MEASURING RADIATION and its EFFECTS

ACTIVITY units

ACTIVITY units

1 **Bequerel** (**Bq**) ≡ 1 radioactive decay per second.

1 **Curie** (**Ci**) ≡ 37 billion **Bq**

ACTIVITY units

1 **Bequerel** (**Bq**) ≡ 1 radioactive decay per second.

1 **Curie** (**Ci**) ≡ 37 billion **Bq**

An isotope with a ***half-life*** of $T_{½}$ has a ***mean lifetime*** of

$$\tau = T_{½}/\ell n\, 2 \approx 1.44\, T_{½}$$

and a ***decay rate*** of $\lambda = 1/\tau$

ACTIVITY units

1 **Bequerel** (**Bq**) ≡ 1 radioactive decay per second.

1 **Curie** (**Ci**) ≡ 37 billion **Bq**

An isotope with a ***half-life*** of $T_{½}$ has a ***mean lifetime*** of

$$\tau = T_{½}/\ell n\, 2 \approx 1.44\, T_{½}$$

and a ***decay rate*** of $\lambda = 1/\tau$

so a sample of $\boldsymbol{N}$ such nuclei will have an ***activity*** of

$$\boldsymbol{A} = \lambda N = N\, \ell n\, 2/T_{½} \text{ Bq}$$

(if $T_{½}$ is measured in *seconds*)

ACTIVITY units

1 **Bequerel** (**Bq**) ≡ 1 radioactive decay per second.

1 **Curie** (**Ci**) ≡ 37 billion **Bq**

An isotope with a ***half-life*** of $T_{½}$ has a ***mean lifetime*** of

$$\tau = T_{½}/\ell n 2 \approx 1.44\, T_{½}$$

and a ***decay rate*** of $\lambda = 1/\tau$

so a sample of $\boldsymbol{N}$ such nuclei will have an ***activity*** of

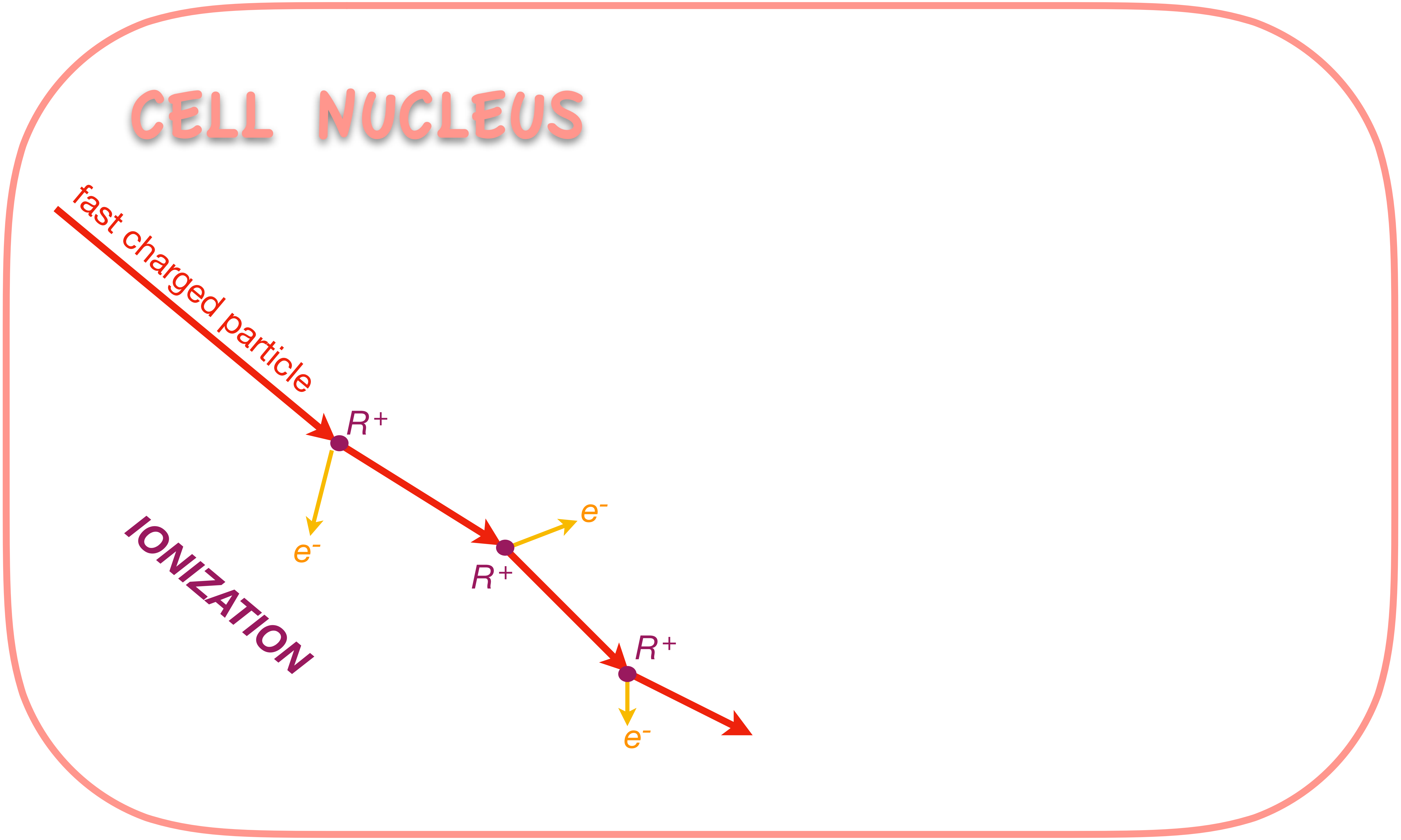
$$\boldsymbol{A} = \lambda N = N \ell n 2 / T_{½} \text{ Bq}$$

(if $T_{½}$ is measured in *seconds*)

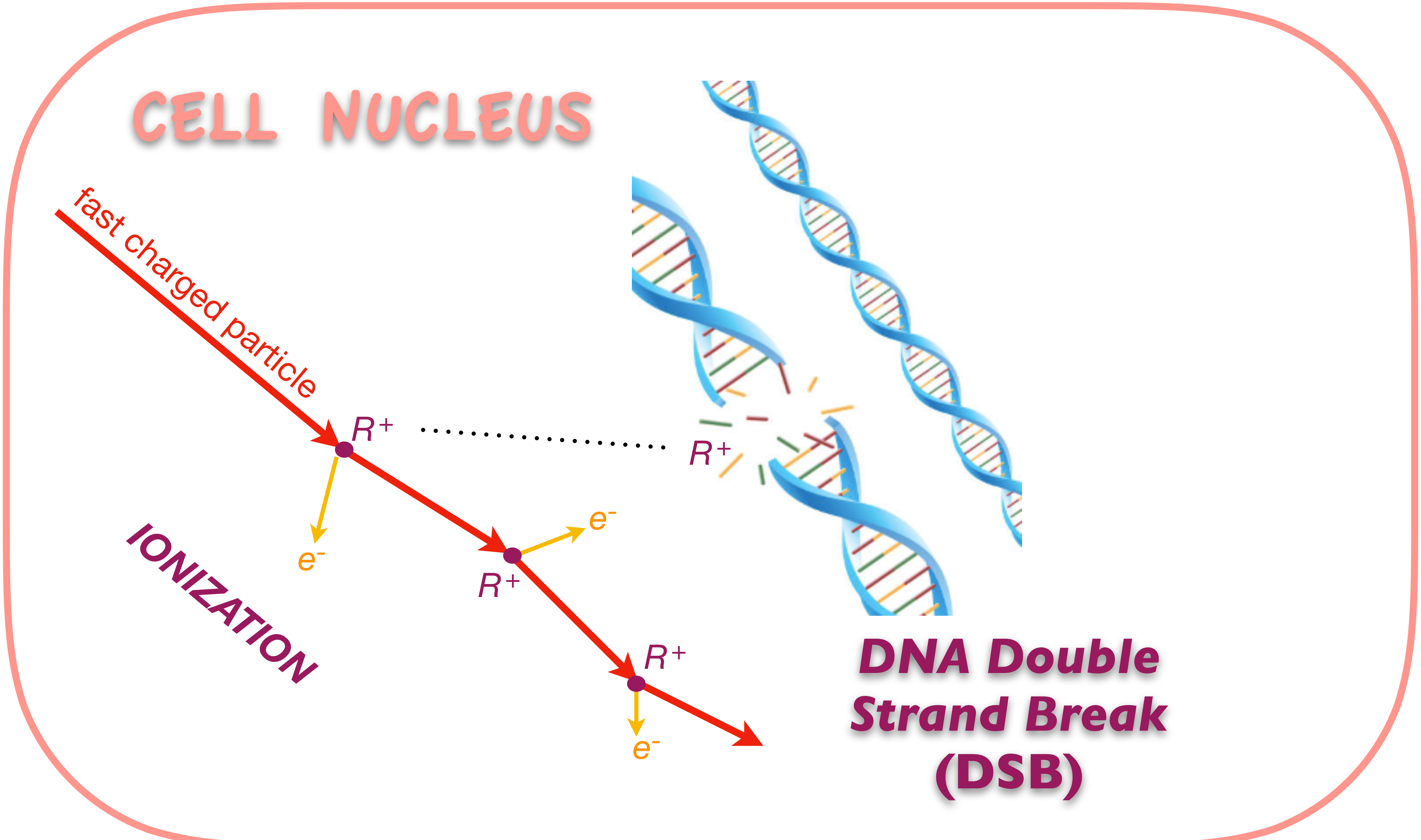
Note: the *activity is higher* if the *lifetime is shorter*. (But not for long!)

*What does Radiation **DO** to us?*

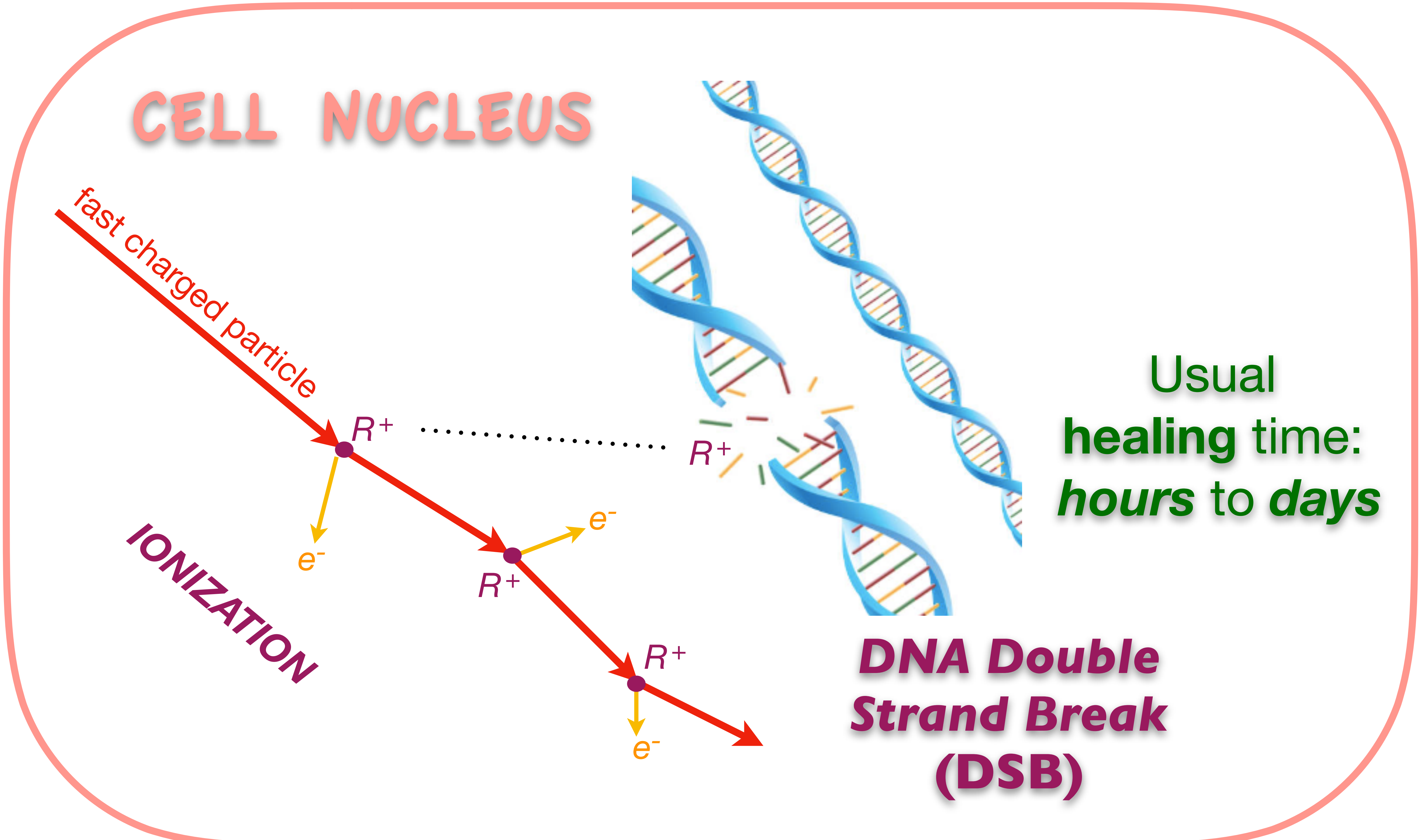
What does Radiation **DO** to us?



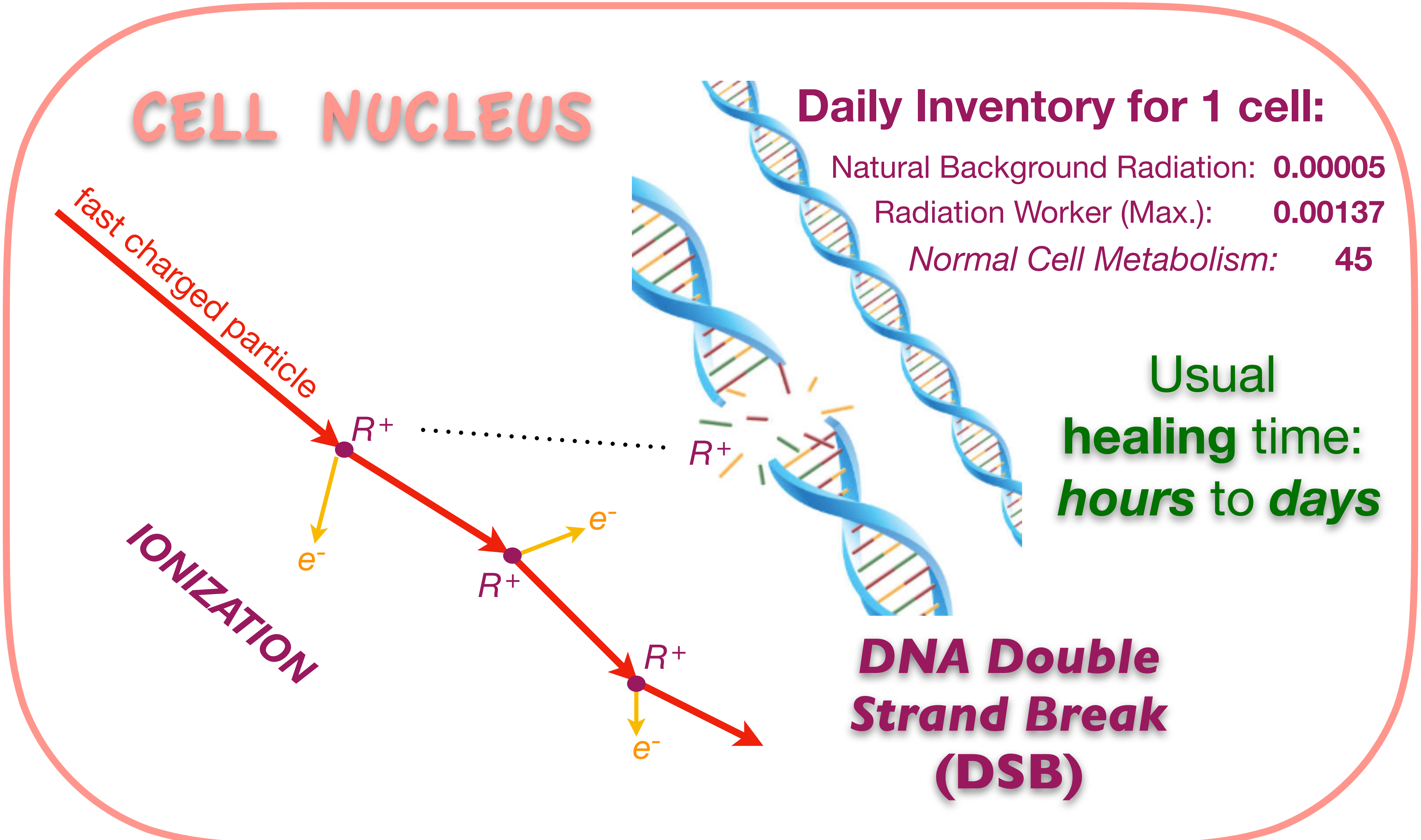
What does Radiation **DO** to us?



*What does Radiation **DO** to us?*



What does Radiation **DO** to us?



Ionizing Radiation → DNA Strand Breaks

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing…

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing…

- **Cell Reproductive Death** [most common]

Cells usually survive for their natural lifetimes — a few days for hair follicles, skin and mucous membrane cells; "forever" for brain cells and some muscle cells.

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing…

- **Cell Reproductive Death** [most common]

Cells usually survive for their natural lifetimes — a few days for hair follicles, skin and mucous membrane cells; "forever" for brain cells and some muscle cells.

- **Genetic Mutation** [most subtle]

Damaged *gamete* cells → *mutations* (usually fatal to foetus; almost always detrimental to the individual offspring…)

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing…

- **Cell Reproductive Death** [most common]

  Cells usually survive for their natural lifetimes — a few days for hair follicles, skin and mucous membrane cells; "forever" for brain cells and some muscle cells.

- **Genetic Mutation** [most subtle]

  Damaged *gamete* cells → *mutations* (usually fatal to foetus; almost always detrimental to the individual offspring…)

- **Cancer** [most unpleasant]

  Runaway replicative zeal of a misguided cell…

DOSE units

1 **rad** ≡ 100 erg/g (energy deposited per unit mass)

1 ***gray*** (**Gy**) ≡ 100 **rad** ≡ 1 J/kg. (standard international unit)

DOSE units

1 **rad** ≡ 100 erg/g (energy deposited per unit mass)

1 ***gray*** (**Gy**) ≡ 100 **rad** ≡ 1 J/kg. (standard international unit)

*R*elative *B*iological *E*ffectiveness (***RBE***) "fudge factor":

- X-rays, γ-rays & β-rays (fast electrons): *RBE* = 1 (by definition)
- Slow neutrons: average *RBE* ≈ 3. (Variable!)
- Fast neutrons, protons & α-rays: *RBE* = 10.
- Fast heavy ions: *RBE* = 20.

DOSE units

1 **rad** ≡ 100 erg/g (energy deposited per unit mass)

1 ***gray*** (**Gy**) ≡ 100 **rad** ≡ 1 J/kg. (standard international unit)

*R*elative *B*iological *E*ffectiveness (***RBE***) "fudge factor":

- X-rays, γ-rays & β-rays (fast electrons): *RBE* = 1 (by definition)
- Slow neutrons: average *RBE* ≈ 3. (Variable!)
- Fast neutrons, protons & α-rays: *RBE* = 10.
- Fast heavy ions: *RBE* = 20.

REM (R, *R*oentgen *E*quivalent to *M*an):

1 R ≡ *RBE* × **rad**.

(1 mR ≡ *milliREM* ≡ 10^{-3} R.)

sievert (standard international unit):

1 *sievert* (**Sv**) ≡ *RBE* × ***gray*** = 100 *REM*

Problems with **DOSE UNITS:**

Problems with **DOSE UNITS:**

No mention of ***over what time*** the dose is *delivered*.

∴ Implicitly *assumed* that DNA damage is ***accumulative***.

Safety standards usually limit mSv *per **year***.

But normal cell oxygen metabolism also causes DNA DSB…

…and most DNA DSB ***heal*** within ***hours***.

Meanwhile, a healthy ***immune*** system is constantly eliminating lone cancer cells.

Still, the rare ***permanent*** DSB may occur, and under constant irradiation the number of such defects ***does*** accumulate.

Maximum Permissable *Occupational* Doses

USA & Canada

Maximum Permissable *Occupational* Doses

USA & **Canada**

- Non-Radiation Worker: **1** mSv/year *vs*. **1** mSv/year
- Radiation Workers: **50** mSv/year *vs*. **50** mSv/year

Maximum Permissable *Occupational* Doses

USA & **Canada**

- Non-Radiation Worker: **1** mSv/year *vs.* **1** mSv/year
- Radiation Workers: **50** mSv/year *vs.* **50** mSv/year

- Natural Background (at sea level): **1.8** mSv/year
- Cosmic Ray Muons *alone*: **0.3** mSv/year (at sea level)

Maximum Permissable *Occupational* Doses

USA & Canada

- Non-Radiation Worker: **1** mSv/year *vs*. **1** mSv/year
- Radiation Workers: **50** mSv/year *vs*. **50** mSv/year

- Natural Background (at sea level): **1.8** mSv/year
- Cosmic Ray Muons *alone*: **0.3** mSv/year (at sea level)

- Kerala Coast, India: **3.3** to **60** mSv/year
- Guarapari beach, Brazil: **175** to **482** mSv/year
- Ramsar region, Iran: up to **260** mSv/year

Maximum Permissable *Occupational* Doses

USA & Canada

- Non-Radiation Worker: **1** mSv/year *vs.* **1** mSv/year
- Radiation Workers: **50** mSv/year *vs.* **50** mSv/year
- Natural Background (at sea level): **1.8** mSv/year
- Cosmic Ray Muons *alone*: **0.3** mSv/year (at sea level)
- Kerala Coast, India: **3.3** to **60** mSv/year
- Guarapari beach, Brazil: **175** to **482** mSv/year
- Ramsar region, Iran: up to **260** mSv/year
- Abdominal/Pelvic CT scan: **20-30** mSv (*all at once*)

Maximum Permissable Occupational Doses

USA & Canada converted to *μSv per day*

Maximum Permissable Occupational Doses

<u>USA</u> & <u>Canada</u> converted to *μSv per day*

- Non-Radiation Worker: **3** μSv/day *vs*. **3** μSv/day
- Radiation Workers: **137** μSv/day *vs*. **137** μSv/day

Maximum Permissable Occupational Doses

USA & Canada converted to *μSv per day*

- Non-Radiation Worker: **3** μSv/day *vs*. **3** μSv/day
- Radiation Workers: **137** μSv/day *vs*. **137** μSv/day
- Natural Background (at sea level): **5** μSv/day
- Cosmic Ray Muons *alone*: **1** μSv/day (at sea level)

Maximum Permissable Occupational Doses

USA & Canada converted to *µSv per day*

- Non-Radiation Worker: **3** µSv/day *vs*. **3** µSv/day
- Radiation Workers: **137** µSv/day *vs*. **137** µSv/day

- Natural Background (at sea level): **5** µSv/day
- Cosmic Ray Muons *alone*: **1** µSv/day (at sea level)

- Kerala Coast, India: **9 to164** µSv/day
- Guarapari beach, Brazil: **480** to **1320** µSv/day
- Ramsar region, Iran: up to **712** µSv/day

Maximum Permissable Occupational Doses

USA & Canada converted to *μSv per day*

- Non-Radiation Worker: **3** μSv/day *vs*. **3** μSv/day
- Radiation Workers: **137** μSv/day *vs*. **137** μSv/day
- Natural Background (at sea level): **5** μSv/day
- Cosmic Ray Muons *alone*: **1** μSv/day (at sea level)
- Kerala Coast, India: **9 to164** μSv/day
- Guarapari beach, Brazil: **480** to **1320** μSv/day
- Ramsar region, Iran: up to **712** μSv/day
- Abdominal/Pelvic CT scan: **20,000-30,000** μSv (*all at once*)

EFFECTS of Penetrating *Radiation*

EFFECTS of* Penetrating *Radiation

- **Instant Death**: ~ **50** Sieverts [Sv] "*whole-body*" can wipe out the central nervous system (CNS) *when delivered all at once*.

EFFECTS of Penetrating *Radiation*

- **Instant Death**: ~ **50** Sieverts [Sv] "*whole-body*" can wipe out the central nervous system (CNS) *when delivered all at once*.
- **Overnight Death**: ~ **9** Sv whole-body may accomplish the same thing in about a day.

EFFECTS of Penetrating *Radiation*

- **Instant Death**: ~ **50** Sieverts [Sv] "*whole-body*" can wipe out the central nervous system (CNS) *when delivered all at once*.
- **Overnight Death**: ~ **9** Sv whole-body may accomplish the same thing in about a day.
- **Ugly Death**: ~ **5** Sv → severe *radiation sickness* (nausea, hair loss, skin lesions, *etc*.) as short-lived cells fail to provide new generations to replace their normal mortality. Complications (infection) usually kill. Some recover completely but may develop leukemia years later; offspring (if any) may have genetic mutations.

EFFECTS* of Penetrating *Radiation

- **Instant Death**: ~ **50** Sieverts [Sv] "*whole-body*" can wipe out the central nervous system (CNS) *when delivered all at once*.
- **Overnight Death**: ~ **9** Sv whole-body may accomplish the same thing in about a day.
- **Ugly Death**: ~ **5** Sv → severe *radiation sickness* (nausea, hair loss, skin lesions, *etc.*) as short-lived cells fail to provide new generations to replace their normal mortality. Complications (infection) usually kill. Some recover completely but may develop leukemia years later; offspring (if any) may have genetic mutations.
- **Sub-Acute Exposures**: ~ **1** Sv whole-body delivered all at once → no immediate symptoms, but possible leukemia (rarely, years later).

Why there is so much disagreement

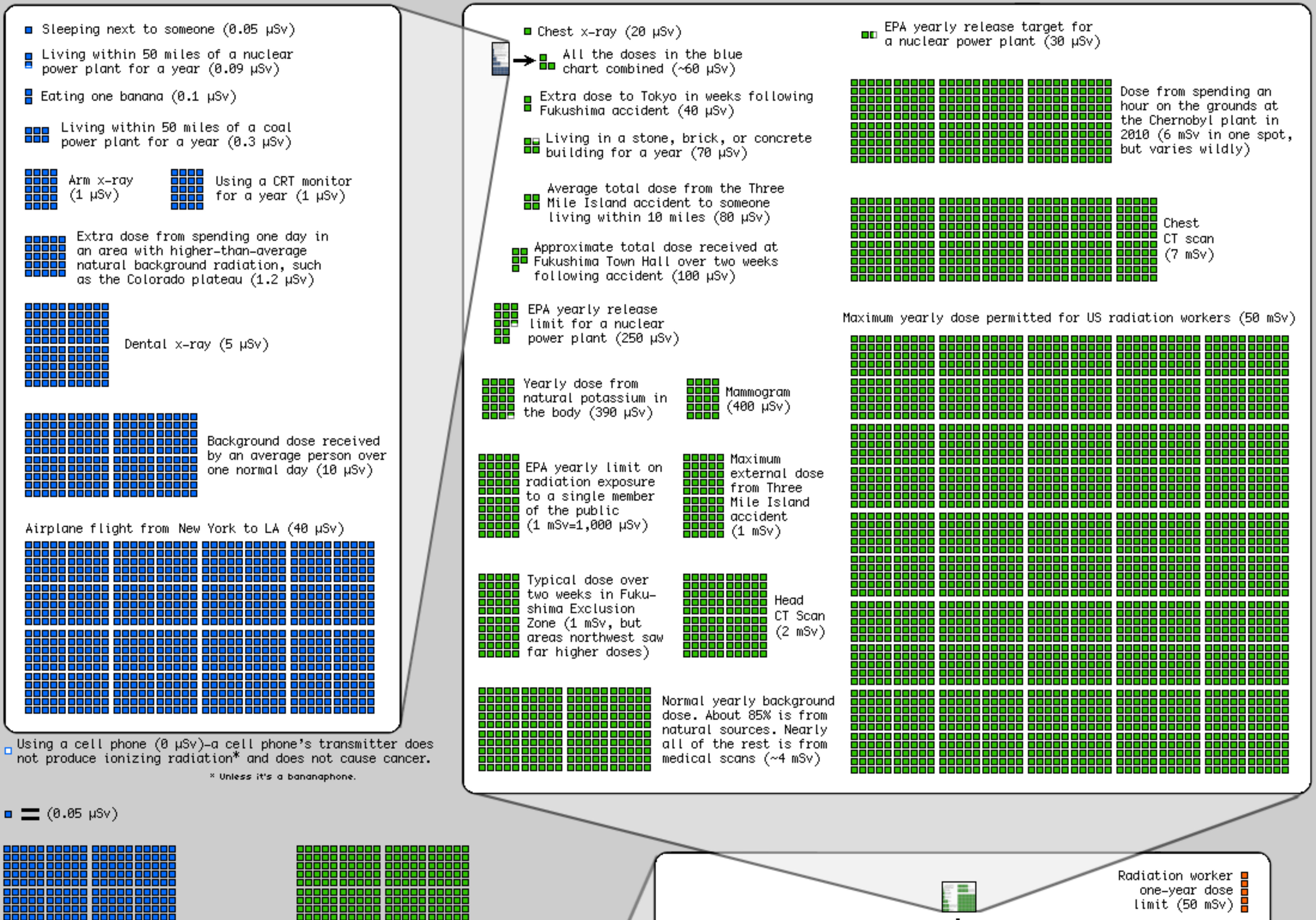
Why there is so much disagreement

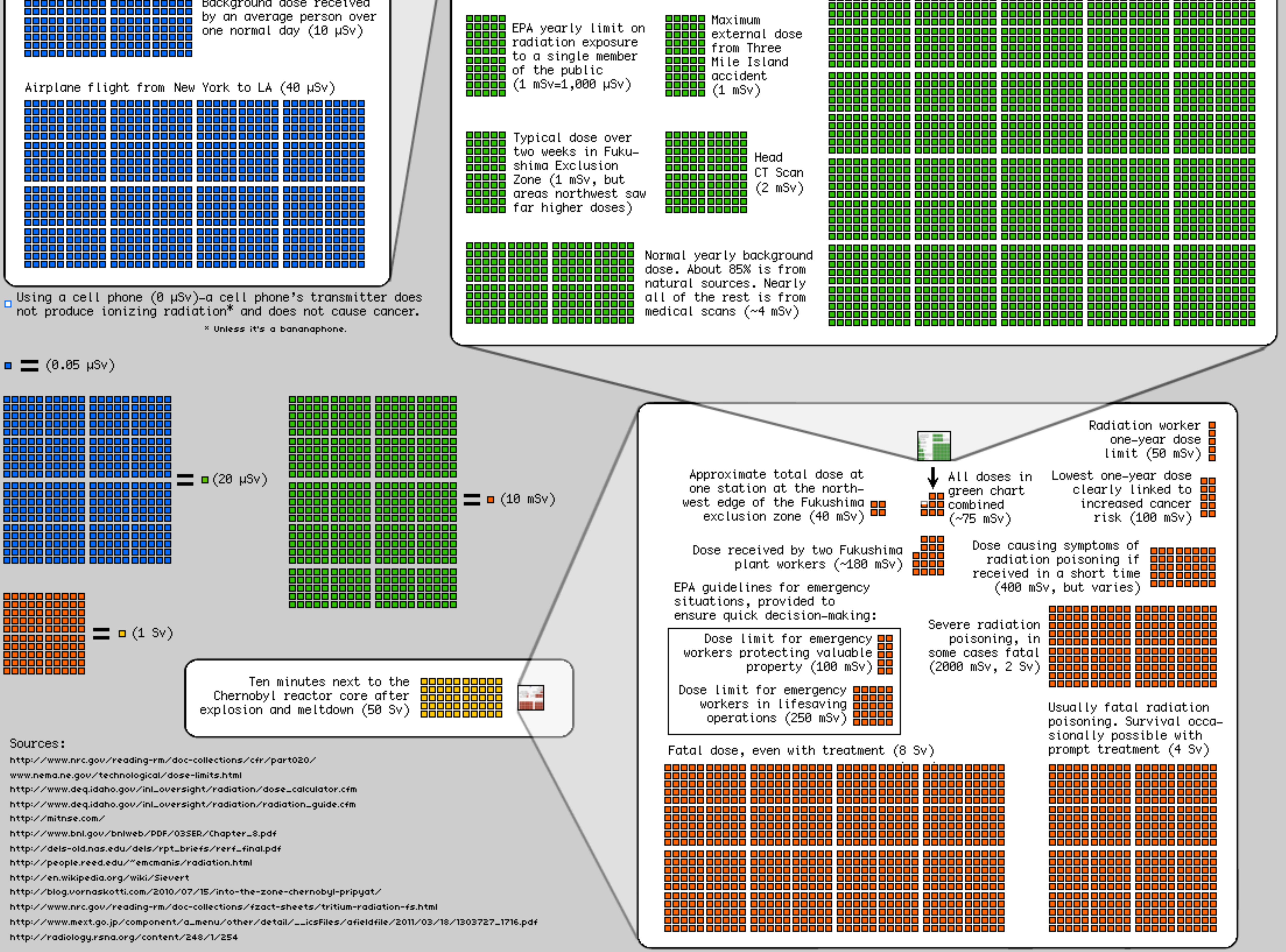
It is hard to calculate how much harm is done by a given amount of radioactivity. We can fairly easily calculate the ***activity*** of a certain amount of a given radioisotope, and then we can fairly easily find how much *energy* its ionizing radiation deposits *per kg* of flesh; but the same energy deposited by one type of particles can be an order of magnitude worse for you than the same amount of energy deposited by another type of particles; and it makes a *huge* difference whether that energy is deposited *all at once* or spread out over time, because *the damage* ***heals***. Moreover, many of these “fudge factors” are based on empirical observations that are not rigorously quantitative.

As a result, it’s very tempting to make qualitative ***comparisons***, especially with “natural background radiation”. But even then we have disagreements on how a *low* dose should be compared with a *high* dose….

Radiation Dose Chart

This is a chart of the ionizing radiation dose a person can absorb from various sources. The unit for absorbed dose is "sievert" (Sv), and measures the effect a dose of radiation will have on the cells of the body. One sievert (all at once) will make you sick, and too many more will kill you, but we safely absorb small amounts of natural radiation daily. Note: The same number of sieverts absorbed in a shorter time will generally cause more damage, but your cumulative long-term dose plays a big role in things like cancer risk.





Sources:

http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/
www.nema.ne.gov/technological/dose-limits.html
http://www.deq.idaho.gov/inl_oversight/radiation/dose_calculator.cfm
http://www.deq.idaho.gov/inl_oversight/radiation/radiation_guide.cfm
http://mitnse.com/
http://www.bnl.gov/bnlweb/PDF/03SER/Chapter_8.pdf
http://dels-old.nas.edu/dels/rpt_briefs/rerf_final.pdf
http://people.reed.edu/~emcmanis/radiation.html
http://en.wikipedia.org/wiki/Sievert
http://blog.vornaskotti.com/2010/07/15/into-the-zone-chernobyl-pripyat/
http://www.nrc.gov/reading-rm/doc-collections/fzact-sheets/tritium-radiation-fs.html
http://www.mext.go.jp/component/a_menu/other/detail/__icsFiles/afieldfile/2011/03/18/1303727_1716.pdf
http://radiology.rsna.org/content/248/1/254

Chart by Randall Munroe, with help from Ellen, Senior Reactor Operator at the Reed Research Reactor, who suggested the idea and provided a lot of the sources. I'm sure I've added in lots of mistakes; it's for general education only. If you're basing radiation safety procedures on an internet PNG image and things go wrong, you have no one to blame but yourself.

Thresholds and Linearity

Thresholds and Linearity

We have data on the survivors of *Hiroshima* and *Nagasaki*. We also have data on the people exposed to high radiation levels at *Chernobyl*. We know roughly how much their probability of (*e.g.*) thyroid cancer was heightened over time by exposure to Iodine-131, and we know how many suffered immediate effects of "radiation sickness". What we *don't* know so well is how people are affected by much *lower* levels of radiation exposure. One reason for this is that we don't have a "**control group**" of people who are not exposed to ***any*** radiation. There are no such people! Your *bones* are radioactive.

Thresholds and Linearity

We have data on the survivors of *Hiroshima* and *Nagasaki*. We also have data on the people exposed to high radiation levels at *Chernobyl*. We know roughly how much their probability of (*e.g.*) thyroid cancer was heightened over time by exposure to Iodine-131, and we know how many suffered immediate effects of "radiation sickness". What we *don't* know so well is how people are affected by much *lower* levels of radiation exposure. One reason for this is that we don't have a "**control group**" of people who are not exposed to ***any*** radiation. There are no such people! Your *bones* are radioactive.

One model is "*LNT*" — a simple *L*inear model with ***N***o *T*hreshold: that is, we assume there is no such thing as a "harmless" amount of radiation, that radiation damage *never heals*, and that the probability of harm is *proportional* to the radiation dose. This model has the sole advantage of simplicity. And yet it is the *basis for all regulations*.

Thresholds and Linearity

We have data on the survivors of *Hiroshima* and *Nagasaki*. We also have data on the people exposed to high radiation levels at *Chernobyl*. We know roughly how much their probability of (*e.g.*) thyroid cancer was heightened over time by exposure to Iodine-131, and we know how many suffered immediate effects of "radiation sickness". What we *don't* know so well is how people are affected by much *lower* levels of radiation exposure. One reason for this is that we don't have a "**control group**" of people who are not exposed to ***any*** radiation. There are no such people! Your *bones* are radioactive.

One model is "*LNT*" — a simple ***L***inear model with ***N***o ***T***hreshold: that is, we assume there is no such thing as a "harmless" amount of radiation, that radiation damage *never heals*, and that the probability of harm is *proportional* to the radiation dose. This model has the sole advantage of simplicity. And yet it is the *basis for all regulations*.

The "***Threshold***" model assumes that the "normal background" radiation level is *harmless*, and may even be *beneficial* up to a point ("***hormesis***"). There is plentiful evidence for the latter.

Maximum Permissable Occupational Doses

USA & Canada converted to *μSv per day*

- Non-Radiation Worker: **3** μSv/day *vs*. **3** μSv/day
- Radiation Workers: **137** μSv/day *vs*. **137** μSv/day

- Natural Background (at sea level): **5** μSv/day
- Cosmic Ray Muons *alone*: **1** μSv/day (at sea level)

- Kerala Coast, India: **9 to164** μSv/day
- Guarapari beach, Brazil: **480** to **1320** μSv/day
- Ramsar region, Iran: up to **712** μSv/day

- Abdominal/Pelvic CT scan: **20,000-30,000** μSv (*all at once*)

Maximum Permissable Occupational Doses

<u>USA</u> & <u>Canada</u> converted to *μSv per day*

- Non-Radiation Worker: **3** μSv/day *vs*. **3** μSv/day
- Radiation Workers: **137** μSv/day *vs*. **137** μSv/day

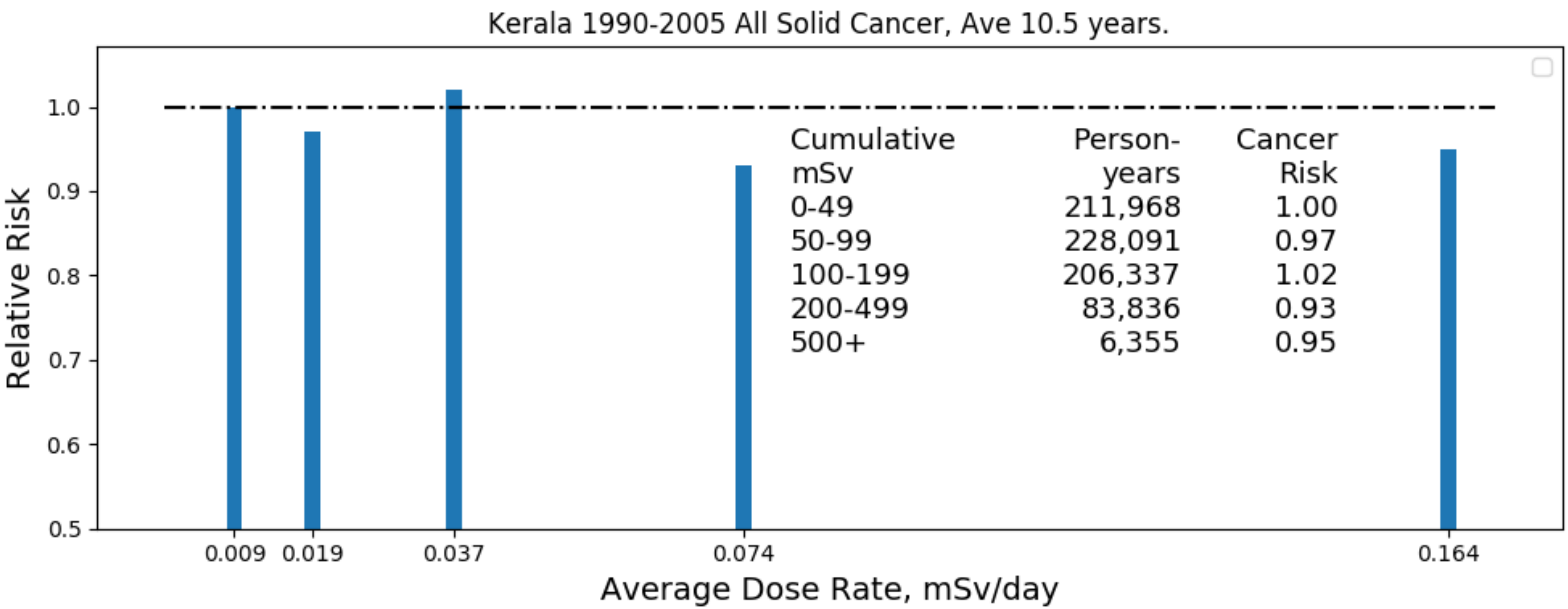
- <u>Natural Background</u> (at sea level): **5** μSv/day
- Cosmic Ray Muons *alone*: **1** μSv/day (at sea level)

- Kerala Coast, India: **9 to164** μSv/day
- Guarapari beach, Brazil: **480** to **1320** μSv/day
- Ramsar region, Iran: up to **712** μSv/day

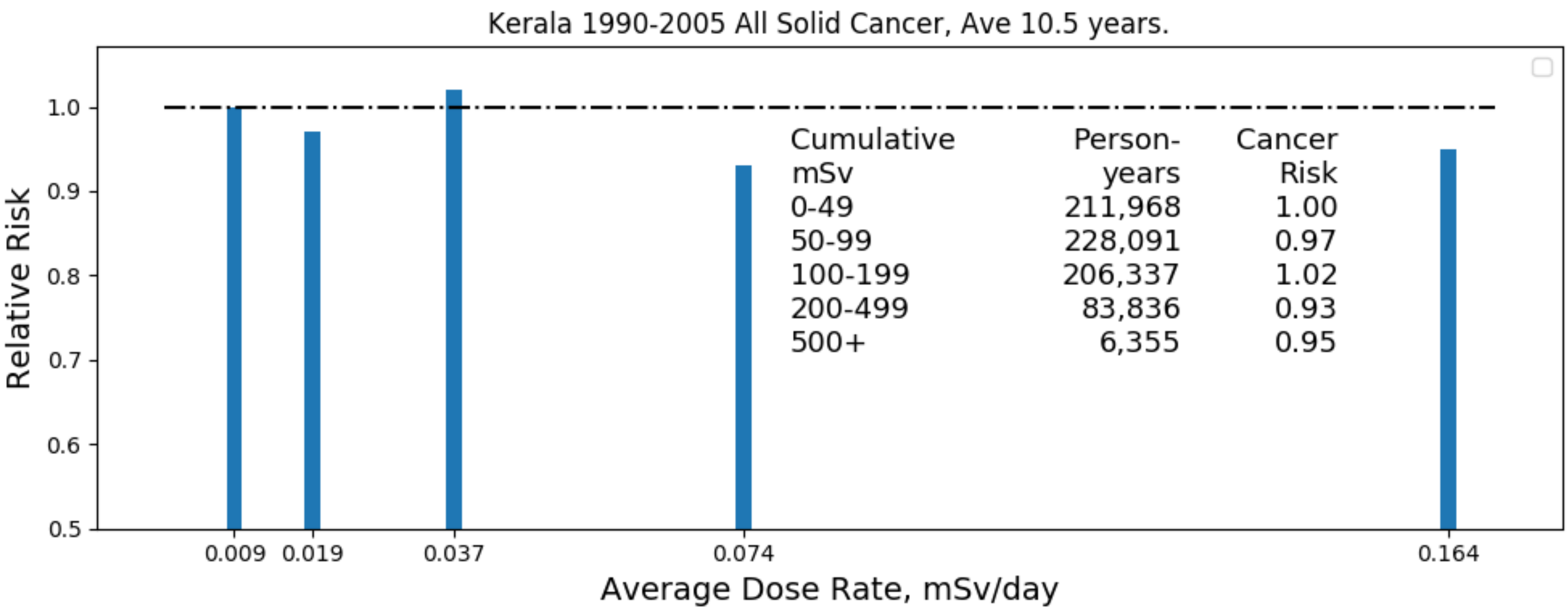
LOWER than average incidence of cancer

- Abdominal/Pelvic CT scan: **20,000-30,000** μSv (*all at once*)

Kerala data


Kerala 1990-2005 All Solid Cancer, Ave 10.5 years.
Relative Risk
1.0
0.9
0.8
0.7
0.6
0.5
Cumulative mSv
Person-years
Cancer Risk
0-49 211,968 1.00
50-99 228,091 0.97
100-199 206,337 1.02
200-499 83,836 0.93
500+ 6,355 0.95
0.009
0.019
0.037
0.074
0.164
Average Dose Rate, mSv/day

Kerala data



The Kerala coast is one of the ***wealthiest*** regions of India.
Health is strongly influenced by **wealth**.
But *wealth* is **not** correlated with *radiation dose*.