Astrophysical Flames, Flame Instabilities, and Ignition in White Dwarfs

or
How `grungy gastrophysics' will save cosmology

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CITA | ICAT

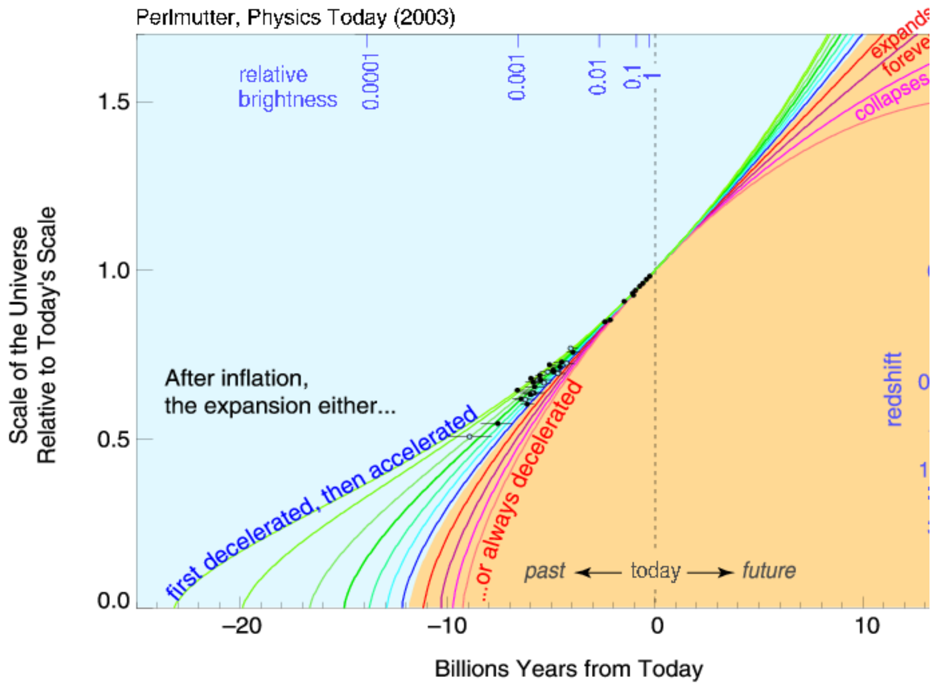
Supernovae Ia


Supernova 1994D (STScI)

- Very bright events
  - Few x 10^{51} ergs
  - ~28 day rise time
  - No H in spectrum
- Can outshine host galaxy
- Can be seen at great distances
- Leave behind no remnant
- ~0.6 M_o of Nickel produced

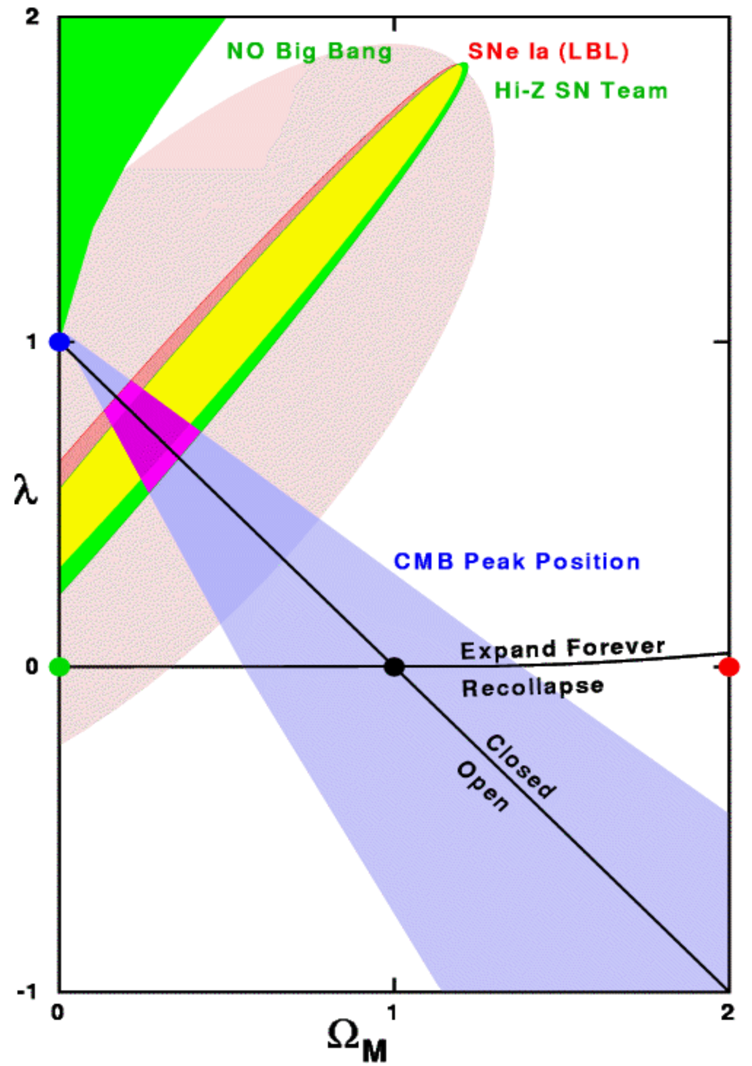
Supernovae Ia in Cosmology

- Presumed standardizable candles
- Seen at significant redshift
- Can construct distance-redshift relation



Supernovae Ia in Cosmology

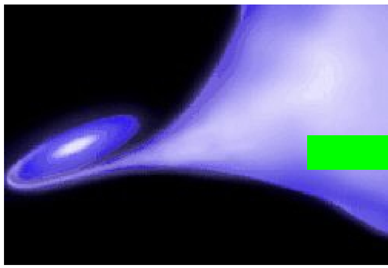
- SNIa (distance-z relation) give information orthogonal to other cosmological probes (eg, CMB)
- Important for constraining cosmology
- But SNIa mechanism – and phenomenology – still not understood!



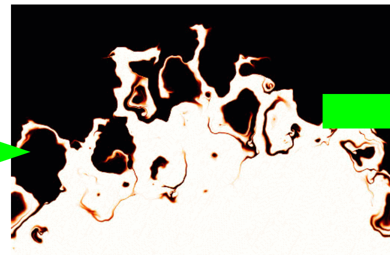
Ned Wright

Supernova Ia Mechanism

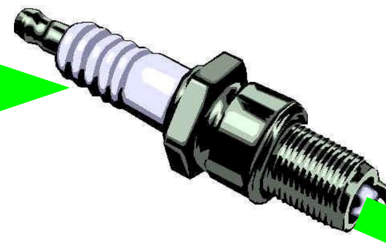
accretion



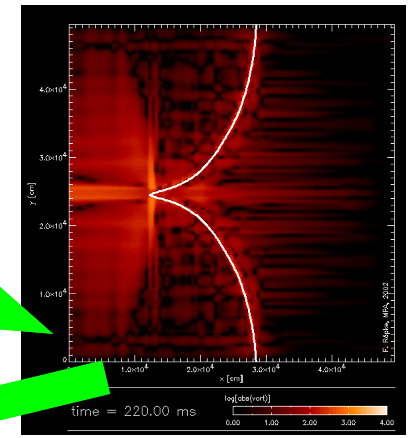
simmering



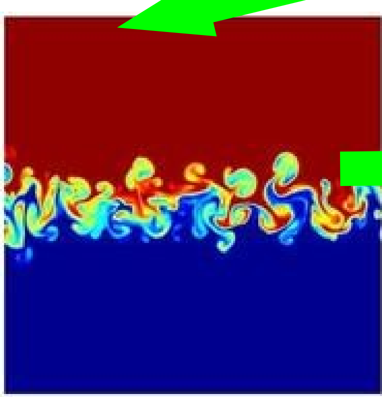
ignition



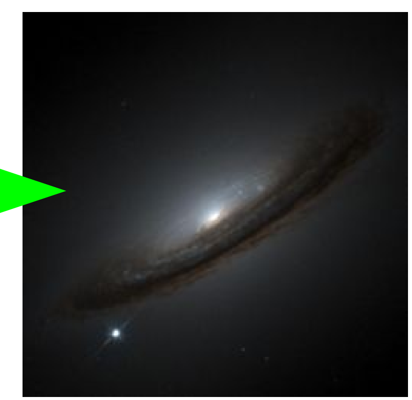
flame propagation



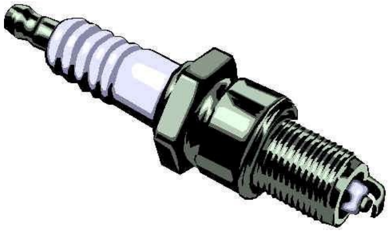
instabilities



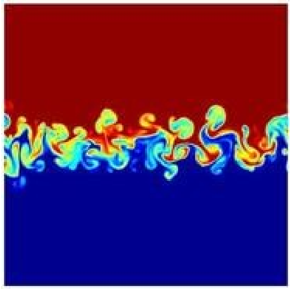
detonation?



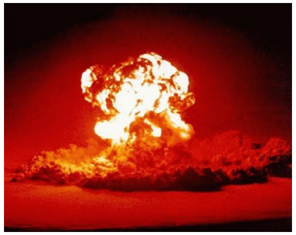
Big Combustion Questions of Supernova Type Ia



- Ignition
  - How?
  - Where? How many points?



- Turbulent Burning
  - Turbulent flame speed? Flame-generated turbulence?



- Transition to Detonation
  - Does one happen?
  - How?
- **These change Type Ia explosions, and may introduce non-uniformities**

Problem: Complexity

- Highly nonlinear multiphysics problem – need computation
- Many scales (time, space) involved:
  - Ignition can happen on very small/fast scales
  - Flame thickness < 1mm; det thickness < 1cm
  - Turbulence on (all!) intermediate scales to ~6000km
- Must look at pieces individually before putting them together
- Some pieces: low speed flows (Mach 10^{-5} !) - current generation of astrophysical codes have difficulties

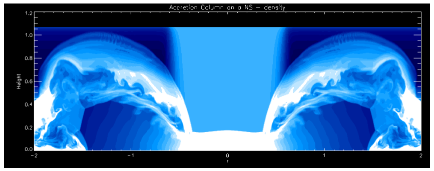
Approach: Understand fundamental aspects of astro combustion

- Microphysics
- Ignition mechanism
- Flame speeds, acceleration mechanism
- Needed for any Type Ia supernovae scenario

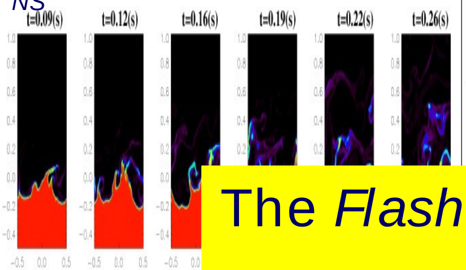
Approach: Understand fundamental aspects of astro combustion

- Ignition
  - One-Zone
  - Small regions
- Flame, Detonation propagation
  - Instabilities
  - Turbulent speeds
  - Effect of B-fields
- How to put these into increasingly large-scale simulations

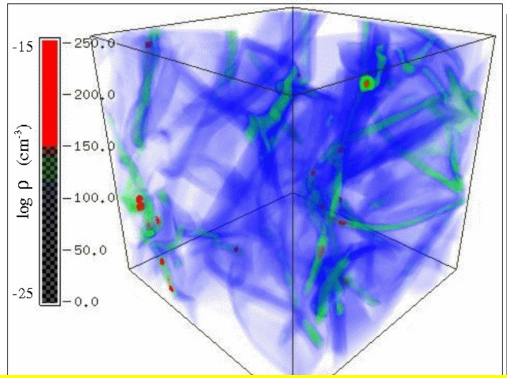
An important tool: The Flash Code

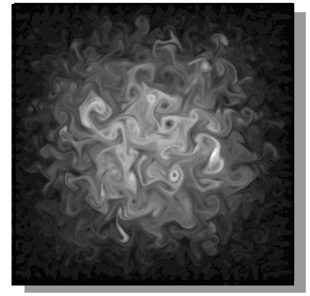


Shortly: Relativistic accretion onto NS

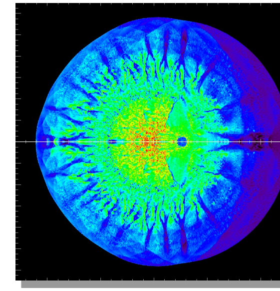


Wave breaking

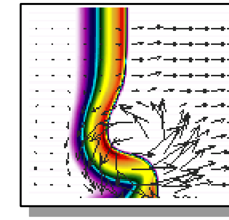




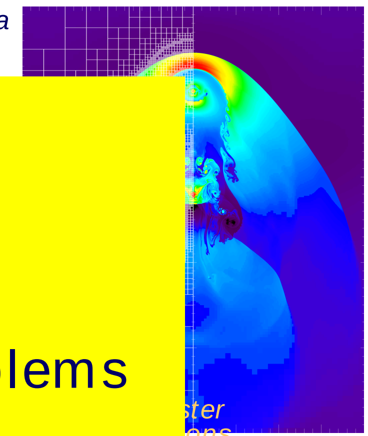
Compressed turbulence



Type Ia Supernova



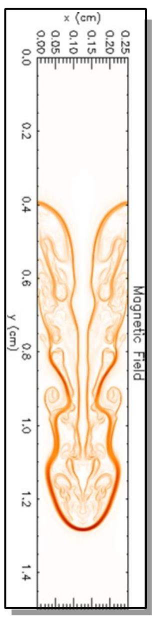
Flame-vortex interactions



...ster ...ons

The *Flash* code:

- ➔ AMR high-speed reactive flow solver
- ➔ Lots of additional physics
- ➔ Is modular / well architected
- ➔ Can solve a broad range of (astro)physics problems
- ➔ Is highly portable
  - Runs on most available massively-parallel systems
  - Runs on this laptop
- ➔ Scales and performs well
- ➔ Carefully tested and validated
- ➔ Is available online: http://flash.uchicago.edu



Magnetic Rayleigh-Taylor

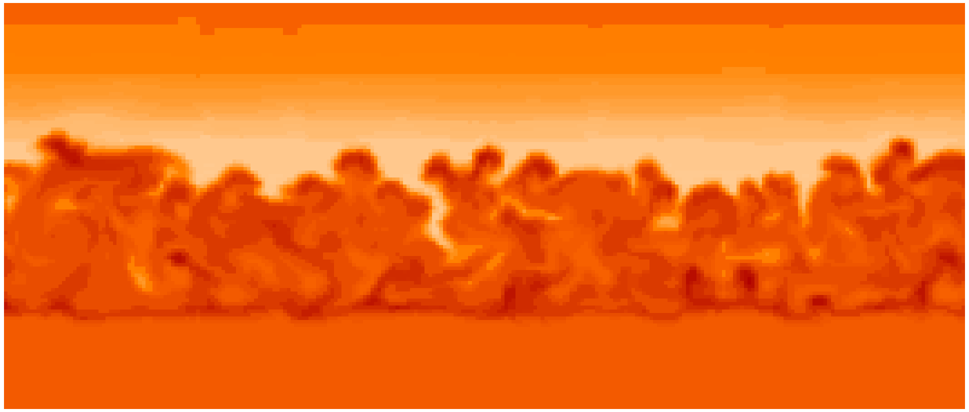
Cellular detonation

Helium burning on neutron stars

Orzag/Tang MHD vortex

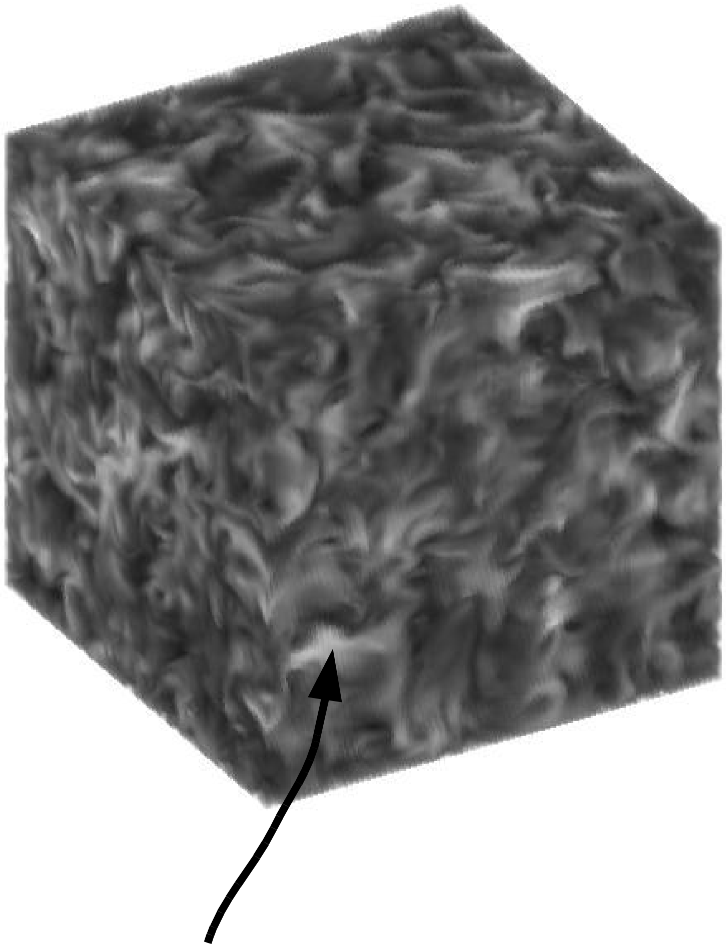
Richtmyer-Meshkov instability

Smoldering/Simmering



- Can happen over very long timescales (~1000 yrs)
- Secular increase in temperature
- Relatively little fuel depletion
- Convective motions
- Burning doesn't propagate

Turbulent Ignition

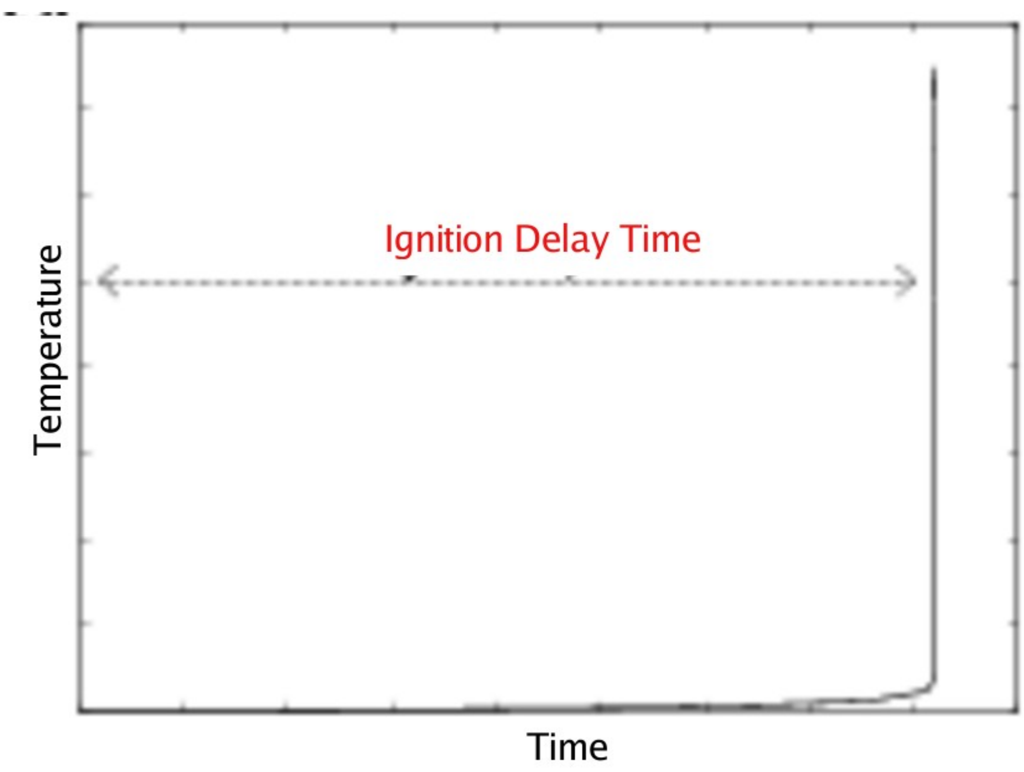


Does this hotspot ignite a flame?
Detonation? Or just fizzle?

- Lots of little hotspots
- #, size of igniting points can change how explosion looks
- Stochastic ignition – mechanism for variability?
- Ignition has been a complete unknown

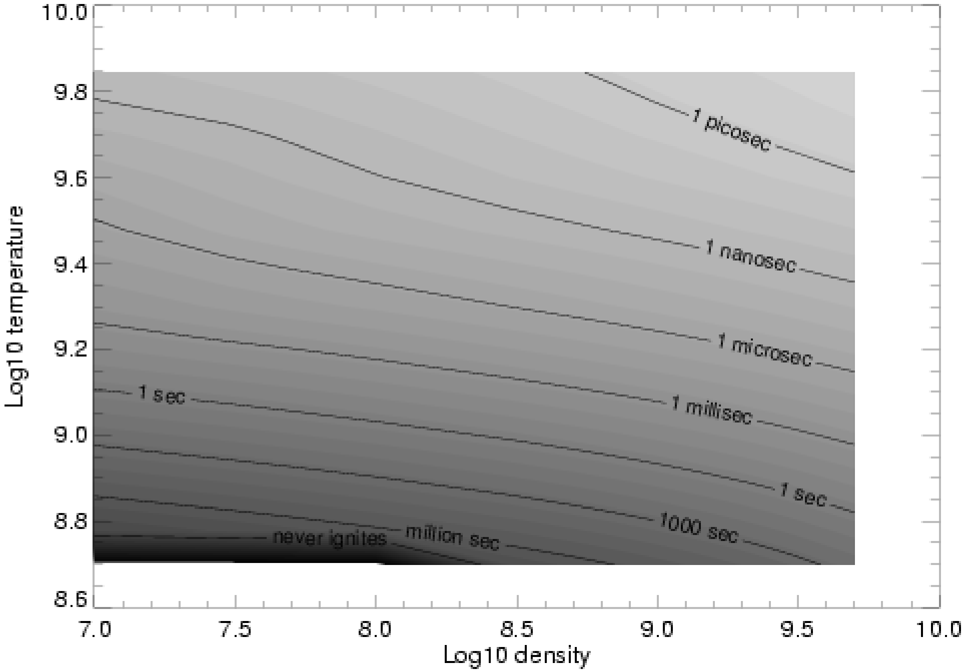
Simplest Ignition: One zone models

- Consider ignition in one zone
- Long leadup to runaway
- What are ignition delay times?
  - Only if ignition timescale faster than hydro, diffusion, can zone ignite



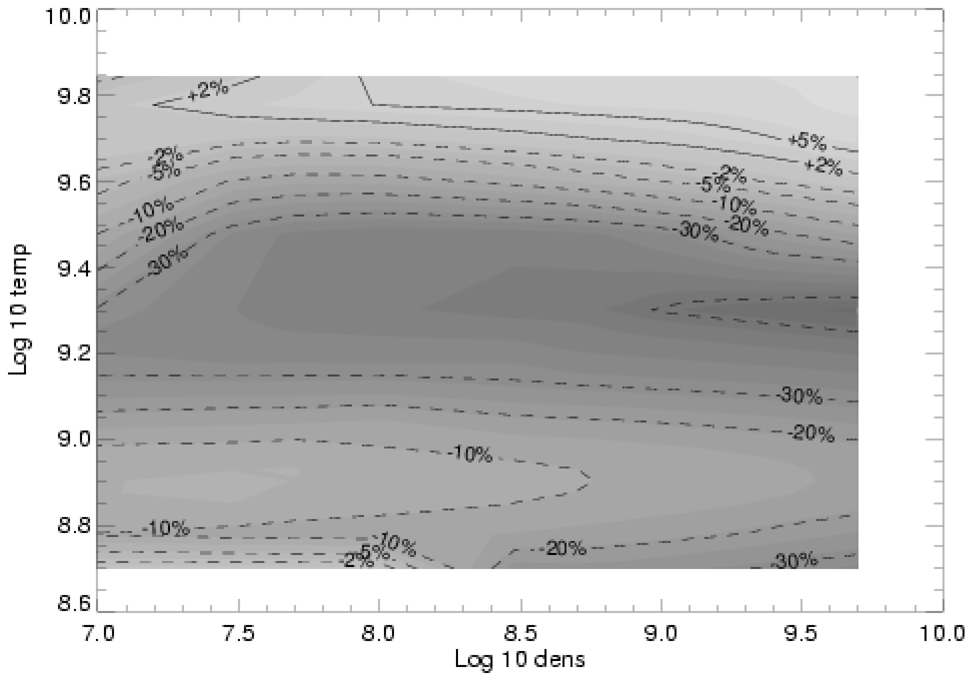
Ignition Times

- Large (7000++ calculations) parameter study of ignition time as function of dens, temp, composition.
- Fairly simple fitting functions
- With F. Timmes, LANL



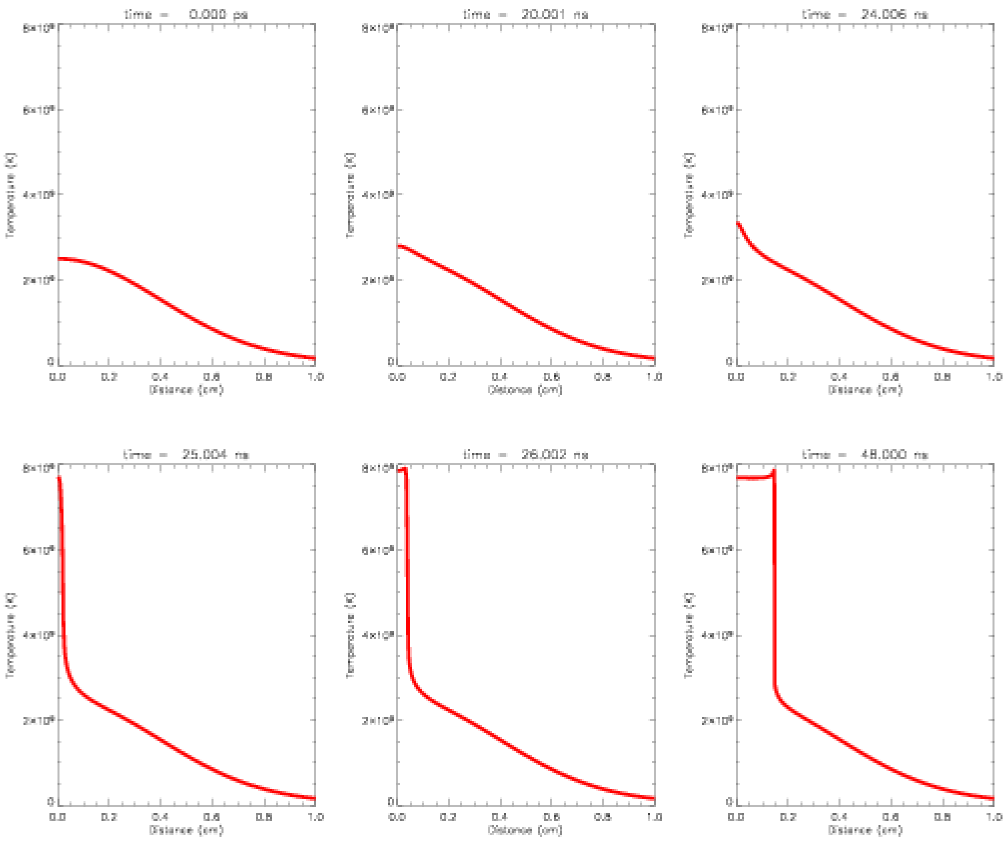
Ignition Times

- Surprise:
  - Metallicity reduces ignition time
  - Even modest amount of added Neon can reduce ignition times 20-30% +
  - Ignition occurs at **rare** peaks at tails of PDFs; this can greatly increase probability of points igniting.
  - Different state at ignition time for metal-rich WD?

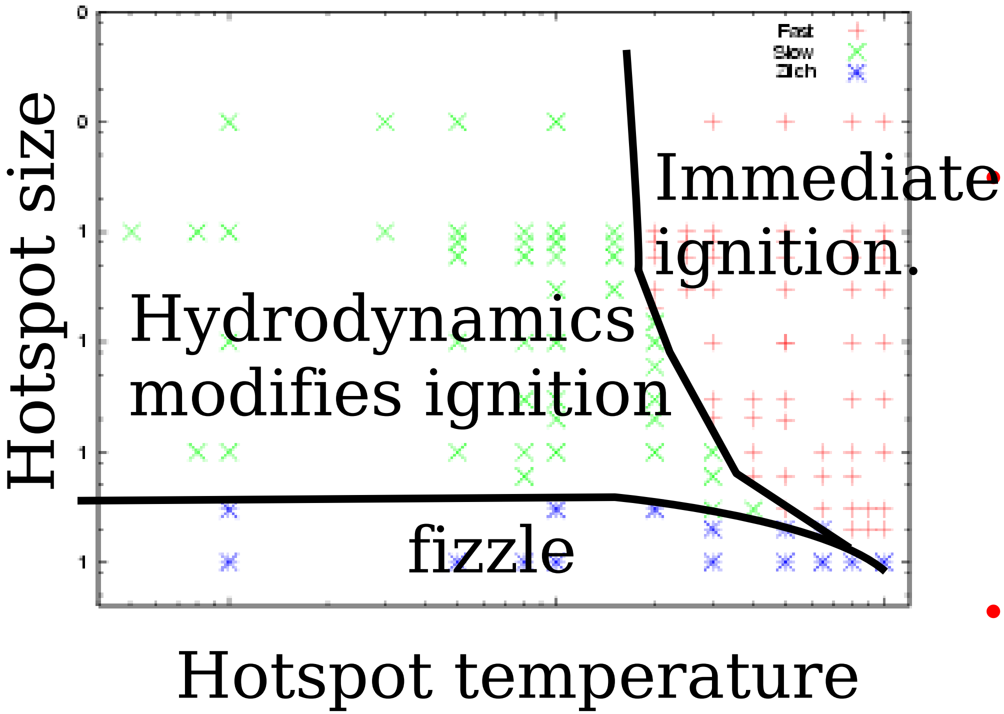


Isolated spherical hotspots

- Given one-zone results, start including other physics
- Thermal conduction, hydrodynamics compete with burning
- 1d spherical hotspot ignition
- With D. Doucette, SMU/CITA
- What are the `flammability limits?'



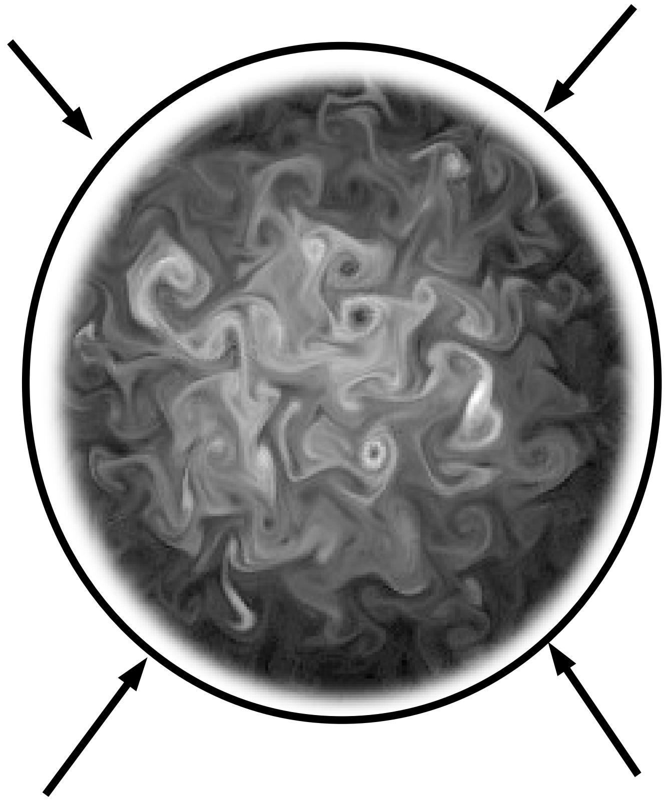
Isolated spherical hotspots



- Big parameter study largely done
  - $(\lambda, \rho, T_o, T_{max})$
- Scaling roughly consistent with analytical expectations, but high accuracy matters for tail of turbulent PDF
- Work to extend parameter study, complete analysis ongoing.

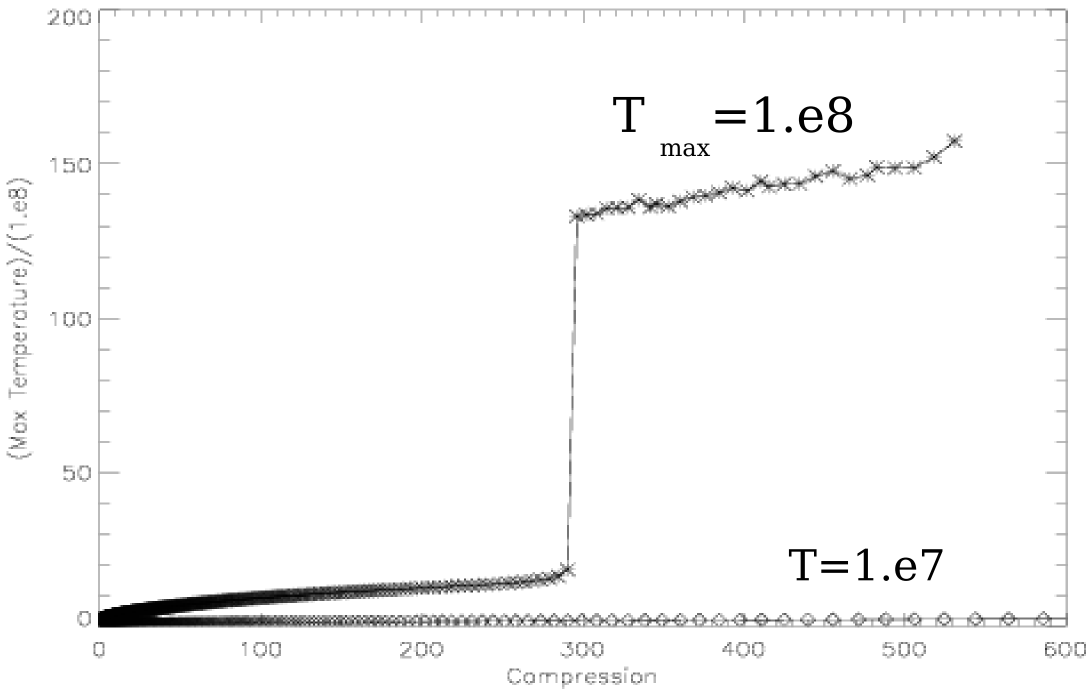
Crushed hotspots

- What if assumption of quiescent medium fails?
- Region of large compression (pulsational detonation model, WD mergers)
- Simulations examining large-scale compression can't see small hotspots
- How much easier does turbulence make ignition in compressed region?
- Work done with C. Hiratsuka, SMU/CITA

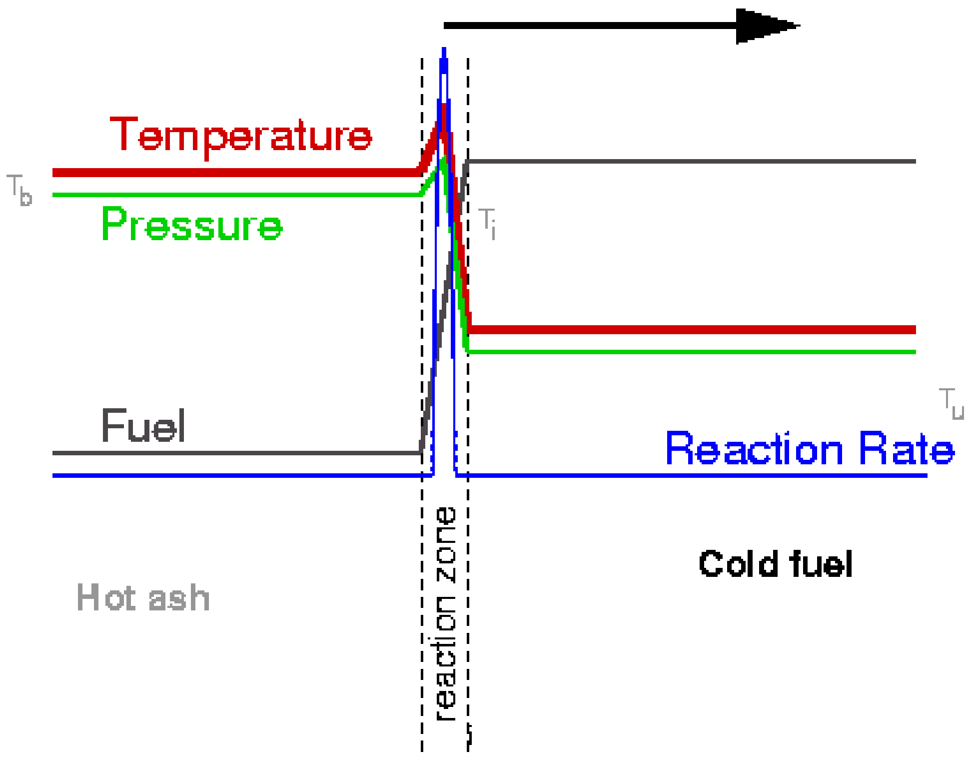


Crushed hotspots

- Large parameter study largely completed
  - $(\lambda, \rho, T_o, T_{max}, \tau)$
- Compression timescale $\tau \sim$ ignition timescale
- Can start to answer: `how much is ignition threshold lowered with turbulence'?
- Work to extend parameter study, complete analysis ongoing.



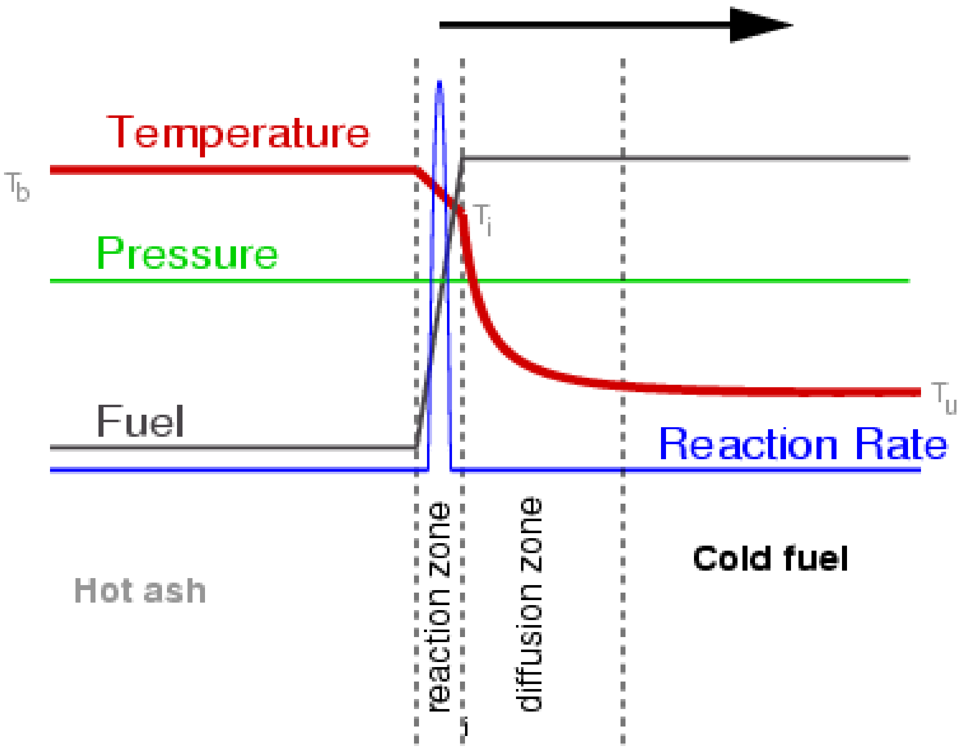
Detonations



- Supersonic burning
- Shock wave heats, compresses fuel
- Fuel ignites, driving shock
- Detonation speed depends on total energy release and compressibility
- Not easily quenched, accelerated

Deflagrations (flames)

- Subsonic burning wave
- Very slow
- Heat diffuses outwards, igniting more fuel
- High temperature dependence (like chemical flames):
  - Narrow reaction zone
  - Wide diffusion zone
- Flame speed depends on reactions, diffusion

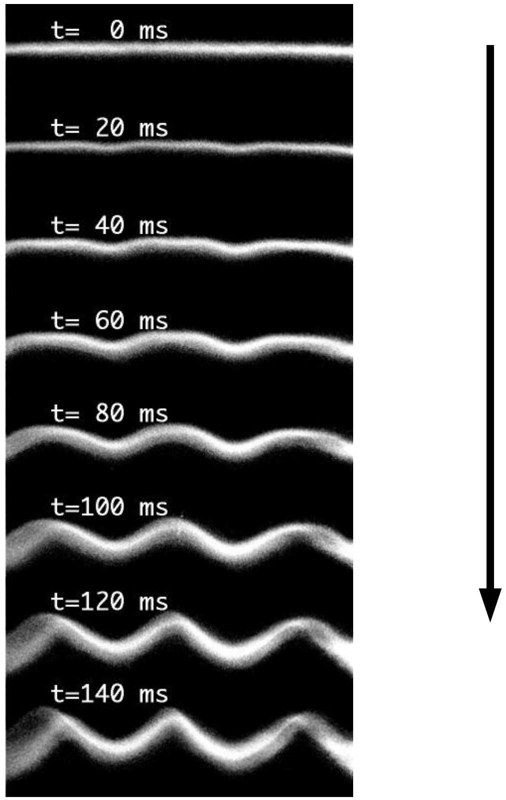


Burning in Supernova

- Simmering happens over long time (in some scenarios) – then rapid burning begins.
- Detonations are fast, energetic enough that they can't easily be quenched
- \`Prompt' detonation turns entire white dwarf into Nickel
  - This isn't seen
    - Light curve
    - Intermediate elements in ejecta
- Flame doesn't burn fast enough to give supernova energetics
- Burning wave must begin as flame, accelerate.

Landau-Darrieus Instability

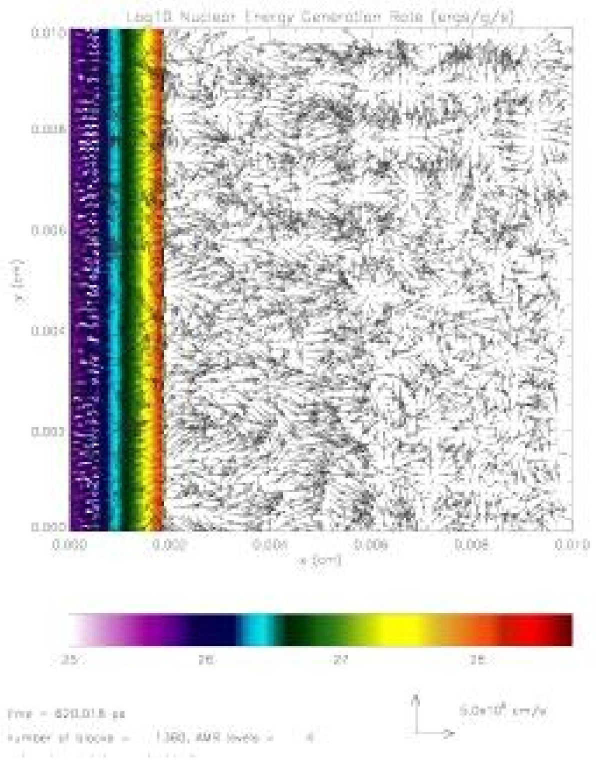
- Planar flame front
- Initial wrinkle grows in time
- Driven by density jump across moving interface
- Grows fastest at small scales
- More wrinkling → more surface area → more burning

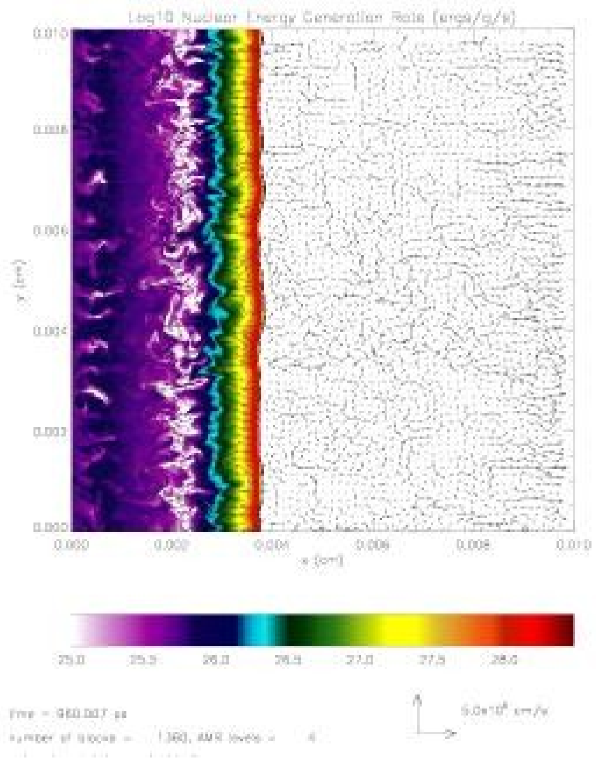


Clanet & Searby (1998)

Effect of Curvature, Strain

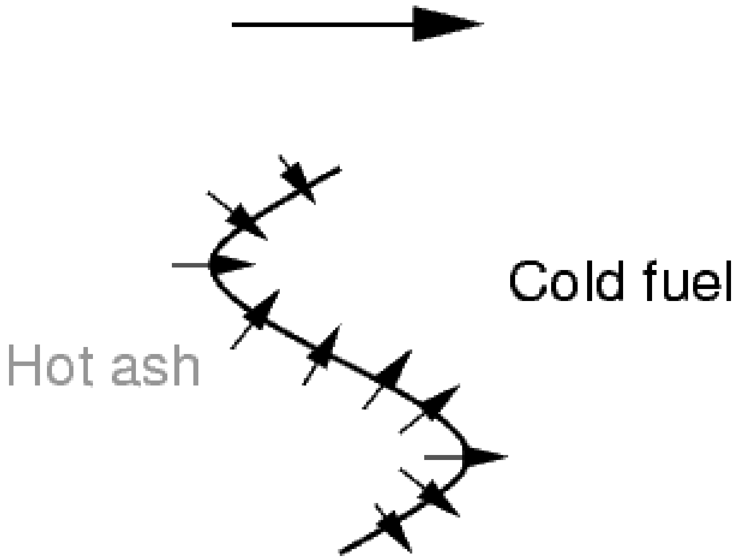
- Why does this flame remain so flat?



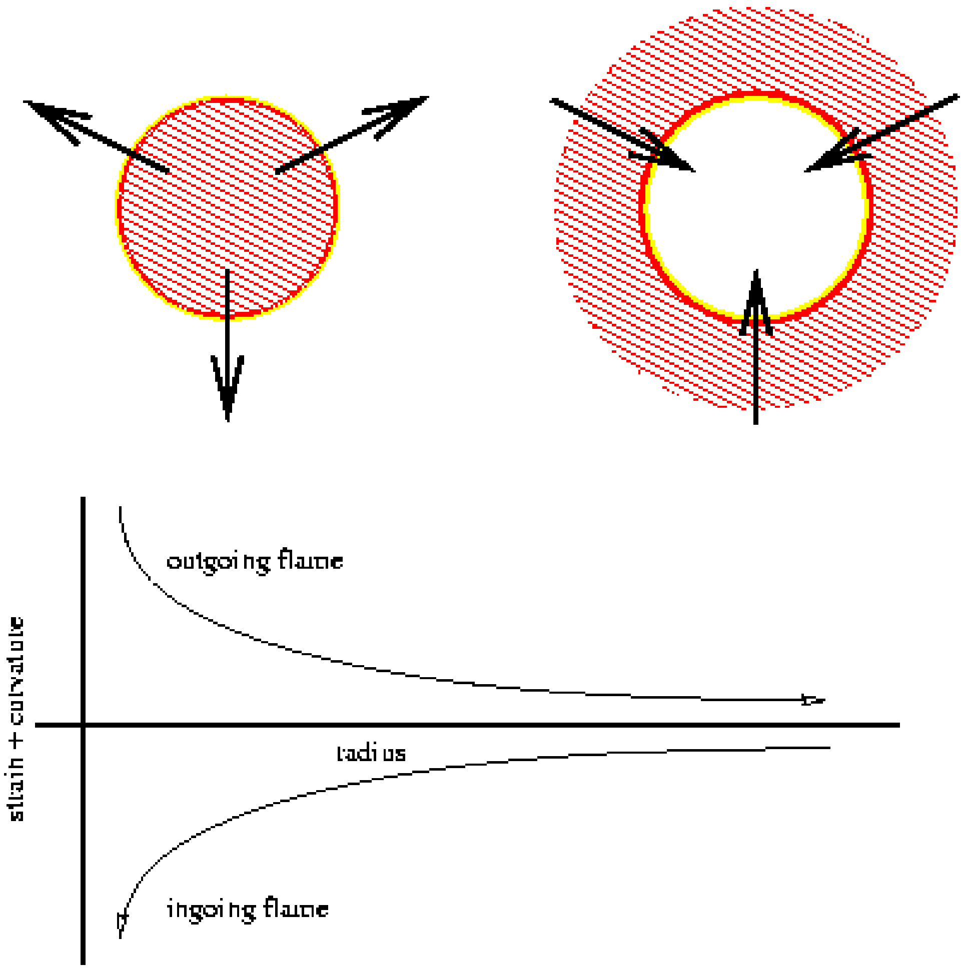


Effect of Curvature, Strain

- Geometry affects heat transport
  - Negative curvature focuses transport, speeding flame
  - Positive curvature dilutes transport, slowing flame
- Flame resists wrinkling on small scales.
- Chemical flames have species diffusion which counteracts this



Physical Setup



- Inward/outward propagating 1d spherical flame
- Ignite w/ top-hat hot ash region beside cold fuel
- Flame ignites, propagates
- At different radii, strain+curvature varies
- Can read off flame velocity vs. strain+curvature
- With M. Zingale (Chicago)

Results

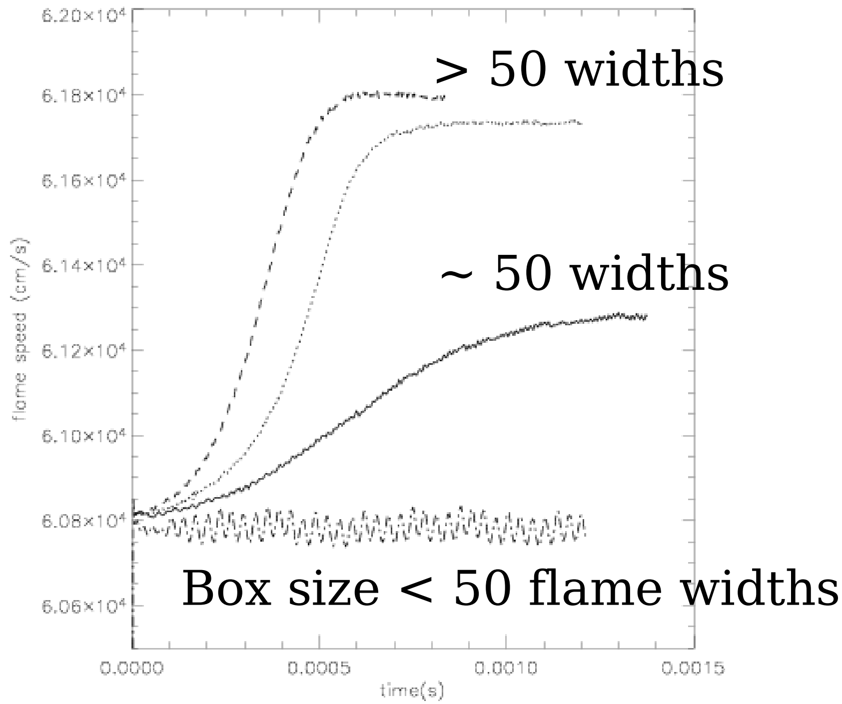
- Lack of species diffusion means that astrophysical flames act against strain/geometry to flatten
- Effect depends on composition, weakly on density (degeneracy)
- Quantified effect can be put into (eg) level-set method to improve models
- Given predictions for turbulence, can build increasingly accurate models for burning in turbulent velocity field.

Predictions

- Flame Stability
  - Stable to LD on different scales, depending on composition
    - ~10 flame thicknesses (pure carbon)
    - ~50 flame thicknesses (50% carbon)

Predictions confirmed:

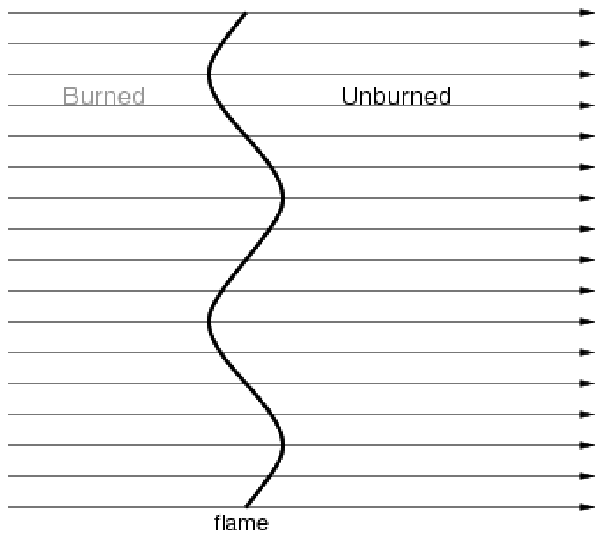
- UCSC, LBL CCSE
  - Fully resolved multidimensional simulations of LD
  - Various densities, 50% Carbon/Oxygen flames
  - Instabilities completely suppressed if box < 50 flame widths; partially suppressed at 50; unsuppressed at larger sizes

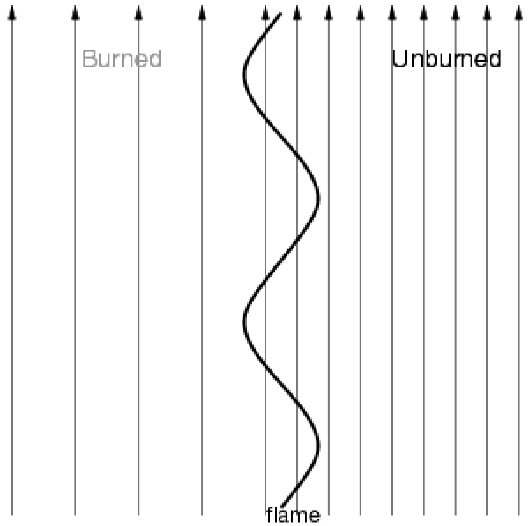


Effect of Magnetic Fields

- Landau-Darrieus: Purely hydrodynamic
- Significant Magnetic Fields on some white dwarfs:
  - Surface fields: $10^8 – 10^9$ G
  - Interior fields: ?? but potentially much higher
- Naively, magnetic field lines will provide tension against wrinkling

Magnetic Landau-Darrieus



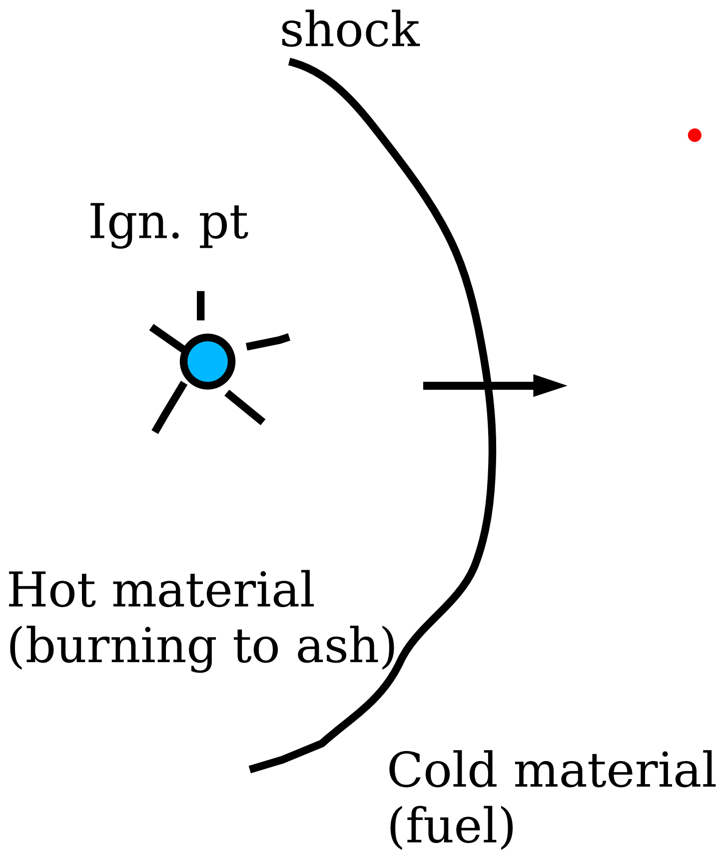


- Consider flame as thin interface propagating parallel to or perpendicular to magnetic field lines
- Perform linear theory analysis

Results

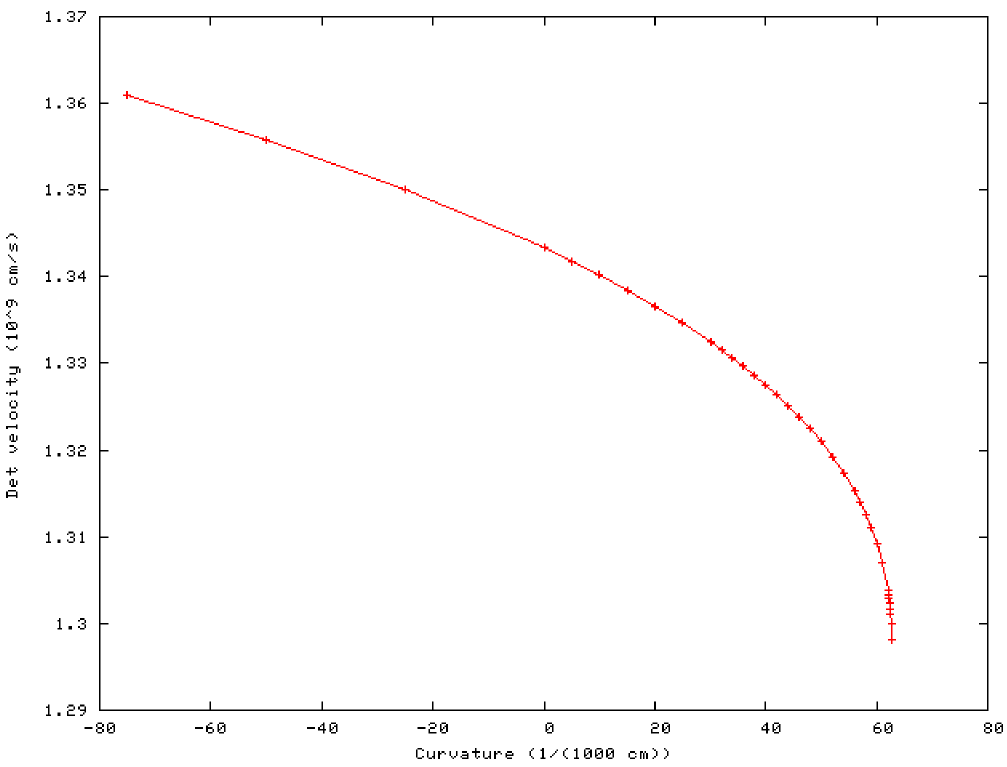
- Globally likely small effect in White Dwarfs
  - Local importance? Turbulence will rapidly generate regions where speeds are comparable (Cattaneo 1999)
- Globally important on surface of neutron stars
- Trans-Alfvénic regime?
  - Flame can grow slowly, but emit forward Alfvén waves
  - Flame-generated magnetic turbulence?
- Apart from instabilities, magnetic field can also directly effect flame speed

Detonation from a point



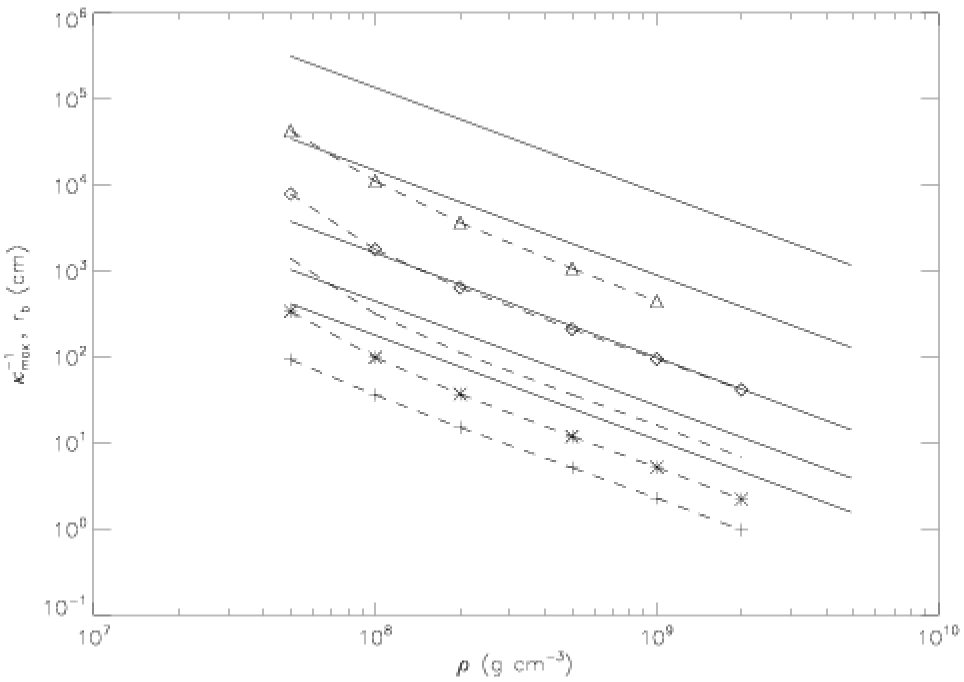
- Detonation – shock-propagating burning
- Ignition of Detonation by shock:
  - Shock must **slow down** to detonation speed before steady detonation can ignite
  - Naively, this gives condition for detonation: r(v = shock speed) = ignition thickness
  - This condition **far** too leniant!

Detonation from a point



- Can calculate steady state shock speed, structure as function of curvature
- Curvature **greatly** affects shock speed
- (More than flame; directly modifying burning region)
- Beyond certain curvature, no steady detonation exists

Detonation from a point

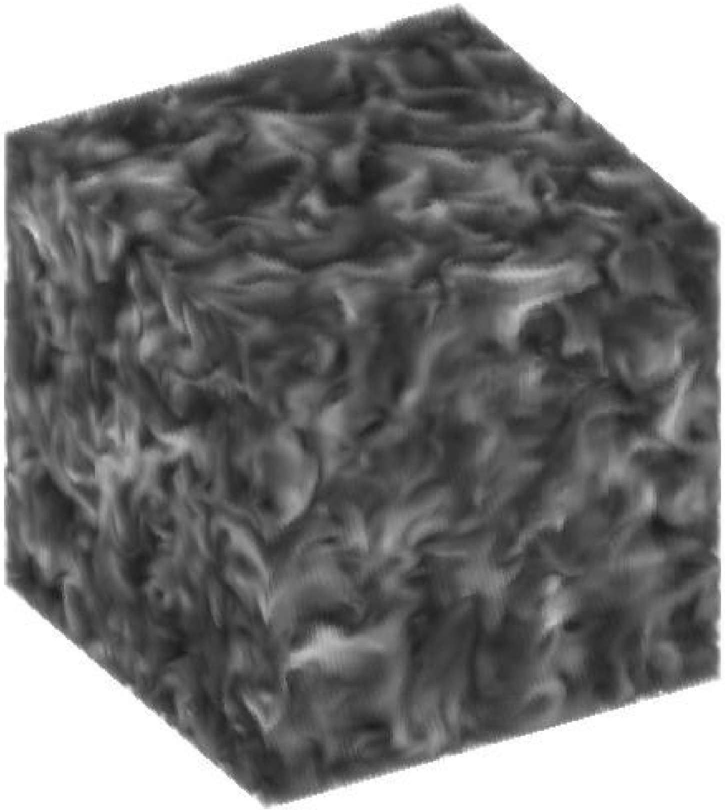


- Required size of hotspots ~ 4500 detonation thicknesses!
- Meters to ~km.
- Very hard to get that large a local ignition
- Hard to have local-powered detonation ignition

Towards larger scales

- Ignition, flames, are small scale very complex pheonomeon
- Considerably better understood, can be inputs into large scale simulations
- Intermediate scales:
  - Reactive White Dwarf Turbulence
- Large scales:
  - Merging white dwarfs
  - Pulsational Explosions
  - Single white dwarf

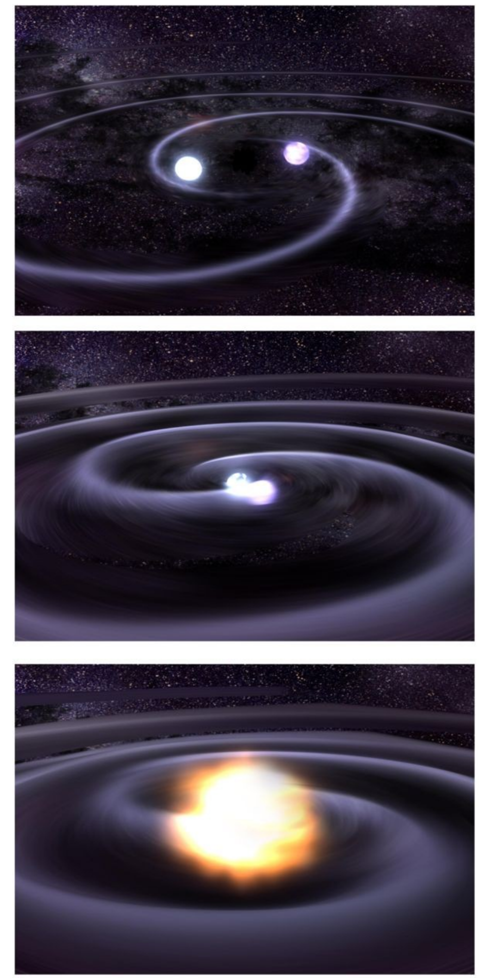
Reactive WD turbulence



- Turbulence generated by convection increasingly understood
- Can do `turbulence in a box' simulations to carefully examine resulting temperature PDFs
- Given what we know about hotspots, can start to understand connection between turbulence & ignition
- Starting now, but will need low-speed hydro solver...

Merging White Dwarfs

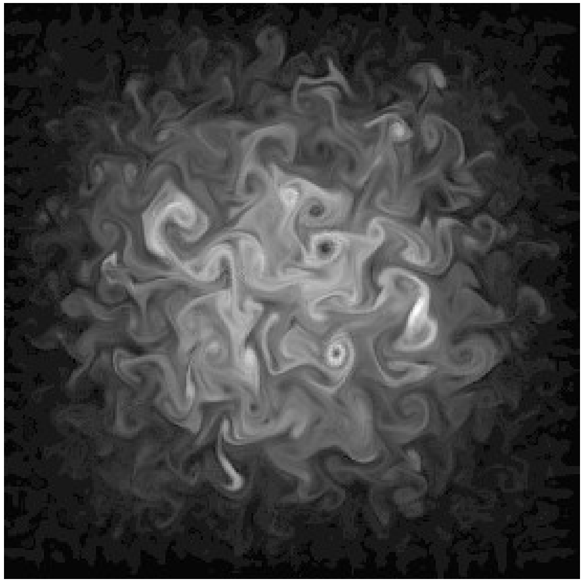
- One mechanism for Type Ia
- Cannot resolve small-scale turbulence
- But can potentially plug in its effects
- Large scale 3d simulations, FLASH (Gadget?)
- With N. Ivanova (CITA)



NASA/GSFC/T. Strohmayer

Pulsational Detonation

- In this scenario, initial \`explosion' fails, WD recollapses
- WD now has lots of velocities, hot ash; mixes in with fuel
- Recollapse triggers explosion (detonation?)
- Follow turbulence as far as possible, interpolate and use info from crushed hotspot simulations.



Conclusion

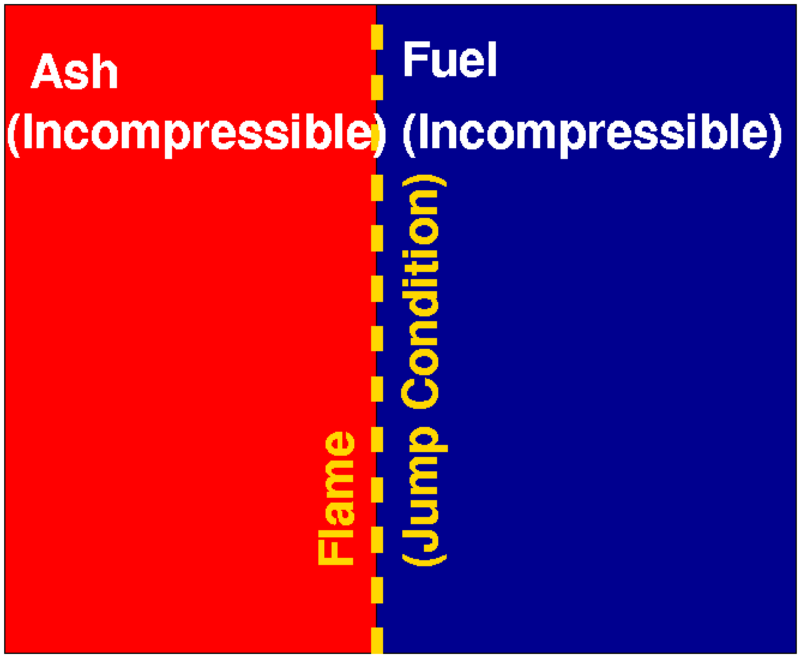
- Slowly understanding pieces of the Type Ia problem
- Field still wide open
- Great computational problem: interesting physics to look at from 1-zone integrations to large-scale 3d global simulations.
- New code/algorithm development needed (low-Mach number solvers)
- Many different scenarios to examine. But even the ones that don't turn out to generate Type Ia **do** occur, and are almost certainly observable

Effect of Curvature, Strain

flame speed — planar speed — non-dim curvature/strain

- Markstein Relation $S_l = S_l^0 (1 + Ma\,Ka)$
- Flame speed linear in curvature + strain
- Very robust empirically for terrestrial flames.
- Astrophysical flames:
  - Does relation hold?
  - Magnitude of effect?
  - Can Ma be measured?
- Work done with M. Zingale, Chicago

Linear Stability Problem



$$[B_n]=0$$

$$[\varrho U_n]=0$$

$$\varrho U_n[U_t]-\frac{B_n}{4\pi}[B_t]=0$$

$$\varrho U_n[U_n]+[p+\frac{B_t^2}{8\pi}]=g z_f[\varrho]$$

$$[U_n B_t]+B_n[U_t]=0$$