Can particle beam therapy be improved using helium ions?

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Visit http://www.meduniwien.ac.at/hp/radonc/

and many others ......

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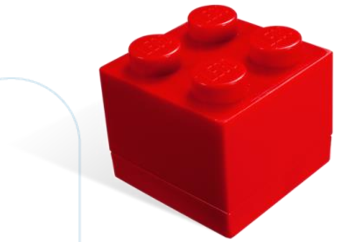
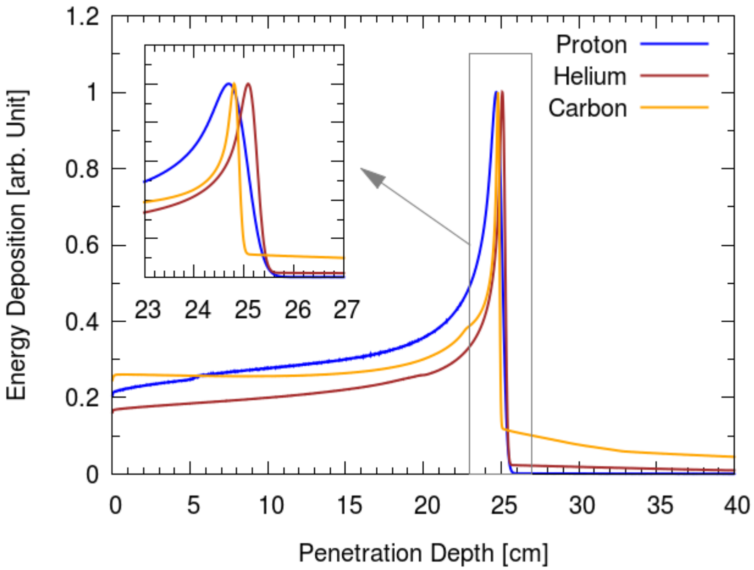
Particles with current clinical applications

- Protons
  - ➔ Light particles
    - Range straggling
    - Beam broadening
    - Simple RBE calculations (low LET)
- Carbon ions
  - ➔ Heavy, composited particles
    - Break up (fragmentation) effects
    - Demanding RBE calculations (high LET)

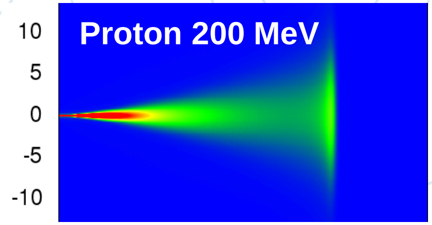


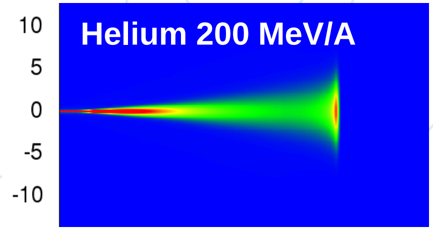
Helium Ions – A promising alternative ?

- Helium Ions
  - ➔ ~50 % of beam broadening compared to p (sharper beam penumbra)[1]
  - ➔ Small fragmentation tail (compared to ^{12}C)
  - ➔ Simple RBE calculations (low LET like p)
- Initial experience at LBNL
  - ➔ More than 2000 patients treated



[1]Ströbele et al (2012) Z Med Phys 22: 170-178





Increasing interest for helium

- 1978 – 1992 patient treatments at LBNL
  - ➔ Long term follow-ups promising
- 2006 new biological data from HIMAC
- RBE – LET comparison of particles
- Start of modelling
  - ➔ Dose calculation models
  - ➔ Biological modelling
- Treatment planning studies
- 2015 – HIT experimental ^{4}He beamline

Raju, Radíol (1972),
Linstad, IJROBP(1990),
Castro, IJROBP (1997)

Kase, RadRes (2006)

Soerensen, ActaOncol(2012),
Burigio, PMB (2015)

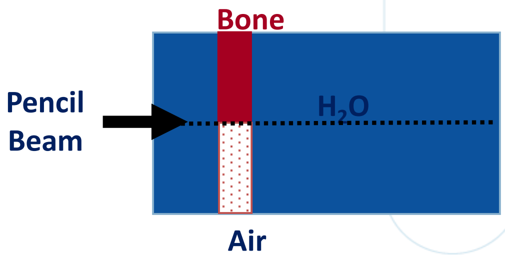
Ströbele, Z Med Phys (2012),
Limandri, Phys Rev E Stat Nonlin Soft Matter Phys (2014)

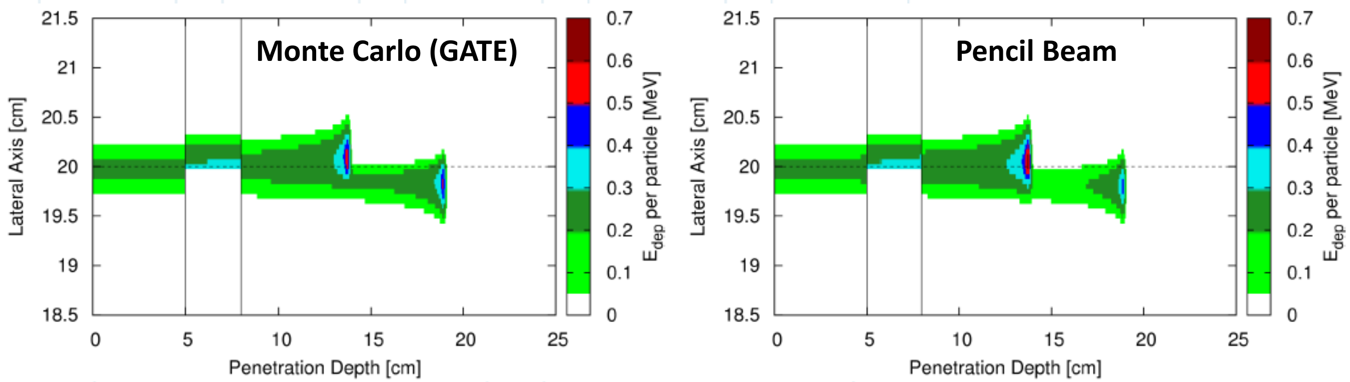
Villagrasa, Radiat Prot Dosimetry(2014),
Fuchs, MedPhys (2015),
Mairani, PMB (2016)

Grün, MedPhys (2015),
Knäusl, Acta Oncol (in print)

^{4}He-Ion PB dose calculation algorithm

- Main pencil beam (PB) characteristics:
  - ➔ Longitudinal dose deposition: LUT for water (water equivalent depth scaling)
  - ➔ Lateral dose deposition: Gaussian broadening for multiple scattering & correction for nuclear interactions using Voigt-function
- Development and successful validation using MC simulations





- ➔ γ - Index criteria of 2%/2mm fulfilled

[2] Fuchs et al (2012)MedPhys 39: 6726-6737

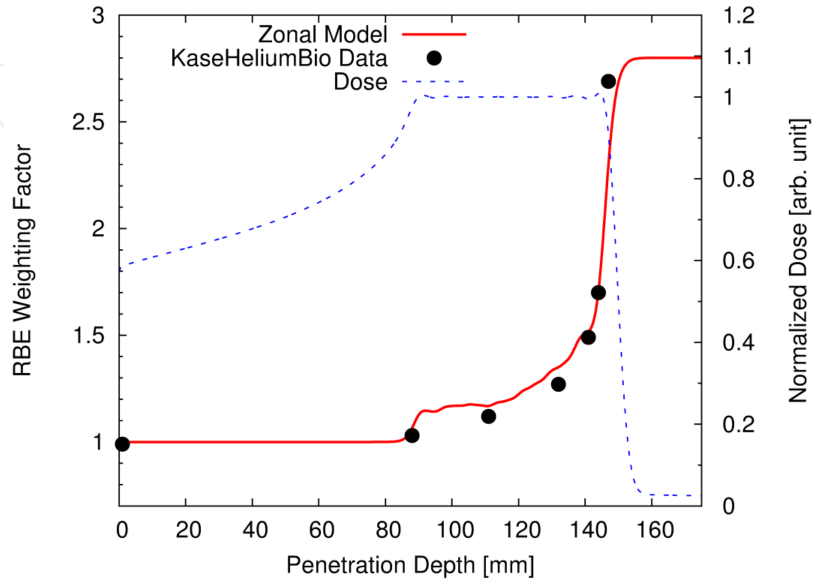
^{4}He-Ion PB dose calculation algorithm II

Fuchs et al (2015)MedPhys 42: 5157-5166

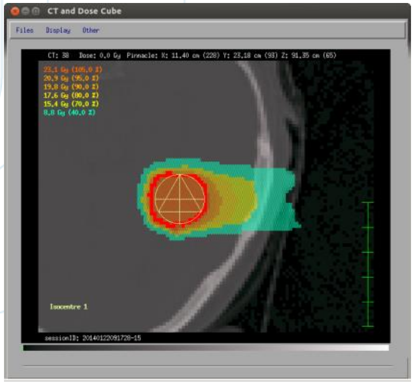
- Biological modeling employing ‚zonal‘ model
  - ➔ RBE ranging from 1.0 to 2.7
  - ➔ Data from (historical) literature and LET taken into account

    (e.g. Raju et al (1971) ActaOncol 10: 353-357

    Kase et al (2006) RadRes 166: 629-638)

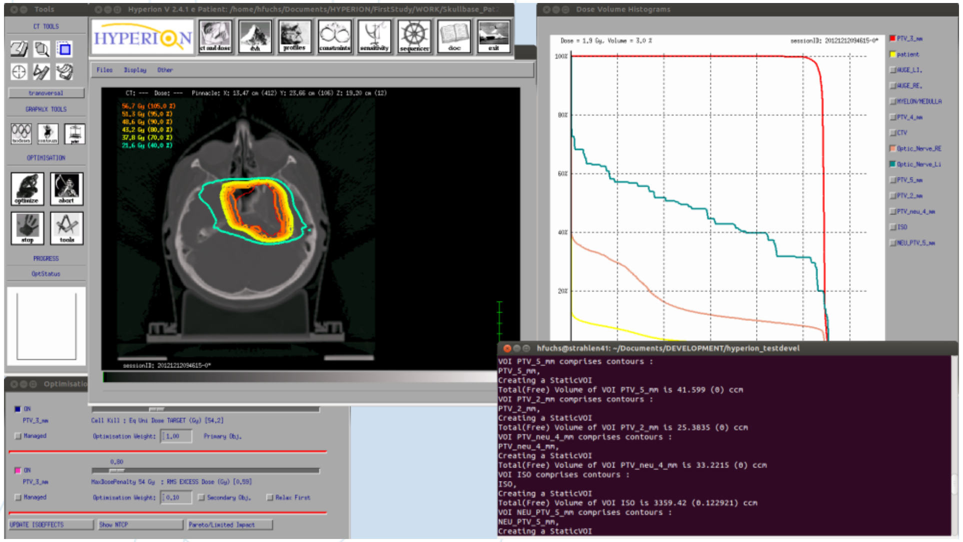


- Implemented into customized development version of the TPS Hyperion



Treatment planning study

- Expectations:
  - ➔ Sharper dose fall off
  - ➔ Lower dose to surrounding tissue
- Treatment planning study
  - ➔ New biological model
    - Protons (RBE 1.0 - 1.6)
    - Helium (RBE 1.0 - 2.7)
- Who would benefit most?
  - ➔ Paediatric patients



Patient collective

- Neuroblastoma patients (NB) (11 patients, 21.0 Gy(RBE)) &

  Wilms tumour patients (WT) (4 patients, 14.4 Gy(RBE) + 10.8 Gy(RBE))

  → CTV: preoperative GTV and areas of local lymph node enlargement

  (+ Boost on macroscopic tumor remainder after surgery for WT)

- Hodgkin Lymphoma patients (HL) (9 patients, 19.8 Gy(RBE))

  → CTV: involved lymph nodes at diagnosis adapted to post-ChT anatomy

- Ependymoma (EP) (5 patients, 54 Gy(RBE))

  → CTV: tumour bed and macroscopic residual tumour

- Ewing sarcoma (EW) (4 patients, 54 Gy(RBE) or 36 + 18 Gy(RBE))

  → CTV: tumour extent at diagnosis + 2cm margin

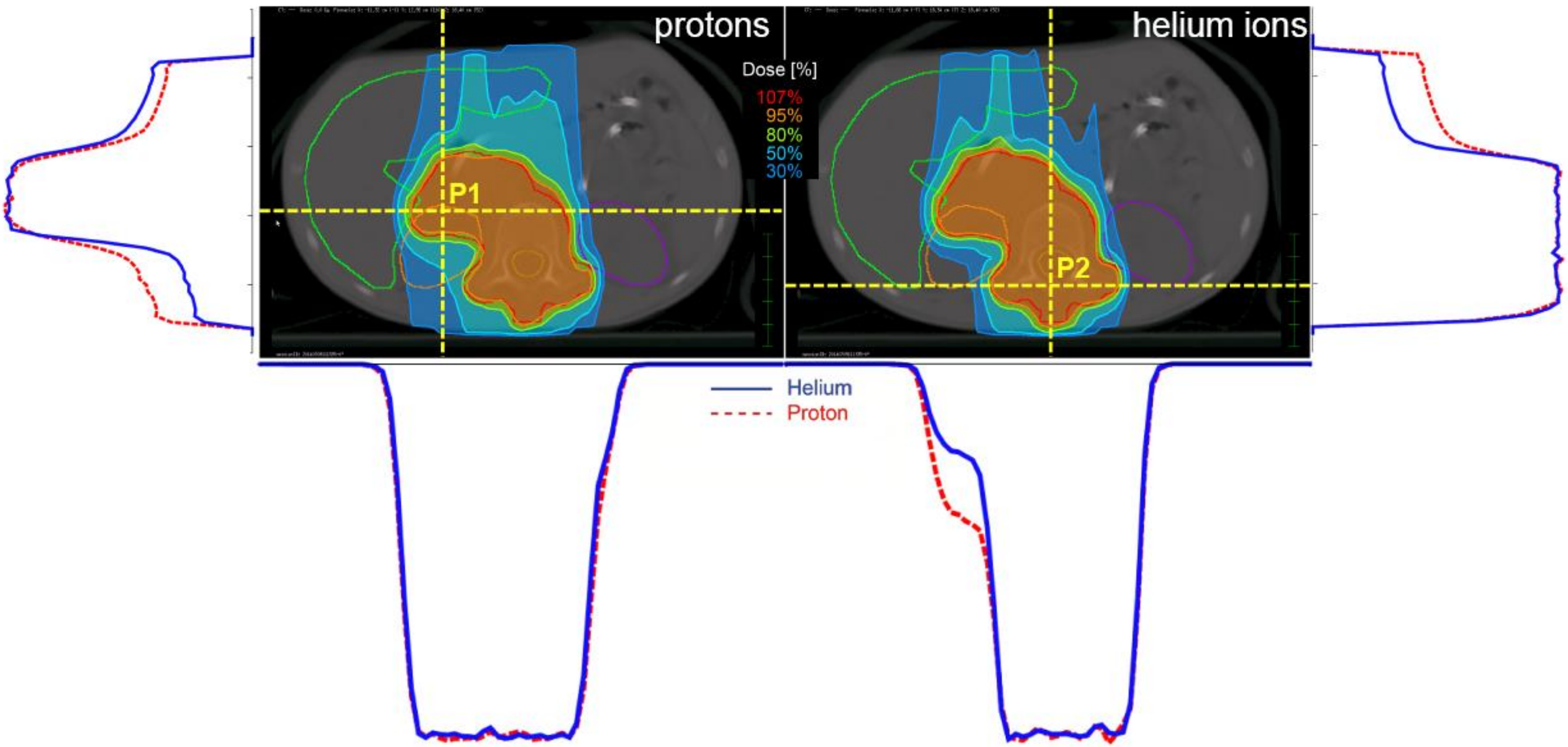
Volumina & treatment planning

- Rather large target volumes

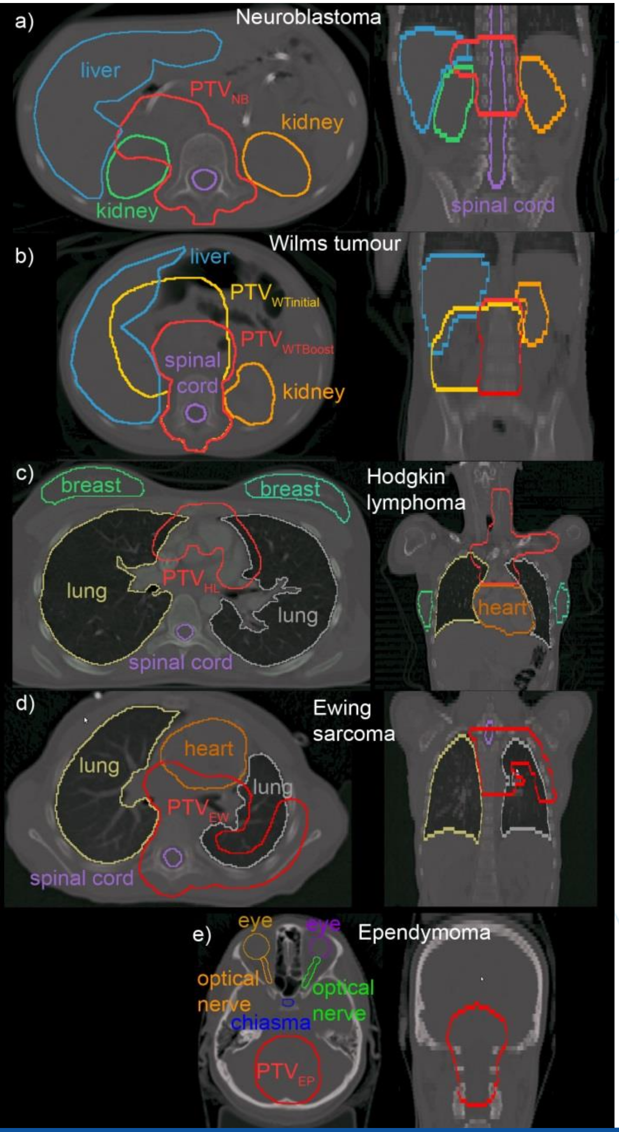
Indication	Median PTV volume ± SD	Range of PTV volume
Neuroblastoma	424 ± 164 ccm	233 – 753 ccm
Hodgin	763 ± 375 ccm	327 – 1497 ccm
Wilms	468 ± 115 ccm	297 – 580 ccm
Ependymoma	625 ± 279 ccm	375 – 1015 ccm
Ewing sarcoma	223 ± 46 ccm	174 - 279 ccm

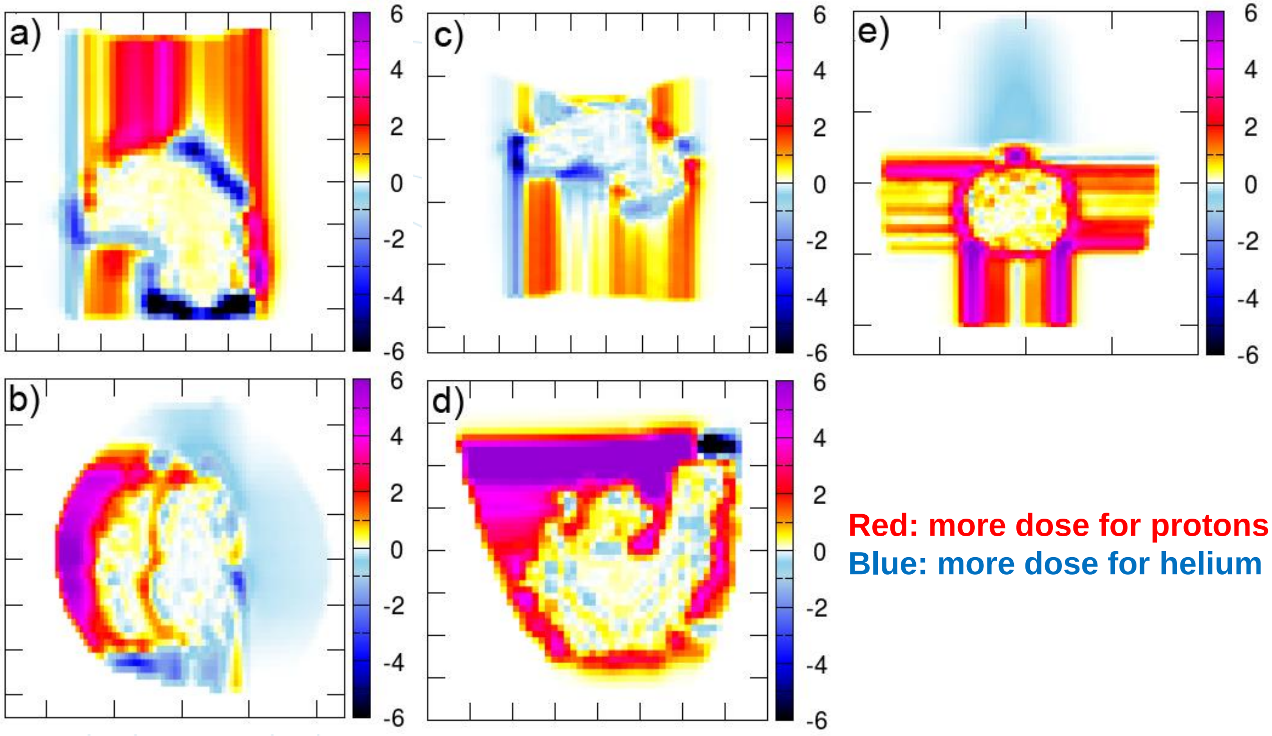
- Treatment planning using development version of hyperion
  - ➔ 1-3 beams from anterior-posterior (or lateral direction)
  - ➔ PTV: CTV + 0.8-1.5 cm + Vertebral body (5 mm margin) under 14 y

Representative Neuroblastoma patient



Dose Difference Maps



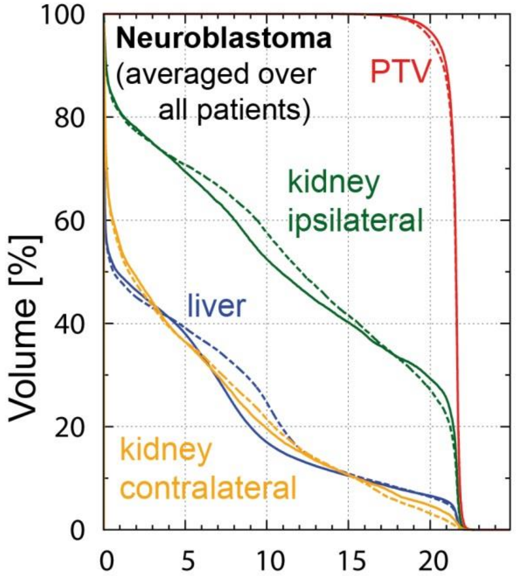


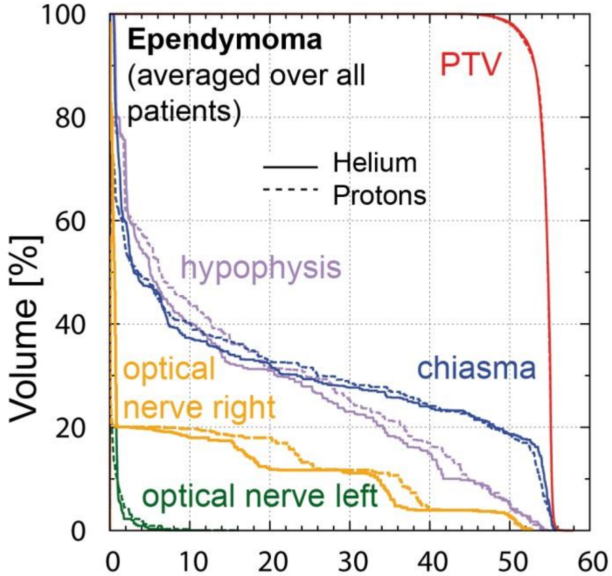
Red: more dose for protons

Blue: more dose for helium

- Direct comparison shows benefits for helium ions

Averaged DVHs





Neuroblastoma	Protons	Helium
PTV (V95%) [%]	95.4 (95.1-96.0)	96.9 (95.2-98.0) *
Body $V_{2\%}$ [%]	32.9 (19.7-49.3)	32.2 (19.2-47.5)
Body $V_{50\%}$ [%]	18.8 (9.5-31.8)	16.6 (8.4-25.5)
Liver $D_{50\%}$ [Gy(RBE)]	0.1 (0.1-9.9)	0.1 (0.1-8.7)
Kidney ipsi $D_{50\%}$ [Gy(RBE)]	10.4 (0.9-21.5)	7.7 (0.6-21.5) *
Kidney contra $D_{50\%}$ [Gy(RBE)]	1.0 (0.2-10.1)	1.0 (0.1-7.7) *
Conformity (ideal = 1) [3]	90.1 (86.7-91.5) *	89.2 (73.5-91.3)

Ependymoma	Protons	Helium
PTV (V95%) [%]	96.0 (95.3-97.1)	95.8 (95.2-98.3)
Body $V_{2\%}$ [%]	22.4 (12.4-31.6)	21.9 (12.0-31.5)
Body $V_{50\%}$ [%]	6.1 (4.5-8.8)	5.8 (4.2-8.7)
Chiasma $D_{50\%}$ [Gy(RBE)]	1.6 (0.1-53.7)	2.3 (0.6-54.3)
Hypophysis $D_{50\%}$ [Gy(RBE)]	8.3 (0.1-44.2)	6.6 (0.7-41.3)
Conformity (ideal = 1) [3]	80.7 (73.4-81.6)	78.4 (75.9-83.0)

[3] *Paddick I (2000) J Neurosurg*

Results

+ Improved PTV coverage & slightly lower doses for all OARs using ^{4}He
+ Smaller volumes receiving low dose regions using ^{4}He

- For large tumor volumes nearly identical dose distribution
- Benefits dependent on indication

- Only some differences significant – bigger patient cohort
- Dosimetric differences smaller than expected

  → Conservative approach (beam data, biology …)

Realisation potential

- Synchrotron based facilites can handle Helium ions
  - ➔ New ion source required
  - ➔ Retuning of beamline and magnets
- Gantries
  - ➔ In theory possible
  - ➔ Existing gantries:
    250 MeV proton ~ 125 MeV/u ^{4}He
  - ➔ Required energies: 121 - 228 MeV
- IGRT
  - ➔ Sharper dose fall off makes image guidance more essential

Future Steps – almost there

- Technical side
  - ➔ Gantry development
    - Higher magnetic fields compared to protons
  - ➔ Accelerator development
    - Laser acceleration, cyclotrons..
- Application side
  - ➔ Biological and physical experiments to fine tune models
  - ➔ Treatment planning studies
    - More indications, bigger cohorts

Thanks for your attention!