ASC

Office of Science
U.S. Department of Energy

Thermonuclear Supernova
A Successful Failure

Tomek Plewa

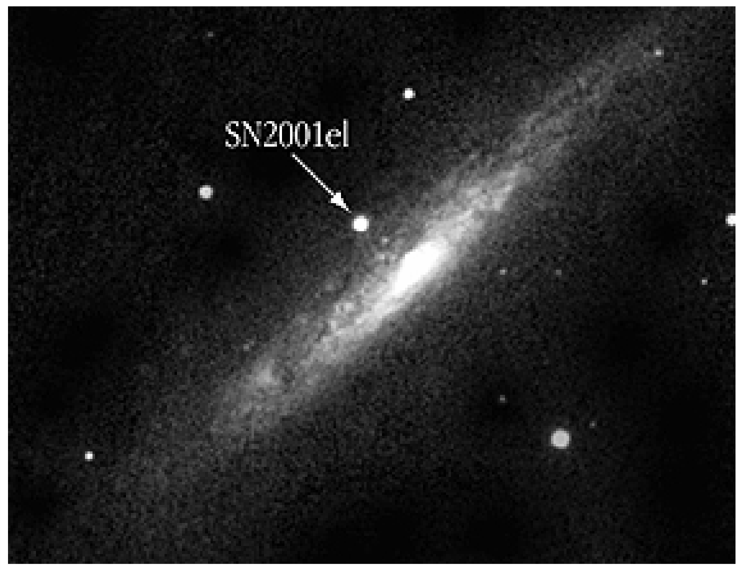
Paths to Exploding Stars: Accretion and Eruption
KITP, UCSB
March 2007

Outline

- Why do we care?
- The explosive ZOO
- Simulation technology: Mueller’s eye opener
- Forgotten tale of the ICs
- Close but no cigar: pure deflagrations
- Detonating Failed Deflagrations
- DFD model validation
- Summary

Why Do We Care?

COBE



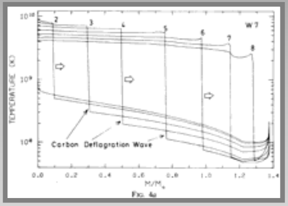
ESO

- SN Ia are crucial for galactic chemical evolution.
- Probes allowing study of expansion and geometry (Ω_M, Ω_Λ) of the Universe
- Offer constraints on the nature of dark matter
- Provide astrophysical setting for basic combustion problems.

SN Ia Theory Cosmic Timescale

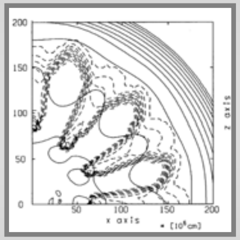
1960s

- WD explosion proposed for Type Ia (Hoyle & Fowler)
- 1D detonation model (Arnett)



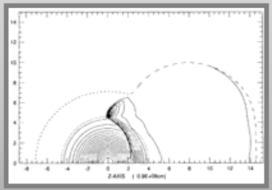
1970s

- detonation models (several groups)
- deflagration models (Nomoto)



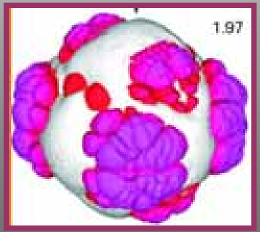
1980s

- improved 1D deflagration models (Nomoto’s group)
- first 2D deflagration model (Mueller & Arnett)



1990s

- 2D and 3D deflagration models, DDT (Khokhlov)
- non-standard models 2D He detonations (Livne & Arnett)
- small scale flame turbulence (Niemeyer & Hillebrandt)



2000s

- 3D deflagration models (NRL, MPA, Barcelona, Chicago)
- 3D DDT models (NRL)

The Explosive Zoo: The D-rich Family

DET DEF subCh DD PDD TDD LDET GCD PRD DFD WDM

DET	Arnett (1969), Hansen & Wheeler (1969)
DEF	Nomoto et al. (1976)
subCh	Woosley & Weaver (1994), Livne & Arnett (1995)
DD	Khokhlov (1991)
PDD	Ivanova et al. (1974), Khokhlov (1991) (pulsating)
TDD	Khokhlov (1991; tampered, common envelope)
LDET	Yamaoka et al. (1992; late)
GCD	PCL2004
PRD	Bravo & Garcia-Senz (2006)
DFD	P2007, PK2007
WDM	Iben & Tutukov/Webbink (1984), Hachisu et al. (1986) Benz (1990), Guerrero et al. (2004)

Ewald Müller's Eye Opener

simulate, v. (Oxford English Dictionary, 2nd ed, 1989)

> 1. a. trans. To assume falsely the appearance or signs of (anything); to feign, pretend, counterfeit, imitate; to profess or suggest (anything) falsely.

Ex.: 1874 L. STEPHEN Hours Libr. (1892) I. i. 9

> *These […] show the pleasure which he took in simulating truth.*

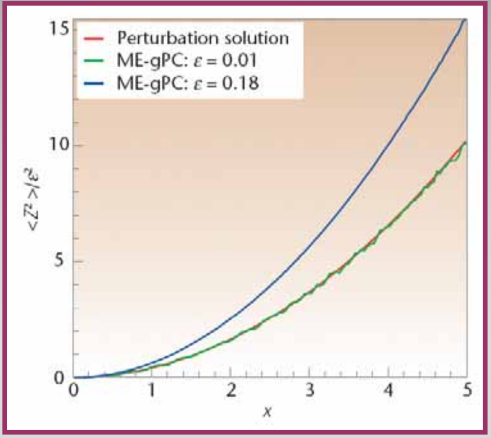
Simulation Aspects Worth Remembering

The initial conditions (push) may predetermine the outcome (alpha-group RTI)

Memory of the initial conditions may survive for long

Numerical transients can be important (Zhang/flame)

Insight often comes from different application (Rosner/nova)



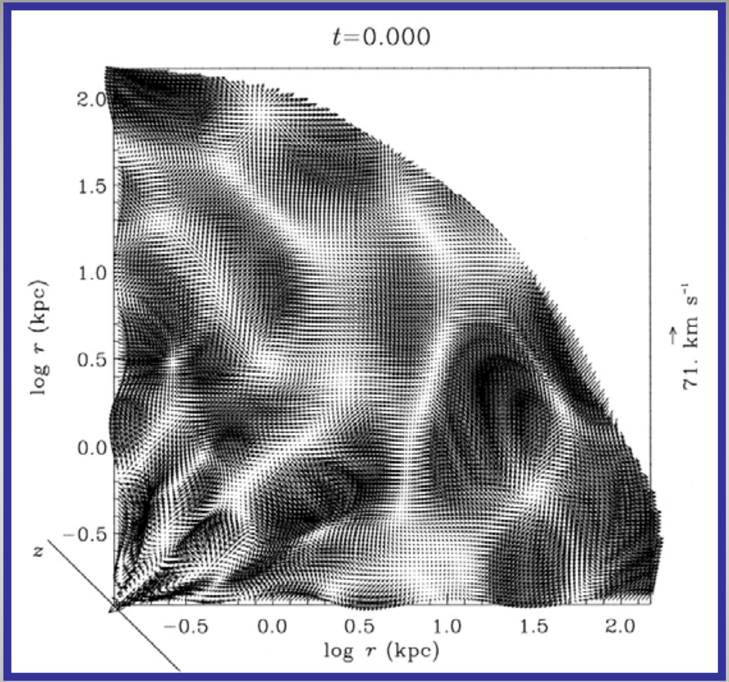
Lin et al. (2007)

Simulations have a potential of producing arbitrarily complex unverifiable results

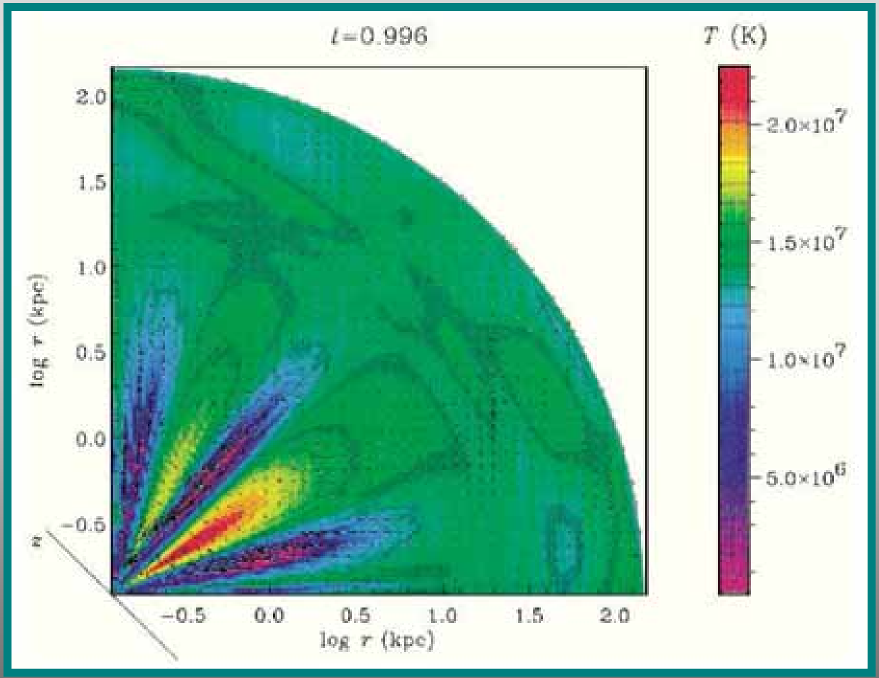
Computer models are becoming more realistic – they are NOT realistic!!

Example: GCD - The Real Story

Robust procedure: the outcome insensitive to small perturbations.



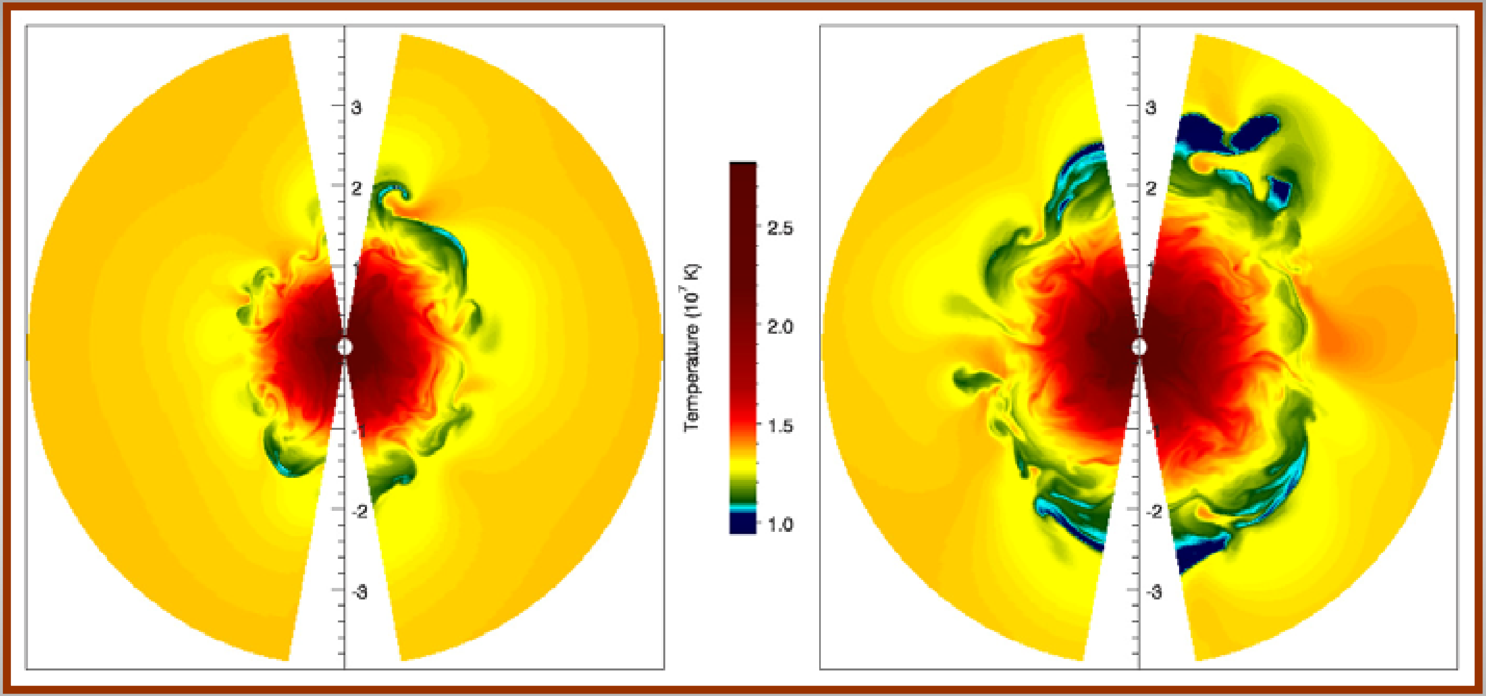
Różyczka: What happens if the perturbations are random?



Kritsuk, Böhringer, & Müller (1998)

GCD - The Real Story

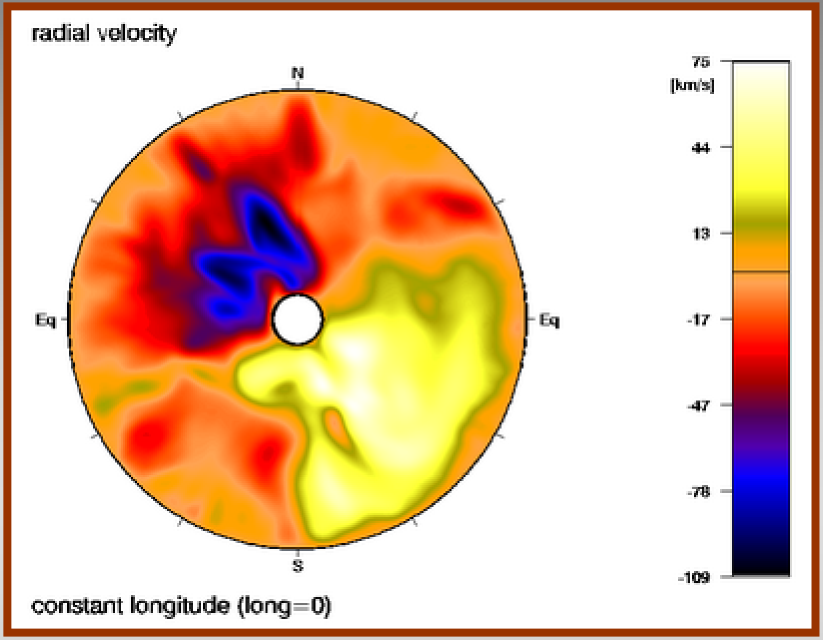
Robust procedure: the outcome insensitive to small perturbations.



Kritsuk, Plewa, & Müller (2001)

Large scale core convection…

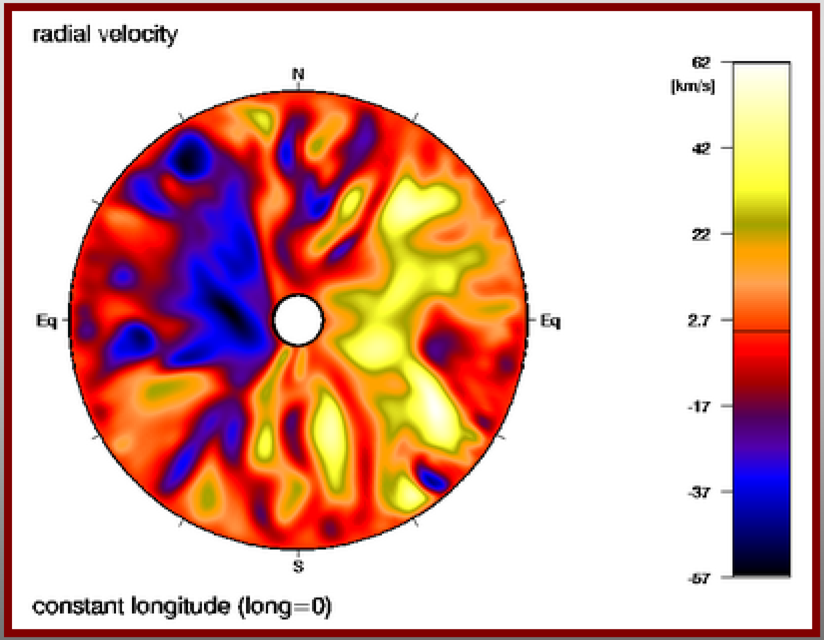
Simplifying Scenario Warning



Kuhlen, Woosley, & Glatzmaier (2005)

non-rotating

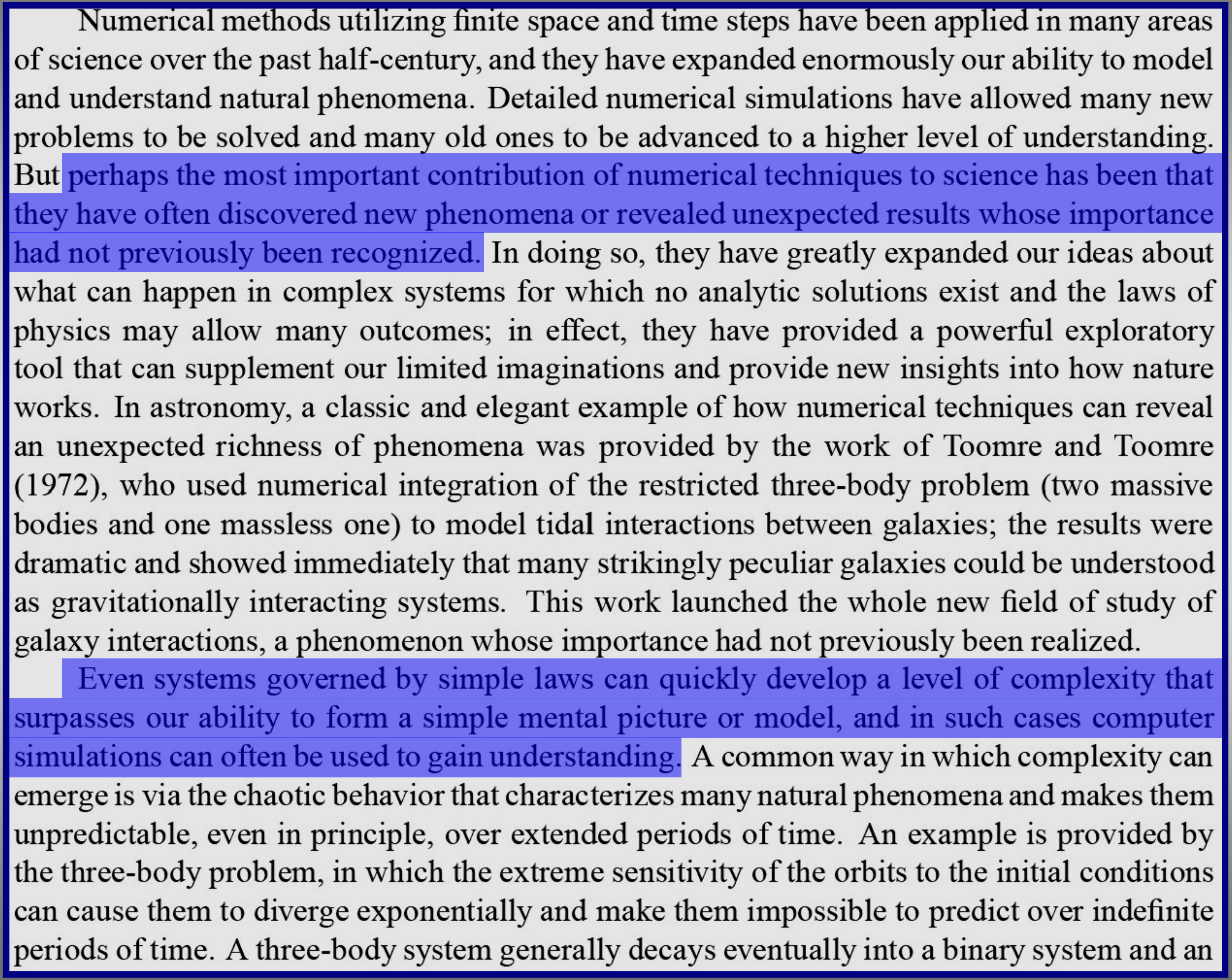
rotating



Kuhlen et al.

Problem of (over)simplification will reappear later in this talk.

Larson's Reflection



Numerical methods utilizing finite space and time steps have been applied in many areas of science over the past half-century, and they have expanded enormously our ability to model and understand natural phenomena. Detailed numerical simulations have allowed many new problems to be solved and many old ones to be advanced to a higher level of understanding. But perhaps the most important contribution of numerical techniques to science has been that they have often discovered new phenomena or revealed unexpected results whose importance had not previously been recognized. In doing so, they have greatly expanded our ideas about what can happen in complex systems for which no analytic solutions exist and the laws of physics may allow many outcomes; in effect, they have provided a powerful exploratory tool that can supplement our limited imaginations and provide new insights into how nature works. In astronomy, a classic and elegant example of how numerical techniques can reveal an unexpected richness of phenomena was provided by the work of Toomre and Toomre (1972), who used numerical integration of the restricted three-body problem (two massive bodies and one massless one) to model tidal interactions between galaxies; the results were dramatic and showed immediately that many strikingly peculiar galaxies could be understood as gravitationally interacting systems. This work launched the whole new field of study of galaxy interactions, a phenomenon whose importance had not previously been realized.

Even systems governed by simple laws can quickly develop a level of complexity that surpasses our ability to form a simple mental picture or model, and in such cases computer simulations can often be used to gain understanding. A common way in which complexity can emerge is via the chaotic behavior that characterizes many natural phenomena and makes them unpredictable, even in principle, over extended periods of time. An example is provided by the three-body problem, in which the extreme sensitivity of the orbits to the initial conditions can cause them to diverge exponentially and make them impossible to predict over indefinite periods of time. A three-body system generally decays eventually into a binary system and an

Larson (2007)

1 + 1 = 2

We often think that when we have completed our study of one we know all about two, because "two" is "one and one." We forget that we still have to make a study of "and."“

Sir Arthur Eddington

We need to study and understand separate components.

We also need exploratory integrated simulations to learn about connections.

However, we do not even understand one’s!!

Some of the One's

Channels for progenitors

- Binary evolution
- Population synthesis

Initial conditions

INCITE 2004

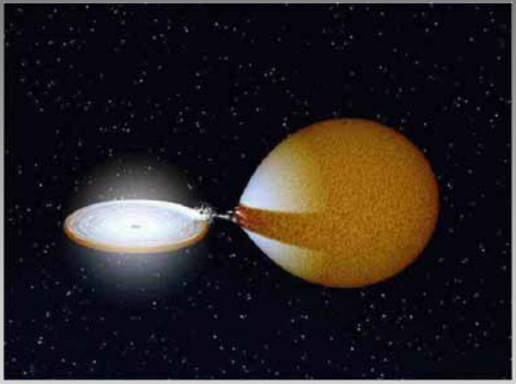
- State of the stellar core
- Metallicity
- Rotation profile
- Magnetic fields

Basic physics

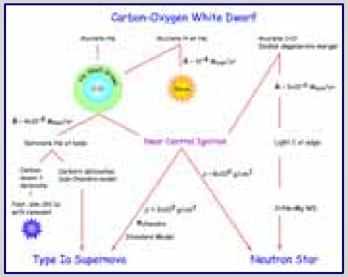
- Flame on intermediate scales
- Unsteadiness
- DDT

Numerics

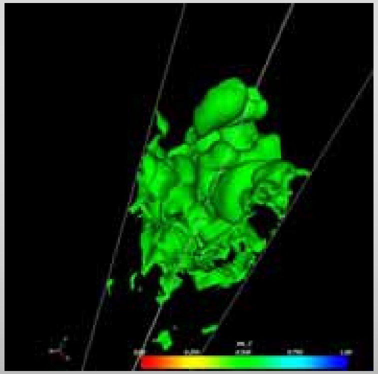
- Multiphysics coupling
- Nucleosynthesis postprocessing



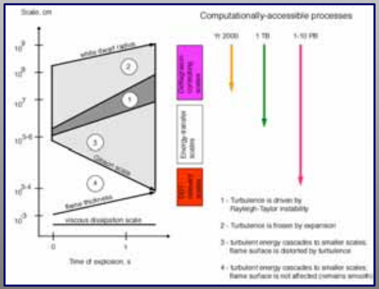
R. Hynes



F. Timmes

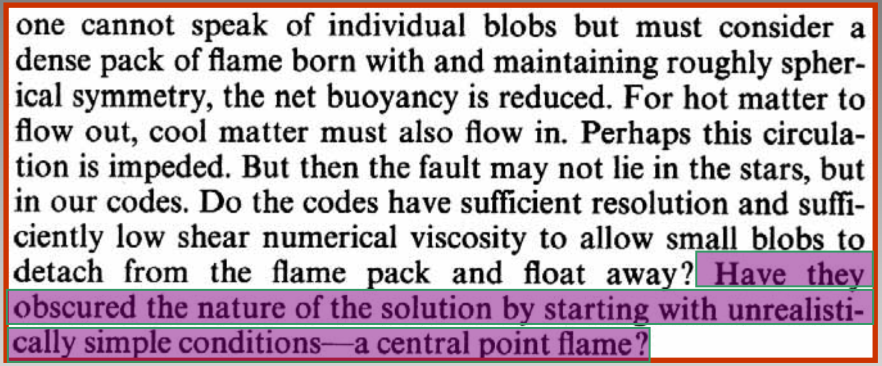


Zhang et al. (2007)



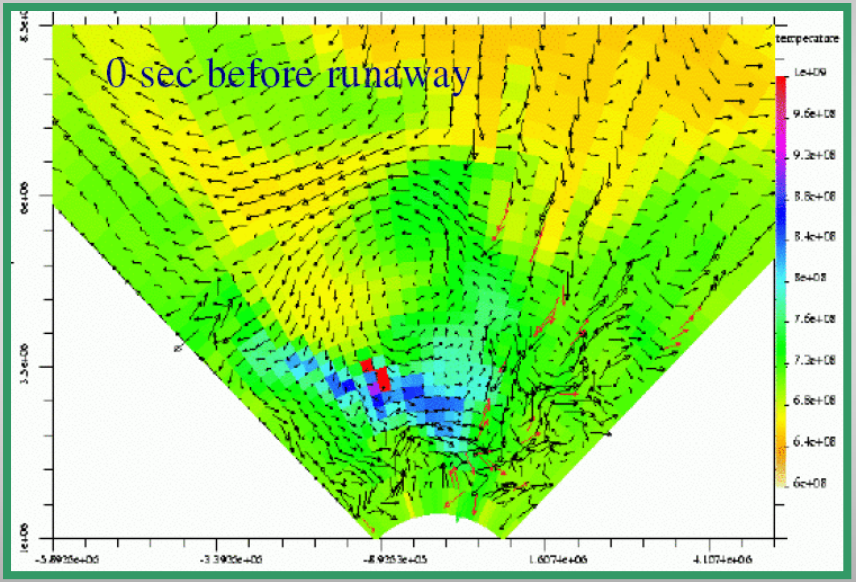
Khokhlov (2003)

Initial Conditions



one cannot speak of individual blobs but must consider a dense pack of flame born with and maintaining roughly spherical symmetry, the net buoyancy is reduced. For hot matter to flow out, cool matter must also flow in. Perhaps this circulation is impeded. But then the fault may not lie in the stars, but in our codes. Do the codes have sufficient resolution and sufficiently low shear numerical viscosity to allow small blobs to detach from the flame pack and float away? Have they obscured the nature of the solution by starting with unrealistically simple conditions—a central point flame?

Garcia-Senz & Woosley (1995)



Höflich & Stein (2002)

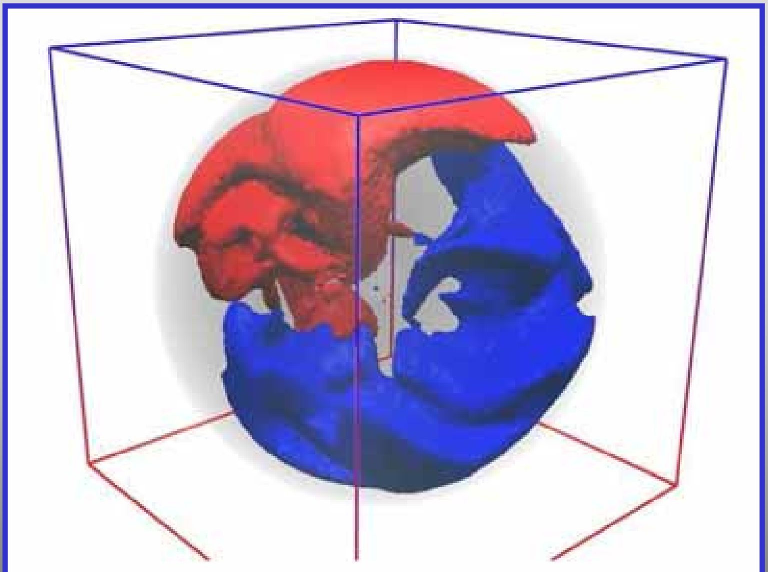
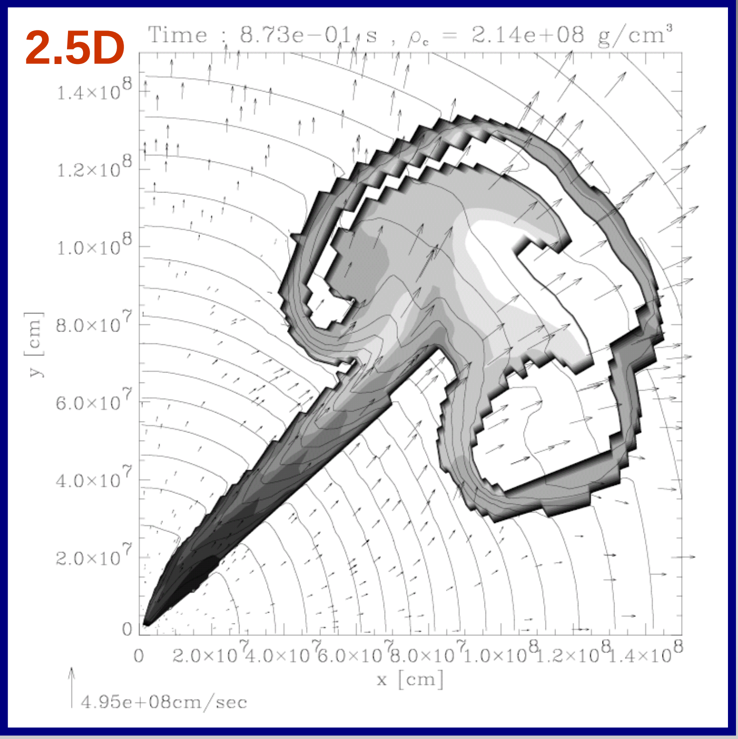


Fig. 5.— Two iso-velocity surfaces at $|v_r| = 40$ km/s. The sharp division between infalling (red) and outflowing (blue) material clearly demonstrates the dipole nature of the flow.

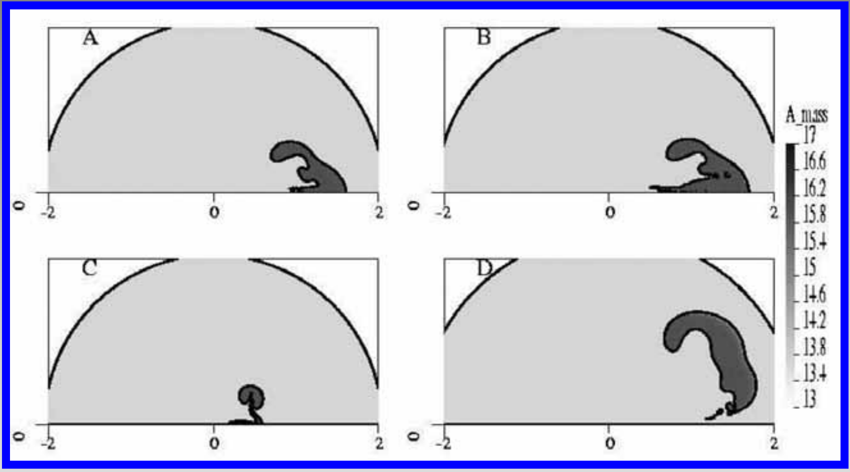
Kuhlen, Woosley, & Glatzmeier (2005)

Single Bubble, Three Different Methods…

2.5D

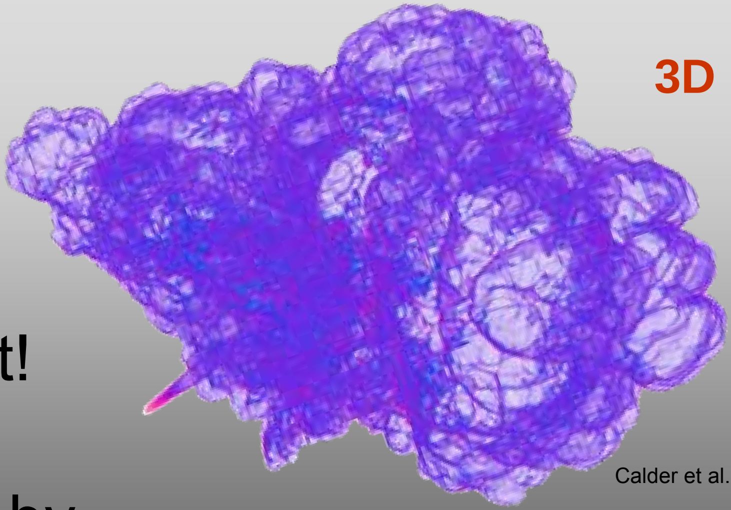


Niemeyer, Hillebrandt, & Woosley (1996)



2.5D

Livne, Asida, & Höflich (2005)



3D

Calder et al. (2004)

…and virtually the same result!

This is followed by…

Lots of Waiting…

Initial Conditions So Far

Garcia-Senz & Woosley (1995)
Niemeyer, Hillebrandt, & Woosley (1995)
Höflich & Stein (2002)
Woosley, Wunsch, & Kuhlen (2004)
Calder et al. (2004)
Livne, Asida, & Höflich (2005)
Kuhlen, Woosley, & Glatzmeier (2005)

Based on analytic, semi-analytic, and numerical models, the most likely outcome of a mild ignition is the off-center deflagration.

Major Sins of Classic Central Deflagrations

Context: Branch-normal Ias

1. Uniformly mixed ejecta, unburned low-velocity carbon

2. Explosion energies too low, need ~50% more burning

3. Initial conditions either too idealized or defined ad hoc

4. Large Ni-rich structures visible at maximum light

5. Insufficient production of intermediate mass elements

Some Recent Evidence

Garcia-Senz et al. (2007)

- difficult to produce > 0.2 $M_\odot$ of IME
- M_{IME} correlates with M_{IGE}
- difficult to explain low energy explosion events

Wang et al. (2006): SN 2004dt (VLT)

- highly aspherical high-velocity burned regions
- globally asymmetric residual fuel

Fesen et al. (2006): SNR 1885 (HST)

- neutronized central region: high-density burn
- free of IME
- degree of mixing smaller than in deflagrations

Gerardy et al. (2007): SN 2003hv, SN 2005df (MIR, Spitzer)

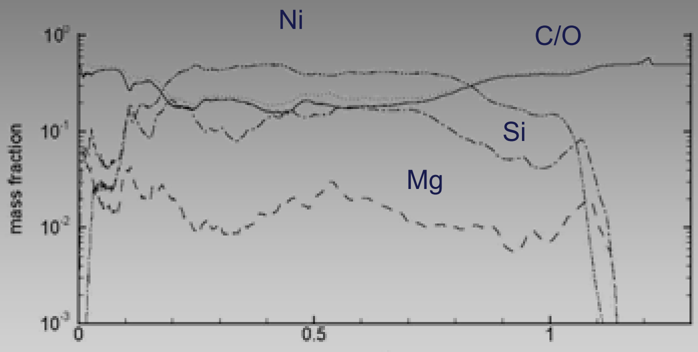
- chemically stratified ejecta
- Ar and Ni shifted in velocity in respect to Co

Motohara et al. (2007): SN 2003hv, SN 2005W (NIR, Subaru)

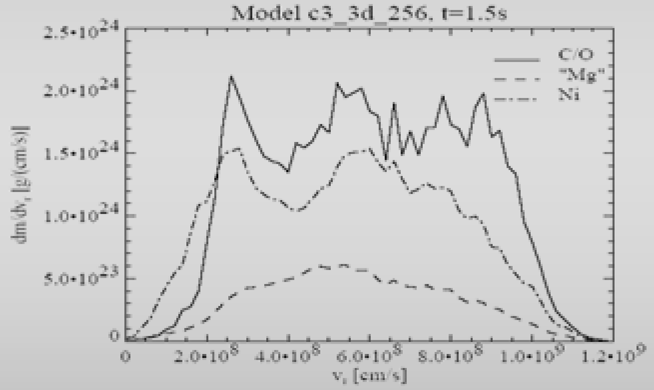
- flat-topped NIR lines: burning at high densities
- line center shift: asymmetric, off-center explosion

Ejecta Composition: Pure Deflagrations

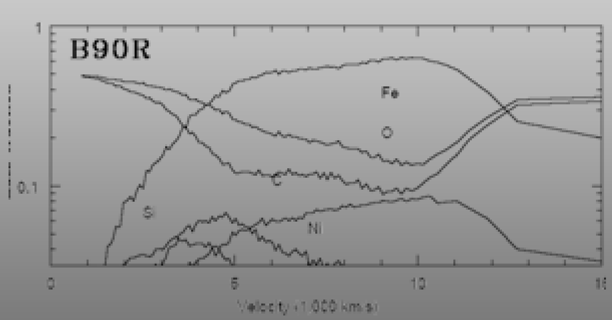
Röpke et al. (2005)



Gamezo et al. (2003)

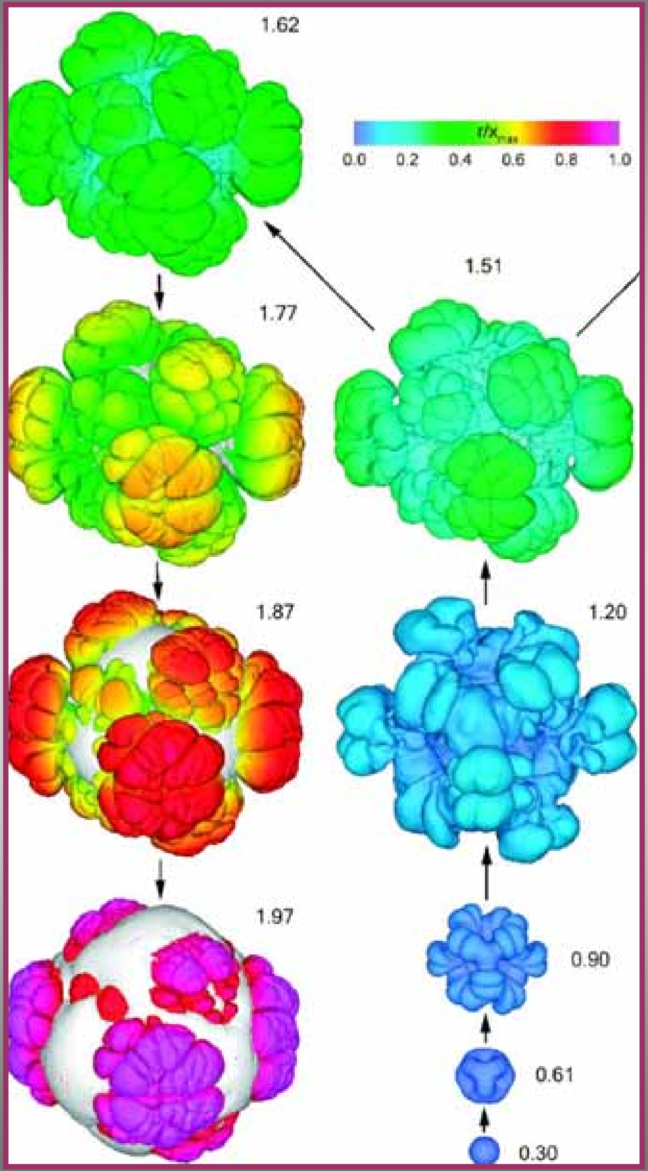


Reinecke et al. (2002)

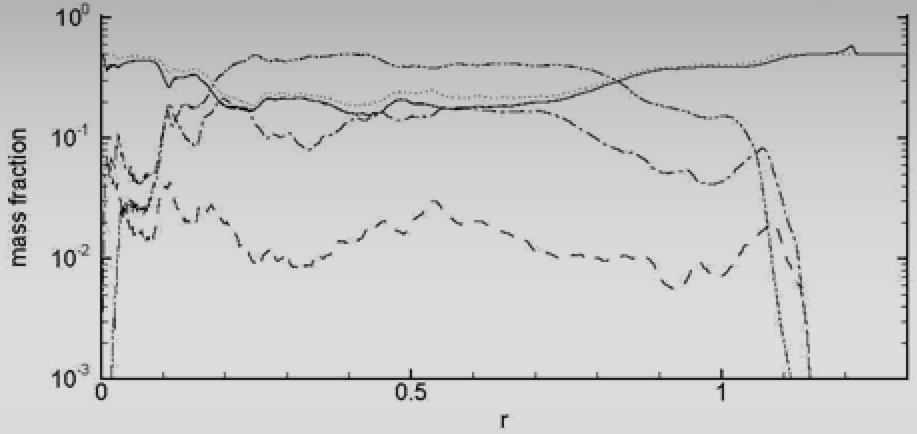


Garcia-Senz & Bravo (2004)

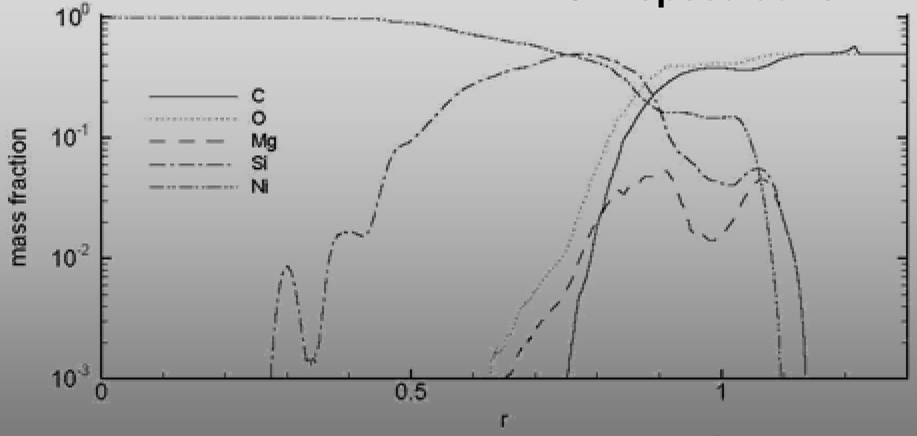
Stratification, Energy: Speculative DDT



3-D pure deflagration

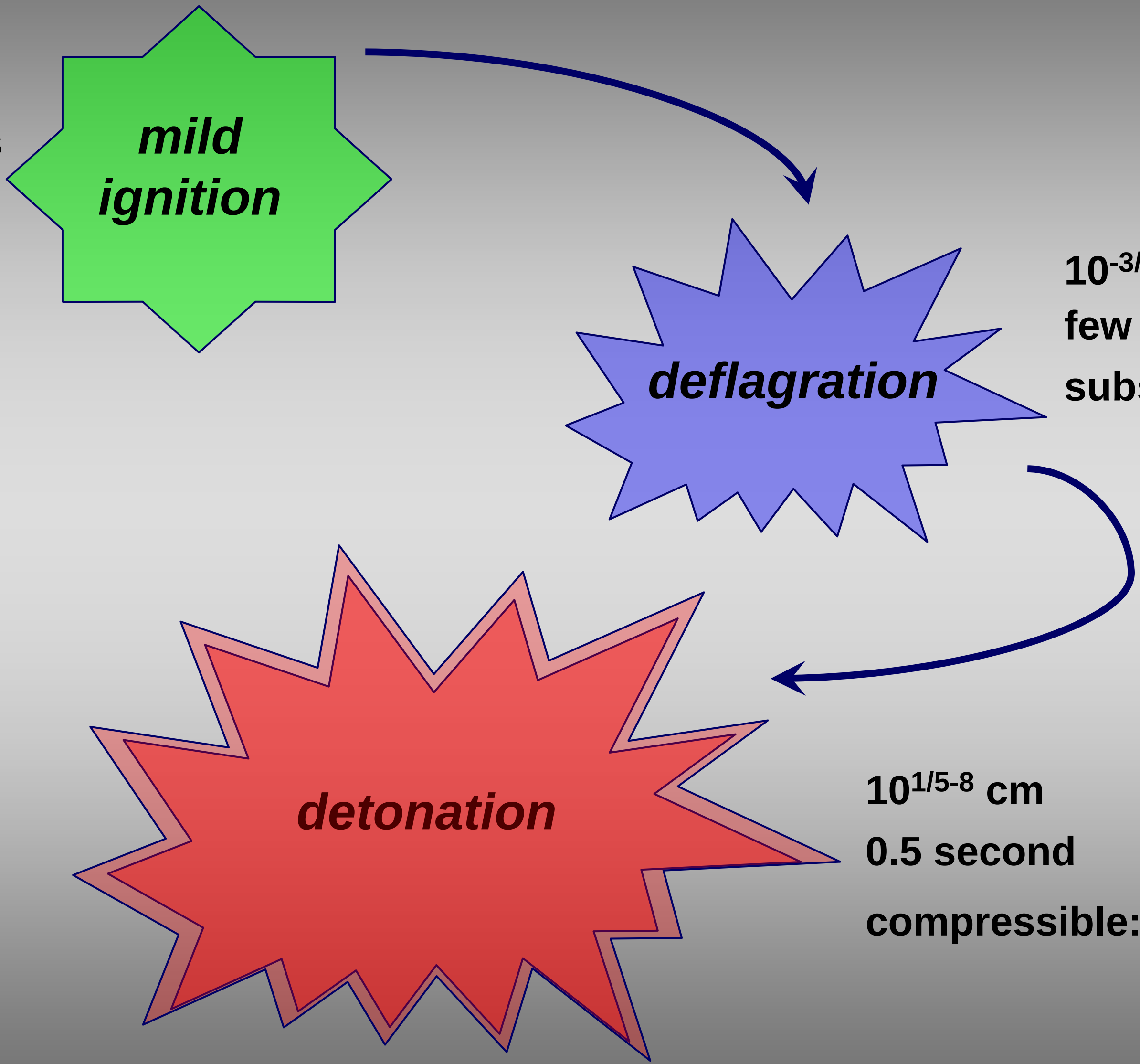


3-D speculative DDT



Gamezo et al. (2003)

Preferred SN Ia Scenario



$10^{2/4-7}$ cm

10^{10} seconds

deeply subsonic, Ma ~ 10^{-4}

$10^{-3/5-8}$ cm

few seconds

subsonic: Ma ~ 0.3

$10^{1/5-8}$ cm

0.5 second

compressible: Ma ~ 2

What is DFD

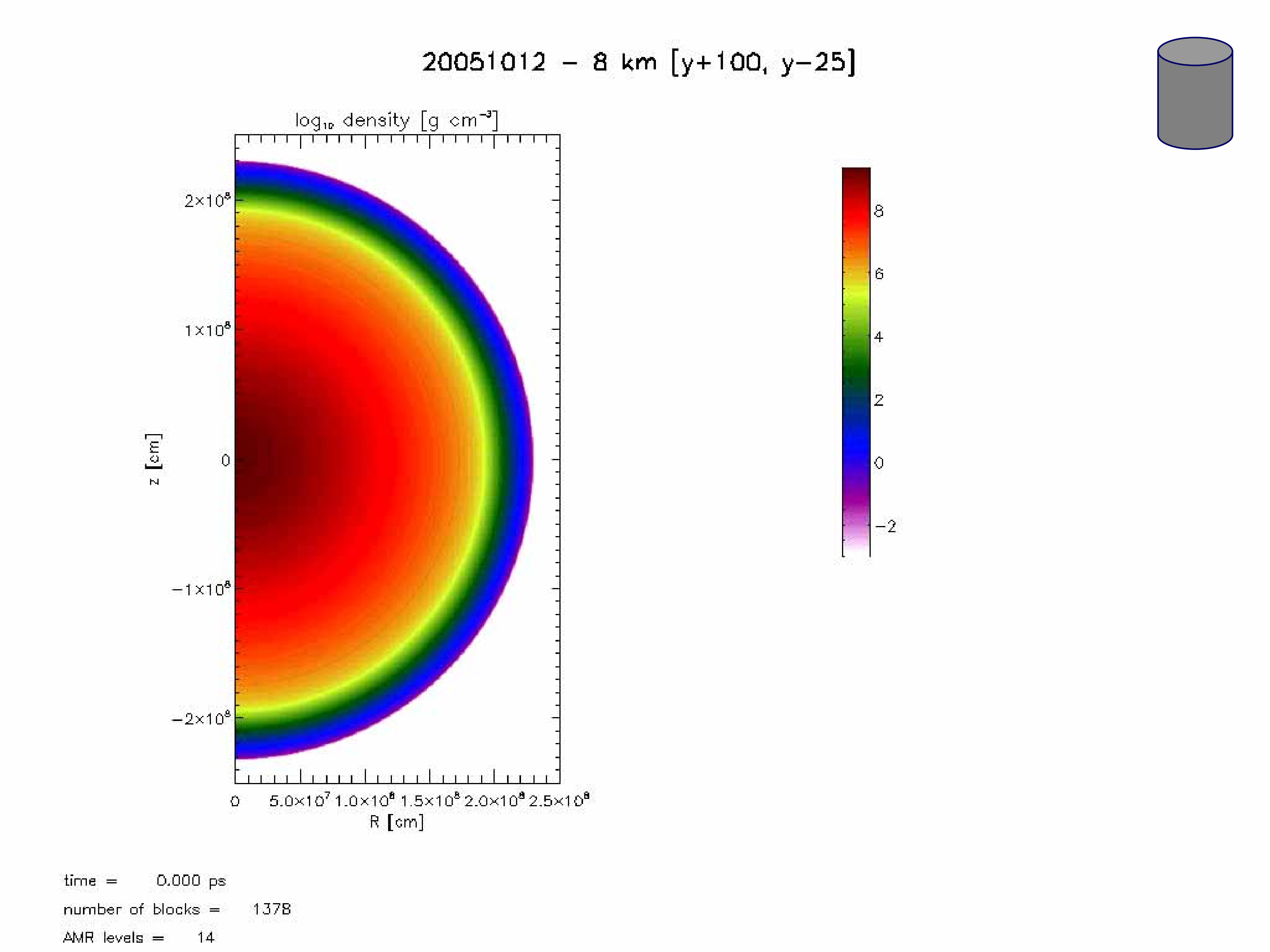
DFD is a delayed detonation model: deflagration followed by a detonation

Detonation is inertially (and not gravitationally) confined (mea culpa!)

Transition density understood in terms of amount of preexpansion

Controlled by physics of both deflagration
and detonation (+ transition)

Double-bubble DFD


20051012 – 8 km [y+100, y–25]

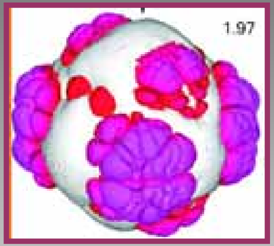
time = 0.000 ps

number of blocks = 1378

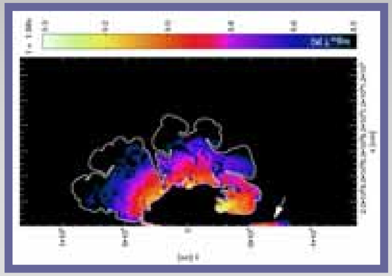
AMR levels = 14

Some DFD-related Work

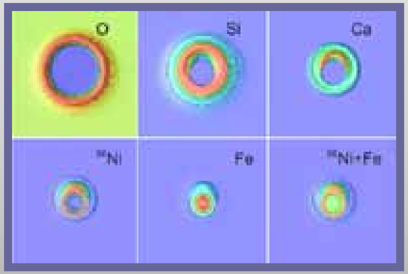
- **Gamezo et al. (2004, 2005)**
  - 3D DDT models, but deep ignition



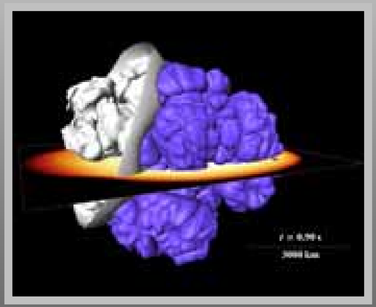
- **Röpke, Woosley, & Hillebrandt (2007)**
  - Parameter study in both 2D and 3D
  - Found important correlations
  - Partial confirmation of this work



- **Fesen et al. (2007) SNR 1885**
  - 2D off-center DD by-hand model
  - Used by Gerardy et al. (2003hv, 2005df)



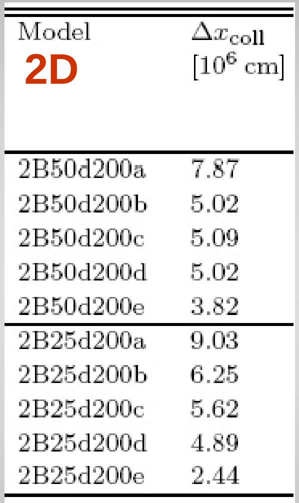
- **Röpke & Niemeyer (2007)**
  - 3D off-center DD by-hand models



Comments on Röpke et al.

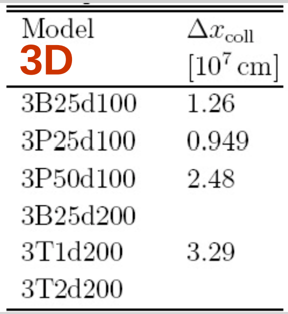
- Collision process modeling
  - **Substandard resolution**

    order of magnitude lower in 2D, even more in 3D



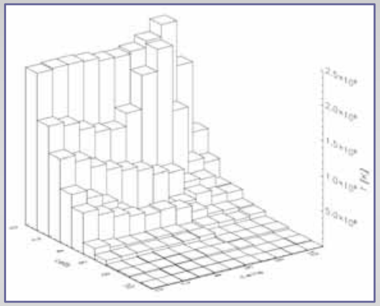
2D

Model	Δx_{coll} [10^6 cm]
2B50d200a	7.87
2B50d200b	5.02
2B50d200c	5.09
2B50d200d	5.02
2B50d200e	3.82
2B25d200a	9.03
2B25d200b	6.25
2B25d200c	5.62
2B25d200d	4.89
2B25d200e	2.44



3D

Model	Δx_{coll} [10^7 cm]
3B25d100	1.26
3P25d100	0.949
3P50d100	2.48
3B25d200	
3T1d200	3.29
3T2d200	



← 700 km →

  - **Simplified approach to detonation**

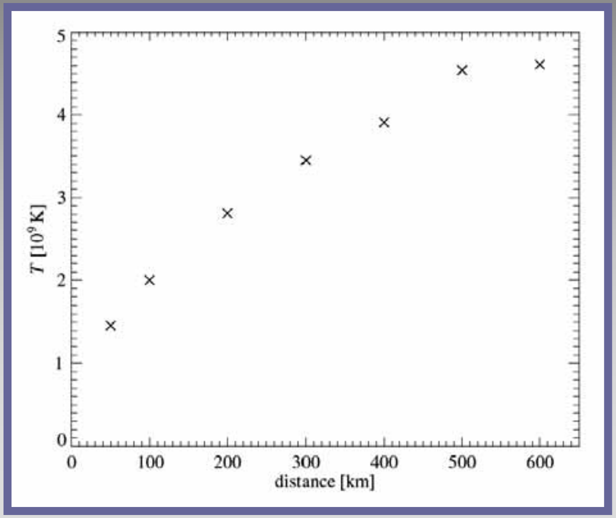
    no feedback from nuclear burning

    necessary but not sufficient detonation criterion

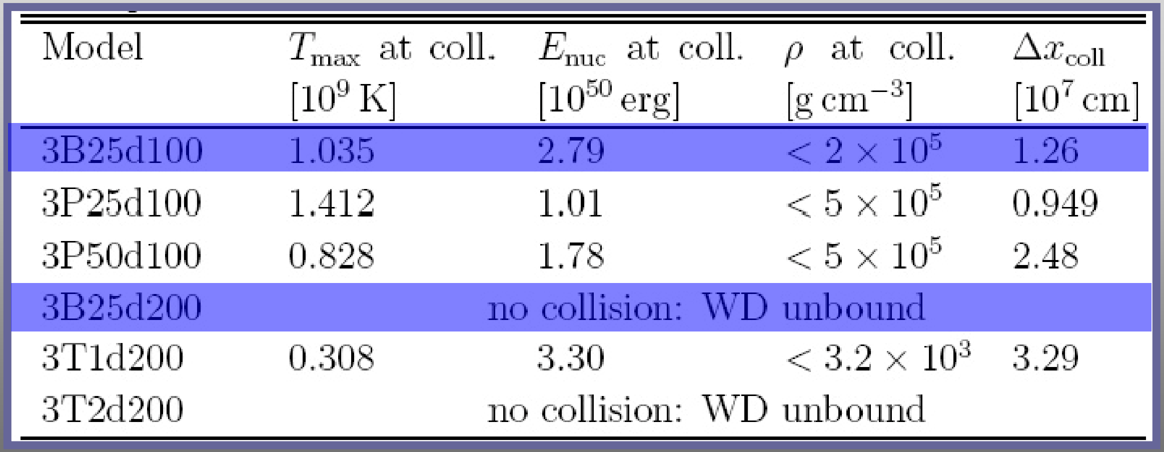
    same is true for some preignition models (Kuhlen, Woosley, & Glatzmaier, Zingale & Dursi); Höflich & Stein are exception but have other problems; Townsley et al. model as well?

Comments on Röpke et al.

- **System on the loose?**
  - Important correlation $T_{col}(Z_{bub})$



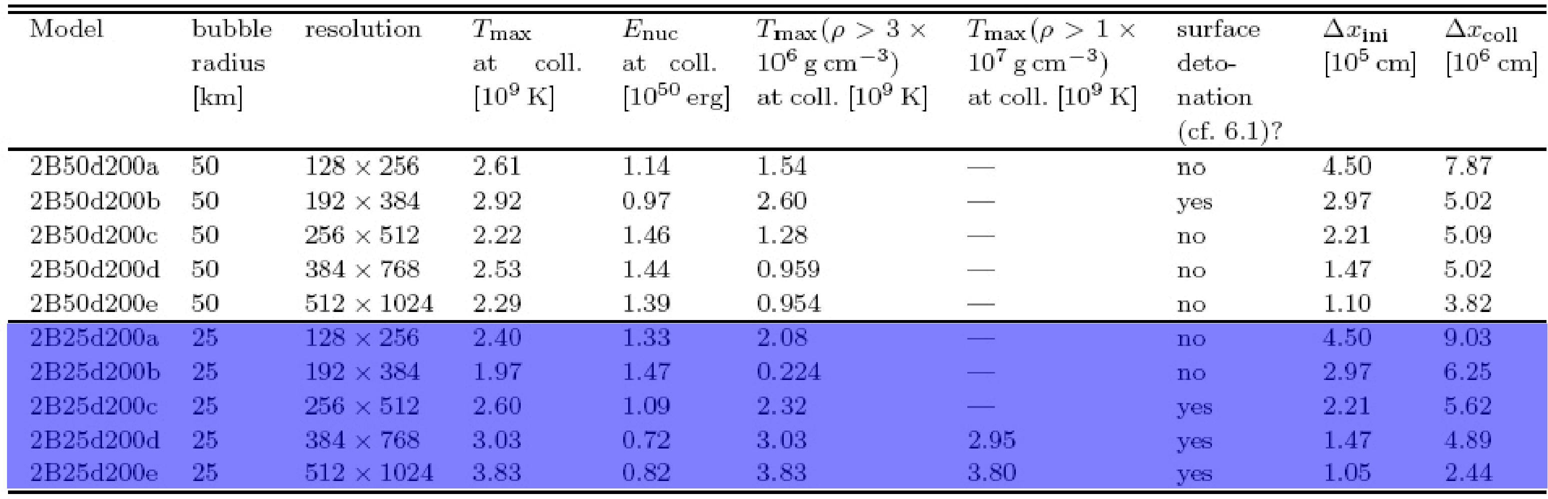
  - But 3D 100/200 RWH **results inconsistent (and counterintuitive)**



Model	$T_{\max}$ at coll. $[10^9\,\mathrm{K}]$	E_{nuc} at coll. $[10^{50}\,\mathrm{erg}]$	ρ at coll. $[\mathrm{g\,cm^{-3}}]$	Δx_{coll} $[10^7\,\mathrm{cm}]$
3B25d100	1.035	2.79	$< 2 \times 10^5$	1.26
3P25d100	1.412	1.01	$< 5 \times 10^5$	0.949
3P50d100	0.828	1.78	$< 5 \times 10^5$	2.48
3B25d200	no collision: WD unbound			
3T1d200	0.308	3.30	$< 3.2 \times 10^3$	3.29
3T2d200	no collision: WD unbound			

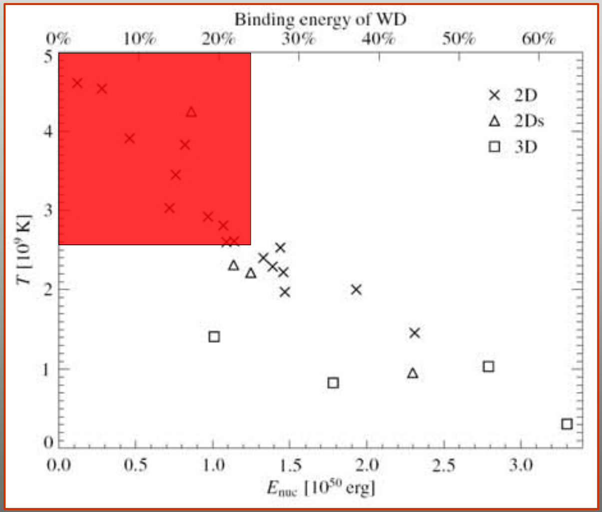
Comments on Röpke et al.

- **Numerical convergence**
  - At higher resolution deflagration is less energetic (+results in higher-res)



Model	bubble radius [km]	resolution	$T_{\max}$ at coll. [10^9 K]	$E_{\rm nuc}$ at coll. [10^{50} erg]	$T_{\max}(\rho > 3 \times 10^6\,{\rm g\,cm^{-3}})$ at coll. [10^9 K]	$T_{\max}(\rho > 1 \times 10^7\,{\rm g\,cm^{-3}})$ at coll. [10^9 K]	surface detonation (cf. 6.1)?	$\Delta x_{\rm ini}$ [10^5 cm]	$\Delta x_{\rm coll}$ [10^6 cm]
2B50d200a	50	128 × 256	2.61	1.14	1.54	—	no	4.50	7.87
2B50d200b	50	192 × 384	2.92	0.97	2.60	—	yes	2.97	5.02
2B50d200c	50	256 × 512	2.22	1.46	1.28	—	no	2.21	5.09
2B50d200d	50	384 × 768	2.53	1.44	0.959	—	no	1.47	5.02
2B50d200e	50	512 × 1024	2.29	1.39	0.954	—	no	1.10	3.82
2B25d200a	25	128 × 256	2.40	1.33	2.08	—	no	4.50	9.03
2B25d200b	25	192 × 384	1.97	1.47	0.224	—	no	2.97	6.25
2B25d200c	25	256 × 512	2.60	1.09	2.32	—	yes	2.21	5.62
2B25d200d	25	384 × 768	3.03	0.72	3.03	2.95	yes	1.47	4.89
2B25d200e	25	512 × 1024	3.83	0.82	3.83	3.80	yes	1.05	2.44

  - **But this works in favor of hot spot formation!!**



Comments on Röpke et al.

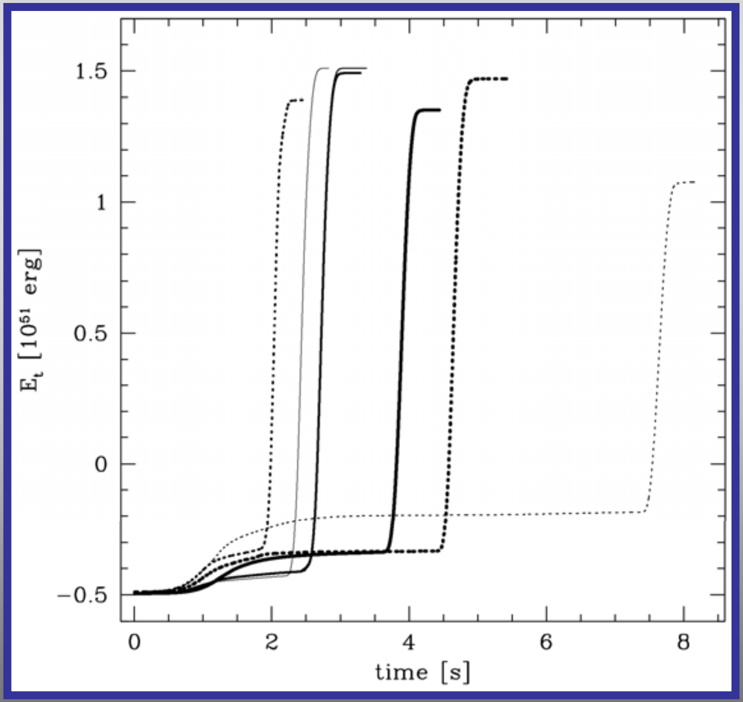
Realistic, better resolved models needed.

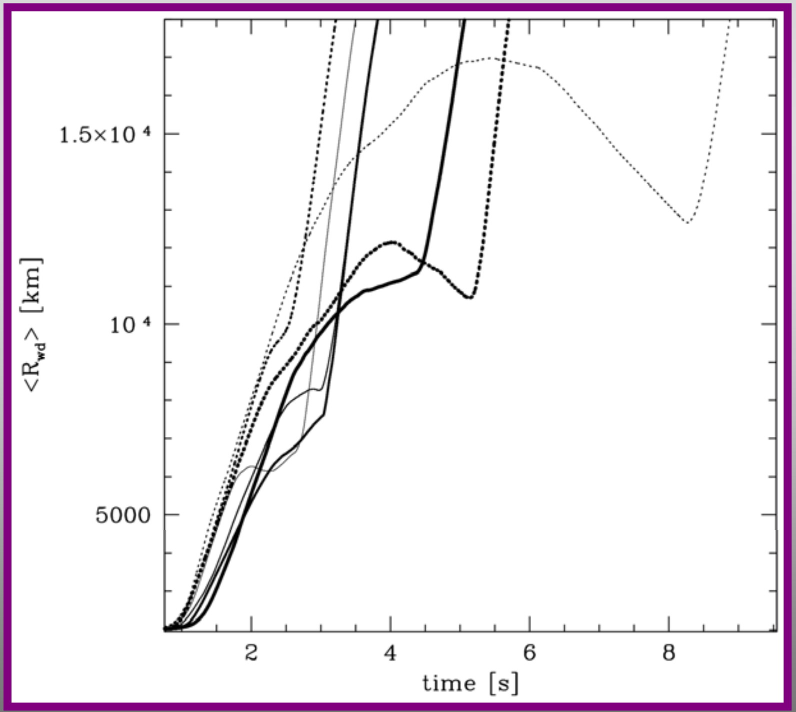
Comments on Röpke et al.

Realistic, better resolved models needed!

DFD Phases

- Deflagration
- Transition to detonation (takes finite amount of time)
- Detonation





Deflagration Modeling: A "Side" Comment

Cabot & Cook (2006): Re number effects on RTI

BG/L model on 3072^3 grid (Re~10^4)

The starting length-scale problem

Our results suggest that proper representation of fine-scale initial perturbations is essential for obtaining the correct growth history.

Basic physics problem

- *[...] it seems prudent to ensure that the model for turbulent flame speed faithfully reproduces RTI physics before invoking other schemes to increase the burning rate, such as multi-point ignition, background turbulence from thermal convection and/or deflagration-to-detonation transition.*

DFD Phases: Deflagration

- Weaker compared to Gamezo-like models
- Takes place at large radii rather than close to the core
- **Amount of energy released controls expansion**
- **Expansion sets the ICs for a detonation**
- Controls the mass and composition of the expelled material
- Controls surface flow energetics (kinematics and orbital motion)

Transition To Detonation

SDT: shock-to-detonation transition

observed in DFD but uncertain, other possibilities available

Zel'dovich's gradient mechanism

self-ignition wave transforms into a detonation when the speed of ignition train approaches sound speed

Oppenheim's detonation bubbles

shock-compressed gas explodes in neighboring exothermic centers producing spherical blast waves – these collide resulting in the onset of detonation kernels that lead to detonation

SWACER: shock wave amplification through coherent energy release

(Lee et al. 1978, Khokhlov, Oran, & Wheeler 1997)

Oppenheim's amplified by the Zel’dovich gradient mechanism

Shock To Detonation Transition

Most are through some form of "microexplosions" - strong vs. mild ignition modes. Presence of induction time gradients associated with temperature and composition gradients seems common.

SDT is a strong, volumetric violent process rather than from exothermic centers (hot spots) in compressed region. As in strong detonation, weak waves are present.

Necessary conditions

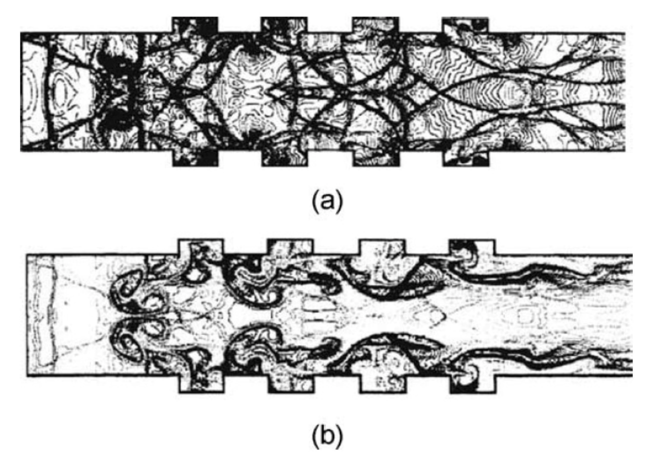
- presence of a shock wave
- gas energy sufficient to sustain reignition in expanding gas

Aspects

- compression
- induction time
- auto-ignition (energy transfer to support constant shock propagation)
- fuel composition

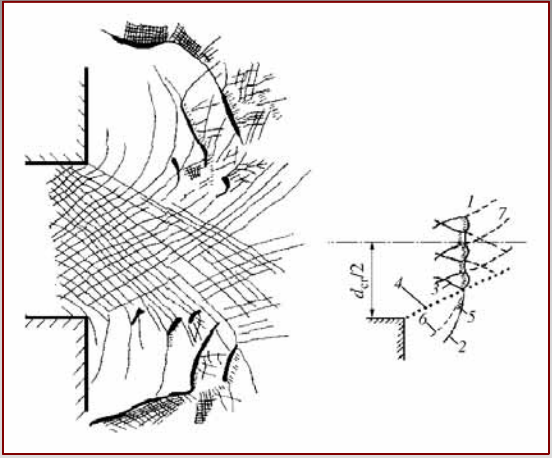
Transition To Detonation Examples

diverging-contracting tube



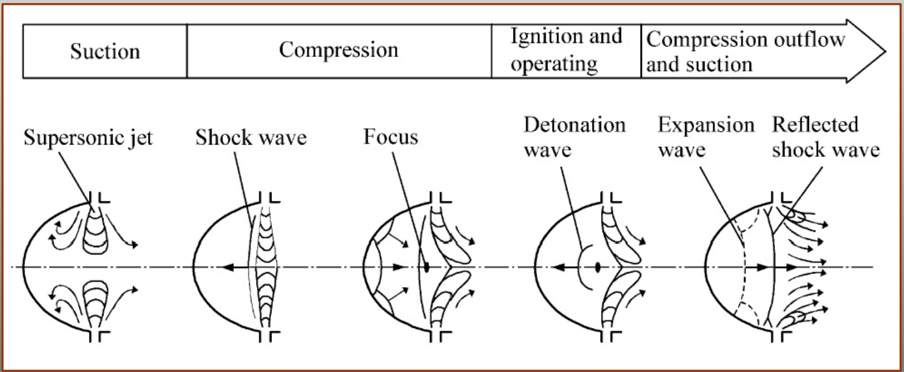
Yu (2001)

expanding nozzle



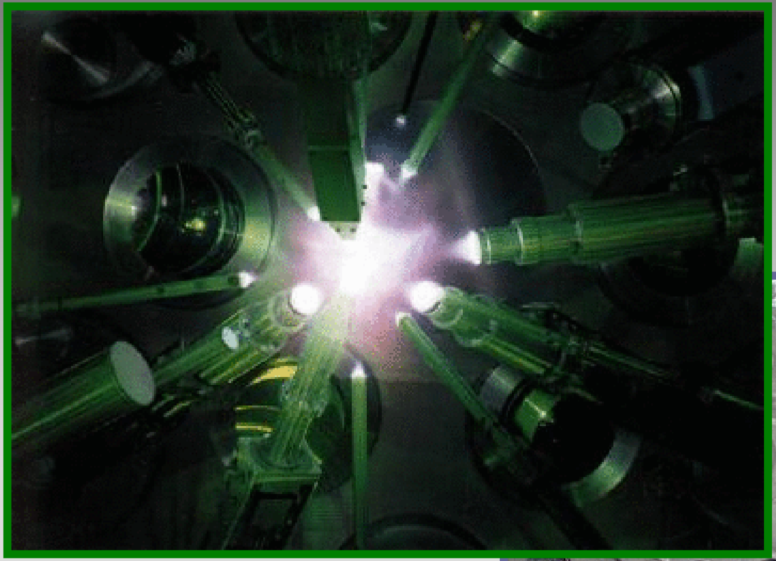
Gelfand et al. (1991)

resonator PDE



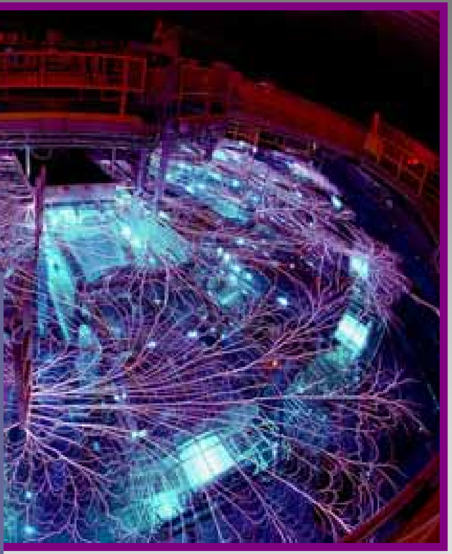
Levin et al. (2001)

DFD/Inertial Confinement Fusion

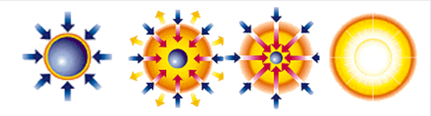


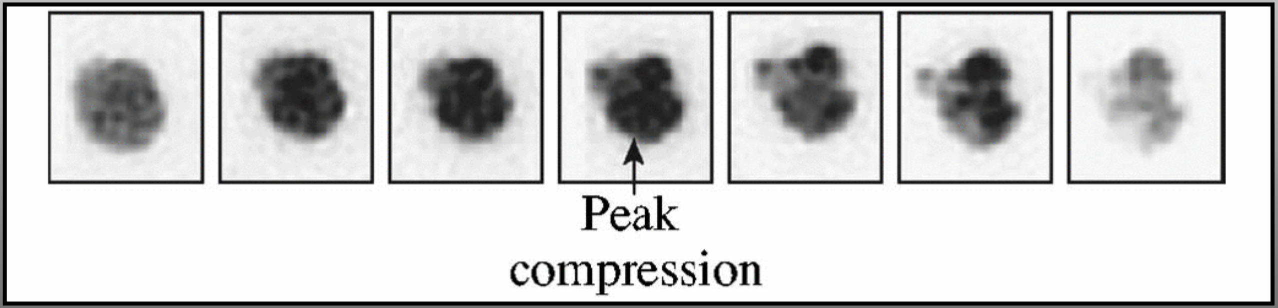
Omega/Rochester

NIF/LLNL



Z-machine/SNL



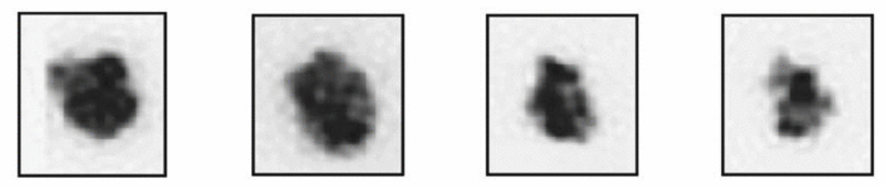


Smalyuk et al. (2007)

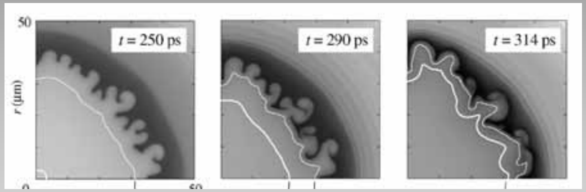
DFD/Perturbations

ICF experiment – different ICs

ICF simulation – single ICs

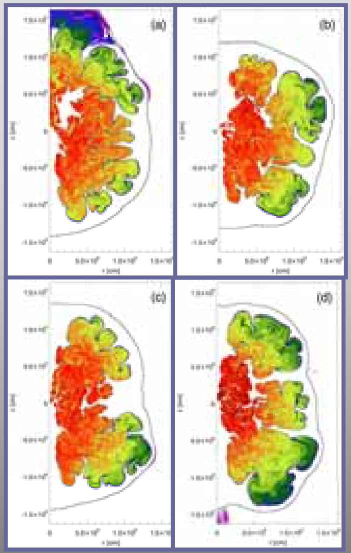


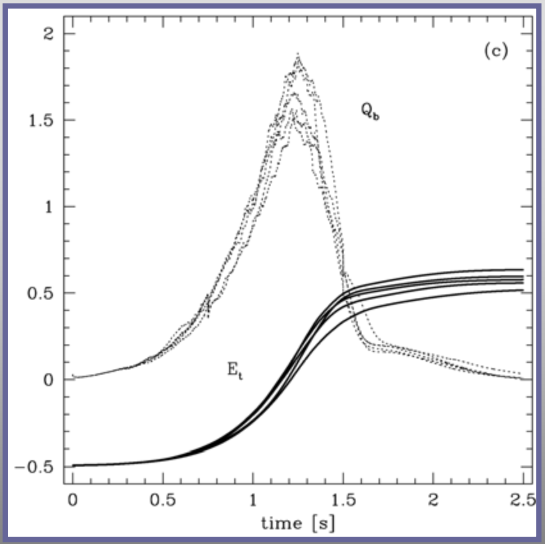
Smalyuk et al. (2007)



Atzeni et al. (2005)

classic
deflagration
+
small
perturbations





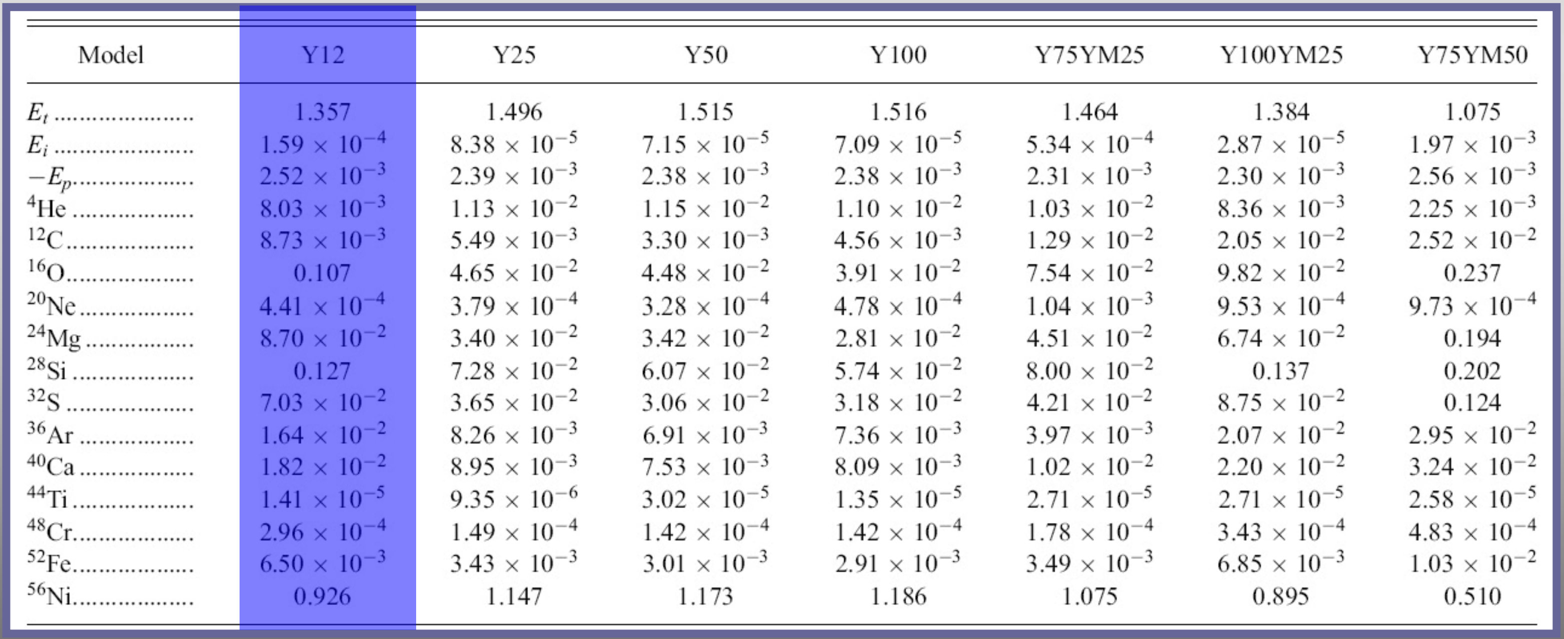
> 0.07 foe

DFD Detonation Phase

- **Ejecta mildly aspherical**
  - progenitor perturbed
  - finite shock-crossing time on non-static background
  - crossing-time short, < 0.5 second
- **Bulk of nucleosynthesis (alpha network)**
  - burns at local densities + compression factor
  - penetrates both unburned and burned material
- **Leaves very little unburned material ($< 0.1\ M_{\odot}$) behind**
  - may leave pockets in outer layers
  - the core region fully burnt
- **Current model energy/nickel mass estimates are upper limits**
  - realistic WD is not pure C/O
  - nuclear network is only approximate

Final Model Properties

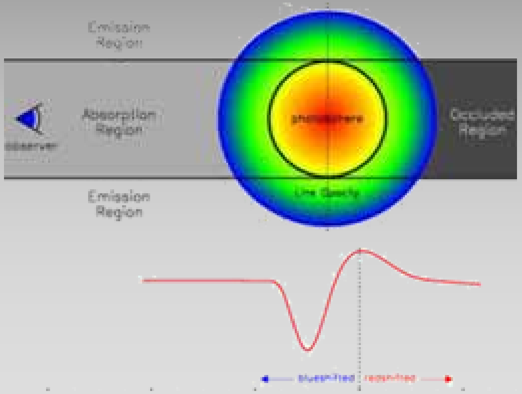
- Ejecta mildly aspherical
- Clumpy outside, smooth inner part
- Very little unburned material and only at high velocities
- Current yields approximate, > 0.1-0.3 $M_\odot$ IME, ~1 $M_\odot$ IGE
- E_{exp} = 1.2 - 1.3x10^{51} ergs

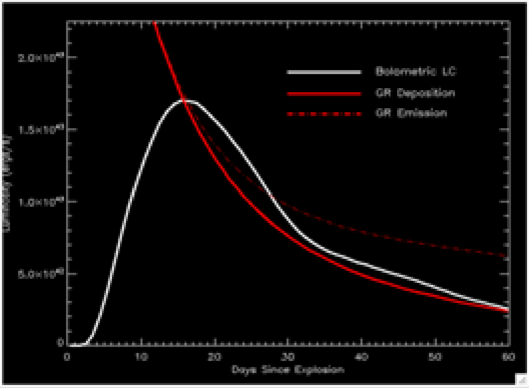


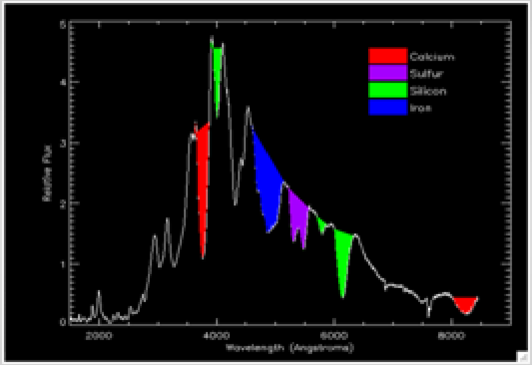
Model	Y12	Y25	Y50	Y100	Y75YM25	Y100YM25	Y75YM50
E_t	1.357	1.496	1.515	1.516	1.464	1.384	1.075
E_i	1.59×10^{-4}	8.38×10^{-5}	7.15×10^{-5}	7.09×10^{-5}	5.34×10^{-4}	2.87×10^{-5}	1.97×10^{-3}
$-E_p$..................	2.52×10^{-3}	2.39×10^{-3}	2.38×10^{-3}	2.38×10^{-3}	2.31×10^{-3}	2.30×10^{-3}	2.56×10^{-3}
^{4}He	8.03×10^{-3}	1.13×10^{-2}	1.15×10^{-2}	1.10×10^{-2}	1.03×10^{-2}	8.36×10^{-3}	2.25×10^{-3}
^{12}C....................	8.73×10^{-3}	5.49×10^{-3}	3.30×10^{-3}	4.56×10^{-3}	1.29×10^{-2}	2.05×10^{-2}	2.52×10^{-2}
^{16}O....................	0.107	4.65×10^{-2}	4.48×10^{-2}	3.91×10^{-2}	7.54×10^{-2}	9.82×10^{-2}	0.237
^{20}Ne..................	4.41×10^{-4}	3.79×10^{-4}	3.28×10^{-4}	4.78×10^{-4}	1.04×10^{-3}	9.53×10^{-4}	9.73×10^{-4}
^{24}Mg.................	8.70×10^{-2}	3.40×10^{-2}	3.42×10^{-2}	2.81×10^{-2}	4.51×10^{-2}	6.74×10^{-2}	0.194
^{28}Si	0.127	7.28×10^{-2}	6.07×10^{-2}	5.74×10^{-2}	8.00×10^{-2}	0.137	0.202
^{32}S	7.03×10^{-2}	3.65×10^{-2}	3.06×10^{-2}	3.18×10^{-2}	4.21×10^{-2}	8.75×10^{-2}	0.124
^{36}Ar	1.64×10^{-2}	8.26×10^{-3}	6.91×10^{-3}	7.36×10^{-3}	3.97×10^{-3}	2.07×10^{-2}	2.95×10^{-2}
^{40}Ca	1.82×10^{-2}	8.95×10^{-3}	7.53×10^{-3}	8.09×10^{-3}	1.02×10^{-2}	2.20×10^{-2}	3.24×10^{-2}
^{44}Ti...................	1.41×10^{-5}	9.35×10^{-6}	3.02×10^{-5}	1.35×10^{-5}	2.71×10^{-5}	2.71×10^{-5}	2.58×10^{-5}
^{48}Cr...................	2.96×10^{-4}	1.49×10^{-4}	1.42×10^{-4}	1.42×10^{-4}	1.78×10^{-4}	3.43×10^{-4}	4.83×10^{-4}
^{52}Fe...................	6.50×10^{-3}	3.43×10^{-3}	3.01×10^{-3}	2.91×10^{-3}	3.49×10^{-3}	6.85×10^{-3}	1.03×10^{-2}
^{56}Ni...................	0.926	1.147	1.173	1.186	1.075	0.895	0.510

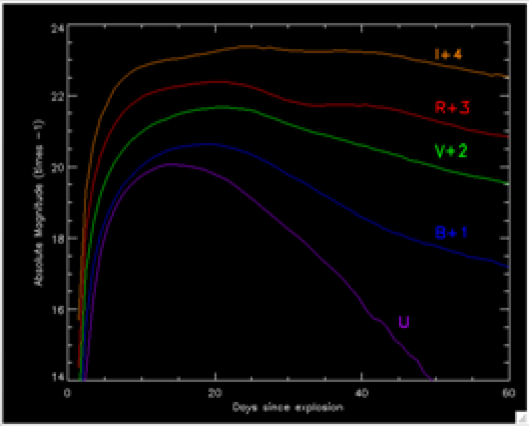
Model Validation – Radiative Transfer

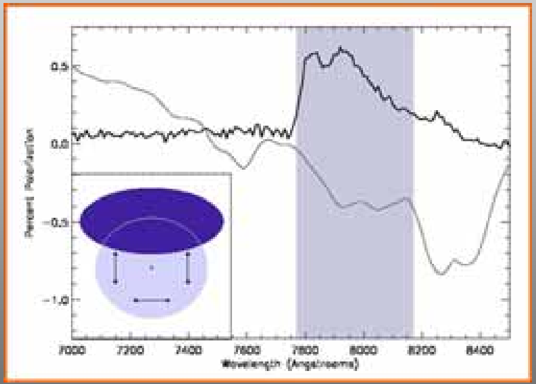
Kasen, Thomas, & Nugent (2006): Multi-dimensional time-dependent Monte Carlo radiative transfer









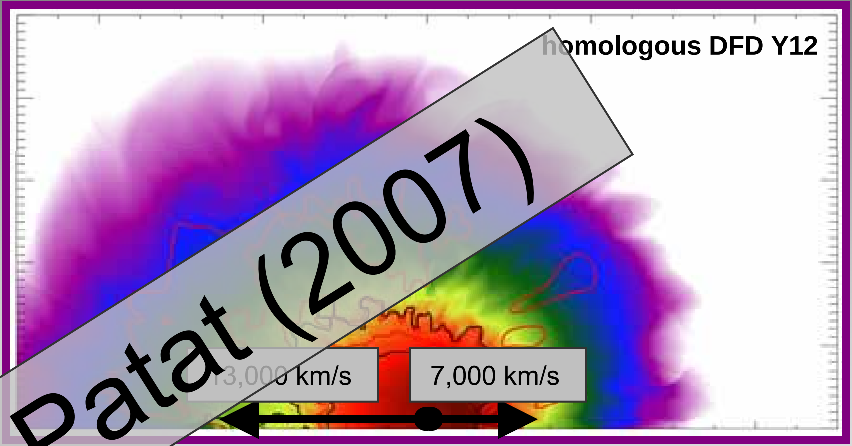


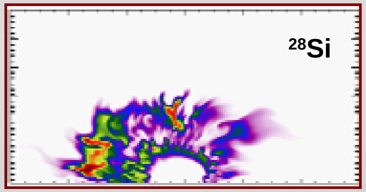
Y12 DFD Model Validation: Polarization

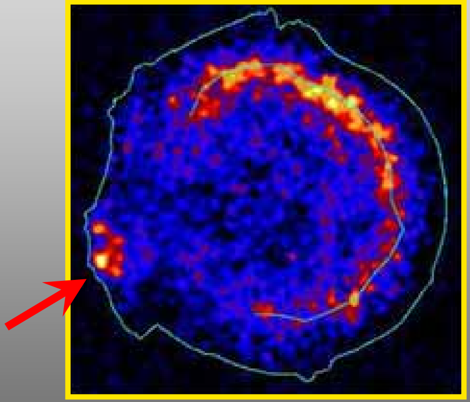
Polarization: ejecta morphology

- **Outermost ejecta**
  - smooth layer
  - unburned material (oxygen/carbon)
- **Outer IME shell**
  - strongly perturbed, clumpy layer
  - IME elements
- **Inner IME shell + IGE core**
  - smooth region, stratified
  - IME/IGE elements (silicon shell over nickel core)
  - can possibly be probed with xray/SNRs

Wang, Baade, & Patat (2007)





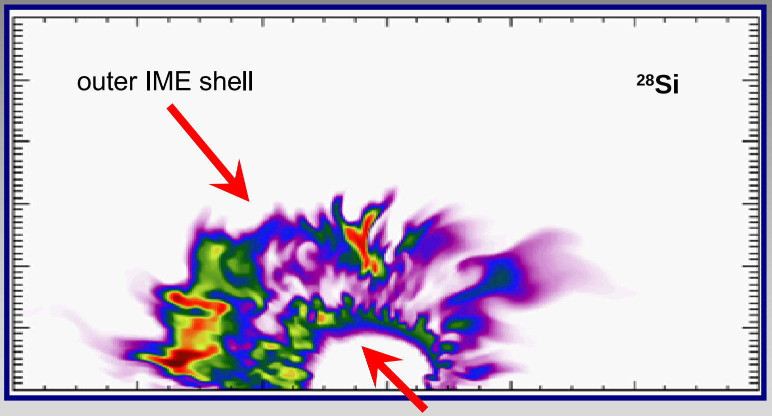


Warren et al. (2005)

Y12 DFD Model Validation: Polarization

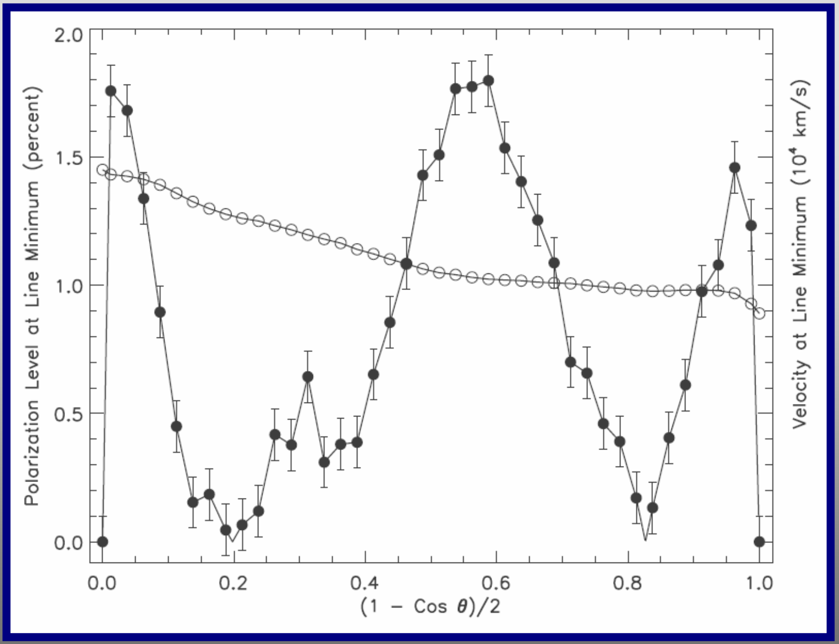
Polarization: ejecta morphology

- **Outer IME shell**
  - strongly perturbed, clumpy layer
  - IME elements



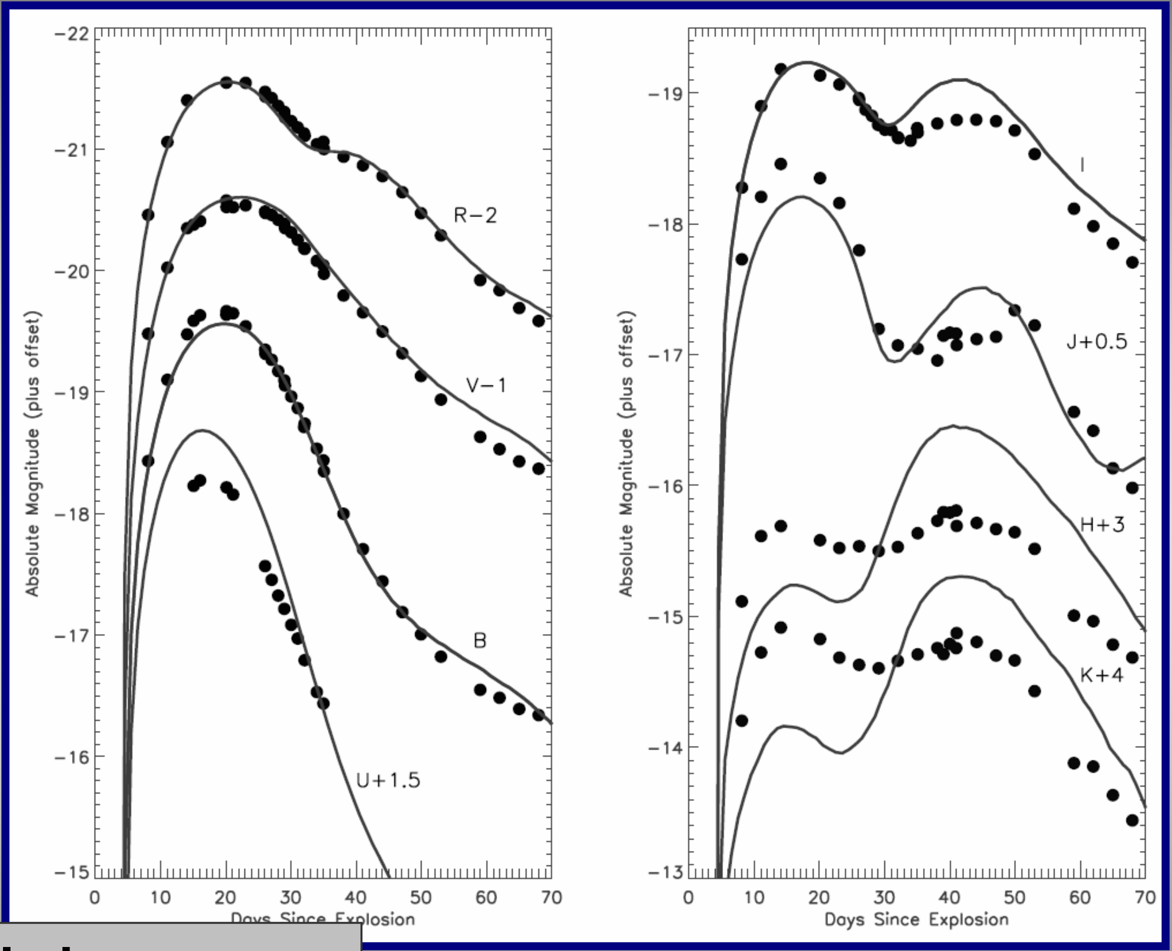
IME asphericity

controlled by the deflagration phase in the DFD model



Kasen & Plewa (2007)

Y12 DFD Model Validation: LC/SN 2001el

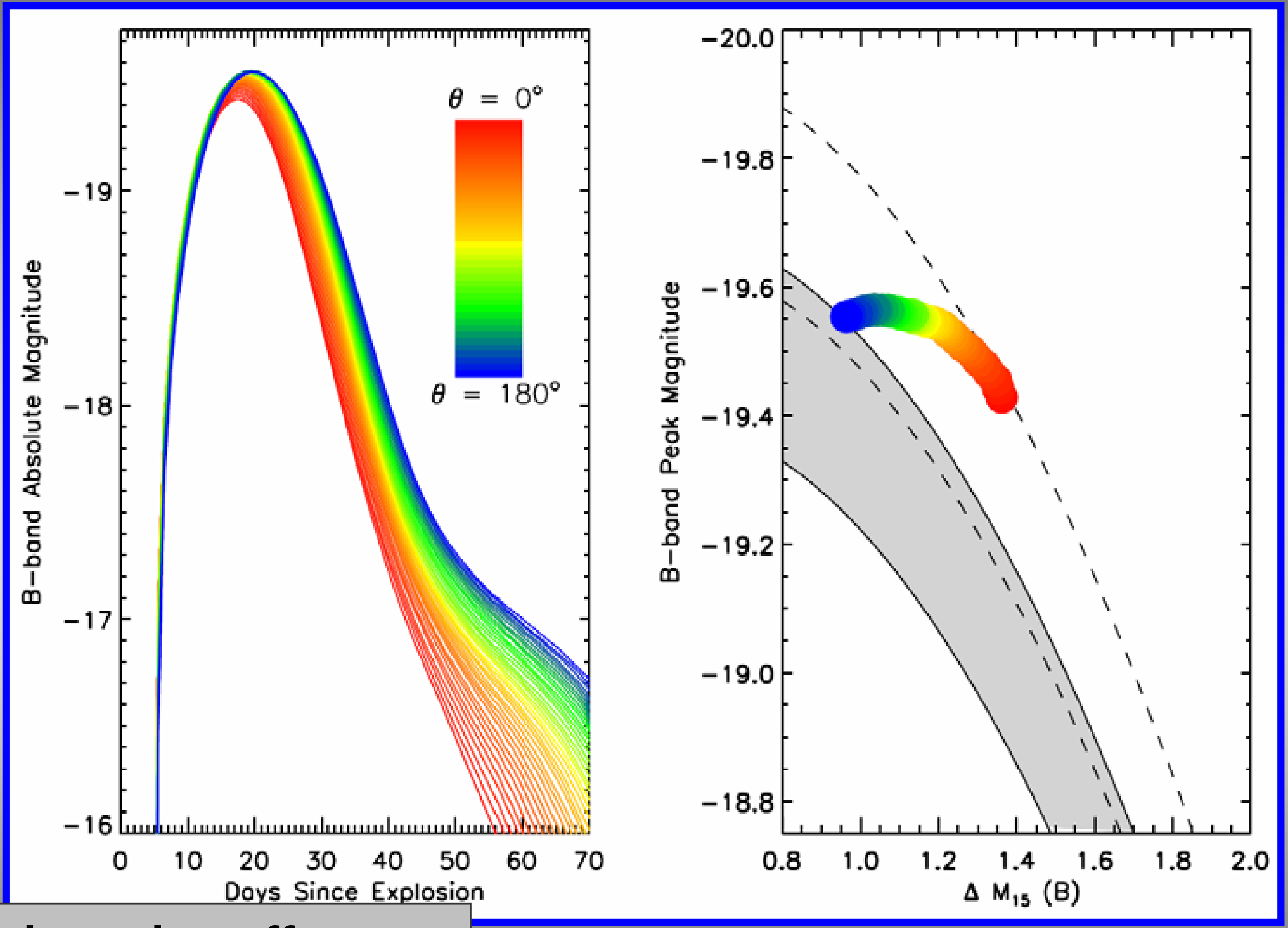


Equatorial view

Reasonable quality, comparable or better than W7

Kasen & Plewa (2007), Krisciunas et al. (2003)

DFD/Phillips Relation

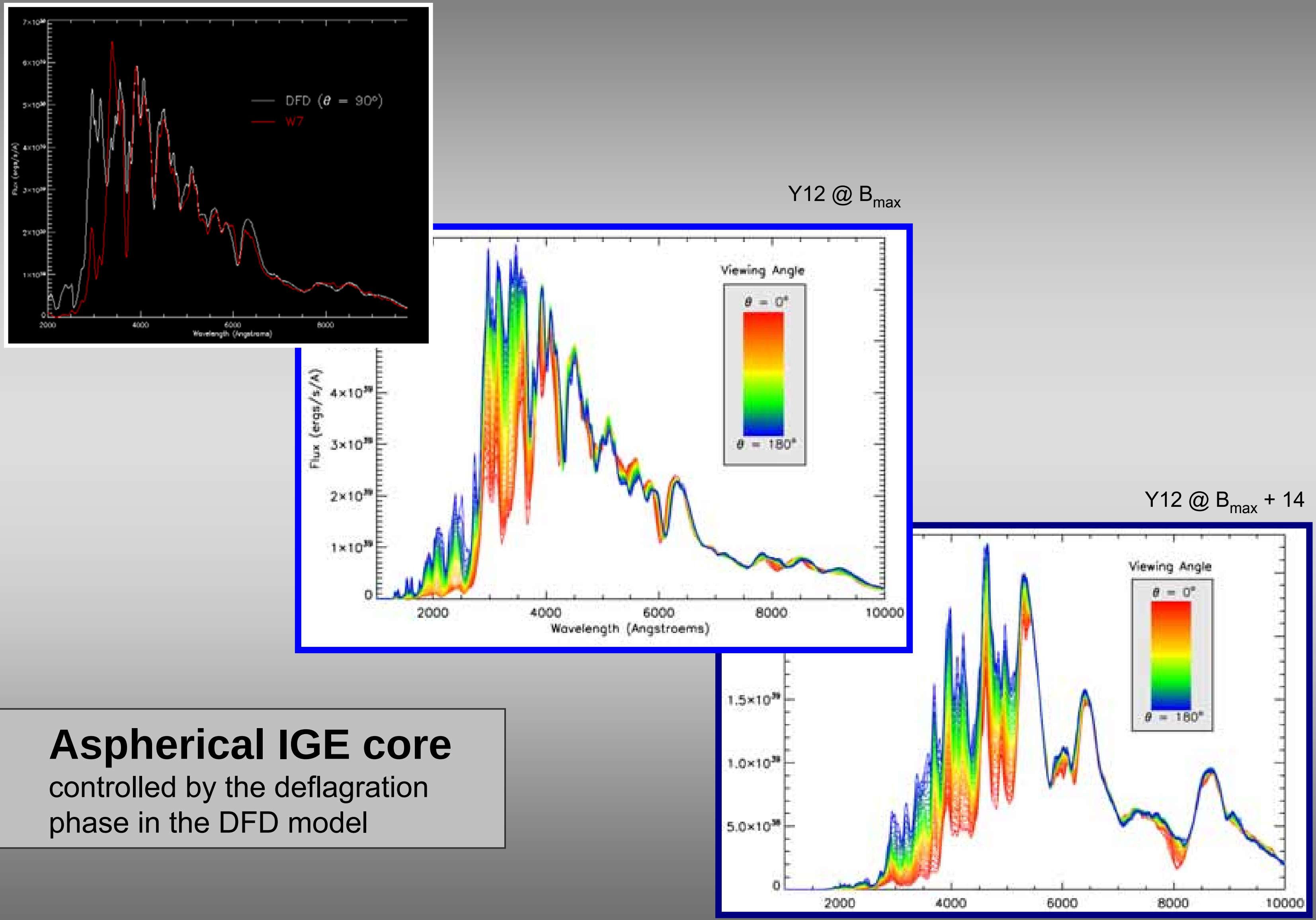


Kasen & Plewa (2007)

Orientation effects

controlled by the deflagration phase in the DFD model

DFD Model Validation: Spectroscopy



Y12 @ B_{max}

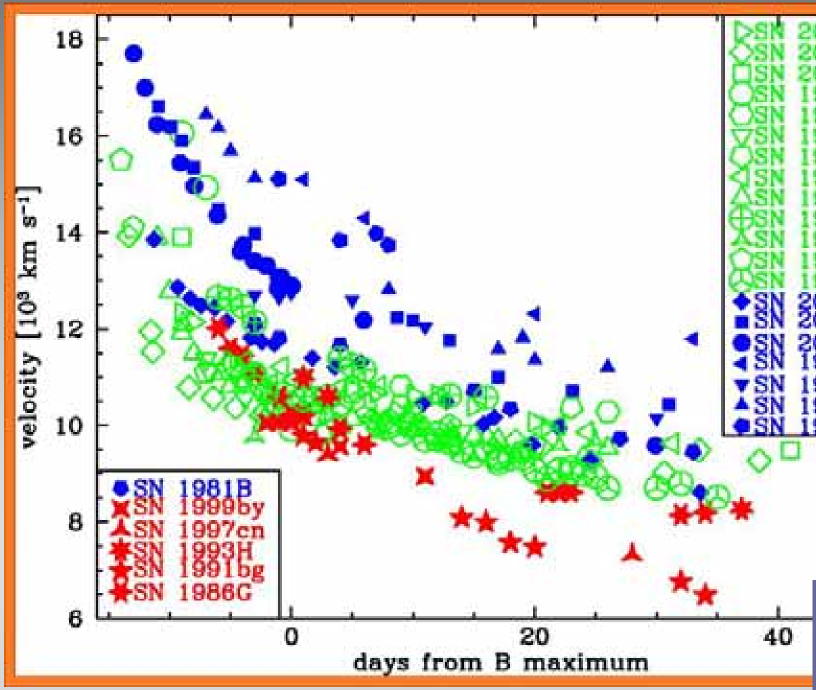
Y12 @ B_{max} + 14

Kasen & Plewa (2007)

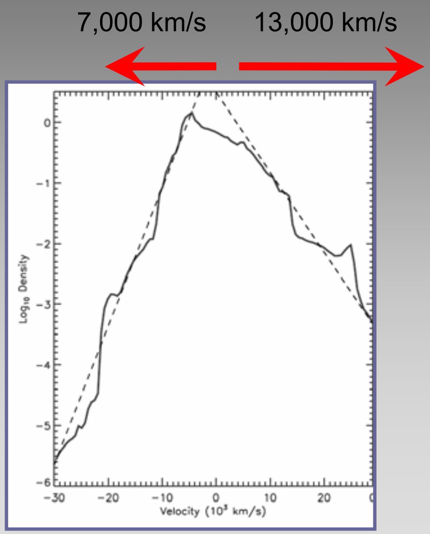
Aspherical IGE core

controlled by the deflagration phase in the DFD model

DFD Model Validation: Velocity Evolution

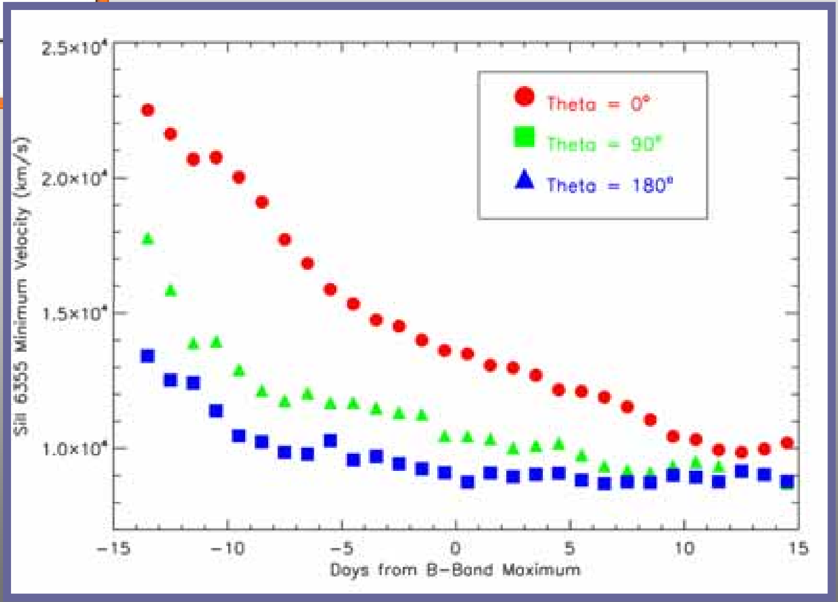


Benetti et al. (2005)



Orientation effects

controlled by the deflagration phase in the DFD model



Kasen & Plewa (2007)

DFD Model Validation: HVF

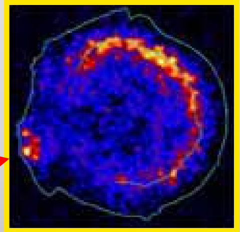
Spectroscopy: high-velocity features

- **Growing body of evidence**

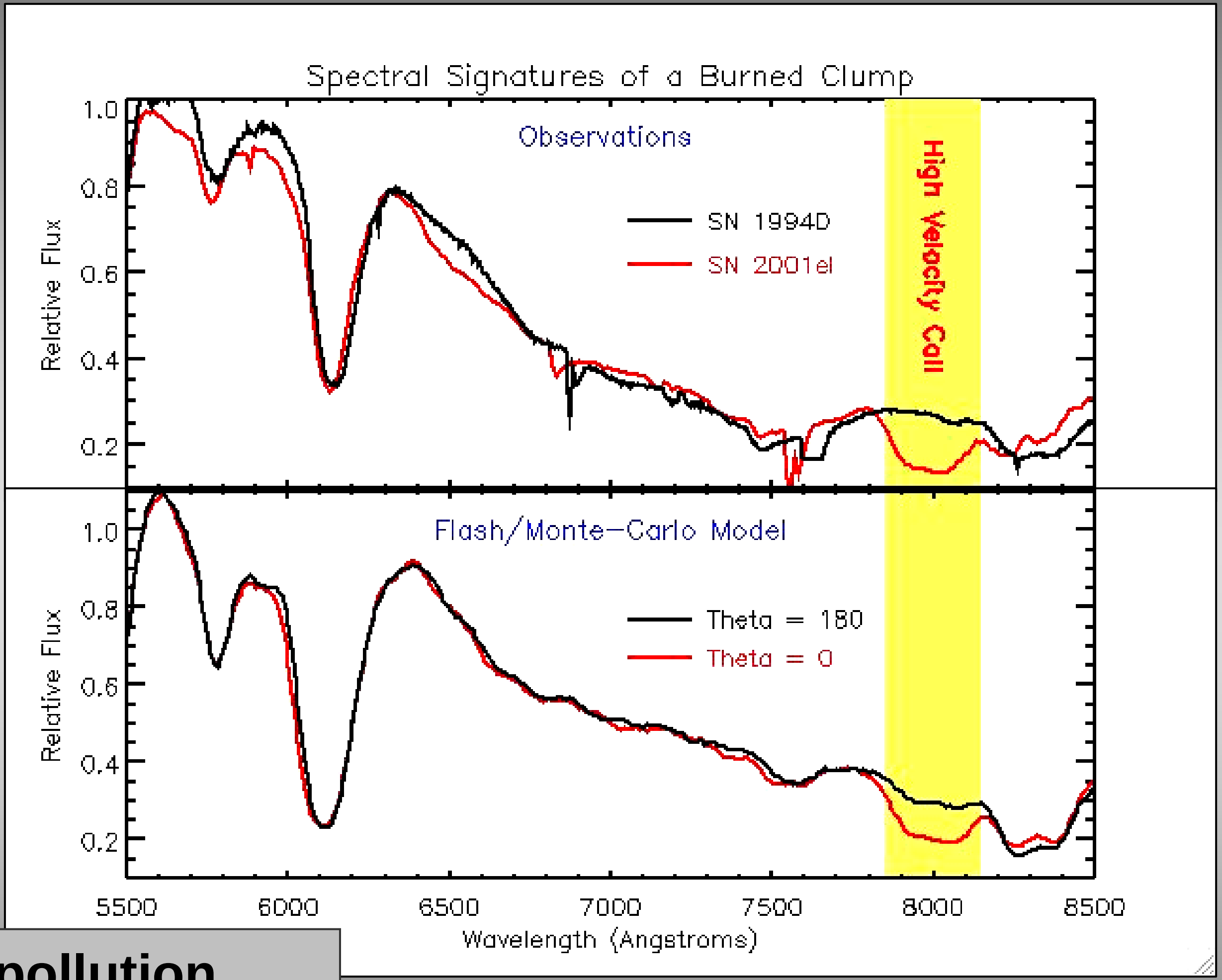
  SN 1990N SN 1991T SN 1992A SN 1994D SN 1999ee SN 2000cx SN 2001el SN 2002bo SN 2002er SN 2003du SN 2005cf 2005cg (Mazzali et al. 2005, Garavini et al. 2007)

- **Theory**
  - impossible to obtain in detonations
  - highly unlikely in pure deflagrations
  - equally hard in DD (Yamaoka et al. 1992)
  - CSM interaction (Gerardy et al. 2004, Quimby et al. 2006)
  - combination of factors (Tanaka et al. 2006)
  - DFD feature (Kasen & Plewa 2005)

DFD Model Validation: IME



Warren et al. (2005)



Kasen & Plewa (2005)

Surface pollution

controlled by the deflagration phase in the DFD model

Some Intriguing Observations

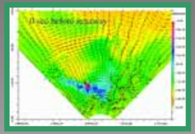
- **HVF require IME-enhanced material detached from bulk ejecta**
  - Hard to imagine in deflagrations
  - Perhaps possible in DD given transition below 10^7 g cm^{-3} (wavy IME production)

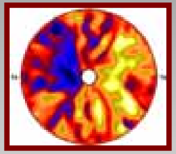
- **Polarimetry indicates the outer layers are clumpy but the IGE core is smooth**
  - Pure deflagrations are likely to produce turbulent cores
  - DD as well if detonation cannot penetrate through ashes
  - And even if it can, how to retain clumpy structure at high velocities?

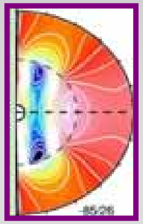
- **MIR observations are indicative of high-density burning products in the central region of ejecta**
  - How pure is it?
  - Do we model deflagration correctly?
  - Is it another indication of off-center late detonation?
  - Or perhaps progenitors we use are not realistic?

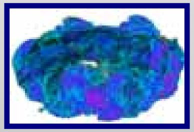
Progressive Core Growth Ignition

- Consider a C/O Chandrasekhar mass WD
- Convective rotating core ⇒ temperature fluctuations ⇒ sparks
- Bubbles are known to be unstable, gravity is low, buoyancy inefficient, but turbulence strong ⇒ breakup, quenching
- Core heating ⇒ progenitor (pre)expansion ⇒ lower central density moderates burning
- Convective core consumes fuel ⇒ becomes rich in stable IGEs, grows in size ⇒ spark production moves to larger radii
- Greater buoyancy, role of turbulence decreases ⇒ sparks more stable
- Once stable enough ⇒ successful *overshoot* ⇒ **ignition**


Höflich & Stein


Kuhlen et al.


Browning et al.


Zingale et al.

What Does It Give Us?

Partially pre-expanded progenitor

Stable IGE in the core

IGE composition possibly from variable density/slow expansion

Global asymmetry due to rotation

Need a low-Mach flow solver: poster by Ju Zhang

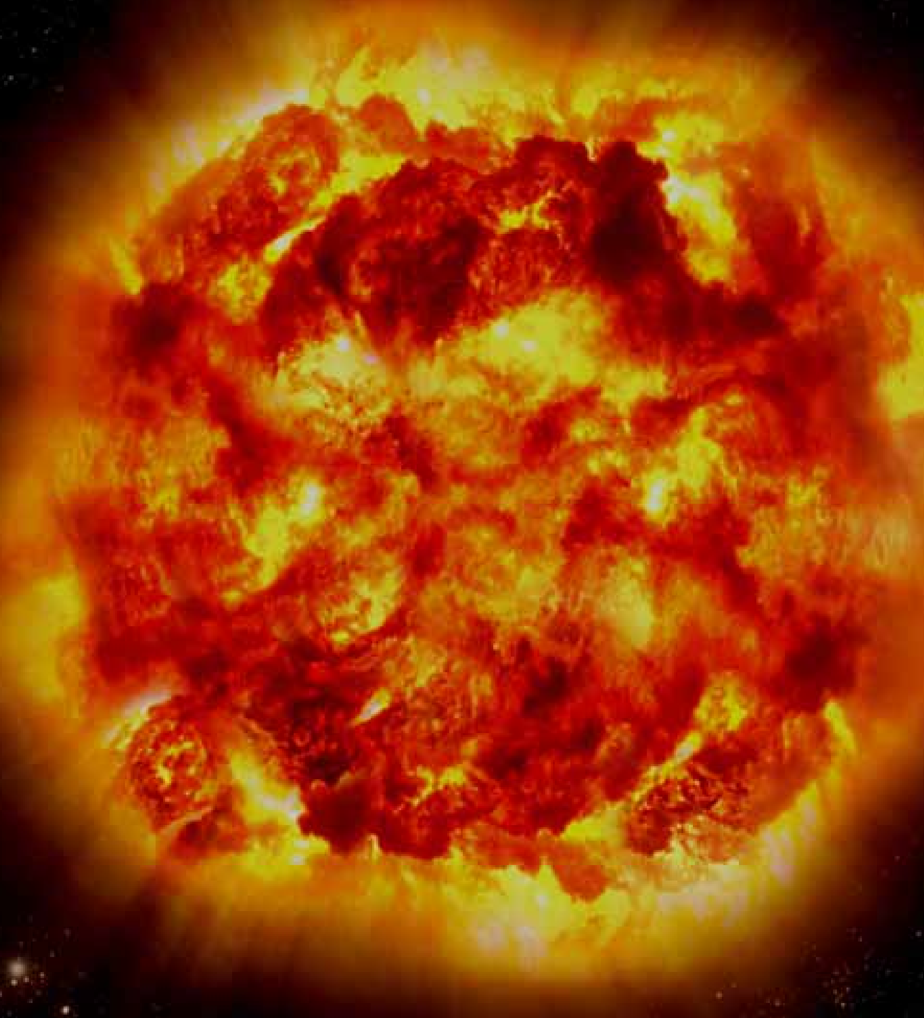
Y12 Detonating Failed Deflagration Model

- subject to detailed validation process
- matches key characteristics of observed objects
- room for improvement identified
  - too luminous, crude nucleosynthesis, polarized low velocity lines, inadequate RT

- emphasized importance of the initial conditions
- detonation in inertially confined flow
- natural chain of events – no user intervention
- for now the only not “by hand” DD model

CP1: The initial conditions
CP2: The detonation fuse

To be continued!



ESO (2006)