Ares: A Performance Portable Tool to Simulate Supernovae Based on the Parthenon Framework

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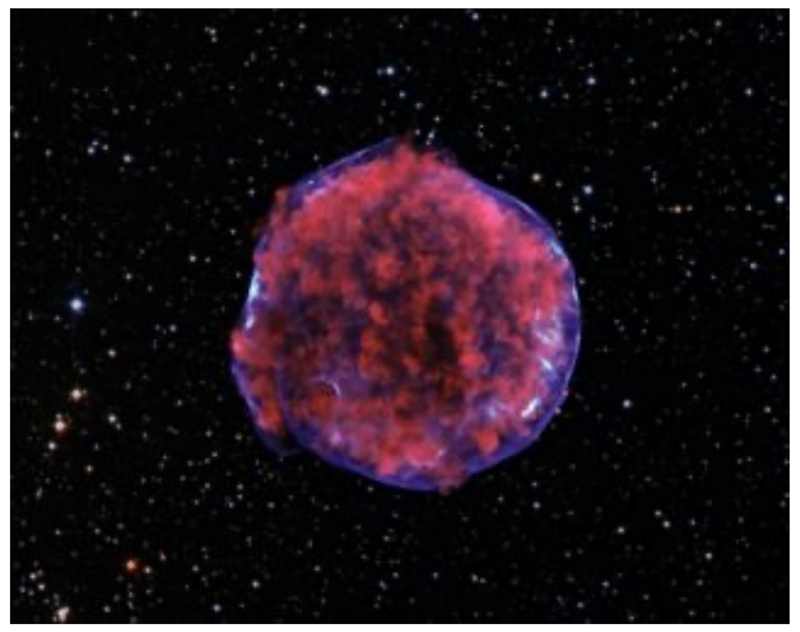
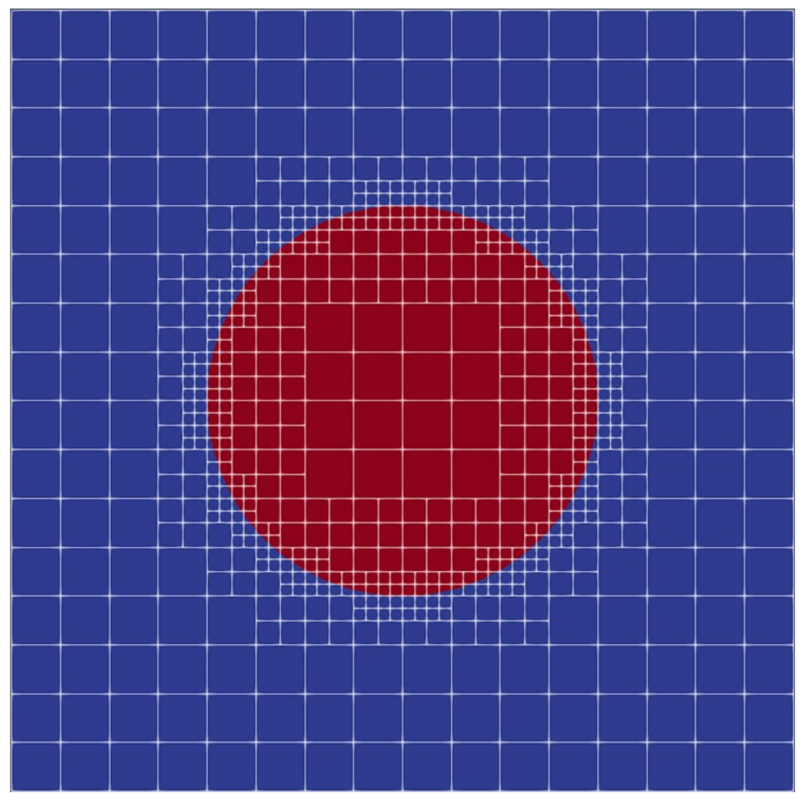
Type Ia Supernovae are highly energetic thermonuclear explosions of white dwarfs,

which serve as standardizable distance markers that are essential for investigating the accelerating expansion of our Universe. The explosion physics that trigger these events are ***inherently multi-scale***, ranging from the usual diameter of a white dwarf at about $4{\times}10^3$ to 10^4 km to the carbon flame thickness ~ 10^0 cm, which poses a huge challenge in performing hydrodynamical simulations of these systems. To resolve the physical mechanism at every scale possible, we employ state-of-the-art **adaptive mesh refinement (AMR)** techniques within our hydro solvers.



Tycho type Ia supernova remnant (SN 1572)
Credit: X-ray: NASA/CXC/Rutgers/K. Eriksen et al.; Optical: DSS



However, these AMR-enabled simulations require *immense computational resources*.

Most existing codes are only designed to run on homogeneous CPU-only systems and are at risk of losing their competitiveness as there is a general shift towards heterogenous HPC architectures. There exist several efforts to enable these codes for GPUs, however, they are vendor specific. Solutions for performance portability like **Kokkos** facilitate these developments.

Inspired by this problem, we create the **first performance portable multi-physics massively-parallel hydrodynamics code Ares** based on the Parthenon AMR framework, which enables us to reach resolved scales that are out of reach for current state-of-the-art codes.

Multi-physics capabilities of Ares

Ares is built on the **Parthenon** framework for adaptive mesh refinement on distributed HPC clusters. We extend this framework by adding solvers for gravity, thermonuclear burning, and equation of state (EOS) necessary to simulate type Ia explosions.

Nuclear Network

To simulate the energy released through nuclear burning process, we solve the equations of **nuclear statistical equilibrium** (NSE) for the mass fractions of nuclides.

Self-Gravity

To implement self-gravity in our simulations, we built a **monopole gravity solver**, creating a 1D gravity profile based on a shell-averaged density profile.

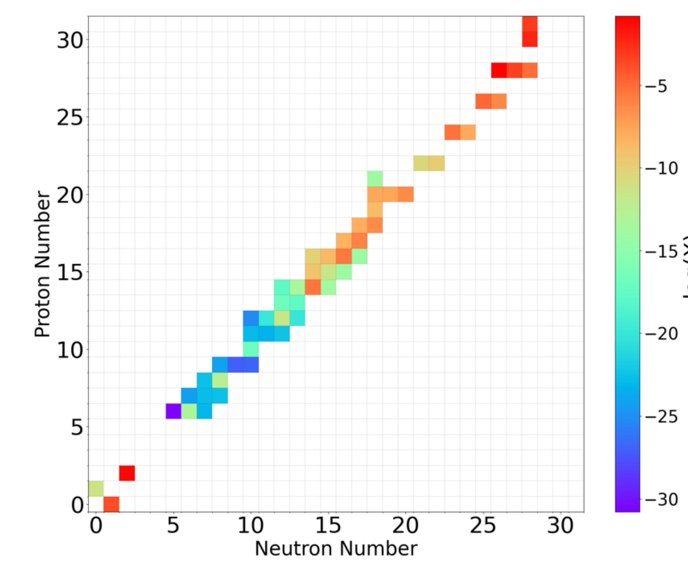
Equation of State

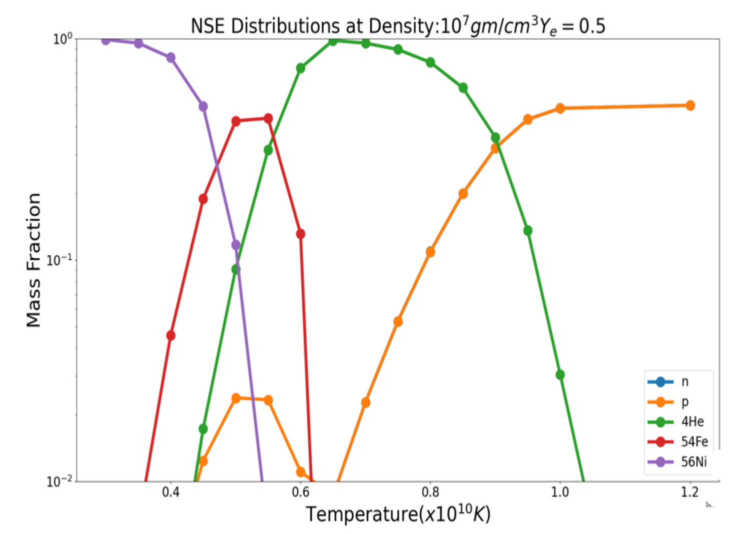
For the equation of state, we incorporated our extension of the existing **Singularity-EOS to include Helmholtz EOS** to support conditions in the degenerate gas interior of white dwarfs.

Initial Conditions

We simulate a 50/50 C/O composition 1.378 $M_\odot$ white dwarf with an isothermal profile of temperature $5{\times}10^5$ K and a central density of 5.4×10^7 g/cm³ , against an ambient density of 10^{-3} g/cm³ in a $(2{\times}10^4\ \text{km})^3$ physical domain. We use a 128^3 grid and apply AMR refining on second order derivatives of density, with up to 7 AMR refinement levels.

Nuclear Isotopic Abundances at NSE

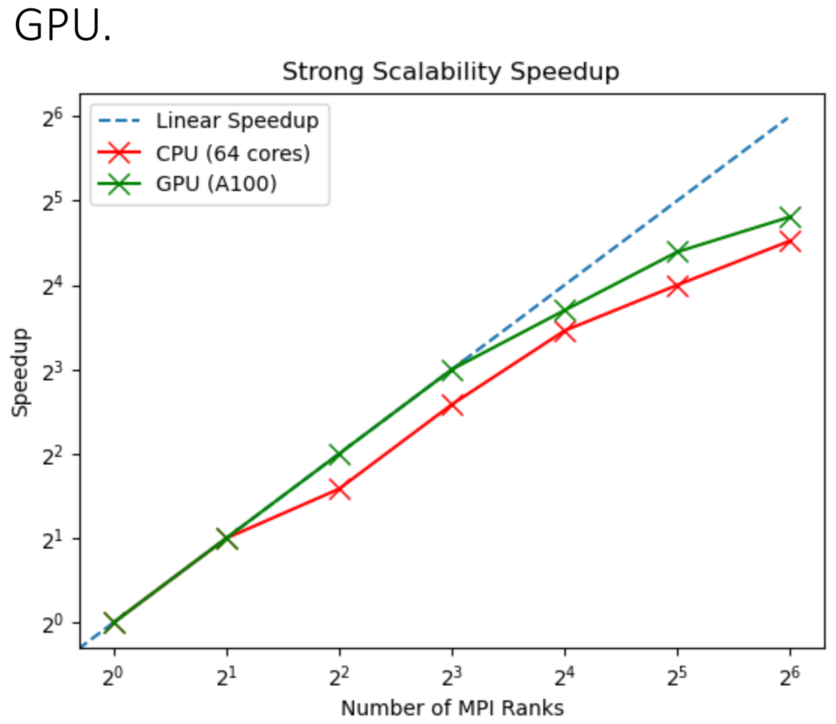




Nuclear statistical equilibrium (NSE) is the unique nuclear composition of a system when strong interactions are in equilibrium for a given set of thermodynamic state variables and electron fraction. We solve the NSE equations for the mass fractions of 55 nuclides, including the effects of temperature dependent nuclear partition functions. The energy in each step is calculated from the difference in composition between consecutive steps.

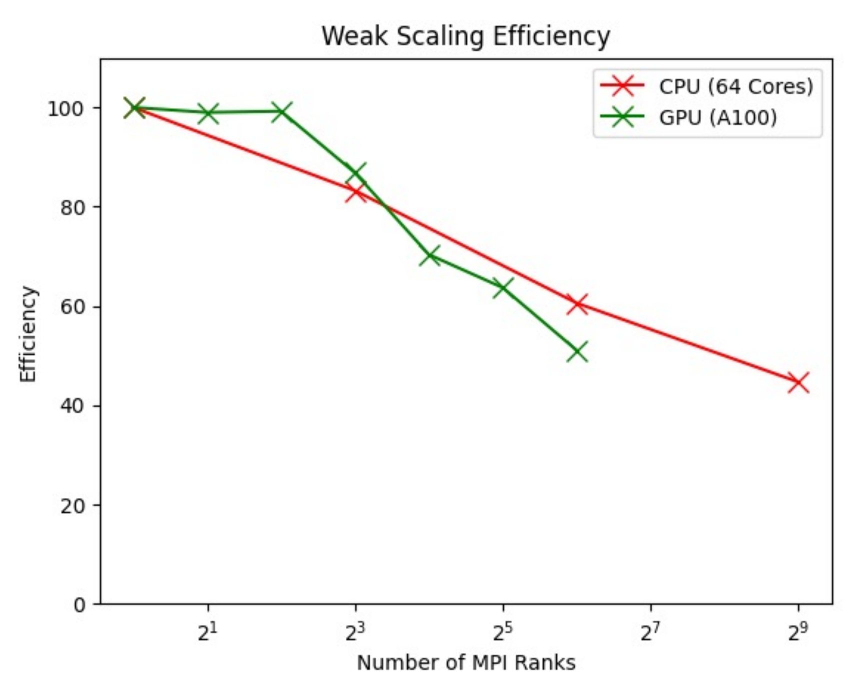
Scaling Study

We conducted scaling studies by evaluating Ares on a toy ideal gas sphere problem for 1000 cycles on Chicoma. We varied MPI ranks from 1 to 64, with each rank using either 64 OpenMP-enabled CPU cores or 1 GPU.

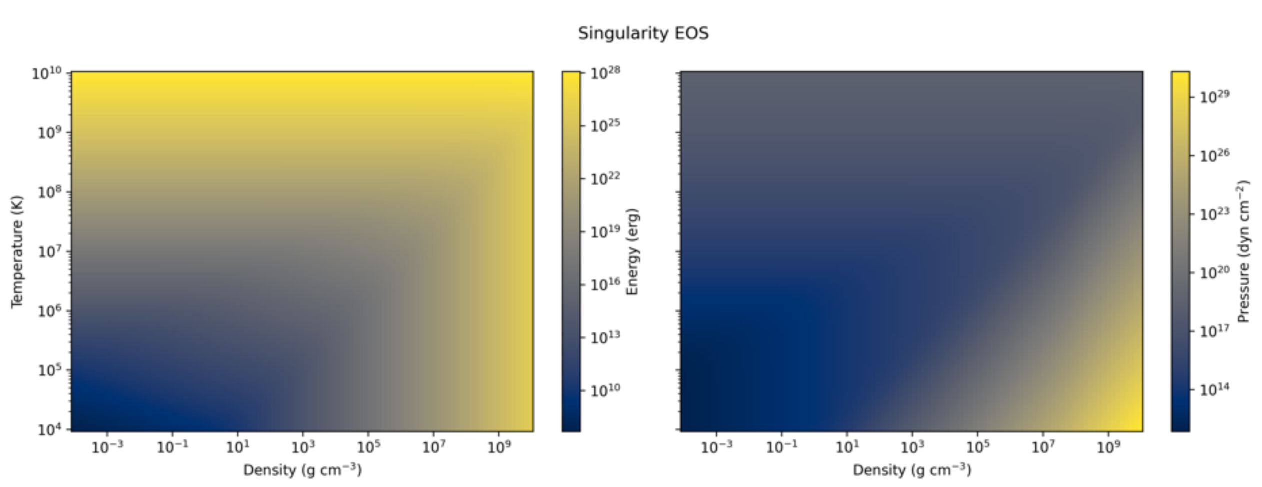


With adaptive mesh refinement enabled, strong scaling shows perfect speedup up to 8 GPUs, and near-linear scaling for both CPU and GPU ranks. **On average, ranks with one GPU were 34% faster than ranks with 64 CPU cores.**

Our largest run shows that Ares can scale to a mesh size of at least 1024³ using 512 CPU ranks. The weak scaling plot outlines the loss of efficiency due to global communications with a 55% loss in efficiency at the largest scale.

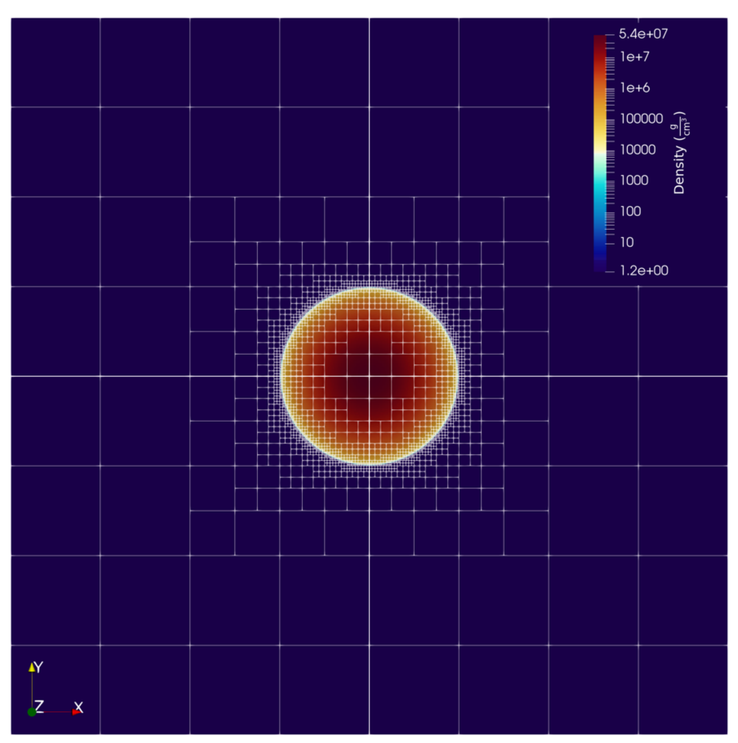


Helmholtz Equation of State

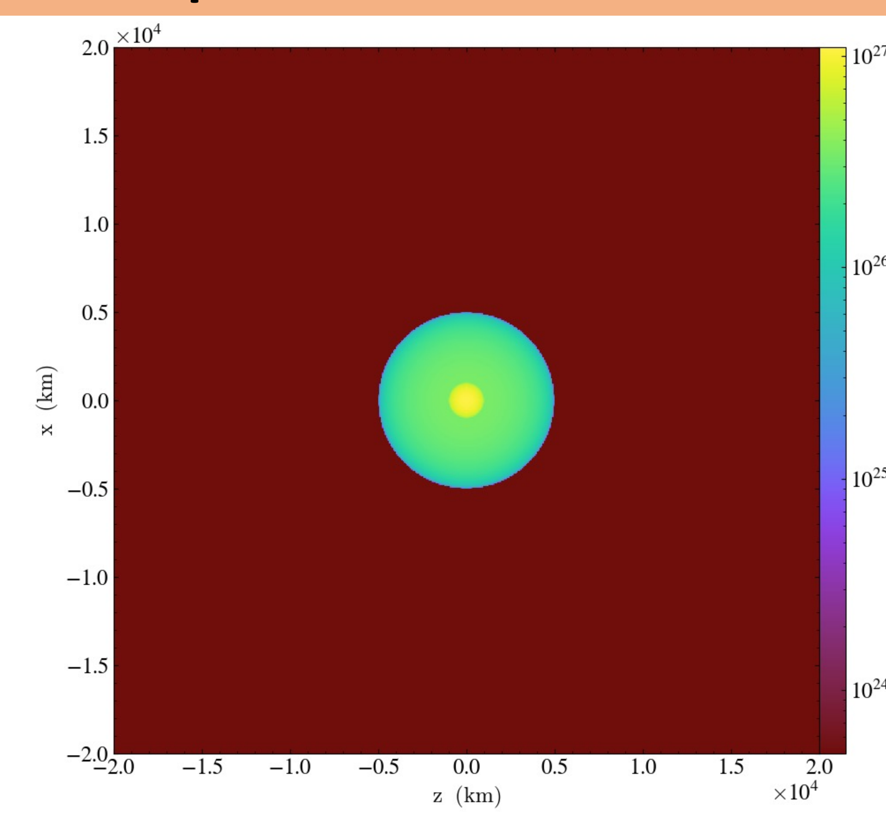


The internal energy and pressure calculated using the Helmholtz equation of state for an equal-mass fraction mixture of C-12 and O-16 in temperatures and densities relevant for degenerate stellar interiors.

Simulation Snapshot



AMR grid at initialization plot produced with Paraview 5.10.1



White dwarf with an ignition hotspot of temperature set at 7 x 10⁹ K plot produced with Python package yt.

Milestones

- Implemented a multi-physics hydrodynamics code using the Parthenon framework
- Added a monopole solver for self-gravity
- Integrated a general nuclear network with 55 species for nuclear burning at nuclear statistical equilibrium
- Incorporated a tabulated Helmholtz EOS to the existing Singularity EOS module to enable support for degenerate stellar interiors
- Utilized Kokkos for performance portability
- Simulated a sub-Chandrasekhar mass white dwarf with an initial ignition hotspot triggered at the center of the star which propagates outward and disrupts the star
- Code dependencies: C++ 17, MPI 4.1.5, HDF5 1.15.0, GCC 12.2.0

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