MULTI-PHOTON DETECTOR BLUR ESTIMATION IN TOTAL-BODY MODULAR PET SCANNERS

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IMPET

The IMPET project proposes innovative, AI-enhanced multiphoton imaging solutions for industrial applications:

- *Porous Materials*: novel 3D imaging – Quantum Decoherence modelling or Positronium (Ps) Lifetime for spatial analysis of pores and defects
- *Opaque Fluids*: enhanced Positron Emission Particle Tracking (PEPT) for dynamic flow analysis in opaque fluids (e.g. liquid metals as nuclear reactor coolants).
- *The Goal*: industrial scanner design and software for scientific and commercial use capable of PEPT and quantum decoherence imaging.

Objective

Design an accurate representation of resolution effects in the detector space for multi-photon PET modalities, namely *Ps lifetime imaging* (PLI), suitable for the total-body PET scanners made of traditional crystal blocks or plastic scintillators.

Motivation

System matrix[1] decomposition:

$$\mathbf{A} = \mathbf{NDLXH}$$

norm.
detector resolution
atten.
e^+ rng.
geom. proj.

components more important in PLI

β+γ decay:

– ***No sinograms*** (too complex for **2γ + prompt**), *list-mode*, new methods required for **A** modelling

– ***Sensitivity*** **×30 – ×100** lower than for 2γ PET: $\beta^+\gamma/\beta^+$ yield, detection probability, prompt energy depend on isotope (^{22}**Na**, ^{124}**I**, ^{44}**Sc**, ^{68}**Ga**...)[2-4]

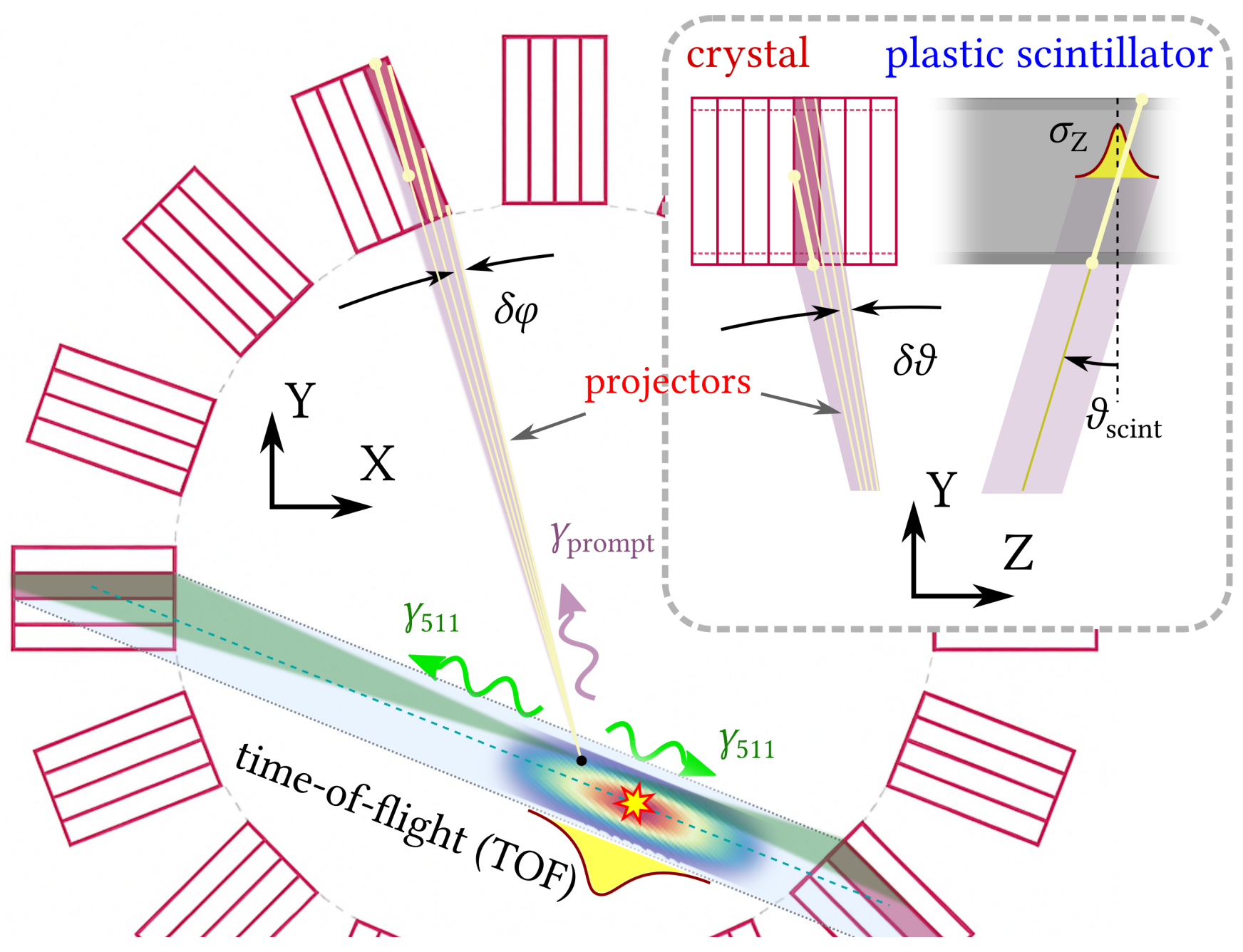
– ***More data needed*** for positronium (**Ps**) *lifetime spectra decomposition*, per voxel in particular[5]

– Multi-layer geometries and parallax effect in *total-body* scanners ***enhance detector blur*** **D**[6]

– ***Attenuation*** for β+γ (prompt) is *shift-variant*[5]

– Significant ***positron range*** (except ^{22}**Na**)[2, 7]

Concept and grid model



2D: detection probability is a sum of ***projector integration*** for 3 photons with energies E_k[5].

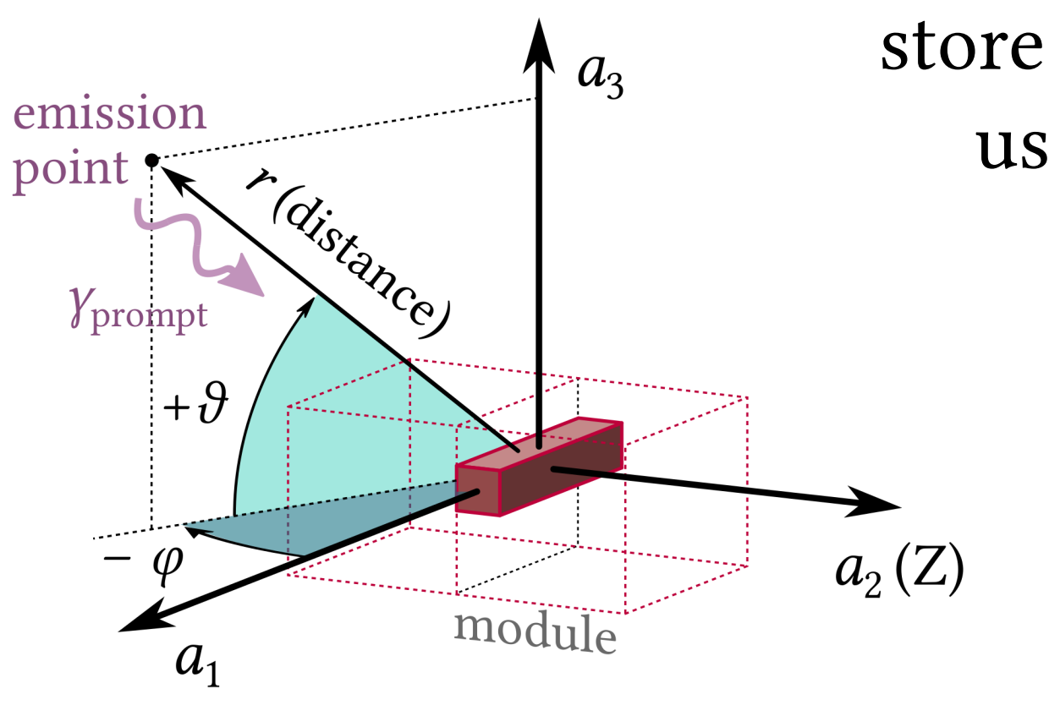
$$P_j = \sum_{k=1}^{3} \int_{\varphi_k^{(\mathrm{min})}}^{\varphi_k^{(\mathrm{max})}} P_{kj}(E_k)\,d\varphi$$

3D: only account for obliqueness $\vartheta_{\mathrm{scint}}$ (plastic scintillator) or full solid angle integration (crystal)

$$P_{\mathrm{prompt}} = \frac{1}{4\pi} \int_{\varphi^{(\mathrm{min})}}^{\varphi^{(\mathrm{max})}} \int_{\vartheta^{(\mathrm{min})}}^{\vartheta^{(\mathrm{max})}} p(\vartheta, \varphi) \sin\vartheta\, d\vartheta\, d\varphi$$

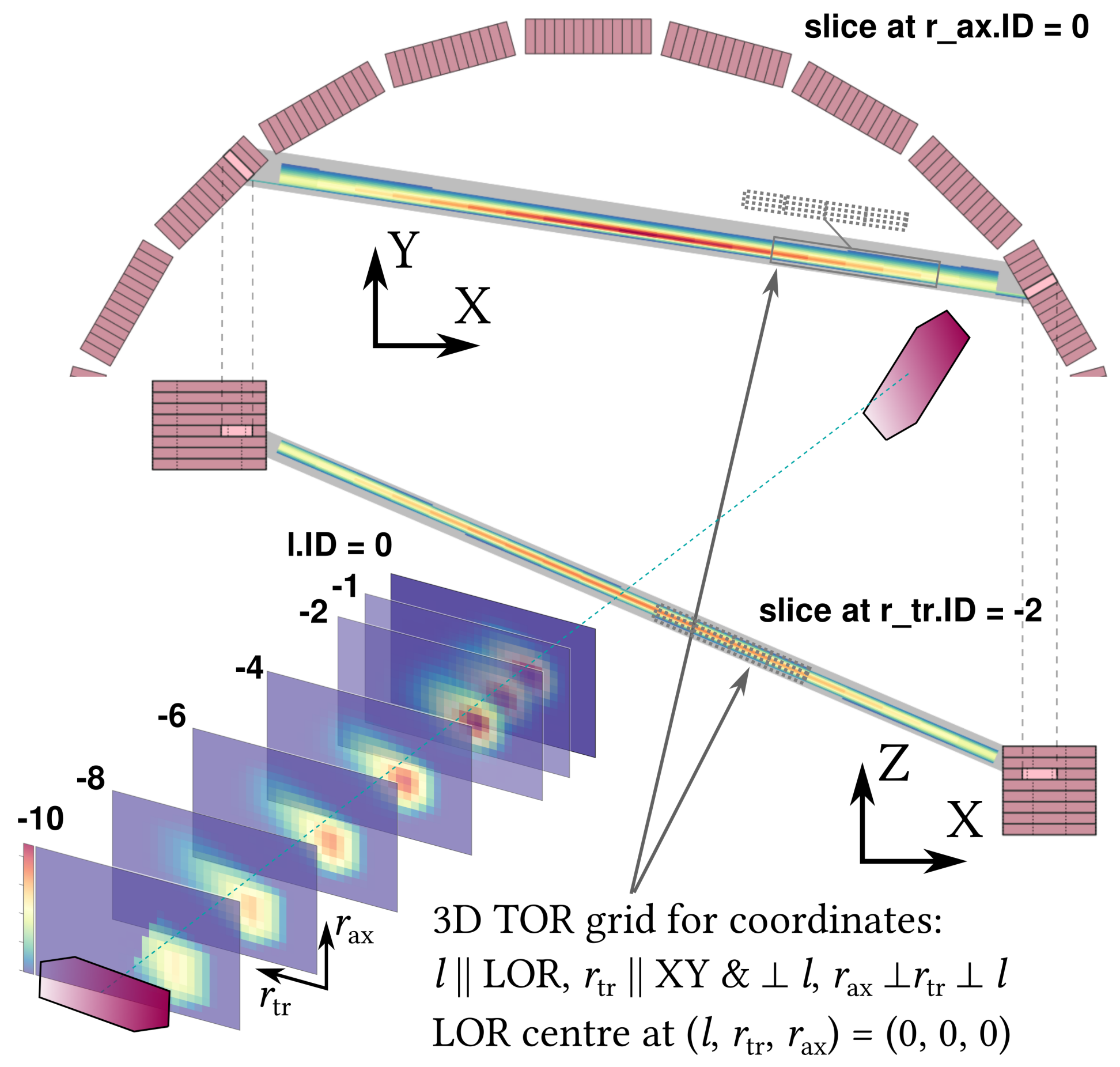
$$P_{\mathrm{B2B}} = \frac{1}{4\pi} \int_{\varphi^{(\mathrm{min})}}^{\varphi^{(\mathrm{max})}} \int_{\vartheta^{(\mathrm{min})}}^{\vartheta^{(\mathrm{max})}} p_1(\vartheta, \varphi)\, p_2(\pi - \vartheta, \varphi + \pi) \sin\vartheta\, d\vartheta\, d\varphi$$

Prompt/one-photon model: define spherical grid for (r, φ, ϑ), only 1/8th of one module is sufficient to store. For voxels in between use interpolation to get detection probability.



Easy to adapt for both scintillator strips and crystals

2 photons (back-to-back, B2B): the smoothest direction is l – along line-of-response (LOR), i.e. less quantisation. *More perturbation* – on $r_{\mathrm{tr}} \times r_{\mathrm{ax}}$ slices. *Axial extension is* ***pseudo-2D*** for plastic strips: add obliqueness angle $\vartheta_{\mathrm{scint}}$ as third grid dimension and fixed axial blur $\pm 3\sigma_Z$[5,6].



3D TOR grid for coordinates:
$l \parallel$ LOR, $r_{\mathrm{tr}} \parallel$ XY & $\perp l$, $r_{\mathrm{ax}} \perp r_{\mathrm{tr}} \perp l$
LOR centre at $(l, r_{\mathrm{tr}}, r_{\mathrm{ax}}) = (0, 0, 0)$

Ps lifetime histograms for voxels are collected from all events as weights (***many*** from ***one***)

$$w_{\epsilon j} = \theta_j \frac{\ell_{\epsilon j}^{(\mathrm{pr})}\, \chi_{\epsilon j}\, \eta_{\epsilon j}}{\sum\limits_{j' \in \mathcal{J}_\epsilon} \ell_{\epsilon j'}^{(\mathrm{pr})}\, \chi_{\epsilon j'}\, \eta_{\epsilon j'}\, \theta_{j'} + \hat{b}_{\epsilon j}}$$

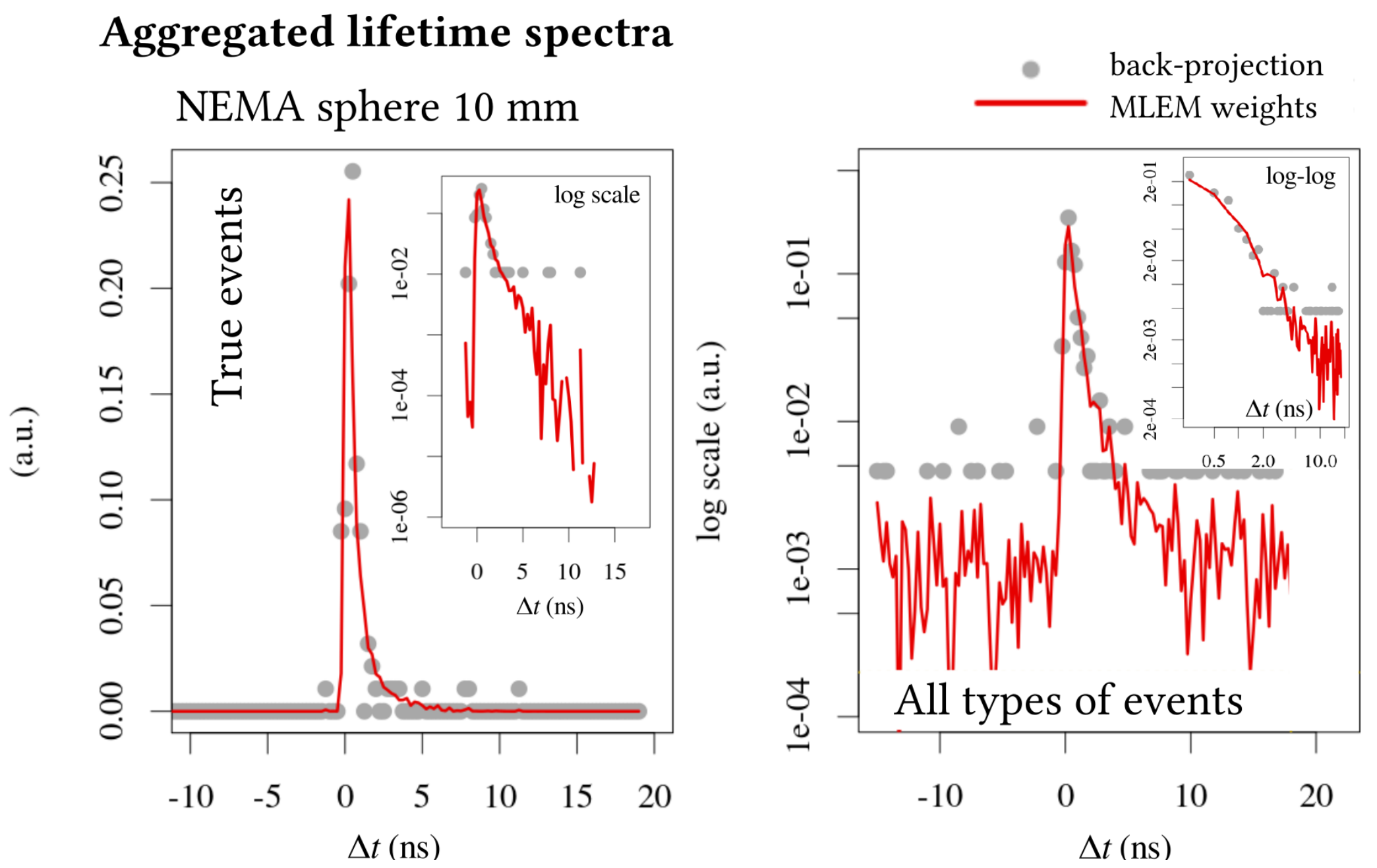
$$\ell_{\epsilon j}^{(\mathrm{pr})} \equiv \ell_{h_\epsilon, j}^{(\mathrm{pr})},\ \chi_{\epsilon j} \equiv \chi_{(it)_\epsilon, j},\ \eta_{\epsilon j} \equiv \eta_{h_\epsilon, j},\ \hat{b}_{\epsilon j} \equiv \hat{b}_{c_\epsilon, j}$$

ϵ – event, j – voxel, i – bin (B2B), h – prompt crystal
$\theta_j = q_j^{(\mathrm{pr})} \theta_j^{(\mathrm{B2B})}$ – PET activity multiplied by prompt sensitivity
c encodes combination (i, h), t – TOF
χ, η – cover **X**, **D** and (geom.) **N**, for B2B and prompt, resp.
$\ell_{h_\epsilon, j}^{(\mathrm{pr})}$ – attenuation factor for a prompt emitted from j to h_ϵ
$\hat{b}_{c_\epsilon, j}$ – additive factor, normalised by $\ell_j^{(\mathrm{B2B})}$

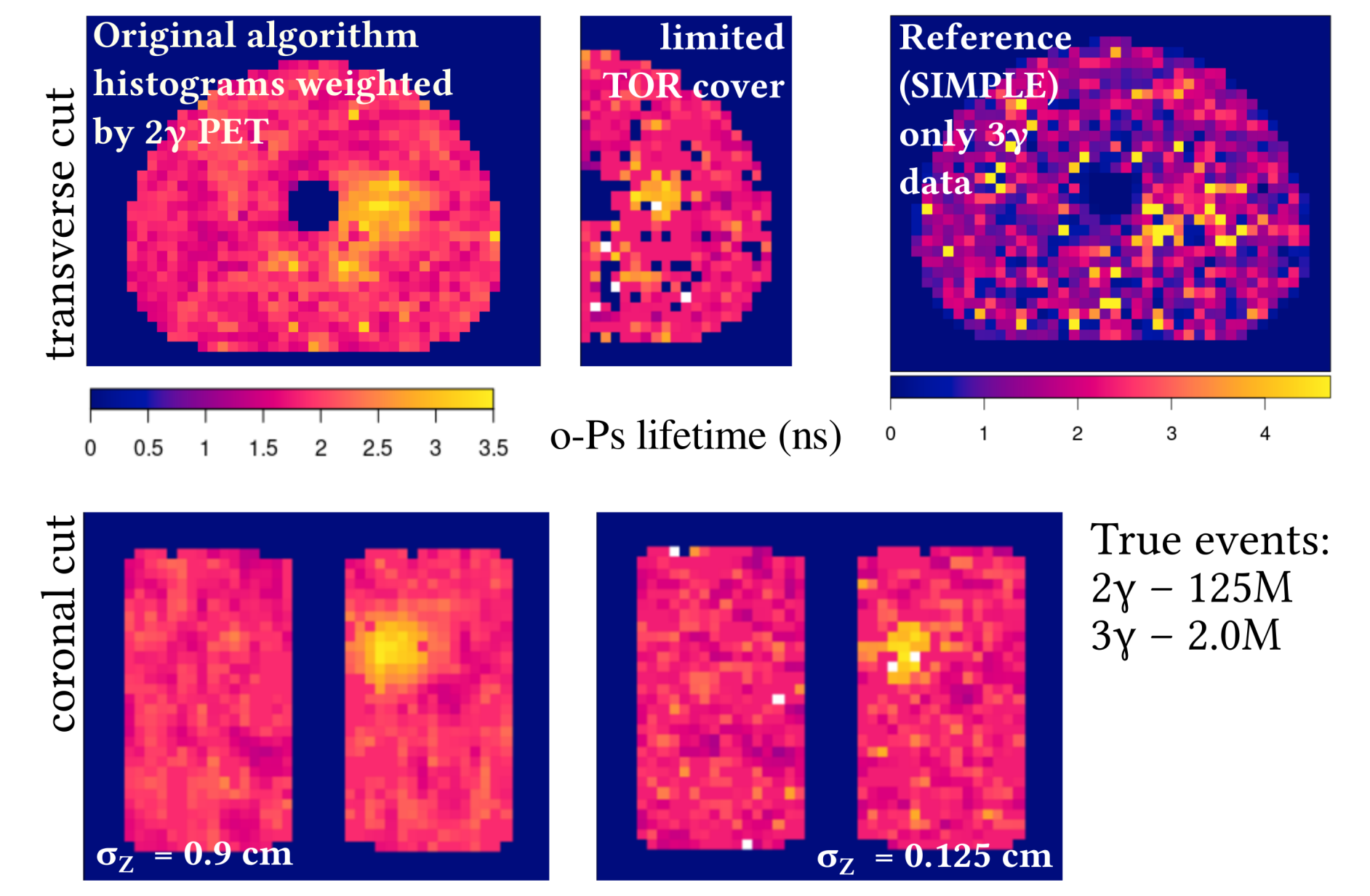
Results (plastic scintillators)

Simulated **NEMA IEC** in a J-PET replica (24 by 13 strips 6 mm × 25 mm × 500 mm), CRT = 235 ps, ^{22}**Na** (59MBq), ***ortho-Ps lifetime*** $\tau_{\text{o-Ps}}$ = 1.84 ns (cold volume and capillaries), from 3.5 ns to 1.5 ns – in spheres. Scan time ~ 10,000 s (**Geant4**)

Aggregated lifetime spectra



PLI (true events)



True events:
2γ – 125M
3γ – 2.0M

Data reduction strategies (2γ)

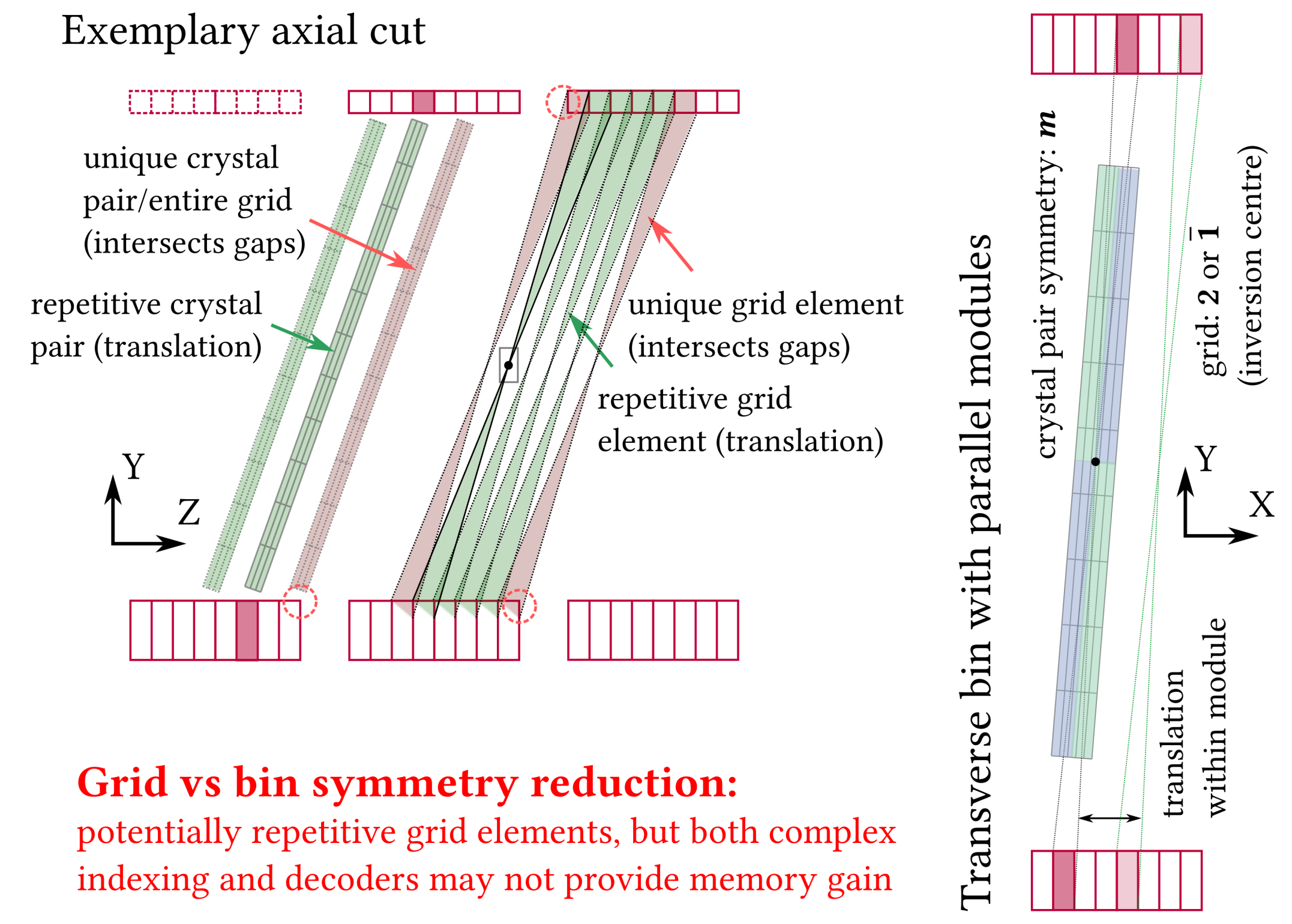
Not a problem for plastic strips (~50MB SM size)
Modules/blocks of crystals: use symmetries.

Use **Hermann–Mauguin** notation (see e.g. [8]).
Transverse symmetry – ***nm:*** *rotational* (***n*** circularly arranged modules), with *mirror* plane (***m***).
Only $n/2$ combinations is sufficient to store.

Table 1. Symmetries for grid and bins on transverse plane

	Arbitrary module pair Arbitrary crystal pair	Arbitrary module pair Crystals opposite each other	Parallel modules Arbitrary crystal pair	Parallel modules Crystals opposite each other
Crystal pair	***m***	**1**	***m***	***mm***
Grid element	**1**	***m***	**2** or $\bar{\mathbf{1}}$	***mm***

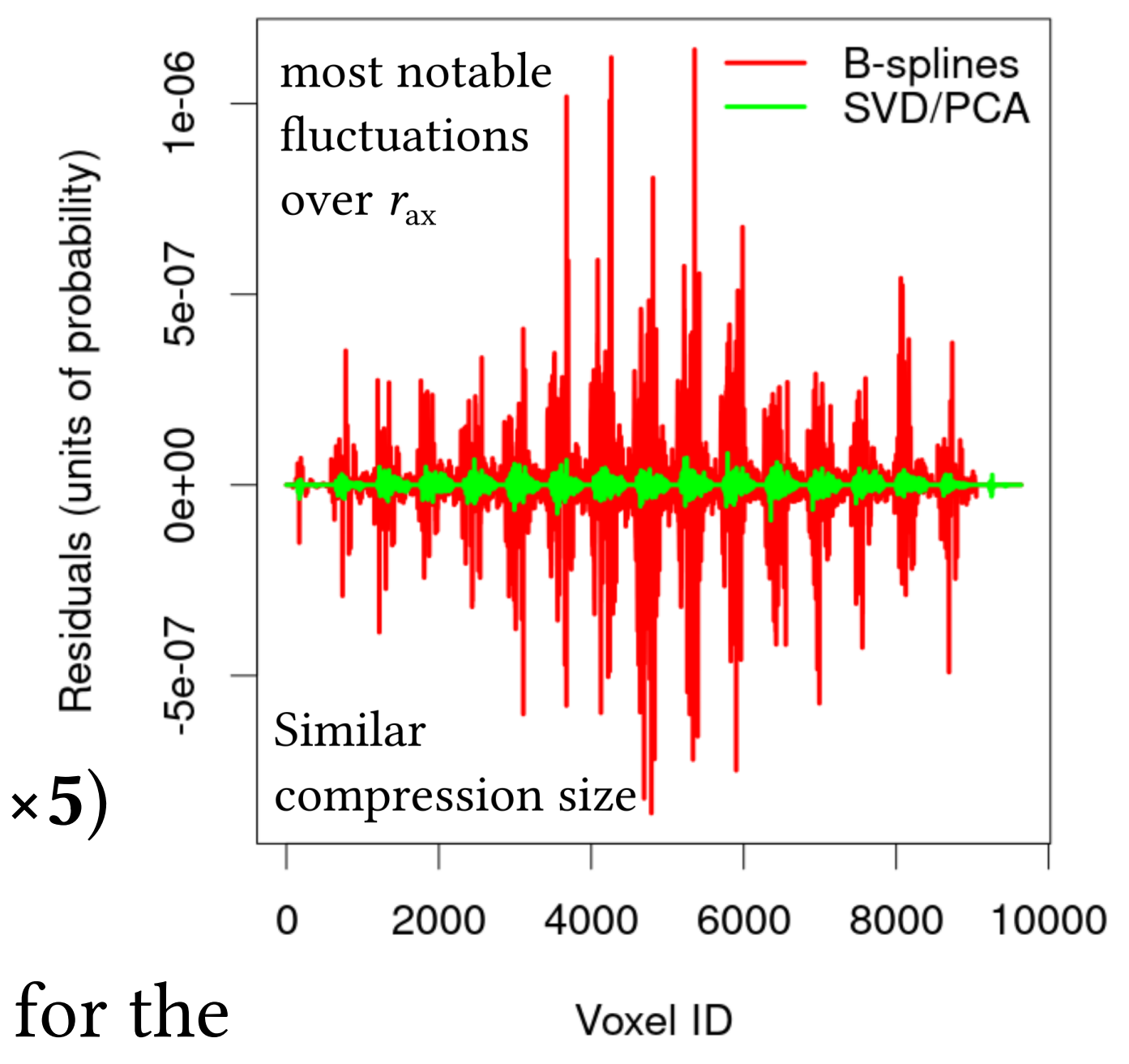
Translation symmetry – the most beneficial in **axial** direction, where module pairs are perfectly aligned. ~30-50% of repetitive bins.



Grid vs bin symmetry reduction:
potentially repetitive grid elements, but both complex indexing and decoders may not provide memory gain

Current solution – SVD/PCA over $r_{\mathrm{tr}} \times r_{\mathrm{ax}}$ slices (various <u>axial crystal IDs</u>, other IDs fixed) +**16-bit** compression.

Data compression options



Much lower MRSE than for B-splines.

Reduction:
~**100** PCA comp.
for **513 pixels**
per slice (*more than* **×5**)

Estimated SM size for the test scanner (24×8 modules, each 13×8 cryst. of 7mm×8mm×25mm): **1.8–3.0 GB** (depending on no. of components). For Siemens Quadra: **20-50 GB.**

Summary

Detector resolution is a major factor in multiphoton imaging, such as PLI. Based on the prior solution for the elongated scintillator detectors, a 3D multi-projector SM modelling with PCA compression is proposed, potentially also suitable for the conventional 2γ PET imaging.

Acknowledgements

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