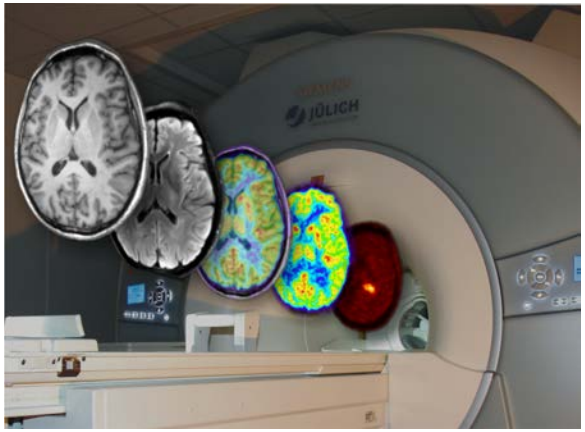


JÜLICH
FORSCHUNGSZENTRUM

# An Introduction to the Basics of PET Imaging

N. Jon Shah
Institute of Neuroscience and Medicine – 4
Research Centre Juelich
52425 Juelich
GERMANY

# Outline

Introduction

- *PET Basics*
- *Example Measurement*

Overview Processing Workflow

Required Data Corrections in Detail

- *Attenuation*
- *Randoms*
- *Normalisation*
- *Compton Scattering*
- *Decay & Deadtime Correction*
- *Calibration*

Mitglied der Helmholtz-Gemeinschaft

JÜLICH
FORSCHUNGSZENTRUM

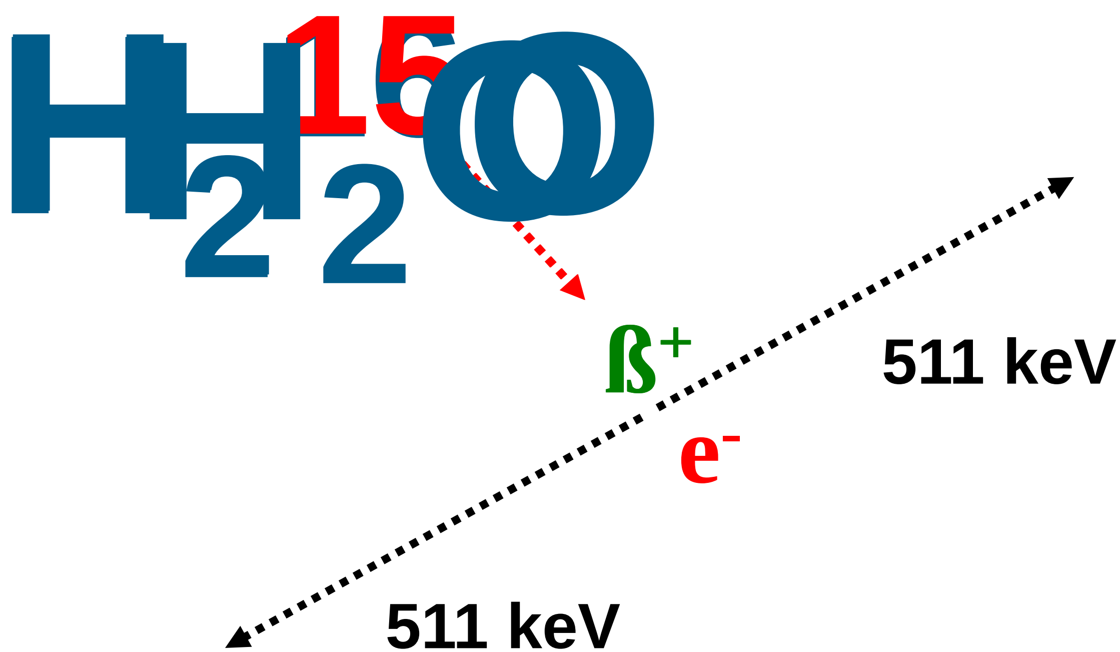
# Example of
# Functional Imaging Using PET

- **Mental activity needs energy.**
- **Substrates providing energy (glucose and oxygen) must be transported to the brain.**
- **This transport can be observed with PET.**

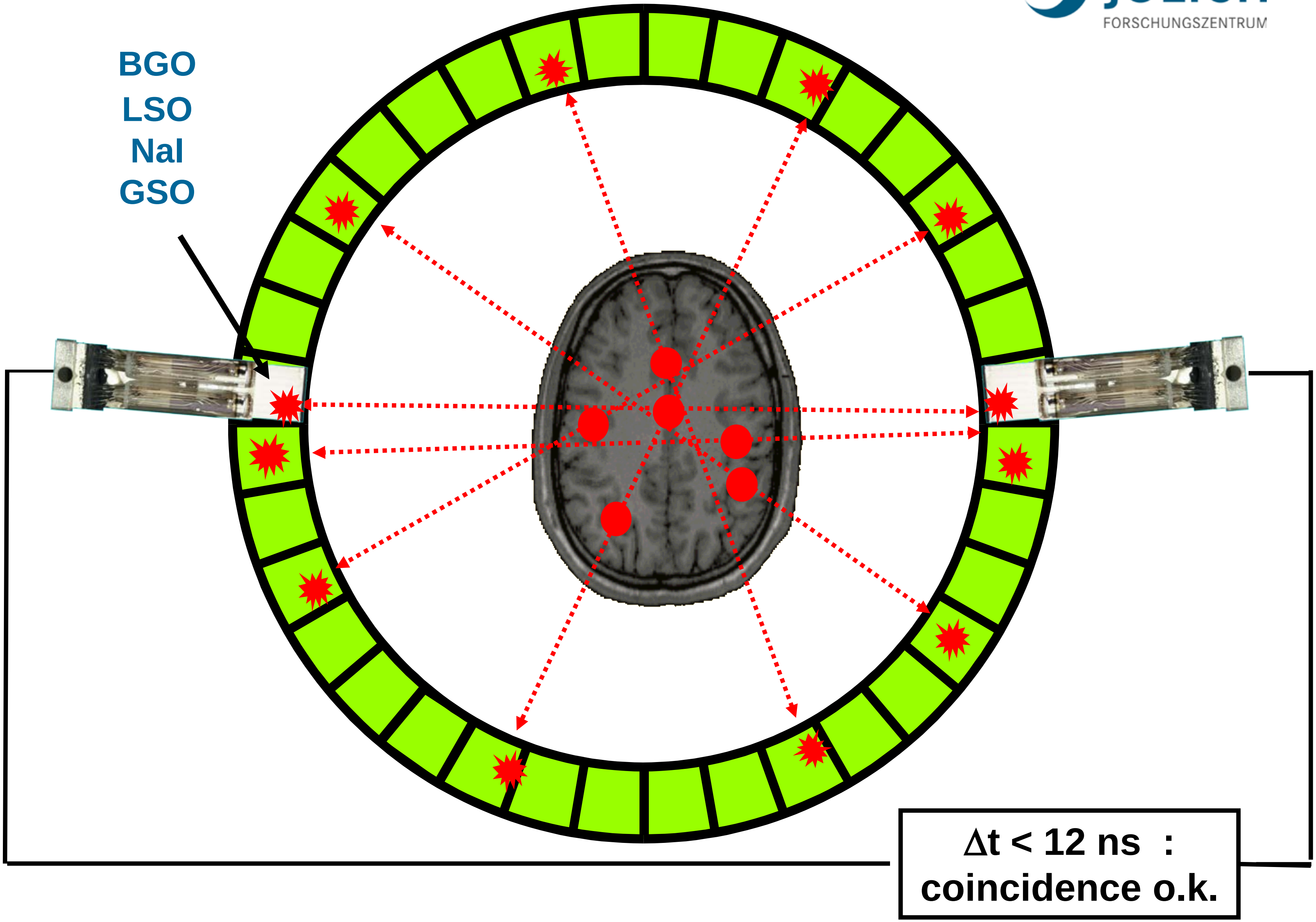
# Using „radiating“ water

# blood flow becomes visible

# Water is distributed within the body corresponding to blood flow



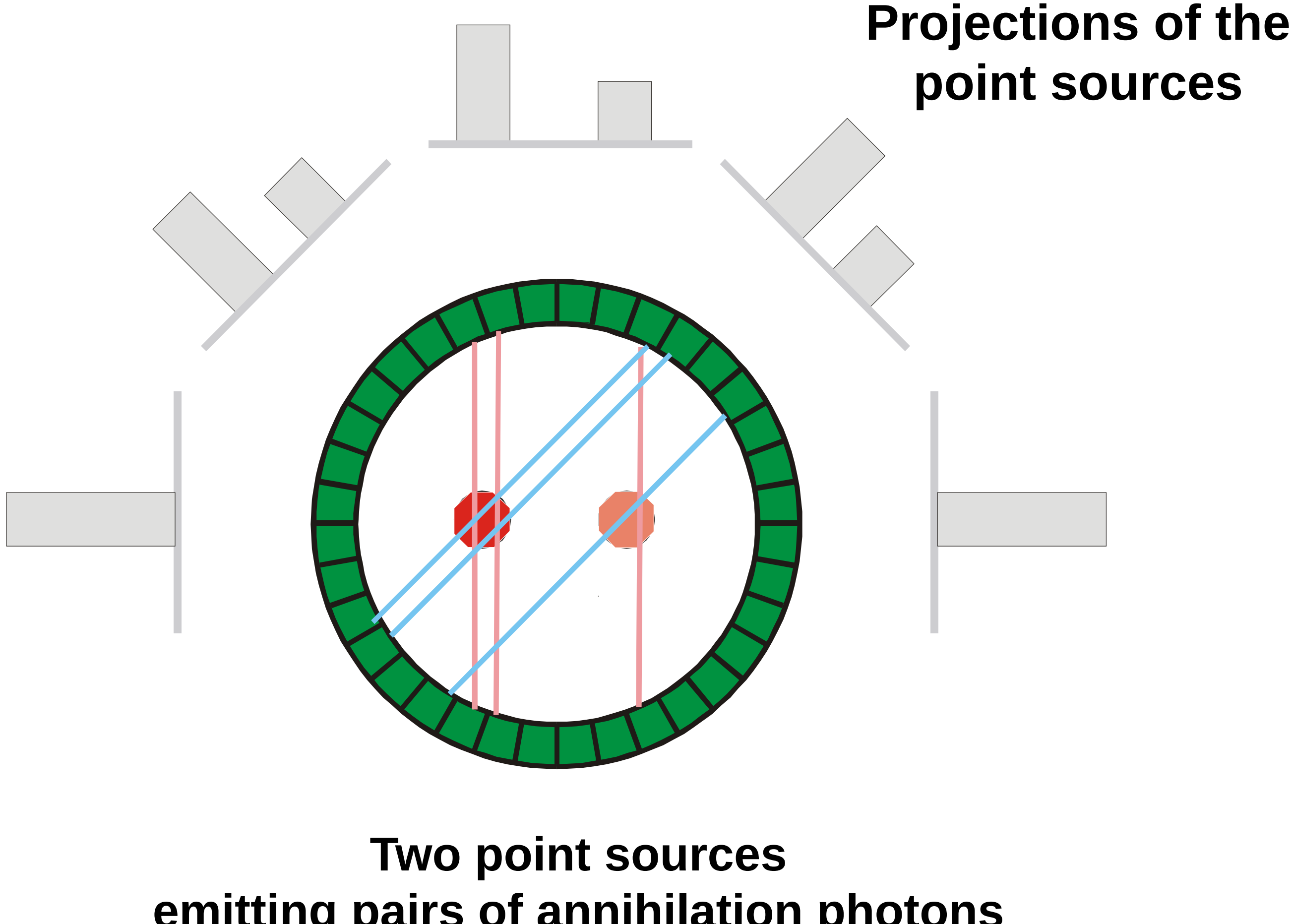

ECAT


BGO
LSO
NaI
GSO
Δt < 12 ns :
coincidence o.k.

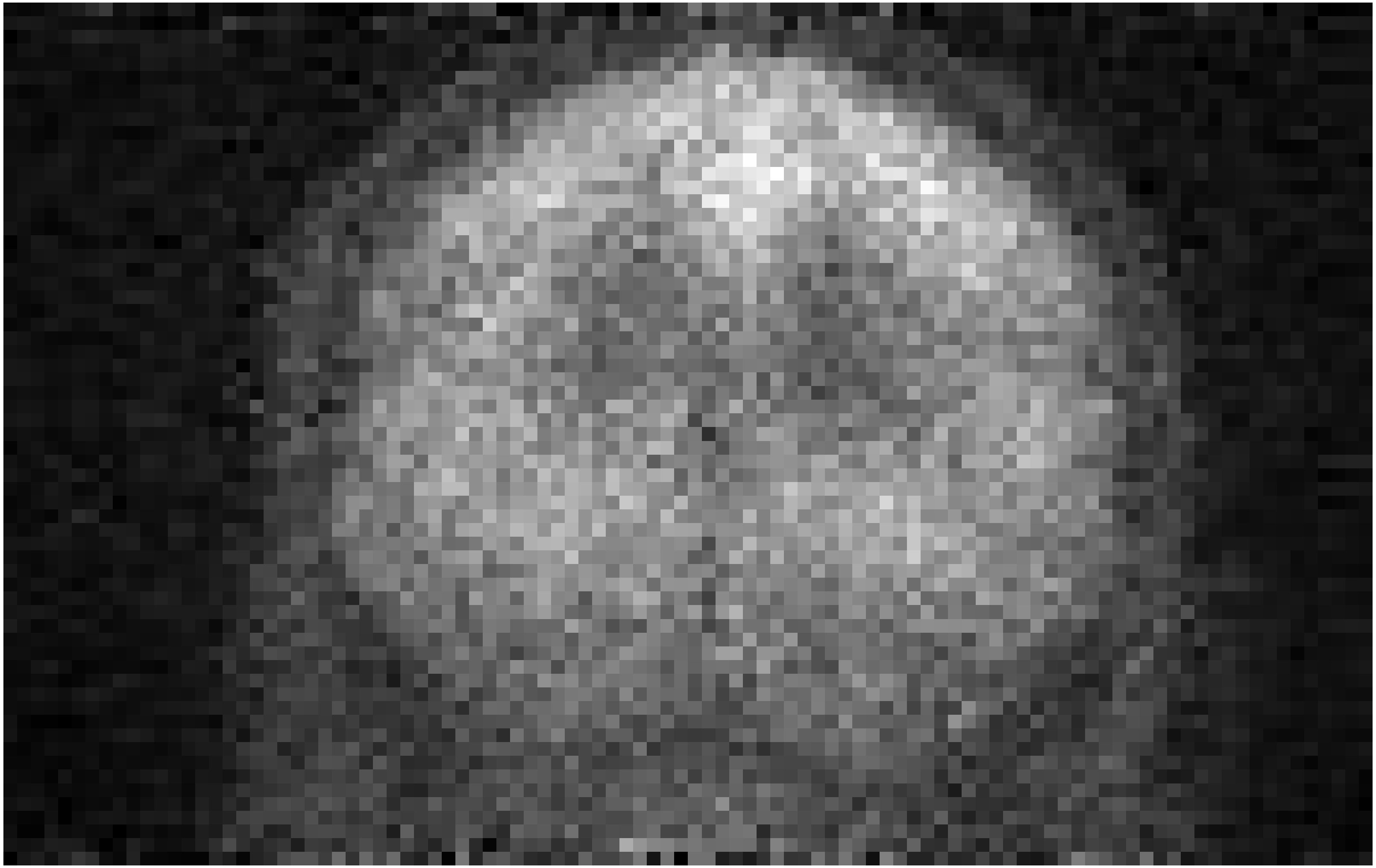
Mitglied der Helmholtz-Gemeinschaft

JÜLICH FORSCHUNGSZENTRUM

# The ring detector records pairs of annihilation photons by looking into the object from different views

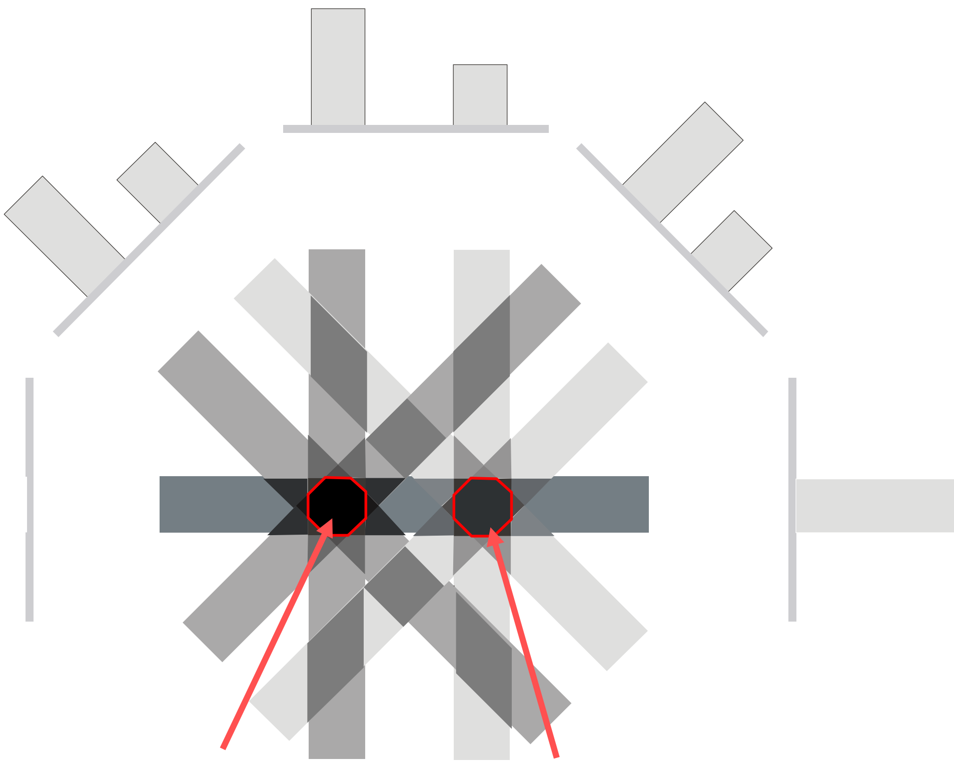


# Projections seen from around the head - activity used: $^{18}F$-fluoro-deoxy-glucose

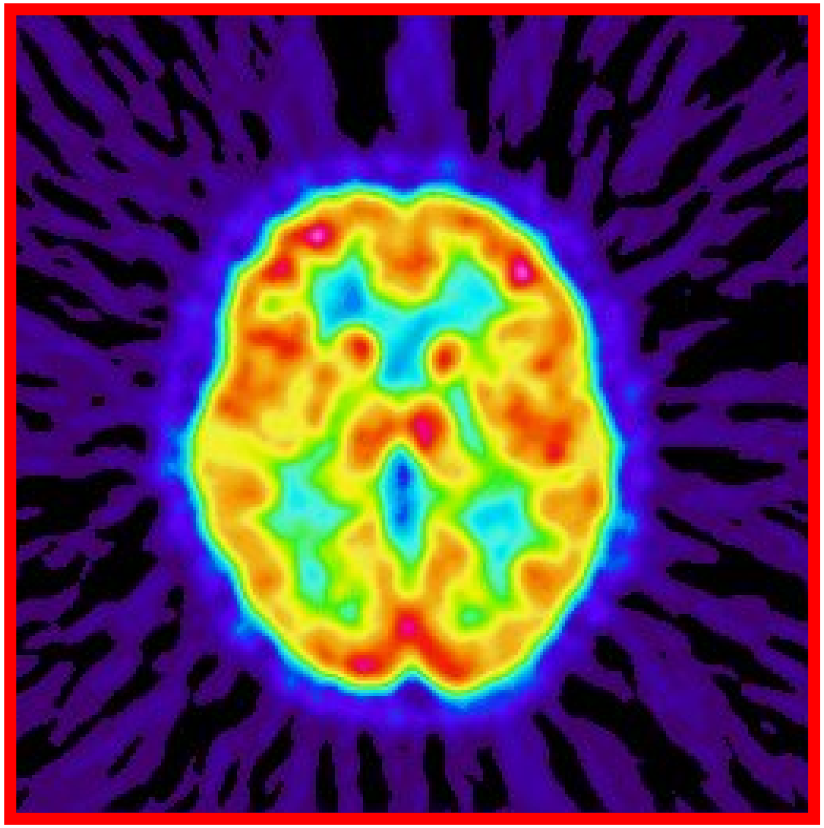


# Image Reconstruction:

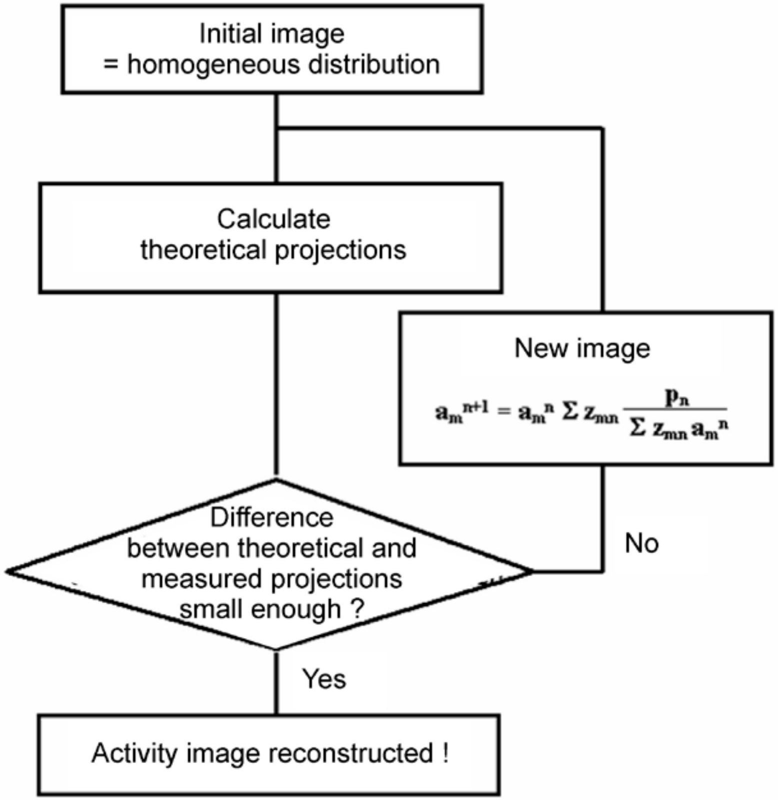
## Backprojection of the measured projection data and superposition



## Analytic Reconstruction by Filtered Backprojection



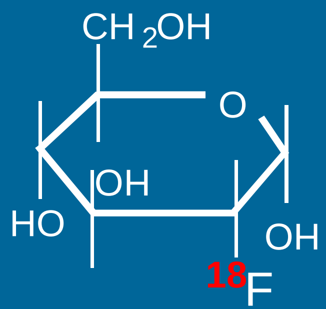
## Algebraic Reconstruction by Iterative Solving of Matrix System



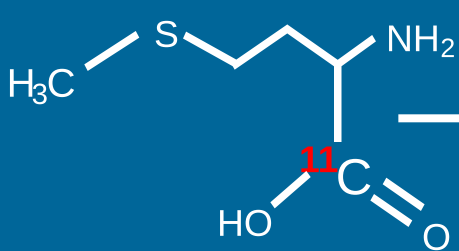
# Metabolic Functions Visualised by "Natural" Tracer Molecules Labelled with Positron Emitters

$H_2{}^{15}O$ → **Perfusion**

$^{15}O_2$ → **Oxygen Consumption**

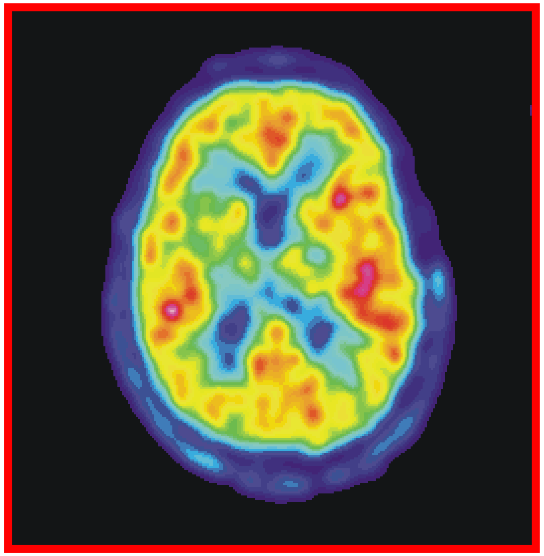



→ **Glucose Consumption**



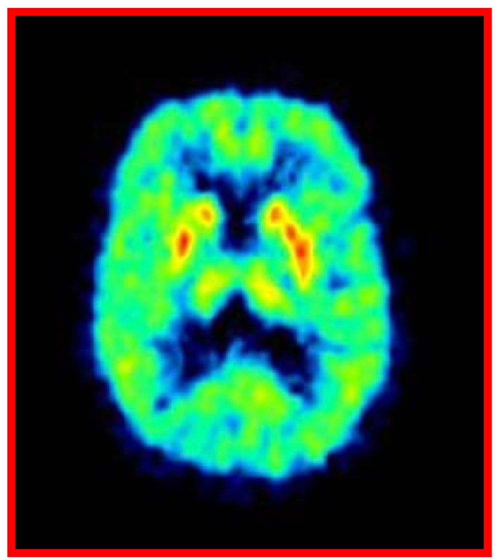

→ **Transport of Amino Acids**

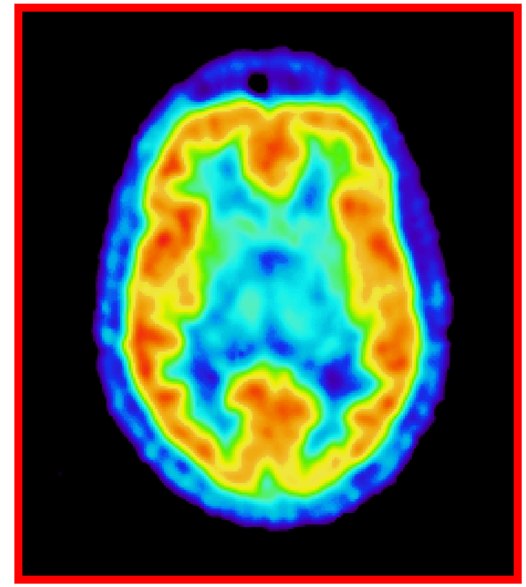
Visualised



**$H_2{}^{15}O$**
**Cerebral blood flow**

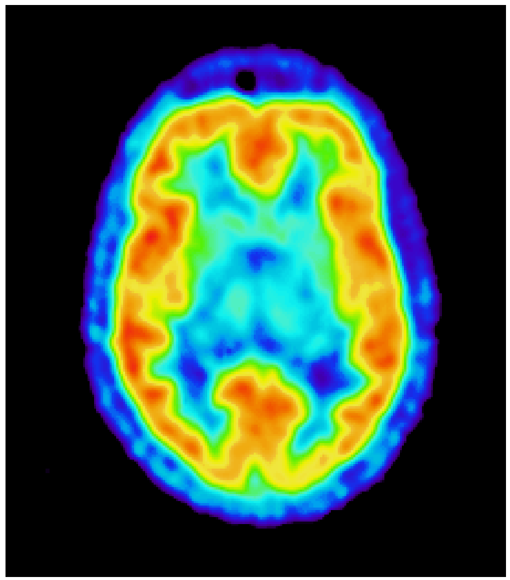
**$^{11}C$-SDZ GLC756:**
**dopamine**
**receptors**

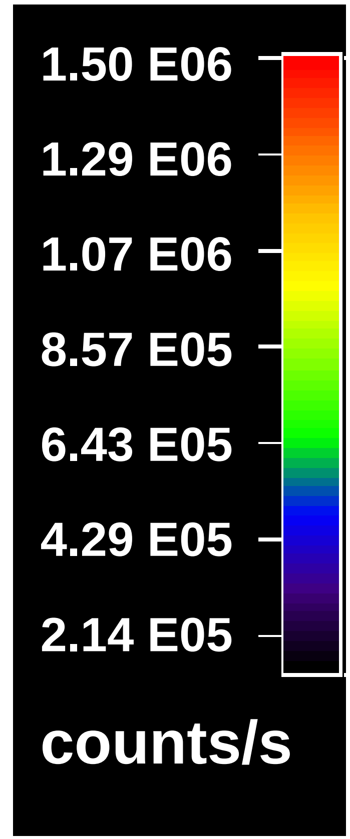




**$^{18}F$-Altanserin:**
**serotonin**
**receptors**

# Visualisation of Radioactivity

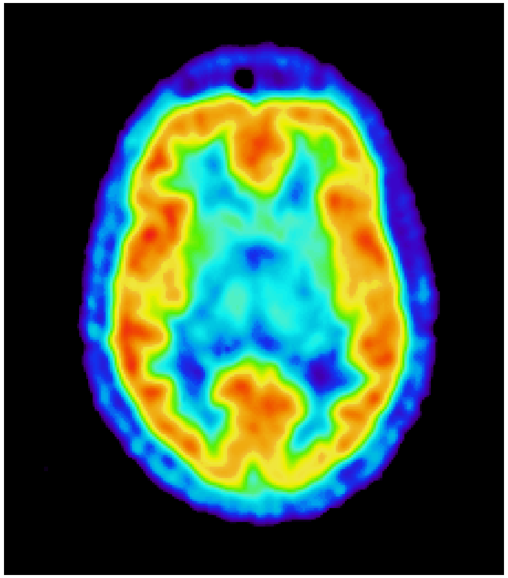




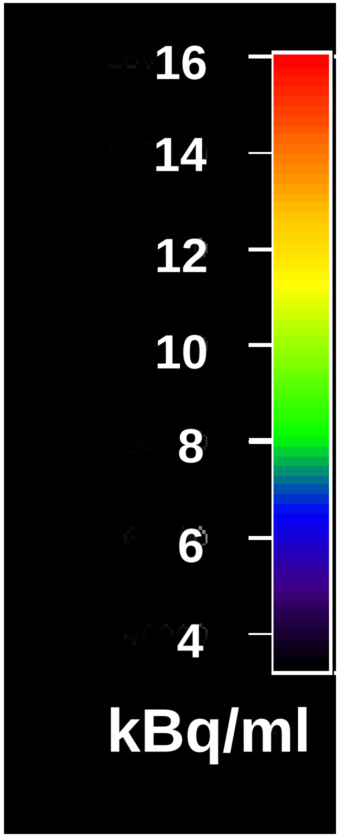

**$^{18}$F-Altanserin**

**⇨ serotonin receptors**

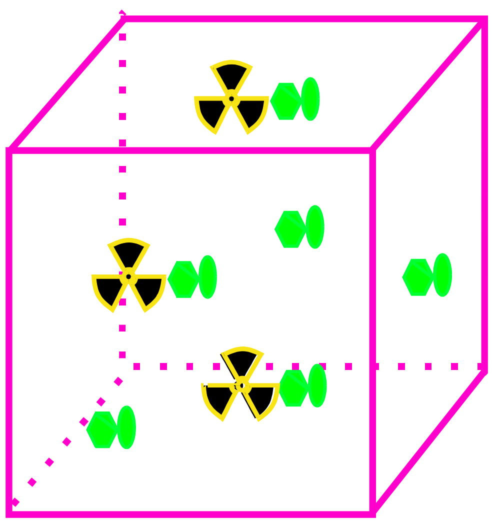
# Quantification of Radioactivity Concentration



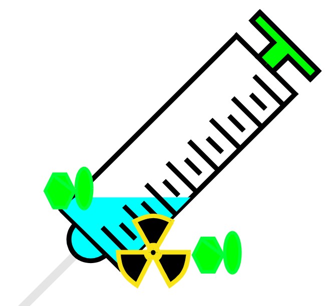
Measurement of $^{18}$F-altanserin uptake



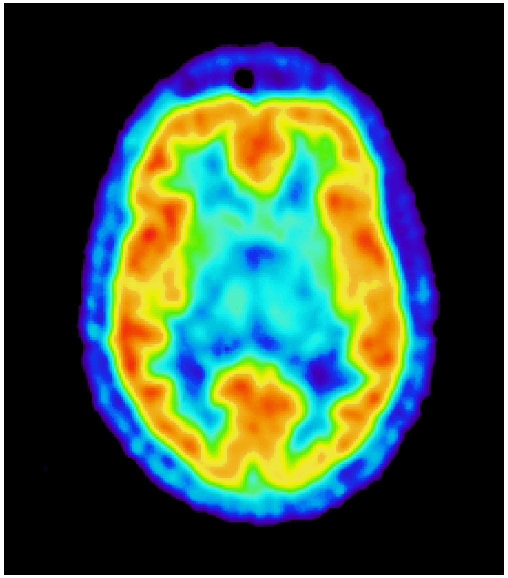
# From Radioactivity Concentration (kBq/ml) to Mass Concentration (µmol/ml)



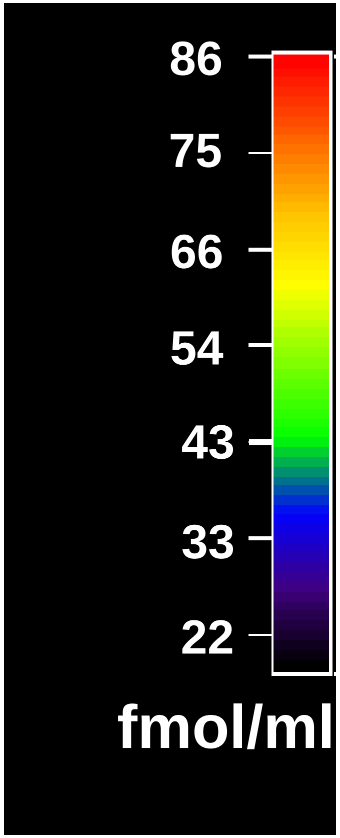
$$\frac{m_{Tissue}}{c_{PET}} = \frac{m_{Syringe}}{c_{Syringe}}$$



# Quantification of Mass Concentration

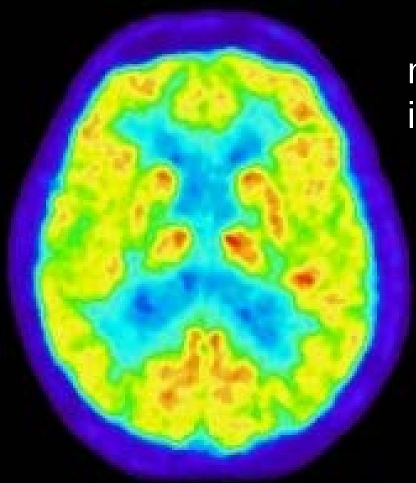


Measurement of altanserin concentration

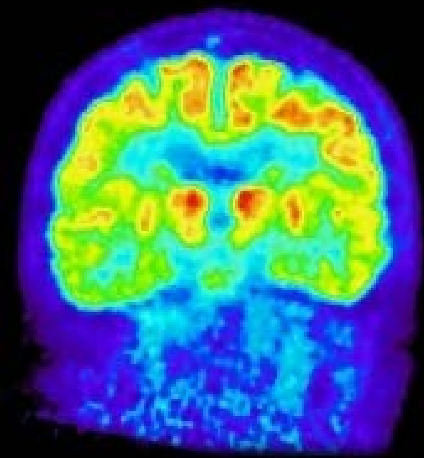


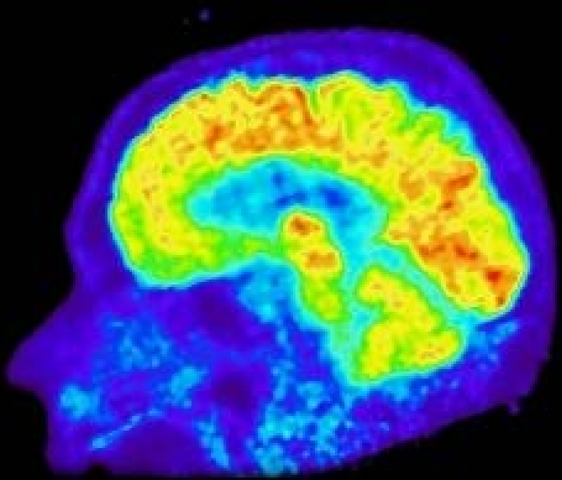
# Simultaneous PET-MR patient measurements

**$^{18}$Flour-Deoxy-Glucose-PET**



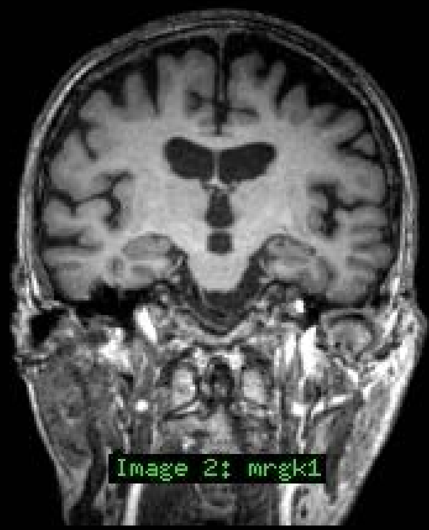
metabolic
information



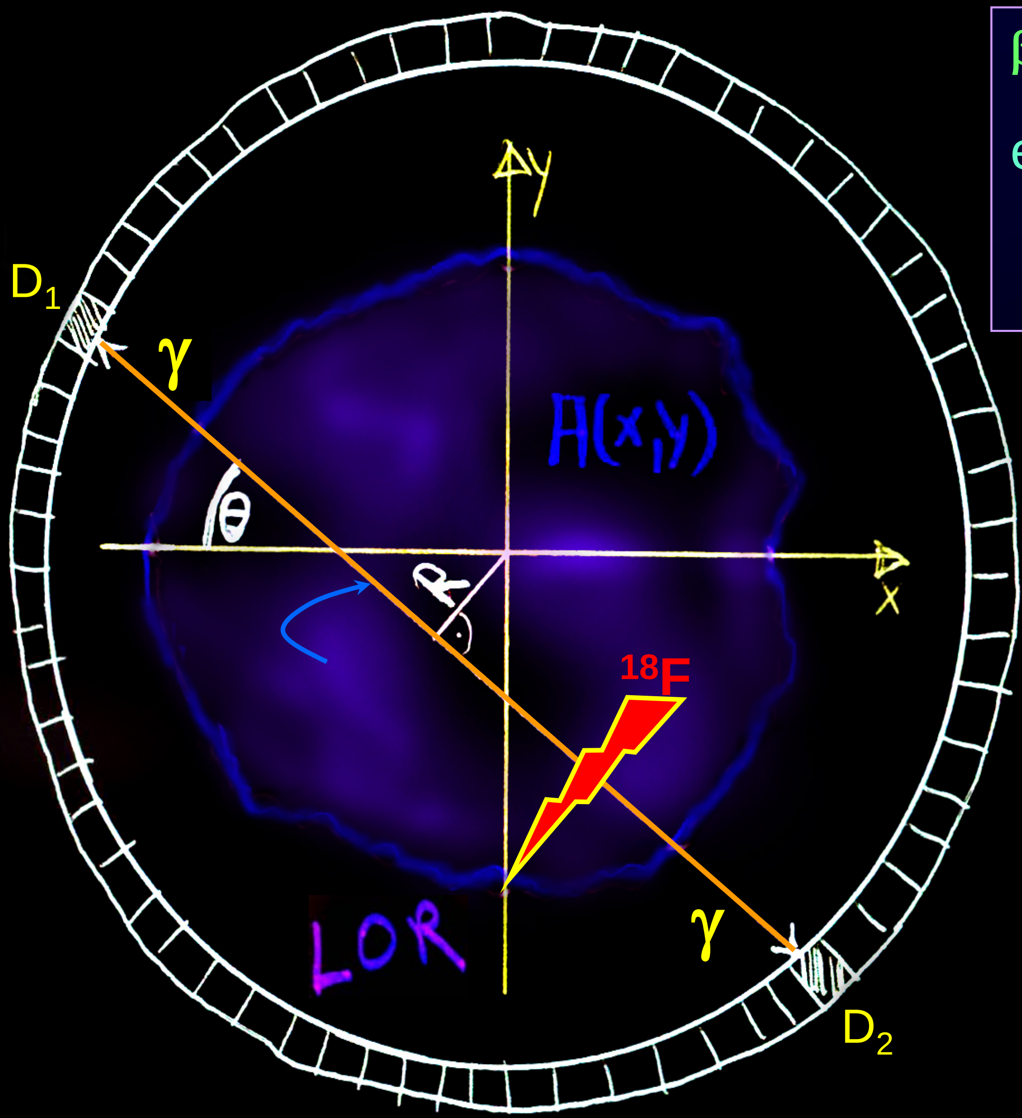


**simultaneous MR (T1 MPRAGE)**

anatomical
information




## First Principle: Positron-Emission-Tomographie (PET)




β decay process of metabolic tracer:

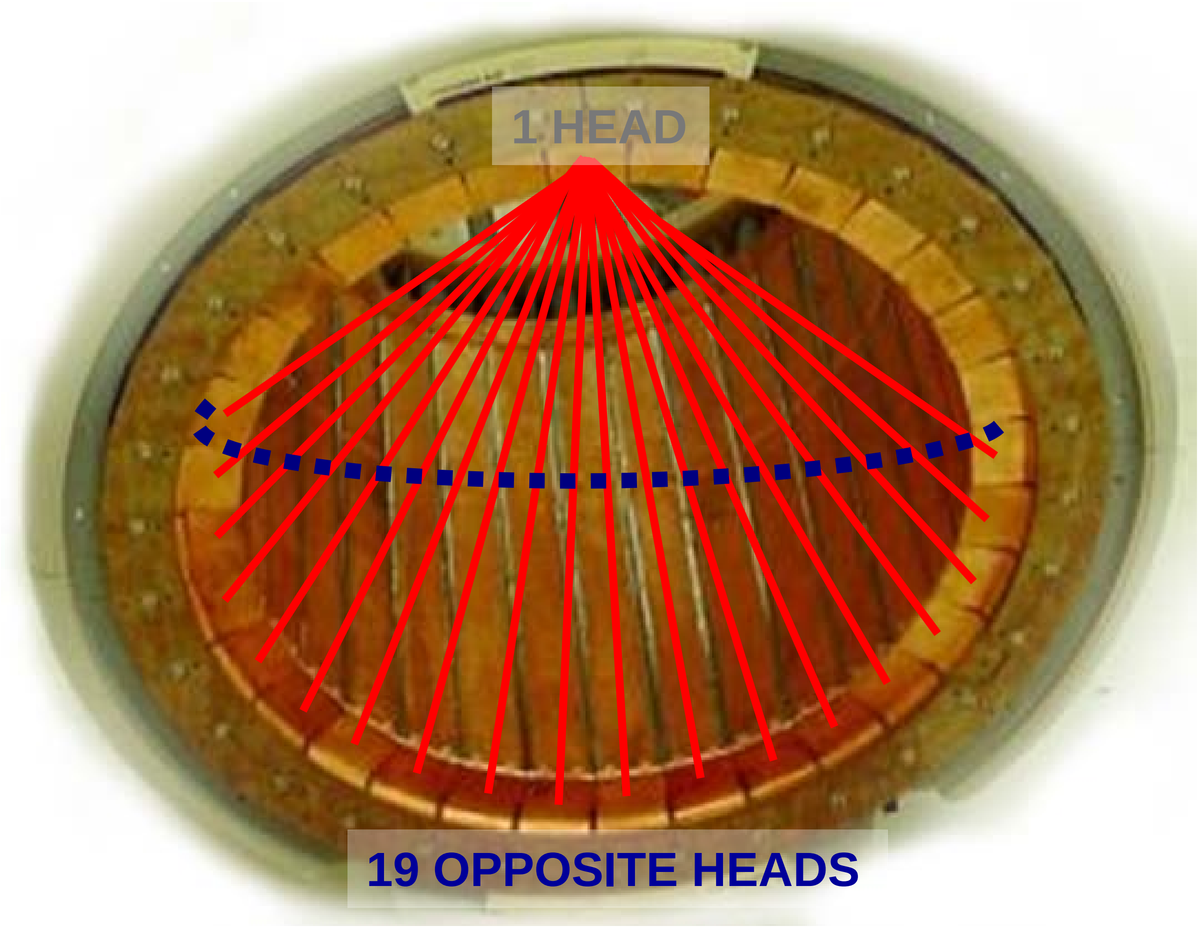
e.g.: $^{18}F$ --> $^{18}O$ + $e^+$ + $\blacksquare_e$

$e^+$ $e^-$ --> γ

detector combination ( $D_1$ , $D_2$ )

line of response (R, θ)

# 3D data acquisition



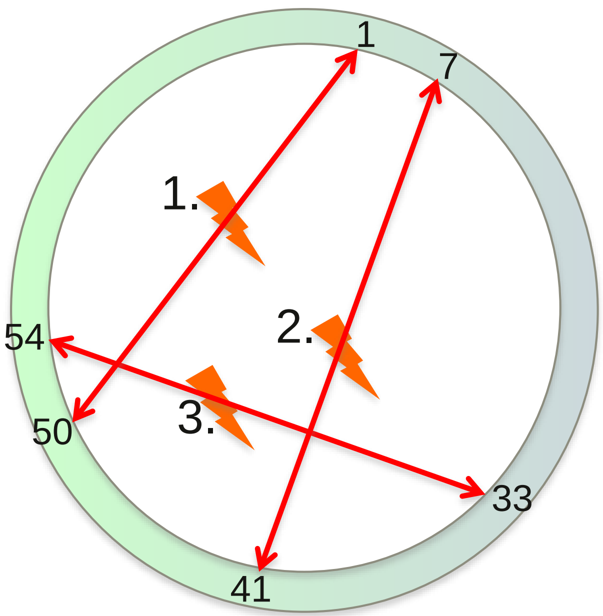

144 crystals / block
6 blocks / modul
32 moduls

→ **27648 detector crystals**

→ **227 million detector combinations (Lines-Of-Response)**

# BrainPET Data Formats (I)

**List Mode (LM) Data:**
list of detected coincidences
in chronological order




store pairs of detector numbers

1. event: ( 1 ,50)
2. event: ( 7 ,41)
3. event: (33,54)


additional tags are periodically inserted:

- time tags
- count rate tags
- external trigger tags

# BrainPET Data Formats (II)

**List Mode (LM) Data**

event ( 1, 50)
event ( 7, 41)
$t_1$
event (33, 54)
event (29, 52)
event (17, 20)
event ( 1, 50)
x
x
x
$t_2$
event (33, 54)
x
x

select data
of specific
period of time
(time frame)

List Mode
Sorter

**Line-of-Response (LOR) Data:**
sum of detected coincidences
for any detector pair

( 0, 50) --> #0
( 0, 51) --> #0
( 0, 52) --> #2
......
( 1, 50) --> #1
.....
.....
(33, 54) --> #2
.....
.....

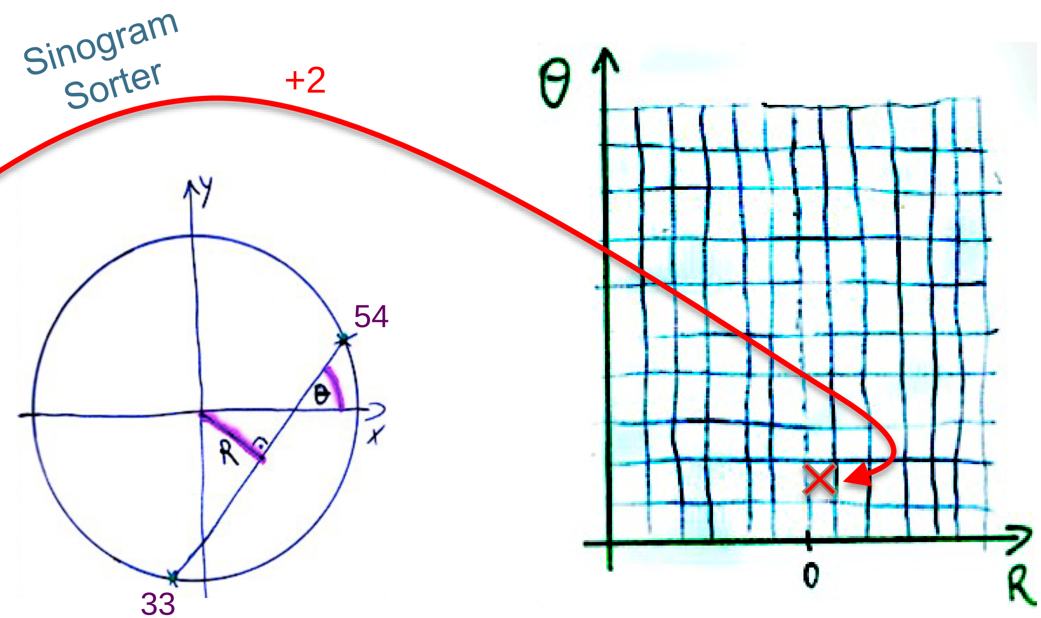
230 million
detector pairs

# BrainPET Data Formats (III)

**Sinogram Data:**
geometrical sorting
of LOR data into projections

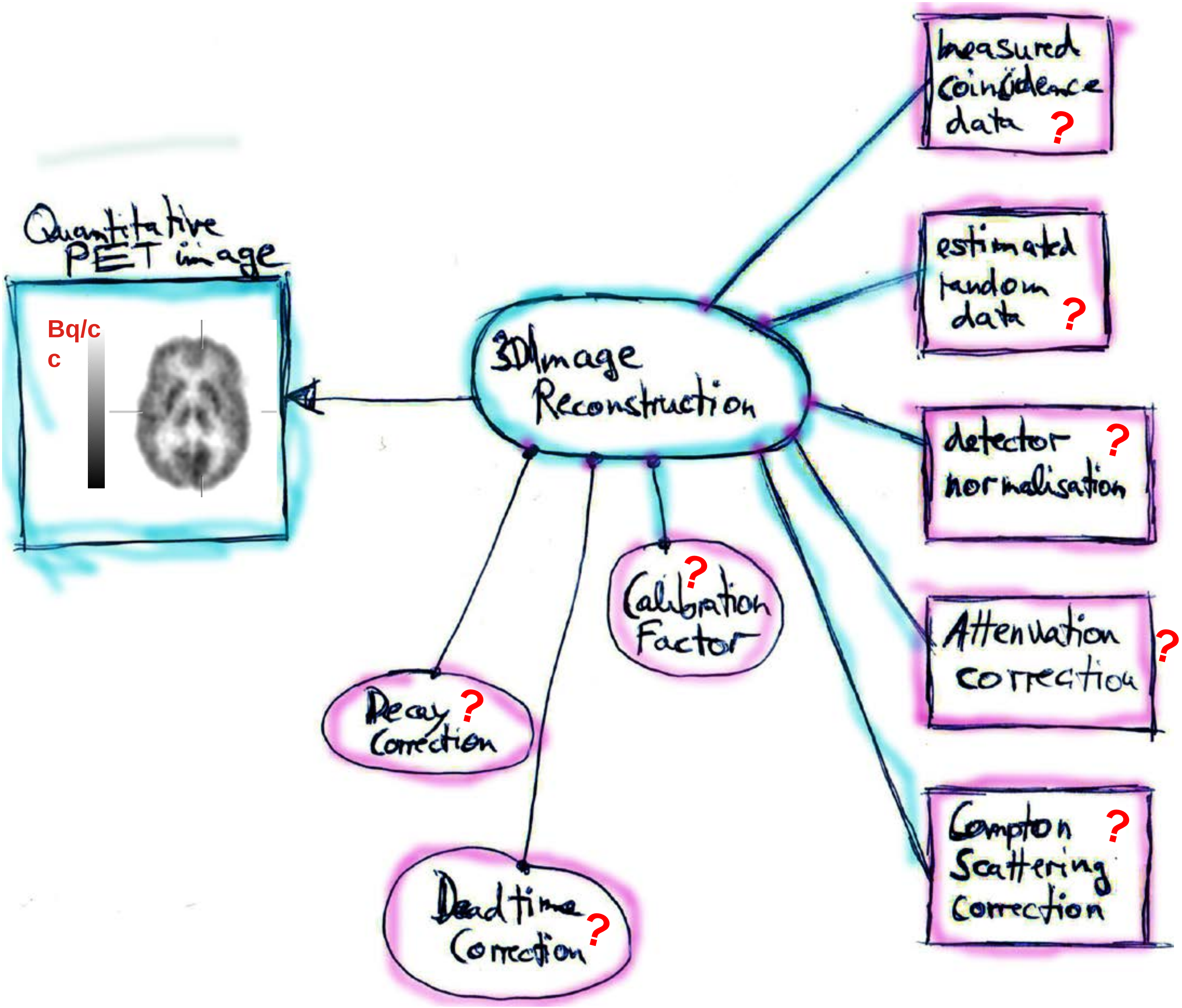
**LOR Data**

( 0, 50) --> #0
( 0, 51) --> #0
( 0, 52) --> #2
......
( 1, 50) --> #1
.....
.....
(33, 54) --> #2
.....
.....

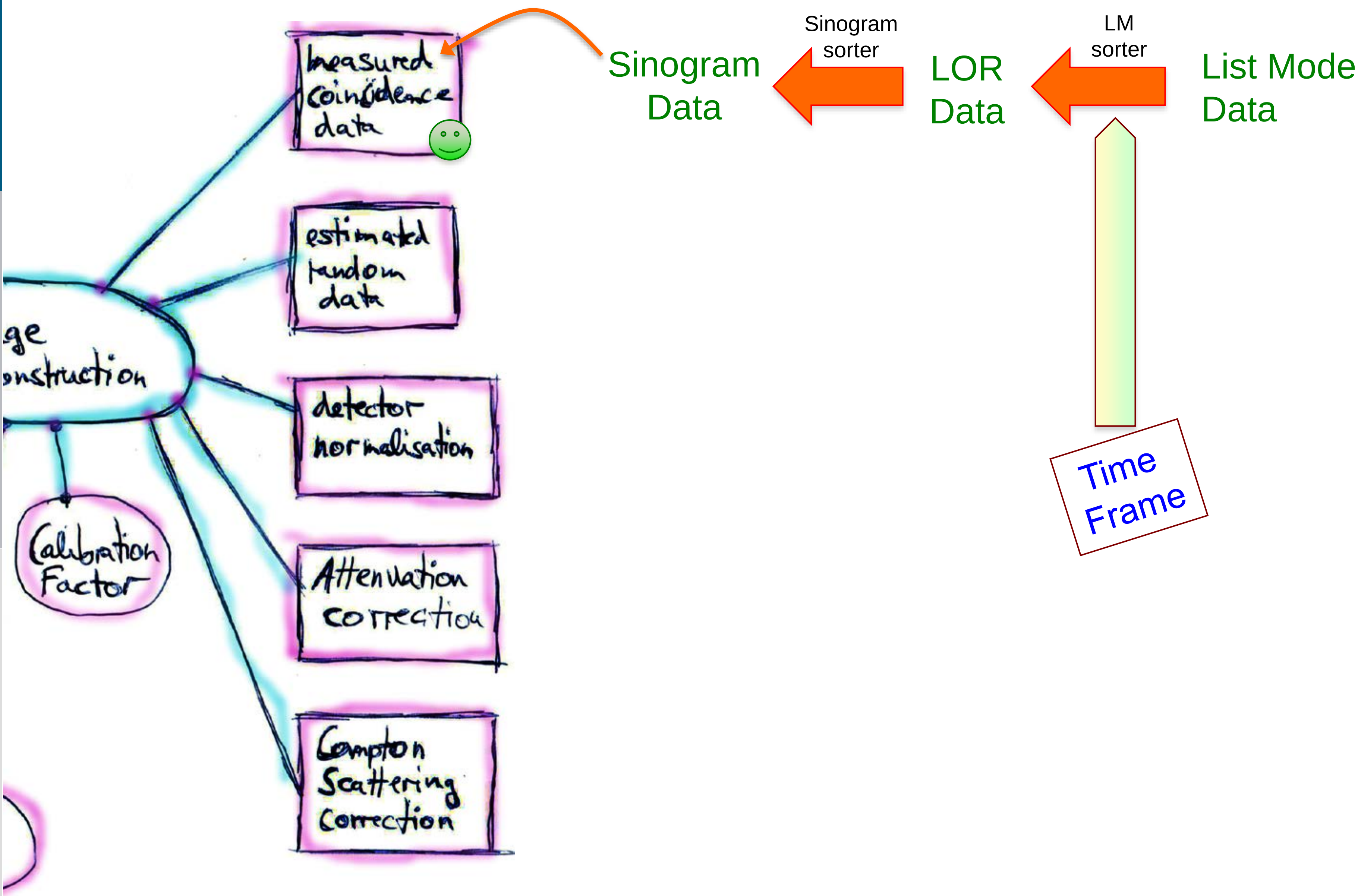



$\{ D_1, D_2 \} \rightarrow \{ R , \theta \}$

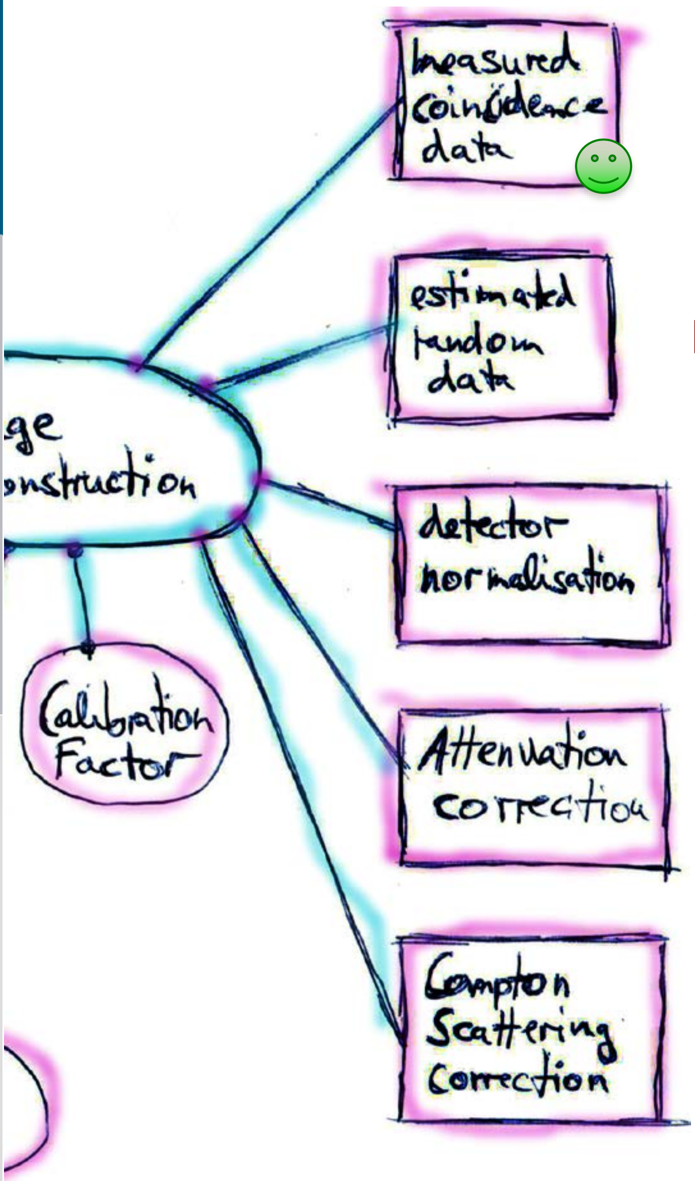
# Inputs for Quantification



# Measured Coincidence Data (Prompts)

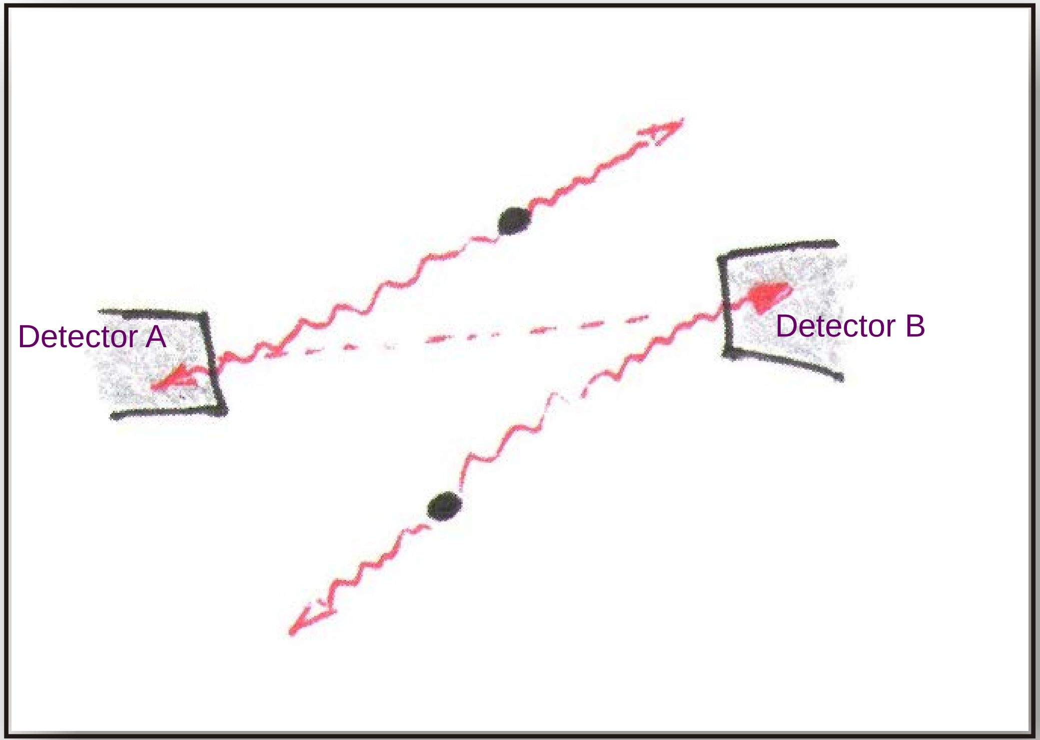


# Estimated Random Data




**Randoms Correction ??**

# Unavoidable Random Coincidences



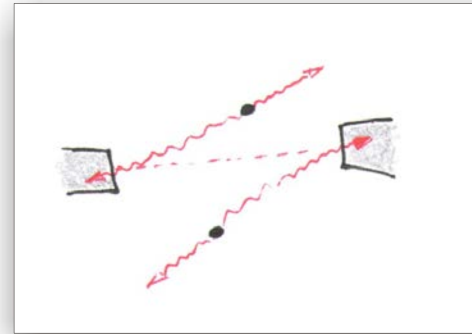

Events (measured) = Events (true) + Events (random)

(signal)

(background, exact value unknown)

# Probability of Catching Randoms

- **Expected Rate of Randoms**



$$R_{AB} = 2\,\tau\,S_A\,S_B$$

R : Random Rate for Detector Pair (A,B)

$S_A$, $S_B$ : Single Count Rates of detectors

$\tau$ : Coincidence Timing Window (12 ns)

- **Direct Measurement: "*Delayed Window*"**

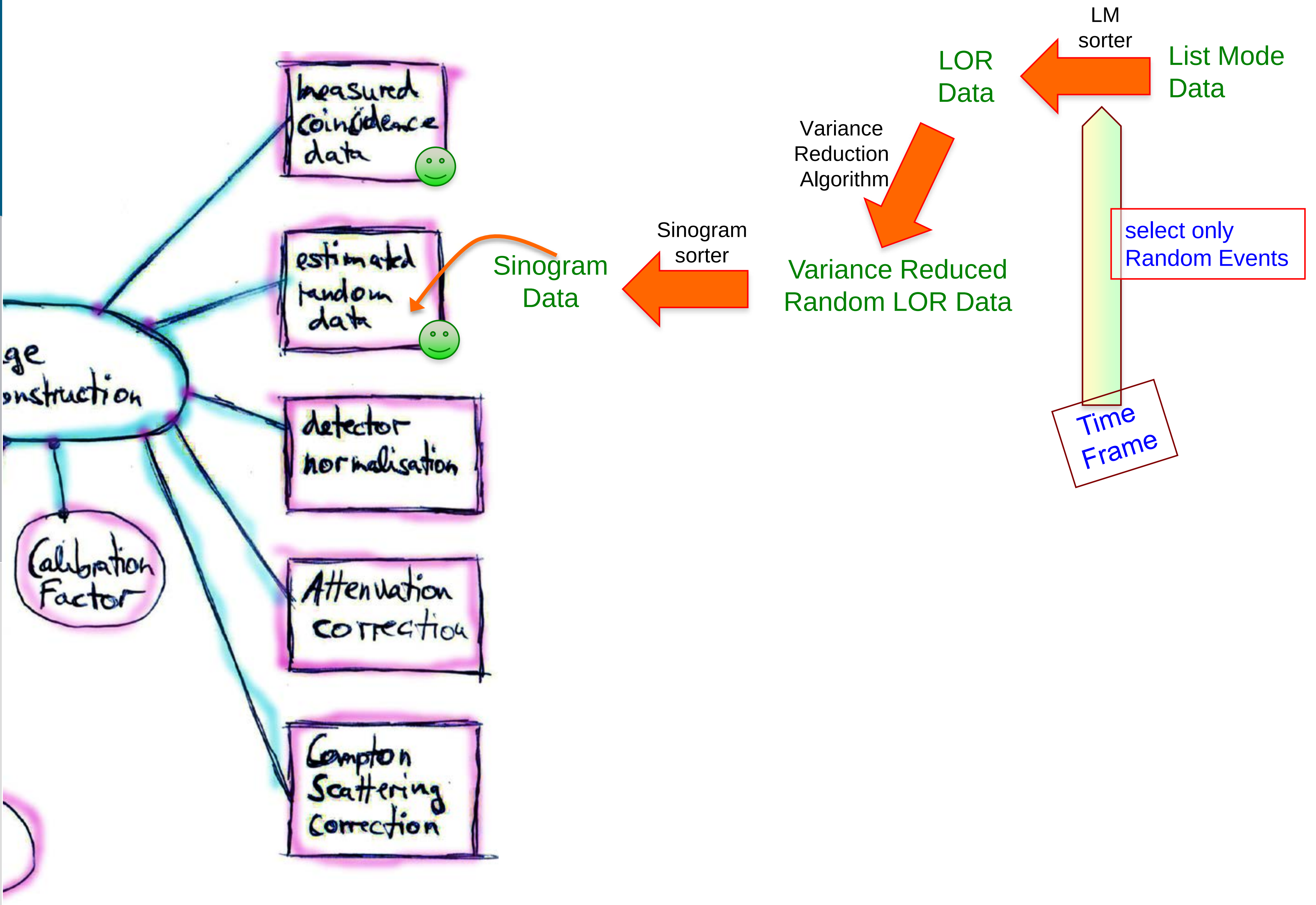
Acquire Pseudo Coincidences due to Timing Offset $T_{off}$

true coincidences: $| t_a - t_b | < \tau$

random coincidences: $| t_a - t_b + T_{off} | < \tau$

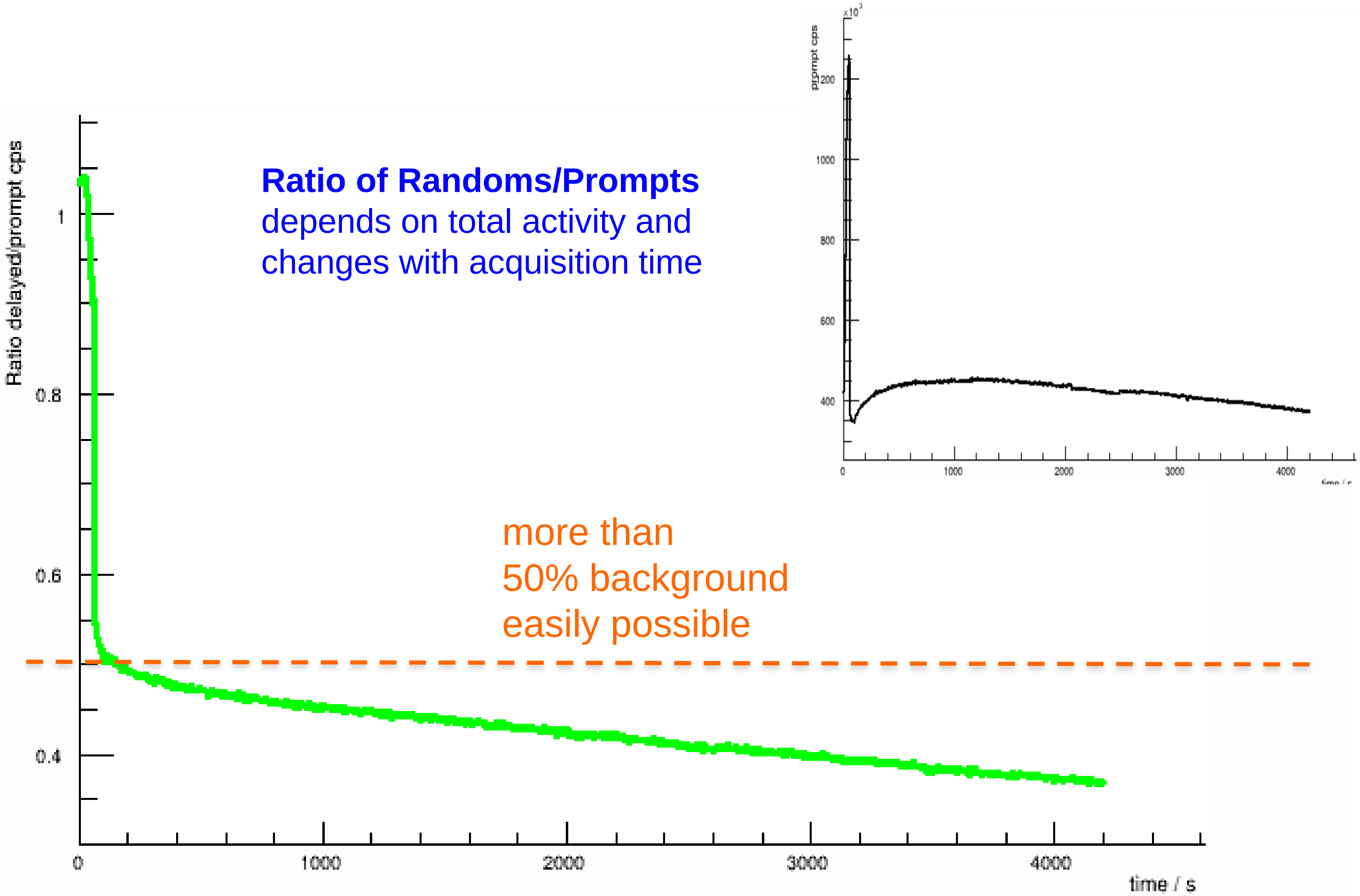
Detected Random Coincidences
also inserted into List Mode Stream during Acquisition

# Estimation of Randoms



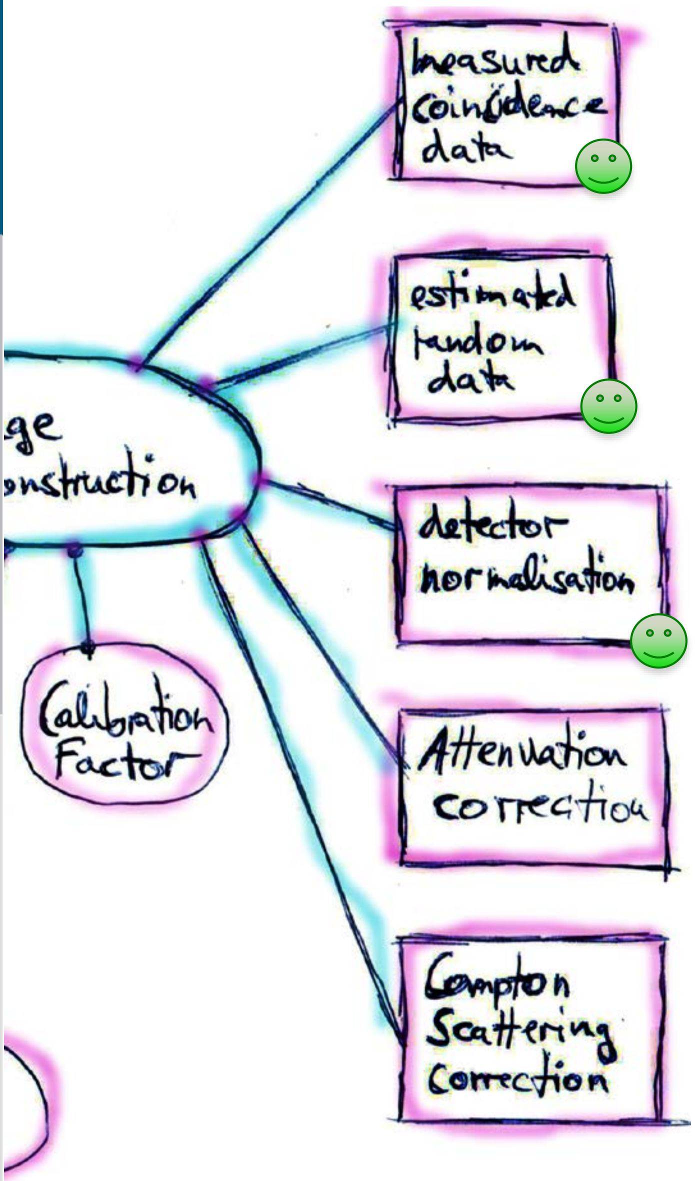
# Example: Patient Measurement

**Ratio of Randoms/Prompts**
depends on total activity and changes with acquisition time




more than
50% background
easily possible

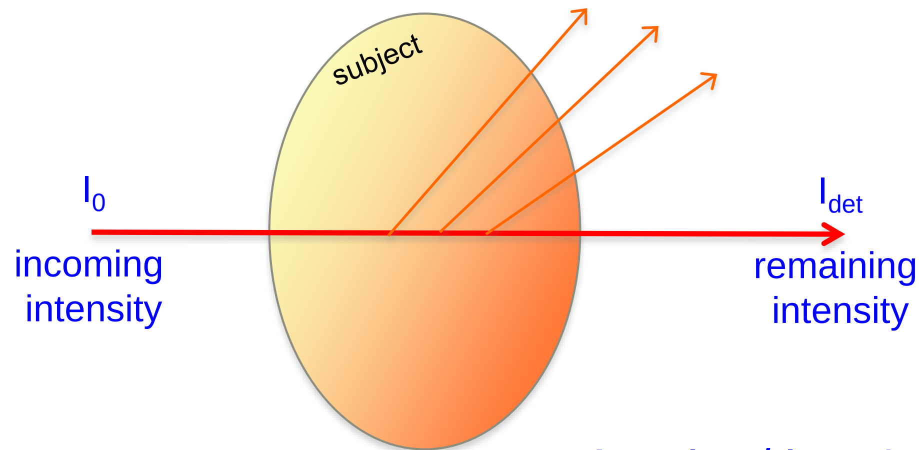
# Attenuation




**Attenuation ??**

# Attenuation

Subject & any material causes attenuation of emitted radition



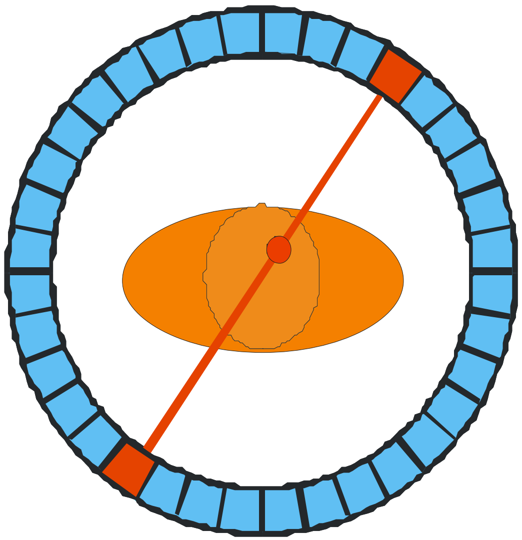

$A_x = I_{det} / I_0 < 1$

$A_x$ mainly depends on electron densities along path

Compton scattering is the dominant effect causing attenuation
(deflection of radiation)

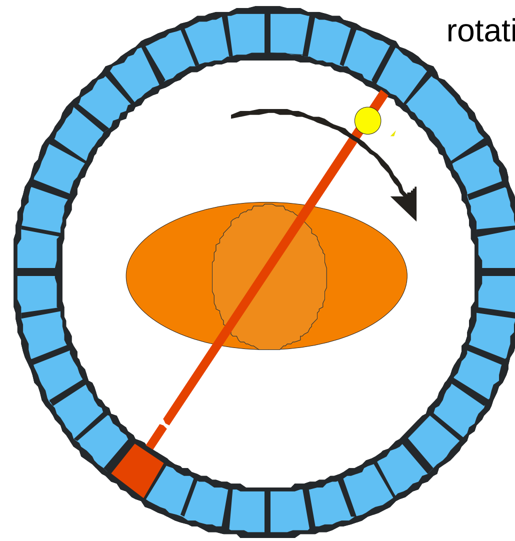
# Attenuation Correction (direct measurement)

Emission Measurement



$$I_{LOR} = \int A(x,y)\, dl \; * \; ACF_{LOR}$$

Transmission Measurement




$$ACF_{LOR} = \exp\left( - \int \mu\,(x,y)\, dl' \right)$$

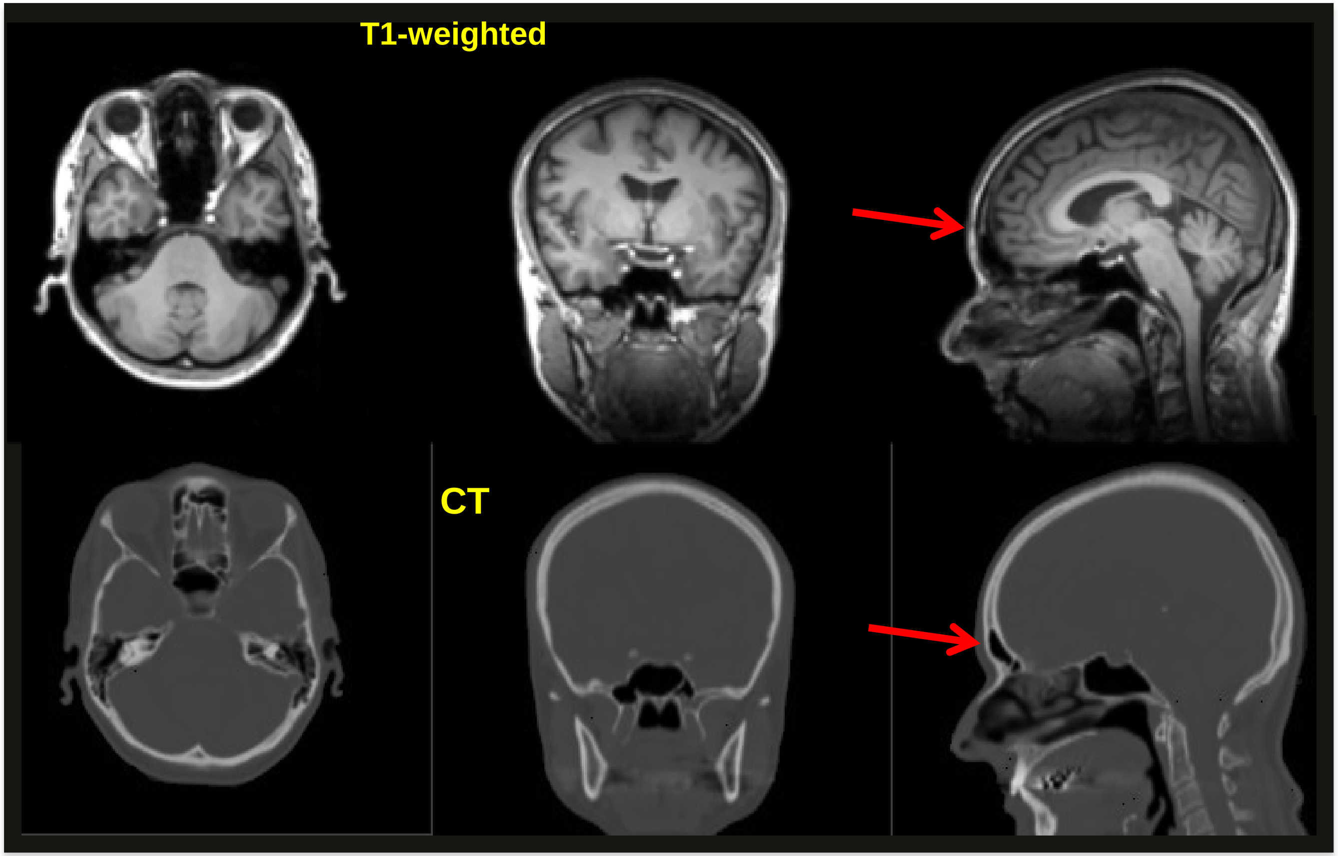
ACF → attenuation correction factor
A → activity distribution
μ → attenuation values

# Attenuation Correction (from MR measurement)

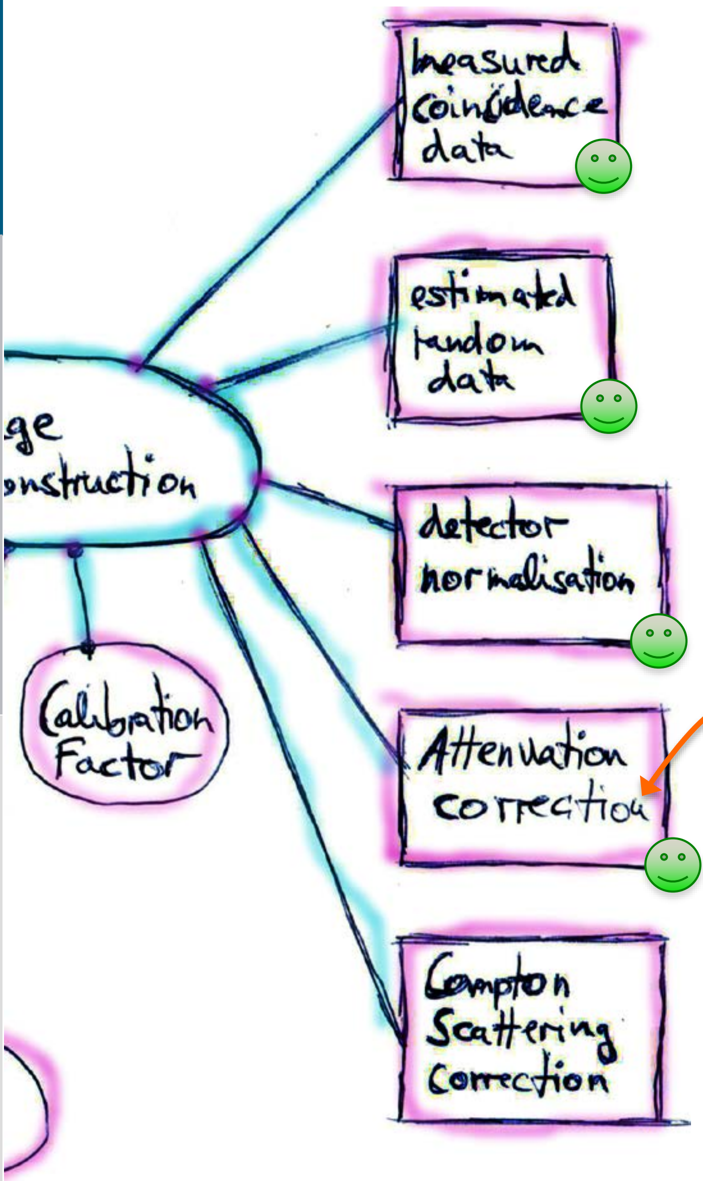
**Challenge:**

MR information provides no direct estimate of photon attenuation

(e.g. bone + cavities -> no Signal in Standard-MR-Seq.)

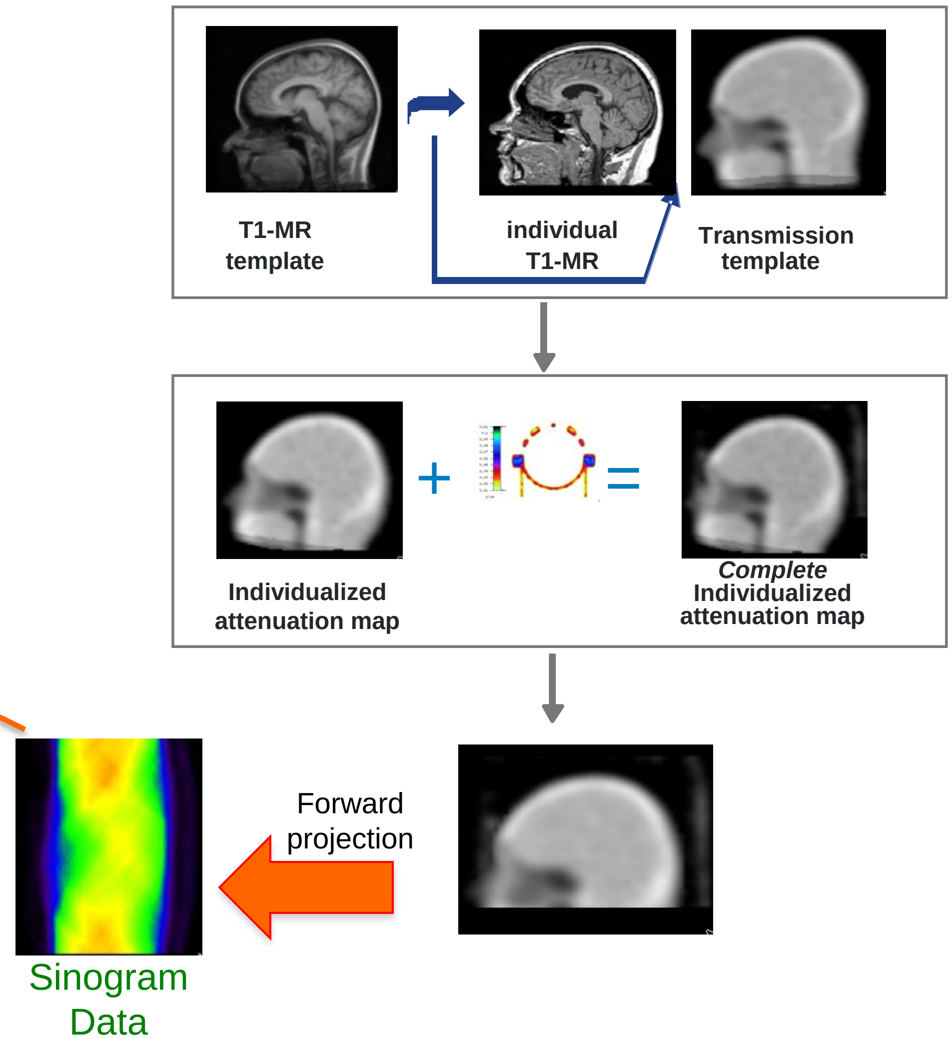


# Attenuation Correction

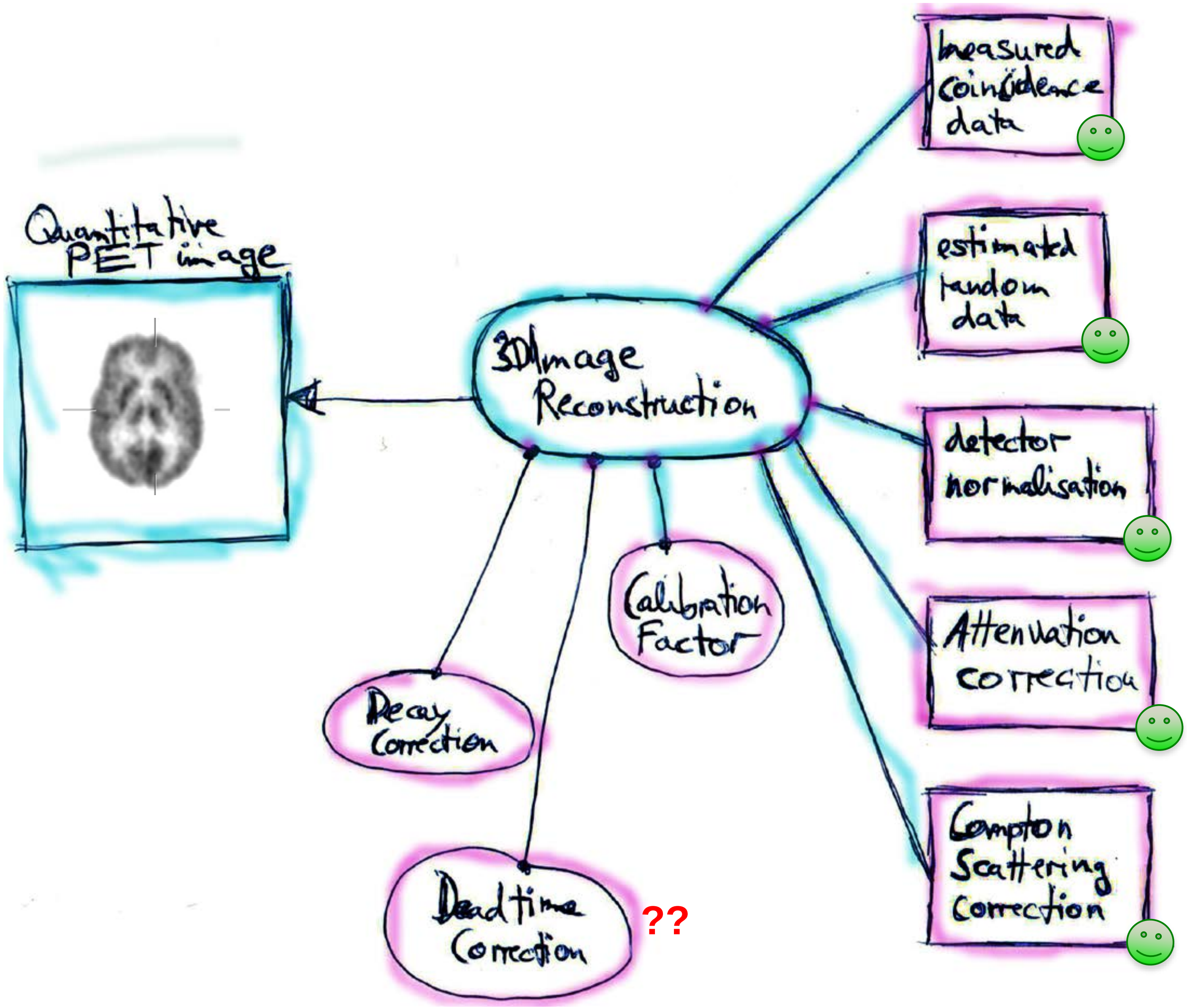



### Template based Approach

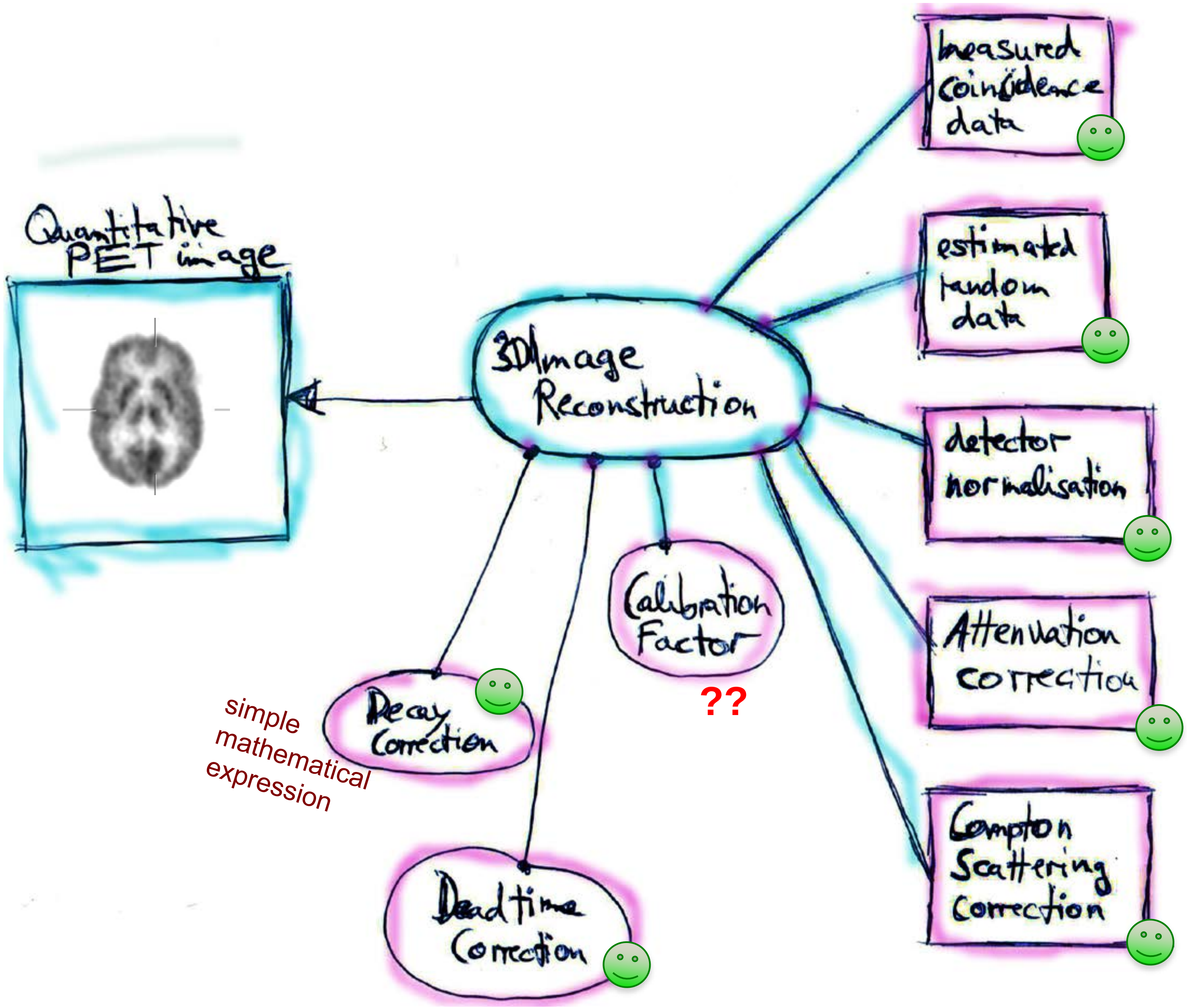
Rota Kops E et al, IEEE 2009 Proceedings: pp. 2530



# Deadtime Correction

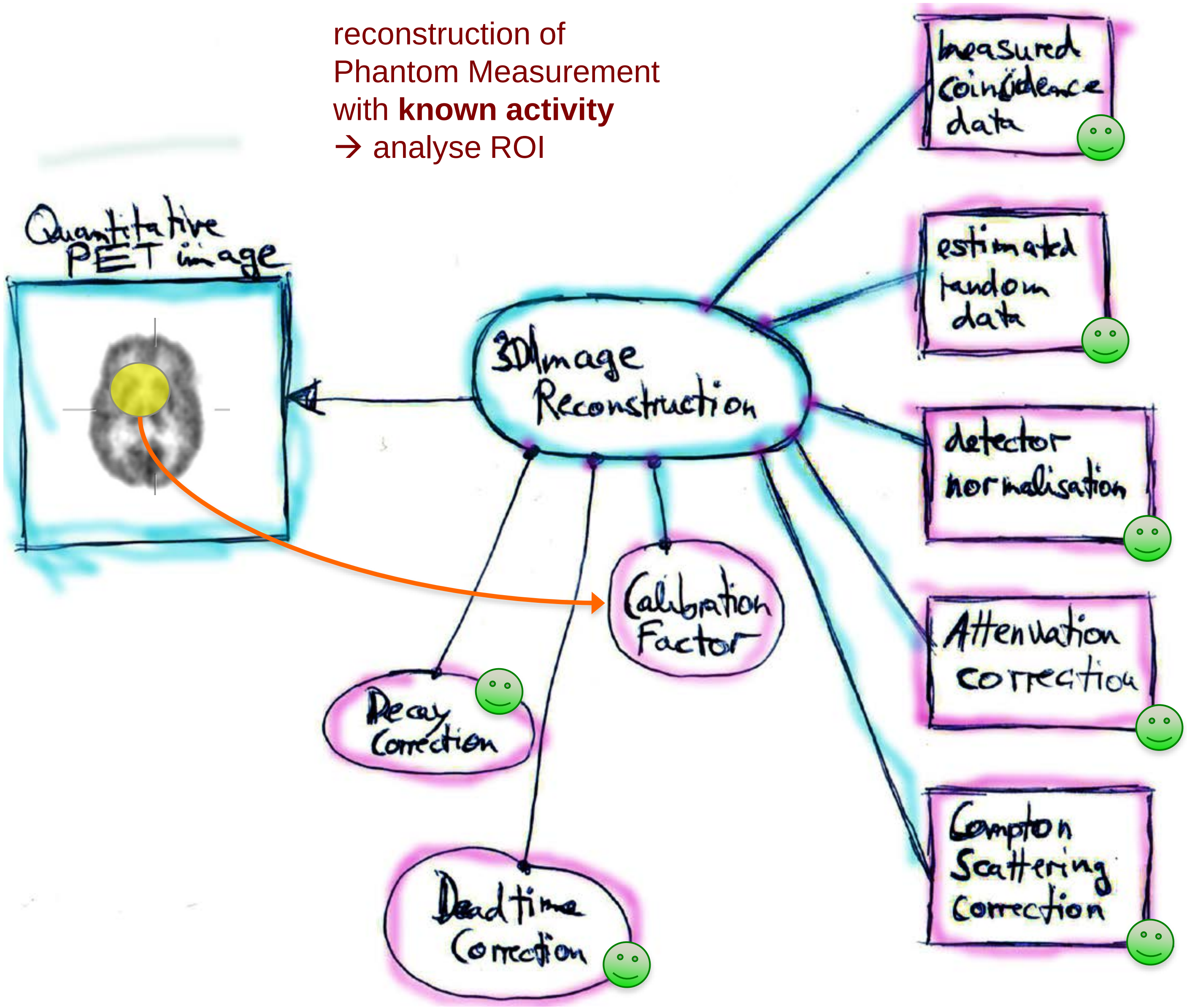


# Deadtime Correction



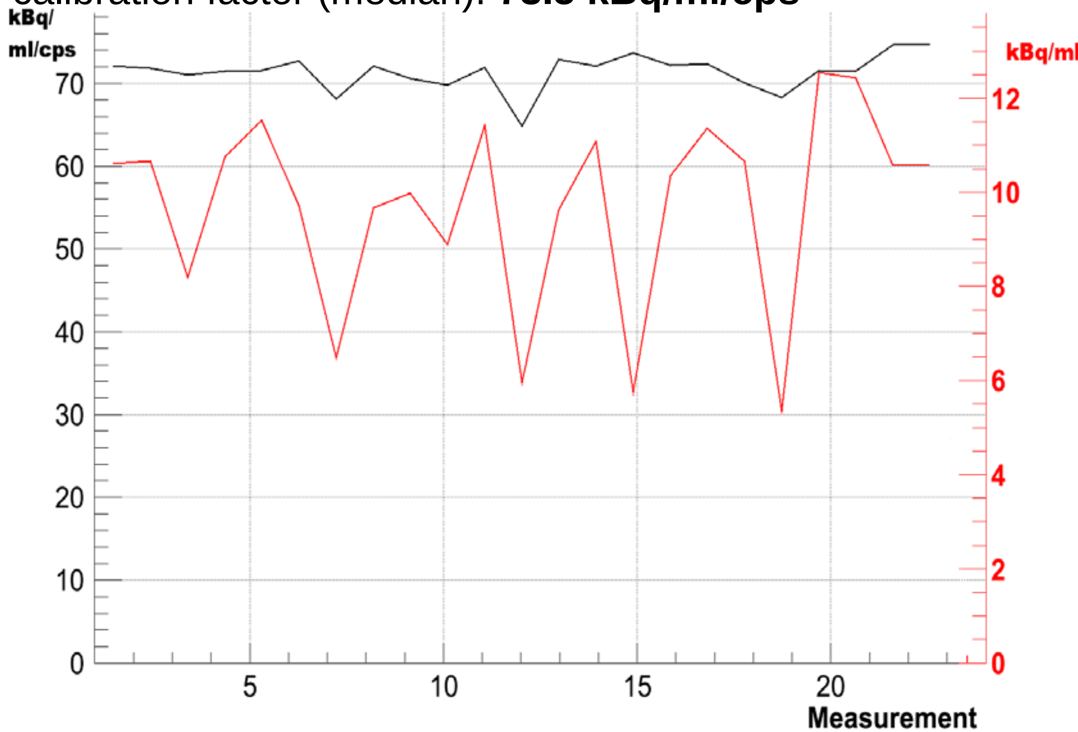
# Calibration Measurement

reconstruction of
Phantom Measurement
with **known activity**
→ analyse ROI



# Calibration Measurements

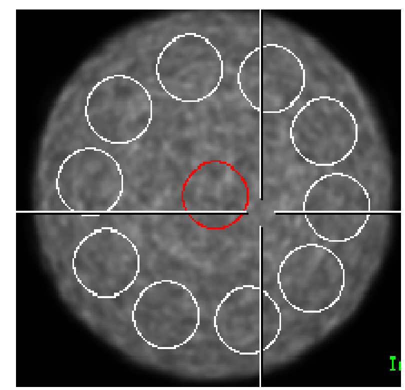
calibration factor (median): **73.5 kBq/ml/cps**




calibration factor

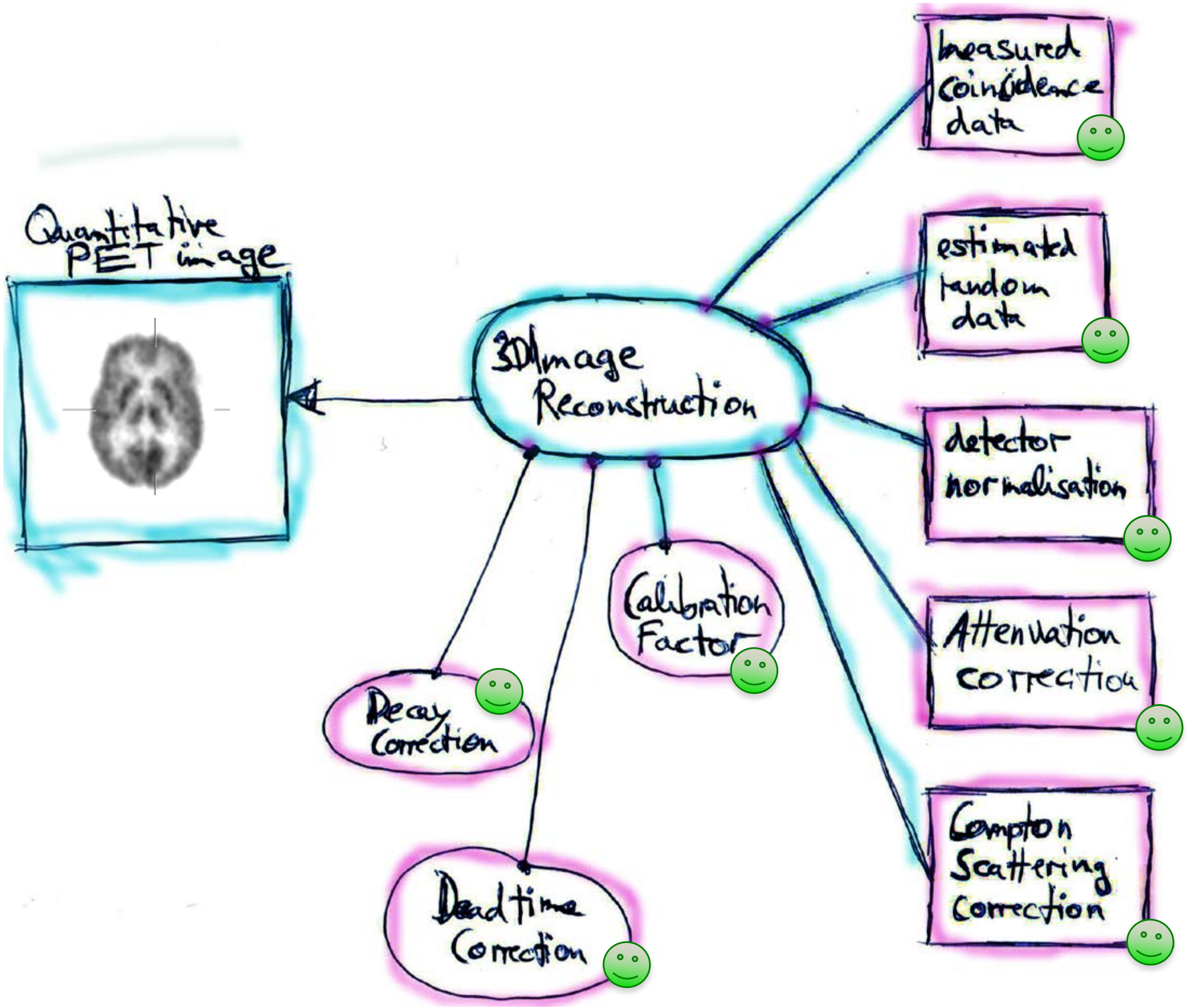
activity
concentration
within phantom

cylinder phantom
(filled with $^{18}F$)

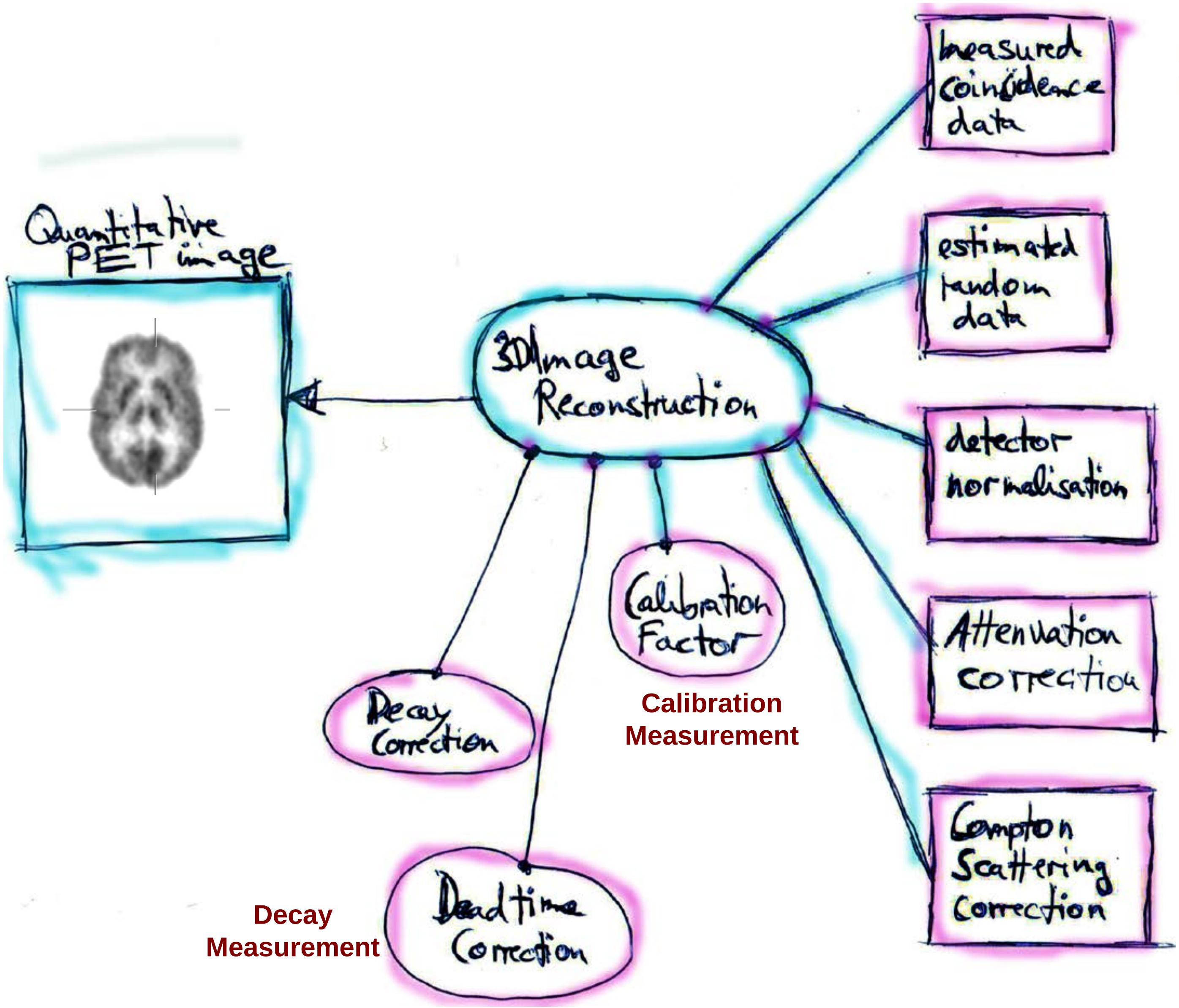


region of
interest

thanks to
Christoph Weirich


Quantitative PET image
3D Image Reconstruction
measured coincidence data
estimated random data
detector normalisation
Attenuation correction
Compton Scattering Correction
Calibration Factor
Decay Correction
Deadtime Correction

# Overview of Inputs for Quantification




Patient Measurement

Normalisation Measurement

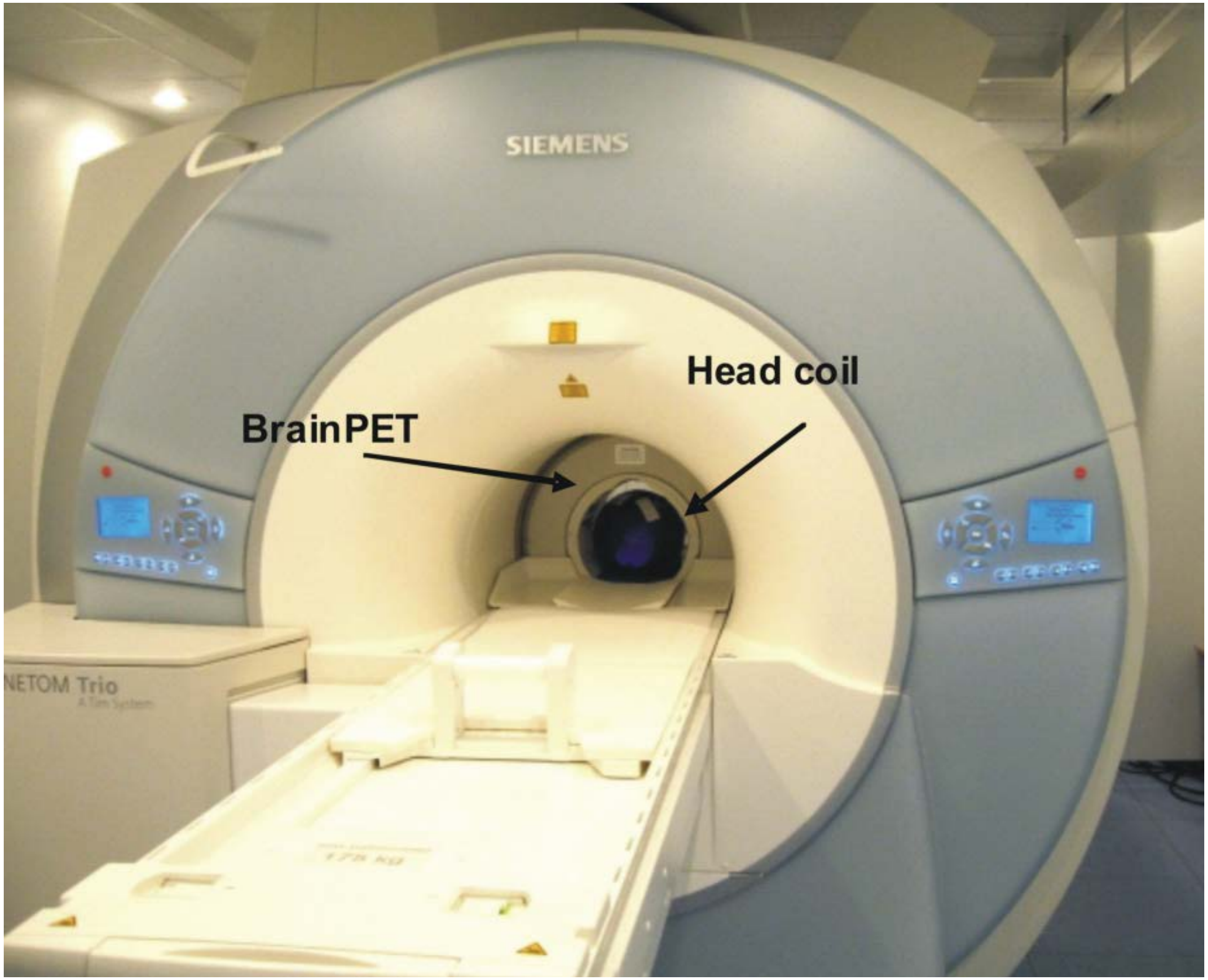
MR Measurement

Calibration Measurement

Decay Measurement

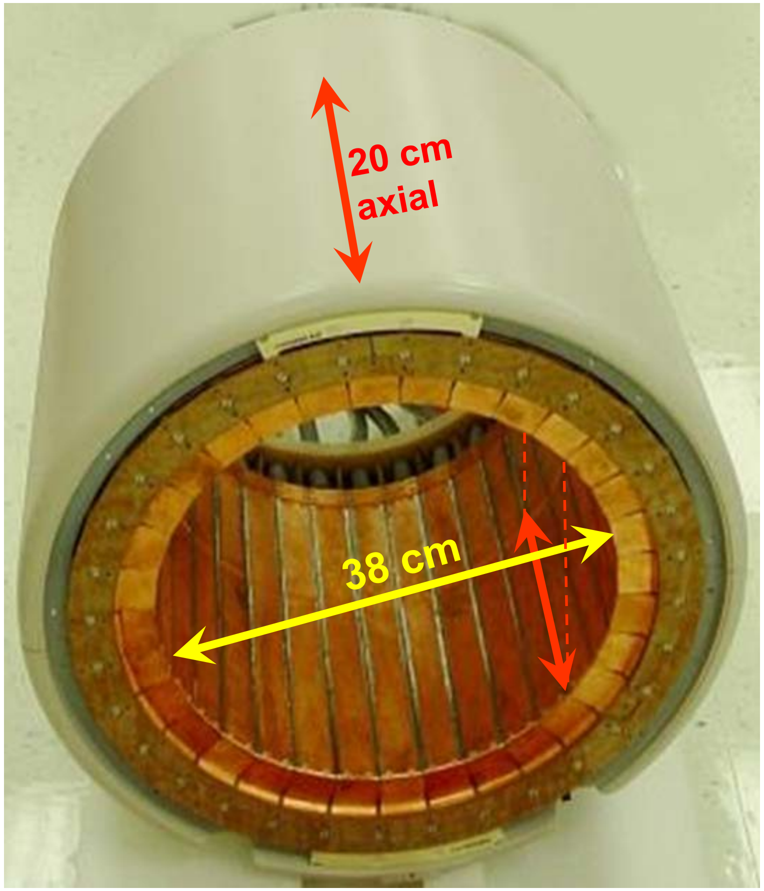
# Quantitative PET Imaging with Hybrid MR-PET Scanners

# BrainPET in 3T-Tim-Trio MR

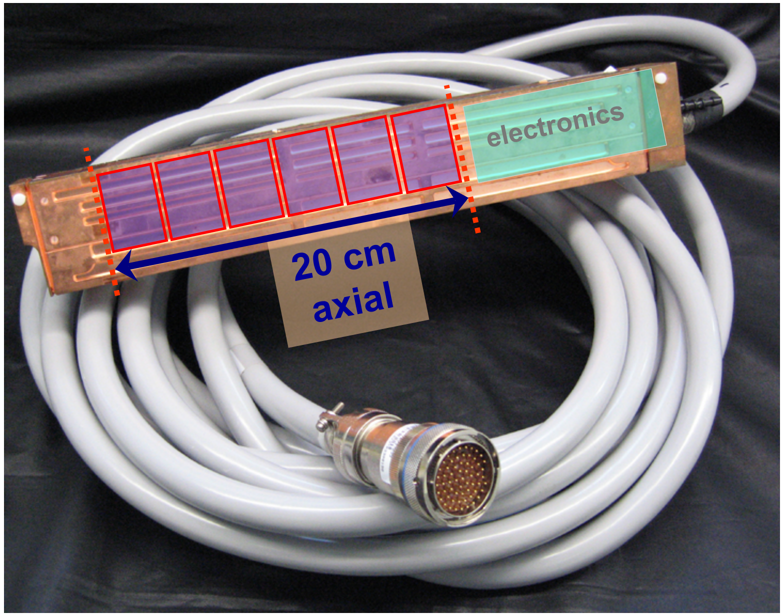


# BrainPET insert

**<u>scanner with 32 heads</u>**

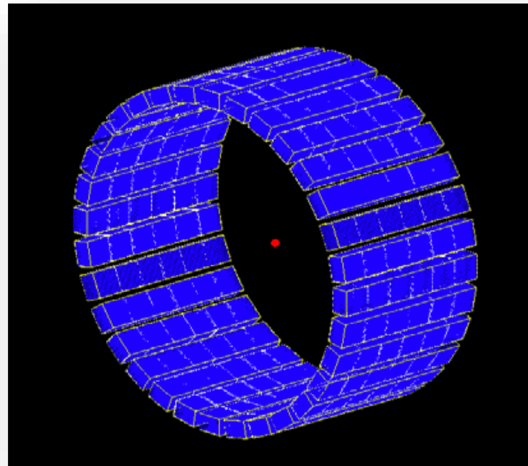


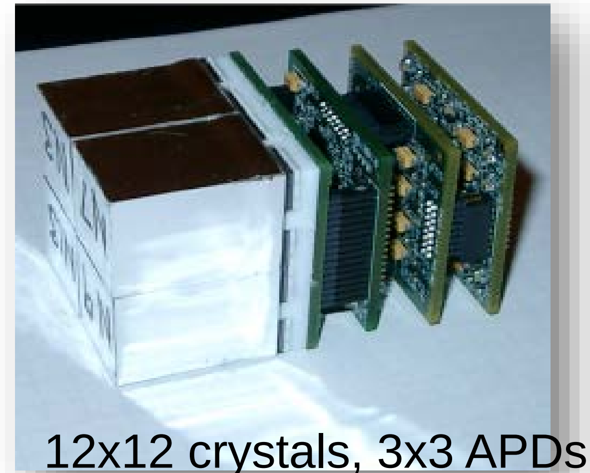

**<u>single detector head</u>**




- copper shielded against MR influence
- 6 PET detector blocks / head
- 12 x 12 crystals / block
- 2.5 x 2.5 x 20 mm$^3$ LSO crystal
- 3 x 3 APD / block

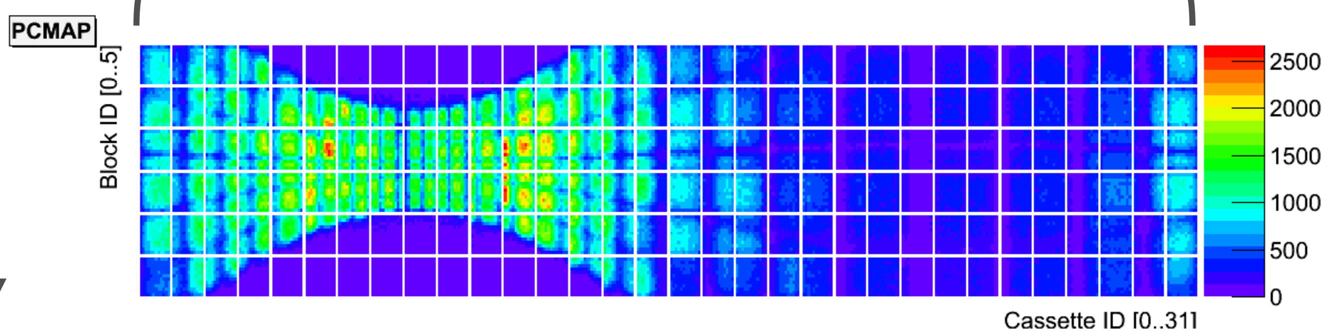
# Design and Structure of the BrainPET





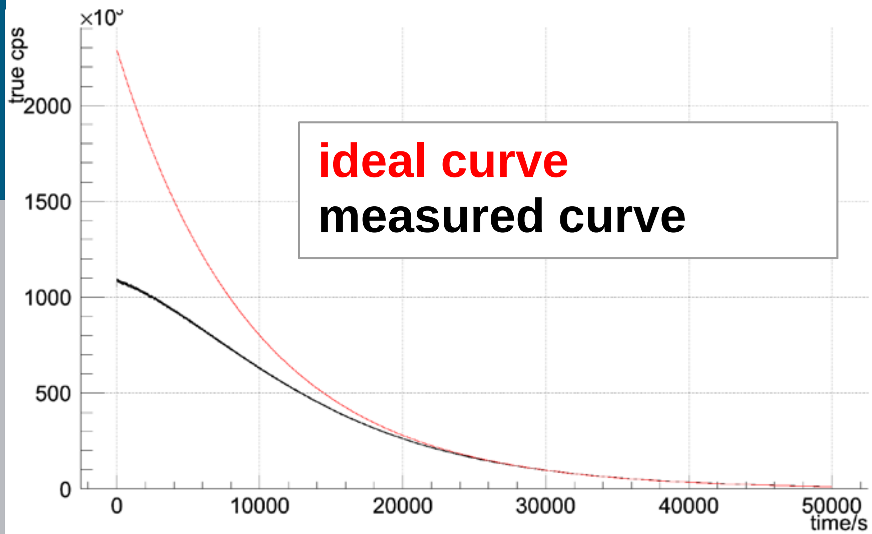

**unrolled detector**

**72 detector rings**

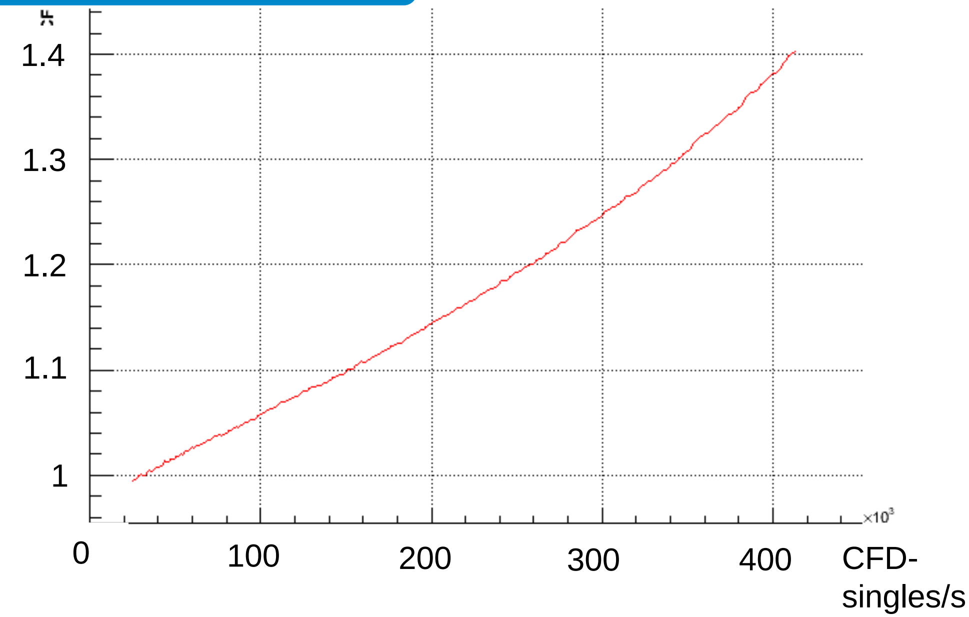


# Measurement Effect: Deadtime

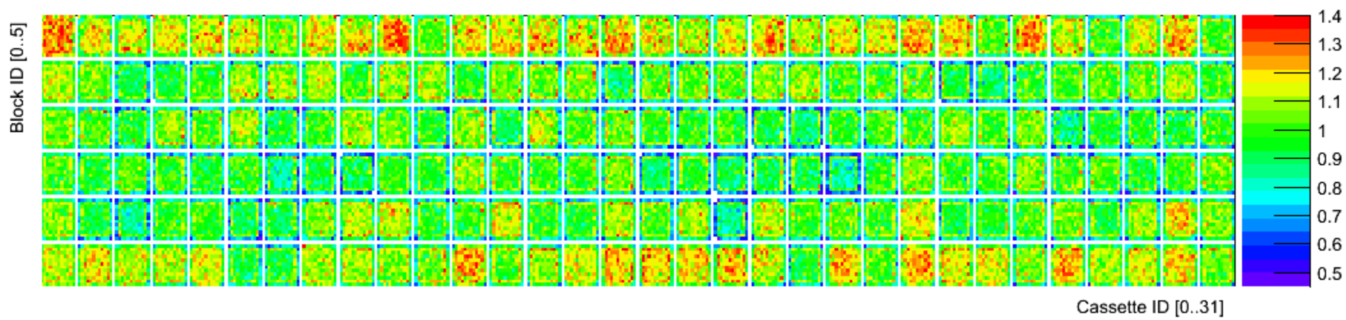
## PET countrate:



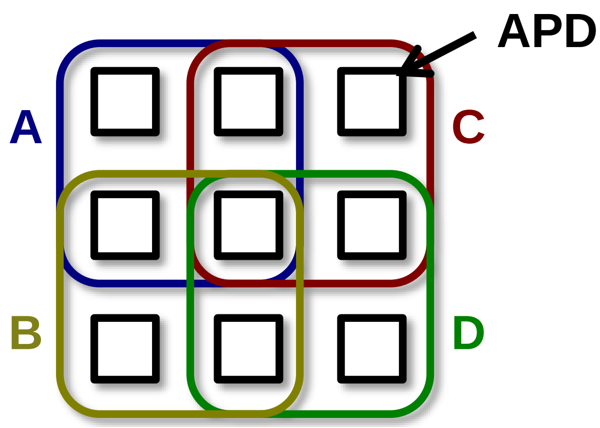

## deadtime effect:



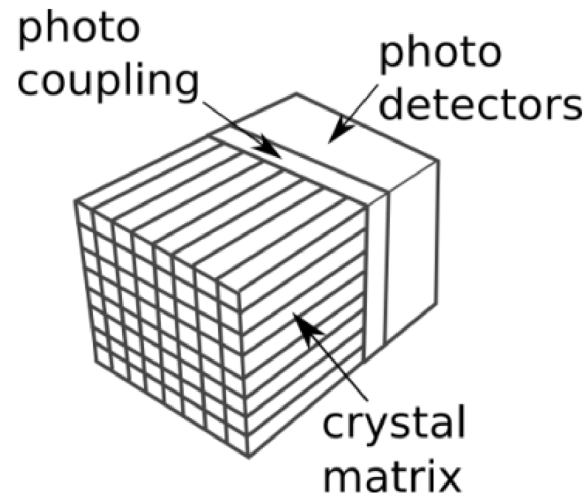

## deviation from global correction factor:



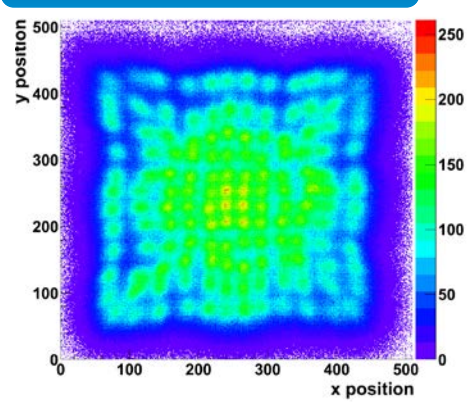
# Measurement Effect: Pile-up



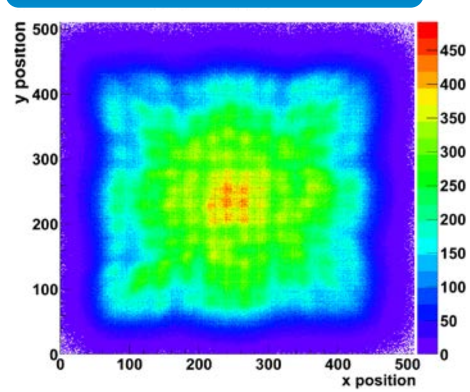

Anger principle



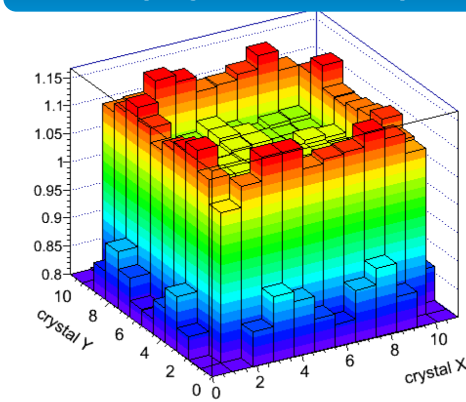

at low countrate:




at high countrate:

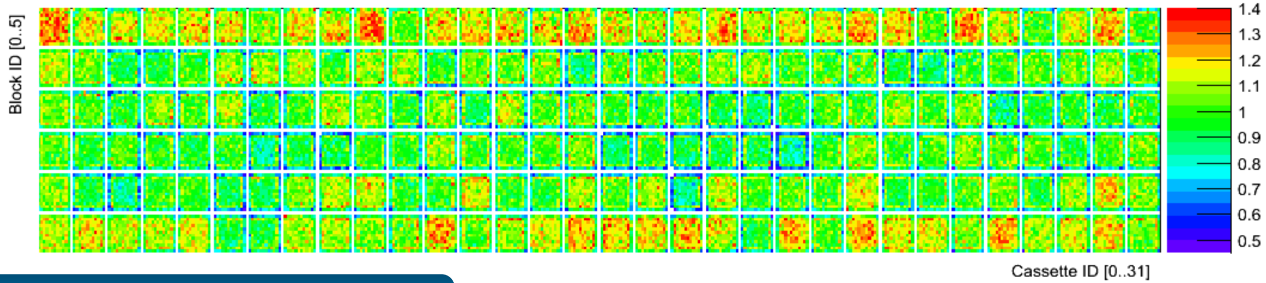



ratio (crystal level):

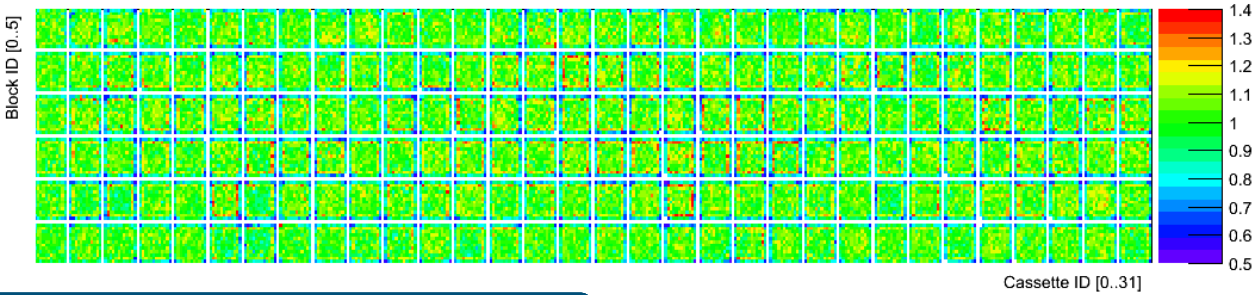


# Dynamic Correction

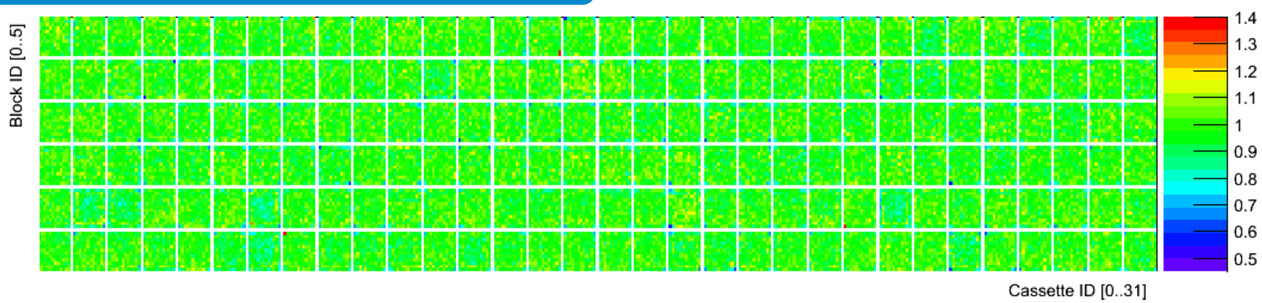
## global correction value:



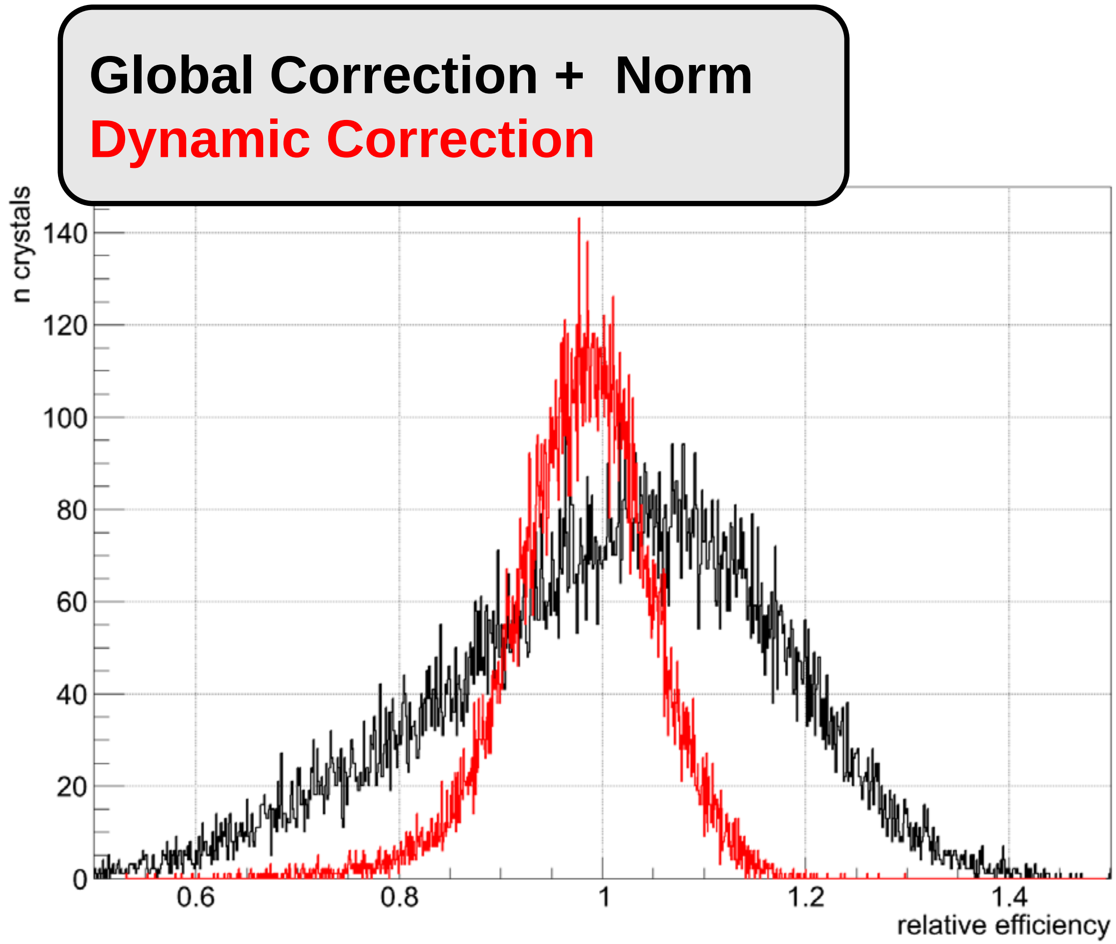

## only block-based correction:



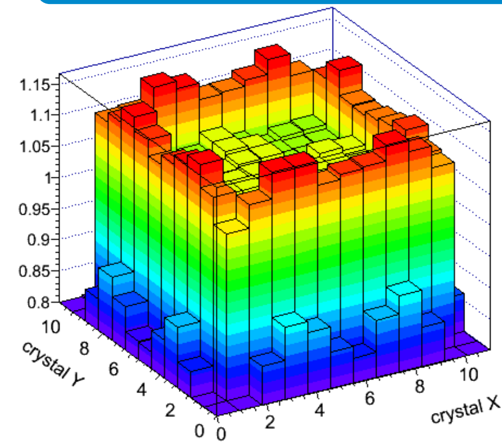

## block-based and Pile-up correction:



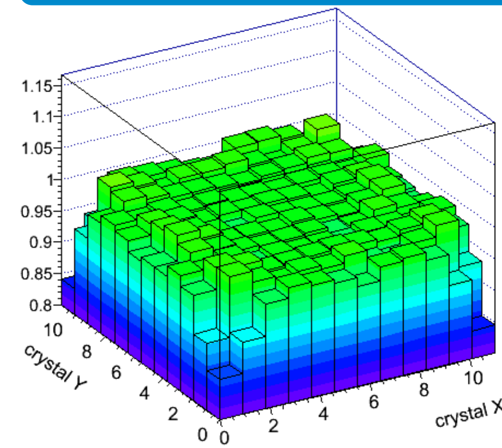
# Dynamic Correction




before correction:




after correction:



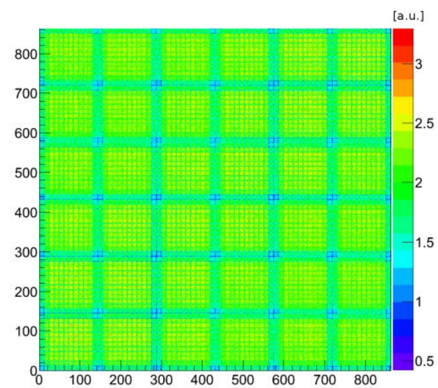

**Weirich C.**, Scheins J., Gaens, M., Herzog H., Shah N.J. *Combined Deadtime and Pileup Correction for the MR-compatible BrainPET scanner.* Conference Record of the IEEE NSS/MIC Seoul, South Korea, 2013

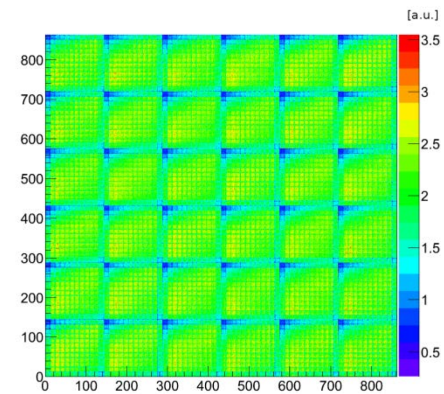
# Integration: Norm, Deadtime and Pile-up

Correction Value $c_{ij}$:

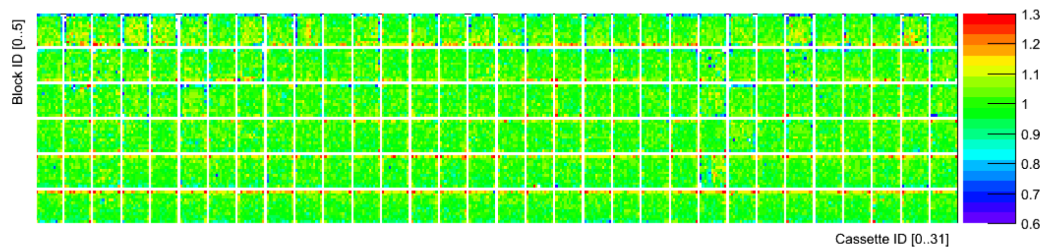
$$c_{ij} = \frac{1}{g_{ij}\ \varepsilon_{stat,i}\ \varepsilon_{stat,i}\ \varepsilon_{dyn,i}\ \varepsilon_{dyn,j}}$$

Geometric Component $g_{ij}$:

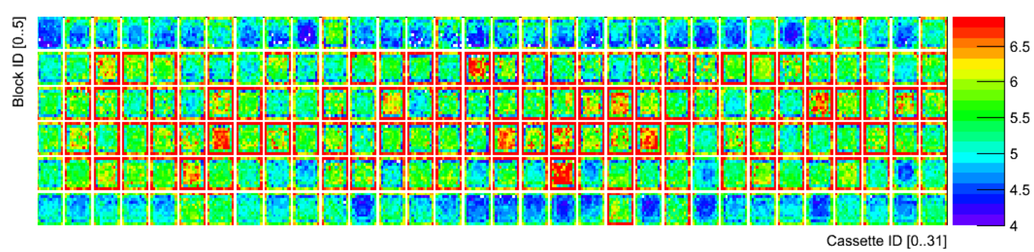


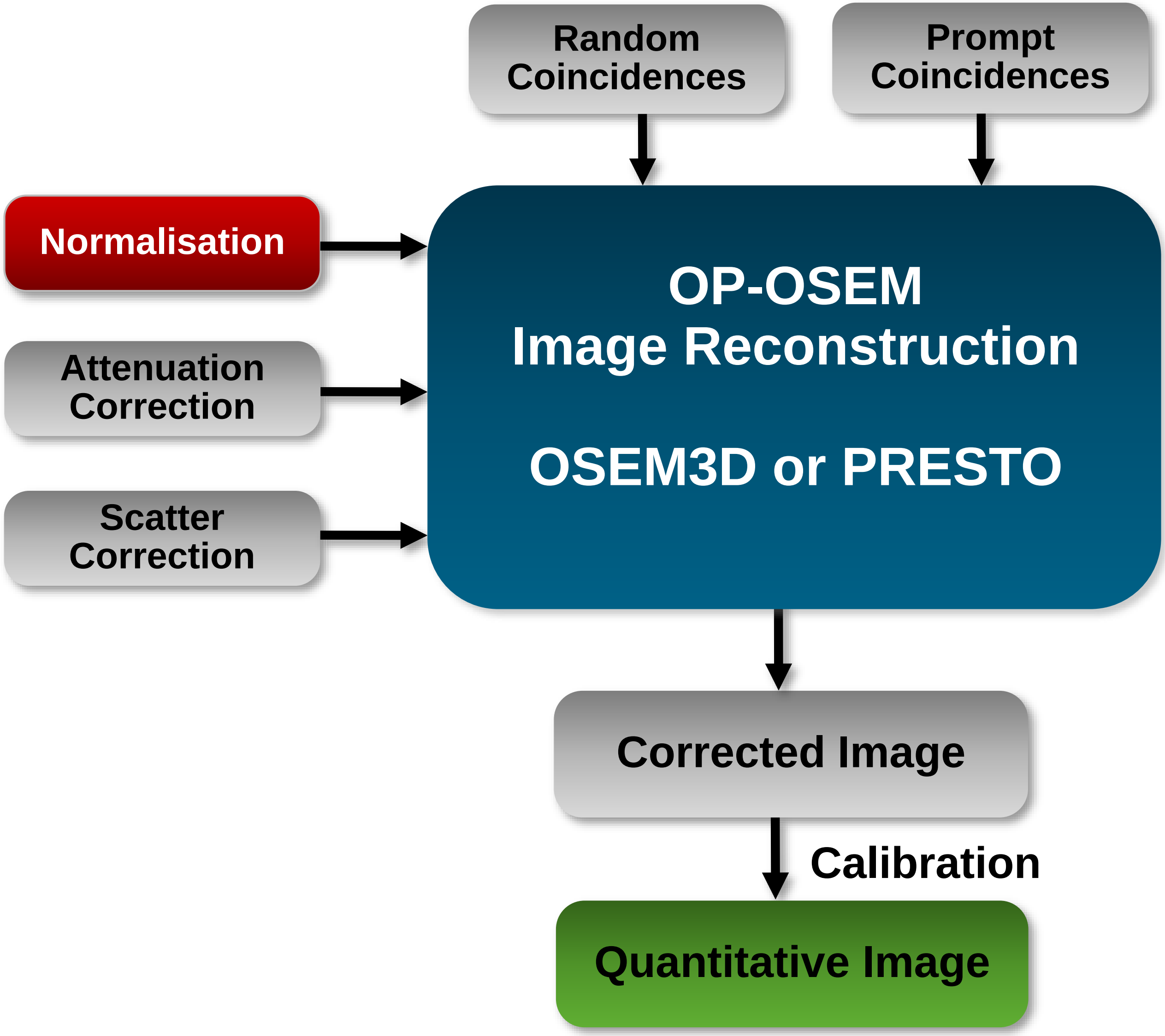

Static Crystal Efficiency $\varepsilon_{stat,i}$:




Dynamic Crystal Efficiency $\varepsilon_{dyn,i}$ :

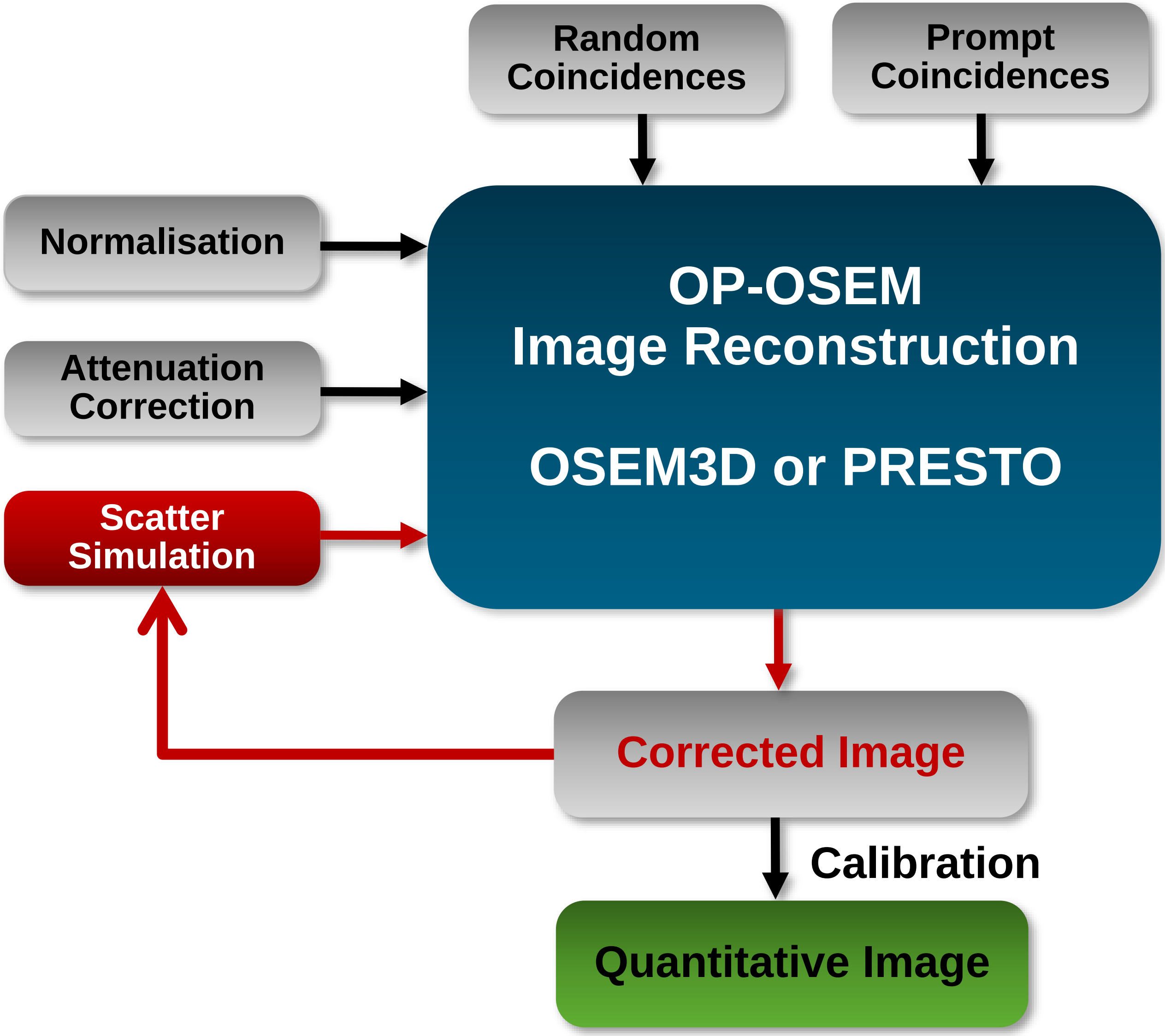


# Reconstruction: Quantitative Imaging



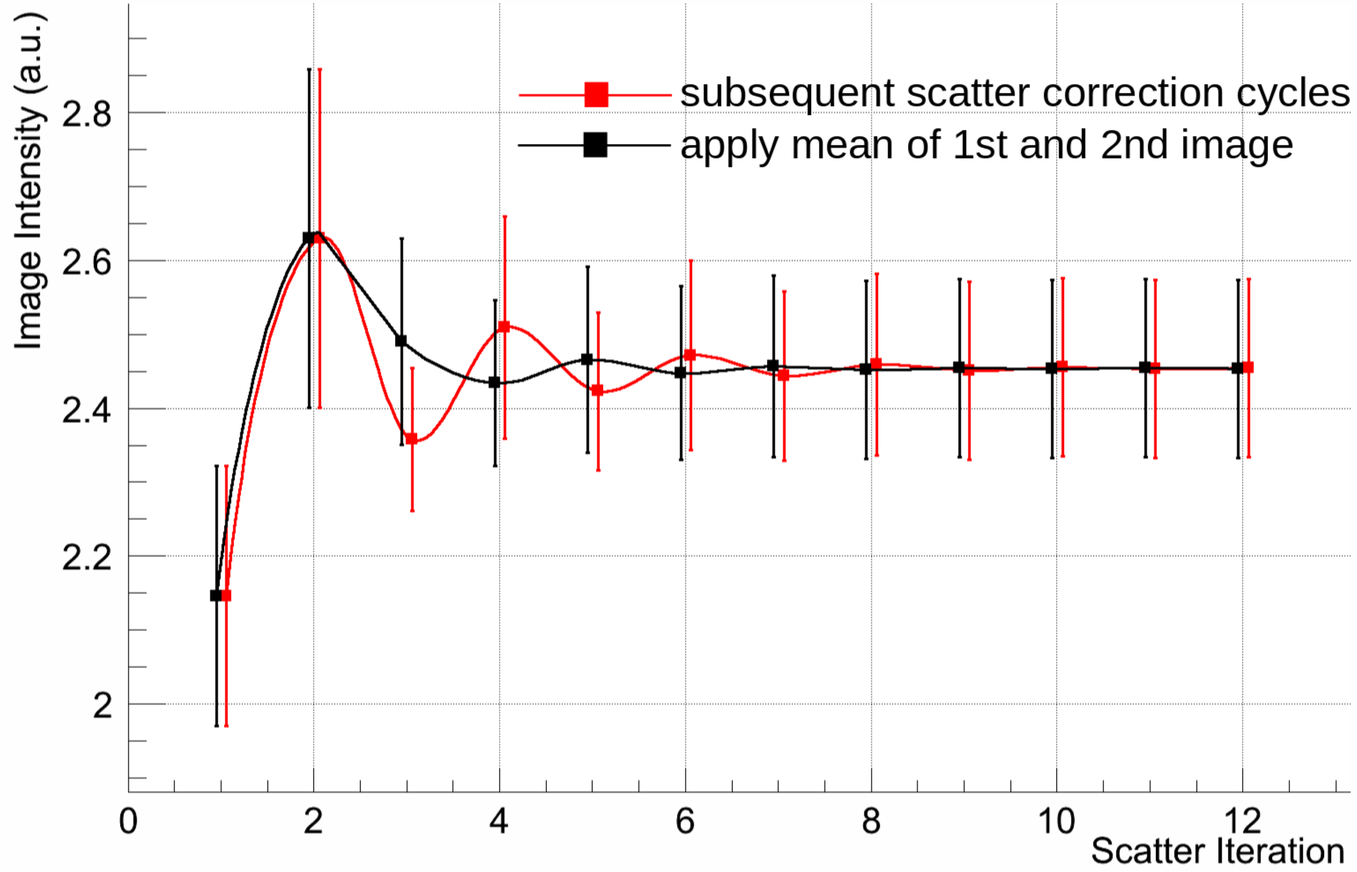

**Weirich, C.**, Scheins, J., Lohmann, P., Tellmann, L., Herzog, H., Shah, N.J. *Quantitative PET Imaging with a 3T MR-PET Hybrid Scanner. (2012). Nuclear Instruments & Methods In Physics Research A.*

# Scatter Correction




Watson…

# Scatter Correction

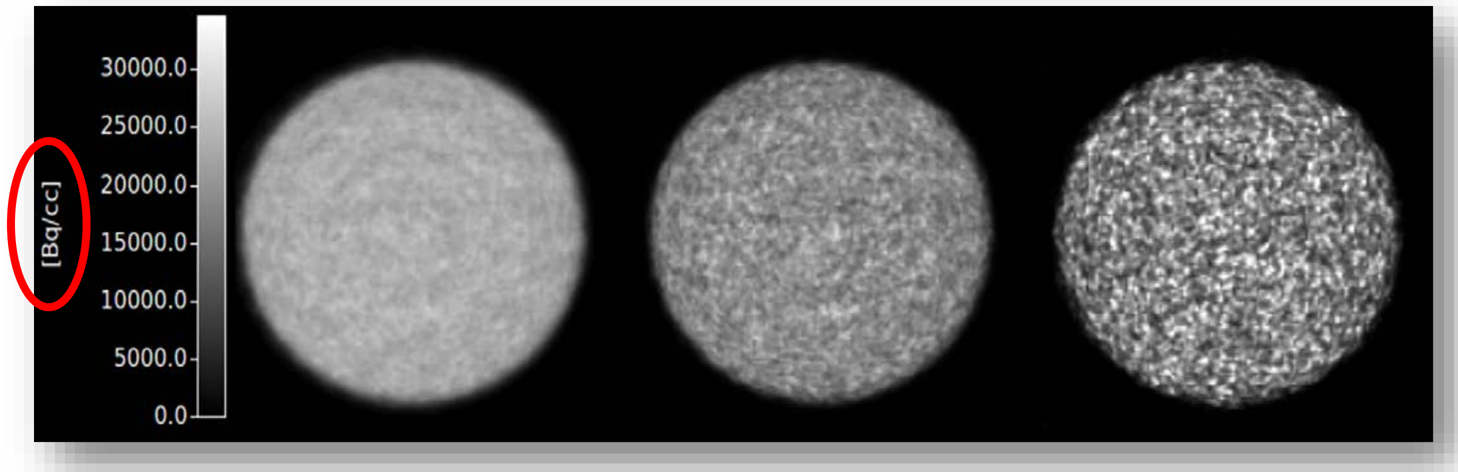


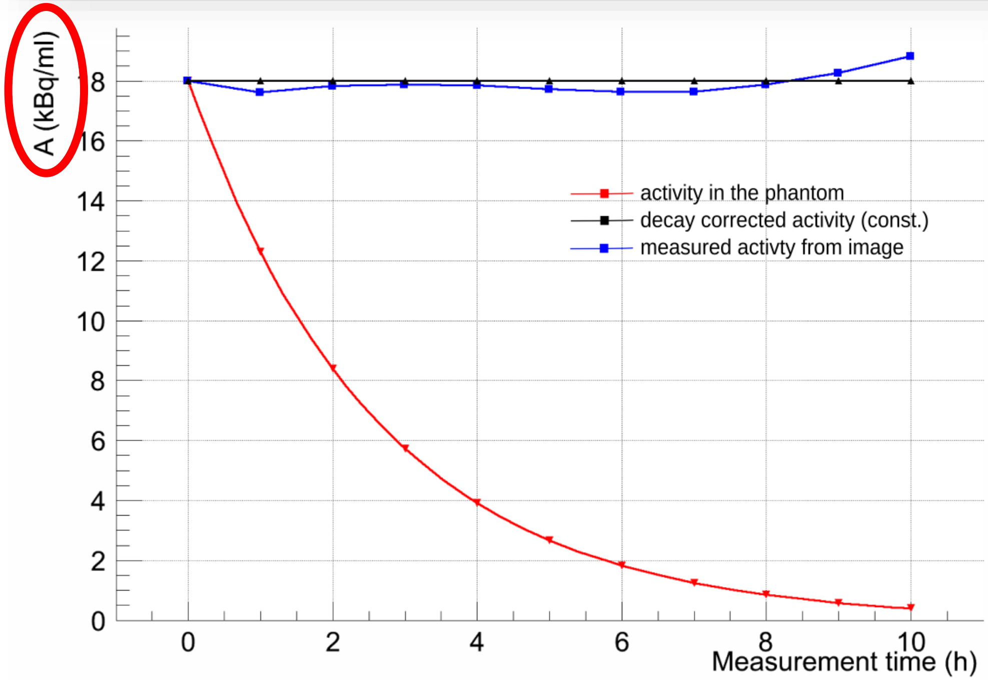

I. Hong

# Validation in Phantom Studies

**Weirich, C.**, Daun, A., Scheins, J., Tellmann, L., Herzog, H., Shah, N.J. *Long Term Quantitative Stability of the MR Compatible BrainPET Insert.* Conference Record of the IEEE NSS/MIC, 2011

# Validation in Phantom Studies

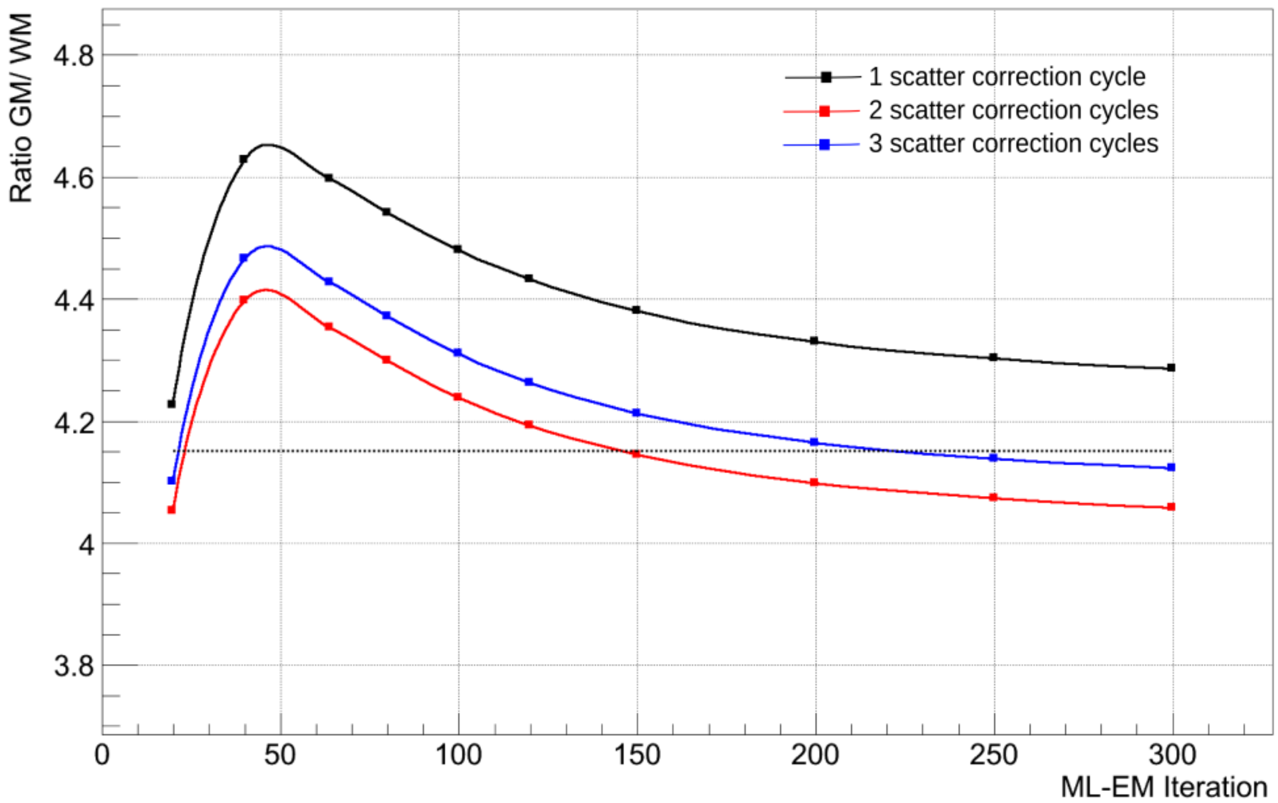



- ✓ **Image homogeneity**
- ✓ **Absolute quantificaton**

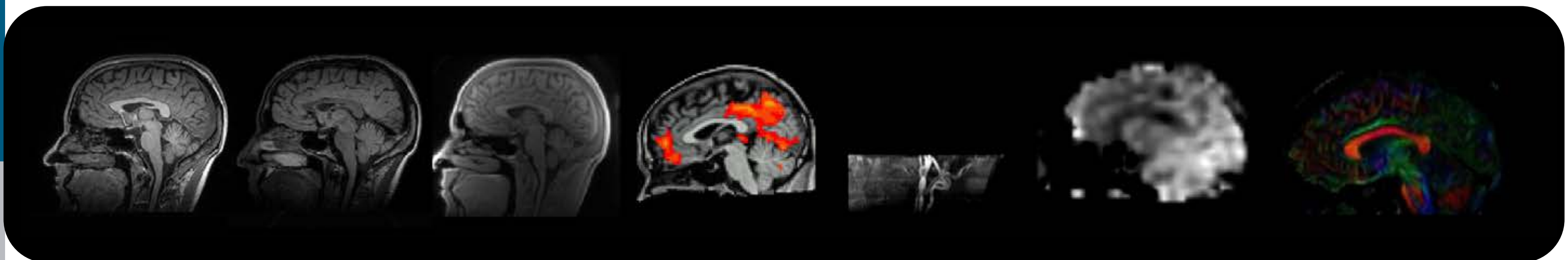
# Scatter Correction

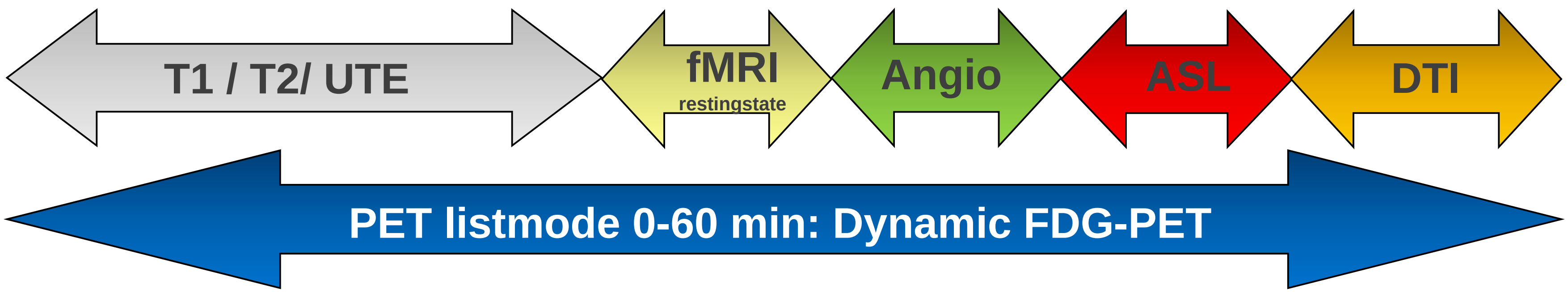
**GM/WM:**
**4.15 / 1**

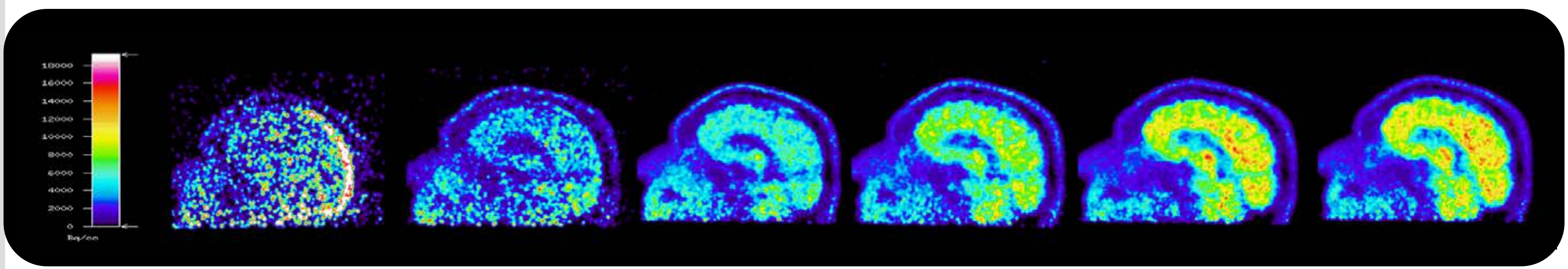


# Hybrid MR-PET

## dynamic FDG-PET with MRI

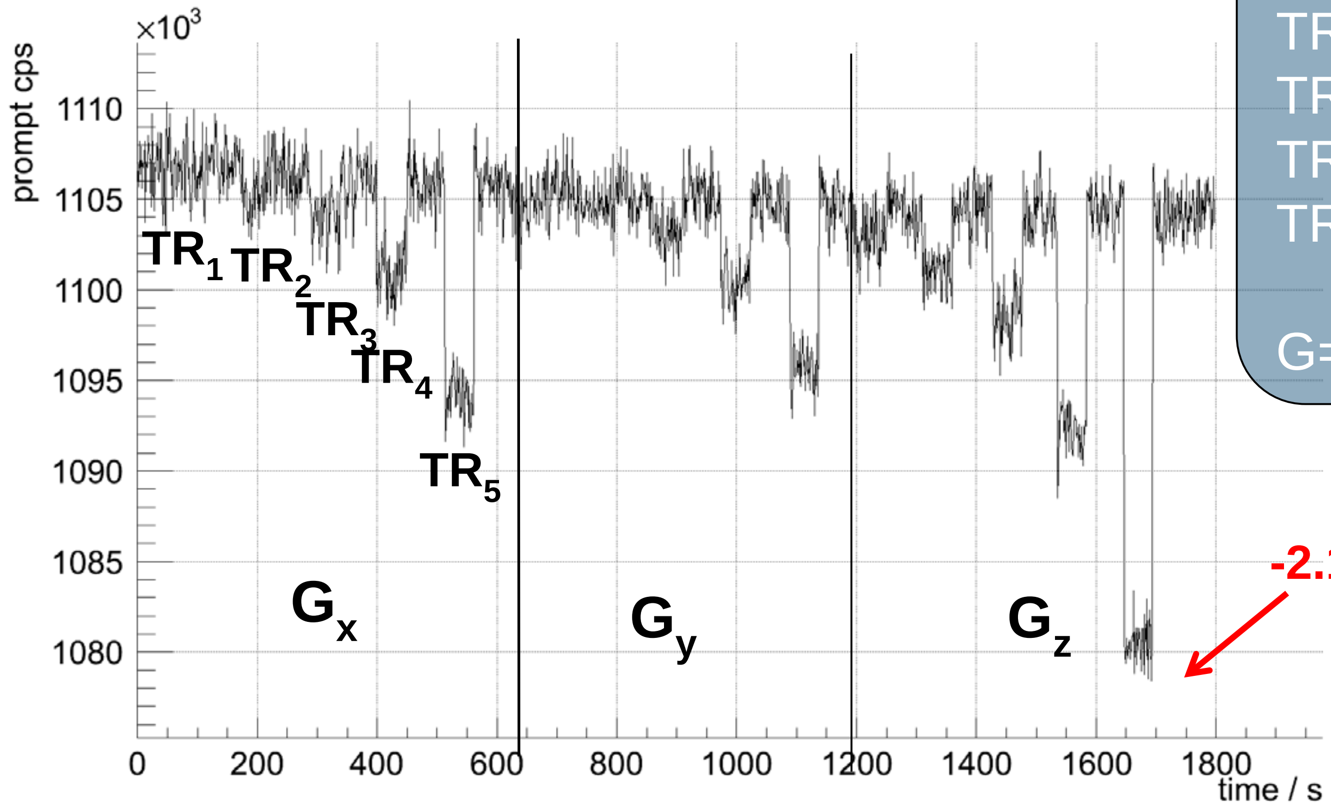




# Influence of MRI on PET Countrate

**Here: varying gradient repetition time (TR)**




$TR_1$ = 20.0 ms
$TR_2$ = 10.0 ms
$TR_3$ = 5.0 ms
$TR_4$ = 2.5 ms
$TR_5$ = 1.2 ms

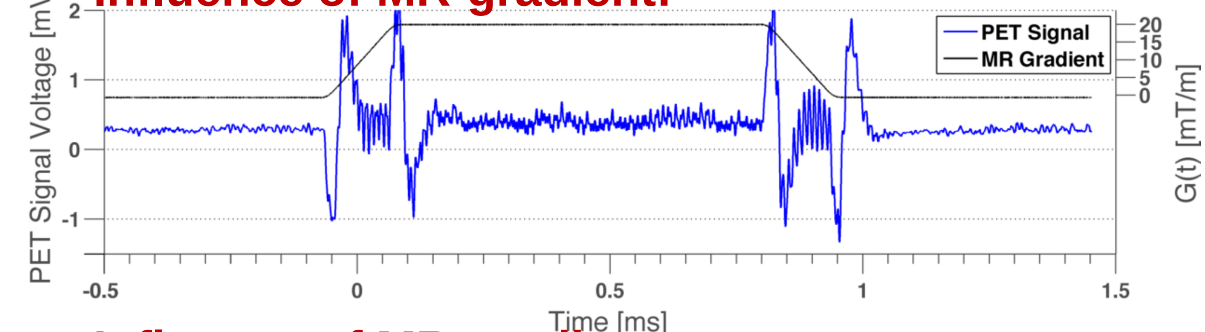
G=20 mT/m


**Weirich C.**, Brenner D., Tellmann L., Herzog H., Shah N.J. *Systematic Investigation and Correction of MR Influences on Simultaneous PET Measurements*. ISMRM, vol. 1, 2011

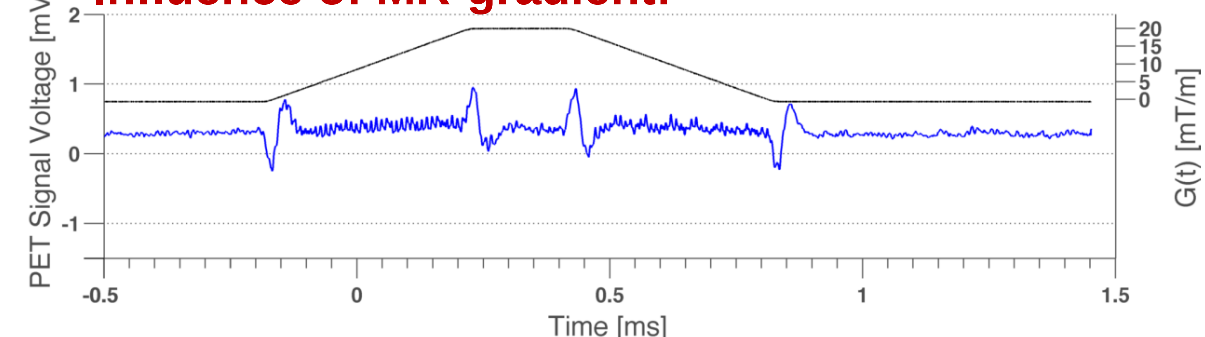
Brenner D., **Weirich C.**, Scheins J., Besancon E., Tellmann, L., Herzog, H., Shah NJ., *New Insights into PET Count Rate Reduction during Simultaneous MR-PET Measurements.* ISMRM 2012

# Analysis of PET Detector Signals

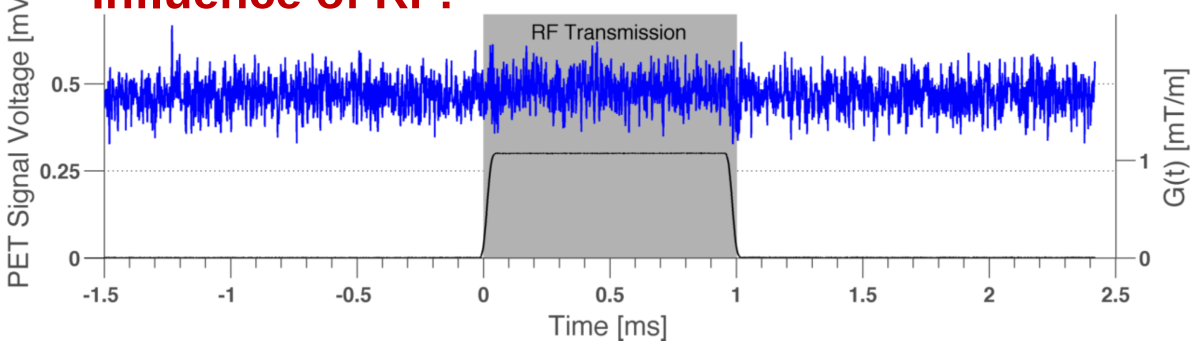
## Influence of MR-gradient:




## Influence of MR-gradient:

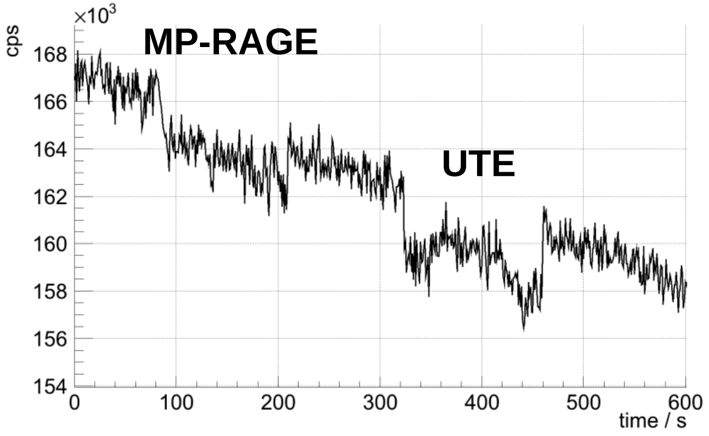



## Influence of RF:

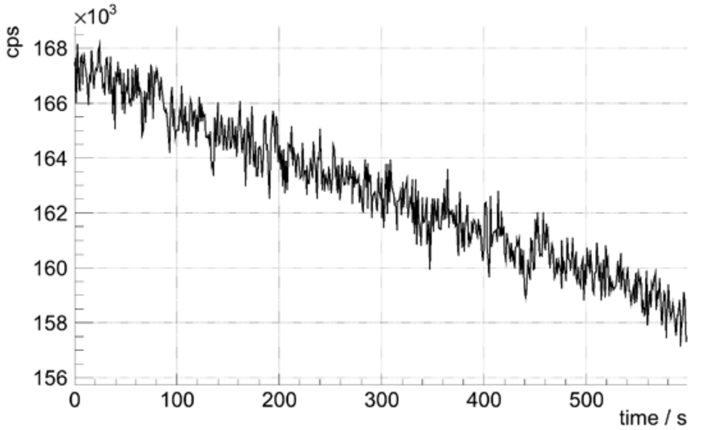


# Correction of MR Influences

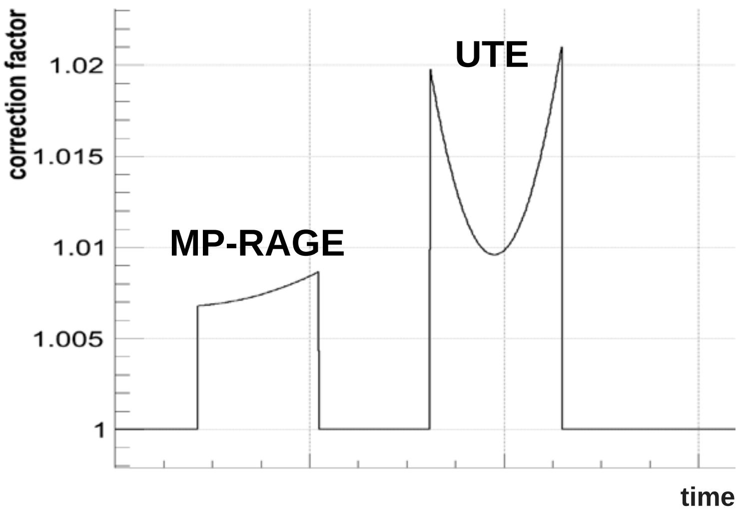
## Uncorrected Countrate:




## Corrected Countrate:

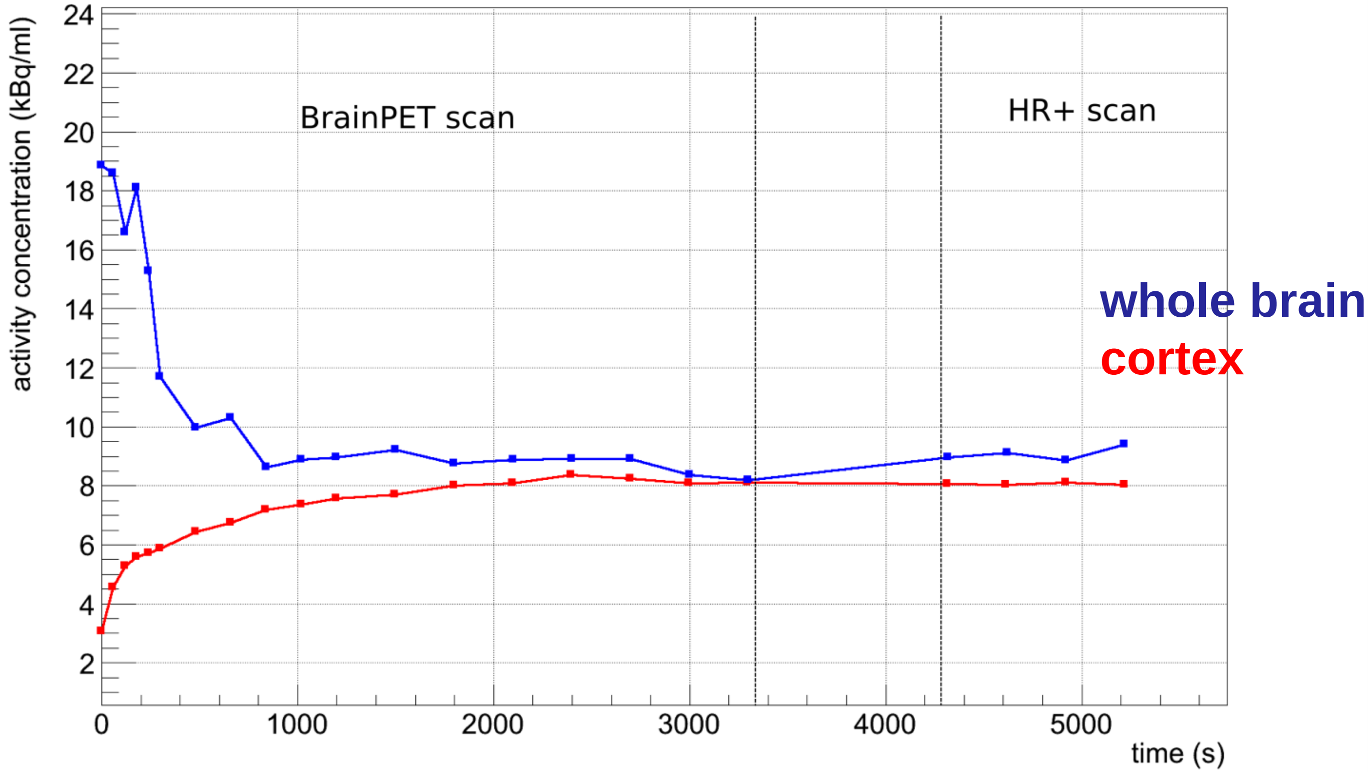


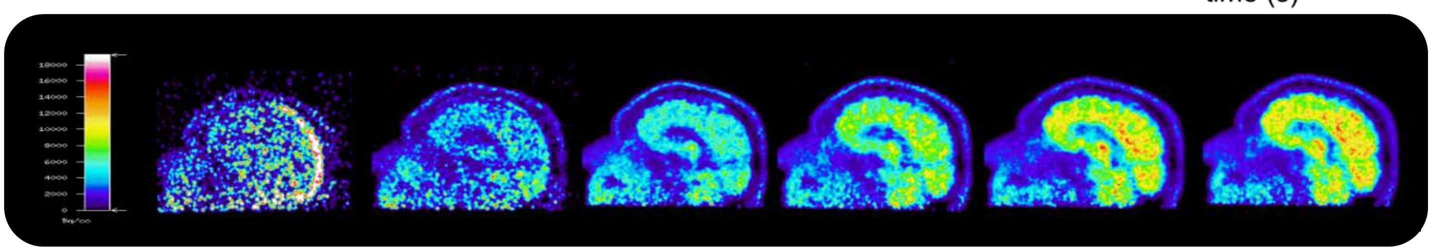

## Correction Factor




**Weirich, C.**, Brenner, D., Scheins, J., Tellmann, L., Herzog, H., Shah, N.J. *Analysis and Correction of Count Rate Reduction during Simultaneous MR-PET Measurements with the BrainPET Scanner*, IEEE Transactions on Medical Imaging, (2012)

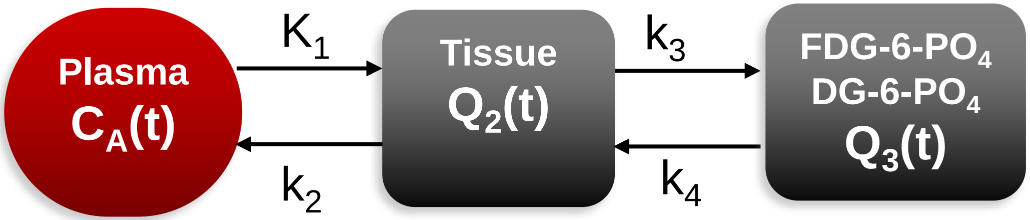
# Cross Calibration of PET Scanners

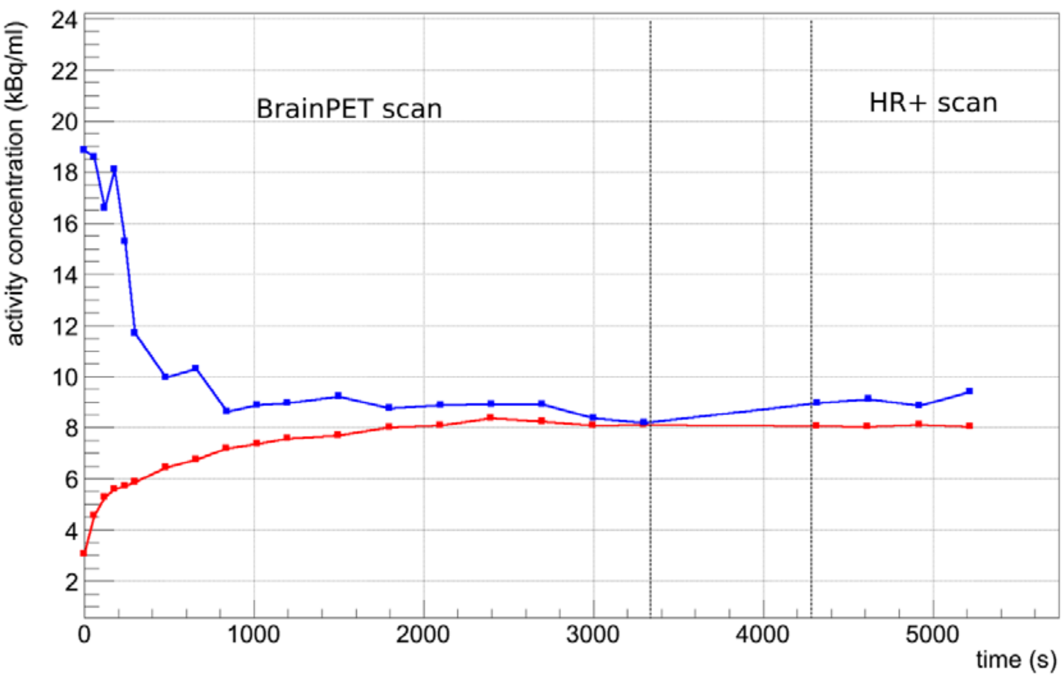


# Parametric Image

## Quantitative Energy Consumption of the Human Brain

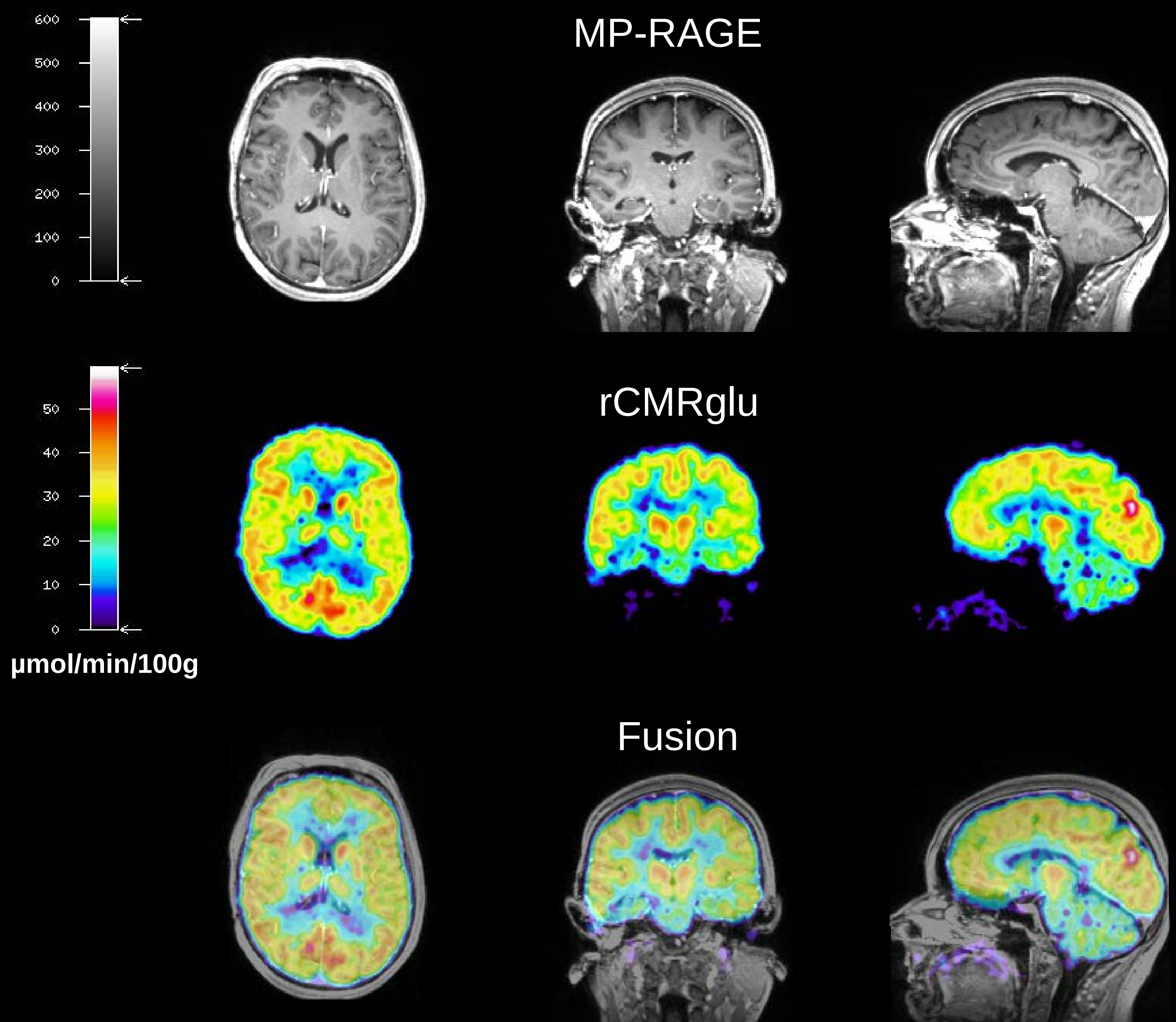



Patlak…

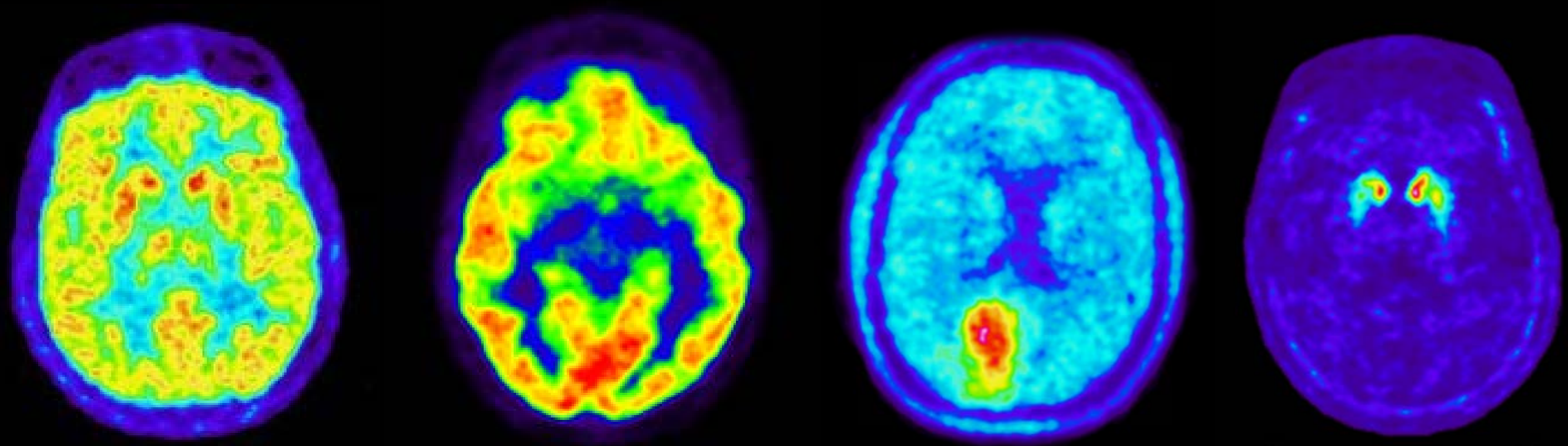
# Parametric Image

## Quantitative Energy Consumption of the Human Brain



# Impact of the Quantification Workflow

***in vivo* PET-Scans with different tracers:**




Total number of *in vivo* scans:

Studies….

# Conclusions

- ✓ Quantitative PET imaging from counts to parametric images
- ✓ Corrections were designed, implemented and optimised
- ✓ Integrated reconstruction workflow has been implemented
- ✓ Quantification error has been determined in phantom studies
- ✓ Human studies are carried out applying the 3T MR-BrainPET
- ✓ Long term stability of the system has been shown