Research Activities of the Molten Salt Reactor Team at LPSC

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With contributions of the CNRS MSFR Team *(Axel LAUREAU, Michel ALLIBERT, Max BEGUE, Louiliam CLOT, Lydie GIOT, Jad HALWANI, Daniel HEUER, Léo LAFFAY (Stellaria/CNRS), Thibault LE MEUTE (now ASNR), Anna MAITRE (CEA/CNRS), Thomas SORNAY (now Newcleo))*

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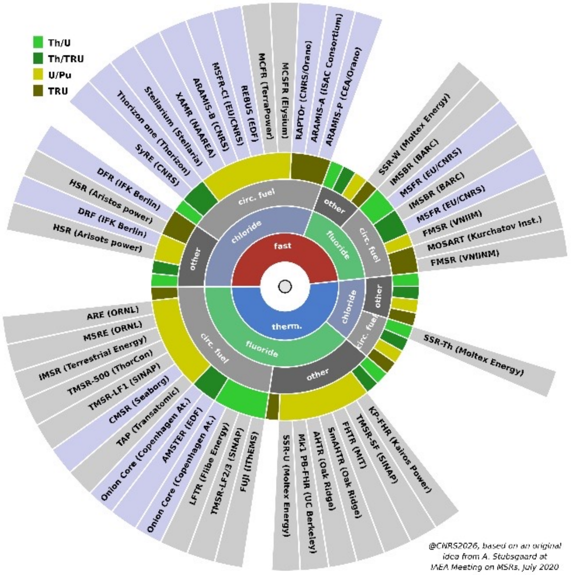
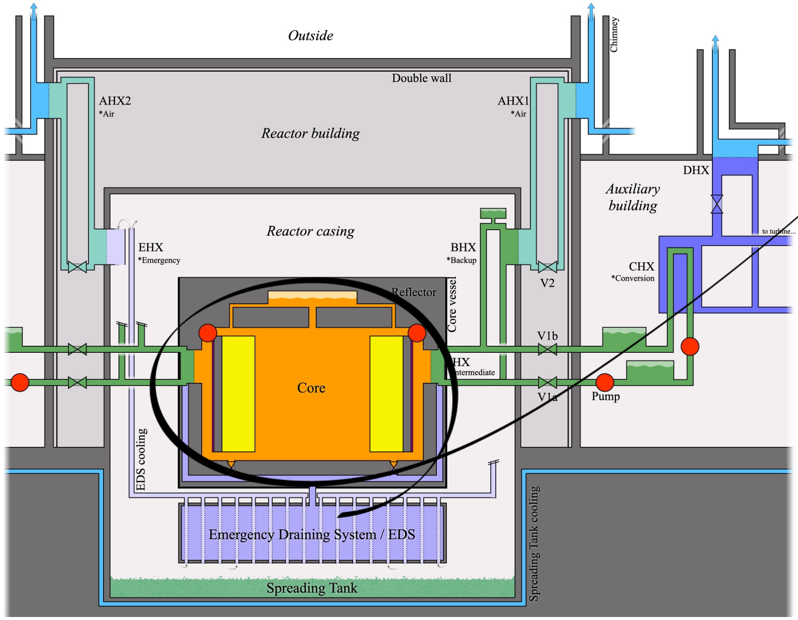
Reactor physics and MSR: challenges and needs





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(Multi)physics for core design

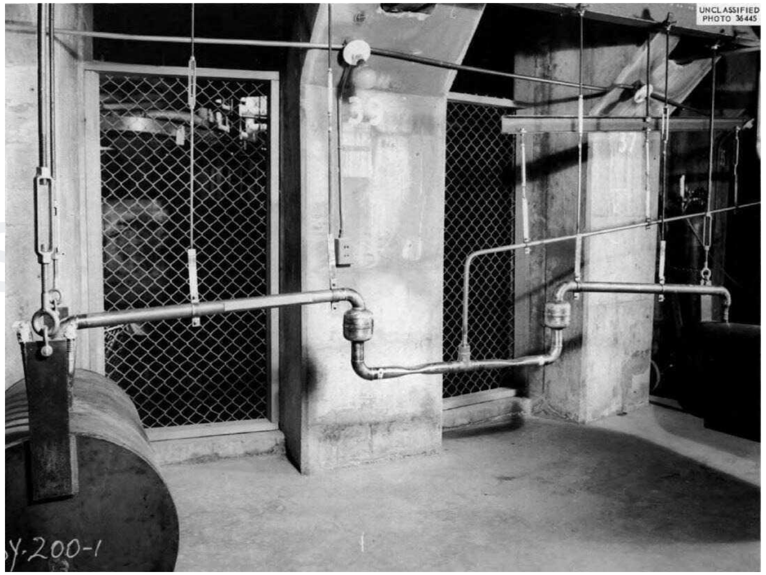
MSR innovation vs. solid-fuel reactors:

- Flexible reactor design and operation regarding fuel composition, operational flexibility (load following), and power level
- No classical solid fuel fabrication (cladding, assembly) required
  → *Potential* reduced cost and easier to add waste (MA) into the fuel for burning
- Elimination of most accident and accident escalation (over-accident) initiators
  → This results in a reactor with *potentially* a high level of intrinsic safety

("paper reactor")

What feedback? The ARE, the MSRE, (the MSBR)

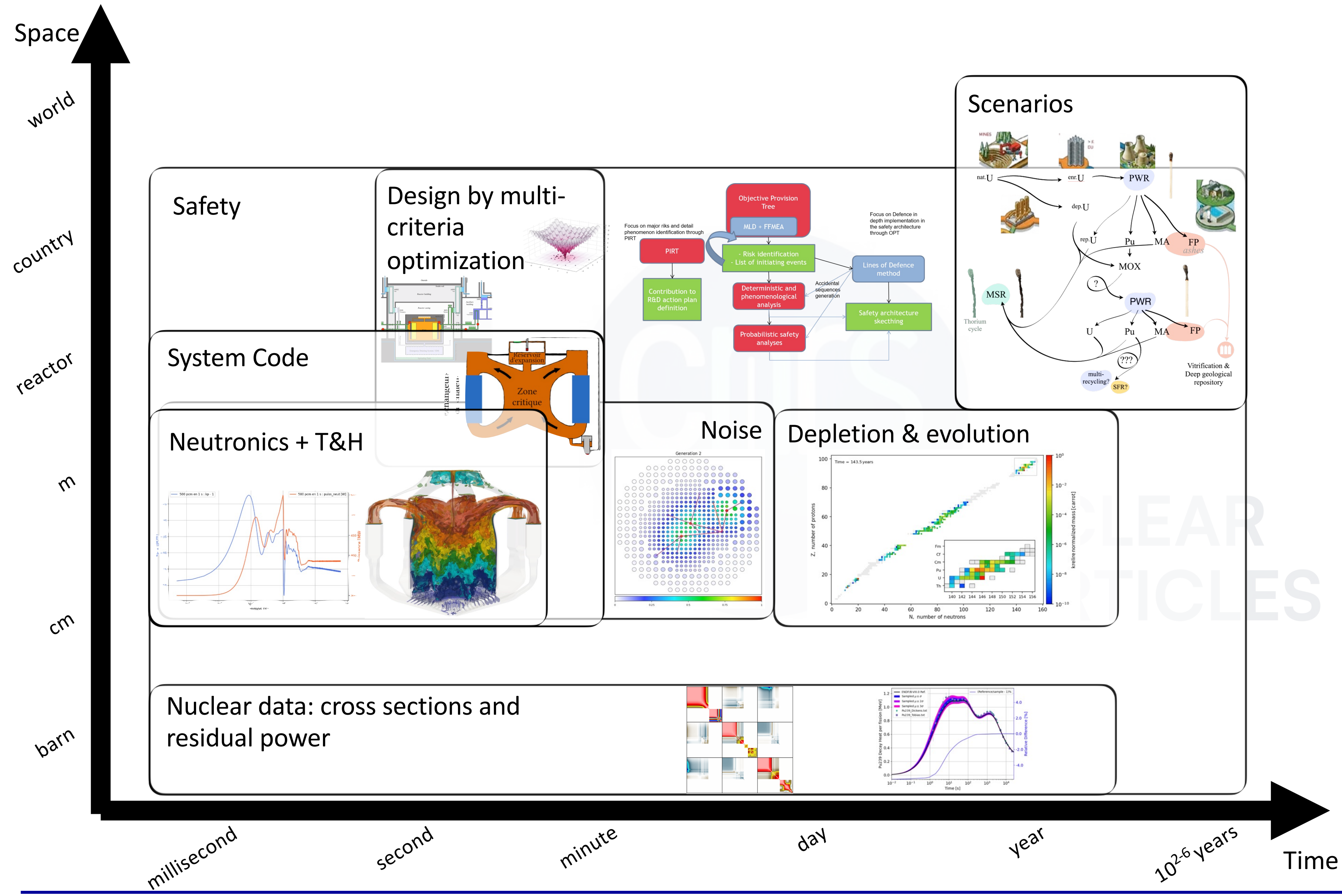
core structure



freeze valve

[@MSRE - Oak Ridge National Laboratory]

Research Activities on Reactor Physics and MSR at LPSC



Using a liquid and usually circulating fuel impacts many disciplines...

- Research on a MSR requires adaptations to study multiple aspects of reactor physics
  - ➞ models
  - ➞ codes
  - ➞ data / experiments
- Let's take a step-by-step an overview our research domains and activities

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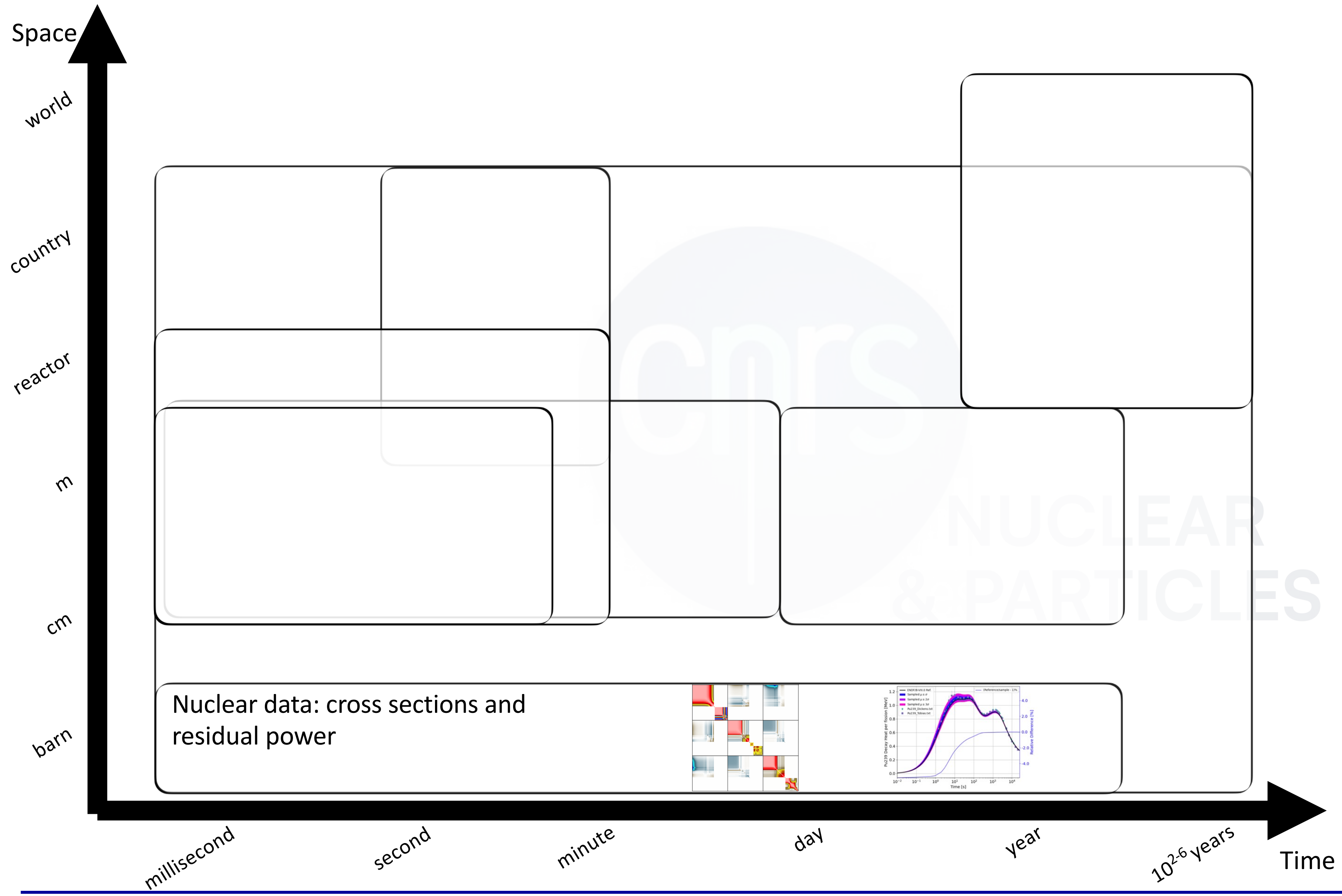

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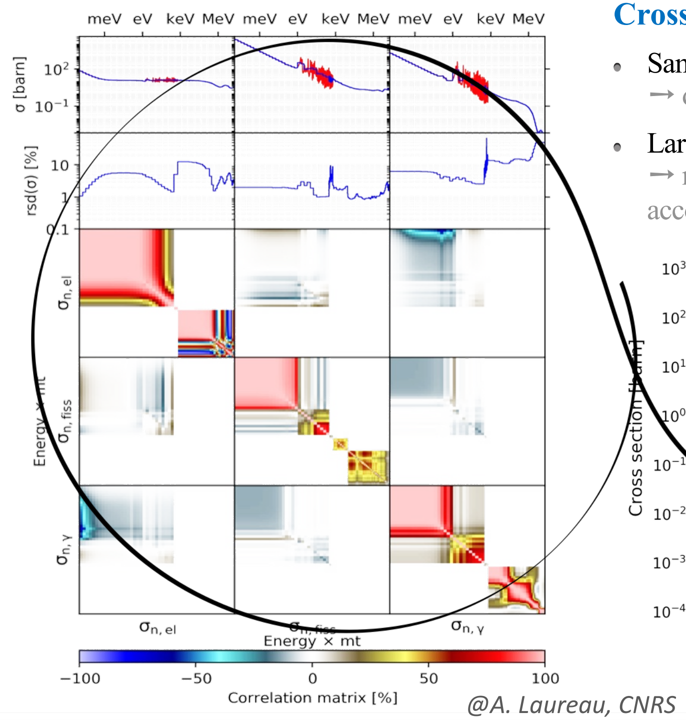
Nuclear Data, Cross-Sections and Residual Power

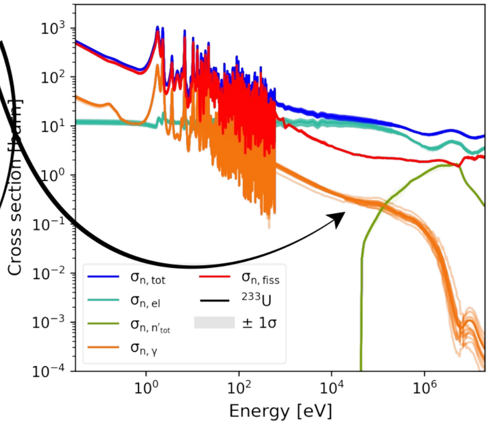
Nuclear data: cross sections and residual power

- Contributors differ from PWR
  → Fast spectrum, cycle, Pandemonium effect
- New issues
  → Share of residual power in gaseous/metallic (non soluble) fission products
- Multiple uncertain data
  → Cross-sections, fission yields, decay data, isomeric ratio
- Which impact on core design choices and on safety?



Cross section uncertainty propagation

- Sampling from covariance
  → direct / correlated sampling calculation
- Large uncertainties on MSR
  → methodology to constrain results according to measurements

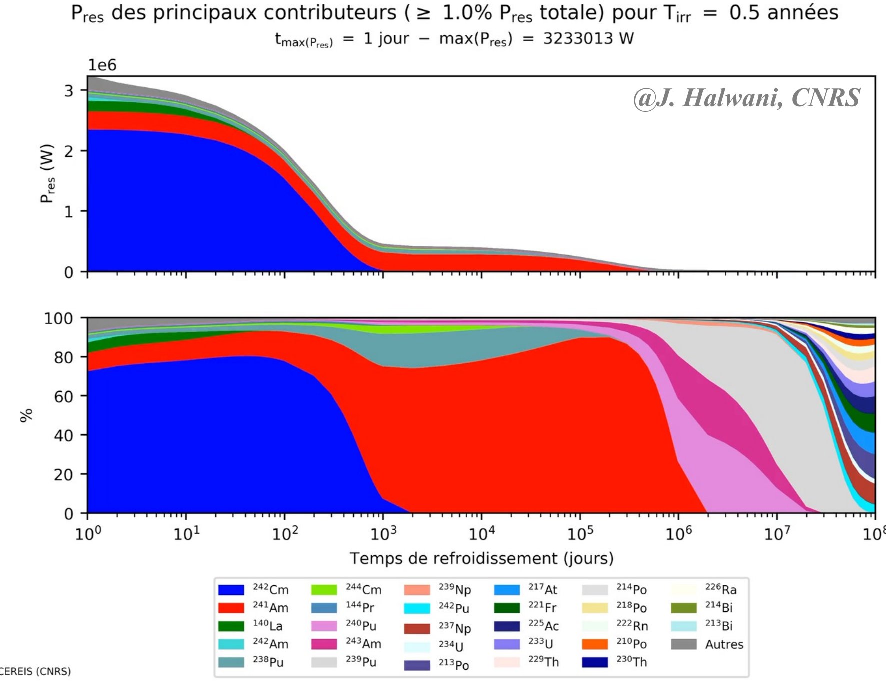


^{233}U ENDF/B-VIII.0 - NJOY21

Residual power

- Contributors identification
- Propagation to T&H coupling and grace period estimation

→ ***See panel TR4 on Safety***



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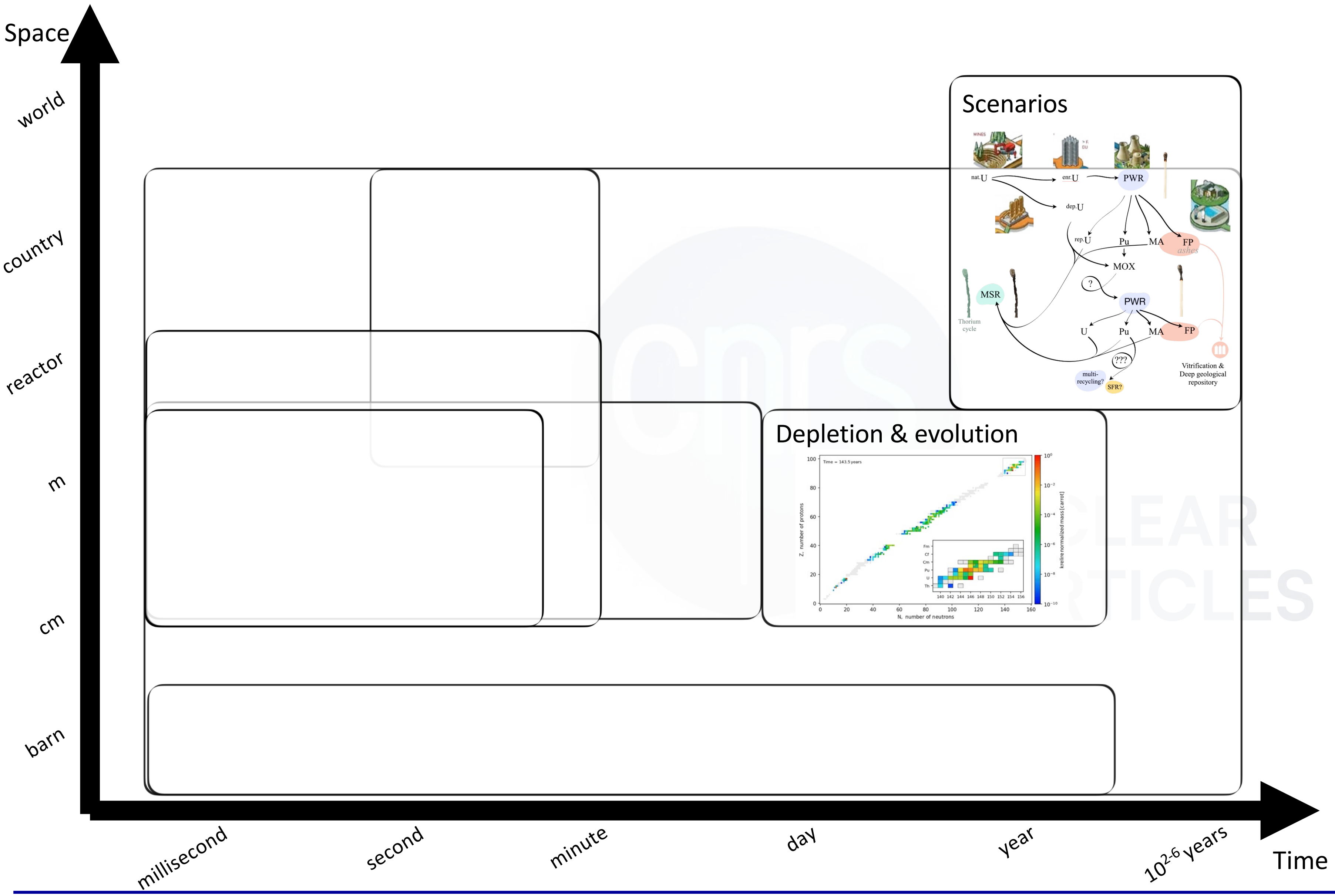

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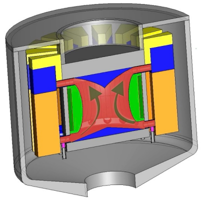
Scenarios + Depletion & Evolution

Objective - how can we design a MSR core targeting to

- Reduce waste radiotoxicity / disposal size
- Breeding fissile matter
- Mix fleet combining of reactor types: PWR+MSR or PWR+SFR+MSR (Pressurized Water Reactor / Sodium Fast Reactor)

Depletion calculation principle



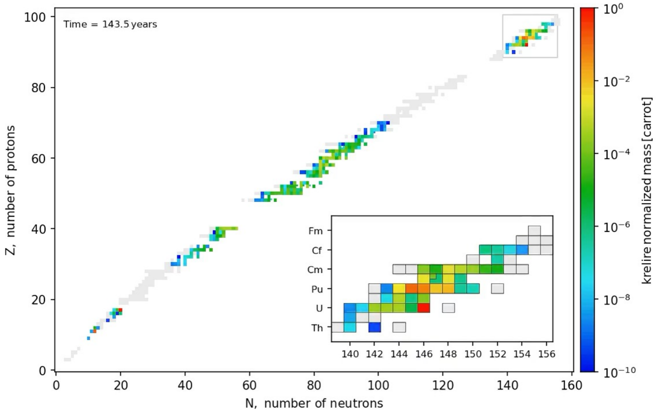
Neutron transport Boltzman

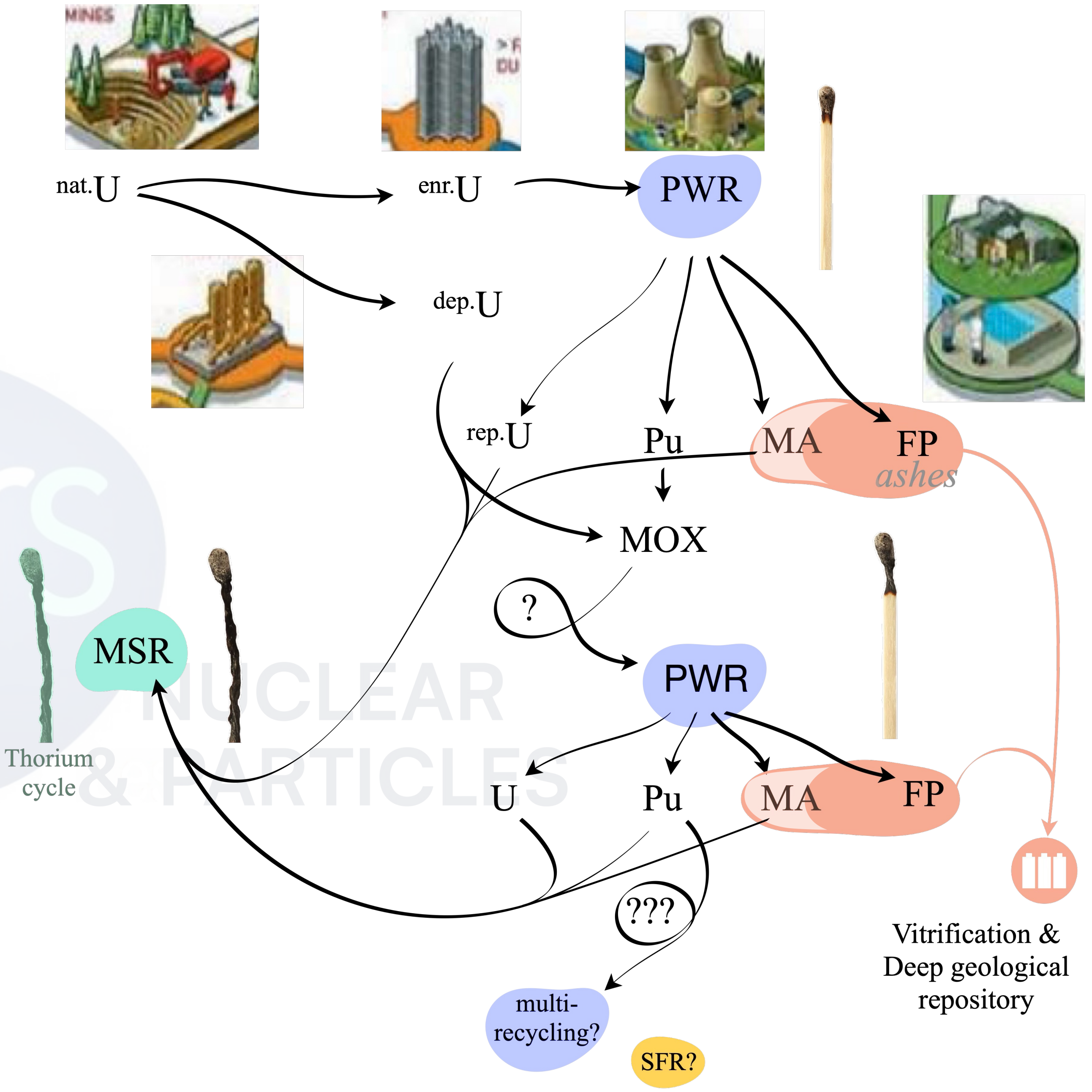
$k_{\text{eff}}, \langle\sigma\phi\rangle$

Temporal integration Bateman

$\frac{dN_i}{dt}$

$$\frac{dN_i}{dt} = \underbrace{\sum_j \left(\left\langle \sigma_{j\to i}\phi\right\rangle + \lambda_{j\to i}\right) N_j}_{\text{source: reaction, decay}} - \underbrace{\sum_j \left(\left\langle \sigma_{i\to j}\phi\right\rangle - \lambda_{i\to j}\right) N_i}_{\text{sink: reaction, decay}} \underbrace{- \lambda_i^{\text{processing}} N_i + A_i}_{\text{modification: outlet, supply}}$$





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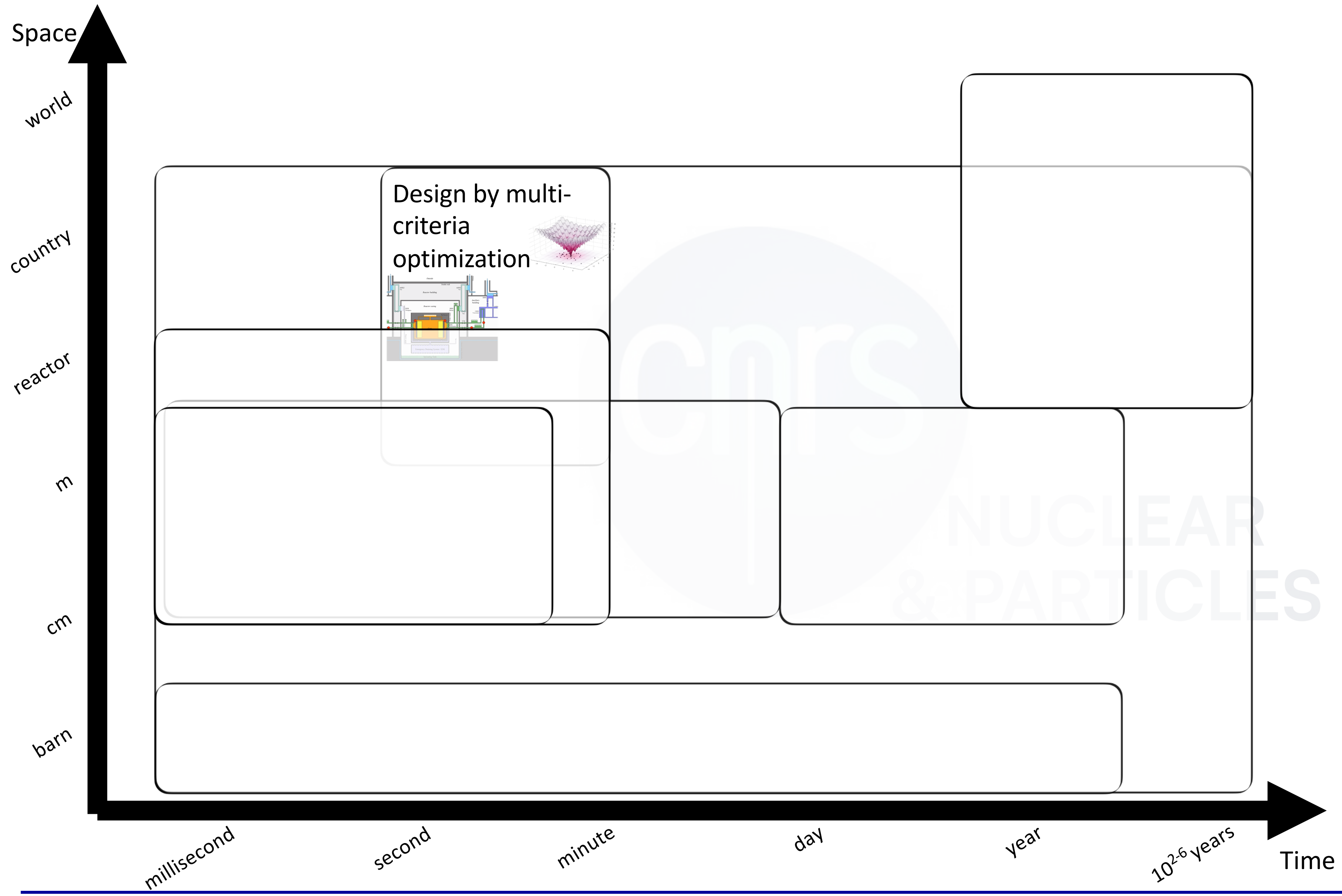

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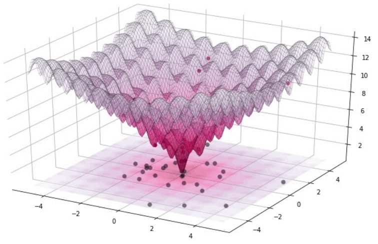
Design by Multi-Criteria Optimization

Issues

- Sizing the (neutro)-hydraulics of a MSR fuel circuit requires >100 parameters
  ⟶ Genetic algorithm / Multicriteria optimization

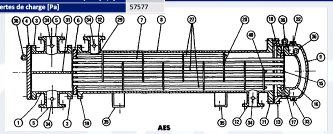
Differential evolution [@wikipedia]



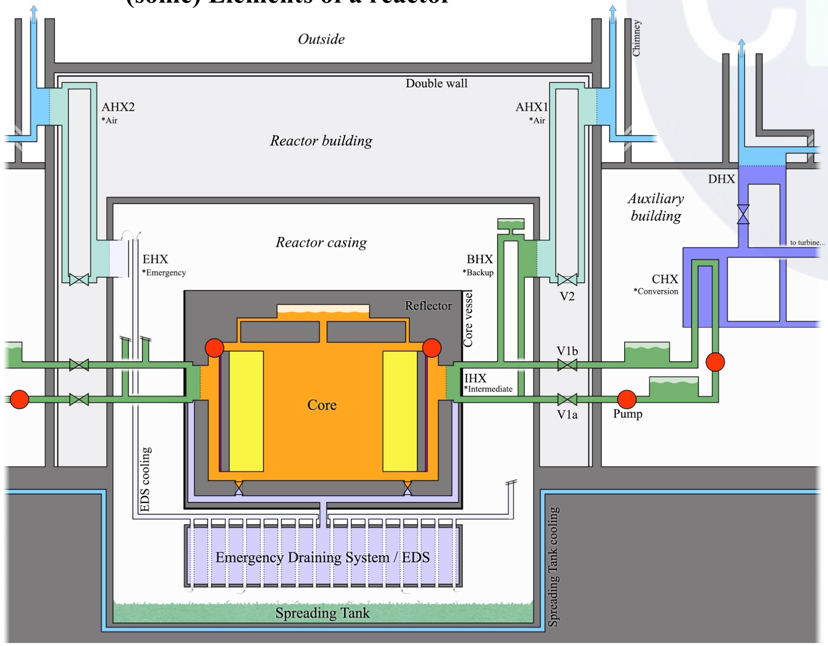
Heat exchanger parameters

Circuit combustible	
Diamètre réacteur [m]	3.649853
Cœur : Fraction de sel combustible en cœur	0.1997984
Cœur : Volume de sel combustible [m3]	5.804148
Cœur : nombre de secteurs effectif	6
Cœur : masse totale de sel combustible [kg]	16288.81
Cœur : Pertes de charge totales [Pa]	1006194
Cœur	
Cœur : Volume du cœur [m3]	1.15966
Cœur : Diamètre du cœur [m]	0.9659233
Cœur : Hauteur du cœur [m]	1.582542
Cœur : Température de criticité [K]	899.9793
Cœur : Température d'entrée [K]	850
Cœur : Température de sortie [K]	949.9586
Cœur : débit total de sel combustible [kg/s]	4568.12
Cœur : Puissance spécifique [MW/m3]	258.6603
Cœur : Puissance demandée [MW]	299.9579
Tuyaux	
Tuyaux : Angle tuyau haut	18.13089
Tuyaux : Angle tuyau bas	5.146329
Tuyaux : Diamètre [m]	0.2800584
Tuyaux : Longueur totale d'une boucle [m]	2.829603
Tuyaux : Volume totale [m3]	1.710414
Tuyaux : Vitesse maximum dans les tuyaux [m/s]	4.469088
Tuyaux : Pertes de charge [Pa]	57577

Echangeur intermédiaire	
Echangeur intermédiaire : Débit massique du fluide chaud [kg/s]	761.3534
Echangeur intermédiaire : Débit massique du fluide froid [kg/s]	361.031
Echangeur intermédiaire : Pertes de charge du fluide chaud [Pa]	948504.7
Echangeur intermédiaire : Pertes de charge du fluide froid [Pa]	685565.5
Echangeur intermédiaire : Puissance échangée [MW]	49.99458
Echangeur intermédiaire : Coefficient d'échange	3405.763
Echangeur intermédiaire : DTLM [K]	74.33272
Echangeur intermédiaire : Hauteur totale de l'échangeur [m]	2.679754
Echangeur intermédiaire : Pincement chaud [K]	87.27975
Echangeur intermédiaire : Pincement froid [K]	117.2697
Echangeur intermédiaire : Pvol Extraite [MW/M3]	102.2358
Echangeur intermédiaire : Volume d'un échangeur [m3]	0.4890123
Echangeur intermédiaire : Vitesse calandre [m/s]	2.537534
Echangeur intermédiaire : Diamètre calandre [m]	0.6839302
Echangeur intermédiaire : Nombre de tubes	1629
Pompe primaire	
Pompe primaire : Débit Massique [kg/s]	761.3534
Pompe primaire : Débit Volumique [m3/s]	0.2752998
Pompe primaire : Hauteur élévation [m]	37.08789
Pompe primaire : Vitesse de rotation [tr/min]	173.0208
Pompe primaire : Diamètre [m]	0.7096236
Pompe primaire : Vitesse spécifique	90.78233
Pompe primaire : Diamètre spécifique	1.352462
Pompe primaire : Volume [m3]	0.1107629
Pompe primaire : Hauteur [m]	0.2800584



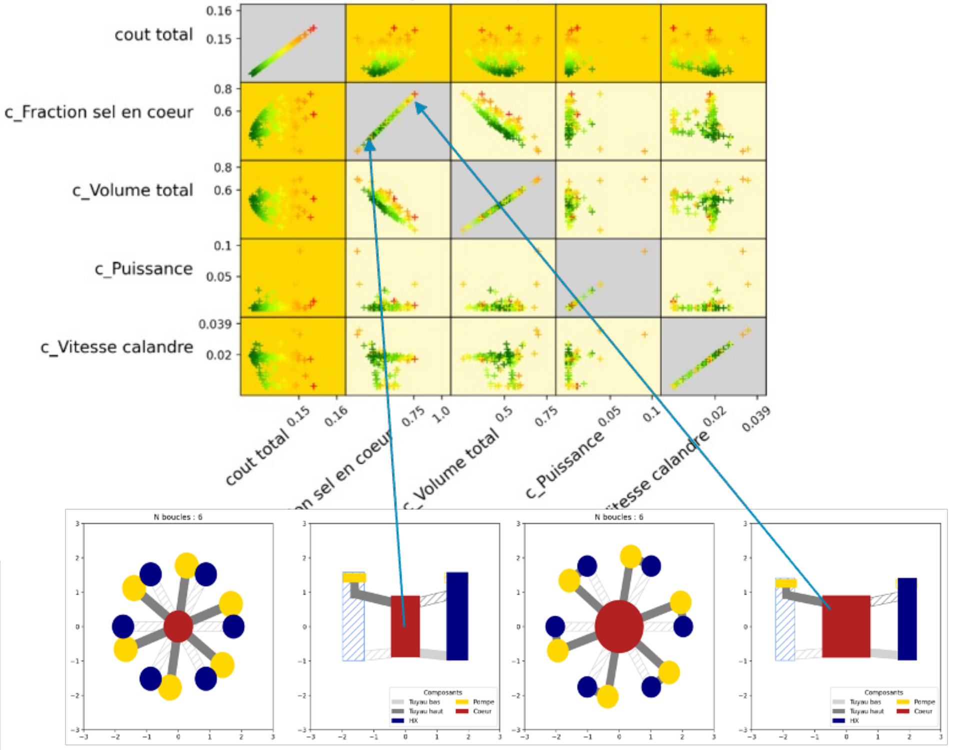
(some) Elements of a reactor



Principle

- 0D modeling of the whole system components with correlations
- Optimization and analysis of the Pareto optimum
  ⟶ iterative approach to fill the gaps

@T. Sornay, CNRS / Framatome



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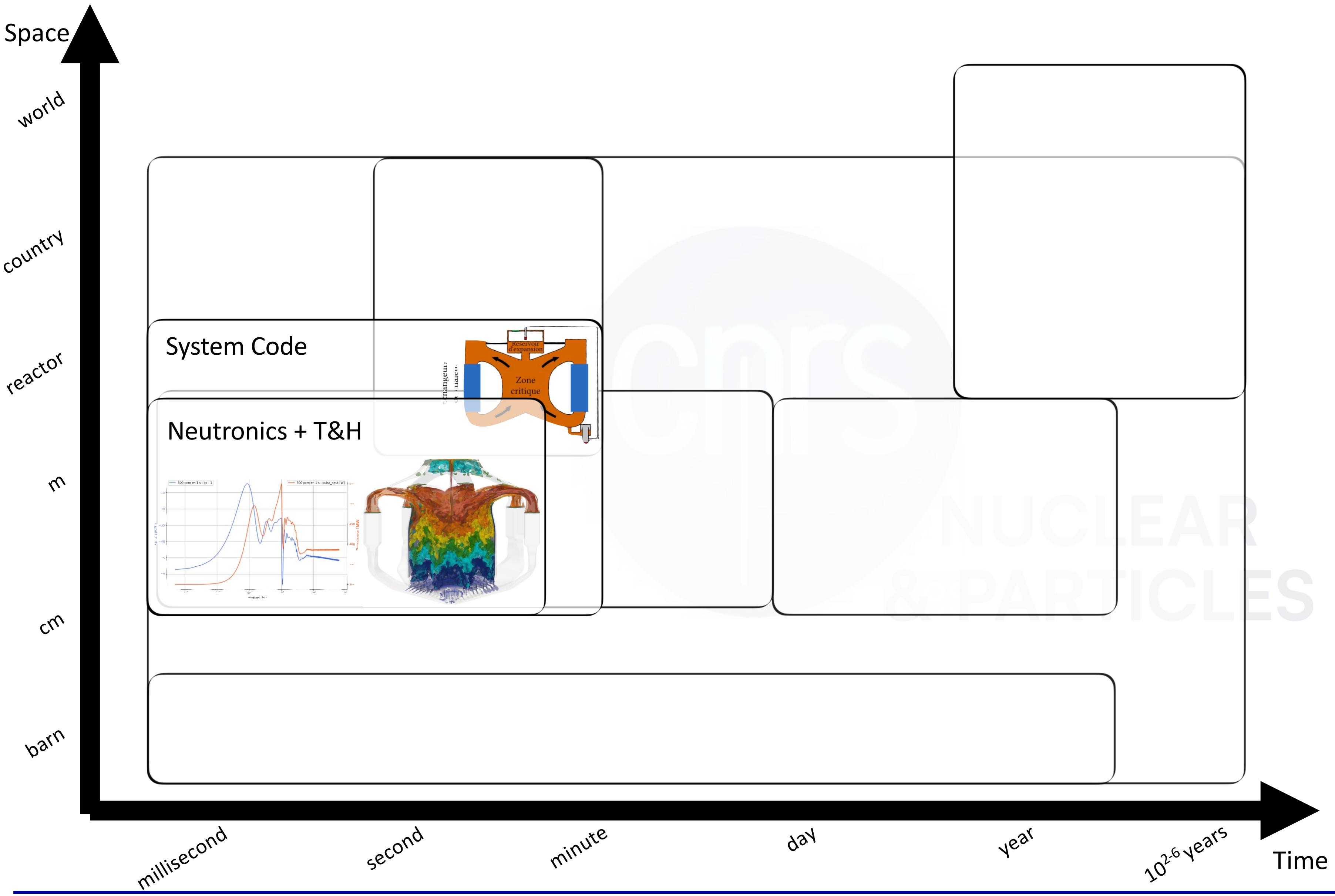

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Neutronics, T&H and System Studies

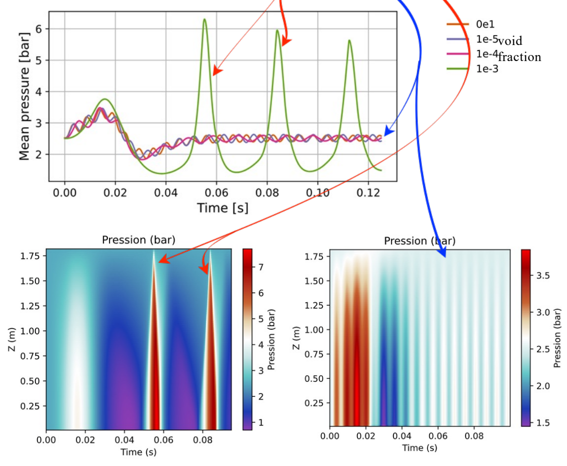
Neutronics (Boltzman equation) + Thermal-Hydraulics (Navier Stokes equation)

- Delayed neutron precursors (which stabilize the chain reaction) are mobile, and the Monte Carlo transport approach is too computationally intensive
  - → Development of a Green's function approach TFM (Transient Fission Matrix)
  - → Advanced point kinetics with precursor tracking
- Strong coupling to Thermal-Hydraulics
  - → CFD (3D) for classic transient: pump loss, reactivity insertion, load following
  - → Multi 1D for system code
  - → Recent focus on fast transient with pressure wave - delay in density feedback

Shock wave propagation development and study

1D with bubbles & coupling

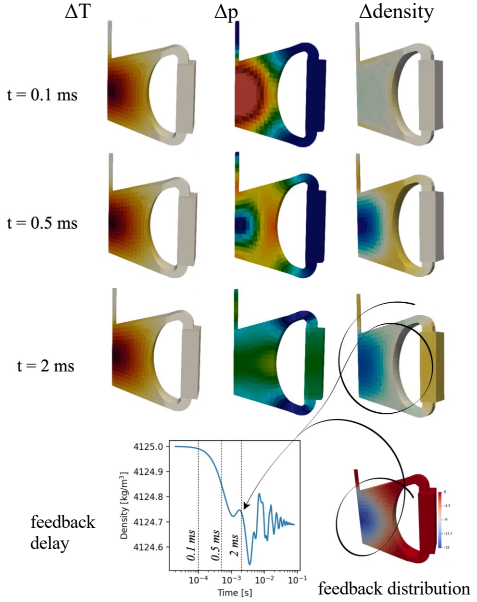
- Shock wave (Ma > 1)
  - → discontinuity
- Acoustic wave (Ma = 1)



@Anna Maître – CEA/CNRS-LPSC

3D without bubbles

- Complex pressure distribution
  - → (very) slow calculation

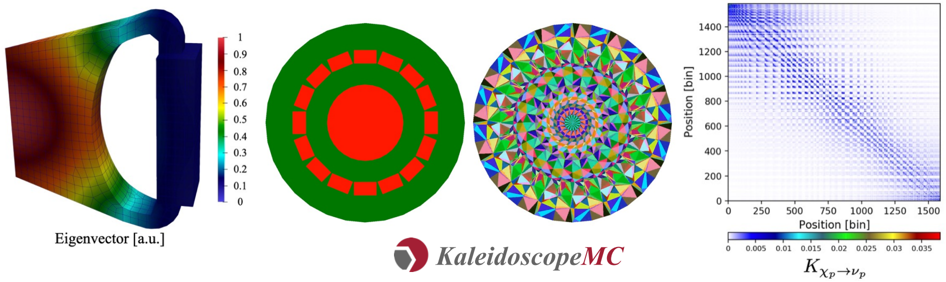


@Thibault Le Meute - LPSC/Naarea

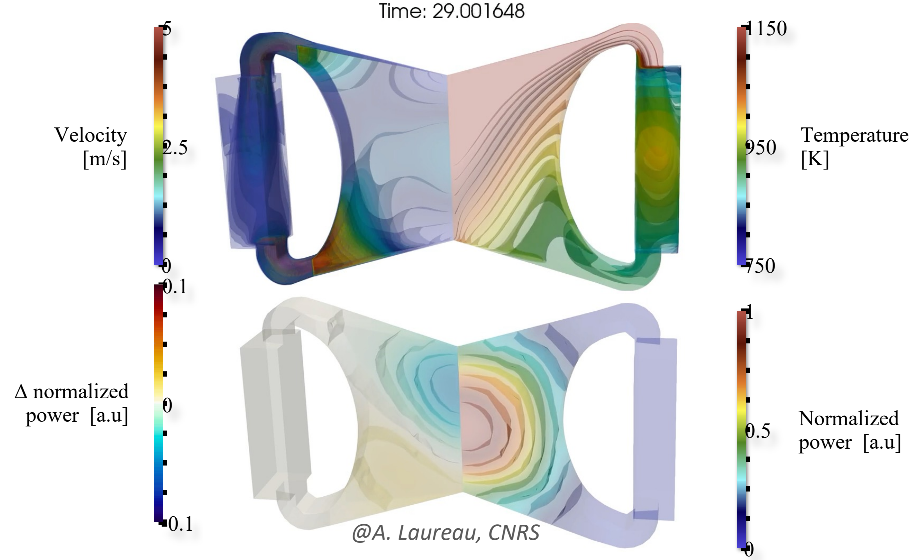
Neutronics (Boltzman) + Thermal-Hydraulics (Navier Stokes)

- Implementation of a Green's function approach (TFM - Transient Fission Matrix) with Correlated sampling (local perturbation) in the OpenMC code
  - → From O(1) to O(N^3) complexity

Development in OpenMC code



Example of MSFR transient study (reactivity insertion +10000 pcm/s in 0.1s)



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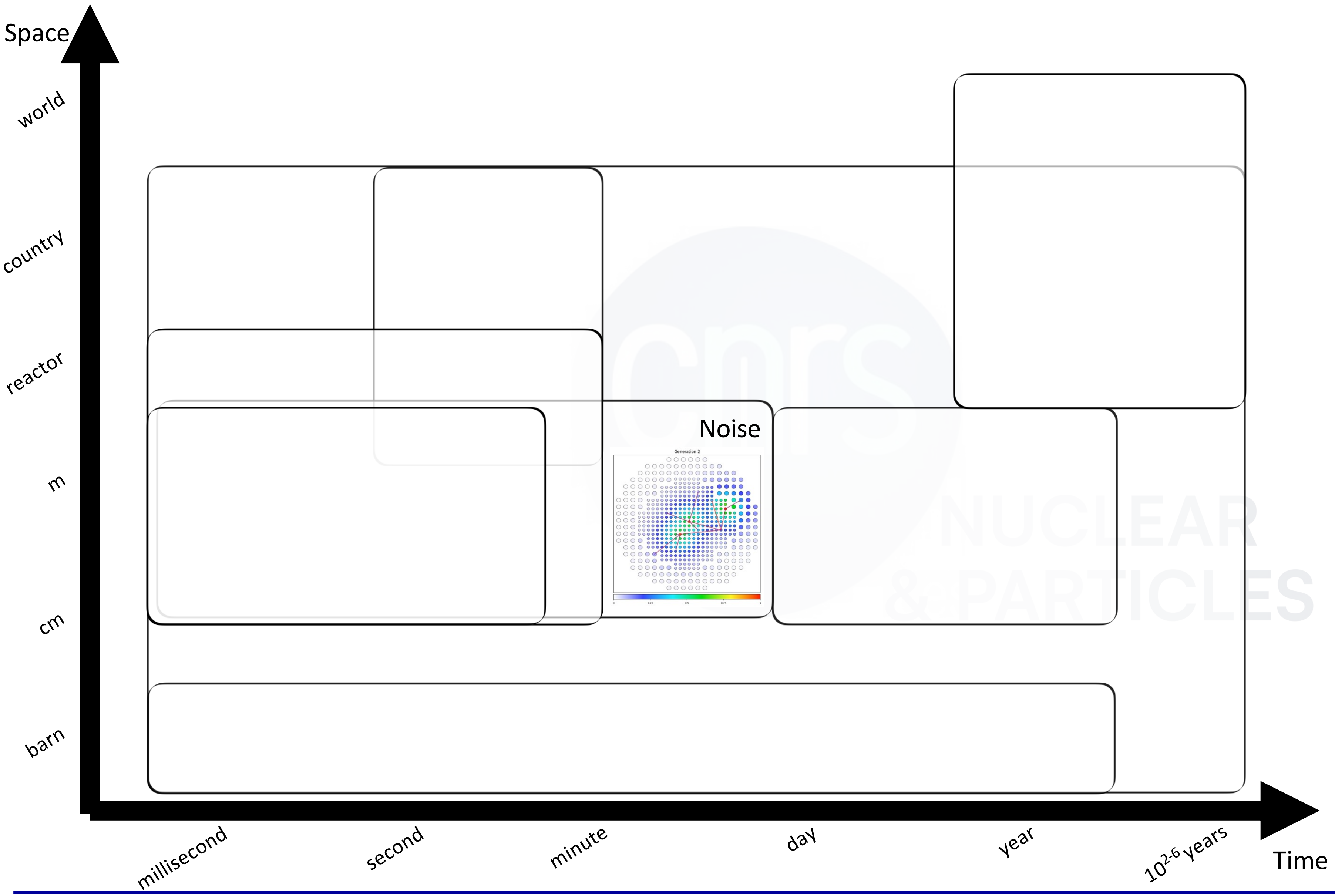

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Neutron Noise

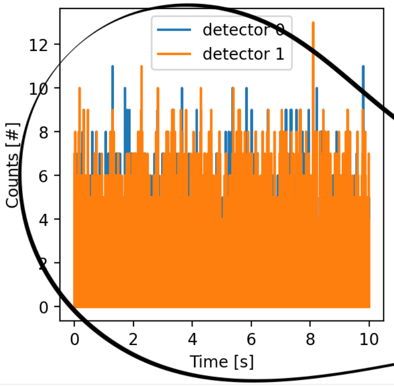
The pile noise characterizes the kinetic and safety parameters of the core (neutron chains originating from delayed neutrons), while the power noise is used for diagnostics of reactor operation

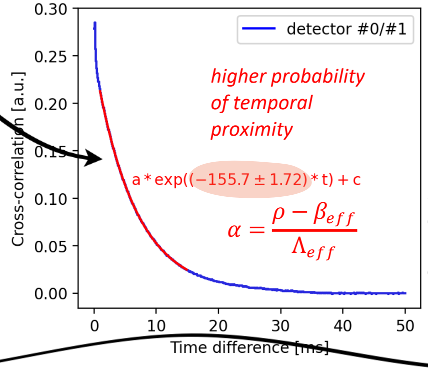
→ What is the impact of turbulence on the delayed neutron source?

→ Extremely long Monte Carlo calculations

Detector "noise" = signal (high frequency and intrinsec to the physics of the neutron chains)

- Events in detector = +1 in corresponding bin

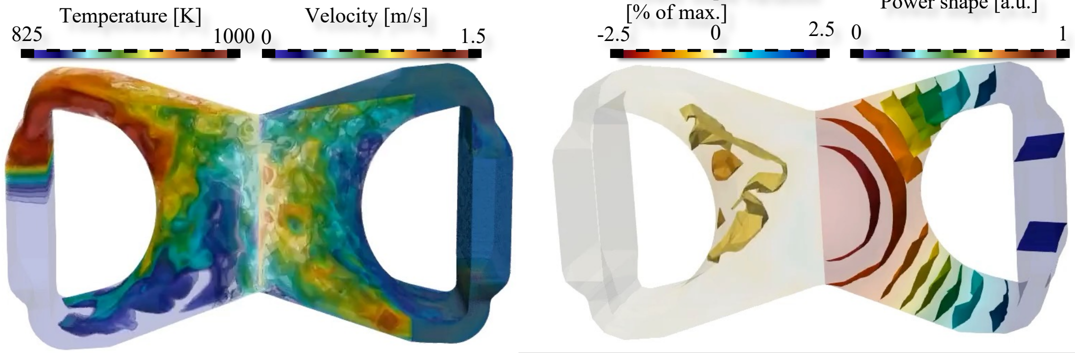




Indirect measurement of a parameter related to the stability of the chain reaction

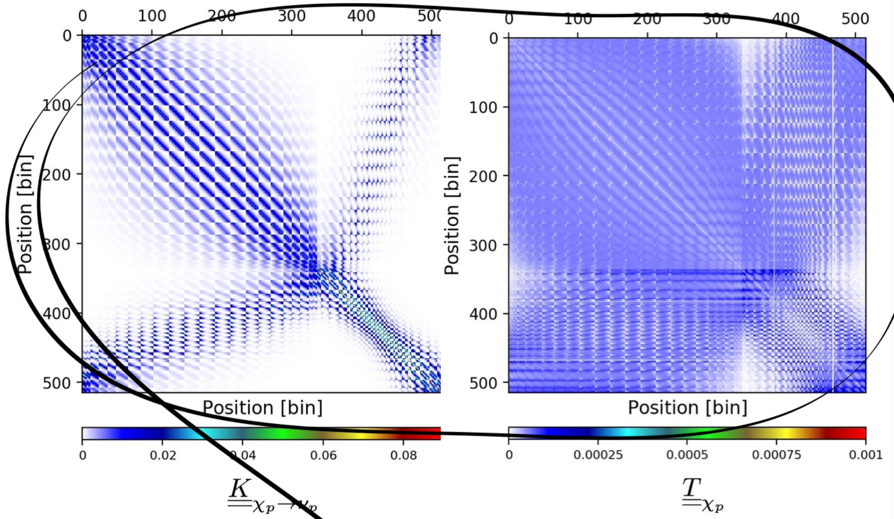
Application to MSR

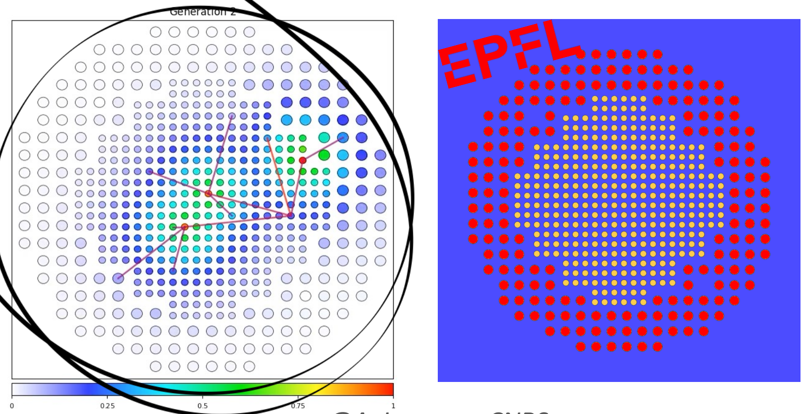
- Turbulence induced noise
  - → Temperature and thus power fluctuations
  - → Delayed neutron precursor position



Neutron shower – Example on the CROCUS reactor @EPFL

- Utilization of Green functions (fission matrices) to sample new tracks
  - → MC to determinist to MC ☺
- ~400 times faster than classic Monte Carlo





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Thank you for your attention!