Miniature Scintillating Detectors and SiPMs:

a brief Summary and a few Applications

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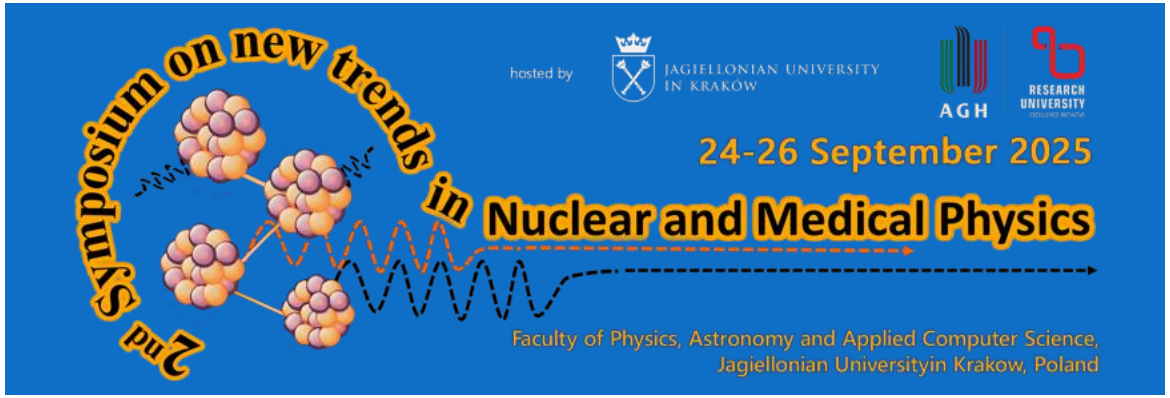

INFN LNS

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DMNR

RADSIEVE

HELNEM

PI3SO

micado

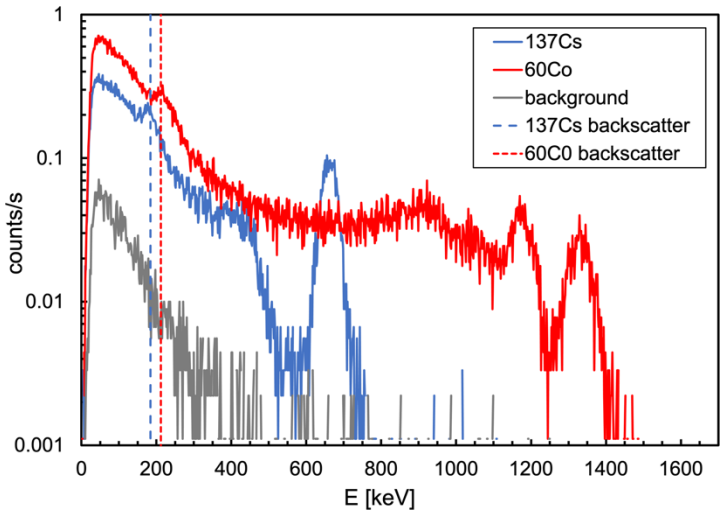
CLEANDEM

PREDIS

Our activities during the last two decades → **more and more use of SiPM**

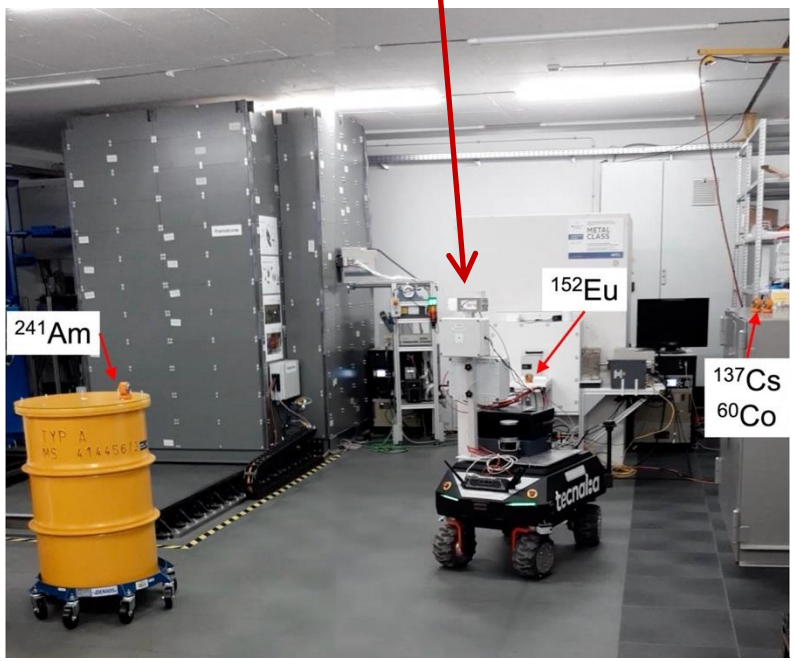
...in particular quite recently...

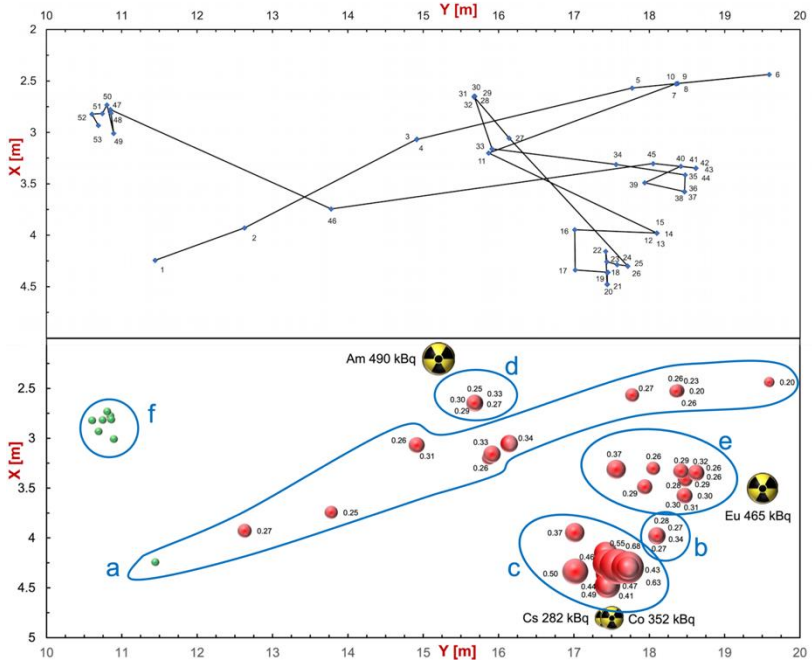
Robotic inspection system in radioactive environment



1cm³ CsI(Tl) scintillator
+
6mm × 6mm SensL SiPM

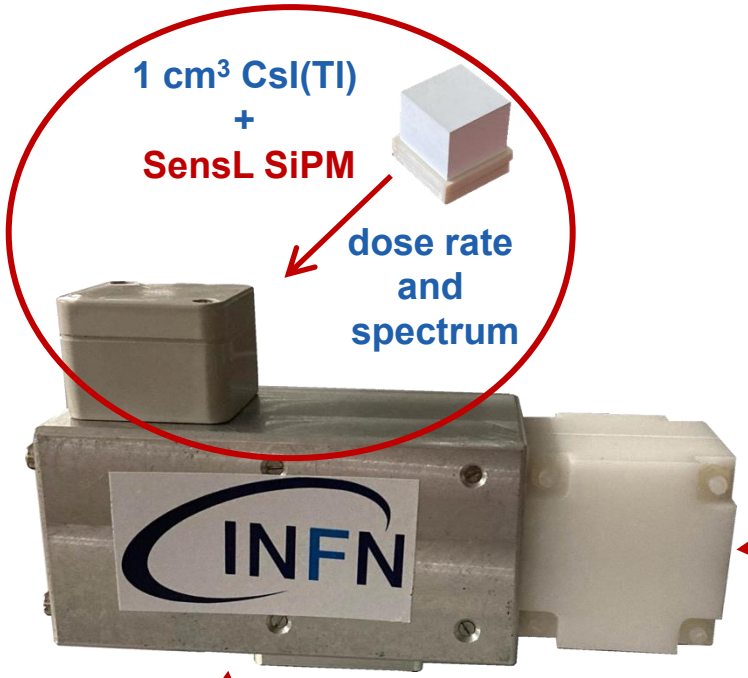
MiniRadMeter



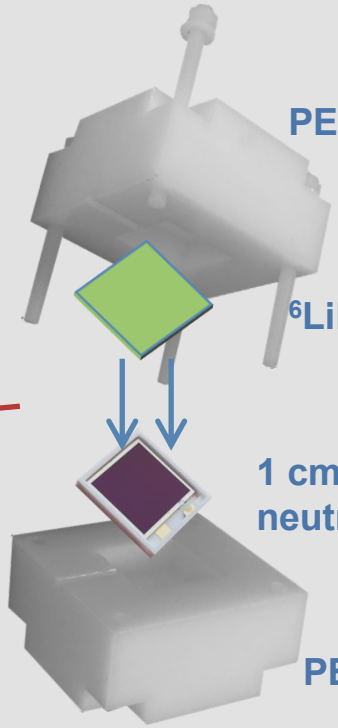


CLEANDEM

MiniRadMeter: gamma and neutron dose rate monitor



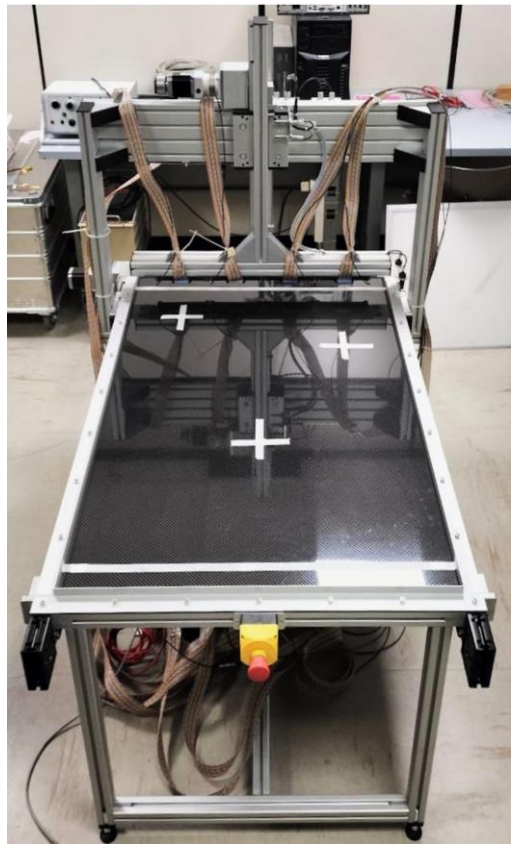
Front-end electronics
Raspberry computer
WiFi + Ethernet

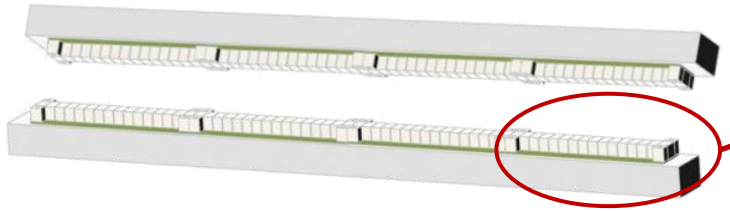


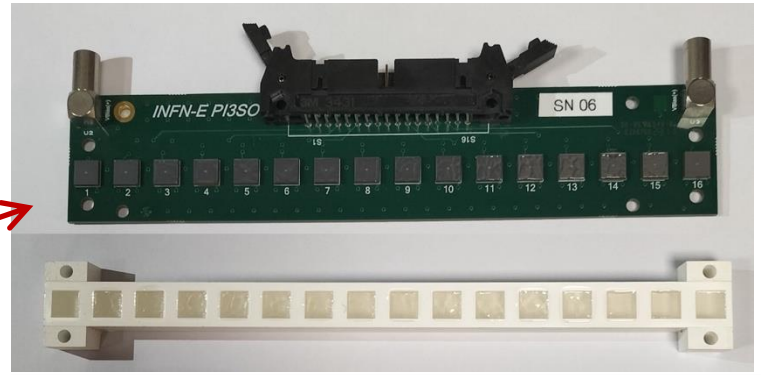
Proximity Imaging Scanner for Sort and Segregate Operations

PI3SO

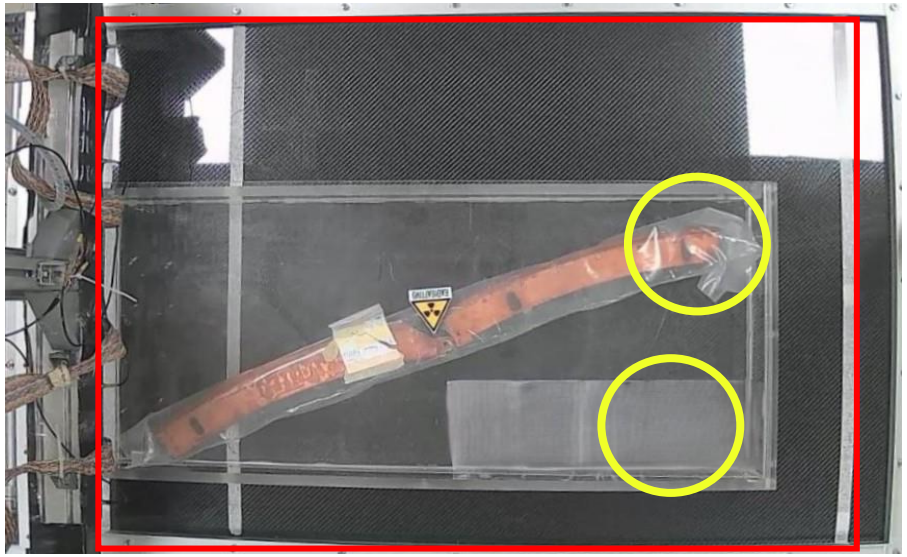
128 × 1cm³ CsI(Tl) scintillators +
128 6mm × 6mm Hamamatsu SiPM

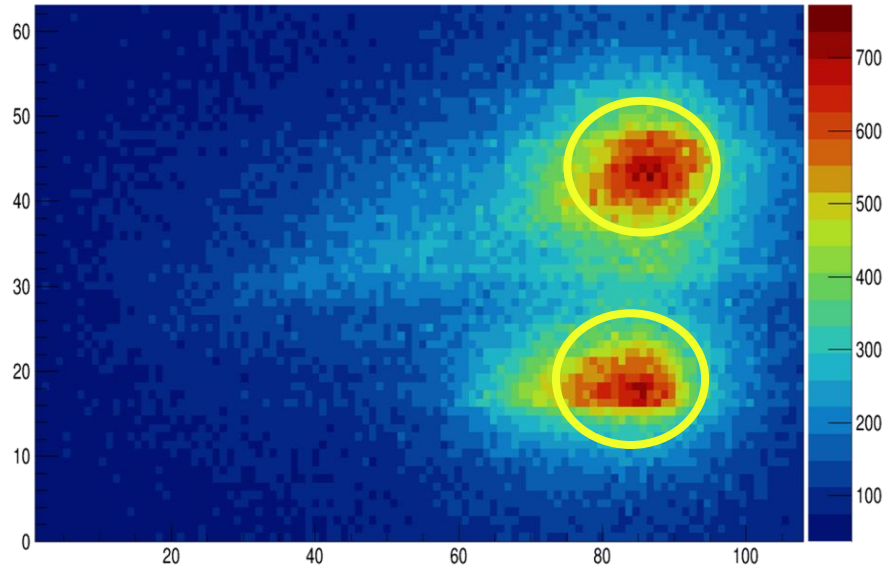






× 8





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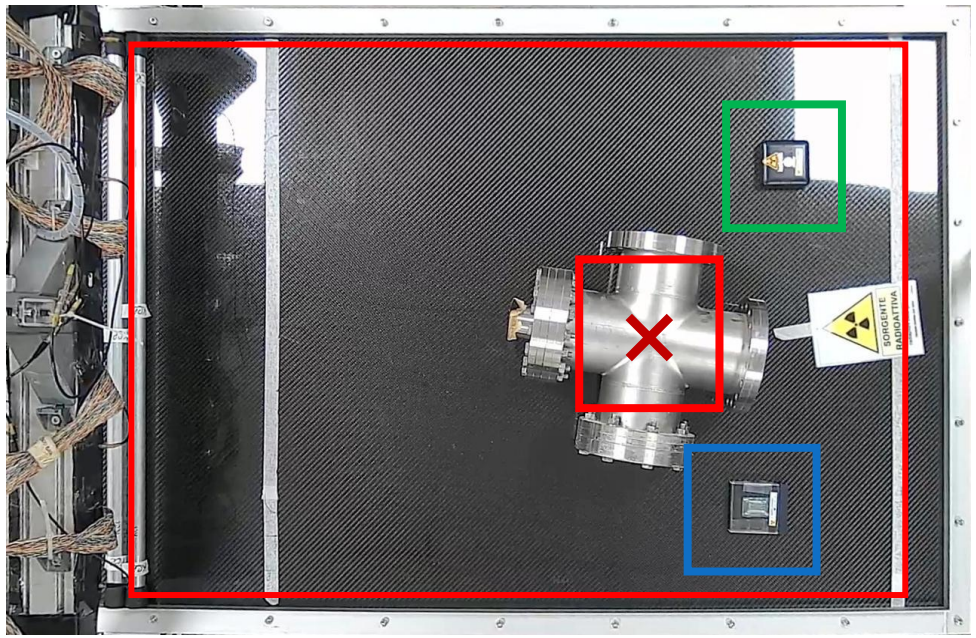
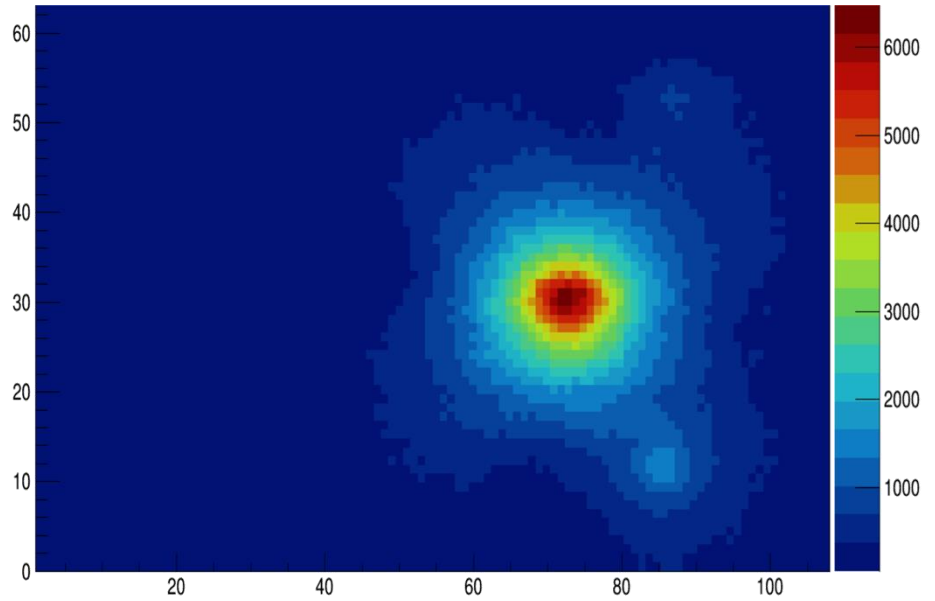
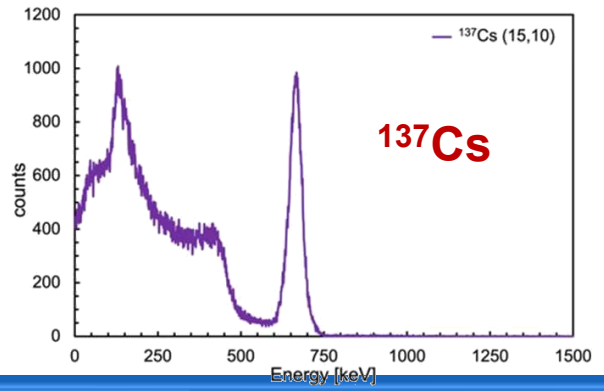
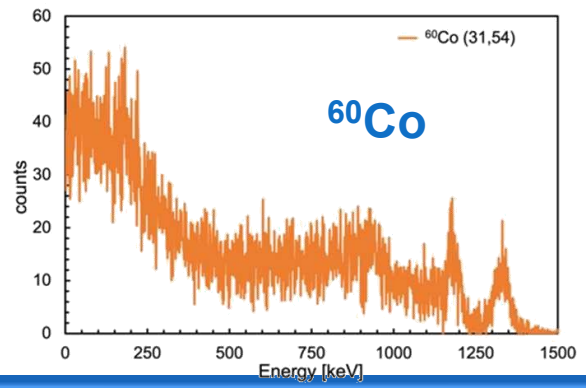
1.4MBq ^{137}Cs 12,6kBq ^{22}Na

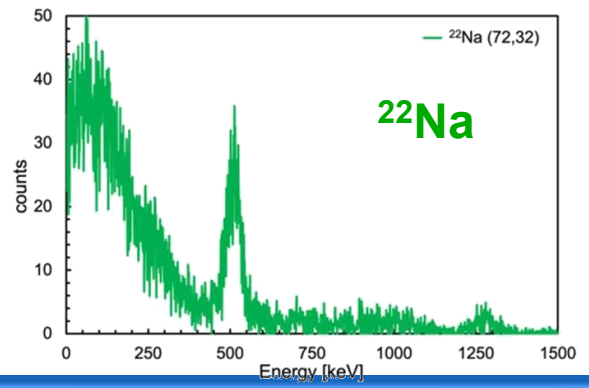


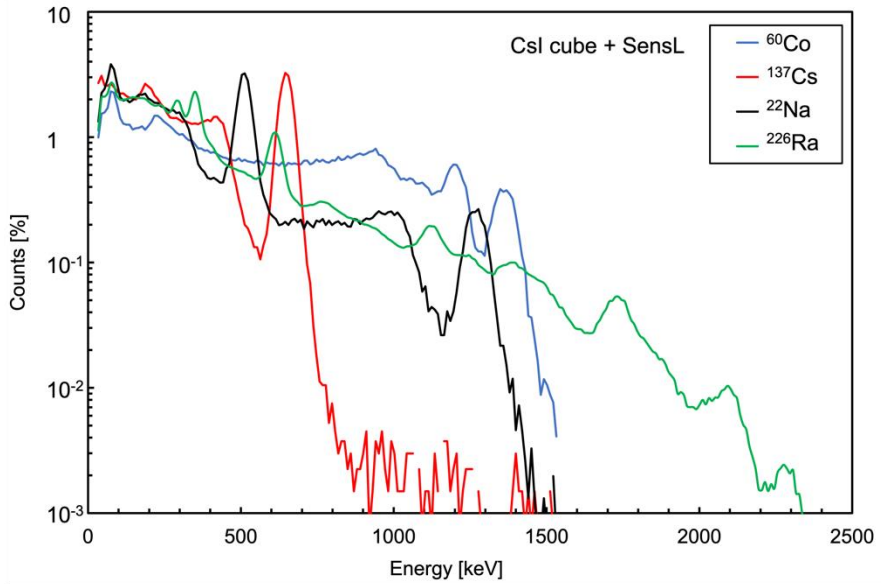
50,0kBq ^{60}Co

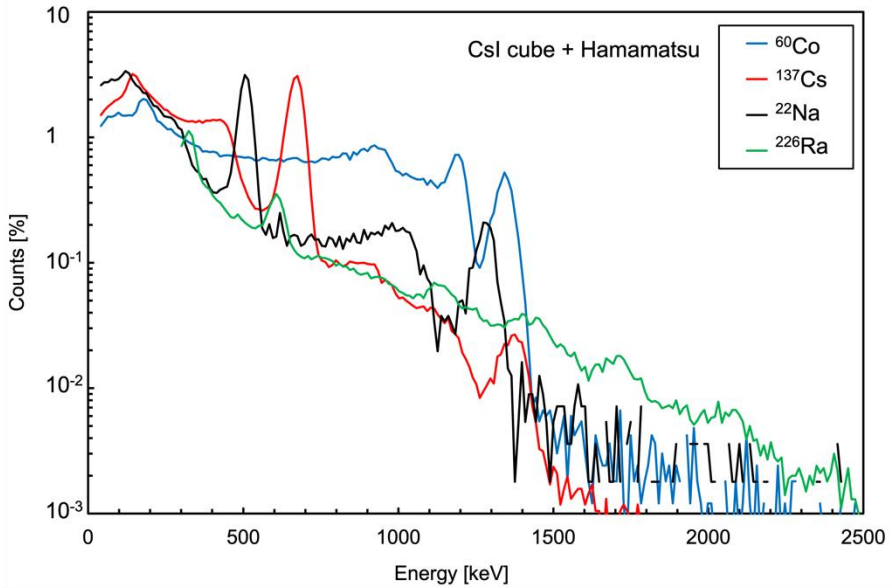


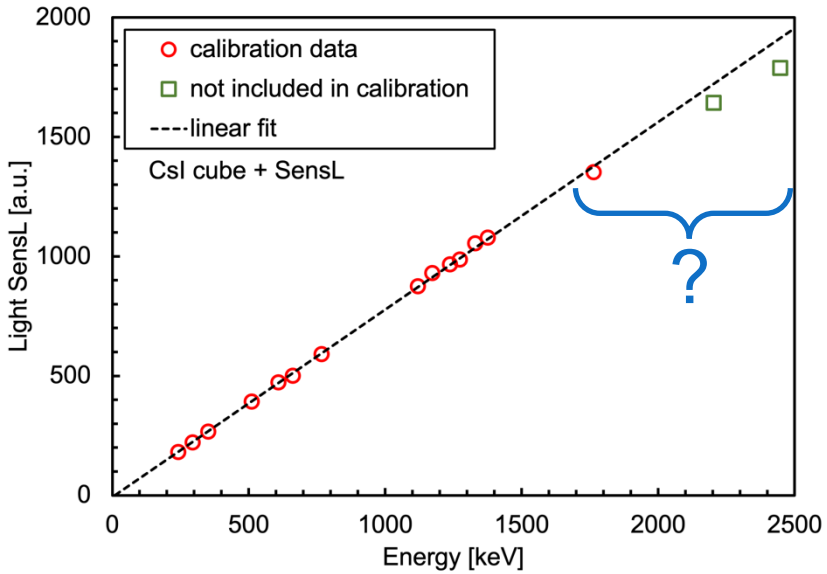


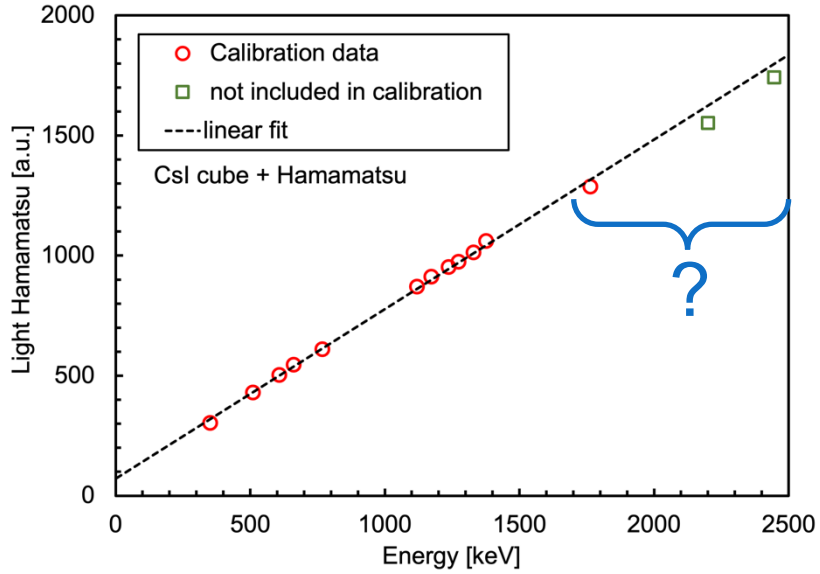






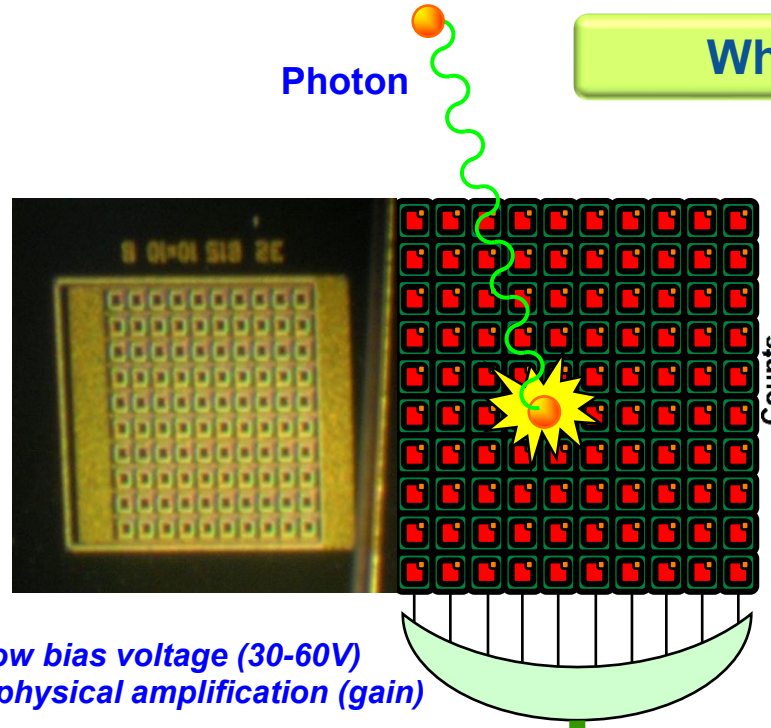






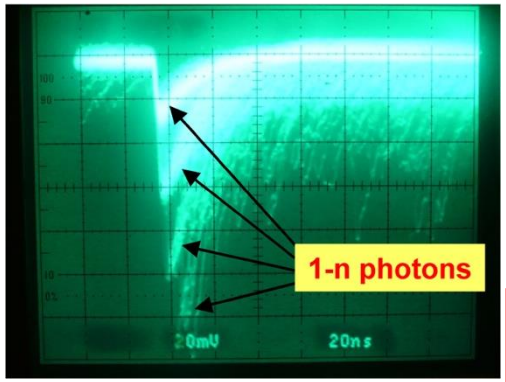
are the SiPMs non linear?

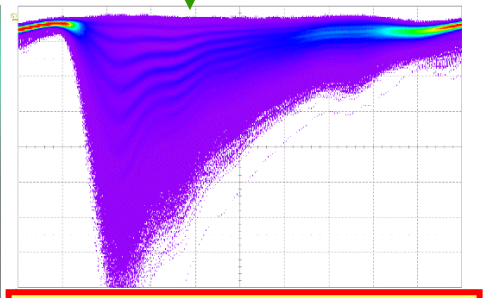
What is a SiPM?



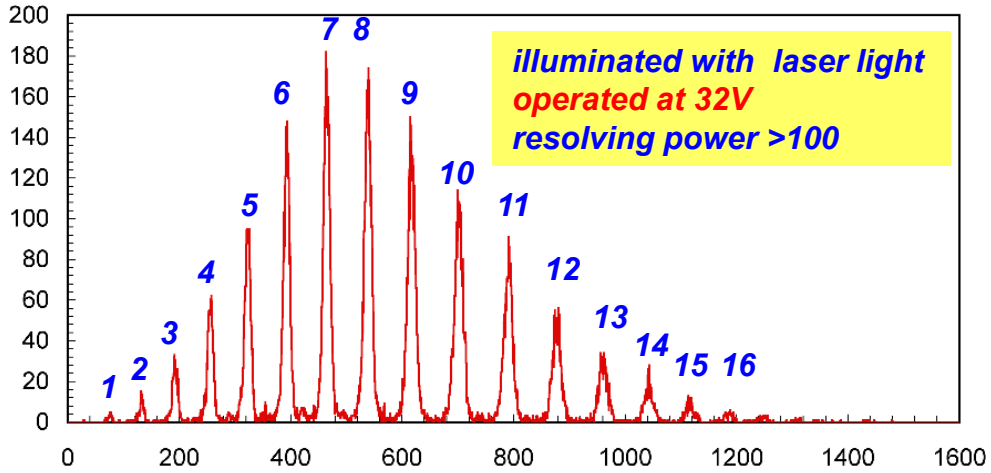
low bias voltage (30-60V)
high physical amplification (gain)

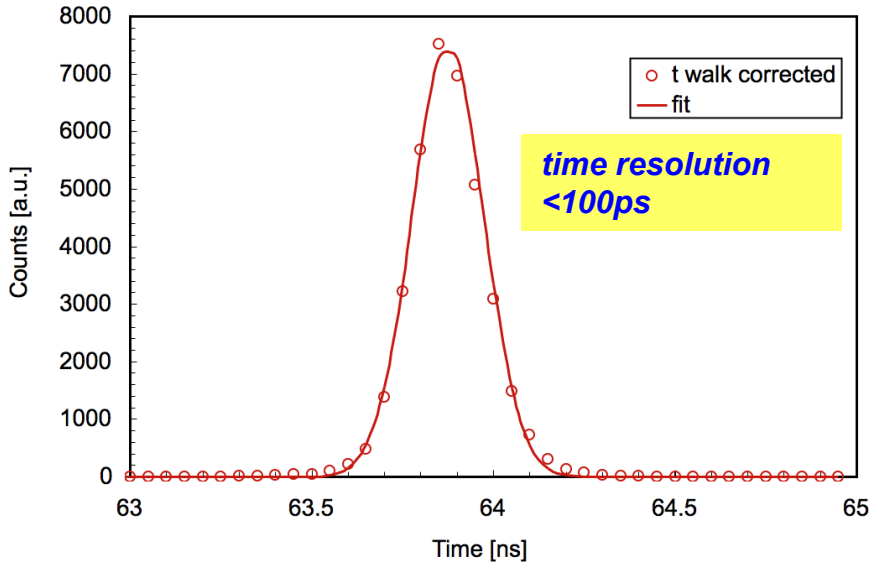
1 photon gives rise to a signal of ≈10^6 electrons





1-cell ⇒ charge = k
n-cells ⇒charge = nk

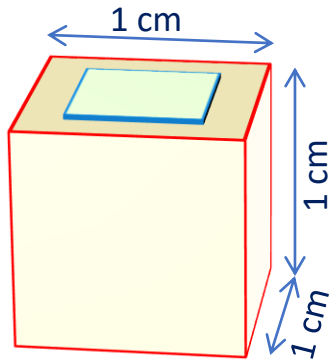


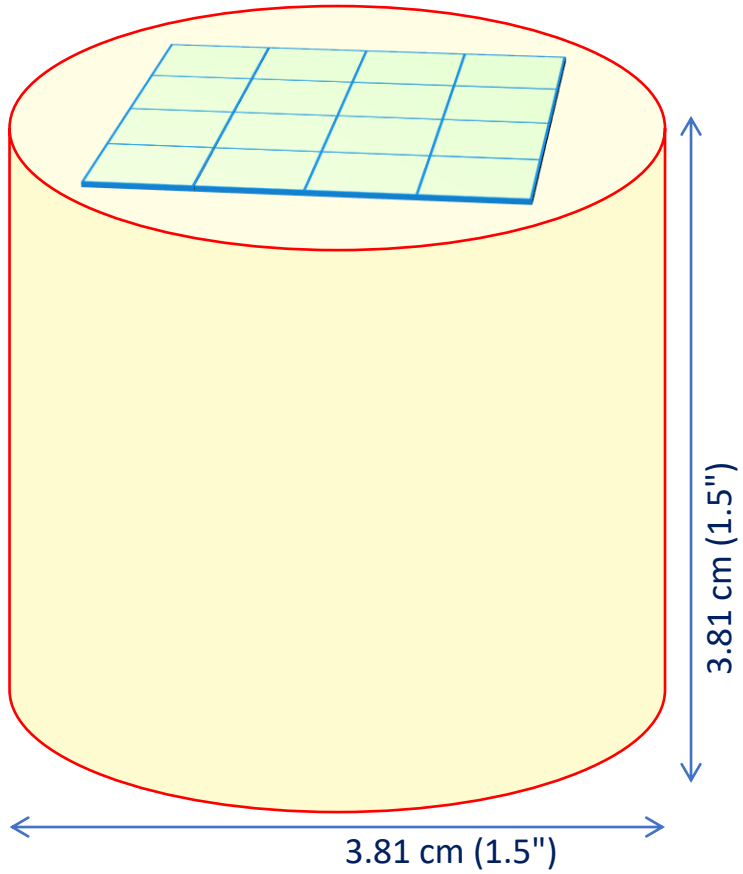


The model

we modeled

- 2 geometries: cube, cylinder
- 2 SiPMs 6mm × 6mm:
  - SensL MICROFC−60035−SMT
  - Hamamatsu S14160-6050HS
- 5 crystal types:
  - CsI(Tl)
  - LaBr3(Ce)
  - CeBr3
  - BGO
  - NaI(Tl)

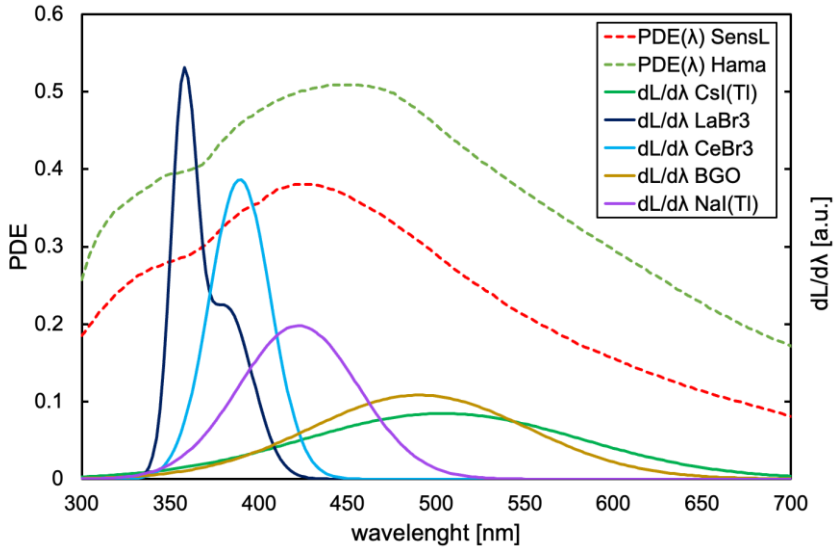


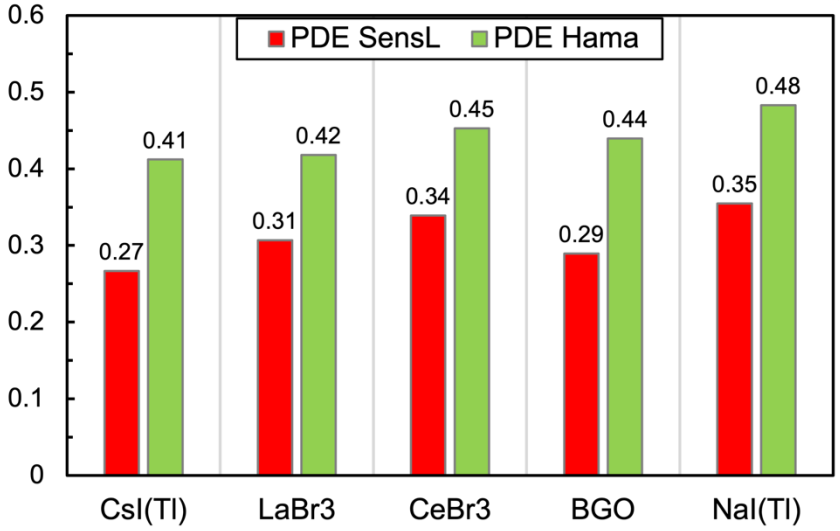


weighted the PDE with the light emission spectrum

	CsI(Tl)	LaBr3(Ce)	CeBr3	BGO	NaI(Tl)
Light yield [photons/keV]	60	70	70	10	45
Decay time [ns]	960	30	20	300	250
Refractive index at λ max	1.8	1.9	2.1	2.1	1.8
Weighted PDE SensL [%]	**27%**	**31%**	**34%**	**29%**	**35%**
Weighted PDE Hamamatsu [%]	**41%**	**42%**	**45%**	**44%**	**48%**

	MICROFC−60035−SMT SensL (now OnSemi)	S14160-6050HS Hamamatsu
number of microcells	18980	14331
microcell recharge time [ns]	100	92





Simple naive model for the light collection efficiency

No geometry considered

Photon produced inside hits the inner surface

Assume it hits the SiPM with probability ε equal to the area ratio

Otherwise it is reflected *(r)* or absorbed *(1 - r)*

P_1 = probability of collection after 1 step

P_n = probability of collection after n steps

$$P_1 = \varepsilon$$

$$P_2 = \varepsilon(1-\varepsilon)r$$

$$P_3 = \varepsilon[(1-\varepsilon)r]^2$$

...

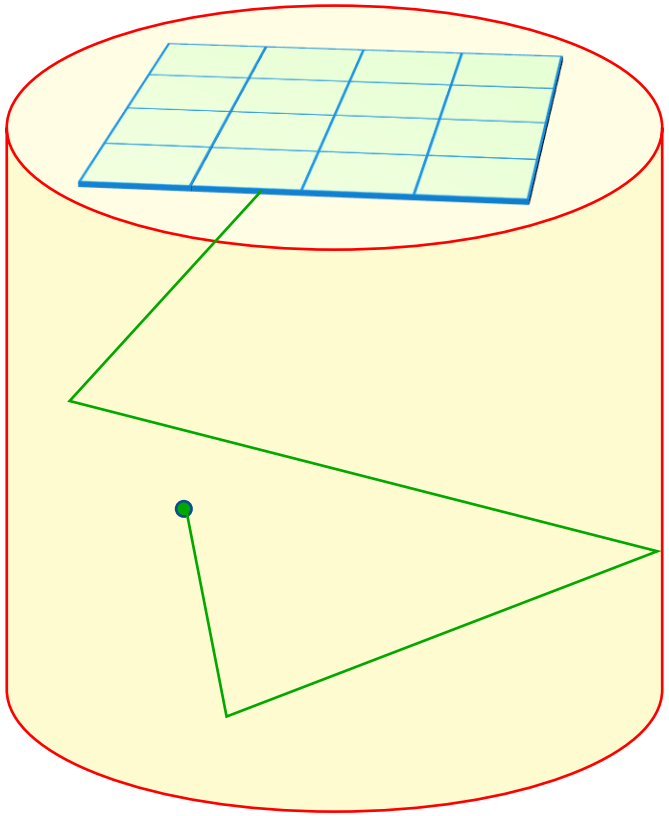
$$P_n = \varepsilon[(1-\varepsilon)r]^{n-1}$$

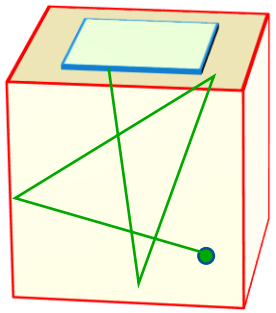
$$P = \sum_n P_n = \sum_n \varepsilon[(1-\varepsilon)r]^{n-1} = \varepsilon\frac{1-[(1-\varepsilon)r]^n}{1-(1-\varepsilon)r} \approx \frac{\varepsilon}{1-r+r\varepsilon}$$

Light collection efficiency P = overall collection probability

P calculated for r = 0.9 to 1.0, step = 0.01

Cross-check with a GEANT4 Monte Carlo model

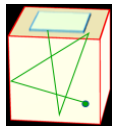


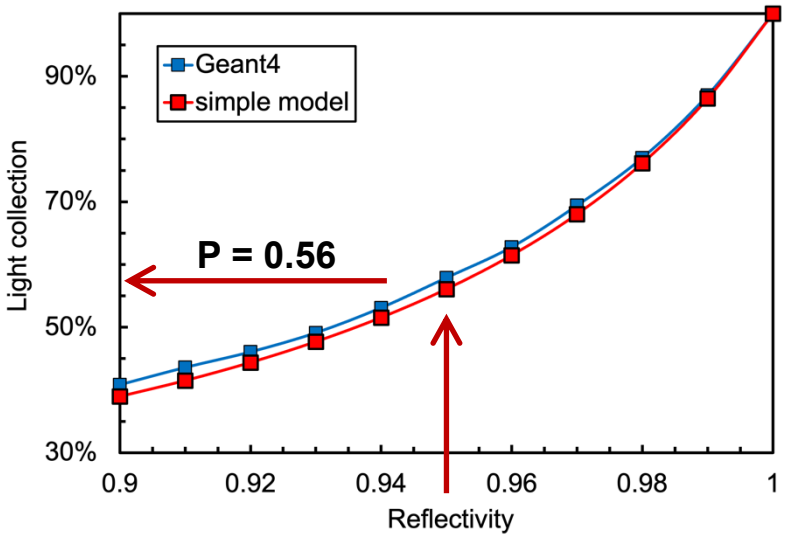


- Lambertian inner (white) surface reflection (distributed as $\cos\vartheta$)
- 10^5 photons were generated and tracked in each run
- 11 runs in cubic geometry (r = 0.9 to 1.0, step=0.01)
- 11 runs in cylindrical geometry (r = 0.9 to 1.0, step = 0.01)

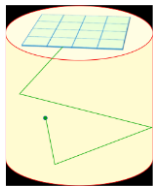
Light collection efficiency P = n. of photons on the SiPM / 10^5

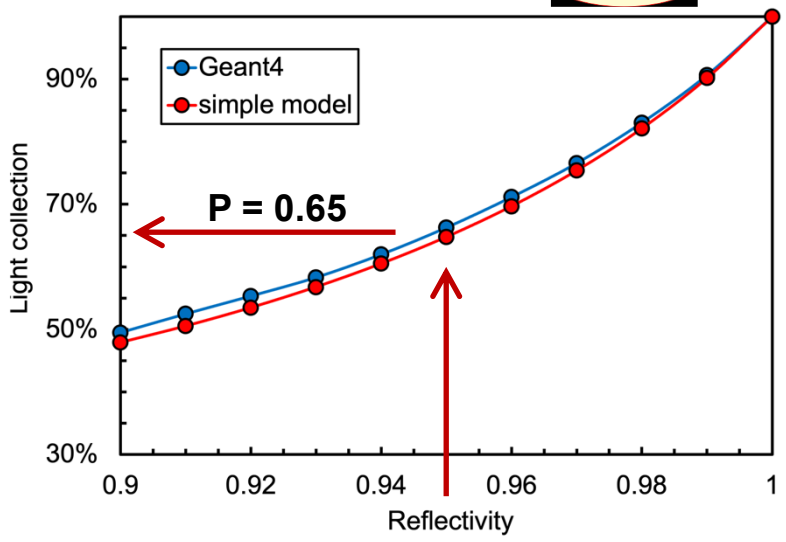
Cube ε = 0.06





Cylinder ε = 0.084





At r = 0.95 the difference is ≤ 2%

...curiously...

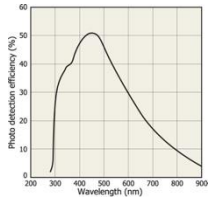
...if using $\varepsilon^{+} = \varepsilon \times 1.067$...

...the difference reduces to ≈ 0.1%

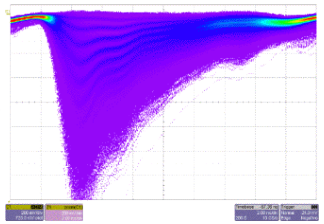
Chosen a realistic value of r = 0.95

Multiple hit effect on SiPM?

q photons | impinge on a SiPM with m microcells | and photon detection efficiency p | trigger f hits



PDE



$$f(q) = m\left[1 - \left(1 - \frac{p}{m}\right)^{q}\right]$$

exact formula (binomial distribution)

$$\lim_{n\to\infty}\left(1 + \frac{x}{n}\right)^{n} = e^{x}$$

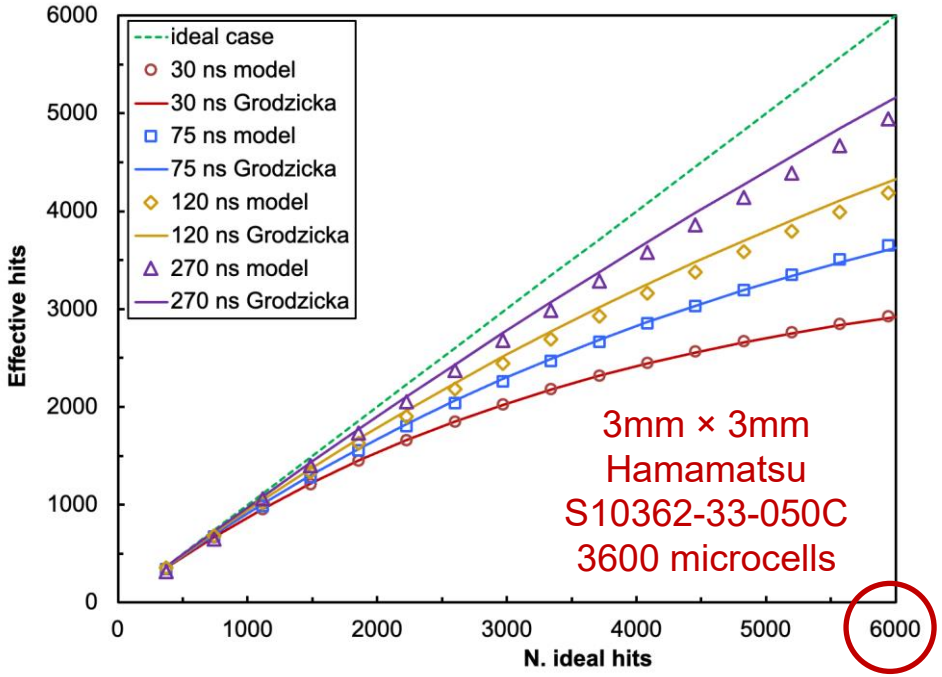
exploit the notable limit

$$f(q) = m\left(1 - e^{-\frac{pq}{m}}\right)$$

perfect approximation

- follow the time evolution
- in 5ns steps
- disable the triggered cells
- during their recharge time

Comparison of our model with the Grodzicka formula gaussian-shaped light pulses



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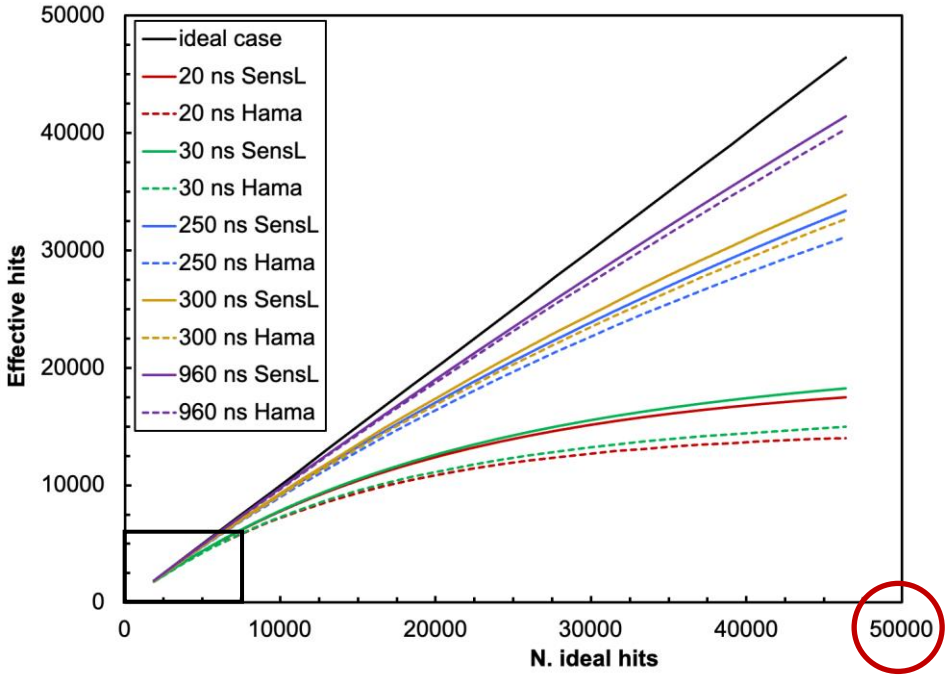
New method for evaluating effective recovery time and single photoelectron response in silicon photomultipliers

Martyna Grodzicka*, Tomasz Szczęśniak, Marek Moszyński, Marek Szawłowski, Krystian Grodzicki

National Centre for Nuclear Research, A. Soltana 7, PL 05-400 Świerk, Otwock, Poland

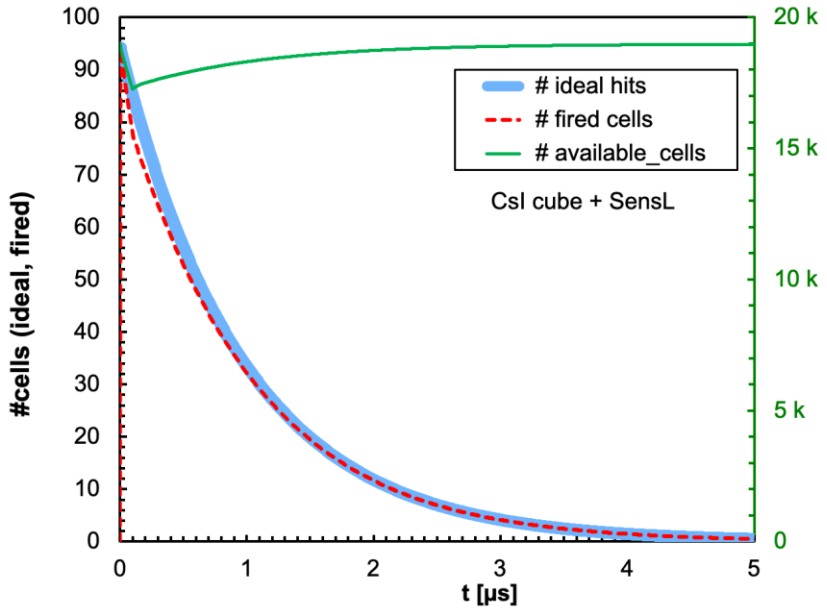
Comparison of our model with the extrapolation of Grodzicka formula Intense exponential-shaped light pulses

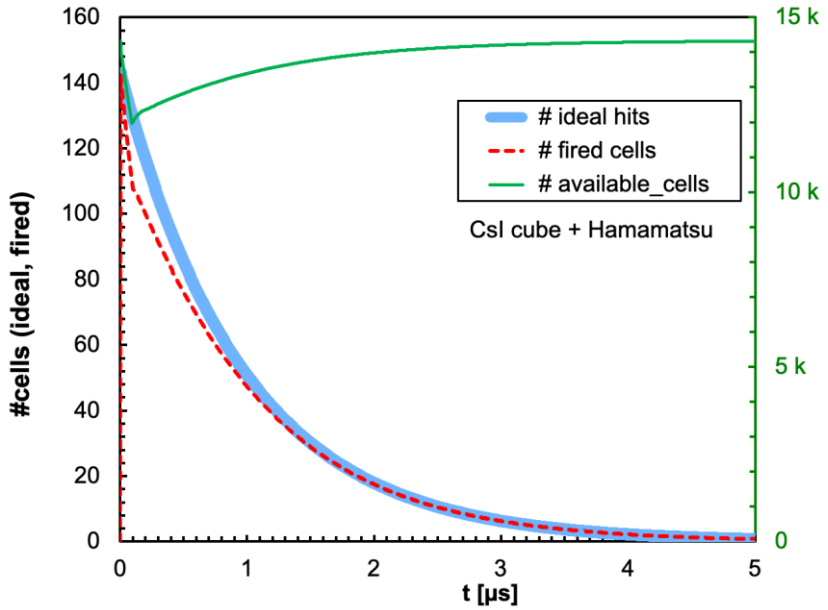


18980 microcells SensL MICROFC−60035−SMT
14331 microcells Hamamatsu S14160-6050HS

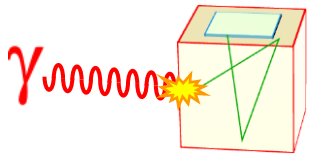
Different results due to
- **exp vs gauss pulse shape**
- **following time evolution**

CsI(Tl) | τ = 960 ns | L.Y. = 60 Ph/keV





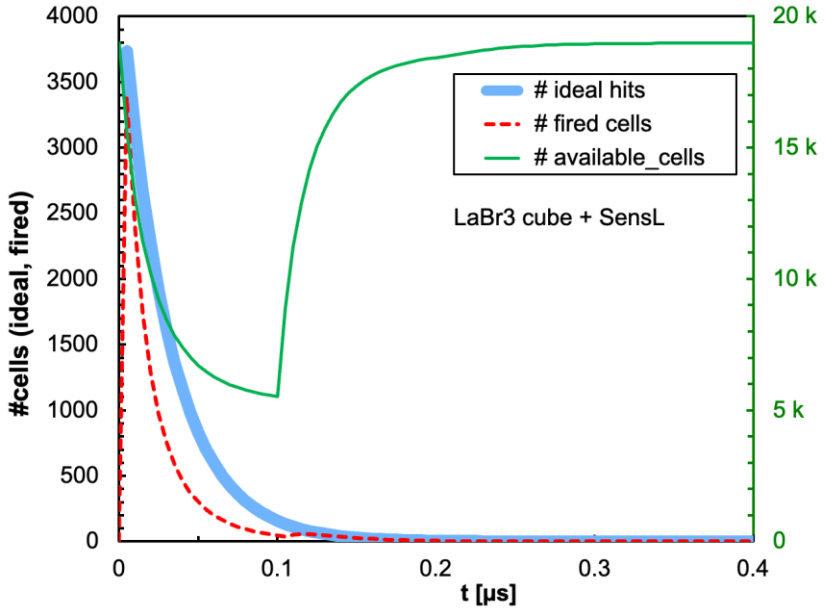
2 MeV deposited gamma ray

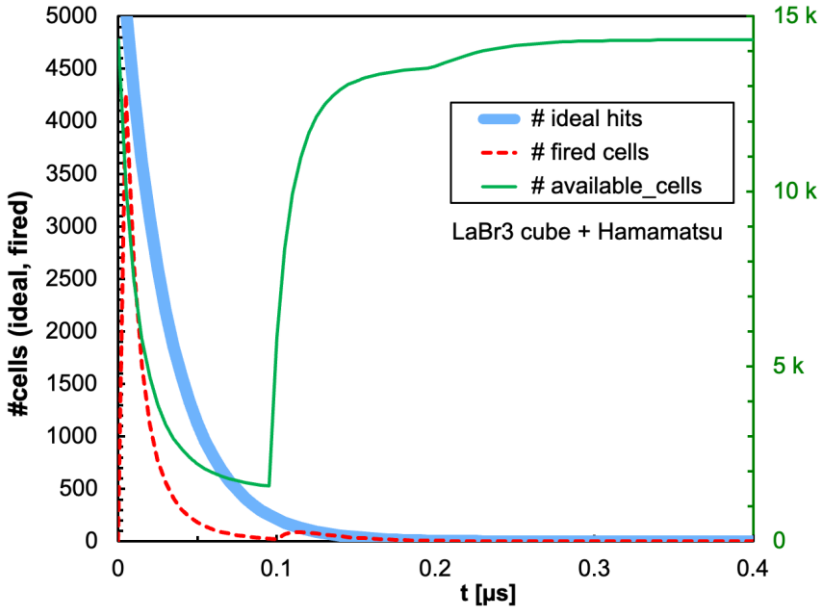


SensL 18980 cells
weighted PDE = 27%

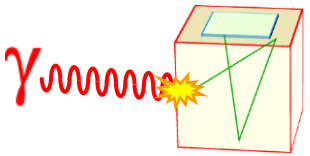
Hamamatsu 14331 cells
weighted PDE = 41%

LaBr3(Ce) τ = 30 ns L.Y. = 70 Ph/keV





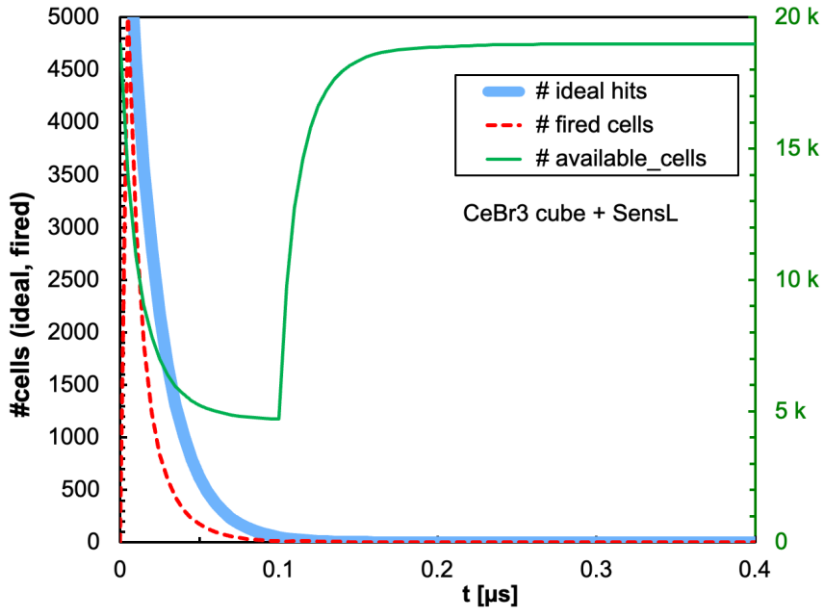
2 MeV deposited gamma ray

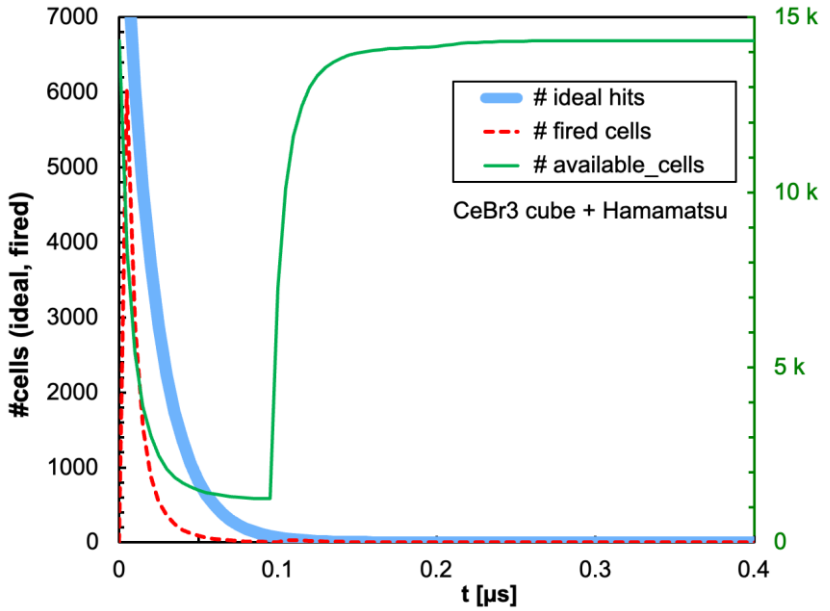


SensL 18980 cells weighted PDE = 31%

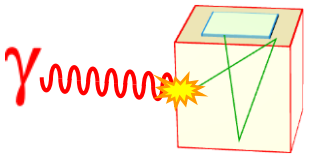
Hamamatsu 14331 cells weighted PDE = 42%

CeBr3 | **τ = 20 ns** | **L.Y. = 70 Ph/keV**





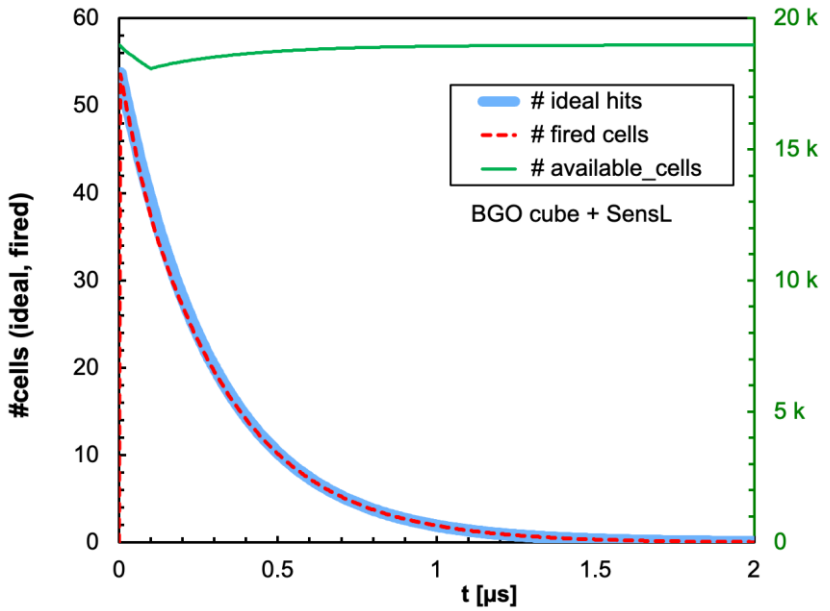
2 MeV deposited gamma ray



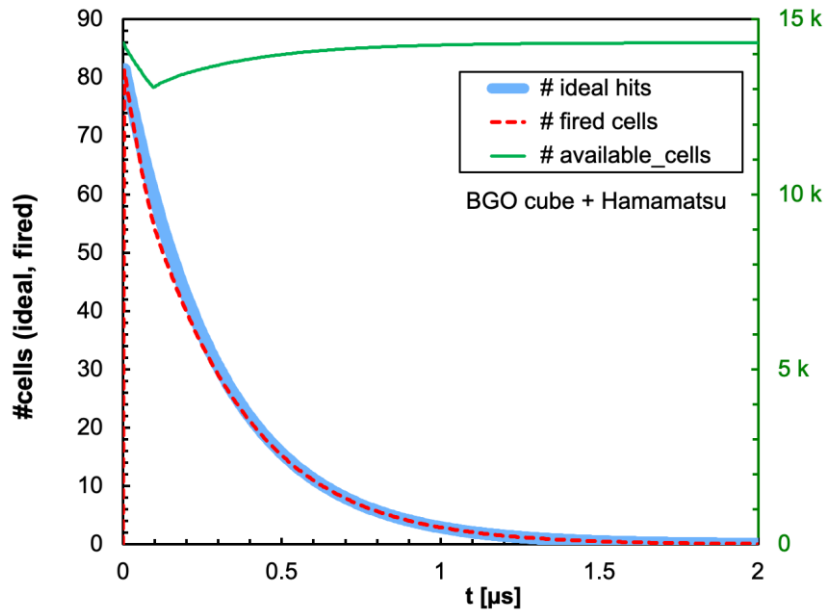
SensL 18980 cells
weighted PDE = 34%

Hamamatsu 14331 cells
weighted PDE = 45%

BGO τ = 300 ns L.Y. = 10 Ph/keV

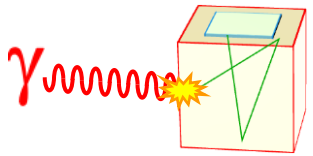


SensL 18980 cells
weighted PDE = 29%



Hamamatsu 14331 cells
weighted PDE = 44%

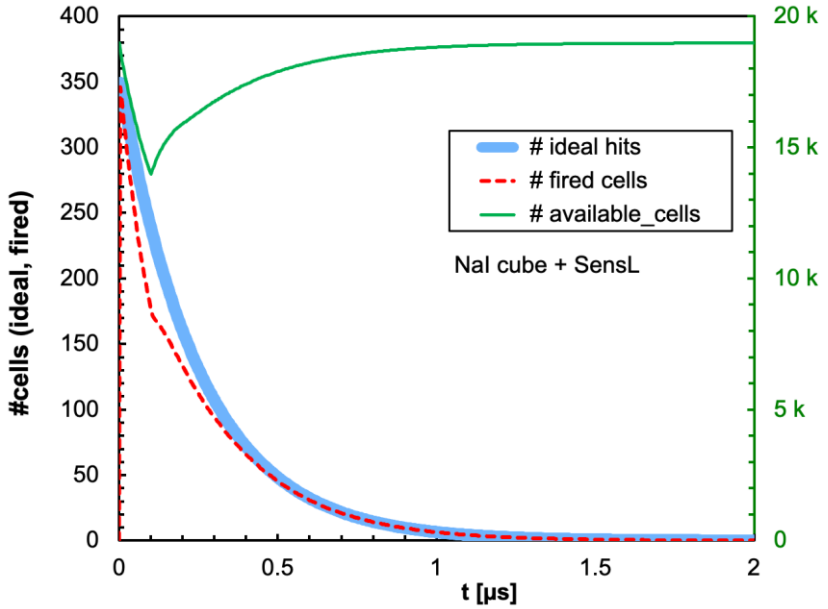
2 MeV deposited gamma ray



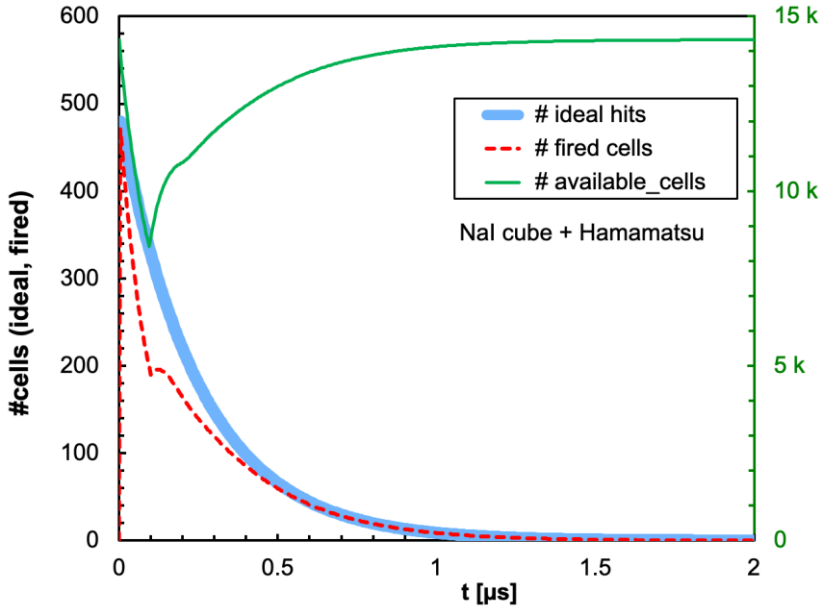
NaI(Tl)

τ = 250 ns

L.Y. = 45 Ph/keV

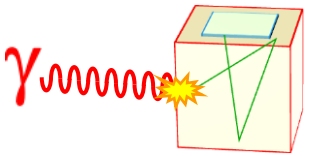


SensL 18980 cells
weighted PDE = 35%



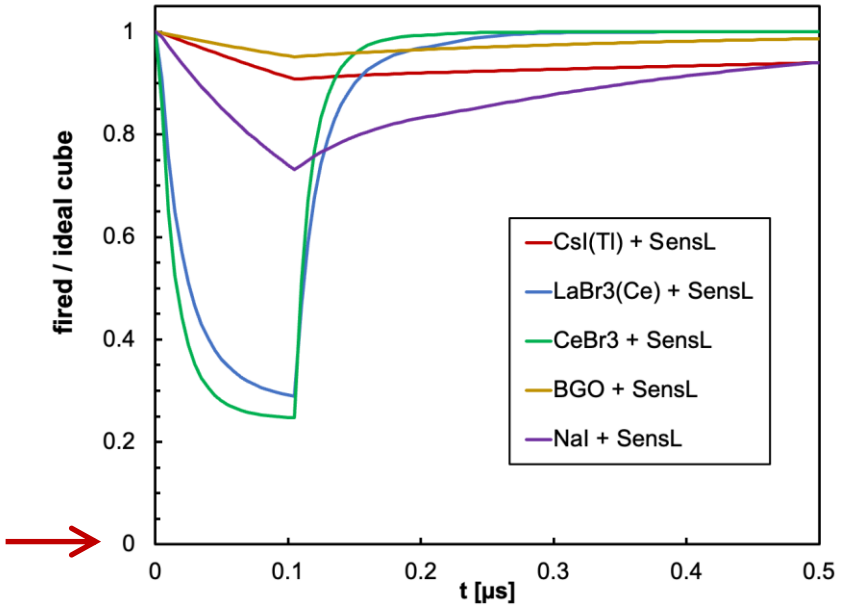
Hamamatsu 14331 cells
weighted PDE = 48%

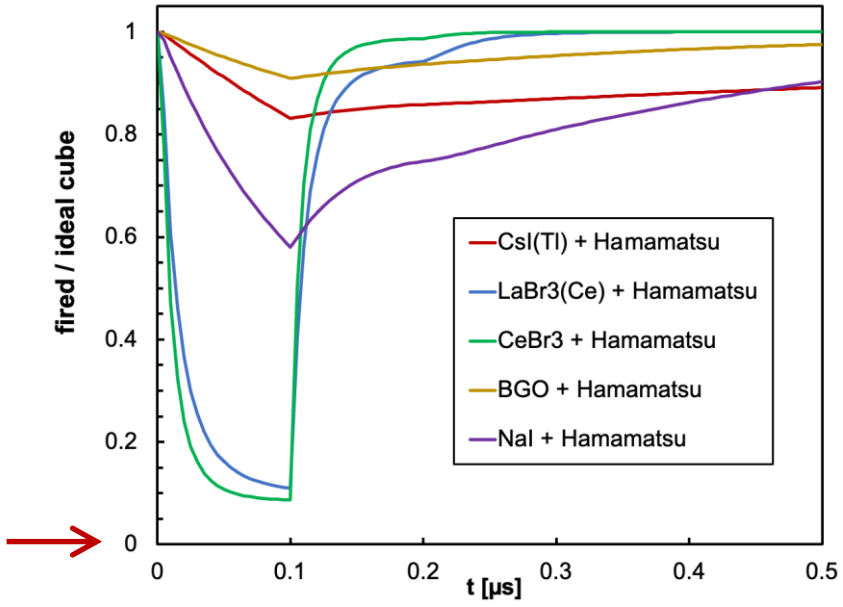
2 MeV deposited gamma ray

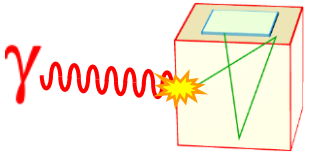


fired to ideal #microcells ratio

2 MeV deposited gamma ray



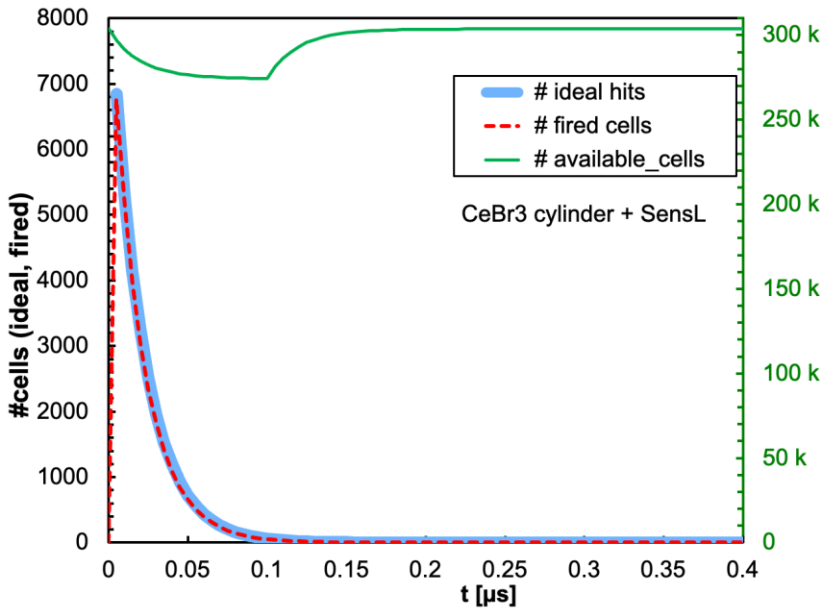


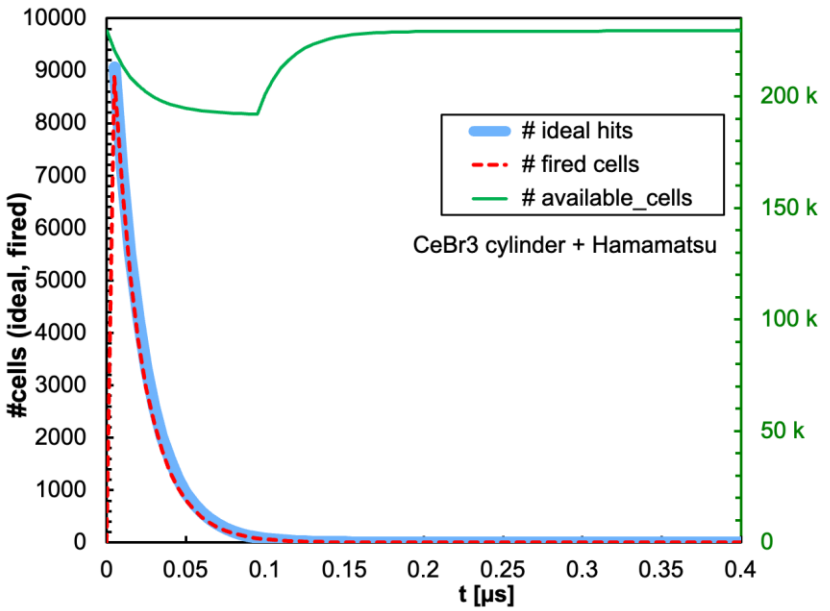


SensL 18980 cells

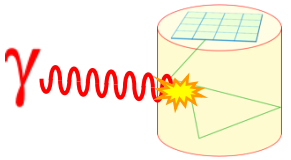
Hamamatsu 14331 cells

CeBr3 τ = 20 ns L.Y. = 70 Ph/keV





2 MeV deposited gamma ray

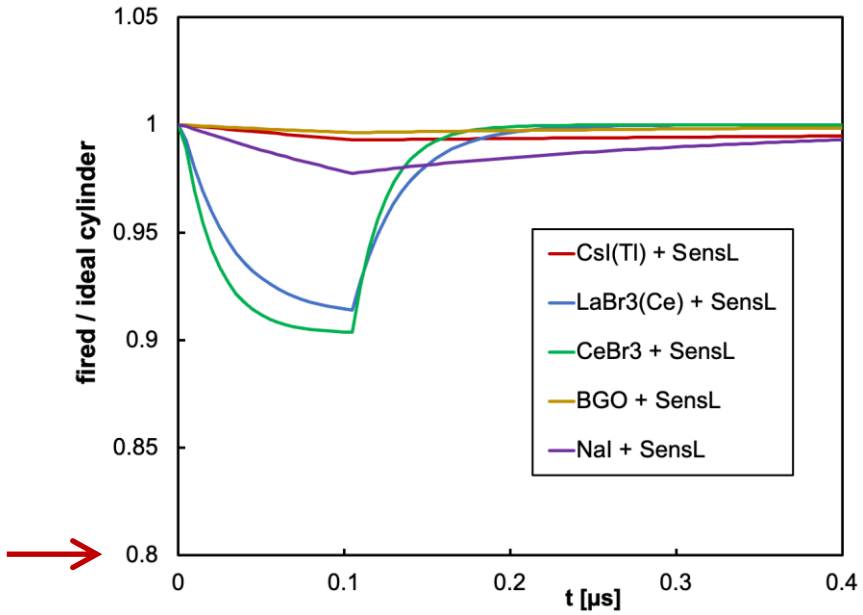


SensL 18980 × 16 cells weighted PDE = 34%

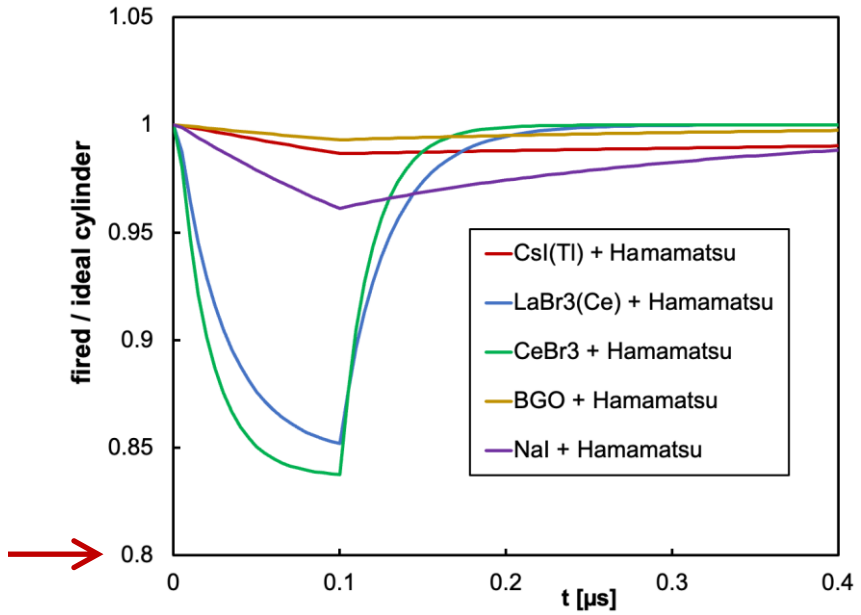
Hamamatsu 14331 × 16 cells weighted PDE = 45%

fired to ideal #microcells ratio

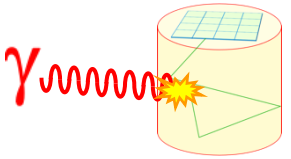
2 MeV deposited gamma ray



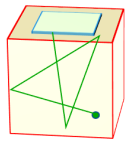
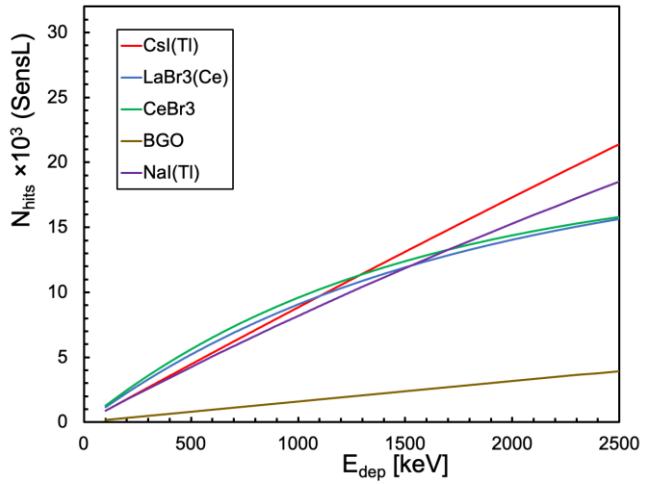
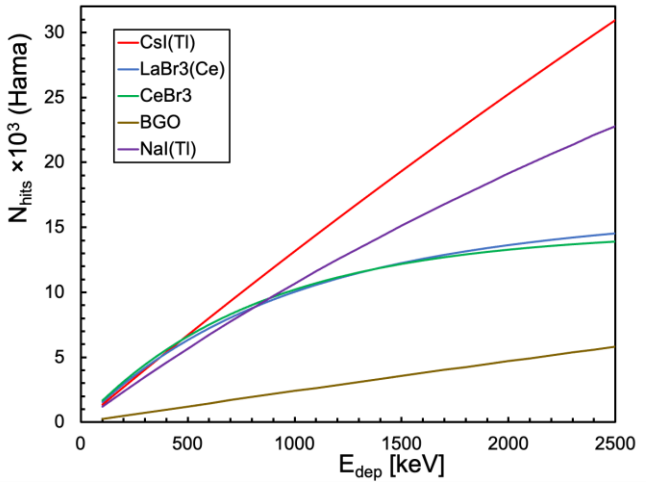
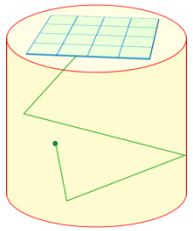
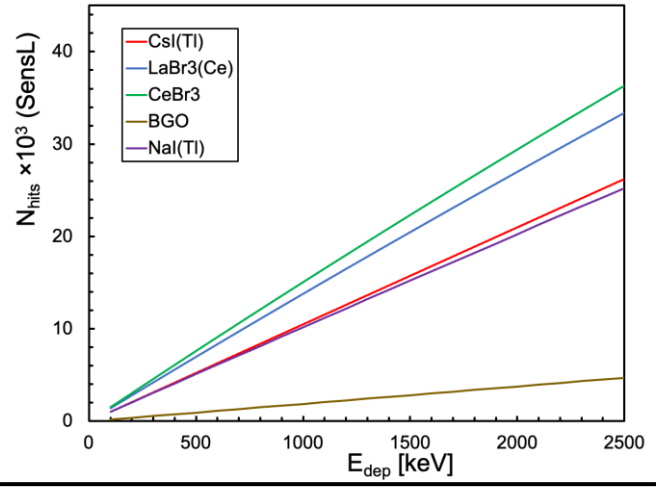
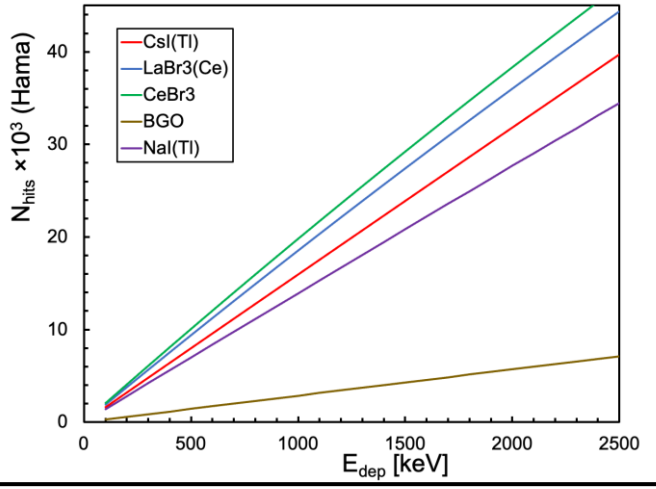
SensL 18980 × 16 cells

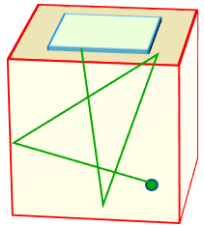


Hamamatsu 14331 × 16 cells

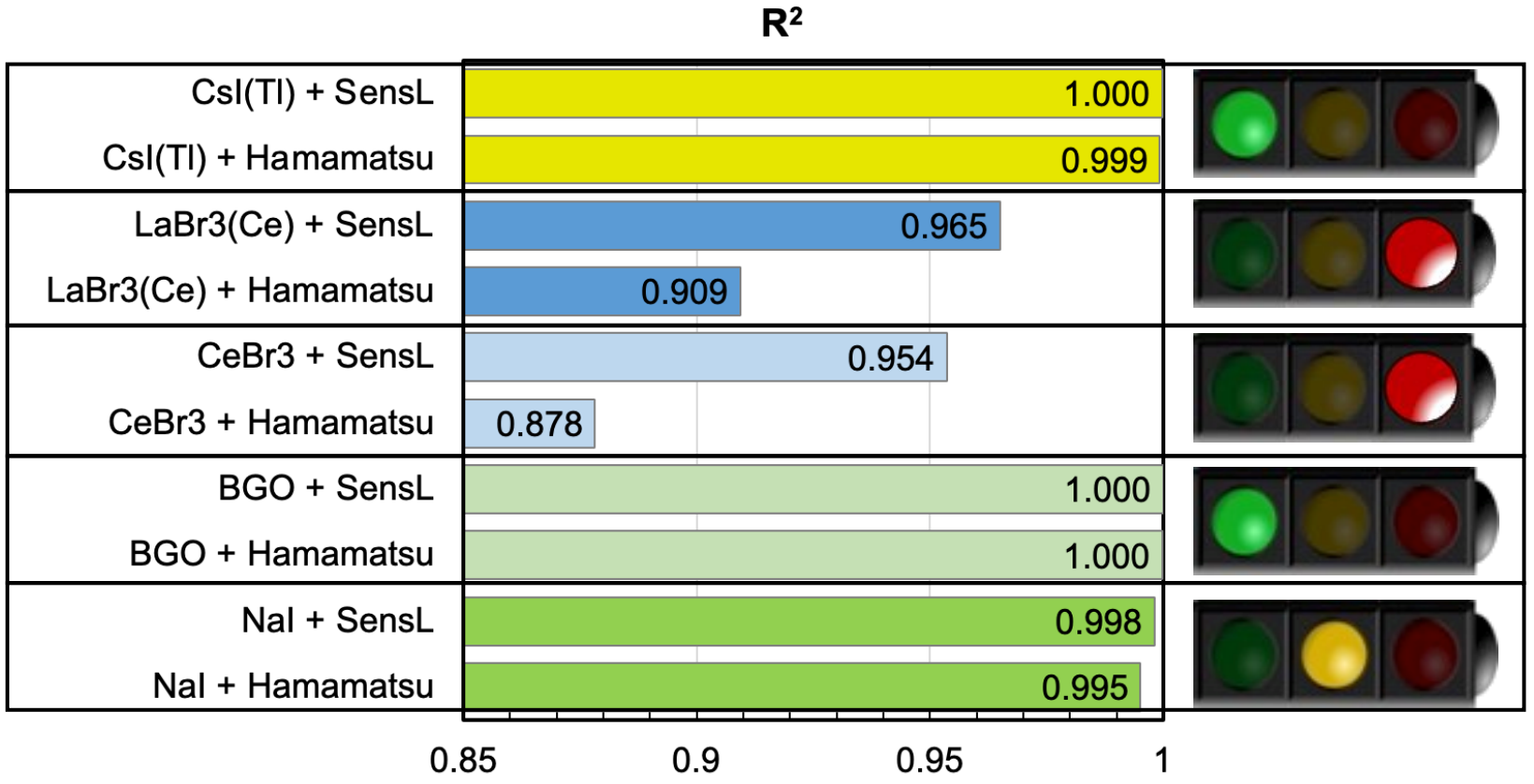


Response linearity

	SensL 18980 cells, smaller PDE	Hamamatsu 14331 cells, larger PDE	
			1 SiPM
			16 SiPMs



Response linearity: R^2 from linear fit



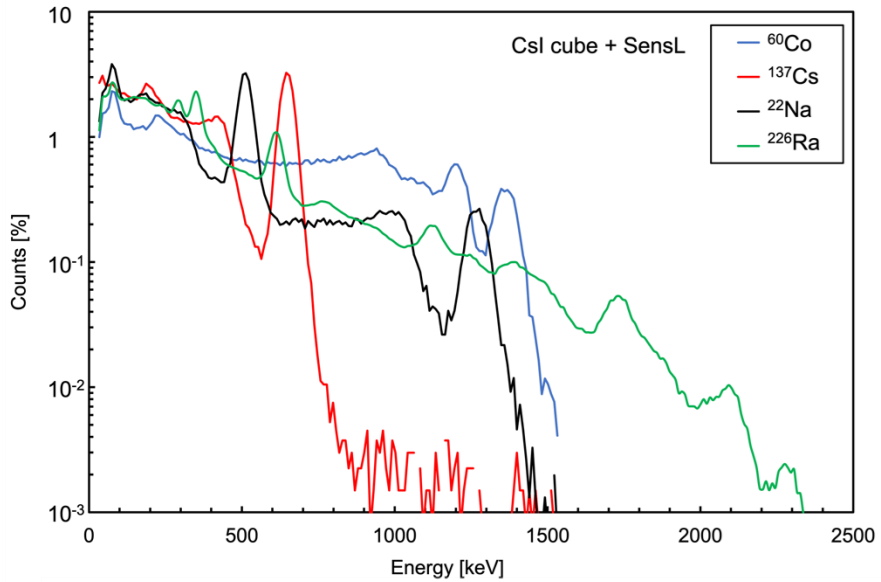
perfect

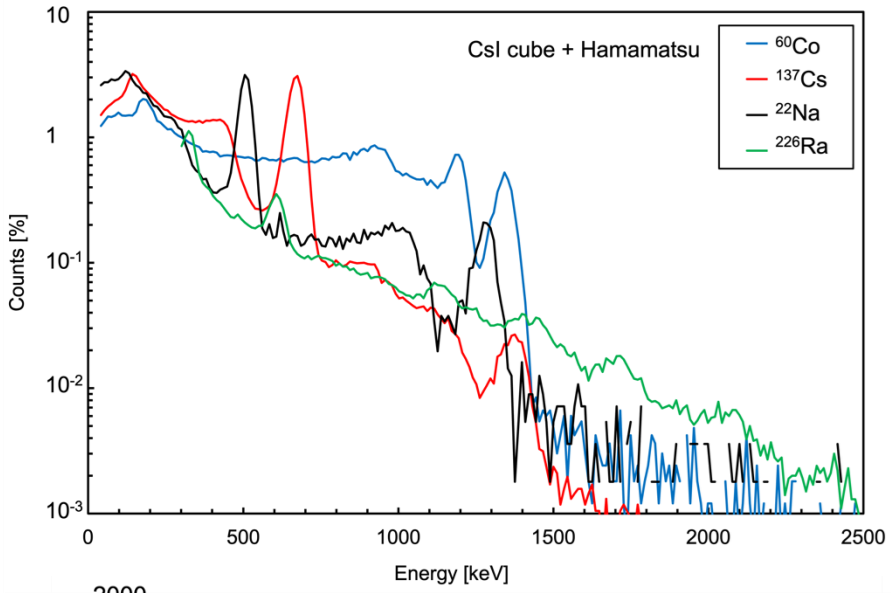
unsuited

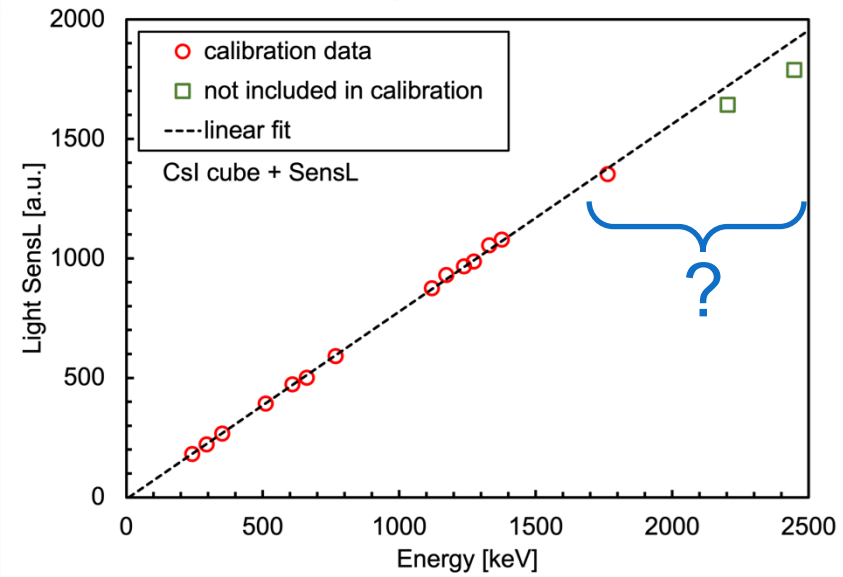
unsuited

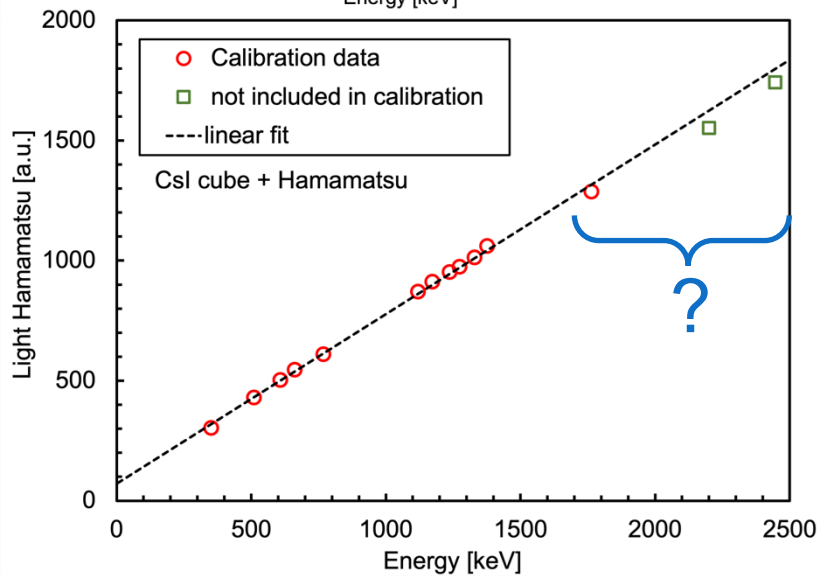
linear but poor light yield

reasonable









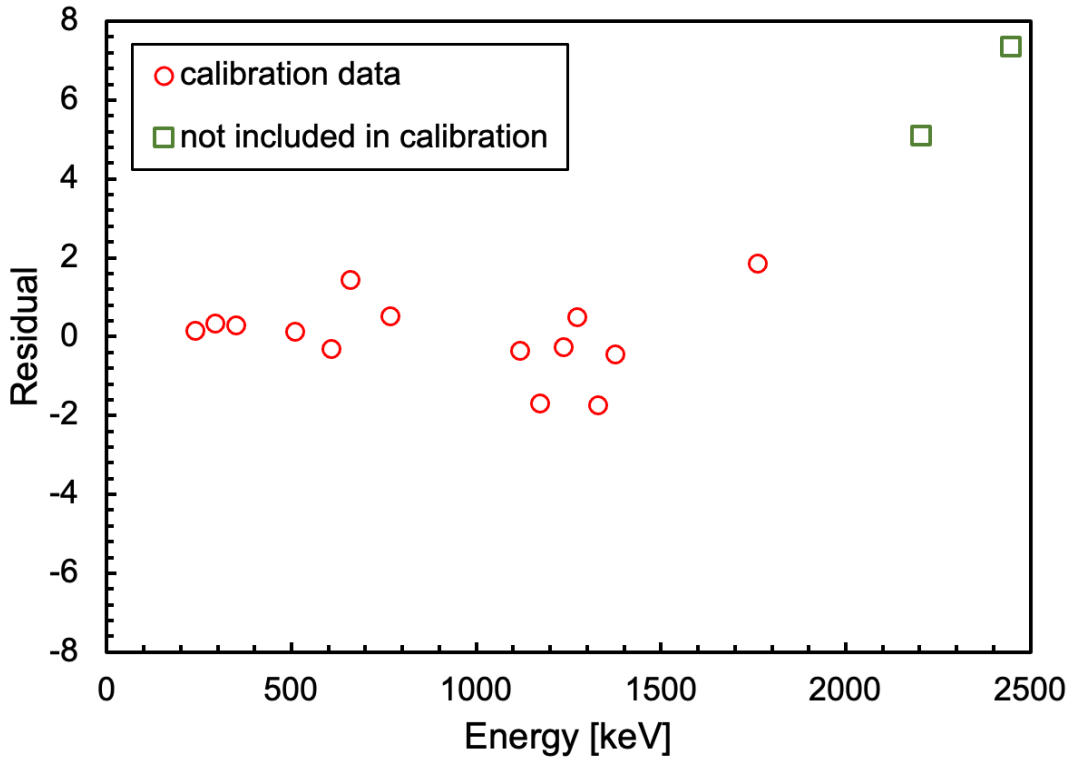
is one SiPM + CsI(Tl) cube non-linear?

Not really, likely it is CsI(Tl) non-linearity

also reported by other authors

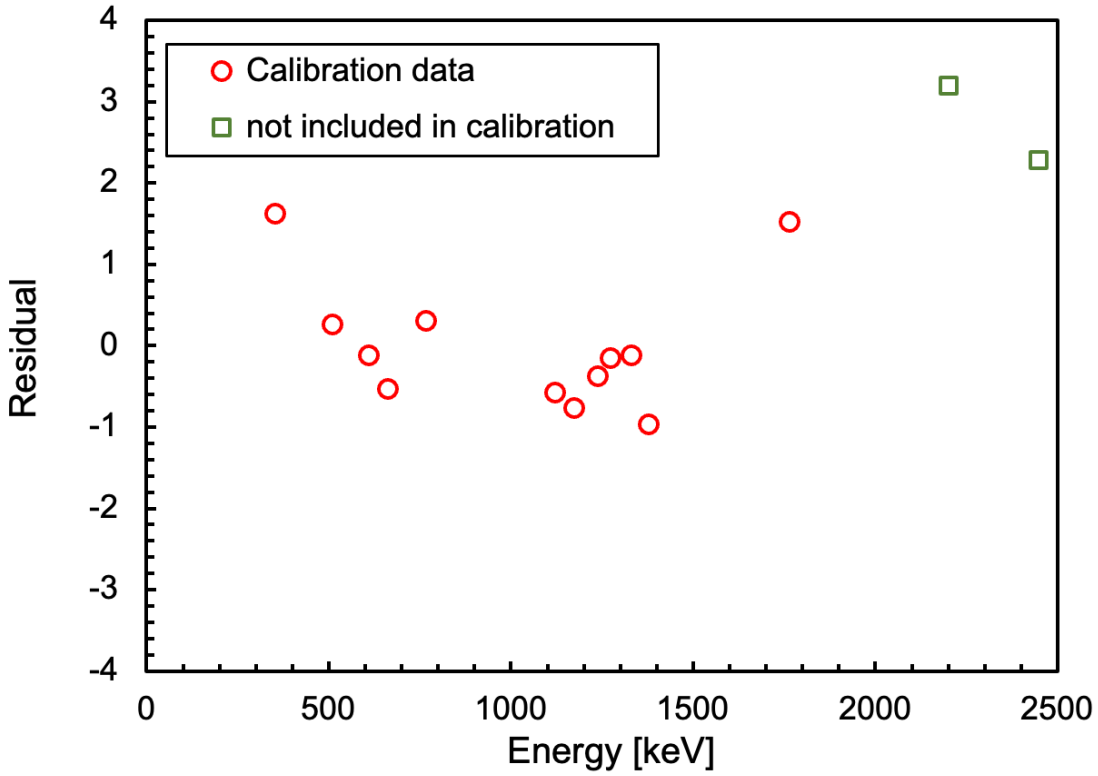
Residuals

CLEANDEM

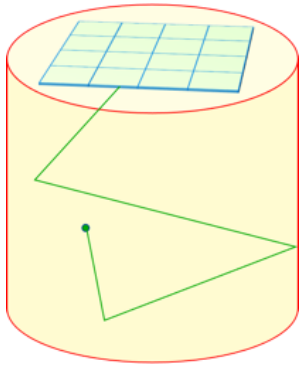


SensL

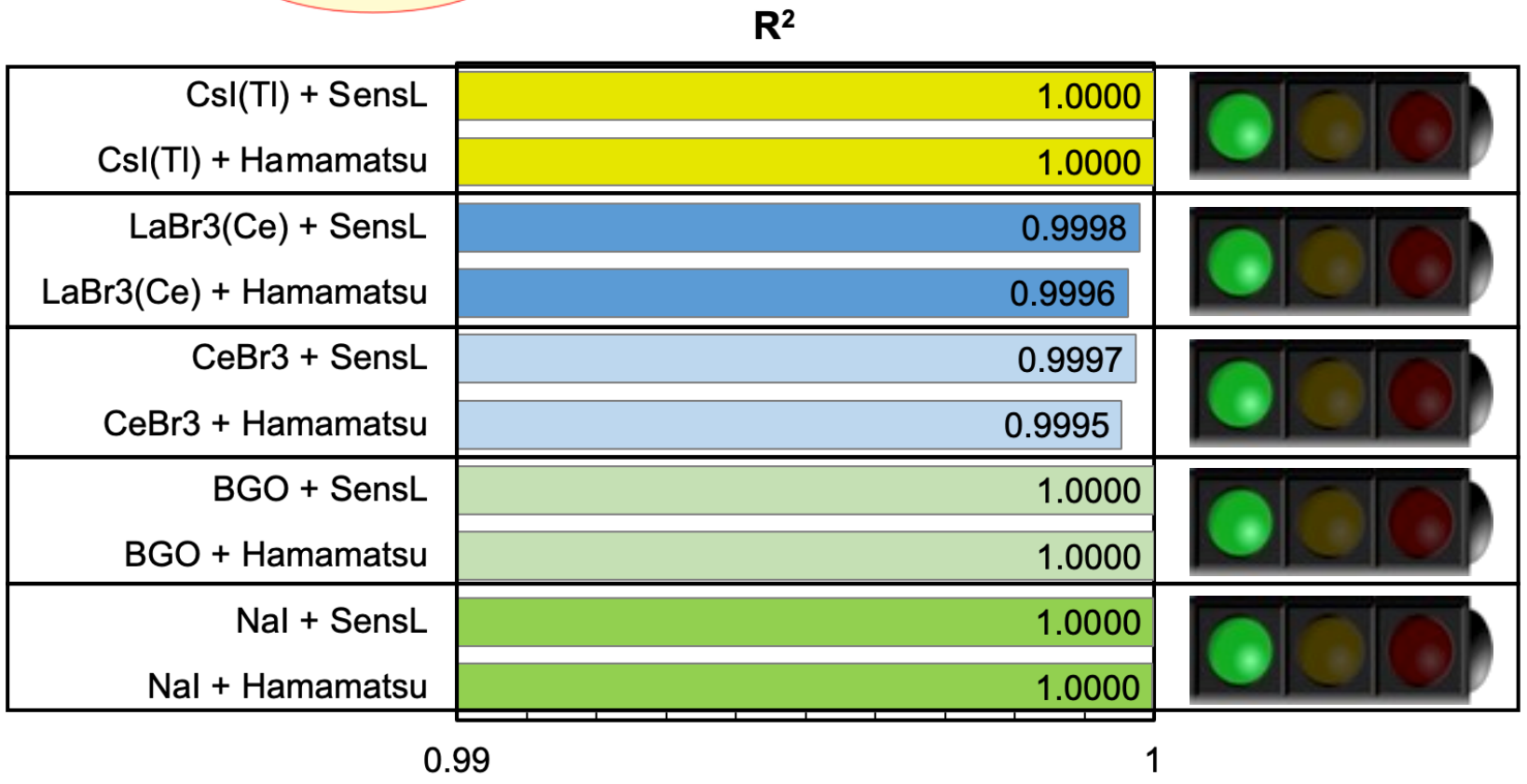
PI3SO



Hamamatsu



Response linearity: R^2 from linear fit



perfect

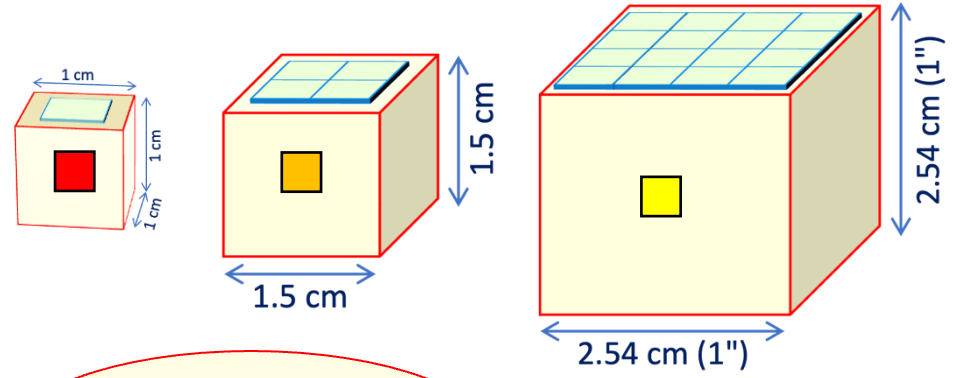
very good, perfect E resolution

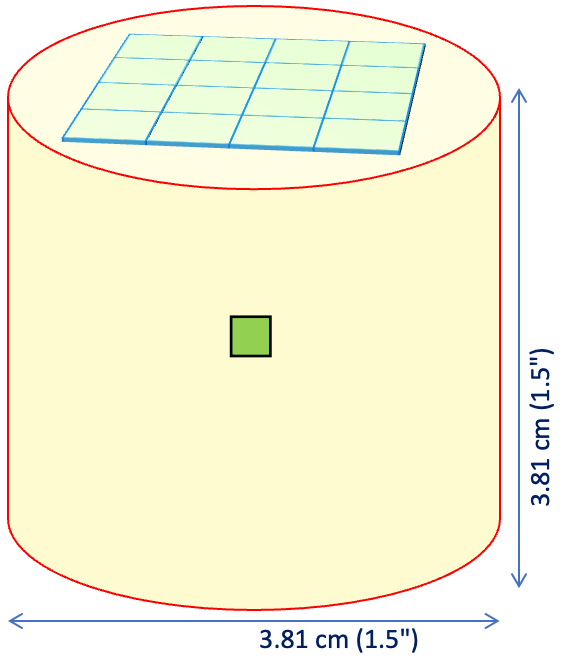
very good, perfect E resolution

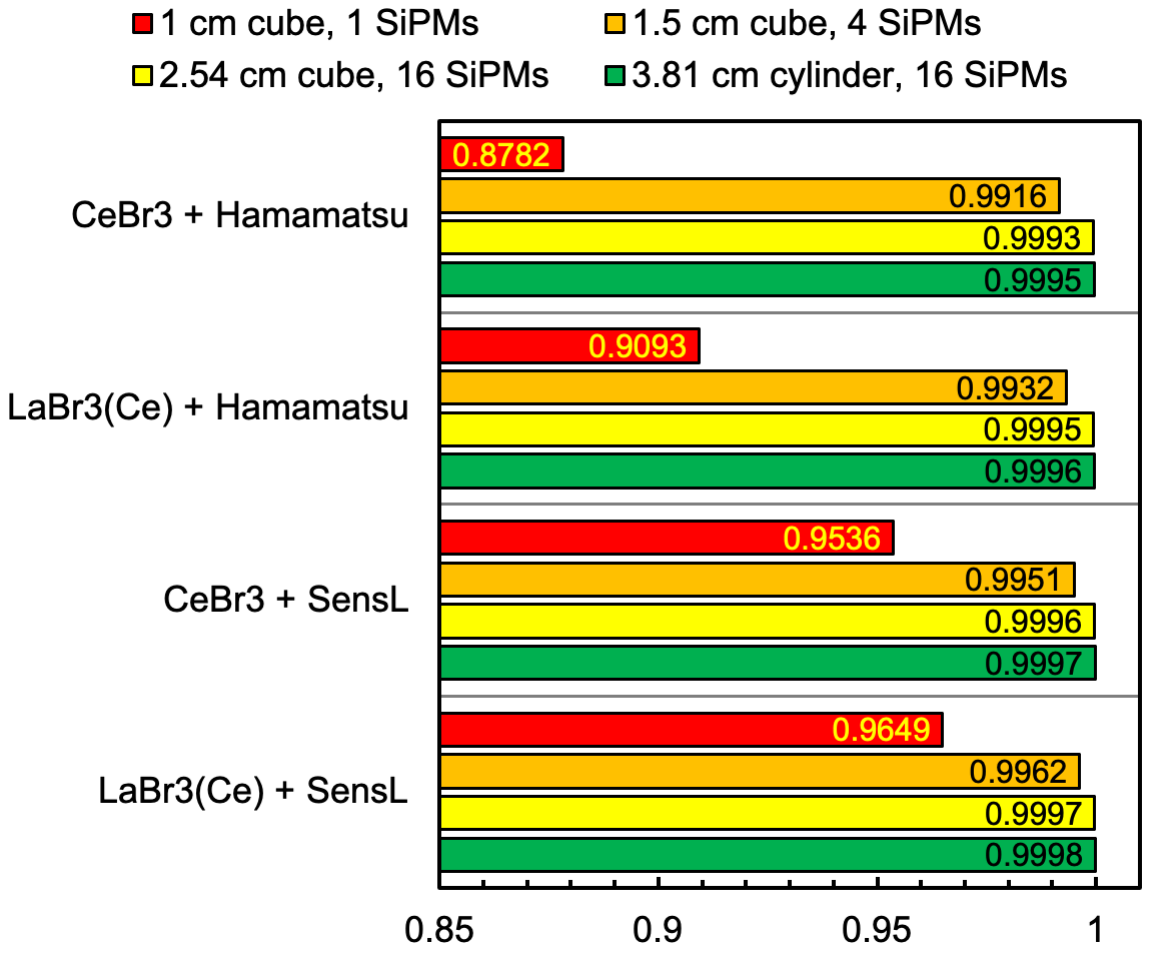
perfect but poor light yield

perfect

Additional configurations investigated behavior with LaBr3(Ce) and CeBr3







Summary

- Model and tools developed to quickly evaluate the response of SiPM *
- Studied possible non-linearity of SensL and Hamamatsu 6mm × 6mm SiPMs when coupled to CsI(Tl), LaBr3(Ce), CeBr3, BGO, NaI, scintillators in different geometries and in arrays
- CsI(Tl) is the best candidate for small crystal and single SiPM, also good for bigger crystals
- Bigger crystals with 4 × 4 SiPM array perfect for LaBr3(Ce) and CeBr3

Paper submitted to Sensors
Preprint available at https://doi.org/10.20944/preprints202509.0685.v1

* The tools are available on request in form of MS Excel workbooks, just send me an email at FINOCCHIARO@LNS.INFN.IT

Paper submitted to Sensors
Preprint available at https://doi.org/10.20944/preprints202509.0685.v1

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THANK YOU