# Numerical Investigation of Radiation Hydrodynamic Instabilities at Scale with FleCSI-HARD

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## Introduction

### Instabilities in Radiation Hydrodynamics

- Intense radiation energy can significantly affect the hydrodynamic instabilities leading to complex flow-phenomenon
- Modeling such physics with **Radiation Hydrodynamics** (RHD) is common in Astrophysics, high-energy-density physics, and inertial confinement fusion
- We solve coupled RHD equations using a **HARD** (**H**ydrodynamic **A**nd **R**adiative **D**iffusion) solver built on **FleCSI** (Flexible Computational Science Infrastructure) framework

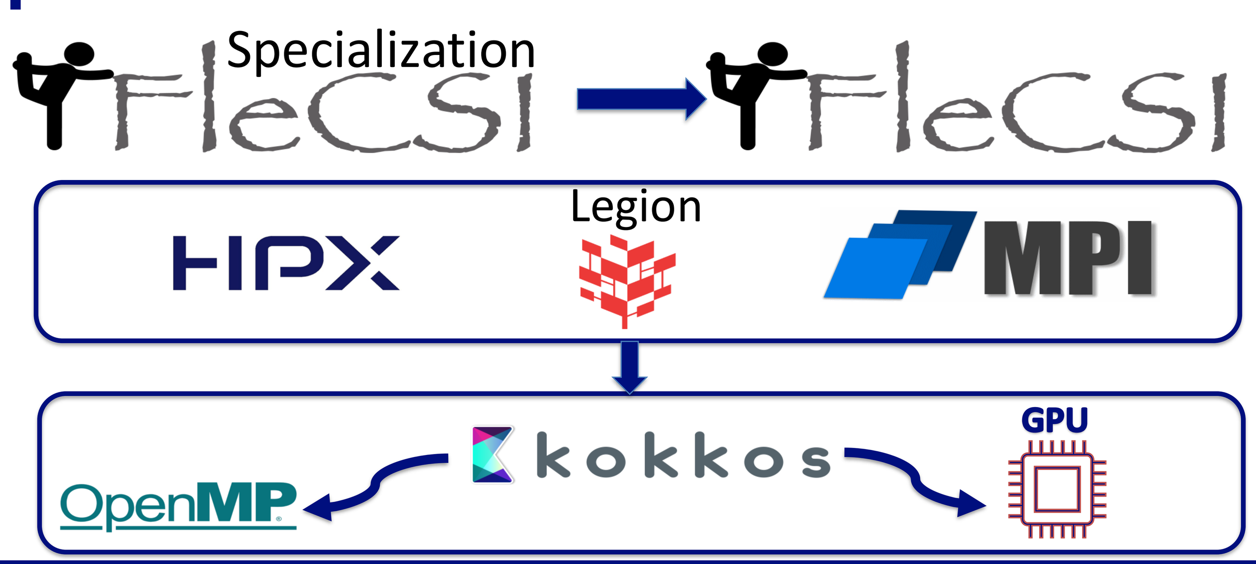
$$\partial_t \begin{bmatrix} \rho \\ \rho v \\ e \\ \boldsymbol{E} \end{bmatrix} + \nabla \cdot \begin{bmatrix} \rho v \\ \rho v v^T + p\boldsymbol{I} \\ (e+p)v \\ \boldsymbol{E}v \end{bmatrix} = \begin{bmatrix} 0 \\ f \\ \dot{q} + f \cdot v \\ -\nabla \cdot \boldsymbol{F} - \boldsymbol{P} \cdot \nabla v - \dot{q} \end{bmatrix}$$

### Adaptive Flux Limited Diffusion

- Provides a closure model for the radiation energy, pressure and force
- A practical and efficient closure for both optically thick and thin regions
- Caps the radiative flux so it never exceeds the physically allowed speed-of-light limit, preventing unphysical overshoots

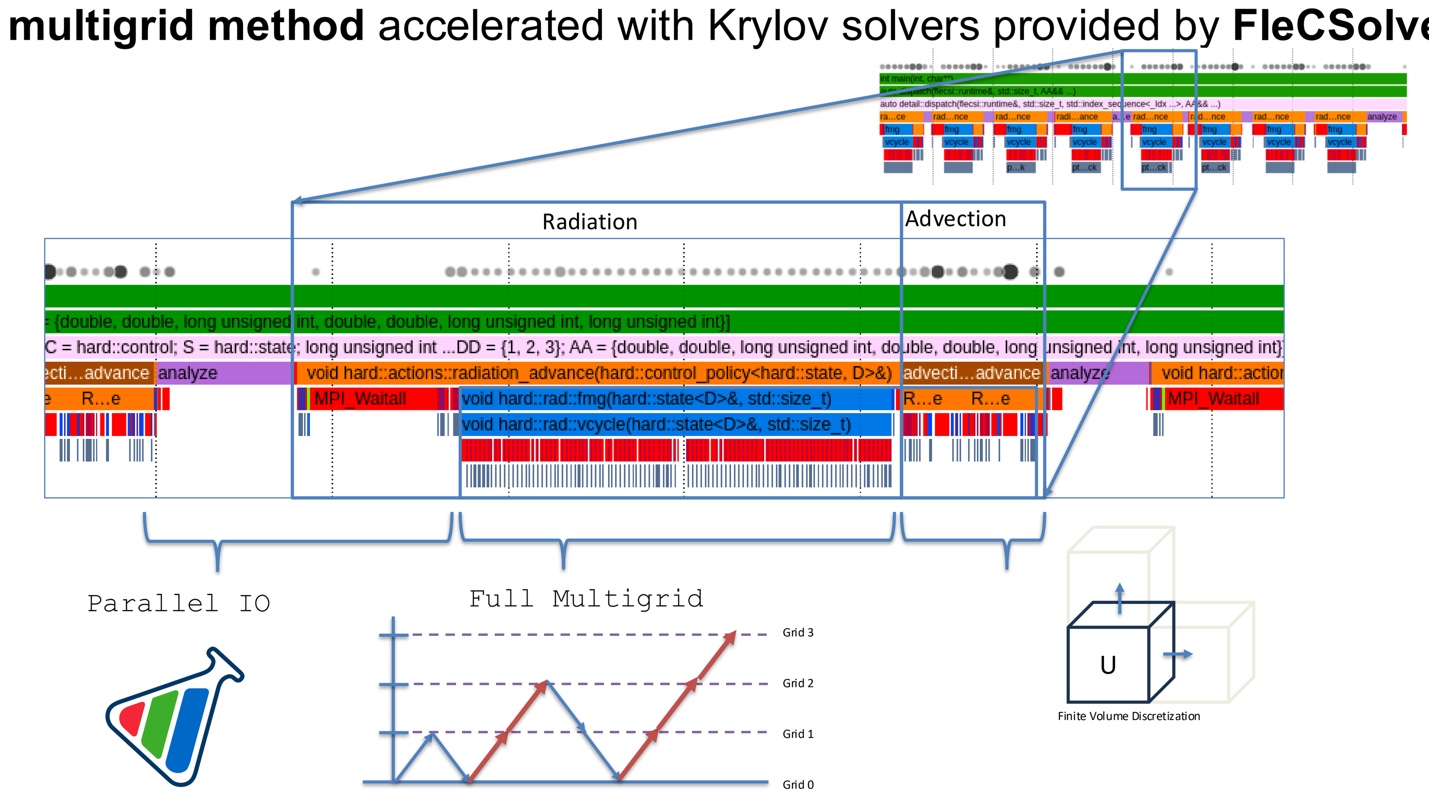
$$F_{rad} = -D\nabla E, \qquad where\ D = \frac{c\lambda}{\kappa}$$

## Computational Framework



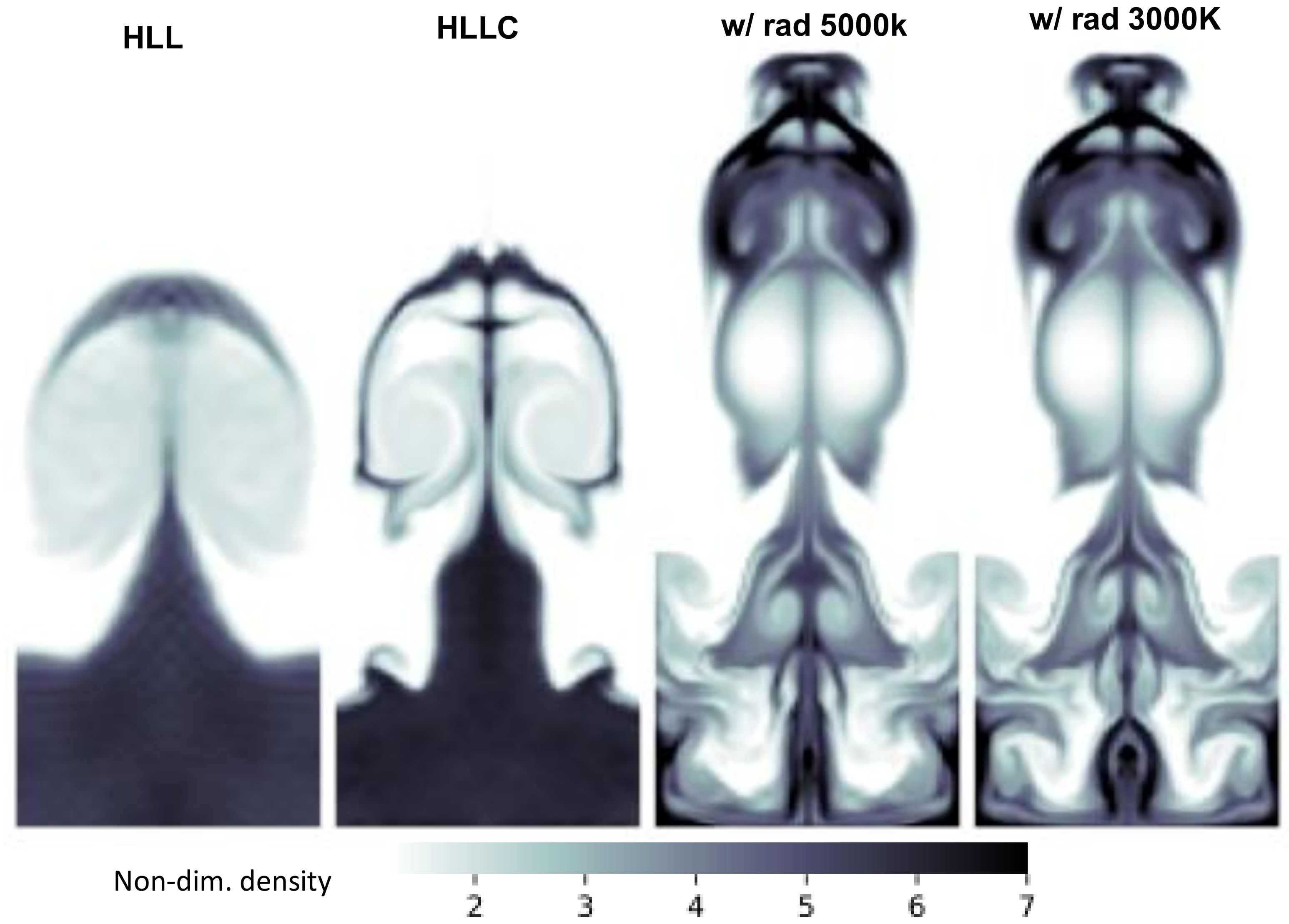

## Numerical Methods

- A system of partial differential equations for RHD are solved using **grid-based finite volume discretization**
- The different time scale between fluid and radiation is addressed via an **implicit-explicit Runge–Kutta time-integration** method
- The time-dependent radiation diffusion effects are solved with a **geometric multigrid method** accelerated with Krylov solvers provided by **FleCSolve**

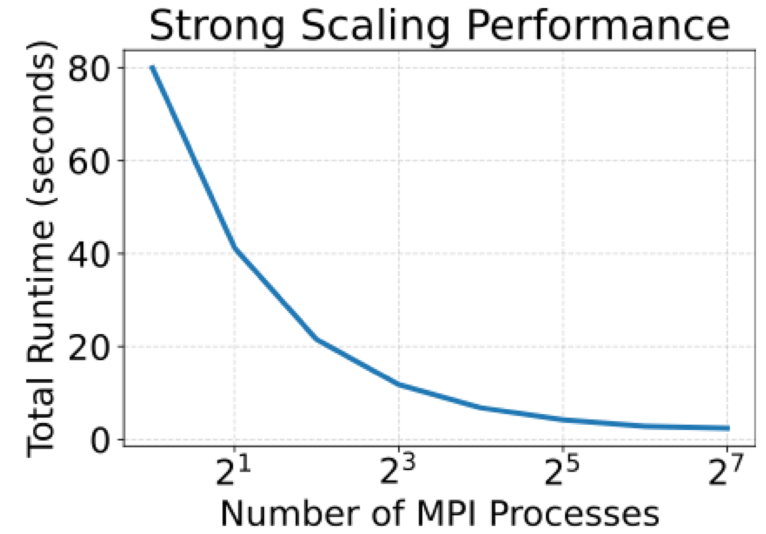


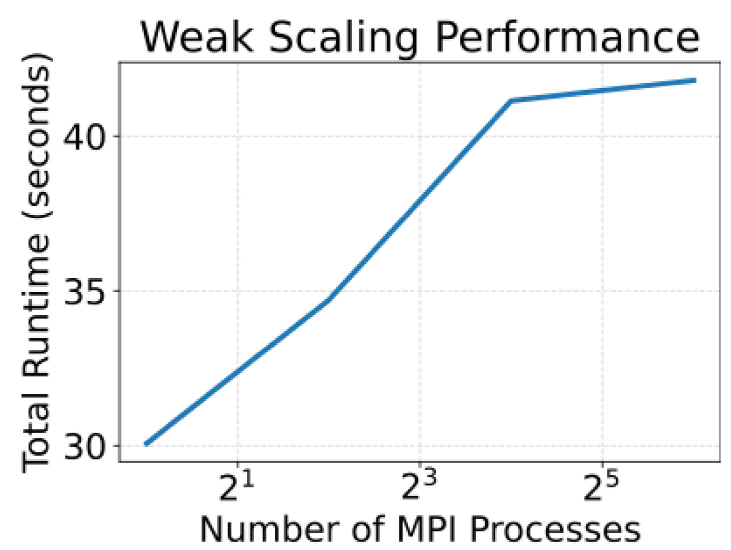

## Richtmyer-Meshkov (RM)

- **RM Instability** occurs when a shock hits a perturbed interface between two fluids of different densities
- Simulation of the instabilities using HLL and HLLC flux schemes confirms HLL diffuses instability quicker
- Different radiation intensities proportionally modifies the instability growth




## Parallel Performance



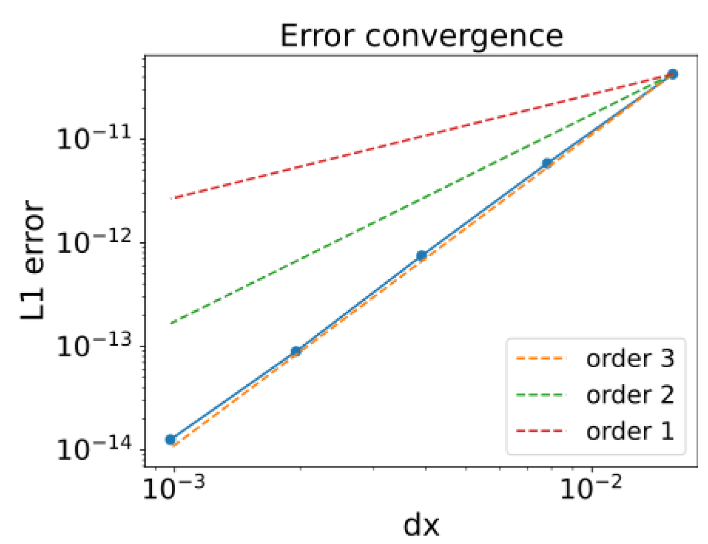




We ran some preliminary scalability studies based on these additions using Kelvin-Helmholtz in two dimensions.

- Left plot: strong scalability on one node, up to 128 MPI ranks on Chicoma.
- Right plot: weak scaling up to 64 ranks on the Darwin test bed. We are currently working at generating GPU results.

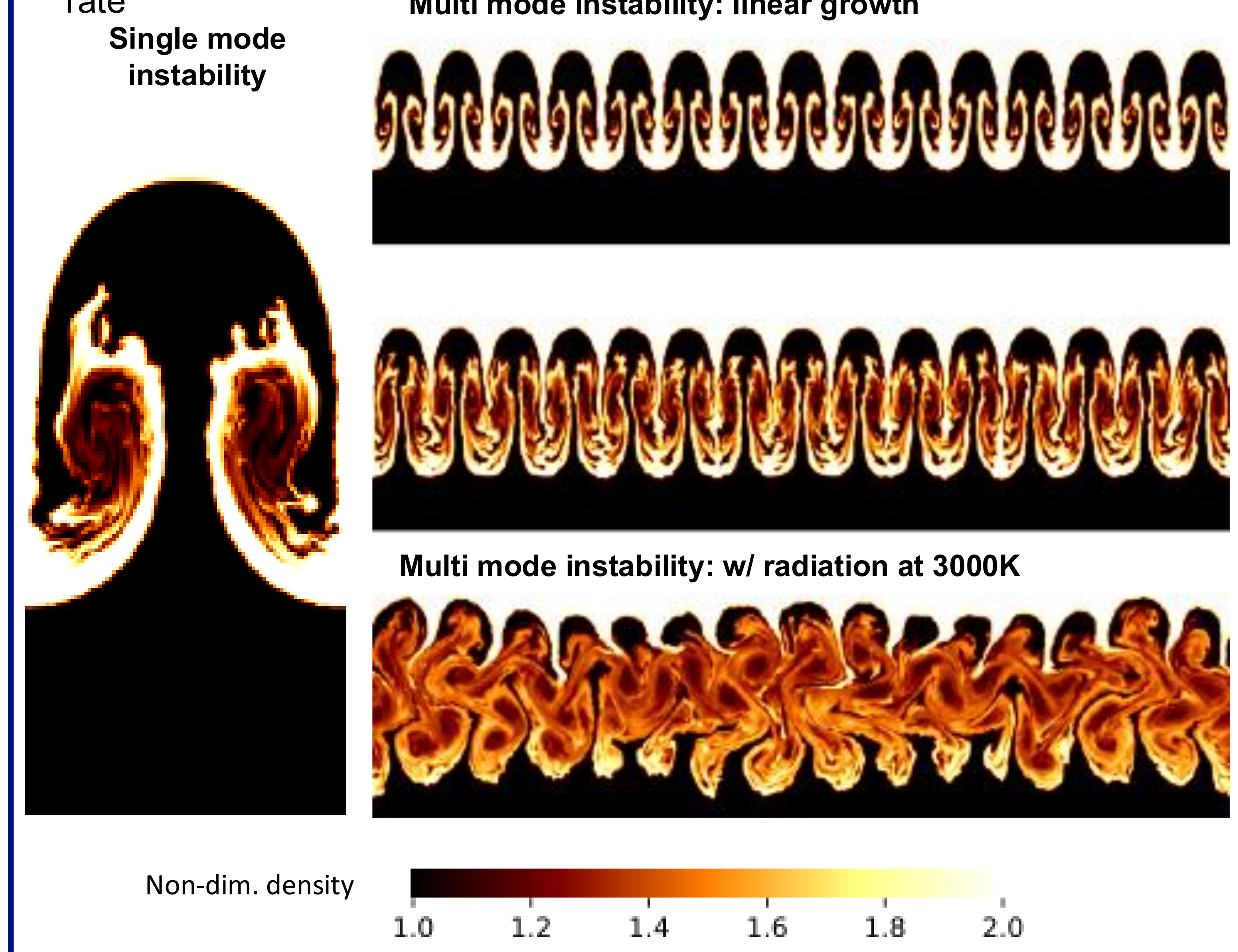
## Convergence Test

- 2nd SSP-RK time integration schemes were implemented with WENO5z-HLLC flux reconstruction scheme
- 3rd order convergence was observed as shown in the figure below and verified against acoustic-wave problem



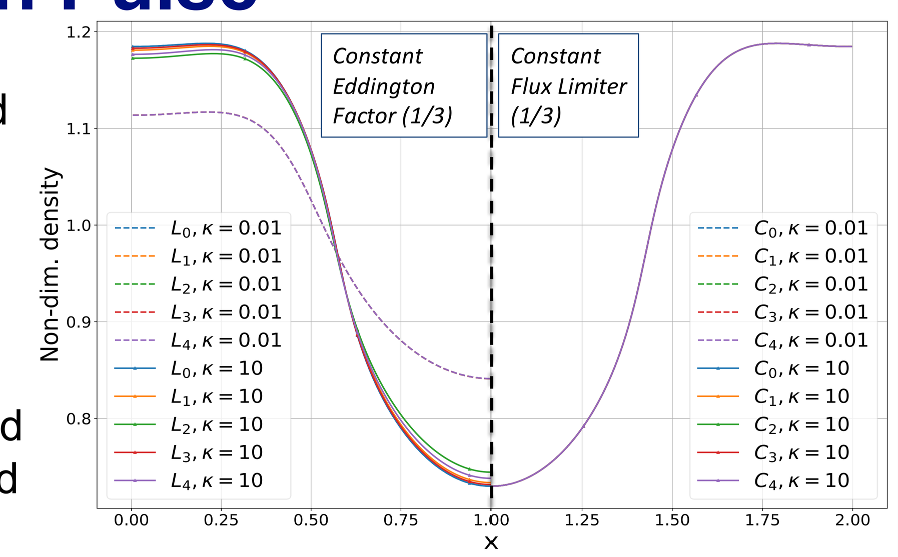

## Rayleigh-Taylor (RT)

- **RT instability** occurs at the interface between two fluids of different densities when subjected to acceleration (e.g., gravity)
- **Single- and multi-mode perturbations** lead to different growth patterns
- Single-mode forms distinct mushroom structures, while multi-mode creates interacting, periodic mushroom clouds with non-linear mixing at later stages
- Presence of radiation field dramatically modifies the instability and growth-rate




## Radiation Gaussian Pulse

- Gaussian variation in radiation energy for constant background hydrodynamic parameters
- Test case to validate implementation of radiation diffusion solver
- Effect of different closure and limiter schemes on radiation and hydrodynamic quantities studied




## Future Work

- ❑ Multigroup method for modelling radiation transport
- ❑ IMEX time integration schemes are being implemented
- ❑ Integration of FleCSolve's time integrators and new preconditioners
- ❑ Optimization and performance testing on accelerators
- ❑ Characterize the growth rate of instabilities with and without radiation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