Numerical challenges in SNIa modeling

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Some Important Topics in Type Ia SN

(Combustion in a Chandrasekhar mass WD)

Remarks with a Skeptical Flavor

1. Unknown Initial Conditions : the ignition mechanism (TNR)

2. Sub-grid Models for Deflagration (turbulent speed) – how good they are ?

3. Ignition of a Detonation in the Outer Layers and GCD ?

4. Ignition of Detonation deeper inside – deflagration to detonation transition (DDT) and Delayed Detonation models (DD)

1. The Problem of Initial Conditions

The problem is to characterize the distribution in space and time of hot spots at which flame front may develop.

a. Why this is important ?

The R-T unstable deflagration phase is found much more sensitive to "anything" than previously expected.

Different initial conditions can lead to very different results, from the "single bubble catastrophe" (and GCD ?)

to almost healthy explosion

(Livne E., Asida S. and Hoeflich P. Ap.J.,632,443,2005)

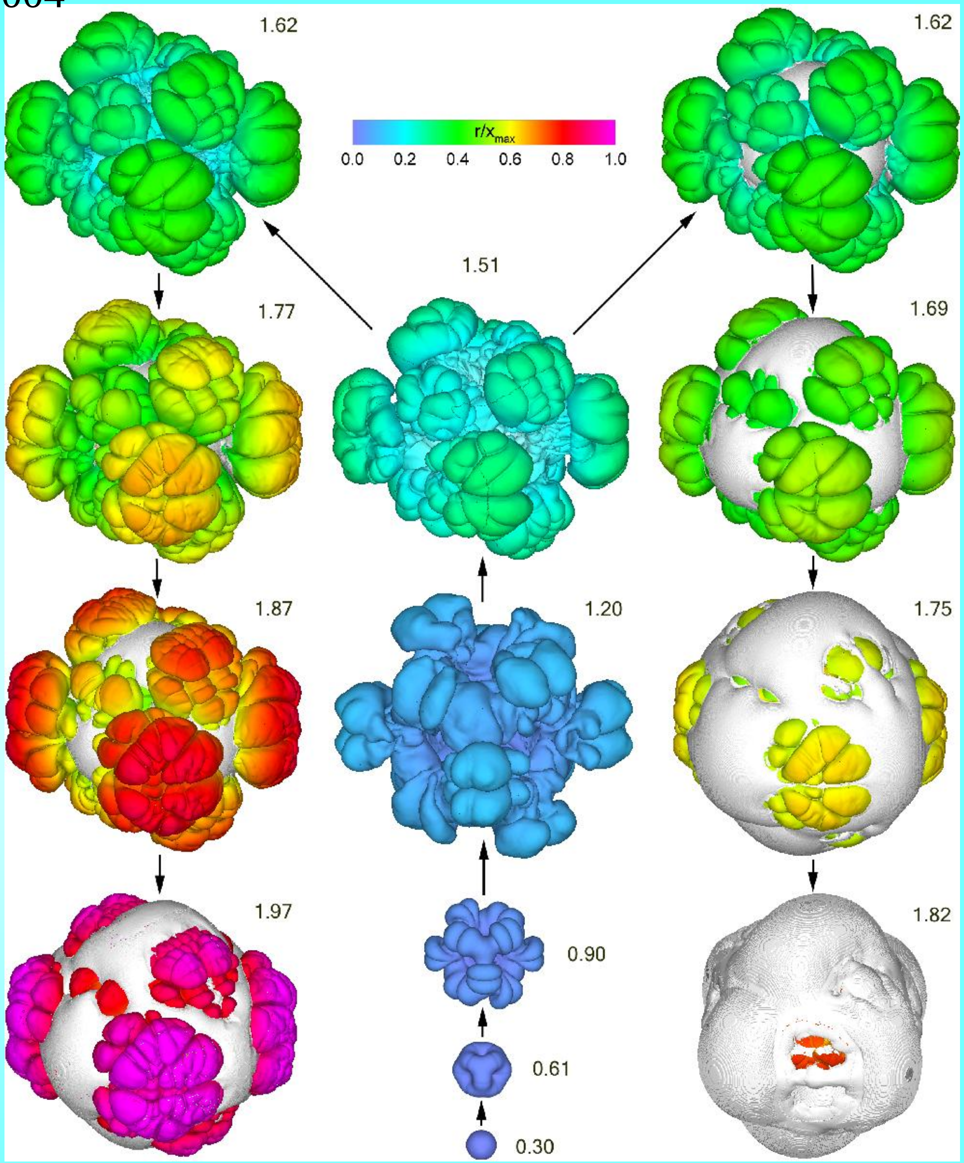
Examples of Regular Ignition

- The flame starts at many ignition points located at a small region near the center

- The flame starts from a small hot sphere

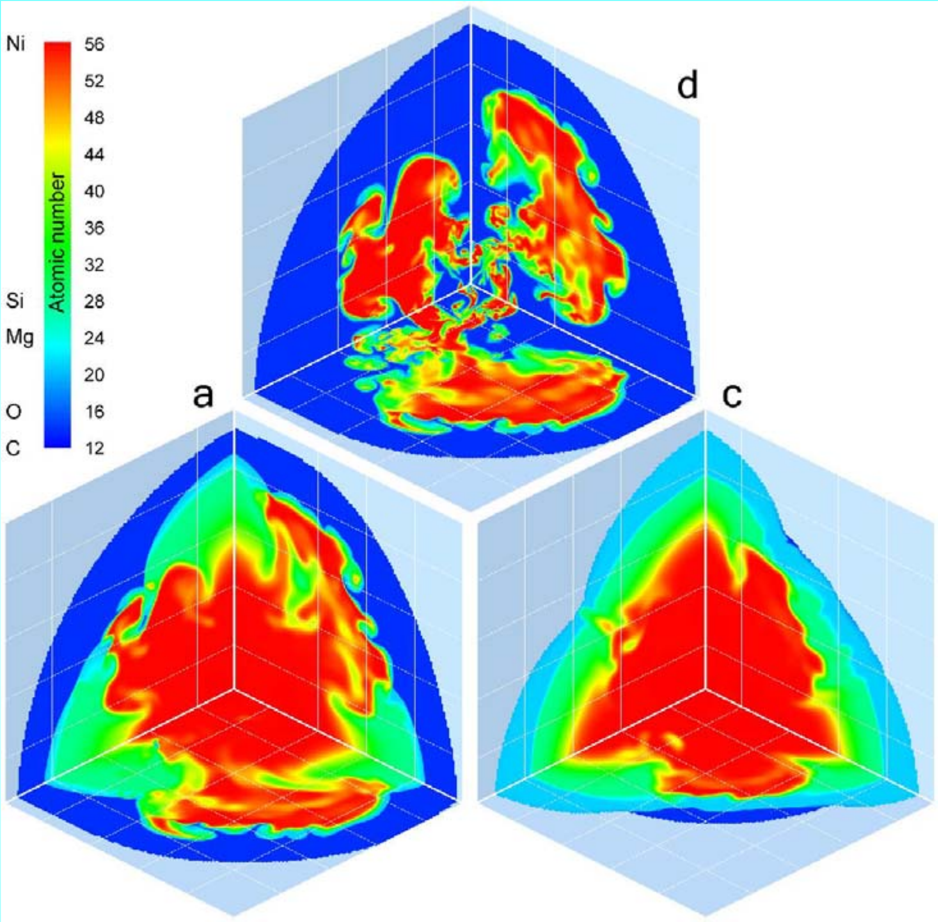
From: Gamezo, Khokhlov & Oran, 2004

Fig. 1. Development of a turbulent thermonuclear flame (colored surface) and a detonation (gray surface) in a carbon-oxygen WD. Numbers show time in seconds after ignition. Central column shows the deflagration stage. Left and right columns correspond to delayed detonation cases (a) (detonation starts at 1.62 s) and (c) (detonation starts at 1.51 s), respectively. Flames at 0.30, 0.61, 0.90, and 1.20 s are plotted at the same scale. Further flame growth is shown by the color scale that changes with distance from the flame surface to the WD center. $x_{max} = 5.35 \times 10^8$ cm.



From: Gamezo, Khokhlov & Oran, 2004

Fig. 2. Concentration field in the exploding WD computed for deflagration (d) and delayed-detonation (a,c) models defined in Table 1. Times are 1.94, 1.94, and 1.82 s for cases d, a, and c, respectively. The color map shows the average atomic number A of the material for x = 0.05, y = 0.05, and z = 0.05 planes. The coordinate grid is spaced by $0.2x_{max}$. $A = \Sigma X_i A_i$, where X_i are mass fractions of C, O, Mg, Si, Ni defined in Appendix A.



From: Ropke & Hillebrandt, 2004

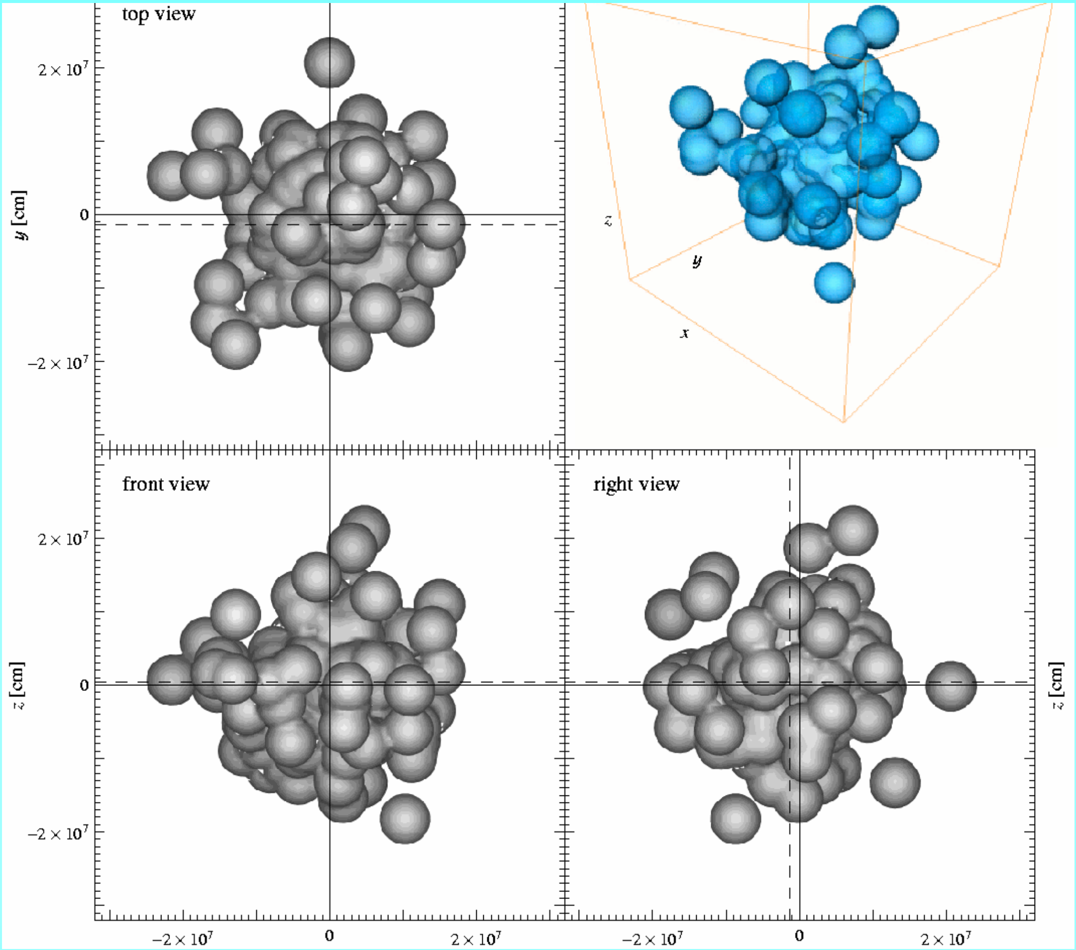


Fig. 2. Initial flame shape of model *f1*. In the projections, the solid lines indicate the center of the WD, while the dashed lines indicate the center of the flame configuration (the x-coordinates coincide at the chosen scale of the plot).

From: Ropke & Hillebrandt, 2004

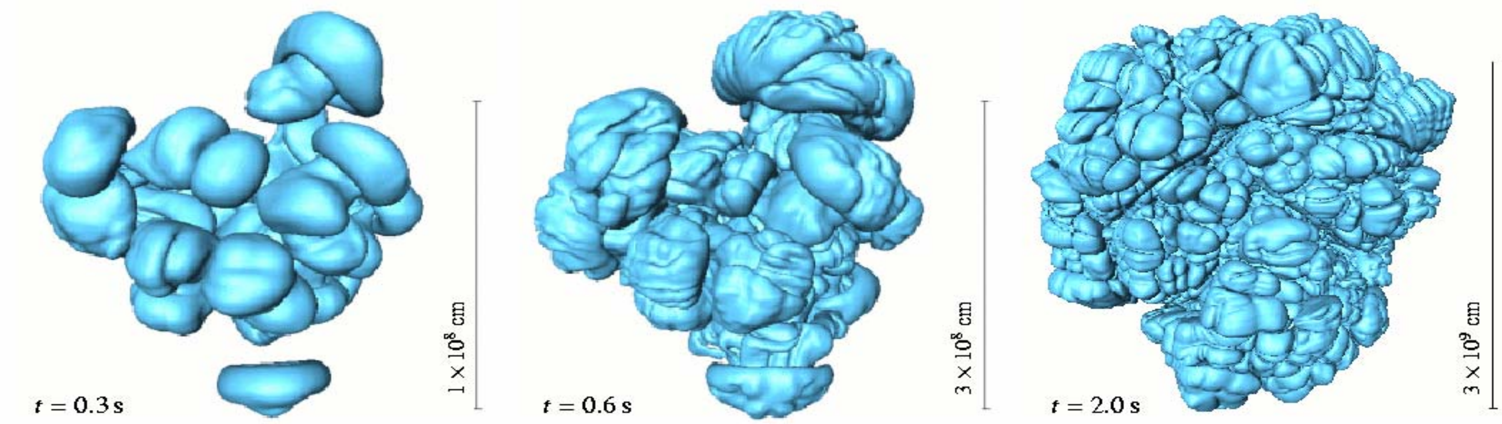


Fig. 4. Flame evolution in model *f1_512*.

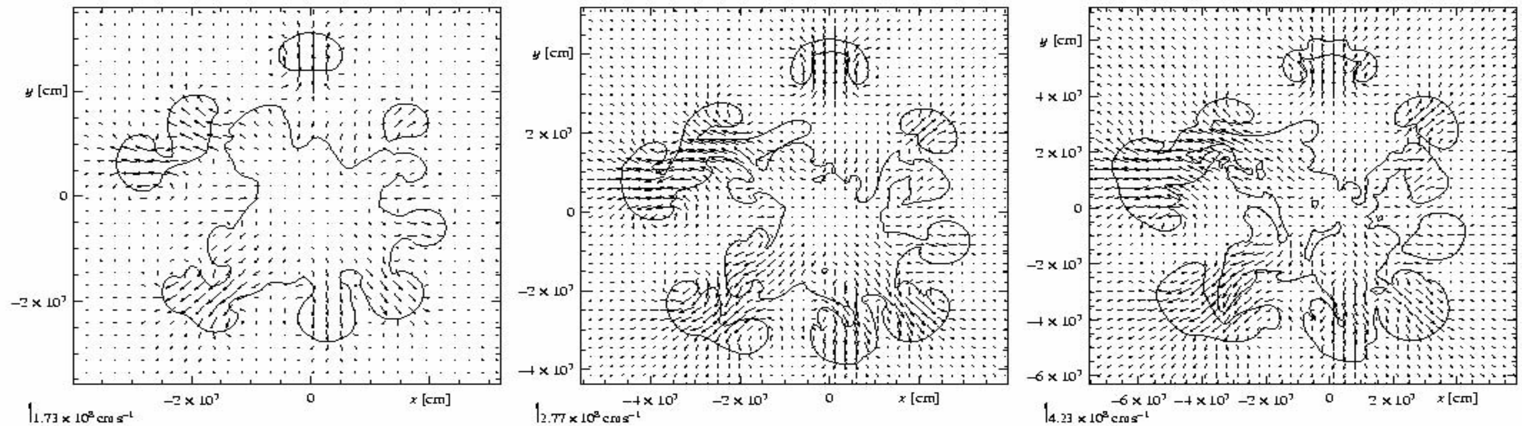


Fig. 5. Velocity fields in two-dimensional slices of the *f1* model at $t = 0.1$ s (left), $t = 0.2$ s (center), and $t = 0.3$ s (right) at $z = -4.0 \times 10^5$ cm, $z = -4.0 \times 10^5$ cm, and $z = -4.4 \times 10^5$ cm, respectively.

Examples of Irregular ignition

Bubbles in V2D simulations with different locations of a few ignition points

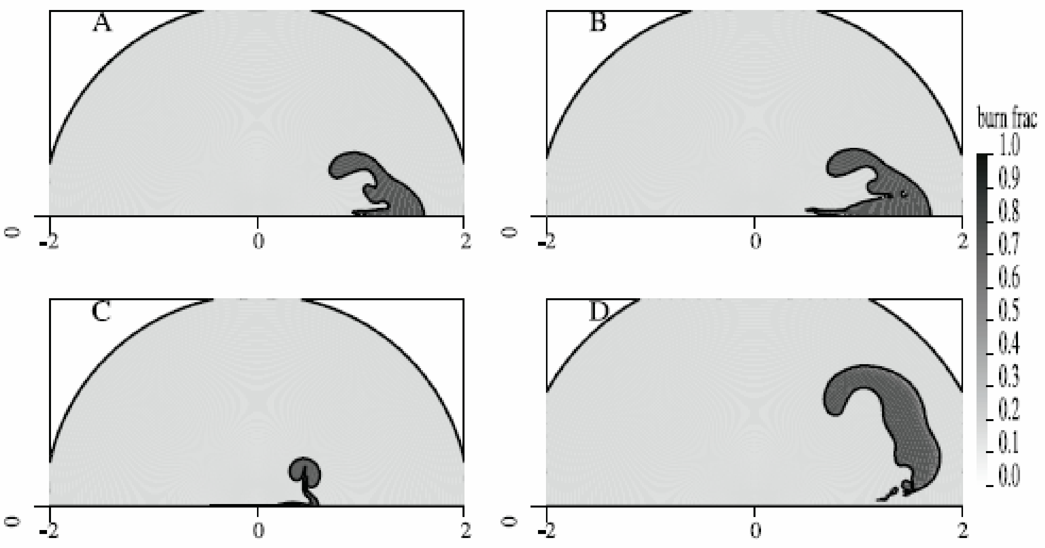


FIG. 2.—Burning region of simulations with a single off-center ignition at $T = 1.2$ s. The unit scale on the axes is 1000 km. Four simulations are presented: (*a*) ignition at $r = 20$ km; (*b*) ignition at $r = 20$ km with an initial convective velocity field; (*c*) ignition at $r = 10$ km; (*d*) ignition at $r = 100$ km.

A single bubble will float to the surface after incinerating roughly 5 percent of solar mass.

What happens next ?

Pulsation ?   GCD ?

From: Plewa, Calder & Lamb, 2004

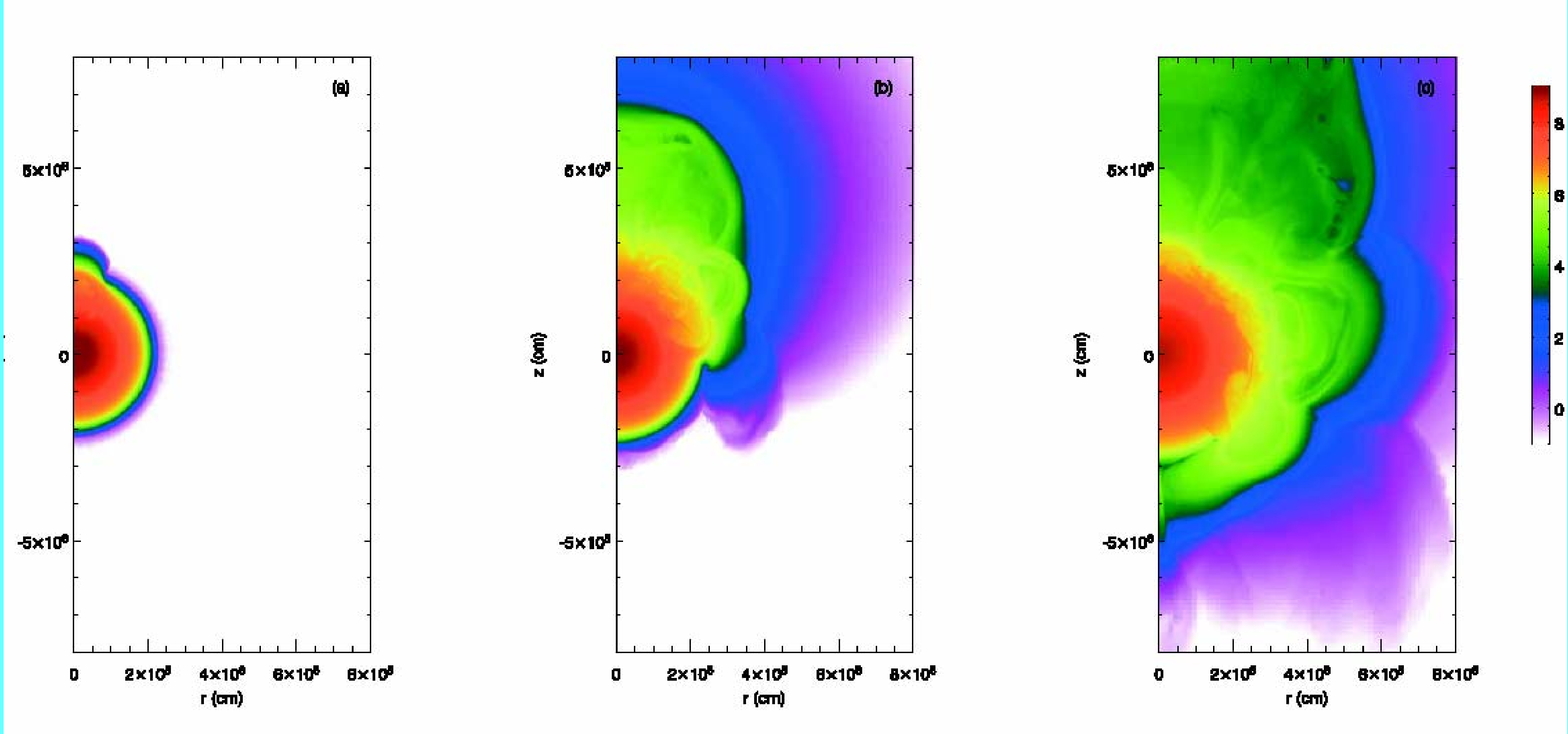


FIG. 1.—Evolution of the white dwarf following an essentially central ignition. Density in log-scale is shown for the innermost approximately one-sixth of the simulation domain. (*a*) Bubble breakout ($t = 0.9$ s). The material is expelled radially, and the high pressure of the burned bubble material produces a lateral acceleration of the outer layers of the star. (*b*) Bubble material expands above the star as the fuel-rich surface layers reach the equator in their race across the stellar surface ($t = 1.4$ s). Note that most of the surface layers are closely confined to the star. (*c*) Focusing of the fuel-rich streams just prior to the detonation ($t = 1.9$ s). Note the presence of the dense conical region stretching down along the symmetry axis beginning at $(r, z) = (0, -3 \times 10^8)$ cm.

From: Plewa, Calder & Lamb, 2004

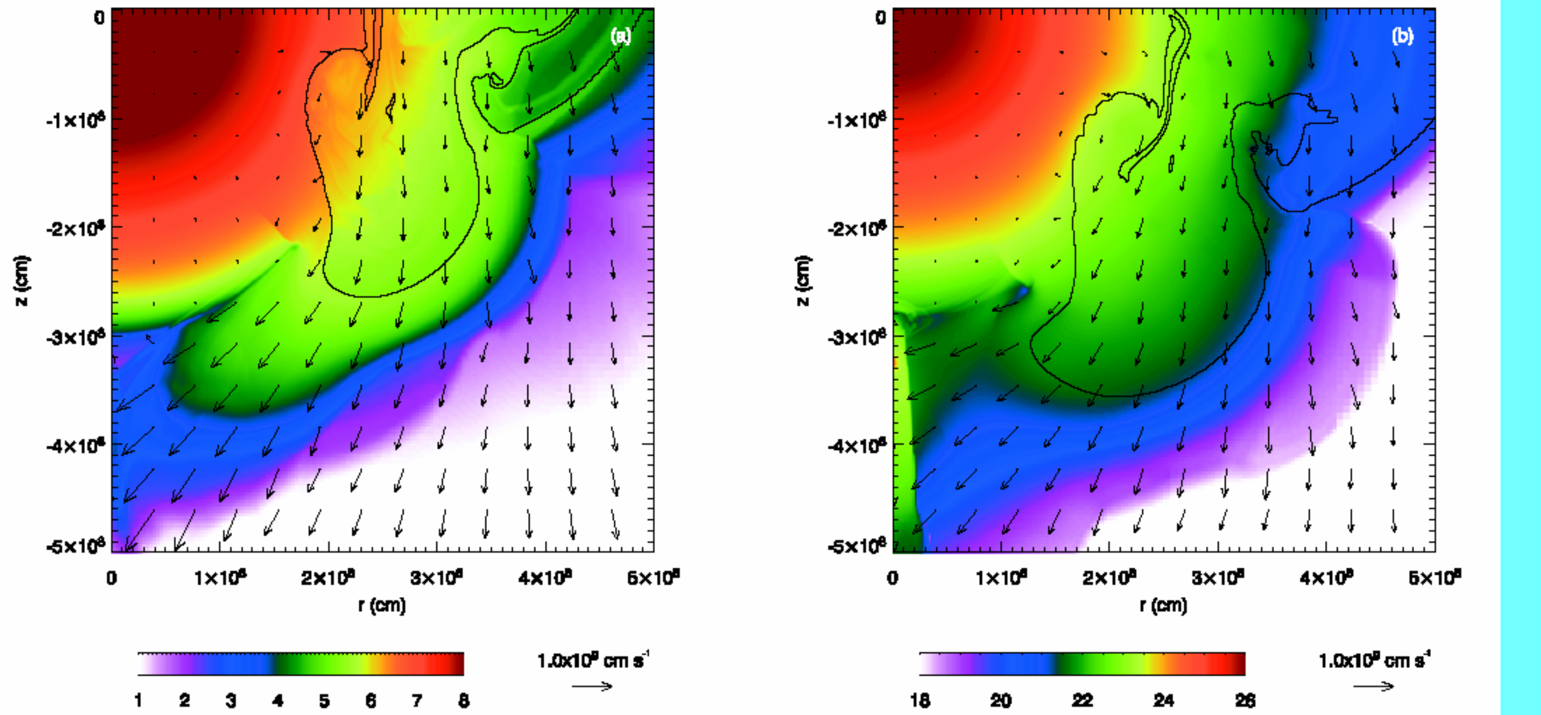


FIG. 2.—Evolution of the surface flood across the lower half of the star. (*a*) Density in log-scale at $t = 1.85$ s. Note the density gradient in the stream of fast-moving material. The interior of the star remains highly radially symmetric; only relatively low-density regions are perturbed by the surface flow. (*b*) Pressure in log-scale at the ignition of the detonation ($t = 2.005$ s). The ignition point can be seen as a small overpressured region located near the symmetry axis at $(r, z) \approx (0, -3.25 \times 10^8)$ cm. The shock wave preceding the bubble material is located in the low-density stellar layers near $(r, z) \approx (1.1 \times 10^8, -2.4 \times 10^8)$ cm. The contour marks the position of the advancing front of nuclear ash. Vectors show the velocity field; the velocity can be determined by comparing the length of the vectors with the length of the fiducial vector (1×10^9 cm s^{-1}).

b. Previous Attempts to Compute the TNR

Hoeflich & Stein 2002 - show the importance of large scale feature , bubbles and spikes, during the early TNR

Woosley, Wunch & Kuhlen 2004 – stress the turbulent nature of the process

The Astrophysical Journal, 568: 779–790, 2002 April 1

ON THE THERMONUCLEAR RUNAWAY IN TYPE Ia SUPERNOVAE: HOW TO RUN AWAY?

P. Höflich[1] and J. Stein[2]

Received 2001 April 12; accepted 2001 December 5

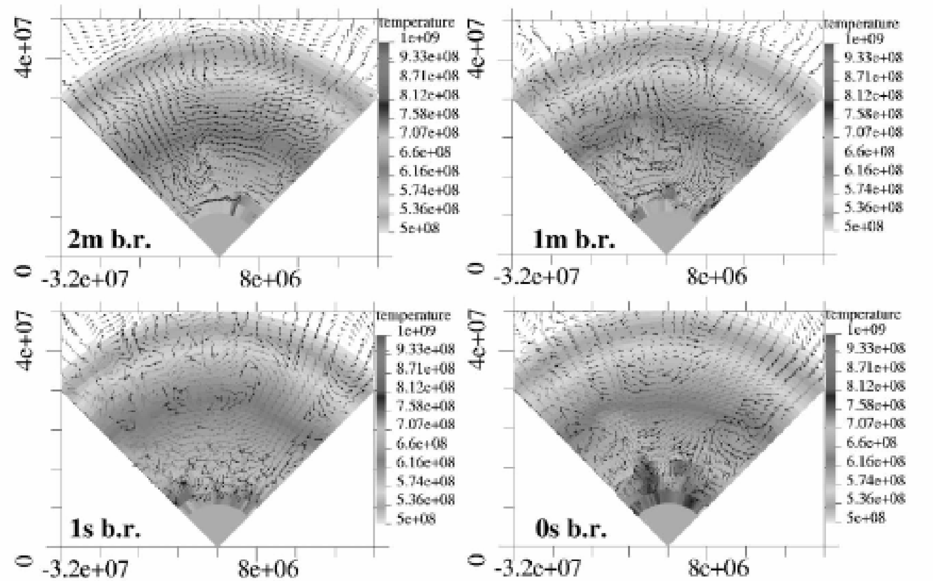


Fig. 7.—Final evolution of the temperature structure up to the runaway. In the lower left plot, the runaway occurs in the second red zone from the left right at the inner boundary ($T = 1.74 \times 10^9$ K). In addition, the velocity field is given. Black, red, and green vectors correspond to velocity ranges of 0–50, 50–100, and 100–150 km s^{-1}, respectively. [*See the electronic version of the Journal for a color version of this figure.*]

Stein & Hoeflich : TNR occurs during re-compression of partially burned material as it sinks convectively toward the center. The first hot spot appears at a few tens km from the center (30-50 km)

The numerical challenge – 3D simulations of the convective core (200-300 km) in the WD for about 2 minutes !!, while the temperature rises from 600 million K to 1 billion K.

But : current simulations can hardly reach turbulence regimes because the "grid Reynolds number" is too low

2. Sub-grid Models for Deflagration (turbulent speed) – How good they are ?

a. "Turbulent Flame Speed " – how to use it and how to calibrate it ?

or – what is the connection between hydrodynamical instabilities and the area of the surface of the flame at various scales ?

(Livne 1993, Khokhlov 1995, Niemeyer & Hillebrandt etal. since 1995, Hillebrandt this workshop)

an example : scale dependent RT speed - Vturb(l) = 0.5*sqrt(g*l)

g = effective local gravity

l = the size of a grid cell

Calibration of Vturb is usually done in ideal conditions (a box) which are very different from those exist in a star !!

Zhang, Ju; Messer, O. E. Bronson; Khokhlov, Alexei M.; Plewa, Tomasz

On the Evolution of Thermonuclear Flames on Large Scales, ApJ, 656, 347, 2007

b. Convergence ?

Numerical results should converge to the same result regardless the sub-grid model !

The slope of a converge line displays the quality of the sub-grid model !

(W. Schmidt, J. C. Niemeyer, W. Hillebrandt, F. K. Ropke : A&A, 450,283,2006)

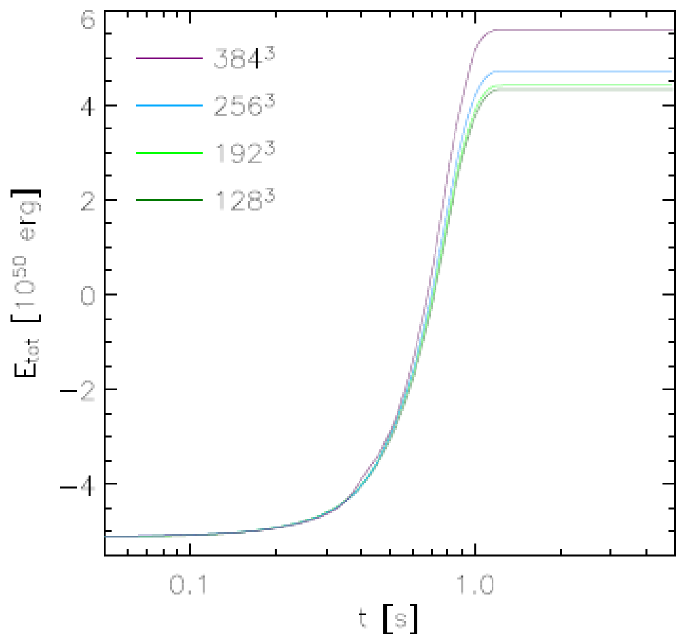


Fig. 3. Time evolution of the total energy for the same simulations as in Fig. 2

3. Ignition of Detonation in the Outer Layers and GCD ?

Two scenarios : failed deflagration is followed by either :

a. A strong pulsation which is followed by an accretion shock which triggers detonation (E. Bravo & D. Garcia-Senz, ApJ,642,L157)

NOT CONFIRMED in high resolution simulations using 2 1D Lagrangean Codes (Livne, Hoeflich , unpublished).

The problem may be attributed to the low accuracy of SPH simulations in the outer layers ?

b. GCD (Gravitational Confined Detonation, Plewa, Calder & Lamb , ApJ 612,L37 and later publications).

A Subject under intensive investigations now using FLASH.

Both scenarios are subject to three major uncertainties :

i) They are both very sensitive to the strength of the pulsation, the pre-expansion and the amount of burning in the first deflagration phase. This in turn is determined again by unknown initial conditions.

ii) Triggering a detonation in nuclear (degenerate) fuel can NOT be computed using Eulerian codes on stars scales !!

iii) At low densities appropriate to the outer layers of a pre-expanded WD this is very difficult.

(Ropke, Woosley & Hillebrandt, astro-ph/0609088)

4. Ignition of a Detonation deeper inside

(deflagration to detonation transition)

a. Off-center DDT

(Livne, ApJ 527,L97 1999; Gamezo, Khokhlov & Oran, ApJ 623,337 2005, Ropke & Niemeyer 2007)

related now to GCD models

Probably the Model which Produces the Best Agreement with Current Observations –

- Badenes etal. ApJ, 645, 1373, 2006 (Tycho)
- Fesen etal. astro-ph/0611779, (SN1885)
- Motohara etal. astro-ph/0610303 , (SN2003hv, SN2005w)
- Gerardy etal. astro-ph/0702117, (SN2003hv, SN2005df)
- Mazzali etal., astro-ph/0702351, (a large sample)

2D Simulations with Off-Center DDT

(Livne, ApJ 527,L97 1999)

Assumption : Transition to detonation is a "rare event".

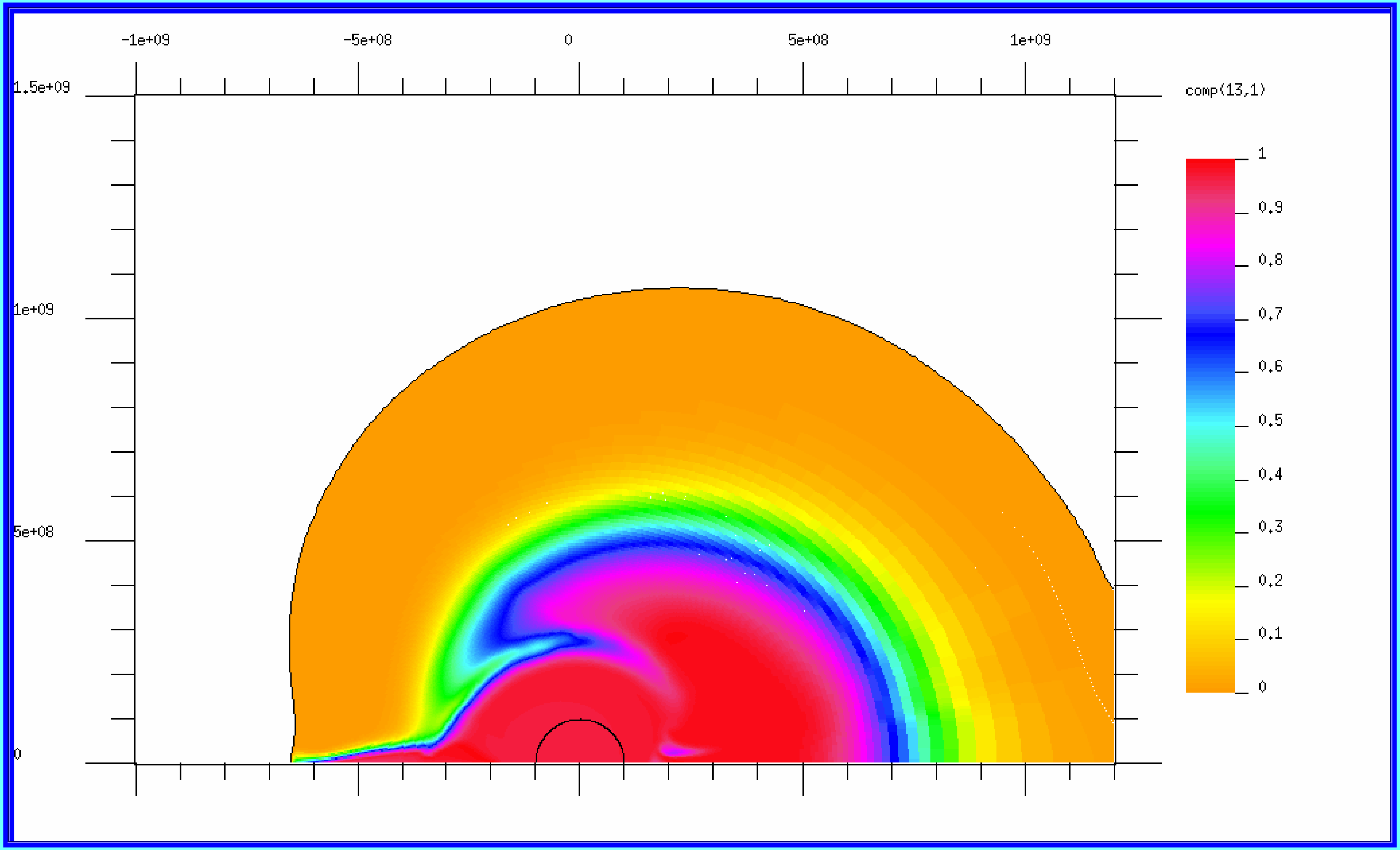
Therefore : transition to detonation in a spherical shell is much less probable than point transition.

The main effect : Detonation in Expanding Envelope,

some interesting effects : The shells structure is preserved with different asphericities for different composition shells !!

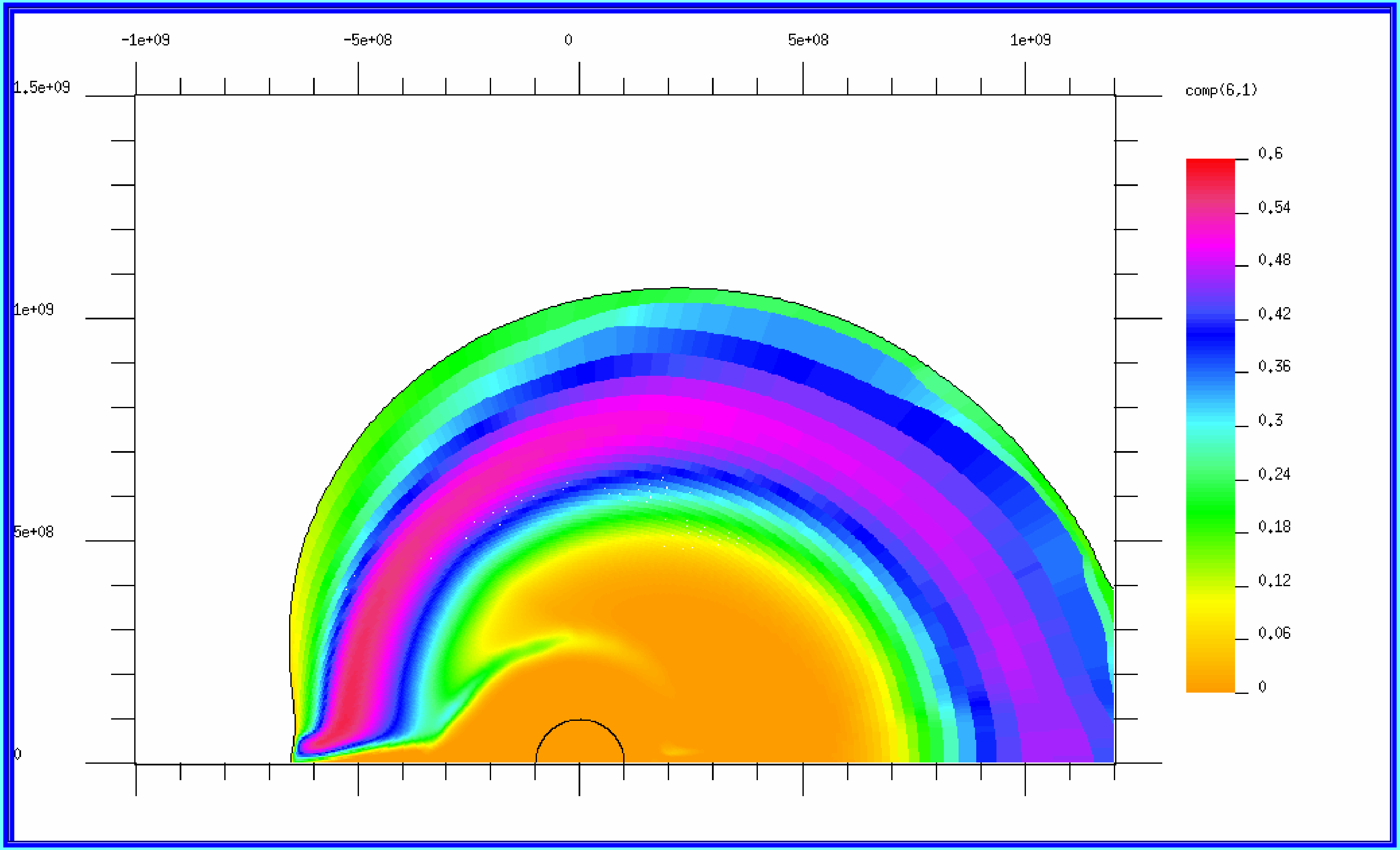
NEEDS MORE WORK

X(Ni)   T=0.8



-1e+09
-5e+08
0
5e+08
1e+09
1.5e+09
1e+09
5e+08
0
comp(13,1)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

X(Si) T=0.8



-1e+09
-5e+08
0
5e+08
1e+09
1.5e+09
1e+09
5e+08
0
comp(6,1)
0.6
0.54
0.48
0.42
0.36
0.3
0.24
0.18
0.12
0.06
0

b. Incomplete burning in DDT

(Livne, in Cosmic Explosion in 3D – Asymmetries in SNe and GRBs,2004; Maier, A.; Niemeyer, J. C., A&A 451,207,2006)

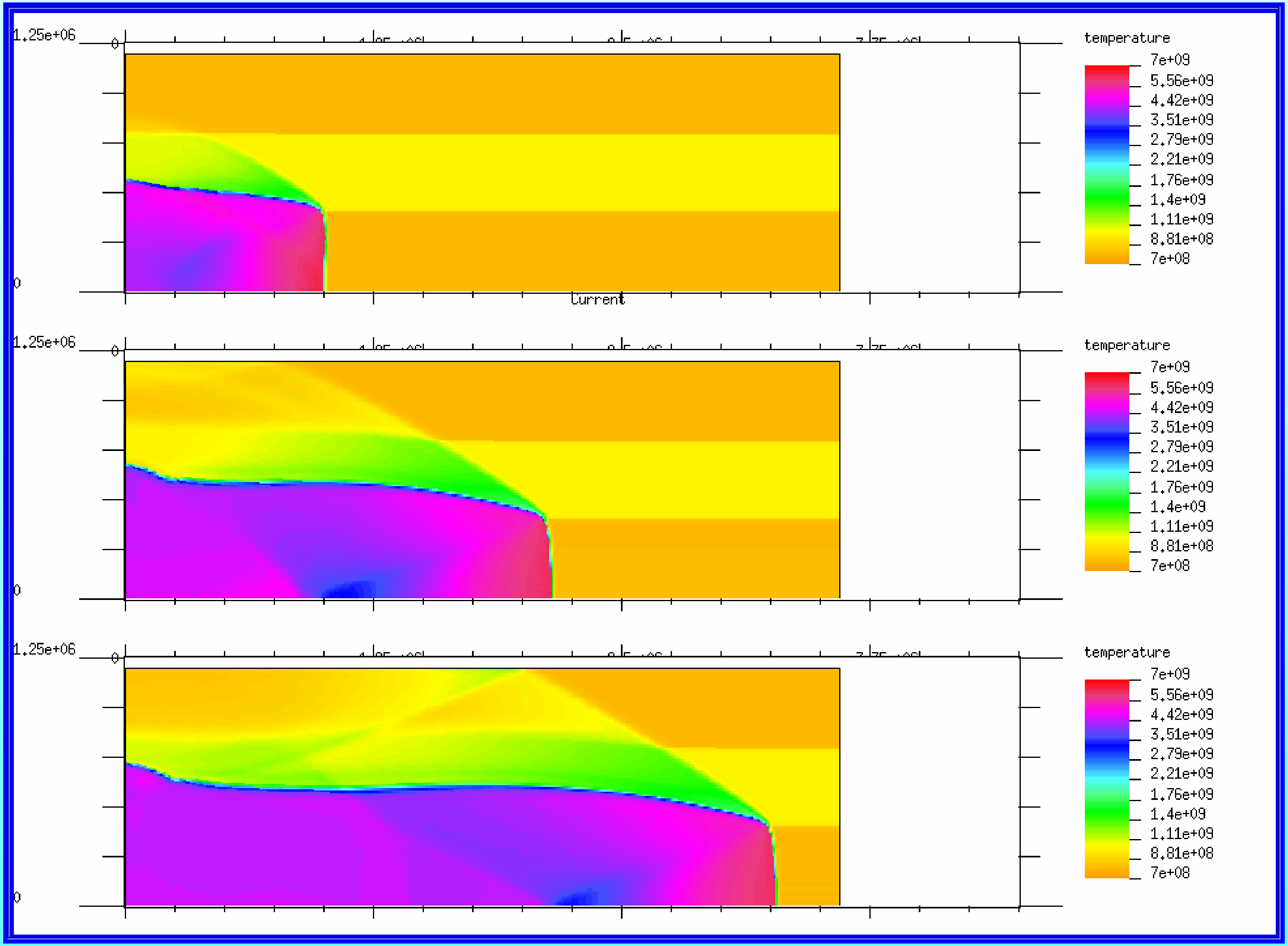
A numerical result : A detonation in C+O fuel can not jump over pockets of previously burned material

Implications :

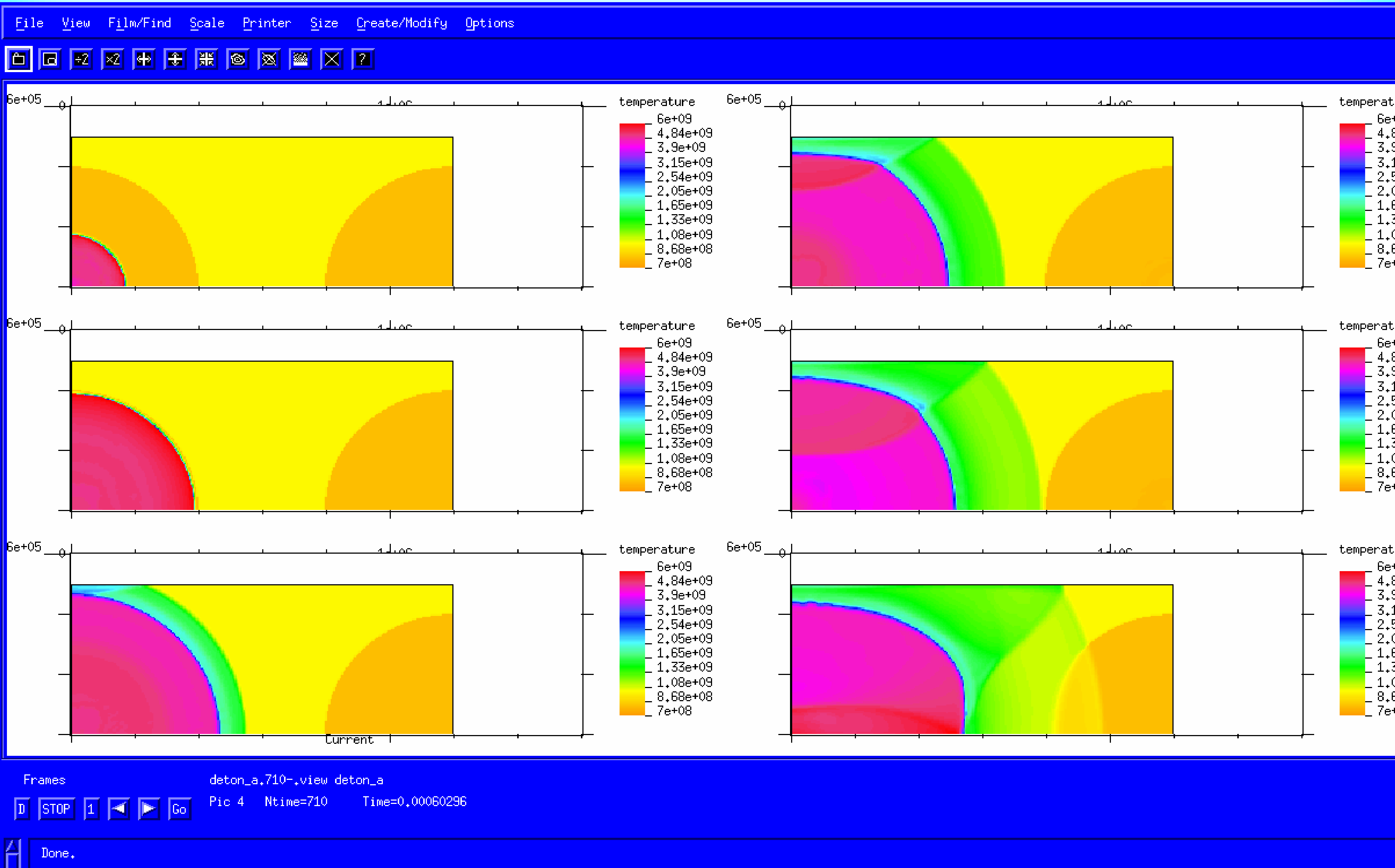
i. If isolated pockets of unburned fuel survive the deflagration phase they will not burn during the following detonation phase.
ii. Quenching of the front ? (Maier & Niemeyer)

NEEDS BETTER QUANTATIVE UNDERSTANDING

Detonation in a channel



Bubble-bubble interaction



Future Challenges

1. TNR - hardly accessible by current computing capabilities
   but should be addressed as a major uncertainty !!
2. DDT – A key issue that should be studied on small scales
   in multi-D - hard but possible.
3. Edge lit detonations and GCD - probably marginal and
   are even more sensitive to both IC and details of the
   early deflagration phase :
   number of ignition points, amount of ash bubbles, pulsation.
4. How asymmetries are related to off-center DDT ?
   can be done with current tools.
5. Convergence of different sub-grid models – MPA, Chicago
   and NRL (Khokhlov, Gamezo & Oran) is essential.