4D Monte Carlo
...and some comments on robust optimisation

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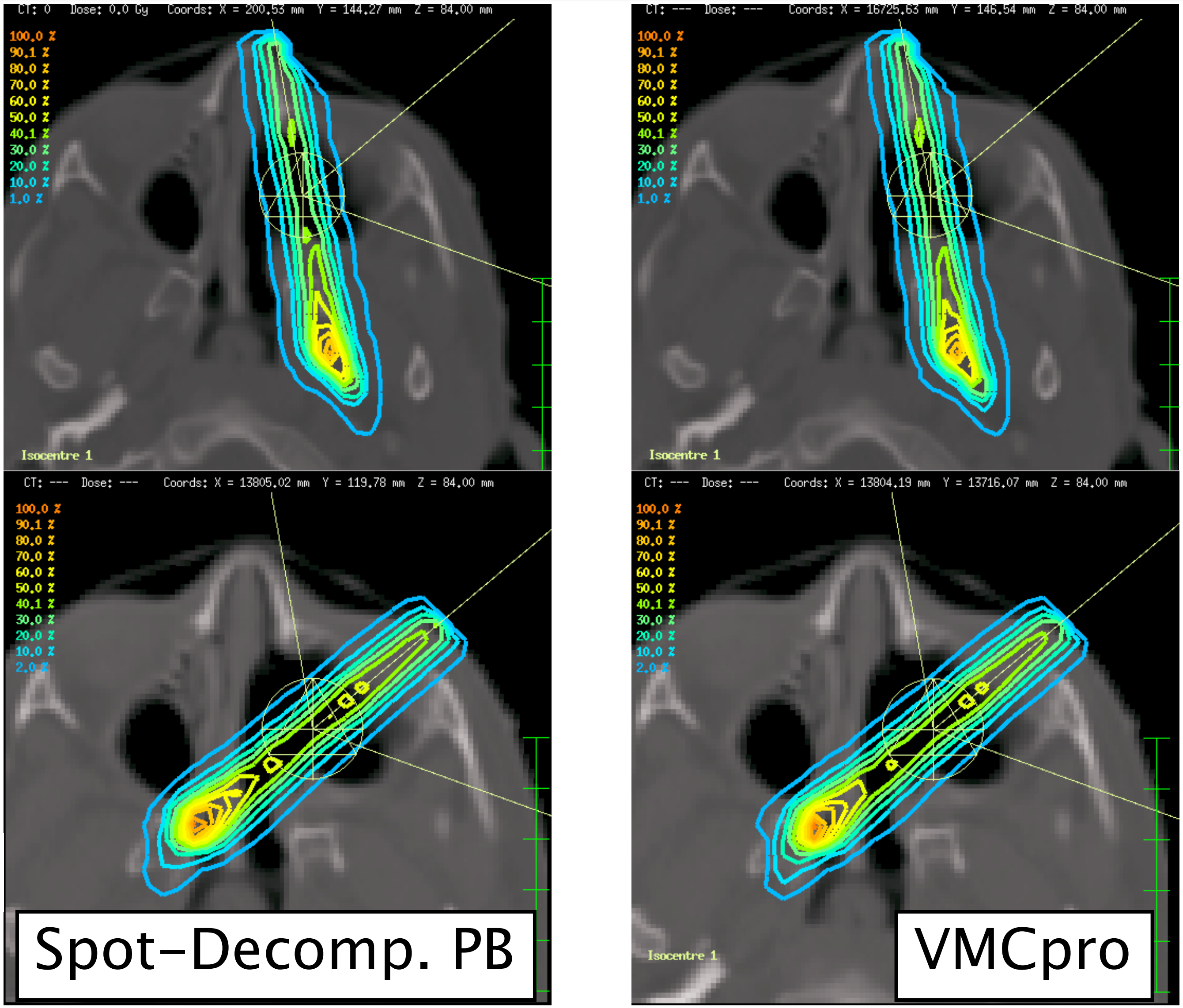
Nobody needs Monte Carlo for protons because it is more accurate



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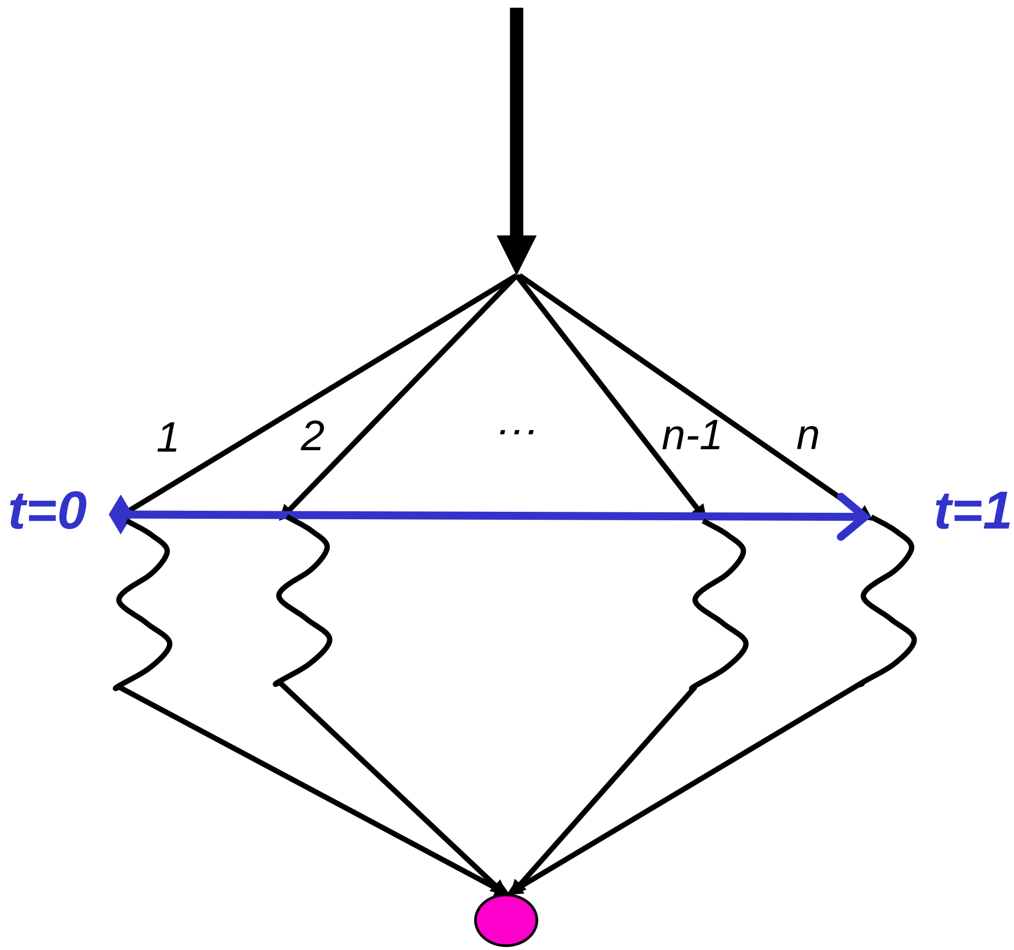
Reminder: Monte Carlo makes hard maths easier

For example: simulation of dynamic processes



Start a particle history

History branches into
n discrete states….

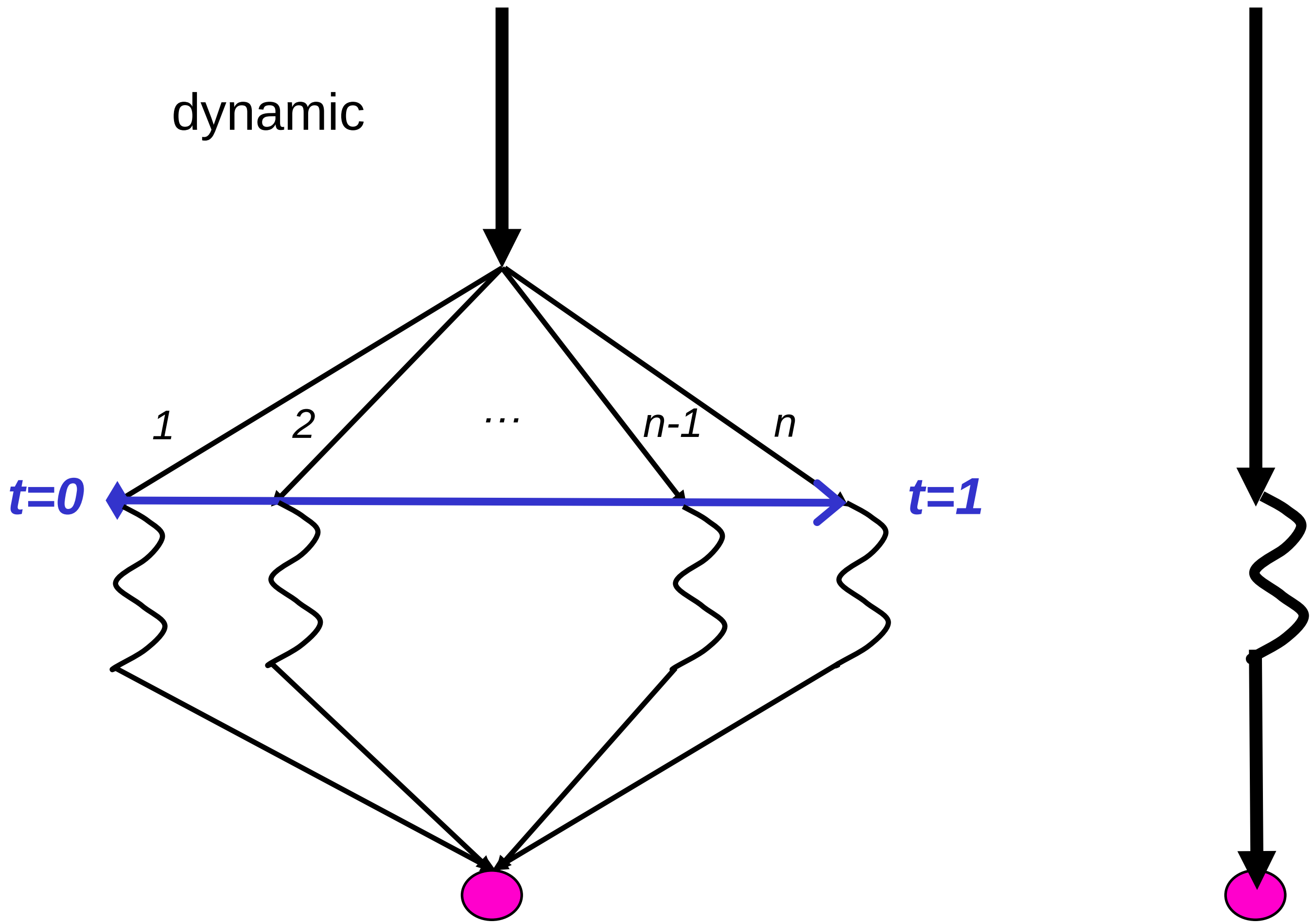
…according to a random number t

…perform simulations…

…and merge results

Reminder: Monte Carlo makes hard maths easier

How many histories are necessary to achieve the same statistical uncertainty?



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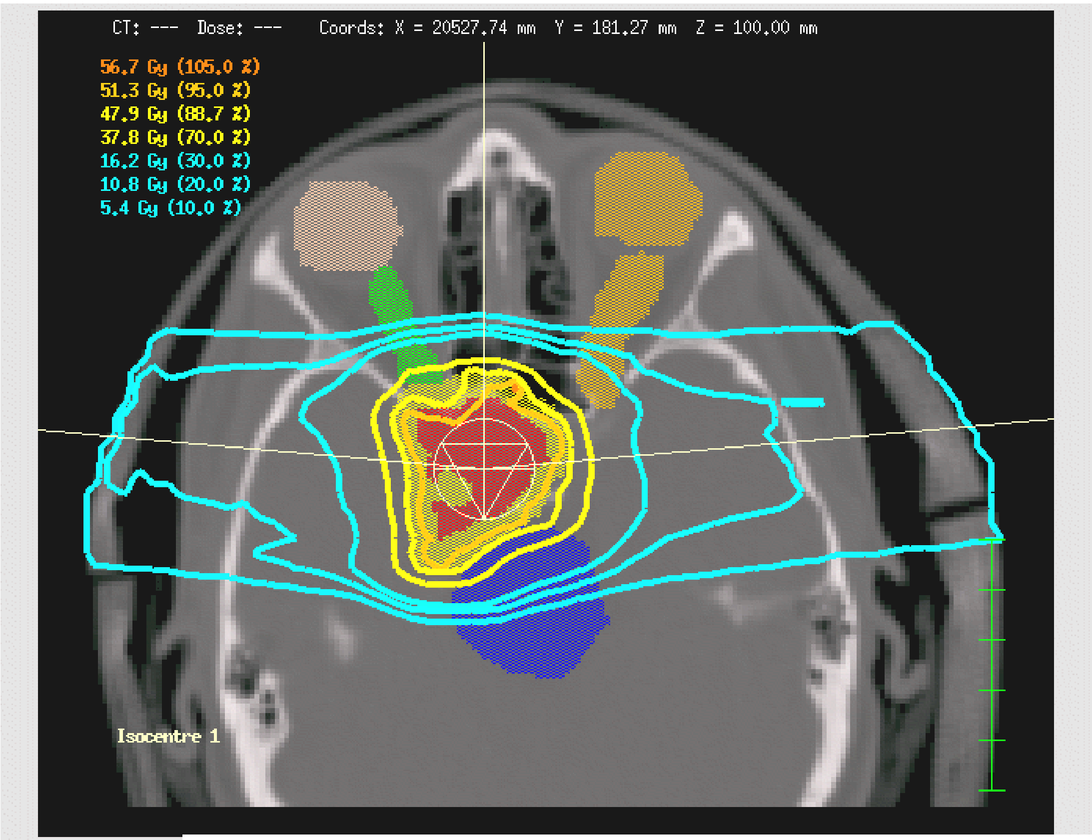
For example, random setup errors



Isocentre shift is sampled according to a Gaussian for each history
= expected dose of a treatment with infinitely many fractions

0 mm = standard deviation

courtesy M. Soukup

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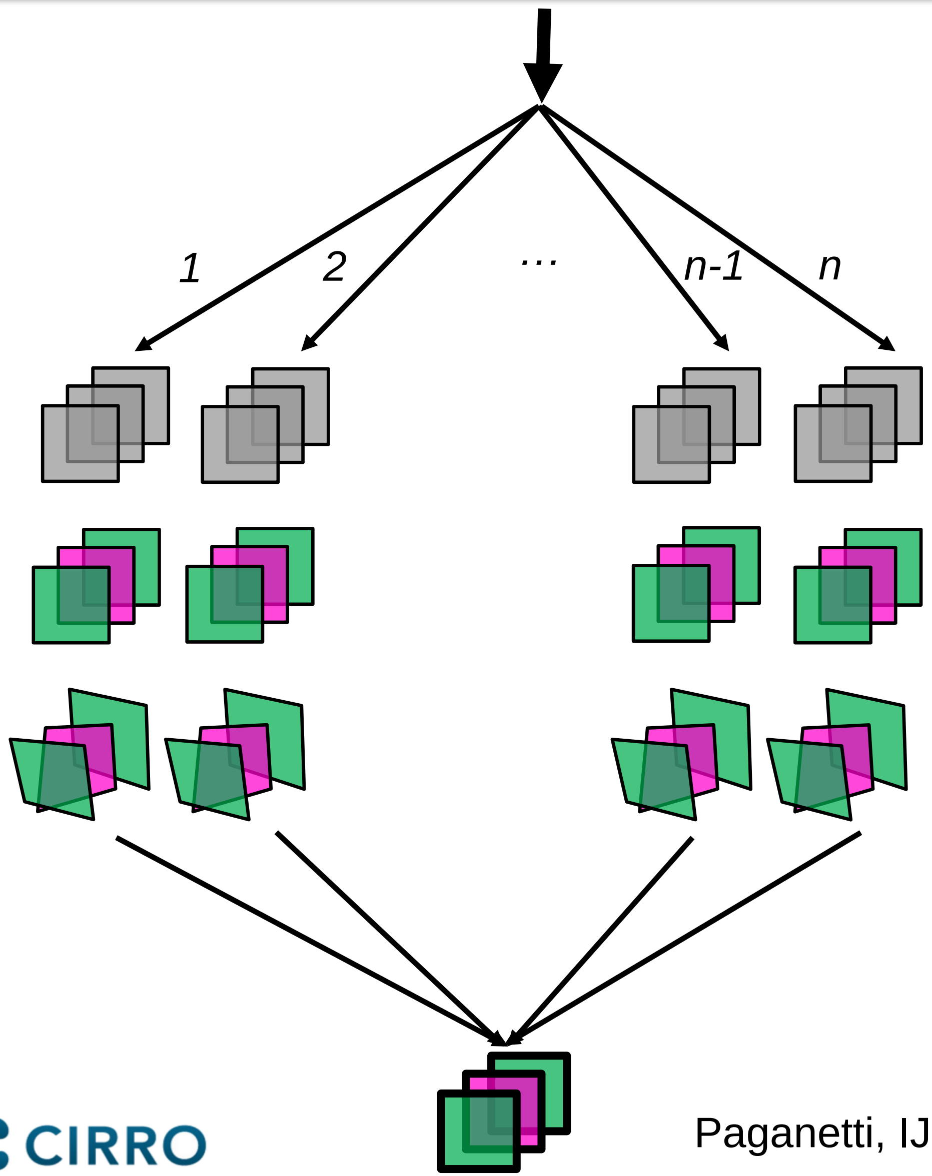
The conventional (naive ?) way of 4D MC



n geometry instances

n doses

n warped doses

accumulation to reference geometry

Paganetti, IJROBP 60, 2004

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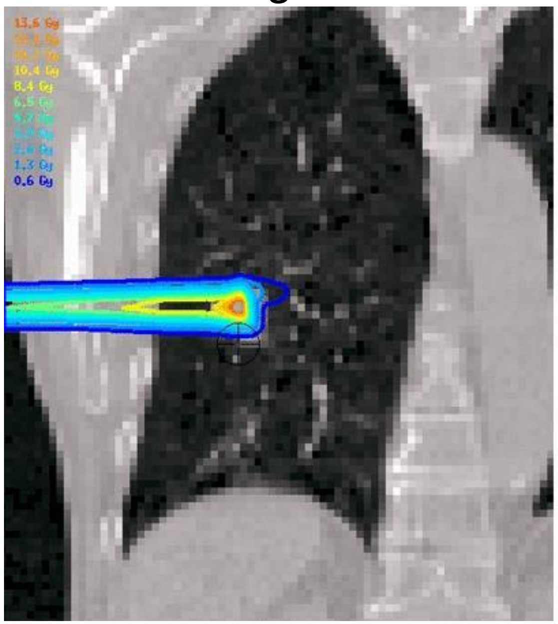
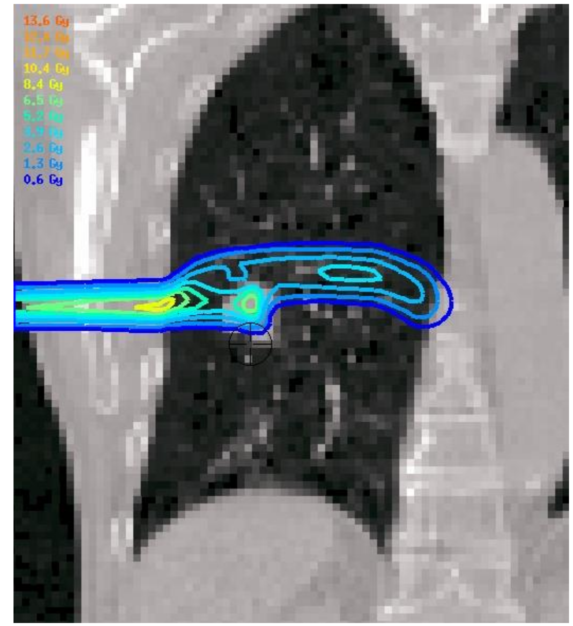
Tissue-Eye-View:
expected dose-to-moving-tissue

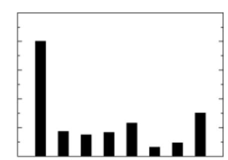
proton spot dose…
in different geometries



TISSUE EYE VIEW



accumulation in reference geometry using breathing PDF (rel. time spend in the breathing phases)



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courtesy M. Soukup, HYPERION M. Söhn

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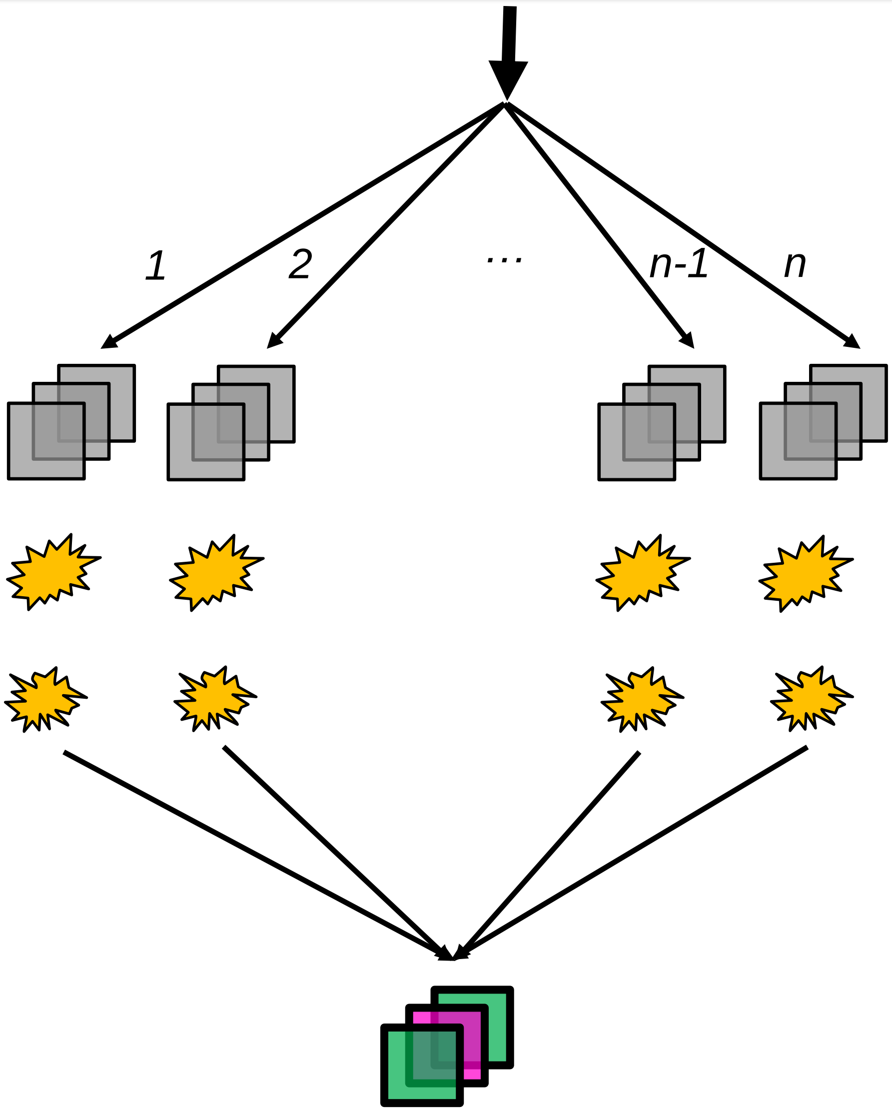
Energy transfer 4D MC: deposition warping



n geometry instances

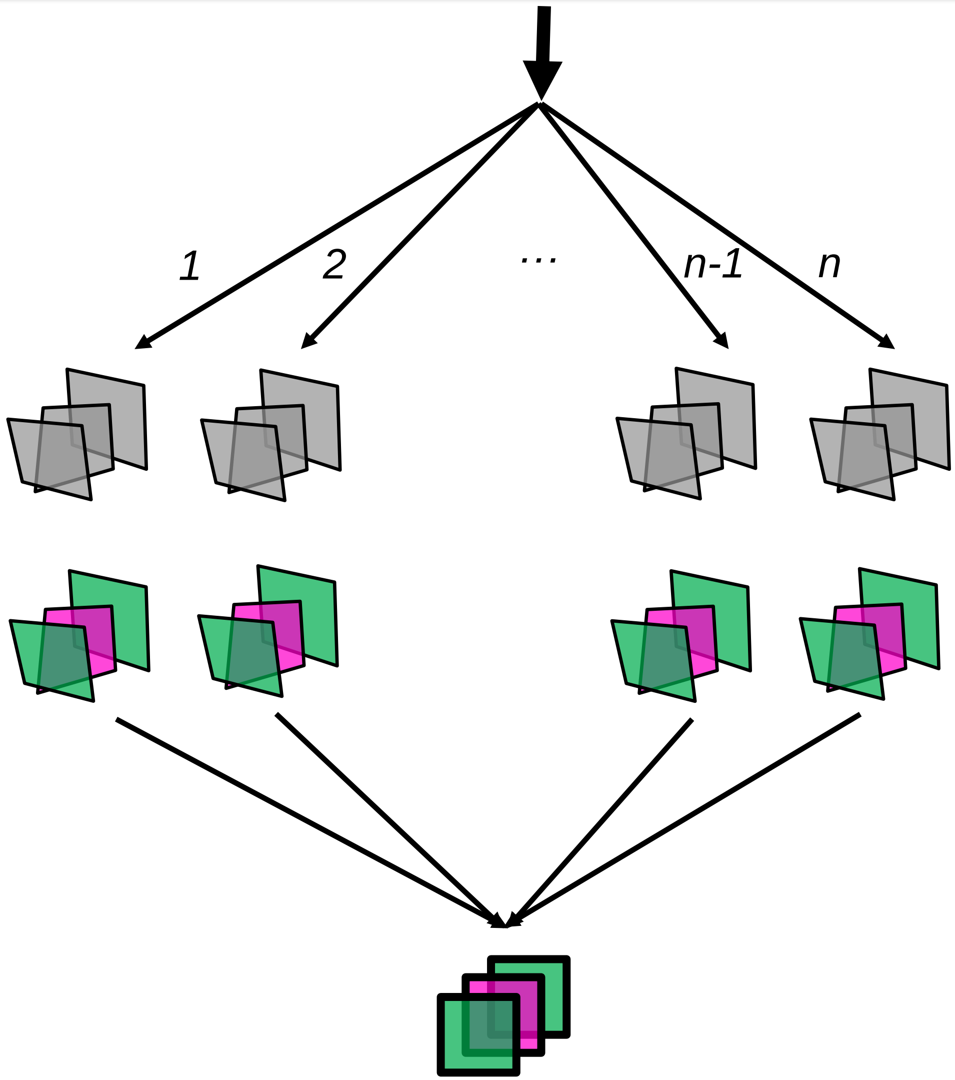
for each event

warped events

accumulation

Siebers, Med. Phys. 35, 2008

The intrepid way of 4D MC



n warped geometry instances

n warped doses

accumulation to
reference geometry

Heath/Kawrakow, PMB 56, 2011

Things to consider about spatial resolution

- Monte Carlo computes the mean energy deposition in a scoring volume (voxel) – averaging effects on gradients.

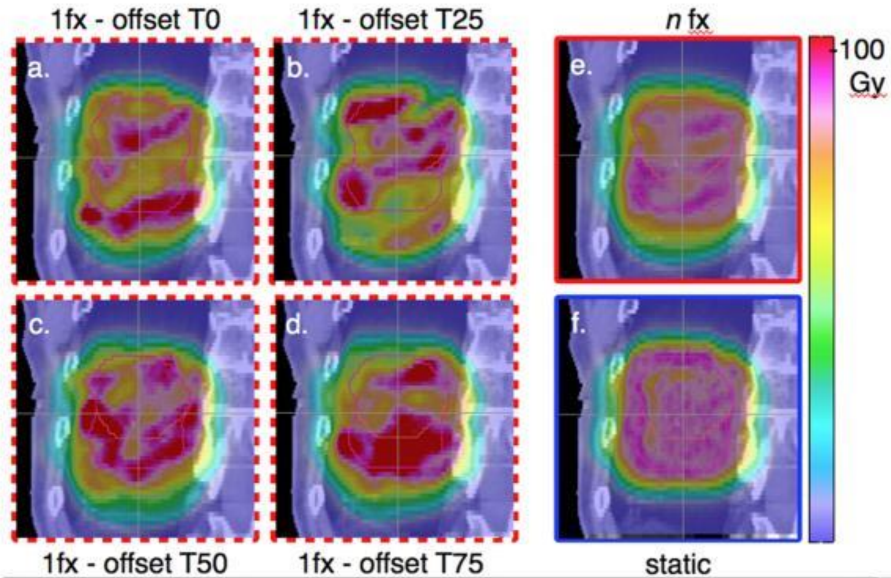
- The tracking grid and the scoring grid do not have to match – scoring could be performed on a finer grid.

- MC speed is mostly achieved by reducing the tracking resolution and by increasing the cutoff energy of electrons – i.e. by a loss of spatial resolution. Therefore, resolution costs much.

- The dose computation doesn´t have to be more precise in space than the deformable image registration.

More things to consider: implicit averaging

The MC speed advantage remains for validation computations, e.g. for the interplay effect, if the scanning pattern AND the synchronous breathing motion are known.



Grassberger IJROBP 86, 2013

However, every new scenario is a full MC dose computation: *implicit averaging. Robustness analysis* often calls for *explicit averaging.*

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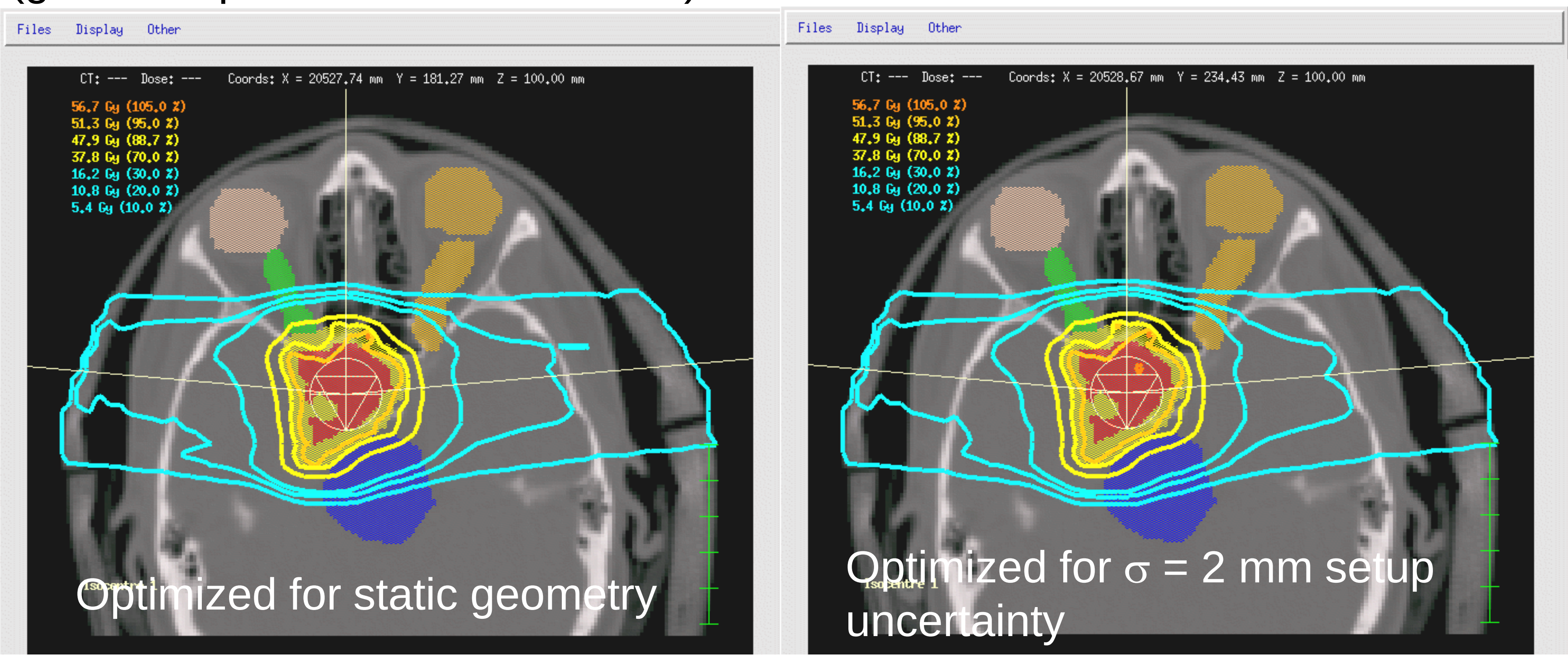
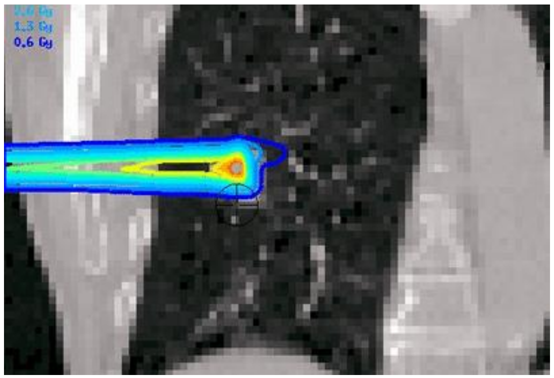
Optimisation with 4D MC: compensation of random errors

Robust Planning against rigid random setup errors with zero systematic error: blurred spot doses as input to IMPT optimizer, optimize expected dose (given the presumed uncertainties)

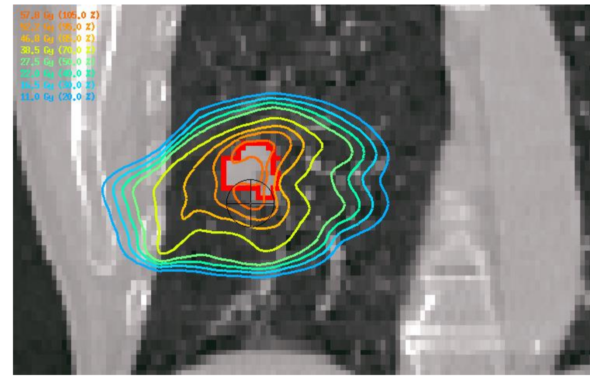


courtesy M. Soukup

Optimisation with 4D MC: compensation of periodic movements in Tissue-Eye-View



Applied dose of static ITV planning



courtesy M. Soukup, HYPERION M. Söhn

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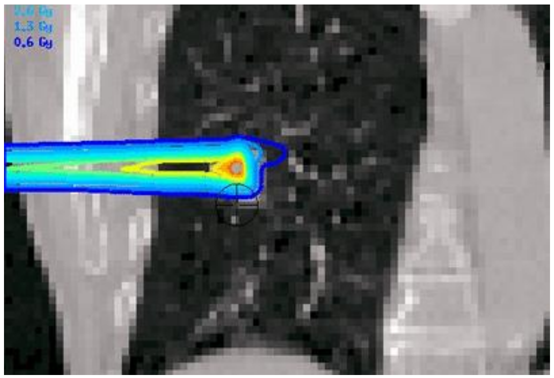
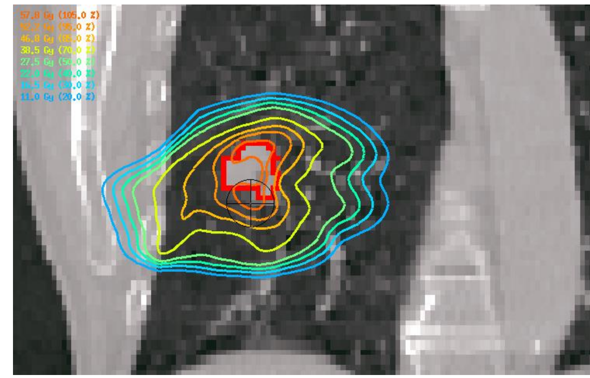
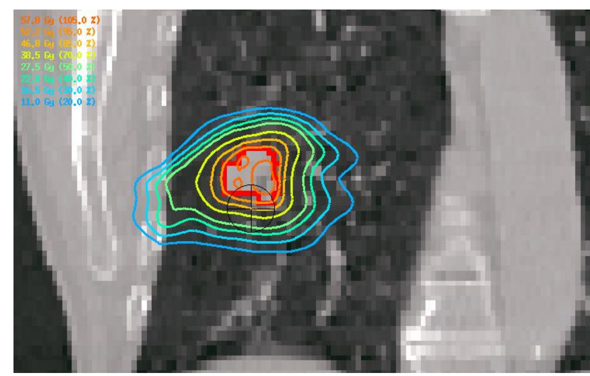
Optimisation with 4D MC: compensation of periodic movements in Tissue-Eye-View



Applied dose of static ITV planning



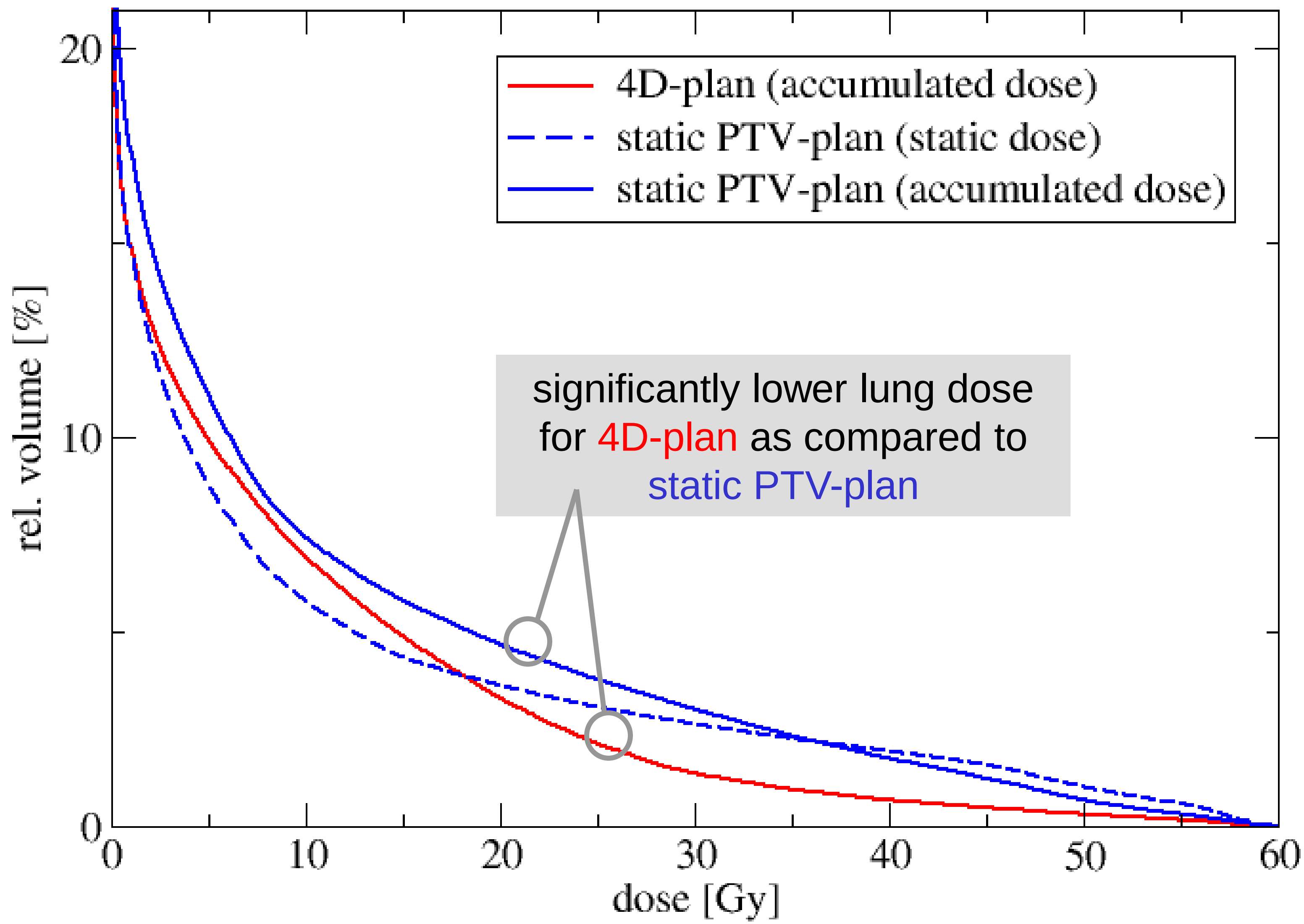
Applied dose of 4D-TEV planning



Of course, TEV depends crucially on the correctness of the input motion prediction.
There seems to be a need for gating&adaptation

CIRRO courtesy M. Soukup, HYPERION M. Söhn Aarhus University Hospital

PTV vs TEV: DVHs of ipsilateral lung



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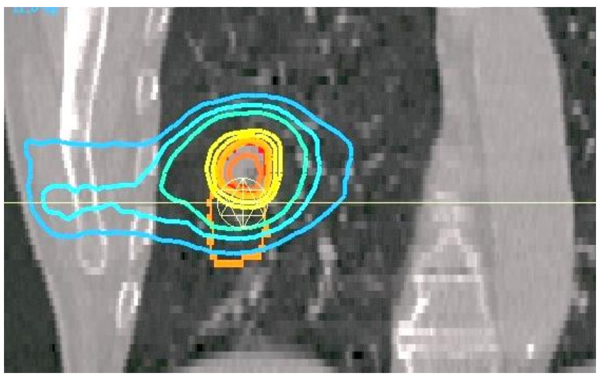
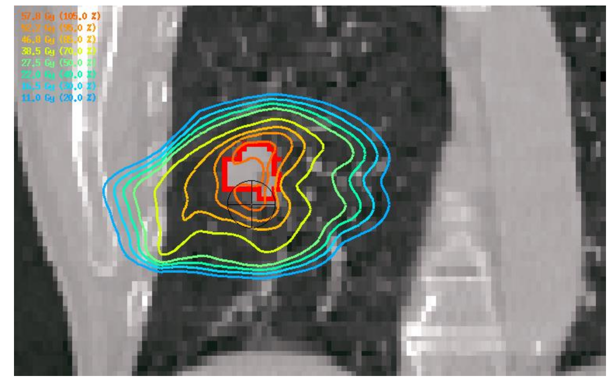
Optimisation with 4D MC: compensation of periodic movements in Tissue-Eye-View

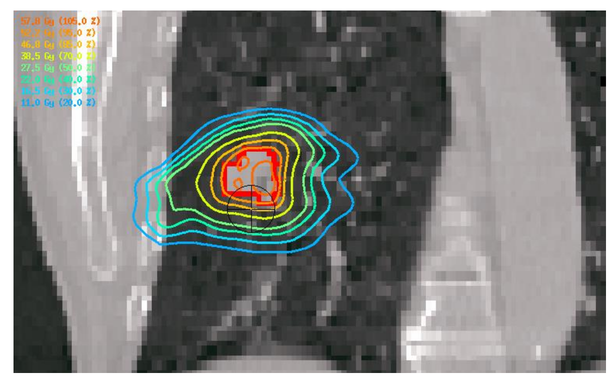


For comparison:
4D-TEV photon SBRT

Applied dose of static ITV planning



Applied dose of 4D-TEV planning



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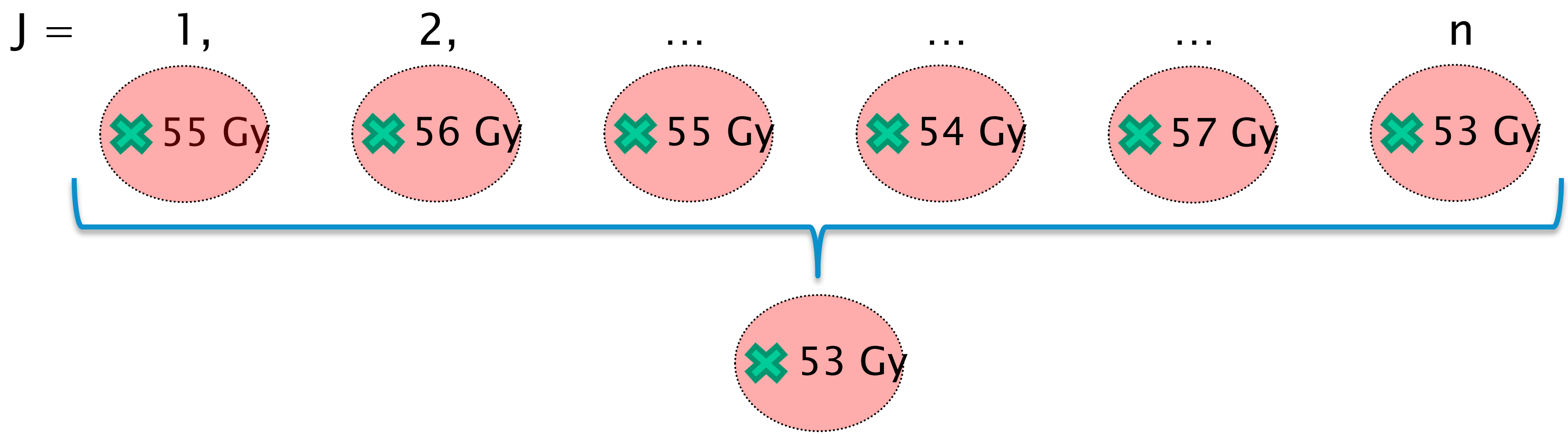
Recall: Robust optimisation via the worst case approximation



For each geometric instance, take the lowest (highest) dose *at each point.*

$$F = \sum_{i \in V} f(D_i) \longrightarrow F = \sum_{i \in V} f(\min_J D_{i,J})$$

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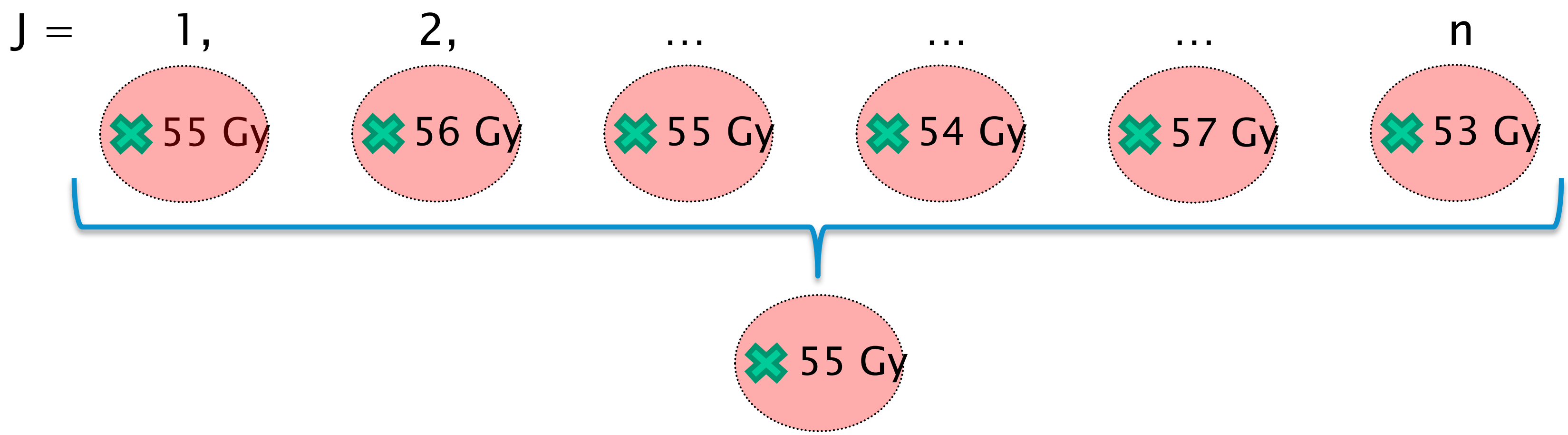
Compare: Robust optimisation via the expected dose approximation



For each geometric instance, take the mean dose *at each point.*

$$F = \sum_{i \in V} f(D_i) \longrightarrow F = \sum_{i \in V} f(< D_i >_J)$$

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Variants of Robust Optimisation – a photon`s guy point of view

- Obviously, worst-case and mean dose robust optimisation are related, but the former is much more aggressive.
  Is this really desired?

- For photon therapy, there have been at least 9 suggestions for robust optimisation. *Clueless?*

- Robust optimisation approaches differ in
  + the type of uncertainty addressed
  + the effect of uncertainties on the dose distribution
  + the (statistical) concept of quantifying robustness

Worst case approximation vs. mean dose approximation

J = 1, 2, … … … n

WC 55 Gy 56 Gy 55 Gy 54 Gy 57 Gy 53 Gy

…requires n distinct dose calculations, which limits the dimensionality and sampling density of the uncertainty space

MD via 4D-MC 55 Gy

…requires *one* distinct dose calculation, with *arbitrary* dimensionality and sampling density of the uncertainty space

The compensation of errors by robust optimisation

effectiveness

cost in the as-planned population

accept the unforeseen

compensate for the unforeseen randoms

compensate for the unforeseen systematics

prevent the unforeseen

MD

WC

Frederiksson Med Phys 39 2012

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Summary

Monte Carlo is ideal in a research setting because it invites extensions (like 4D) very generously.

Advantages for clinical grade use are not so clear – depend on the circumstances.
Stellar use case: verification of applied dose including interplay etc.

(Robust) treatment planning: MC offers unexplored exciting possibilities.