Systematic uncertainty budget for a novel diamond microdosimeter

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About microdosimetry

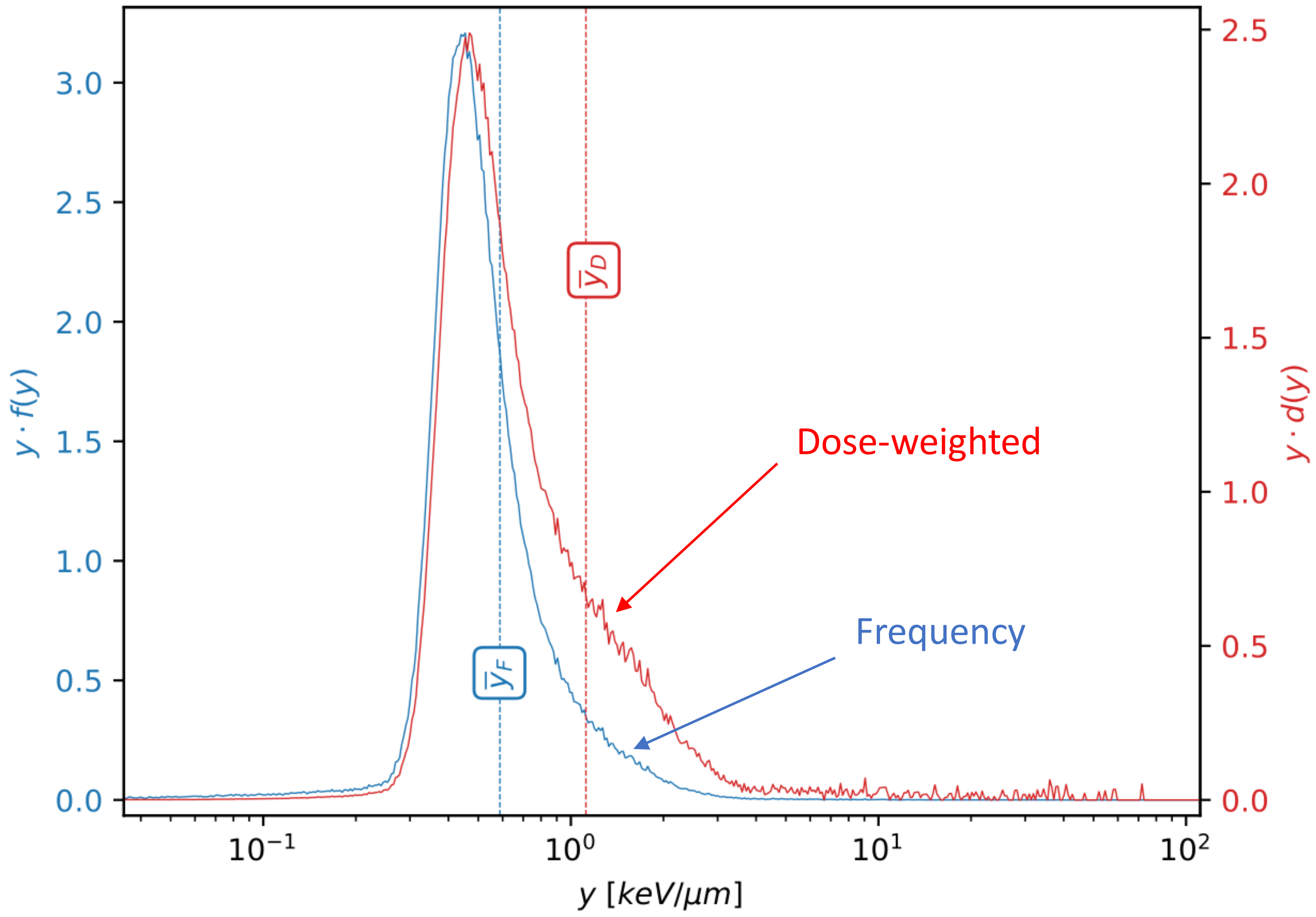
- stochastic approach
- lineal energy: $y = \frac{\varepsilon}{\bar{l}}$

single-interaction energy deposit

mean path-length inside detector

- studied via distributions $f(y)$, $d(y)$…
- … and respective means $\overline{y_F}, \overline{y_D}$

can be related to traditional dosimetric quantities (i.e. LET) with some caveats



What microdosimetry lacks

- no fully comprehensive uncertainty budget
  - for use in experimental/clinical settings
- standardisation across the whole field
  - comparing papers between groups is often difficult
  - making comparisons with radiobiology/dosimetry papers even more
- not used in treatment planning

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← if we fix this…

← … and this…

← … maybe we'll get closer to this

The microdiamond detector

used throughout this study

- chemical vapour deposition diamond detector
  - originally developed at Tor Vergata
  - currently used as part of collaboration between Tor Vergata, Surrey, and NPL

- intrinsic diamond acts as SV
  - possible thickness in 1—50µm range
  - relatively large surface (50µm, 250µm, 500µm, … width)

- lot of experimental data in literature
  - … but not quite as much as other detector types

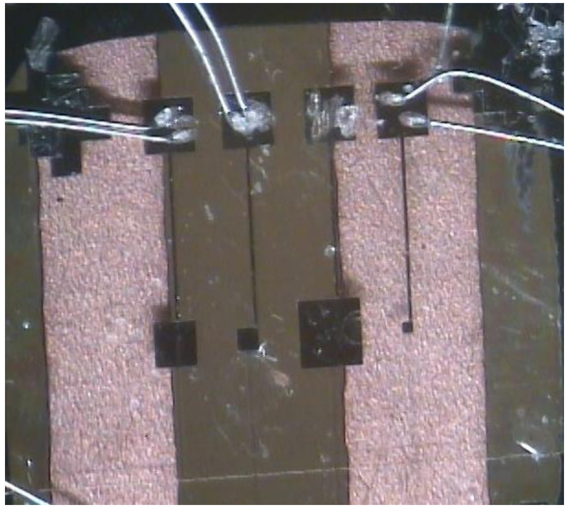
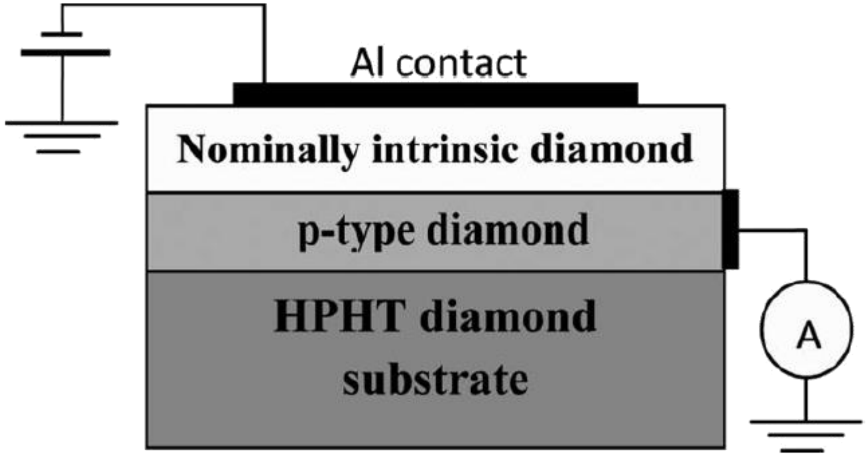


Photo by G. Parisi

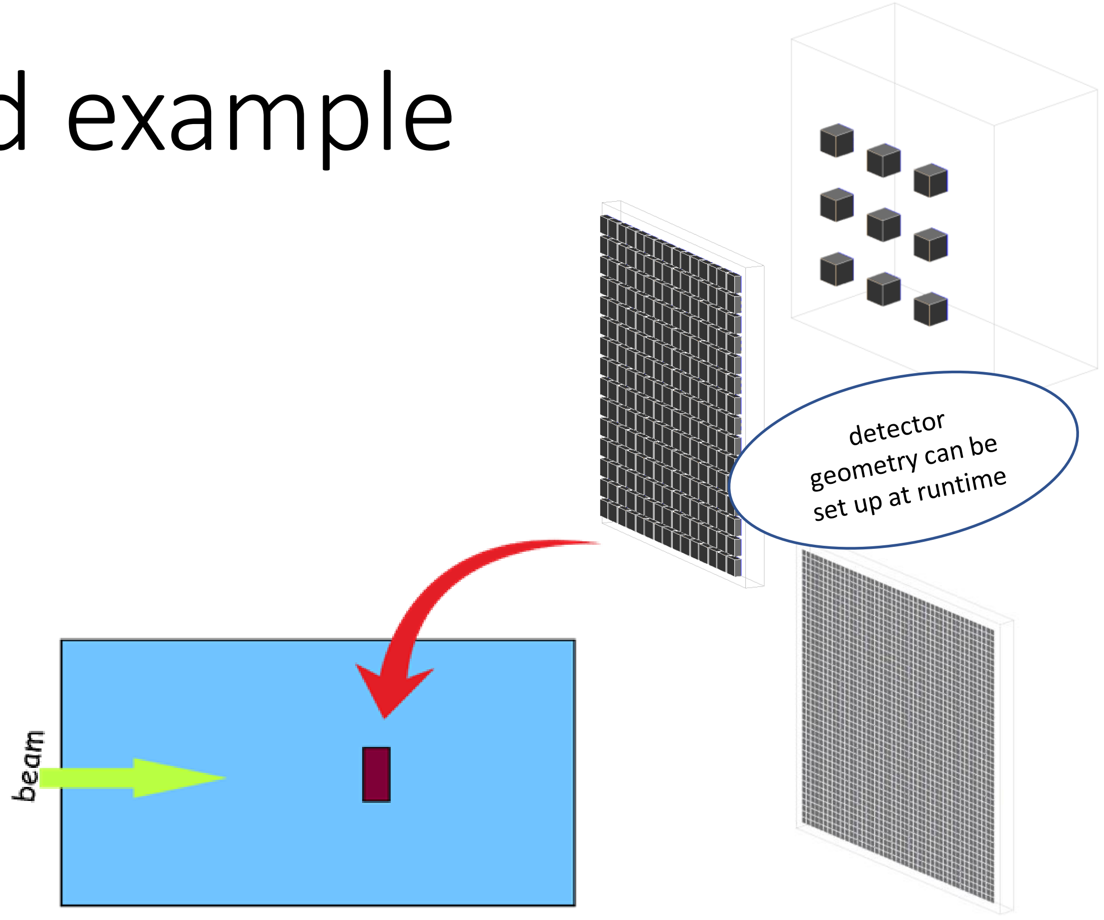


Angelone et al., 2011

Radioprotection advanced example

as of the next Geant4 release

- simulates several microdosimetric detectors
  - type, shape, and position can be changed via macro
  - can be placed in an array to speed up simulations
- scores ε, l, and Z of secondaries
- provides basic data analysis for microdosimetry
  - spectra, means, and RBE (requires ROOT or Python)
- simulates a simple clinical setup
  - detector in a water phantom
  - (optional) detector in a vacuum (for space application)

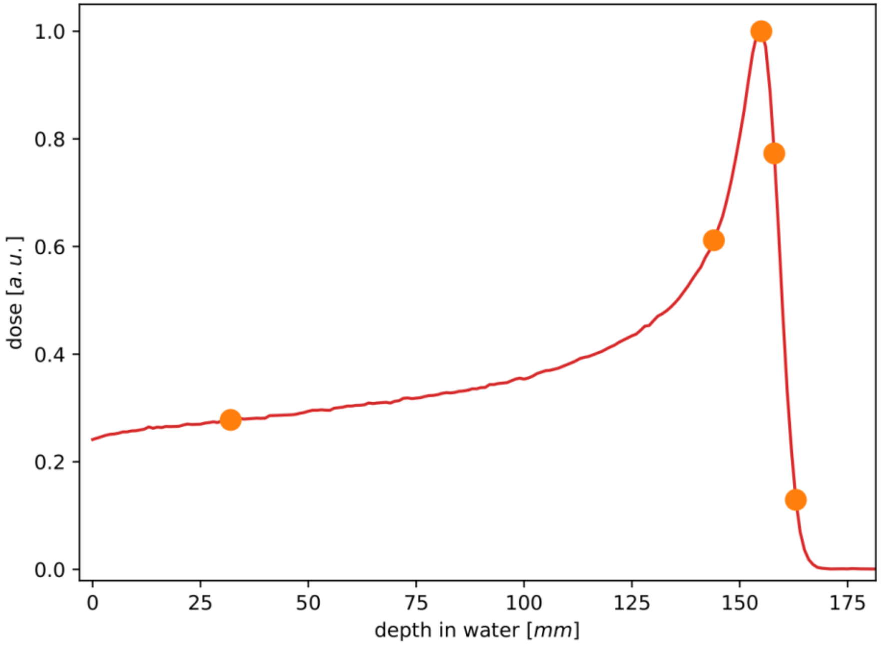


- allows fixing consistent target statistics
  - the simulation stops after n events in the SV

Detector characterisation + uncertainty budget

- test the effect of several parameters
  - set large ranges (detector characterisation) or small variations (uncertainty budget) of a detector parameter
  - run simulations in parallel and collect the spectra

- comparison carried out along a Bragg curve
  - for each parameter, several depths in water along a 150MeV curve (σ=1.5MeV spread)



- spectra are compared via their means…
  - $\bar{y}_F$, y^*, and $\bar{y}_D$

$$y^* = \frac{{y_0}^2}{\bar{y}_F} \int (1 - \exp(-y^2/{y_0}^2)) \cdot f(y)\, dy$$

similar to $\bar{y}_D$ at low y, but adds an exponential cut-off at higher y

- … and the resulting RBE
  - MKM RBE (function of y^*) for HSG (late responding tissue)
  - weight function RBE for crypt cells (early responding tissue)

Here's a selection of the results so far…

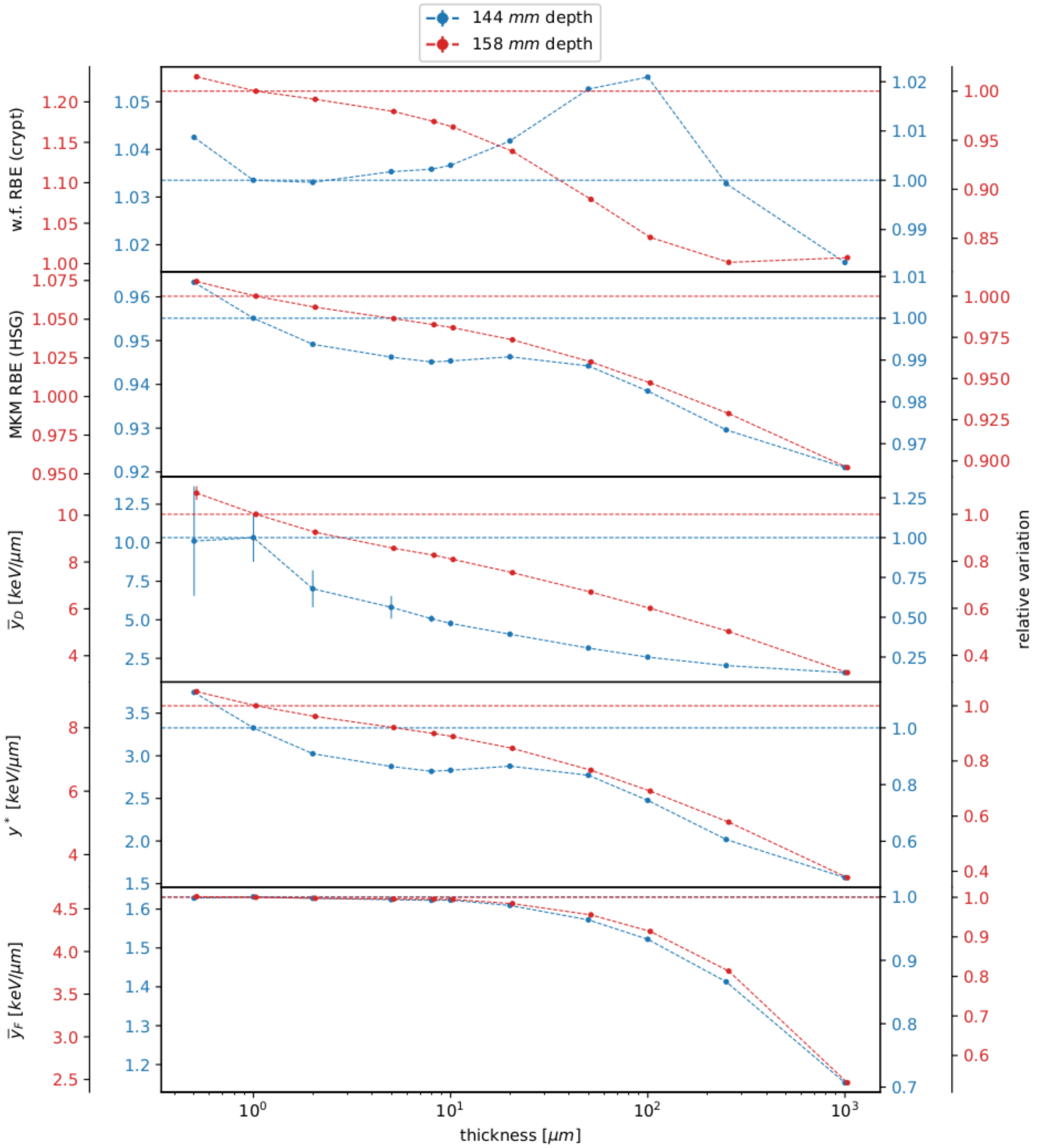
Detector characterisation

1/3: effect of SV thickness variation

- increasing the SV thickness strongly reduces the means
  - varying $\bar{l}$ with the thickness works well for crossers, but not for stoppers
  - $\bar{y}_D$ very affected by high energy stoppers, so it is heavily affected by thickness variations
  - $\bar{y}_F$ is not, and shows minimal variations up to 20µm
  - y^* has an intermediate behaviour

- both RBEs show small variations compared to those seen in the means

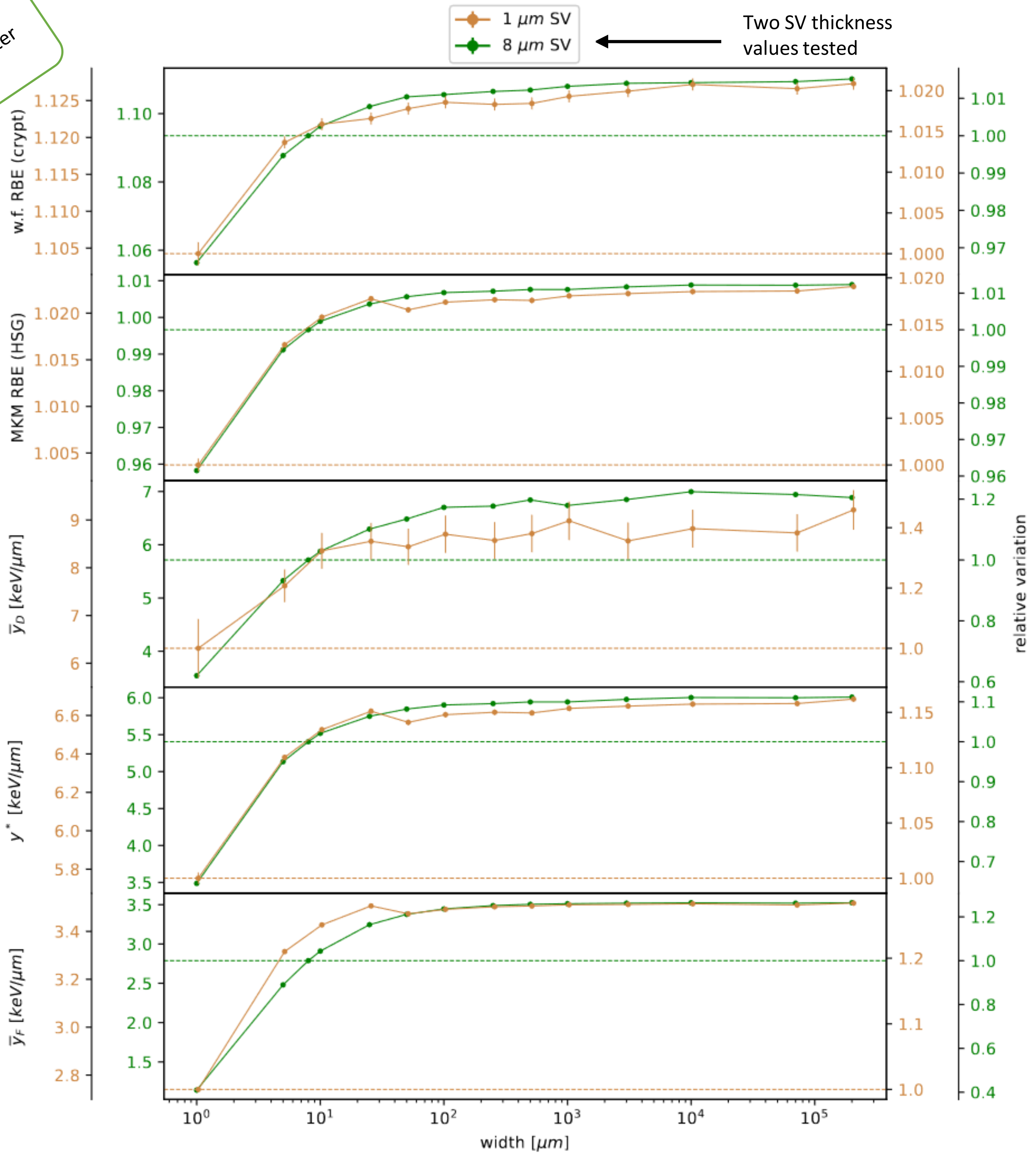
- little to no variation of these trends with depth



Detector characterisation

2/3: effect of SV width variation

- increasing the SV width increases the means
  - wider SV = fewer electrons escape laterally
  - $\bar{y}_F$, y^*, $\bar{y}_D$, and the RBEs show similar trends
  - … but the means have large relative variations, the RBE much smaller ones
  - plateau past 100µm: lateral escape becomes negligible
- thicker SVs show stronger variations
  - larger lateral surface = more electrons can escape
- stronger variations at lower depths
  - faster protons = wider electron penumbra
  - same trend but larger relative variations are larger

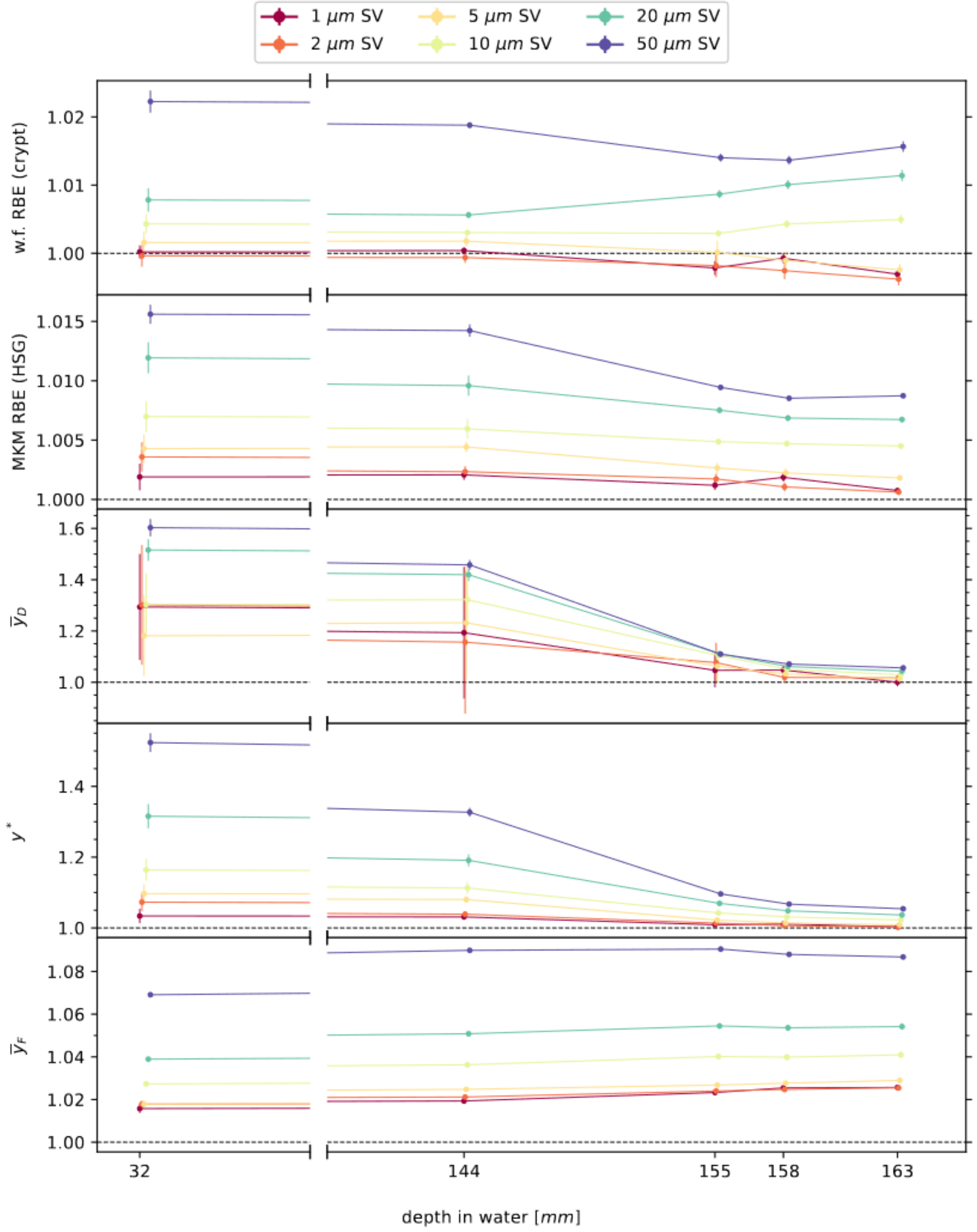


Detector characterisation

3/3: water conversion factor

On the ordinate: ratio between the mean measured for the diamond detector with the conversion factor, and the same mean measured in a water SV

- 0.32 conversion factor to y [Davis et al. 2014]
  - scales y to the values of an equivalent water SV 3.1 times larger
  - its accuracy is tested here by replacing the SV with a water volume and calculating the relative variation this causes to the mean
- the conversion factor works very well overall
  - especially for the RBEs and $\bar{y}_F$
  - … but its accuracy decreases for thicker SVs and at lower depths
- discrepancies due to high y secondaries
  - high energy, low range particles with high Z
  - manually removing events past the main peak of $d(y)$, all variations on the right become < 5%

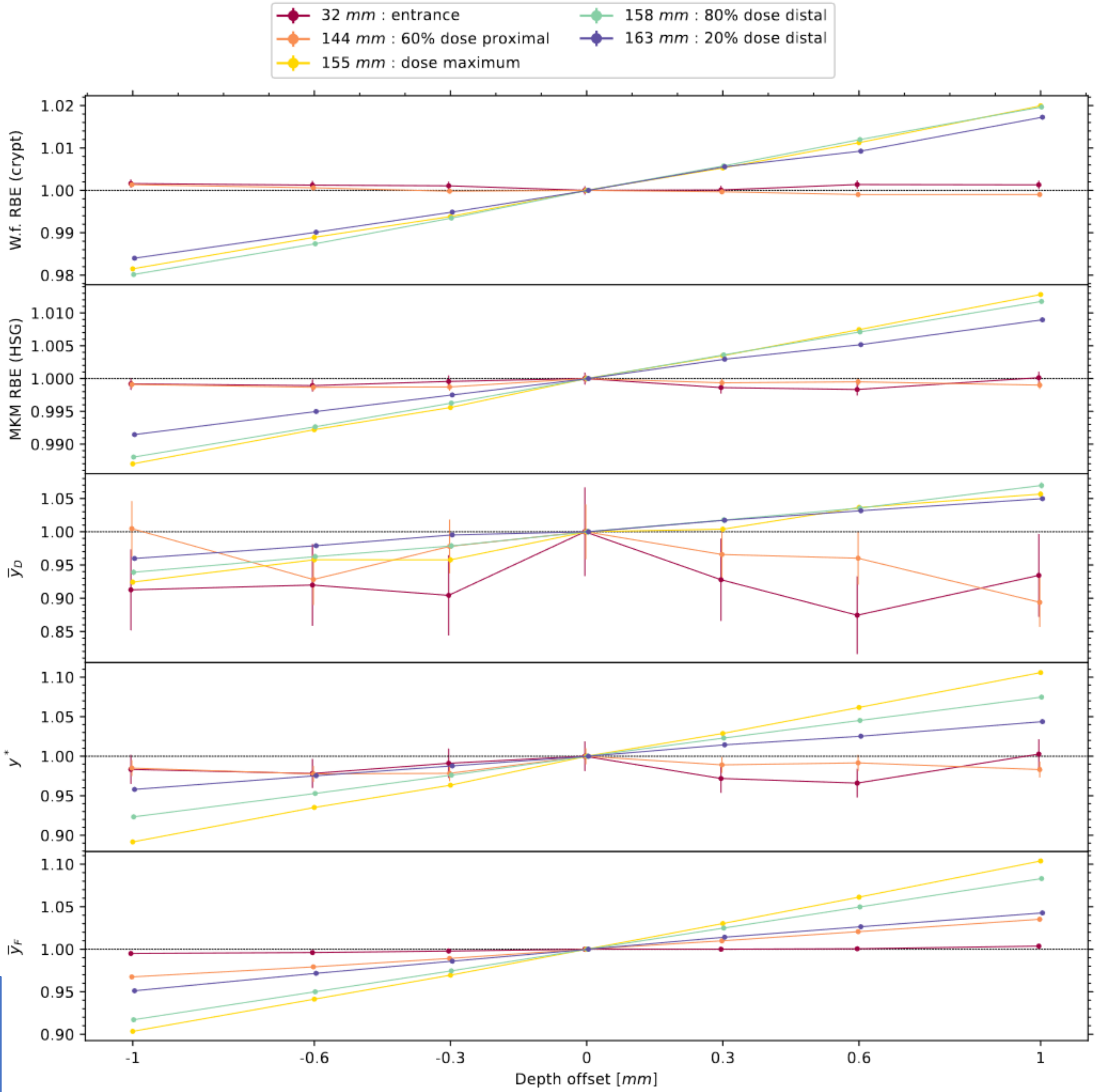


Uncertainty budget

1/2: error due to detector positioning

- effect on the mean of depth (in water) uncertainties
  - for small offsets from the nominal value it results in a linear variation of the means
  - the resulting relative variation is highest between the peak and the beginning of the distal region
- the variation can be quite large
  - around the peak a 1mm uncertainty causes a 10% error on the means
  - … but the error on the RBEs is much smaller

On the ordinate: ratio between the mean in the offset and in the nominal position



Uncertainty budget

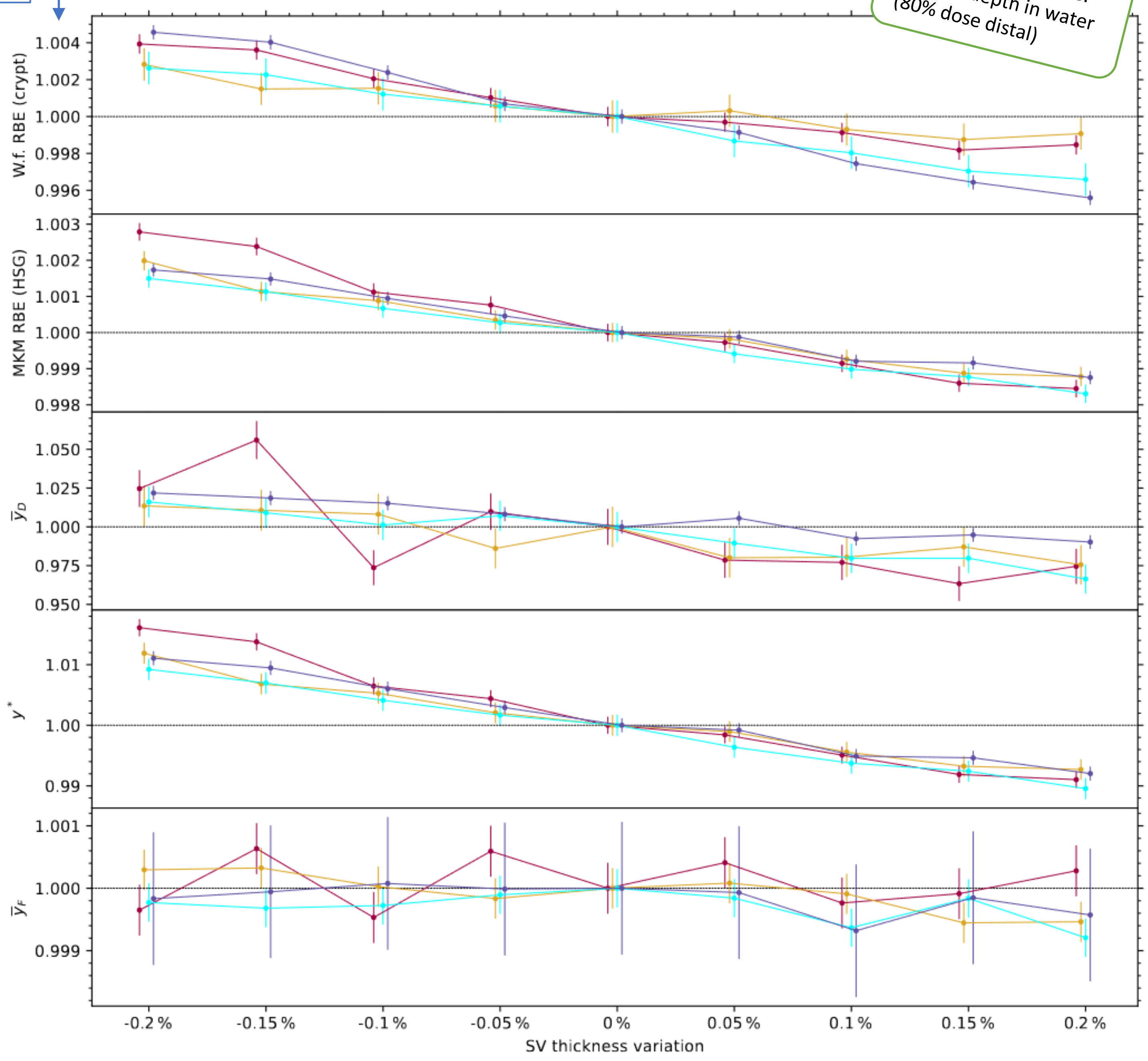
2/2: error due to SV size uncertainty

- small variations in SV size
  - corresponding to uncertainties typically found experimentally
  - the effect on the means and RBEs is consistent with that seen in the detector characterisation
  - RBEs have negligible errors, and that of $\bar{y}_F$ is below the statistical uncertainty
  - y^* and $\bar{y}_D$ can vary up to 5%
  - … but in $\bar{y}_D$ this is often hidden by statistical fluctuations

- some depth dependence
  - y^* variation goes from around 5% in the entrance to 2% in the distal part
  - … however almost no dependence on nominal SV thickness only a small one in the distal edge

On the ordinate: ratio between the mean from the varied and nominal depth

Shown in this picture: 158mm depth in water (80% dose distal)



Overall conclusions

- most parameters/uncertainties influence $\bar{y}_D$ more than $\bar{y}_F$
  - … and y^* has an intermediate behaviour
  - because most of the parameters tested affect the high energy tail much more than the main peak
  - a notable exception is the SV width

- both RBEs are weakly affected
  - uncertainties have a small effect on the RBE
  - huge variation of the detector’s geometric parameters are required to see a significant RBE change
  - this is good if we want a consistent RBE for a given depth in a given beam…
  - … but it’s bad if we want our RBE models to reflect the physical properties of the detector

do current RBE models lack sensitivity to variations in the microdosimetric spectrum?

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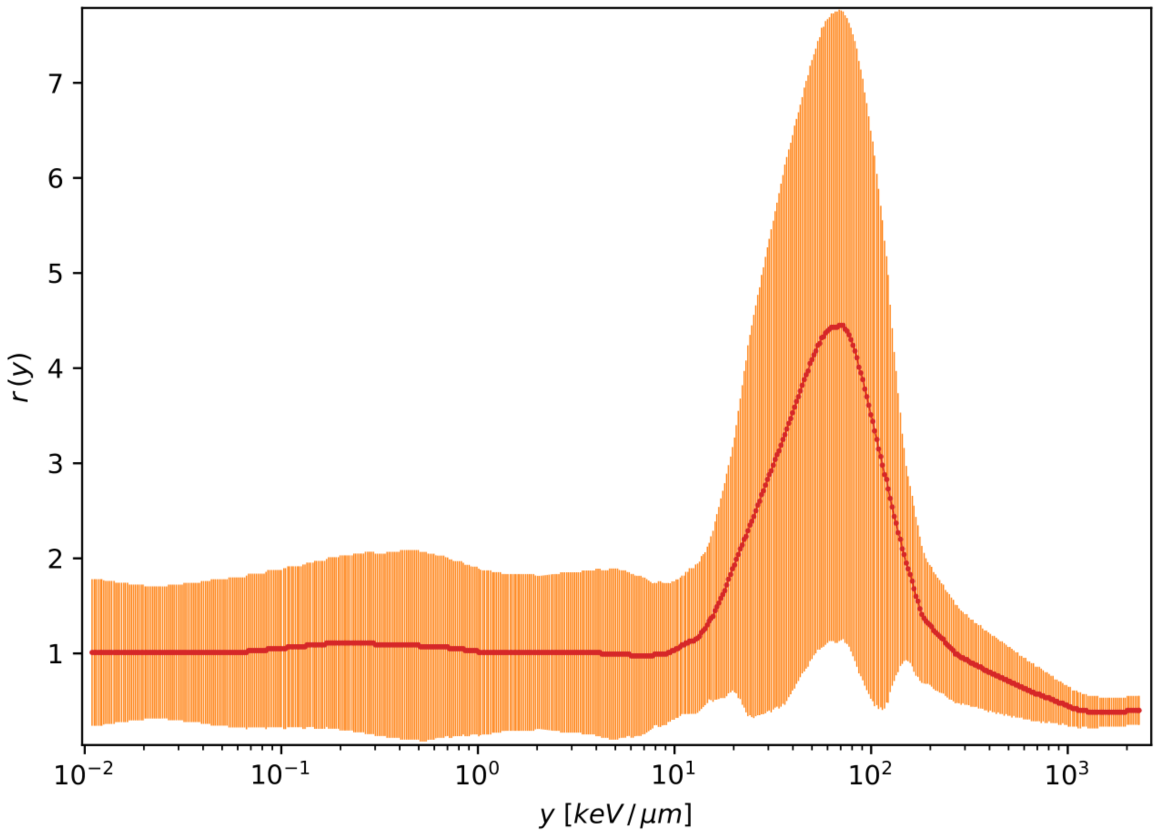
the end

Backup slides

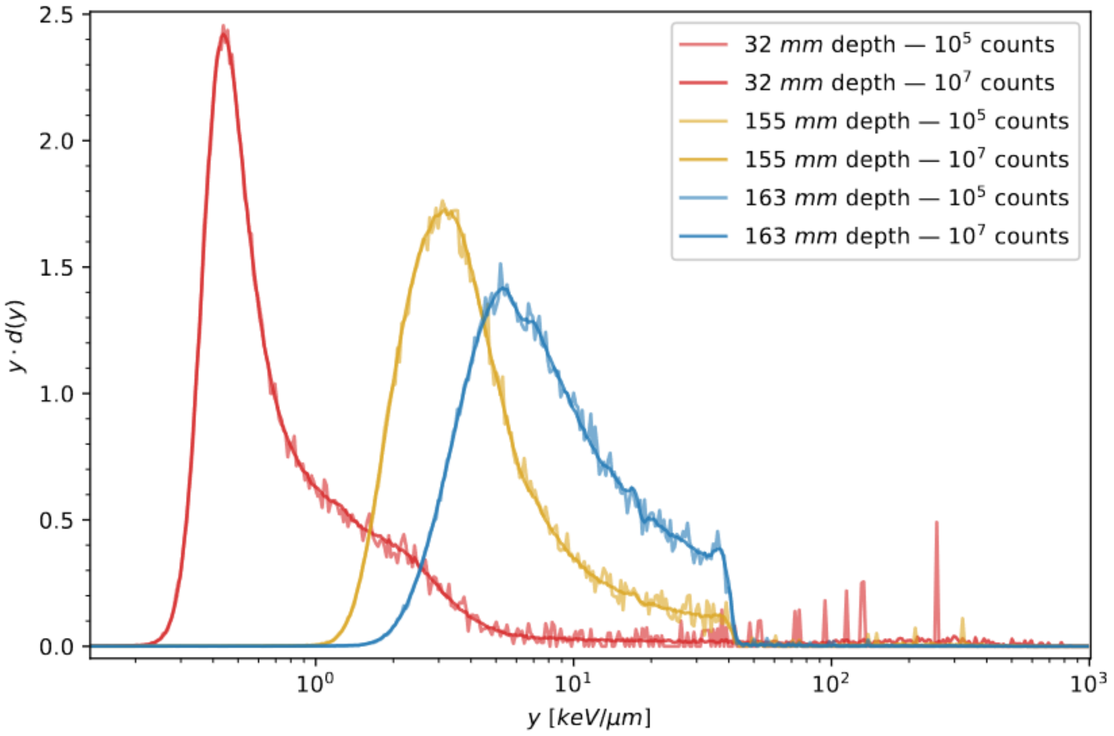
RBE weight function

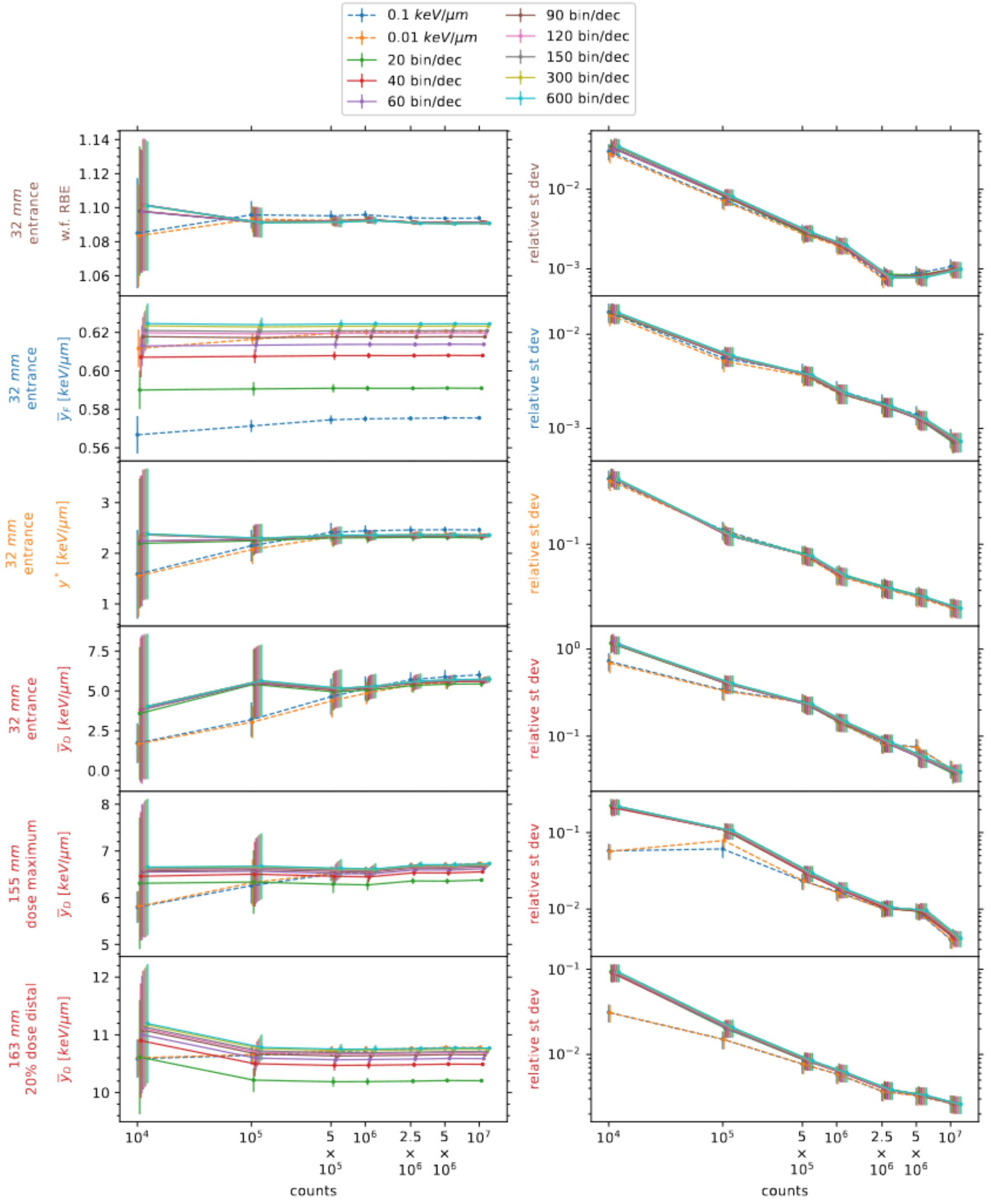
from Loncon et al. 1994

- can weight the whole spectrum
- gives only a specific RBE
- only some projectile-target combinations

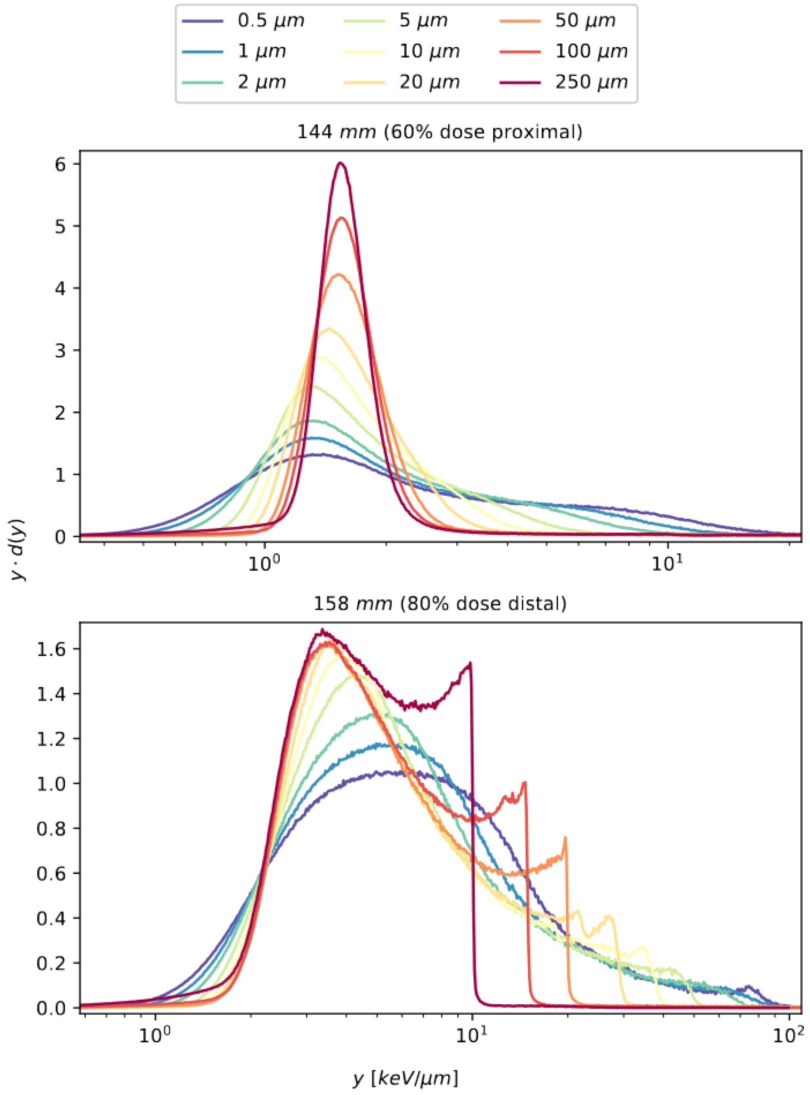


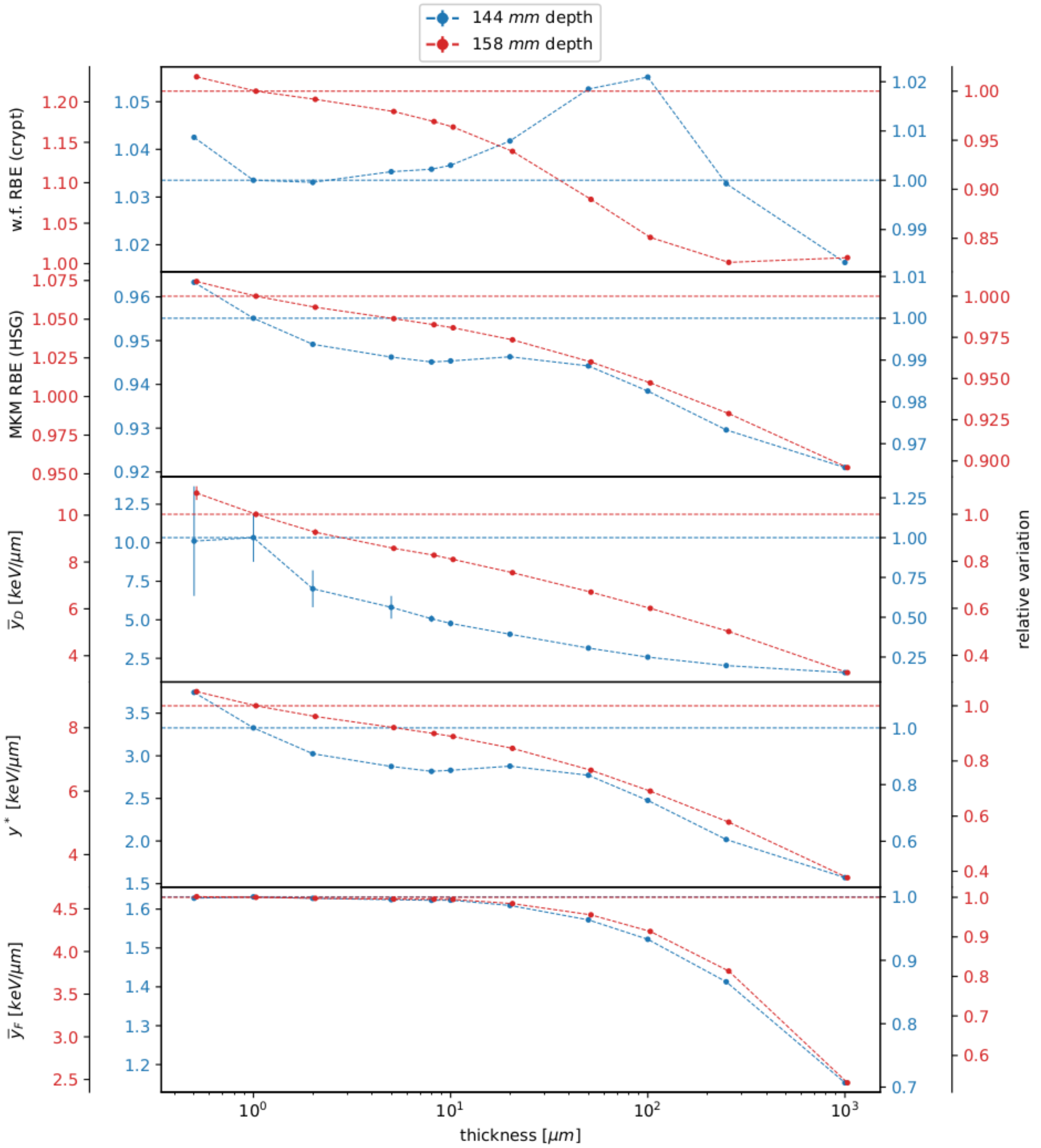
Statistical uncertainty





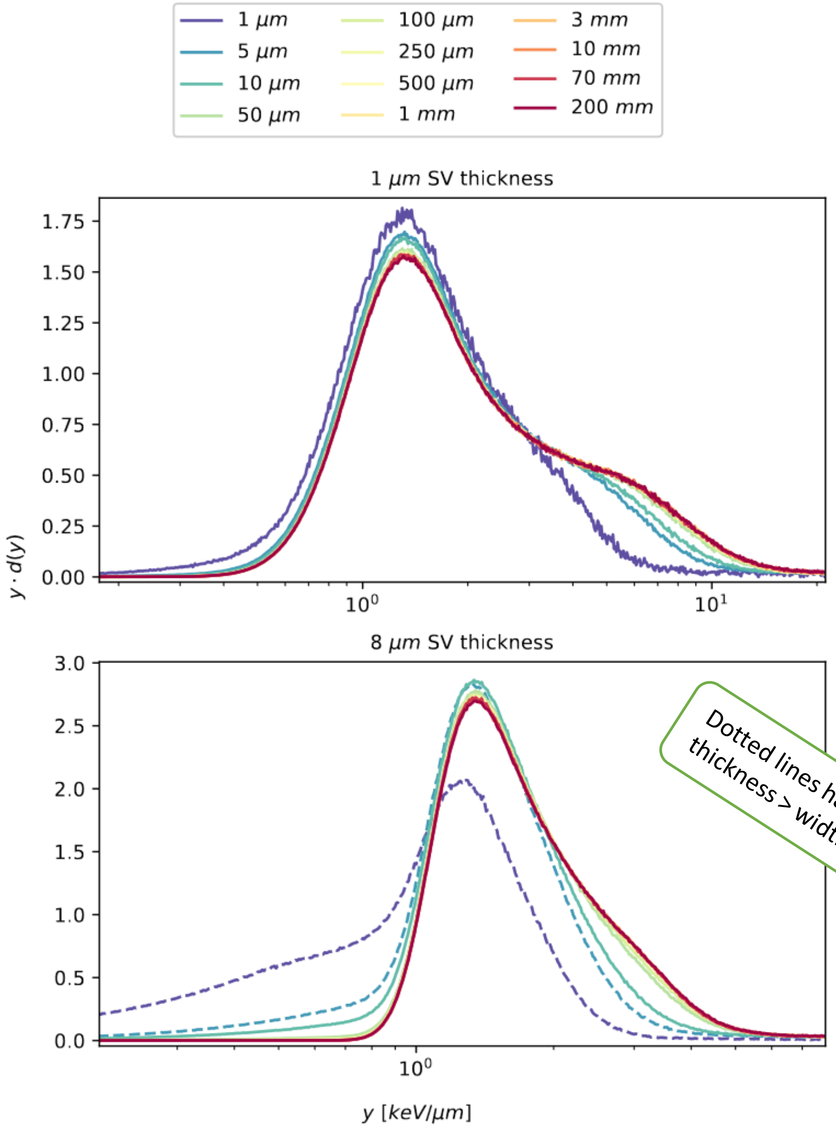
Thickness variation



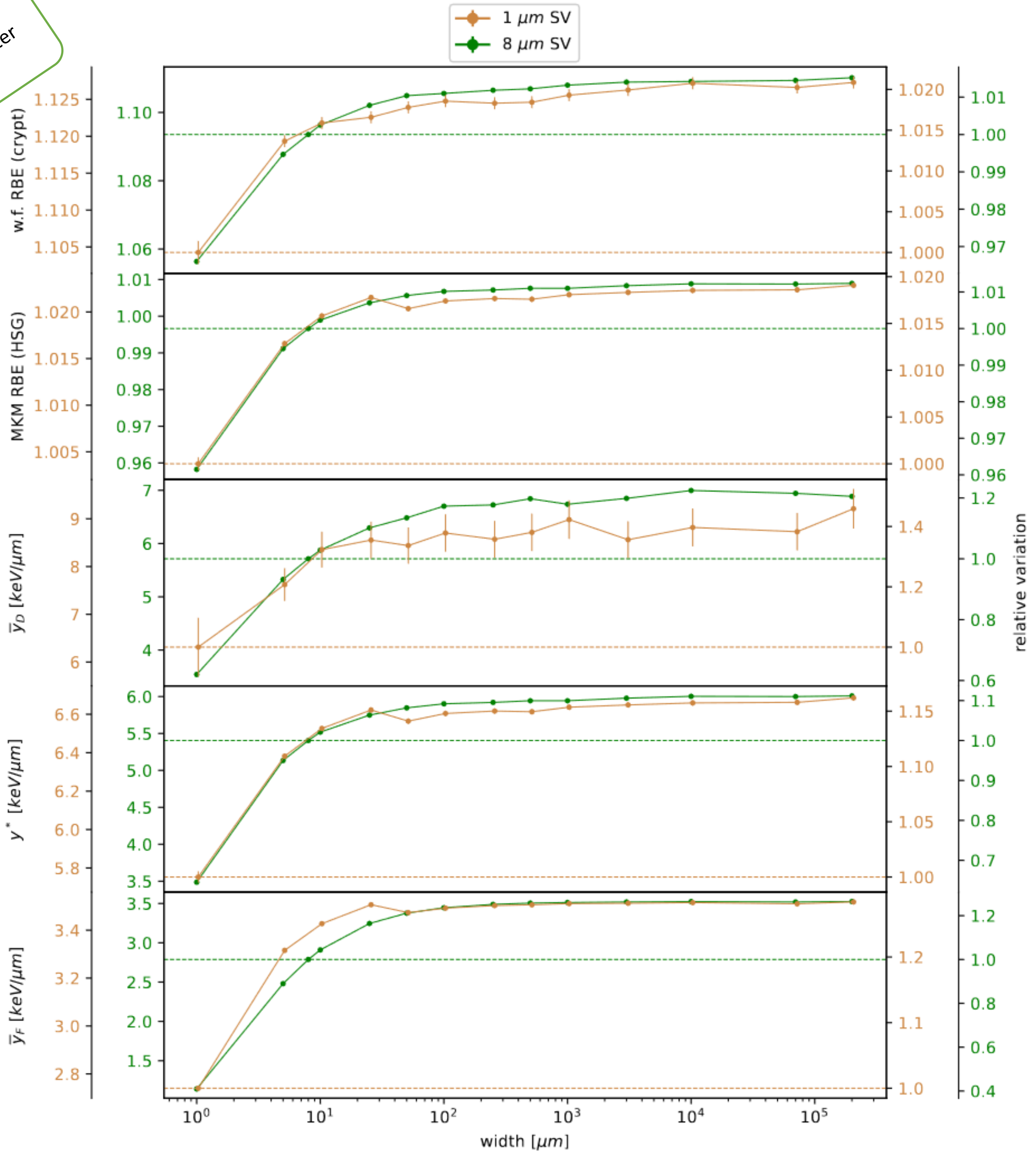


Width variation

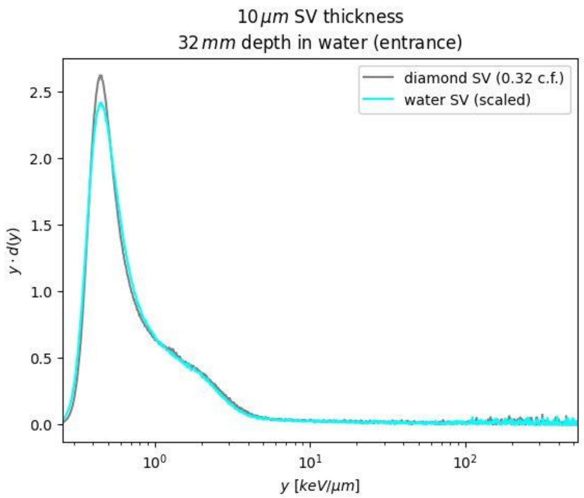
Shown in this picture: 155mm depth in water (dose maximum)

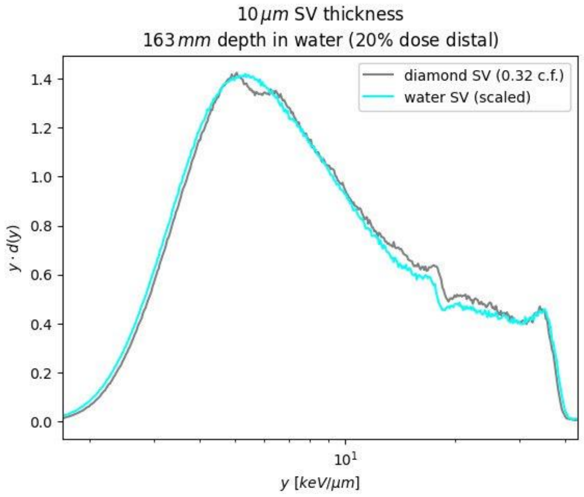


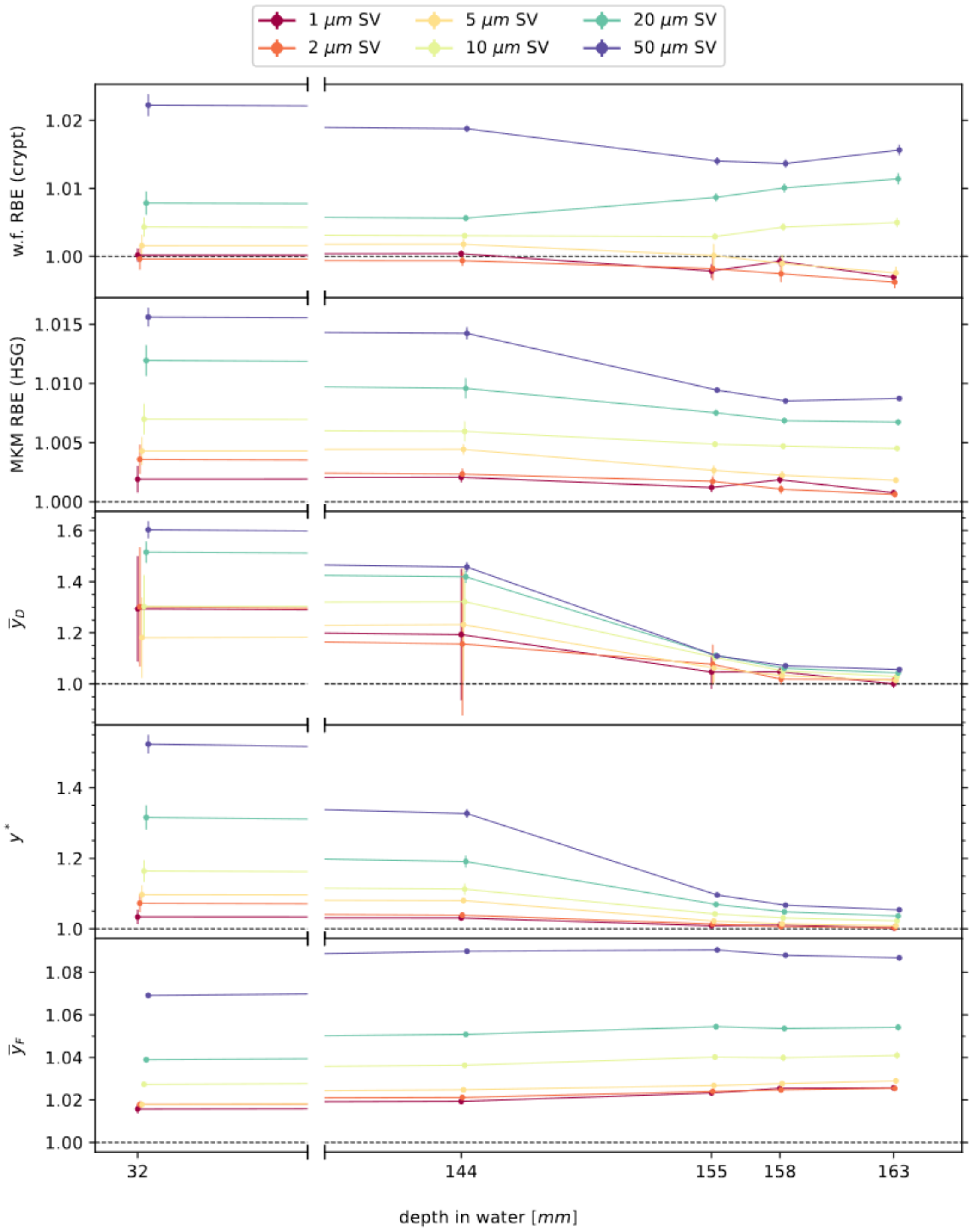
Dotted lines have thickness > width



Conversion factor

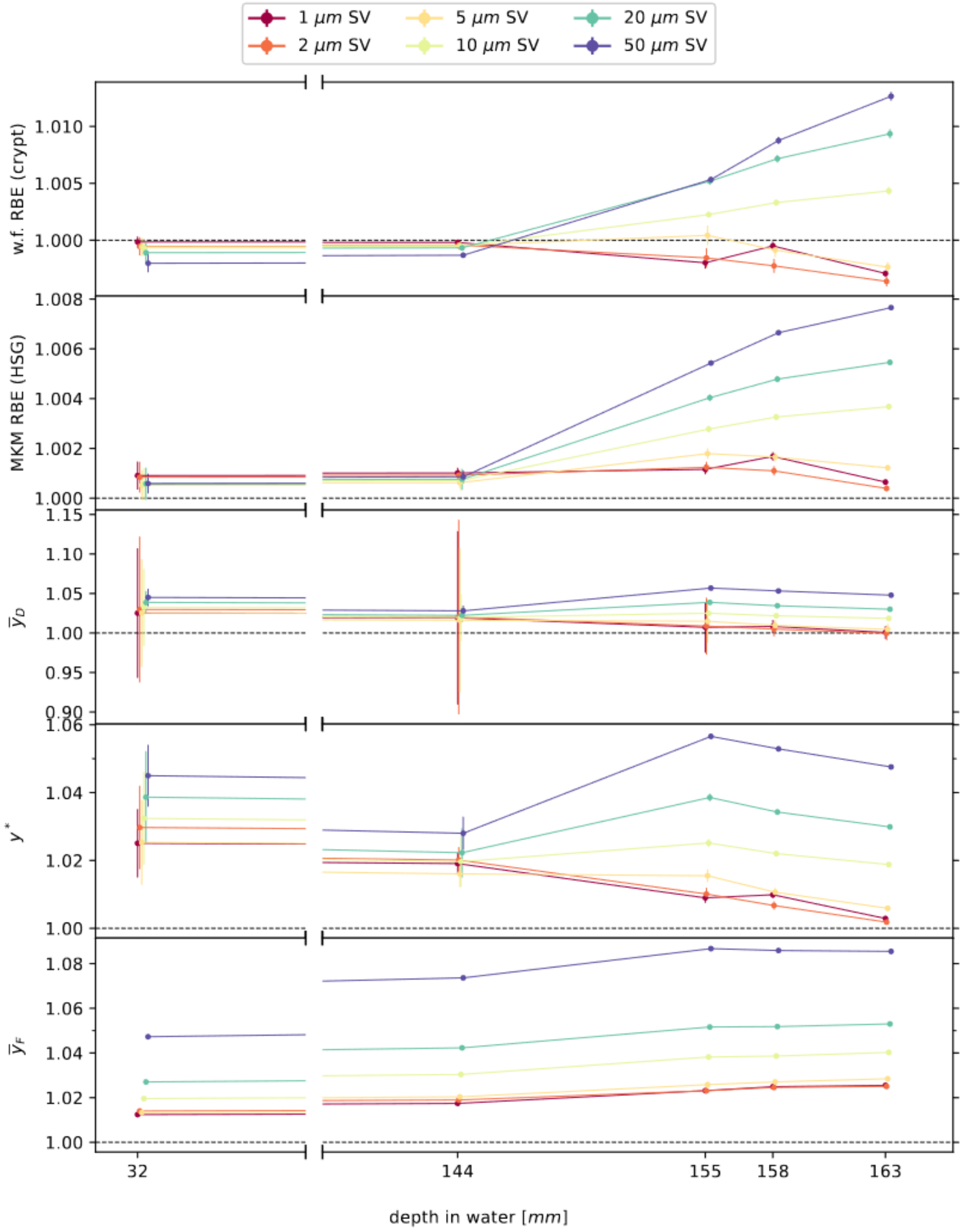


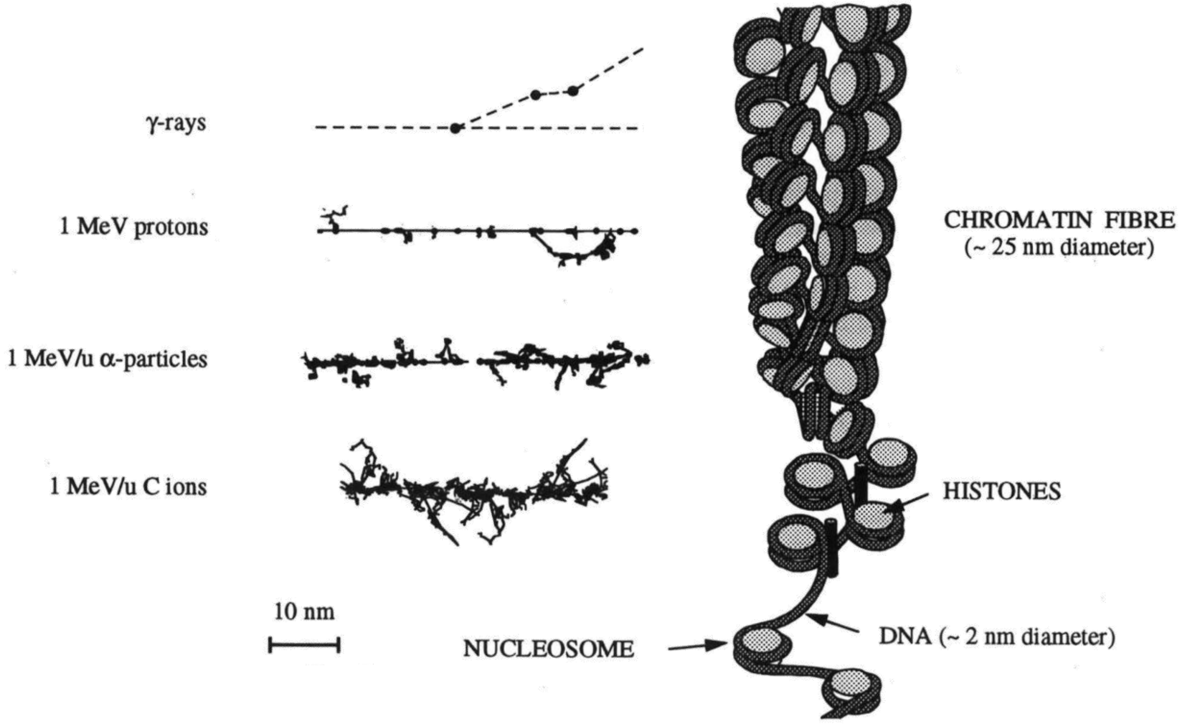




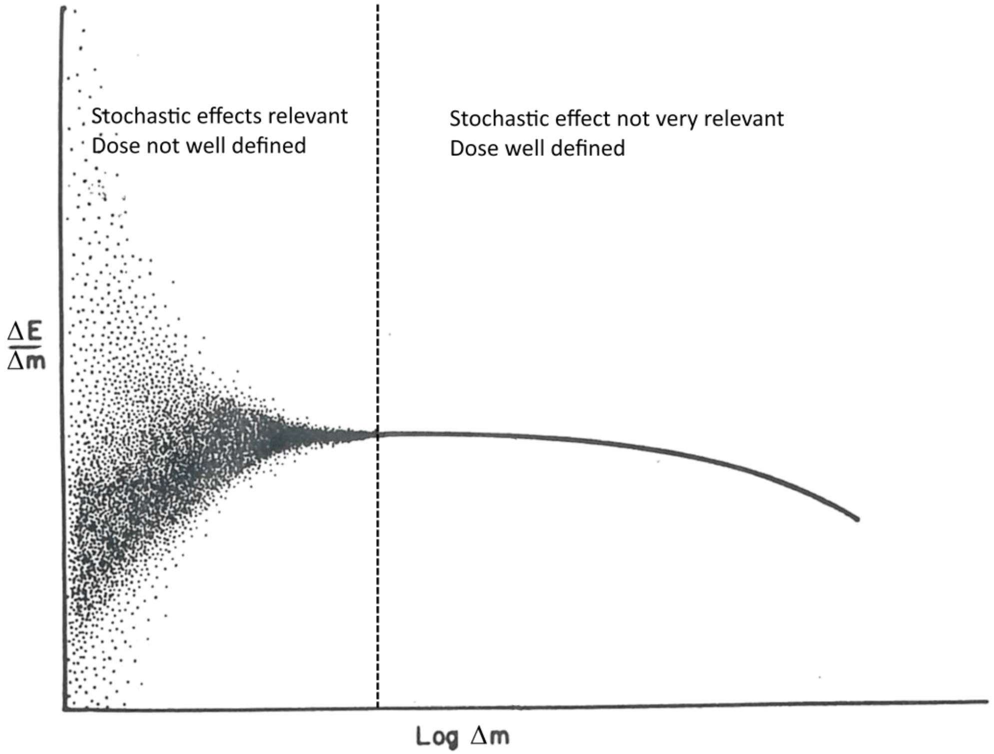
Conversion factor

without events past the tail





γ-rays
1 MeV protons
1 MeV/u α-particles
1 MeV/u C ions
10 nm
NUCLEOSOME
CHROMATIN FIBRE
(~ 25 nm diameter)
HISTONES
DNA (~ 2 nm diameter)



Stochastic effects relevant
Dose not well defined
Stochastic effect not very relevant
Dose well defined
ΔE/Δm
Log Δm