Some physical bases of particle therapy with protons and ions

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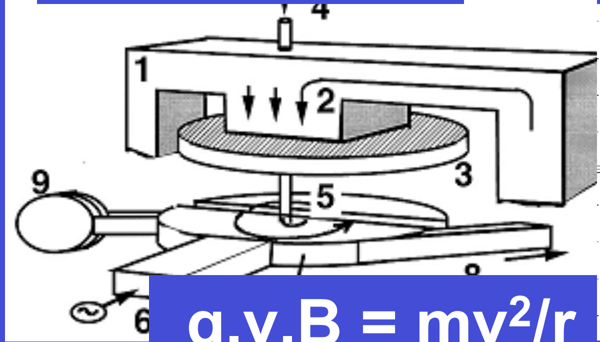
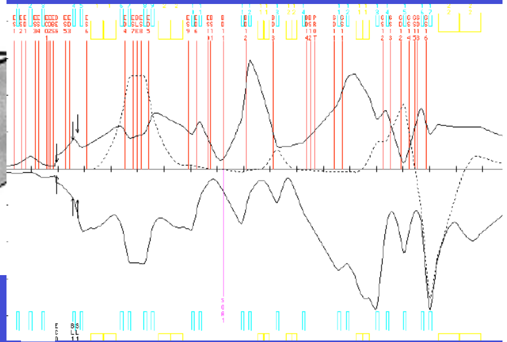
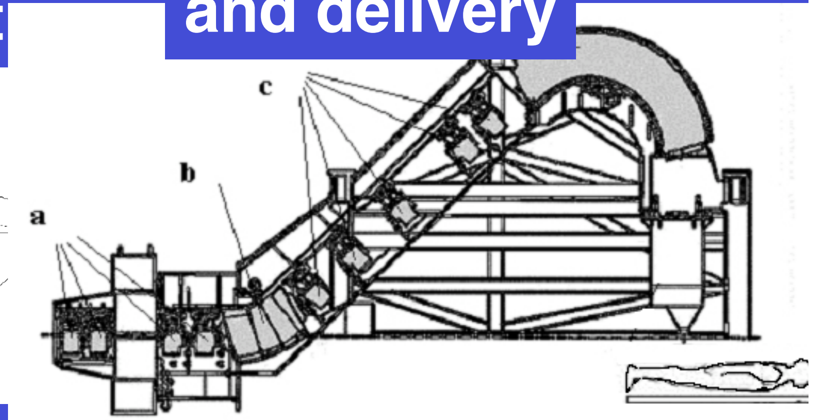
What is « Hadrontherapy » for a physicist?

Accelerators **Beam transport** **and delivery**

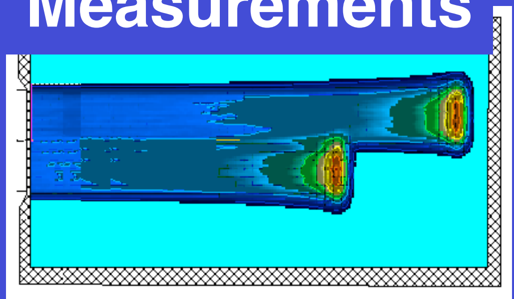


$q.v.B = mv^2/r$

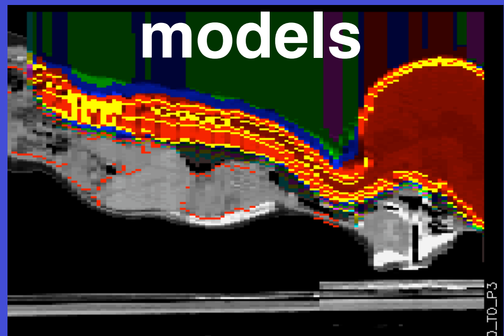




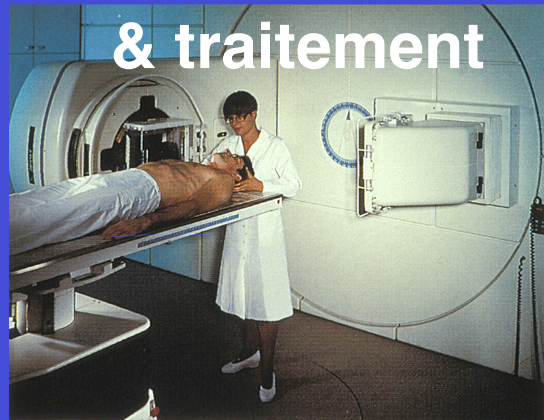
Measurements



models



& traitement



$$(dE/dx) = 4 \pi z_{eff}^2 e^4 N_A Z/A \, m_e v^2 \; \{ \ln (2mv^2/ I \, (1-\beta^2)) - \beta^2 - \Sigma(Ci/Z) \}$$

$$\theta_0 = 14.1 \; z / p v \quad \{ \mathrm{sqrt} (L / L_R) \; (1 + \log(L / L_R) / 9) \}$$

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« Hadrontherapy » for the physician

2．筑波大学の陽子線治療成績

筑波大学の陽子線治療は、１９８３年以来色々な部位を対象に行われていますが、なかでも日本人に多い深部臓器がんに主体を置いているという特徴があります。表５に治療部位と治療成績を揚げました。これまでの経験で、皮膚、頭頚部、肺、食道、肝臓、子宮、膀胱、前立線などで満足すべき結果が得られています。

第６図から第14図までは、実際に陽子線で治療した患者さんの写真です。

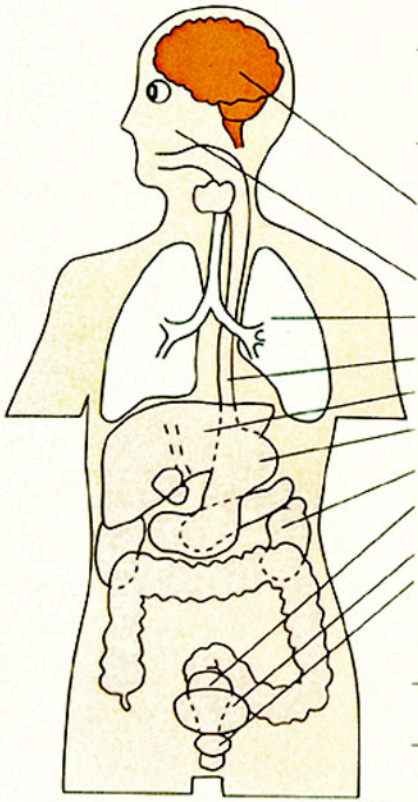
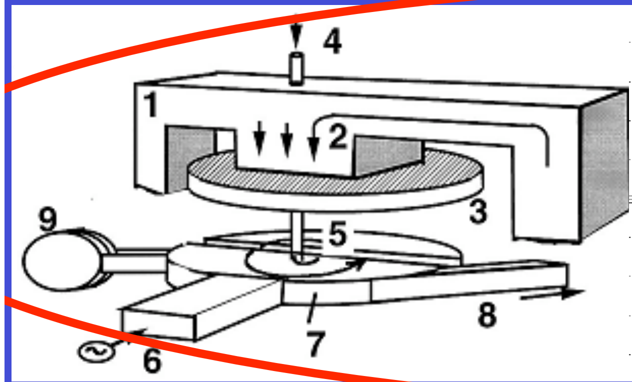
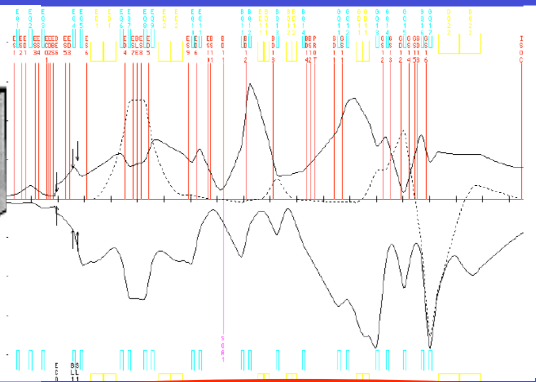
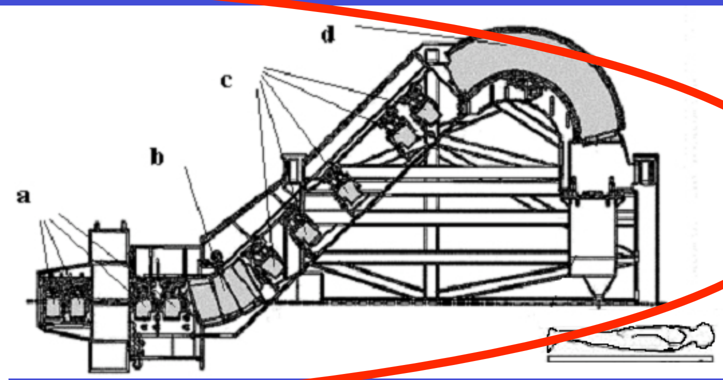


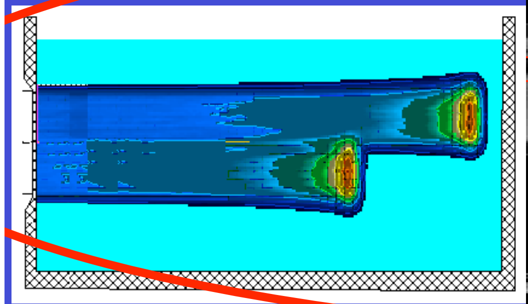
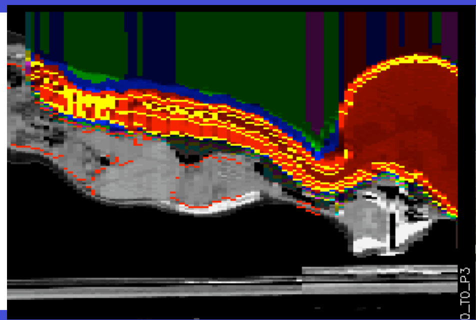
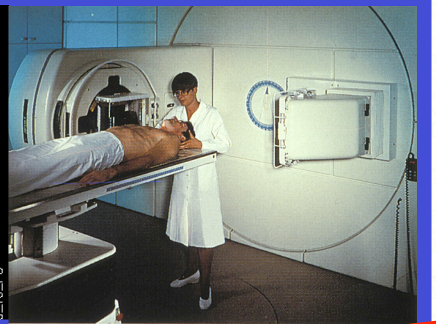
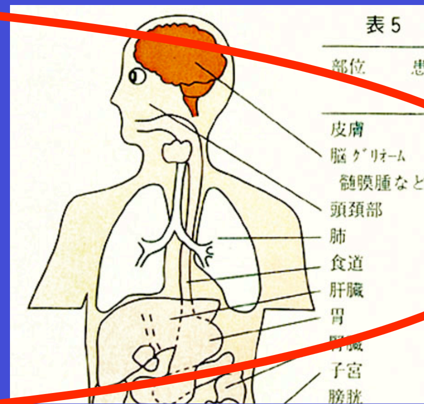
表５　筑波大学の陽子線治療結果

部位	患者数	局所治癒率推定(%)	３年生存率	後遺症
皮膚	8	7 (87.5)	87.5	0
脳 ｸﾞﾘｵｰﾑ	13	3 (23.1)	18.5	3
髄膜腫など	9	8 (88.9)	75.0	0
頭頚部	15	11 (73.3)	81.5	0
肺	19	14 (73.7)	54.1	1
食道	23	18 (78.3)	51.6	3
肝臓	30	26 (86.7)	25.5*	0
胃	5	3 (60.0)	61.0	0
腎臓	5	2 (40.0)	60.0	0
子宮	24	21 (87.5)	72.7	3
膀胱	12	8 (66.7)	62.5	2
前立腺	7	7 (100.0)	68.6	0
小児腫瘍	4	4 (100.0)	75.0	0
その他	4	3 (75.0)	100.0	1
合計	178	135 (75.8)		13(7.1%)

*肝機能良好例の3年生存率75.0%



Goals of this introduction on physical bases:

1) **Qualitative (myself) & Quantitative data (Mike Moyers)**
2) **Interactions particles:**
   - **with electric & magnetic fields**
   - **with matter (beam shaping devices, patient,…)**

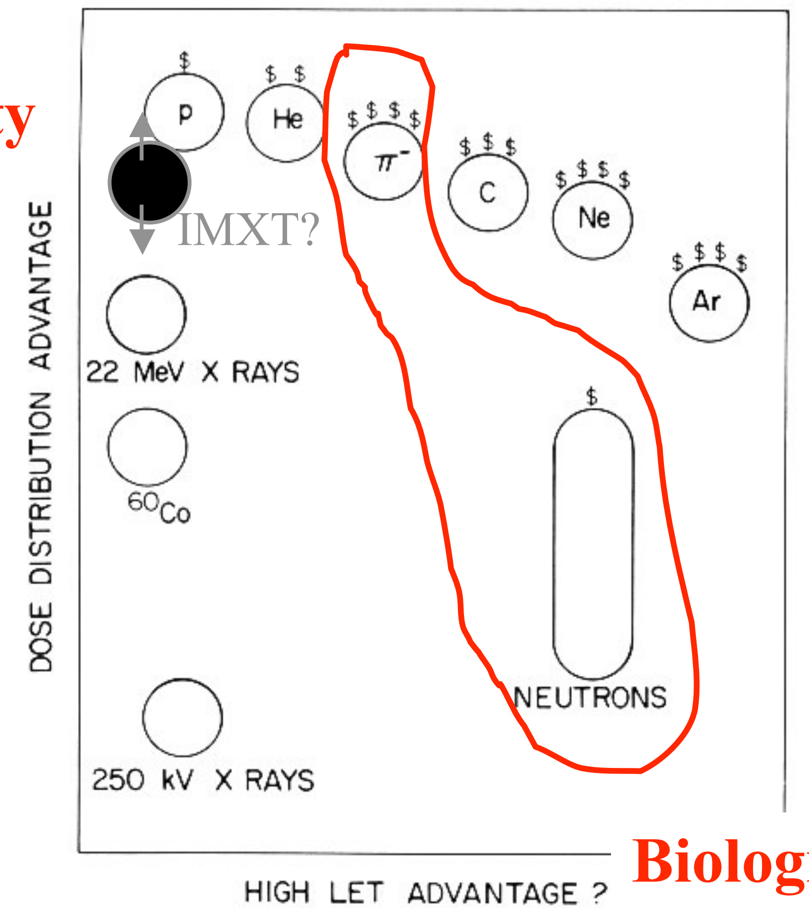
I. Which particles are we talking about?

« Hadrons » in therapy

Physical selectivity and/or Radiobiological effects

* pions
* fast & slow neutrons
* protons
* light and heavy ions

Physical selectivity

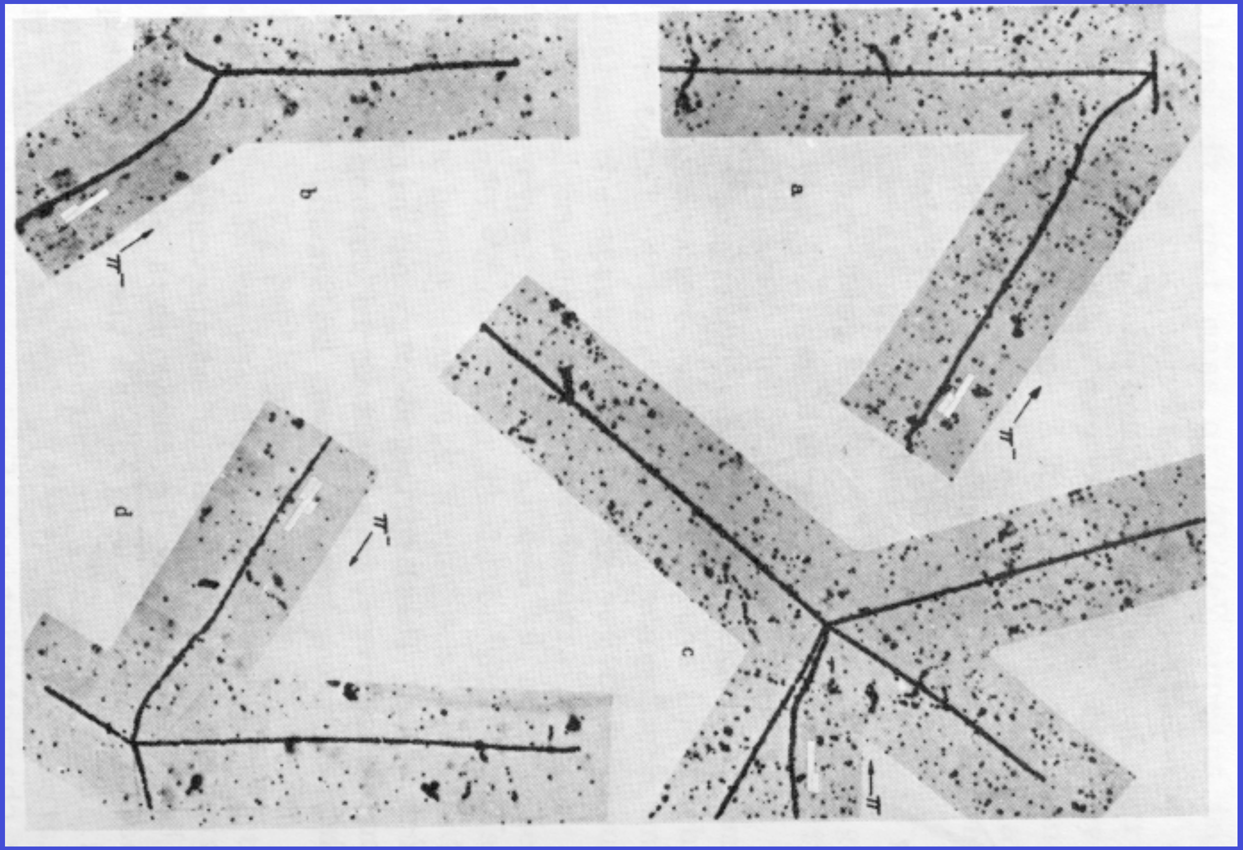


Biological Advantages

Raju & Koehler, 1980

Pi meson (pions)

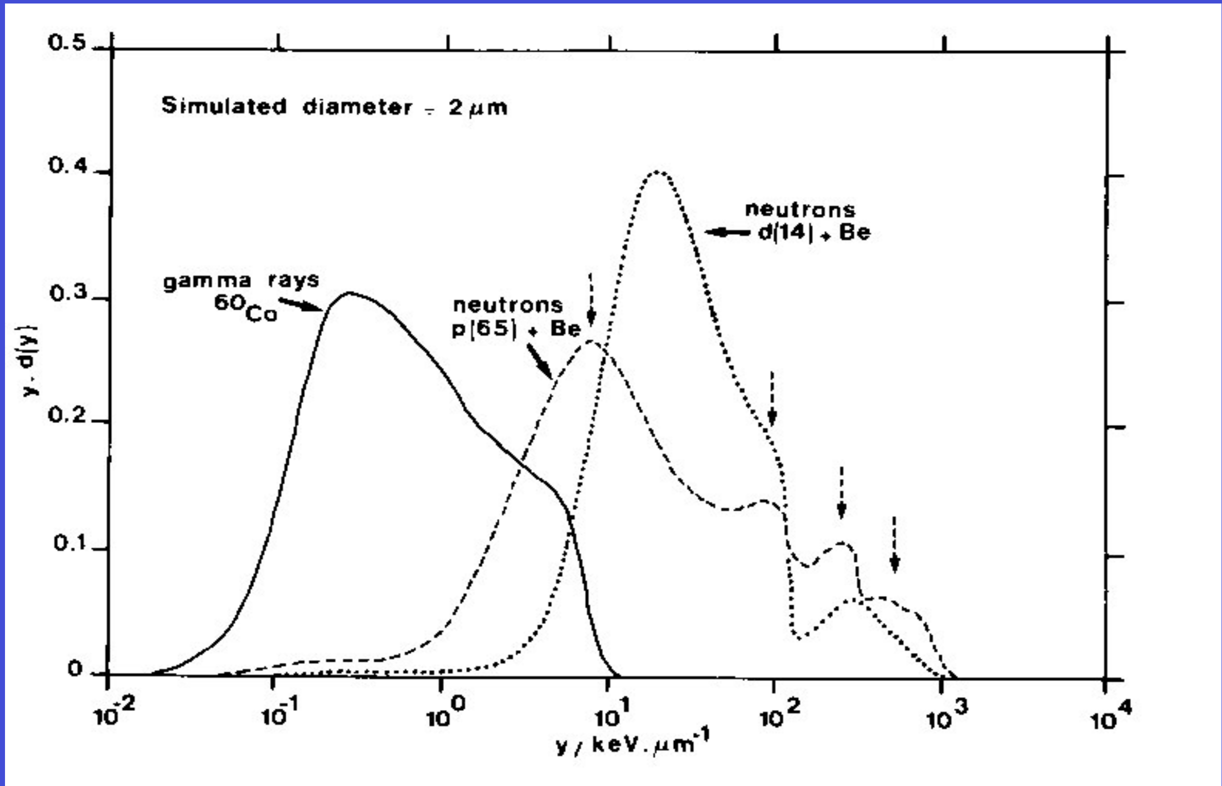
* « Ideal particles »? High expectations in 60 's
* « Star » near end of range (p,α,h.i.,n,γ)



Raju, 1980

<u>NEUTRONS :</u> * Depth dose similar to photons (eg: 8 MV)

* High LET -> High RBE



Menzel,1990

* ↘ OER : lower radioresistance of hypoxic cells

* ↘ importance of sublethal lesions: ↘ n° of fractions

* ↘ differences in radiosensitivity : cell cycle, different tissues

« Hadrons » in therapy

Physical selectivity and/or Radiobiological effects

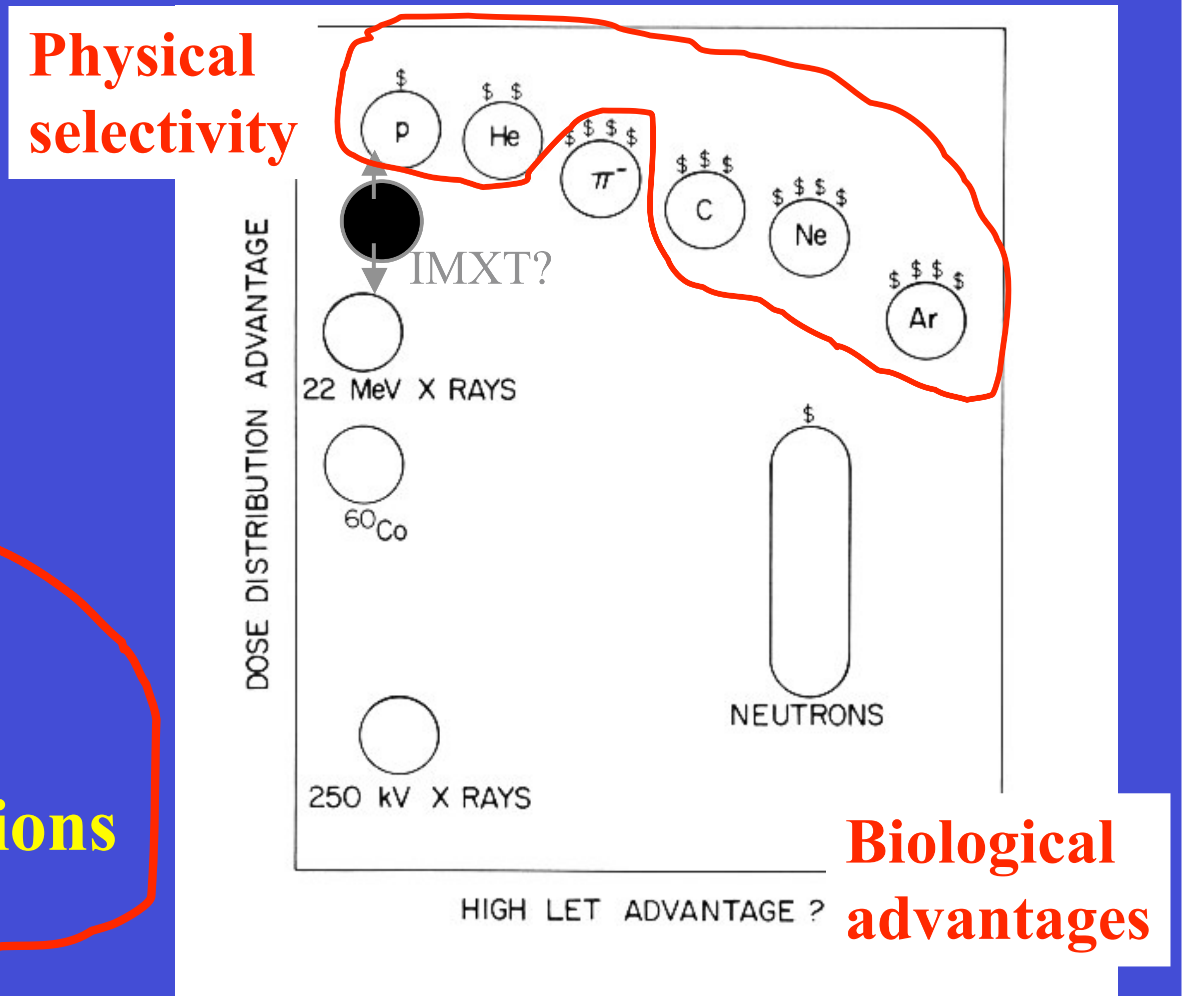
* pions

* fast

& slow neutrons

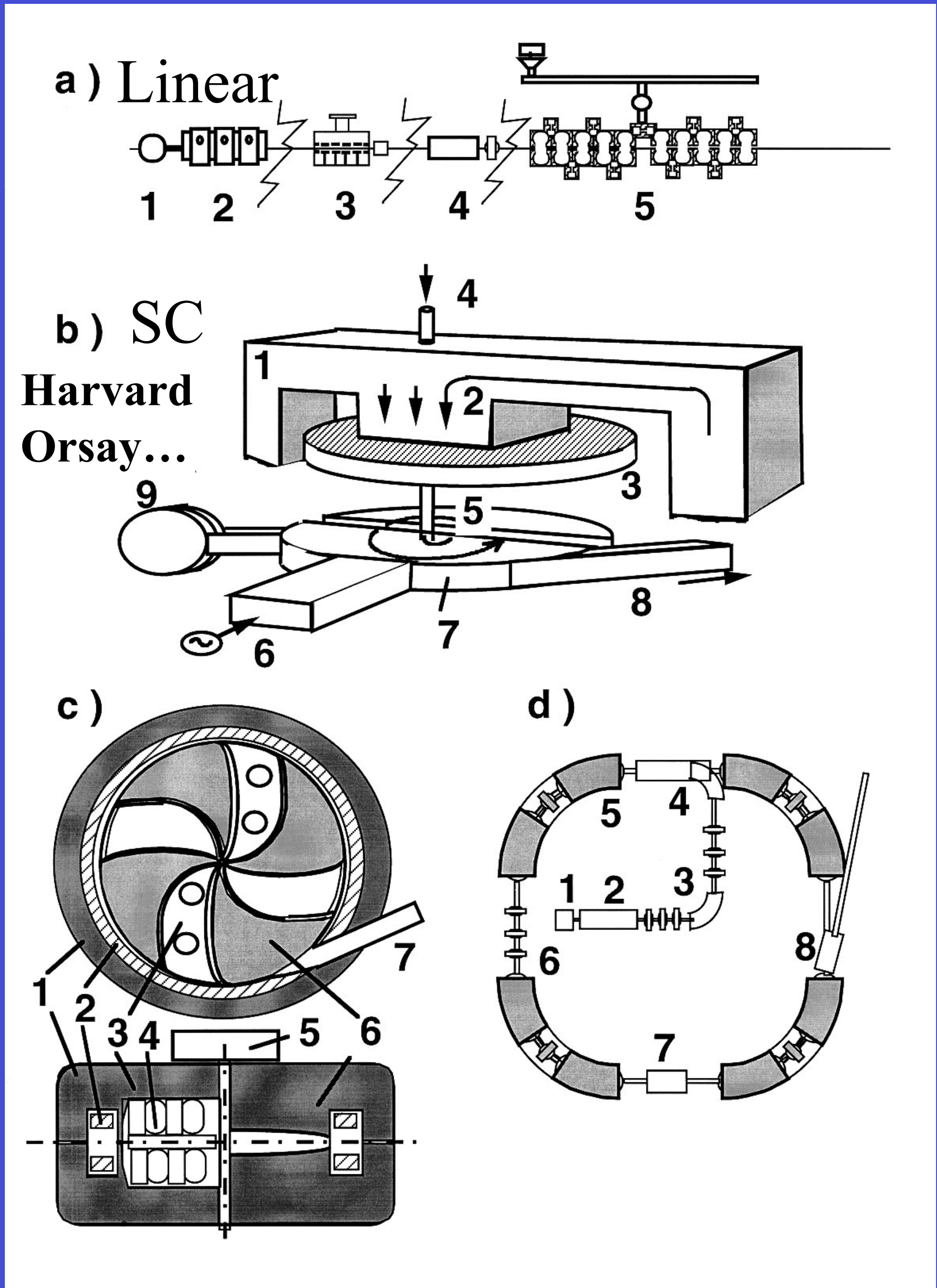
* protons

* light and heavy ions

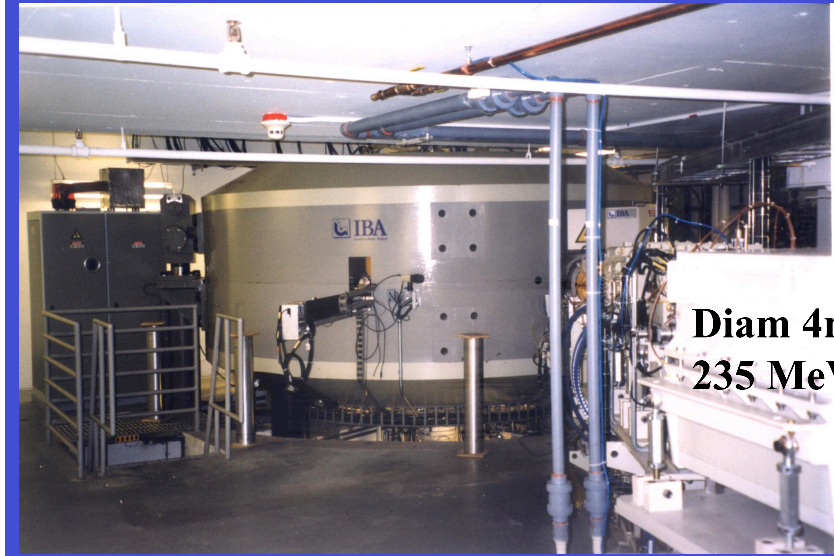


Raju & Koehler, 1980

II. Interaction of charged particles with Electric (E) & Magnetic (B) fields



c) Cyclotron (IBA, Accel,…) : Y.Jongen

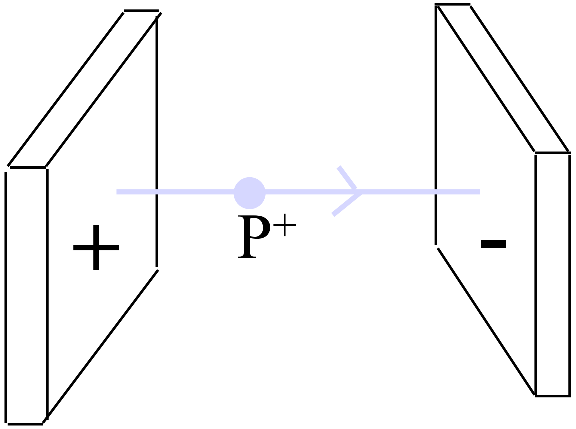


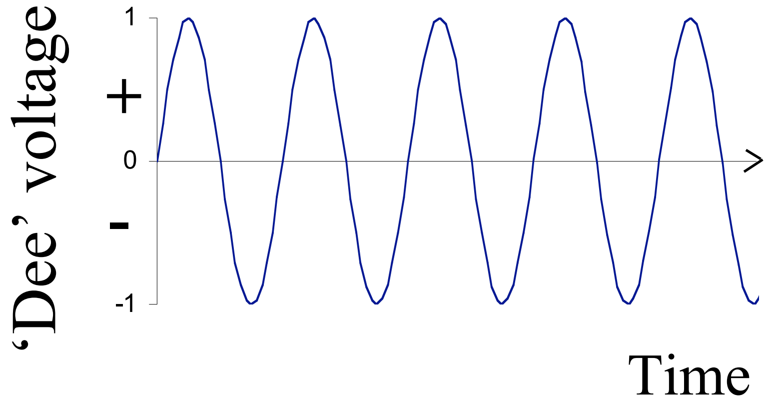
d) Synchrotron : G.Coutrakon

(Mitsubishi, Hitachi,Optivus, Siemens,..

J.Flanz: new approaches

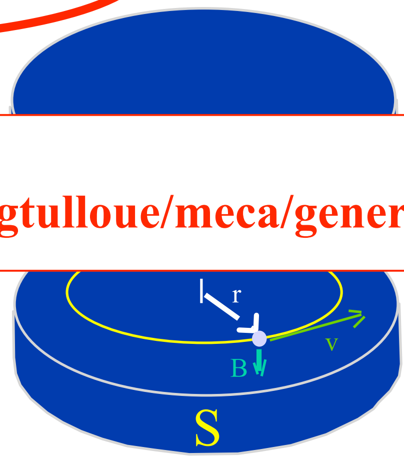
Beam production





Acceleration of a Charged Particle by Electric field in a magnetic field

$$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \wedge \mathbf{B})$$



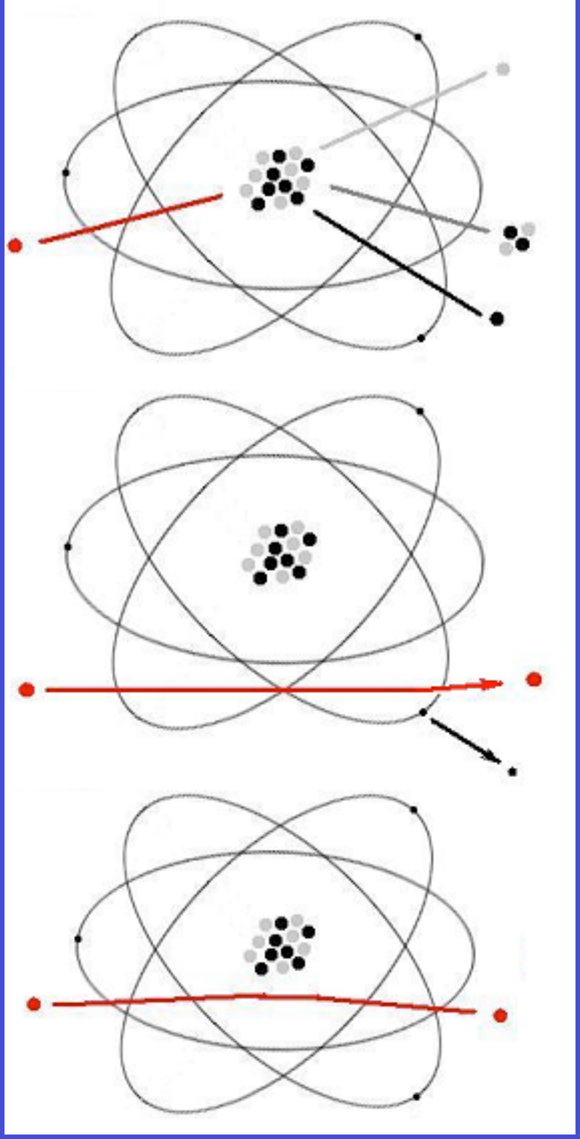
Genevieve.Tulloue
www.sciences.univ-nantes.fr/physique/perso/gtulloue/meca/general.html

'Dee' Electrodes in Magnet

Particle Motion in Magnetic Field

III. Interaction of charged particles with Matter

Many interactions of particles with matter …
But keep 3 :



Inelastic collision w/nuclei :
neutrons & others

Inelastic collision with electrons:
Dose

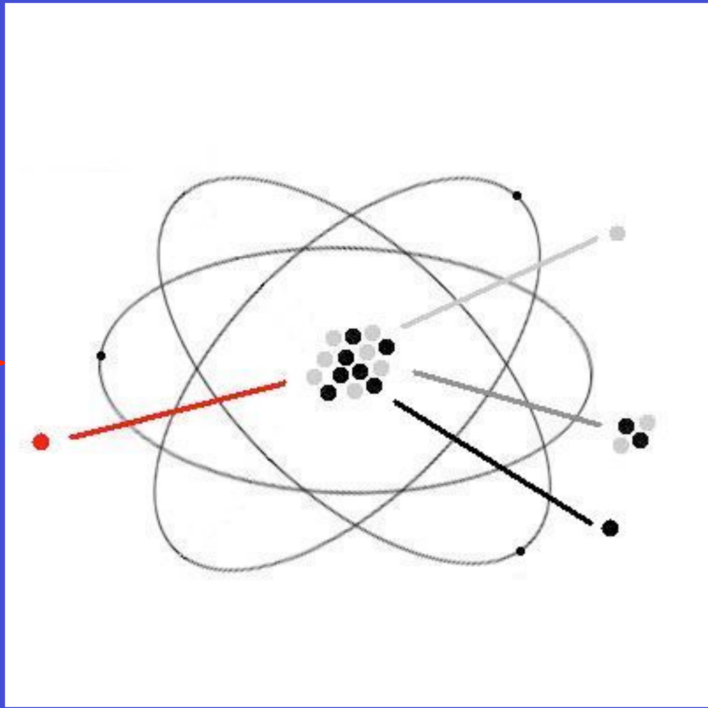
Elastic collision w/nuclei:
« multiple Coulomb scattering » :
all the effects you do not know why

BEAM-TARGET INTERACTIONS :

Mid & High Energy :
(10-250 MeV protons)

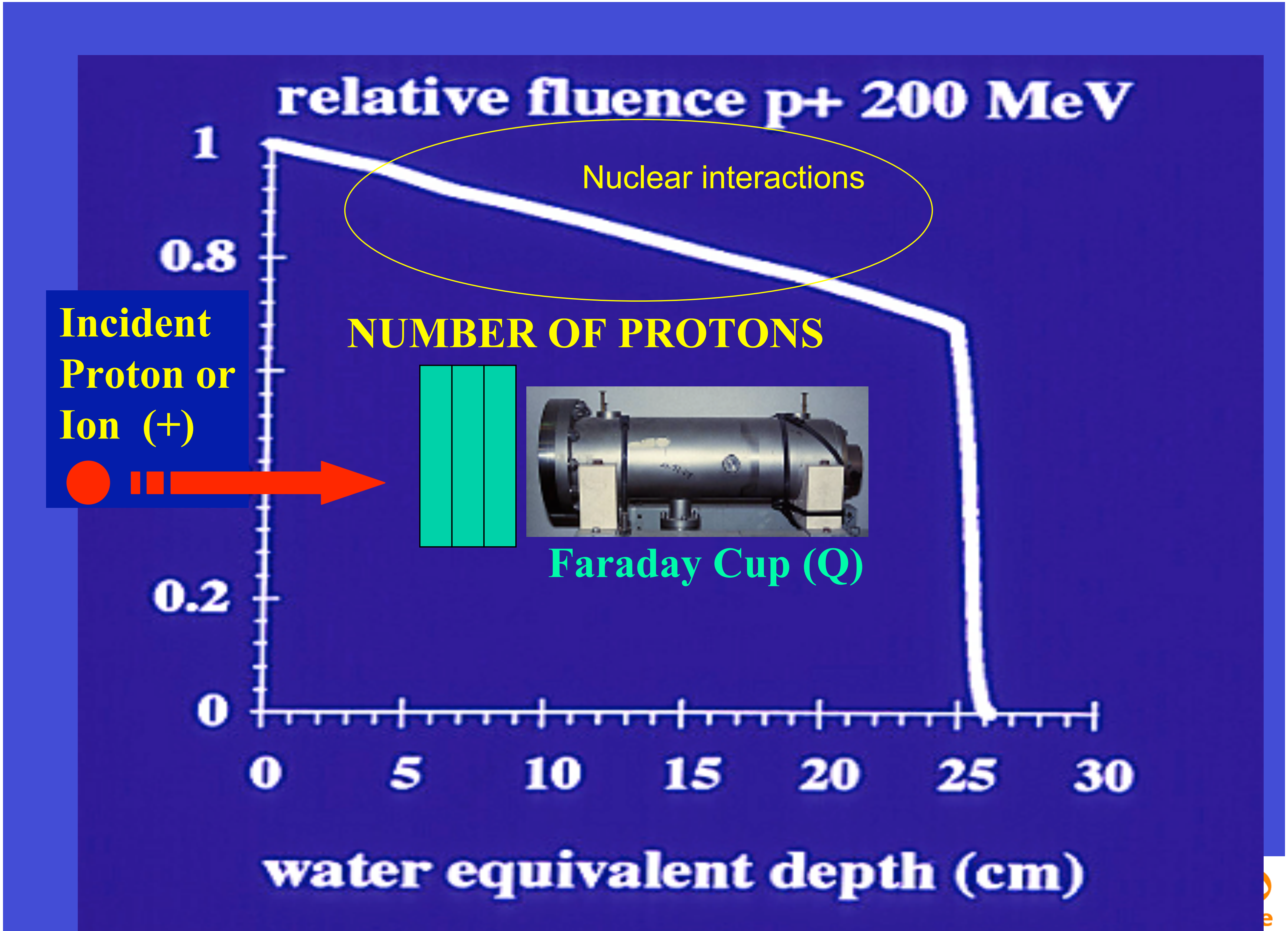
Inelastic collision w/nucleus & nuclear reactions

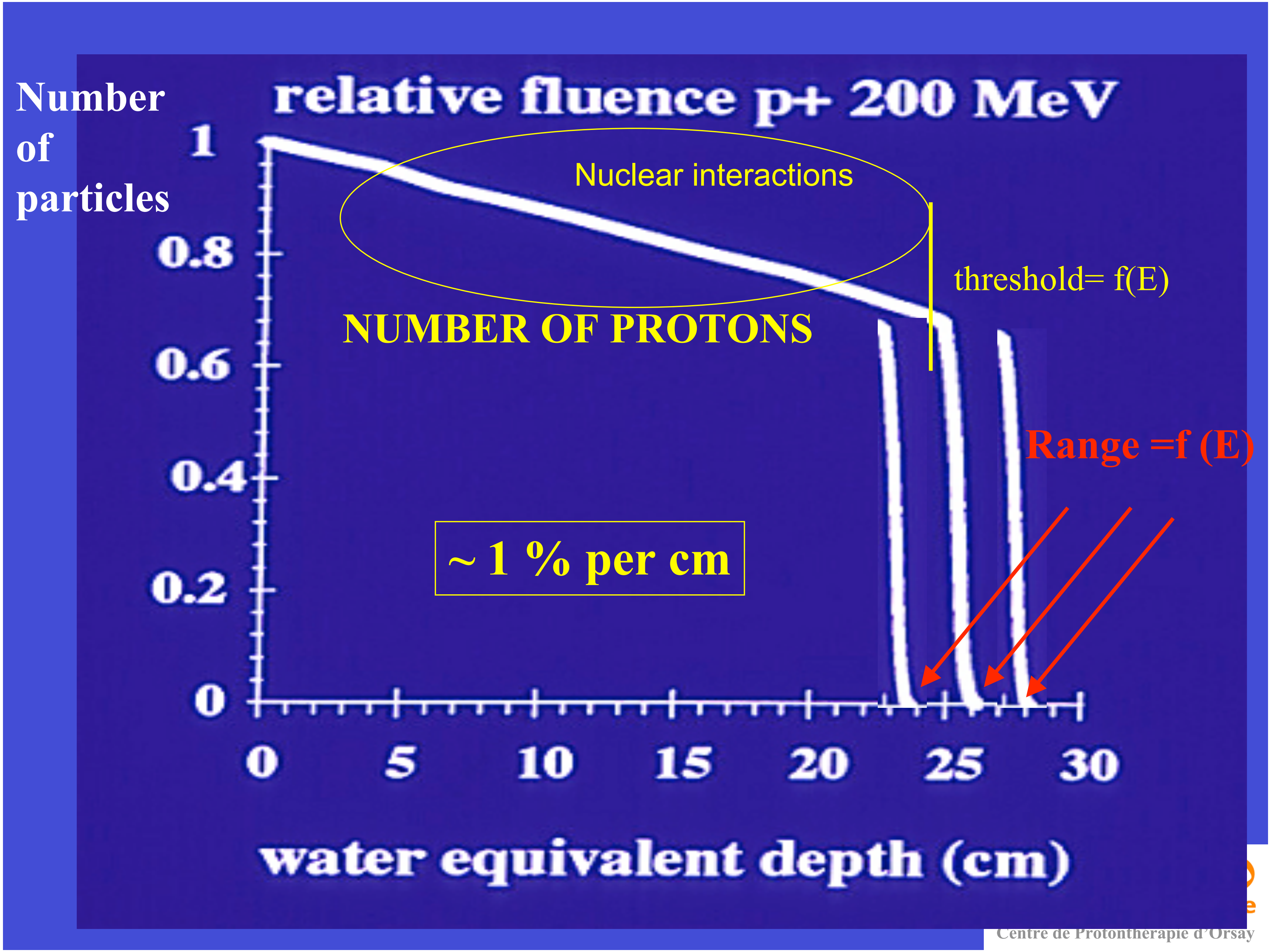
Incident Proton or Ion (+)



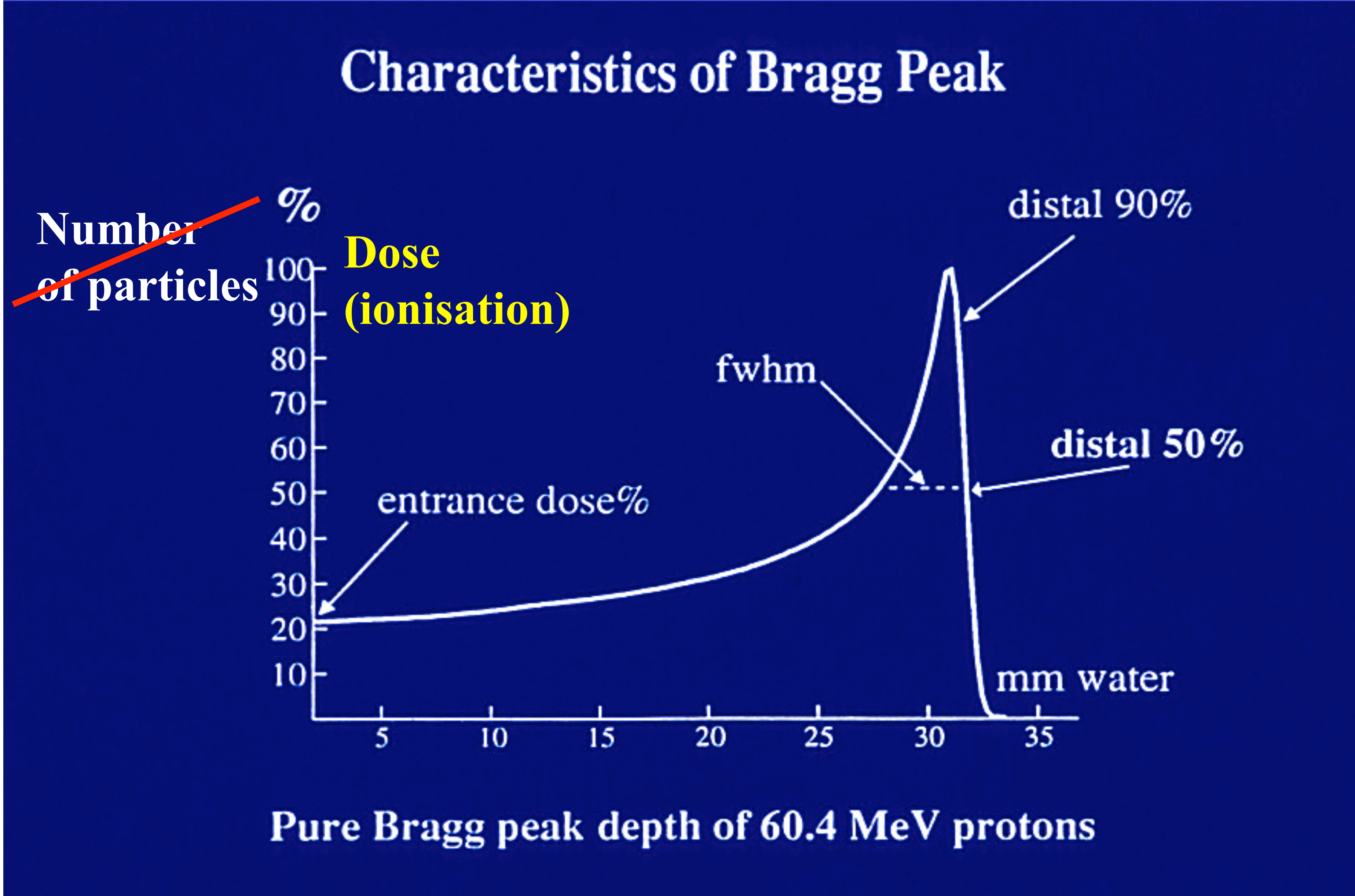
- Neutrons:
  shielding
  patient dose
- Fragments
- Protons (large angles)
- Activation → gamma,…
  Accelerator, Beam line
  Patient →PET

→ *Disappearance of incidental protons*


relative fluence p+ 200 MeV
1
0.8
0.2
0
Nuclear interactions
NUMBER OF PROTONS
Incident
Proton or
Ion (+)
Faraday Cup (Q)
0
5
10
15
20
25
30
water equivalent depth (cm)


Number of particles
relative fluence p+ 200 MeV
Nuclear interactions
threshold= f(E)
NUMBER OF PROTONS
Range =f (E)
~ 1 % per cm
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
water equivalent depth (cm)

So, why do we have a « Bragg peak »?

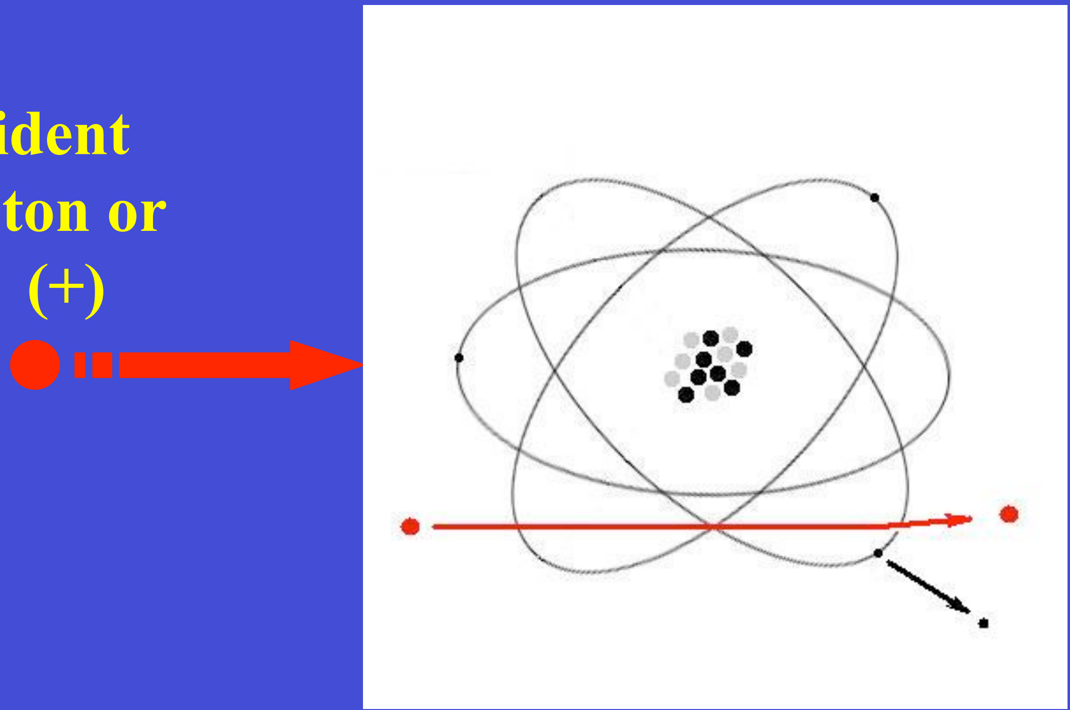


BEAM-TARGET INTERACTIONS :

Intermediate Energy (0.1- 250 MeV)

<u>Inelastic Collision with electrons</u>

Incident Proton or Ion (+)



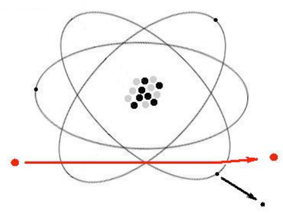
-Protons : E loss & very small angle

-Electrons: Ionization, excitation

Addition of <u>Small Amounts</u> of Converted Energy per Unit Mass

« CEMA »

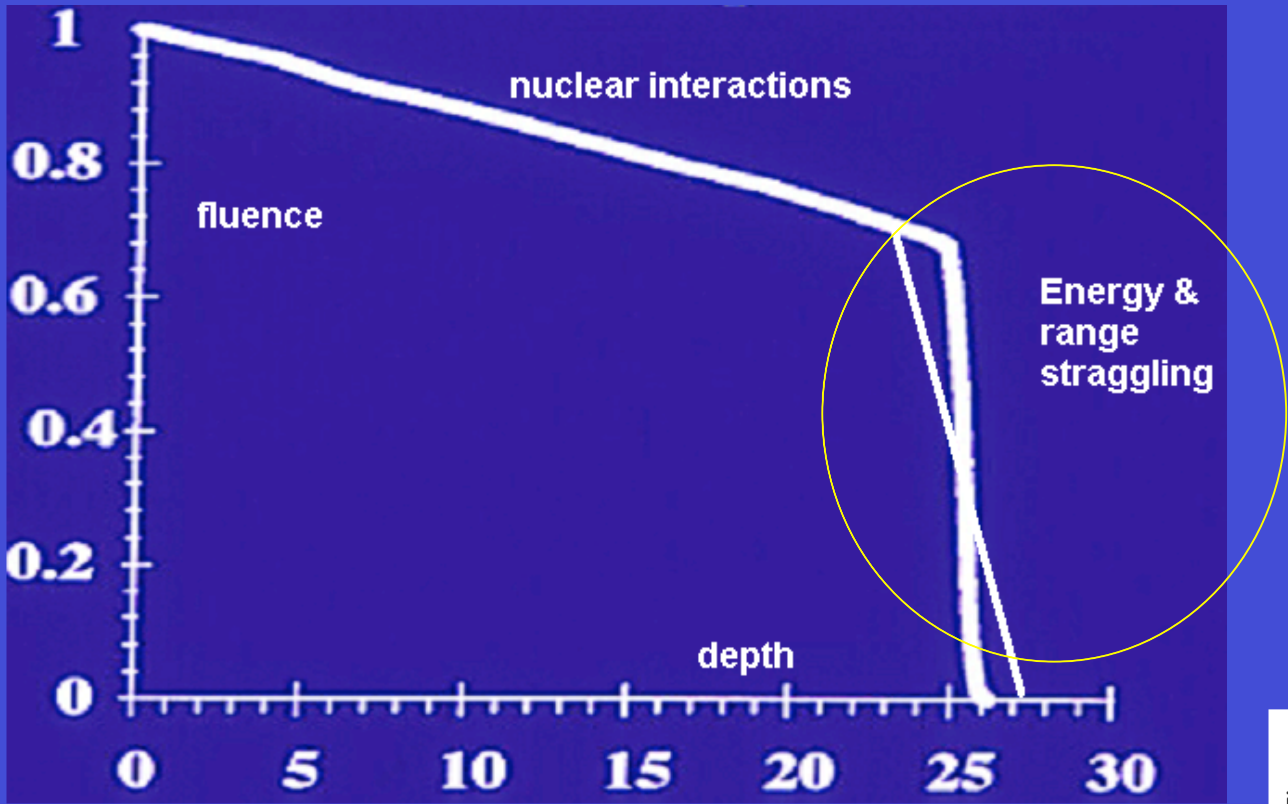
<u>Collisions with electrons : </u> keep 3 concepts



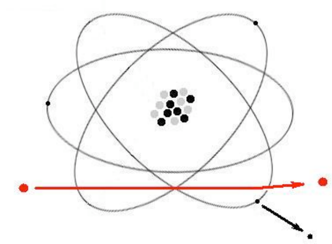
1st concept) :

Large number of events loosing small energy

Statistical ➔ <u>" range straggling"</u>



Collisions with electrons

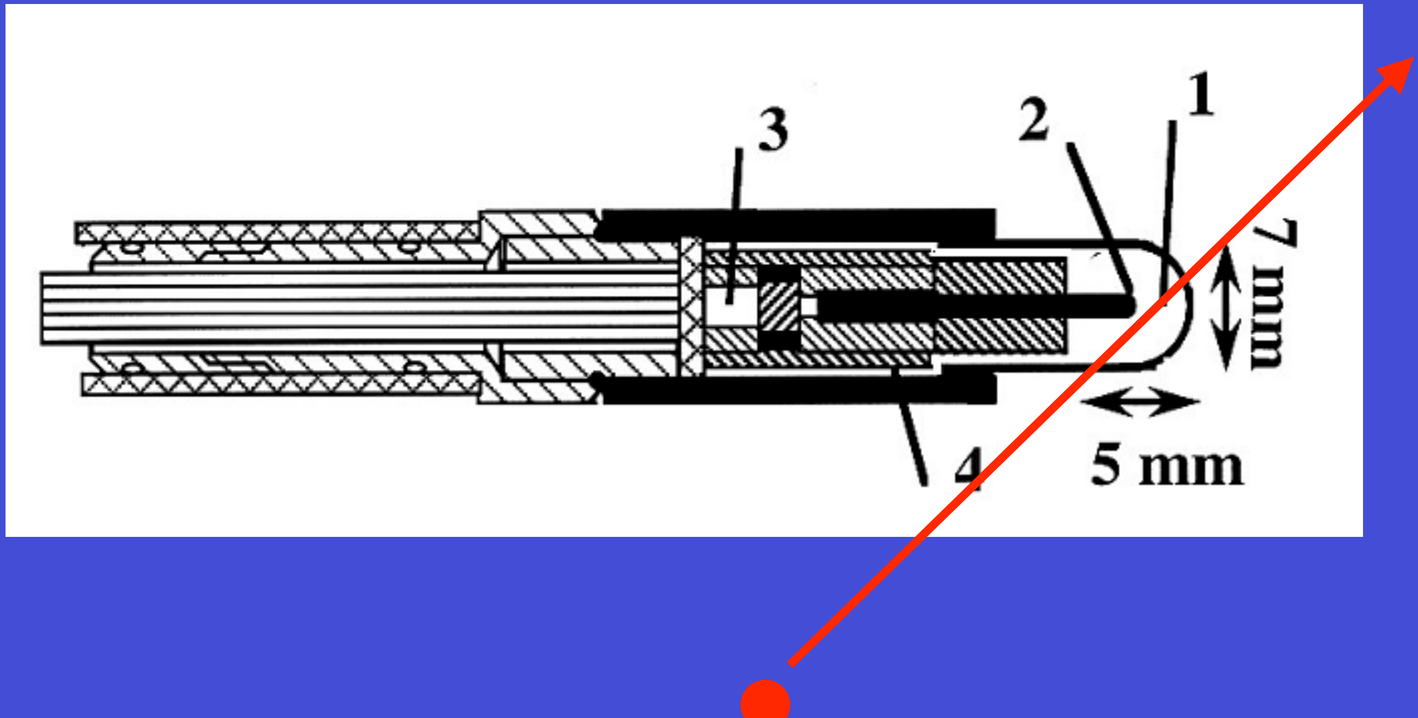


2nd concept) Statistics

➔ not always the same energy lost

W : mean energy to form an ion pair

Ex in air : ~ 34.8 J/C ➔ Protocols for ion chamber dosimetry



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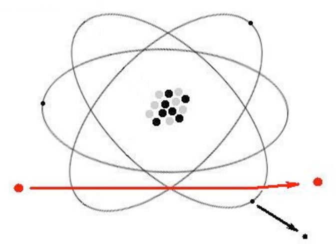
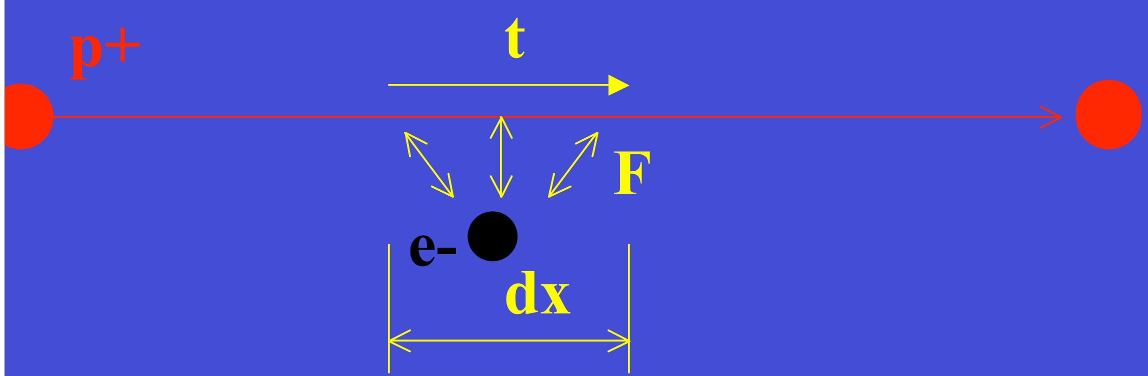
Collisions with electrons



3rd concept) **Stopping Power « S » = dE / dx**

Mean Energy dE lost in electronic collisions while traversing a distance dx [MeV / mm]



$$(dE/dx) = 4 \pi z_{eff}^2 e^4 \frac{(N_A Z)}{A m_e v^2} \{ \ln (2mv^2 / I (1-\beta^2)) - \beta^2 - \Sigma(Ci/Z) \}$$

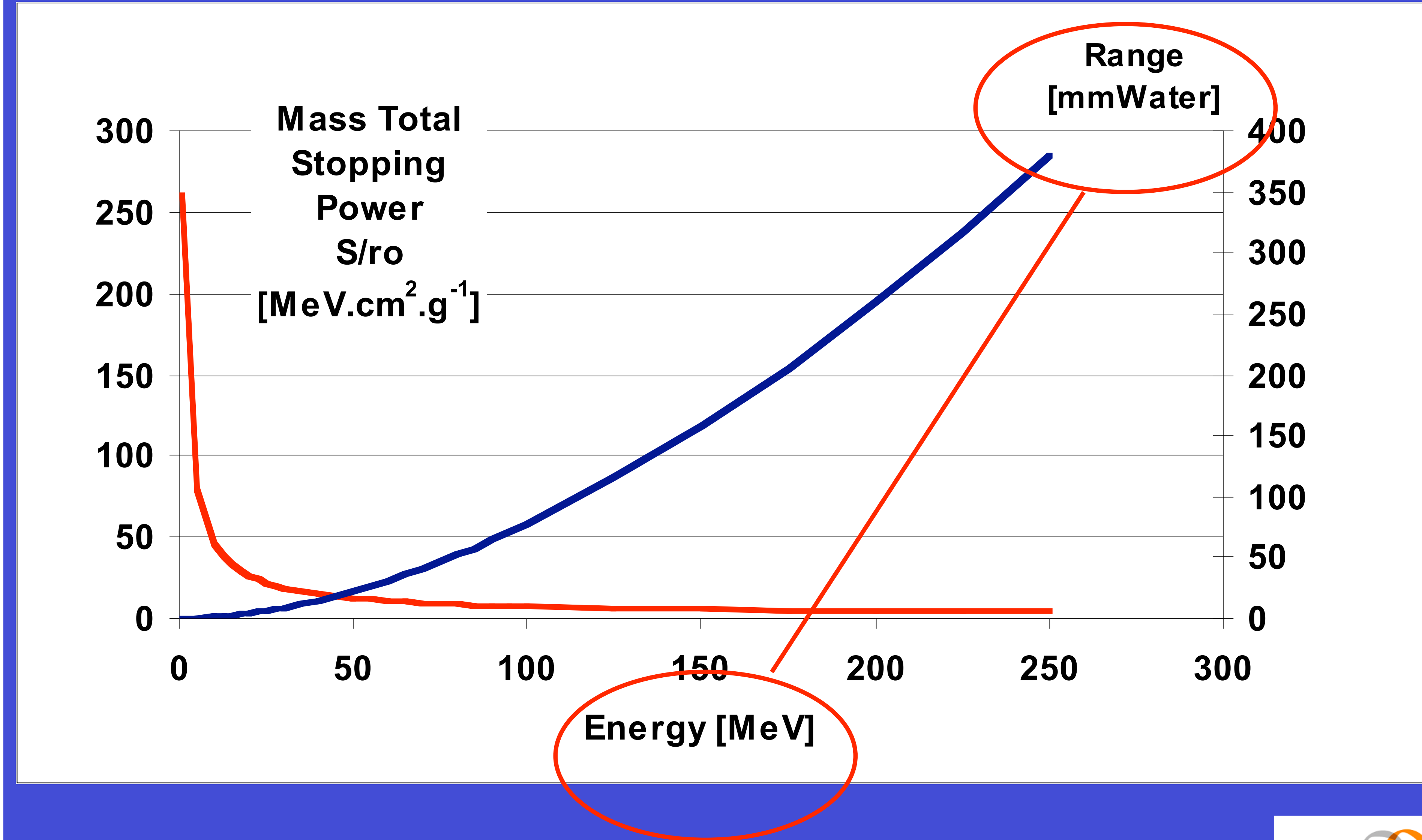
Small Energy → High Stopping Power

A bit of fun: the « S power »
Or the power of Skate Board

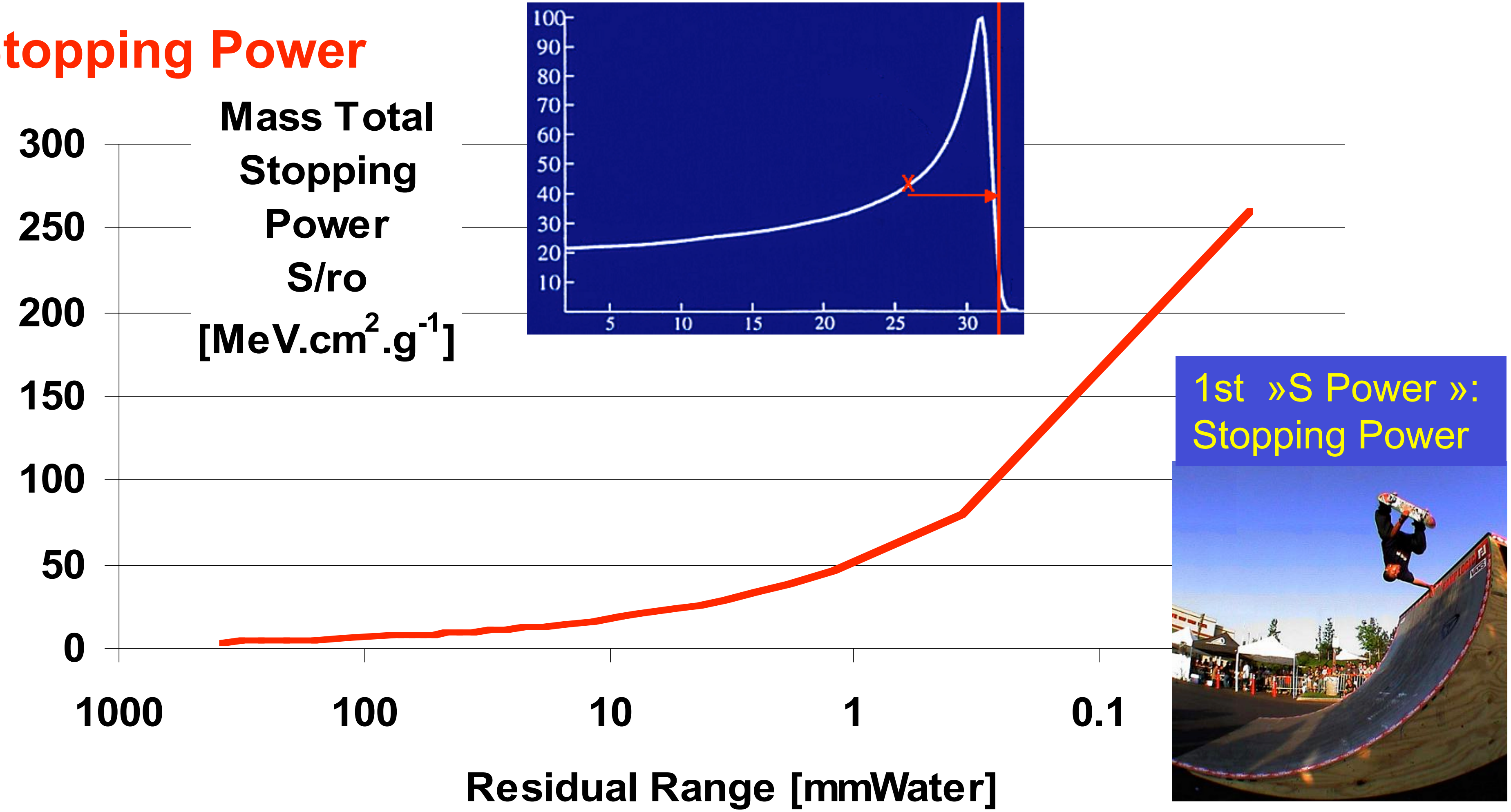
1) **<u>Stopping power</u> increases with depth like a skate ramp**

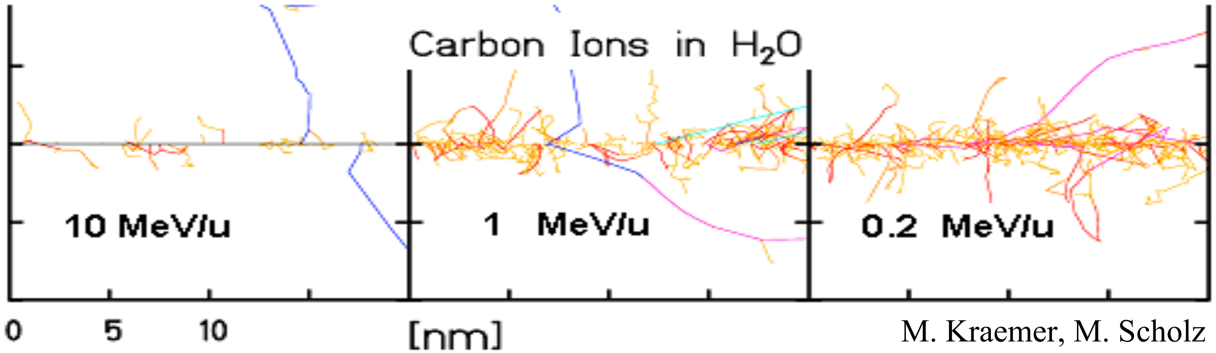
2) **<u>Scattering power</u> increases with depth like a skate ramp**

Stopping Power and Range = f (E)

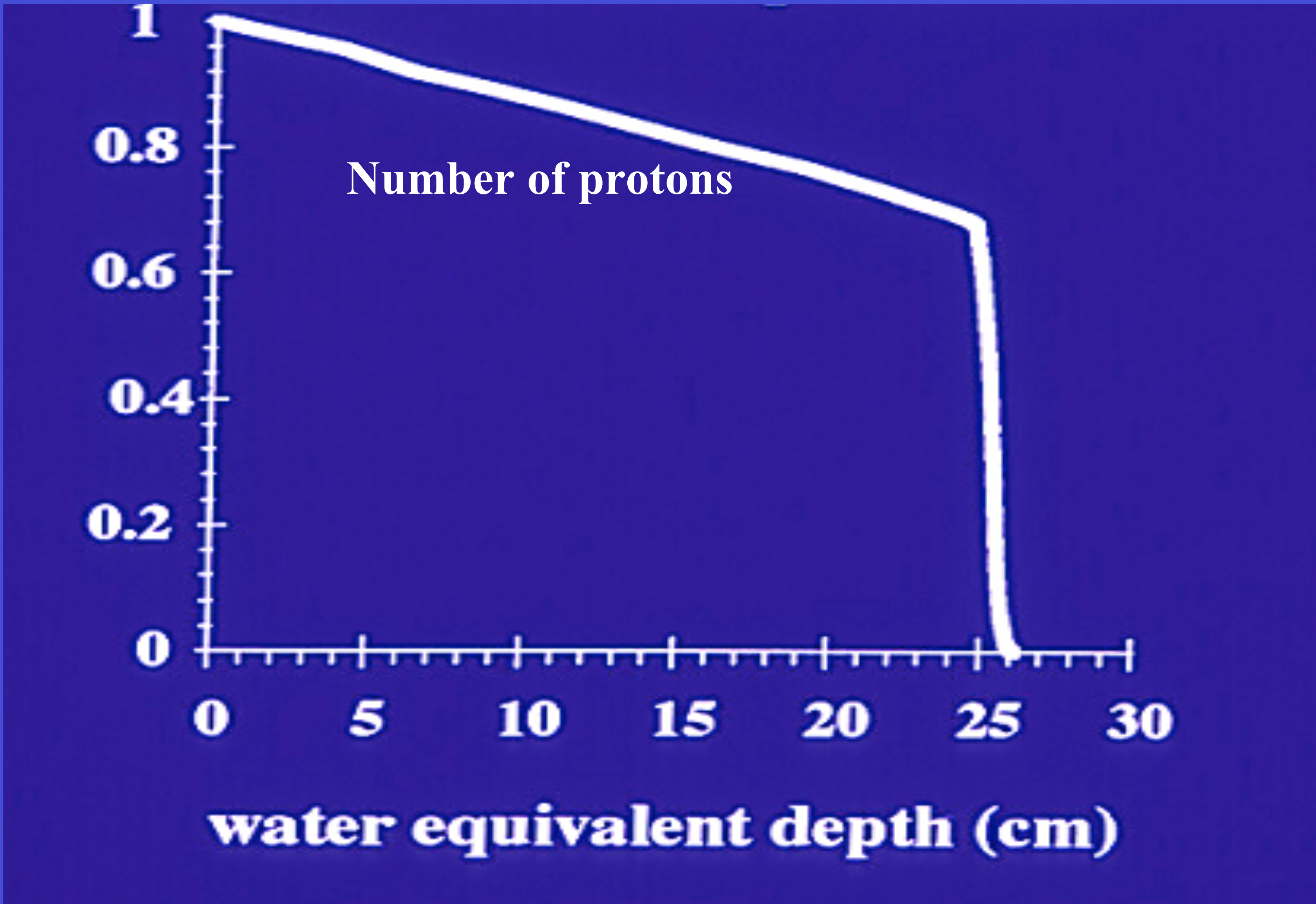


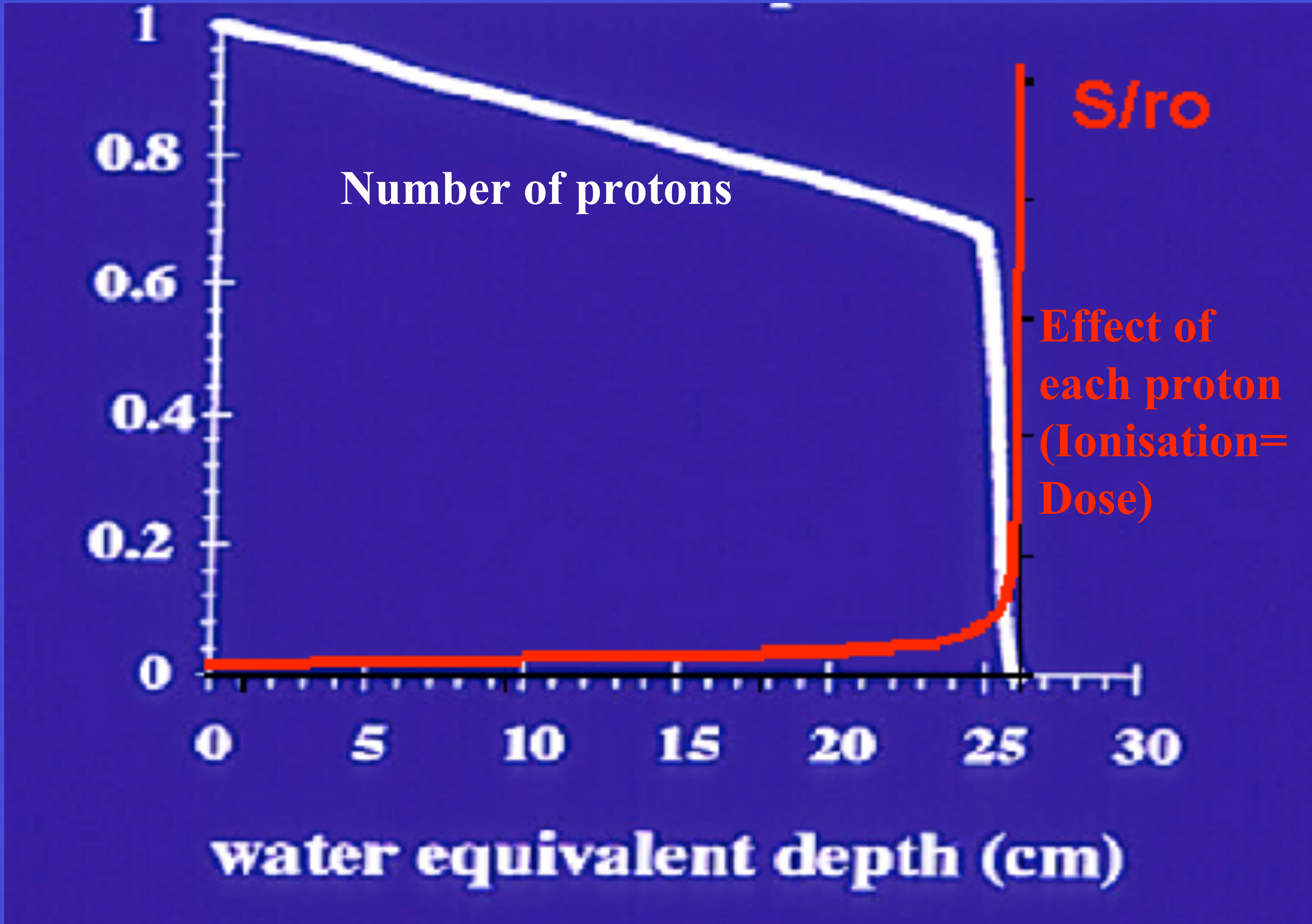
Stopping Power

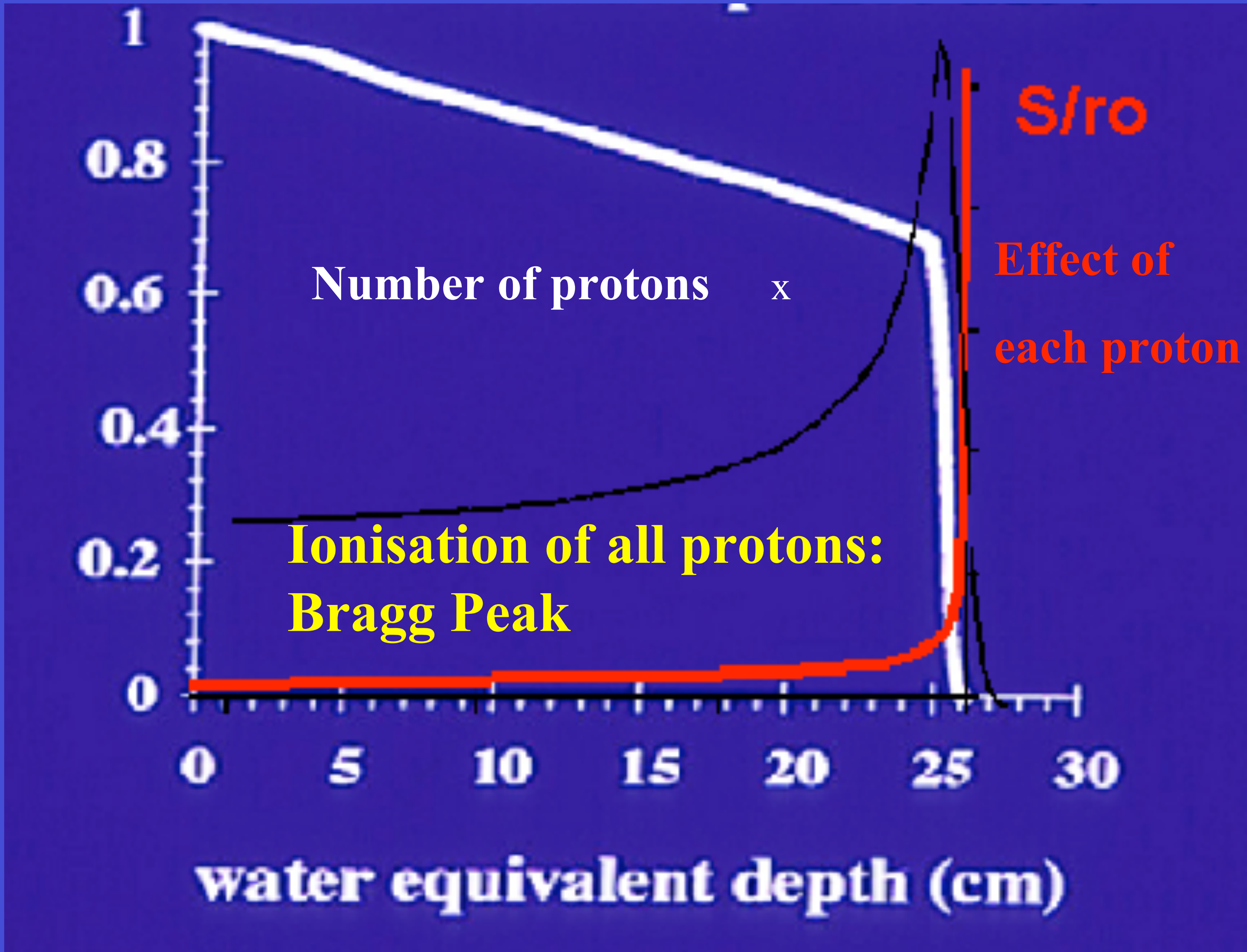




M. Kraemer, M. Scholz

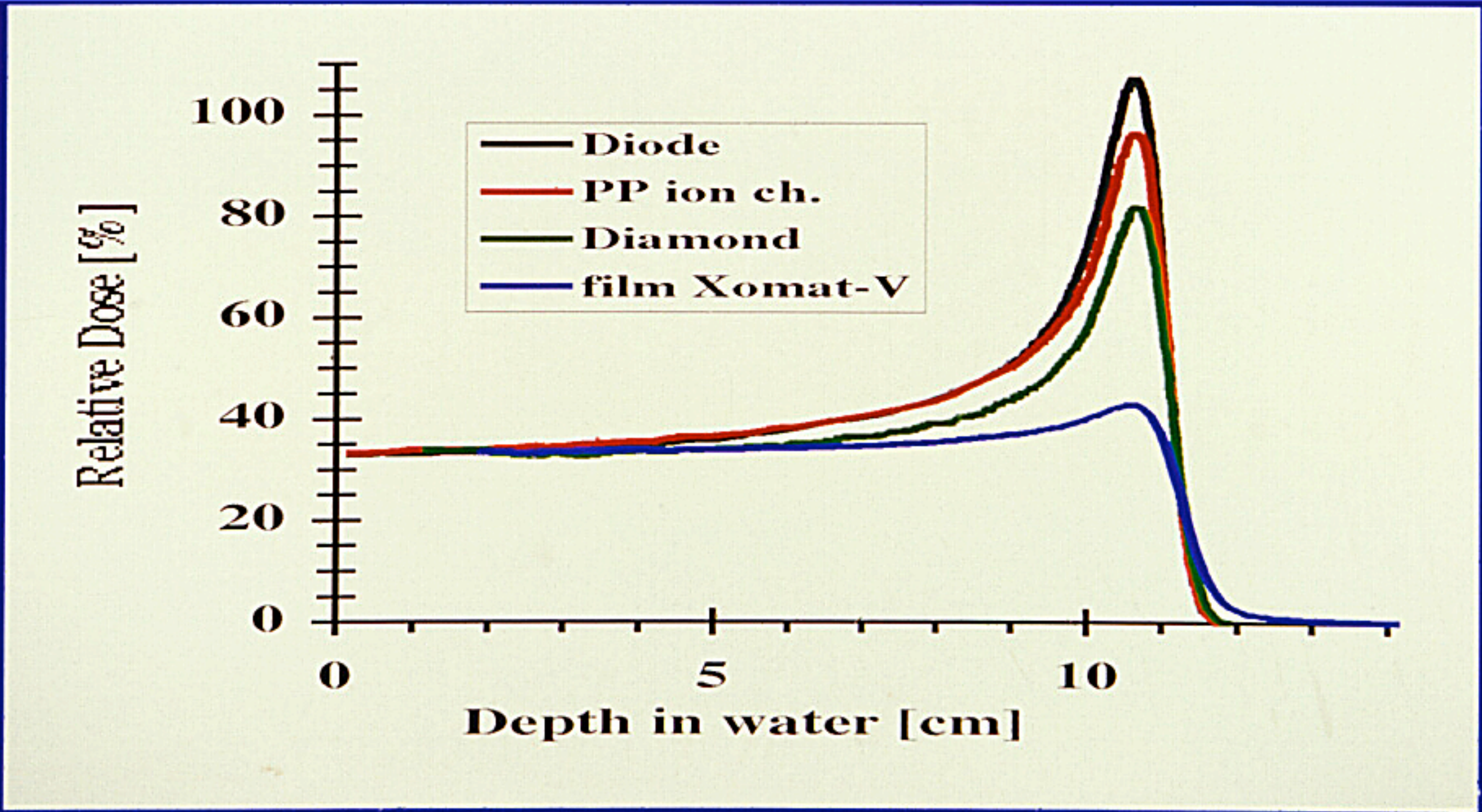

1
0.8
0.6
0.4
0.2
0
Number of protons
0
5
10
15
20
25
30
water equivalent depth (cm)


1
0.8
0.6
0.4
0.2
0
Number of protons
S/ro
Effect of each proton (Ionisation= Dose)
0
5
10
15
20
25
30
water equivalent depth (cm)



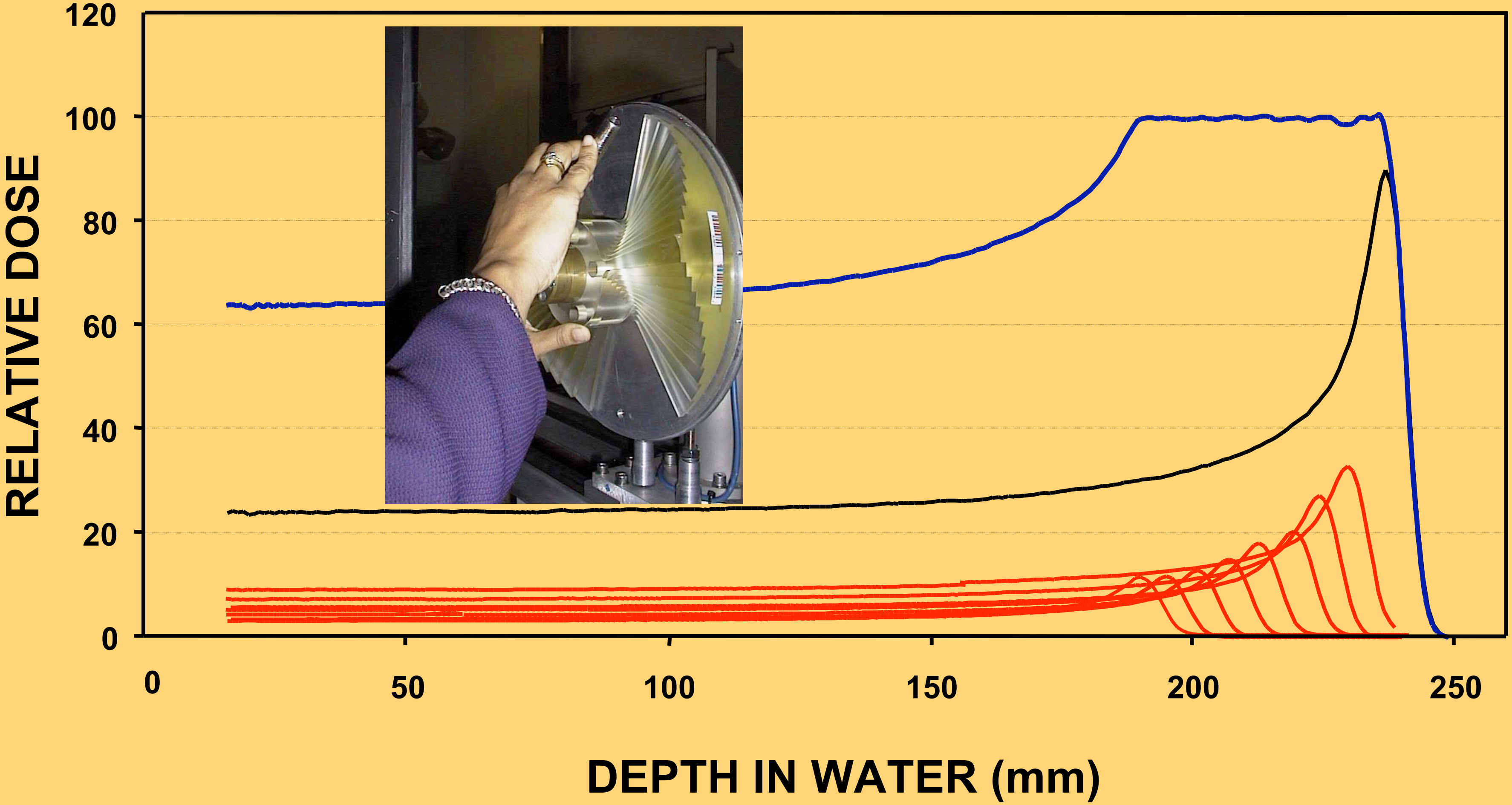
1
0.8
0.6
0.4
0.2
0
S/ro
Number of protons x
Effect of
each proton
Ionisation of all protons:
Bragg Peak
0 5 10 15 20 25 30
water equivalent depth (cm)

Stopping power effect on detectors: saturation…



→ **Test any detector in the peak area to know its response to S/ro !**

Spread-out Bragg Peak (SOBP)



(Niek Schreuder & Orsay)

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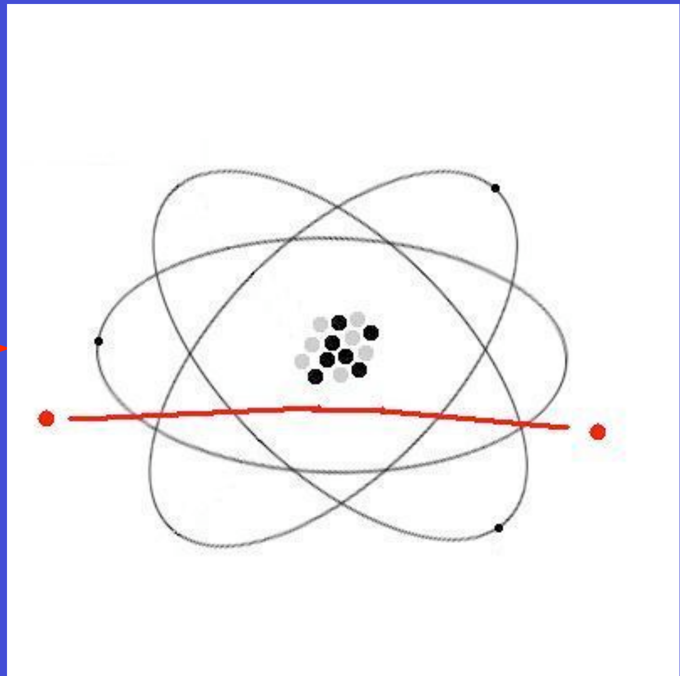
BEAM-TARGET INTERACTIONS :

<u>**Elastic collision w/nucleus**</u>

Incident Proton or Ion (+)

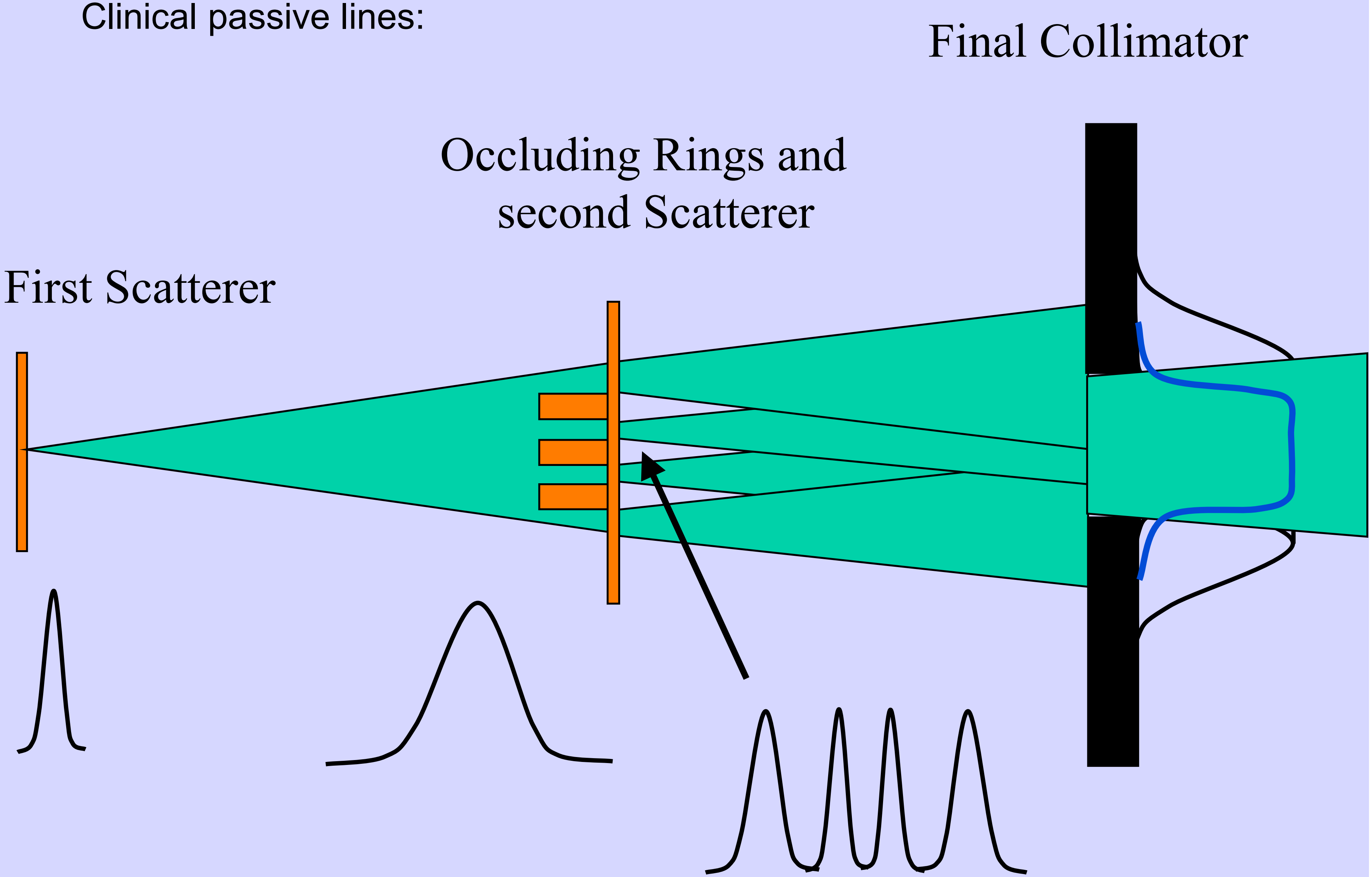


Coulomb multiple small angle scattering

→ ***after traversing a thin foil*** → ***~ gaussian***

$$\theta_0 = 14.1 \frac{z}{p\,v} \{ \mathrm{sqrt}\,(L / L_R) \; (1 + \log(L / L_R) / 9) \}$$

Clinical passive lines:



(from Niek Schreuder,Indiana)

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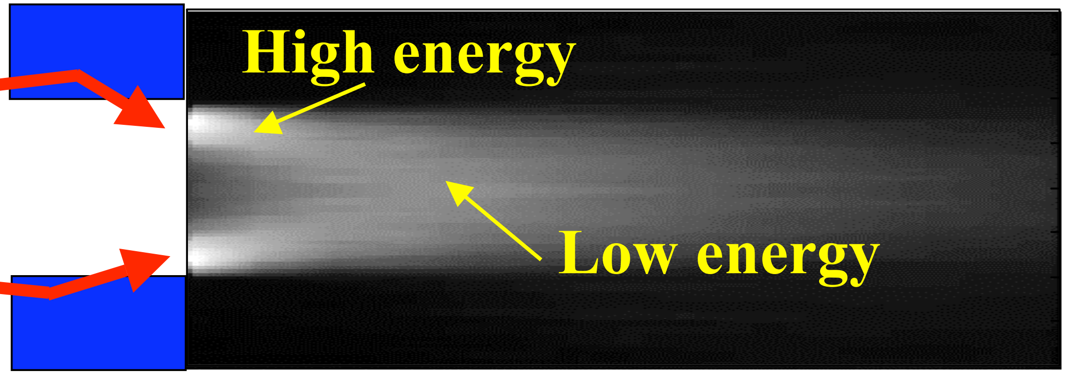
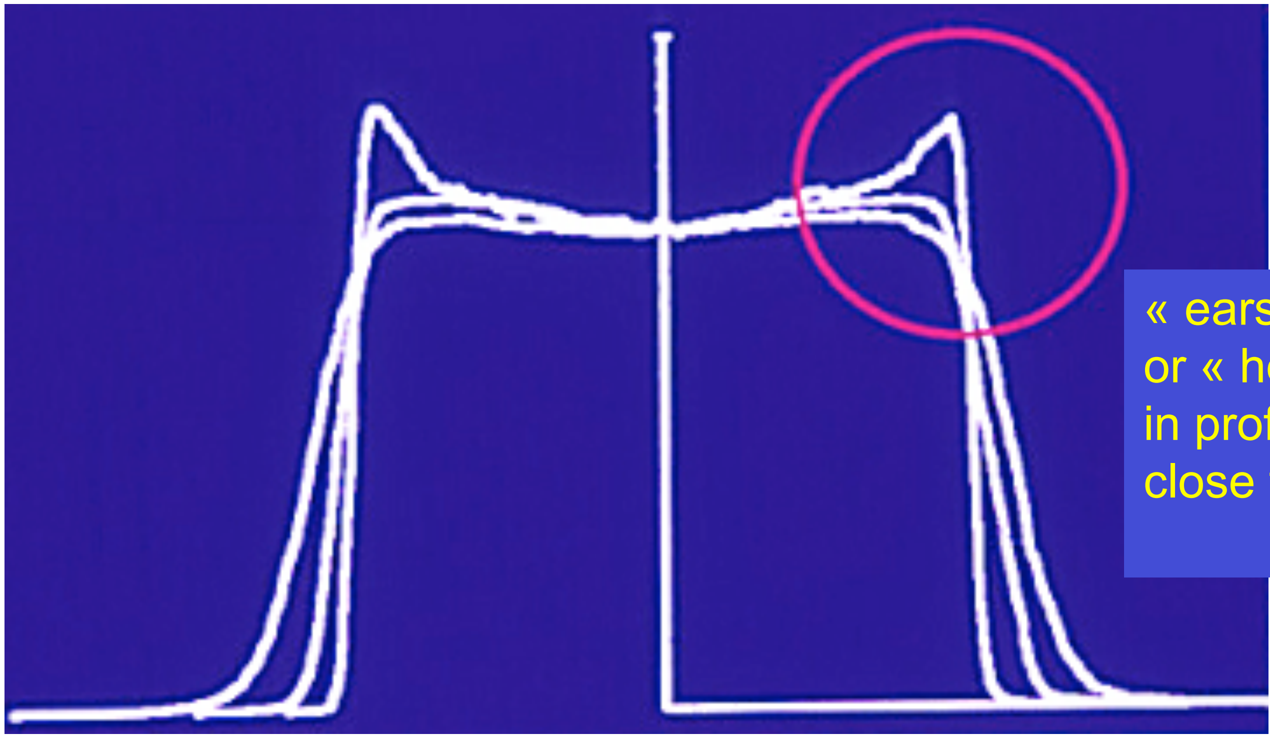
spreading “ears”

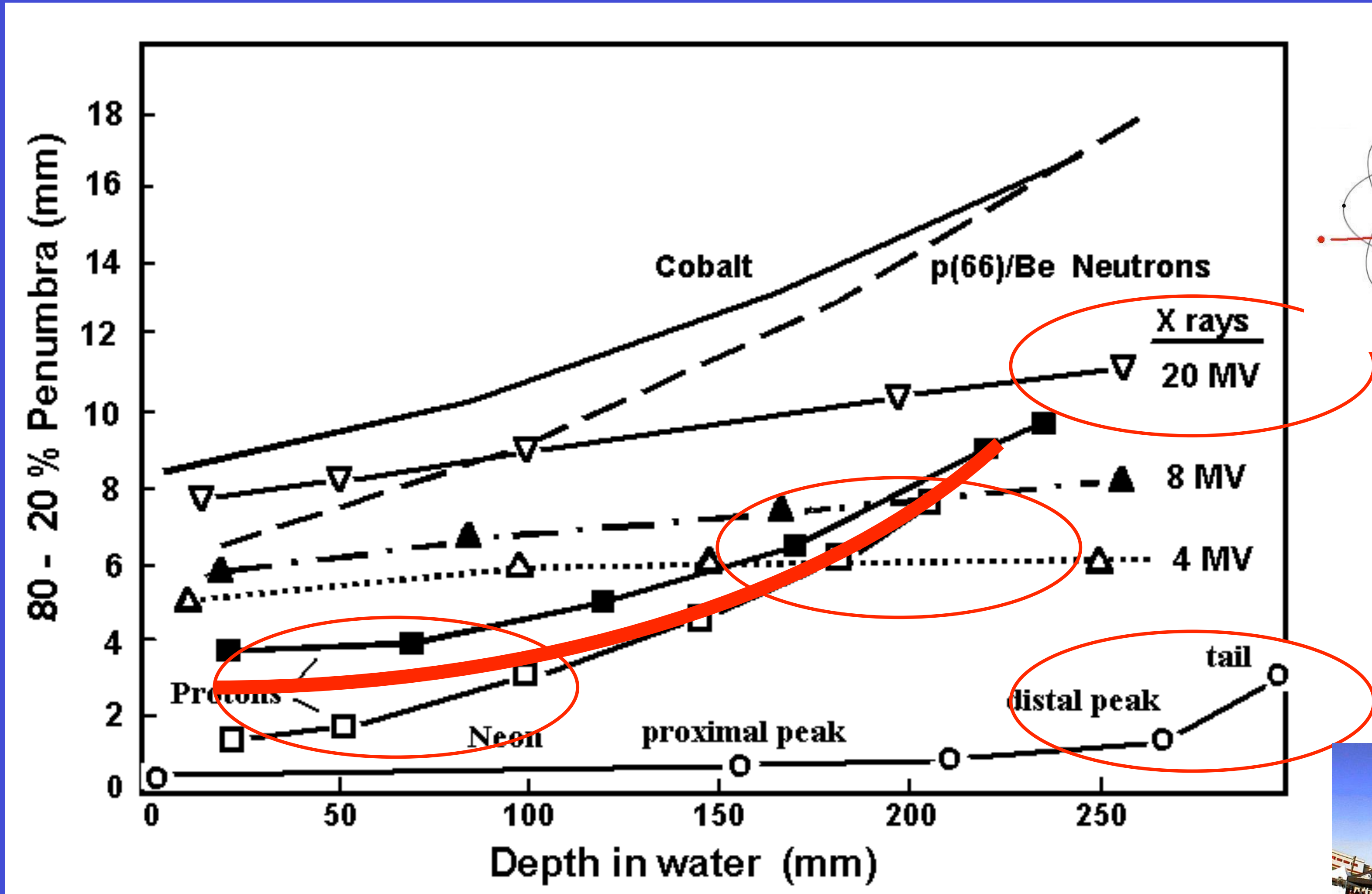
(van Luijk et al)

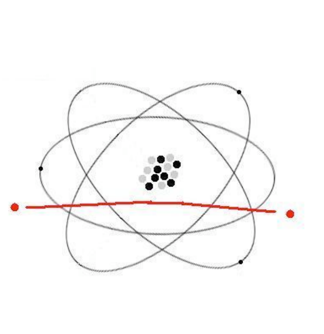




« ears »
or « horns »
in profiles
close to collimators

Lateral penumbra in depth : (multiple) Scattering Power





2nd »S Power »: Scattering

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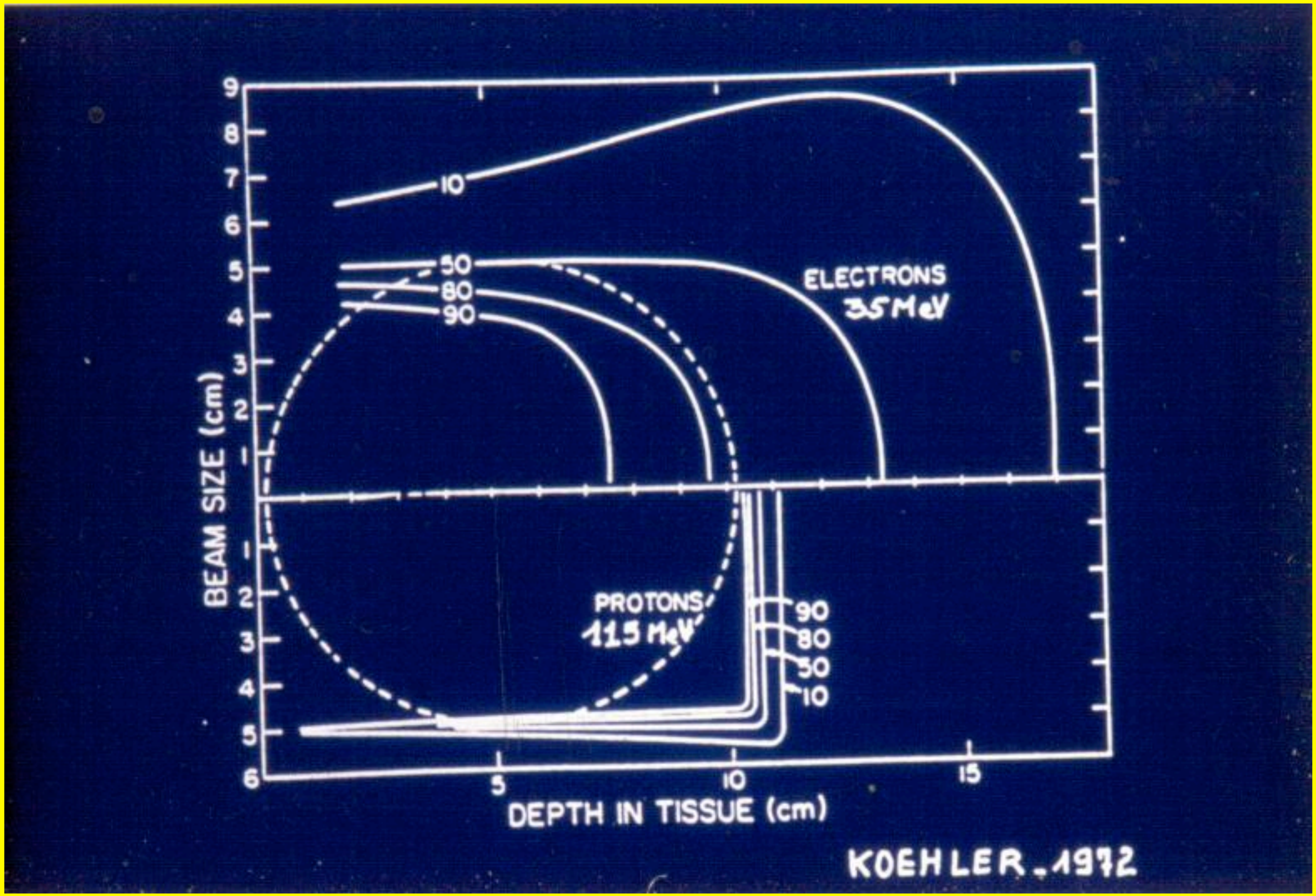
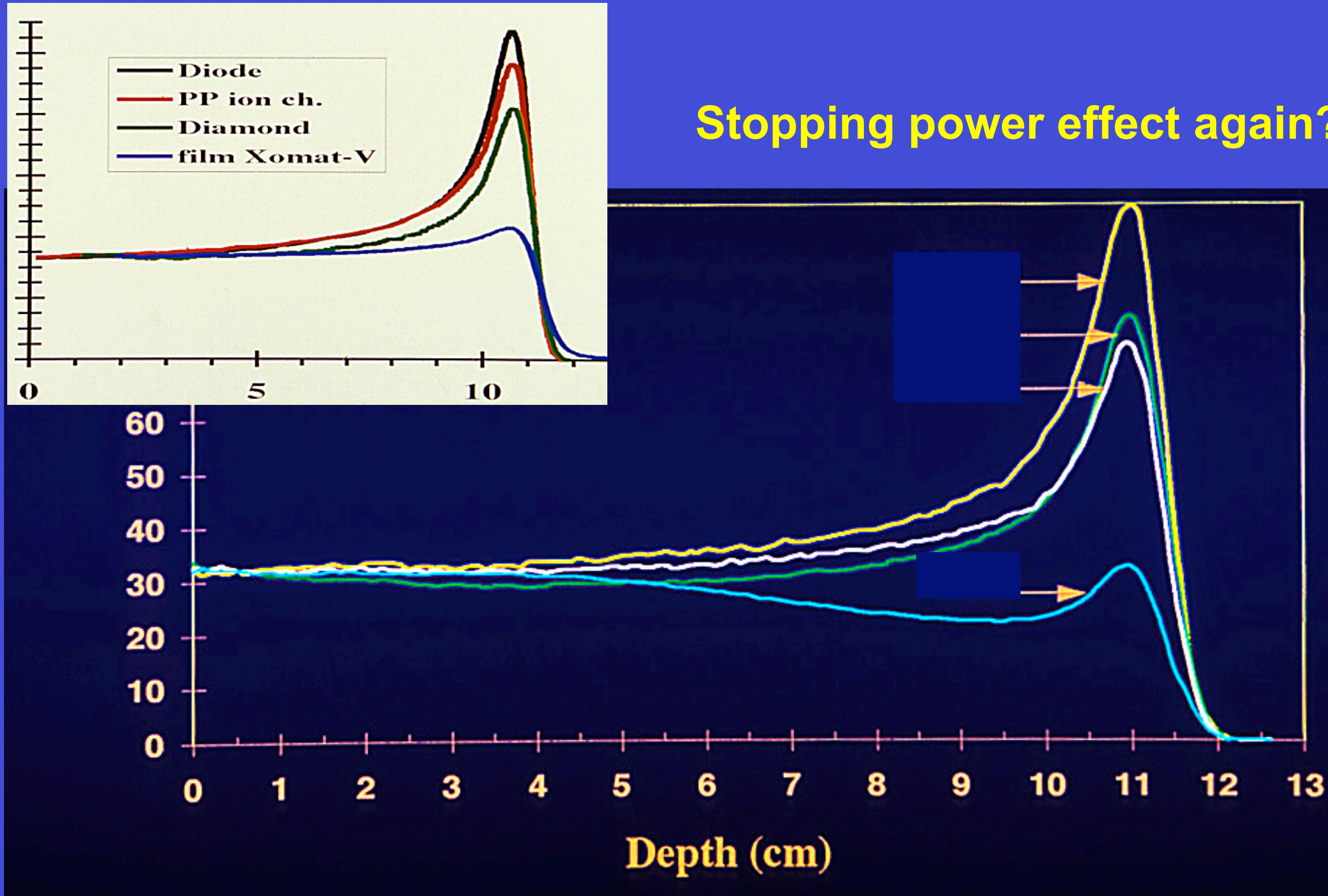
2nd big advantage of protons: « low scattering »

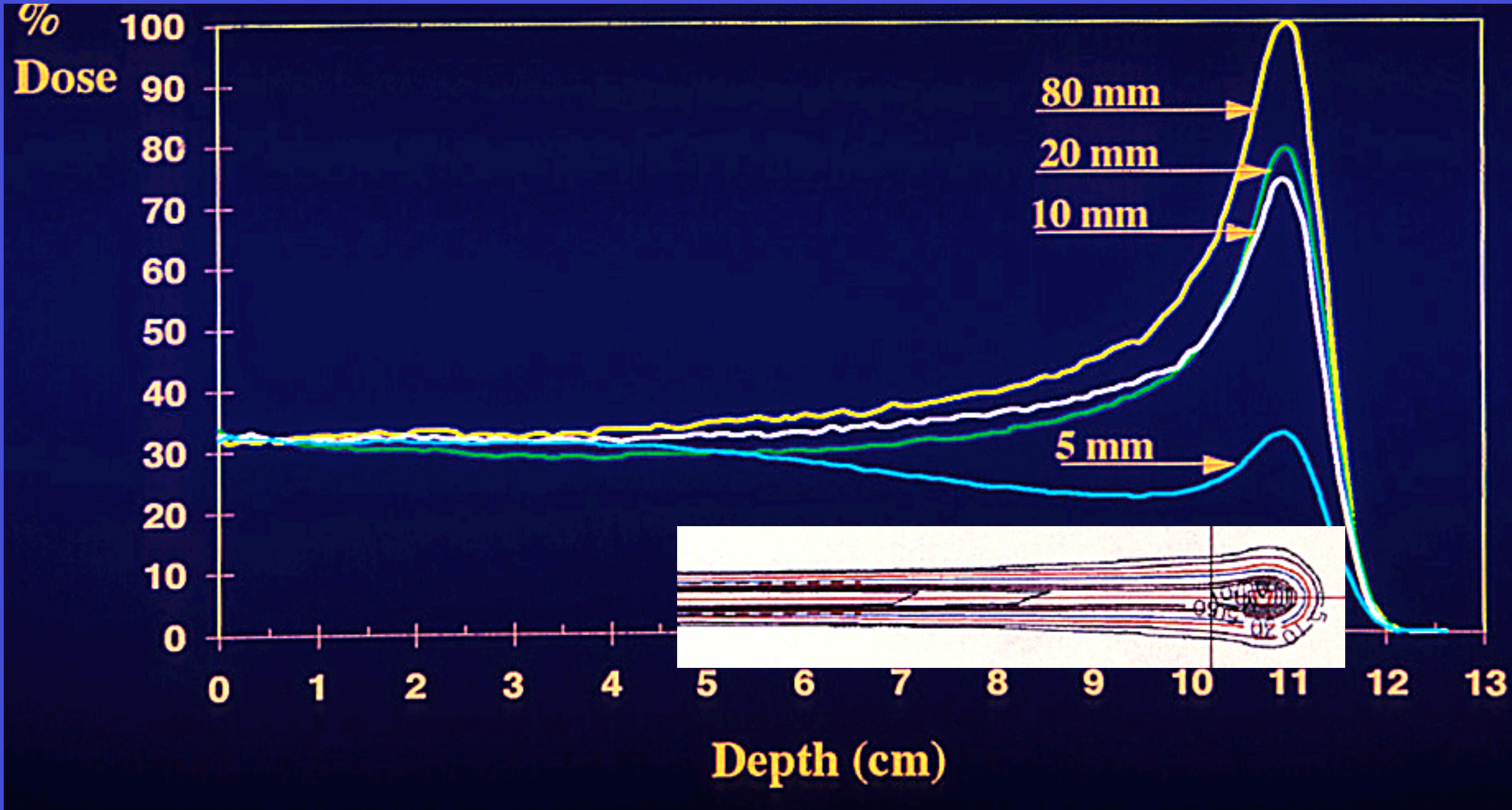


Do you remember… ?

Stopping power effect again?

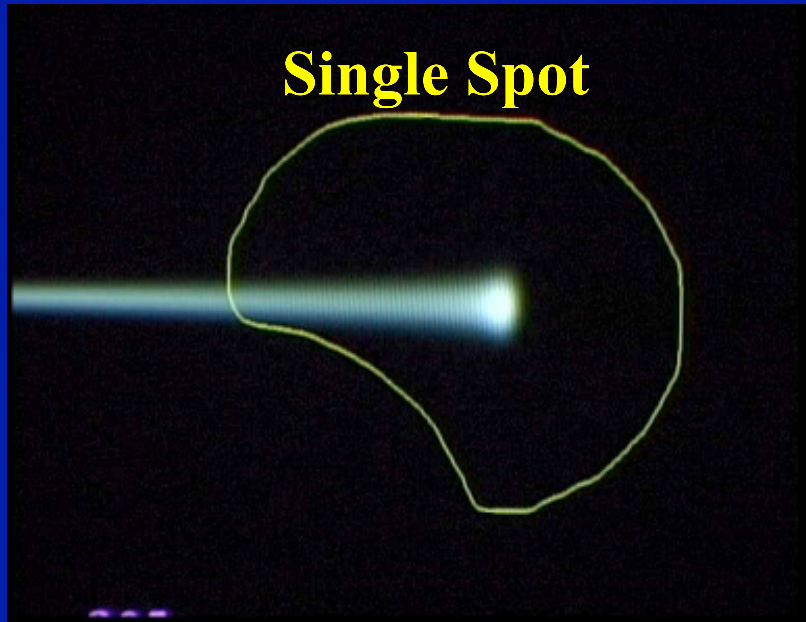


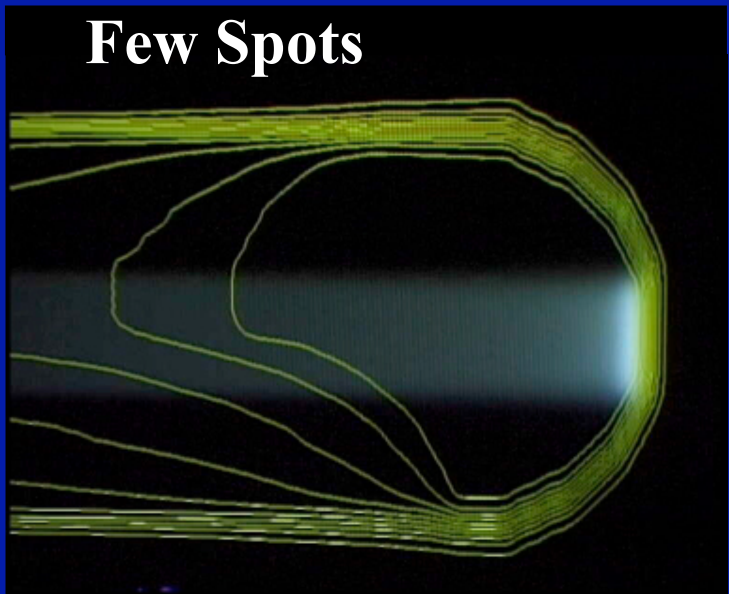
Stopping power effect again?
No, this time is the scattering power! ☺

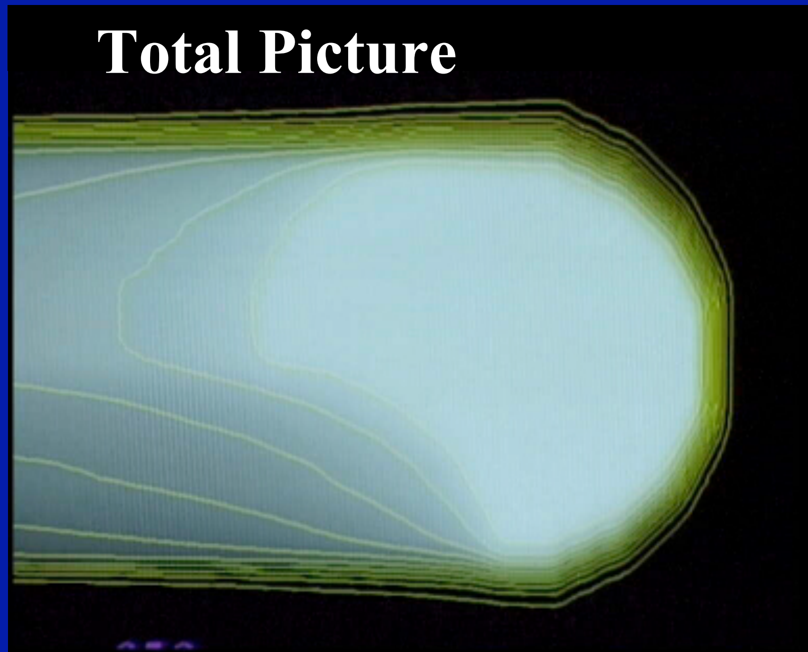


Spot Scanning Principle

Pictures from PSI







« Hadrons » in therapy

Physical selectivity and/or Radiobiological effects

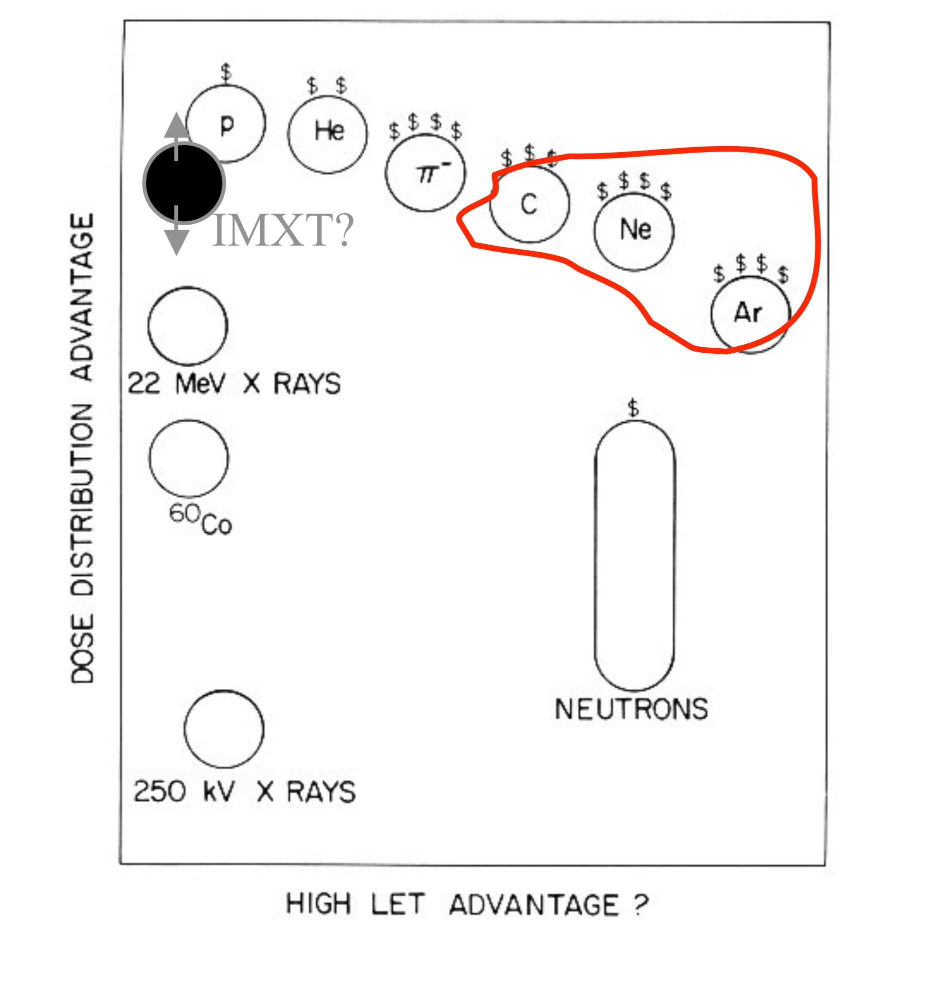
*** pions**

*** fast**

& slow neutrons

*** protons**

*** light and heavy ions**

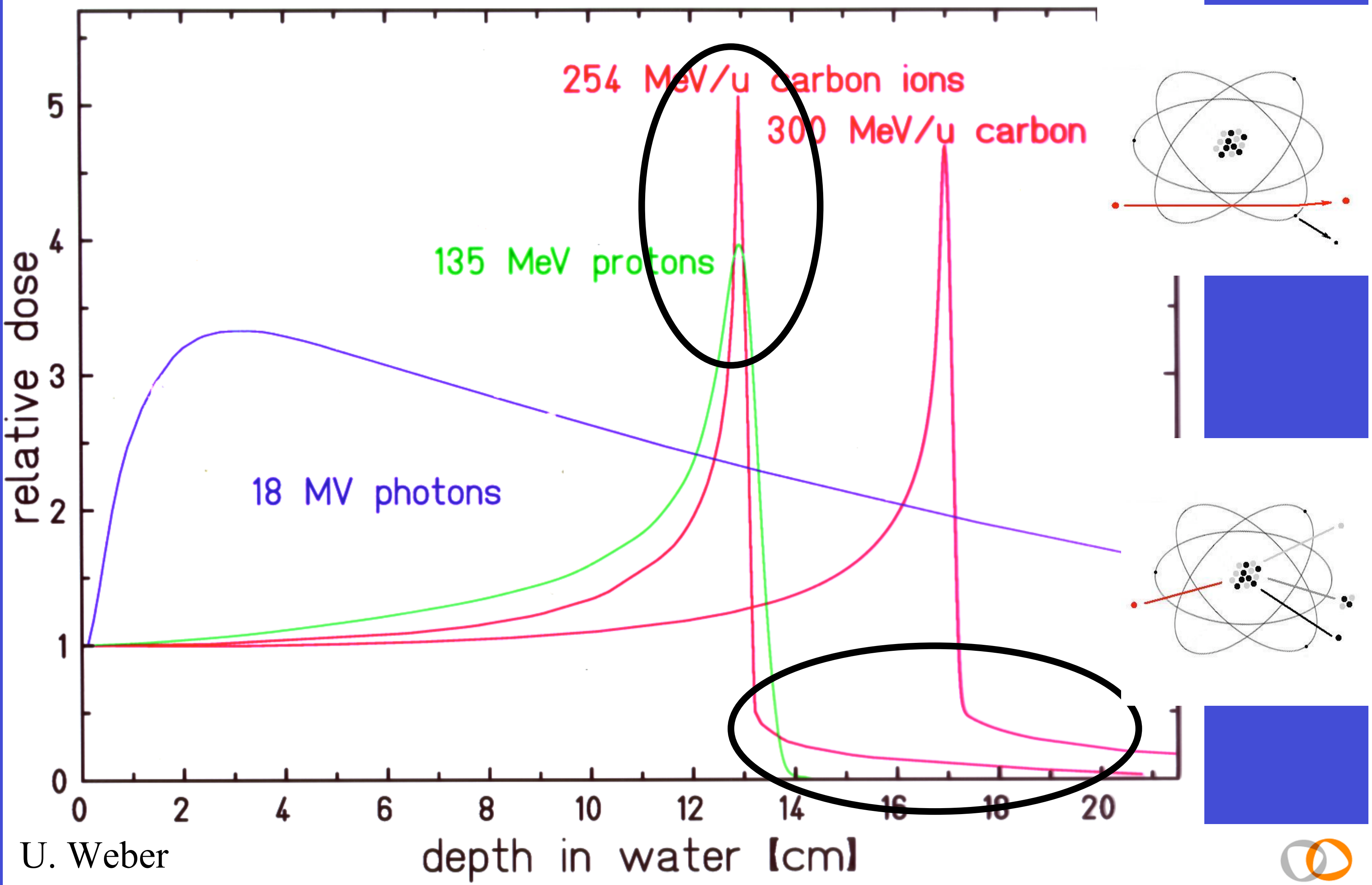


Raju & Koehler, 1980

HEAVY IONS

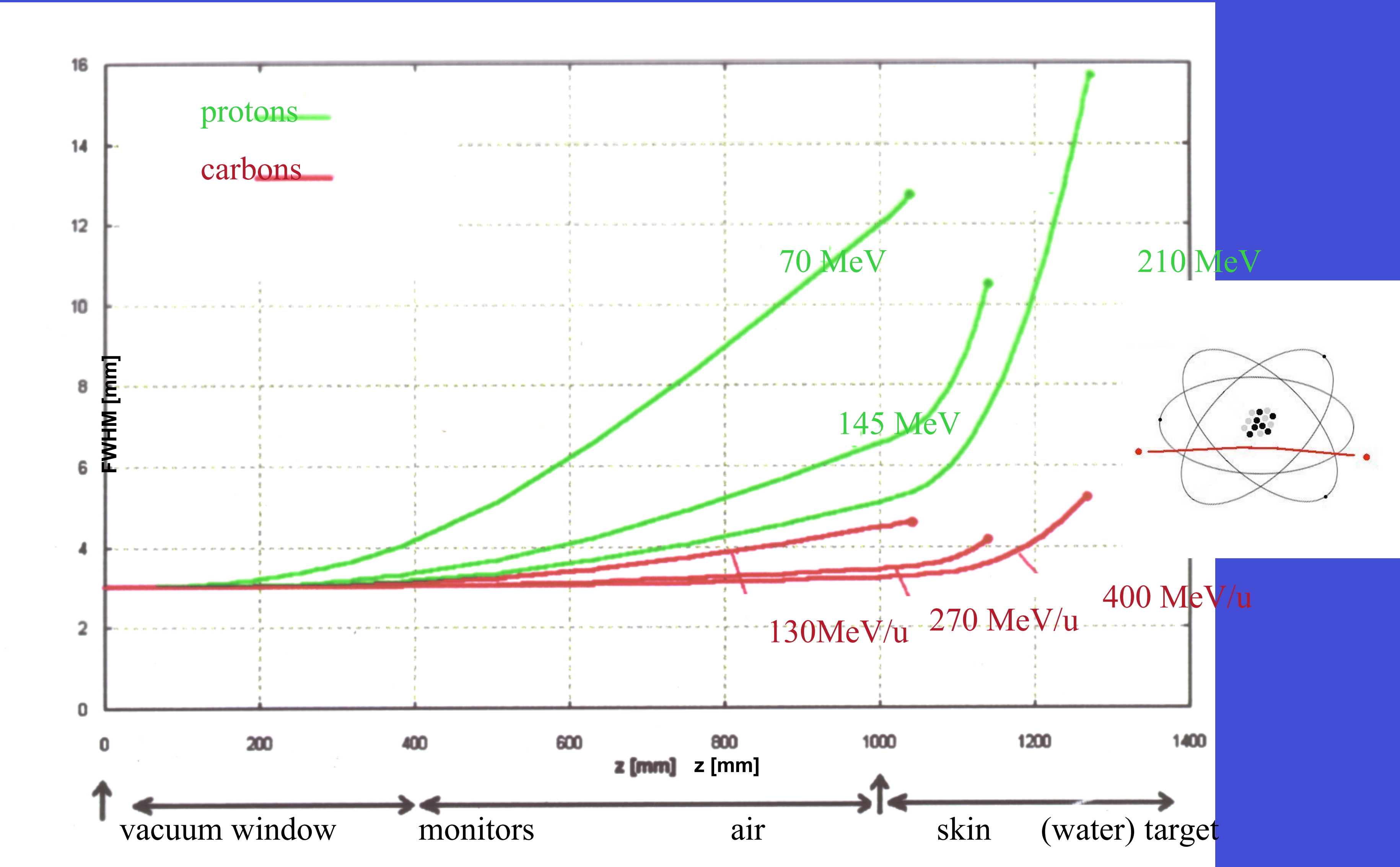
… having.the Stopping power as a larger « **weighting** » factor

Depth dose distribution of various radiation modalities



U. Weber

Beam scattering for a real scanning setup (exit window, monitors, air, patient)



Calc. U.Weber, RKA AG

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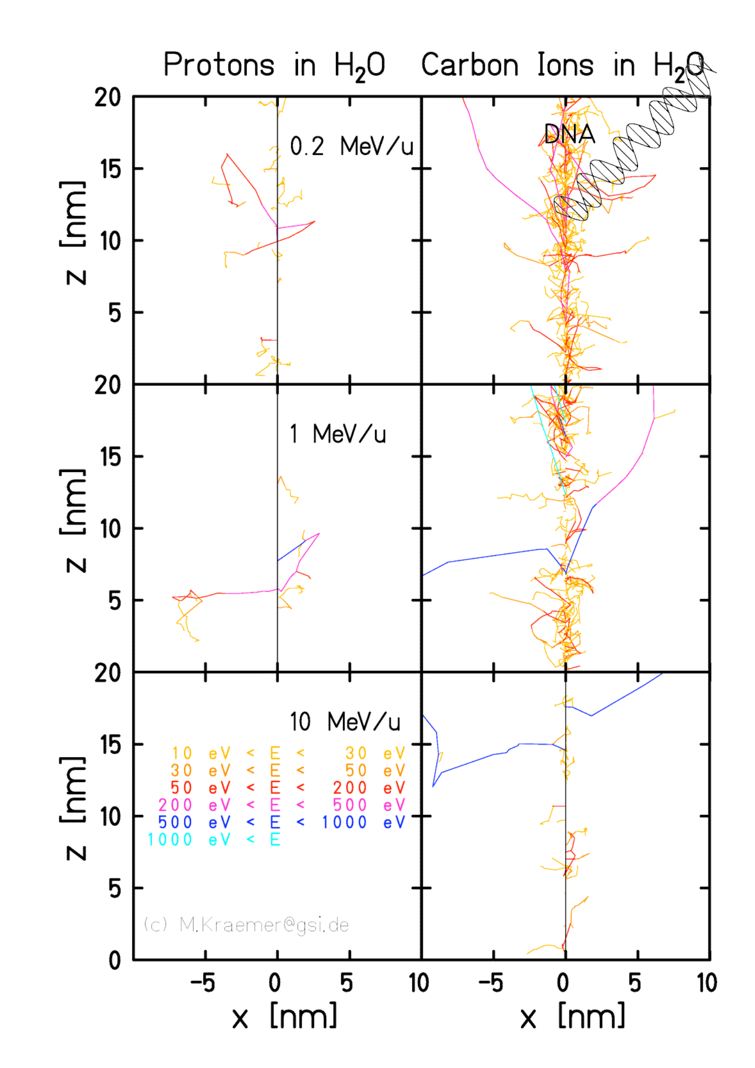
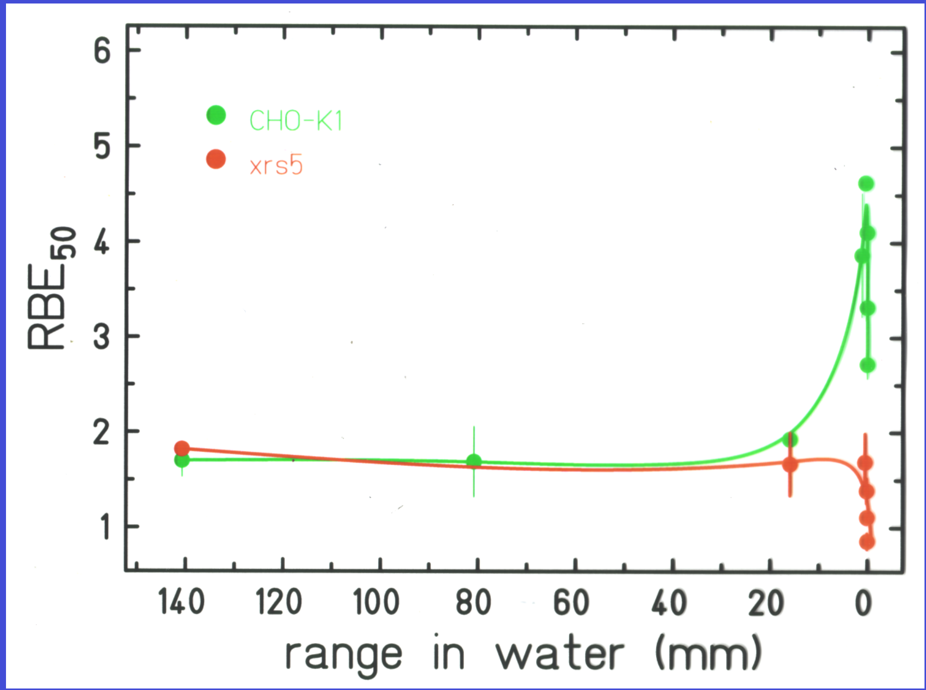
Radiation Biology:

Dose distribution in nanometer scale

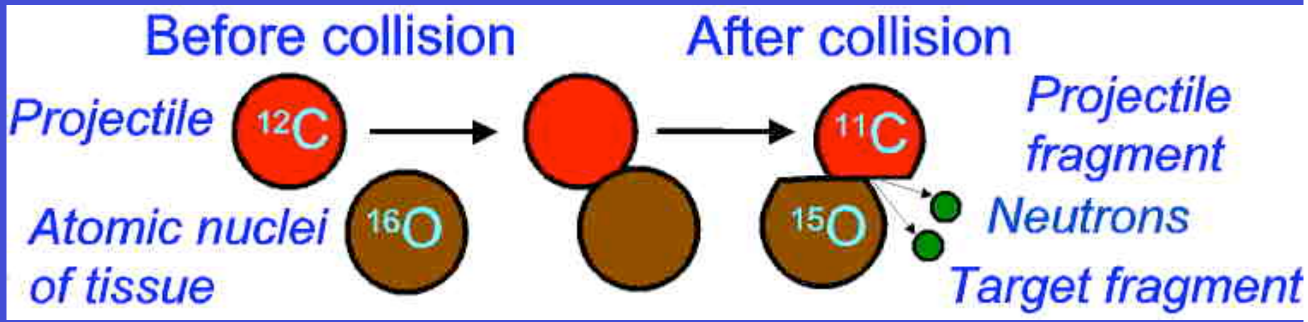


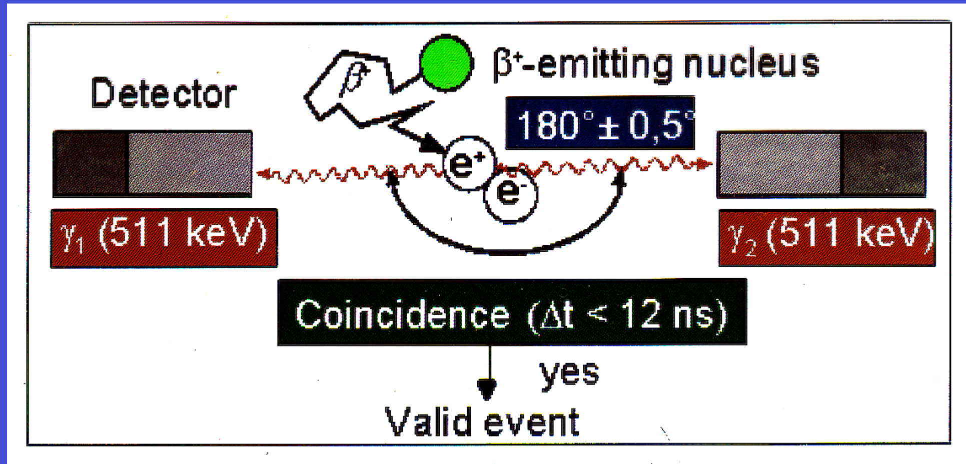
RBE for repairing and non-repairing cells

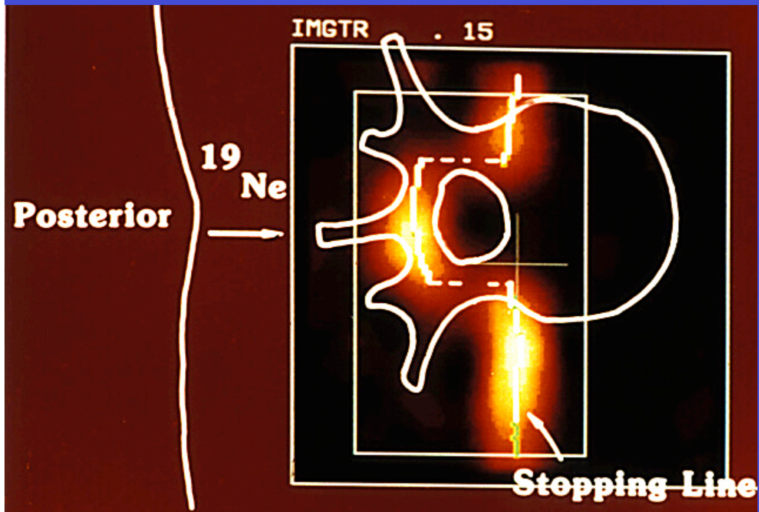


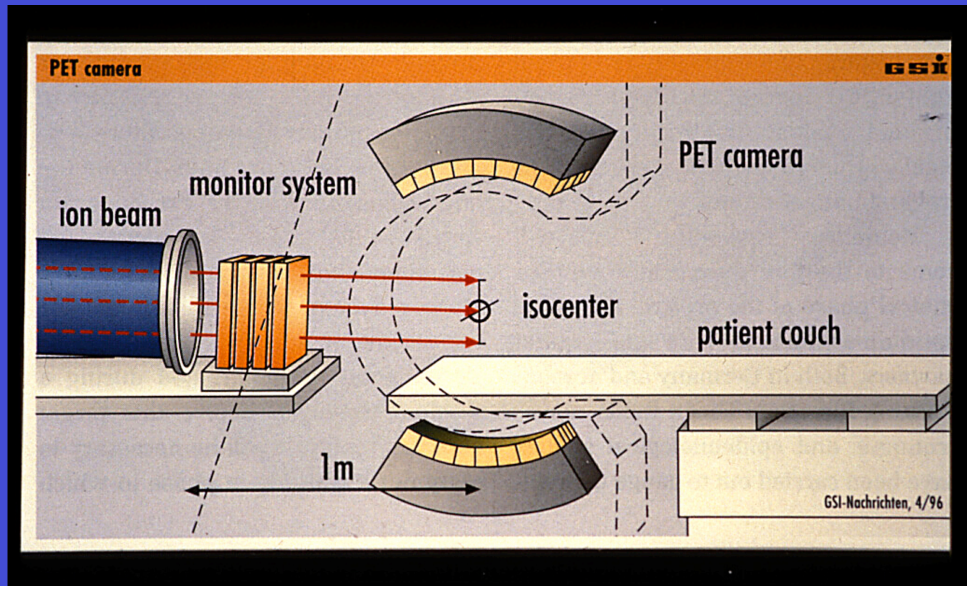
Kraemer, Weyrather, Scholtz, Kraft, …

Positron Emission Tomography (PET)









W. Enghardt, FZ Rossendorf

G. Kraft & coworkers, B.Chu

Berkeley, GSI & Heidelberg

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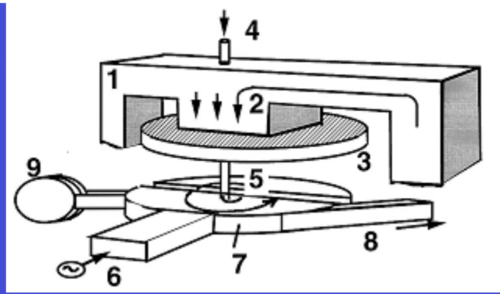
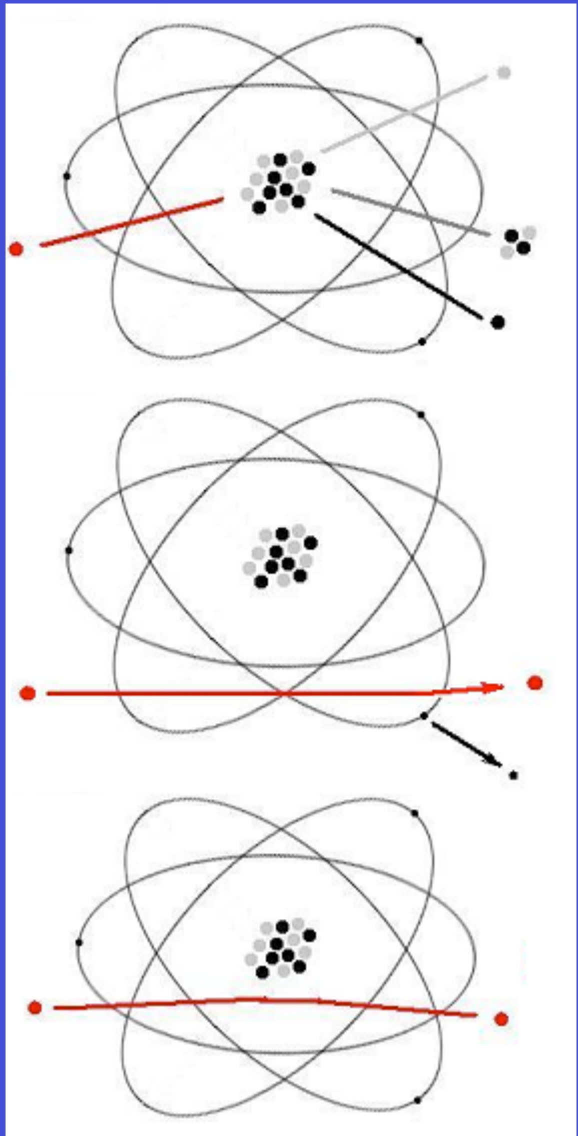
Conclusions :

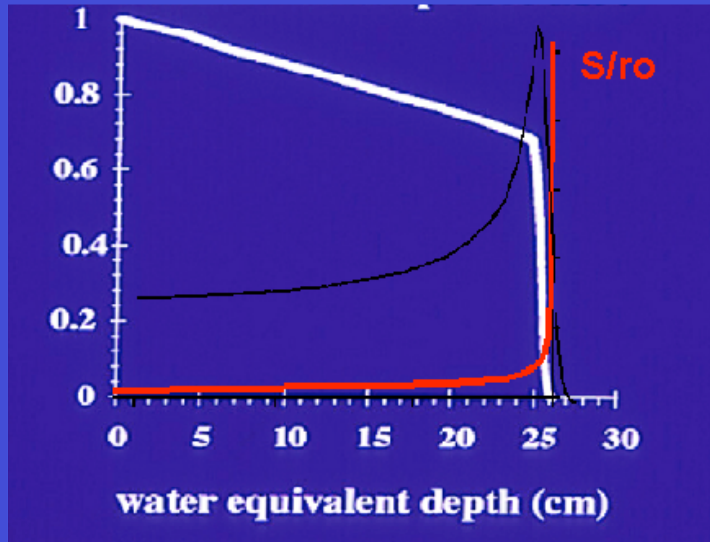
$$F = q(E + v \wedge B)$$



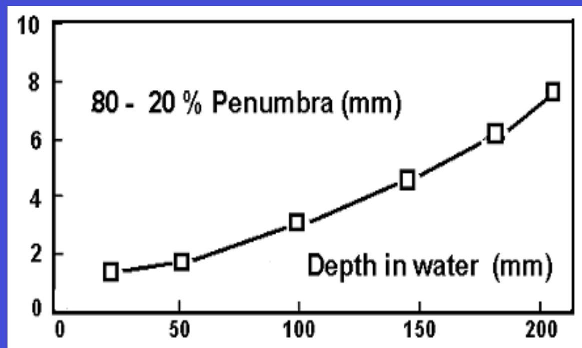
Neutrons & co …



Ionisation
(= Dose)



Multiple
Scattering



« This is not an apple »

« This is not a patient »

→ **Go to clinics !**

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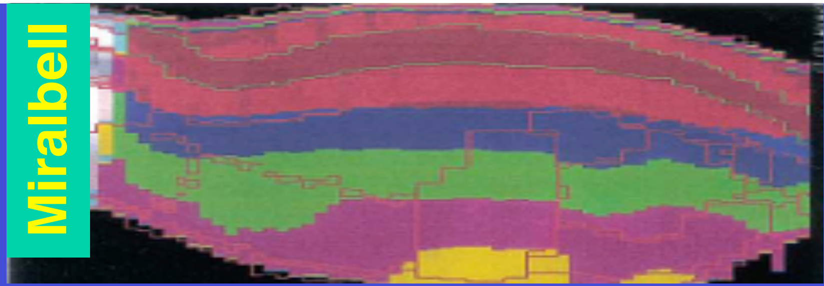
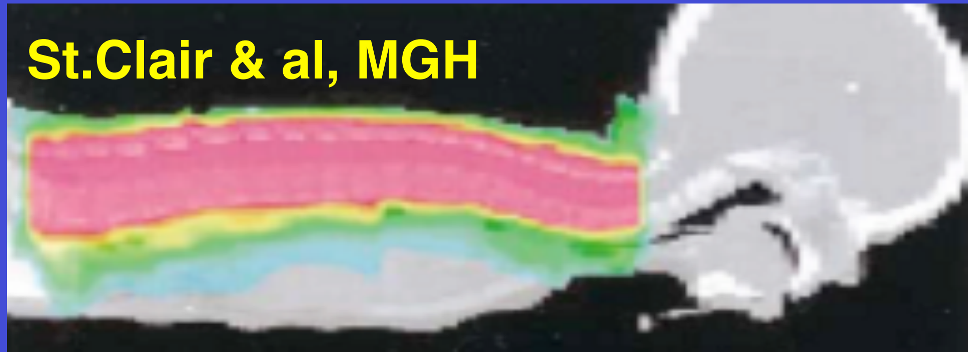
PEDIATRICS (medulloblastoma)

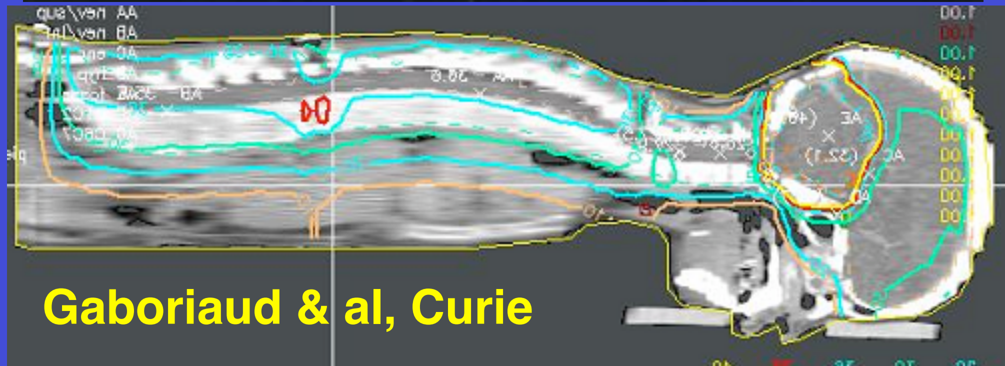
Photons



IMXT



Electrons + photons



Protons