Thermonuclear Supernovae

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A Possible Supernova

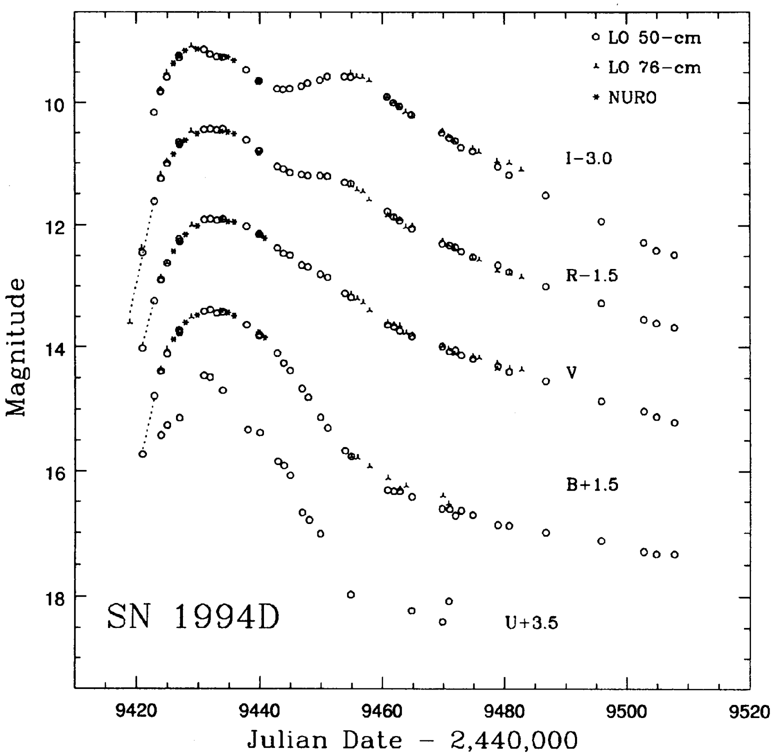
Deflagration Detonation Transition Scenario

Outline

- Observing and characterizing supernovae
  - Supernova types – observational and physical
  - Type Ia supernova consistency and variation
- The makeup of the universe
  - How constituents determine expansion history and how it is observed
  - Supernovae as luminosity distance measures
  - Measuring the dark energy equation of state
- The origin of thermonuclear supernovae
  - White dwarf stars
  - Binary evolution and accreting systems
- The supernova explosion
  - Deflagration
  - Detonation
  - Ejecta abundances
- Systematic dependencies and uncertainties
  - Dependence on metallicity and stellar population age
- Other explosion scenarios

Thermonuclear Supernovae

NASA, ESA, The Hubble Key Project Team, and The High-Z Supernova Search Team



"lightcurve" – brightess vs. time

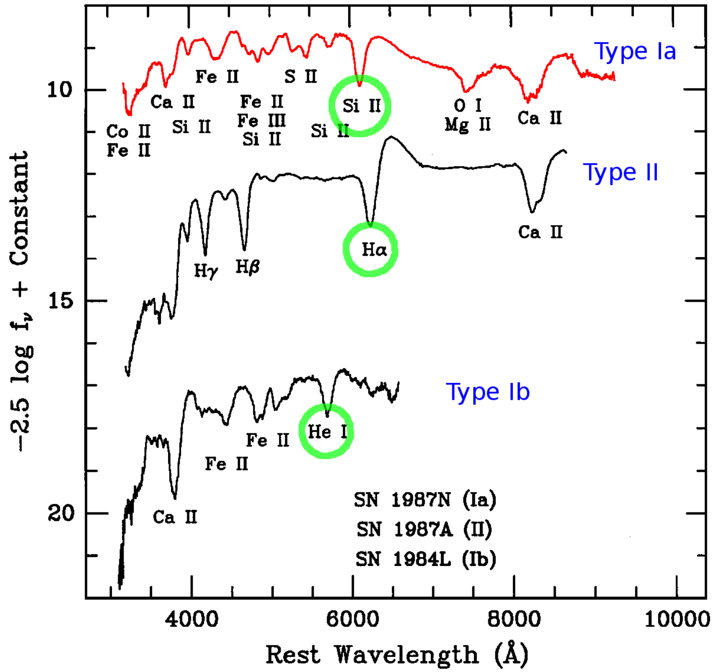
Richmond et al. 1995, AJ, 109, 2121

Type Ia supernova 1994D in the galaxy NGC 4526 – a prototypical "normal" SN Ia

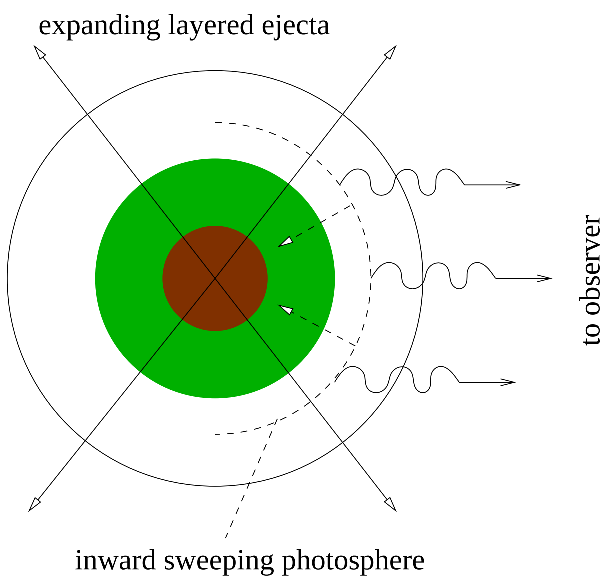
- Brightness comparable to entire galaxy
- Bright for a few weeks with a long, slow decay

Supernova Types

Observational



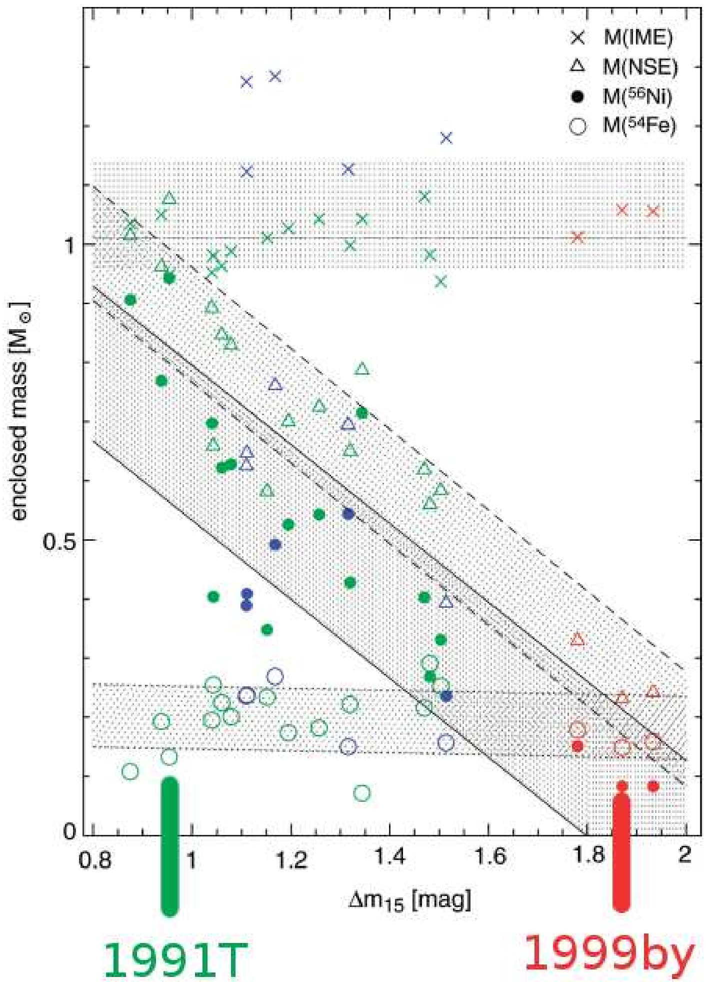
Filippenko 1997, ARA&A, 35, 309

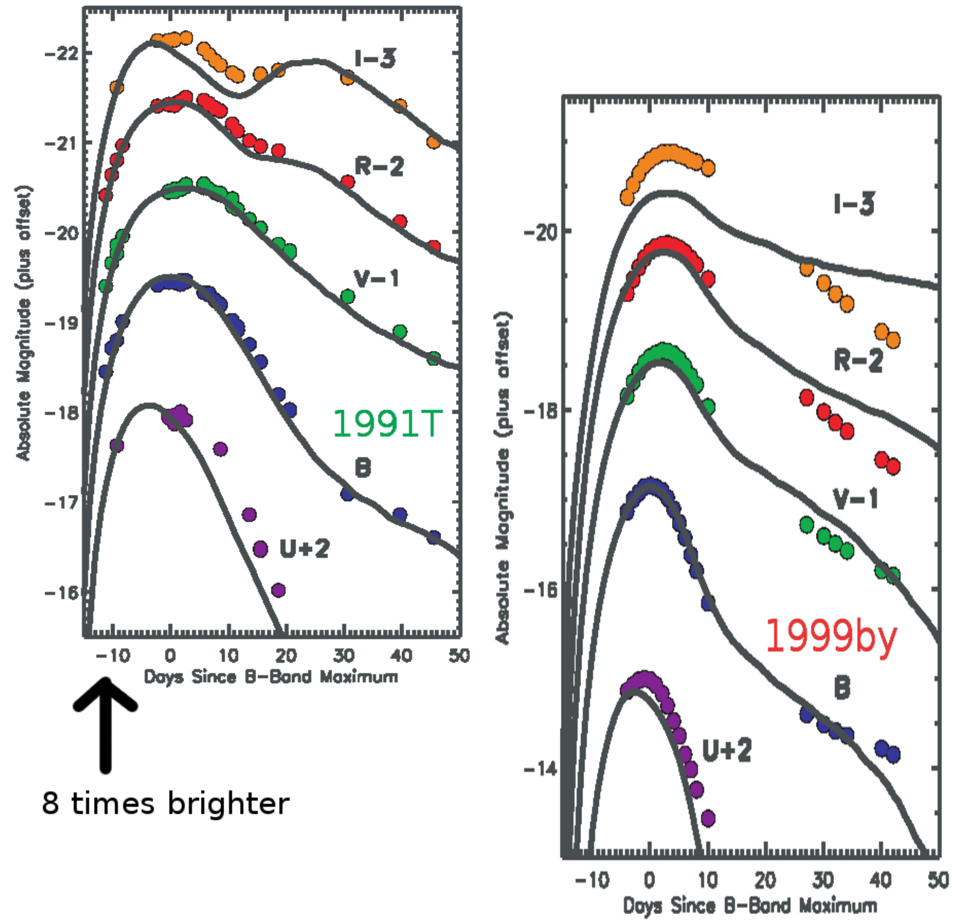


Physical

- Thermonuclear
  - Type Ia (No Hydrogen, Helium; clear Silicon)
  - Arise from remnants of binary stars
  - Material indicates explosive nuclear burning
  - No remnant
- Core collapse
  - Type II, Ib, Ic
  - Arise from death of massive stars
  - Collapse of stellar core to neutron star or black hole

SN Ia consistency and variation





- Same total burned/ejected mass
- Mass of radioactive ^{56}Ni ejected determines brightness and duration

Theoretical cases with various amounts of ^{56}Ni reproduce observations

Woosley et al. 2007, ApJ, 662, 487

Makeup of the Universe

Universe consists of 4 major components

- Radiation (currently negligible fraction of mass-energy) $\rho \propto a^{-4}$
- Matter ($\Omega_{\rm M} \approx 0.27$)
  - Normal ($\Omega_b \approx 0.05$) $\rho \propto a^{-3}$
  - Dark, non-baryonic
- Dark Energy ($\Omega_\Lambda \approx 0.73$) $\rho \propto a^{-3(1+w)}$ $P = w\rho$

Their contribution to the mass-energy density ρ determines the evolution of the scale factor $a = 1/(1+z)$, which measures the relative expansion of the universe.

For observation this is expressed via its effect on the luminosity distance

$$D_L = \frac{c(1+z)}{H_0} \int_0^z \left[\Omega_M (1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}\right]^{-1/2} dz'$$

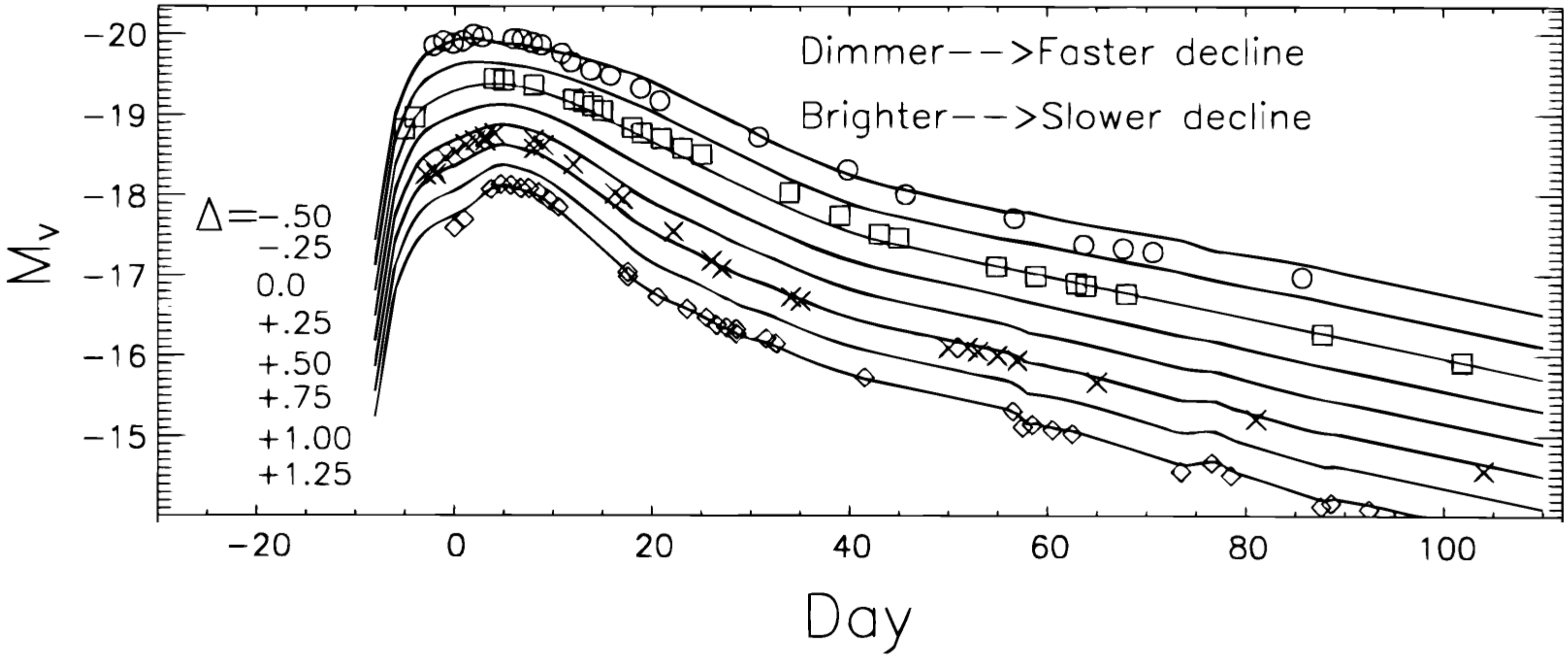
for a flat universe.

Carroll, Press, Turner 1992, ARA&A, 30, 499; Riess et al. 1998, AJ, 116, 1009; Garnavich et al. 1998, ApJ, 509, 74

Given an object of known brightness, L, the luminosity distance can be determined easily from the observed flux, F, on earth via

$$F = \frac{L}{4\pi D_L^2} \ .$$

Standardized Supernovae



Riess et al. 1996, ApJ, 473, 88

Branch normal Type Ia Supernovae show a good correlation between brightness and lightcurve shape (rise and decline rate). Called the Phillips relation.

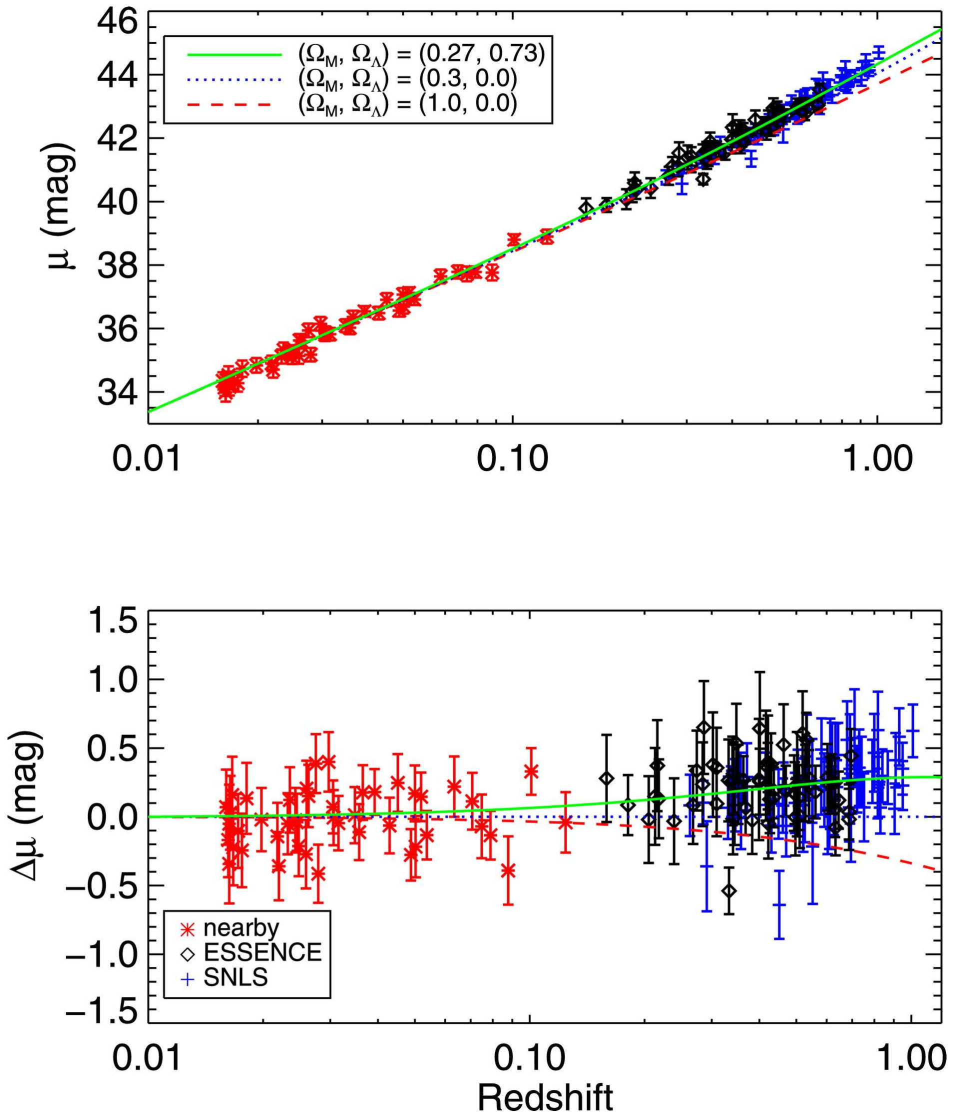
Modeled by constructing an empirical template from many (typically 10-20) nearby supernovae which is then used to infer brightness of distant objects. Current effort continues to improve this calibration sample.

Must also account for things like dust in host galaxy $\rightarrow$ dimming and spectral "reddening". This means spectral characteristics (dependence of brightness on wavelength) is important to determine actual brightness.

Distance-Redshift Measurements

Recent analysis includes data from previous surveys.
Many results of this kind were first published in 1998.

(Riess et al. 1998, AJ, 116, 1009; Perlmutter et al. 1999, ApJ, 517, 565)



Wood-Vasey et al. 2007, ApJ, 666, 694

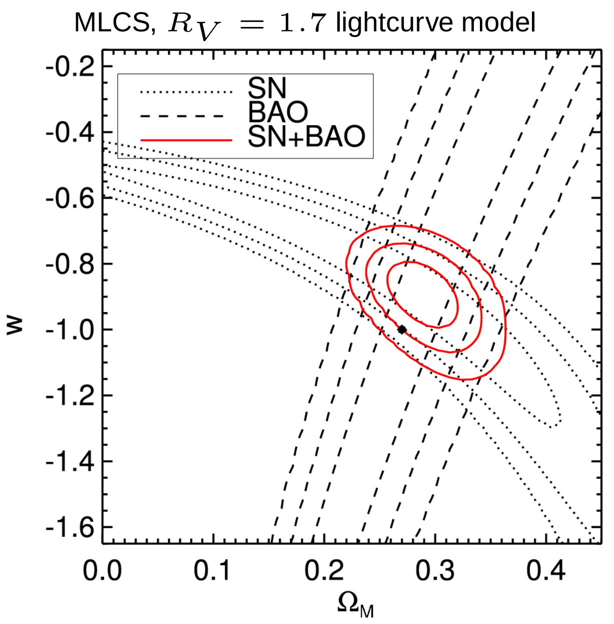
Favored cosmological parameters
$\Omega_M = 0.27, \Omega_\Lambda = 0.73$
This is the best fit assuming $w = -1$ (cosmological constant).

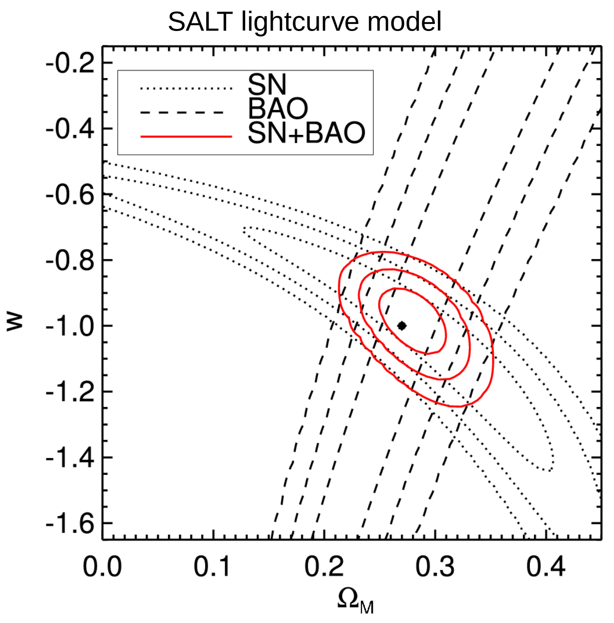
Reference is shown as $(\Omega_M, \Omega_\Lambda) = (0.3, 0.0)$ because other measurements favor $\Omega_M = 0.3$.

larger magnitude = dimmer, so distant supernova are dimmer than if there were no dark energy component.

Constraining w

- Shown: 1, 2 and 3 σ contours constraining w.
- Comparison of two empirical "lightcurve-fitters" (models), MLCS and SALT
- These use different (but overlapping) samples for training and different detailed methods to estimate absolute brightness
- MLCS, the "better" one, is not quite consistent with "concordance" cosmology.
- Appreciable differences in empirical model. Demonstrates deficiencies in the current fully-empirical modelling of the underlying supernova lightcurves.
- In the near future, Theory should be able to improve this modelling by providing a better handle on intrinsic color variations.



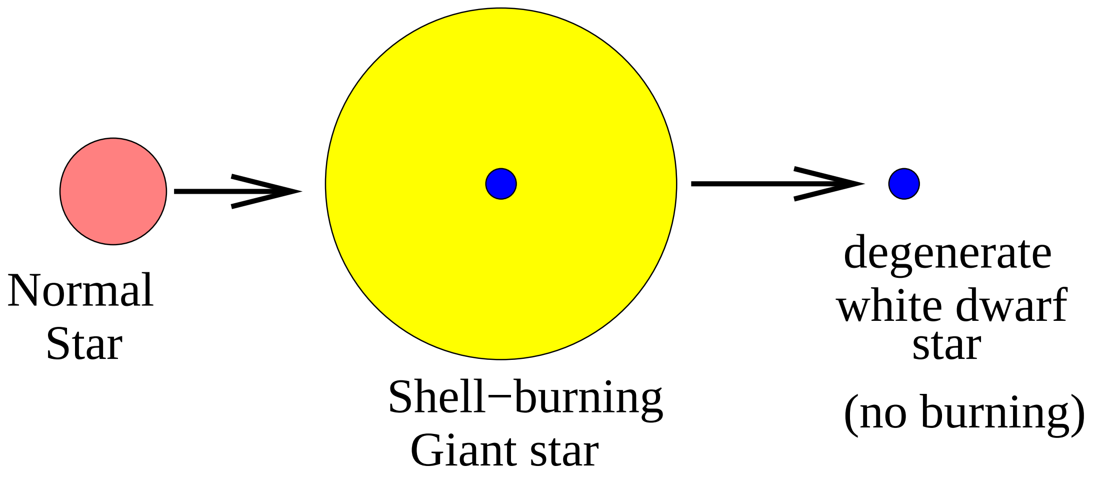


Hicken et al. 2009, ApJ, 700, 1097

The Origin of Nuclear Supernovae

White Dwarf Stars

- Remnant formed by all stars $\lesssim$8-10$M_\odot$
- $\frac{1}{100}$ of solar radius
- Made of carbon and oxygen – fusion products of H and He
- Maximum mass similar to total ejected in SN Ia
- Right products if burned just right



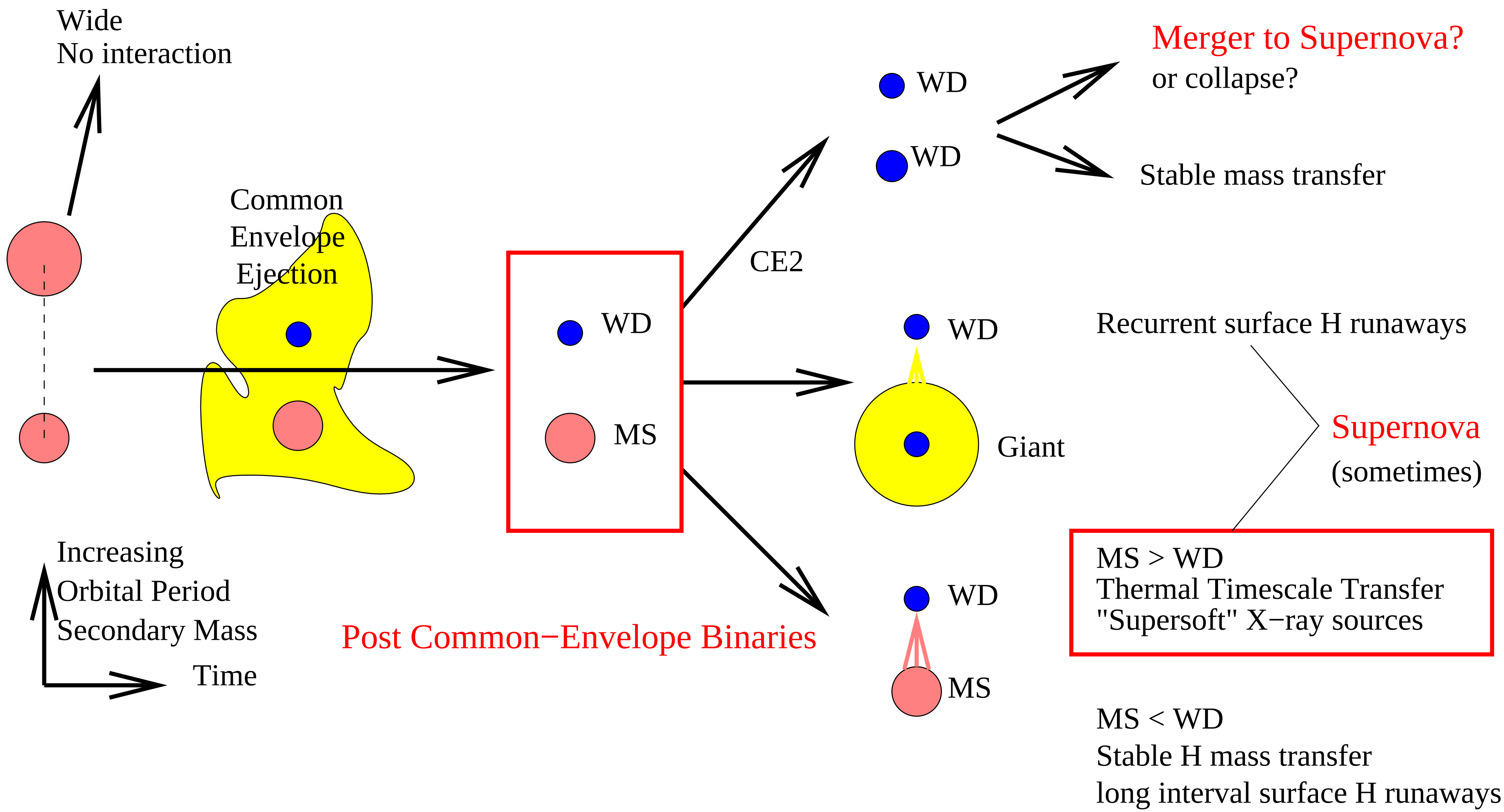
Normal, Giant star: supported by heat (kinetic particle motion)

Degenerate white dwarf: supported by Pauli exclusion

Maximum mass:
Chandrasekhar mass $1.4M_\odot$
central density arbitrarily steep (singular) function of total mass
density/temperature triggers fusion or electron capture

Need to add mass to white dwarf!

Binary Evolution



Main Channel: MS star mass $>$ WD mass – Thermal Timescale Mass Transfer

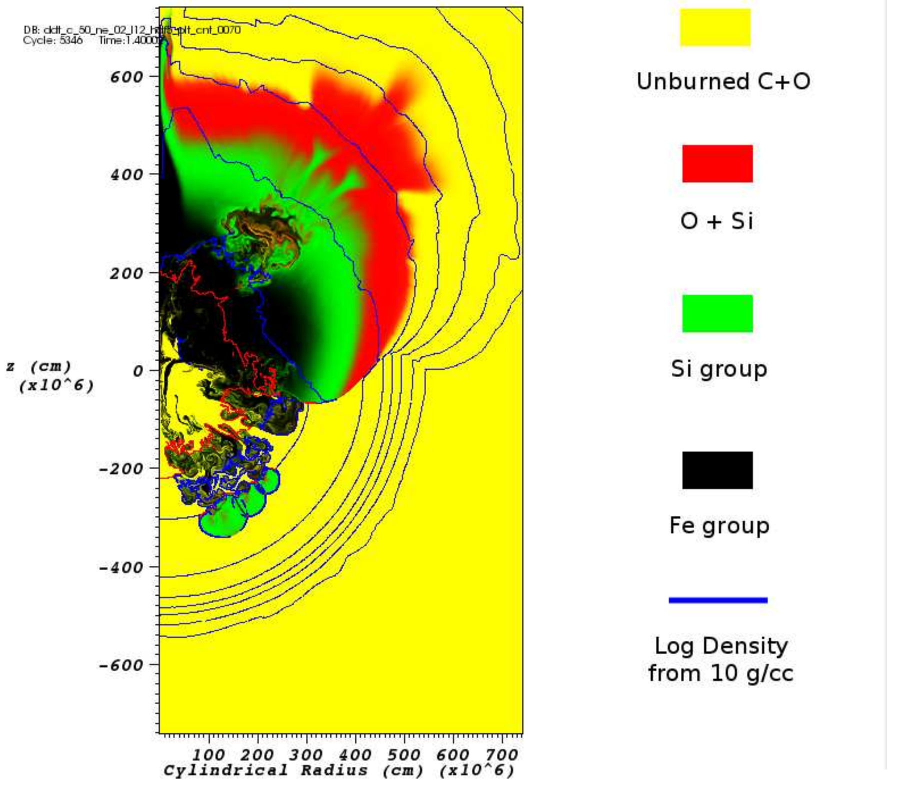
Deflagration Detonation Transition

"DDT" – A (direct) transition to detonation is hypothesized to occur when the flame front reaches densities $\sim 10^7$ g/cc. This is most of the way towards the surface of the star.

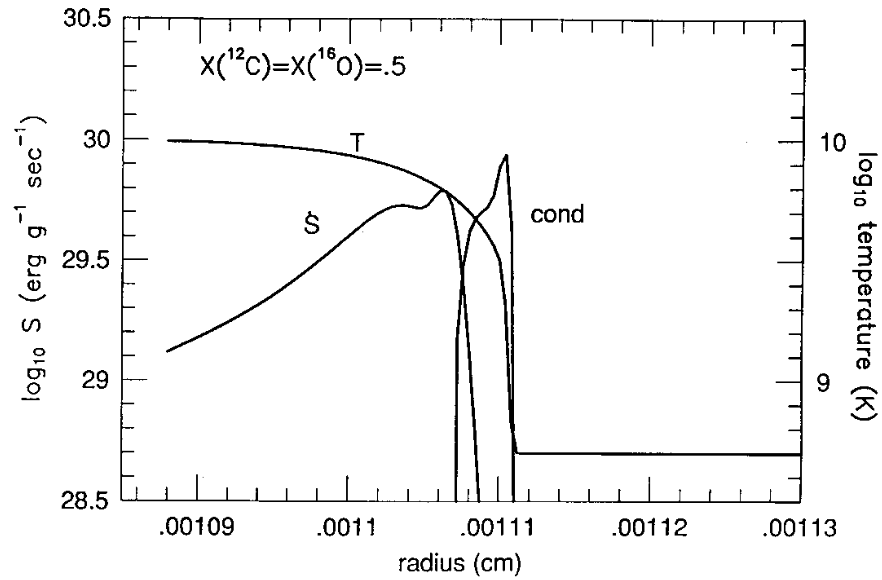
- Allows star to expand so that intermediate elements are formed when detonation sweeps through outer layers.
- Detonation homogenizing layers – but unclear if it does so enough in interior to match observation

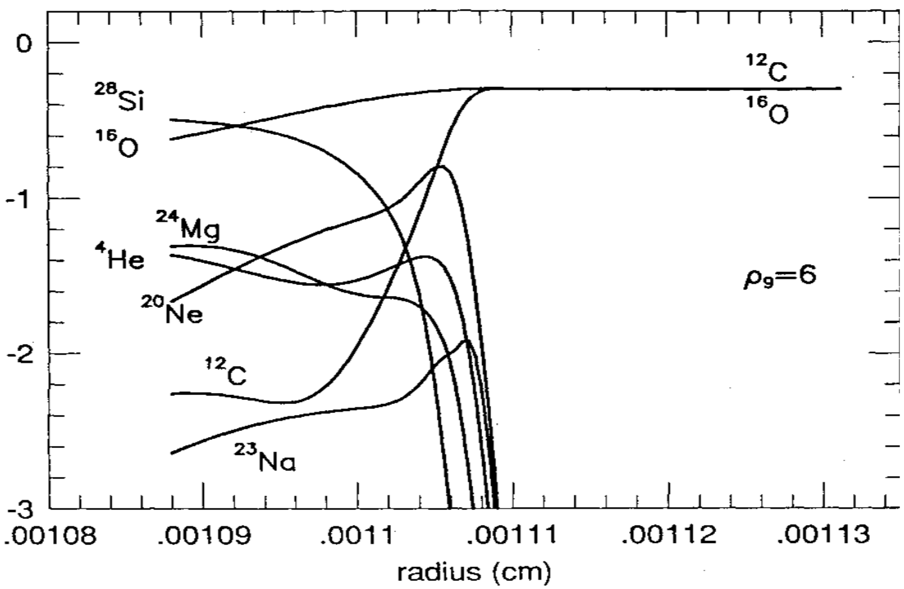
But there are problems

- Requires rather a rather symmetric ignition process - which is unclear if it is realistic.
- Demonstrating transition with explicit simulation is extremely difficult. Makes prediction of transition density hard.



Deflagration Front





Timmes & Woosley 1992, ApJ, 396, 649

Thermonuclear burning begins with sub-sonic propagating flame front. (negligible pressure jump across burning front)

Thin flame: planar reaction front propagating in direction of normal

- Heat released in burning propagates diffuses into fresh fuel
- Balance between heat production and and diffusion sets propagation speed of planar reaction front

Key differences from terrestrial premixed combustion

- heat diffusion (via electron conduction) is much more effective than species diffusion
- viscous scale small compared to flame width

Turbulent Flame LES

Understanding of scale-dependence of flame and turbulence structure especially important for large eddy simulations (LES)

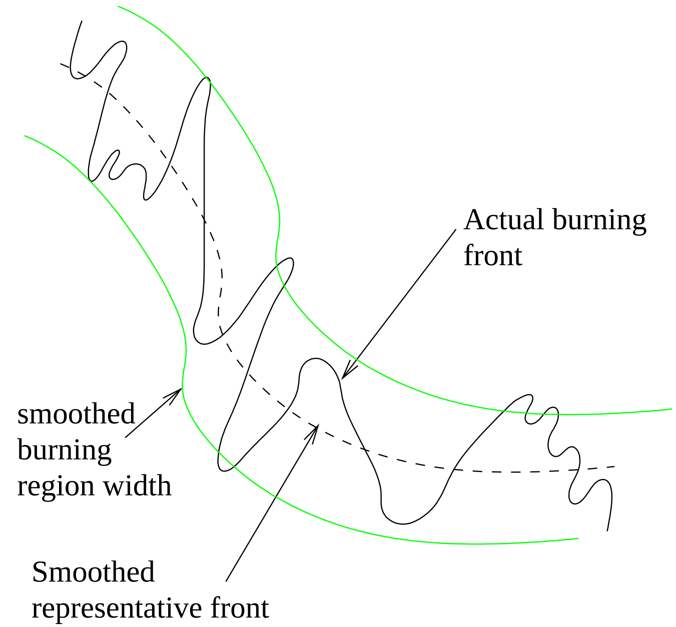
Flame:

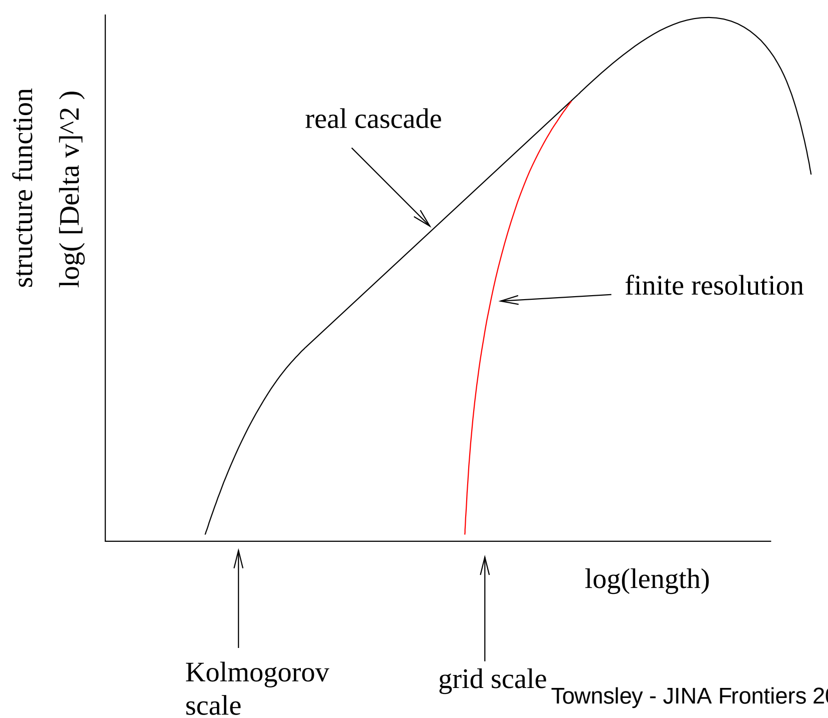
- Track smoothed front ("flame brush") with additional dynamics
- Alternative: treat, $\Sigma =$ surface area per volume, with some additional dynamics

Turbulence:

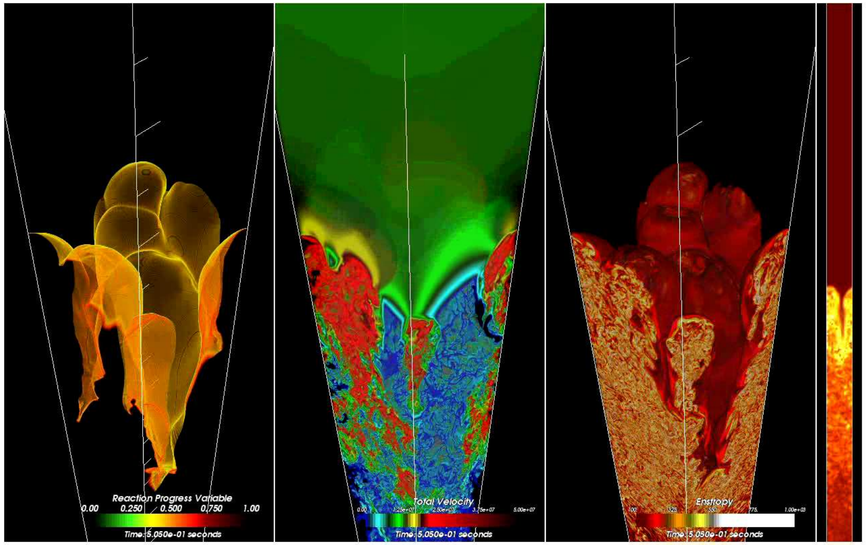
- Track unresolved turbulence energy
- Variety of available models
- Application of available models to flames still unclear

Want to understand mechanism for flame surface and turbulence creation and its dependence on and behavior with scale

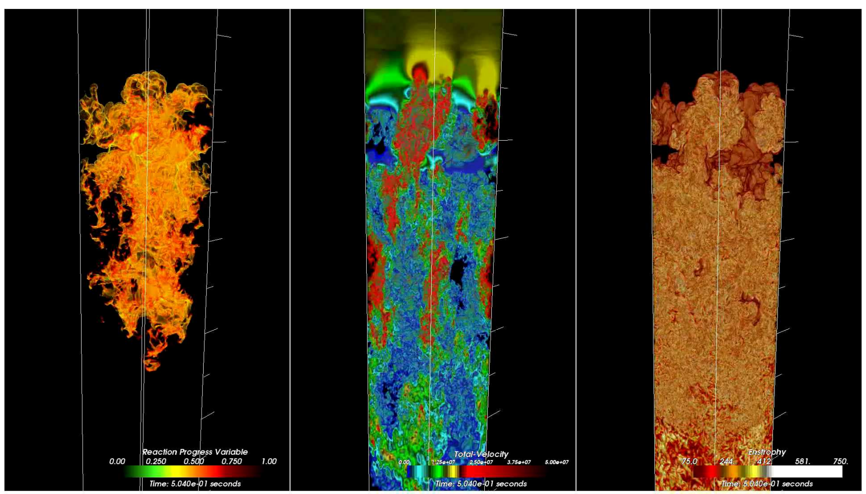




Flame Structure Study



$L/\lambda_c = 5.4$ ($Fr = 0.01$)



$L/\lambda_c = 134$ ($Fr = 4 \times 10^{-4}$)

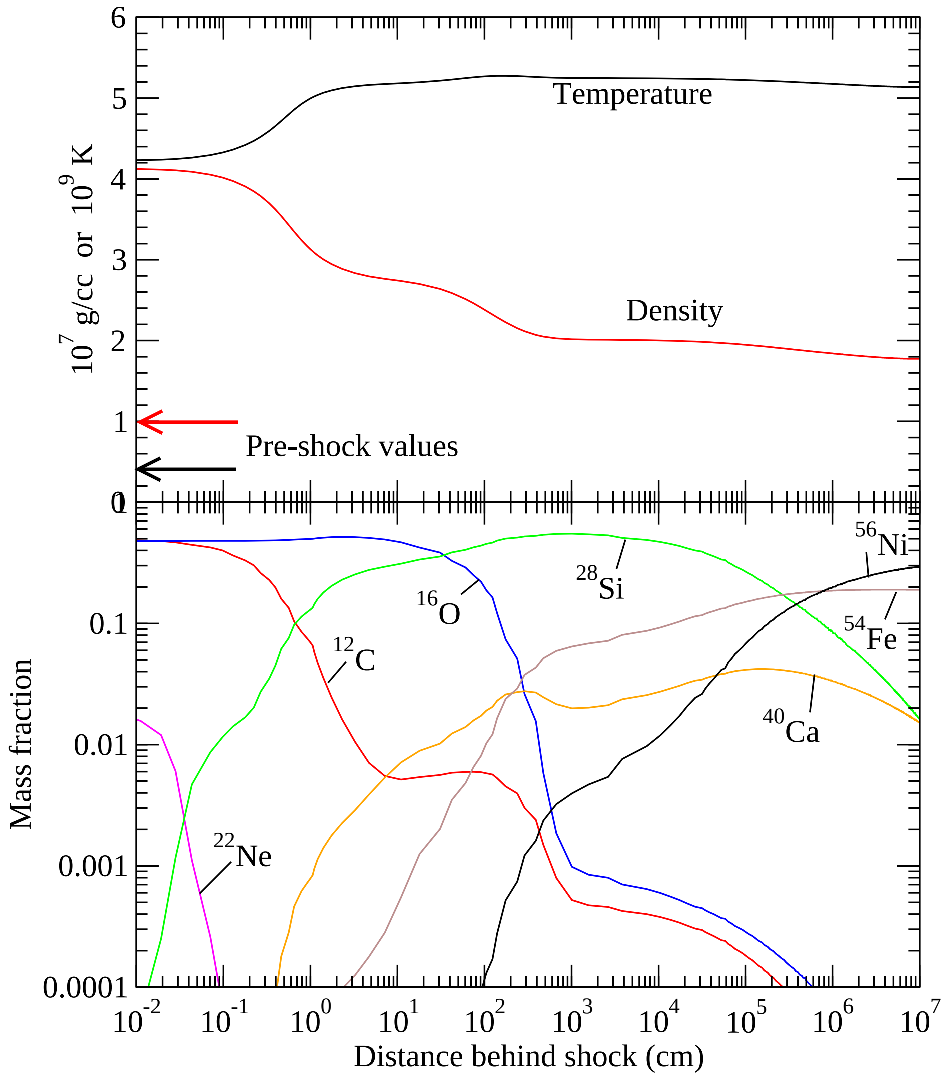
Differences from "terrestrial" flames:
(but even those are not understood)

- Turbulence is very inhomogeneous
- Turbulence dissipation scale very small

Flame structure study
vary relative strength of buoyancy

- $L/\lambda_c = 134$ offers a much larger dynamic range of surface structure
- Real problem has L/λ_c up to 10^5
- Turbulence field still appears constrained behind flame surface
- Opportunity for calibration of subgrid enhancement of flame surface area

Detonation



Burning occurs behind a propagating supersonic shock

- Heat release supports onward propagation of shock
- Only a small subset of nuclides shown (actually 200 in this calculation)
- Burning structure manifest at a wide range of scales from microns to kilometers
- 3 main stages: (also in deflagration)
  C consumption
  O consumption
  Si $\rightarrow$ Fe-group
- Si results from "incomplete" burning

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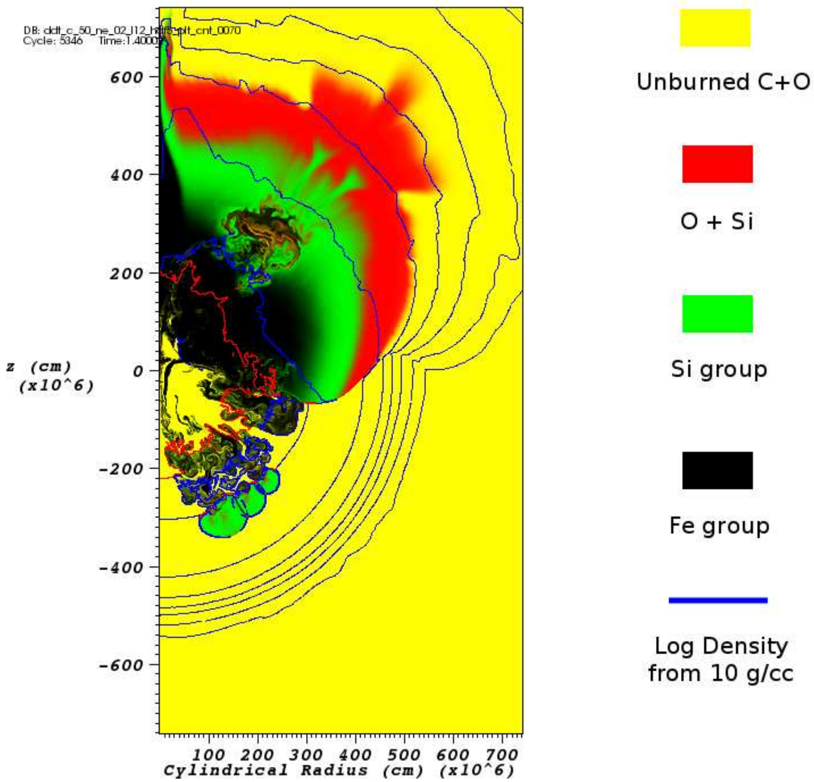
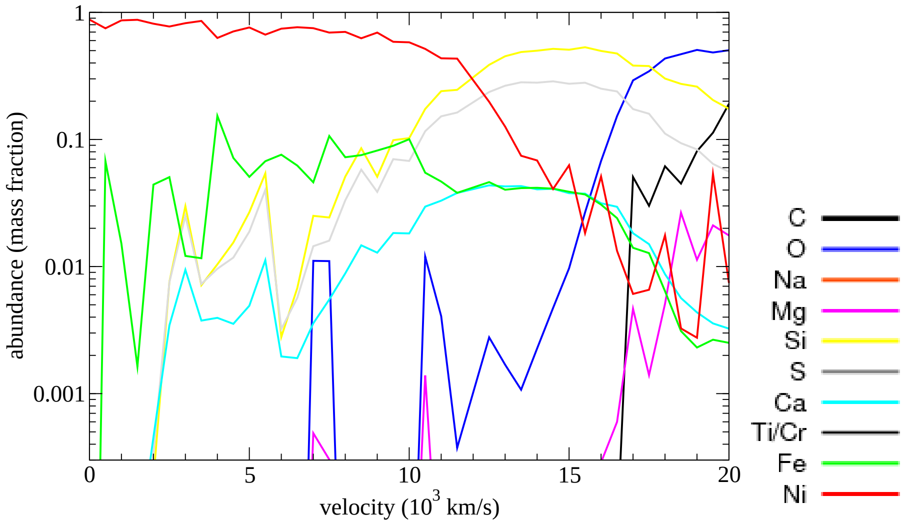
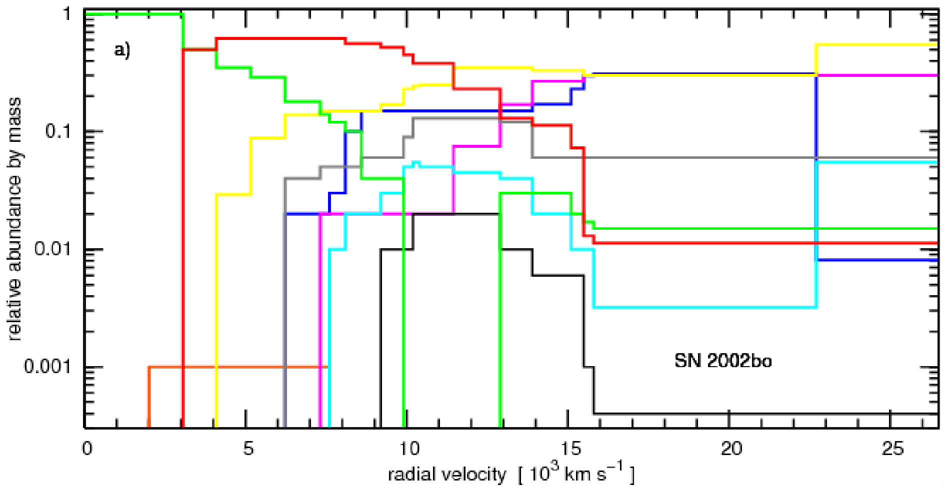


Ejecta Abundance Profile

"realization 2" from Townsley et al. 2009, ApJ, 701,1582





SN2002bo from Stehle et al. 2005, MNRAS, 360, 1231

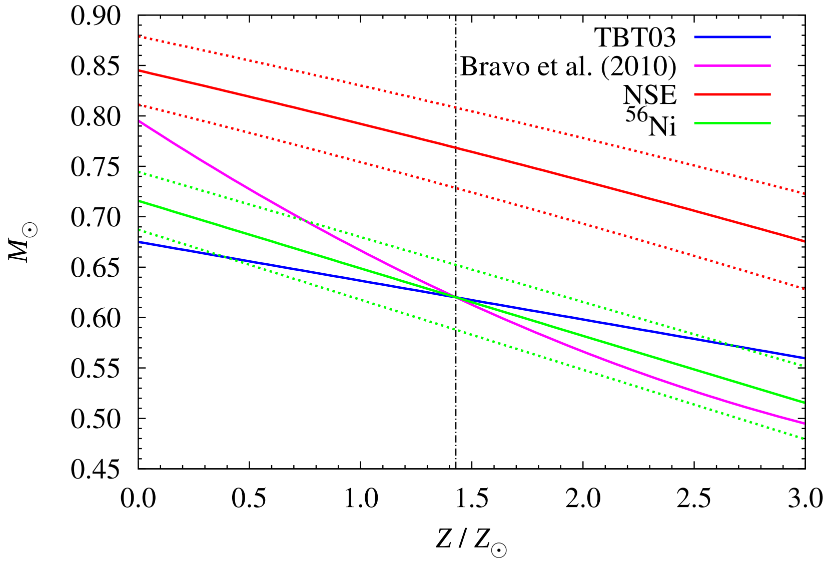
Results from central ignition (imposed symmetry) in 2 dimensions with transition to detonation at density of 10^7 g/cc

- Distribution of species in expansion velocity can be used as diagnostic when compared to observed spectral evolution
- Photosphere of supernova "sweeps" inward as ejecta expands, giving a snapshot of each concentric layer of ejecta
- Model shown lacks stable Fe core region. Perhaps an effect of the lack of resolution of flame strucure.

Systematic Dependences

Metallicity Dependence

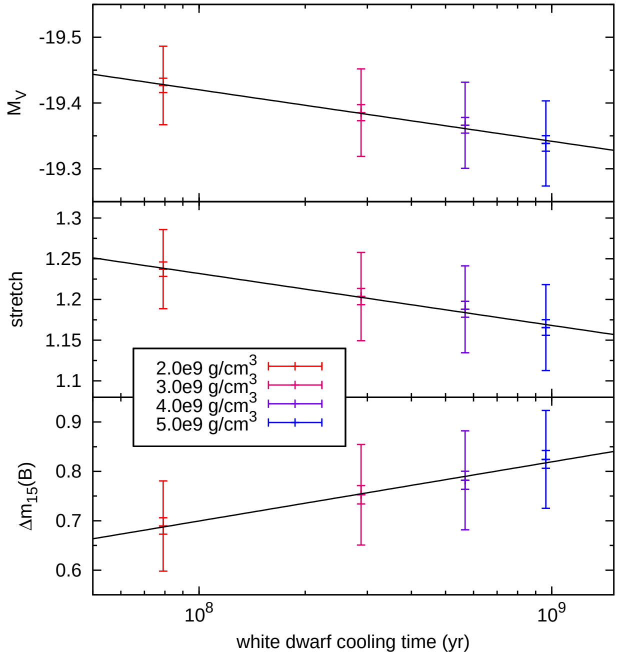
- More "metals" implies more neutrons = less ^{56}Ni
- also changes deflagration speeds changes DDT density



Jackson et al. 2010, ApJ, 720, 99

Dependence on age of stellar population

- older, cooler WDs ignite at higher density
- higher density = more e^- capture = less ^{56}Ni



Krueger et al. 2010, ApJL, 719, 5

Other Explosion Scenarios

Deflagration-Detonation Transition (DDT) Scenario most successful at explaining spectral observations
but has serious uncertainties
including a lack of apparent progenitors

Categories:
Single degenerate vs. double degenarate (SD vs. DD)
Chandrasekhar vs. sub-chandrasekhar (C vs. SC)

examples (there are more than these)

- full deflagration (SD, C)
- surface eruption and detonation (GCD) (SD, C)
- helium shell triggered carbon detonation (SD, SC)
- violent WD merger (DD, SC)

sub-Chandrasekhar must be not too much so or they don't followed the observed brightness-decline relation

Summary

Thermonuclear Supernovae as cosmological probes:

- Already quite successful
- Hope to improve – a clearer theoretical understanding would help significantly
- Huge amounts of data continue to come in from surveys with cosmological motivations

Stellar Origins:

- Still many unknowns – lack a scenario which clearly works
- Progress to be made in better understanding general parent population
- Need clearer relations to supernova outcome

Thermonuclear Supernovae:

- Several working explosion mechanisms
- Stochastic ignition could explain spread of outcomes
- Still work ahead on flame modeling and ignition conditions

Collaborators: Alan Calder, Ed Brown, Frank Timmes, Aaron Jackson, Brendan Krueger, David Chamulak, Ivo Seitenzahl, Fang Peng, Shimon Asida, Natalia Vladimirova, Casey Meakin, Robert Fisher, George Jordan, Nathan Hearn, Brad Gallager, Don Lamb, Jim Truran