first light

11th November 2021

Multivariate Sensitivity Analysis of Radiation-Hydrodynamics Modelling of Uniaxially Driven ICF Systems

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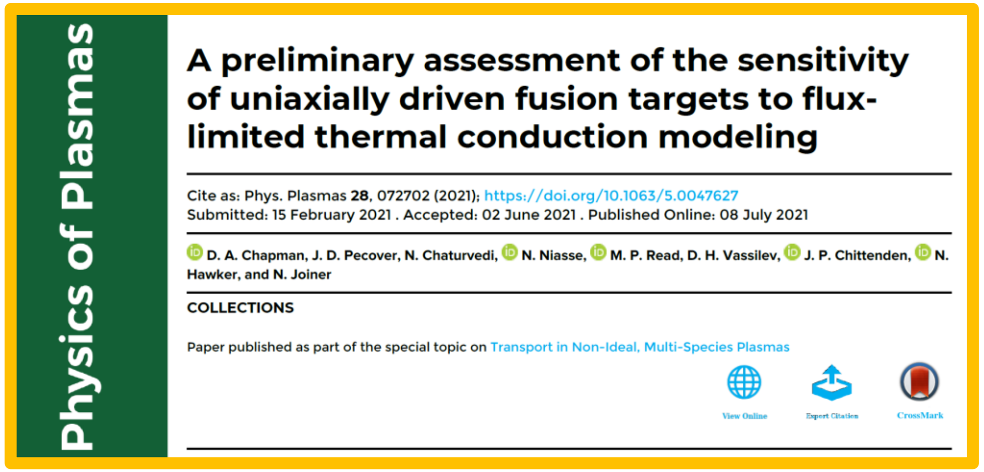
Overview of presentation

- Recap of initial work: Derentowicz-Kaliski uniaxially driven ICF target
- Scope of new multivariate study
- Options hyperspace sampling
- Design of target performance metrics
- Multivariate sensitivity analysis results
- Preliminary work: non-local ionic heat flow model
- Summary and conclusions

Our previous work used single-perturbation sensitivity study to investigate modelling uncertainties in a conical ICF target



Physics of Plasmas

A preliminary assessment of the sensitivity of uniaxially driven fusion targets to flux-limited thermal conduction modeling

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COLLECTIONS

Paper published as part of the special topic on Transport in Non-Ideal, Multi-Species Plasmas

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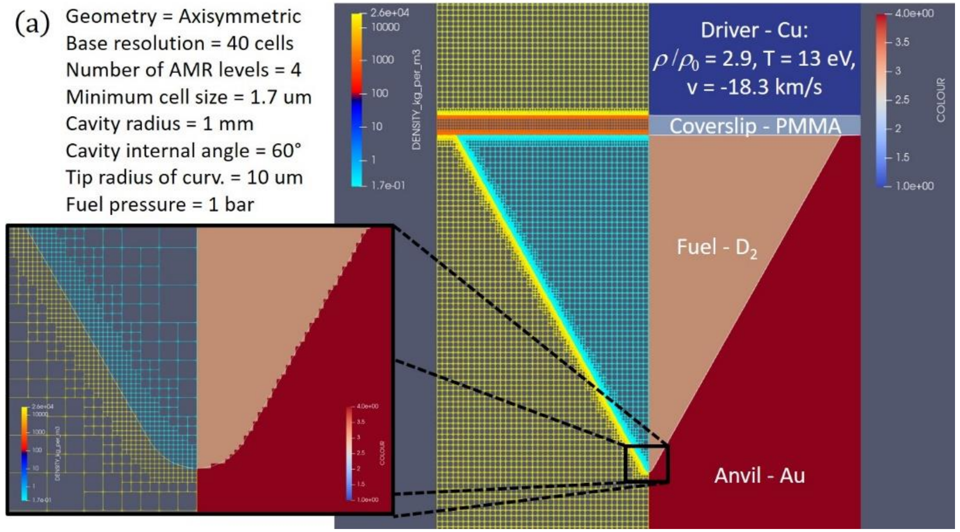
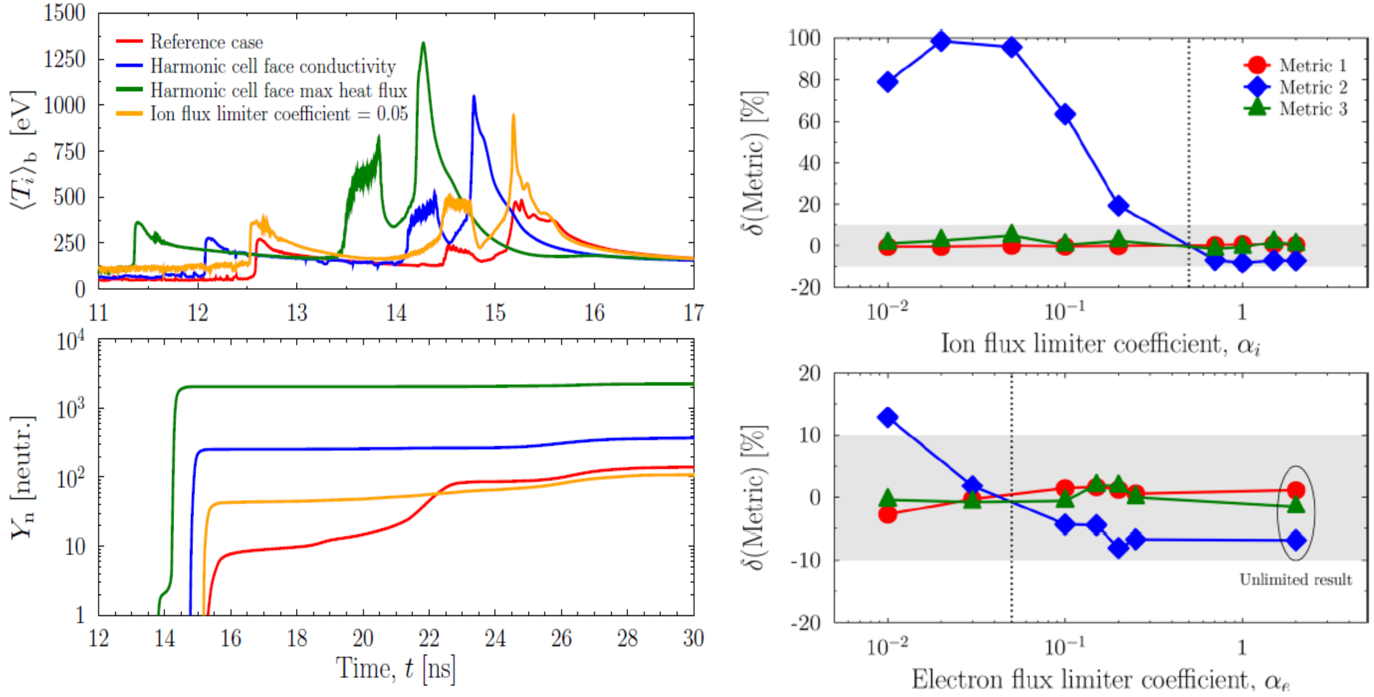
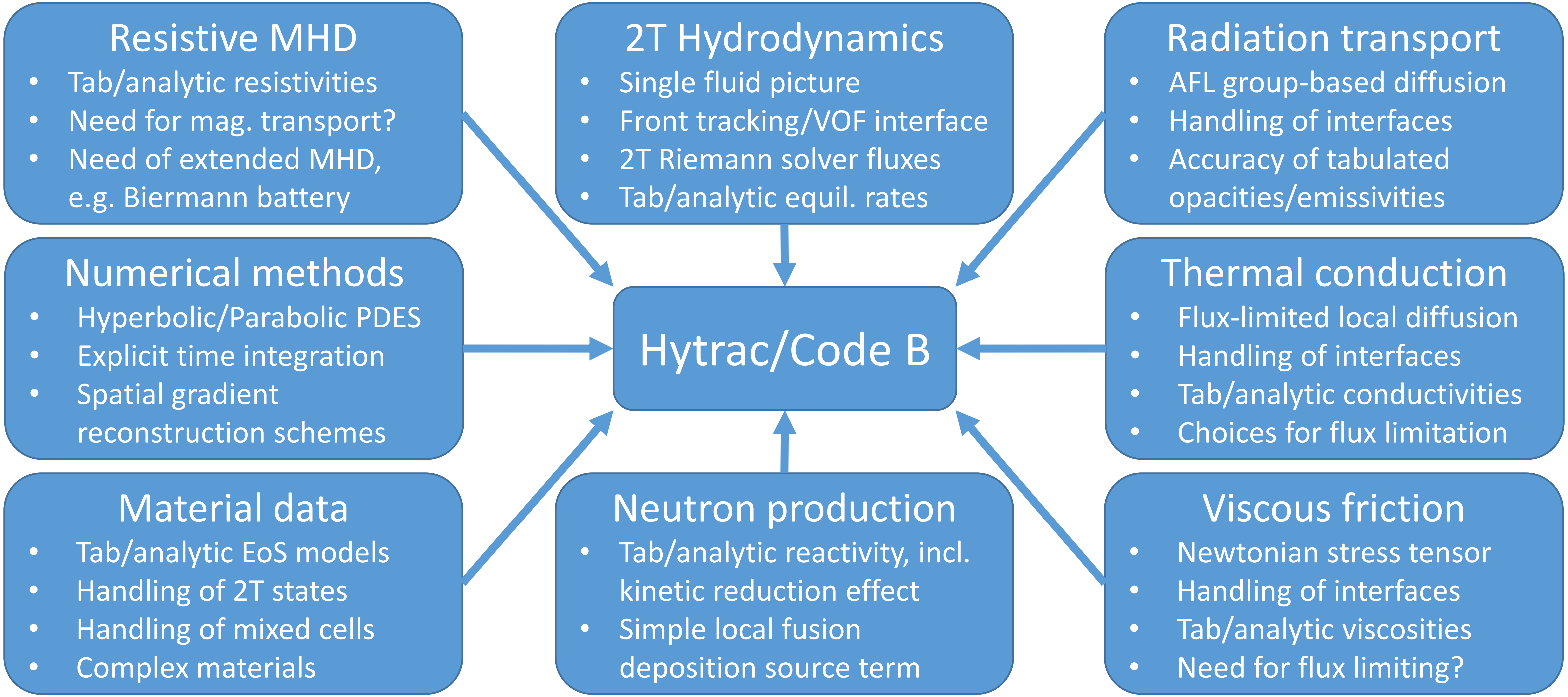


(a) Geometry = Axisymmetric
Base resolution = 40 cells
Number of AMR levels = 4
Minimum cell size = 1.7 um
Cavity radius = 1 mm
Cavity internal angle = 60°
Tip radius of curv. = 10 um
Fuel pressure = 1 bar



- Estimate of heat flux at material interfaces found to be the biggest handle on fusion performance
- **Small values of ion heat flux limiter coefficient also important – suggestive of non-local ion transport**

Multiphysics radiation-hydrodynamics modelling requires a huge number of (often highly uncertain) coupled phenomena



Resistive MHD

- Tab/analytic resistivities
- Need for mag. transport?
- Need of extended MHD, e.g. Biermann battery

2T Hydrodynamics

- Single fluid picture
- Front tracking/VOF interface
- 2T Riemann solver fluxes
- Tab/analytic equil. rates

Radiation transport

- AFL group-based diffusion
- Handling of interfaces
- Accuracy of tabulated opacities/emissivities

Numerical methods

- Hyperbolic/Parabolic PDES
- Explicit time integration
- Spatial gradient reconstruction schemes

Hytrac/Code B

Thermal conduction

- Flux-limited local diffusion
- Handling of interfaces
- Tab/analytic conductivities
- Choices for flux limitation

Material data

- Tab/analytic EoS models
- Handling of 2T states
- Handling of mixed cells
- Complex materials

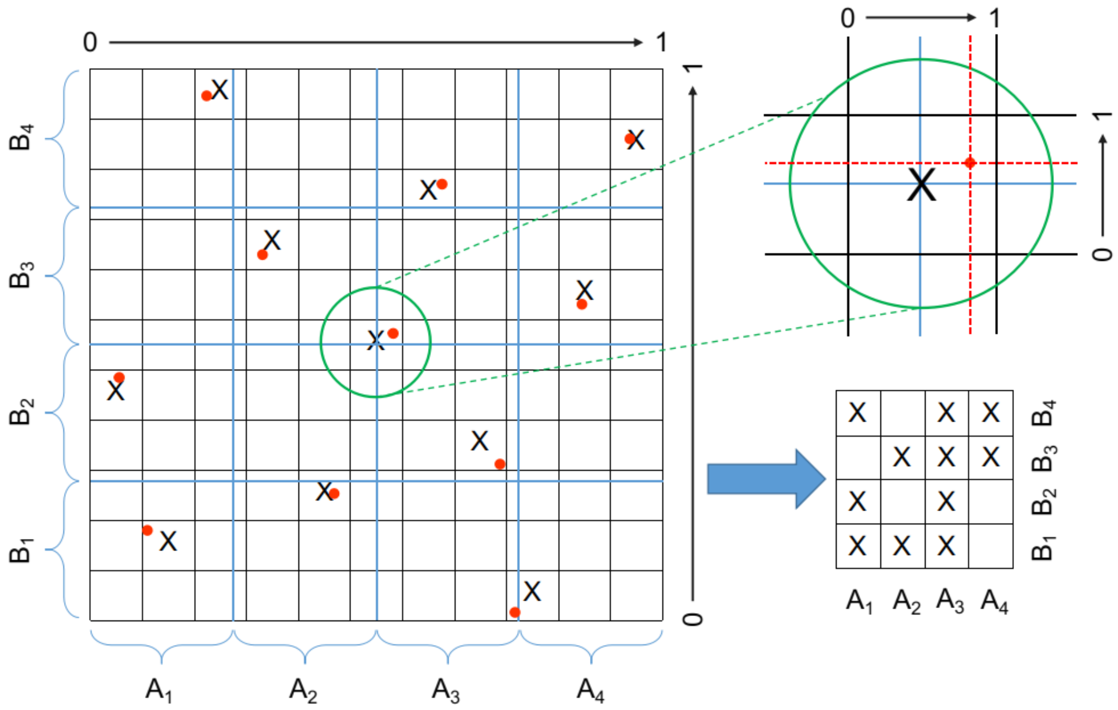
Neutron production

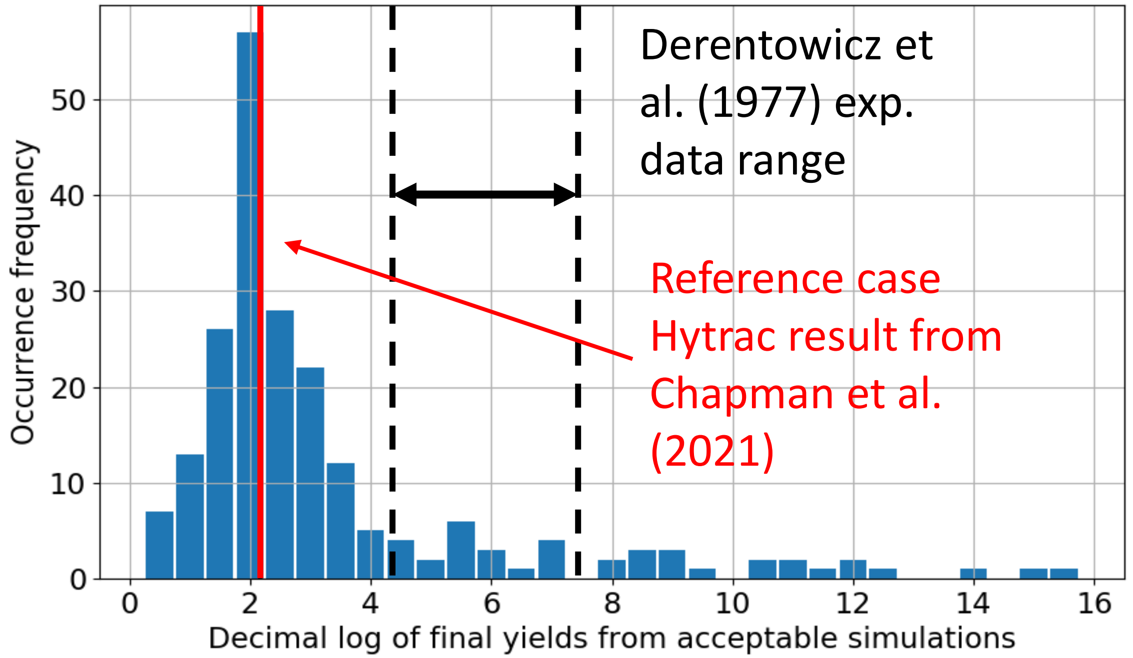
- Tab/analytic reactivity, incl. kinetic reduction effect
- Simple local fusion deposition source term

Viscous friction

- Newtonian stress tensor
- Handling of interfaces
- Tab/analytic viscosities
- Need for flux limiting?

Even focusing on a small subset of the available options, our study contains > 64 trillion possible simulation configurations!



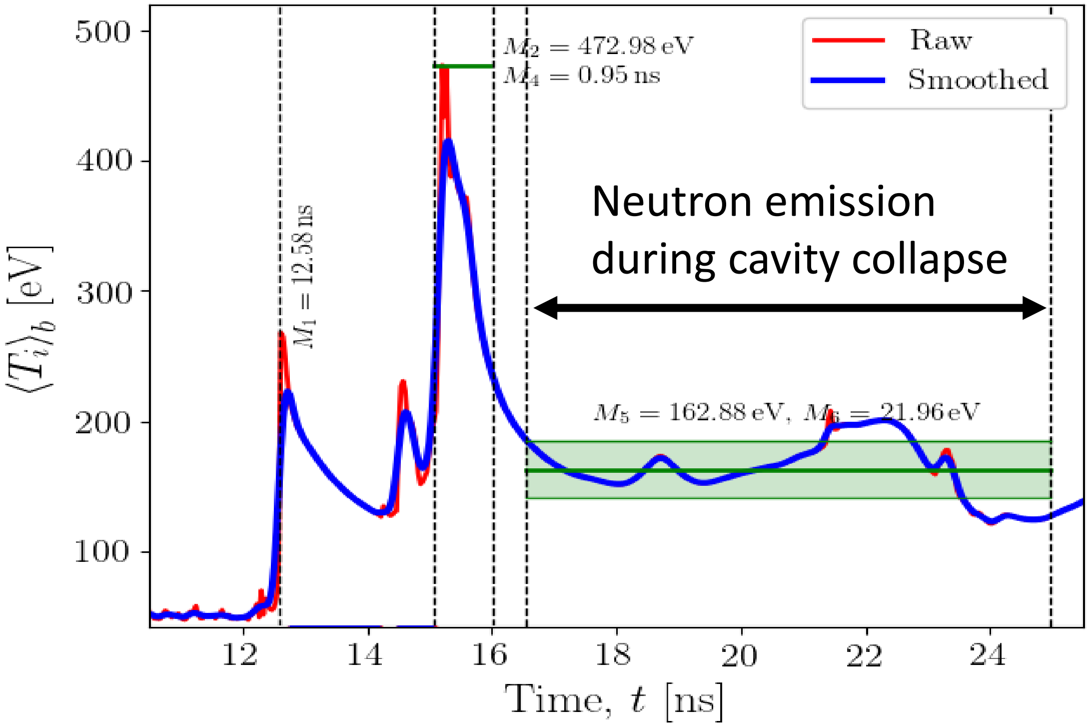


Derentowicz et al. (1977) exp. data range

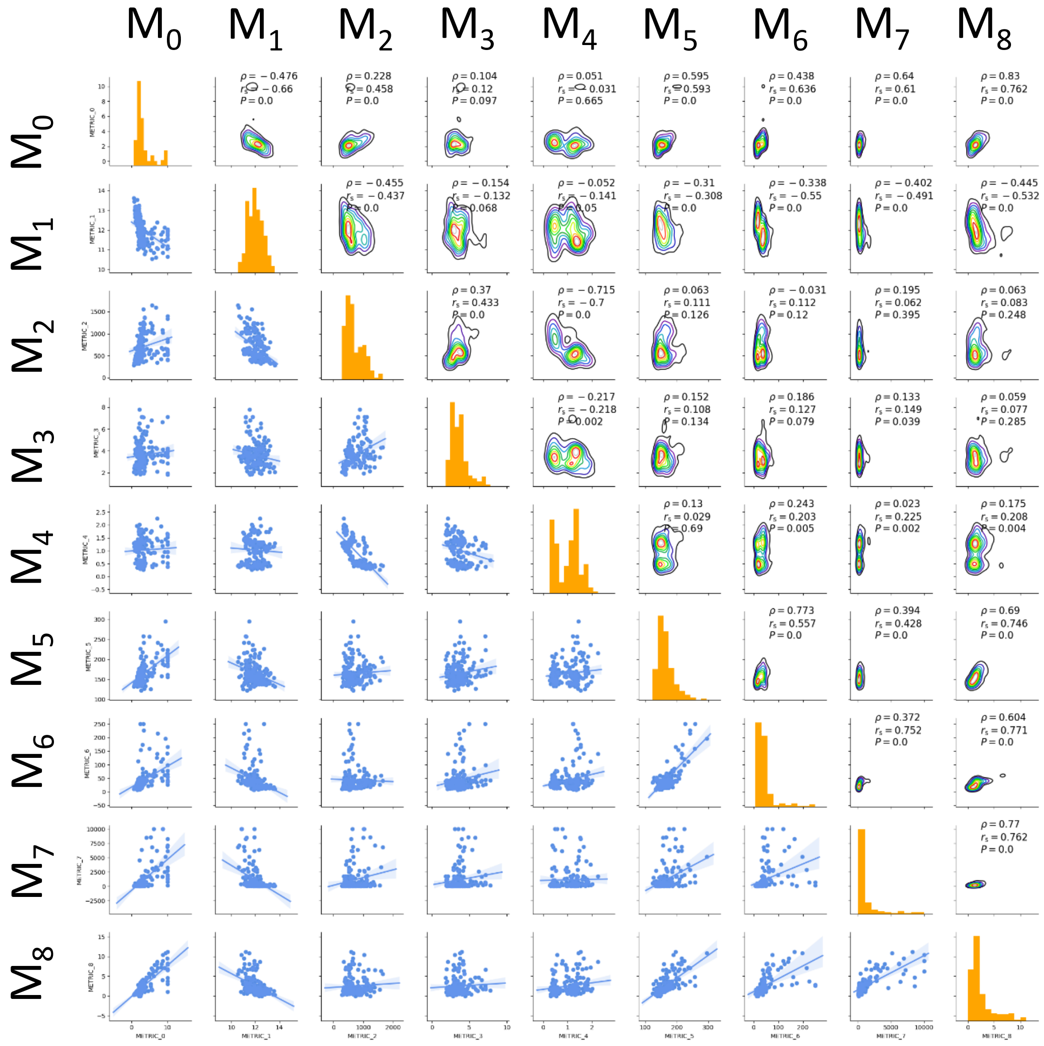
Reference case Hytrac result from Chapman et al. (2021)

- Use a ‘Latin hypercube’ space-filling design to sample space with **1000** simulations
- 210 simulations ran for long enough to contribute to yield statistics
- **Long distribution tail suggests final yield is an unreliable performance indicator**

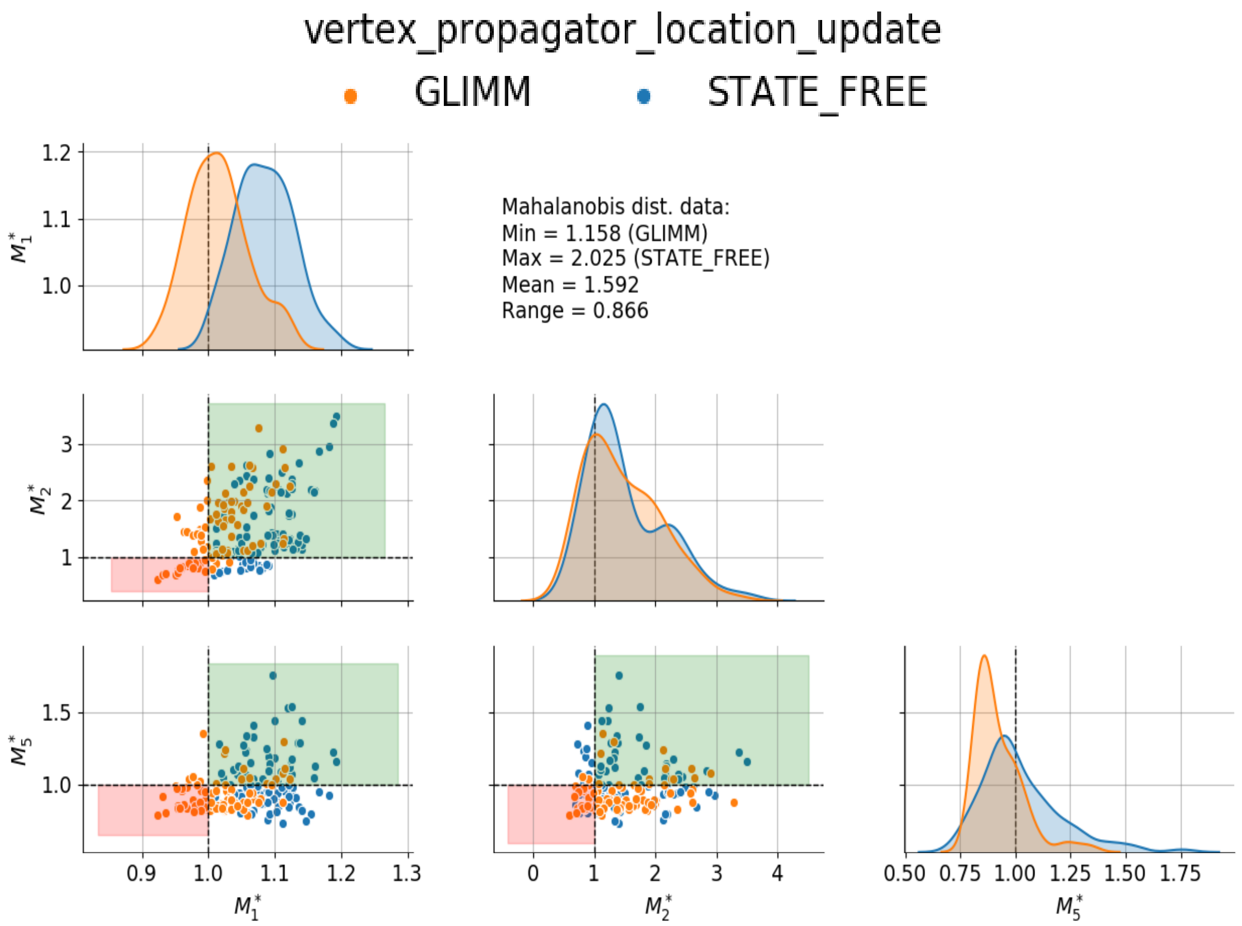
Performance is quantified by more robust metrics which are correlated to the distribution of final neutron yields



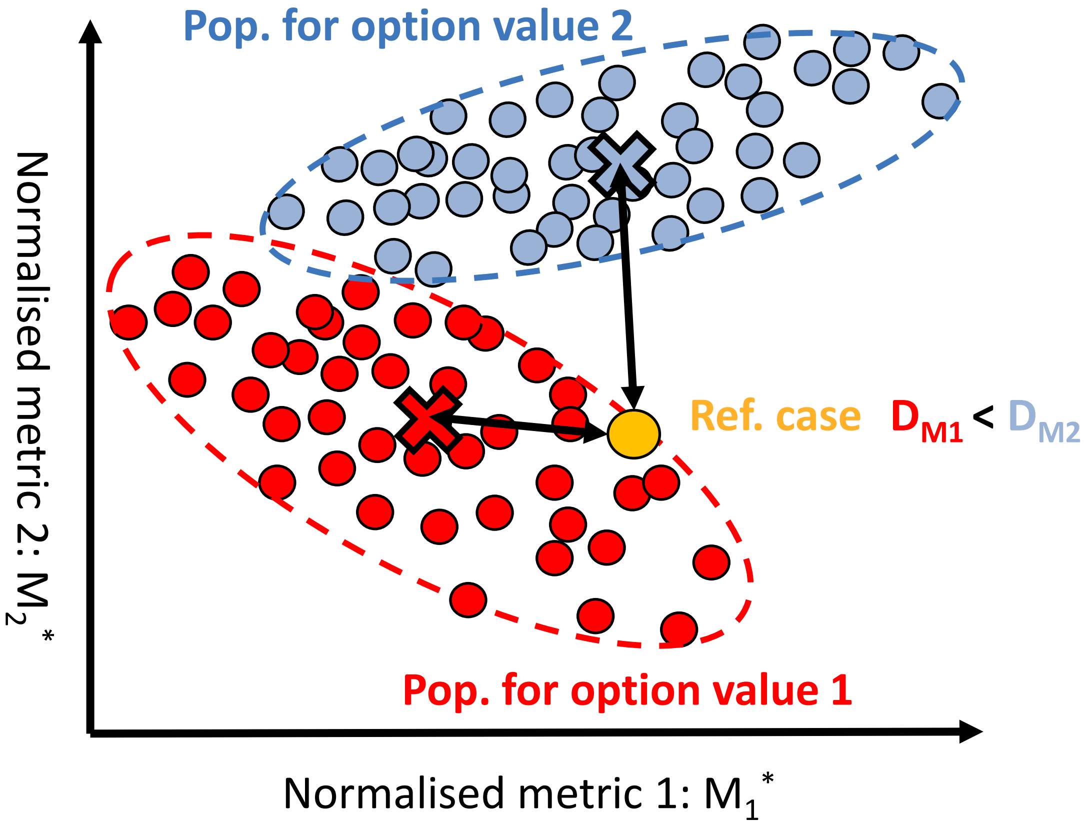
- Three most useful metrics are:
  M_1 : Initial reflection time of shock from axis
  M_2 : Peak BWA ion temp. at main reverb.
  M_5 : Av. BWA ion temp. during collapse phase



Sensitivity of performance to each set of option values is assessed by comparing Mahalanobis distances to ref. case



Mahalanobis dist. data:
Min = 1.158 (GLIMM)
Max = 2.025 (STATE_FREE)
Mean = 1.592
Range = 0.866



$$D_M(\mathbf{M}^*) = \left[(\mathbf{M}^* - \boldsymbol{\mu})^T \cdot \underline{\boldsymbol{\Sigma}}^{-1} \cdot (\mathbf{M}^* - \boldsymbol{\mu})\right]^{1/2}$$

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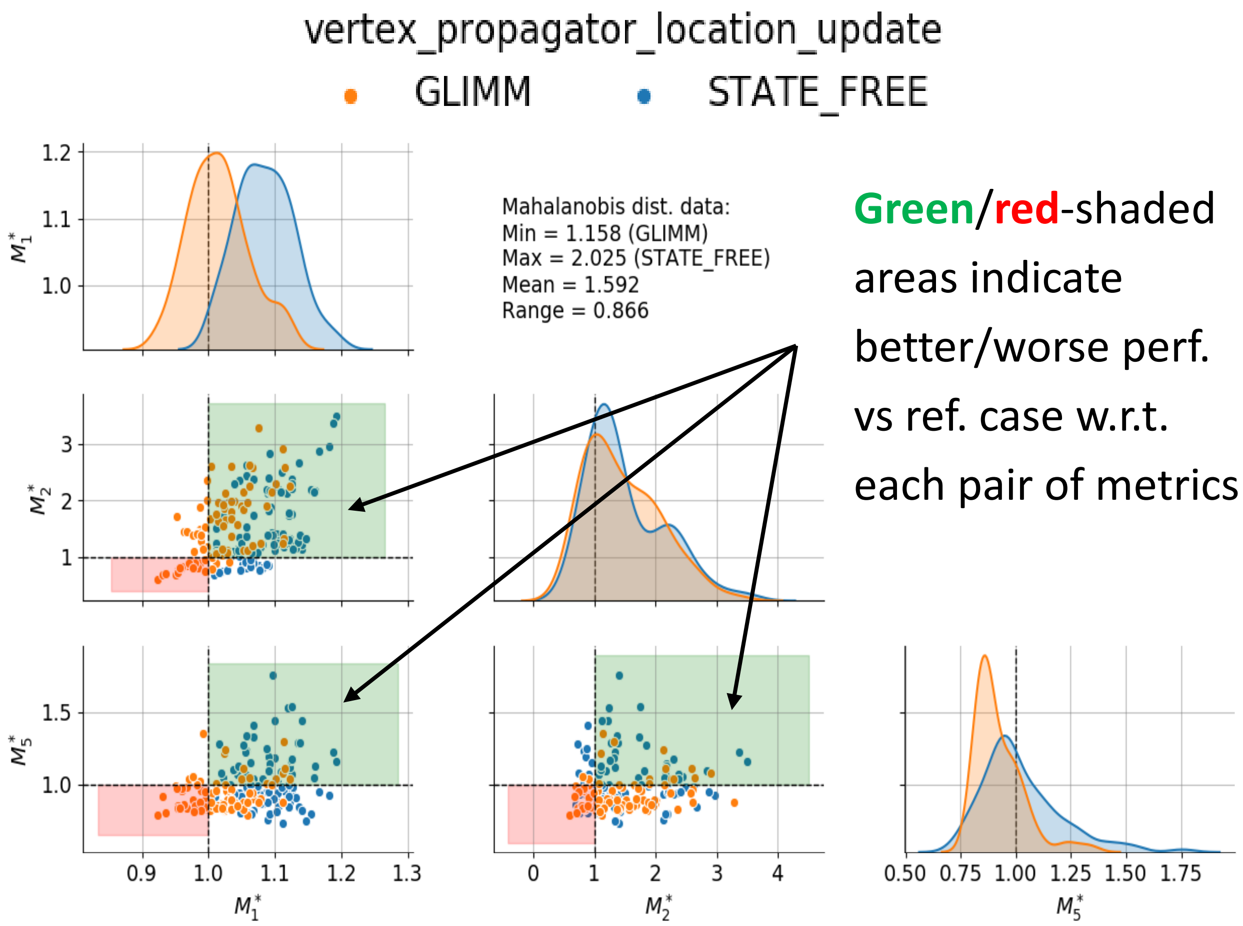
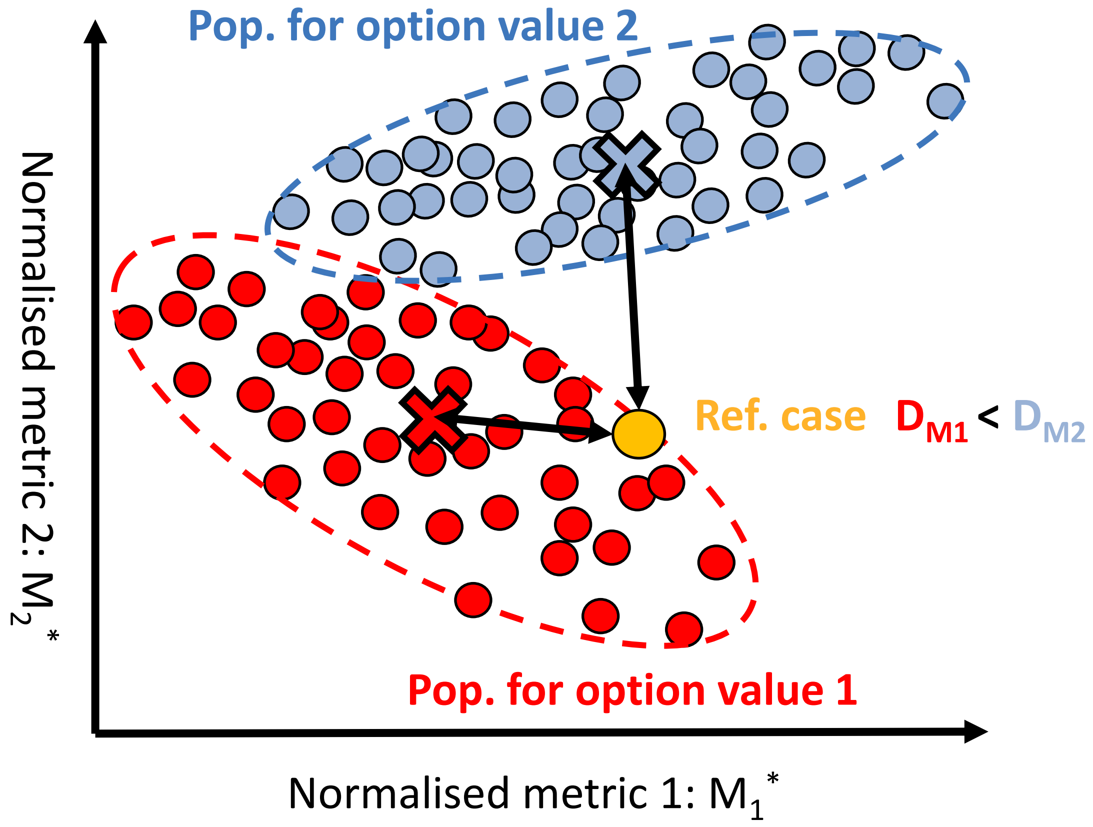


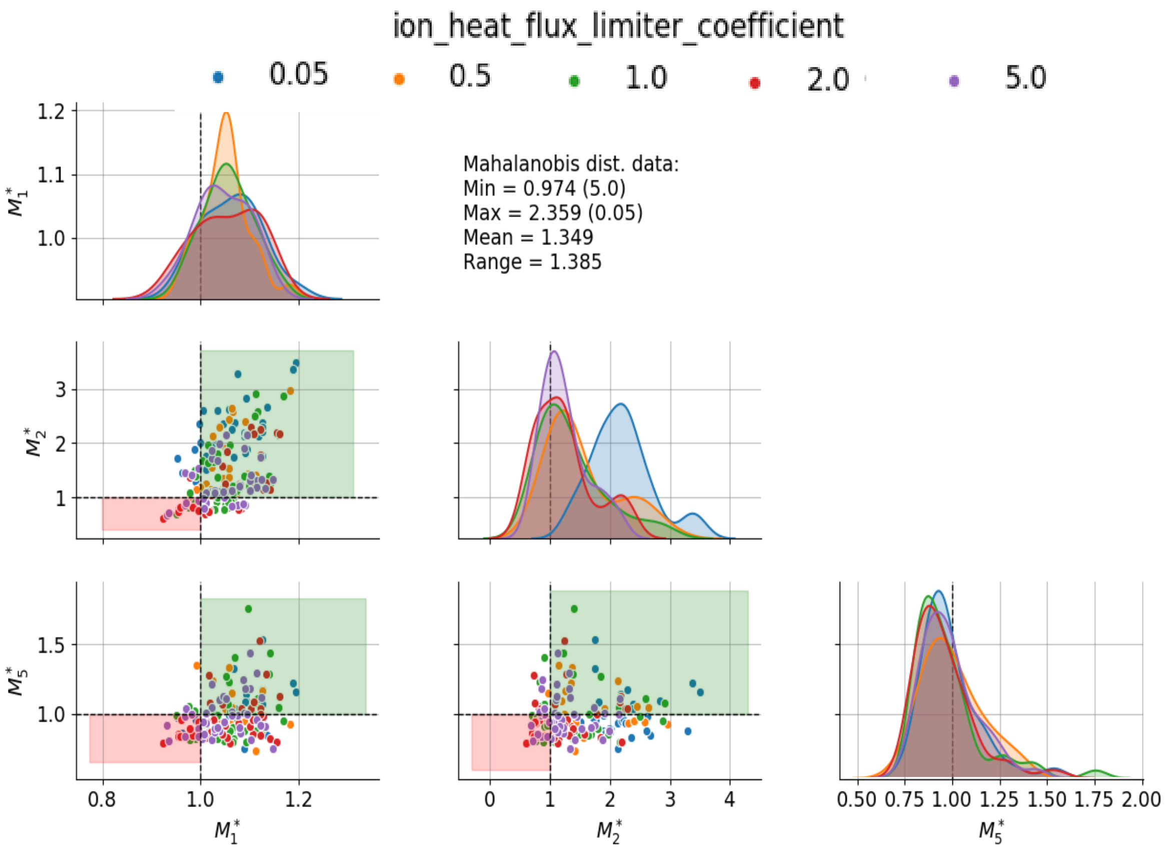
Mahalanobis dist. data:
Min = 1.158 (GLIMM)
Max = 2.025 (STATE_FREE)
Mean = 1.592
Range = 0.866

Green/**red**-shaded areas indicate better/worse perf. vs ref. case w.r.t. each pair of metrics

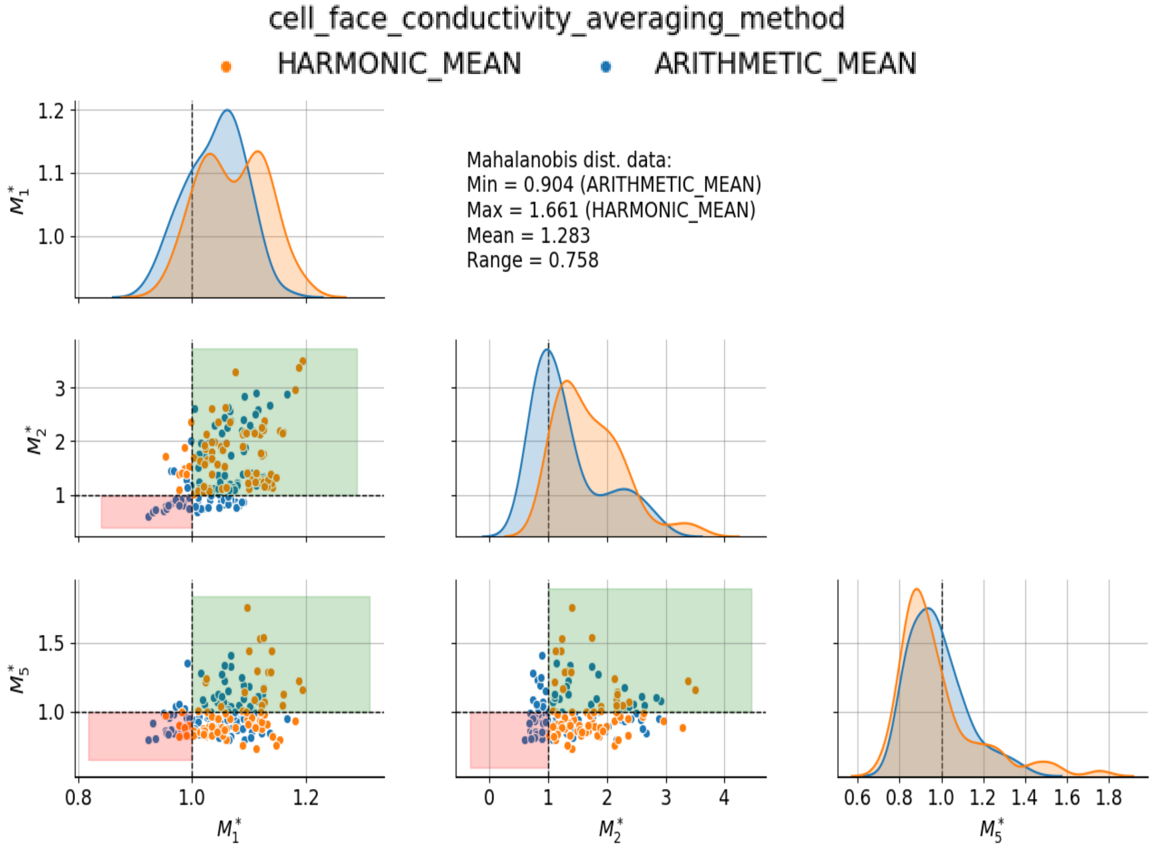


$$D_M(\mathbf{M}^*) = \left[(\mathbf{M}^* - \boldsymbol{\mu})^T \cdot \underline{\boldsymbol{\Sigma}}^{-1} \cdot (\mathbf{M}^* - \boldsymbol{\mu})\right]^{1/2}$$

As with our previous study, flux-limited ion transport and modelling of thermal conduction at interfaces are important!

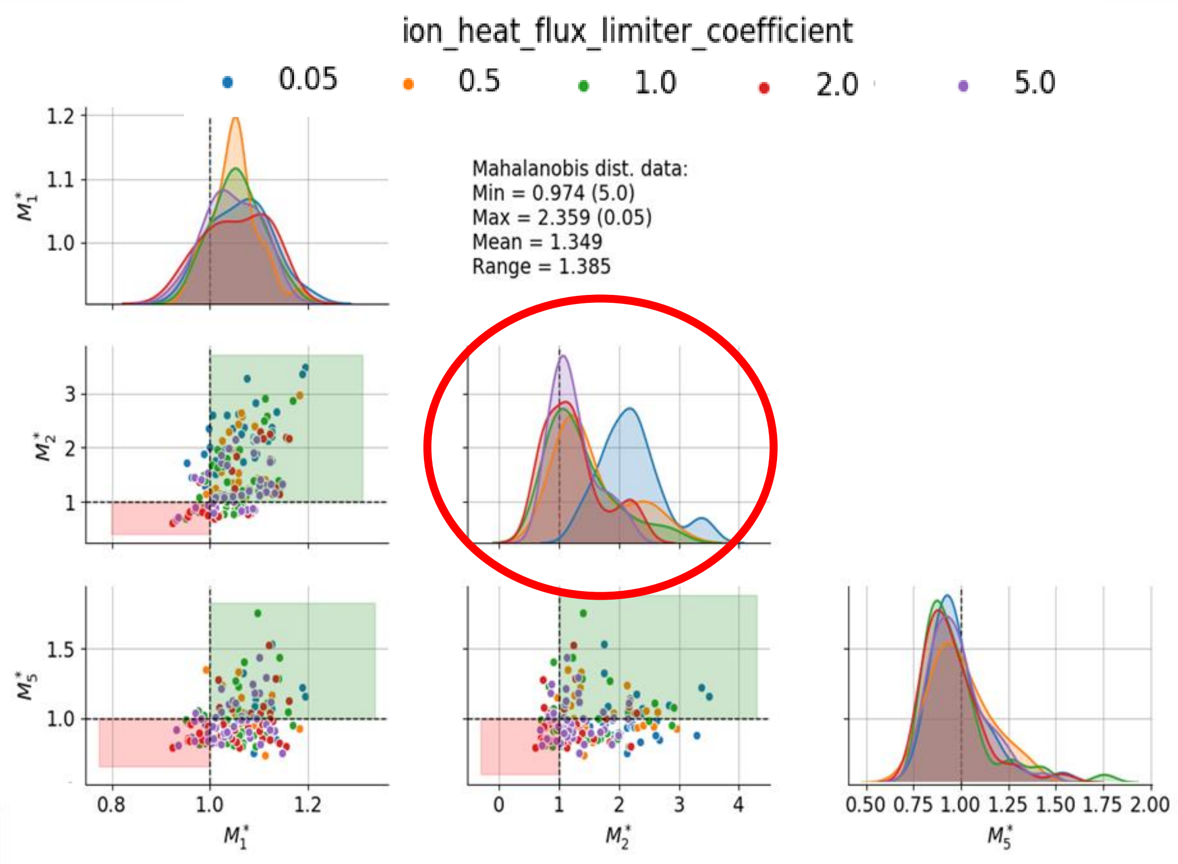


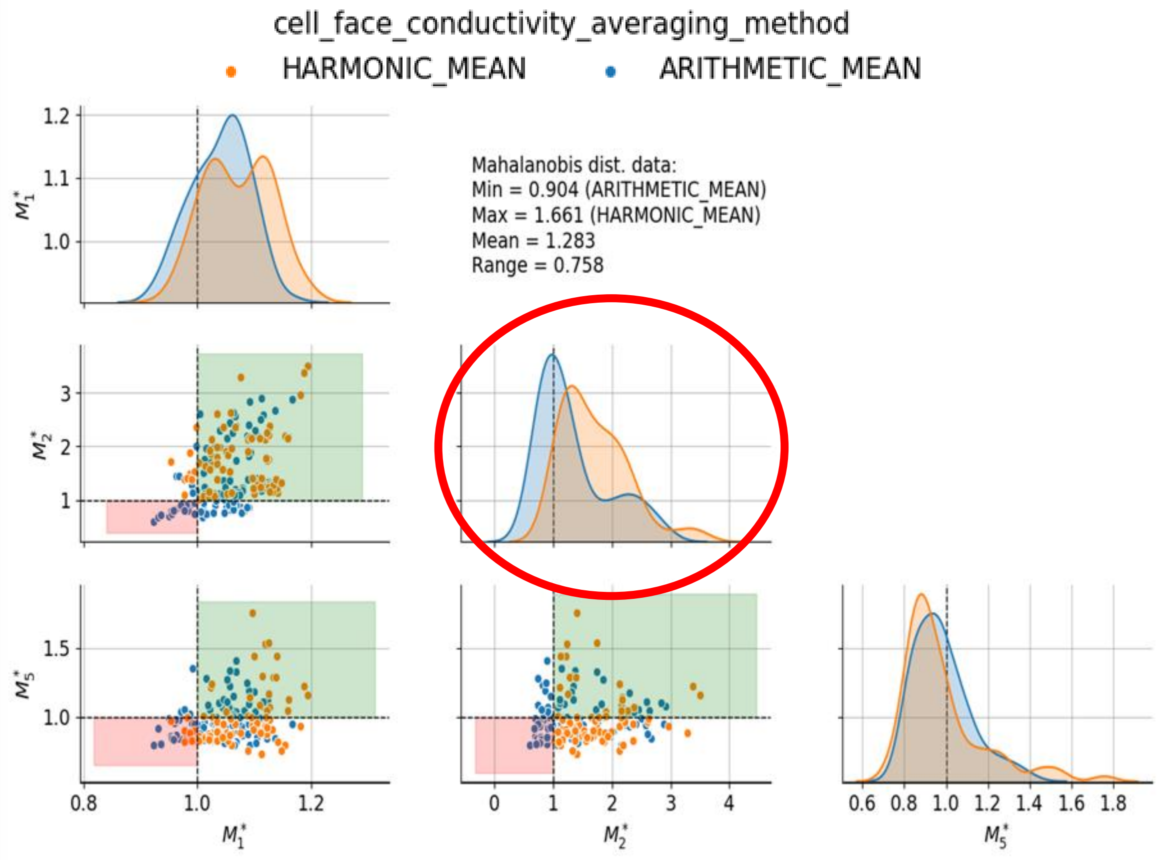
Mahalanobis dist. data:
Min = 0.974 (5.0)
Max = 2.359 (0.05)
Mean = 1.349
Range = 1.385



Mahalanobis dist. data:
Min = 0.904 (ARITHMETIC_MEAN)
Max = 1.661 (HARMONIC_MEAN)
Mean = 1.283
Range = 0.758

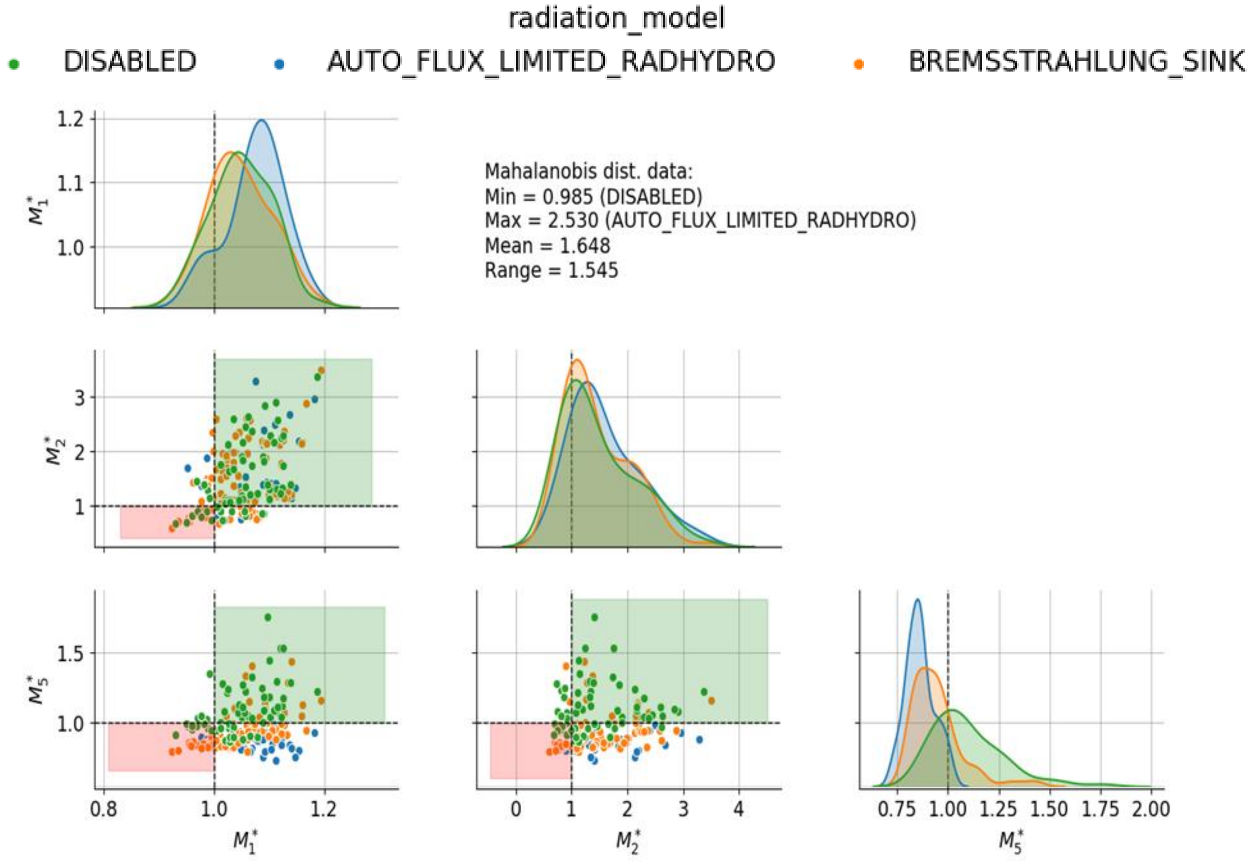
As with our previous study, flux-limited ion transport and modelling of thermal conduction at interfaces are important!



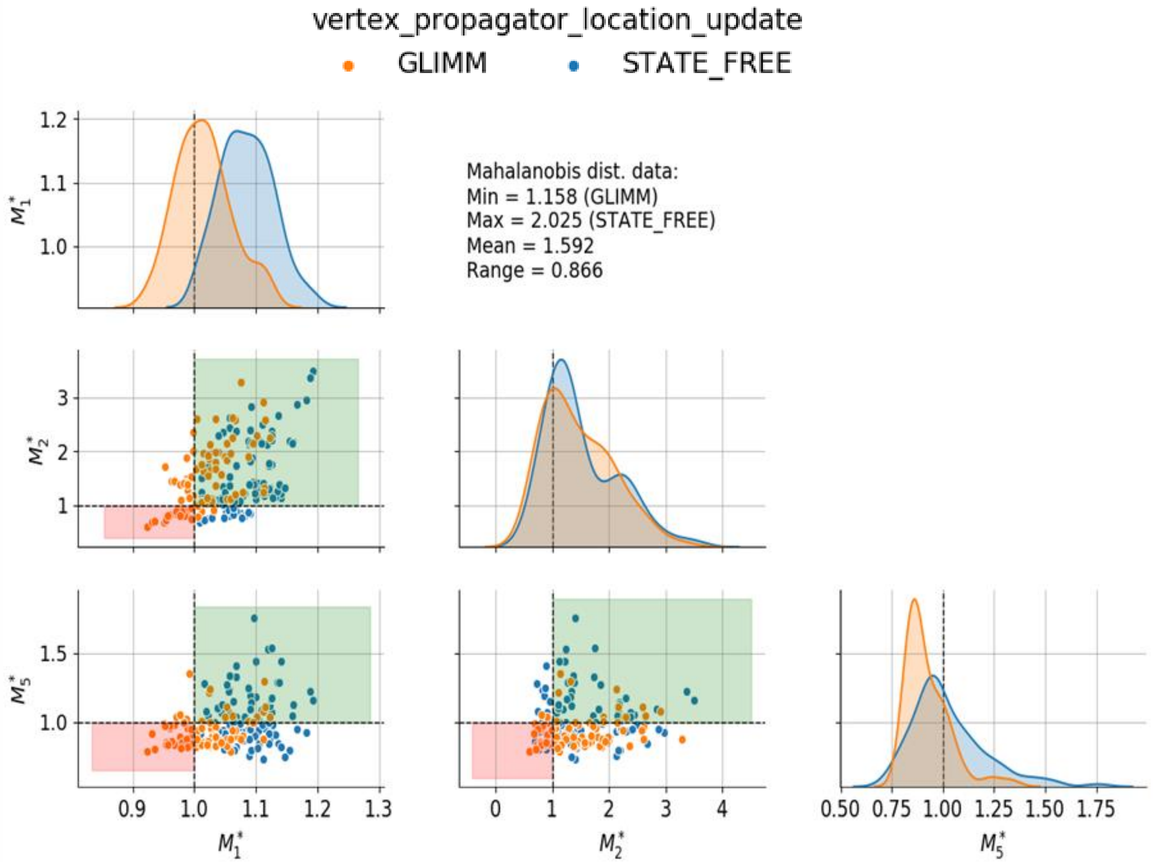


- Reducing ionic conduction losses improves performance from hotter main reverb
- See Adam Fraser's talk **(ZO03.00006)** for dedicated comparison to experiments

Other import factors identified by our analysis are the impact of radiation transport and the implementation of front tracking



Mahalanobis dist. data:
Min = 0.985 (DISABLED)
Max = 2.530 (AUTO_FLUX_LIMITED_RADHYDRO)
Mean = 1.648
Range = 1.545



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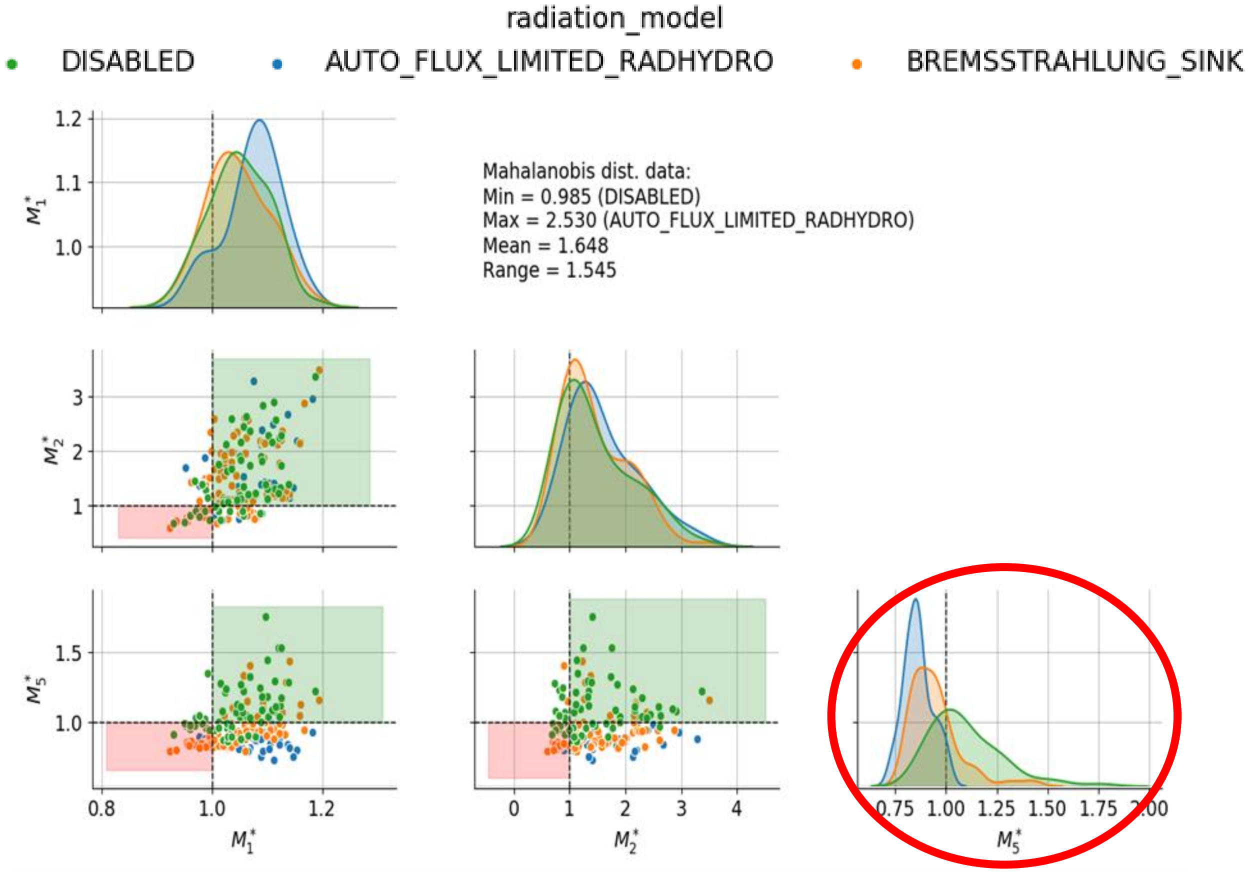

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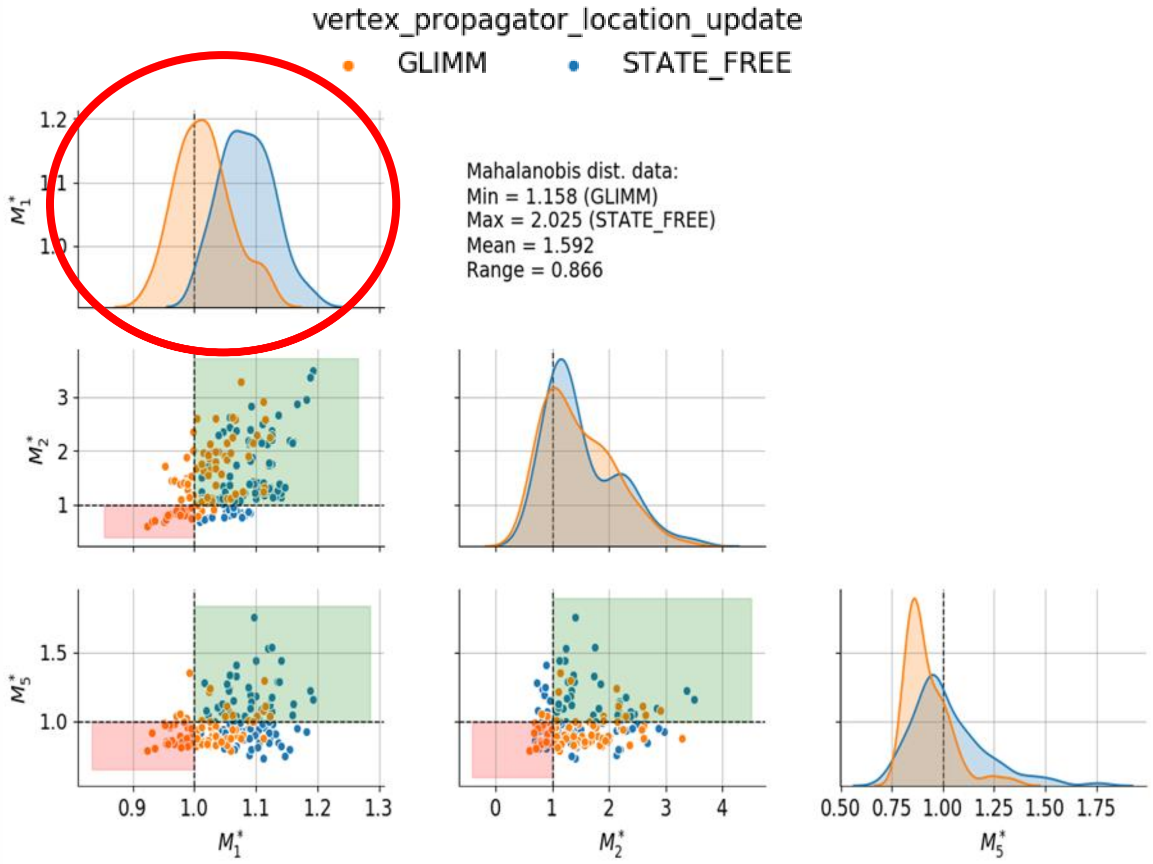

Mahalanobis dist. data:
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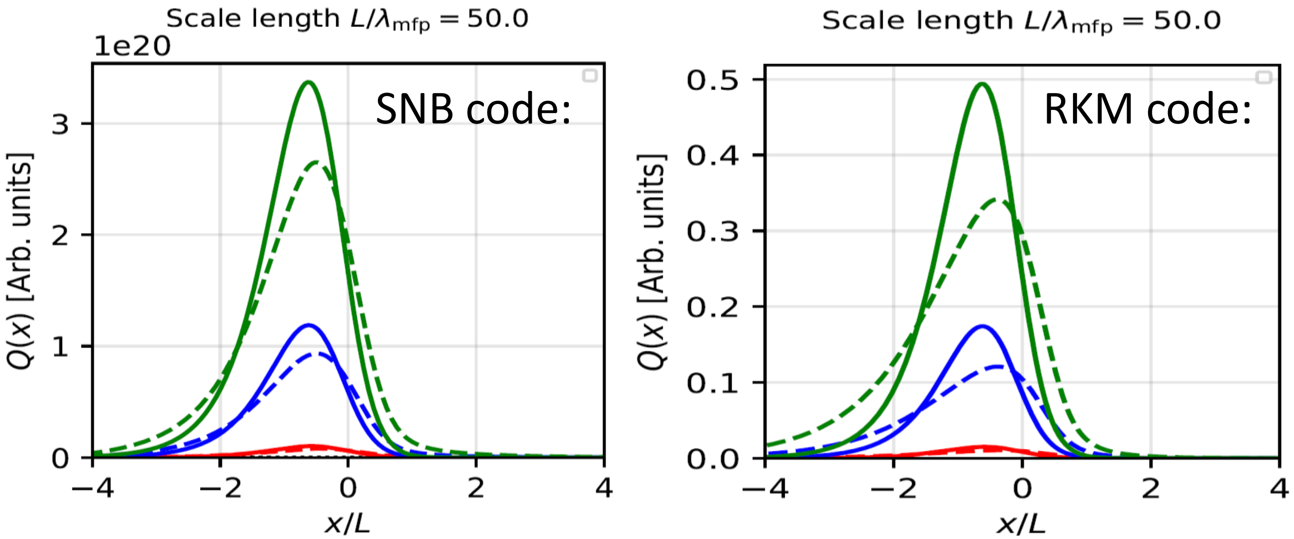
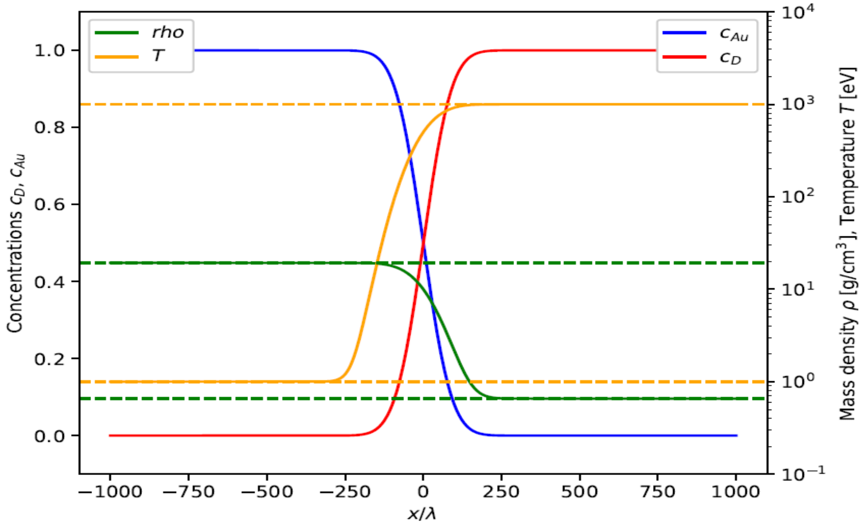
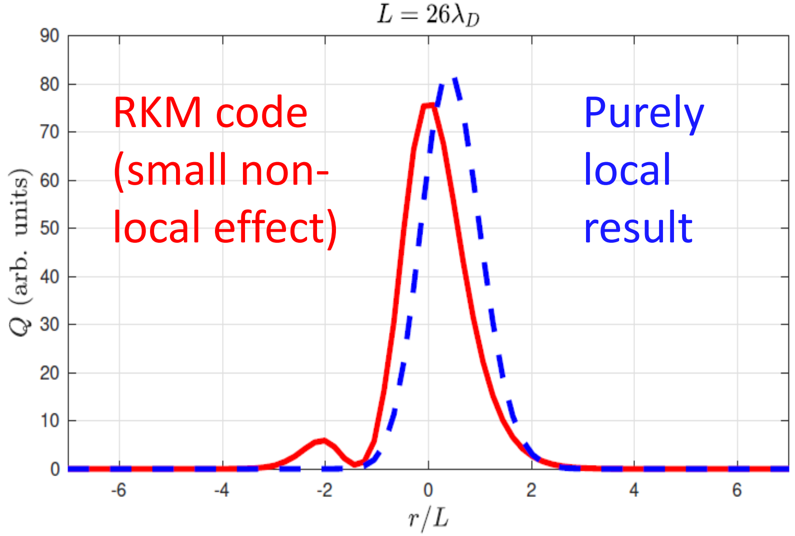
- Rad losses/transport mainly reduces performance by cooling cavity collapse phase
- Lower fidelity front tracking leads to faster incident shock

We have begun development of a reduced kinetic model for ionic heat transport using a well-established approach



- Similar method to reactivity reduction model **[McDevitt et al. PoP 2014, Kagan et al. PRL 2015]**
- Qualitatively good agreement with well-known SNB model for non-local electron heat flux
- **Initial D-Au interface test shows surprisingly little impact on heat flux profile vs local limit**





Summary and conclusions

- We have expanded on our recent work **[Chapman et al. PoP 2021]** to undertake a new multivariate sensitivity study based on a uniaxially driven ICF target **[Derentowicz et al. J. Tech. Phys. 1977]**
- 1000 simulations run over very large options space sampled using space-filling design
- Three performance metrics constructed in lieu of neutron yields
- Impact on performance of option values assessed through Mahalanobis distance of stratified distributions to a robust reference case
- **Results strengthen previous work: non-local ionic transport remains a crucial factor**
- **Front tracking scheme and radiation transport physics are also major sensitivities**
- **Work on reduced kinetic model for ionic heat flux is underway:** good agreement with SNB for electronic test cases but D-Au interface test requires more work to understand

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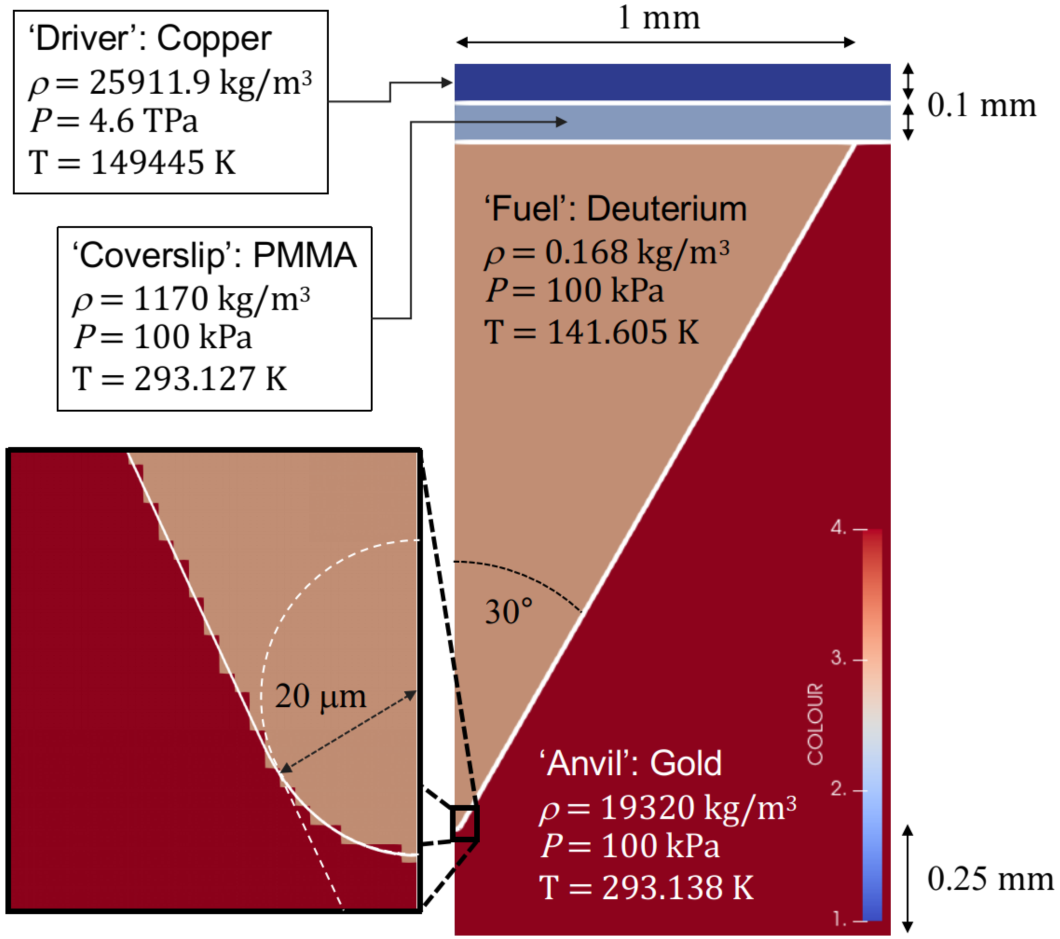
Thank you for your attention
Please get in touch

dave.chapman@firstlightfusion.com

Additional slides

Reference case setup – resolution of 1.7 um (smallest cells) using base resolution of 40 and AMR level 5

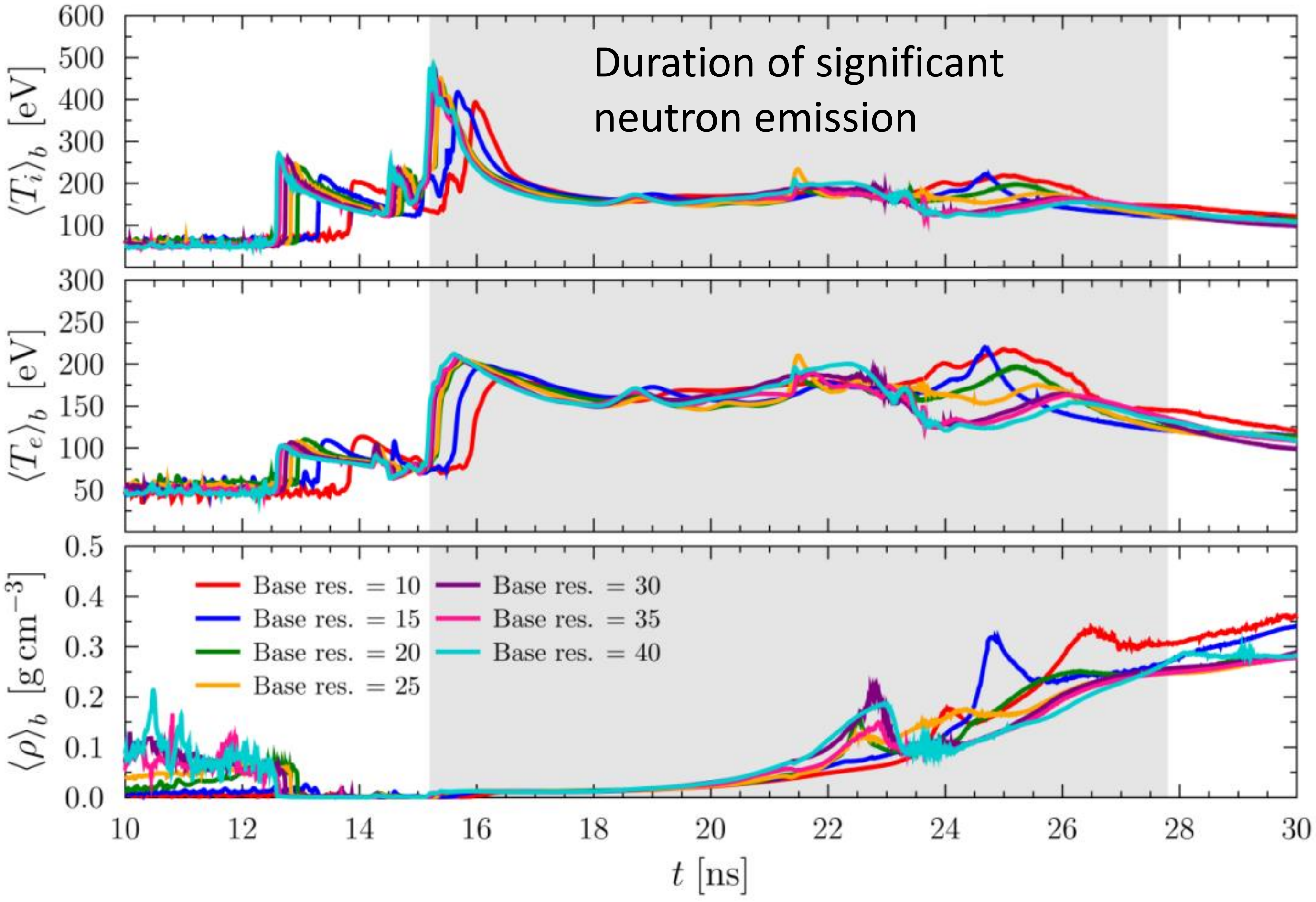


'Driver': Copper
$\rho = 25911.9$ kg/m³
$P = 4.6$ TPa
T = 149445 K

'Coverslip': PMMA
$\rho = 1170$ kg/m³
$P = 100$ kPa
T = 293.127 K

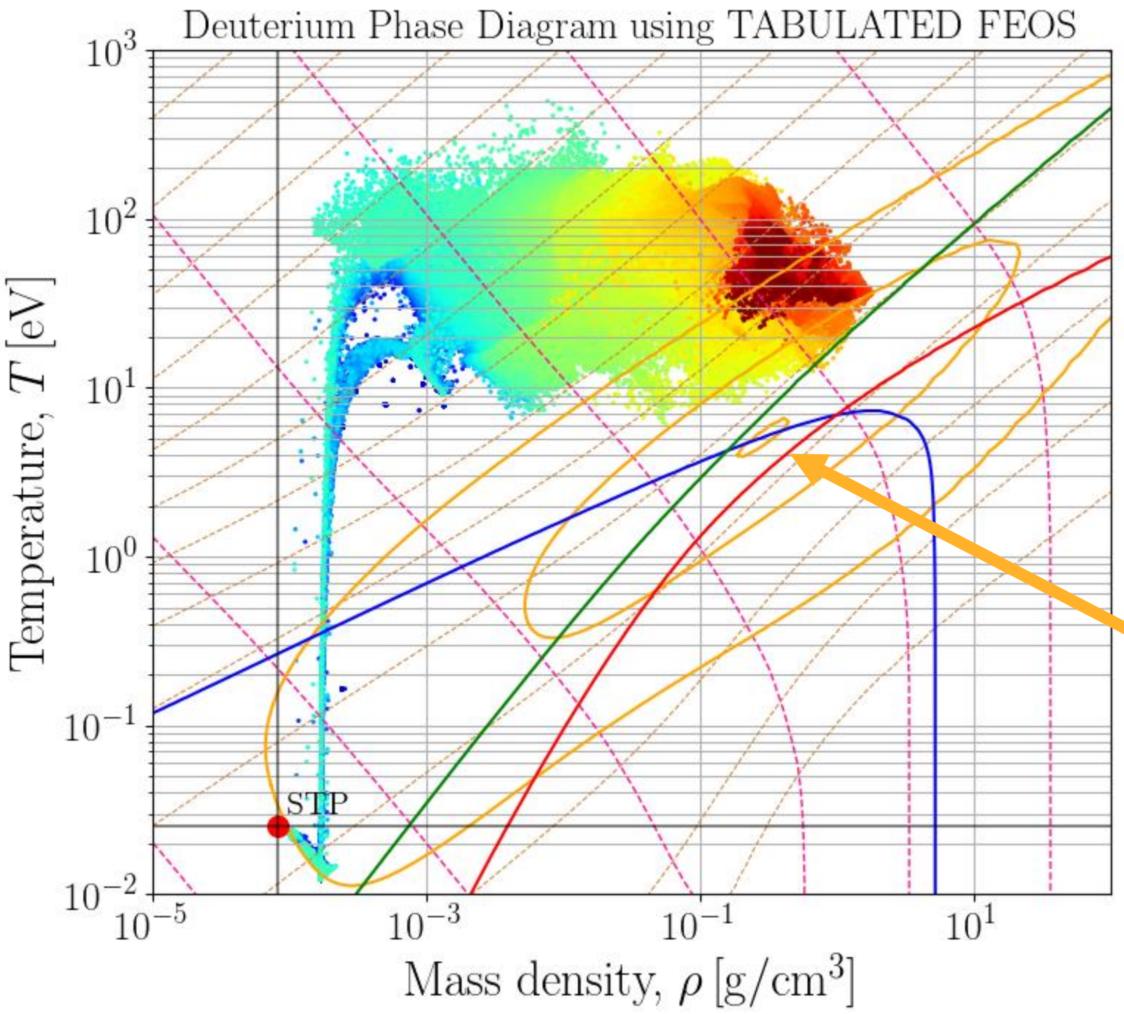
'Fuel': Deuterium
$\rho = 0.168$ kg/m³
$P = 100$ kPa
T = 141.605 K

'Anvil': Gold
$\rho = 19320$ kg/m³
$P = 100$ kPa
T = 293.138 K



Duration of significant neutron emission

Scaling factors are applied to plasma microphysics using a novel 'targeted' approach based on Murillo WDM parameter



- Applying large multipliers to quantities in regimes with low uncertainty (weakly coupled plasmas) is unreasonable
- Use 'WDM parameter' **[Murillo PRE 2010]** to apply multipliers in proportion to how 'non-ideal' a state is:

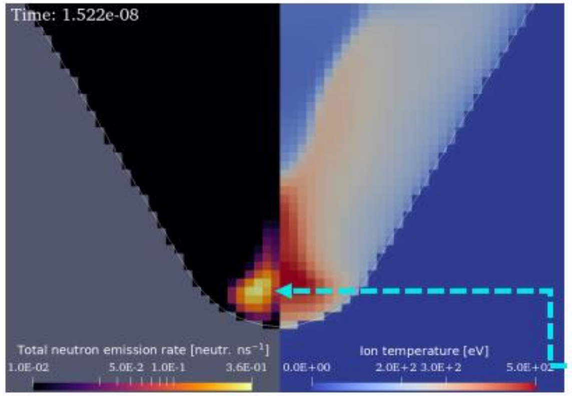
$$W(\rho, T_e) = S(\Theta)S(\Gamma_{ee}), \;\; S(x) = 2/(x + 1/x)$$

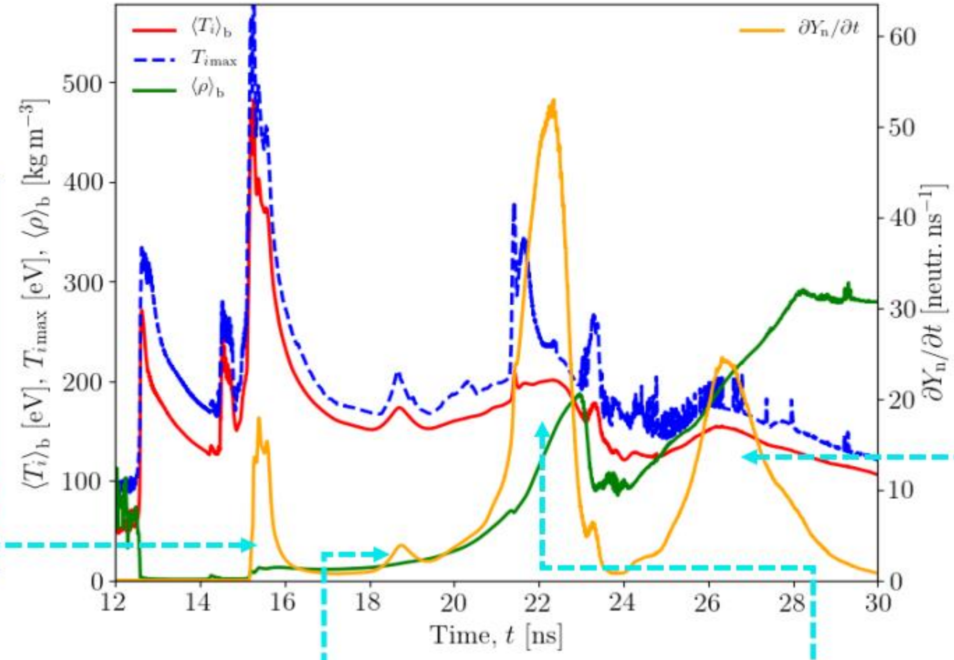
$$s'(\rho, T_e) = 1 + (s - 1)W(\rho, T_e)$$

- Large multiplier values only occur when Θ ~ 1 and Γ_{ee} ~ 1, i.e. in PMMA and Au

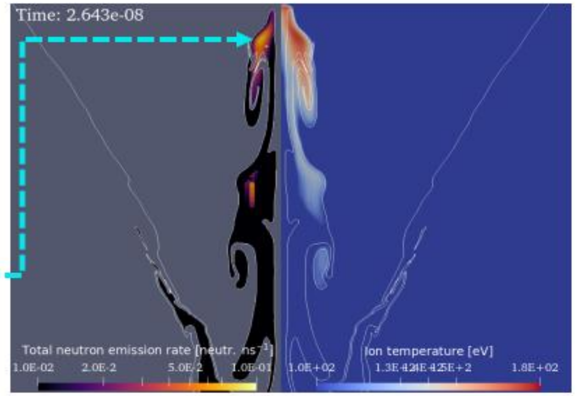
BWA ion temperature probe contains a lot of useful information which is strongly indicative of the fusion output

Heating and compression produced by incident shock reflection from cavity tip

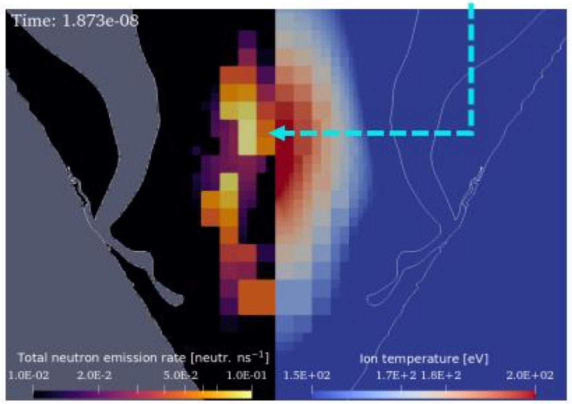


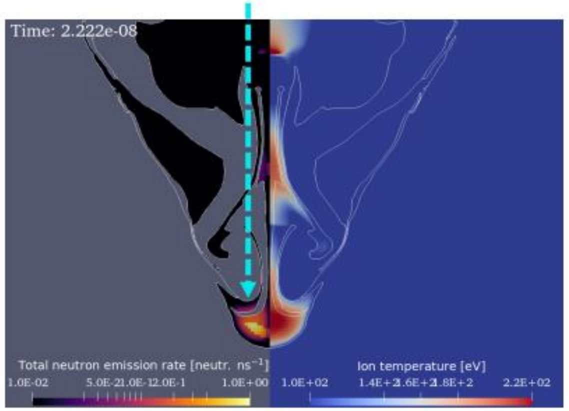


Small pocket of hot fuel compressed to high density within plastic eddy structure



Localised temperature and density spike produced at axis after infalling jets begin to recompress expanding shocked fuel onto axis





Jets recompress fuel into cavity tip. The bulk of the yield at this stage comes from the tip

Sims are pooled as: successful/failed/killed/acceptable → processable/analysable (194/1000 in total)