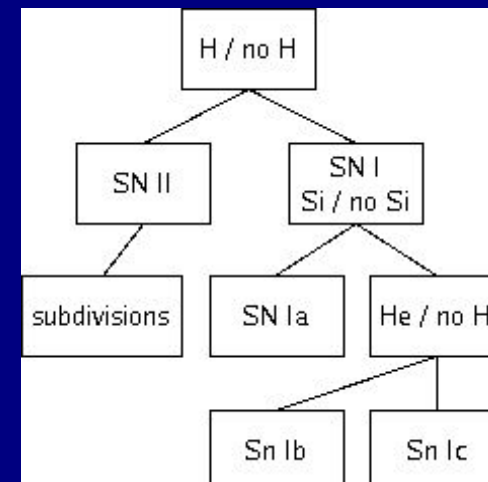


Nucleosynthesis in Thermonuclear Supernovae

Bernhard Müller, MPA Garching

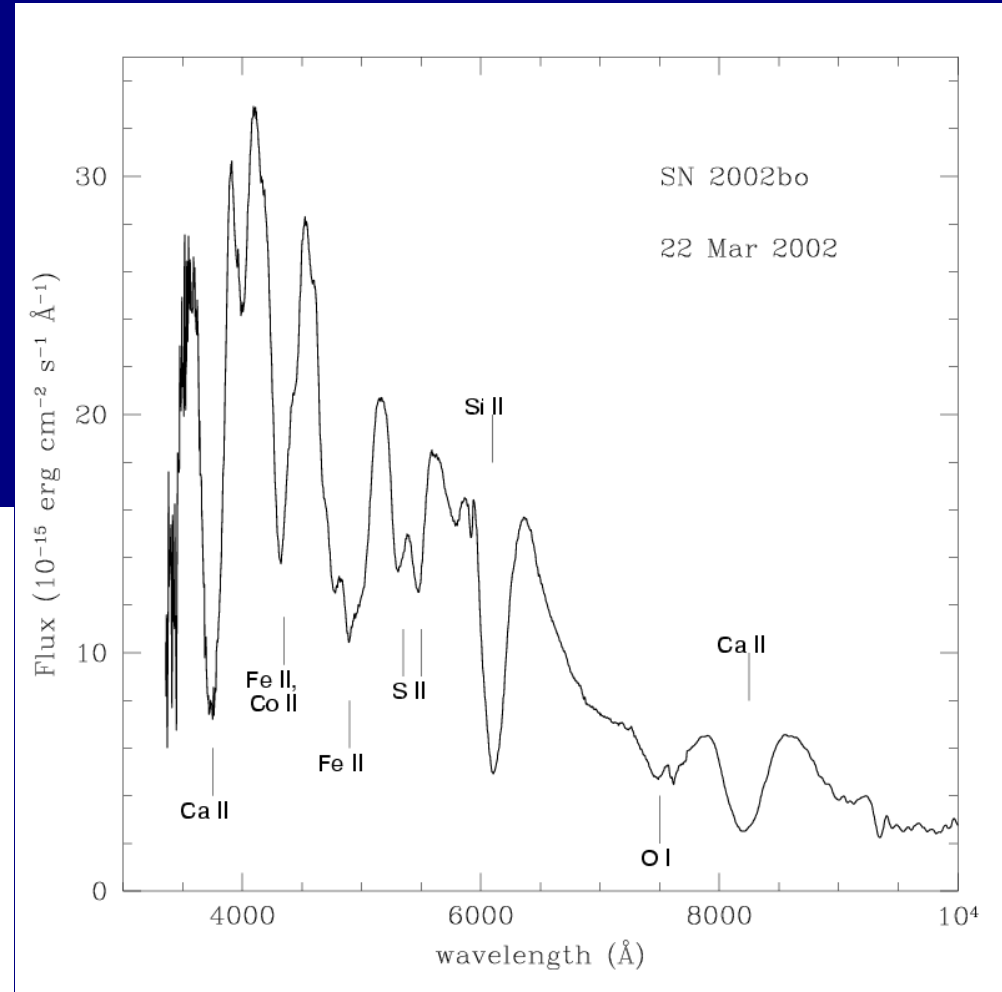
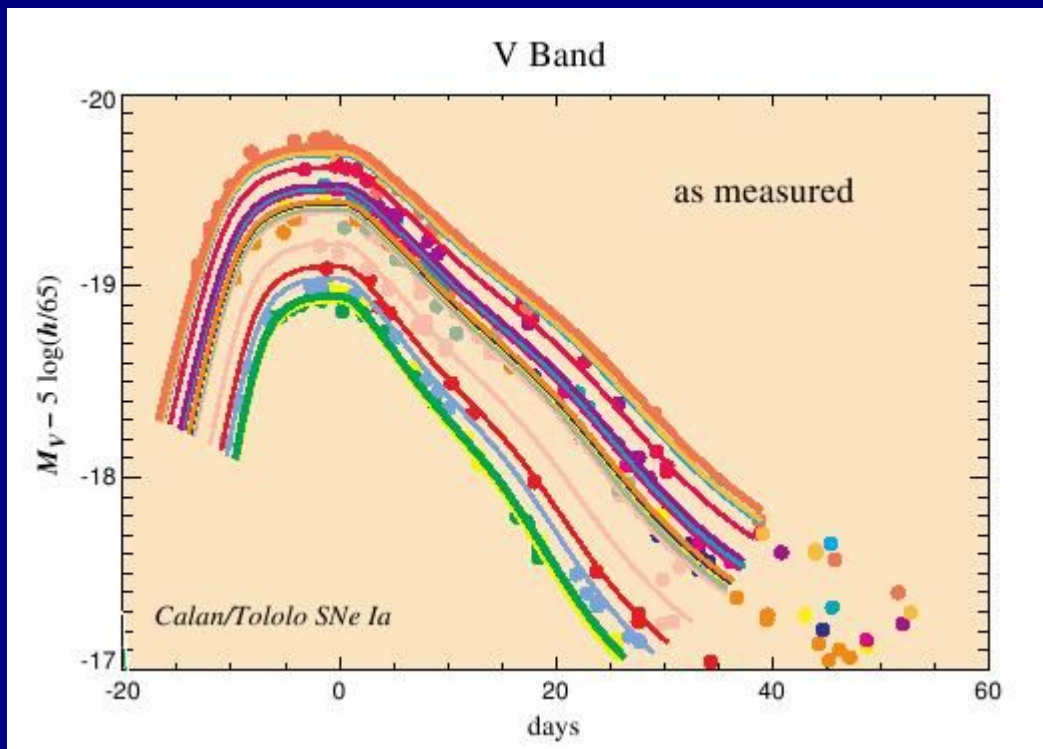
Introduction

- Supernovae classified according to maximum light spectra:
- Subclass Ia: small scatter in maximum luminosity → important as “standard candles” for cosmology
- SNe Ia originate from the mononuclear explosions of C+O white dwarfs, different scenarios possible:
 - Chandrasekhar mass models
 - Sub-Chandrasekhar mass models
 - White dwarf mergers



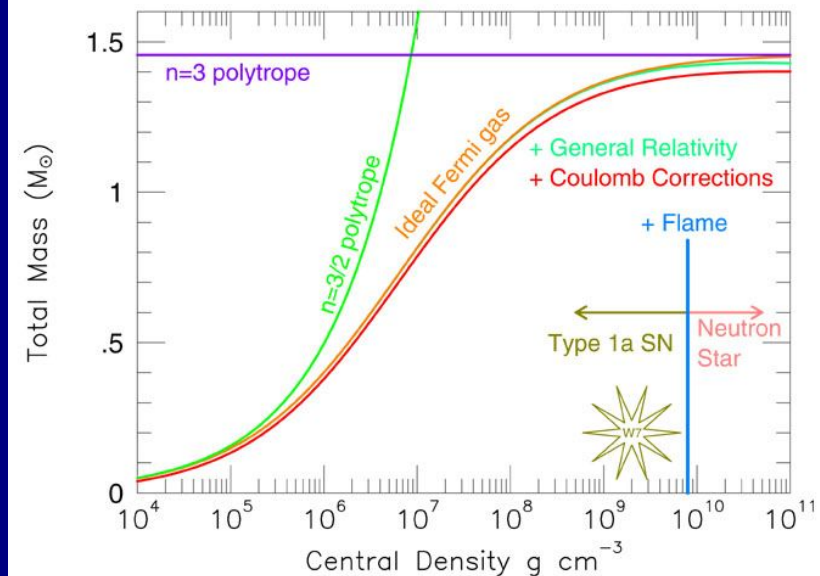
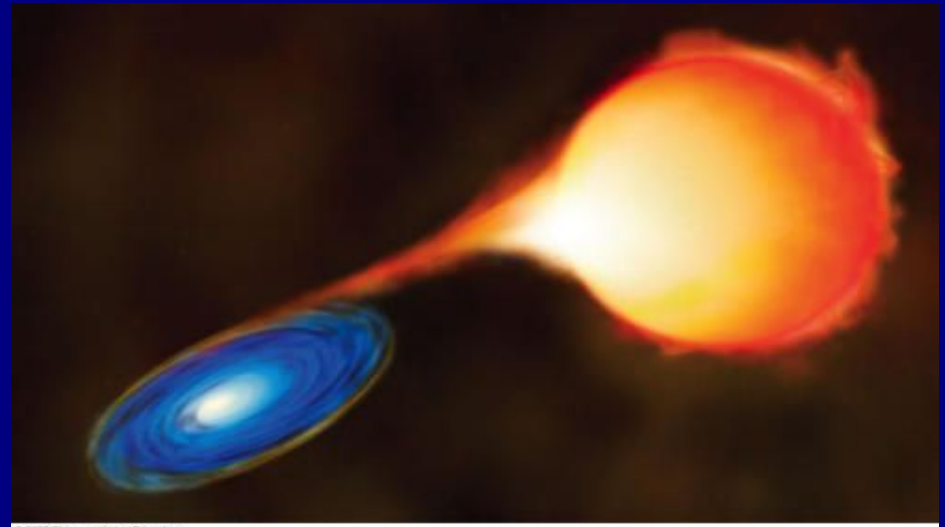
Observational Facts – What is synthesized?

- Lightcurve powered by decay $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$: estimation of produced mass of ^{56}Ni possible, usually a few $1/10 M_{\odot}$
- Spectra also indicate presence of intermediate mass elements



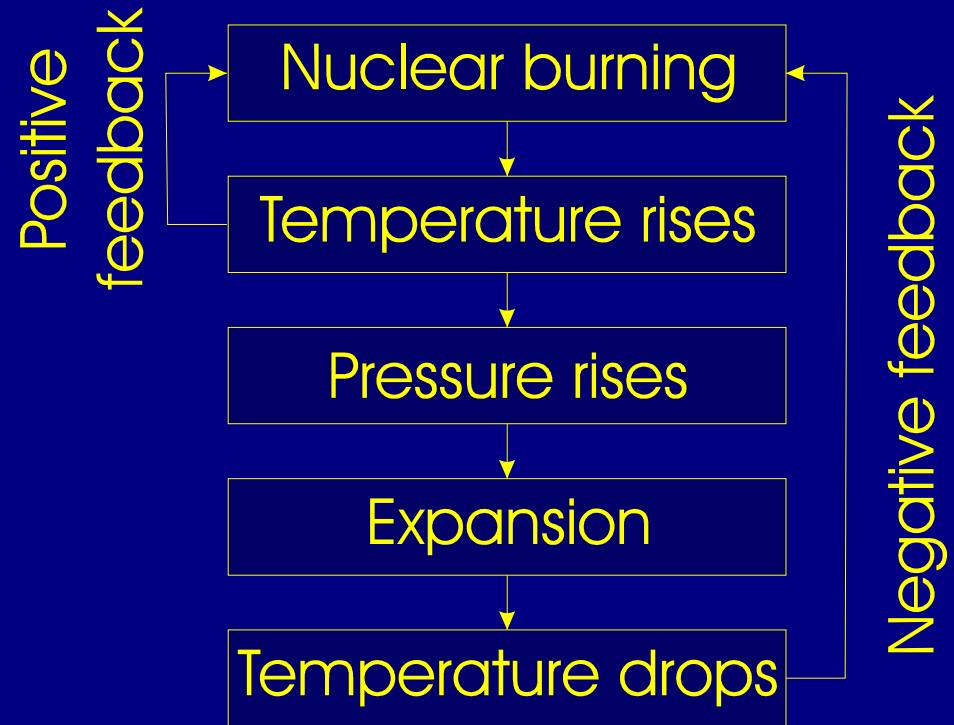
Basic Scenario – Chandrasekhar Mass Models

- White dwarf accretes H and He from companion star at an appropriate rate (avoid explosive hydrogen burning)
- Density and temperature increase significantly as M_{WD} approaches the Chandrasekhar mass
- Ignition of C possible as nuclear energy generation rate exceeds cooling losses
- Convective burning phase ensues



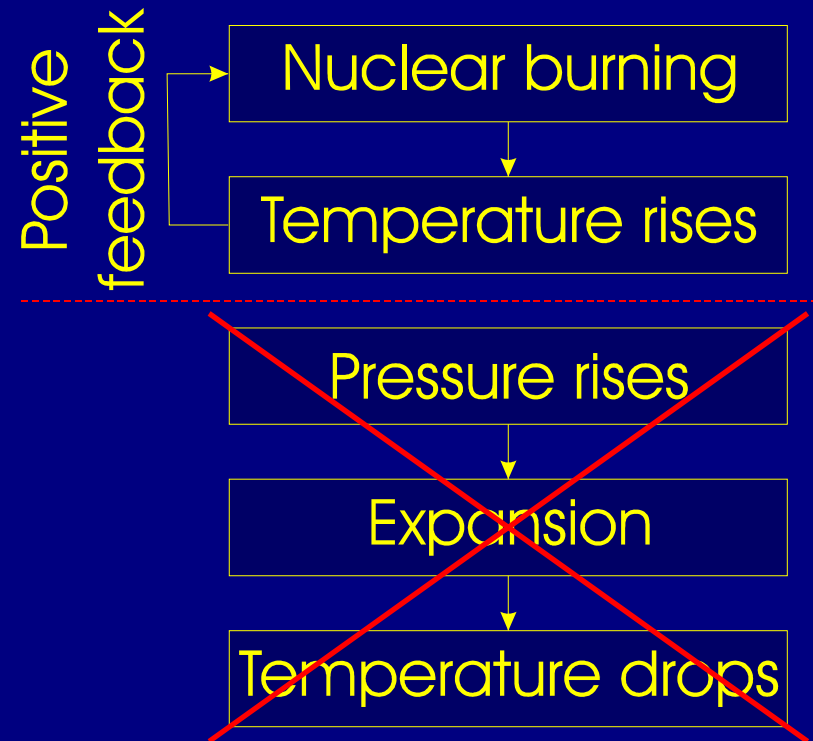
Thermonuclear Runaway

- In non-degenerate matter: self-regulation of nuclear burning



Thermonuclear Runaway

- In non-degenerate matter: self-regulation of nuclear burning
- In degenerate matter: lack of pressure feedback allows thermonuclear runaway



Final composition

- Nuclear reaction rates extremely sensitive to temperature (and density)
- $T=3\times 10^9\text{K}\dots 4\times 10^9\text{K}$: only C and Ne burn and produce ^{16}O , ^{24}Mg , ^{28}Si , etc.
- $T=4\times 10^9\text{K}\dots 5\times 10^9\text{K}$: O also burnt, ^{28}Si and few slightly heavier elements produced
- At higher temperatures (beyond $5\times 10^9\text{K}$): photodisintegration of ^{28}Si provides α -particles, subsequent α -captures build up heavier nuclei (iron group)
- Careful: thresholds always depends on typical dynamical time-scale! (values quoted for model W7 of Nomoto et al. (1984))

NSE and freeze-out

- At sufficiently high temperature: reactions involving α , p and n (and inverse processes) fast enough to maintain equilibrium distribution: condition for chemical potentials $\mu({}_N^A Z) = N \mu(n) + Z \mu(p)$
- Abundance of nucleus ${}_N^A Z$ with binding energy $B({}_N^A Z)$ determined by Saha equation:

$$Y({}_N^A Z) \sim G \frac{({}_N^A Z)}{2^A} \left(\frac{\rho}{T} \right)^{A-1} A^{3/2} \exp \left(\frac{B({}_N^A Z)}{T} \right) Y_n^N Y_p^Z$$

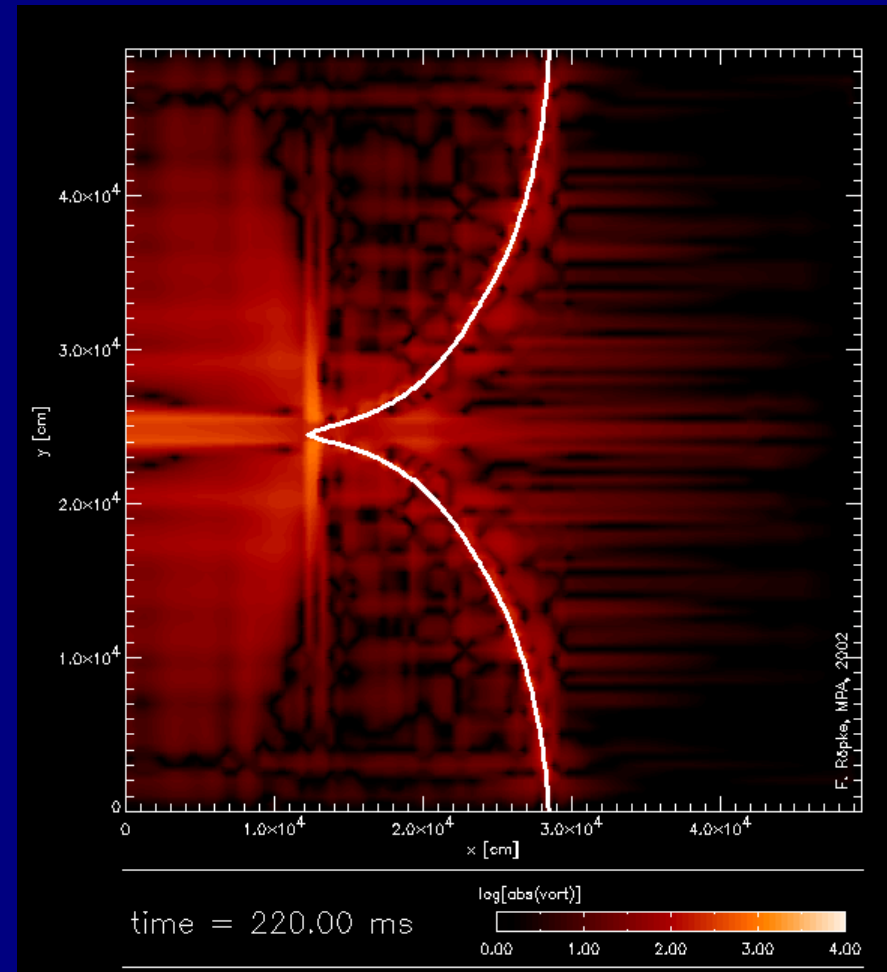
- Constraints: $\sum_i A_i Y_i = 1$; $\sum_i Z_i Y_i = Y_e$
- Weak interactions not in equilibrium: abundances still depend on *total* neutron-to-proton-ratio or, equivalently, the electron fraction Y_e
- Final abundances (more or less) determined by NSE composition at freeze-out temperature (where NSE breaks down)

Explosive Burning – Detonation or Deflagration?

- Detonation waves
 - unburned material ignited by shock compression
 - moves supersonically → no expansion of pre-shock material in WD
 - Hence: burning at high densities, only iron group elements produced
- Deflagration
 - ignition by diffusive heat transfer
 - moves subsonically, flame speed set by thermal diffusivity χ and burning time-scale τ : $v_{\text{flame}} \sim \sqrt{(\chi\tau)}/\tau$
 - laminar flame too slow to burn sufficient material into iron group elements and to unbind the WD

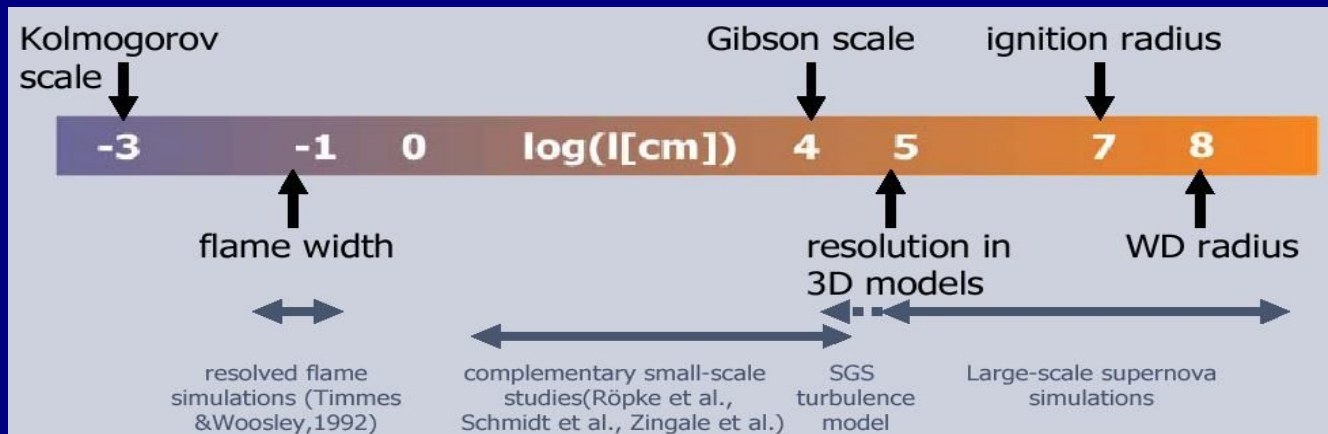
Turbulent Combustion

- Flame subject to hydrodynamical instabilities:
 - Landau-Darrieus instability of thin flames (stabilized in non-linear regime)
 - In SN Ia: low-density ashes below unburned material of higher density \rightarrow Rayleigh-Taylor instability \rightarrow full turbulence
- Instabilities increase the flame's surface, and hence its velocity



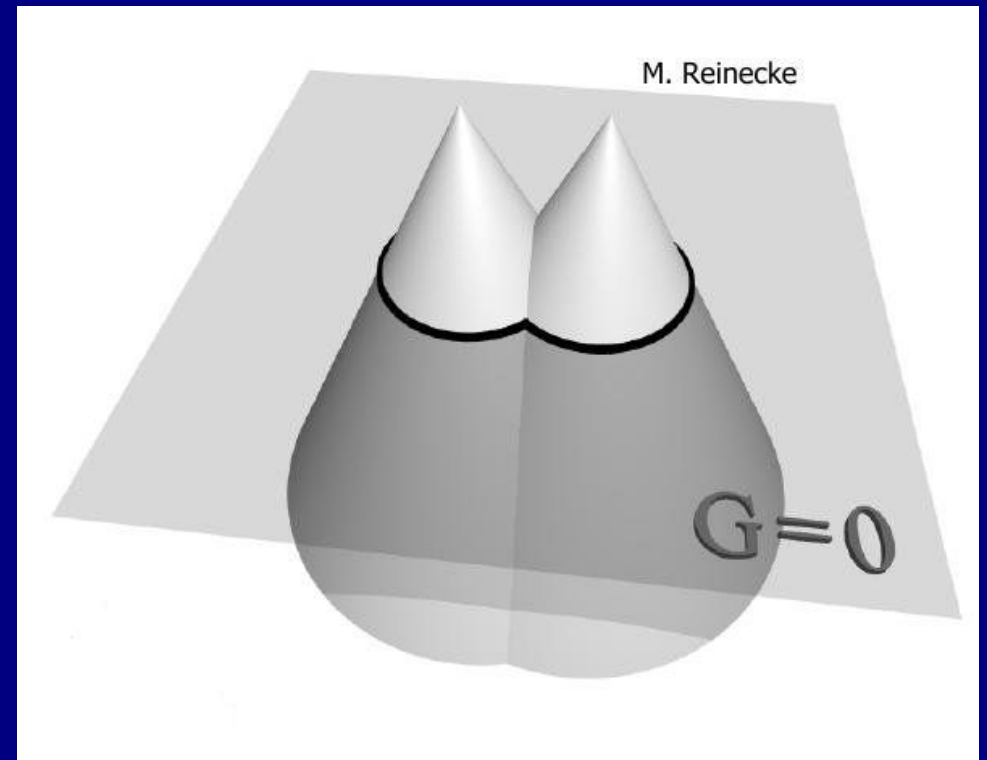
Turbulent Combustion

- RT and Kelvin-Helmholtz instabilities induce turbulent cascade with Kolmogorov scaling for mean velocity of turbulent eddies: $v_T \sim l^{1/3}$
- $v_T > v_{\text{flame}}$ above *Gibson scale*
 l_{Gibs} : turbulent motions wrinkle and increase flame surface
- For $l \gg l_{\text{Gibs}}$: only $v_T(l)$ determines effective flame speed
- At late stages: transition to distributed burning possible ($l_{\text{Gibs}} < d_{\text{flame}}$), above treatment no longer applies

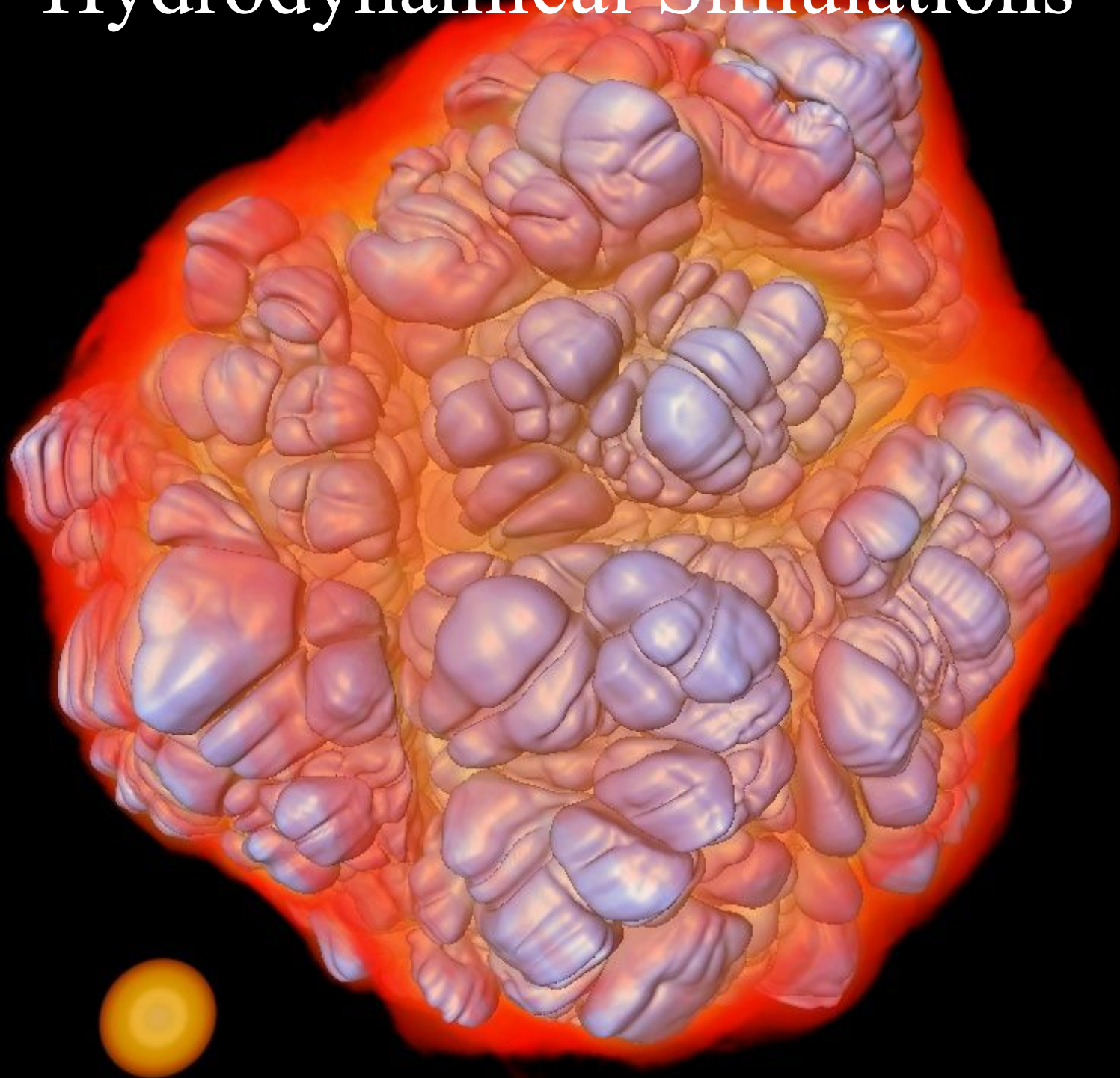


Hydrodynamical Simulations

- Impossible to resolve flame (width $\approx 1\text{mm}$) in full-scale simulation of White Dwarf ($r \approx 10^8\text{cm}$)
- Flame modelled as discontinuity, propagated using level-set method (alternatives: reaction-diffusion methods...)
- Flame speed determined by sub-grid model for turbulence
- Simplified treatment of chemical composition: only α , ^{12}C , ^{16}O , Mg, Ni considered

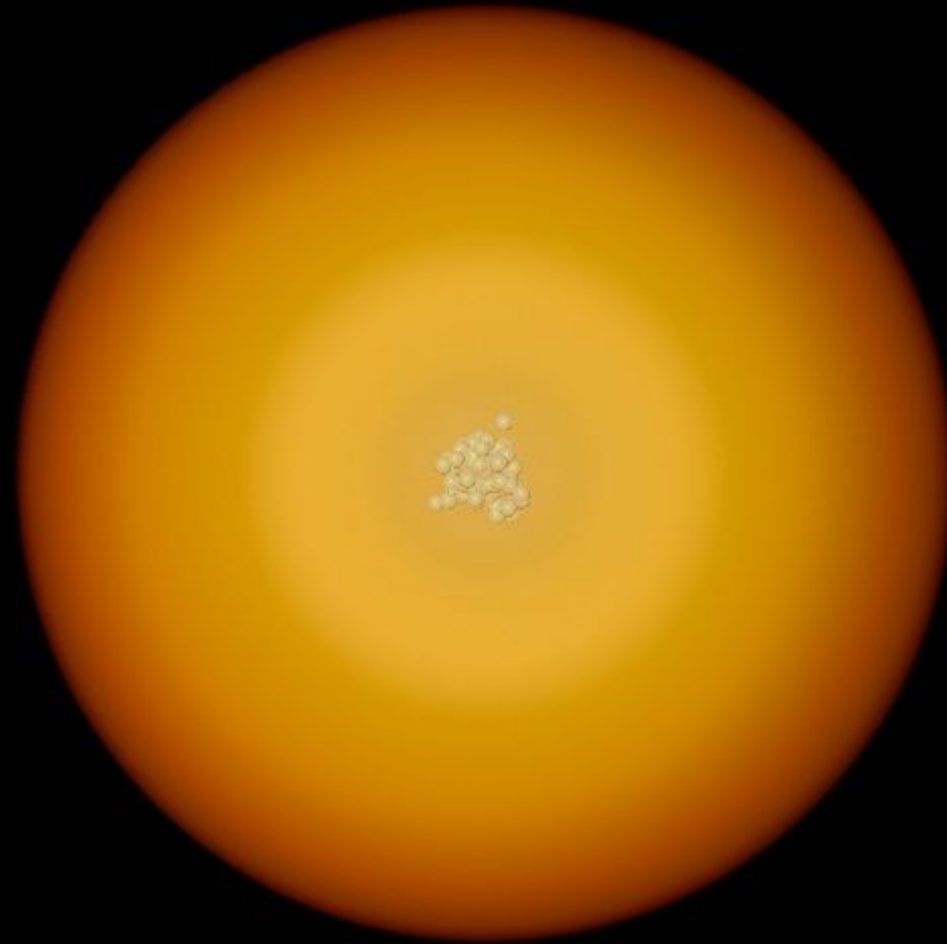


Hydrodynamical Simulations



full 3D model
($t=2s$)

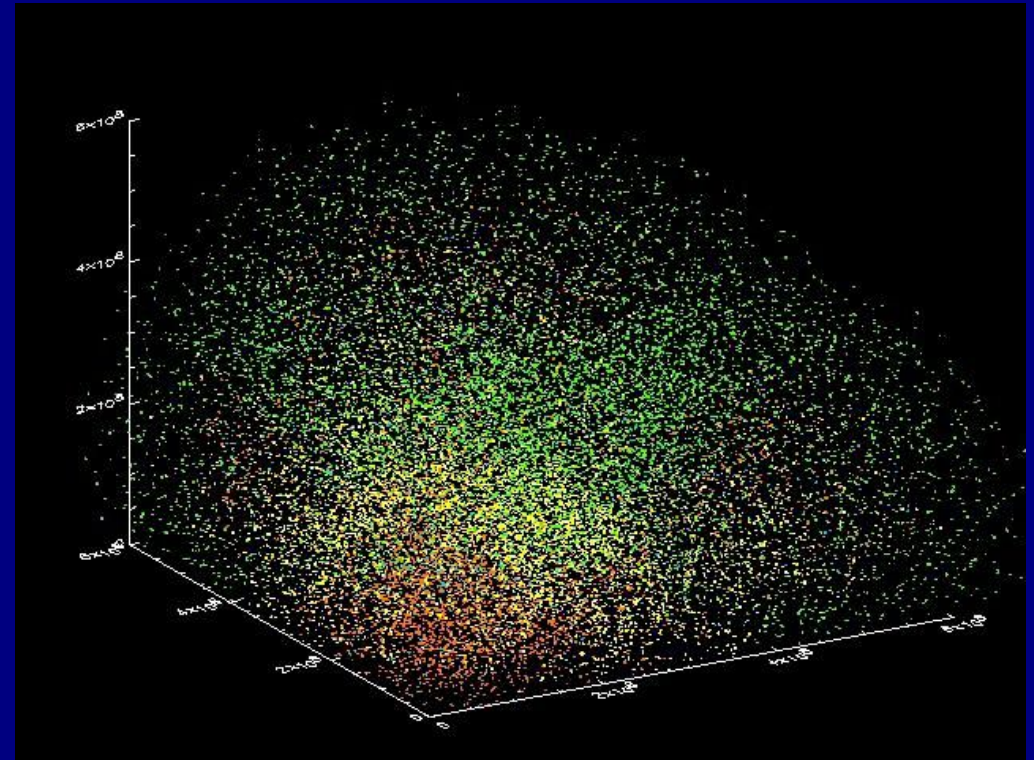
Hydrodynamical Simulations



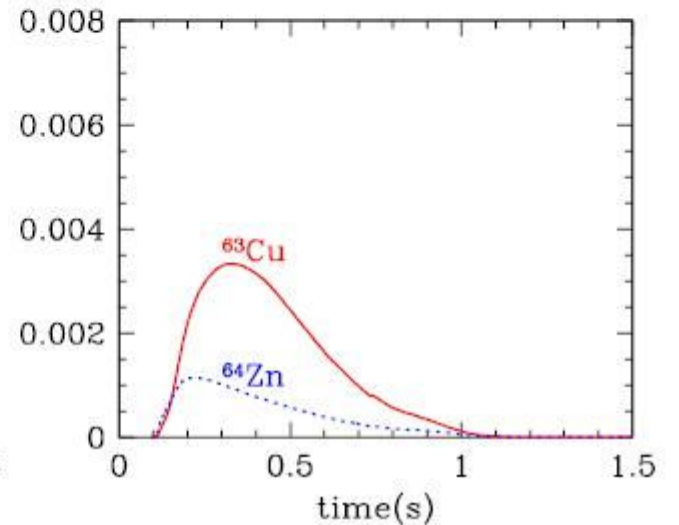
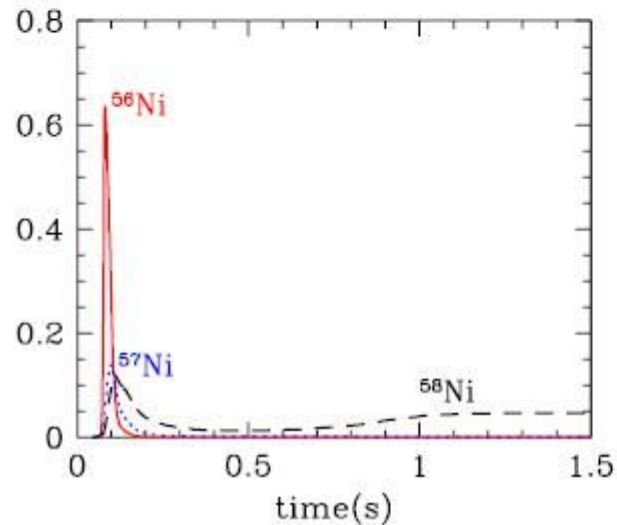
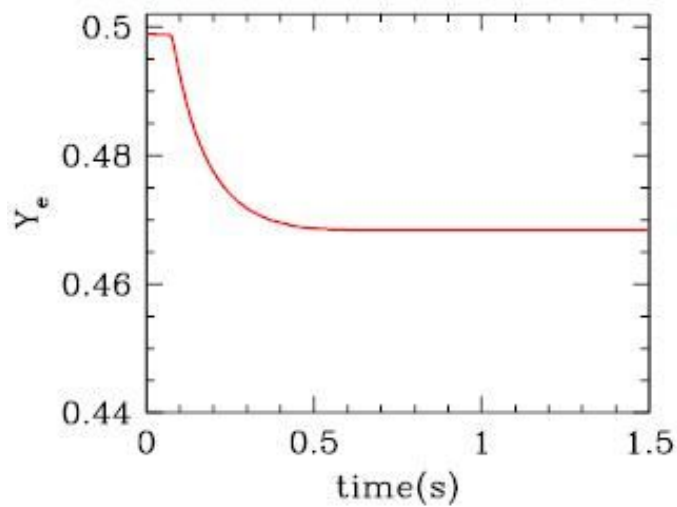
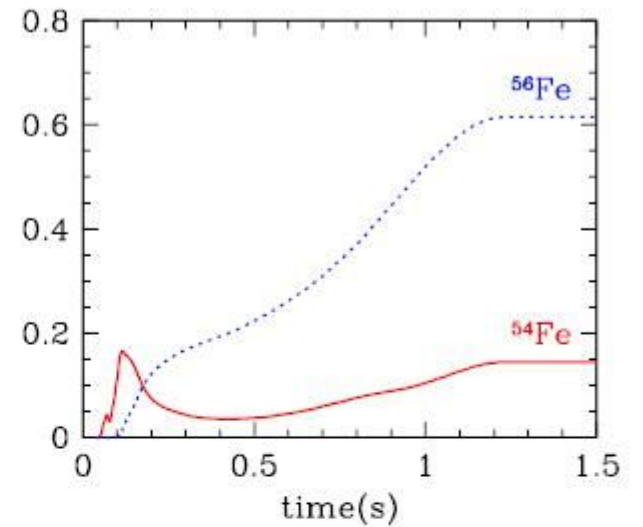
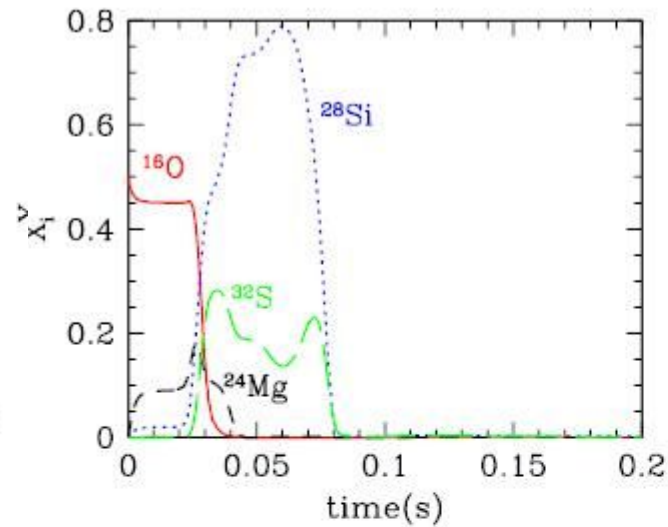
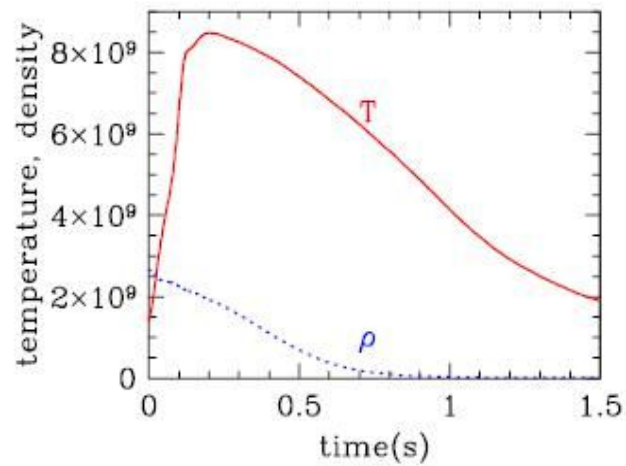
full 3D model
(start of
simulation)

Analysis of Nucleosynthesis in Thermonuclear Supernovae

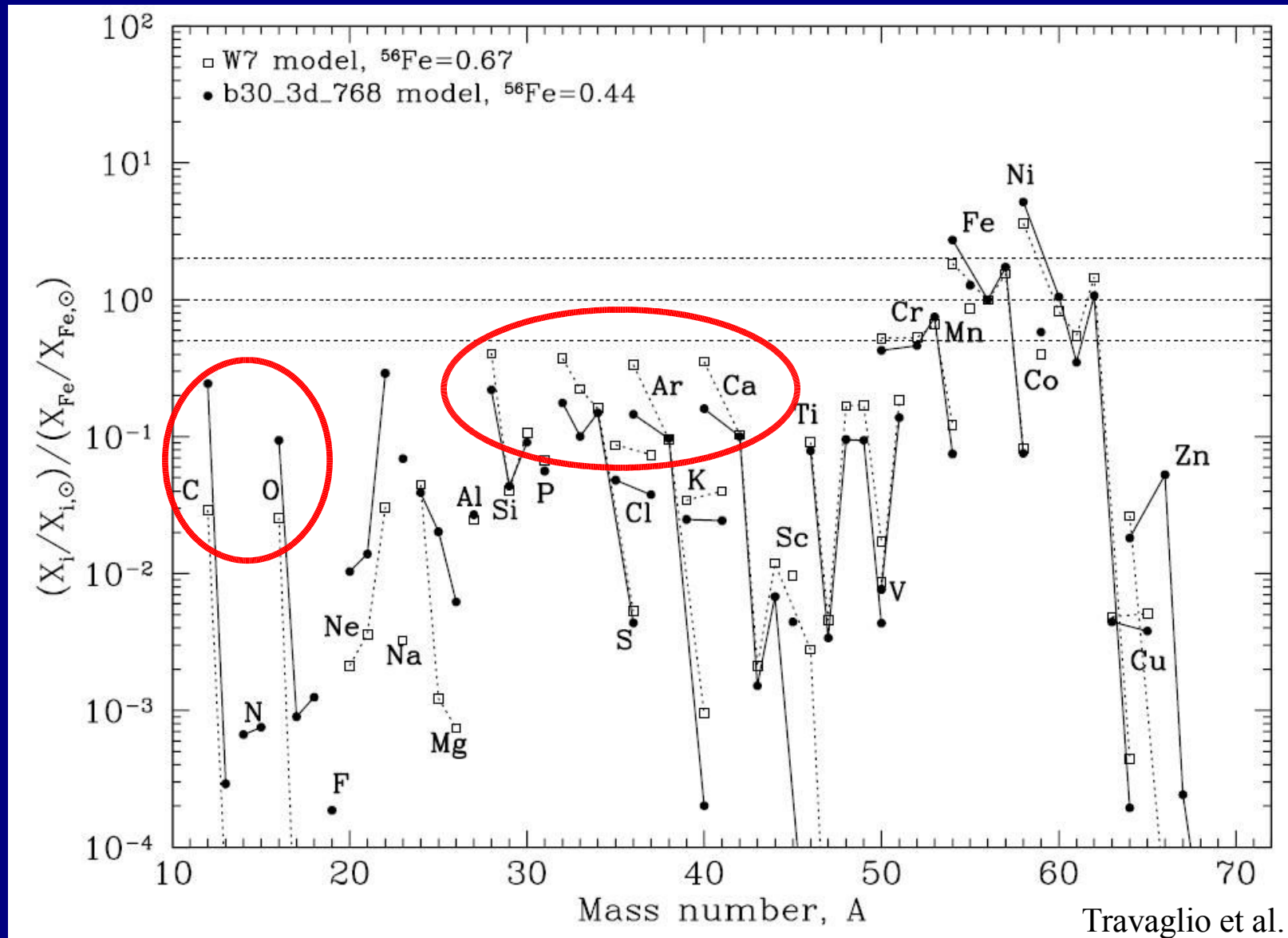
- Detailed nucleosynthesis studies: larger networks needed
- Evolve nuclear abundances for *tracer particles* advected with the flow according to their (ρ, T) -history in a post-processing step
- Example: Travaglio et al. (2004):
 - 19683 tracer particles (compare numer of grid cells: 16777216)
 - network with 383 species (up to ^{98}Mo) and inclusion of electron capture rates



Evolution of a tracer particle



Production factors compared to “tuned” 1D results

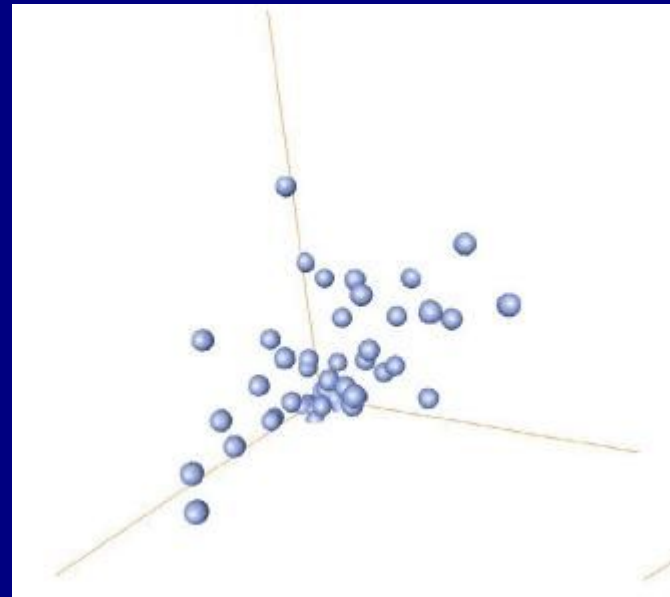


Comparison to “tuned” 1D results

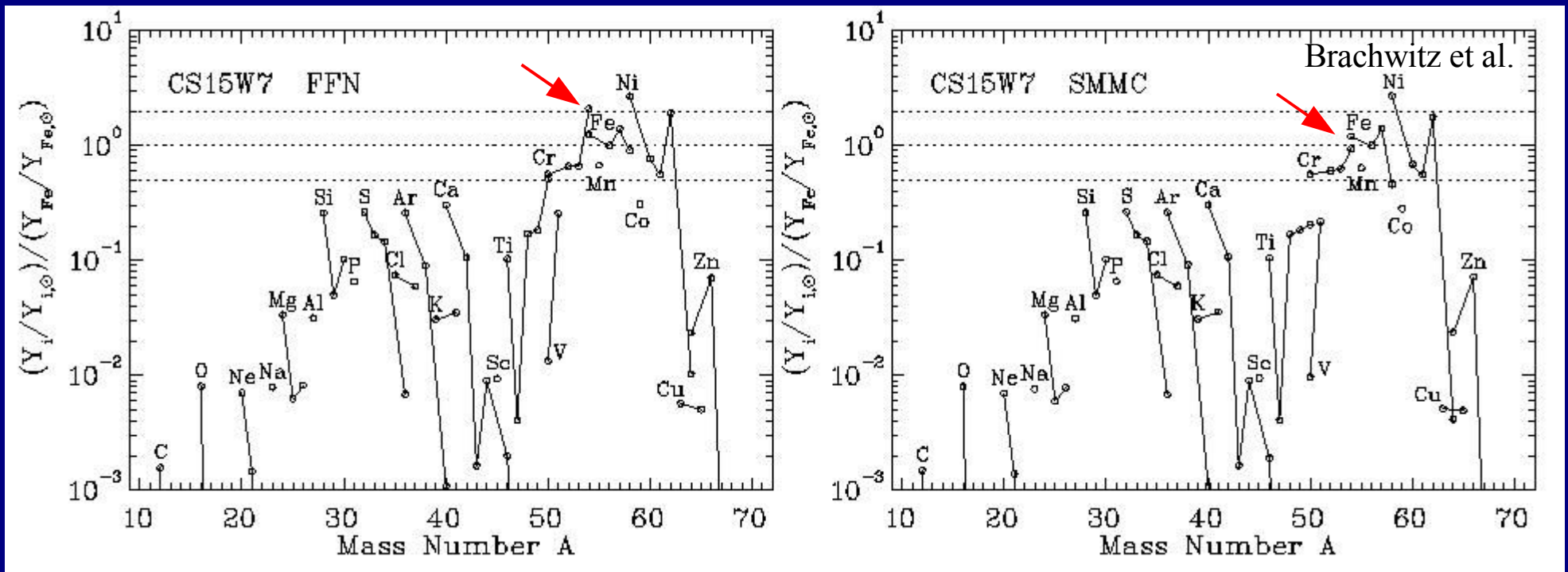
- Different amount of unburned C, O and for C/O ratio
- Weaker production of some intermediate mass elements (S, Cl, Ar, K, Ca)
- Overall: realistic nucleosynthesis results for current multi-dimensional explosion models

Model Variation – Effects on Nucleosynthesis results

- Number, form and position of ignition spots are still free parameters!
- Agreement with “standard” model (mass of ^{56}Ni and of unburned C and O) seem to require a reasonably high number of ignition spots (30 or more)
- C/O ratio in WD does not strongly affect Ni-mass
- Metallicity Z may influence final composition through initial abundance of ^{22}Ne : 20% variation of Ni mass possible for $Z/Z_{\odot}=0.5\dots3$



Influence of Nuclear physics



FFN (Fuller, Fowler & Newman) reaction rates

shell model calculation

Improved electron capture rates reduce overproduction of certain neutron-rich nuclei

References

- Hillebrandt&Niemeyer, “Type Ia Supernova Explosion Models”, *Ann.Rev.Astron.Astrophys.* 38 (2000) 191
- Röpke, “Multi-dimensional numerical simulations of type Ia supernova explosions”, *Rev.Mod.Astron.* 19 (2006) 127
- Nomoto et al., *APJ* 286 (1984) 644
- Nomoto et al., *APJ* 279 (1984) L23
- Travaglio et al., *APJ* 425 (2004) 1029
- Iwamoto et al., *APJS* 125 (1999) 439
- Brachwitz et al. *APJ* 536 (2000) 934
- Steiner & Gaudsichy (ed.), *Computational Method for Astrophysical Fluid Flow* (Springer)
- Arnett, *Supernovae and Nucleosynthesis* (Princeton University Press)
- Movies: www.mpa-garching.mpg.de/~wfh/SN-movies/