Understanding the radioactivity at Fukushima

A physics and engineering perspective

Prof. Ben Monreal
UCSB Department of Physics

Q&A Panel:
Ben Monreal
Prof. Theo Theofanous, UCSB Chem E.
Prof. Patrick McCray, UCSB History

- Introduction to radioactivity
- Radiation hazards and health
- What escapes in a meltdown?
- Where does it go?
- How worried should we be?

Periodic Table of the Elements

Chemistry Reference Sheet

California Standards Test

"Tritium" (hydrogen)

Key

11 — Atomic number
Na — Element symbol
Sodium — Element name
22.99 — Average atomic mass*

	1 1A												13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1	1 **H** Hydrogen 1.01	2 2A																2 **He** Helium 4.00
2	3 **Li** Lithium 6.94	4 **Be** Beryllium 9.01											5 **B** Boron 10.81	6 **C** Carbon 12.01	7 **N** Nitrogen 14.01	8 **O** Oxygen 16.00	9 **F** Fluorine 19.00	10 **Ne** Neon 20.18
3	11 **Na** Sodium 22.99	12 **Mg** Magnesium 24.31	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 **Al** Aluminum 26.98	14 **Si** Silicon 28.09	15 **P** Phosphorus 30.97	16 **S** Sulfur 32.07	17 **Cl** Chlorine 35.45	18 **Ar** Argon 39.95
4	19 **K** Potassium 39.10	20 **Ca** Calcium 40.08	21 **Sc** Scandium 44.96	22 **Ti** Titanium 47.87	23 **V** Vanadium 50.94	24 **Cr** Chromium 52.00	25 **Mn** Manganese 54.94	26 **Fe** Iron 55.85	27 **Co** Cobalt 58.93	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.55	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92	34 **Se** Selenium 78.96	35 **Br** B 79.90	36 **Kr** Krypton 83.80
5	37 **Rb** R 85.47	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.91	40 **Zr** Zirconium 91.22	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.91	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.87	48 **Cd** Cadmium 112.41	49 **In** Indium 114.82	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.76	52 **Te** Telluri 127.6	53 **I** Iodine 126.90	54 **Xe** Xe 131.29
6	55 **Cs** Cesium 132.91	56 **Ba** Ba 137.33	57 **La** Lanthanum 138.91	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.21	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.97	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.38	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98	84 **Po** Polo (20	85 **At**	86 **Rn**
7	87 **Fr**	88 **Ra**	89 **Ac** ium (227)	104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (266)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (269)	109 **Mt** Meitnerium (268)									

Iodine

Cesium

Uranium and Plutonium

58 **Ce** Cerium 140.12	59 **Pr** Praseodymium 140.91	60 **Nd** Neodymium 14	61 **Pm** Promethium (145)	62 **Sm** Samariu	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04	n	71 **Lu** Lutetium 174.97
90 **Th** Thorium 232.04	91 **Pa** Protac ium 231. 4	92 **U** Uranium 238.03	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	95 **Am** Amer um (24)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)		103 **Lr** Lawrencium (262)

* If this number is in parentheses, then it refers to the atomic mass of the most stable isotope.

Different elements

Boron		B7 1.4 MeV (3/2-)	B8 770 ms 2+ EC2α	B9 0.54 keV 3/2- 2pα	B10 3+ 19.9	B11 3/2- 80.1	B12 20.20 ms 1+ β-3α
Beryllium	Be5	Be6 92 keV 0+ 2p	Be7 53.29 d 3/2- EC	Be8 6.8 eV 0+ 2α	Be9 3/2- 100	Be10 1.51E+6 y 0+ β-	Be11 13.81 s 1/2+ β-α
Lithium	Li4 2-	Li5 1.5 MeV 3/2- p	Li6 1+ 7.5	Li7 3/2- 92.5	Li8 838 ms 2+ β-2α	Li9 178.3 ms 3/2- β-n	Li10 1.2 MeV n
Helium	He3 1/2+ 0.000137	He4 0+ 99.999863	He5 0.60 MeV 3/2- n	He6 806.7 ms 0+ β-	He7 160 keV (3/2)- n	He8 119.0 ms 0+ β-n	He9 0.30 MeV (1/2-) n
Hydrogen	H1 1/2+ 99.985	H2 1+ 0.015	H3 12.33 y 1/2+ β-	H4 2-	H5	H6	6
	n1 614.8 s 1/2+ β-	2		4			

Different isotopes

http://nndc.lbl.gov

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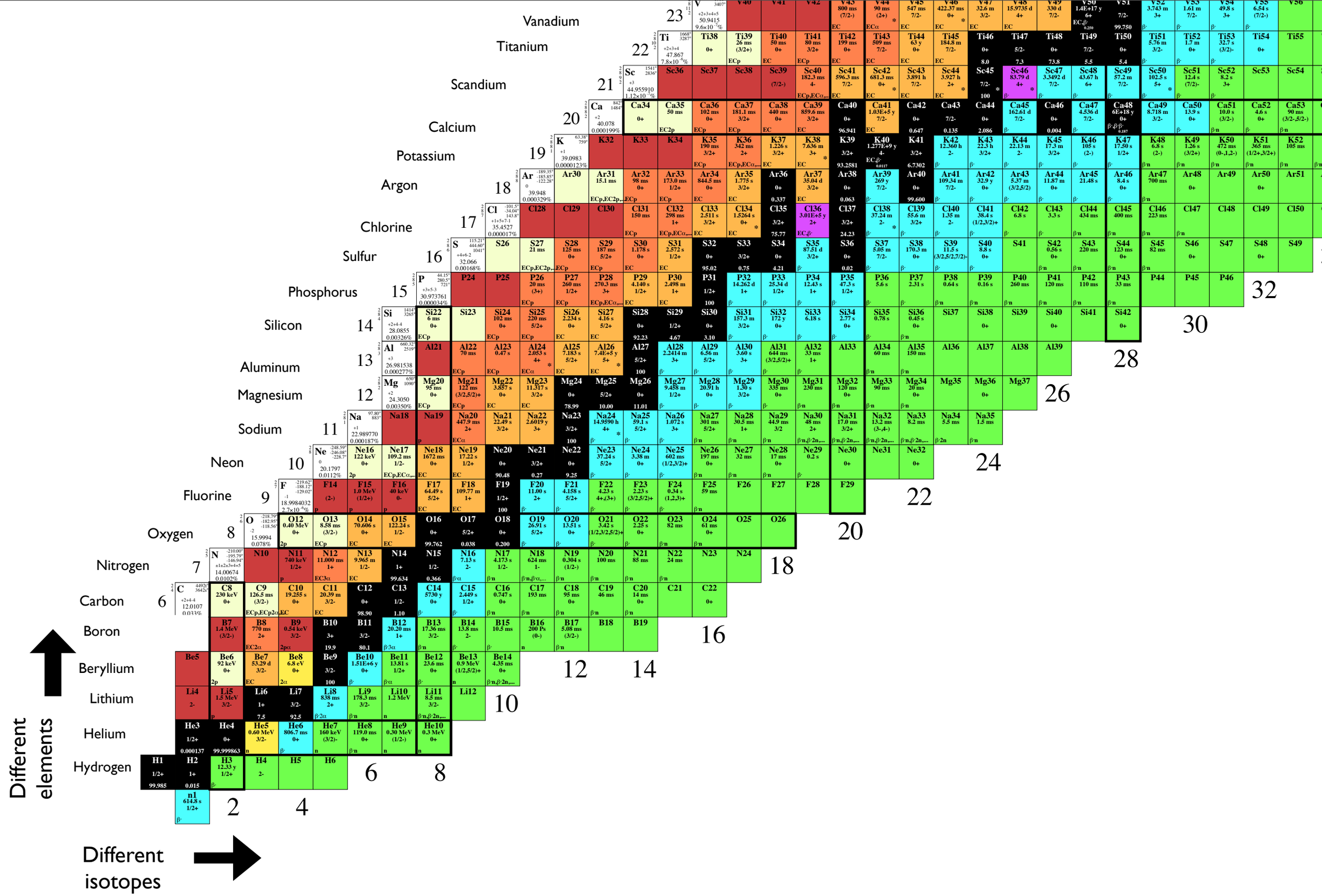
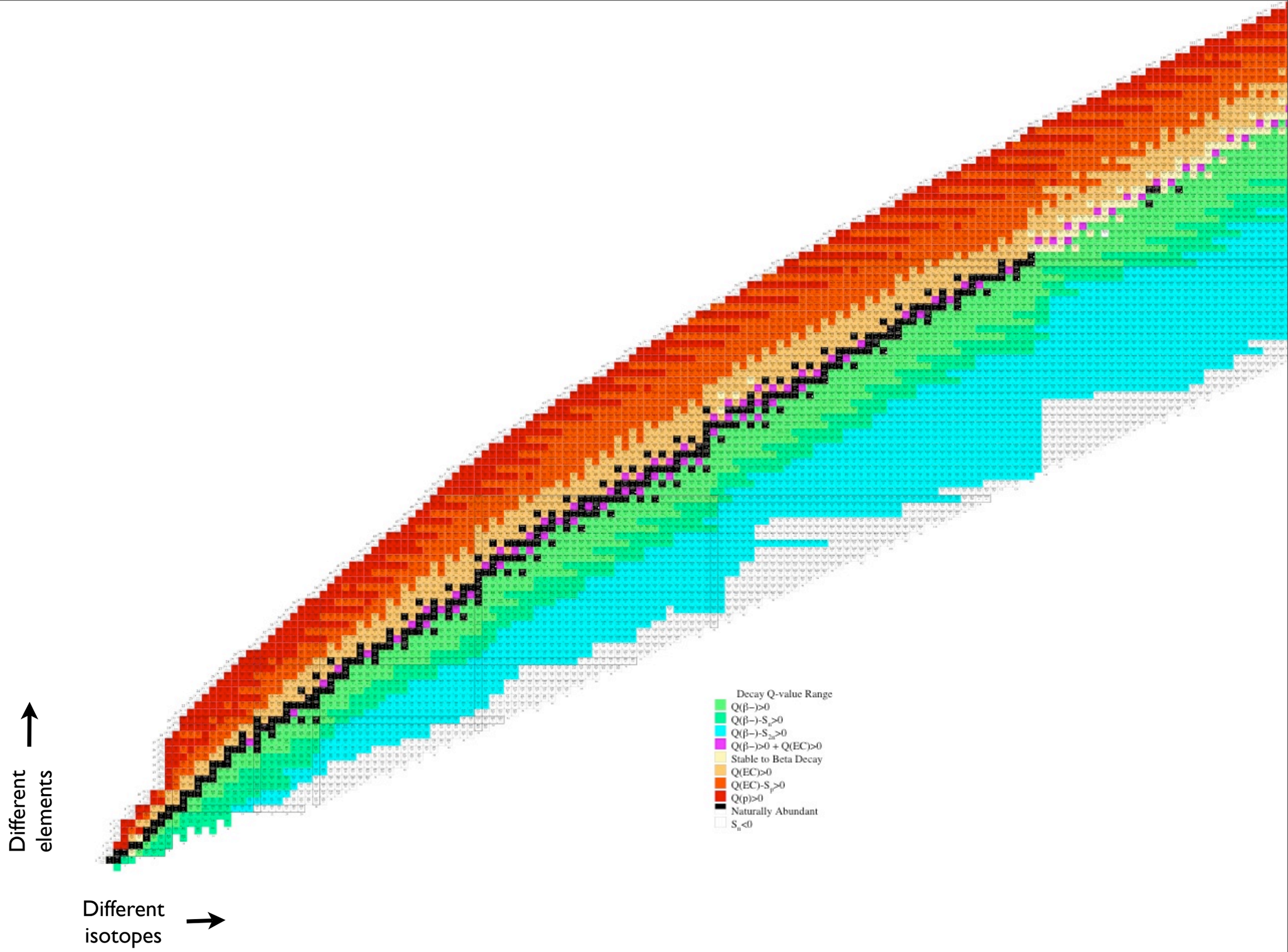


Ben Monreal, UCSB Physics 3/11


Decay Q-value Range
Q(β−)>0
Q(β−)-S_n>0
Q(β−)-S_2n>0
Q(β−)>0 + Q(EC)>0
Stable to Beta Decay
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Naturally Abundant
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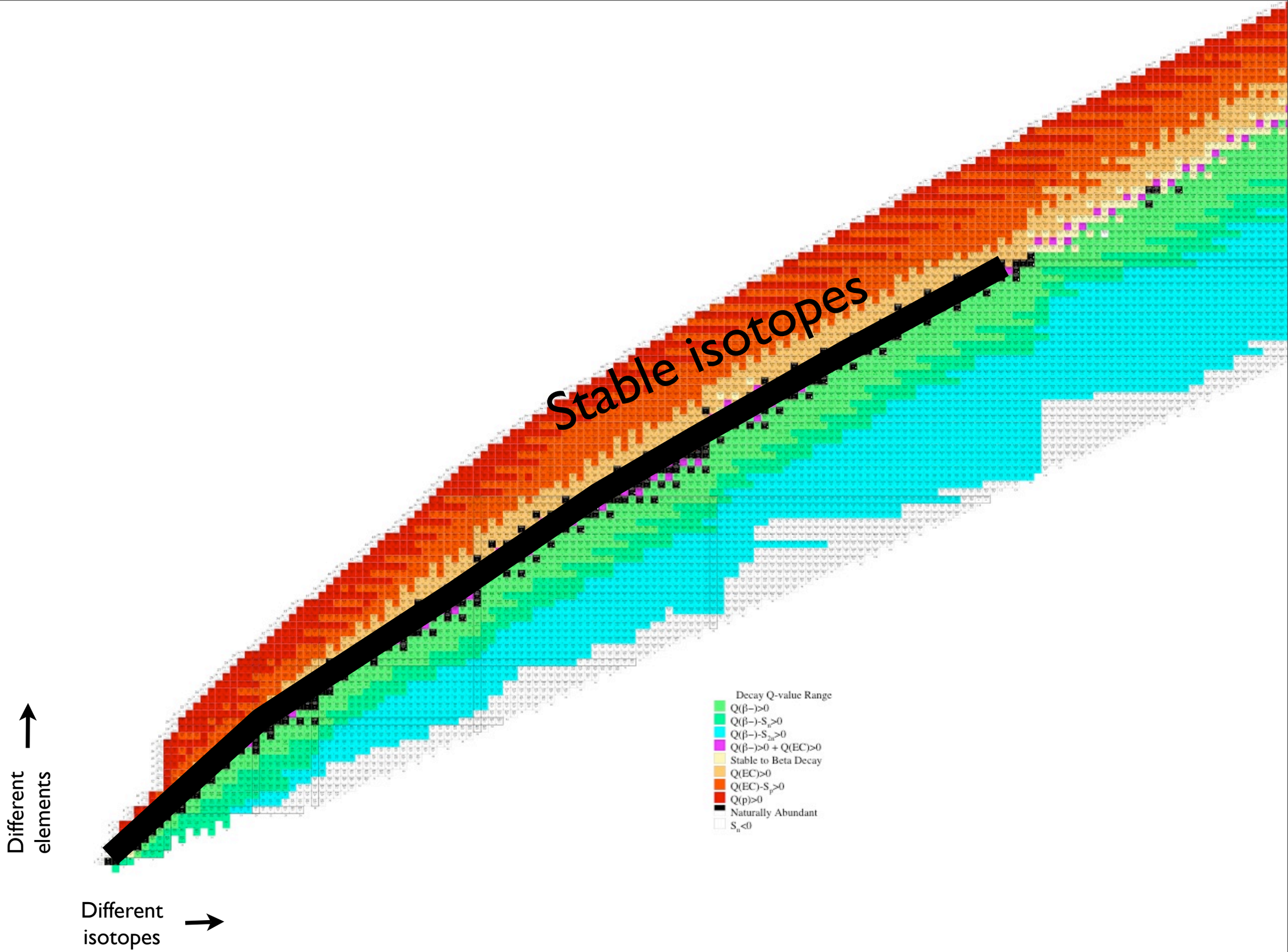
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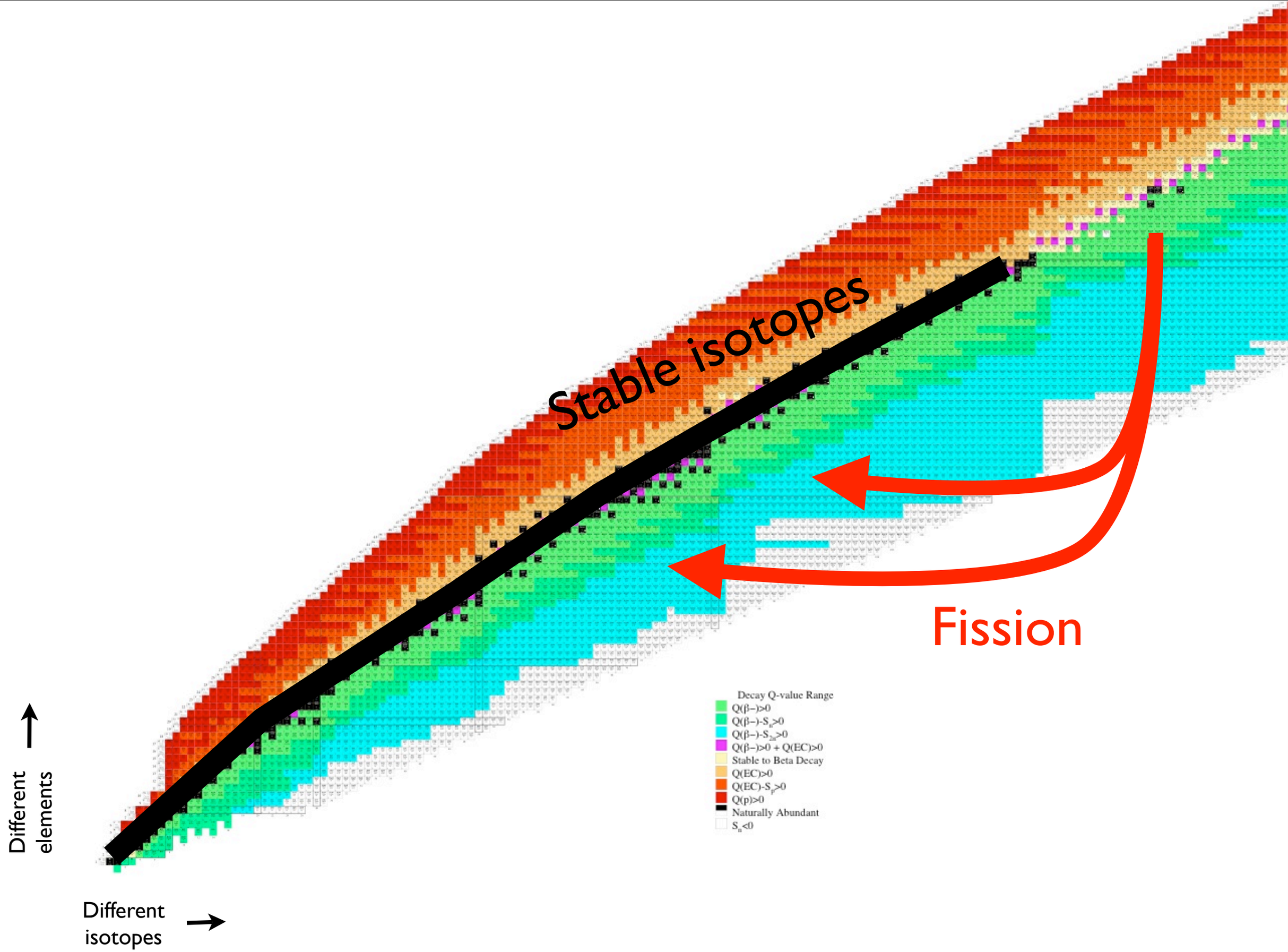
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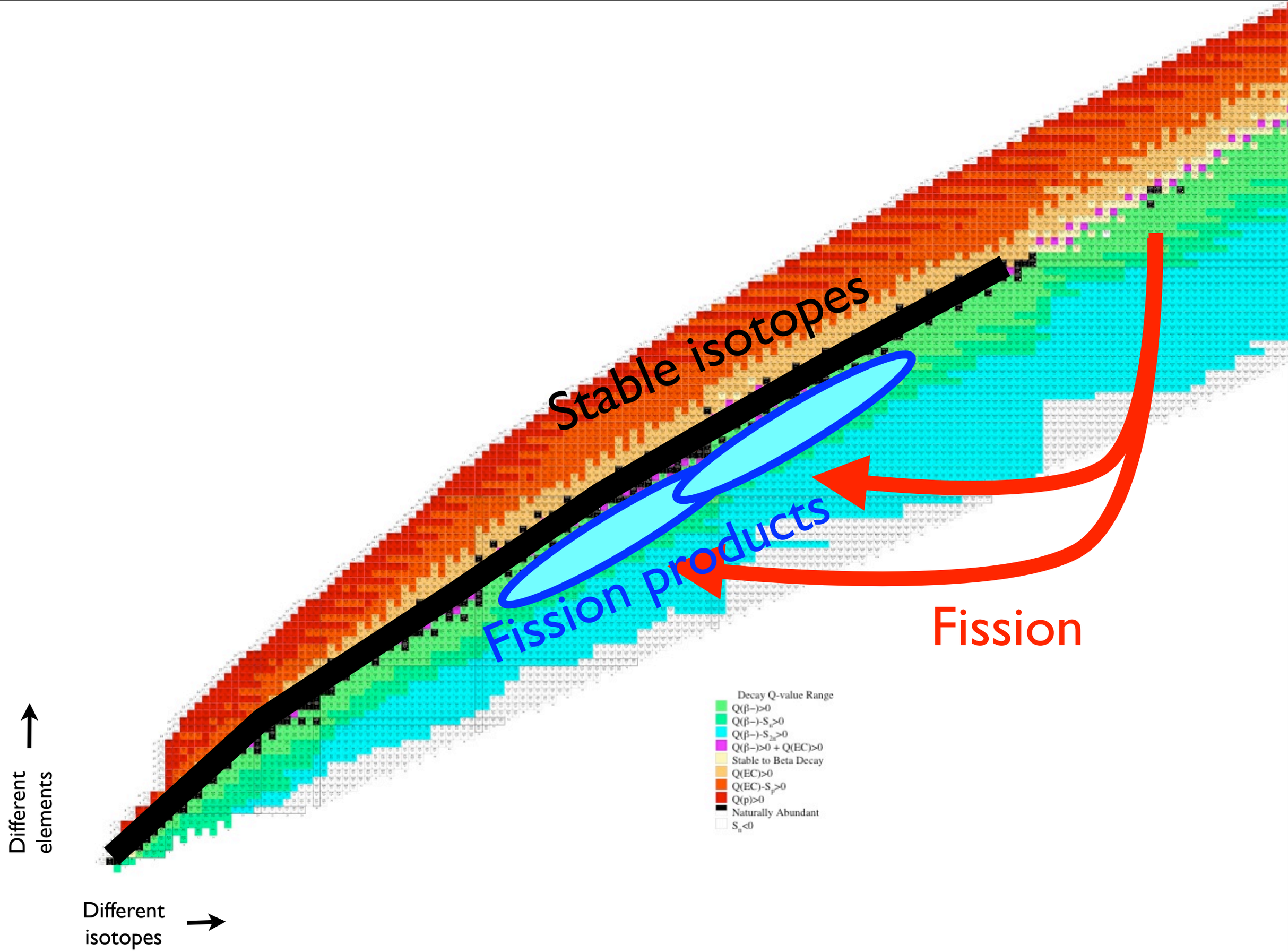
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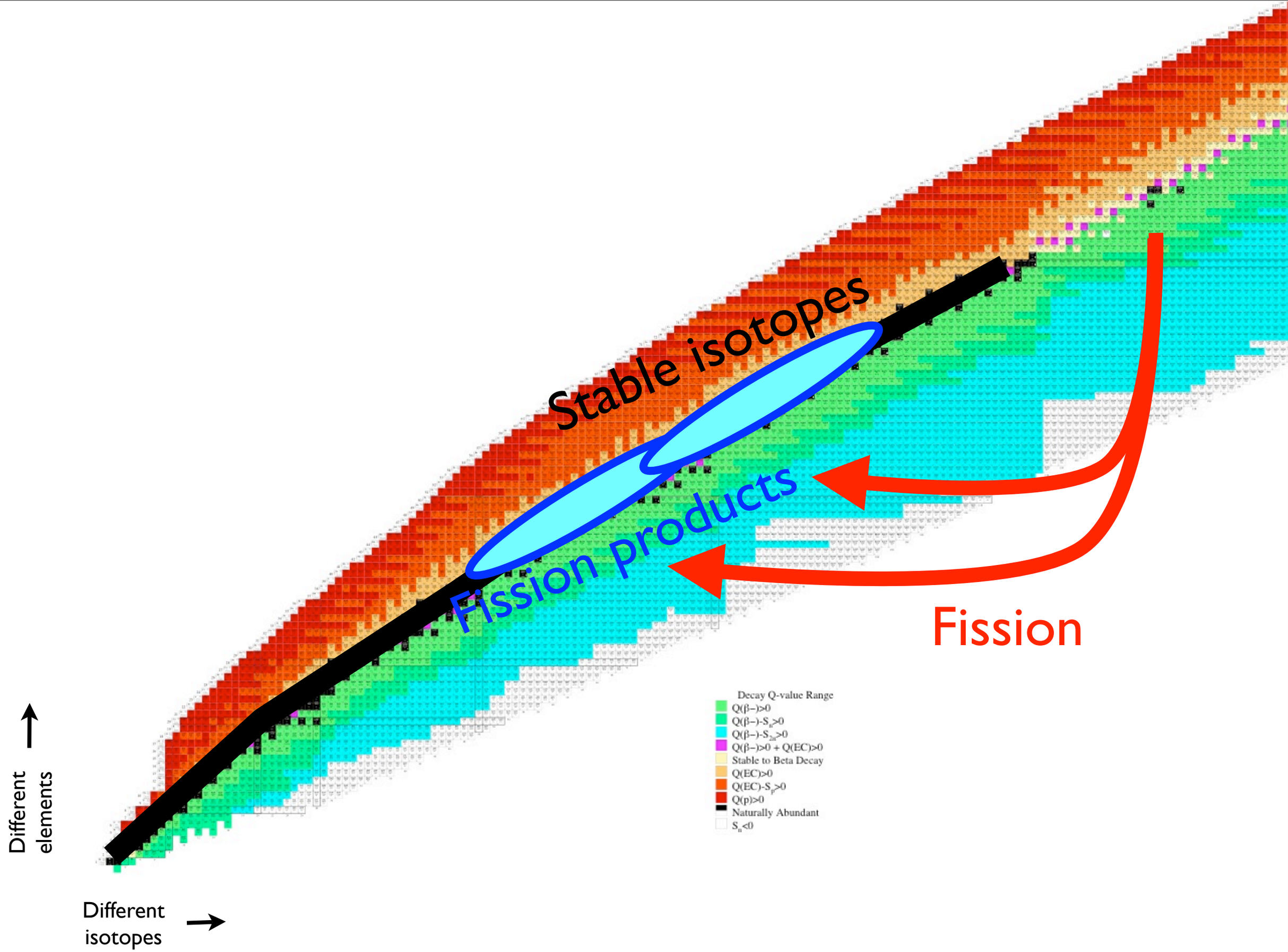
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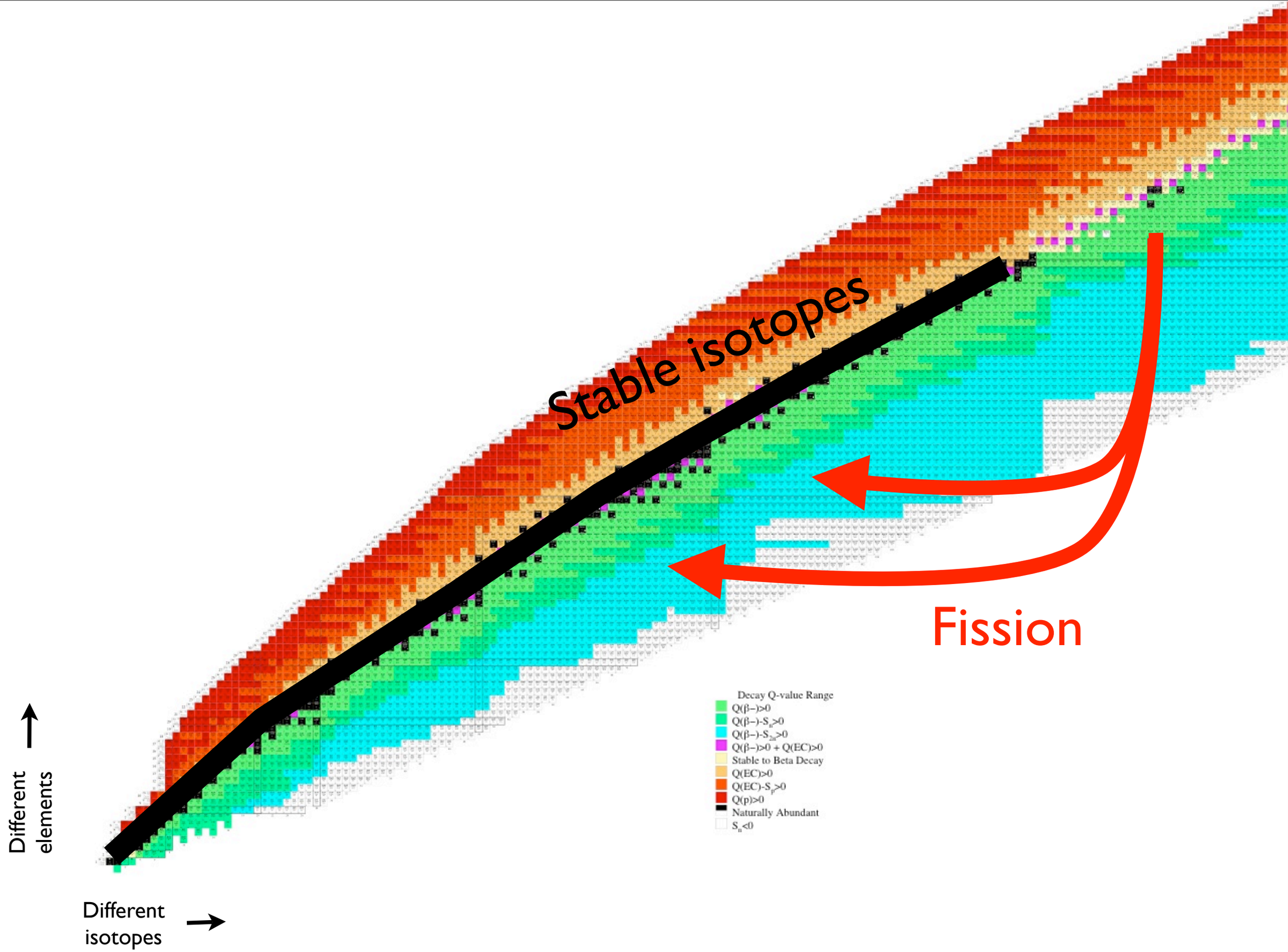
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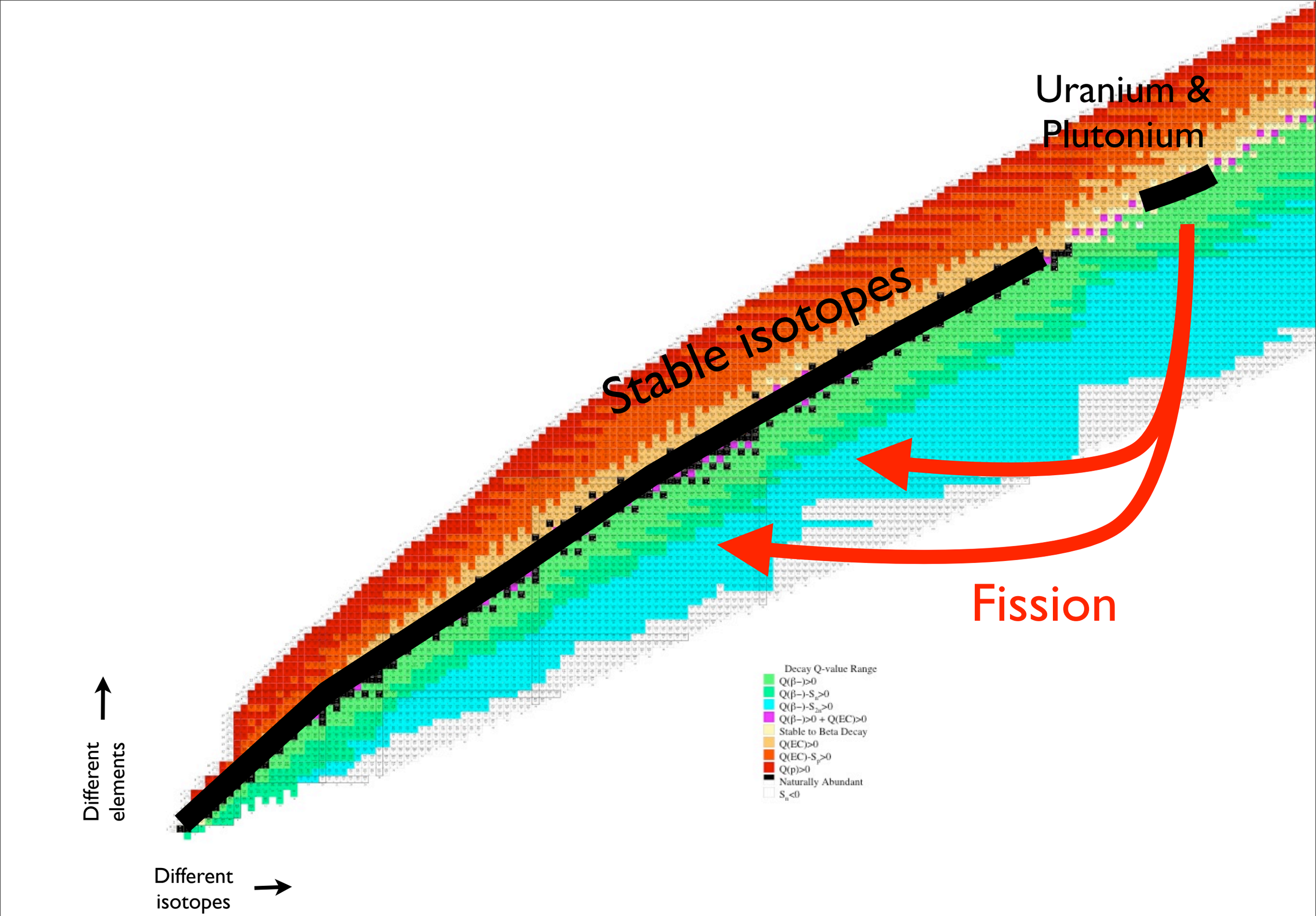
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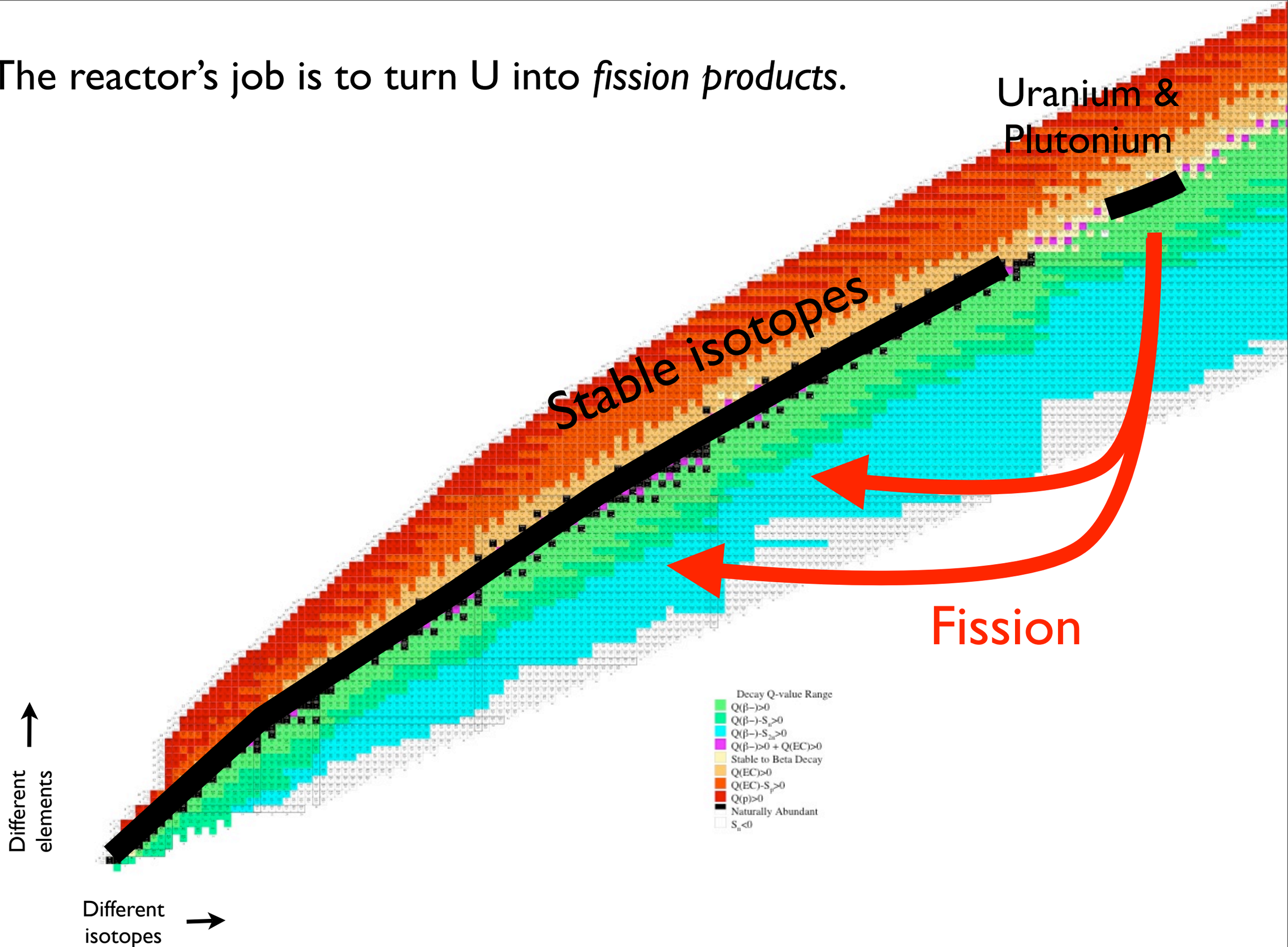
The reactor's job is to turn U into *fission products*.



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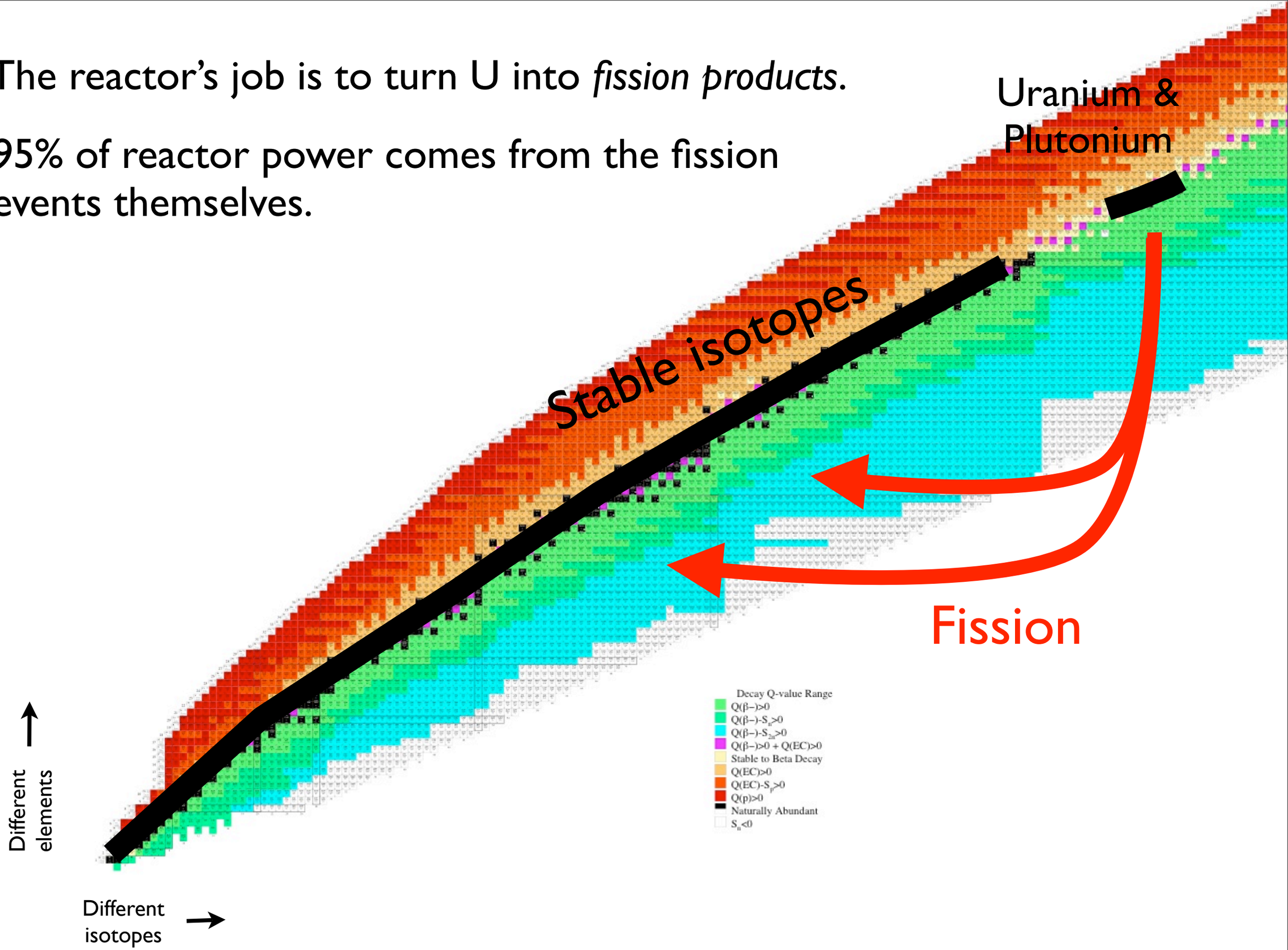

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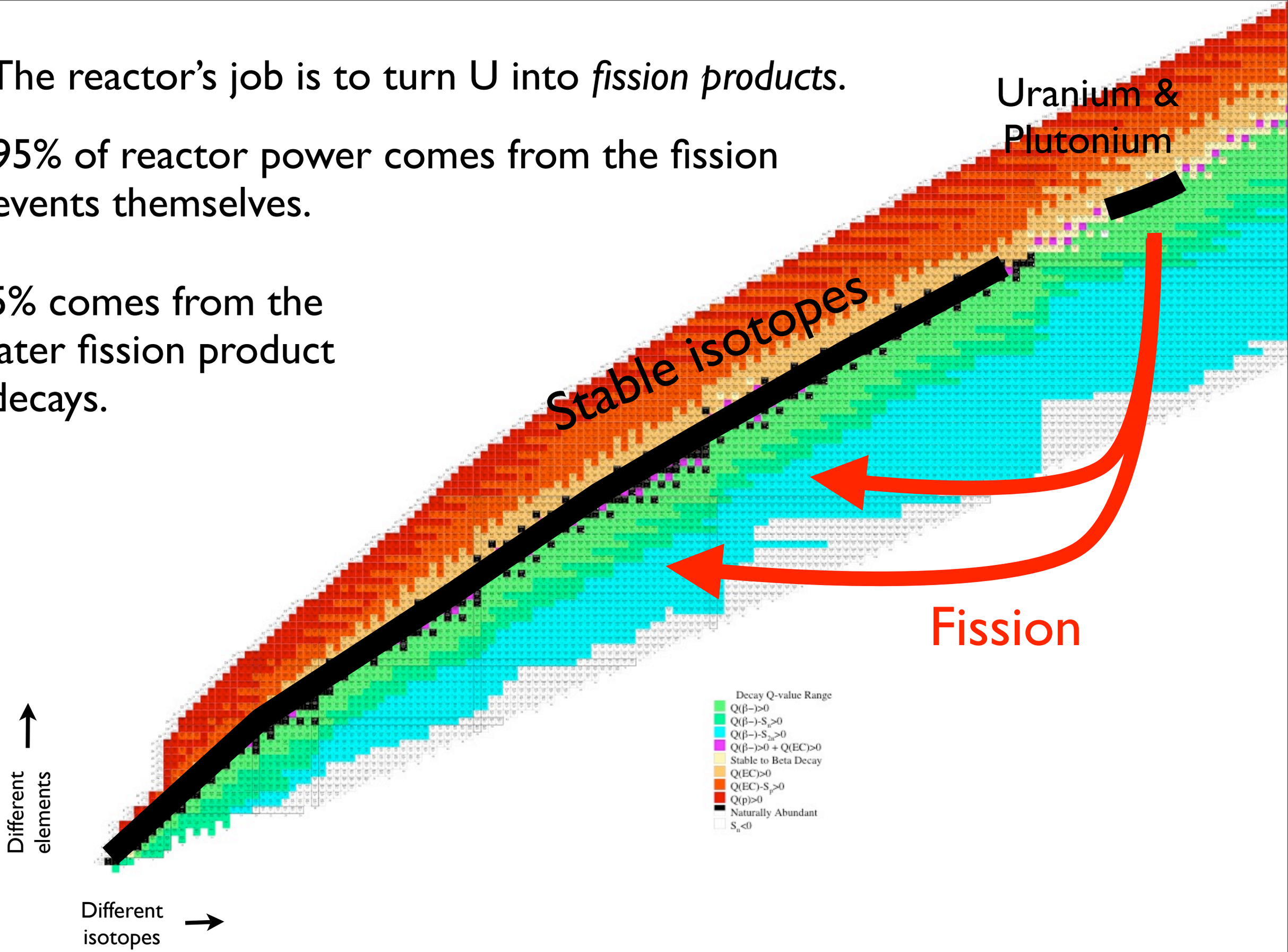

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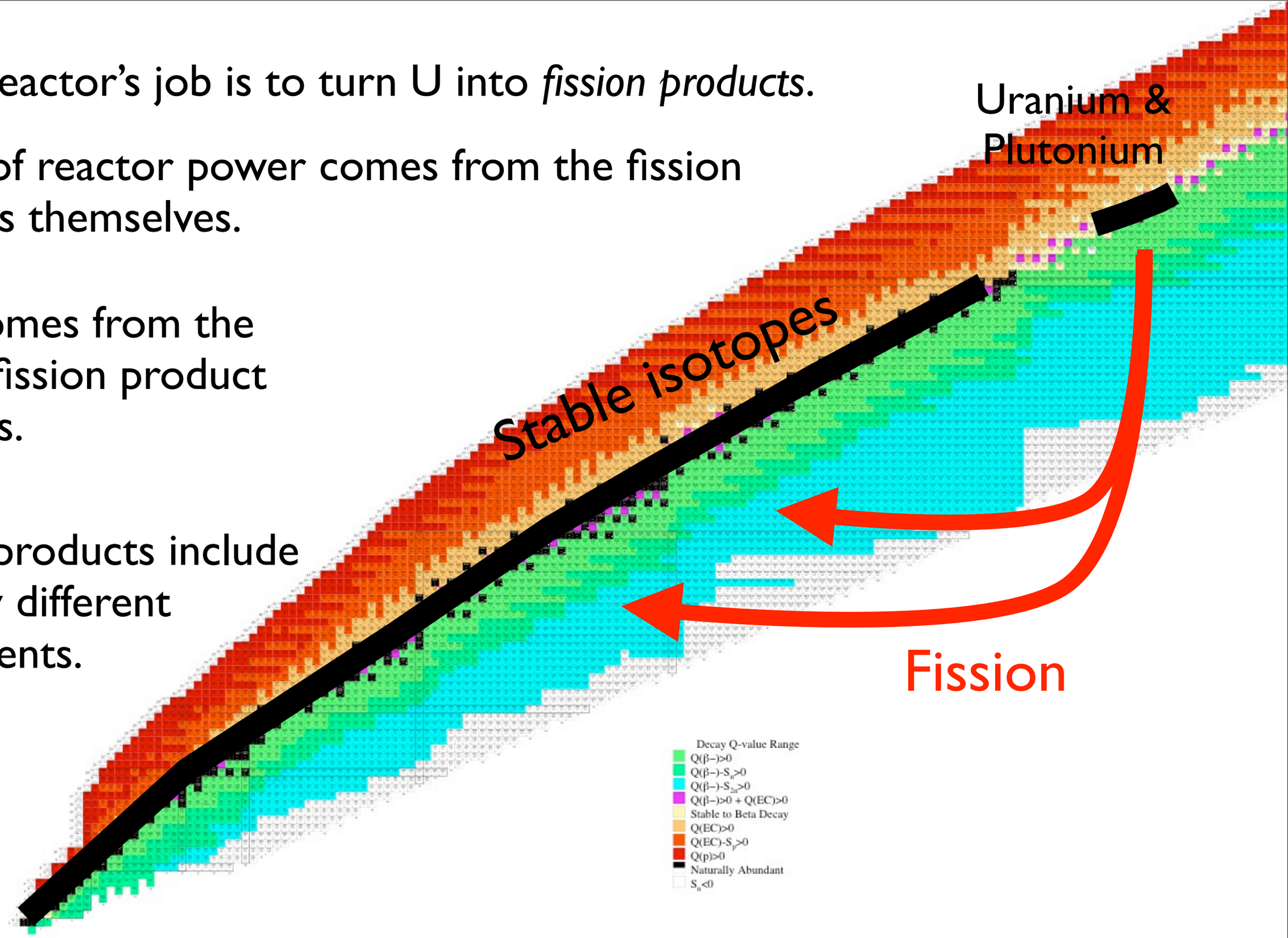
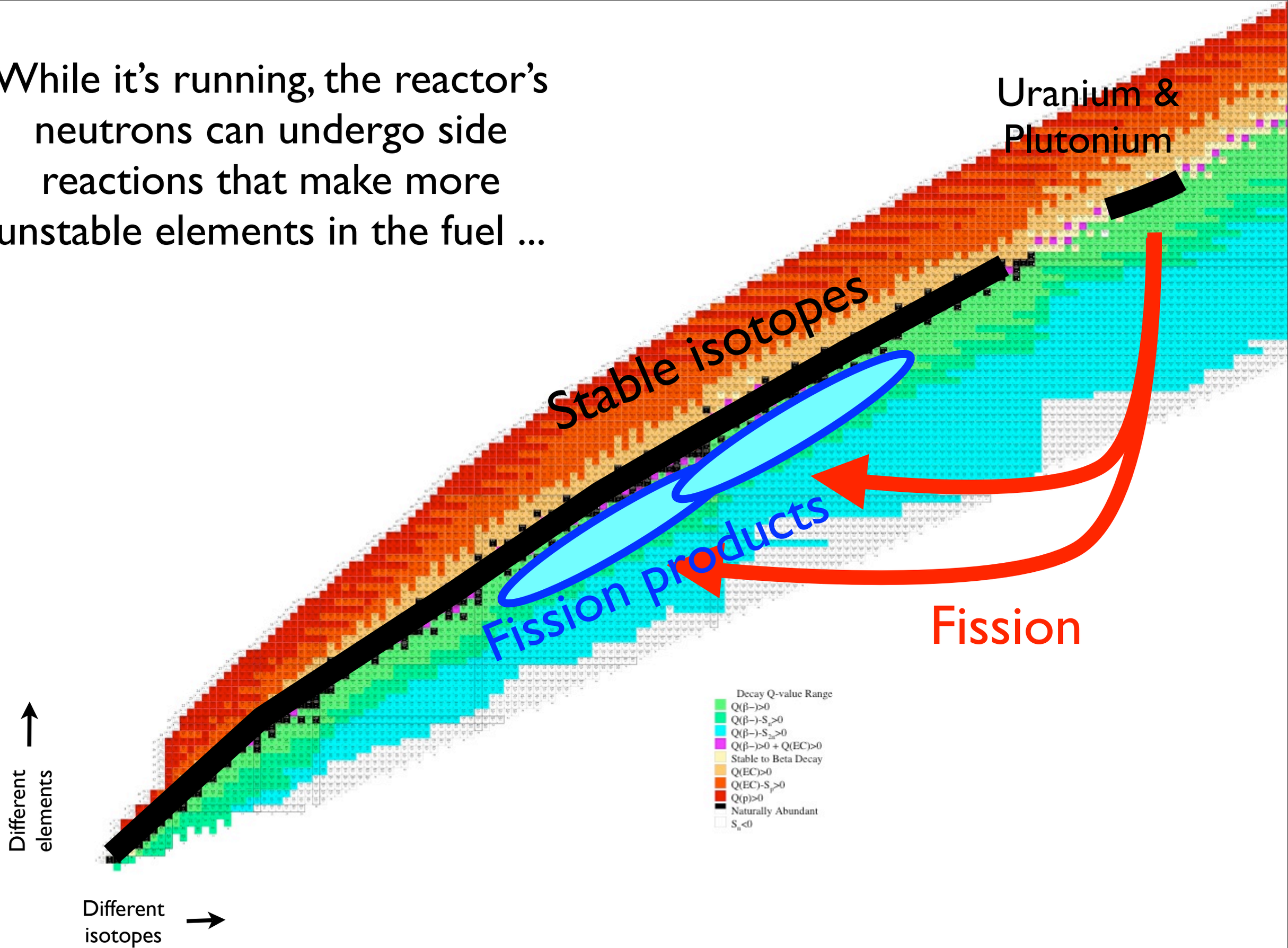
The products include many different elements.



While it's running, the reactor's neutrons can undergo side reactions that make more unstable elements in the fuel ...



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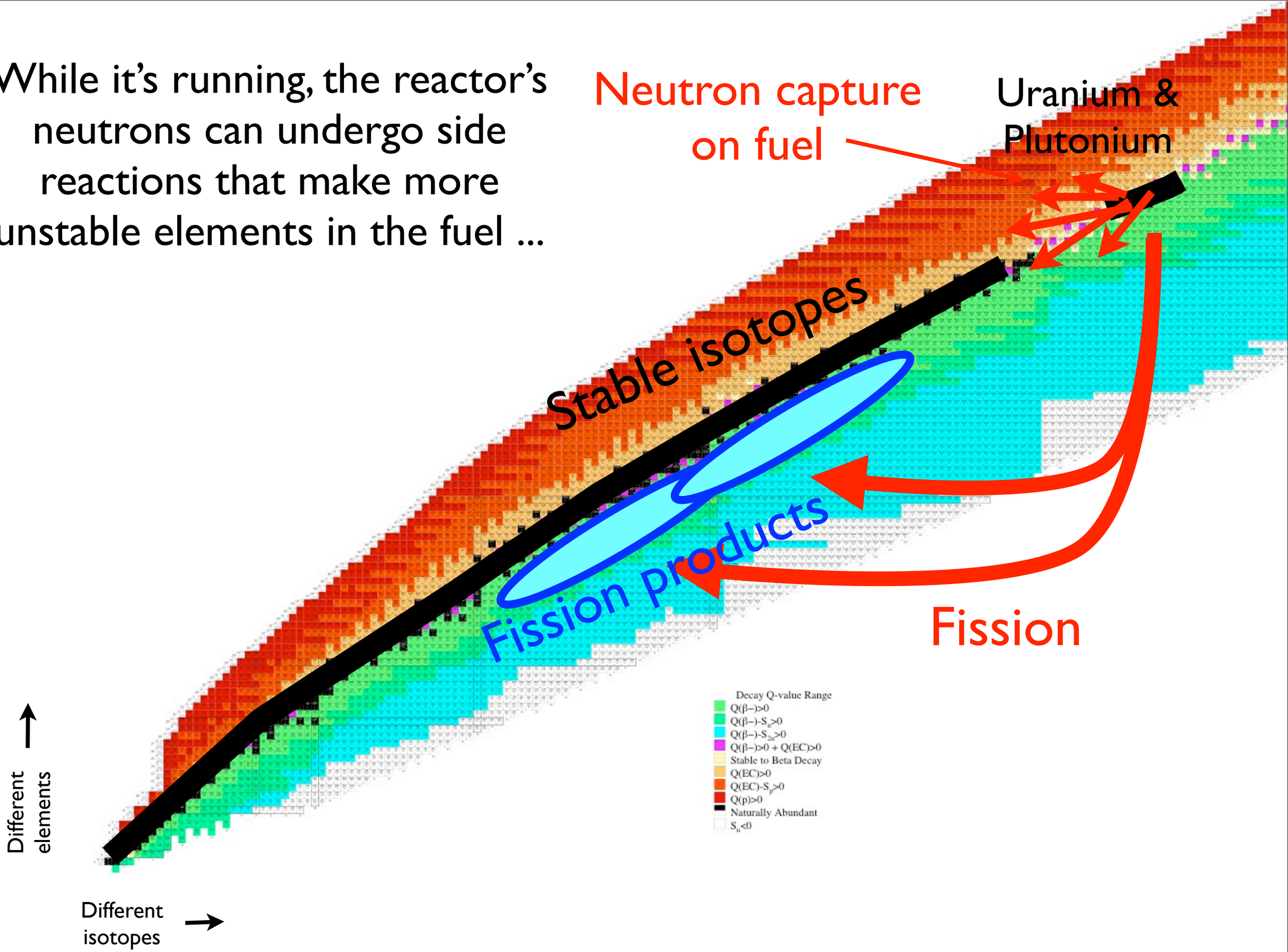

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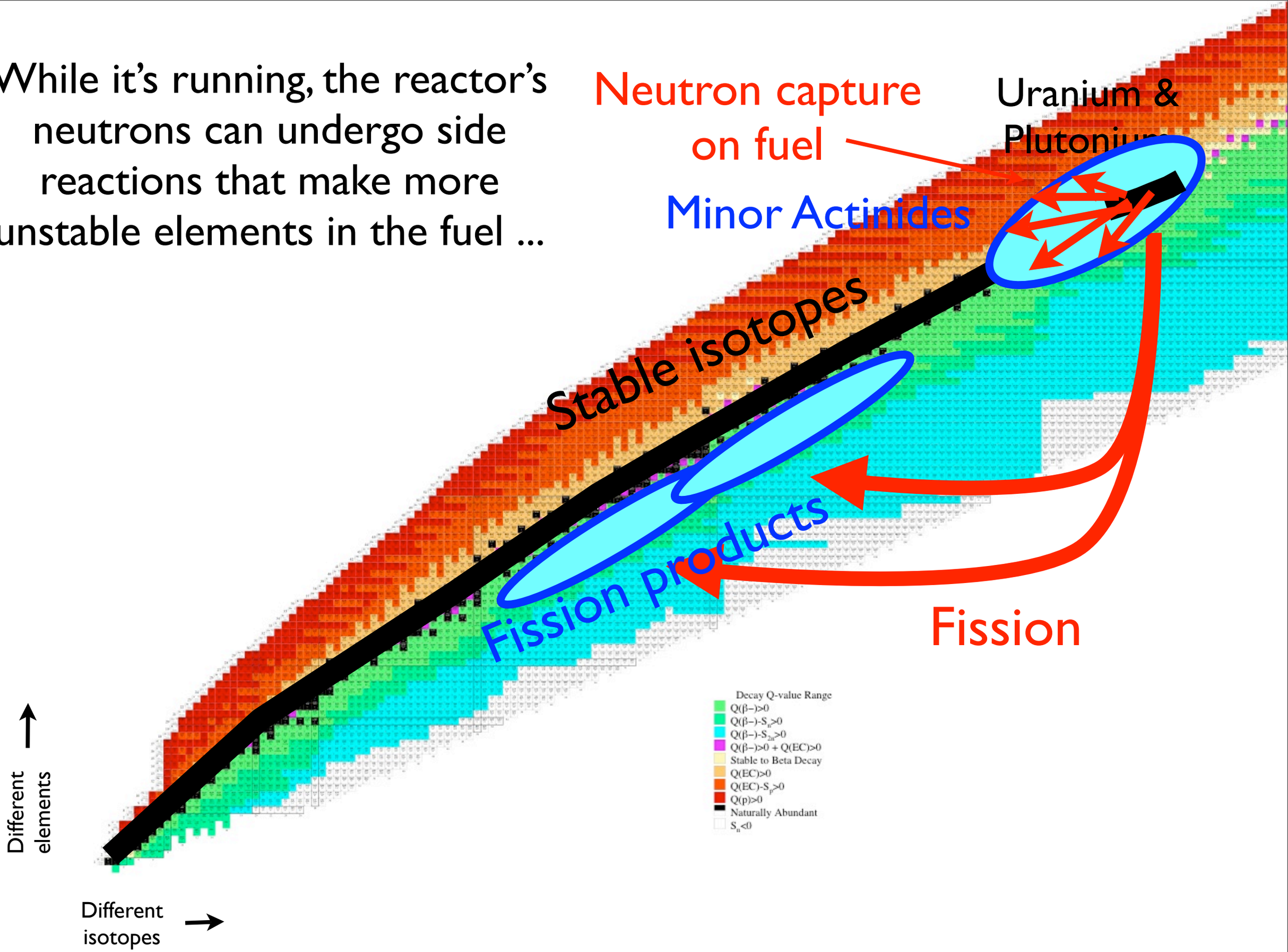

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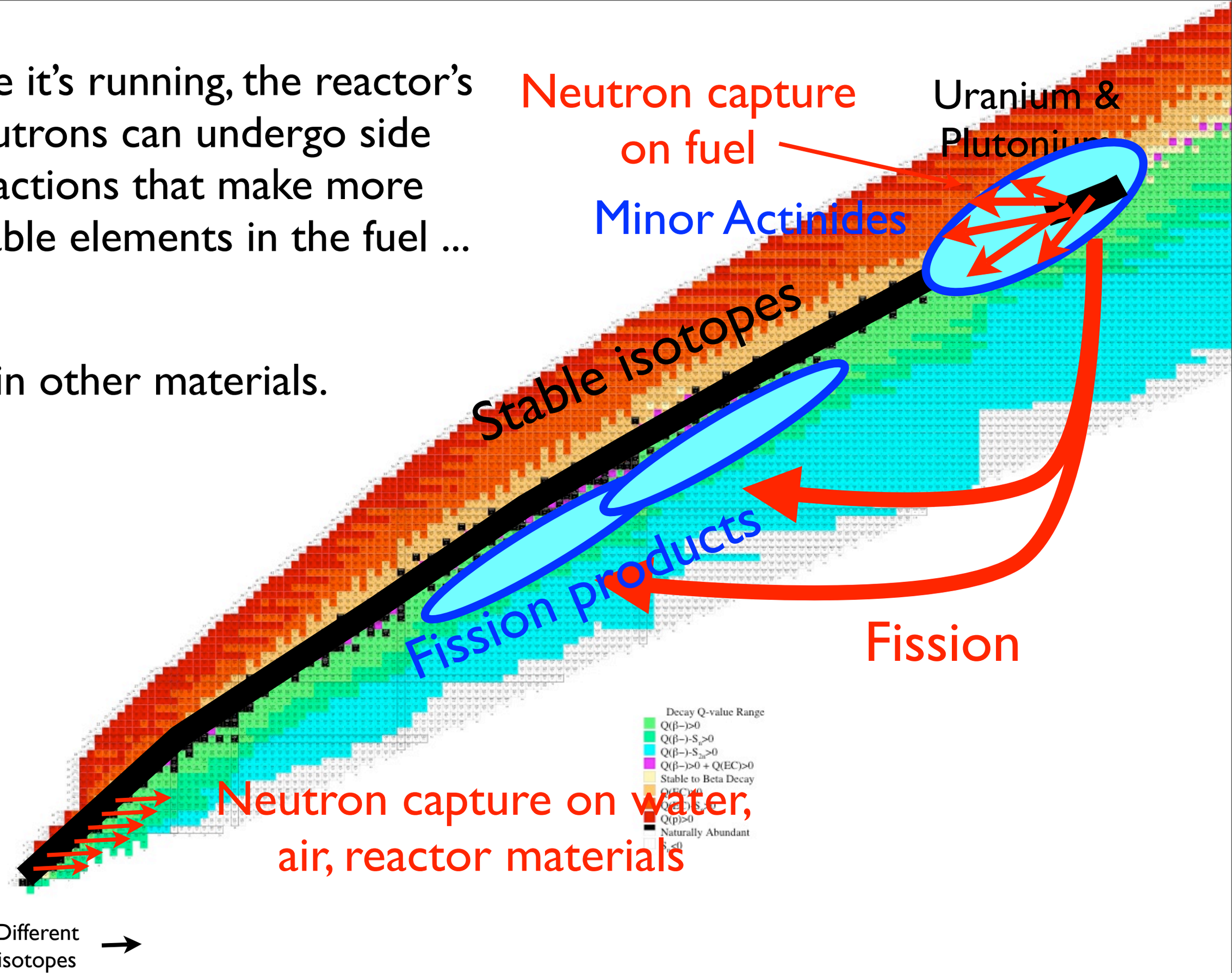

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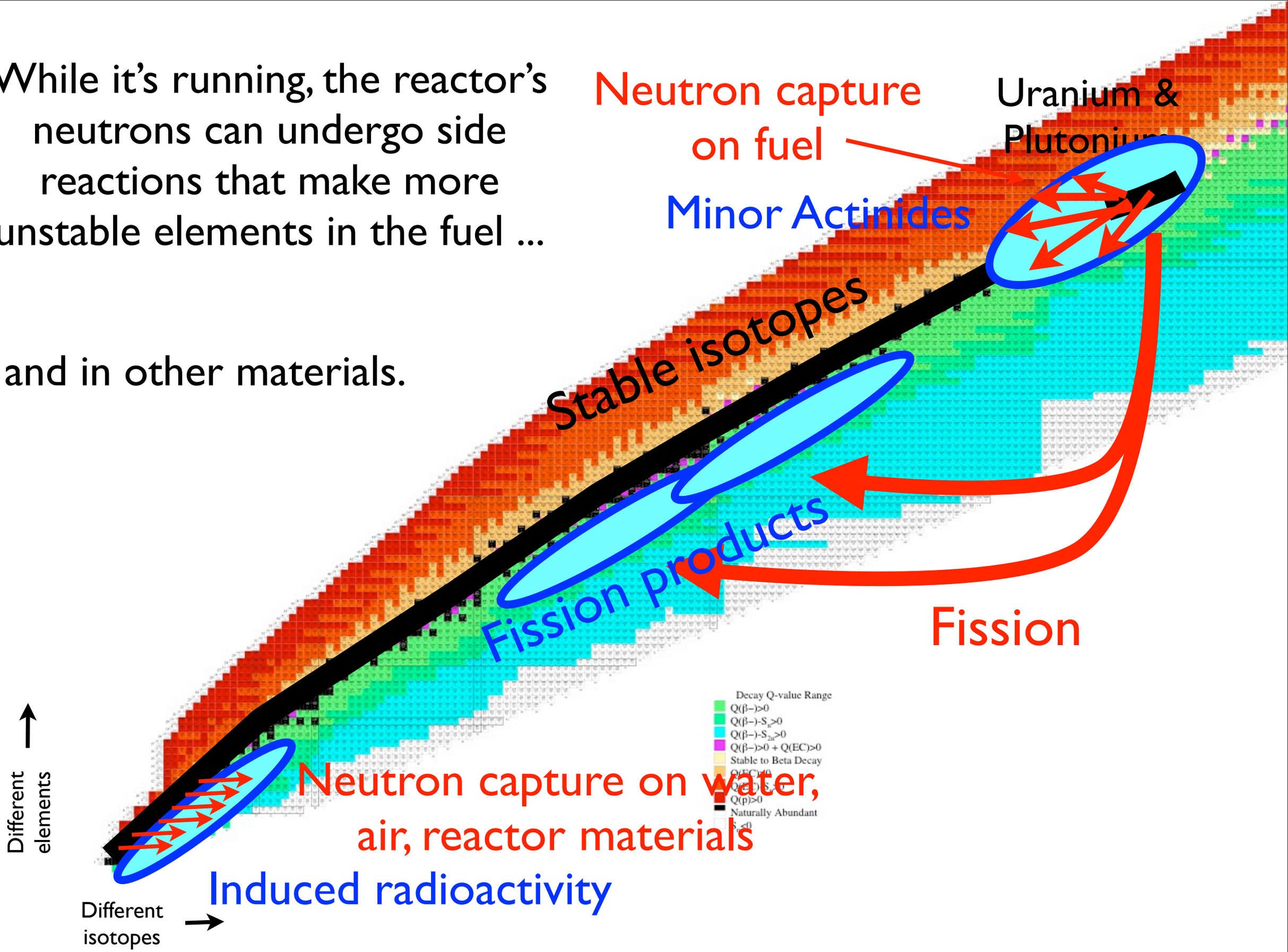
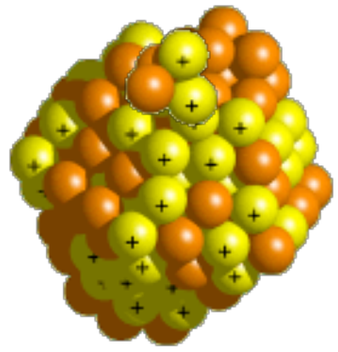


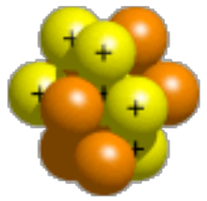
Radiation damage

Alpha decay: common in minor actinides (damages every 10th atom it passes.)



^{222}Rn

Beta & gamma decay: fission products (damages every 3000th atom it passes.)



^{14}C

Radiation damage

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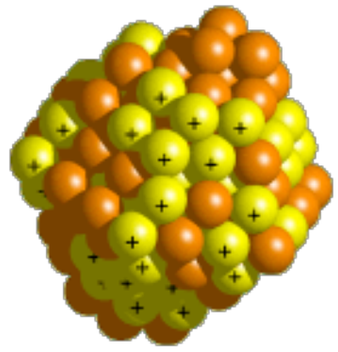

$^{222}Rn \rightarrow {}^{218}Po + {}^{4}He$

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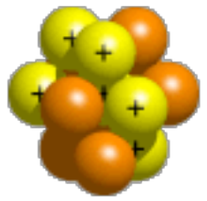

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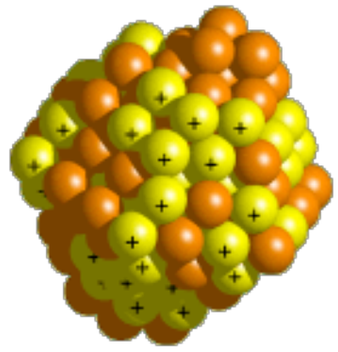

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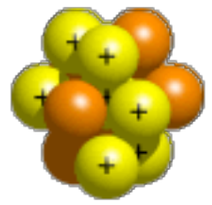


$^{14}C \rightarrow {}^{14}N + e^{-} + \nu$

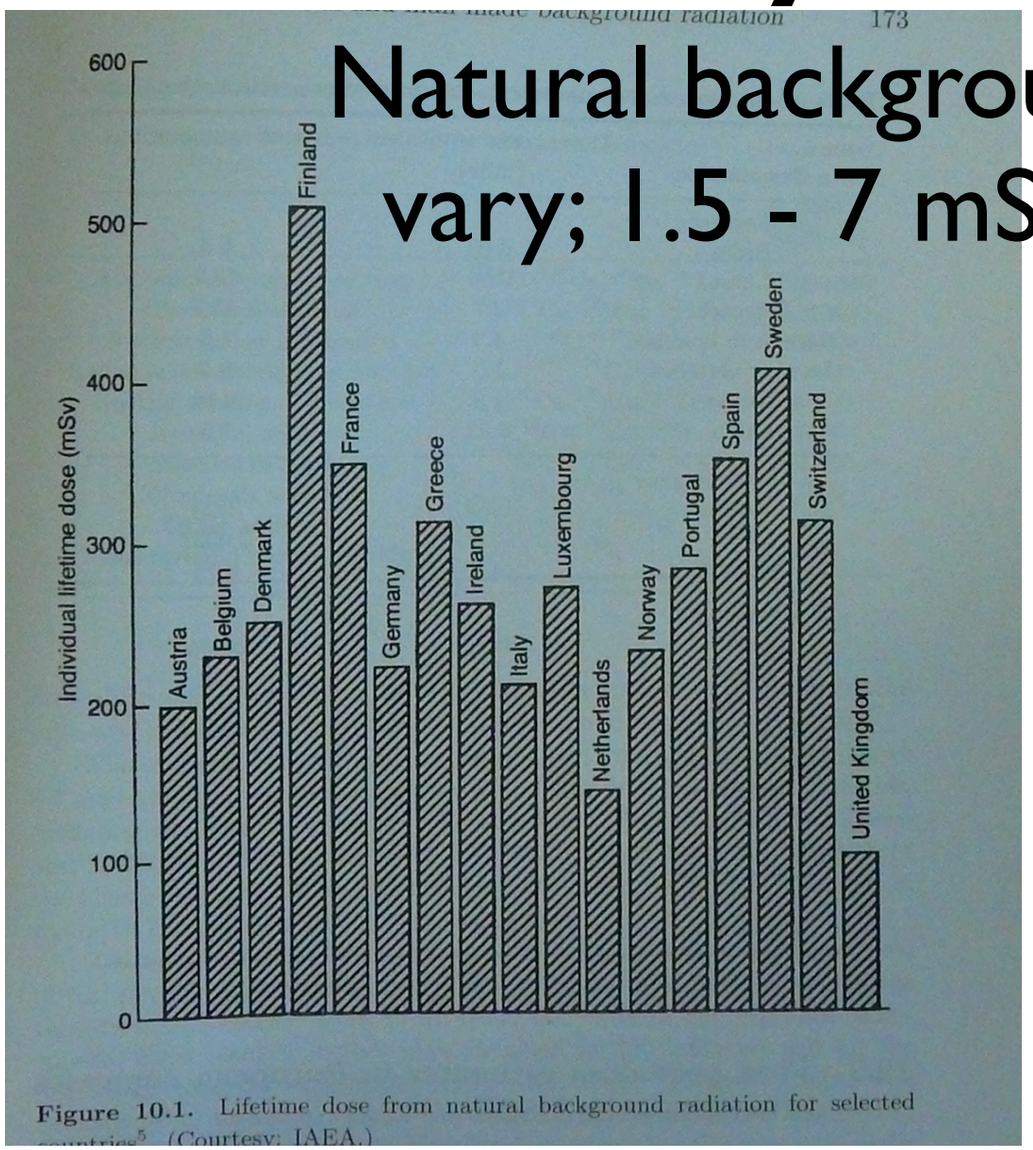
How much damage?

- One **becquerel** = 1 decay per second
- One **curie** = 37 billion decays per second.
  - A measure of amount, as in "There are 20 million curies of ^{137}Cs in the fuel pond"
- One **gray** = absorbing 1 billion ^{238}U decays, or 10 billion ^{137}Cs decays, per gram of body mass
- One **sievert** = absorbing 0.05B ^{238}U decays, or 10B of ^{137}Cs, per gram of body mass
  - A measure of "dose" = fraction of body's chemical bonds damaged.

For fission products, gray = sievert

Radiation numeracy

- You are all getting irradiated right now.
  - natural ^{40}K in your body: ~0.2 mSv/yr.
  - natural ^{222}Rn in the air: ~1 mSv/yr.
- Moving to Denver? Add ~1 mSv/yr.
- Are you a flight attendant? Add ~few mSv/yr.



Lesson: *a few milliSieverts dose is not worth worrying about at all. (but mSv/h rate can add up.)*

"Chernobyl Record" R.F. Mould, IOP 2000

Radiation and cancer

Ionization ≈ DNA damage *(rarely)*

DNA damage ≈ changed cells *(rarely)*

changed cells ≈ cancer *(rarely)*

Type of cancer	Extra cases per 10000 people with 1000mSv doses
Leukemia	3
Breast	7
Thyroid	1.6
Lung	4
Stomach	5
Colon	2

Lesson: *1 Sv = 1000 mSv is a risk you would go out of your way to avoid, like texting while driving.*

From John D. Boice, Natl. Cancer Institute
in "Health Effects from Exposure to Low-Level Ionizing Radiation", IOP 1996

Acute radiation sickness

Lesson: *>5 Sv = run for your life*

- *Extraordinarily rare.*
  - "Slotin Incident": 21 Sv, victim died 9 d later
  - "Daghlian incident": 5 Sv, victim died 1 month later
  - Goiania accident: 5 Sv/hr medical source got loose. 4 dead (all > 5 Sv), 15 hospitalized (all betwen 0.5 and 5 Sv).
  - Chernobyl first-responders: dose rates of 10 Sv/hr in many areas; 30 dead, 200 hospitalized
  - Many victims of Hiroshima and Nagasaki

Units in the news

The New York Times

Last Defense at Troubled Reactors: 50 Japanese Workers

Radiation close to the reactors was reported to reach 400 millisieverts per hour on Tuesday after a blast inside reactor No. 2 and fire at reactor No. 4, but has since dropped back to as low as 0.6 millisieverts at the plant gate.

← we know 5000 mSv = fatal

so 400 mSv/hr for would be fatal

if you had 5000/400 = 12 hours

0.6 mSv per hour

1000 mSv = texting while driving

1000/0.6 = two months

wnn world nuclear news

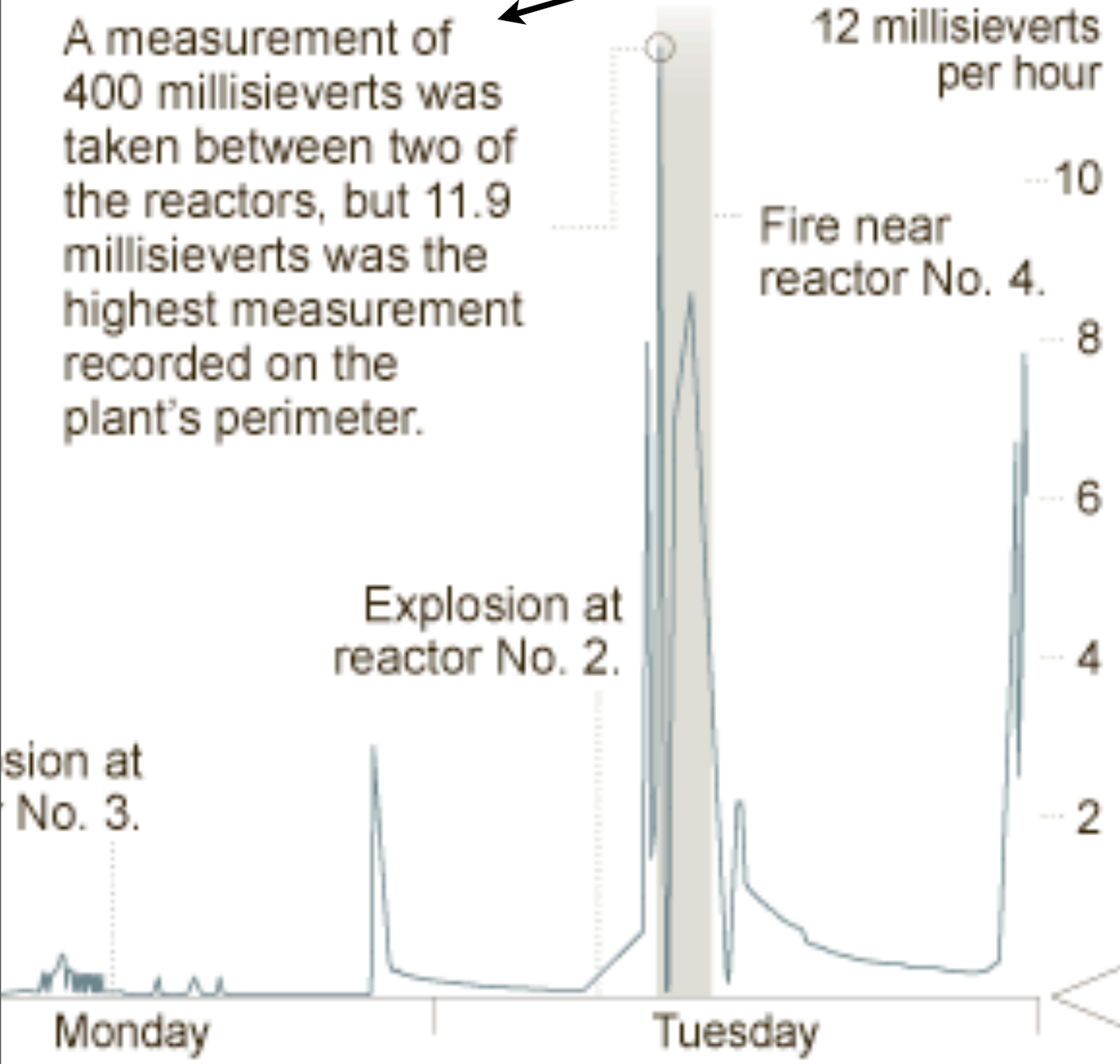
Radiation levels on the edge of the plant compound briefly spiked at 8217 microsieverts per hour but later fell to about a third that.

← 8000 μSv/hr = 8 mSv/hr

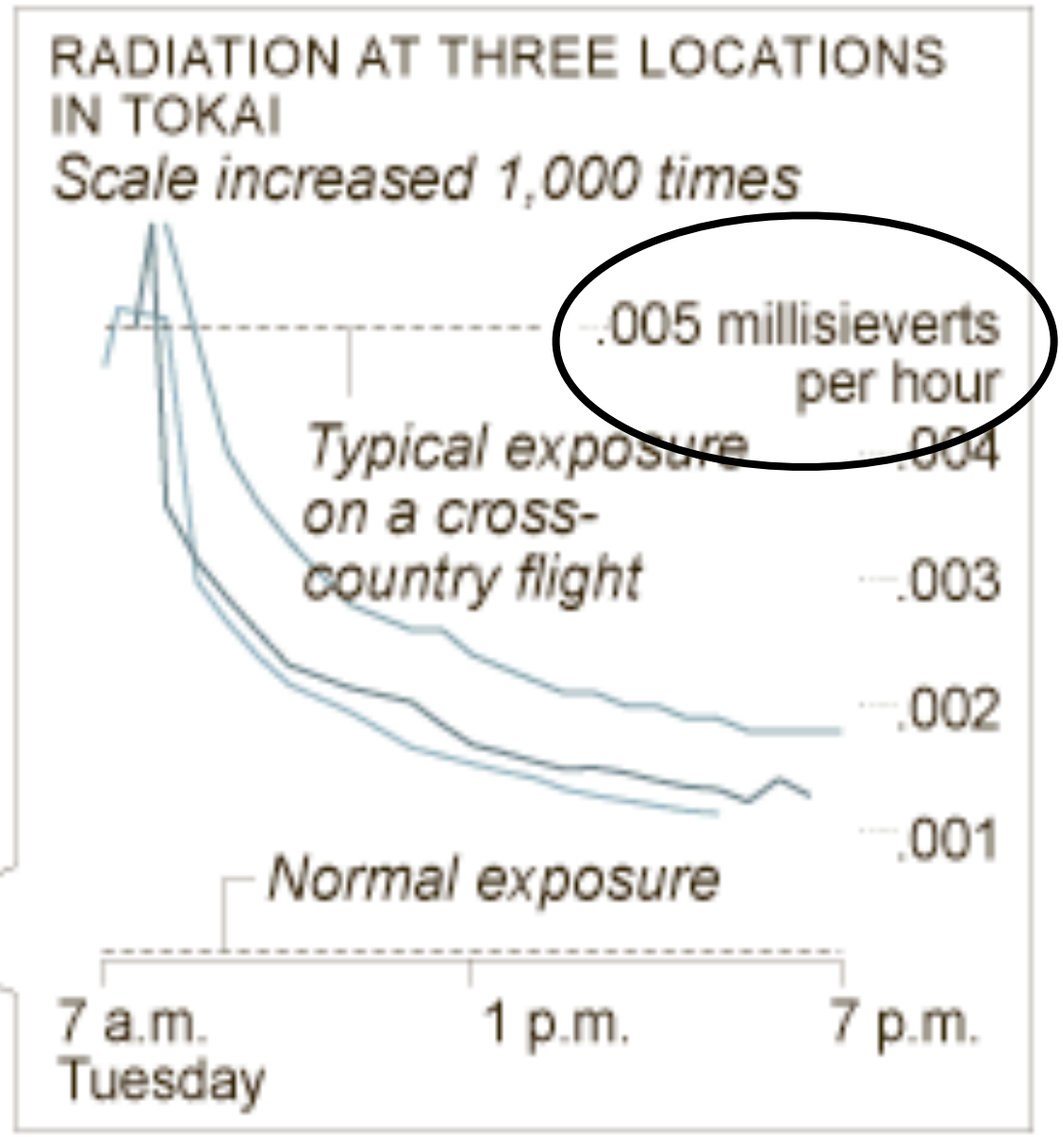
They meant "millisieverts *per hour*"

NYTimes.com

A measurement of 400 millisieverts was taken between two of the reactors, but 11.9 millisieverts was the highest measurement recorded on the plant's perimeter.

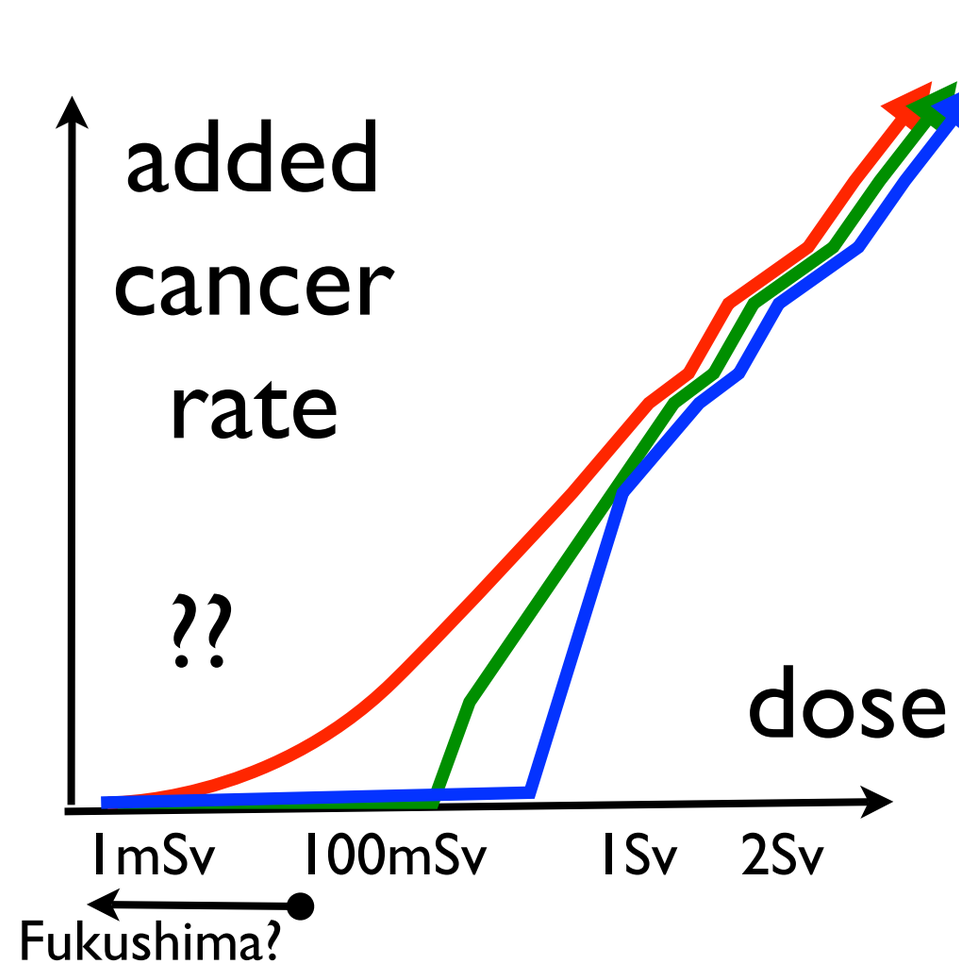


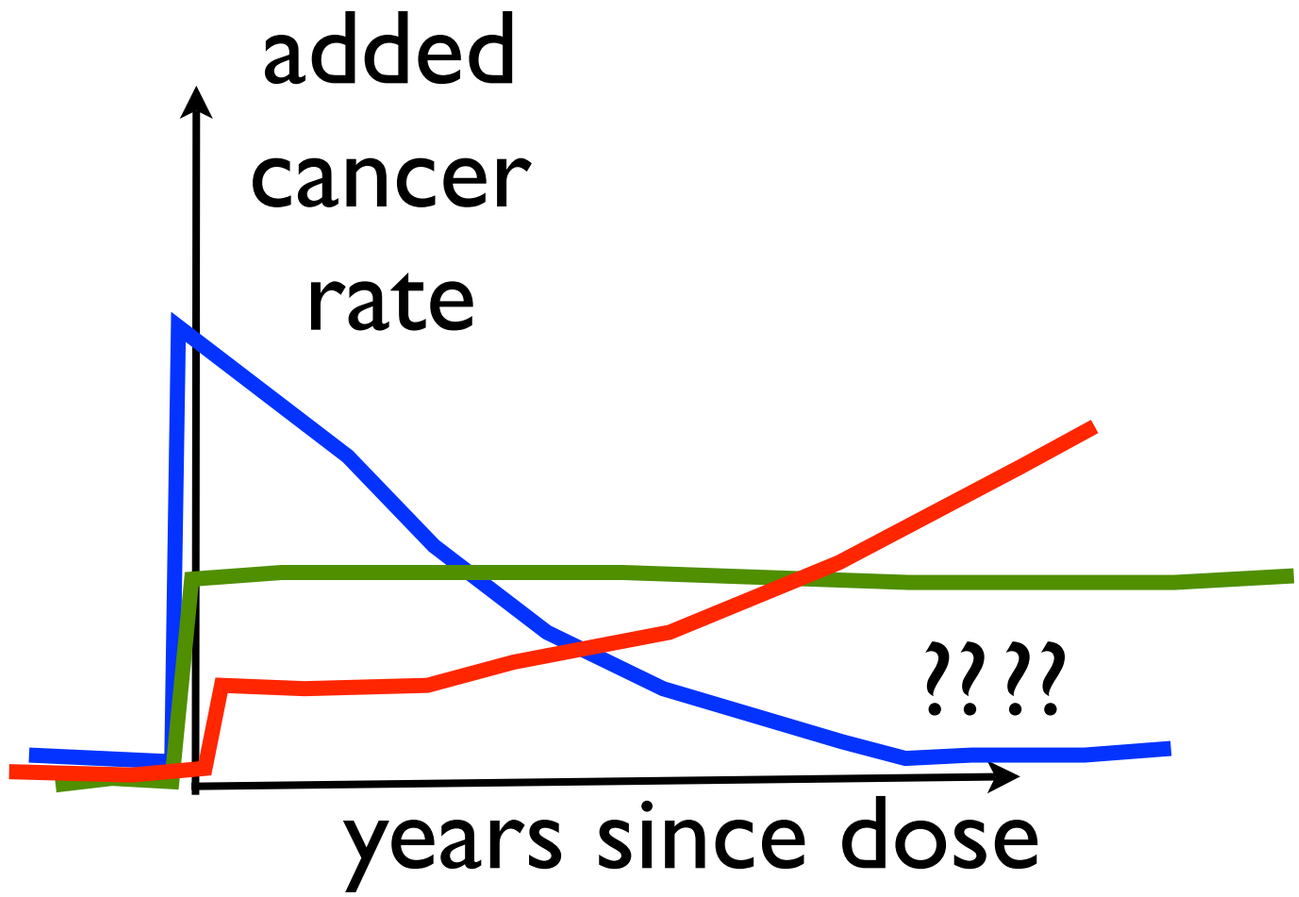
Elevated radiation levels were detected in many southern cities, but levels were far below those that pose health risks, and they were falling.



Are low doses proportionally dangerous?

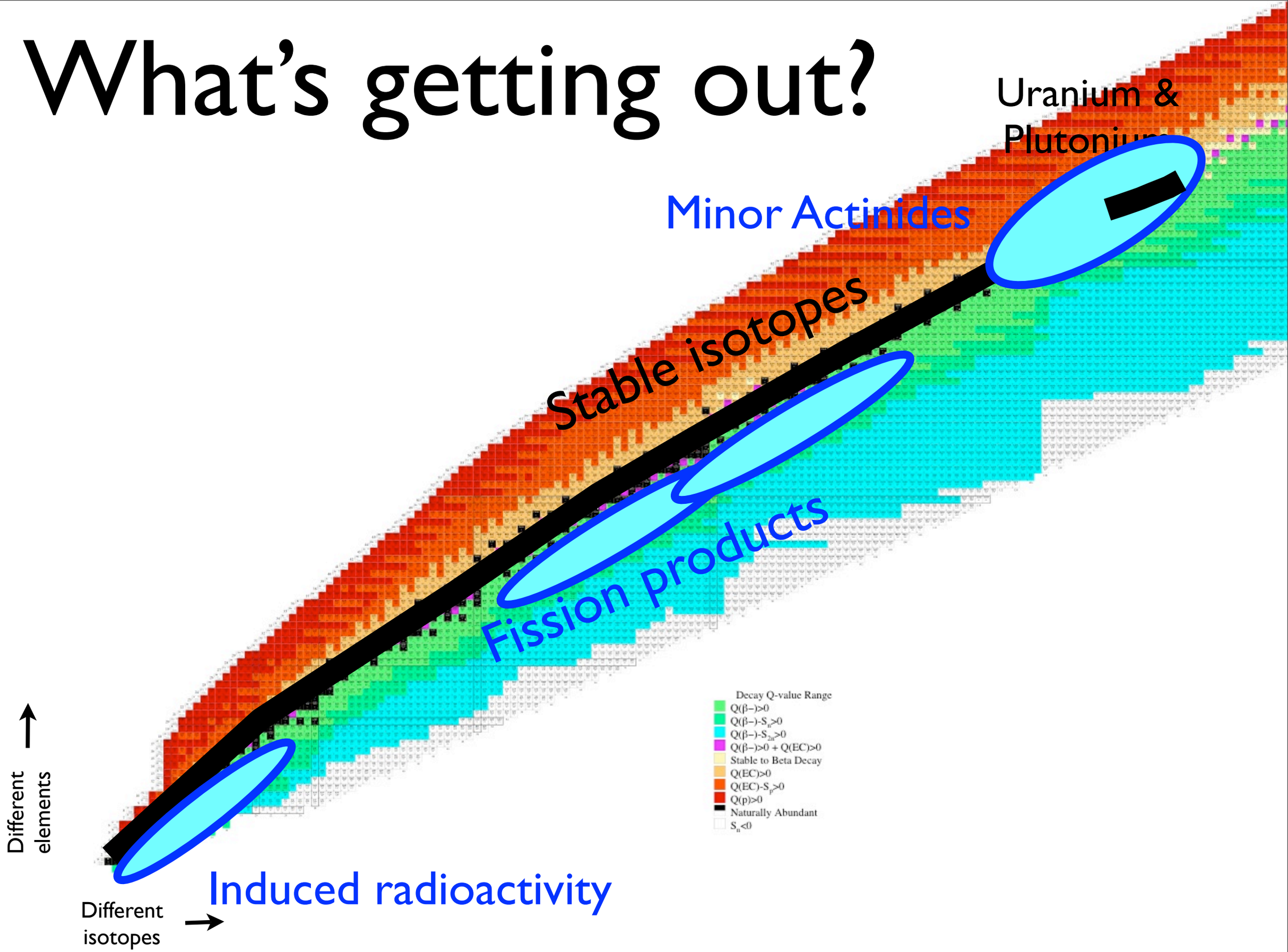
- Probably?? There is no case where a small extra risk was *detectable*. (Chernobyl area: thyroid cancer at 100 mSv)





"Health effects of low-level exposure to ionizing radiation", ed. Hendee & Edwards, IoP 1996

What's getting out?



Periodic Table of the Elements

Chemistry Reference Sheet

California Standards Test

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4	19 **K** Potassium 39.10	20 **Ca** Calcium 40.08	21 **Sc** Scandium 44.96	22 **Ti** Titanium 47.87	23 **V** Vanadium 50.94	24 **Cr** Chromium 52.00	25 **Mn** Manganese 54.94	26 **Fe** Iron 55.85	27 **Co** Cobalt 58.93	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.55	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92	34 **Se** Selenium 78.96	35 **Br** Bromine 79.90	36 **Kr** Krypton 83.80
5	37 **Rb** Rubidium 85.47	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.91	40 **Zr** Zirconium 91.22	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.91	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.87	48 **Cd** Cadmium 112.41	49 **In** Indium 114.82	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.76	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90	54 **Xe** Xenon 131.29
6	55 **Cs** Cesium 132.91	56 **Ba** Barium 137.33	57 **La** Lanthanum 138.91	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.21	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.97	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.38	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
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Key

11 — Atomic number
Na — Element symbol
Sodium — Element name
22.99 — Average atomic mass*

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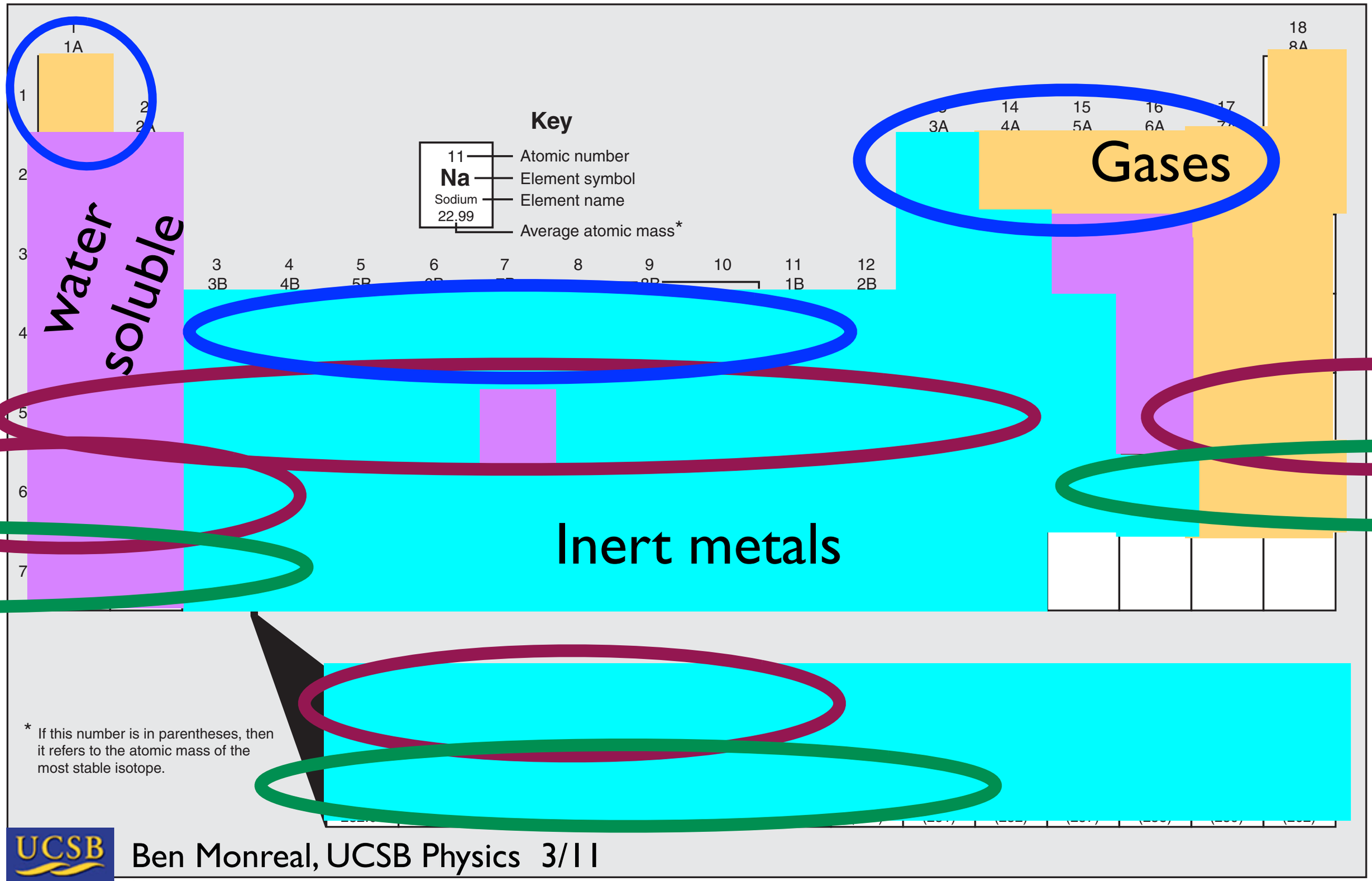

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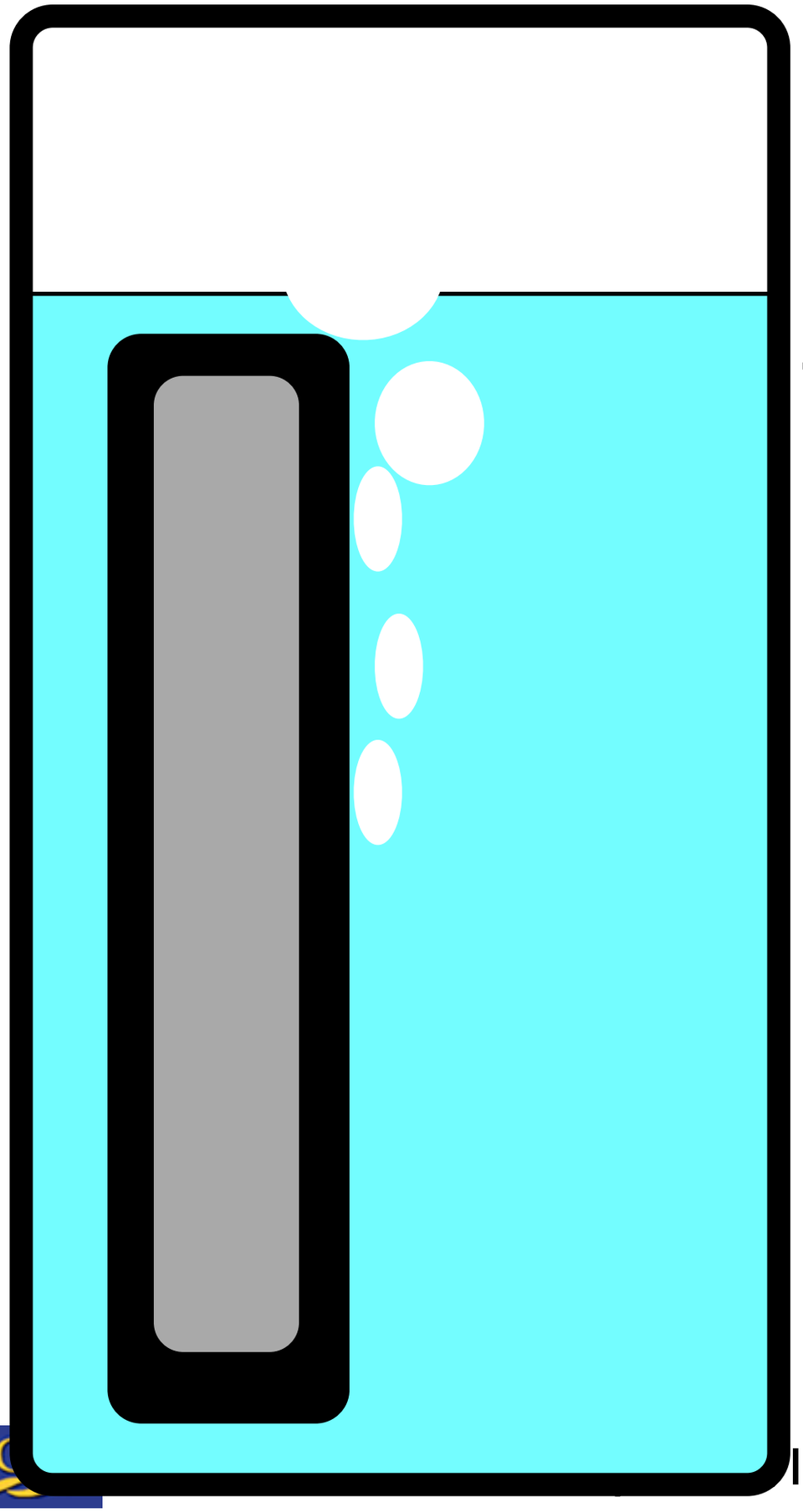


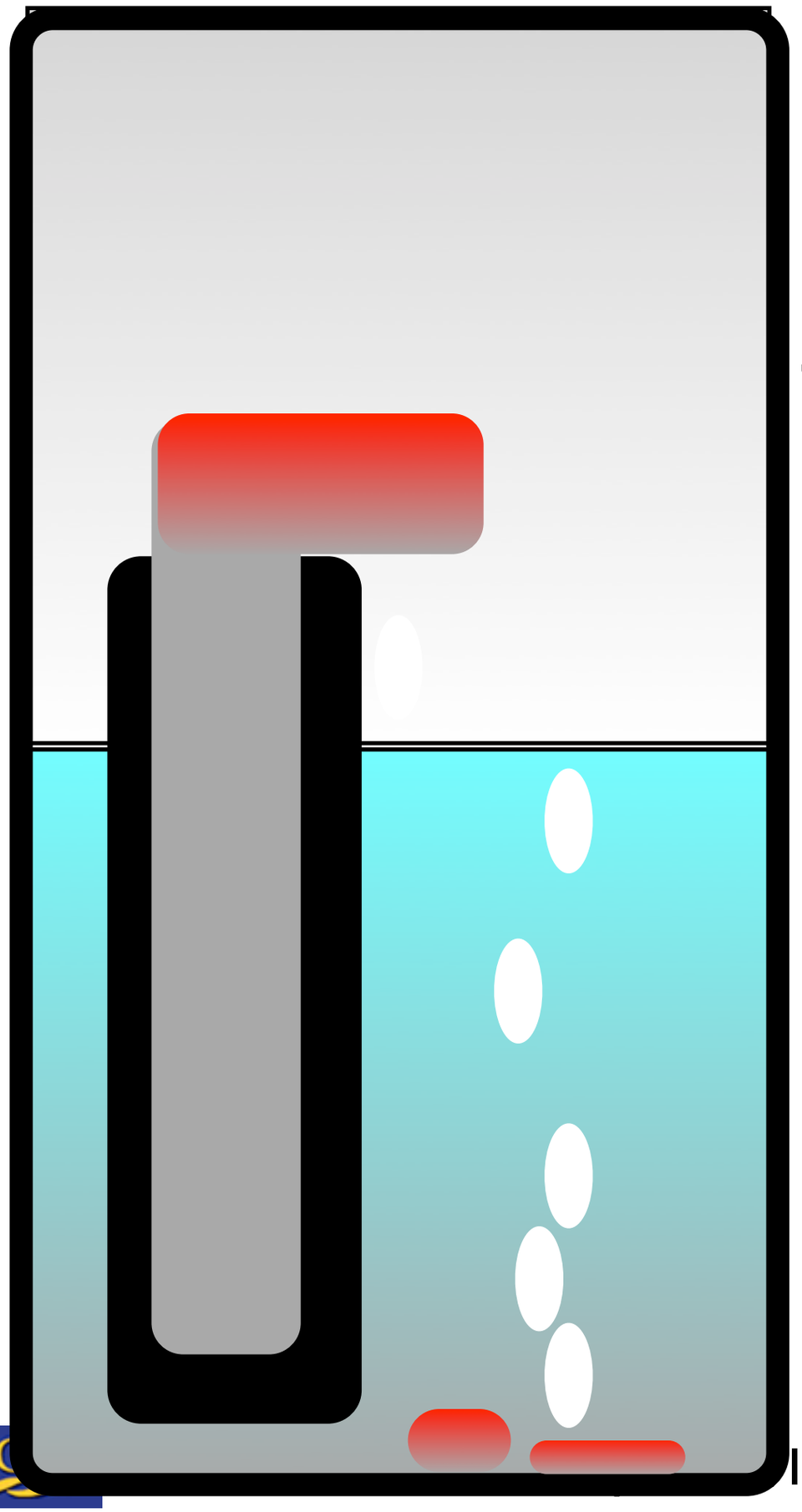
Healthy reactor:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
activation products

In steam:
activation products

In environment:
practically nothing



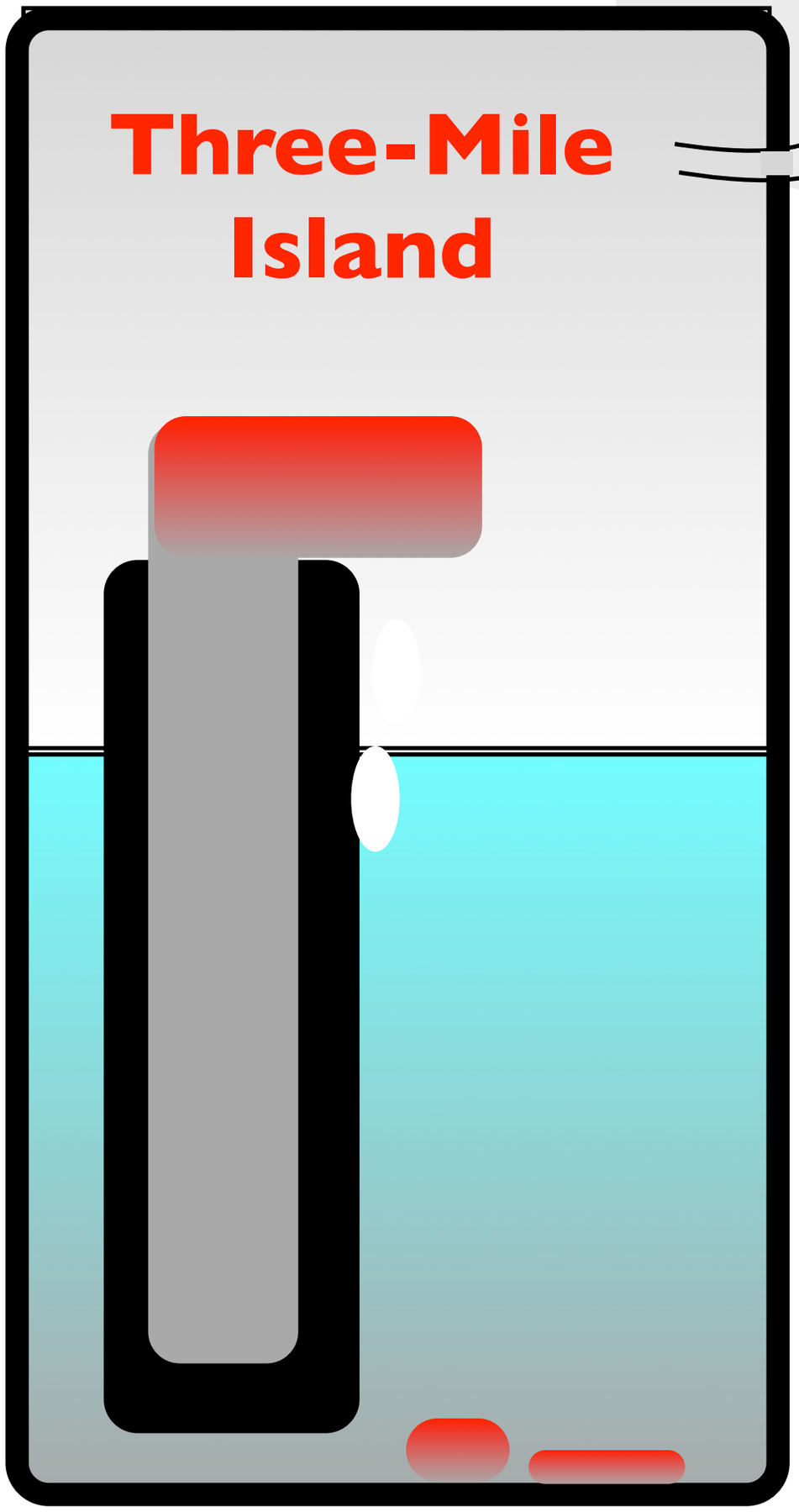
Meltdown:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
fission products like Cs, I, Tc

In steam:
fission products like Xe, Kr, Rn

In environment:
practically nothing



Meltdown + emergency venting:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
fission products like Cs, I, Tc

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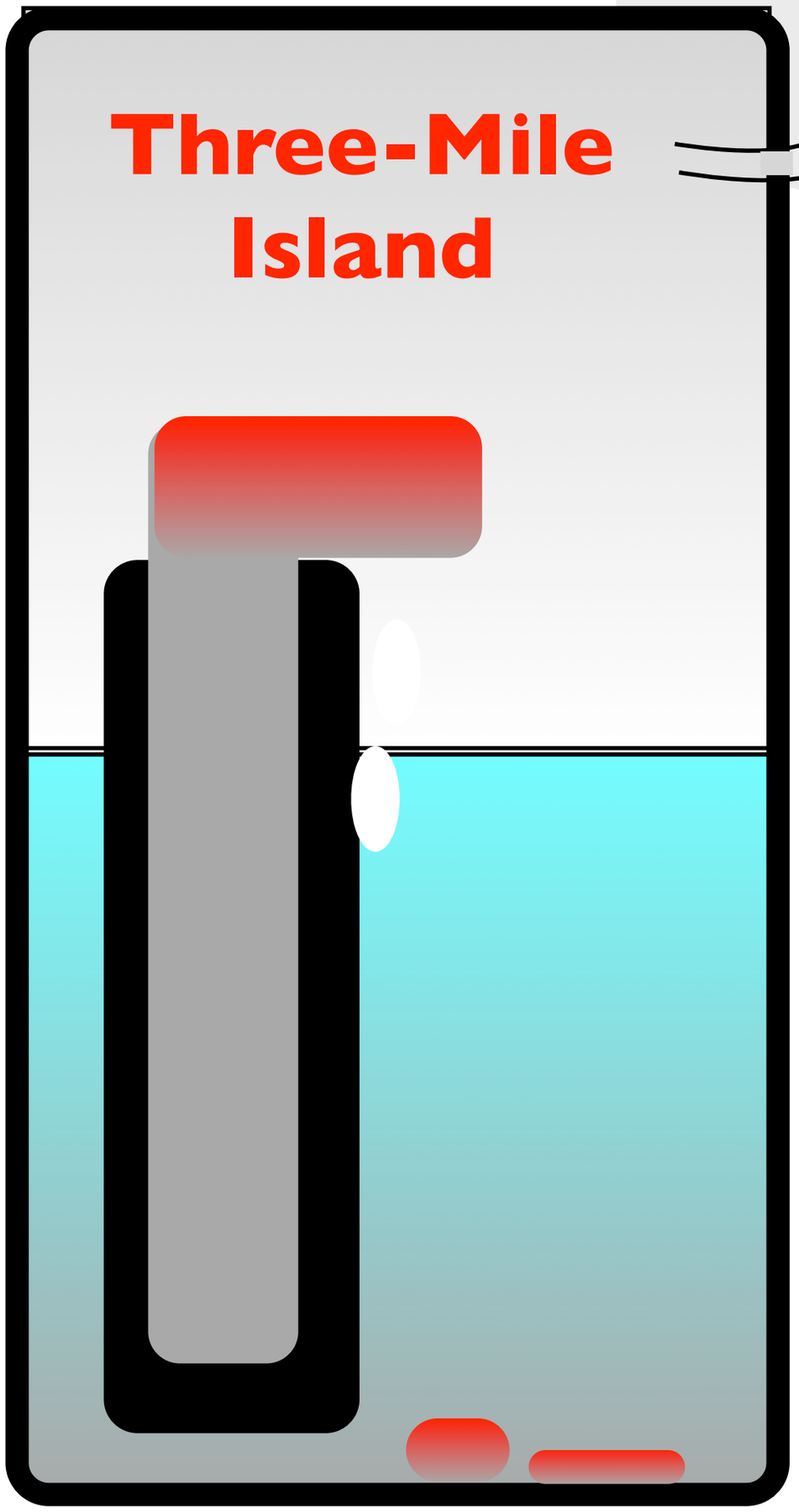
In environment:
practically nothing
~~Xe, Kr, Rn~~



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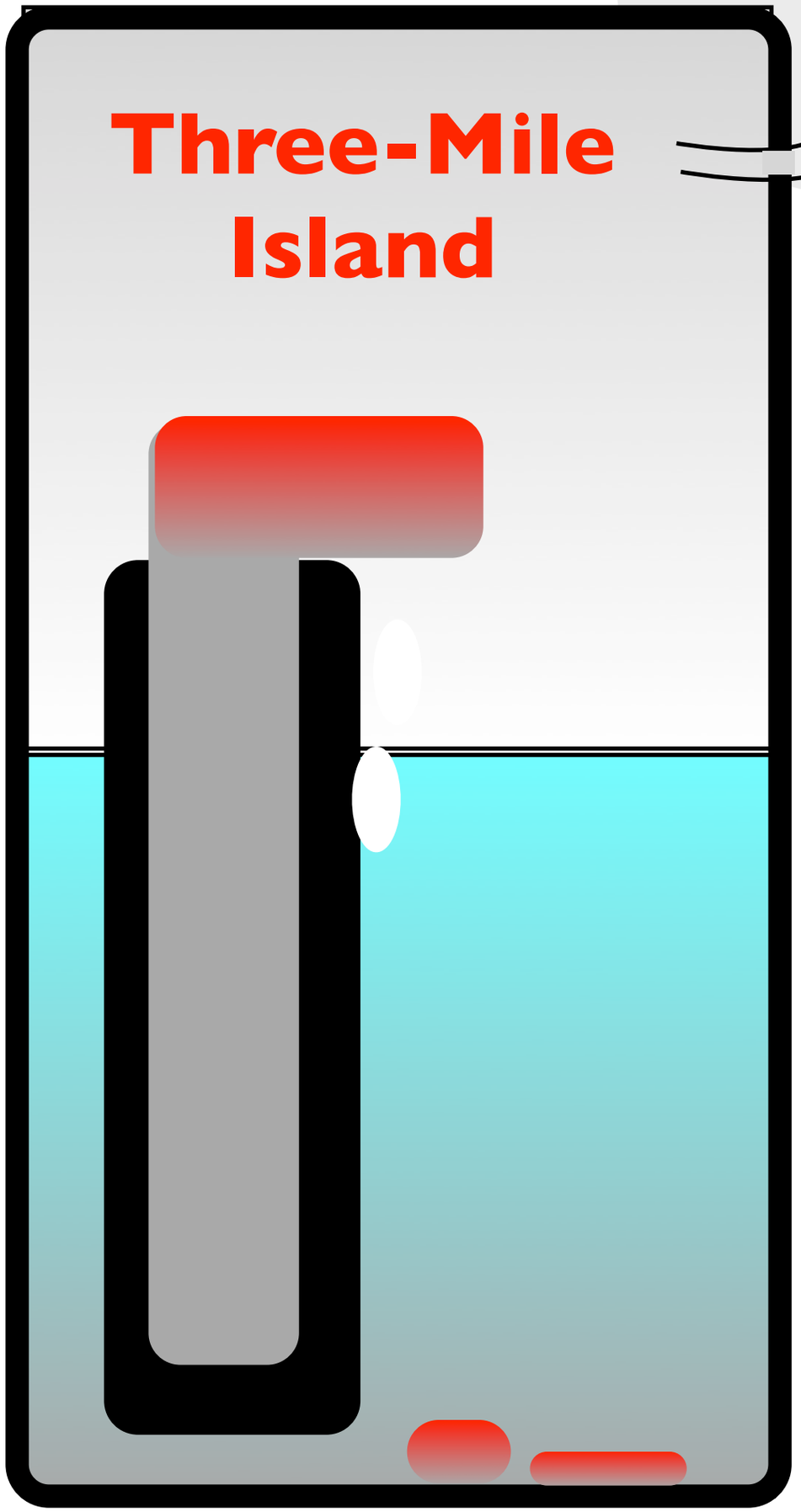

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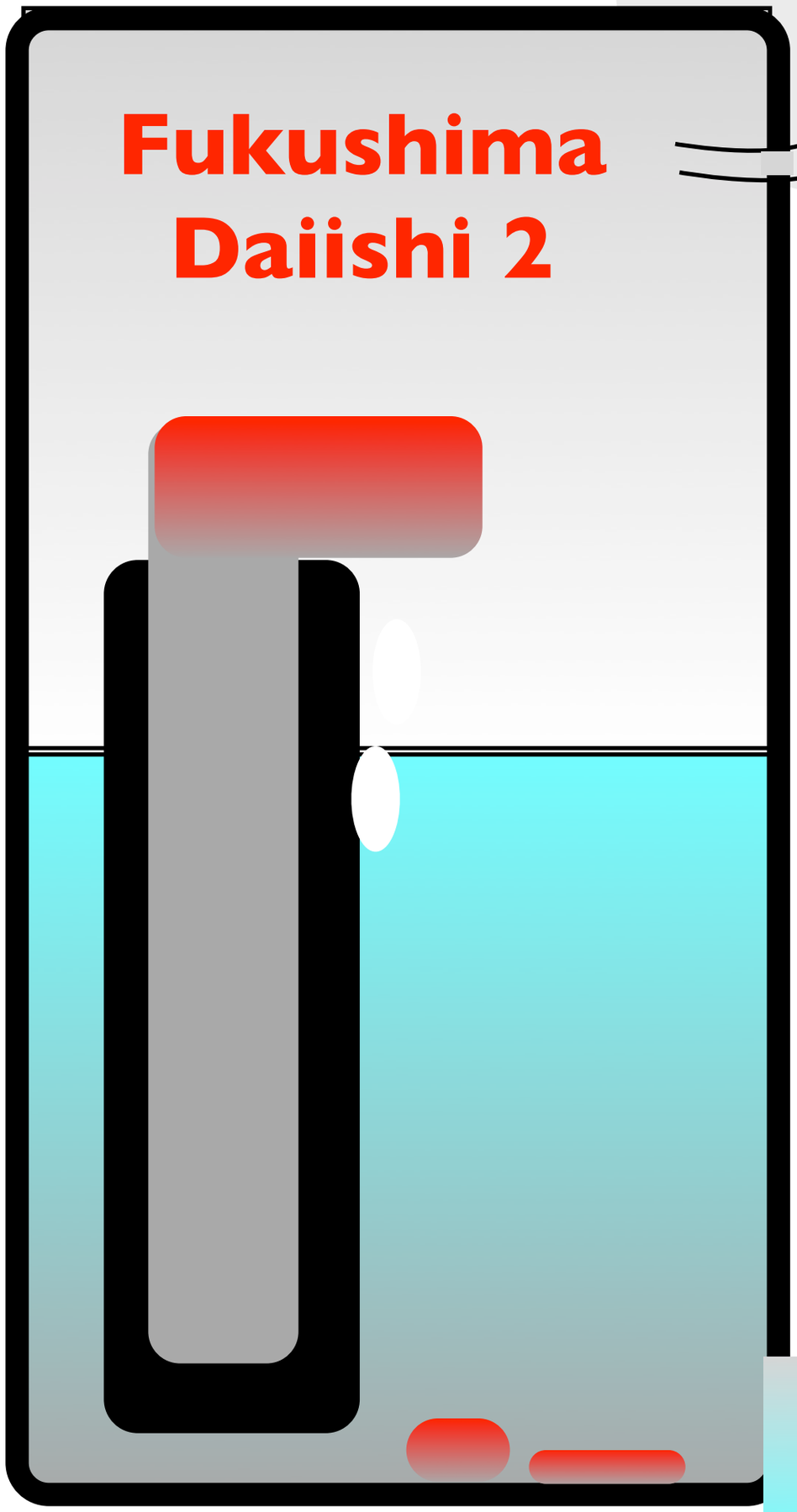


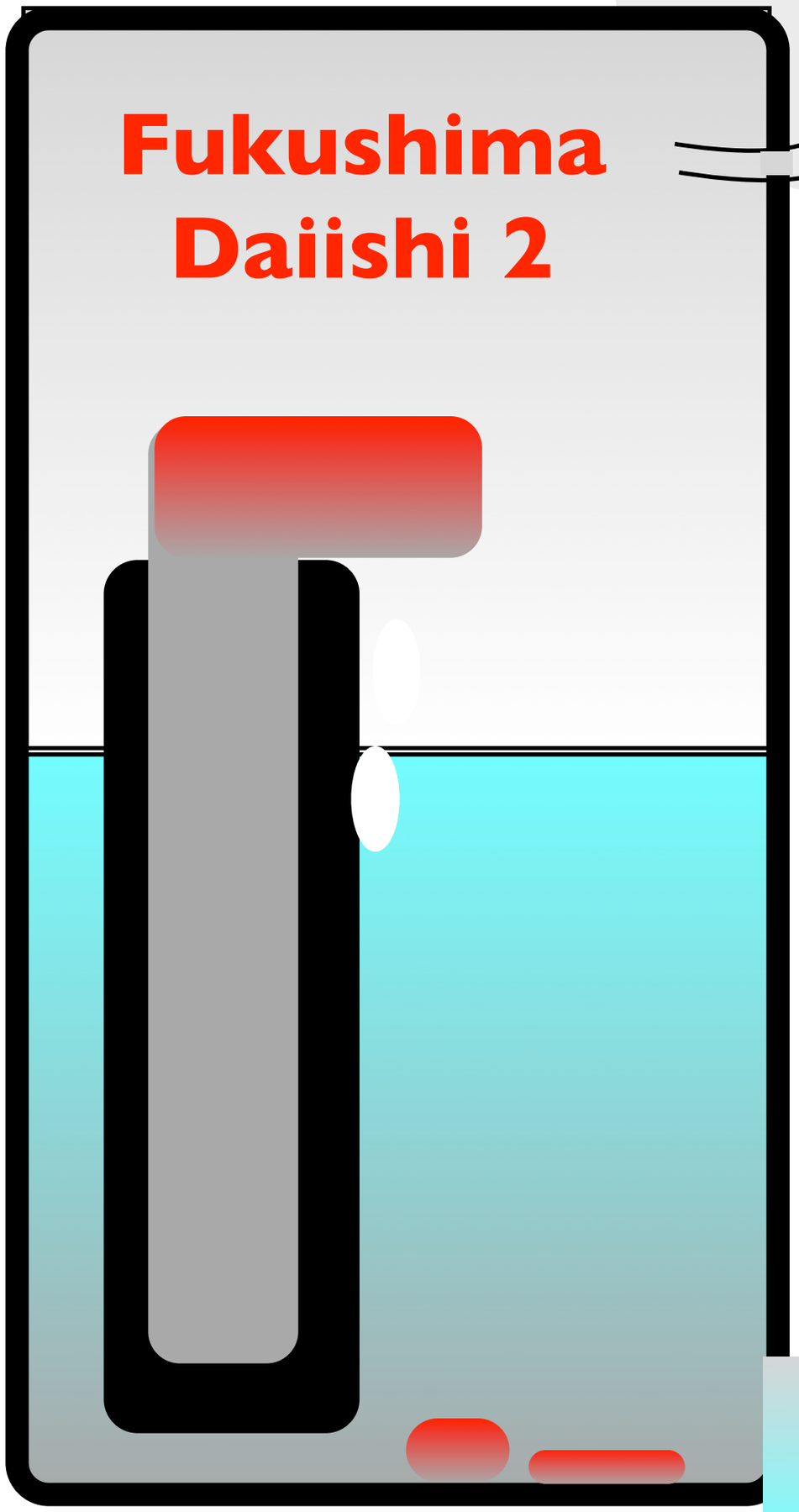
Meltdown + containment failure:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
fission products like Cs, I, Tc

In steam:
fission products like Xe, Kr, Rn

In environment:
Xe, Kr, Rn

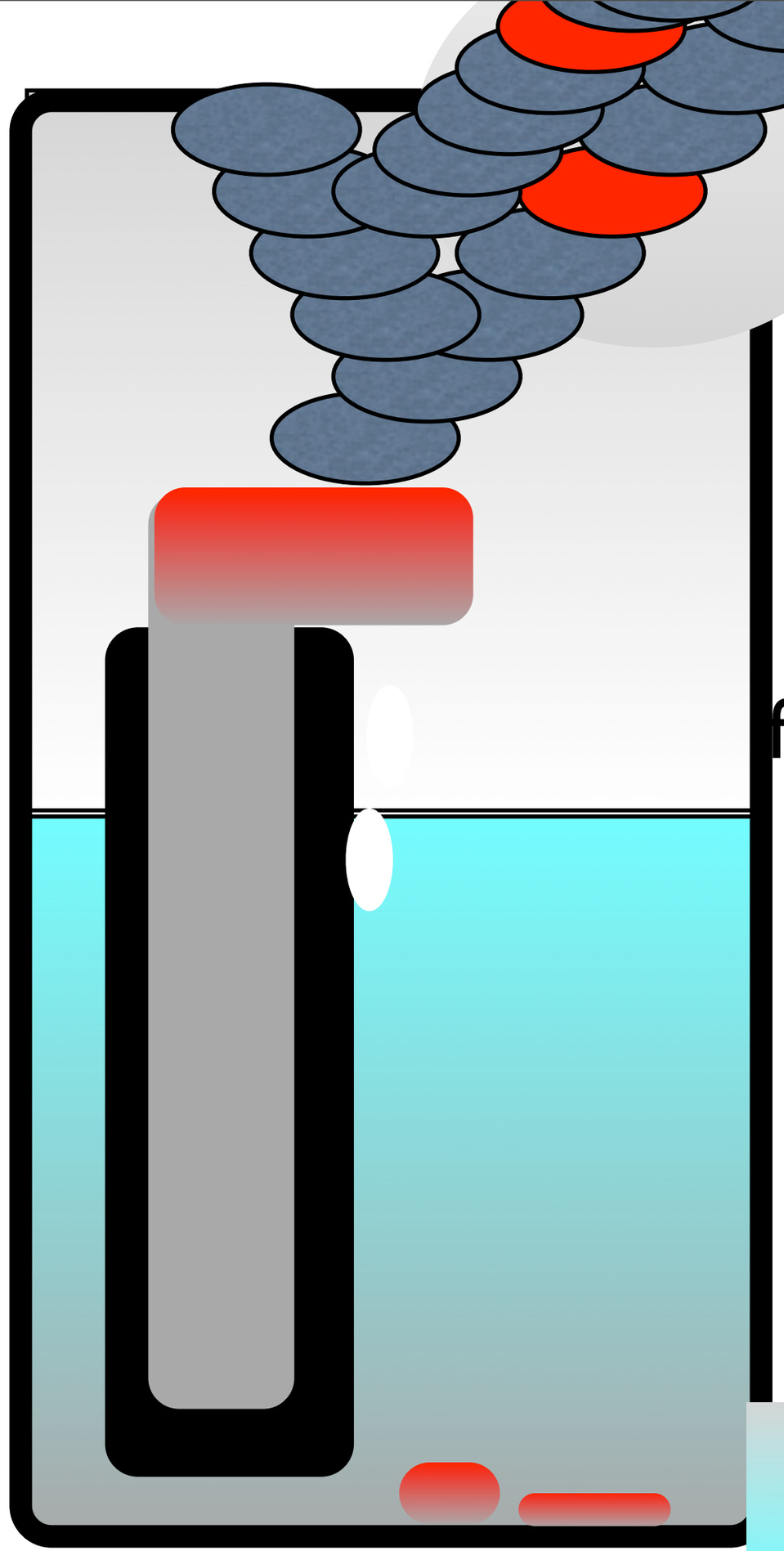


Meltdown + containment failure:

In Zircalloy casing:
fuel + fission products + actinides

In steam:
fission products like Xe, Kr, Rn

In environment:
Xe, Kr, Rn, Cs, I, Tc



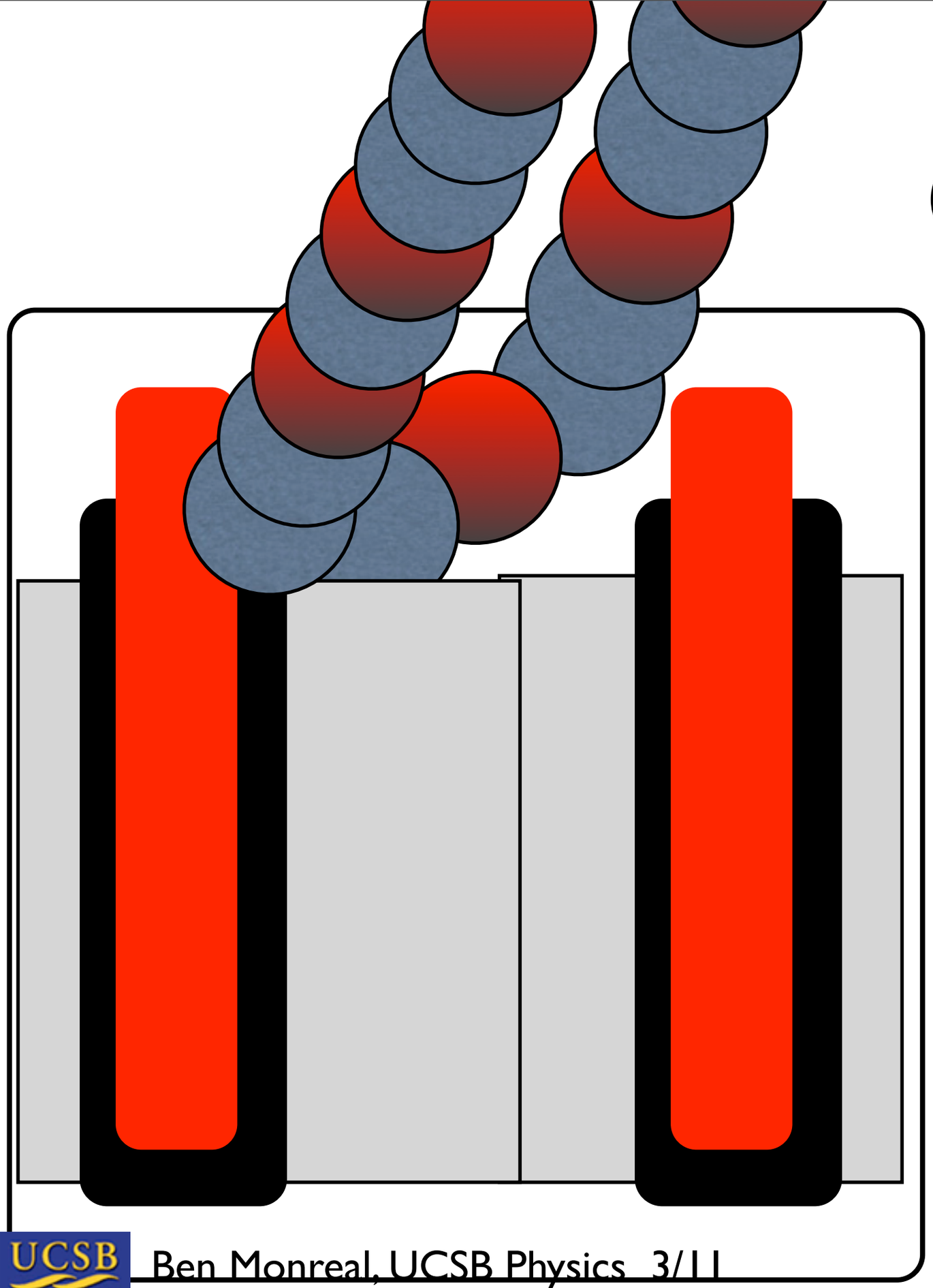
Meltdown + fuel fire

In Zircalloy casing:
fuel + fission products + actinides

In environment:
fuel + fission products + actinides

Briefly happened at Fukushima spent-fuel pools? (reports vary?)

This is very bad but
still not as bad as Chernobyl



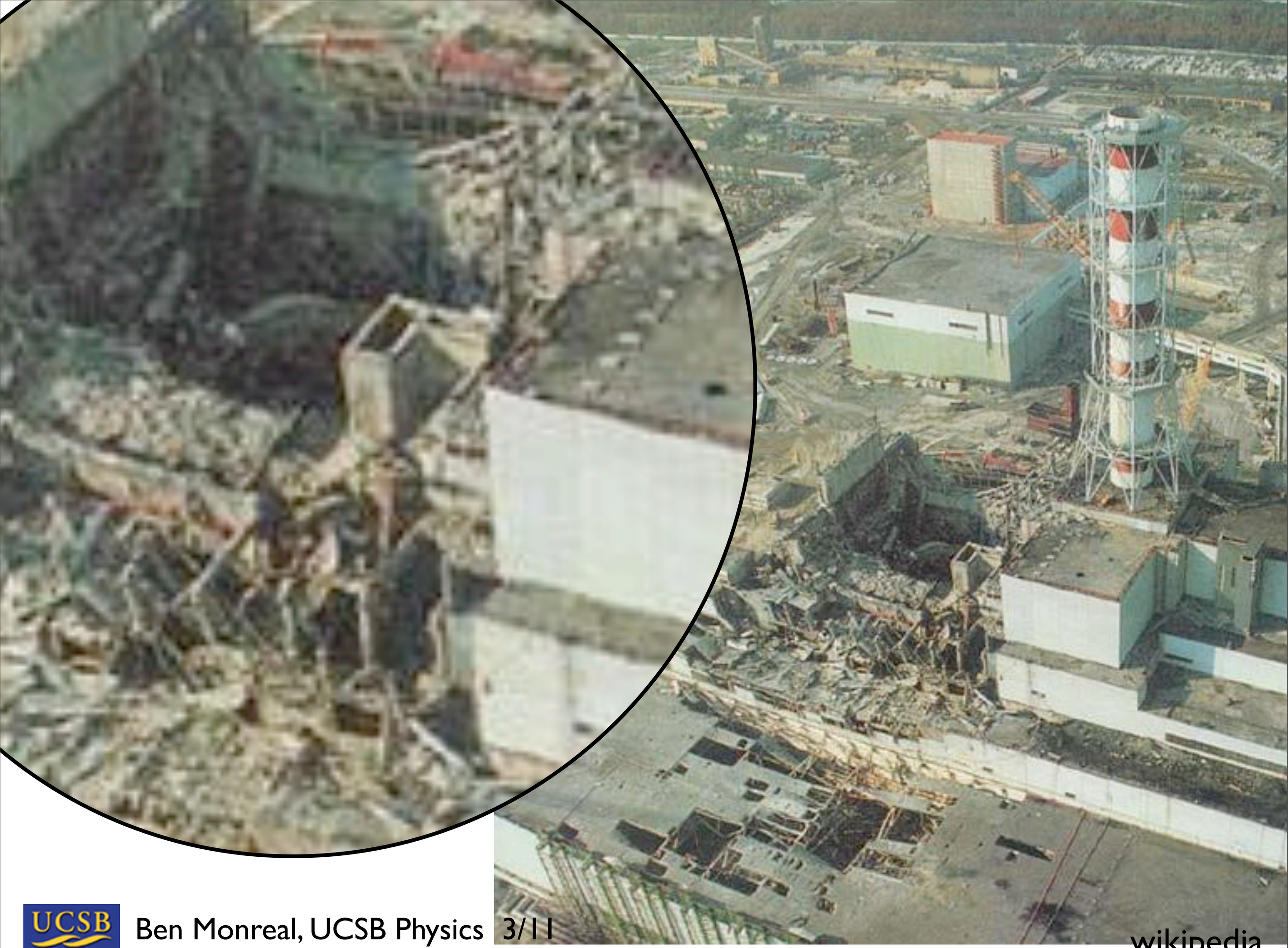
Chernobyl

no real "containment vessel"

Core filled with graphite (fuel for huge fire)

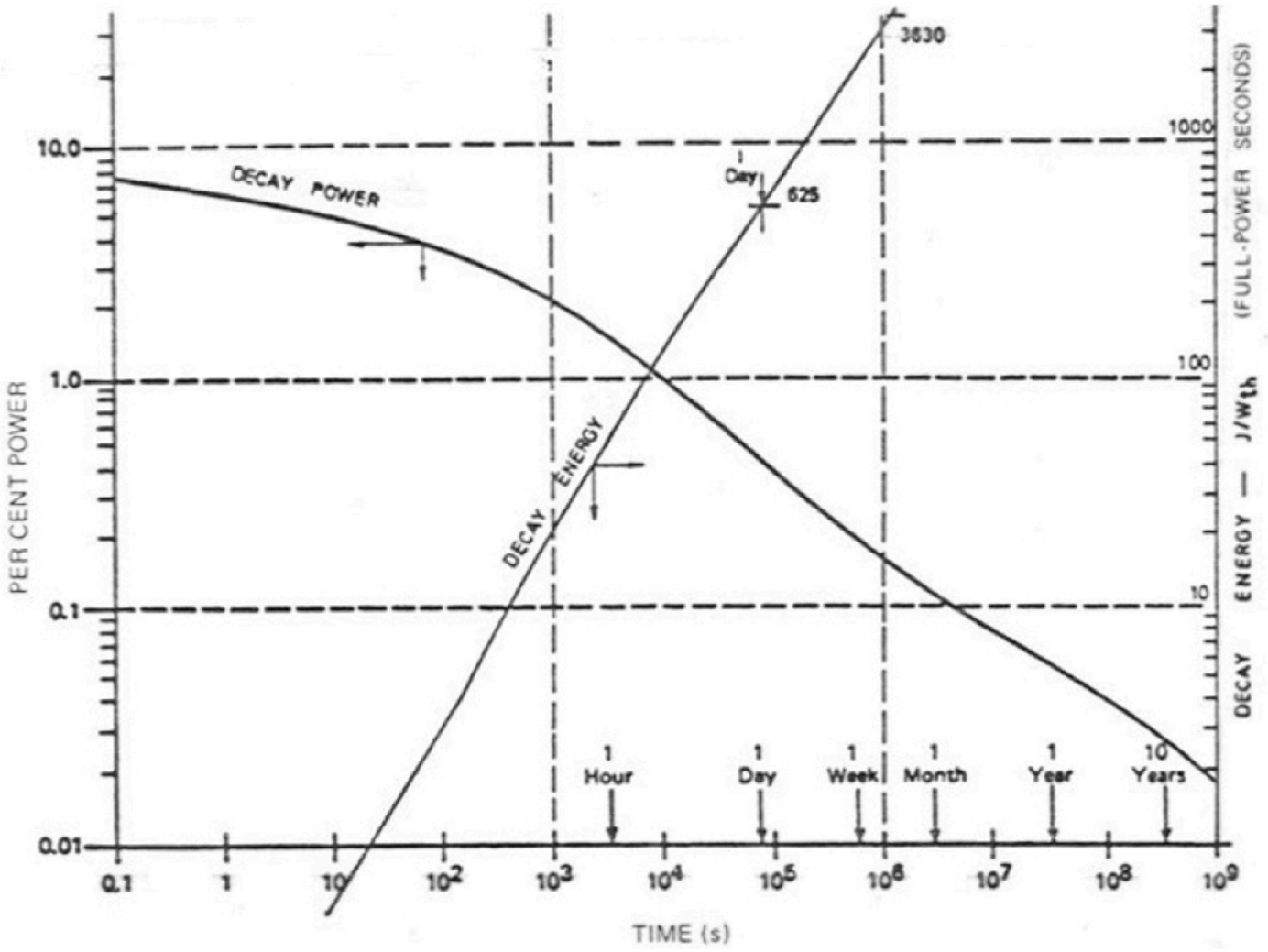
Reactor *fissioning during explosions and fire*

(Fukushima reactors have now been "off" for 5 days)



wikipedia

Saving graces at Fukushima



- *Reactor survived earthquake intact (!!!!!)*
- Shut down properly
- First hour of containment saved factor of 5x
- First day: factor 20x
- Evacuation
- Biggest fire risk is 100-day-old spent fuel, i.e. 100x less radioactive than Chernobyl material

Nuclides to watch

Nuclide	Half-life	Effect at Chernobyl
^{131}Iodine	8 days	quick ~0.5 mSv dose to everyone in Eastern Europe
^{137}Cesium	30 years	Additional ~1 mSv over 30y
^{90}Strontium	30 years	Lower amount than Cs, but accumulates in bone
^{241}Plutonium	9 years	Large doses near reactor site; easier to decontaminate

Cooper, Randle, and Sokhi, Wiley 2003

In case of fire ... soot

Nuclide	Half-life
^{95}Zirconium	60 days
^{99}Molybdenum	3 days
^{103}Ruthenium	40 days
^{141}Cerium	30 days
^{140}Barium	14 days

- Worst concern to first responders. Weather may move soot plumes around (Chernobyl: bad plumes to 60km)
- *This is what the "stay indoors" advisories are talking about. Soot in your driveway doesn't dose you; soot on your clothes does.*
- Can be cleaned from streets/buildings. Agriculture, fisheries have to wait it out (or remove top 10cm soil)

Conclusions

- The worst general-public effects of Chernobyl were *stress/fear;* HUGE education/communication failure
  - You have the information: count the millisieverts and decide how to respond
- My feeling: the worst-case radiation hazards from Fukushima are mitigatable and local
  - (early evacuation + controls on ^{131}I in food)
- My feeling: the global radiation hazard is nil.
  - The best way to reduce worldwide low-level radiation releases is ... stop burning coal
- Save your energy for those affected by the tsunami and "50 plant workers" at Fukushima