First Flames: Burning, Turbulence and Buoyancy

Jonathan Dursi (CITA), Frank Timmes (LANL), Mike Zingale (SUNY SB)

CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut canadien d'astrophysique theorique

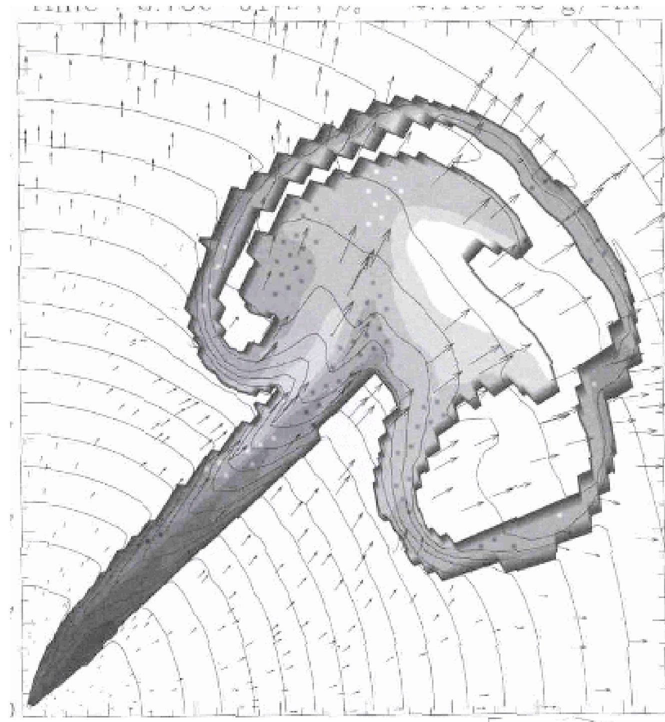
Flame Ignition

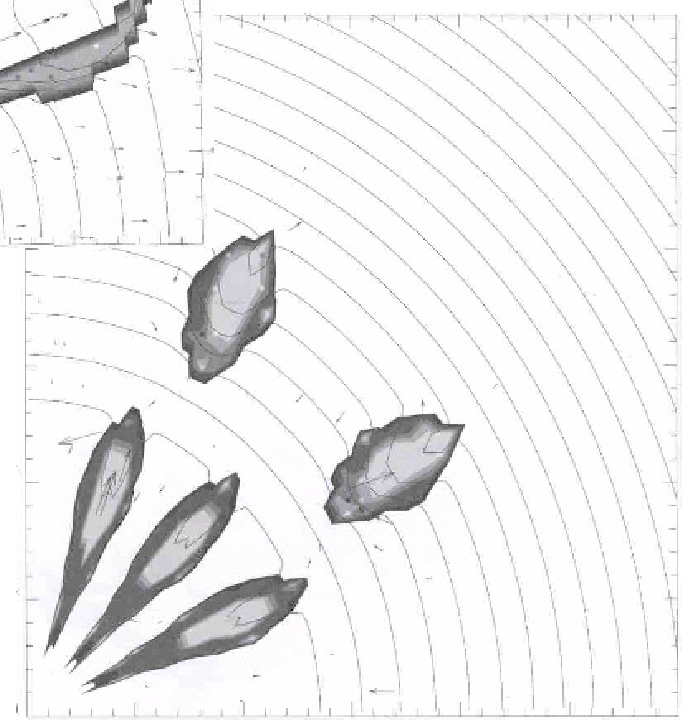
Nigel Gorbold, Univ. Colorado

- Highly nonlinear, transient phenomenon
- Interaction of nuclear reactions, conductivity, hydrodynamics
- Difficult to model

Ignition

- Turbulent conditions
- Many potential `flashpoints'
- Important to understand where/ when points do ignite

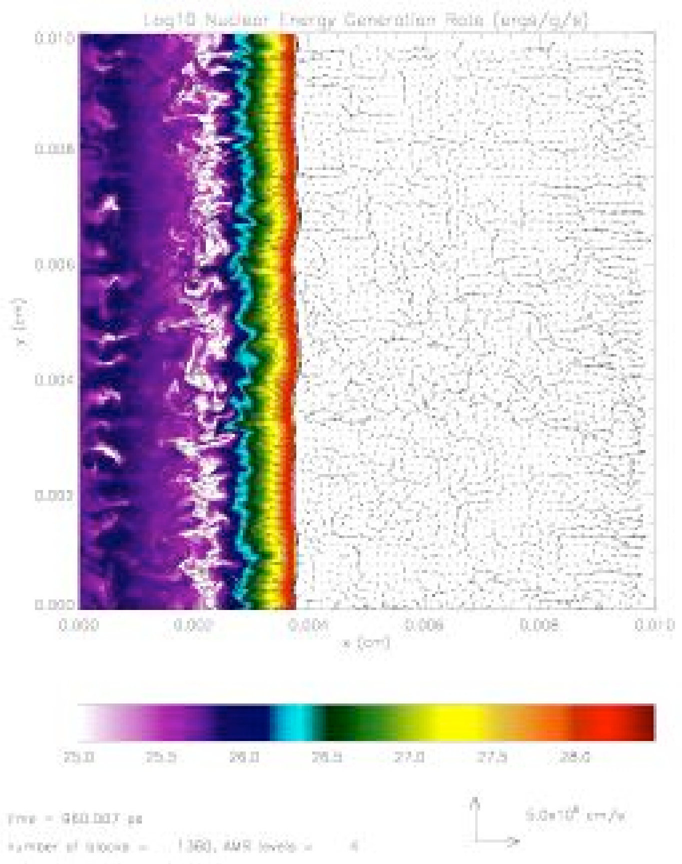




Niemeyer, Hillebrandt & Woosley (1996):

success of explosion can depend sensitively on number, location of ignition points

Early Burning



- Ignition can occur on ~cm scales
  - Not resolved by large-scale simulation
- For initial conditions in large-scale simulations, need to map
  - turbulence $\longrightarrow$ ignition points
  - ignition $\longrightarrow$ early flame bubbles

Outline

- Some notes on ignition
  - One-zone
  - Flame (ongoing)
  - Detonation
- Early burning: what happens next?
  - Characteristic size of flame bubbles
  - Flame model?

Our contributions

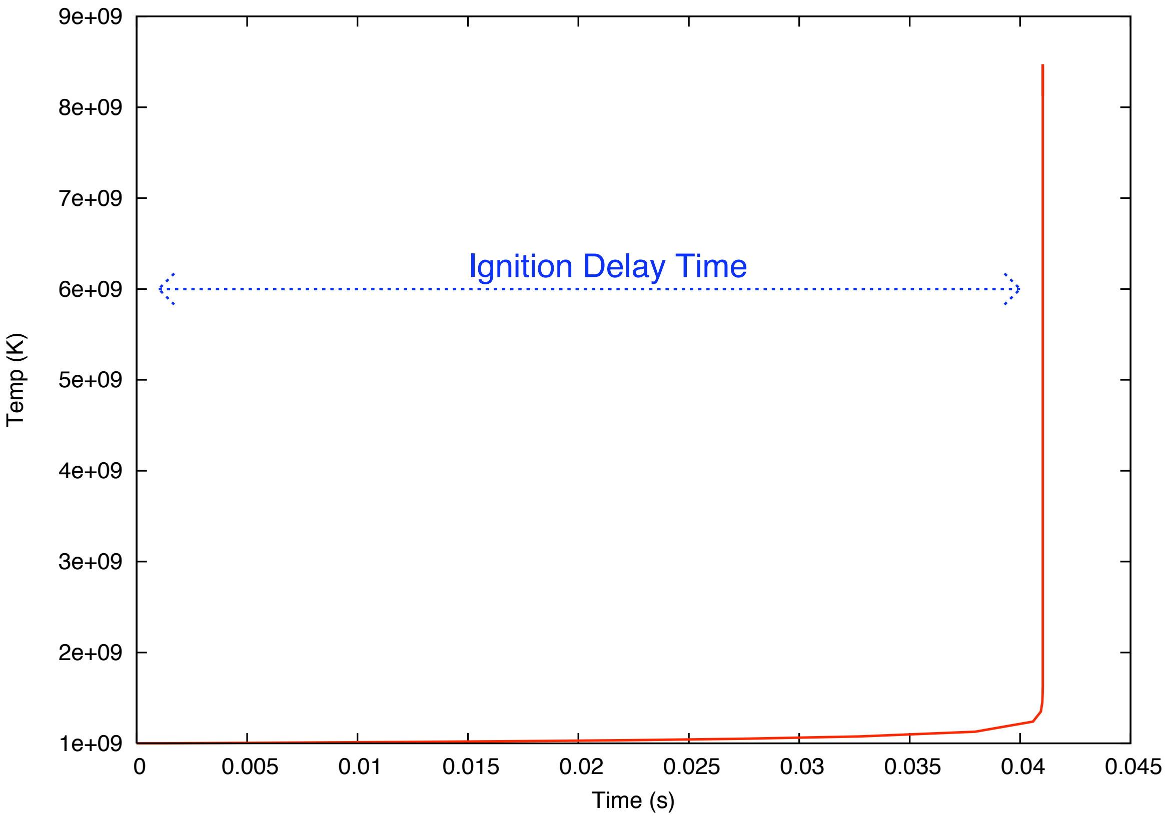
- Dursi & Timmes 2006:
  - One-zone ignition times
  - Very hard to ignite det^{n} at low densities: need much more than local supersonic flow. Geometric constraint.

Our contributions

- Zingale & Dursi 2007:
  - Under given conditions, there is a characteristic size of a flame bubble - larger is shredded by motions, turbulence
  - This characteristic size may lead to new flame model

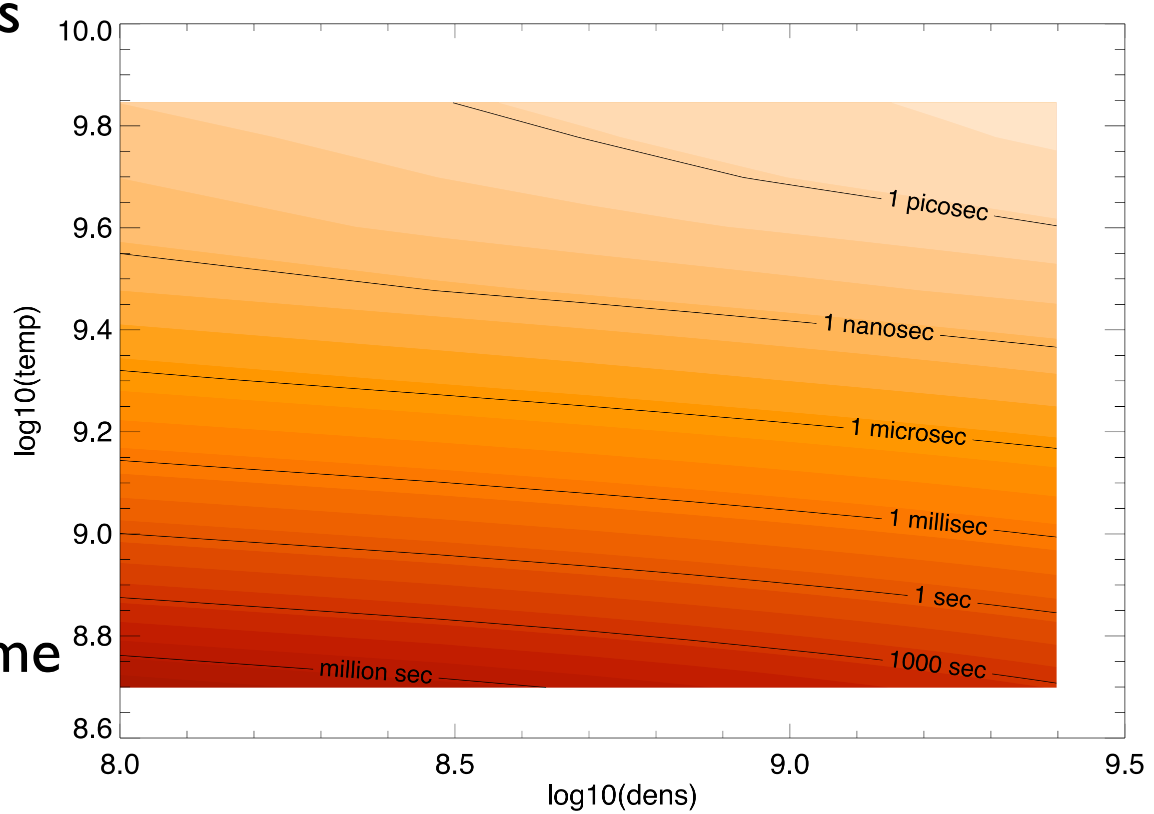
One-zone ignition

- Ignition: interaction of:
  - `chemistry'
  - hydrodynamics
  - conduction
- Even in one-zone model (no hydro, $cond^n$) not trivial



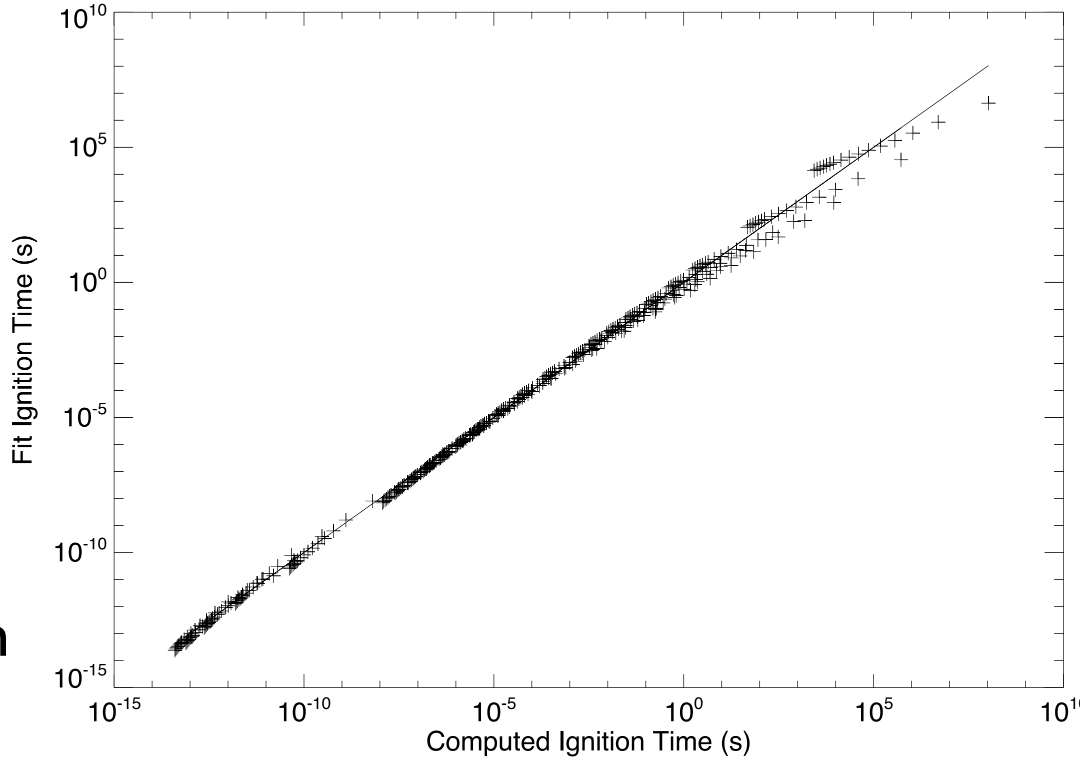
One-zone ignition

- `map out' ignition times for various conditions
- Density, temp, comp.
- Measurement of a `burning time'
  - ignition if burning time faster than flow, conduction times



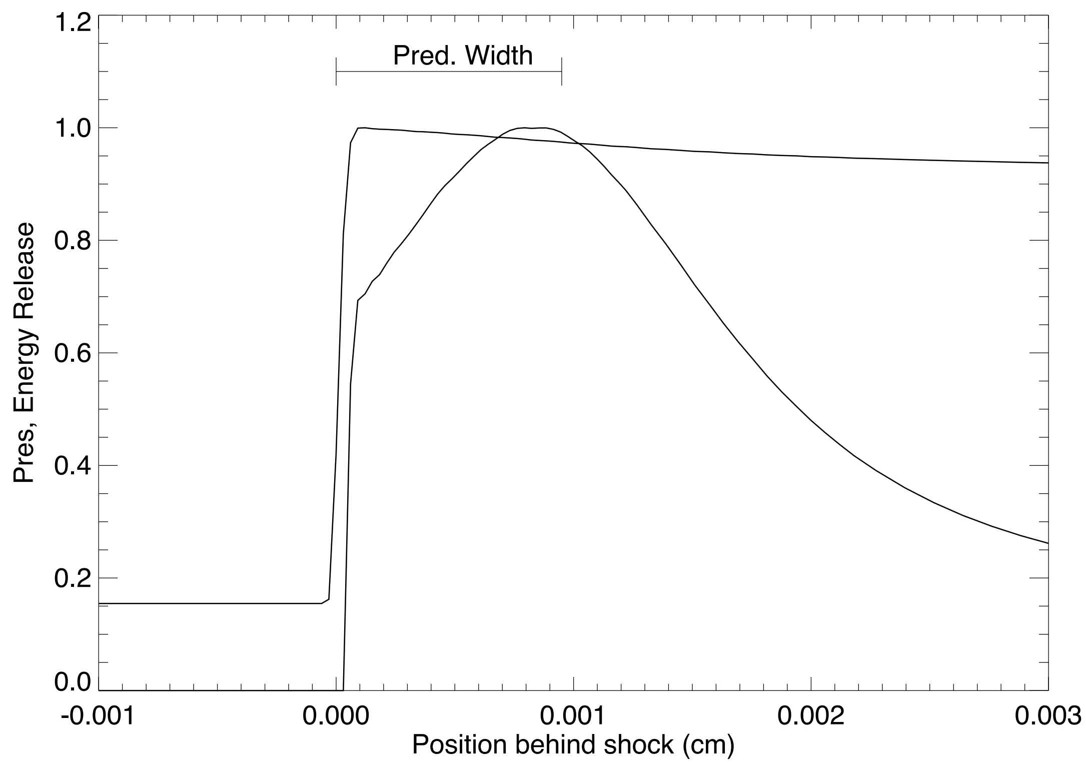
One-zone ignition

- ~7000 calculations
- Can build ignition time fitting function
- Quite good over ~15 orders of magnitude in ignition time
- Surprising dependence on composition - eg, even modest amount of Ne



One-zone ignition time

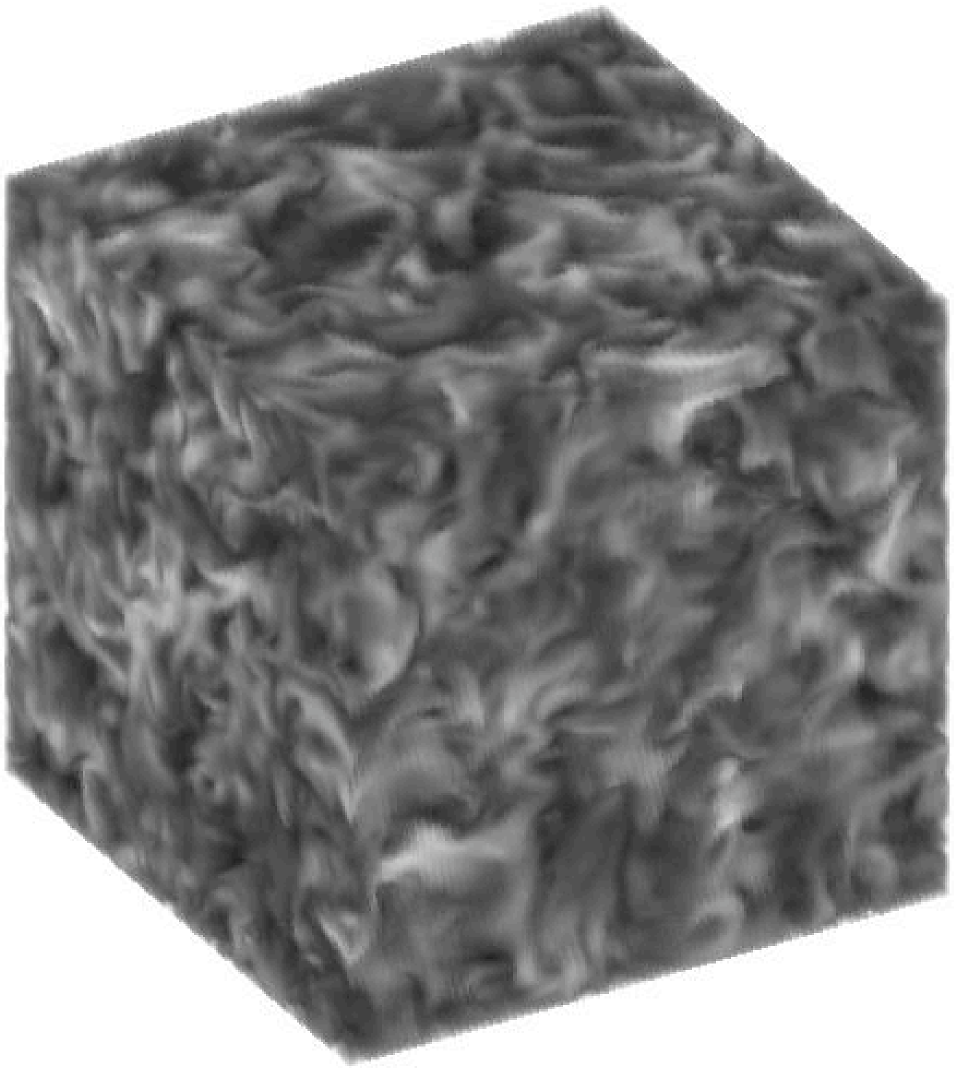
- Necessary input into ignition models
- Ignition time τ_i must be compared to flow (τ_h) and conduction (τ_c) time scales
- Also directly gives detonation thickness - distance behind shock where burning occurs



Flame ignition

- Only a small part of the question we really want answer to:

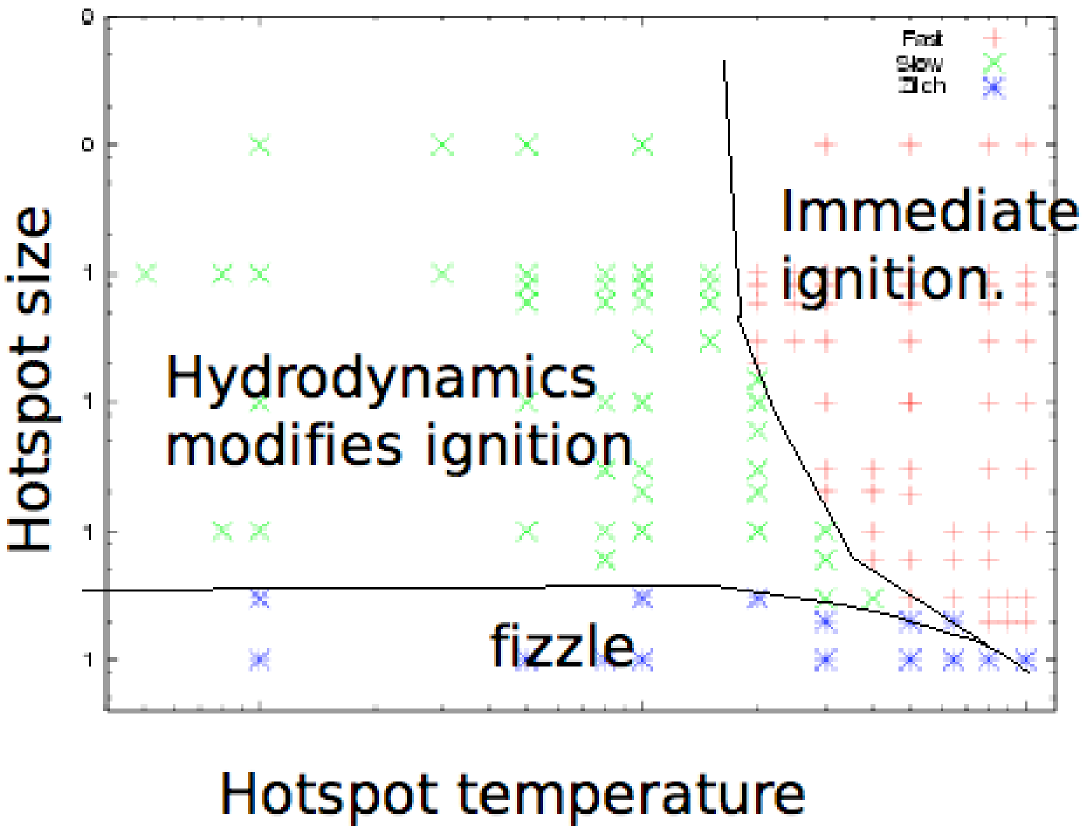
- Given a particular turbulent hotspot, can that point ignite before eddies/conduction diffuse it away?



Spark-ignited counterflow flames:
Mastorakos, Marchione, Ahmed, Balachandran, Cambridge

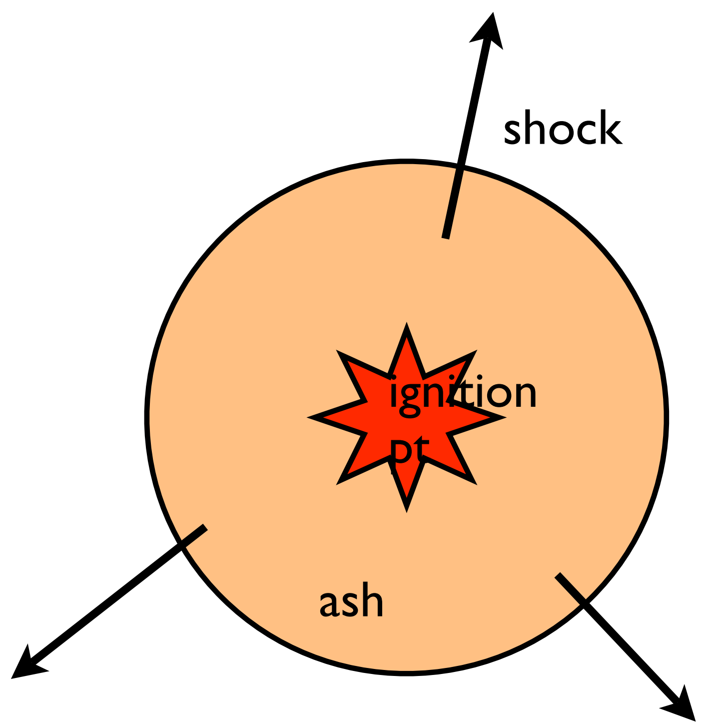
Flame ignition

- Simplified setup:
- Spherical gaussian hotspot, quiescent flow
- Even still, huge parameter space
- Work with undergraduate students Doucette, Hiratsuka, ongoing



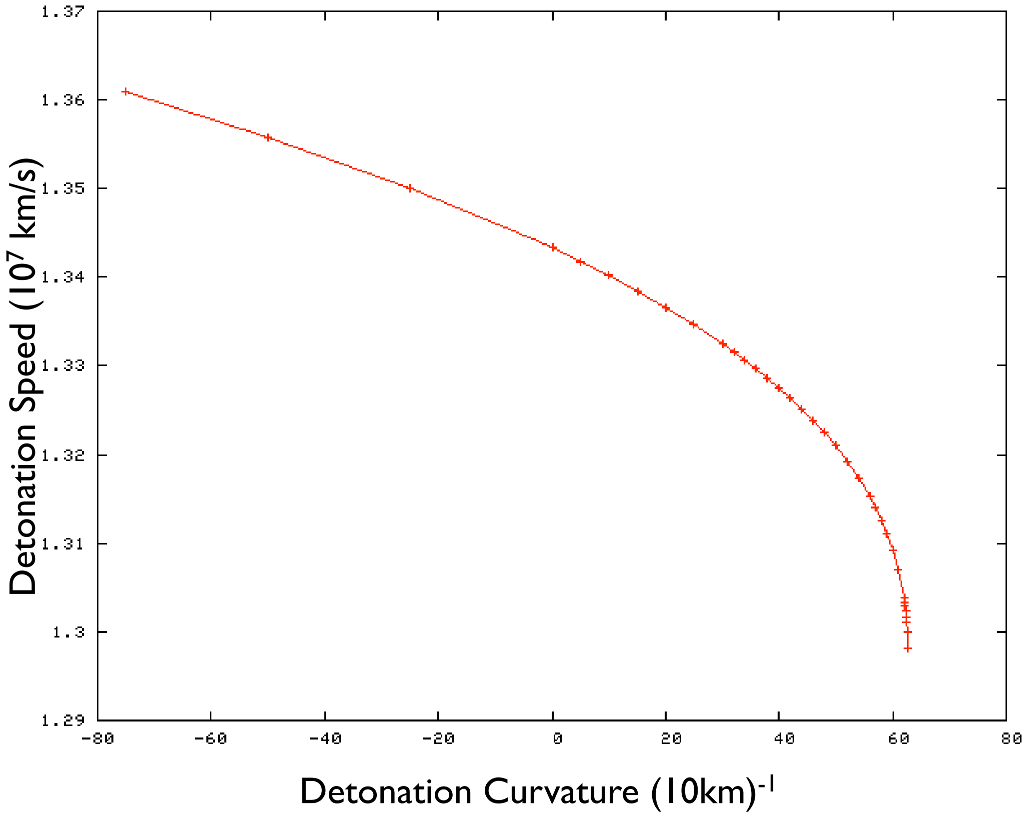
Detonation Ignition

- Ignition at a point -- drives hot shock
- Shock must *slow down* to detonation speed for detonation to ignite
- How big a region? Naively, about a shock thickness $(D\tau_i)$
- About a factor of 5000 too small!



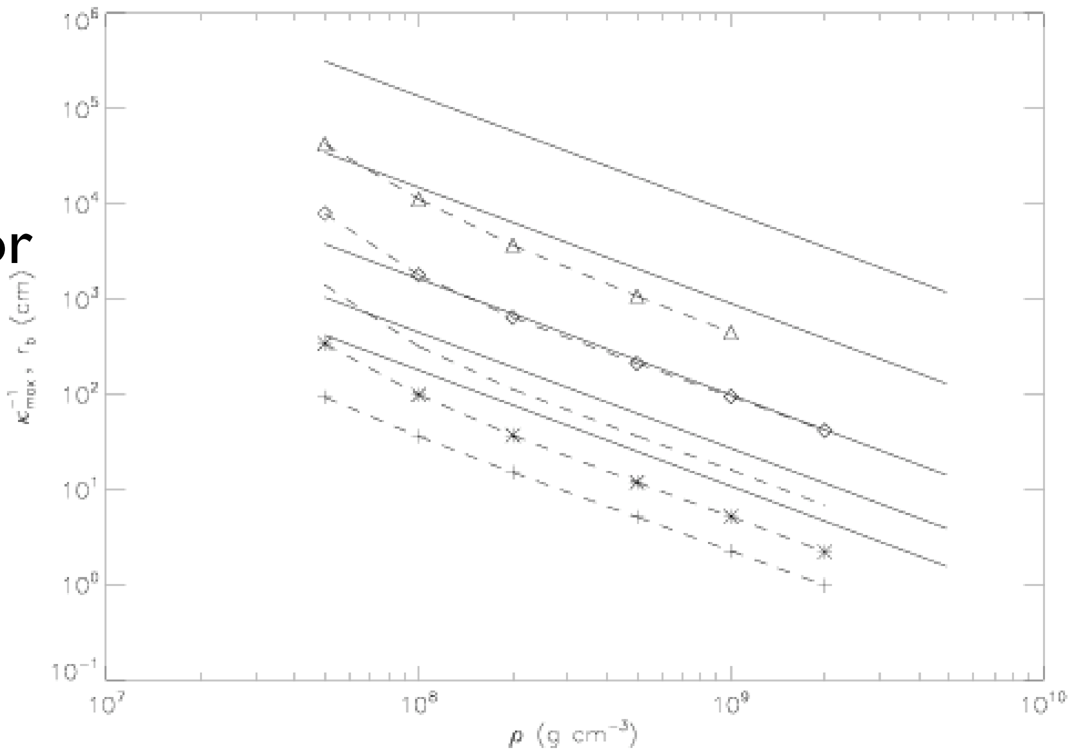
Detonation Ignition

- Curvature strongly modifies detonation
- Speed drops with curvature
- Beyond certain point, no steady detonation.
- Size of region must be ~5000 detonation thicknesses



Detonation Ignition

- Corresponding physical size of region grows rapidly with decreasing density
- By 5×10^7, already ~km for low carbon fraction
- **Hard** for purely local process to ignite detonation
- But **very easy** to spuriously numerically ignite detonation

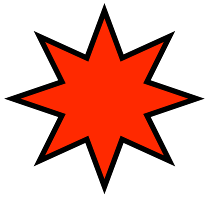


Outline

- Some notes on ignition
    - One-zone
    - Flame (ongoing)
    - Detonation
- Early burning: what happens next?
    - Characteristic size of flame bubbles
    - Flame model?

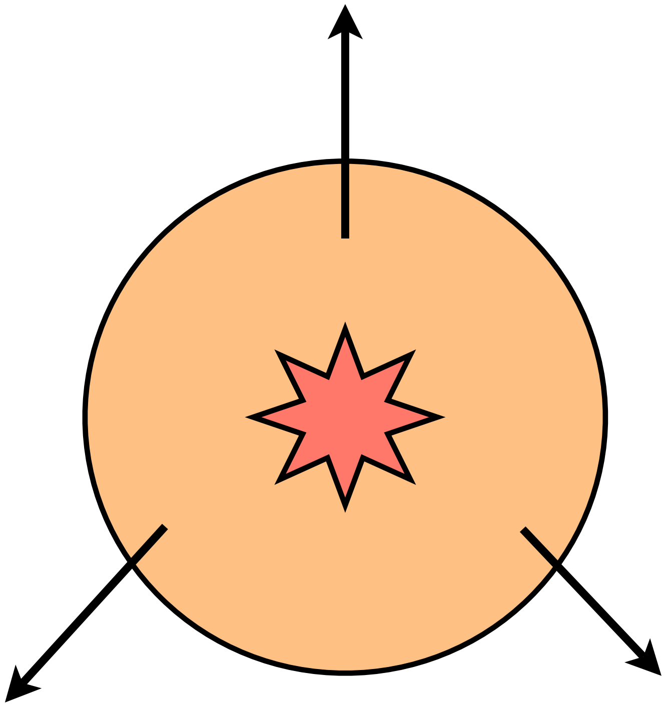
First Burning

- Once a point ignites, what can happen?



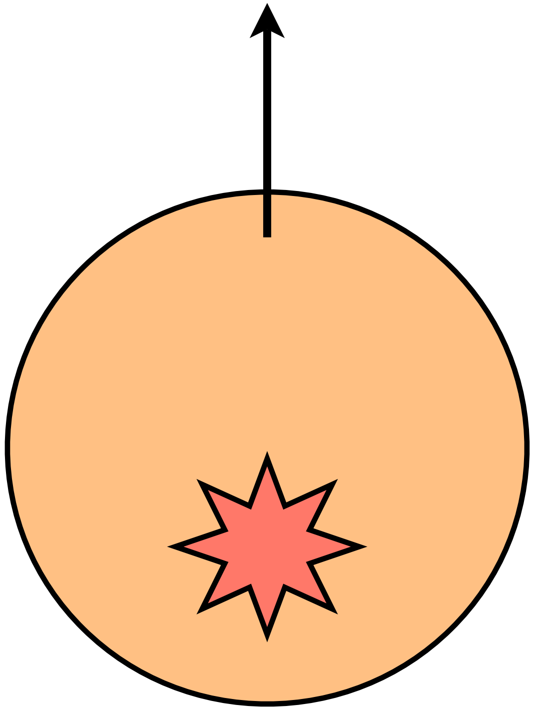
First Burning

- Once a point ignites, what can happen?
  - Spherical flame burning outwards



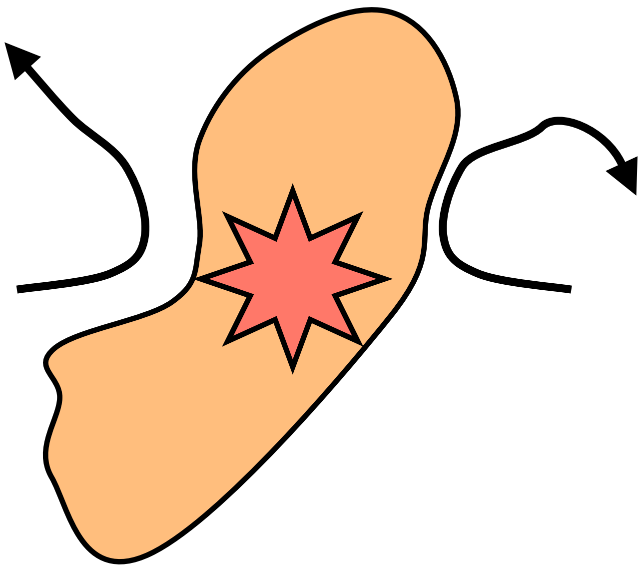
First Burning

- Once a point ignites, what can happen?
  - Buoyant rise



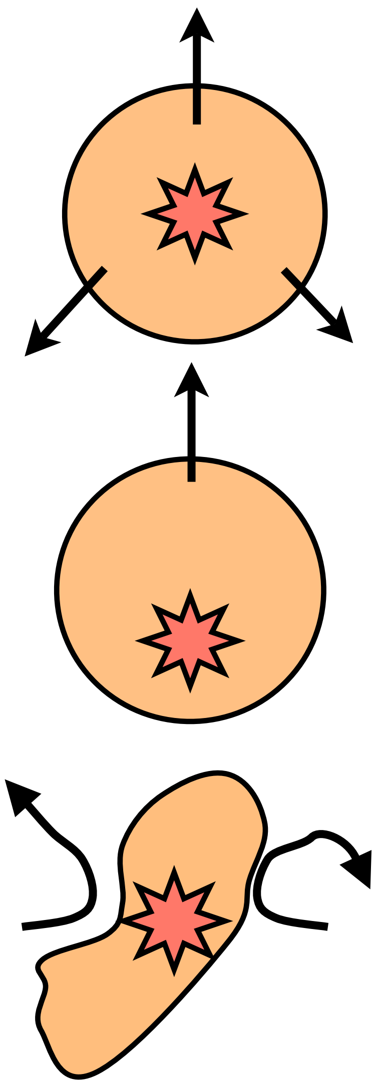
First Burning

- Once a point ignites, what can happen?
  - Distortion by turbulence

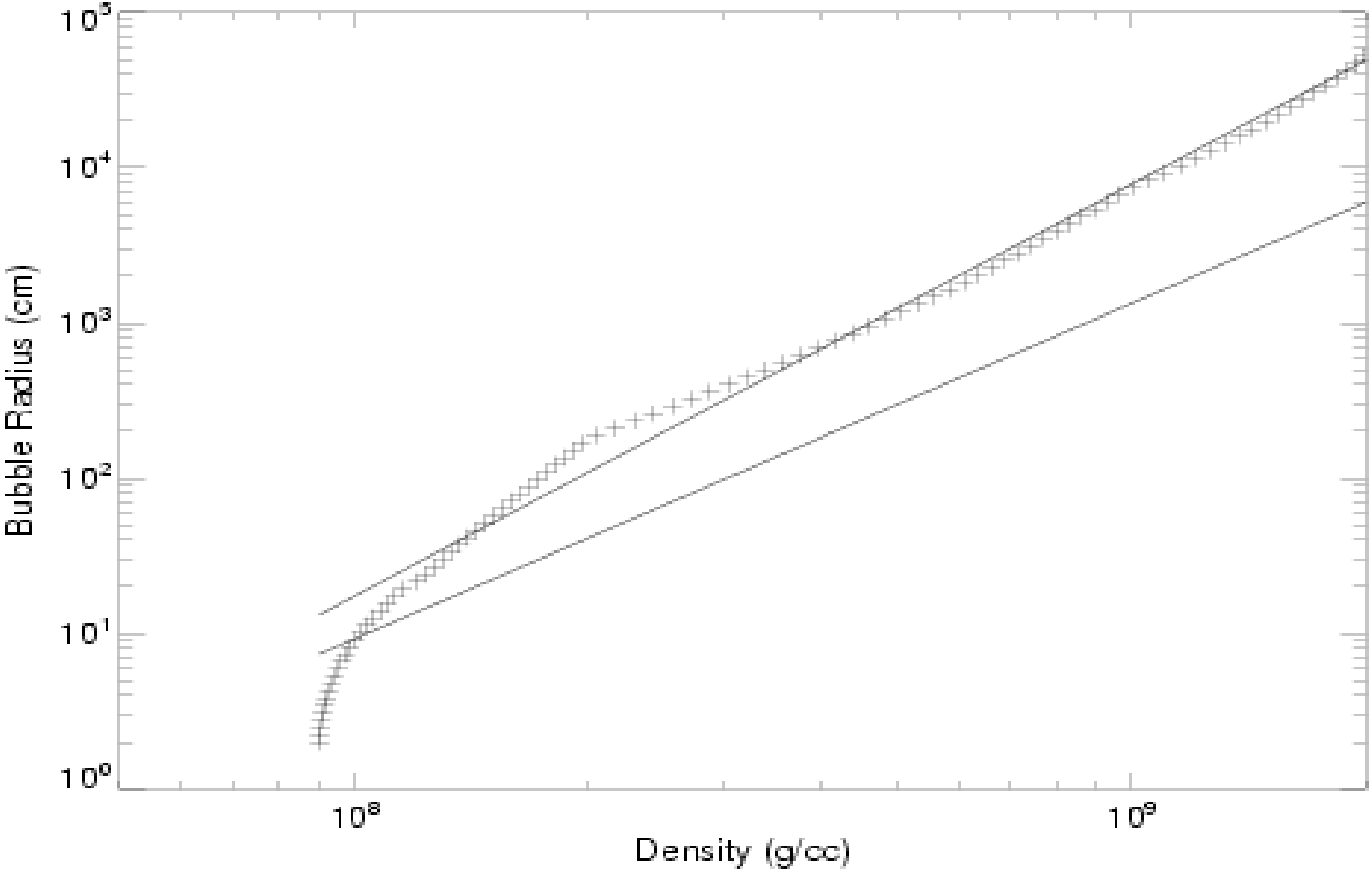


First Burning

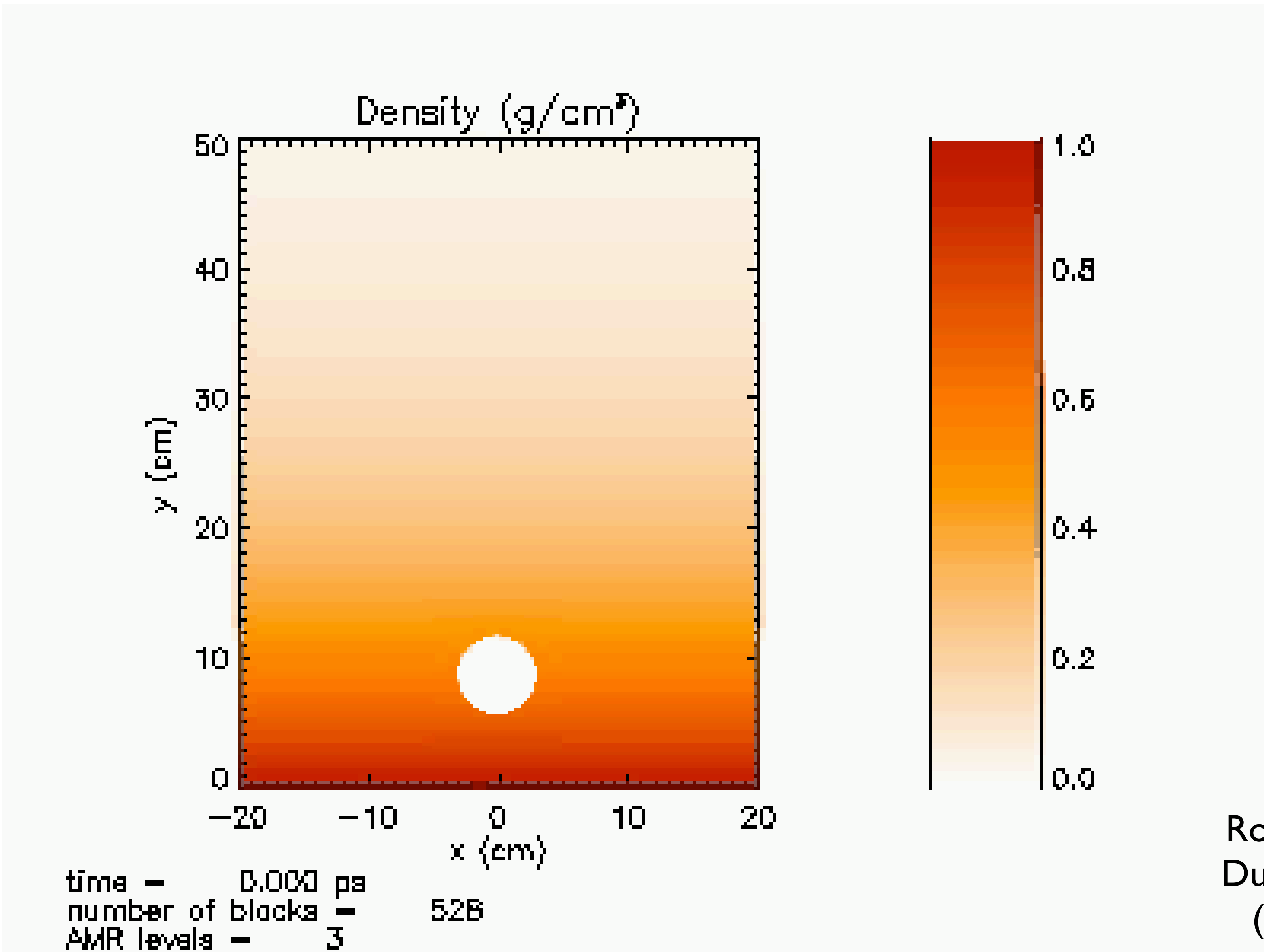
- Each has characteristic velocity
- Flame speed fixed at given dens
- Others bubble-size dependent
- Flame speed always wins until grows



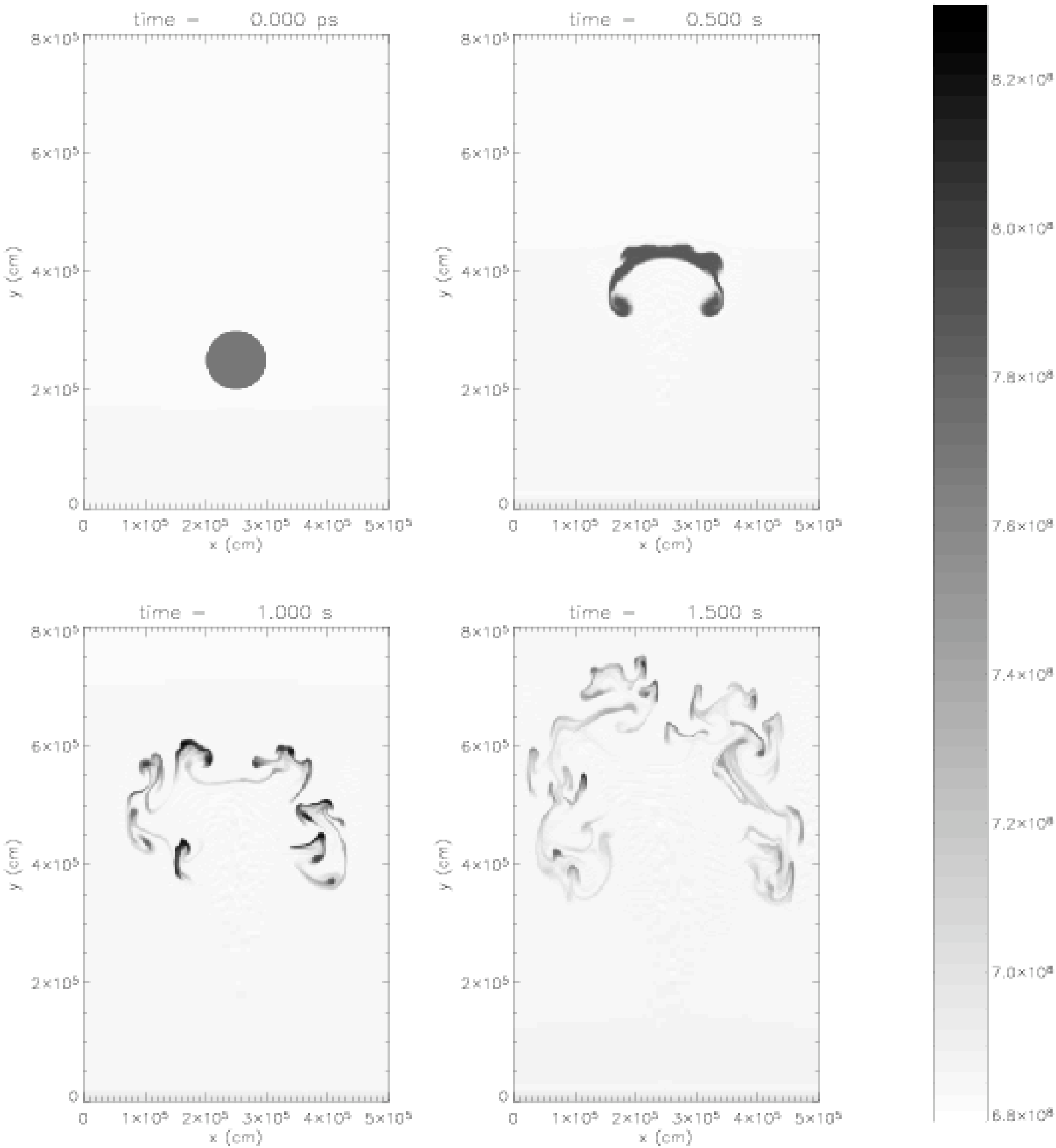
Size where flame speed stops dominating



What happens then?



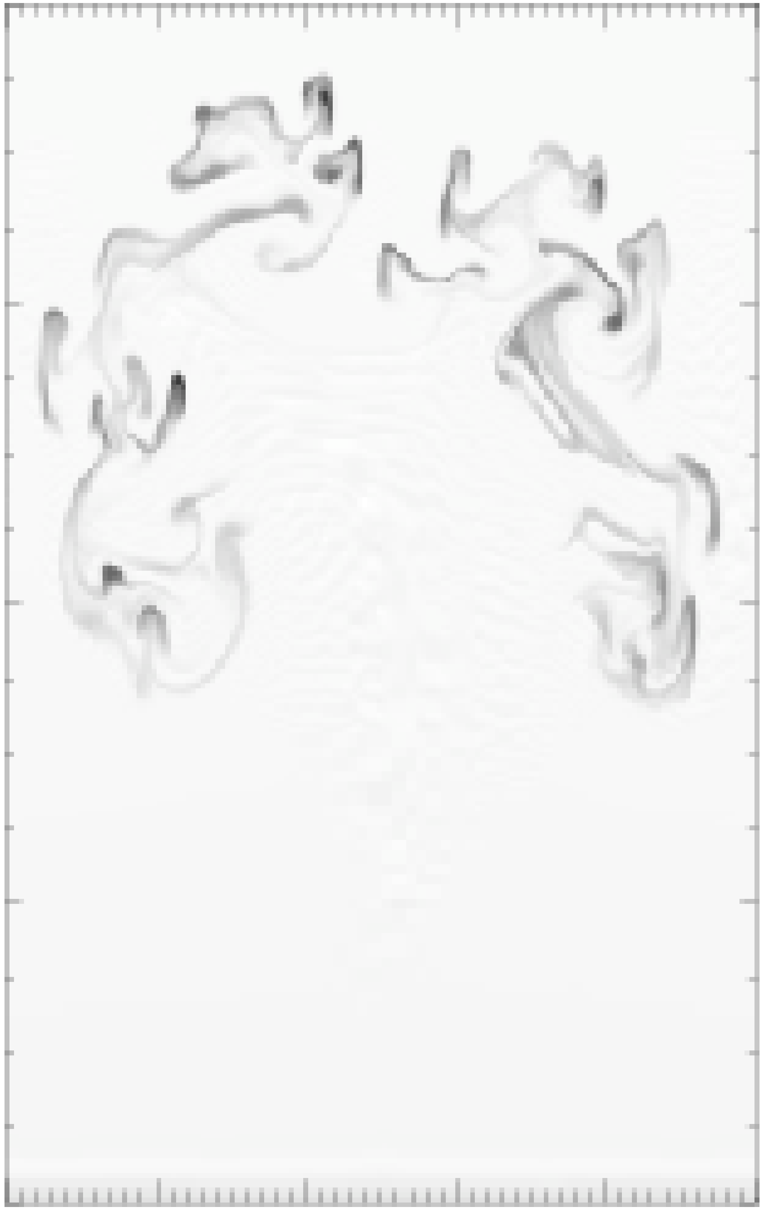
Robinson, Dursi et al (2003)



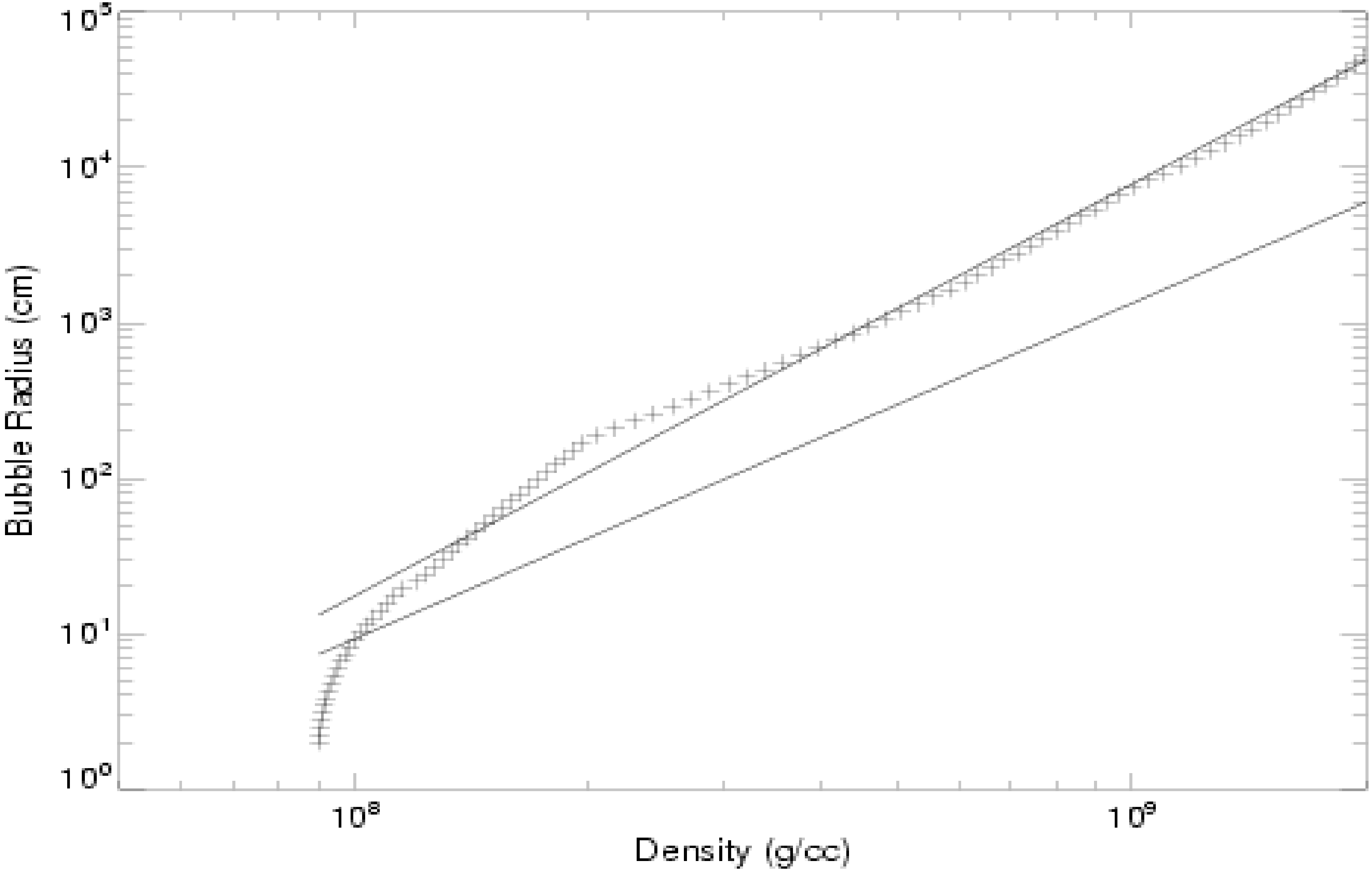
Iapichino et al, (2006)

Buoyant rise

- Vortical motions of bubbles own rise tear it apart
- Unless flame speed is faster
- Balance sets characteristic flame bubble size

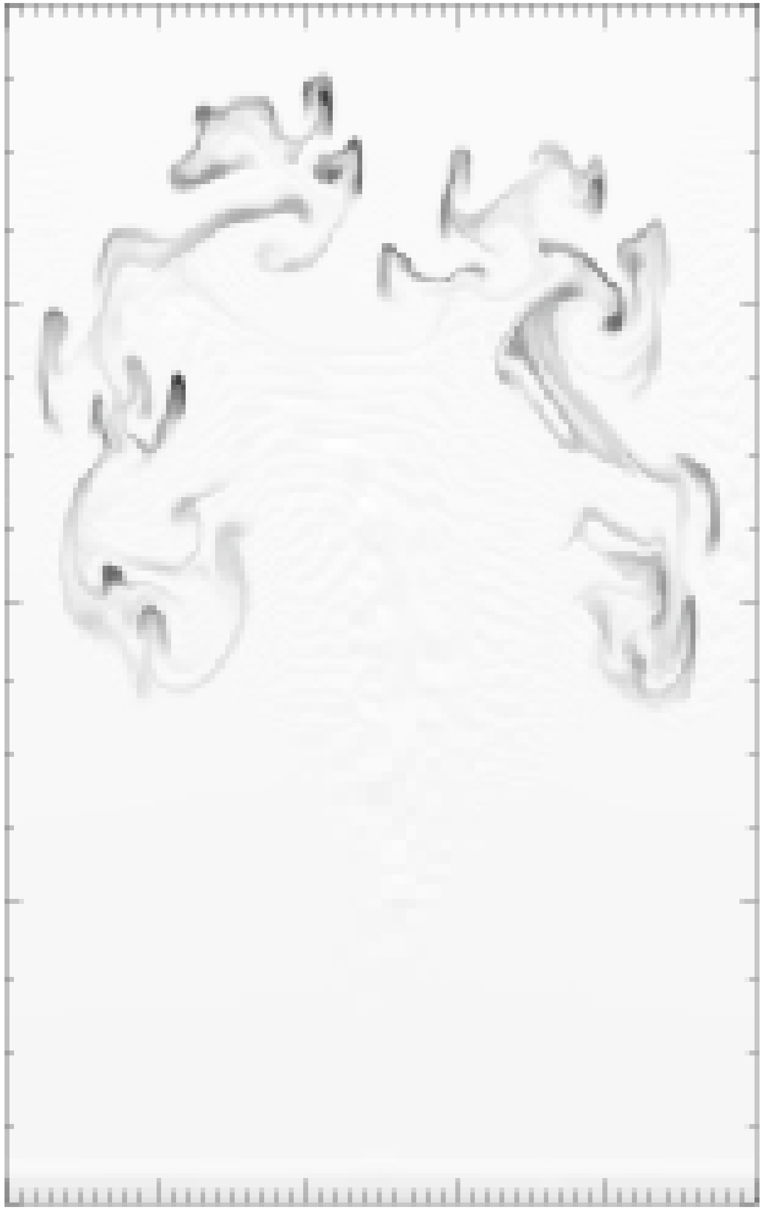


Balance between two sets bubble size



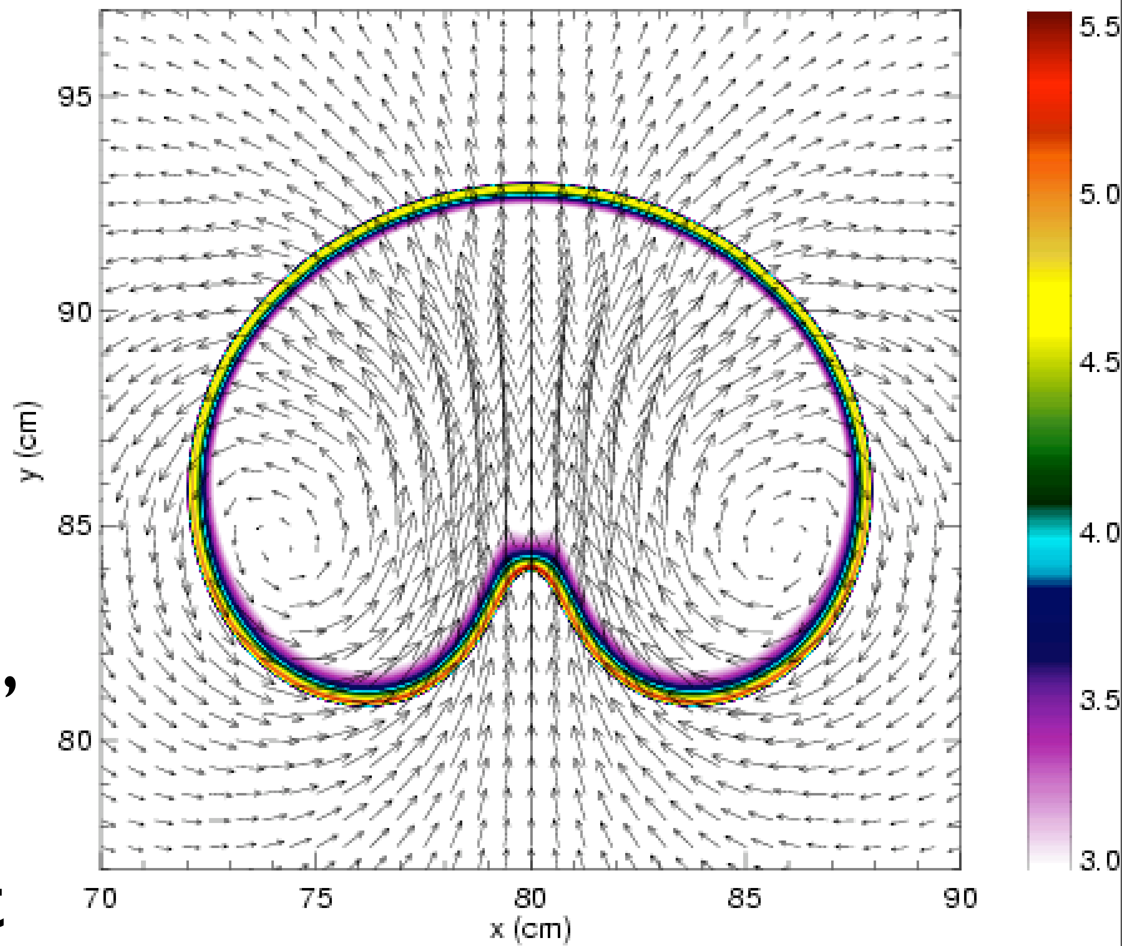
Characteristic bubble Size

- Sets initial condition `flame bubble' size for large-scale simulation (~0.5 km)

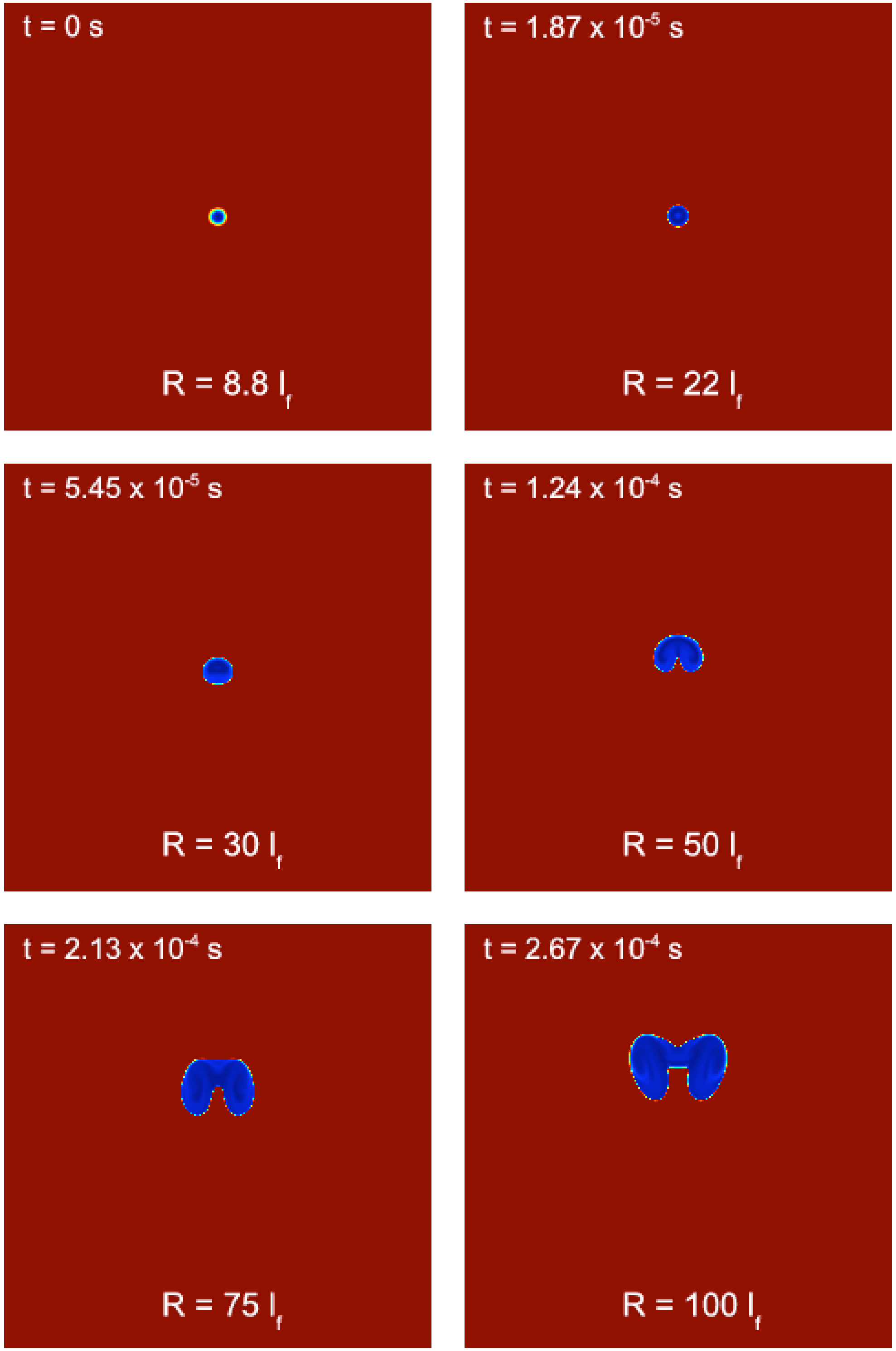


Compared against simulations

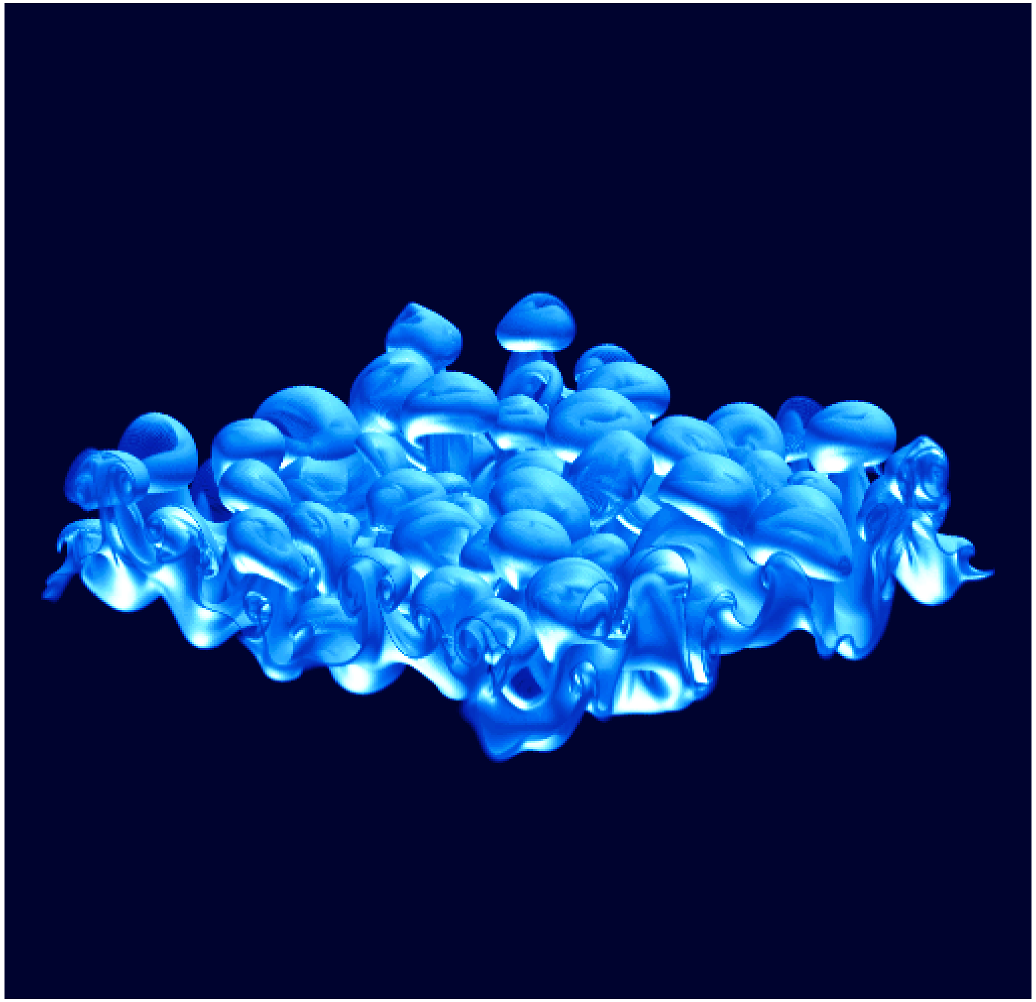
- Semi-analytic calculations comparisons of velocities checked with `real' flame code developed at LBNL (Zingale, Bell, Day, Rendleman)
- Note non-constant flame properties!



- Simple semi-analytic model for this case: flame speed ~ rise speed between 30-50 flame thicknesses in size



Flame modeling



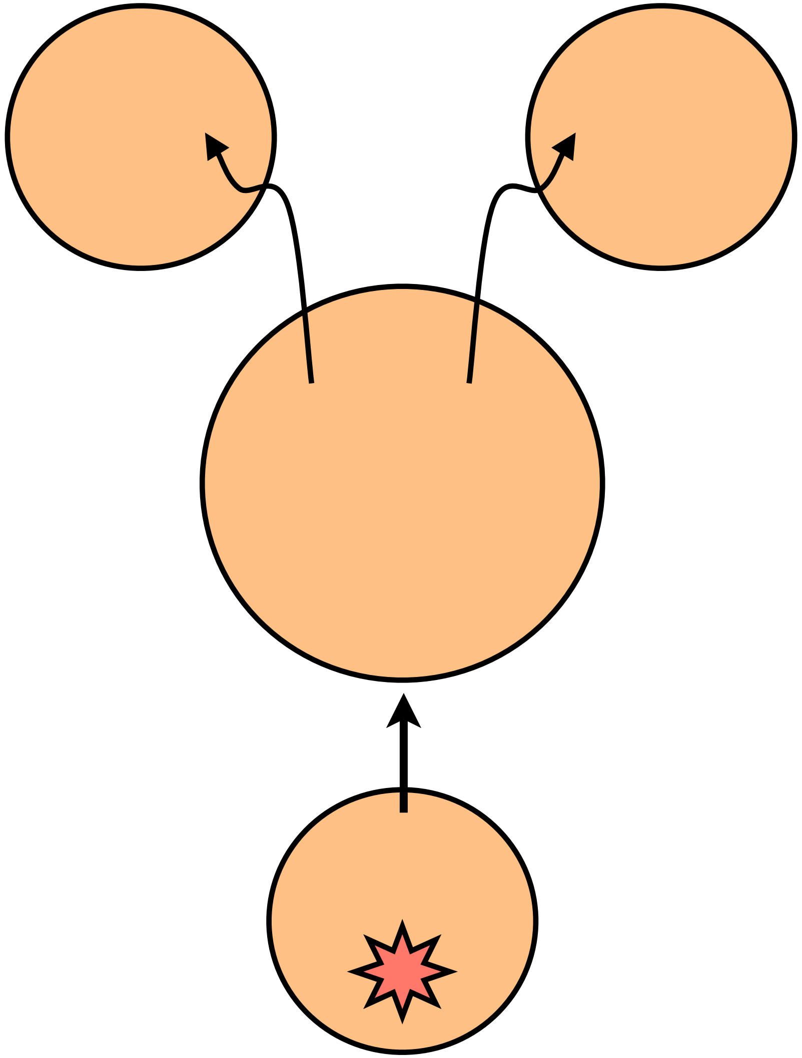
Zingale et al, (2005)

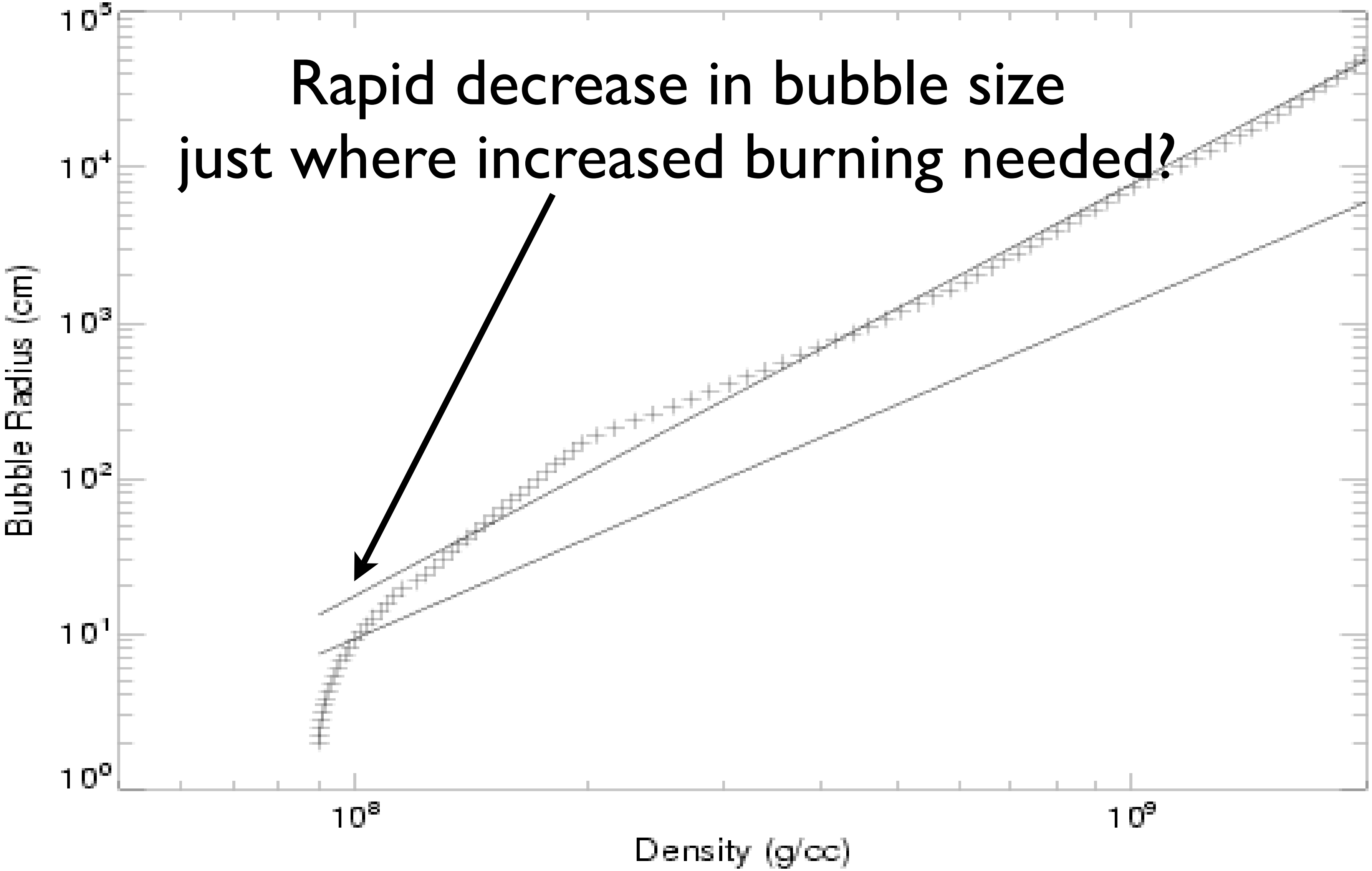
- Flame modeling based on planar picture of flame
- Simulations w/ ~50 flame thicknesses
- Turbulent, RT corrugation
- But much larger range of scales

`Fragmenting Bubbles' Flame Model

- Volume V burning outwards, fragmenting into characteristic volumes

$$\frac{d\mathcal{V}}{dt} = \left(\frac{3\mathcal{V}}{R_f}\right)\dot{R}.$$





Rapid decrease in bubble size
just where increased burning needed?
Bubble Radius (cm)
Density (g/cc)
10⁰
10¹
10²
10³
10⁴
10⁵
10⁸
10⁹

Conclusions

- Flames burn out significantly (~km) before they start to rise
- Initial conditions need roughly this res
- Found typical burning bubble size
- Rapid decrease in size - increased burning?
- Is planar flame model appropriate?

Characteristic Bubble Size

- Can also predict if burns through centre
- If ignites within ~25 km will certainly burn through centre
- No remaining pool of fuel