CANDIDATE THERAPEUTIC IONS:
a physics account

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overview

Monte Carlo simulation setup

a sample history

energy deposition & energy balance

fluence

escapes

treatment monitoring

rare interactions

energy deposition →

- senescence
- necrosis
- apoptosis
- mutation
- chromosome damage
- mitotic catastrophe
- genetic instability
- cell repair?

the scope of this work

A PHYSICS ACCOUNT

applicable to

present and future

radiobiological models

this work is not about selecting the best ion

but to provide a physics resume

probably no single ion is The Best, a mix is our best bet

→ Brahme 2010 Plans for Ion Radiation Therapy at Karolinska Institute and University Hospital
4th Japanese-European Joint Symp on Ion Cancer Therapy

simulation setup: the beam

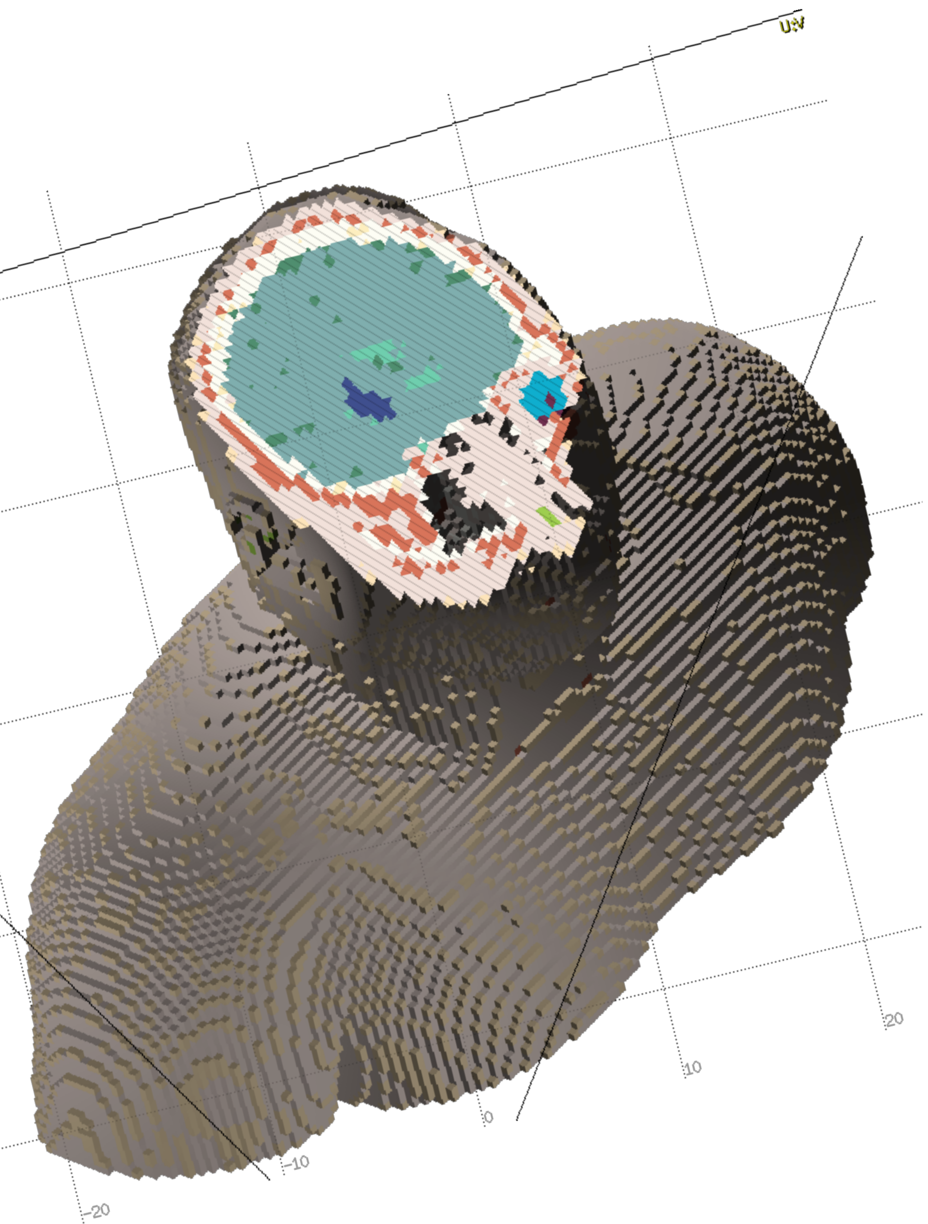
	MeV/u
proton	104.8 ~ 107.8
^{4}He	418.0 ~ 429.8
^{7}Li	120.4 ~ 123.8
^{9}Be	144.9 ~ 149.0
^{10}B	176.2 ~ 181.2
^{12}C	196.0 ~ 202.0
^{16}O	232.0 ~ 239.0
^{20}Ne	266.0 ~ 273.0

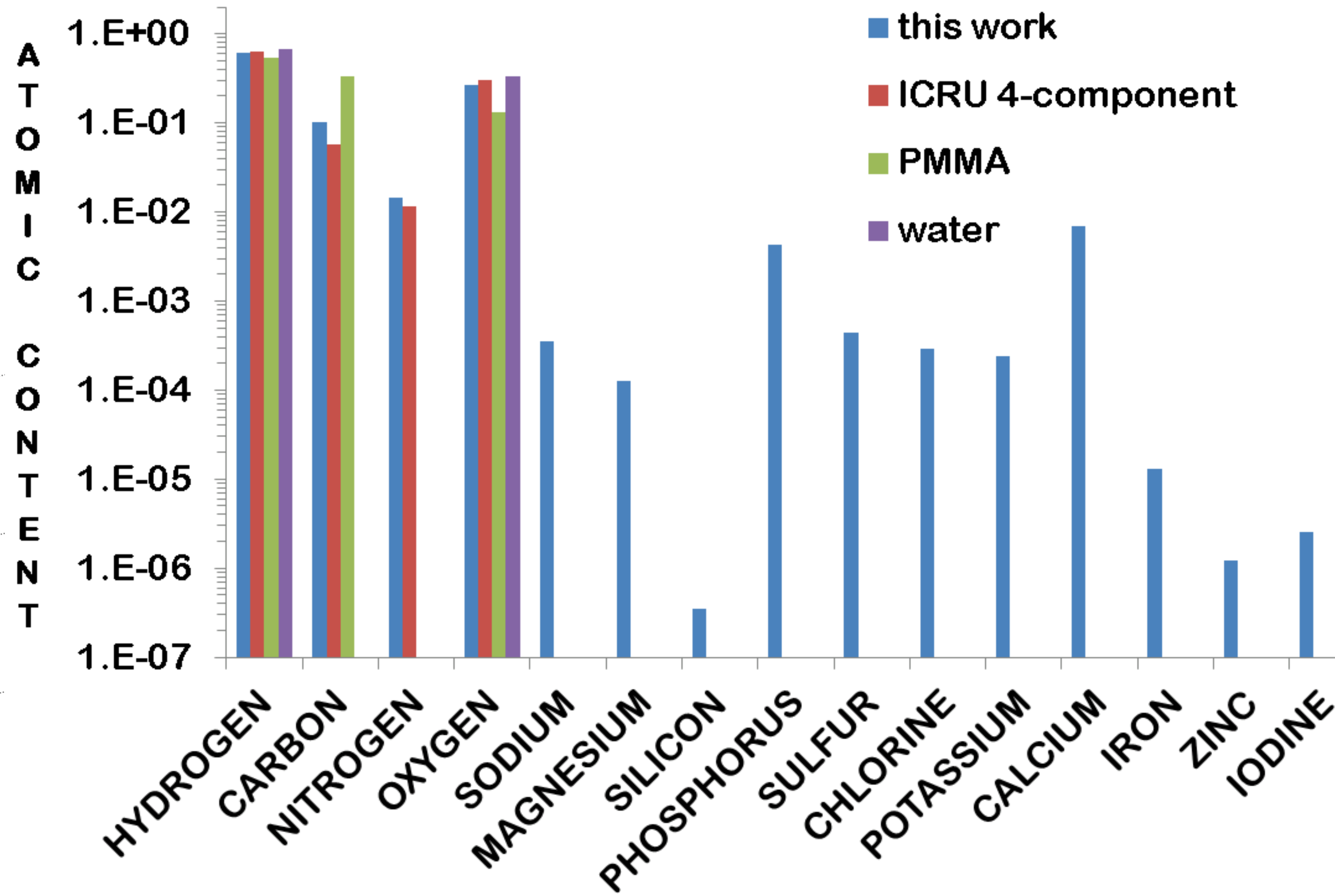
energies chosen to form a hypothetical SOBP at 8.0 to 8.4 cm depth, filling a voxel

so that dose profiles may be normalised for sensible inter-ion comparison without restricting the analysis to a specific clinical target dimension

Monte Carlo code:
FLUKA version 2012

simulation setup: the phantom

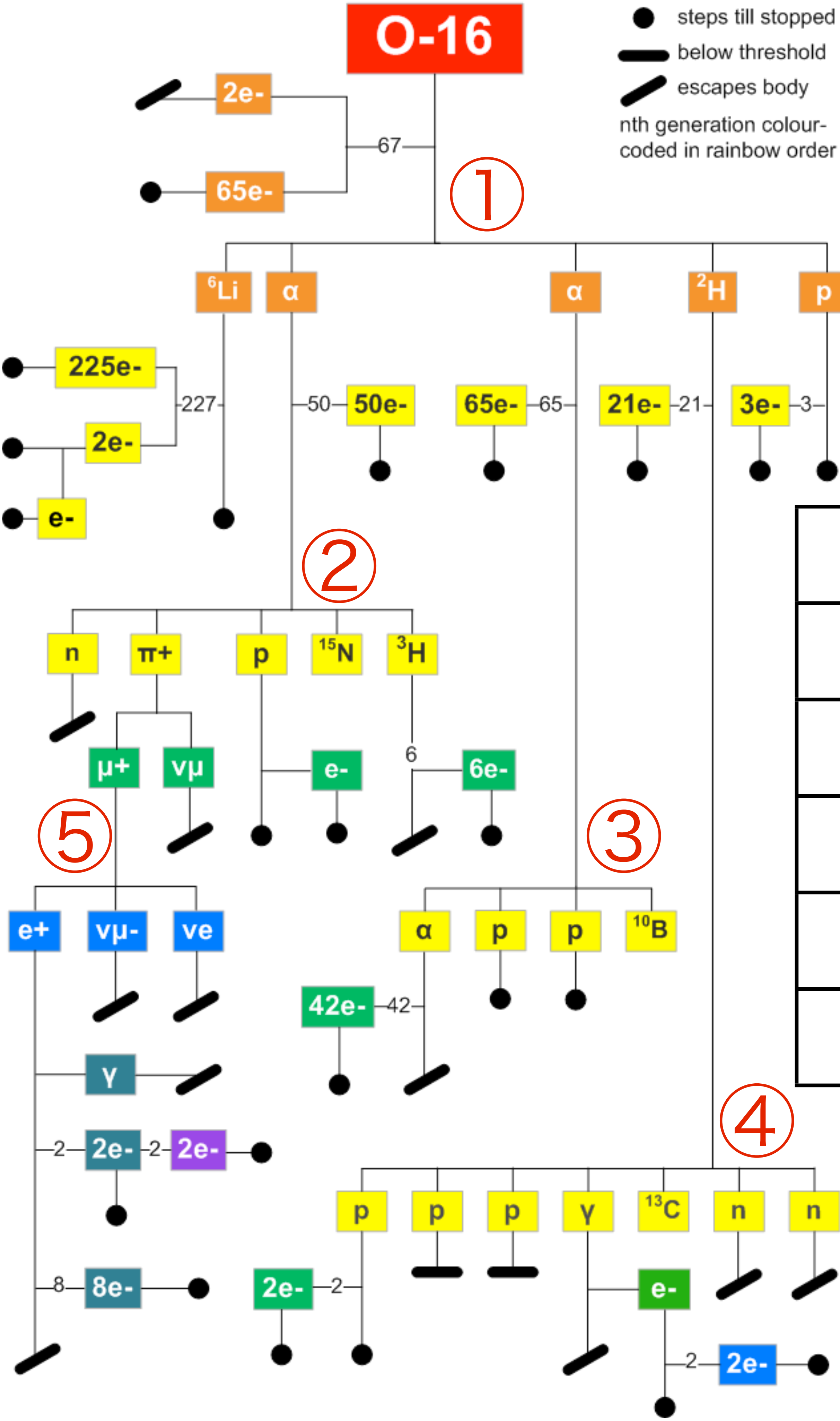




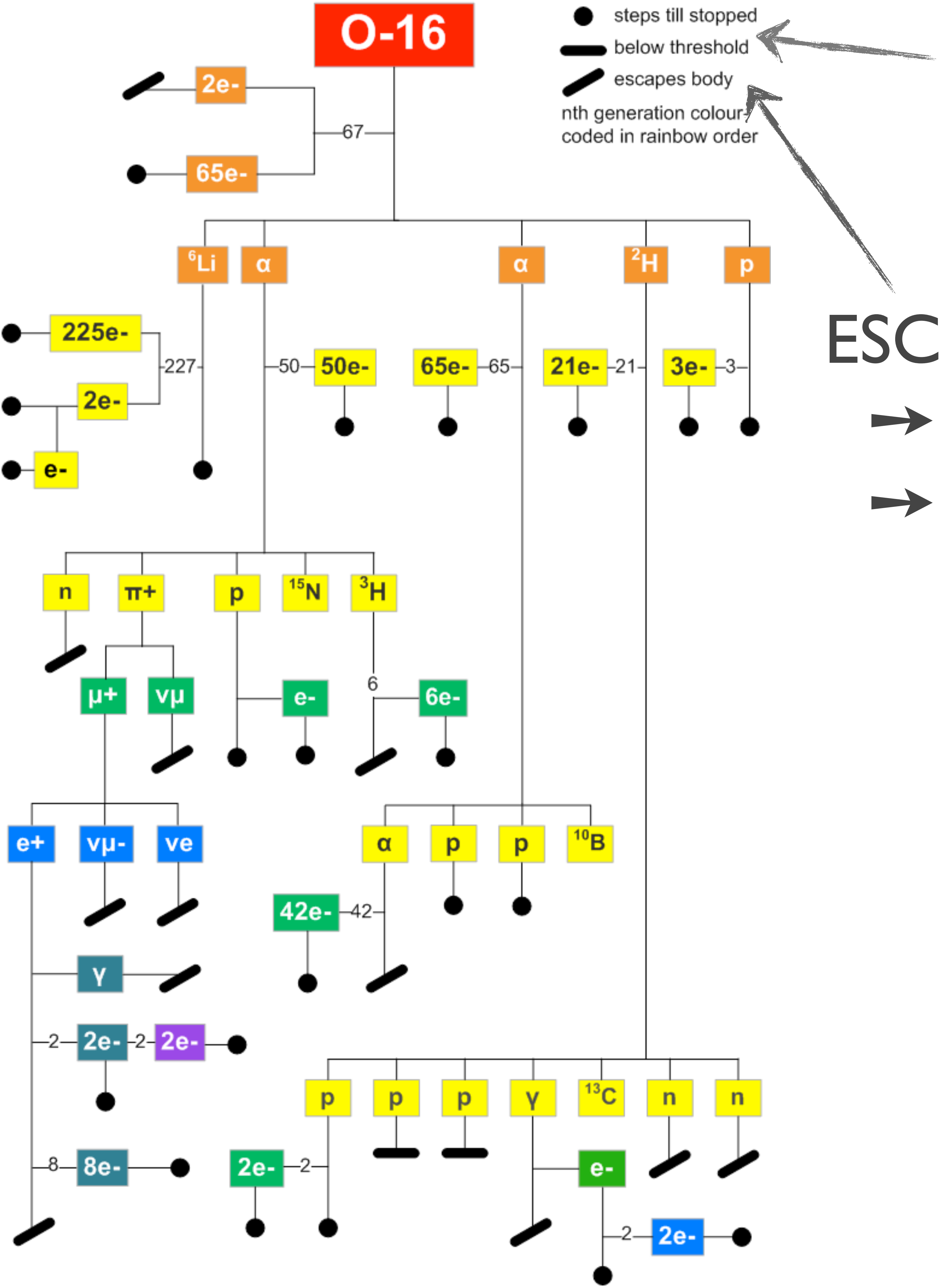
VIP-Man anthropomorphic voxel phantom segmented into 62 tissue types by George Xu *et al* [Health Physics 78(5) 2000]

Tissue type in each voxel was converted to density and elemental composition according to ICRP-89 and ICRU-44

^{16}O THERAPY: A SAMPLE HISTORY FROM FLUKA



	ns	MeV	local target
①	0.800	3027	H, muscle
②	1.15	747	O, caudate nucleus
③	1.32	463	C, white matter
④	1.43	387	O, white matter
⑤	827	0.00	O, caudate nucleus



ENERGY DEPOSITION

→ treatment planning

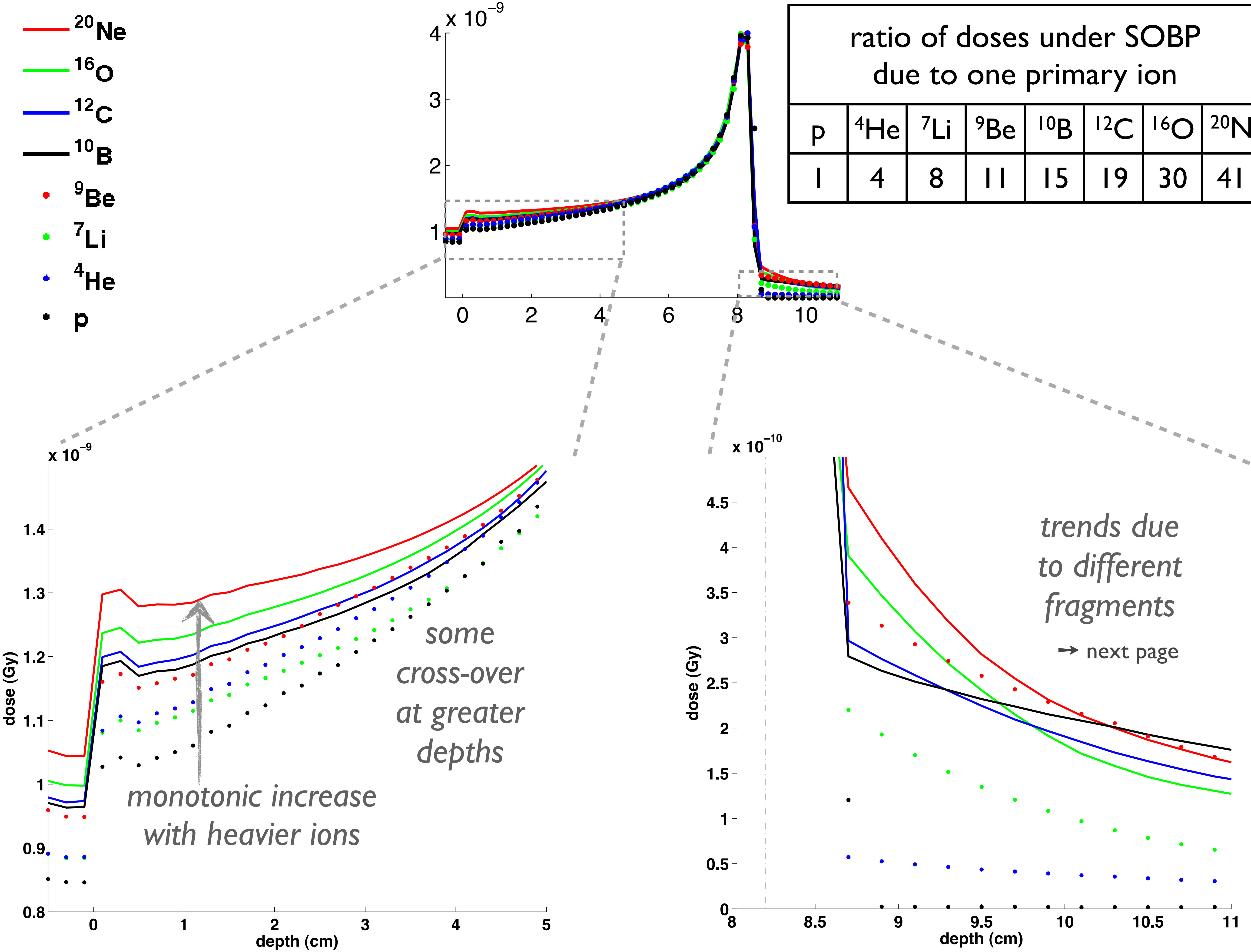
ESCAPES

→ treatment monitoring

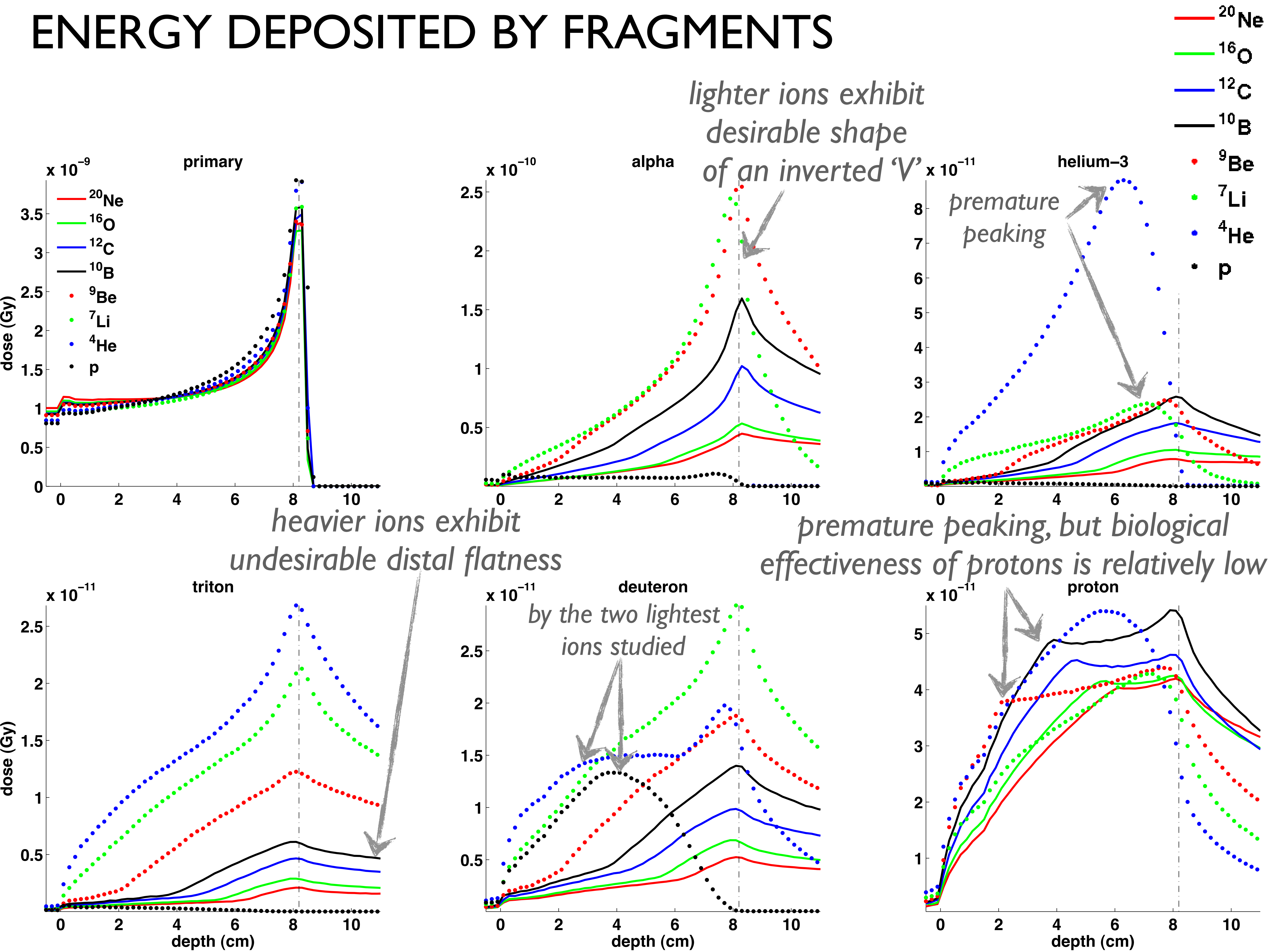
→ radiation protection & shielding

ratio of doses under SOBP due to one primary ion

p	^{4}He	^{7}Li	^{9}Be	^{10}B	^{12}C	^{16}O	^{20}N
1	4	8	11	15	19	30	41



ENERGY DEPOSITED BY FRAGMENTS



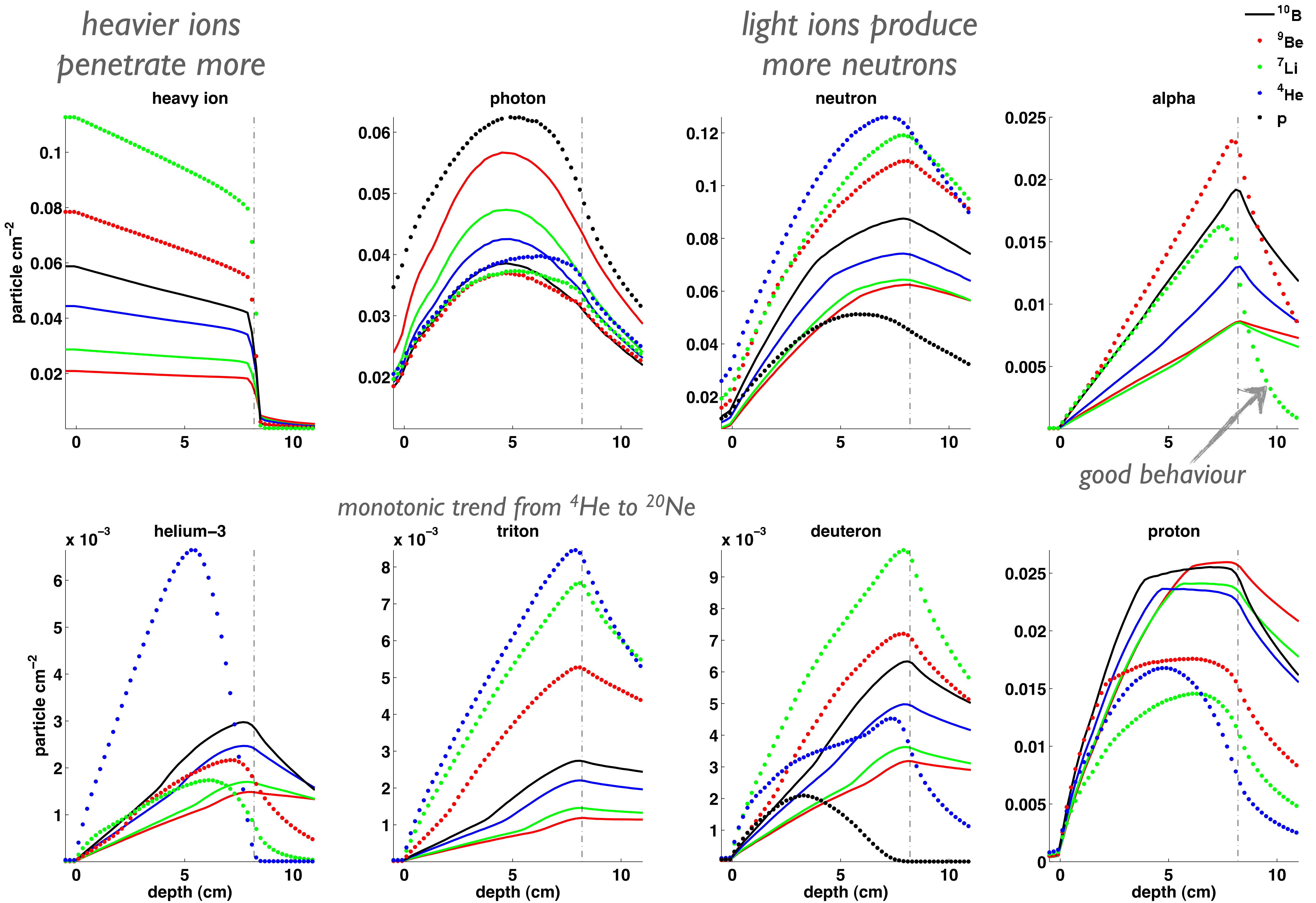
TOTAL ENERGY DEPOSITED PER BEAM KINETIC ENERGY

p	^{7}Li	^{12}C	^{16}O	^{20}Ne
1	0.96	0.95	0.94	0.92

WHERE WAS THE REMAINING ENERGY SPENT

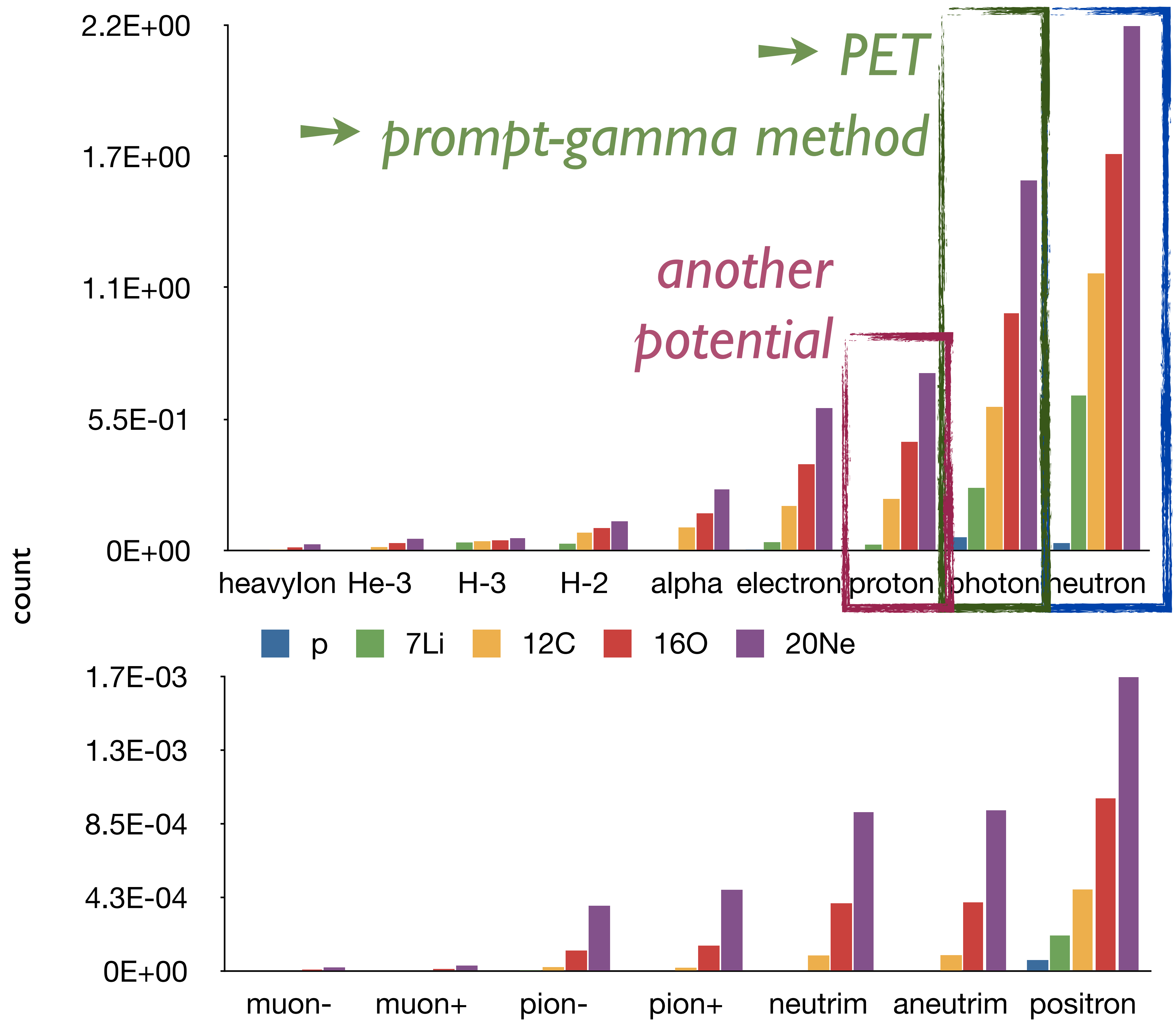
% ENERGY SPENT	p	^{7}Li	^{12}C	^{16}O	^{20}Ne
hadron dE/dx	95.5	91.9	88.7	86.9	84.9
nuclear binding	-1.7	-1.7	-1.4	-1.2	-1.1
escapes	0.7	4.2	6.1	7.5	9.2

FLUENCE normalised to dose in target



ESCAPES normalised to dose in the target for treatment monitoring

major source of noise



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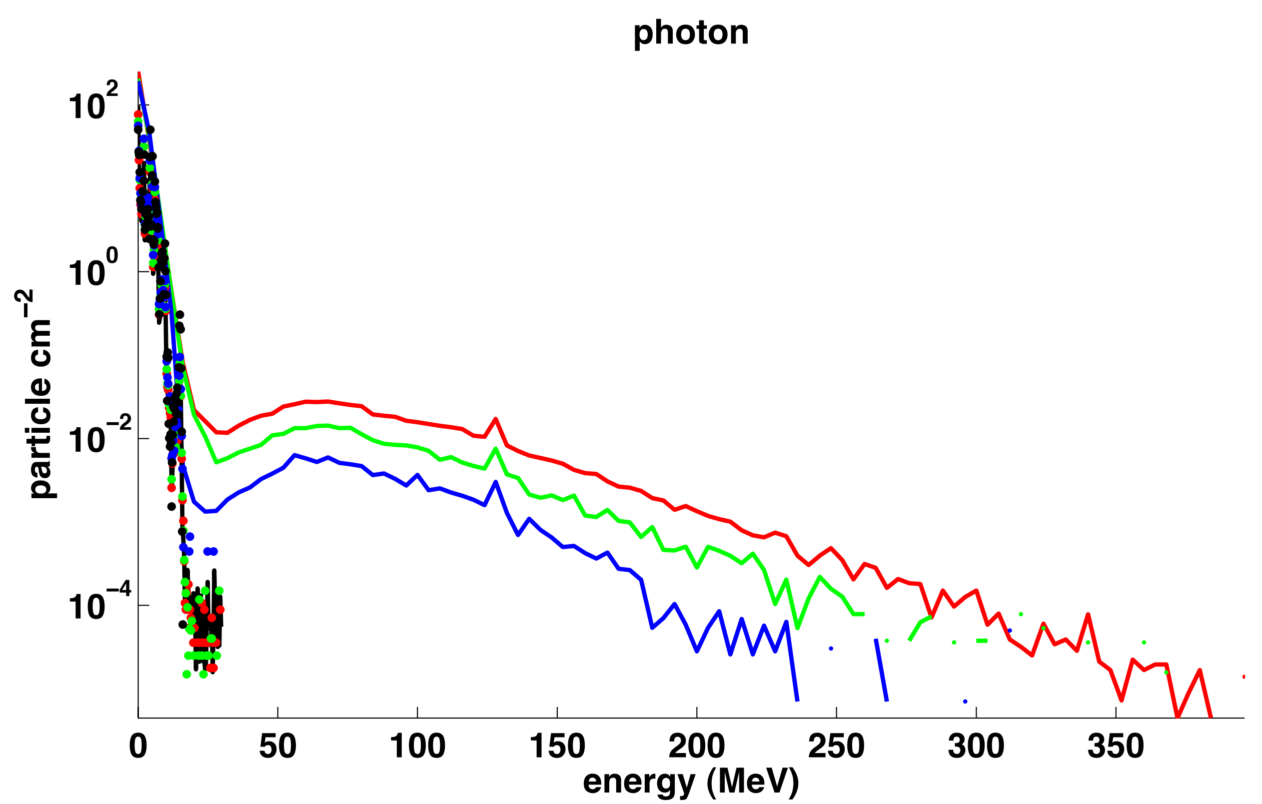
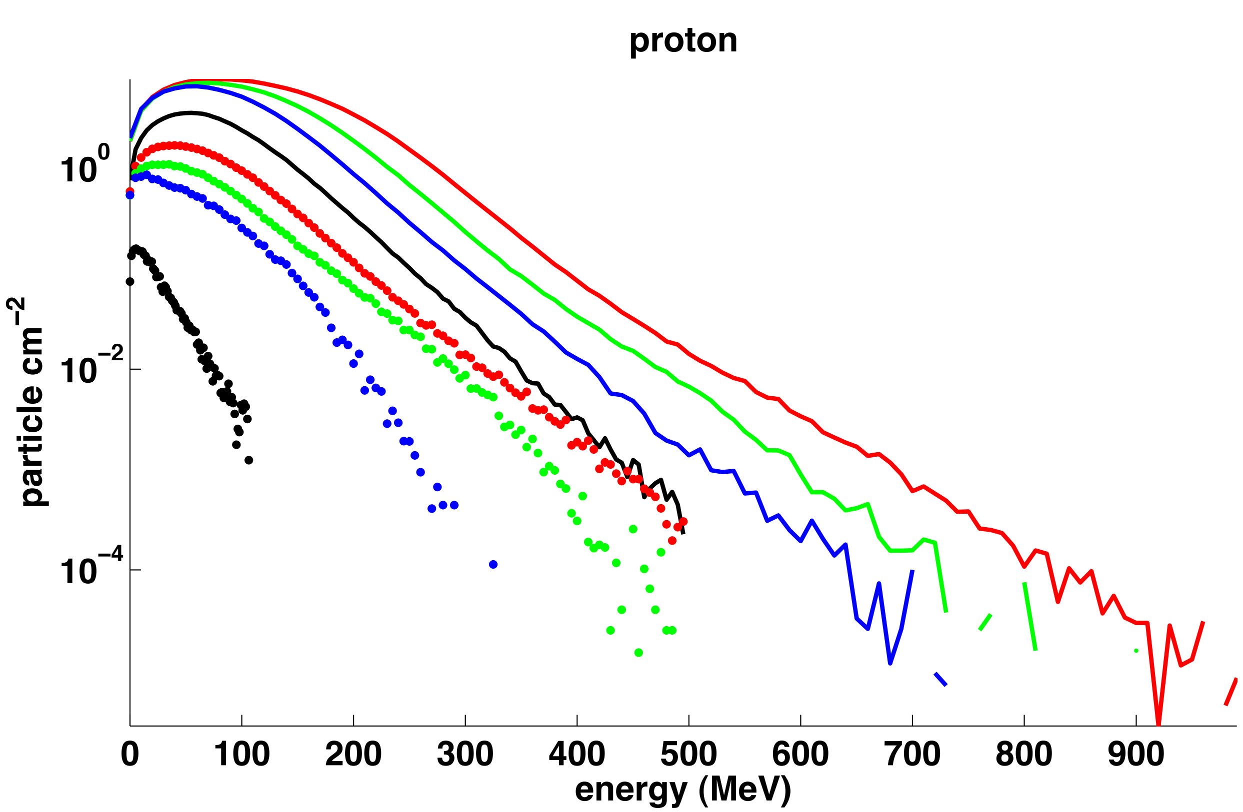
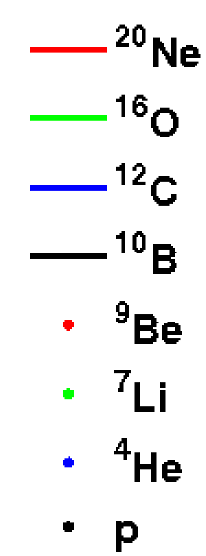
EXIT SPECTRA

normalised to dose in the target







ESCAPES for treatment monitoring

Main challenges:

- beam-patient setup optimised not for escapes (out of the body) but for dose deposition (in the body)
- low SNR requires specialised detector setup, backprojection and filtering (energy, angle, time)

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3 LEVELS OF DEMAND
on the spatial profile of exit particles

<table>
<tr><td>I</td><td>A DISTINCT ICON
AT THE POSITION OF
THE BRAGG PEAK</td><td>TO KNOW
THE DEPTH OF
THE BRAGG PEAK</td><td rowspan="2">ACHIEVABLE
WITH
SUFFICIENT
FILTERING</td></tr>
<tr><td>II</td><td>A GRADIENT
RISING AND DROPPING
IN UNISON WITH
THE BRAGG CURVE</td><td>TO INFER
ENERGY DEPOSITION
AT LEAST QUALITATIVELY</td></tr>
<tr><td>III</td><td>A CURVE
QUANTITATIVELY TRACING
THE BRAGG CURVE</td><td>TO RECONSTRUCT
DOSE DEPOSITION
IN THE BODY</td><td>TOO AMBITIOUS
FOR NOW;
INEVITABLE EMPLOYMENT
OF FUDGE FACTORS</td></tr>
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muon+ creation

	inelastic	decay
^{7}Li	2E-06	2E-06
^{12}C	3E-06	9E-05
^{16}O	1E-05	4E-04
^{20}Ne	5E-05	9E-04

per history

muon+ interactions

	decay
^{7}Li	2E-06
^{12}C	9E-05
^{16}O	4E-04
^{20}Ne	9E-04

per history

pion+ creation

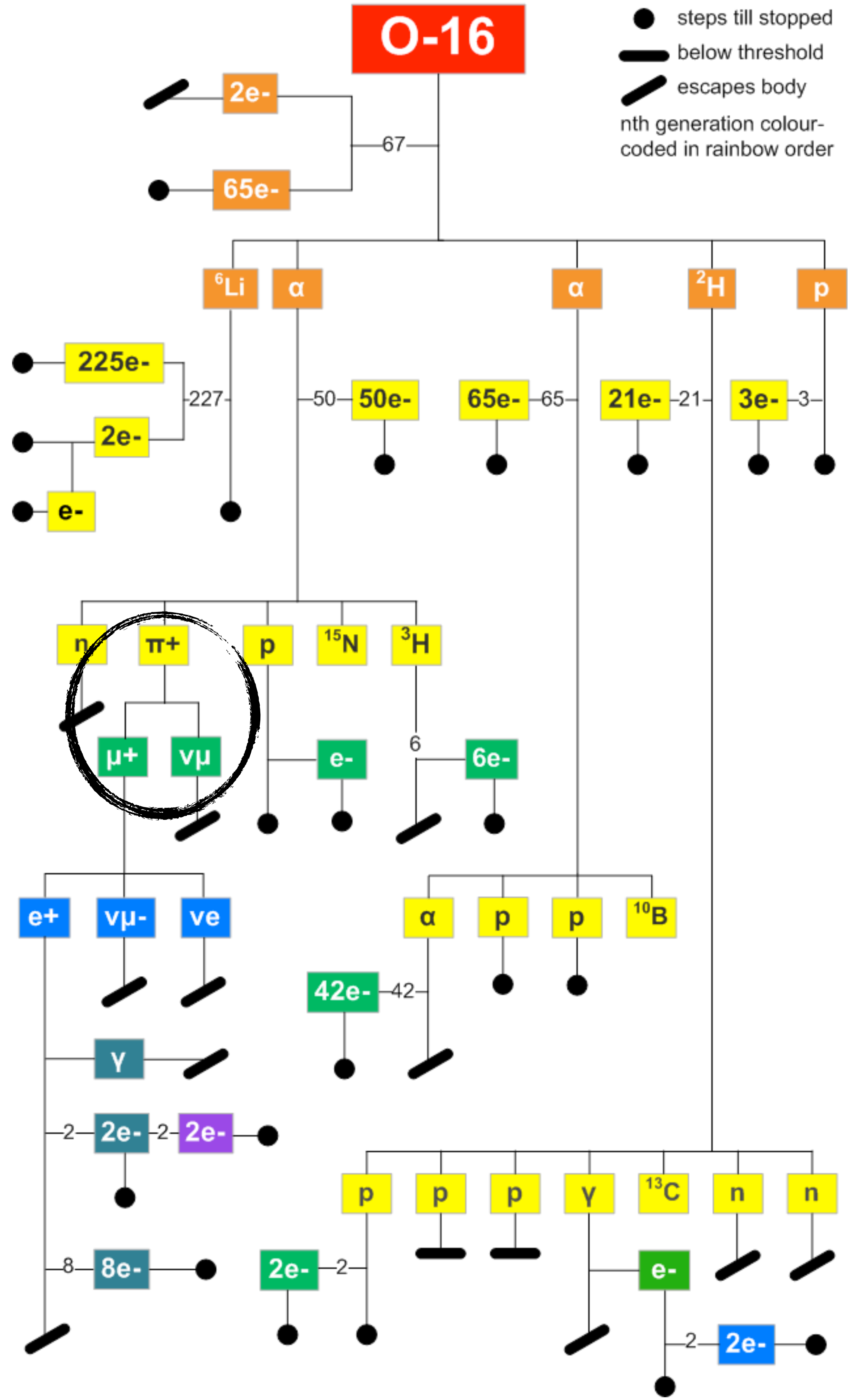
	inelastic
^{7}Li	3E-06
^{12}C	1E-04
^{16}O	6E-04
^{20}Ne	1.5E-03

per history

pion+ interactions

	elastic	inelastic	decay
^{7}Li			2E-06
^{12}C	3E-06	4E-06	9E-05
^{16}O	2E-05	2E-05	4E-04
^{20}Ne	6E-05	7E-05	9E-04

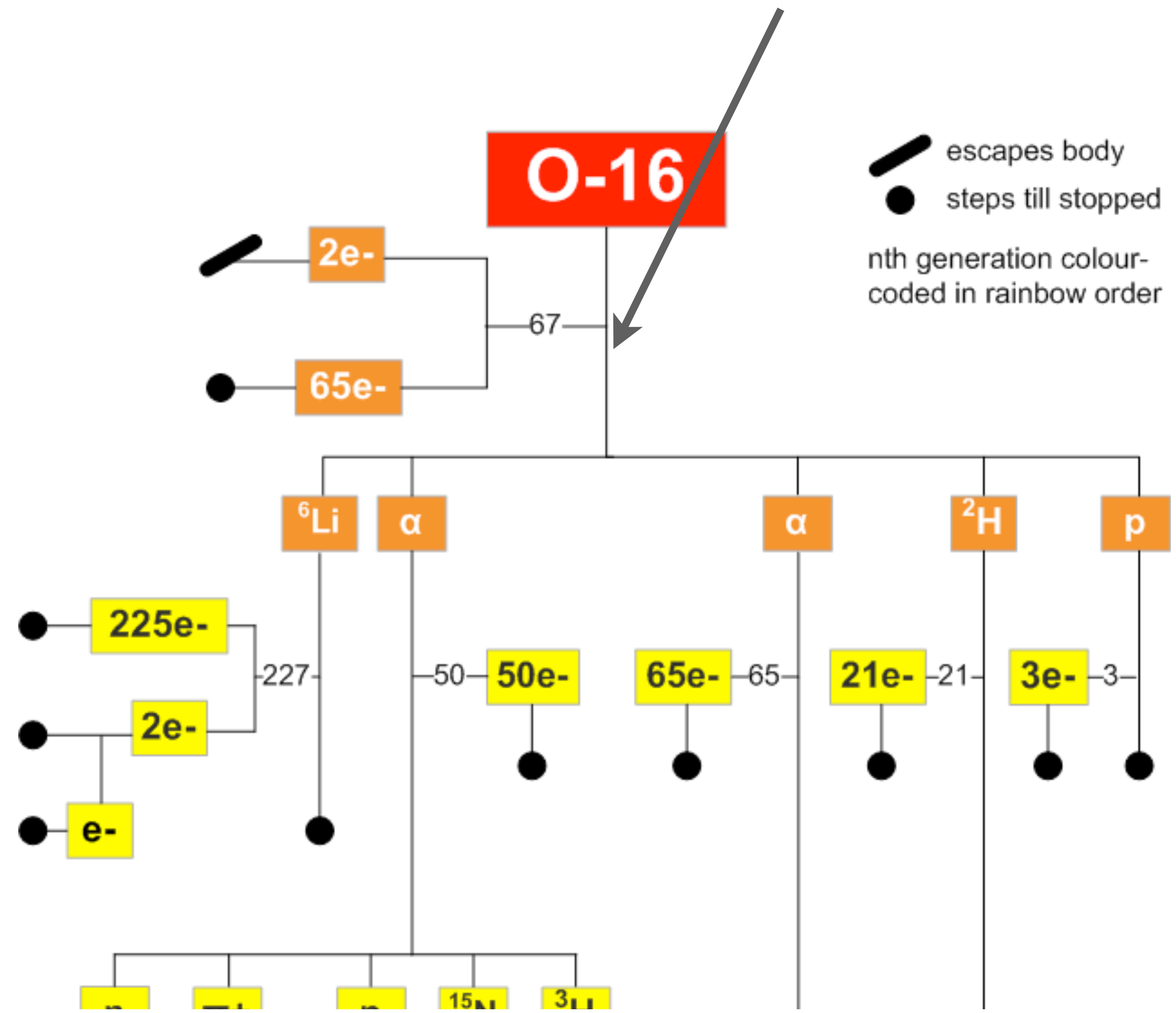
per history



WHAT'S RARE, WHAT'S NOT

% primaries which collide non-elastically				
p	^{7}Li	^{12}C	^{16}O	^{20}Ne
11	34	40	47	53

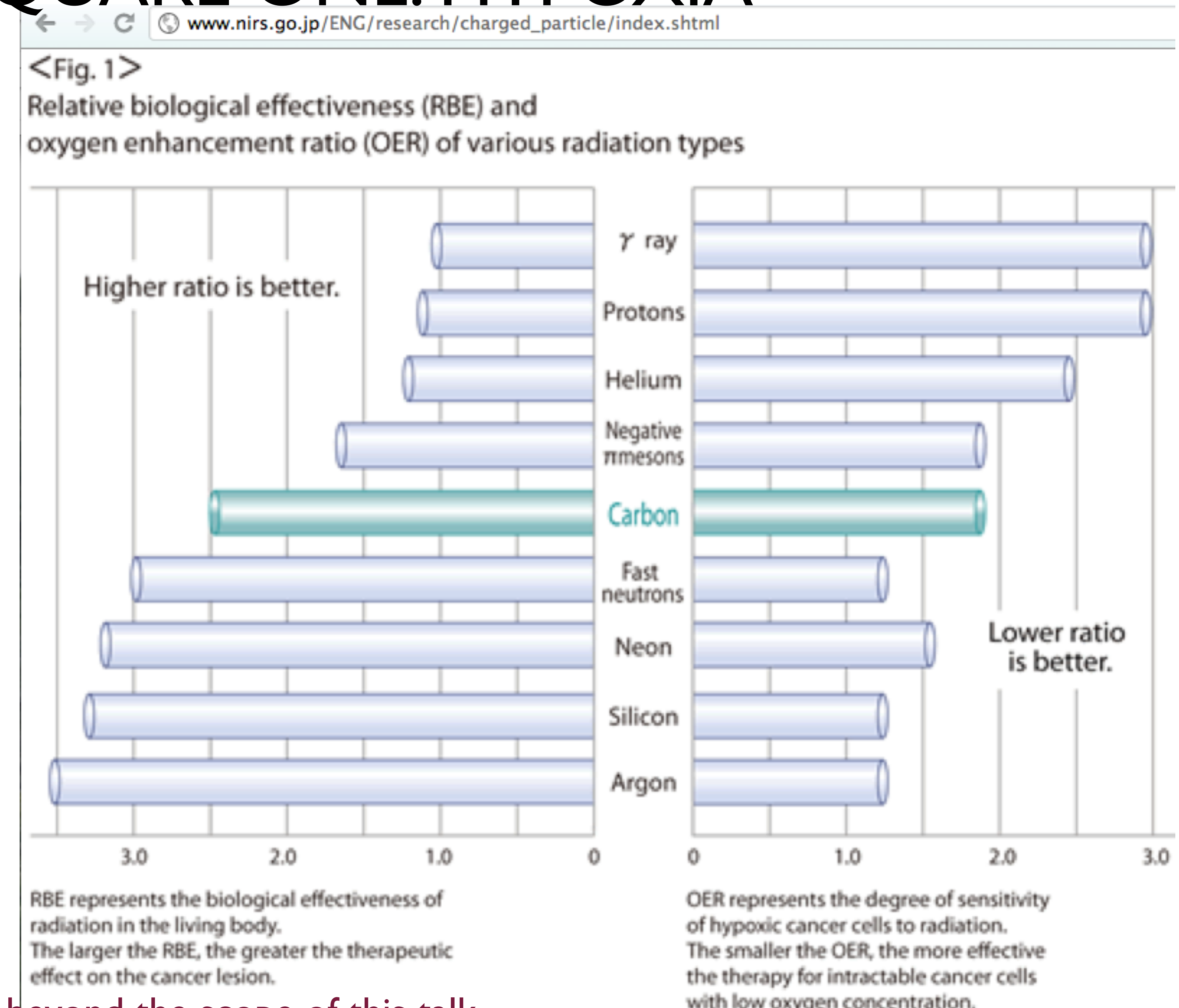
many will stop at this point without colliding non-elastically



PHYSICS & BEYOND

THE CASE FOR CARBON?

-- BACK TO SQUARE ONE: HYPOXIA§



§ hypoxia is very interesting but beyond the scope of this talk

→ molecular imaging

→ 3γ PET: *Variation of 3γ-to-2γ ratio from ^{18}F in haemotological components measured using the GAMMASPHERE*
Chin MPW et al 2009 Nucl. Instrum. Meth. A 604 (1) 331

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