New regimes for supernova-relevant Rayleigh-Taylor experiments on the National Ignition Facility

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Aaron R. Miles

Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551

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Many individuals, teams, and institutions contribute to this work

- University of Michigan
  - F.W. Doss, R.P. Drake, M.J. Grosskopf, E.C. Harding, C.M. Huntington, C.M. Krauland, C.C. Kuranz, D.C. Marion, E. Myra

- LLNL
  - H.-S. Park, B.A. Remington, H.F. Robey, M.J. Edwards, W. Hsing, C.J. Keane, D.H. Kalantar, B. Maddox, B. Young, R.J. Wallace

- General Atomics: J.D. Kilkenny, E. Giraldez

- LANL: G. Kyrala

- University of Chicago: N. Hearn

- T. Plewa: Florida State University

- University of Texas: J.C. Wheeler

- University of Arizona: W.D. Arnett

Outline

- Interfacial instabilities play an important role in supernova (SN) explosion dynamics

- SN-relevant instability experiments on the Omega laser are useful, but energy-limited

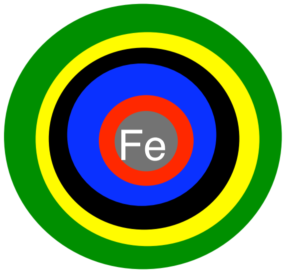
- New regimes will be accessed through experiments at the National Ignition Facility (NIF)
  - Divergent multi-interface experiment scaled to Type II core-collapse SN
  - Divergent large-initial-amplitude experiment relevant to Type Ia thermonuclear SN
  - Planar radiatively-stabilized experiment

- Summary and conclusions

Simplified supernova (SN) taxonomy

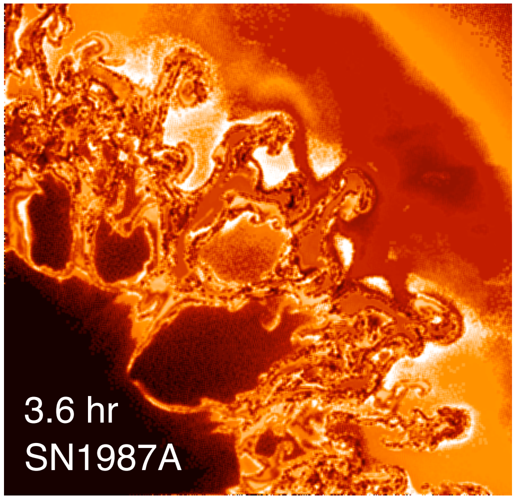
Progenitor | **Explosion stage** | **Remnant stage**

Core collapse (Type II)



Massive star

+ Binding energy/ nucleon curve =>



Muller, Fryxell, and Arnett,
Astron. Astrophys. 251 (1991)

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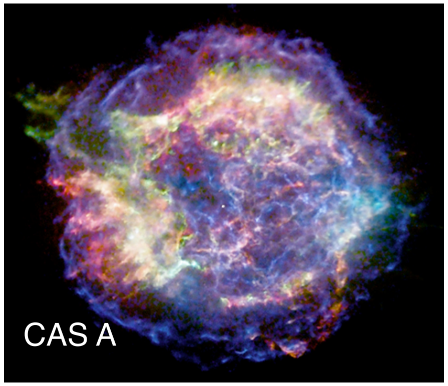


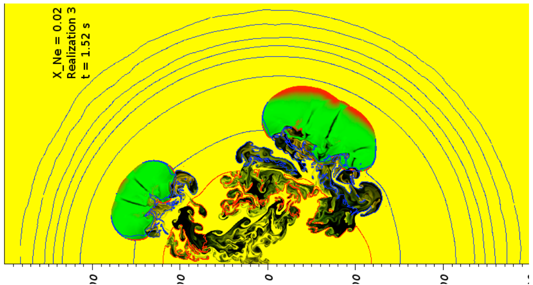
NASA/CXC/MIT/UMass Amherst/
M.D.Stage et al.

Thermo-nuclear (Type Ia)

C/O white dwarf

+ $$\left[\left(\frac{dM}{dt}\right) > 0\right]$$ =>

Accretion



D.M. Townsley et al., ApJ 701,1582(2009)

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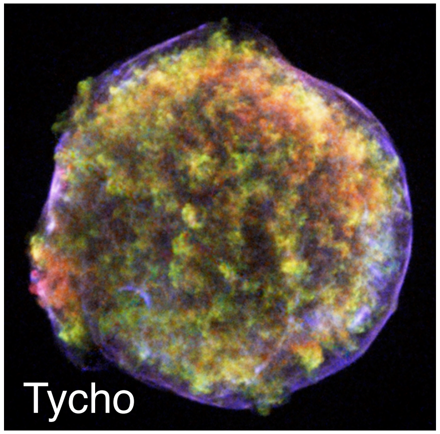


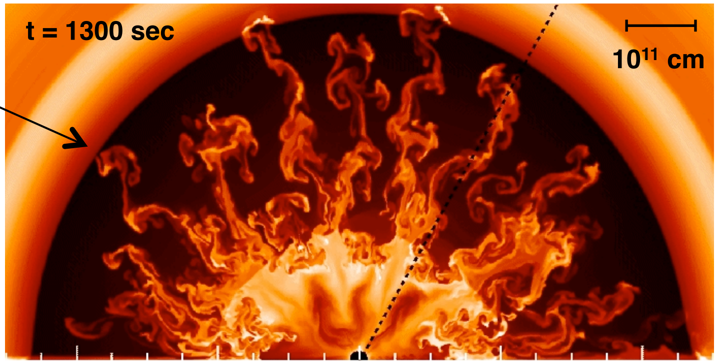
http://chandra.harvard.edu/photo/
2005/tycho/index.html

Core-collapse SNe: Steep density gradients at composition interfaces are driven unstable by the blast wave

Observe very fast mixing of core material into the outer layers of the star - Not typically seen in 2D simulations

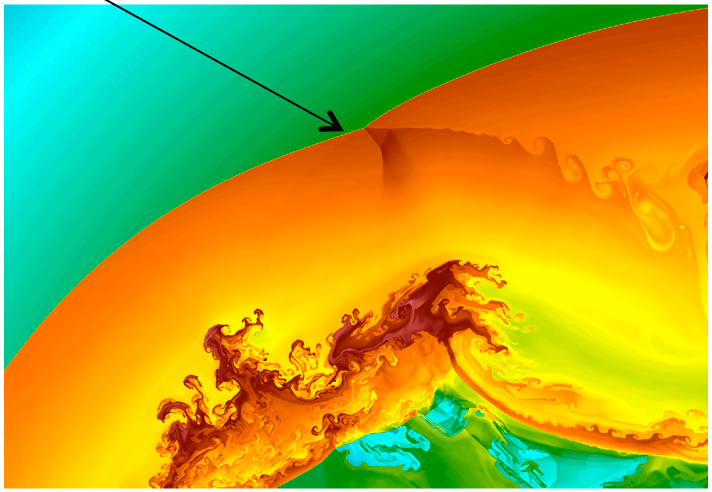
- Large-amplitude low-modes can give high velocities early enough via Richtmyer-Meshkov instability
  - Convection yields perturbed shocks as well as interfaces
- Interaction of multiple mixing zones
- Transition to inherently 3D turbulent mixing zone following growth to large amplitudes: Numerical simulations limited in attainable effective Reynolds number

Minutes to hours



Kifonidis et al., Astron. Astrophys. **408**, 621 (2003).

Seconds to minutes



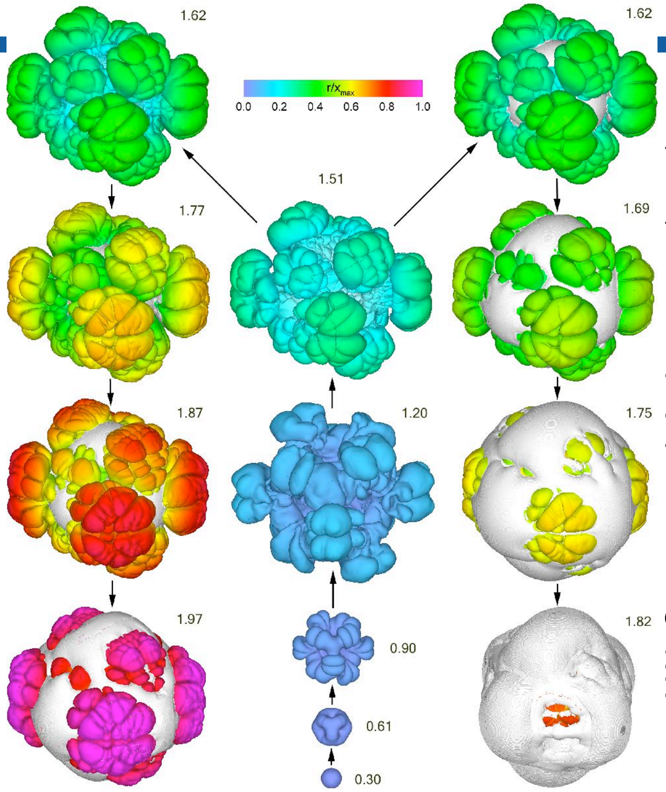
http://people.sc.fsu.edu/~tomek/SNII/index.html12

Thermonuclear SNe: Many questions remain about the explosion process

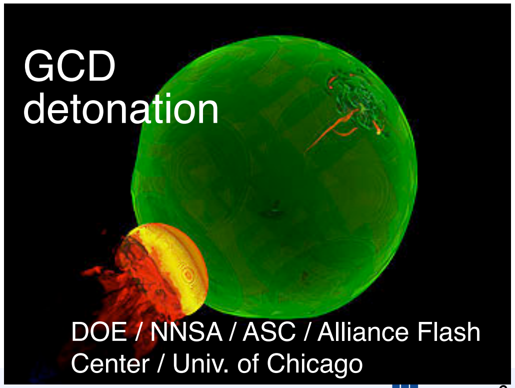
- Observations favor explosion models with transition from an initial subsonic deflagration phase to a supersonic detonation phase (DDT)

- Deflagration phase
    - Carbon “cooking” yields rising ash bubbles that are unstable to buoyancy-driven instabilities
    - Bubble boundaries are unstable deflagration fronts that become corrugated and turbulent, and propagate much faster than the laminar flame speed
    - Turbulent flame propagation speeds are not known from first principles

- Detonation-deflagration mechanism is unknown (several are proposed) and often proscribed ad-hoc in calculations

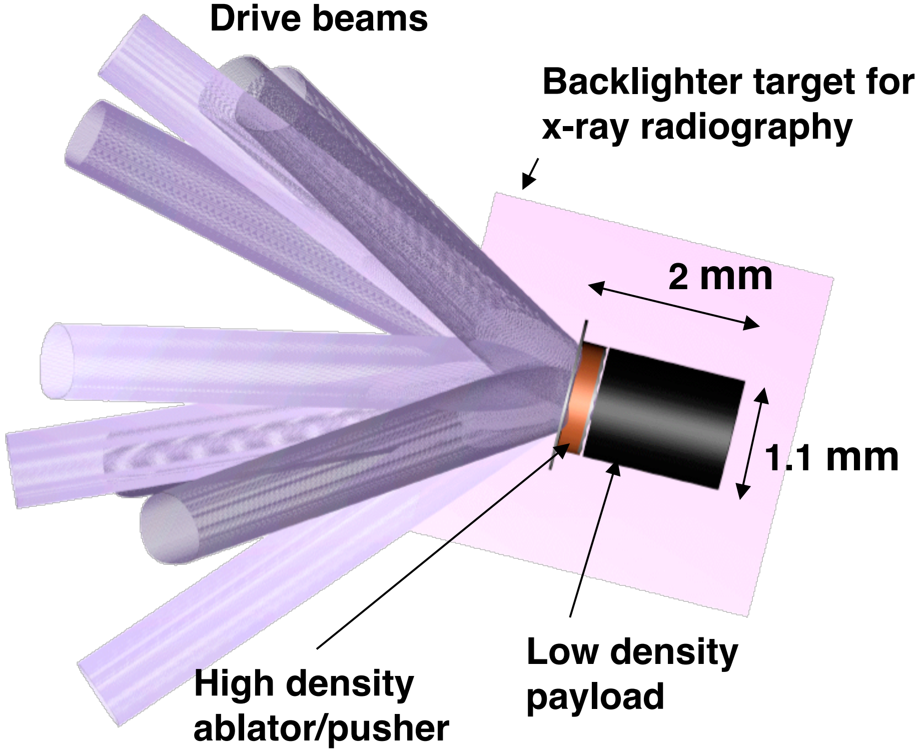


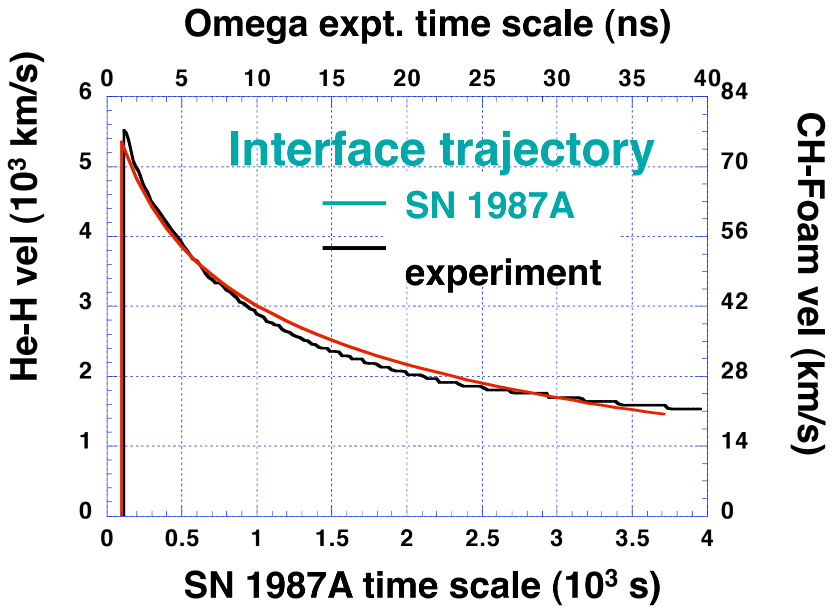
V.N. Gamezo et al, ApJ 623, 337 (2005)



DOE / NNSA / ASC / Alliance Flash Center / Univ. of Chicago

Euler scaling provides connection between laboratory and astrophysical systems (SNRT targets)





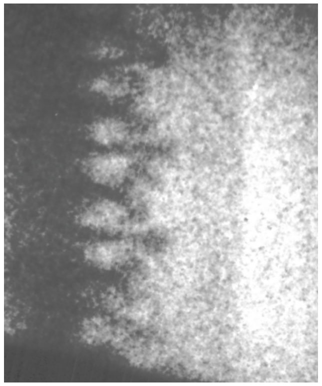
$$\left[\frac{h}{\tau\sqrt{\frac{P}{\rho}}}\right]_{SN} \sim \frac{10^{11}cm}{10^{3}s\sqrt{\frac{10Mbar}{0.01g/cc}}} \sim \left[\frac{h}{\tau\sqrt{\frac{P}{\rho}}}\right]_{exp} \sim \frac{100\mu m}{10ns\sqrt{\frac{1Mbar}{1g/cc}}}$$

- Machined perturbations at plastic/foam interface
- Laser energy is nominally ~5 kJ in a 1 ns pulse that drives a M~15 blast wave into the target

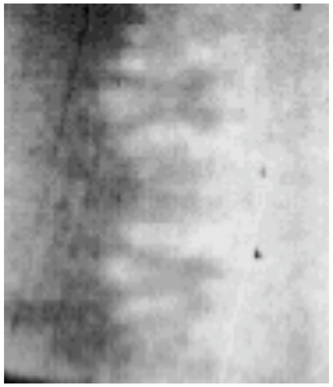
X-ray radiography is used to diagnose SNRT laser experiments with a wide range of initial conditions

2D Single-mode

2D Two-mode

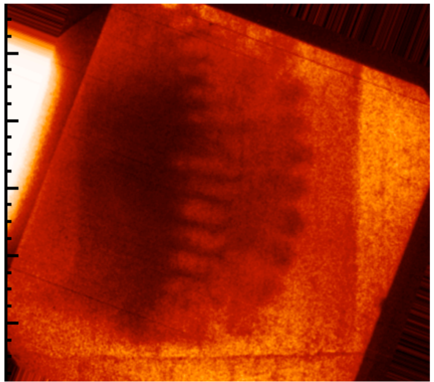


2D Eight-mode



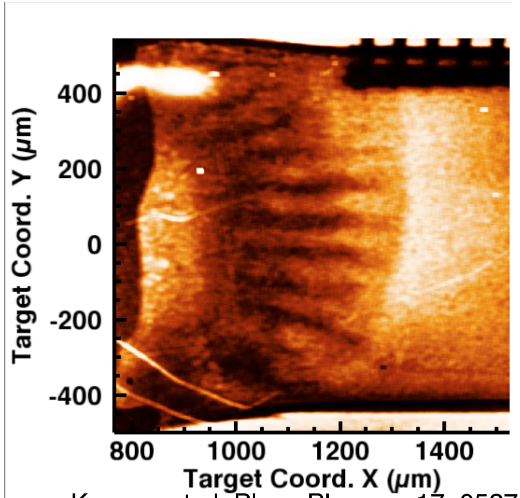
Miles, et al, Phys. Plasmas 11, 3631 (2004)

2D Short on long shows transition to turbulence



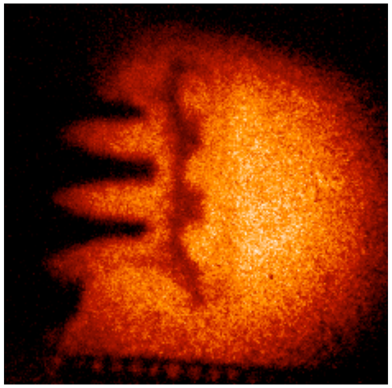
Miles, et al, Phys. Plasmas 11, 5507 (2004)

3D “Egg-crate”



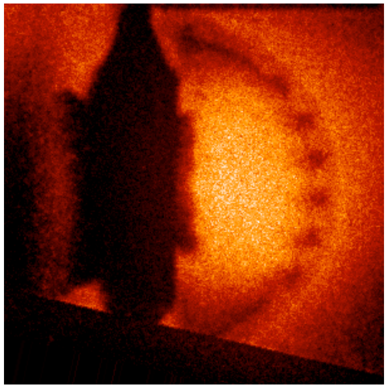
Kuranz, et al, Phys. Plasmas 17, 052709 (2010)

Multi-interface coupling



Robey, et al, Phys. Plasmas 8(5), 2446 (2001)

Spherical divergence



Drake, et al, Astrophys. J., 564, 896 (2002).

A more energetic laser driver would significantly extend the Omega platform

Omega experiments capture important aspects of the full problem:

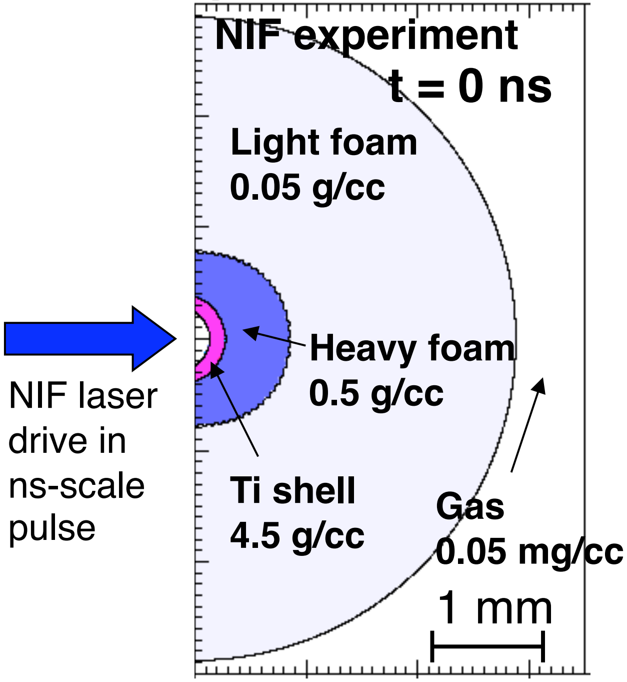
- Time-dependent acceleration
- Compressibility: density and velocity gradients that give decompression & stretching
- Shocks with resultant RM contribution

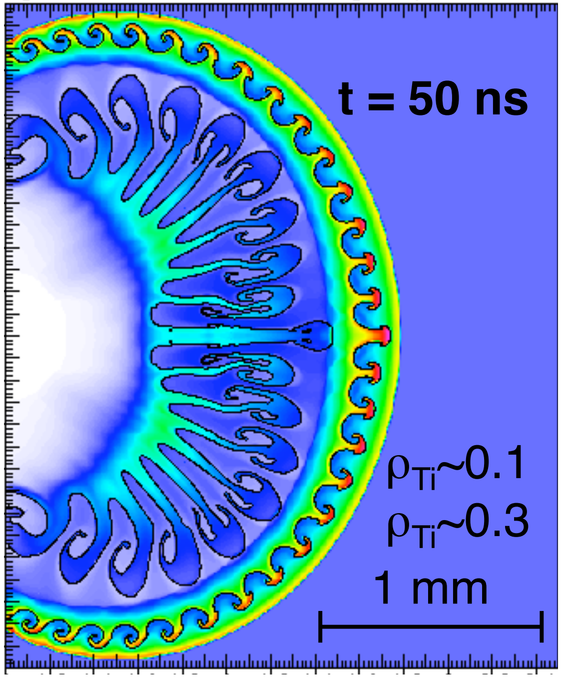
Limited Omega energy restricts the platform flexibility:

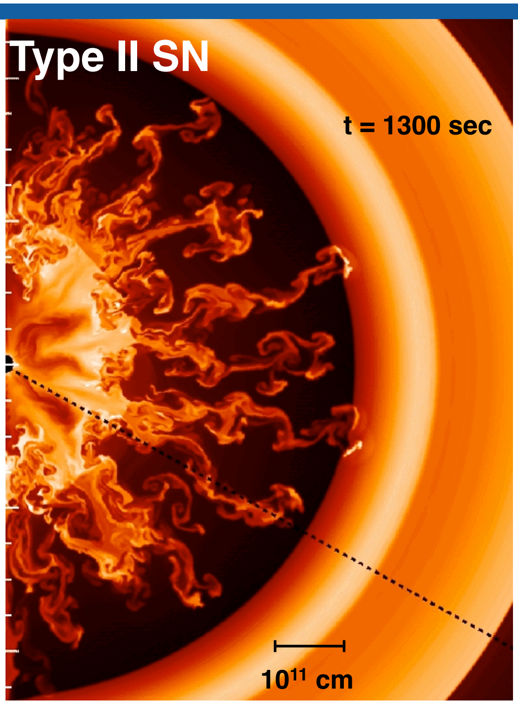
- Energy density in spherically divergent experiment falls off like $1/R^3$ rather than 1/R
- Evolution time-scale of diagnosable scales makes it difficult to observe transition to turbulence
- Shocks are non-radiative

Maximum Omega energy is 60 kJ
Maximum National Ignition Facility (NIF) energy is 1800 kJ (30xOmega)

NIF experiment #1: Divergent Type II experiment to test mass-scaled multi-interface interaction



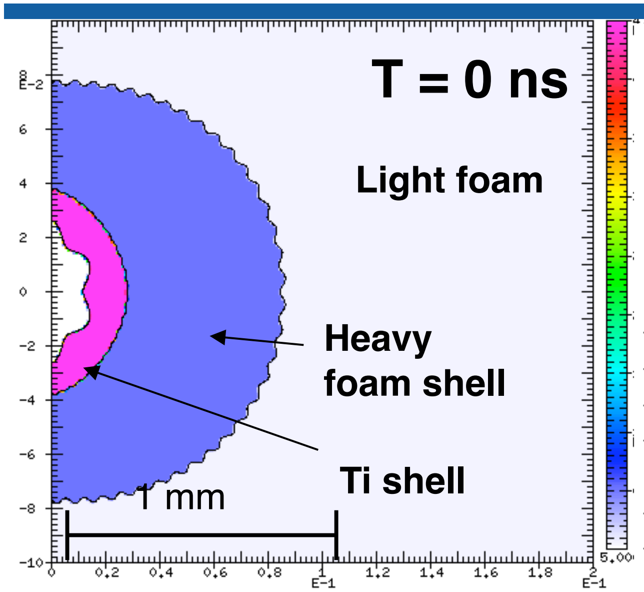




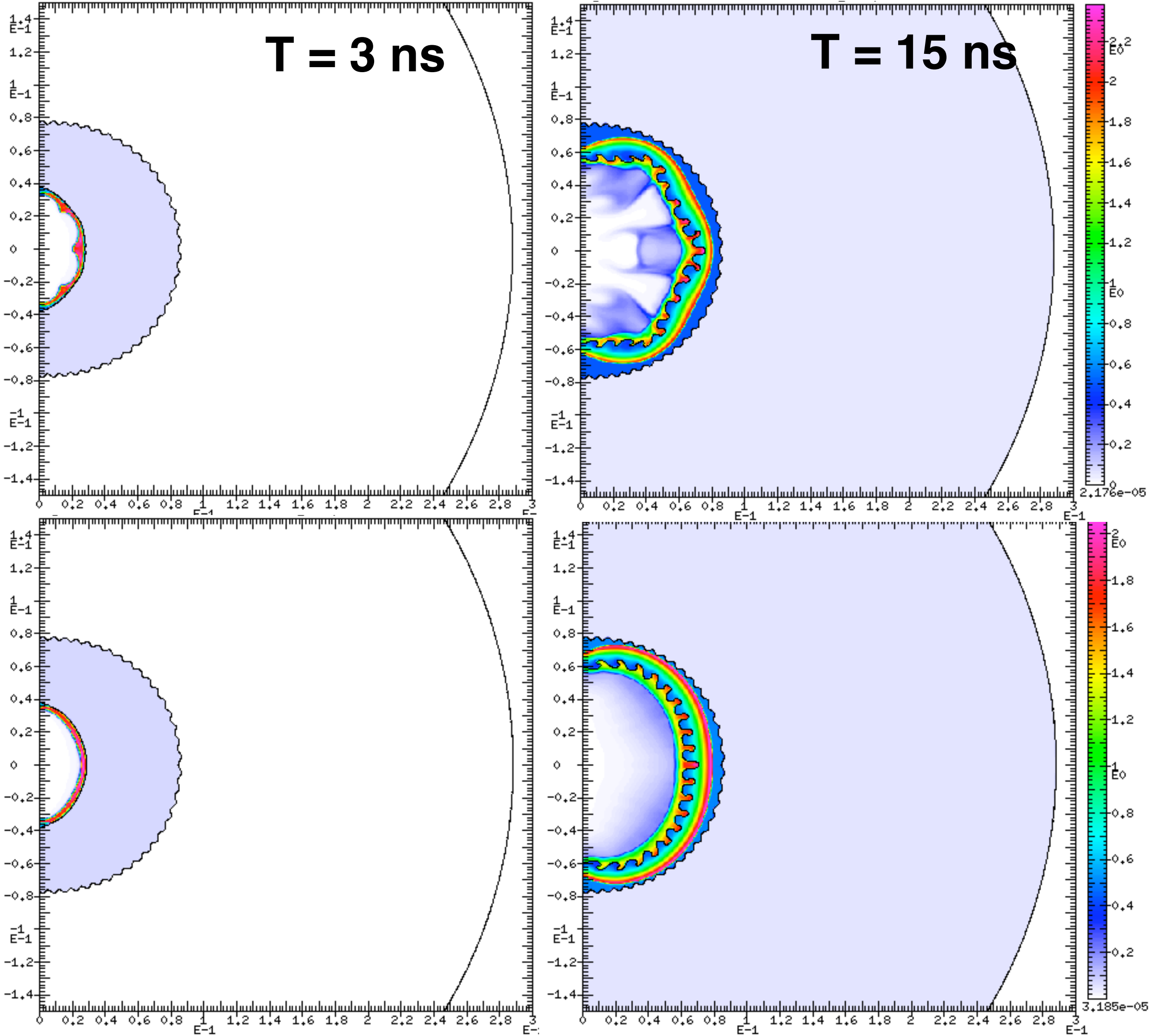
Kifonidis et al., Astron. Astrophys. **408**, 621 (2003).

		Fe/Si	Si/O	(C+O)/He	He/H	H/ISM
$15M_\odot$ progenitor of Kifonidis et al:	**r[km]**	1376	6043	29800	708000	3.5e7
	$M_r/M_\odot$	1.32	1.50	1.68	4.20	15.0
	$M_r/M_{Si/O}$	0.88	1.00	1.12	2.80	10.0
NIF experiment with multiple interfaces at mass-scaled positions			Ti/(H. foam)		(H. foam)/(L. foam)	(L. foam)/gas
	r[μm]		280		855	2883
	$M_r/M_{Ti/CH}$		1.00		2.80	10.0

Oblique incident shock gives low-mode RM and enhanced inner spike penetration

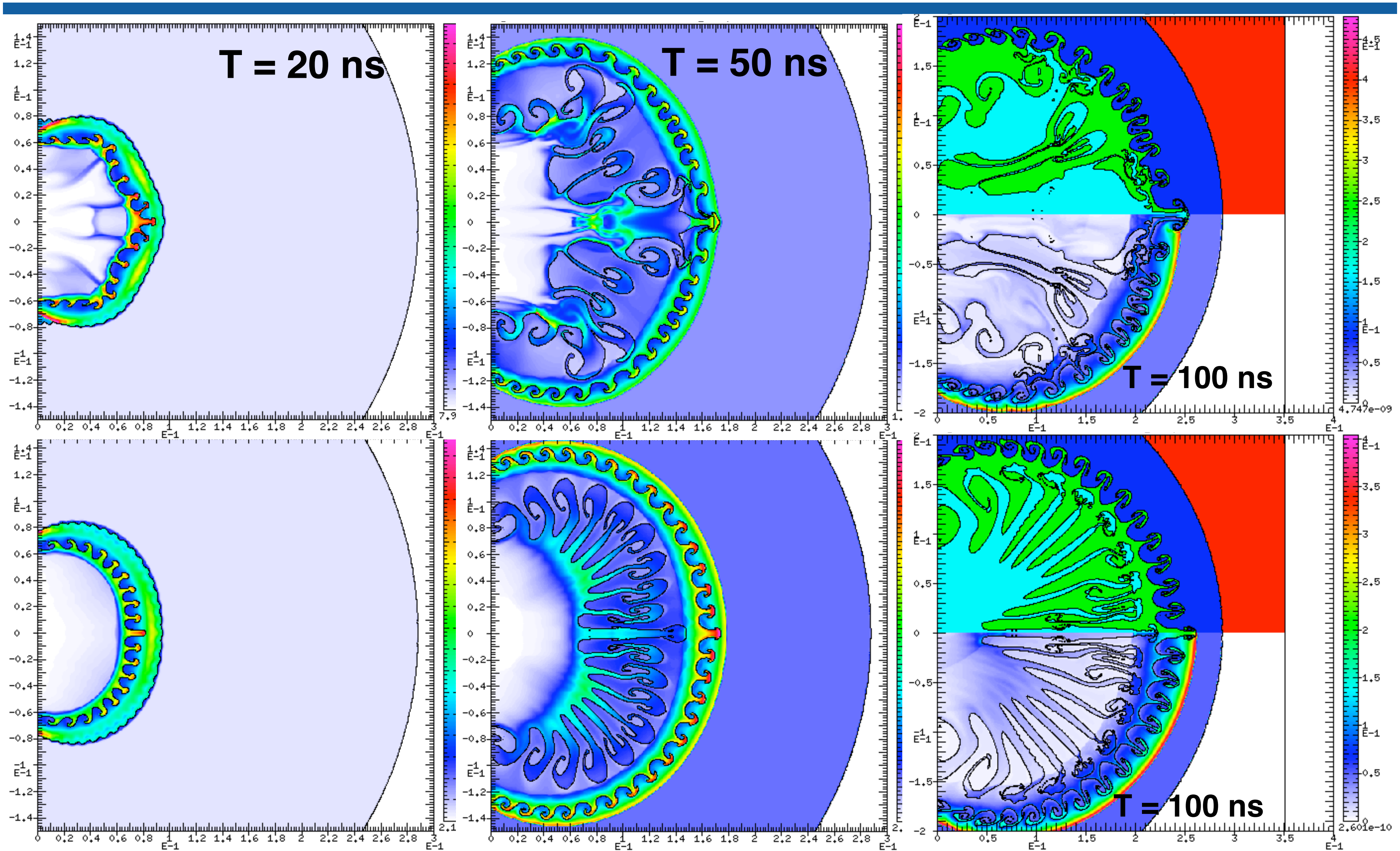


- Large-amplitude low mode on the irradiated surface produces a perturbed shock that seeds RM on the Ti/foam interface
- Will large-amplitude low-mode RM allow metal to escape into the H surrogate before formation of the reverse shock in the heavy foam?



snbw120/snbw121

Oblique incident shock gives low-mode RM and enhanced inner spike penetration



snbw116/snbw120

Linking the supernova explosion and remnant stages: Are there connections between their instability structure?

Can explosion-phase instabilities in thermonuclear supernovae explain why the perturbed interface in Tycho is “too close” to the forward blast wave shock

- Large-scale ash bubbles can perturb the outgoing detonation wave after delayed detonation

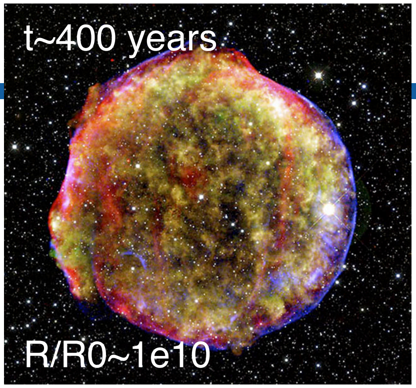
- Large-amplitude low-mode perturbed shock should drive RM instability growth at the outer surface of the star

- Signature of the instability might survive into the remnant stage and perturb the forward shock out to scaled Tycho time

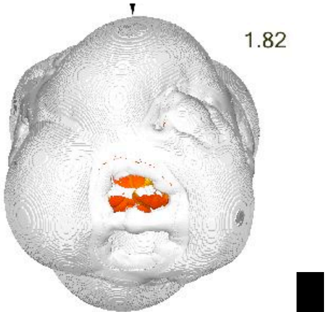
- SNR calculations are initiated with spherical explosion profiles from models or simulations (neglect RM)

Is the implicit assumption that SNR instabilities are independent of the explosion initial conditions valid?

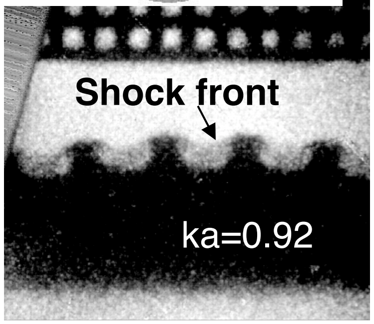
Analytic modeling predicts RM always dominates initially and remains significant for large-amplitude initial conditions



Observed spectral peak @ mode 6



V.N. Gamezo et al, ApJ 623, 337 (2005)



S.,G. Glendinning et al

OMEGA RM experiment, Glendinning et al

Shock proximity occurs when the perturbation grows faster than the shock recession speed

$$u_{RM} = ka_0 A^* u_{i0}$$

$$u_{i0} = \frac{2}{\gamma + 1} v_{i0}$$

$$\frac{u_{RM}}{v_{i0} - u_{i0}} = \frac{2ka_0 A^*}{\gamma - 1}$$

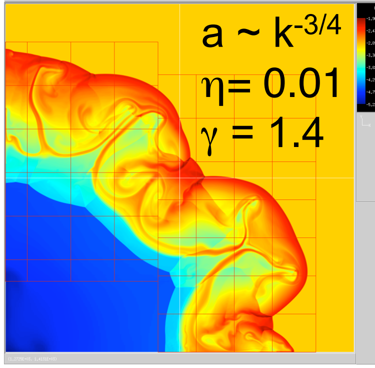
Shock proximity when $ka_0 > \frac{\gamma - 1}{2A^*}$

$ka_0 > \left\{\frac{1}{3}, 0.2, \frac{1}{6}\right\}$ for $\gamma = \left\{\frac{5}{3}, 1.4, \frac{4}{3}\right\}$ and $A^* = 1$

Shock proximity is caused by large initial amplitude or high compressibility

RM dominates ↔ RT dominates

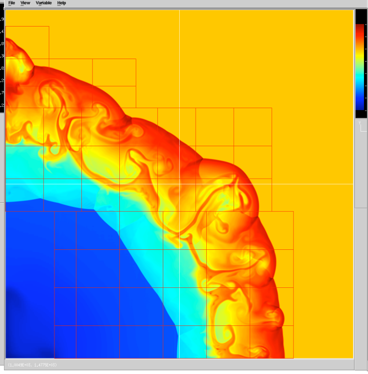
$(ka)_6 = 1.0$



$L = 8.9\ r_i = 1.9\ r_m$

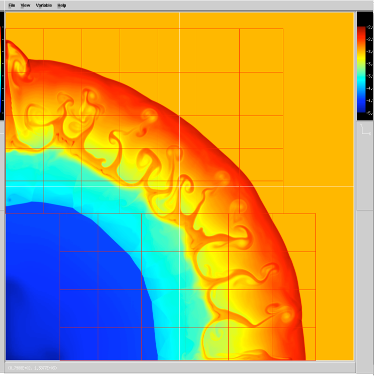
snbw44

$(ka)_6 = 0.2$



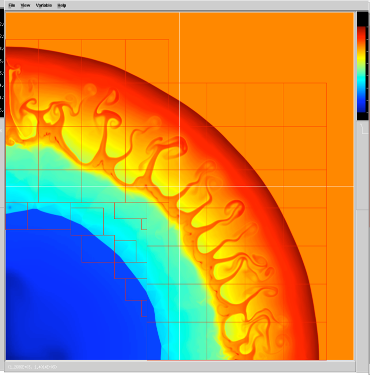
snbw49

$(ka)_6 = 0.05$



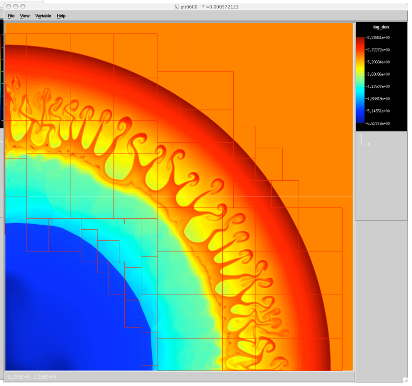
snbw47

$(ka)_6 = 0.01$



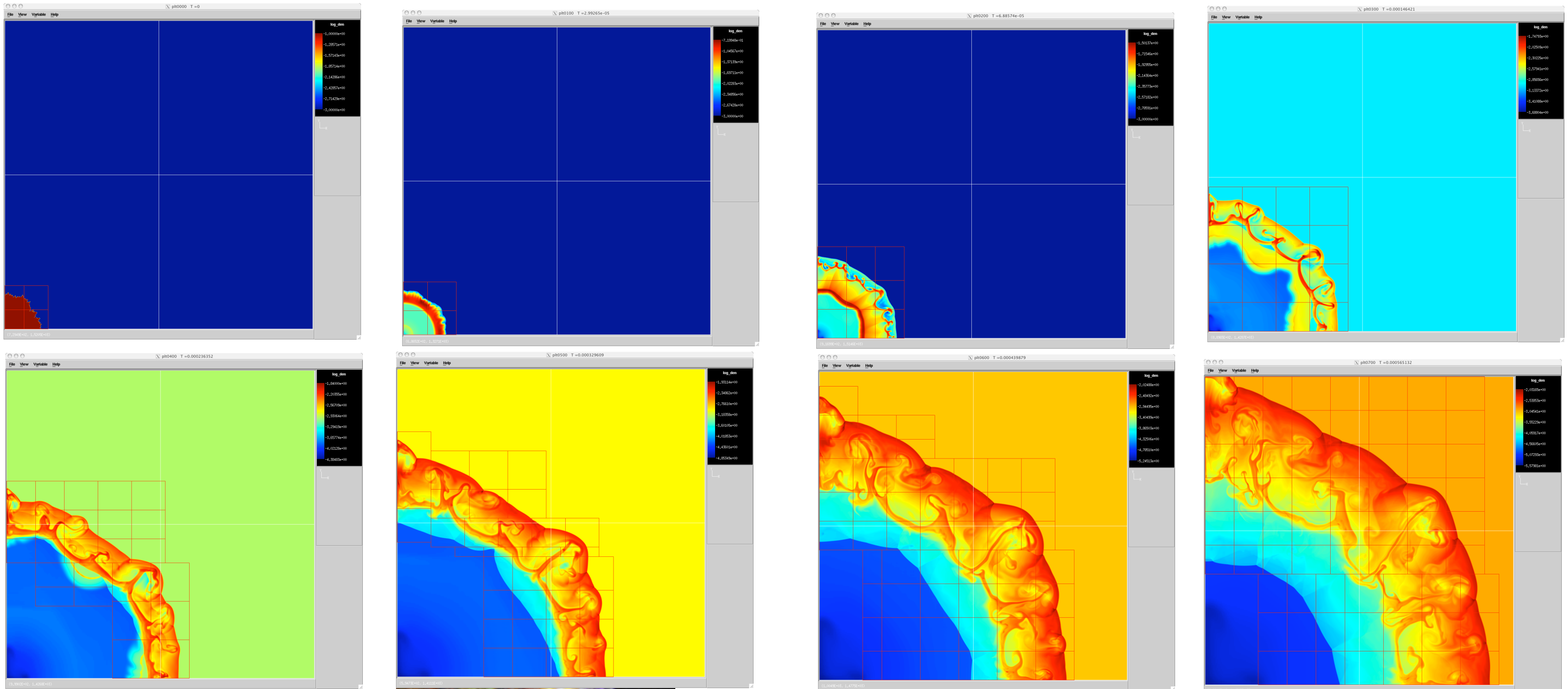
snbw48

$(ka)_6 = 0.0$



snbw50

NIF experiment #2: Large initial amplitude perturbation gives proximate shock at present scaled Tycho radius

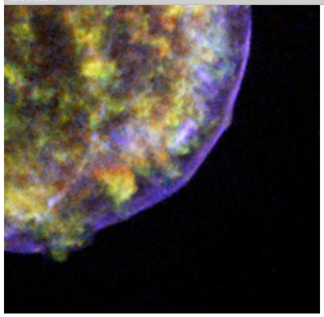


$L=8.9\ r_i = 1.9\ r_m$

$(ka)_6 = 0.2$

$a \sim k^{-3/4}$

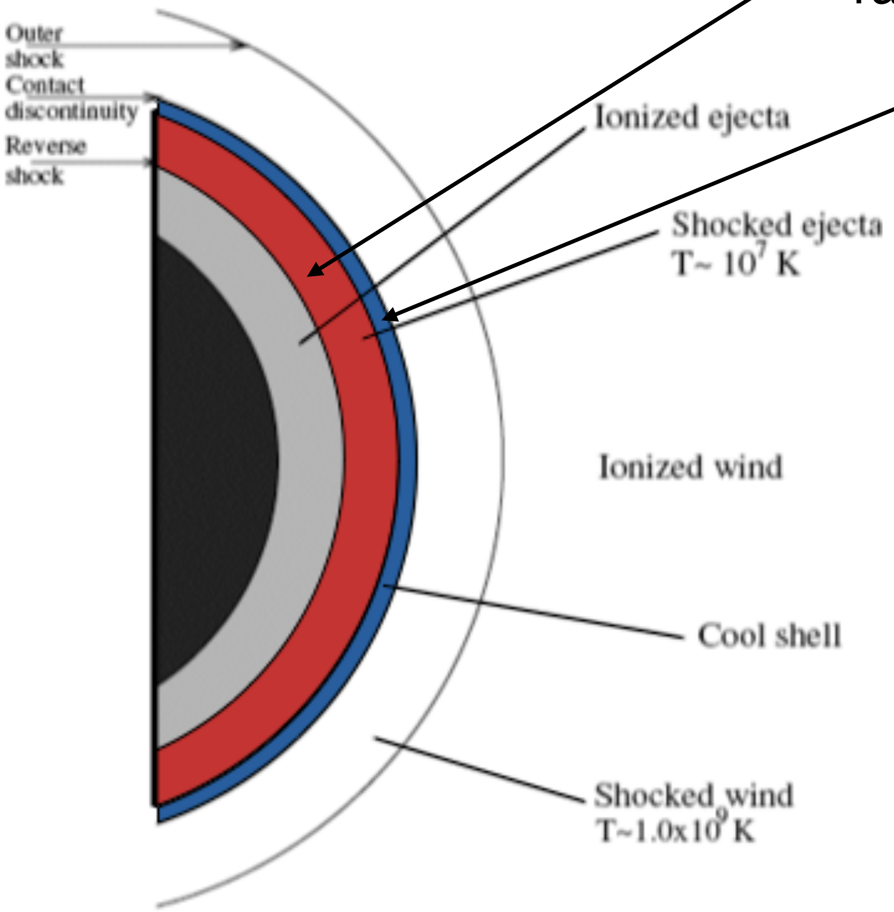
$\eta = 0.01$



Late-time instability structure in Type Ia SNe might be indicative of deflagration-to-detonation transition and reflect deflagration phase dynamics

Core-collapse of a red supergiant: How does radiative heating affect the evolution of blast-wave-driven instabilities?

Nymark et al., A&A 2006



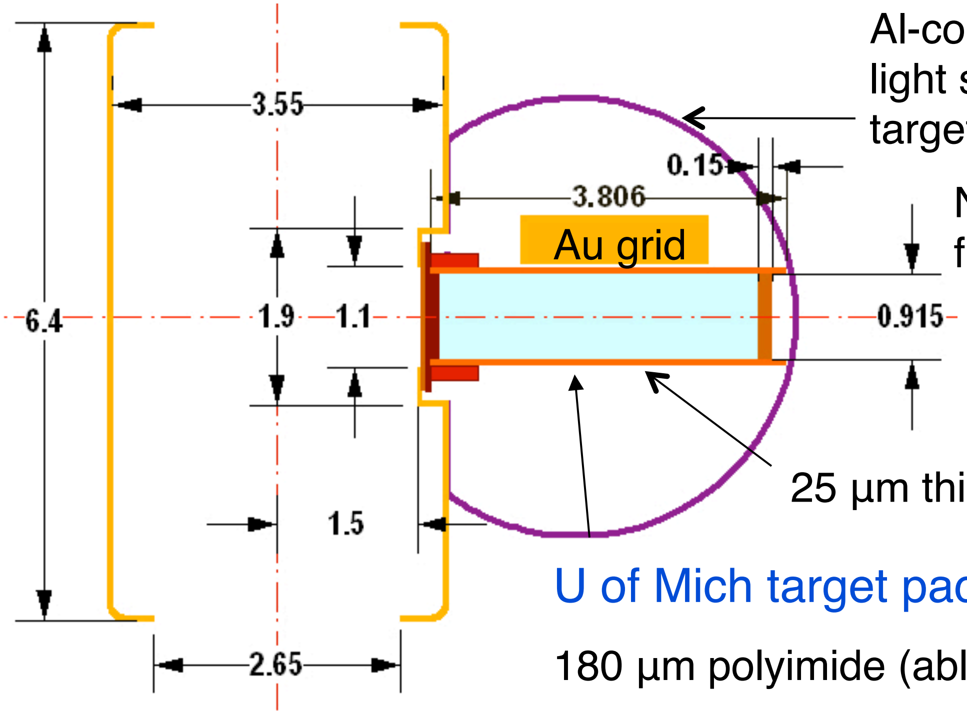
Shocked layer is strongly radiative

Cool shell is Rayleigh Taylor unstable (not shown)

- Radiative shocks are common in astrophysical systems where temepratures are high and densities are low

- Radiative effects are typically not included in SN hydro simulations

NIF experiment #3: Radiative SNRT (RADSNRT) target has been developed and will be shot within the year

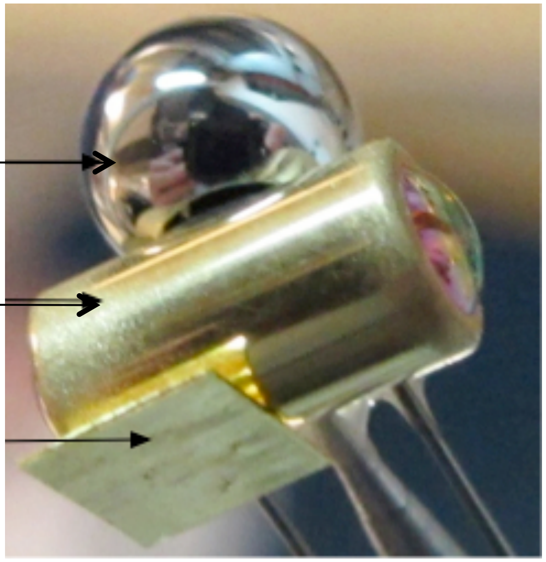


Al-coated unconverted light shield (contains target package)

NIF 0.7 scale gas-filled hohlraum

Au shield

25 µm thick polyimide tube



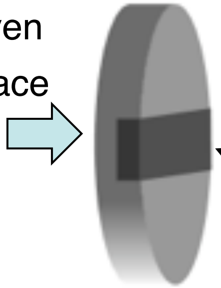
U of Mich target package

180 µm polyimide (ablator)

2-D ripple patter (λ=71 µm)

3.8 mm 25 mg/cc SiO_2 foam

2D single mode Rayleigh-Taylor seed perturbations target

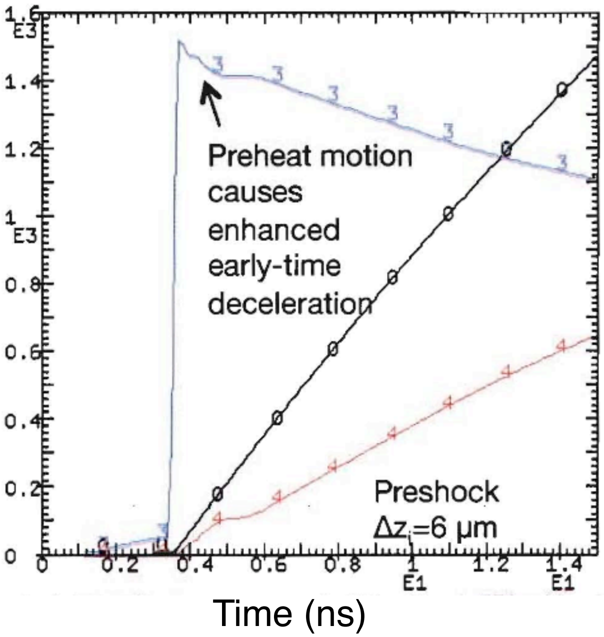


Driven surface

75 µm thick 250 µm wide CHI (3%) tracer strip

High-temperature and low-temperature cases can be compared to isolate radiative effects

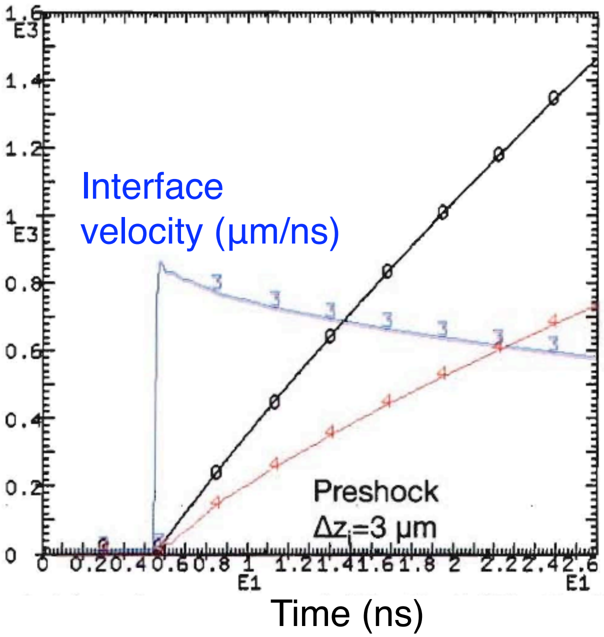
High laser drive (radiative)	Low laser drive (nonradiative)
E = 600 kJ	E = 200 kJ
Tr = 330 eV	Tr = 250 eV



Preheat motion causes enhanced early-time deceleration

Preshock Δz_i=6 µm

Preshock a=2.31 µm



Interface velocity (µm/ns)

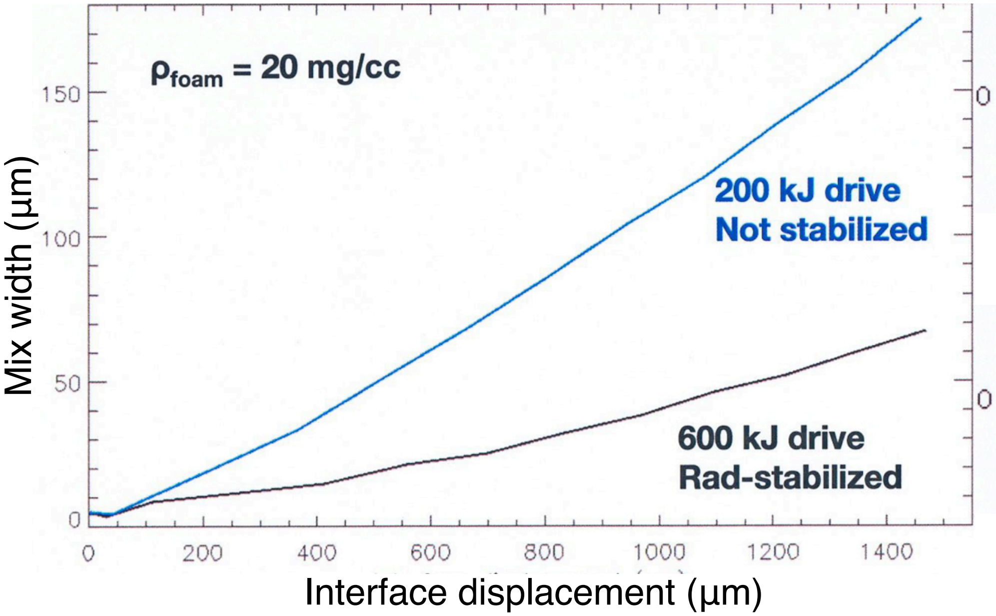
Preshock Δz_i=3 µm

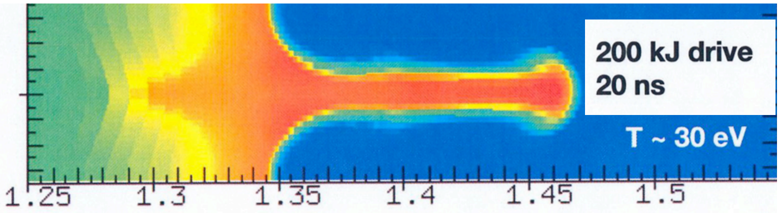
Interface displacement (µm)

$$f_{RT} \propto \int dt \sqrt{g(t)}$$

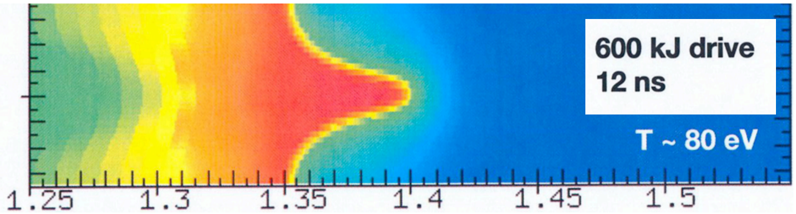
Preshock a=2.38 µm

Simulations predict large difference between high- and low-drive cases at RT-growth-function-scaled times





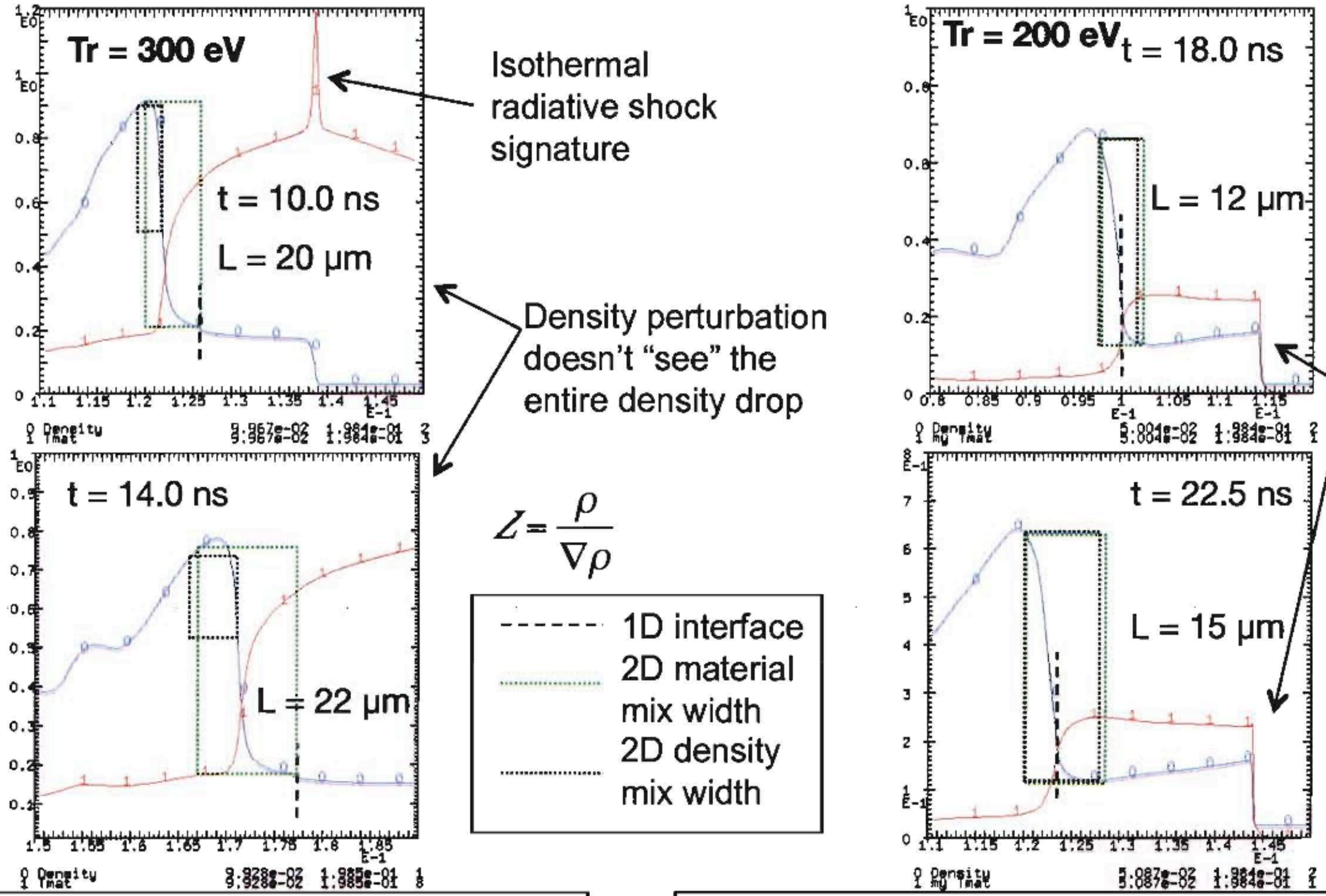
Low T => Non-radiative shock & hydro-dominated growth



High T => Radiative shock and suppressed RT

High-T drive gives 2-3x slower growth and very different spike morphology when compared at equal interface displacement or RT growth function

RTI in high-T planar blast-wave-driven RADSNRT is ablatively stabilized by radiation from the shock-heated foam



Isothermal radiative shock signature

Density perturbation doesn't "see" the entire density drop

Classical non-radiative blast wave profiles

Density

Temperature

$$L = \frac{\rho}{\nabla\rho}$$

- - - - - - 1D interface

······ 2D material mix width

······ 2D density mix width

- Plastic spike material does not get ahead of 1D interface position
- Density perturbation falls falls continually further behind 1D interface position

- Density and material mix widths are approximately coincident and centered about 1D interface position
- Low-drive density gradient scale length is comparable to high-drive case

Snrt150d/snrt151d

NIF is poised to open new frontiers in SN-relevant blast-wave-driven instability experiments

- Interfacial instabilities play an important role in core-collapse and thermonuclear supernova explosions and remnants

- SN-relevant instability experiments on the Omega laser are useful, but energy-limited

- New regimes will be accessed through experiments at the National Ignition Facility (NIF)
    - Divergent multi-interface experiment will study mass-scaled outward transport of core material in core-collapse Type II Sne
    - Divergent large-initial-amplitude experiment will study interplay of RM and RT and resultant connections between explosion and remnant stages of Type Ia thermonuclear SNe
    - Strongly-driven planar experiment will study radiative stabilization of the blast-wave-driven interface instability