Therapy with protons and ion beams

Biomedical Physics Lecture
WiSe 2012/13

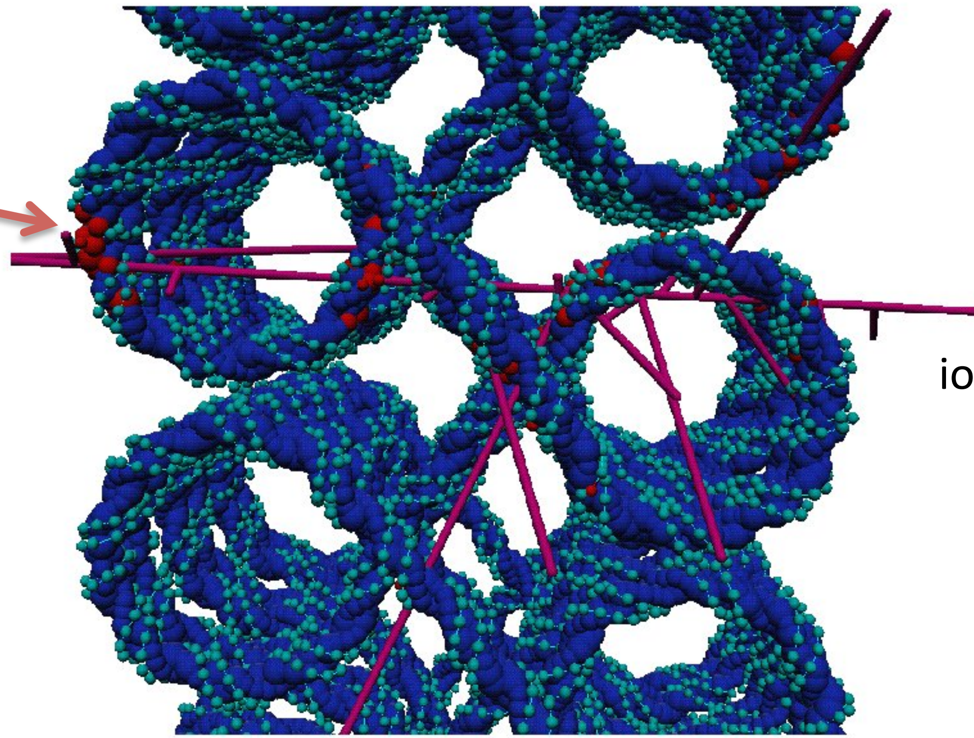
many slides from J. Willkens (TUM)

Key questions:

- How does ion cancer therapy work?
- What is the **physics** behind it?
- How can physics try to overcome limits?

Basic principle

radiation damage to DNA



ion track

ionization events by ion impact

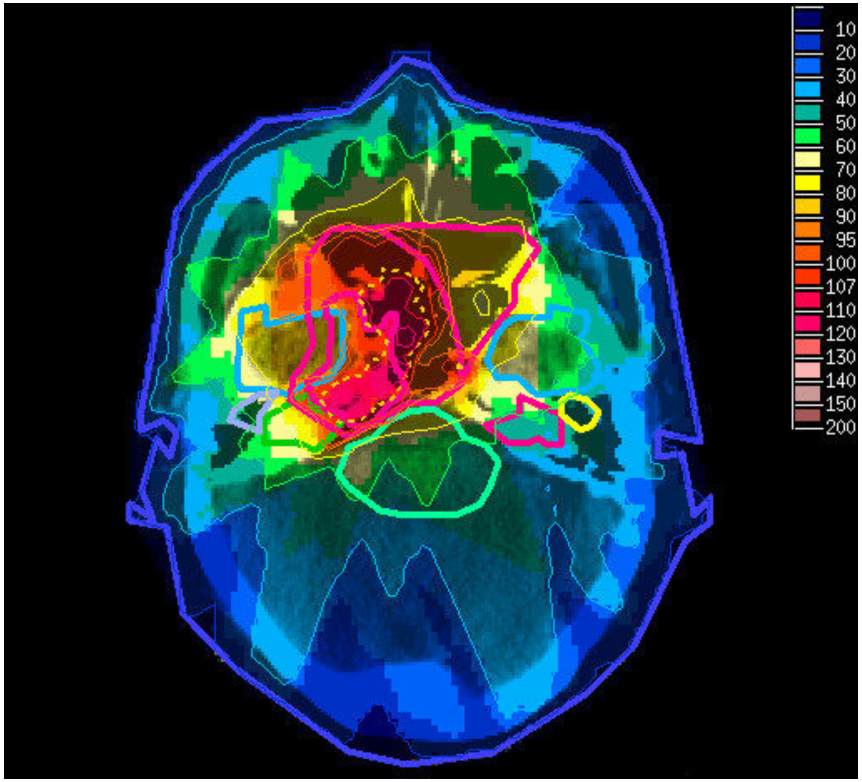
- direct single/ double strand break
- generation of free radicals

→ DNA damage → cell death

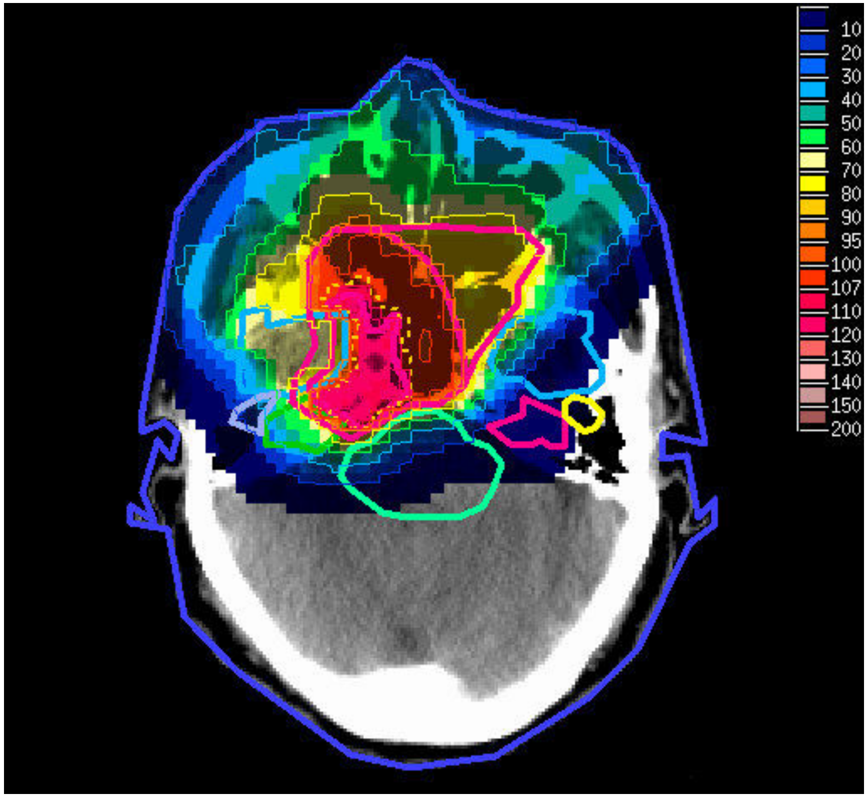
What is better? Protons or photons?

Comparison of photons and protons

Photon IMRT



Proton IMPT

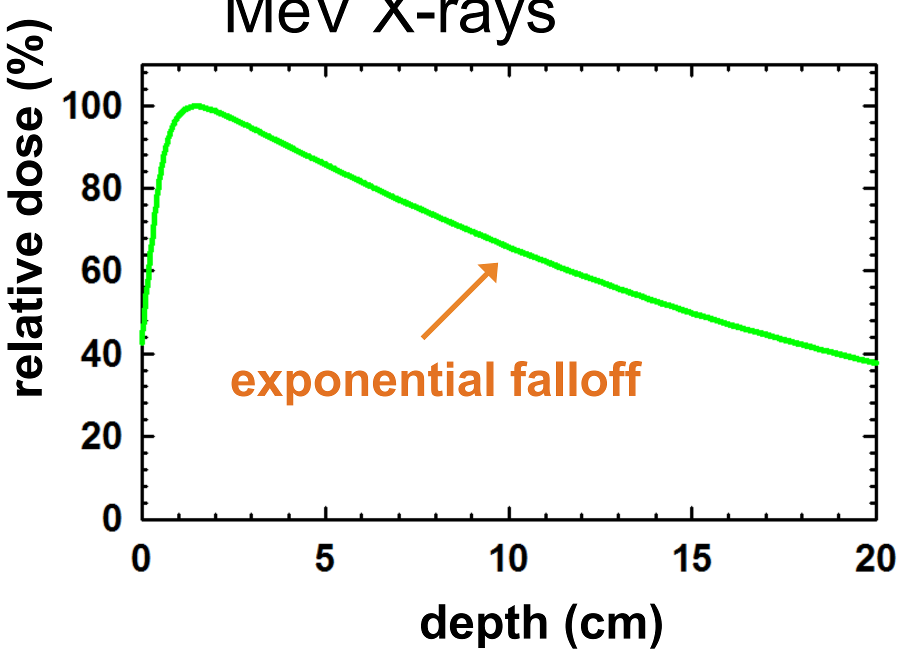


nasopharyngeal carcinoma

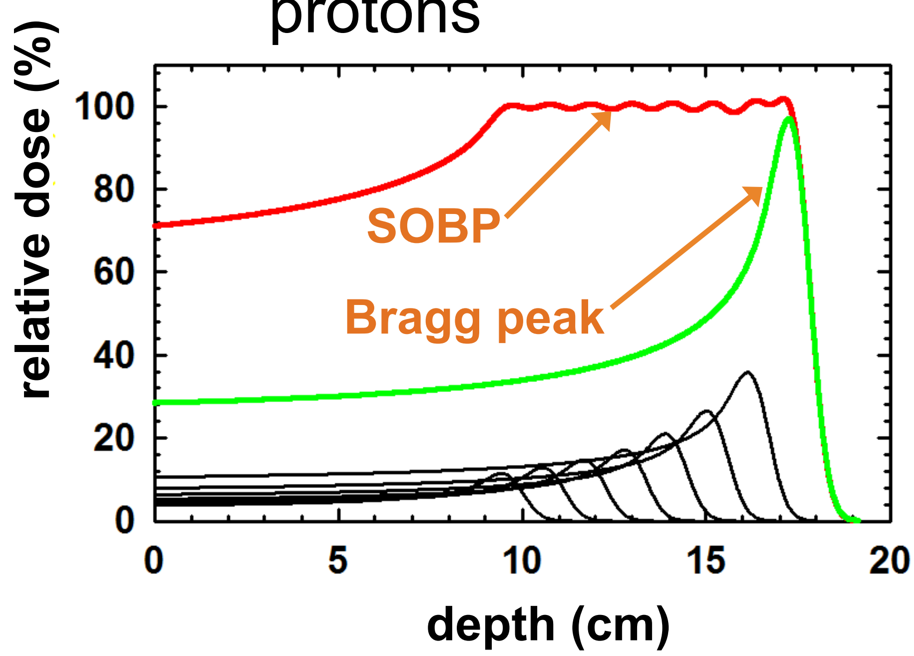
Taheri-Kadkhoda, Wilkens *et al.* 2008 *Radiation Oncology* **3**:4

Motivation for proton therapy: depth dose curves

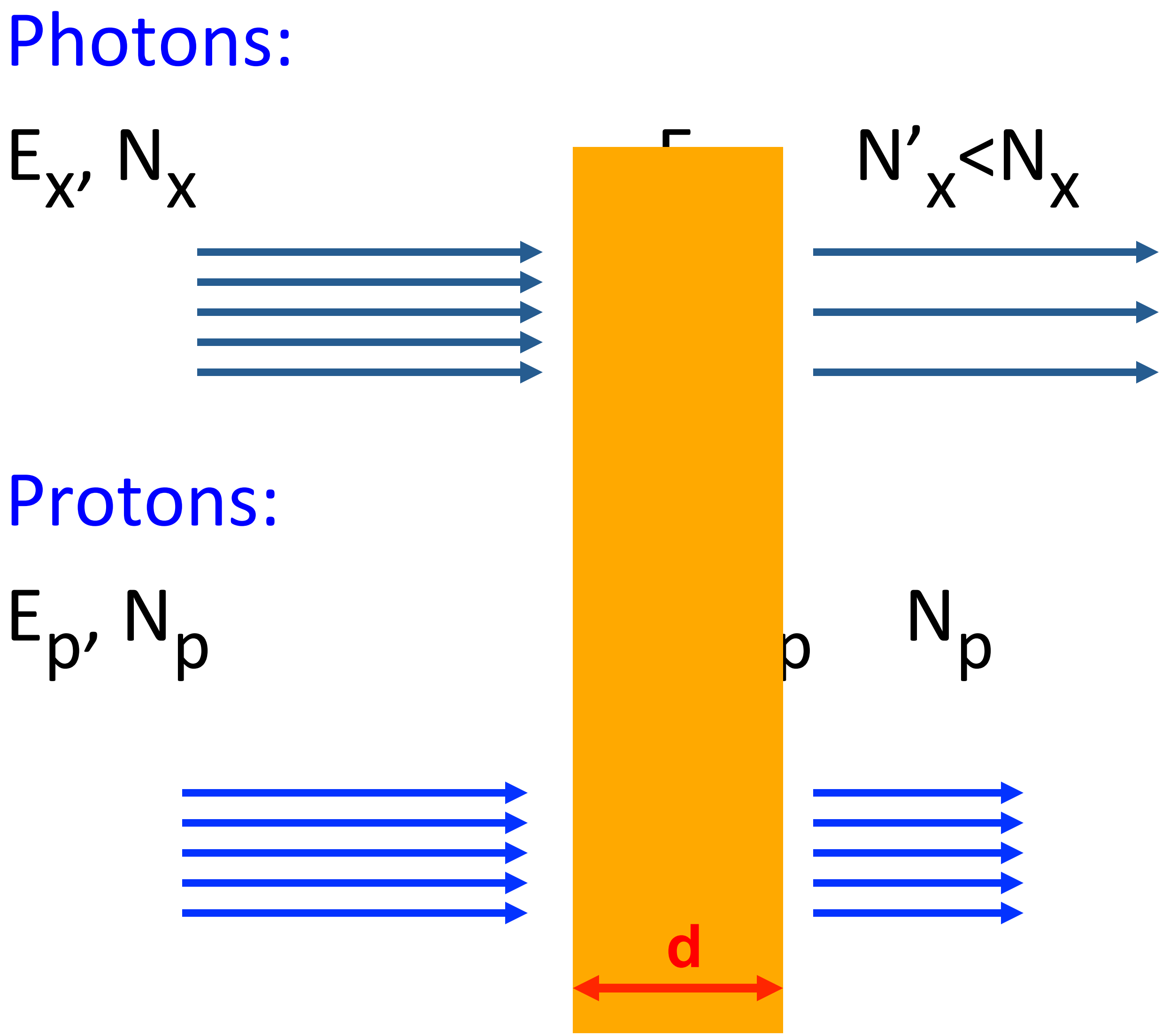
MeV X-rays



protons

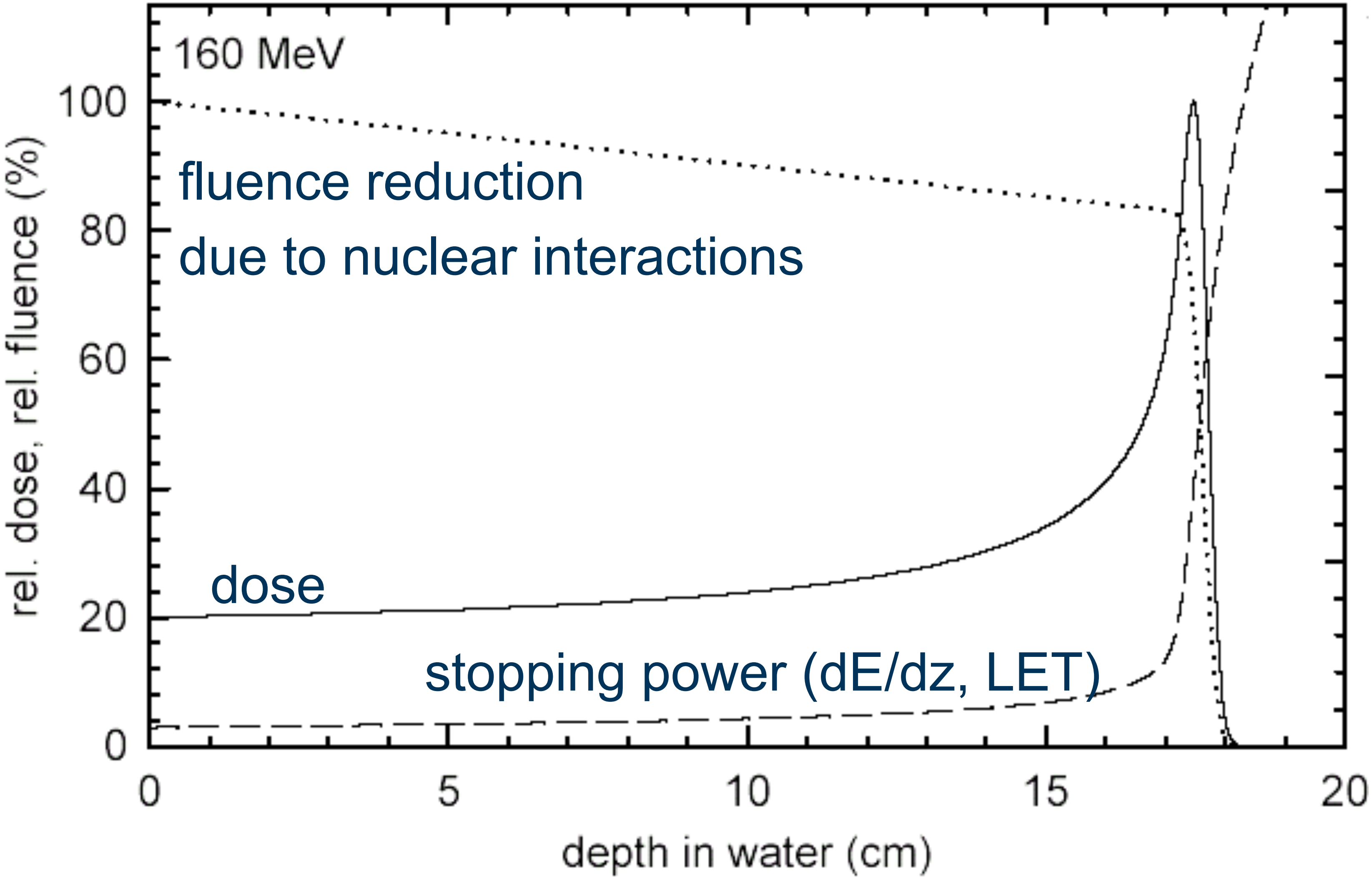


Difference between **photons** and **protons**

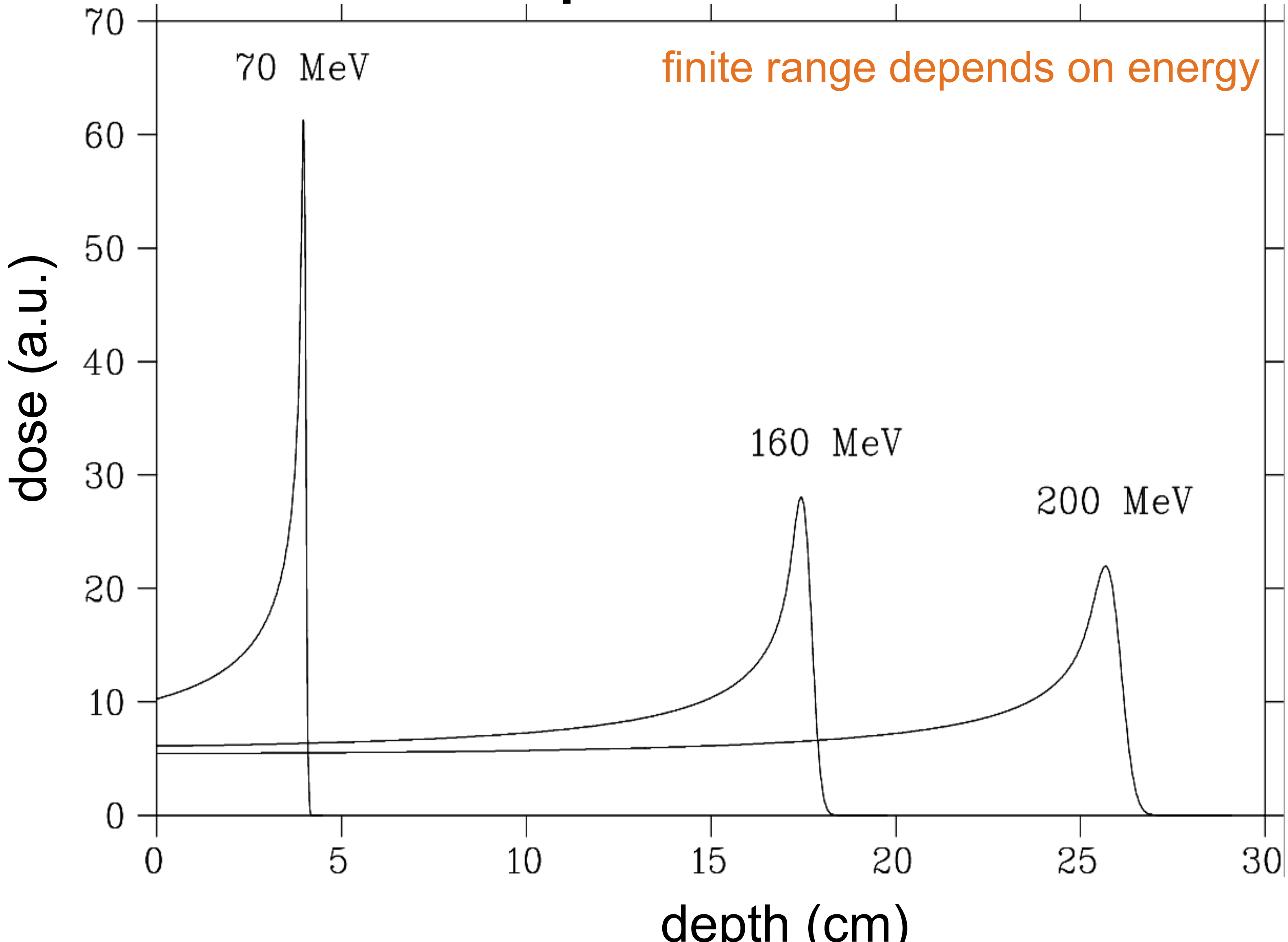


Bragg peak: stopping power

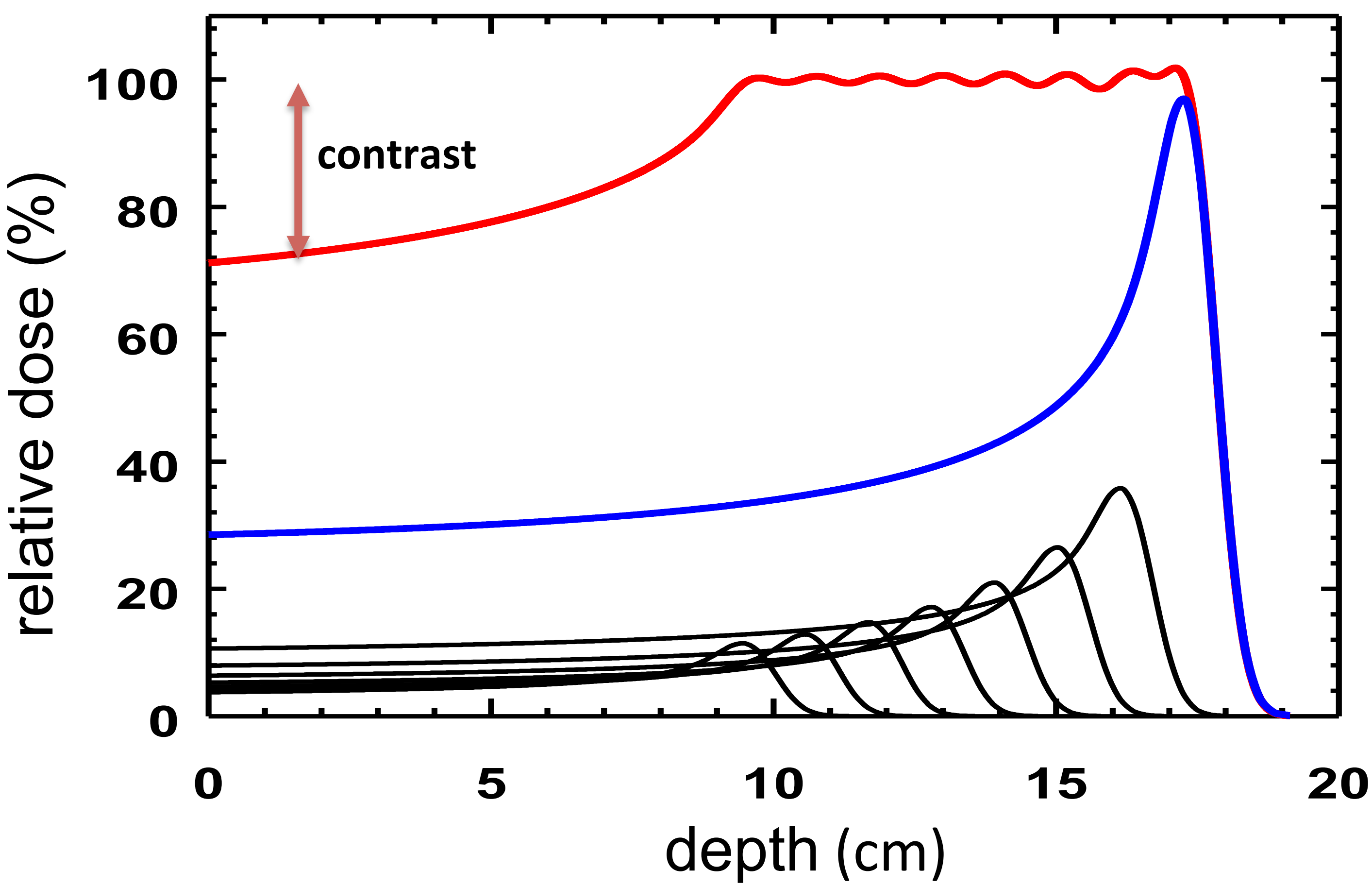
$$\frac{dE}{dz} = -4\pi n \frac{Z_{eff}^2 e^4}{m_e v^2} \left\{ \ln \frac{2 m_e v^2}{I(1-(v/c)^2)} - (v/c)^2 \right\}$$



Proton depth dose curves



Spread-out Bragg peak (SOBP)

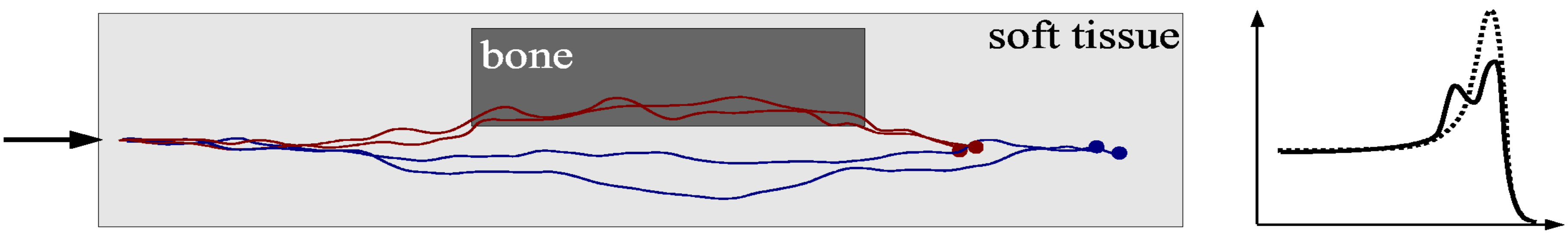


Proton / ion specific **problems**

range uncertainties:

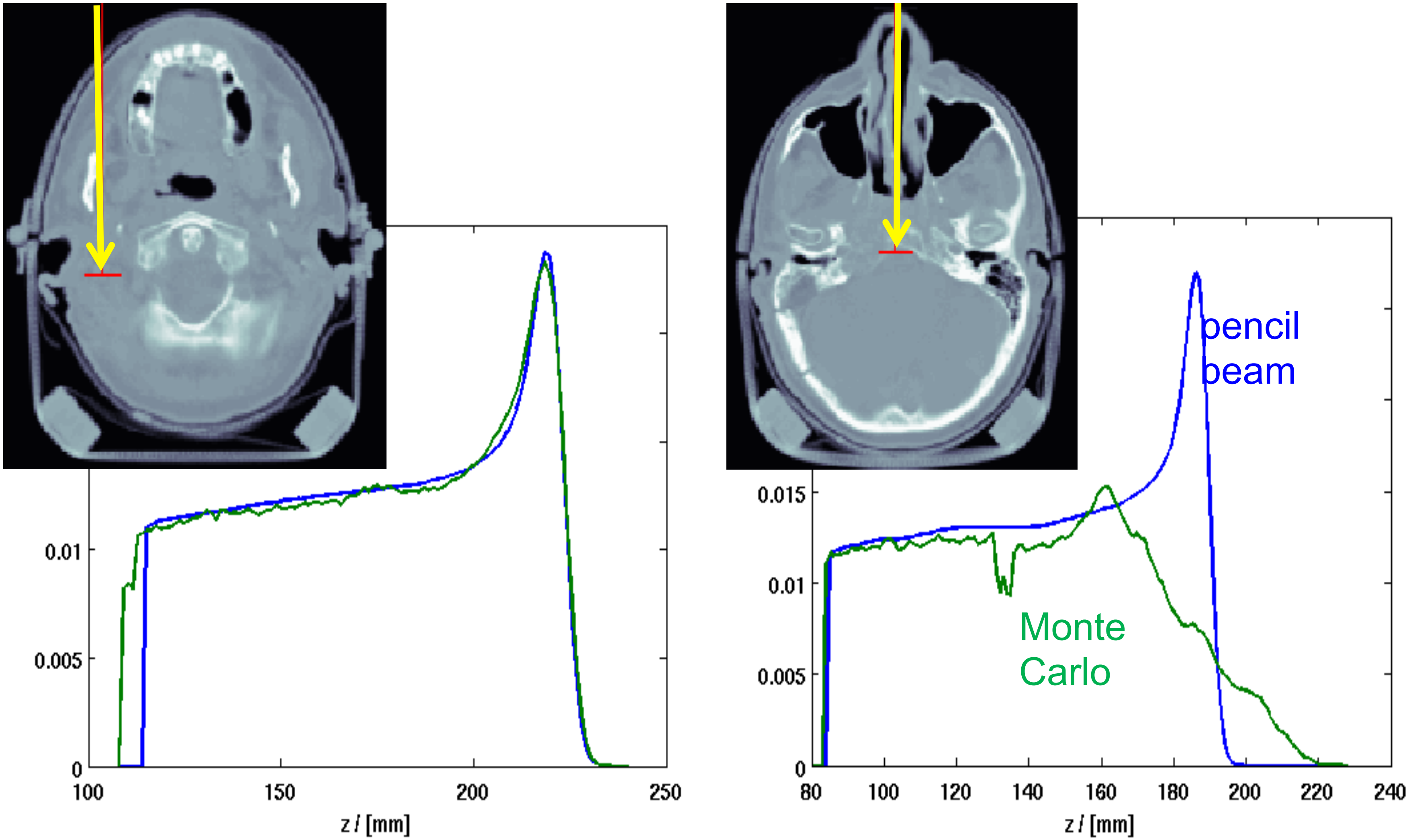
The advantage of protons is that they stop, the disadvantage is that we do not know where.

sensitive to lateral heterogeneities:



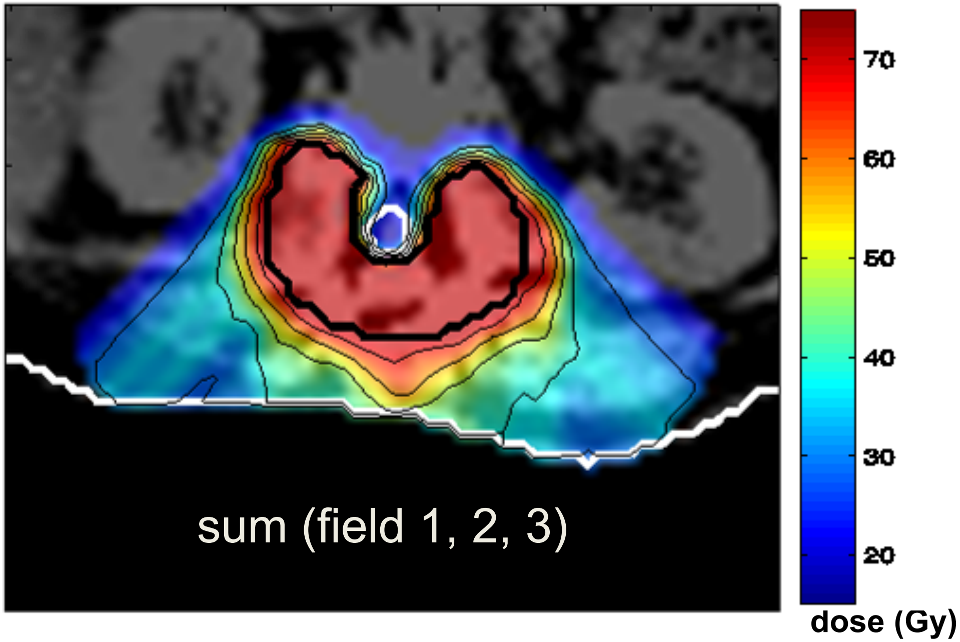
Lomax 2008 *PhysMedBiol*

Degradation of the Bragg peak



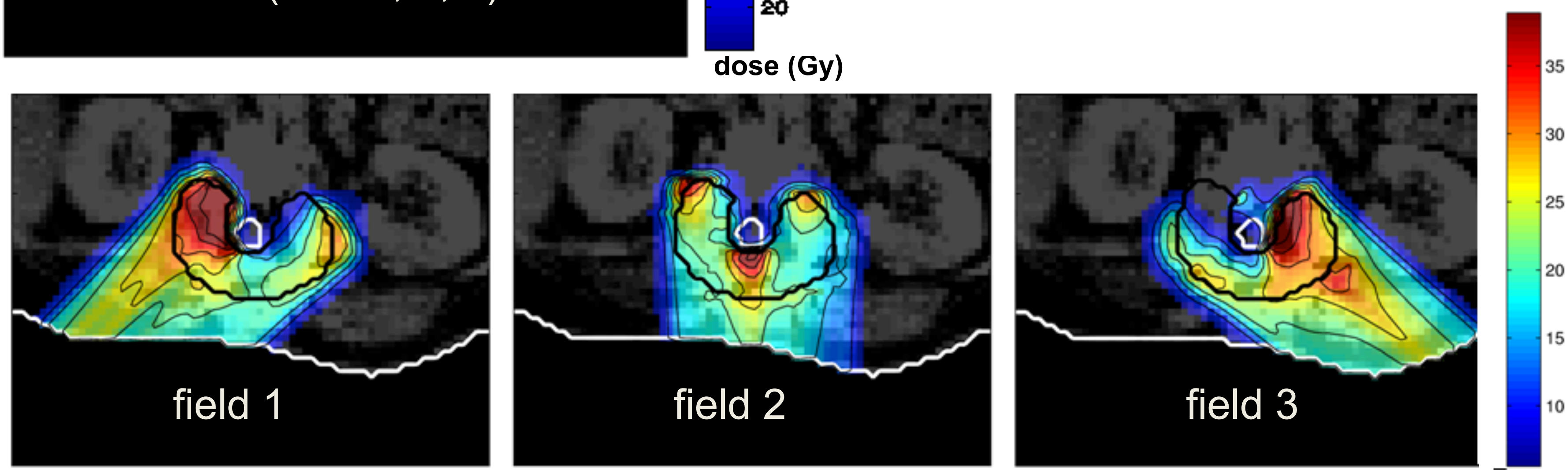
Pflugfelder et al. 2007 *MedPhys* **34**(4) 1506-1513

Range uncertainties

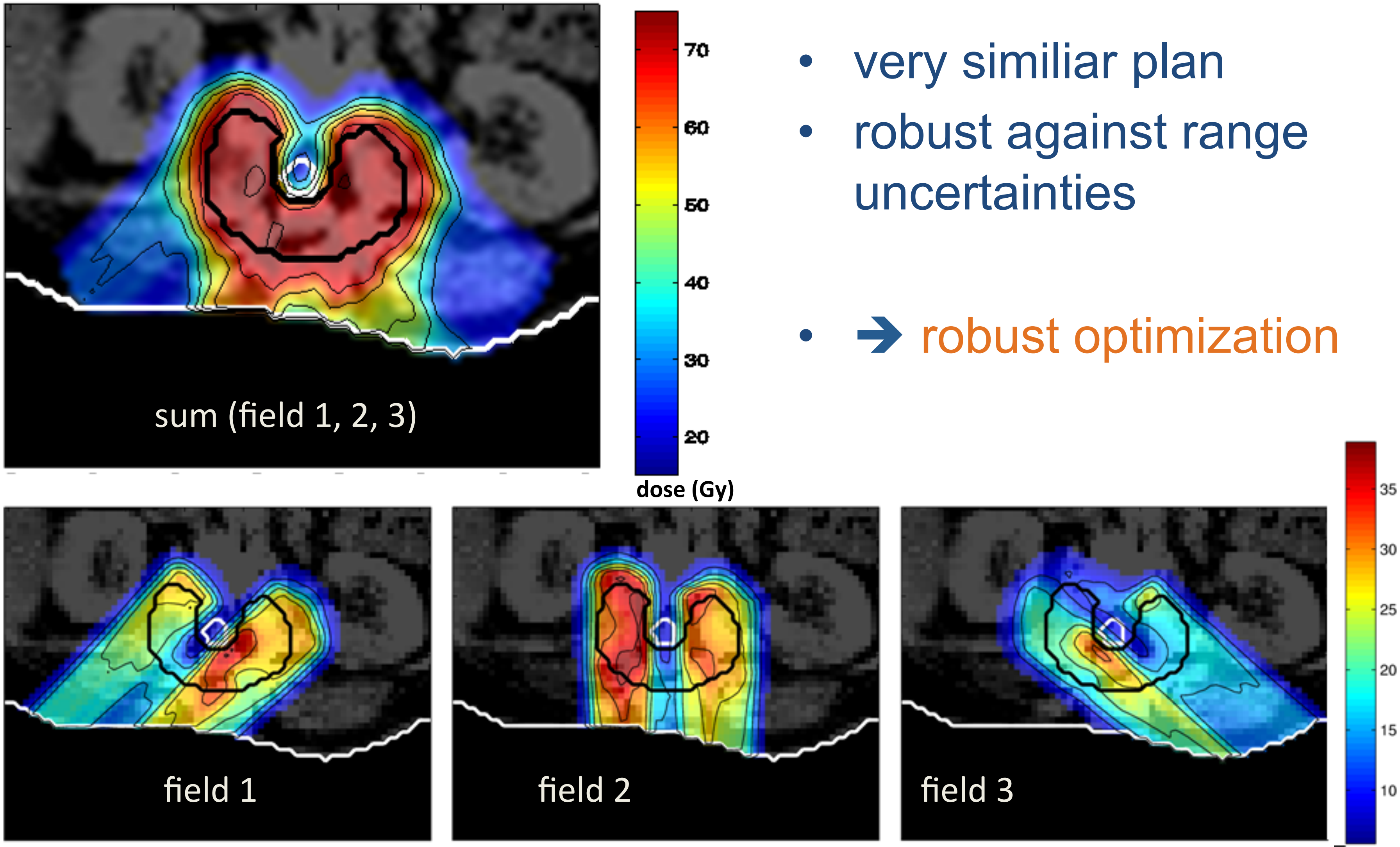


IMPT plan (3 fields)

- good dose distribution
- but: very sensitive to range uncertainties



Range uncertainties 2

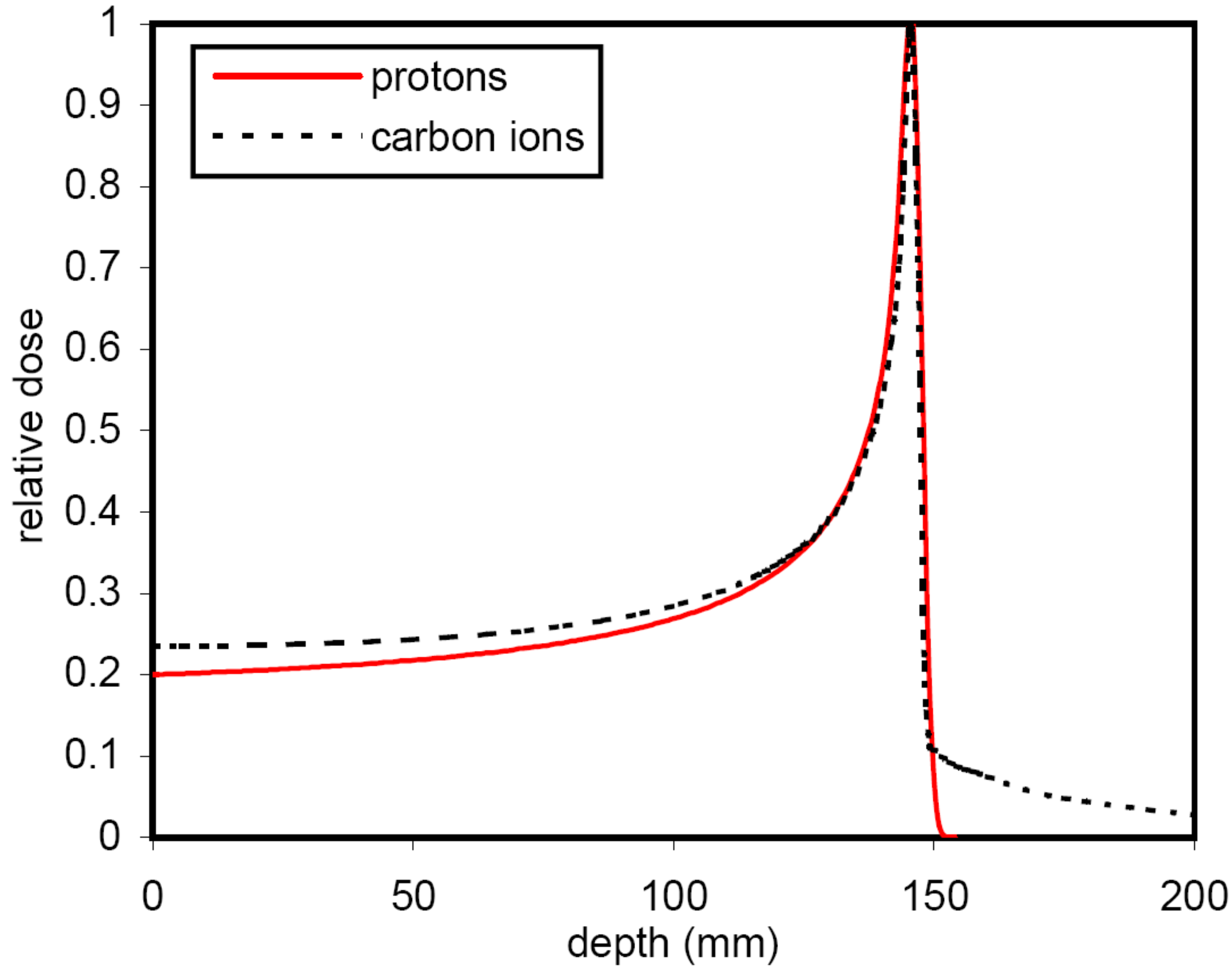


- very similiar plan
- robust against range uncertainties
- ➔ robust optimization

Pflugfelder *et al.* 2008 *PMB* **53**(6)

What is better? Protons or carbon ions?

Depth dose curves for protons and C12 ions



p:

145 MeV

σ_E = 0.3 MeV

C12:

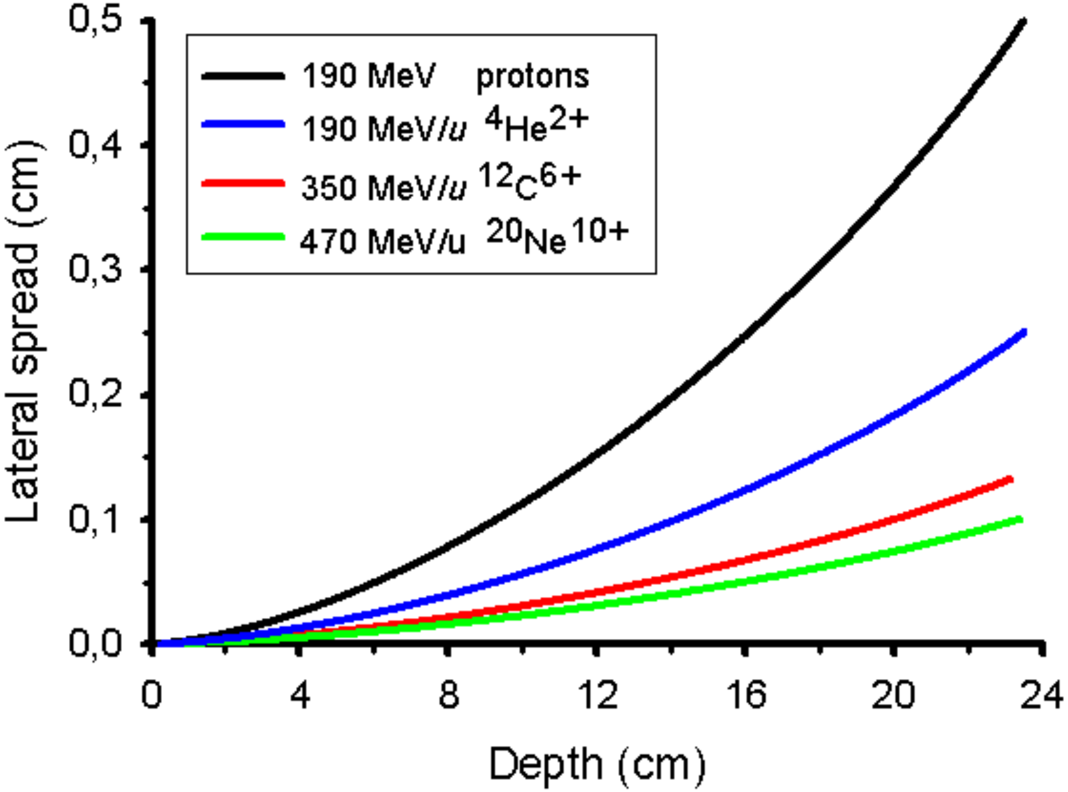
276 MeV/u

ripple filter

light ions: “fragmentation tail”

(secondary particles from nuclear interactions)

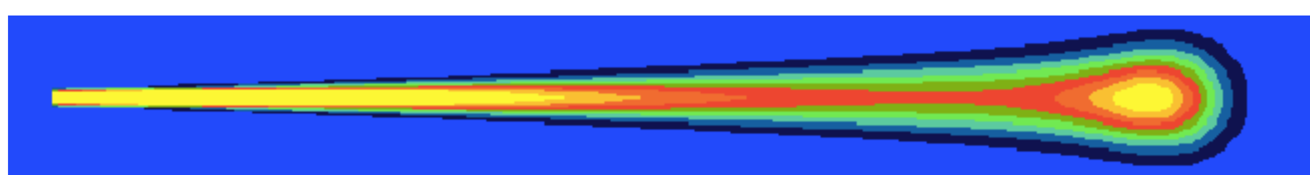
Lateral spread of particle beams



Multiple Coulomb scattering:

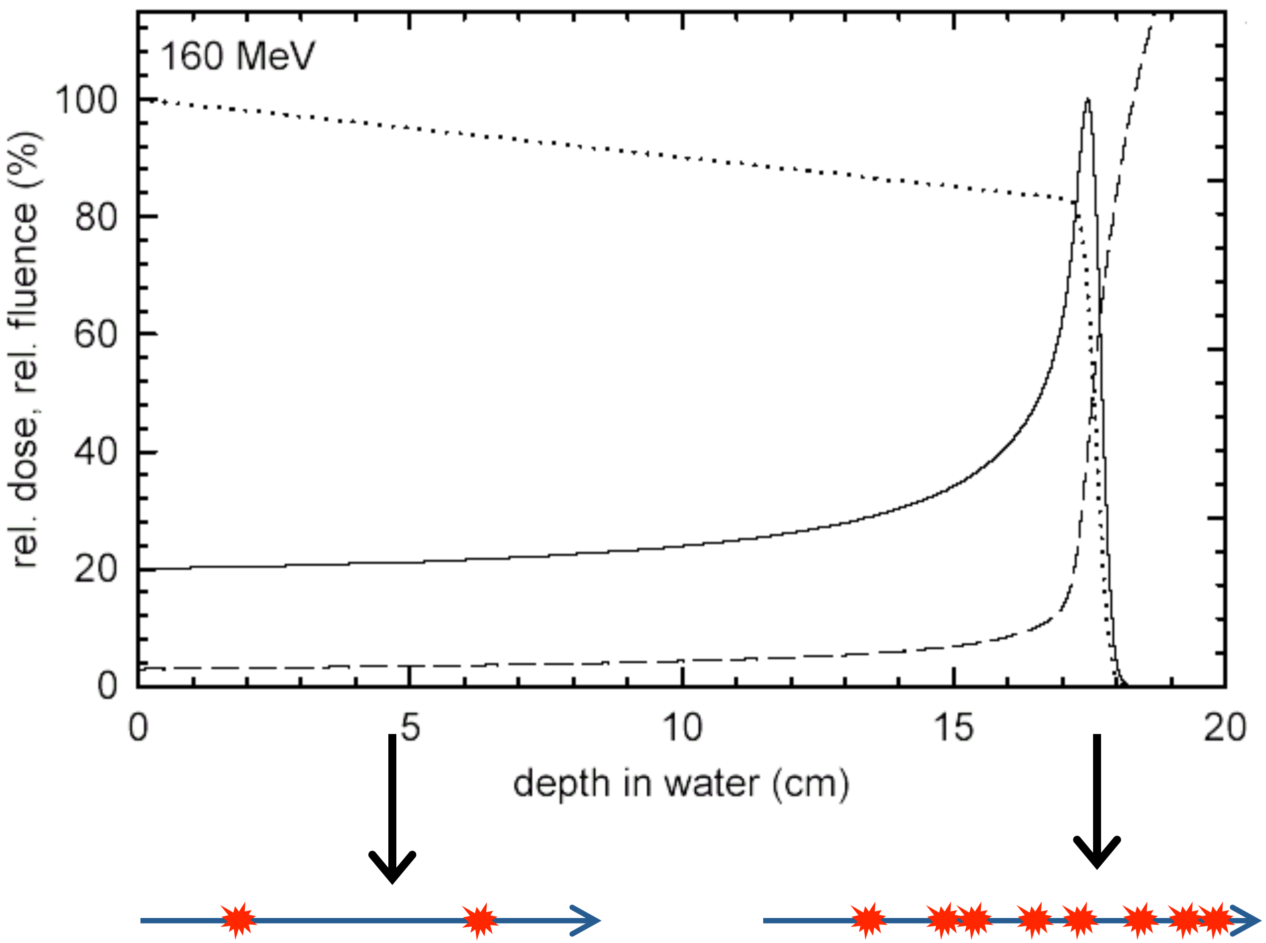
➔ beam gets broader with depth

➔ **potential advantage of carbon ions**



Proton pencil beam in water

Biological **effectiveness**

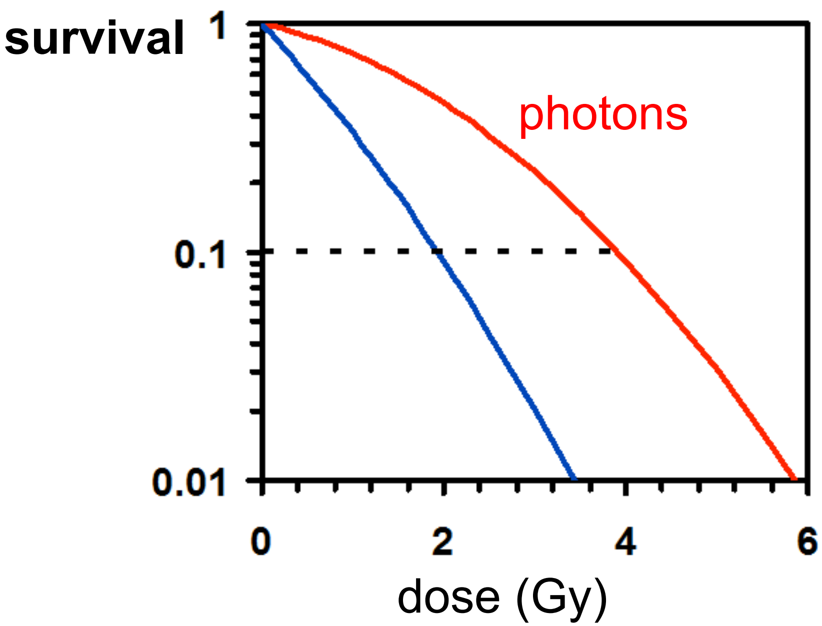


low LET

high LET

biologically more effective

The relative biological effectiveness



Definition of the RBE:

$$RBE = \frac{D_{photon}}{D_{hadron}}$$

for the same biological effect

The RBE depends on:

- particle type (p, ^{12}C, …), dose, LET, loc. energy spectrum
- tissue type, biological endpoint

RBE(proton) ≈ 1.1

RBE(carbon ion) ≈ 2 … 5

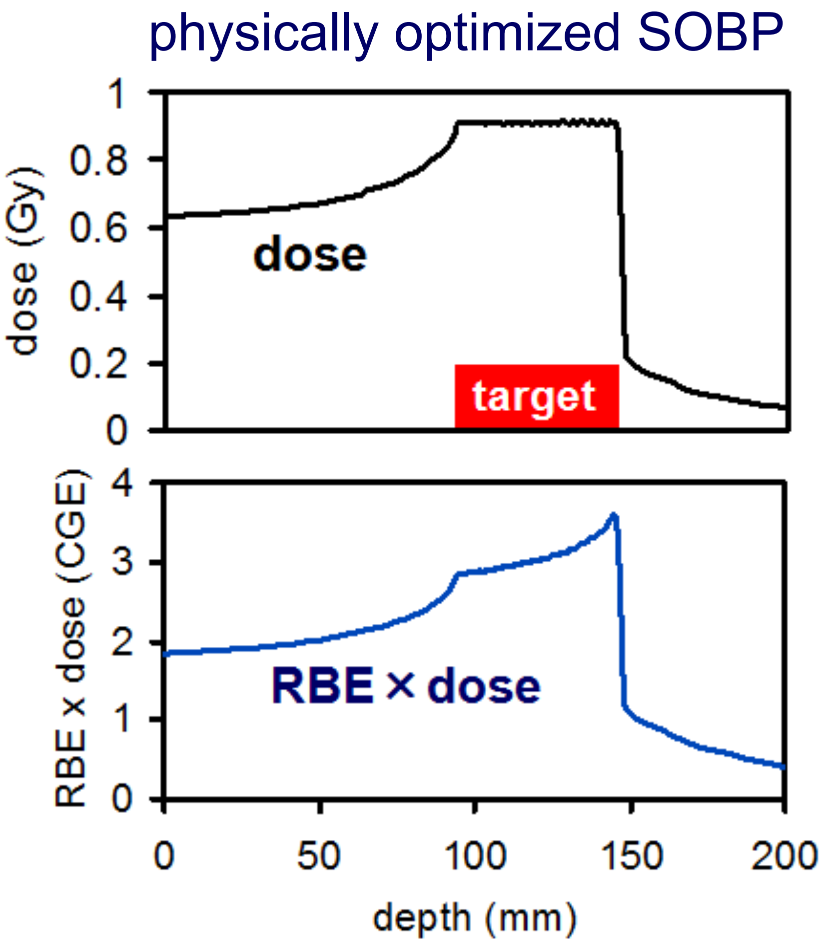
RBE-weighted absorbed dose

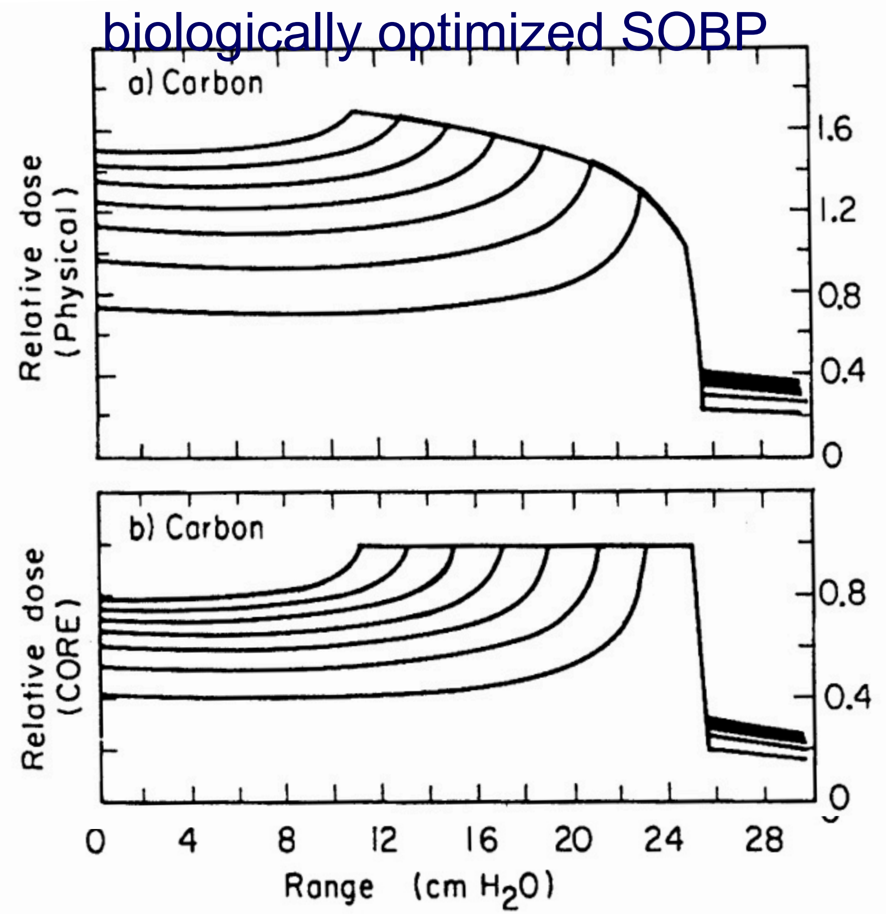
- Knowledge of the RBE is required
  - for dose prescription
  - for comparison with photon plans
  - to transfer clinical experience

- "RBE-weighted absorbed dose" = RBE(x,y,z) × dose(x,y,z)
  - units: Gy(RBE) [ICRU] (formerly: GyE or CGE)

  - hypothetical (!) photon dose distribution
    with the same biological effect

Biological optimization for carbon ions





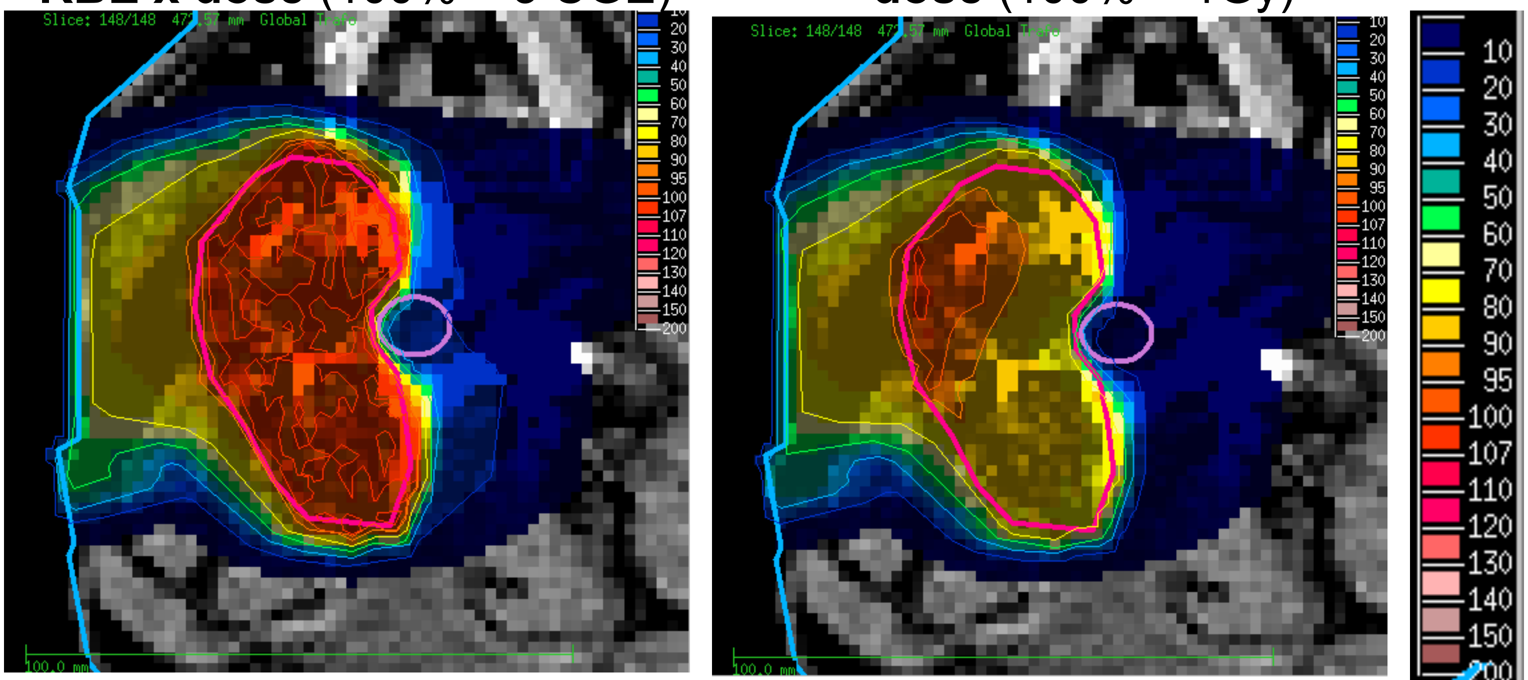
→ optimize RBE×dose instead of the dose

Chen *et al.* 1979 *IJROBP* **5**(10) 1809-19

Example: carbon ion planning

Single field plan

RBE x dose (100% = 3 CGE) **dose** (100% = 1Gy)



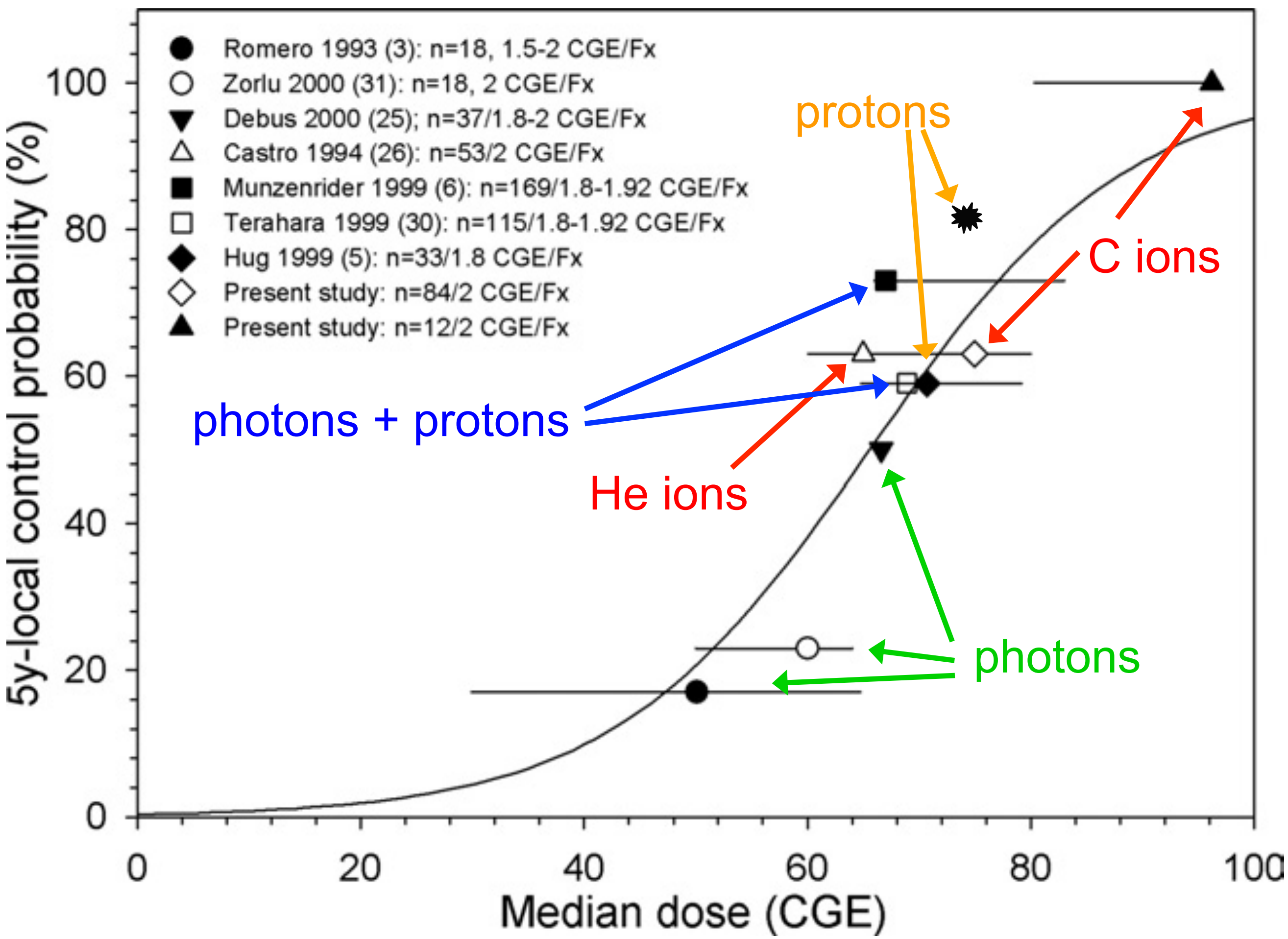
(RBE for chordoma cells)

Wilkens *et al.* 2006 *PMB* **51** 3127

Problem: large uncertainties in clinical RBE values!

- difficult to validate

Clinical experience for skull-base chordomas



Schulz-Ertner *et al.* 2007
IJROBP **68**(2) 449-457

Summary

Advantages of proton / ion beams in radiotherapy

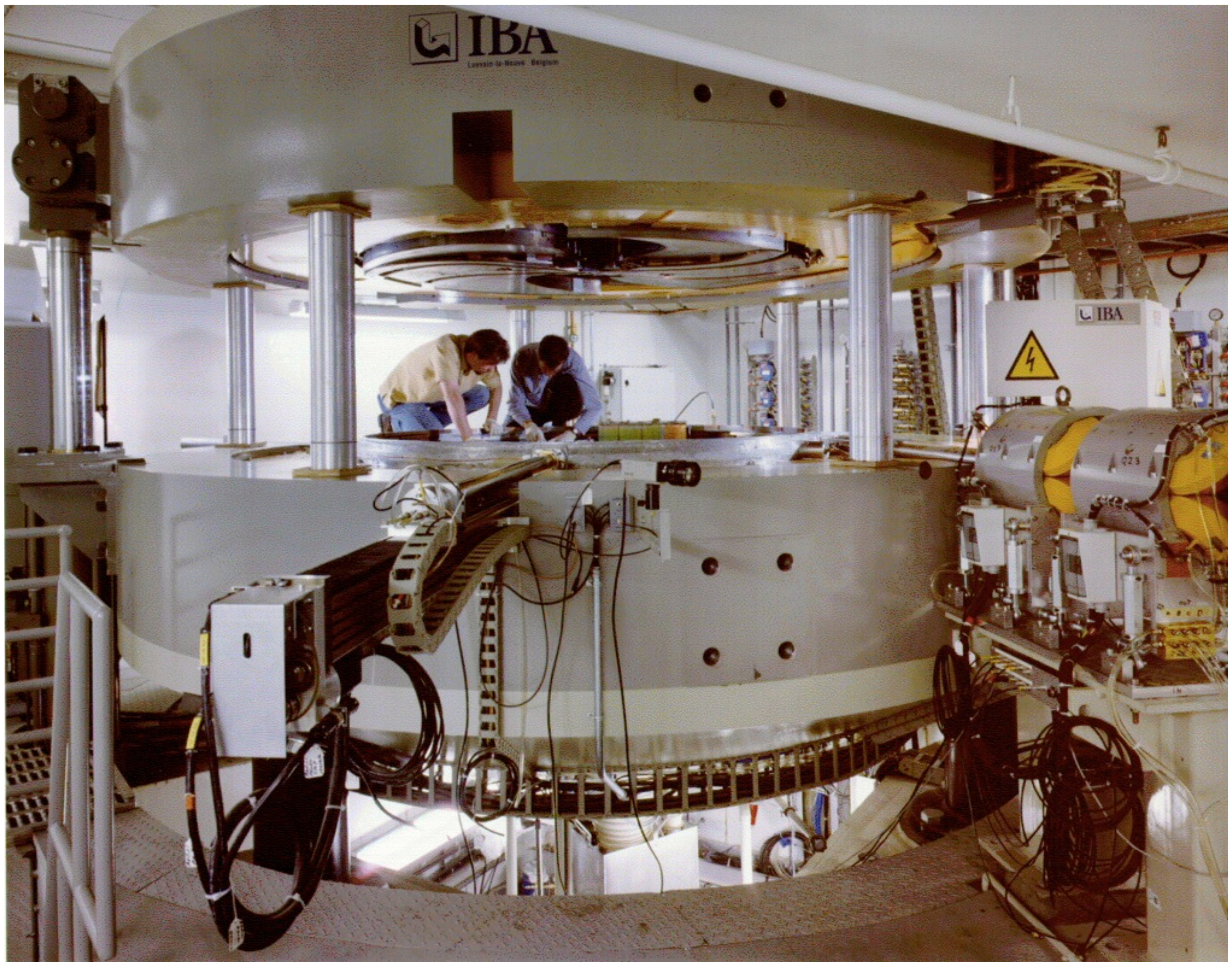
- improved sparing of normal tissue (or higher dose to target)
- potential RBE advantage for carbon ions

Risks / uncertainties

- range uncertainties: large effects on dose
- degradation of Bragg peak in inhomogeneous media
- biological uncertainties:
  ~5-10% for protons, ~20-30% for ions?

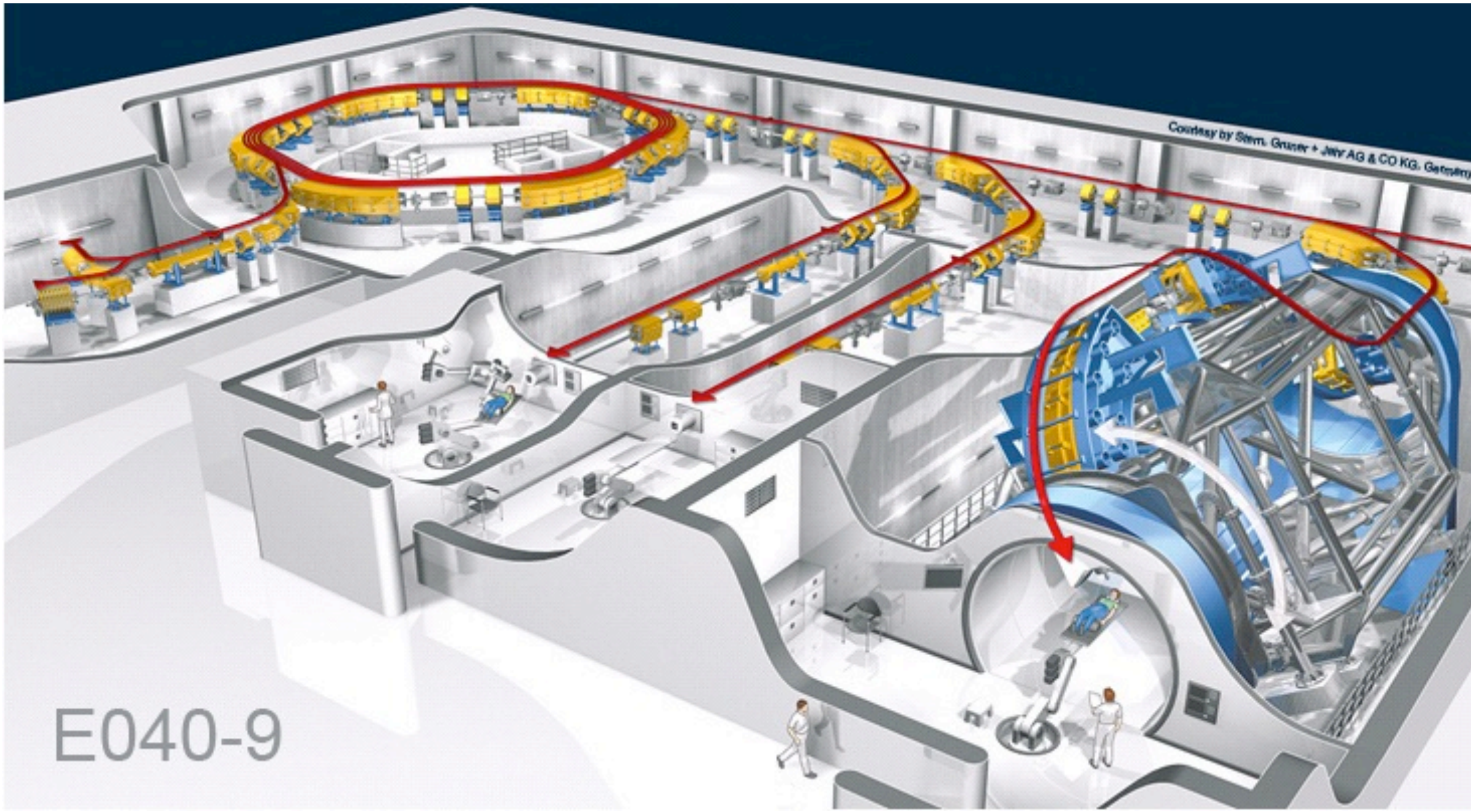
How large is a proton cancer therapy facility?

Cyclotron for protons



Proton cyclotron, Boston (IBA)

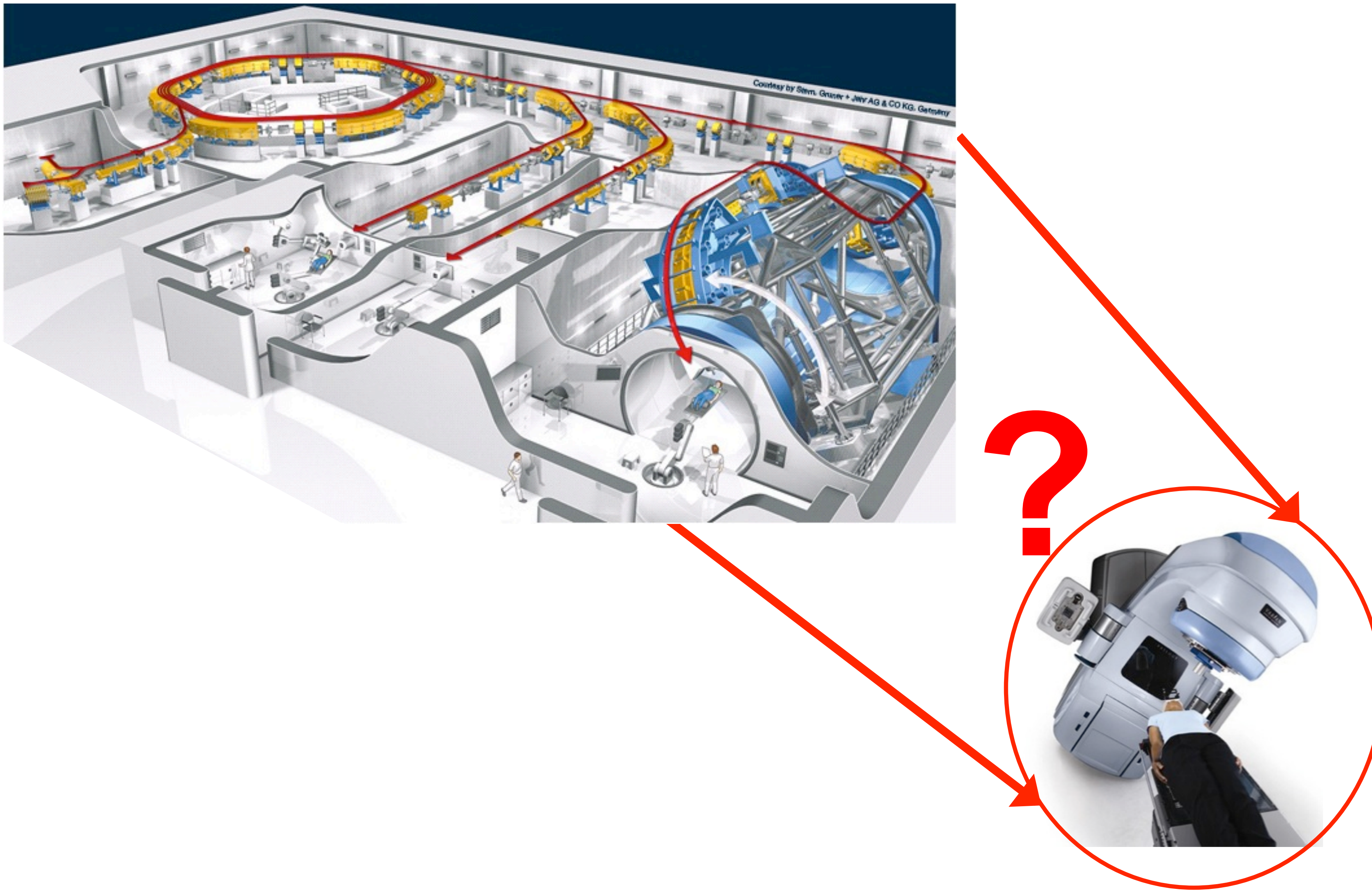
Heidelberg Ion Therapy Centre (HIT)



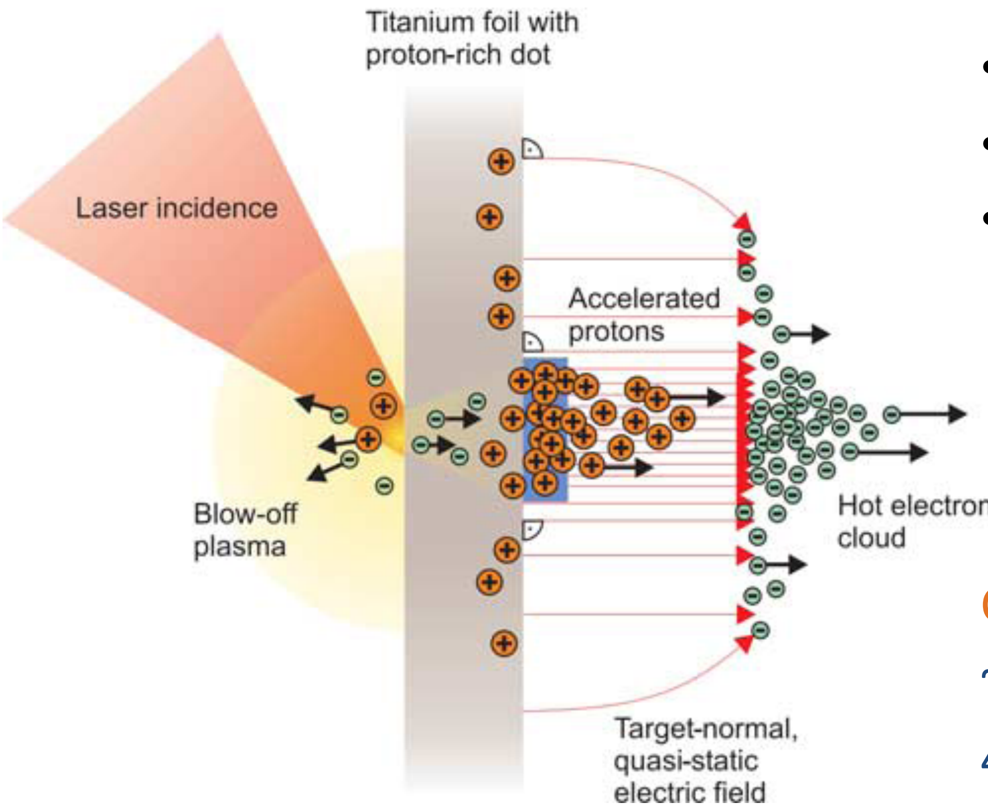
Protons and carbon ions
p: up to 250 MeV
C: up to 430 MeV/u

5000 m²
Gantry: weight ~ **600 t**, size 13 m x 20 m

Can one shrink this huge size?



Laser-Plasma **Ion** Acceleration



- intensity > 10^{19} W/cm^2
- puls length ~ 10-100 fs
- target thickness ~ nm to µm

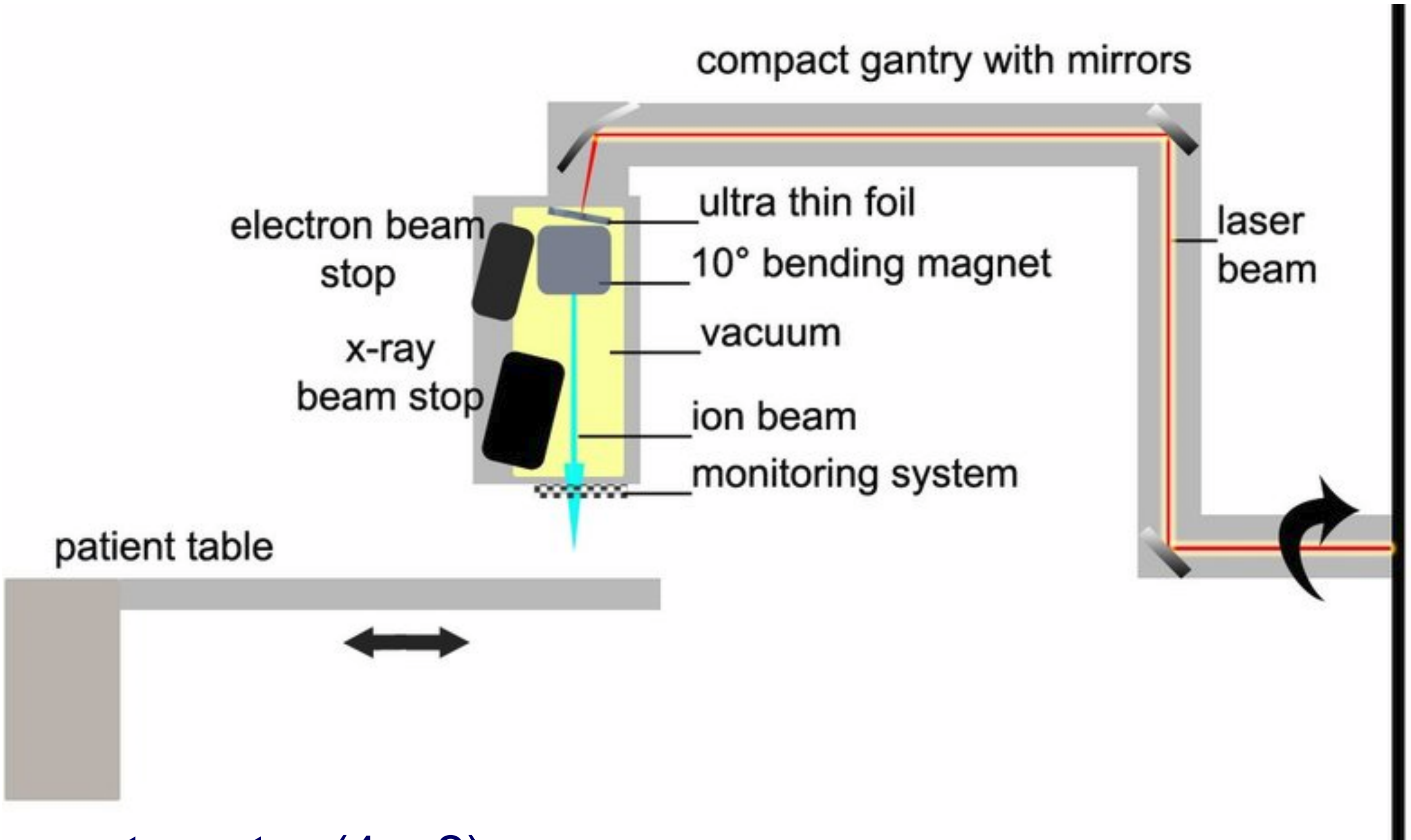
Current world records:

~100 MeV protons

40 MeV/u C ions

Schwoerer *et al.* 2006 *Nature* **439**

Laser-based ion beam radiation therapy?



Compact gantry (4 m?)
Multiple treatment rooms
protons and carbon ions
~500 m²

Assumptions:

- (quasi-)monoenergetic spectrum
- energy and # of particles adjustable by laser parameters