Stony Brook Nuclear Astrophysics

Progress toward realistic type Ia supernova models

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Improvements to Flame Model

- Energetics of flame and post-flame evolution (Calder et al., Townsley et al.)
- Noise/stability of model flame (Townsley et al.).
- (Removal of) effect of curvature due to thickened ADR flame (Asida et al.)
- Ongoing verification of the turbulent sub-grid model (Zhang et al.)
- Migration from Flash2 to Flash3
  - Migration to non-permanent guard cell mode of PARAMESH3 (memory saving)
  - Switch to Ye, Q formalism (memory saving)
  - Streamlining/improving of self-gravity module (in progress)

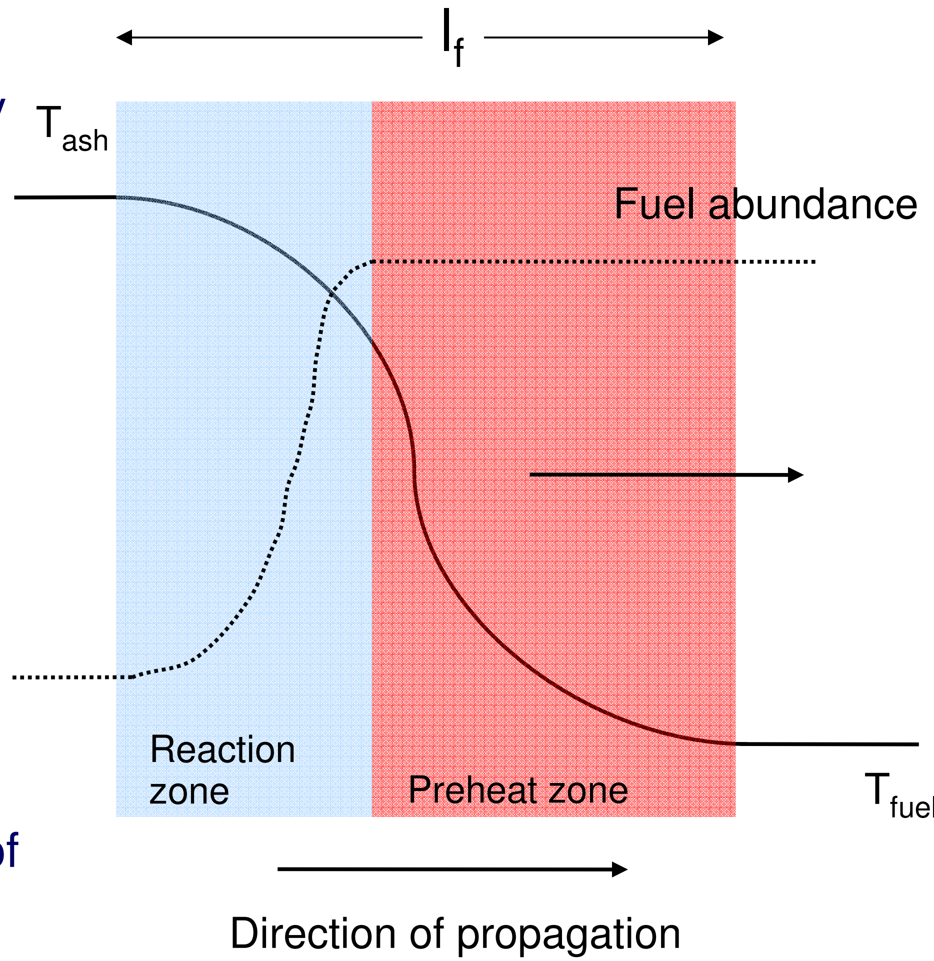
Astrophysical Flames

A burning front may propagate supersonically (detonation) or subsonically (deflagration/flame).

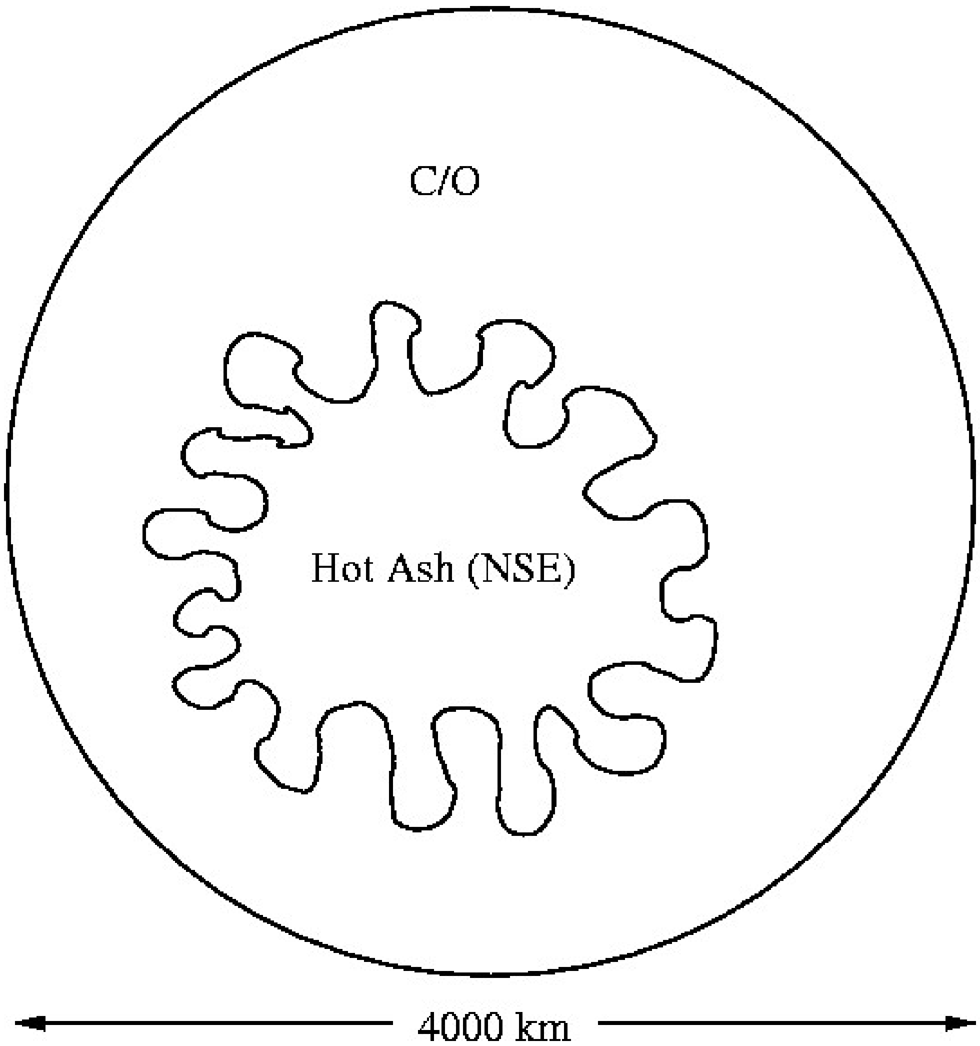
An astrophysical flame propagates via the conduction (transport) of heat that pre-heats the fuel, initiating the reactions.

The schematic shows a simple, one-reaction case of a deflagration.

Somewhat aside: Most contemporary Ia models incorporate a transition from a deflagration to a detonation. The physics of such a transition is under active study.



Fluid Instability in a Type Ia Supernova

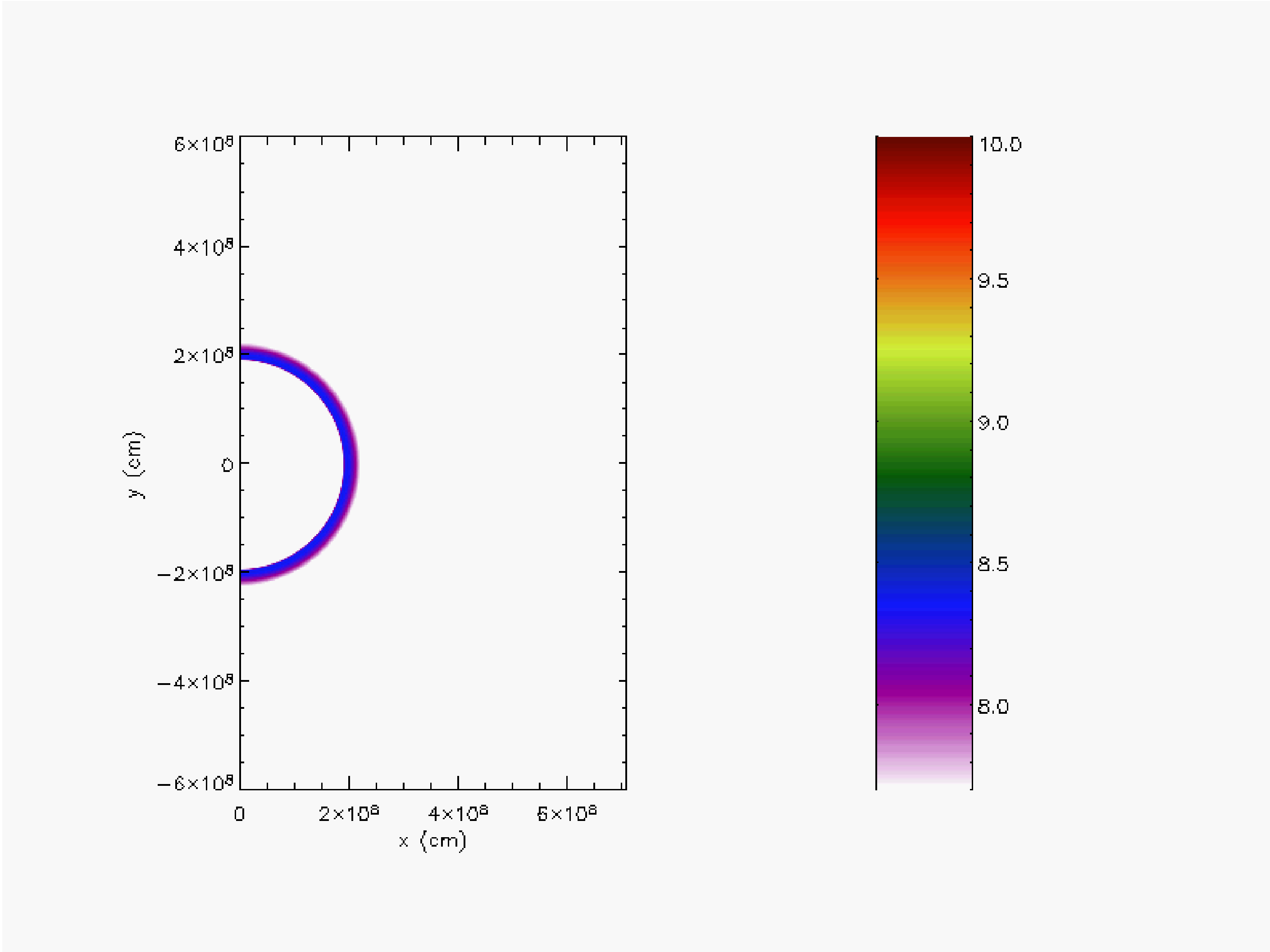


Note: Even with AMR, the disparate scales of Ia necessitate use of a model flame and a sub-grid-scale model for turbulent combustion.

Use an Advection Diffusion Reaction (ADR) scheme to propagate a thickened flame.

Subgrid model should capture effects of RTI on unresolved scales.

One senario: Gravitationally Confined Detonation



- Run on IBM BG/L at Watson

Flame Model Implemented in Flash

- “Thick flame” based on an advection-reaction-diffusion equation model (Khokhlov 1995) Δ = 4 zones
  - Flame speed is input parameter to the model
  - Input flame speed is the maximum of the laminar or the turbulent model speed, $S = \max(S_{lam}, S_{sub})$
  - S_{lam} from Timmes and Woosley (1992)
  - S_{sub} from Khokhlov (1995)
- Two principal parts to the problem:
  - Flame model
    - ADR scheme for thick flame including energy release in stages
    - Evolution of the NSE ash.
  - Sub-grid-scale model for turbulent combustion

Evolution Equations

Euler:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \nabla P = \rho \mathbf{g}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + P)\, \mathbf{v} \ = \ \rho \mathbf{v} \cdot \mathbf{g} + S$$

$$P = P\,(\rho, E)$$

Gravity:

$$\mathbf{g} = -\nabla \Phi, \quad \text{where} \ \ \nabla^2 \Phi\,(\mathbf{r}) = 4\pi G \rho\,(\mathbf{r})$$

Advection of scalars:

$$\frac{\partial X \rho}{\partial t} + \nabla \cdot (X \rho \mathbf{v}) = 0$$

Evolution Equations

ADR:

$$\frac{\partial \phi}{\partial t} + \mathbf{v} \cdot \nabla \phi = \kappa \nabla^2 \phi + \frac{1}{\tau} R\left(\phi\right)$$

κ and τ set to produce the input flame speed.

Reactions:

$$R(\phi) = \begin{cases} R_0 = \text{const.}, & \text{if} \quad \phi_0 \leq \phi \leq 1 \\ 0, \text{otherwise} \end{cases} \qquad \text{top hat}$$

$$R\left(\phi\right) = \tfrac{1}{4}\phi\left(1-\phi\right) \qquad \text{KPP}$$

$$R\left(\phi\right) = \tfrac{f}{4}\left(\phi-\epsilon_1\right)\left(1-\phi+\epsilon_2\right) \qquad \text{sKPP}$$

where $0 < \epsilon_1, \epsilon_2 < 1$ and $f = f\left(\epsilon_1, \epsilon_2\right)$

Energetics Procedure

- Perform self-heating (one-zone) network calculations with contemporary reaction rates (including weak reactions) and Coulomb effects.
  - Energy release
  - Time scales for stages of burning
  - Compare to DNS flames where possible for verification.
- Track long-term evolution of NSE (binding energy and neutronization) with NSE code consistent with network calculations.
- Incorporate both into multi-stage flame model and dynamic NSE ash.
- Test, test, and test some more.
  - ADR scheme (verify and quantify noise and curvature effects)
  - Non-energetics test: Verify subgrid turbulence model

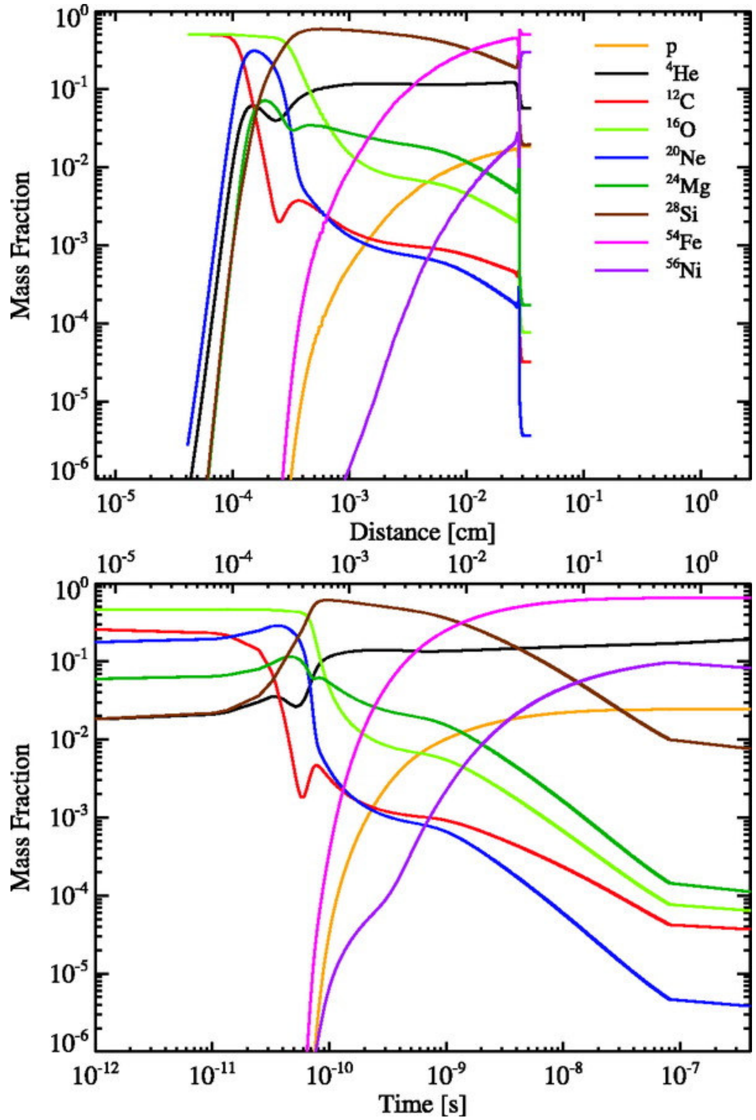
Nuclear Flames

DNS

C/O Fuel

Self-heating

C/O Fuel



ρ = 10^9 g/cm^3

Ash (→ NSE)

Both with aprox19 network

Ash (→ NSE)

← Flame propagation

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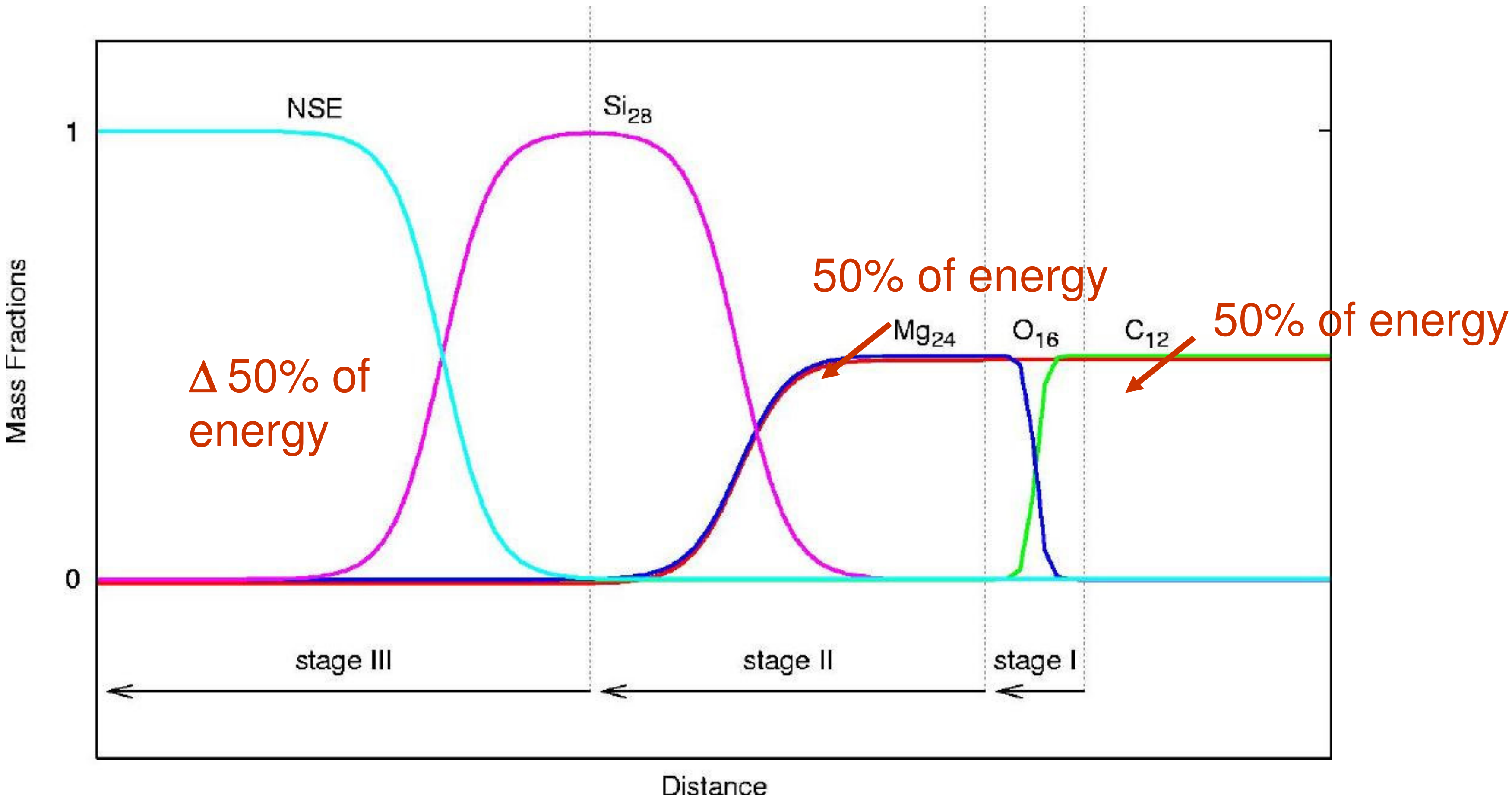
Three-Stage Flame Model

- Energy released in flame and ash are both important



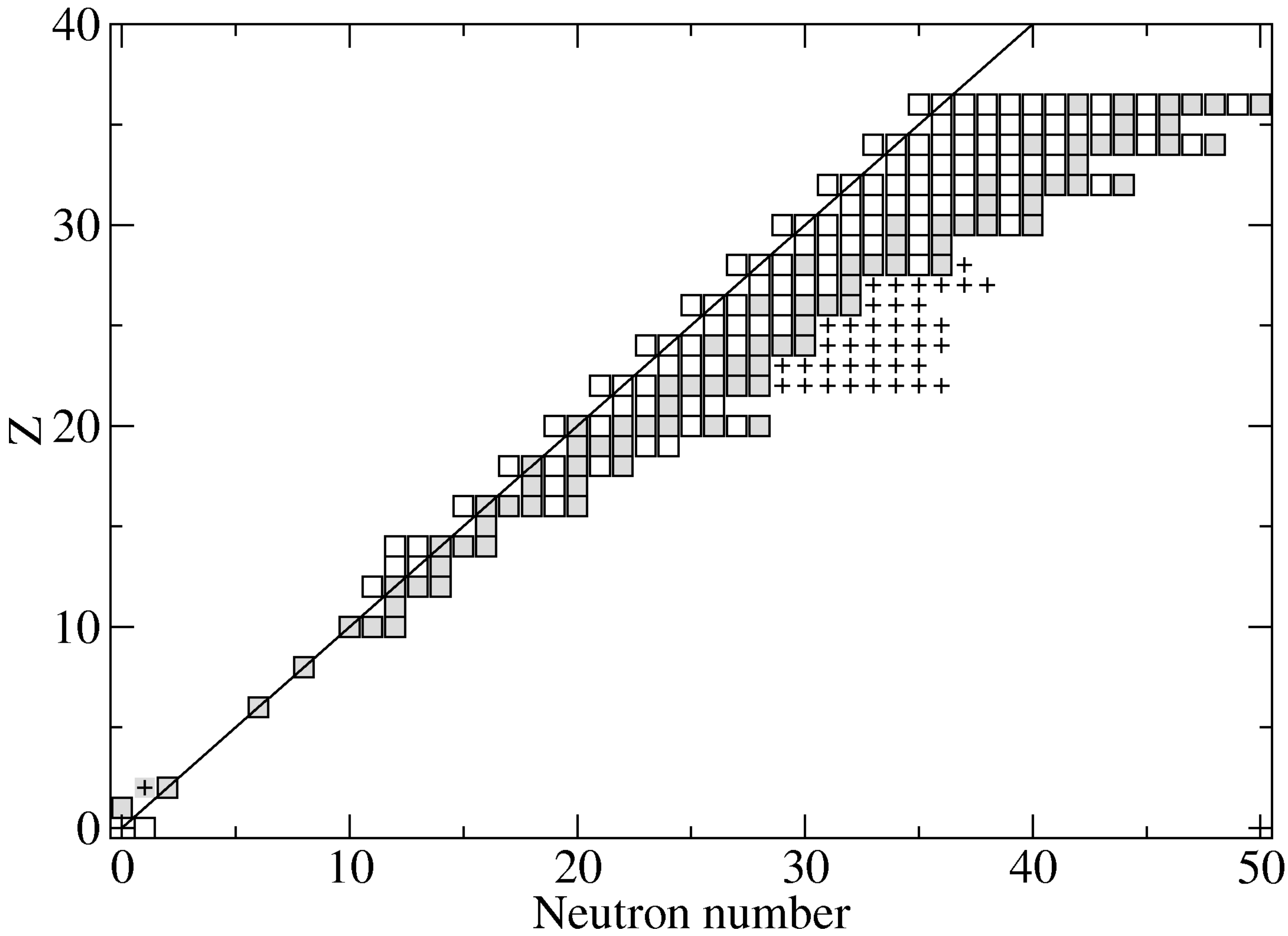
Flame propagation →

NSE and Self-Heating Calculations

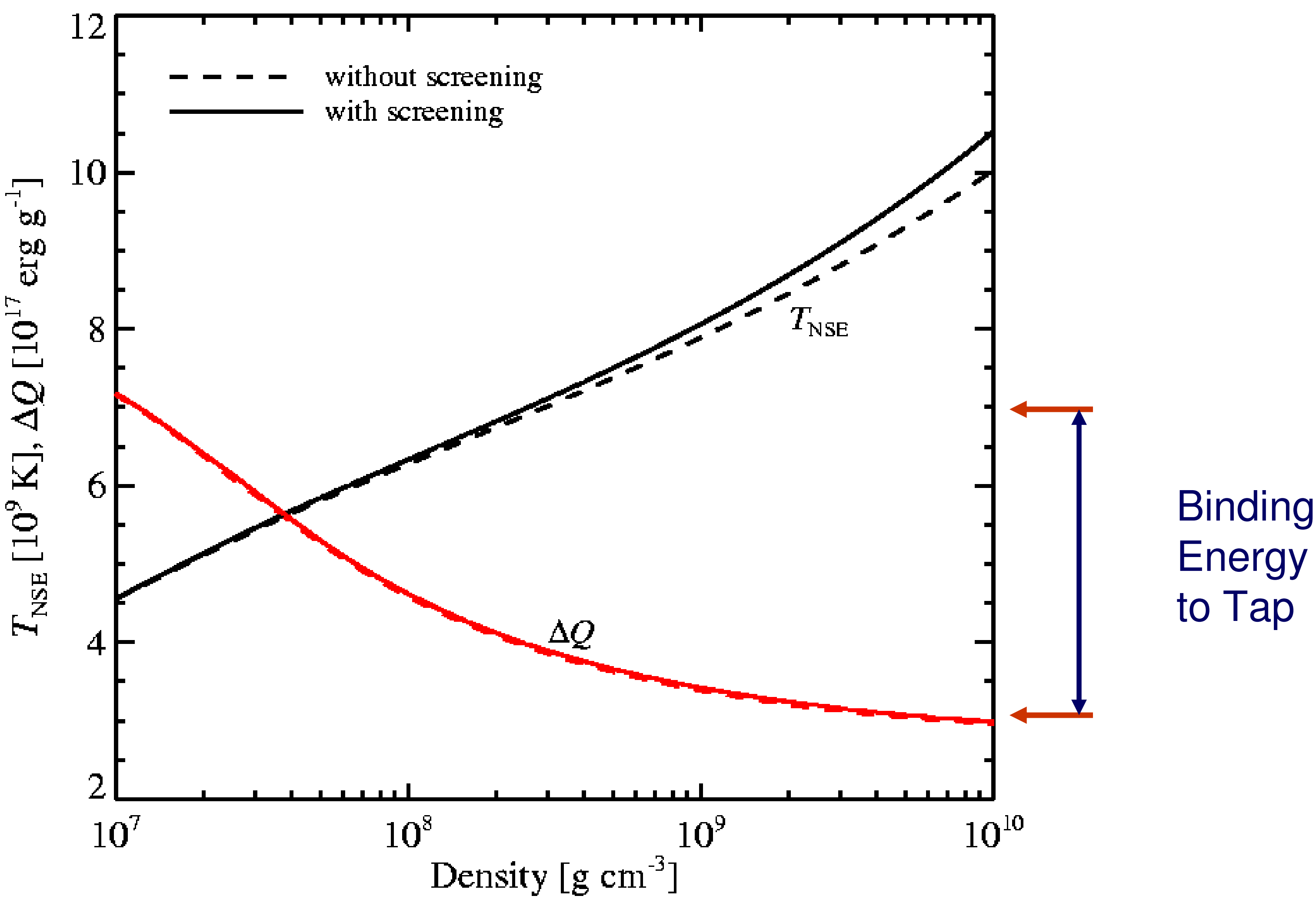
- Nuclear Statistical Equilibrium code:
  - Solves NSE equations for 238 nuclides
  - Recent work has more (443)
  - Includes excited states (Rauscher et al. 1997)
  - Includes Coulomb corrections to Helmholtz free energy
  - Calculates energy, ν loss rates, and neutronization rates

- Self-heating network code: Isochoric (constant volume) and isobaric (constant pressure) burning
  - 200 nuclide network
  - Temperature dependent nuclear partition functions from Rauscher and Thielemann (2000)
  - Reverse rates derived for first time self-consistently from forward rates with Coulomb effects included
  - Include electron screening (Wallace et al.1982)
  - Isobaric and isochoric results

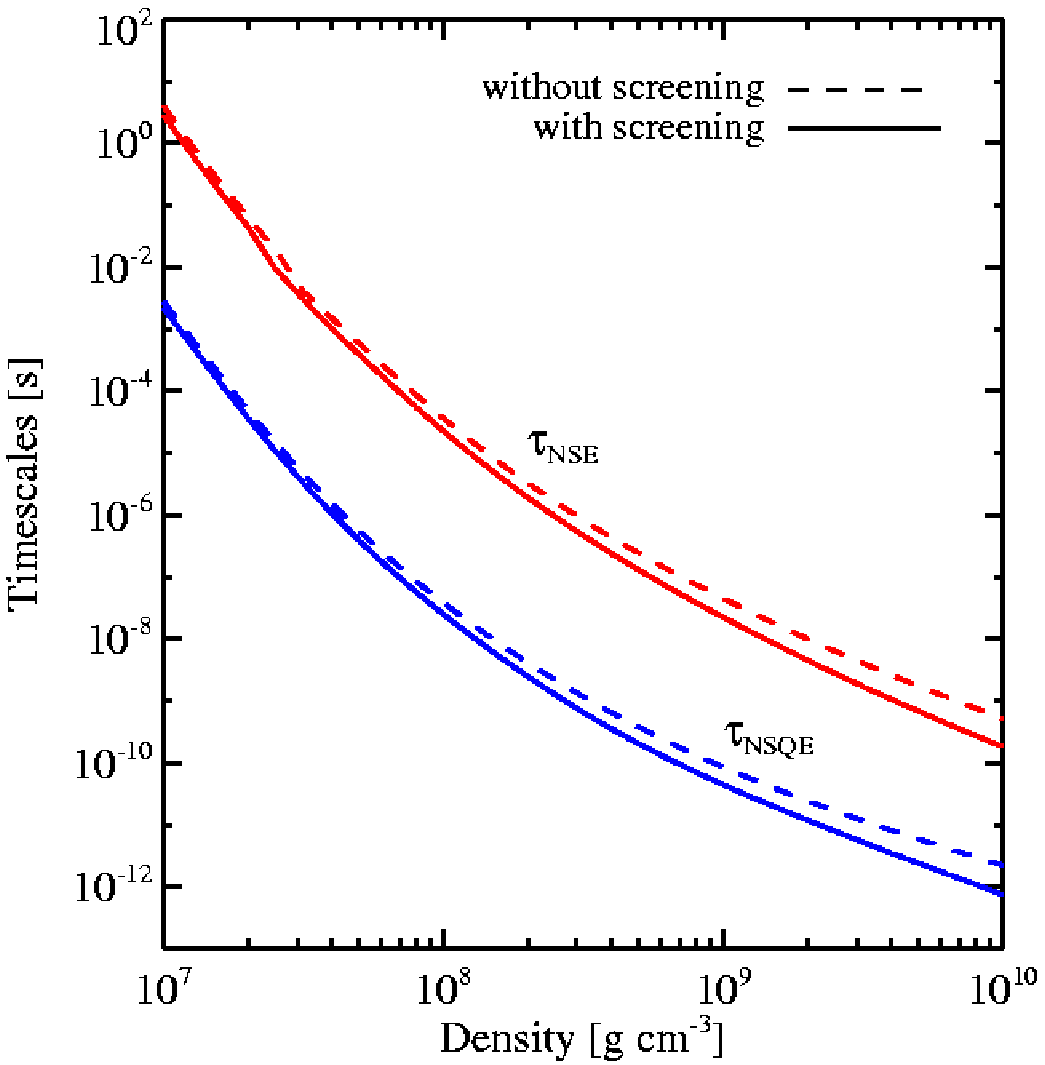
Nuclides involved



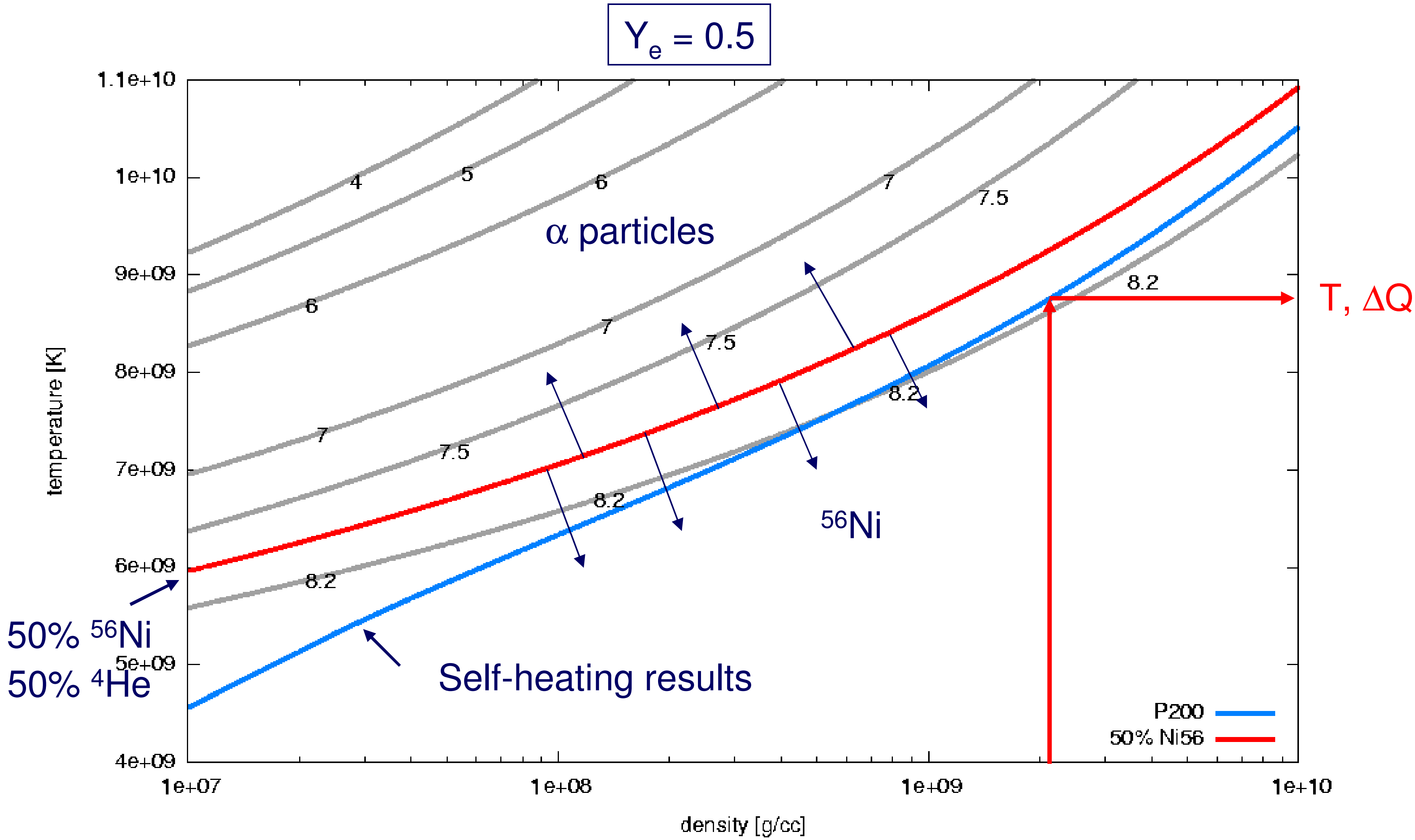
Self-Heating Network Study



Self-Heating Network Study

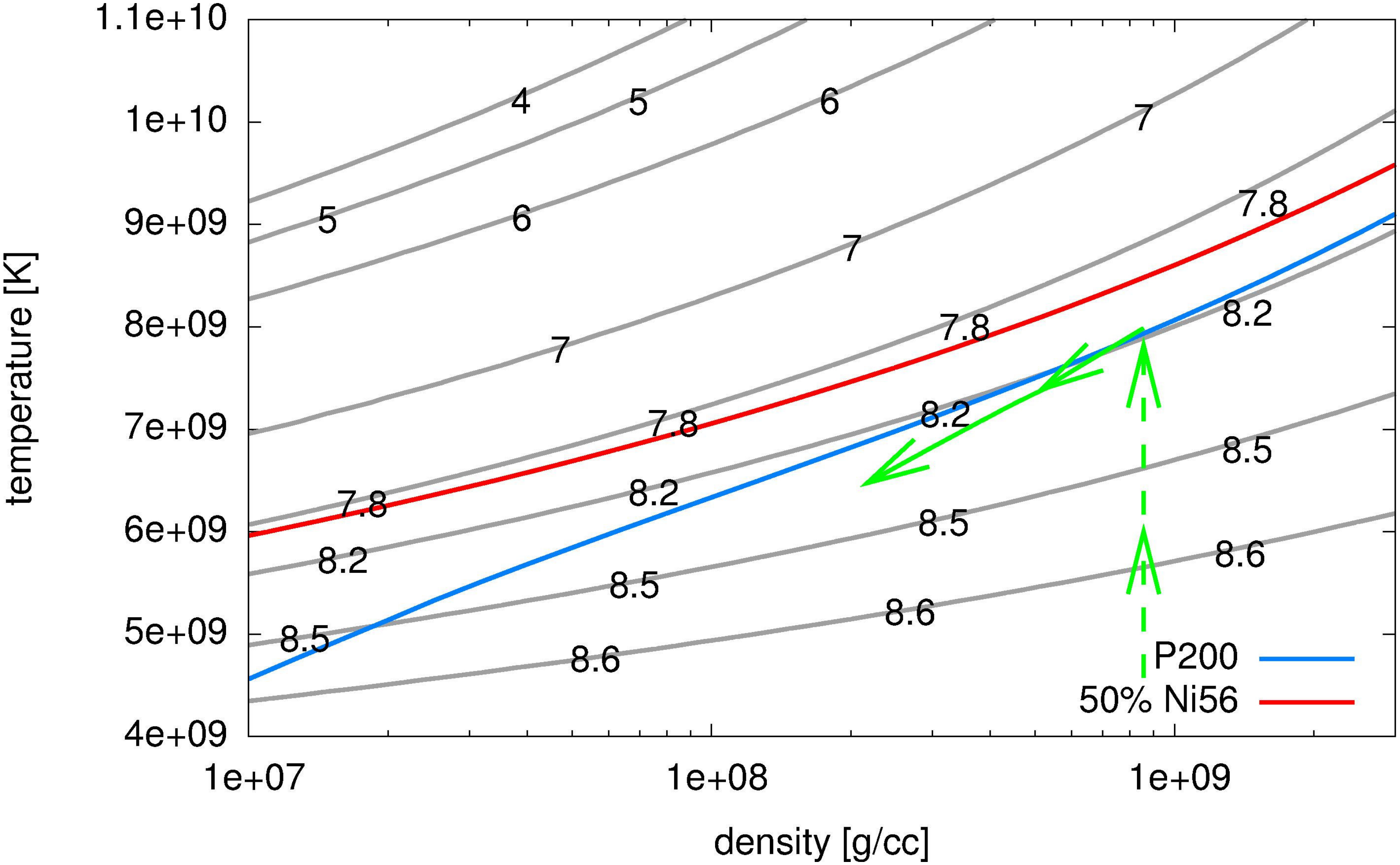


Average Binding Energy per Nucleon



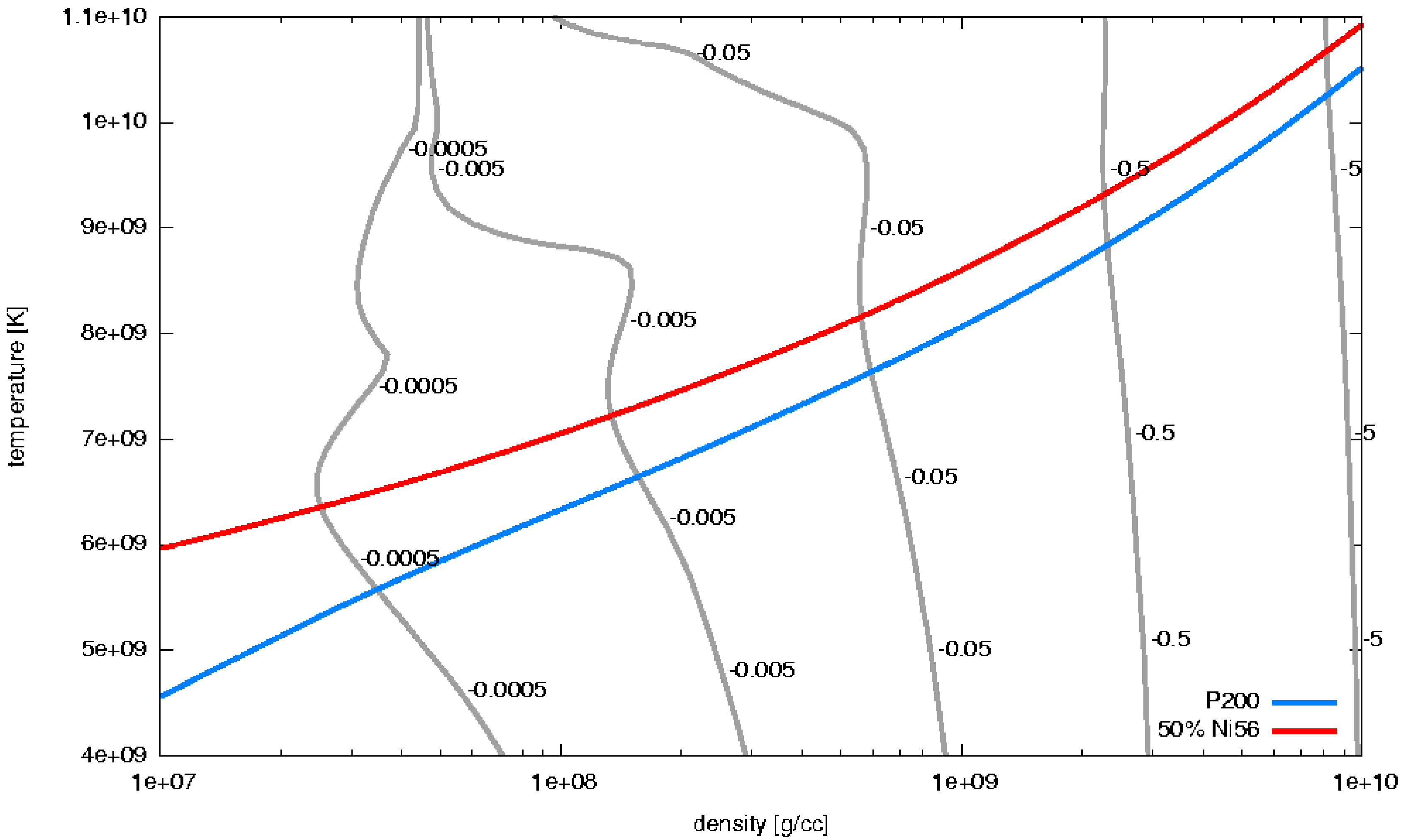
Post Flame Energy Release

$Y_e = 0.5$

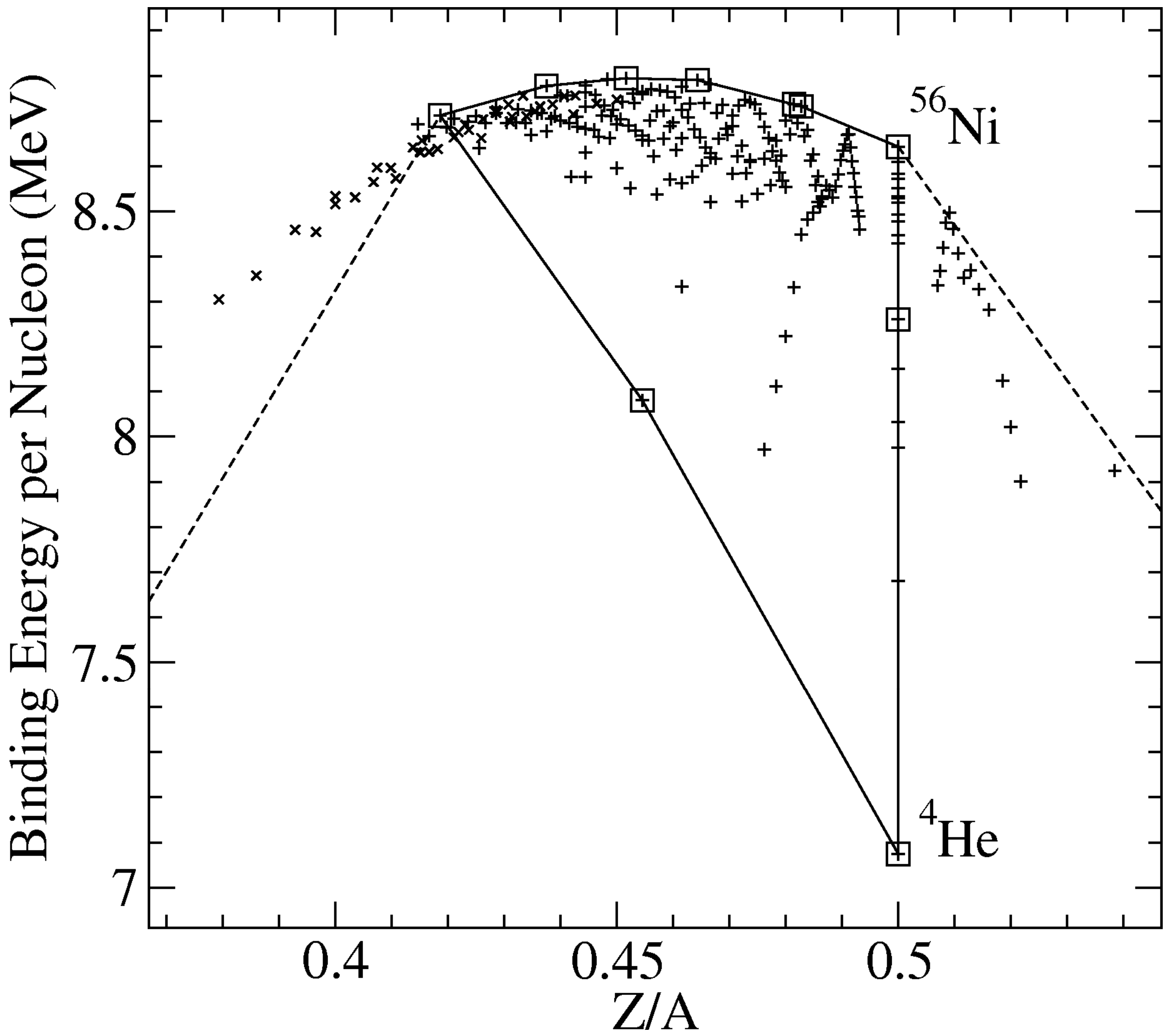


Neutronization Rates

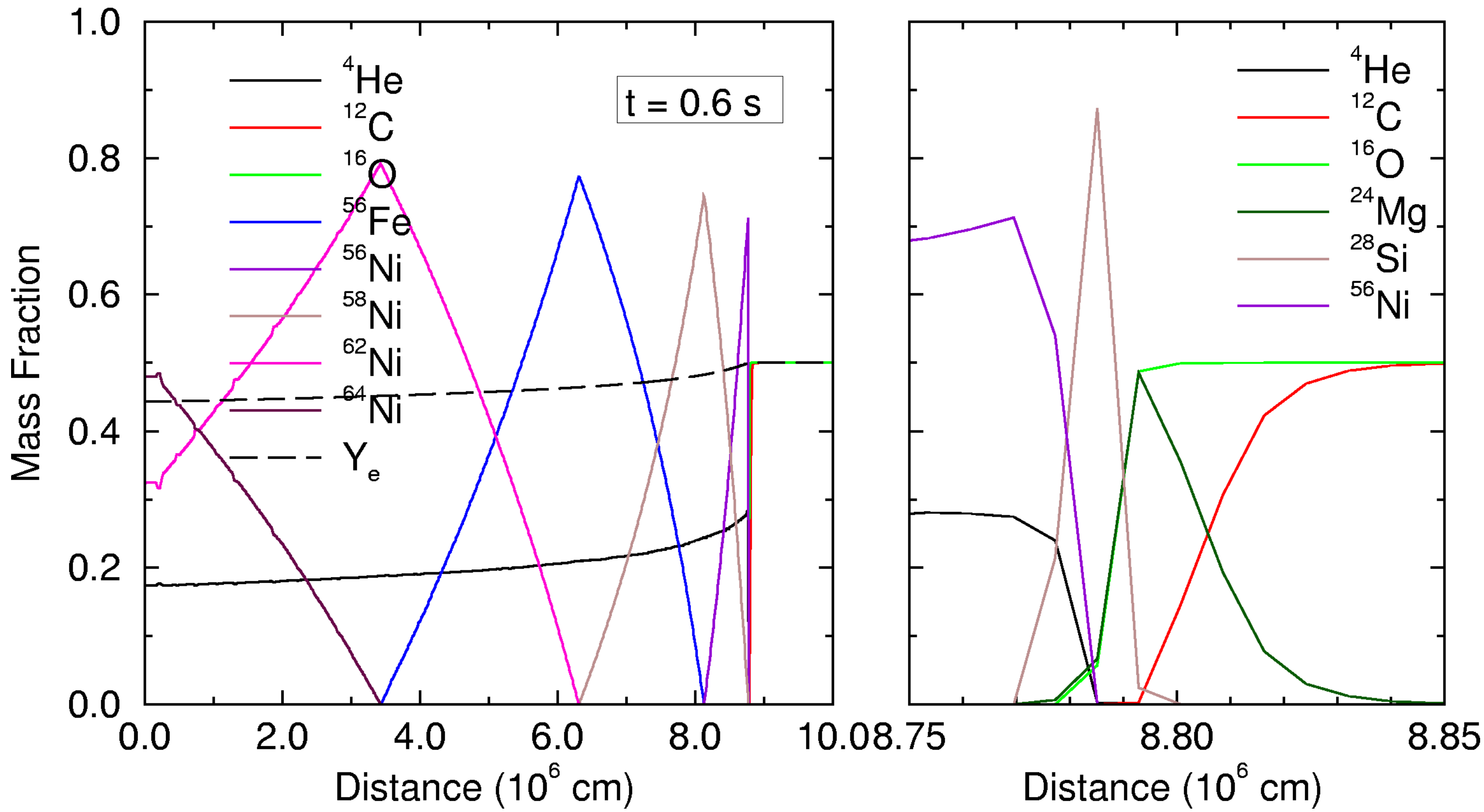
$Y_e = 0.5$



Surrogate Nuclei



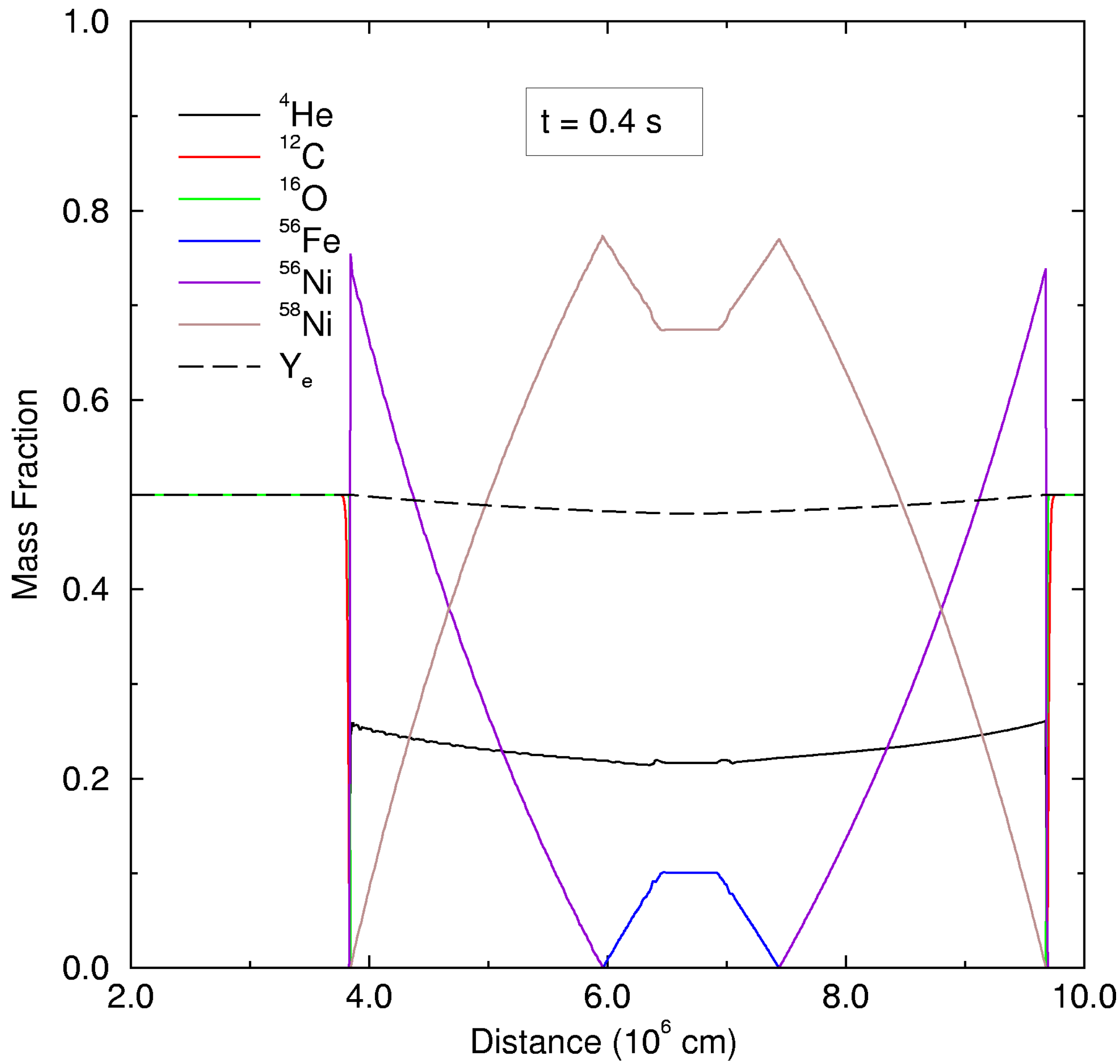
Three-Stage Flame Model



Flame propagation →

$\rho = 3 \times 10^9$ g/cm^3

Verification Test



$\rho = 10^9$ g/cm^3

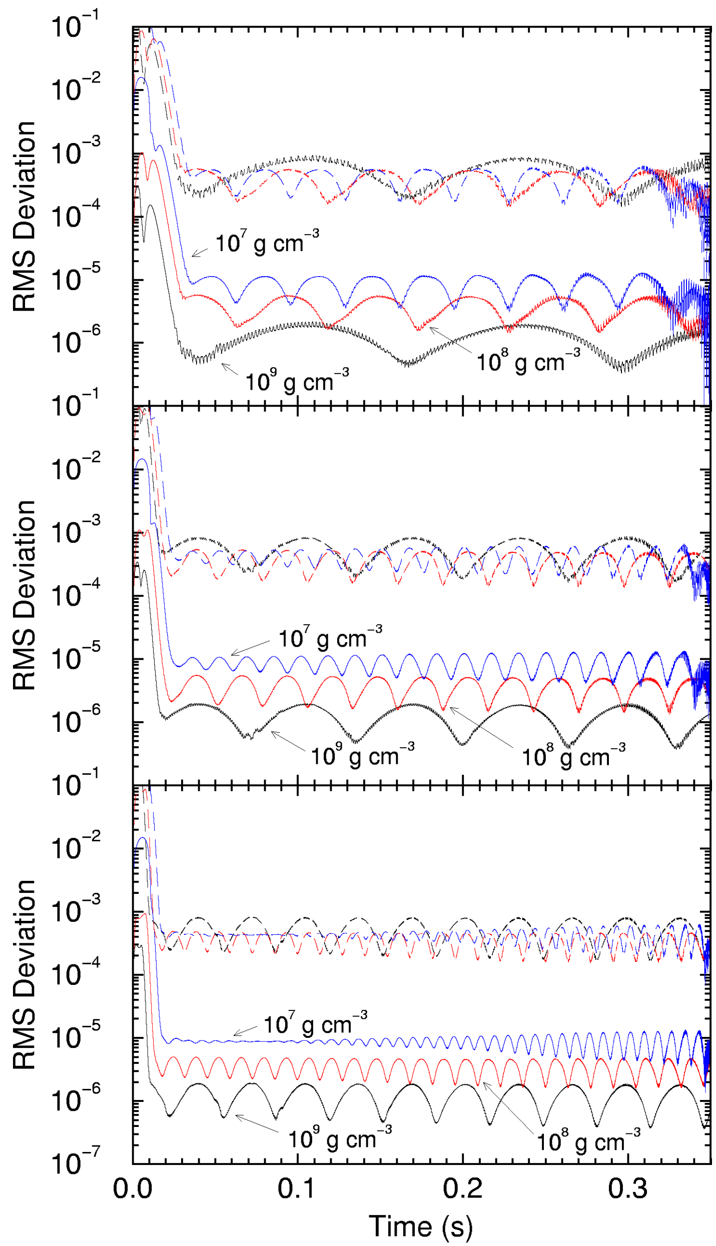
Noise quantification

s = 6 X 10⁶ cm/s

256 zones

512 zones

1024 zones



← velocity results

← pressure results

$$\mathrm{dev_{RMS}}(x) = \sqrt{\langle x^2 \rangle - \langle x \rangle^2}$$

…and that leads us to

QUESTIONS AND DISCUSSION

Bibliography

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