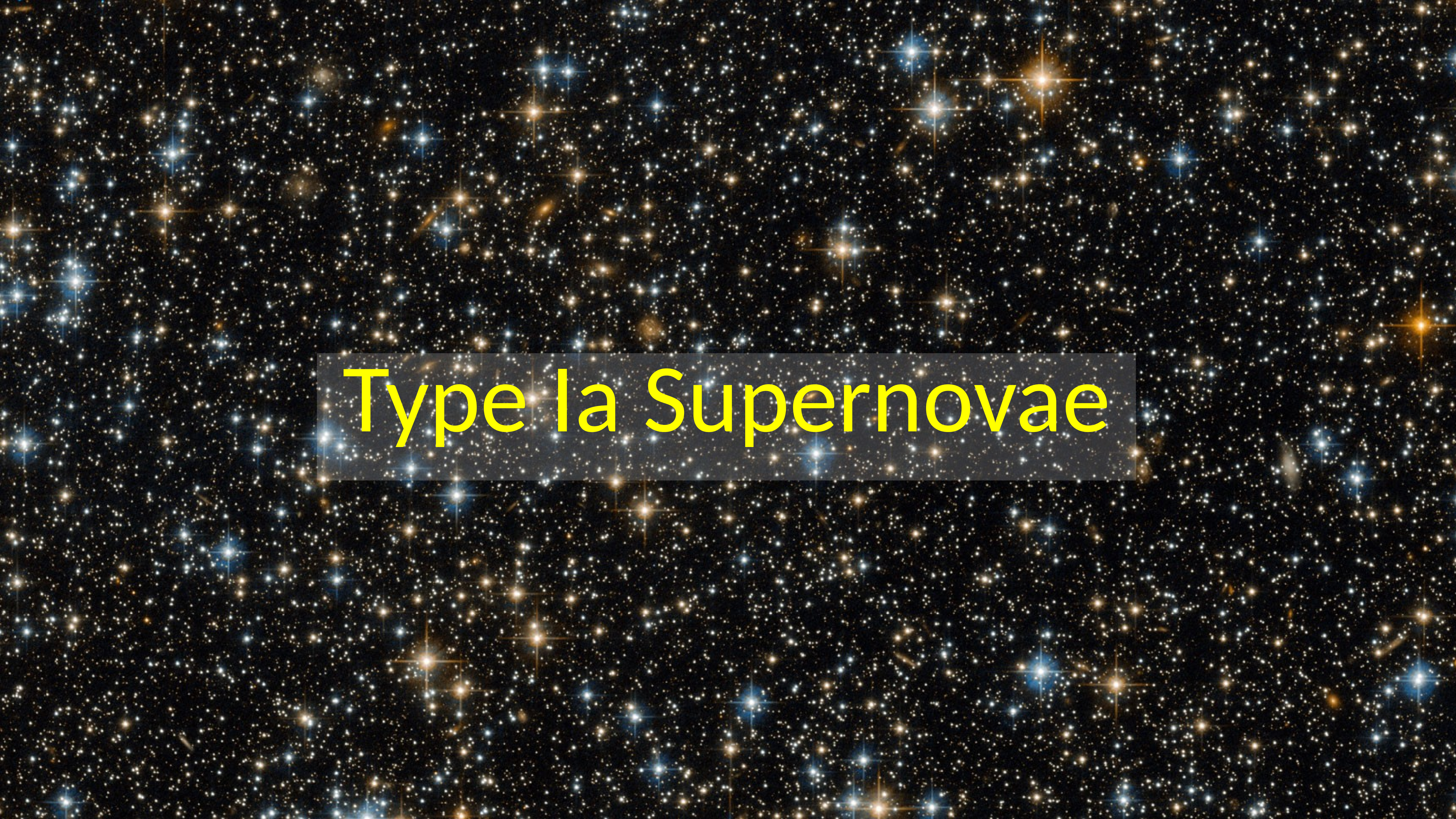
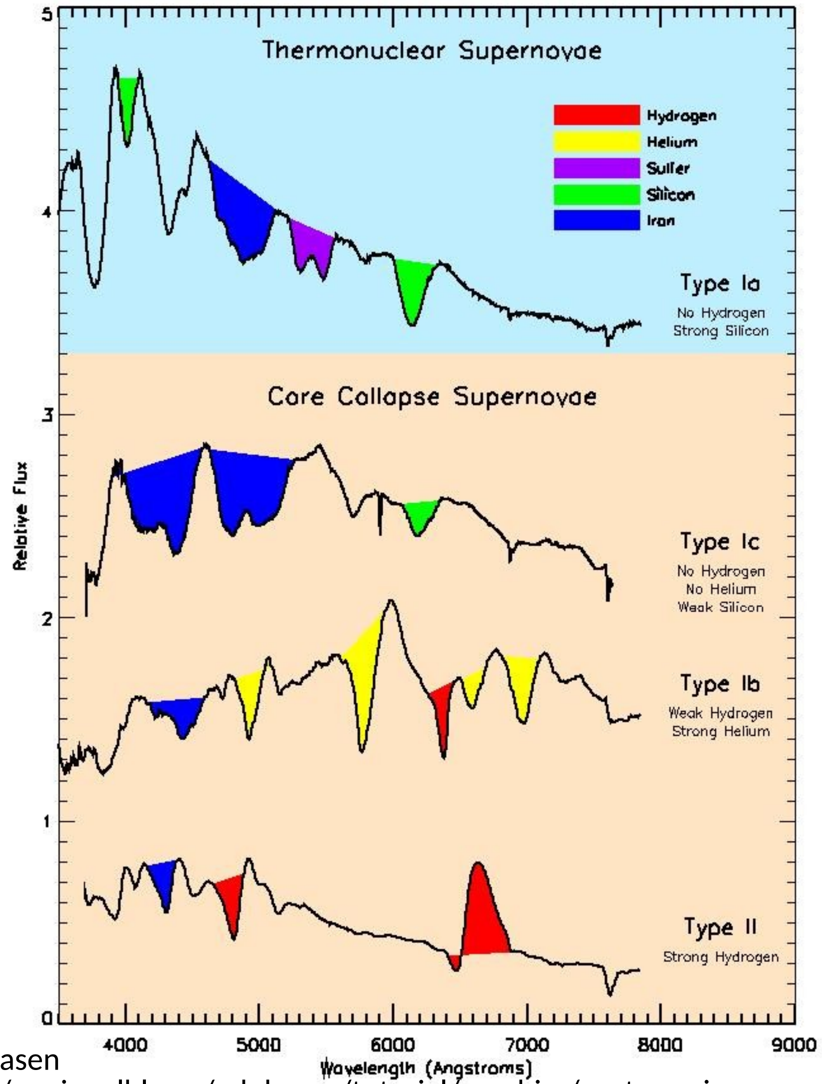


Type Ia Supernovae

Supernovae



Dan Kasen
http://panisse.lbl.gov/~dnkasen/tutorial/graphics/sn_types.jpg

- Fundamentally two types:
  - Gravitationally powered
  - Thermonuclear powered
- Observational classification more complicated
  - Type I: no H in spectrum
    - Ia: strong Si lines
    - Ib: strong He, weak Si
    - Ic: weak He
  - Type II: strong H in spectrum
- Observational pace is accelerating:
  - 1 per century in our galaxy
  - 1 – 10 per second in the observable Universe

Supernovae

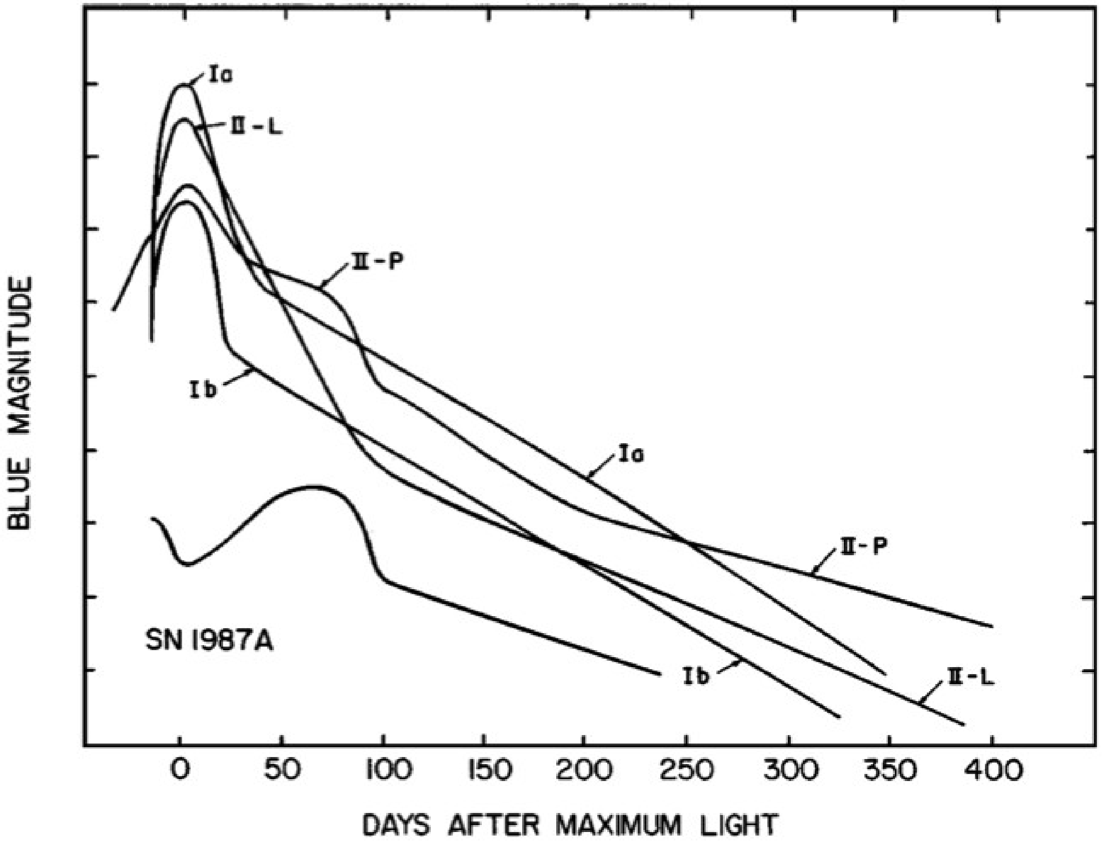
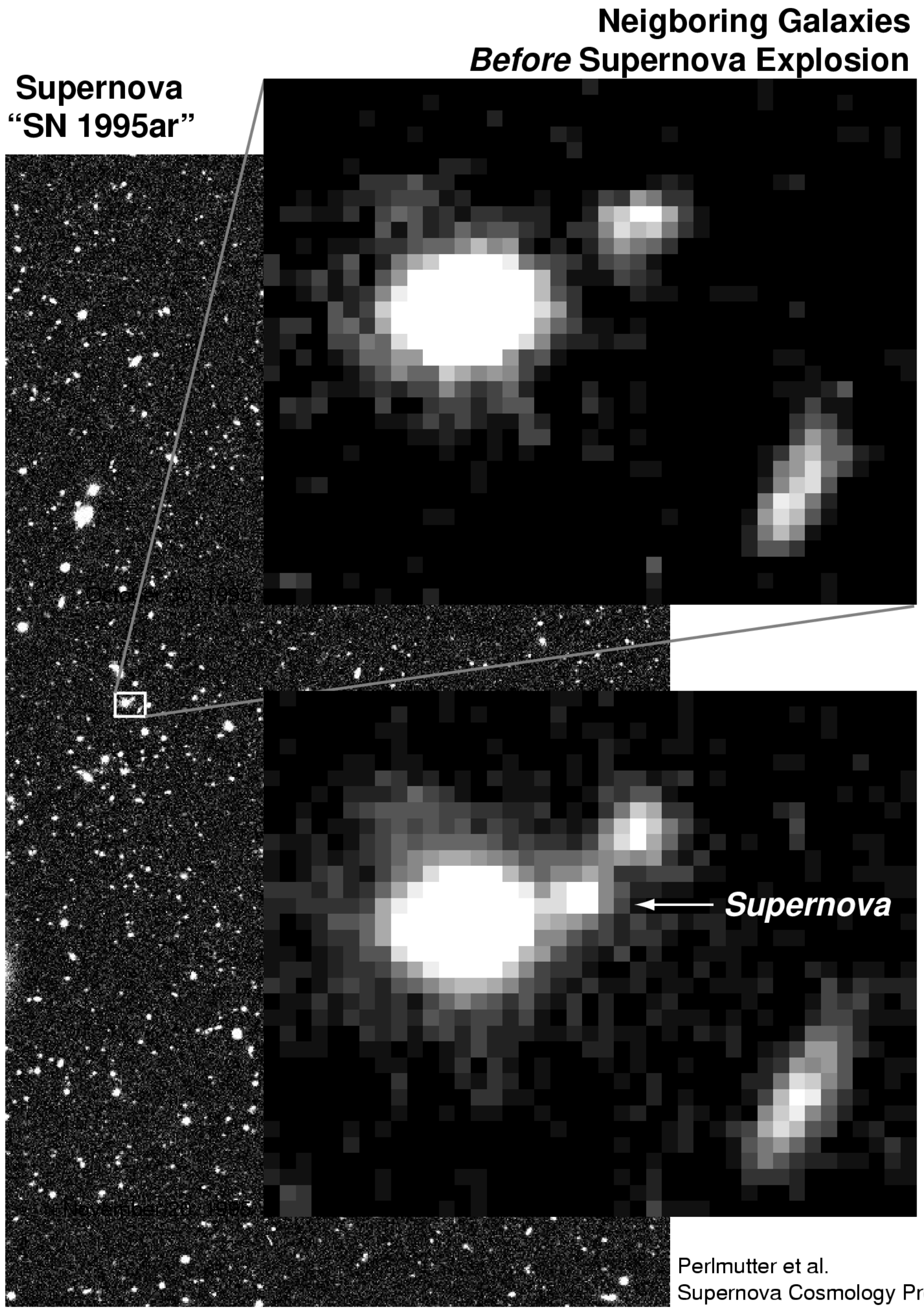


Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusally luminous.

Figure Credit: Wheeler, J. C., & Harkness, R. P. 1990, RPPh, 53, 1467

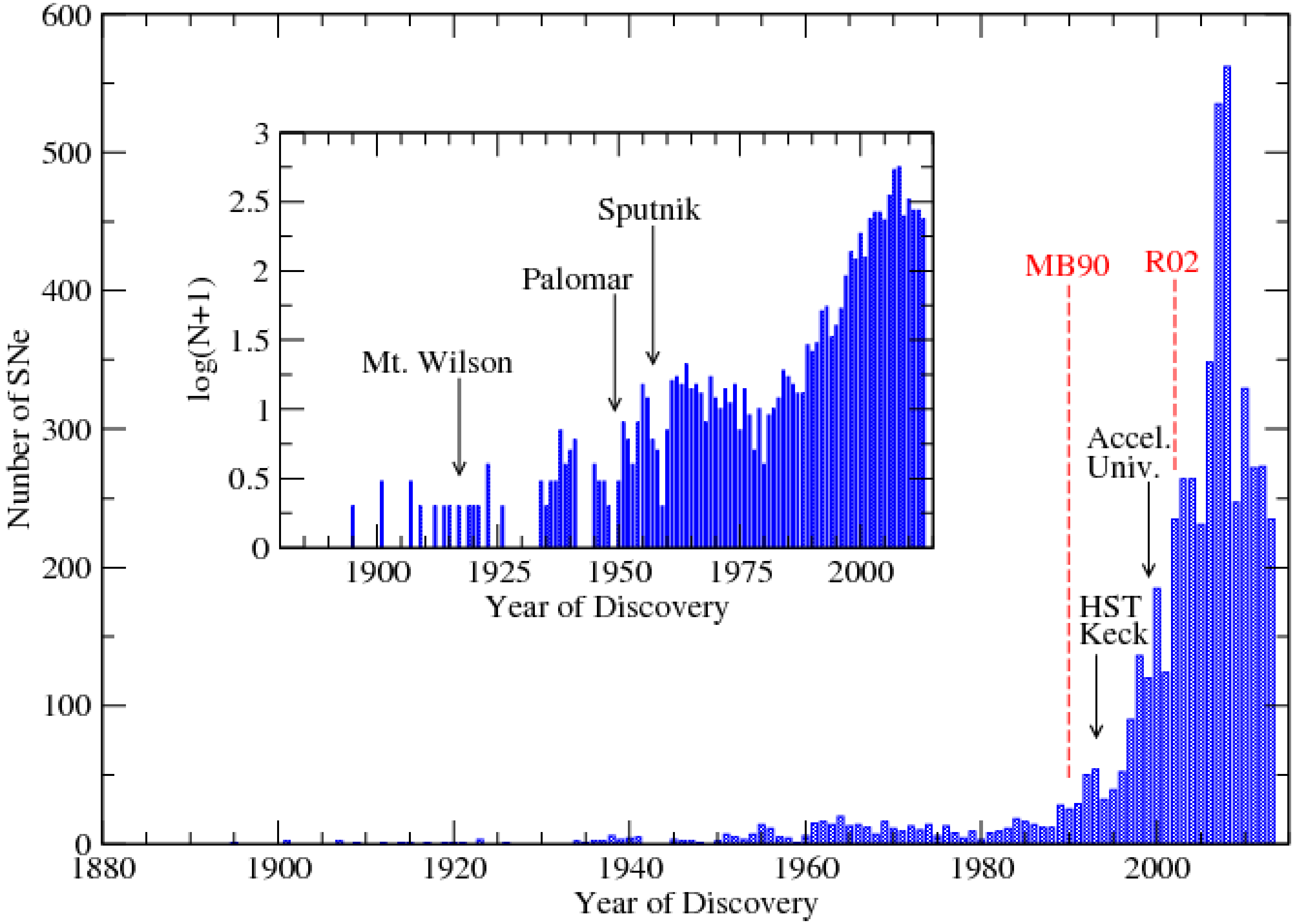
Supernov

- Observers look for a sudden increase in the brightness of a galaxy.
- Follow-up observations tell whether it is a Type Ia supernova or core-collapse



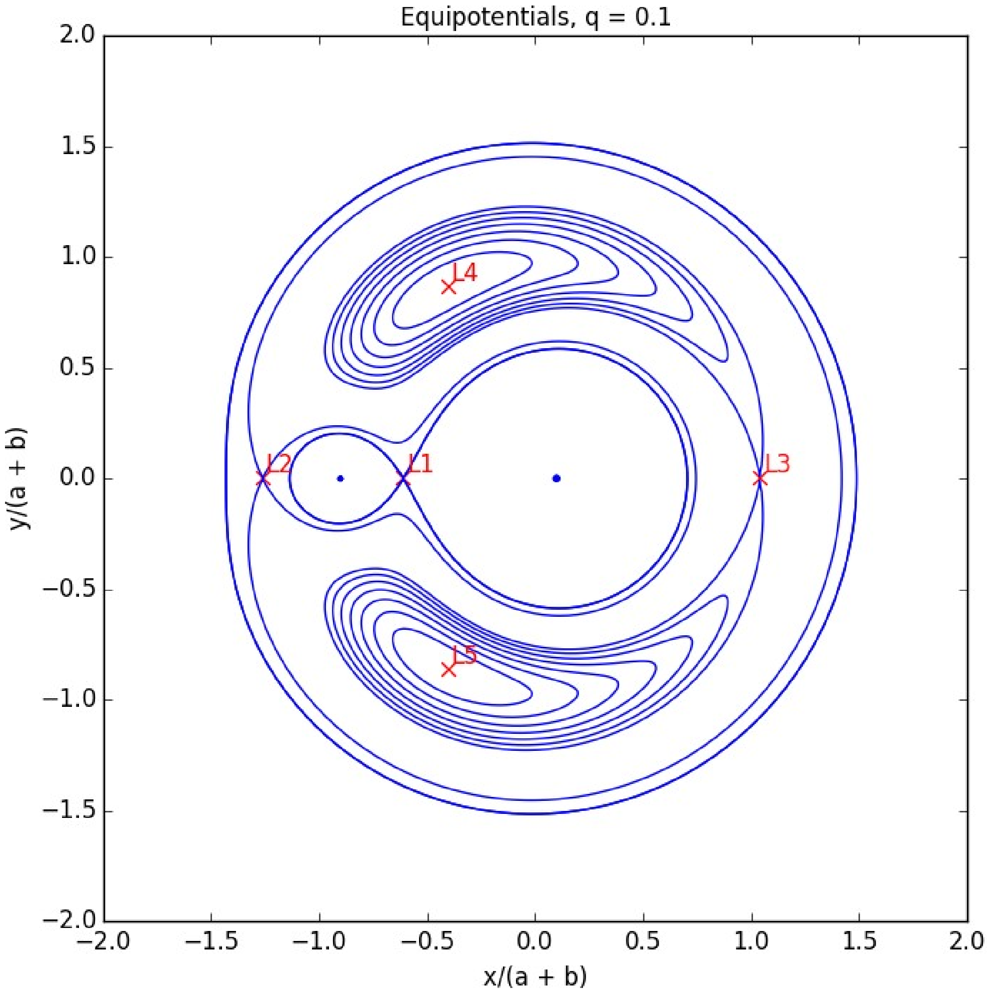
Perlmutter et al.
Supernova Cosmology Project

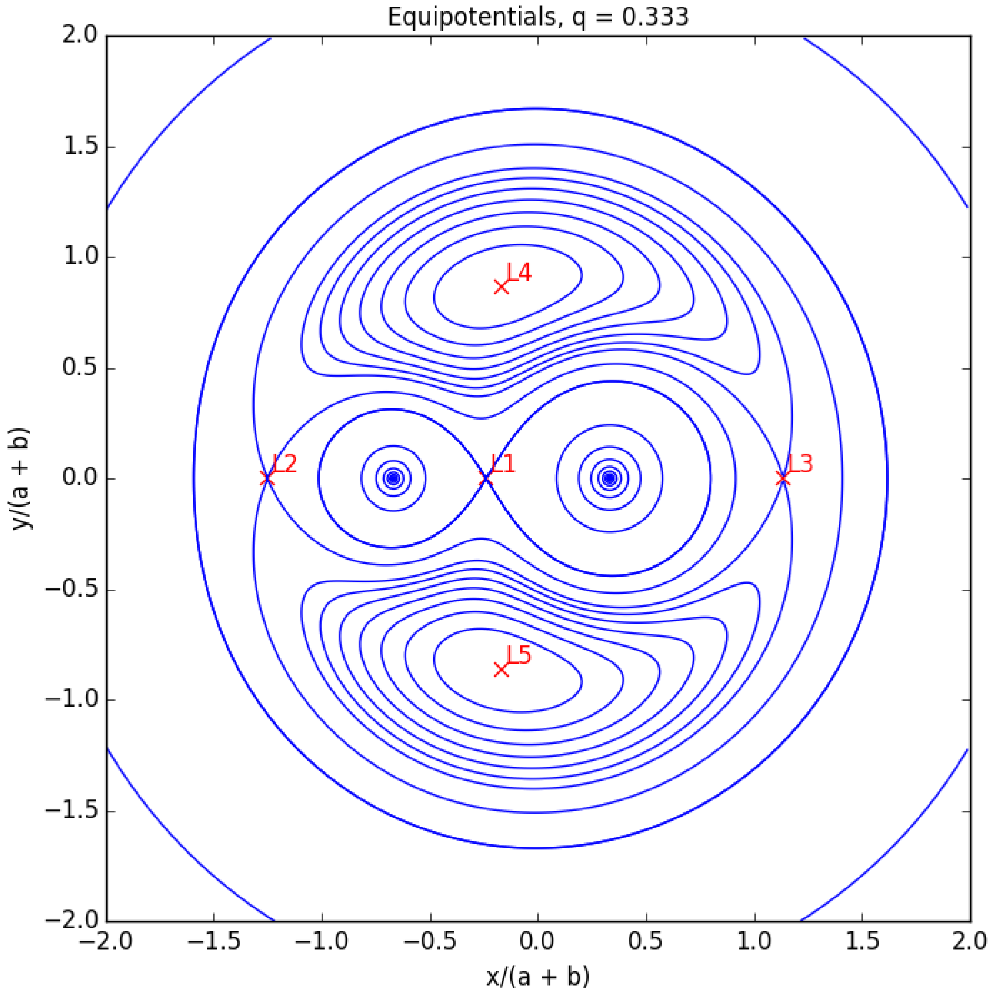
Supernovae



Absolute-Magnitude Distributions of Supernovae - Richardson, Dean et al. Astron.J. 147 (2014) 118 arXiv:1403.5755

Equipotentials





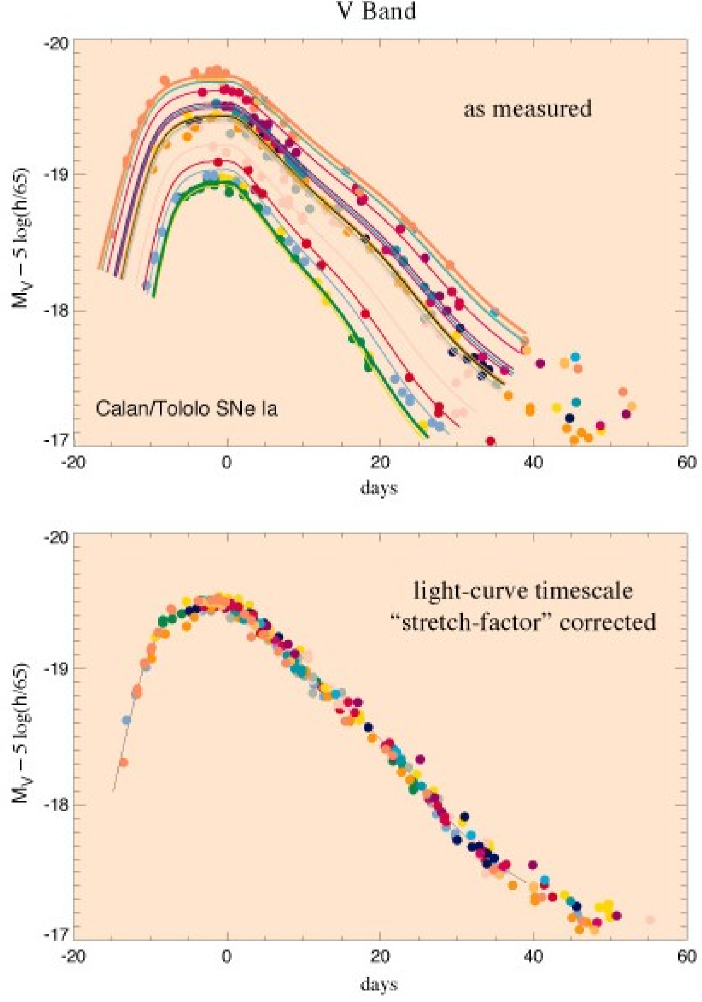
https://github.com/zingale/astro_animations/tree/master/binary_exoplanets/equipotentials

Binary Explosion Taxanomy

- WD systems:
  - classical / recurrant nova: thermonuclear explosion of H layer on surface of WD
  - dwarf nova: instability in the accretion disk that dumps a lot of material onto WD surface at once
  - Type Ia supernova: thermonuclear explosion of an entire WD (or pair)
- NS systems:
  - X-ray burst: thermonuclear explosion of H layer on surface of NS
  - short gamma-ray burst: merger of two NSs
  - binary X-ray pulsar: accretion funneled onto magnetic poles of rapidly rotating NS
- BH systems:
  - accretion onto BH gives rise to X-ray emission (ms timescale rules out NS)

Type Ia Supernovae Observations

- Bright as host galaxy, L ~10^{43} erg s^{-1}
- Radioactive ^{56}Ni powers the lightcuve



Phillips (1993), Perlmutter et al. (1997)

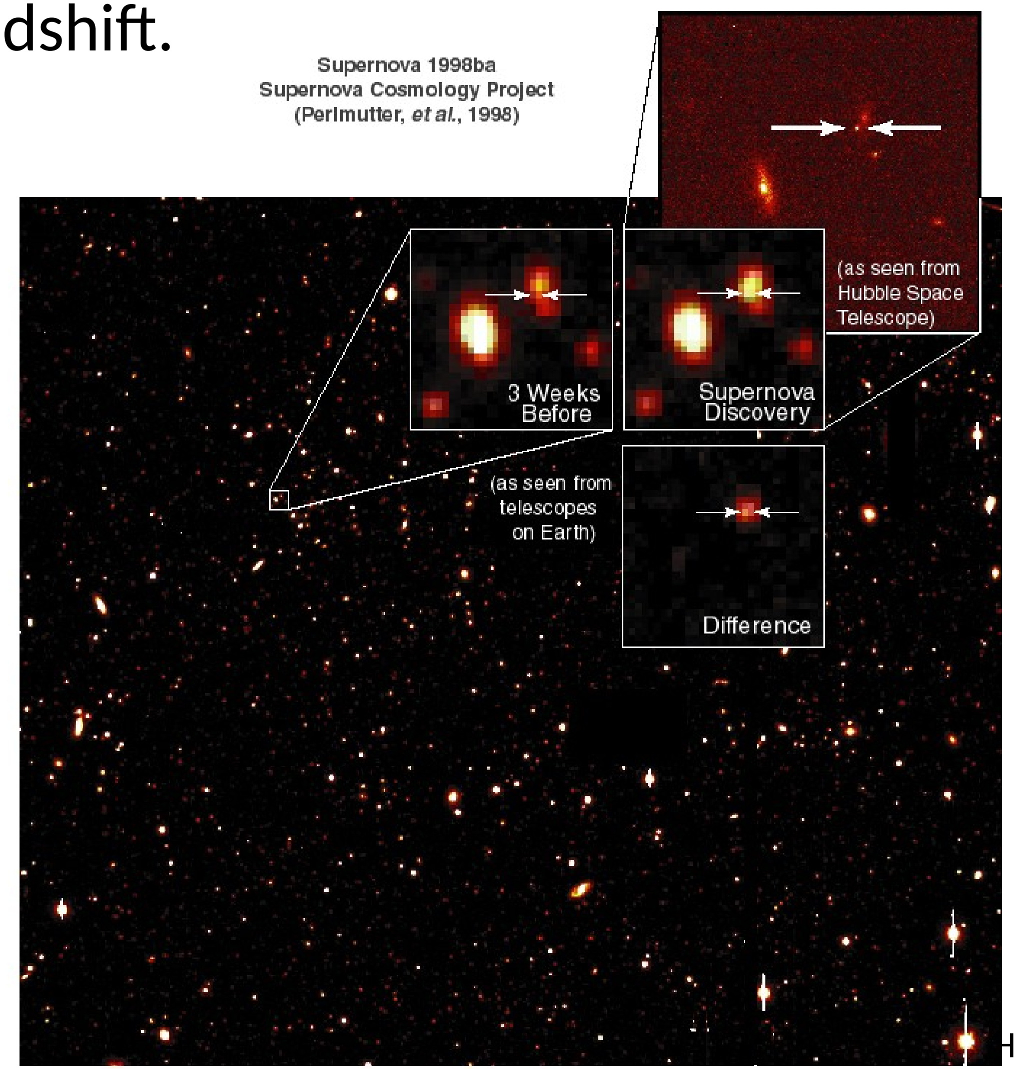
SN 1994D (High-Z SN Search team)

- No H seen in spectra, but strong Si, Ca, and Fe lines
- Occur in old stellar populations
- Lightcurve is robust
  - SNe Ia act as standard candles.

Type Ia Supernovae Observations

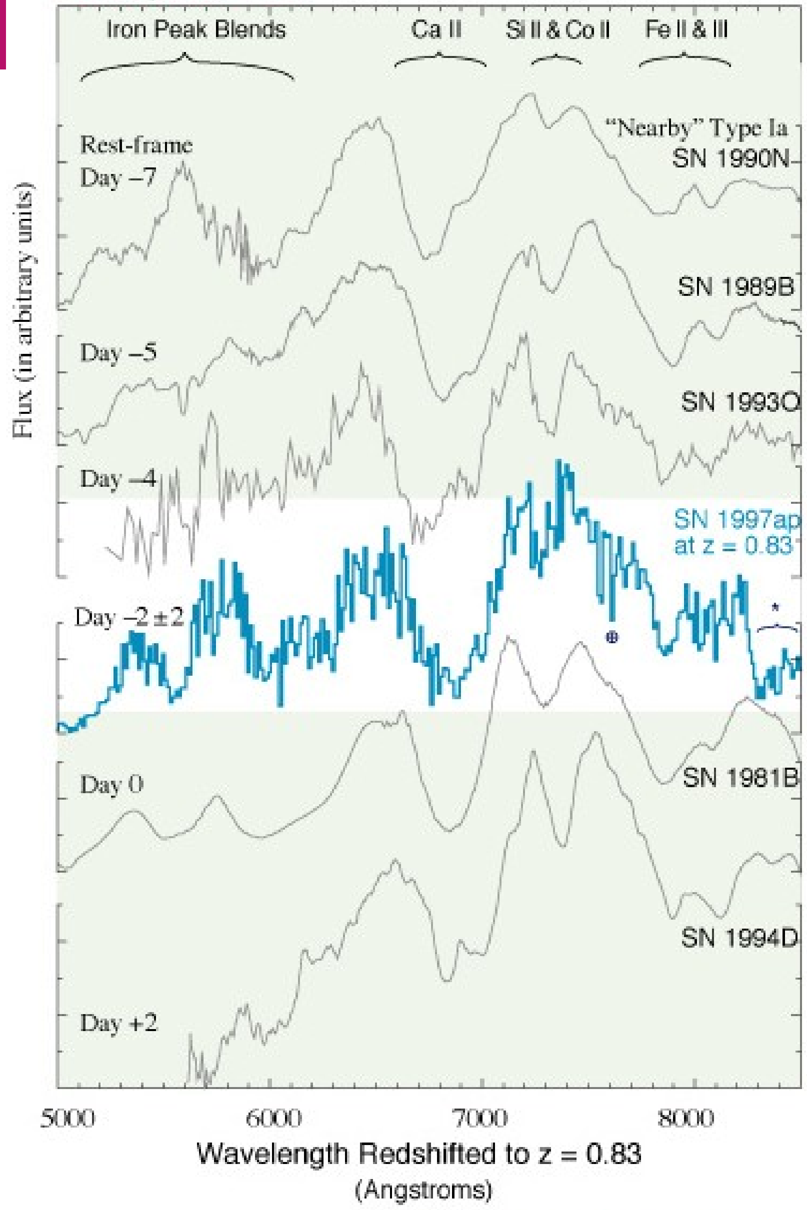
- Spectra of SNe Ia look similar regardless of redshift.

Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)



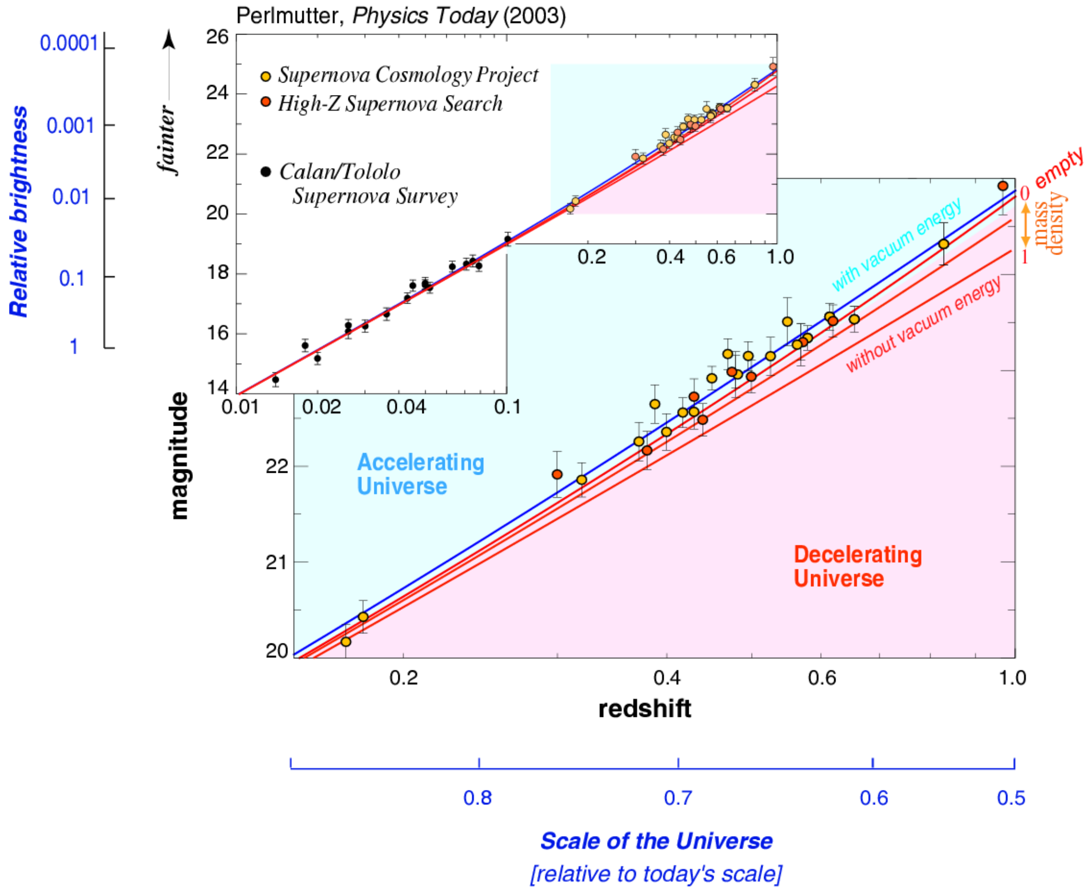
. . . at z = 0.83

−4 days (before) max observer frame
= −2 days rest frame



Perlmutter, et al., Nature (1998)

Type Ia Supernovae Observations



- Plotting the distance verse redshift produces a Hubble diagram.
- Distance supernovae allow us to determine the cosmological parameters.
- In 1998, this led to the discovery that the expansion rate of the Universe is accelerating.

Type Ia Supernovae Observations

- Observations show that these explosions are robust
- Theoretical challenge is to explain why they can be this robust

SNe Ia: Back of the Envelope

- We can get a feel for the energetics involve through a simple back of the envelope calculation
  - Chandra mass WD has a radius of ~2000 km
- Gravitational PE:

$$\Omega \sim \frac{GM^2}{R} \sim 2.6 \times 10^{51} \text{ erg}$$

- Nuclear energy from burning all the C:
  - Simplified reaction:

$$14 {}^{12}\mathrm{C} \longrightarrow 3 {}^{56}\mathrm{Ni}$$

    - Binding energy of ^{12}C nucleus: 92.172 MeV
    - Binding energy of ^{56}Ni nucleus: 484.008 MeV
  - Burning 14 C gives off 162 MeV

$$E_{\text{nuclear}} \sim \frac{M}{14 \cdot 12 m_p} 162 \text{ MeV}$$

$$= 2.6 \times 10^{51} \text{ erg}$$

SNe Ia: Back of the Envelope

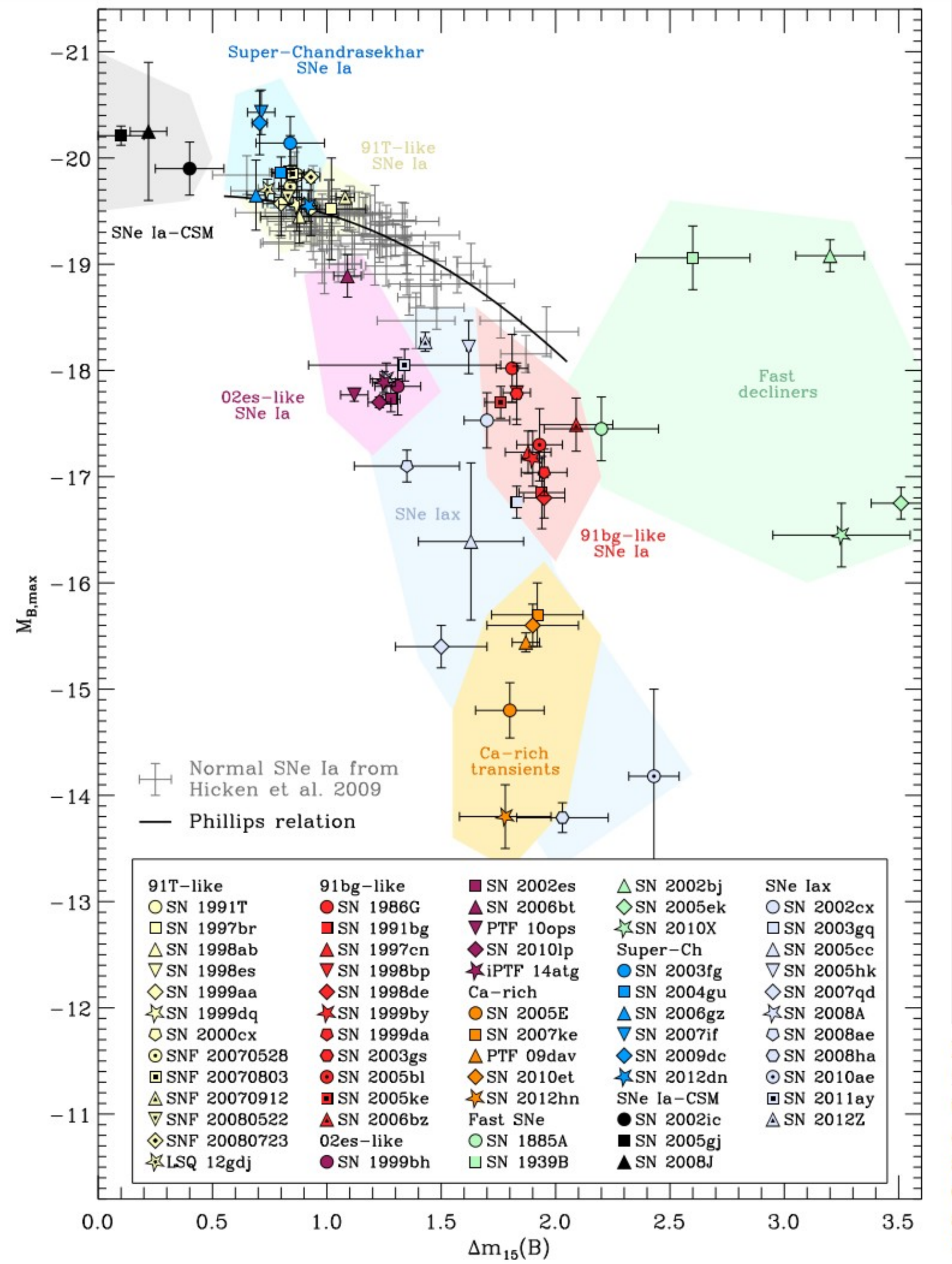
- Caveats:
  - WD is a mix of C/O, so energy / gram from burning is slightly lower
  - Not all C/O burns, and not everything will burn to Ni
  - Gas has internal energy, so nuclear energy release needed to unbind the star is lower than Ω
- This gives us a sense that the basic picture can work:
  - Burn ~ a Chandra mass of C/O and you can unbind the WD
- SNe Ia are bright because ^{56}Ni radioactively decays—this powers the lightcurve

Diversity of Observations

(see Maoz et al. 2014, ARAA)

- We see a lot of these events and are beginning to understand sub-classes
  - Superluminous: some showing more than a Chandra-mass of Ni
  - Subluminous events?
  - SNe Iax:
    - low photosphere velocity, hot, peak L very low
    - Maybe 20-50 of these per 100 normal SNe Ia (Foley et al. 2013)
    - Perhaps these are failed deflagrations?
- We've never see the progenitor system before explosion though!
- Delay time distribution: time between star formation and SNe Ia explosion
  - DD can give broad range of delay times (merger-time relates to post-common envelope separation)

Diversity of SN Ia



Note: as much as 30% of SN Ia don't follow the Phillips relation

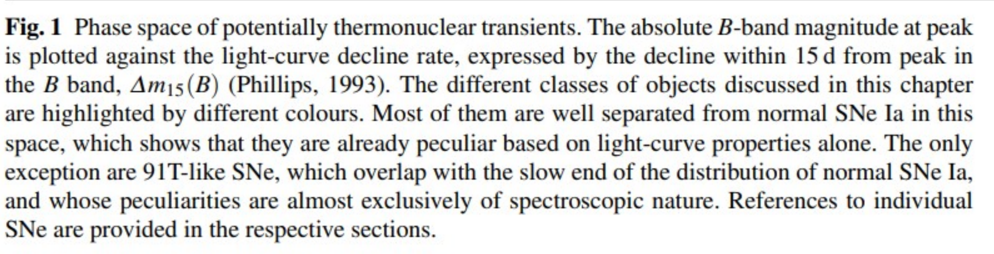


Fig. 1 Phase space of potentially thermonuclear transients. The absolute *B*-band magnitude at peak is plotted against the light-curve decline rate, expressed by the decline within 15 d from peak in the *B* band, $\Delta m_{15}(B)$ (Phillips, 1993). The different classes of objects discussed in this chapter are highlighted by different colours. Most of them are well separated from normal SNe Ia in this space, which shows that they are already peculiar based on light-curve properties alone. The only exception are 91T-like SNe, which overlap with the slow end of the distribution of normal SNe Ia, and whose peculiarities are almost exclusively of spectroscopic nature. References to individual SNe are provided in the respective sections.

(Taubenberger 2017)

Diversity of SN Ia

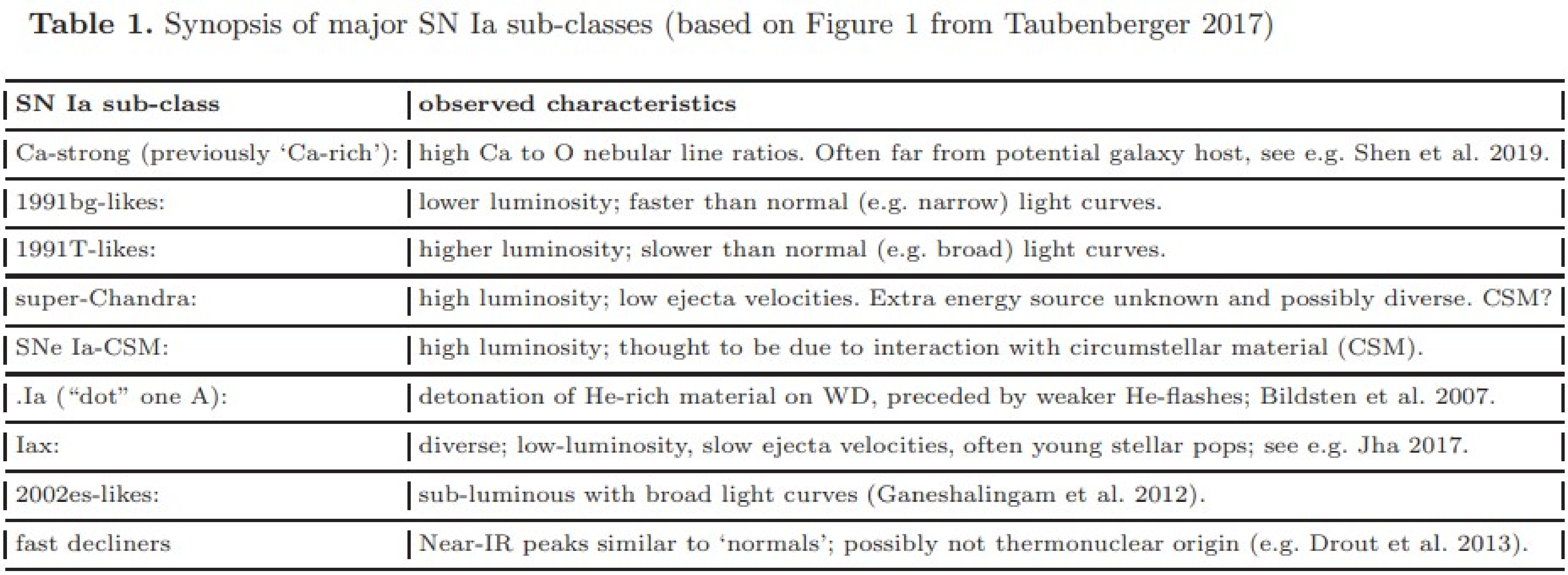
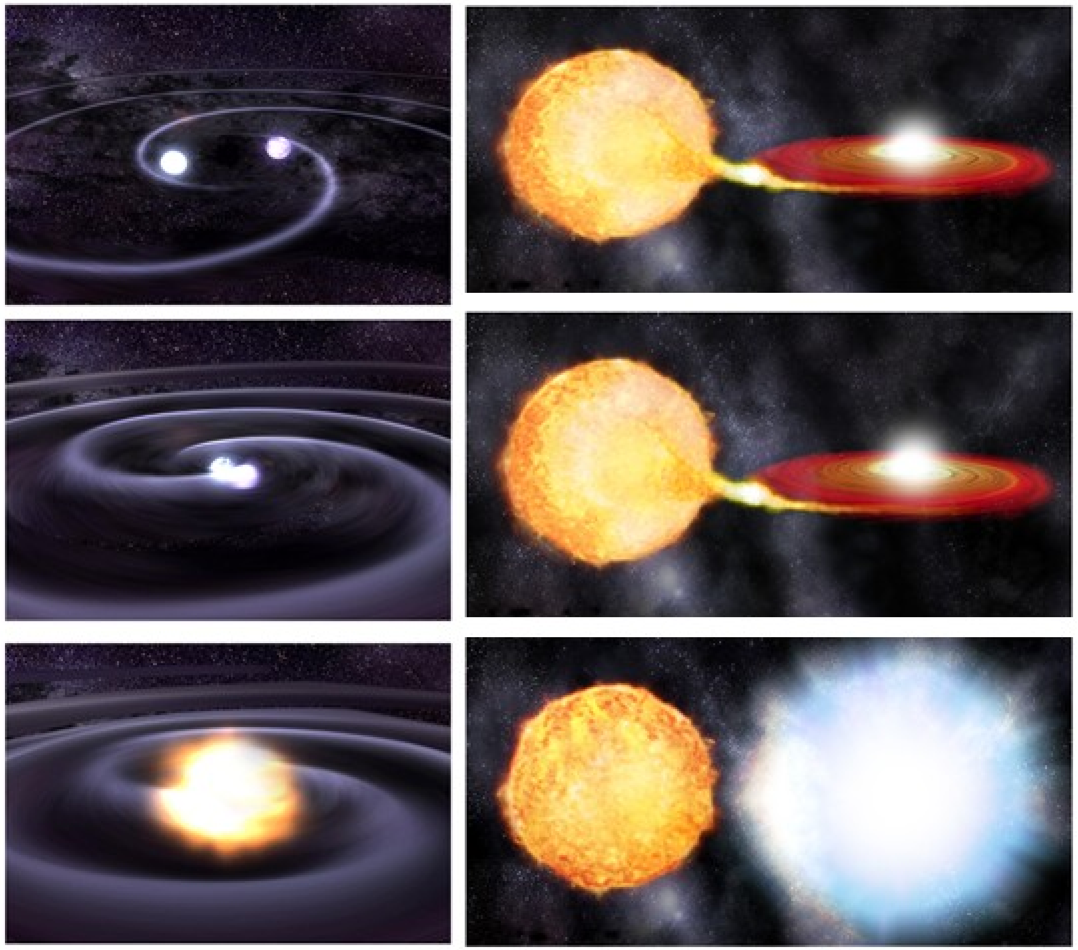


Table 1. Synopsis of major SN Ia sub-classes (based on Figure 1 from Taubenberger 2017)

SN Ia sub-class	**observed characteristics**
Ca-strong (previously 'Ca-rich'):	high Ca to O nebular line ratios. Often far from potential galaxy host, see e.g. Shen et al. 2019.
1991bg-likes:	lower luminosity; faster than normal (e.g. narrow) light curves.
1991T-likes:	higher luminosity; slower than normal (e.g. broad) light curves.
super-Chandra:	high luminosity; low ejecta velocities. Extra energy source unknown and possibly diverse. CSM?
SNe Ia-CSM:	high luminosity; thought to be due to interaction with circumstellar material (CSM).
.Ia ("dot" one A):	detonation of He-rich material on WD, preceded by weaker He-flashes; Bildsten et al. 2007.
Iax:	diverse; low-luminosity, slow ejecta velocities, often young stellar pops; see e.g. Jha 2017.
2002es-likes:	sub-luminous with broad light curves (Ganeshalingam et al. 2012).
fast decliners	Near-IR peaks similar to 'normals'; possibly not thermonuclear origin (e.g. Drout et al. 2013).

(from Ruiter 2020)

SNe Ia Progenitors



from astrobites.org (http://astrobites.org/2015/04/07/super-bright-supernovae-are-single-degenerate/) via Wikipedia/Discover

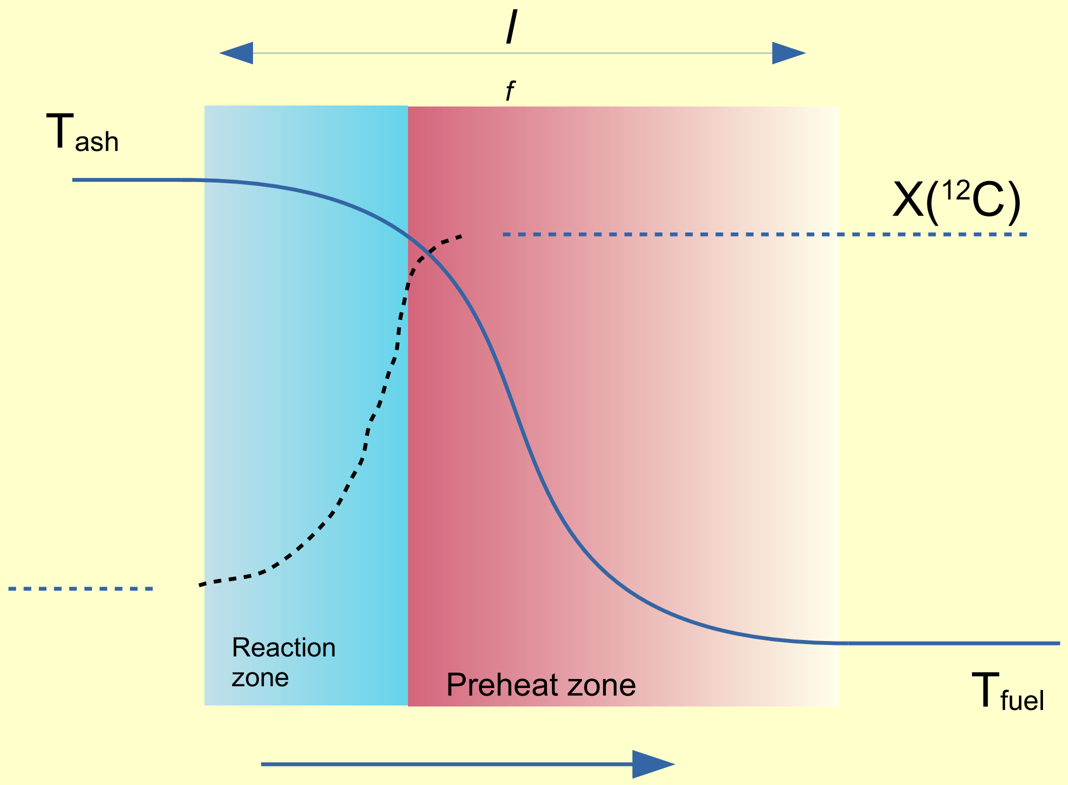
How Can A Burning Front Propagate?

Deflagration

Subsonic

fuel and ash are in pressure equilibrium

heat diffusing from the hot ash raises the temperature of the fuel to the point of ignition

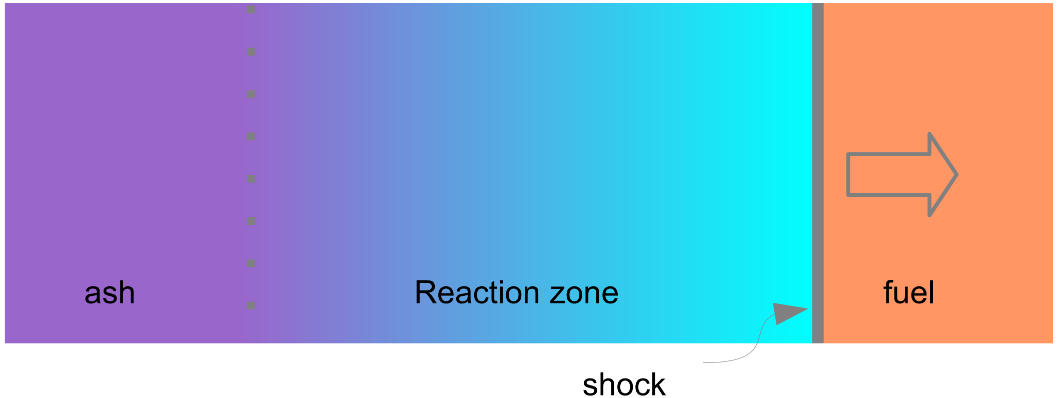


Detonation

supersonic

shock heats fuel to point of ignition

heat release in fuel sustains detonation



A detonation does not give the star time to expand

All the C+O will burn at high density to nickel. No intermediate mass elements produced!

Flame Physics

- Start with the first law of thermodynamics

$$de + Pd(1/\rho) = dq$$

- Our entropy sources are thermal diffusion and reactions:

$$\frac{De}{Dt} + P\frac{D}{Dt}\left(\frac{1}{\rho}\right) = \text{sources}$$

$$\rho\frac{De}{Dt} - \frac{P}{\rho}\frac{D\rho}{Dt} = \rho\epsilon + \nabla\cdot k_{\mathrm{th}}\nabla T$$

- Define the specific enthalpy: h = e + P/ρ

$$\frac{Dh}{Dt} = \frac{De}{Dt} + \frac{D}{Dt}\left(\frac{P}{\rho}\right) = \frac{De}{Dt} - \frac{P}{\rho^2}\frac{D\rho}{Dt} + \frac{1}{\rho}\frac{DP}{Dt}$$

- Pressure is constant across a flame front (it's subsonic)

Flame Physics

- Our enthalpy evolution is

$$\rho \frac{Dh}{Dt} = \cancelto{0}{\frac{DP}{Dt}} + \rho\epsilon + \nabla \cdot k_{\mathrm{th}} \nabla T$$

  - here we used the fact that flames are subsonic to say that the pressure of a fluid element does not change with time (in an open domain)

- Expressing h = h(p, T), we have:

$$\frac{Dh}{Dt} = \left.\frac{\partial h}{\partial T}\right|_p \frac{DT}{Dt} + \left.\frac{\partial h}{\partial p}\right|_T \cancelto{0}{\frac{DP}{Dt}}$$

- Leaving us with a diffusion-reaction equation

$$\rho c_p \frac{DT}{Dt} = \nabla \cdot k_{\mathrm{th}} \nabla T + \rho\epsilon$$

Flame Physics

- Let's look at the timescales
  - Diffusion (neglecting reactions):

$$\frac{DT}{Dt} = \frac{1}{\rho c_p} \nabla \cdot k_{\mathrm{th}} \nabla T \approx \mathcal{D} \nabla^2 T$$

    - here the diffusion coefficient is: $\mathcal{D} = k_{\mathrm{th}}/(\rho c_p)$
    - dimensional analysis gives the characteristic timescale: $t_{\mathrm{diff}} \approx \delta^2/\mathcal{D}$
  - Burning (neglecting diffusion):

$$t_{\mathrm{burn}} \approx \left(\frac{1}{\epsilon} \frac{\partial \epsilon}{\partial t} \right)^{-1} \sim \left(\frac{1}{\epsilon} \frac{\partial \epsilon}{\partial T} \frac{dT}{dt} \right)^{-1} \sim \left(\frac{1}{c_p} \frac{\partial \epsilon}{\partial T} \right)^{-1}$$

    - assuming a power law, with some reference density and temperature:

$$\epsilon = \epsilon_0 \rho^\alpha T^\nu \quad \rightarrow \quad \partial \epsilon / \partial T = \nu \epsilon_{\mathrm{ref}} / T_{\mathrm{ref}}$$

$$t_{\mathrm{burn}} \approx \frac{c_p T_{\mathrm{ref}}}{\nu \epsilon_{\mathrm{ref}}}$$

Flame Physics

- A laminar flame is in equilibrium between diffusion and reactions:

$$t_{\mathrm{diff}} = t_{\mathrm{burn}}$$

- solving for the diffusion length gives an estimate for the laminar flame width

$$\delta \sim \left(\frac{k_{\mathrm{th}} T_{\mathrm{ref}}}{\nu \epsilon_{\mathrm{ref}} \rho} \right)^{1/2}$$

- and the flame speed is based on how long it takes to burn across this width:

$$v_f \sim \frac{\delta}{t_{\mathrm{burn}}} \sim \left(\frac{\nu \epsilon_{\mathrm{ref}} k_{\mathrm{th}}}{\rho c_p^2 T_{\mathrm{ref}}} \right)^{1/2}$$

- Note the main dependence:

$$v_f \sim \sqrt{\epsilon k_{\mathrm{th}}} \qquad \delta \sim \sqrt{\frac{k_{\mathrm{th}}}{\epsilon}}$$

Flame Physics

- Temperature evolution governed by (assuming constant pressure)

$$\rho c_p \frac{DT}{Dt} = \nabla \cdot k_{\mathrm{th}} \nabla T + \rho \epsilon$$

- Flame speed and width scale as:

$$v_f \sim \sqrt{\epsilon k_{\mathrm{th}}} \qquad \delta \sim \sqrt{\frac{k_{\mathrm{th}}}{\epsilon}}$$

Flame Physics

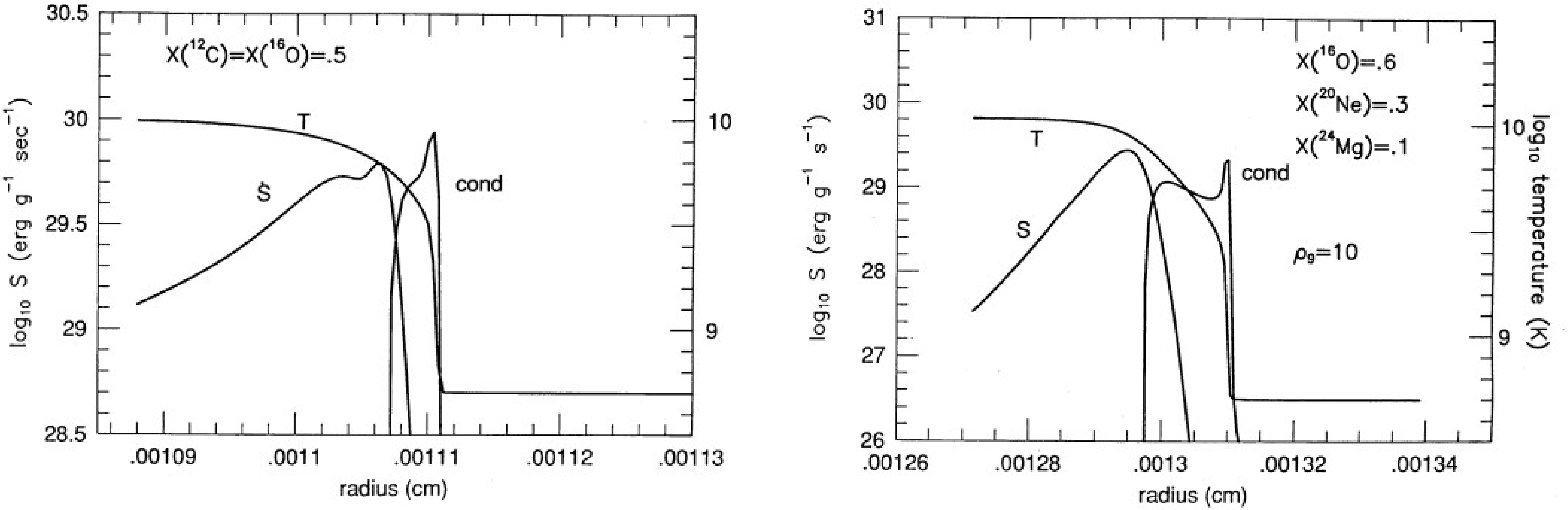


FIG. 3*a*

FIG. 3*b*

FIG. 3.—Magnitudes of the total nuclear generation rate, the energy conduction rate, and the temperature as a function of distance across the flame front for (*a*) a C+O mixture and (*b*) a O+Ne+Mg mixture. The flame is propagating to the right. The critical temperature T_{crit} is defined in the steady state when the energy generation within the flame equals the energy diffusion rate, here about 5×10^9 K. The sharp temperature gradient that occurs when energy is first diffused into a zone accounts for the spike in the energy conduction rate curve.

(Timmes & Woosley 1992)

Flame Physics

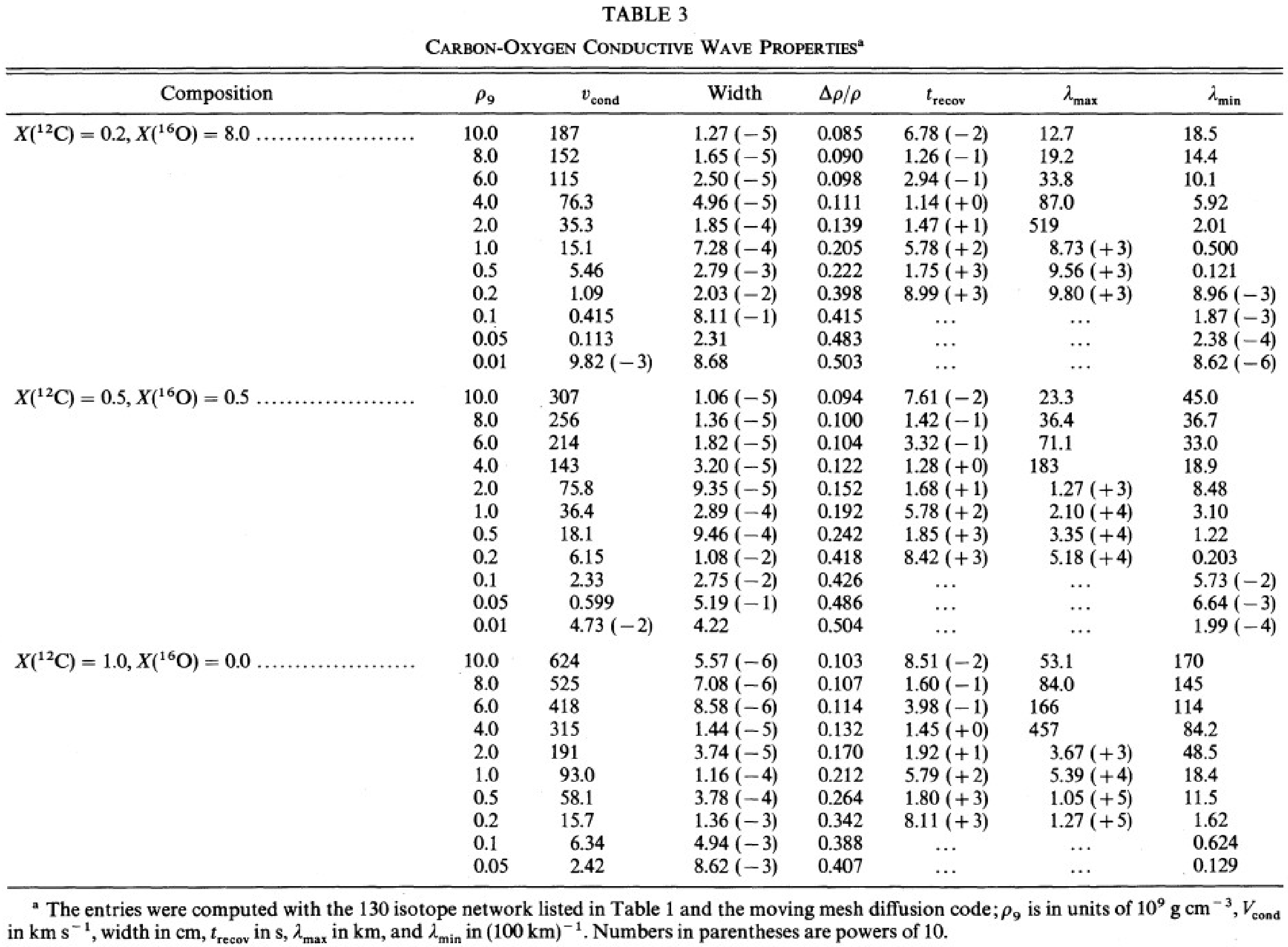


TABLE 3

CARBON-OXYGEN CONDUCTIVE WAVE PROPERTIES[a]

Composition	ρ_9	$v_{\rm cond}$	Width	$\Delta\rho/\rho$	$t_{\rm recov}$	$\lambda_{\rm max}$	$\lambda_{\rm min}$
$X(^{12}\mathrm{C}) = 0.2, X(^{16}\mathrm{O}) = 8.0$	10.0	187	1.27 (−5)	0.085	6.78 (−2)	12.7	18.5
	8.0	152	1.65 (−5)	0.090	1.26 (−1)	19.2	14.4
	6.0	115	2.50 (−5)	0.098	2.94 (−1)	33.8	10.1
	4.0	76.3	4.96 (−5)	0.111	1.14 (+0)	87.0	5.92
	2.0	35.3	1.85 (−4)	0.139	1.47 (+1)	519	2.01
	1.0	15.1	7.28 (−4)	0.205	5.78 (+2)	8.73 (+3)	0.500
	0.5	5.46	2.79 (−3)	0.222	1.75 (+3)	9.56 (+3)	0.121
	0.2	1.09	2.03 (−2)	0.398	8.99 (+3)	9.80 (+3)	8.96 (−3)
	0.1	0.415	8.11 (−1)	0.415	...	...	1.87 (−3)
	0.05	0.113	2.31	0.483	...	...	2.38 (−4)
	0.01	9.82 (−3)	8.68	0.503	...	...	8.62 (−6)
$X(^{12}\mathrm{C}) = 0.5, X(^{16}\mathrm{O}) = 0.5$	10.0	307	1.06 (−5)	0.094	7.61 (−2)	23.3	45.0
	8.0	256	1.36 (−5)	0.100	1.42 (−1)	36.4	36.7
	6.0	214	1.82 (−5)	0.104	3.32 (−1)	71.1	33.0
	4.0	143	3.20 (−5)	0.122	1.28 (+0)	183	18.9
	2.0	75.8	9.35 (−5)	0.152	1.68 (+1)	1.27 (+3)	8.48
	1.0	36.4	2.89 (−4)	0.192	5.78 (+2)	2.10 (+4)	3.10
	0.5	18.1	9.46 (−4)	0.242	1.85 (+3)	3.35 (+4)	1.22
	0.2	6.15	1.08 (−2)	0.418	8.42 (+3)	5.18 (+4)	0.203
	0.1	2.33	2.75 (−2)	0.426	...	...	5.73 (−2)
	0.05	0.599	5.19 (−1)	0.486	...	...	6.64 (−3)
	0.01	4.73 (−2)	4.22	0.504	...	...	1.99 (−4)
$X(^{12}\mathrm{C}) = 1.0, X(^{16}\mathrm{O}) = 0.0$	10.0	624	5.57 (−6)	0.103	8.51 (−2)	53.1	170
	8.0	525	7.08 (−6)	0.107	1.60 (−1)	84.0	145
	6.0	418	8.58 (−6)	0.114	3.98 (−1)	166	114
	4.0	315	1.44 (−5)	0.132	1.45 (+0)	457	84.2
	2.0	191	3.74 (−5)	0.170	1.92 (+1)	3.67 (+3)	48.5
	1.0	93.0	1.16 (−4)	0.212	5.79 (+2)	5.39 (+4)	18.4
	0.5	58.1	3.78 (−4)	0.264	1.80 (+3)	1.05 (+5)	11.5
	0.2	15.7	1.36 (−3)	0.342	8.11 (+3)	1.27 (+5)	1.62
	0.1	6.34	4.94 (−3)	0.388	...	...	0.624
	0.05	2.42	8.62 (−3)	0.407	...	...	0.129

[a] The entries were computed with the 130 isotope network listed in Table 1 and the moving mesh diffusion code; ρ_9 is in units of 10^9 g cm^{-3}, $V_{\rm cond}$ in km s^{-1}, width in cm, $t_{\rm recov}$ in s, $\lambda_{\rm max}$ in km, and $\lambda_{\rm min}$ in (100 km)$^{-1}$. Numbers in parentheses are powers of 10.

(Timmes & Woosley 1992)

Flames must accelerate significantly!

Progenitors

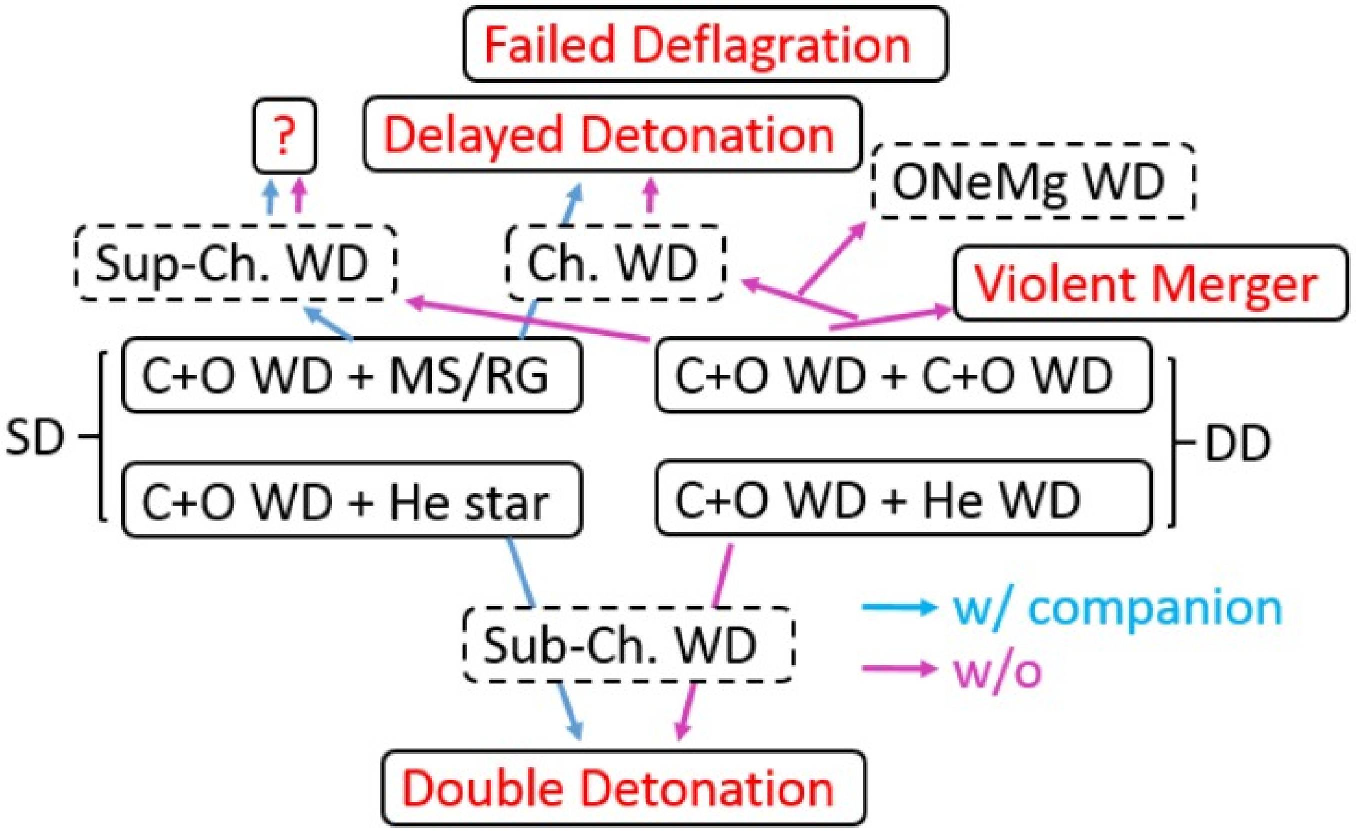


Fig. 2. A schematic 'flowchart' of SN Ia progenitor models related to the SD and DD scenarios. See the text for details.

(Maeda & Terada 2016)

SN Ia Progenitors

- Extremely likely that more than one progenitor model contributes to SN Ia
- Basic explosions:
  - Delayed detonation
  - Prompt detonation
- Can also have failed explosions (flame doesn't transition into detonation?)
  - Maybe the Iax population?

- Classes:
  - Chandra mass (usually called single degenerate) exploding via delayed detonation
  - Sub-Chandra WD exploding via double detonation
    - Donor can be He or HeCO WD
  - WD mergers (sometimes called double degenerate):
    - Explosion can be delayed, look like Chandra case
    - Alternately can ignite via He and look like double detonation

See great review by Ruiter 2020

Type Ia Supernovae

- Early favored picture: single Chandra-mass WD
- Cannot detonate from start to finish
  - This was shown in 1970s by Arnett
  - Detonation is supersonic → outer layers don't know a burning front is coming, so they cannot pre-expand
  - Burning takes place at too high of a density, over produces Ni-group, doesn't make intermediate mass elements
- Pure deflagration is also unlikely
  - Models show that this can leave behind unburned carbon near the center
- Deflagration-detonation transition?
  - Mechanism is not understood

Chandra vs. Merging WDs

- Chandra mass
  - Explosion begins as we approach Chandra mass
  - High density of core can allow e-capture reactions → make neutron rich isotopes
  - Has to begin as a subsonic burning front, then transition to detonation

- Pros:
  - Some SNe Ia show circumstellar material (PTF11kx) that can only be explained in SD context
  - Some nuclei require high densities (e-captures favored), e.g. SNR 3C 397
  - UV pulse seen in early lightcurve (4 days; Cao et al. 2015) suggests interaction with companion
- Cons:
  - We don't see surviving companion in remnants
  - Observations and population synthesis don't produce enough Chandra-mass WDs

Chandra vs. Merging WDs

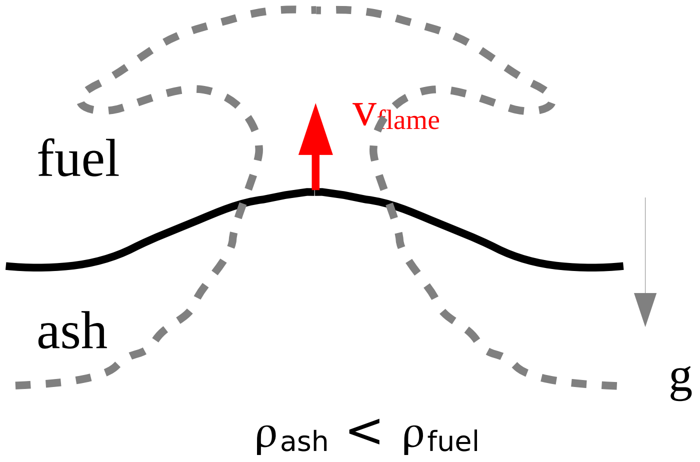
- Merging WDs
  - Sum of WD > Chandra mass
  - Originally disfavored because of potential for accretion-induced collapse
  - He might be critical in triggering detonation

- Pros:
  - We can explain the entire SNe Ia rate just based on the observed number of WD-WD systems we see
  - SN 2011fe was one of the most intensely studied supernova—no features in its spectra suggesting a companion
  - SN 2007if and SNLS 03D3bb are super-Chandra—more than 1.4 $M_\odot$ of Ni produced
- Cons:
  - Theoretical models show the potential for accretion-induced collapse to a neutron star

Outstanding Questions in SNe Ia

- General consensus: thermonuclear explosion of a carbon/oxygen white dwarf
- What is the progenitor?
  - Diversity of observations suggests multiple progenitor channels
  - Single white dwarf or merging white dwarf?
  - Chandra or sub-Chandra mass?
- Chandra mass channel:
  - What are the initial conditions?
  - Does the burning front remain subsonic?
- WD mergers:
  - Can we avoid the accretion induced collapse?
  - Can we get an explosion that looks like a SNe Ia?
- What is the physical basis for the width-luminosity relationship in the lightcurve?
  - Some variation in the explosion is needed to account for the diversity in explosions.

Wrinkling the Flame



Rayleigh-Taylor Instability:

This is a buoyancy driven instability. The hot ash behind the flame rises and the cool fuel ahead of the flame falls downward.

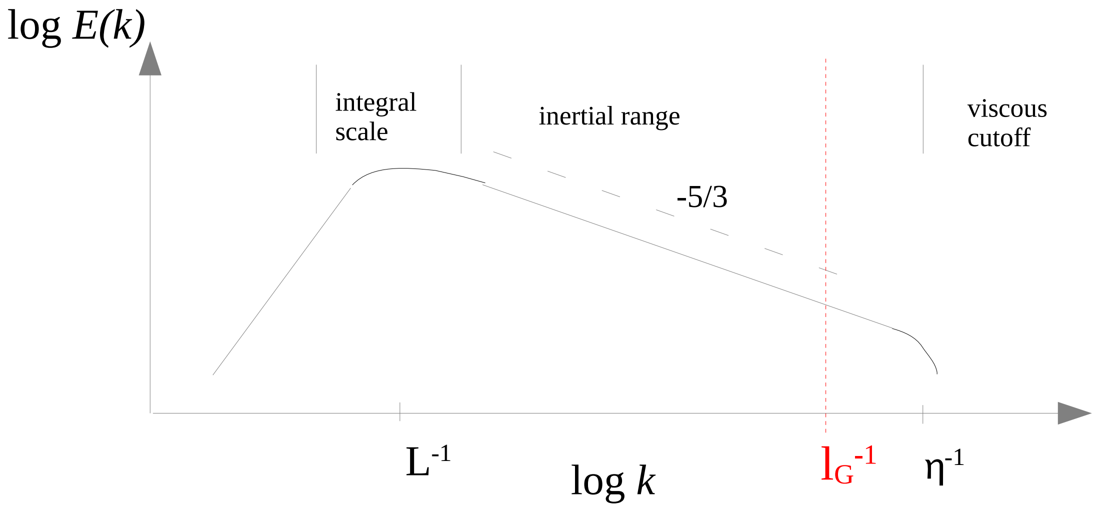
Large amounts of surface area generated.

Turbulence:

Turbulence is characterized by random motions. Instabilities create vorticity on the large scales that cascades down to smaller and smaller scales.

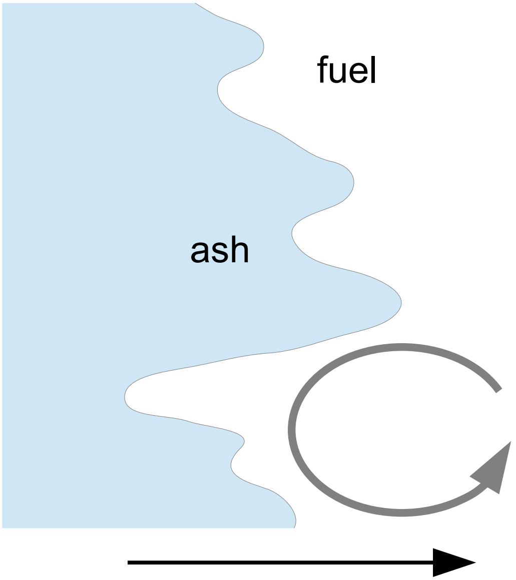
Kolmogorov: KE disipation rate is constant across scales:

$$u^3/l = \epsilon$$



adapted from Peters (2000)

Transition to Distributed Burning



Flame begins as flamelet

Flame is a continuous surface

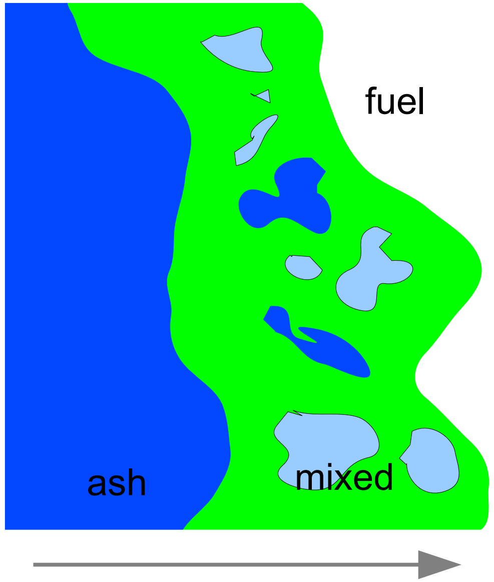
Turbulence serves solely to wrinkle the flame, increasing the area

Transition to distributed burning regime ~10^7 g cm^{-3}

Mixed region of fuel + ash develops

May be possible to quench the flame

Possible transition to detonation



Transition to Distributed Burning

- Gibson scale—flame speed is comparable to the turbulence speed
  - turbulence can directly affect the flame structure
  - Kolmogorov turbulence:

$$l = L \left(\frac{u}{U}\right)^3$$

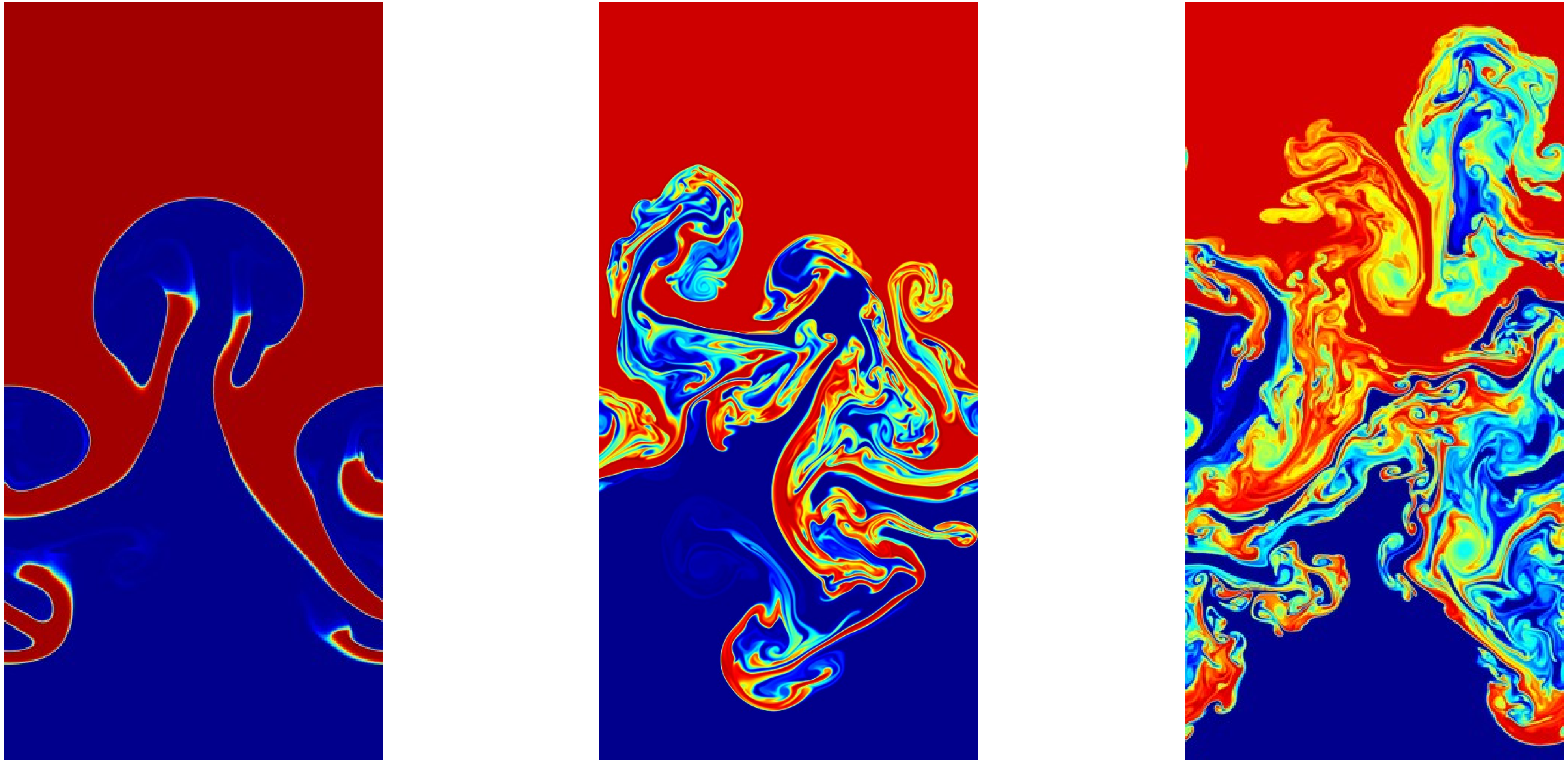
    - here, L is the integral scale and U is the turbulent intensity at the integral scale

$$l_G = L = \left(\frac{v_f}{U}\right)^3$$

  - Flames get thicker as they encounter lower densities
  - For C/O flames, we are at the Gibson scale at densities of ~ 10^7 g/cc

Transition to Distributed Burning

(Bell et al. 2004, ApJ, 608, 883)



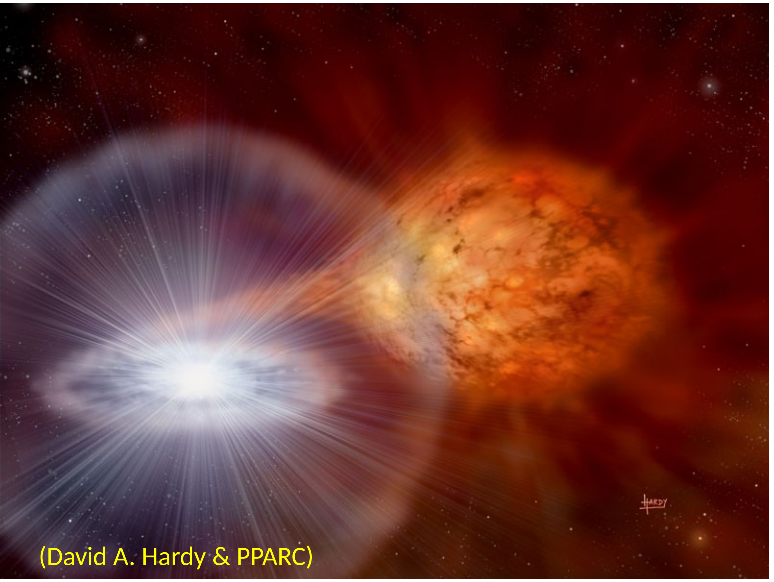
As ρ decreases, RT dominates over burning.

ρ

At low ρ, flame width is set by mixing scale.

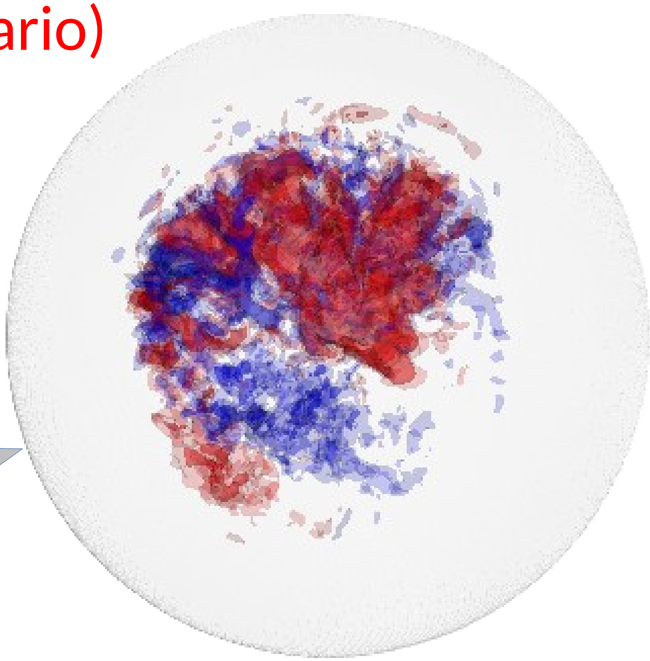
Type Ia Supernovae

(Chandra-mass single-degenerate scenario)



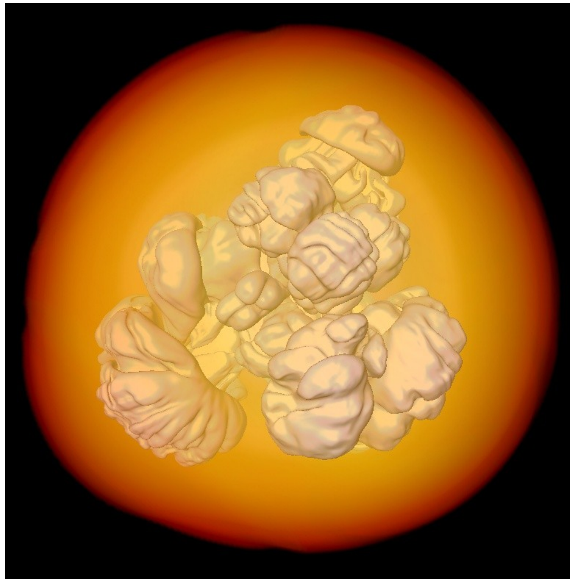
(David A. Hardy & PPARC)

1 Accretion from binary companion. Grows to M_{ch}



2 "Smoldering" phase—central T rises → flame born

3 Flame propagation. Initially subsonic, but detonation transition?



(Roepke and Hillebrandt 2005)

4 Explosion! Lightcurve powered by Ni decay. Width / luminosity relation.

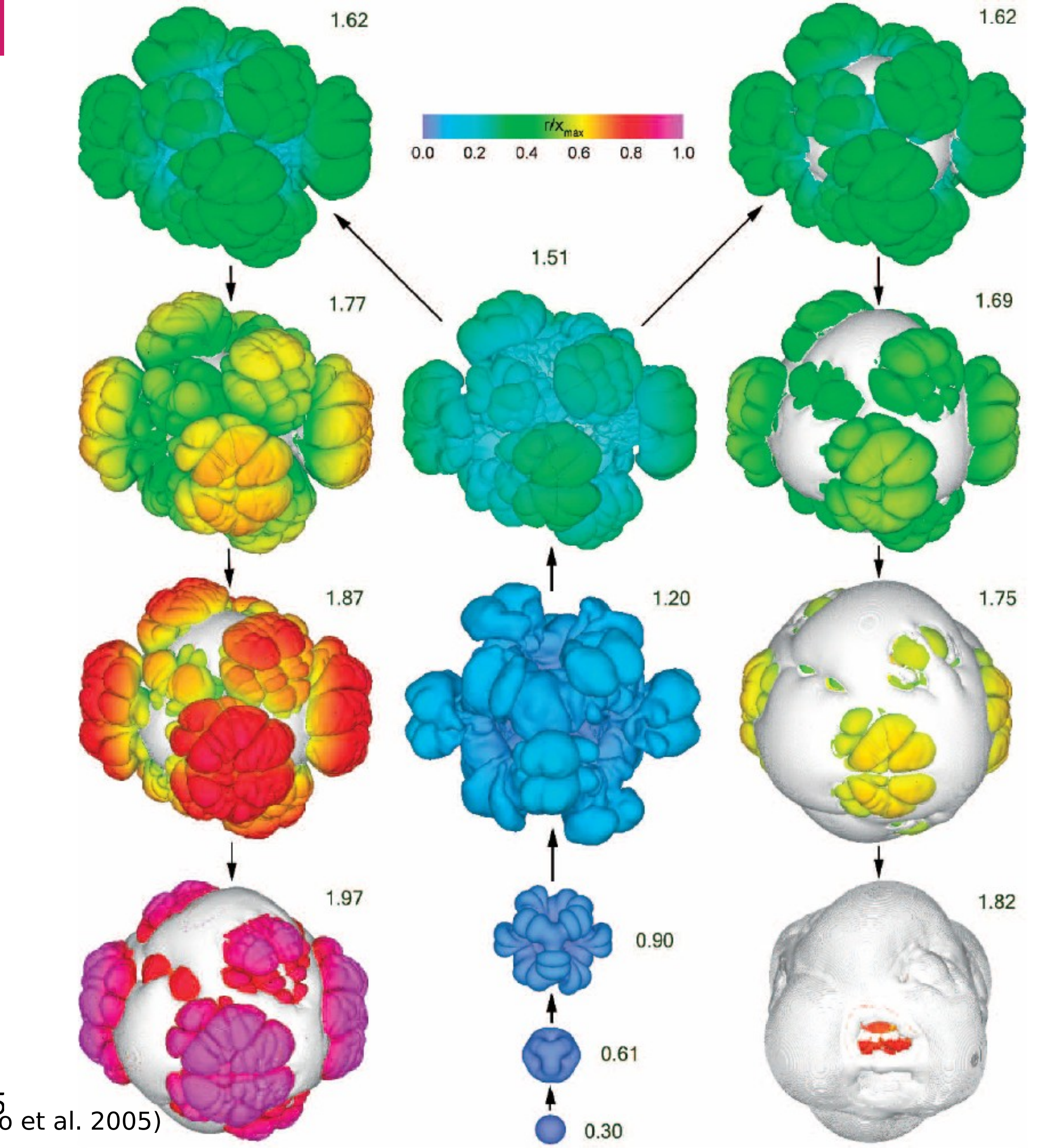
SN 1994D (High-Z SN Search team)

Explosion Requirements

- Flame must accelerate to ~ 1/3 c_s
- Must produce intermediate mass elements (Si, S, Ar, Ca).
- Produces ~ 0.6 $M_\odot$ ^{56}Ni.
- How does the flame accelerate?
  - Flame instabilities (Landau-Darrieus, Rayleigh-Taylor)
  - Interaction with turbulence?
  - Increase surface area ⇒ increase flame speed.

Transition to Detonation

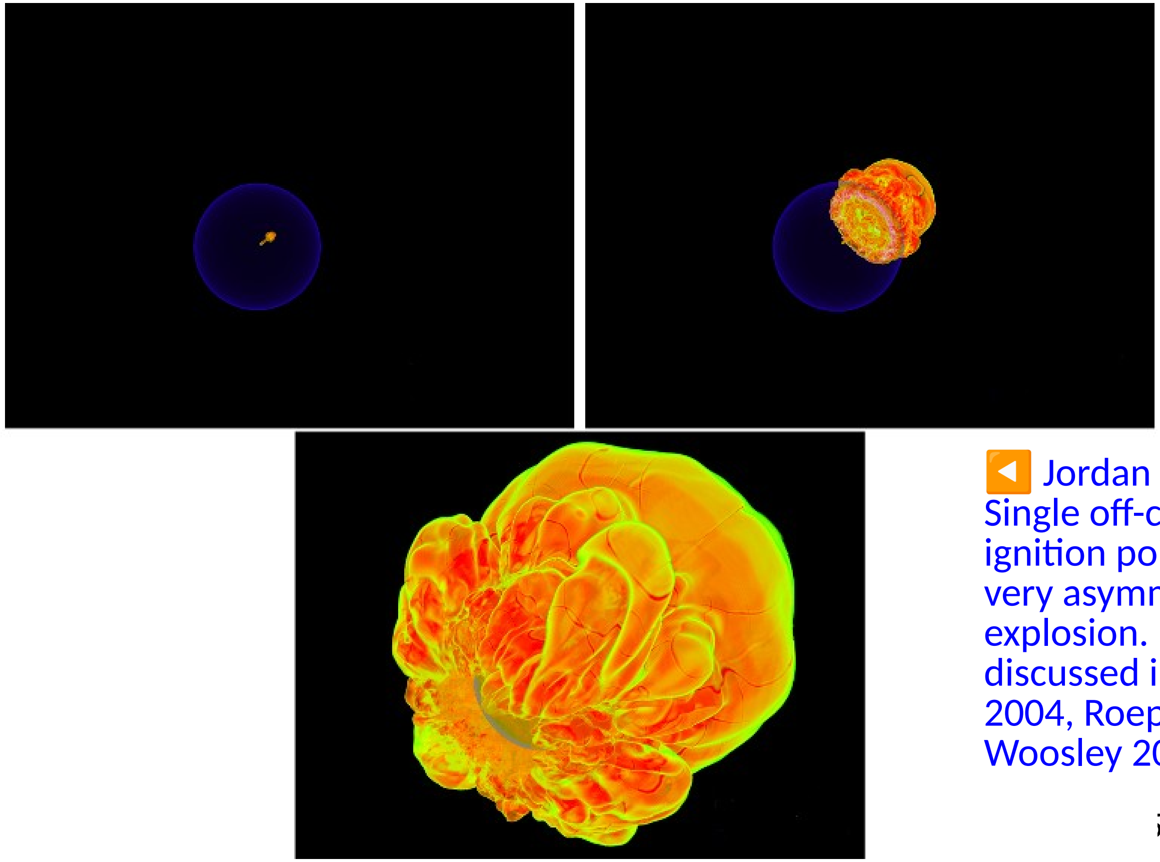
- Pure deflagration models leave behind unburned C/O near the center
- Perhaps at some point, we transition to detonation!
- How this transition actually happens (and even whether it is possible at all) is still unknown



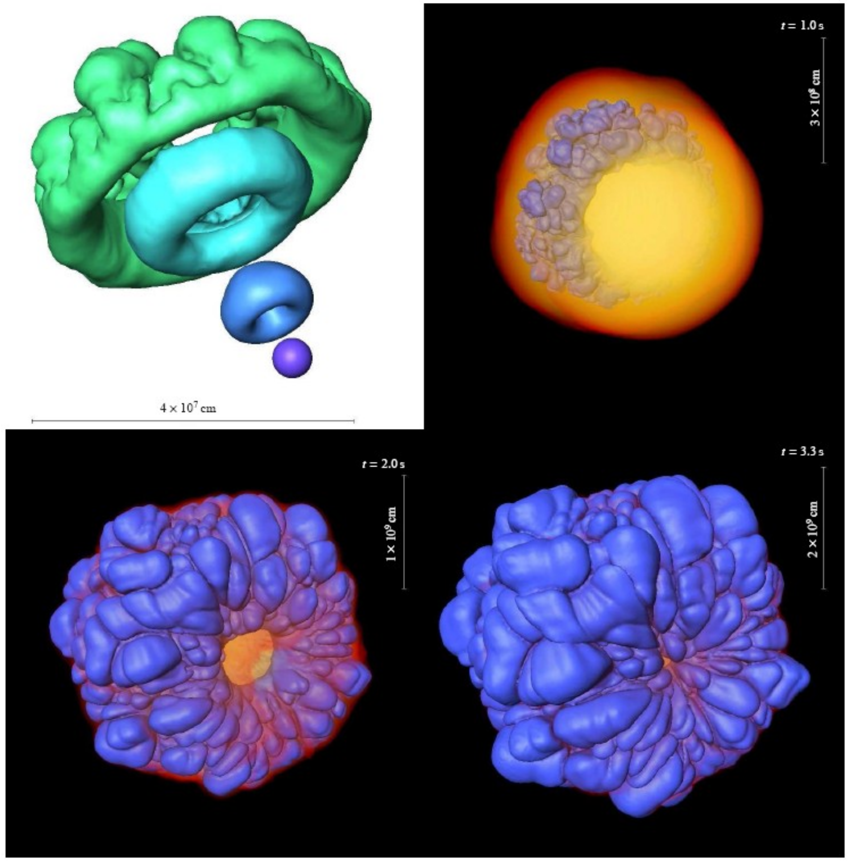
(Gamezo et al. 2005)

Computational Challenges

- We cannot simultaneously resolve the star and the thin flame
- Flame and sub-grid models are used



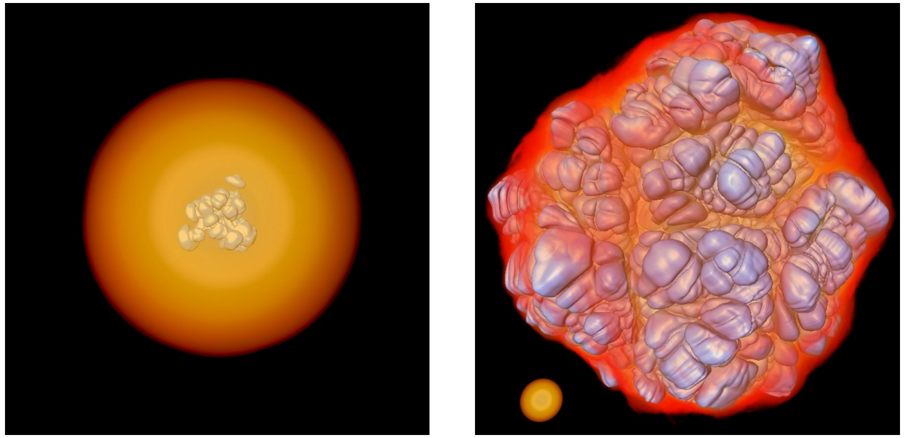
◀ Jordan et al. 2007: Single off-centered ignition point leads to very asymmetric explosion. Also discussed in Plewa et al. 2004, Roepke and Woosley 2006.



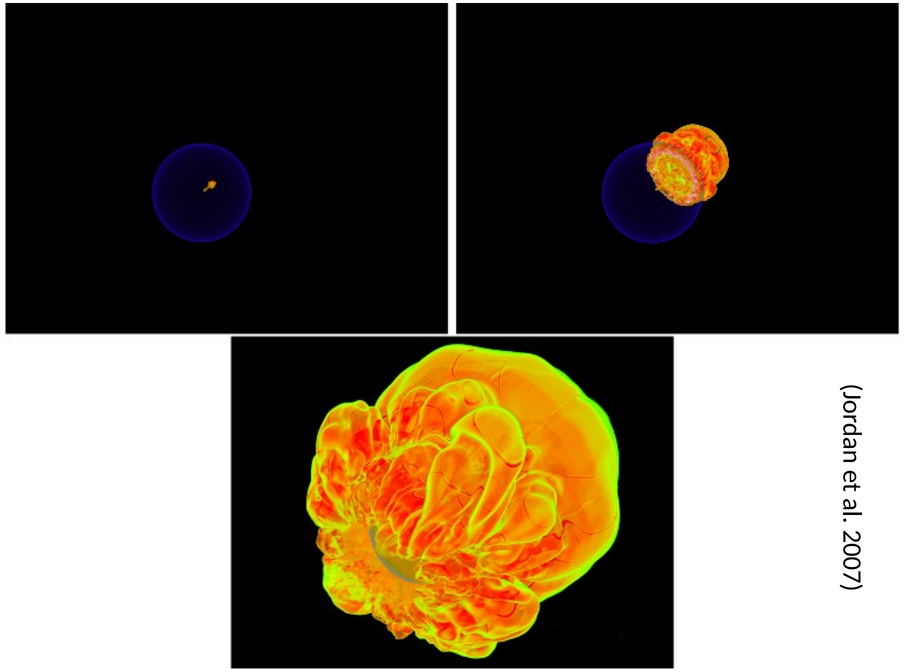
▲ Roepke and Woosley tested this in 3-d and found that this mechanism was not robust.

SNe Ia Ignition

▼ Roepke and Hillebrandt: ignition seeds in many points distributed around the center.



(Roepke and Hillebrandt 2005)



(Jordan et al. 2007)

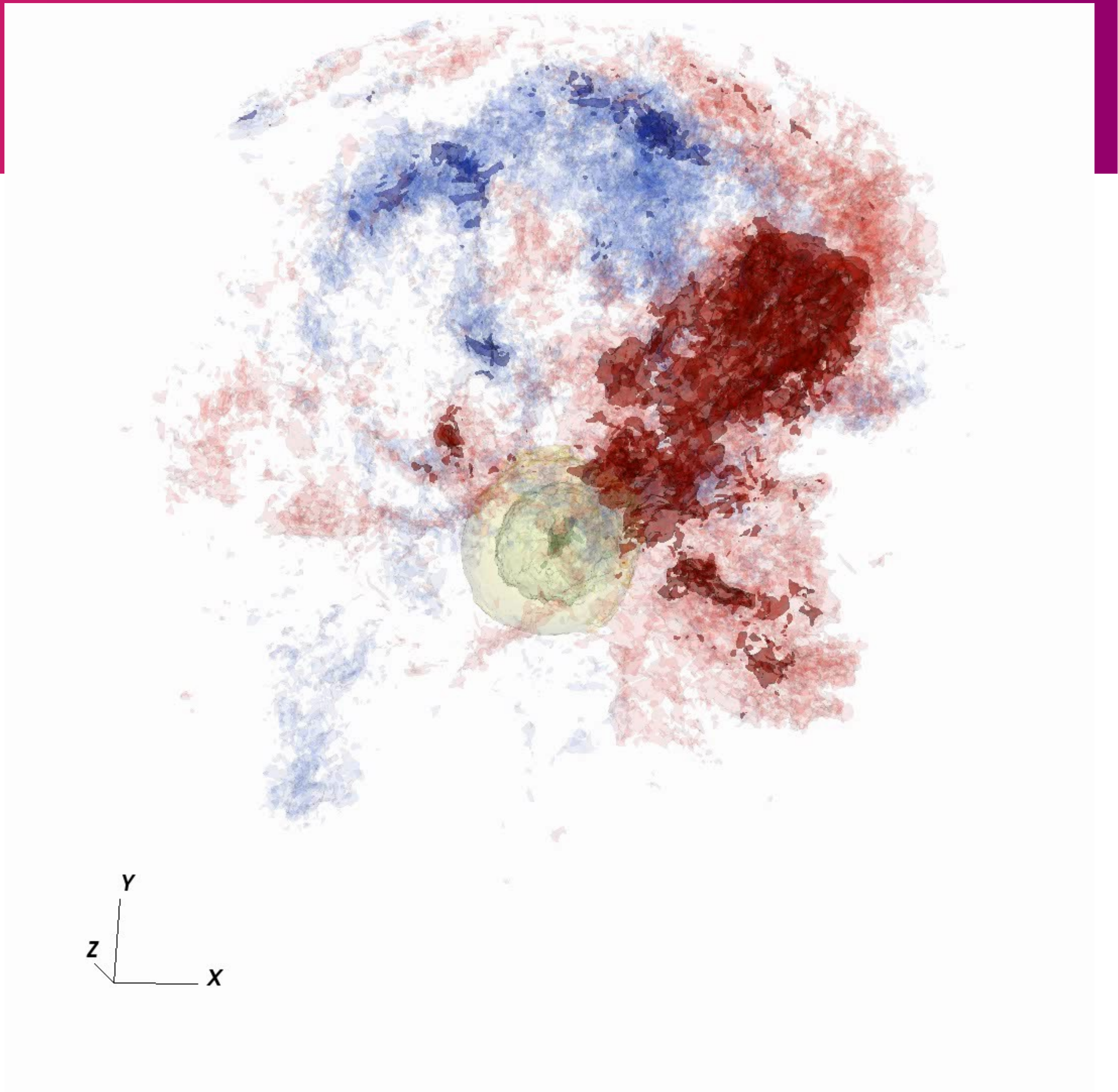
◀ Jordan et al. 2007: Single off-centered ignition point leads to very asymmetric explosion. Also discussed in Plewa et al. 2004, Roepke and Woosley 2006.

- Explosion outcome very sensitive to spatial and temporal distribution of initial flames (ignition points)
  - Single point on/off-center vs. multi-point explored by various groups
- Majority of explosion calculations begin with no initial velocity field

… what does nature do?

Dipole Convection

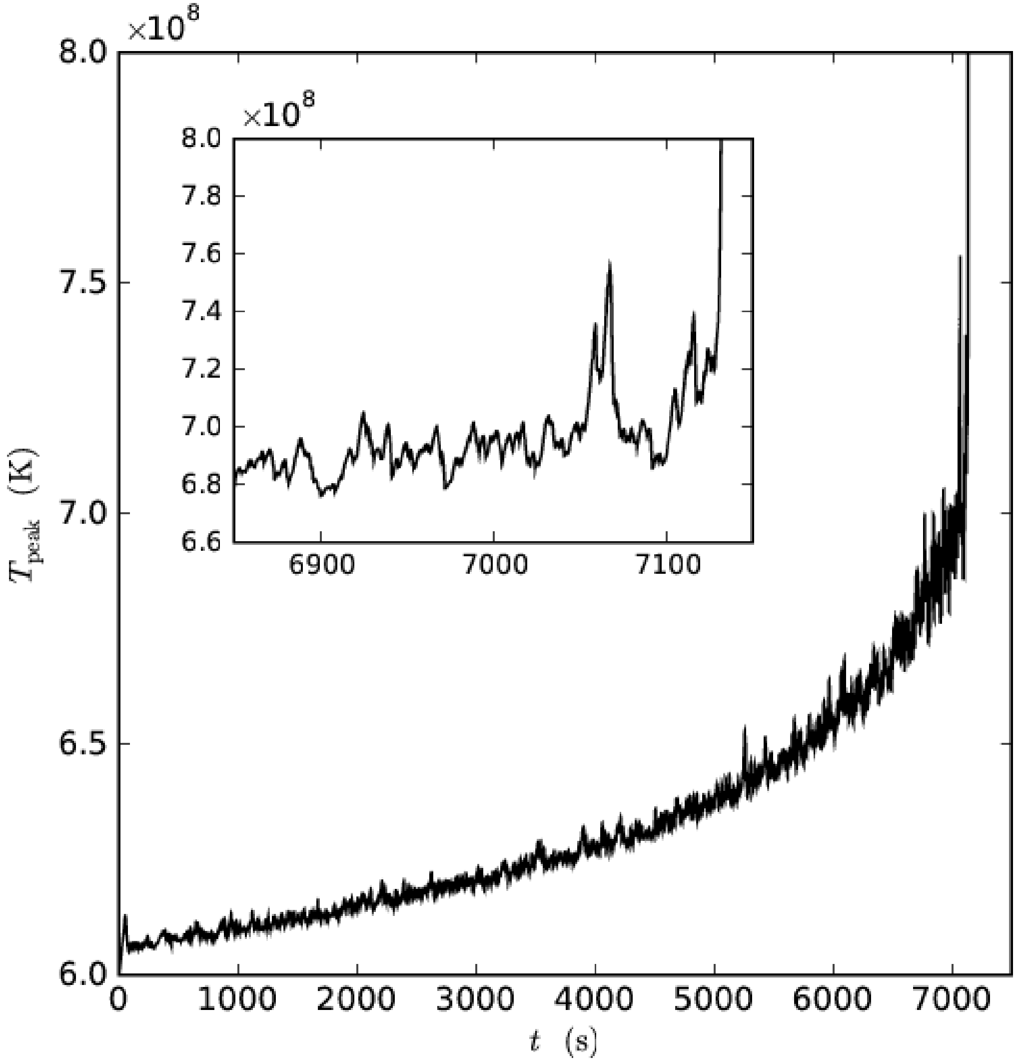
- Dipole feature seen in previous calculations better described as a jet
  - Asymmetry in radial velocity field
- Direction changes rapidly



Radial velocity field (red = outflow; blue = inflow) in an 1152^3 non-rotating WD simulation.

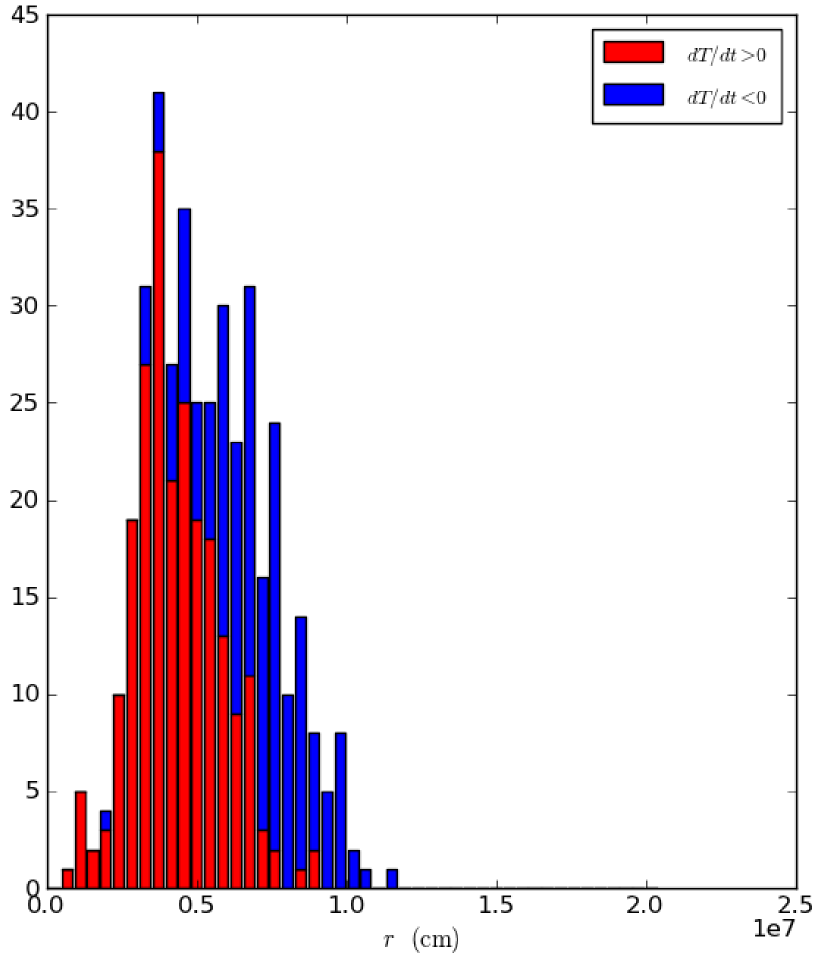
Nonlinear Runaway

- Temperature increase nonlinear
  - Ignition occurs as T crosses 8 x 10^8 K
  - “Failed” hotspots seen toward the end.



Ignition Radius Likelihood

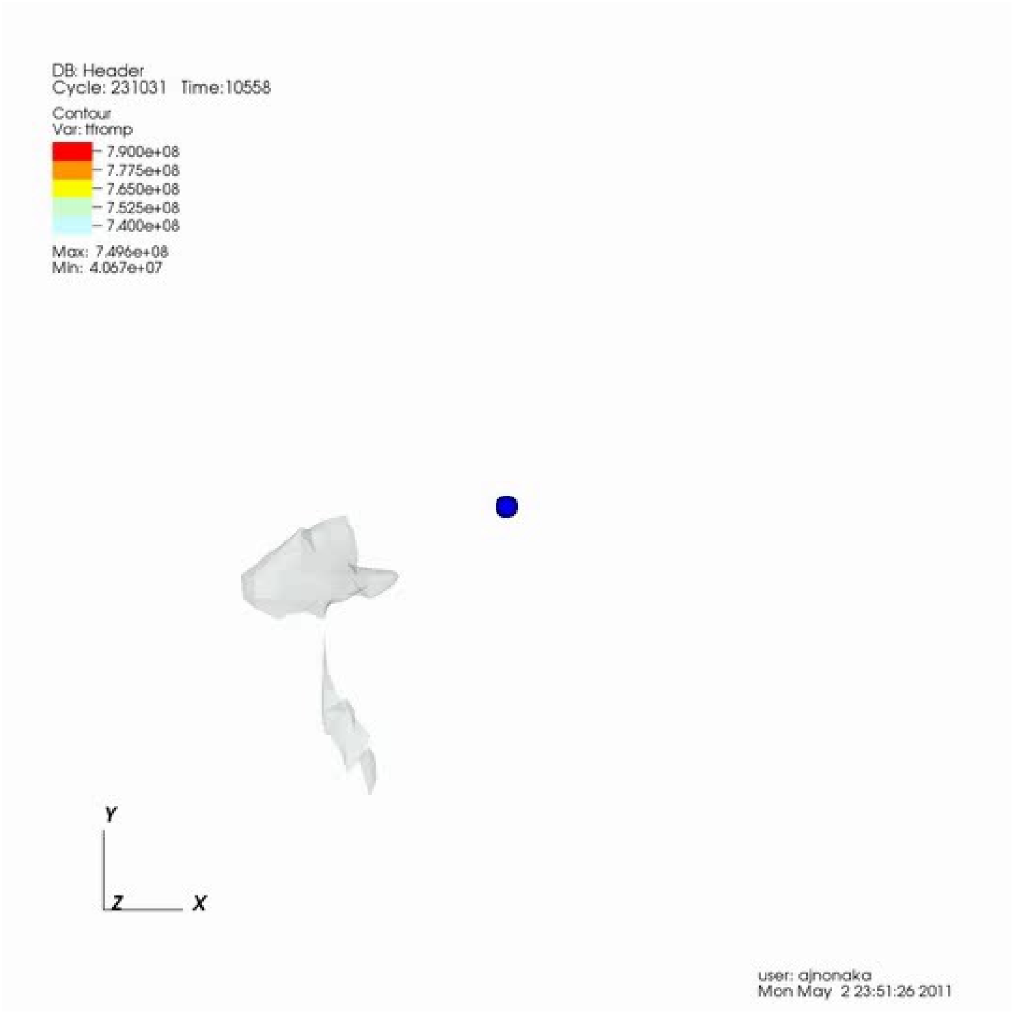
- Distribution of likely ignition locations
  - Average hotspot radius over 1 s intervals
  - Consider final 200 s of evolution
- Vast majority of hotspots are moving outward from the center
- Off-center ignition likely



► Histogram of likely ignition radii from 576^3 non-rotating model. Hotspot radii are averaged into 1 s intervals and colored by sign of temperature change

Multiple Ignition?

- Disable burning in a hot spot once it ignites to allow further evolution
- Second hot spot is not present over a short timescale
- Single-point, off-center ignition most likely.



Matching Observables

- Today it is possible to take an explosion and do radiation transfer to compare with lightcurves and spectra
- e.g. Roepke et al. 2007

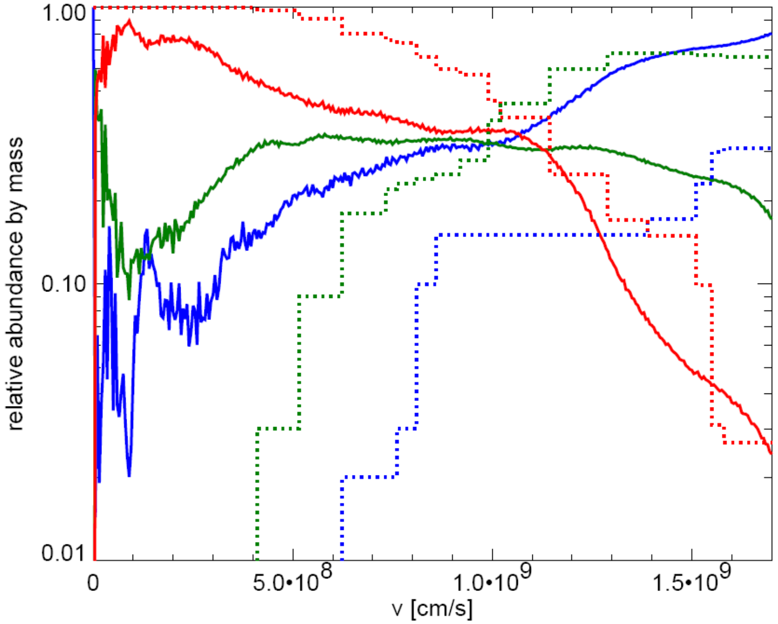


FIG. 4.— Spherically averaged composition resulting from the hydrodynamical explosion simulation (solid lines) compared to the findings of the abundance tomography of SN 2002bo (dotted lines). Iron group element abundances are shown in red, intermediate mass elements in green and unburned material in blue.

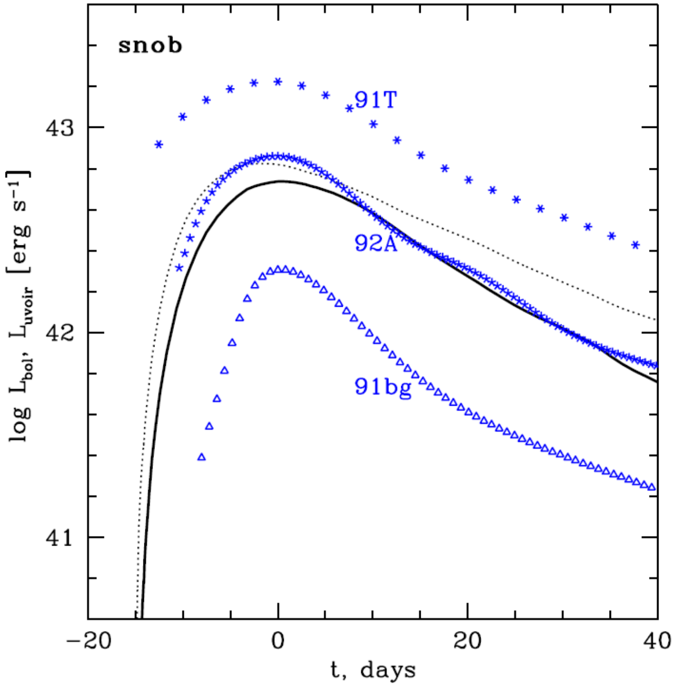


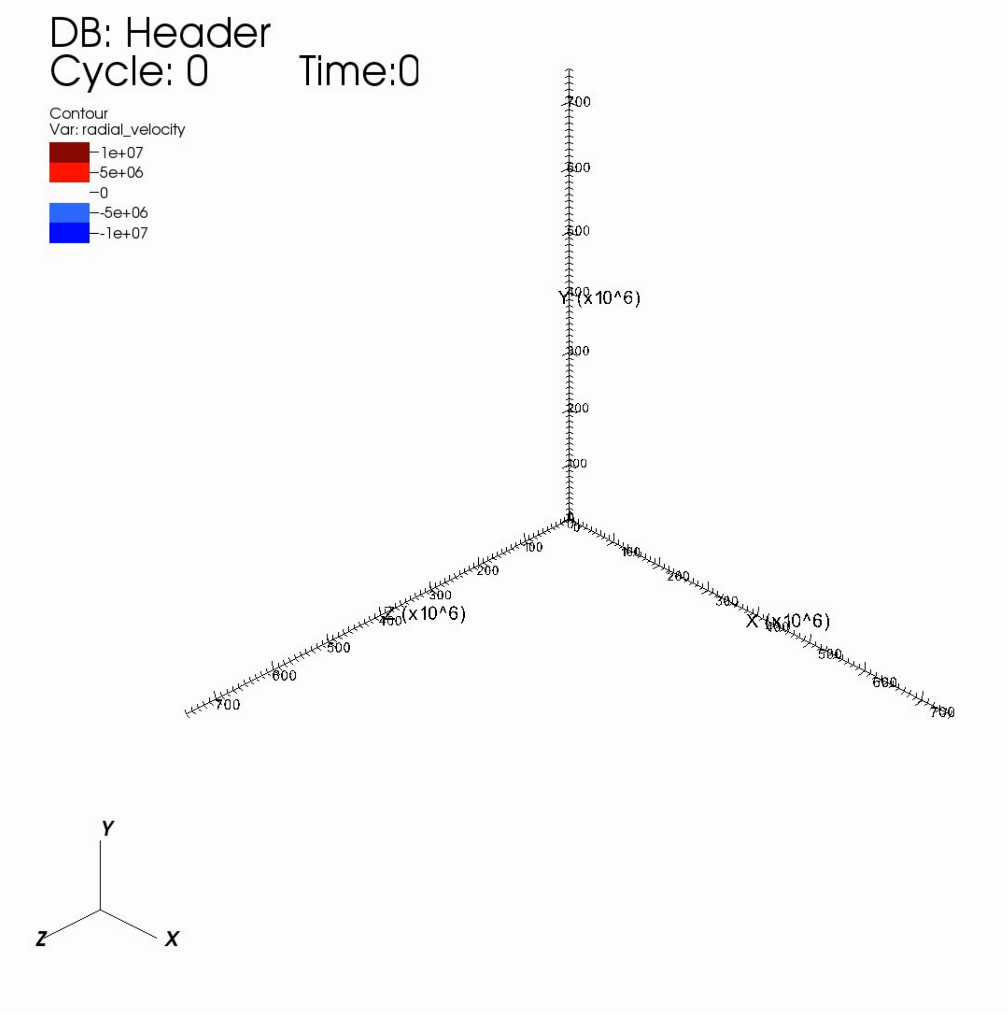
FIG. 5.— Bolometric light curve derived for our model (black curves; solid is the "UVOIR-bolometric" light curve and the complete bolometric light curve is dotted.) The blue dotted curves correspond to observed bolometric light curves (Stritzinger et al. 2006).

Double Detonation SN Ia Models

- Basic idea:
  - Burning begins in an accreted helium layer on the surface of a low(er) mass white dwarf
  - Detonation
- How does the burning transfer to the C/O core?
  - Edge lit: direct propagation of detonation across interface. May require ignition at altitude
  - Double detonation: compression wave converges at core, ignites second detonation at the center of the WD
- Main problem: how much surface He is too much?
- What does the ignition in the He layer look like?

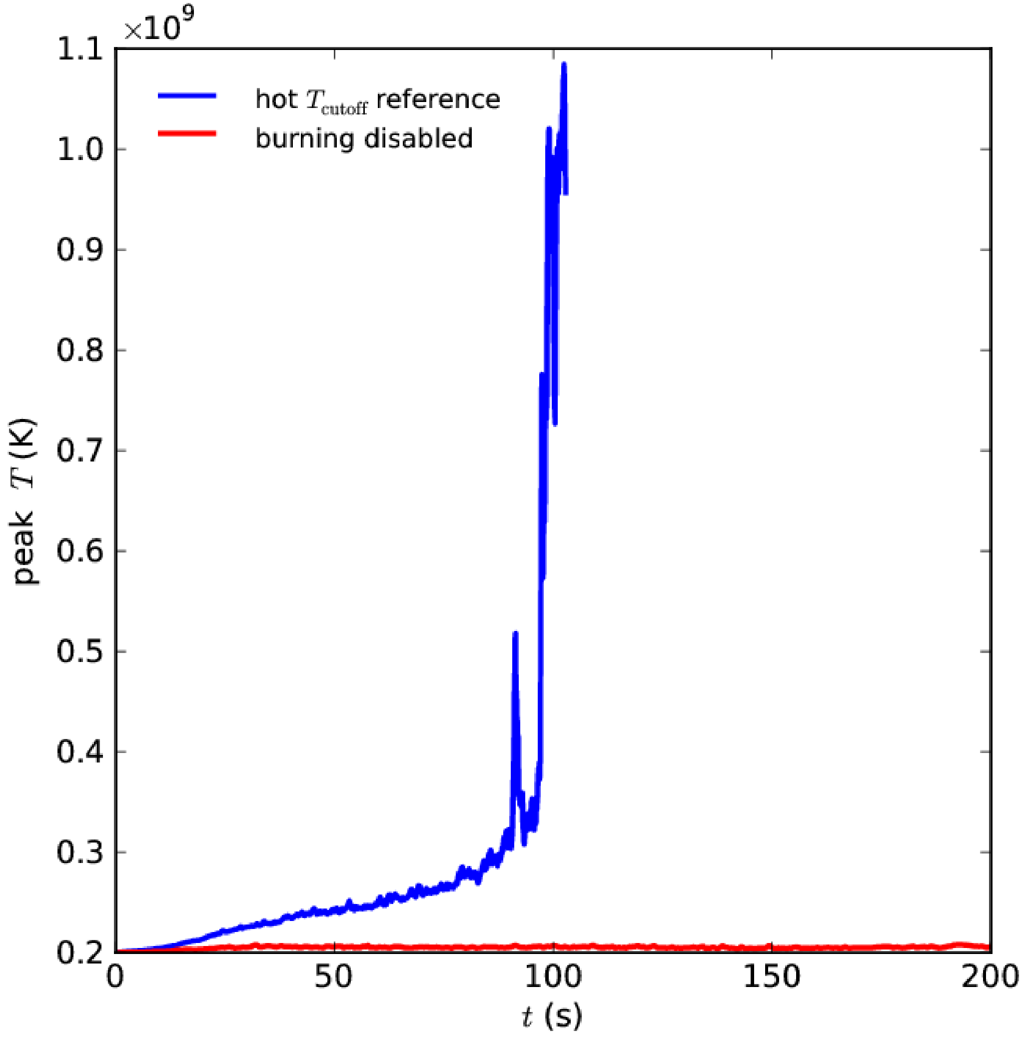
Convective Structure

- Cellular/granular pattern forums
- Length scale seems converged with resolution
- Hot spots rise up and expand
- Potentially multiple hot spots simultaneously

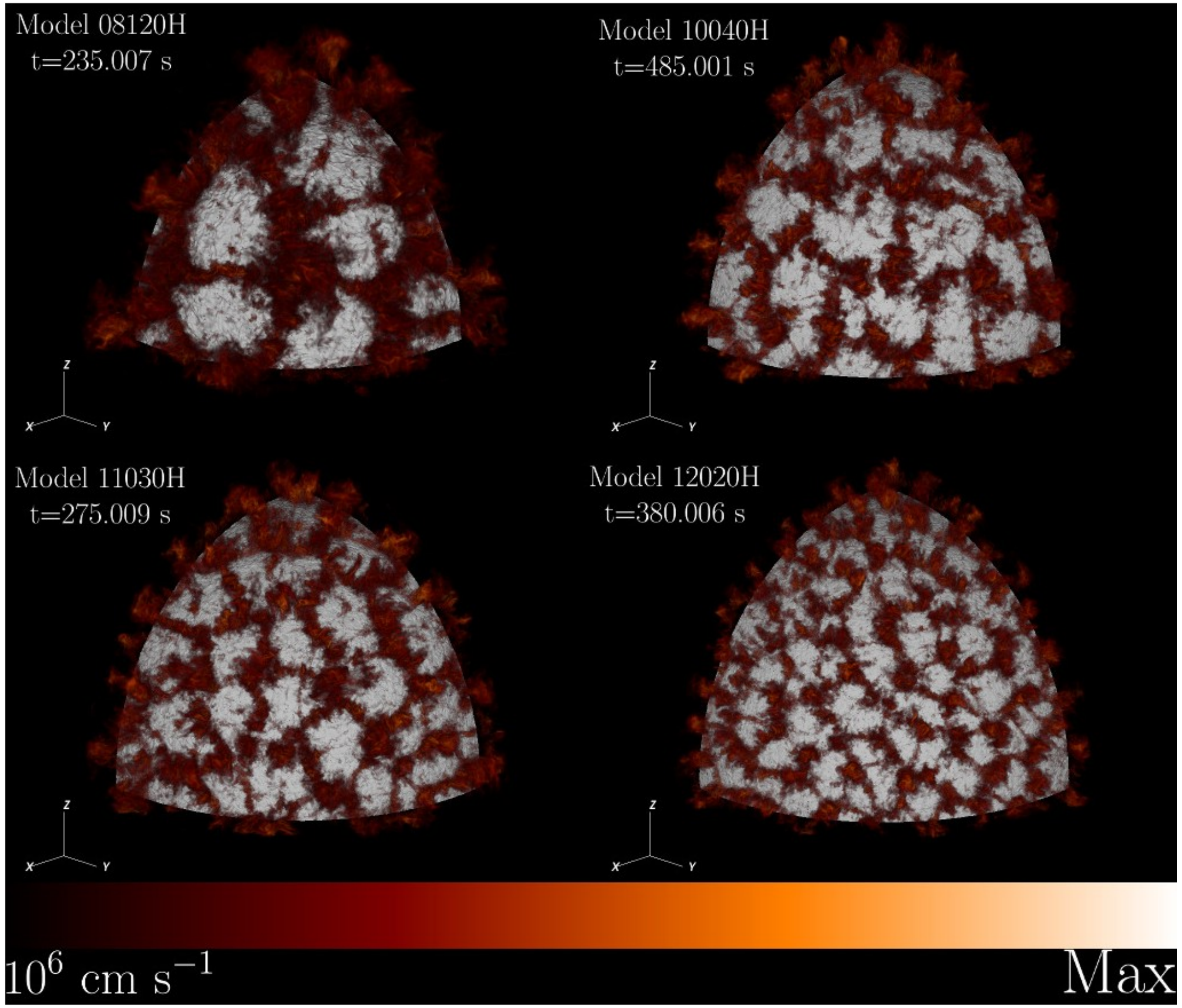


Runaway

- Runaway driven by 3-alpha and $^{12}C(\alpha,\gamma)^{16}O$
  - Next set of calculations will use a bigger network

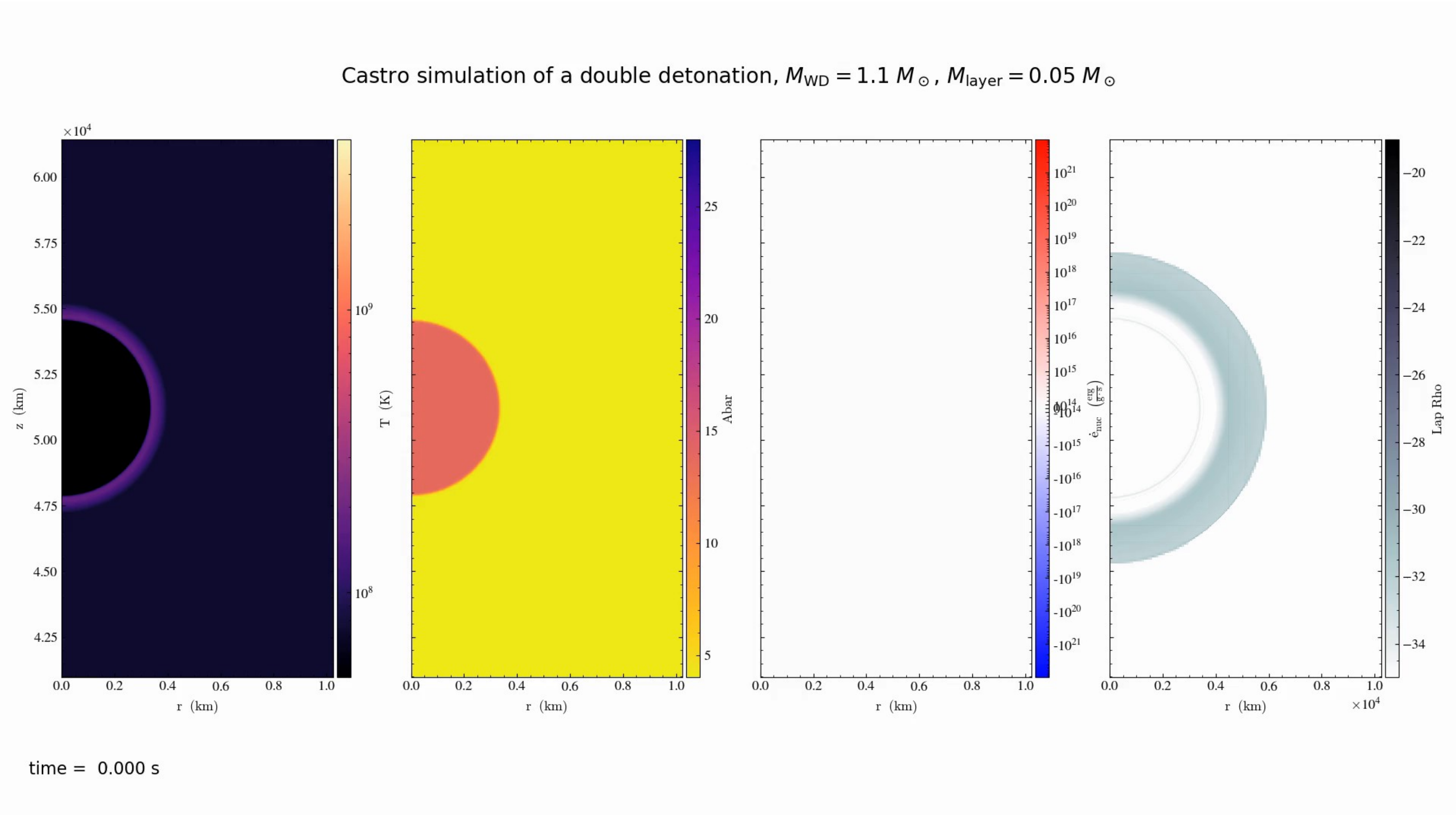


Sub-Chandra He Convection



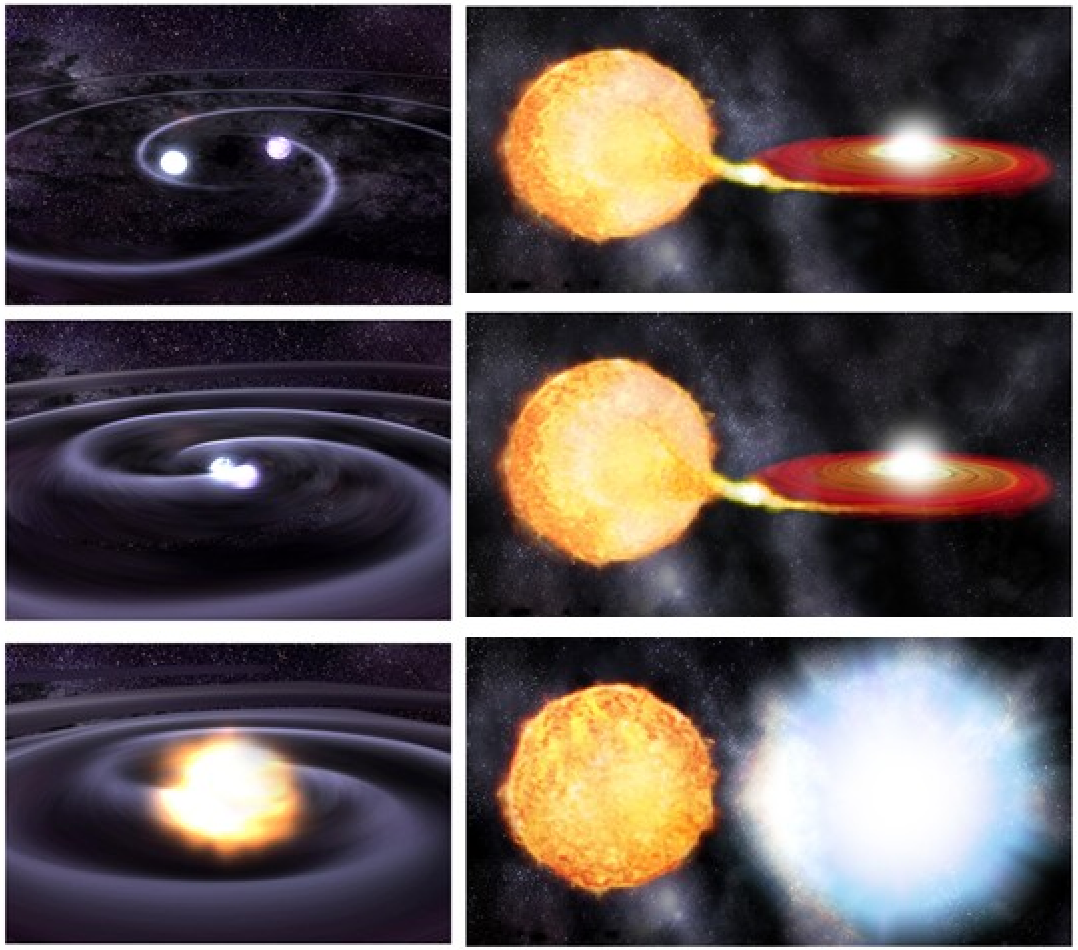
- Suite of different initial models run
  - Some required multiple levels of refinement
- Three types of outcomes
  - Localize runaway on short timescale
  - Nova-like convective burning
  - Quasi-equilibrium (?)

Zingale


Castro simulation of a double detonation, $M_{\rm WD} = 1.1\ M_\odot$, $M_{\rm layer} = 0.05\ M_\odot$

time = 0.000 s

SNe Ia Progenitors



from astrobites.org (http://astrobites.org/2015/04/07/super-bright-supernovae-are-single-degenerate/) via Wikipedia/Discover

WD Mergers

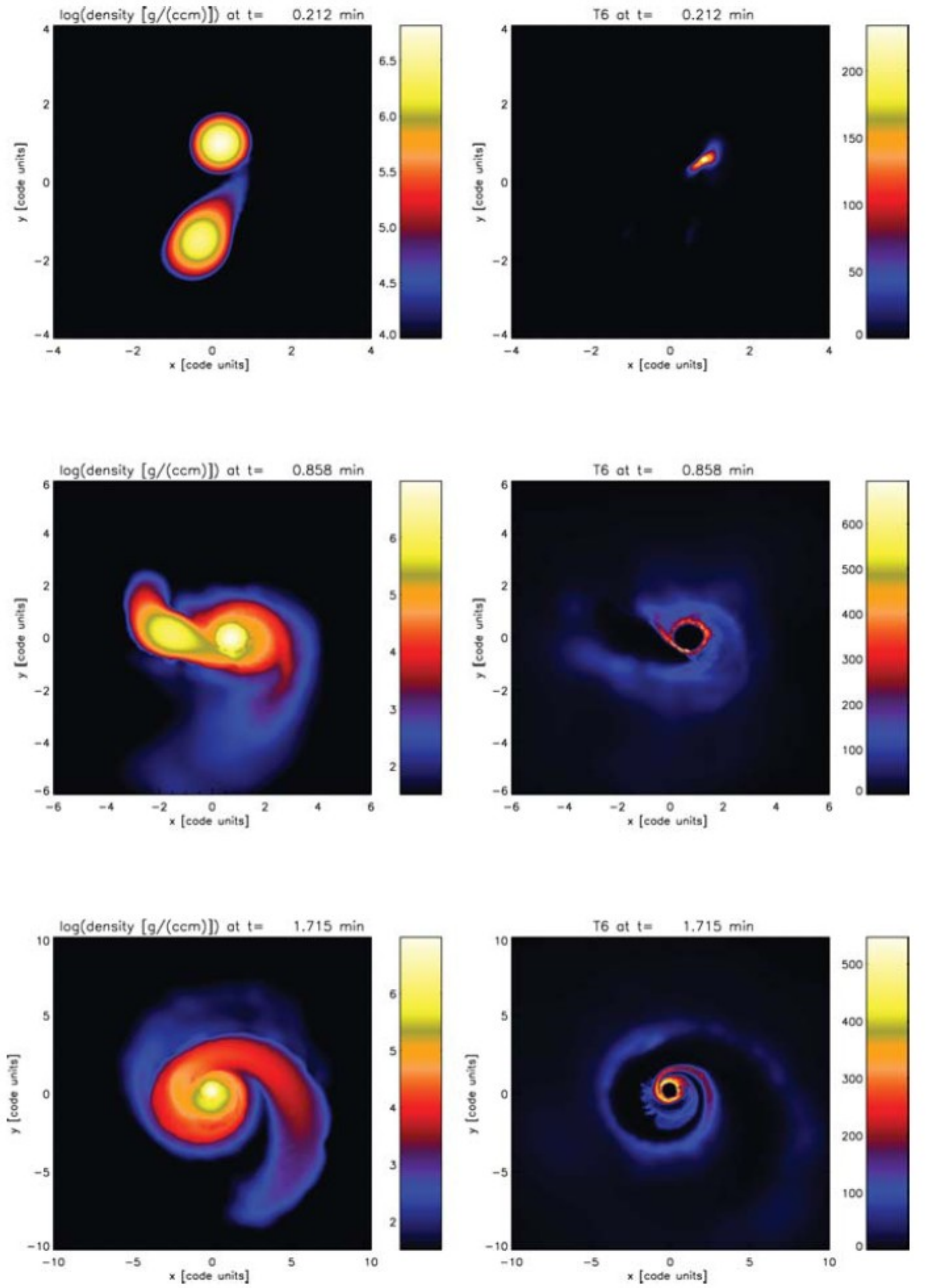
- First question to ask: are there enough WD+WD systems that can merge in a reasonable time frame to account for SNe Ia?
  - Answer appears to be “yes”:
    - Badenes & Maoz (2012) looked at 4000 WDs in SDSS data and model the merger rate (based on radial velocity measurements)
    - Find merger rate of 1.4 x 10^{-13} yr^{-1} $M_{\odot}^{-1}$ (consistent with measured Ia rate), but most likely they are sub-Chandra mergers

WD Mergers

- Next question: if two WDs inspiral, are you guaranteed to get a Ia?
  - Not necessarily
  - Saio & Nomoto (1985): C ignites at edge of C/O WD and burns inward, converting it into O/Ne/Mg WD
    - Accretion induced collapse
  - Models show that the only way to avoid AIC is for the C/O from the disrupted secondary to accrete slowly, so heating doesn't ignite C
- No simulations to date have followed the inspiral, disruption, coalescence, and explosion
  - Special cases exist: head-on collisions, equal mass WDs, …

WD Mergers

- E.g.: Yoon et al.
- Merger remnant leads to slow accretion onto core, can avoid AIC (but hasn't been shown)



(Yoon, Podsiadlowski, and Rosswog, 2007)

Figure 2. Dynamical evolution of the coalescence of a 0.6 $M_\odot$ + 0.9 $M_\odot$ CO white dwarf binary. The panels in the left-hand column show the density in the orbital plane, the panels in the right-hand column the temperature in units of 10^6 K. Lengths are in code units ($= 10^9$ cm).

Violent Mergers

- Maybe the merger can avoid an accretion phase and instead violently merge when the two stars make contact
- Works best for mass ratios near 1
- E.g. Pakmor et al. 2012

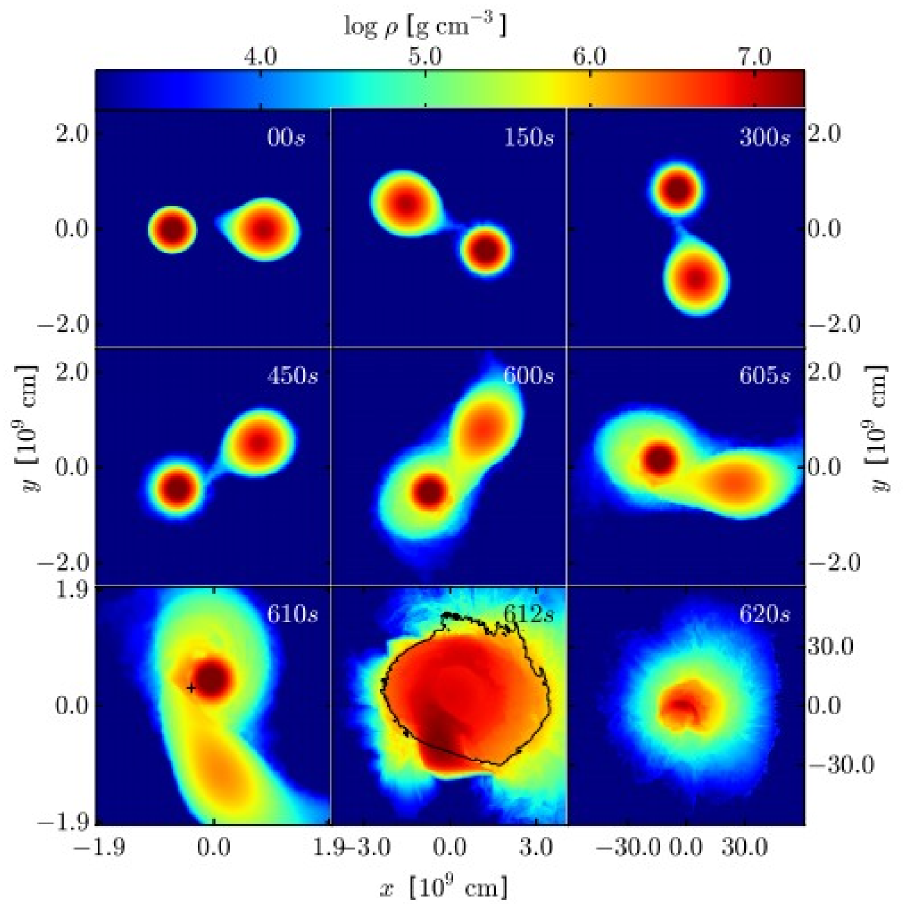
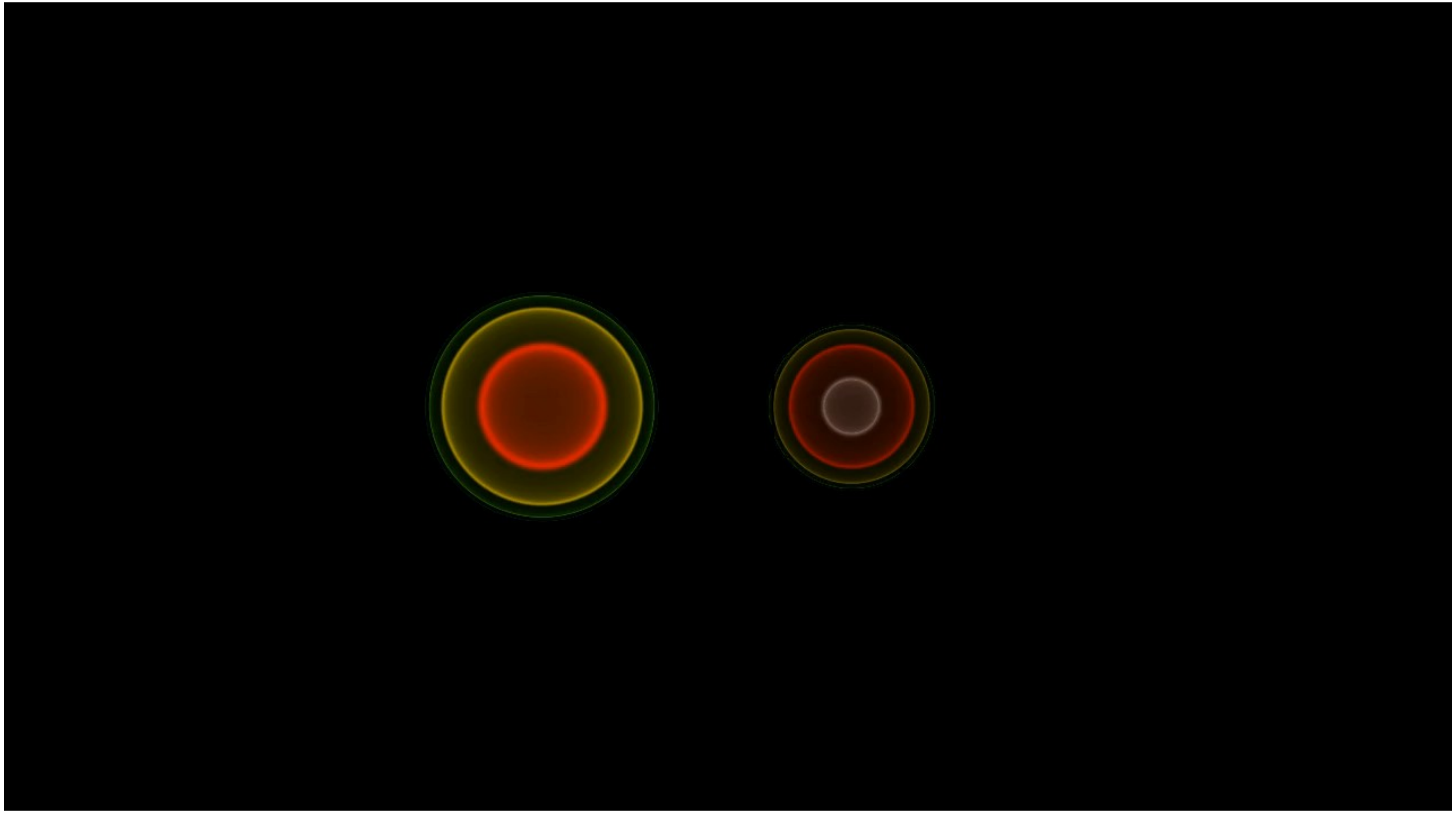


Figure 1. Snapshots of the merger of a 1.1 $M_\odot$ and a 0.9 $M_\odot$ carbon–oxygen white dwarf and the subsequent thermonuclear explosion. At the start of the simulation the binary system has an orbital period of ≈35 s. The black cross indicates the position where the detonation is ignited. The black line shows the position of the detonation front. Color coded is the logarithm of the density. The last two panels have a different color scale ranging from 10^{-4} g cm^{-3} to 10^{6} g cm^{-3} and 10^{4} g cm^{-3}, respectively.

WD mergers



Violent Mergers

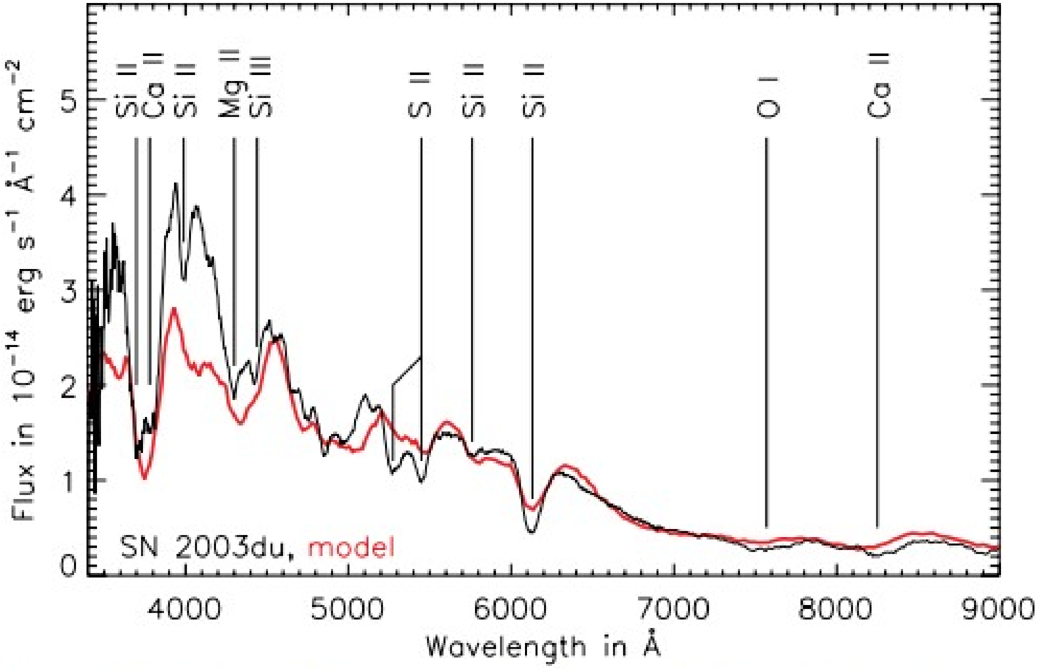


Figure 4. Maximum light spectrum of our model. The red line shows the spectrum of our model one day after maximum light in the *B* band. The black line shows the observed spectrum of SN 2003du (Stanishev et al. 2007) at the same time.

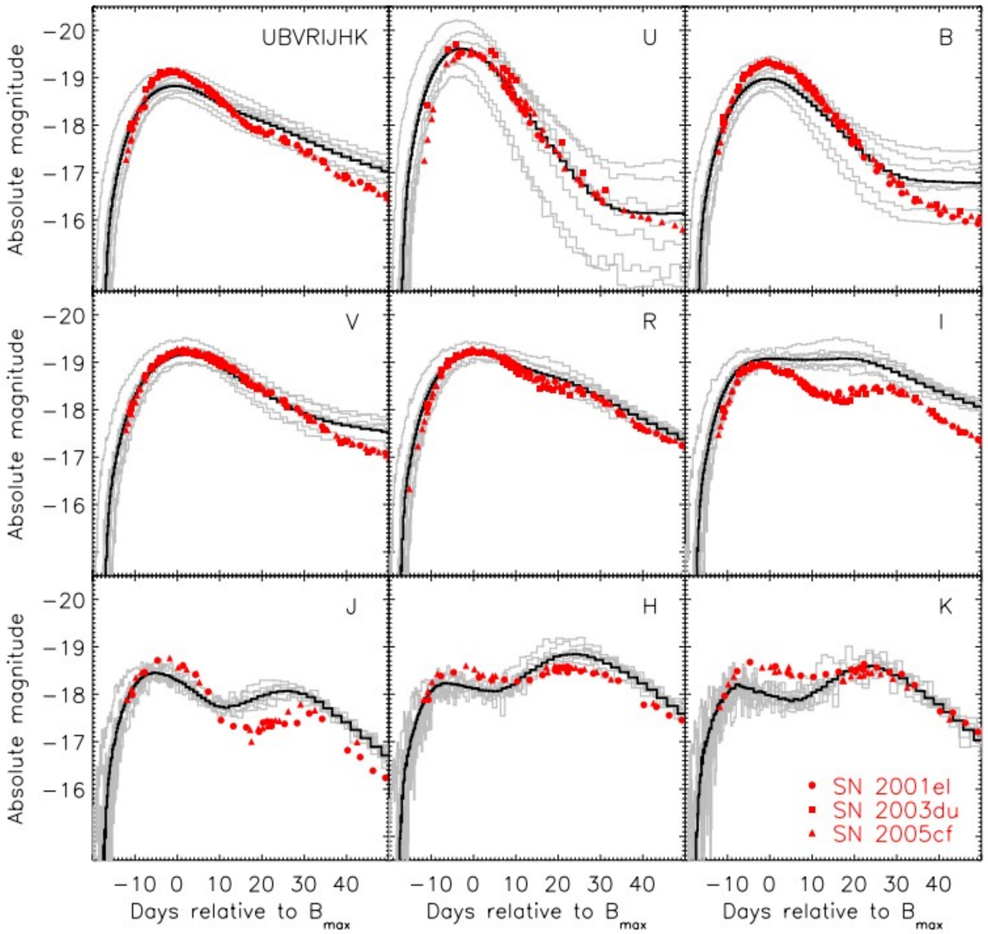
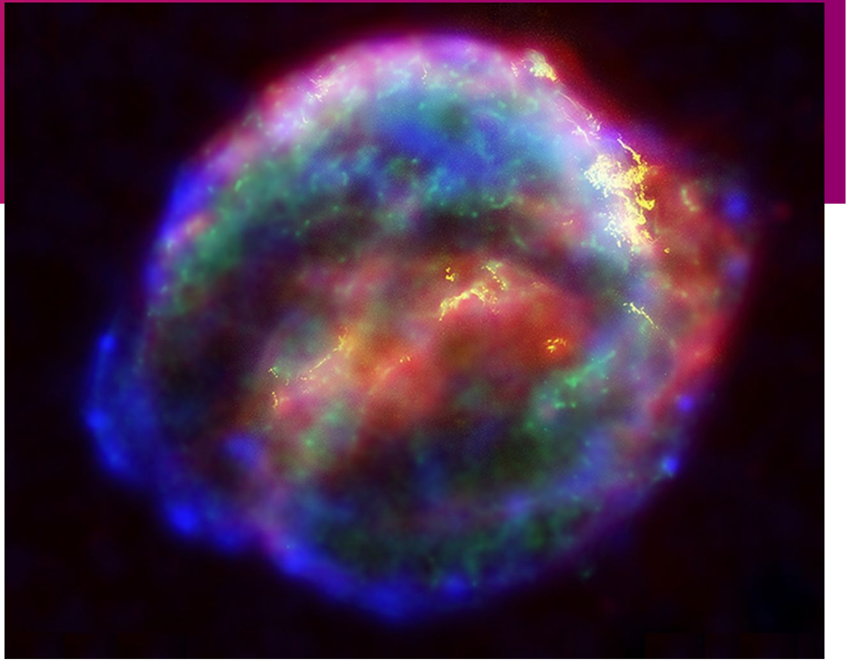


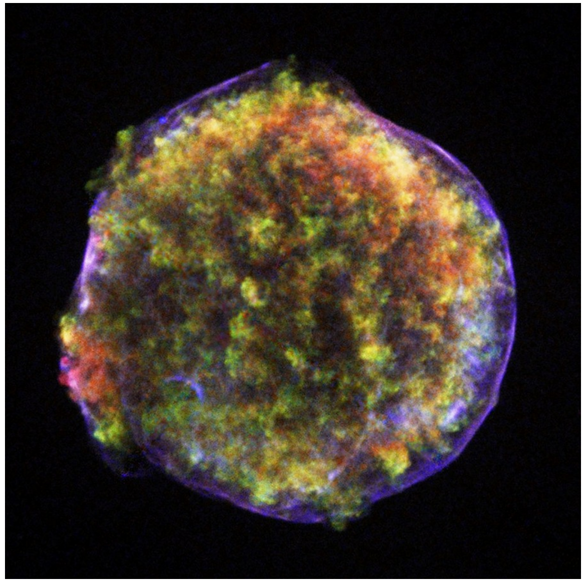
Figure 3. Light curves of our model. The panels from top left to bottom right contain *UBVRIJHK* bolometric and broadband *U,B,V,R,I,J,H,K* light curves. The black line corresponds to the angle average of the model. Gray histograms show light curves along seven different lines-of-sight representative for the scatter caused by different (100) viewing angles including the most extreme light curves. The time is given relative to *B*-band maximum. The red symbols show observational data of three well-observed normal SNe Ia, SN 2001el (Krisciunas et al. 2003), SN 2003du (Stanishev et al. 2007), and SN 2005cf (Pastorello et al. 2007).

What's Left Behind?

- Mostly spherical remnant
- No compact object left behind
- No evidence for a companion star
- Some clumping and high-velocity metal features suggest slight asymmetries in the explosion



SN 1604 (Kepler's supernovae) in our galaxy.



SN 1572 (Tycho's supernovae) in our galaxy.