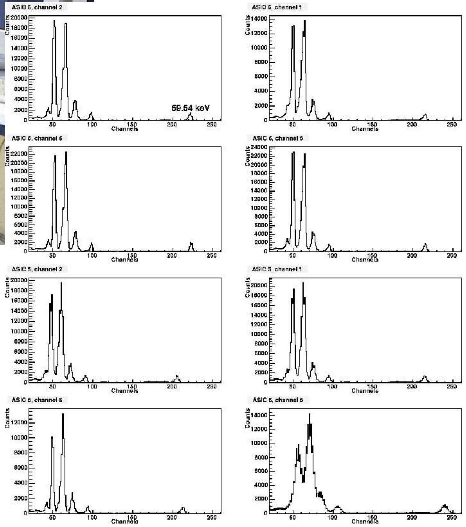
ASIC design and testing



- ICARUS ASIC fot PICsIT
- ICARUS-SDD for SDD readout
- RUA ASIC

SDD testing and system realization





SDD/CsI module for the MEGA Compton telescope

Conclusions

Architectural design

- a (possibly segmented) coded mask instrument can fit all scientific requirements and technical constrain
- there is room for weight reduction, still satisfying the basic sensitivity requirements

Detector

- the SDD/CsI technique is a consolidated technique
- it can conjugate low energy (2-20 keV) efficiency with good energy resolution (5% FWHM @ 5.6 keV) with high energy efficiency up to several hundreds keV in a single compact device
- **all scientific requirements can be achieved with already available devices, no technology improvement is required**