



Fundamentals of LFR technology and Accelerator Driven Systems (ADS)

Julio PACIO - 17 February 2026

IAEA National training course on Heavy Liquid
Metal Cooled Fast Reactors

Pitesti, Romania

Wet Bulb Globe Temp



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Heat claims more than 175,000 lives annually in Europe, latest data shows

Relative Humidity (%)

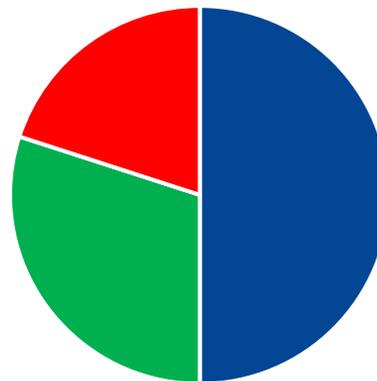
	20	22	24	
0	14.8	16.1	18.0	1
5	15.3	16.7	18.7	1
10	16.0	17.4	19.4	2
15	16.5	18.0	20.1	2
20	17.1	18.7	20.8	2
25	17.6	19.3	21.4	2
30	18.2	19.8	22.0	2
35	18.7	20.3	22.6	2
40	19.3	20.9	23.2	2
45	19.7	21.5	23.8	2
50	20.2	22.0	24.3	2
55	20.7	22.4	24.8	2
60	21.1	22.9	25.4	2
65	21.6	23.2	25.9	2
70	22.1	23.9	26.4	2
75	22.5	24.4	26.9	2
80	22.9	24.8	27.4	2
85	23.3	25.2	27.8	2
90	23.7	25.7	28.3	2
95	24.2	26.1	28.7	3
100	24.5	26.5	29.1	3

NOTE: This chart is calculated at atmospheric pressure of 1AT

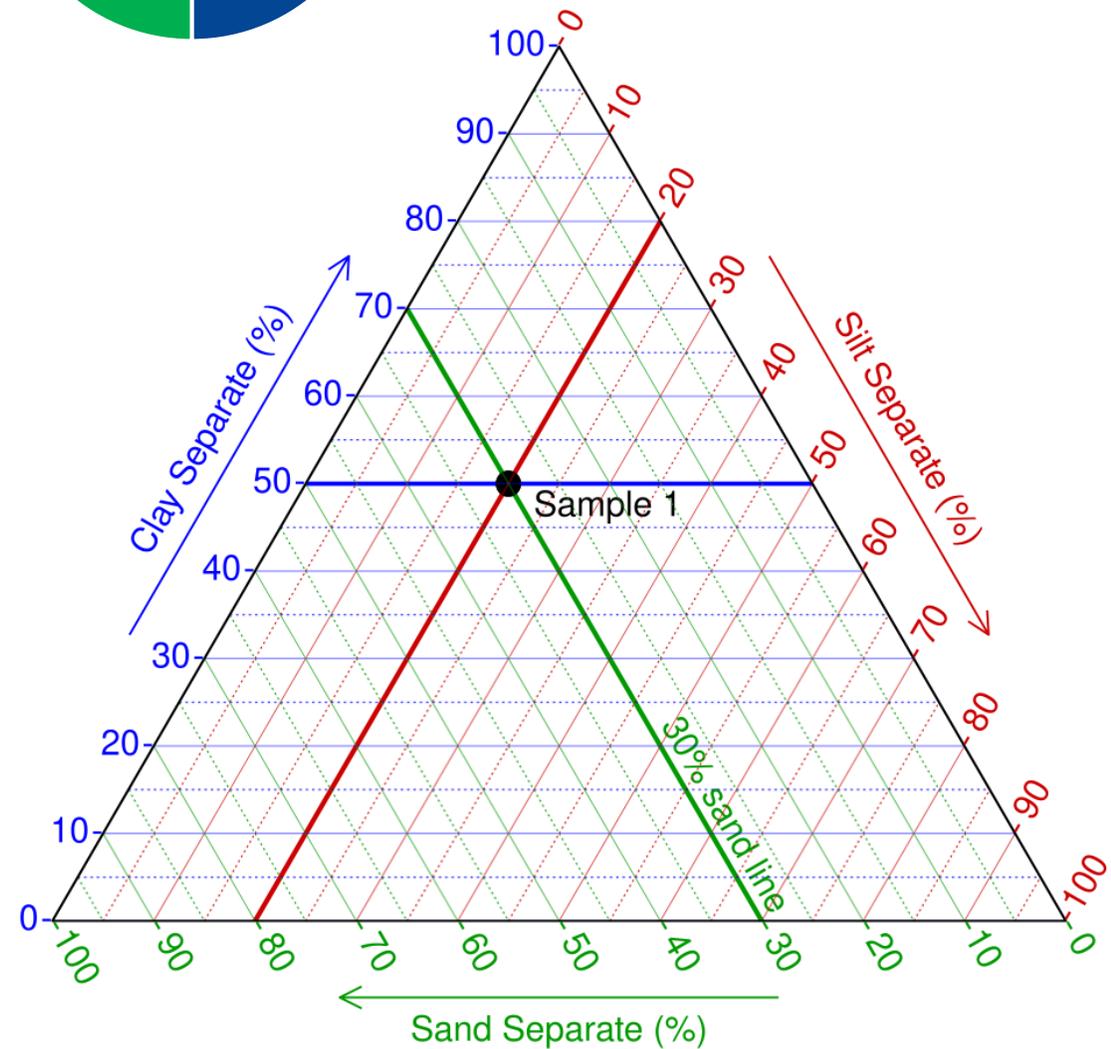
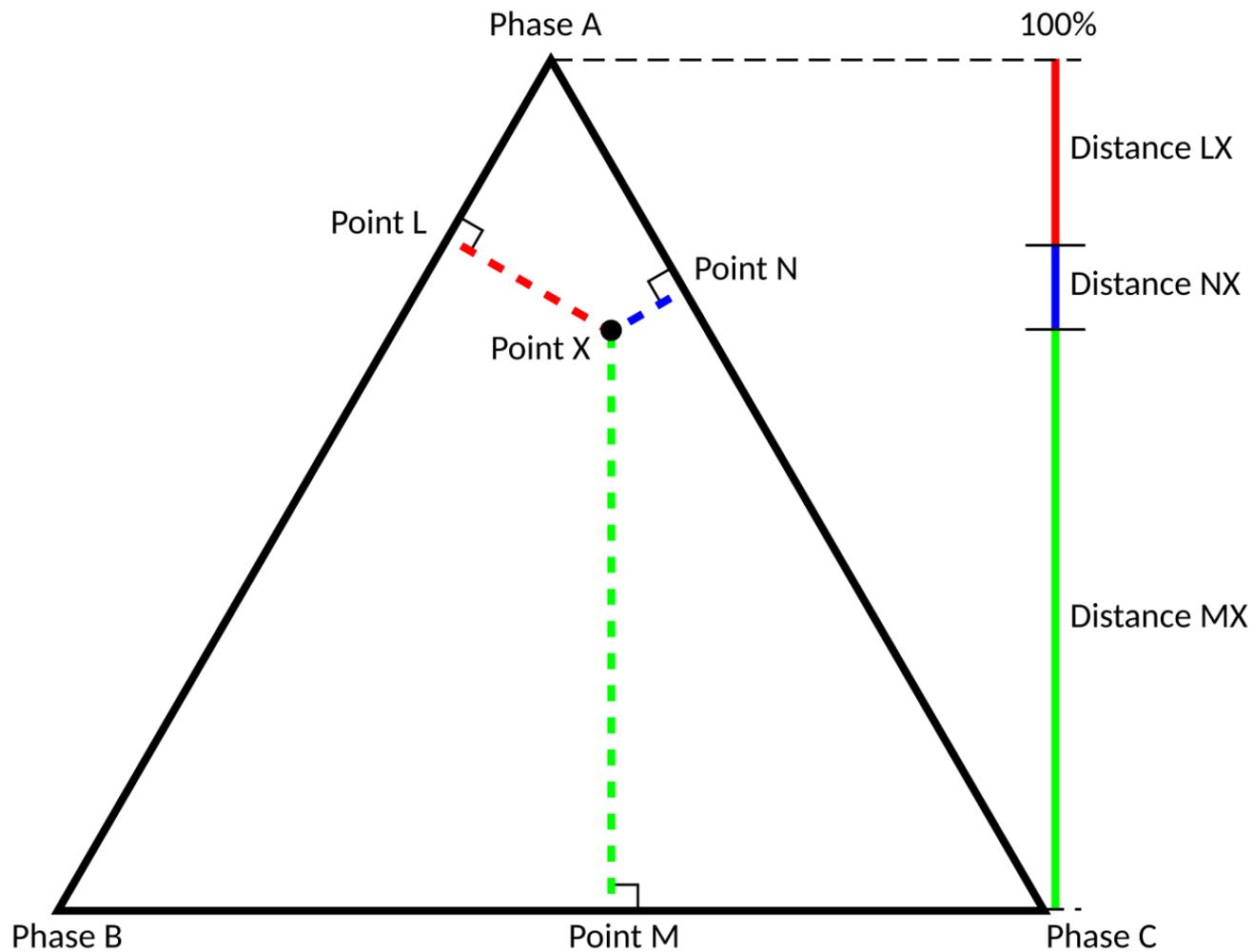


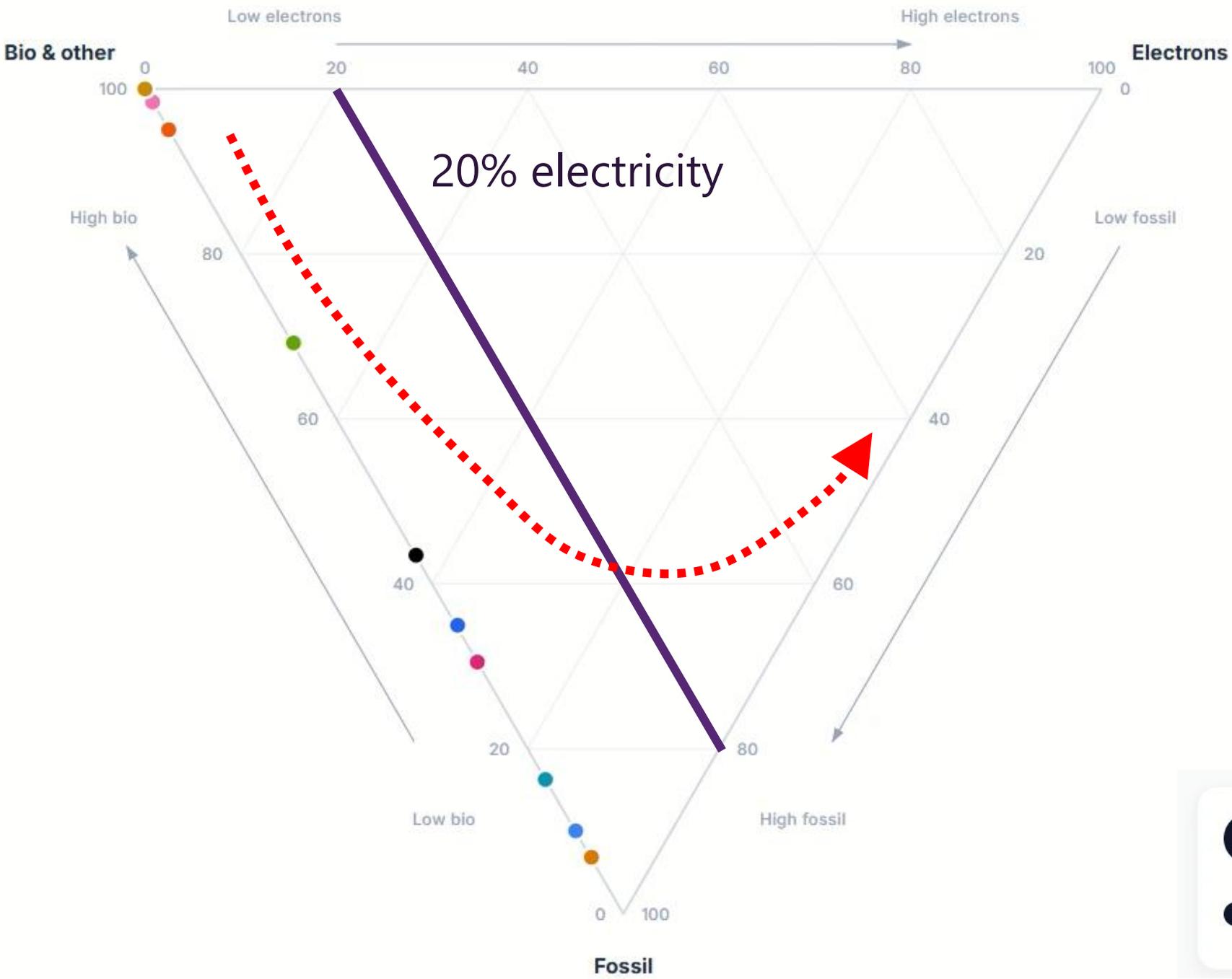
© Unsplash/Andrew Seaman | Staying cool during a heatwave is especially important for children who have a harder time regulating their body temperature than adults.

Ternary plots



- Clay
- Sand
- Silt





A Three-Way View of Energy History

Deep dive tool

Historical Final Energy Mix Trajectories

Source: IIASA, IEA, Electrotech Revolution team analysis

- Europe
- Middle East & Africa
- World
- China
- France
- Germany
- India
- Italy
- Japan
- Nigeria
- United States

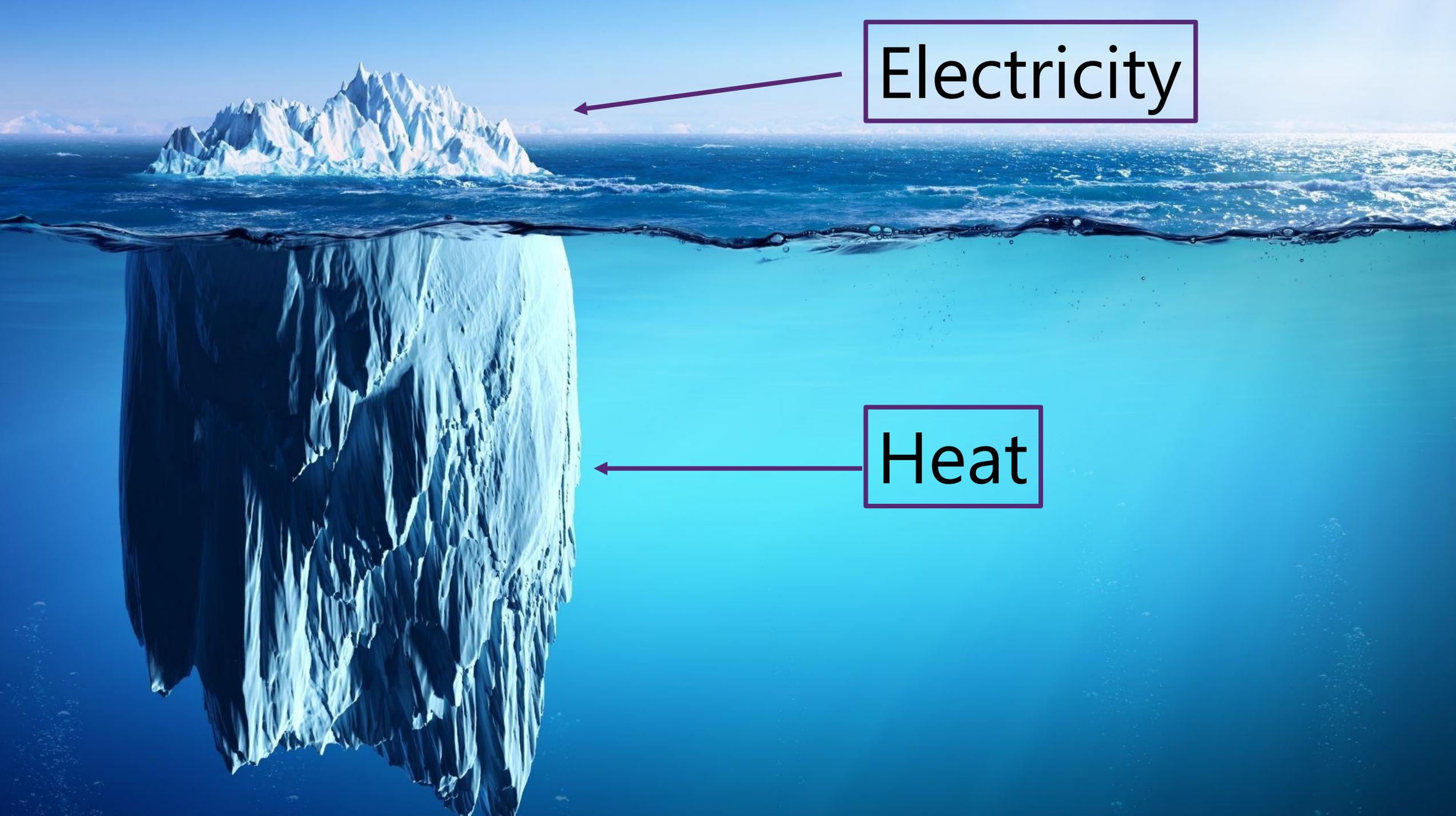
▶ 1900 1x 2x 5x

●

Electricity



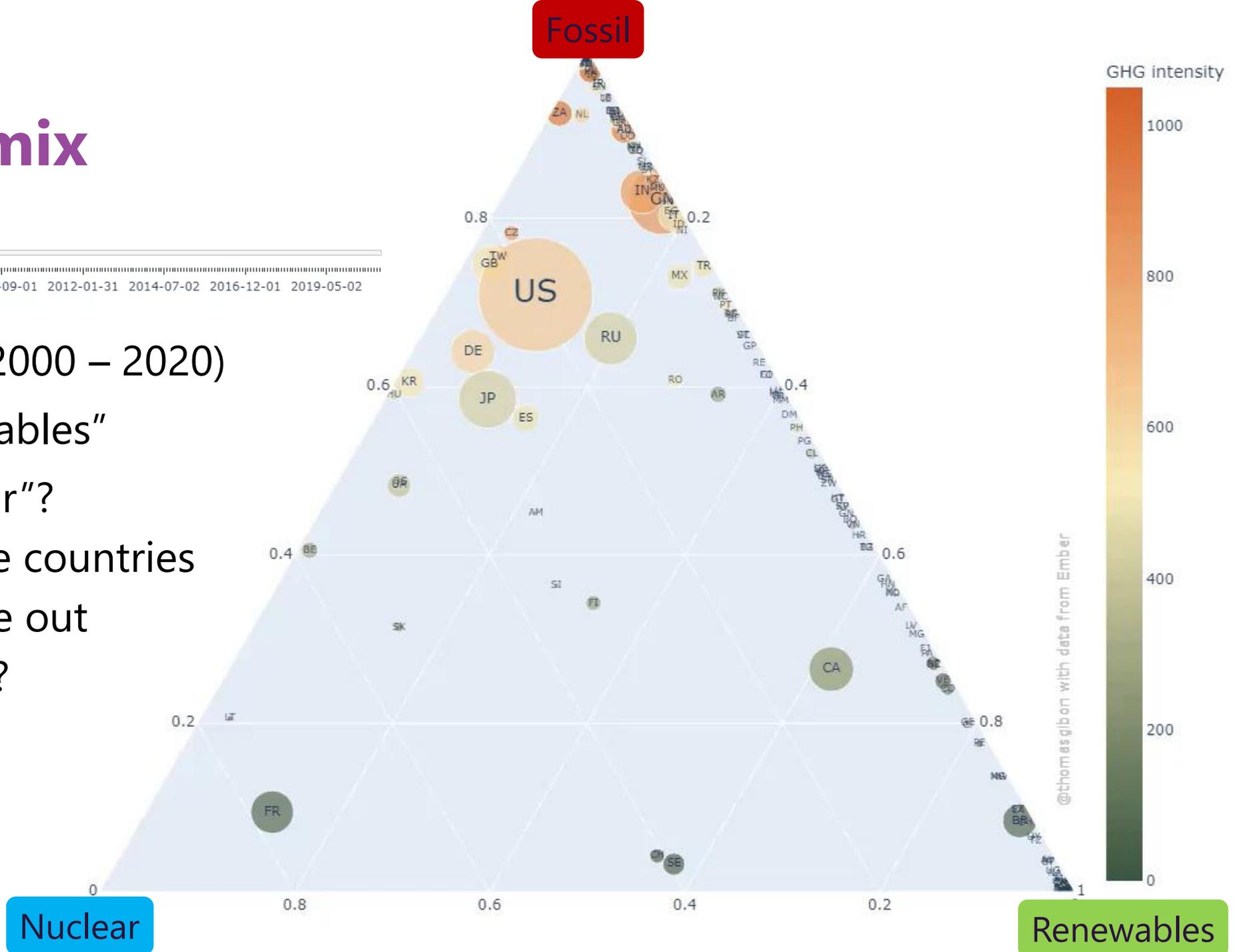
Heat



Electricity mix

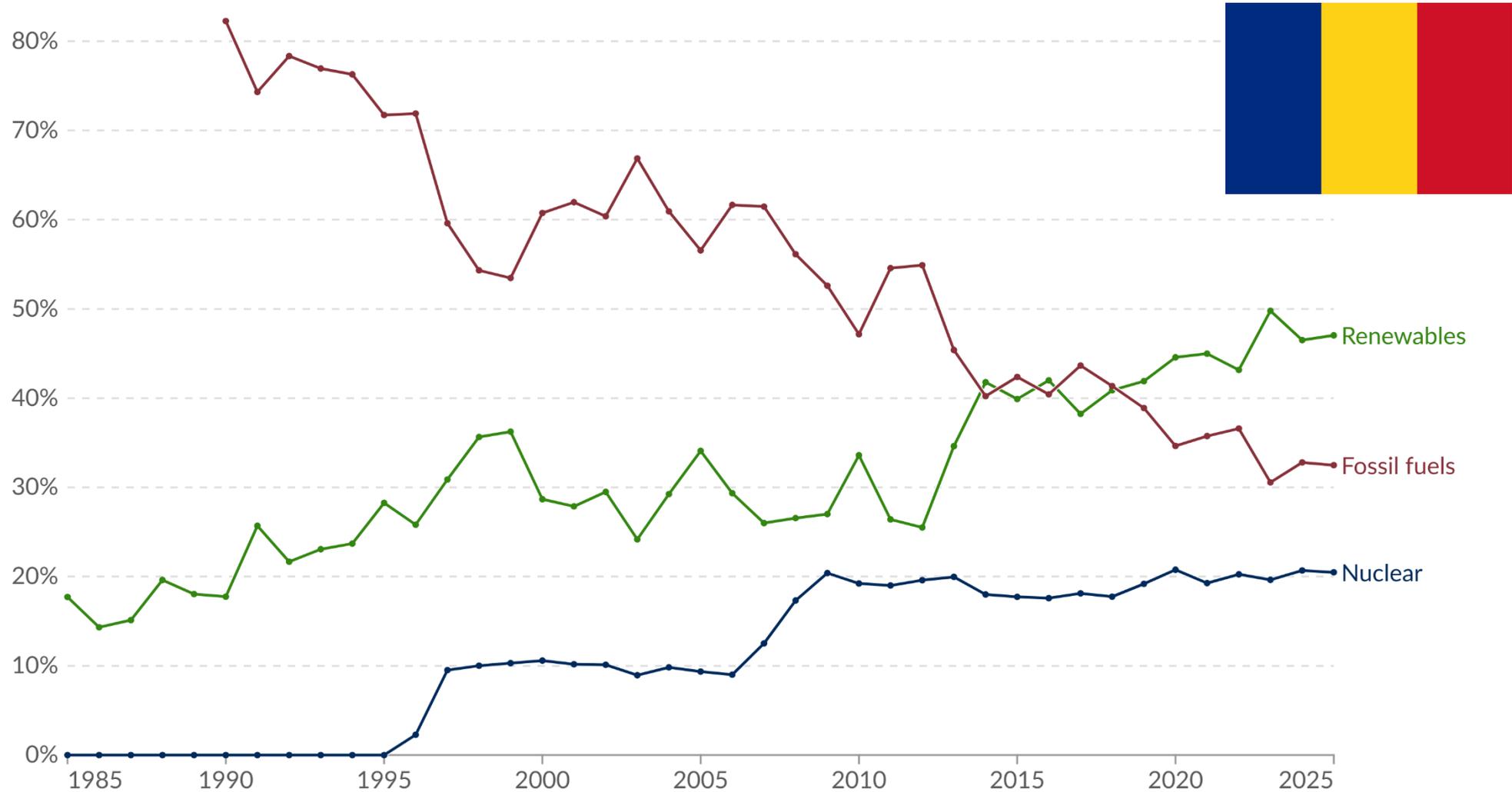


- All countries (2000 – 2020)
- “Rise of renewables”
- “Rise of nuclear”?
 - Only in some countries
 - Others phase out
 - Renaissance?
- Goals 2050



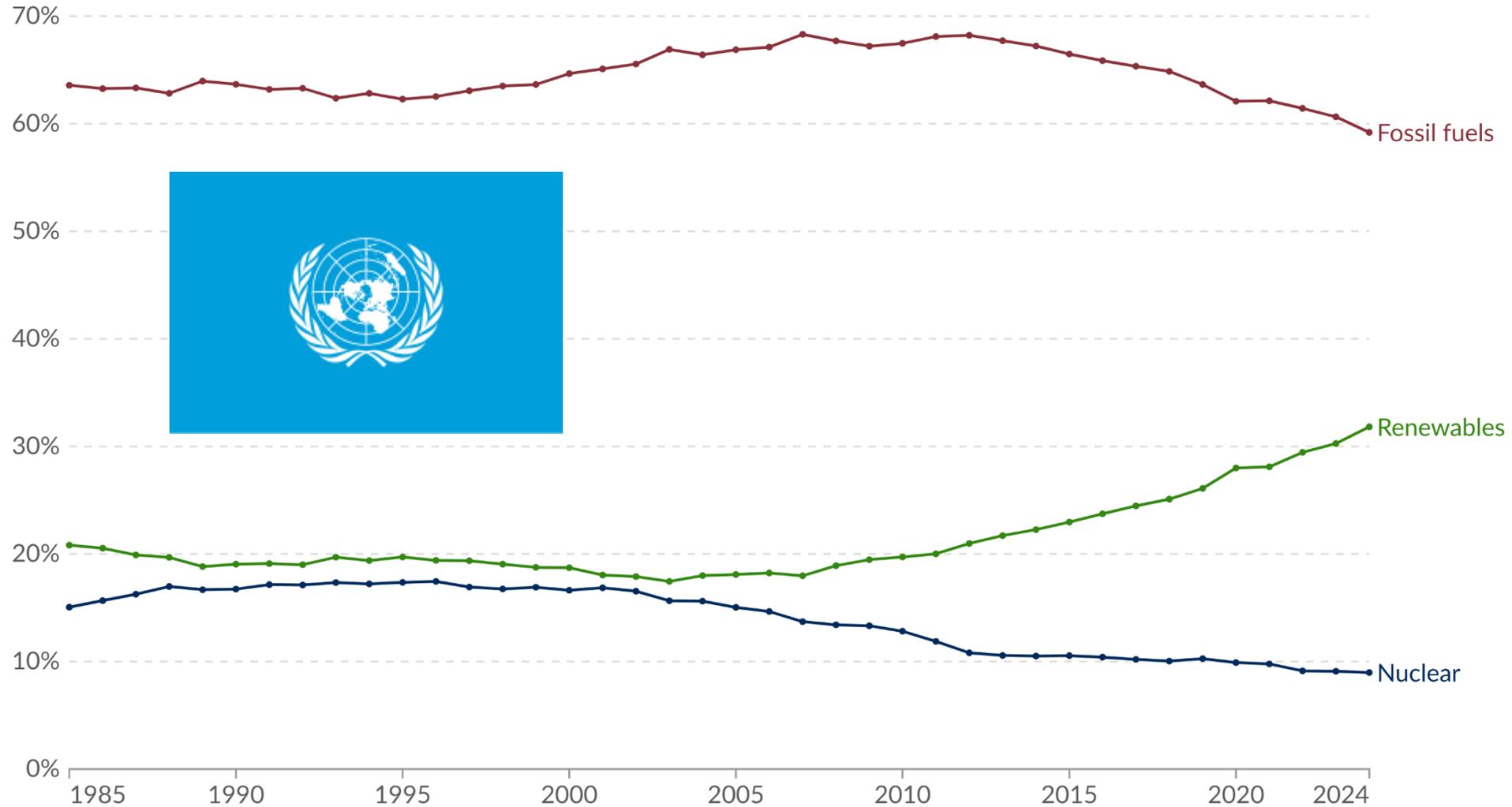
Share of electricity generation from fossil fuels, renewables and nuclear, Romania

Measured as a percentage of total electricity produced in the country or region. Fossil fuels include coal, oil, and gas. Renewables include solar, wind, hydropower, bioenergy, geothermal, wave, and tidal.



Share of electricity generation from fossil fuels, renewables and nuclear, World

Measured as a percentage of total electricity produced in the country or region. Fossil fuels include coal, oil, and gas. Renewables include solar, wind, hydropower, bioenergy, geothermal, wave, and tidal.



Nuclear energy has two key challenges

- LCOE [€/MWh]
- Other value streams?
- High construction cost and long construction times
- No standard design
- Low O&M costs
- Interest rates

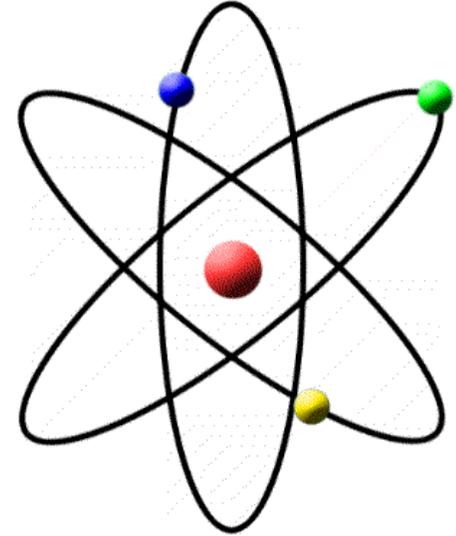
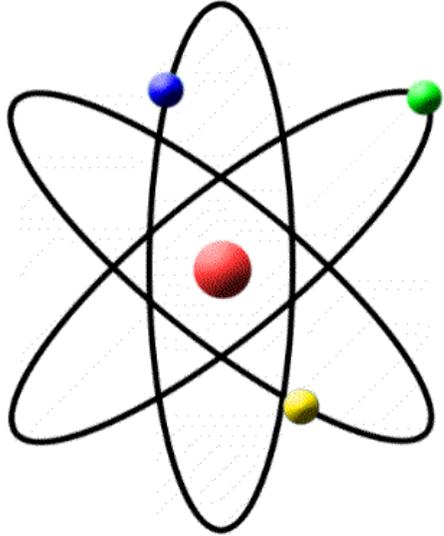


Magic
solution?

- Nuclear safety?
- Nuclear security?
- Nuclear safeguards (proliferation)?
- Nuclear waste
- Decommissioning
- Famous accidents
- Although regulated, lack of trust

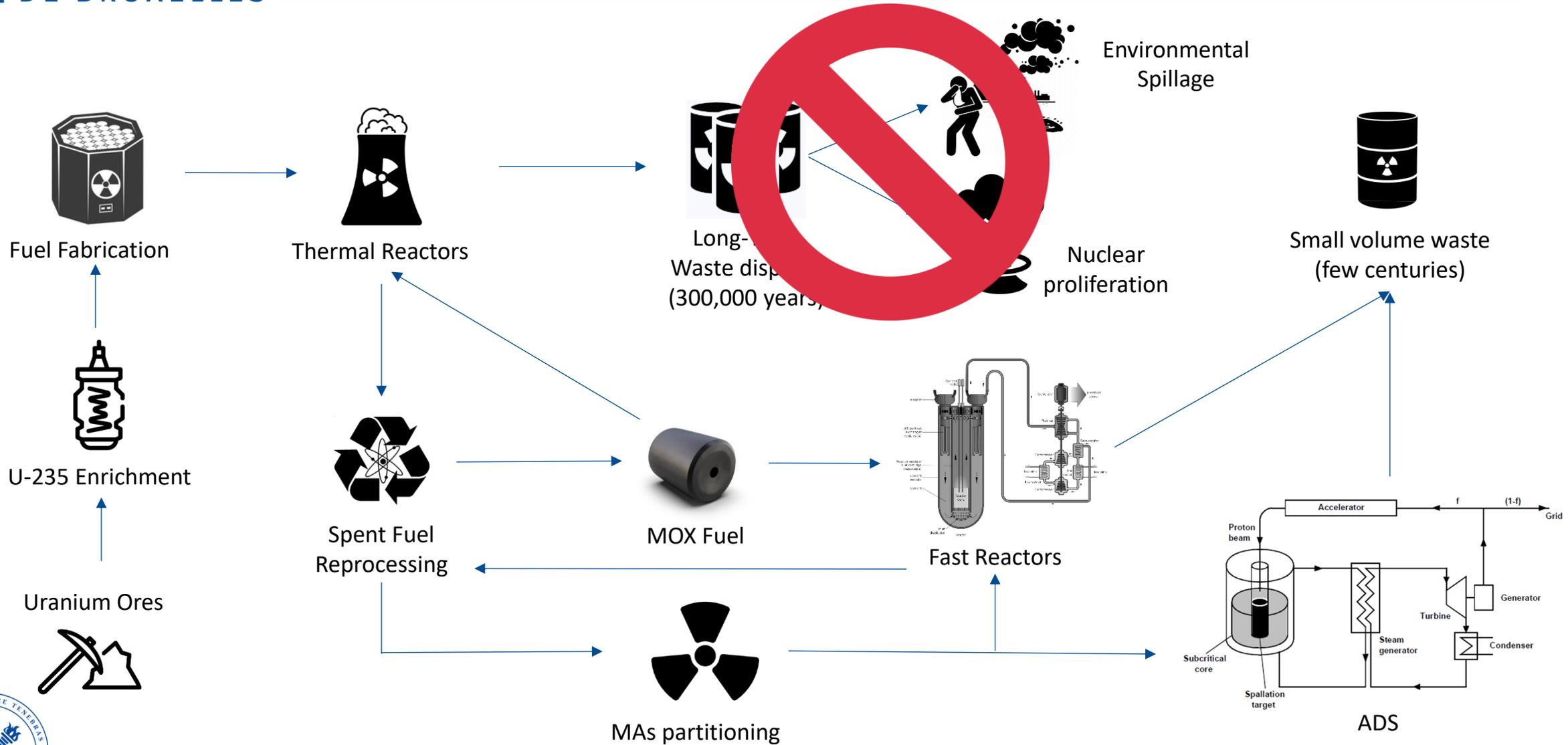
INDIANA JONES

and the



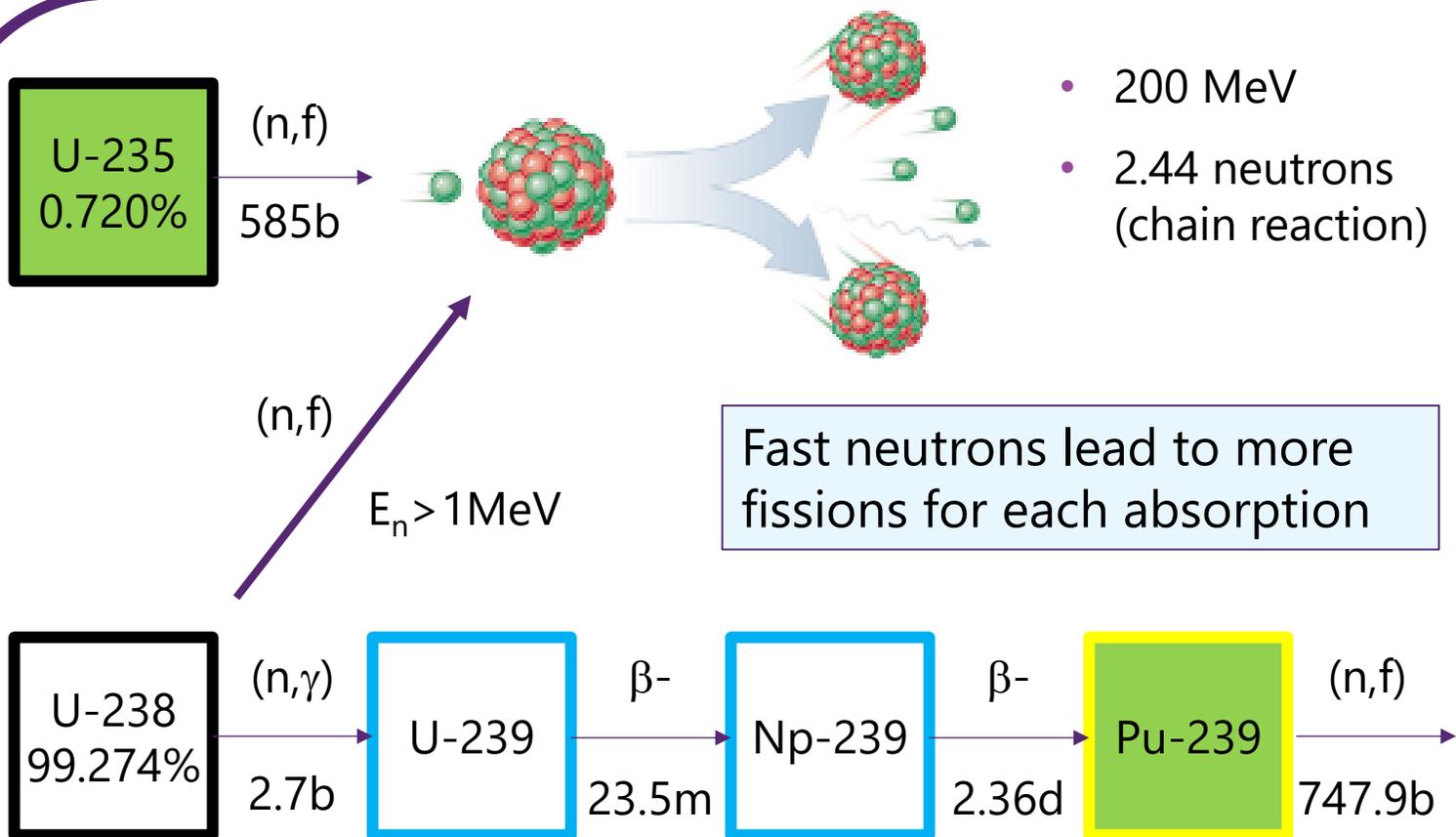
HOLY GRAIL OF THE NUCLEAR INDUSTRY

The Holy Grail: The Closed-Fuel Cycle



Why (lead) fast neutron reactors?

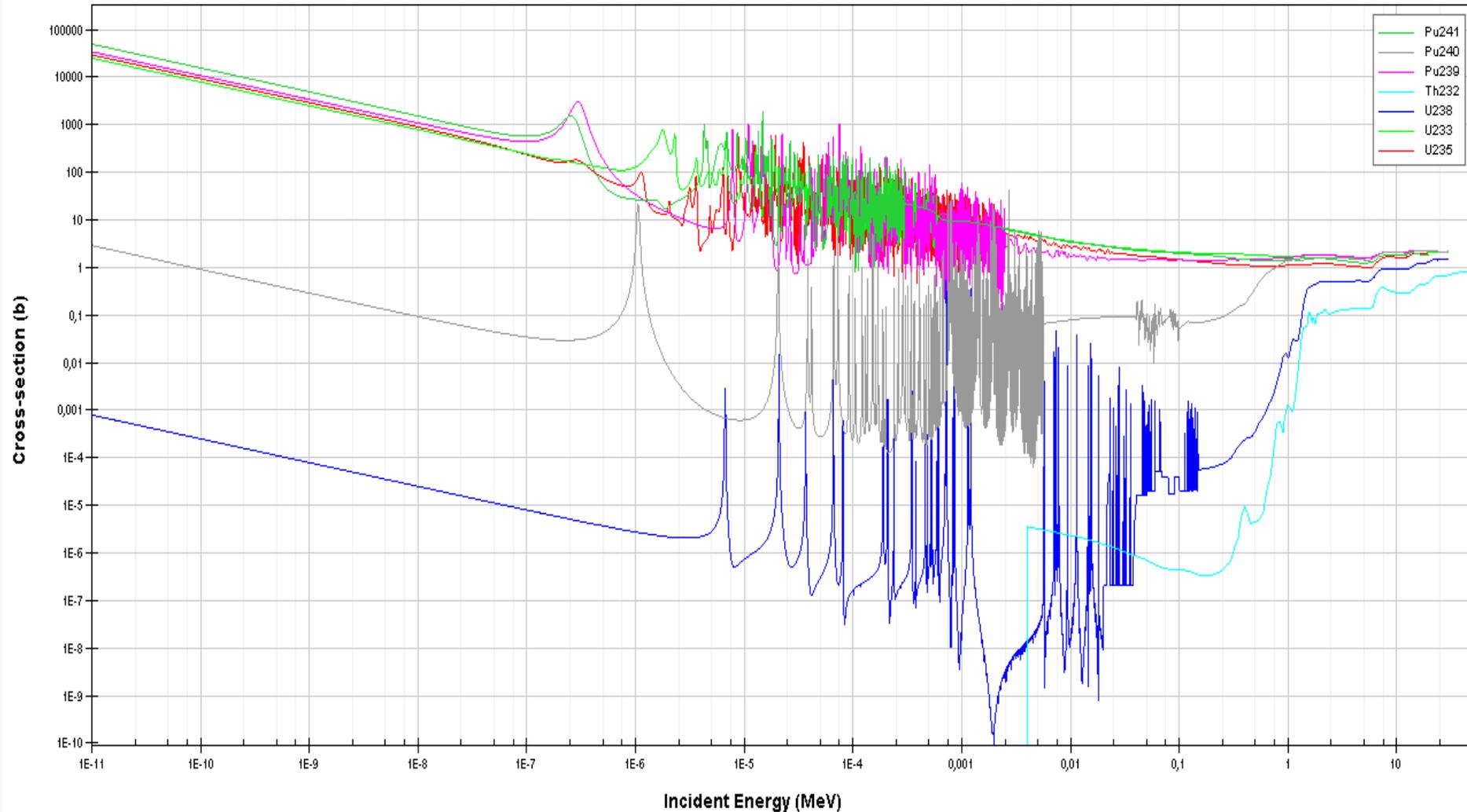
A reactor is a **box** where certain reactions take place in a controlled **environment**



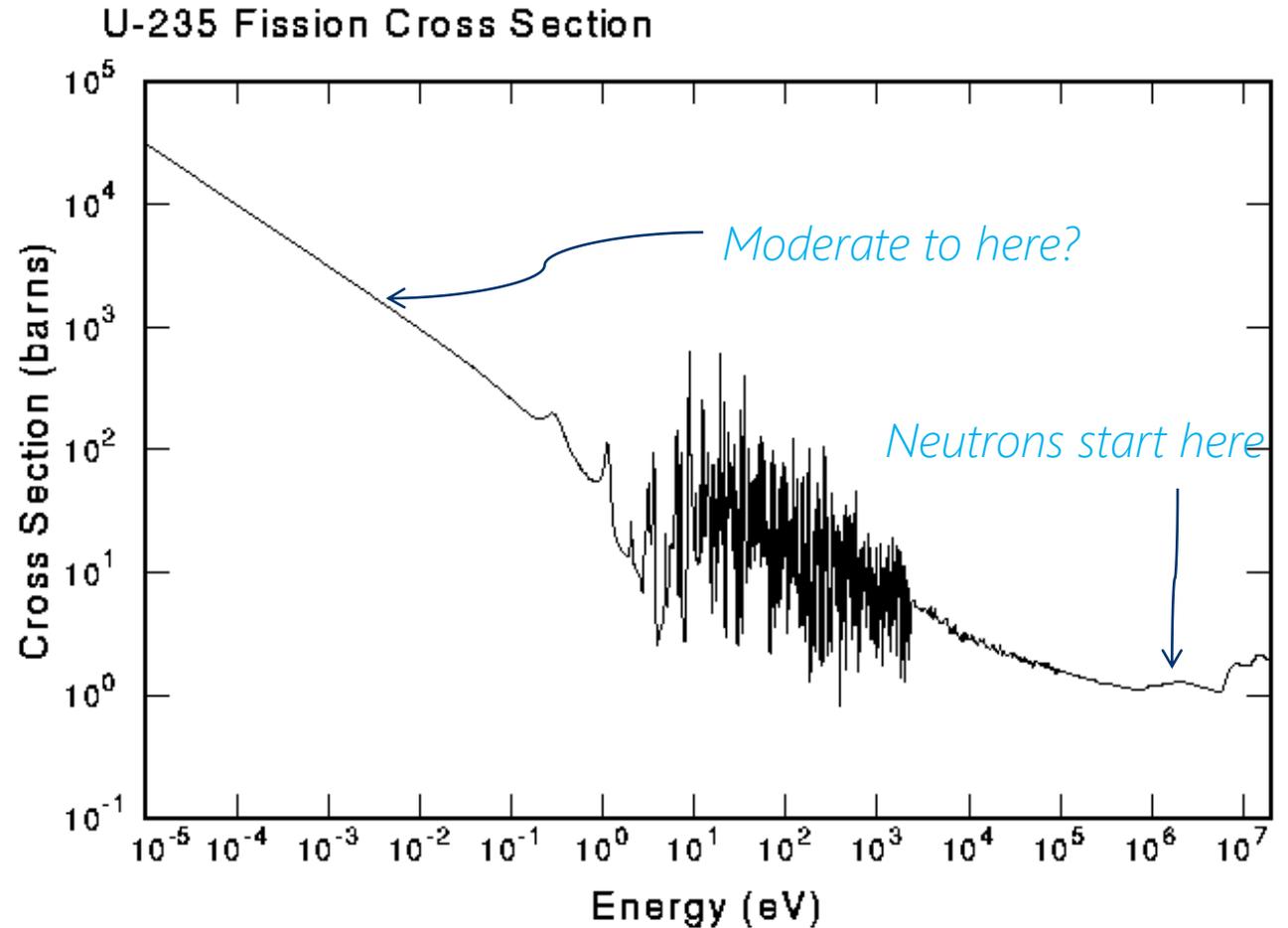
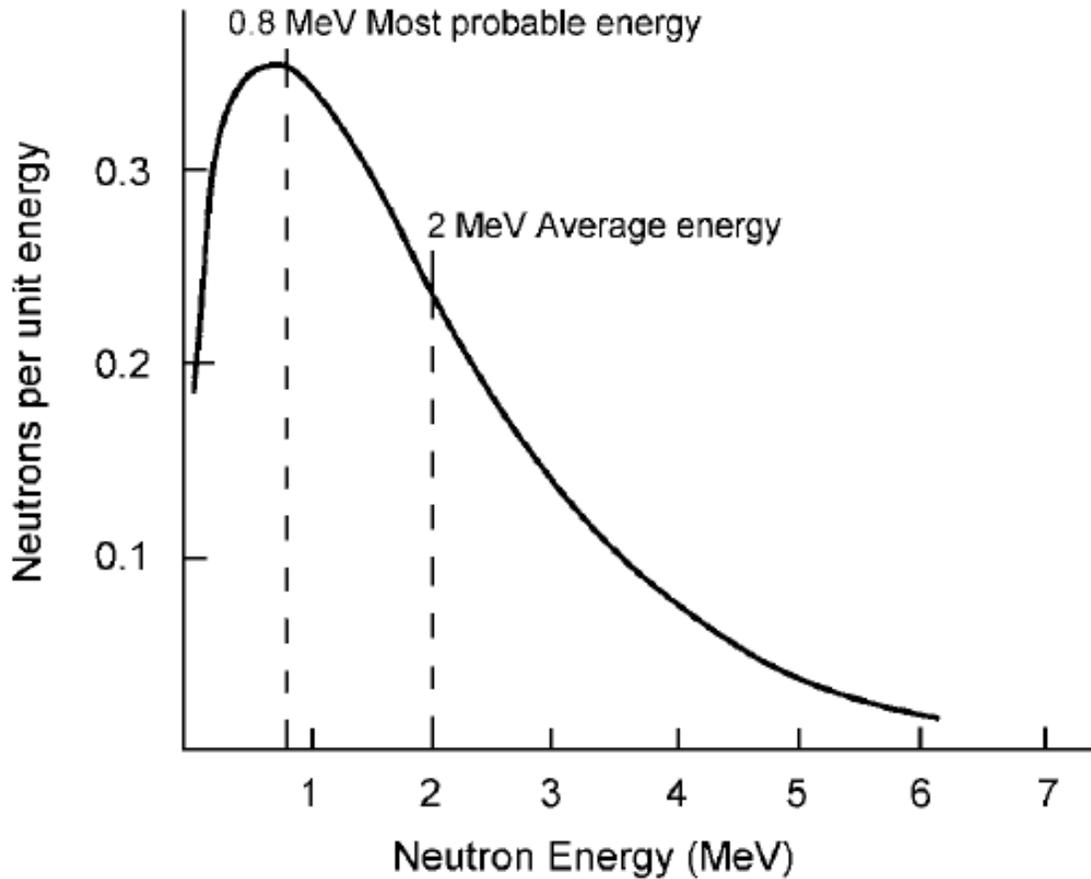
	Fast	Thermal
U-235	80%	81%
U-238	17%	10%
Np-237	27%	2%
Pu-238	70%	8%
Pu-239	86%	64%
Pu-240	55%	1%
Pu-241	87%	75%
Pu-242	52%	2%
Am-241	21%	1%
Am-243	23%	1%
Cm-244	45%	6%

Nuclear fission – Cross sections

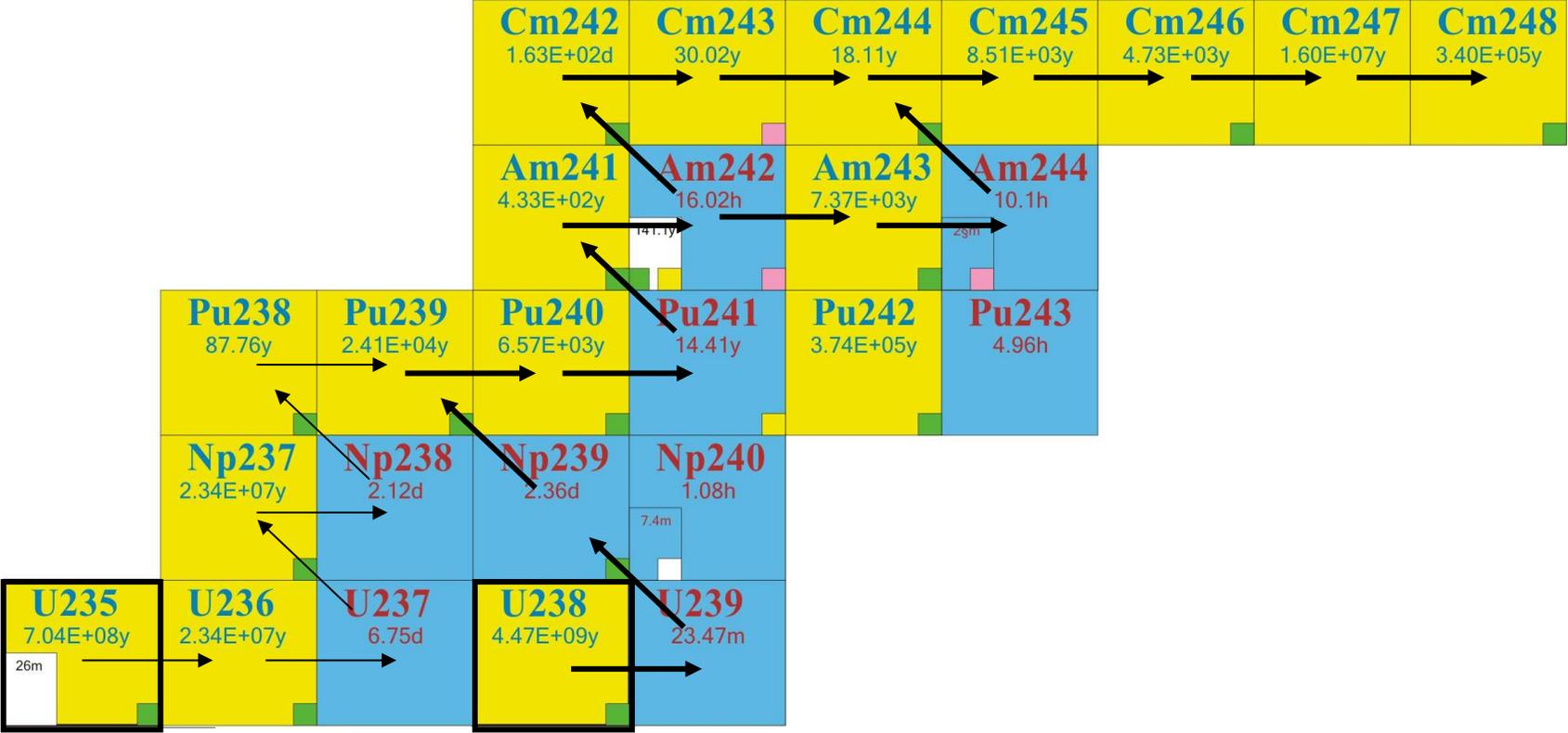
Incident neutron data / ENDF/B-VII.1 // MT=18 : (z,fission) total fission / Cross section



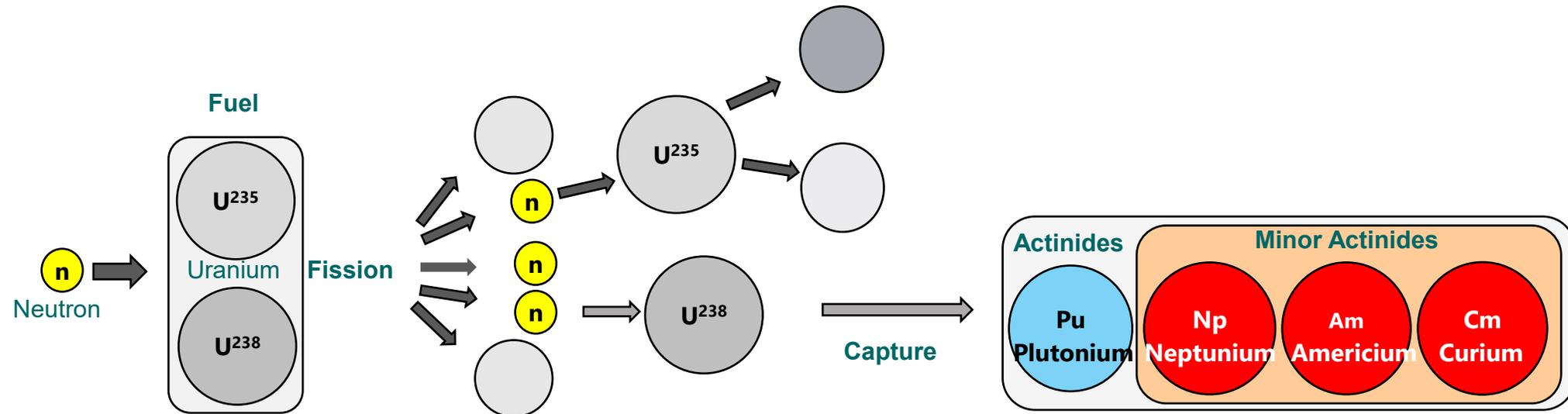
Nuclear fission – Energy spectrum



Nuclear fission – Actinide production



What is the problem? High-level nuclear waste

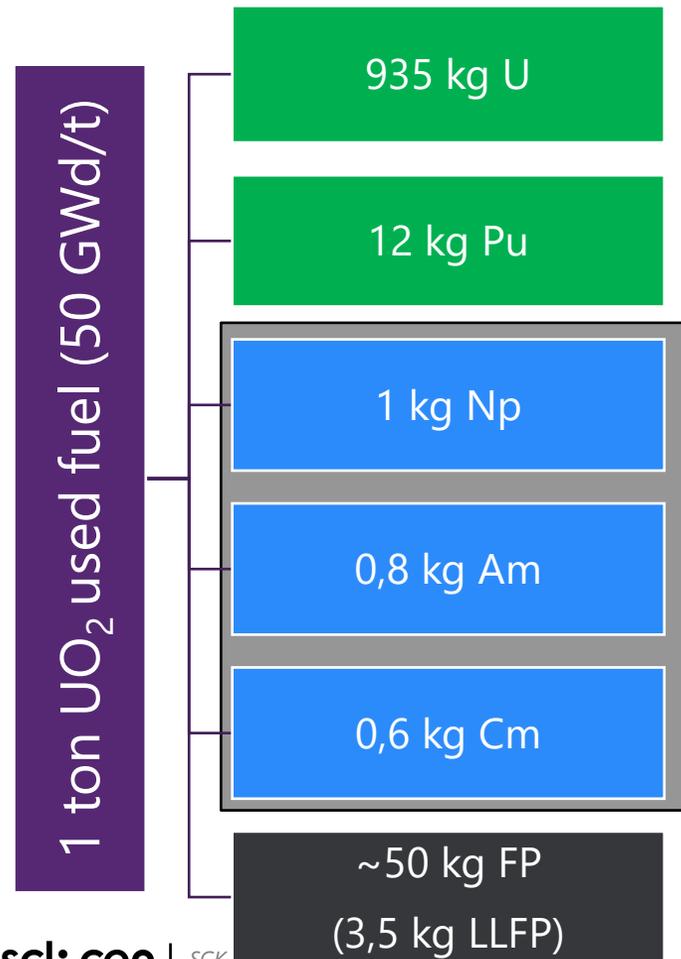


Minor Actinides

high radiotoxicity long lived waste that are difficult to store due to:

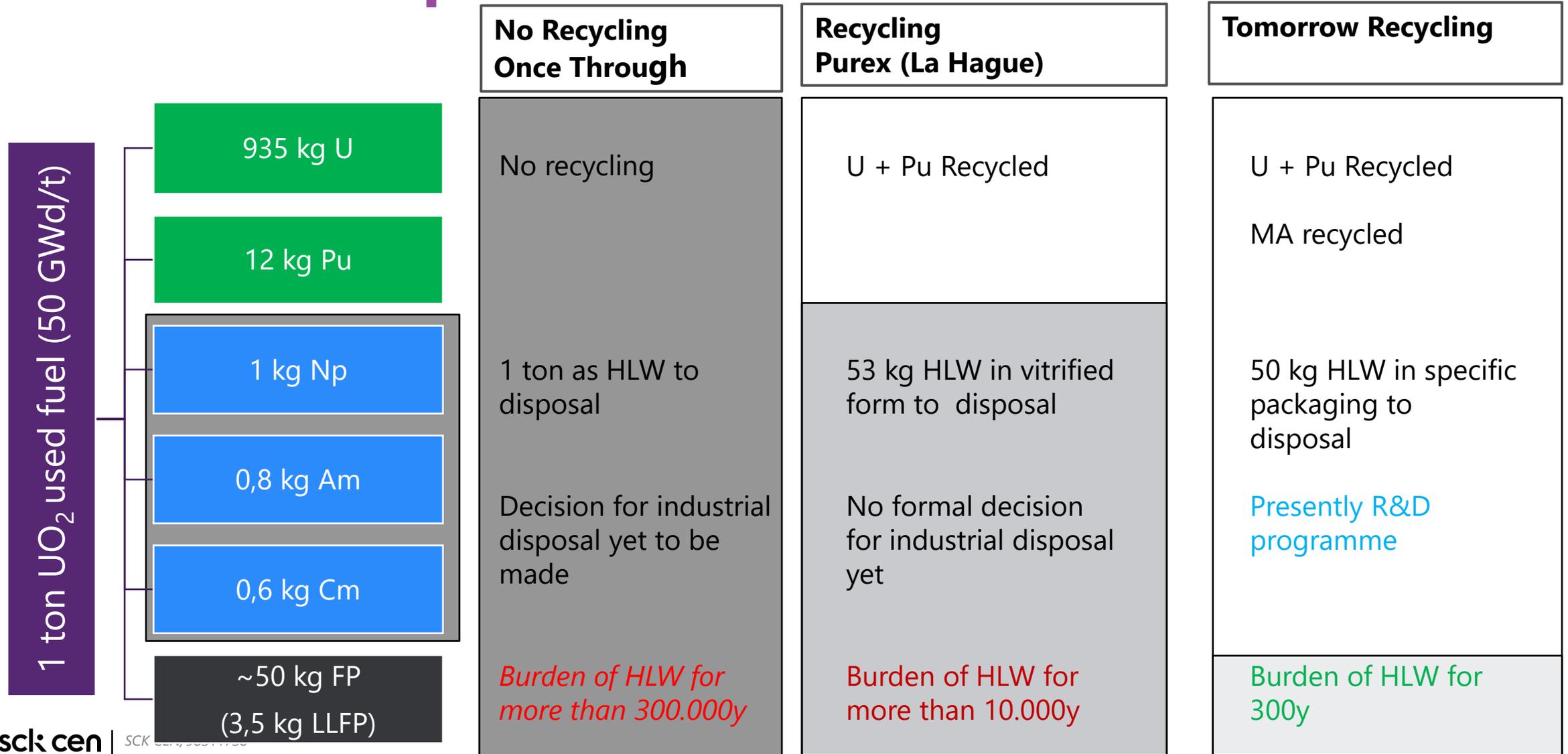
- Long lived (>1,000 years)
- Highly radiotoxic
- Heat emitting

What is the problem?

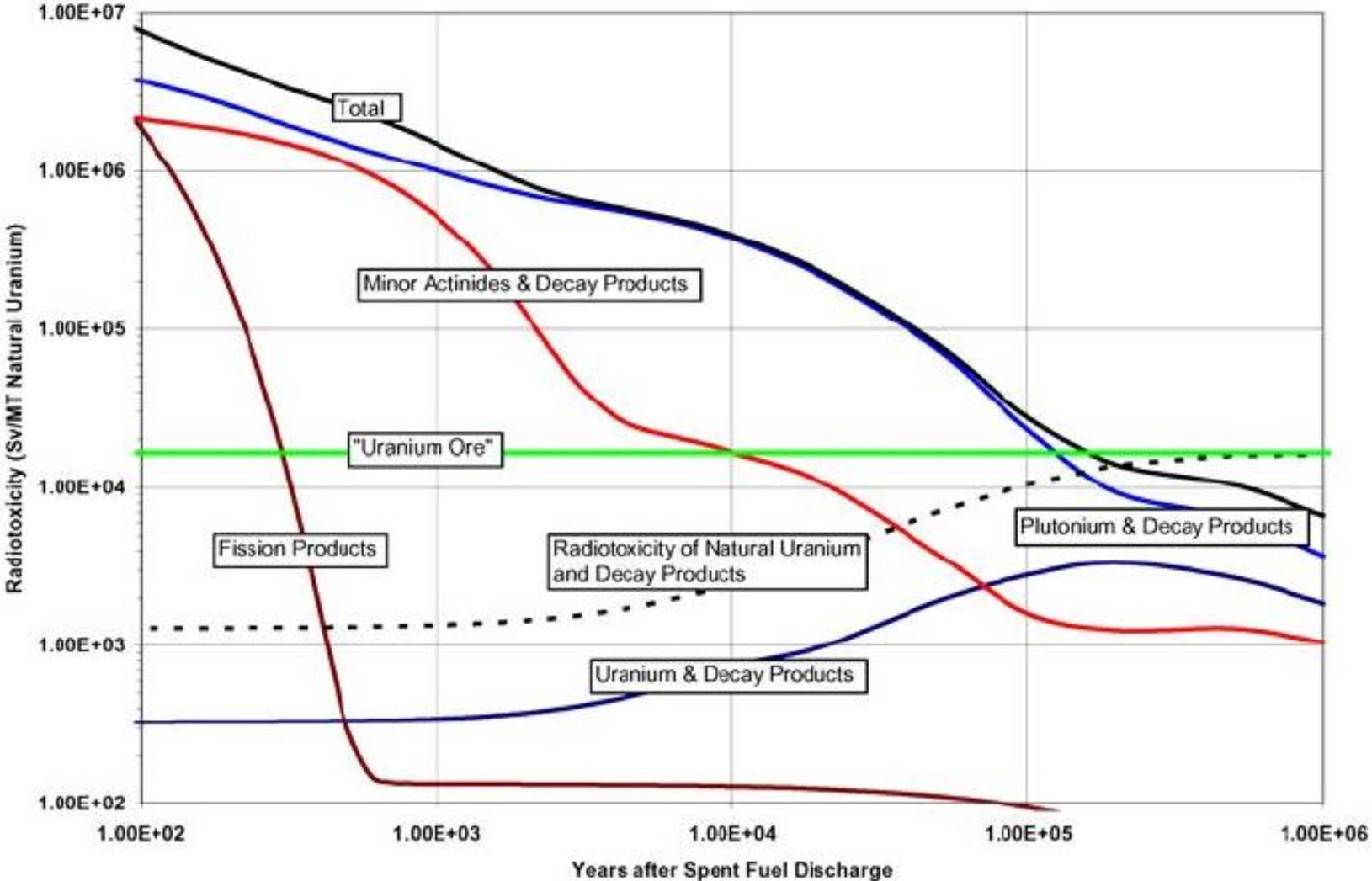


- Efficient use of resources
 - We only use <<1% of the Uranium we mine
 - At current consumption rates, worldwide proven reserves for only 150 years
- Waste
 - Way more used fuel going to waste than needed
 - Radiological burden

What is the problem?



Radiotoxicity of spent fuel

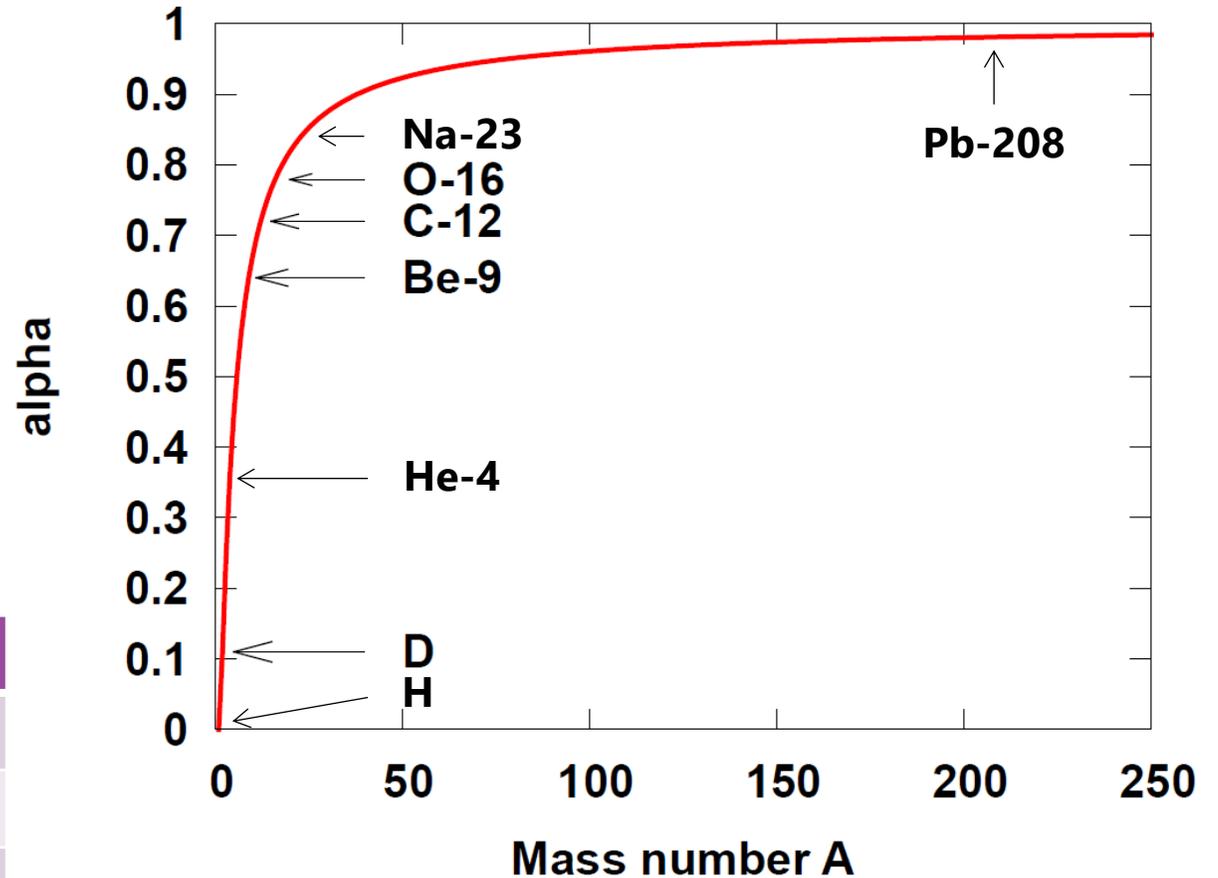


Moderation – Neutron energy loss per collision

- For a target with mass A:

$$\alpha E_i \leq E_f \leq E_i \quad \alpha = \left(\frac{A - 1}{A + 1} \right)^2$$

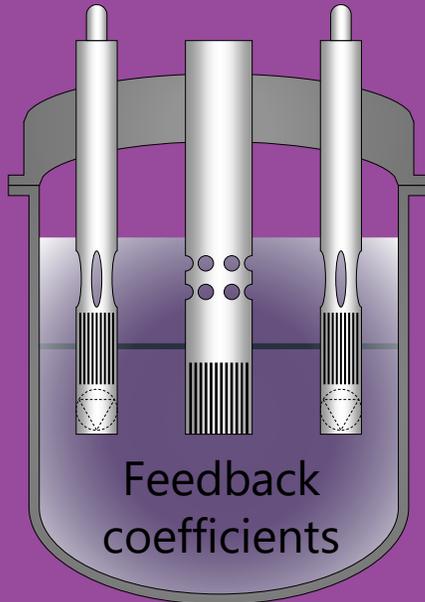
Fast reactors cannot be cooled by water



	Melting point	Boiling point
Sodium	98 °C	883 °C
Lead	327 °C	1749 °C
FLiBe (LiF-BeF ₂)	459 °C	1430 °C
Helium (gas)	-272°C	-269°C

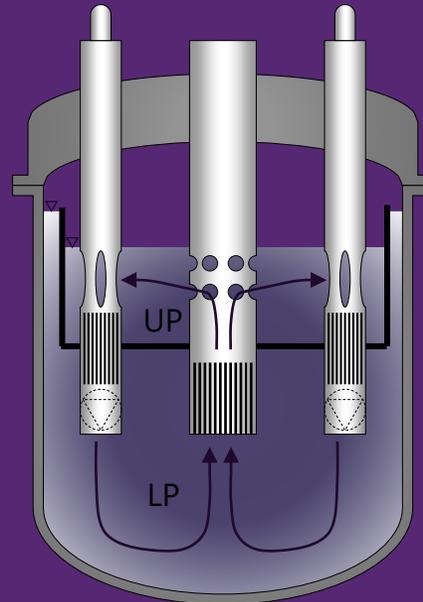
LFRs are excellent at the 3 Basic Safety Functions

Control
the reaction



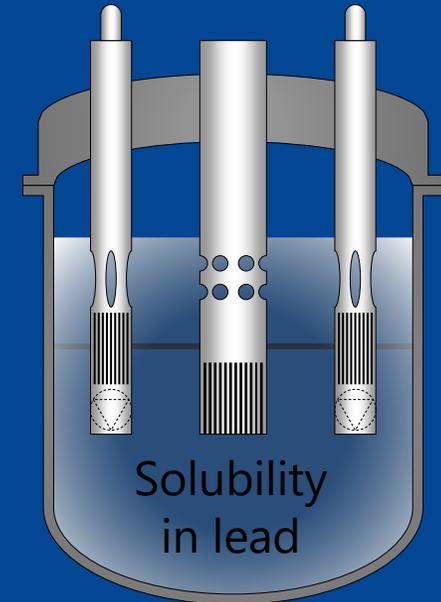
SFR?

Cool
the fuel



GFR?

Contain the
radioactive substances

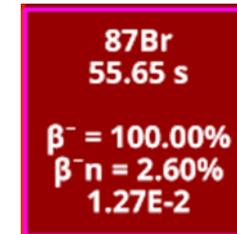
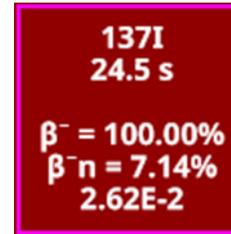


MSR?

Fast reactors to burn minor actinides (waste)

- Reactor control depends on delayed neutron fraction β

$$\beta = \frac{\text{precursor atoms}}{\text{precursor atoms} + \text{prompt neutrons}}$$



← Fission yield (U235)

Fissile isotope	U 235	Pu 239	Am 241	Cm 242	Cm 243
β , pcm	650	220	130	90	40

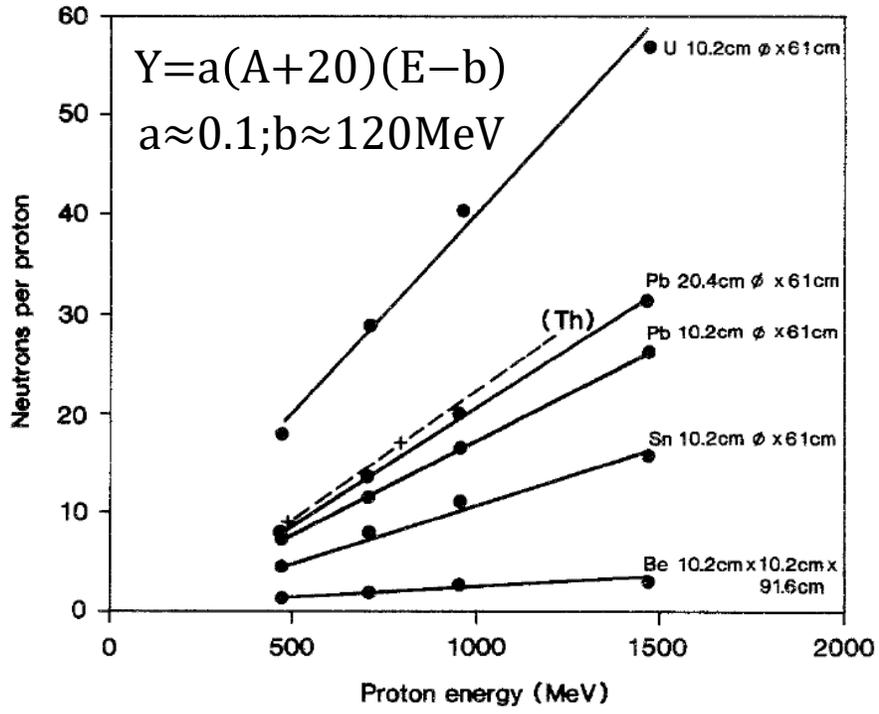
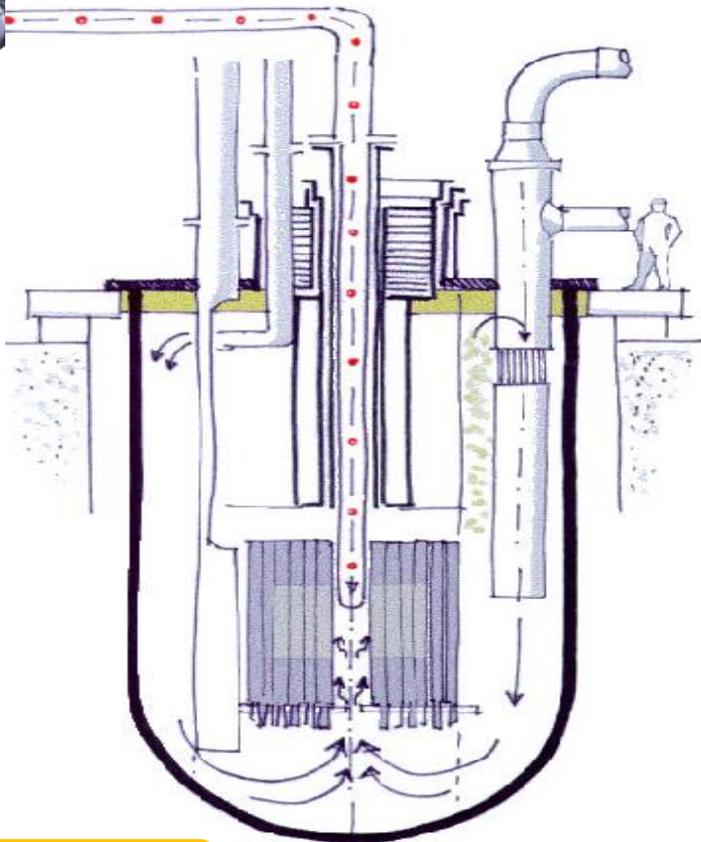
- Fast **critical** reactor can safely load only few % of MA → 2 – 4 kg MA / TWh
- Fast **sub-critical** reactor has no limitation on MA load → ~35 kg MA / TWh

External neutron source by spallation reaction

Proton Accelerator (~1GeV, ~1mA)

Sub-critical reactor ($k_{\text{eff}} < 1$)

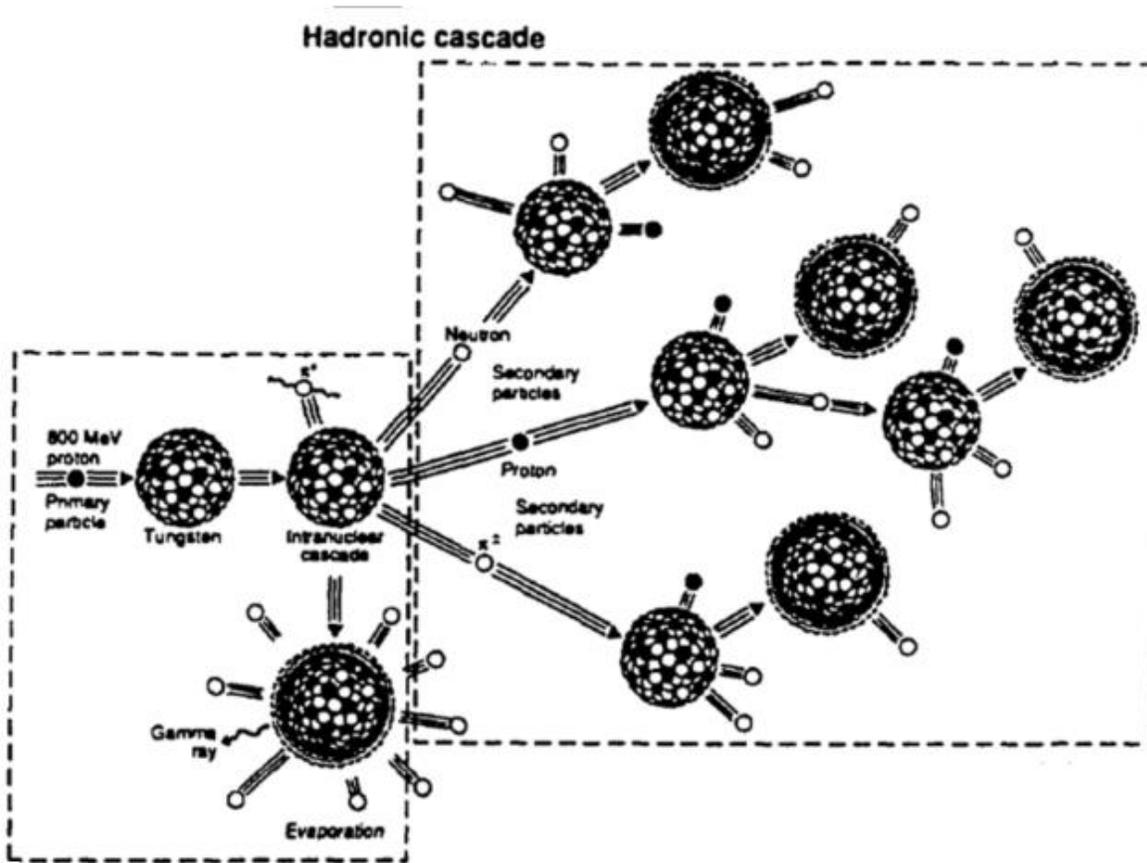
$$M = \frac{1}{1 - k_{\text{eff}}}$$



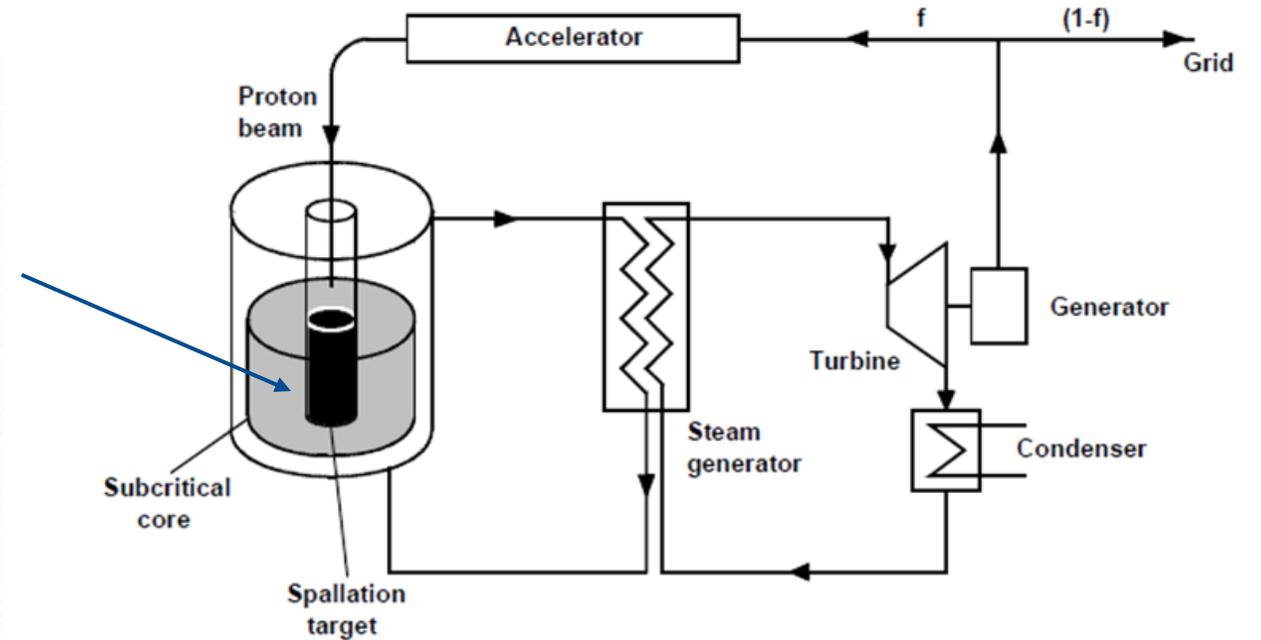
ADS = Accelerator-Driven System



□ Nuclear Spallation: high-efficiency neutron source



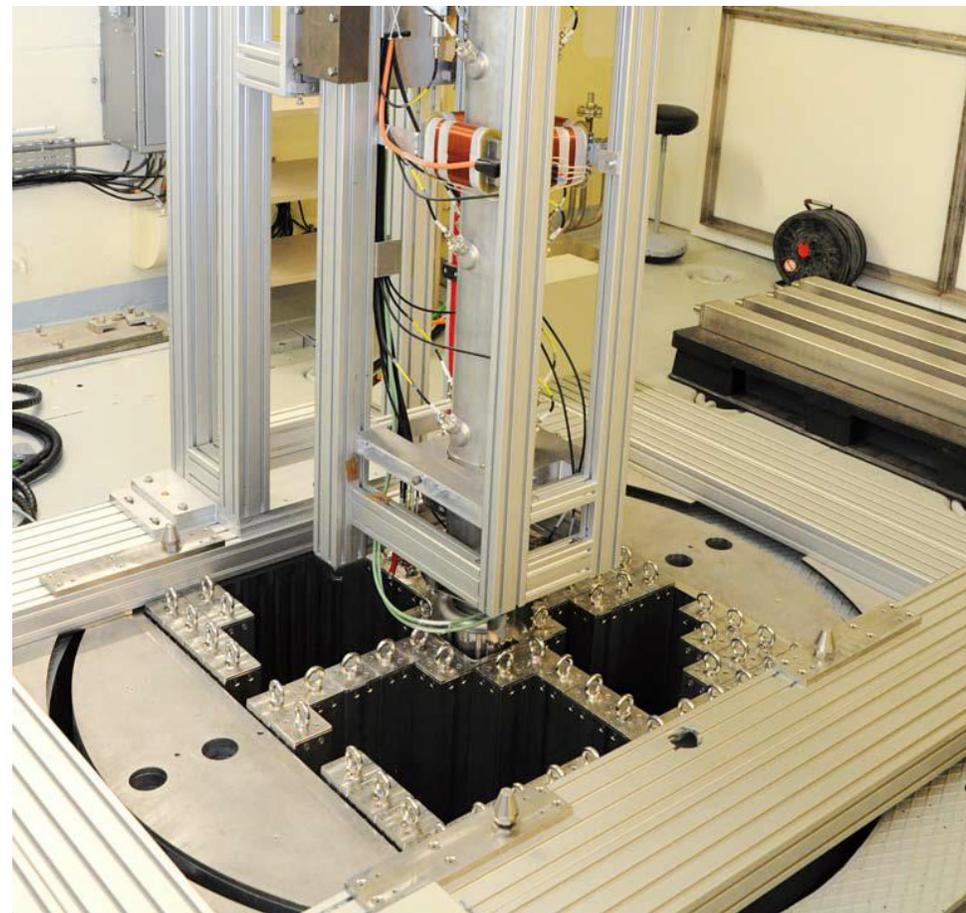
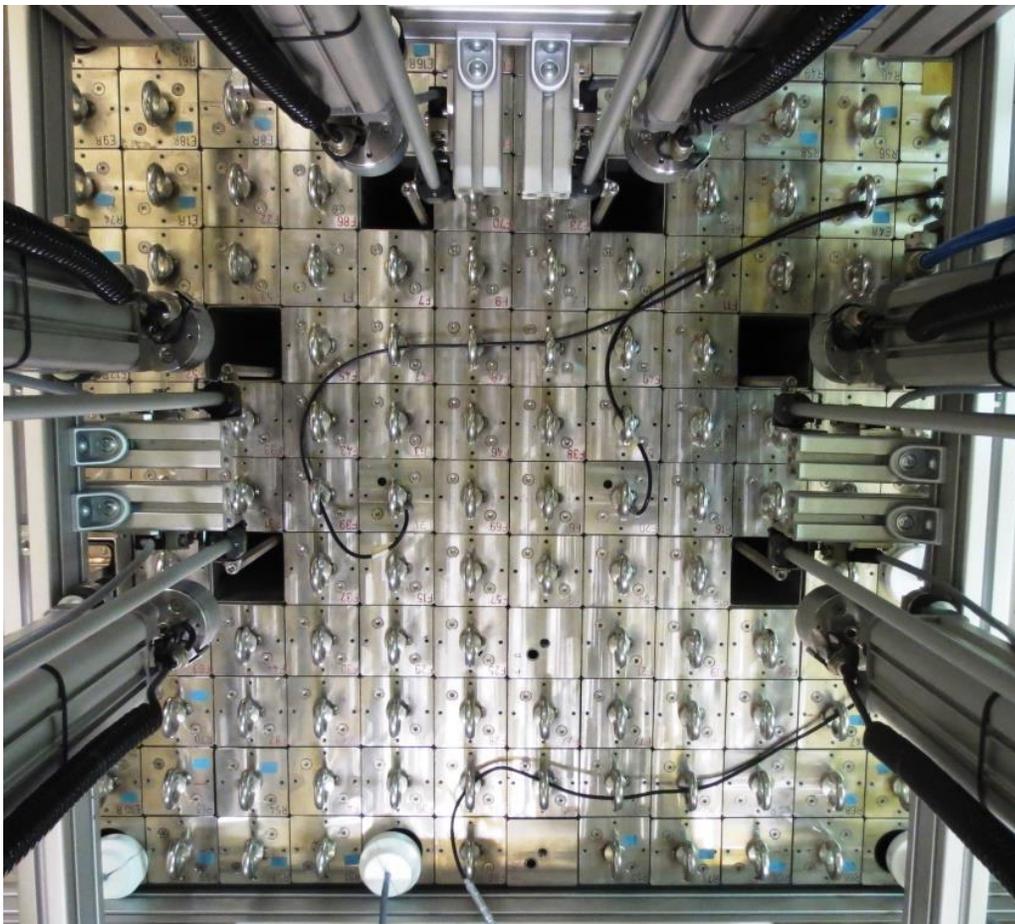
□ ADS system: Reactor + Accelerator



- Sub-critical core
- High loading of MAs (transmuter)
- Shut-down: stop accelerator

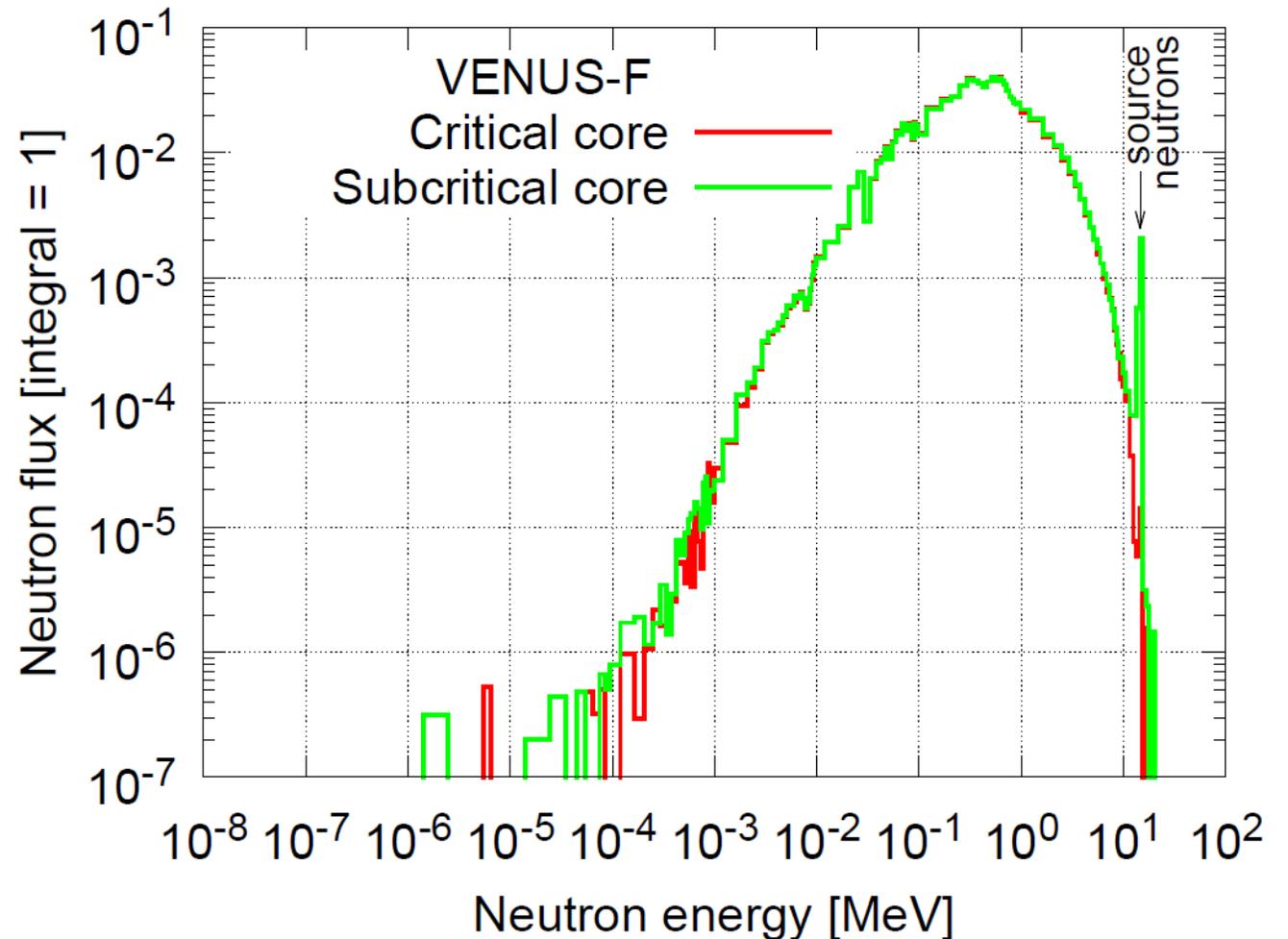


VENUS-F + GENEPI-3C = GUINEVERE ADS

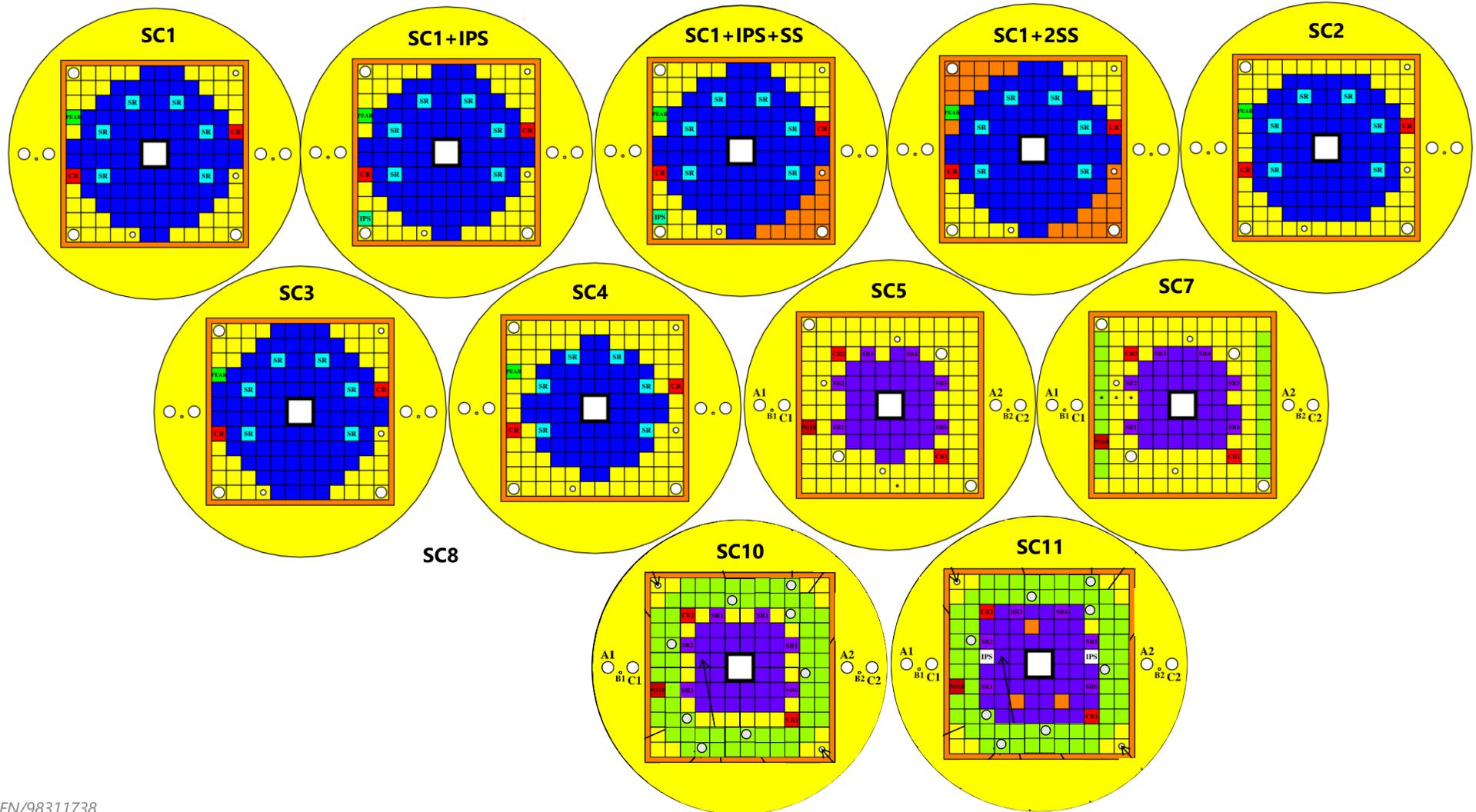


GUINEVER ADS neutron spectrm

- Accelerate D into target with either
 - Titanium-tritium (TiT)
 - Titanium-deuterium (TiD)
- $T(D,n)^4\text{He} \rightarrow 14 \text{ MeV}$
- $D(D,n)^3\text{He} \rightarrow 2.5 \text{ MeV}$
- $\sim 25 \times 10^9 \text{ n/s}$ at 5 kHz

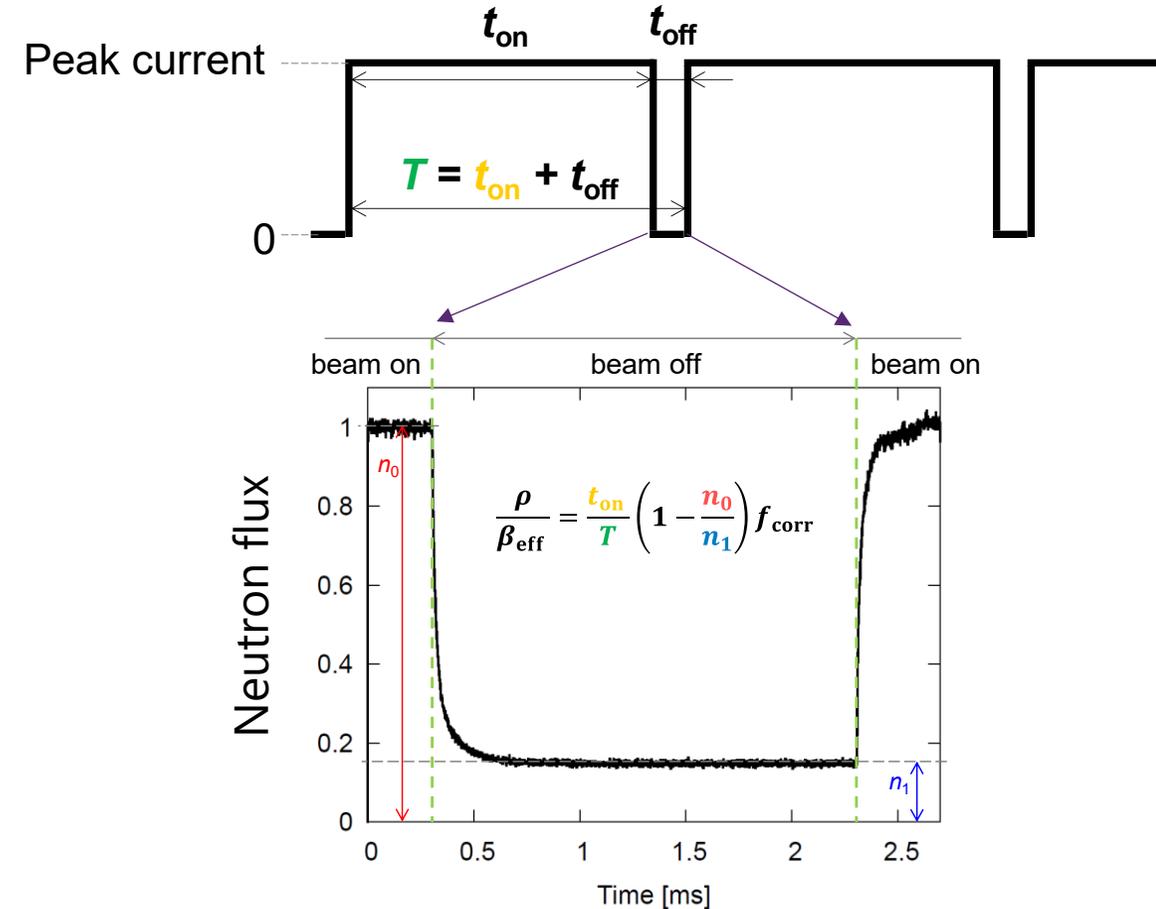


GUINEVER subcritical configurations



GUINEVER sub-criticality measurement

- Fission chambers with ^{238}U deposit selected as the optimal detector type for reactivity monitoring
- *Source jerk method* validated as a reference subcriticality measurement technique



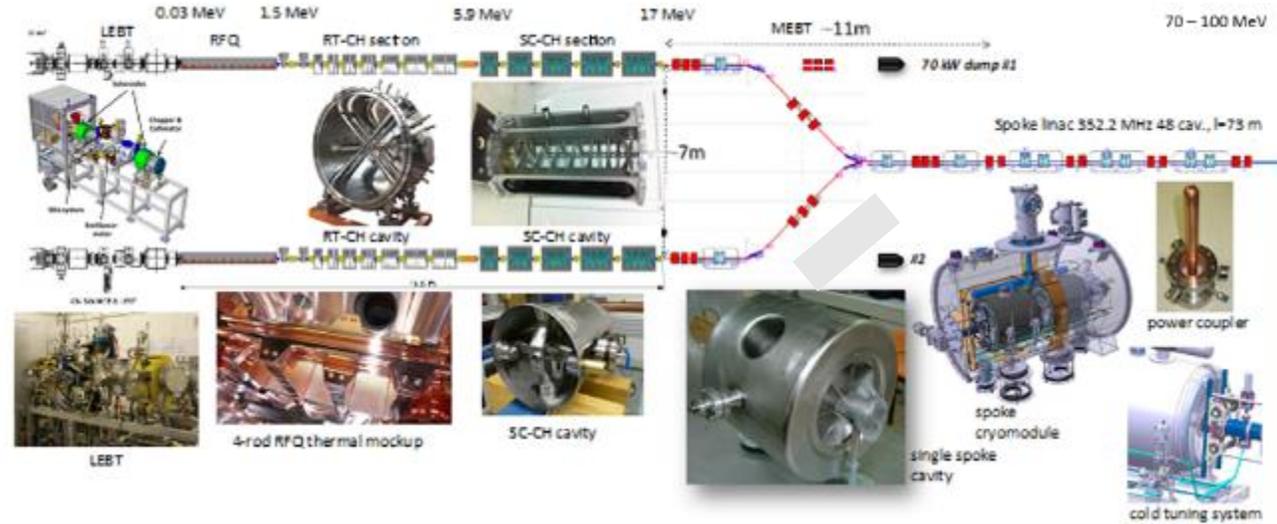
MYRRHA's phased implementation strategy

UNDER CONSTRUCTION

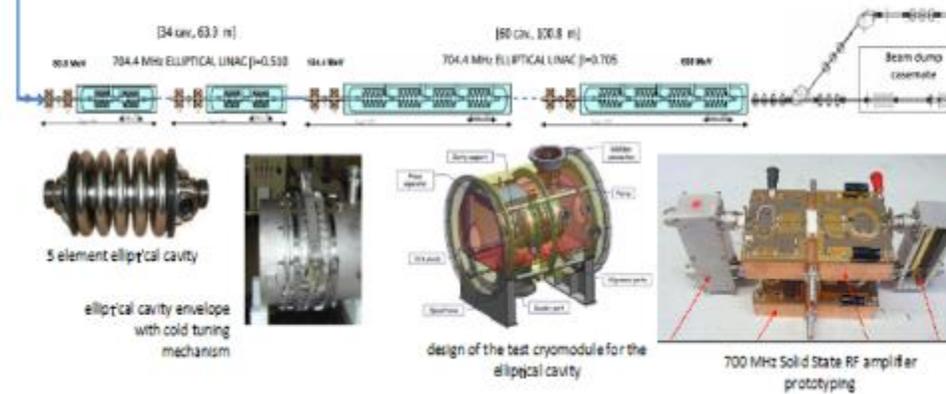
Benefits of the phased approach:

- MYRRHA Phase 1 | MINERVA to be available in Mol at **end of 2029**
- spreading the investment costs
- successful milestone then next step. Reducing technical & financial risks

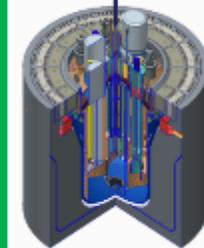
Phase 1 – 100 MeV + Proton Target Facility



Phase 2 – 600 MeV



Phase 3 – Reactor



MYRRHA Phase 1 | MINERVA Facility construction started in September 2024





MYRRHA | MINERVA Groundbreaking Ceremony
Mol, 25th June 2024

2023



2024



2025



For more information

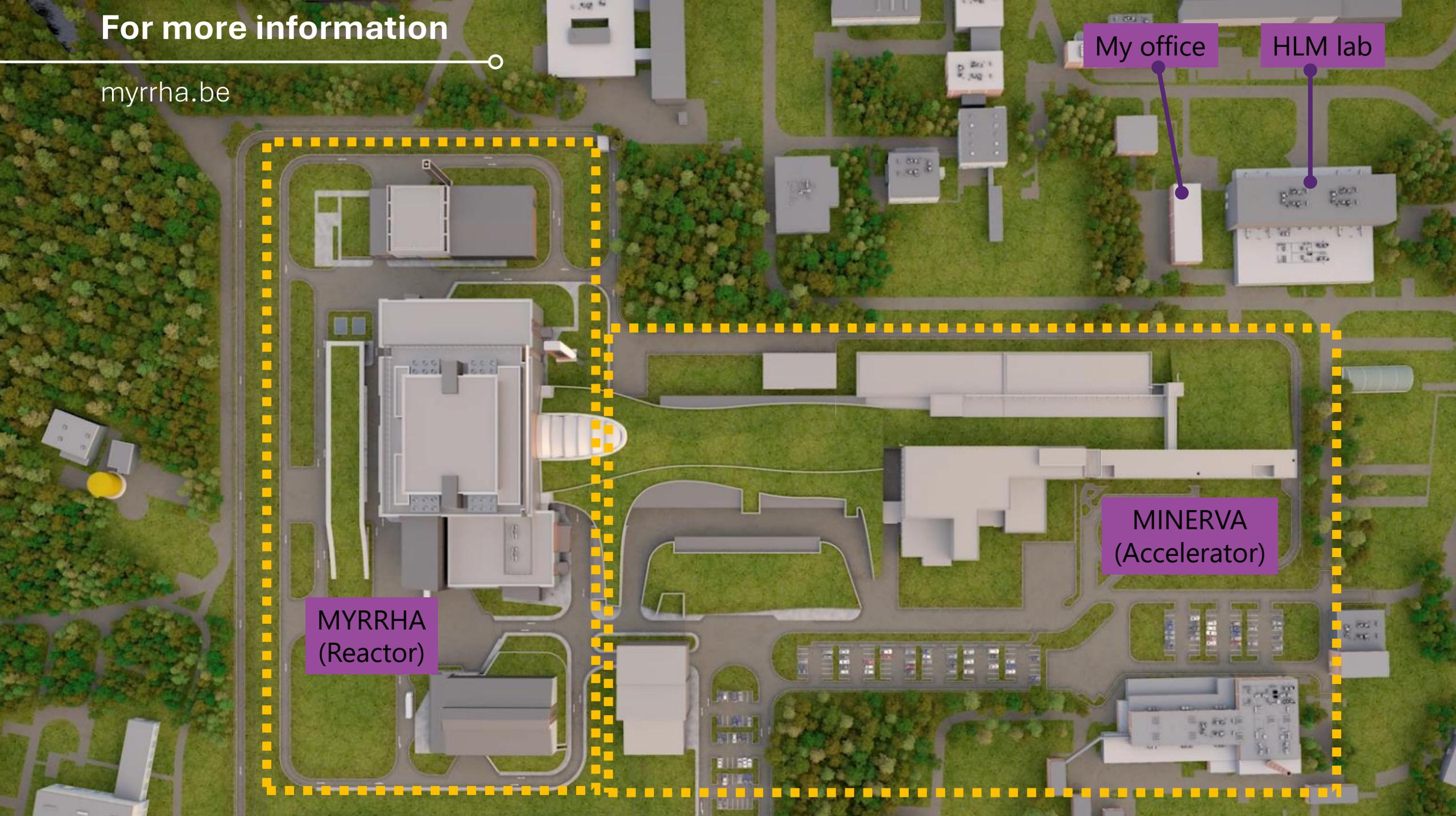
myrrha.be

My office

HLM lab

MYRRHA
(Reactor)

MINERVA
(Accelerator)

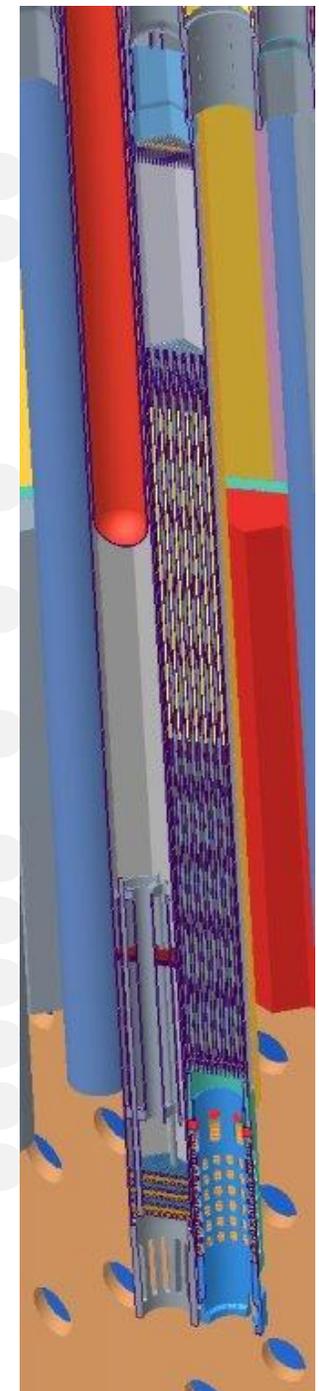
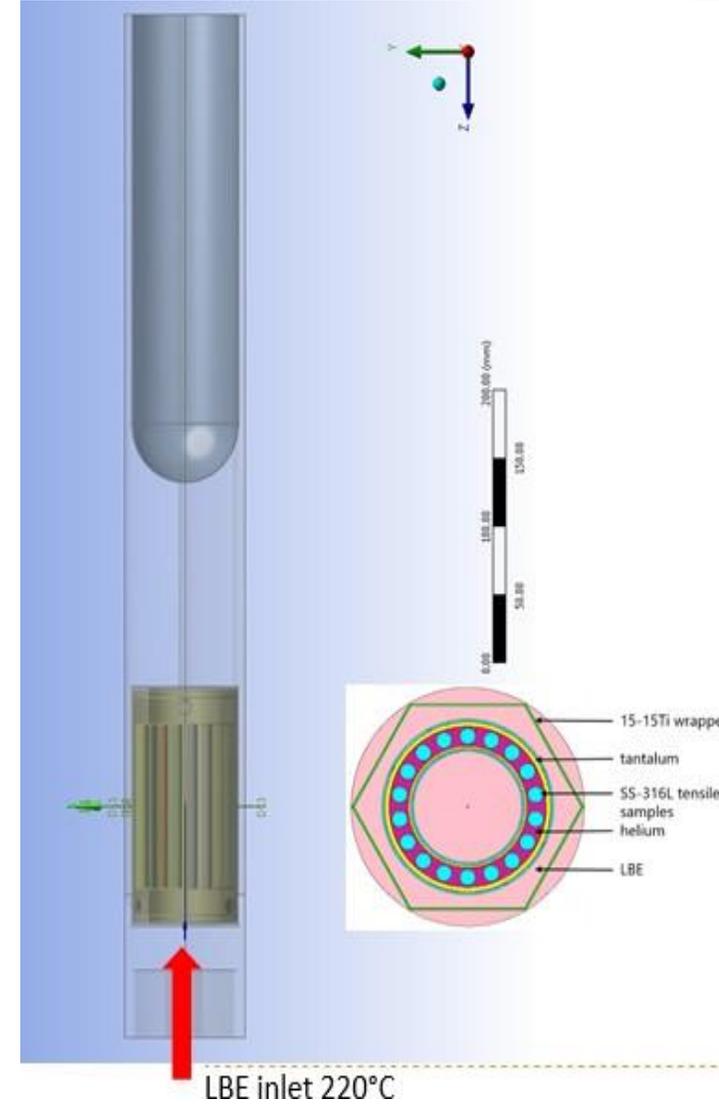
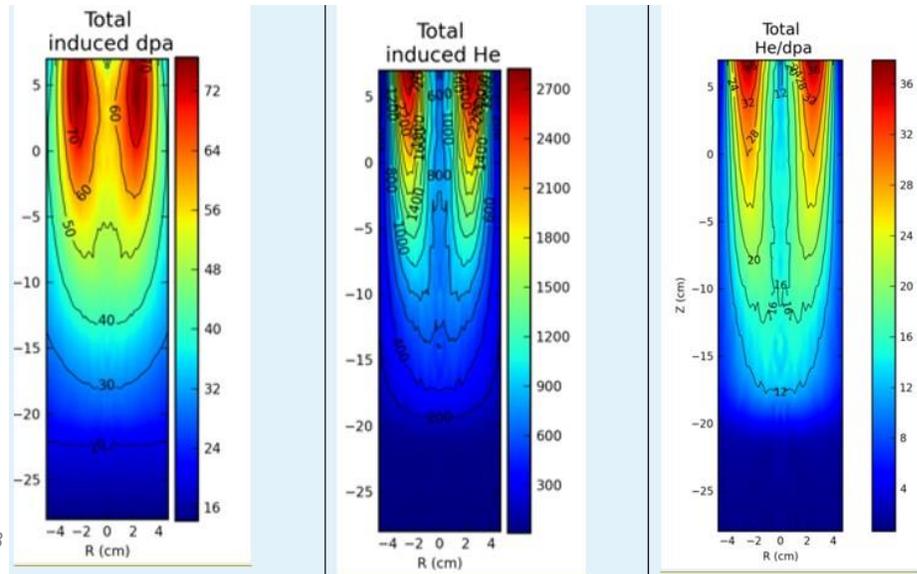




Spallation target assembly (STA)

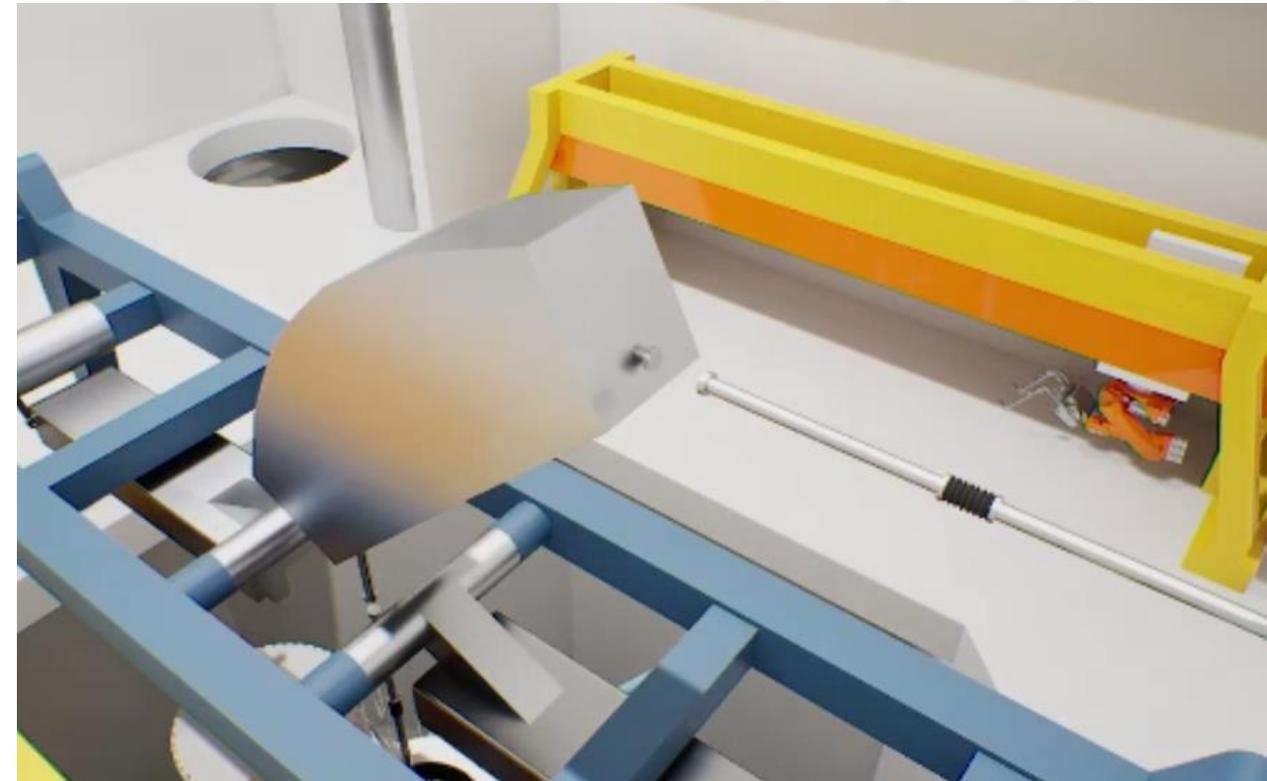
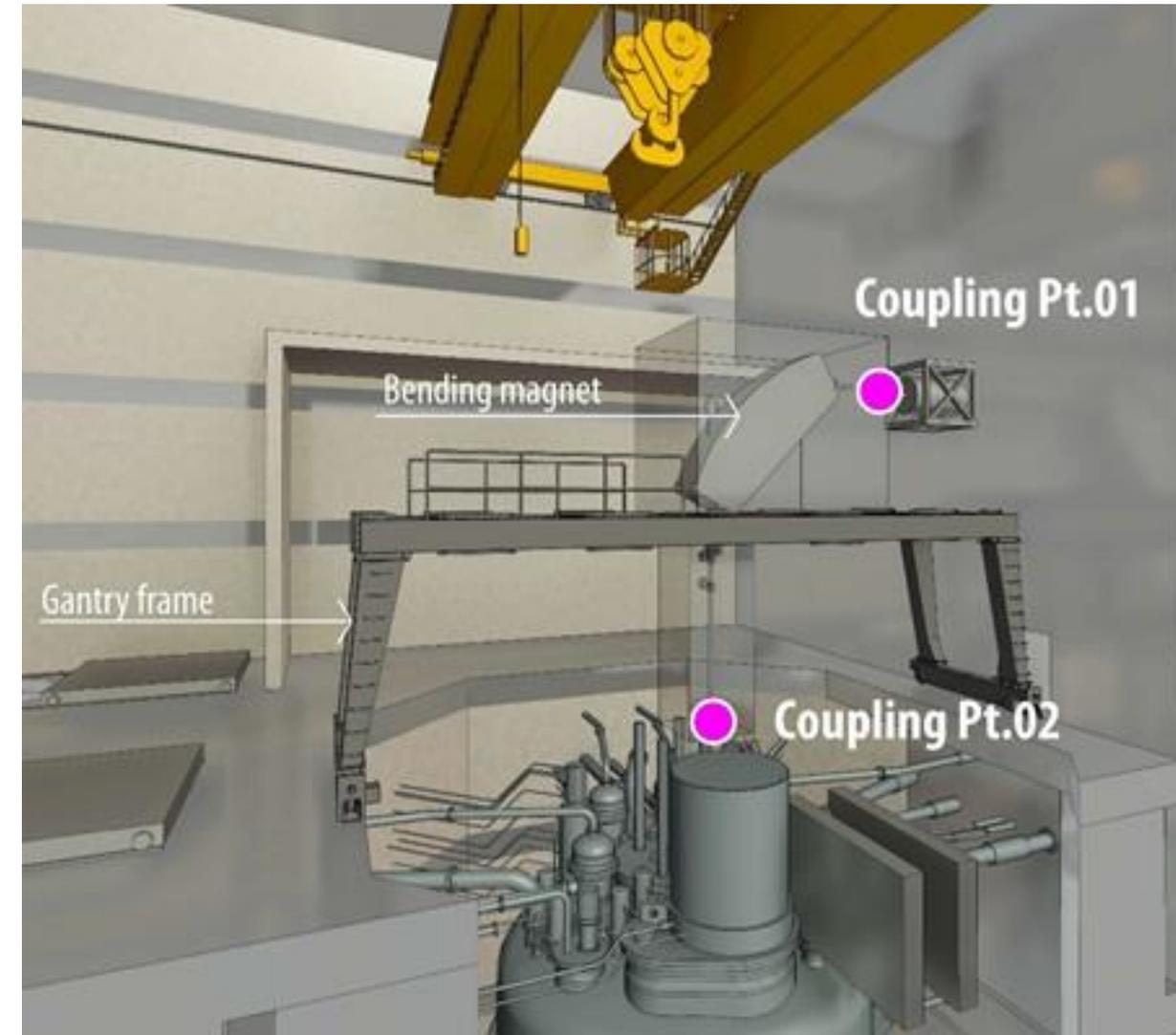
IPS occupying the central (sub-critical) core position to bring the proton beam into the core

- Beam tube + Hemispherical beam window (T91)
- Hexagonal wrapper (15-15Ti)



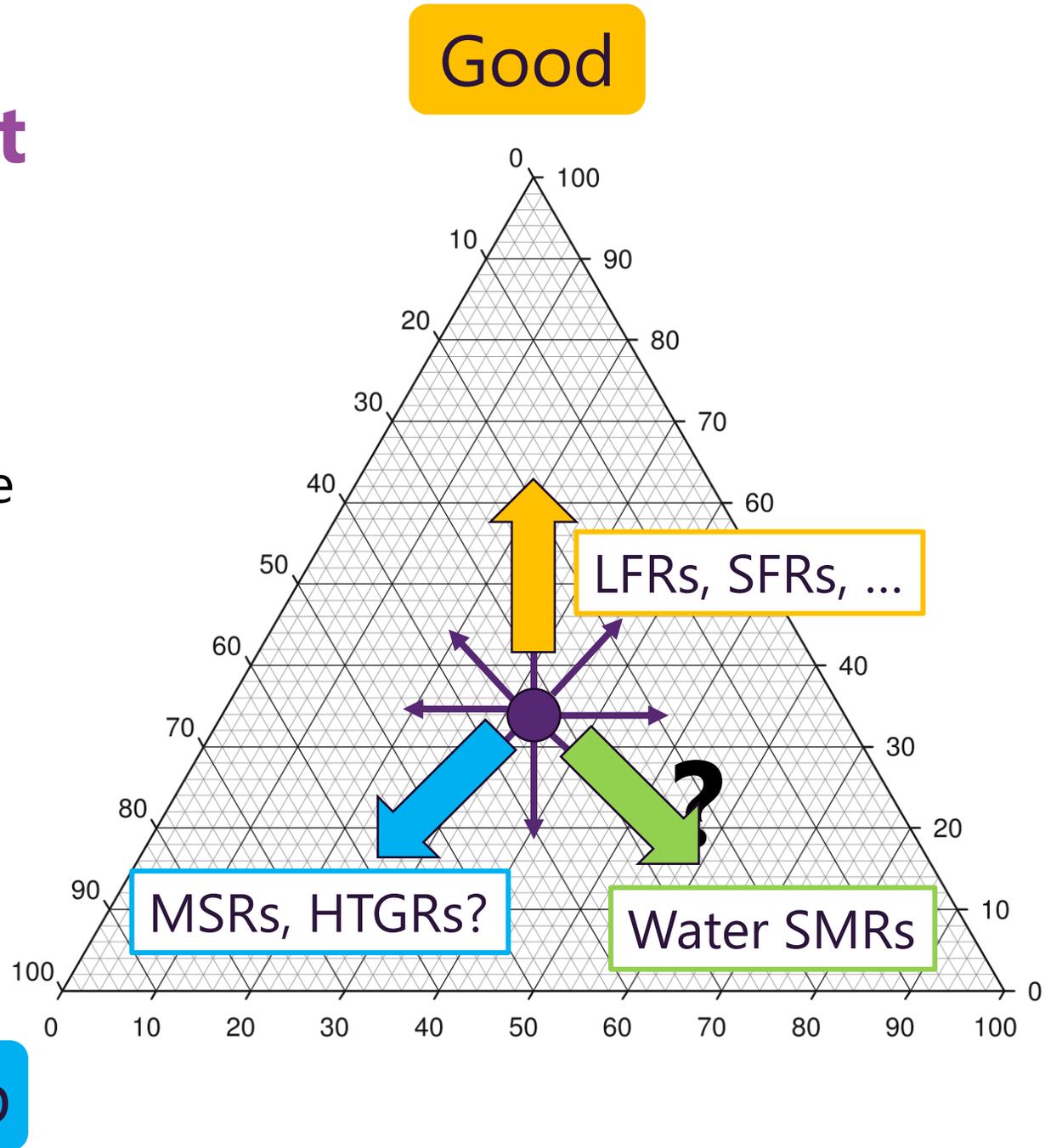
Spallation target assembly (STA)

Connection Proton Beam – Spallation Target and Reactor:
Space, instrumentation and utilities included in the conceptual design



The perfect project does not exist

- Choose 2 out of 3
- No absolute numbers here
- Take now as the reference
- In which direction is the nuclear industry moving?

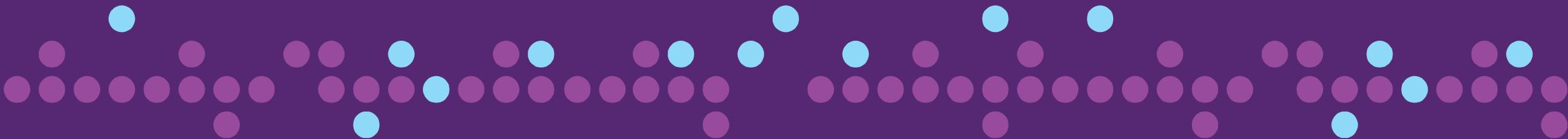


Key messages to remember

Concluding remarks

- Energy revolution, with nuclear as part of the mix
- Two key challenges: costs and public acceptance
- LFRs and ADSs address the topic of closing the fuel cycle
 - Many technological synergies
- Nuclear physics are very clear: we need fast neutrons
- LFR as a critical reactor in an equilibrium cycle
- ADS as a subcritical reactor, in an “actinide burner” approach
- MYRRHA project in Belgium: accelerator under construction
- General roadmap: Technology demonstrator(s) → FOAK → NOAK

Thank you!



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