Particle Therapy Masterclass

Treatment planning : How to localize and accurately irradiate a tumor

Jennifer Hardt & Dr. Niklas Wahl
Contact: jennifer.hardt@dkfz-heidelberg.de

Group “Radiotherapy Optimization“
Division of Medical Physics in Radiation Oncology

Radiation therapy - structure

- Patient fixation
- Imaging (esp. CT, but also MRT or PET)
- Identification & delineation of tumor volume and organs on 3D image
- Treatment planning
- Verification & quality assurance
- Patient positioning
- Irradiation (several “fractions“)

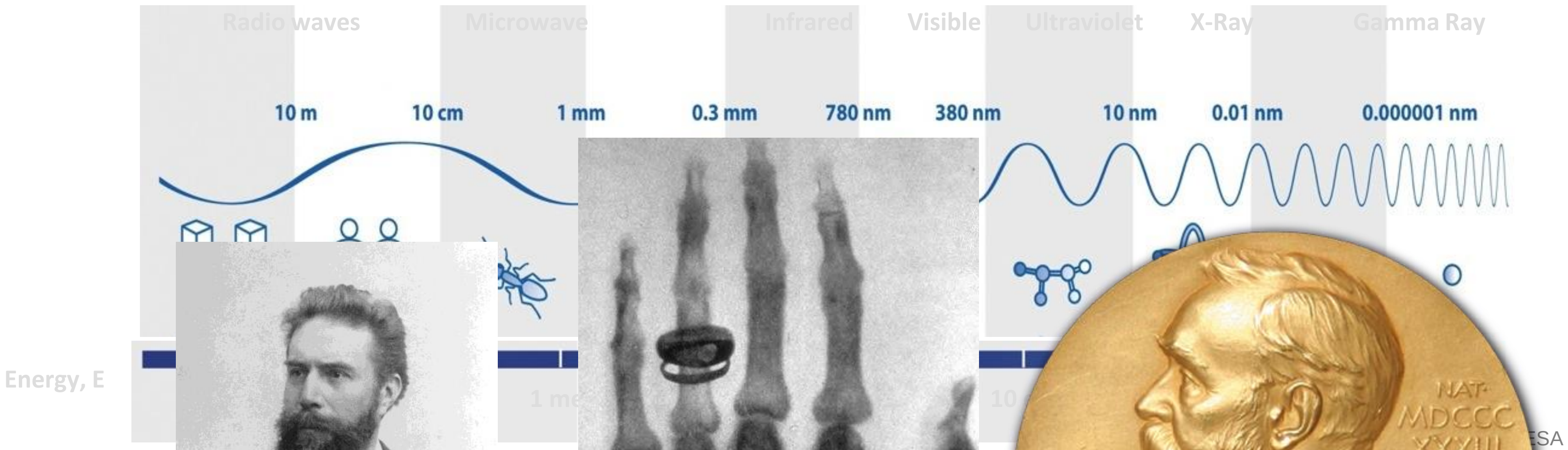
Adapted from W. Schlegel & A. Mahr: 3D Conformal Radiation Therapy Springer Multimedia DVD

A treatment plan should …

- ... fulfil clinical requirements (“The physician prescribes”) …
- ... based on biological processes (cell death) …
- ... induced by chemical & physical processes (reactions & interactions) …
- ... by means of numerical simulation (dose calculation / optimization)

→ Interdisciplinary **inverse problem**

Imaging: X-ray




[1]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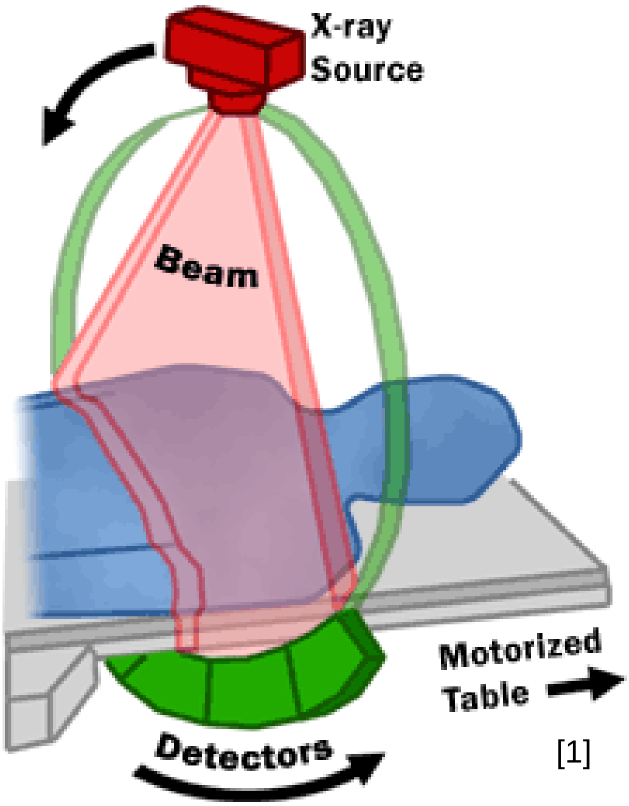
1901

[1] anonym (https://commons.wikimedia.org/wiki/File:Roentgen2.jpg), „Roentgen2", marked as public domain, more details on Wikimedia Commons: https://commons.wikimedia.org/wiki/Template:PD-EU-no author disclosure
[2] Wilhelm Röntgen; current version created by Old Moonraker. (https://commons.wikimedia.org/wiki/File:X-ray_by_Wilhelm_Röntgen_of_Albert_von_Kölliker's_hand_-_18960123-02.jpg), „X-ray by Wilhelm Röntgen of Albert von Kölliker's hand - 18960123-02", marked as public domain, more details on Wikimedia Commons: https://commons.wikimedia.org/wiki/Template:PD-old
[3] Photograph: JonathunderMedal: Erik Lindberg (1873-1966) (https://en.wikipedia.org/wiki/File:Nobel_Prize.png), „Nobel Prize", marked as public domain, more details on Wikimedia Commons: https://commons.wikimedia.org/wiki/Template:PD-US

Imaging: Computed tomography

“3D X-ray”



[1]

[2]

[1] FDA – Radiation emitting products – Medical X-ray Imaging – What is Computed Tomography? - Accessed from https://www.fda.gov/radiation-emitting-products/medical-x-ray-imaging/what-computed-tomography on 15.02.2021.
[2] daveynin from United States (https://commons.wikimedia.org/wiki/File:UPMCEast_CTscan.jpg), „UPMCEast CTscan“, https://creativecommons.org/licenses/by/2.0/legalcode

Slide by courtesy of Dr. Simeon Nill

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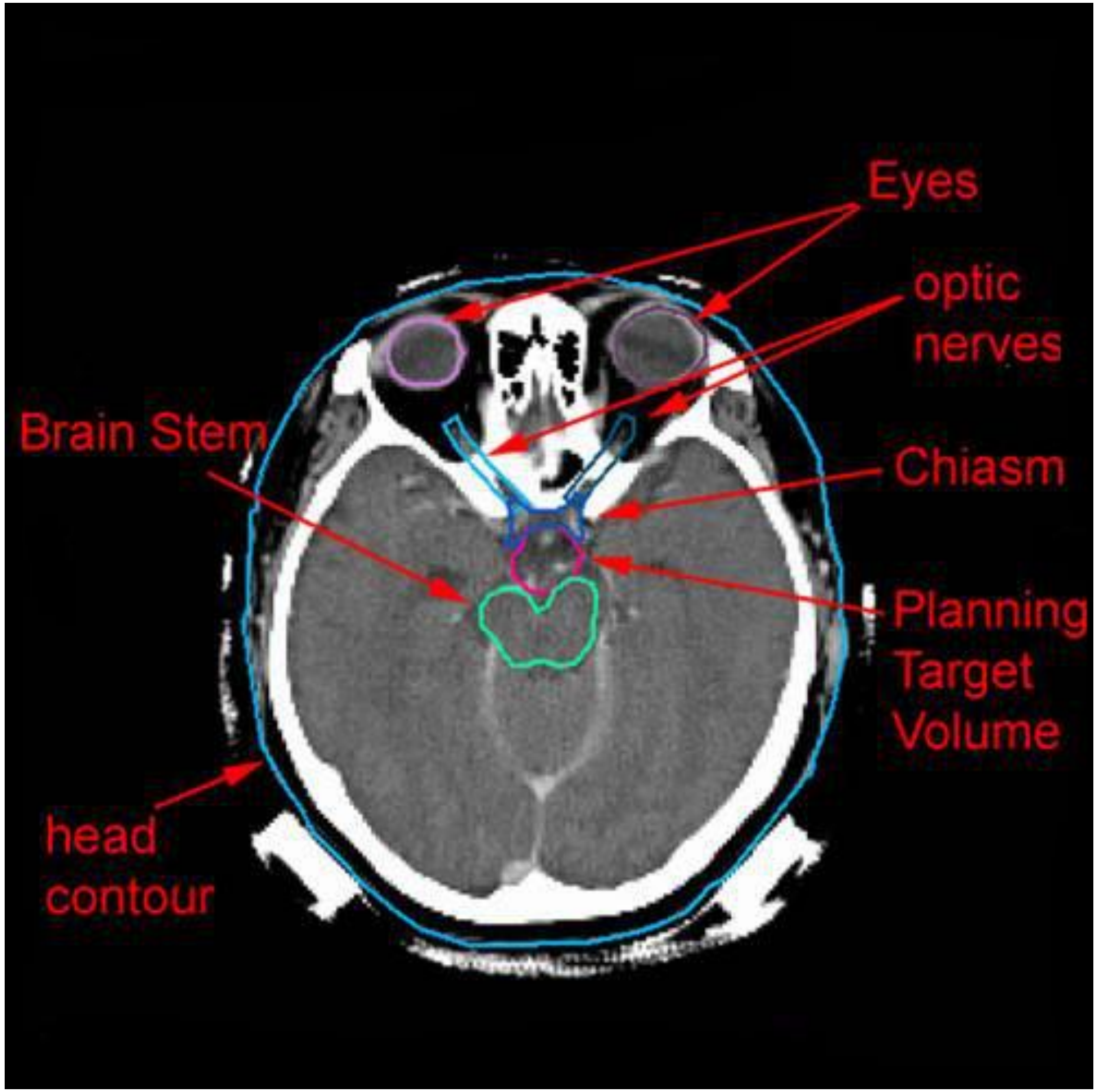
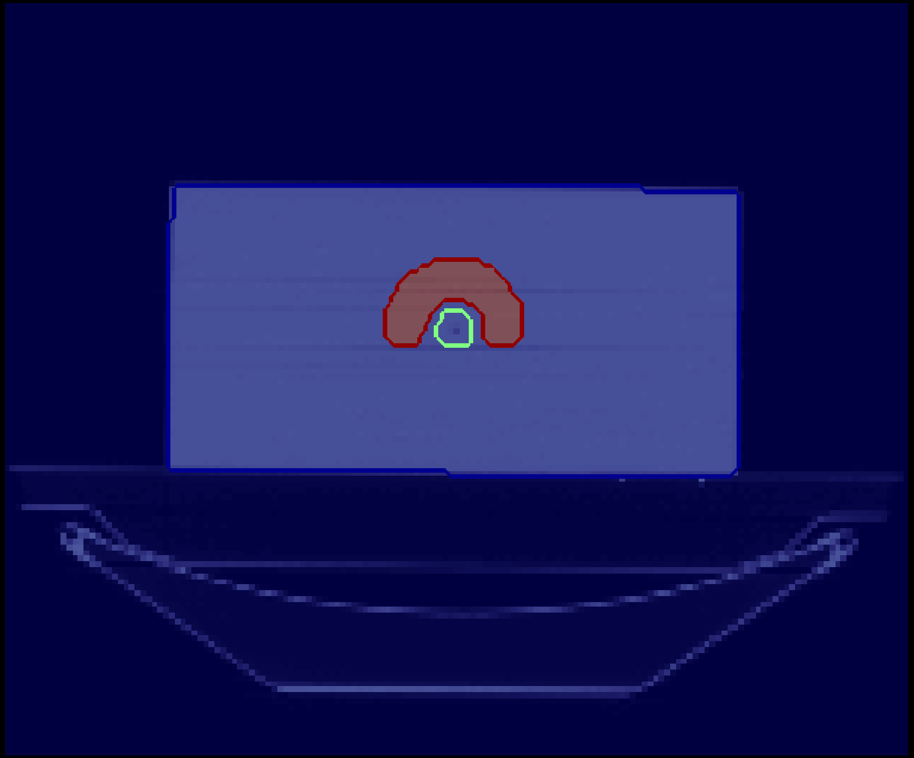


W. Schlegel & A. Mahr: 3D Conformal Radiation Therapy Springer Multimedia DVD

Slide by courtesy of Dr. Simeon Nill

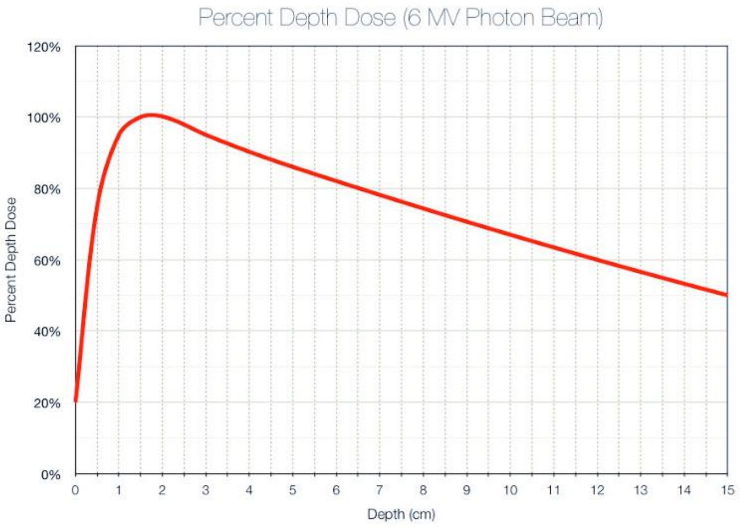
The ideal dose distribution



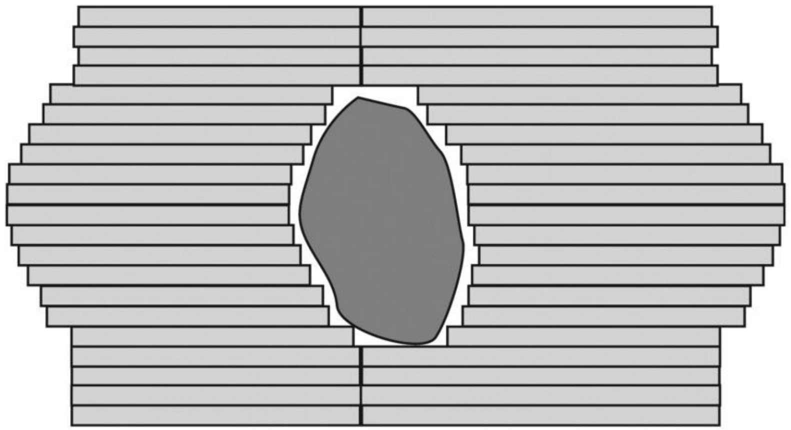
- High / prescribed dose in the tumor
- No dose in normal tissue

Modern 3D-planning with photons

Photon beam

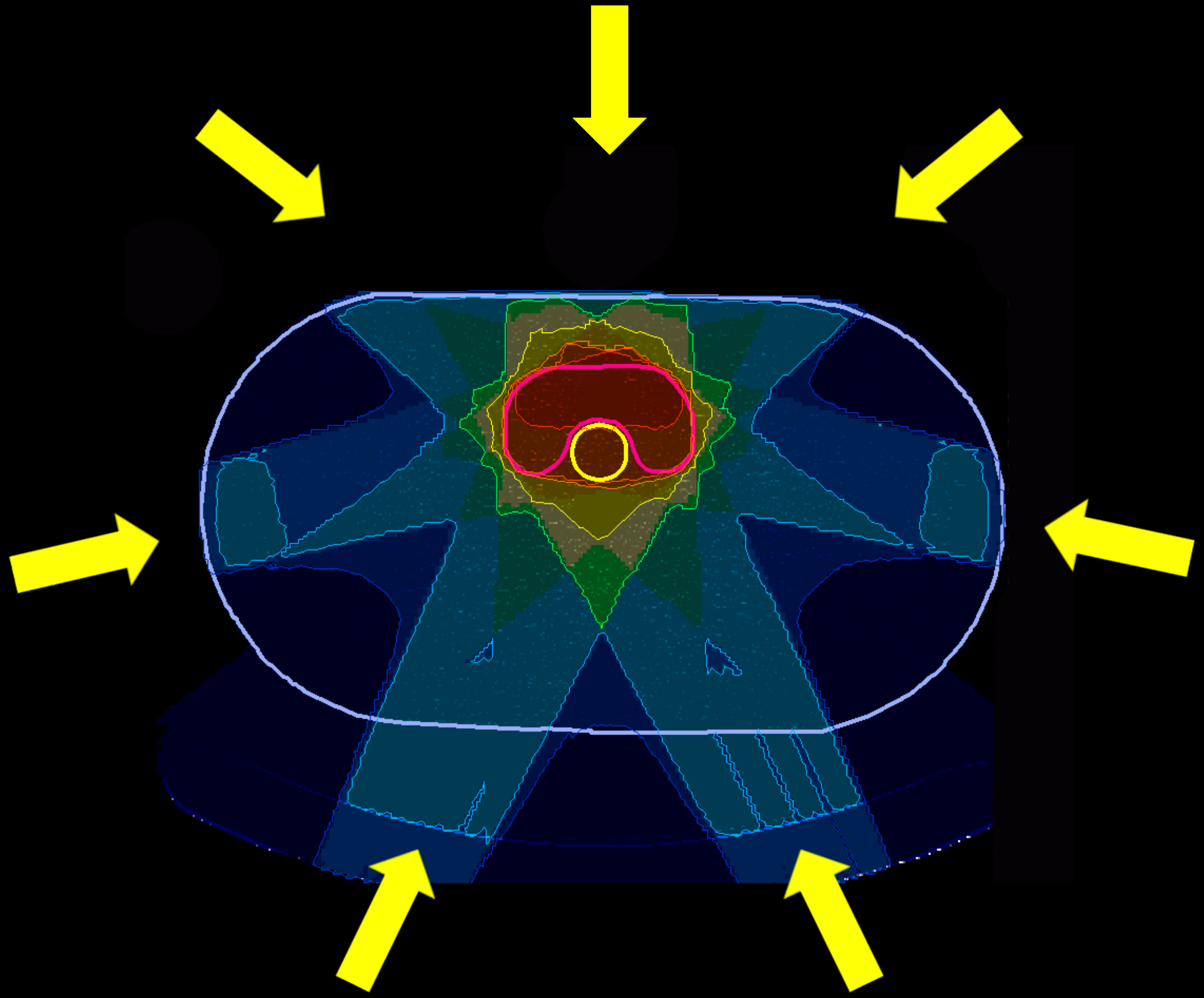


collimator



→ Adaptation of the photon beam to the tumor shape

A realistic dose distribution



Can we do better?

YES CAN

[1]

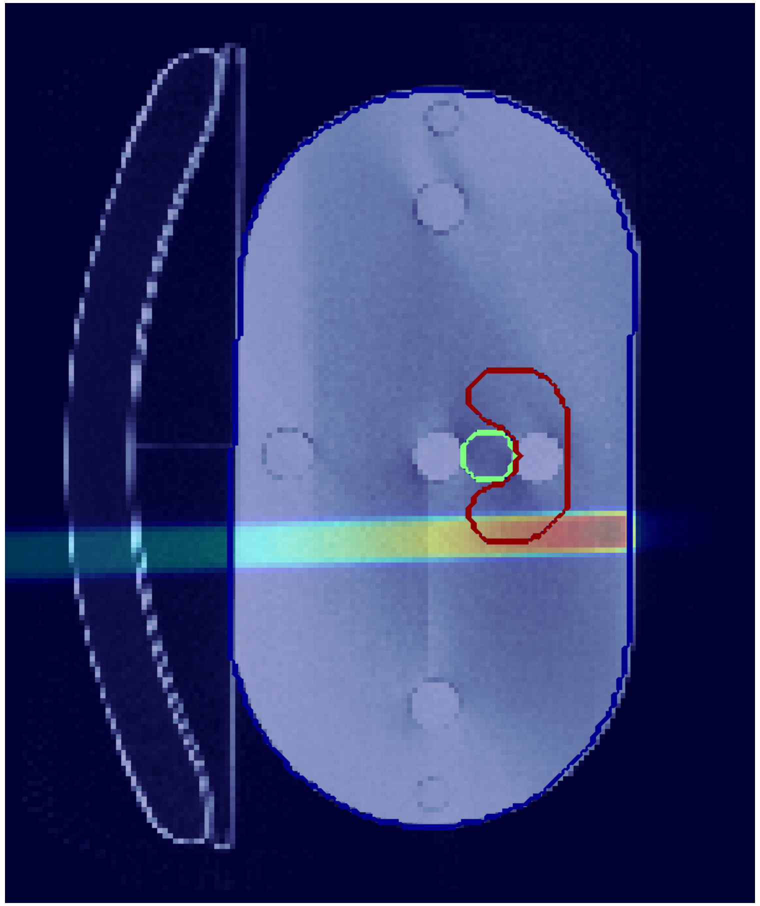
[1] The Obama-Biden Transition Project (https://commons.wikimedia.org/wiki/File:Poster-sized_portrait_of_Barack_Obama_OrigRes.jpg), „Poster-sized portrait of Barack Obama OrigRes“, size adapted, https://creativecommons.org/licenses/by/3.0/legalcode

The concept of the „pencil beam“

- „Multi-leaf“ collimator are able to generate fine beams (pencil beams)

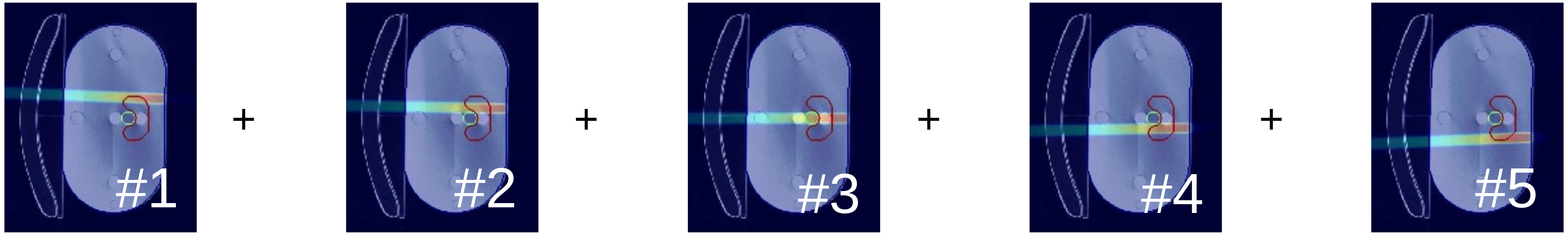
- We calculate their dose using various algorithms. Examples:
  - **Analytical Pencil beam**
    Precomputed / measured dose curves in water are “scaled” to the patient
    → deterministic, very quick, but inaccurate
  - **Monte Carlo**
    Simulation of individual particle trajectories (“histories”) through the patient
    → stochastic, slow, but mostly more accurate

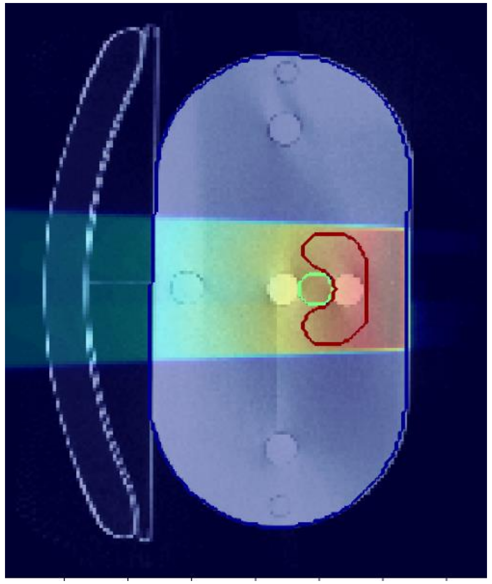
#4



i.e.: We are able to simulate and “modulate” our beams

The concept of the „pencil beam“





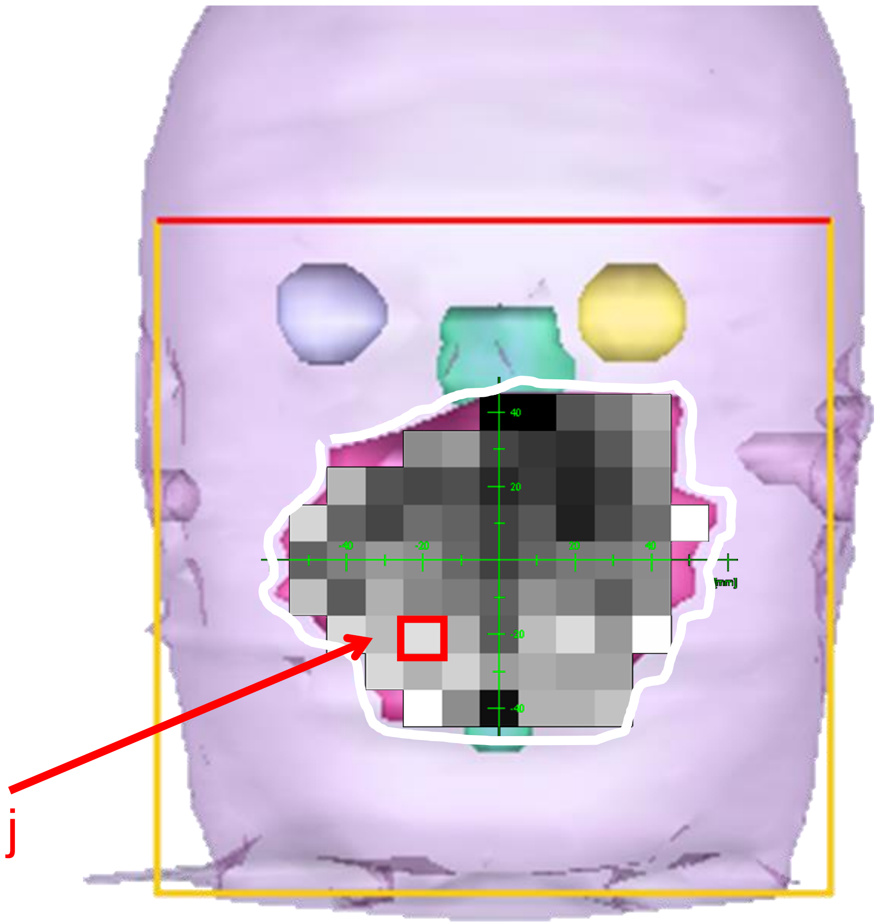
= homogeneous beam

Intensity modulation with pencil beams

Pencil beams form “pixel” in the beam cross-section
(or the fluence, respectively)

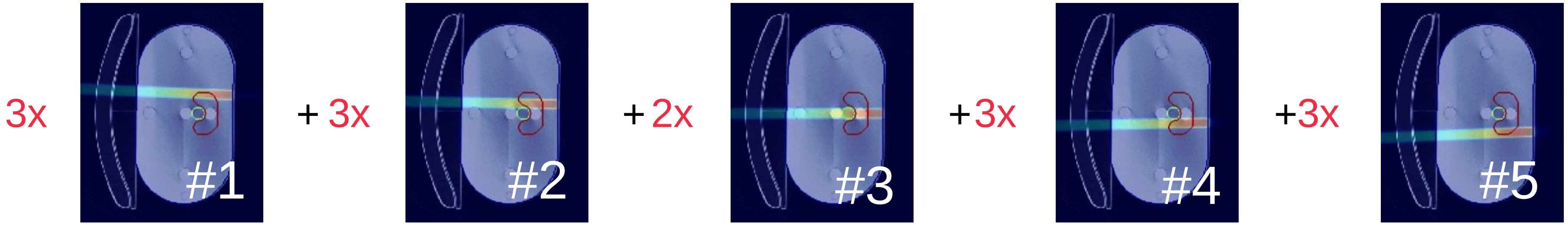
= “bixel” (**B**eam + P**ixel**)

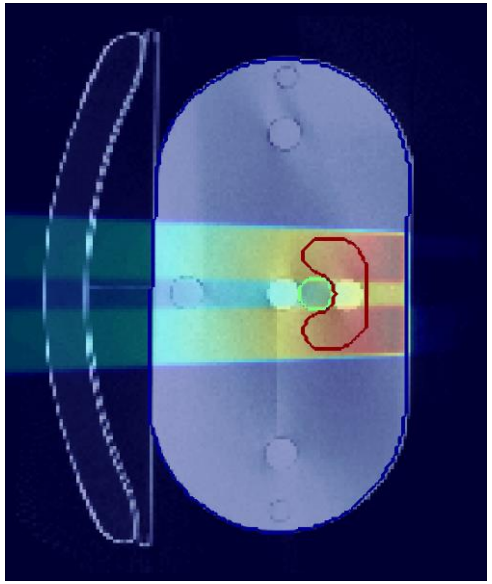
We weight all pencil beams
(more/less photons) differently



Bixel j

Intensity modulation with pencil beams





Different bixel weights
= intensity modulated beam

- Number of pencil beams:
  ~100-1000 per beam
- Number of beams: 5 to 12

→ Not manually determinable

Objective functions for minimization

- Clinical requirements for the radiation plan are translated into mathematical functions

„ Irradiate the tumor homogeneously with 54 Gy....“

$$f_{\text{Tumor}} = \frac{1}{N_T} \sum_{i \in T} (d_i - d_T)^2$$

„ with minimal average radiation dose in the tissue“

$$f_{\text{OAR}_1} = \frac{1}{N_S} \sum_{i \in S} d_i$$

„ and simultaneous reduction of dose in an organ at risk below 10 Gy.

$$f_{\text{OAR}_2} = \frac{1}{N_S} \sum_{i \in S} \Theta\left(d_i - d_M\right)\left(d_i - d_M\right)^2$$

➢ Minimization of these functions under consideration of the physical beam properties!

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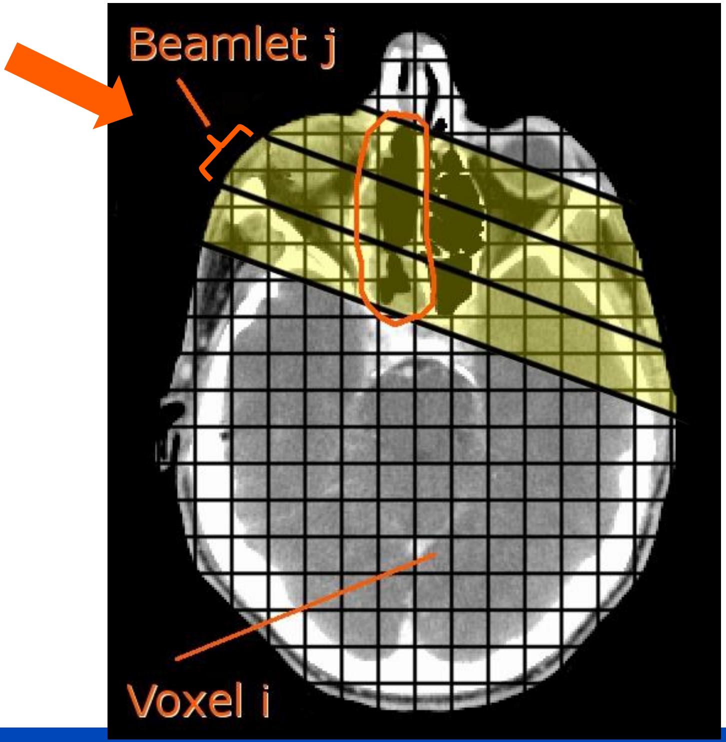


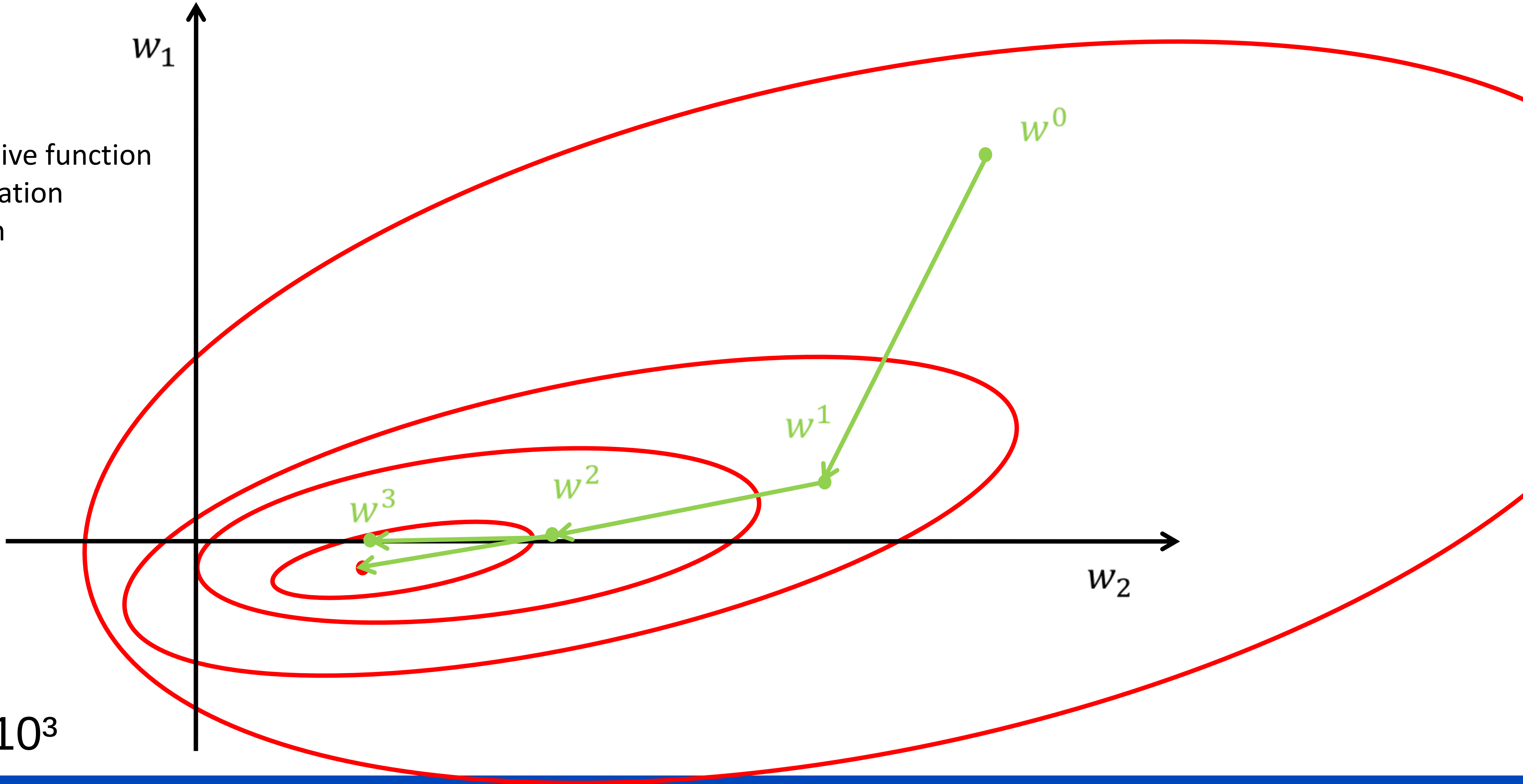
typically: 0.2 – 2 GB

photons ~ 1000 parameter
particles ~ 30000 parameter

$$f_{\text{Tumor}} = \frac{1}{N_T} \sum_{i \in T} (d_i - d_T)^2$$

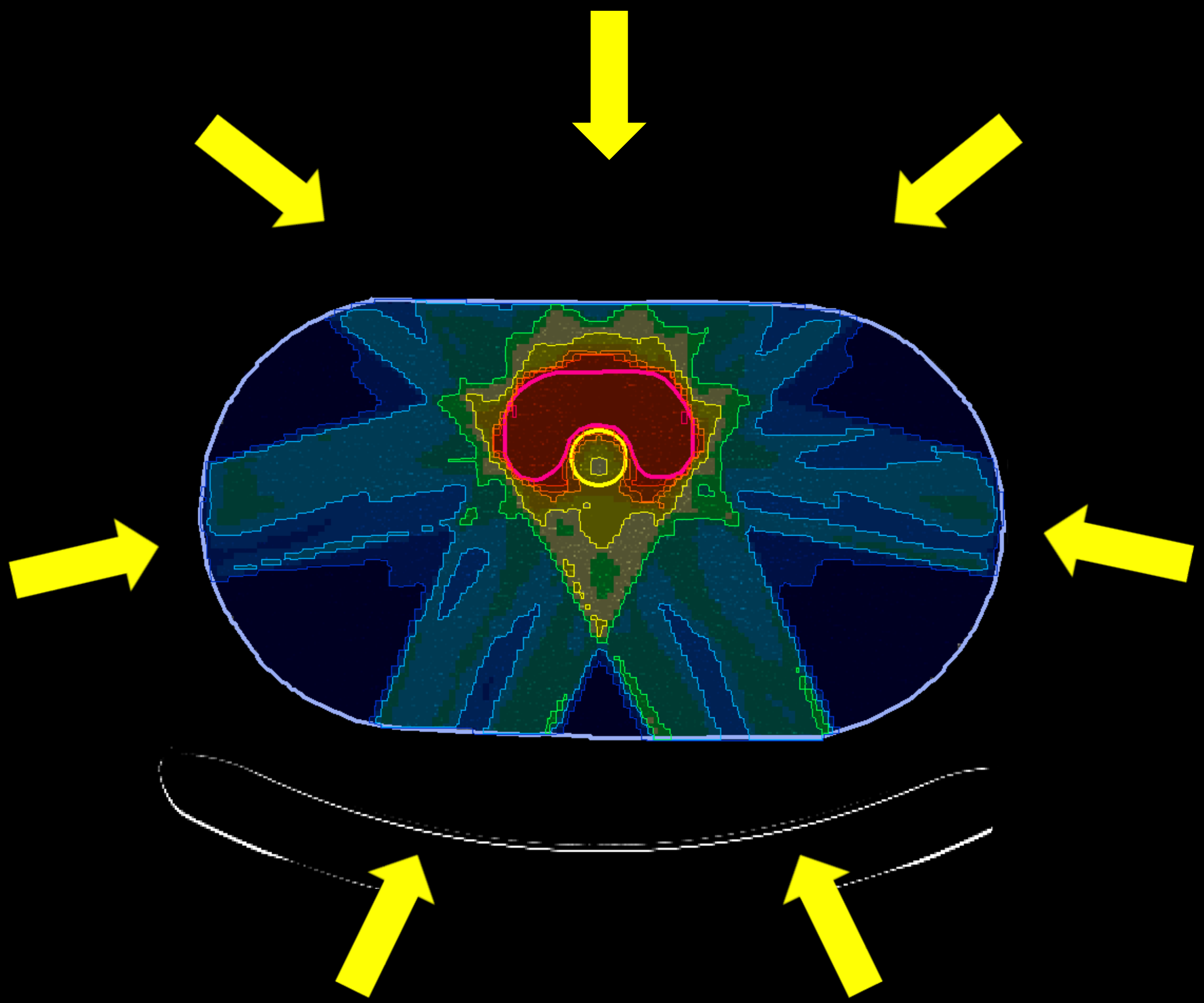
Optimizing the weights – finding the minimum by Newton's method

1. starting point
2. calculate objective function
3. gradient / derivation
4. search direction
5. step size
6. back to step 2



dimensionality: 10^3

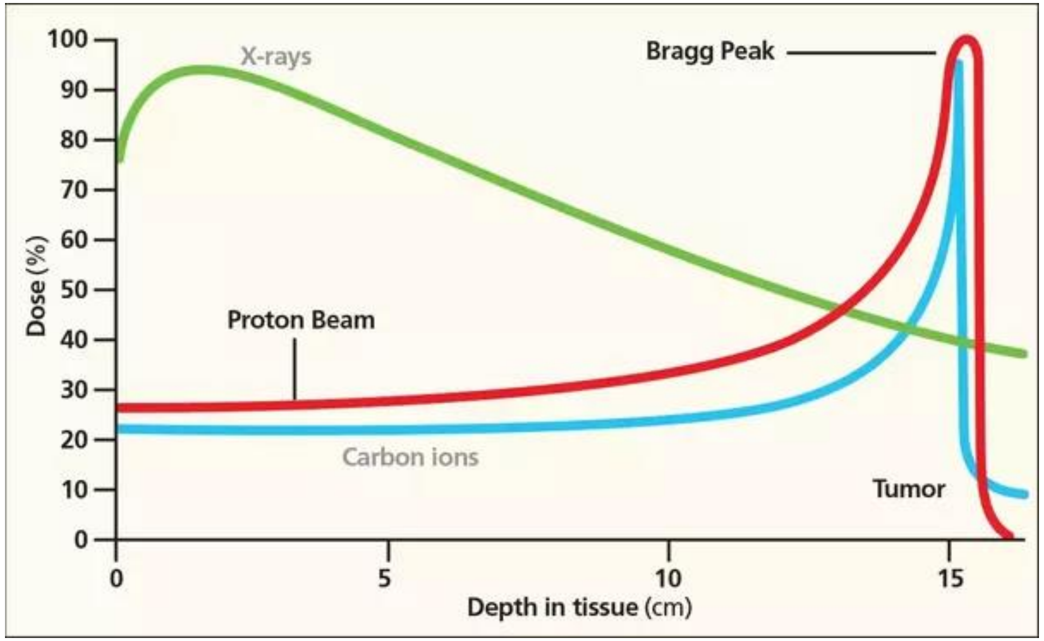
Intensity modulated treatment plan – dose distribution



With particles it gets much better…

- particle accelerators produce “natural“ pencil beams

  improved dose distribution (Bragg-Peak) in theory



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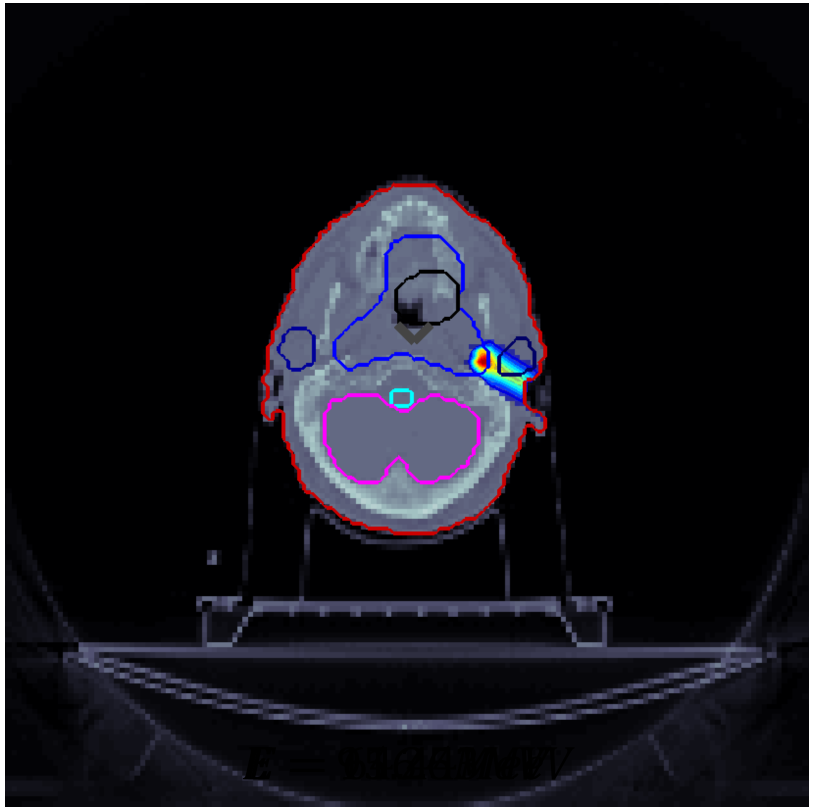


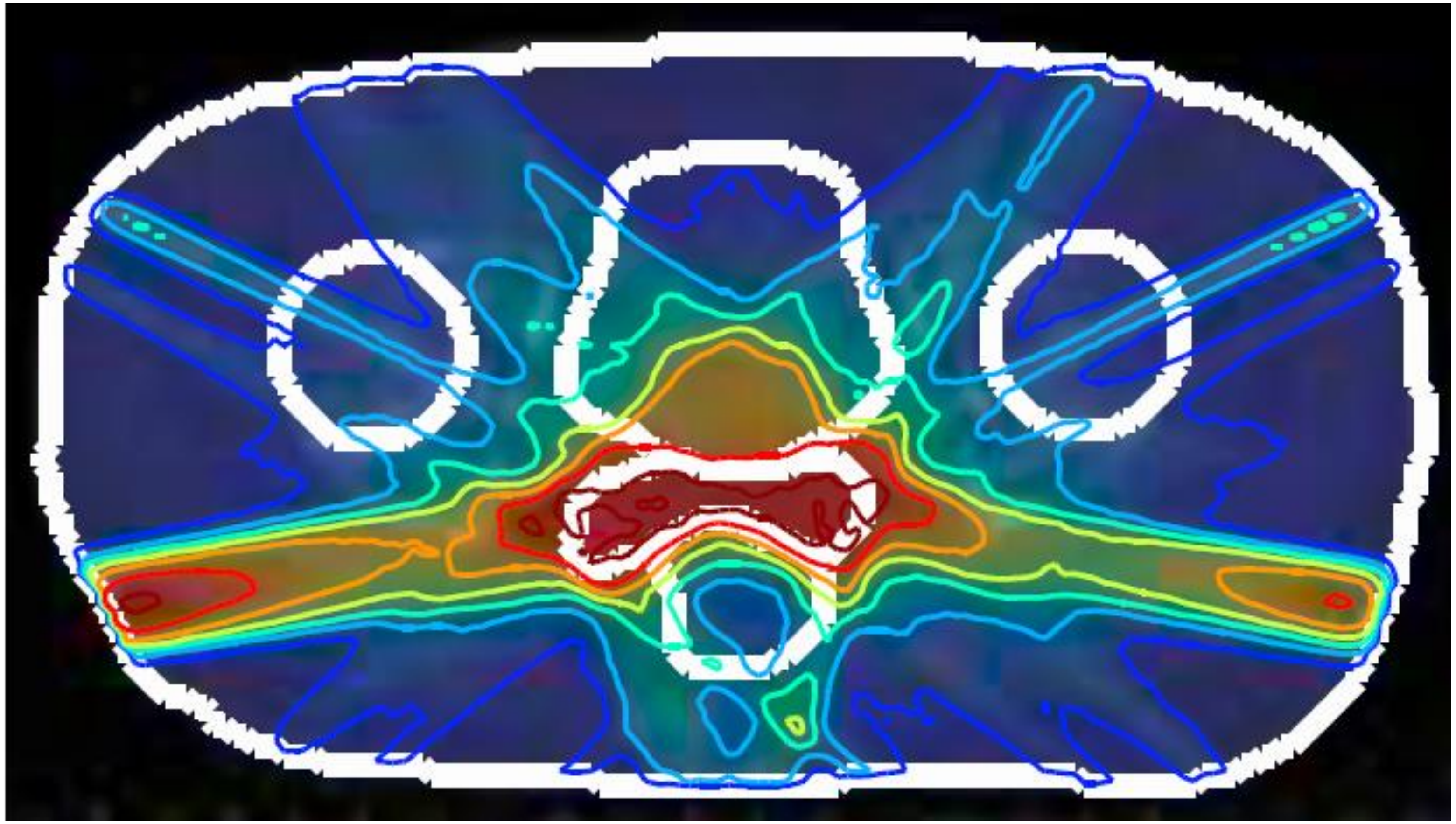
[1] Quora – In which ways could gold atoms, protons or neutrons be brought safely into human brain tissue – lBragg Peak and the Proton Difference. Accessed from https://www.quora.com/In-which-ways-could-gold-atoms-protons-or-neutrons-be-brought-safely-into-human-brain-tissue on 15.02.2021.

How do we analyze a plan / a dose?

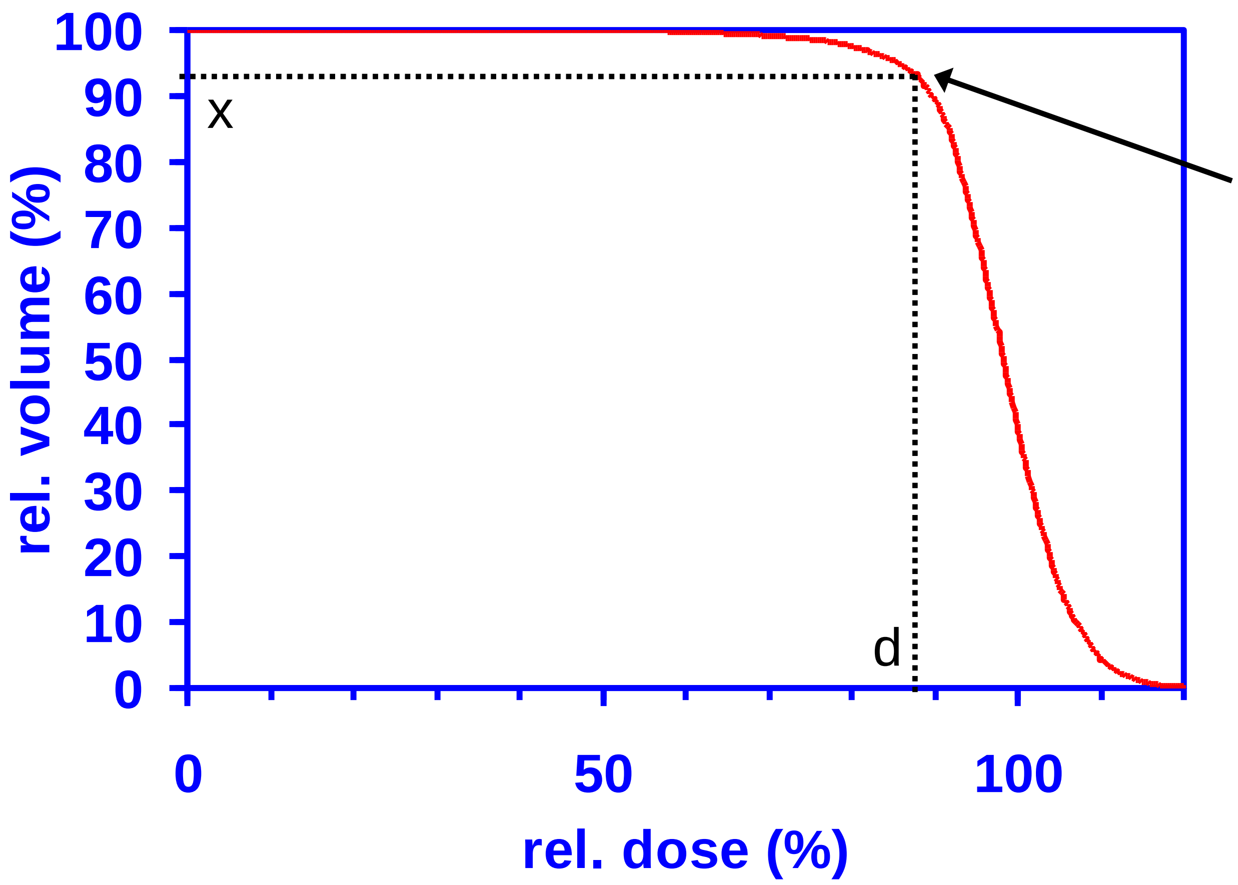
Evaluation of the
2D tomographic images

Dose statistics:
Mean, maximum, minimum dose

Dose-volume histograms
2D display of the 3D dose distribution

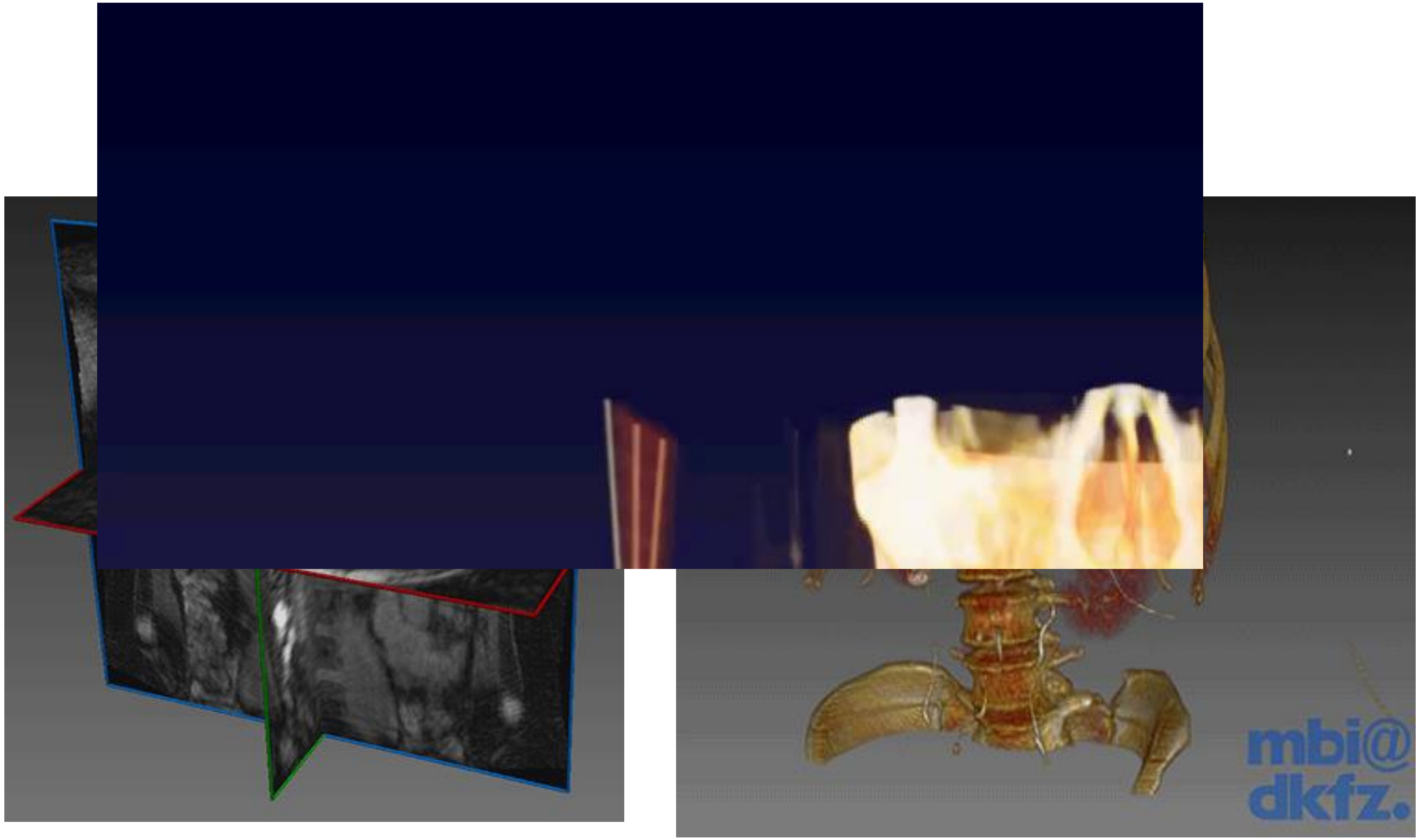


Dose-volume histograms



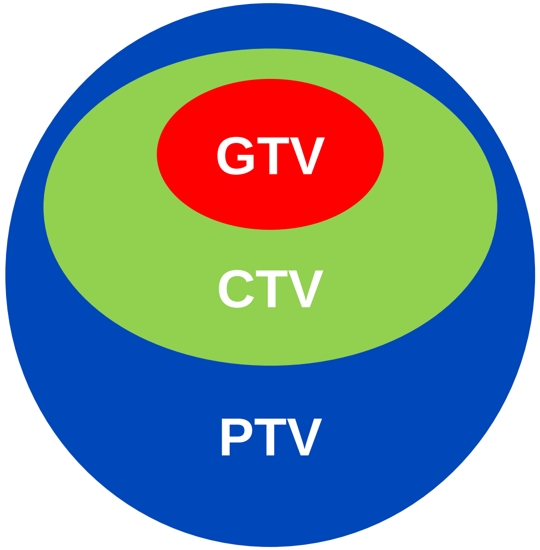
x% of the volume obtains at least d% of the prescribed dose

Problem: Dealing with uncertainties



Animations courtesy of Paul Merca & Markus Stoll

Target volume



GTV = Gross tumor volume

tumor volume that is visible on the images

CTV = Clinical target volume

includes the GTV and regions where invisble tumor tissue is expected

PTV = Planning target volume

safety margin to take uncertainties into account

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Summary

- a CT with delineated organs / tumors servers as a basis for treatment planning
- we can calculate the dose in the CT
- using numerical optimization we are able to weight particle beams differently to obtain suitable dose distributions
- finally, we are able to statistically analyze our plans with dedicated methods (e.g. dose-volume histograms)

Questions?