Type Ia Supernova Explosion Models

deflagrations, detonations, and all that - with questions and open issues

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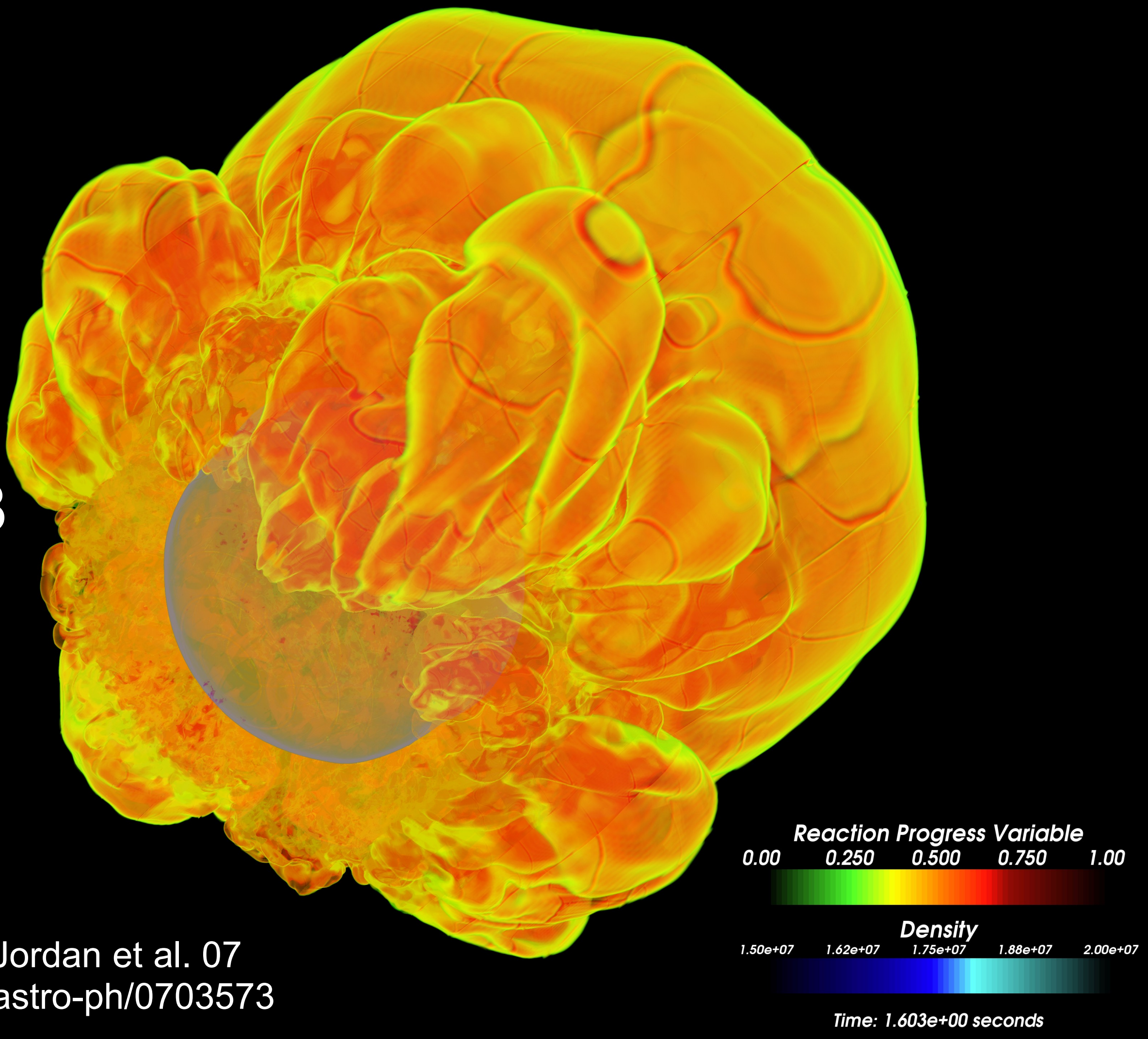
IAS Coffee
Princeton, February 6 2008

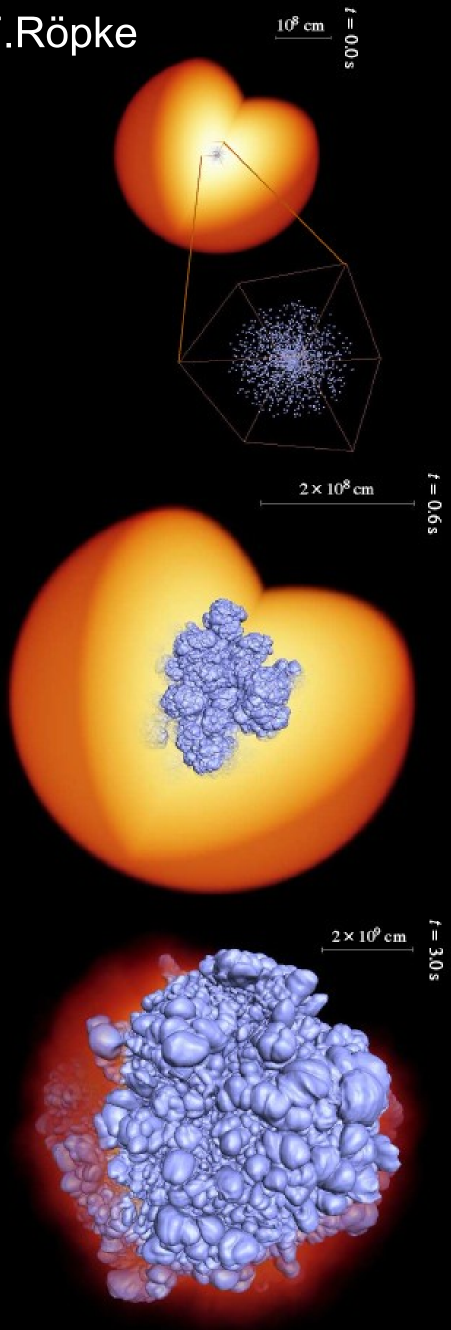
With thanks to
Eduardo Bravo (UPC/IEEC)



Jordan et al. 07
astro-ph/0703573

Menu

- **Basic Ingredients**:
  - Initial conditions: C+O WDs and how to ignite a thermonuclear runaway.
- **Some Recipes**:
  - Thermonuclear burning regimes and flame propagation regimes.
- **Entrées**:
  - The 1D Picture: Deflagrations, detonations, delayed detonations.
  - The 3D Picture: Name your own model.
- **Dessert**:
  - Observations and apologies



F.Röpke

Type Ia SNe: the Chicken and Egg problem

SN 1994D in
NGC 4526 (P. Challis)

Type Ia Supernovae (SNe) are the result of the thermonuclear explosion of a C+O white dwarf prompted by accretion in a binary system

REVIEWS: Branch et al. 95, PASP 107, 1019; Branch & Khokhlov 95, Phys. Rep. 265, 53; Hillebrandt & Niemeyer 00, ARA&A 38, 191.

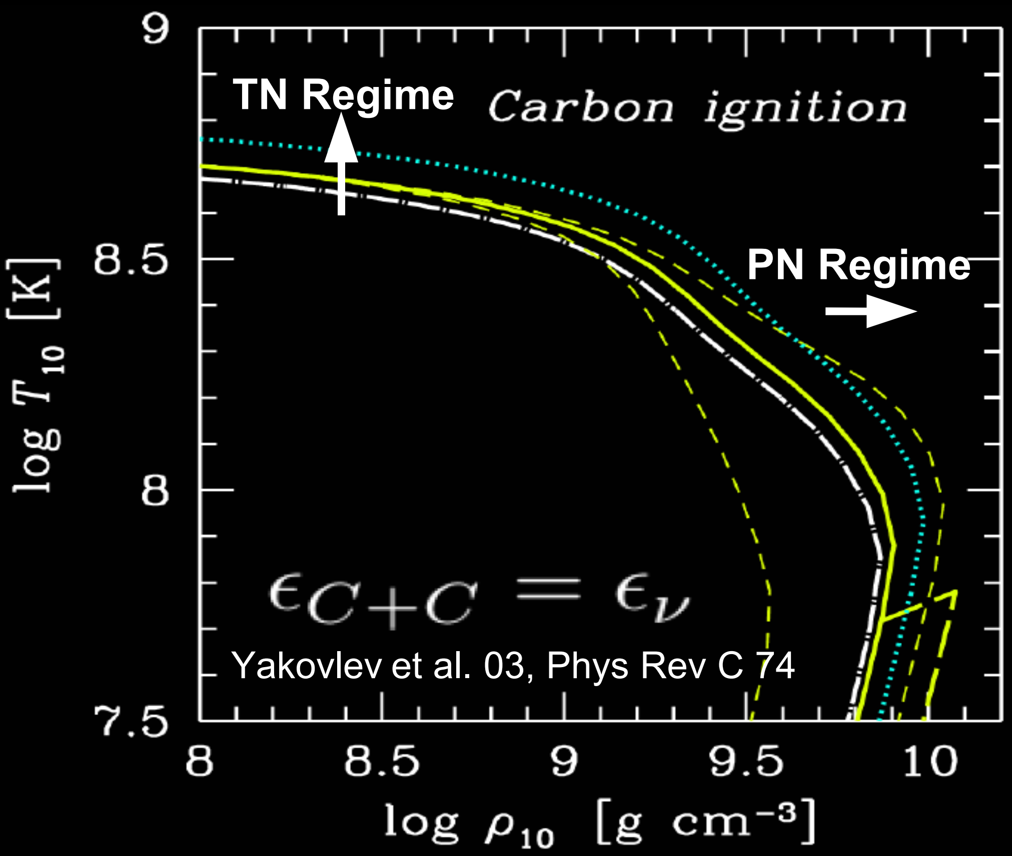
Also check KITP site: http://online.kitp.ucsb.edu/online/snovae07/ (Talks by Bildsten, Timmes, Hillebrandt)

Nature KNOWS how to produce Type Ia SNe in a consistent, robust, repeatable way.

- Almost all the explosion models in the literature **ASSUME** that the WD is formed of equal amounts of ^{12}C and ^{18}O by mass (with traces of ^{22}Ne) and that it is close to M_{Ch}.

- So far, stellar astrophysicists have not figured out a way to produce C+O WDs of M_{Ch} (either through standard single-star evolution or by 'growing' a WD of lower mass).

Why M_{Ch}?



Yakovlev et al. 03, Phys Rev C 74

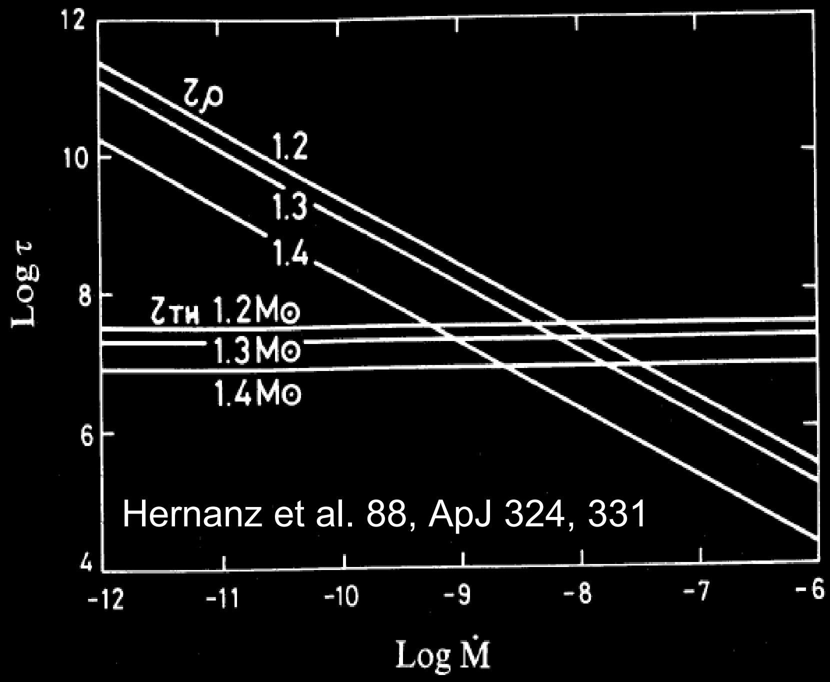
- A WD mass close to M_{Ch} is needed in order to ignite C in the pycnonuclear regime at the WD center:

$M_{WD}=1.25\ M_\odot \rightarrow \rho_c=3\times10^8$ g cm^{-3}

$M_{WD}=1.37\ M_\odot \rightarrow \rho_c=3\times10^9$ g cm^{-3}

- The thermodynamic structure (ρ, T profile) of an accreting WD is determined by thermal diffusion and accretion-induced compression.

- Ignition in mildly degenerate conditions (i.e., in the outer layers) has to be avoided! ⇒ AIC



Hernanz et al. 88, ApJ 324, 331

Explosive Burning Regimes

Carles Badenes
IAS 02/06/08

- Explosive nuclear burning (SNe, novae, X-ray flashes) is different from hydrostatic nuclear burning (stellar evolution).

- We require $\tau_{HD} \approx \tau_{nuc} \Rightarrow T_{peak}$, ρ_{peak}.

- For C+O fuel we have [Woosley 86, SAAS-FEE school]:

  - Explosive C burning: $1.8 \lesssim T_9 \lesssim 2.3 \Rightarrow {}^{20}Ne$, ${}^{24}Mg$

  - Explosive Ne burning: $2.3 \lesssim T_9 \lesssim 3.0 \Rightarrow {}^{16}O$, ${}^{24}Mg$

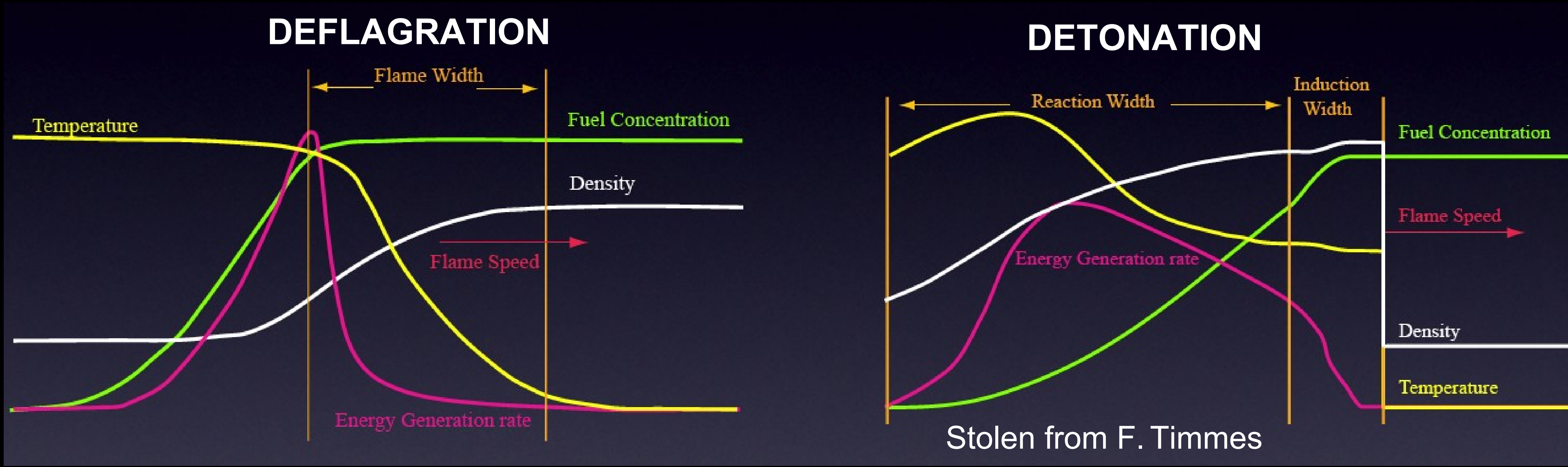
  - Explosive O burning: $3.1 \lesssim T_9 \lesssim 3.9 \Rightarrow {}^{28}Si$, ${}^{32}S$

  - Explosive Si burning: $4.0 \lesssim T_9 \lesssim 5.0 \Rightarrow {}^{36}Ar$, ${}^{40}Ca$, ${}^{56}Ni$

  - Nuclear Statistical Equilibrium (NSE): $T_9 > 5.0 \Rightarrow {}^{56}Ni$, but also ${}^{54}Fe$, ${}^{58}Ni$ (depending on ρ)

Deflagrations and Detonations

- A self-sustained wave of exothermic chemical reaction spreading through a homogeneous combustible mixture is known to occur either as a subsonic deflagration (premixed flame) or supersonic detonation.
  - Deflagrations are mediated by heat diffusion.
  - Detonations are mediated by a strong shock.



Stolen from F. Timmes

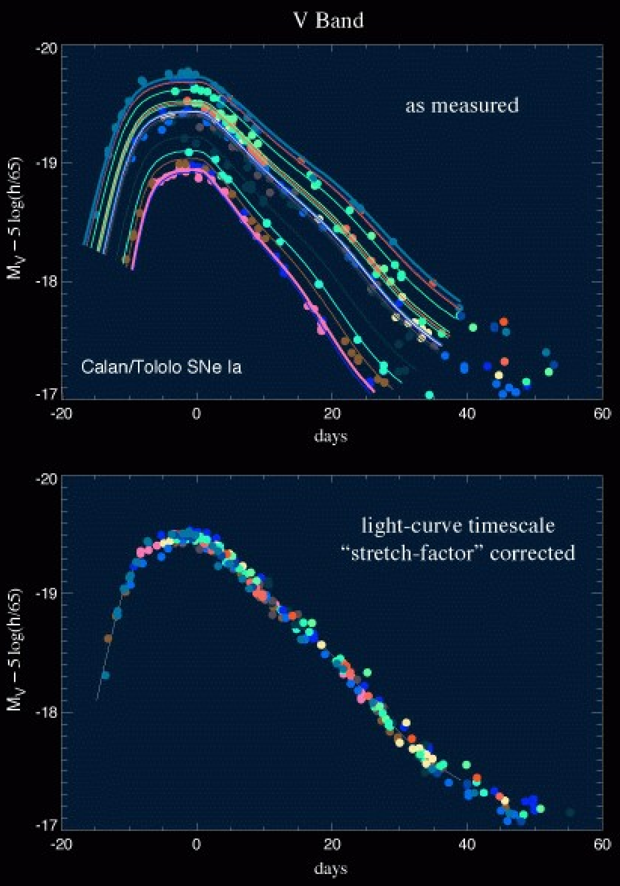
The mode of propagation of the burning front through the WD determines the nucleosynthesis ⇒ structure of the SN ejecta

What makes a successful model?

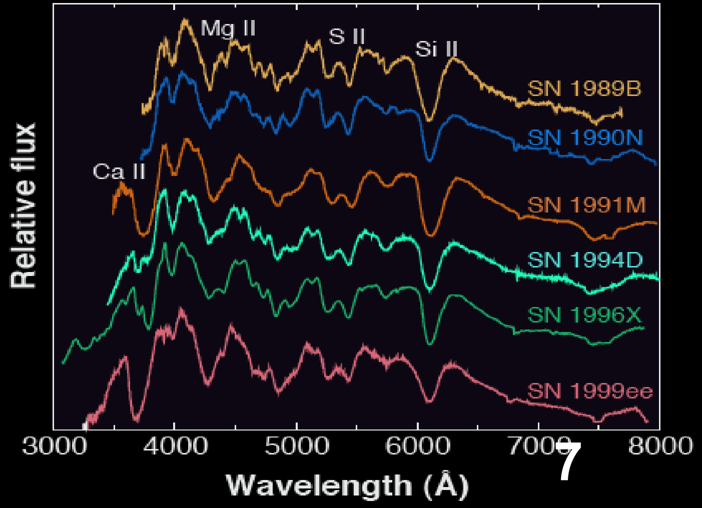
Starting from a 1.38 $M_\odot$ C+O WD, a successful model needs to produce (in a repeatable and robust way):

- 0.1-1.0 $M_\odot$ of ^{56}Ni for the light curve, but very little of it in the outer layers
- 0.2-0.4 $M_\odot$ of Si, S, Ar, Ca and not too much O close to the ^{56}Ni for the spectrum
- <0.1 $M_\odot$ of n-rich isotopes (^{54}Fe, ^{58}Ni) for the nucleosynthesis
- Allow for some diversity for the light curve width-luminosity relation

The way to do this is to start with a slow deflagration, pre-expand the WD and then increase the burning front speed to avoid quenching.



Supernova Cosmology Project



Branch 03, Sci 299, 53

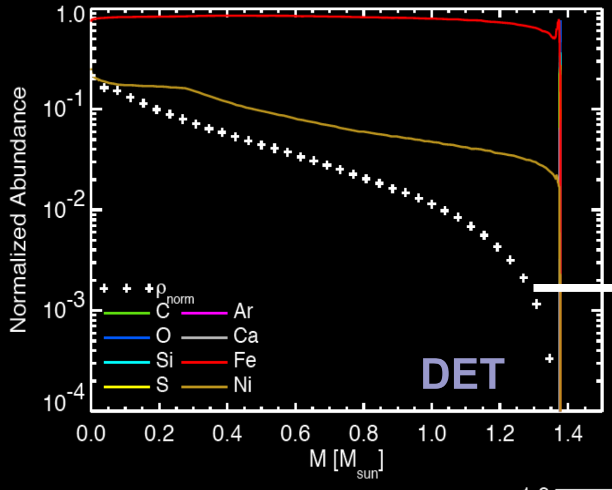
The 1D Picture

- **Prompt Detonations**. Burning at high T, $\rho \Rightarrow$ NSE $\Rightarrow$ Fe-peak nuclei (^{56}Ni). Very energetic.

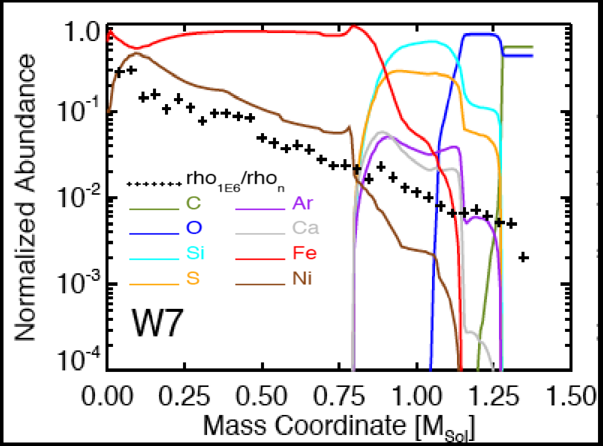
- **Pure Deflagrations**. Burning at lower T, $\rho \Rightarrow$ departure from NSE $\Rightarrow$ IMEs: Si, S, Ar, Ca. Flame quenches $\Rightarrow$ unburnt C+O. Less energetic.

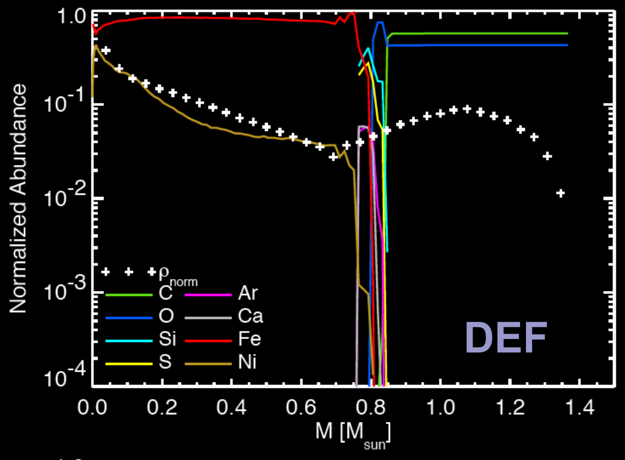
- **Delayed Detonations**. More IMEs and E_k than DEF. Transition to detonation imposed artificially at ρ_{tr}.

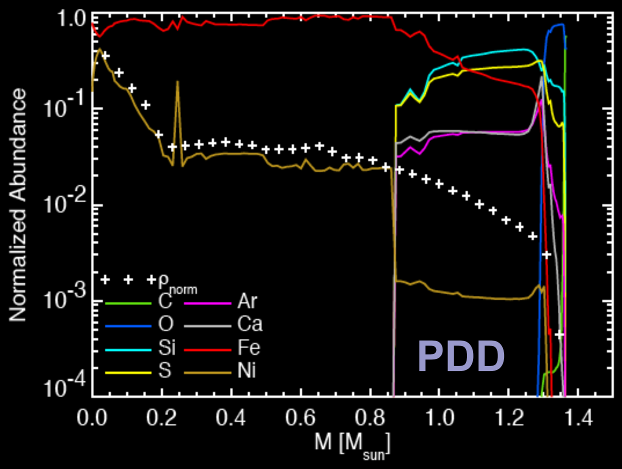
- **Pulsating Delayed Detonations**. Explosion 'fizzles' and detonation happens upon recollapse of the WD (still imposed).

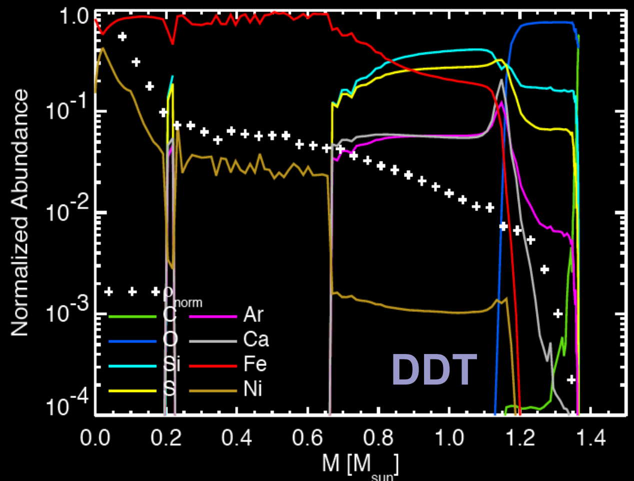


~ exponential density profile



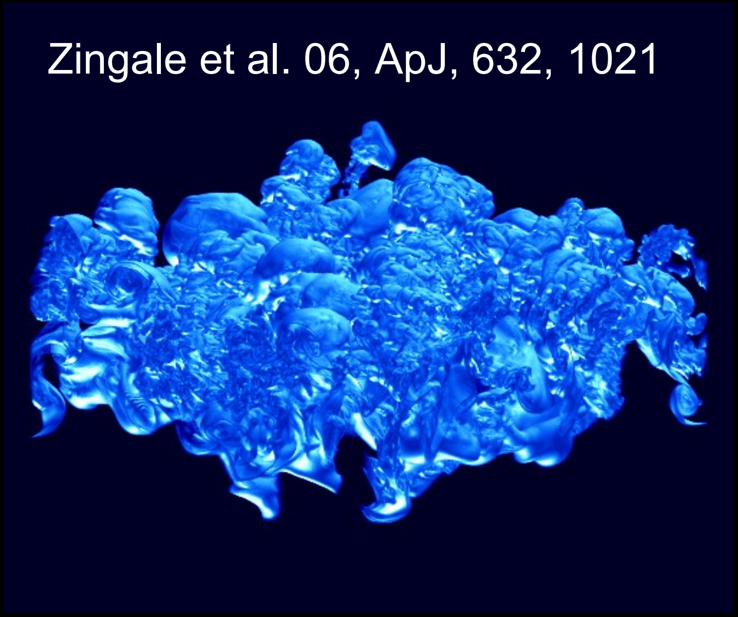






The 3D Picture: New Ingredients

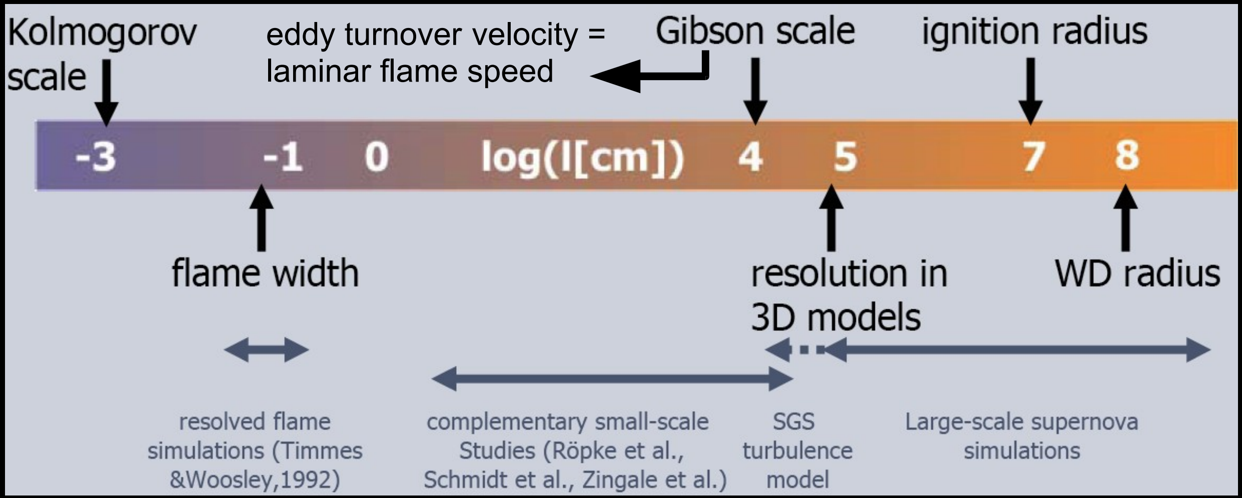
- The ignition parameter space opens up: how many ignition points? where are they located? [Kuhlen et al. 06, ApJ 640, 407].
- Inside the pre-explosion WD, Reynolds number is Re$\sim10^{14}$; Rayleigh number is Ra$\sim10^{25}$ $\Rightarrow$ **extremely vigorous convection and turbulence**:
  - Subsonic burning fronts become dynamically unstable.
  - Buoyancy of hot ashes in cold fuel.



Zingale et al. 06, ApJ, 632, 1021

The flame width ($10^{-1} \rightarrow 10^{1}$ cm) and the star ($10^{8} \rightarrow 10^{9}$ cm) cannot be resolved at the same time $\Rightarrow$ subgrid models to resolve all scales down to the Gibson scale (below, turbulence does not affect flame propagation)

Stolen from F. Röpke



Kolmogorov scale

eddy turnover velocity = laminar flame speed

Gibson scale

ignition radius

-3 -1 0 log(l[cm]) 4 5 7 8

flame width

resolution in 3D models

WD radius

resolved flame simulations (Timmes &Woosley,1992)

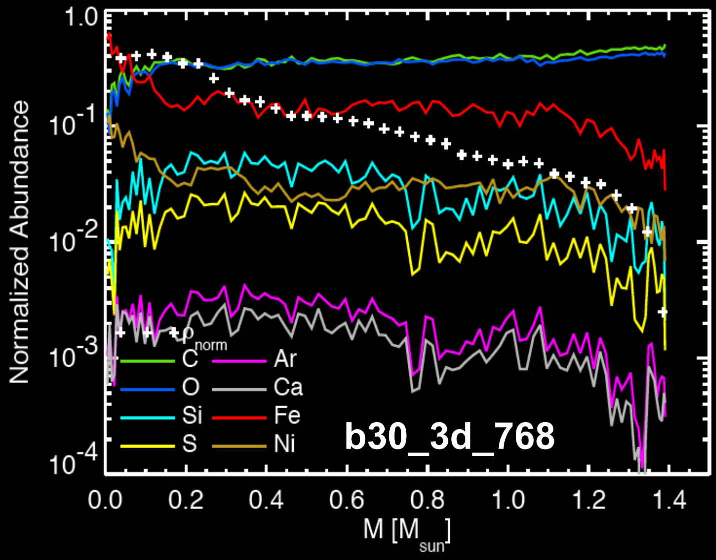
complementary small-scale Studies (Röpke et al., Schmidt et al., Zingale et al.)

SGS turbulence model

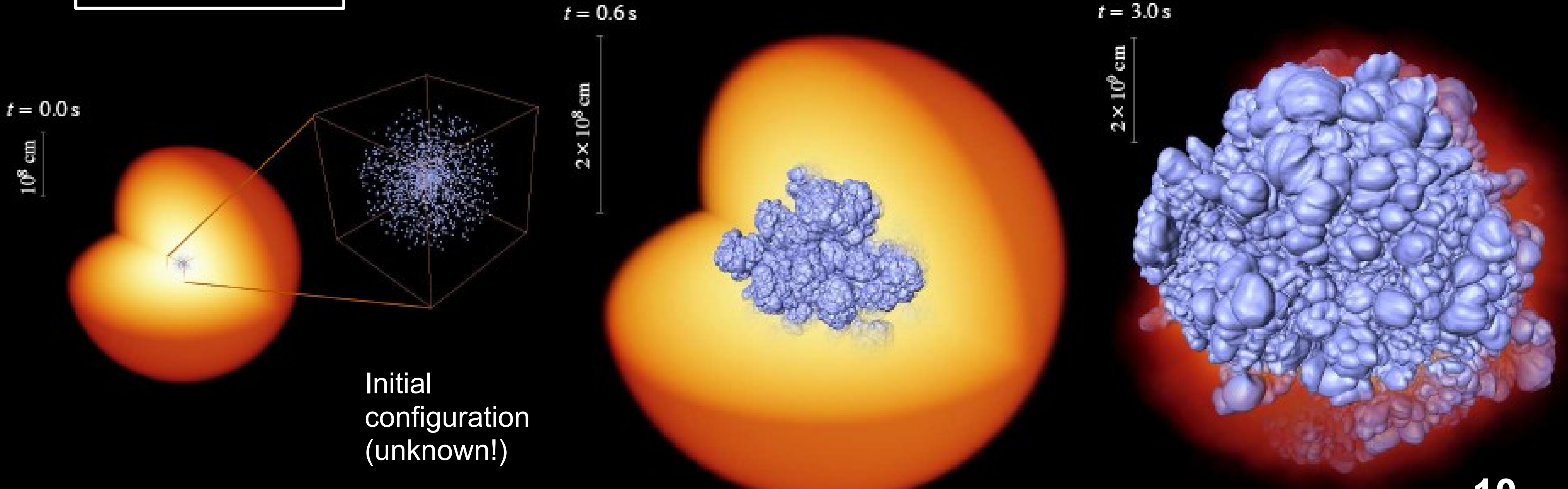
Large-scale supernova simulations

The 3D Picture: Deflagration Models

- Several studies using 3D codes. [Travaglio et al. 04, A&A 425, 1029; Gamezo et al. 03, Sci 299, 77; García-Senz & Bravo 05, A&A 430, 585]. **Results converge:**
  - ~50% of WD remains unburnt. Low E_k, low yield of IMEs.
  - Explosion is dominated by turbulence and buoyancy ⇒ **well-mixed ejecta.**



3D Deflagration
Model by F. Röpke



Initial configuration (unknown!)

Deflagration to Detonation Transitions

- In chemical combustion, deflagration to detonation transitions happen routinely (but not repeatably) in laboratory experiments in the presence of walls or obstacles.

- In order to make the transition to detonation, a region of a certain critical size ($V_c \sim l_c^3$) has to run away as a unit ($t_s(l_c) \sim l_c/u_s$):

  - Fractal mechanism ⇒ turbulent deformation of the flame surface creates a fractal structure that burns material very quickly. Requires flame velocity$\sim u_s$.

  - Induction time gradient mechanism (Zeldovich mechanism) ⇒ flame moves along a preconditioned volume where the temperature gradient is such that a detonation ensues.

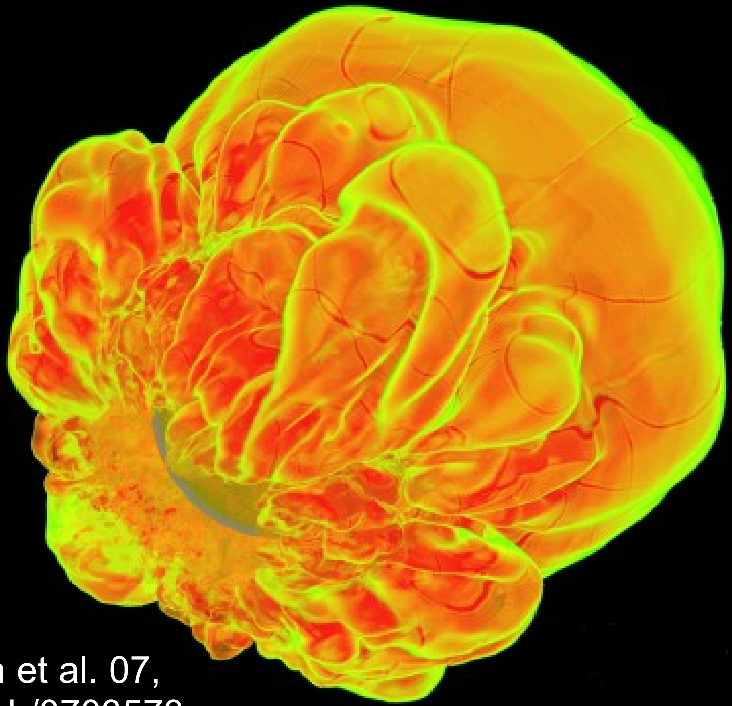
- There is an open debate on whether this can happen at all inside an exploding WD [Khokhlov et al. 97, ApJ 478, 678; Niemeyer 99, ApJ 523, L57; Röpke 07, ApJ 668, 1103; Woosley 07, ApJ 668, 1109].

Self-consistent transitions?

- Ongoing efforts to model the **deflagration to detonation transition** in a self-consistant way using 3D codes:

Gravitationally Confined Detonations

[Plewa et al. 04 ApJ 612, L37]

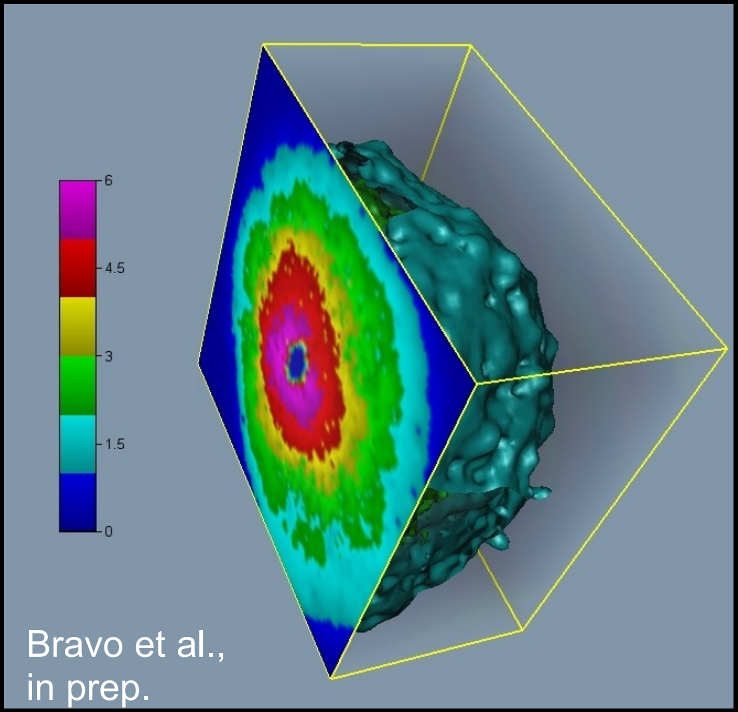


Jordan et al. 07, astro-ph/0703573

Transition happens at the antipodal point of the surface break-out of a single buoyant bubble [see also Röpke et al 07, ApJ 660, 1344].

Pulsating Reverse Detonations

[Bravo & García-Senz 06 ApJ 642, L157]



Bravo et al., in prep.

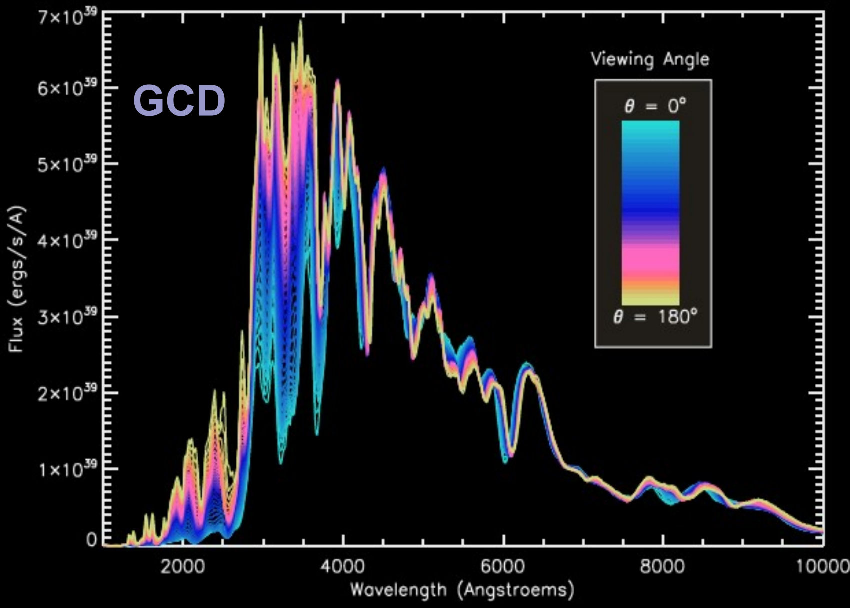
Transition happens at an accretion shock formed after a failed explosion.

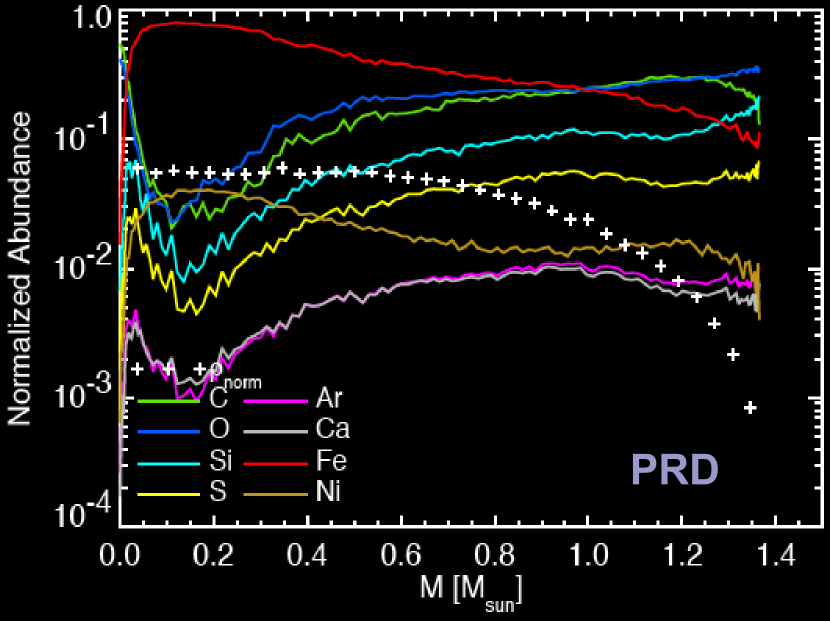
Self-consistent transitions?

- Issues with 'self-consistent' 3D models:
  - GCDs:
    - A more or less pronounced axial asymmetry is unavoidable. This might be in conflict with spectropolarimetric observations [Leonard et al. 05, ApJ 632, 450] and SNR morphology [Badenes, don't hold your breath].
  - PRDs:
    - More symmetric in principle, but plumes of NSE material at large radii are problematic [Baron et al. 08, ApJ 672, 1038].
- 3D versions of delayed detonation models (with imposed transitions) are available in the literature [Gamezo et al. 05, ApJ 623, 337; Bravo & García-Senz 08, A&A 478, 843; Röpke in progress].

Large scale full-star models have limitations

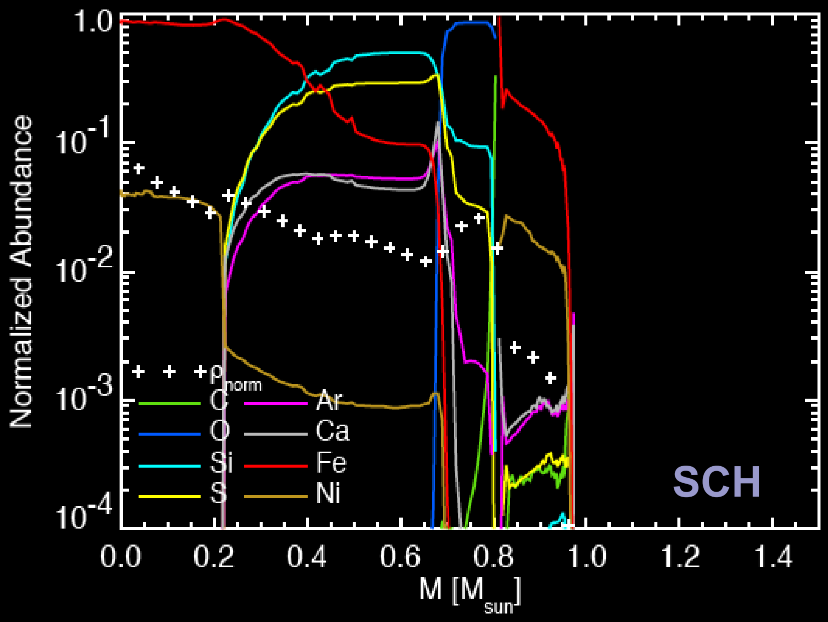
Kasen & Plewa 07, ApJ 662, 459



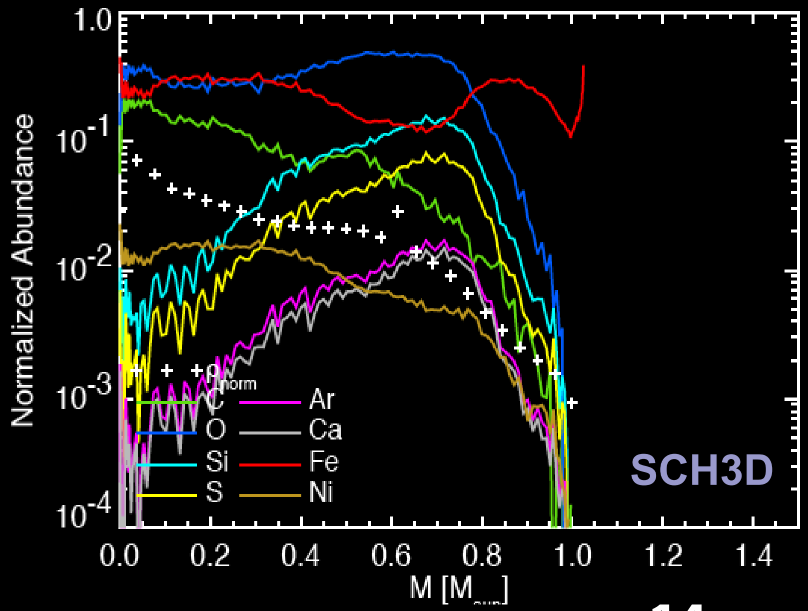


Sub-Chandrasekhar Models

- If a sub-Ch WD accumulates a large He layer on the surface and this layer is ignited under degenerate conditions, a powerful shock wave converges onto the center. This might trigger a thermonuclear runaway that explodes the entire WD well below M_{Ch} ('double detonations', 'surface detonations', 'He ignitors').



- The idea seems to work also in 3D [García-Senz et al 99, A&A 349, 177; Fink et al. 07, A&A 476, 1133].

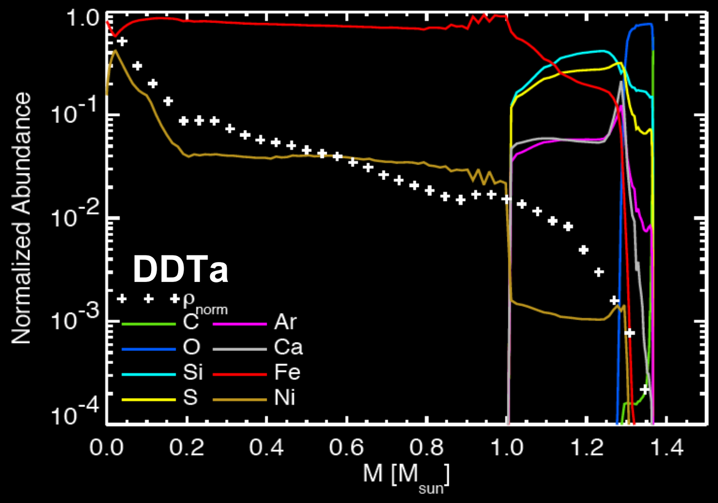


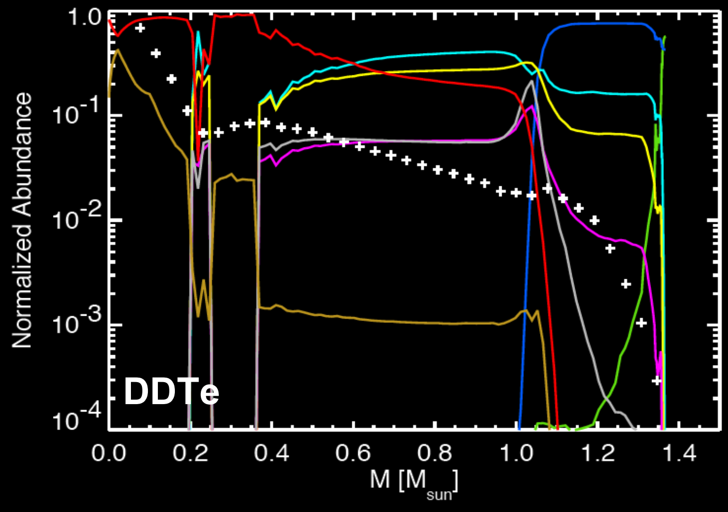
- Outer layers are full of NSE material.

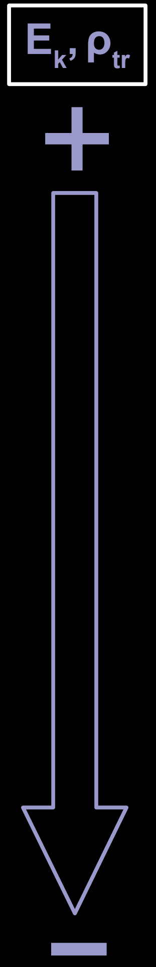
- Do these objects exist?

Comparison to Observations: SNe

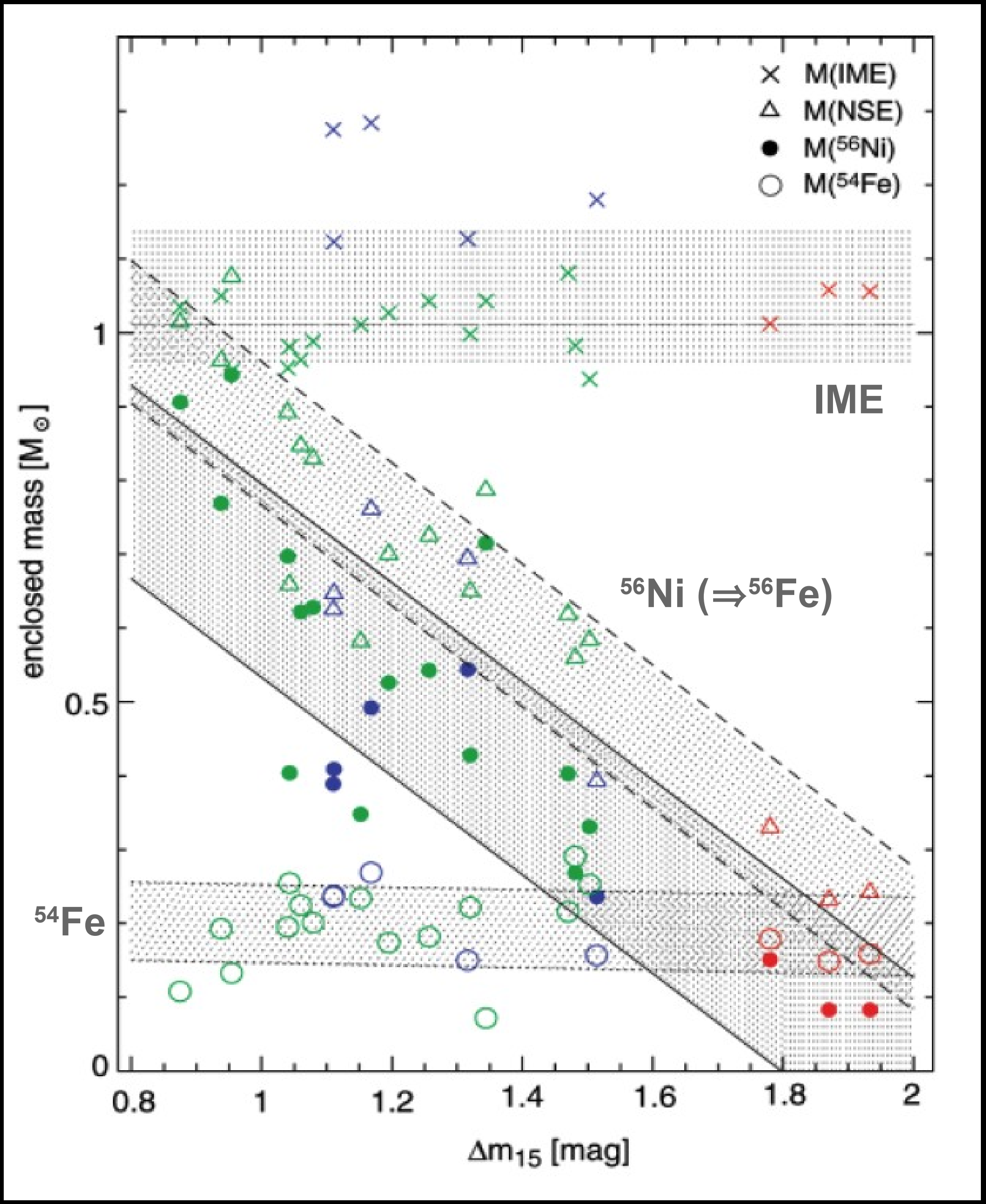
- Phenomenological 1D **delayed detonation** (DDT) models provide the best match to Type Ia SN observations.







Mazzali et al. 07, Sci 315, 825 [23 Type Ia SNe]



Comparison to Observations: Tycho SNR

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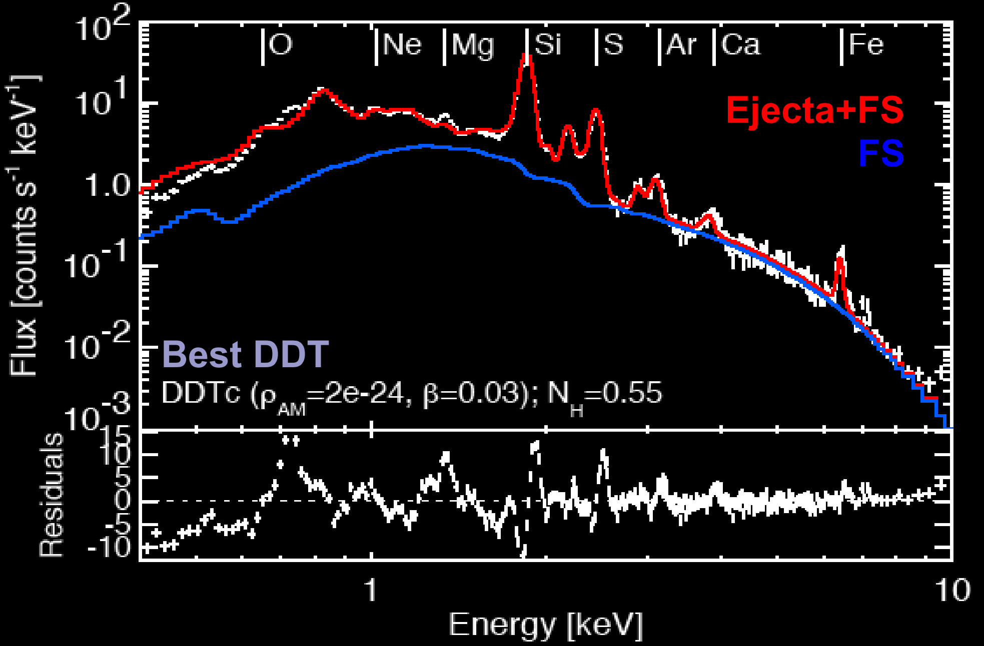
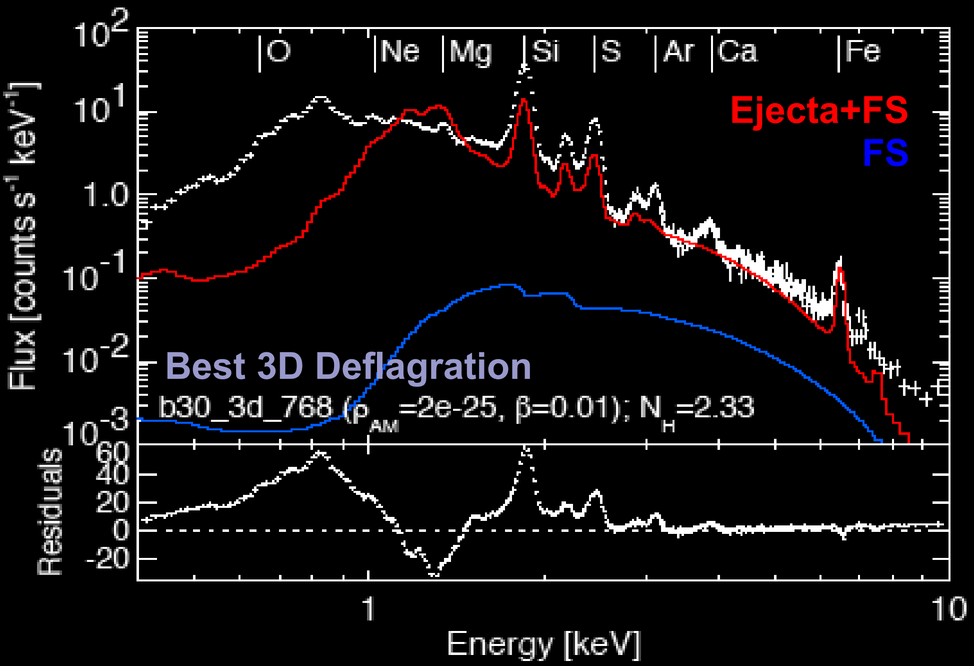
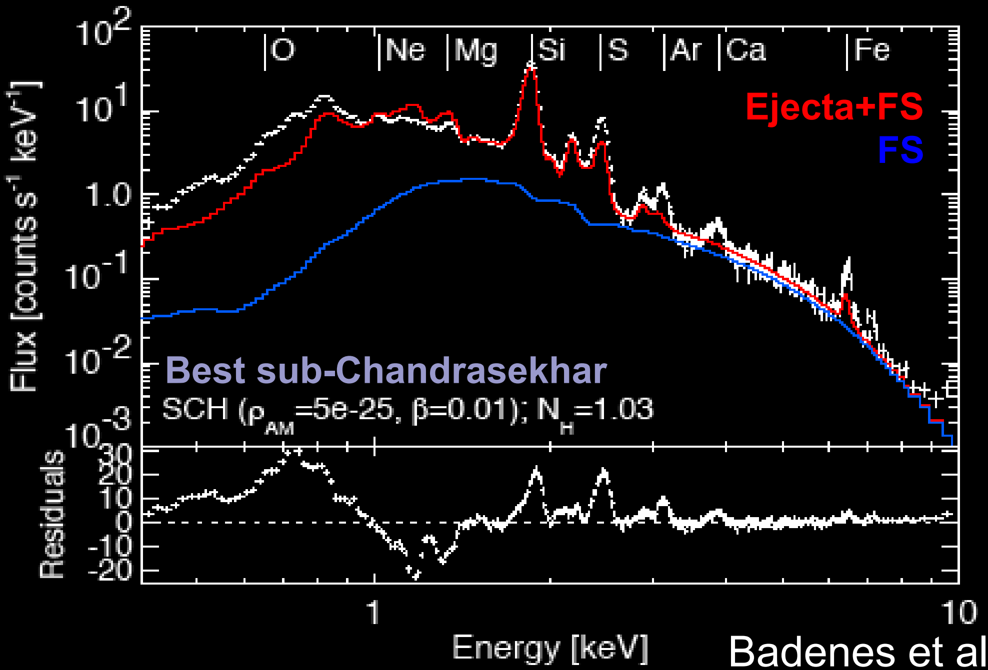
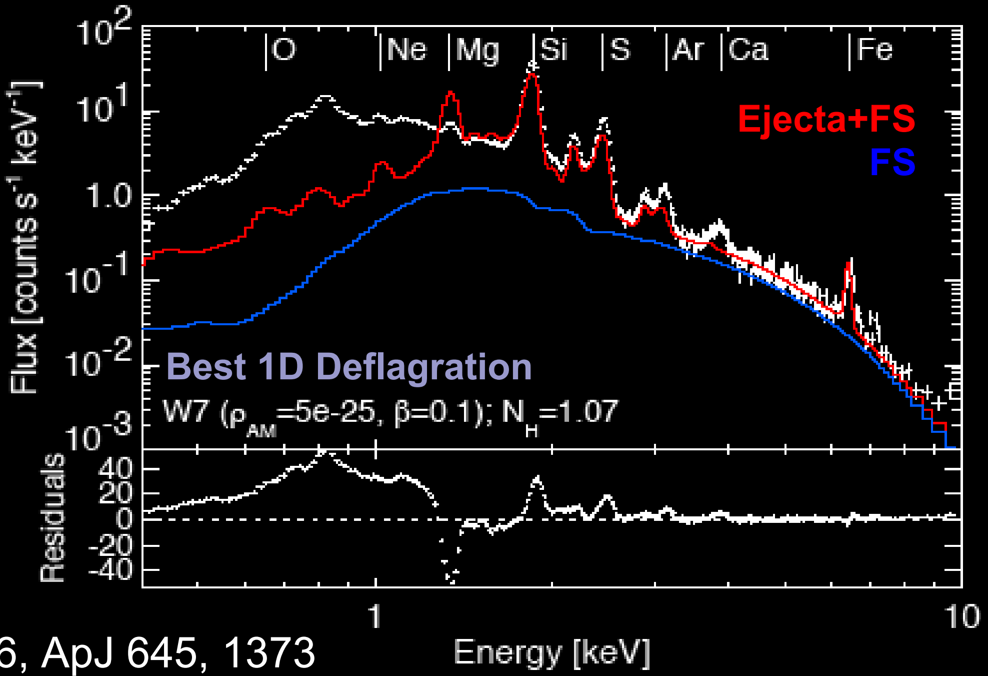




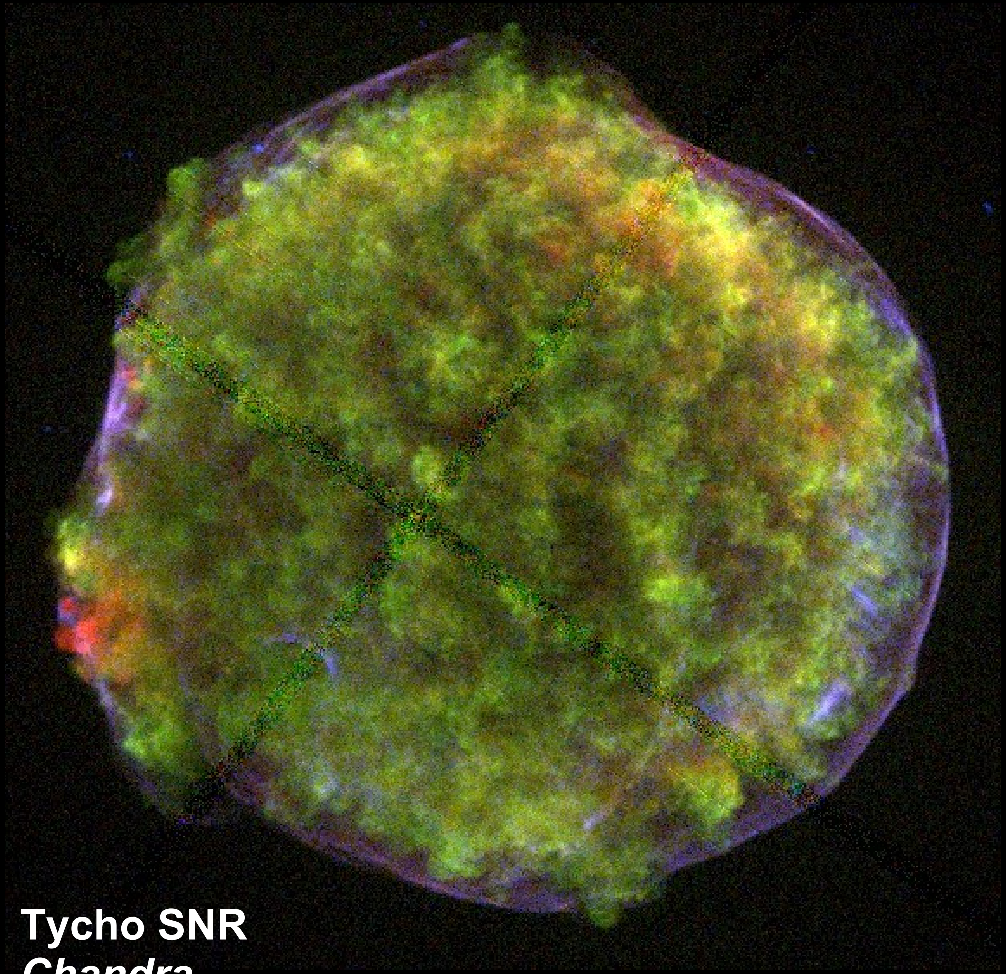




Badenes et al. 06, ApJ 645, 1373

The Best Benchmark for 3D Models

Kepler SNR
Chandra



Tycho SNR
Chandra