# Improved Woodcock tracking on Monte Carlo simulations for medical applications

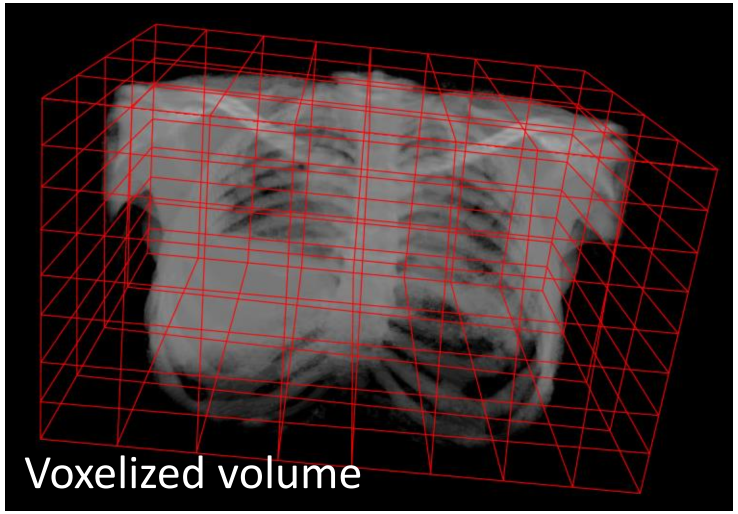
A. Behlouli, J. Bert, D. Visvikis

LaTIM, INSERM UMR1101, Brest, France

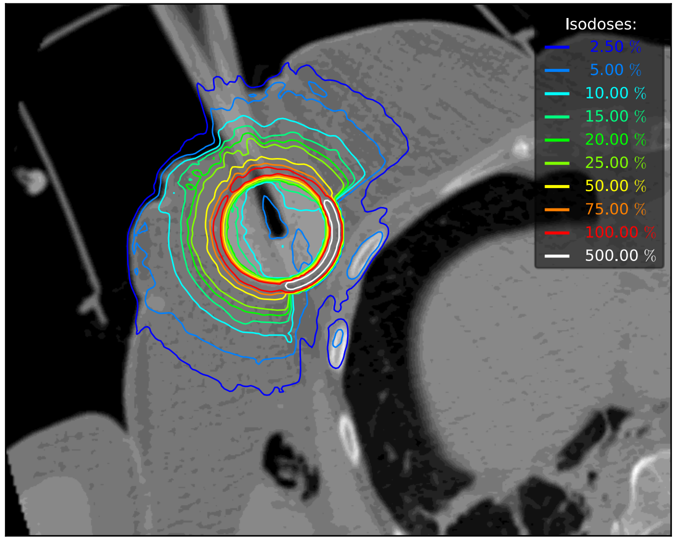
MCMA2017 15-18 October 2017 Napoli, Italy

# Context and issues

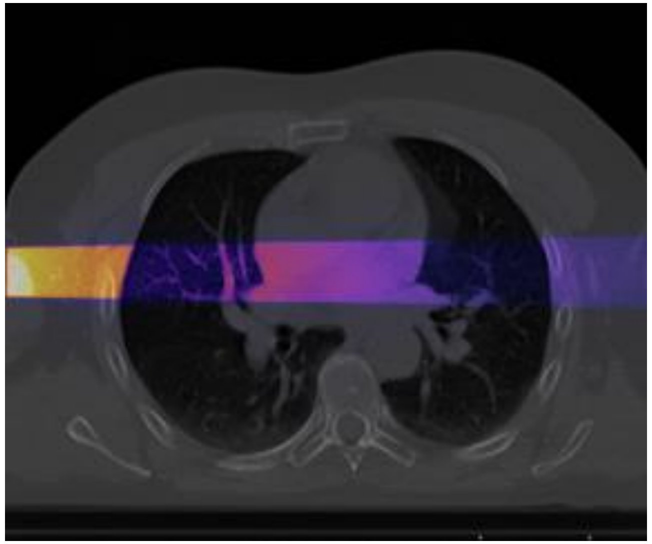
- Monte Carlo simulations are associated with long execution times
  - Especially for medical applications (voxelized volume navigation, million of analytical boxes)
- 1st solution: GPU based Monte Carlo simulation
  *Jia et al. 2014, Phys. Med. Biol.*



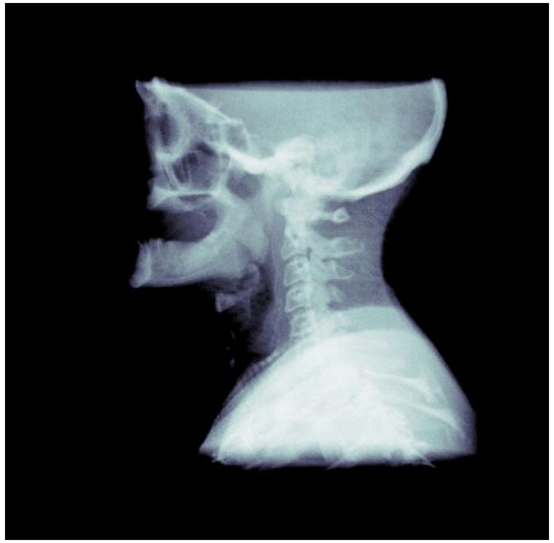
# GGEMS: GPU GEant4-based Monte Carlo Simulations




Intra-Operative Radiotherapy



External Beam Radiotherapy



Medical Imaging

**x80-x150**

*Bert et al. 2016, IEEE NSS-MIC*
*Bert et al. 2016, Phys. Med. Biol.*
*Garcia et al. 2016, Phys. Med. Biol.*
*Lemaréchal et al. 2015, Phys. Med. Biol.*
*Bert et al. 2013, Phys. Med. Biol.*

# Context and issues

- MCS are associated with long execution times
  - Especially for medical applications (voxelized volume navigation, costly intersection tests)
- 1st solution: GPU based Monte Carlo simulation

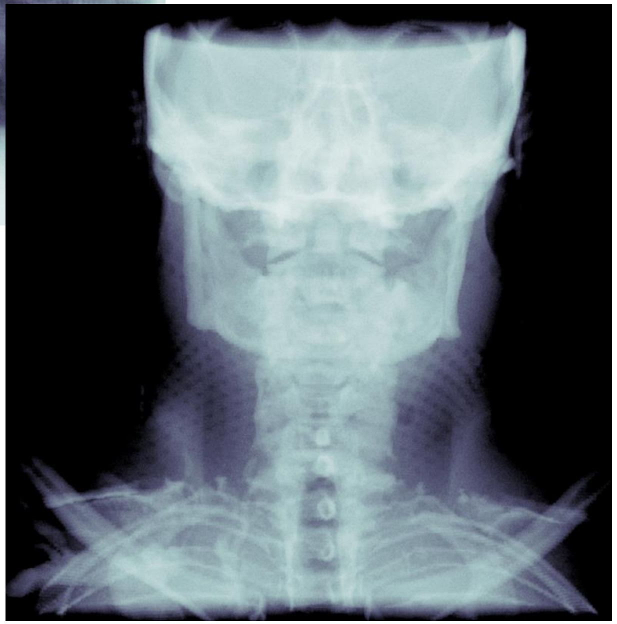
  *Jia et al. 2014, Phys. Med. Biol.*
  - Not enough fast for some applications

    GGEMS (GPU NVIDIA GTX980Ti): 1h30min / projection
- 2nd solution: Variance Reduction Technique (VRT)
  - Woodcock tracking, well suitable for voxelized volume

    *Woodcock et al. 1965, Proc. Conf. App. of Computing Methods to Reactor Problems*

    *Rehfeld et al. 2009, Phys. Med. Biol*

2.8 billions of particles
2000 counts/pixel



2.8 billions of particles
2000 counts/pixel

# Woodcock tracking

- Rejection based method (fictitious interaction)
- Interaction distances are sampled without the need of checking voxel boundaries

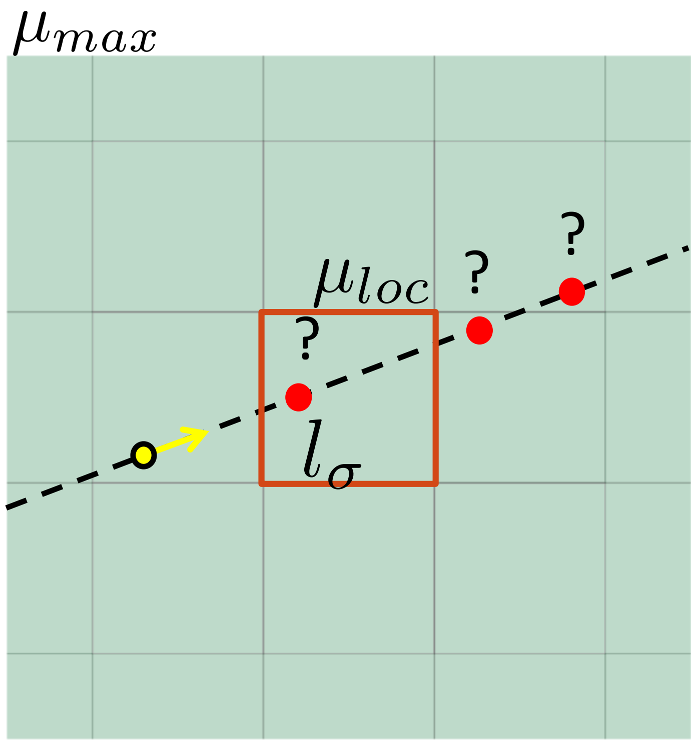
i. Determine the most attenuating material $\mu_{max}$

ii. Sample interaction distance: $l_\sigma = -\log \frac{\xi}{\mu_{max}(E)}$

iii. Move the particle without checking voxel boundaries

iv. Accept or not this interaction $p = \frac{\mu_{loc}(E)}{\mu_{max}(E)}$

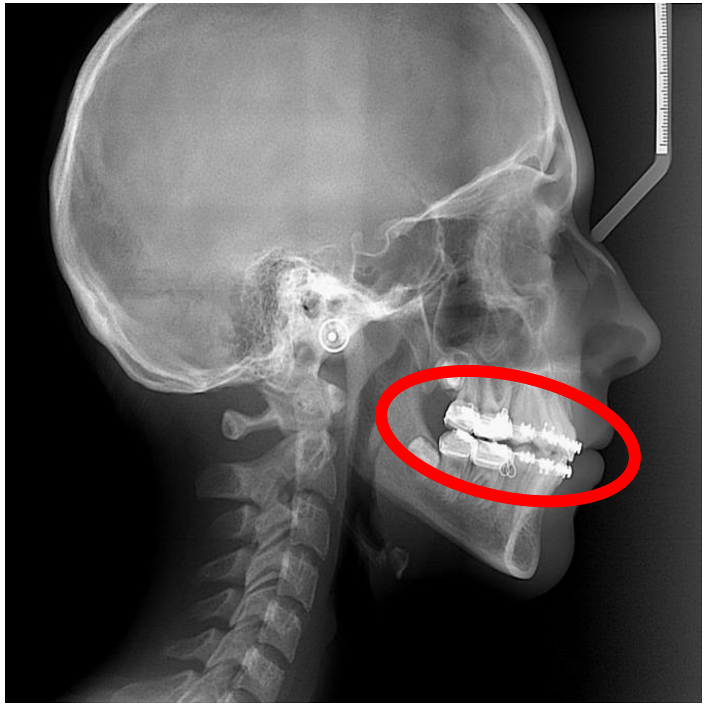
v. If accepted, resolve the physical discrete process

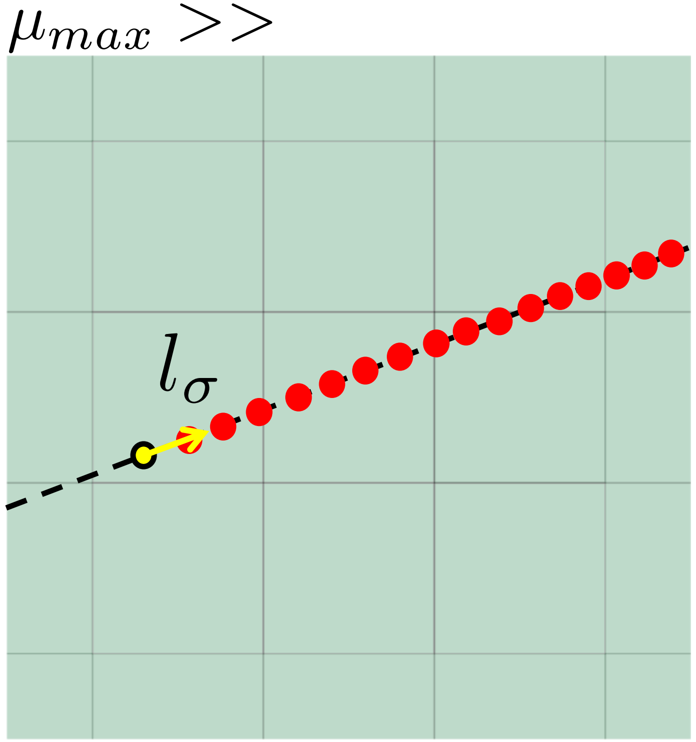


# Woodcock tracking

- Soft tissues, but also …
- … high attenuating material (bones, metal implants)

- High sampling (event within soft tissues)
- Small efficiency gain compared to regular tracking

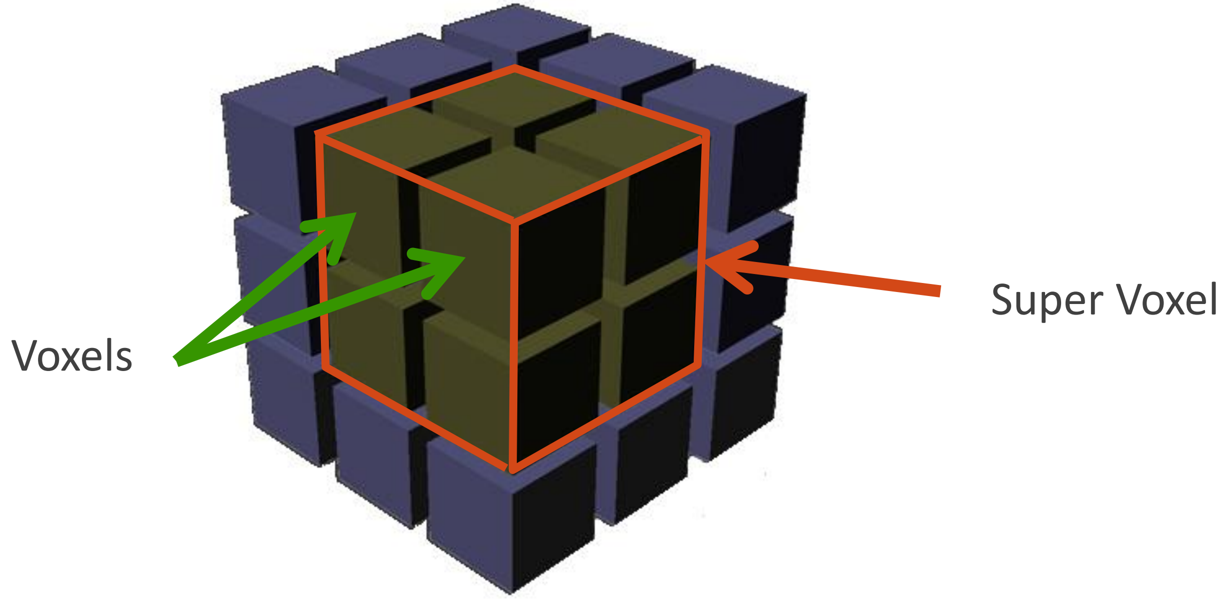




# Super voxel  concept

Volume rendering (smoke animation)

**Szirmay-Kalos et al. 2012,**
Free Path Sampling in High Resolution Inhomogeneous Participating Media, Computer Graphics




Super Voxel

- Group voxels into super voxels
- Not a merge
- Super voxel store parameters that are representative of the contained voxels

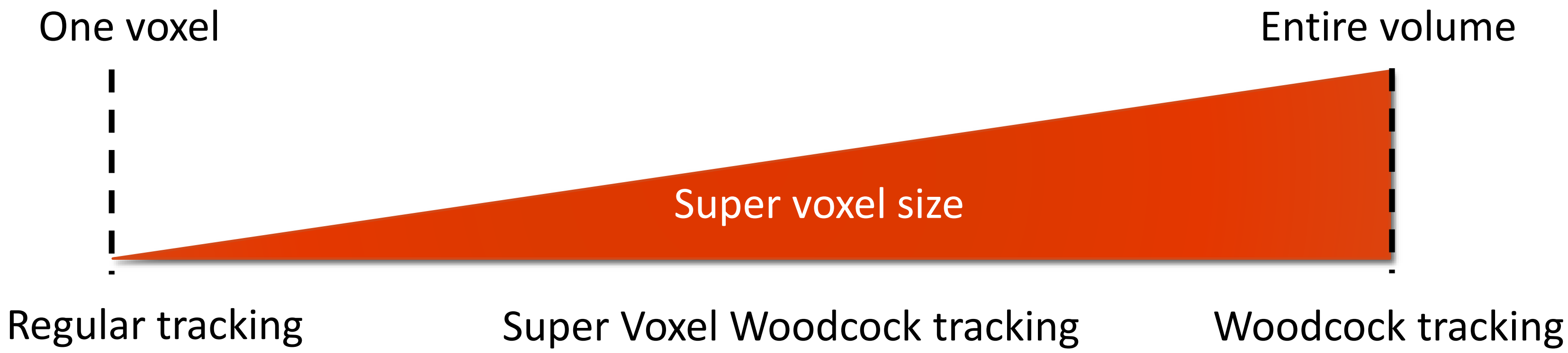
# Super Voxel Woodcock (SVW)

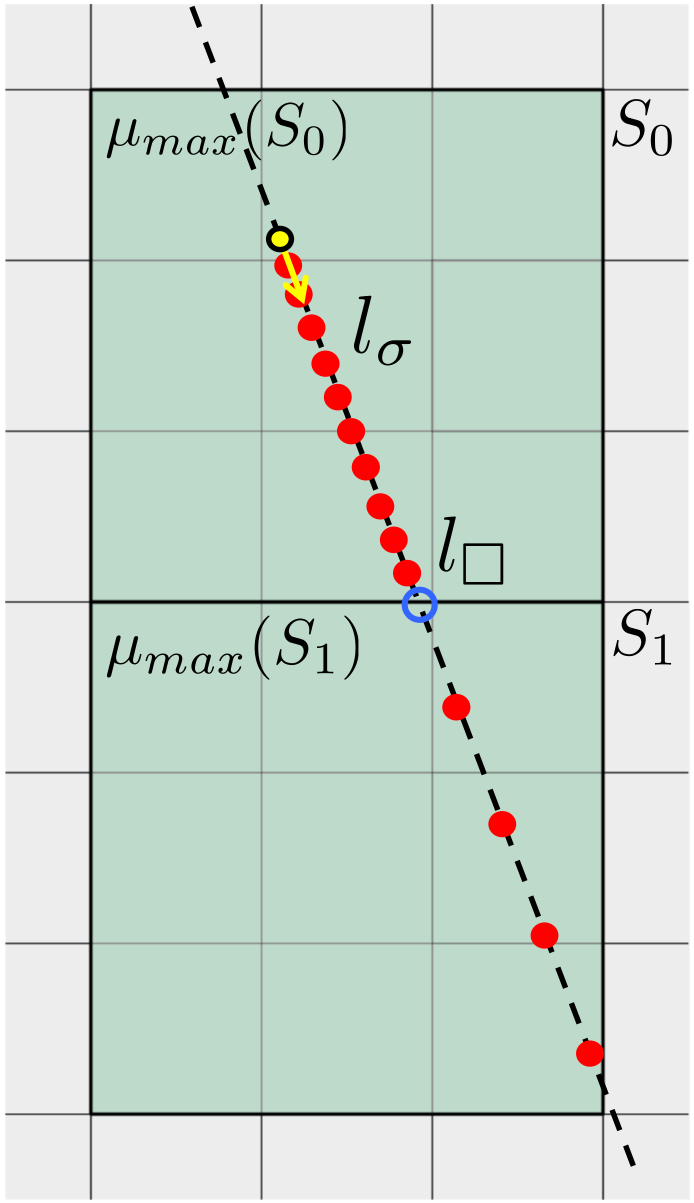
- Woodcock tracking per super voxel
- Most attenuating material per super voxel

- Particle tracking is adapted within each super voxel

- Boundary between super voxels $l_\square$

- SVW tracking: combine regular and woodcock tracking



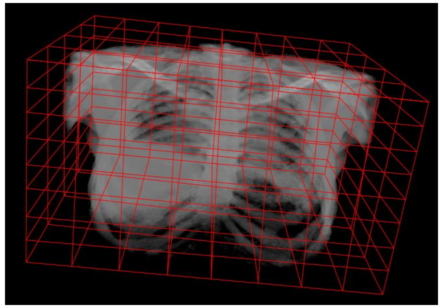



# GPU implementation

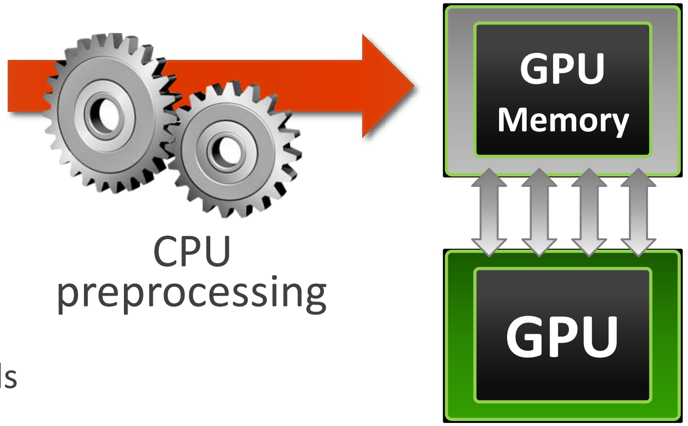
- Implemented within GGEMS library

- Each super voxel: index of the most attenuating material (per energy bin)
- Pre-calculated table is sent to the GPU global memory

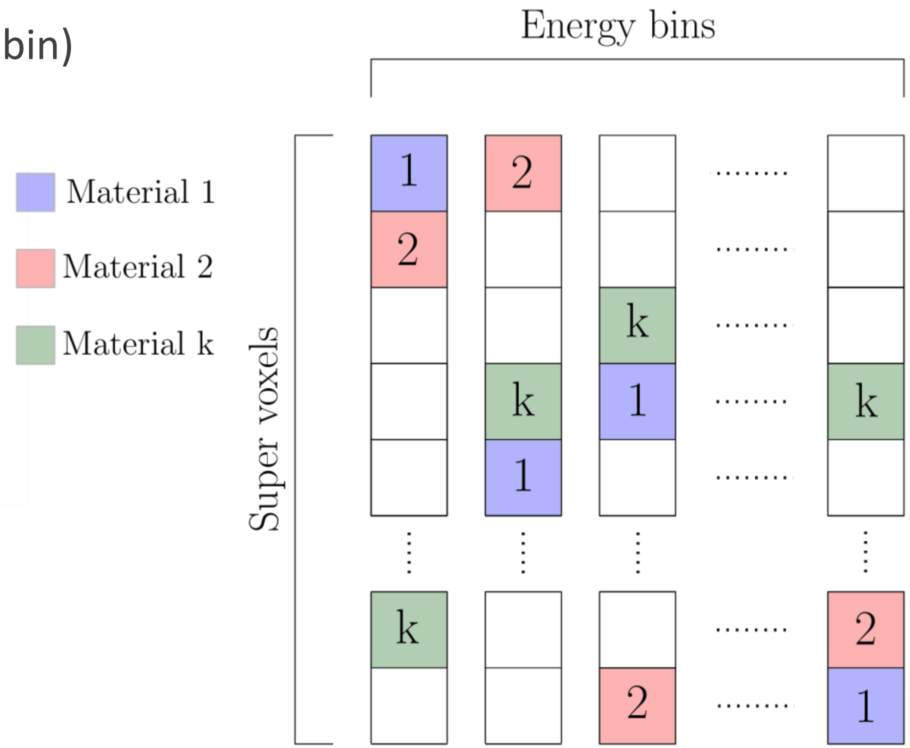
- Example:



Voxelized volume
288 x 241 x 164 voxels
$SVW_{20}$ 15 x 13 x 9 super voxels
Energy bins 220




Allocated memory 3 MB



# Application-based evaluation study (1/2)

**Transmission tomography** (single projection of CBCT)

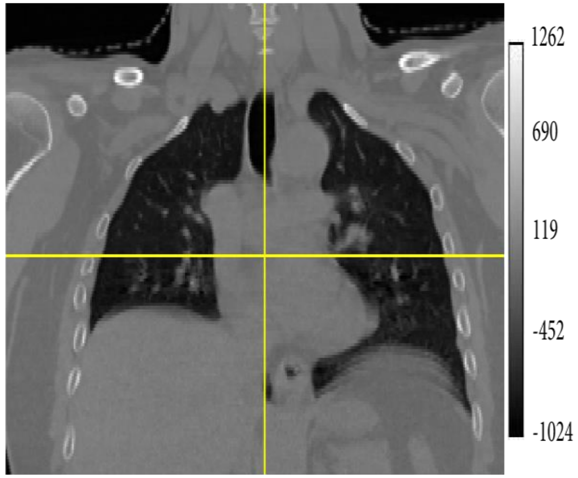
- Classic tube voltage of 120 kVp and a 2 mm aluminium filter
- Cone beam source: size 0.6 x 1.2 $mm^2$, aperture 8.7°

- Patient thorax phantom:
  - 41 materials,
  - 288 x 241 x 164 voxels,
  - spacing of 1.27 x 1.27 x 2.0 $mm^3$

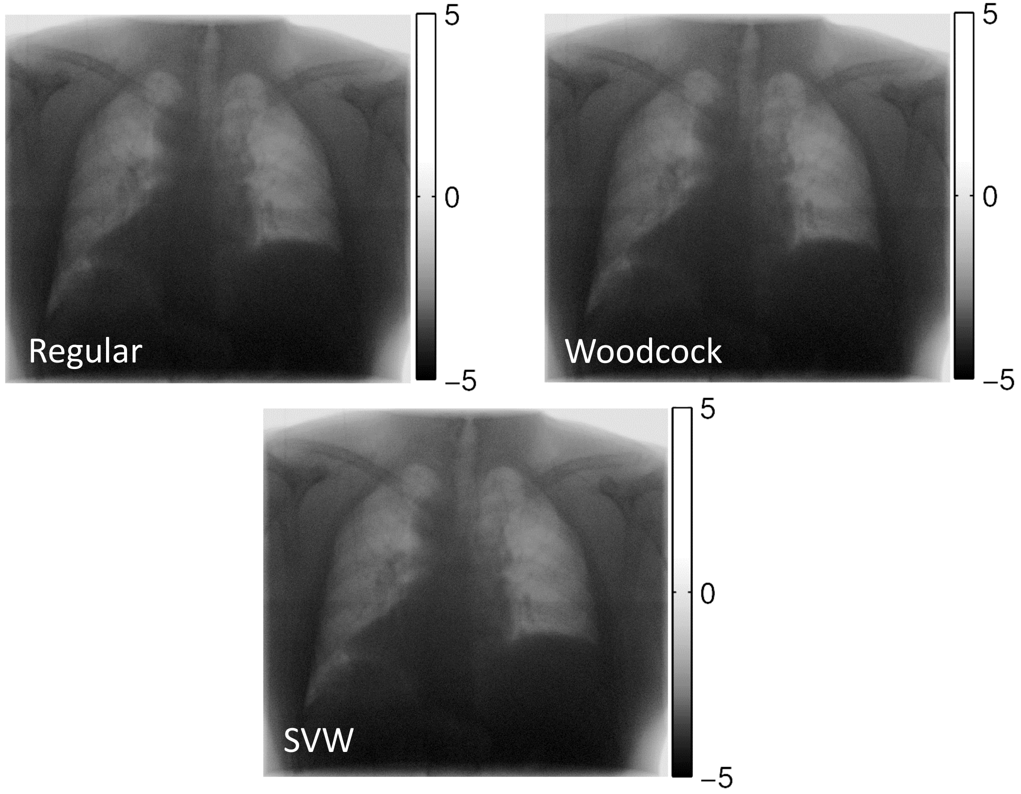
- Flat panel detector:
  - field of view of 1332 x 1242 $mm^2$
  - pixel size of 0.368 x 0.368 $mm^2$

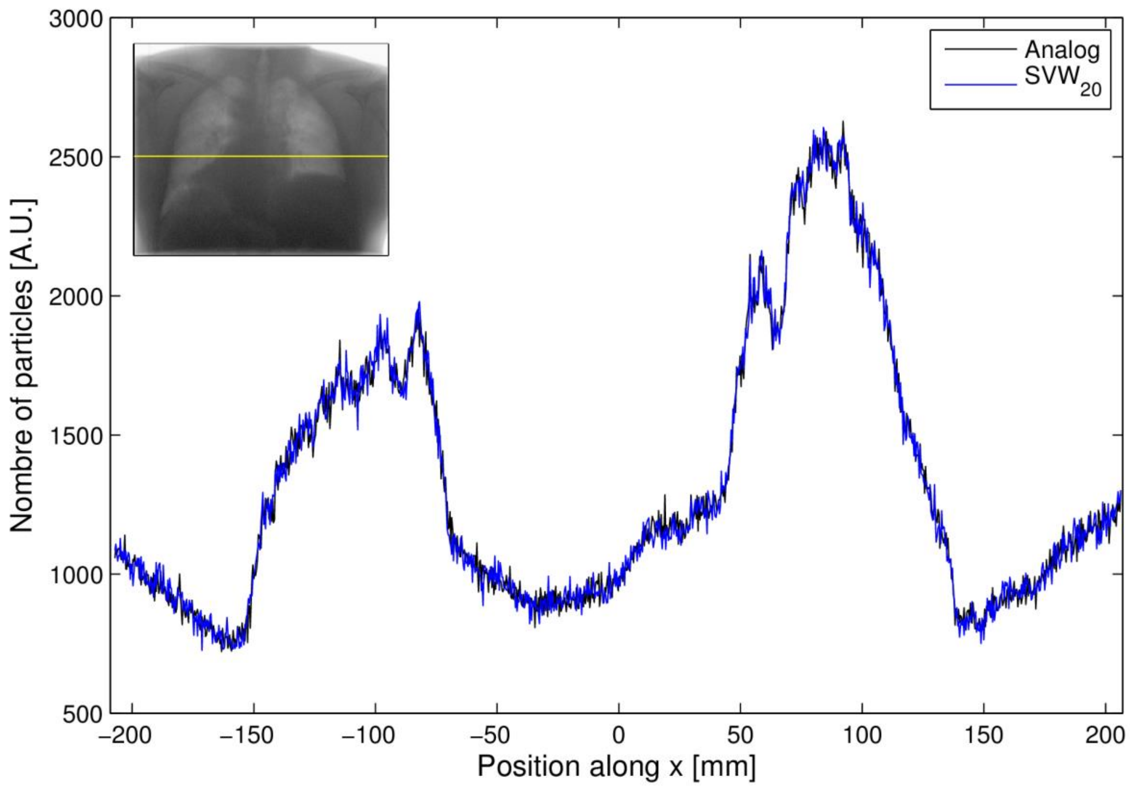
- Photons emitted from the x-ray source:
  - $10^{10}$ photons
  - ~1900 counts/pixel

- Super voxel: 20 x 20 x 20 voxels (fixed after a parametric study)



# Application-based evaluation study (1/2)




| Method | Simulation time | Acceleration factor |
|---|---|---|
| Regular | 5 h 7 m 18 s | - |
| Woodcock | 2 h 4 m 39 s | 2.4 |
| $SVW_{20}$ | 39 m 38 s | **7.7** |

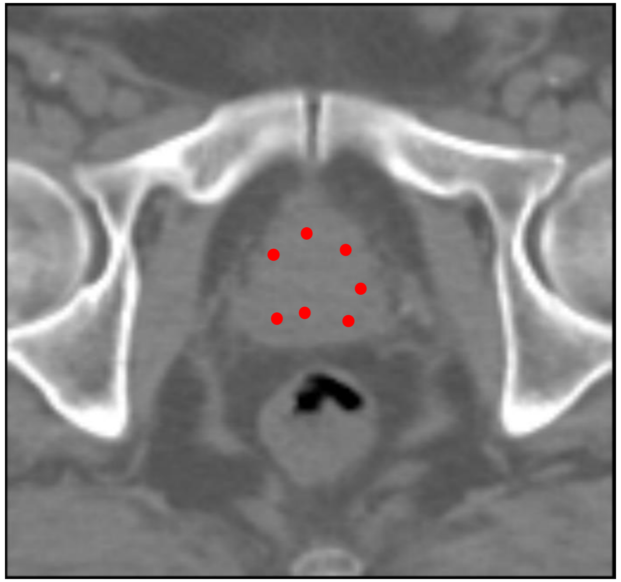
GTX 1050 Ti

Pascal 768 cores 1.392 GHz

# Application-based evaluation study (2/2)

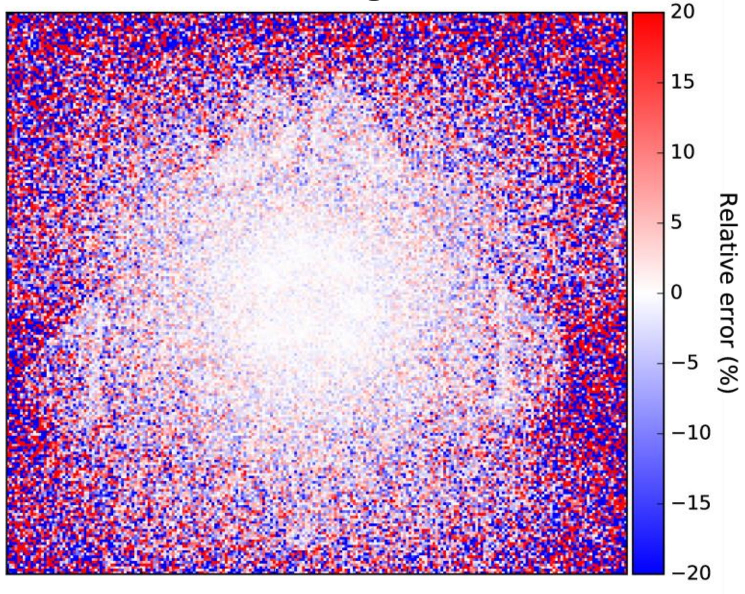
**Low-dose rate prostate brachytherapy**

- Patient pelvic phantom:
  - 233 x 211 x 61 voxels,
  - spacing of 0.78 x 0.78 x 2 $mm^3$
- Sources:
  - Treatment plan from VariSeed™ (Varian Medical Systems, Palo Alto, CA, USA)
  - $^{125}I$ seeds (STM1251 model)
- Photons emitted:
  - Total of $10^9$ photons
  - Dose uncertainty within the prostate less than 1%
- Super voxel: 25 x 25 x 25 voxels (fixed after a parametric study)

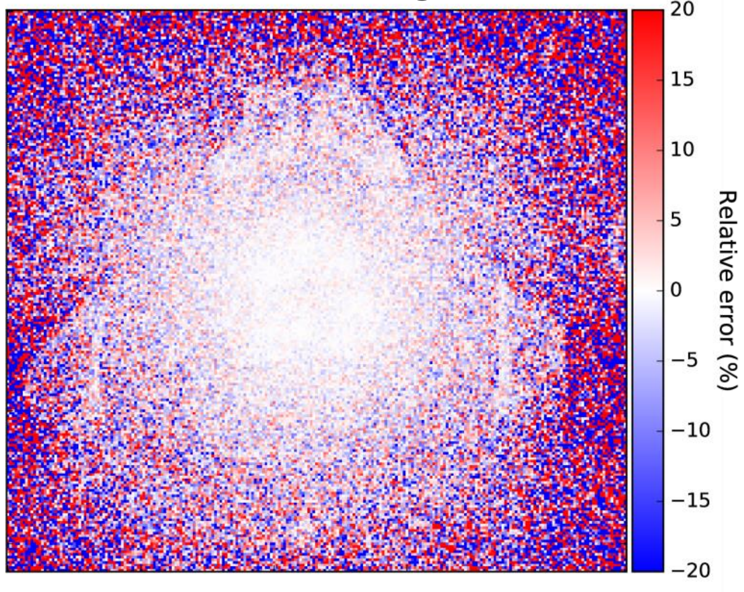


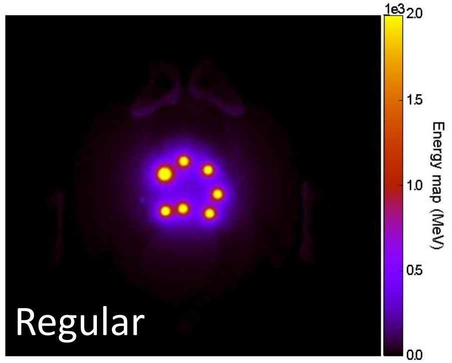
# Application-based evaluation study (2/2)

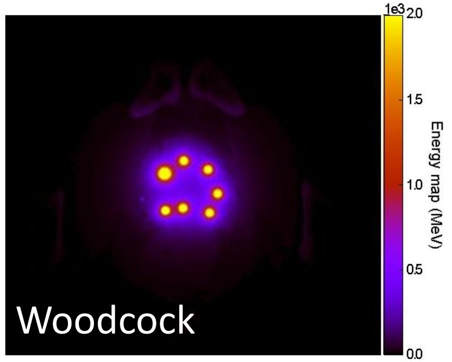
Relative dose error: regular vs Woodcock

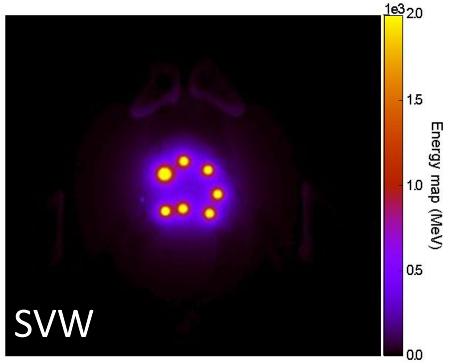



Relative dose error: regular vs SVW




GTX 1050 Ti

Pascal 768 cores 1.392 GHz

| Method | Simulation time | Efficiency | Acceleration factor |
|---|---|---|---|
| Regular | 19 m 14 s | $1.59 \times 10^5$ | - |
| Woodcock | 14 m 00 s | $2.19 \times 10^5$ | 1.3 |
| $SVW_{25}$ | 3 m 27 s | $8.87 \times 10^5$ | **5.6** |

$$\text{Efficiency} = \frac{1}{\text{Uncertainty}^2 \times \text{Simulation time}}$$

# Conclusion and perspectives

- Super Voxel Woodcock:
  - Combine the Woodcock technique and the regular voxelized navigation using the super voxel concept
  - Unbiased method (does not introduce approximations)
- Evaluation using two clinical applications cases:
  - LDR prostate brachytherapy
  - Transmission tomography
- Future works:
  - Test the SVW in patient case with a metal implants (dental amalgam)
  - Possible combination of this method with the TLE technique

Thank you
for your attention