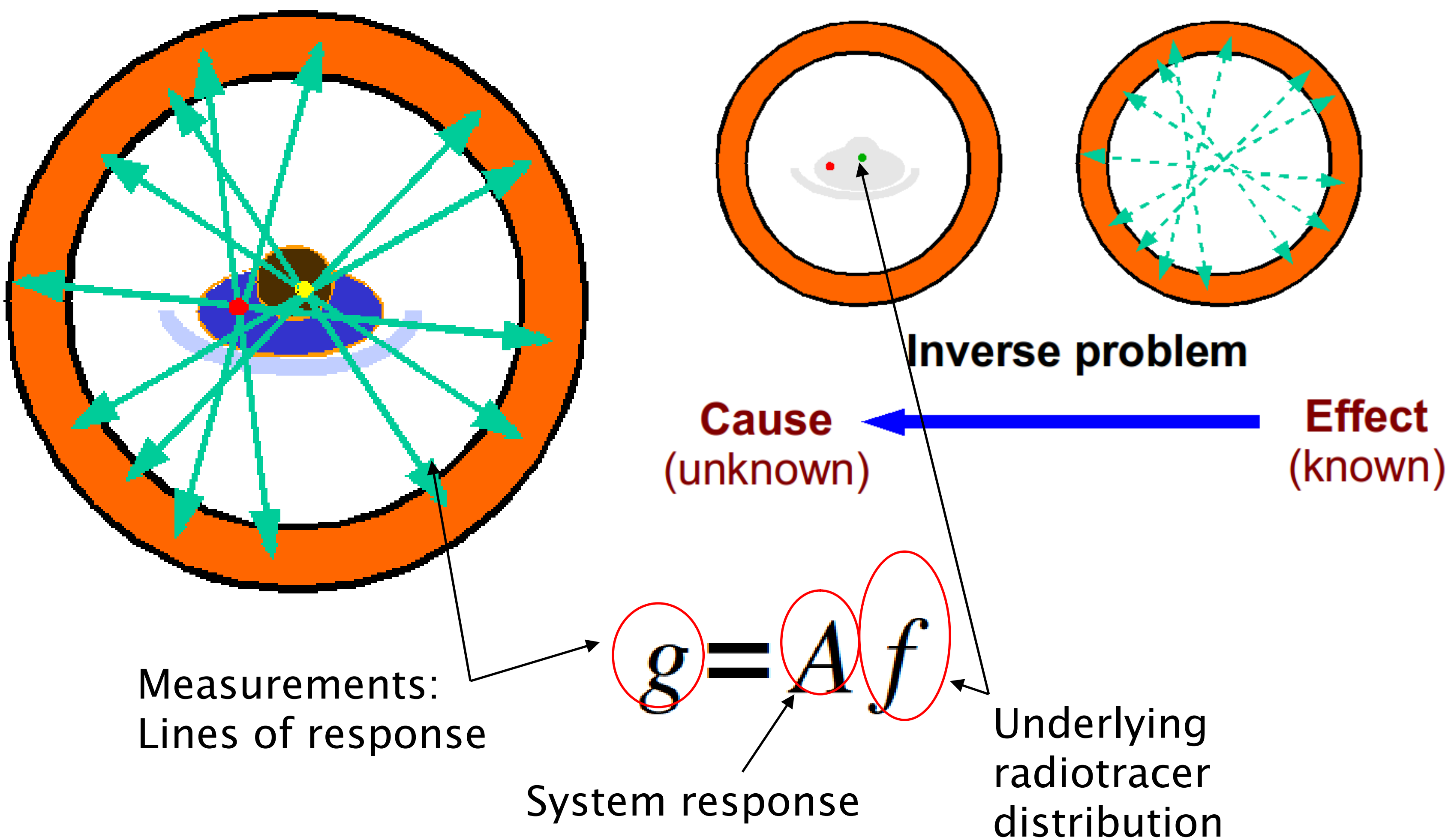
Software approaches for improving image quality in PET

J. Cabello on behalf of the **IRIS** group
Instituto de Fisical Corpuscular (IFIC),
CSIC/Universidad de Valencia, Valencia, Spain

Overview

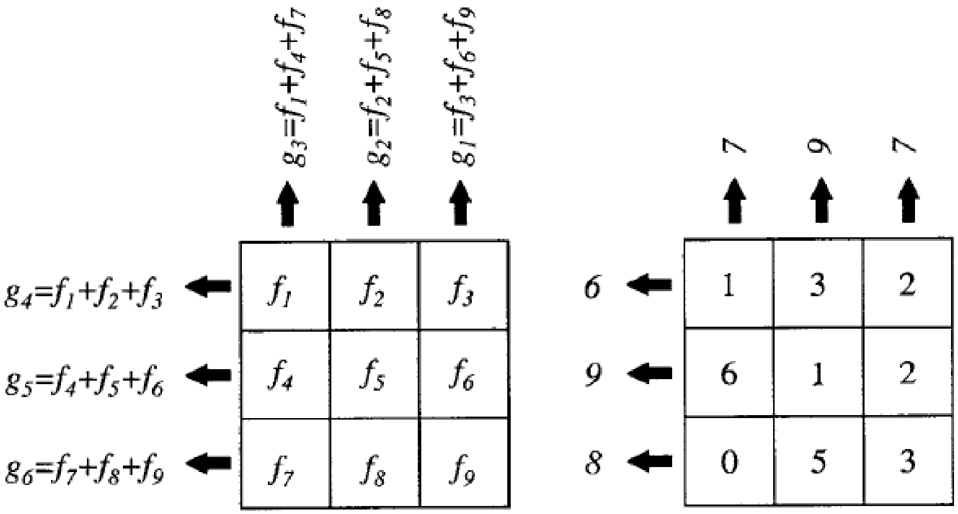
- PET: Image reconstruction
- Image quality in PET
- Novel basis functions
- Motion correction
- Randoms compensation
- Compton image reconstruction
- Global conclusions

PET: Image reconstruction



PET: Image reconstruction

- Example



$$\underbrace{\begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \\ g_5 \\ g_6 \end{bmatrix}}_{g} = \underbrace{\begin{bmatrix} 001001001 \\ 010010010 \\ 100100100 \\ 111000000 \\ 000111000 \\ 000000111 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \\ f_8 \\ f_9 \end{bmatrix}}_{f}.$$

$$\begin{cases} g_1 = f_3 + f_6 + f_9 \\ g_2 = f_2 + f_5 + f_8 \\ g_3 = f_1 + f_4 + f_7 \\ g_4 = f_1 + f_2 + f_3 \\ g_5 = f_4 + f_5 + f_6 \\ g_6 = f_7 + f_8 + f_9. \end{cases}$$

PET: Image reconstruction

- Reconstruction methods
  - Analytical methods: Are based on assumptions that usually do not hold in ET. This might cause severe artefacts.
  - Statistical Iterative methods: It is possible to model the Poisson nature of the particles emitted by the radiotracer and it is possible to model de system response.

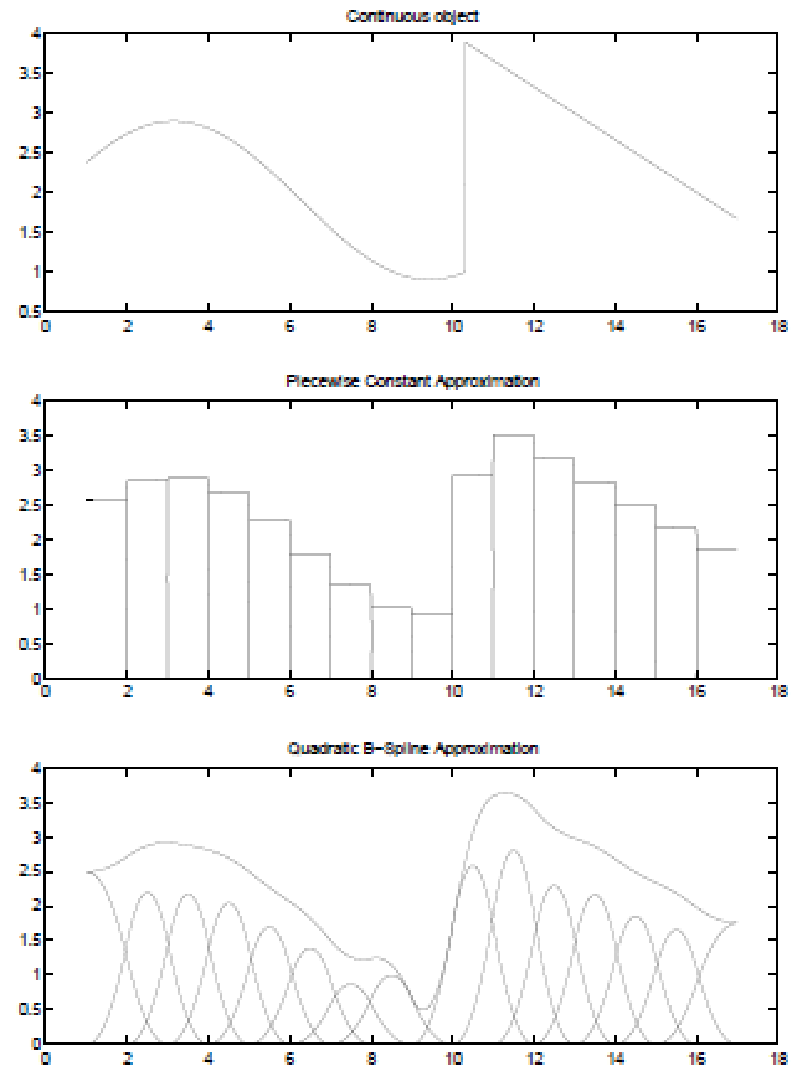
  Reconstruction reconstruction methods are based on these **five components**:

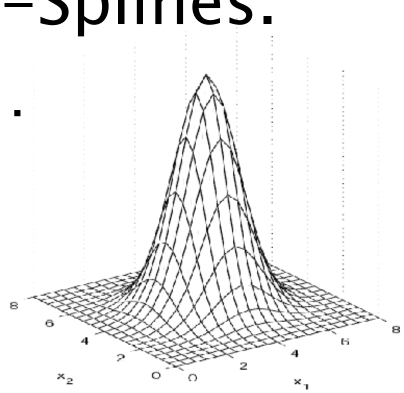
  - Object parameterization → Basis functions.
  - System response model → Physics.
  - Measurement statistical model → Poisson, Gaussian, shifted Poisson...
  - Cost function → Maximum Likelihood, least squares, penalized least squares...
  - Iterative Algorithm → Expectation Maximization, conjugate gradient, steepest descent...

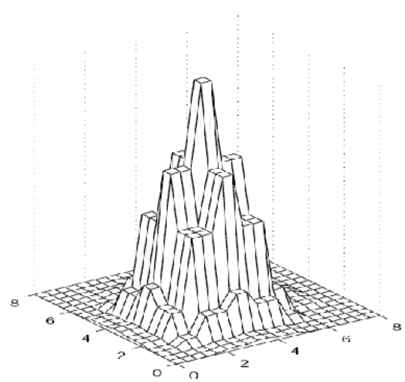
PET: Image reconstruction

- Basis functions, used to discretize *f*.
  - Natural voxels.
  - Polar voxels.
  - Kaisser-Bessel window functions (Blobs).
  - B-Splines.
  - …

$$g = Af$$







Continuous function ➔ Discrete function

PET: Image reconstruction

- System response, defined by *A*, that represents the link between the measurements and the underlying distribution:

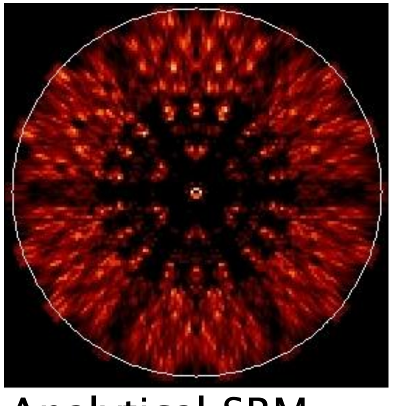
$$g = A f$$

  - Scanner geometry.
  - Scatter in the object or in the scintillator.
  - Object attenuation.
  - Patient motion.
  - Detector response.
  - Detector efficiency.
  - Crystal penetration.
  - Positron range.
  - Non-collinearity between pairs of gammas.

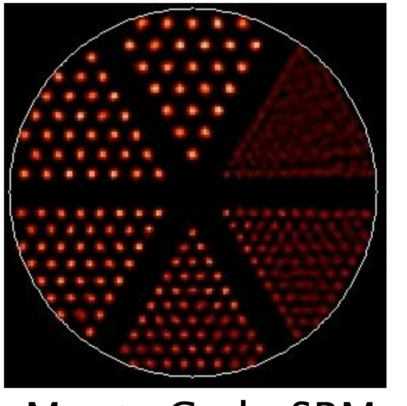
  ...

Image quality in PET

- Instrumentation and Image reconstruction are the two pillars in which PET is based.
- A scanner with high performance instrumentation still has the need for an image reconstruction algorithm tailored to the scanner.
  - Accurate algorithm.
  - Accurate System Response model.
  - Compensation of image degradation phenomena.



Analytical SRM



Monte Carlo SRM

Novel basis functions (Motivation)

- Basis functions are used to discretize the image space and the SRM.

$$g = A f$$

- The SRM represents the probability of interaction of a photon originated in voxel *b* and detected in the Tube of Response (TOR) *d*, *p(b,d)*.
- The size of the SRM escalates with the number of voxels in the FOV and the number of TORs.
- With current pre-clinical scanners the number of elements contained in a SRM is of the order of 10^{12}–10^{15} elements.

Novel basis functions (Motivation)

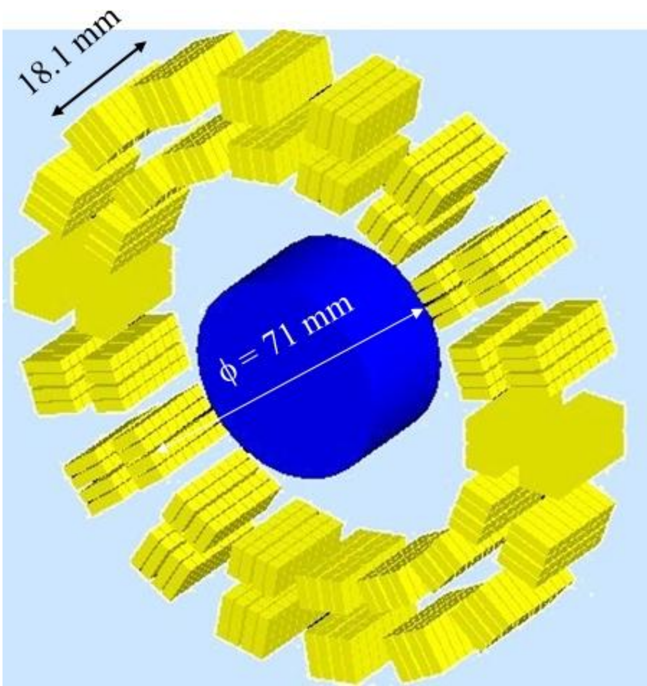
- This work simulates the SRM using Monte Carlo methods.
- This approach is extremely lengthy!
- Our approach exploits the scanner cylindrical symmetries using **polar** voxels as basis functions, significantly reducing the number of elements to simulate, hence making the simulation shorter.
- Additionally, the use of the local GRID facility, further reduces the time necessary to simulate the SRM.
  - A total of $3.7\ 10^{10}$ emissions were simulated ($4.3\ 10^{6}$ emissions per voxel) in 85 hours.

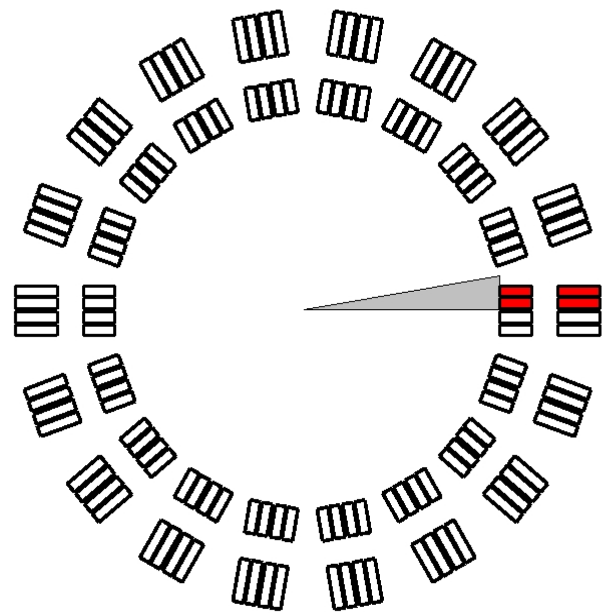
Novel basis functions (Motivation)

- Alternatively, the use of spherically symmetric functions (blobs) instead of Cartesian or polar voxels has been also investigated.
- Blobs are known to reduce statistical noise under the basis of a more appropriate description of the underlying continuous tracer distribution.
- Blobs overlap between them, adding an extra level of complexity. This is the reason why they are not used in clinical practice yet.

Novel basis functions (Materials and Methods)

- This work is based on the pre-clinical scanner MADPET-II.



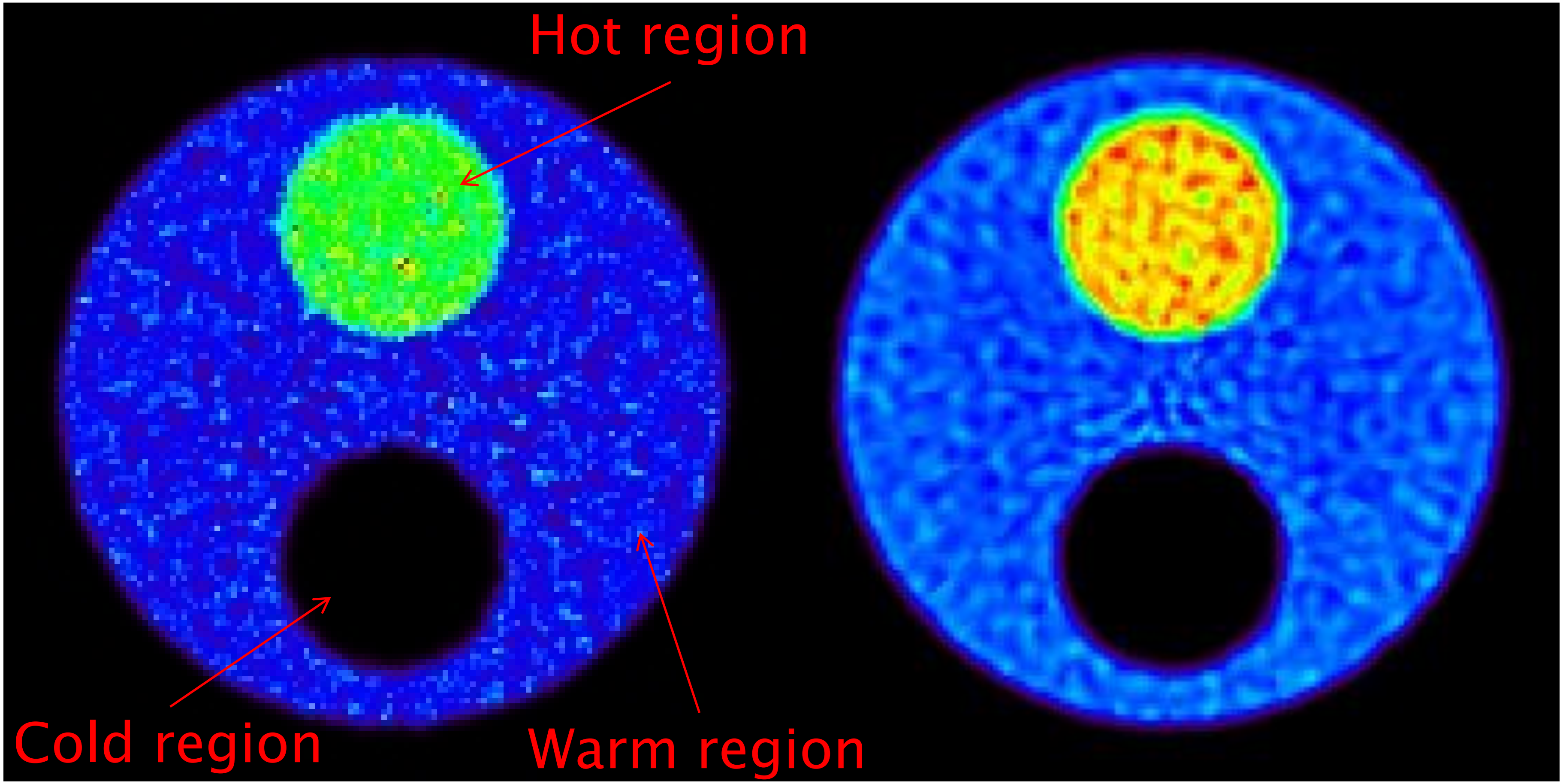


Novel basis functions (Blobs)

- Cubic voxels are always chosen as a matter of simplicity, but it is known that is a basis function that represents too crudely the continuous underlying distribution.
- Blobs have been used in the past to replace Cartesian voxels. Here we use them to replace polar voxels, reducing the intrinsic complexity of using overlapping blobs.

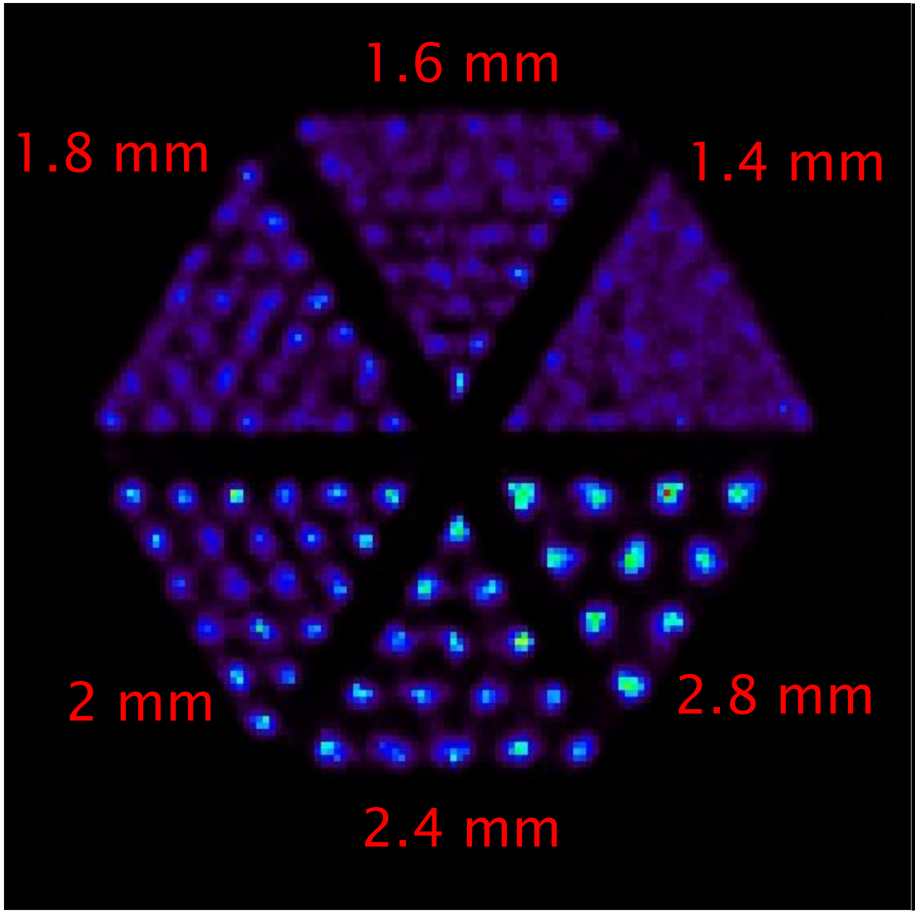
Novel basis functions (Blobs-Results)

Polar voxels: Blobs:

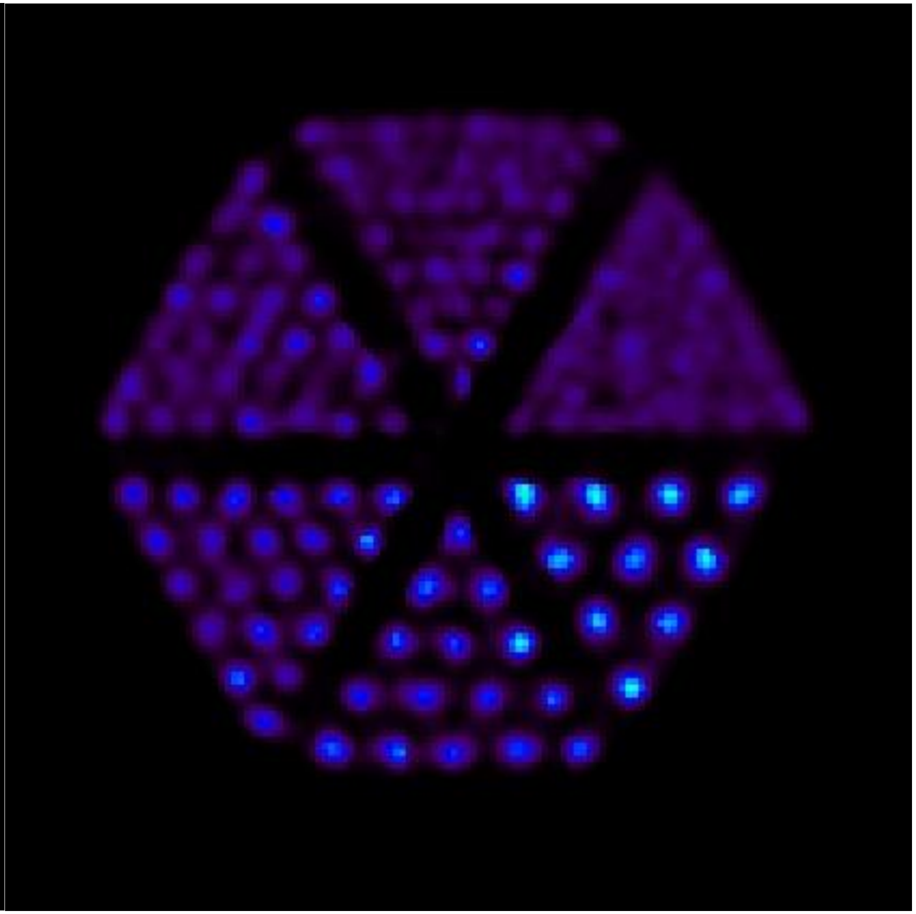


Novel basis functions (Blobs–Results)

Polar voxels:



Blobs:



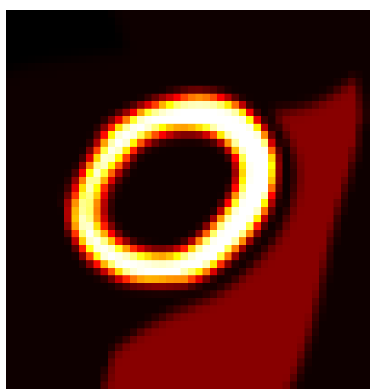
Novel basis functions (Conclusions)

- Polar voxels have shown their comparable performance compared to Cartesian voxels, significantly reducing the necessary simulation time to obtain the SRM and reducing the SRM file size to store.

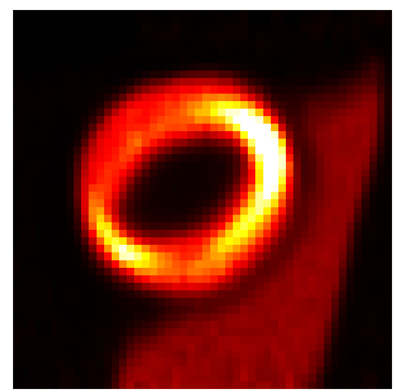
- Blobs have shown to improve the CNR of reconstructed images at the cost of slightly degrading spatial resolution and increased complexity.

Motion correction (Problem statement)

- Involuntary patient motion while scanning is a degrading factor that affects spatial resolution.
- Cardiac PET suffers from **respiratory motion** and **cardiac motion.** If this motion is ignored in the reconstruction, the resulting image suffers from motion blurring:



Ideal tracer distribution



Reconstruction ignoring motion

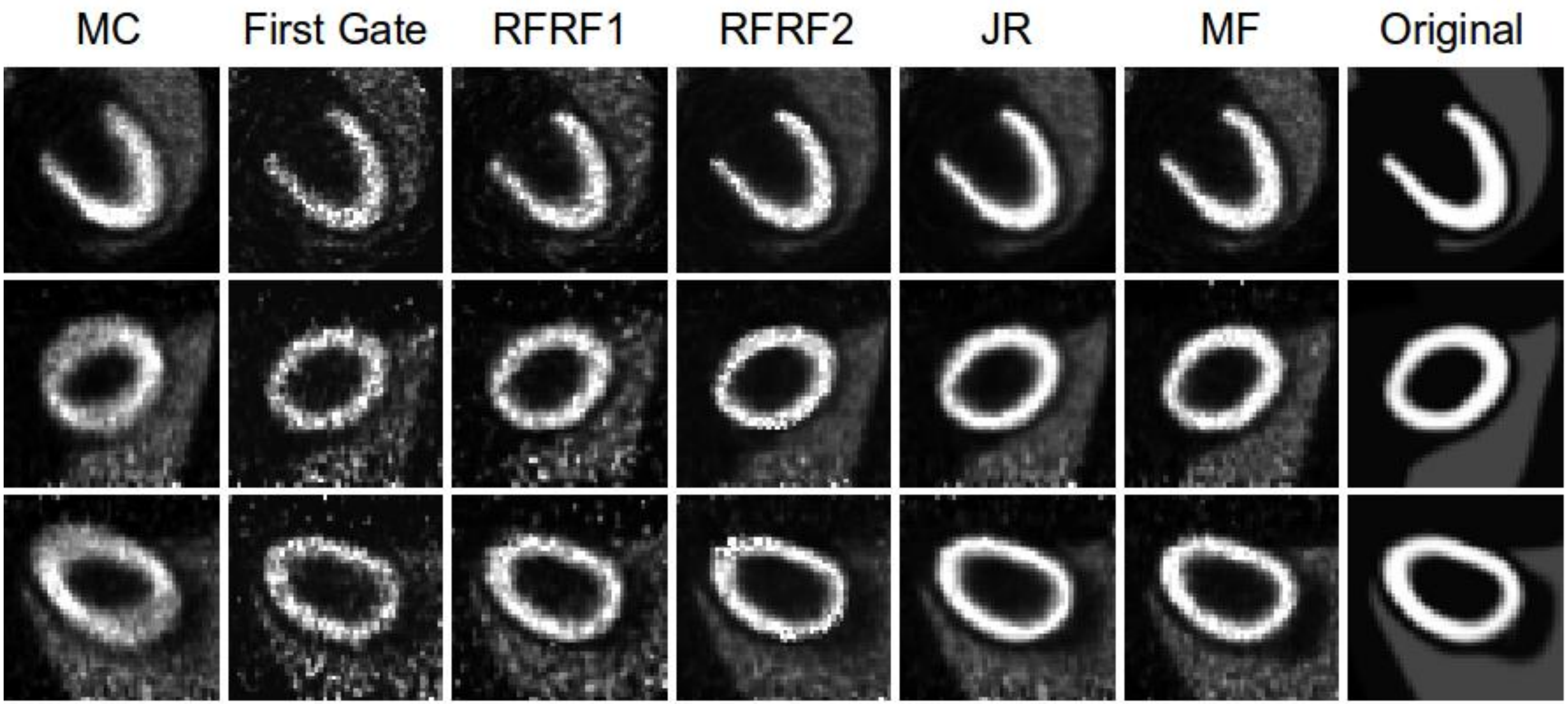
Motion correction (Background)

- The typical approach is to use GATING and reconstruct independent GATED data sets.
- These are subsequently deformed to match a reference reconstructed image.
- This approach suffers from extremely poor statistics in each GATED data set, leading to poorly reconstructed images and poorly deformed images.

Motion correction

- Typically a motion model is initially assumed.
- Out approach is **Joint reconstruction** where the motion model and the final image are unknown.
- This algorithm alternatively estimates the object motion and tracer distribution iteratively.
- Regularization of reconstructed data is used to reduce the effect of noisy data.

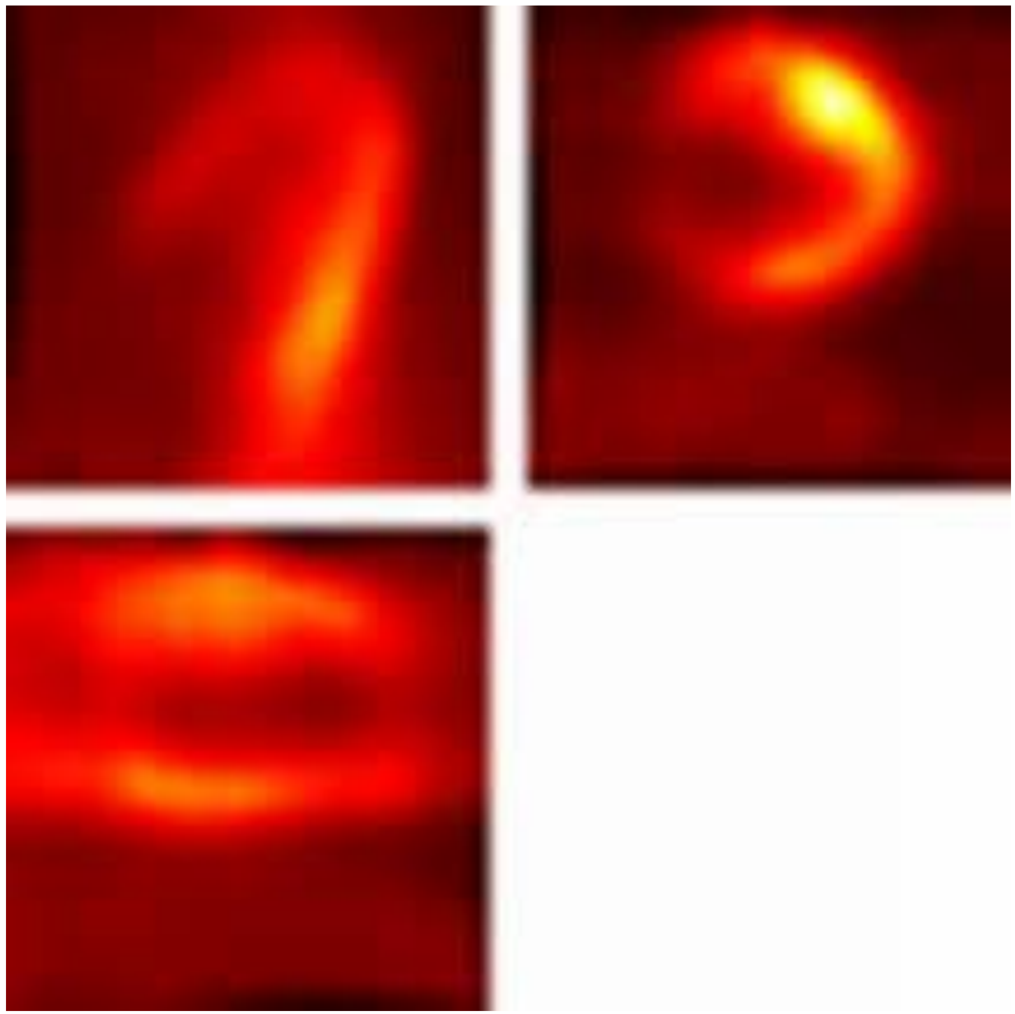
Motion correction (Results)



Motion correction (Conclusions)

- A motion correction algorithm is included in the reconstruction algorithm.
- No assumption about the motion model estimation is needed.
- The algorithm has been tried with simulated and clinical data producing successful results in both cases.
- The improvement over reconstruction with present motion is specially high for low statistics experiments.

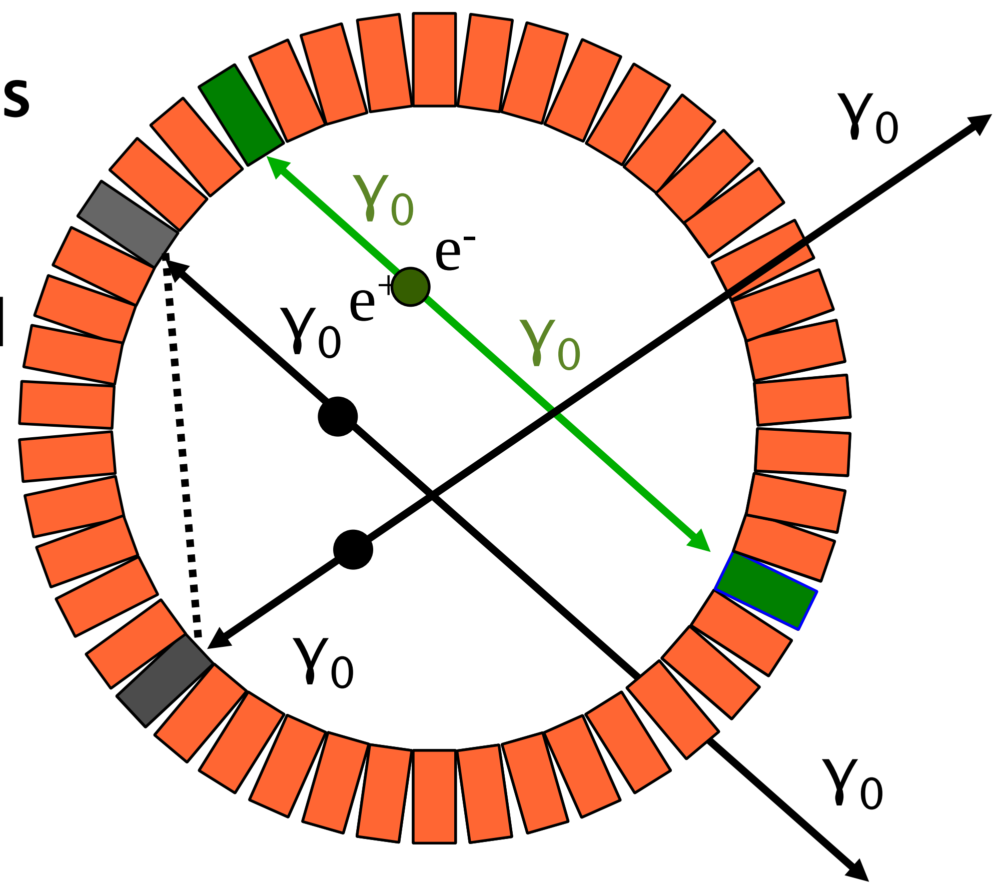
Motion correction (Conclusions)



Randoms compensation (Problem statement)

- PET is based on the detection of the **two photons emitted in a e+ annihilation**.

- A **random** coincidence occurs when **two photons** that were **not originated in the same positron annihilation** are detected as a coincidence.



Randoms compensation (Problem statement)

- Randoms are one of the most **important source of image degradation in PET.** They reduce contrast and hamper quantitative studies.
- Their negative effects **can be partially compensated provided a good random rate estimation** method is available.

Randoms compensation (Background)

- There exist several randoms estimation methods such as Singles rate, delayed window or time histogram.
- Singles Rate (SR).
  - Based on the measurement of singles rates: $R_{ij}=2\tau S_i\ S_j$
  - Extremely easy to implement
  - Small statistical noise, based on counting singles (much more than coincidences)
  - Precise but inaccurate It systematically overestimates the true rate (biased).

Randoms compensation

- Singles True (ST).
  - Include the contributions of the (unknown) trues:

    $R_{ij} = 2t\,[S_i - S_k T_{ik}][S_j - S_k T_{jk}]$
  - Accurate and precise
    - $T_j = S_k T_{jk}$ are not accessible in real acquisitions.

- Singles True iterative (STi).
  - Iteratively estimate T_{ij}:

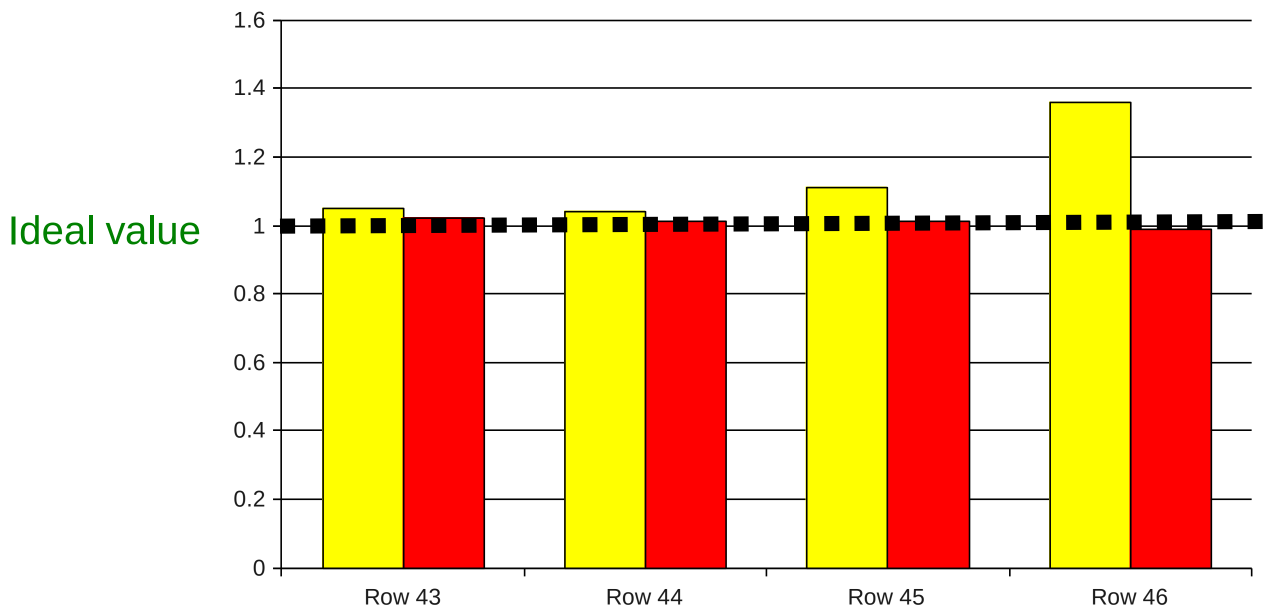
    $R^{(k+1)}_{ij} = 2\tau\,[S_i - T^{(k)}_i][S_j - T^{(k)}_j]$

    $T^{(k)}_j = P_j - R^{(k)}_j$
  - Accurate and precise
  - Requires few iterations

Randoms compensation (Results)

R^{method} / R^{true}

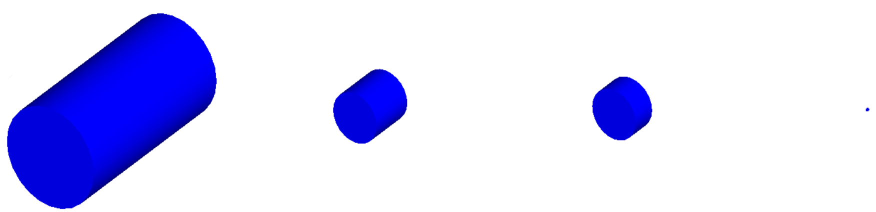
$$R^m \equiv \sum_{ij} R_{ij}$$



A = 0.01 mCi
[400,750] keV

SR

ST



Rat-like	**Mouse-like**	**Cylinder**	**Point -like**
ϕ = 70 mm	ϕ = 35 mm	ϕ = 35 mm	ϕ = 2 mm
h = 140 mm	h = 70 mm	h = 17.8 mm	(sphere)

Randoms compensation (Conclusions)

- **STi always improves SR** estimations while keeping its good features.

- Even for wide energy windows (ie. those with LET < 255keV) the STi estimation is better than SR.

- **For conventional energy windows STi provides the correct value.**

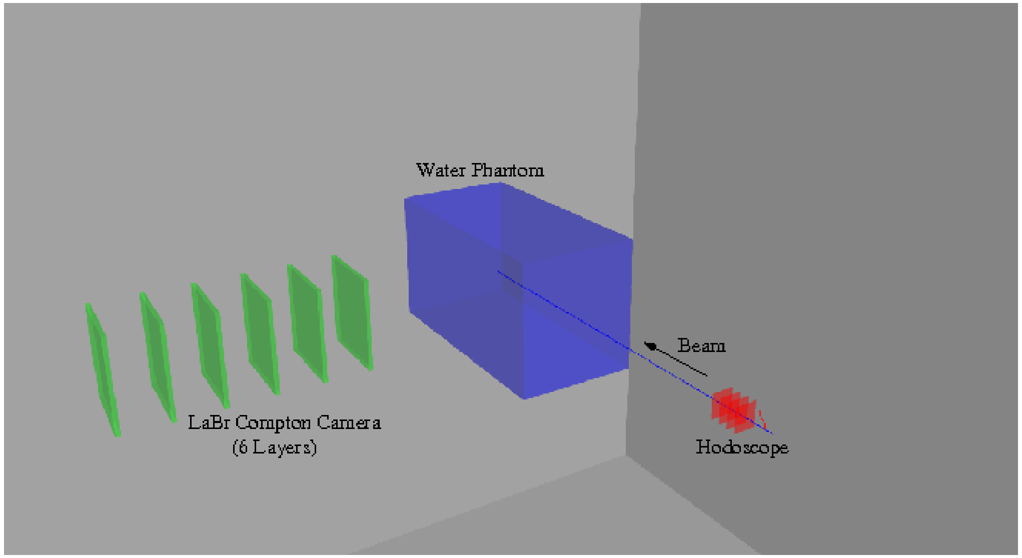
Compton image reconstruction (Motivation)

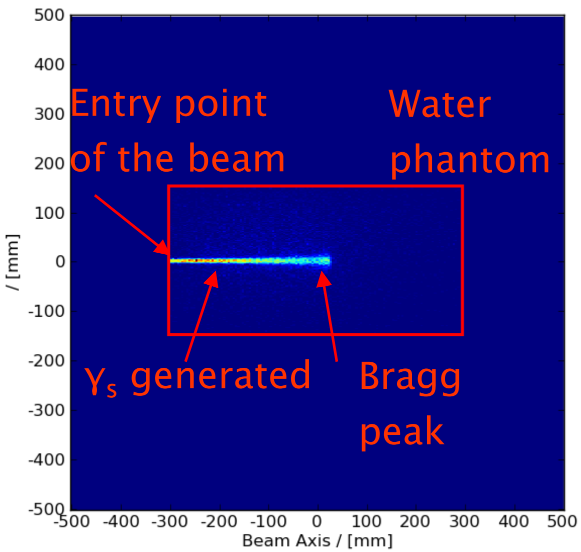
- Hadron therapy is an enhanced method of cancer treatment.
- Difficult to determine spatial distribution of dose applied to the patient.
- Treatment near delicate tissue requires **beam monitoring during treatment.**
  - In-beam PET.
  - Compton imaging.
- This research project aims to use image reconstruction methods of the **beam path** using **only 2 interactions** events. Due to this **energy** and the **radioisotope distribution** are unknown variables → 4D problem!

Compton image reconstruction (Simulated setup)

Simulation geometry:

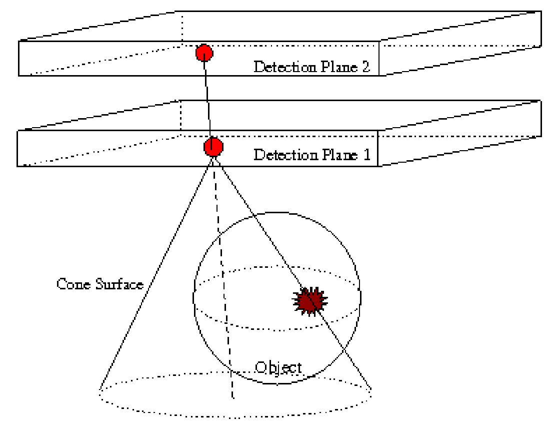
A proton beam hitting on a water phantom, simulating the patient. The generated γ photons in the phantom are detected with a set of LaBr slabs.



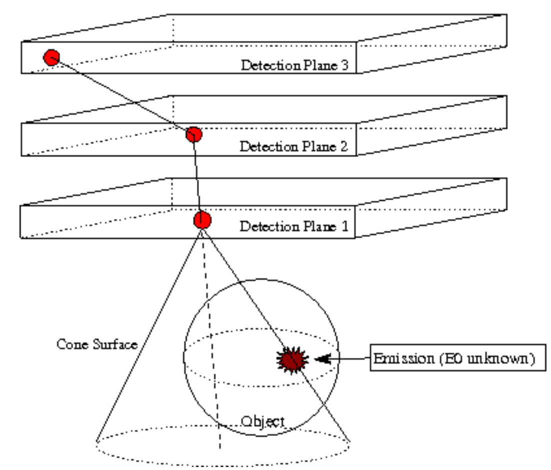


Compton image reconstruction

- The goal is to provide **accurate beam definition.**
- A good reconstructed image depends on a good estimation of the incident energy E_0 in the first scatter to obtain θ.
- Two data sets can be used:
  - 2 interactions events: No energy estimation but “high” sensitivity.
  - 3 interactions events: Good energy estimation but low sensitivity.

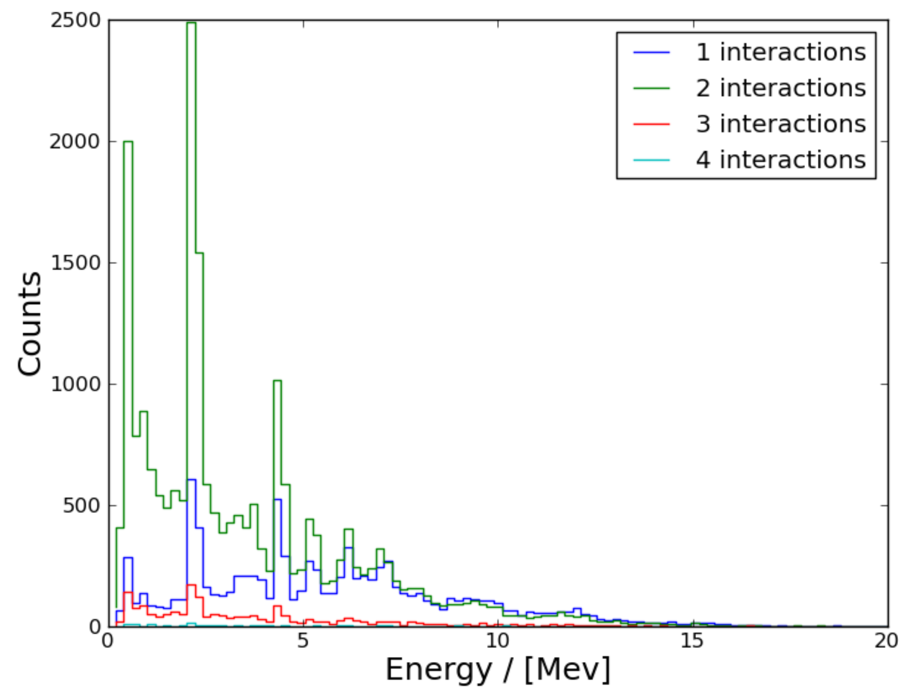


3D Image Space



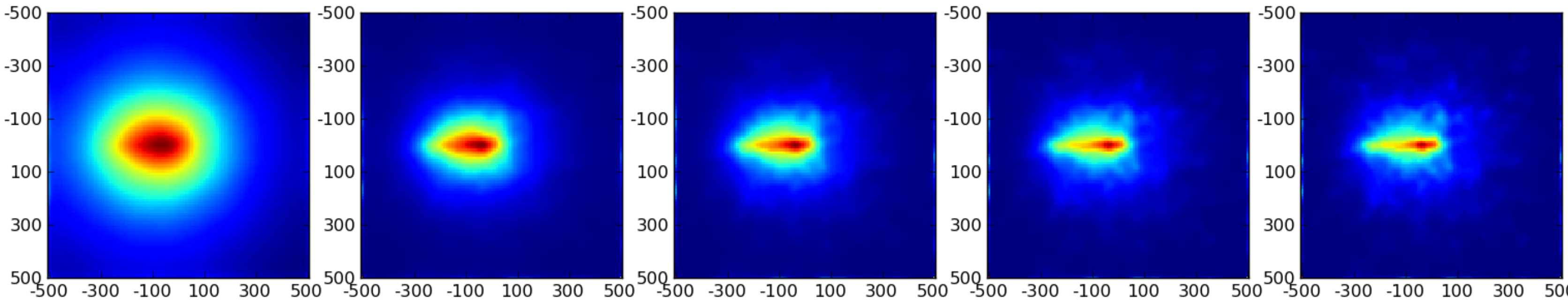
Compton image reconstruction (Spectral imaging)

- Compton imaging should capture data from the full spectral range.
- Spectral information can help to obtain more accurate spatial distribution reconstruction.



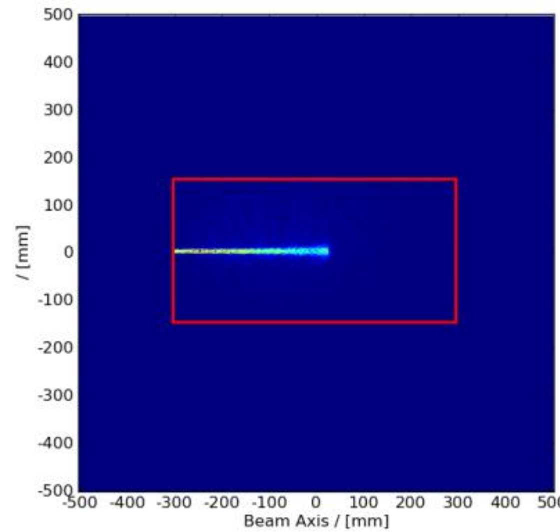
Compton image reconstruction (Results)

- Reconstructed images using 2 interactions events.



Iterations

Ideal image



Compton image reconstruction (Conclusions)

- Compton imaging can provide an alternative or additional way of beam monitoring in hadron therapy.

- Preliminary results have shown encouraging beam reconstruction.

- It is still necessary to work on how to obtain extra information from the spectral information.

Global conclusions

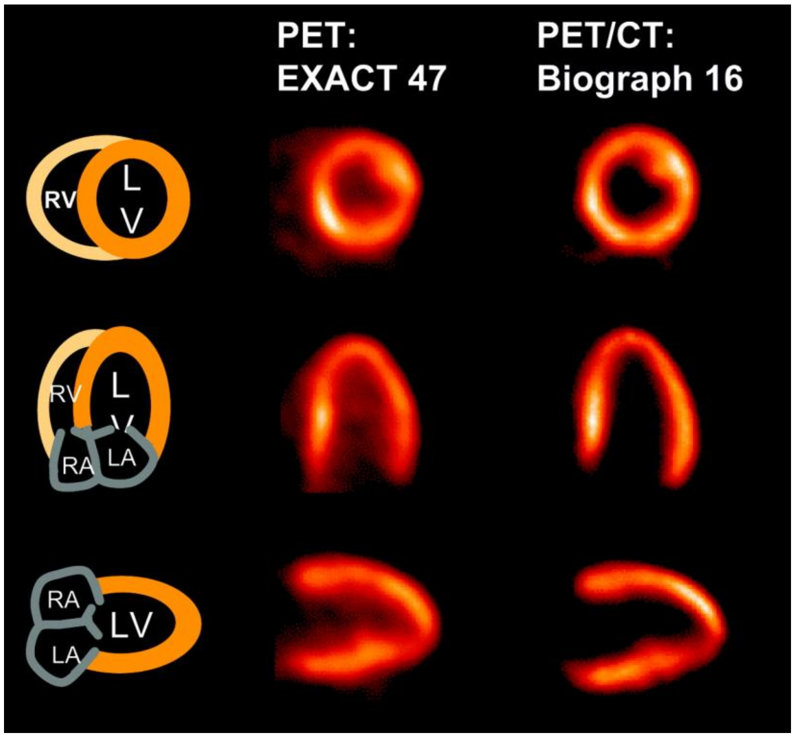
- The IRIS group deals with different approaches to improve image quality in PET.
- To increase Contrast to Noise ratio and improve spatial resolution are always the main aims.
- To obtain the highest performance of each scanner tailored models and algorithms are developed, in order to exploit the peculiarities of each scanner.

... but do all these improvements translate in to better images from a clinical point of view???

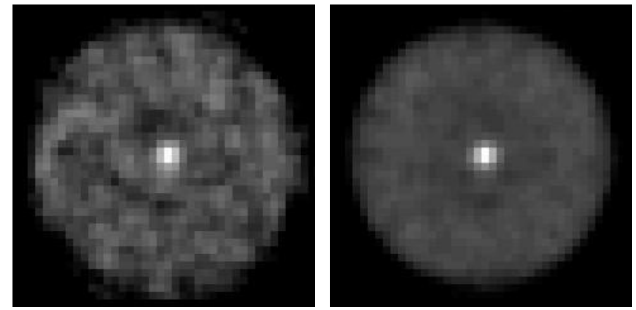
- There is a missing link between medical physicists and medical doctors that is necessary to cover.

Global conclusions

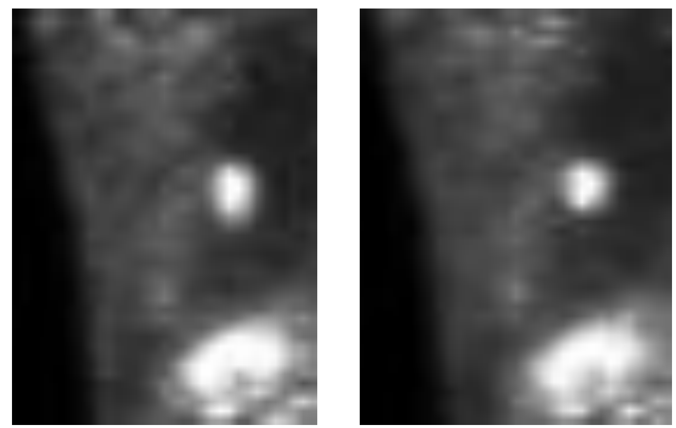
Attenuation correction by using a CT scanner [1].



Time of flight PET [2].



Motion correction.



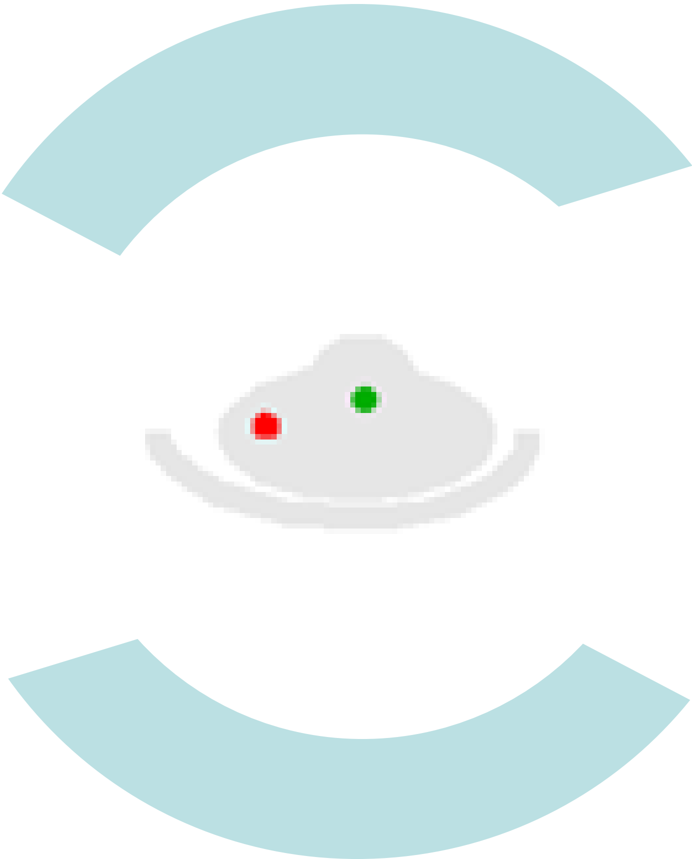
[1] M. Schwaiger, S. Ziegler and S. G. Nekolla . 2005. PET/CT: Challenge for Nuclear Cardiology. 2005. JNM, 46(10):1664-1678.

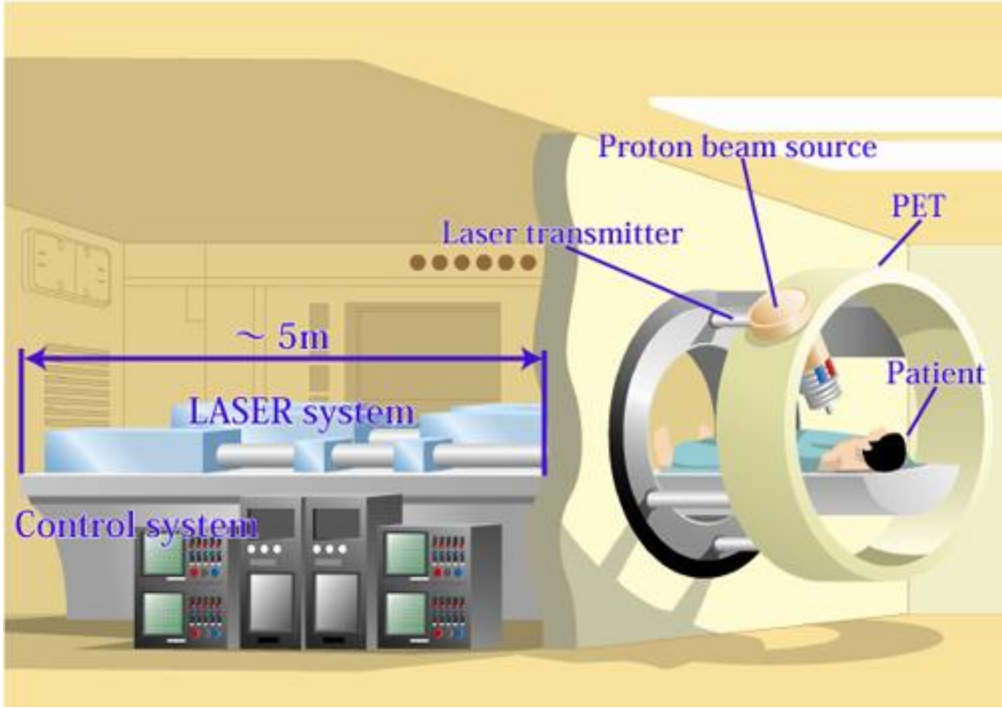
[2] W. Moses, 2006. LNBL.

THANK YOU FOR YOUR ATTENTION!

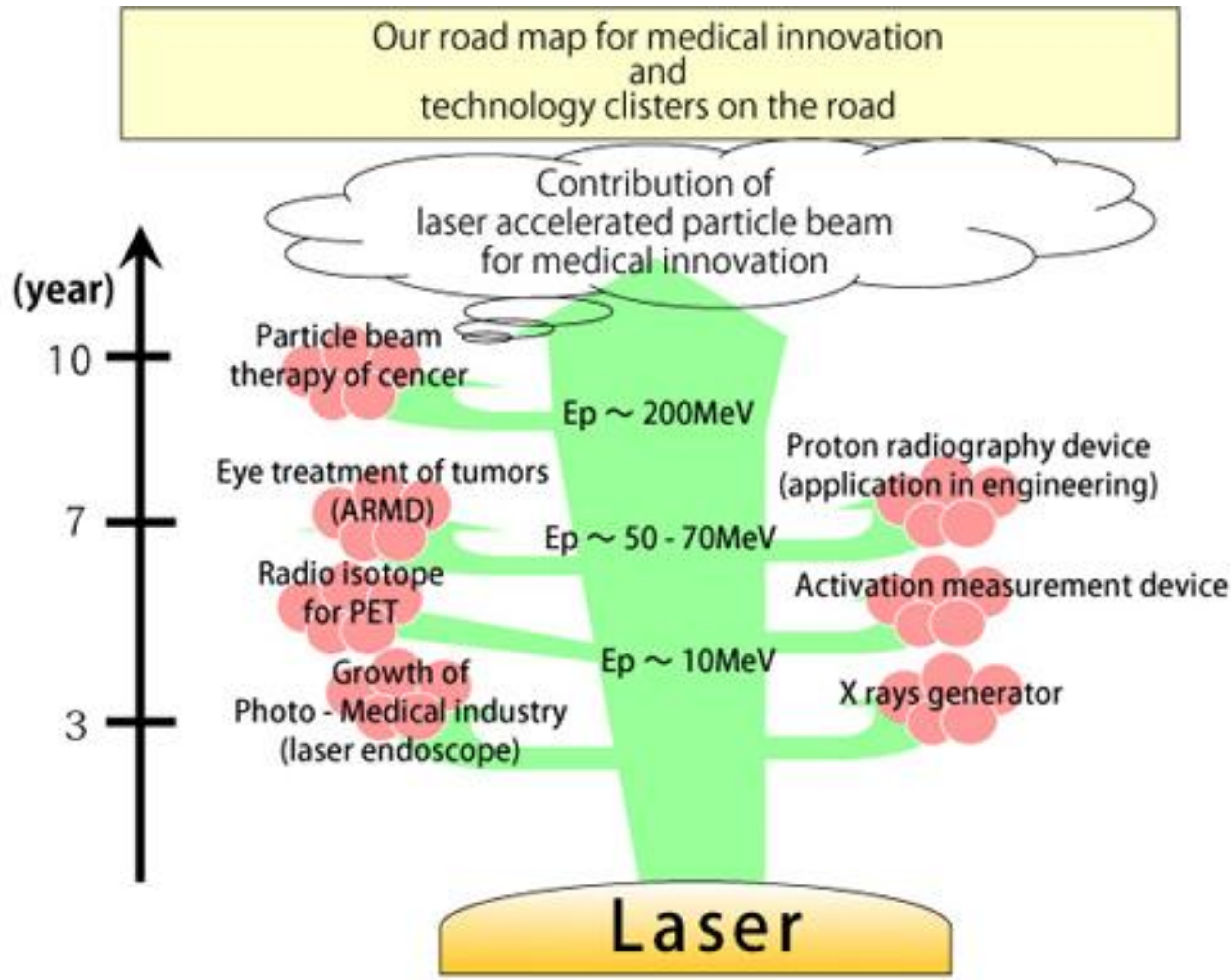
System Response Matrices

- Calculated through **analytical** methods.
  - Fast but low accuracy of physical effects.
- **Measured** moving a point source across the FOV.
  - Slow (measurements are time consuming) but very accurate.
- **Simulated** using **Monte Carlo** methods.
  - Trade-off between speed and accuracy.
  - It can be speed up using the GRID.





http://wwwapr.kansai.jaea.go.jp/pmrc_en/org/



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Radiation Dose Distribution