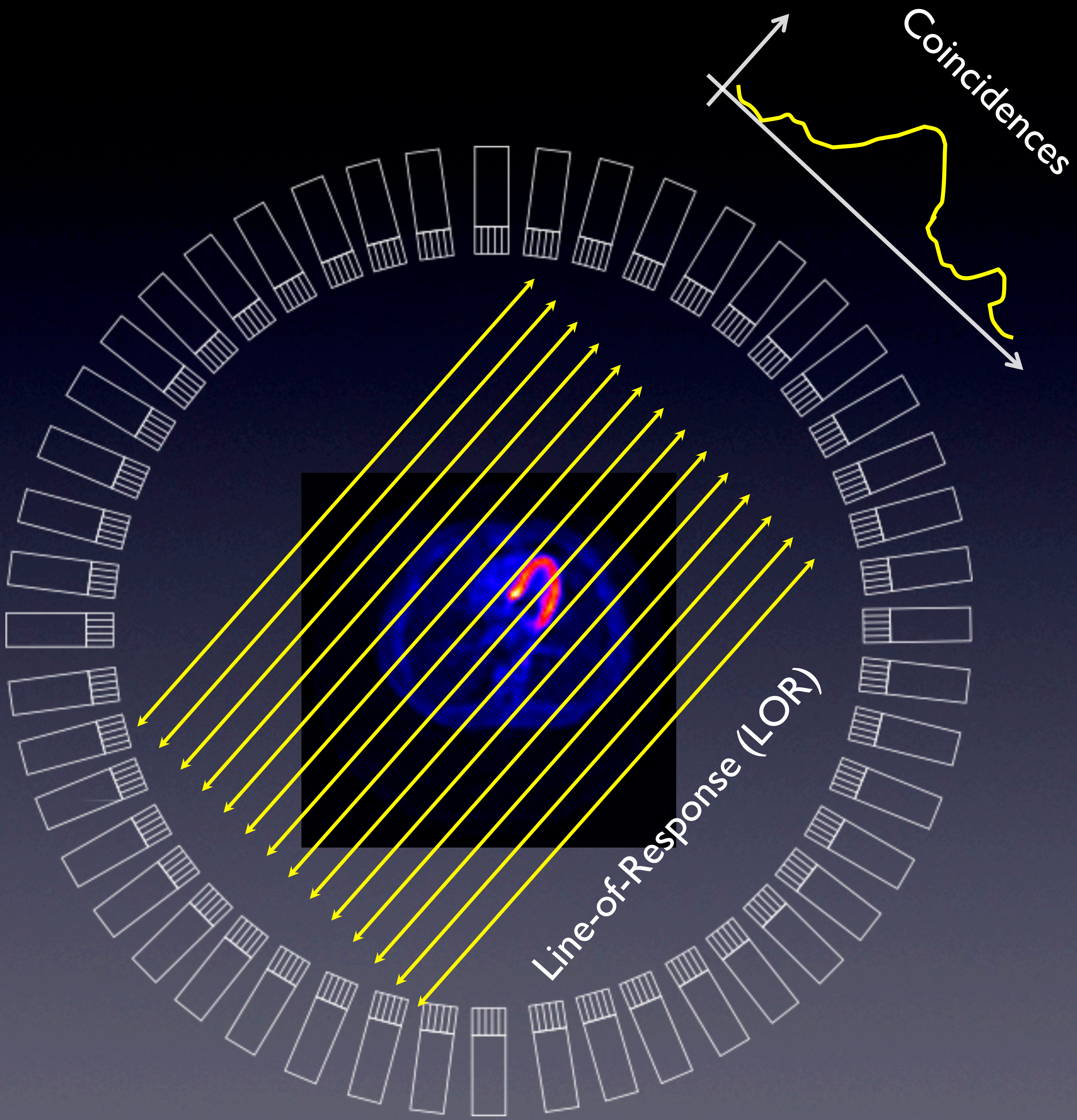
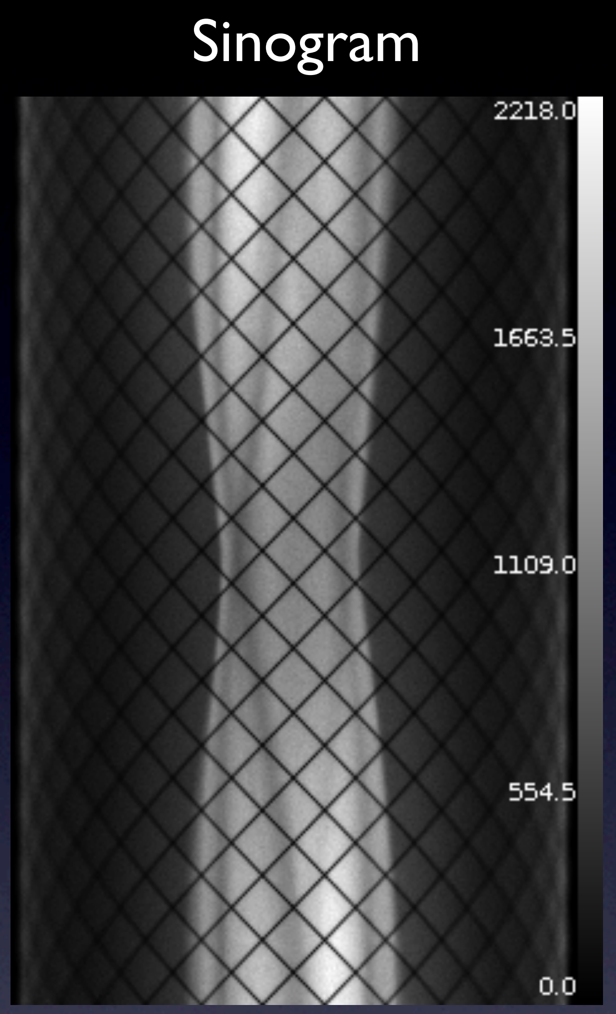
3D PET list-mode reconstruction including all available information provided by the detector

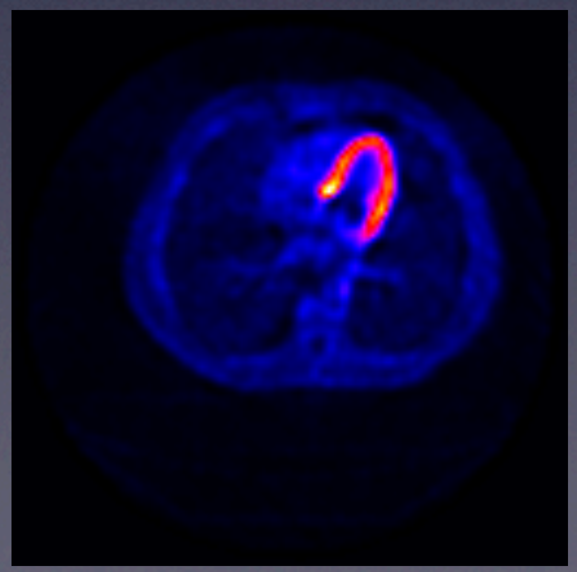
Awen AUTRET[1], Julien BERT[1], Olivier STRAUSS[2] and Dimitris VISVIKIS[1]

[1] Laboratoire du Traitement de l'Information Médicale (LaTIM)
INSERM UMR1101, CHRU Brest
[2] LIRMM, Université Montpellier 2, UMR5506

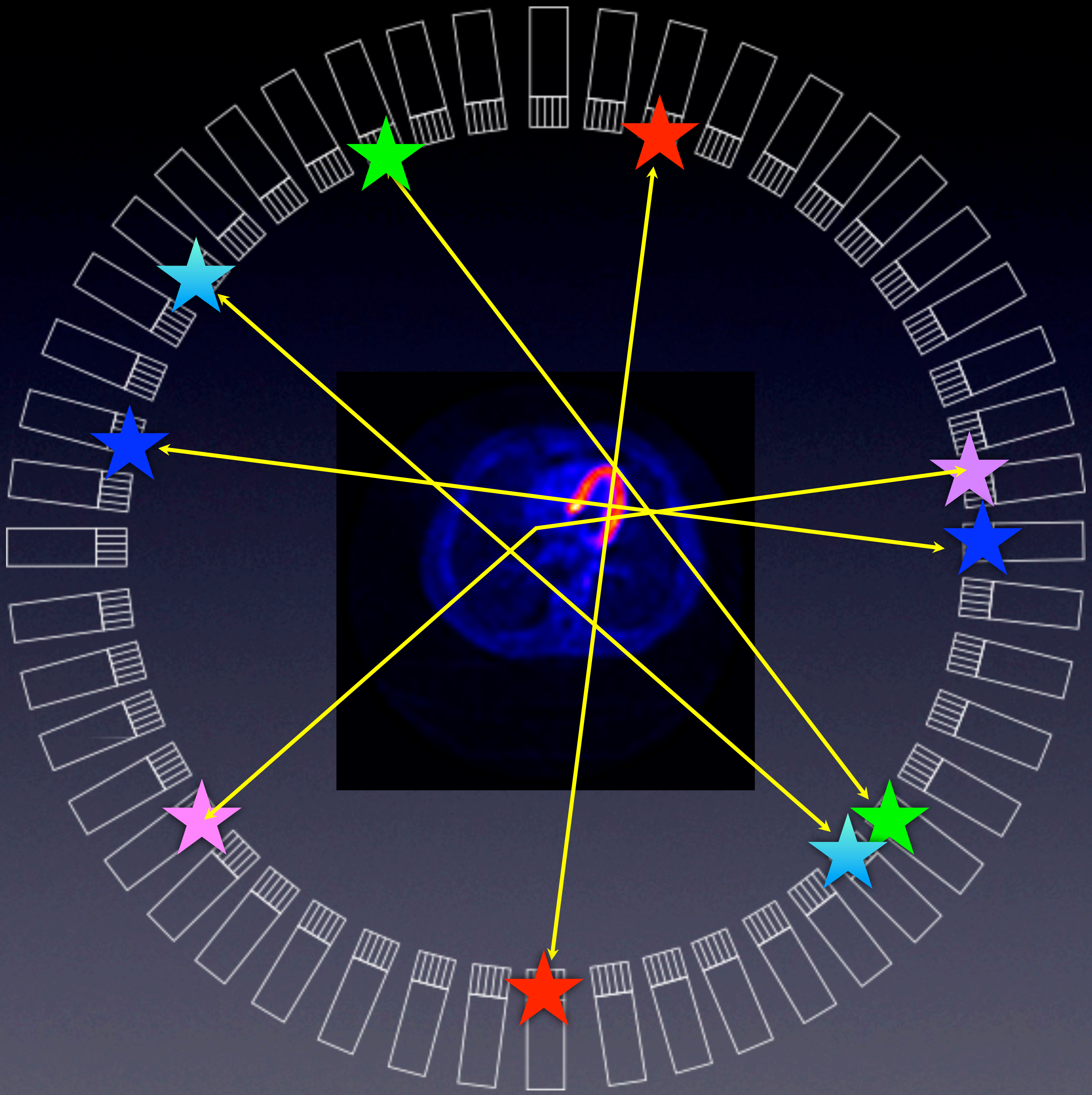
PET reconstruction







PET list-mode reconstruction



List-mode data:

ID1 T1 E1 DOI1
ID2 T2 E2 DOI2
ID3 T3 E3 DOI3
ID4 T4 E4 DOI4
ID5 T5 E5 DOI5
...

List-mode VS sinogram [Rahmim2004]:

- Better spatial sampling
- Better temporal sampling (motion correction)
- More information: TOF, DOI, energy…

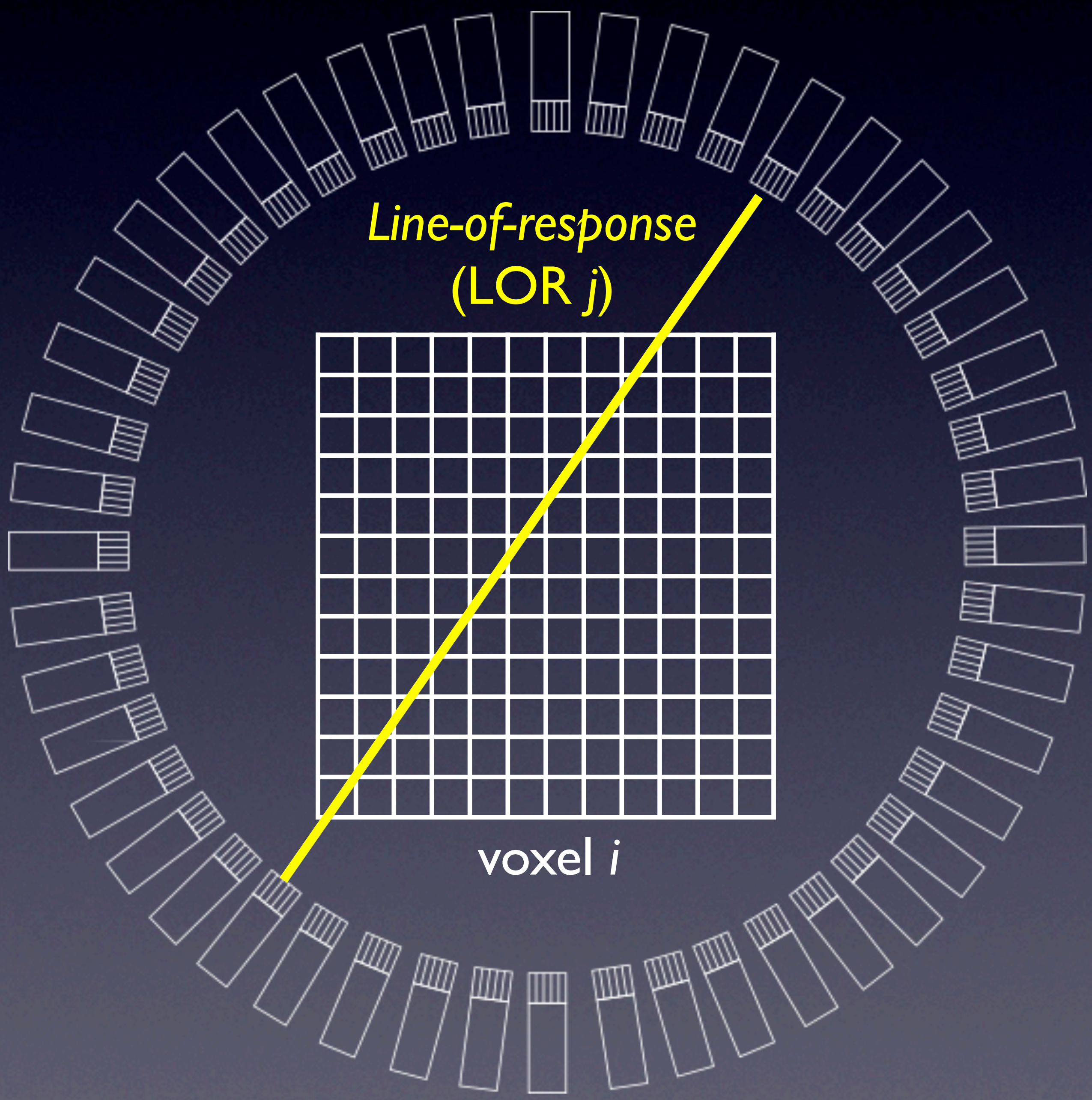
Quantitative clinical reconstruction

Rahmim et al., Phys. Med. Biol., 2004

PET list-mode reconstruction

Iterative reconstruction

- LM-OSEM [Reader1998]
- For each LOR, forward and backward projection



System Matrix (SM)

Probability to detect a positron emission from the voxel *i* with the LOR *j*

store the "contribution" of each LOR in image space

$$card(SM) = (M, N)$$

M is the number of LORs and *N* the numbers of voxels

$$card(SM) = (M, N, t)$$

Huge matrix

- difficult to include additional information
- memory size (specially for GPU)

Reader et al., Phys. Med. Biol., 1998

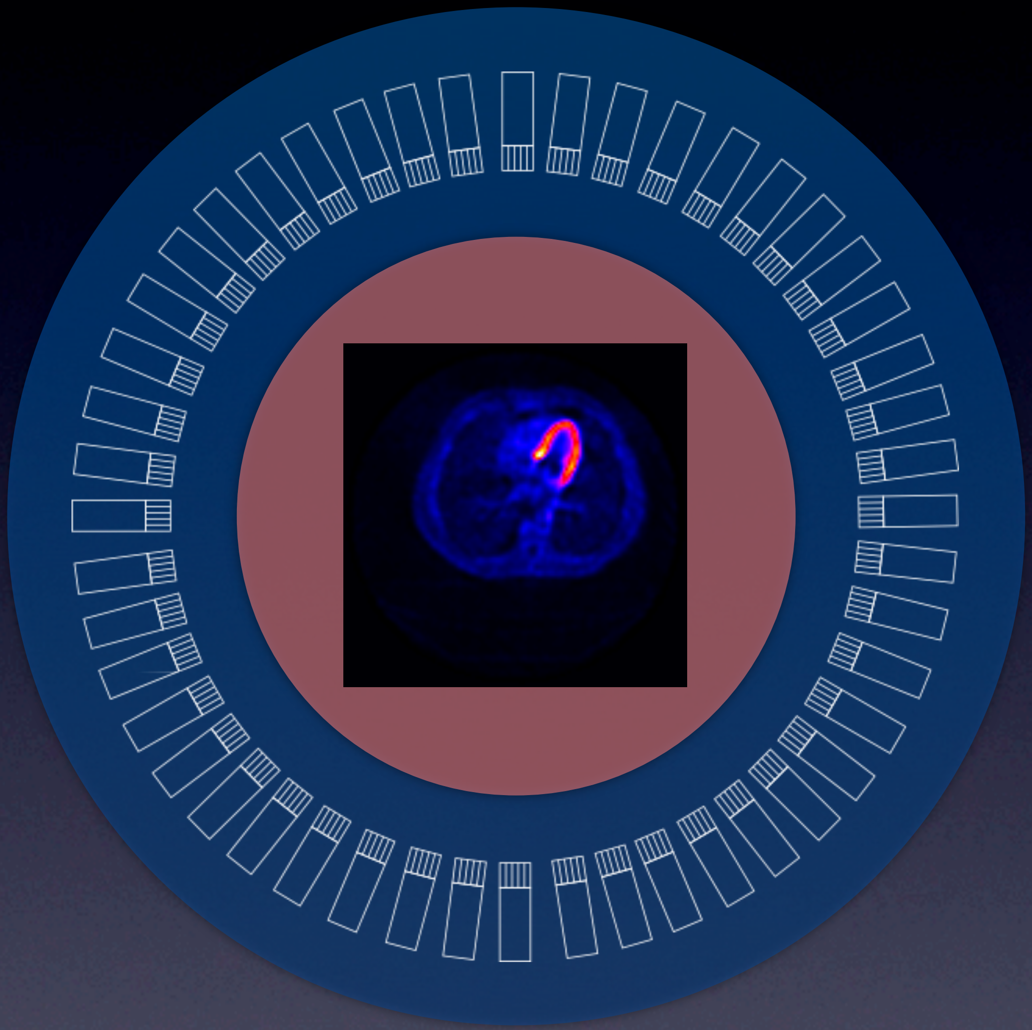
PET list-mode reconstruction

SM decomposition [Qi1998]

$$\underbrace{SM}_{\mathbb{R}^{M\times N}} = \underbrace{\mathcal{P}}_{\text{Scanner}} + \underbrace{\mathcal{M}_{po}}_{\mathbb{R}^{N\times N}} + \underbrace{\mathcal{M}_{pi}}_{\mathbb{R}^{N\times N}}$$

Scanner: $\mathcal{P}$ ($\mathbb{R}^{M\times N}$)

Patient physiology+physics: $\mathcal{M}_{po} + \mathcal{M}_{pi}$ ($\mathbb{R}^{N\times N}$ each)



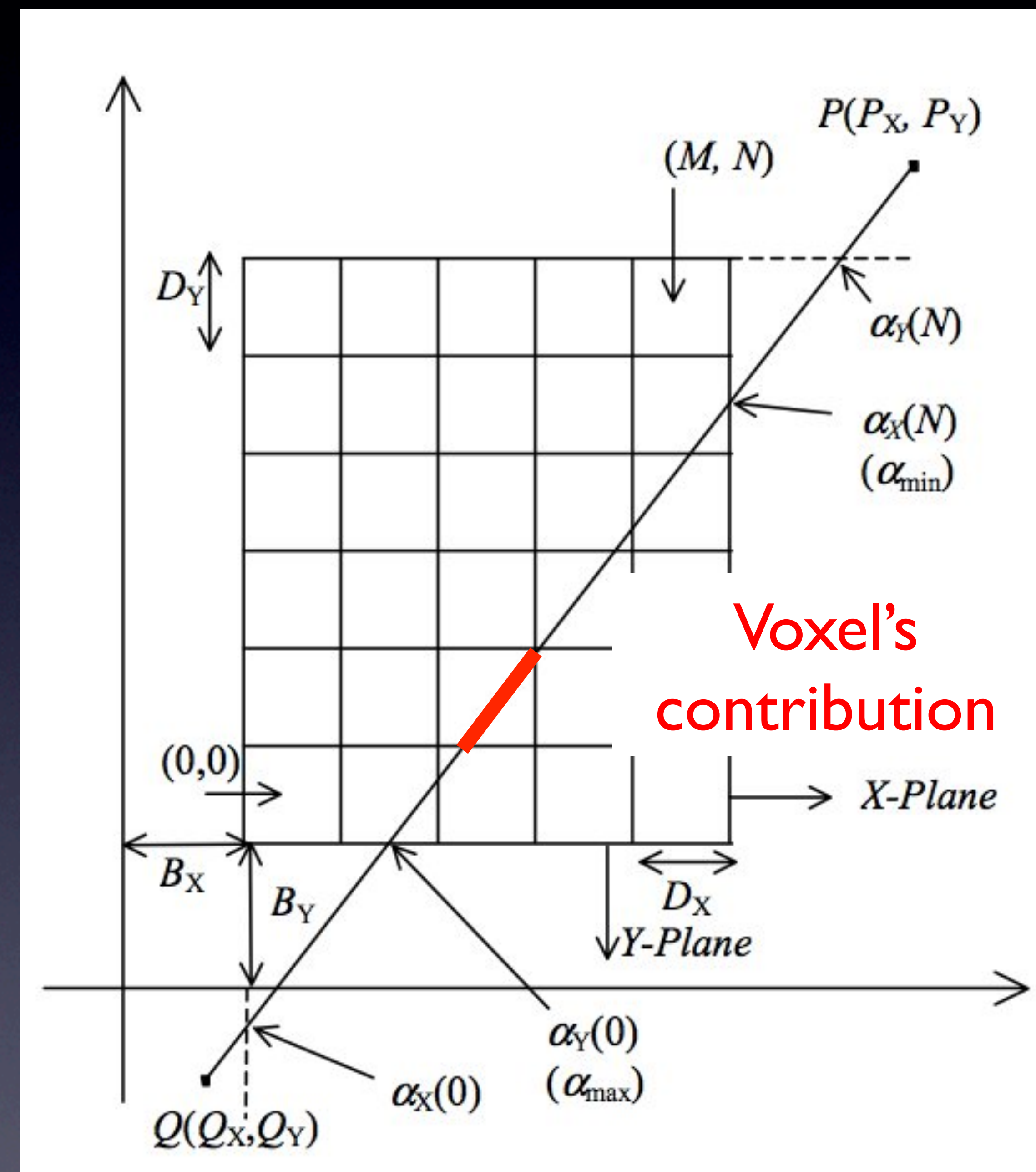
PET list-mode reconstruction

SM decomposition [Qi1998]

$$\underbrace{SM}_{\mathbb{R}^{M\times N}} = \underbrace{\mathcal{P}}_{\text{Scanner}} + \underbrace{\mathcal{M}_{po}}_{\mathbb{R}^{N\times N}} + \underbrace{\mathcal{M}_{pi}}_{\mathbb{R}^{N\times N}}$$

Compute on-the-fly the contribution of the LOR using a projector

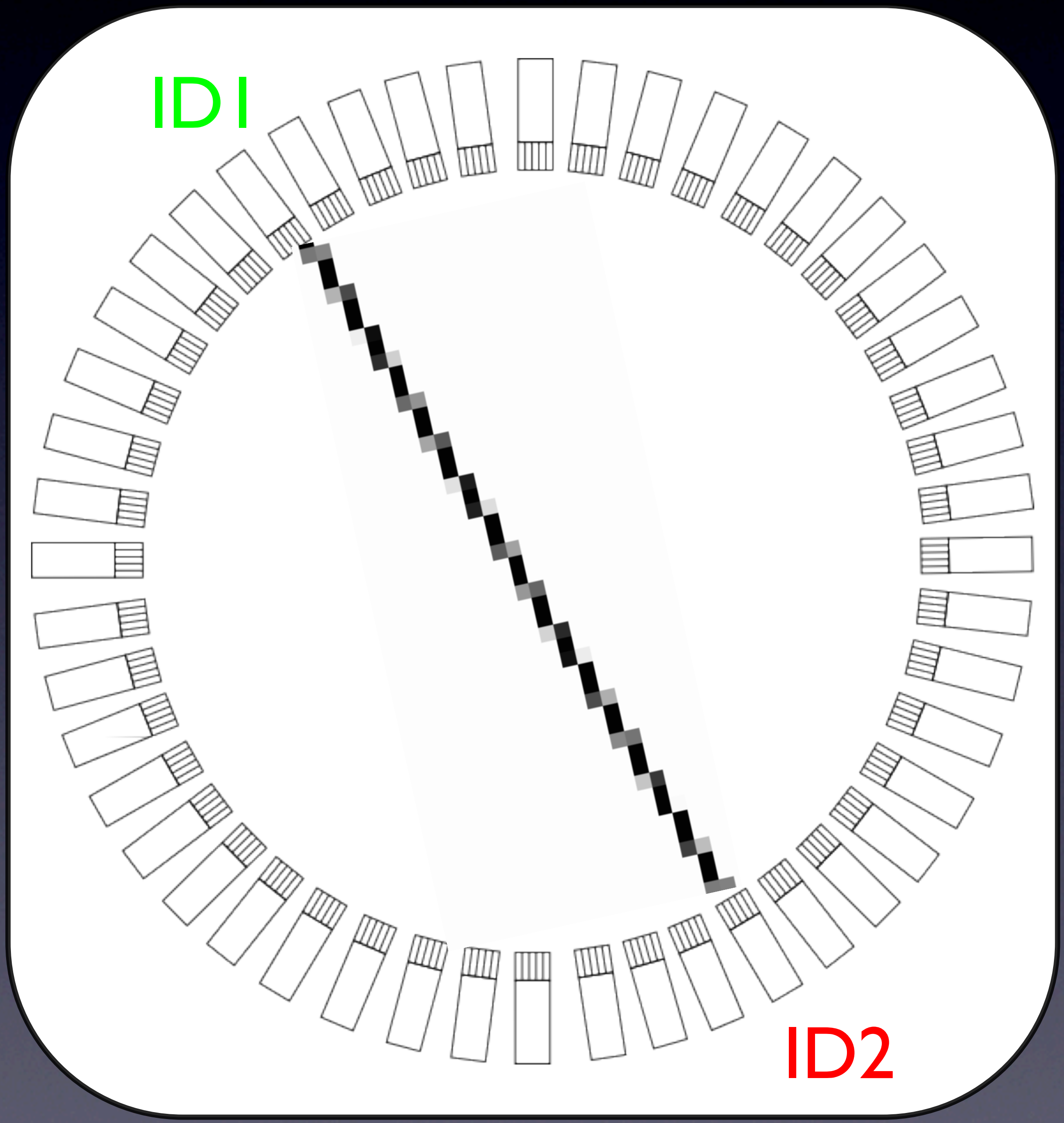
Siddon's algorithm [Siddon1985, Zao2002]



Qi et al., Phys. Med. Biol., 1998
Siddon, Med. Phys., 1985
Zao & Reader, IEEE NSSCR, 2002

PET list-mode reconstruction

Siddon's algorithm is a simple projector
using only detector IDs



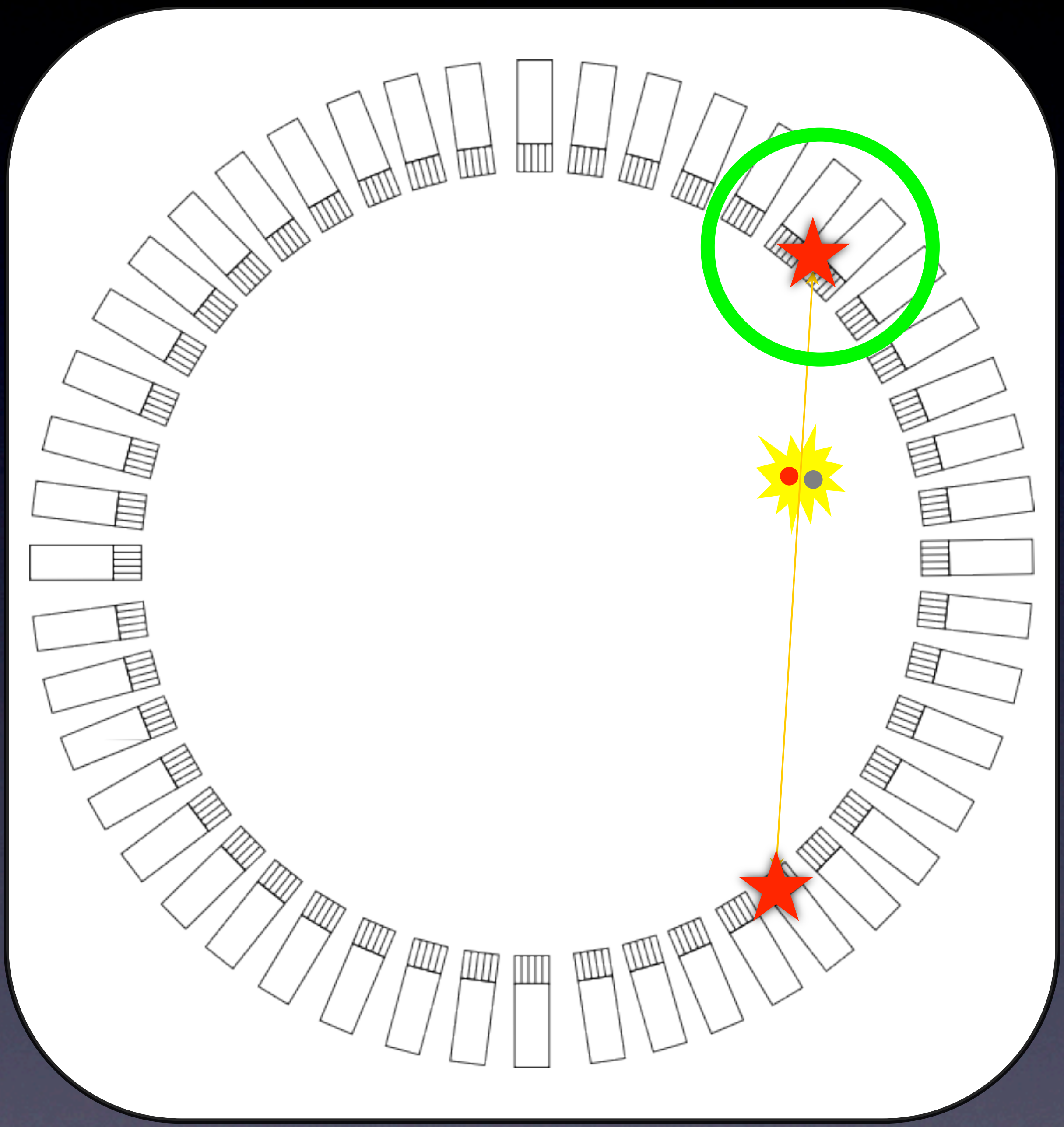
Recent and future detectors are able or will be able to record many kind of information

List-mode data:

ID1 T1 E1 DOI1
ID2 T2 E2 DOI2
ID3 T3 E3 DOI3
ID4 T4 E4 DOI4
ID5 T5 E5 DOI5
...

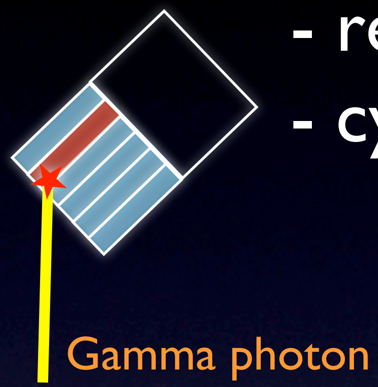
How to use this information within the projector

Considering the detector itself



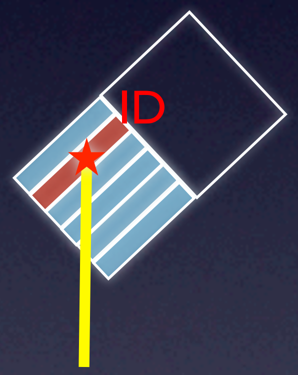
Geometrical effects

- rectangular crystals shape
- cylindrical scanner



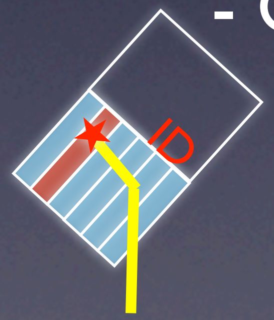
Crystal penetration

- photoelectric effect



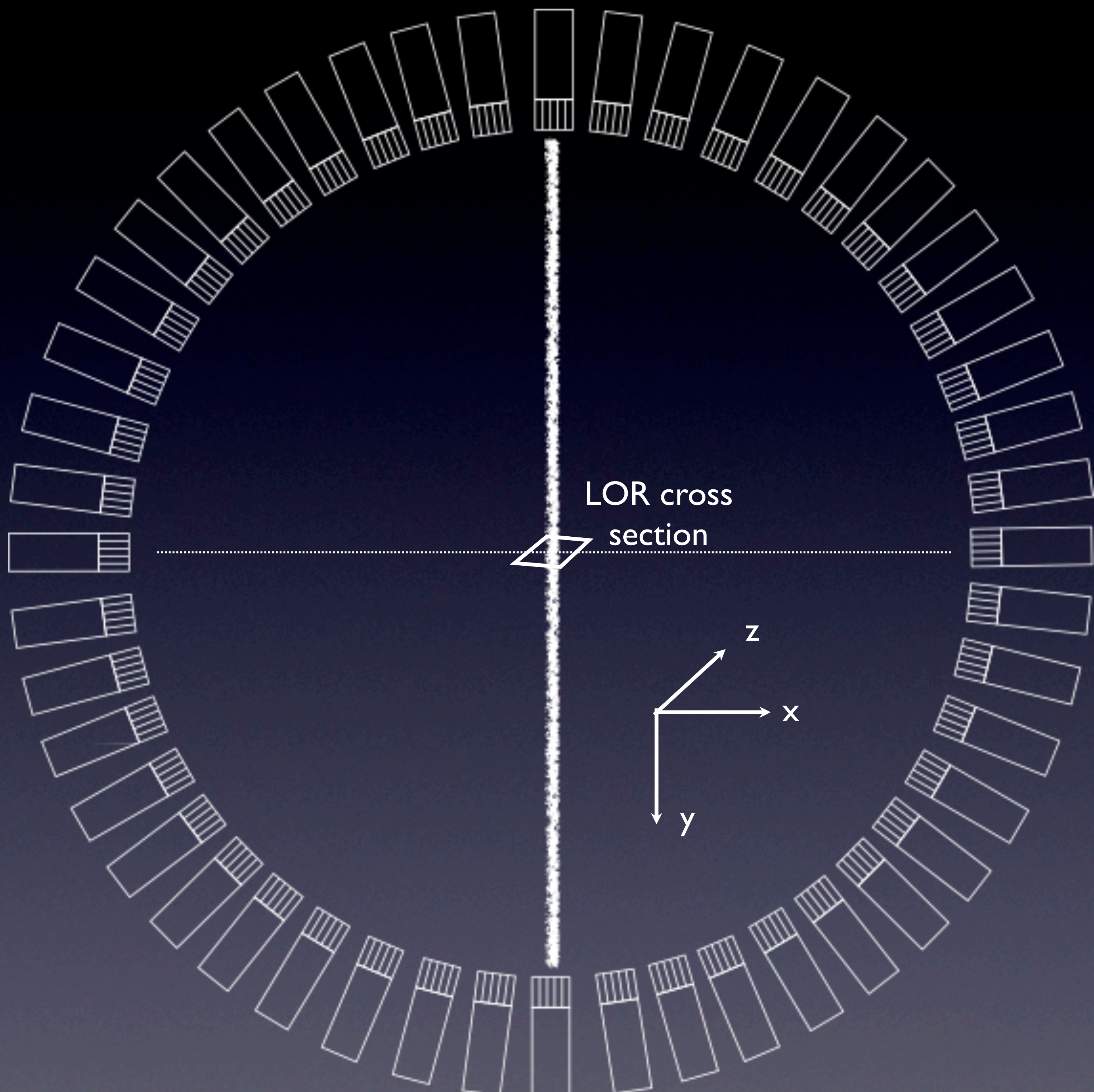
Intra and inter crystal scattering

- Compton scattering

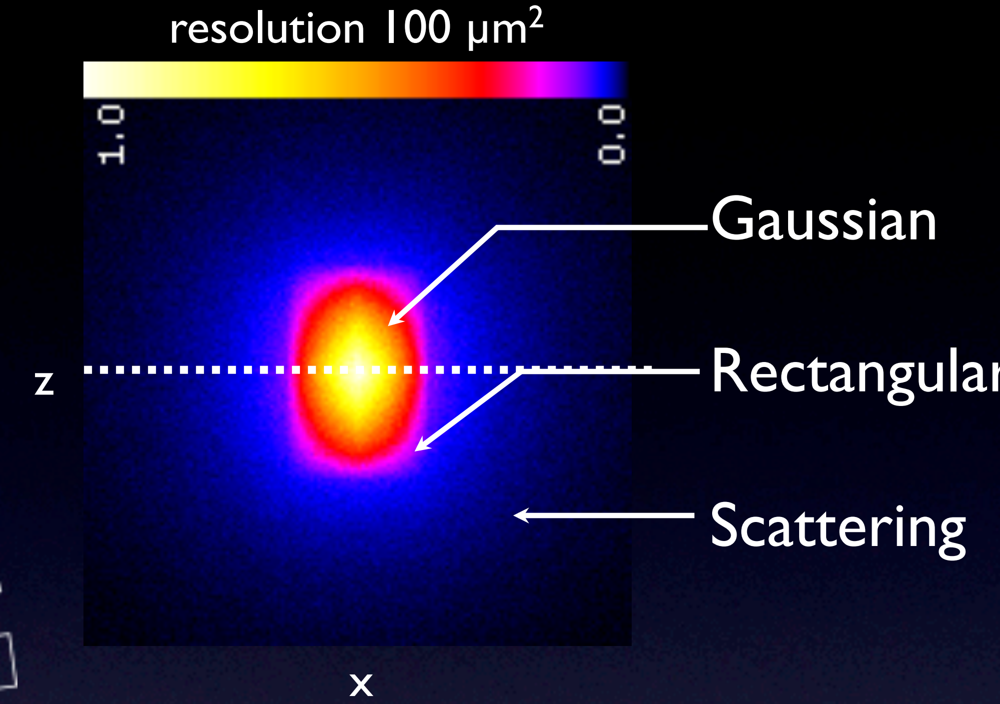


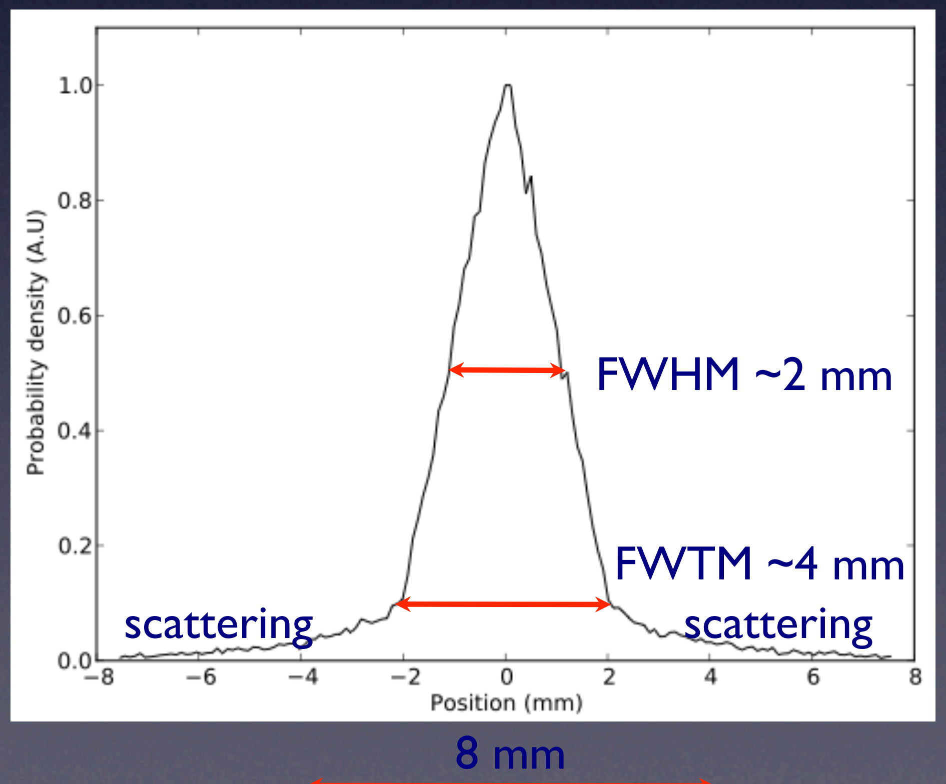
Does Siddon projector (a simple line) is enough?

Considering the detector itself

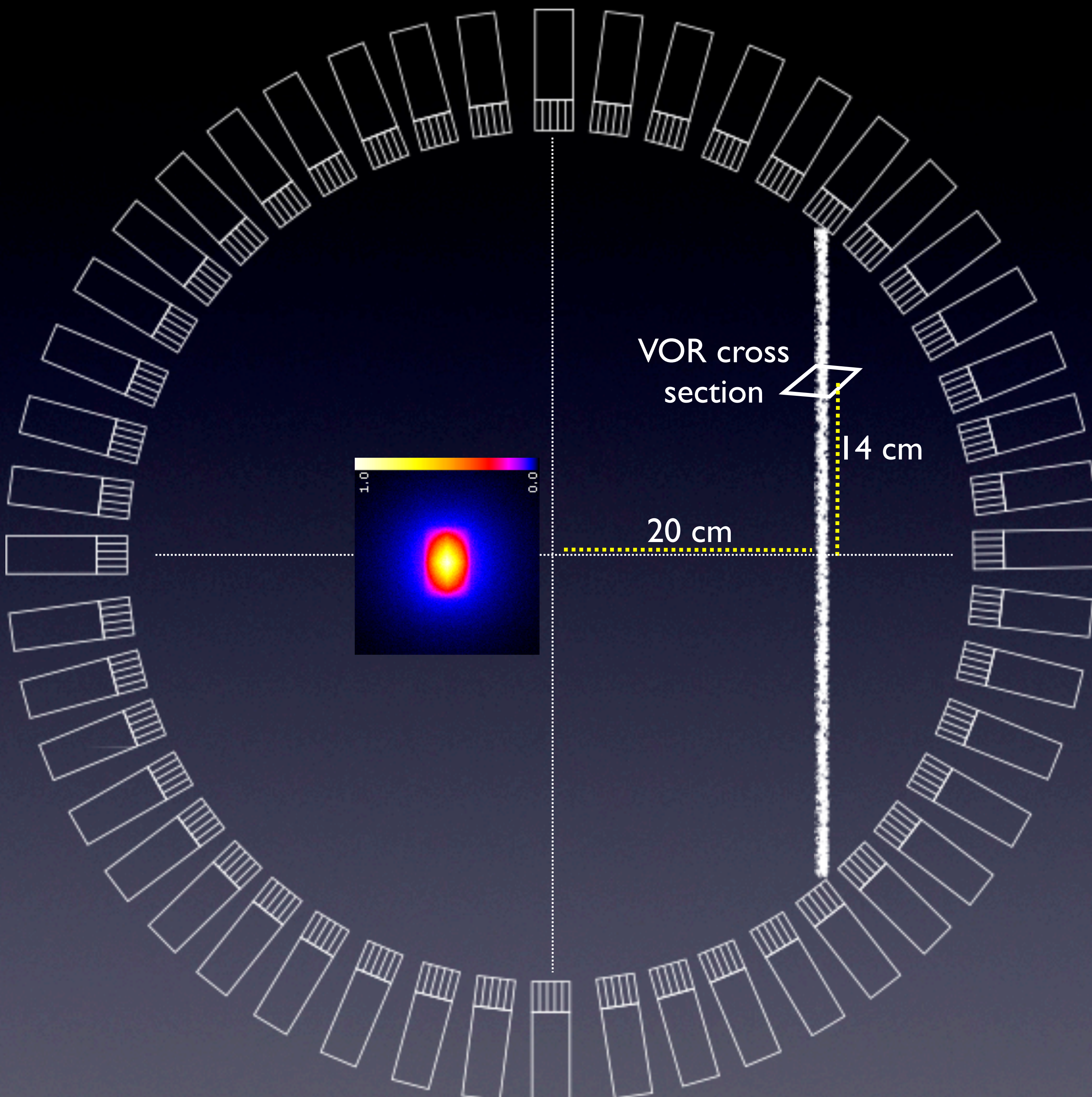


PET Philips GEMINI

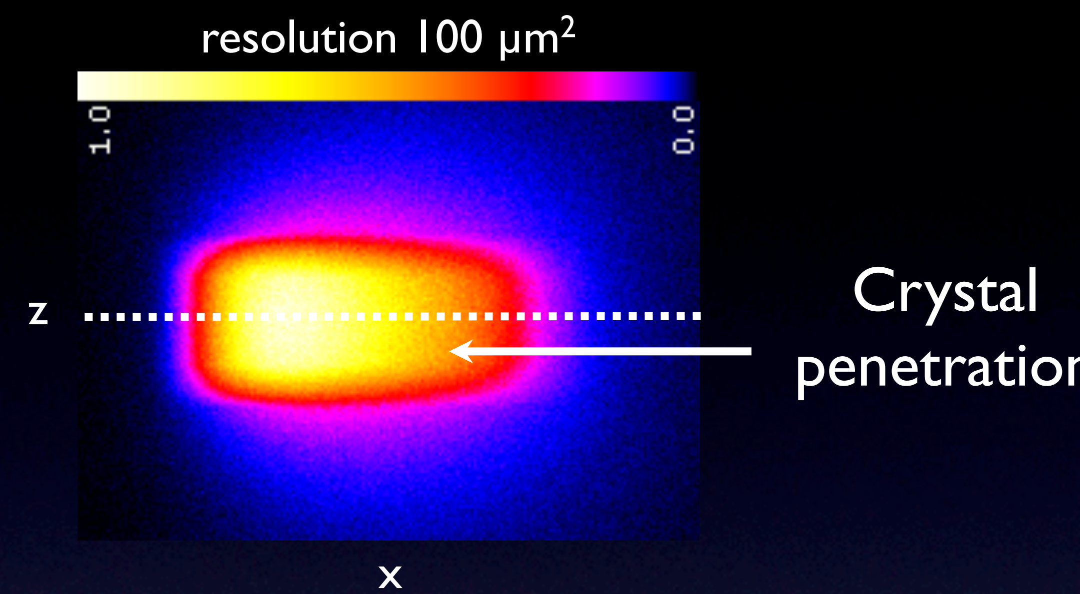


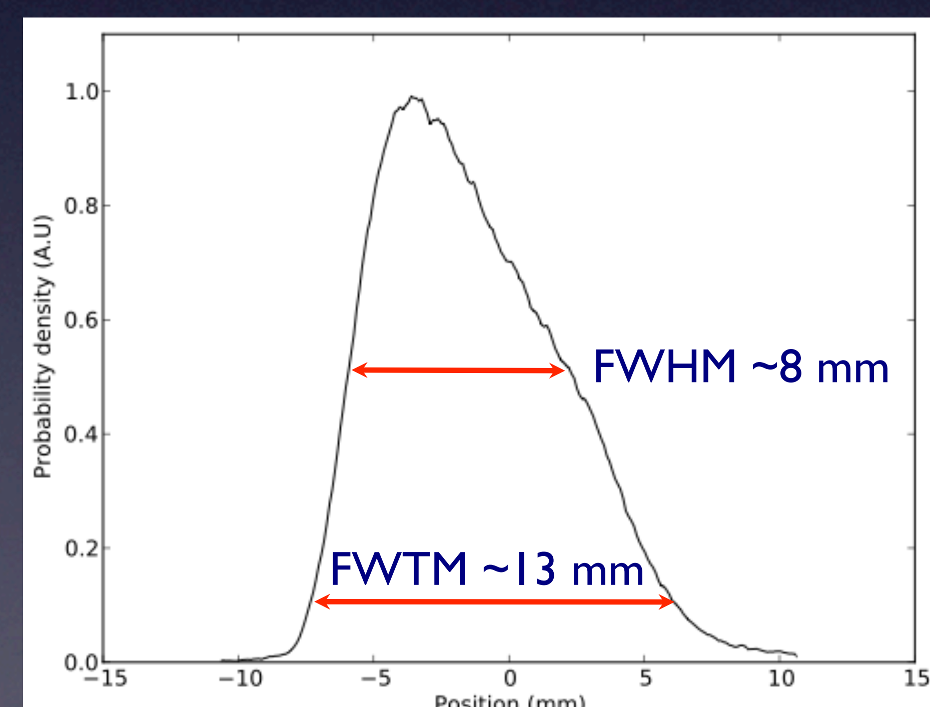


Considering the detector itself

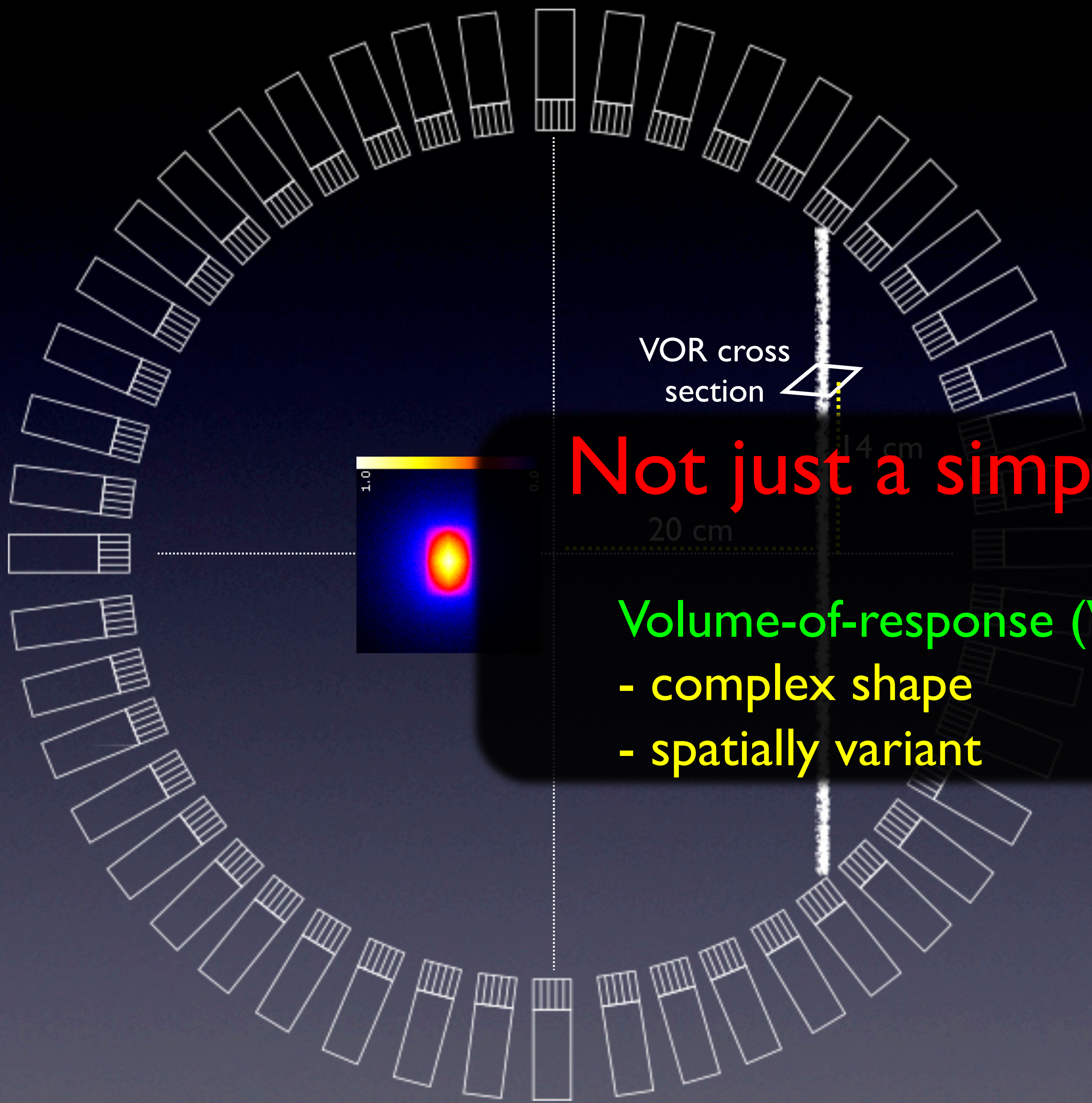


PET Philips GEMINI

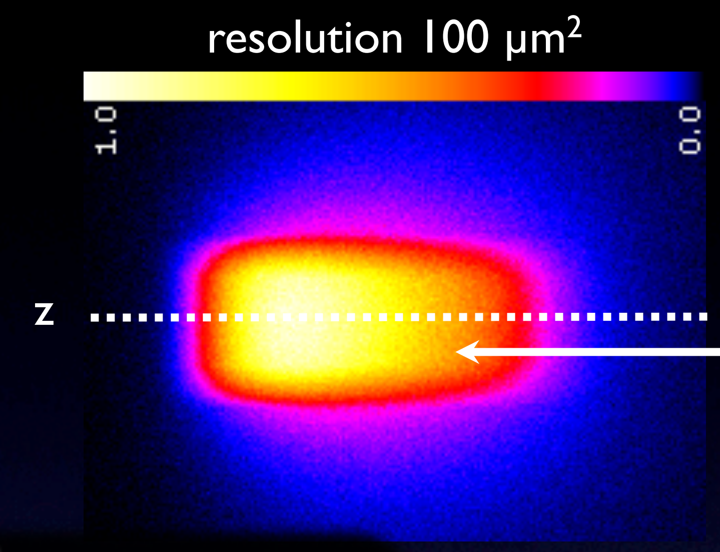




Considering the detector itself

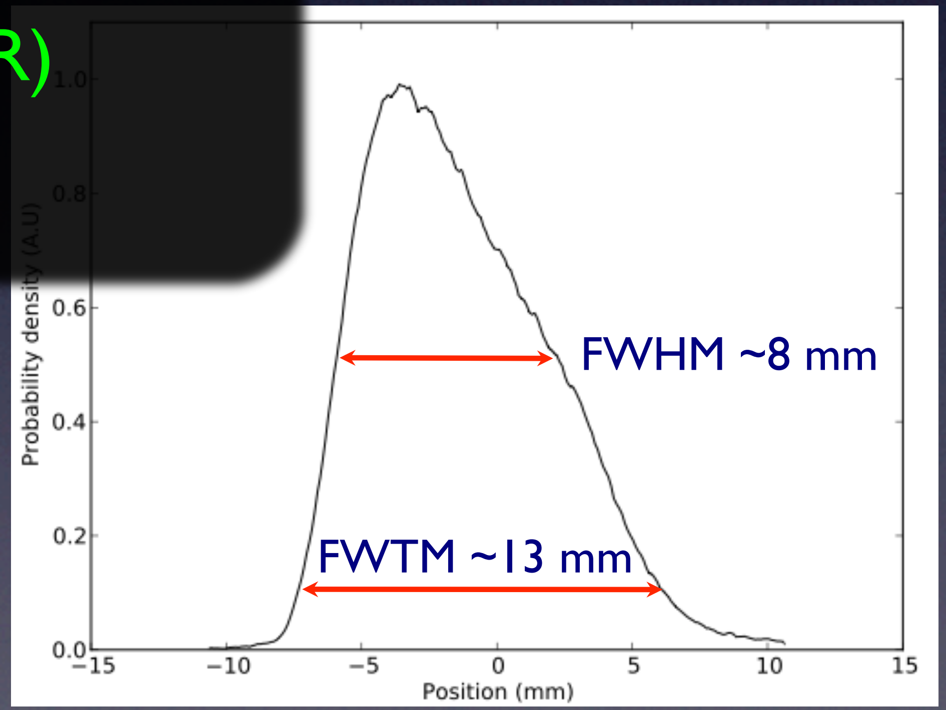


PET Philips GEMINI



Not just a simple line!

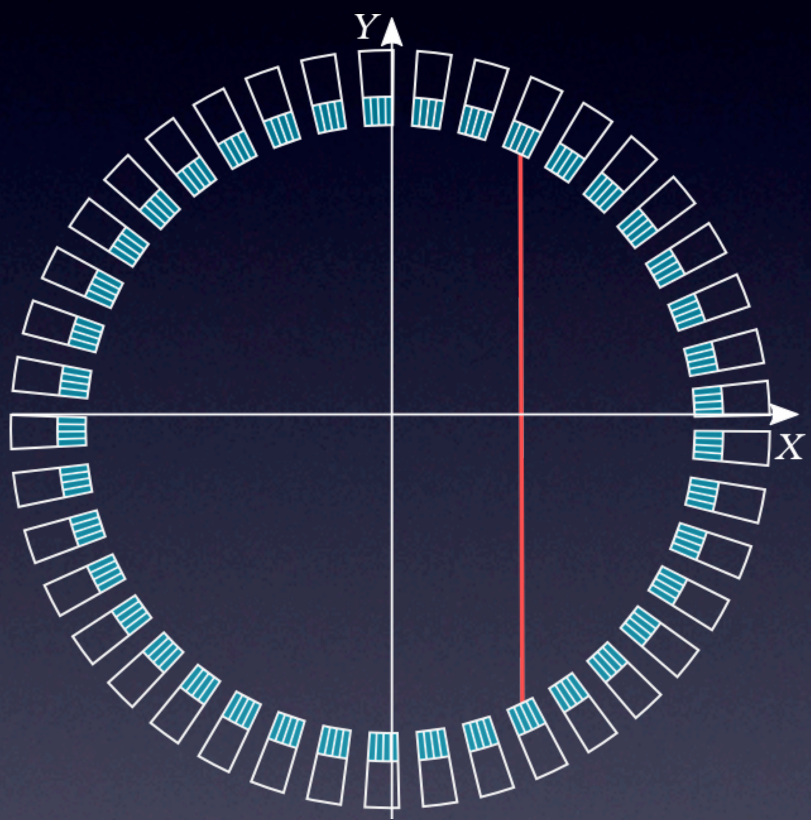
Volume-of-response (VOR)
- complex shape
- spatially variant



Considering the detector itself

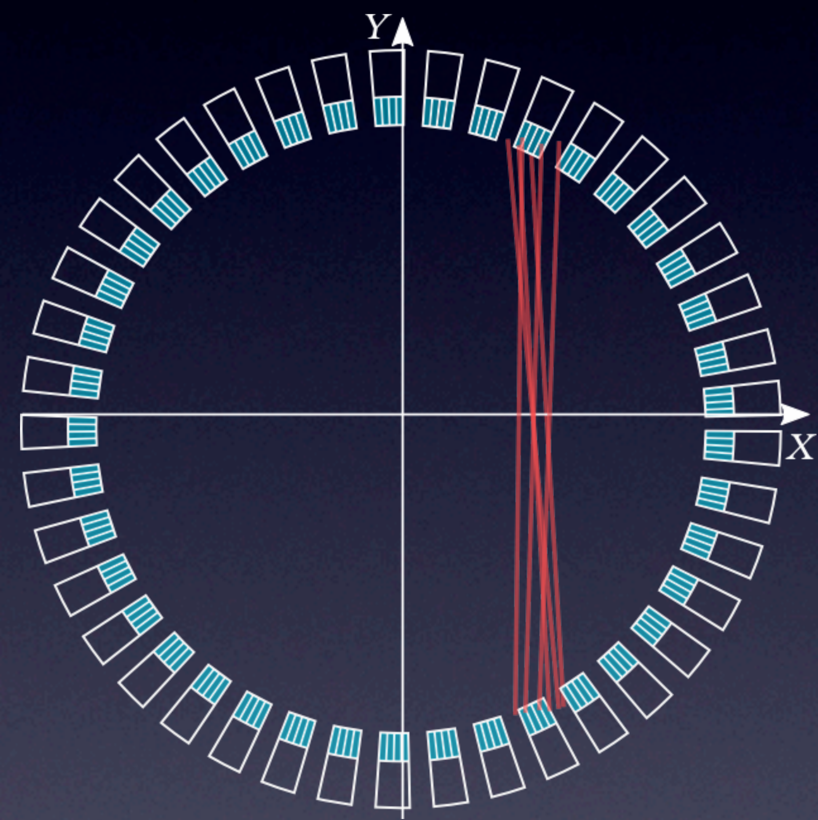
Computes on-the-fly the VOR including the detector effects

Single line
[Siddon1985]



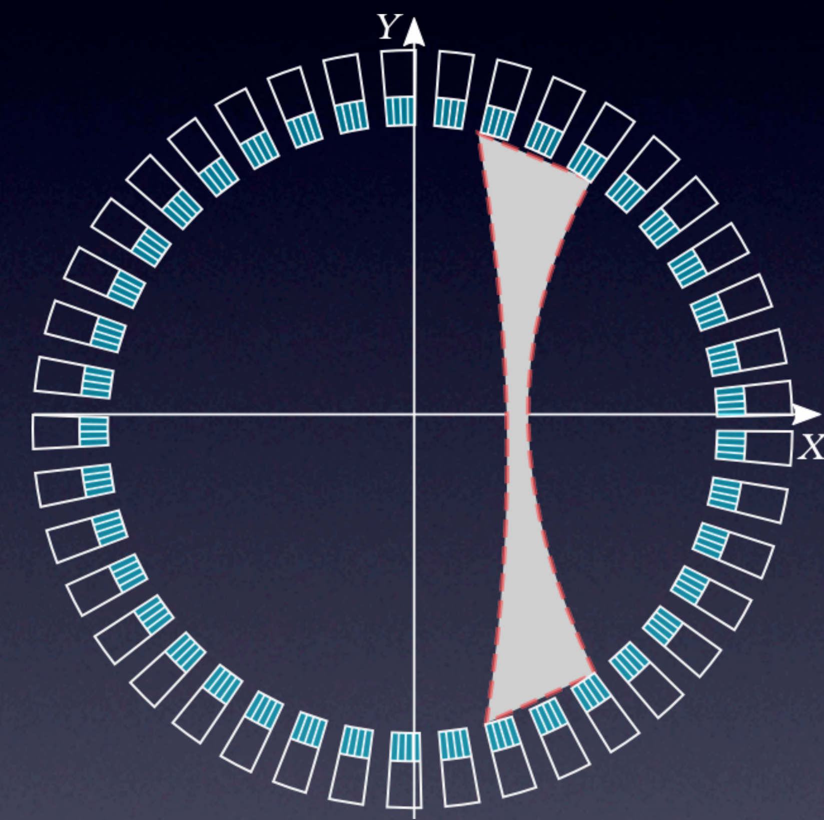
Geometrical effect
Crystal penetration
Crystal scattering

Multiple rays
[Chen2007, Moehrs2008]



Geometrical effect
Crystal penetration
Crystal scattering

VOR modeling
[Ortuño2011, Cui2011]



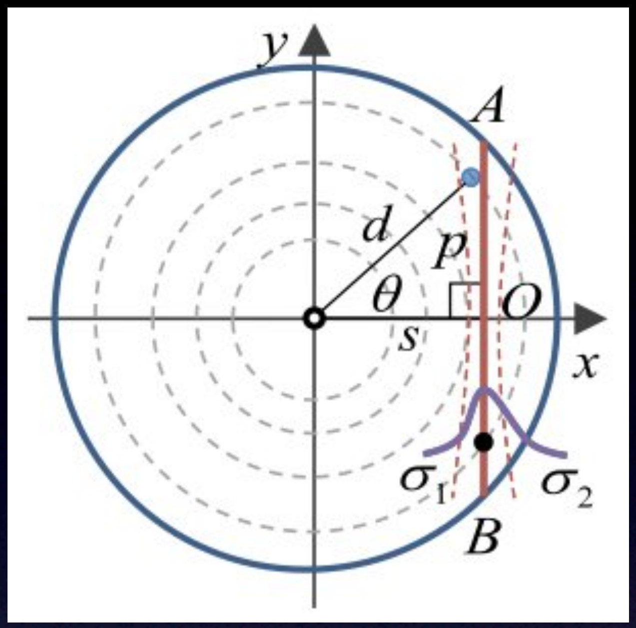
Geometrical effect
Crystal penetration
Crystal scattering

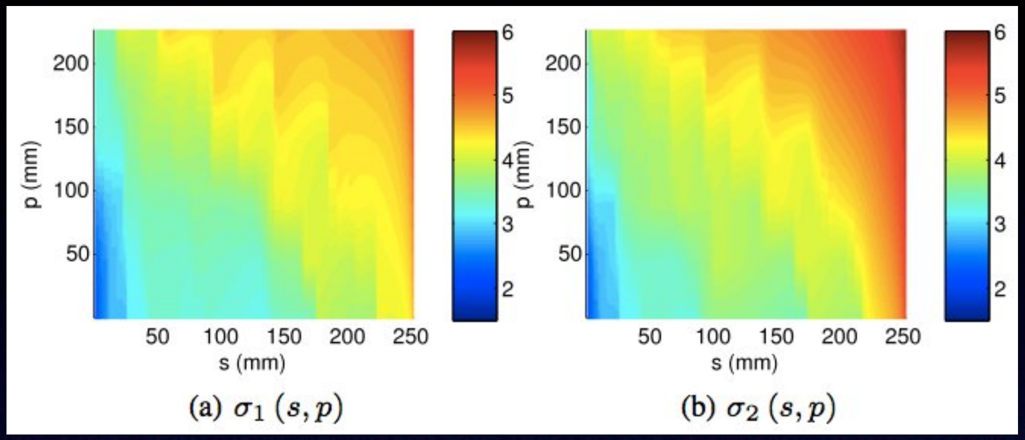
[Cui2011] spatially variant

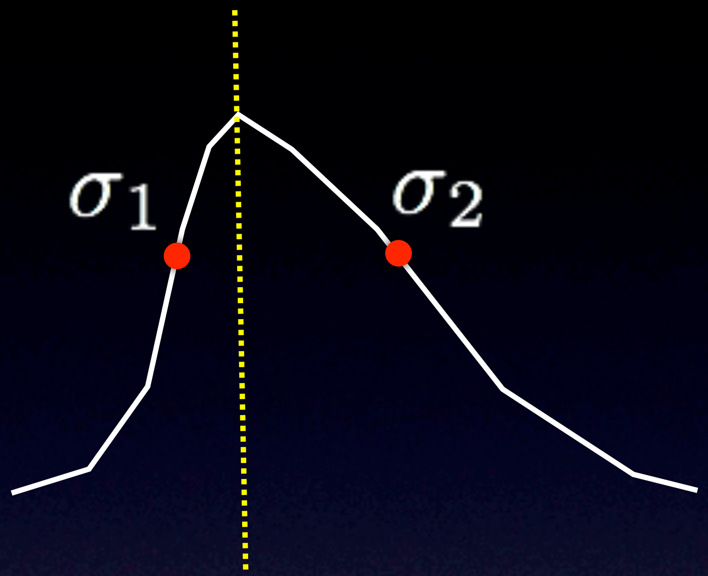
Siddon, Med. Phys., 1985
Moehrs, Phys. Med. Biol., 2008
Chen & Glick, IEEE MIC, 2007
Ortuno et al., IEEE MIC, 2011
Cui et al., IEEE MIC, 2011

Considering the detector itself

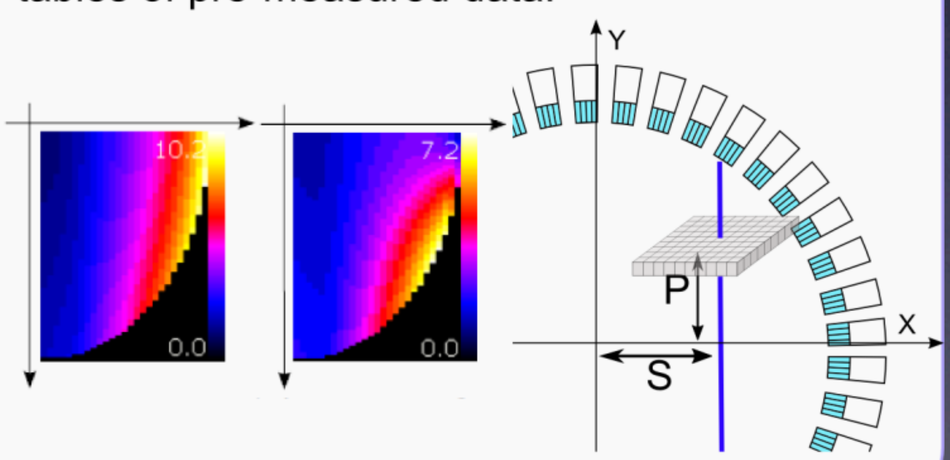
Gaussian VOR modeling [Cui2011a, Cui2011b]



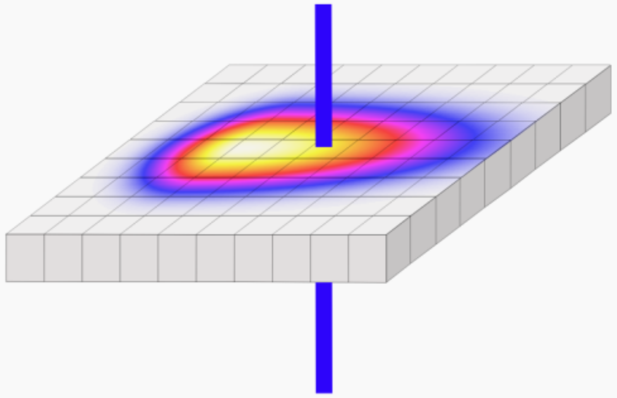




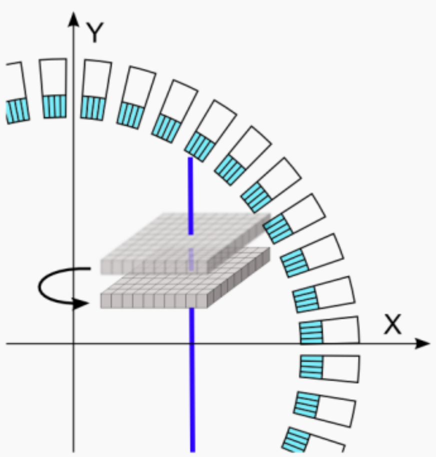
1. From the first slice of the VOR: select σ_{left} and σ_{right} of the gaussian model using the tables of pre-measured data.



2. Render the 2D asymmetrical Gaussian distribution in the current slice.



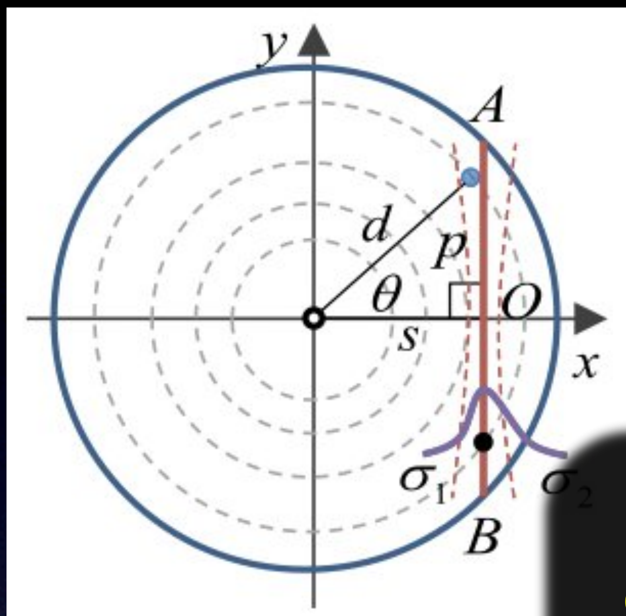
3. Go to the next slice and back to step **1** until the VOR is fully rendered.

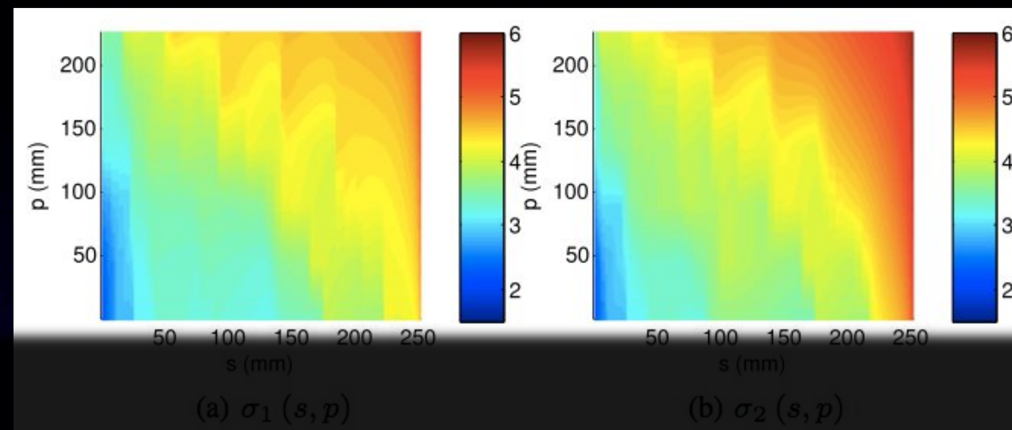


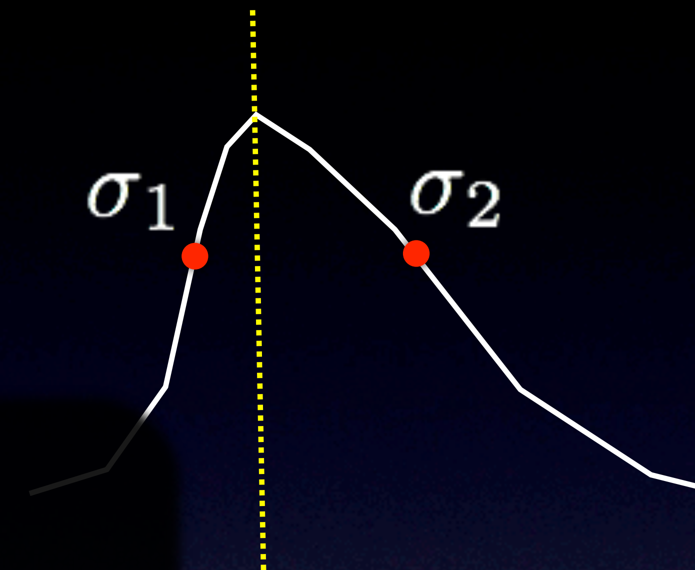
Cui2011a: Cui et al., IEEE MIC, 2011
Cui2011b: Cui et al., Med. Phys., 2011

Considering the detector itself

Gaussian VOR modeling [Cui2011a, Cui2011b]

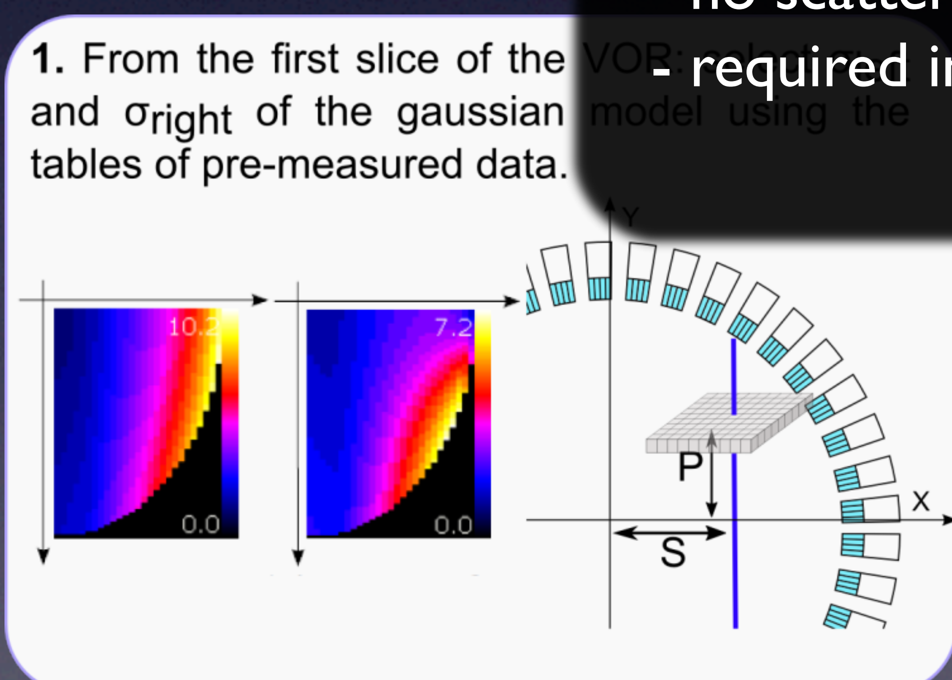


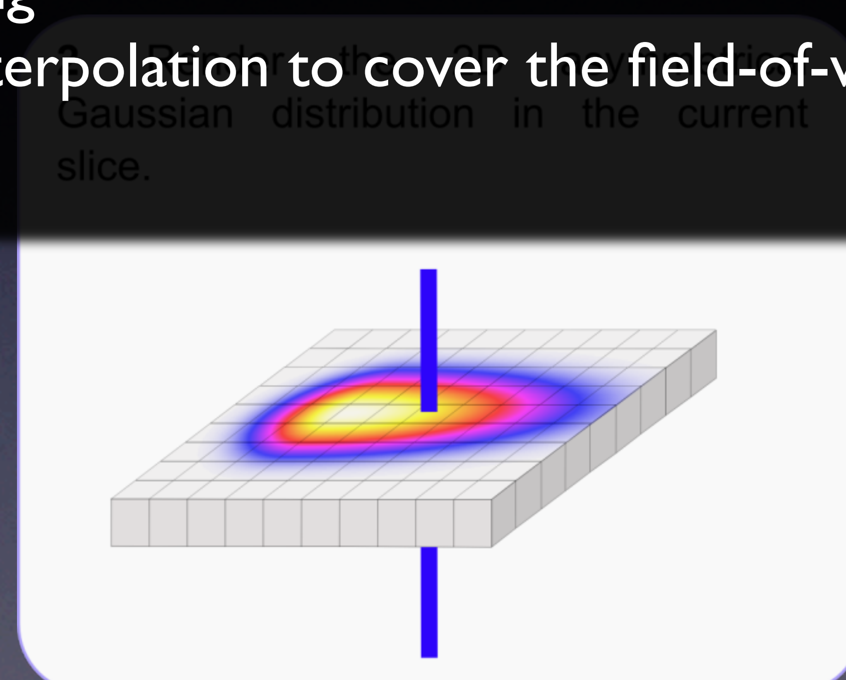


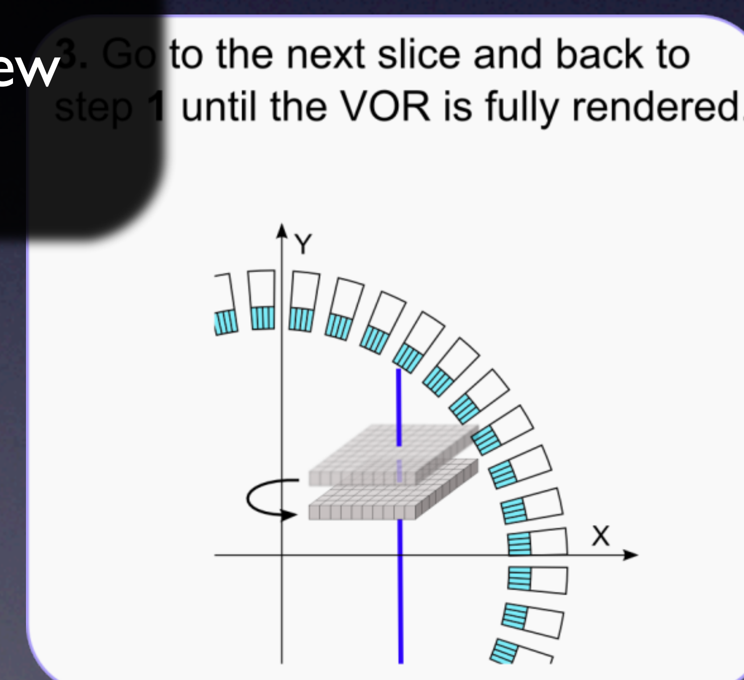


Gaussian as VOR:

- no rectangular shape
- no scattering
- required interpolation to cover the field-of-view





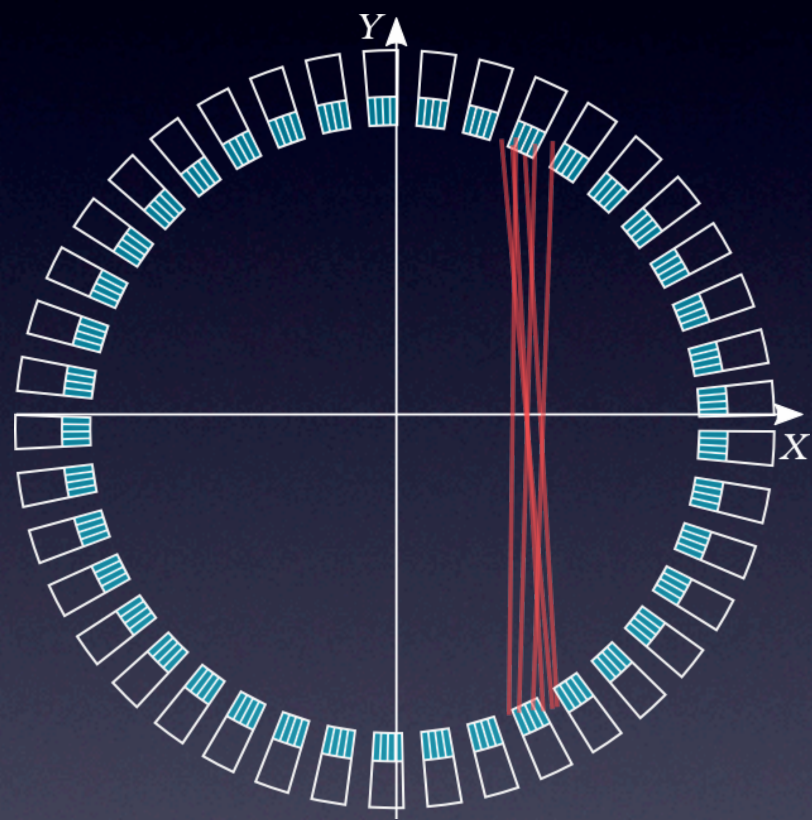


Cui2011a: Cui et al., IEEE MIC, 2011
Cui2011b: Cui et al., Med. Phys., 2011

Considering the detector itself

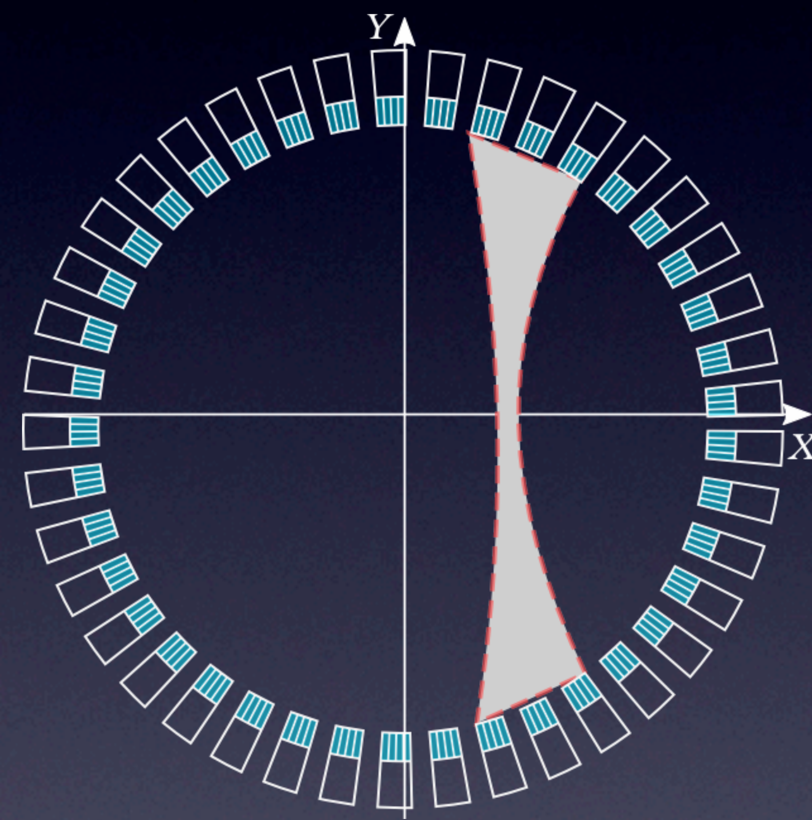
Computes on-the-fly the VOR including the detector effects

Multiple rays
[Chen2007, Moehrs2008]



Geometrical effect
Crystal penetration
Crystal scattering

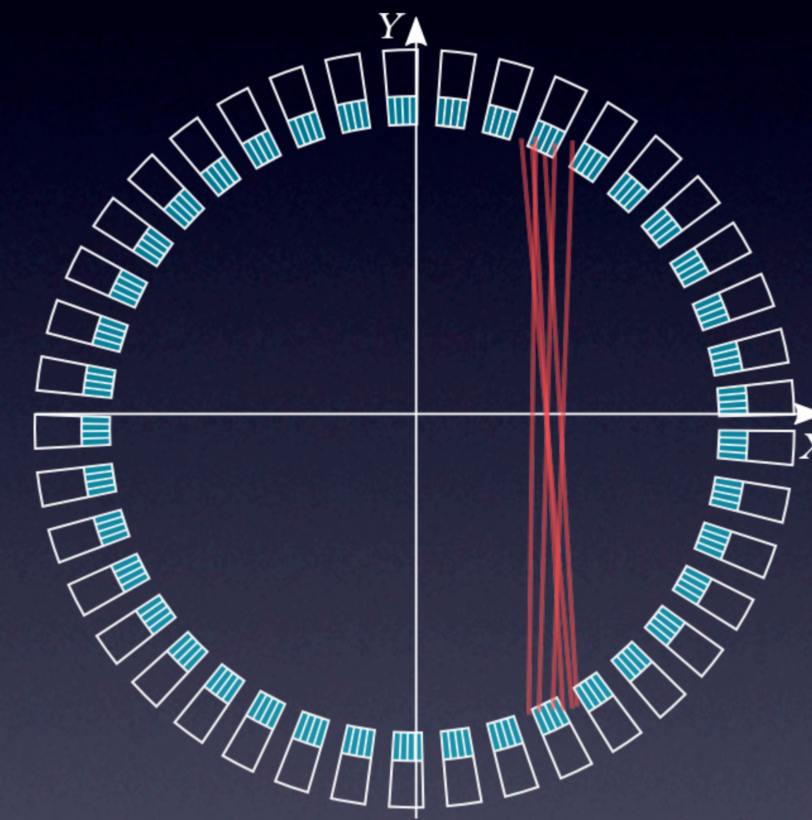
VOR modeling
[ortuño2011, Cui2011]



Geometrical effect
Crystal penetration
Crystal scattering

[Cui2011] spatially variant

Multiple rays VOR modeling
[Autret2012]



Geometrical effect
Crystal penetration
Crystal scattering

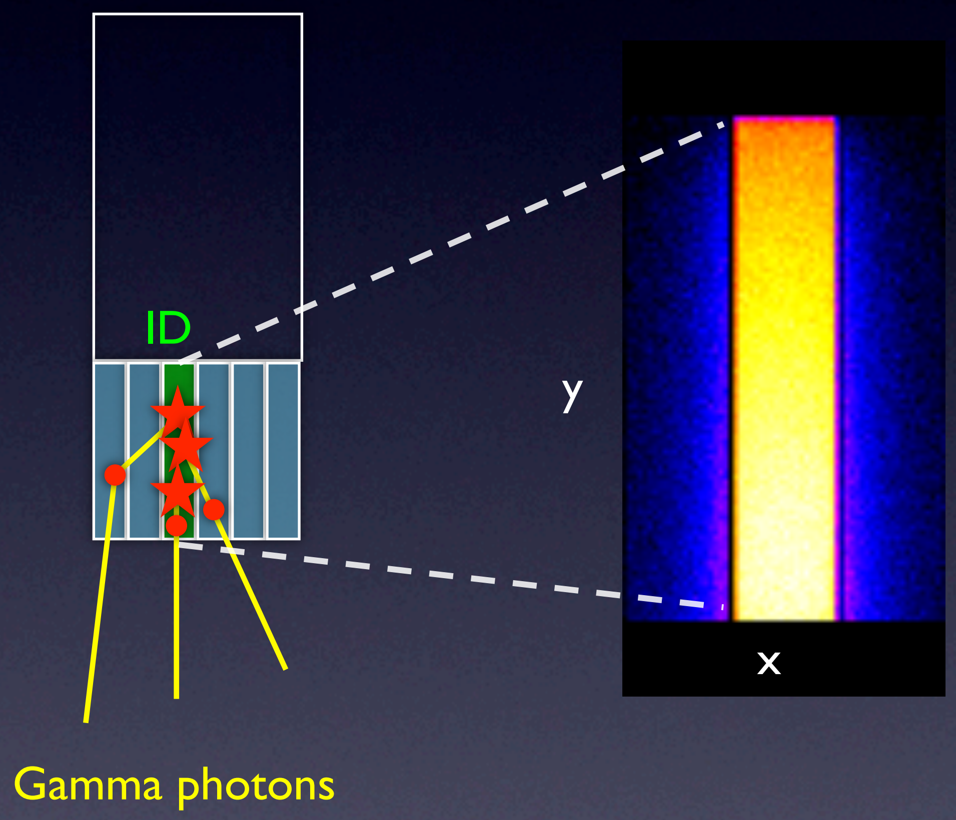
Spatially variant

Moehrs, Phys. Med. Biol., 2008
Chen & Glick, IEEE MIC, 2007

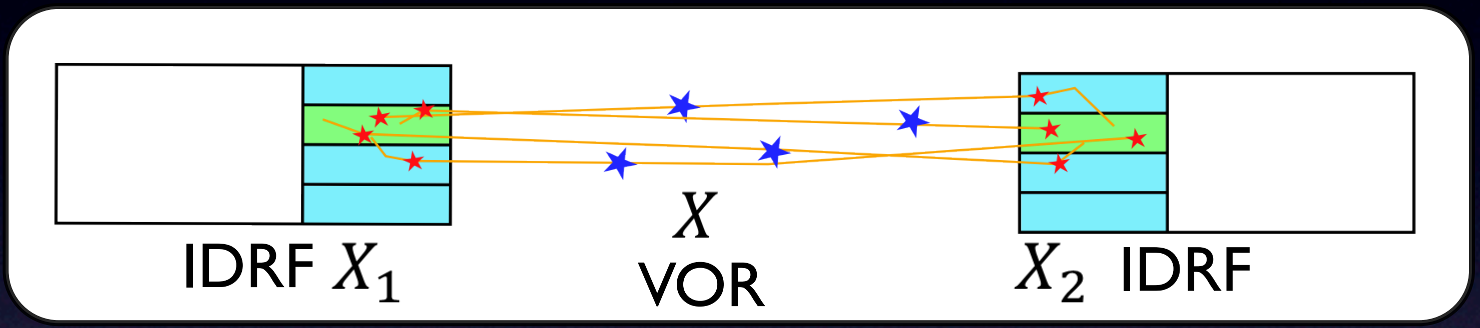
Ortuno et al., IEEE MIC, 2011
Cui et al., IEEE MIC, 2011
Autret et al., IEEE MIC, 2012

Considering the detector itself

Intrinsic Detector Response Function (IDRF)



VOR and IDRFs



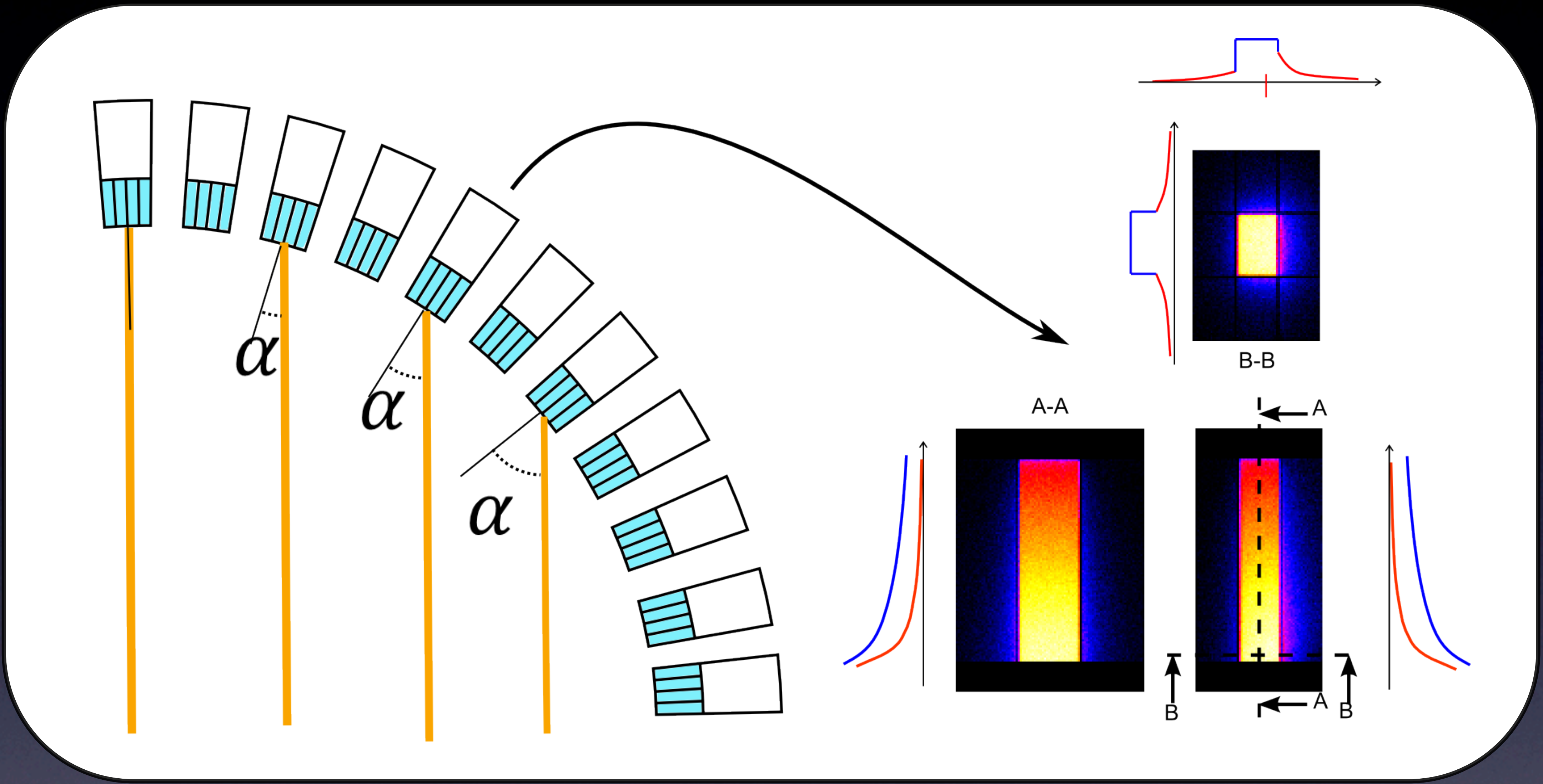
Relationship between the VOR and the IDRFs of both detectors [Gonzalez2011]:

$$\underset{\text{VOR}}{X} = \frac{1}{2}(1-t)\underset{\text{IDRF}}{X_1} + \frac{1}{2}(1+t)\underset{\text{IDRF}}{X_2}$$

Gonzalez et al., IEEE MIC, 2011

Considering the detector itself

Full IDRF modeling based on Monte Carlo simulation [Awen2012]



Analytical model

- Geometrical effect
- Crystal penetration
- Crystal scattering

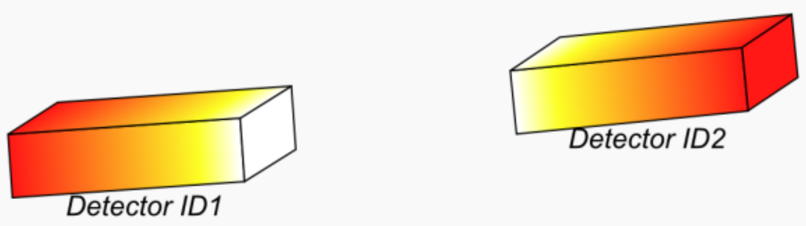
- Spatially variant
- Easy to extend with other information (DOI, TOF, etc)

Autret et al., IEEE MIC, 2012

Considering the detector itself

Iterative Random IDRF Sampling (IRIS) [Autret2012, Autret2013a]

1. Select both IDRF models related to both crystal detectors of the LOR.

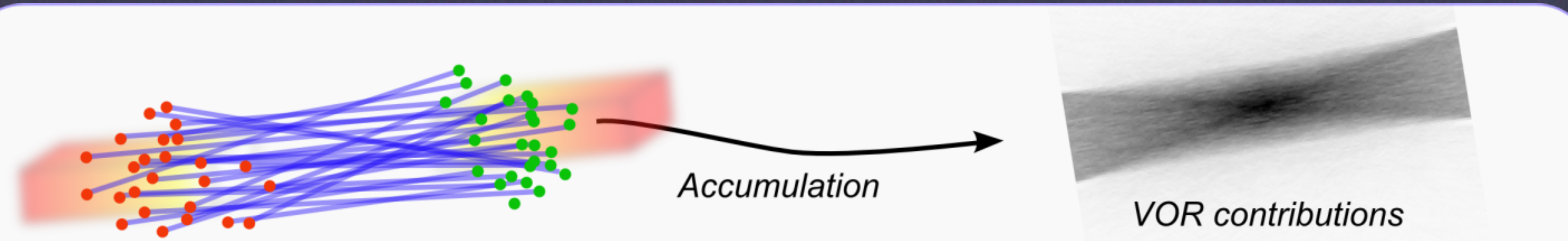


$$X = \frac{1}{2}(1-t)X_1 + \frac{1}{2}(1+t)X_2$$

VOR IDRF IDRF

2. Generate a pair of random points using the IDRF models.

3. Render and accumulate the line connecting the generated pair points with the DDA algorithm [Bert2011].



Autret et al., IEEE MIC, 2012
Autret et al., Fully3D, 2013
Bert & Visvikis, IEEE MIC, 2011

Considering the detector itself

IRIS is easy to use on GPU [Autret2012]

VOR

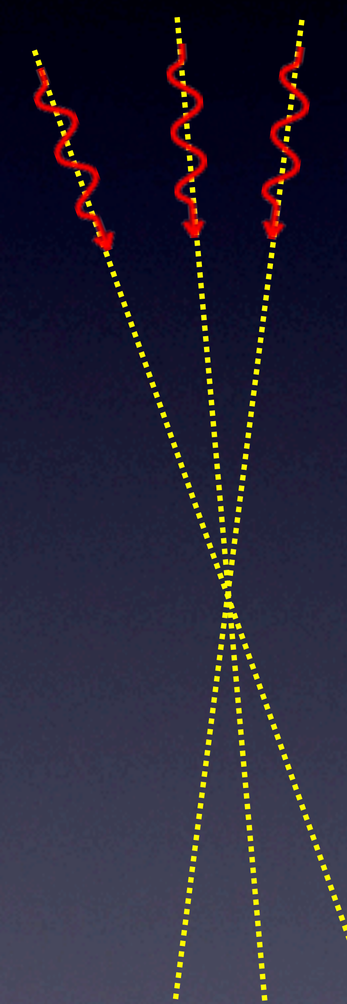
Bloc de *threads*

= VOR

threads

= Line

Lines or LOR

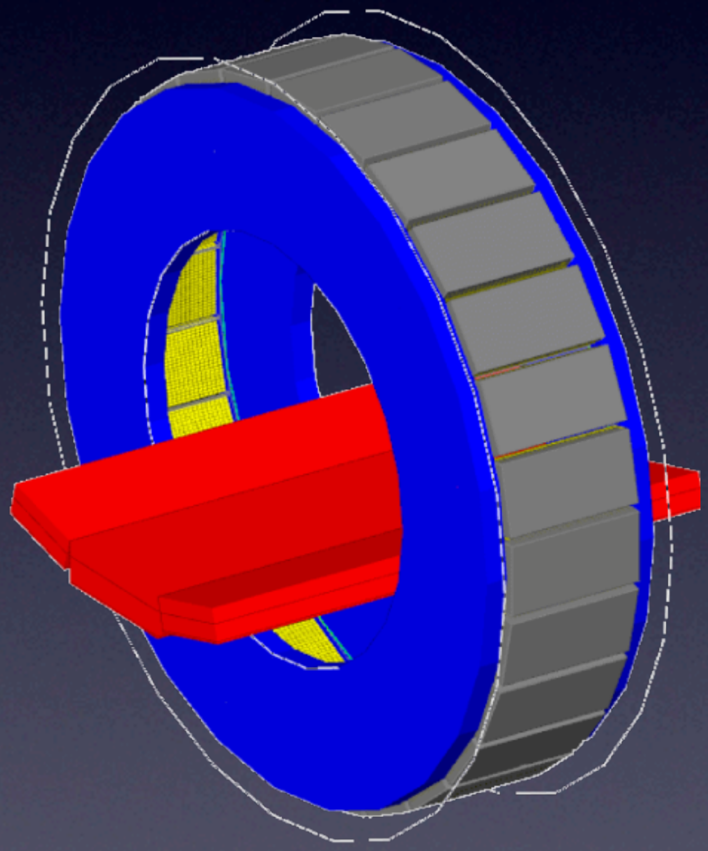


VOR

Autret et al., IEEE MIC, 2012

Evaluation study

Philips PET GEMINI scanner
- Monte Carlo Simulation [Lamare2006] performed with GATE [Jan2011]
- TOF resolution of 500 ps FWHM
- DOI resolution of 1 mm FWHM



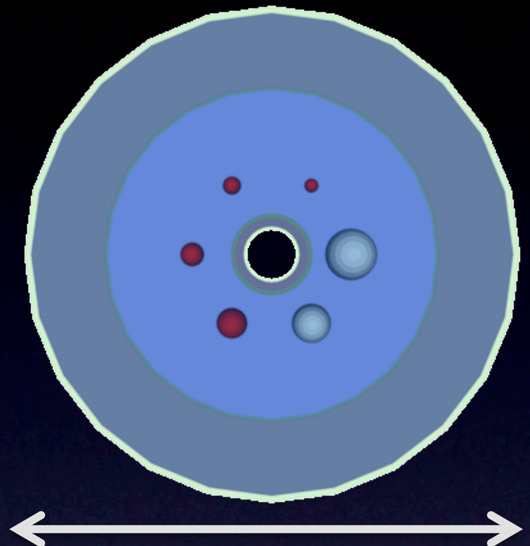
GATE modeling

Lamare et al., Phys. Med. Biol., 2006
Jan et al., Phys. Med. Biol., 2011

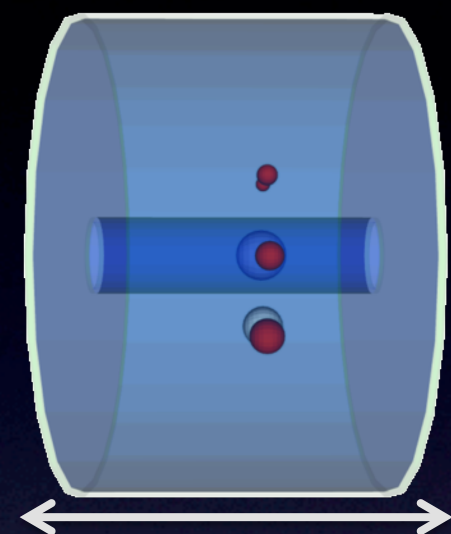
Evaluation study

NEMA IEC NU2-2001 phantom

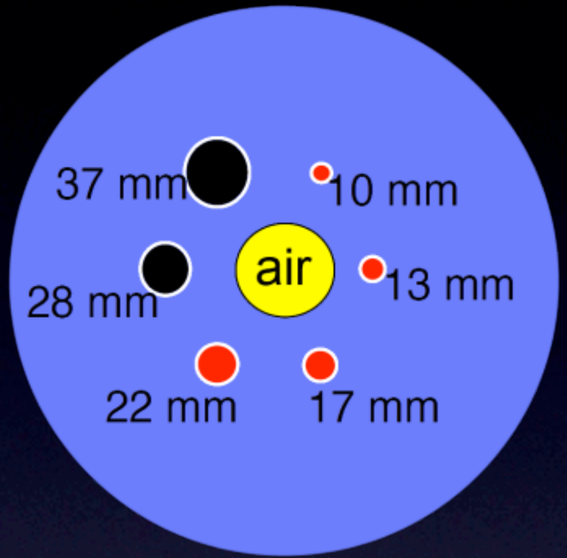
- 12×10^6 true coincidences



300 mm



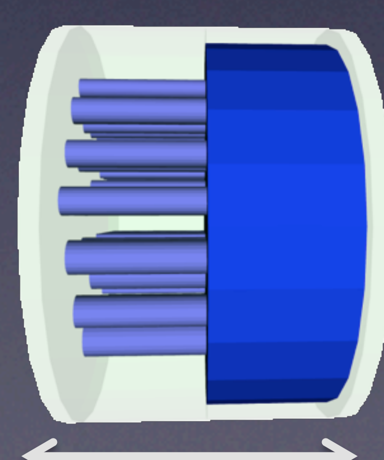
200 mm



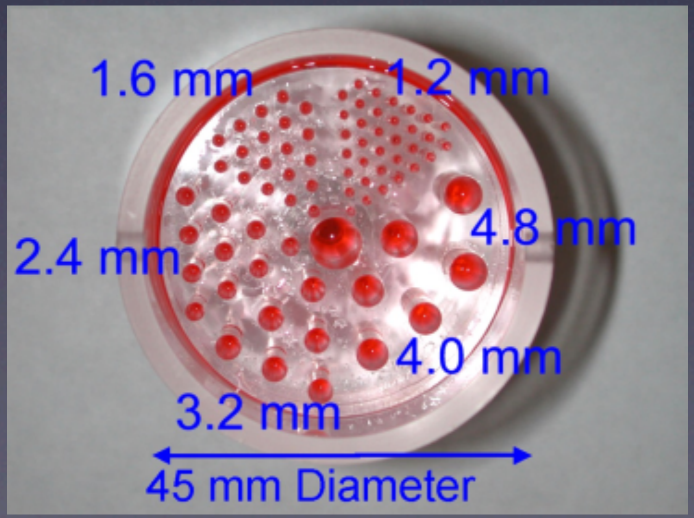
Miniature Derenzo phantom

- One centered inside the FOV
- One 200 mm shifted from the center
- 4×10^6 true coincidences

45 mm



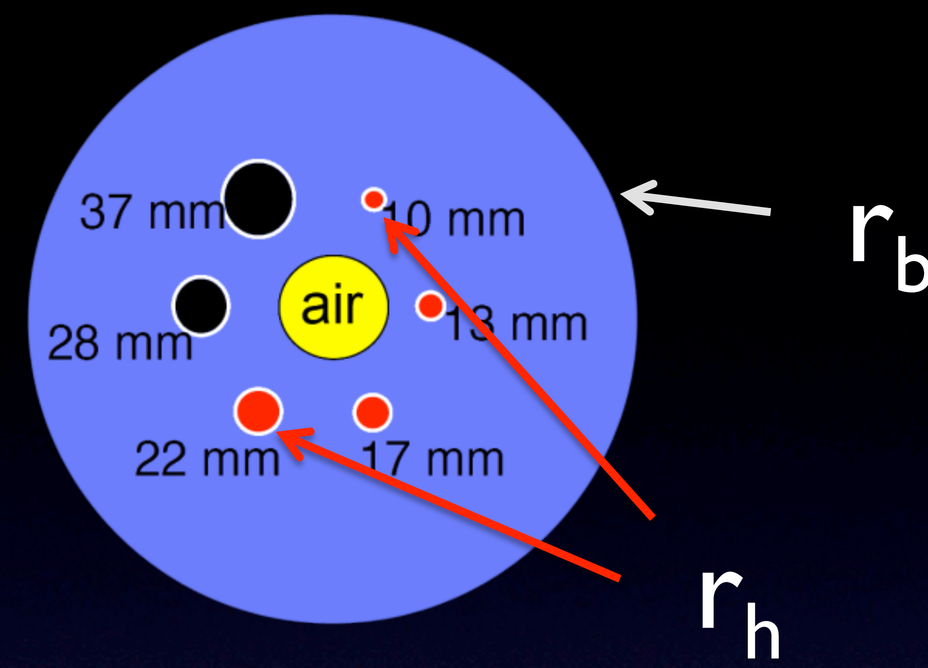
30 mm



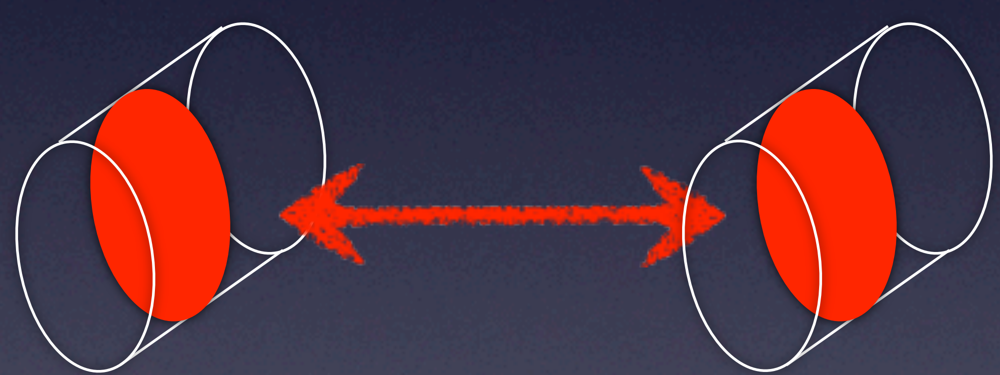
Evaluation study

Contrast Recovery Coefficient (CRC)

$$CRC = \frac{\overline{r_h} - \overline{r_b}}{\overline{r_b}}$$



Signal-to-noise ratio (SNR) [Lodge2010] (background)



Reconstruction 1

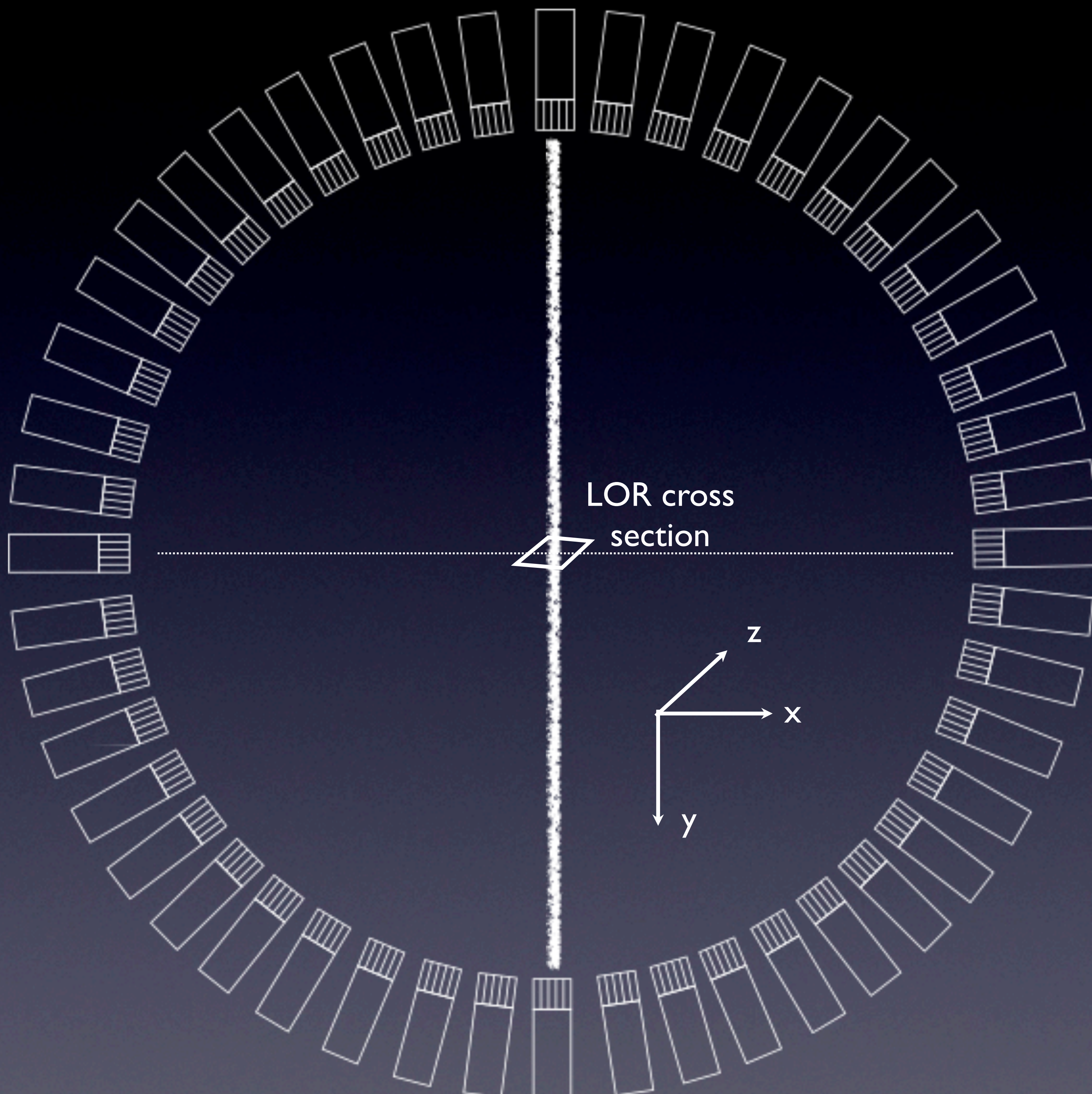
Reconstruction 2

$$m_j = (v1_j + v2_j)/2$$
$$d_j = v1_j - v2_j$$
$$a_i = mean(m)$$
$$dsd_i = std(d)$$

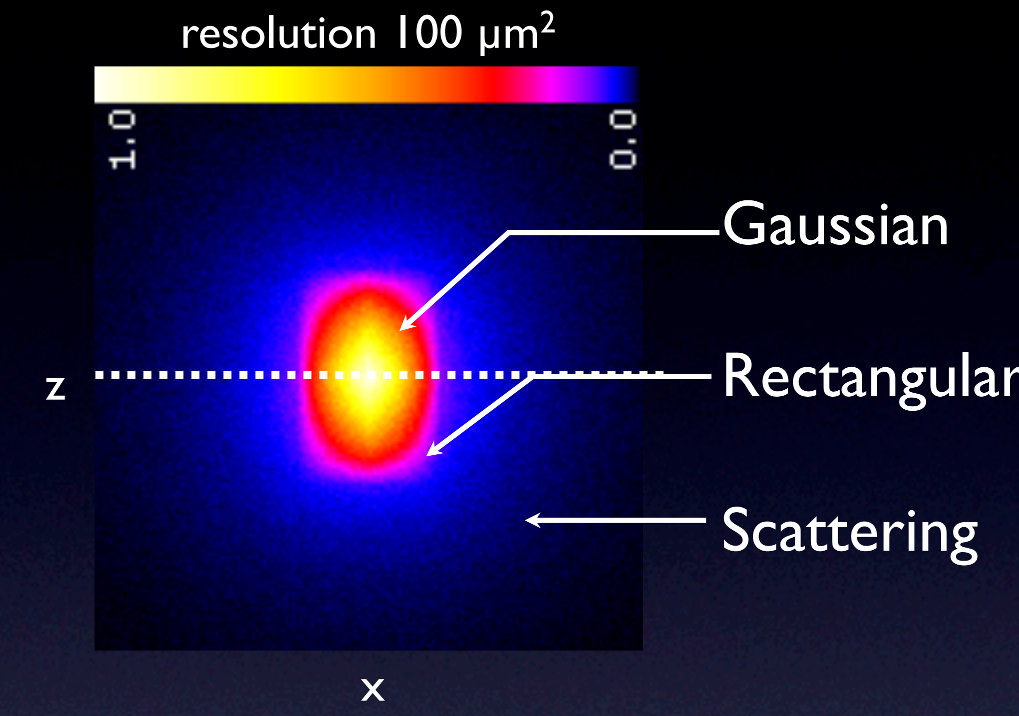
$$SNR = \frac{\sqrt{2}}{S} \sum_i^S \frac{a_i}{dsd_i}$$

Lodge et al., Phys. Med. Biol., 2010

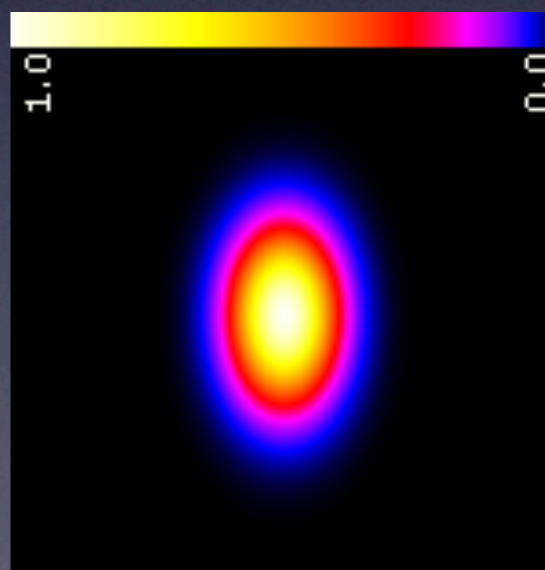
Results



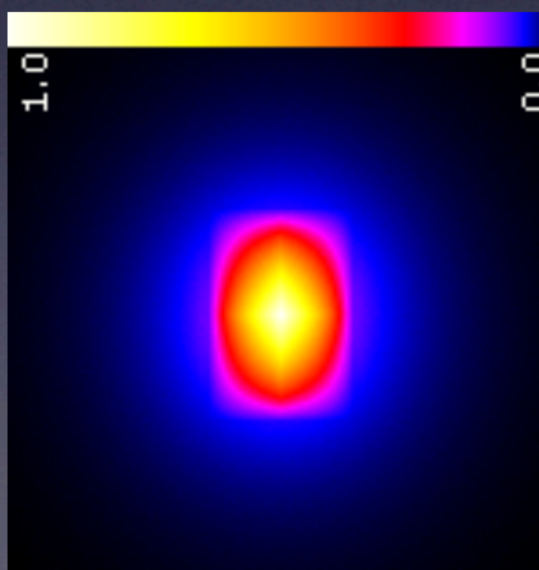
PET Philips GEMINI



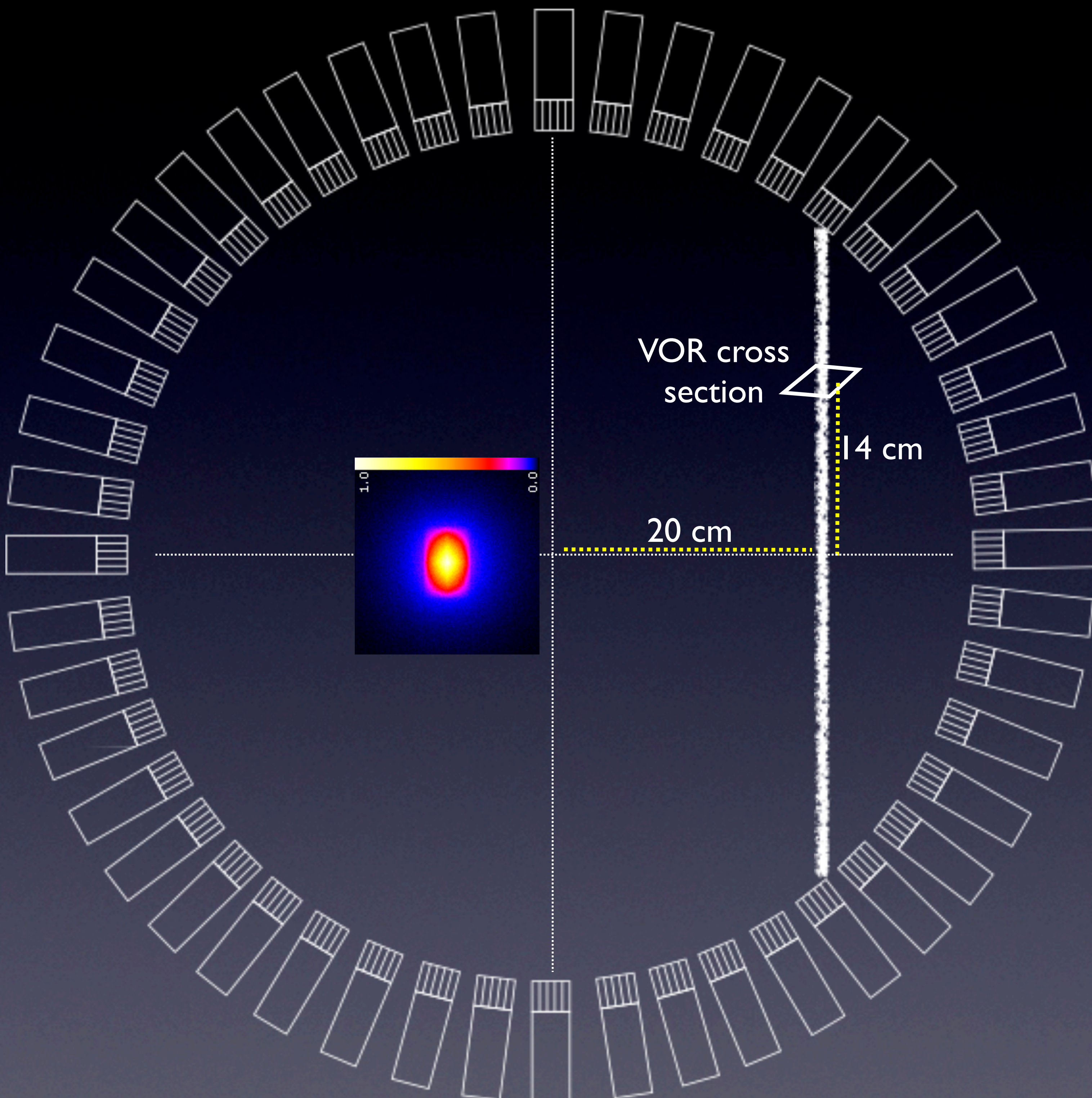
Gaussian



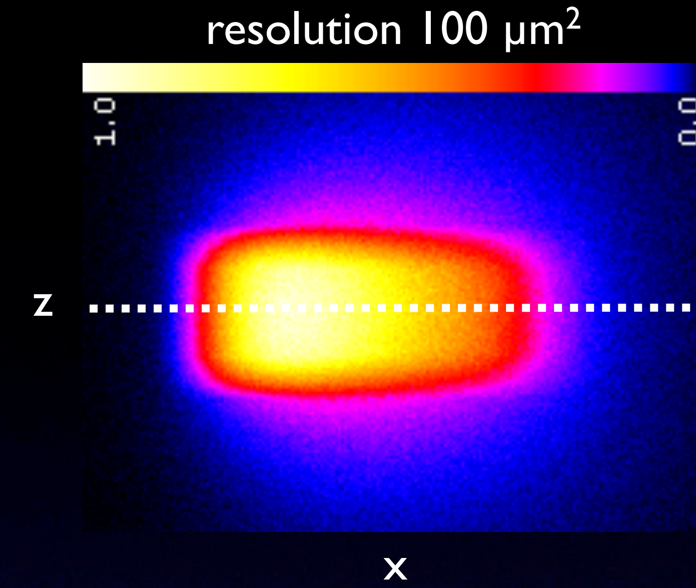
IRIS



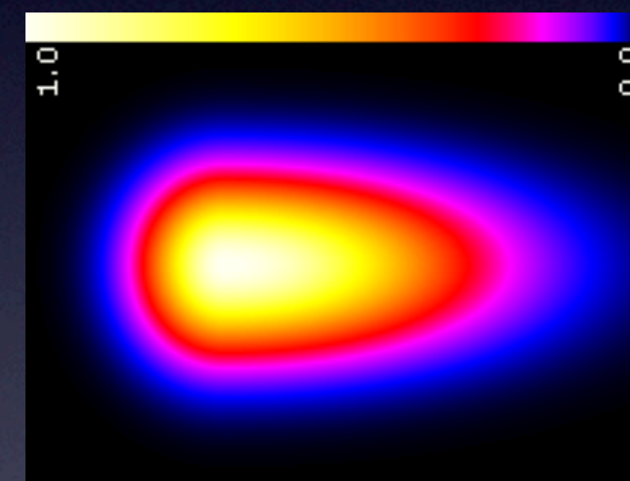
Results



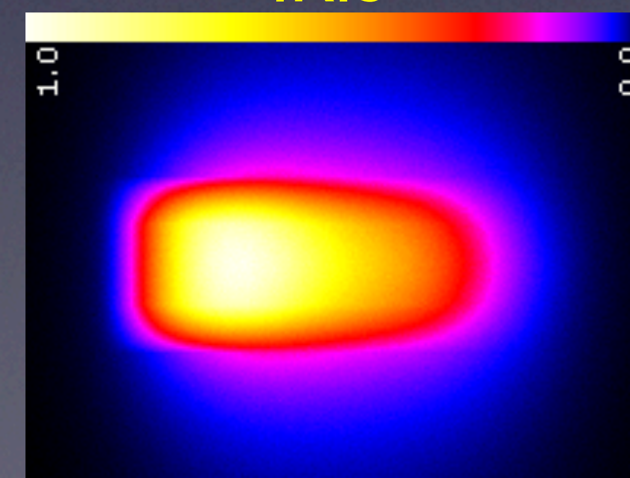
PET Philips GEMINI



Gaussian

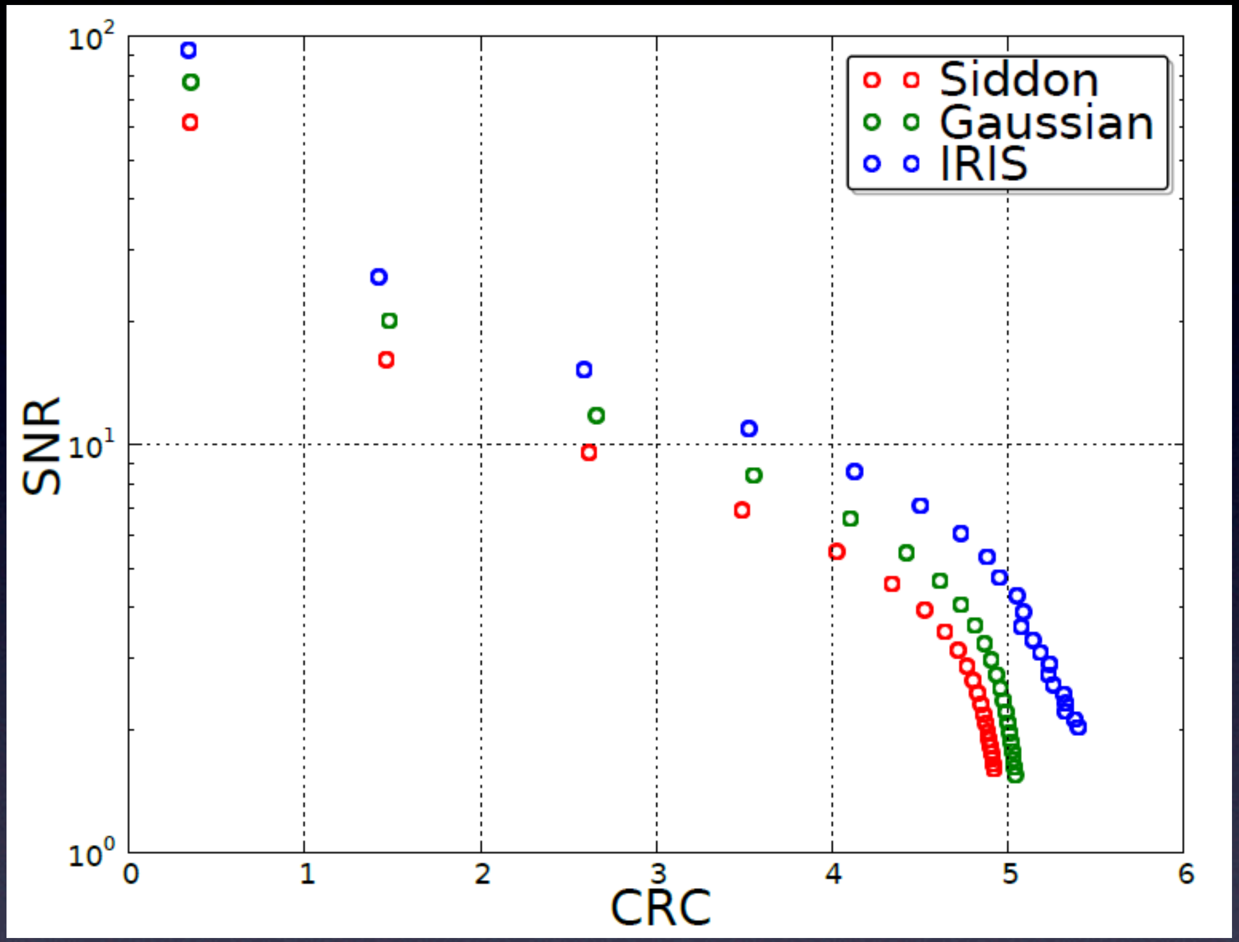


IRIS

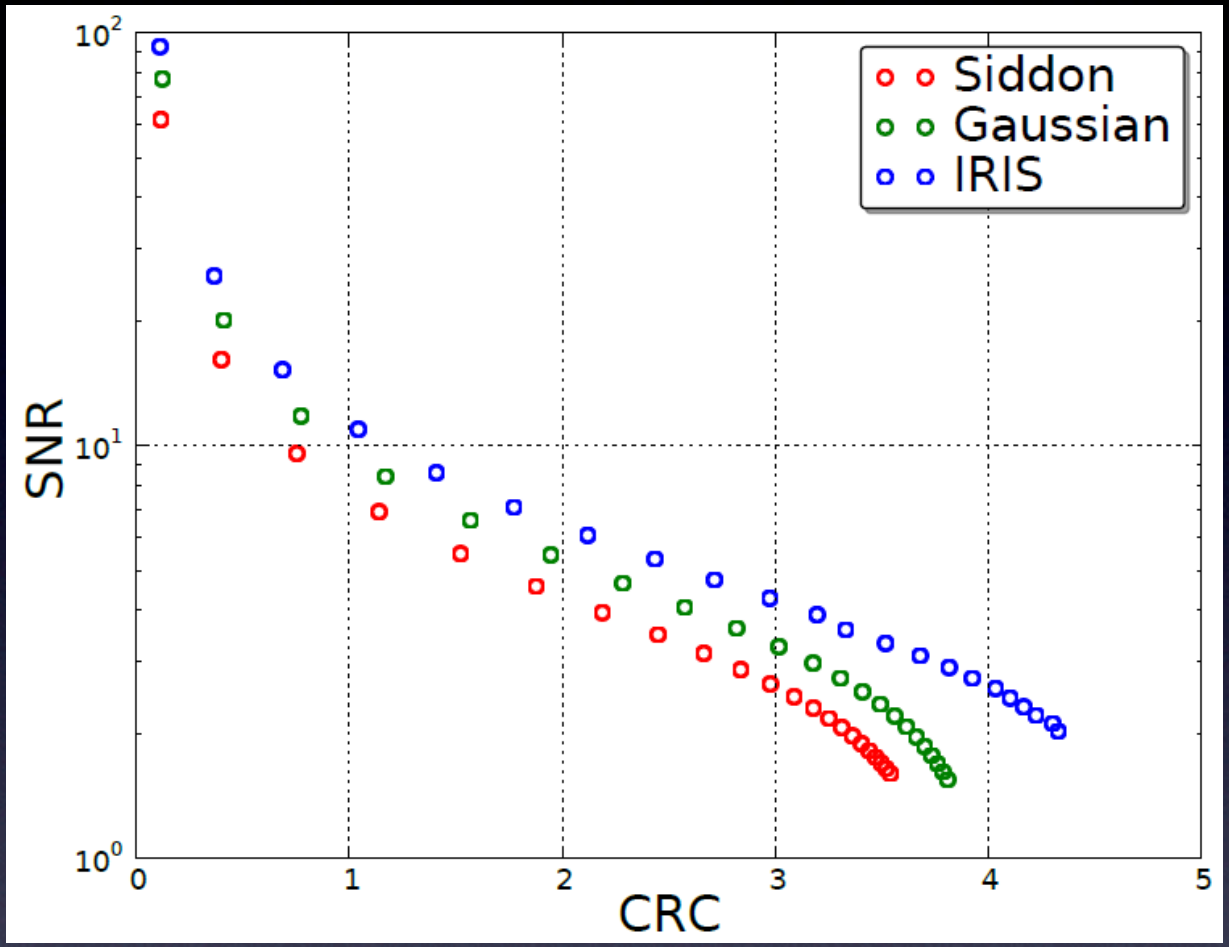


Results

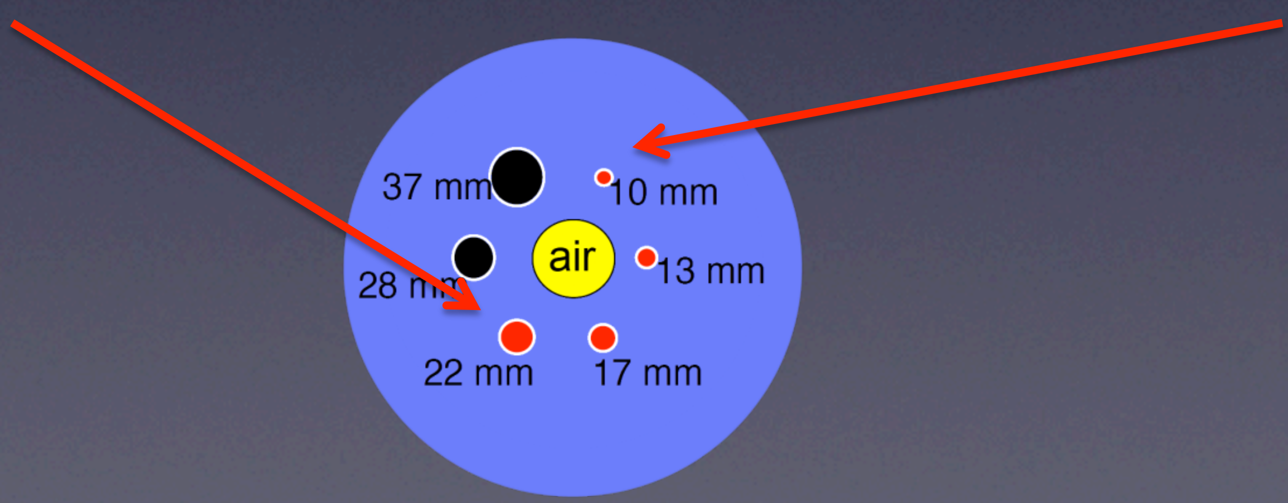
CRC/SNR (LM-OSEM 1 subset 70 iterations) [Awen2013a]



CRC in the biggest hot sphere



CRC in the smallest hot sphere

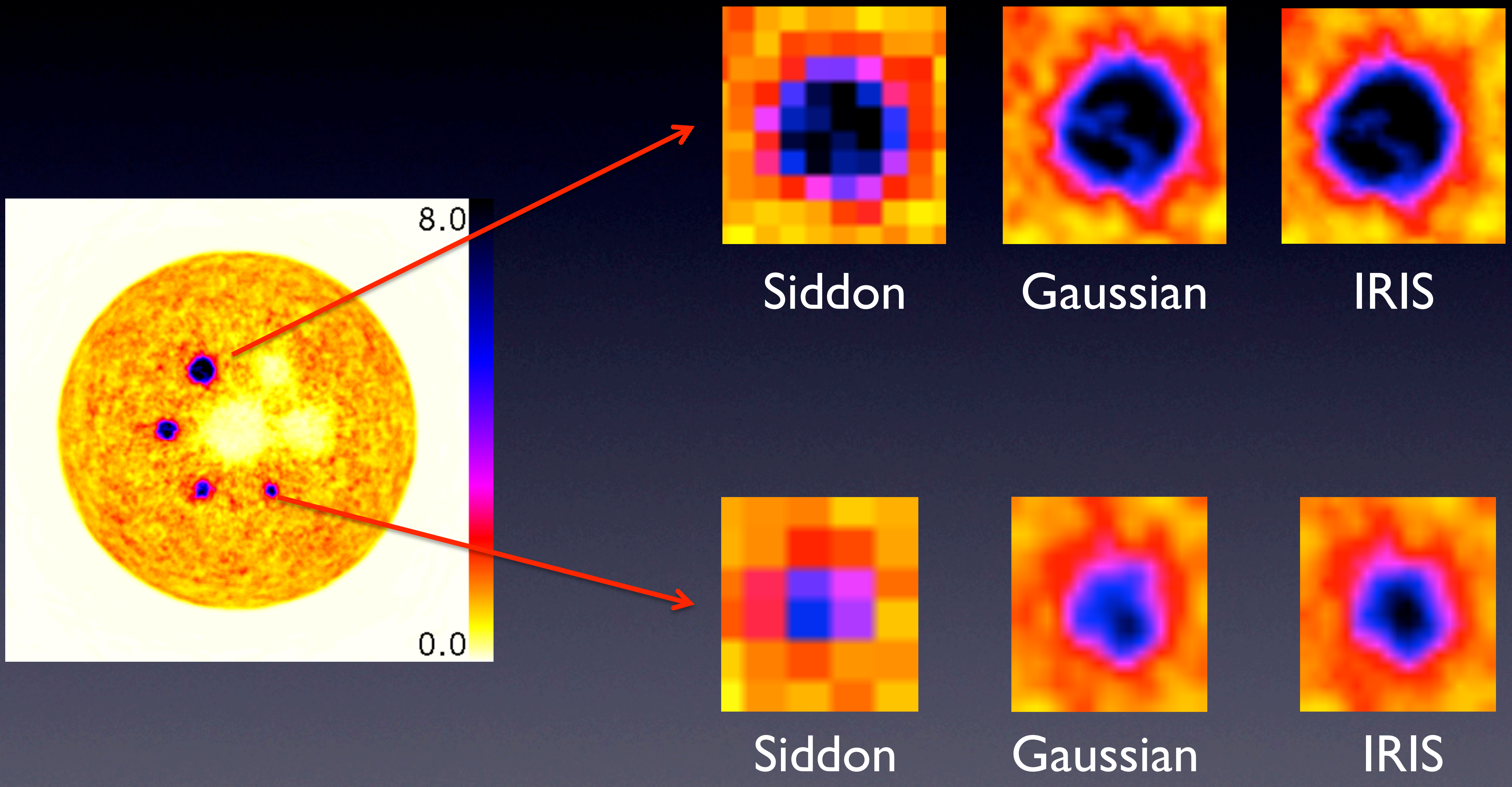


Autret et al., Fully3D, 2013

Results

Image Quality

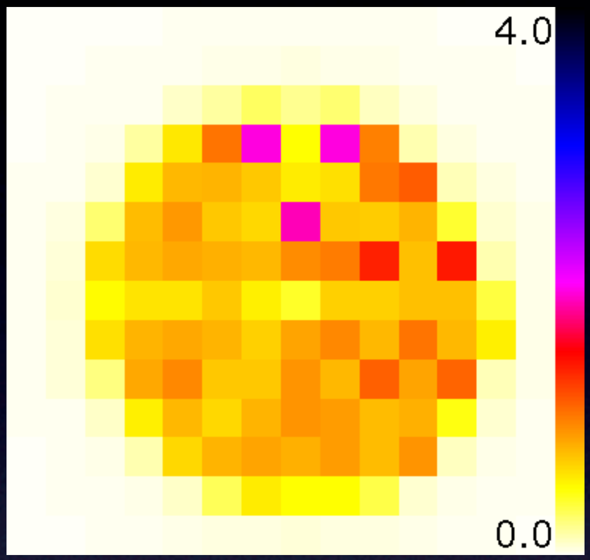
Reconstructed image for the same SNR (=4.5)



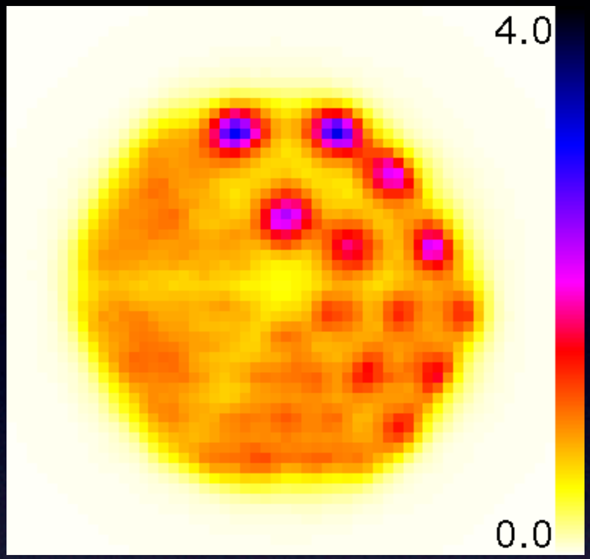
Results

Image Resolution

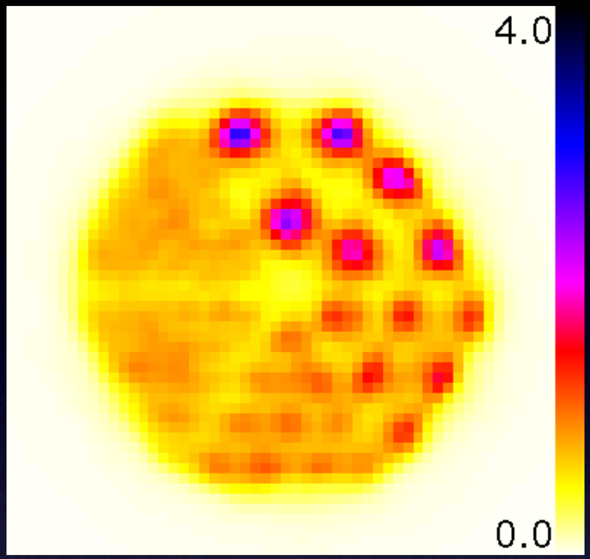
Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)



Siddon

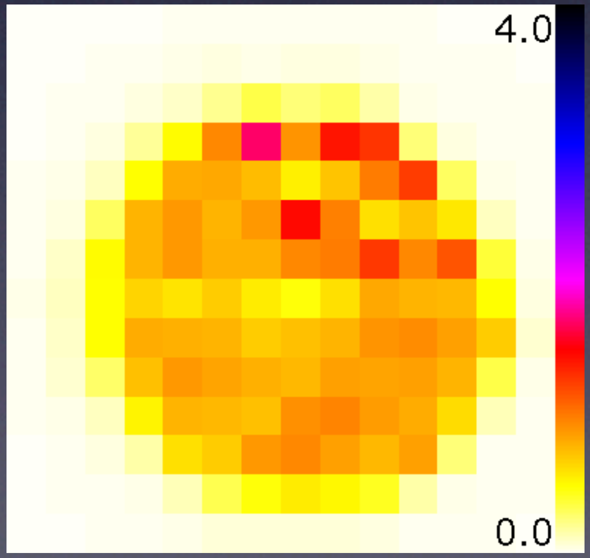


Gaussian

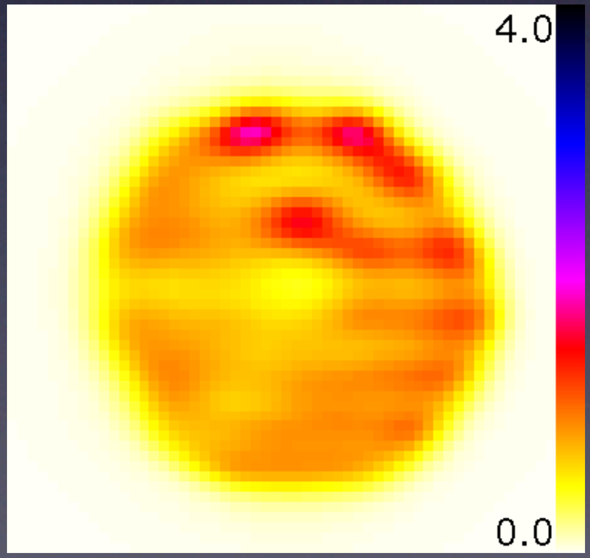


IRIS

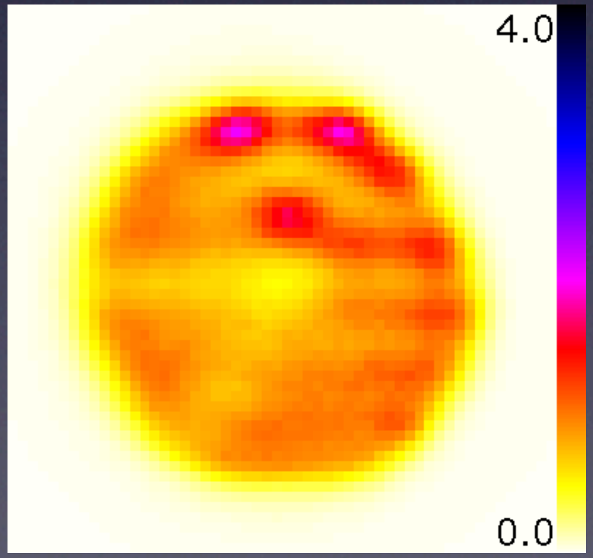
Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)



Siddon



Gaussian

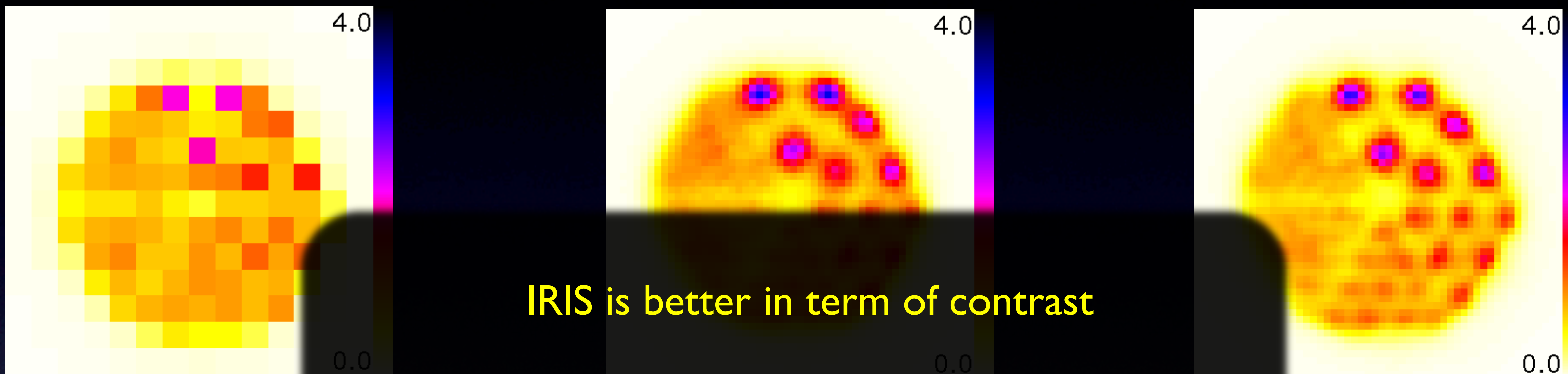


IRIS

Results

Image Resolution

Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)



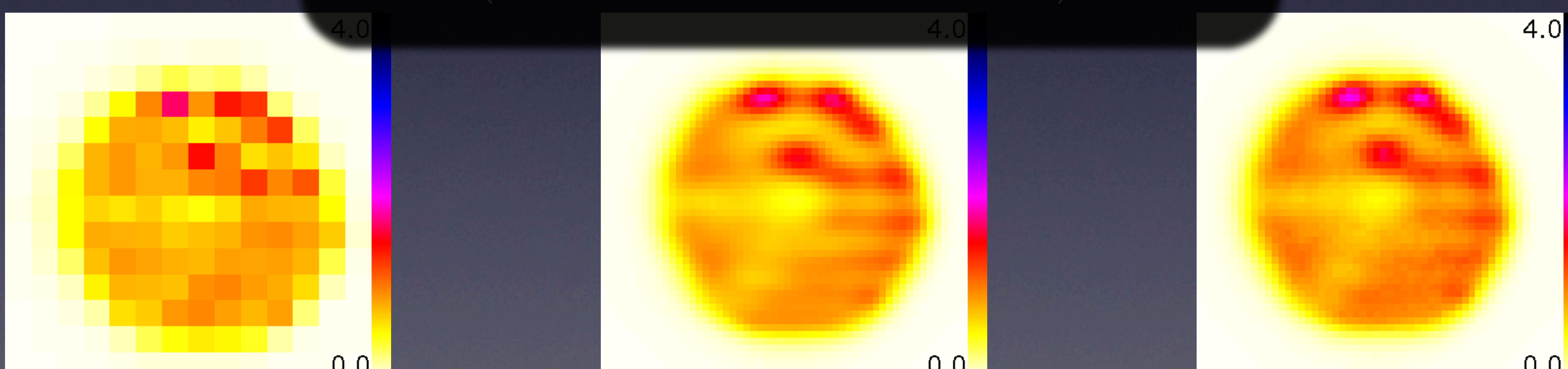
Siddon Gaussian IRIS

IRIS is better in term of contrast

How to improve that?

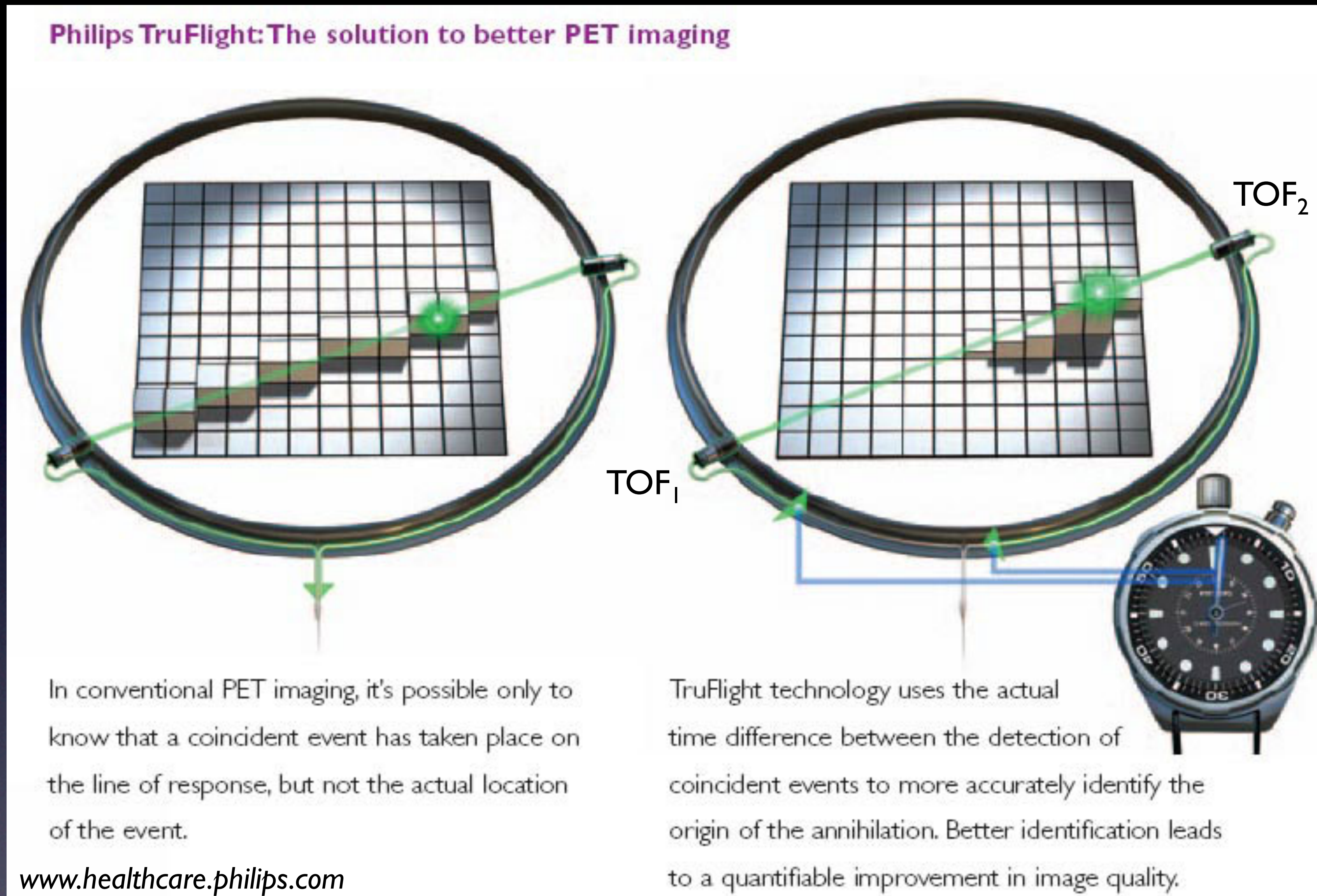
Include more information from the list-mode data

Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)



Siddon Gaussian IRIS

Considering time-of-flight (TOF)



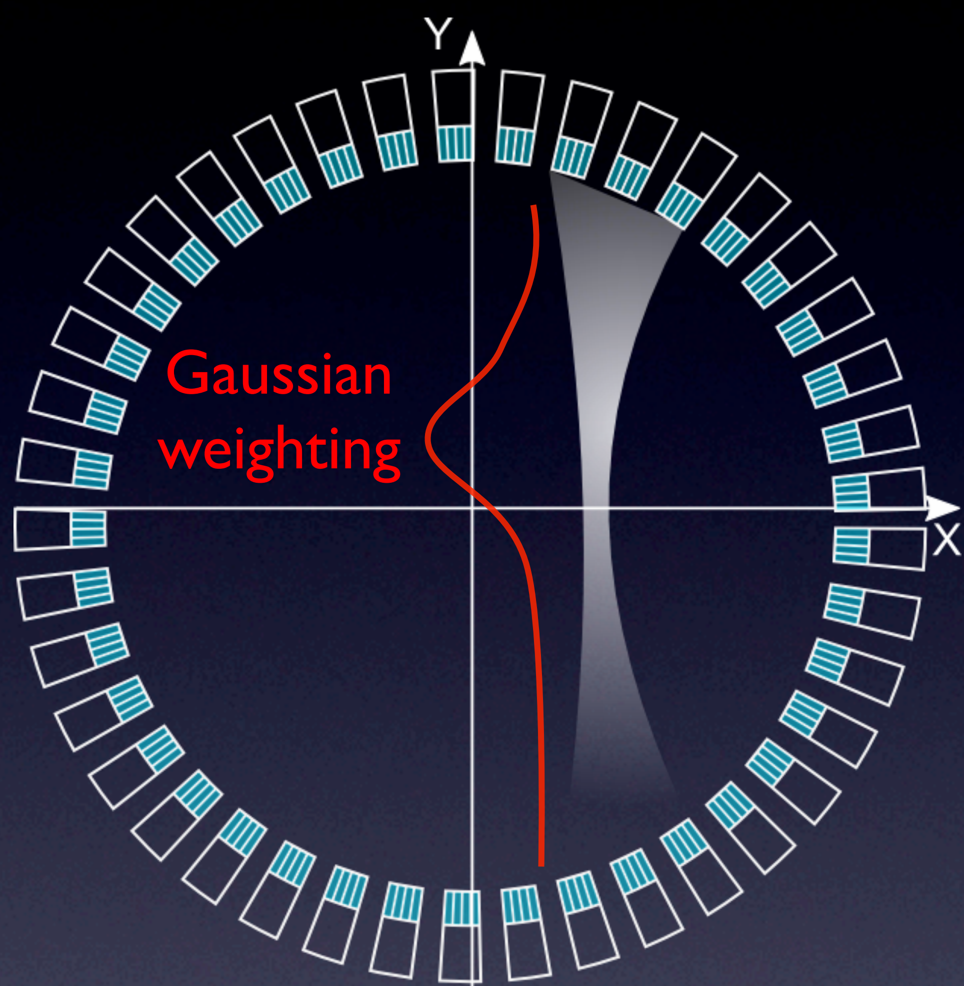
Along the LOR

Along a small part of the LOR

Typical TOF resolution is 500 ps FWHM (7.5 cm)

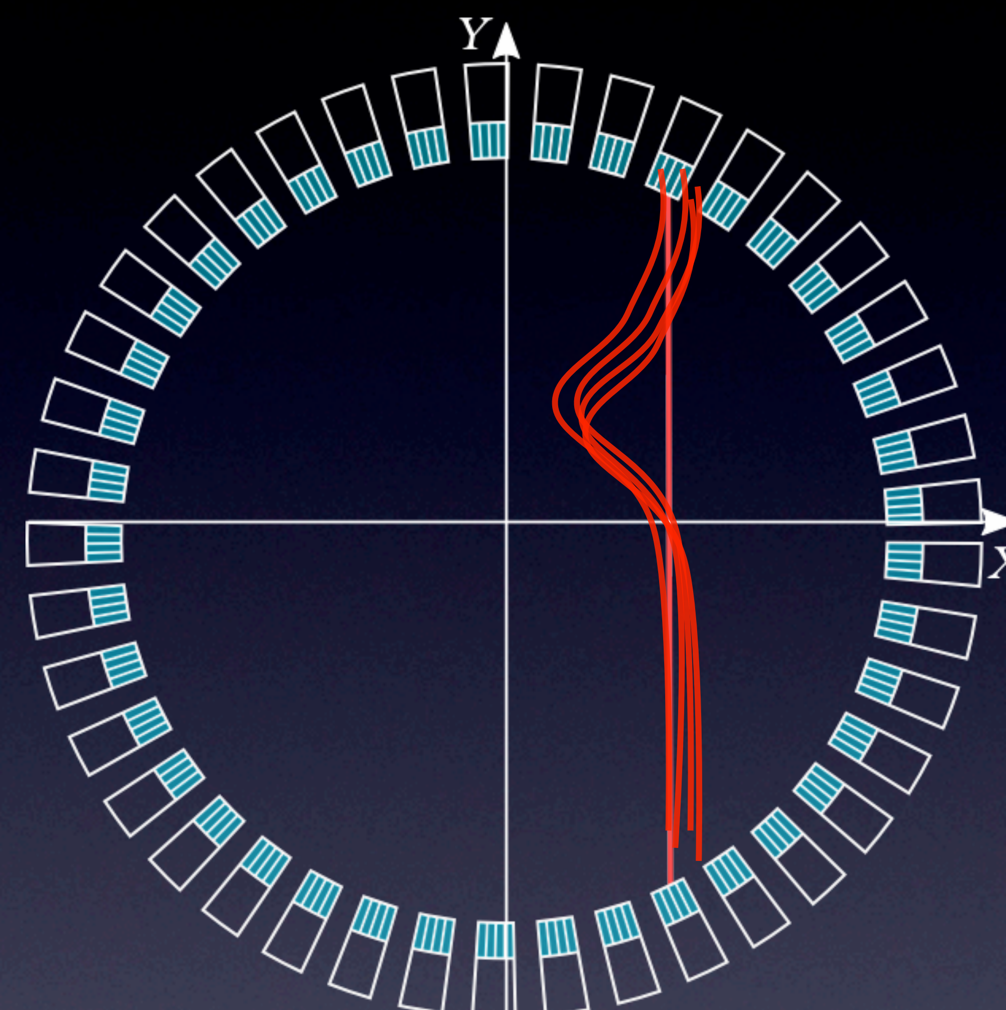
Considering time-of-flight (TOF)

Gaussian projector



Applied on the VOR

IRIS projector



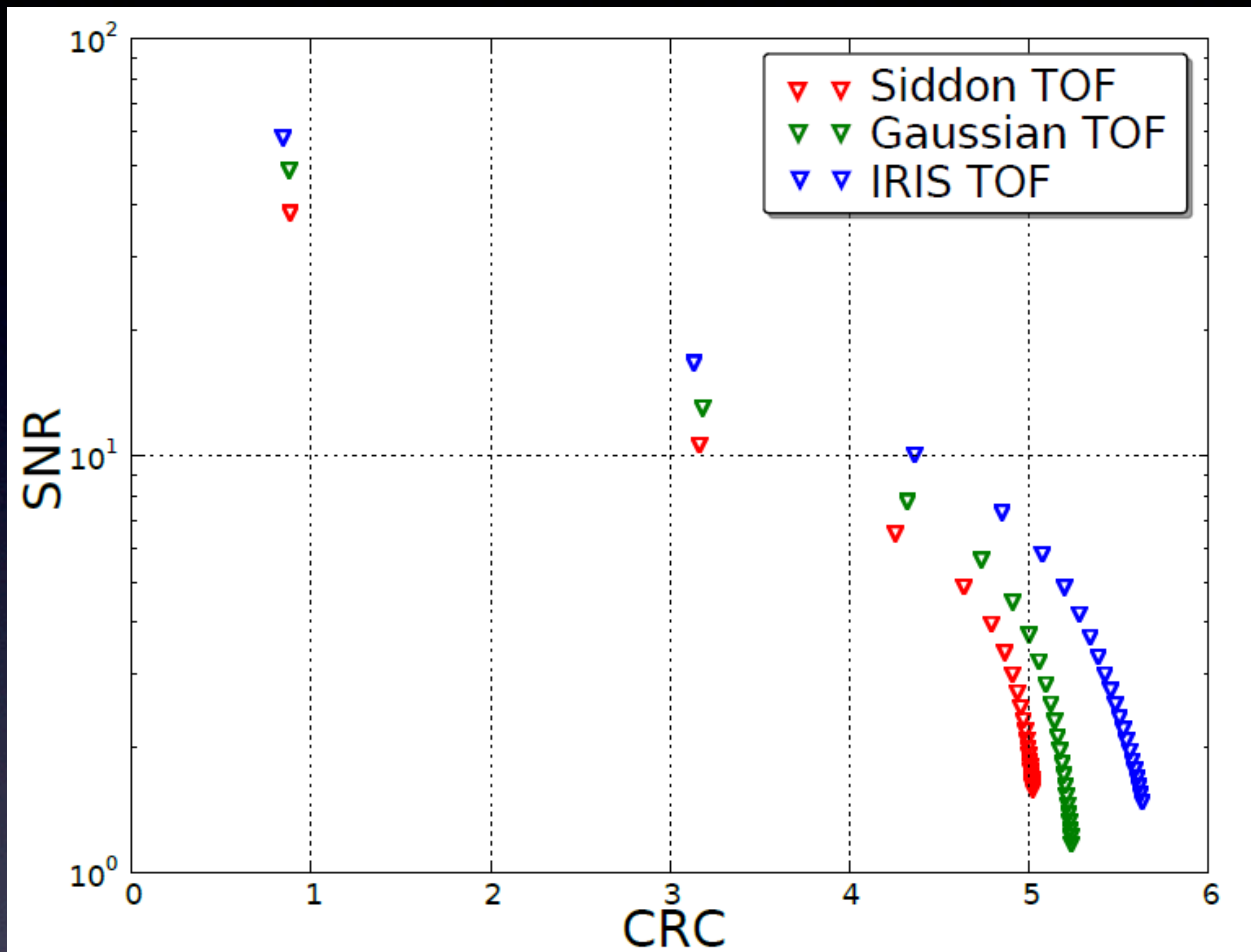
Applied on every random lines

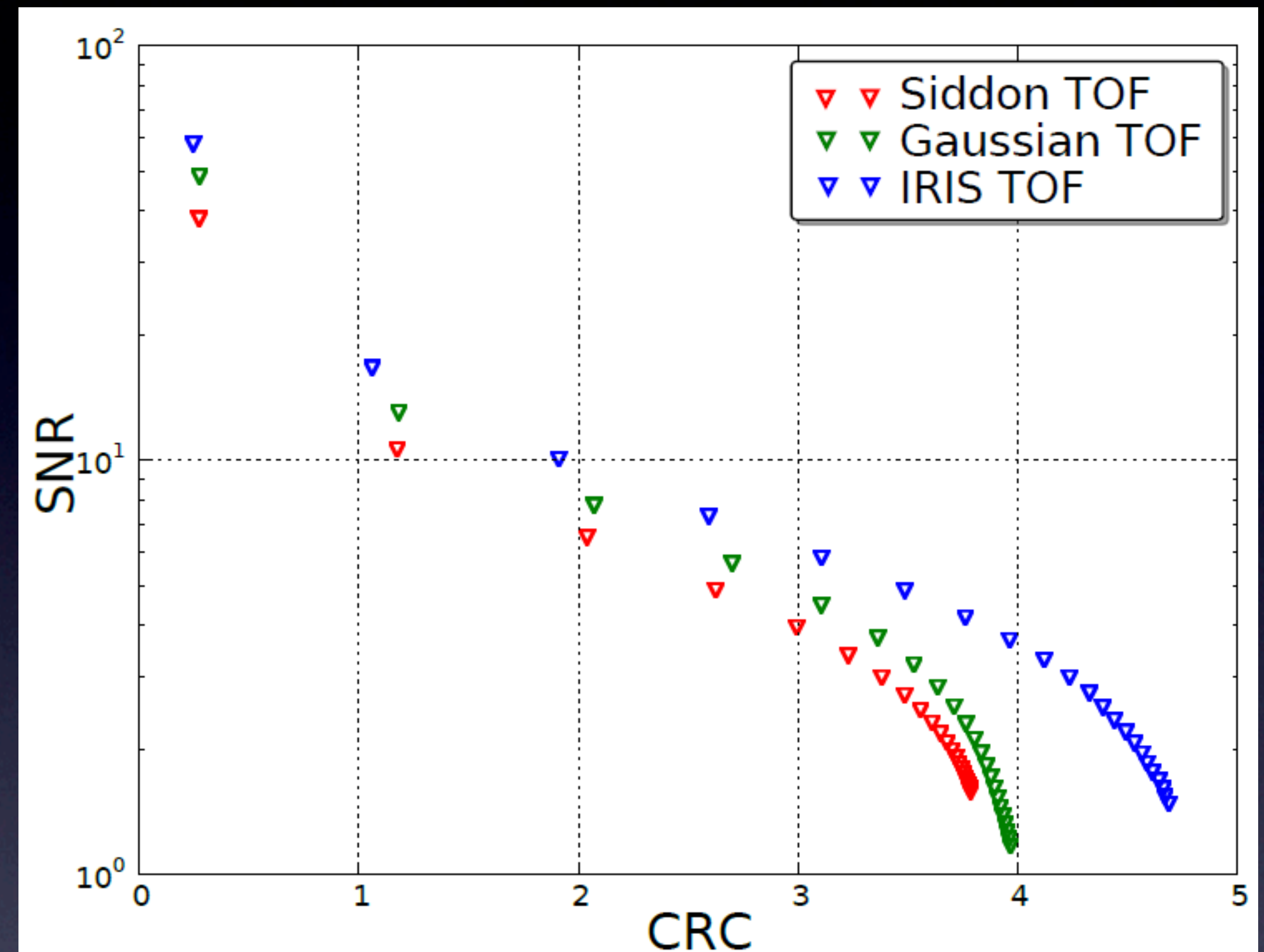
FWHM given by the TOF resolution

TOF weighting can be used on every projector

Results TOF

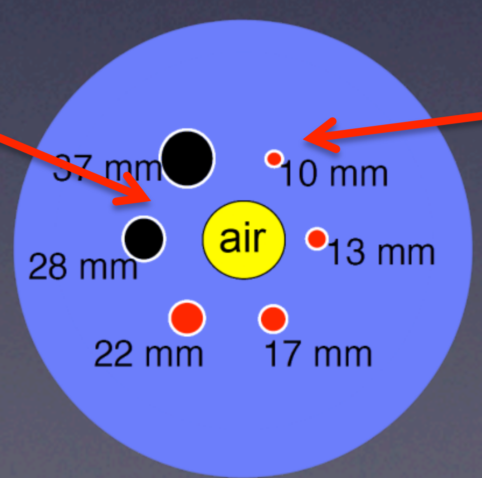
CRC/SNR (LM-OSEM 1 subset 70 iterations) [Awen2013b]





CRC in the biggest hot sphere

CRC in the smallest hot sphere



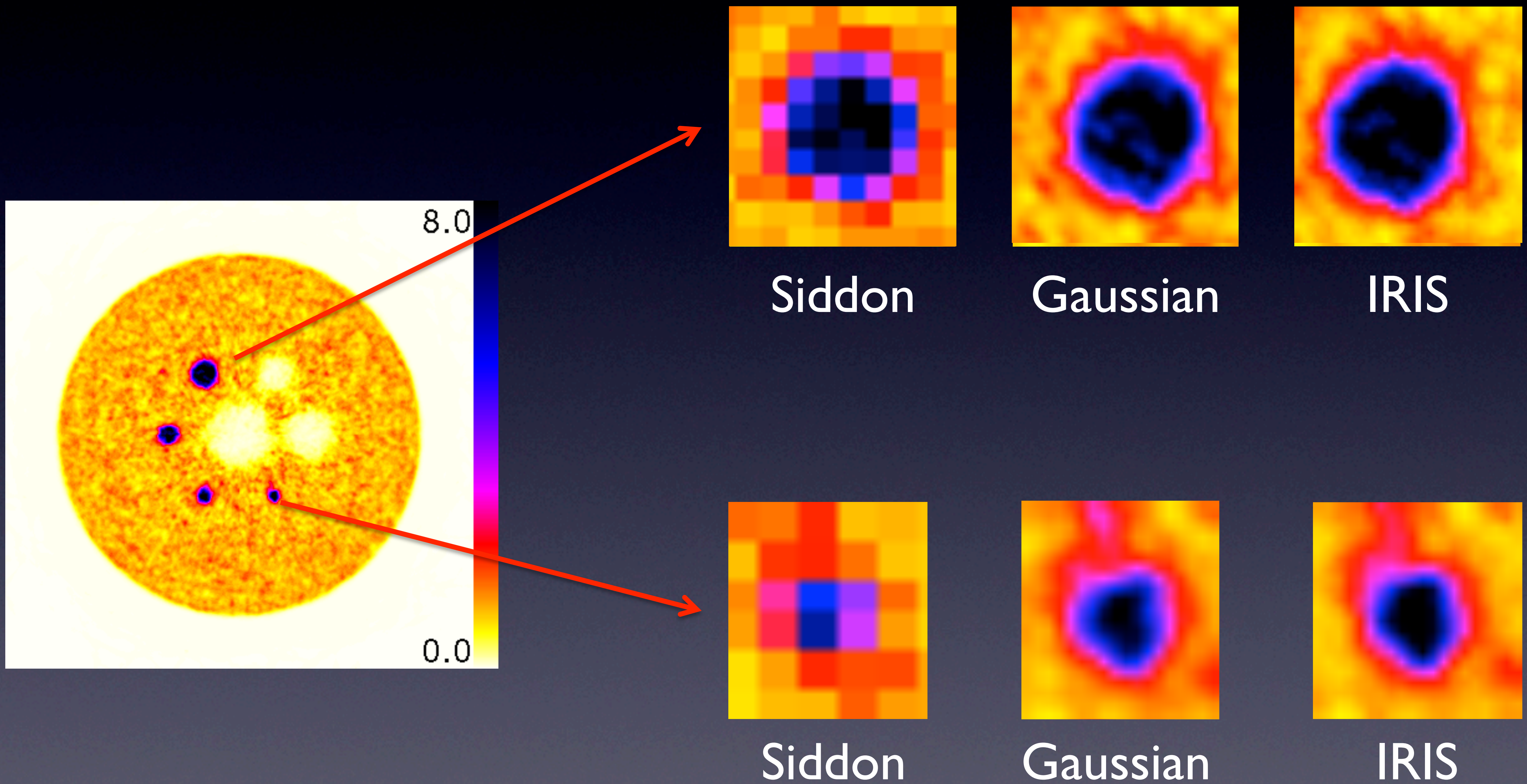
Improve convergence, SNR and contrast

Autret et al., IEEE MIC, 2013

Results TOF

Image Quality

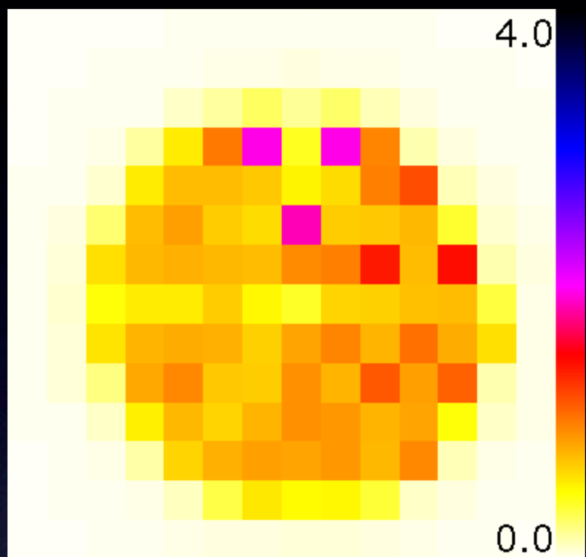
Reconstructed image for the same SNR (=4.5)



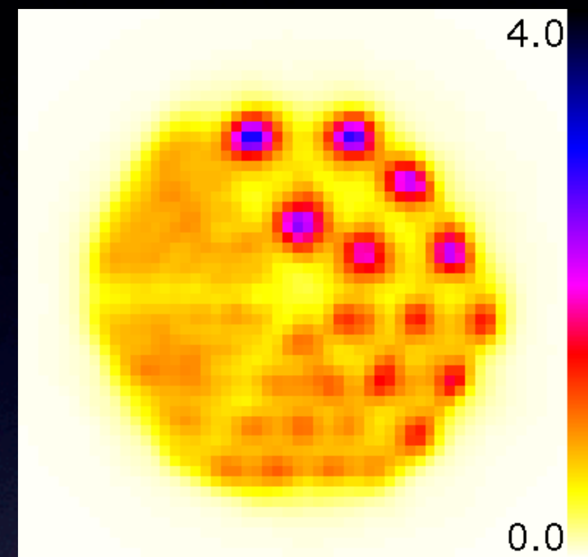
Results TOF

Image Resolution

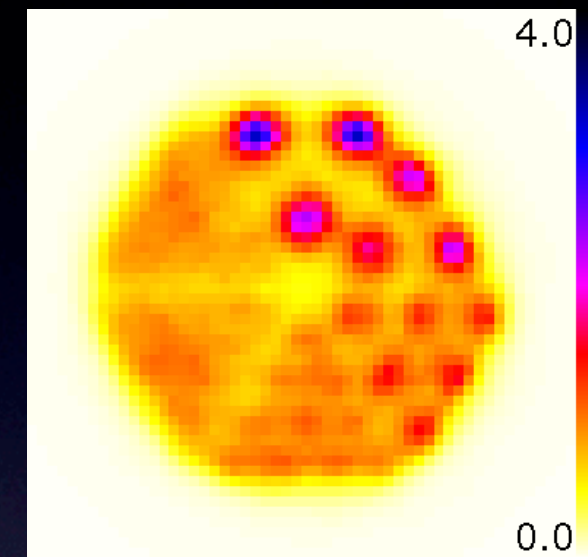
Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)



Siddon

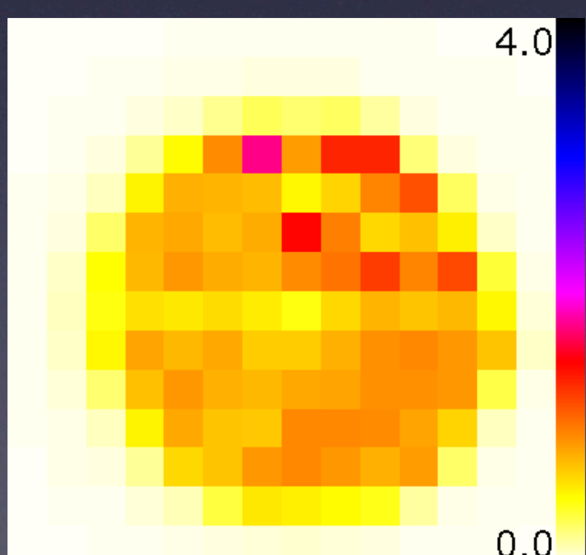


Gaussian

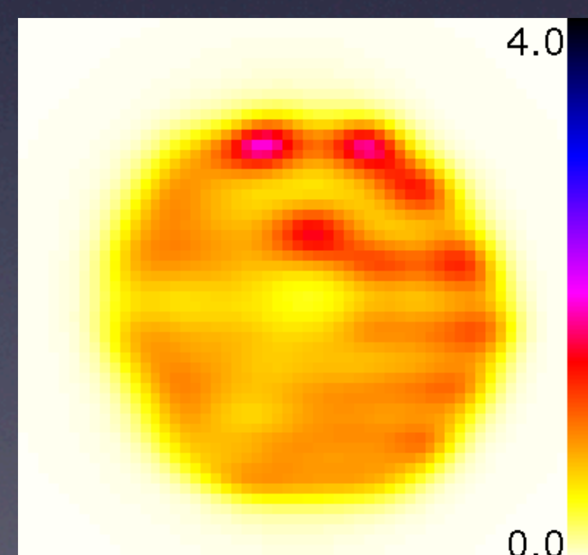


IRIS

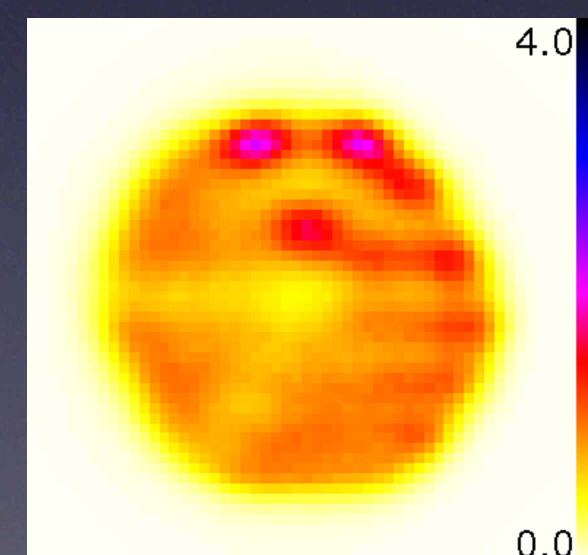
Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)



Siddon



Gaussian

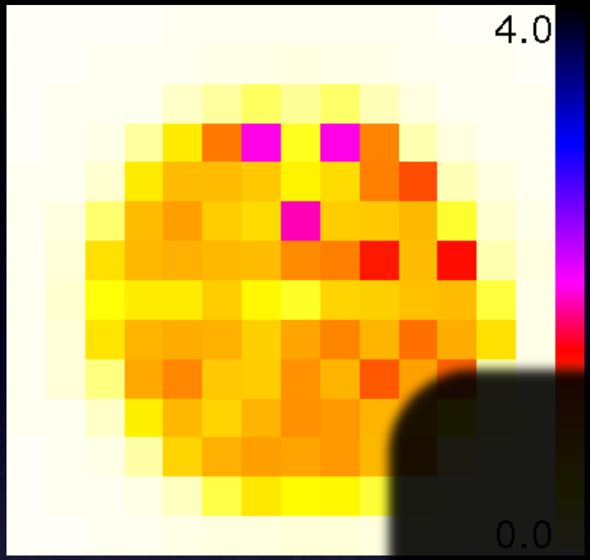


IRIS

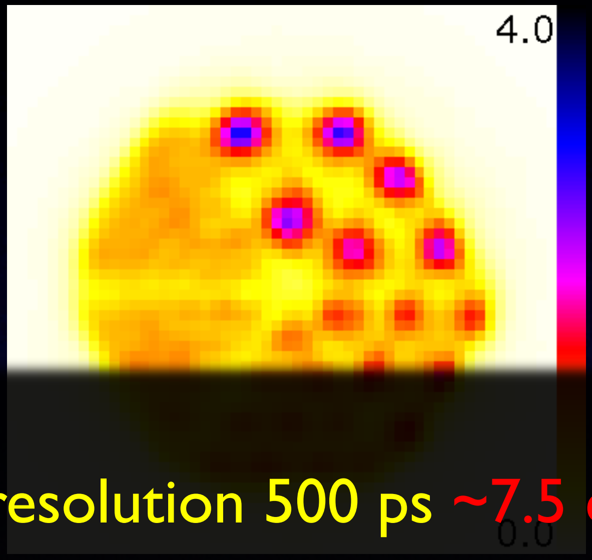
Results TOF

Image Resolution

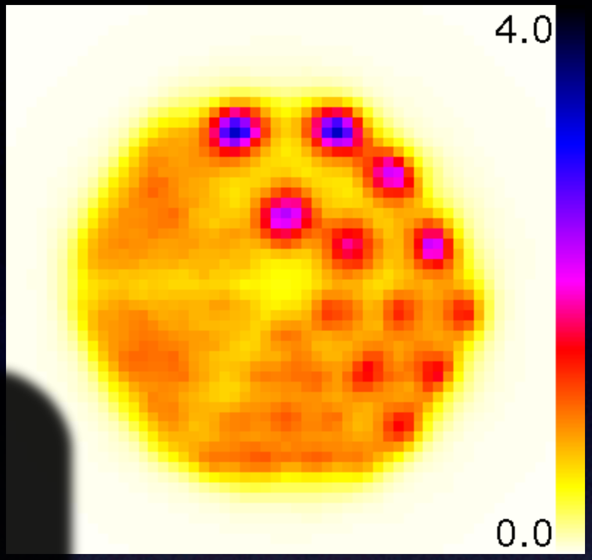
Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)



Siddon



Gaussian



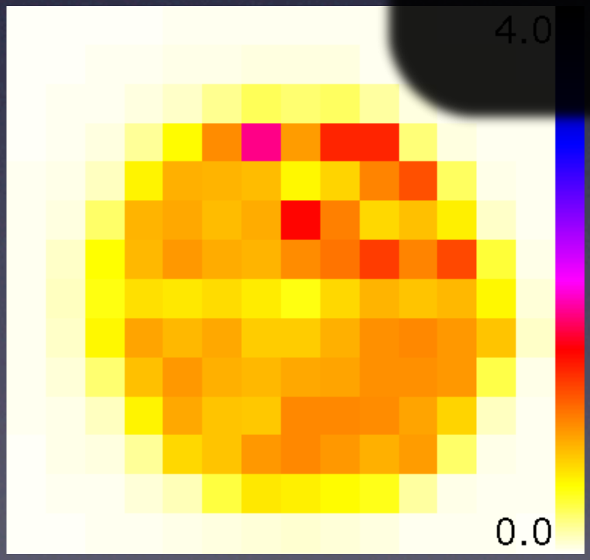
IRIS

TOF resolution 500 ps ~7.5 cm

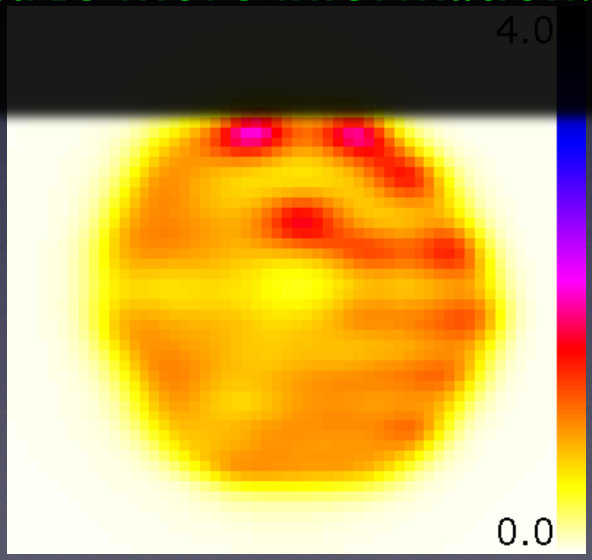
Diameter of the miniature Derenzo phantom: 5 cm

Include more information!

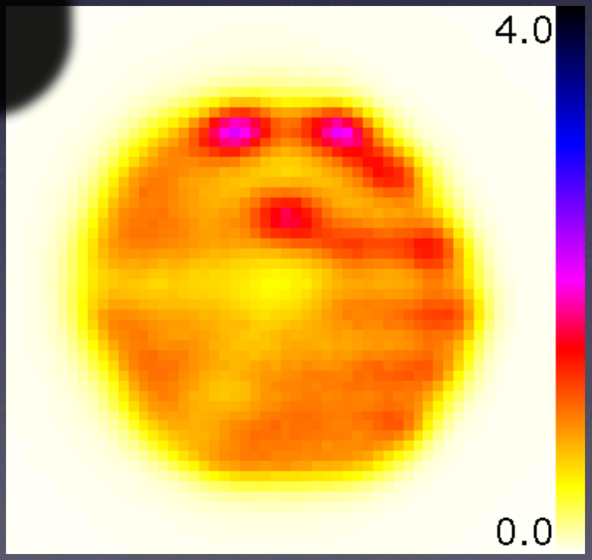
Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)



Siddon



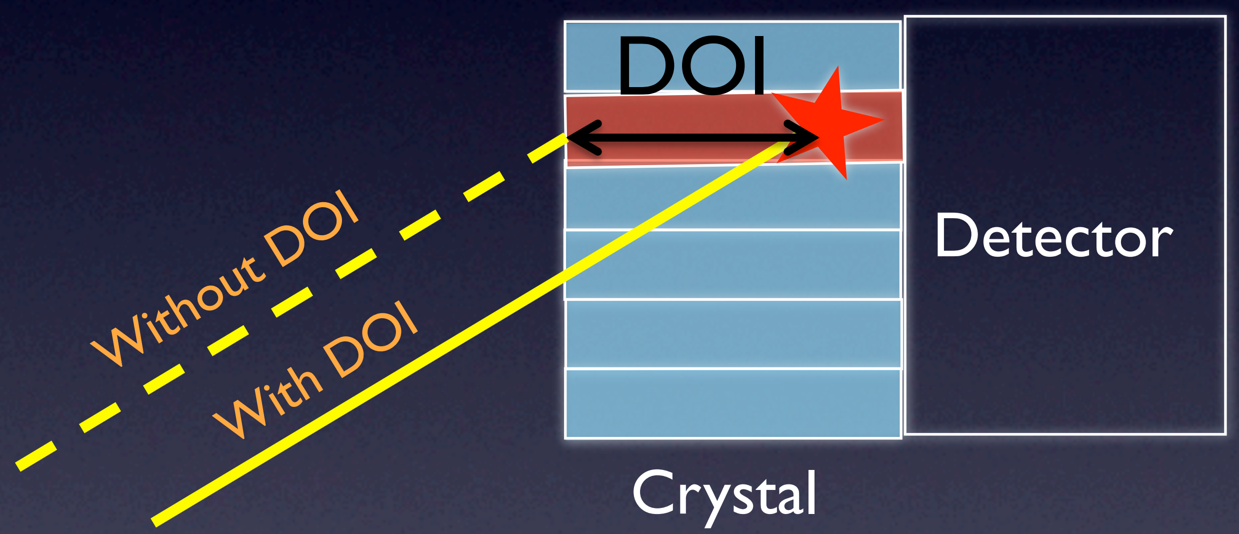
Gaussian



IRIS

Considering Depth-of-Interaction (DOI)

Only available on prototype detector

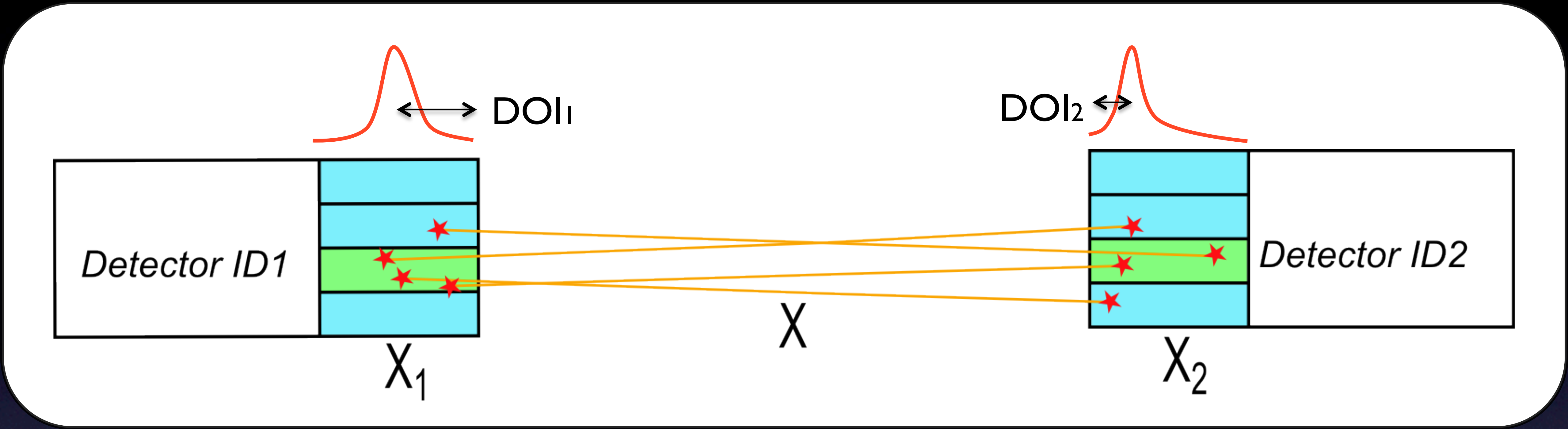


Crystal depth where the photon was detected

Improve LOR location for a given resolution (FWHM 1 mm)

Considering Depth-of-Interaction (DOI)

IRIS projector



Modulate the IDRF with the a Gaussian function given by the FWHM of the DOI resolution

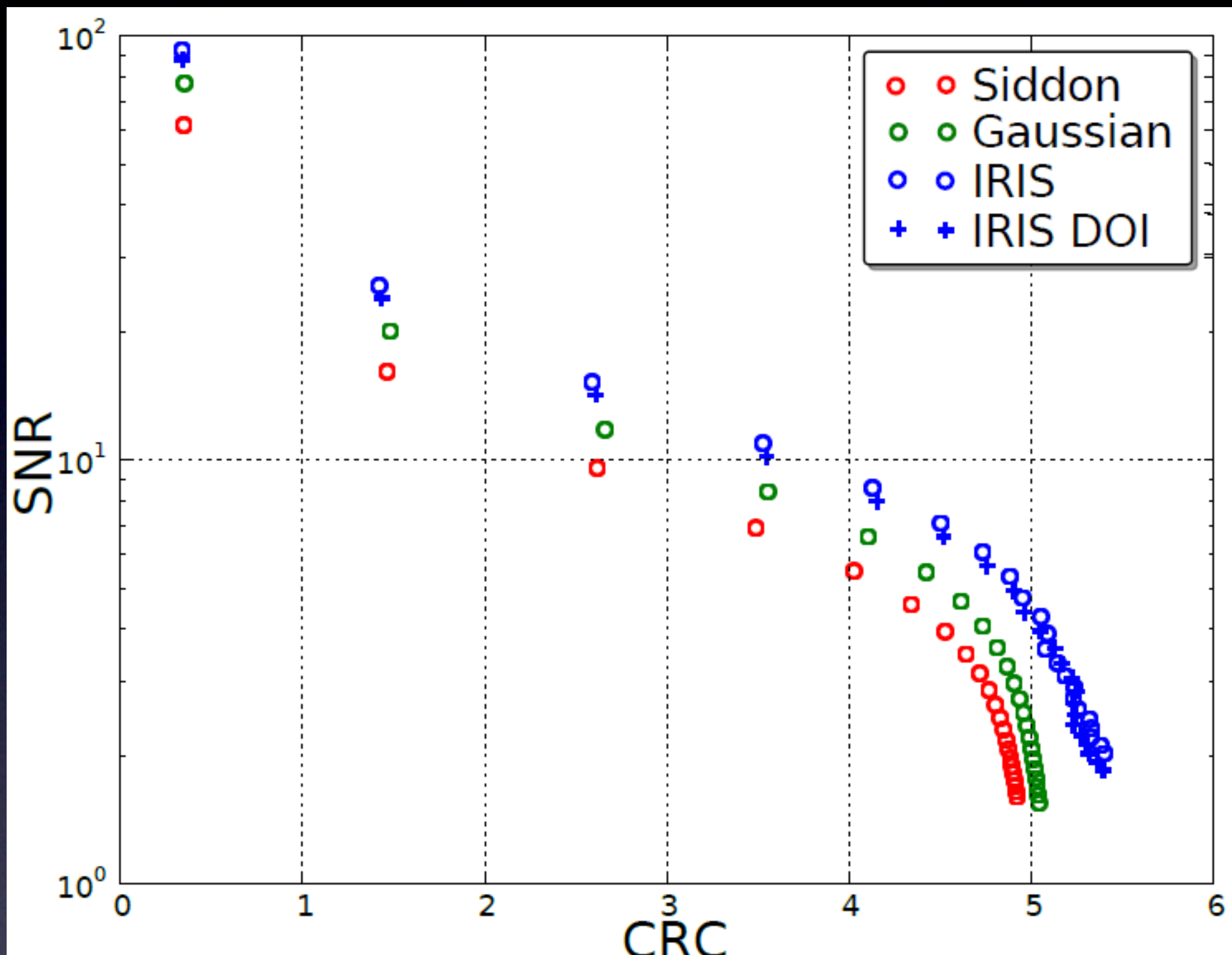
Easy to use with ray or multi-ray projectors (Siddon, Chen, IRIS, etc.)

Difficult for VOR modeling projector (especially Gaussian)

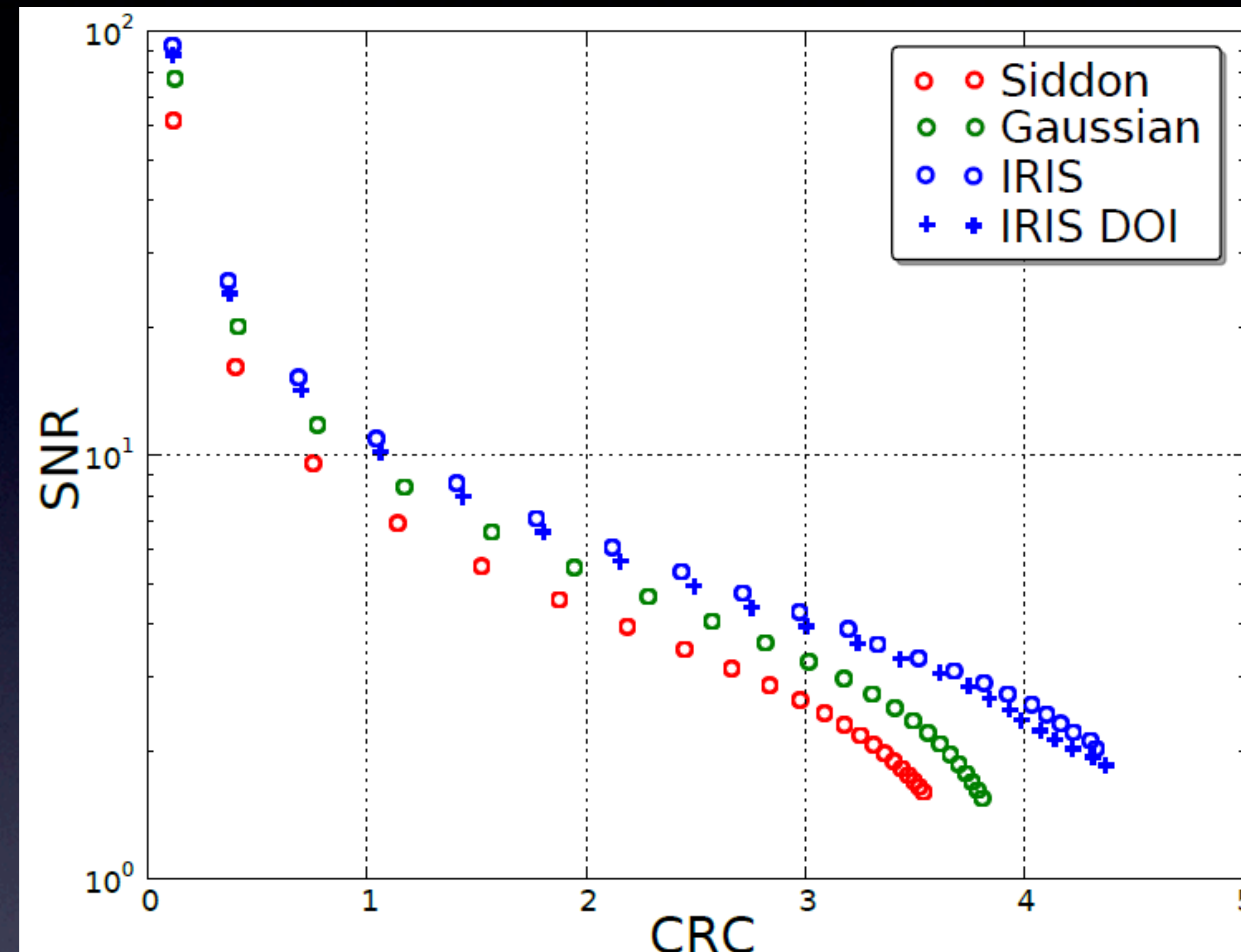
Gaussian model + DOI = Not a Gaussian anymore!

Results DOI

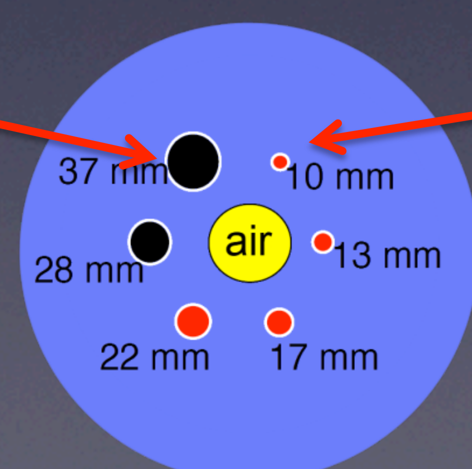
CRC/SNR (LM-OSEM 1 subset 70 iterations)



CRC in the biggest hot sphere



CRC in the smallest hot sphere

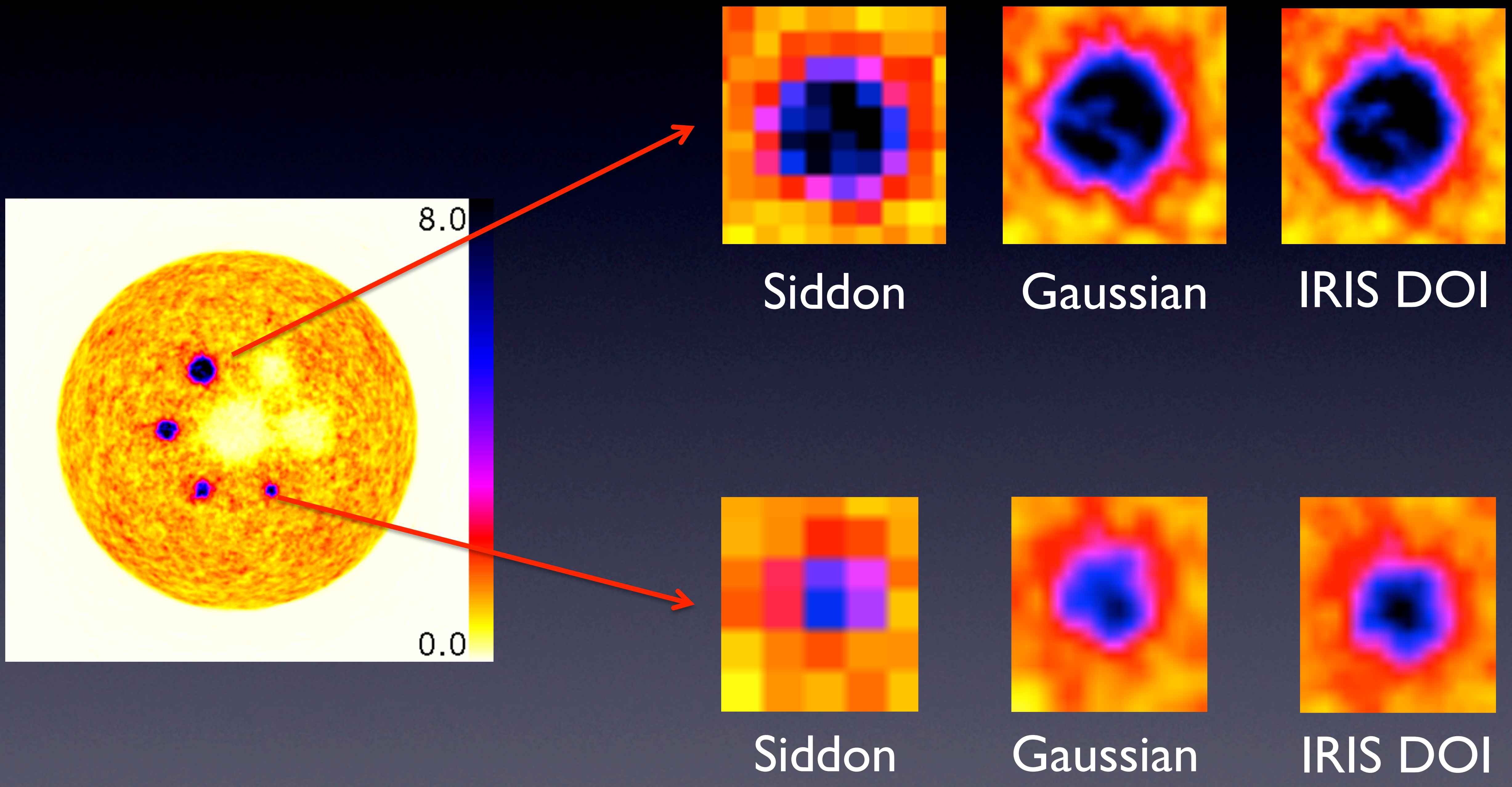


Not really improve the contrast

Results DOI

Image Quality

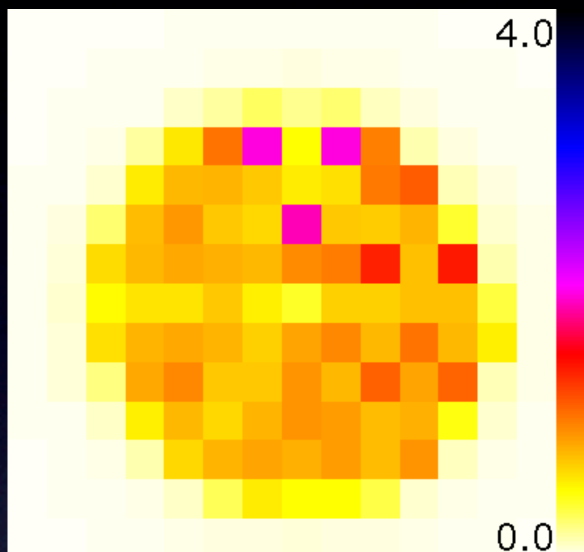
Reconstructed image for the same SNR (=4.5)



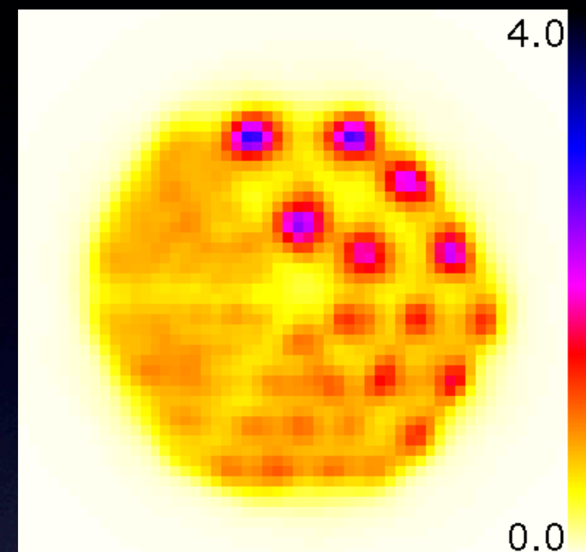
Results DOI

Image Resolution

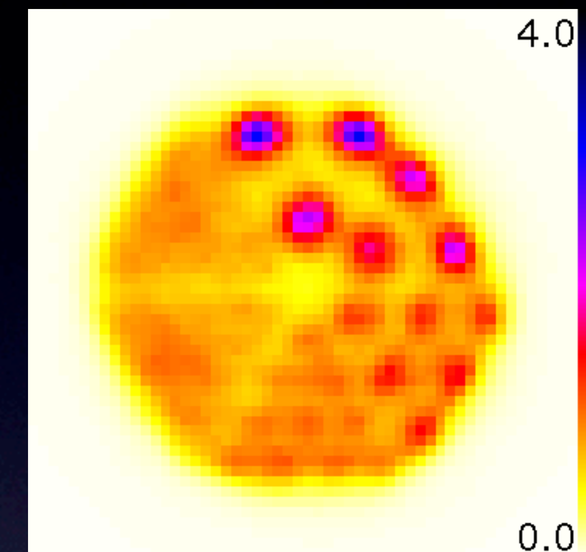
Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)



Siddon

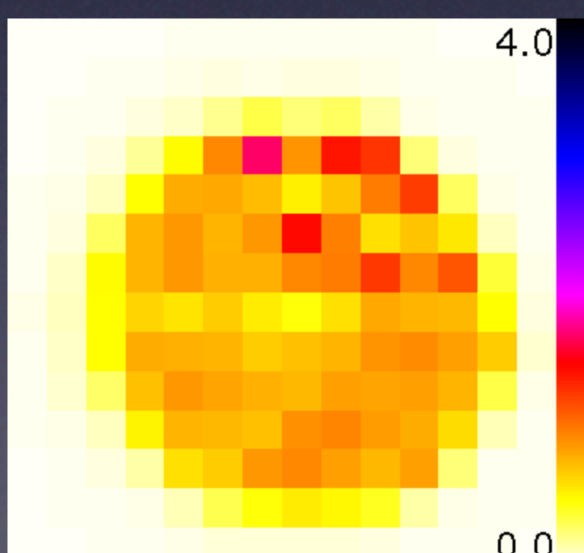


Gaussian



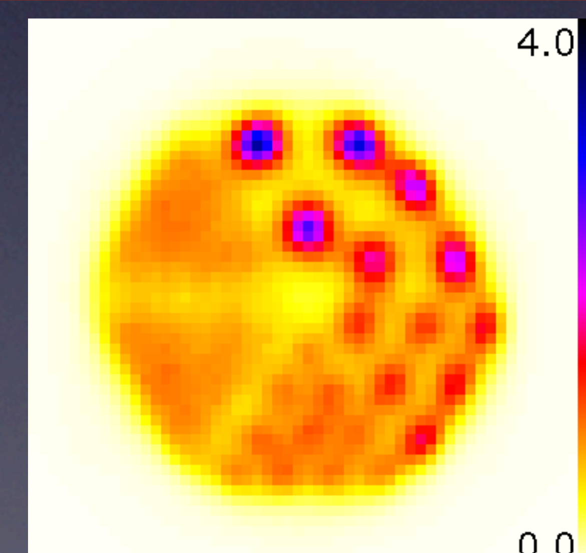
IRIS DOI

Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)



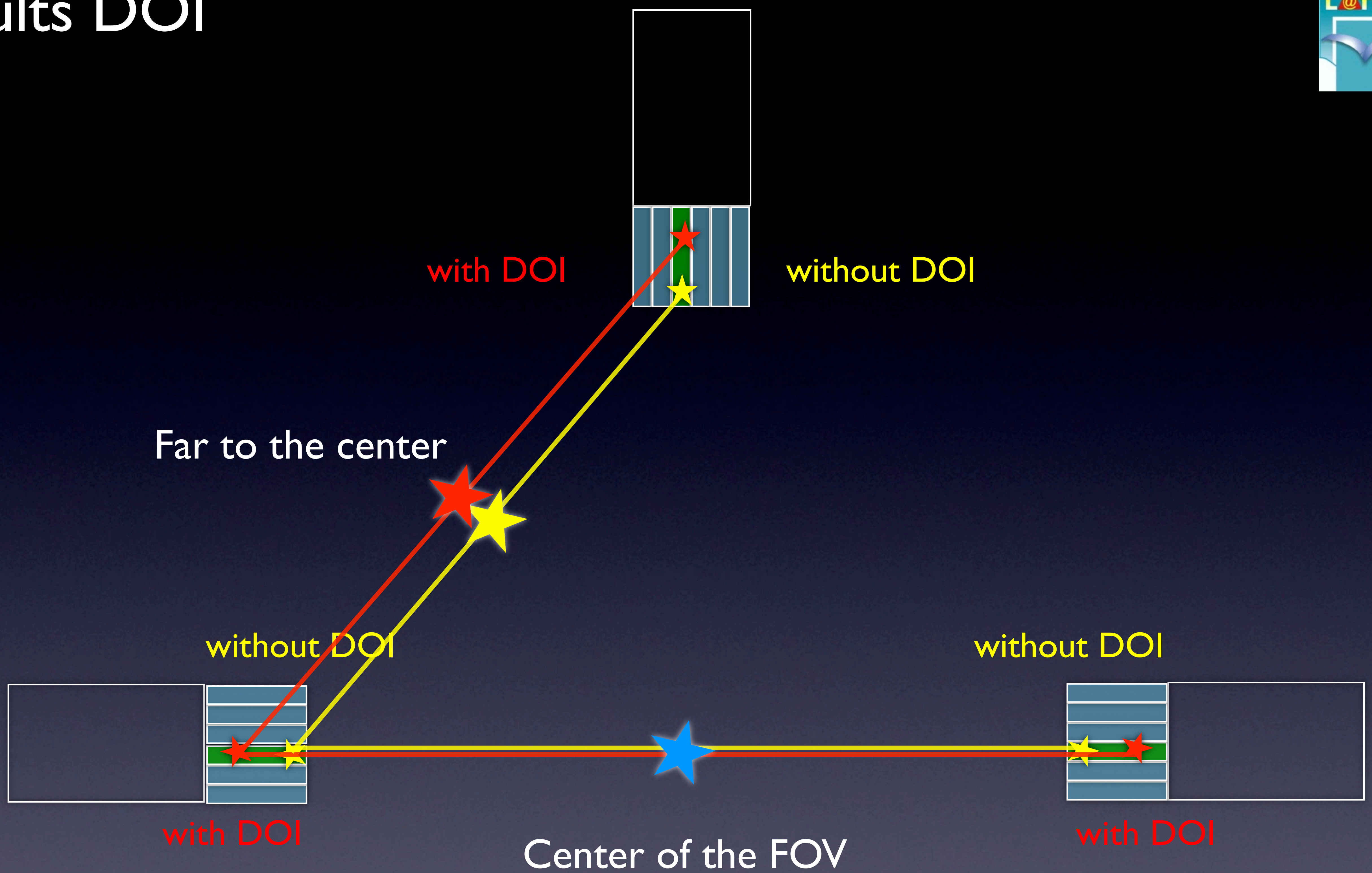
Siddon

Gaussian



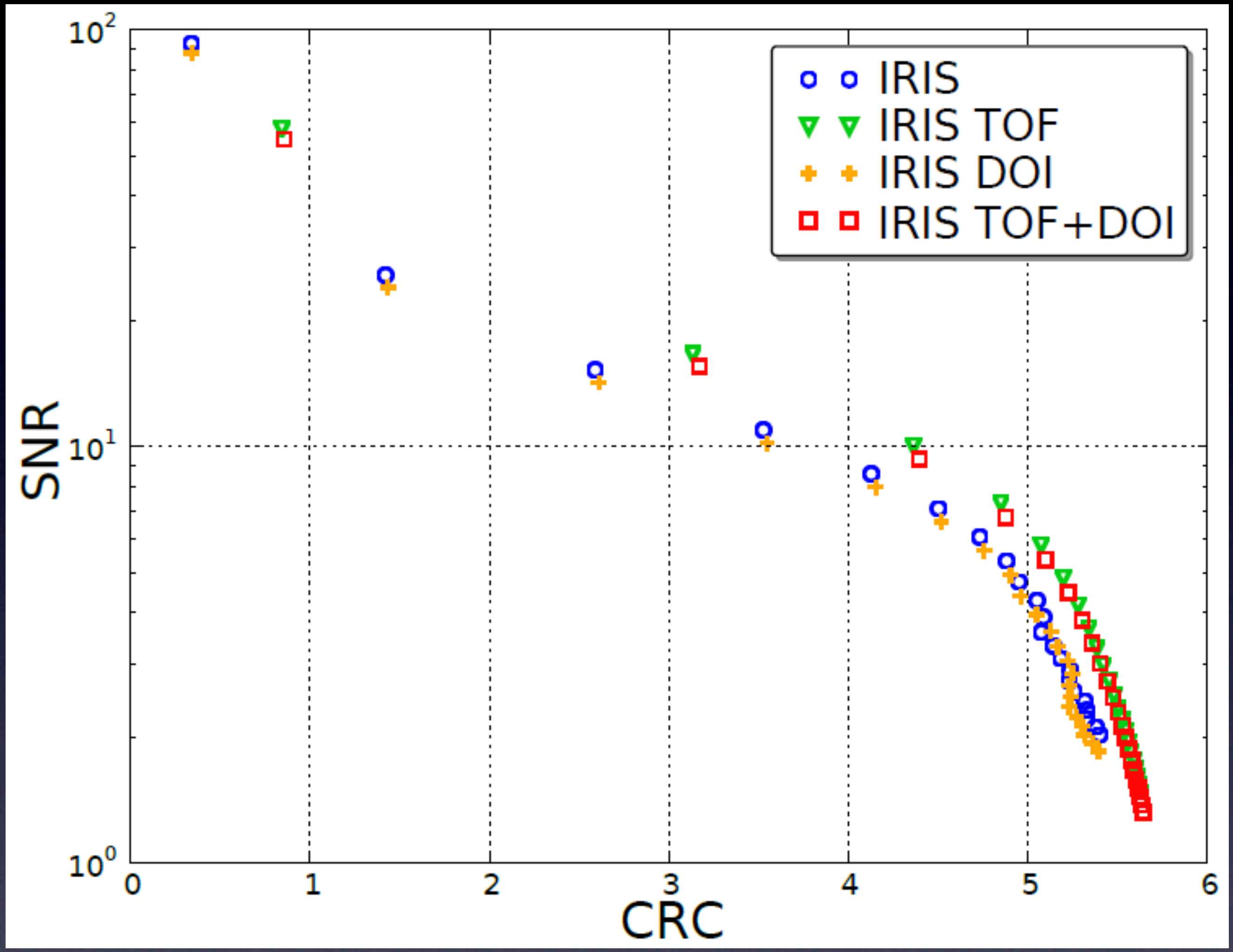
IRIS DOI

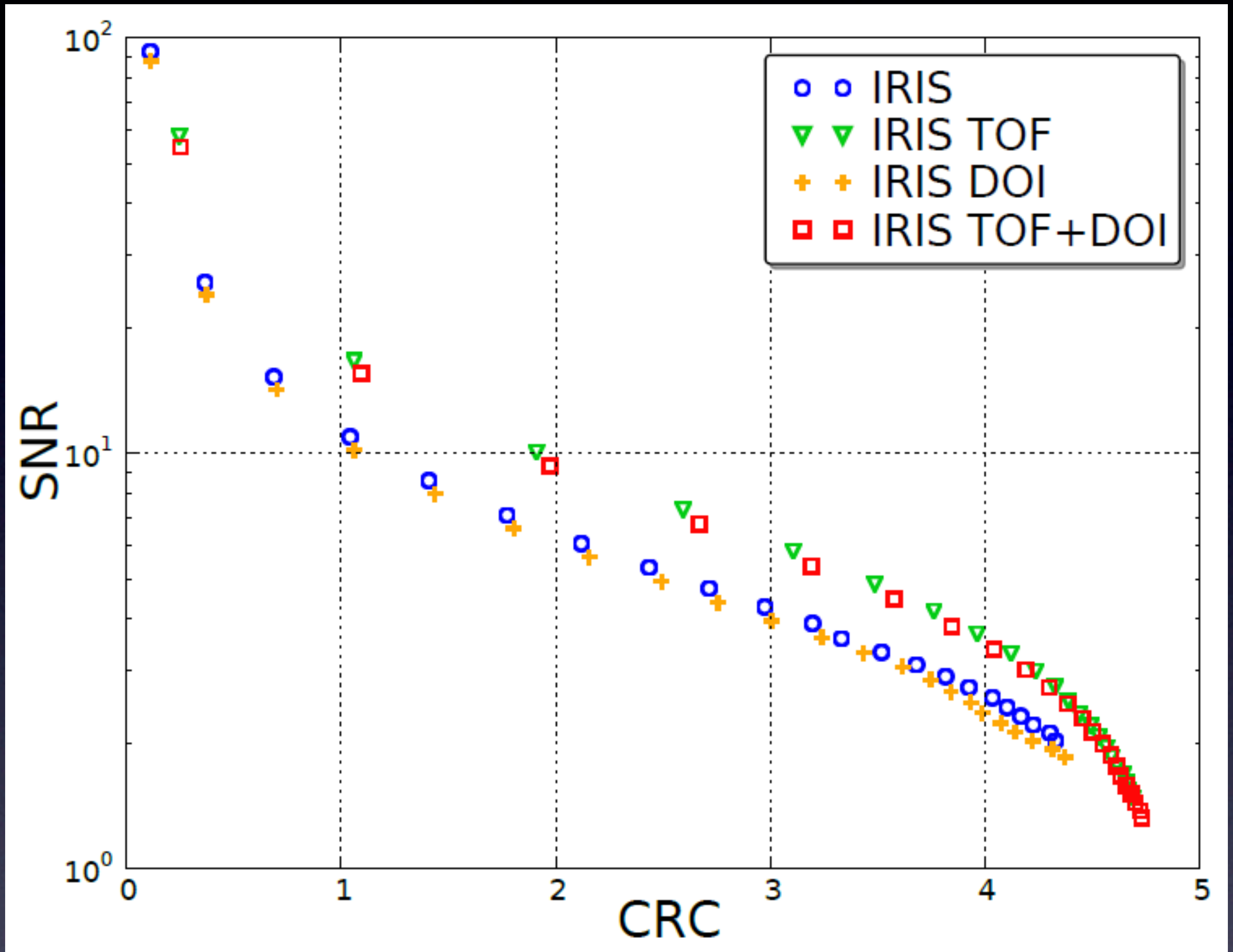
Results DOI


with DOI
without DOI
Far to the center
without DOI
without DOI
with DOI
Center of the FOV
with DOI

Results TOF+DOI

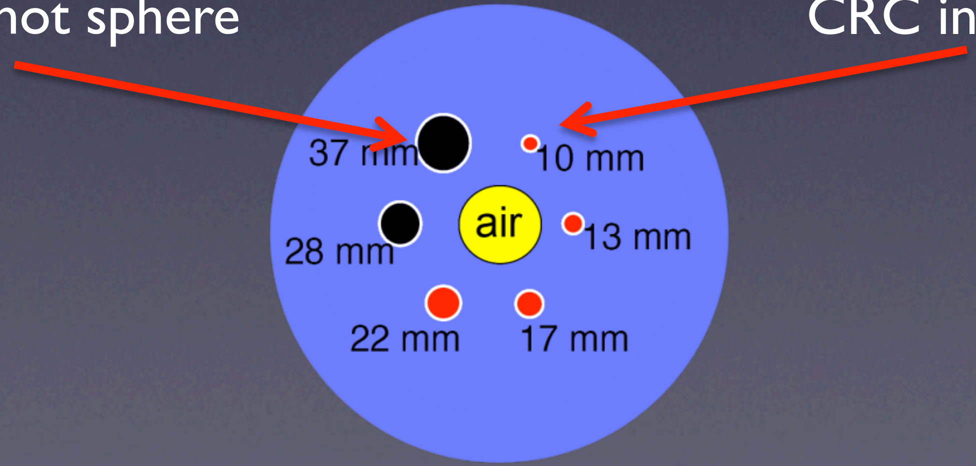
CRC/SNR (LM-OSEM 1 subset 70 iterations)





CRC in the biggest hot sphere

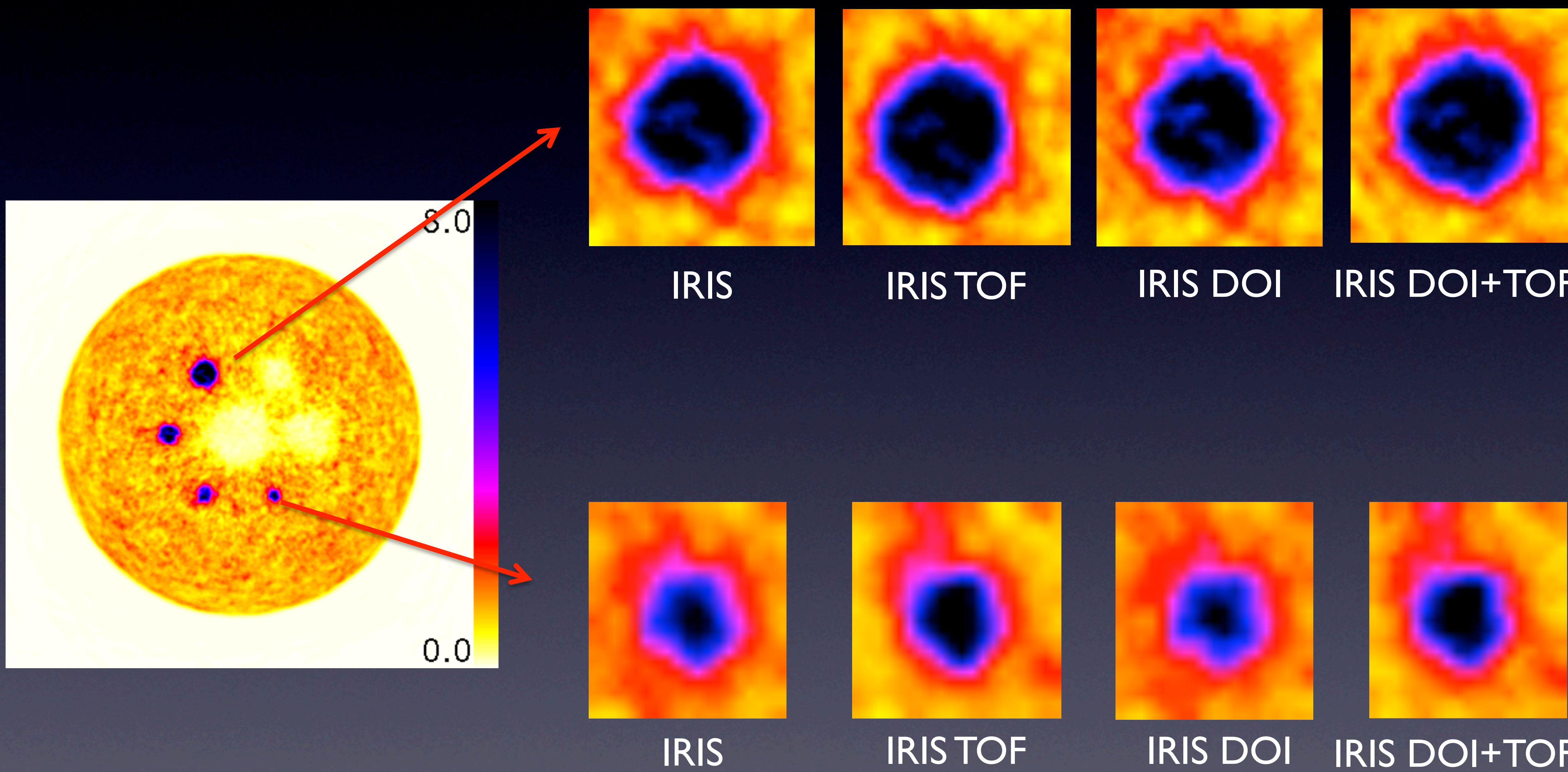
CRC in the smallest hot sphere



Results TOF+DOI

Image Quality

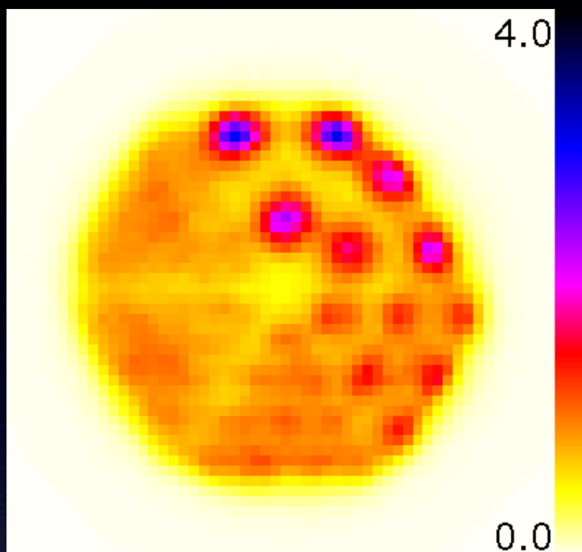
Reconstructed image for the same SNR (=4.5)



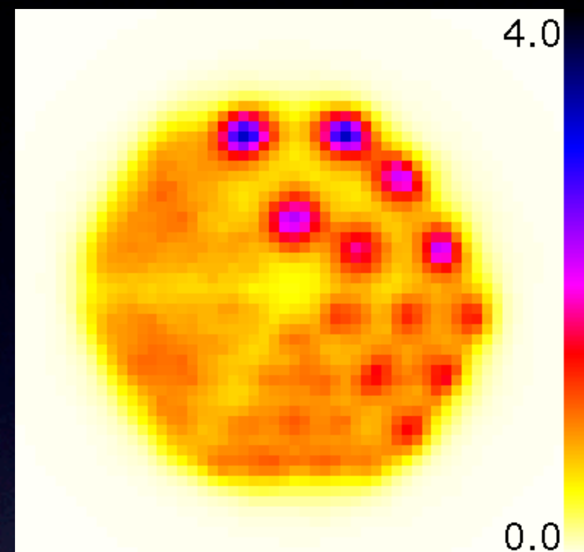
Results TOF+DOI

Image Resolution

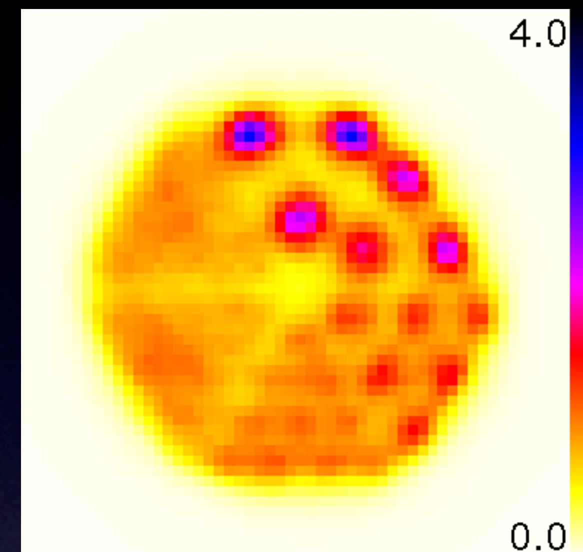
Centered miniature Derenzo (LM-OSEM 1 subset 15 iterations)



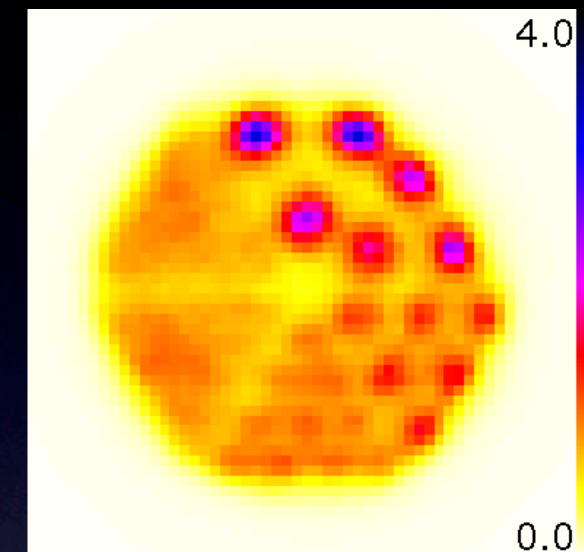
IRIS



IRIS TOF

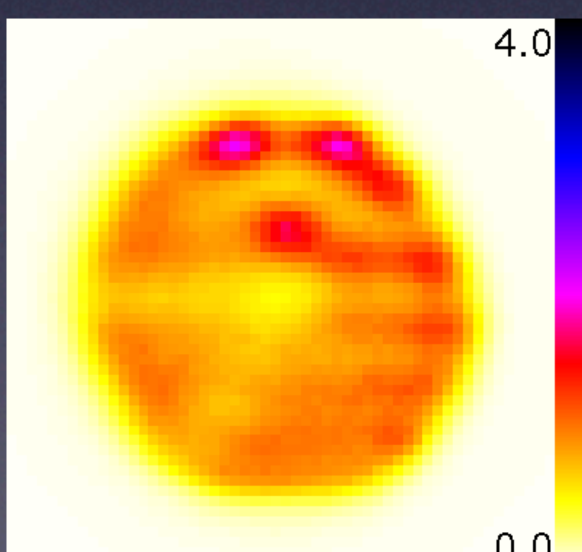


IRIS DOI

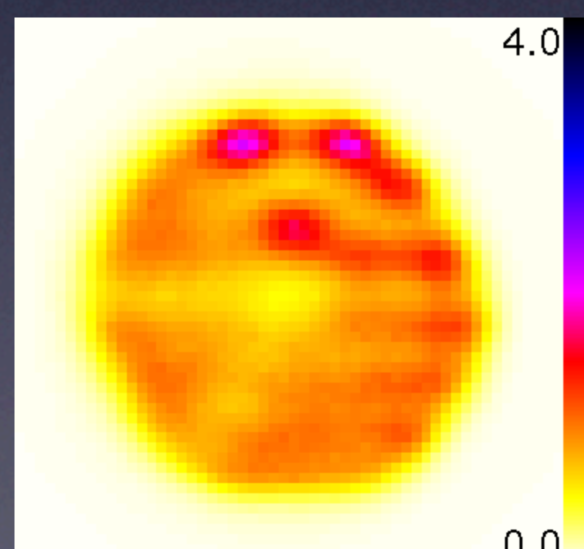


IRIS DOI+TOF

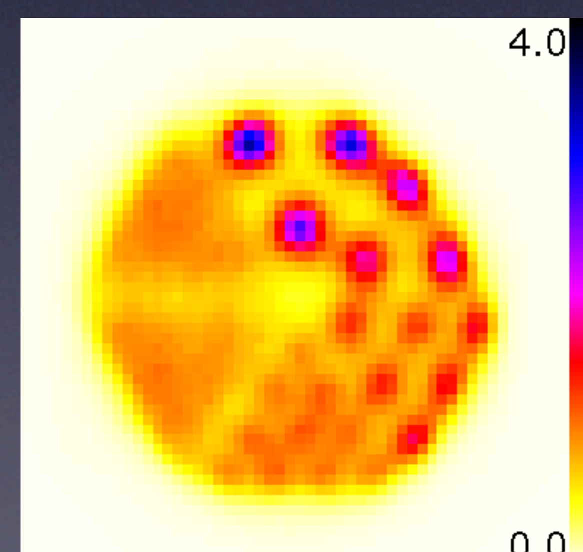
Shifted miniature Derenzo (LM-OSEM 1 subset 15 iterations)



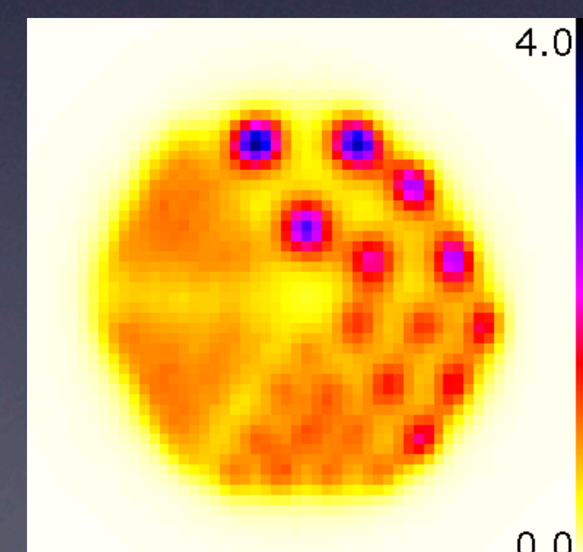
IRIS



IRIS TOF



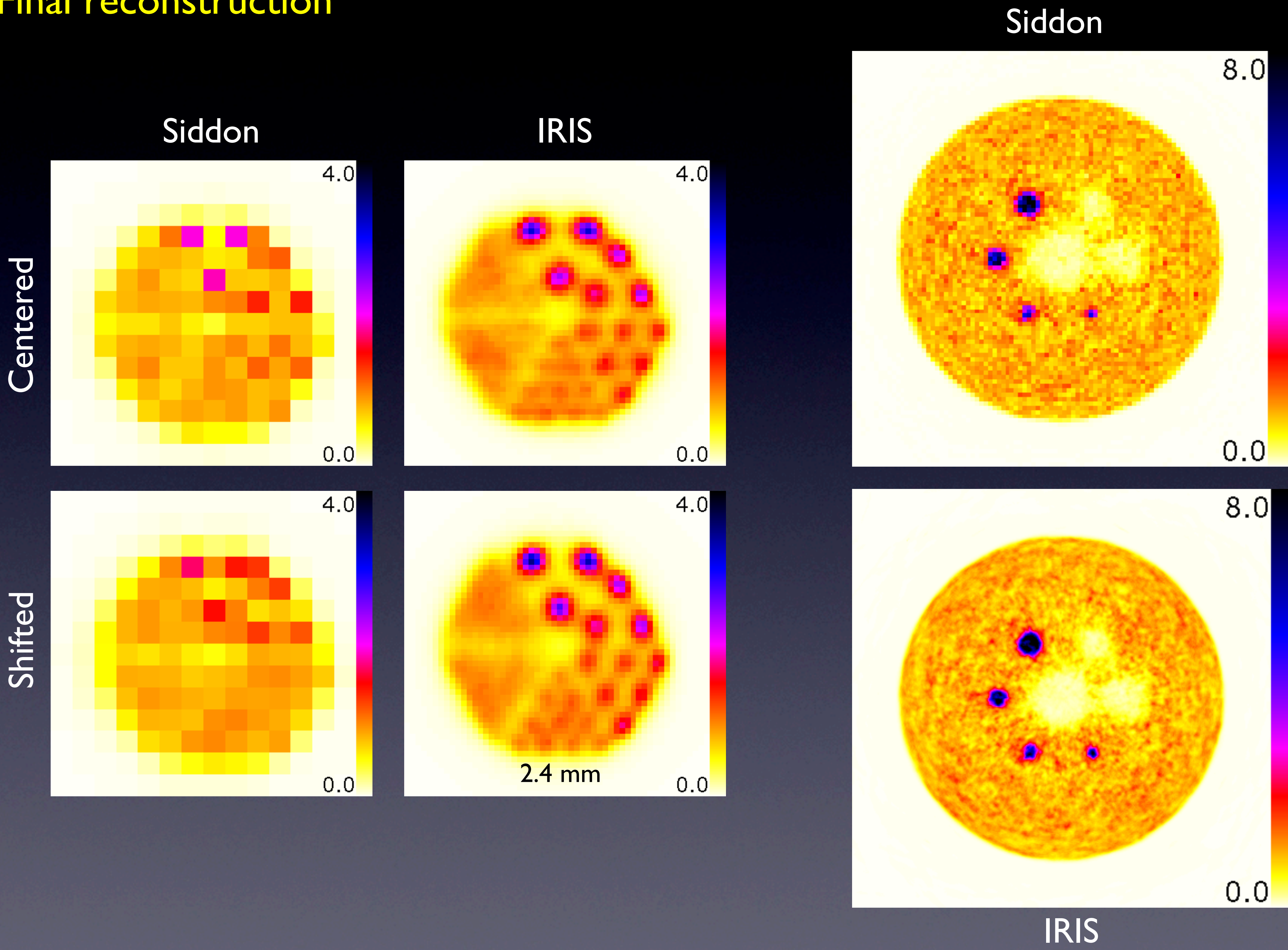
IRIS DOI



IRIS DOI+TOF

Results TOF+DOI

Final reconstruction



Conclusion

New IRIS projector including geometry, TOF and DOI:

- Accurate detector modeling
- Improved image quality and resolution
- TOF: improve image quality (SNR, contrast and convergence)
- DOI: improve image resolution (specially off center)
- Easy to perform on GPU (only need to draw simple lines)

Perspectives:

- Evaluation with different scanner geometry and resolutions of TOF and DOI
- Include other detector information (energy, …)

Thank for your attention

Awen AUTRET, Julien BERT, Olivier STRAUSS and Dimitris VISVIKIS
Laboratoire du Traitement de l'Information Médicale (LaTIM)
INSERM U1101, CHRU Brest