Analysis of scintillating and reflective materials for X-ray Computed Tomography

06/04/22

Nicolò Tuccori

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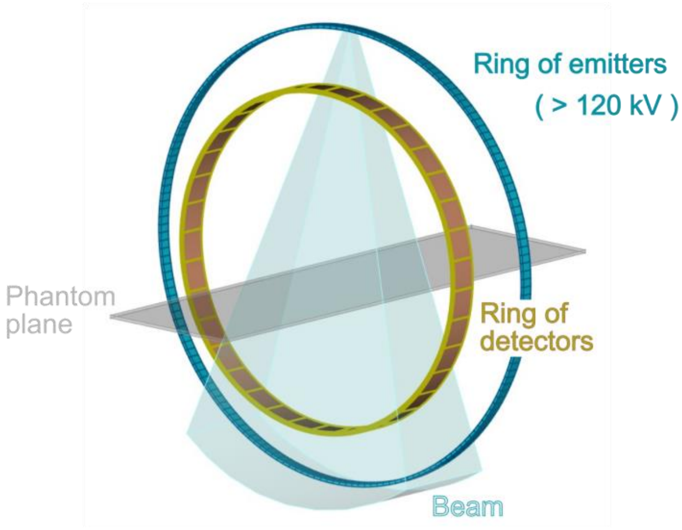
Research problem

FOCUS:
X-ray Computed Tomography



Research problem

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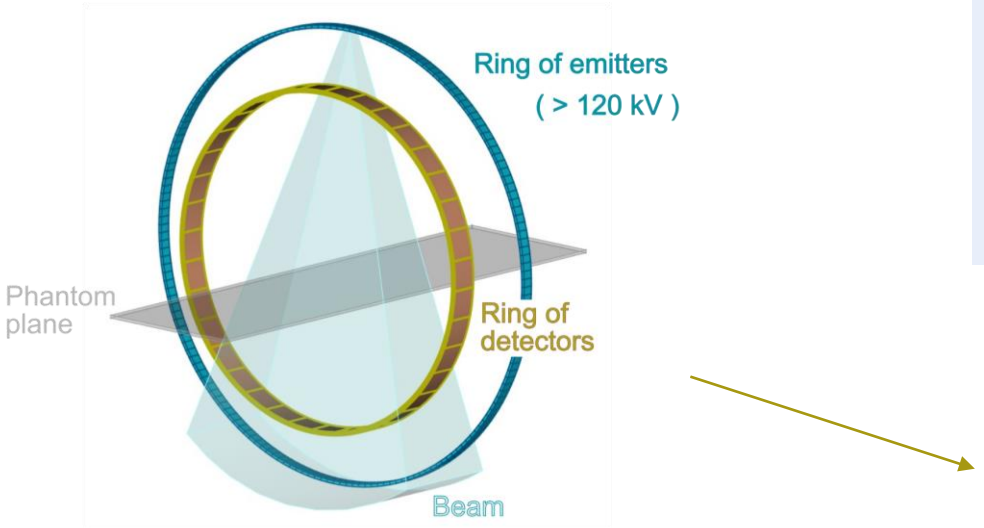
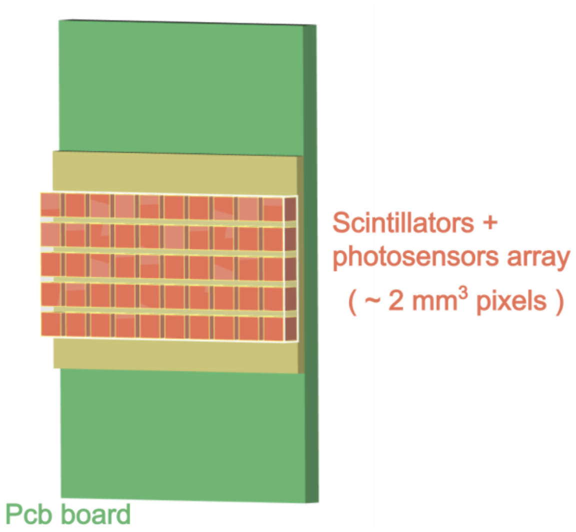


OBJECTIVE:
Investigate potential of
new **scintillators** and **reflectors**
currently on the market



Research problem

METHOD:
Combine *experimental* measurements and *simulations*

Characterization of relevant properties of materials:

- Check suitability for CT
- Implement properties in simulation database

Research problem

METHOD:
Combine *experimental* measurements and *simulations*

Characterization of relevant properties of materials:

- Check suitability for CT
- Implement properties in simulation database

Virtual model of a CT scanner:

- Performance of new materials
- Explore new designs

1st step: Scintillators

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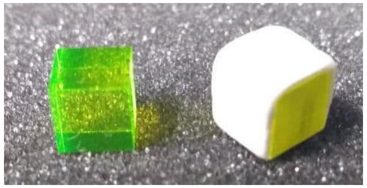
Scintillators - choice

Characterisation of *fast, inorganic scintillators*

WHAT



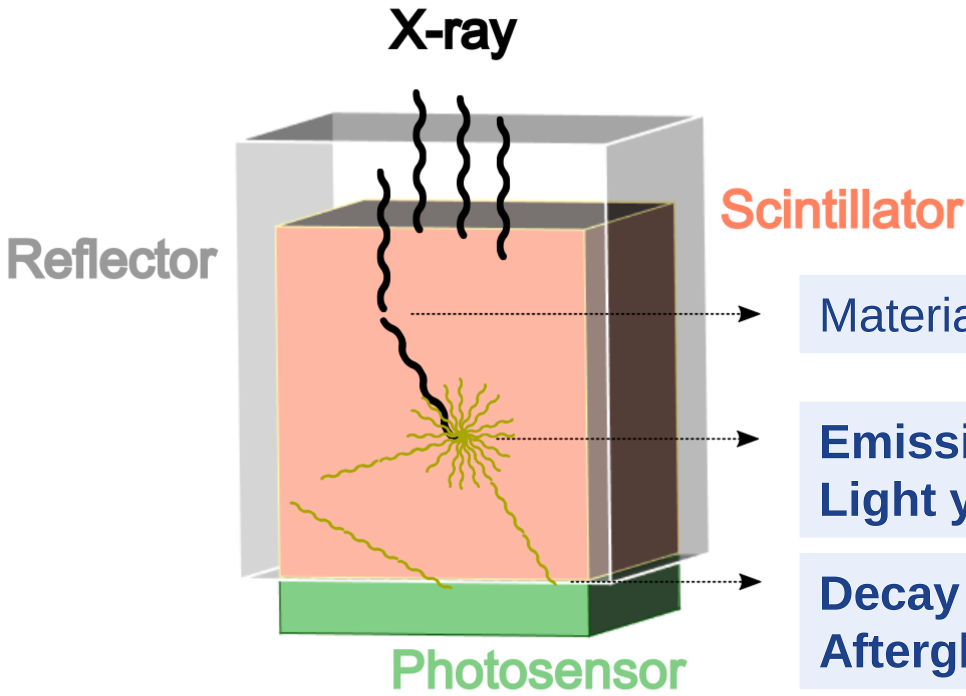
Ce:LYSO	Ce:LuAG
Ce:LuAP	Ce:GAGG
Pr:LuAG	Ce:GGAG

- ✓ Fast (~100 ns)
- ✓ High density and Z
- ✓ Bright (LY > 10 ph/keV)
- ✓ Non hygroscopic
- ✓ Radiation hard
- ✓ Emission in [300,900] nm

Scintillators - properties

Characterisation of *fast, inorganic scintillators*

WHICH PROPERTIES



Material composition

Emission spectrum
Light yield

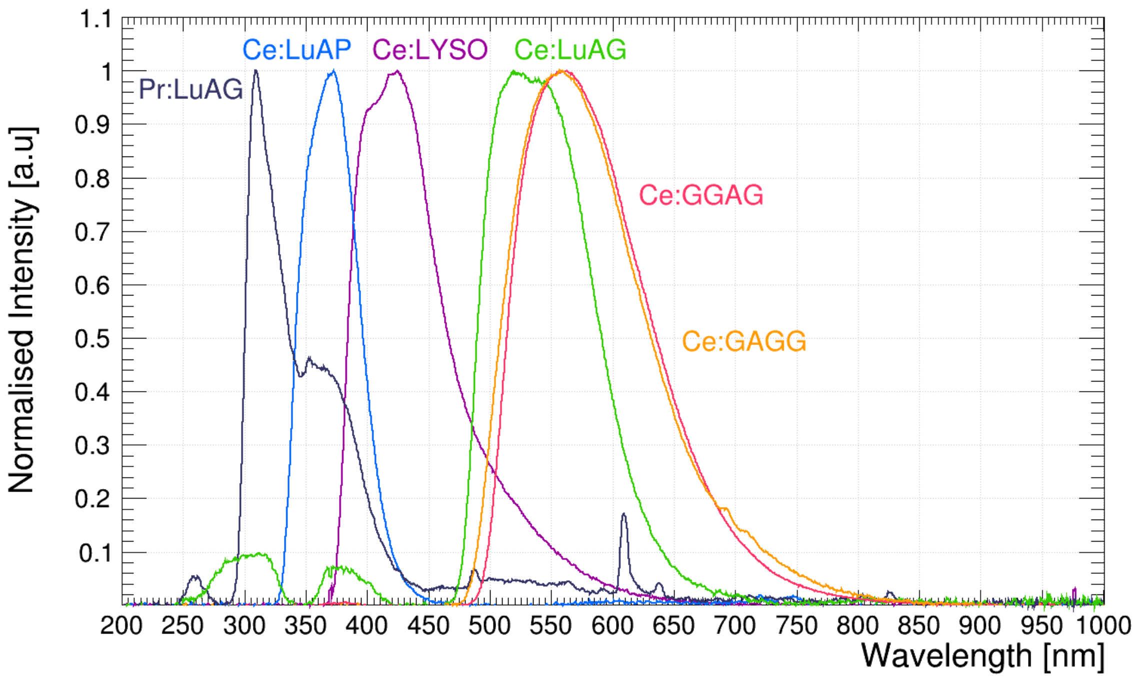
Decay time
Afterglow

Scintillators - results

RESULTS

- **Emission spectrum**

❑ X-ray source + spectrometer



✓ Important to match emission spectrum with

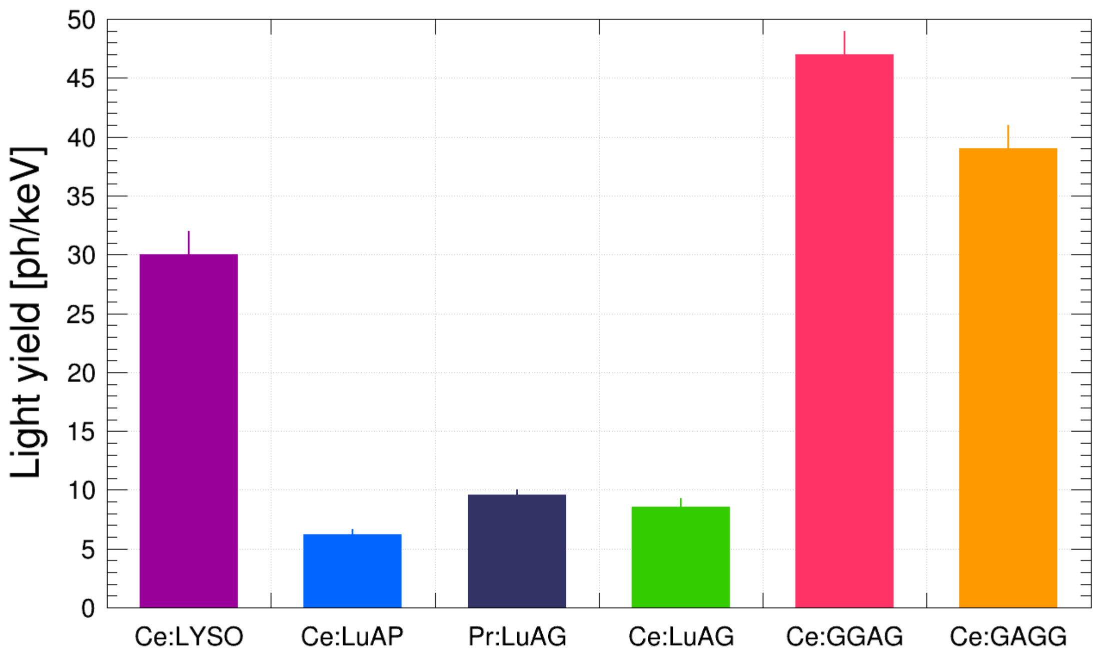
- Reflector property
- Photosensor QE

Scintillators - results

RESULTS

- **Light yield**

❑ Cs^{137} source + fast PMT



✓ Brightest

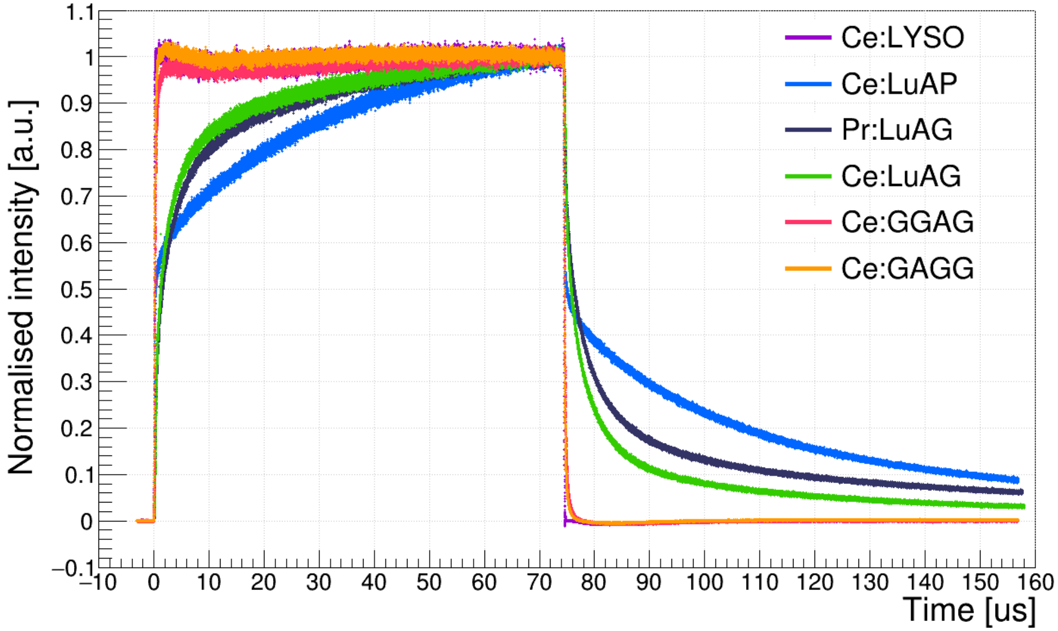
- Ce:LYSO 30±2 ph/keV
- Ce:GGAG 47±2 ph/keV
- Ce:GAGG 39±2 ph/keV

Scintillators - results

RESULTS

- **Afterglow**

❑ Pulsed X-ray source + fast PMT



✓ Neglectable slow components

- Ce:LYSO
- Ce:GGAG
- Ce:GAGG

2nd step: Reflectors

Reflectors – preliminary

Characterisation of *reflective materials* typically used in scintillators arrays:

WHAT

- Samples of several different combinations of epoxy and TiO_2

epoxy	TiO_2
Bisphenol (EP)	Rutile
Cycloaliphatic (CAP)	Anatase

Reflectors – preliminary

Characterisation of *reflective materials* typically used in scintillators arrays:

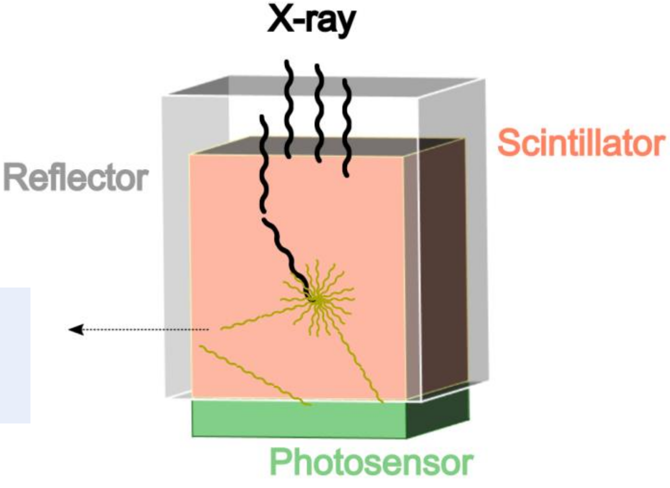
WHAT

- Samples of several different combinations of epoxy and TiO_2

Epoxy	TiO_2
Bisphenol (EP)	Rutile
Cycloaliphatic (CAP)	Anatase

WHICH PROPERTIES

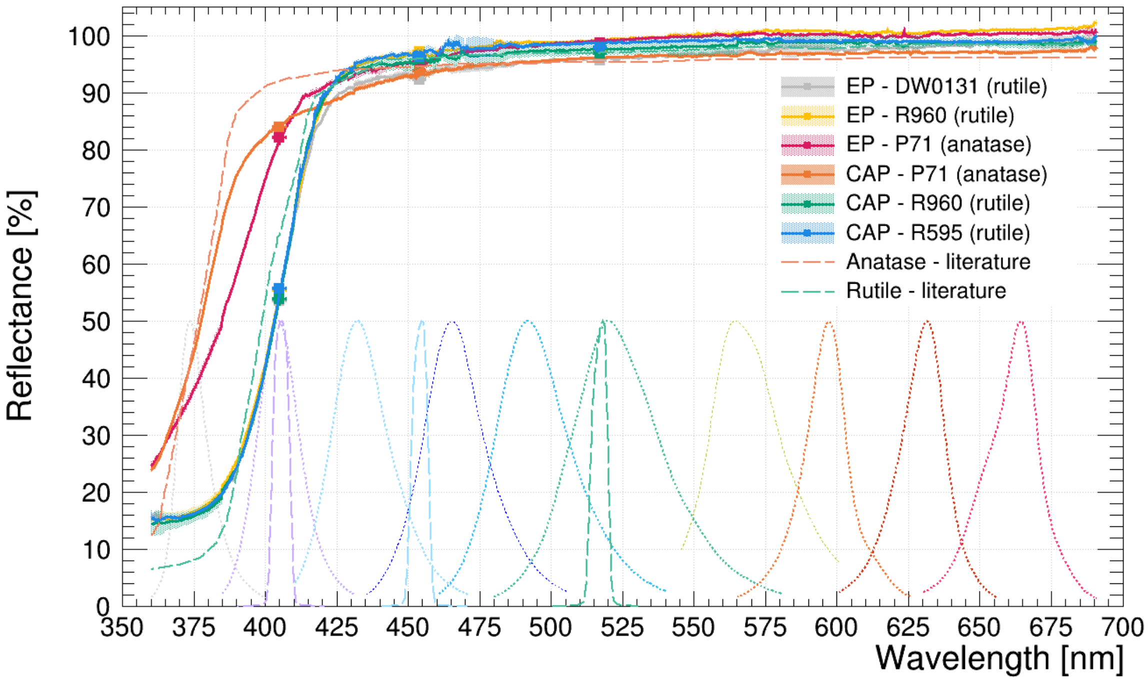
Reflectance spectrum



Reflectors - results

RESULTS

- **Reflectance** → ❑ LED lights + integrating sphere + spectrometer



✓ Rutile and Anatase TiO_2 pigments have different properties

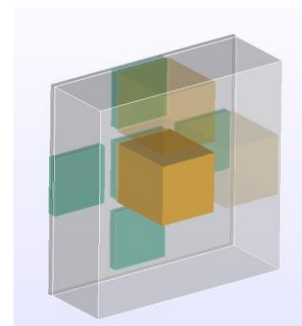
Final step: Simulation

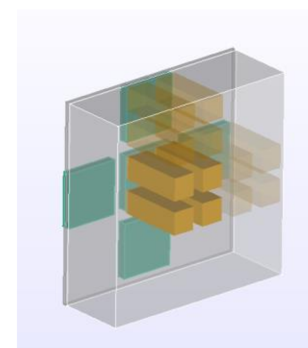
Simulation - model

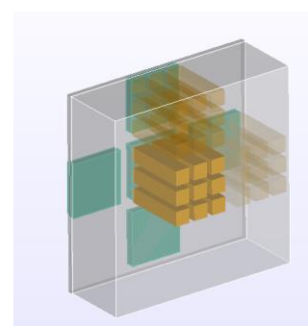
WHAT

- X-ray generator of 160 kV
- Model of an array scintillator of a generic CT scanner detection unit

Analysed scintillators ↷ Analysed reflectors ↷ Array thickness from 0.5 to 5 mm ↷



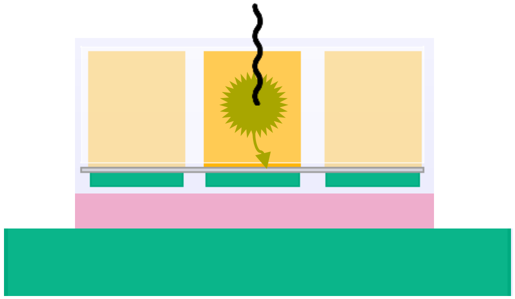




Simulation - properties

WHICH PROPERTIES

Luminescence efficiency

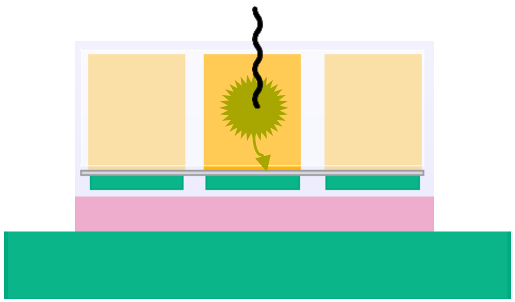
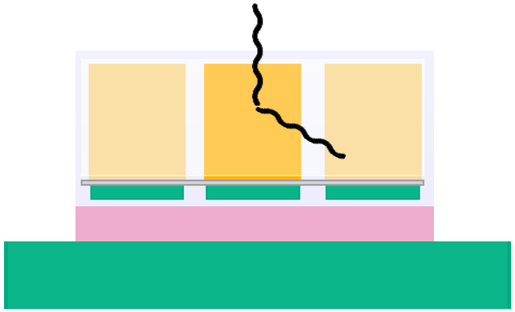
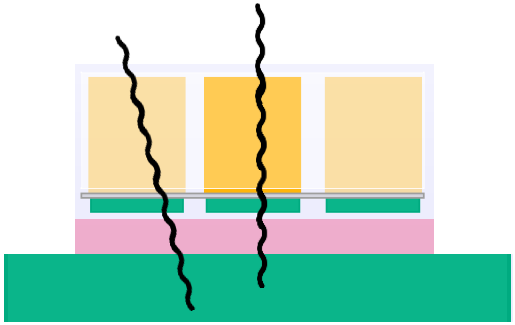


Impacts:

- Signal noise

Simulation - properties

WHICH PROPERTIES

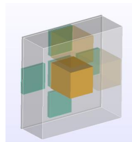
Luminescence efficiency	Inter-pixel crosstalk	Electronics exposure to X-rays
		

Impacts:

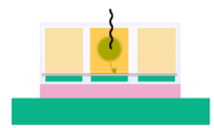
- Signal noise
- Spatial resolution
- Lifetime

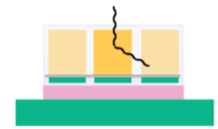
Simulation - results

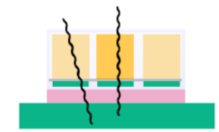
RESULTS



Scintillators ↷ Reflectors ↷ Array thickness



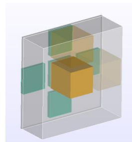




Scintillators	Reflectors	Array thickness	ph mm^{-2} / keV mm^{-2}	%	keV / X-ray mm^{-2}
Ce:LYSO	EP + P71 (anatase)	1.4 mm	3.4 ± 5% Rutile (EP + R960) -8 % CAP (+R595, rutile) -4 % Thickness (>) -1.5 % mm^{-1}	6.3 Thickness (>) +1.6 % mm^{-1}	$10.3 \cdot 10^2$ Thickness (>) -0.8 % mm^{-1}

Simulation - results

RESULTS



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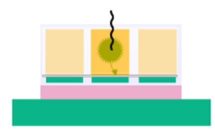

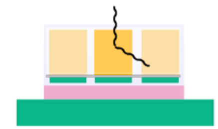

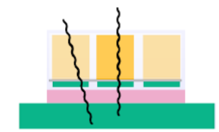

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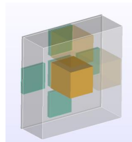
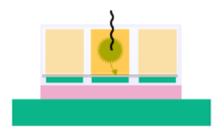
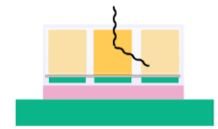
Ce:GAGG	EP + R960 (rutile)	2.0 mm	+ 76% 6.0 ± 10% Anatase (EP + P71) -2 % CAP (+R595, rutile) -6 % Thickness (>) -0.9 % mm^{-1}	+ 19% 7.5 Thickness (>) +1.3 % mm^{-1}	- 6% $9.7 \cdot 10^2$ Thickness (>) -0.7 % mm^{-1}

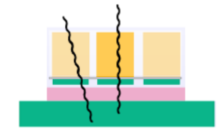
Simulation - results

RESULTS









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Ce:GGAG	EP + R960 (rutile)	2.0 mm	+ 115% 7.3 ± 10% Anatase (EP + P71) -2 % CAP (+R595, rutile) -5 % Thickness (>) -0.9 % mm^{-1}	+ 19% 7.5 Thickness (>) +1.3 % mm^{-1}	- 6% $9.7 \cdot 10^2$ Thickness (>) -0.7 % mm^{-1}

Conclusions & Future plans

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Conclusions

CONCLUSIONS

- ✓ Characterised scintillating and reflective materials for X-ray CT
  - New on the market
  - Ready to be implemented in mass-produced products
- ✓ Developed virtual model of an X-ray CT scanner
  - Experimentally compiled database
- ✓ Evaluated performance of analysed materials in X-ray CT
  - Ce:GAGG and Ce:GGAG most promising scintillators
  - P71 (anatase) and R960 (rutile) among reflectors

Future plans

FUTURE PLANS

Photon-counting CT with scintillators and SiPM:

is it possible?

Standard CT

=

Detect X-ray in a fixed time-window and integrate the generated signals

Photon-counting CT

=

Detect every single X-ray and exploit the energy information

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Back-up slides

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Scintillators: results

Scintillator	Light yield [ph/keV]	Energy resolution [%]	τ 1 [ns]	τ 2 [ns]	τ 3 [ns]	Photolum. peak [nm]	Radiolum. peak [nm]	Afterglow
Ce:LYSO	30 ± 2	10 ± 1	44 ± 2 (100 %)			425	425	low
Ce:LuAP	6.2 ± 0.5	12 ± 1	20.8 ± 0.6 (72.5 ± 0.7 %)	154 ± 12 (7.5 ± 0.3 %)	1405 ± 122 (20.0 ± 0.8 %)	365	370	strong
Pr:LuAG	9.6 ± 0.4	11 ± 1	30 ± 1 (27.5 ± 0.5 %)	165 ± 15 (10.0 ± 0.4 %)	1743 ± 38 (62.4 ± 0.4 %)	310	310	strong
Ce:LuAG	8.6 ± 0.7	14.9 ± 0.5	73 ± 2 (41.2 ± 0.5 %)	1559 ± 47 (58.8 ± 0.5 %)		545	520	strong
Ce:GGAG ceramic	47 ± 2	6.6 ± 0.5	173 ± 3 (82 ± 1 %)	697 ± 15 (18 ± 1 %)		570	560	low
Ce:GAGG	39 ± 3	7.4 ± 0.4	55 ± 1 (41.8 ± 0.8 %)	139 ± 4 (45 ± 1 %)	564 ± 30 (13 ± 1 %)	570	555	low

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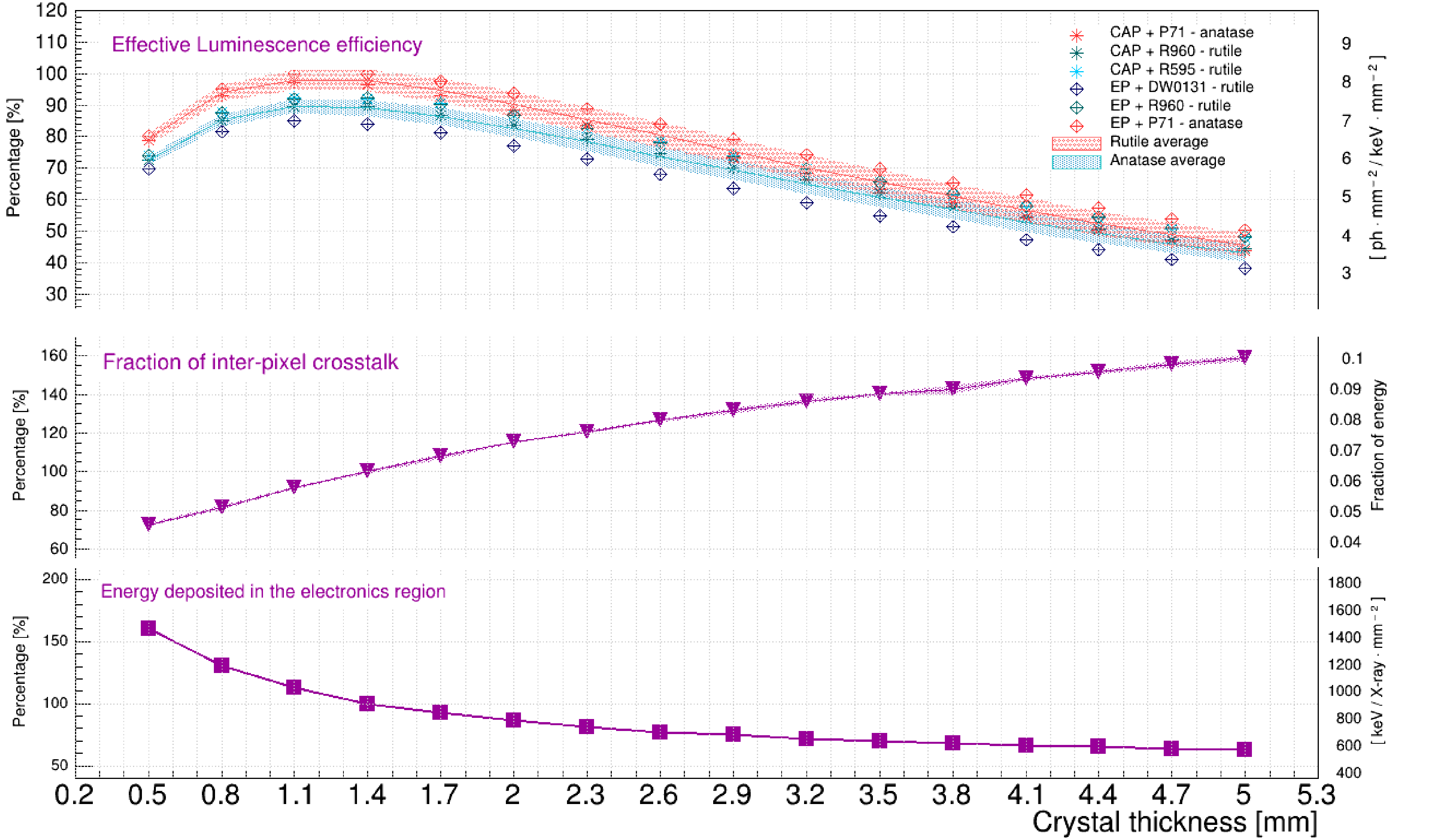
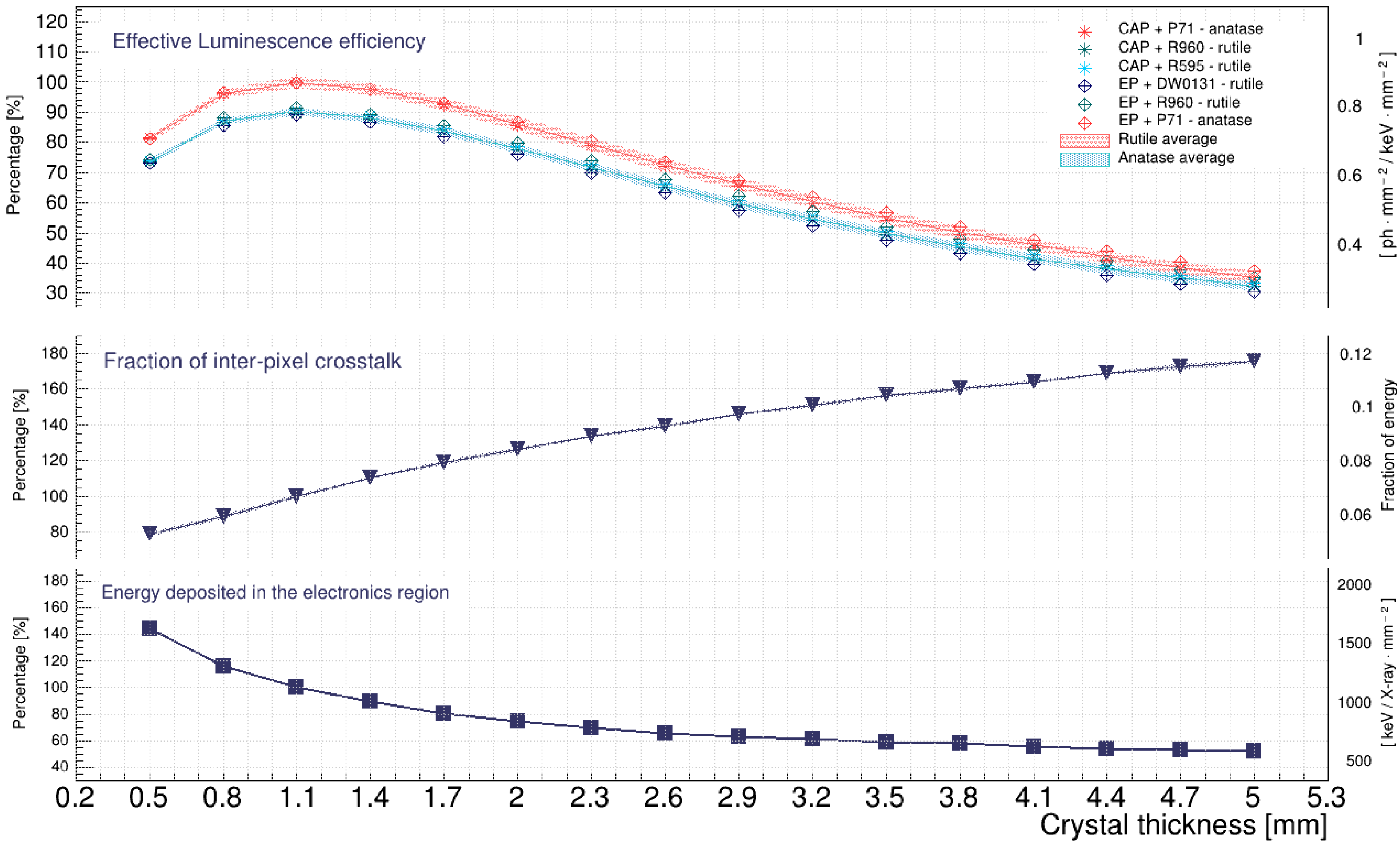
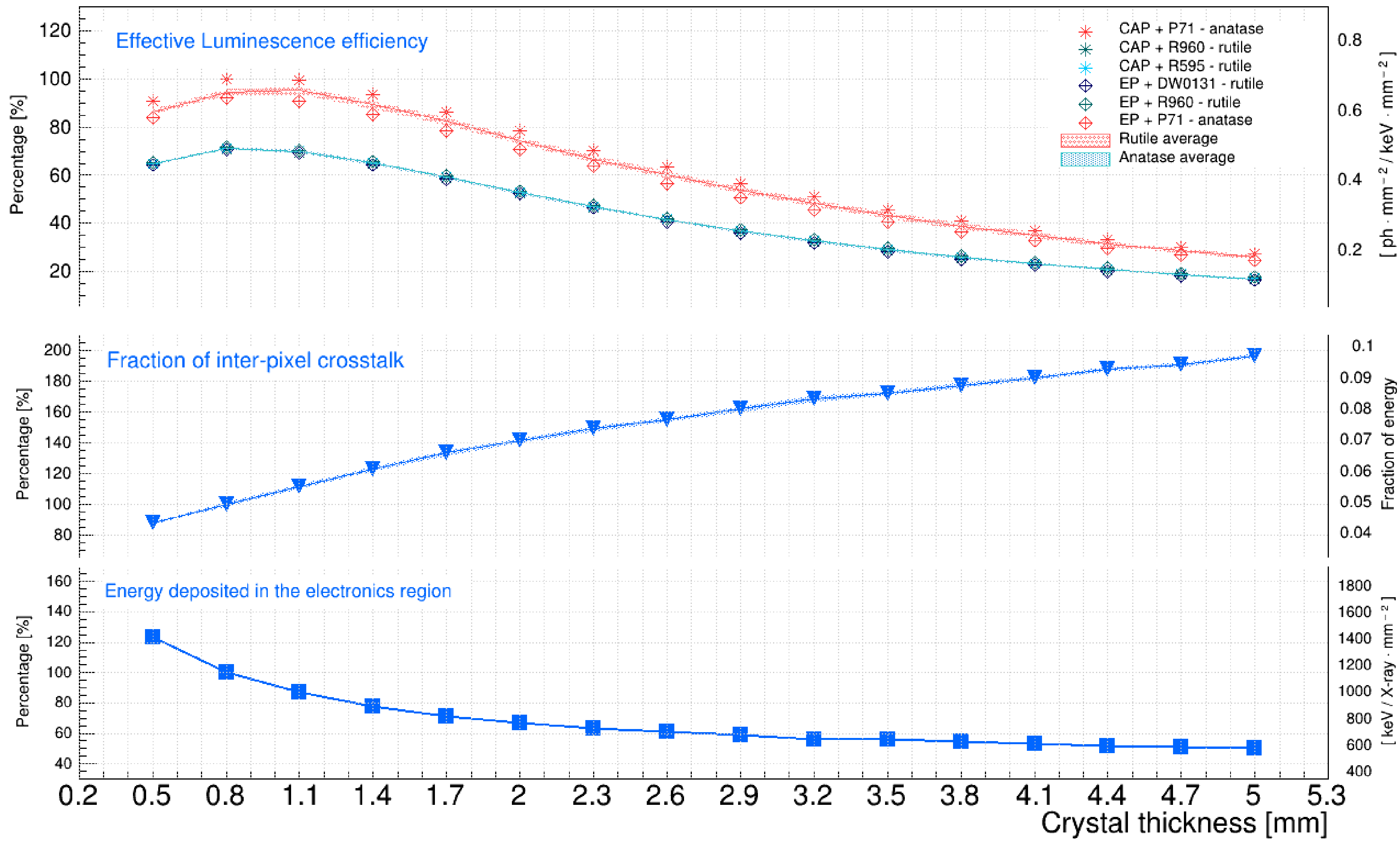
Simulations - LYSO



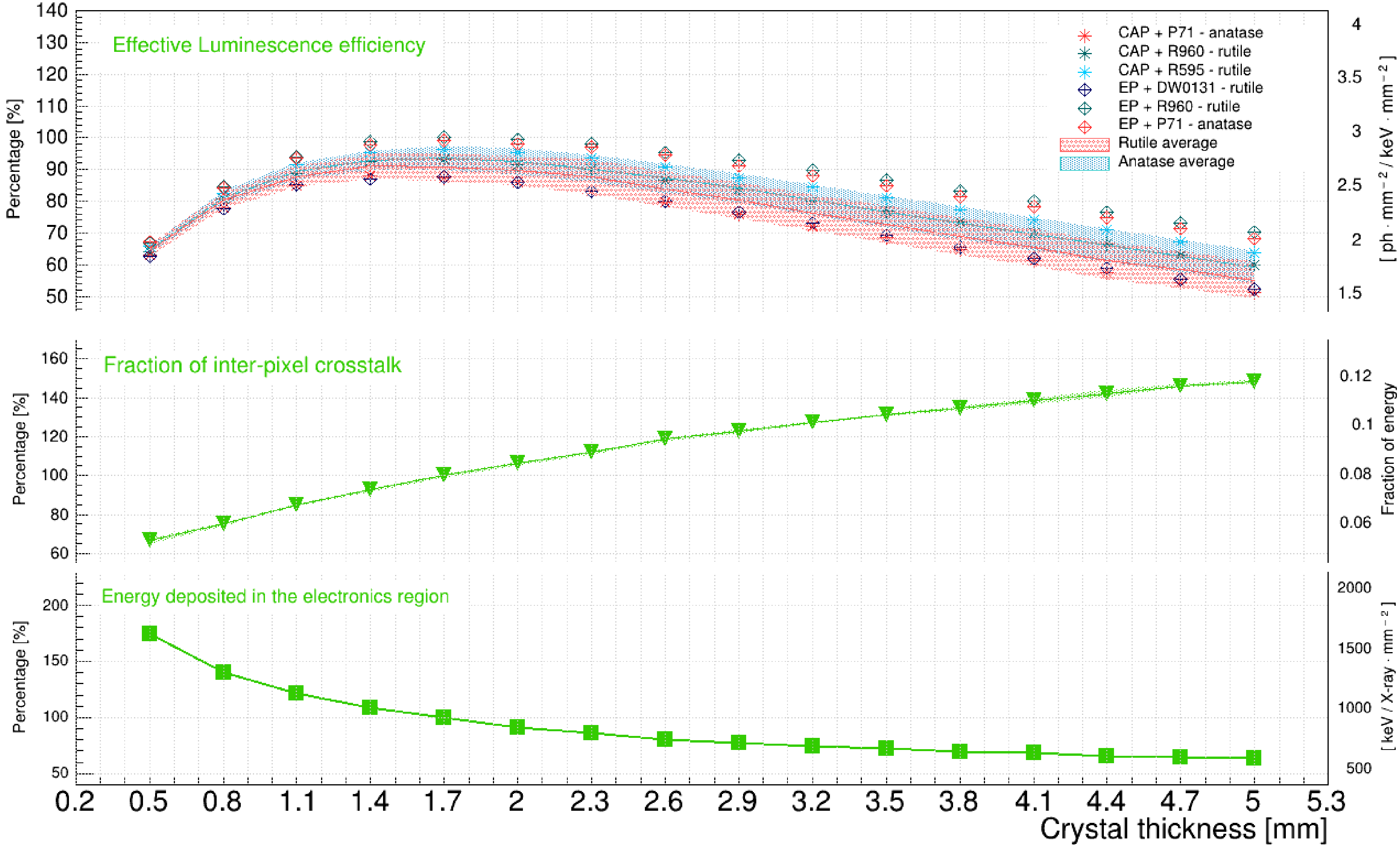
Simulations – Pr:LuAG



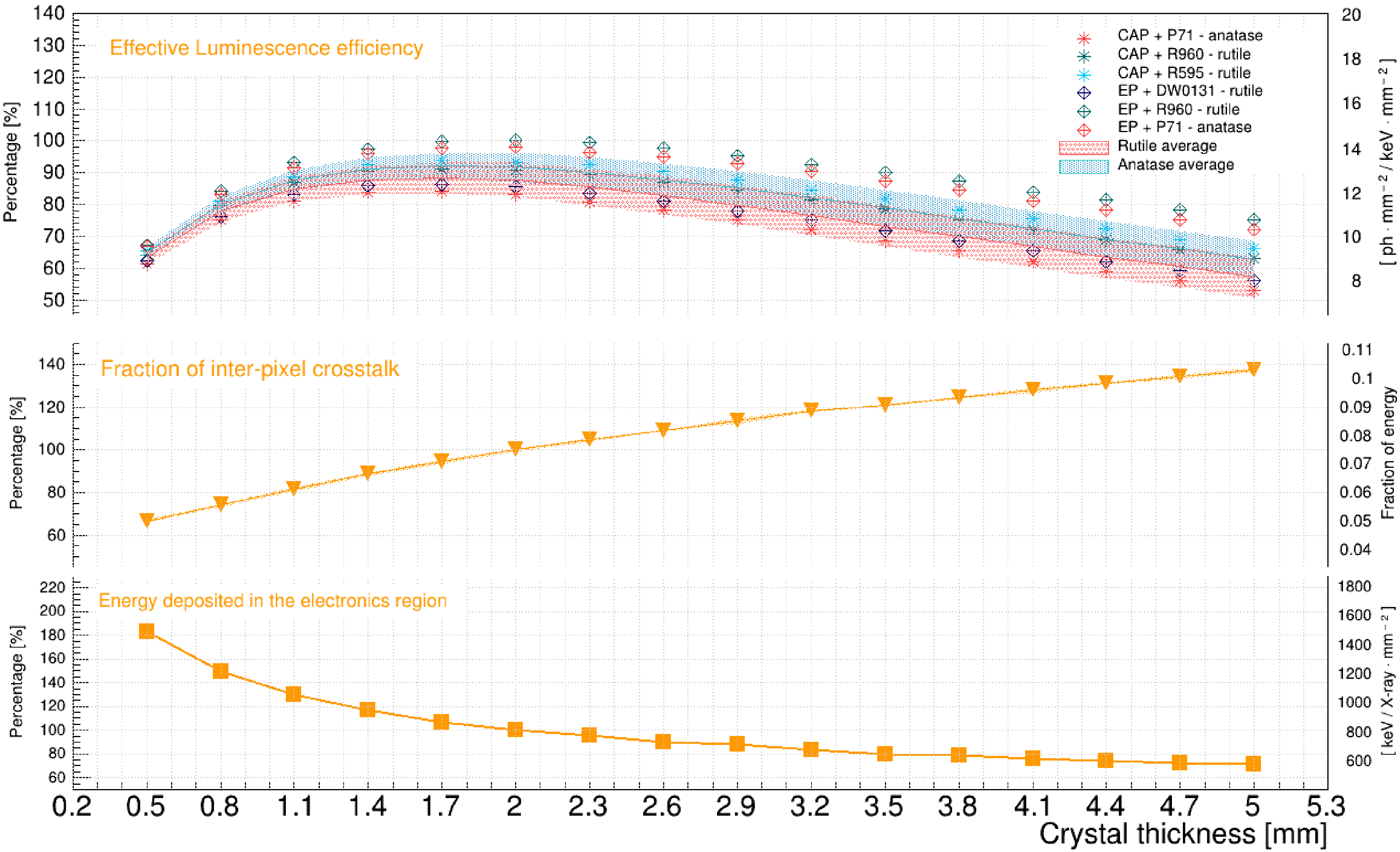
Simulations – Ce:LuAP



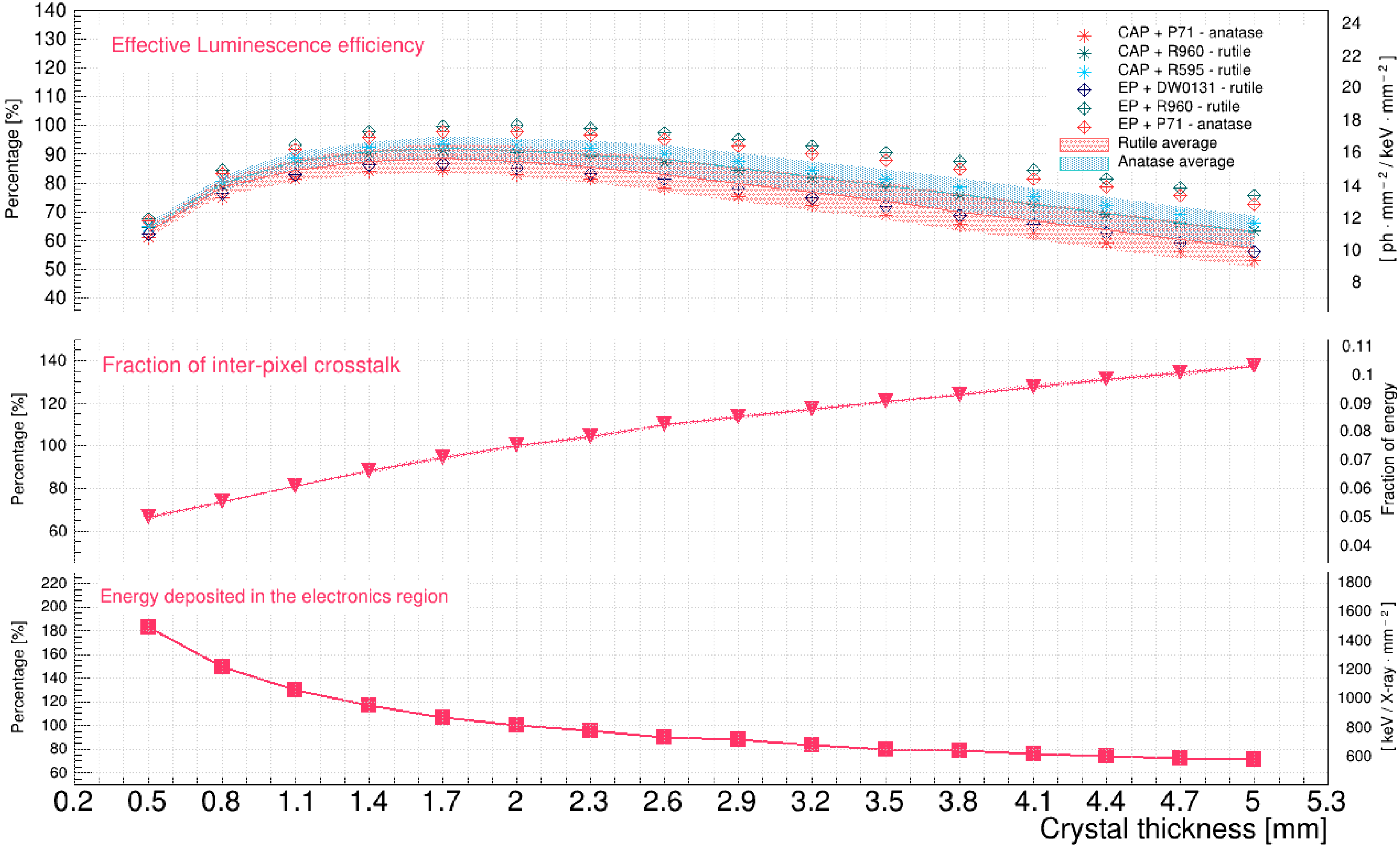
Simulations – Ce:LuAG



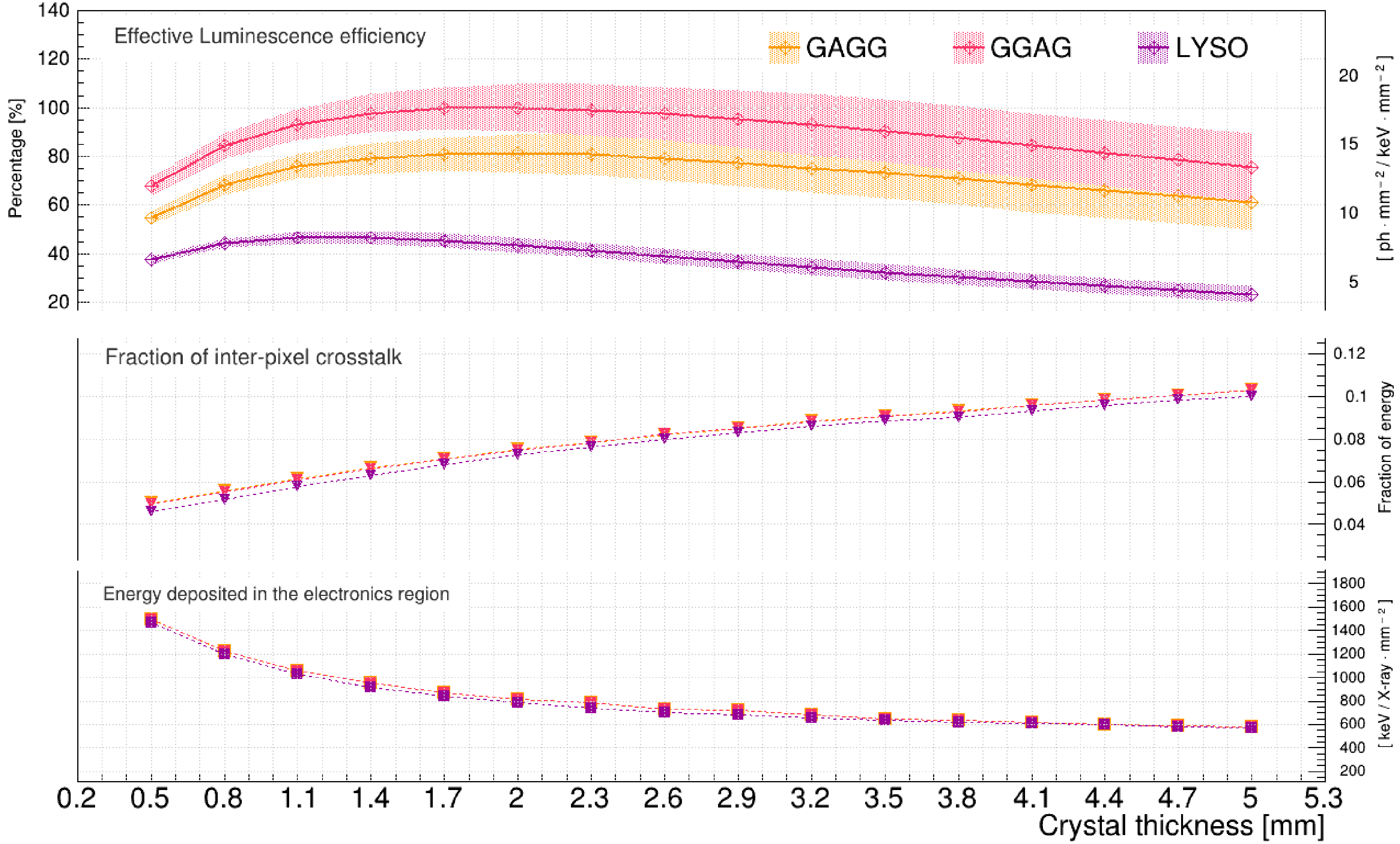
Simulations – Ce:GAGG



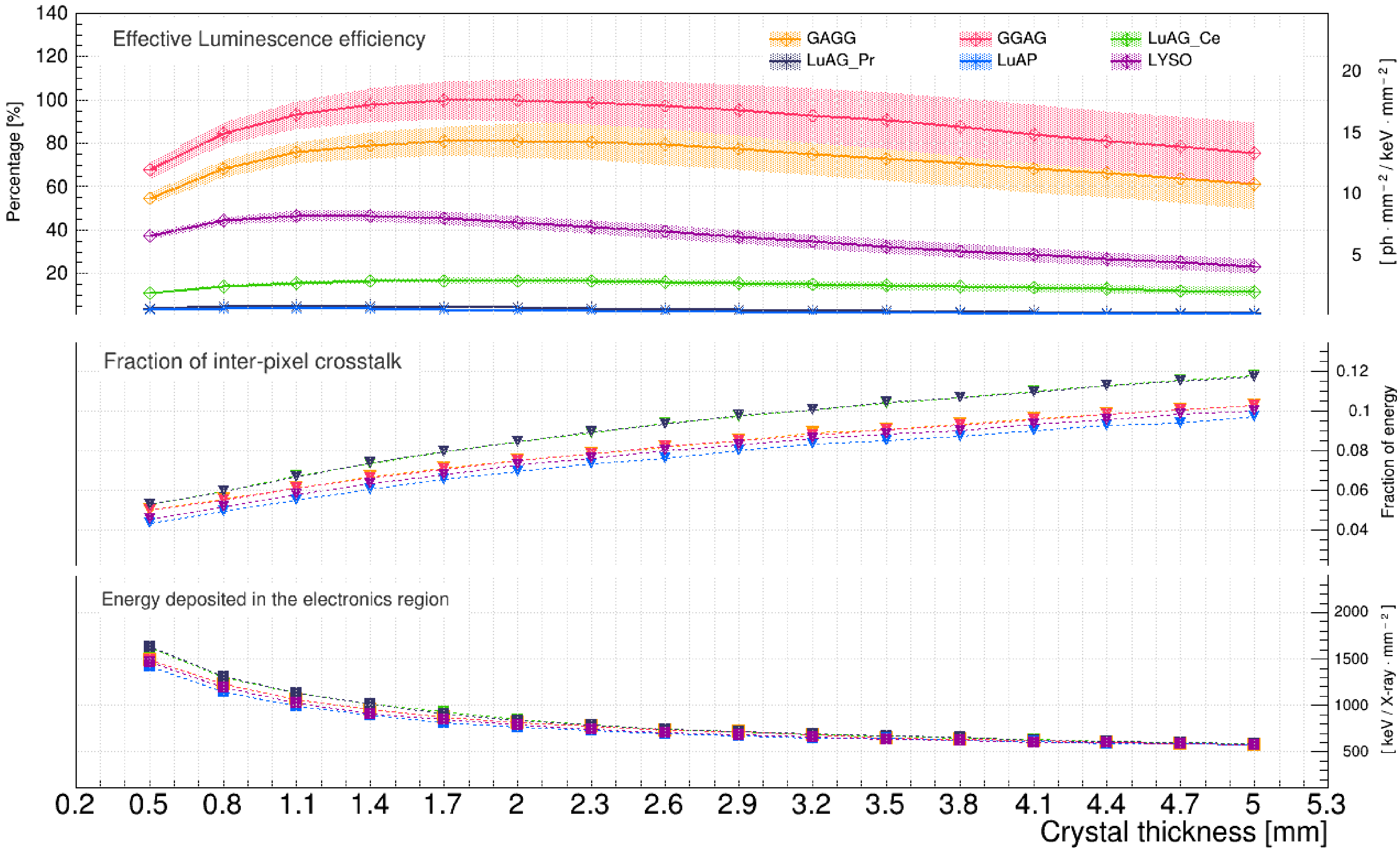
Simulations – Ce:GGAG



Simulations – comparison best



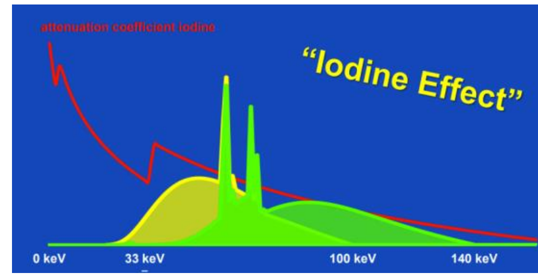
Simulations – all



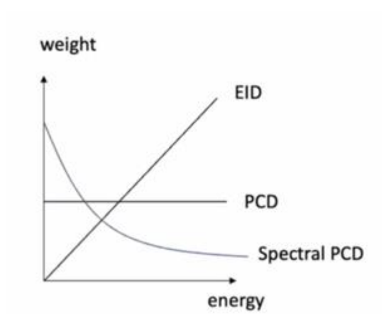
Short course: photon-counting CT

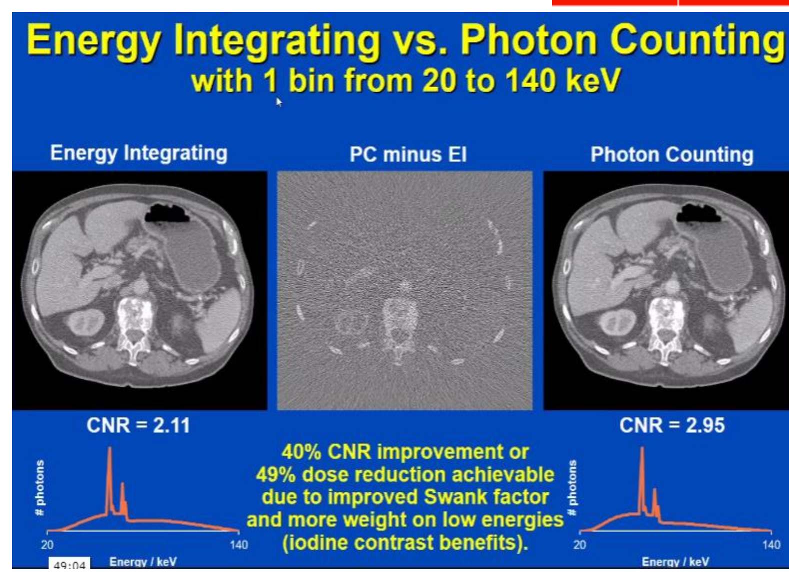
Advantages of PC (done with semiconductors) compared to EI (done with scintillators)

- No electronic noise
- K-edge imaging (e.g. iodine, k-edge @ 33 keV)
    - Lower noise
    - Potential decrease of dose (up to 40%)
    - Better CNR
- Energy bin weighting
    - Lower dose/noise
- (Just for semiconductors):
    - Smaller pixels and no reflective gaps
      >> higher spatial resolution
      (drawback = bad spectral fidelity)



Element	K-edge
O (61%)	< 1 keV
C (23 %)	< 1 keV
H (10%)	< 1 keV
N (2.6%)	< 1 keV
Ca (1.7 %)	4.0 keV
P (1.1%)	2.1 keV
I	**33.2 keV**
Gd	**50.2 keV**
Au	**80.7 keV**
Bi	**90.5 keV**

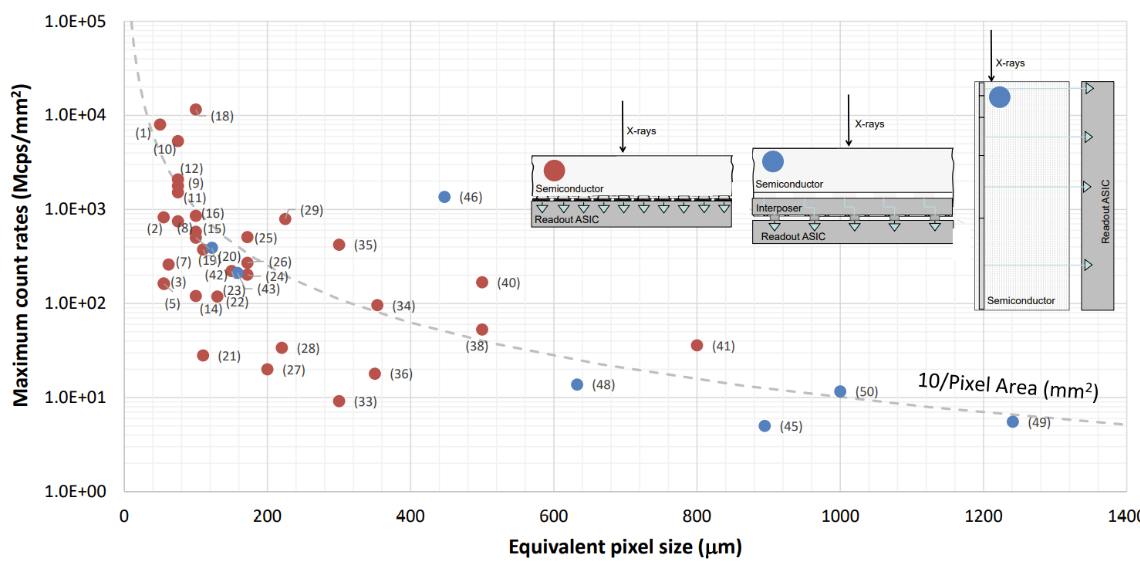




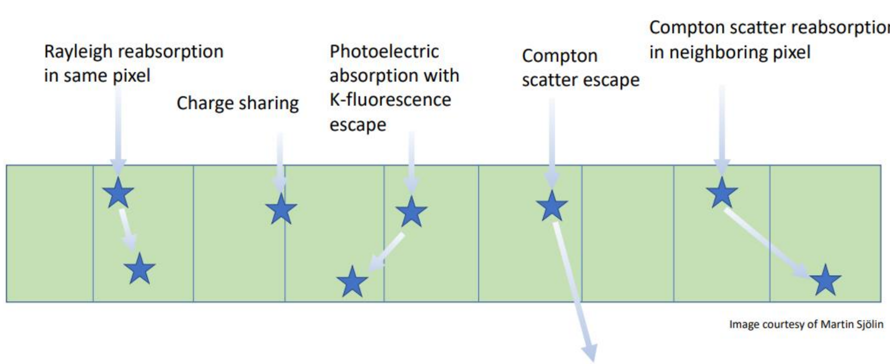
Short course: photon-counting CT

Challenges of PC (done with semiconductors)

- High count-rate performance
- Spectral fidelity
- Cross-talk
- Charge sharing
- High-cost of manufacturing
- Calibration and image reconstruction
- Large amounts of data



Detector material: types of photon interaction



IEEE 2021: photon-counting CT

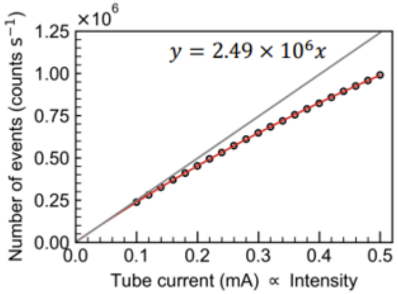
Possible **advantages** of PC-CT with scintillators**:**

- Indirect conversion detectors applied widely in CT scanners, well known technology
- High Z and density
- Cheaper manufacturing cost
- Fast developments in the SiPm technology

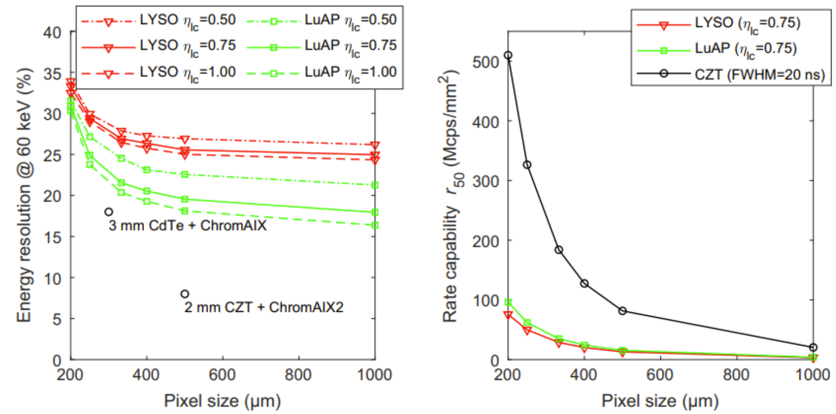
IEEE 2021: photon-counting CT

Challenges of PC-CT with scintillators:

- Lower photon to electron conversion
- Slow decay times >> low count rate



EXPERIMENTAL –
1 mm² YGAG + MPPC



Pixel size = SiPm + scintillator

MODEL - SiPm with SPAD pitch of 30 μm, rate could improve with smaller size (e.g. 15 μm) [1]

- Suffer light dispersion >> cross-talk
- Poor reproducibility of charge packet sizes (i.e. energy resolution)
- Dead space due to reflective gaps
- Not possible small pixels size >> low spatial resolution

[1] Silicon photomultiplier-based scintillation detectors for photon-counting CT: A feasibility study - Sar - 2021 - Medical Physics - Wiley Online Library