Lect2: TYPE Ia SUPERNOVAE

October 9, 2007

"There are Type Ia Supernovae and there is everything else."

SNIa - thermonuclear explosions of degenerate stars.

SNIb,c,d,..., SNIIP, L,... - core collaps in massive stars.

Plan of the lecture

- Important observational evidence
- Basic physics of SNIa explosion
- Current picture (existing models)
- Outstanding problems

IMPORTANT OBSERVATIONAL EVIDENCE

"Important" means that theorists can make sense of it (other observations could be important as well but we do not know at present what they mean).

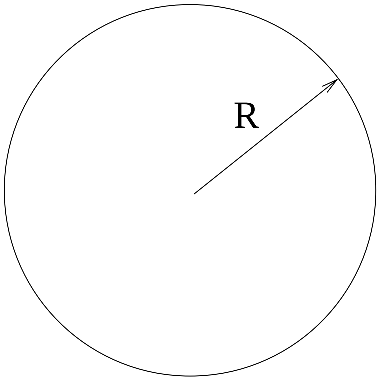
- There is no indication of hydrogen or helium in SNIa.
- Outer layers consist of intermediate mass elements, Si, S, Mg, O, etc. There is little indication of carbon.
- Interior parts of a SNIa consist of slowly moving iron-group elements.
- Typical velocity of a SNIa at maximum is $U \simeq 10^9$cm/s. Outer layers move faster.
- Light curves and spectra look "similar." Maximum brightness varies by $\simeq 10$.
- Brightness, color, and post-maximum decline of a SNIa seem to correlate (Phillips's relation, etc.).

Other observations:

- Indications of asphericity at maximum light (from polarization)
- Supernovae with similar light curves show variations in spectral behavior.
- Statistics of SNIa
- "Weird" supernovae
- Observations of historical SNIa remnants.

STANDARD PICTUIRE

SNIa is an explosion of a Chandrasekhar-mass CO-WD in a binary system.



$$\begin{aligned} &M \simeq 2.8 \times 10^{33}\mathrm{g} \\ &R \simeq 2 \times 10^{8}\mathrm{cm} \\ &\rho_c \simeq (2-6) \times 10^{9}\mathrm{g/cm}^3 \\ &a_s \simeq 5 \times 10^{8}\mathrm{cm/s} \\ &\underline{\underline{\tau_{expl} \simeq R/a_s \simeq 1\mathrm{s}}} \end{aligned}$$

Why a WD? - No hydrogen.

Why CO? - Because He explosion cannot make intermediate-mass elements.

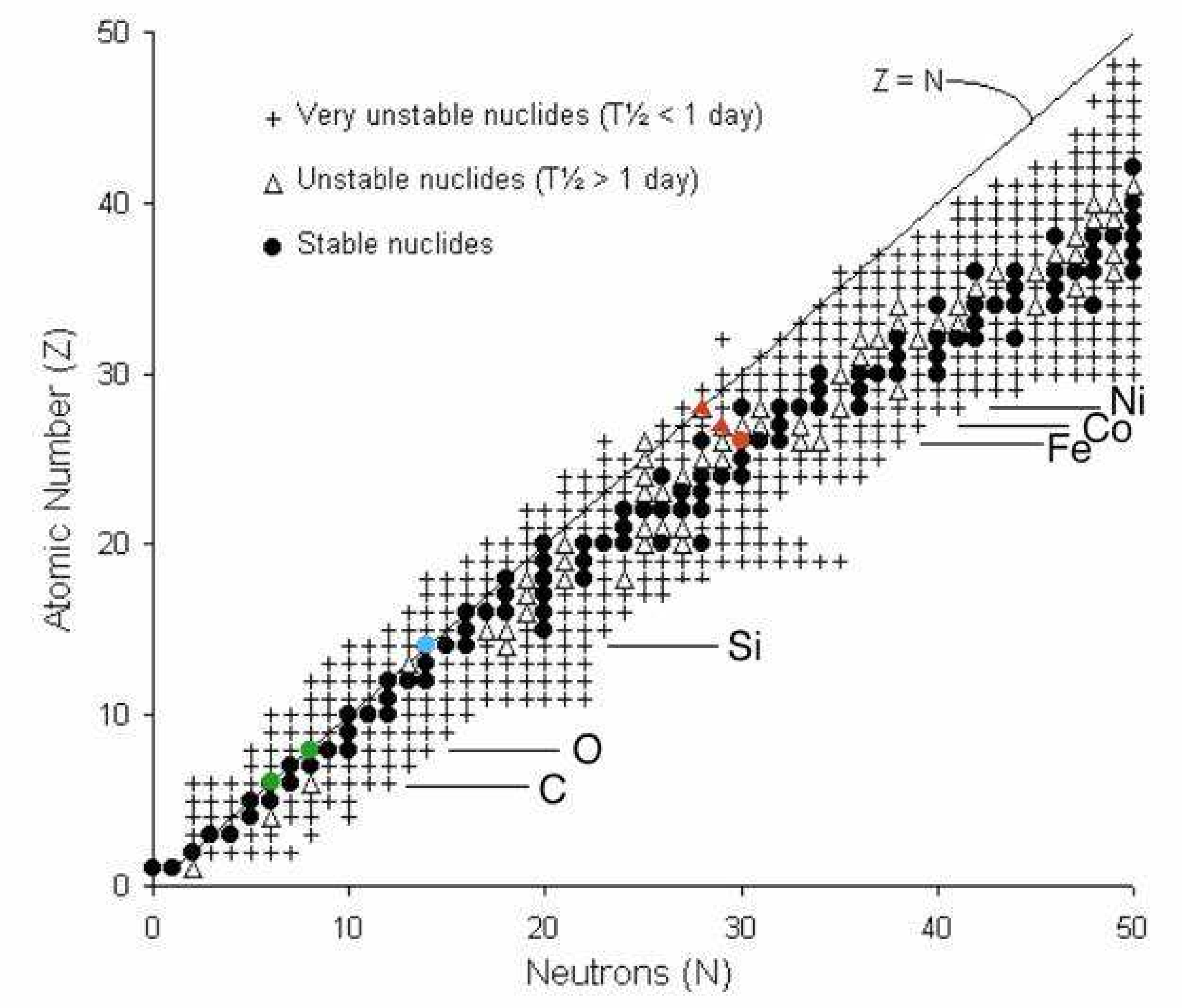
Why τ_{expl} must be comparable to R/a_s? Because $\tau_{expl} >> R/a_s$ cannot cause an explosion, whereas $\tau_{expl} << R/a_s$ requires a carefully synchonized ignition.

Why Chandrasekhar-mass WD? - Seems impossible to ignite a CO-WD otherwise.

Expansion velocity $U \sim 10^9$cm/s translates into $q \simeq 10^{18}$ergs/g $\simeq$ 1Mev/nucleon of energy. This is comparable to what burning of CO to iron can provide.

$q \simeq 10^{18}$ergs/g gives an idea of temperatures during the explosion, $T_{burn} \simeq$ few $\times$ 10^9K.

EXPLOSIVE BURNING IN SNIA



Stages of burning:

- ${}^{12}C +{}^{12} C \rightarrow Ne, Mg, Na, \alpha, p, n$; time-scale τ_{CC}
- Production of Si-group nuclei; binary reactions; time-scale τ_{Si}
- Production of Fi-peak nuclei; controlled by ${}^{12}C \rightarrow 3\alpha$; time-scale τ_{NSE}

$$\tau_{CC} << \tau_{Si} << \tau_{NSE}$$

MAGIC DENSITY, $\rho = 10^7$g/cm^3

Specific heat of degenerate matter, c, increases when density, ρ, decreases.

As a result, burning temperature, $T \sim q/c$, decreases when ρ decreases:

Reaction time-scales τ_{CC}, τ_{Si} and τ_{NSE} are exponential functions of T.

We must compare them with the explosion time-scale, τ_{expl}.

At densities $\rho < 10^7$g/cm^3 we have $\tau_{NSE} << \tau_{expl}$.

Thus, at $\rho < 10^7$g/cm^3 explosive carbon burning will produce Si-group nuclei. At higher densities it will produce Fe-peak.

At $\rho < 10^6$g/cm^3 we have $\tau_{Si} << \tau_{expl}$. explosive carbon burning will produce O, Ne, Mg, Na.

CONCEPT OF DELAYED DETONATION

Chandrasekhar-mass CO-WD has density $>> 10^7$g/cm^3.

We need slow sub-sonic burning to pre-expand the WD and create conditions for Si production.

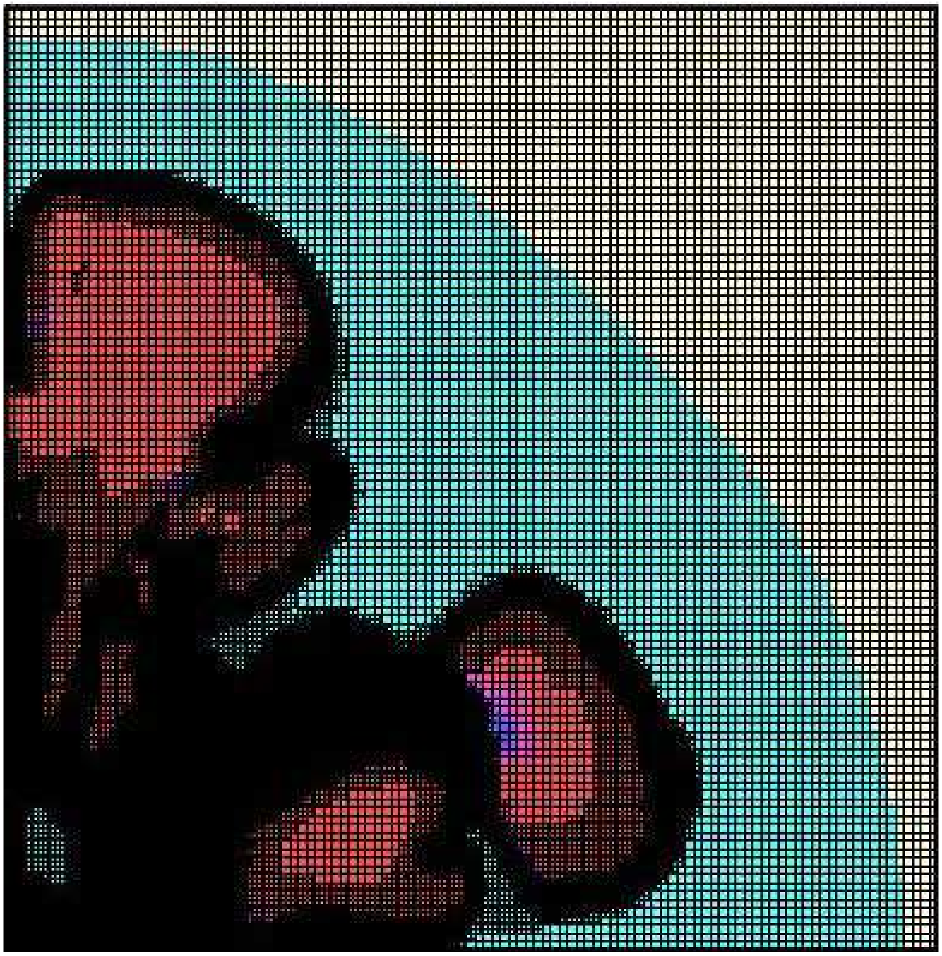
WD begins to expand as soon as it starts burning sub-sonically. But when magic density is reached, the outer layers of a WD already expand supersonically. Sub-sonic combustion cannot catch up with the outer layers and they remain unburned.

If subsonic burning turns into a detonation, the detonation will reach and incinerate the outer layers of a supernova - delayed detonation.

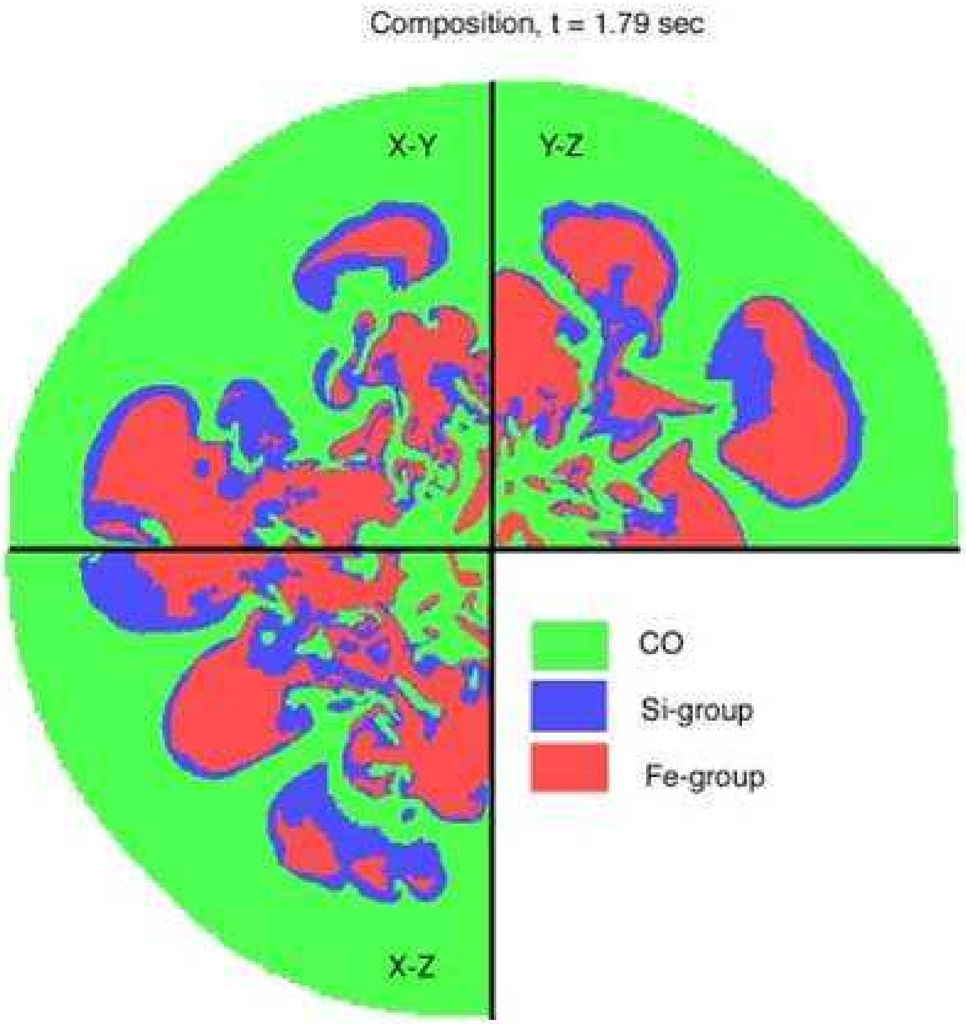
In one-dimensional computations, transition to a detonation is parametrized by a transition density ρ_{tr}. One needs $\rho_{tr} \simeq (0.5 - 3) \times 10^7$g/cm^3 to fit observations.

THREE-DIMENSIONAL SIMULATIONS OF SNIa

Fluid-dynamics code ALLA:
- Reactive-flow Eulerian hydrodynamics.
- Self-gravity.
- Exact EoS.
- 3-stage nuclear kinetics + neutronization of matter.
- Sub-grid model for sub-sonic turbulent burning.
- Parallel, cell-based, fully-threaded-tree AMR.
- Efficient: 10^8 SNIa simulation in less than a week on a 10-proc. cluster.



DEFLAGRATION



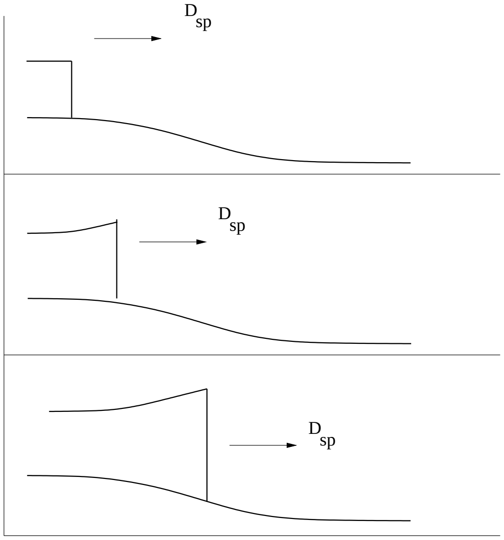
DEFLAGRATION-TO-DETONATION TRANSITION (DDT)

Spontaneous wave of burning: burning can propagate with *any* speed as a result of non-uniform initial condtions (Zeldovich). Spontaneous burning has been experimentally observed.

Suppose $T = T(x)$. Reaction rate R and reaction timescale $\tau = R^{-1}$ depend on T. Therefore reaction may spread spontaneously with a speed

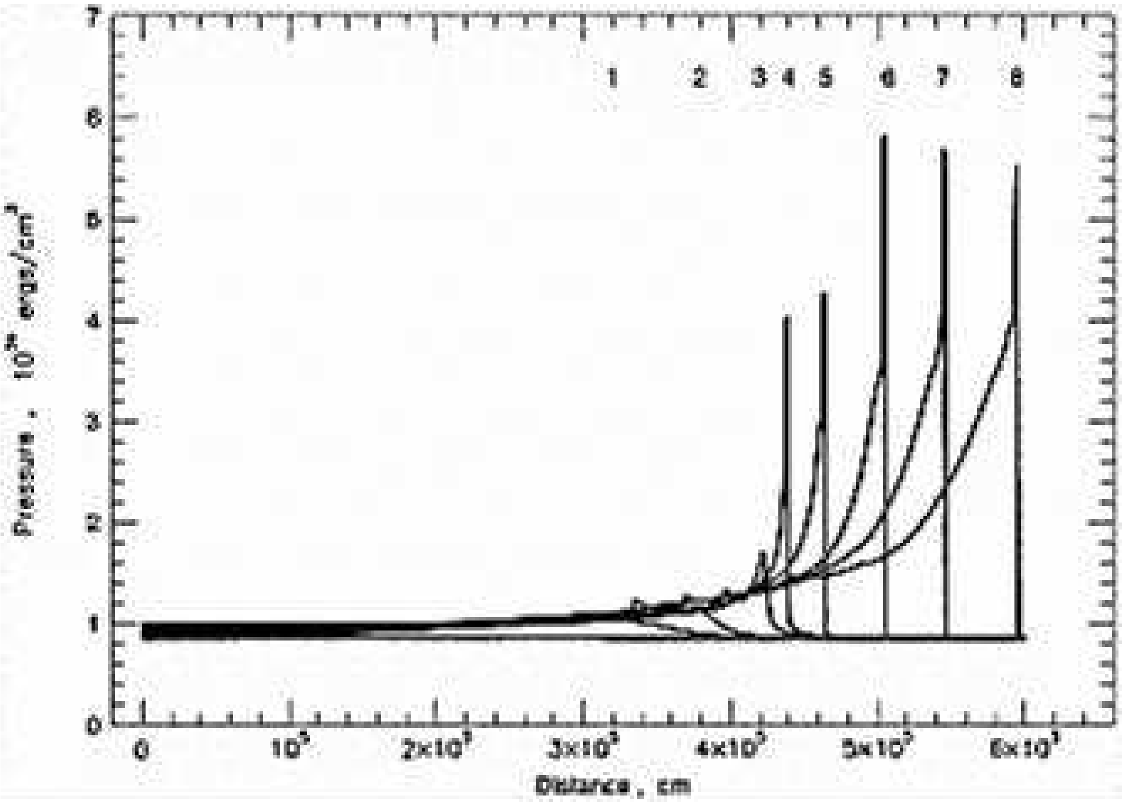
$$D_{sp} \simeq \left(\frac{\partial \tau(T(x))}{\partial x} \right)^{-1} . \tag{1}$$

For certain $T(x)$ spontaneous burning will spread supersonically, $S_{sp} \simeq a_s$, and then transition to a detonation.



CALCULATING DDT IN SNIa

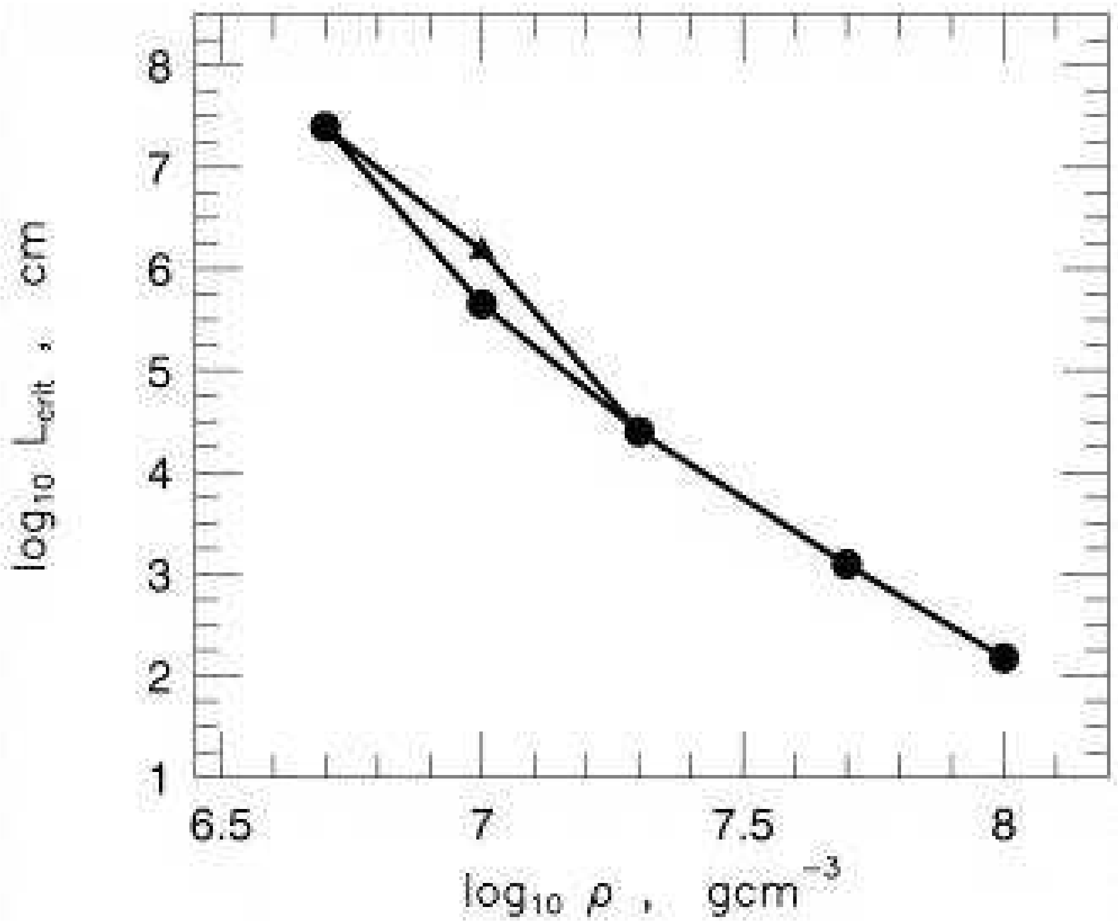
Given initial $T(x)$ in (1) it is easy to calculate spontaneous wave and transition to a detonation in a Type Ia supernova. It is possible to tell exactly if a given $T(x)$ will give rise to a detonation.



It is very difficult to calculate exact initial condition, $T(x)$ for DDT in a supernova for two reasons: (a) formation of $T(x)$ involves instabilities and turbulence, (b) we do not know initial conditions for calculating initial $T(x)$.

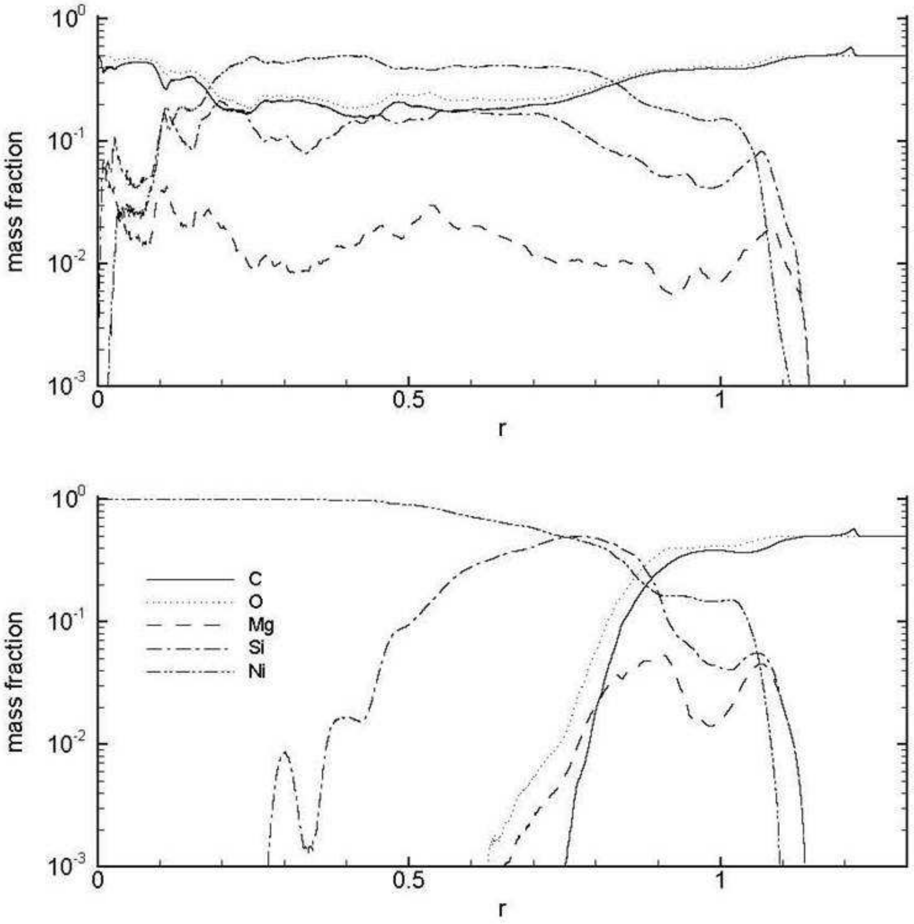
Most probably, formation of $T(x)$ is a probablilistic process and we will never be able to predict DDT in SNIa with 100% probability.

What we can do is to predict the most favorable conditions for DDT - where and when should we expect it to occur?



PREDICTIONS OF THE MODELS

Average composition



Relation between kinetic energy and Ni-mass

- In deflagration models $E_{kin} \propto M_{Ni}$.

- In DD models E_{kin} is approximately the same but M_{Ni} may vary depending on ρ_{tr}. Thus, DD models are able to explain correlations between maximum brightness, color, and postmaximum decline in SNIa.