Trento Institute for
Fundamental Physics
and Applications

Neutron radiobiology: medicine and space

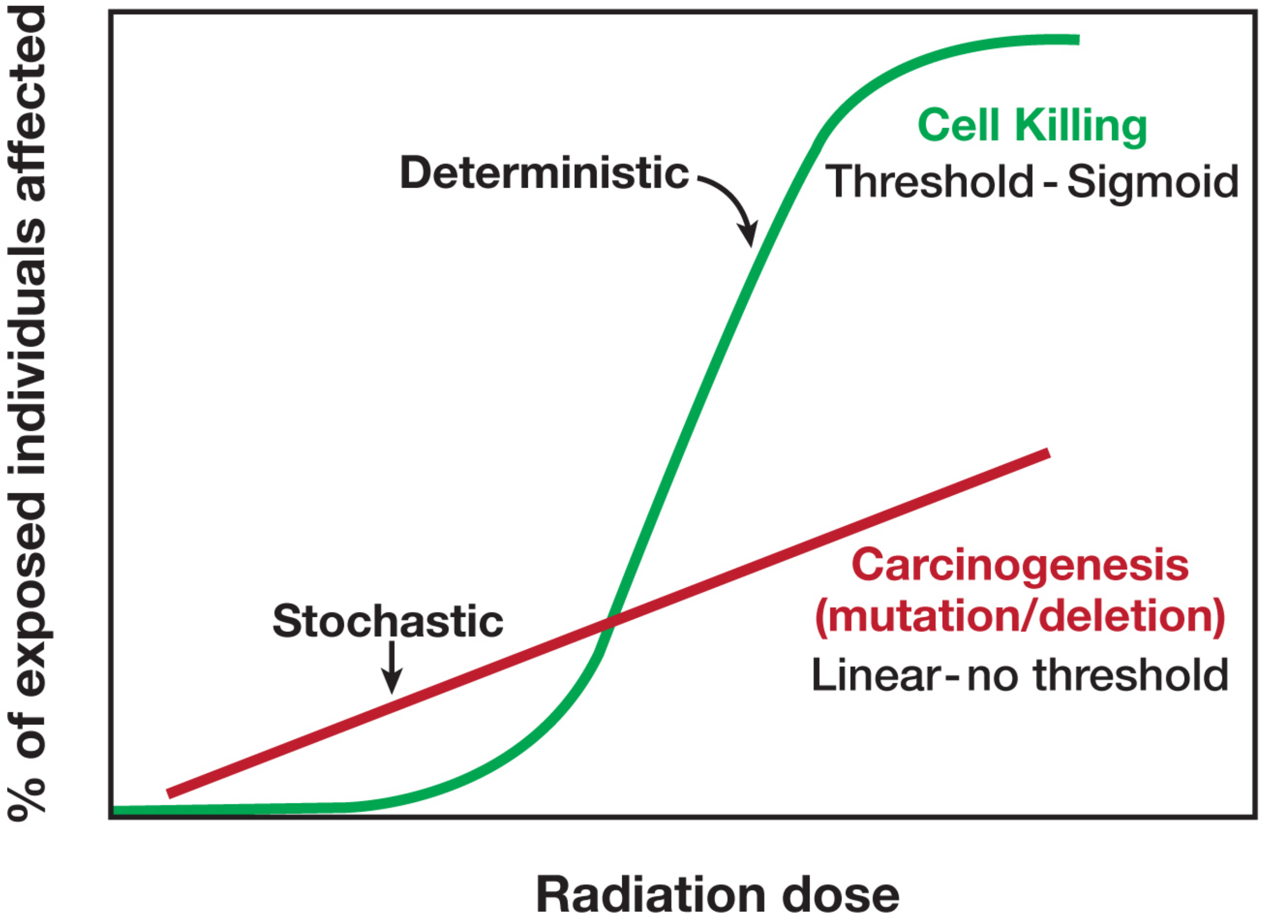
Marco Durante

NDRA-2016 2.7.16

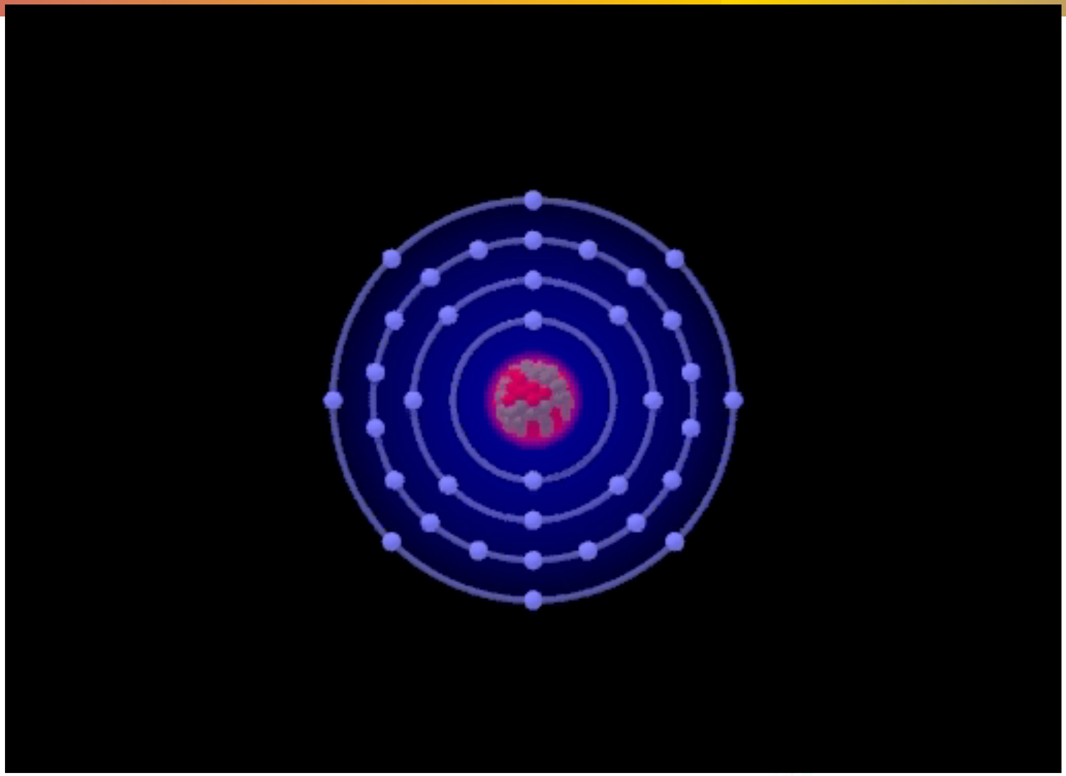
Outline

- Introduction to radiobiology
  - Survival
  - Transformation
- Neutron radiobiology
  - Cell killing
  - Late effects
- Neutron therapy
  - Fast neutron therapy
  - Contamination in charged particle therapy
- Neutrons in space
  - Contribution in dose
  - Shielding
  - Facilities

Radiobiology: radiation as a two-edge sword

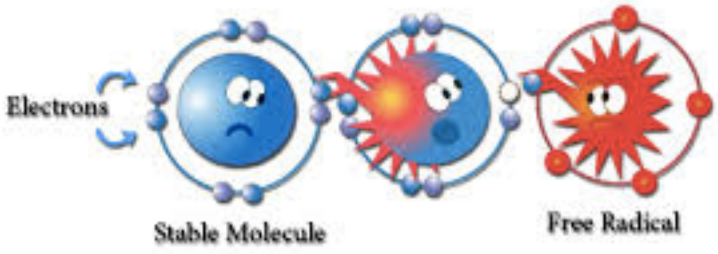


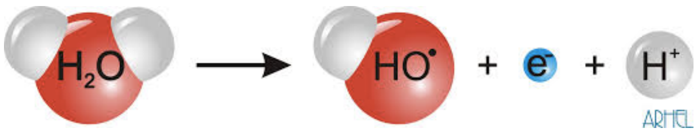
How does radiation injure people?



Direct ionization of biological molecules

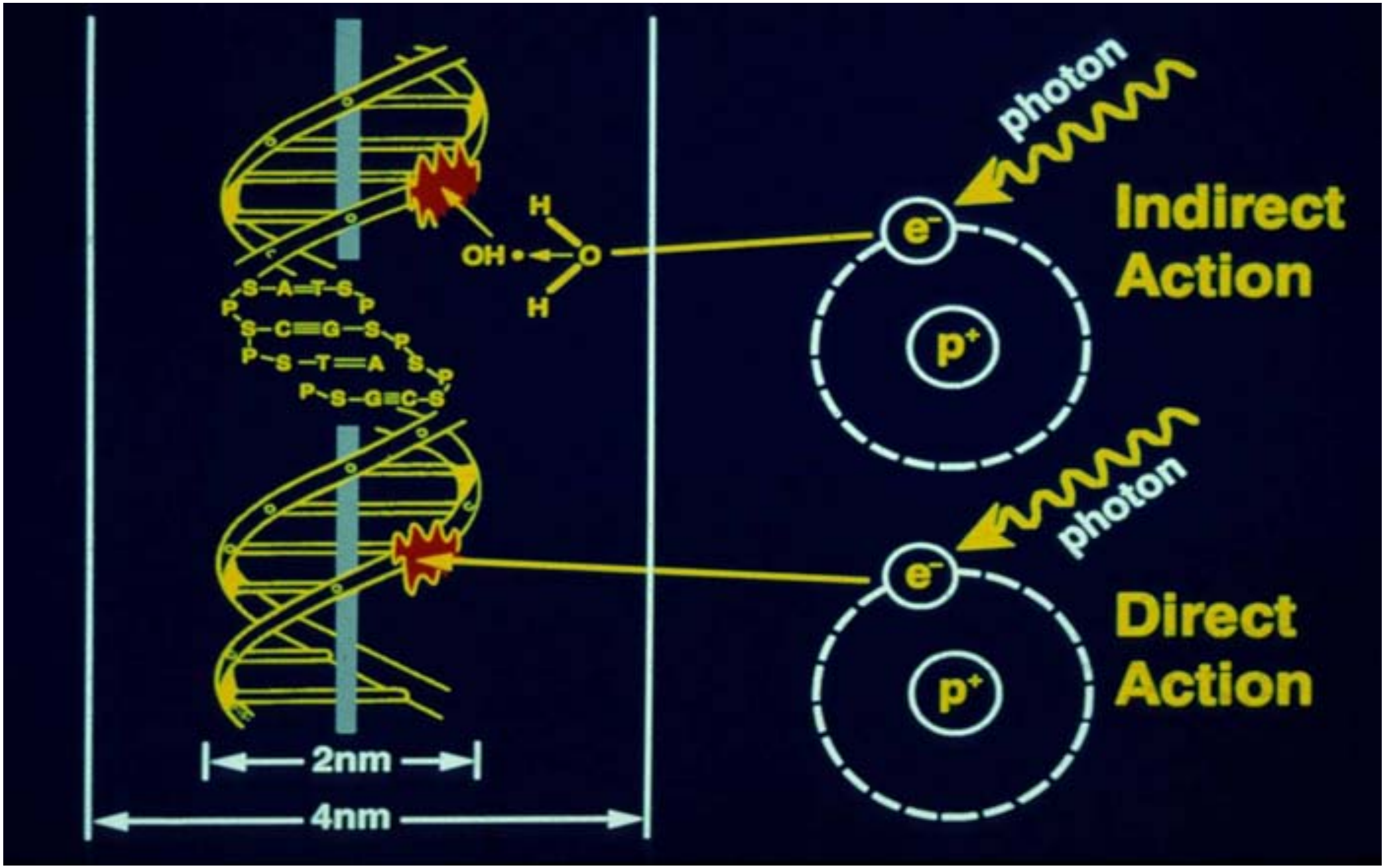
Indirect effect through formation of free radicals in water



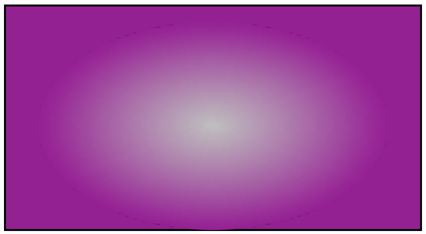


The most unkindest cut of all

(W. Shakespeare, Julius Caesar)

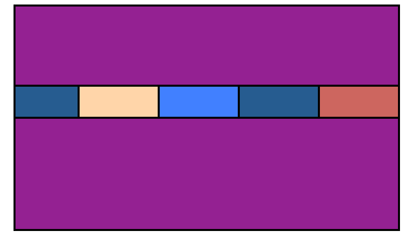


How does this damage from ionizing radiation effect our bodies?

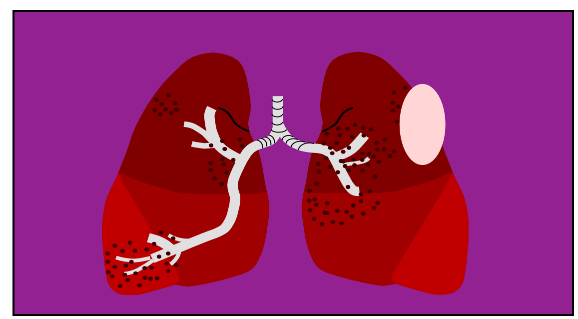


Sufficient Cell Killing

Radiation Sickness



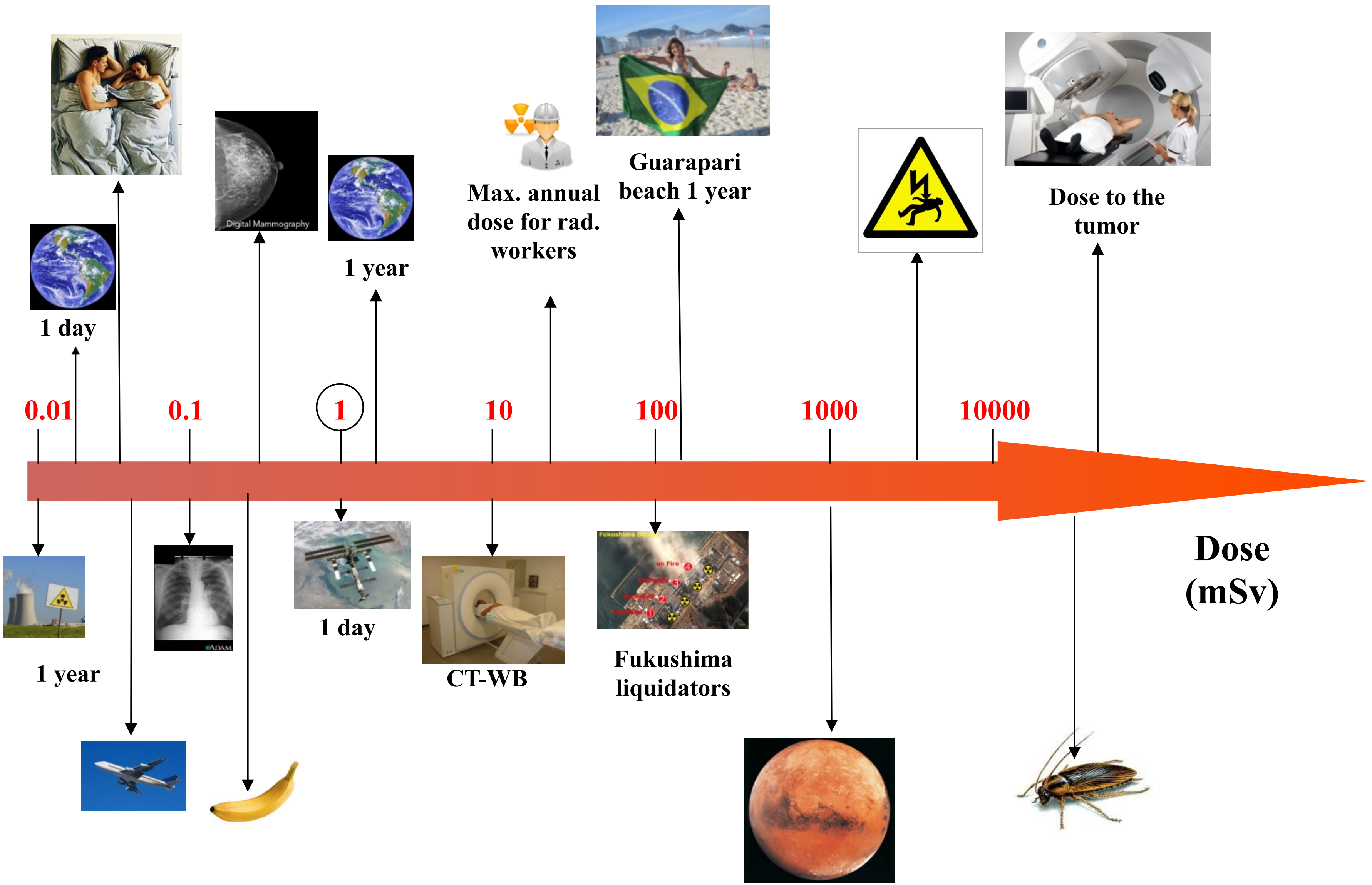
Sufficient Genetic Alterations



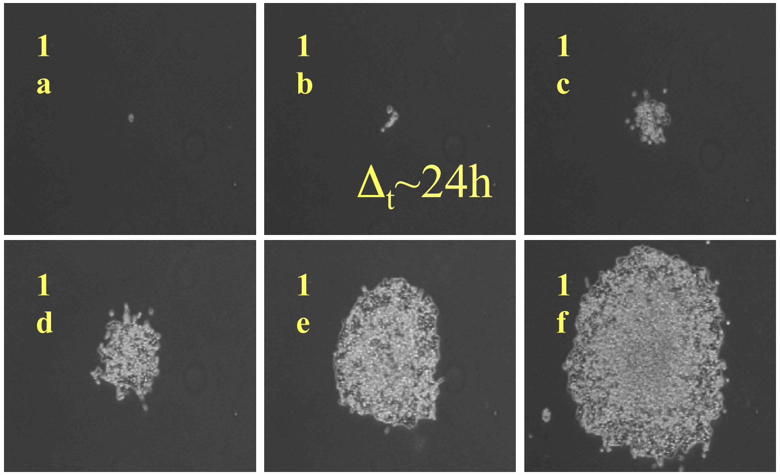
Cancer

$H_T = \Sigma w_R D_{T,R}$ D in gray (Gy)

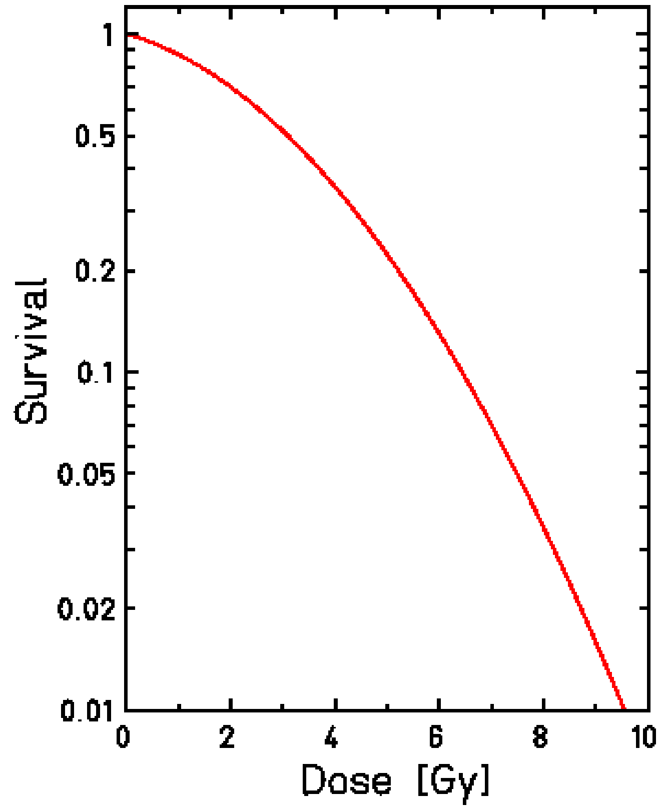
$E = \Sigma w_T H_T$ H, E in sievert (Sv)



Survival after X- or γ-rays



$$S = \frac{N_{col}}{N_{seed}} = e^{-(\alpha D + \beta D^2)}$$



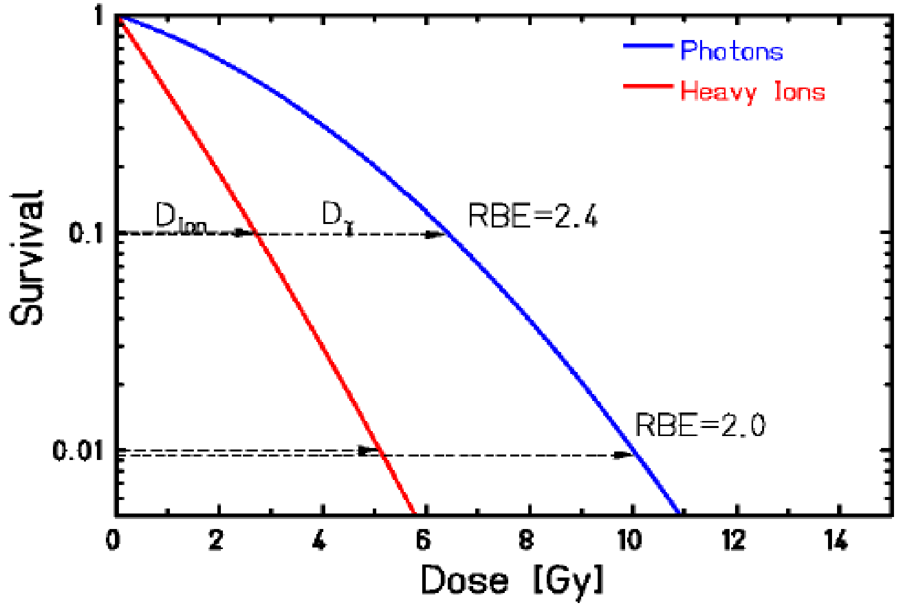
α[Gy^{-1}]: initial slope

β[Gy^{-2}]: bending of curve

α/β[Gy]: dose, at which contribution from linear term = contribution from quad. term

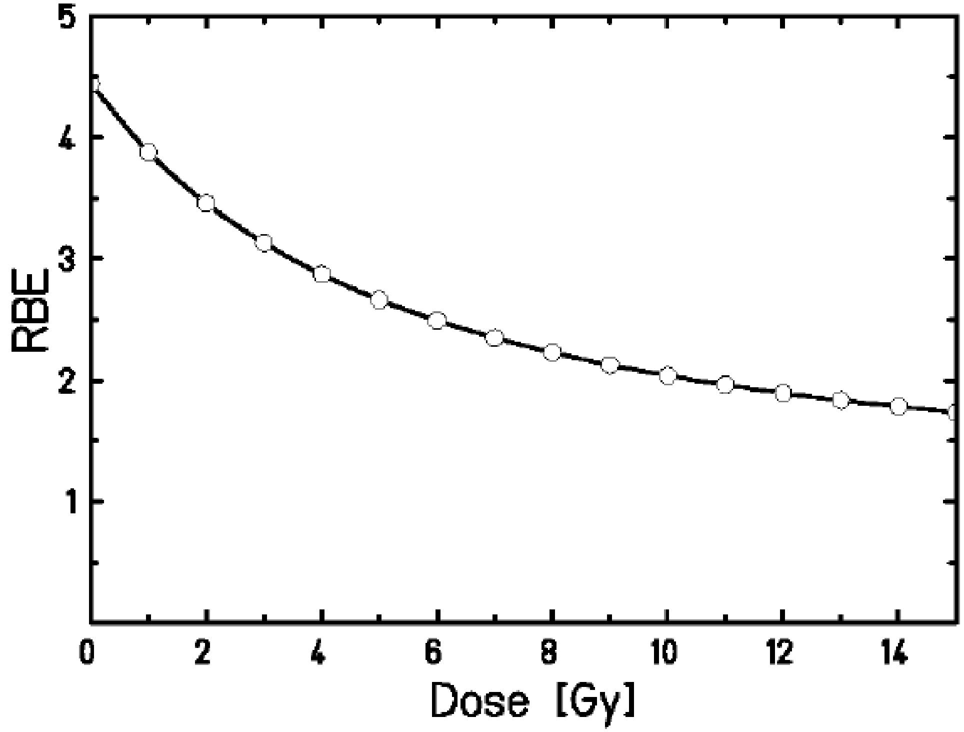
Relative Biological Effectiveness

Comparison of dose values at **Isoeffect-Level!**



$$RBE = \frac{D_\gamma}{D_{Ion}}\bigg|_{Isoeffect}$$

Dose dependence of RBE



$$RBE_{\alpha} = \frac{D_X}{D_I} = \frac{\alpha_I}{\alpha_X}$$

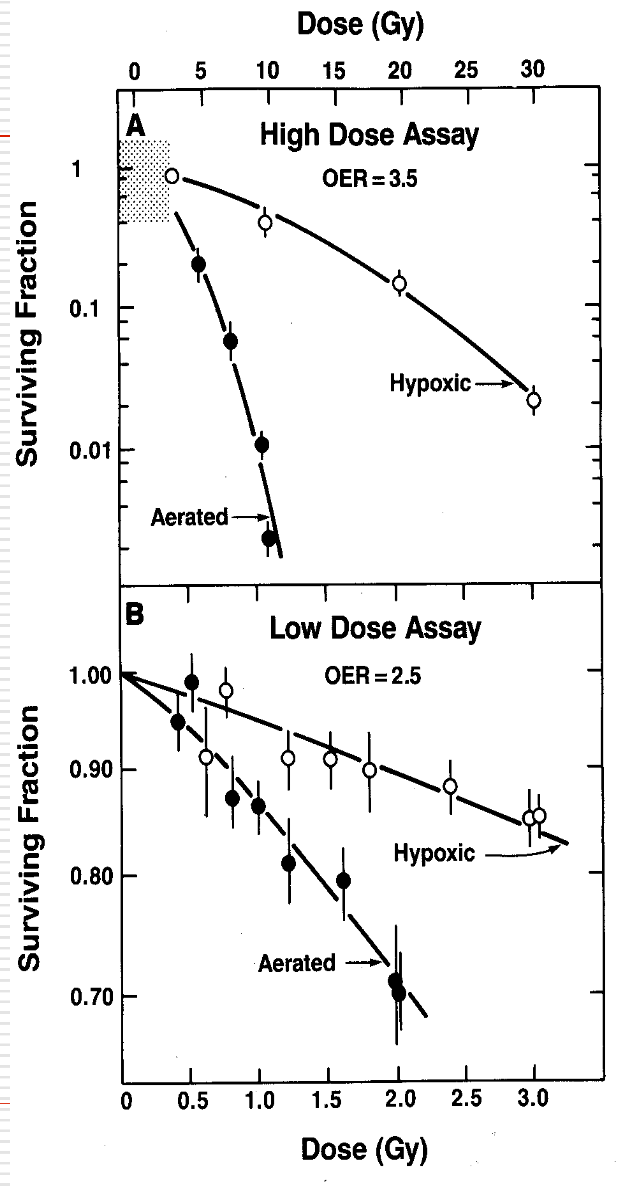
Oxygen Effect

OER:
Oxygen **E**nhancement **R**atio

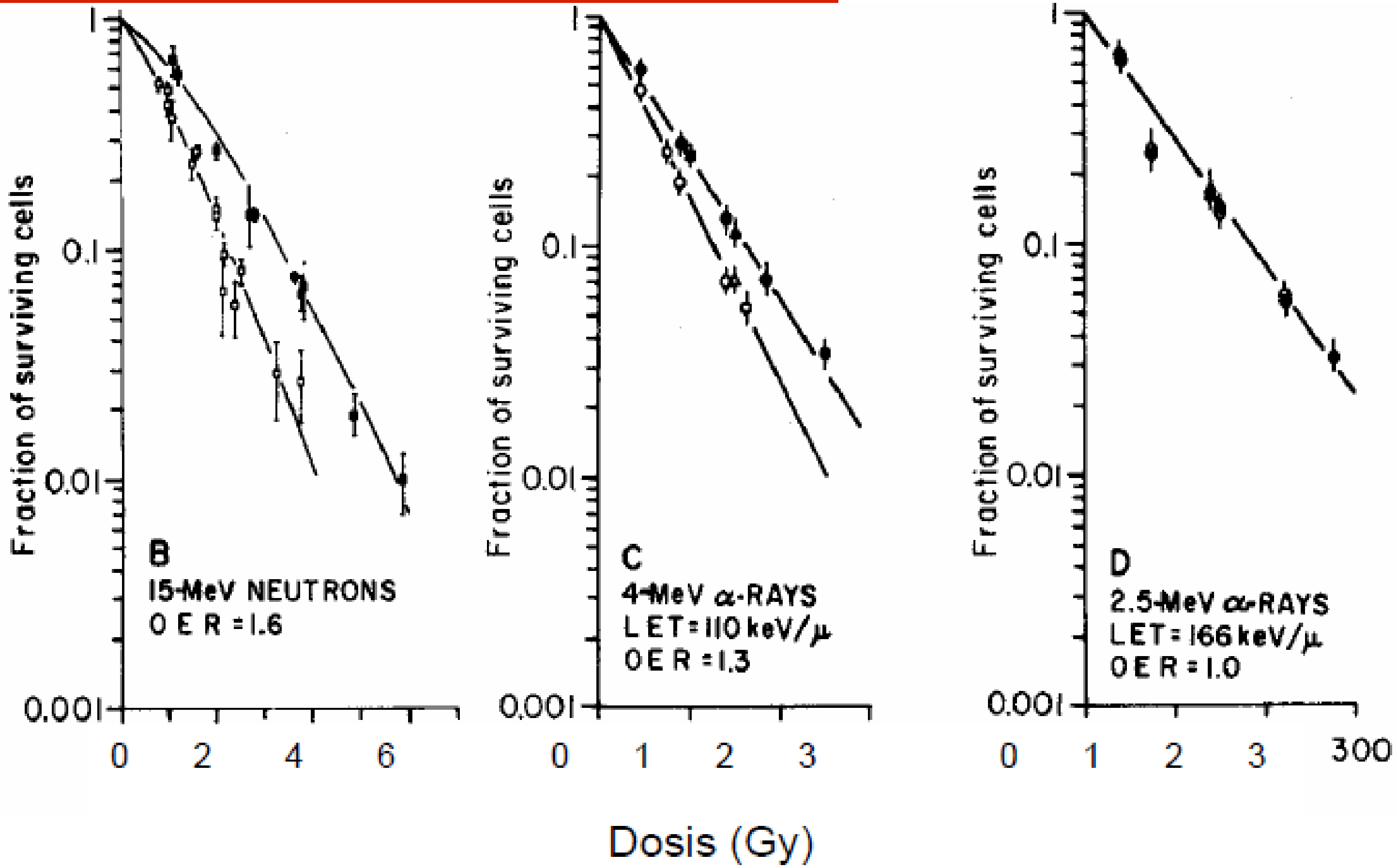
$$OER = \left.\frac{D_{hypoxic}}{D_{normoxic}}\right|_{same effect}$$

$$OER(p) = \left.\frac{D(p)}{D_{normoxic}}\right|_{same effect}$$

$$RBE = \left.\frac{D_x}{D_{ion}}\right|_{same effect}$$



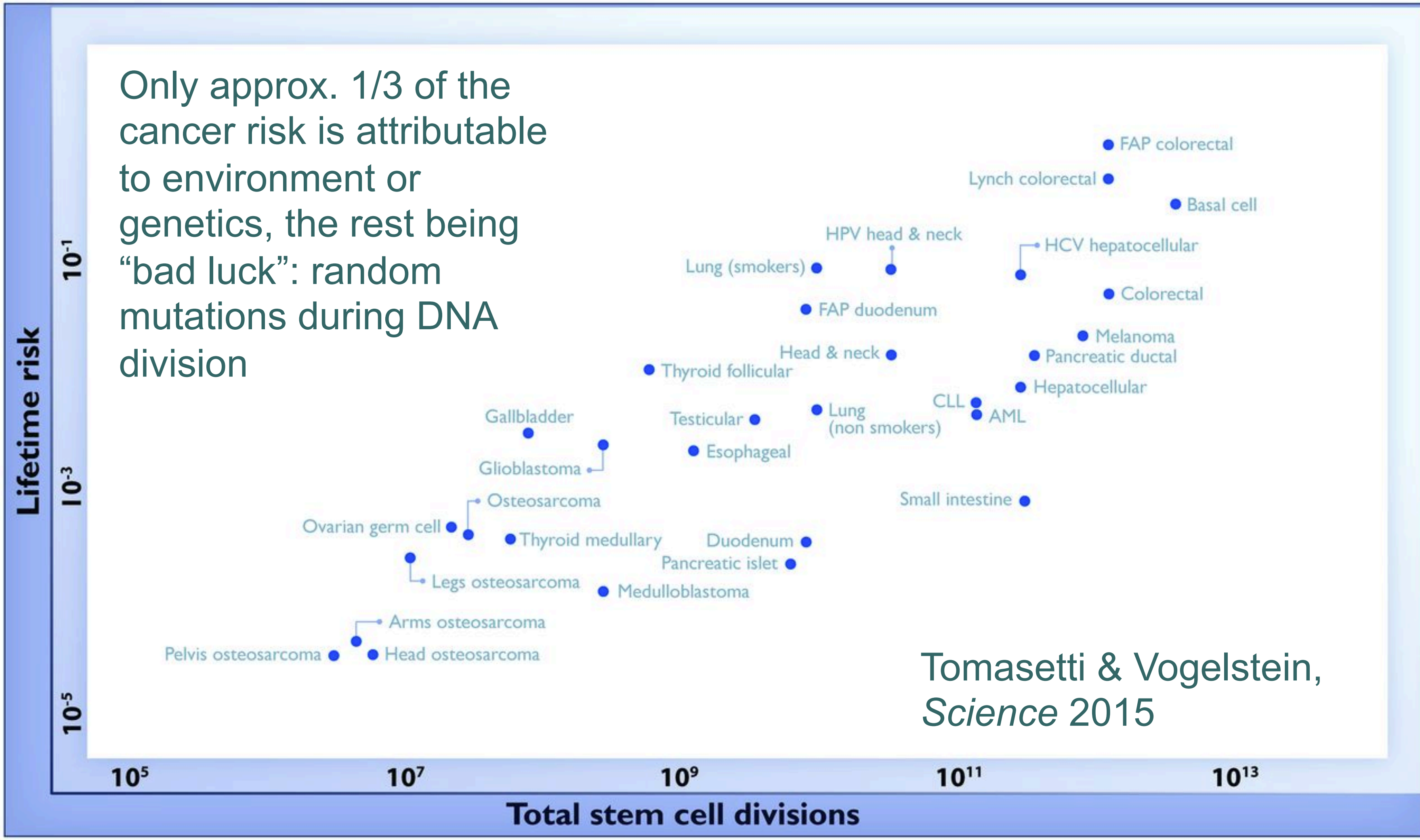
Oxygen effect: LET dependence



Hall 1994

Radiation carcinogenesis

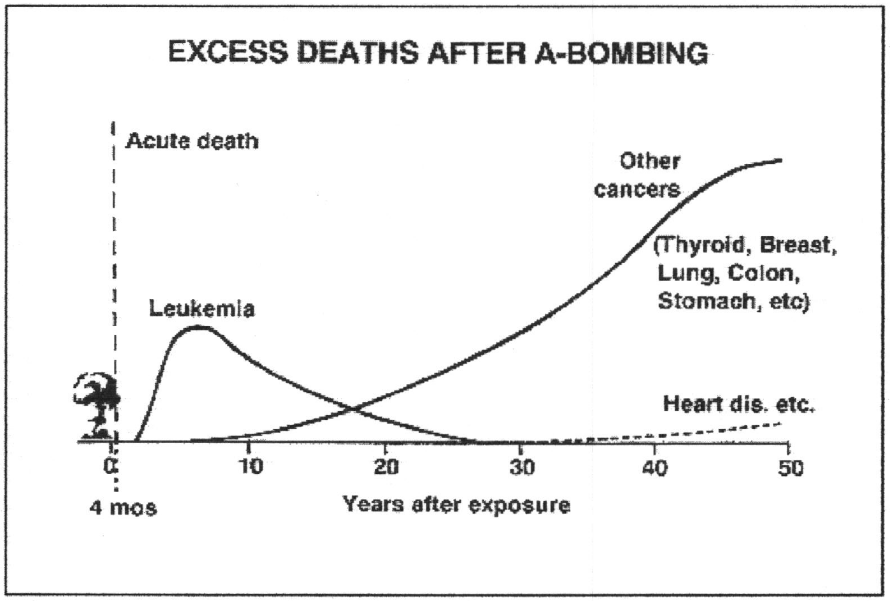
Only approx. 1/3 of the cancer risk is attributable to environment or genetics, the rest being “bad luck”: random mutations during DNA division



Tomasetti & Vogelstein, *Science* 2015

FAP = Familial Adenomatous Polyposis ◇ HCV = Hepatitis C virus ◇ HPV = Human papillomavirus ◇ CLL = Chronic lymphocytic leukemia ◇ AML = Acute myeloid leukemia

Evidence of radiation carcinogenesis



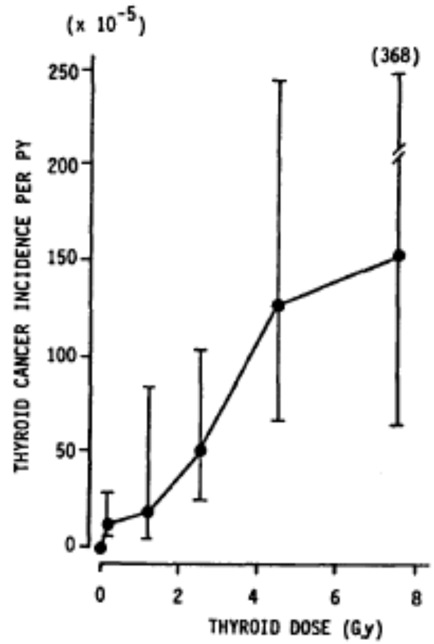
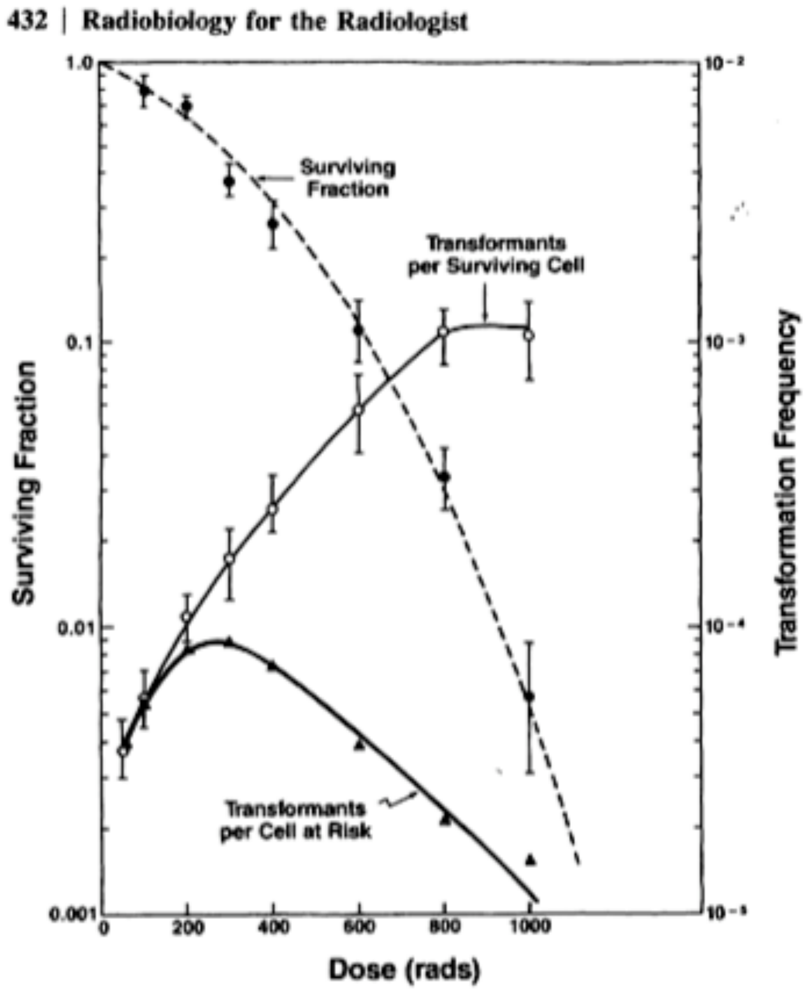


Figure 19–5. Thyroid cancer incidence per person year (PY) as a function of the radiation dose in the thyroid. Rates adjusted for sex, ethnicity, and interval after irradiation. Error bars represent 90% confidence limits. (From Shore RE, Woodard E, Hildreth N, et al: J Natl Cancer Inst 74:1177–1184, 1985)

In vitro dose-response curve



Dose-response curve for the frequency of transformant/ surviving cell using linear-quadratic, but plateaus at high doses

Animal studies

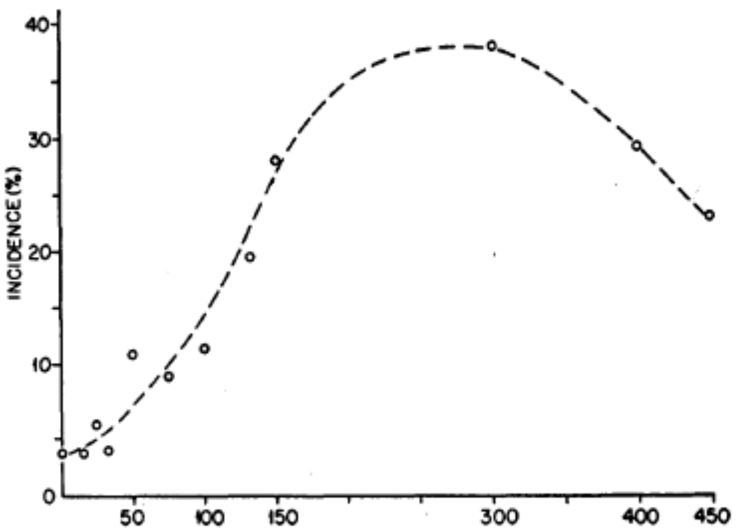
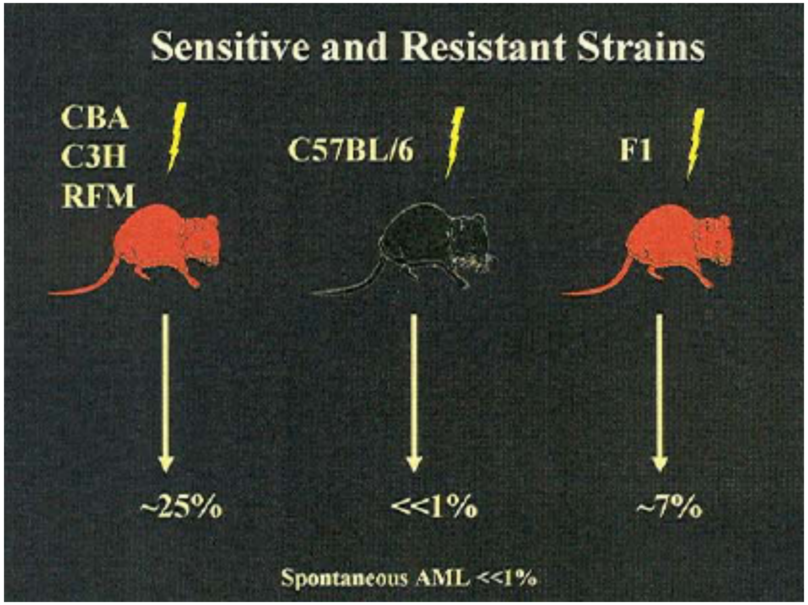


Figure 19–3. Incidence of myeloid leukemia in RF male mice exposed to whole-body x-irradiation. (From Upton AC: Cancer Res 21:717–729, 1961)



The elephant paradox

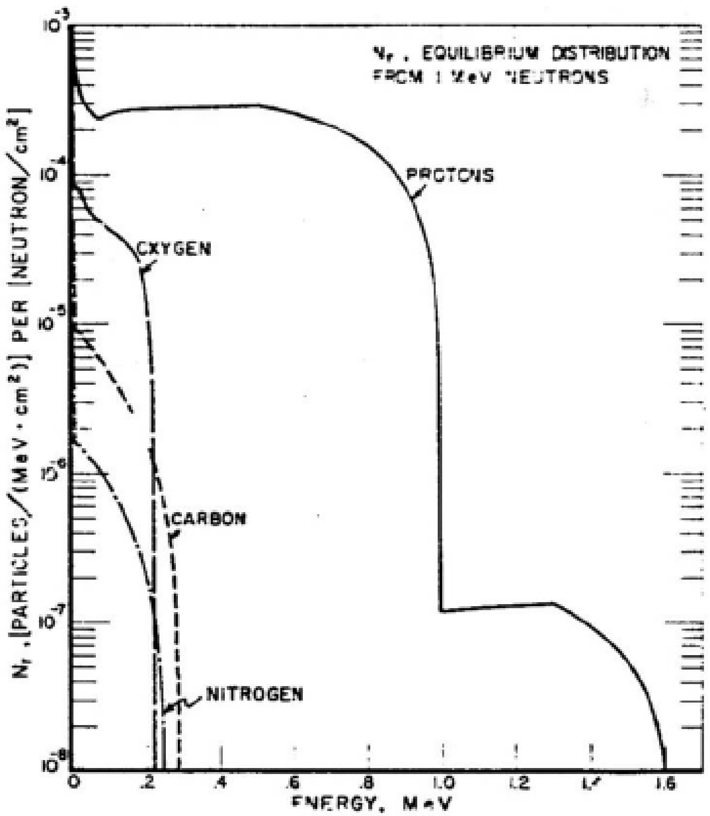
Nature, 8.10.2015

- Cancer is an aging disease, and depends on the number of divisions of the stem cells
- Large, old animals should get more cancers
- However, elephants do not get cancer
- Same is true for other large animals, such as humpback whales
- Recent studies show that elephants have approximately 20 copies of the p53 gene
- As a consequence, their blood cells are very radiosensitive and go into apoptosis
- Instead of repairing DNA damage, injured elephant cells kill themselves to nip nascent tumors in the bud

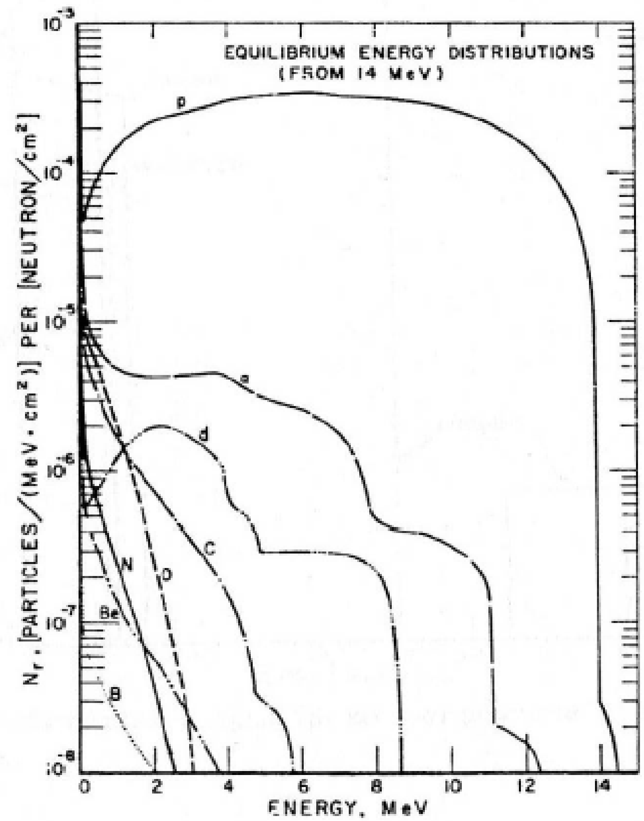
Neutron radiobiology: an old story

Neutrons: secondary charged particle spectra

1 MeV

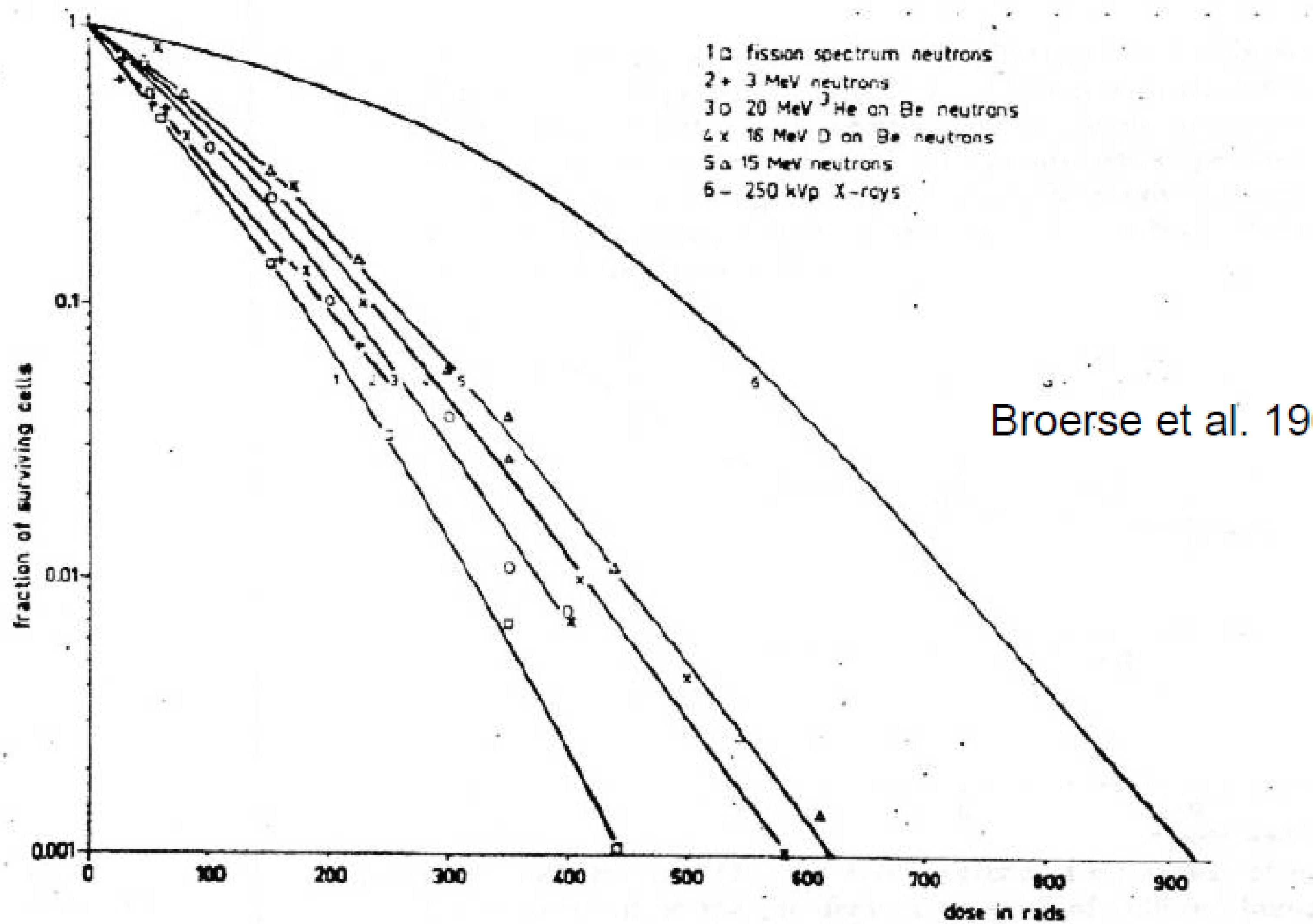


14 MeV



Caswell & Coyne 1972

Neutrons: Survival Curves



Broerse et al. 1968

Figure 3. Survival curves obtained for cultured cells of human origin irradiated with different beams of fast neutrons and with 250 kVp x-rays.

Neutron: Energy dependence of RBE

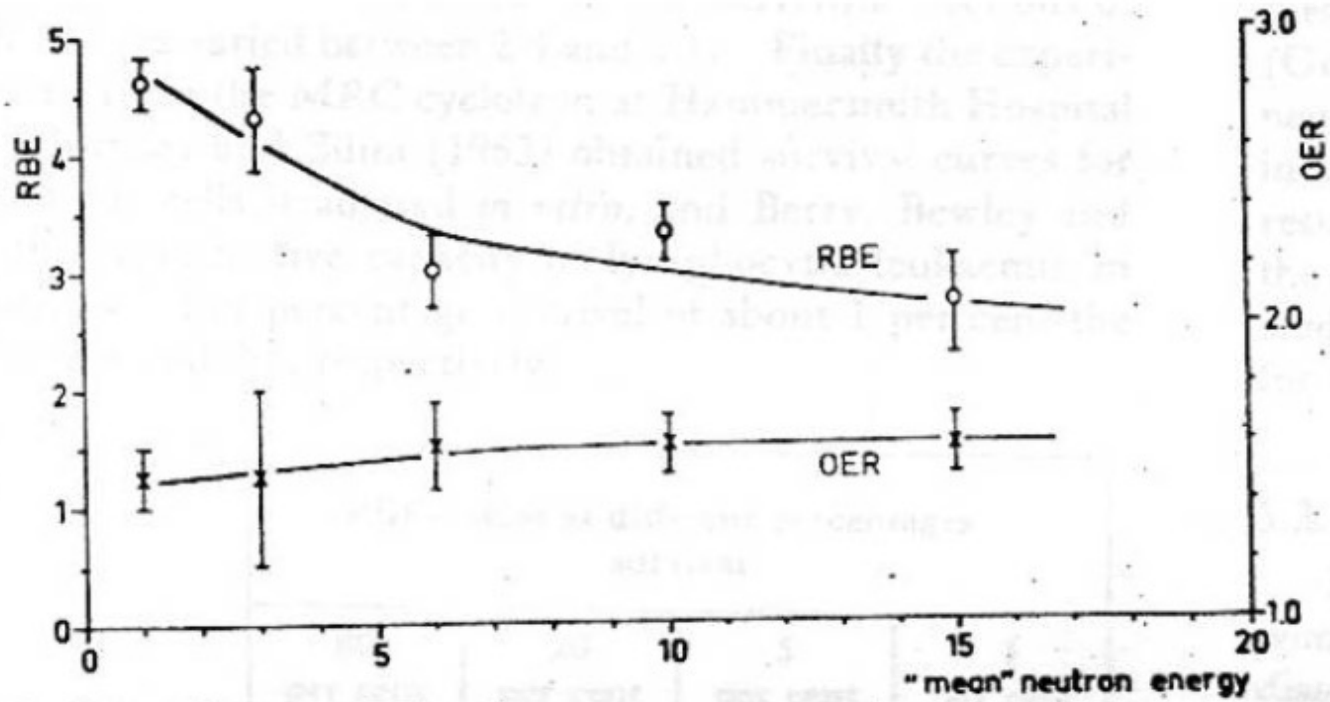
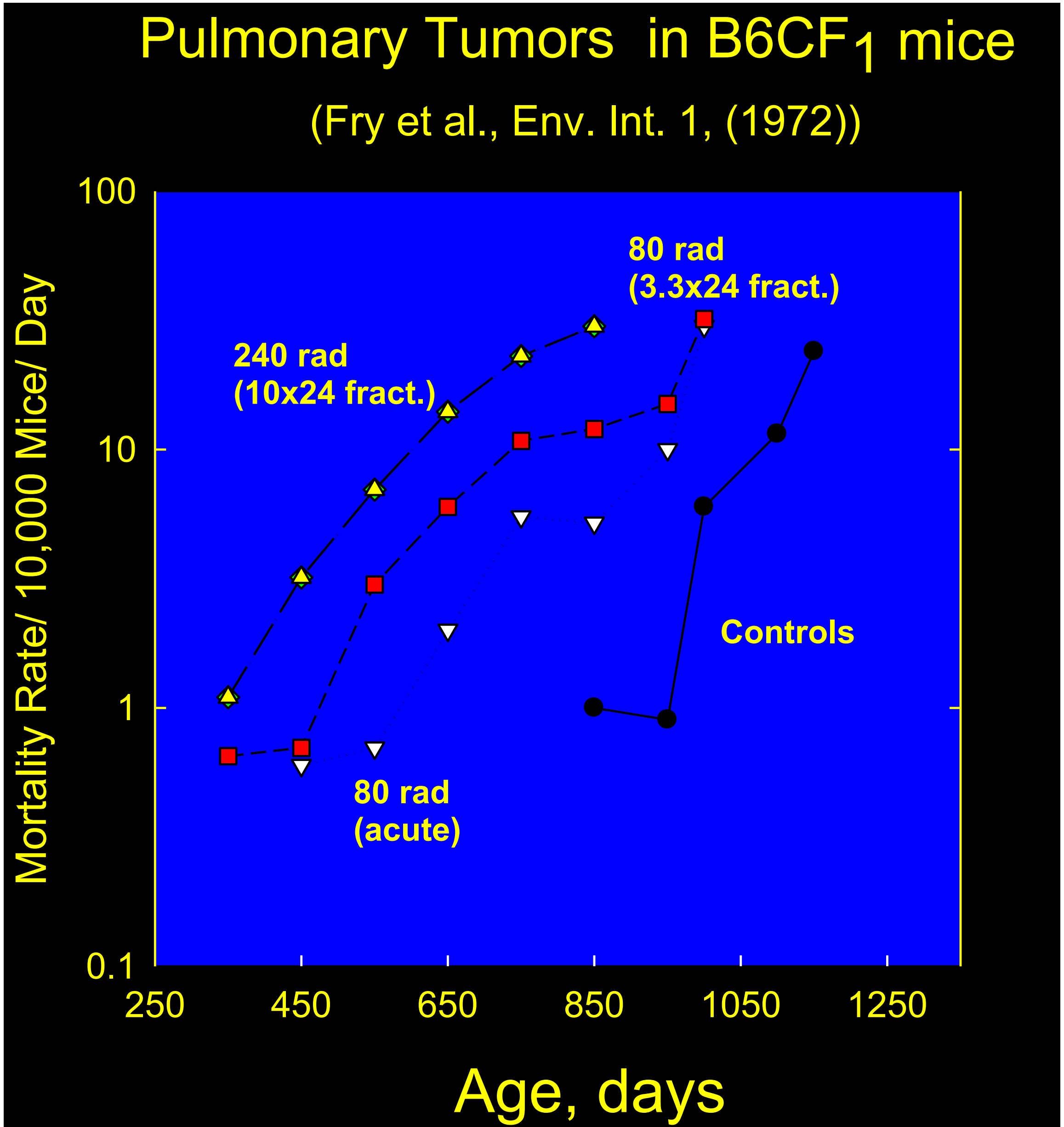


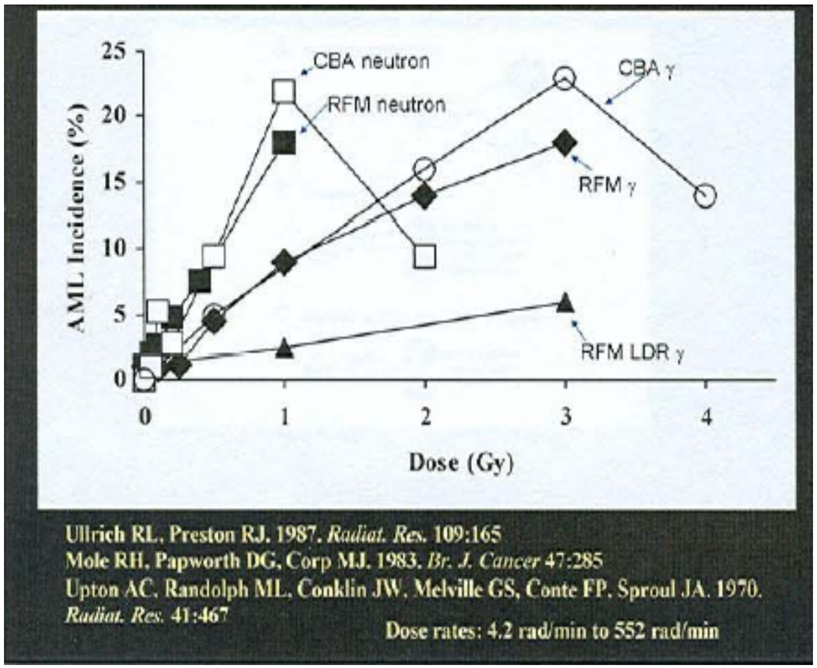
Figure 5. The RBE and OER of fast neutrons as a function of mean neutron energy, for impairment of the proliferative capacity of cultured human cells. The RBE-values correspond to doses producing 50 per cent cell killing.

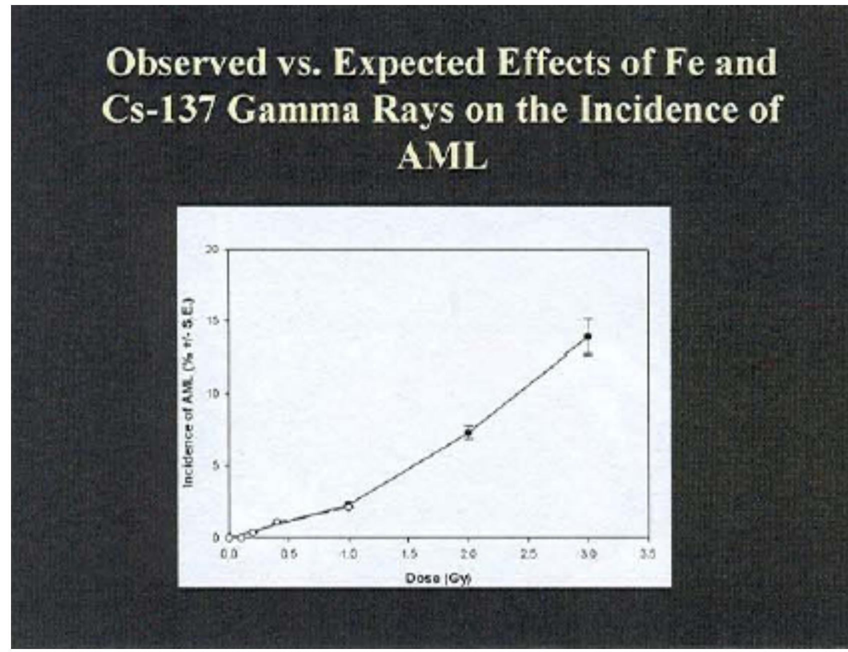
Broerse et al. 1968

“how much” or when”?



Induction of acute myeloid luekemia in mice



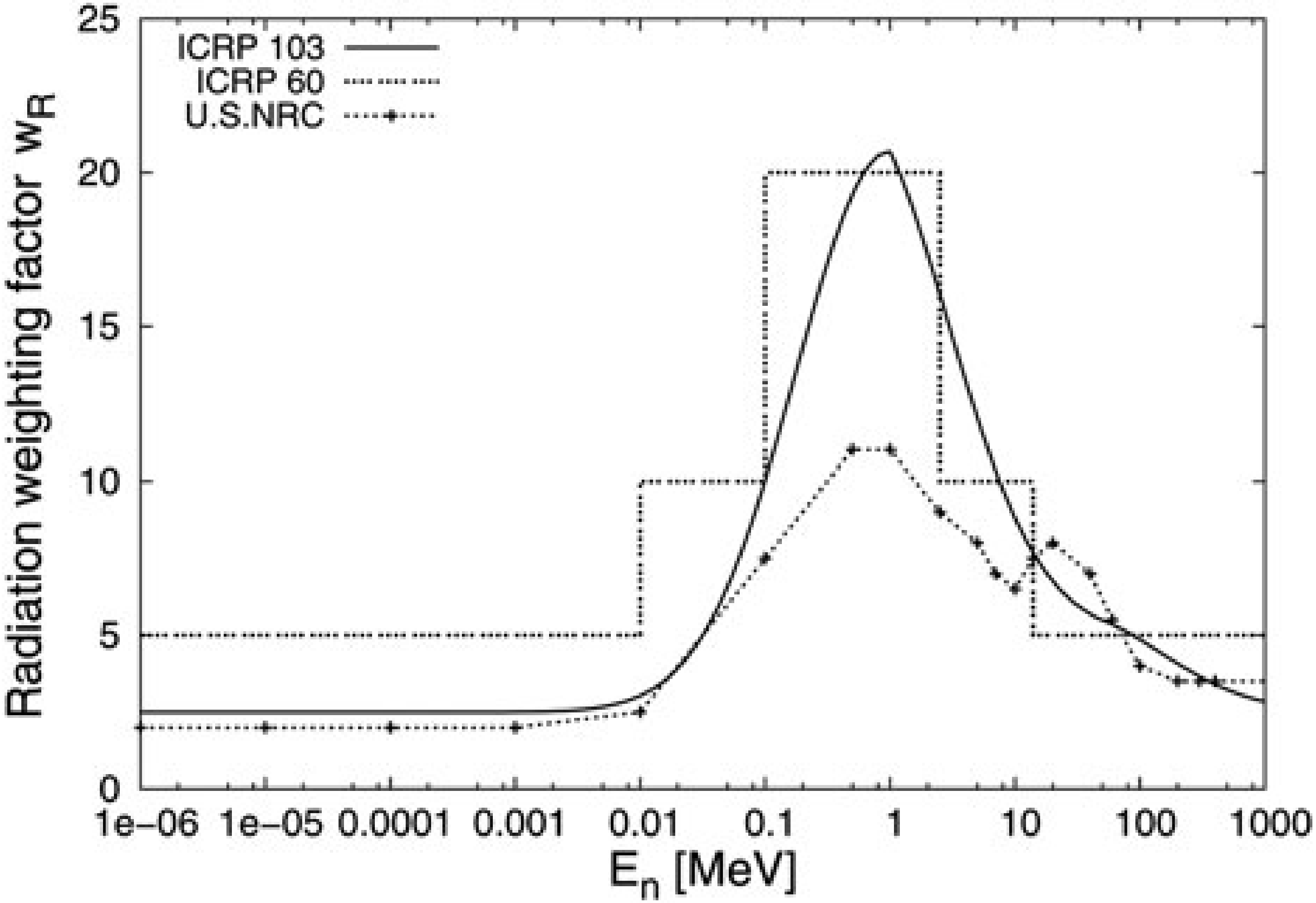


RBE~1 for Fe-ions

RBE ~10 for neutrons

Colorado State University, 2009

Neutron quality factor



$$H_T = \Sigma\, w_R D_{T,R}$$

$$E = \Sigma\, w_T H_T$$

Radiotherapy

Side-effects of Radiotherapy

- Acute (<1 month)
- Depend on area(s) being treated
- Often fatigue can occur
- mucositis/esophagitis, nausea, diarrhea and redness of skin

Late (>1 month)

Pneumonitis/fibrosis of lungs

Hypothyroidism

Xerostomia

Enteritis

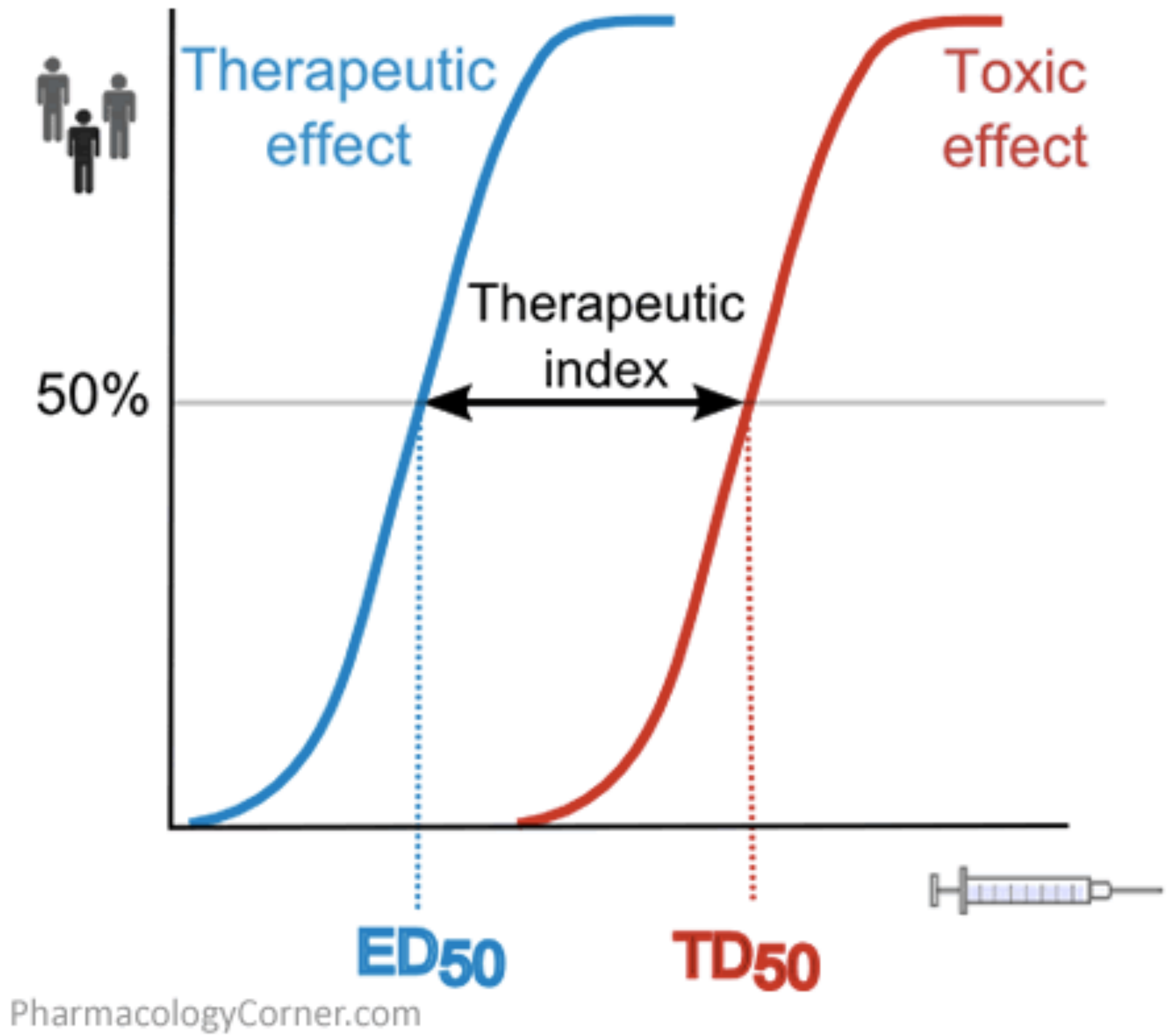
Infertility/menopause

Long-term (10-20 years)

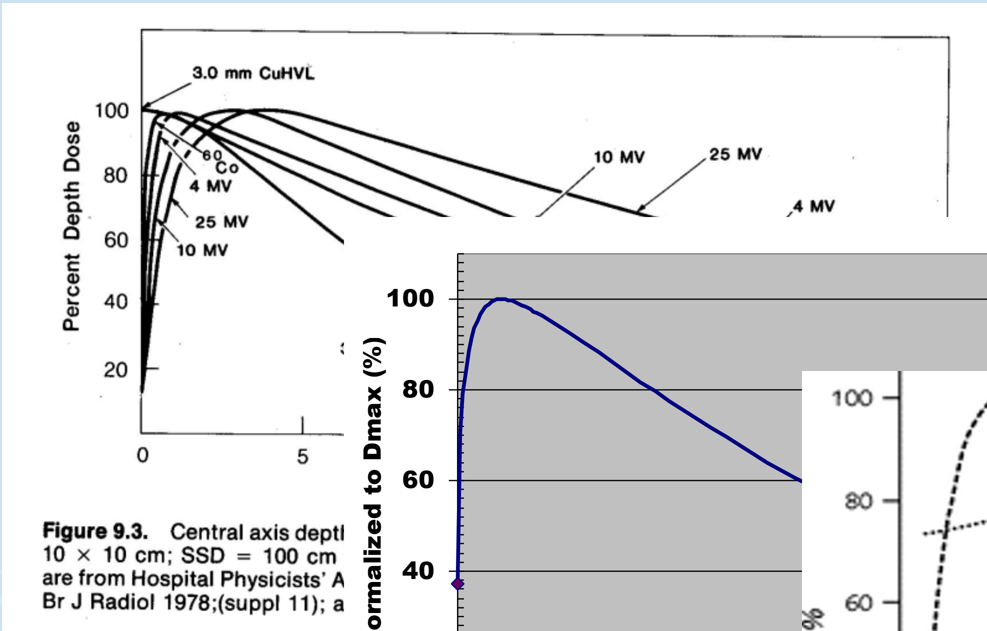
Increased risk of secondary cancers

Increased heart disease if chest region treated

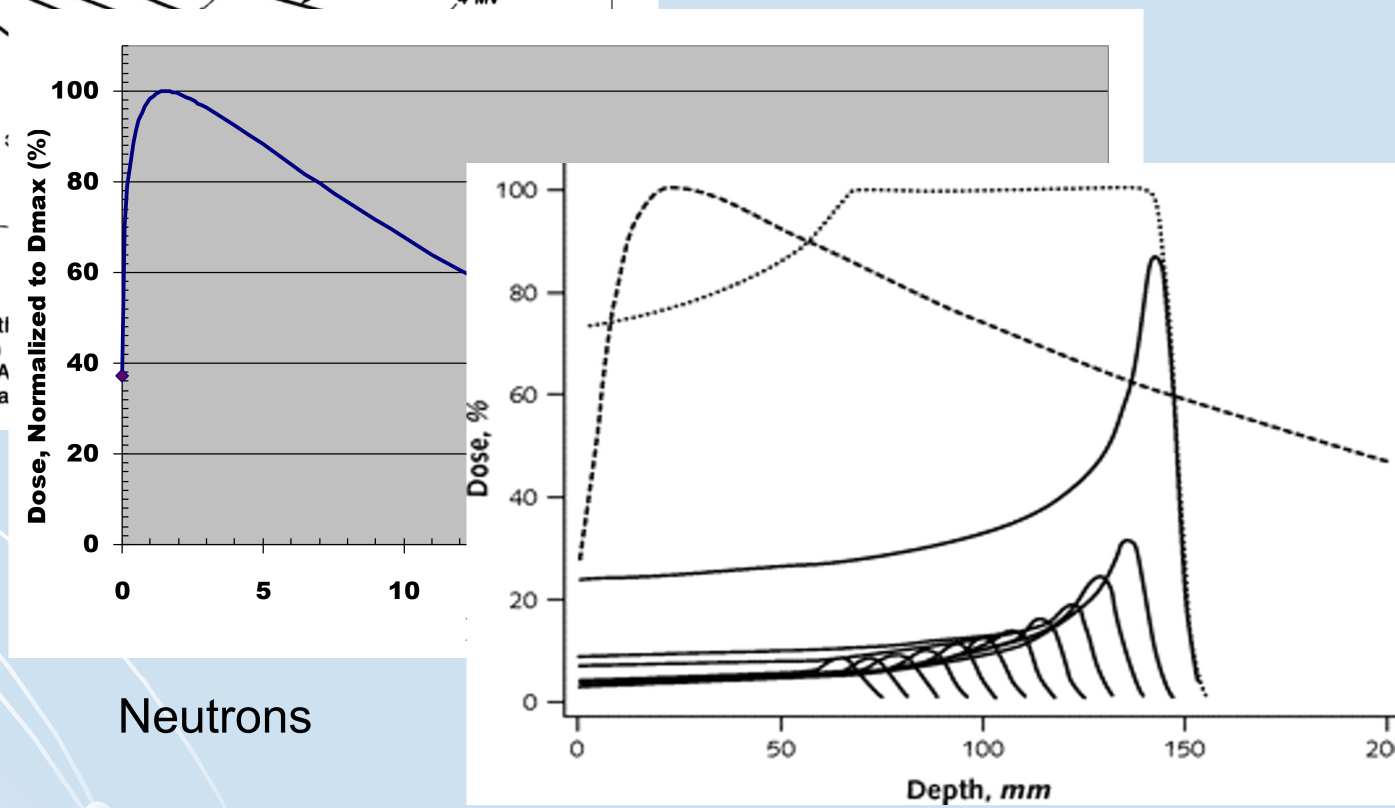
Therapeutic window



Where is the Energy Deposited?



Photons



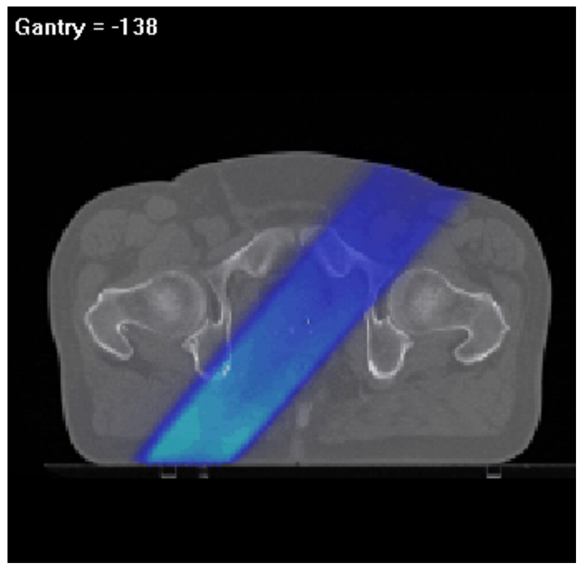
Neutrons

Protons

X-ray dose decrease with depth
We have to cross-fire on the tumor from many angles

Single field

Dose per field



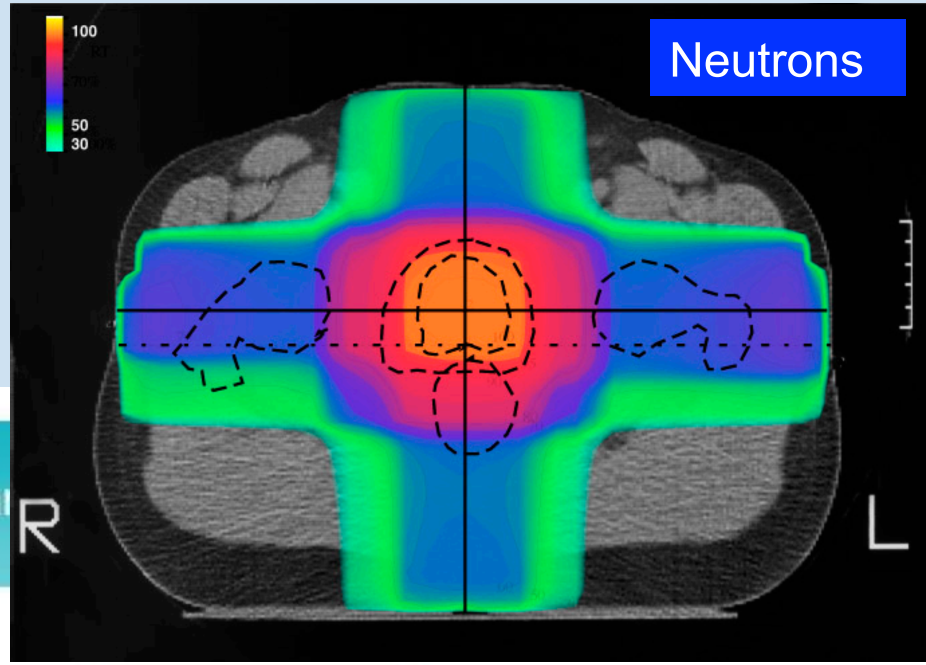
Total dose

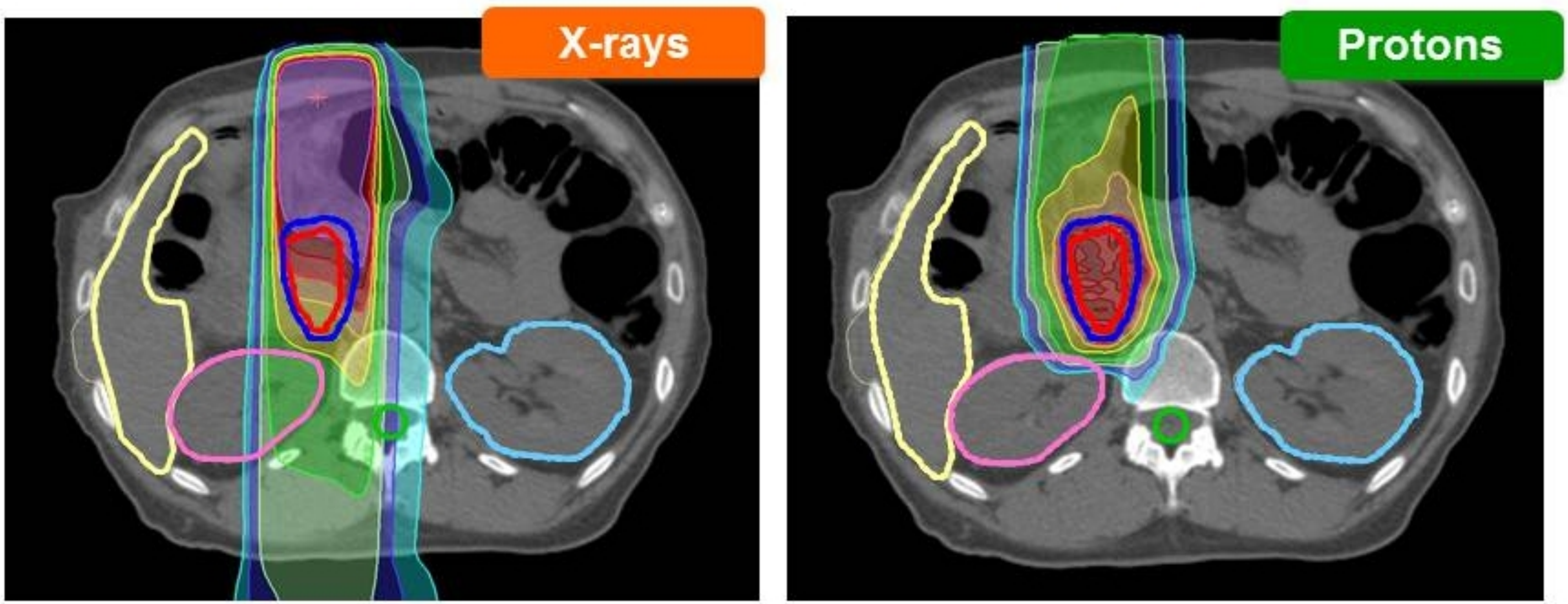
Excellent target conformity
Large normal tissue volume irradiated

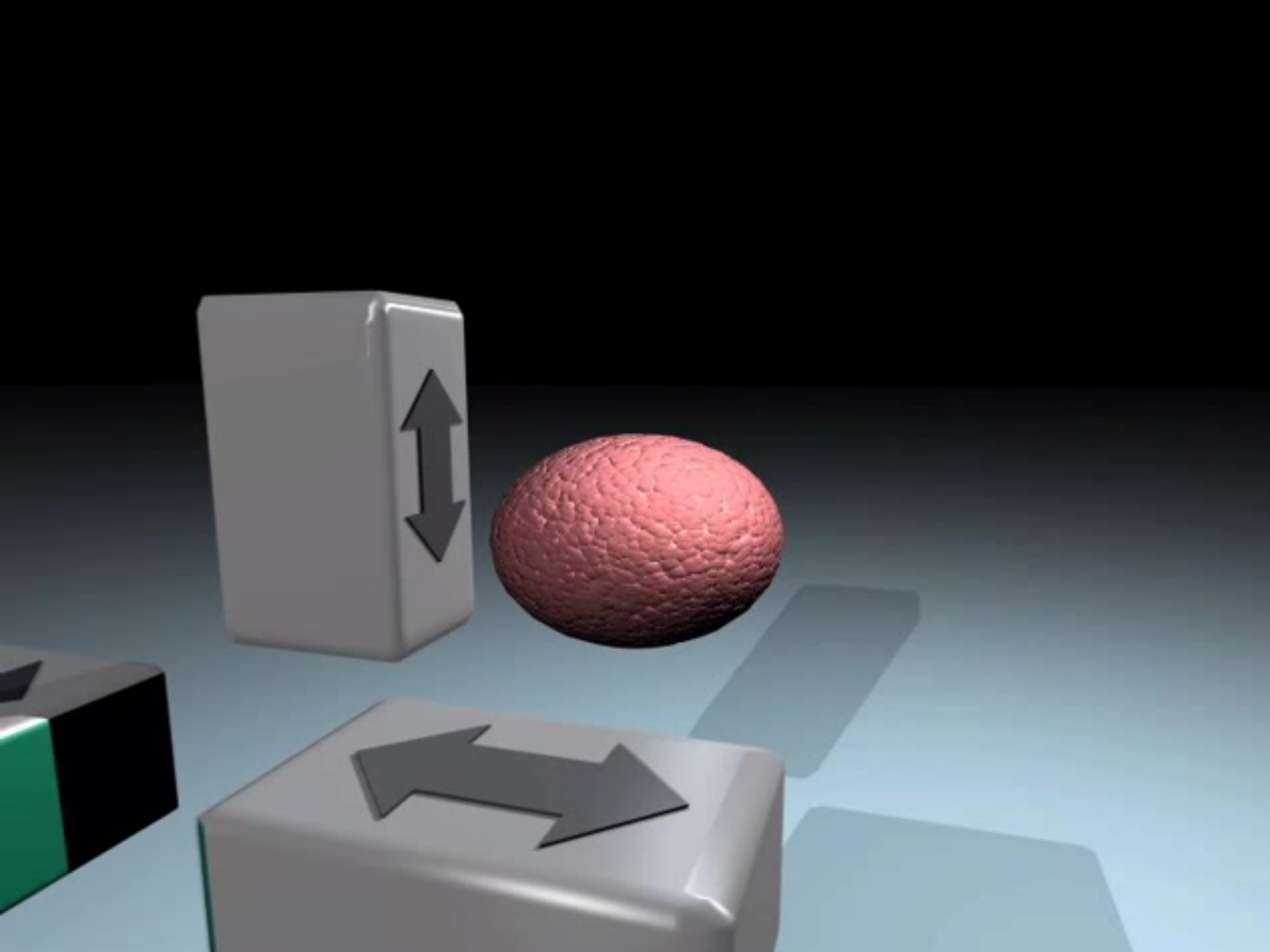
Courtesy B. Mijnheer

Image 2
Theoretical Compar
Protons

RINECKER PROTON THERAPY CENTER





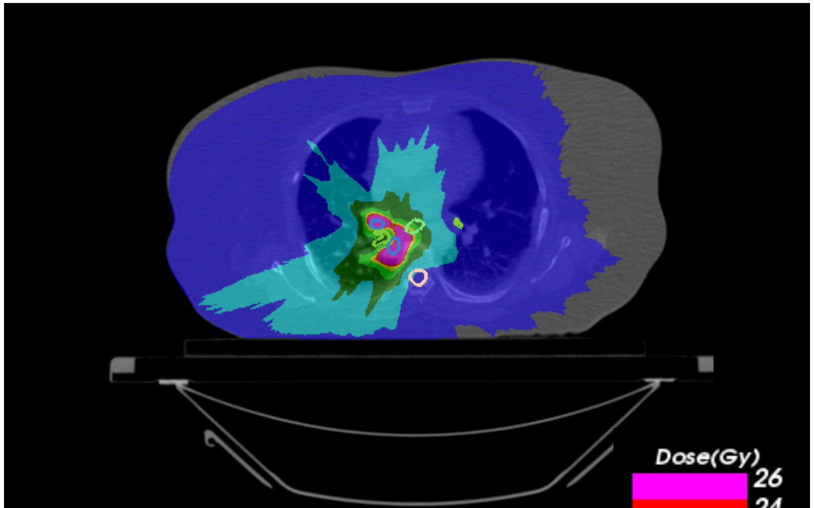


Champalimaud Foundation

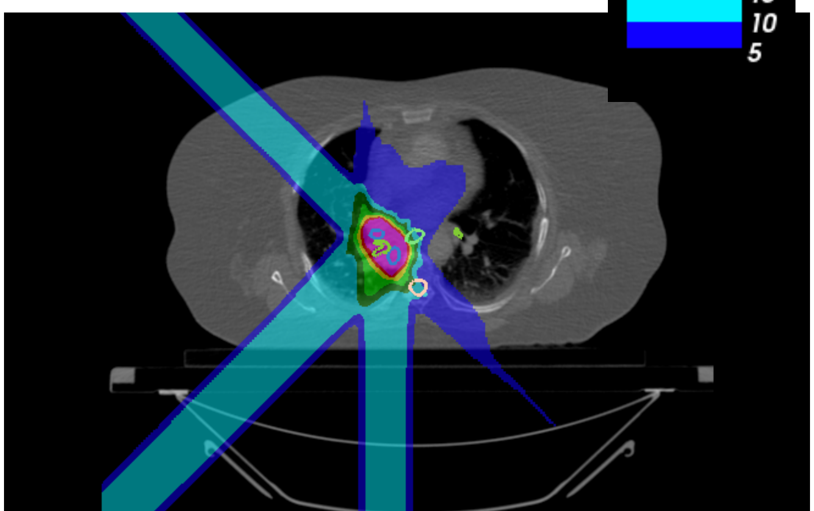
Lung tumors: SBRT vs. C-ions

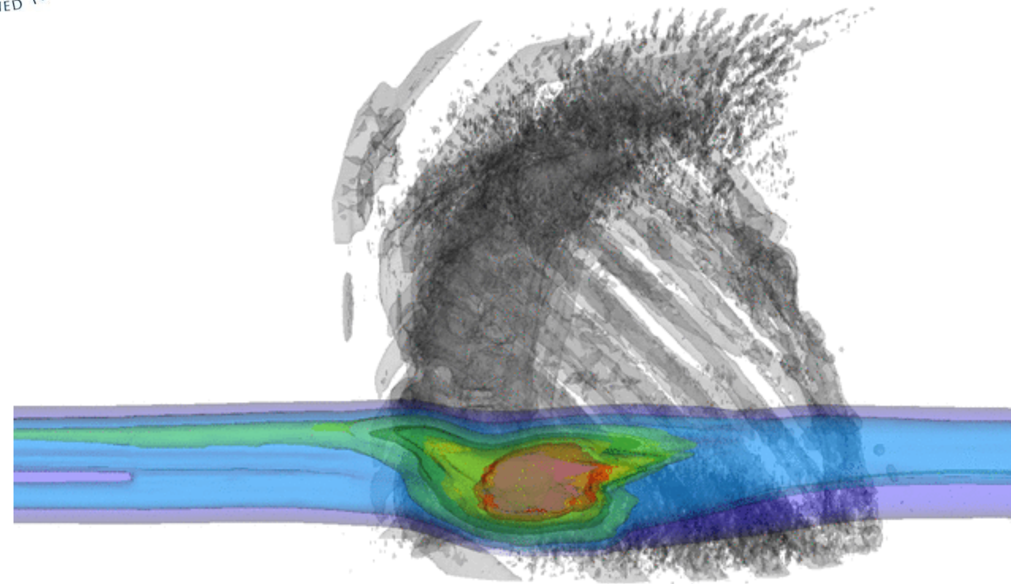
Single fraction, 25 Gy

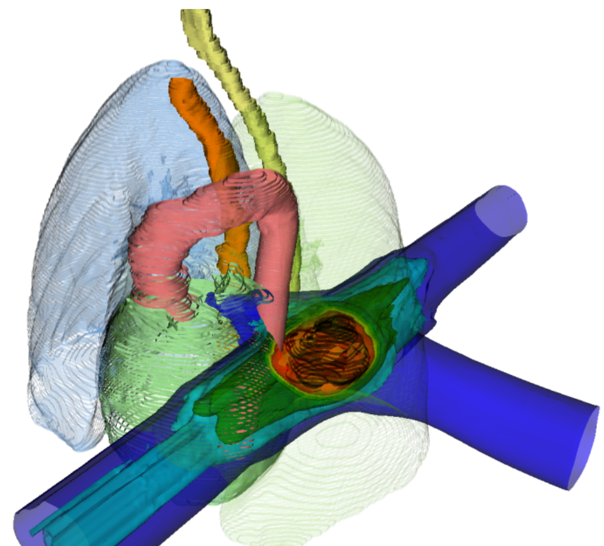
X-rays



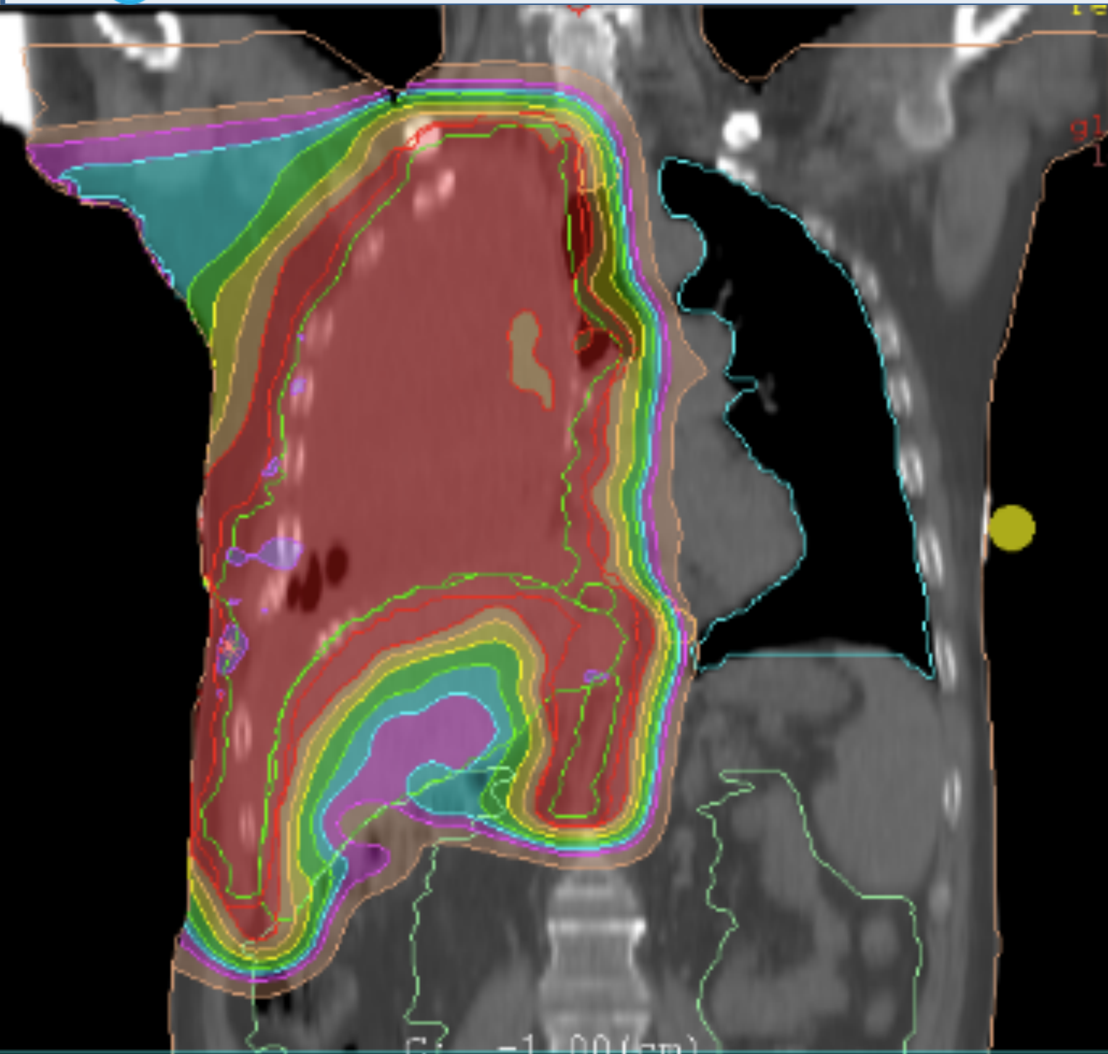
C-ions







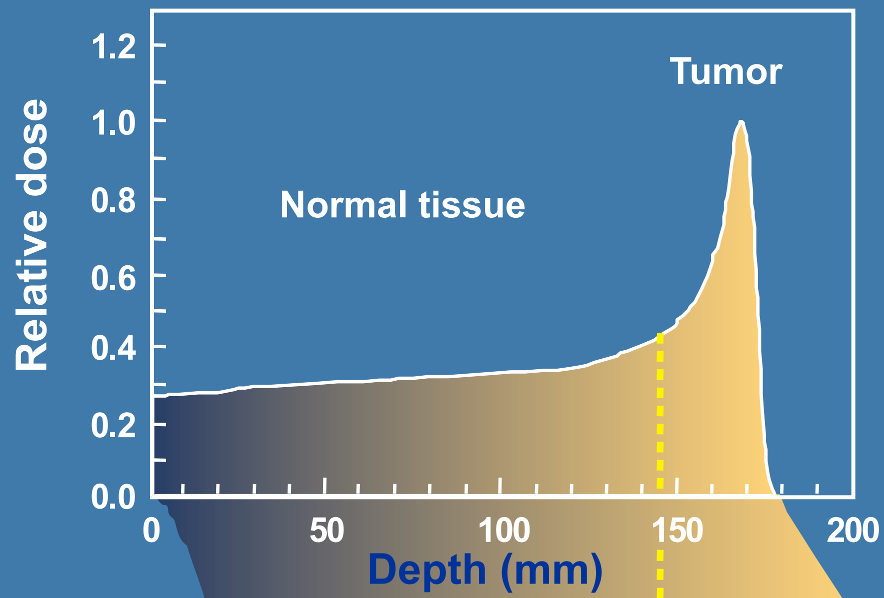
Kristjan Anderle, Ph.D. thesis, TU Darmstadt, 2014



Treatment plan with protons: pleural mesothelioma

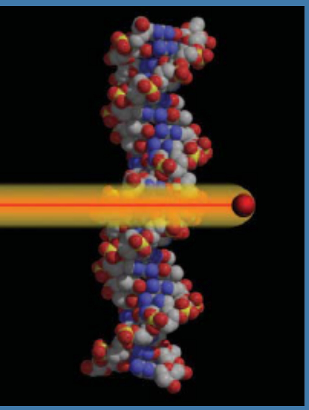
Courtesy of Marco Schwarz, AtrEP, Trento, Italy

Loeffler & Durante, *Nat. Rev. Clin. Oncol.* 2013

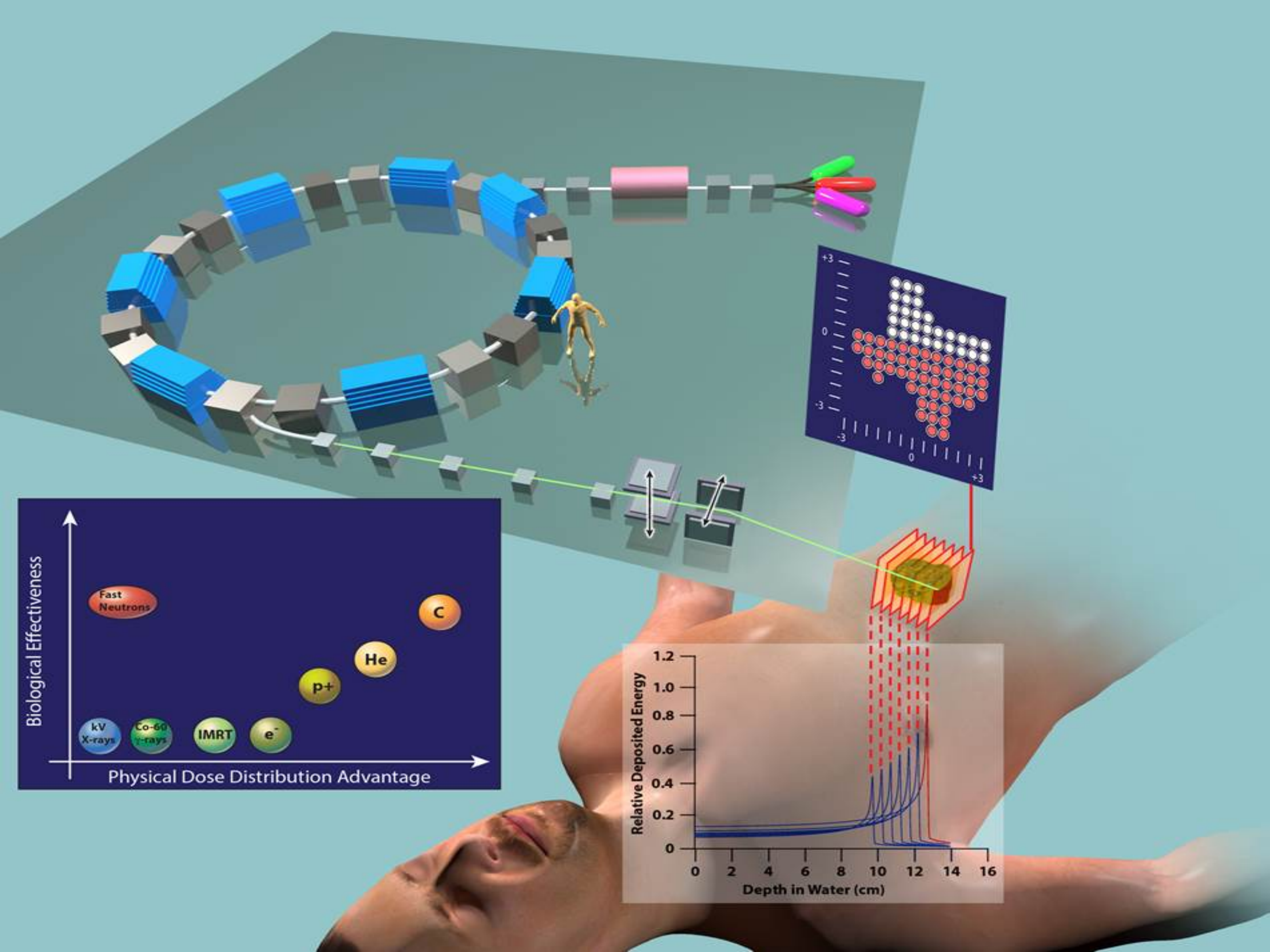


- About 100,000 patients treated with H and 10,000 with C-ions
- >30 particle therapy facilities in operation (6 with heavy ions)
- Many more are under construction or planned

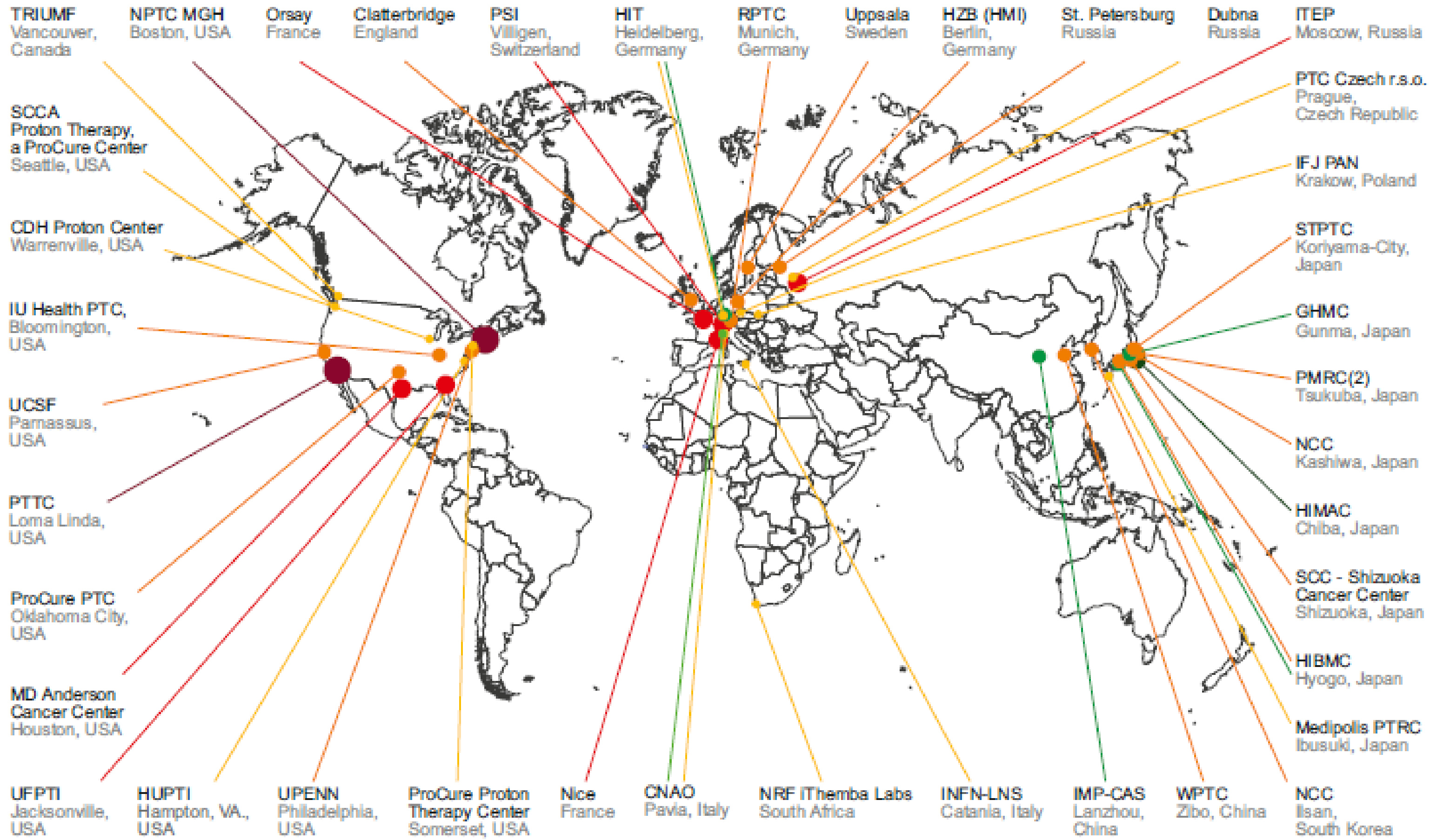
Potential advantages

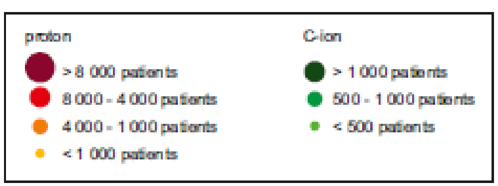


Energy	high	low	
LET	low	high	
Dose	low	high	High tumor dose, normal tissue sparing
RBE	≈ 1	> 1	Effective for radioresistant tumors
OER	≈ 3	< 3	Effective against hypoxic tumor cells
Cell-cycle dependence	high	low	Increased lethality in the target because cells in radioresistant (S) phase are sensitized
Fractionation dependence	high	low	Fractionation spares normal tissue more than tumor
Angiogenesis	Increased	Decreased	Reduced angiogenesis and metastatization
Cell migration	Increased	Decreased	



+3
0
-3
-3
0
+3
Biological Effectiveness
Fast Neutrons
C
He
p+
kV X-rays
Co-60 γ-rays
IMRT
e⁻
Physical Dose Distribution Advantage
Relative Deposited Energy
1.2
1.0
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
Depth in Water (cm)





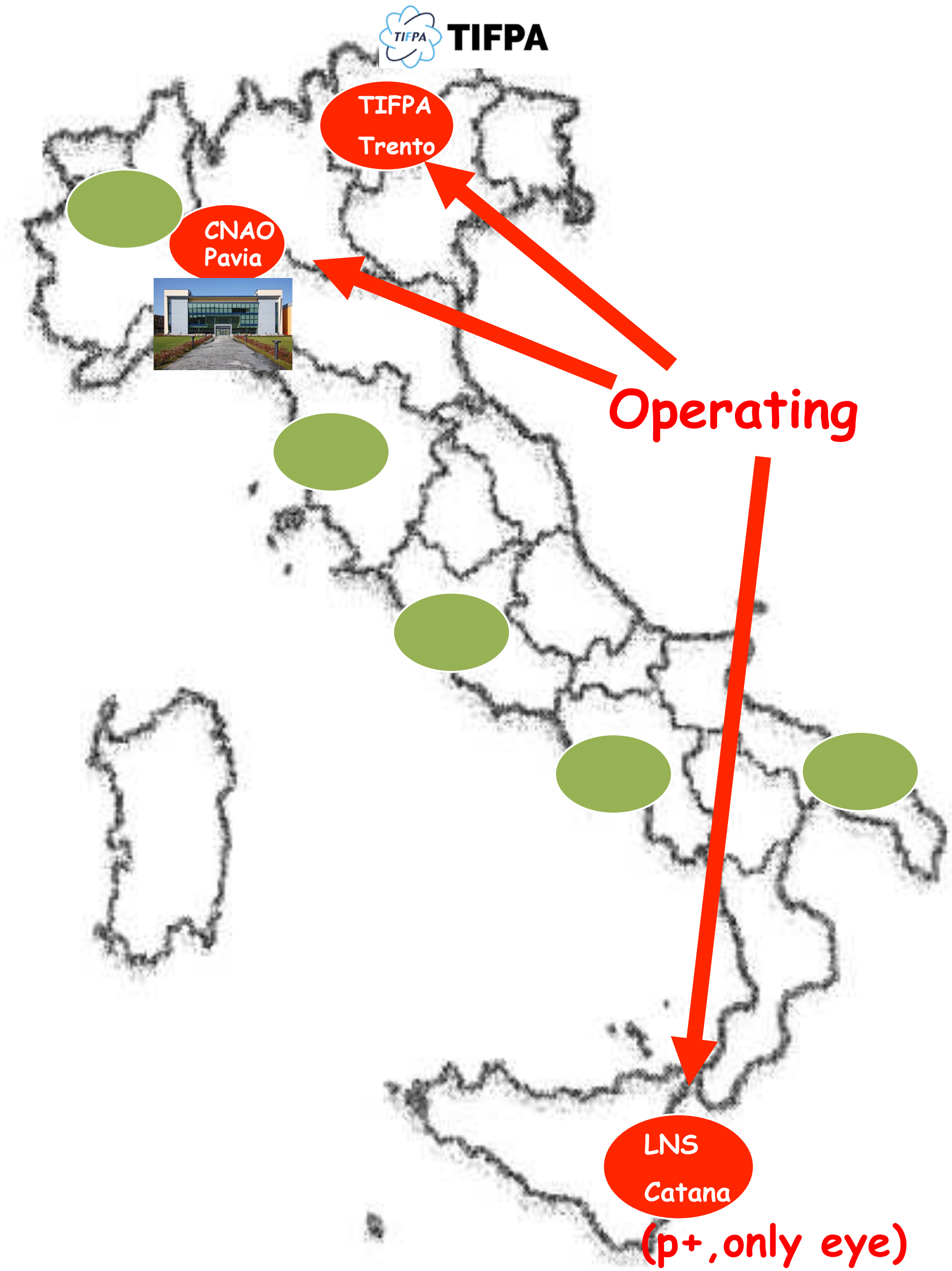
March 2014: 44 proton/7 heavy ion centers
Under construction: 25 proton/ 4 heavy ion centers
Only in USA, 27 new centers expected by 2017

uPECC report „Nuclear Physics in Medicine“, 2014
vailable online www.nupecc.org

ITALIAN NETWORK FOR HADRONTHERAPY

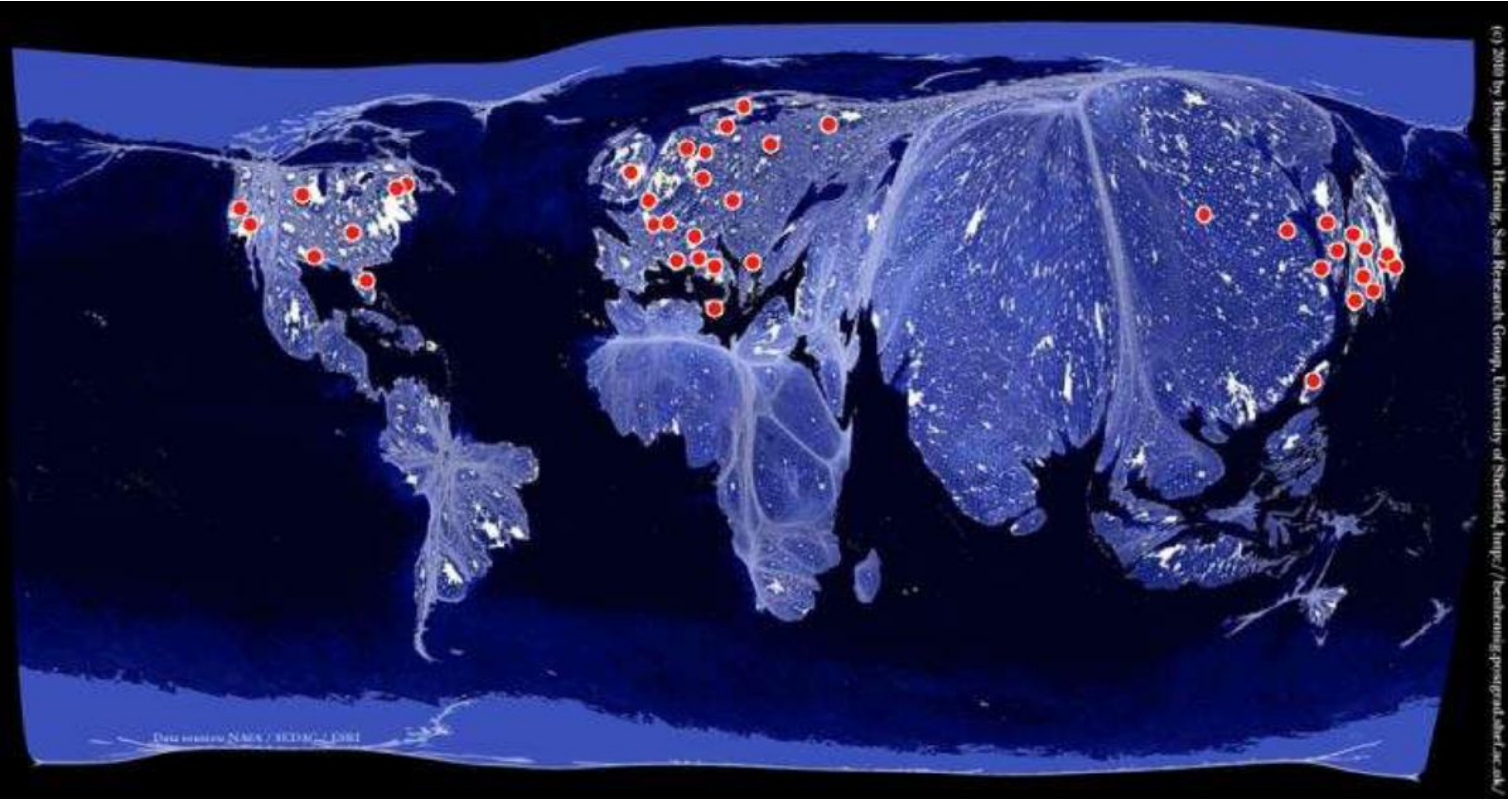
EXISTING CENTRES

INTEREST FOR PROTONS

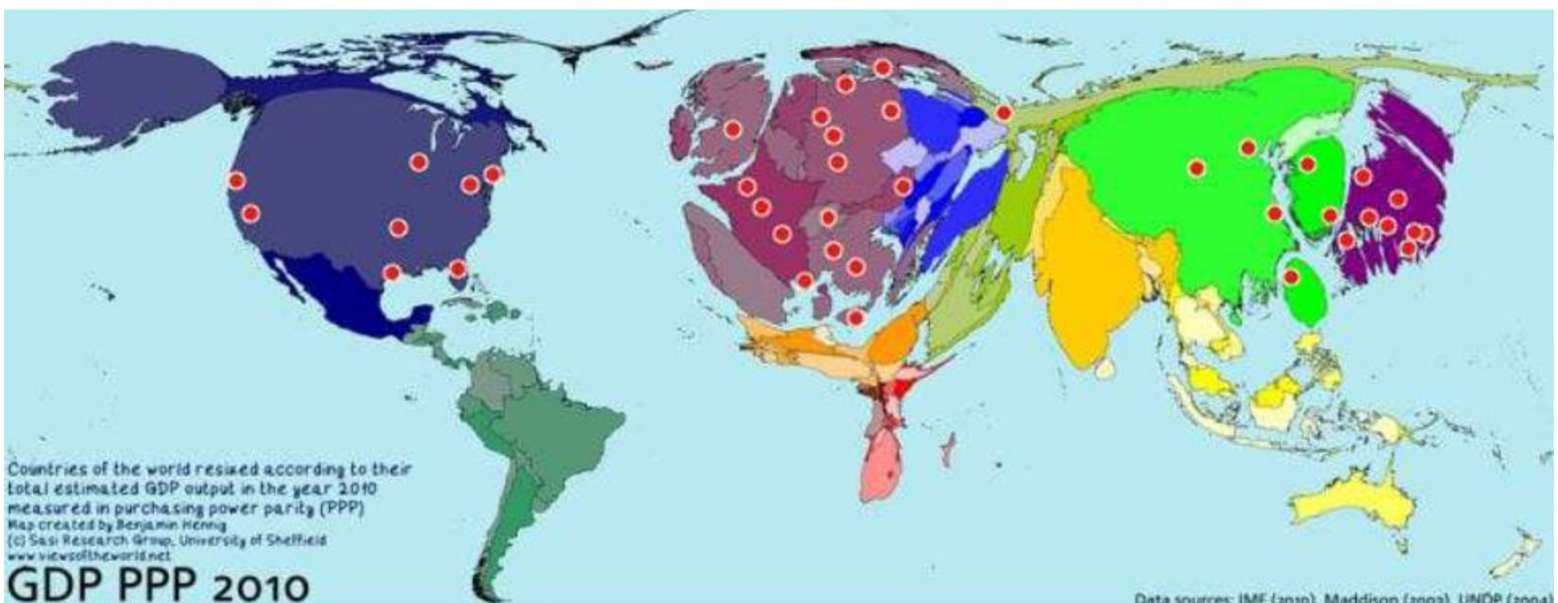



Croton


PROBLEMS
AHEAD
CAUTION

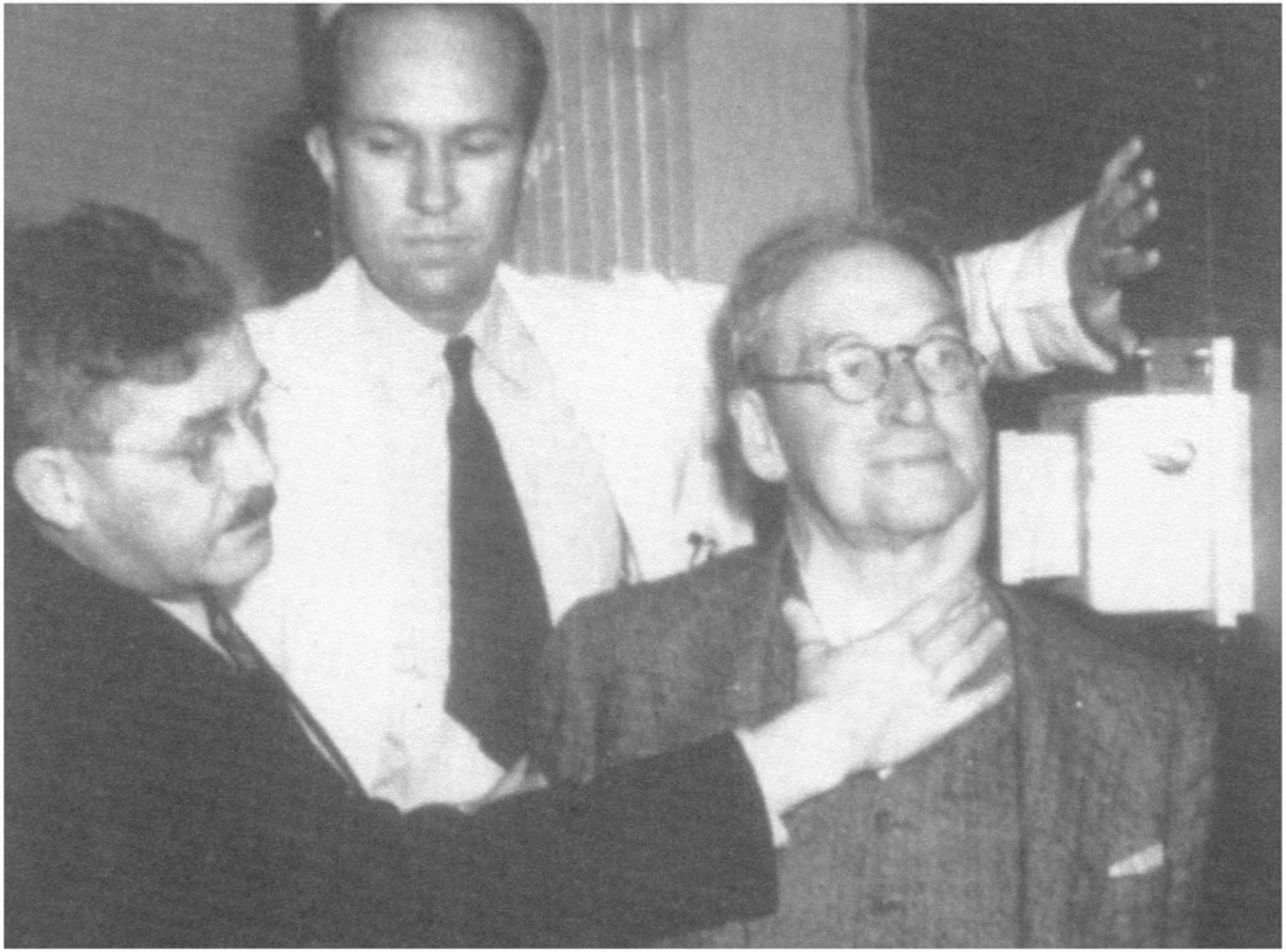


Population – scaled

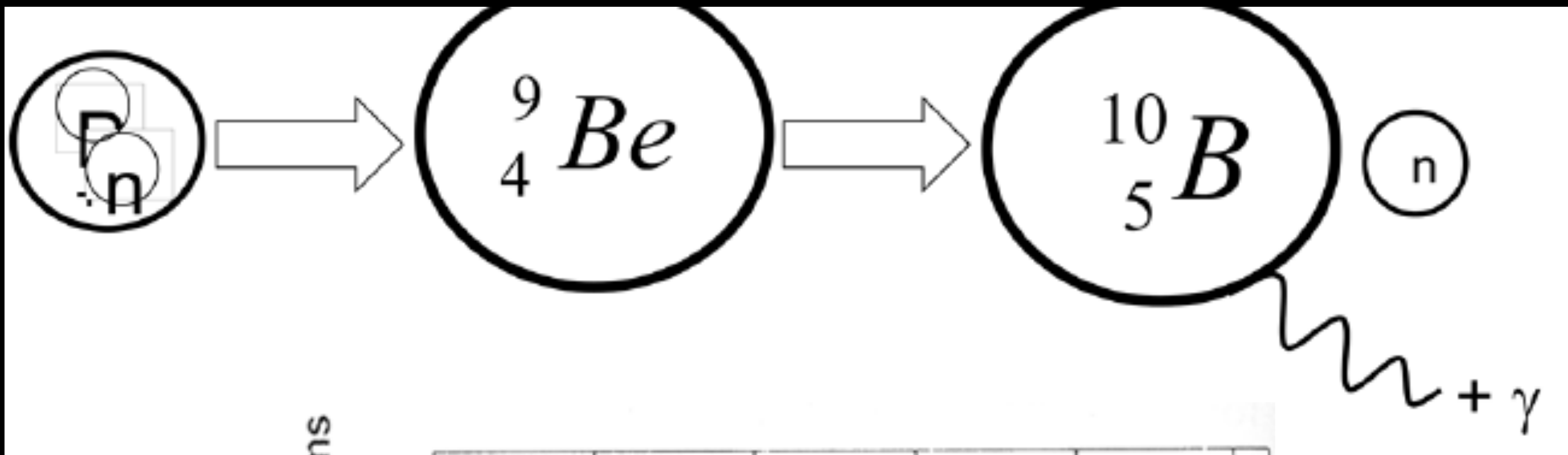


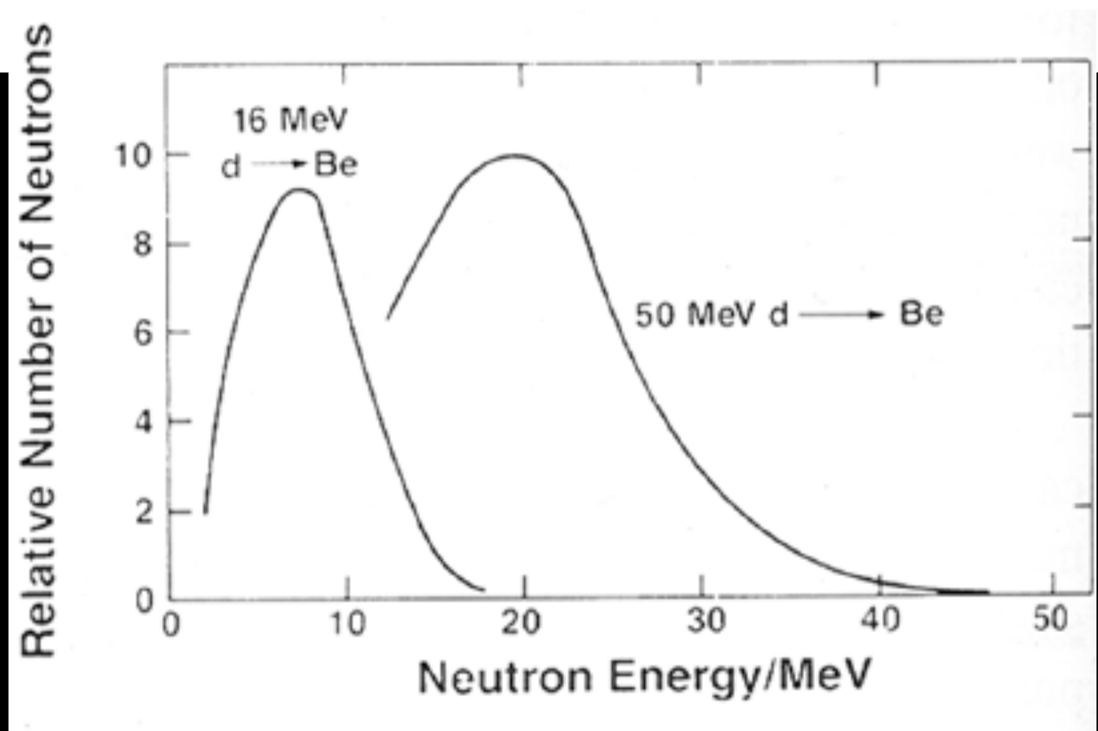
GPD-scaled

1st Neutron Patient
Dr Stone and Dr Lawrence

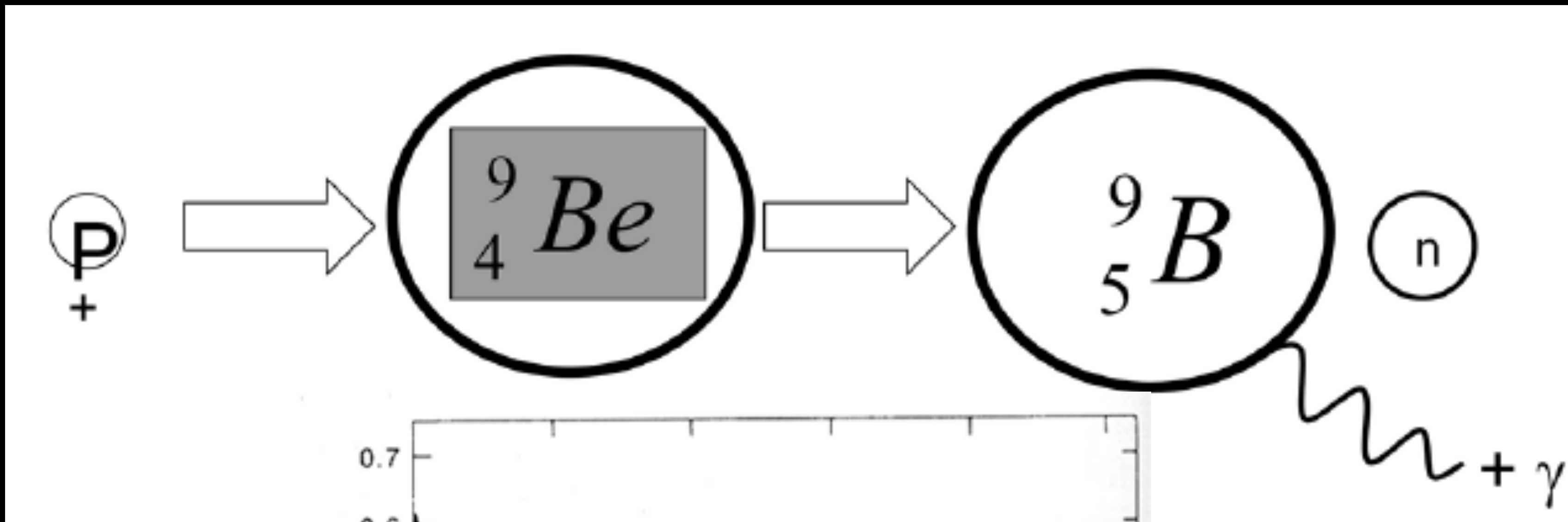


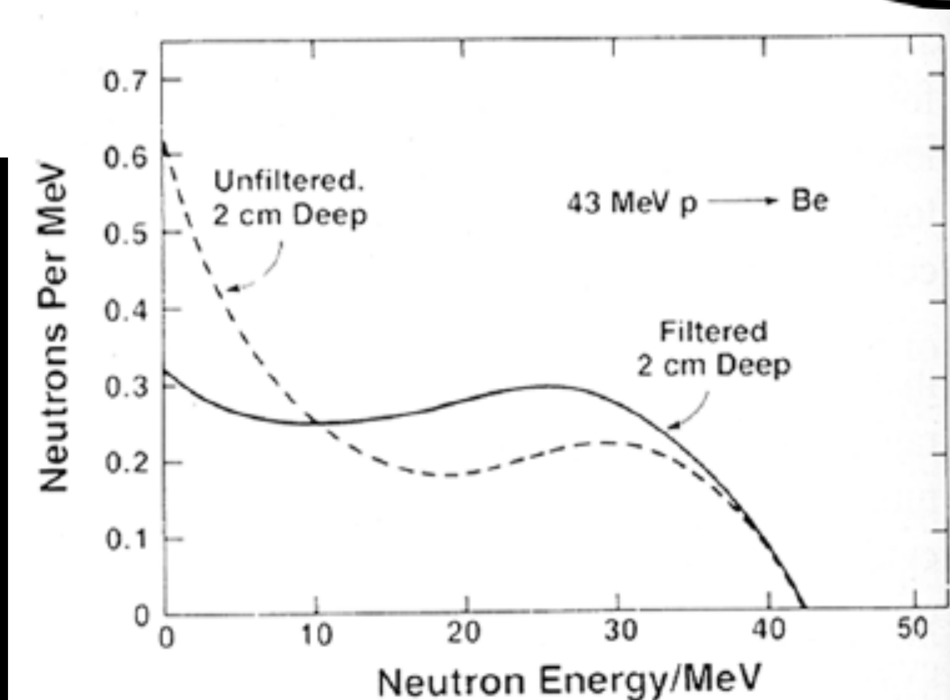
Fast neutron production: d

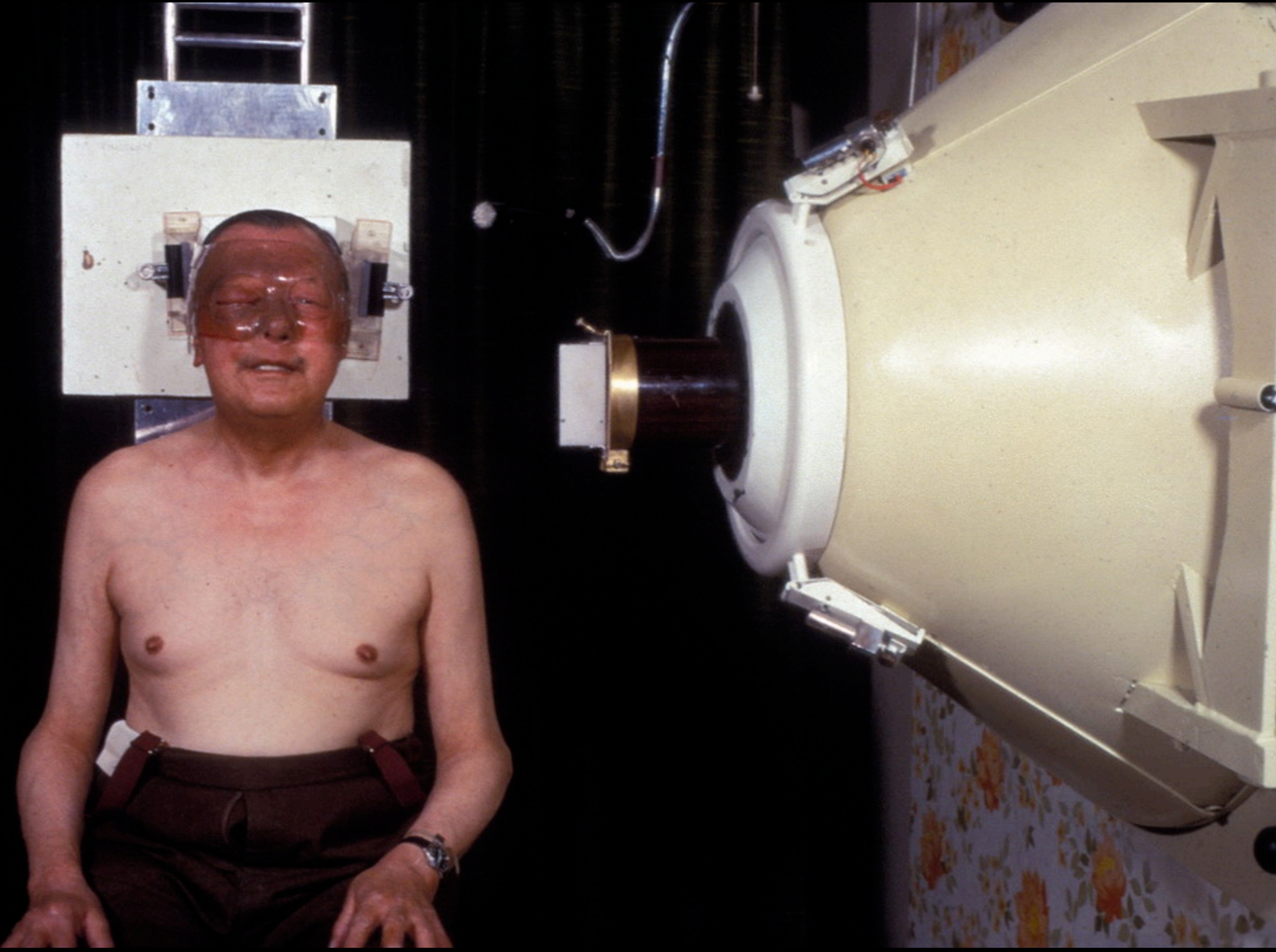




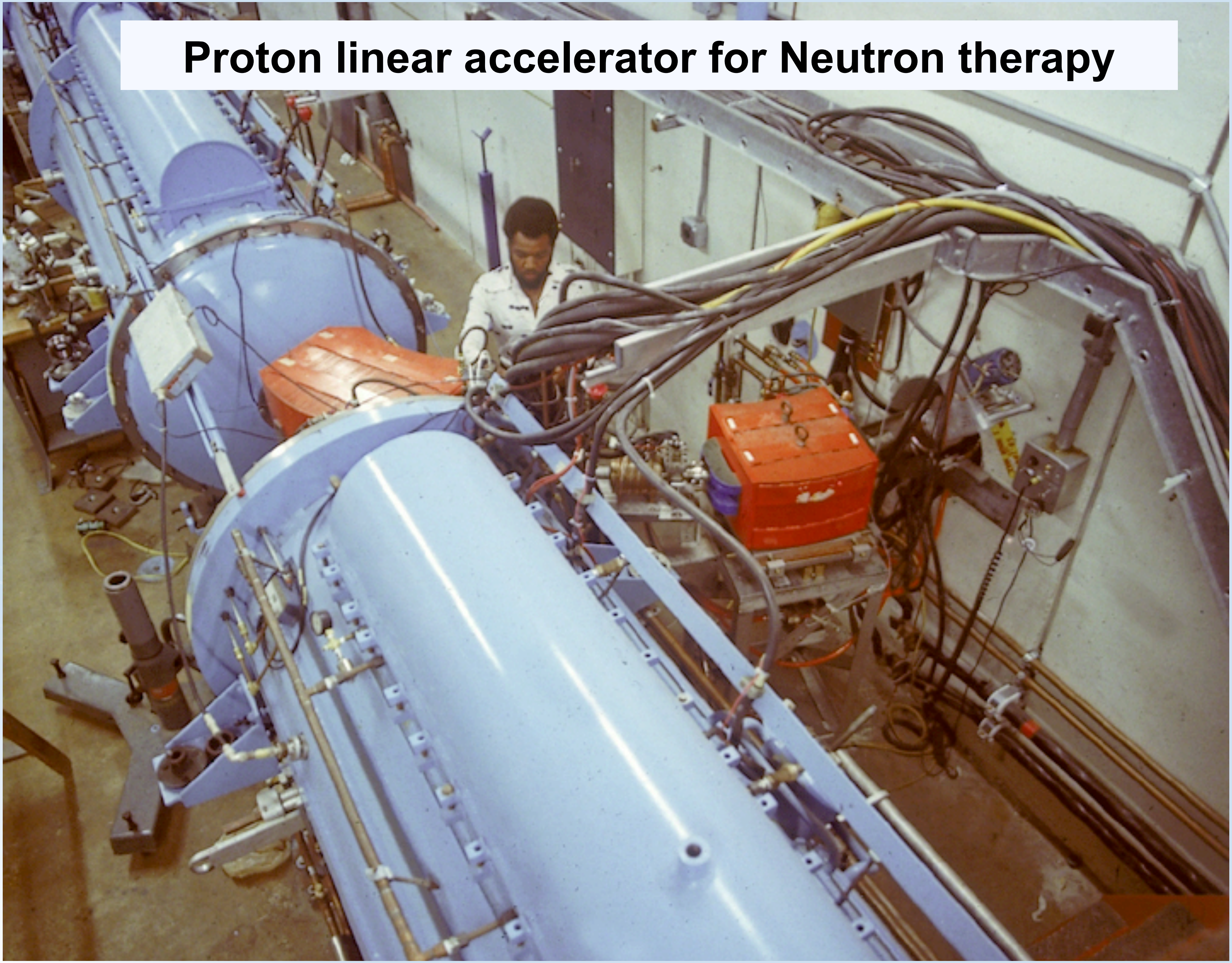
Fast neutron production: p



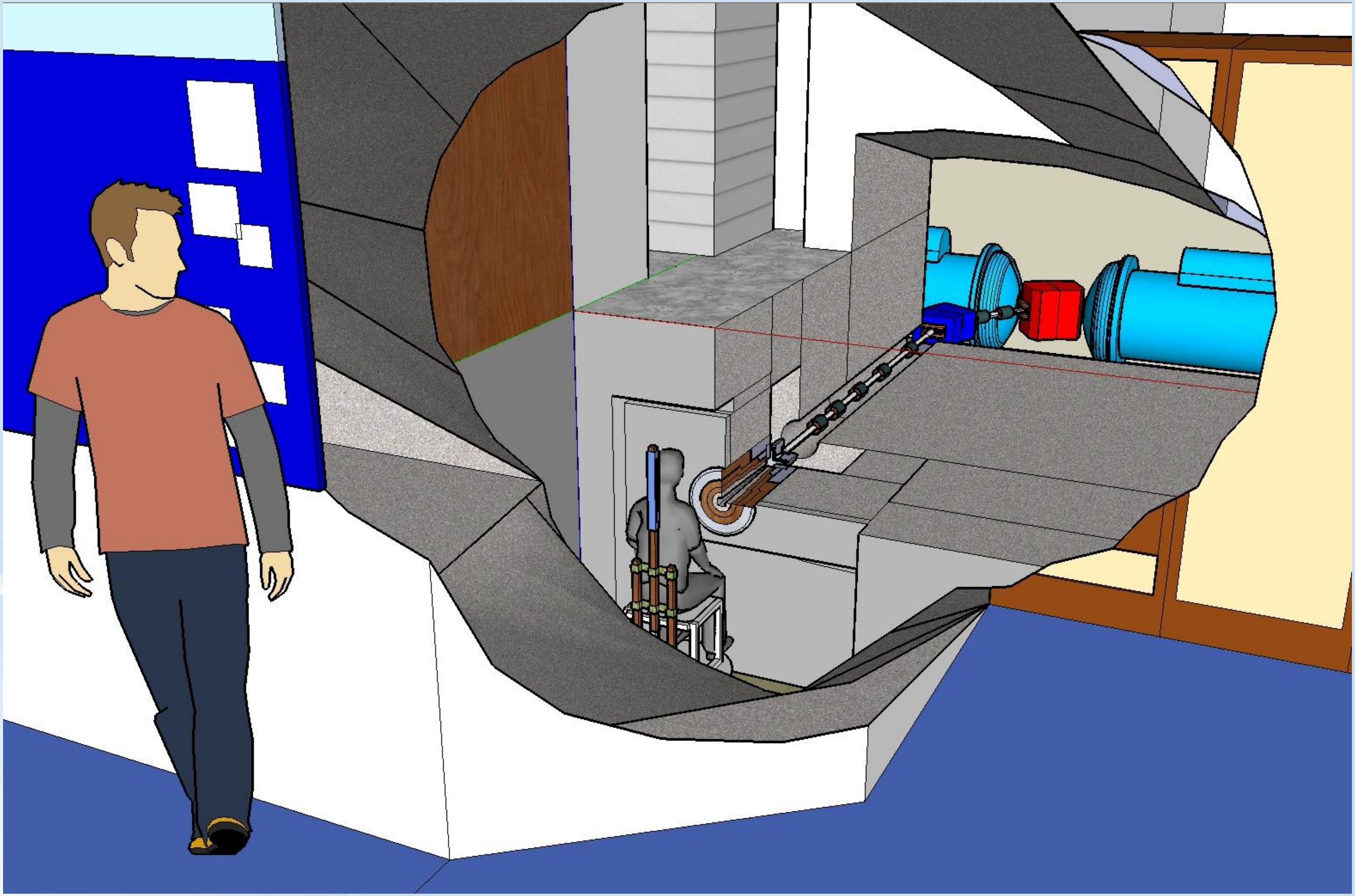




Proton linear accelerator for Neutron therapy



Proton linear accelerator for neutron therapy



The cost of particle therapy

Protons

$$$

Carbon

$$$$($)

Dose Distribution

Photons

$

Neutrons

$$

Exponential

Low

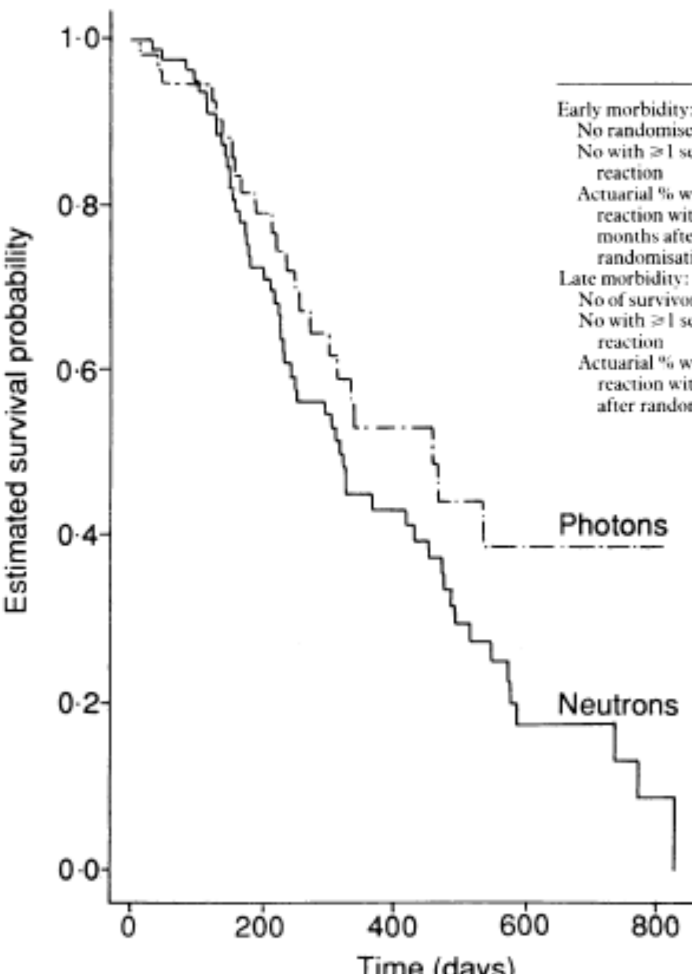
LET

High

High energy neutron treatment for pelvic cancers: study stopped because of increased mortality

R D Errington, D Ashby, S M Gore, K R Abrams, S Myint, D E Bonnett, S W Blake, T E Saxton

BMJ VOLUME 302 4 MAY 1991



	Cervix		Bladder		Rectum			All sites	
	Neutrons	Photons	Neutrons	Photons	Neutrons	Photons	Prostate*	Neutrons	Photons
Early morbidity:									
No randomised	12	15	41	28	31	17	7	90	61
No with ≥1 severe early reaction	1	1	9	2	2	3	0	12	6
Actuarial % with ≥1 severe reaction within three months after randomisation	11	8	27	9	7	23	0	16	12
Late morbidity:									
No of survivors at 90 days	9	14	35	23	30	14	7	80	52
No with ≥1 severe late reaction	2	3	8	4	6	3	0	16	10
Actuarial % with ≥1 severe reaction within one year after randomisation	21	15	40	24	16	27	0	24	21

Fast neutron therapy: unacceptable toxicity, reduced patient survival, treatment (almost) completely discontinued in XXI century

REVIEW OF THE LOCO-REGIONAL CONTROL RATES FOR MALIGNANT SALIVARY GLAND TUMOURS TREATED DEFINITIVELY WITH RADIATION THERAPY

FAST NEUTRONS

Authors	Number of patients	Loco-regional control (%)	
Saroja et al., 1987	113	71	(63 %)
Catterall and Errington,1987	65	50	(77 %)
Battermann and Mijnheer, 1986	32	21	(66 %)
Griffin et al., 1988	32	26	(81 %)
Duncan et al., 1987	22	12	(55 %)
Tsunemoto et al. (in press)	21	13	(62 %)
Maor et al., 1981	9	6	
Ornitz et al., 1979	8	3	
Eichhorn, 1981	5	3	
Skolyszewski, 1982	3	2	
Overall	310	207	(67 %)

STUDY RESULTS

	TWO YEARS
LOCAL CONTROL	
* Photons	17% ± 11%
* Neutrons	67% ± 14%
SURVIVAL	
* Photons	25% ± 14%
* Neutrons	62% ± 14%

European Results in Neutron Therapy of Salivary Gland Tumors

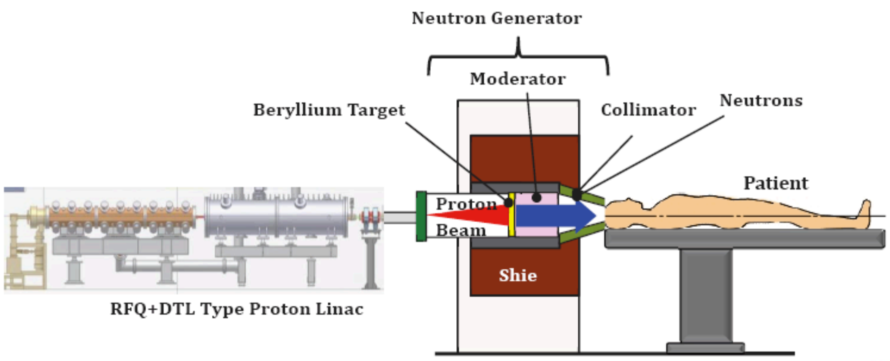
Severe radiation related morbidity

Reference	No.	%
Catterall 1987	8/65	11.8%
Battermann 1986	4/32	12.5%
Duncan 1987	4/26	15.4%
Kovács 1987	2/15	13.3%
Engenhart 1994	2/49	4.1%
Krüll 1995	6/74	8.1%
Lessel 1995	6/38	15.8%
Overall	32/299	10.7%

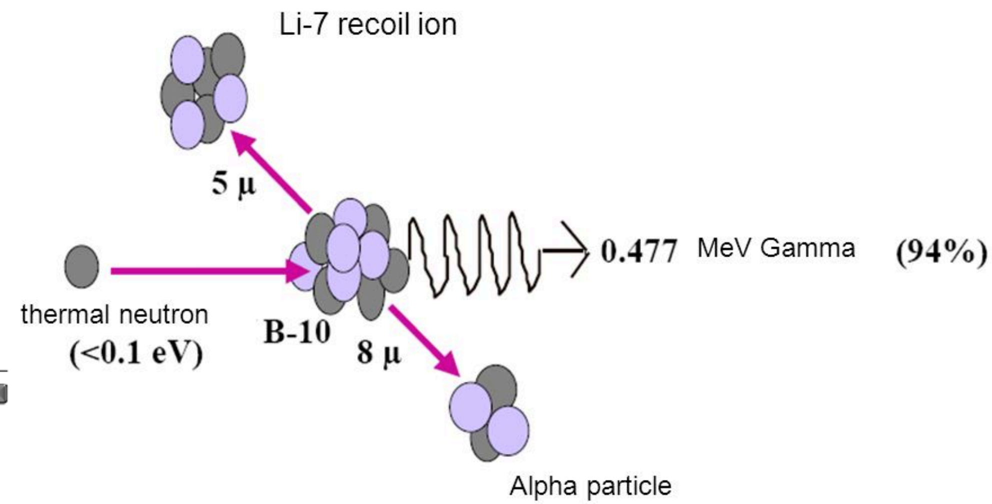
TABLE 1 | Current status of operating neutron facilities worldwide [status as stated at the IAEA Technical Meeting 2013 (F1-TM-44771)].

Location	Source	Mean energy (MeV)	50% depth (cm)	Beam direction	Collimator type	First patient treated	Patients treated (*n*)
University of Washington Medical Center, Seattle, USA	Cyclotron p(50.5) + Be	20	14	Isocentric	Multi leaf	1984	2960
iThemba Laboratory for Accelerator Based Science (LABS), Cape Town, South Africa	Cyclotron p(66) + Be	25	16	Isocentric	Multi blade trimmer	1988	1788
Tomsk Polytechnic University, Tomsk, Russian Federation	Cyclotron d(13.6) + Be	6.3	6	Horizontal	Inserts	1983	1500
FRM II, Technische Universität München, Garching, Germany	Uranium converter	1.9	5	Horizontal	Multi leaf	2007	124

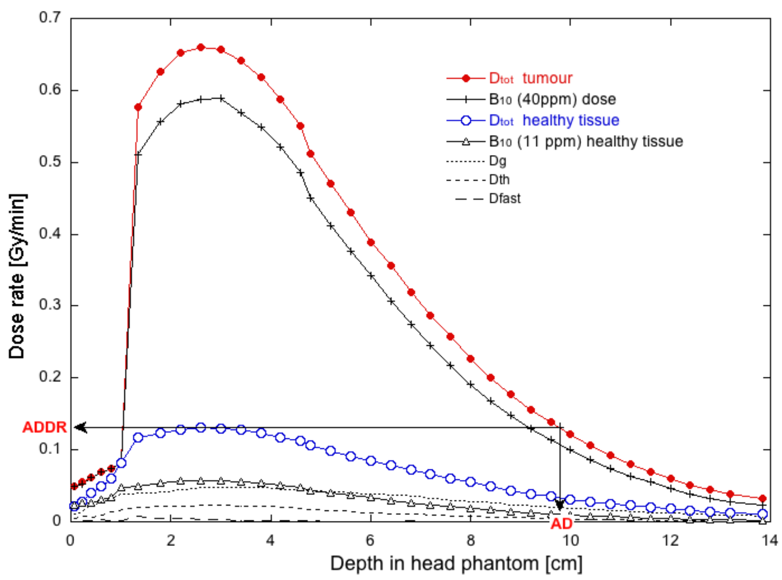
The BNCT Reaction



2.33 MeV of kinetic energy is released per neutron capture: initial LET 200-300 ke V/μm



Thermal cross-section = 3837 barns (that's *very* big…)



The figure shows that the maximum dose rate in healthy tissue of 0.13 Gy/min is reached at 2.6 cm of depth. The tumour tissue would experience the same dose-rate value at 9.8 cm of depth. Deeper tumours would receive lower dose then the healthy tissue maximum dose. At the AD the advantage-depth dose-rate (ADDR in the figure) is 0.13 Gy/min. Clearly, the AD value depends on the tumour-to-healthy-tissue ^{10}B concentration ratio (BR). A thumb rule is to use quasi-thermal neutrons for depths less than 2 cm and epithermal neutrons for deeper depths.

Possible applications: melanoma (shallow tumors) and GBM (boron accumulate in tumor rather than in normal brain)

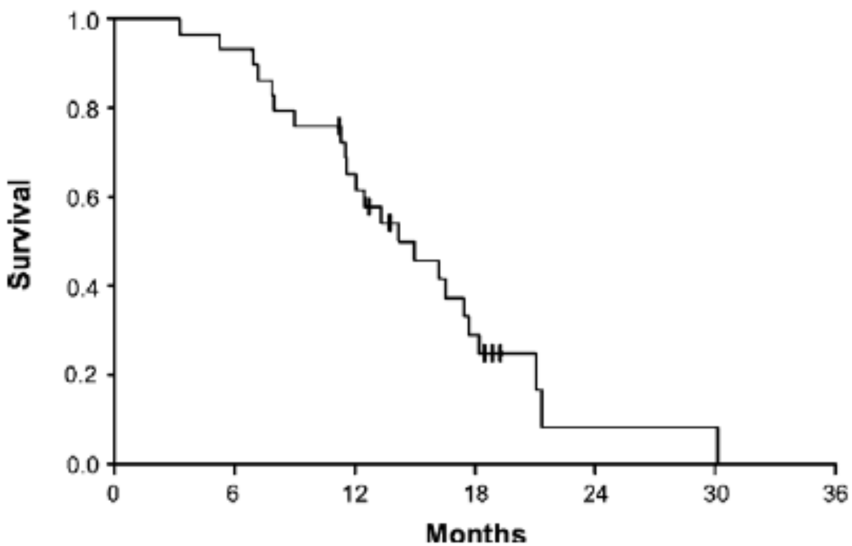
From NuPECC, *Nuclear Physics in Mediicine*, 2014..

Radiotherapy and Oncology 88 (2008) 183–191
www.thegreenjournal.com

Phase II trial of BNCT

Boron neutron capture therapy (BNCT) for glioblastoma multiforme: A phase II study evaluating a prolonged high-dose of boronophenylalanine (BPA)☆

Roger Henriksson[a,*], Jacek Capala[b,c], Annika Michanek[d], Sten-Åke Lindahl[e], Leif G. Salford[f], Lars Franzén[a], Erik Blomquist[g], Jan-Erik Westlin[h], A. Tommy Bergenheim[i]



Adverse events obtained during the study period in 19 of 29 patients		
Type of AE	No. of events	No. of patients
Skin/mucosa	13	8
Seizures (epilepsies)	12	7
Thrombosis	8	6
Abdominal	5	4
Depression	3	3
Aphasia	2	2
CVS	2	2

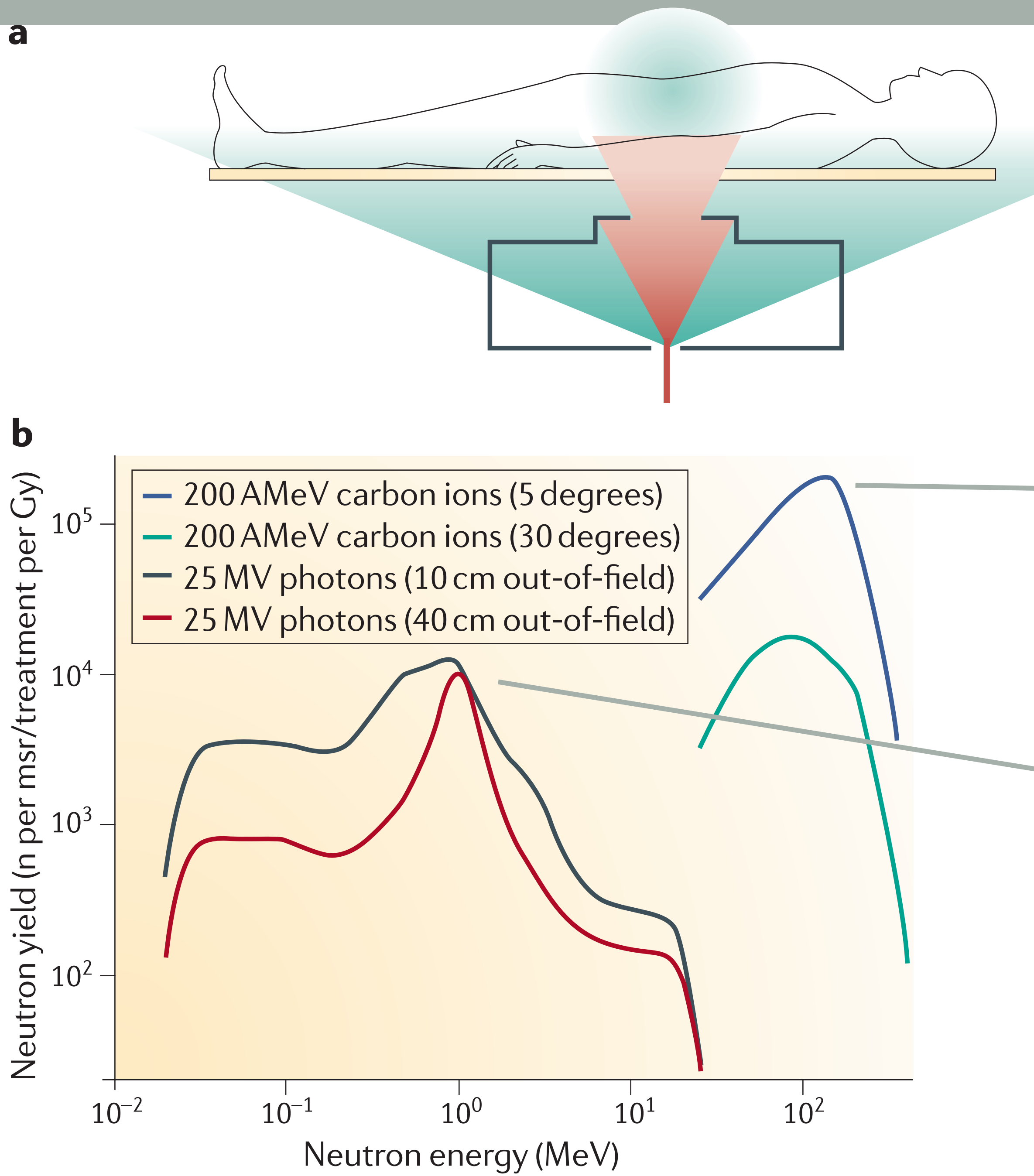
Conclusion: Although, the efficacy of BNCT in the present protocol seems to be comparable with conventional radiotherapy and the treatment time is shorter, the observed side effects and the requirement of complex infrastructure and higher resources emphasize the need of further phase I and II studies, especially directed to improve the accumulation of ^{10}B in tumour cells.

Operative BNCT centers

CENTER	STATES	NEUTRON SOURCE	NEOPLASM	TREATED PATIENTS
Helsinki University Central Hospital, Helsinki, Finland	Europe	FIR-1, VTT Technical Reserch Centre, Espoo	GB and HN	50 GM 2 AA 31 HN
Faculty Hospital of Charles University, Prague, Czech Republic	Europe	LVR-15 Reactor, Nuclear Reserch Institute Rez	GB	5 GM
University of Tsukuba, Tsukuba City, Ibaraki	Japan	JRR-4, Japan Atomic Energy Agency, Tokai, Ibaraki	GB	20 GM 4 AA
University of Tokushima, Tokushima	Japan	JRR-4 (Kyoto University Research Reactor, Osaka)	GB	23
Osaka Medical College and Kyoto University Research Reactor, Kyoto University, Osaka and Kawasaki Medical School, Kurashiki	Japan	KURR	GB, HN, CM	30 GBM 3 AA 7 Men 124 HN
Taipei Veterans General Hospital, Taipei, Taiwan	Republic of China	THOR, National Tsing Hua University, Hsinchu, Taiwan	HN	10
Inst de Oncol. Angel H, Buenos Aires	Argentina	Bariloche Atomic Center	CM and AT	7CM 3 AT

Neutrons as a contamination in radiotherapy

Neutron spectra in radiotherapy

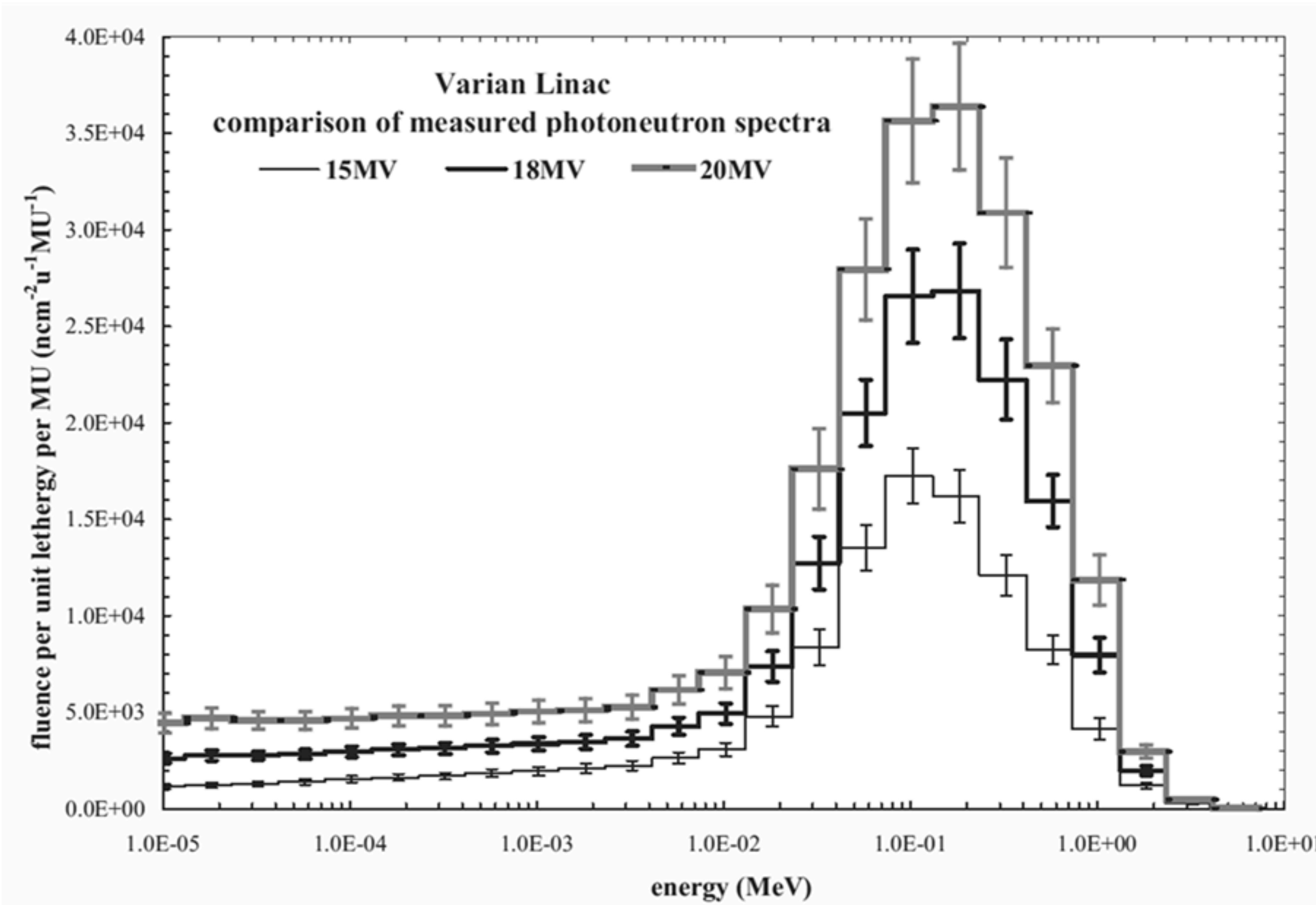


Quasi-elastic peak (particle therapy)

Evaporation peak (high-energy X-ray therapy)

Newhauser and Durante, *Nature Rev. Cancer* 2011

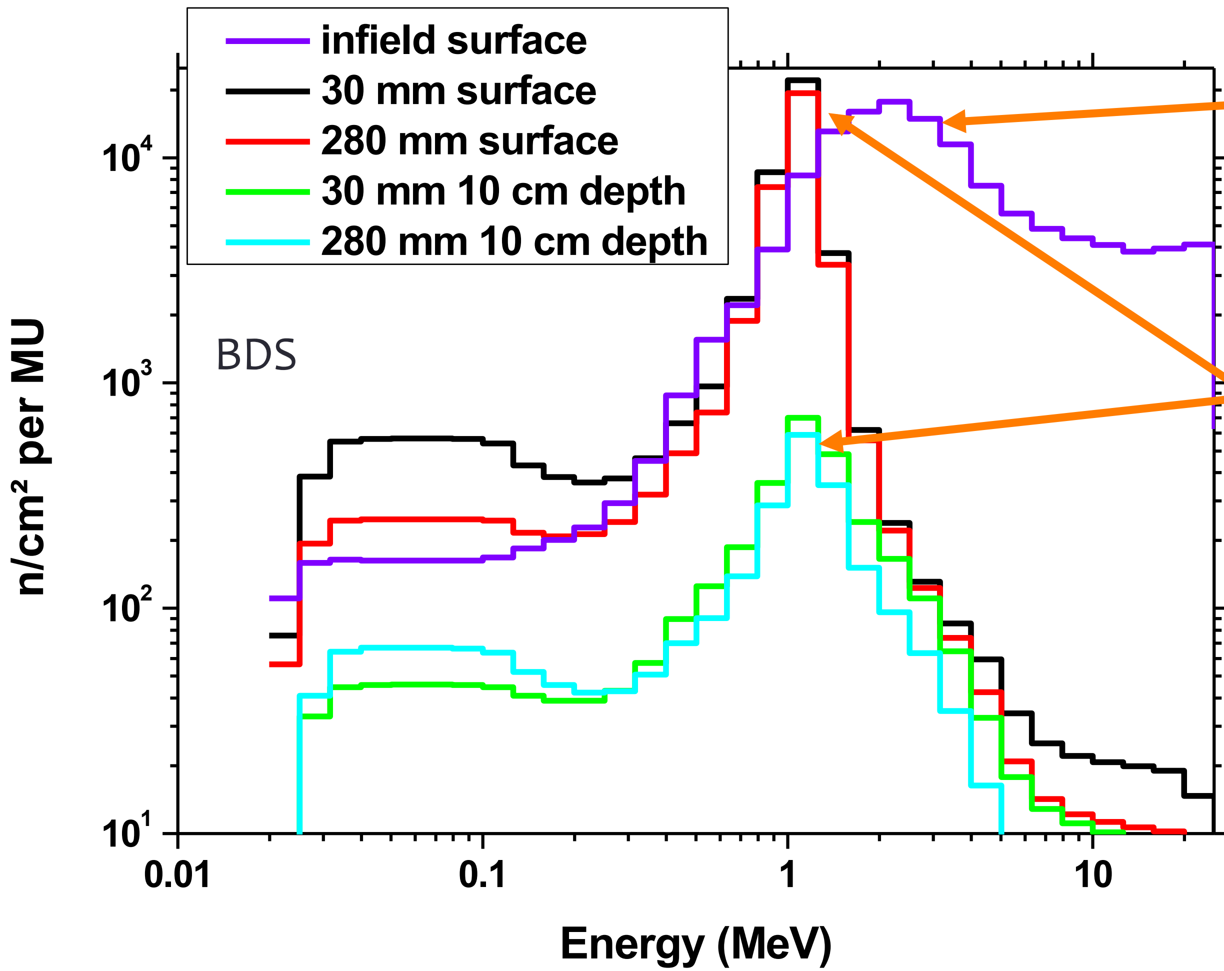
Secondary Neutron Spectra Measured for Varian 18MV



- Howell et al. Medical Physics, Vol. 36, No. 9, 4027-4038 (2009)

18 MV X-rays, 5x5 cm2 field, BDS

Direction: GT, Energy: 18 MV
Field size: 5x5 cm²



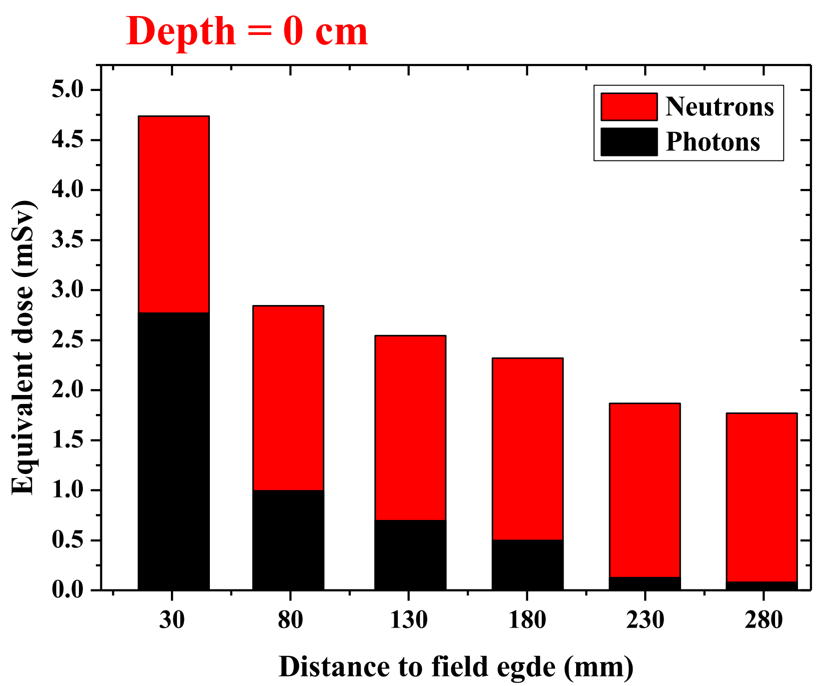
- *Highest neutron fluence and mean energy measured in-field at the surface*
- *All out-of-field spectra peak at 1 MeV*
- *Most of the neutrons are produced in the accelerator head rather than in water*

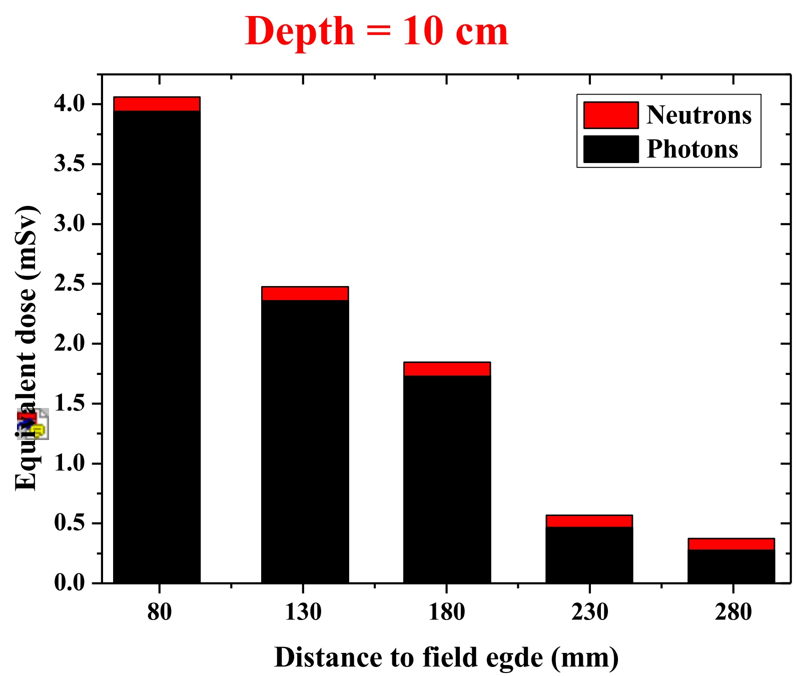
Kaderka et al., *Phys. Med. Biol.* 2012

NEUTRON EQUIVALENT DOSE

Direction: GT, Energy: 18 MV

Field size: 5x5 cm² , BDS

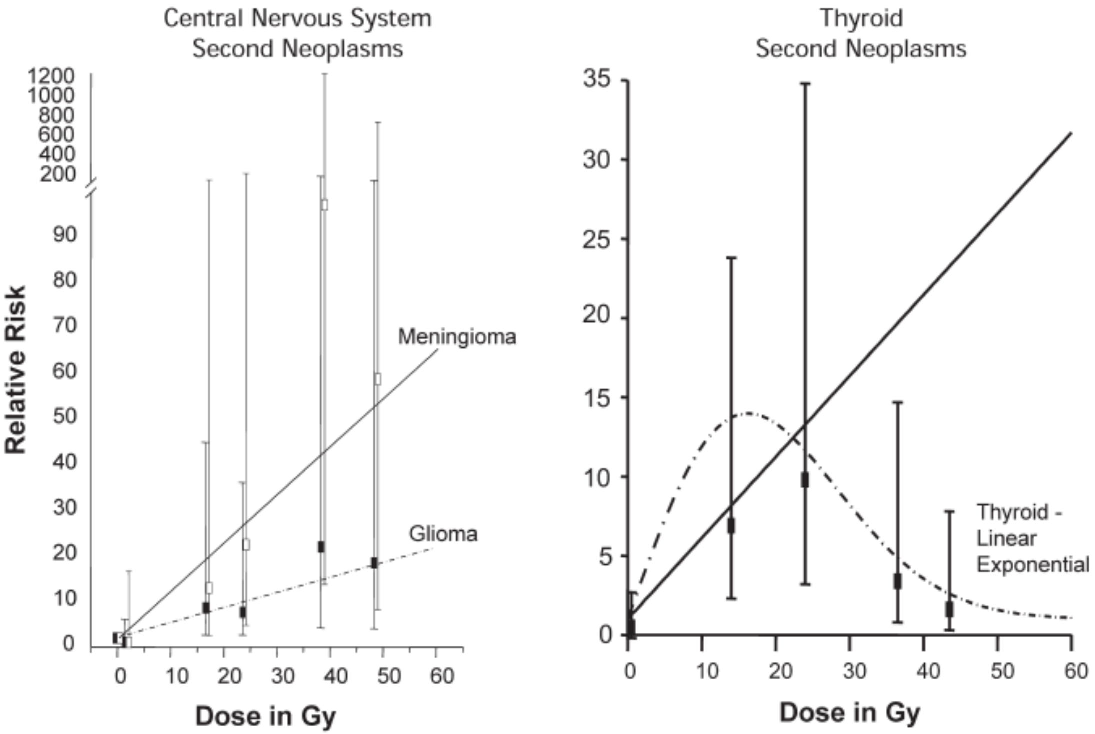




- *Neutrons are the major contributors to the equivalent dose measured outside the field at the surface, but negligible at 10 cm depth*
- *Data from Kaderka et al. Phys. Med. Biol. 2012 support calculations by Howell et al. Med. Phys. 2009 and Ongaro et al. Phys. Med. Biol. 2000*

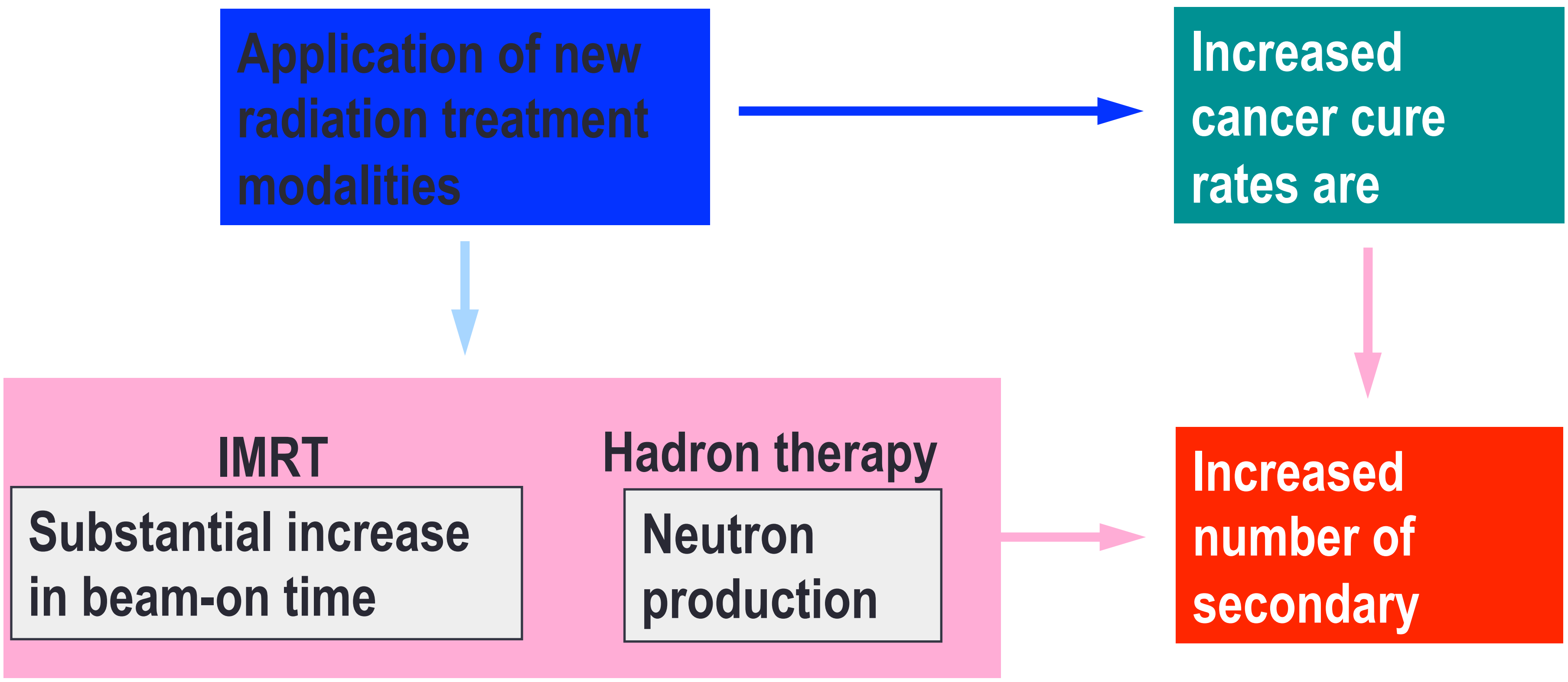
Radiotherapy and SMN

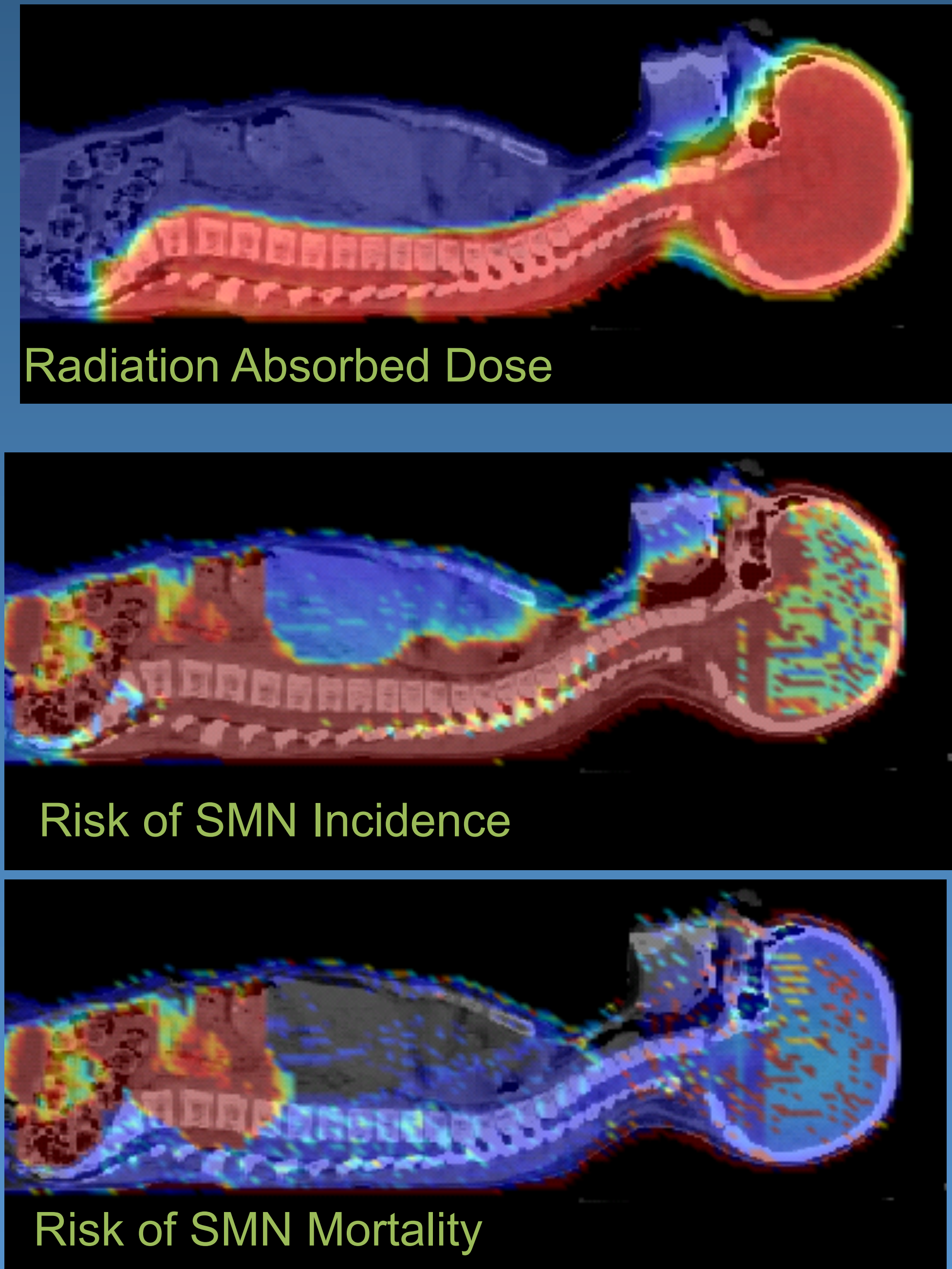
- Cancer survivors represent about 3.5% of US population
- Second primary malignancies in this high-risk group accounts for about 16% of all cancers
- Three possible causes: Continuing lifestyle;Genetic predisposition:treatment of the primary cancer (SMN)



CCSS study, St. Jude et al. 2008-2015 Retrospective cohort of 14,000 survivors of childhood cancer diagnosed between 1970 and 1986

Fast neutrons: second cancers in radiotherapy





Secondary Malignant Neoplasms (SMN) in particle therapy

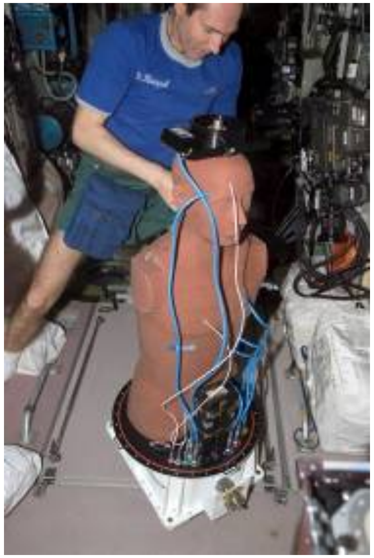
Comparison of relative radiation dose distribution with the corresponding relative risk distribution for radiogenic second cancer incidence and mortality. This 9-year old girl received craniospinal irradiation for medulloblastoma using passively scattered proton beams. The color scale illustrates the difference for absorbed dose, incidence and mortality cancer risk in different organs.

THE UNIVERSITY OF TEXAS
MD Anderson ~~Cancer~~ Center
Making Cancer History

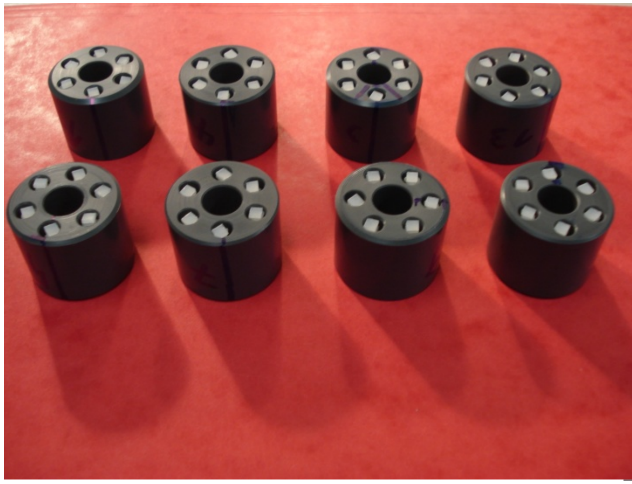
Newhauser & Durante, *Nat. Rev. Cancer* 2011

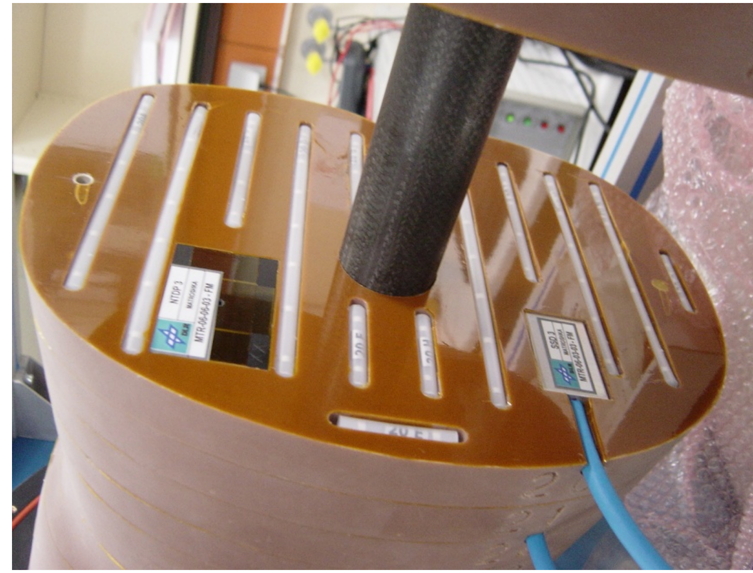
The MATROSHKA facility

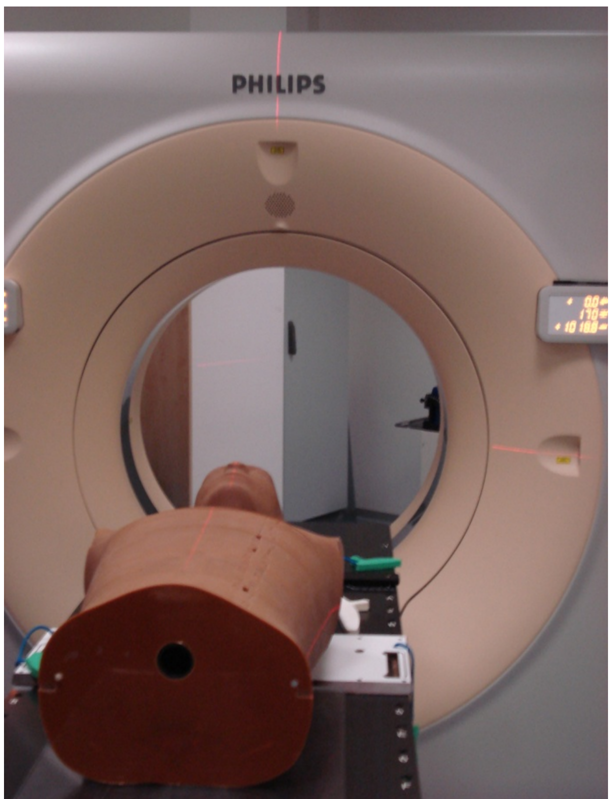
- Standard RANDO phantom of property of DLR (German Aerospace center)
- 850 mm high divided into 34 slices
- Holders for detectors in several slices
- Currently used for space radiation dosimetry inside the ISS

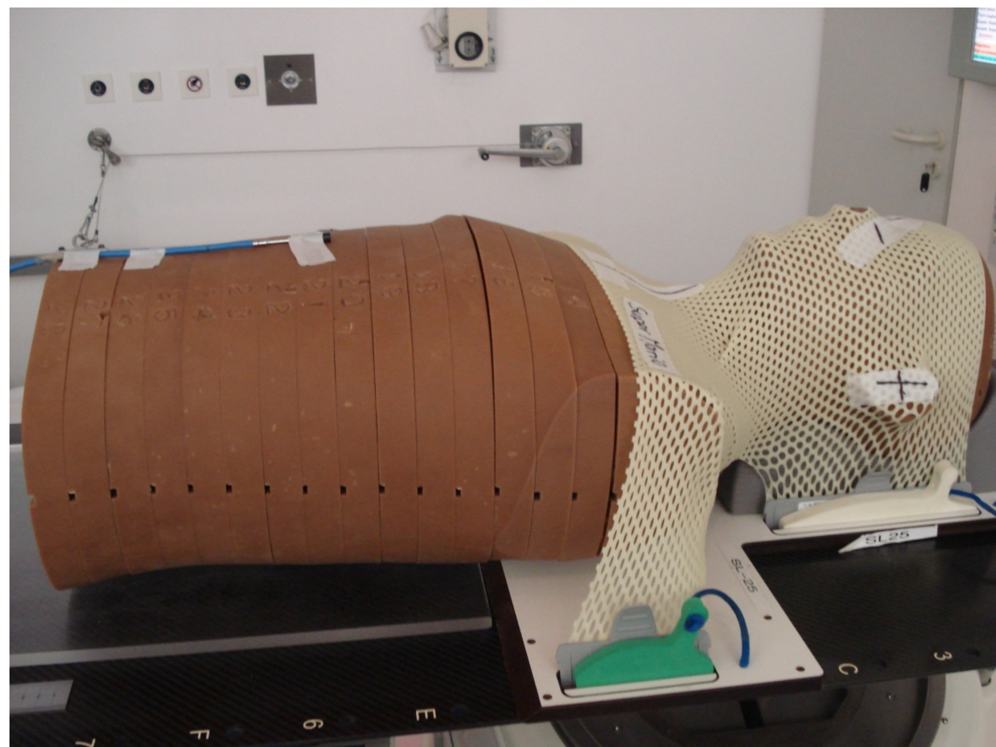


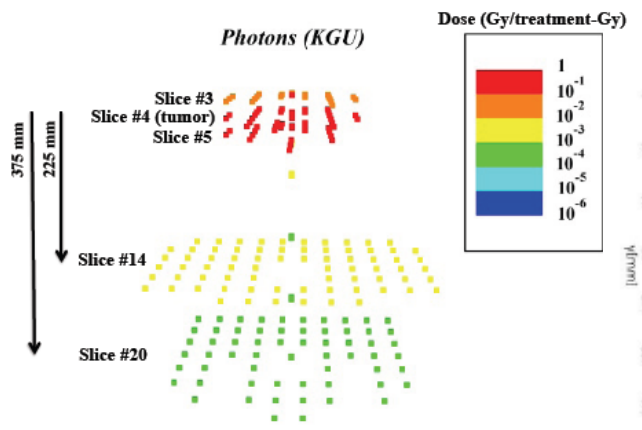
In collaboration with G. Reitz, T. Berger et al. (DLR)

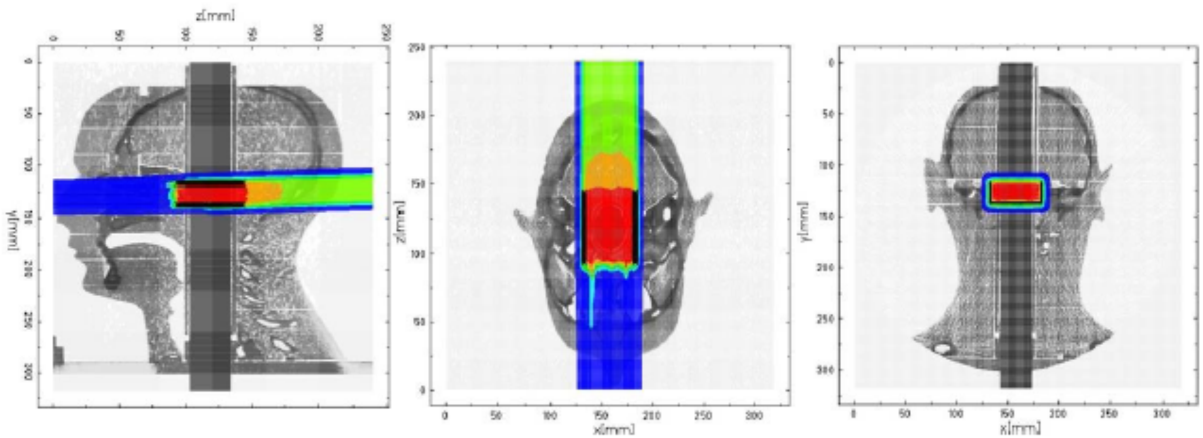


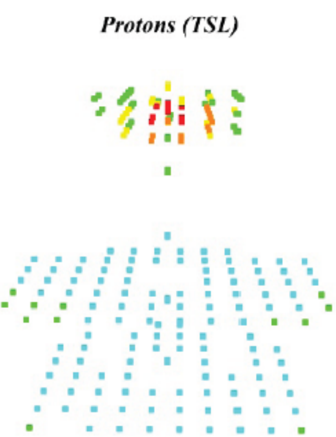


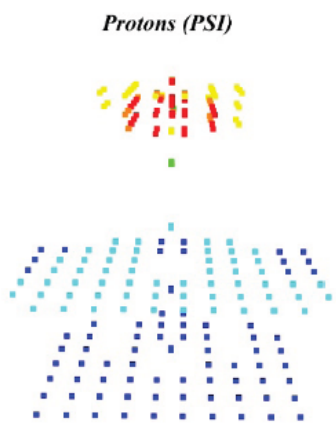

PHILIPS

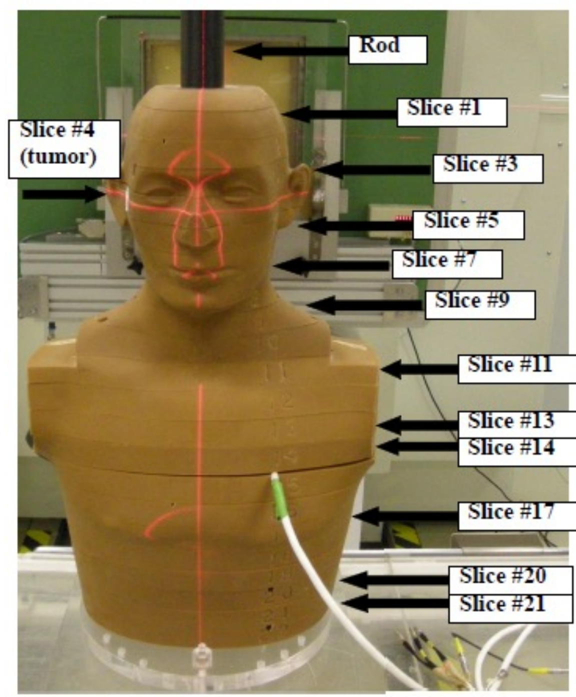


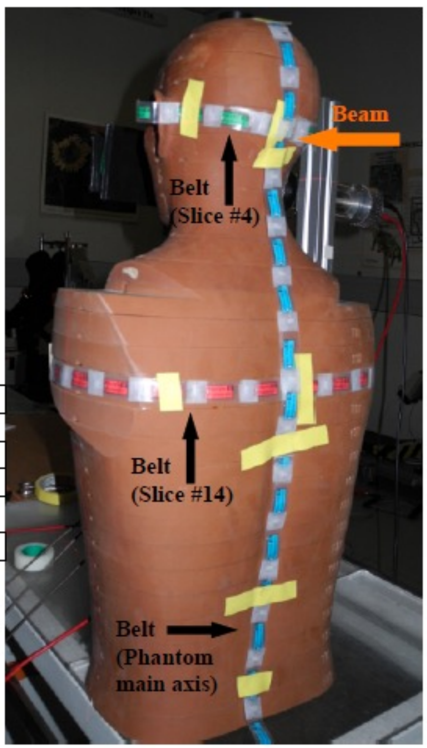

Photons (KGU)
Dose (Gy/treatment-Gy)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Slice #3
Slice #4 (tumor)
Slice #5
375 mm
225 mm
Slice #14
Slice #20

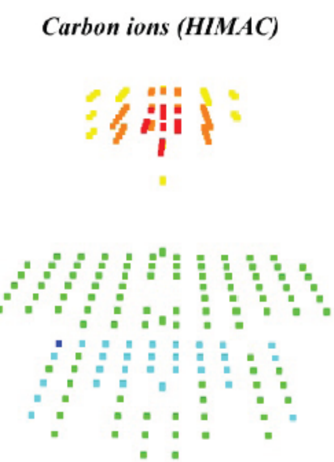

z[mm]
y[mm]
z[mm]
x[mm]
y[mm]
x[mm]

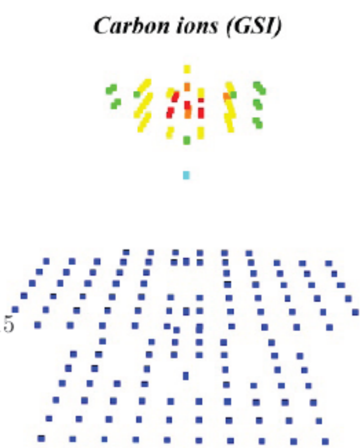

Protons (TSL)


Protons (PSI)


Rod
Slice #1
Slice #4 (tumor)
Slice #3
Slice #5
Slice #7
Slice #9
Slice #11
Slice #13
Slice #14
Slice #17
Slice #20
Slice #21

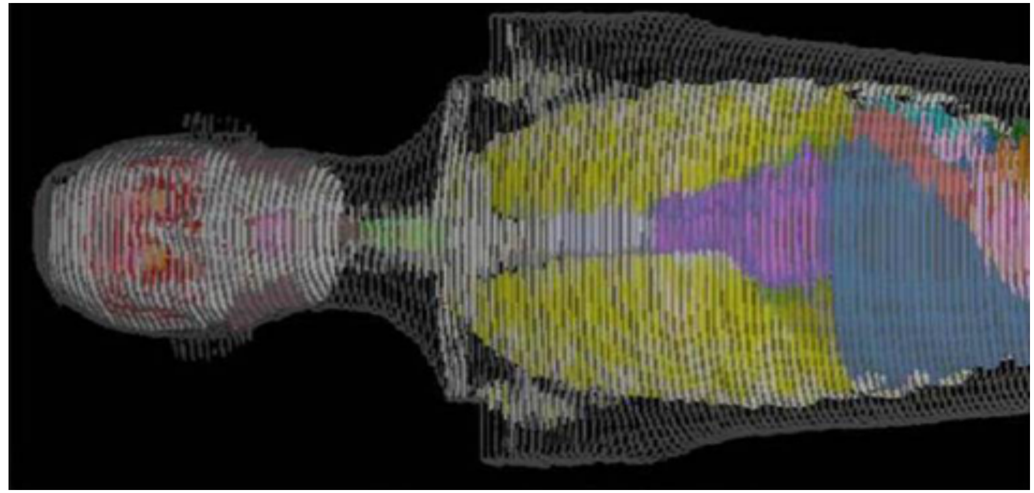

Beam
Belt (Slice #4)
Belt (Slice #14)
Belt (Phantom main axis)


Carbon ions (HIMAC)

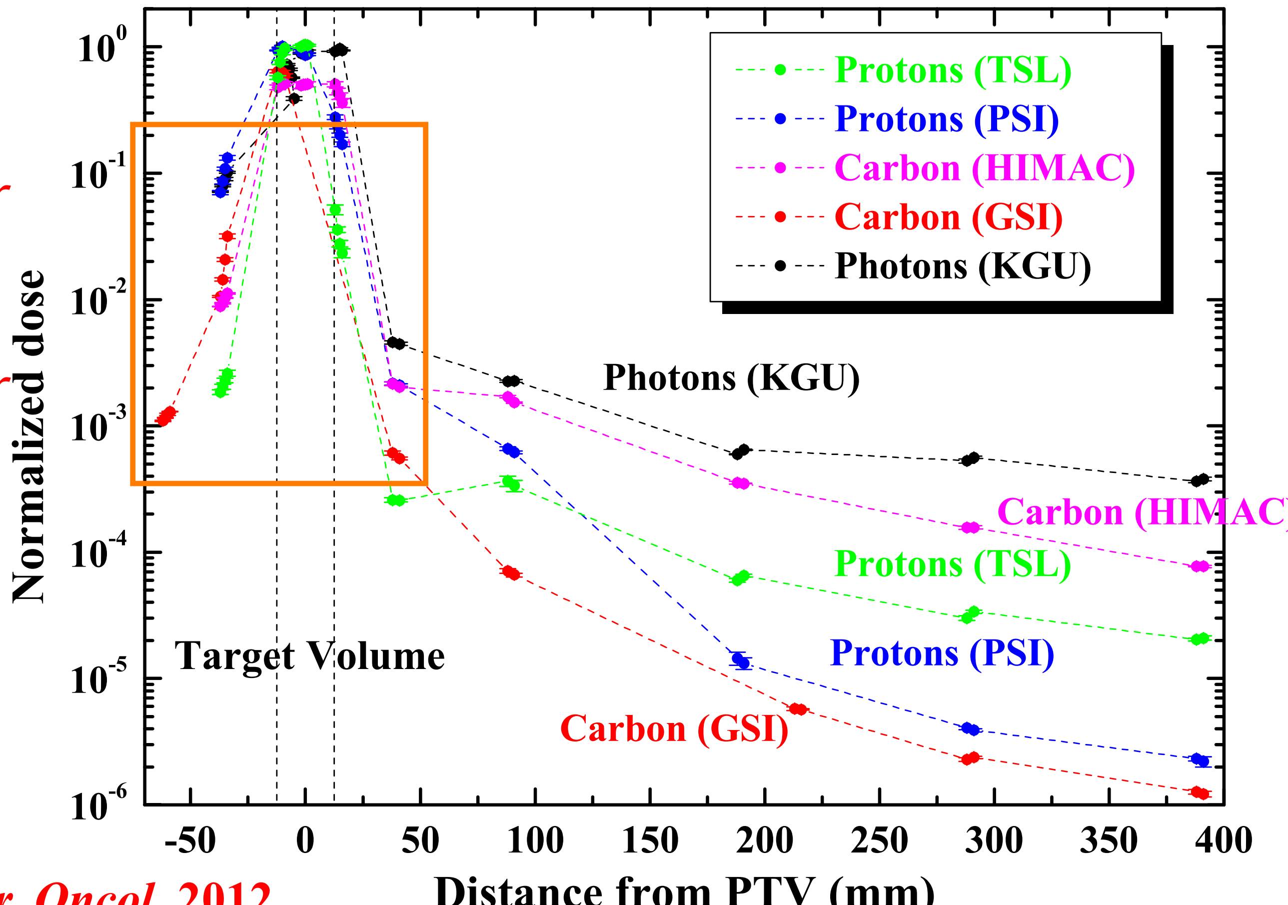

Carbon ions (GSI)

Inner dose

TLD 700



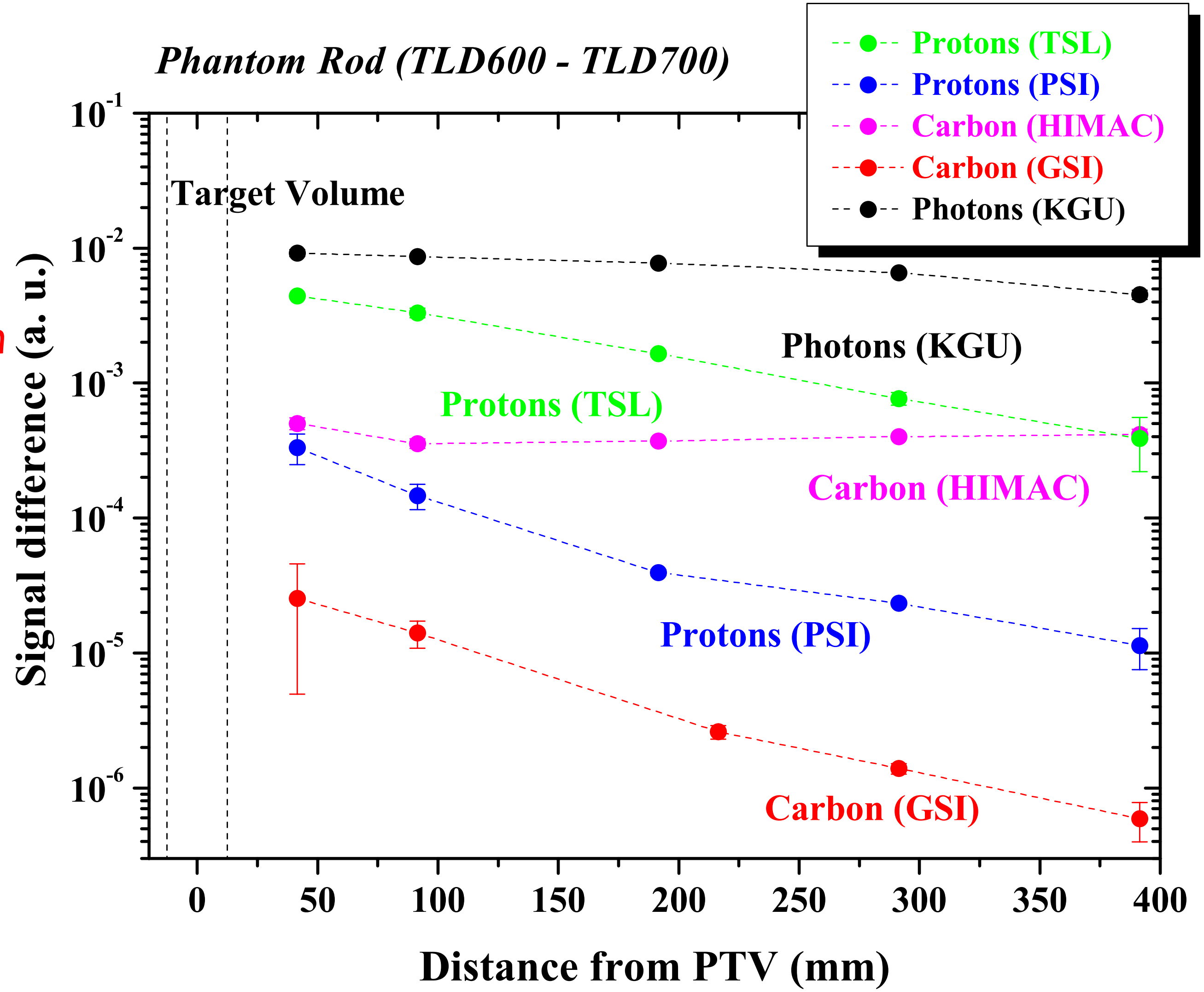
- *Highest out-of-field dose for photons*
- *Higher lateral dose for passive modulation than scanning delivery*
- *Higher lateral dose for protons than carbon ions*
- *Collimator produces sharper field edges*



La Tessa *et al.*, *Radiother. Oncol.* 2012

Neutrons produced by charged particles

- *Highest production of slow neutrons for photons*
- *Passive delivery enhances the production of slow neutrons compared to scanned beams*
- *Scanned carbon ions produce the lowest amount of low-energy neutrons*



La Tessa *et al.*, *Phys. Med. Biol.* 2014

In patient dosimetry
(uterus dose for a pregnant woman)

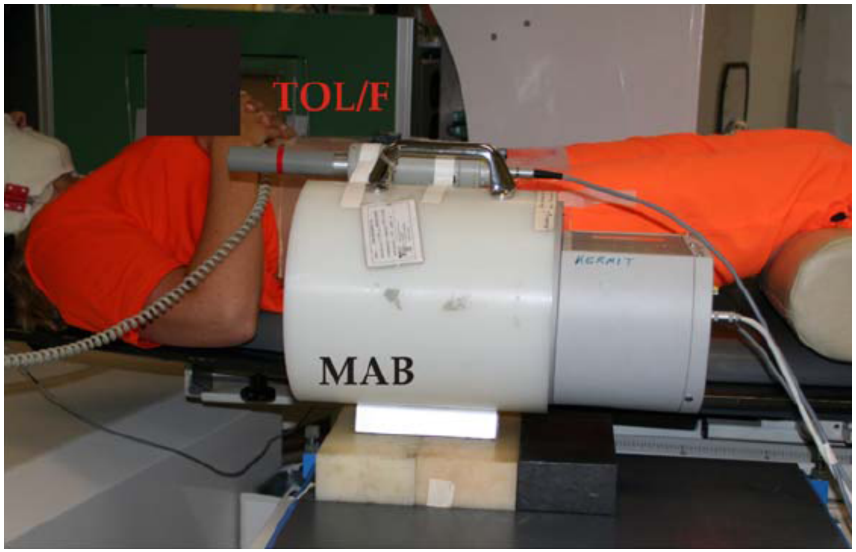


TABLE 1

Measured doses in the pelvic region during the treatment.

	Photon dose (μSv/fraction)	Neutron dose (μSv/fraction)	No. of fractions	Total dose (μSv)
Normal field	3.0[a]	1.4	15	66
Boost field	2.2[b]	1.0	5	16
Total treatment			20	82

[a] Calculated assuming a factor of 1.4 between normal and boost fields as in neutron dose.
[b] Measured by the TOL/F gamma dose rate meter. The passive thermoluminescence dosimeter films did not measure any significant dose above the normal background.

Münter. Heavy ion radiotherapy during pregnancy. Fertil Steril 2010.

Total dose < 0.3 mSv

Very low stray radiation reduced risk of secondary cancers or teratogen effects

Münter *et al., Fertil Steril.* 2010

Neutrons in space

The Space Radiation Environment

Solar particle events (SPE) (generally associated with Coronal Mass Ejections from the Sun):

- medium to high energy protons
- largest doses occur during maximum solar activity
- not currently predictable
- MAIN PROBLEM: develop realistic forecasting and warning strategies

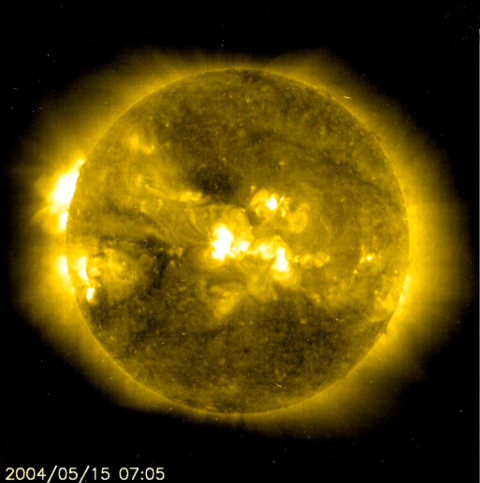
Trapped Radiation:

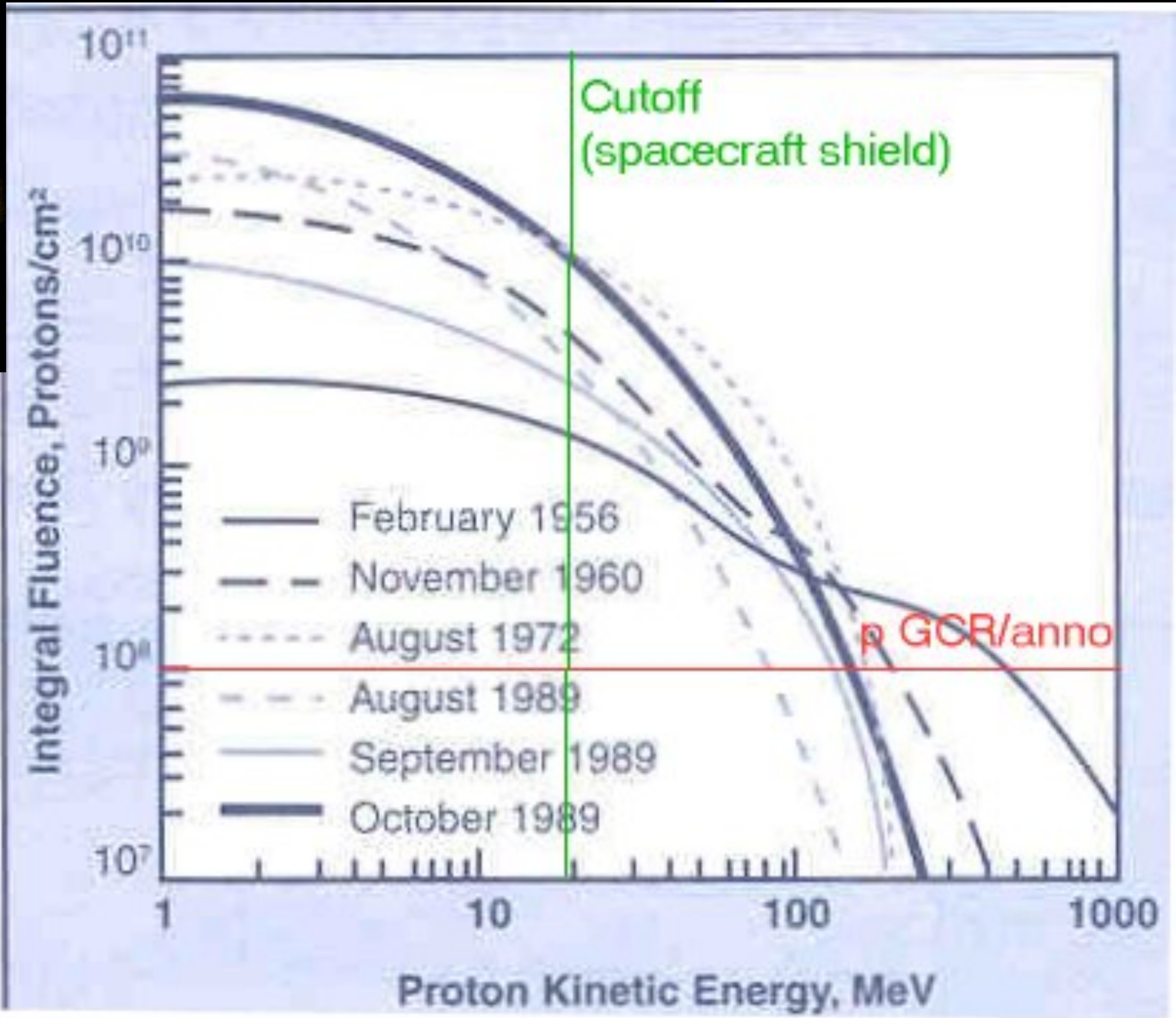
- medium energy protons and electrons
- effectively mitigated by shielding
- mainly relevant to ISS
- MAIN PROBLEM: develop accurate dynamic model

Galactic Cosmic Rays (GCR)

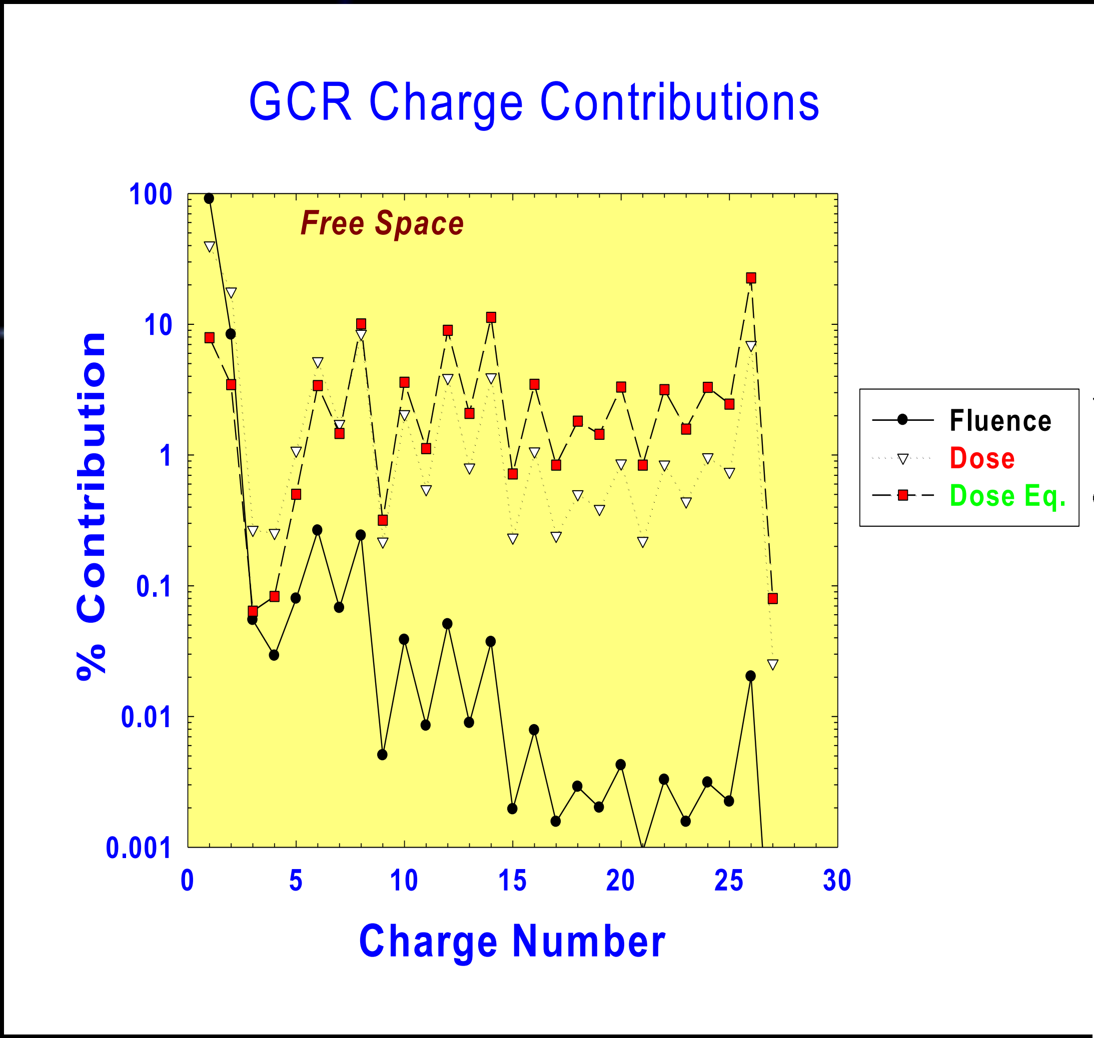
- high energy protons
- **highly charged, energetic atomic nuclei (HZE particles)**
- not effectively shielded (break up into lighter, more penetrating pieces)
- abundances and energies quite well known
- MAIN PROBLEM: biological effects poorly understood but known to be most significant space radiation hazard

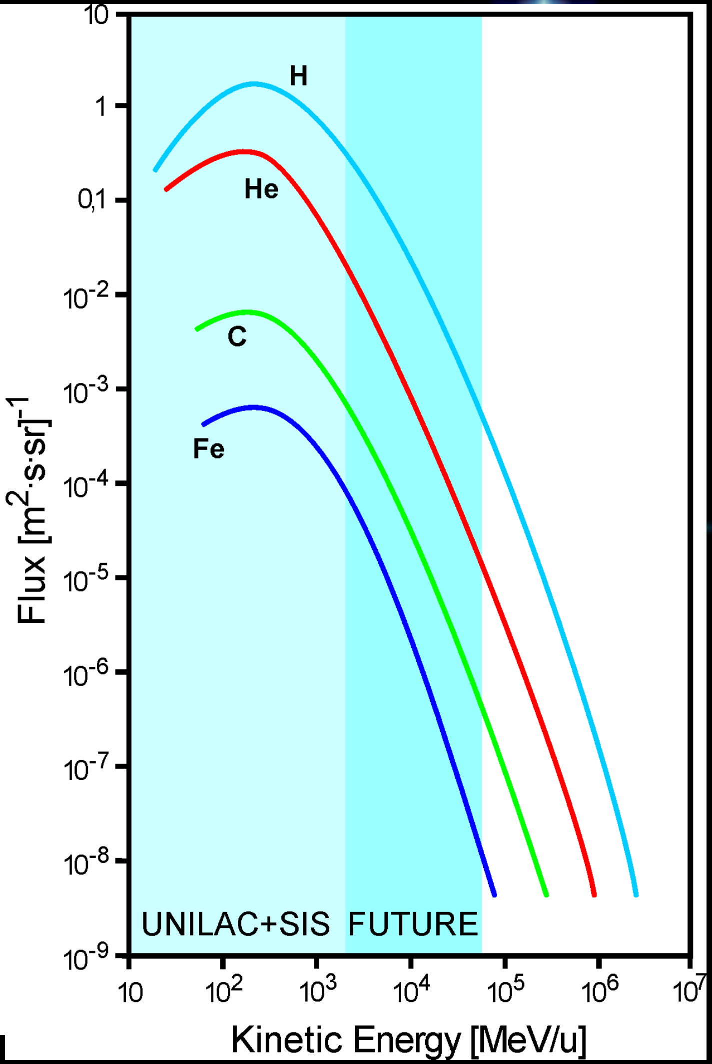
Solar particle events





Galactic Cosmic Radiation





"Best" shielding materials

- Liquid H_2
- Liquid CH_4
-
- Polyethylene (CH_2)
-
- H_2O
-
-
- Al—Inadequate shielding
-
-
- Pb
-

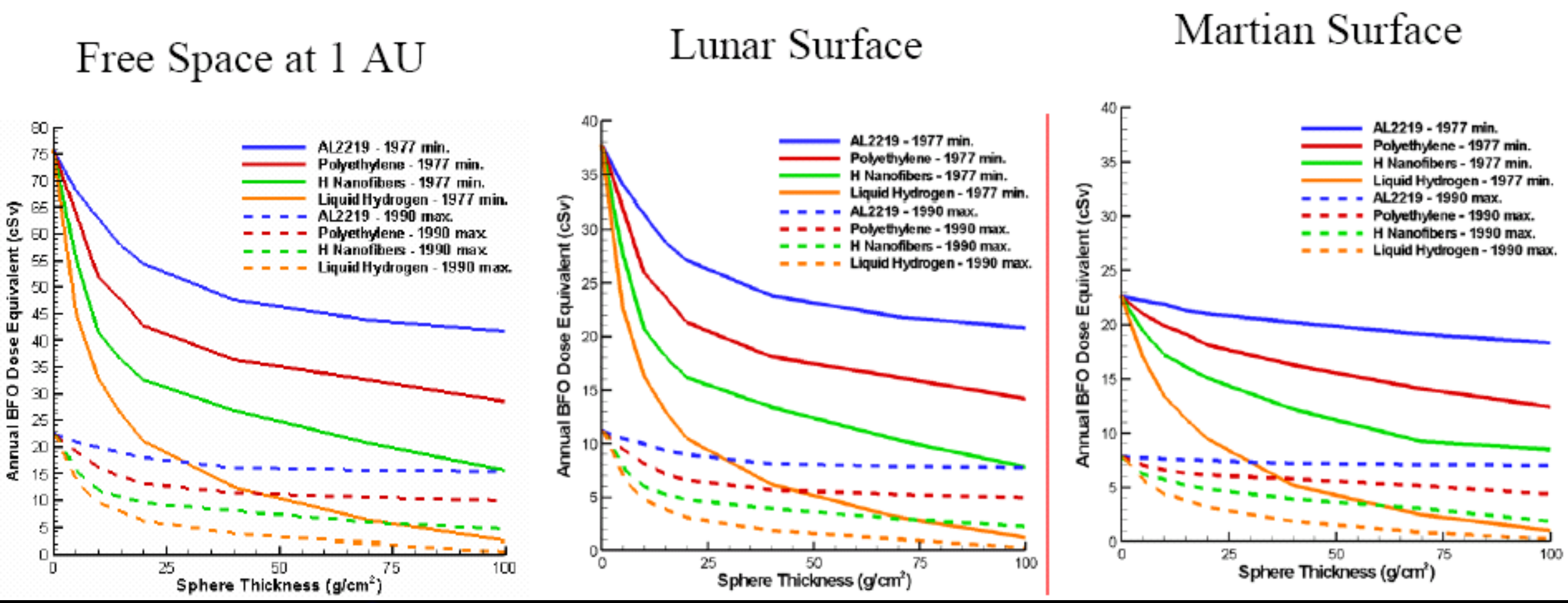
Best

Potential range for new and multi-functional shielding materials: CH_4 adsorption on carbon forms; polymer composites; hydrides and hydride/carbon o hydride/polymer composites

Worst

Projectile interactions per unit target mass:
Ionization ~ Z/A (Bethe-Bloch formula)
Fragmentation ~ $A^{-1/3}$ (Bradt-Peters formula)

Is shielding a solution?



Max GCR dose reduction

Aluminum ~ 30%

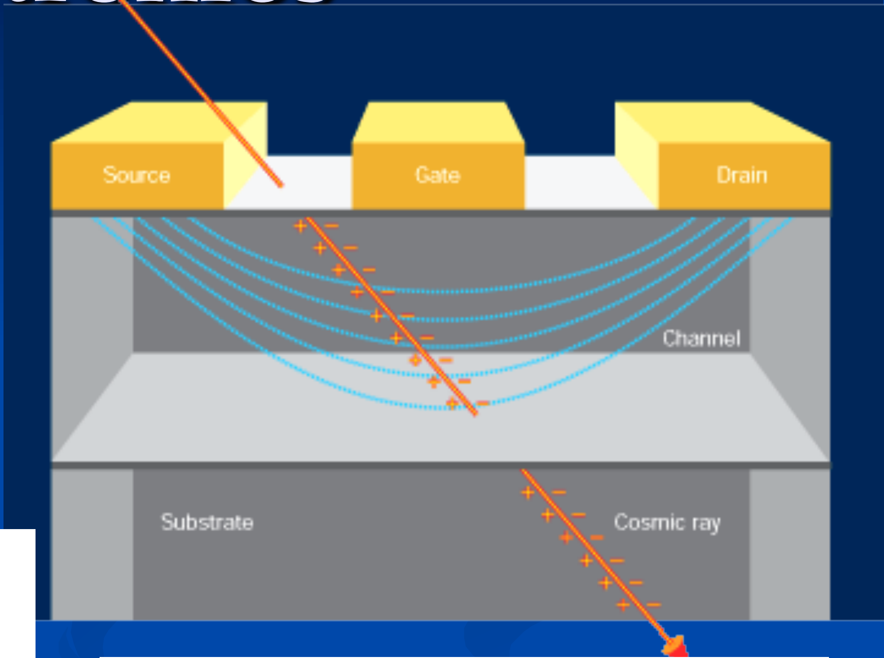
Polyethylene ~ 50%

Liquid hydrogen ~ 90%

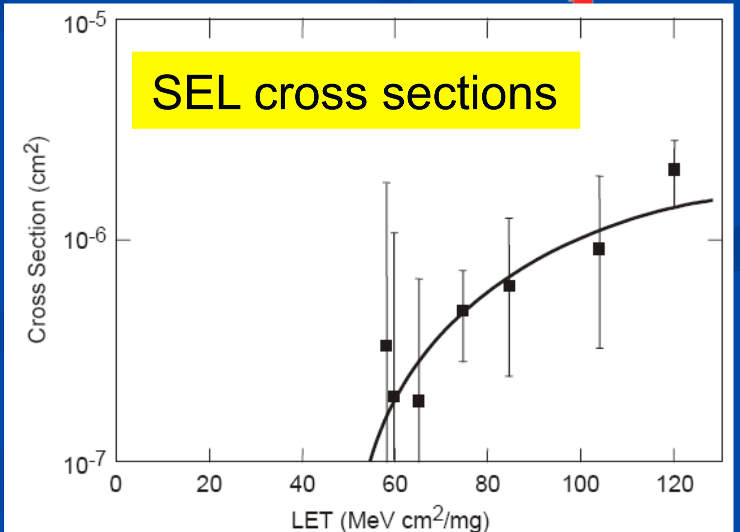
Cosmic ray damage to microelectronics

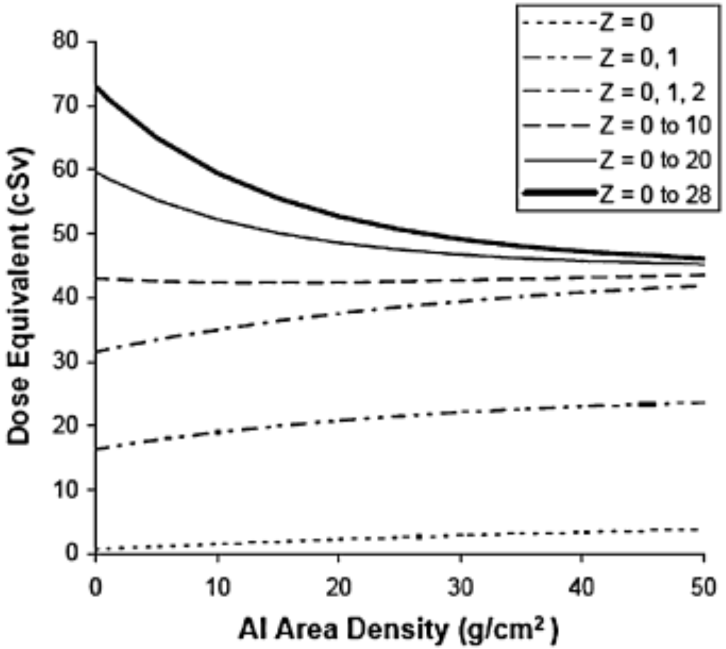
Radiation damage is caused by electron-hole pairs created in SiO_2 or other insulators

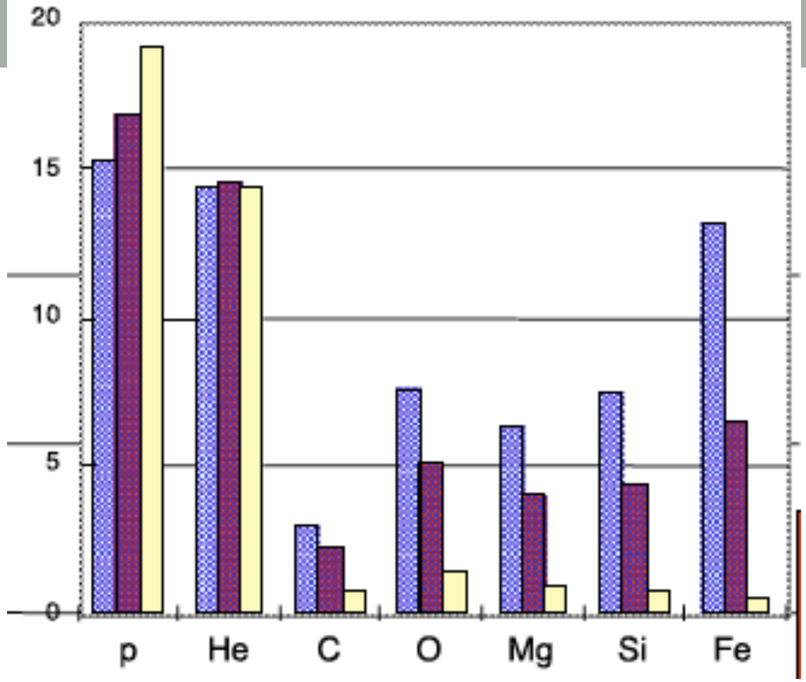
Single event upsets (SEU), total dose effects (TDE), and displacement damage (DD)

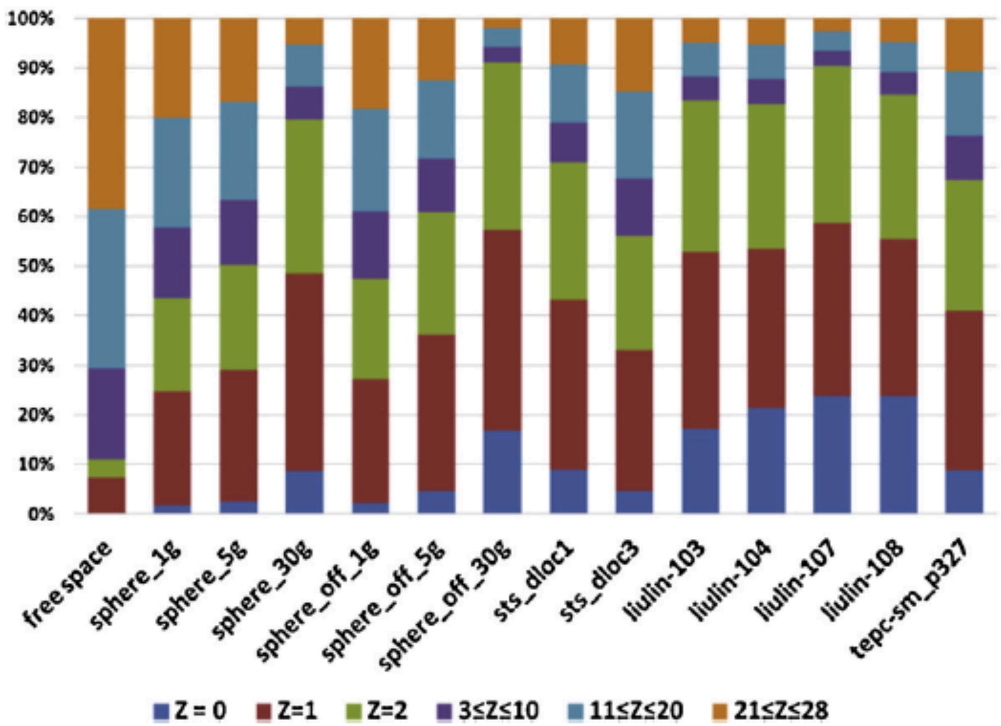


- Special Redesign of 2901 Microprocessor for Galileo
  - Problem identified during design and evaluation
  - Potential “show stopper” for Galileo mission
- Resets in Hubble Space Telescope after Upgrade in 1996
  - Caused by transients from optocouplers
  - Occurred when spacecraft flew through South Atlantic anomaly
- Failures of Optocouplers on Topex-Poseidon
- Resets in Power Control Modules on Cassini
- High Multiple-Bit Error Rate in Cassini Solid-State Recorder

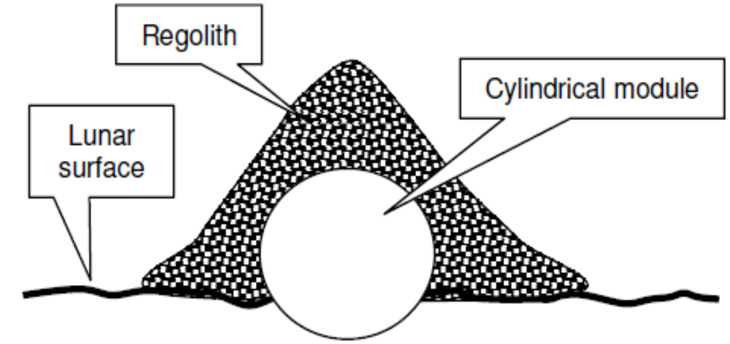


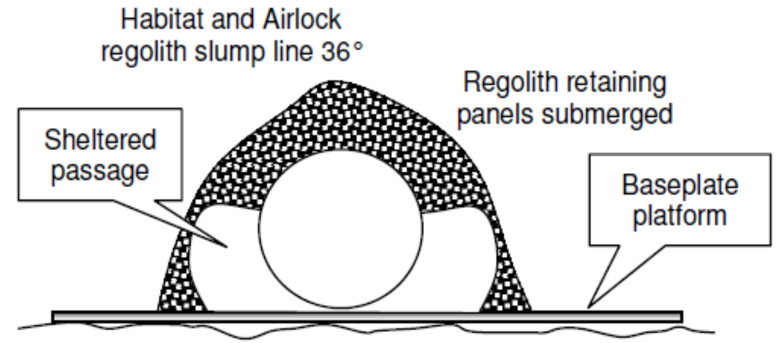


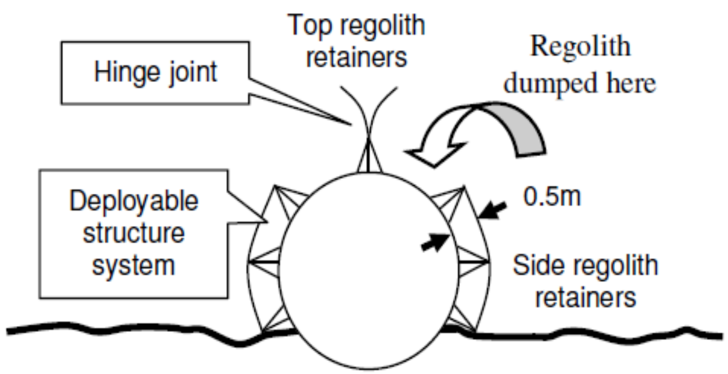


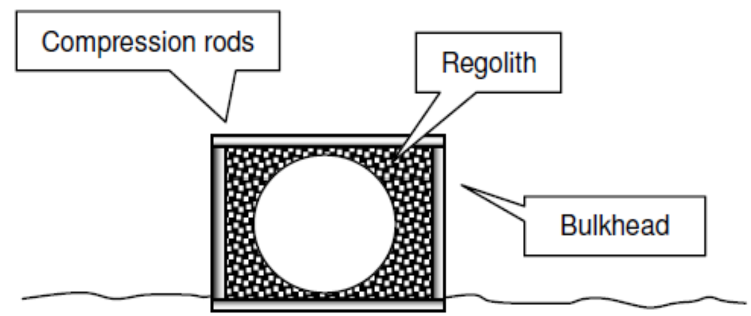


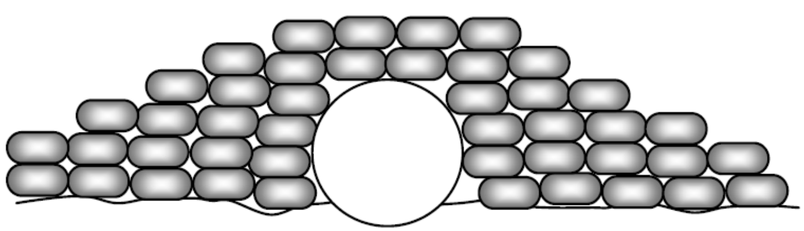
Norbury and Slaba, *Life Sciences in Space Research*, 2014

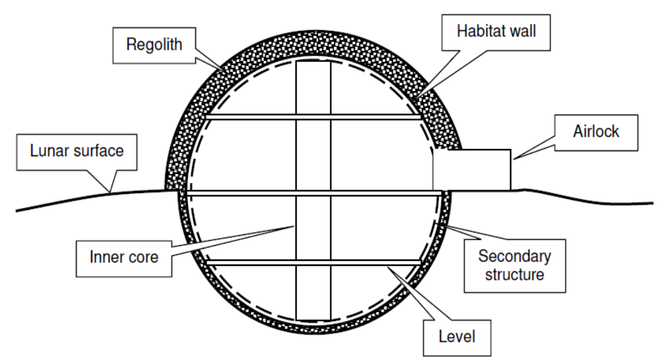

Regolith
Cylindrical module
Lunar surface

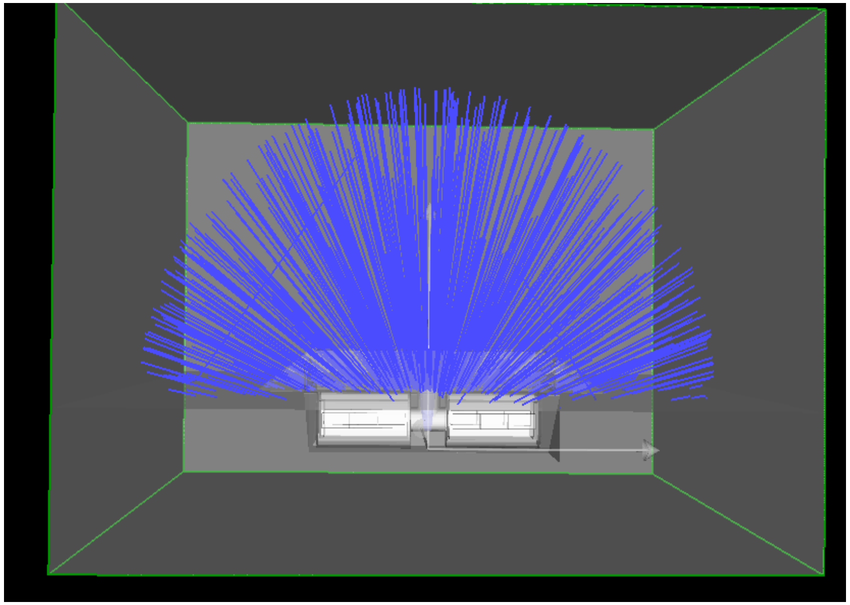

Habitat and Airlock regolith slump line 36°
Regolith retaining panels submerged
Sheltered passage
Baseplate platform

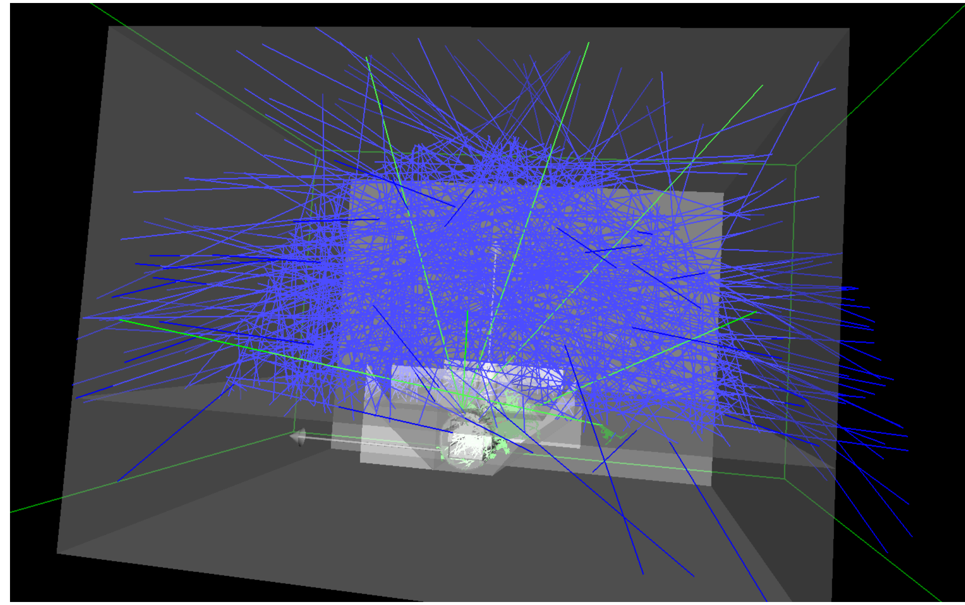

Top regolith retainers
Hinge joint
Regolith dumped here
Deployable structure system
0.5m
Side regolith retainers

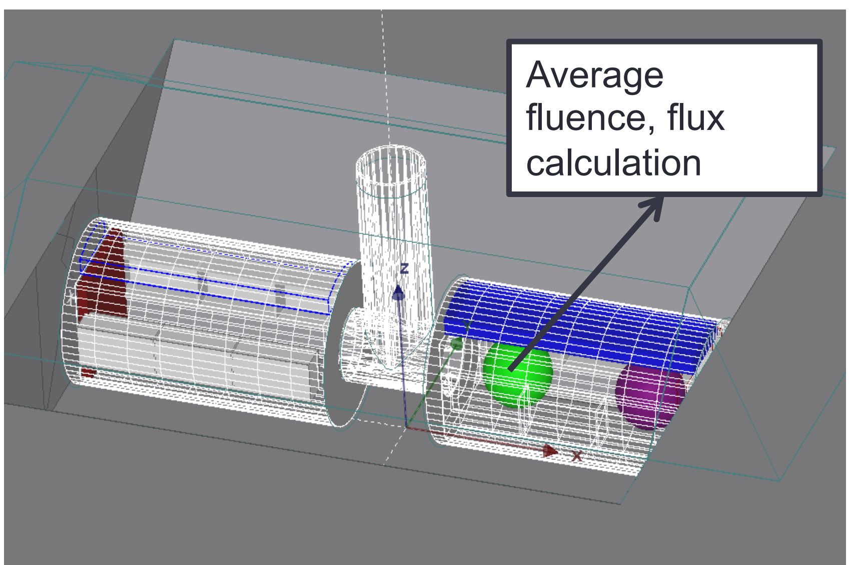

Compression rods
Regolith
Bulkhead

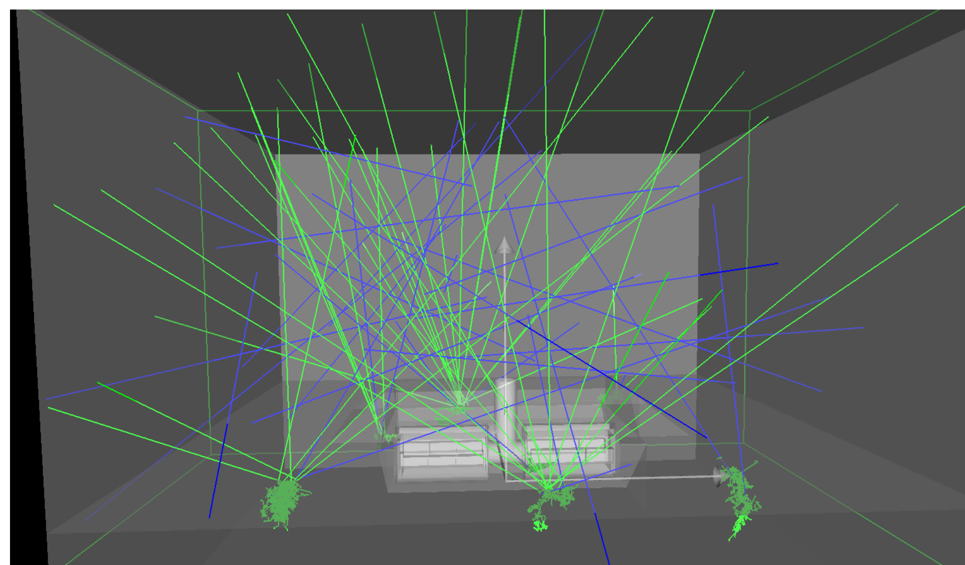



Regolith
Habitat wall
Airlock
Lunar surface
Inner core
Secondary structure
Level

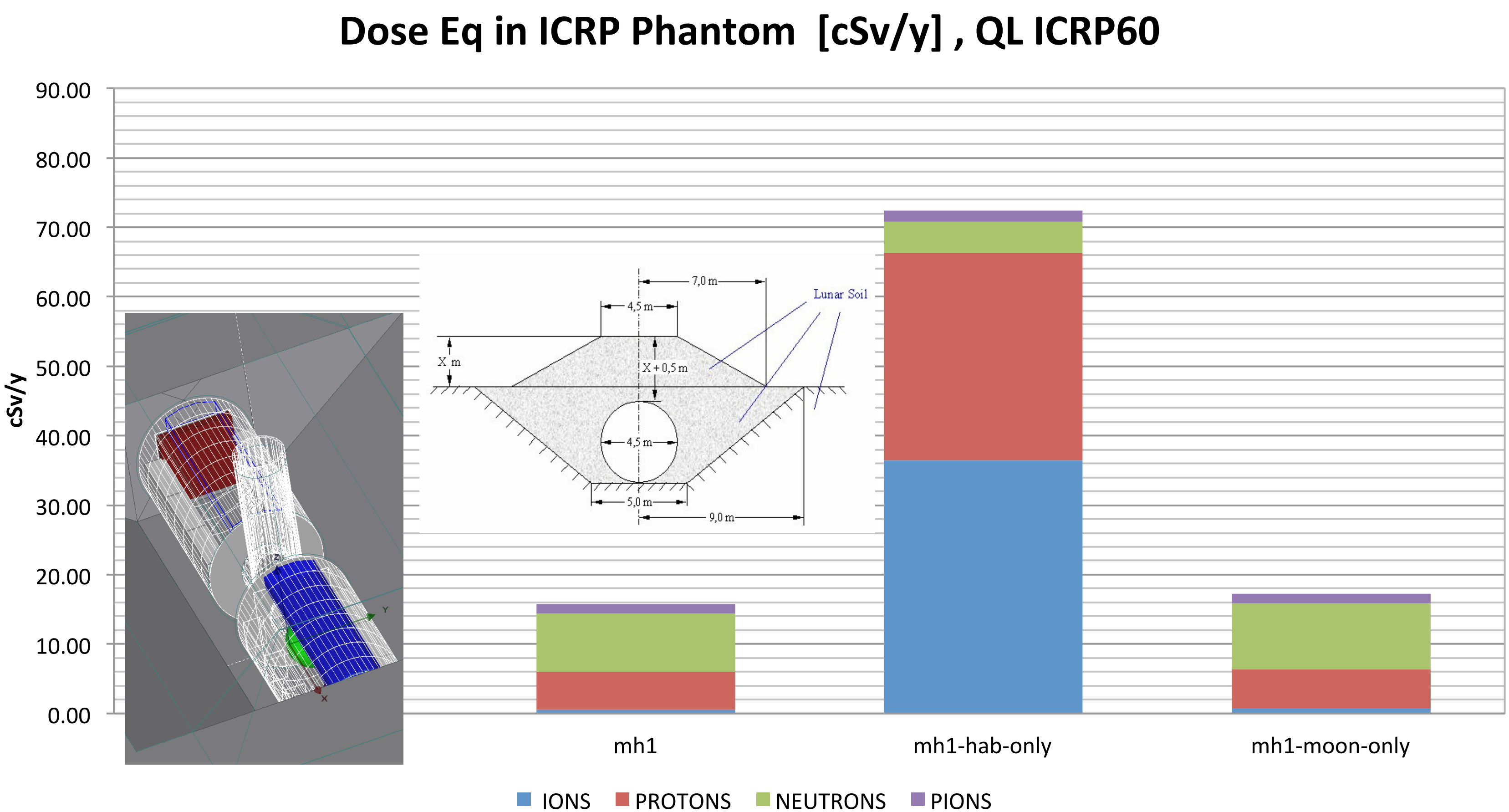


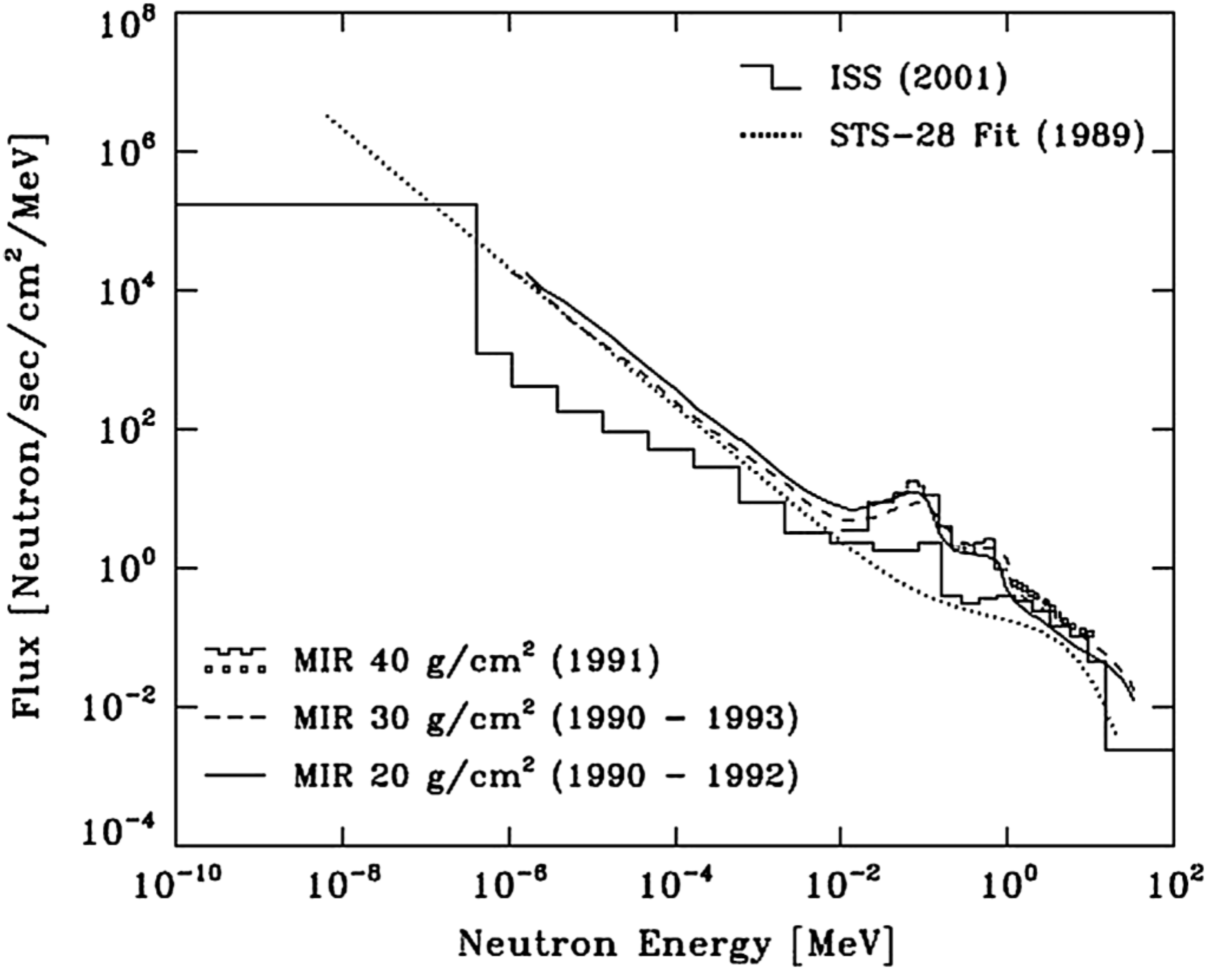



Average fluence, flux calculation
z
x



Effective Dose





Neutrons in space: LEO

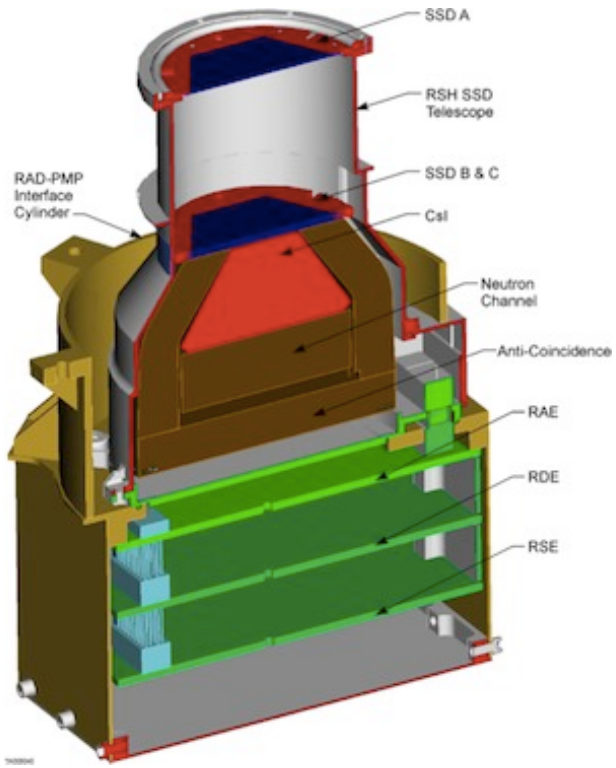
- Dose contribution: 5-15%
- Dose equivalent contribution: 20-50%
- Spectra by Bonner balls (ISS) or nuclear emulsions (Mir)

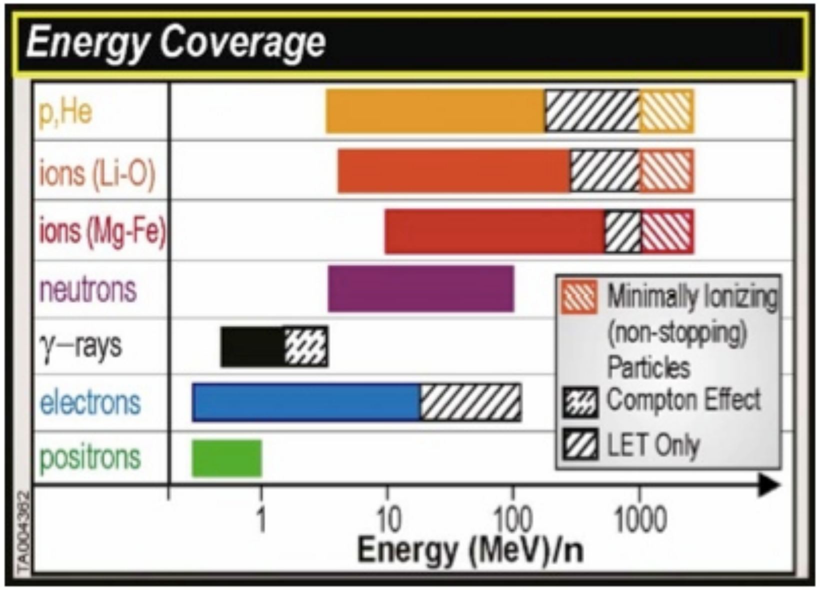
Mission	Altitude (km)	Neutron dose rate (μGy/day)	Charged particle dose rate (μGy/day)	Neutron equivalent dose rate (μSv/day)	Charged particle equivalent dose rate (μSv/day)
STS-55	302	5.9	57.2	52.0	120.1
STS-57	470	25.3	461.9	220.0	859.4
STS-65	306	11.0	75.2	95.0	157.8
STS-94	296	3.7	101.5	30.8	213.9

Durante and Cucinotta, *Rev. Mod. Phys.* 2011

Neutrons in space: MSL

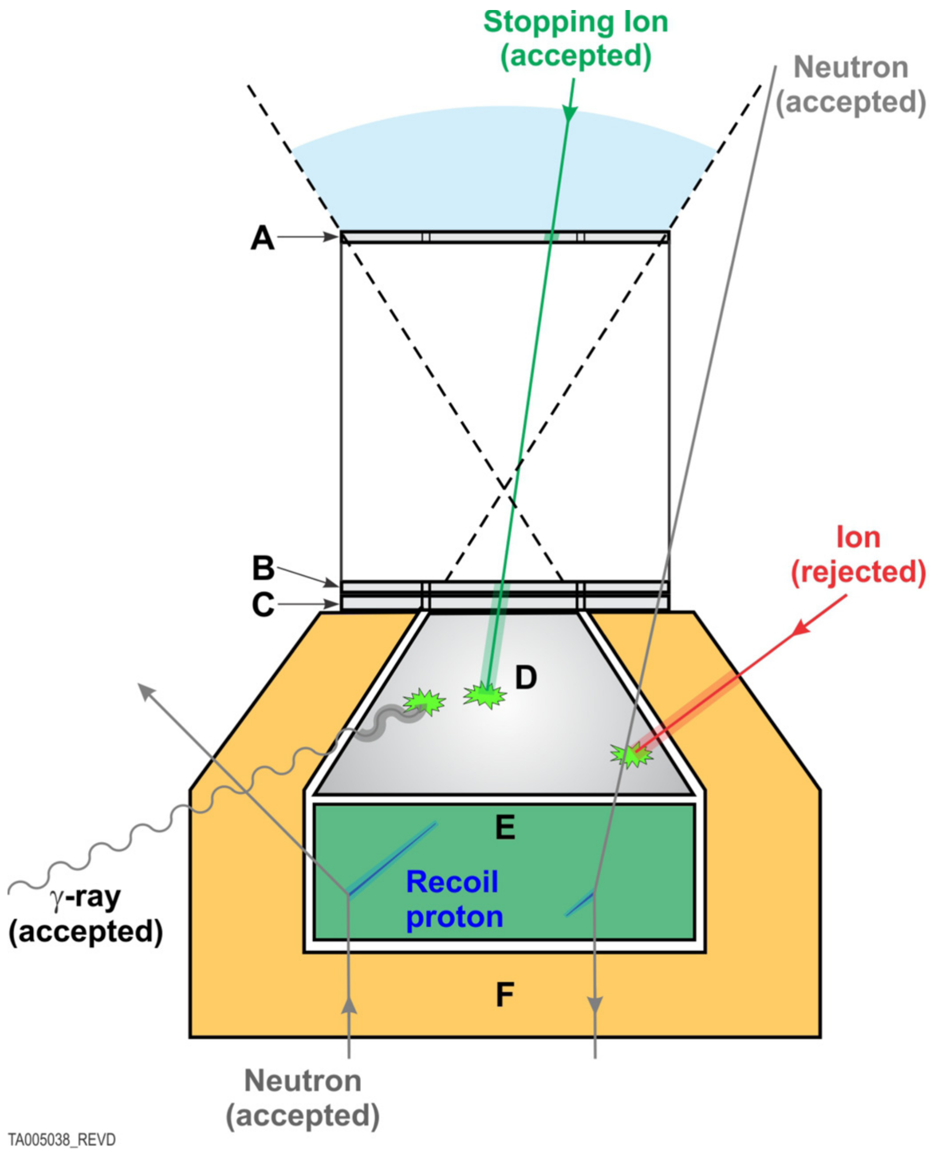
Launched 26.11.2011 – on Mars since 6.8.2012

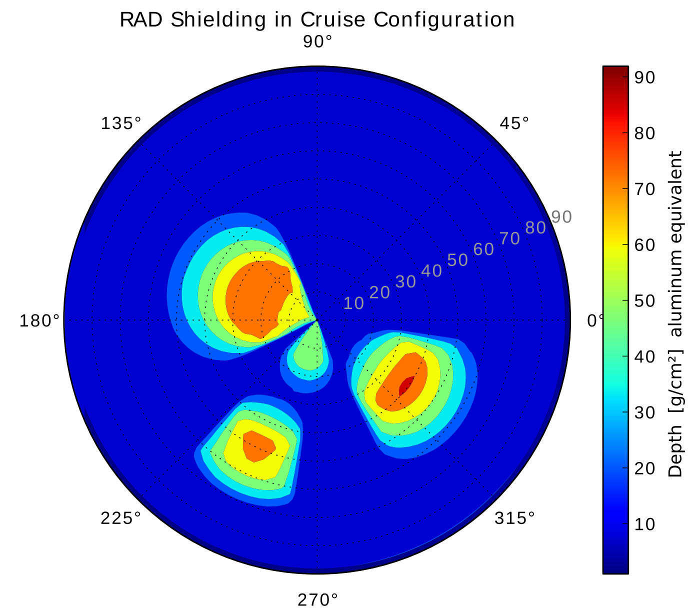




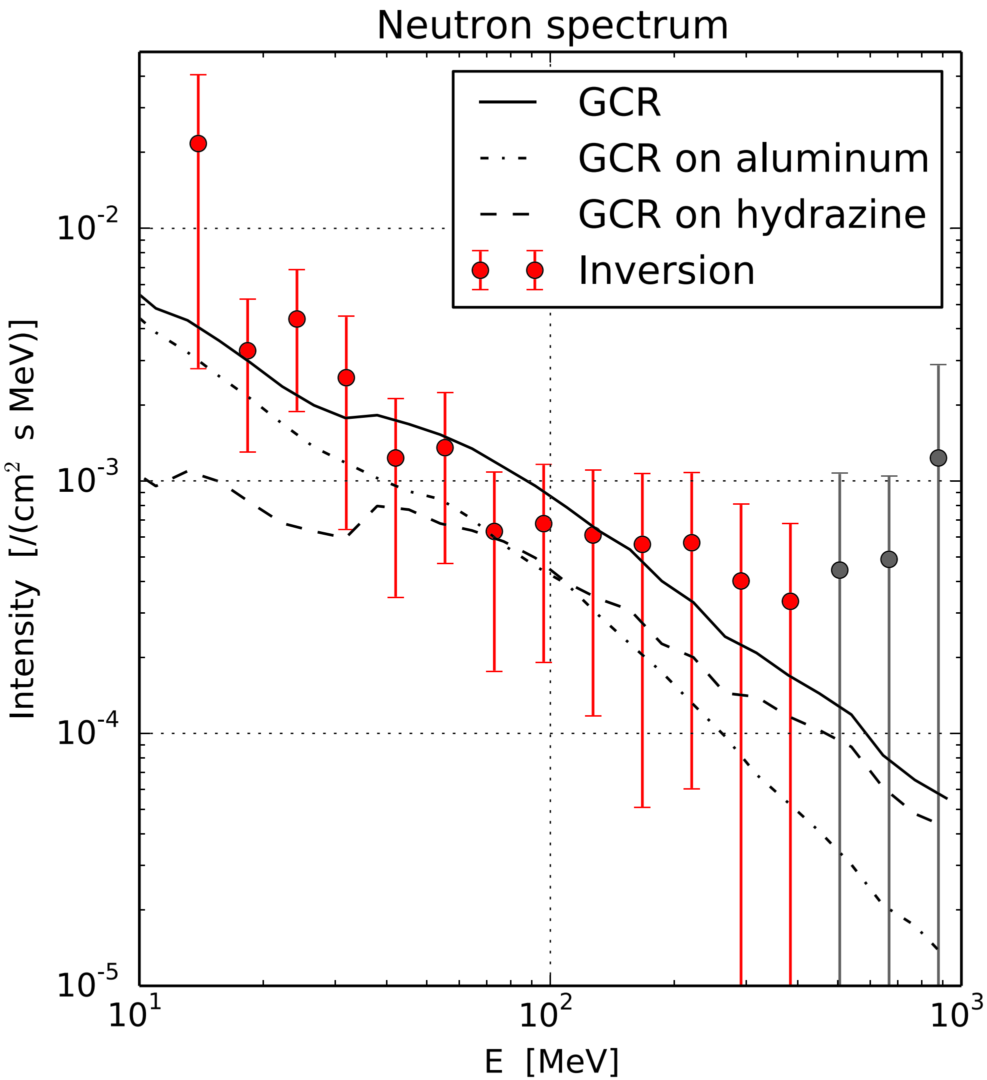
	GCR dose rate (mGy/day)	GCR dose-equivalent rate (mSv/day)	Inspiration Mars (Sv)	Mars sortie (Sv)	Mars base (Sv)
MSL cruise (Zeitlin et al., 2013)	0.46	1.84	0.92	0.7	0.98
MSL on Mars (Hassler et al., 2014)	0.21	0.64			

Neutrons in RAD





Neutrons in deep space



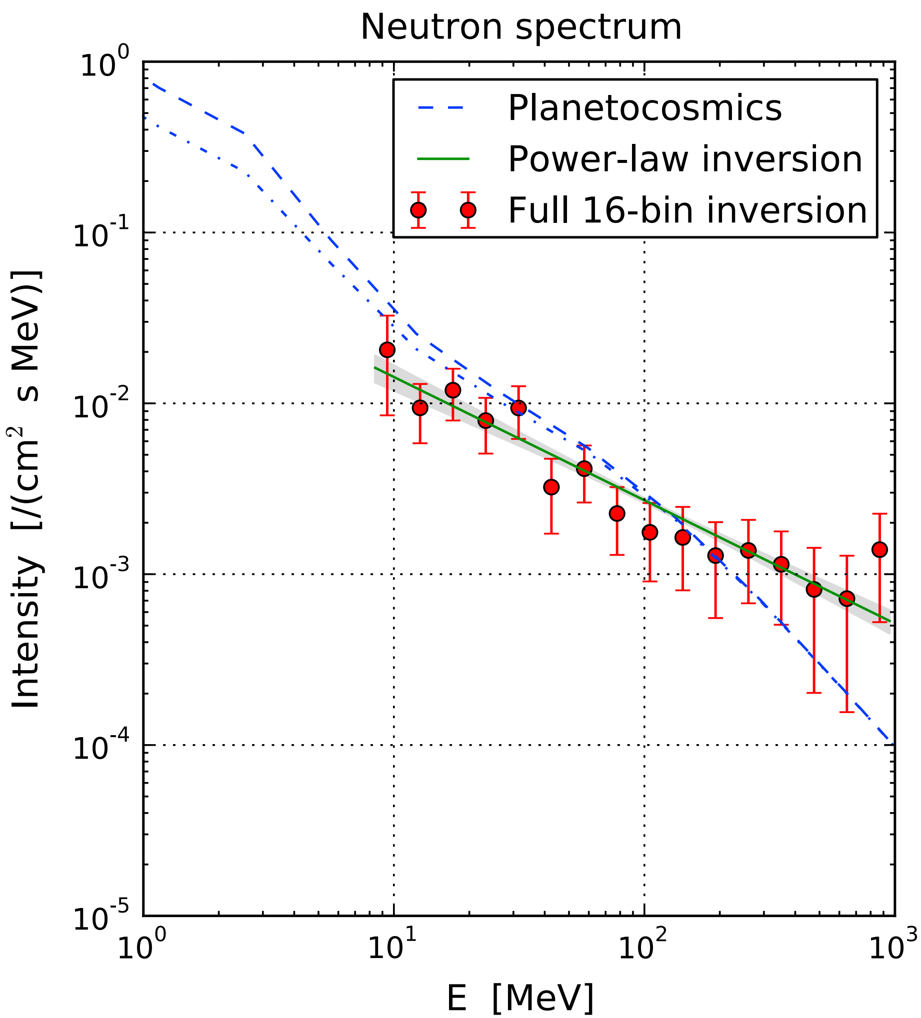
Dose rate and dose equivalent rate for the calculated neutron spectrum. The measurement covers an energy range of 12–436 MeV, the simulation extends this range to 0.1–1000 MeV.

	Measurement	Simulation
Dose equivalent rate	19 ± 5 μSv/day	30 ± 10 μSv/day
Dose rate	3.8 ± 1.2 μGy/day	6 ± 2 μGy/day

Charged particle dose-rate 1840 μSv/day

Koehler *et al.*, *Life Sci. Space Res.* 2015

Neutrons on Mars



Dose equivalent rate $:= 61 \pm 10$ μSv/d

Doserate : 14 ± 3 μGy/d

Charged particle dose-rate 640 μSv/day

Koehler *et al., J. Geophys. Res.*2014

Lack of fast neutrons facilities in Eruope

EURADOS
European Radiation Dosimetry Group e. V.

EURADOS Report 2013-02

Braunschweig, May 2013

There is greater concern about high-energy neutron fields owing to the increasing number of high-energy accelerators in research and medicine and the special consideration given to the occupational exposure to cosmic radiation. In order to study the physics of neutron interactions in these applications, in particular concerning dosimetry, radiation protection monitoring of workplaces, and radiation effects in electronics, particularly those used in aircraft and in spacecraft, well-characterized neutron fields for high energies are needed.

- Louvain, Belgium: closed
- Uppsala, Sweden: closed
- NPI, Czech Republic: max 30 MeV
- NFS, Ganil, France: under construction, max 40 MeV

(….)QMN beams with energies above 40 MeV will be available only in South Africa and Japan, with none in Europe.

Grazie! Thank you! Vielen Dank!