# Comparison of proton CT and dual energy X-ray CT in terms of relative stopping power accuracy: experiment and simulations

G. Dedes[1], J. Dickmann[1], K. Niepel[1], P. Wesp[1], R. P. Johnson[2], M. Pankuch[3], V. Bashkirov[4], S. Rit[5], L. Volz[6,7], R. W. Schulte[4], G. Landry[8,9,1] and K. Parodi[1]

[1] Ludwig-Maximilians-Universität München  [2] U.C. Santa Cruz  [3] Northwestern Medicine Chicago Proton Center

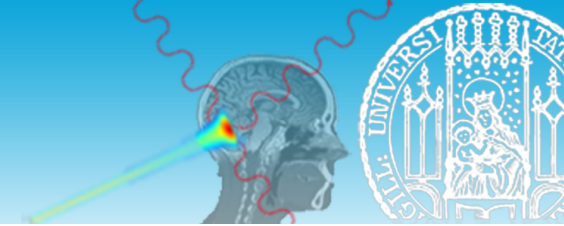[4] Loma Linda University  [5] Université de Lyon, CREATIS  [6] Deutsches Krebsfoschungszentrum (DKFZ)

[7] Heidelberg University  [8] University Hospital, LMU Munich  [9] German Cancer Consortium (DKTK)

5th Annual Loma Linda Workshop, July 2019

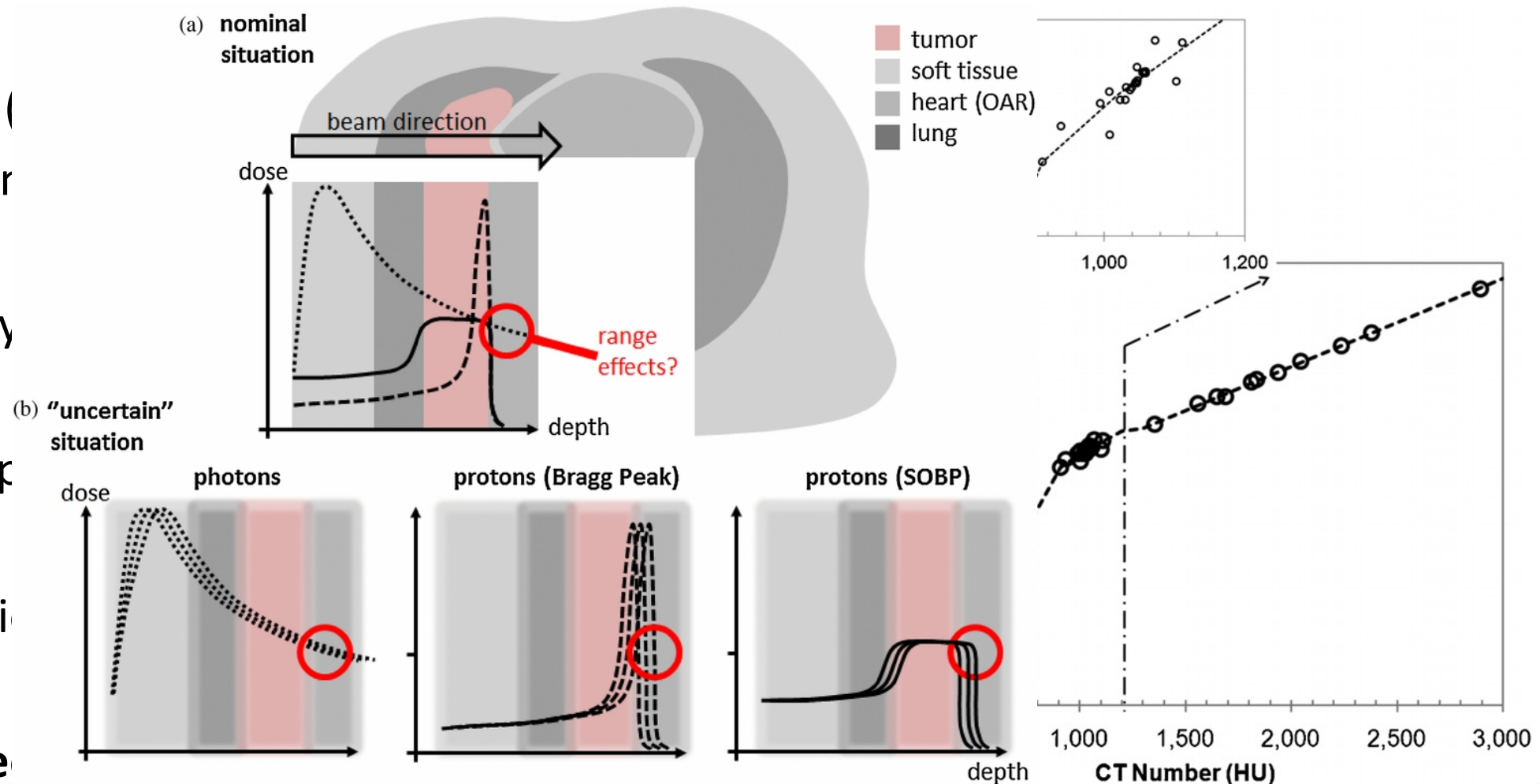- Proton therapy: **accurate** relative proton stopping power (**RSP**) map of patient is essential
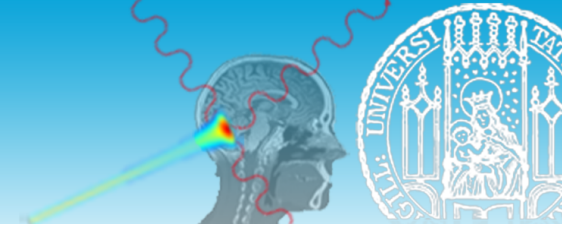
- Current practice ( up to **3%** errors in

- Dual energy X-ray

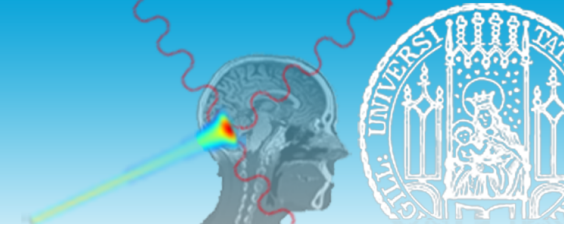- Both modalities p

- The two modaliti

- **Present first dire**

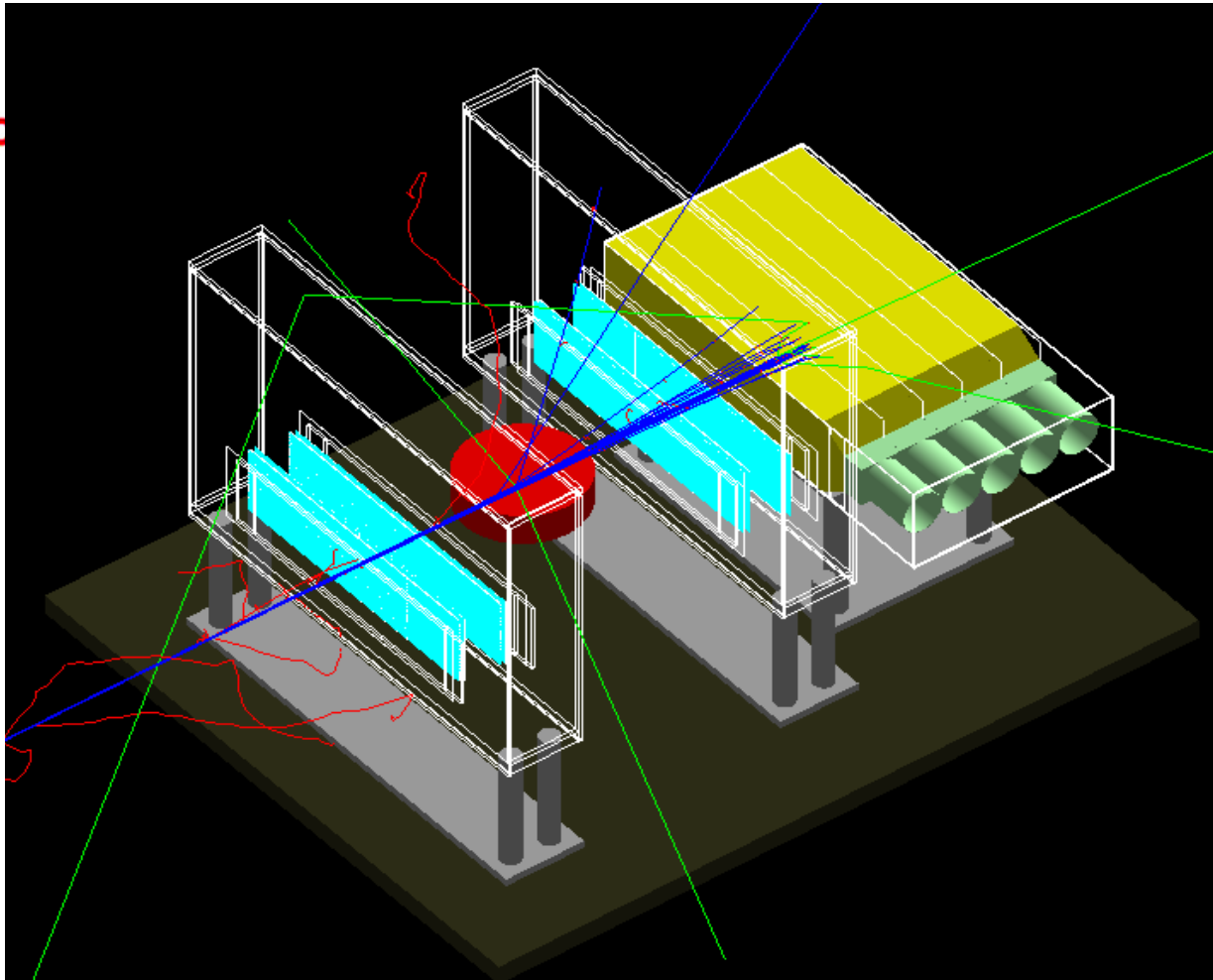# Part 1: pCT – DECT comparison in terms of RSP accuracy

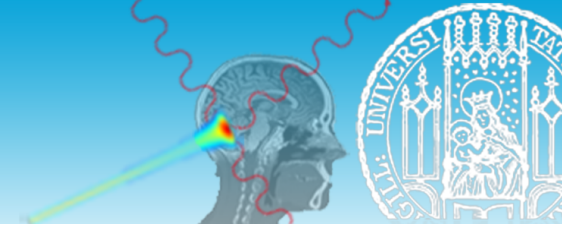**Proton CT phase II prototype scanner (LLU/UCSC)[1]**



Detector

- Silicon strip detector tracker
- 5-stage scintillator - energy detector
- 200 MeV protons

Reconstruction[2]

- Filtered backprojection
- Most likely paths
- 3-σ cuts on energy and angle (on 2 mm x 2 mm pixels)
- 1 mm x 1 mm x 1 mm image grid

[1] Johnson et al., IEEE Trans Nucl Sci 63(1): 52-60          [2] Rit et al., Med Phys. 2013 Mar;40(3):031103
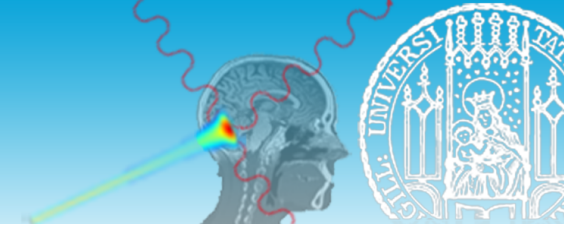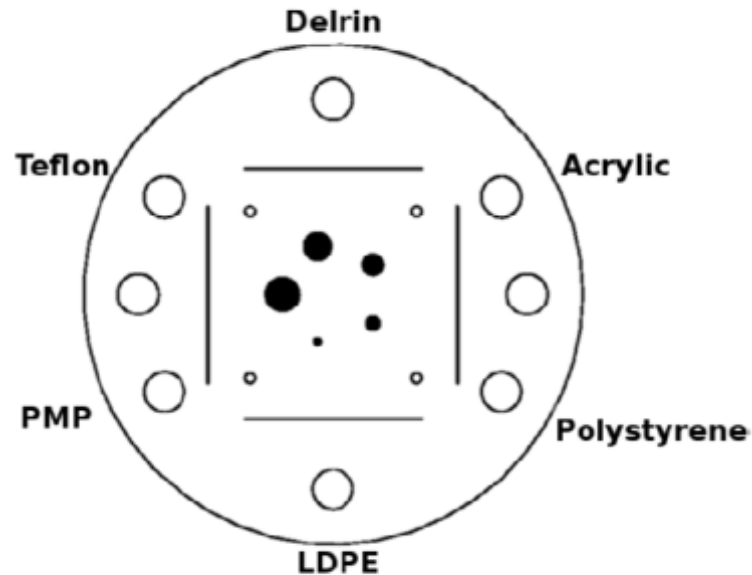
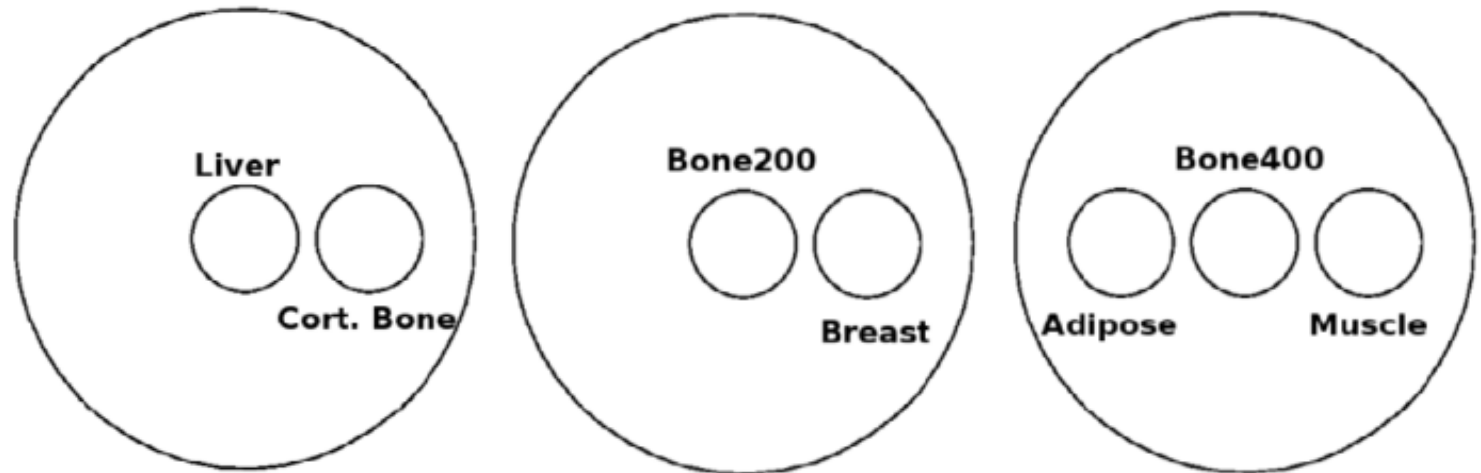## Siemens SOMATOM Definition Force[1]



Dual Source CT is equipped with two X-ray tubes and two detectors
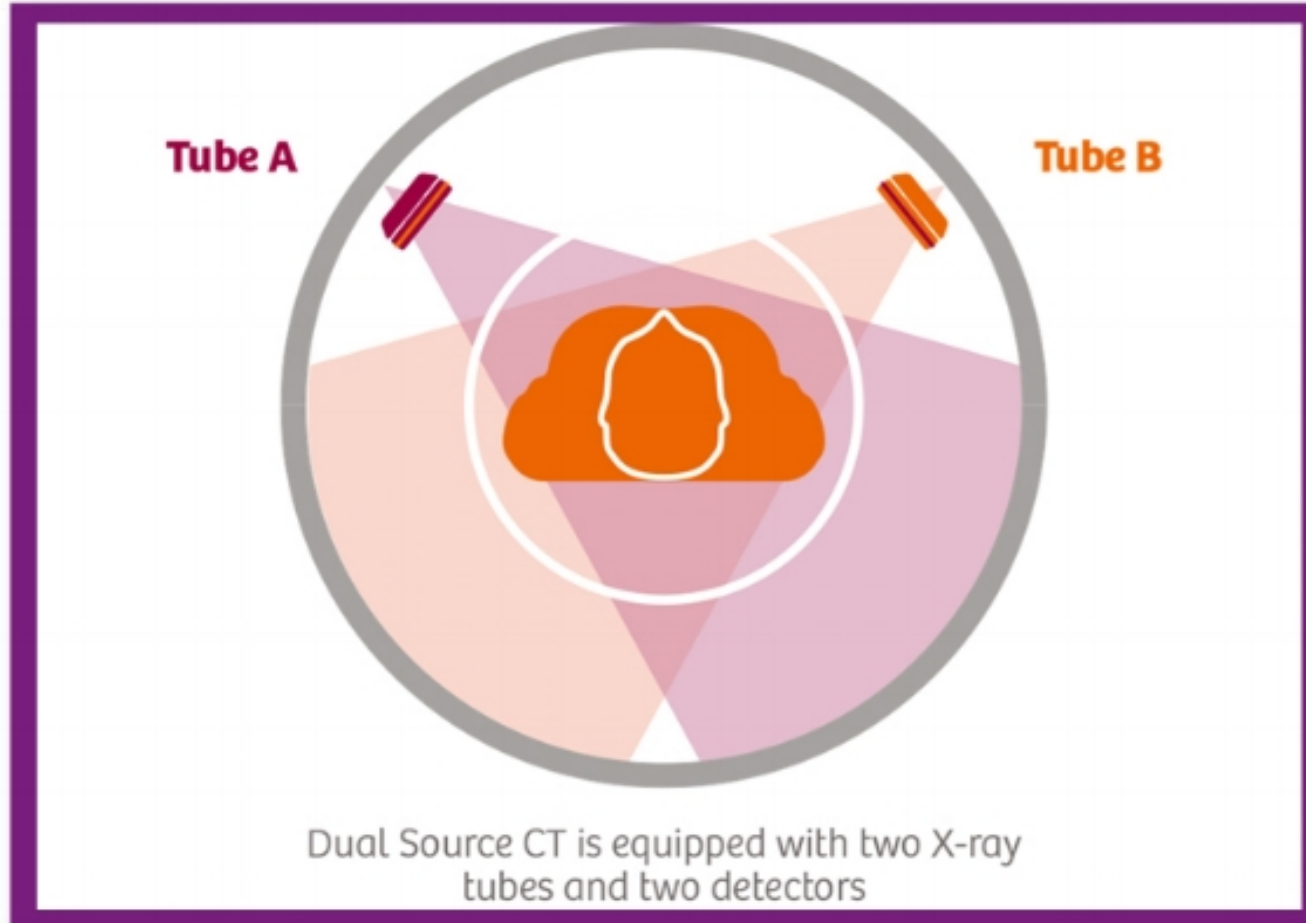
Some scanner info
- Dual source
- 90 kVp and 150 kVp
- Iterative reconstruction (from the vendor)

[1] Almeida et al., Phys. Med. Biol. 63 115008

Catphan CTP404

LMU custom made phantom

- **4** phantoms, containing **13** cylindrical inserts of tissue equivalent plastic inserts
- Covering an RSP range from **0.88** to **1.79**
- Insert radii: **12.2 mm** and **30 mm**
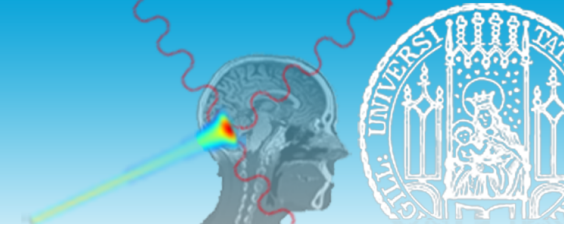- Phantom radii: **130 mm** and **150 mm**

- Reference RSP measured with a variable water column at HIT

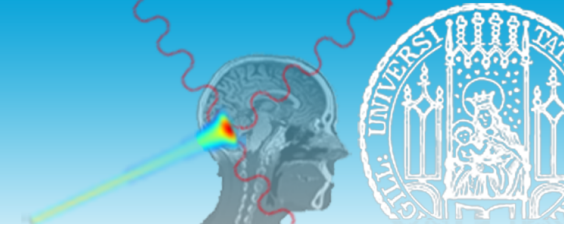| Insert | Phantom | $RSP_{ref}$ |
|---|---|---|
| PMP | CTP404 | 0.88 |
| Adipose | LMU | 0.97 |
| LDPE | CTP404 | 0.98 |
| Breast | LMU | 0.99 |
| Polystyrene | CTP404 | 1.02 |
| Muscle | LMU | 1.06 |
| Liver* | LMU | 1.06 |
| Bone200* | LMU | 1.11 |
| Acrylic | CTP404 | 1.16 |
| Bone400* | LMU | 1.22 |
| Delrin | CTP404 | 1.36 |
| Cort. Bone | LMU | 1.69 |
| Teflon | CTP404 | 1.79 |

# RSP from pCT

- Directly RSP
- From each projection: WEPL (line integral of RSP)
- From the tracker: position and direction information (estimation of curved path)
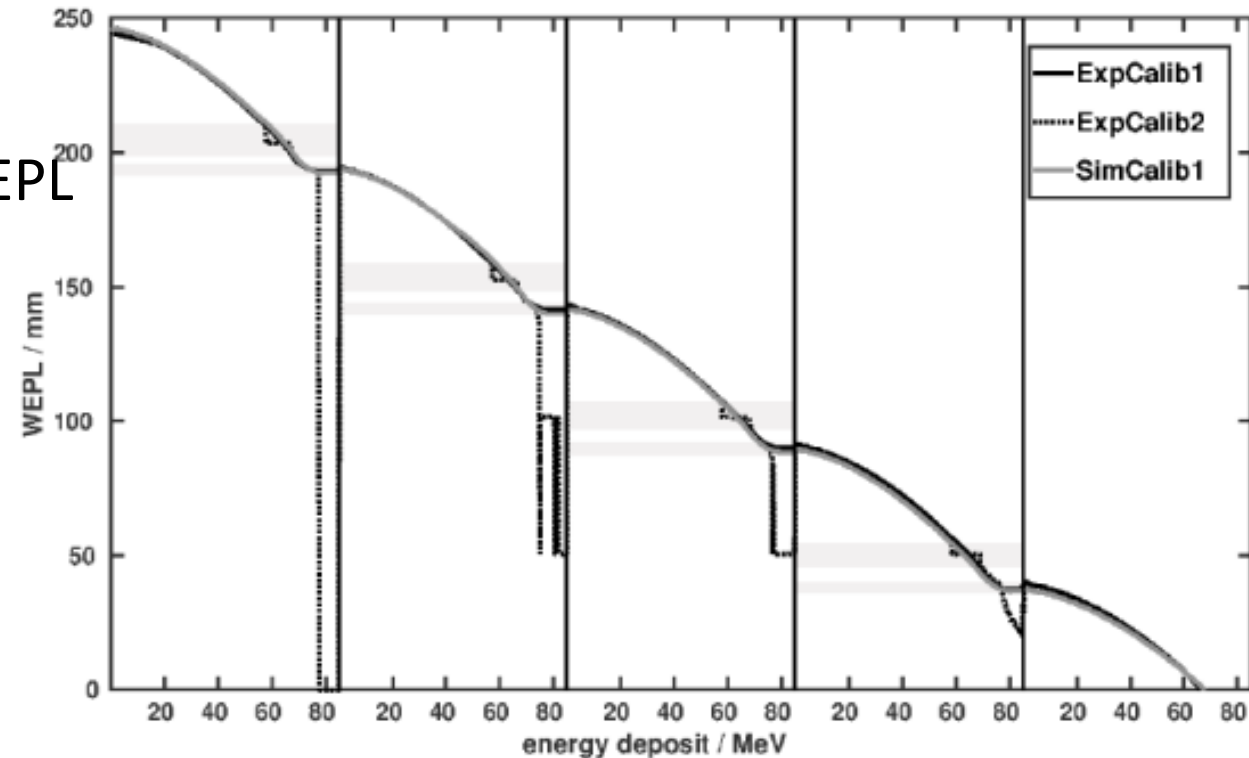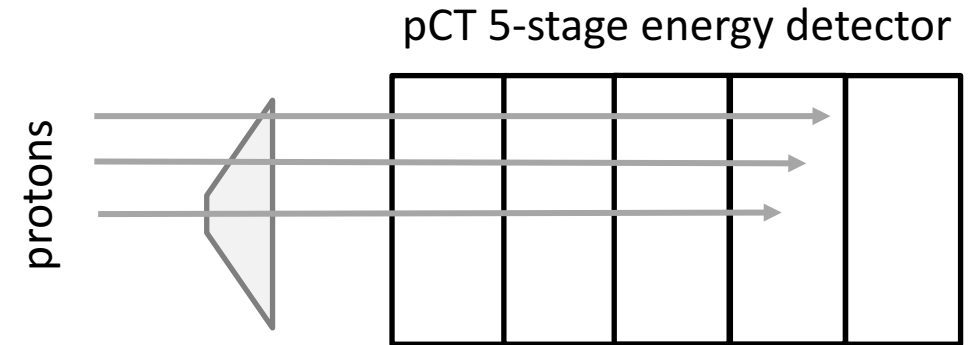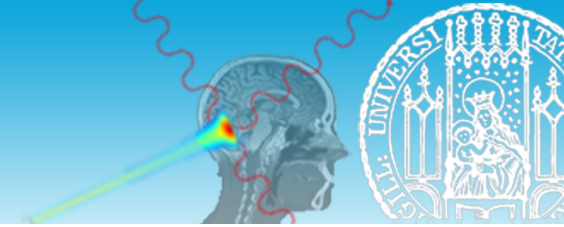- Reconstruction of RSP taking into account curved proton paths



WEPL = RSP*length
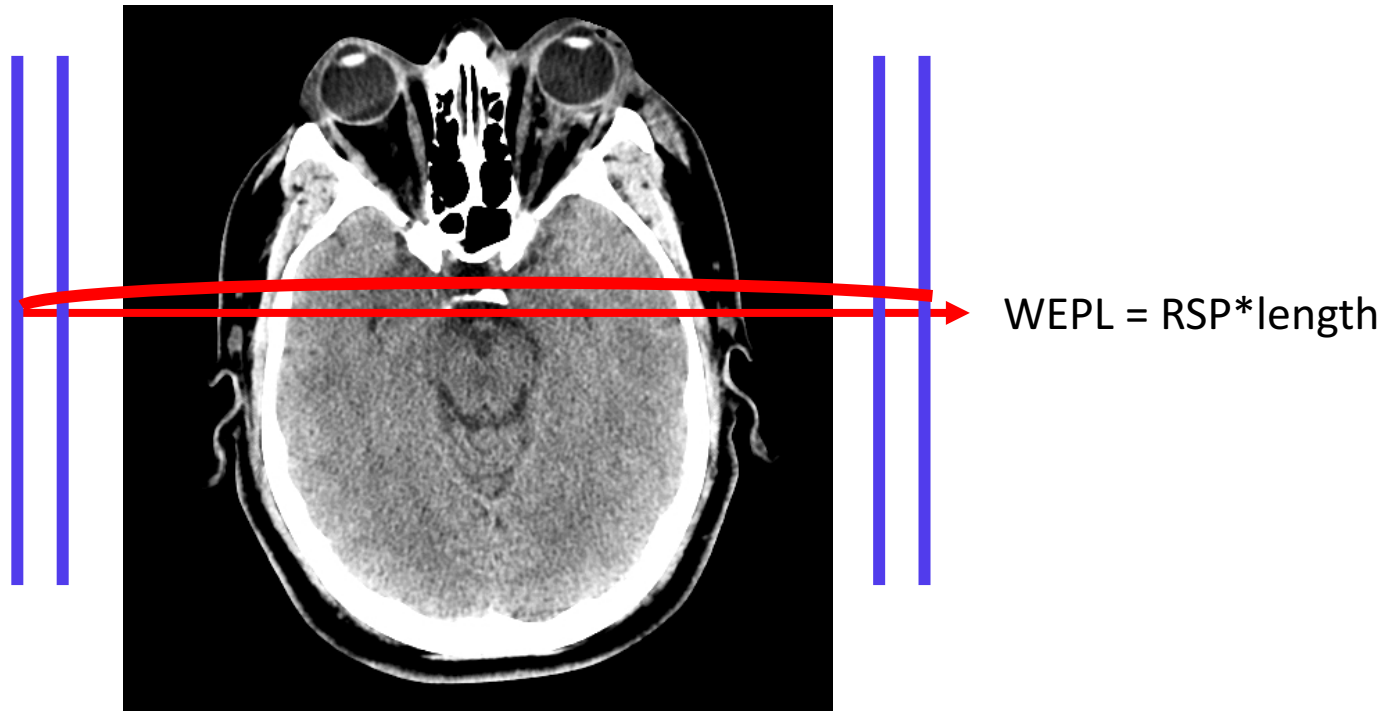
- Remember: 5-stage energy detector

- Inter-stage info: determine the stopping stage

- Intra-stage info: determine stopping within a stage

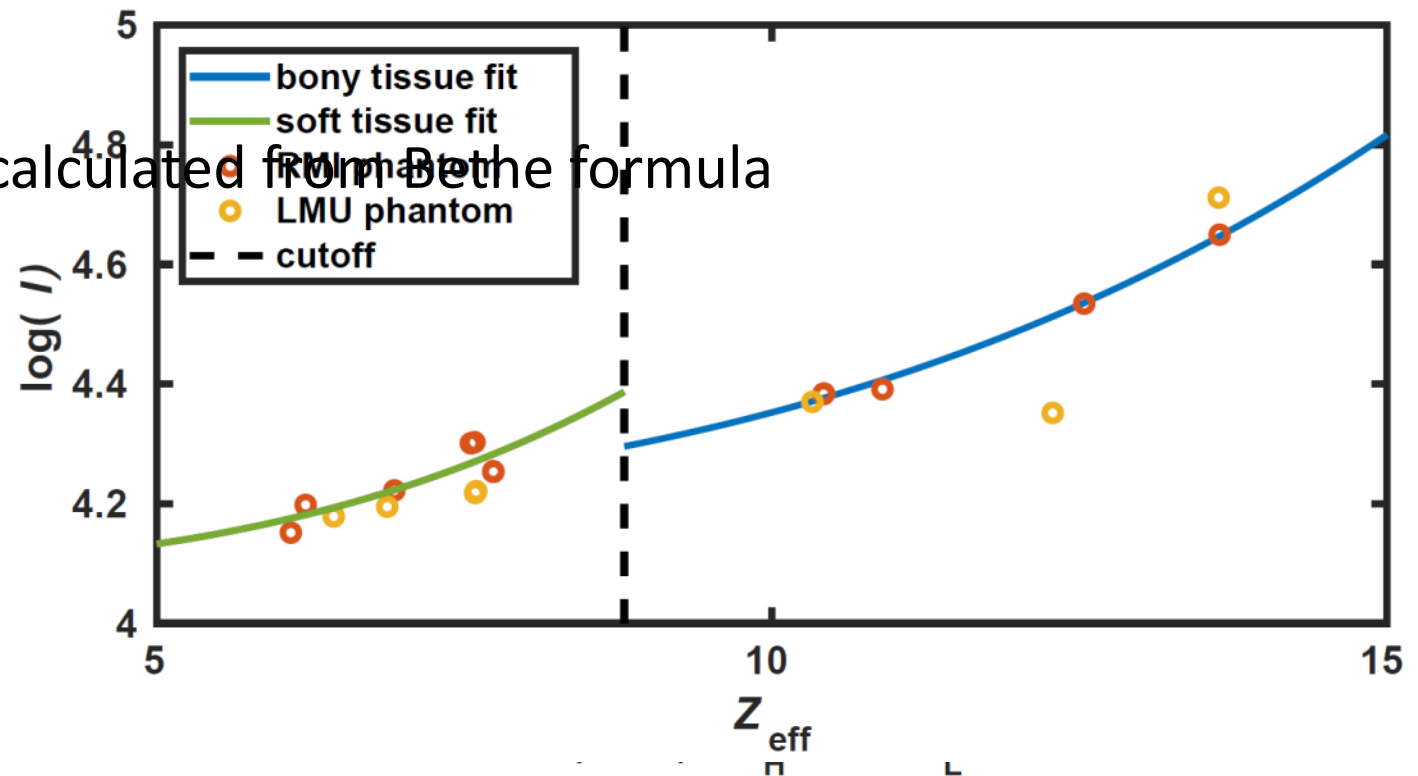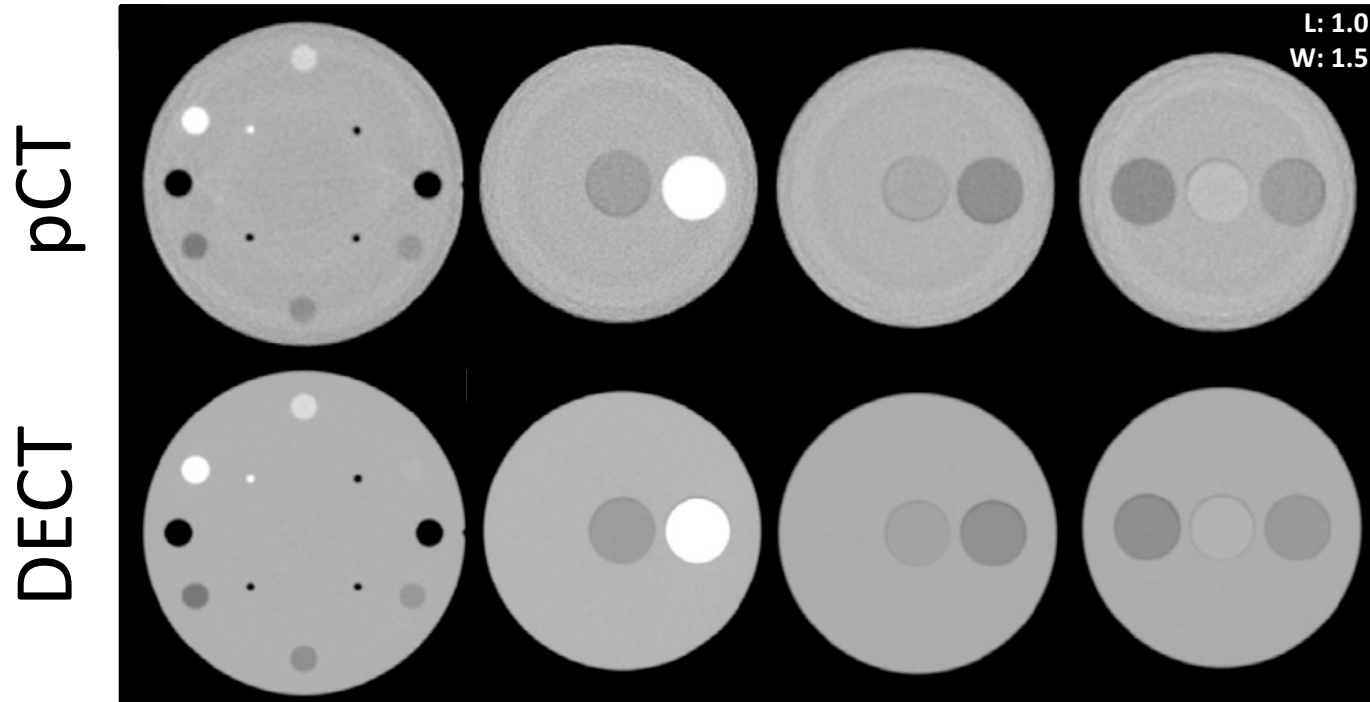- Use a known object to create a calibration between signal in each stage and traversed WEPL

pCT 5-stage energy detector

protons

- Use the HU obtained with the two energies
- Obtain a $\rho_e$ fit
- Knowing $\rho_e$ , obtain a $Z_{eff}$ fit
- Knowing $Z_{eff}$ , obtain an $I$ fit

- Having $\rho_e$ and and $I$, RSP can be calculated from Bethe formula

$$\ln \frac{I}{I_w} = C_1 \left[ \left( \frac{Z_{eff}}{Z_{eff,w}} \right)^{3.3} - 1 \right] - C_0 \, \gamma_0$$
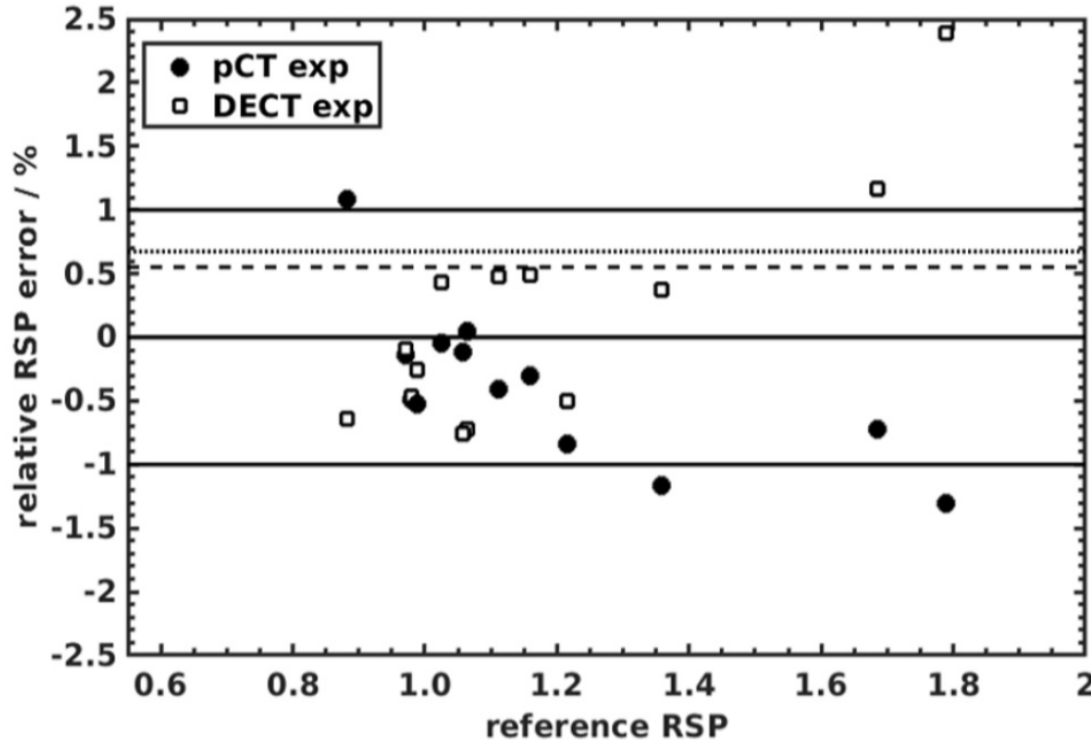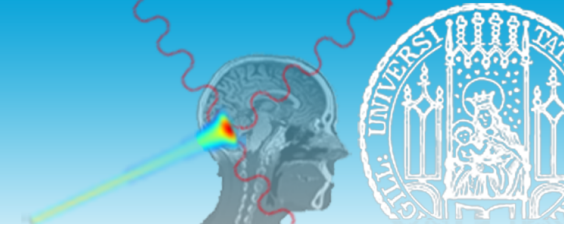
# RSP images



- Imaging dose: **1.5 mGy – 1.9 mGy** for pCT and **35.7** mGy for DECT (DECT noise 40x lower)

- Scan duration: **6 min** for pCT and **14 sec** for DECT

- pCT images contained ring artifacts affecting RSP accuracy

- RSP accuracy mostly within ±1% for both modalities
- Above 1% errors for pCT:
  - Teflon: **-1.31%**,   $RSP_{ref}$ = 1.79
  - Delrin: **-1.16%**,   $RSP_{ref}$ = 1.36
  - PMP: **1.08%**,   $RSP_{ref}$ = 0.88
- Above 1% errors for DECT:
  - Teflon: **2.38%**,   $RSP_{ref}$ = 1.79
  - Cort. Bone: **1.17%**,   $RSP_{ref}$ = 1.69

- Mean absolute percent error over all 13 inserts: **0.55%** for pCT, **0.67%** for DECT

- Mean absolute percent error excluding Teflon insert: **0.49%** for pCT, **0.53%** for DECT

| Insert | Phantom | $RSP_{ref}$ | $pCT_{exp}$ % | $pCT_{sim}^{ideal}$ % | $pCT_{sim}^{real}$ % | DECT % |
|---|---|---|---|---|---|---|
| PMP | CTP404 | 0.88 | $1.08 \pm 0.11$ | $-0.07 \pm 0.09$ | $-0.22 \pm 0.11$ | $-0.64 \pm 0.02$ |
| Adipose | LMU | 0.97 | $-0.14 \pm 0.04$ | $-0.36 \pm 0.03$ | $-0.95 \pm 0.04$ | $-0.09 \pm 0.01$ |
| LDPE | CTP404 | 0.98 | $-0.49 \pm 0.11$ | $-0.18 \pm 0.08$ | $-0.08 \pm 0.10$ | $-0.46 \pm 0.02$ |
| Breast | LMU | 0.99 | $-0.52 \pm 0.04$ | $0.05 \pm 0.03$ | $-0.39 \pm 0.04$ | $-0.25 \pm 0.01$ |
| Polystyrene | CTP404 | 1.02 | $-0.04 \pm 0.10$ | $0.02 \pm 0.08$ | $-0.04 \pm 0.10$ | $0.43 \pm 0.02$ |
| Muscle | LMU | 1.06 | $-0.12 \pm 0.04$ | $-0.44 \pm 0.03$ | $-0.95 \pm 0.03$ | $-0.76 \pm 0.01$ |
| Liver* | LMU | 1.06 | $0.04 \pm 0.03$ | $-0.17 \pm 0.03$ | $-1.47 \pm 0.03$ | $-0.73 \pm 0.01$ |
| Bone200* | LMU | 1.11 | $-0.41 \pm 0.03$ | $-0.14 \pm 0.03$ | $-1.36 \pm 0.03$ | $0.48 \pm 0.01$ |
| Acrylic | CTP404 | 1.16 | $-0.30 \pm 0.10$ | $-0.10 \pm 0.07$ | $-0.44 \pm 0.09$ | $0.49 \pm 0.01$ |
| Bone400* | LMU | 1.22 | $-0.84 \pm 0.03$ | $-0.44 \pm 0.03$ | $-1.11 \pm 0.03$ | $-0.50 \pm 0.01$ |
| Delrin | CTP404 | 1.36 | $-1.16 \pm 0.09$ | $-0.01 \pm 0.07$ | $-0.45 \pm 0.09$ | $0.38 \pm 0.02$ |
| Cort. Bone | LMU | 1.69 | $-0.73 \pm 0.02$ | $-0.21 \pm 0.02$ | $-0.37 \pm 0.02$ | $1.17 \pm 0.01$ |
| Teflon | CTP404 | 1.79 | $-1.31 \pm 0.05$ | $-0.06 \pm 0.05$ | $-1.11 \pm 0.05$ | $2.38 \pm 0.01$ |
| MAPE % | | | 0.55 | 0.17 | 0.69 | 0.67 |
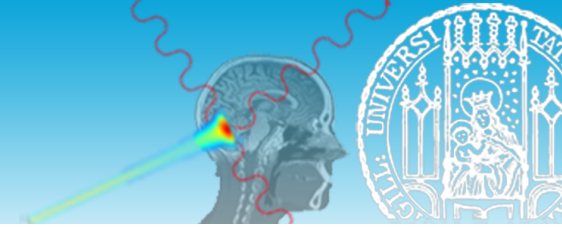
# Part 2: pCT artifacts
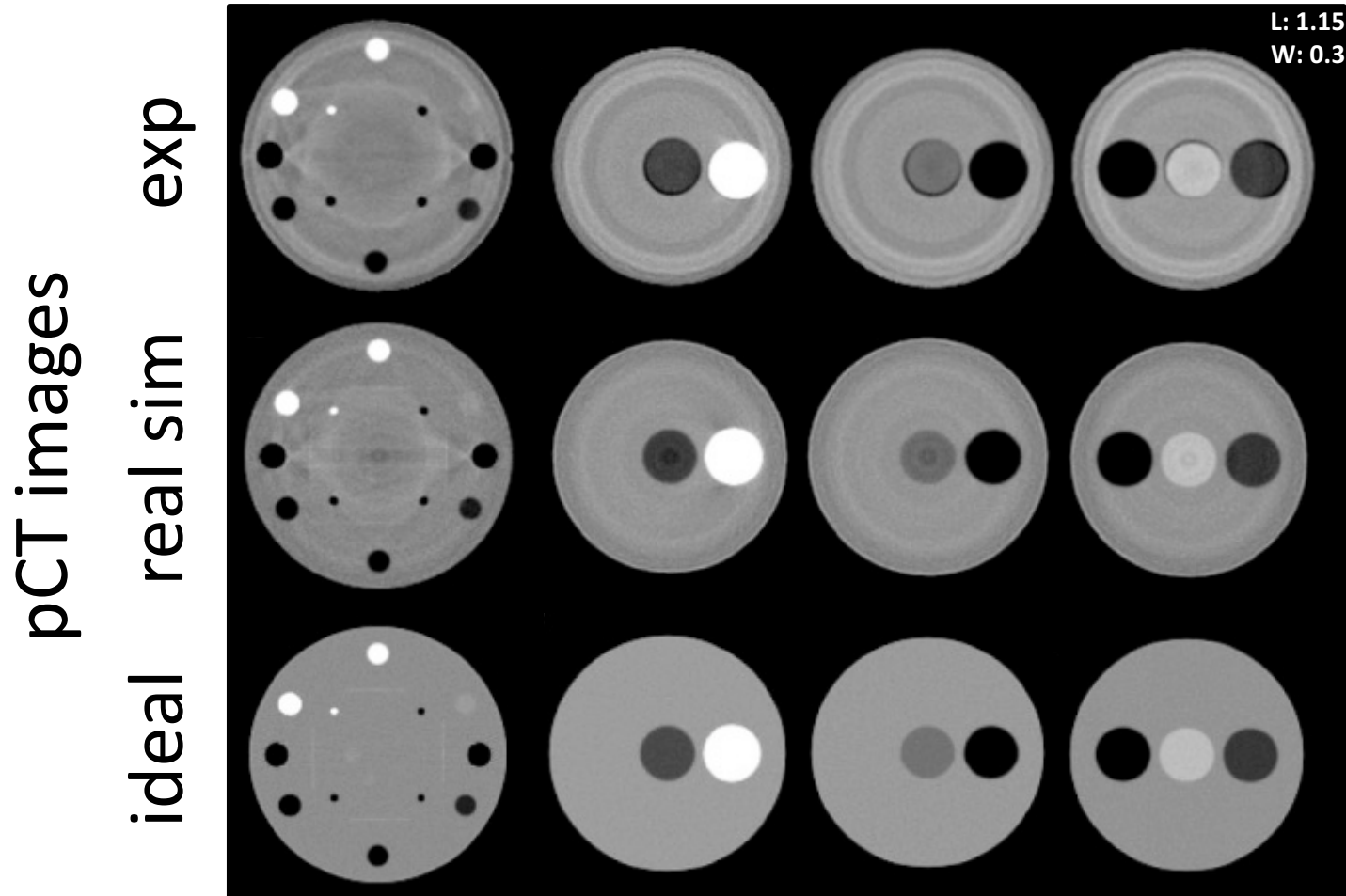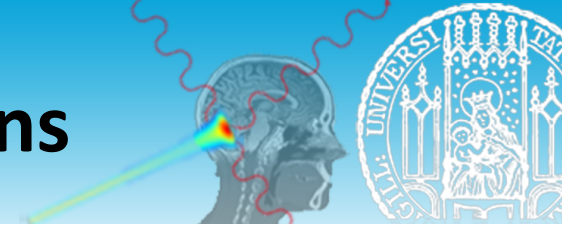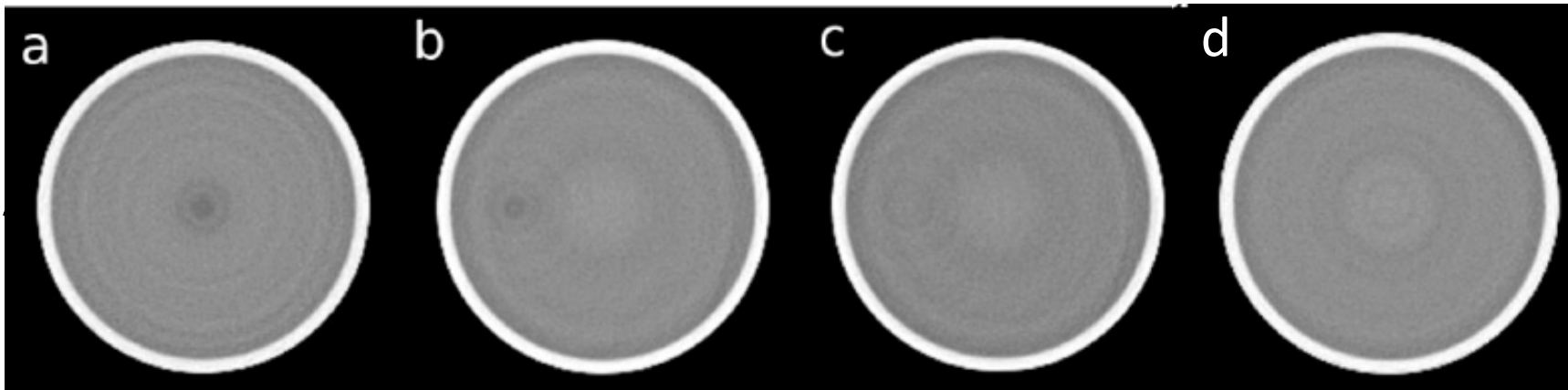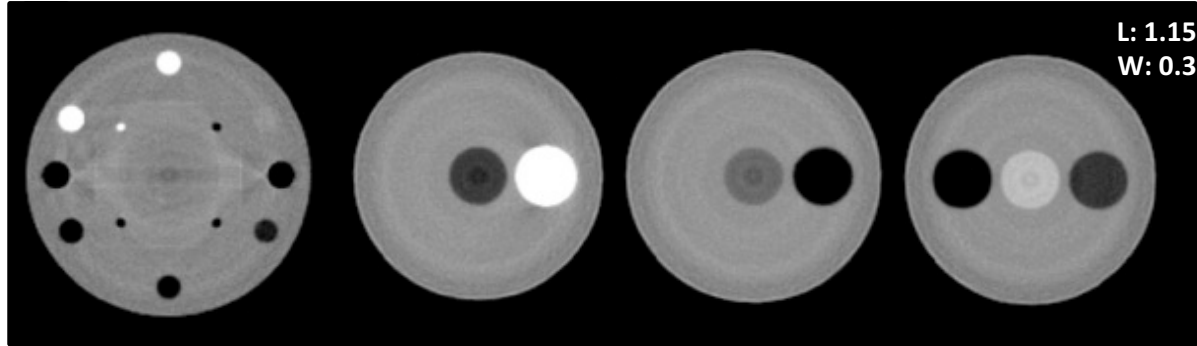
- The observed artifacts (of this magnitude) are not related to the reconstruction algorithm
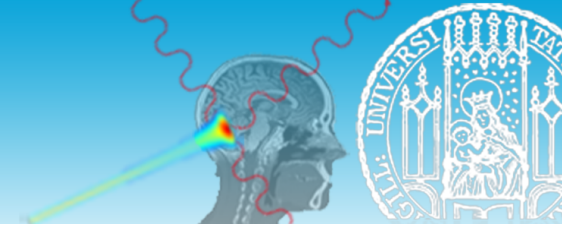
real sim



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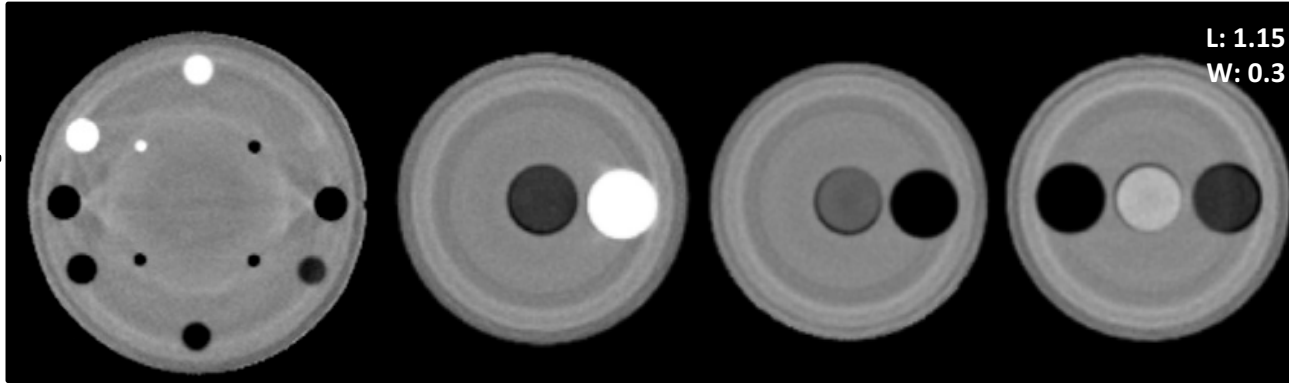- Geant4 code in github containts a fix for the tracker gap geometry

exp

L: 1.15
W: 0.3
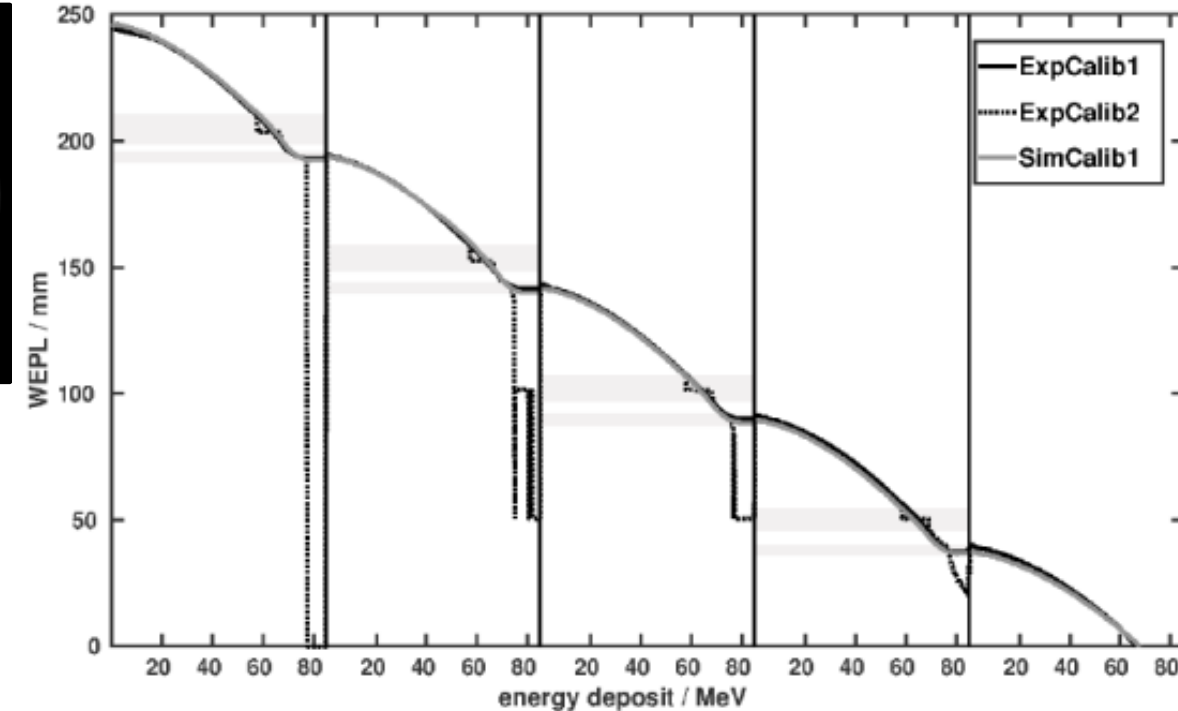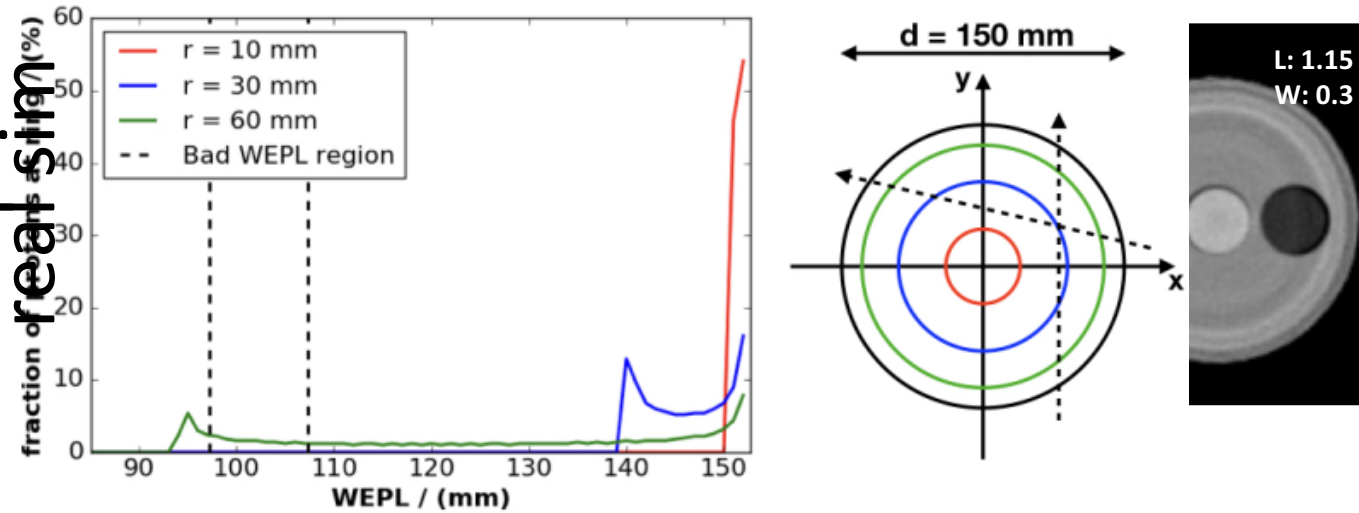
- Lets assume that for some particular WEPLs, our detector is slightly less accurate
- In homogeneous cylindrical objects this results in ring artifacts
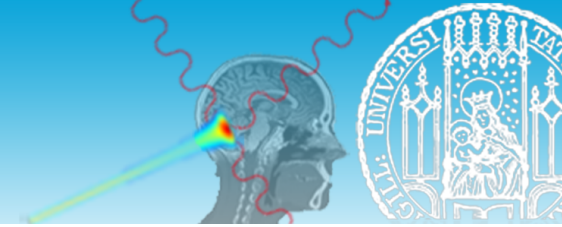- Our calibration curve indicates that there potentially are such WEPL regions

- During acquisition, every voxel is traversed by protons of different WEPLs
- Calculating for each voxel, the fraction of protons which according to the calibration have lower accuracy WEPLs (kink regions and stage interfaces)

# Conclusions
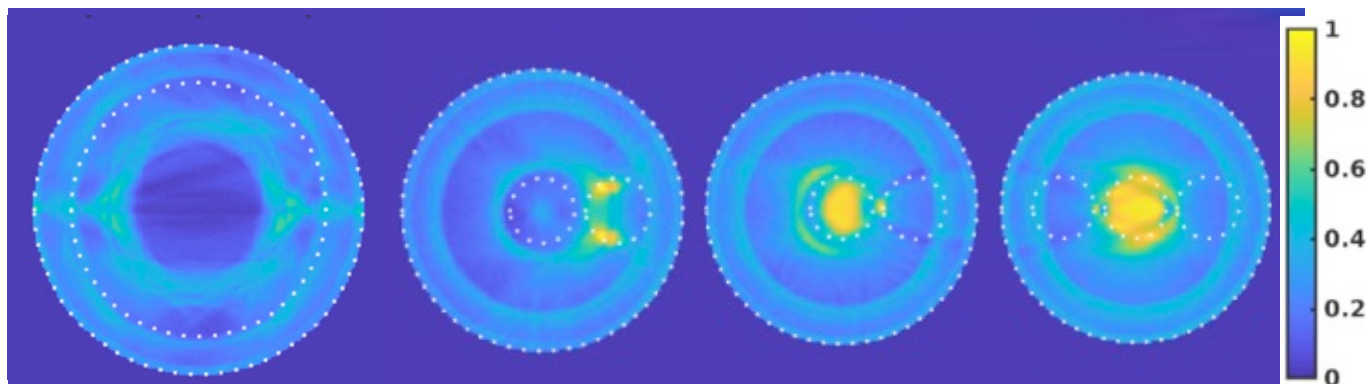
- First direct experimental comparison of pCT and DECT on RSP accuracy

- Both modalities on average well below 1% error (pCT 0.55%, DECT 0.67%)

- pCT phase II prototype already competitive

- pCT promising for low dose, on isocenter, accurate RSP imaging

- Reliable simulation tool for understanding the scanner

- Artifact mitigation can lead to further improvement in pCT RSP accuracy

# Thank you!

Physics in Medicine & Biology

# Experimental comparison of proton CT and dual energy X-ray CT for relative stopping power estimation in proton therapy

Georgios Dedes[1], Jannis Dickmann[2] (iD), Katharina Beatrice Niepel[1], Philipp Wesp[3], Robert P Johnson[4], Mark Pankuch[5], Vladimir A Bashkirov[6] (iD), Simon Rit[7], Lennart Volz[8] (iD), Reinhard W Schulte[9] (iD), Guillaume Landry[1] and Katia Parodi[1] — Hide full author list