A method to predict space radiation biological effectiveness for Galactic Cosmic Rays and intense Solar Particle Events

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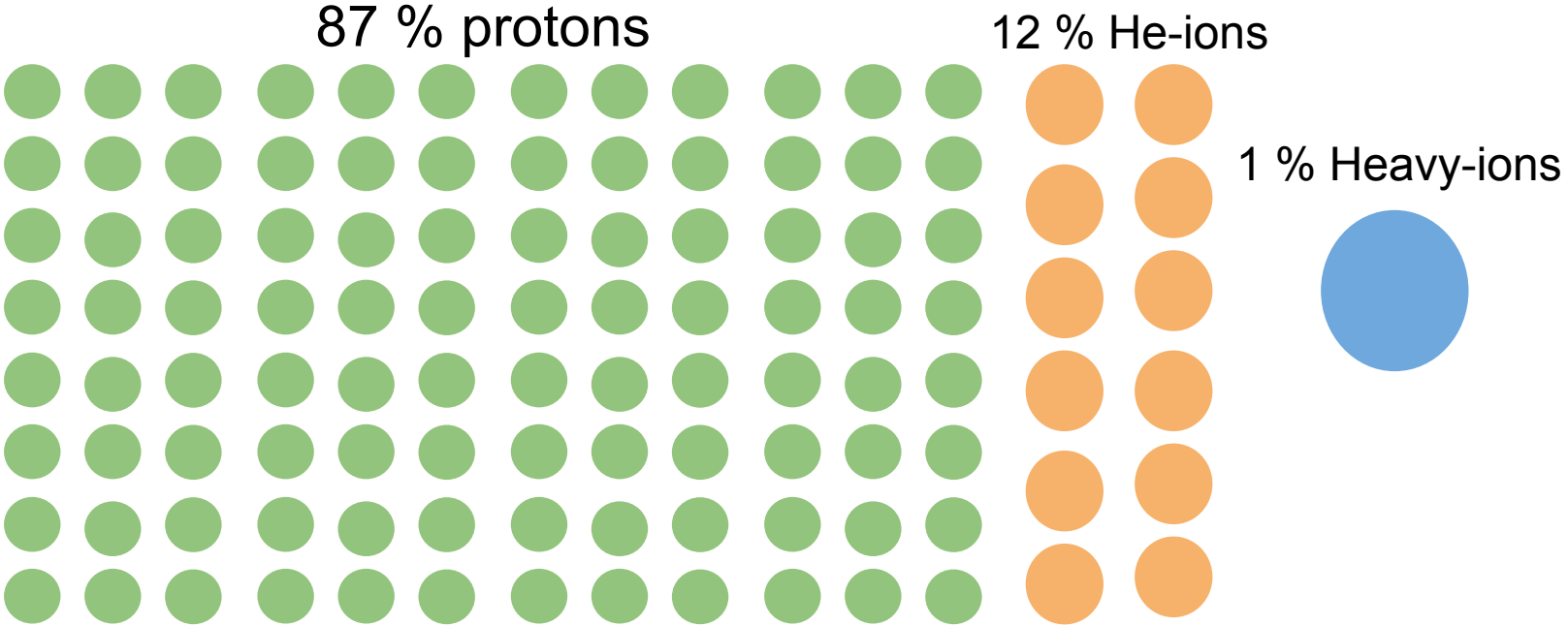
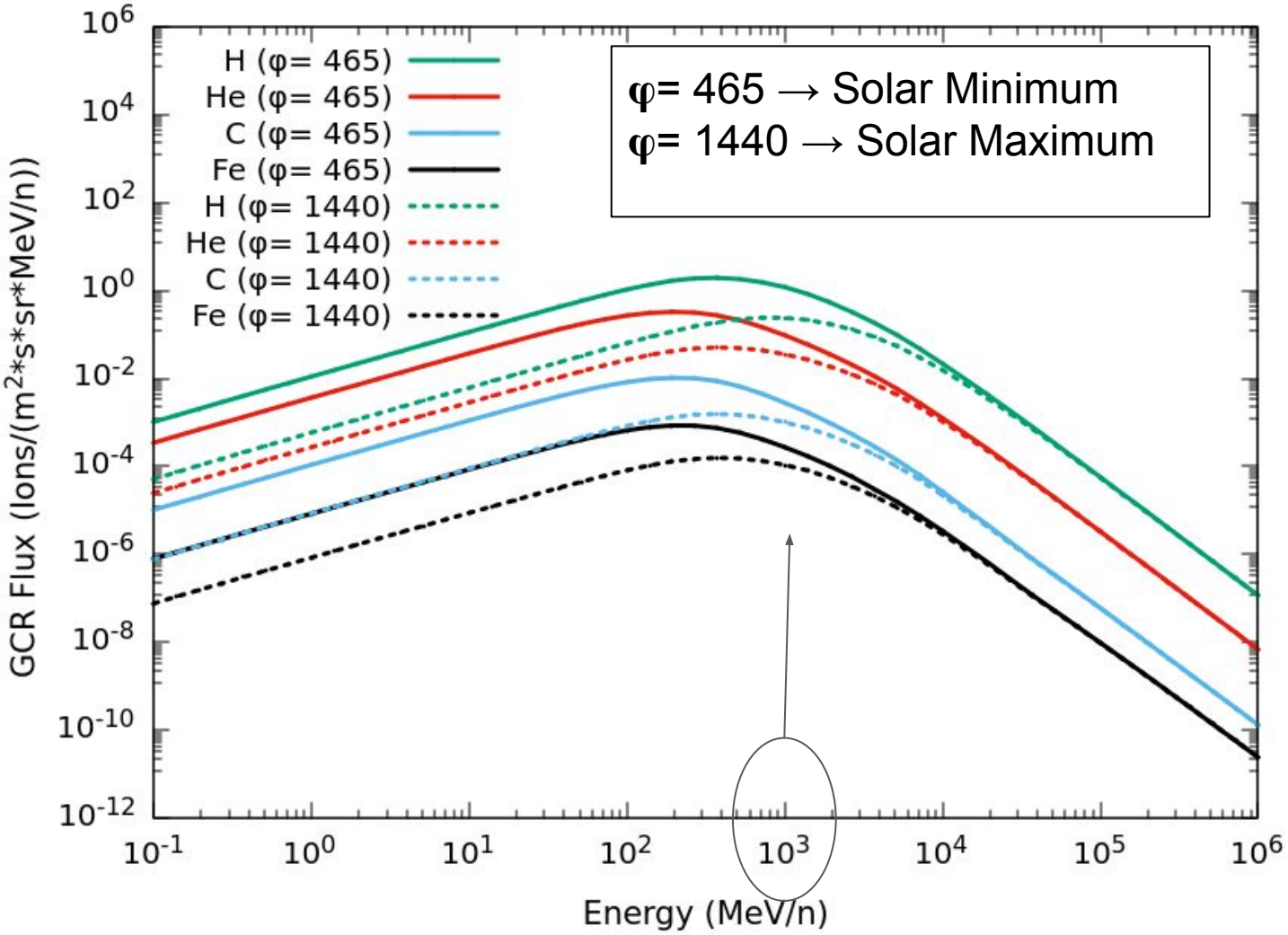
Space Radiation in free space

Galactic Cosmic Rays (GCR)



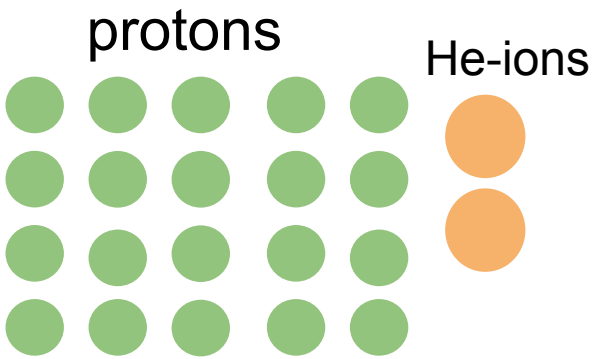
Maximum Dose Rate = 0.5 mGy/day


H (φ= 465)
He (φ= 465)
C (φ= 465)
Fe (φ= 465)
H (φ= 1440)
He (φ= 1440)
C (φ= 1440)
Fe (φ= 1440)
φ= 465 → Solar Minimum
φ= 1440 → Solar Maximum
GCR Flux (Ions/(m2*s*sr*MeV/n))
Energy (MeV/n)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6

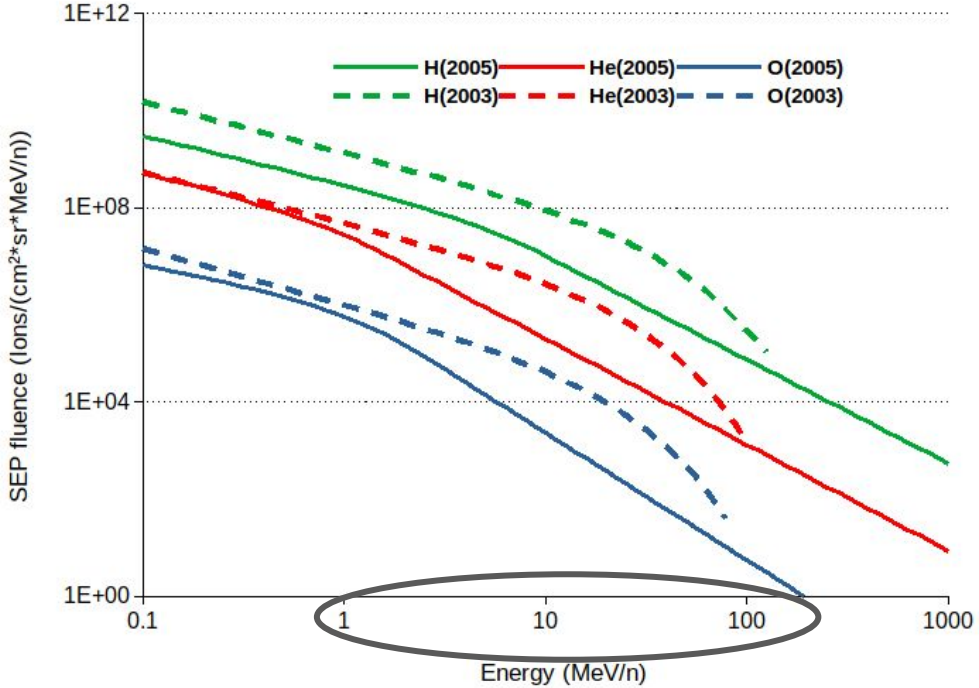
Space Radiation in free space

Solar Particle Events (SPE)

- Up to 10^{11} particles.cm^{-2} in few hours, mainly protons



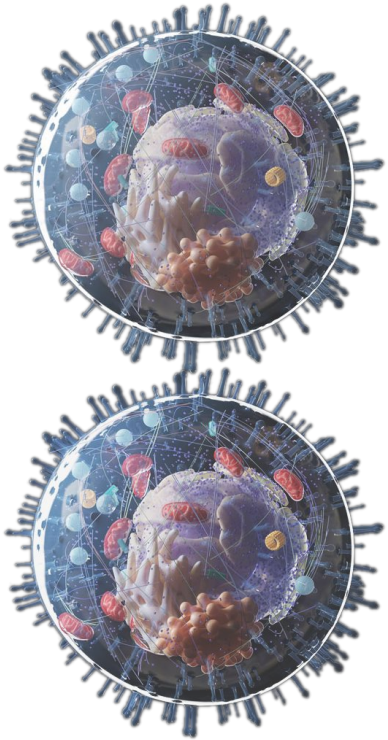
Dose→ Gy/event



Biological damage by space radiation

Relative biological effectiveness

$$RBE = \frac{Dose_{photons}}{Dose_{space\ radiation}}$$



Same biological effect

NCRP recommendations on the RBE values for non-cancer effects to be used for skin and BFO

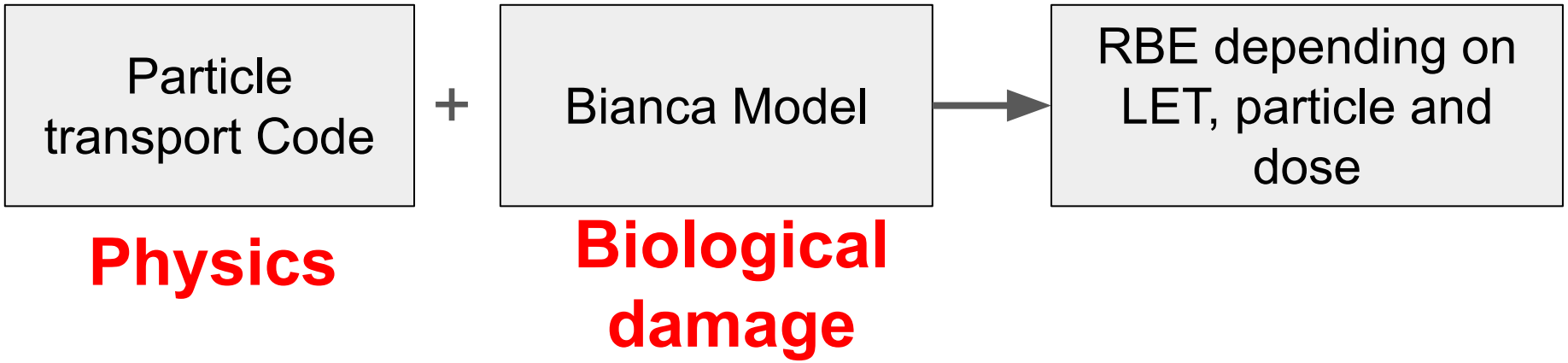
Radiation Type	Recommended RBE	Range
1 to 5 MeV neutrons	6.0	4-8
5 to 50 MeV neutrons	3.5	2-5
Heavy ions	2.5	1-4
Protons > 2 MeV	1.5	-

Fix values

ARES Project

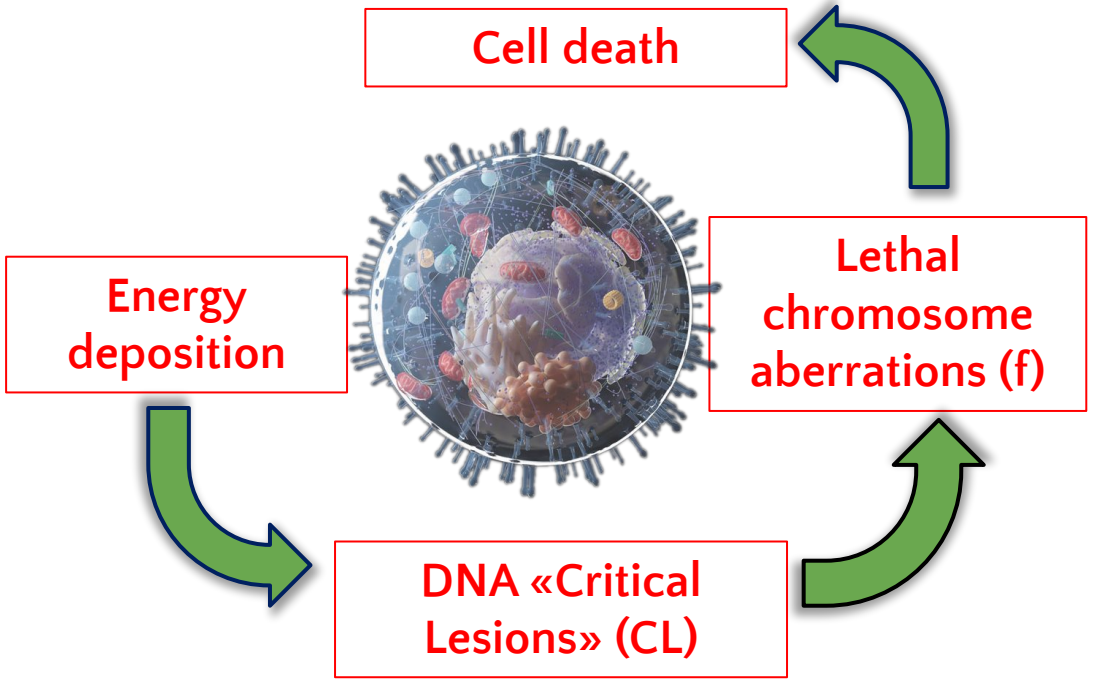
Grant Giovani in CSN5 – 2023/2024

WP1 – Space radiation effects computational studies



BIANCA model developed in Pavia

Main assumption: DNA “critical lesions” lead to chromosome aberrations, and some chromosome aberrations (e.g., dicentrics) lead to cell death



BIANCA model

Example of radiobiological database for V79:

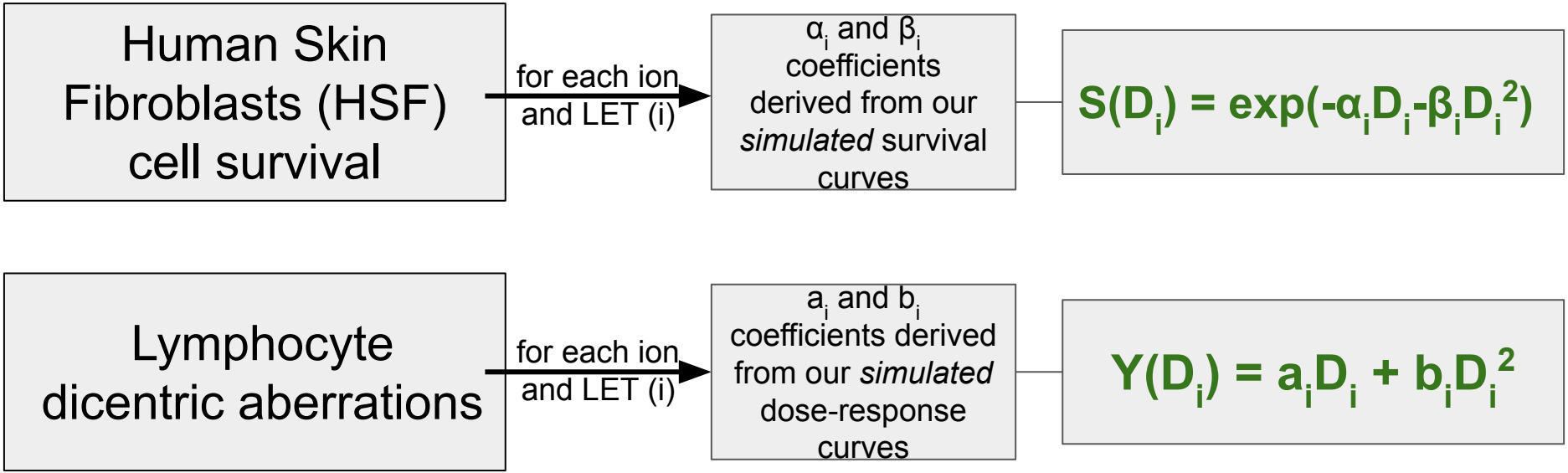
```
Z=1 A=1,2,3
LET     alfa                beta
5      0.161168003608071 0.034227925863557
7.5    0.219155512347106 0.031807059167825
10     0.277730304065006 0.026062986984213
12.5   0.324223249128924 0.031963531745716
15     0.370061833526514 0.032195025167274
17.5   0.421451839190716 0.031121716722449
20     0.482515824349661 0.028525693688078
22.5   0.560520033338037 0.018863044675061
25     0.613244623202487 0.019486893814967
27.5   0.670278414247874 0.018719108913174
30     0.723636950773347 0.019048357687813

Z=2  A=3 (He3)
LET     alfa                beta
5    0.134484868252636 0.033328267759041
10   0.144914045351193 0.039167916406686
20   0.195309536204132 0.055766427339300
30   0.254263496879065 0.086614721872234
40   0.346232798363745 0.110820821623133
50   0.461751927355611 0.125899692117198
60   0.577156328111620 0.149414730517834
70   0.688177599469057 0.170307321062664
80   0.831202131850177 0.173711239896555
90   0.958976414546513 0.178987749762615

Z=2 A=4 (He4)
LET     alfa                beta
5    0.122919965474113 0.0282243396663055
10   0.164742642147497 0.0320256389518587
```

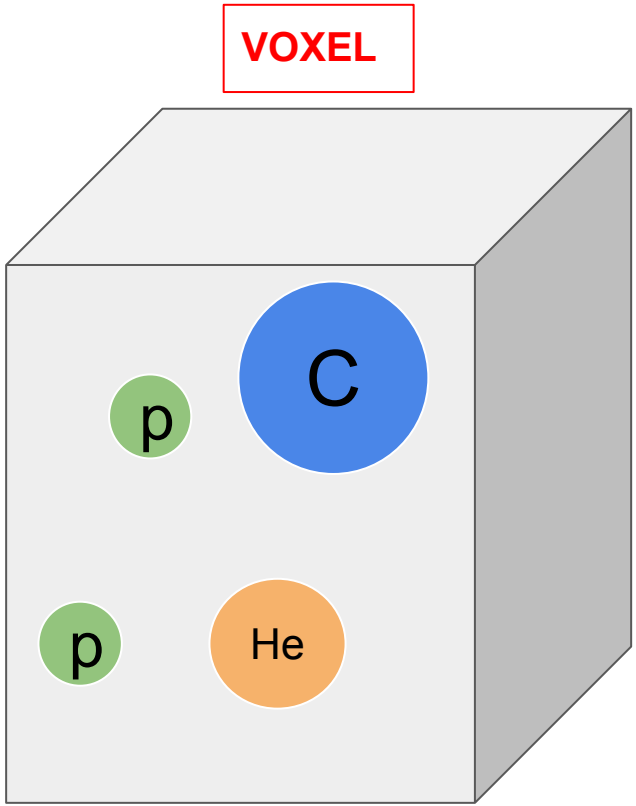
Cell death for each ion and LET:

$$S(D_i) = \exp(-\alpha_i D_i - \beta_i D_i^2)$$

BIANCA model

In this work, two **radiobiological databases** have been generated by **BIANCA** for ions up to iron:





Particle Transport Code
Dose (D_i), LET, particle

BIANCA (α_i,β_i)

$$\alpha = \frac{\sum_i \alpha_i D_i}{\sum_i D_i} \qquad \sqrt{\beta} = \frac{\sum_i \sqrt{\beta_i} D_i}{\sum_i D_i}$$

$$D_X = \frac{\left[-\alpha_X + \sqrt{\alpha_X^2 + 4\beta_X \ln S}\right]}{2\beta_X}$$

RBE= D_x/D

VOXEL

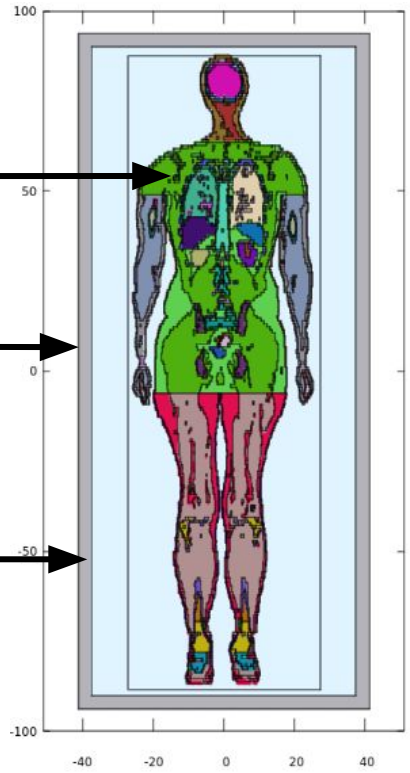
RBE for cell survival → **Related to the induction of early deterministic damage**

SPE: DOSE and RBE calculations

Male and female ICRP phantoms

Cylindrical Al shielding (r=38cm, h=180cm)

Variable thickness (from 0 to 30 g/cm^2)



SPE of August 1972

SPE of October 2003

SPE of August 1972

Female ICRP phantom
Shielding: 10 g/cm^2

Organ	D (mGy)	RBE	G (mGy-eq)	H (mSv)
Av. Skin	444.62	1.47	655.43	669.79
BFO	129.69	1.57	203.14	210.45
Colon	121.24	1.58	191.56	196.91
Lung	150.15	1.56	234.45	239.67
Stomach	113.81	1.58	180.25	186.29
Breast	343.03	1.49	512.62	545.75
Heart	110.05	1.59	174.58	181.03
Bladder	122.50	1.57	192.58	195.00
Oesophagus	110.05	1.59	174.58	181.03
Liver	121.86	1.58	192.37	197.80
Uterus/Cervix	64.25	1.68	108.20	118.08
Ovaries	64.02	1.68	107.44	113.46

SPE of August 1972

Deterministic effects

NASA and ESA limits
(30-day limit)
Skin = 1.5 Gy-Eq
BFO = 0.25 Gy-Eq

Al thickness (g/cm^2)	Equivalent Dose MALE (Gy.RBE)		Equivalent Dose FEMALE (Gy.RBE)	
	Skin	BFO	Skin	BFO
0.3	18.37	1.66	19.27	1.71
1	10.18	1.29	10.62	1.34
2	5.95	0.96	6.19	1.03
5	2.06	0.47	2.16	0.50
10	0.62	0.19	0.65	0.20
20	0.12	0.05	0.13	0.06

SPE of October 2003

Deterministic effects

NASA and ESA limits
(30-day limit)
Skin = 1.5 Gy-Eq
BFO = 0.25 Gy-Eq

Al thickness (g/cm^2)	Equivalent Dose MALE (Gy.RBE)		Equivalent Dose FEMALE (Gy.RBE)	
	Skin	BFO	Skin	BFO
0.3	13.61	0.48	14.60	0.50
1	5.11	0.31	5.44	0.33
2	2.32	0.20	2.38	0.21
5	0.48	0.07	0.51	0.08
10	0.10	0.03	0.11	0.03
20	0.02	0.01	0.02	0.01

Conclusions

- **The BIANCA model, interfaced with a radiation transport code, provided RBE predictions of cell killing (related to deterministic effects) and chromosome aberrations (related to stochastic effects including cancer)**

- **To respect NASA limits, a 650-days Mars Mission should be performed during the solar maximum period. For the SPE of October 2003, a shielding of 5 g/cm^2 is necessary to respect the limits and for the SPE of August 1972 a shielding of 10 g/cm^2 is necessary to respect the limits.**

- **BIANCA allows taking into account that the RBE depends not only on particle type, but also on LET and dose.**

Thanks!

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