Local Ignition in Carbon-Oxygen White Dwarfs: One Zone Ignition, and Spherical Shock Ignition of Detonations

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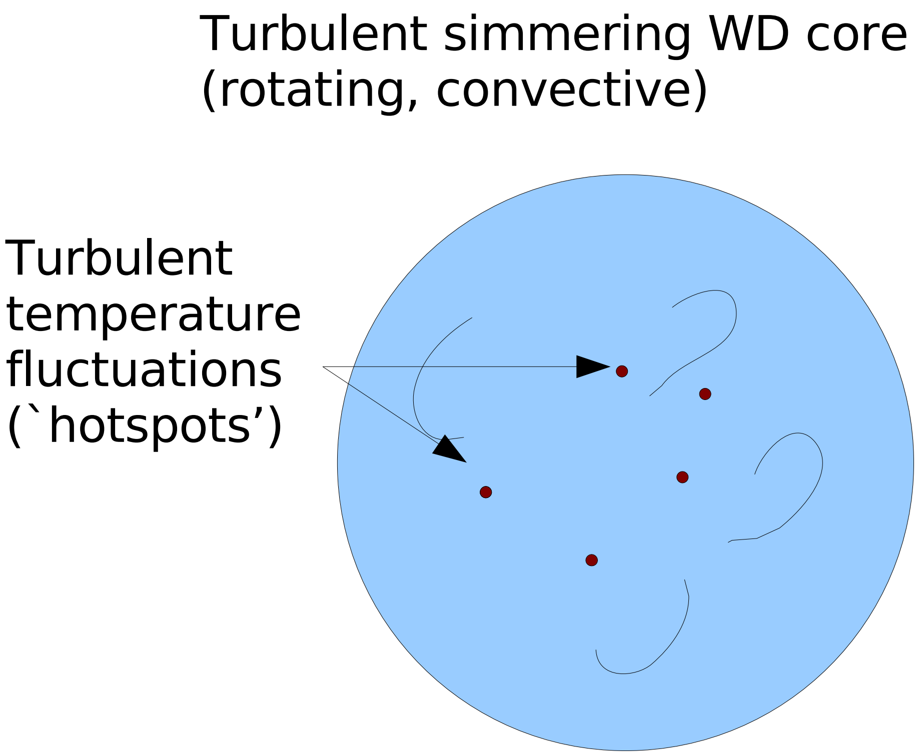
Turbulent ignition of Type Ia supernovae



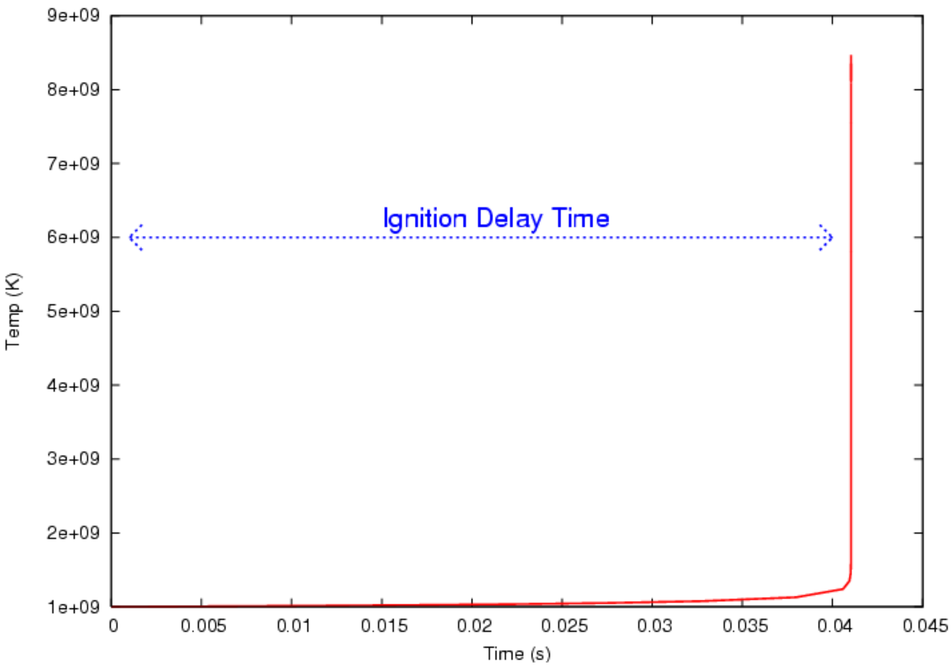
- Burning of C/O white dwarf
- Ignition in a turbulent medium
- **Number, size of ignition points shapes explosion**
- Ignition points are turbulent fluctuations
- **What are conditions necessary for ignition?**

Our Contributions

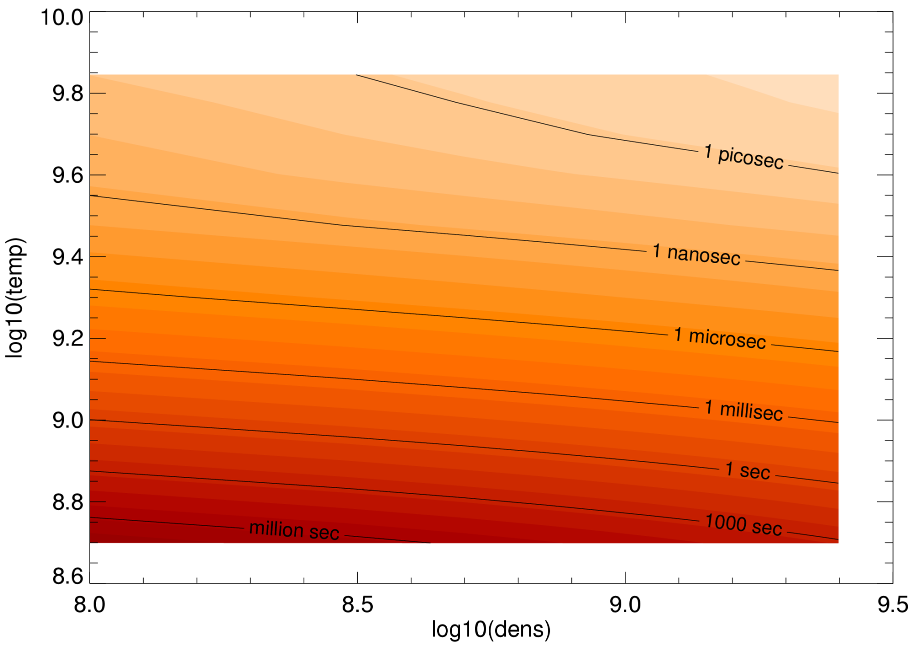
- Simple, accurate fitting formula for ignition times for a range of density, temperature, compositions in one-zone limit
- Small (~few %) amounts of Neon can significantly (~30%) reduce ignition times by filling in link in alpha chain.
- Igniting a detonation by a spherical shock (eg, rapid ignition of a hotspot) is very difficult – requires `matchheads' of ~4500 detonation thicknesses, which can be kilometres at densities of 5×10^7 g cm^{-3}

Ignition Times

- In one zone, time of `simmering' before rapid burning
- Due to v. strong temperature dependence
- Relevant even for multi-dimensional cases – sets burning timescale (for eg comparison to hydro, turbulent, conductive scales)



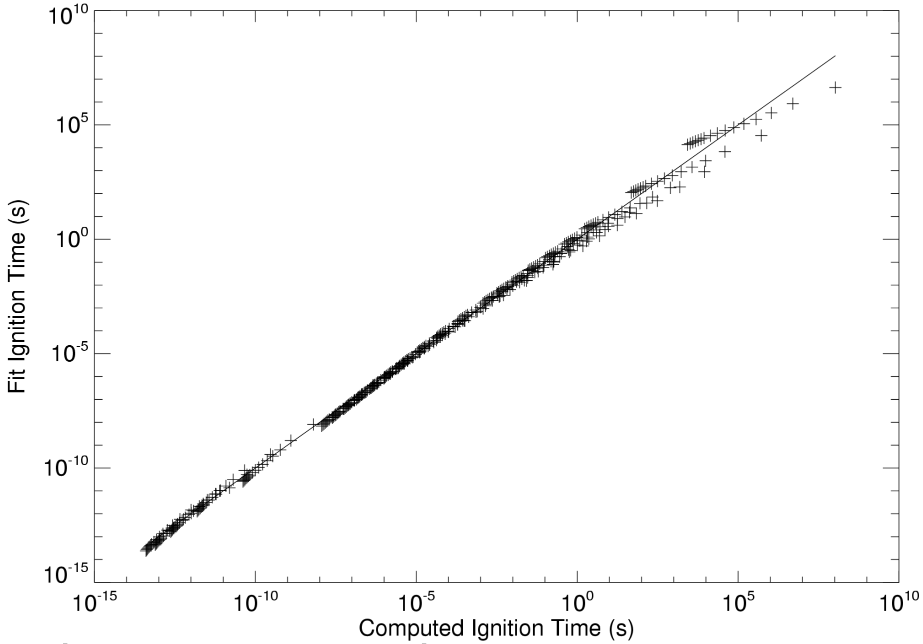
Ignition Times



Constant-pressure ignition times
for 50%/50% Carbon/Oxygen mixture by mass

- Performed ~7000 integrations of one-zone simmering varying carbon fraction, density, temperature
- Ignition time varies over ~25 orders of magnitude

Ignition Times



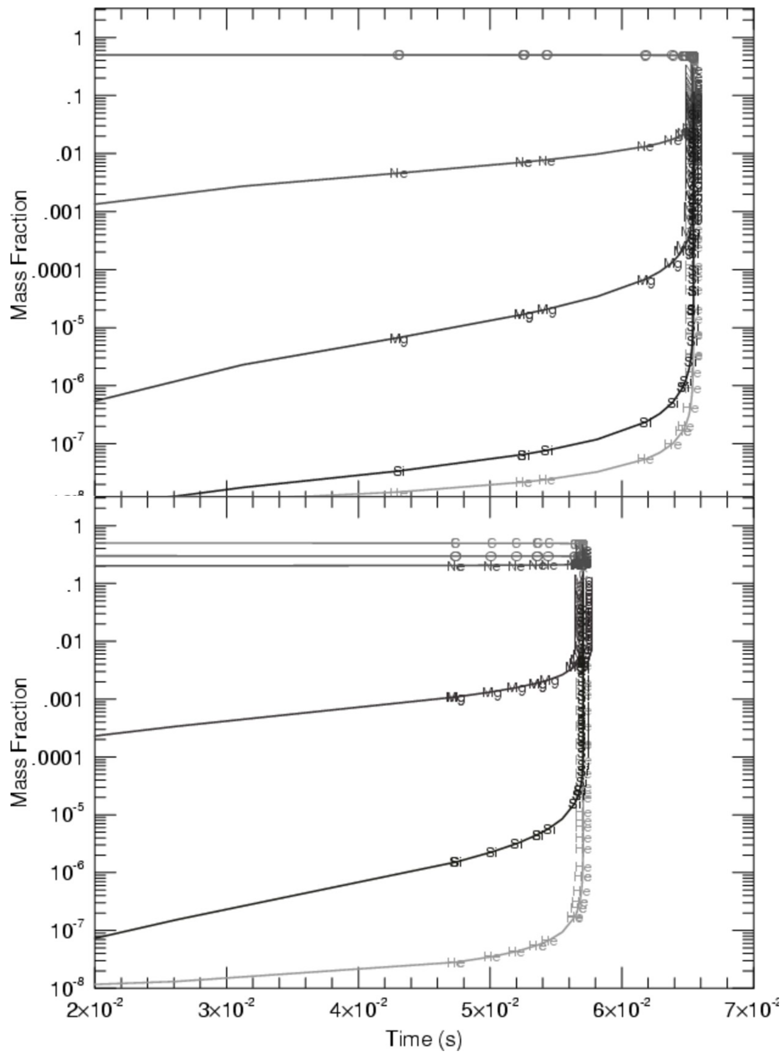
Fit vs. calculated constant-pressure ignition times

- Relatively simple and accurate fitting functions calculated for use in analytic calculations
- Works well over entire range of values

$$\tau_{i,\mathrm{cp}} = 1.15 \times 10^{-5} \mathrm{sec} \left(X_{^{12}C} \rho_8 \right)^{-1.9} f_{cp}(T) \left[1 + 1193 f_{cp}(T) \right]$$

$$f_{cp}(T) = (T_9 - 0.214)^{-7.566}$$

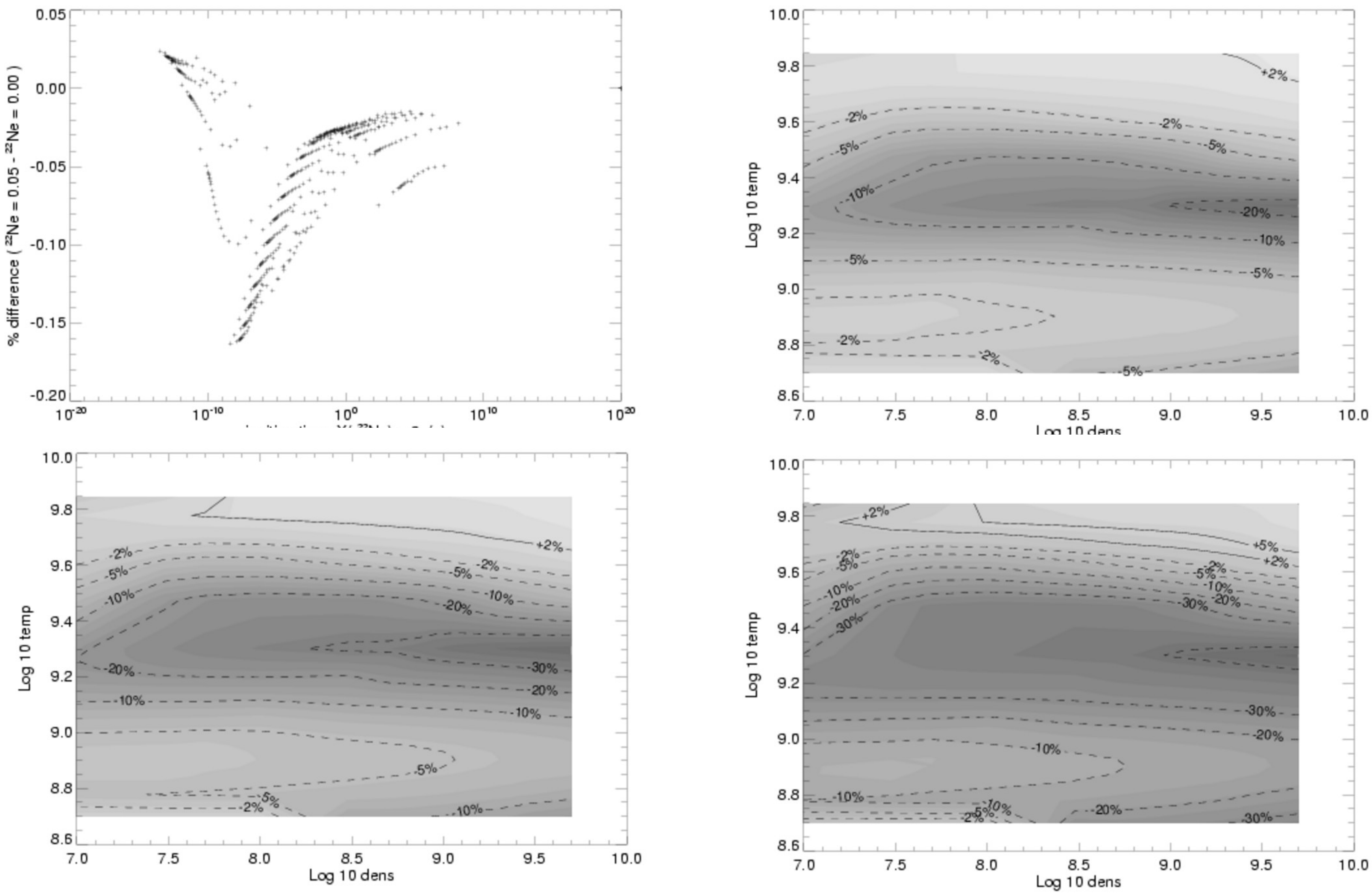
Effect of Neon on Ignition Times



Mass fraction of different species during burning for C/O = 50/50 and C/O/Ne = 50/40/10

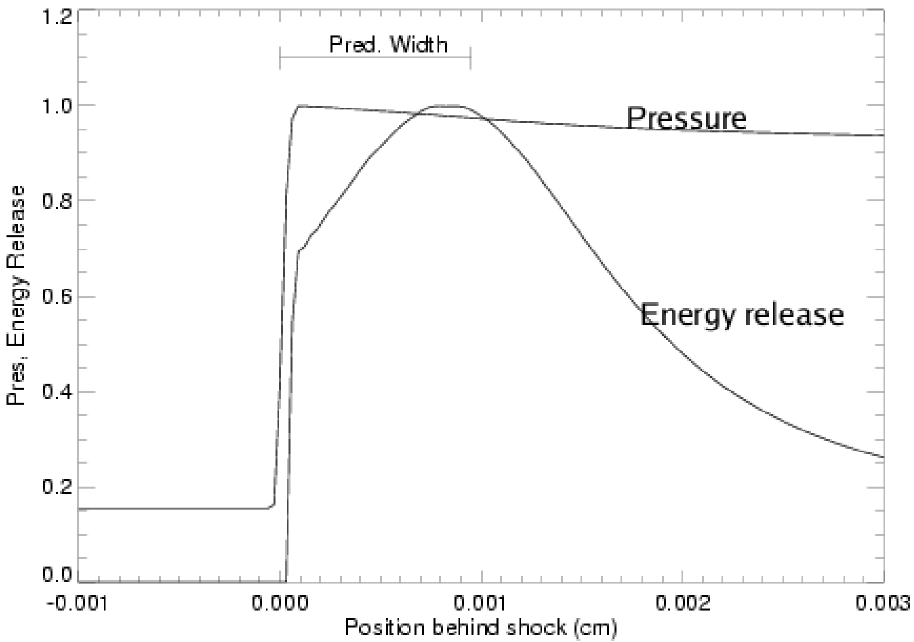
- Metals in ZAMS progenitor typically C/N/O – during helium burning, much of this piles up into Neon
- Neon fills a run on the alpha chain, allowing faster burning
- This allows a ~30% reduction in ignition time

Effect of Neon on Ignition Times



% Reduction in ignition time of a 50% carbon mixture for varying density, temperature, and neon fraction 0.05 (top), 0.1 (bottom left) and 0.2 (bottom right)

Detonation Structure



Pressure and energy release behind the shock of a leftward travelling detonation. Maximum burning occurs after an ignition time in the shocked material

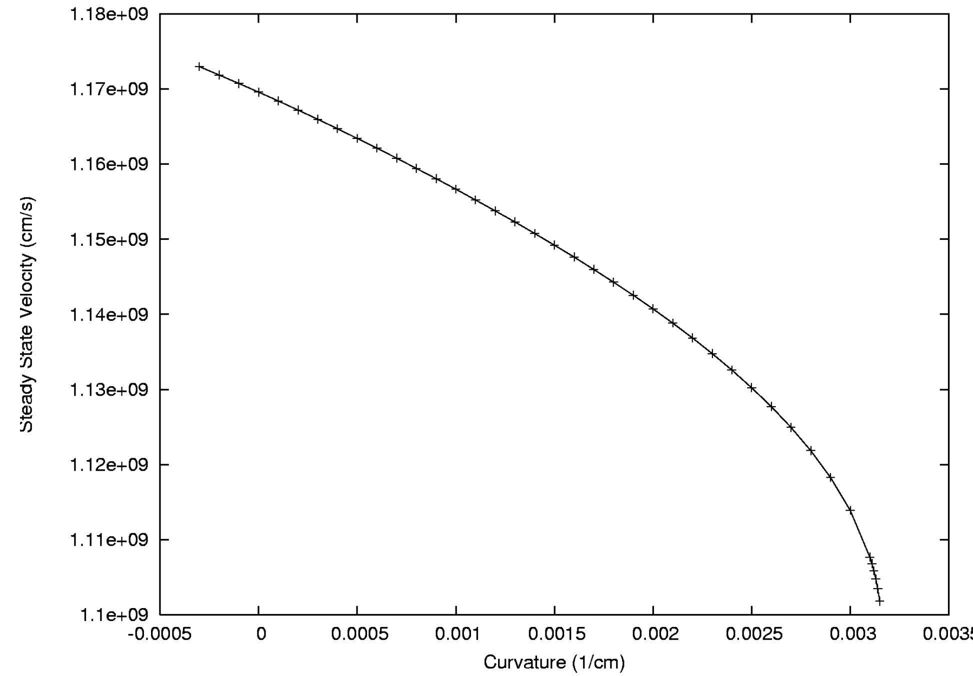
- Ignition doesn't happen immediately behind shock
- Non-zero ignition time for shocked material
- Position of maximum burning behind shock:

$$l_i = D\tau_i$$

- D = detonation speed

Detonation Structure

- Curvature strongly effects detonation structure by modifying this burning region
- He & Clavin (1994) Sharpe (2001)
- Effects detonation speed
- Beyond some curvature, no steady state detonation can exist



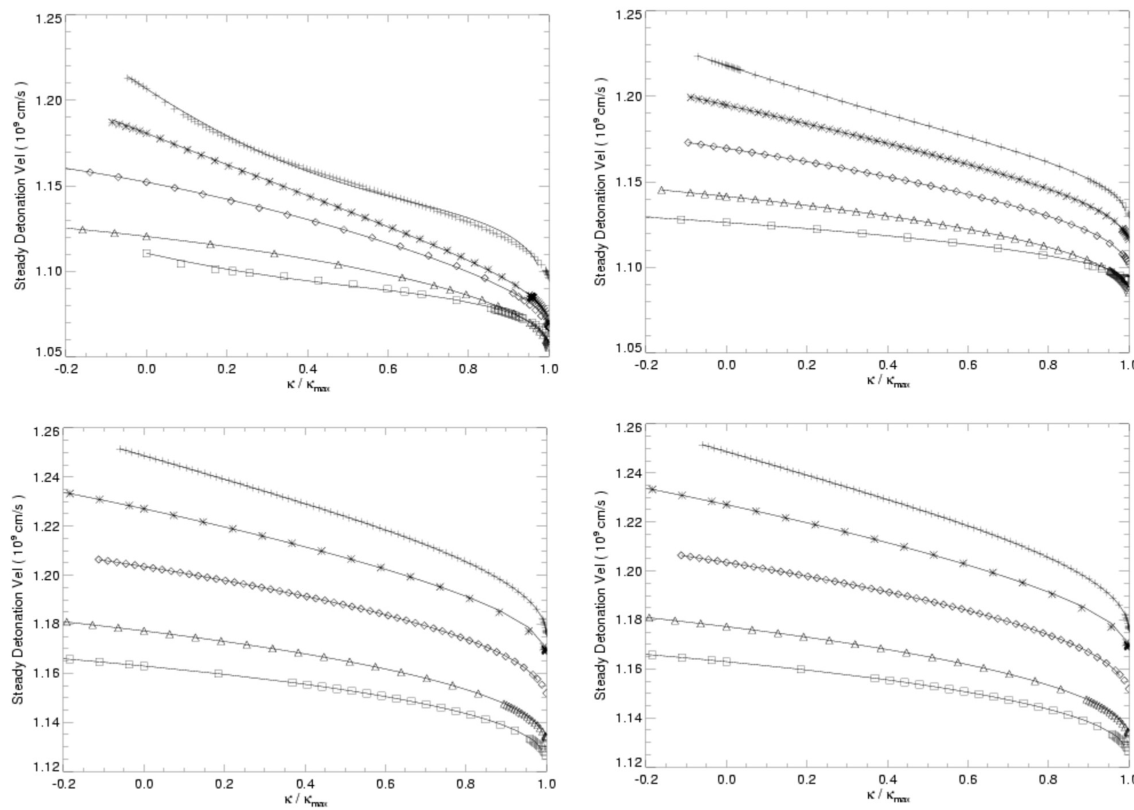
Detonation speed v. curvature for a detonation into 108 g/cc, $T=5\times10^{7}$ K, 50/50 C/O

Detonation Structure

- To launch a successful detonation, must continue driving shock to radius greater than

$$r \approx \kappa_{\max}^{-1}$$

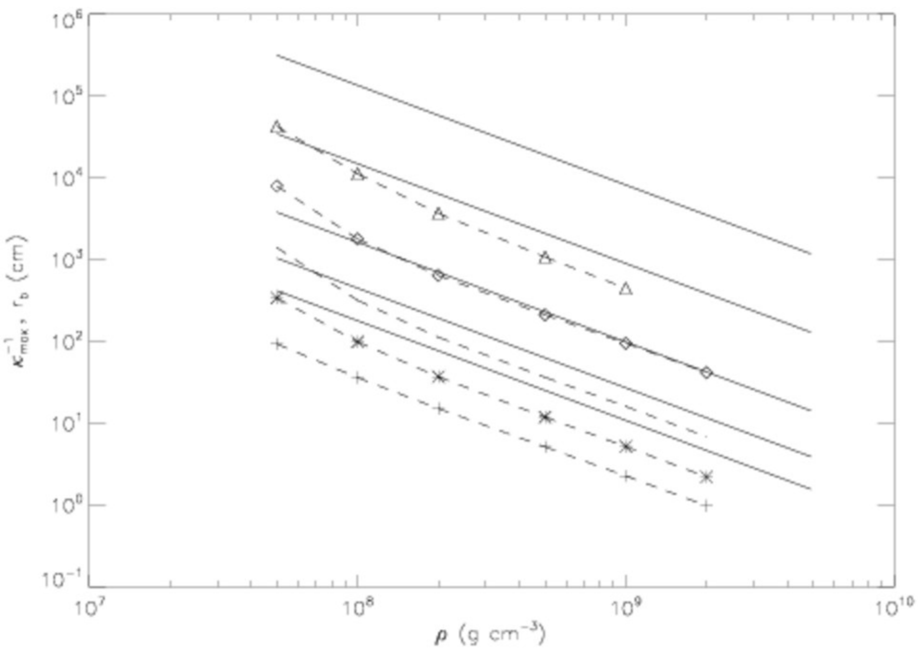
- Calculated maximum curvatures for range of densities, temperatures, compositions



Scaled detonation speeds as a function of curvature for densities of (left to right and top to bottom) 5×10^{7}, 10^{8}, 2×10^{8}, 5×10^{8}, and carbon of 1, 0.75, 5, 0.25.

Minimum Scales for detonation

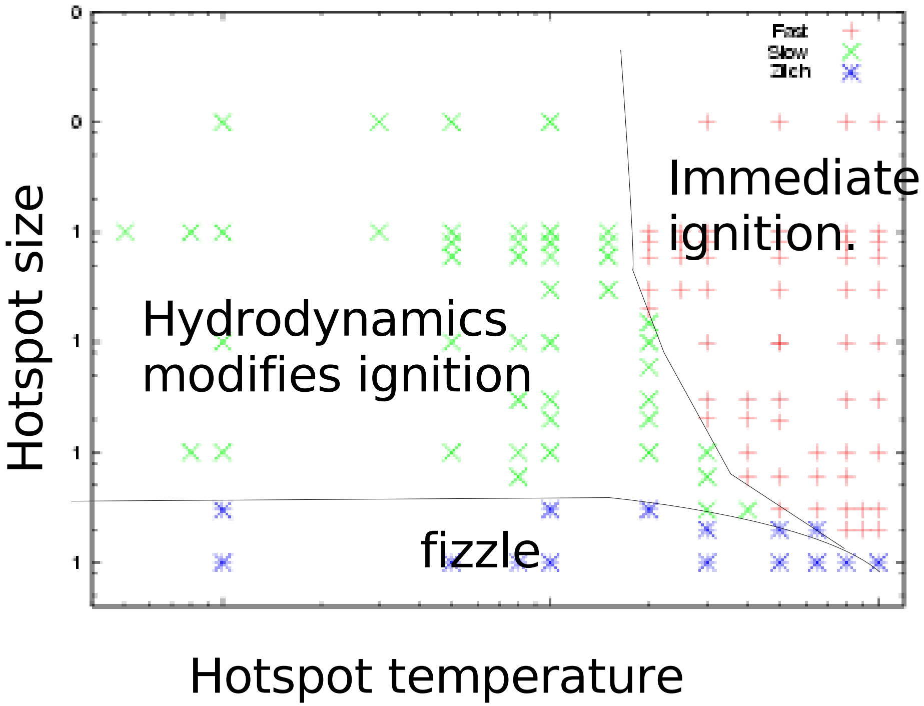
- The required scales are ~4500 detonation thicknesses, which can be O(km) at low ($5x10^7$) densities, carbon fractions
- Helps explain previous numerical work (Niemeyer & Woosley 1997)



Inverse minimum curvature for detonation as a function of density, for carbon fractions of 1/8, 1/4, 1/2, 3/4, and 1; also shown is region which must ignite to release enough energy to drive such a shock

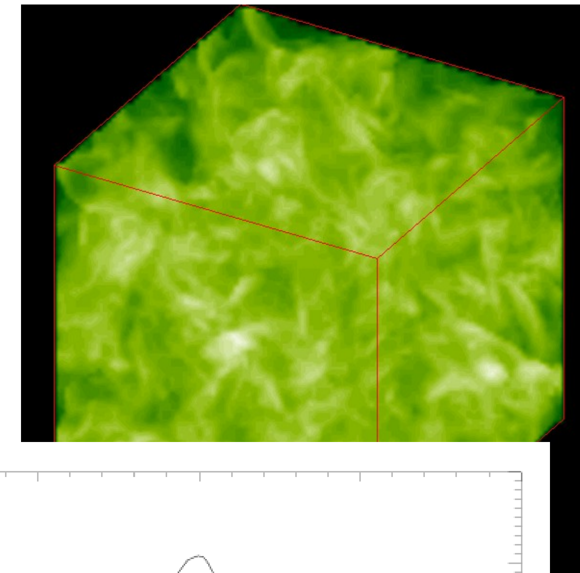
Continuing work

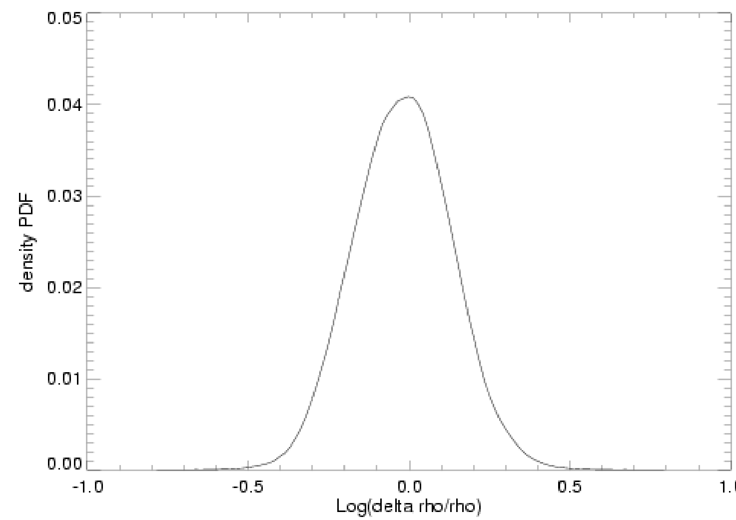
- Many 1d spherical simulations of igniting gaussian hotspots
- Determine `flammability limits'
- Highly nonlinear
- Because of above, compressible code not needed – unlikely to launch detonations on small scales



Continuing work

- Large 1d, 3d simulations of compressible reactive turbulence
- Extract temperature, hotspot PDF
- Need large simulations – ignition points are necessarily rare events
- Do with and without feedback
- Tell a consistent story of turbulent ignition





Progress/Summary

- Ignition mechanism is a possible source of diversity in Type Ia supernovae
- Trying to understand ignition assuming it is a small-scale phenomenon (turbulent hotspots)
- Firm ignition times, now moving on to understanding how burning/hydro/conduction interact in highly nonlinear ignition process
- How intense/intermittent does turbulence have to be to ignite such hotspots?
- Detonation driven by purely local energy release requires large-scale convergence