Development of a predictive modelling capability for ICF plasma experiments produced by high-velocity projectiles

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Motivation

- First Light Fusion (FLF) is researching ICF with novel target designs utilising strong shocks driven by hyper-velocity projectiles using EM launcher systems
- Designing and optimising proprietary target designs requires in-house modelling capability
- **Hytrac** is an Eulerian AMR radiation-hydrodynamics code based on the front tracking approach:
  - High-fidelity shock and interface tracking
  - Multi-temperature description
  - Thermal conduction via explicit STS method
  - Emerging radiation transport capability
  - Multi-material node propagation
  - Parallelised for cluster computing using HPX
- Developed from the ground up to deliver a robust multi-physics tool for ICF problems
- Intensive period of experimental and cross-code validation exercises has recently begun
- Equation of state (EoS) and plasma microphysics (transport and radiative properties) are crucial ancillary capabilities

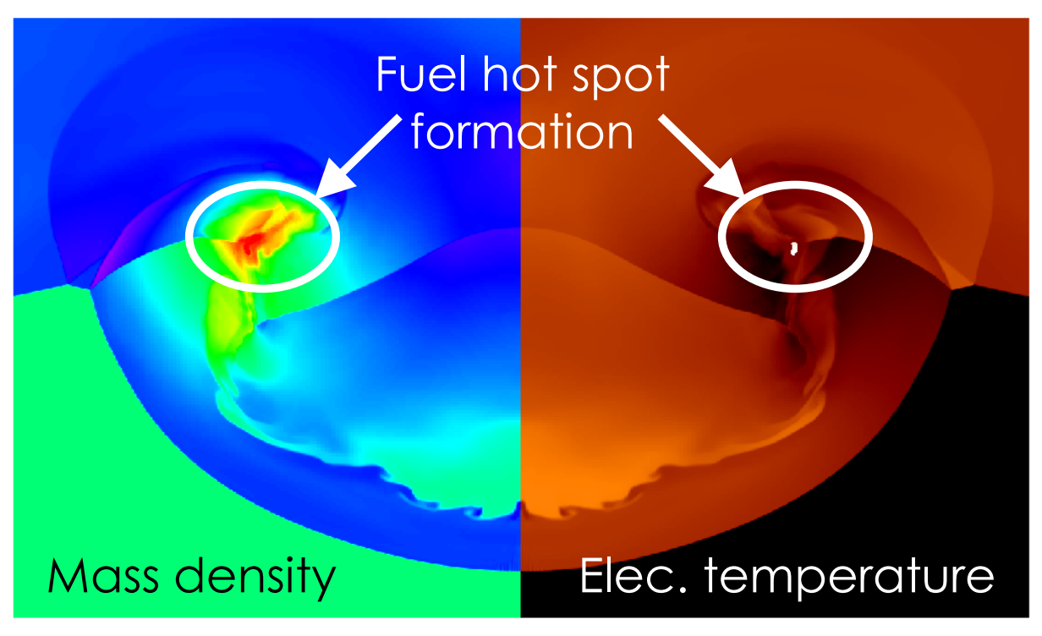


Fig. 1: Hytrac simulation of asymmetric cavity collapse induced by an aluminium projectile moving at 30 km s^{-1}. Hot, dense fuel pocket formation is shown.

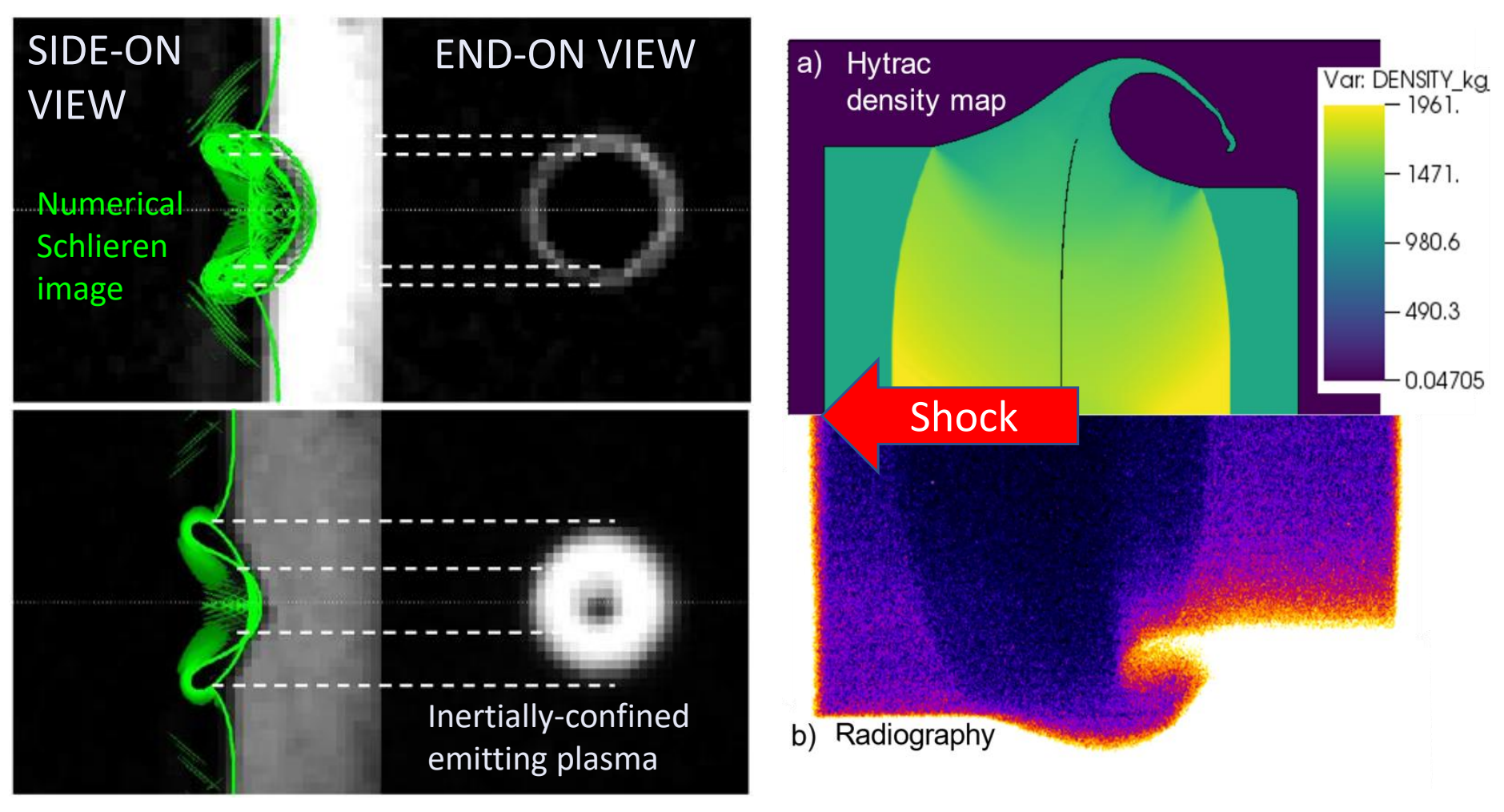


Fig. 2: Comparison of Hytrac simulations to streaked optical shadowgraphy (left) and transmission x-ray radiography (right) show very good agreement.

Development and benchmarking of equation of state model

- FEOS [1] forms the core of our EoS model, but numerous fixes and changes have been necessary
- Comparison to experimental data and ab initio simulations shows generally good agreement
- Investigating use of SpK model [2,3] as core for electron EoS to provide nLTE population kinetics

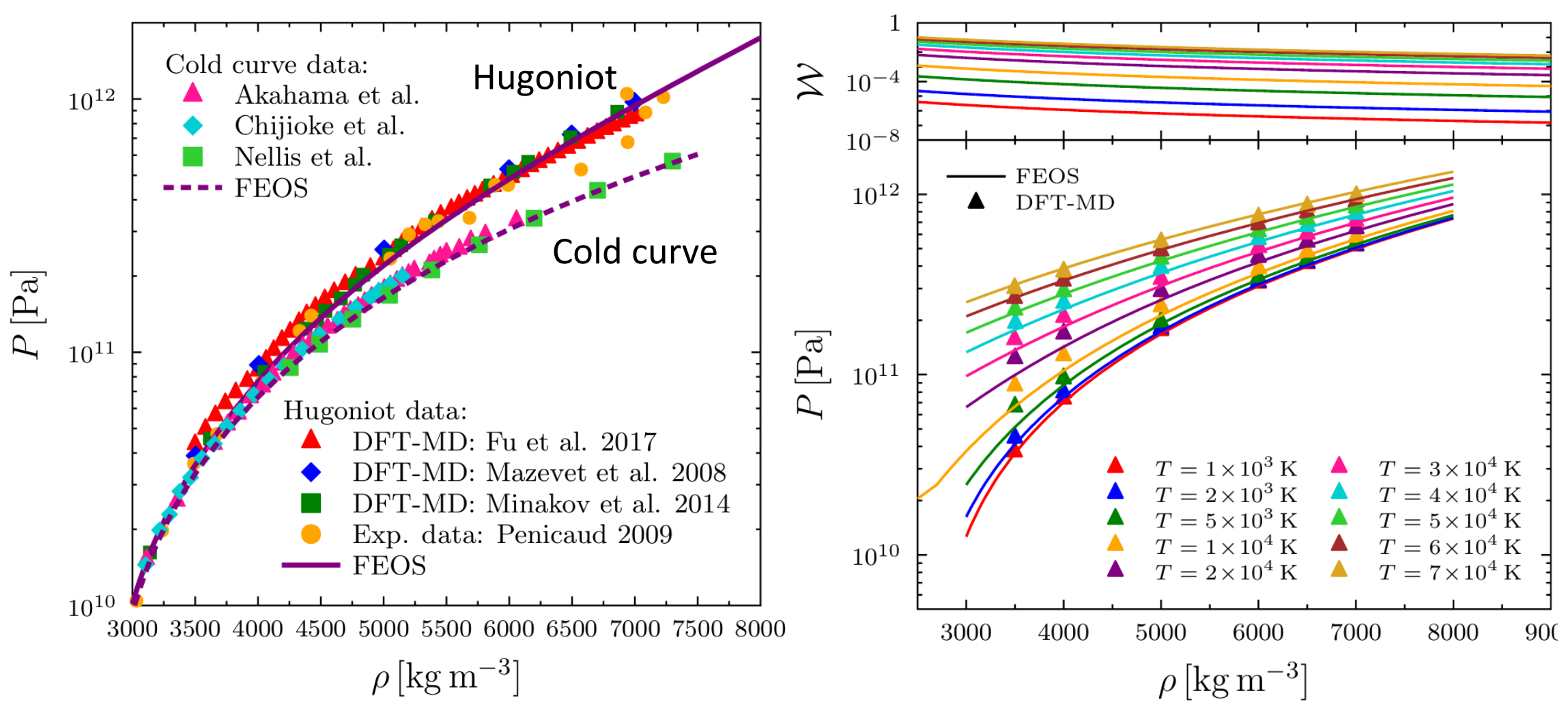


Fig. 3: FEOS compares well to experimental and ab initio data for many materials (here Al). The cold curve and Hugoniot (left) and isotherms across the WDM regime (right) are all reasonably accurate.

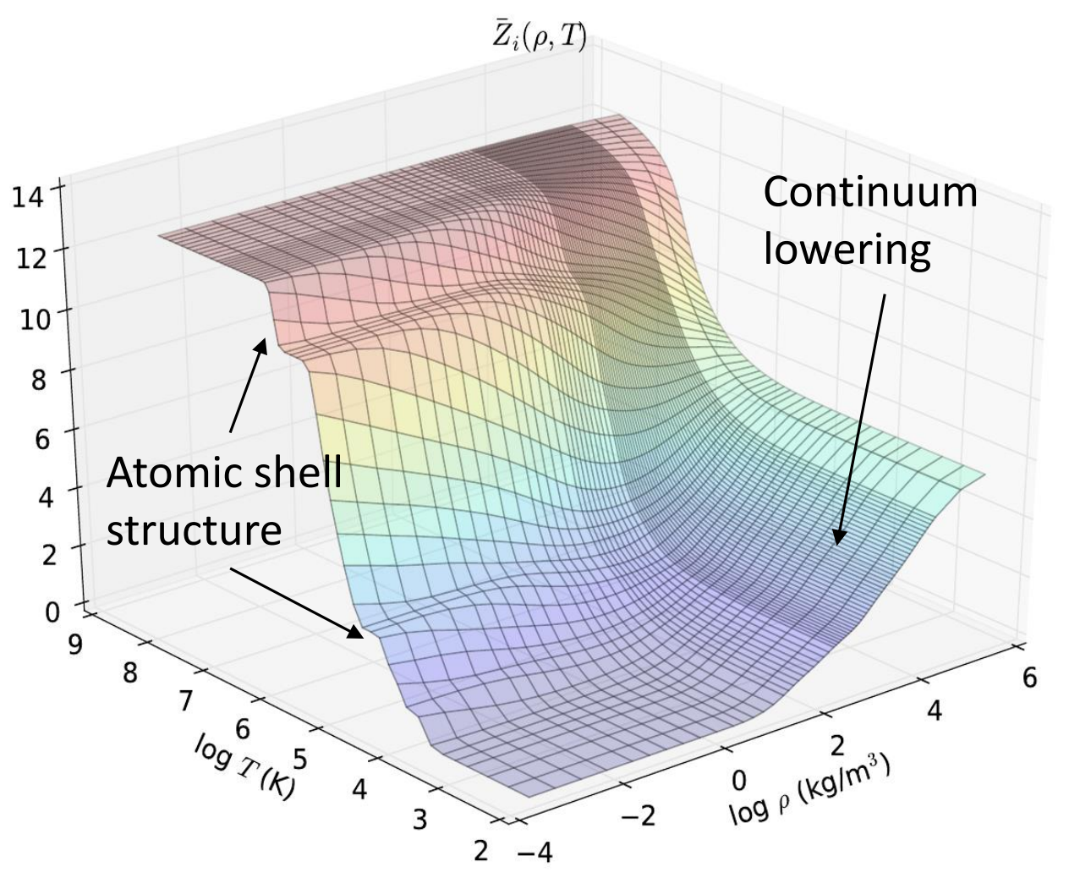


Fig. 4: SpK ionisation table (in LTE mode) for aluminium on the density-temperature plane.

Development and benchmarking of thermal conductivity model

- Thermal conductivities of electrons/ions are required for many materials over a large ρ-T_e-T_i space
- We have developed a flexible and numerically inexpensive improvement to the Lee-More model [4]
- The effective collision time includes weakly coupled e-i scattering [5], path-limited e-i scattering for WDM [6], e-n scattering for weakly-ionised matter [7] and e-ph scattering in metals [8]. Non-degenerate, low-Z plasmas also requires e-e scattering correction [9]:

$$\tau^{\mathrm{eff}}(p)=\frac{1}{\nu_{e-i}(p)+\nu_{e-n}(p)}+\frac{1}{k_1\nu_{e-i}^{\mathrm{WDM}}(p)}+\frac{1}{k_2\nu_{e-ph}}$$

$$I_n(\eta)=\frac{4\omega_{\mathrm{pe}}}{3\sqrt{\pi}}\int_0^\infty \mathrm{d}x\, x^{n+\frac{3}{2}}\,\tau^{\mathrm{eff}}(x\sqrt{2}p_e)\frac{F_{-2}(x^2-\eta)}{F_{1/2}(\eta)}$$

$$\kappa_e=\frac{n_e v_e^2 k_{\mathrm{B}}}{\omega_{\mathrm{pe}}}\left[I_2(\eta)-\frac{I_1^2(\eta)}{I_0(\eta)}\right]\left(\frac{R_e^{-\infty}(\bar{Z}_i)}{1+e^{\eta-\eta_0}}+\frac{1}{1+e^{\eta_0-\eta}}\right)$$

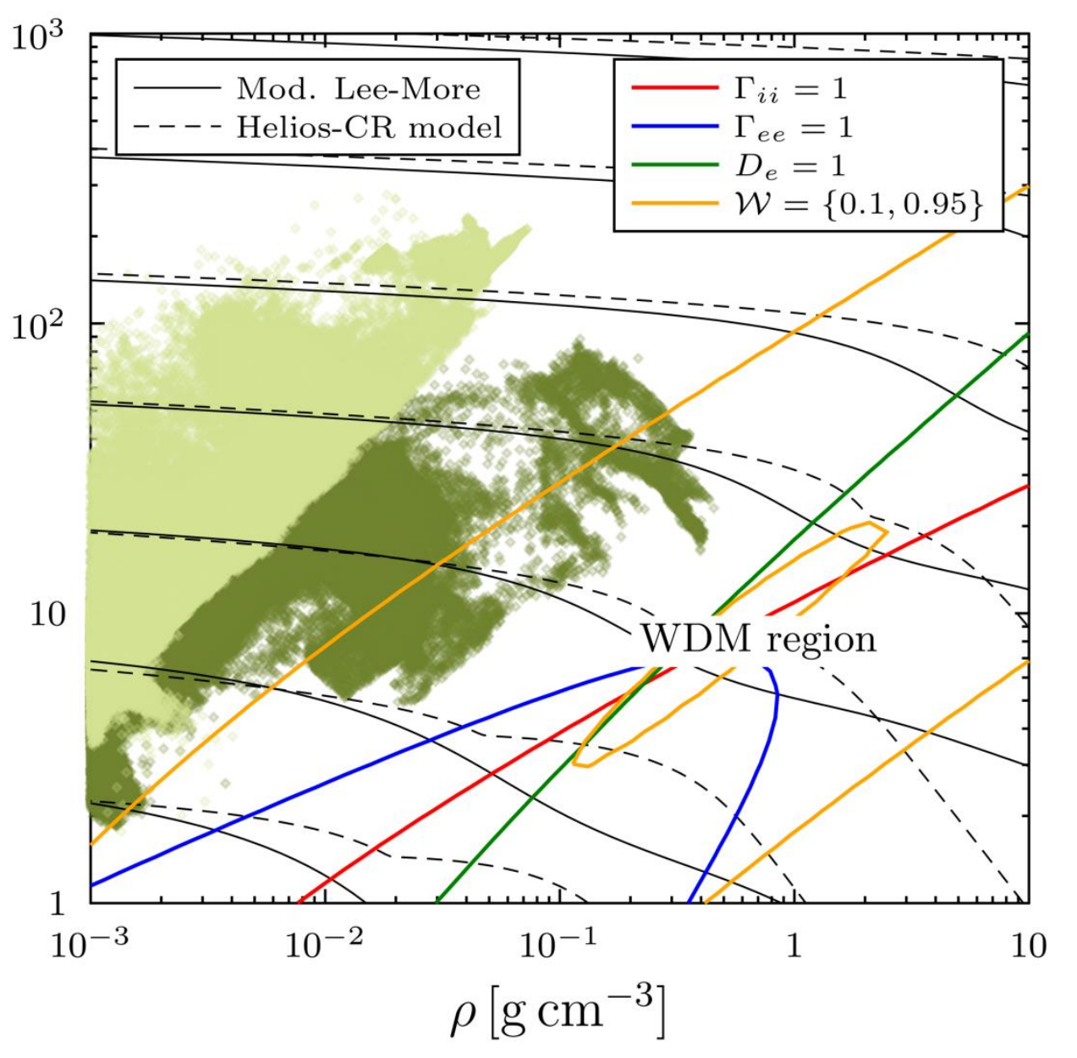
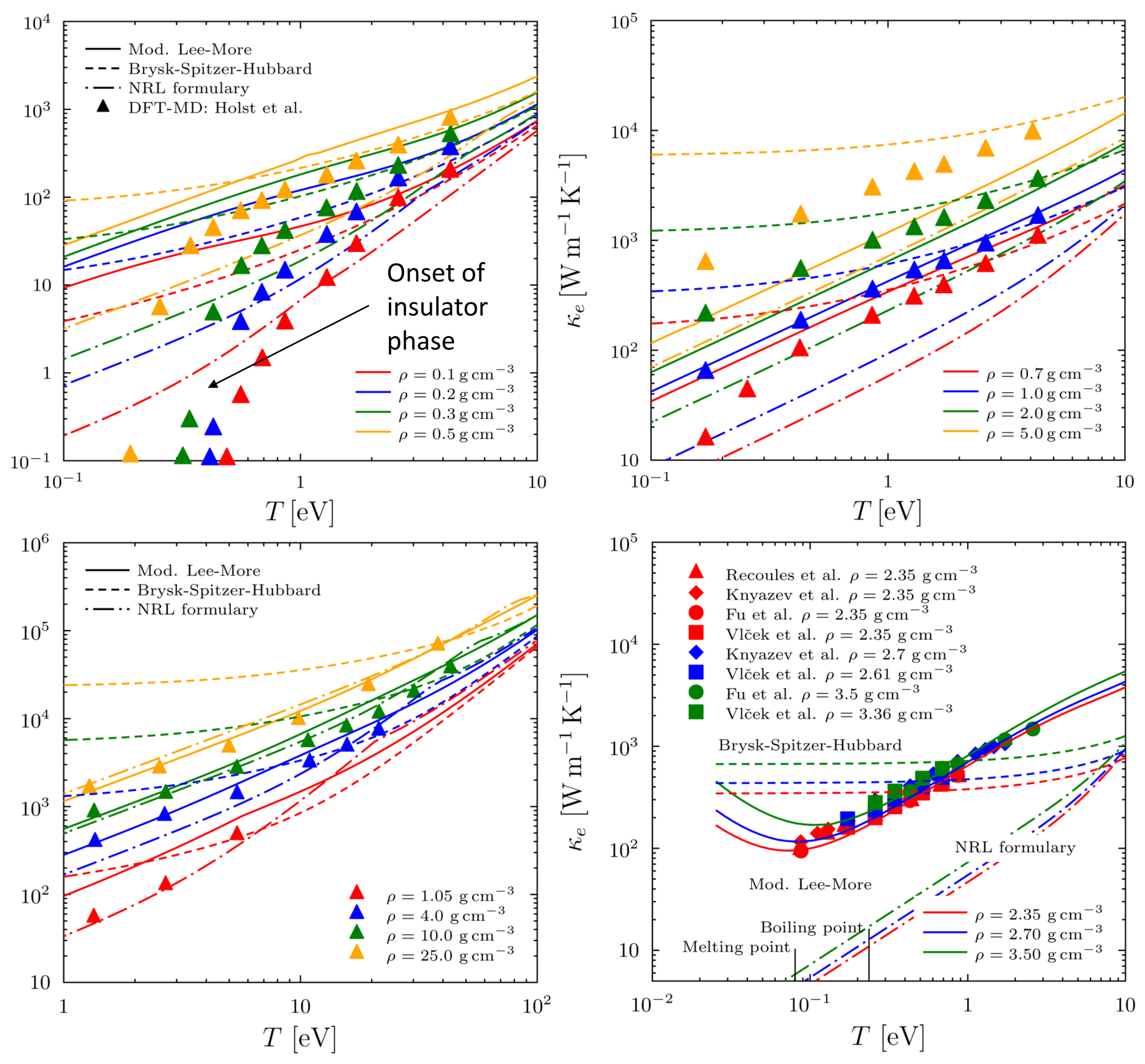


Fig. 5 (right): Simple simulations of 1D spherical implosions demonstrate the importance of thermal conduction losses to the conditions achieved in the deuterium fuel. The FLF model gives significant differences to the simple model in HELIOS-CR under conditions relevant to WDM.



- Comparisons to DFT-MD simulations [10,11] show reasonable agreement for conducting states
- Insulator-conductor transition in hydrogen is clearly still problematic
- Better treatment of weakly-ionised phase is generally needed, but these states are not important for creation and performance of burning fuel
- Plastics and simple metals show very good agreement under challenging conditions
- Improved models for WDM phase are under development – Ichimaru-Tanaka [12,13]

Fig. 6 (left): Comparison of the modified Lee-More thermal conductivity model with DFT-MD data for hydrogen (top panels), CH (bottom left) and aluminium (bottom right).

Comparison of Hytrac and Helios-CR

- First major code-to-code benchmarking exercise recently completed against Helios-CR [14]
- Consider simple axisymmetric geometry (Helios-CR could not sufficiently resolve enough cells in gas for spherical target configuration) – Pre-shocked Al ring collapsing onto D fuel
- Comparisons of mass-weighted average (MWA) fuel conditions show good agreement
- Convergence tested through normalised RMSD time-averaged over stagnation phase
- Generally the codes agree to within ~10%, but Hytrac is currently a little less well-converged (ongoing performance improvements will soon allow for like-for-like comparisons)

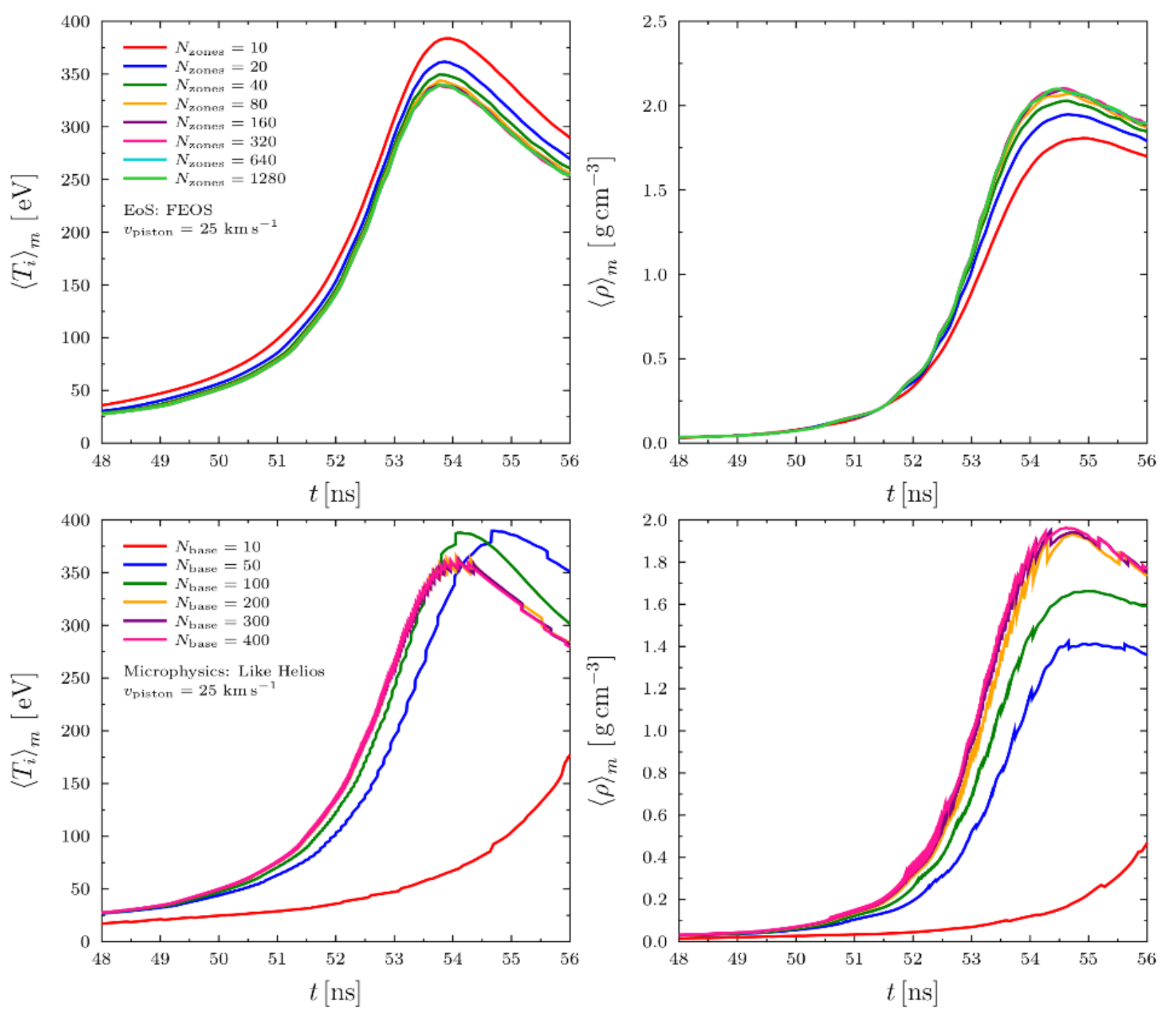


Fig. 7: Convergence of MWA ion temperature (left) and mass density (right) in deuterium fuel from Helios-CR (top row) and Hytrac (bottom row).

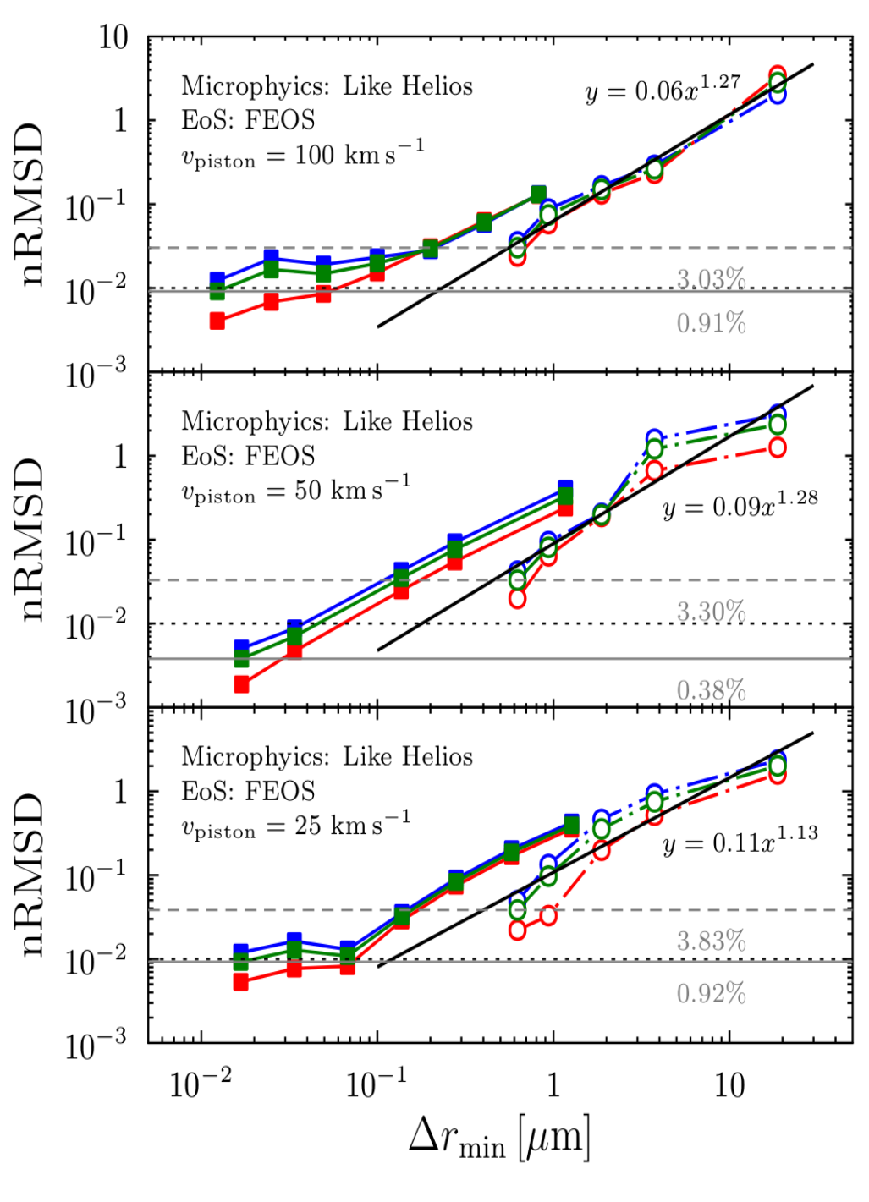


Fig. 8: RMSD convergence metrics for both codes as a function of minimum cell size

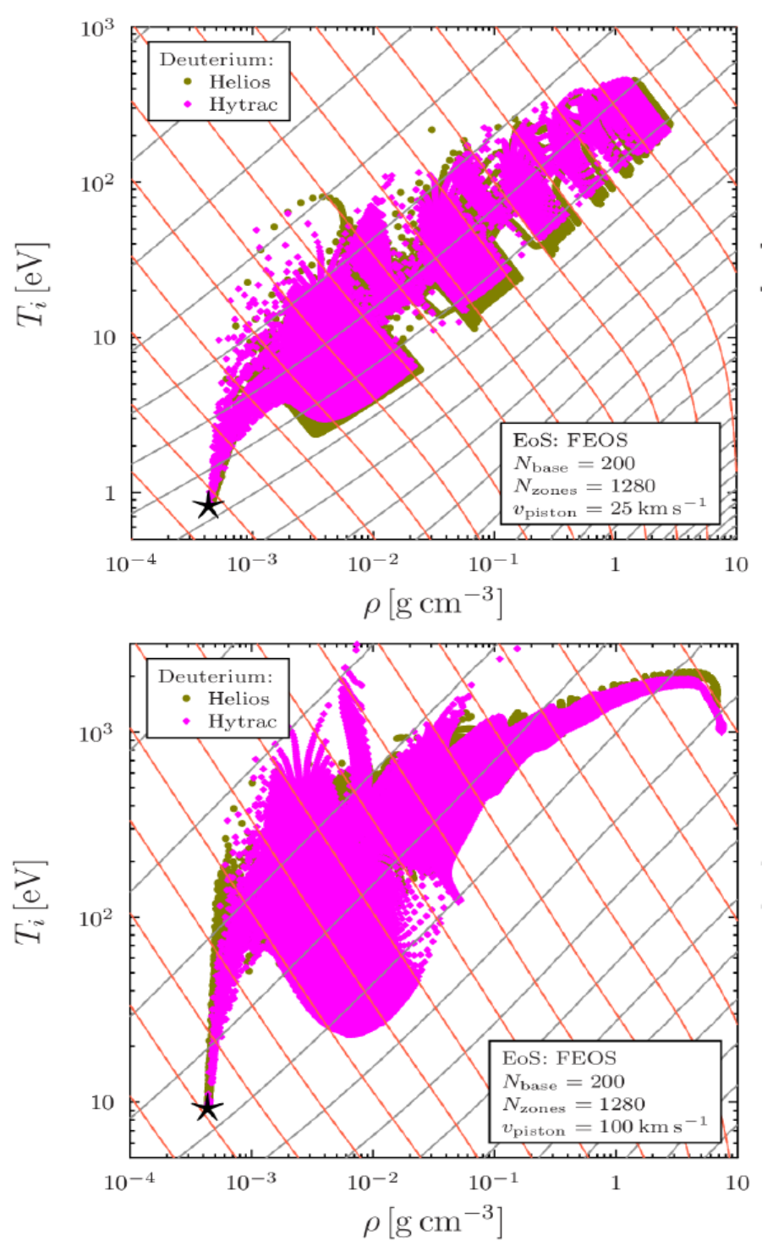


Fig. 9: Cell trajectory plots in the fuel on the density-temperature plane.

Prioritising Hytrac development through sensitivity analysis

- Plasma conditions and fusion performance are minimally affected by choice of microphysics models for these simulations, with largest differences at low temperatures near non-ideal plasma regimes
- Significant differences are seen (~30% in plasma conditions and ~55% in yield) due to EoS models
- Small differences in material pressure near under non-ideal conditions influence fuel evolution

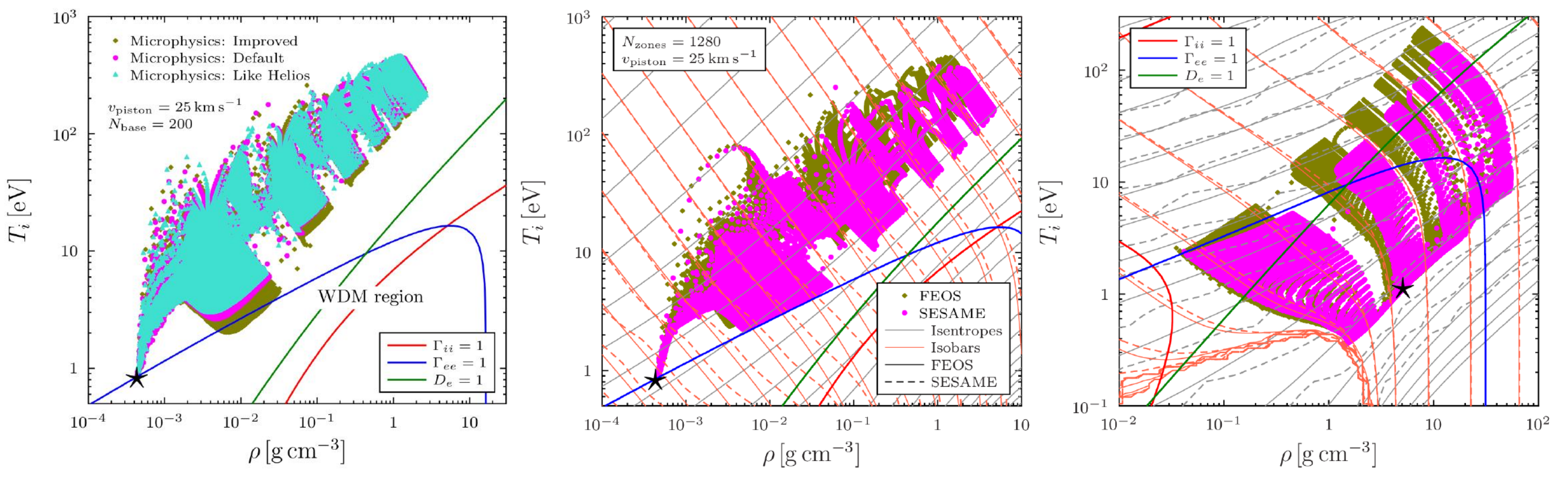


Fig. 10 (above): Cell trajectory plots from Hytrac using different microphysics models (left) and from Helios-CR using different EoS model (middle and right).

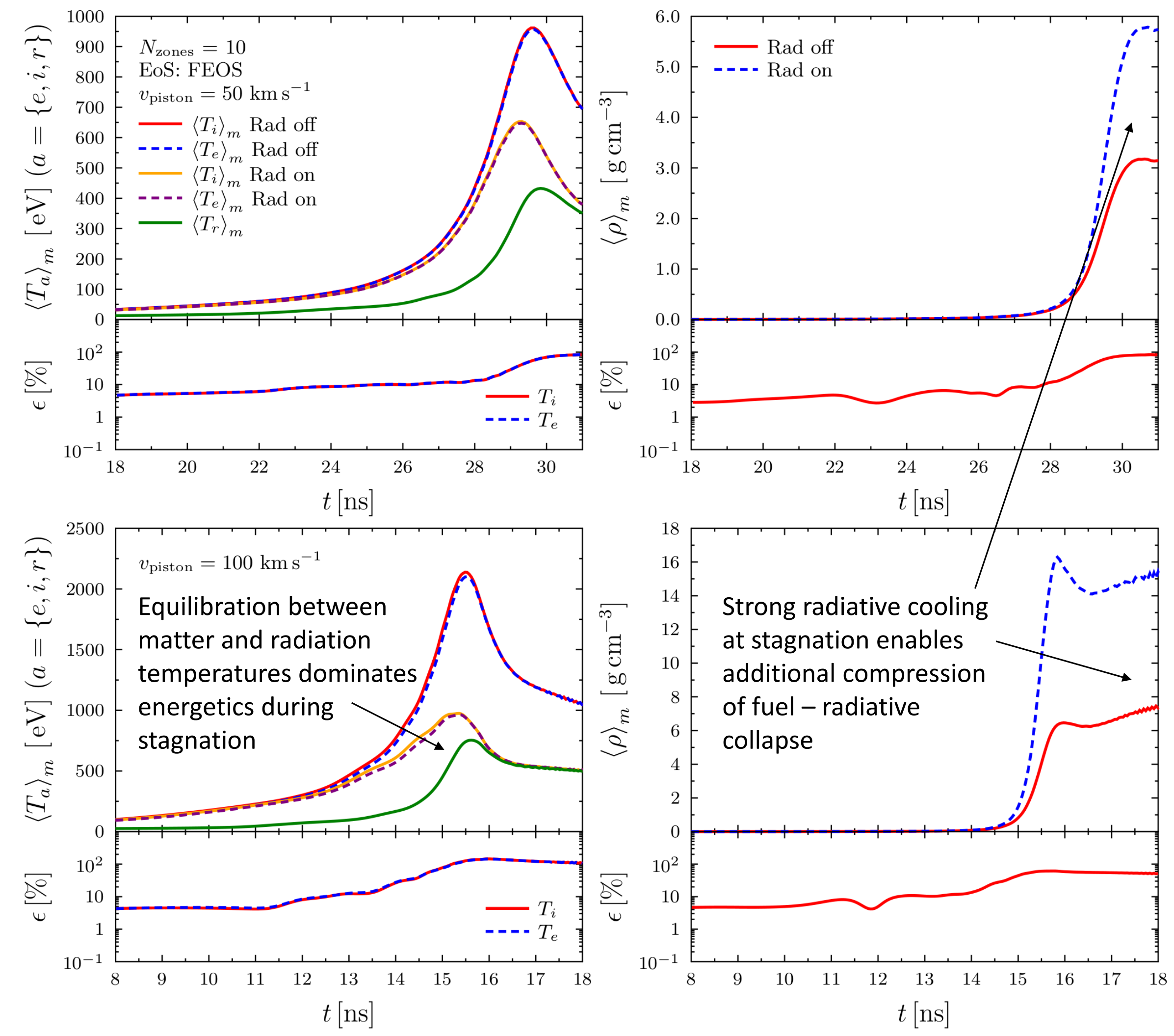


Fig. 11 (left): MWA plasma conditions in deuterium with/without radiation transport.

- Absence of radiation transport (unsurprisingly) has the largest impact on target performance
- Simple loss model in Hytrac is inappropriate during stagnation phase – leads to radiative collapse
- Simple effective radiative conduction model (1T) now being tested for quickly assessing problems
- Next major code milestone will focus on developing multi-group radiation transport (likely $P_{1/3}$ method)

Conclusions and future work

- We have improved and developed the FEOS model in order to work with Hytrac
- Full coupling of SpK to EoS and microphysics is needed (current PhD student at Imperial College)
- More robust treatments for low-temperature effects in both microphysics and EoS are needed
- Improved plasma/WDM phase conductivity with Ichimaru-Tanaka-style model
- Hytrac rapidly developing and demonstrating credibility for ICF modelling against other ICF codes
- Uncertainty in EoS can produce significant differences in stagnated plasma state
- Prioritising radiation transport capability is overwhelmingly the most important development needed

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