www.fluka.org

Recent developments in the FLUKA tools for treatment planning

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on behalf of the FLUKA group

Treatment Planning Systems for Hadrontherapy

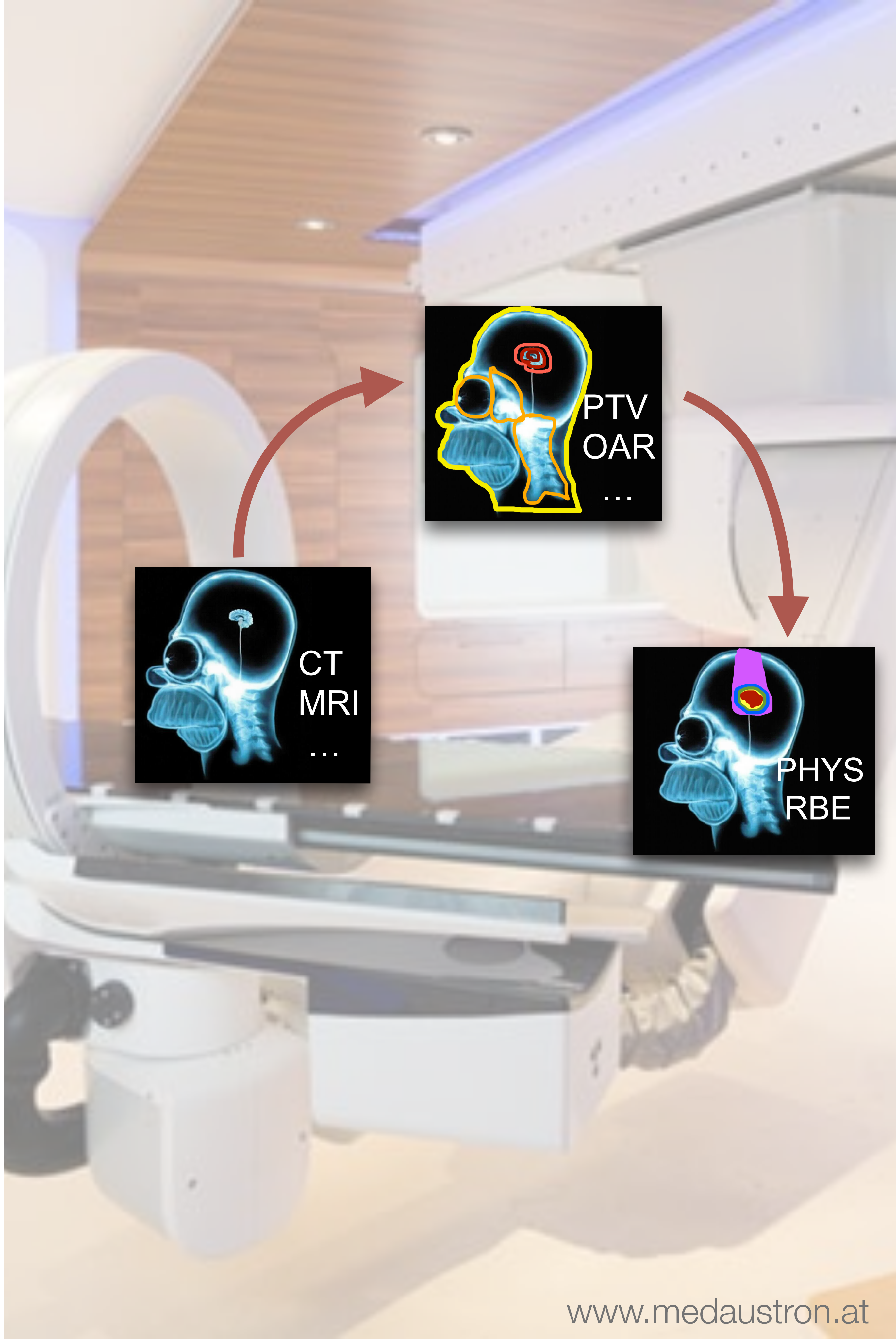
TPS are typically based on **pencil beam scanning algorithms**

Range of the proton/ion beam is mainly based on the **water equivalent depth**

Lateral beam shape is described by Gaussian or double-Gaussian **parametrisation**

Analytical TPS enables **fast** dose calculations and **fast** optimisation

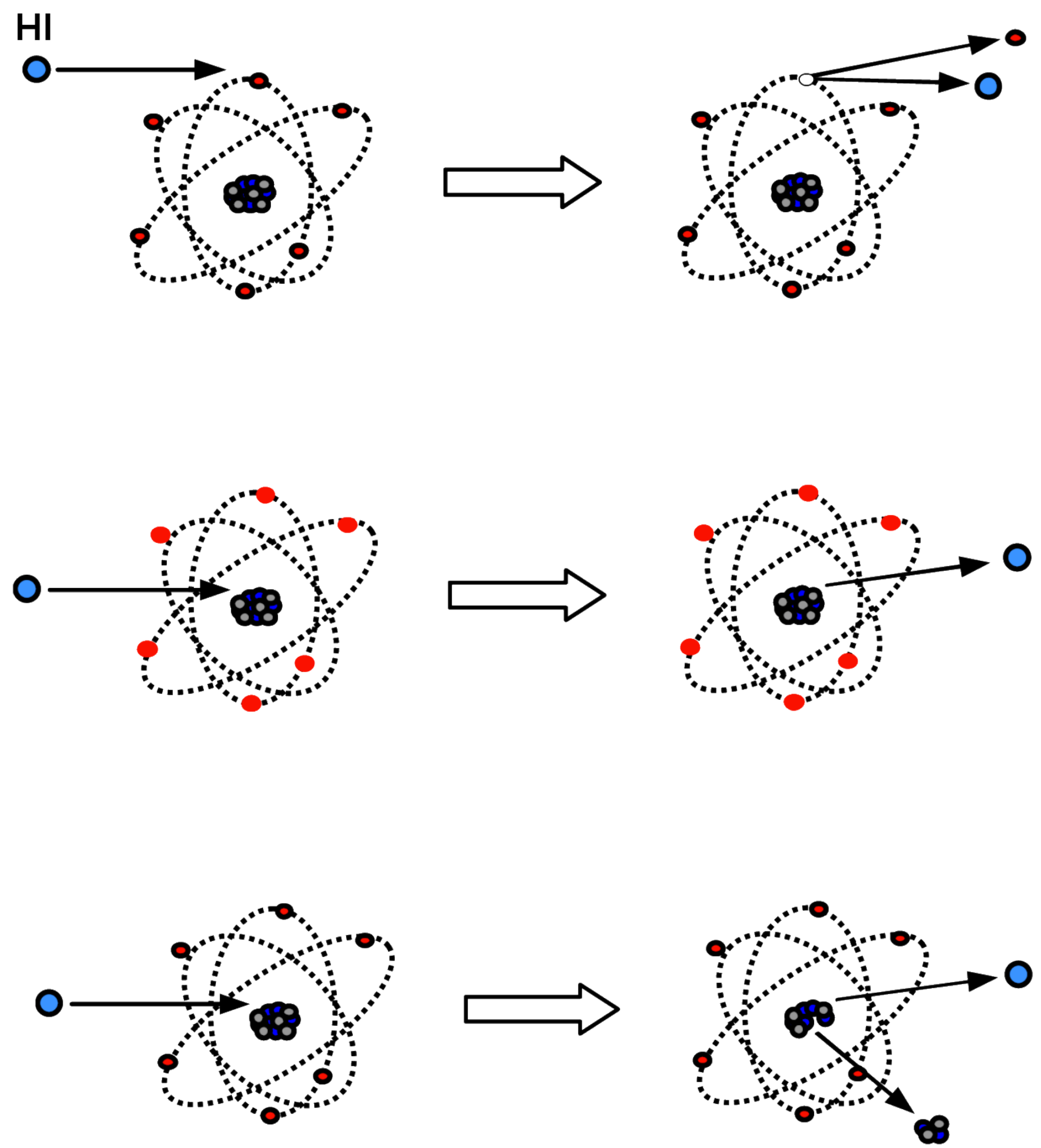
Why do we need Monte Carlo TPS?



Monte Carlo Treatment Planning System

Faithful consideration of the **radiation transport and interactions with matter:**

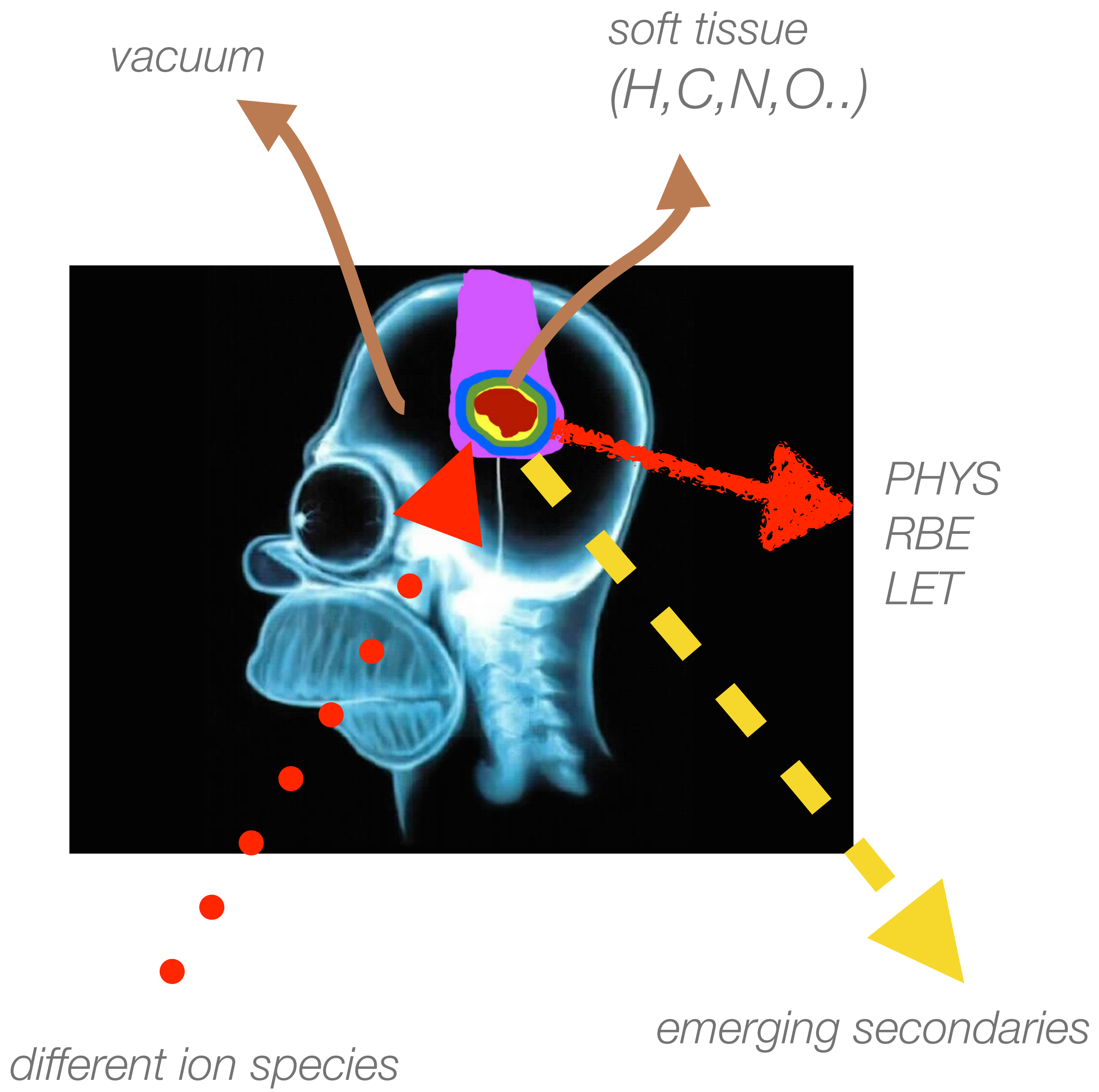
- **Energy Losses** through collisions with atomic electrons (Bethe-Bloch formula with its corrections)
- **Nuclear Reactions** (i.a. fragmentation tails, other secondary particles..)
- **Multiple Coulomb Scattering** (mostly elastic scattering - deflection)



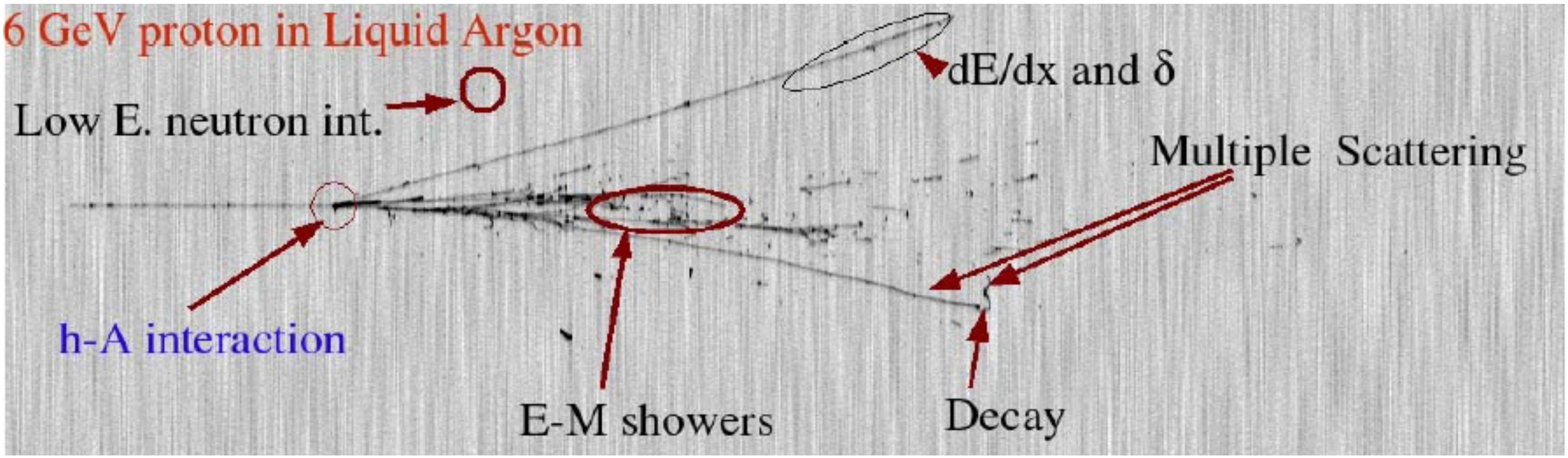
Monte Carlo Treatment Planning System

Capable of handling all components of the expected radiation field

- **Realistic atomic composition** of the patient tissue, limited by the HU to tissue conversion
- Scoring not only physical dose, but also **RBE** dose, dose-weighted **LET**
- Accurate prediction of **emerging secondaries** for in vivo studies
- **Protons and light ion beams**



Interactions and Transport Monte Carlo Code



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- **FLUKA**[1][2] is a general purpose Monte Carlo code
- Joint **CERN-INFN project,** and is continuously undergoing development and benchmarking
- **Maintained and developed** under INFN-CERN agreement and copyright
- More than **9000 users worldwide**

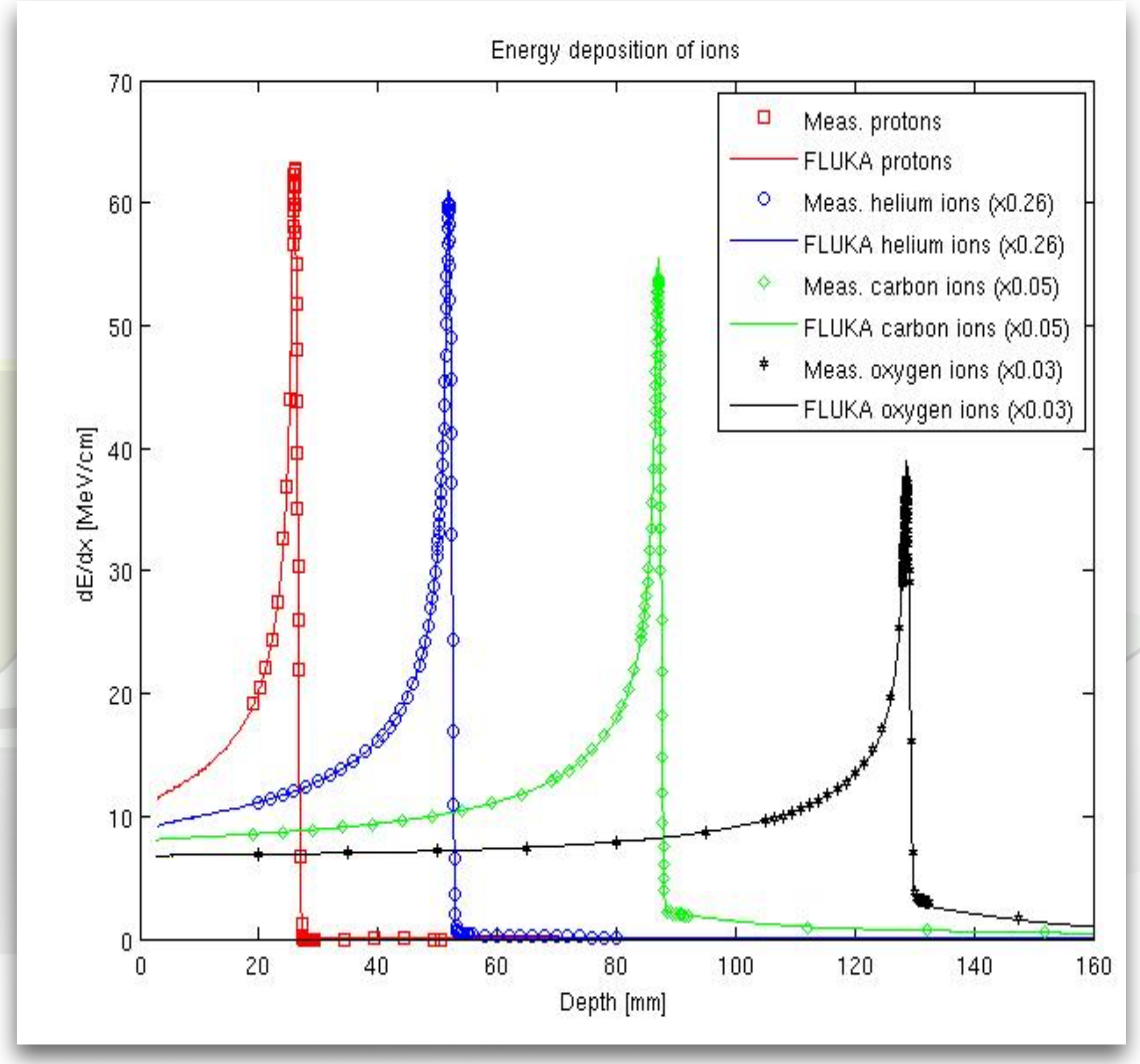
FLUKA Short Description

FLUKA is a general purpose tool for calculations of particle transport and interactions with matter

- All Hadrons (p, n, K, pbar, nbar, (anti)hyperons…)
- Electromagnetic (, e+/-) and μ and ν
- Nucleus-nucleus
- Low energy neutrons (0-20 MeV, multigroup, ENDF…)
- Full mixed field capability
- Transport in magnetic field
- Combinatorial (boolean) and Voxel geometries
- Double capability to run either fully analogue and/or biased calculations
- On-line evolution of induced radioactivity and dose
- Radiation damage predictions (NIEL, DPA)
- User-friendly GUI interface thanks to the Flair interface

FLUKA for Medical Applications

- **At HIT and CNAO (p and C-12)**
  - TPS data generation, verification/optimization
  - Research: new beams, therapy monitoring
  - RBE model comparison NIRS vs. CNAO in carbon ion
- **European Projects:**
  - **ENVISION/ENTERVISION** (β+ emitters, prompt gamma, emerging charged particles
  - **OMA** - Optimization of Medical Accelerators

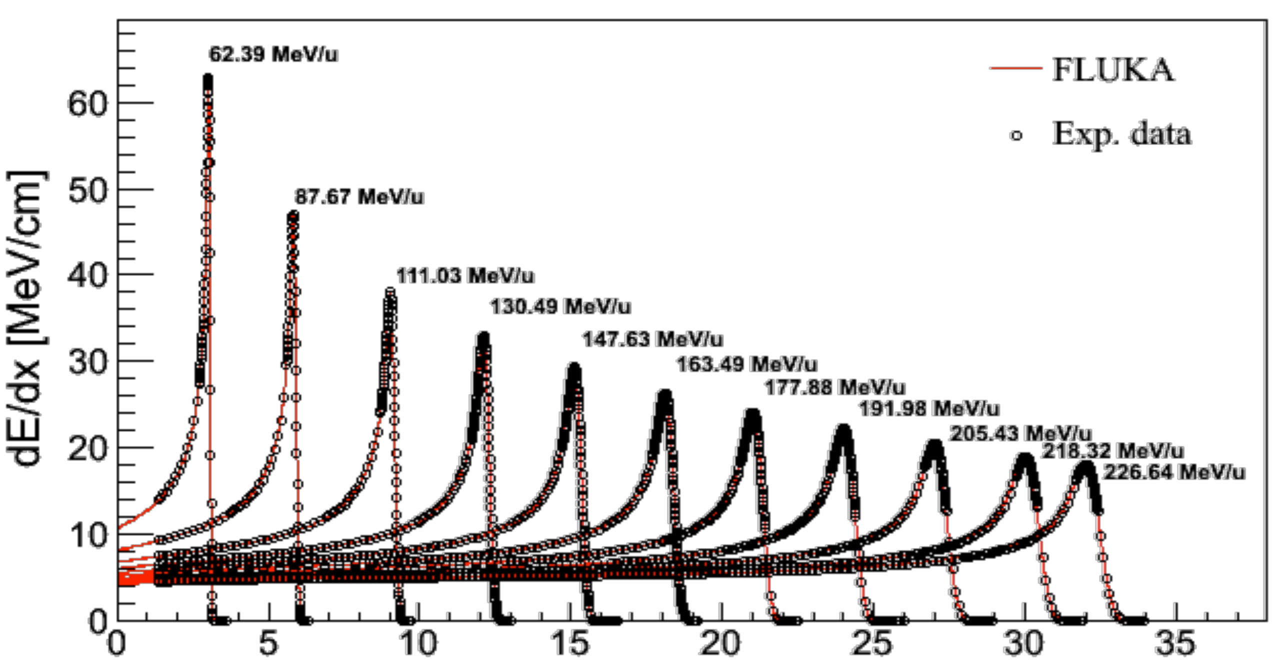


FLUKA simulations of depth–dose profiles of protons and light ions with therapeutic ranges in comparison with measured data at HIT [5]

Generating depth-dose distribution for TP database

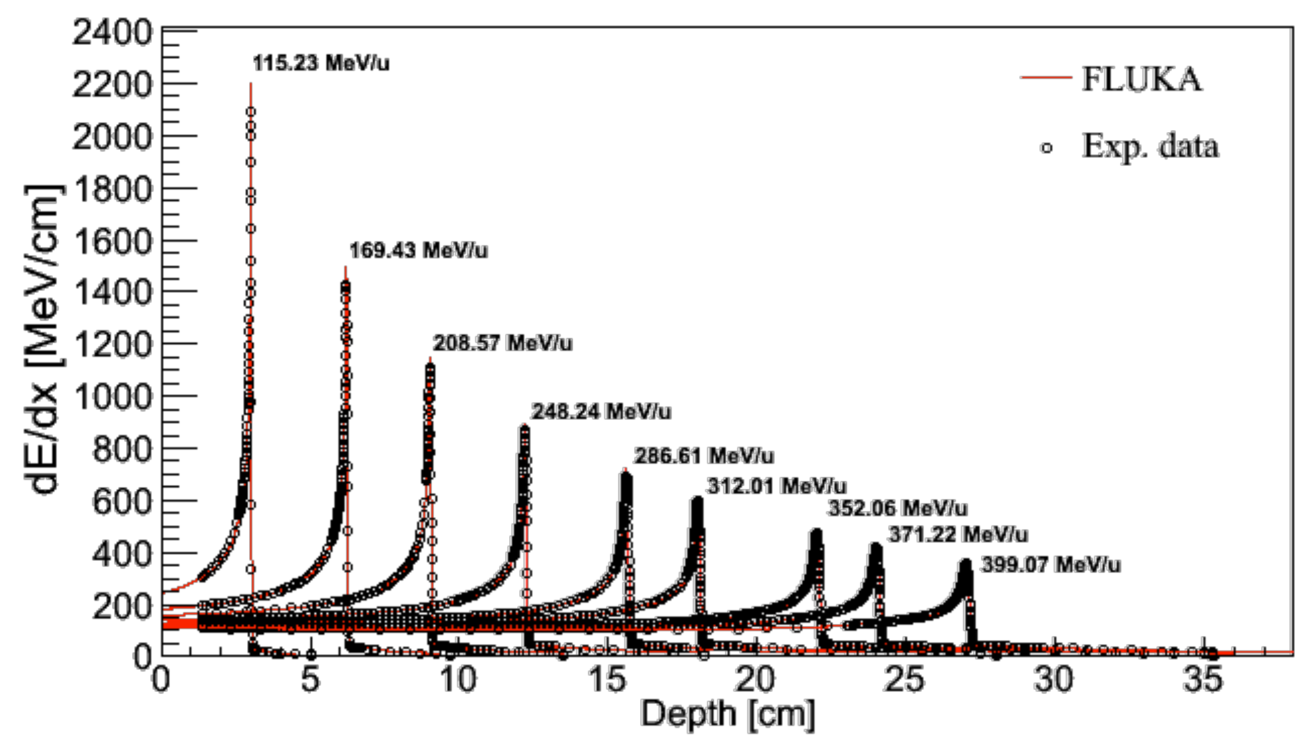
Physics well established. Thoroughly **benchmarked** at single interaction level; i.a. **against depth–dose data and lateral-dose profiles** used for proton and ion-beam therapy

Depth-dose distribution of protons (CNAO) in water wo/with RiFi for the 147 energies in the initial phase of the operation



Mairani, Varenna 2012

Depth-dose distribution of C-12 (HIT)



Courtesy of: Med Phys Group at CNAO and HIT

Flair[3] provides an IDE for all stages of **FLUKA simulations** (input, geometry editor, debugging, post-processing output visualization)

is more than a graphical Interface - it is a **complete integrated working environment** for FLUKA

Front-end

Fully featured Input file Editor;

Geometry: interactive visualization editing, and debugging;

Compilation of the FLUKA Executable;

Running (Spawning on multi-core) and monitoring of the status of one/many run(s)

Back-end

Post processing of FLUKA output

Plot generations with gnuplot

Photorealistic 3D plots with USRBIN data superimposed

Other

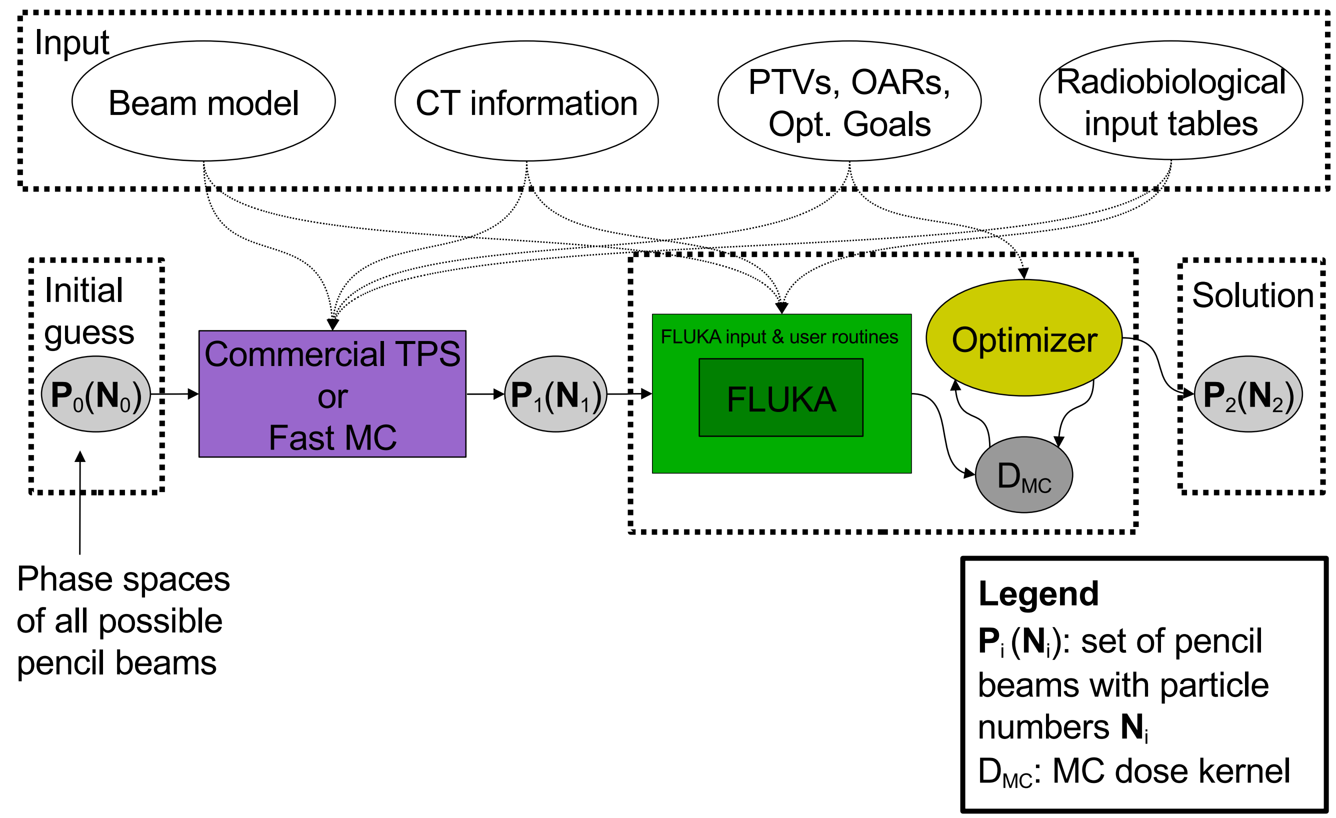
Database of Materials, Isotopes

FLUKA hypertext manual

…

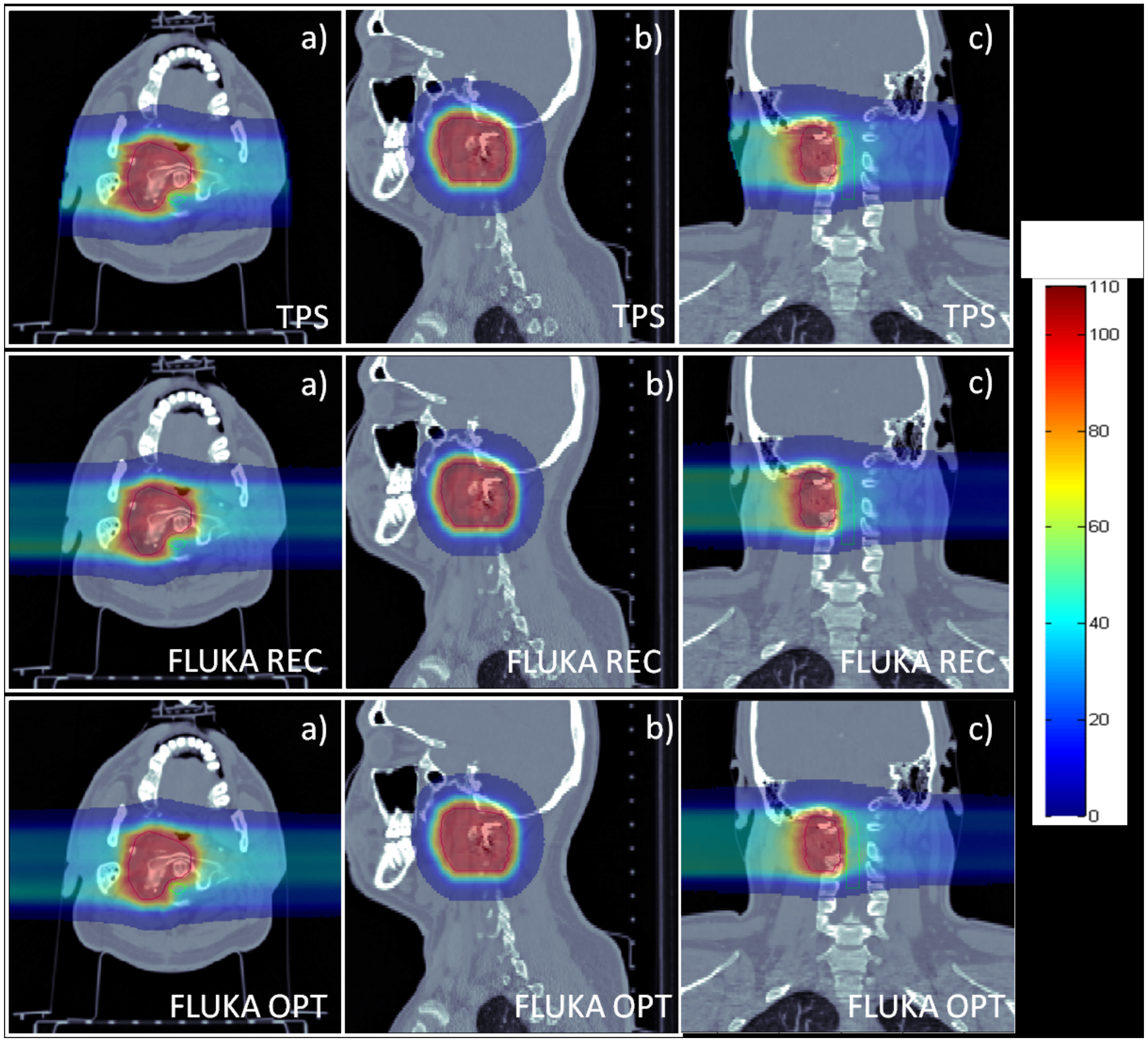
FLUKA based MC Treatment Planing

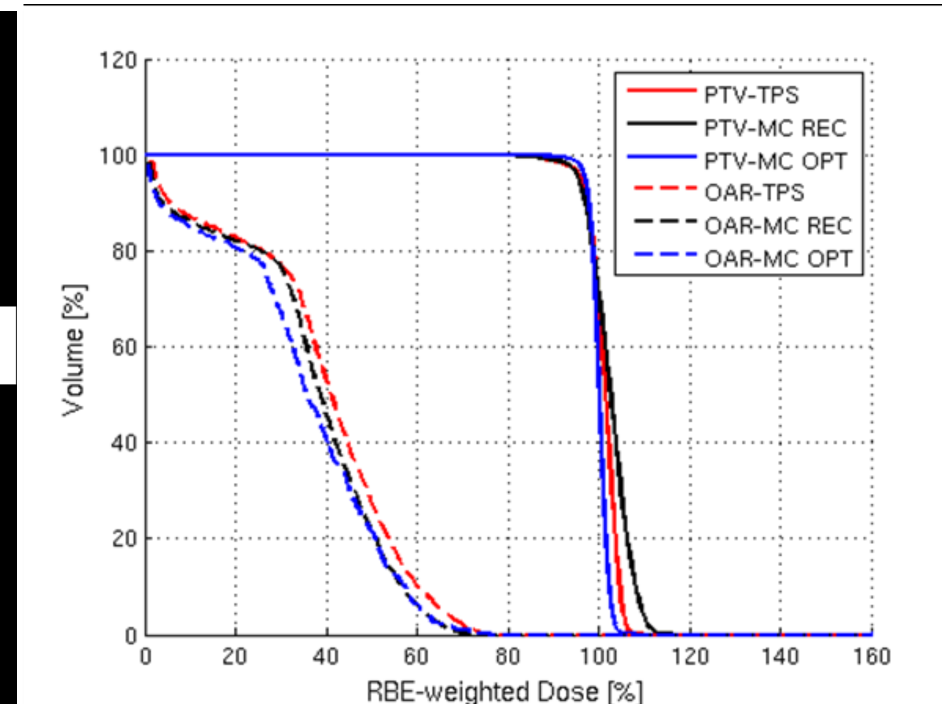
- To **account for geometry and material details and applying realistic treatment conditions** within acceptable CPU time
- To **suggest a better solutions**
- To be used **stand-alone** or as **post re-optimization** of TPS plans
- To be **used in research**: New ions and combined ion fields, testing of new biomodels



Software architecture of the FLUKA MC TPS [4]

FLUKA based MC Treatment Planning

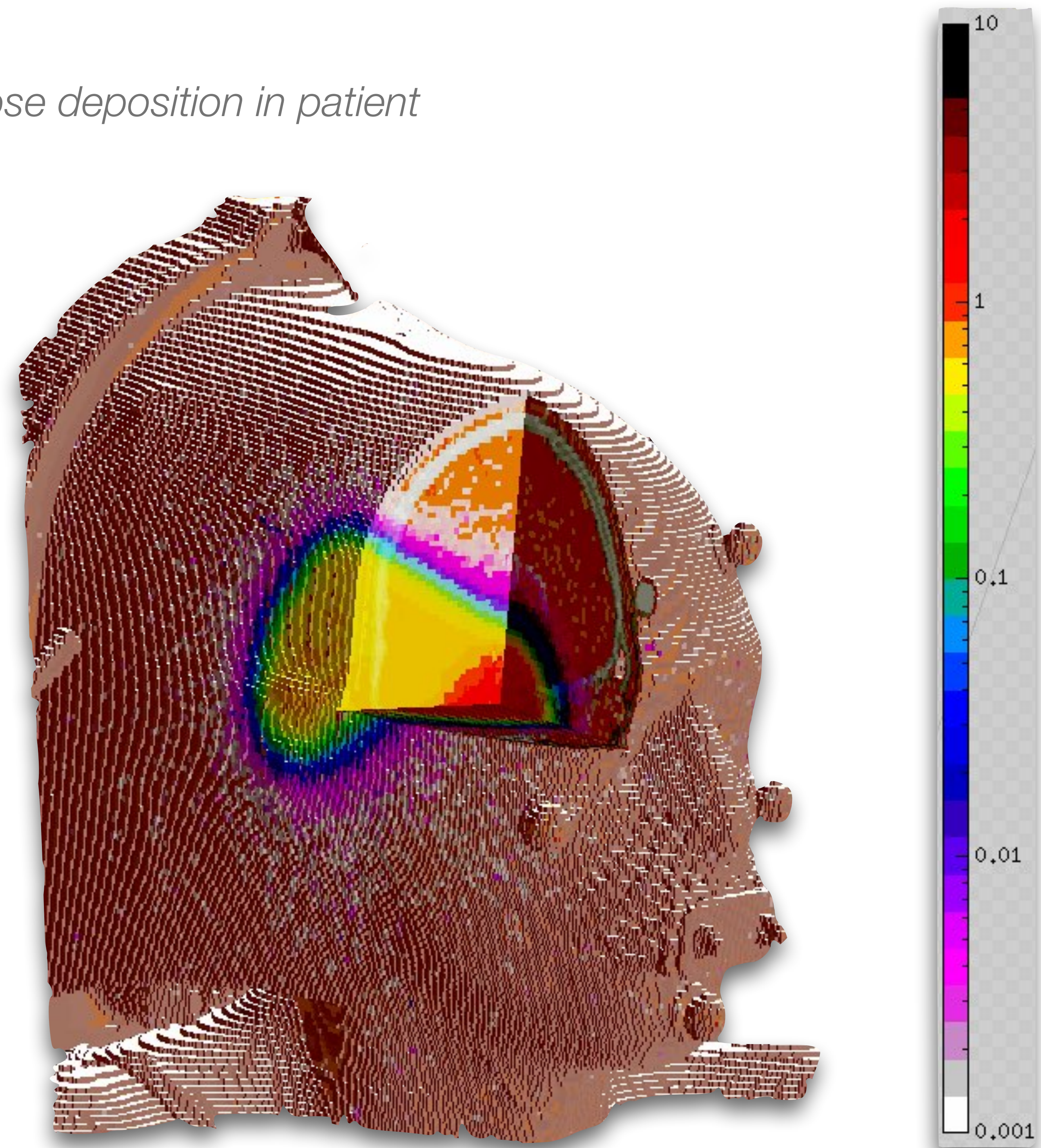




FLUKA RECalculation and FLUKA OPTimization of proton TPS at CNAO[4]

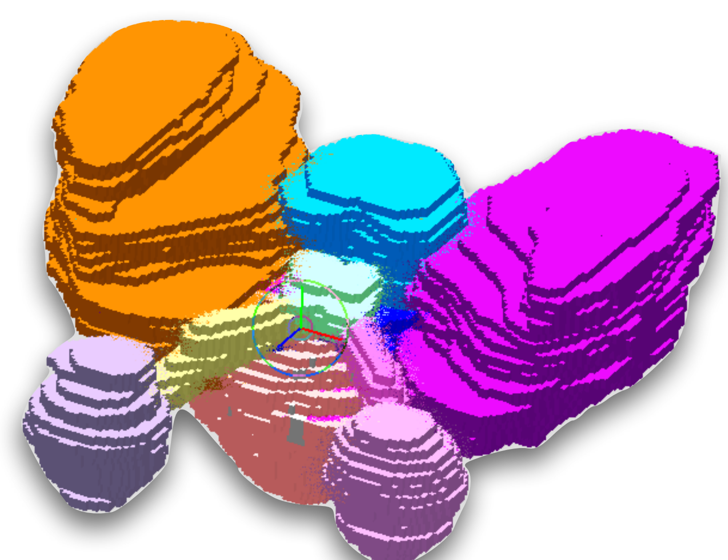
Monte Carlo Simulations are considered as a gold standard for dosimetric calculations in medical physics, although time is the main issue

Dose deposition in patient

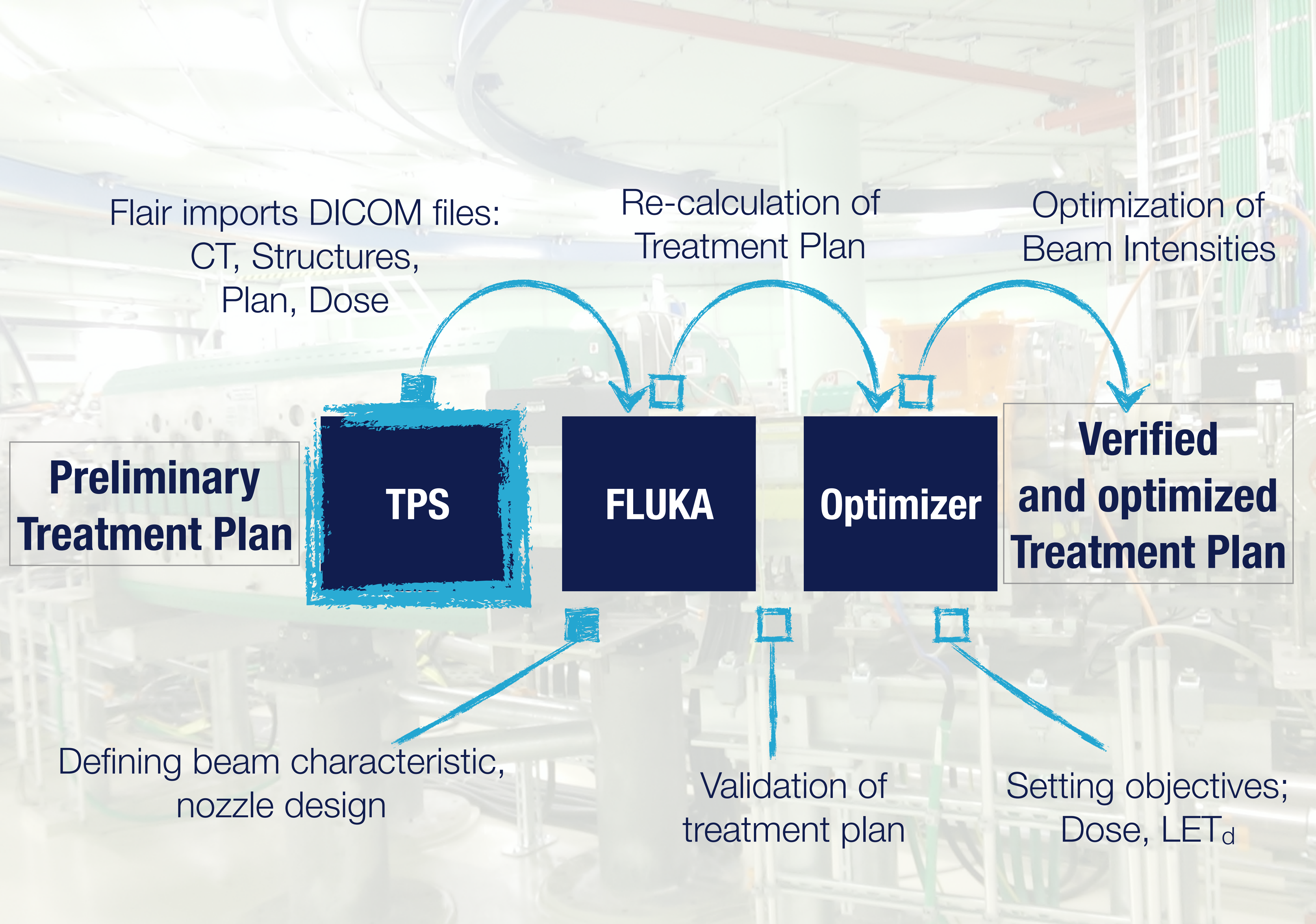


One of the **major contribution factor to the accidents** in the radiation therapy related to the TPS derives from **lack of independent calculations** for beam intensities [4]

Regions of interest (ROI)



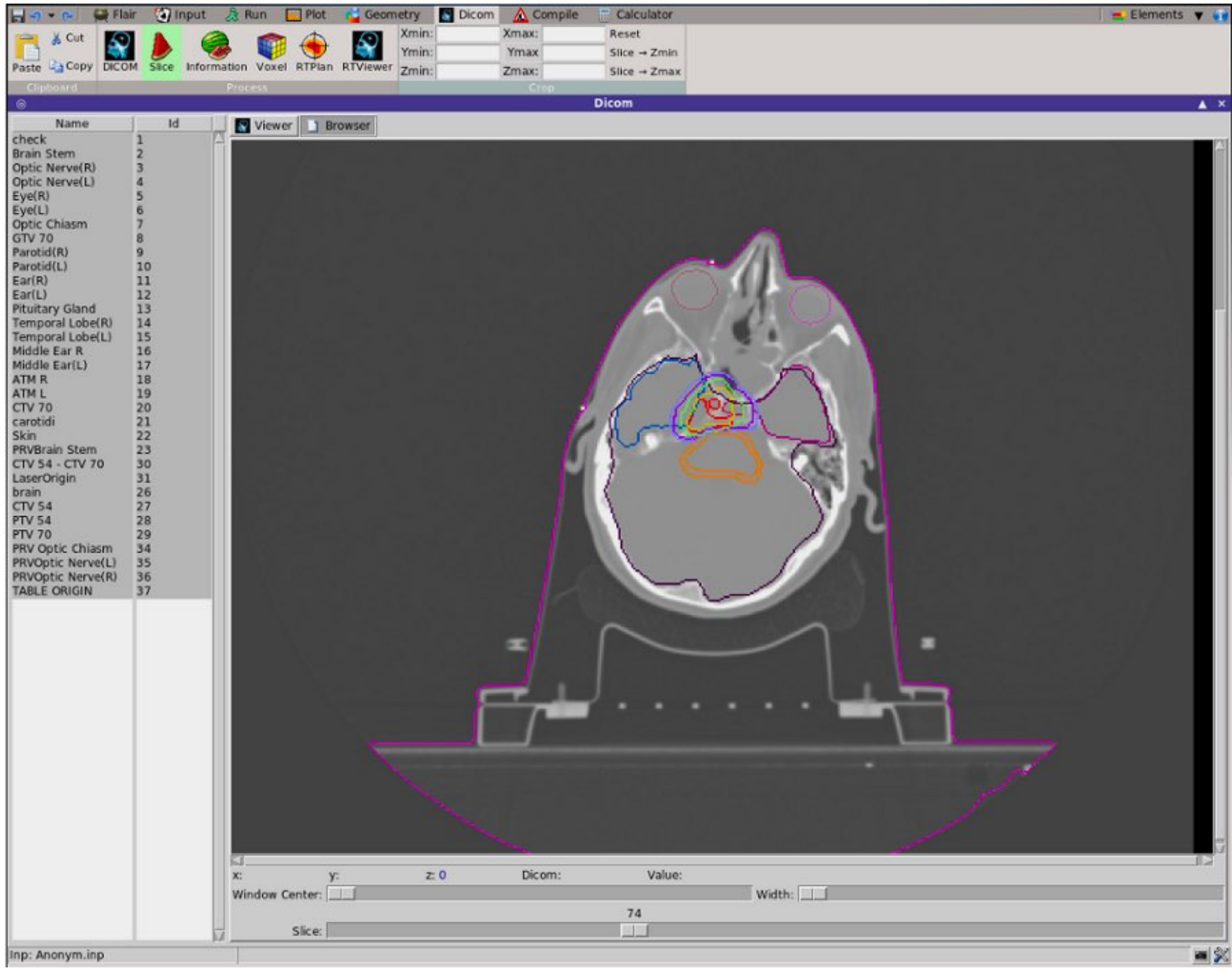
FLUKA and its GUI Flair for Hadrontherapy TPS

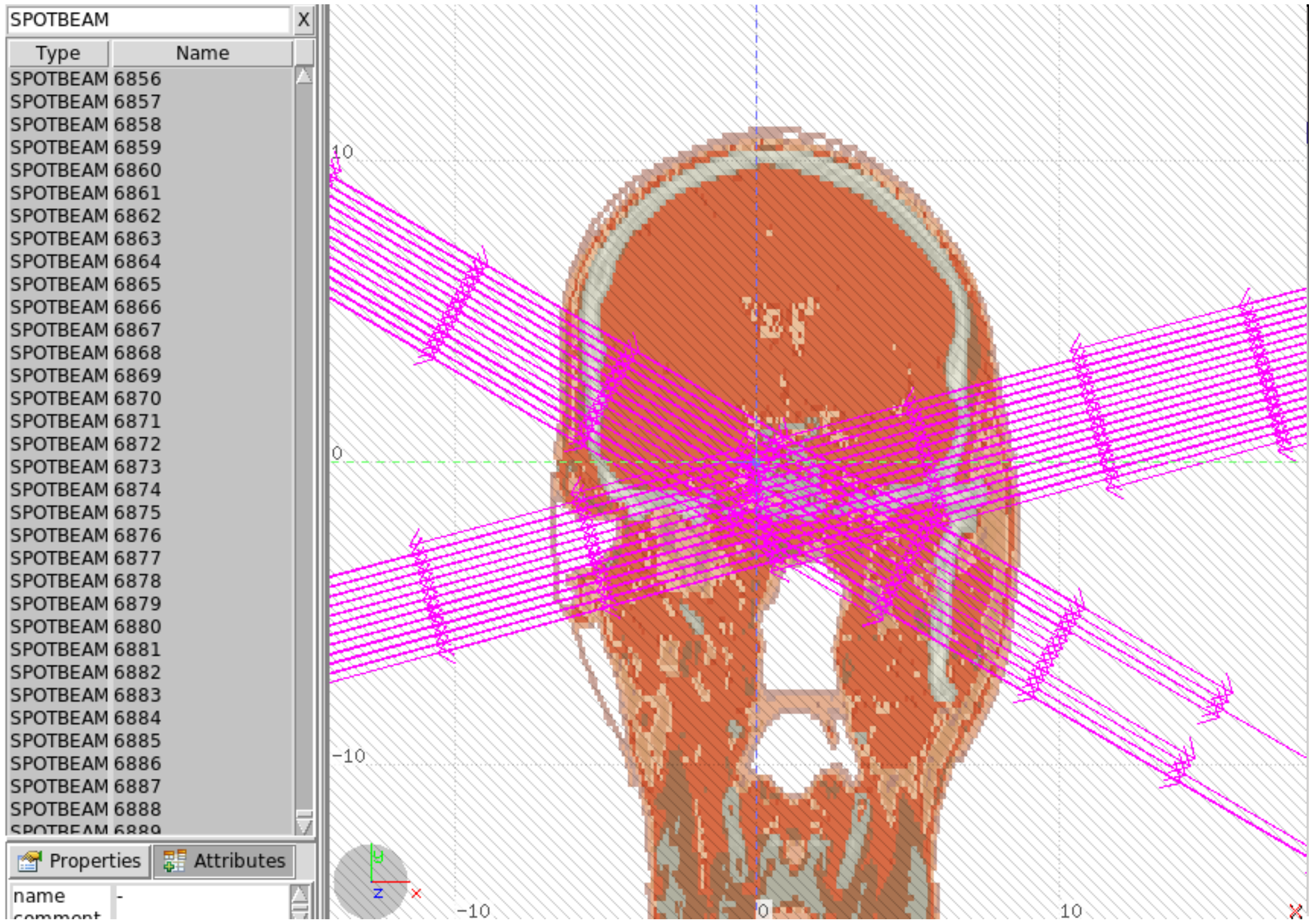


Flair imports DICOM files:
CT, Structures,
Plan, Dose
Re-calculation of
Treatment Plan
Optimization of
Beam Intensities
Preliminary
Treatment Plan
TPS
FLUKA
Optimizer
Verified
and optimized
Treatment Plan
Defining beam characteristic,
nozzle design
Validation of
treatment plan
Setting objectives;
Dose, LET_d

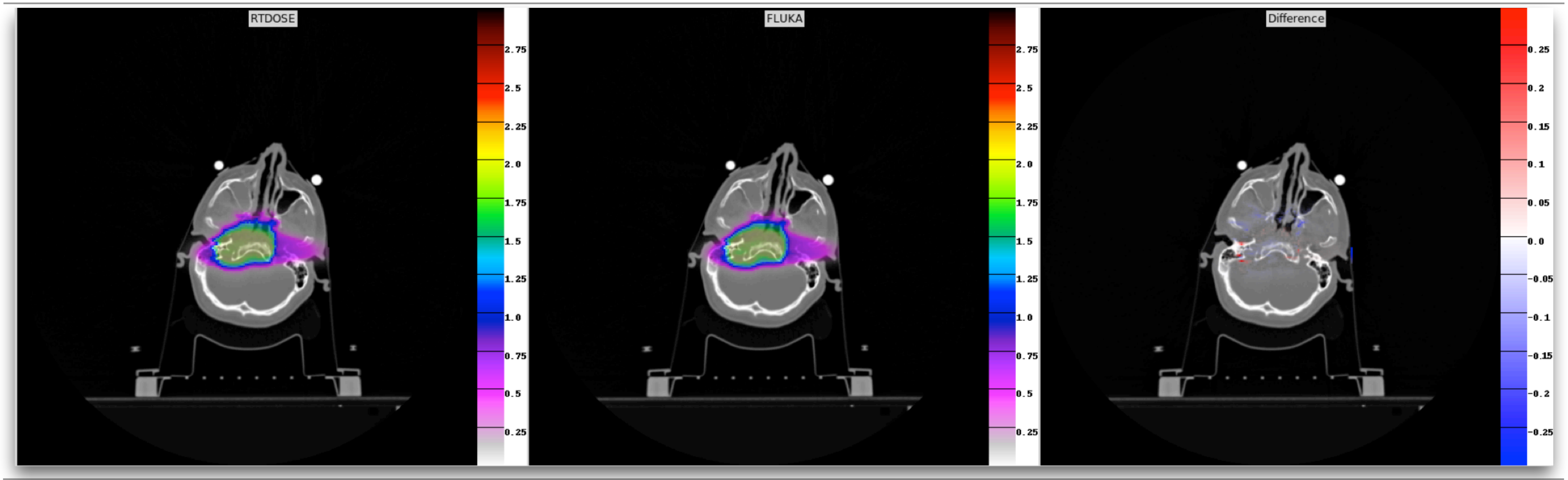
FLUKA and its GUI Flair for Hadrontherapy TPS

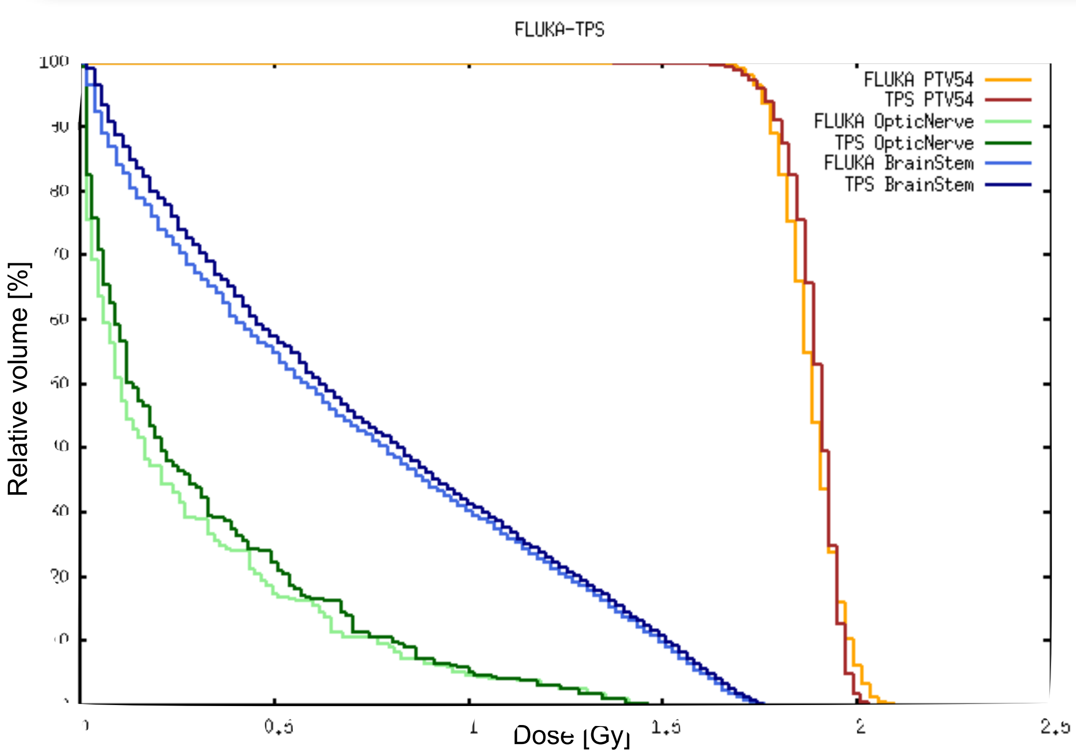
- Process **DICOM standard files** for radiotherapy purposes
  - DICOM CT, MRI importer
  - Automatic material assignment using the Schneider parameterization
  - Importing ROI RTStructures
- Provides easy-to use tool for **treatment plan re-simulation** and quantitative comparison
  - Importing RTPlan
  - Generation of the DVH plots and comparison with the RTDOSe
  - Enables precise description of patient model and beam delivery system





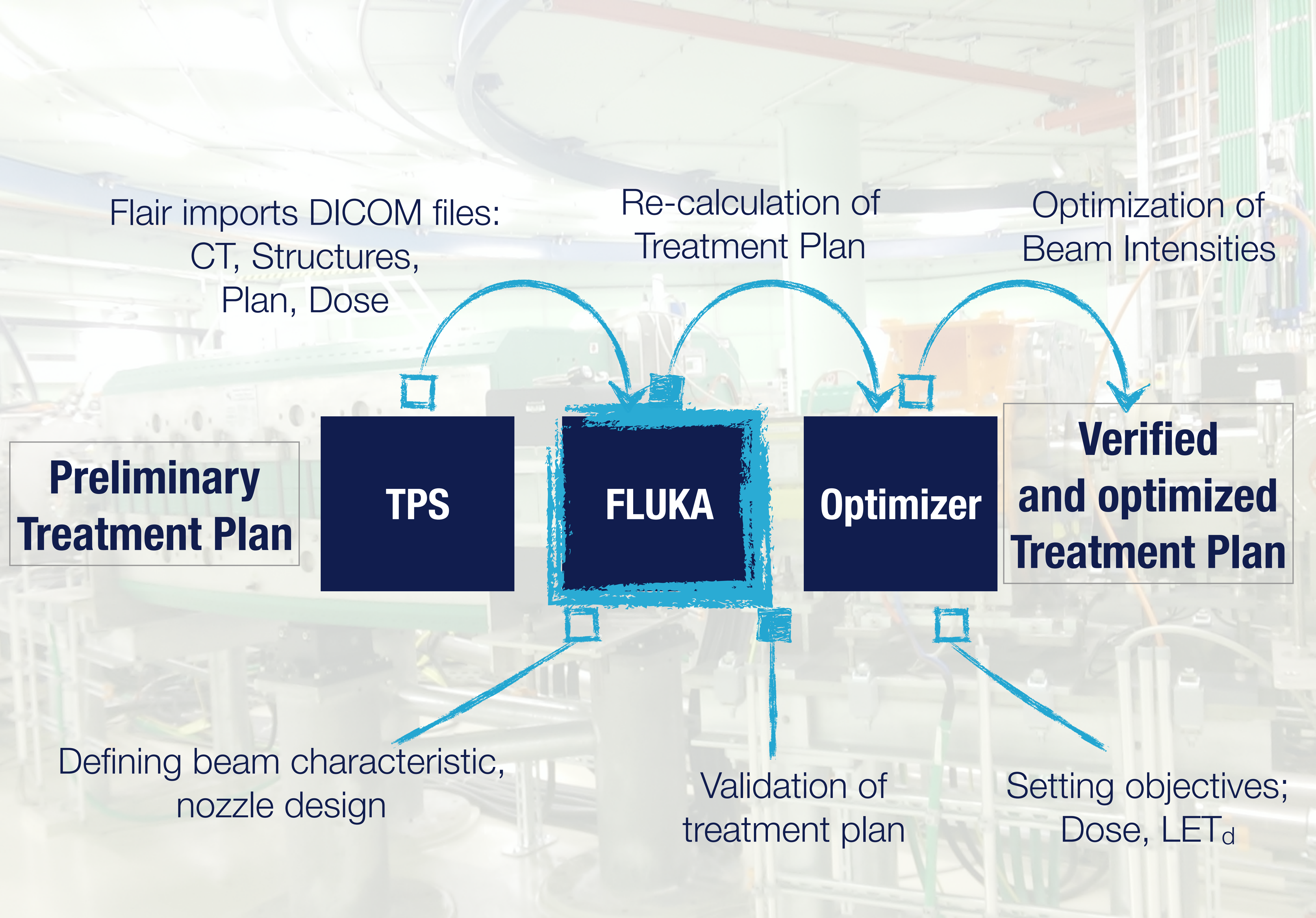
Monte Carlo Treatment Plan recalculations





Proton chordoma patient case (CNAO)

- Calibration of HU to density
- HU to tissue conversion methods
- Ionization potentials of tissue materials
- Accuracy of primary beam description
- Biological dose and LET calculations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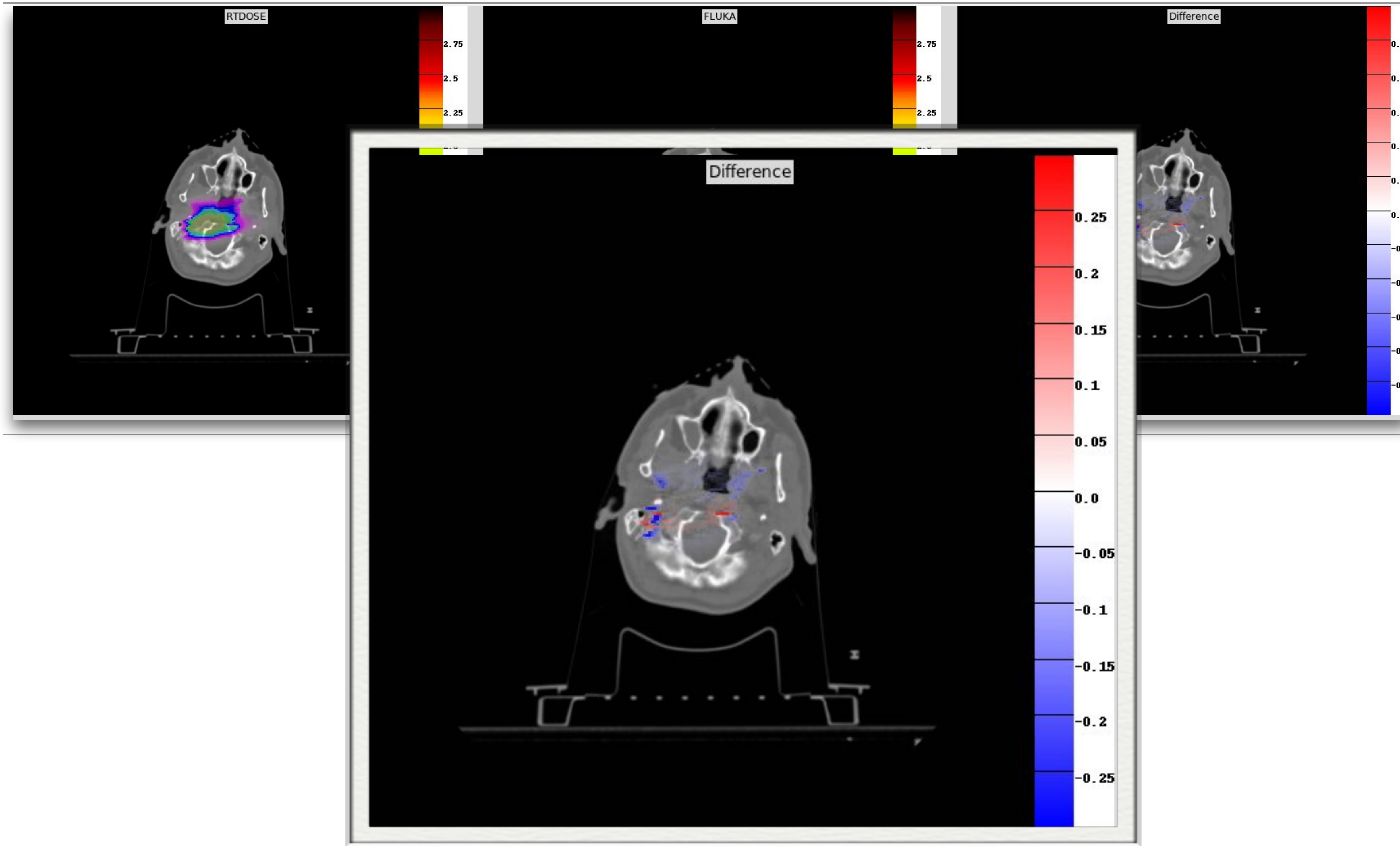
Monte Carlo Treatment Plan recalculations for hadrontherapy / sensitivity studies

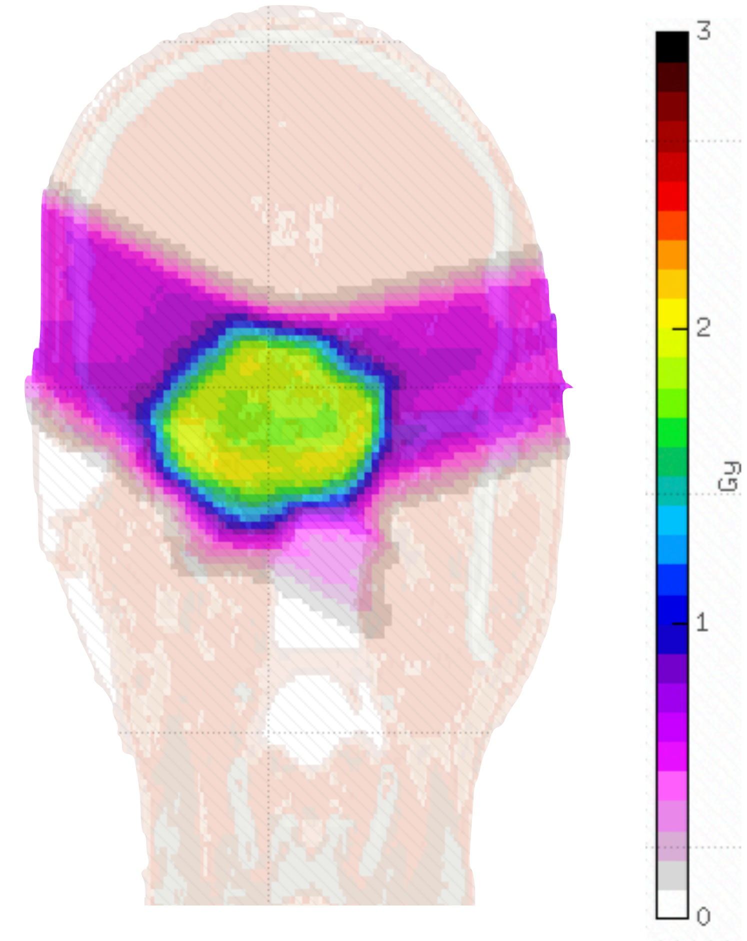
Proton chordoma patient case



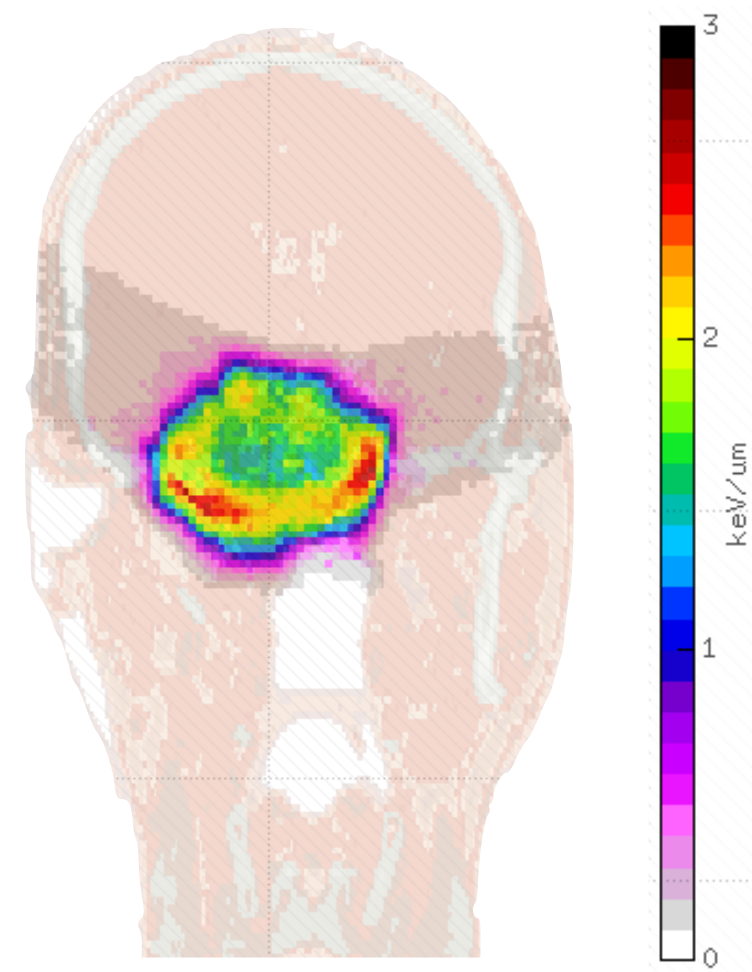
Linear Energy Transfer (LET)

- LET is average amount of energy a particular radiation imparts to the local medium per unit length
- There is a significant correlation between the dose-averaged LET and RBE
- High-LET particles can **reduce the response factor OAR** (oxygen enhancement ratio) leading improvement of the treatment outcome for hypoxic - radioresistive tumors

DOSE



LET_d

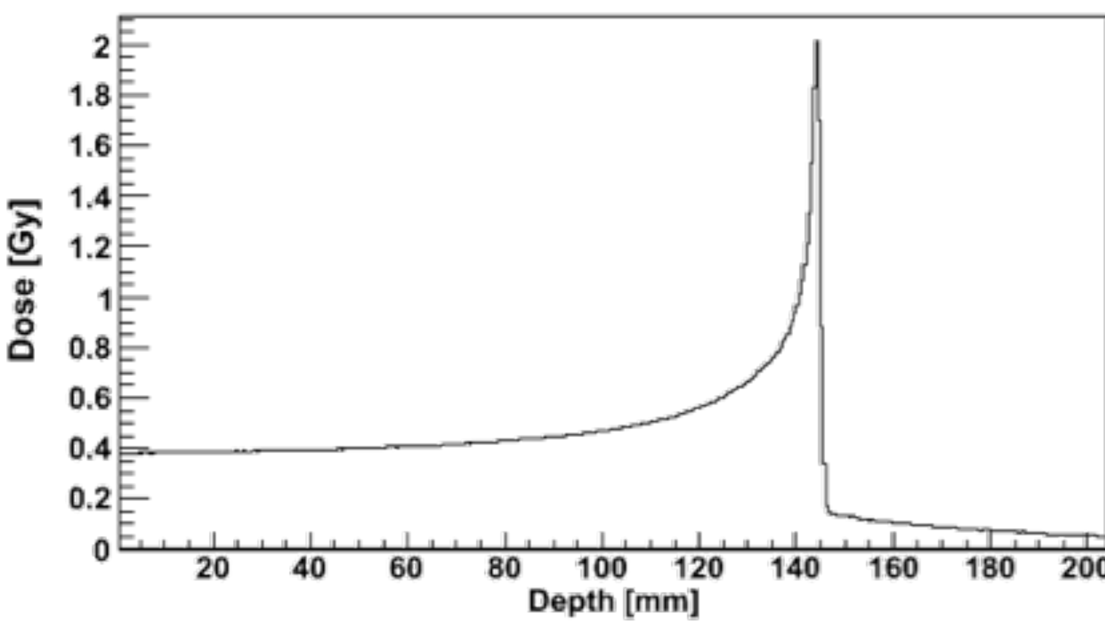


Biologically Oriented Scoring

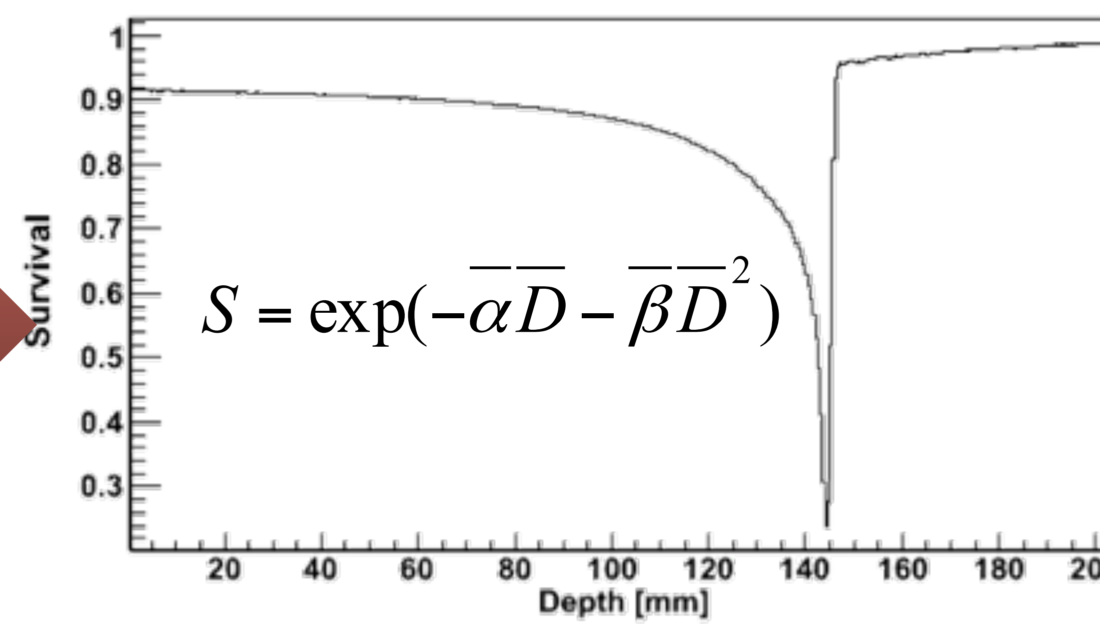
- Under the standard assumption of a **linear-quadratic dose-effect relationship**, for each energy deposition i, FLUKA interpolates from a radiobiological database the αD,i and βD,i parameters for the **specific ion with a certain charge at a certain energy**.

- Then FLUKA **sums up properly the mixed radiation effect applying the Kellerer and Rossi theory** of dual radiation action

Physical dose

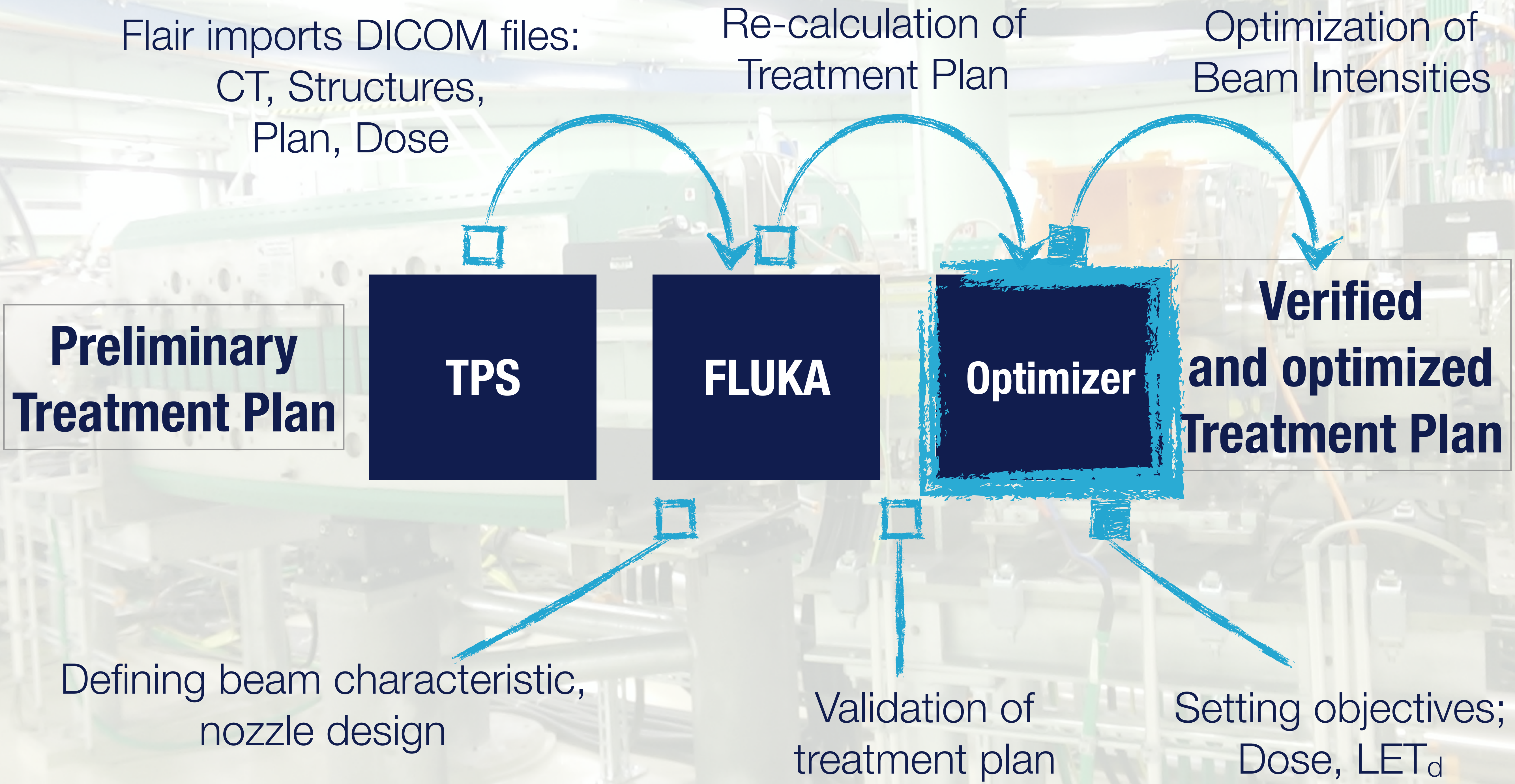


Final result survival curve



$$S = \exp(-\overline{\alpha}\overline{D} - \overline{\beta}\overline{D}^2)$$

270 MeV/u C-12 ions on V79 cell line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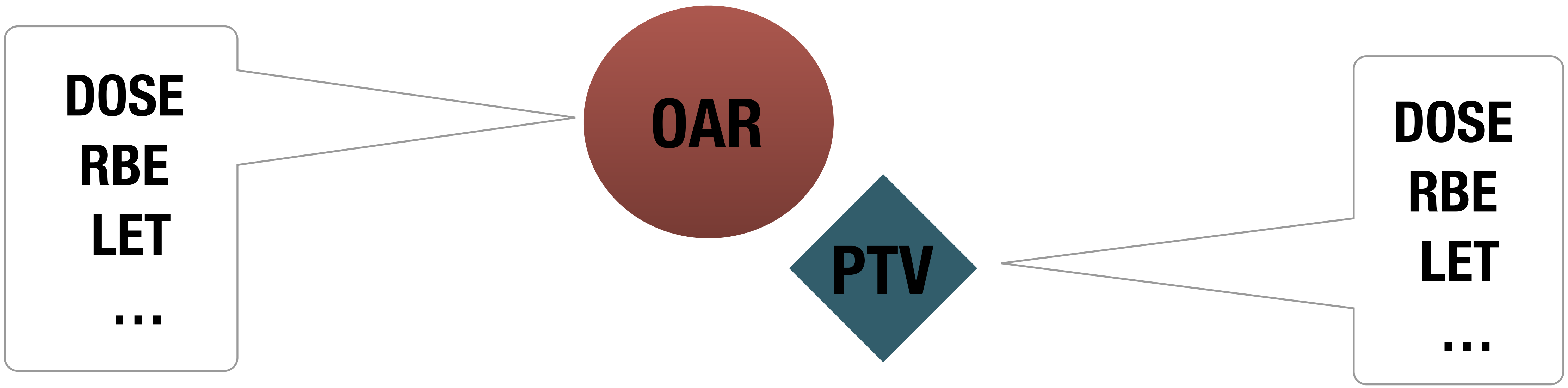
Dose, LETd

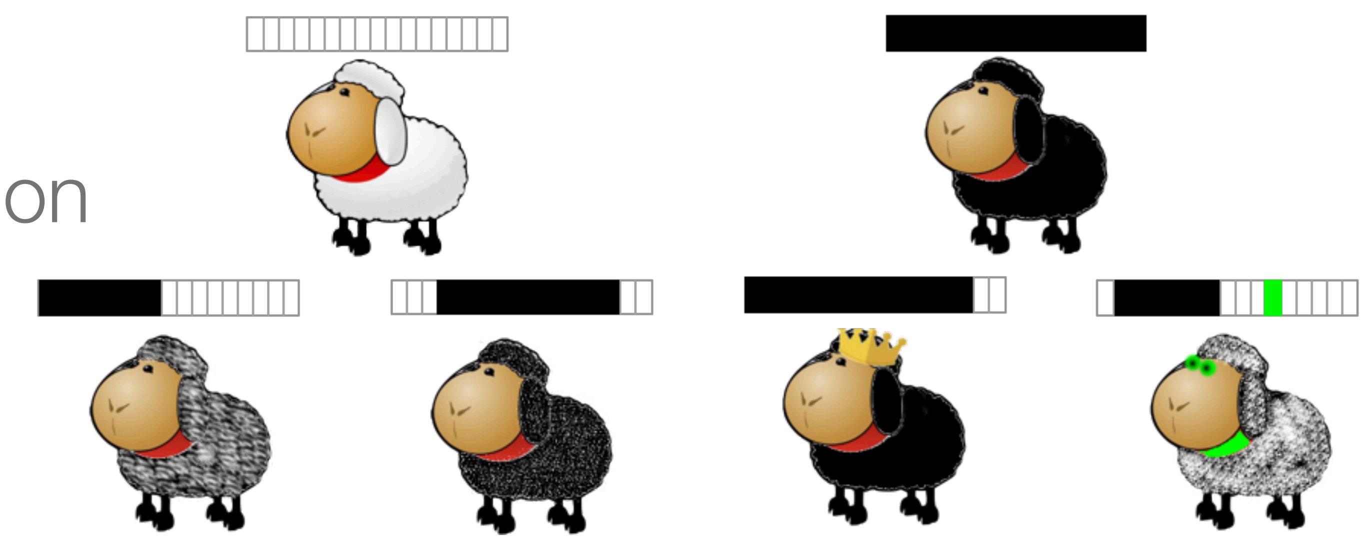
Goals of the MC Treatment Plan Optimization

- **Re-simulation** and validation of the Treatment Plan

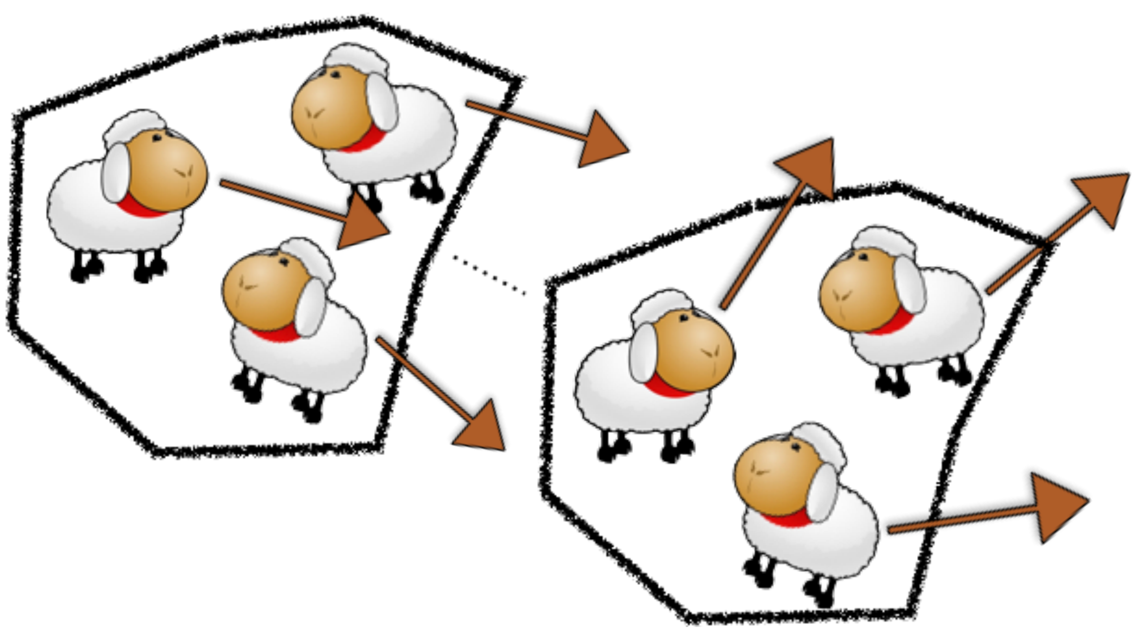


- **Development** of the framework for quick **comparison of algorithms for dose/RBE/LET optimization** based on MC output
- **Evolutionary based algorithm** for better space search: Genetic Algorithms, Particle Swarm Algorithm ..
- Development of the **MultiObjective optimization** algorithms

Evolutionary algorithms for TPS - MultiObjective Problems



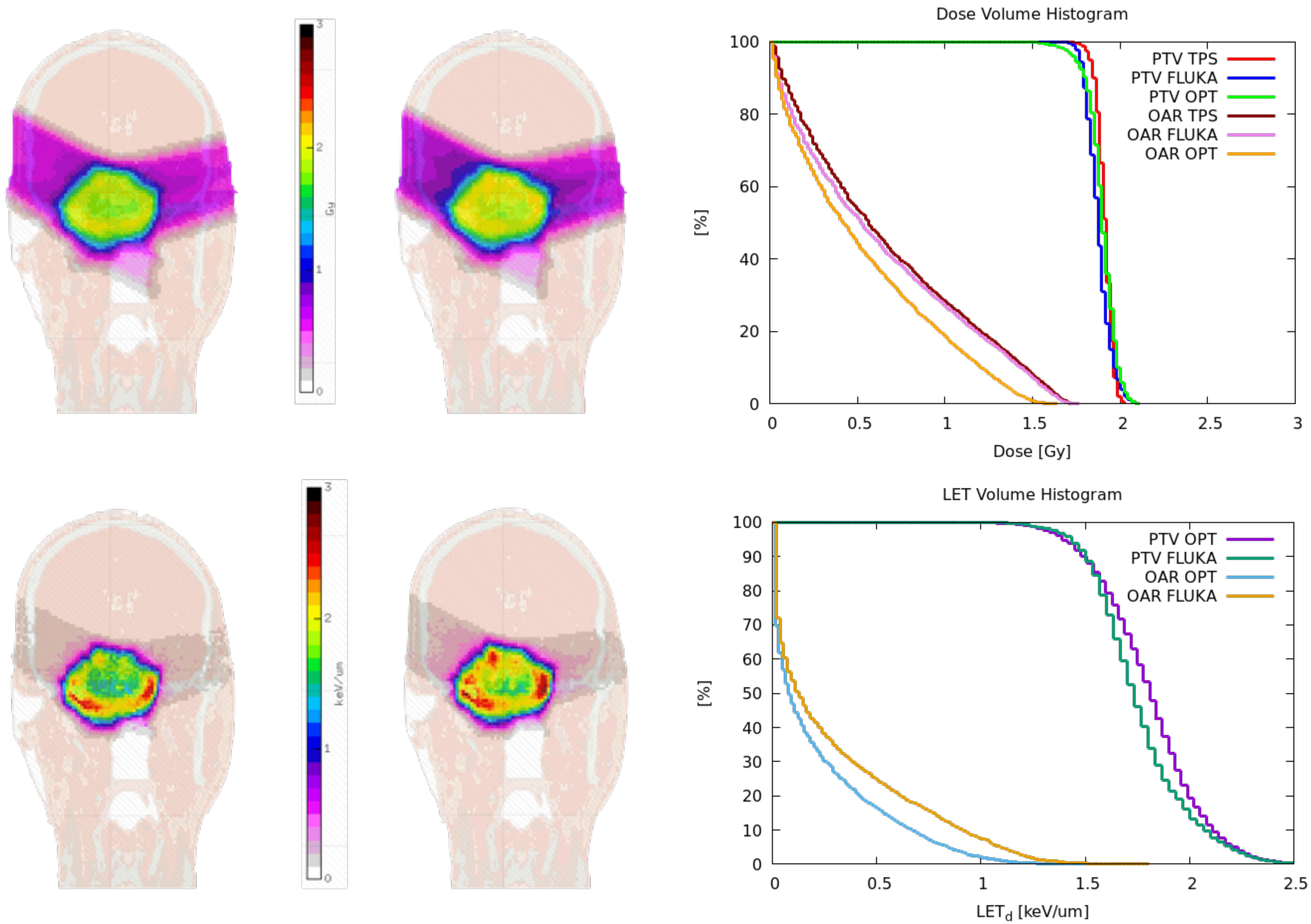
Genetic Algorithm Optimization
Each iteration creates new population using cross-over methods from parent individual solutions



Particle Swarm Optimization
During iterations particles are moving in the search space of the optimization problem changing its position - solutions.

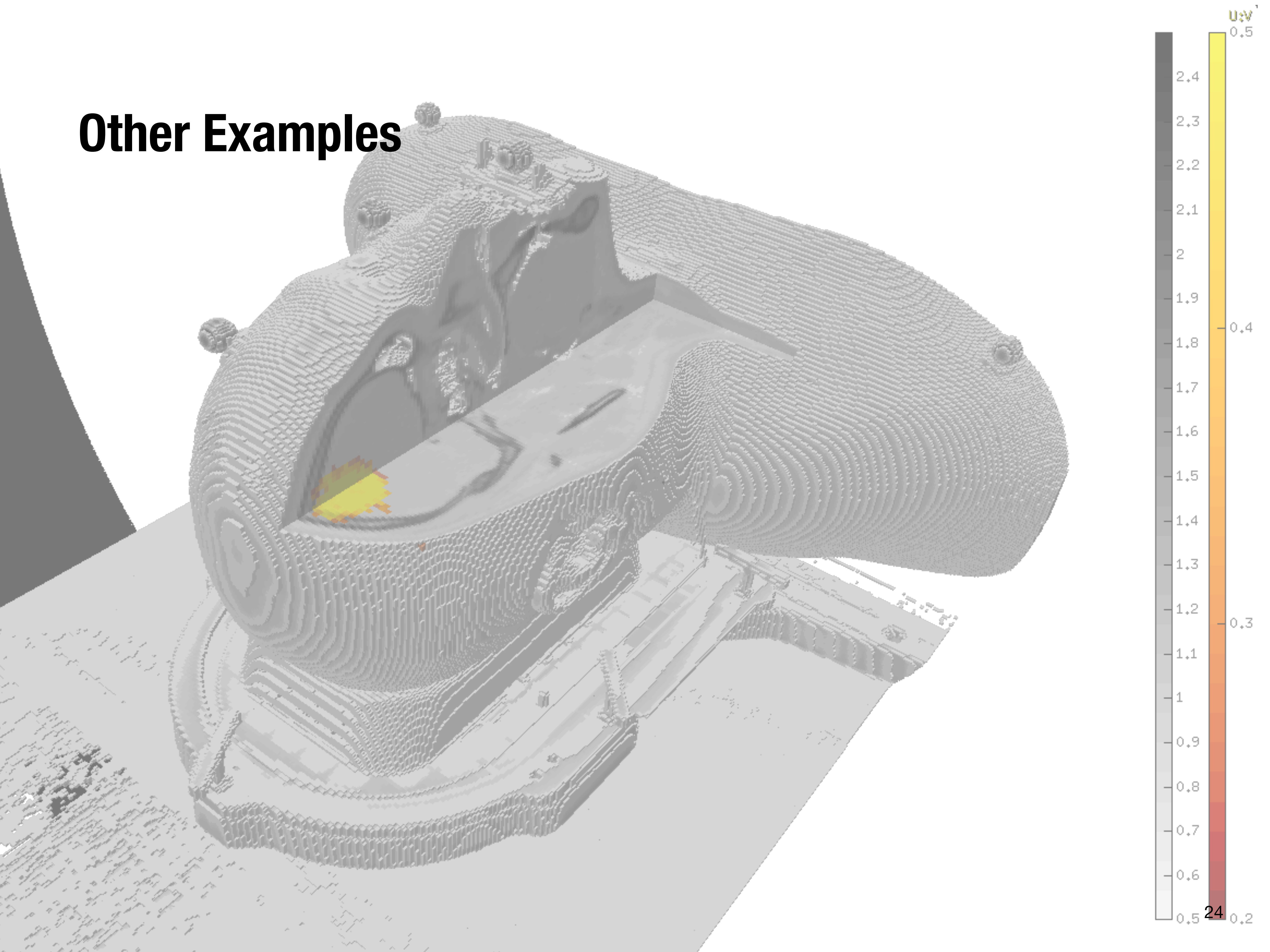
MultiObjective EA - ongoing work with preliminary results

Particle Swarm Algorithm for Dose/LET optimization



Proton TPS - physical dose distribution (top) and LETd distribution (bottom) for FLUKA TPS simulation (left) and FLUKA optimized recalculation (middle), with accompanying Physical Dose-Volume and LET-Volume Histograms

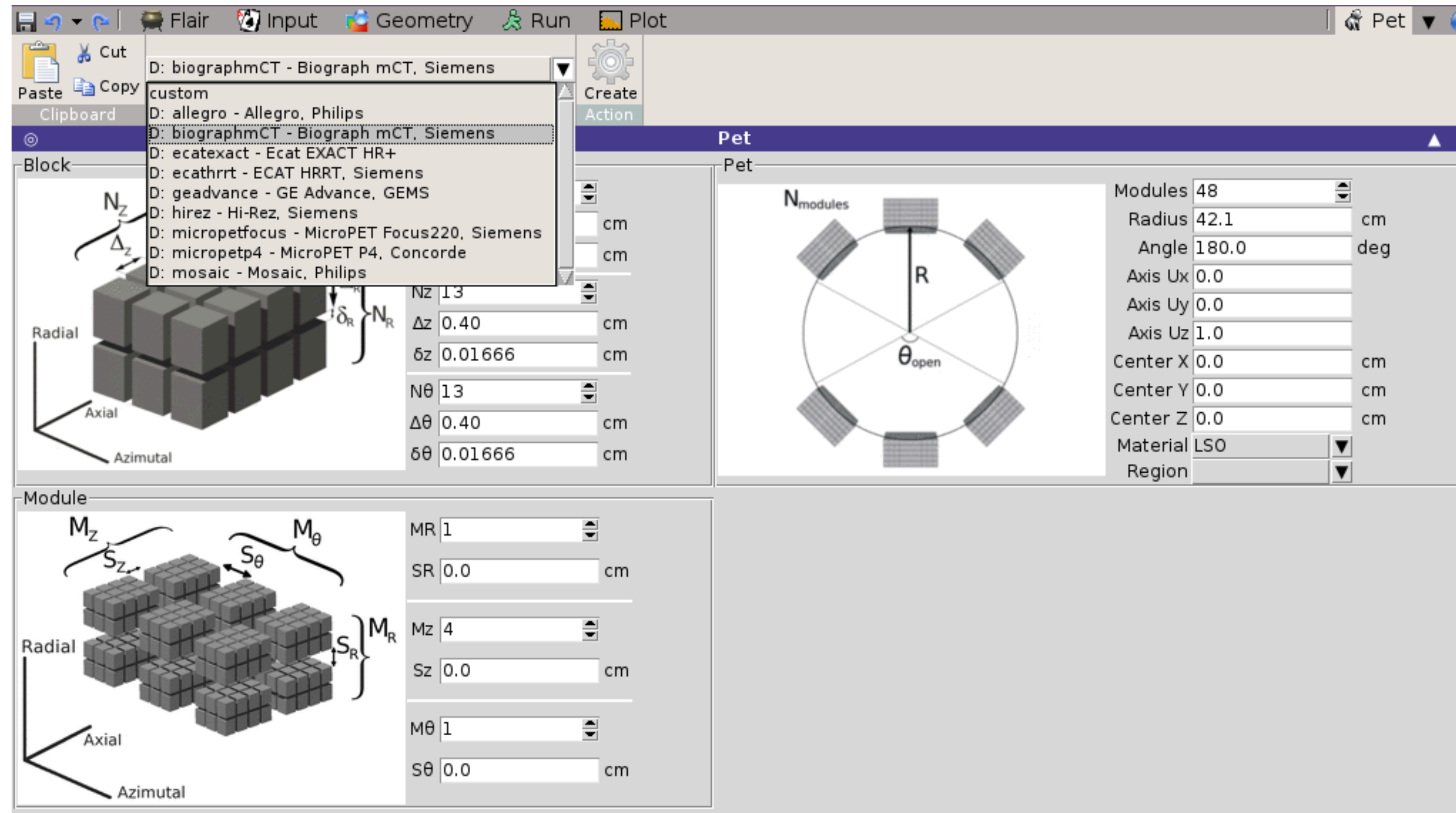
Other Examples

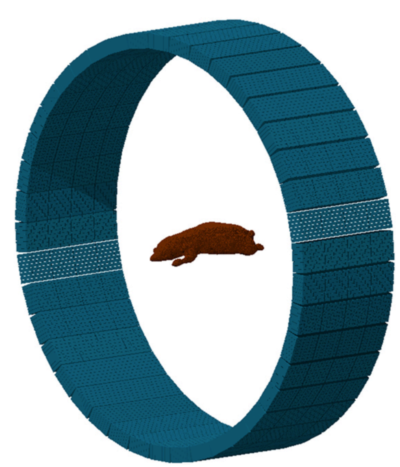


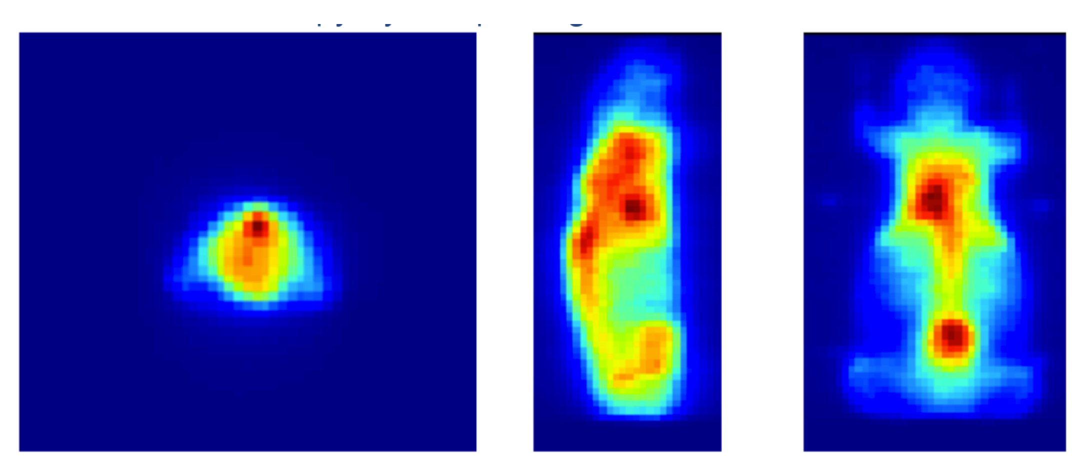
PET simulations

Incorporated **dedicated PET scanner tool**, covering all steps from PET **ring creation** to the **reconstruction** of the image from coincidence events

- Useful for:
  - Inferring the dose map from the β+ emitter distribution
  - Test new PET design/ options



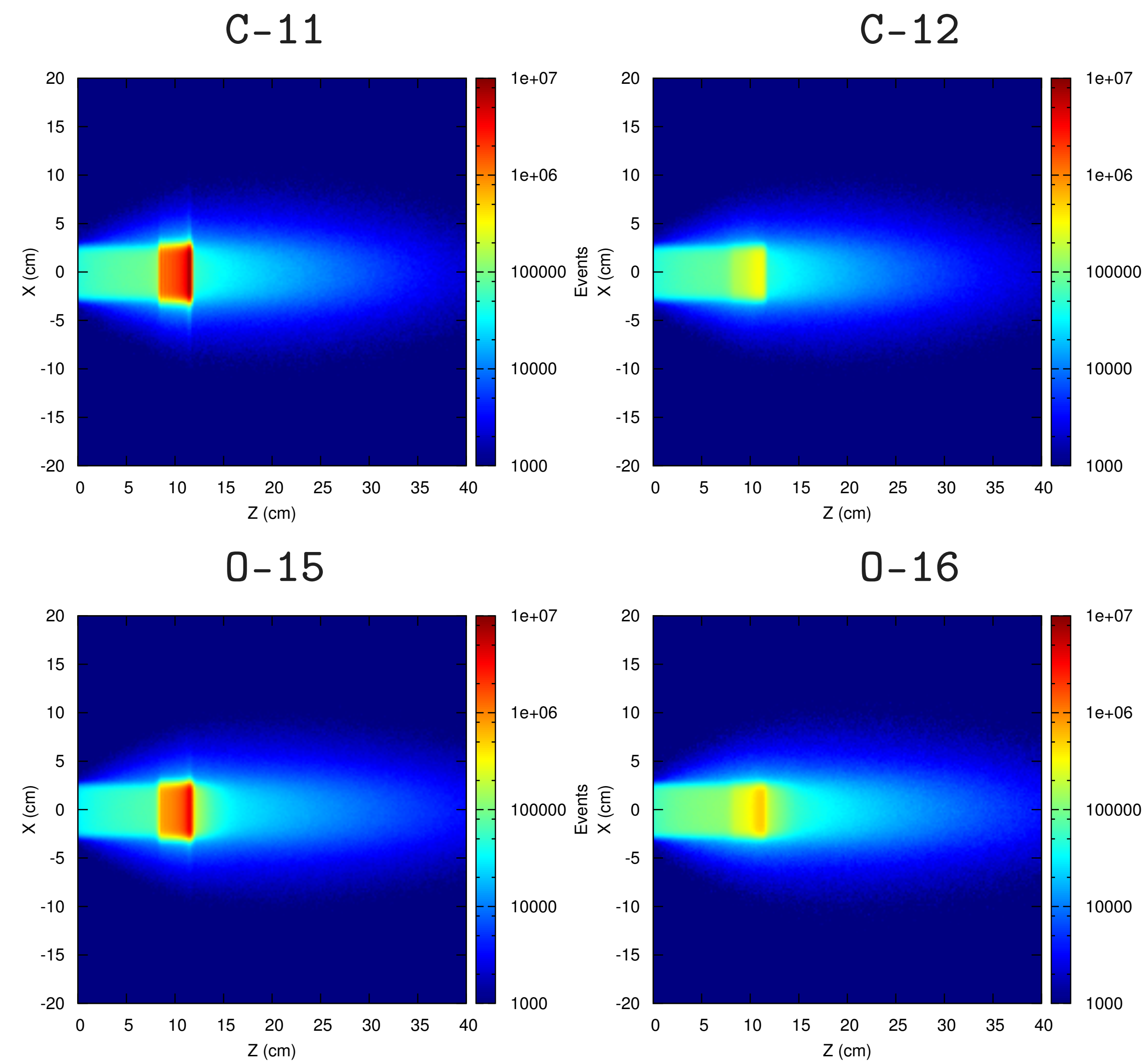


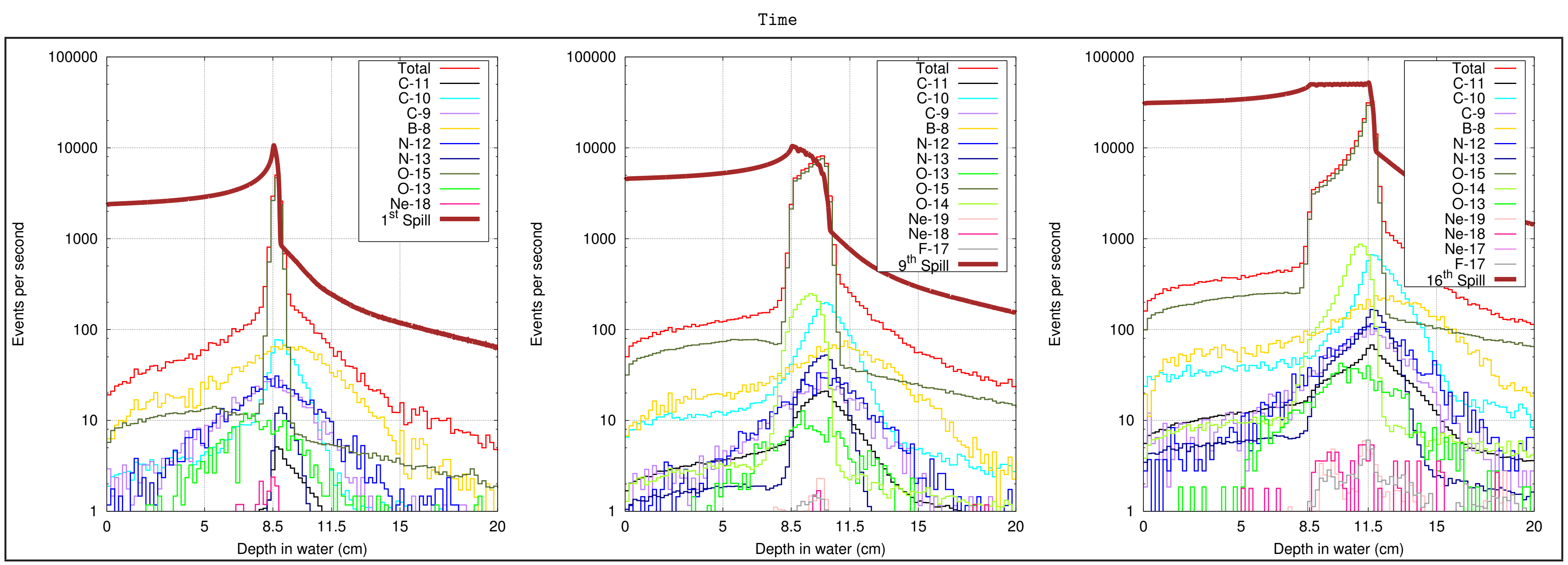


Courtesy of: Pablo Garcia Ortega (Universidad de Valencia, Instituto de Fisica Corpuscular)

Imaging potential of Radioactive Ion Beams

Different **Radioactive Ion Beams** have different imaging potentialities,
depending of their half-life and the half-life of produced fragments





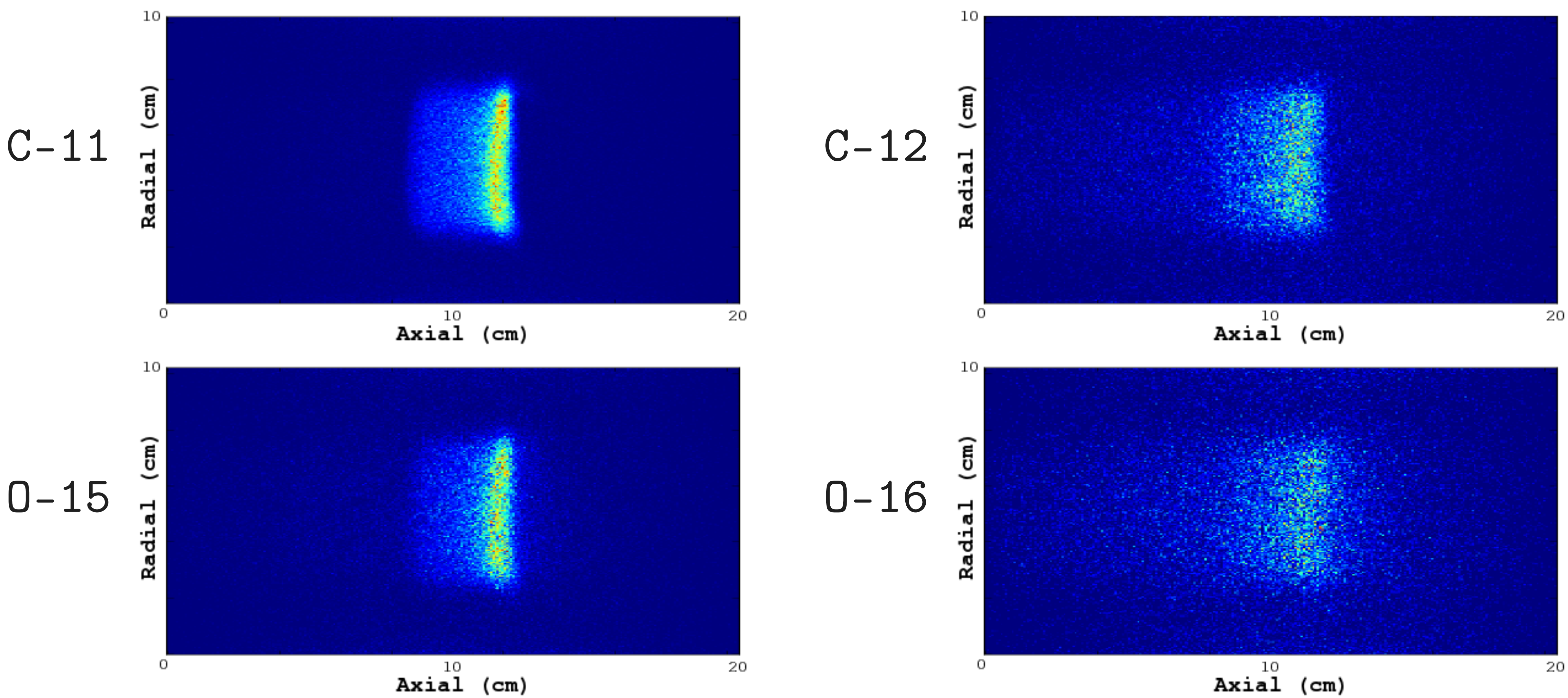
Annihilation Events at Rest, SOBP of 1Gy

Parent isotope discriminated anihilation events at rest rate

Courtesy of: Ricardo dos Santos Augusto (CERN/LMU)

Range Monitoring Results
-Offline Acquisition (from 5 to 30 minutes EOB)

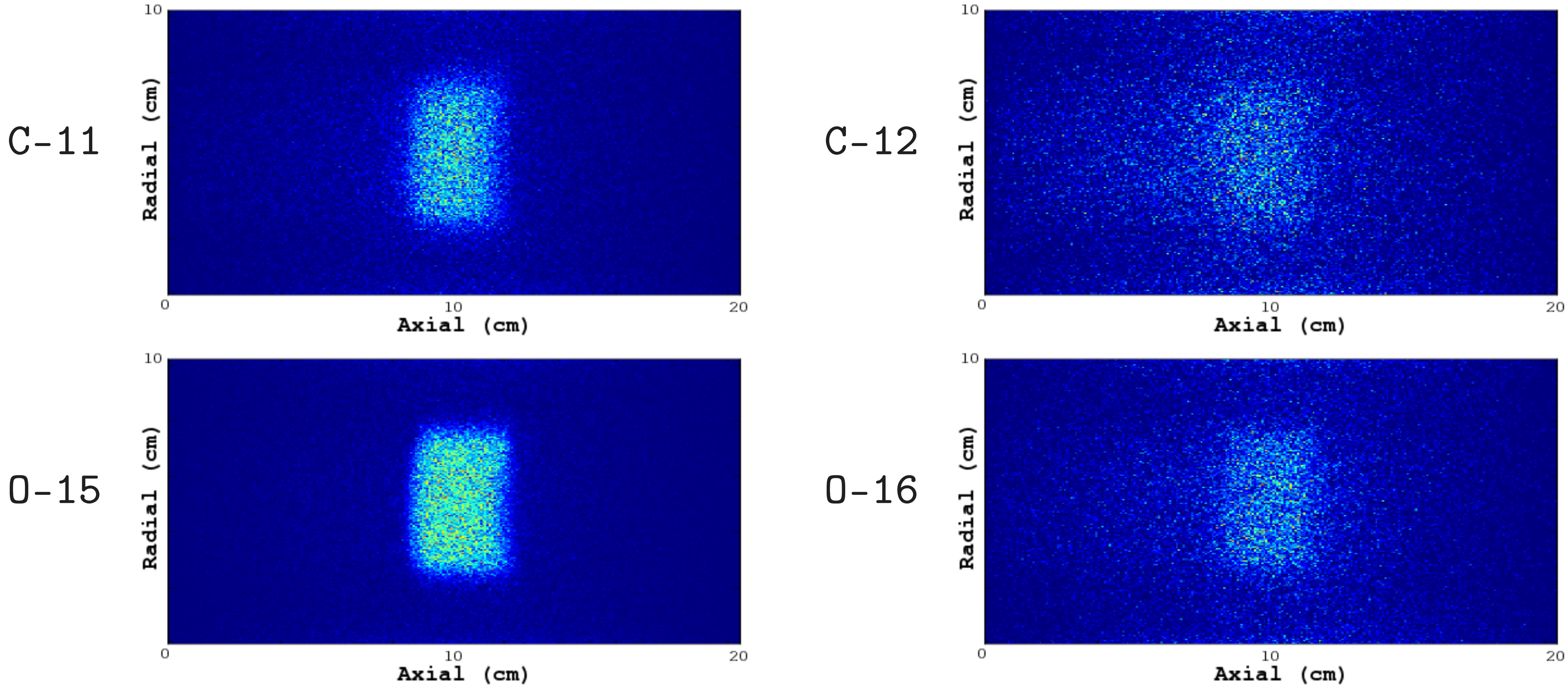
Due to the half-life difference between C-11 and O-15 (~20m & ~2m) - C-11 outperforms O-15 in longer acquisitions after irradiation.



Courtesy of: Ricardo dos Santos Augusto (CERN/LMU)

Range Monitoring Results
-Online Acquisition (beam time duration of 130 s)

Online acquisition modalities are most advantageous for they mitigate the degradation of dose-PET correlation due to biological washout.

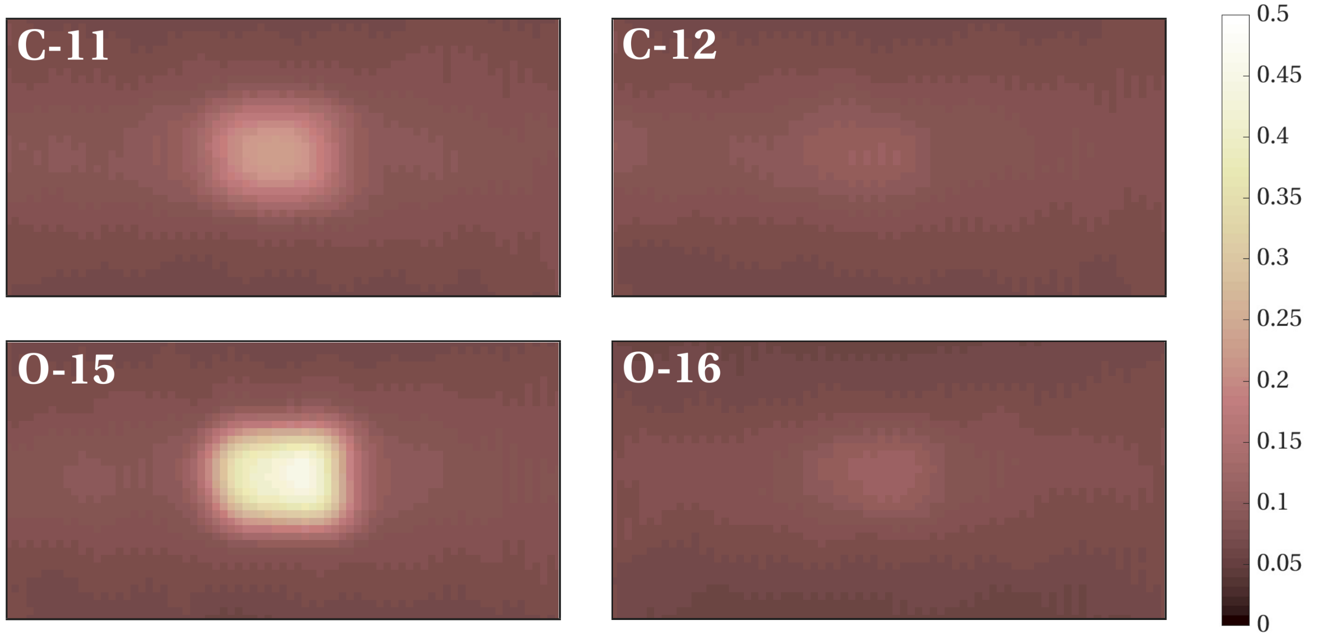


Courtesy of: Ricardo dos Santos Augusto (CERN/LMU)

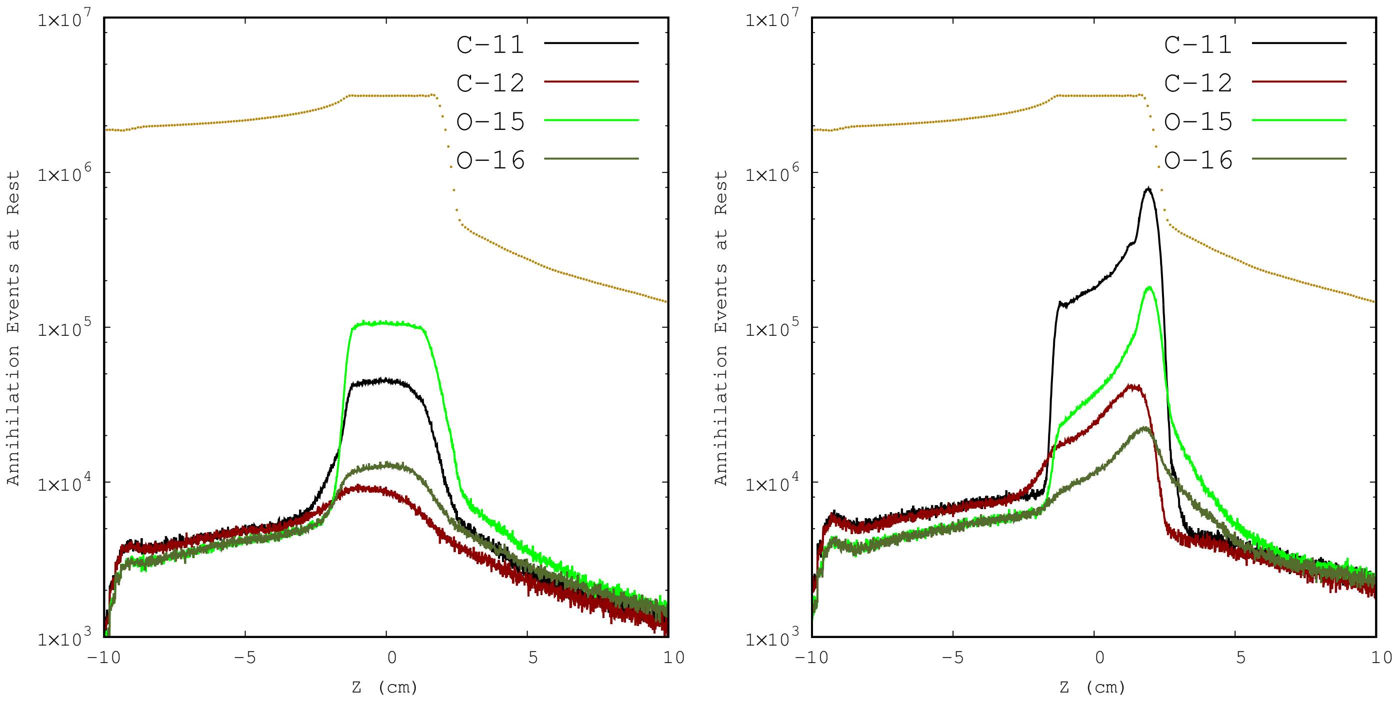
Accounting for the beam time structure

PET imaging can be significantly improved with RIBs, in both online and offline PET modalities, without apparent dose drawbacks.

An attempt to validate the simulation results with experimental data from NIRS-HIMAC is ongoing - to be published in November



PET Sinogram file reconstruction using MLEM Code

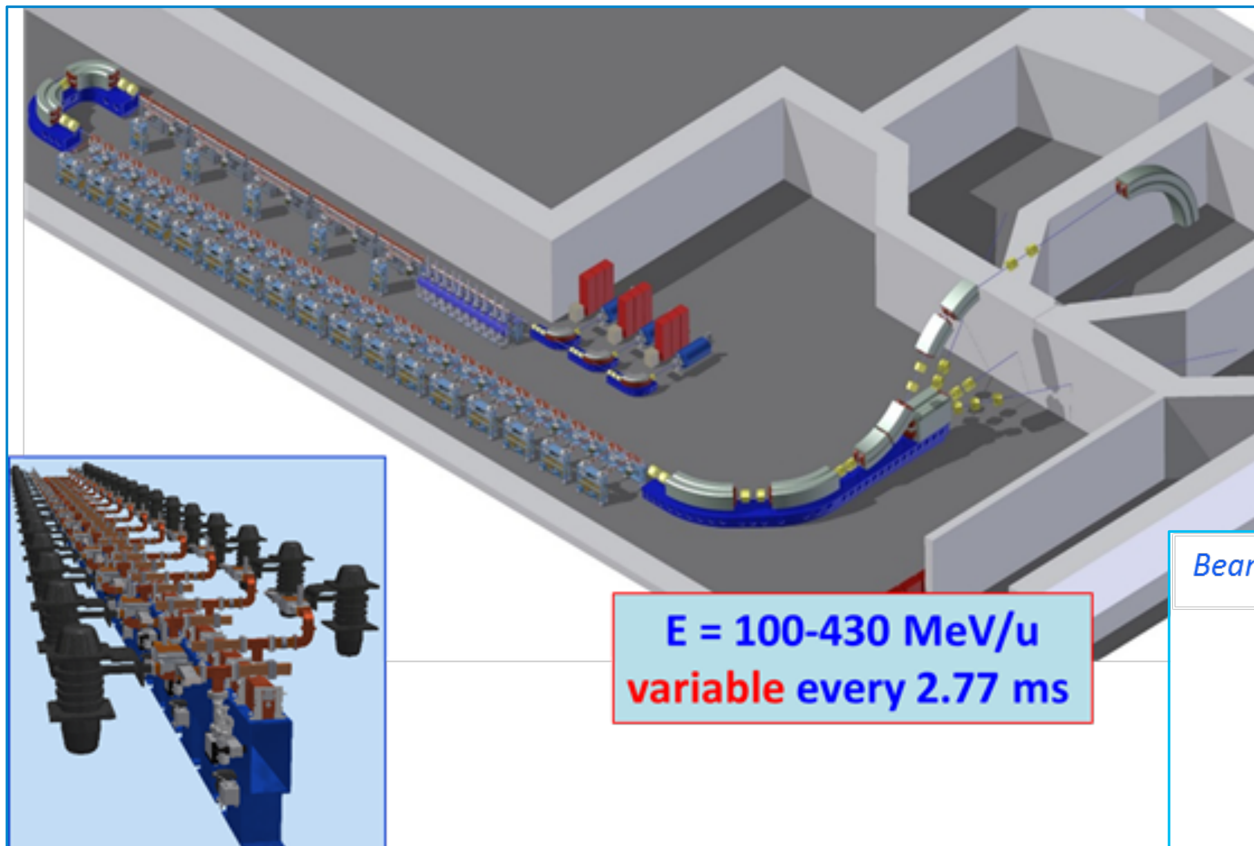


Annihilation events at rest produced during online (left) and offline (right) acquisition (SOBP dose in AU, golden points).

Courtesy of: Ricardo dos Santos Augusto (CERN/LMU)

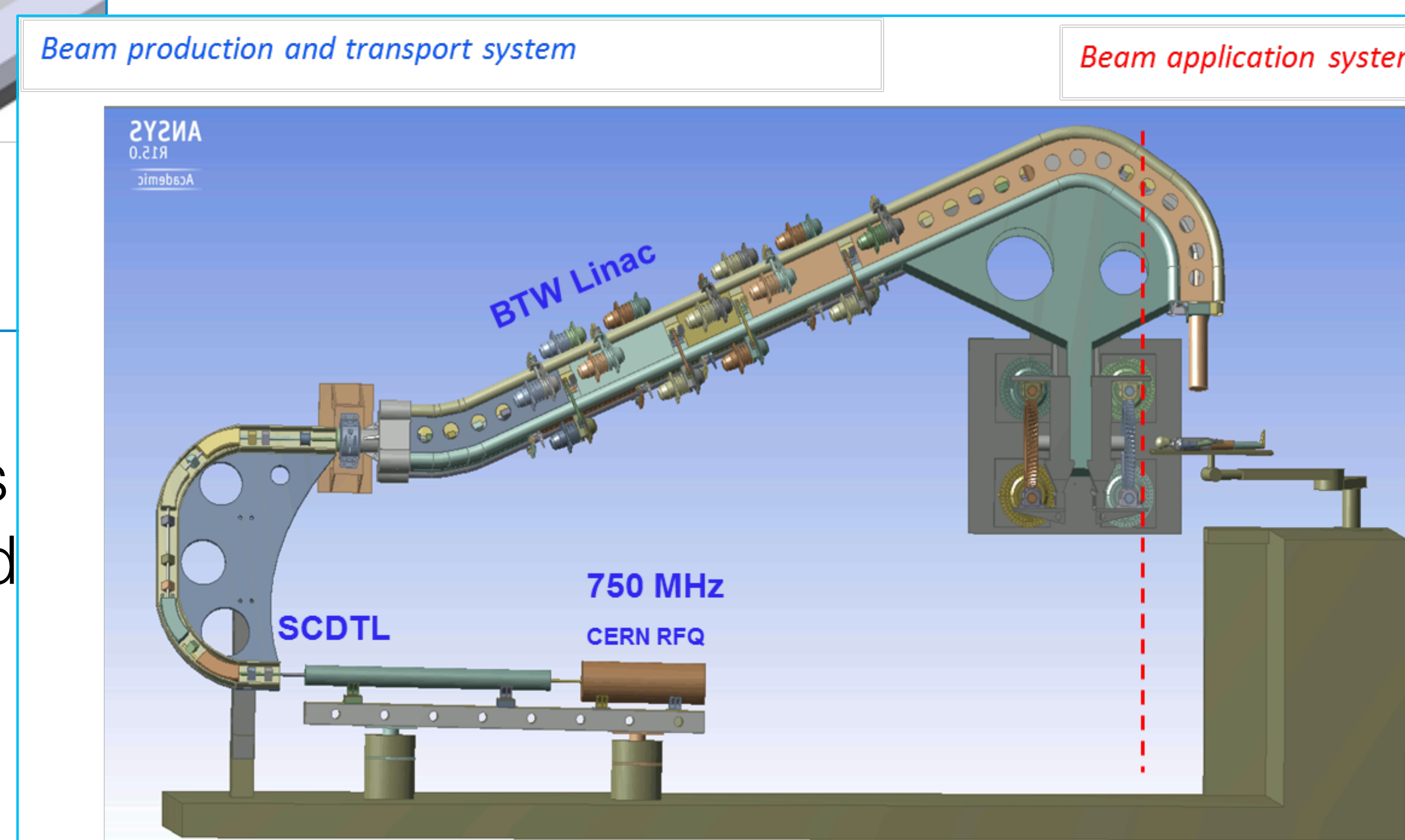
Two projects of TERA Foundation under development

CABOTO = CArbon BOoster for Therapy in Oncology



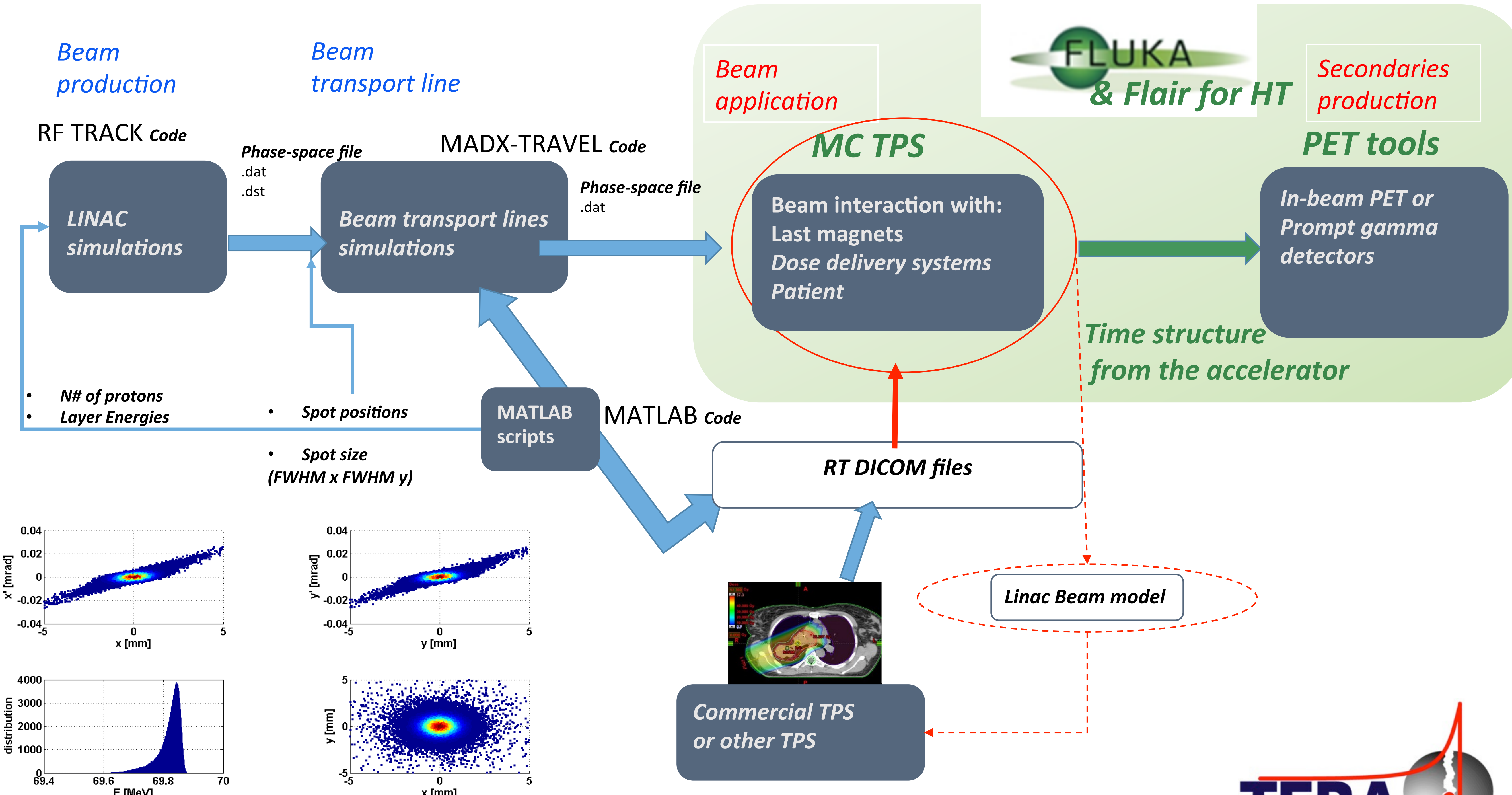
TERA

TULIP- TUrning Linac for Protontherapy



The aim of the **full MC simulations** is to **characterize the linac beams** and understand how the linac beam characteristics influences the DOSE and LET distributions in the patient .

Full Monte Carlo Simulations for new accelerator complex in Hadrontherapy TERA Foundation



Courtesy of: Caterina Cuccagna (TERA Foundation)

Ongoing work

- Ion fragmentation (also space radiation)
- Very light “special” ions: 3He, α, 6Li, 7Li, develop/check of the nuclear model physics
- Different radiobiological parameters/models (eg health tissue/tumor)
- Monte Carlo based TPS with MultiObjective Optimization techniques
- (Software) acceleration techniques

Questions?

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- [1] Böhlen, T. T., Cerutti, F., Chin, M. P. W., Fassò, A., Ferrari, A., Ortega, P. G., Mairani, A., Sala, P. R.,Smirnov, G., Vlachoudis, V. (2014). *The FLUKA Code: Developments and challenges for high energy and medical applications*. Nuclear Data Sheets, 120, 211-214

- [2] Ferrari, A., Sala, P. R., Fasso, A., & Ranft, J. (2005). *FLUKA: A Multi-Particle Transport Code*. CERN 2005-10 (2005), INFN/TC_05/11, SLAC-R-773

- [3] Vlachoudis, V. (2009). *FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA*. Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York

- [4] Mairani, A., Böhlen, T. T., Schiavi, A., Tessonnier, T., Molinelli, S., Brons, S., Battistoni, G.,Parodi K., Patera, V. (2013). *A Monte Carlo-based treatment planning tool for proton therapy*. Physics in Medicine and Biology, *58*(8), 2471–2490

- [5] Battistoni, G., Bauer, J., Böhlen, T. T., Cerutti, F., Chin, M. P. W., Dos Santos Augusto, R., Ferrari, A., Ortega, P. G., Kozlowska, W., Magro G., Mairani A., Parodi K., Sala P. R., Schoofs P., Tessonnier T., Vlachoudis, V. (2016). *The FLUKA Code: An Accurate Simulation Tool for Particle Therapy.* Frontiers in Oncology, 6.