Computing@CSN5: applications and innovations at INFN

Bari - 14-16 Oct 2024

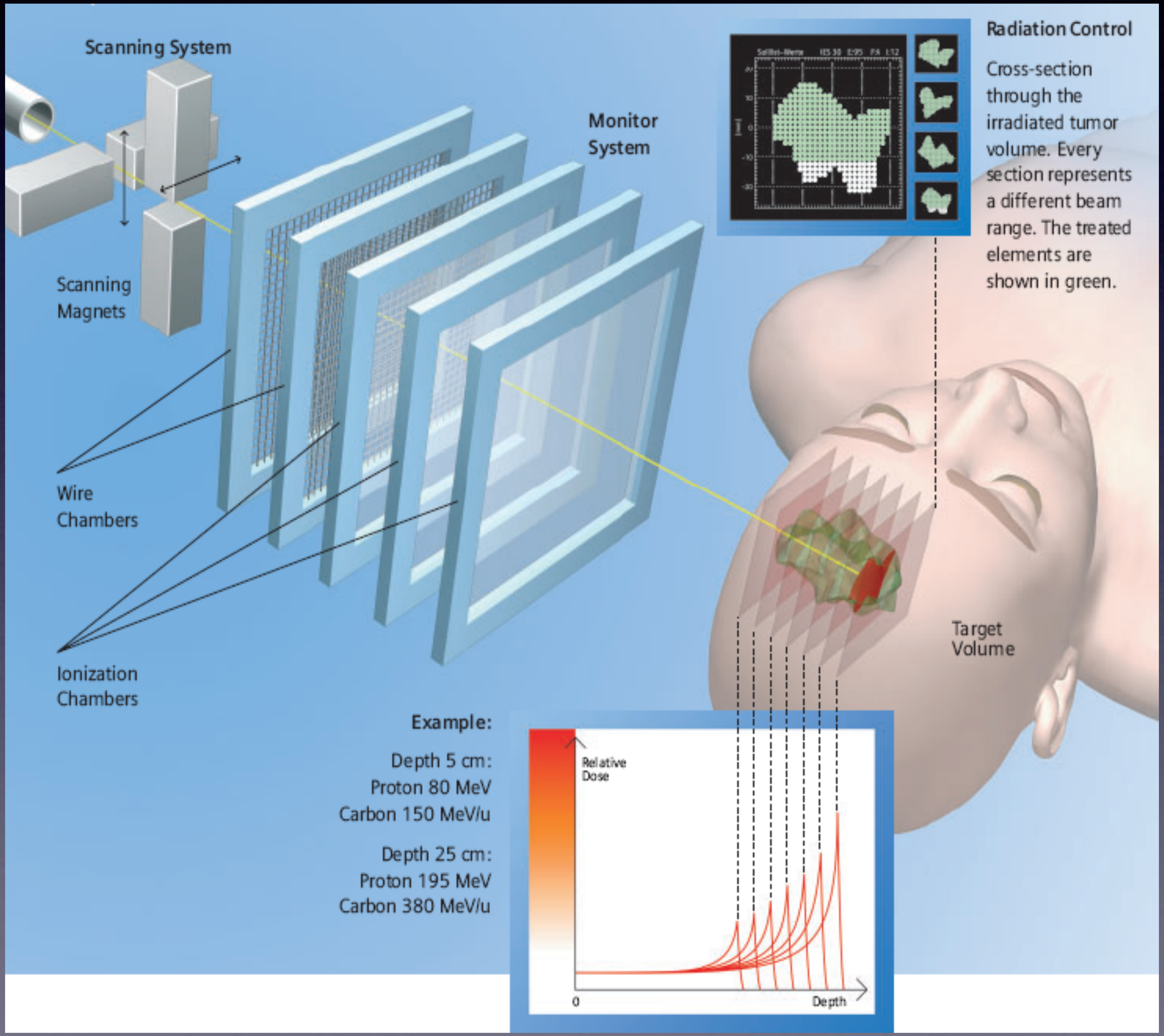
GPU for analytical and Montecarlo calculations in Treatment planning

A. Schiavi
Università di Roma "La Sapienza" and INFN-ROMA1

Outline

1. Treatment planning
2. Analytical kernels (e.g. RIDOS)
3. Fast Monte Carlo (e.g. FRED)
4. Applications

Treatment Planning



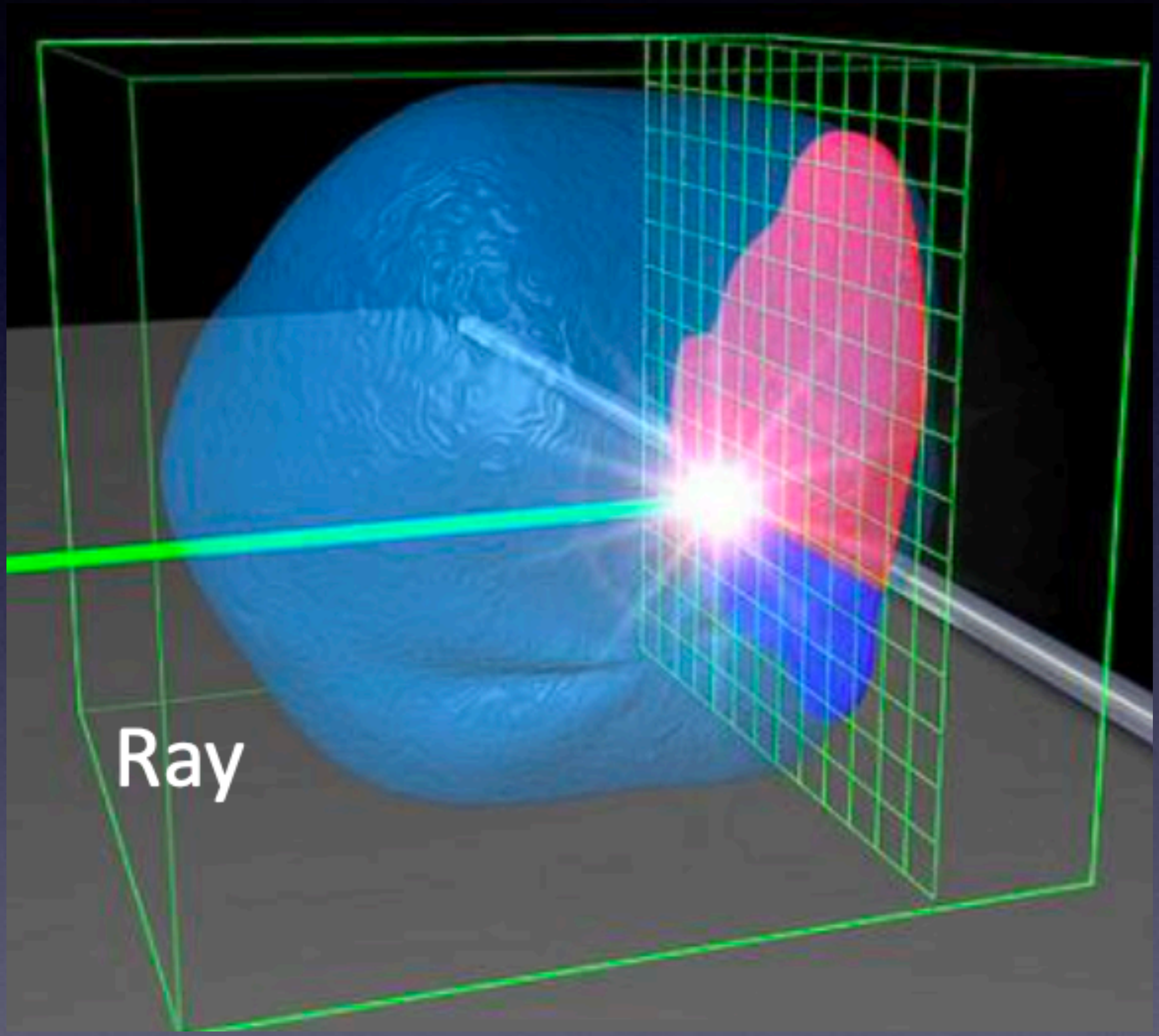
- medical imaging to 3D patient voxelization
- pencilbeam scanning approach
- dose per spot
- optimization constrained by prescription and protocols
- check: forward recalculation

Analytical Kernels

- compute pencilbeam dose on water using MC
- morphing patient geometry into water equivalent geometry
- remapping MC dose onto WEPL scoring grid

RIDOS

Real-Time Ion Dose Planning and Delivery System



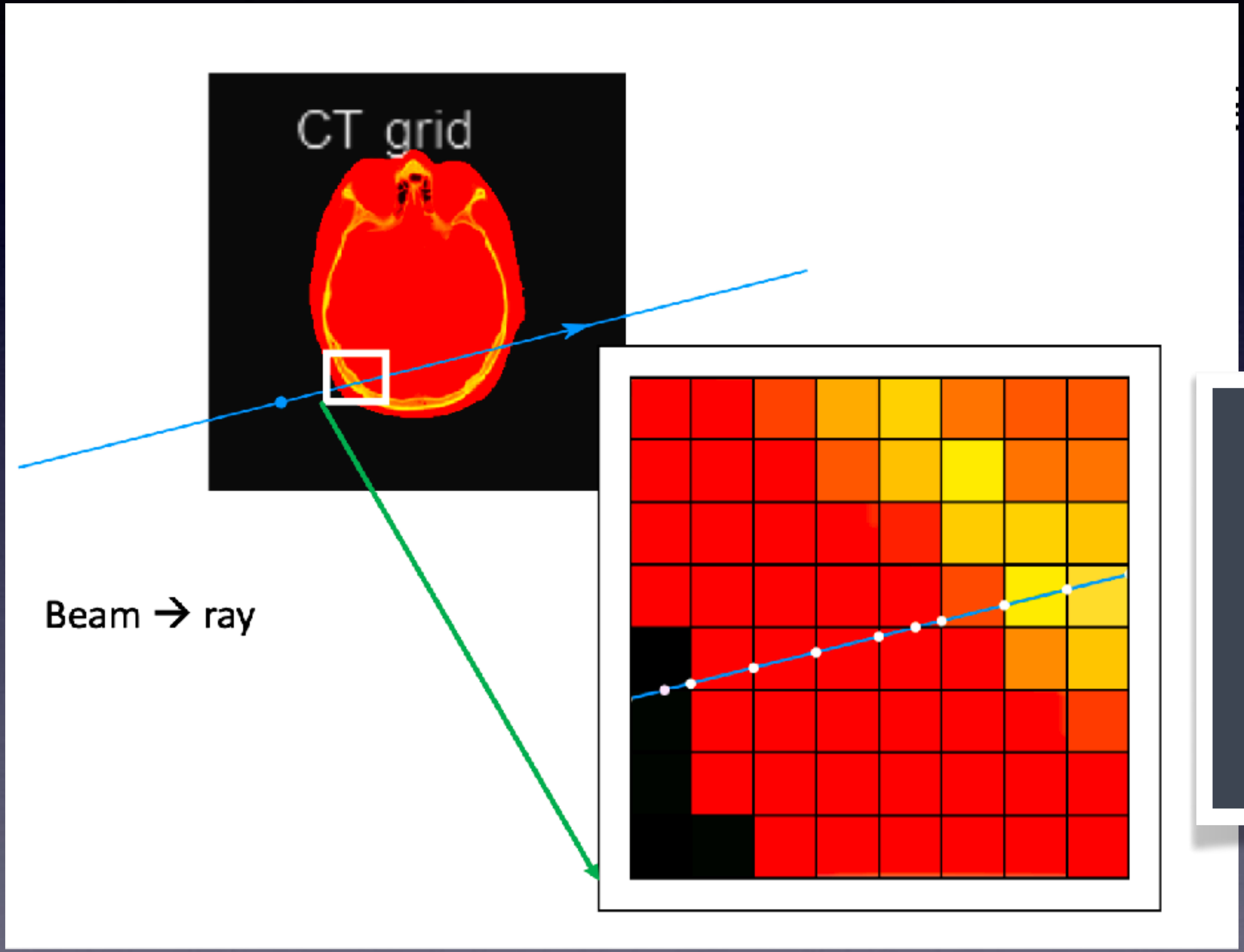
Simona Giordanengo et al, INFN-TO

INFN Research Project

- Young Researcher CSN5 Grant (2014-2016)
- SIG INFN-CSN5
- Marie Curie ETN

implementation of DEK code on GPU
raytracing + remapping
inter-spill (3-5 s) time window

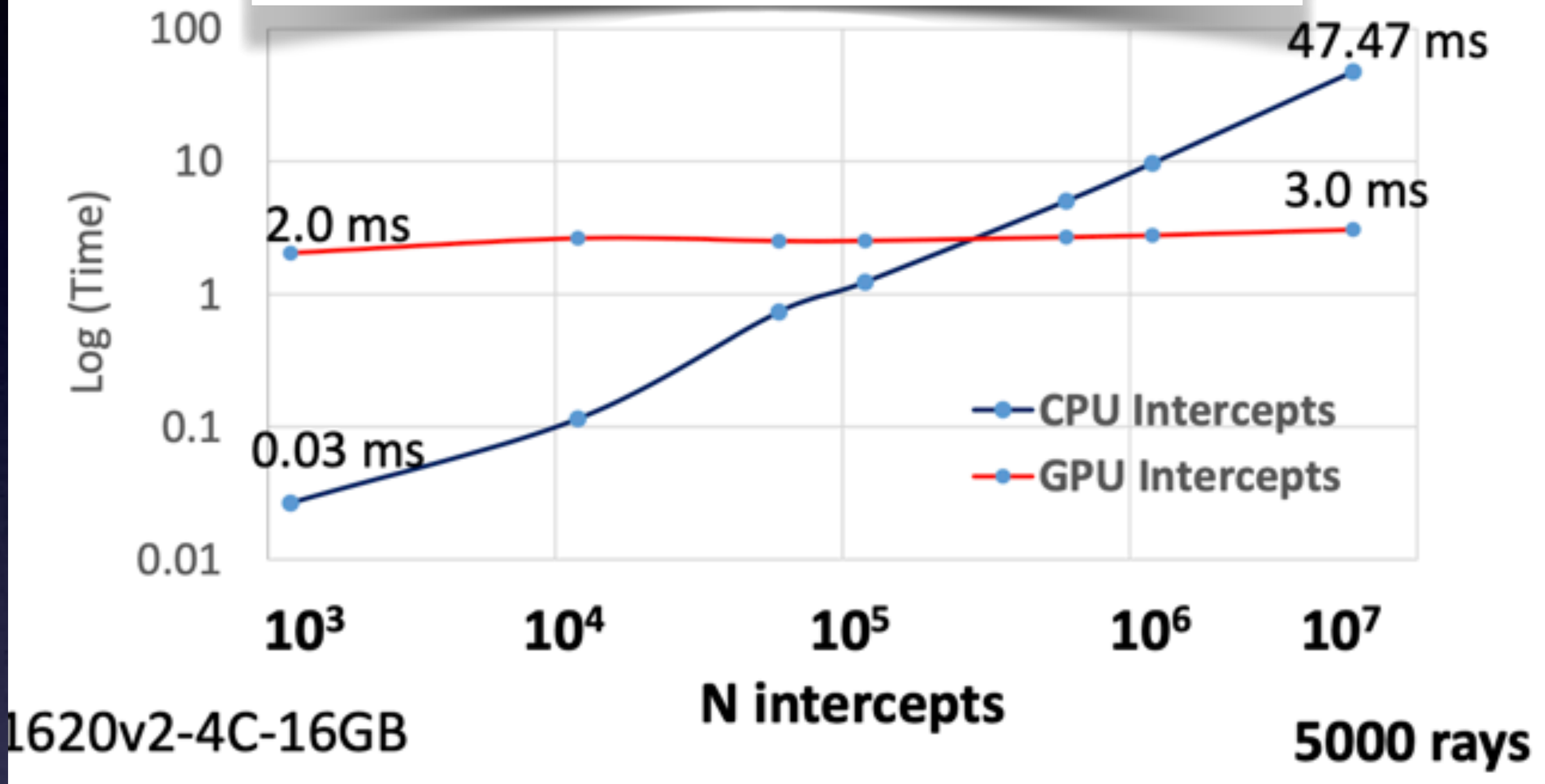
RIDOS Raytracing



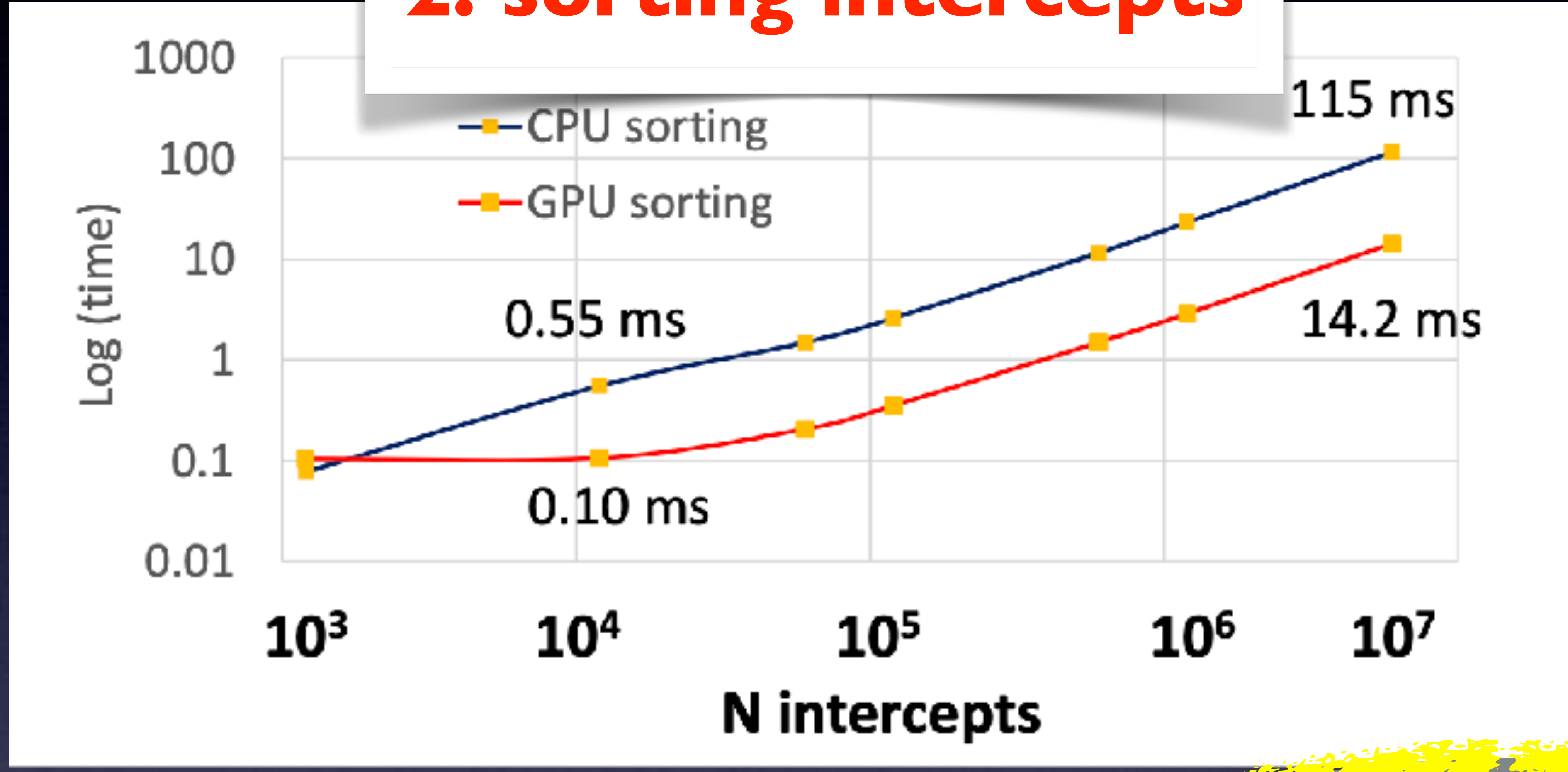
1. find intercepts
2. sort intercepts along beam line
3. determine pathlength of each step

RIDOS Raytracing scaling

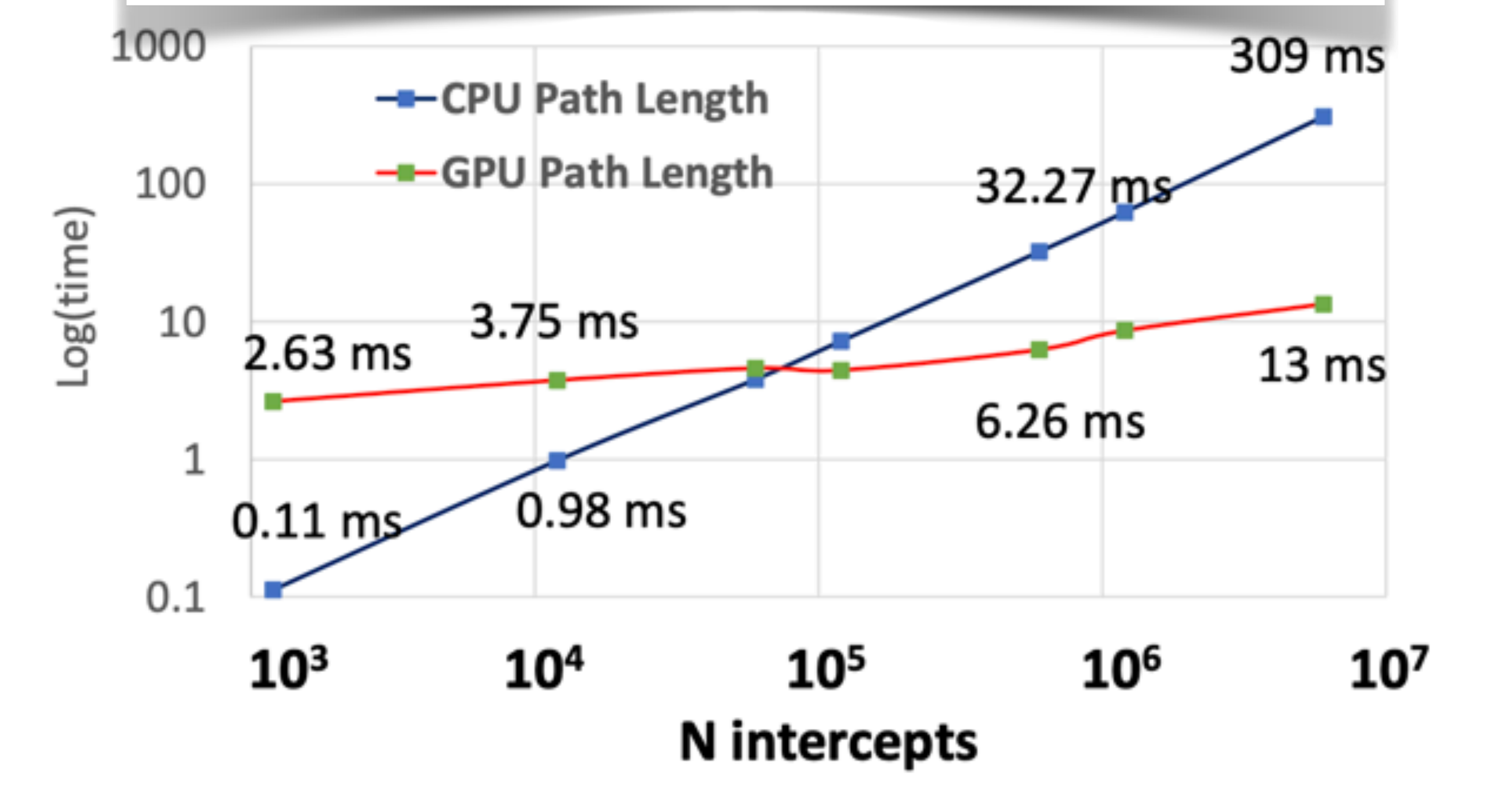
1. finding intercepts



2. sorting intercepts



3. pathlength calculation



CT size = 512 x 512 x 125 (~$3x10^7$ voxels)
COMP_GRID size = 170 x 170 x 125 (~$4x10^6$ voxels)

number of rays = 124800

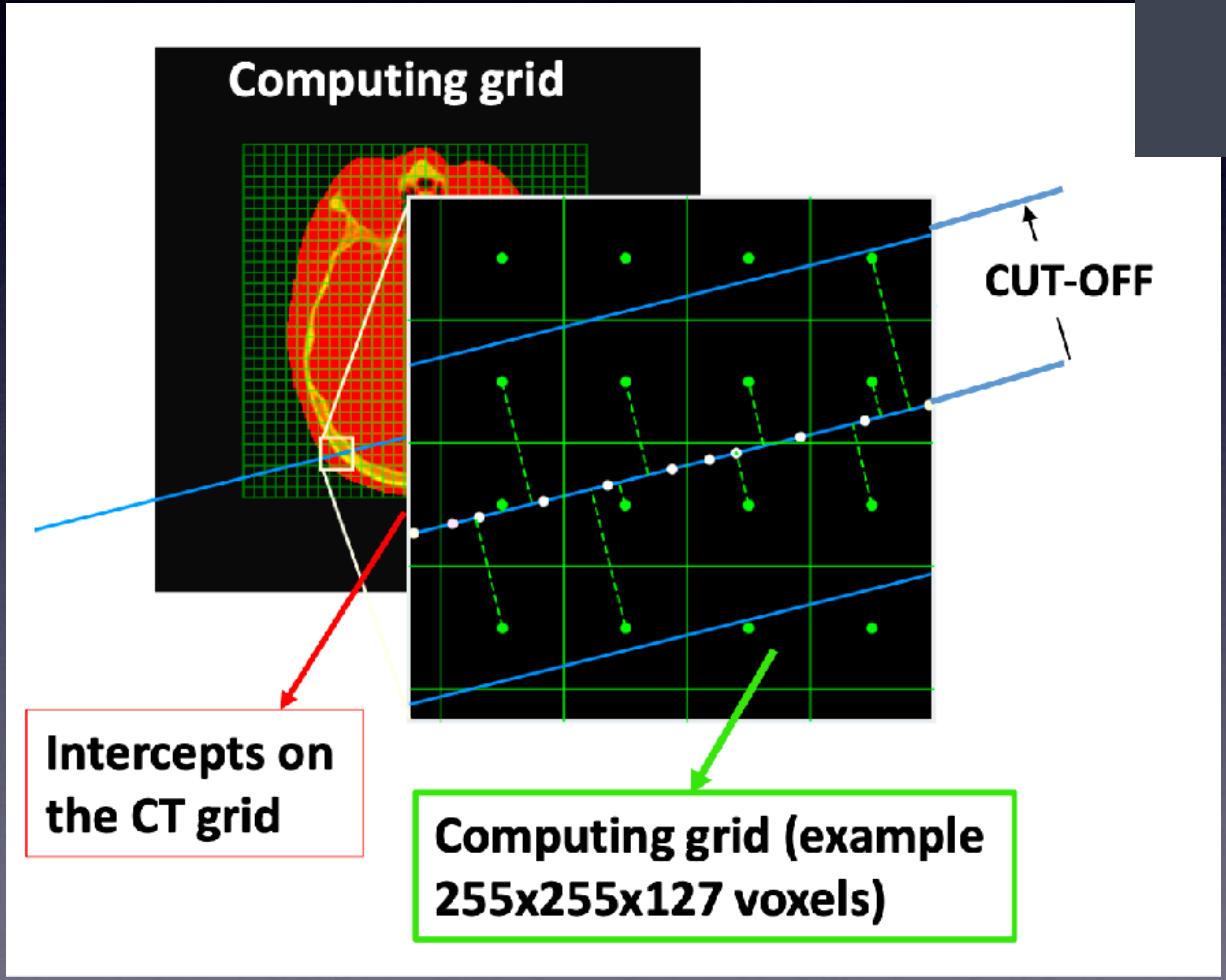
number of energies = 39
Radial cut-off = 10 mm

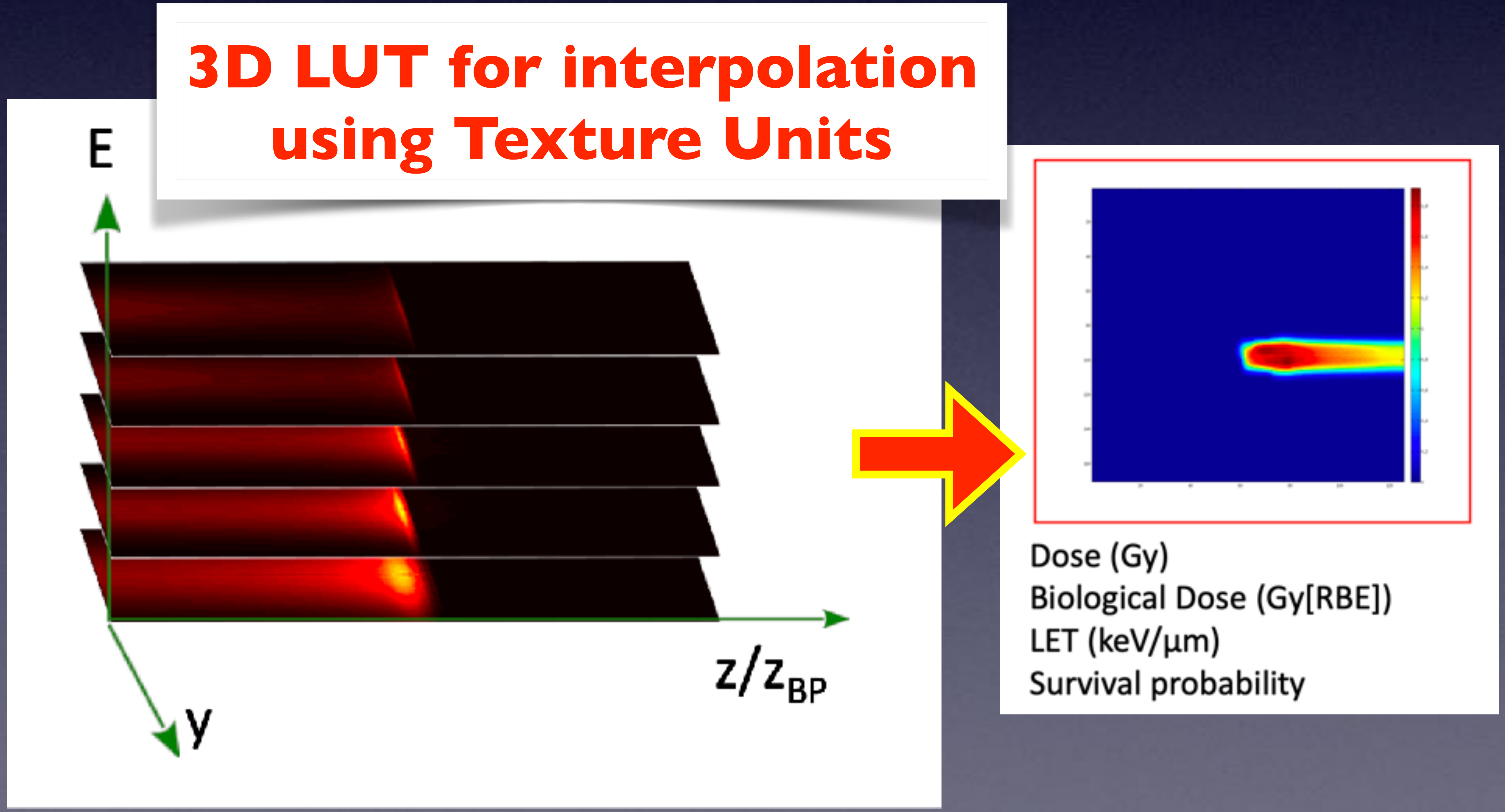
check for updated times in Cosimo Galeone's talk later on today !!!

raytracing step well below 1 s

RIDOS Remapping

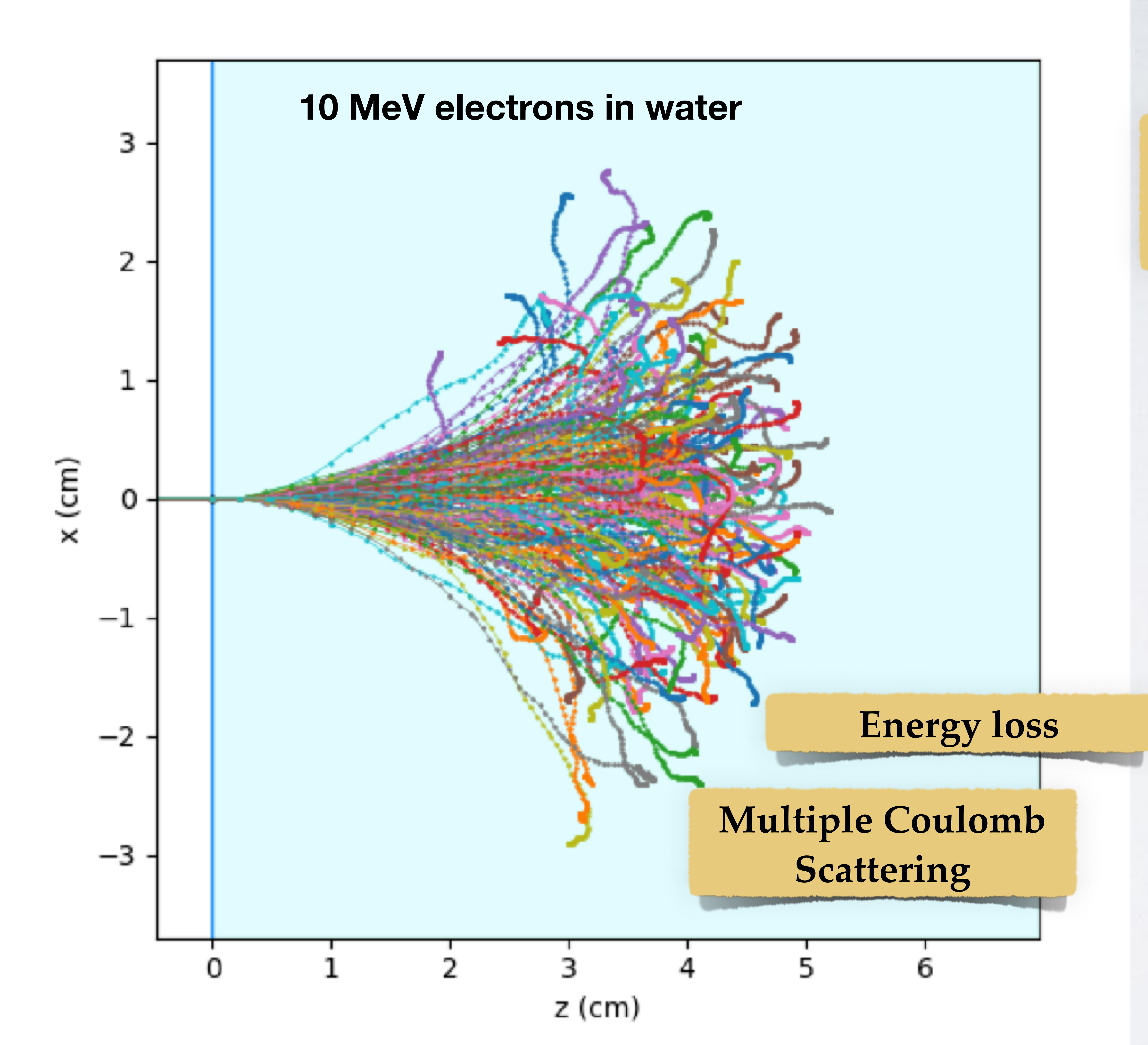
4. convert pathlength to water equivalent depth
5. select voxel on scoring grid using cut-off
6. remap quantities (dose,LET,etc.) using





fast-MC codes on GPU

Monte Carlo simulation: particle tracking



advancing particle position step by step through the medium

separation of processes: condensed histories and discrete events

Energy loss

Multiple Coulomb Scattering

Homogenous vs Heterogenous

water box

water head

real person

but when the beam goes through large density gradients
and heterogenous composition,
the PB algorithm cannot reach adequate accuracy,
then **MC codes win**.

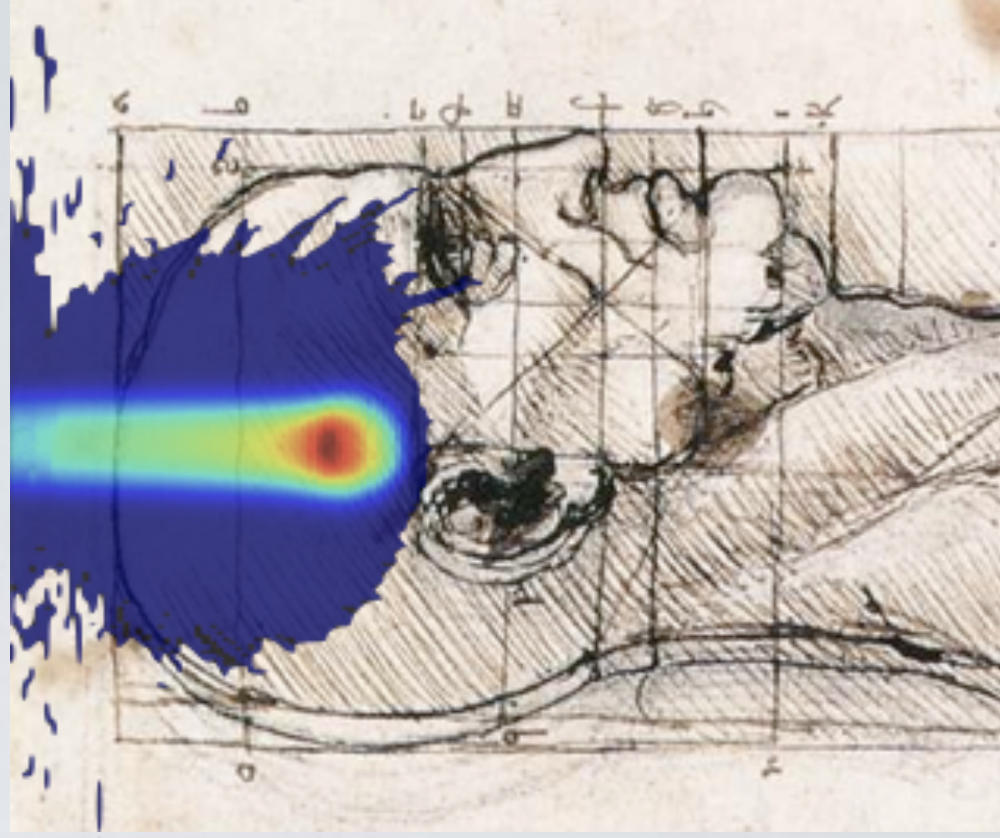
fast MC on GPU

- standard MC algo approach
- full geometry
- full materials
- simplified interaction model

- tracking kernel respectful of GPU hardware constraints
- use FP32 wherever possibile
- LUT for hardware interpolation on Texture units
- explore event-based and history-based kernel solutions

check accuracy using full-MC for the scored quantity (e.g. dose, LETd, …)

FRED

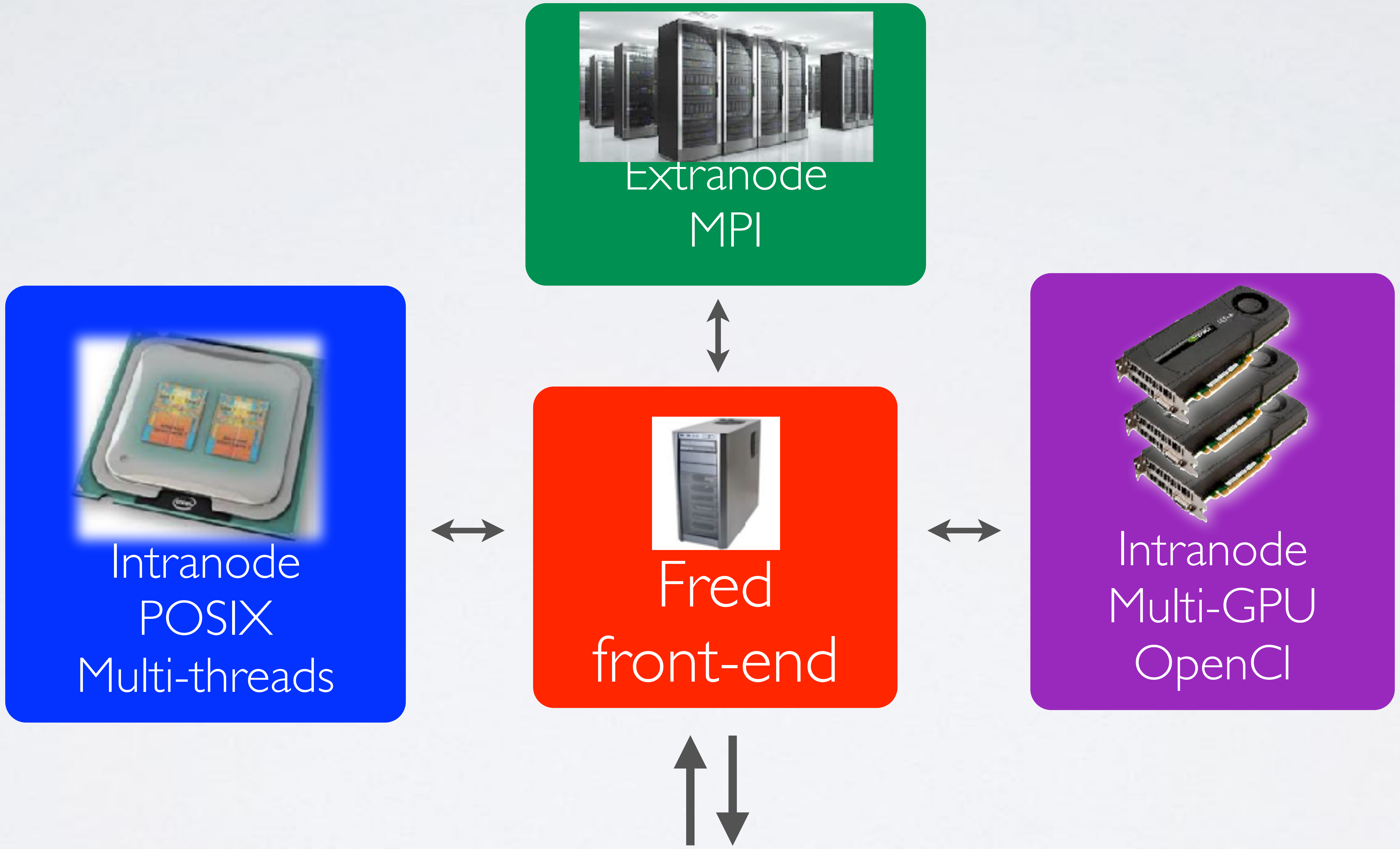


- MC for protons in voxel geometry
- Tabulated total stopping power in water (PSTAR-NIST), energy straggling (Gaussian and Landau-Vavilov regimes)
- MCS models: single-,double-,triple-gaussian, 2 gauss+Rutherford
- Nuclear interactions: elastic and inelastic; fragmentation; local deposition of heavy ions; tracking of secondary protons and deuterons
- HU to density conversion (Schneider-Parodi) and stoppow calibration
- MC-TPS: dose optimization using DDO (Lomax)
- RBE models = fixed 1.1, LETd-based (McNamara,Wedenberg, Carabe, Wilkens, Chen), table-based (LEM1, MKMPIDE)

A. Schiavi et al, *PMB* **62** (2017) 7482–7504

FRED is freely available @ www.fred-mc.org

Parallel execution model in Fred



Tracking performance

Benchmark = dose calculation for 150 MeV protons
in liquid water phantom with 2 mm voxel resolution.

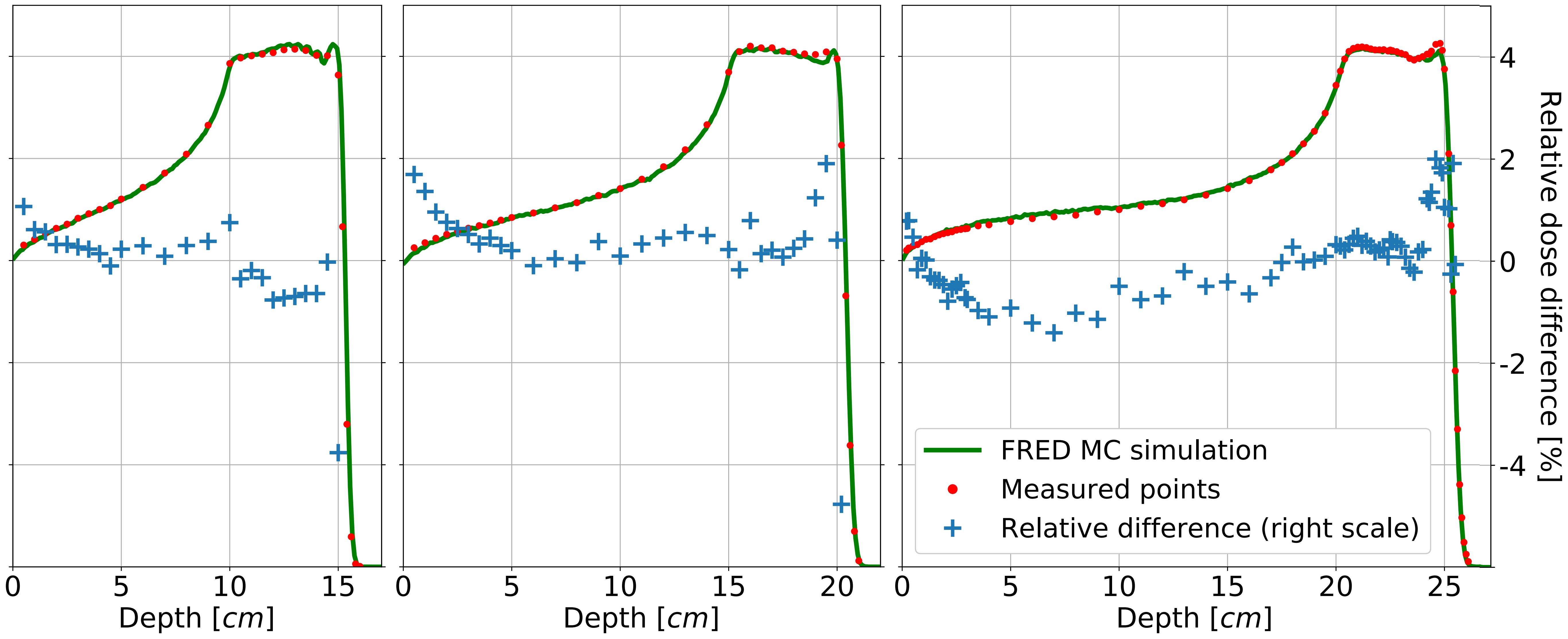
	Hardware	primary/s	Patient plan recalculation*
FLUKA/GEANT4	single CPU core	750	16 days
FRED	single CPU core	15000	19 hours
FRED	single GPU card	10 mln	**2.3 min**
FRED	cluster of 144 GPU cards	300 mln	3 s

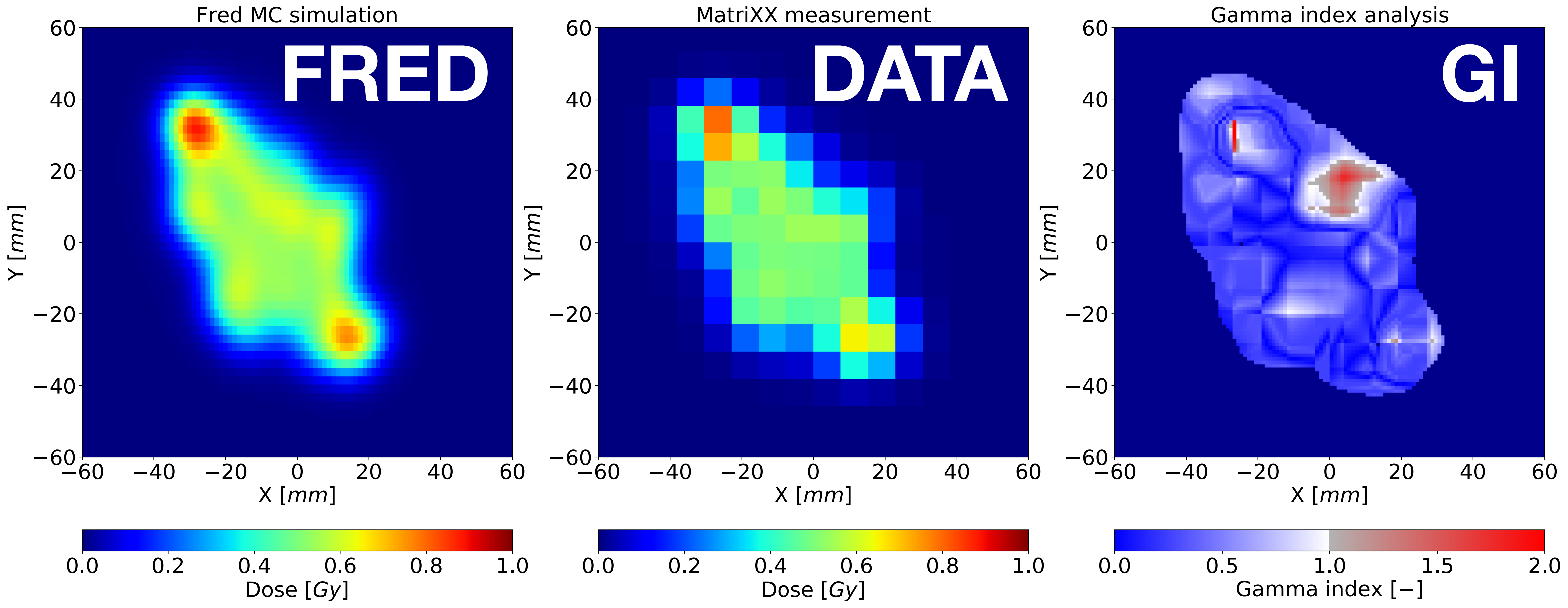
* Patient case: 3-fields Head-Neck plan at 1% of total protons
= 700 mln primaries

FRED
and
Patient-Specific QA

Implementation and **validation** of the clinical beam model

DATA
FRED





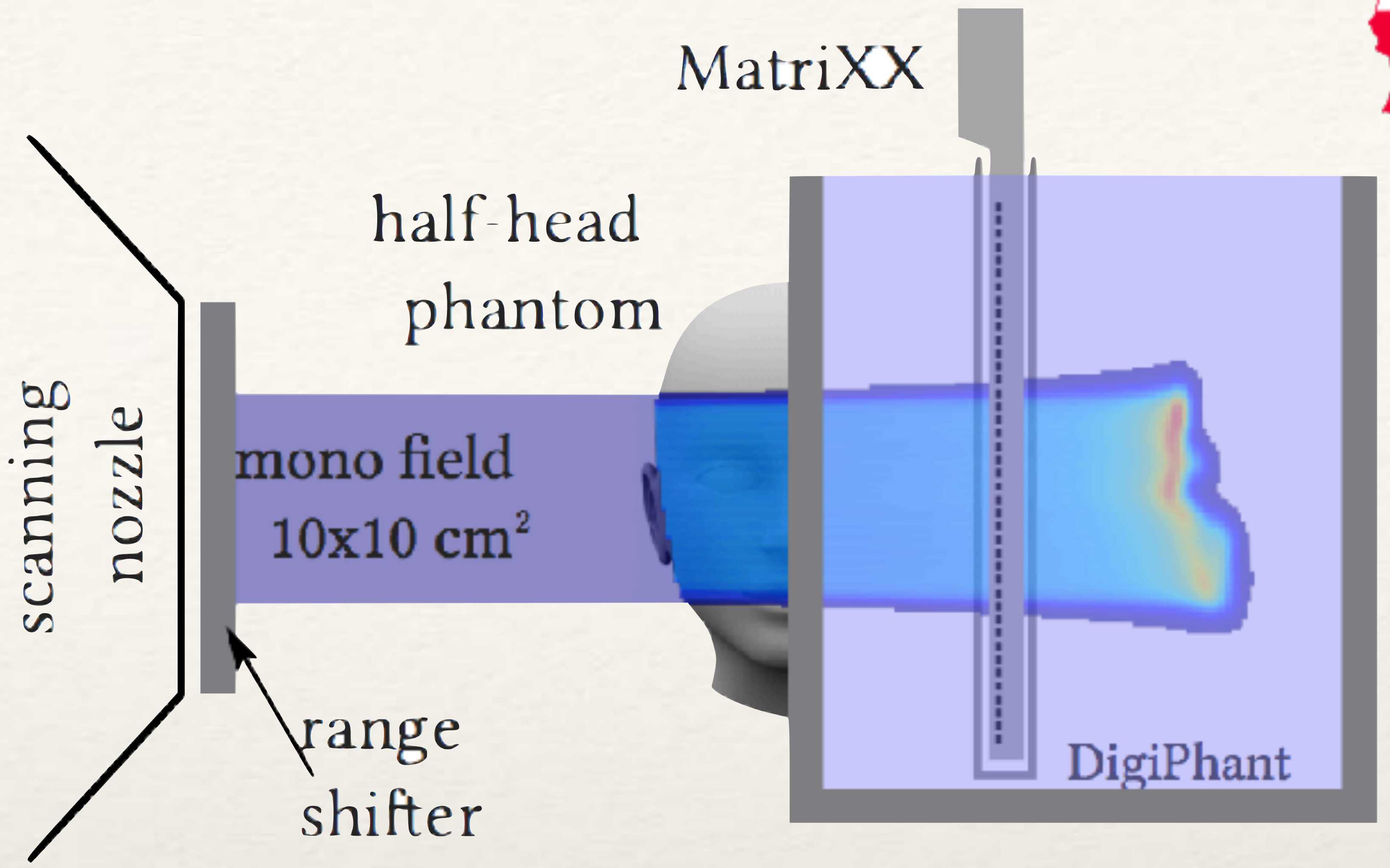
$$\gamma - index = 2mm/3\%$$

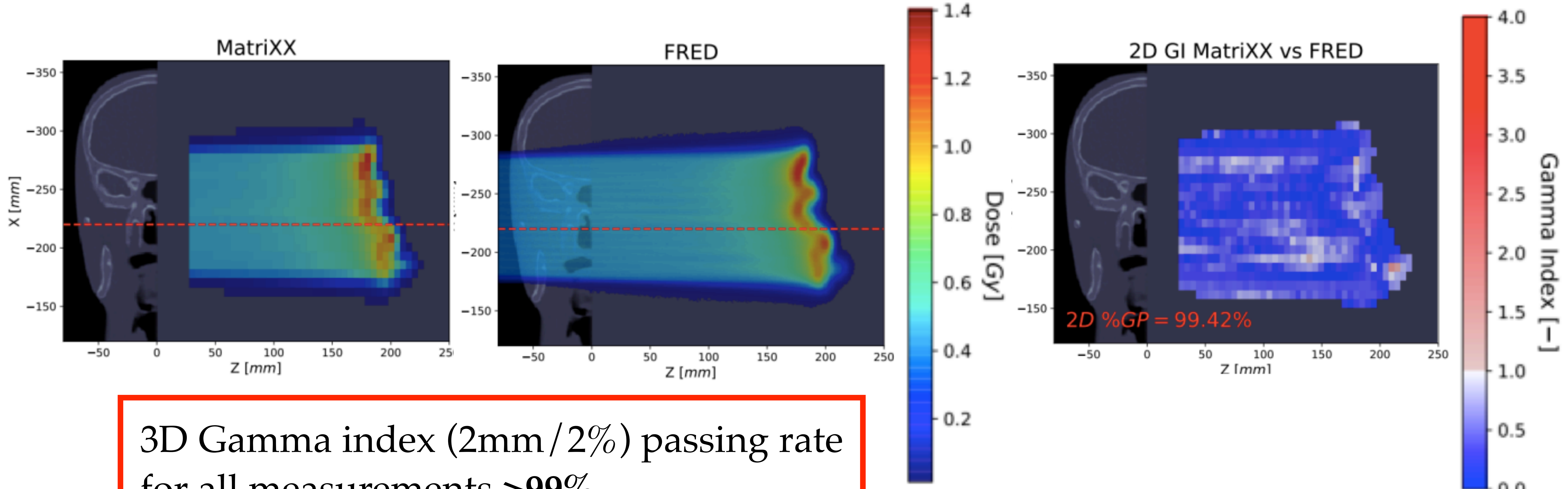
182 patient verification fields
GI: 97.9 (3.3)% (1σ)
3’28 (1’41) min (1σ)

Validation in heterogeneous media

Kraków

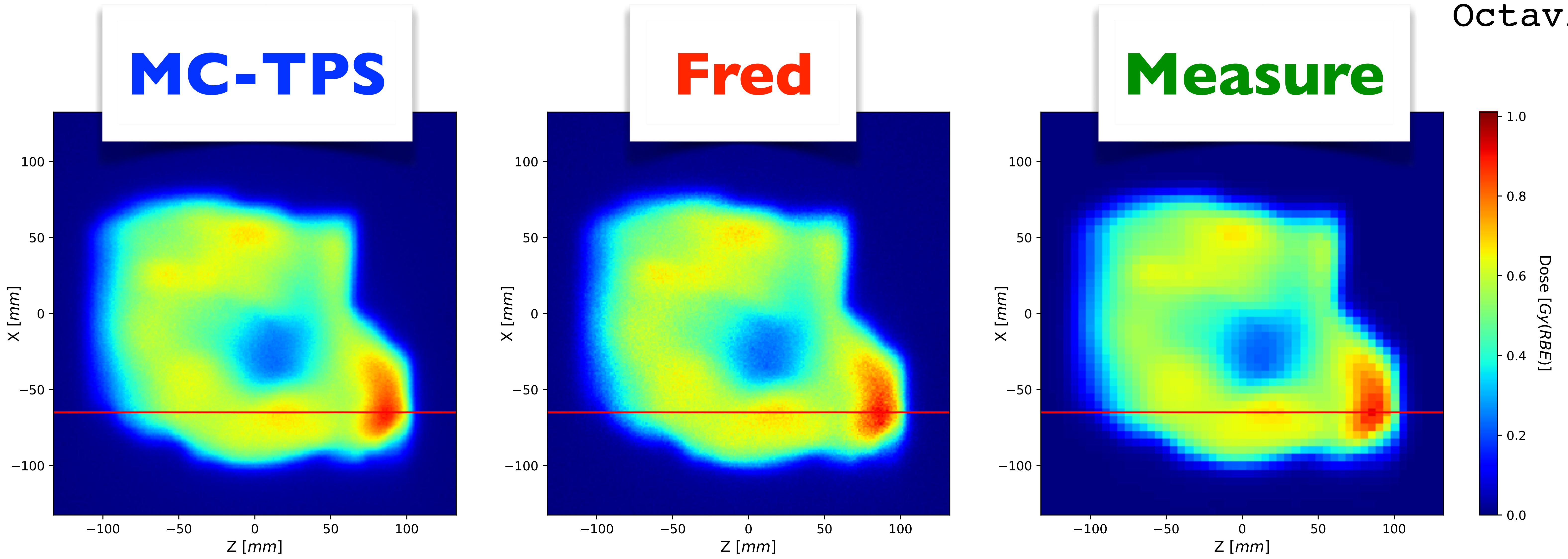
- Heterogeneous head phantom
- MatriXX measurement in water
- Single energy: 100, 150 and 200 MeV
- Range shifter

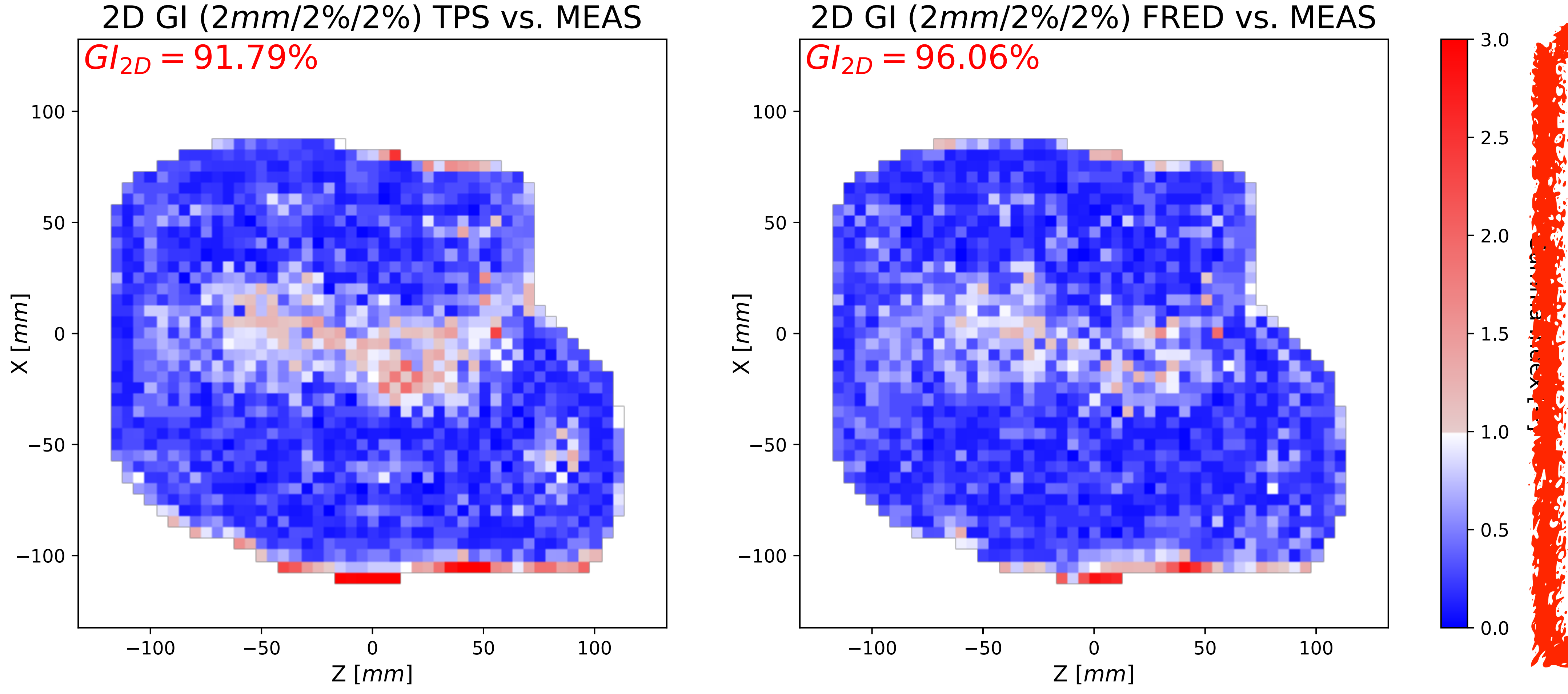




3D Gamma index (2mm/2%) passing rate for all measurements **>99%**

Patient QA @ Maastro





- **From Jul 2020 to Sep 2024:**
  - Recalculated plans with FRED: **4783**
  - Of which machine log-file based: **3137**
  - Passing rate: **99.5 %**
  - Machine time saved: **2392 h**
  - Human time saved: **100 – 300 working days**

R&D with fast MC

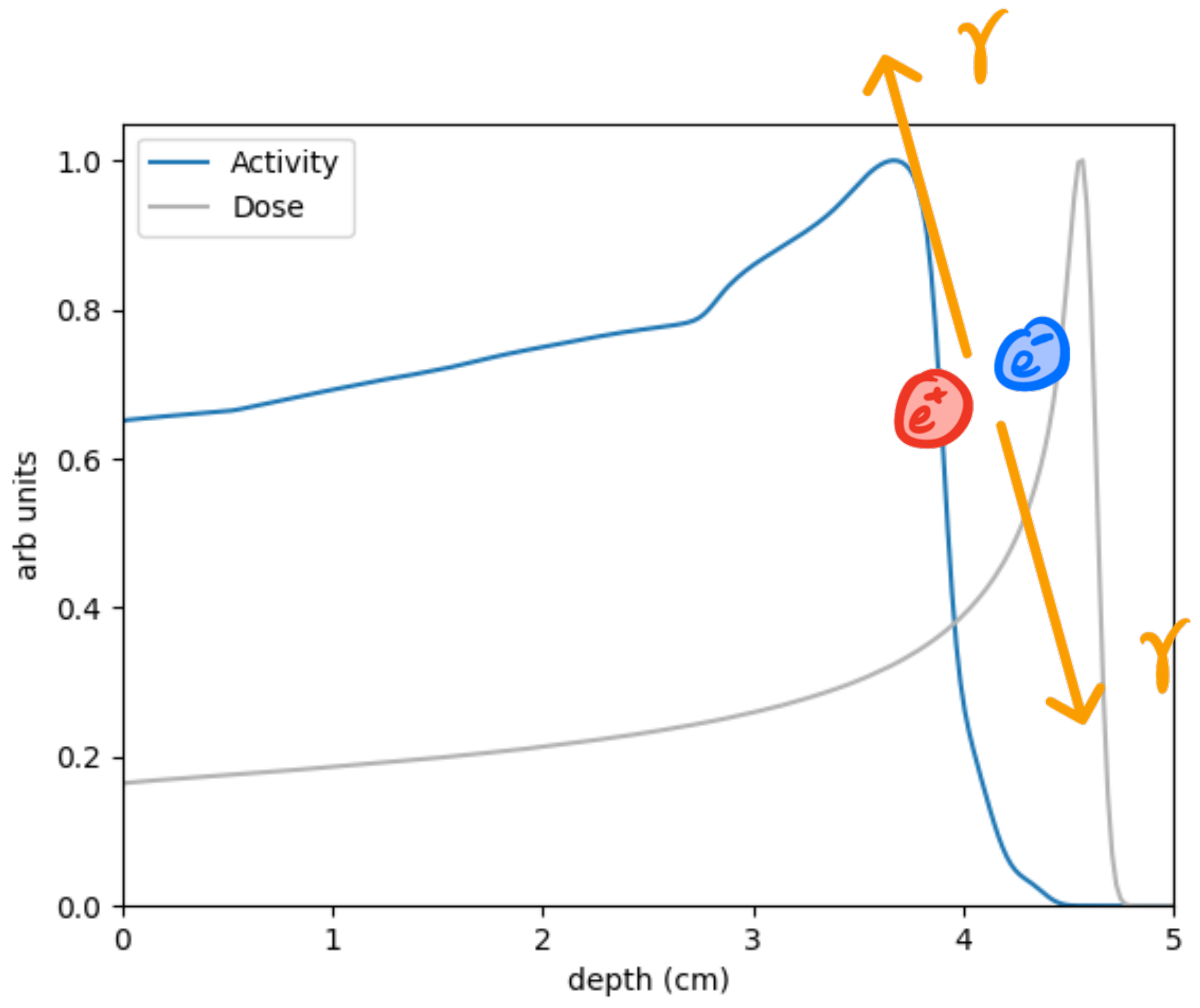
Range verification in proton therapy

PETITION
ETH zürich
PAUL SCHERRER INSTITUT PSI
J-PET
JAGIELLONIAN UNIVERSITY IN KRAKOW

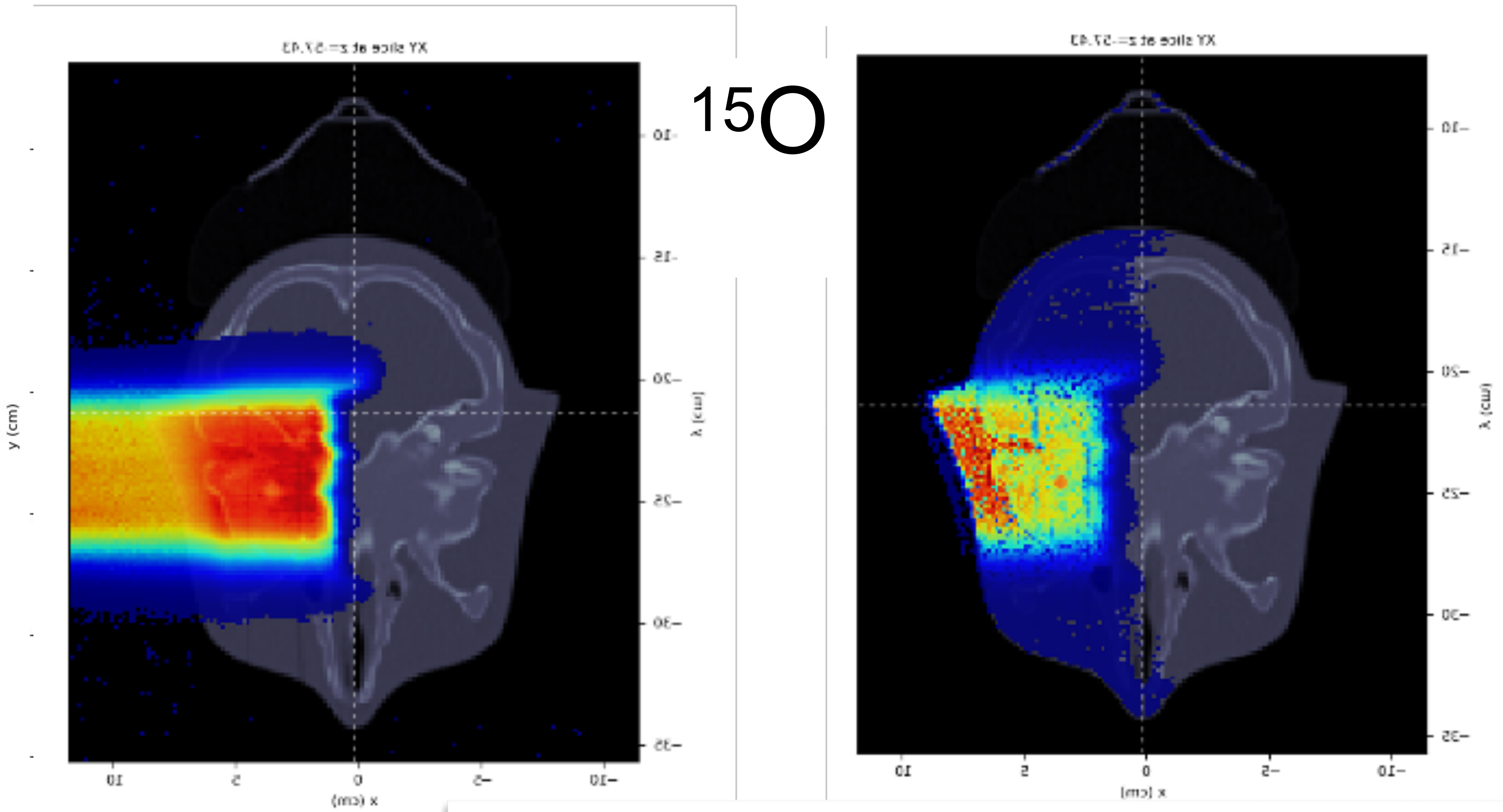
- Positron emitting isotopes are produced during irradiation, e.g.

  $^{16}O + p \rightarrow {}^{15}O + p + n, \quad Q = -15.7\ \text{MeV}, \quad t_{1/2} = 122\ \text{s}$

- Measure resulting activity with a PET detector, verify range, detect interfractional changes



Dose

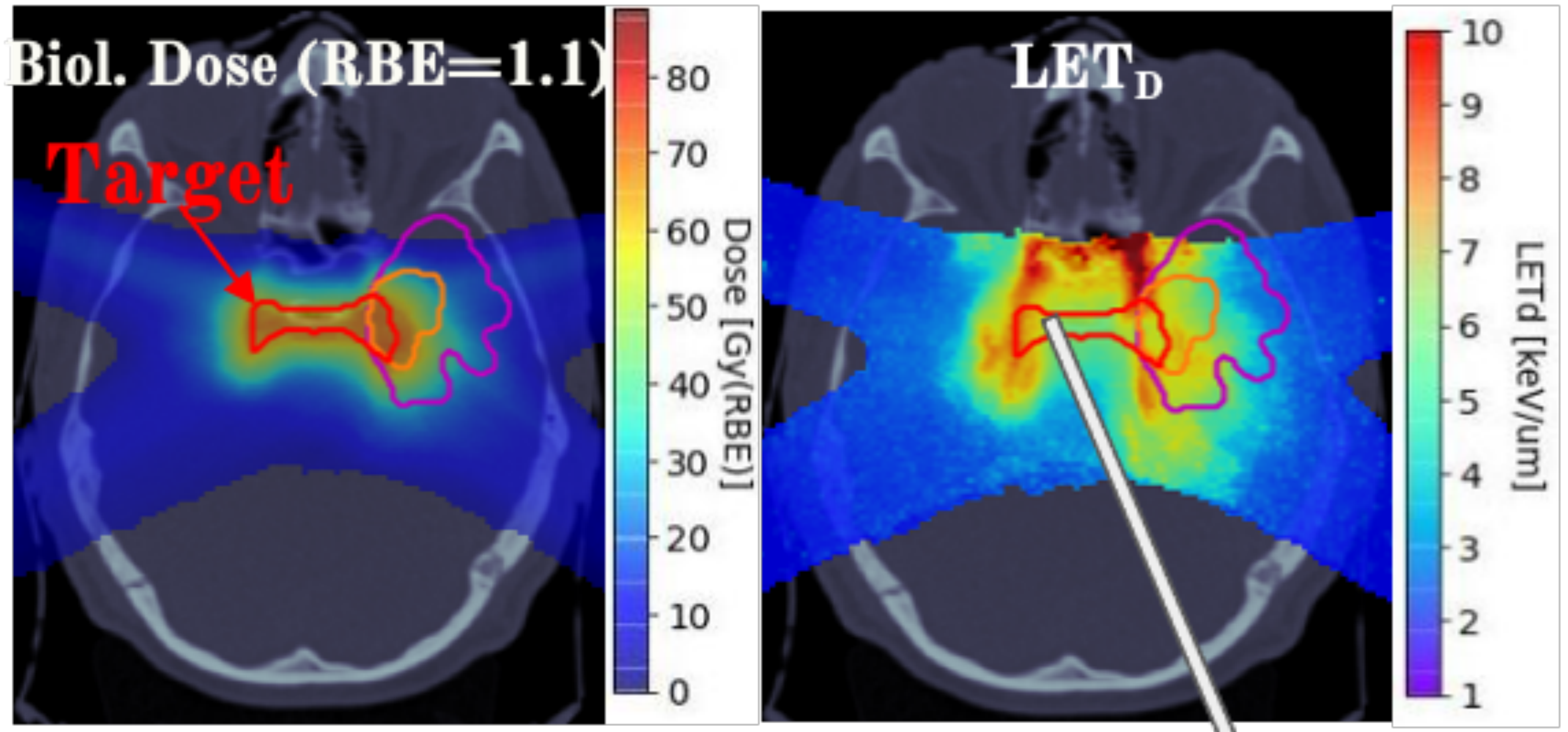


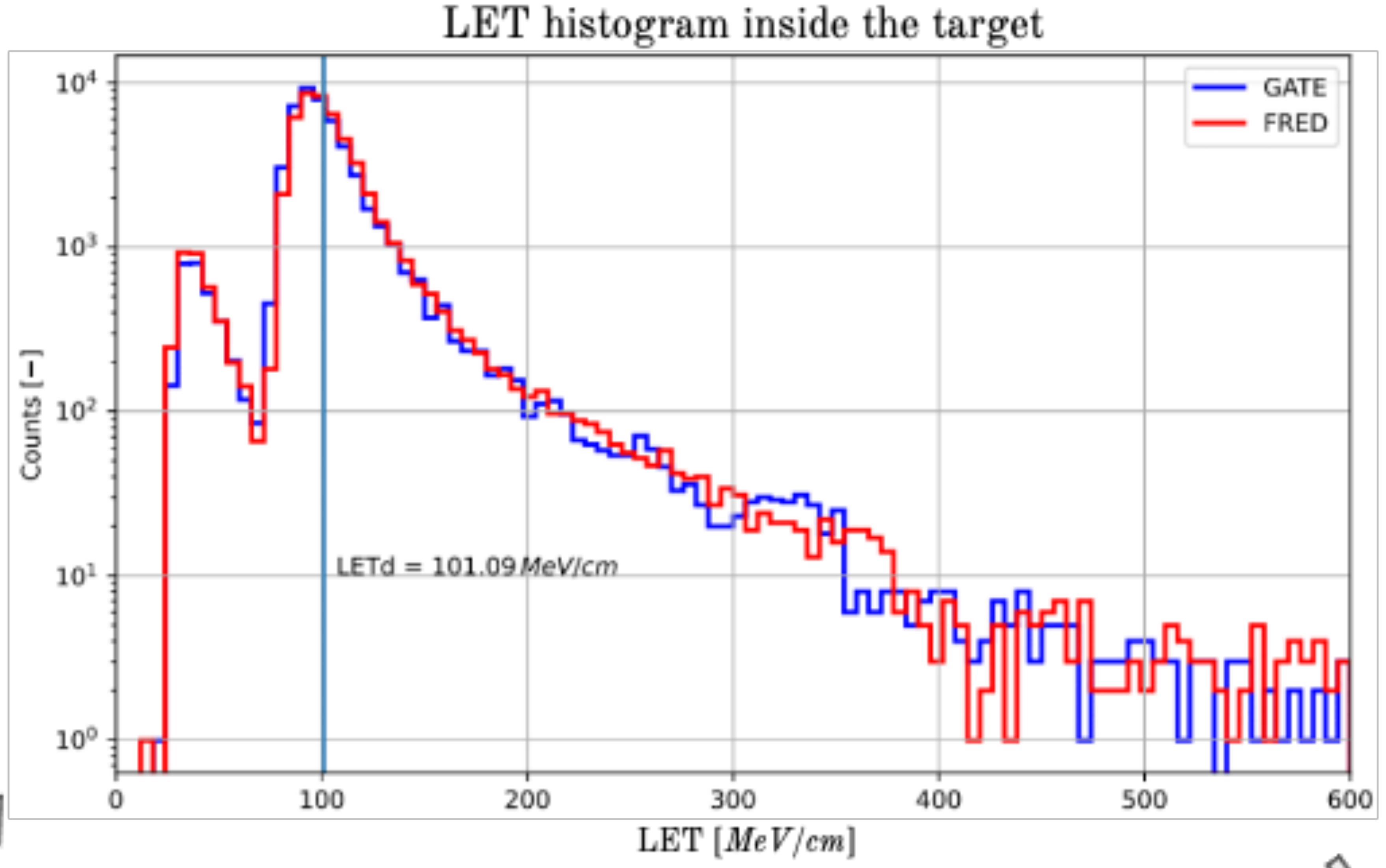
K. McNamara et al, *PMB* **67** (2022) 244001

Radiation Quality in proton therapy

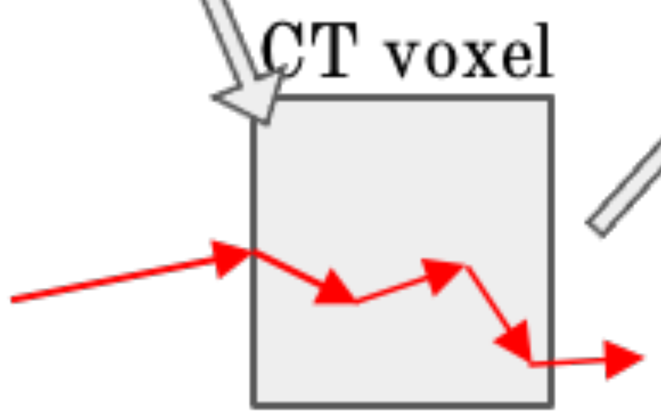
Kraków

Implementation of spectra scorer in Monte Carlo



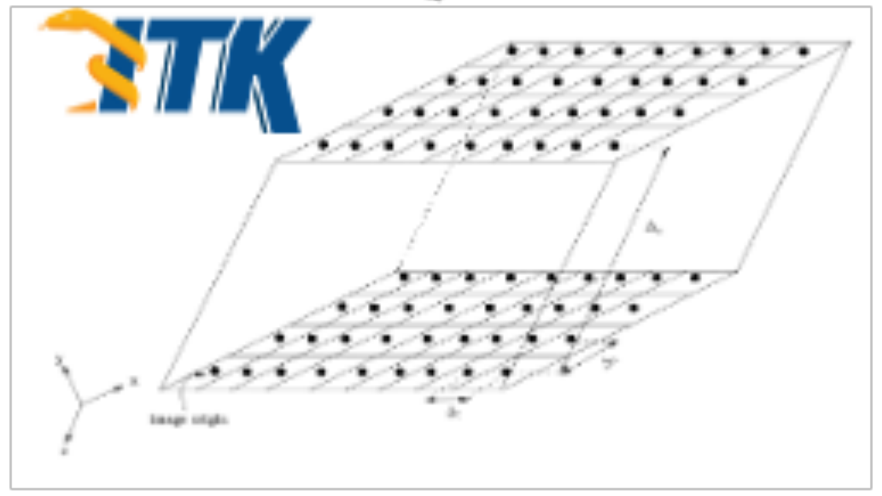


Particles properties (LET, Energy, etc.) saved as histograms



Access to information on each single particle

The histograms for each voxel in 3D geometry (patient CT)



Fred

GATE

GEANT4

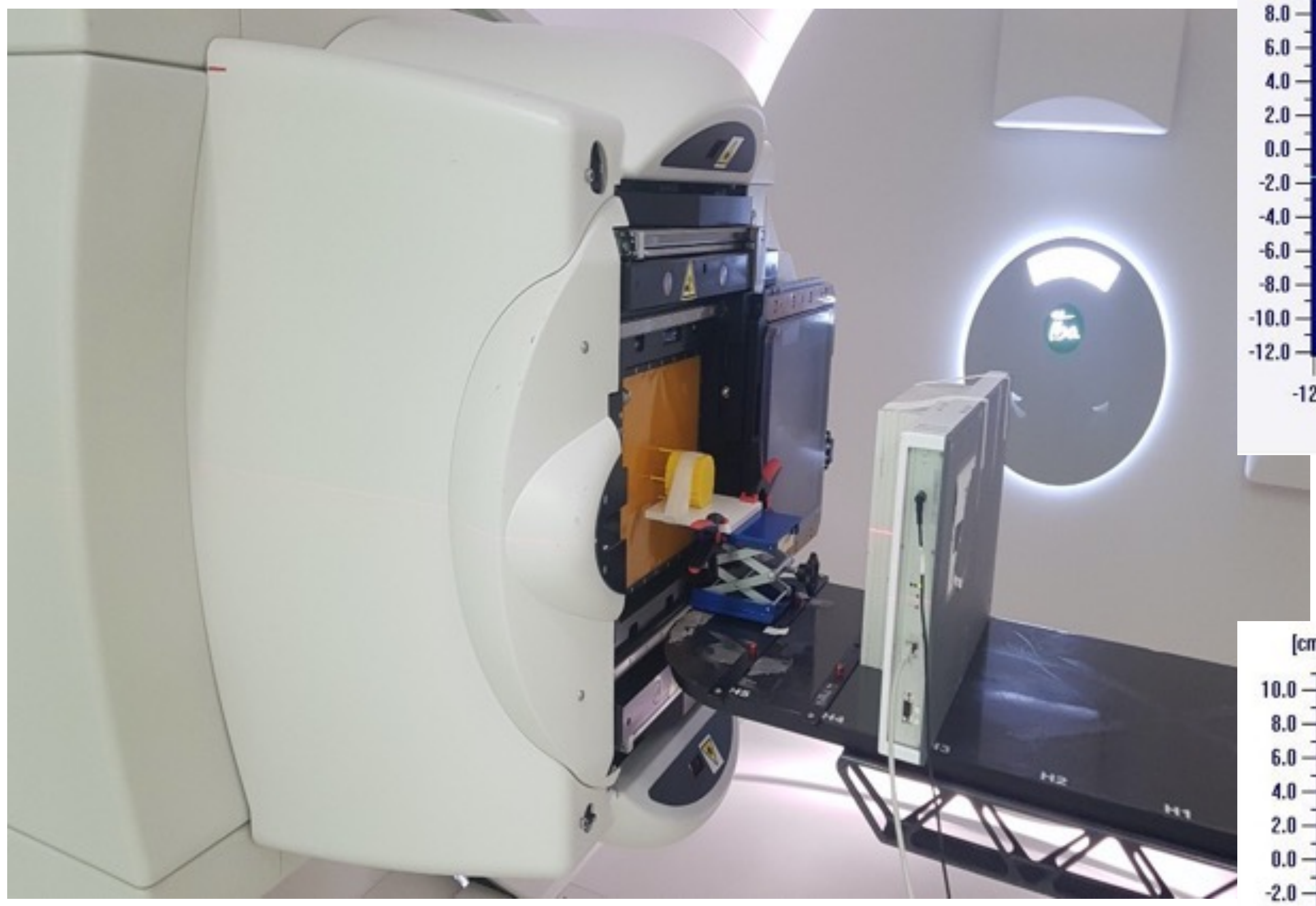
TIFPA Trento Institute for Fundamental Physics and Applications

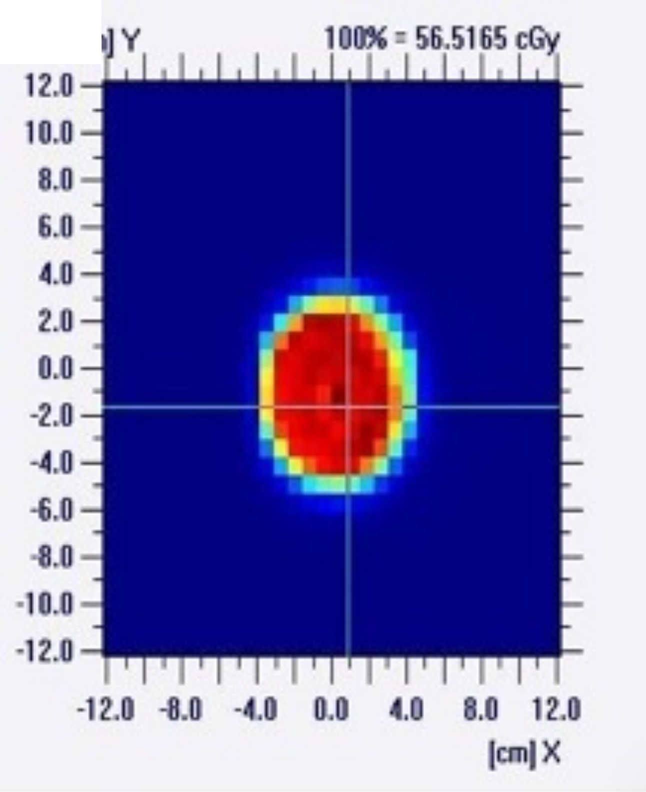
UNIVERSITÀ DI TRENTO

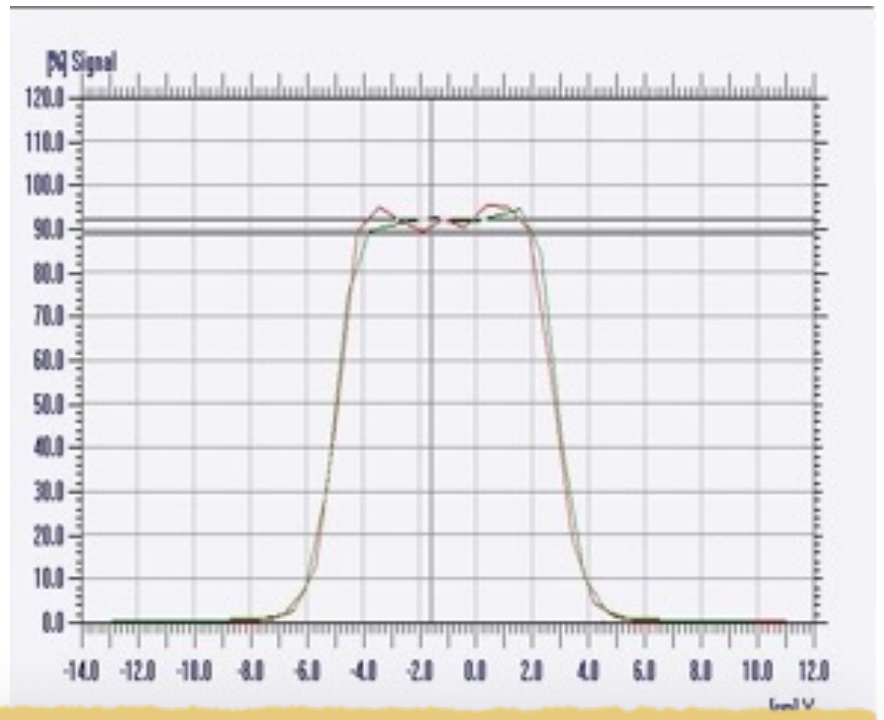
Towards FLASH proton therapy using 3D Range Modulators

3DRM designed and printed

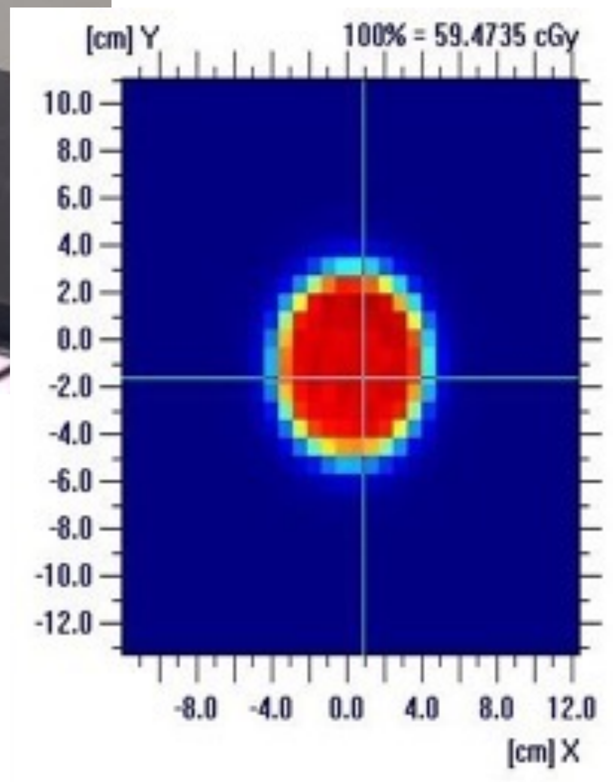
2D MatriXX detector

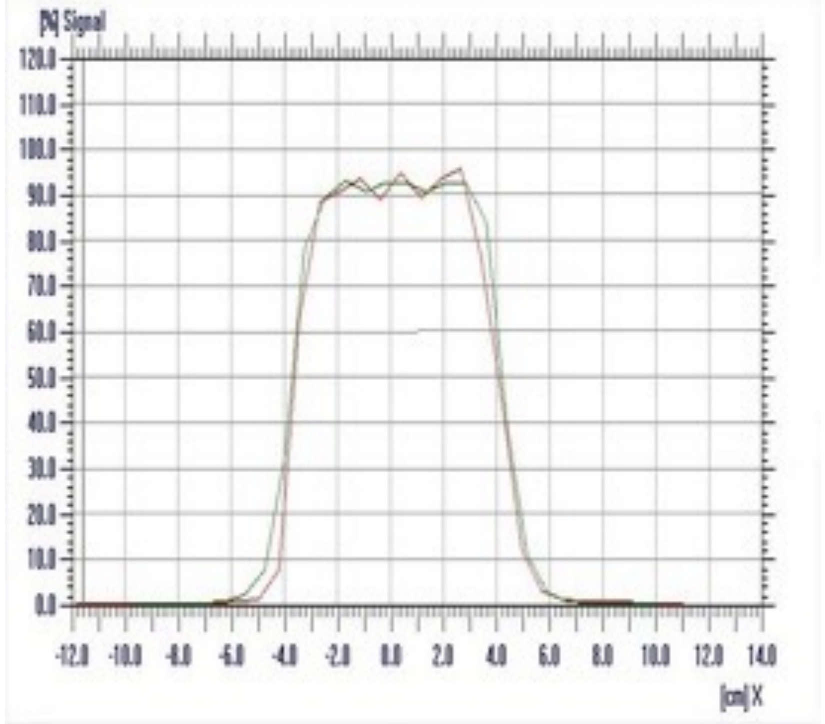






validation in the treatment room





F. Tommasino et al.
FRPT 2022

Collaboration with Rome (Schiavi, Patera et al.) for implementation in FRED fast MC

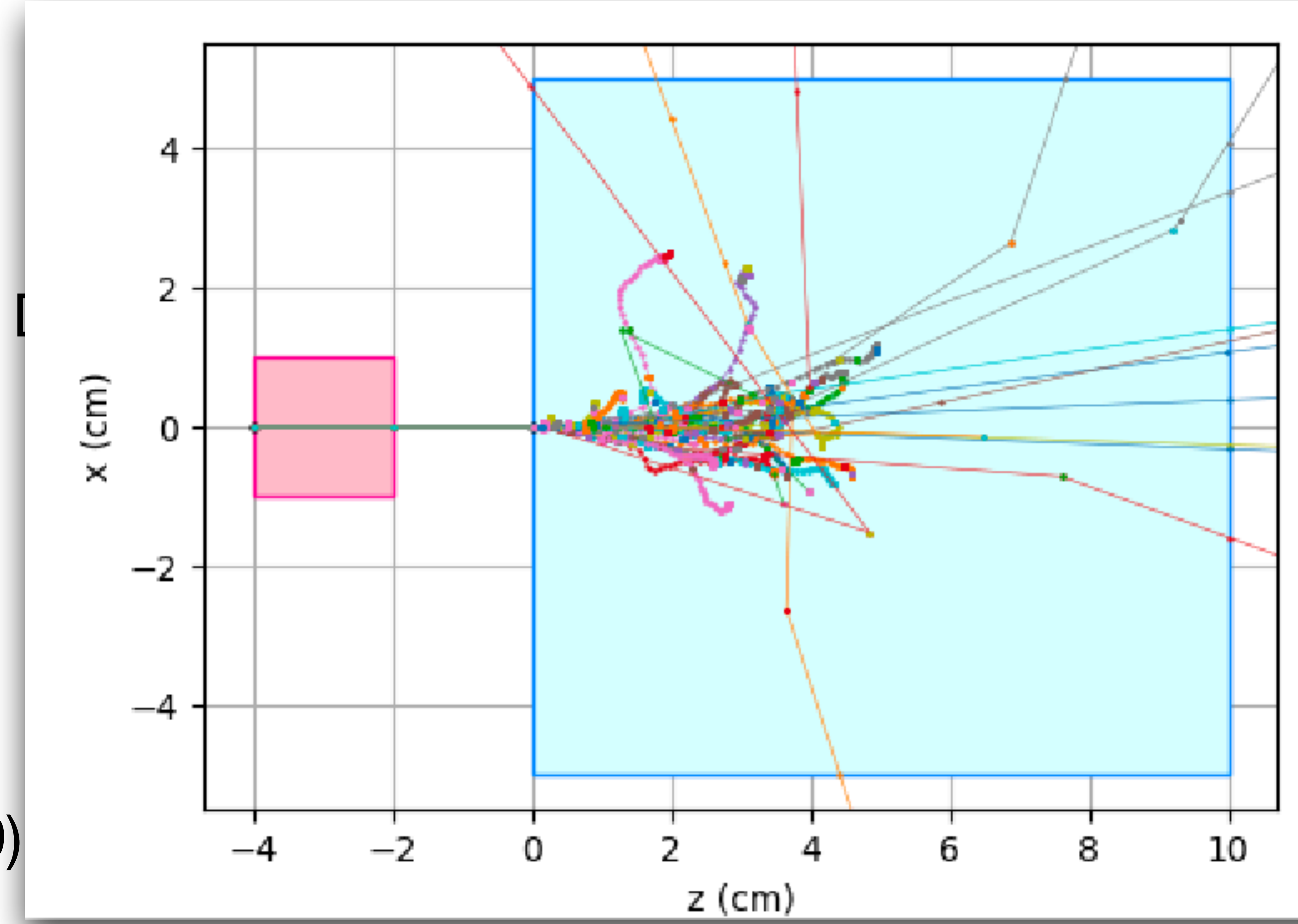
Electromagnetic model in FRED

Continuous processes ($e^- e^+$)

→**dE/dx** from NIST eSTAR database + **straggling** (GEANT4 physics manual 2019)
→**Multiple scattering** (A. A. Al Beteri, D.E. Raeside, Medical Physics 15, 351 (1988) doi: 10.1118/1596230).

Discrete interactions (e^-, e^+, γ):

→**Bremmstrahlung** (dσ/dk from S.M. Seltzer, M.J. Berger, Data Nucl. D Tables 35, 345–418 (1986). doi:10.1016/0092-640X(86)90014-8)
→ **Moller/Bhabha** scattering (GEANT4 physics manual 2019
→ **Coherent scattering** (XCOM NIST database)
→ **Photoelectric** (XCOM NIST database)
→ **Compton** (XCOM NIST database)
→ **Pair production** (XCOM NIST database)
→**Positron annihilation** at rest/ in flight (GEANT4 physics manual 2019)



G Franciosini et al 2023 Phys. Med. Biol. 68 044001

Thin target benchmark

FRED-em models

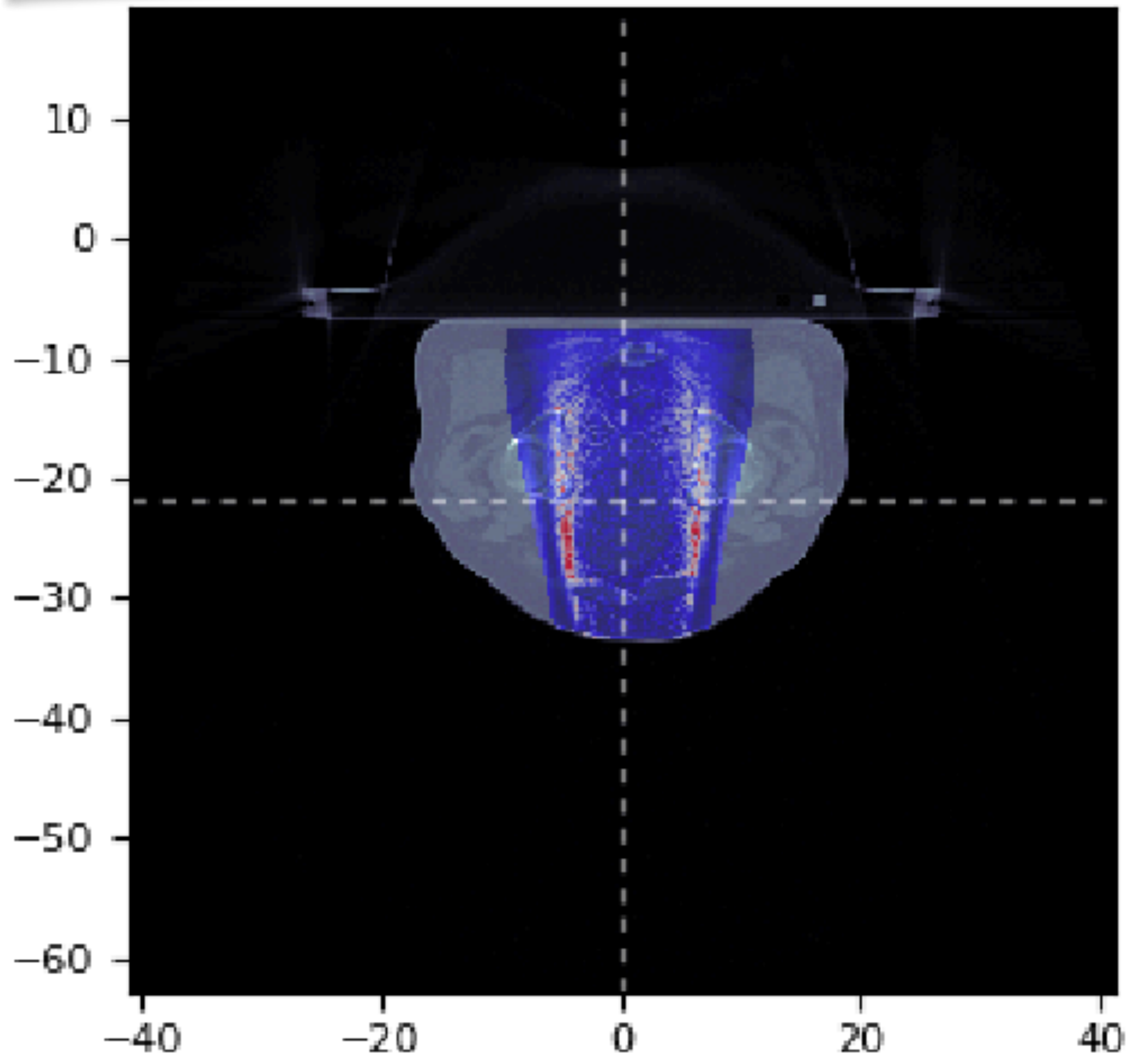
Comparison of **FRED-em** and **FLUKA** on the same setup: a thin target of different materials such as **water**, **PMMA** or element with Z value ranging from 1 (**Hydrogen**) to 79 (**Gold**). We checked the **energy and angle distributions** of each interaction in the **energy range of [1-200] MeV**.

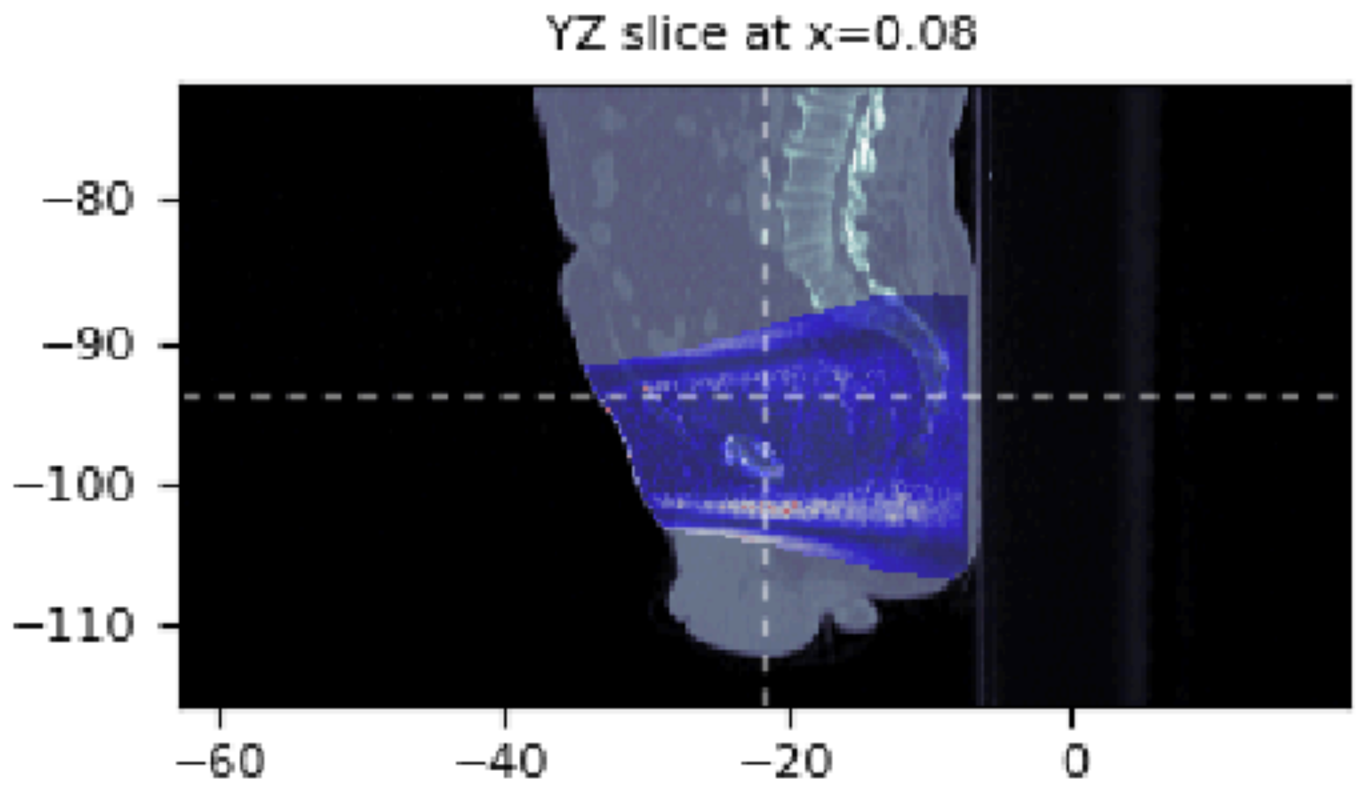
Electrons beam angles @ exit — Energy loss — Bremss photon energy @ exit

Patient test: FRED vs FLUKA

one VHEE field for a prostate treatment

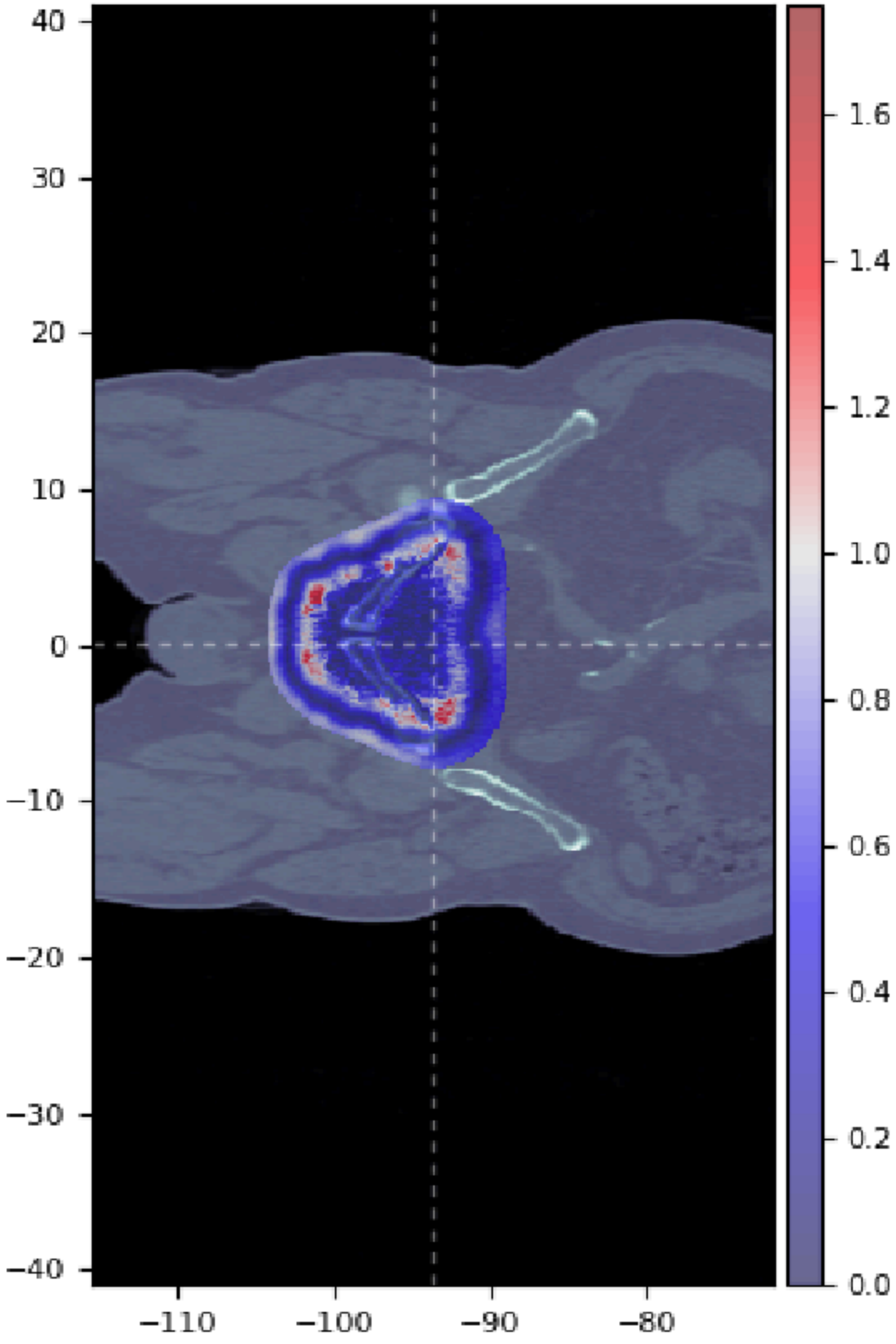
A. Sarti et al, *Frontiers in Oncology* **11** (2021) 777852





GI 2mm/2%
FRED vs FLUKA
Gamma min: 0.00
Gamma max: 1.57
Gamma mean 0.39
Gamma std 0.26

Pass Rate 97.76%

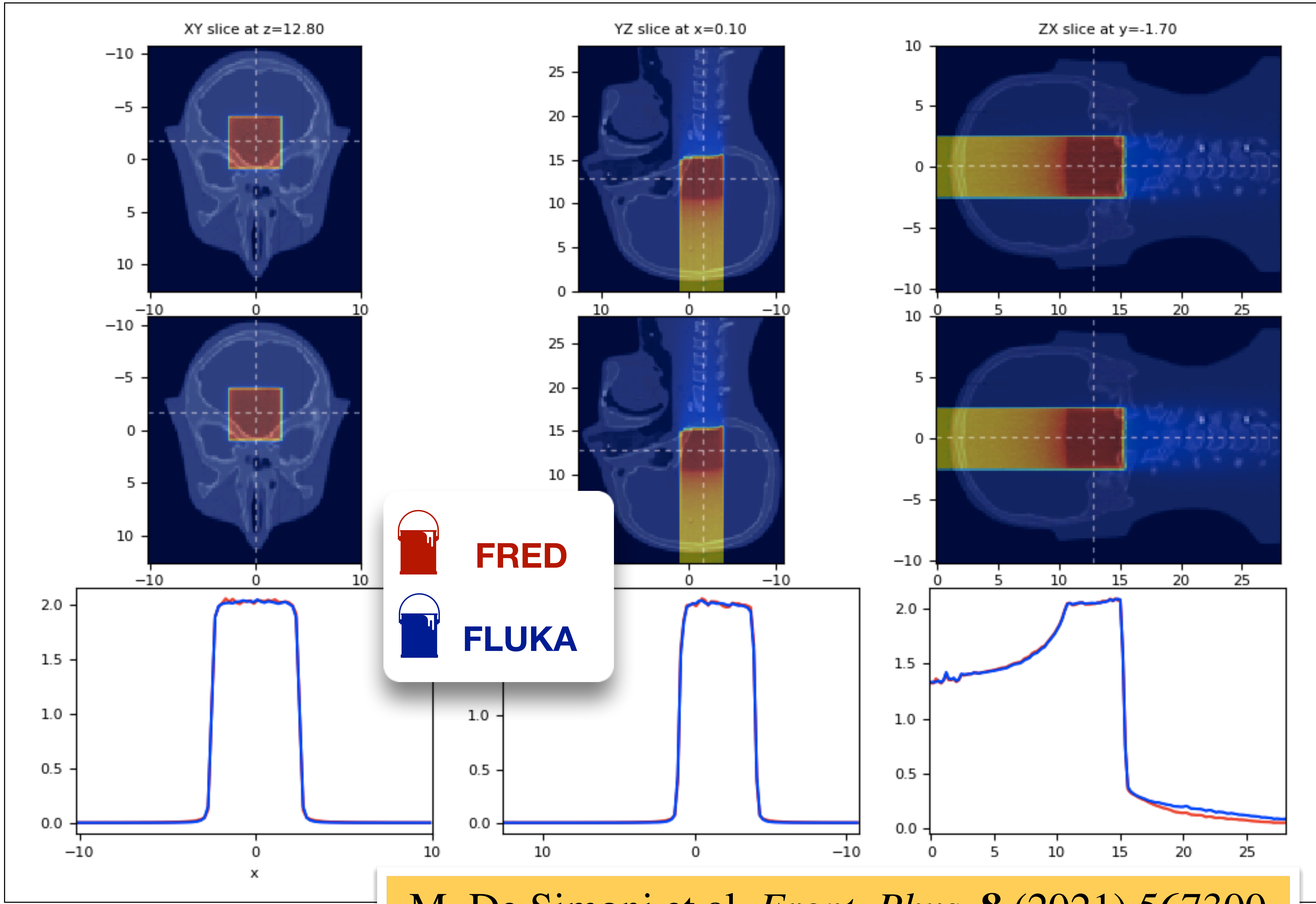


FRED for Carbon beam therapy

Target: (10x10x20) cm^3,
voxel:
(0,5x0,5x0,2) mm^3

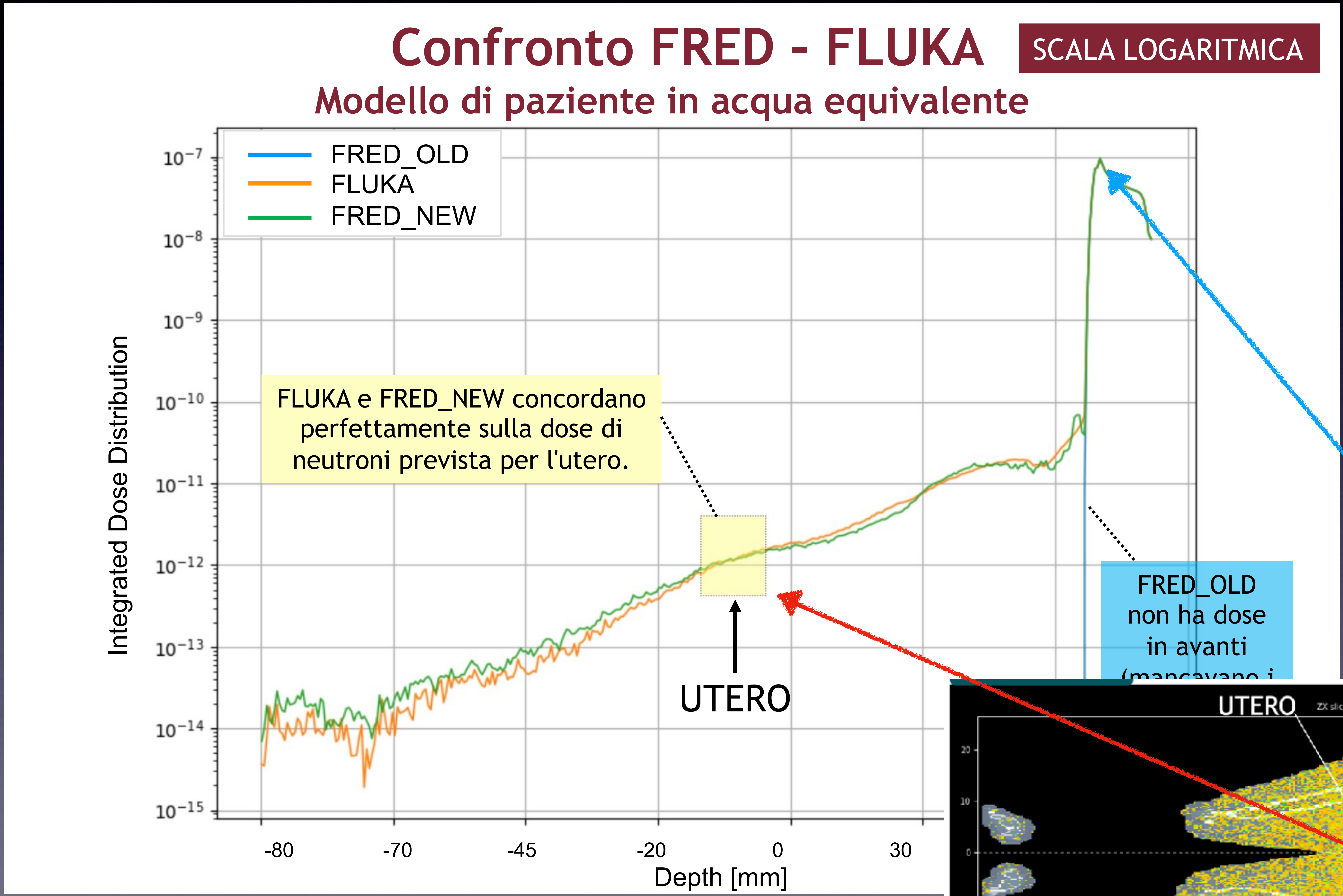
31 square energy layers from 218 to 277 MeV/u with FWHM 5 cm

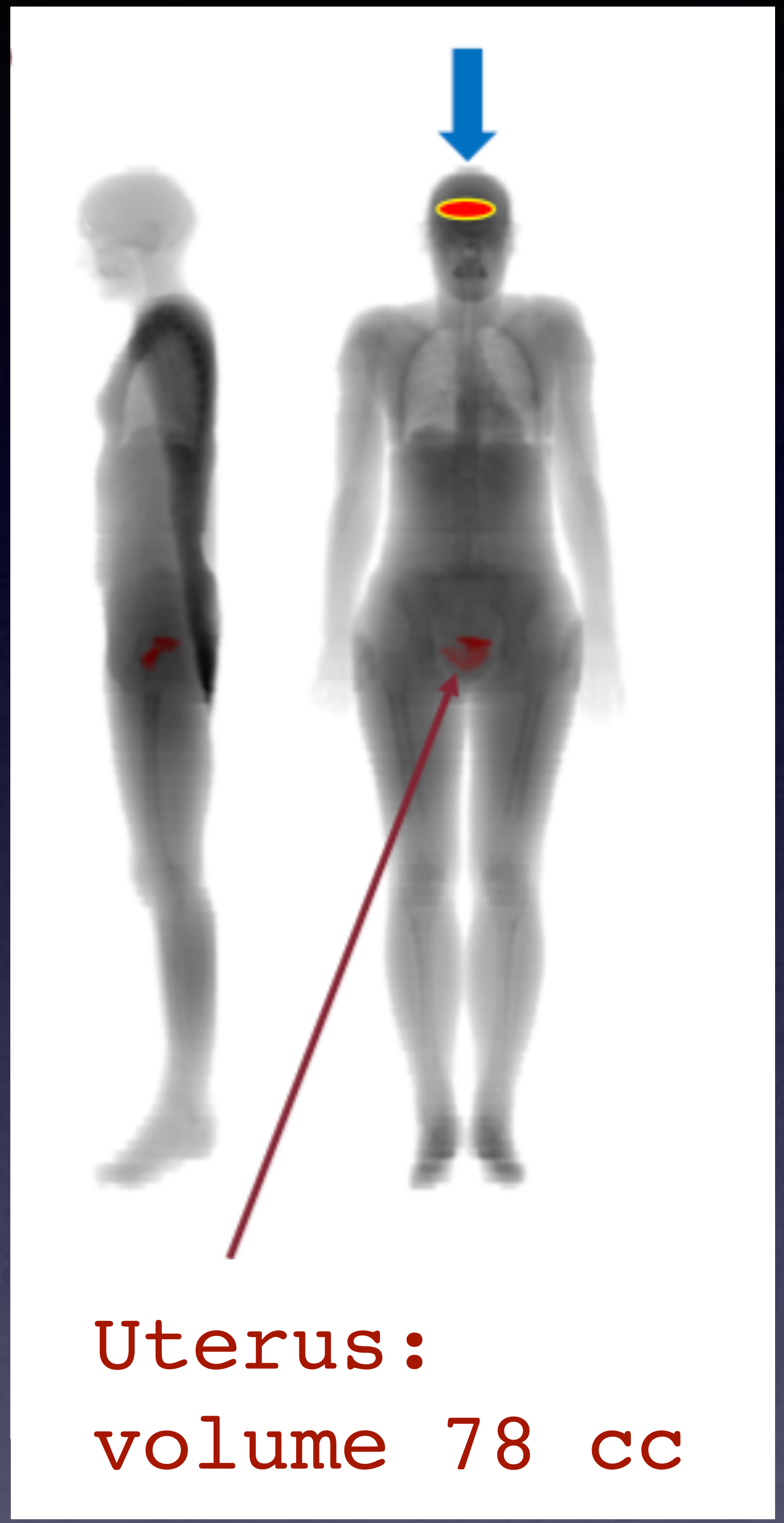
Gamma index
2mm-3%: 99.89%
(DCO 5%)

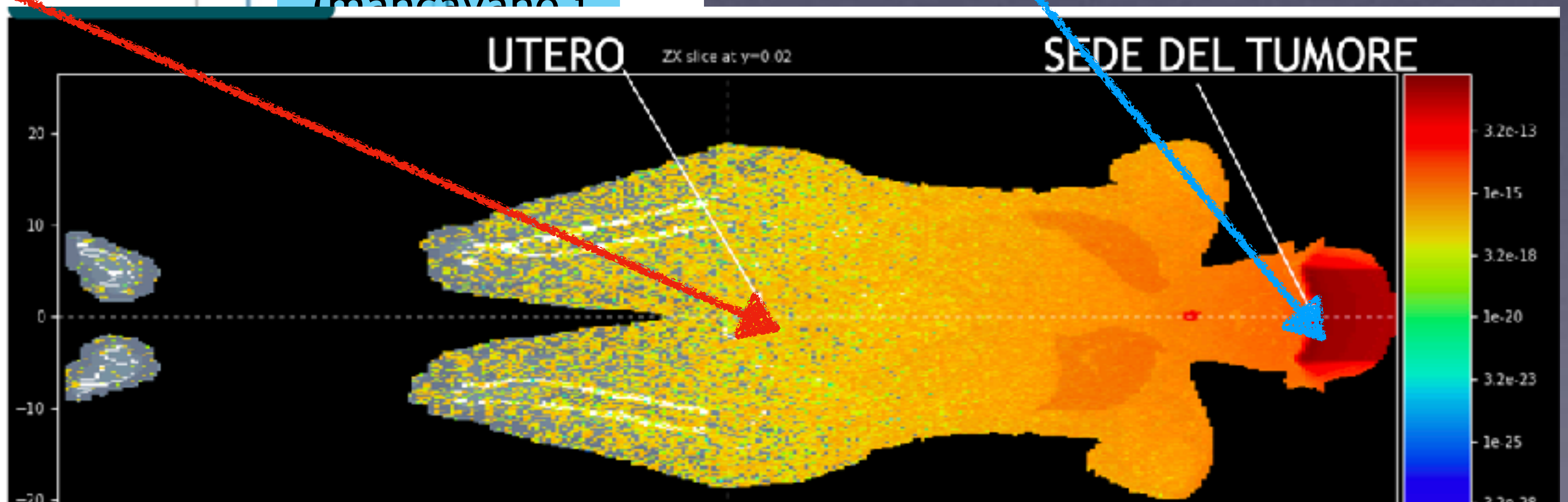


M. De Simoni et al, *Front. Phys.* **8** (2021) 567300

Neutrons for Pregnants in Protontherapy







Fast paRticle thErapy Dose evaluator

Collaboration network

- A. Schiavi, V. Patera, A. Sarti, G. Traini, G. Franciosini, A. Muscato, A. De Gregorio, G.Battistoni, Univ. La Sapienza Roma and INFN (Italy)
- E. Scifoni, F. Tommasino, A. Taffelli, N. Massimo, A. Attili, F. Fracchiolla, Univ. Trento, APSS TN, and TIFPA-INFN
- N. Krah - CREATIS, CNRS/University Lyon (France)
- A. Rucinski, J. Gajewski, M. Garbacz, A. Skrzypek, J. Baran, P. Stasica - JPAN, Krakow (Poland)
- I. Rinaldi - Maastro clinic, Maastricht (Netherlands)
- A. Lomax, C. Winterhalter, K. McNamara, PSI (Swiss)

Conclusions

- TPS now use MC on GPU
- GPU re-implementation is extremely expensive
- costs vs benefits: "real-time", large patient coorts, AI training dataset generation
- application-driven choice of simulation solution
- hence…

… there are no conclusions!