A Mixed Fracture-Matrix Model for Evaluating Well Orientation and Completion Options for the Utah FORGE Site

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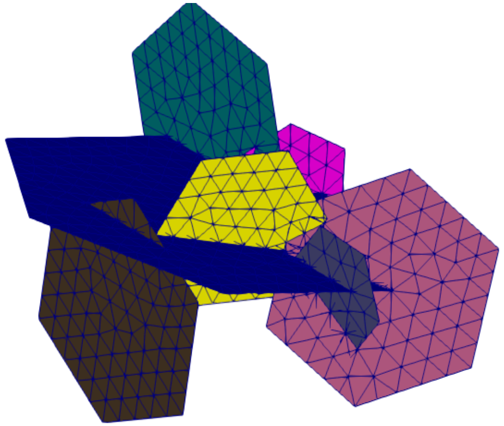
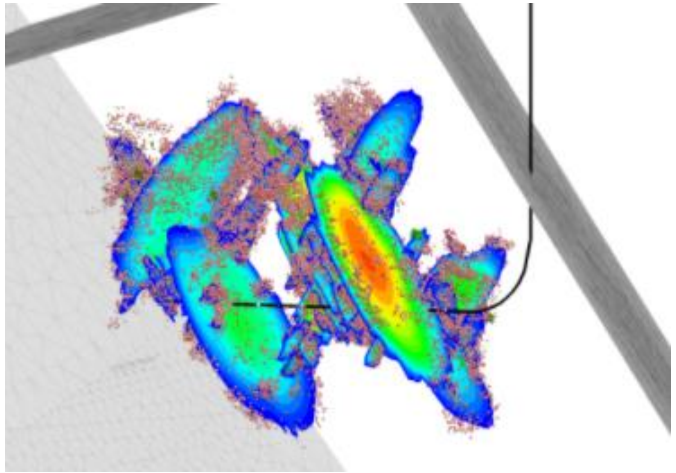
Motivation

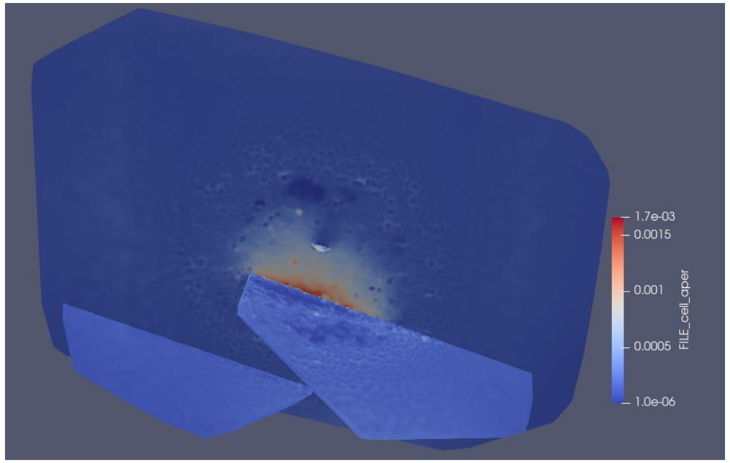
- Simplify DFN modeling workflow
- Efficiently simulate long term performance of geothermal reservoir
  - Simulation of several DFN realizations (Golder)
  - Simulation of stimulated DFNs (ITASCA)
- Perform production well placement sensitivity analysis
- Plan flow through experiments, understand tracer tests.



Golder DFN realization



ITASCA Stimulated DFN

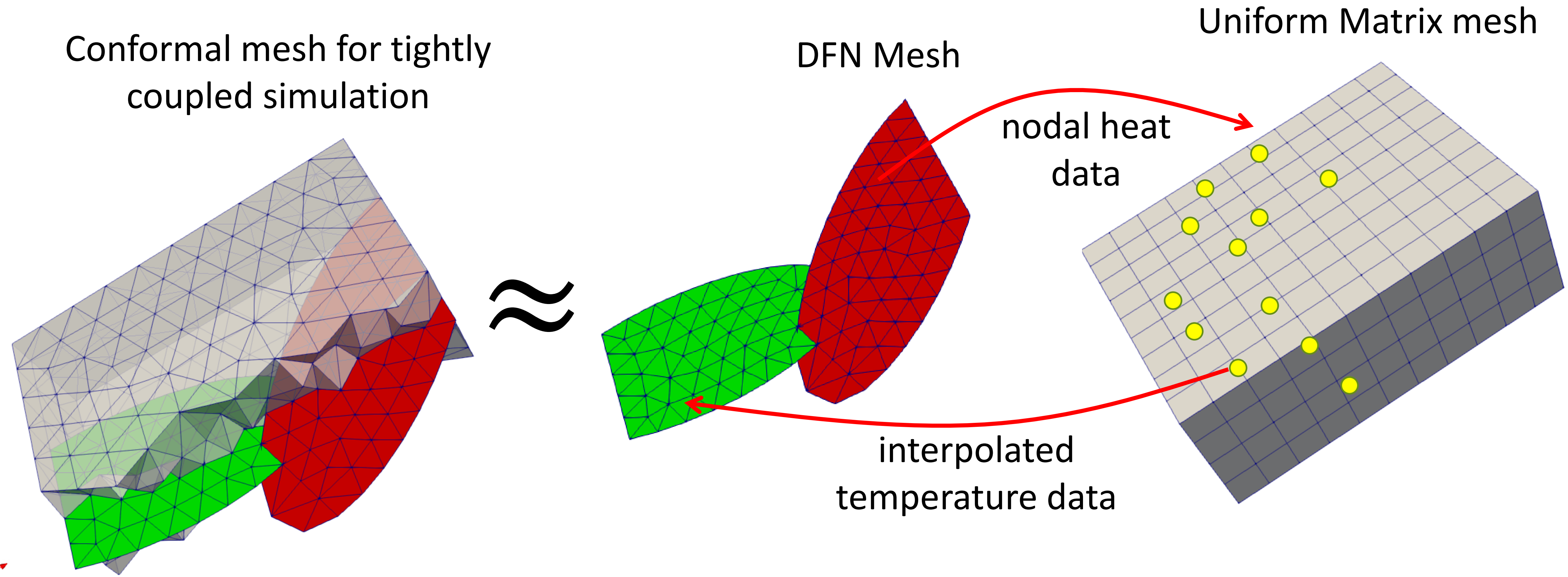


Golder mapping stimulated data

Loose Coupling Algorithm in MOOSE-FALCON

Documentation:
https://mooseframework.inl.gov/modules/porous_flow/flow_through_fractured_media.html

Loose Coupling Algorithm in MOOSE-FALCON



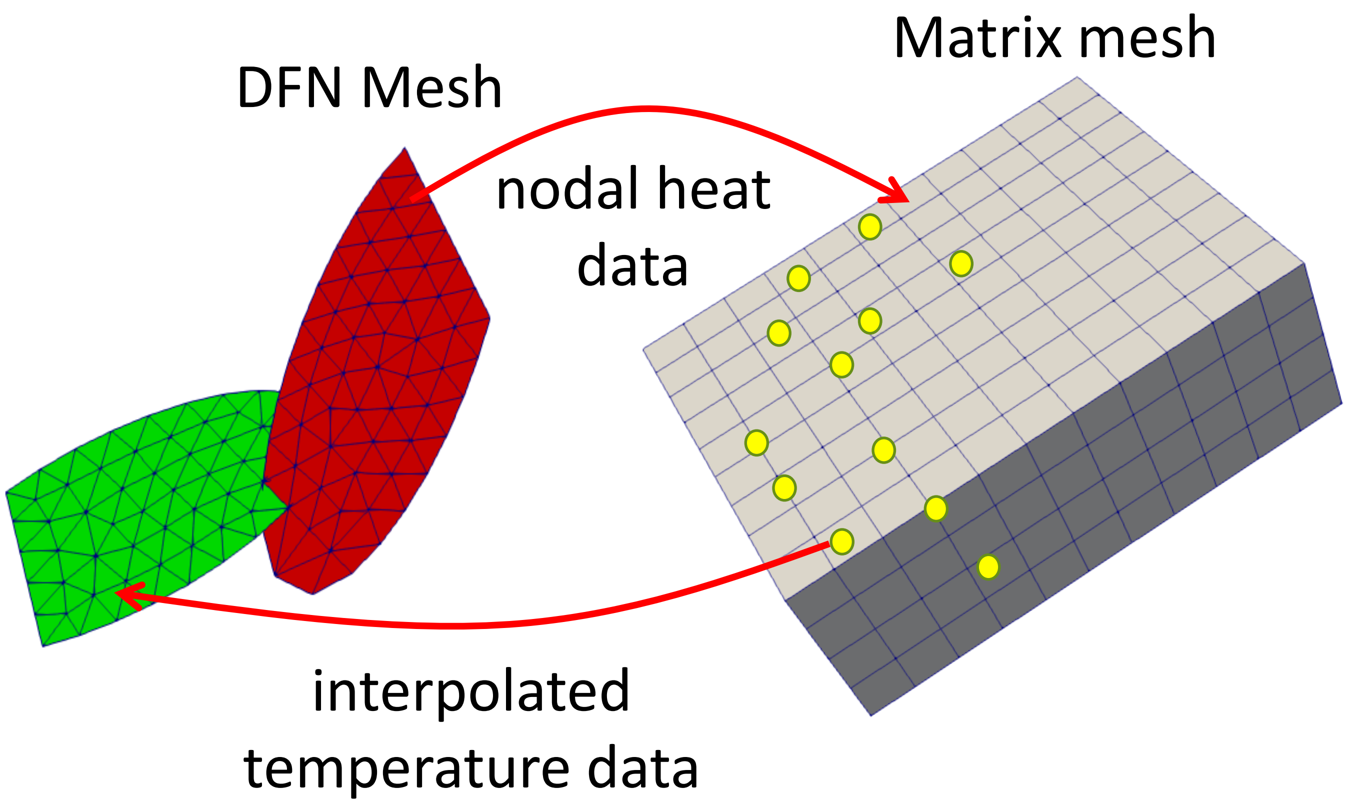
Loose Coupling Algorithm in MOOSE-FALCON

Uses MOOSE MultiApp System:

- Sets up separate computational domains (sub-apps)
- Methods for passing and applying data between domains

Assumptions:

- Matrix properties not affected by Fracture (small fracture aperture)
- Flow through fracture much higher than matrix (insulated BCs on DFN)



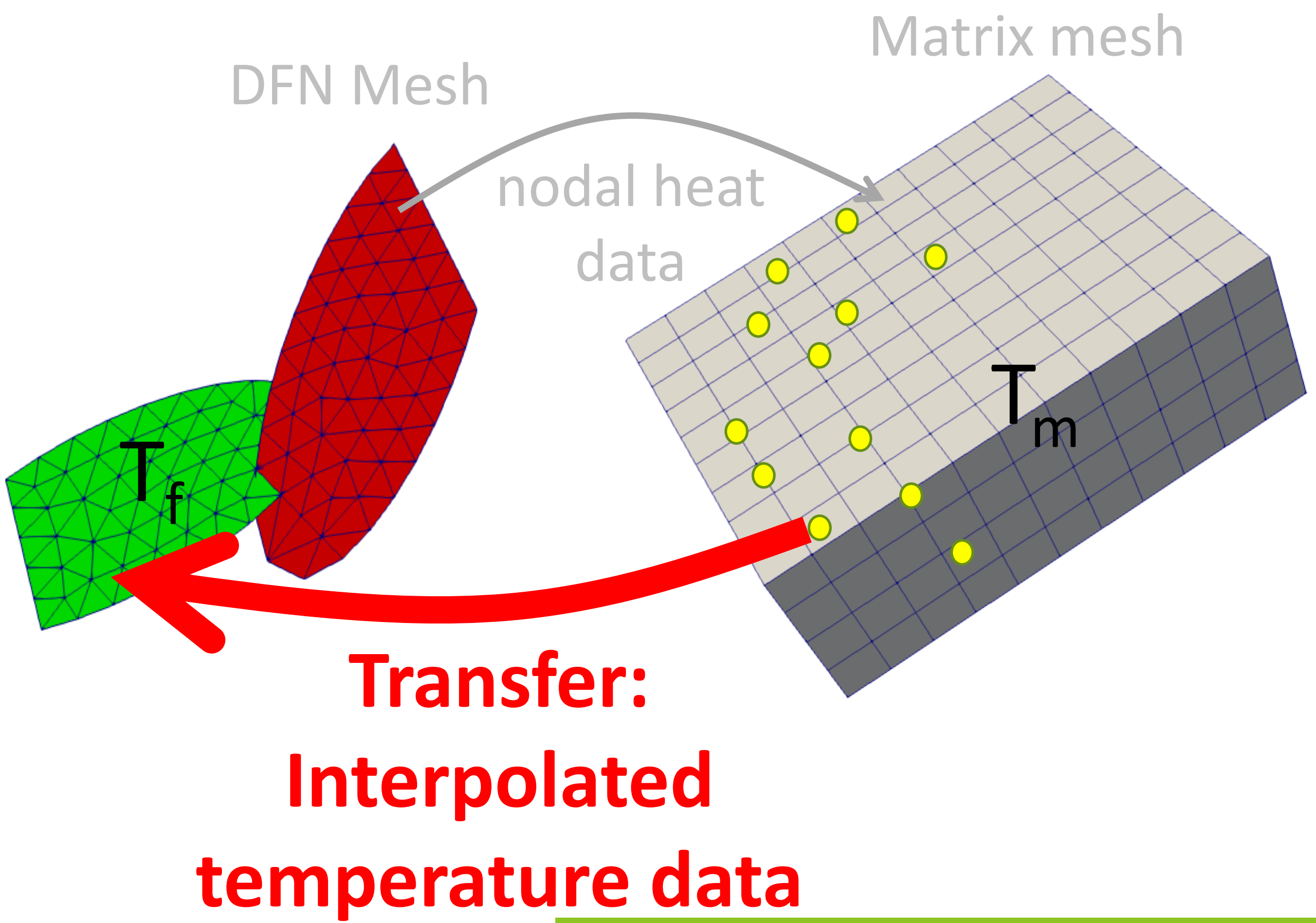
Loose Coupling Algorithm in MOOSE-FALCON

Step 1:
Interpolate Matrix mesh temperature field, T_m, to every node on DFN.

Compute heat transfer from Matrix to DFN based on the temperature difference.

$$Q = h(T_f - T_m)$$

where heat transfer coeff: $h=2\lambda/L$
L is the matrix mesh element length
λ matrix thermal conductivity



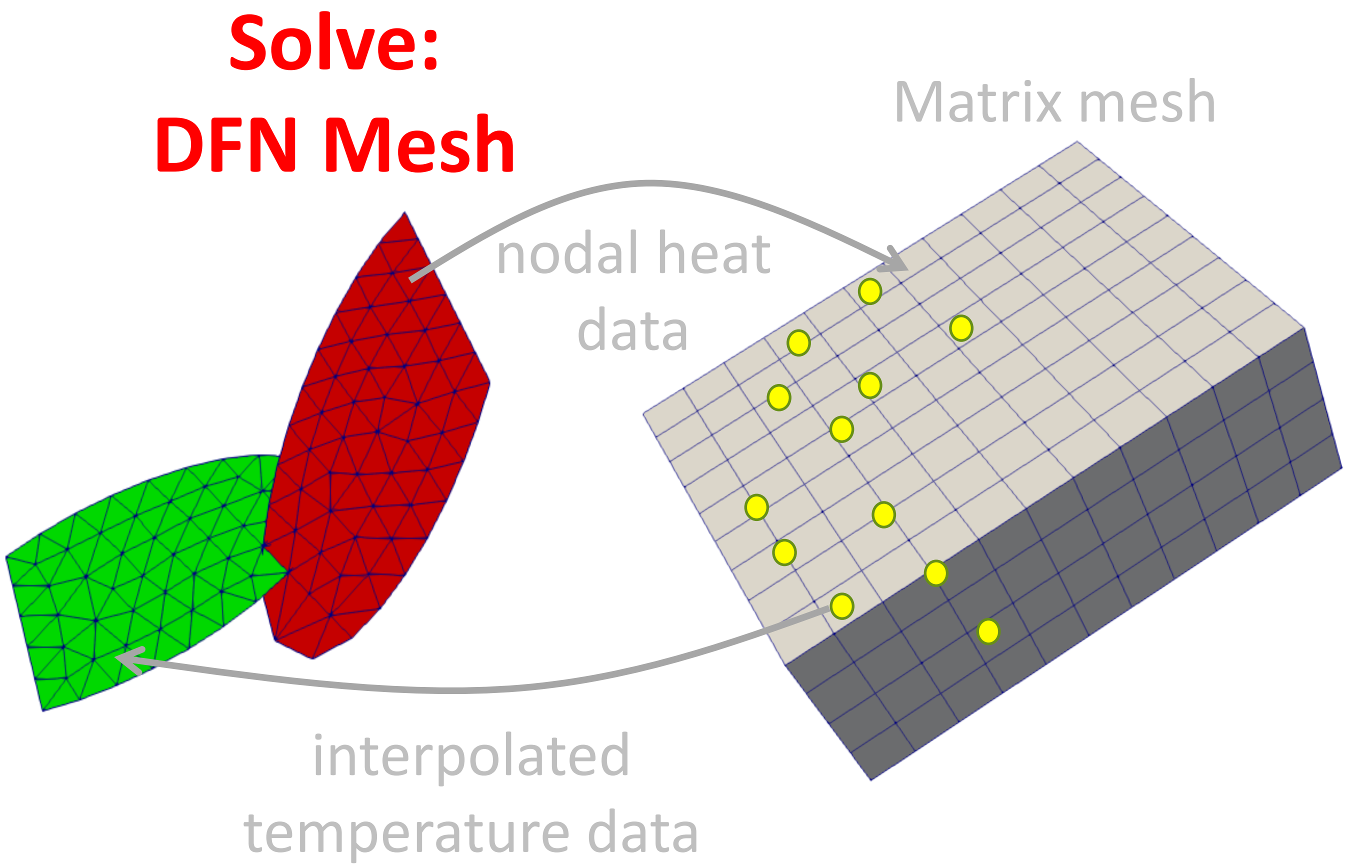
Loose Coupling Algorithm in MOOSE-FALCON

Step 2:
Solve DFN physics.

- Pore pressure and heat diffusion
- Water equation of state
- permeability a function of aperture

  $a=a_o+A(P-P_o)$

  Note: Using constant a_o. Future work to include thermal stimulation and variable a_o

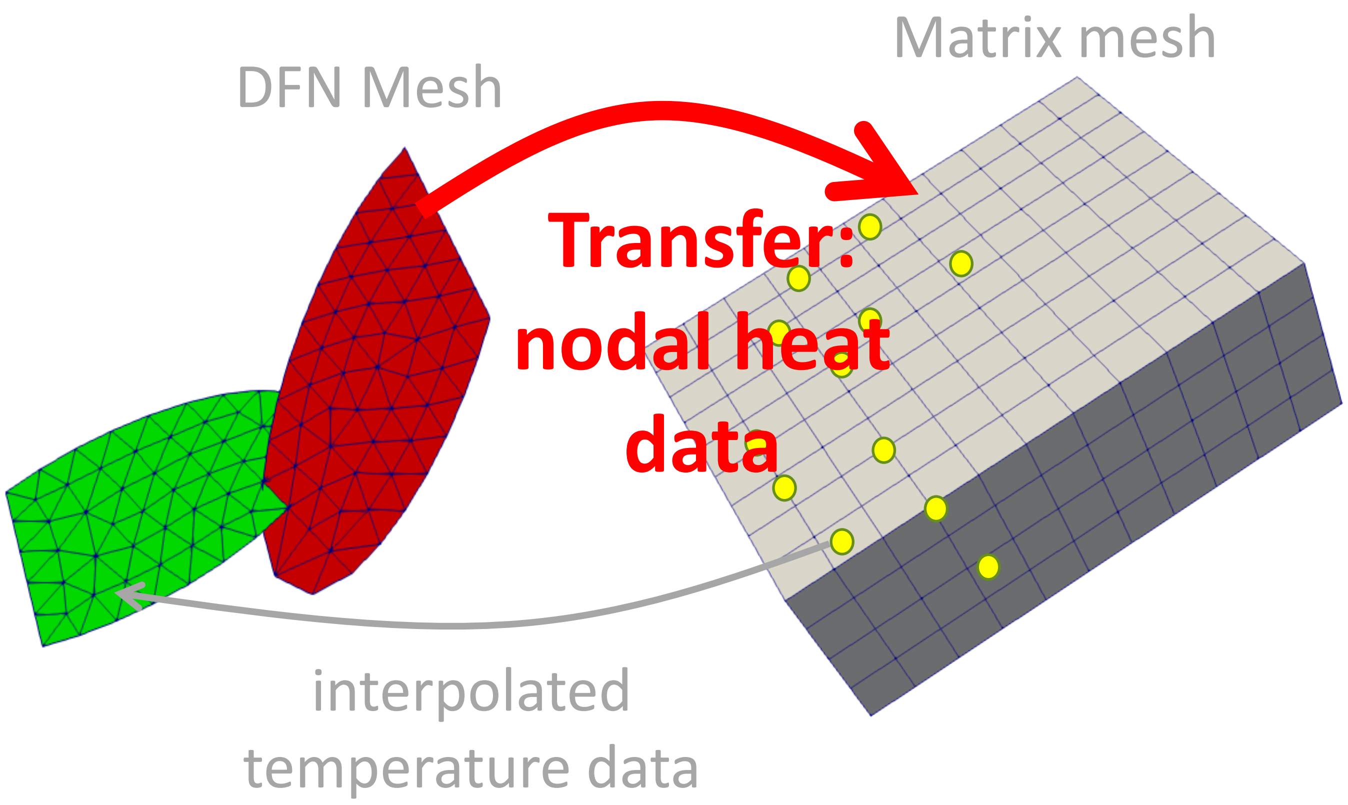


DFN physics are “fast” compared to matrix so multiple small DFN timesteps are taken per larger matrix timestep

Loose Coupling Algorithm in MOOSE-FALCON

Step 3:
Apply the same Q applied to the fracture mesh in step 1 onto the Matrix mesh

-every DFN node produces a point load in the matrix mesh

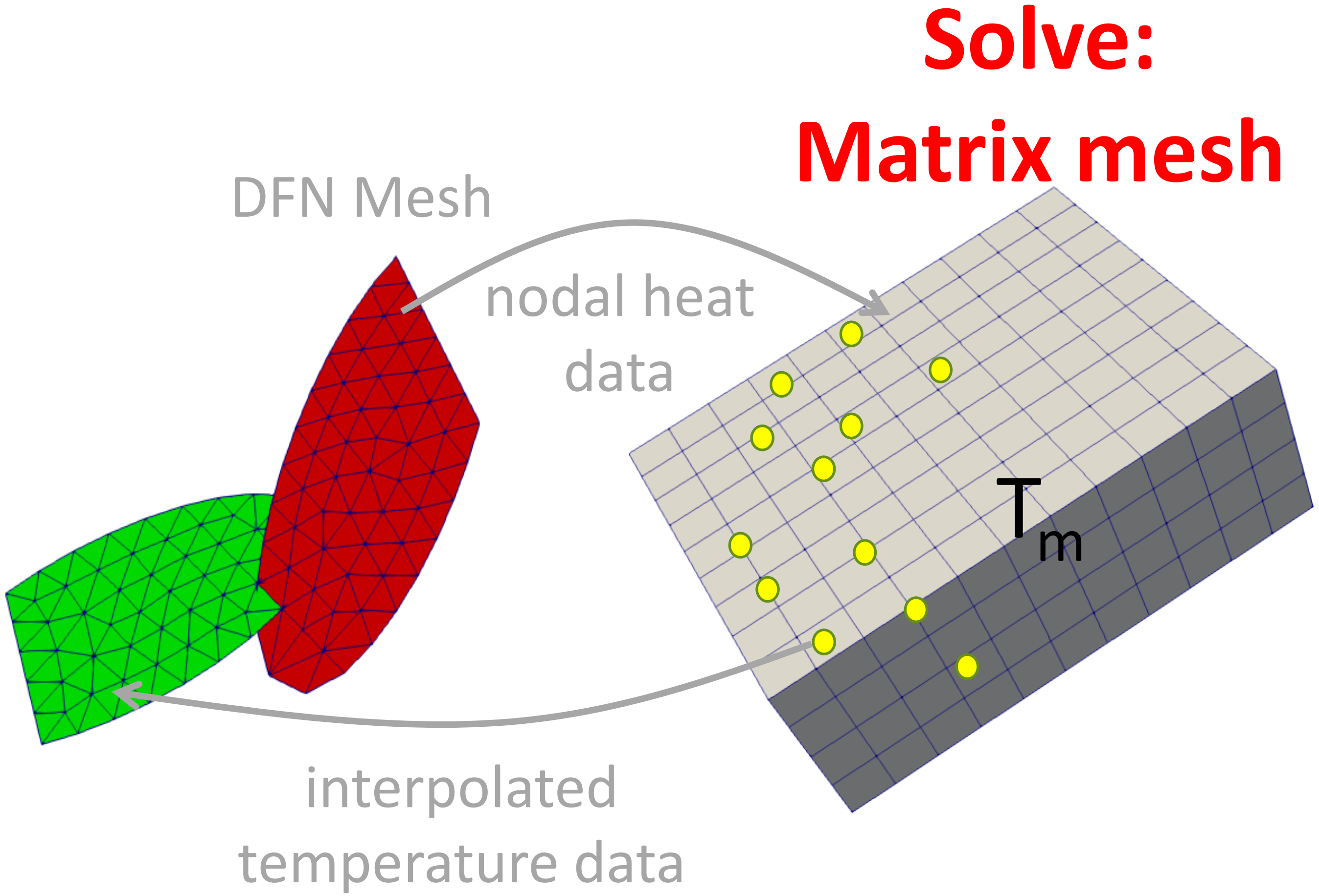


Loose Coupling Algorithm in MOOSE-FALCON

Step 4:
Solve matrix physics to get a new matrix temperature, T_m.

This completes a timestep

Could iterate within a timestep but results suggest it is not necessary

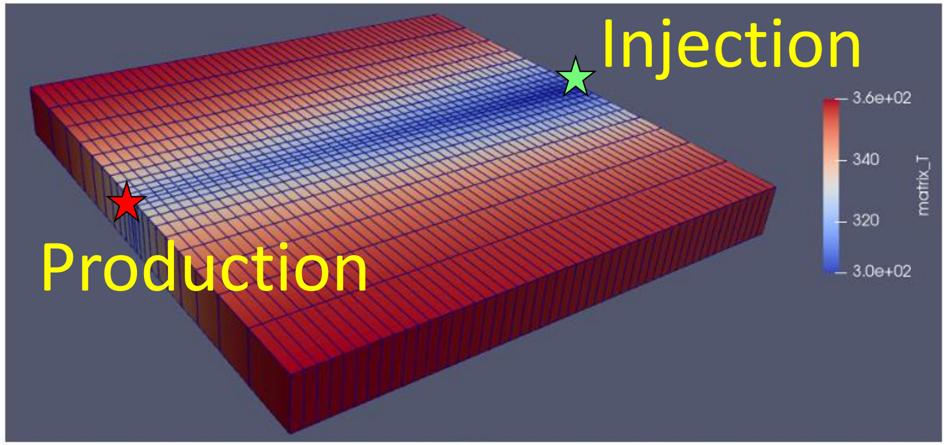


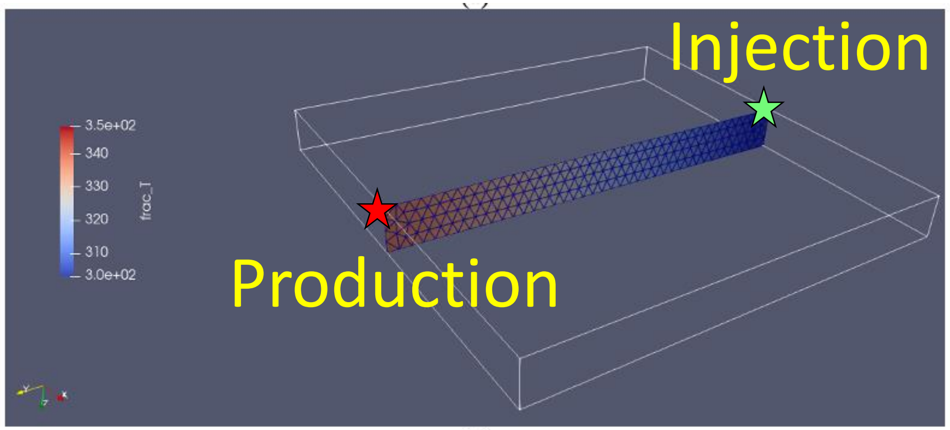
Verification to Gringarten Solution (1975)

Single infinitely long fracture in infinite matrix domain

Parameter	Value
Rock initial temperature	90°C
Rock density	2875 kg/m³
Rock heat capacity	825 J/kg-K
Rock thermal conductivity	2.83 W/m-K
Rock permeability	1e^{-16} m^2
Rock porosity	0.1
Water Flow rate	0.1 kg/s
Water Injection Temperature	30°C
Domain Length	100 m
Domain Width	100 m
Domain Height	10 m
Well spacing	100 m

Temperature field after 3 years

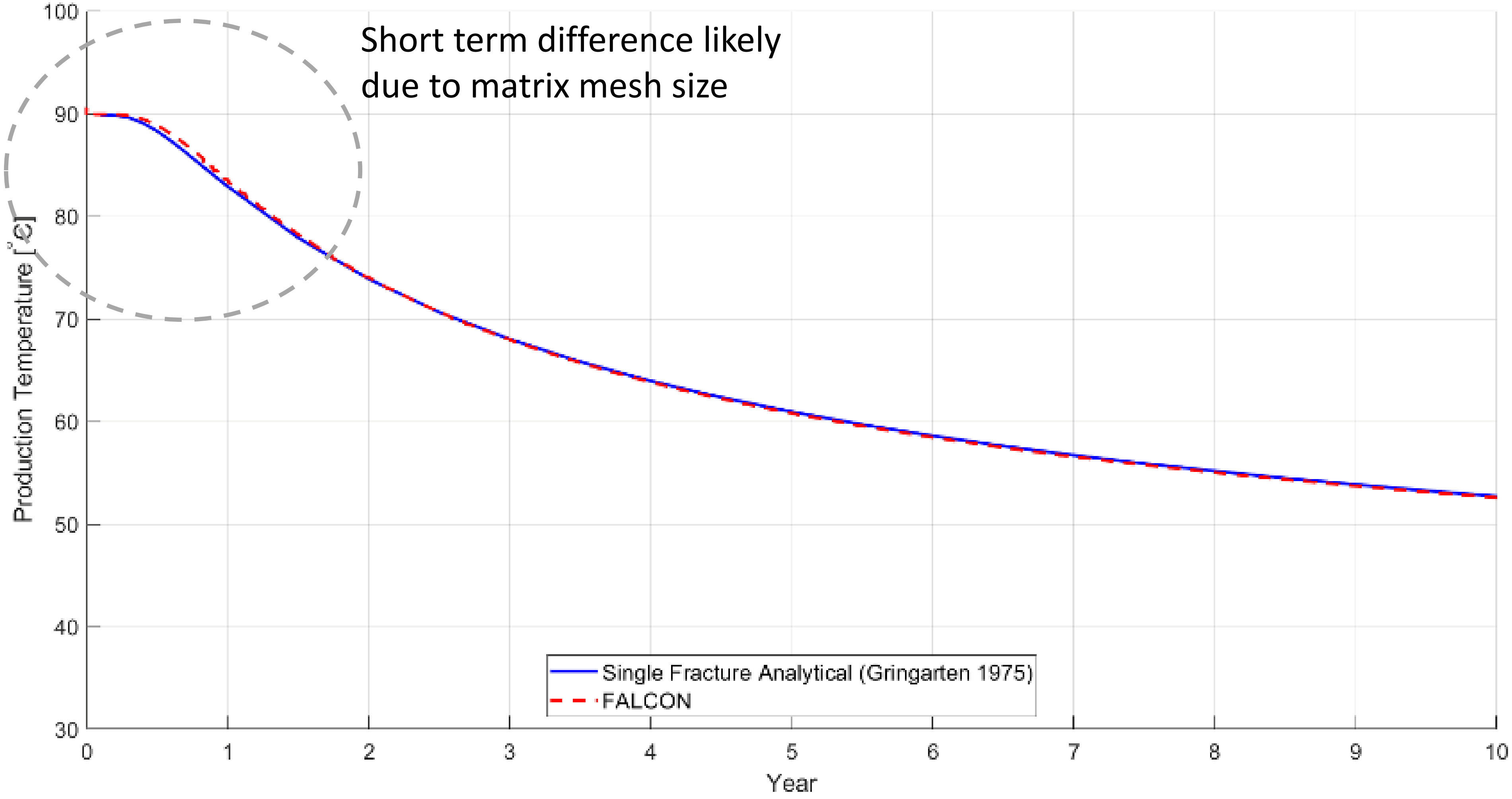




Gringarten, A. C., P. A. Witherspoon, and Yuzo Ohnishi. "Theory of heat extraction from fractured hot dry rock." *Journal of Geophysical Research* 80.8 (1975): 1120-1124.

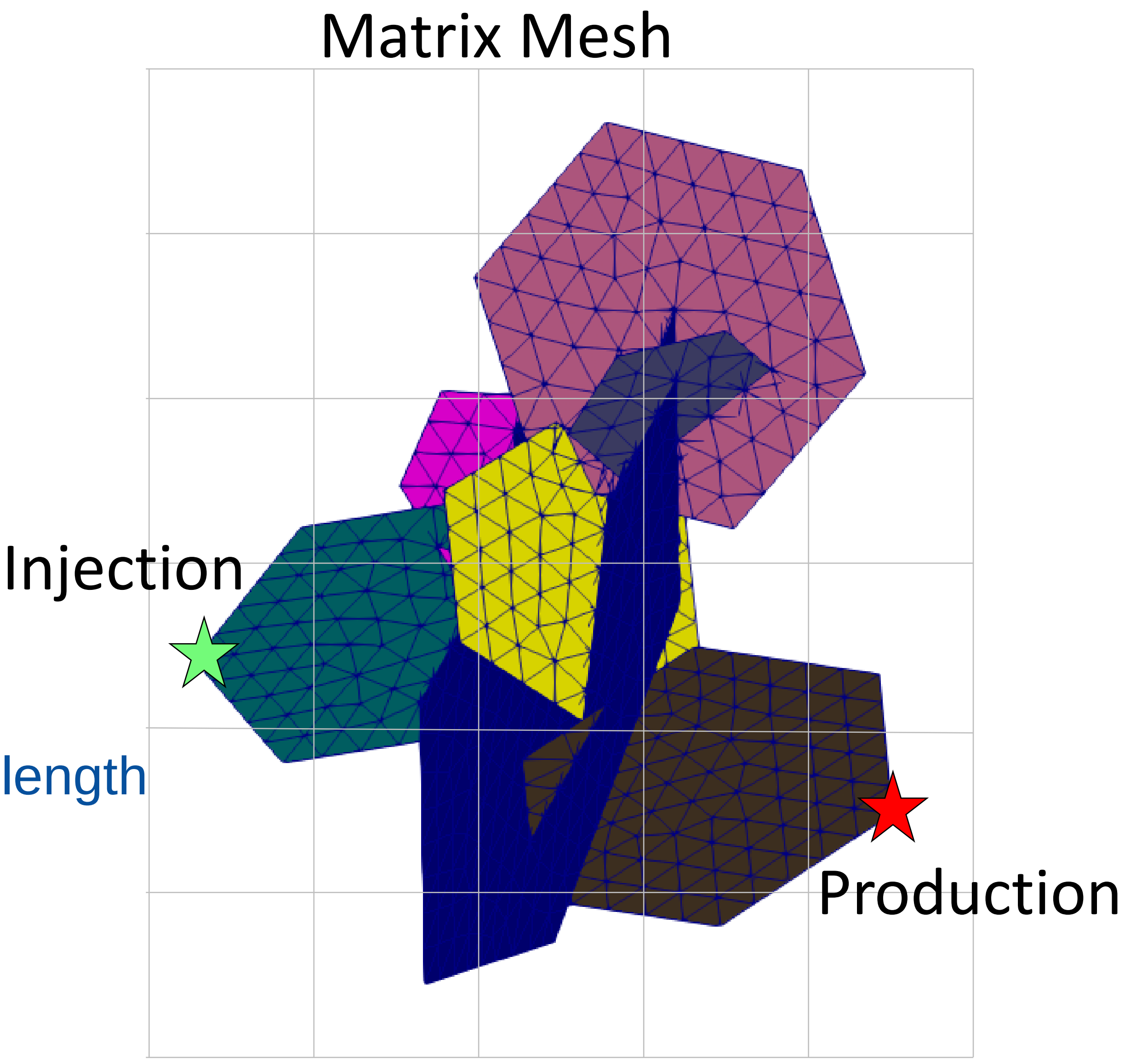
https://mooseframework.inl.gov/falcon/examples/example01.html

Verification to Gringarten Solution (1975)

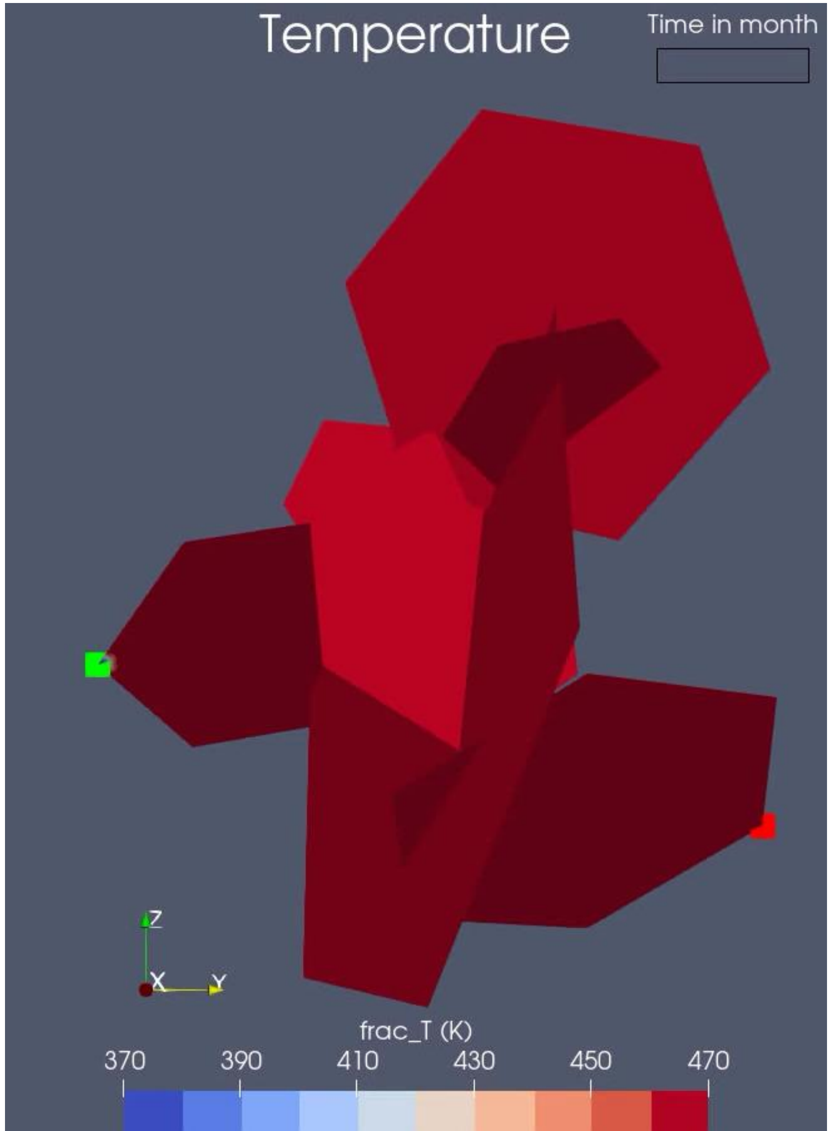


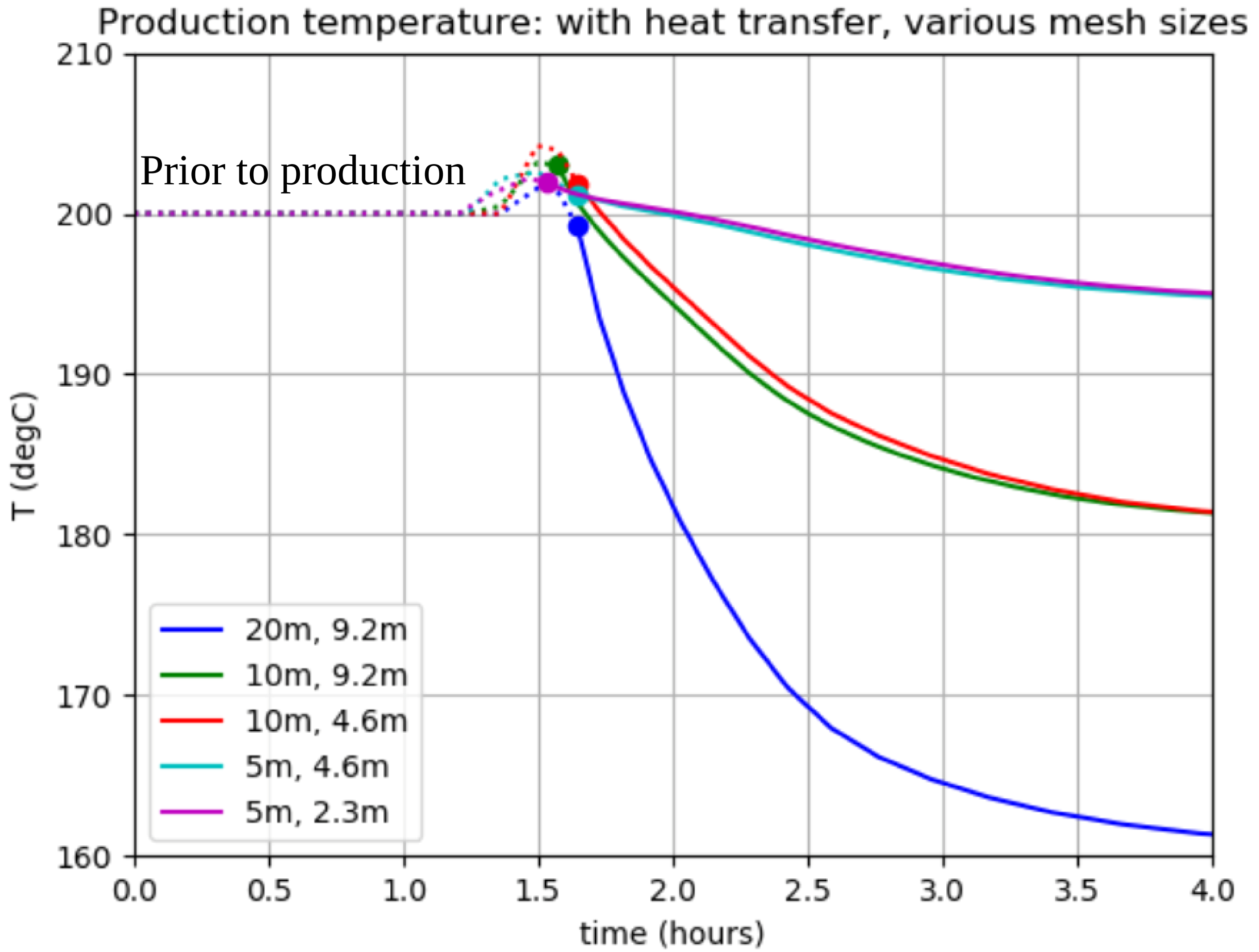
Example DFN Simulation

- DFN:
  - 12 fractures ranging in size 40-150m
  - Permeability:1e-12
- Matrix:
  - 220x170x220m
  - Permeability: 1e-18 m^2
  - λ=5$Wm^{-1}K^{-1}$ scaled by matrix element length
  - P=10MPa (depth = 1km)
  - T=200C
- Injection: 10 $kg.s^{-1}$, 100C
- Production: 10$kg.s^{-1}$



Example DFN Simulation: Mesh Convergence for *Short* Term Production





Example DFN Simulation:
Mesh Convergence for *Short* Term Production

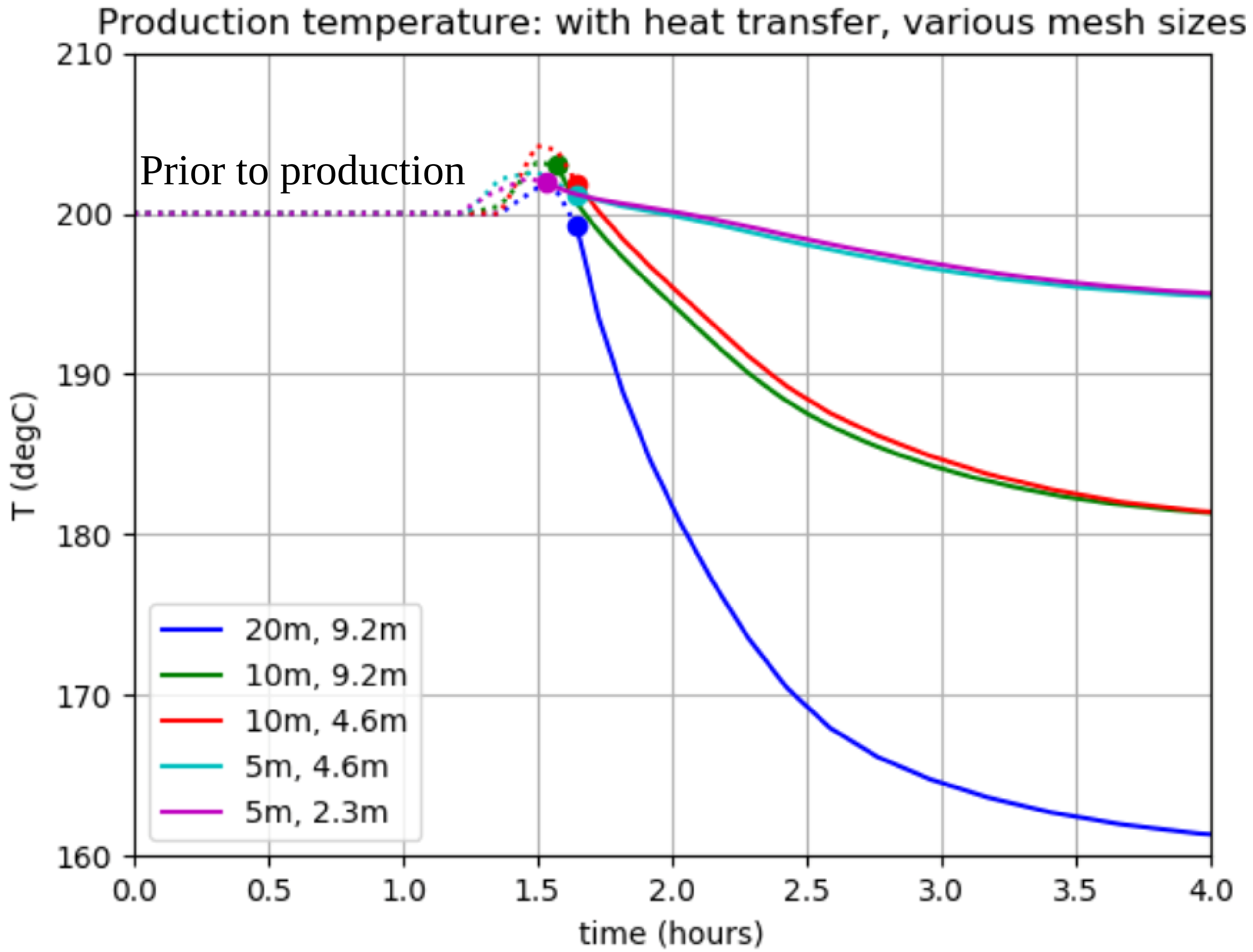
Heat Transfer from Matrix to Fracture:

$Q = h(T_f - T_m)$

$h = 2\,\lambda / L$

Larger **L** -> smaller **h** -> smaller **Q**

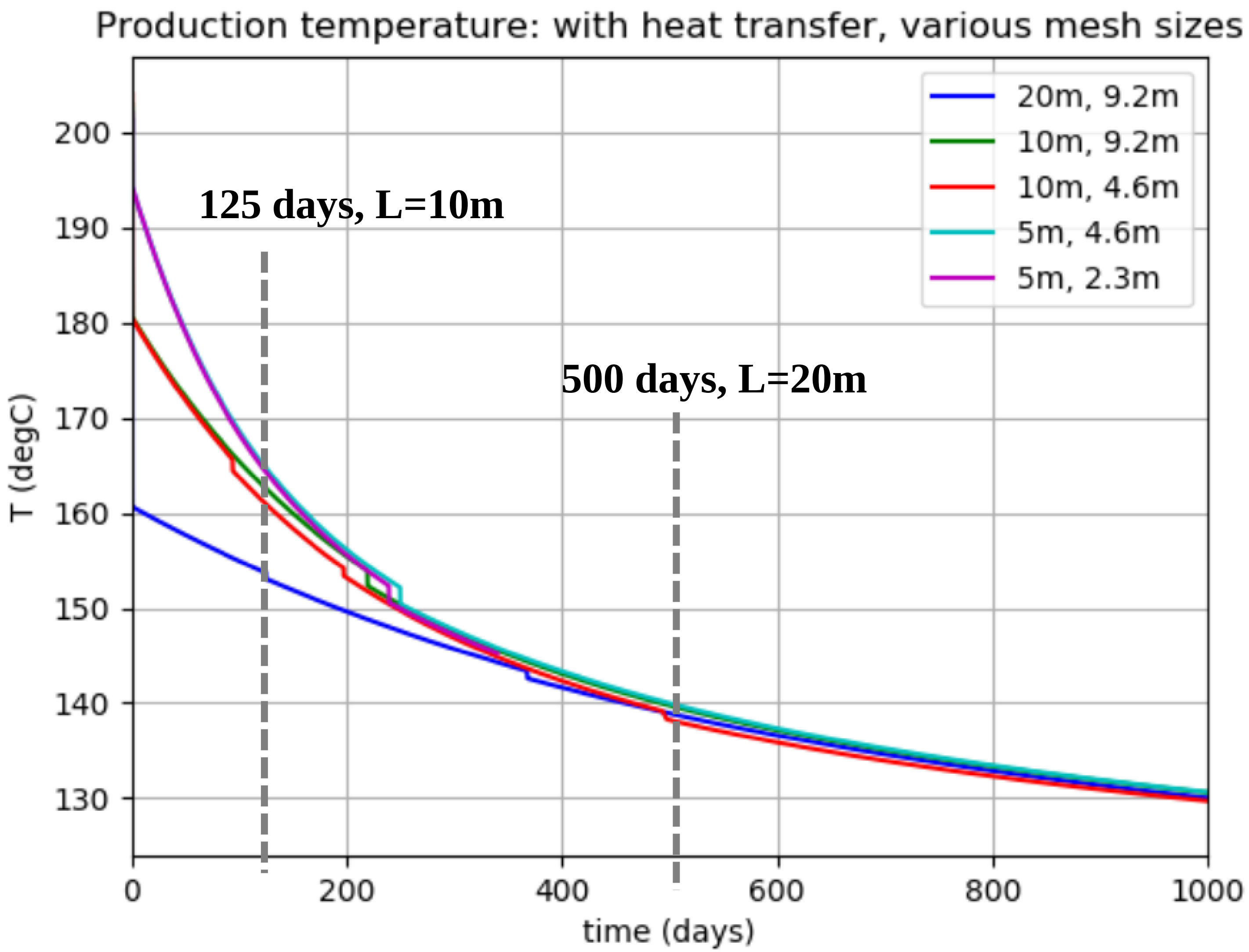
Large matrix elements have a slower heat transfer into the fracture



Example DFN Simulation:
Mesh Convergence for *Long* Term Production

Time Scale based on time it takes a pulse of heat to travel through a Matrix element half length: $\sim c\rho\lambda^{-1}L^2$

Matrix Element Size (m)	Time scale (days)
5	5
10	125
20	500



Example DFN Simulation: Fracture Aperture Change

Testing with Linear Aperture-Pressure function

$a = a_o + A(P - P_o)$

a_o = 0.1 mm

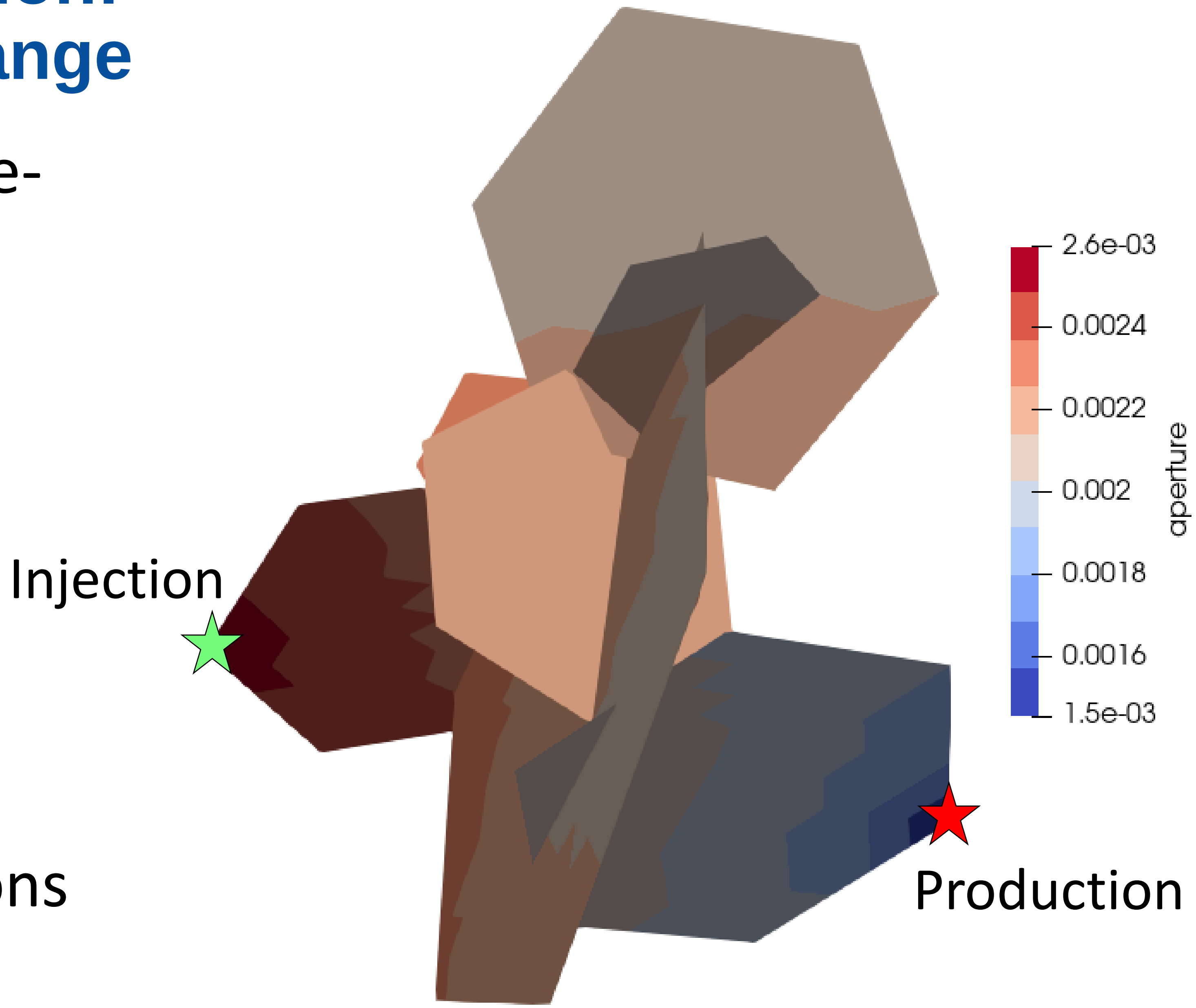
A= 1e-3 m.MPa^{-1} (a pressure increase of 1MPa dilates the fracture by 1mm)

P_0 =10MPa (hydrostatic 1km depth)

The permeability of the fracture is proportional to a^3, with insitu permeability of 10^{-11} m^2 when $a = a_0$

*Develop constitutive relations from XSite stimulation data

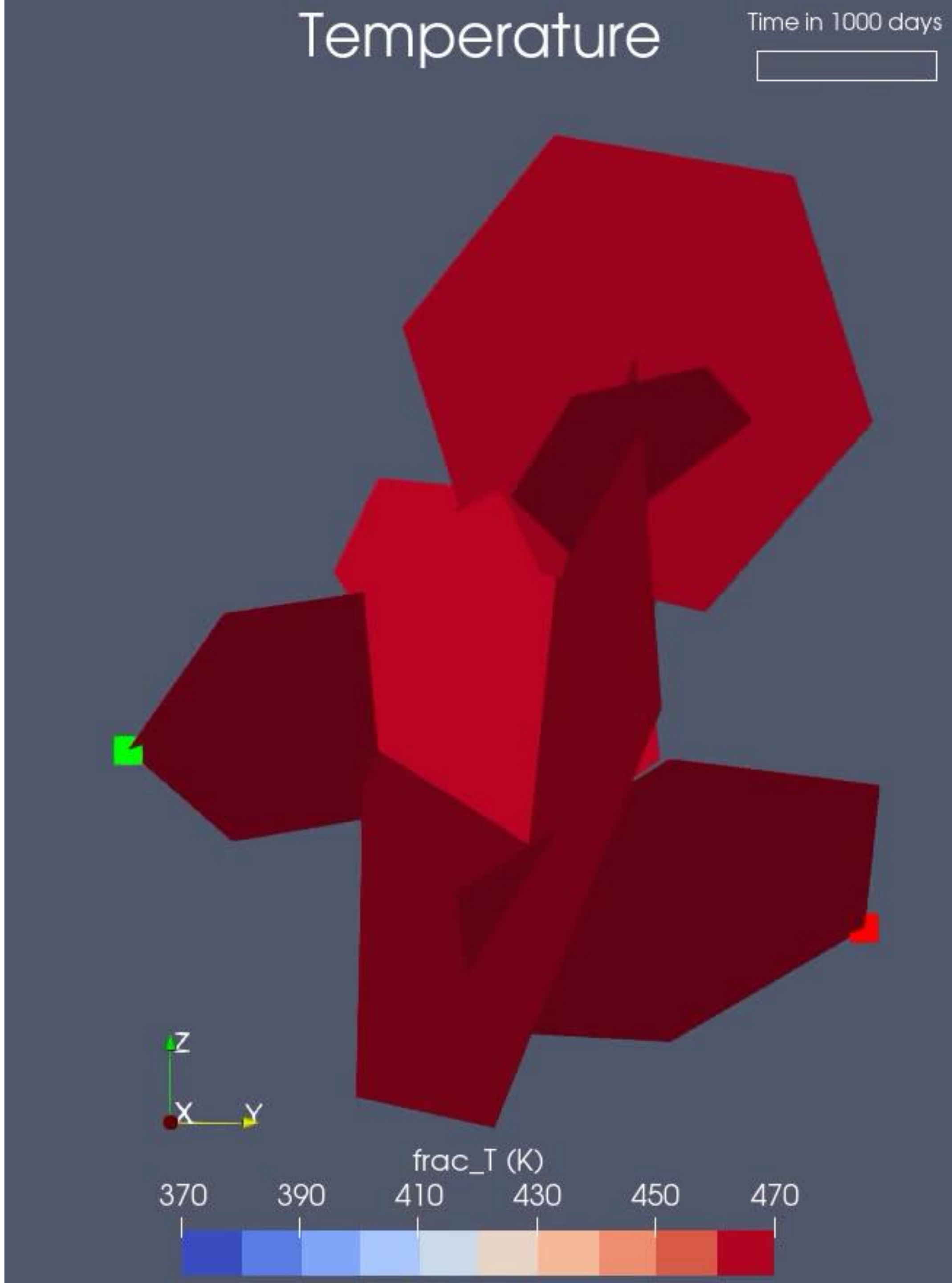
Aperture after 1000 days



Example DFN Simulation: Matrix Cooling

Matrix elements shown cooled by 10C after 1000 days of production

-Matrix temperature gradient needs to be included in aperture

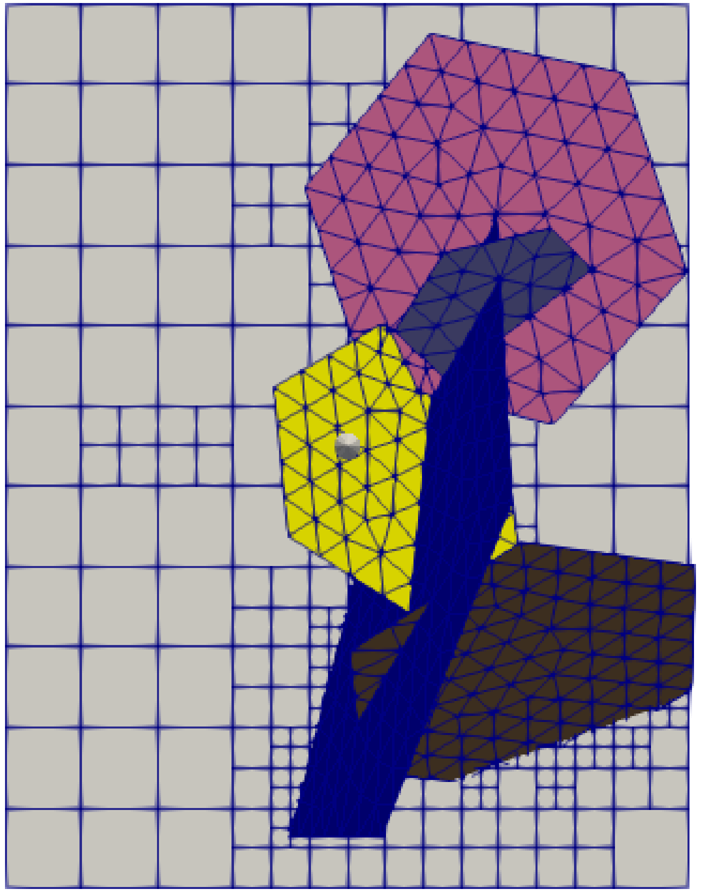


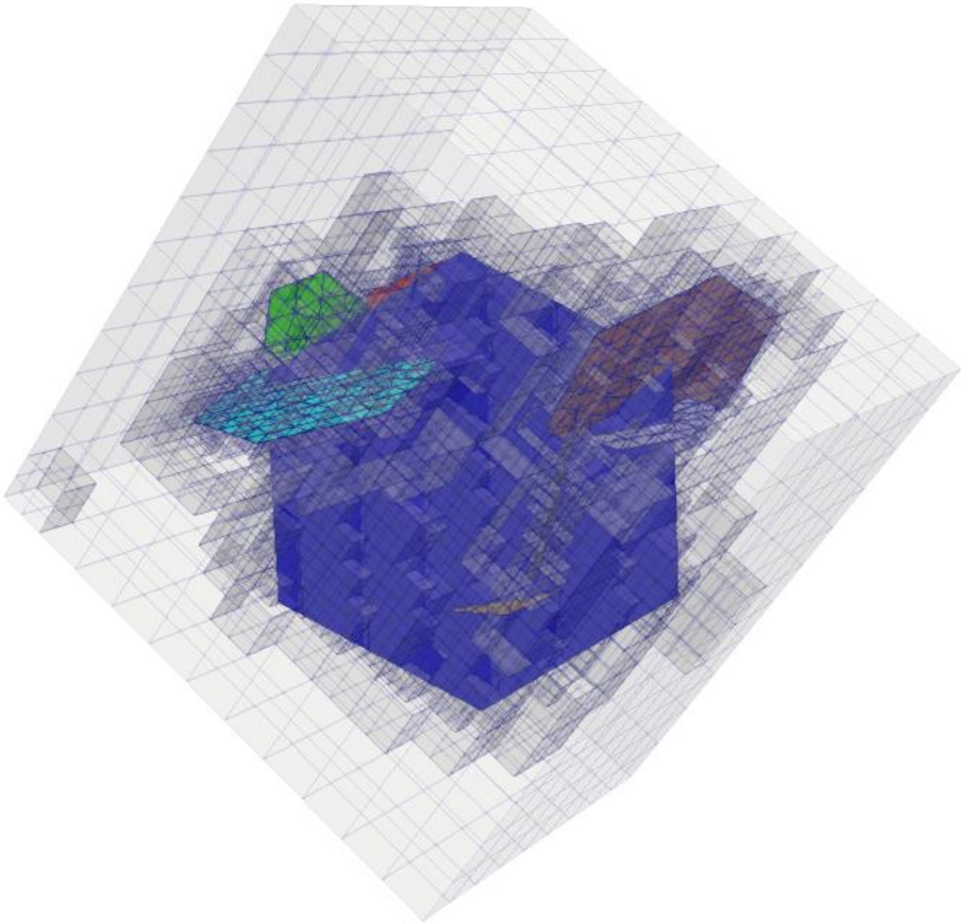
Example DFN Simulation:
Matrix Automatic Mesh Refinement (AMR)

10x reduction in Matrix elements

Two levels of uniform refinement (5m):
69,696 elements

Matrix with 20m mesh AMR with 2 levels of refinement (5m):
6,913 elements





Example DFN Simulation: Matrix AMR speed-up

Matrix Refinement	Number of Matrix Elements	Run Time (minutes)	Matrix Total Nonlinear Iterations	Fracture Total Nonlinear Iterations
Original (20m)	1089	5.3	441	2572
Refine 1 (10m)	8712	18.0	441	2448
Refine 2 (5m)	**69696**	**191.8**	441	2351
AMR 1 (10m)	2286	7.7	441	2444
AMR 2 (5m)	**6906**	**20.2**	441	2375
Refine 2 (5m) (noSubCycle)	69696	717.7	1690	3279

AMR provides 10x speed-up over uniform refinement (5m matrix elements)

Example DFN Simulation: Loose coupling speed-up

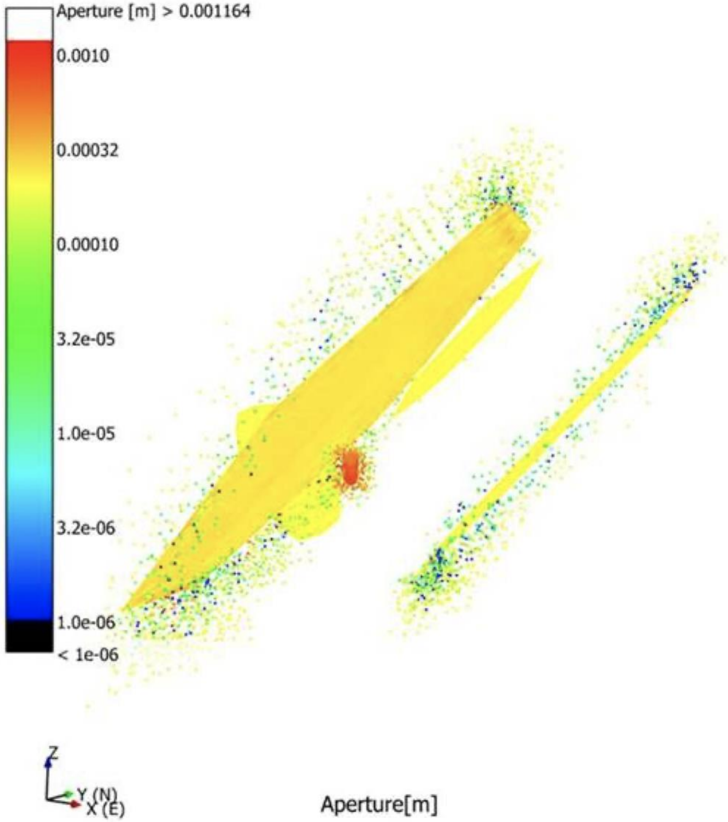
Matrix Refinement	Number of Matrix Elements	Run Time (minutes)	Matrix Total Nonlinear Iterations	Fracture Total Nonlinear Iterations
Original (20m)	1089	5.3	441	2572
Refine 1 (10m)	8712	18.0	441	2448
Refine 2 (5m)	69696	**191.8**	441	**2351**
AMR 1 (10m)	2286	7.7	441	2444
AMR 2 (5m)	6906	20.2	441	2375
Refine 2 (5m) (noSubCycle)	69696	**717.7**	1690	**3279**

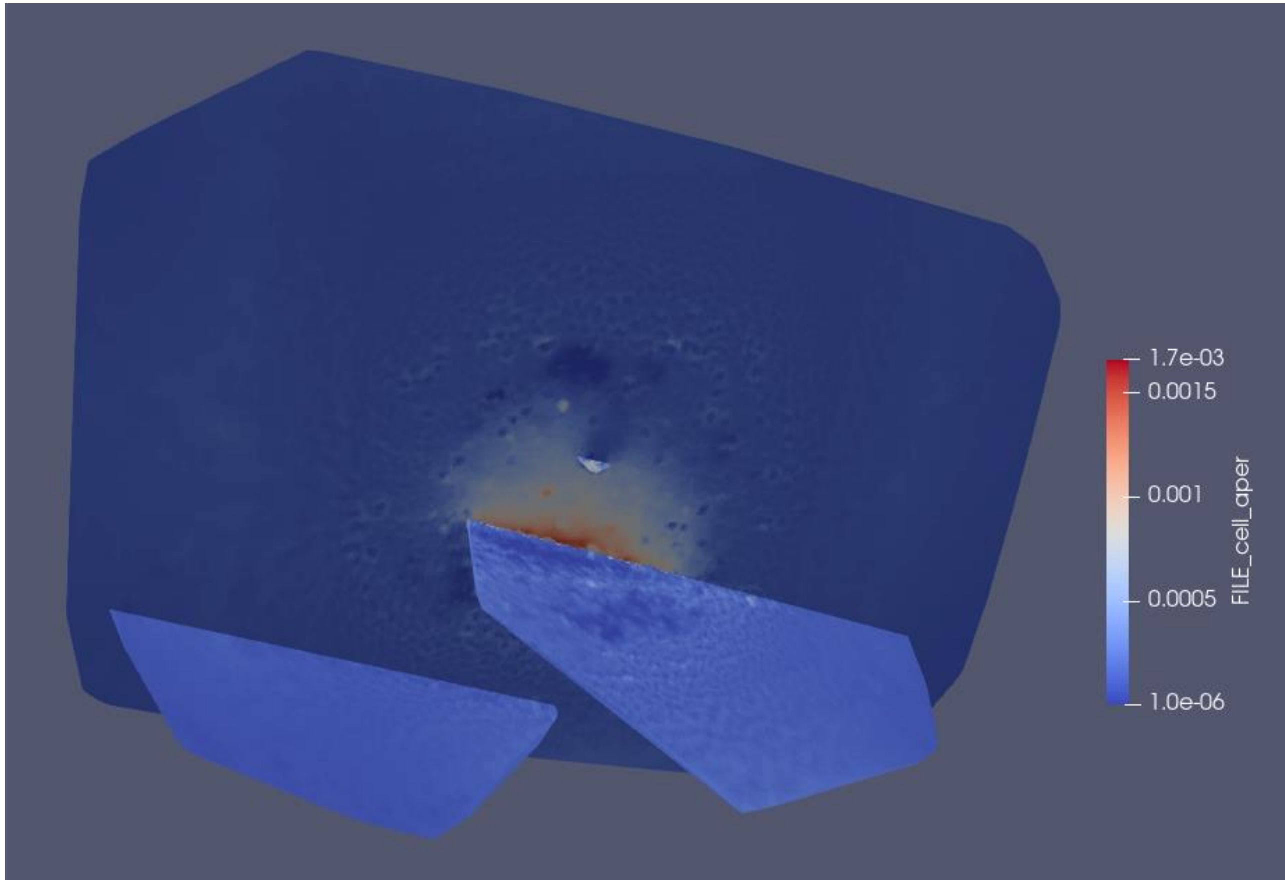
Sub-stepping in Fracture provides ~4x speed-up

Stimulated DFN

Golder is mapping data from ITASCA XSite stimulation to Exodus mesh output

- Aperture and pressure
- Micro-cracking of DFN (fracture extent and connectivity)





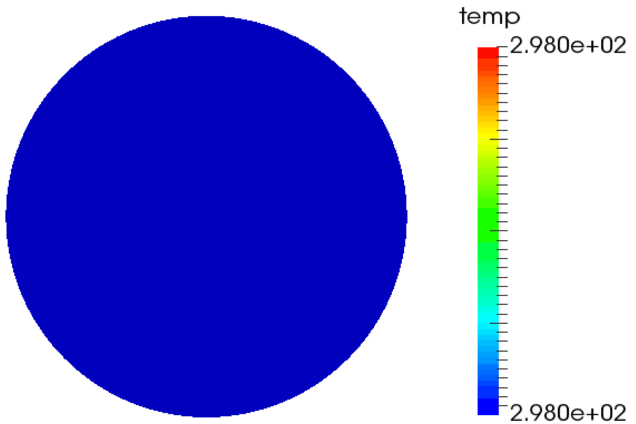
Explicit Fracture/Matrix Modeling (Wen Jiang)

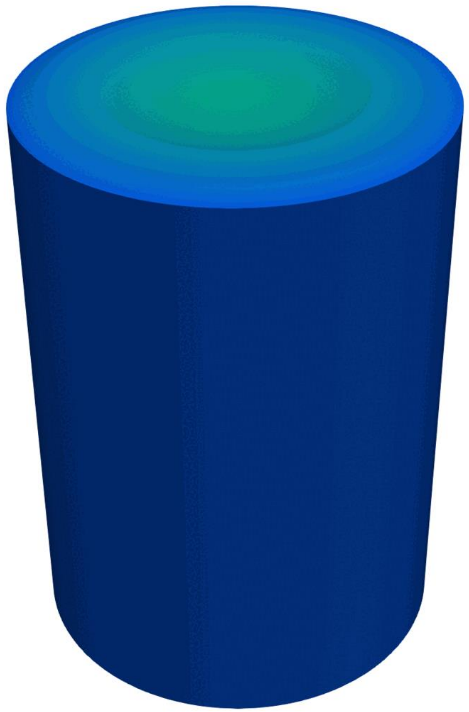
Limitations of loose coupling multiapp approach:

- Matrix ignores the discontinuity created by the fracture
- Current fracture aperture models are based on a constitutive relationships between opening and changes in pressure or temperature

Several fracture methods available in MOOSE:

- Extended finite element method
- Cohesive zone modeling
- Discontinuous Galerkin
- **Phase field fracture**

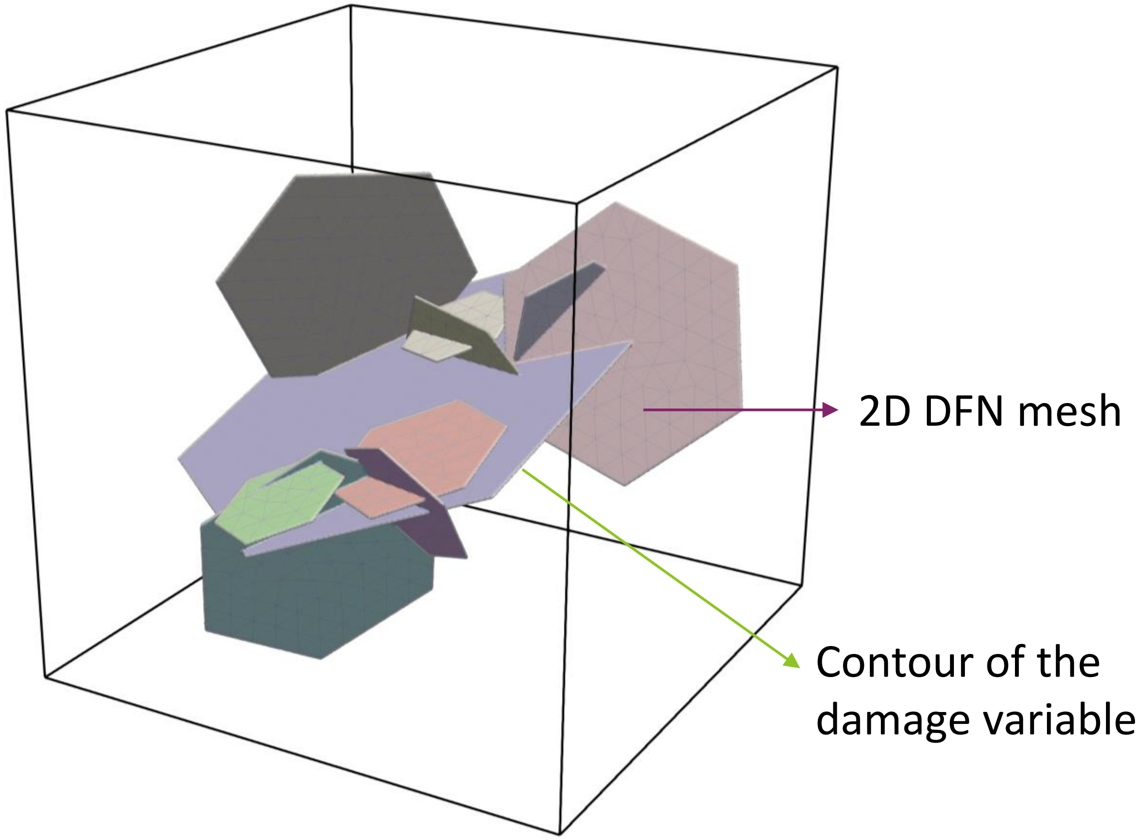


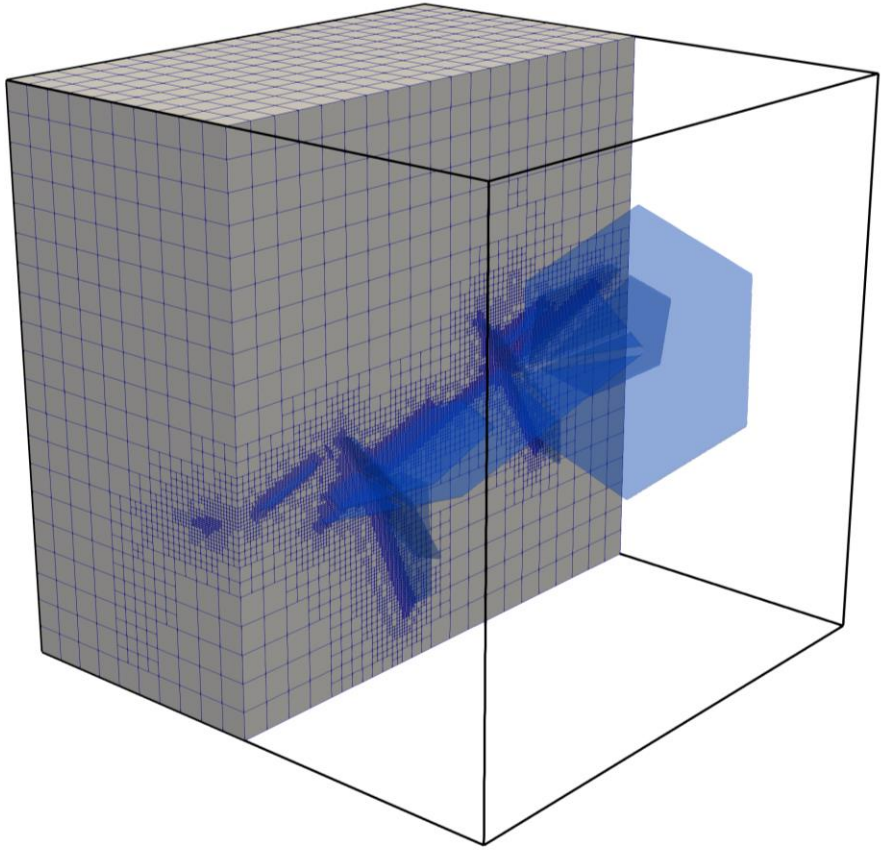


Ceramic nuclear fuel thermal-mechanical fracture modeling with the X-FEM (left) and Phase-field model (right)

Fracture network initialization with phase-field damage variable

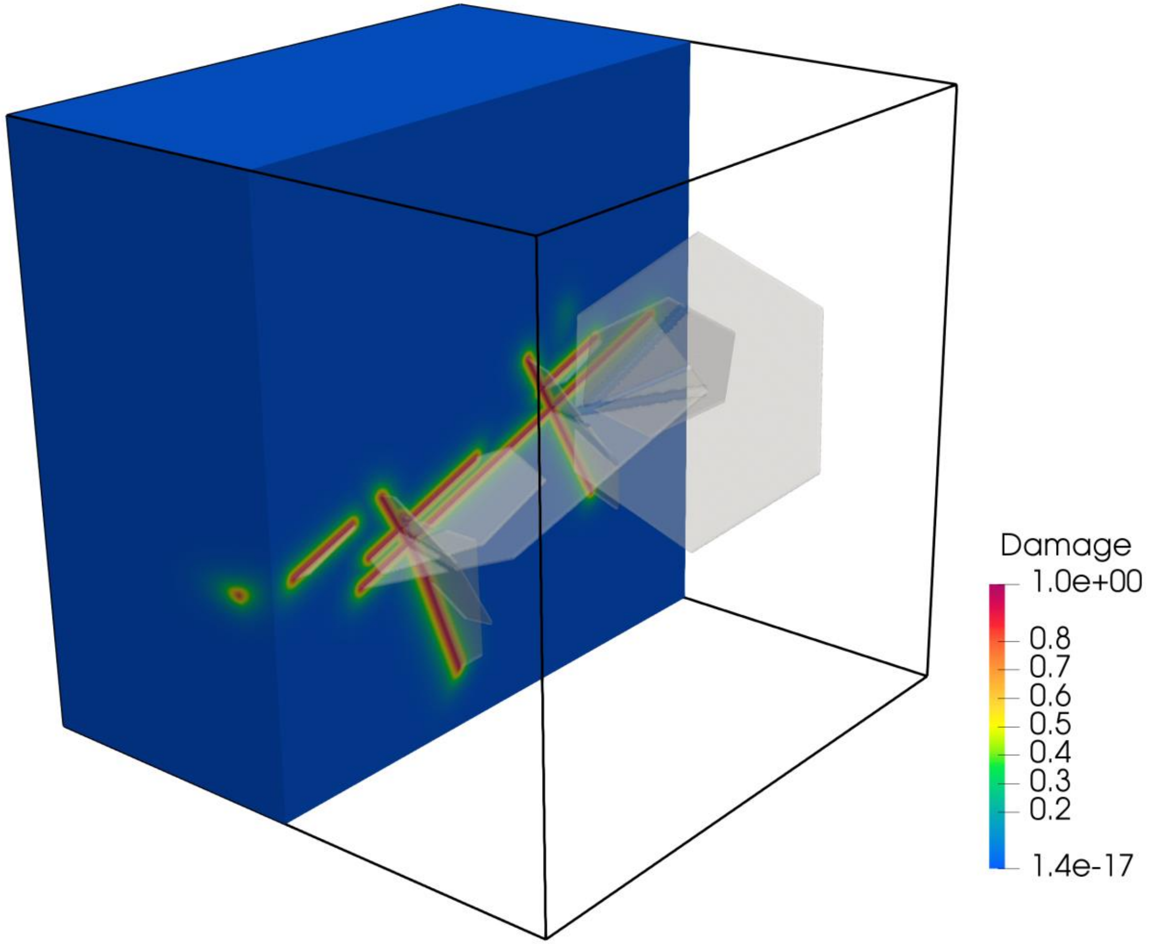
- Compute initial phase-field variable value using DFN mesh.
- 5 levels of refinement of 5m mesh -> 0.3125m mesh at fracture.





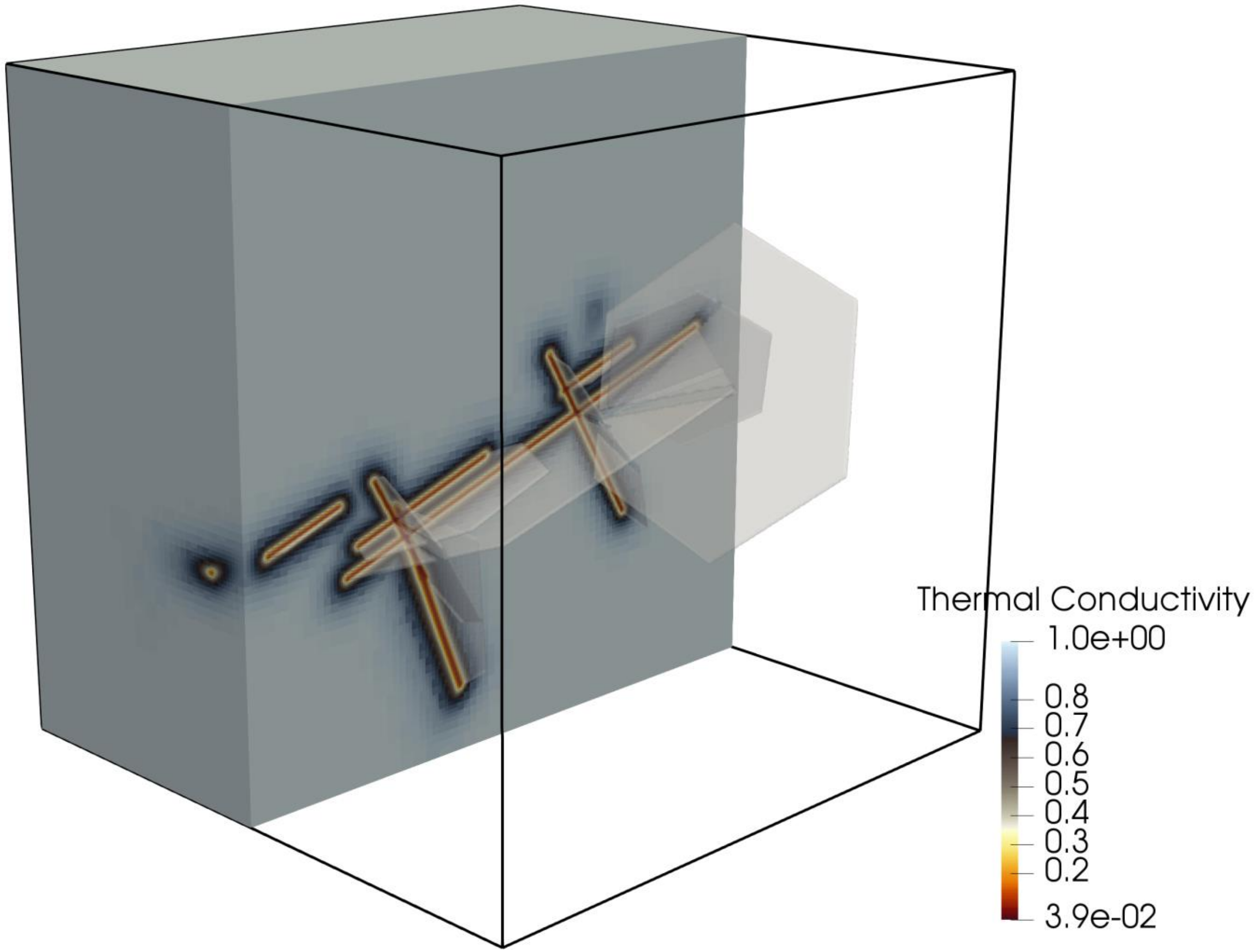
Explicit Fracture/Matrix Modeling

Place damage parameter in fracture phase. Damage reduces elastic constants.



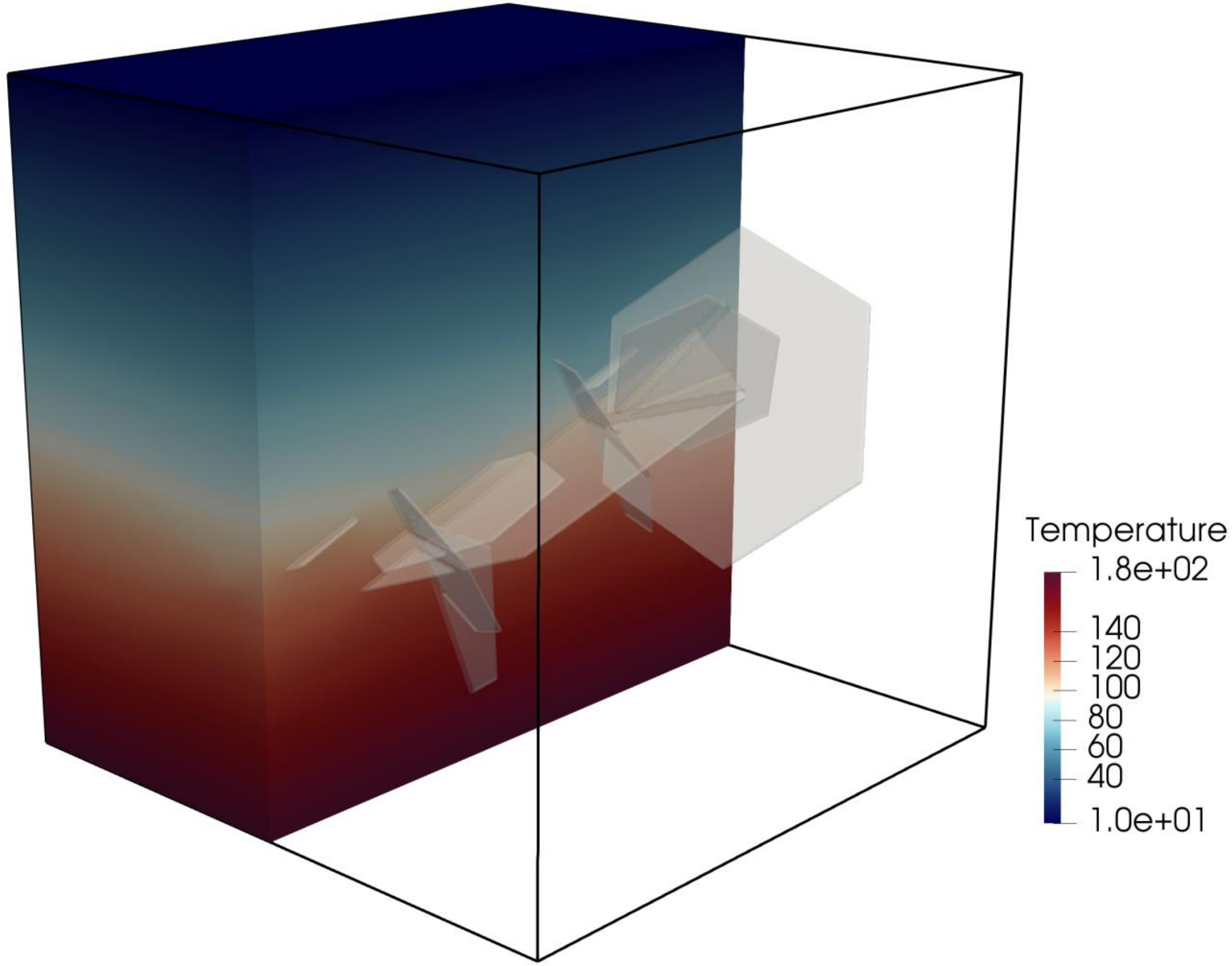
Explicit Fracture/Matrix Modeling

Thermal example to show the effect of a discrete fracture. (physics run on laptop)
Thermal conductivity almost zero in fracture phase.



Explicit Fracture/Matrix Modeling

Deviation from linear temperature profile due to fractures.

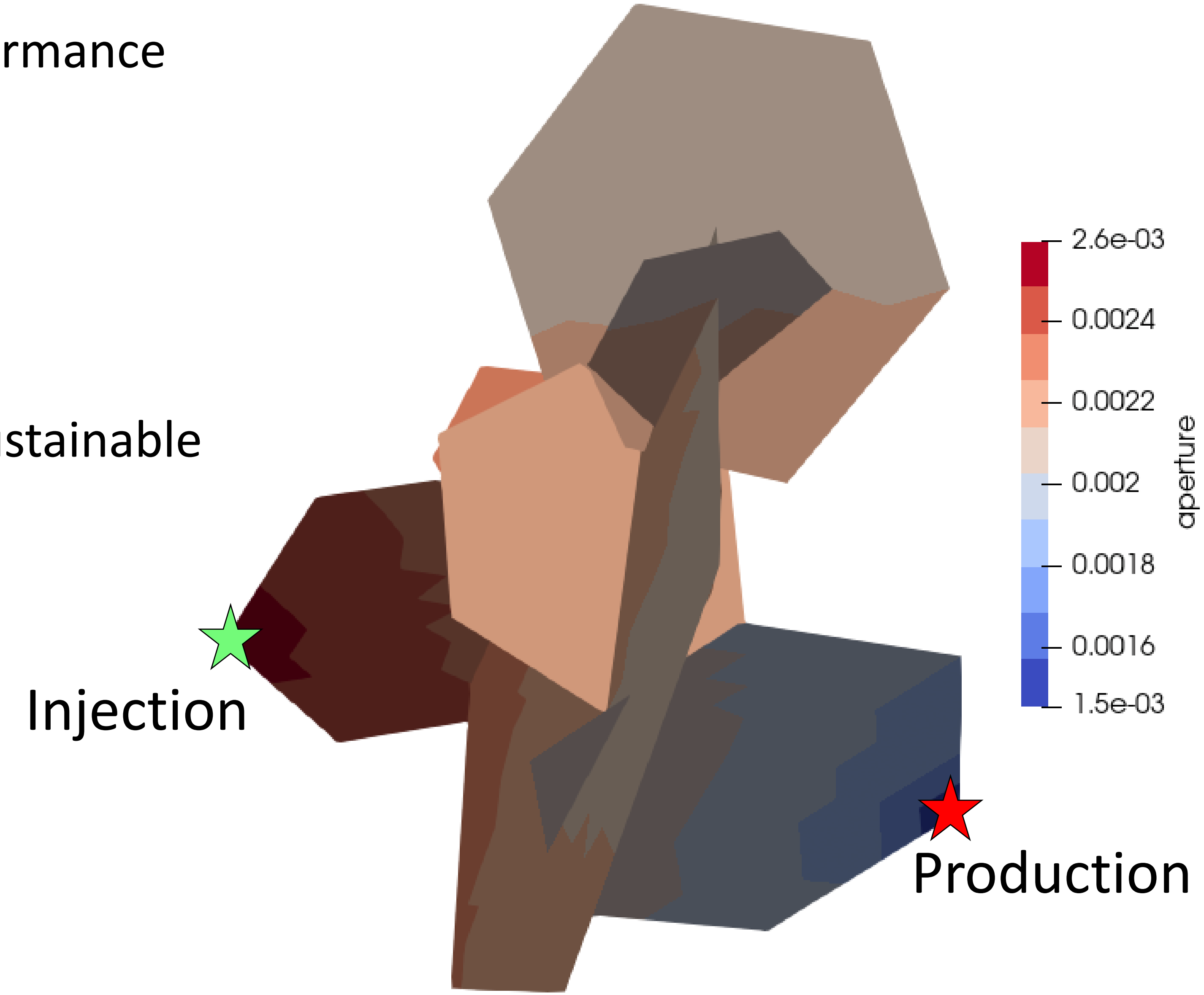


Optimal Production Well Placement (Som Dhulipala)

Evaluate sensitivity of geothermal performance to production location

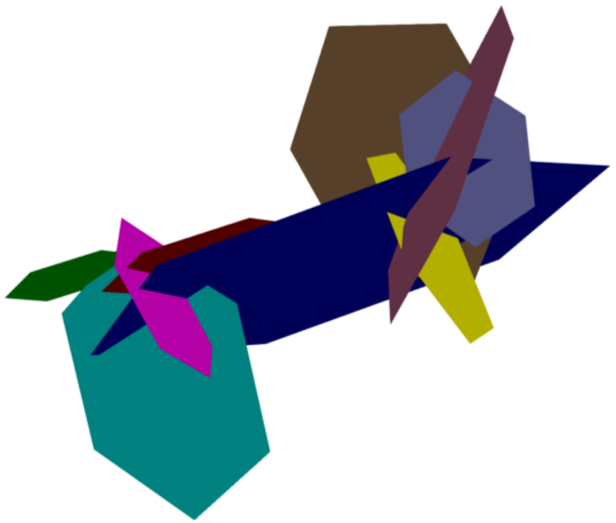
- Fix injection point
- Move Production point
- Maximize Energy output

Useful for experimental planning and sustainable thermal energy recovery.

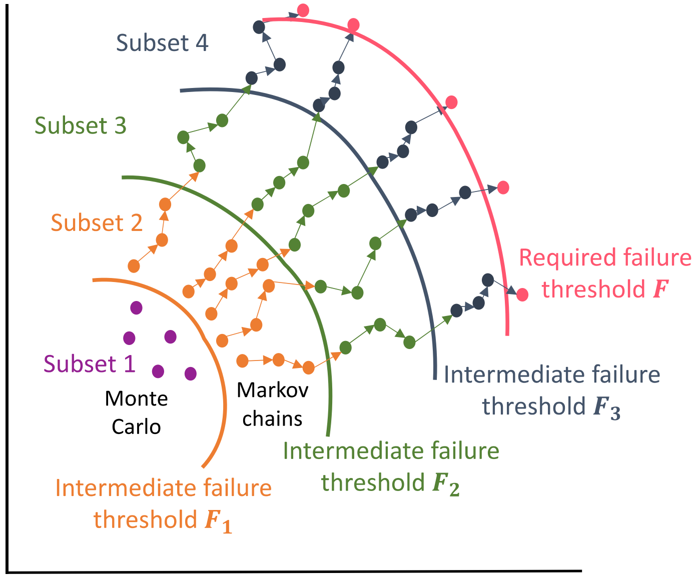


Adaptive Sampling

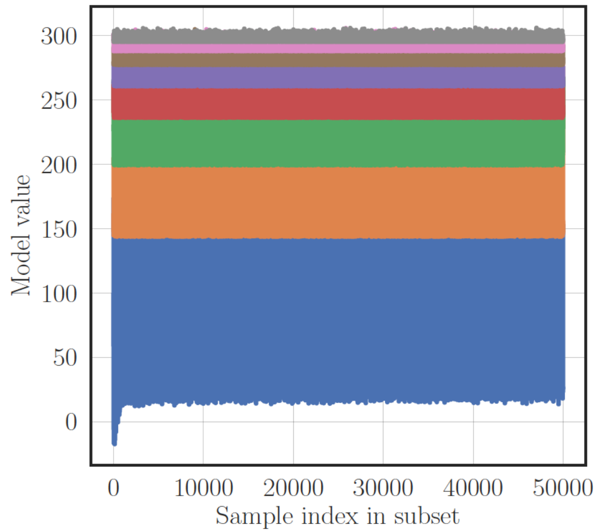
- The energy output from the system depends upon the production location
- Use adaptive sampling to locate the optimal production points
- Parallel subset simulation is an efficient adaptive sampling method which leverages massive parallel computing (each proc runs about 40-50 model evals)
- From one subset to another, the output only increases. This tells us the ***ensemble of extraction points*** such that the output energy always exceeds a certain value.
- Even if each model evaluation takes about 40 mins, we can optimize the extraction location in about 1-2 days using 1000 procs



Location of production point on the fracture planes to optimize the output



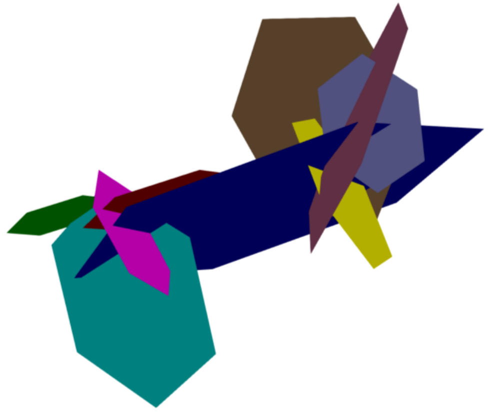
Parallel subset simulation sampler



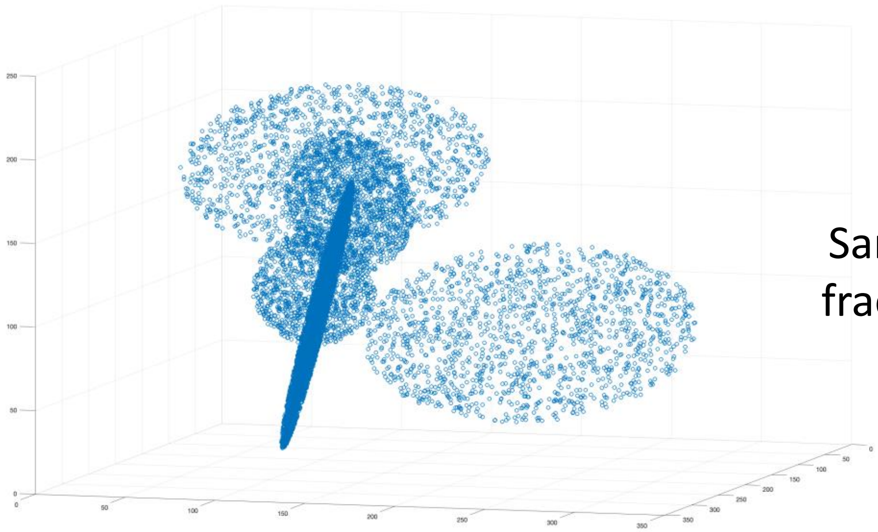
Samples from input space that causes the model output to be greater with subset

Sampling on fracture planes

- Fracture plane sampler in the Falcon to randomly sample extraction locations on different fracture planes
- The sampler currently idealizes each fracture plane as a circle. But we will alleviate this assumption in the future



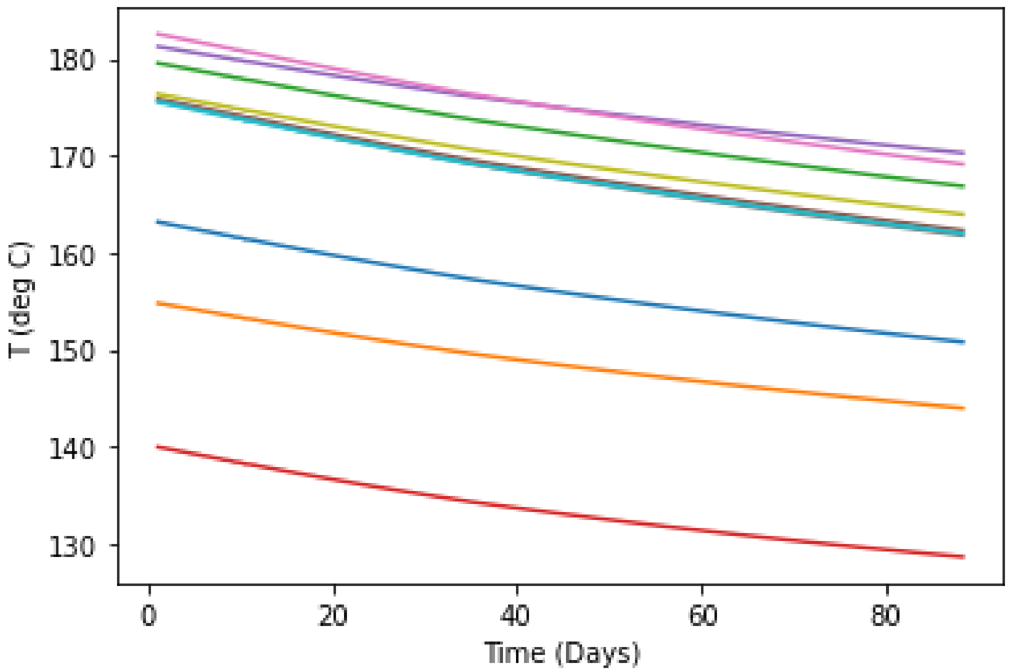
Location of extraction point on the fracture planes to optimize the output

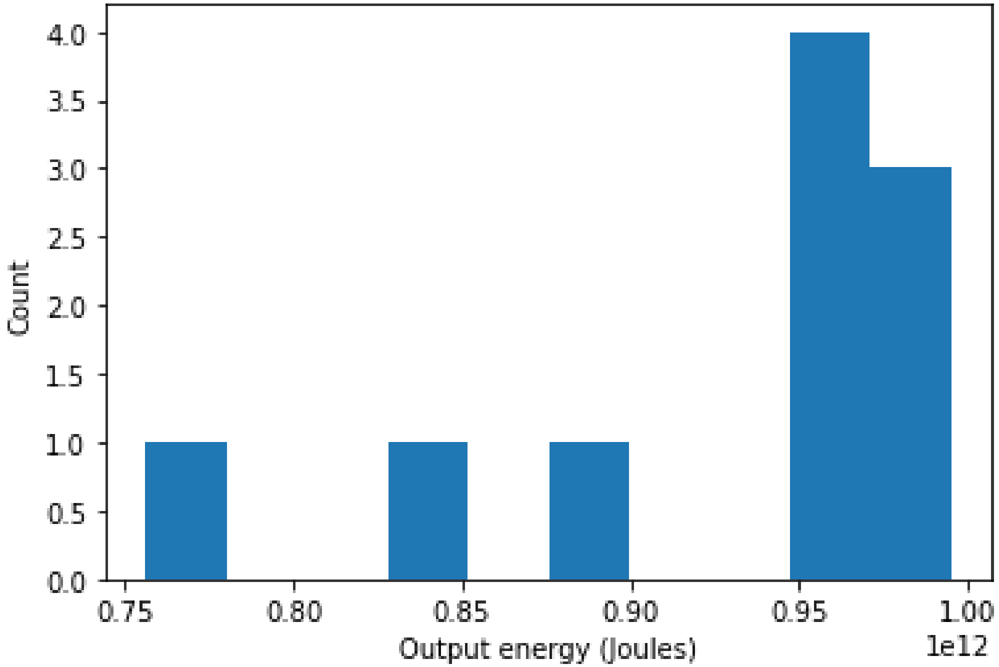


Sampler which idealizes fracture planes as circles

Initial results

- Simple Monte Carlo sampling of the production location to test the Main App -> sub App 1 -> sub App 2 transfer of parameters
- 10 random locations of the production locations
- Temperature and energy outputs depend on the production location
- Next task: Use adaptive sampling (i.e., parallel subset simulation sampler) to optimize the production location





Future Work

- **Simulate long-term geothermal performance of FORGE site with realistic DFNs**
  - Incorporate ITASCA simulation results for 16a stimulation
  - Incorporate results of actual stimulated fracture volume from the upcoming field experiments
- Plan flow through experiments, understand tracer tests
- Operational modeling