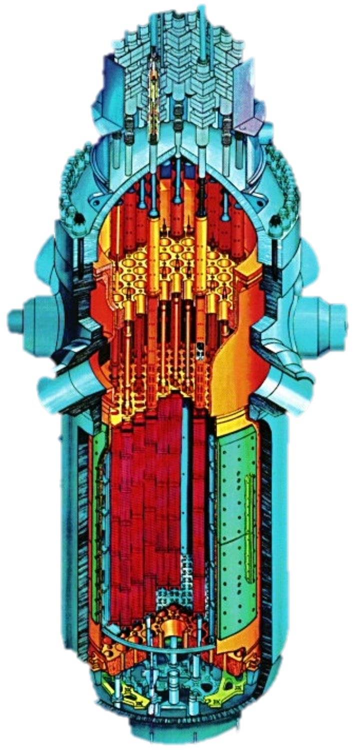
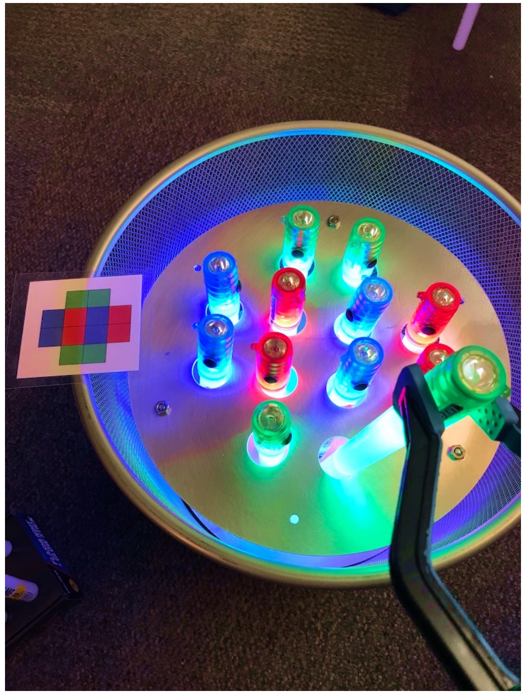
Computational analysis of nuclear reactor transients



What DOE thinks I do



What my mom thinks I do

What I really do

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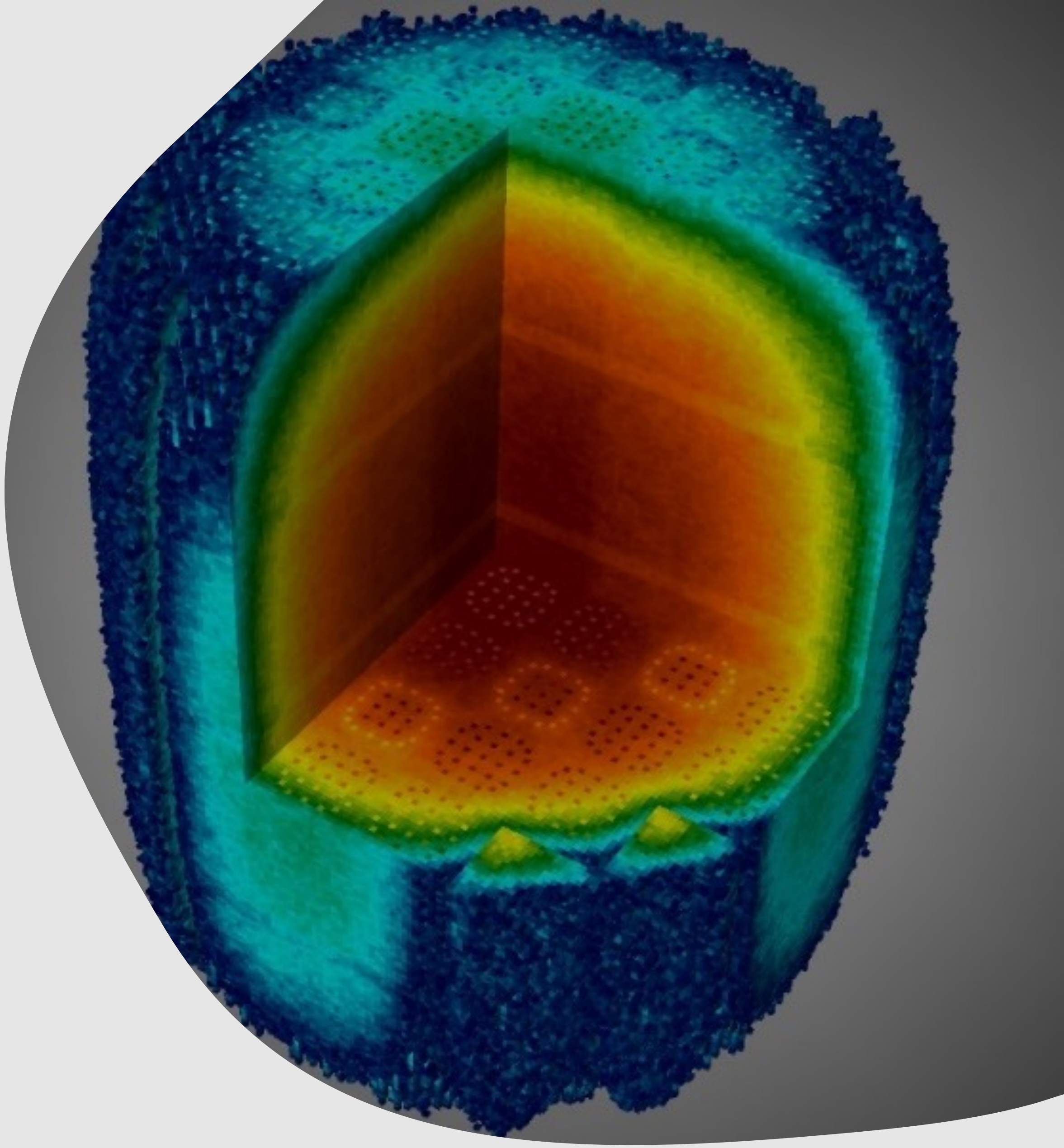
DOE CSGF

Practicums at Los Alamos National Lab

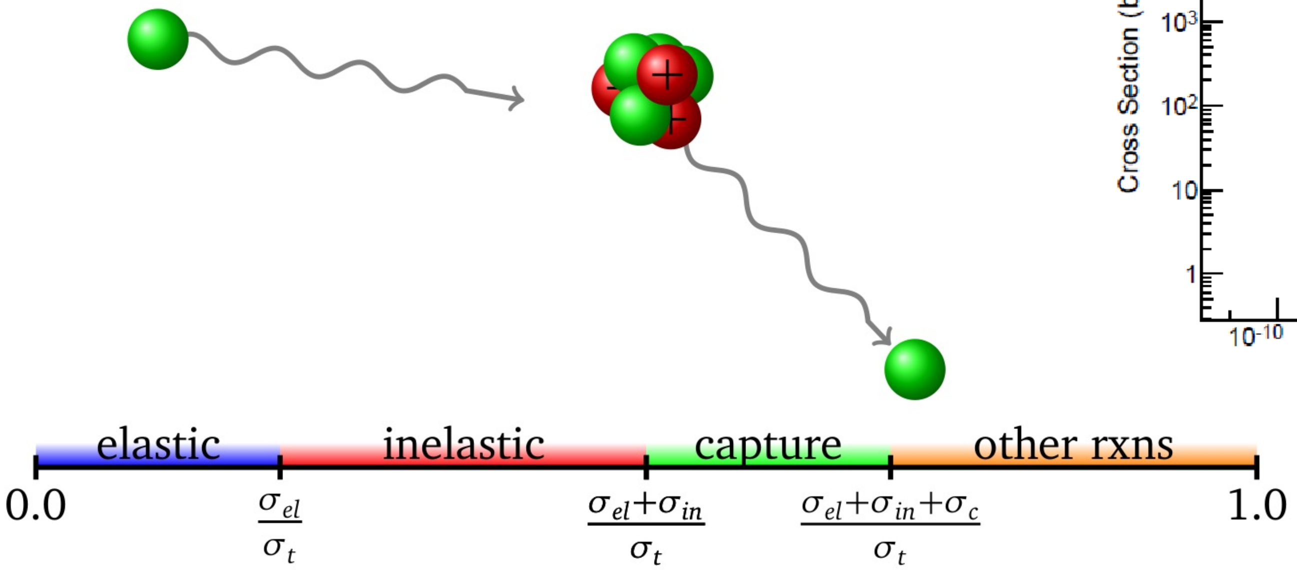
- NEN-2: critical experiments (PHYSOR 2018)
- XCP-3: transient Monte Carlo (ANS Student Conference 2019)
- NEN-5: cross-section generation in Monte Carlo (ANS Annual 2021)

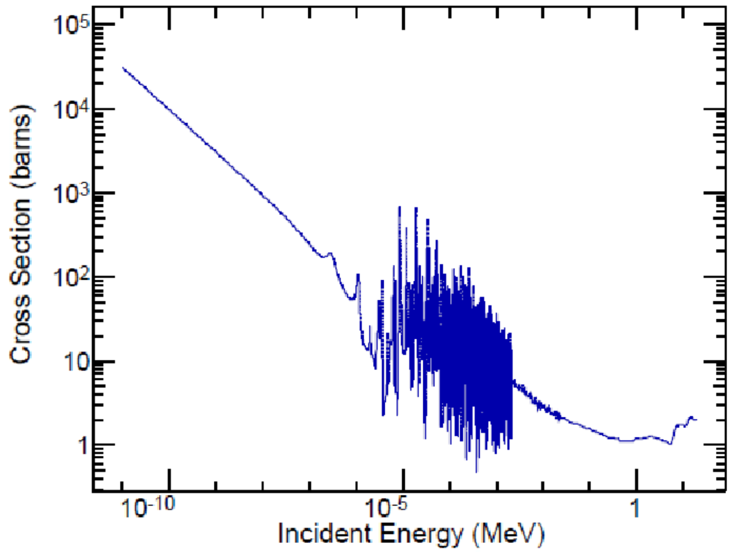
Contents

- Monte Carlo neutronics
- Essentials of nuclear reactors
- High-order/Lower-order schemes



Monte Carlo neutronics





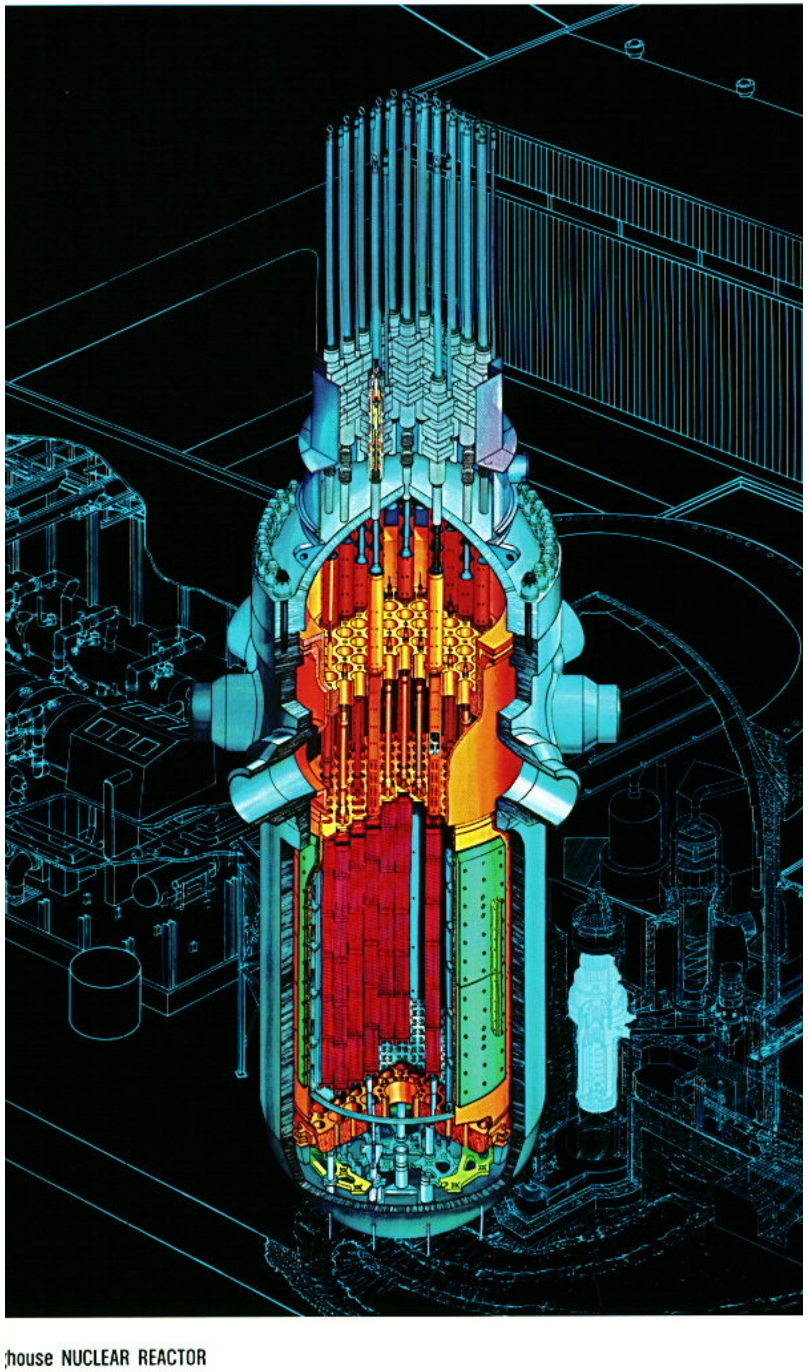
Advantages

- few approximation errors
- continuous energy data
- complex geometries are not limiting
- simplicity

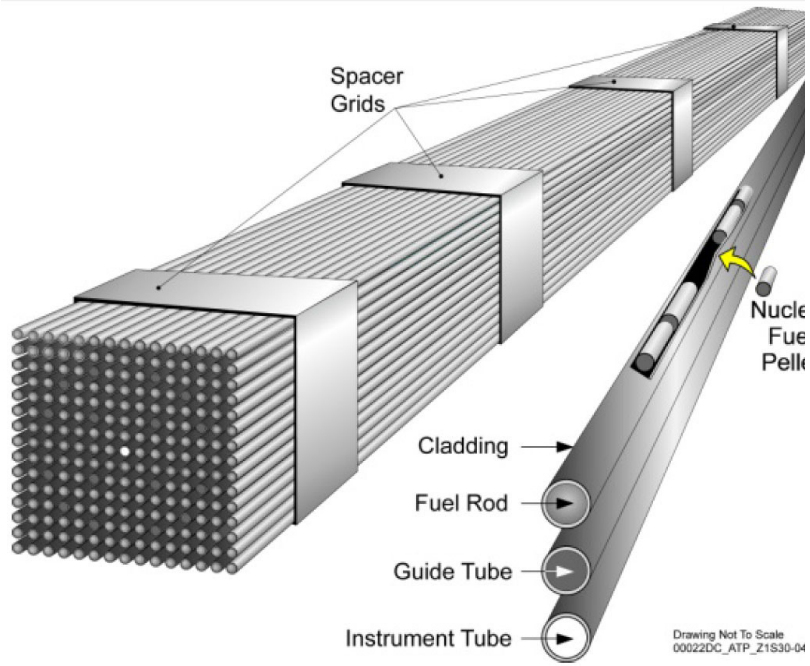
Disadvantages

- computationally expensive
- statistical error

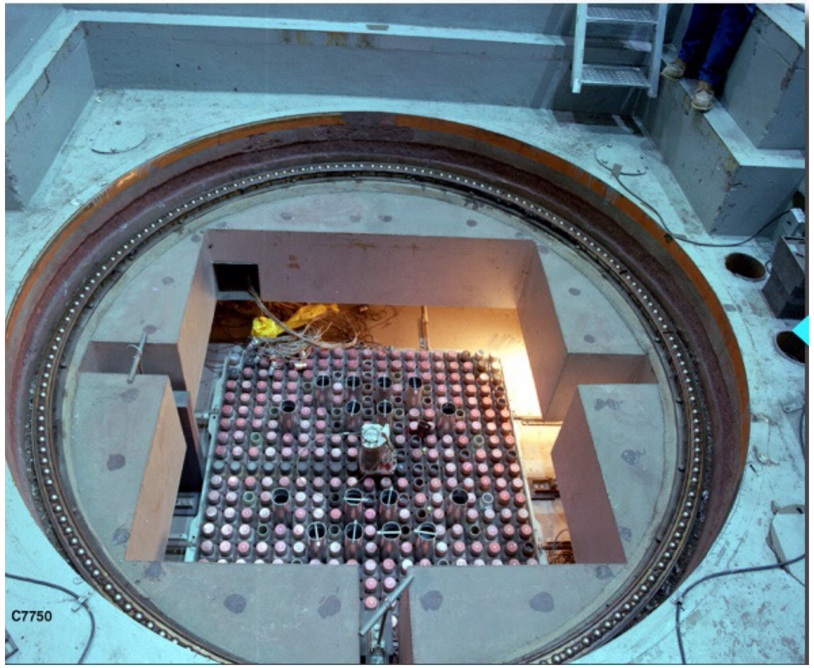
Image credit: Nick Horelik



;house NUCLEAR REACTOR



Spacer
Grids
Nucle
Fue
Pell
Cladding
Fuel Rod
Guide Tube
Instrument Tube
Drawing Not To Scale
00022DC_ATP_Z1S30-04



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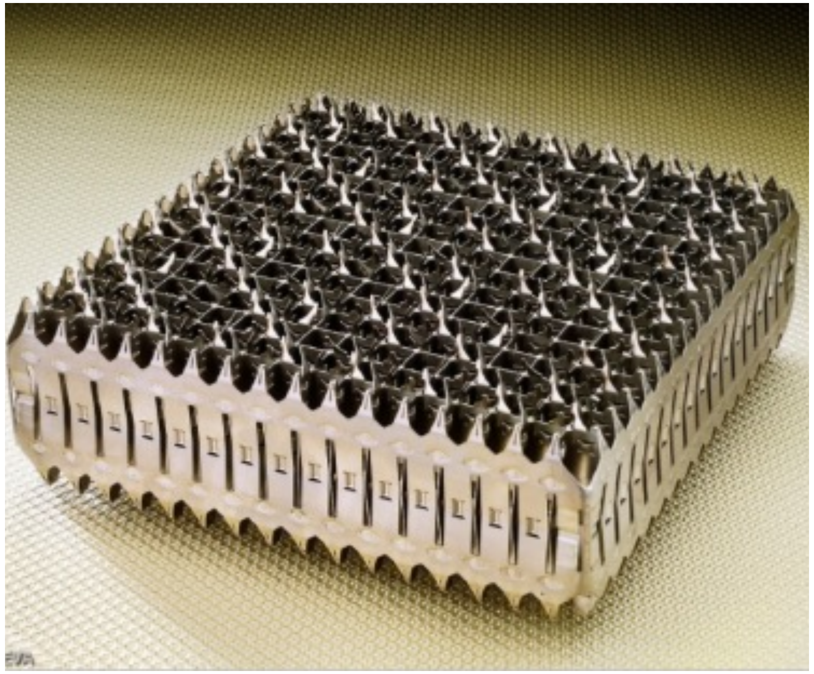
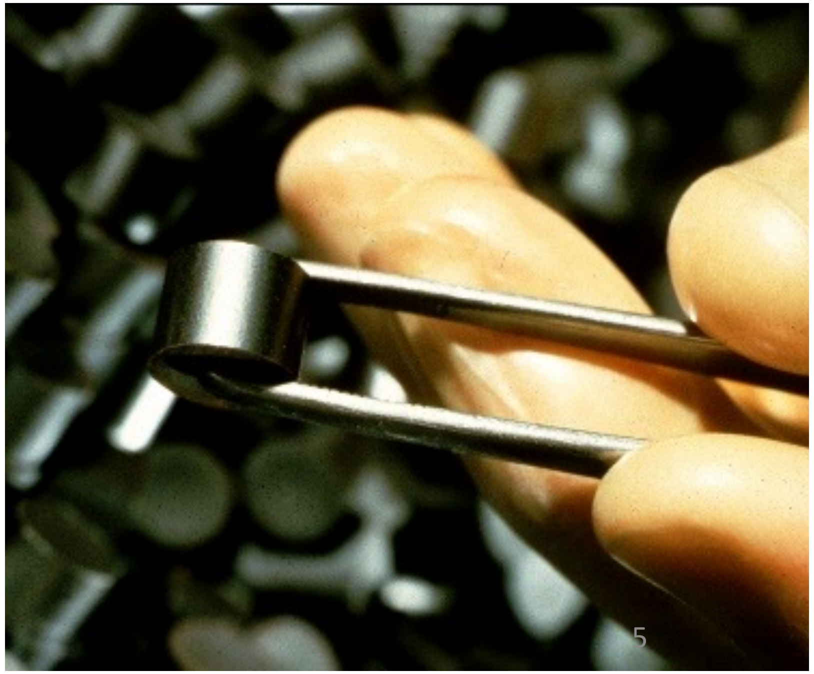
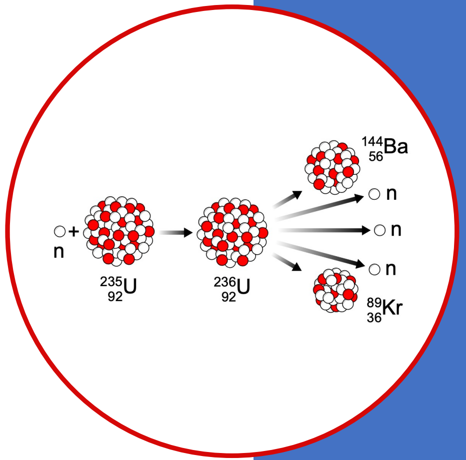




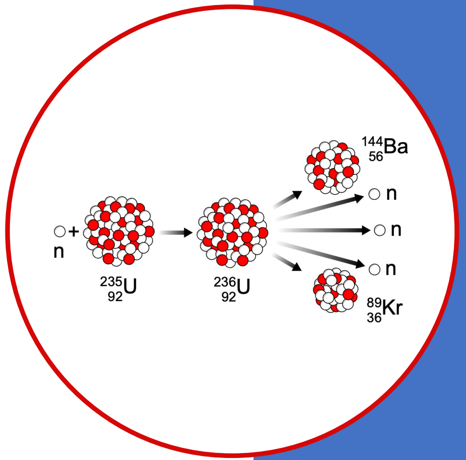
How can we control reactors?

- After fission, excess neutrons are generated.
- These neutrons live ~10^{-4} seconds.
- This suggests a period of 0.1 seconds for any reactor changes, or a power growth rate of e^{10t}.
- Thankfully, ~1% of emitted neutrons are "delayed."

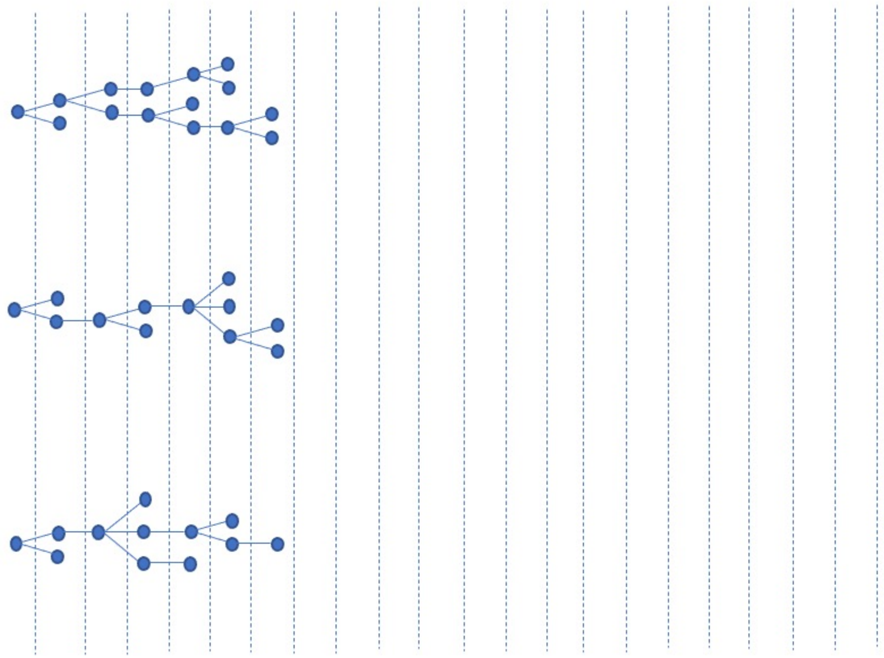


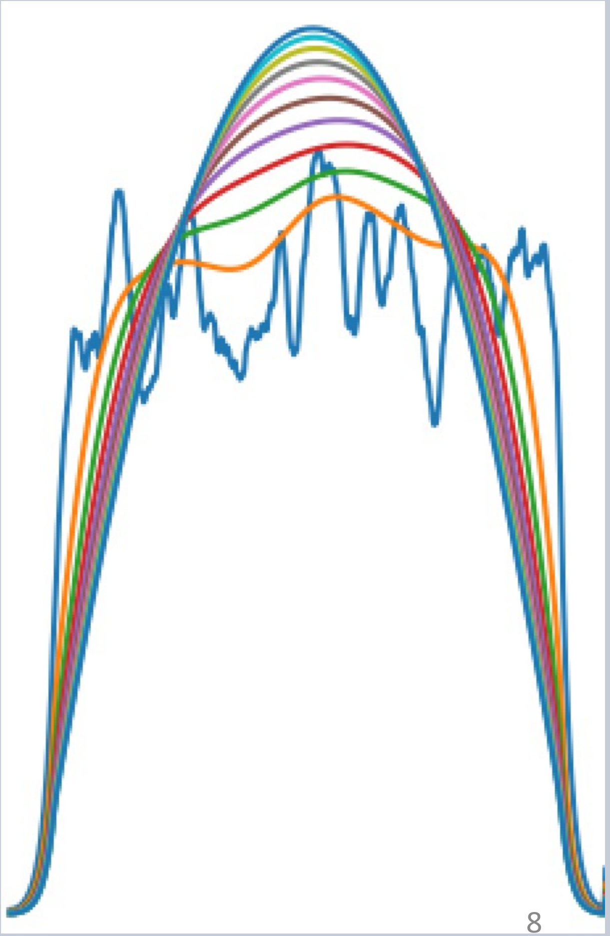
How can we control reactors?

- Delayed neutrons are emitted from unstable fission products.
- This increases our period to ~85 seconds, which is feasible to control by mechanical systems.
- In steady-state, assume all neutrons in secular equilibrium: no need to differentiate prompt & delayed neutrons.
- In transient simulations, delayed neutrons are central to the calculation.

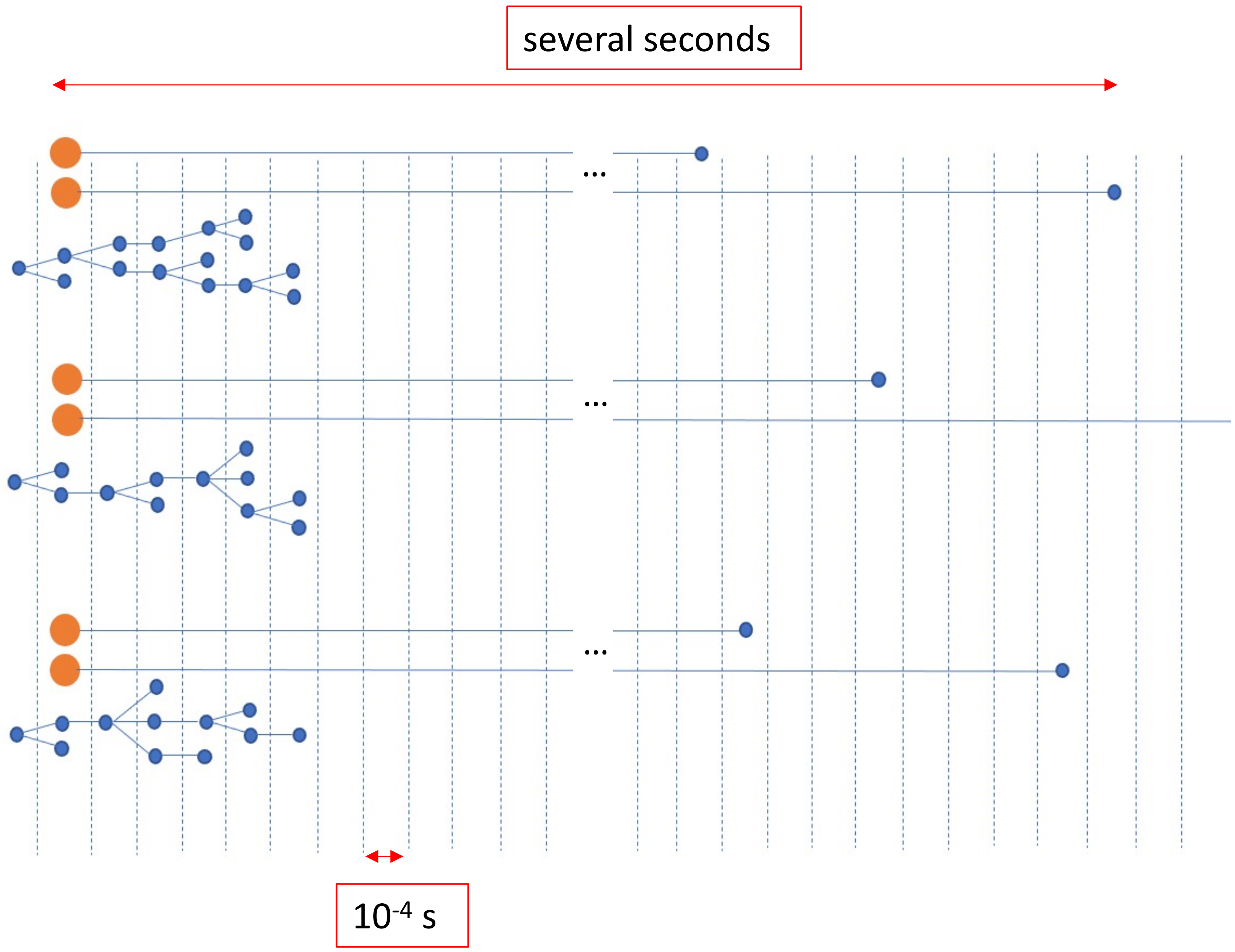


Monte Carlo *steady-state* neutronics



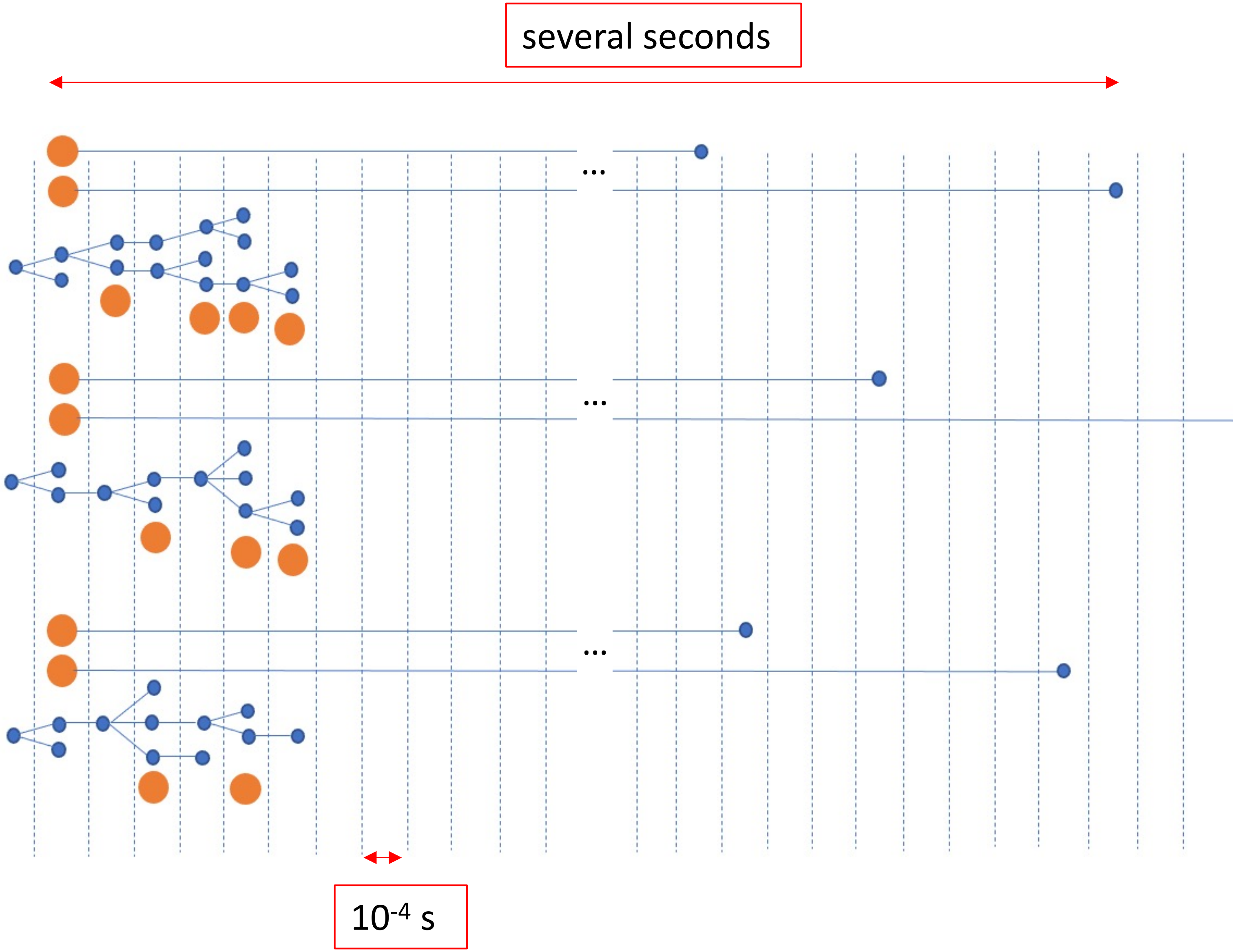


Need to sample millions of neutrons for accuracy!



Monte Carlo *transient* neutronics

- Dynamic Monte Carlo (B.Sjenitzer, 2013)
- Neutrons die off quickly.
- Fission products live much longer.

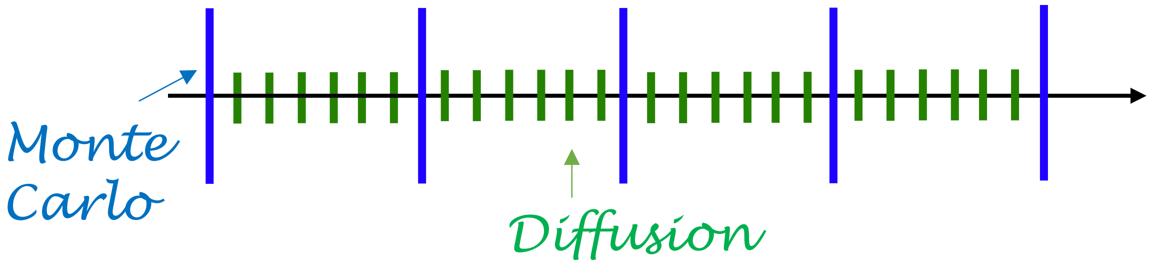


Monte Carlo *transient* neutronics

- Dynamic Monte Carlo (B.Sjenitzer, 2013)
- Neutrons die off quickly.
- Fission products live much longer.
- Causes thousands more fission products than neutrons in a reactor.
- Very expensive to model, but useful & straight-forward

High-order/Low-order schemes

- Decompose the neutron flux into shape & amplitude functions
- Assume that the amplitude changes much faster than the shape
- Expensive shape function calculations occur at the infrequent blue markers



Neutron transport equation

$$\frac{1}{v}\frac{d\Psi}{dt} = \boxed{\text{Streaming term (loss)}} + \boxed{\text{Removal term (loss)}} + \boxed{\text{In-scatter term (gain)}} + \boxed{\text{Fission term (gain)}} + \boxed{\text{Precursor term (gain)}}$$

$$\frac{dC}{dt} = \boxed{\text{Decay term (loss)}} + \boxed{\text{Fission term (gain)}}$$

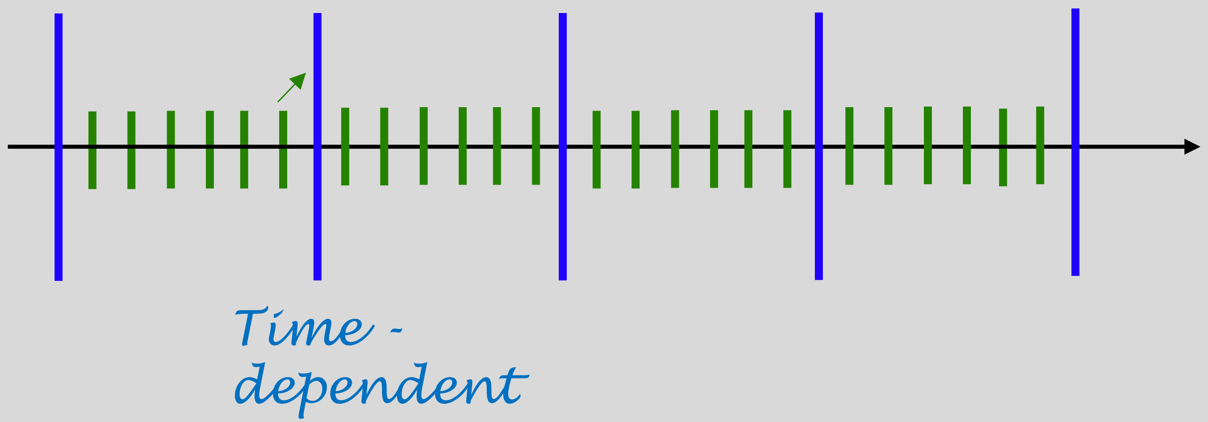
- It is difficult to sample a time-derivative in Monte Carlo, so an approximation for the time-derivatives is often required.
- The “omega method” proposes a frequency approximation.

Omega method

frequency transform the time derivatives

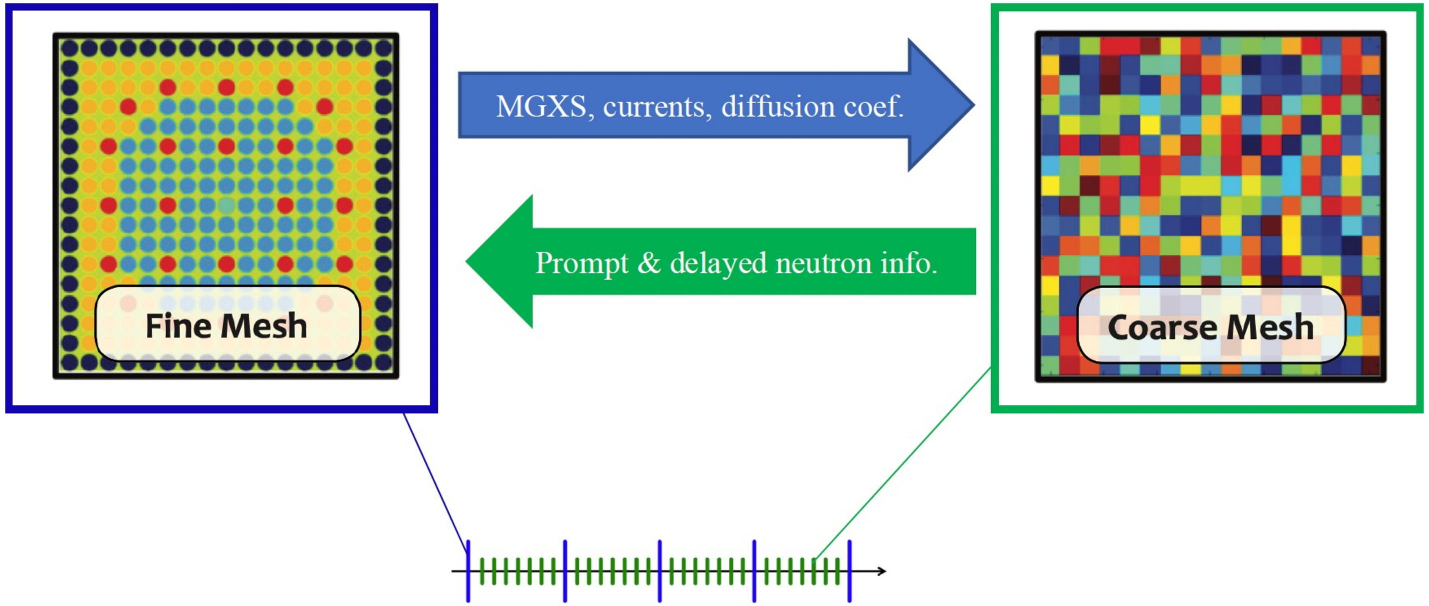
$$\frac{1}{v}\frac{d\Psi}{dt} = \omega^{\mathrm{P}}\Psi$$

$$\frac{dC}{dt} = \omega^{D}C$$



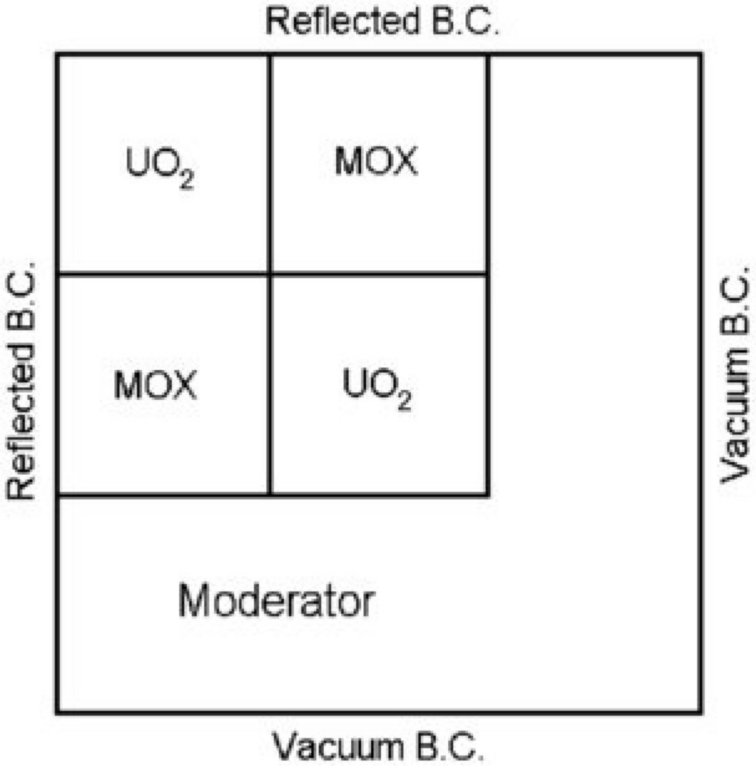
Summary: Updates shape, with a time-dependence term given from low-order method

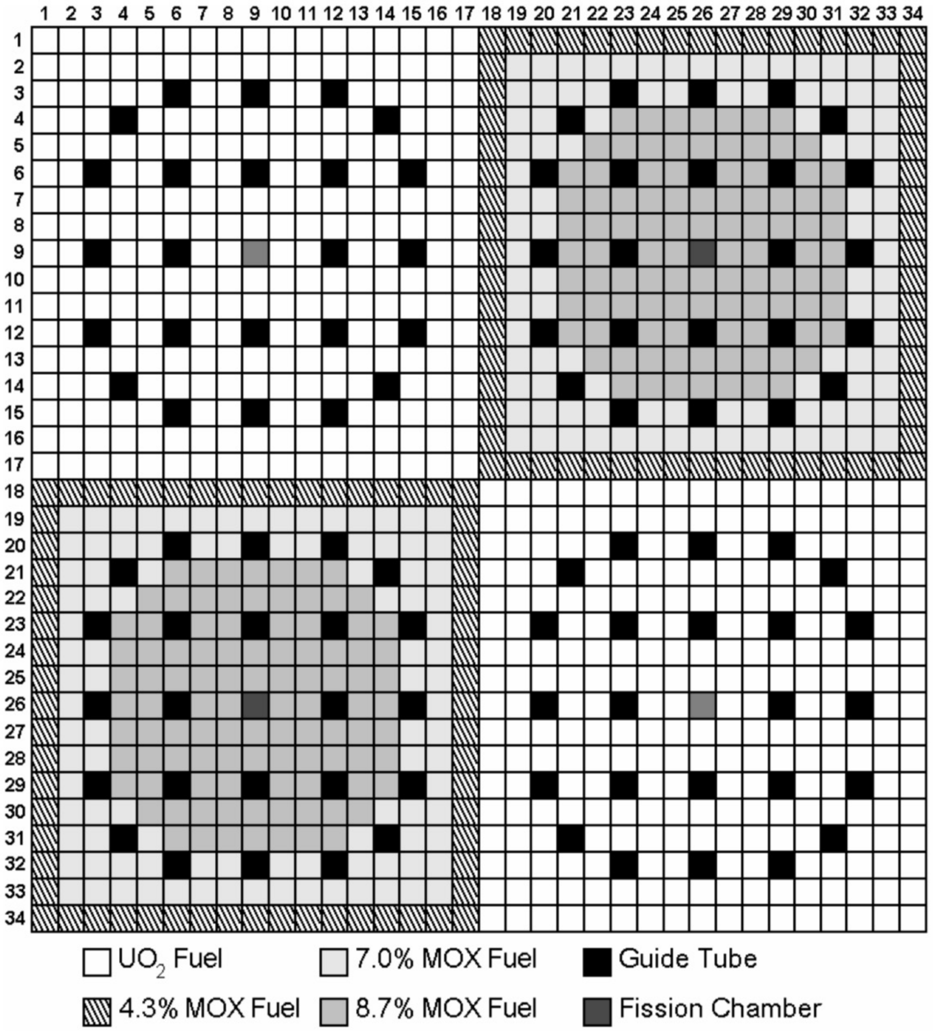
Omega method in Monte Carlo



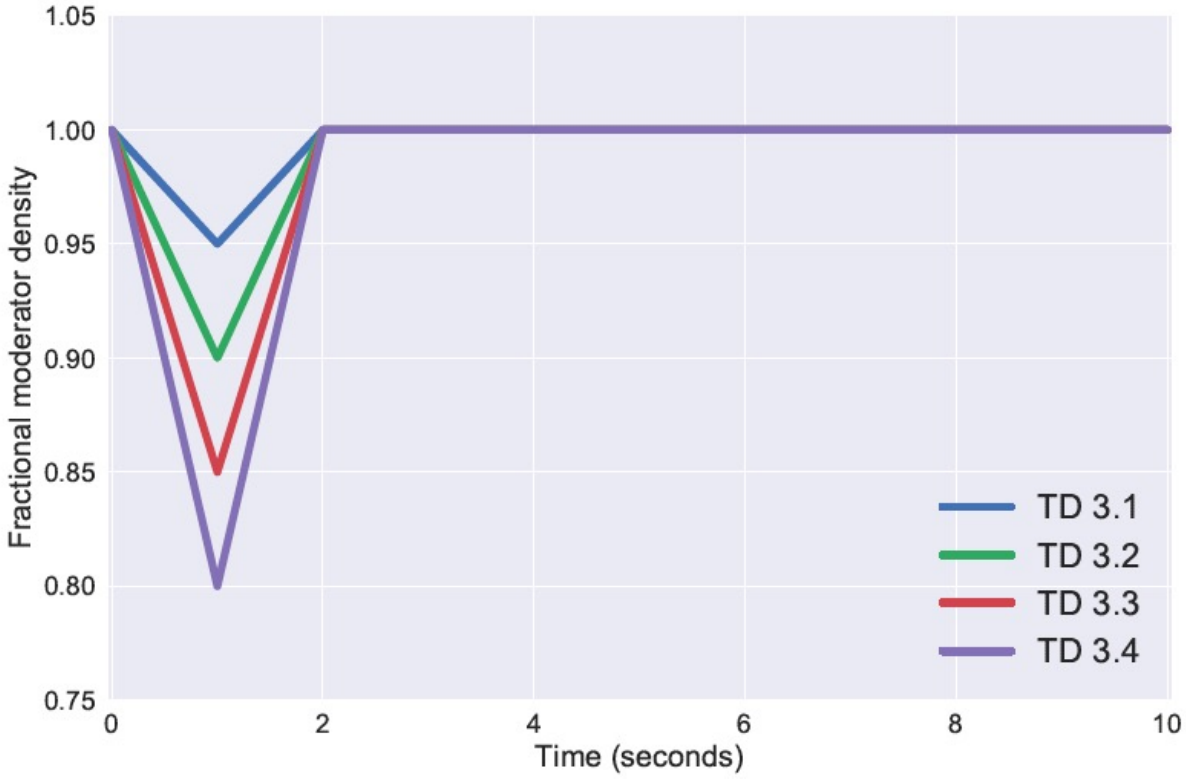
- The challenge for Monte Carlo is calculating the time derivatives.
- The challenge for the diffusion solver is having correct spatial discretization parameters
- Omitting the frequencies collapses to the “adiabatic method”

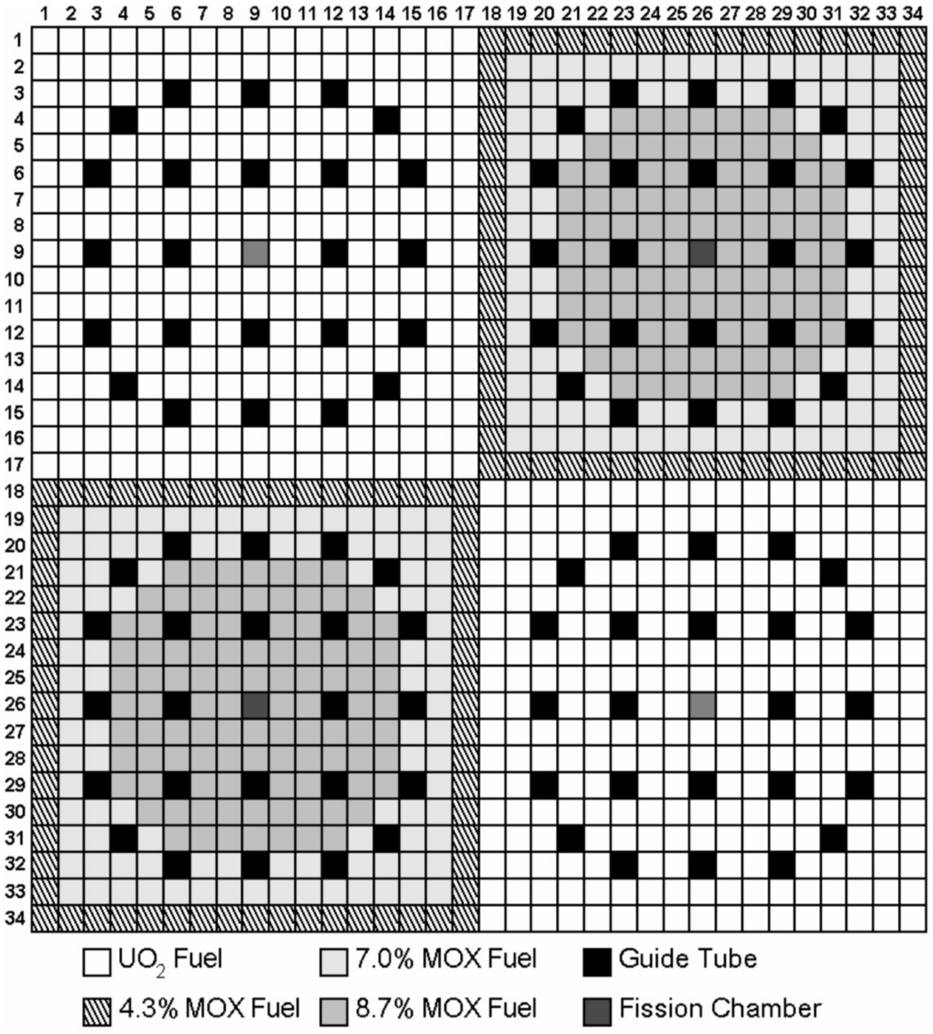
Results: comparing adiabatic & omega



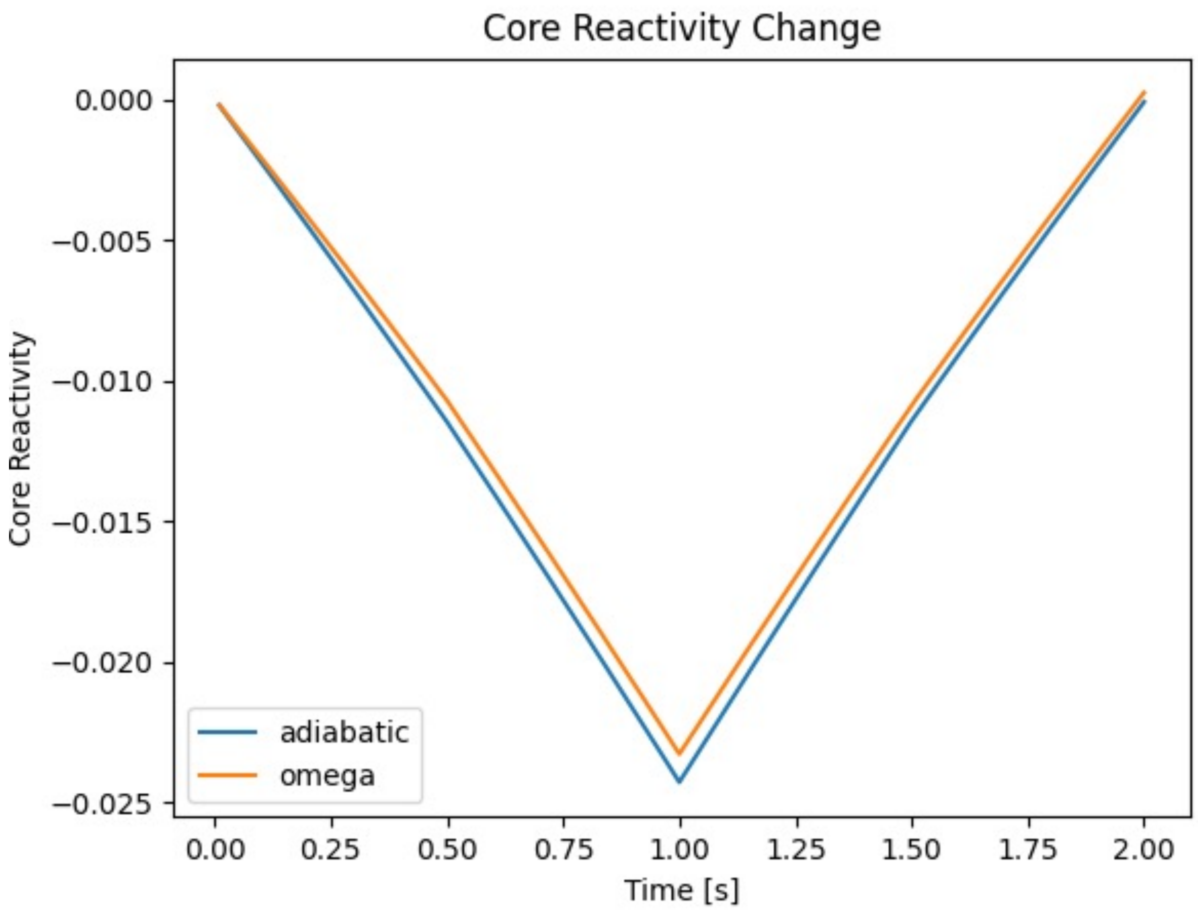


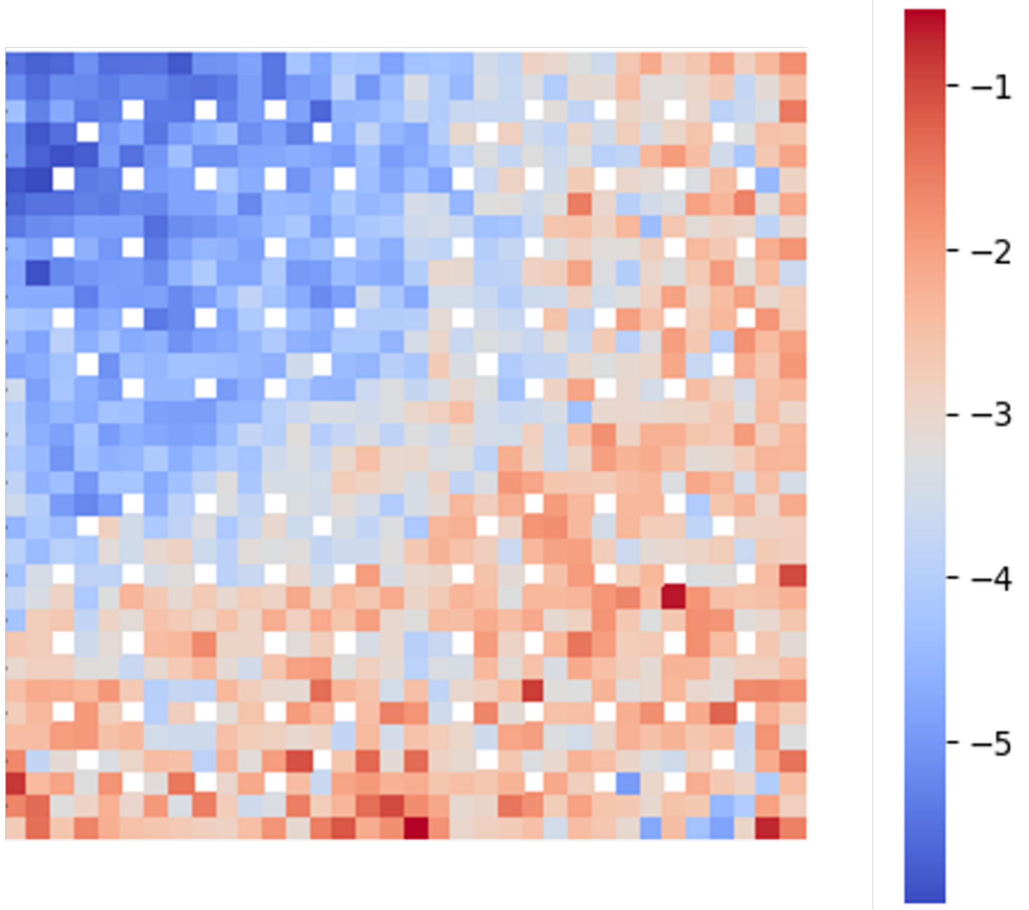
Results: comparing adiabatic & omega



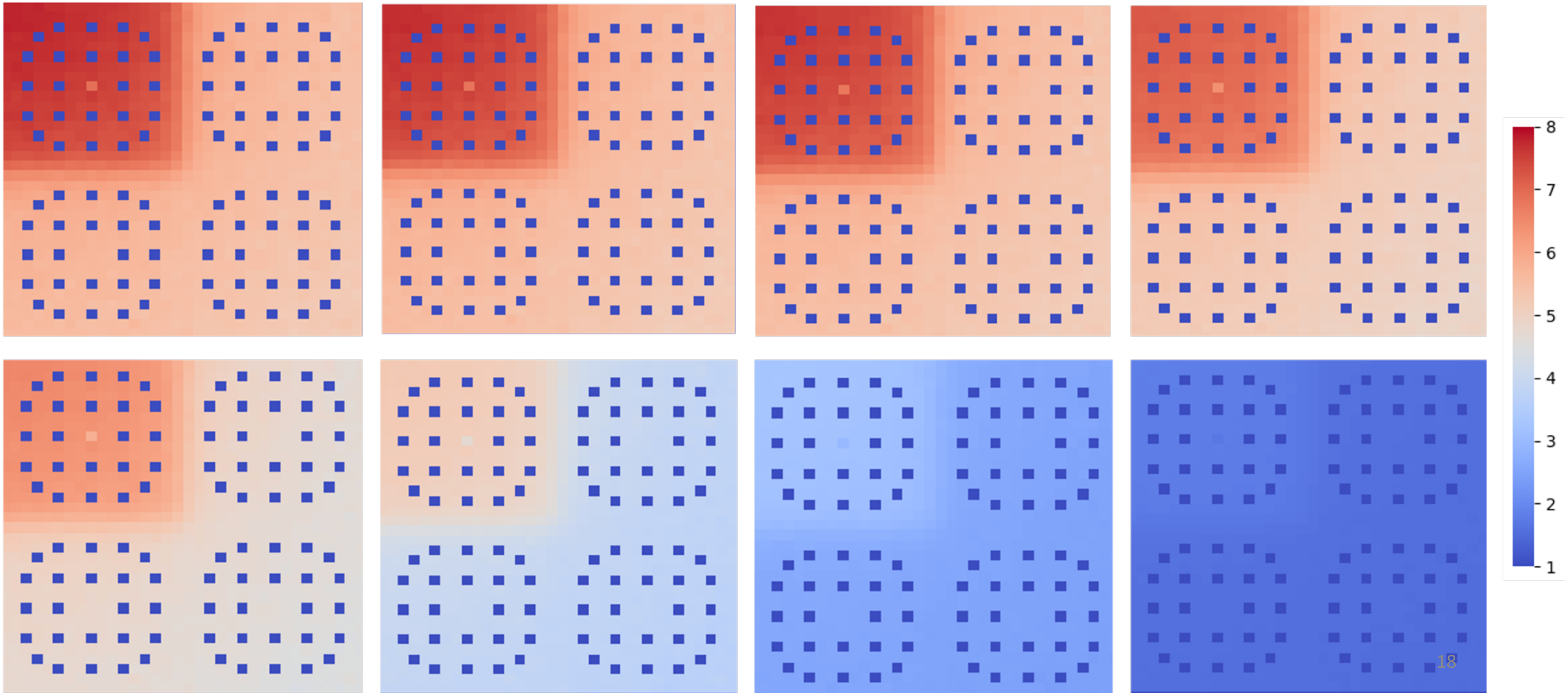


Results: comparing adiabatic & omega





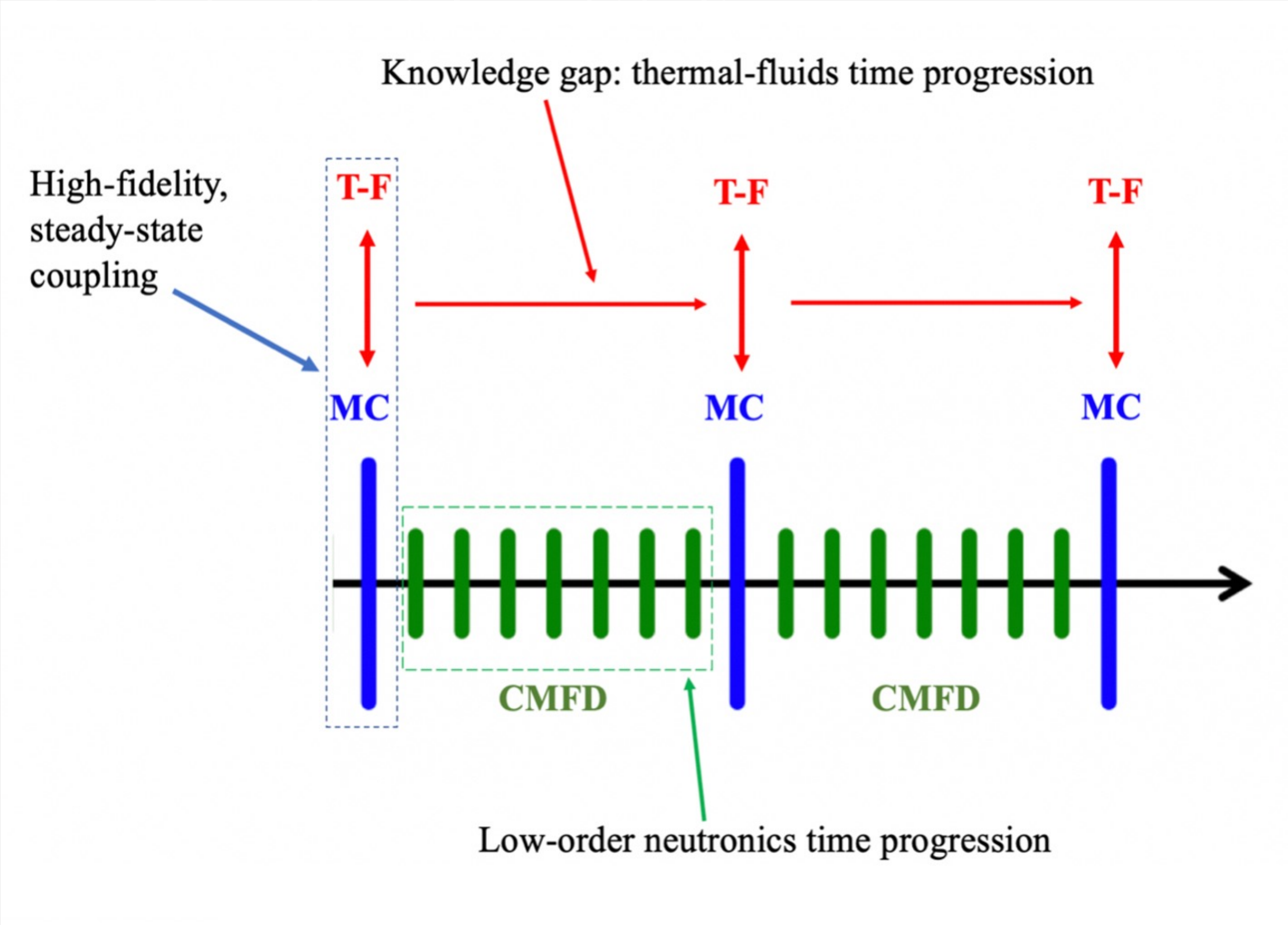
Results: frequencies



Conclusions

- Omega-mode is the bridge we need between diffusion & Monte Carlo
- Allows for modeling transients under 10 seconds
- Currently implemented in OpenMC (find us on Github!)
- This formulation is for prescribed transients only
- A more sophisticated implementation allows for transients to progress naturally

Future work



Knowledge gap: thermal-fluids time progression
High-fidelity, steady-state coupling
T-F
T-F
T-F
MC
MC
MC
CMFD
CMFD
Low-order neutronics time progression