Accretion-induced Thermonuclear Incineration of White Dwarf Stars

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Outline

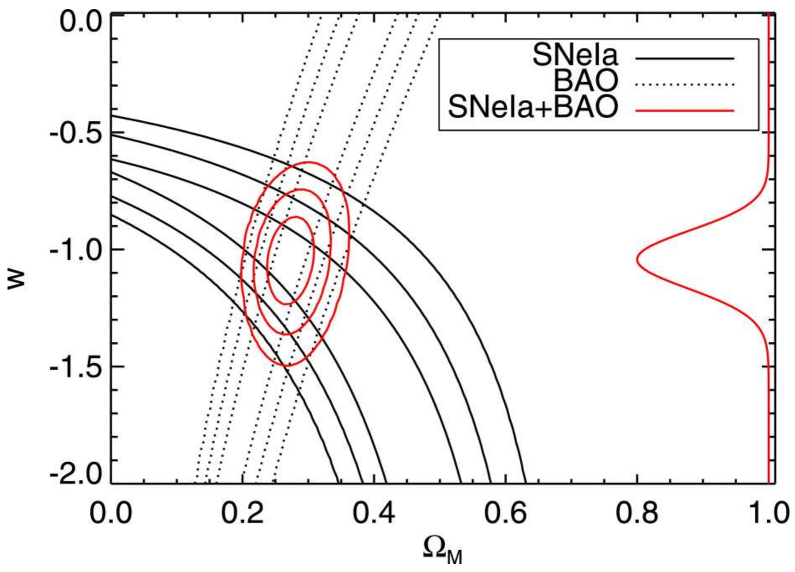
- Compact binaries and the origins of thermonuclear supernovae
  - How accreting white dwarf binaries are created and evolve, uncertainties
  - Comparing scenarios which lead to collapse and those which lead to supernova
- Centrally ignited supernovae
  - central runaway and formation of convective core
  - nuclear flames
  - deflagration-detonation transition
- The numerically efficient EOS that we use for hydrodynamics
- Coulomb EOS corrections, Charge screening of nuclear reactions and the Nuclear statistical equilibrium state.
- The impact of NSE adjustment on the thermodynamic and hydrodynamic properties of buoyant material.
- Importance of buoyancy in supernovae
  - dynamics of bubbles of burned material
  - contrast of supernova mechanisms
  - variation in total burning products from flame ignition conditions

EOS of the Universe

Universe consists of 4 major components

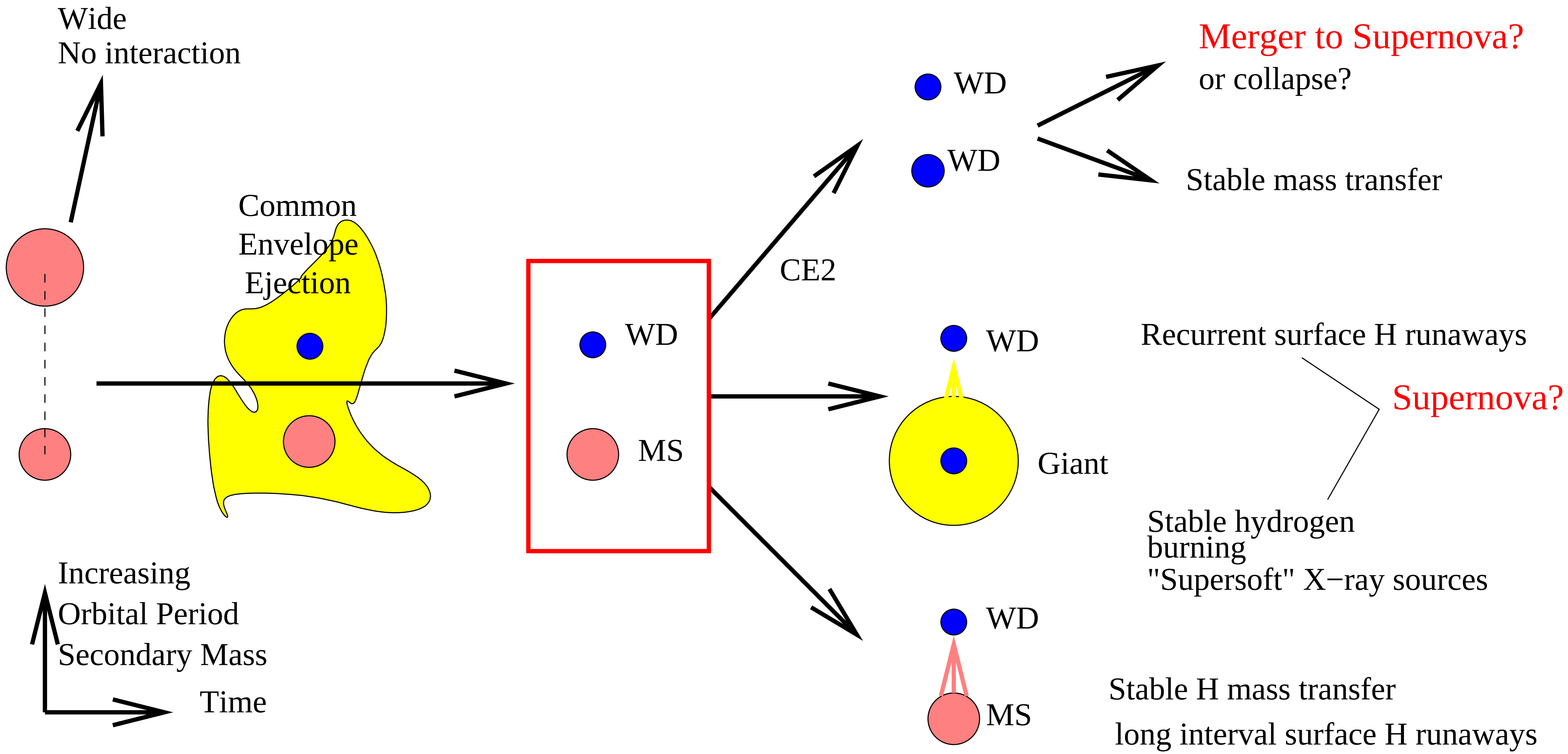
- Radiation (currently negligible fraction of mass-energy) $\rho \propto a^{-4}$
- Matter ($\Omega_{\rm M} \approx 0.27$)
  - Normal ($\Omega_b \approx 0.05$) $\rho \propto a^{-3}$
  - Dark, non-baryonic
- Dark Energy ($\Omega_\Lambda \approx 0.73$) $\rho \propto a^{3(1+w)}$

Their contribution to the mass-energy density ρ determines the evolution of the scale factor a, which measures the relative expansion of the universe ($a = 1$ now).



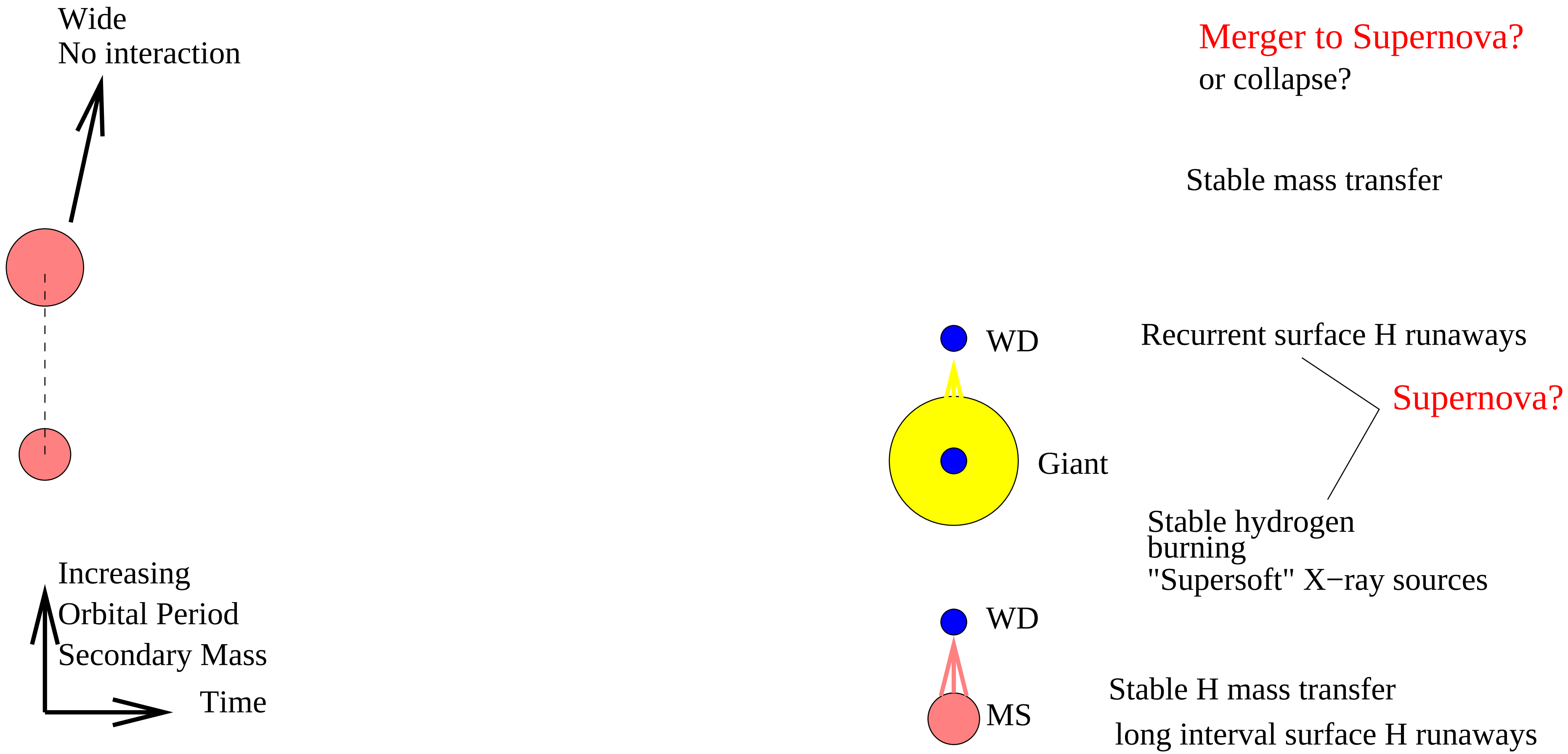
Wood-Vasey et al. 2007, ApJ, 666, 694

Binary Evolution



Post Common Envelope Binaries

Binary Evolution



Progenitor Summary

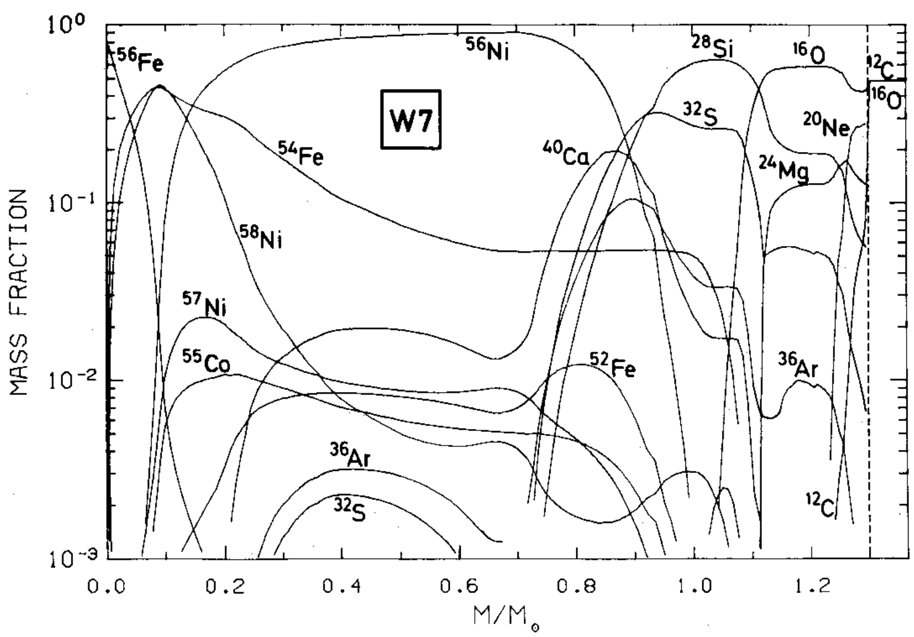
Possible scenarios

- Collapse
  - Double WD merger – Carbon burning initiated near surface releases thermonuclear energy without unbinding the star
  - Centrally ignited ONe WD – electron captures strong enough during deflagration to cause collapse
- Supernova
  - Helium surface detonation igniting carbon detonation – Sub-Chandrasekhar
  - Centrally ignited deflagration near Chandrasekhar mass

Centrally ignited deflagration currently most favorable model from astronomical standpoint. Total masses for observed SNe Ia are all very close to M_{Ch}.

The Origin of Thermonuclear Supernovae

White Dwarf Star near its maximum mass. Provides mechanism for approximate homogeneity of population. Maximum mass due to fusion or electron capture thresholds of constituent nuclei.

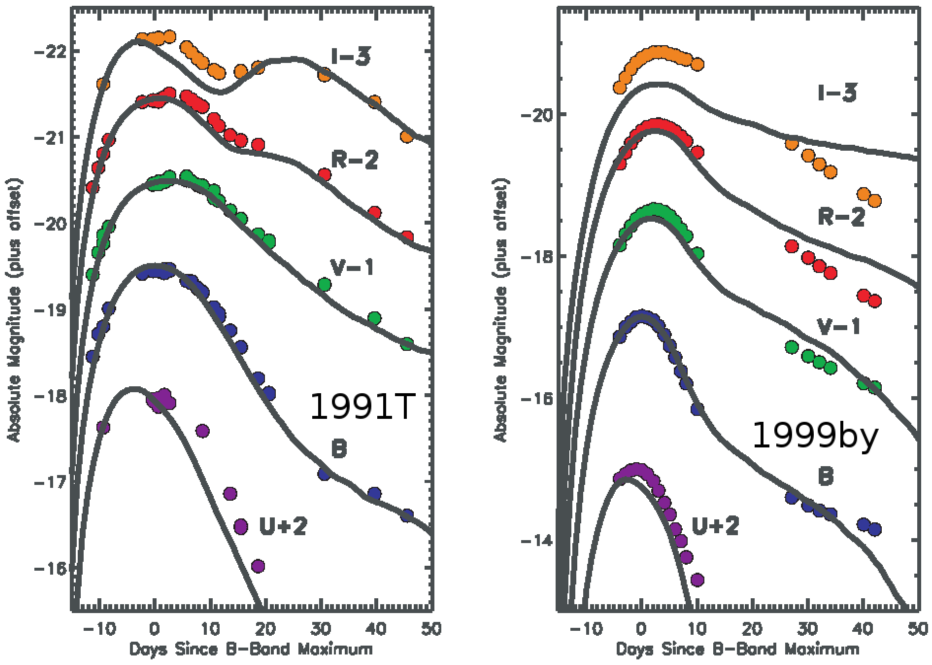


- Observed light due to decay of radioactive Nickel 56 produced in explosive burning.
- Approximately 0.5-0.7 $M_\odot$ produced and ejected in the explosion.
- Arises naturally from thermonuclear incineration of a degenerate dwarf.
- Elements produced in a parameterized burning of a WD match those observed spectroscopically.

Nomoto et al. 1984, ApJ, 286, 644

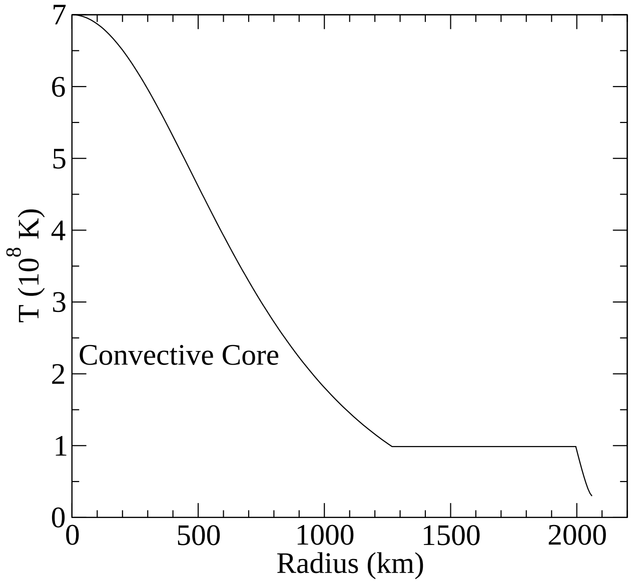
Supernova Explosions

- Intrinsically very bright due to large amount of ^{56}Ni ejected
- Well-characterized empirical relation between brightness and duration
- Progenitor Problem
  - Two leading sources: WD-MS binaries or WD-WD binaries
  - Unclear that either can produce enough WDs near Chandrasekhar mass
- Successful central ignition models
  - Deflagration followed by detonation
  - Mechanism and timing of detonation still uncertain
  - Four general models: full deflagration, deflagration-detonation transition (DDT), pulsational detonation, gravitationally confined detonation (GCD)

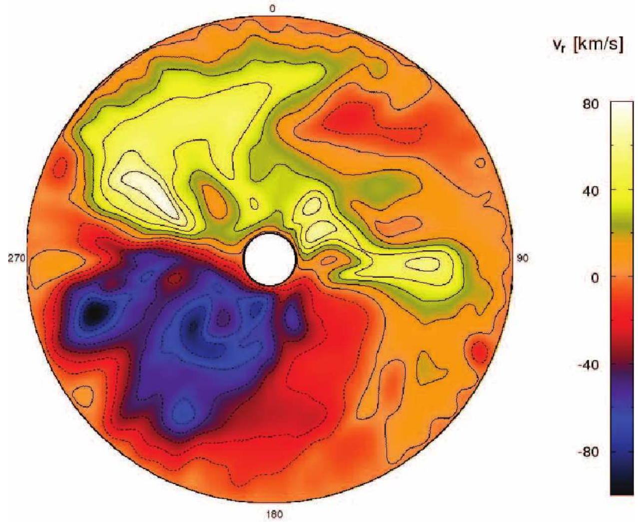


Examples of over- and under-luminous Ias and theoretical cases which reproduce them from Woosley et al. 2007, ApJ, 662, 487

Ignition of Deflagration



thermal profile before flame ignition

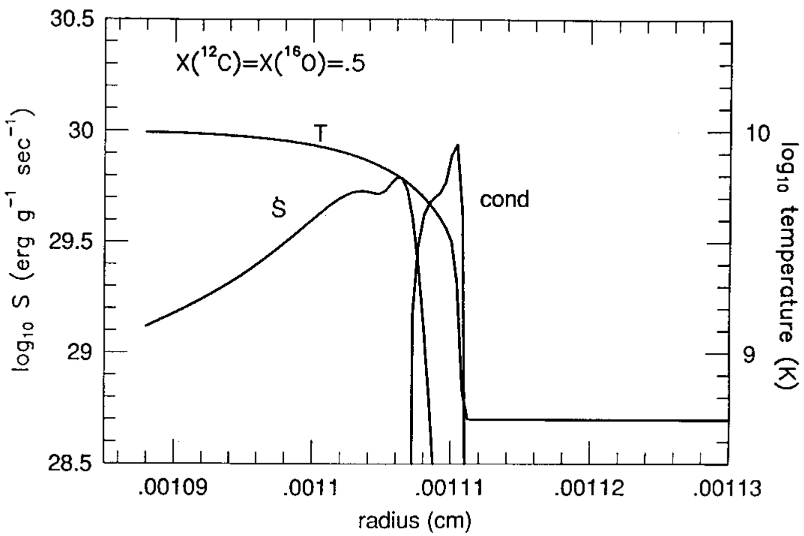


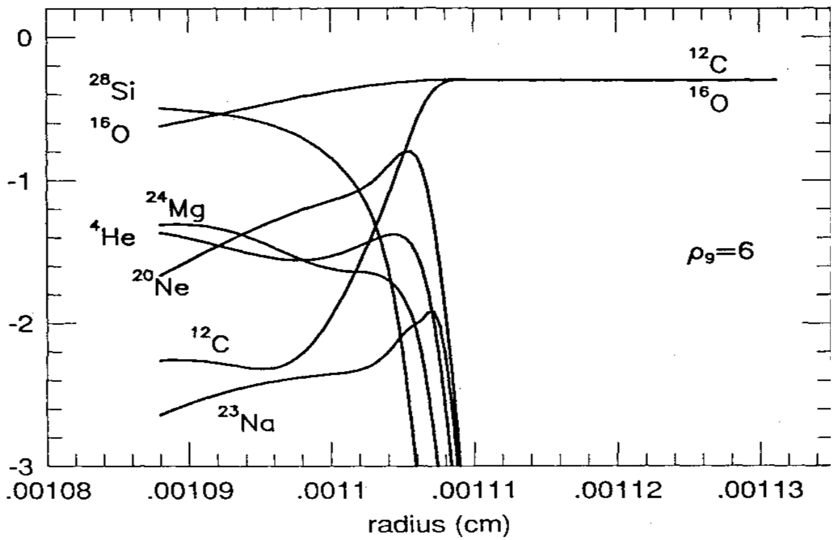
v_r in convection zone

Kuhlen et al. 2006, ApJ, 640, 407

- Deflagration ignites in convective core of WD. Convective velocities ~ 100 km/s. (Woosley, Wunsch, & Kuhlen, 2004, ApJ, 607, 921)
- Highly turbulent: significant phase space of fluctuations above average temperature.
- If ignition points are "rare" the first will appear at the small scales within the first temperature scale height of the center of the star.
- Must go out to 200 km for average temperature to drop by 10% from initial value. There is a good possibility that the first ignition point can be well off-center.

Flame Burning Mode





Thermonuclear burning begins with sub-sonic propagating flame front. (negligible pressure jump across burning front)

Thin flame: planar reaction front propagating in direction of normal

- Heat released in burning propagates diffuses into fresh fuel
- Balance between heat production and and diffusion sets propagation speed of planar reaction front

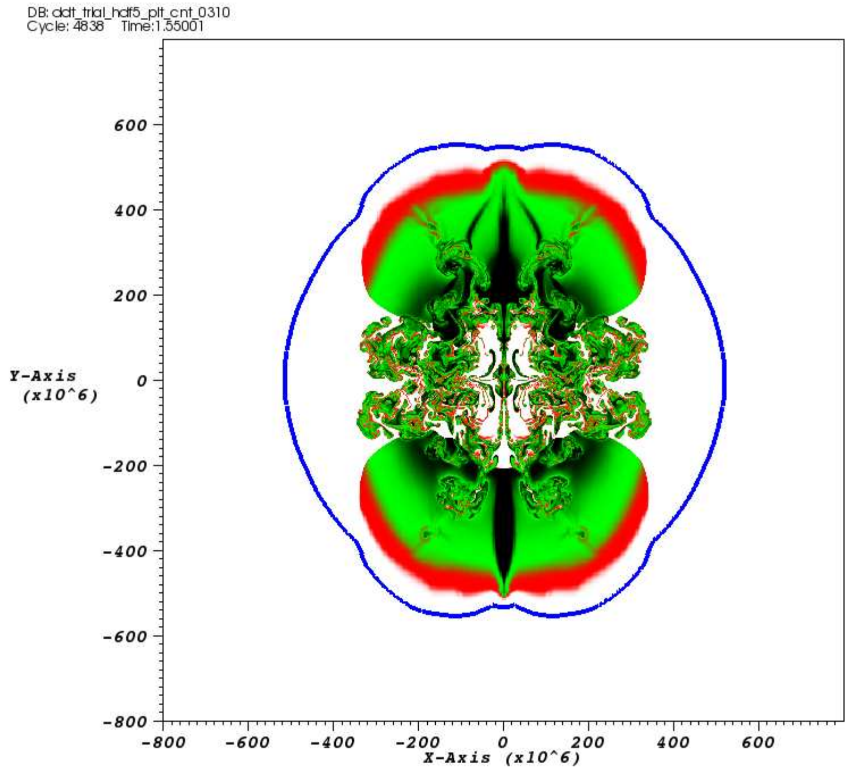
Key differences from terrestrial premixed combustion

- heat diffusion (via electron conduction) is much more effective than species diffusion
- viscous scale small compared to flame width

Deflagration Detonation Transition

"DDT" – A (direct) transition to detonation is hypothesized to occur when the flame front reaches densities $\sim 10^7$ g/cc. This is most of the way towards the surface of the star.

- Allows star to expand so that intermediate elements are formed when detonation sweeps through outer layers.
- Detonation homogenizing layers – but unclear if it does so enough in interior to match observation
- Requires rather a rather symmetric ignition process - which is unclear if it is realistic.
- Demonstrating transition with explicit simulation is extremely difficult. Makes prediction of transition density hard.



Ashes of Carbon Burning + oxygen
Silicon-group material
Iron-group material

Fast, Consistent EOS

Contributions to EOS (Timmes & Arnett 1999, ApJS, 125, 277)

- Photons (Analytic)
- Relativistic electrons of arbitrary degeneracy (tabulated)
- Ideal gas of Ions (Analytic)
- (weak) Coulomb corrections ($\Gamma \lesssim 10$) in average-ion approximation (Analytic fit)

Computational requirements on EOS (Timmes & Swesty 2000, ApJS, 126, 501)

- Fast – invertible (obtain P, T, c_s etc from $\mathcal{E}, \rho$) in about 100 μs (~ 300 flops).
- Thermodynamically consistent
  - necessary for energy conservation over many steps in compressible hydrodynamics code
  - Achieved by interpolating Helmholtz potential and its derivatives using biquintic Hermite polynomials to obtain consistent, continuous derivatives.

Nuclear degrees of freedom are not in EOS here. Treated separately by tracking nuclear energy release (discussed next).

Consistency of NSE and screening

We wish to treat NSE in simulations with an efficient parameterized treatment based on

$$\bar{q}_{\mathrm{NSE}}(\rho, T, Y_e) = \sum_i \frac{BE_i}{A_i} X_i$$

calculated from having μ_i equal for all species, but to post process thermal histories with a nuclear network.

Requires close consistency between direct NSE and network calculations.

Developed with Ivo Seitenzahl and Fang Peng

NSE from energetics

Direct solution of statistical equilibrium is obtained by equating the chemical potentials of all species.

$$\mu_i = \mu_j \quad \rightarrow \quad m_i c^2 + \mu_i^{\rm id} + \mu_i^{\rm C} = m_j c^2 + \mu_j^{\rm id} + \mu_j^{\rm C}$$

This form arises from using the linear mixing rule to construct the free energy of the system

$$F(T,\rho,N_i) = \text{rest mass} + F^{\rm id} + \sum N_i kT f_C(\Gamma_i)$$

where $\Gamma_i = Z_i^{5/3} e^2 (4\pi n_e/3)^{1/3}/kT$.

So that

$$n_i = g_i \left(\frac{2\pi m_i kT}{h^2}\right)^{3/2} \exp\left[\frac{Z_i\mu_p^{\rm id} + N_i\mu_n^{\rm id} + Q_i - \mu_i^C + Z_i\mu_p^C}{kT}\right].$$

and μ_p and μ_n are found by constraining the mass and charge.

This allows direct determination of ratios of n_i in terms of binding energies.

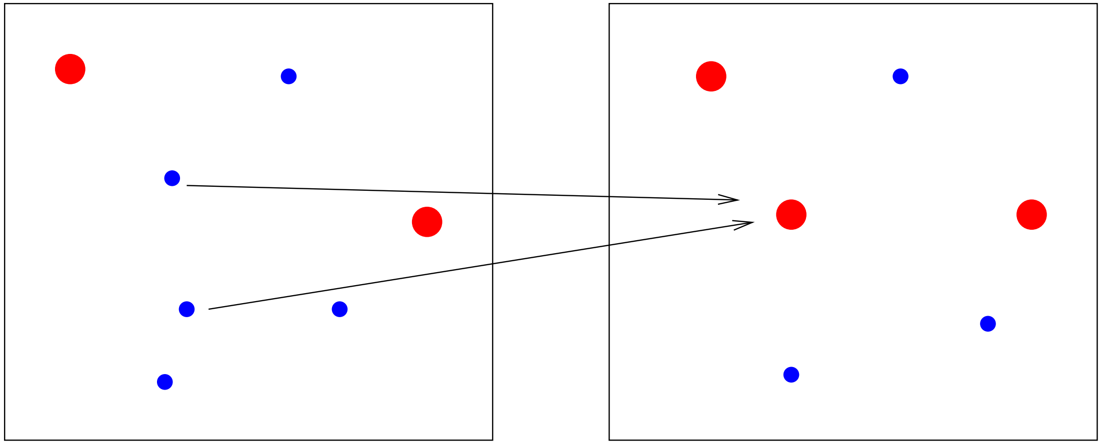
NSE from reaction rates

The charge field due to electrons and the many-body effects of the ion gas change the pair correlation function.
The lowest order effect is for this to decrease the energy barrier by

$$\Delta F = F(M,N) - F(M-2,N+1) = 2\mu_Z - \mu_{2Z}$$

where $F(M,N)$ is the free energy for M ions of charge Z and N ions of charge $2Z$.

(Jancovici 1977, J.Stat.Phys. 17, 357)



This leads to an increase in the correlation function at the origin of a factor of $\exp(-\Delta F/kT)$, creating a similar enhancement of the reaction rate:

$$\langle \sigma v \rangle = \langle \sigma v \rangle_0 \exp\left[f_C(\Gamma_i) + f_C(\Gamma_j) - f_C(\Gamma_k) \right]$$

for a reaction $i + j \to k$.

A consistent treatment

Obtained by using the NSE equations:

$$\mu_i = \mu_j \quad \rightarrow \quad m_i c^2 + \mu_i^{\rm id} + \mu_i^{\rm C} = m_j c^2 + \mu_j^{\rm id} + \mu_j^{\rm C}$$

and the inverse reaction relations:

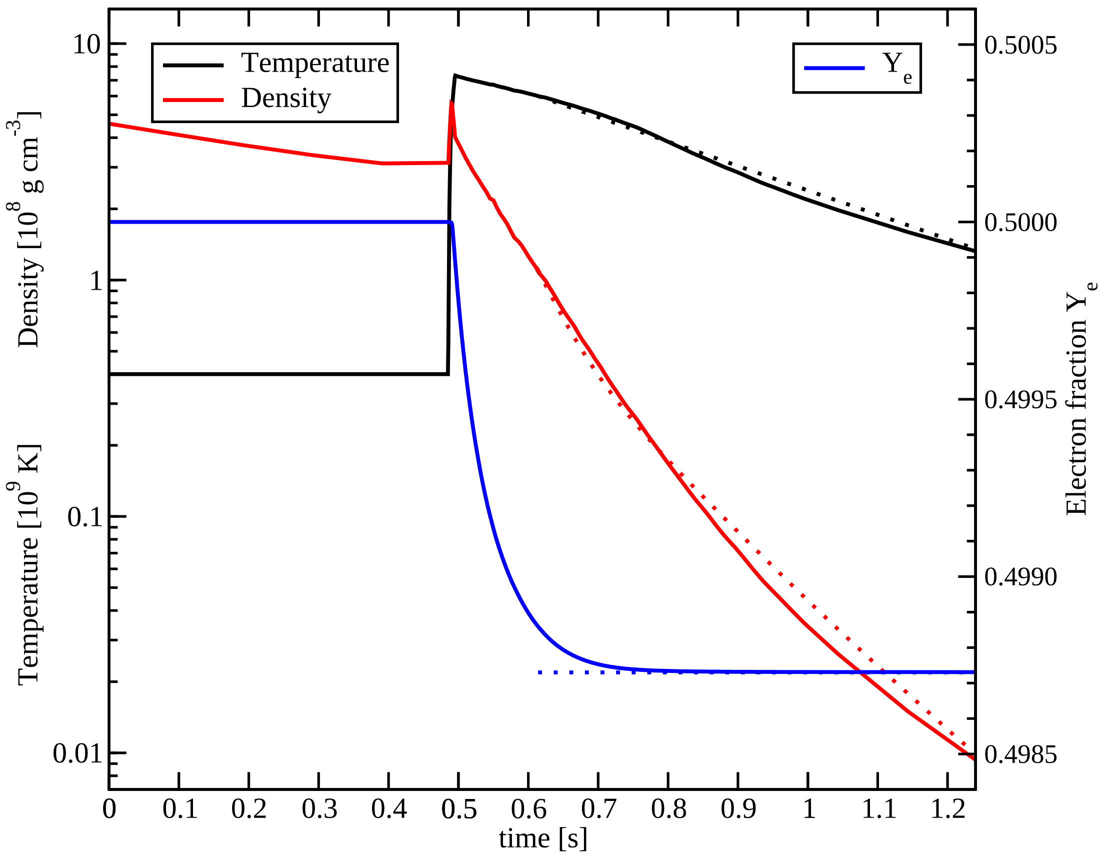
$$\frac{\langle\sigma v\rangle_r}{\langle\sigma v\rangle_f} = \left(\frac{n_i n_j}{n_k n_l}\right)_{\rm NSE} \quad = \quad \frac{g_i g_j}{g_k g_l}\left(\frac{m_i m_j}{m_k m_l}\right)^{3/2} \times \exp\left(\frac{Q_i + Q_j - Q_k - Q_l}{kT}\right)\exp\left(\frac{-\mu_i^{\rm C} - \mu_j^{\rm C} + \mu_k^{\rm C} + \mu_l^{\rm C}}{kT}\right)$$

With this, a screened forward rate is converted directly into a screened reverse rate.

Putting this in is often necessary because often the same fits are not used for the Coulomb correction $f(\Gamma)$ for the screening and the EOS.
Additionally, there are other small quantum corrections added to the screening that do not appear in the EOS.

Consistency check

Check consistency by comparing the amount of electron captures which occurred in the simulation to the level determined by post-processing the same thermal history.



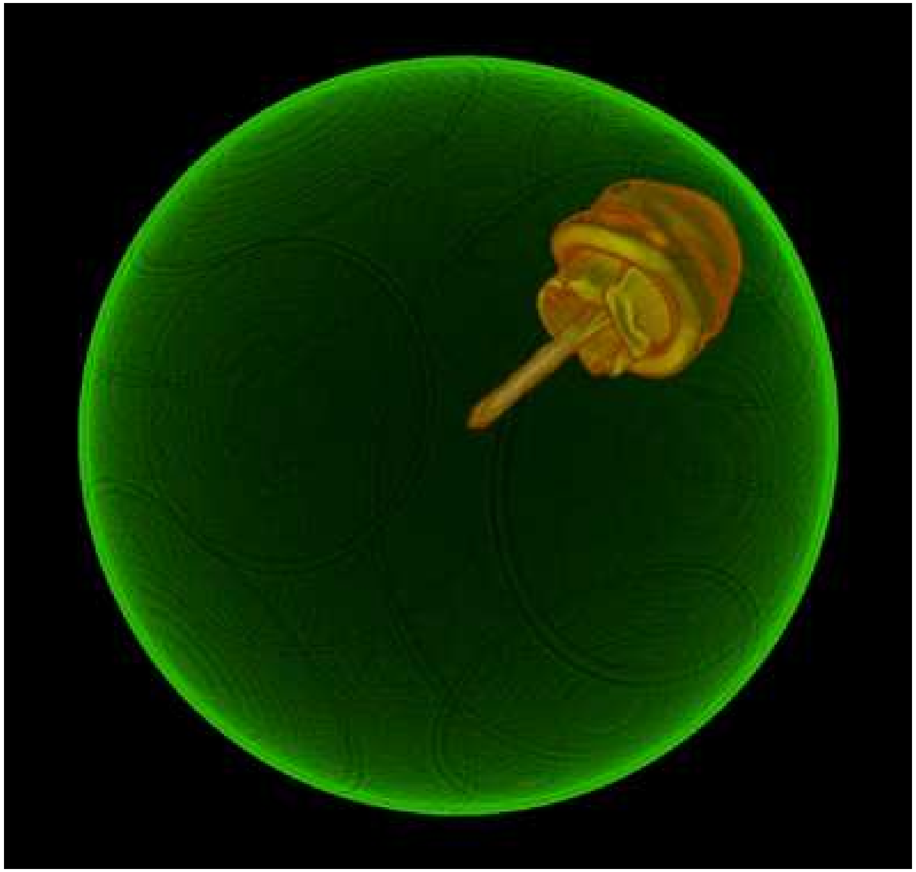
Courtesy Ivo Seitenzahl and Casey Meakin

Excellent agreement demonstrates that the NSE state (composition) matches between the direct NSE and the network.

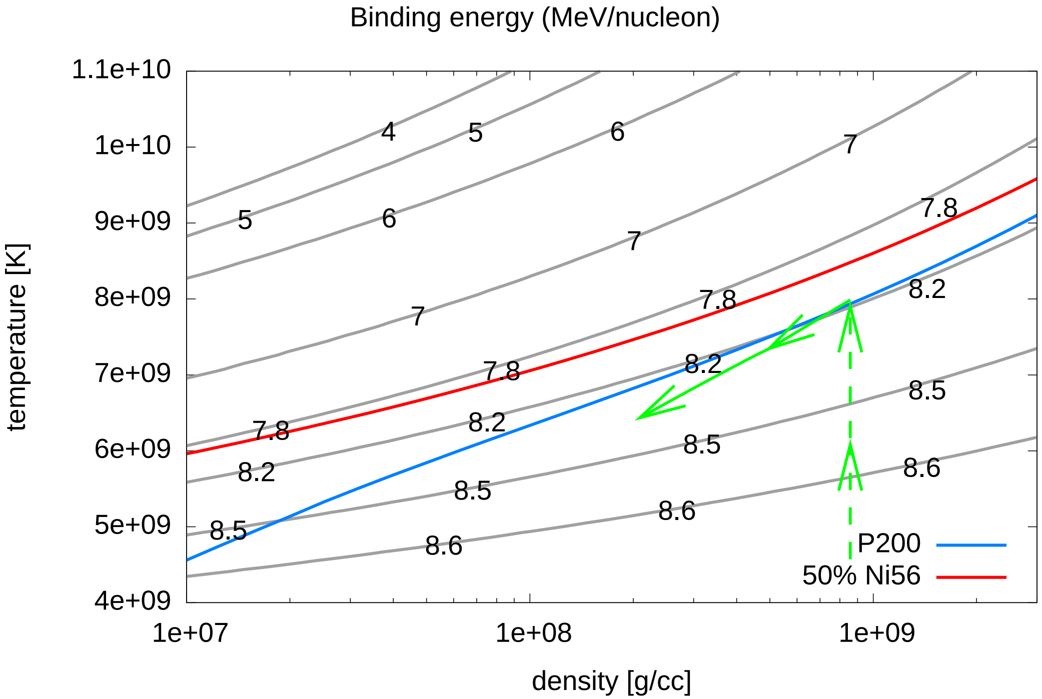
Importance of Buoyancy

A small offset of the ignition point from the center of the star leads to a very asymmetric deflagration.

- Does not lead to release of enough energy before reaching DDT density to provide realistic yields.
- Might lead to alternative site and mechanism to ignite detonation.
- Better understanding of the ignition conditions and the early evolution of the flame is required.



Energy released during rise



Calder, Townsley, et al. 2007, ApJ, 656, 313

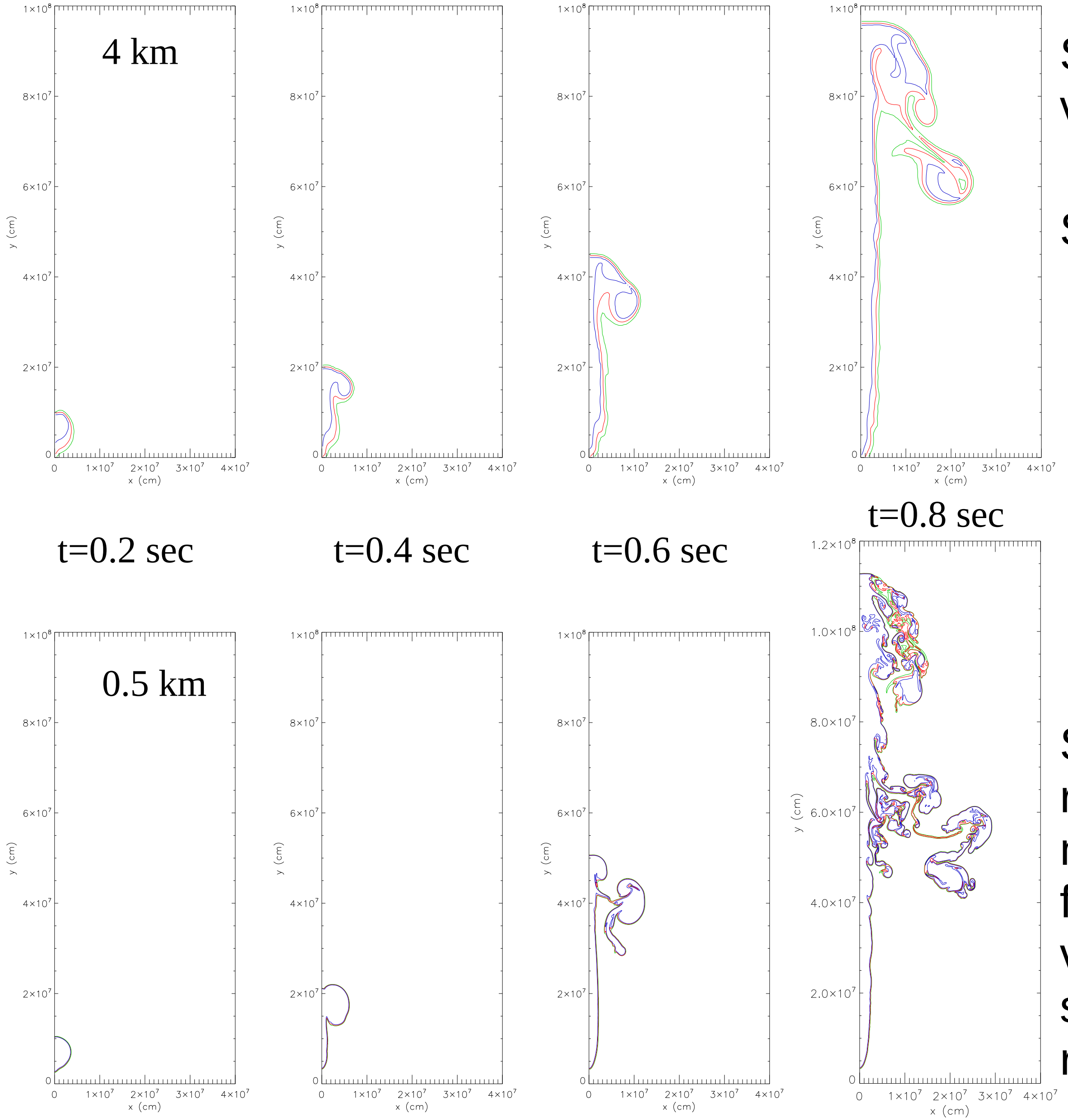
Townsley, Calder, et al. 2007, ApJ, 668, 111

Burning generally ends in Nuclear Statistical (Quasi-) Equilibrium.

Binding energy of ash state is not fixed, but evolves as fluid expands to lower density. More energy is released by the net recapture of the equilibrium ^{4}He.

Nearly 1/3 of total final energy release comes well after the passage of the reaction front, during expansion of the NSE material.

Evolution of Flame Bubble



Shown: contours of progress variable $\phi =$ 0.1, 0.5, and 0.9.

Stages of evolution:

1. Laminar evolution:
   $r_{\rm bub} \lesssim \lambda_c$
2. Resolved R-T:
   $\Delta x < \lambda_c < r_{\rm bub}$
3. Unresolved R-T:
   $\lambda_c < \Delta x$

Some clear dependences on resolution: sharper features, more localized flame front, faster rise, different shed vortex. Also general similarities through the resolved R-T phase.

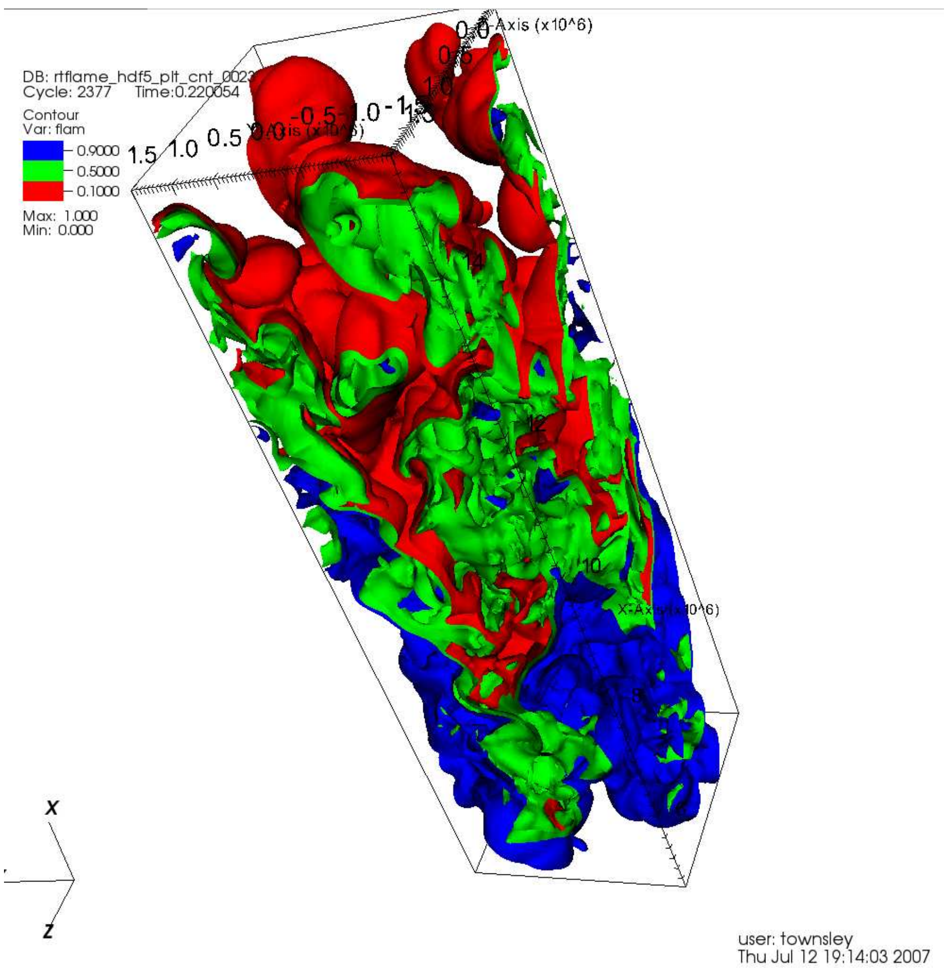
Turbulent Flames

Strong turbulence generated by buoyancy instability (Rayleigh-Taylor) and fast rising plumes perturb flame surface and accelerate burning

Precise evolution of turbulent flame difficult to simulate due to challenge of achieving high Reynolds numbers in simulation

Flame in flamelet regime (well-characterized by a burning surface) out to densities below 10^7 g/cc. Then becomes distributed.

Still studying how turbulence is produced by buoyancy and subsequently interacts with flame surface. Probing unanswered questions in transport of turbulence.



$$\lambda_c/L = 1/134$$

supernova: $\lambda_c/L \sim 10^{-5}$

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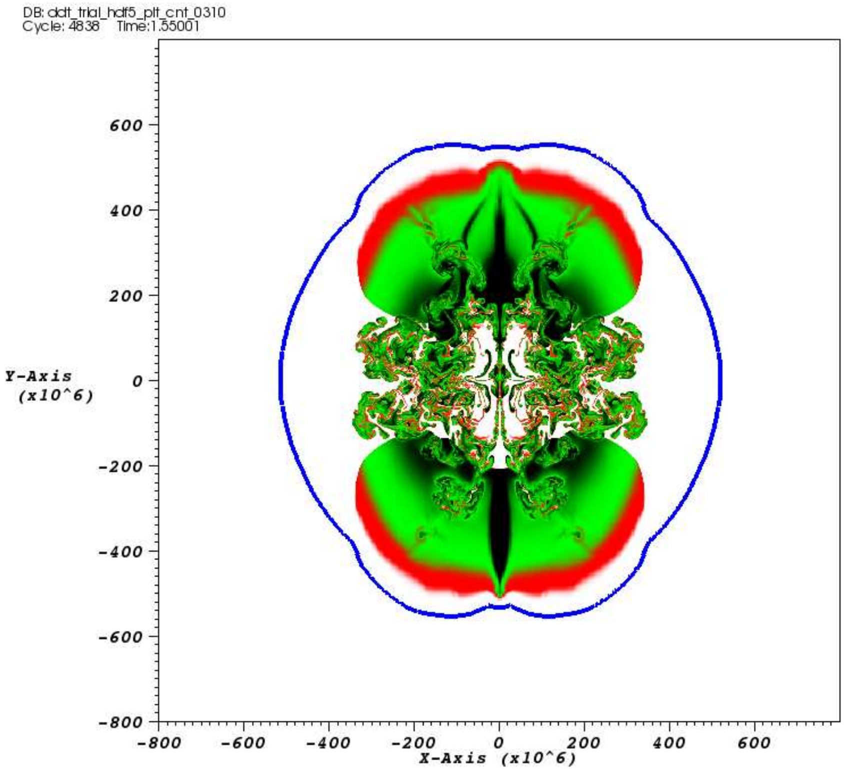
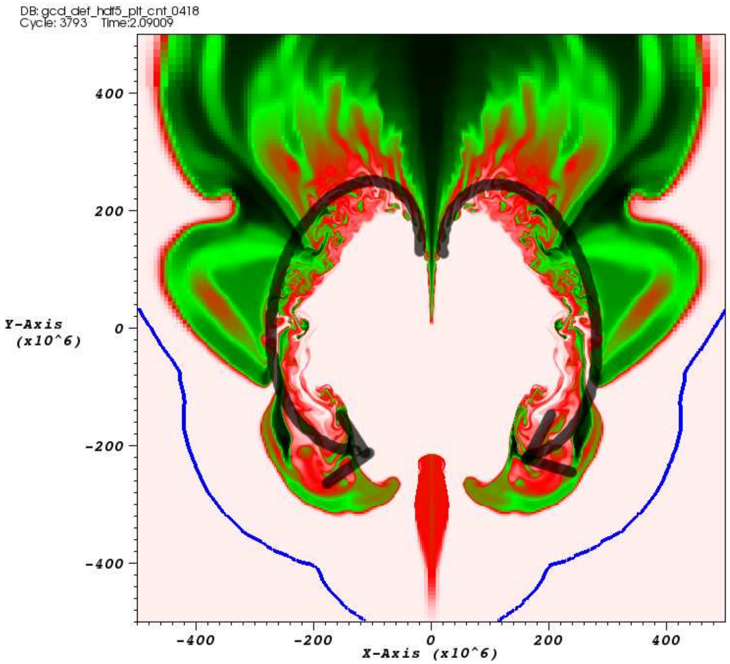
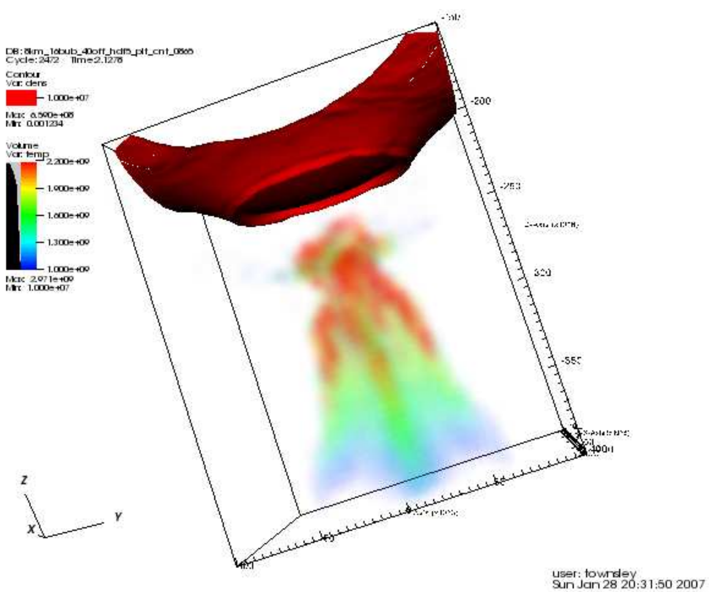


Ashes of Carbon Burning + oxygen
Silicon-group material
Iron-group material

Gravitationally Confined Detonation



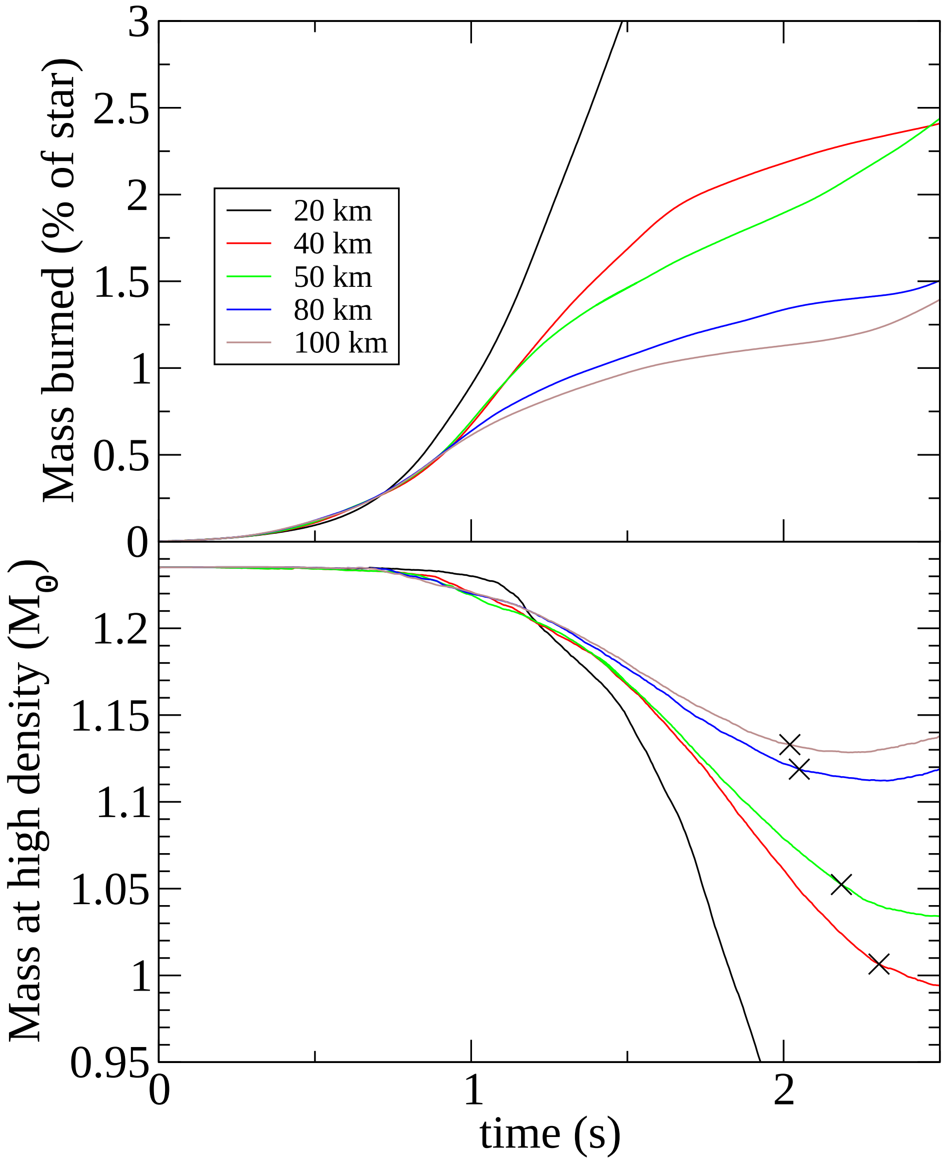


Mildly off-center ignition can lead to a catastrophic buoyancy instability. Burning flamelet escapes surface of star before consuming much stellar material.

- Case shown has 40 km offset with star of 2000 km radius
- Confined hot material flows over surface, converges and creates a compressed region.
- Subsequently a detonation initiated near the surface can ensue.
- Most of star is burned in detonation phase leading to a large amount of ^{56}Ni.
- Transition to detonation is simpler and more predictable.

Studies in 3 dimensions with thermal reactions suppressed are used to understand converging flow characteristics which lead to detonation.

Dependence on Initial Condition



Outcome of deflagration phase determines density of material during detonation phase. (True for multi-d study of any Def-Det-type scenario.)

- Larger offsets burn less material, releasing less energy
- Causes less expansion and more dense material (shown is mass with $\rho > 5 \times 10^7$ g/cc.
- More ^{56}Ni should be be produced by larger offsets
- Timing of detonation ignition ($\times$) also significant

Summary

Stellar Origins:

- Still many unknowns – lack a scenario which clearly works
- Progress to be made in better understanding general parent population
- Need clearer relations to supernova outcome

Have a fast EOS which works well for hydrodynamics

- Coulomb corrections well characterized for supernova
- For collapsing objects some improvements might be necessary

Thermonuclear Supernovae:

- Several working explosion mechanisms
- Buoyancy of burned material an essential characteristic
- Still work ahead on flame modeling and ignition conditions
- Stochastic ignition could explain spread of outcomes