Type Ia Supernovae

Astrophysical Seminar

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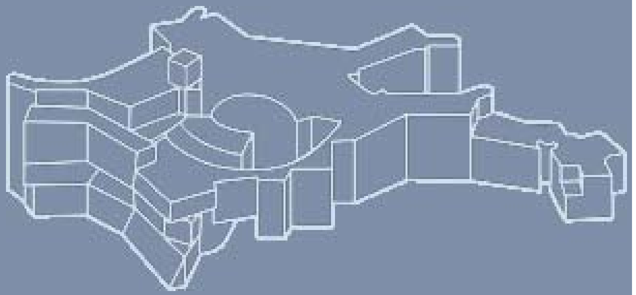


The challenge

1. Cosmology

- new cosmological standard picture initiated by SN Ia measurements
- undone homework to SN Ia community: explain peak luminosity-light curve shape relation used to calibrate cosmological distance measurements

- next step: can dark energy equation of state be constrained by SN Ia observations?
- No, unless we can control the systematics.
- only way to get a handle on the systematics: modeling from "first principles" (→ 3d neccessary) in conjunction with high quality observations of nearby objects

The challenge: nearby observations

2. Observations of nearby objects

- over past years reached quality so that it is possible to constrain/discriminate between models

  (MPA contribution via European Research Training Network) → especially spectroscopic data
- 3 examples:

Example 1: Late time (nebular) spectra (Kozma et al., in prep.)

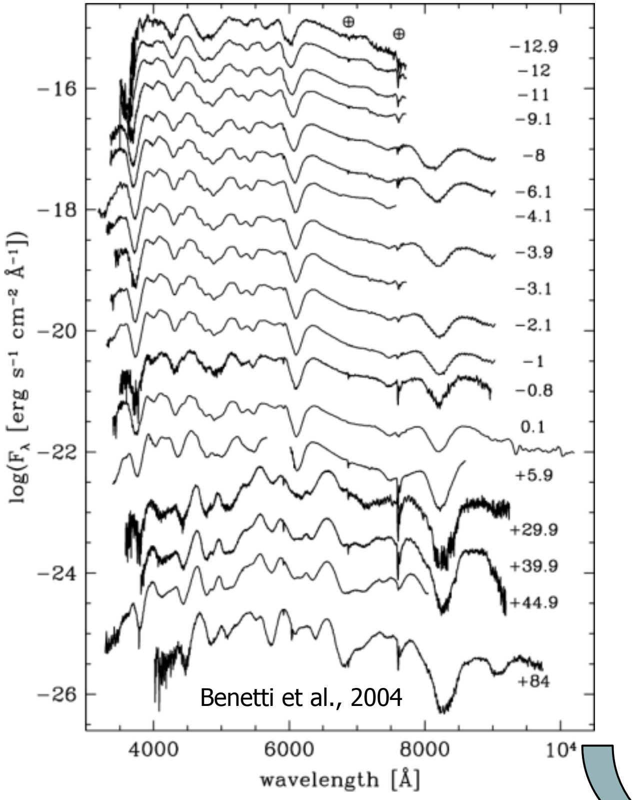
- look into the center of the explosion products → hints for explosion mechanism

Example 2: Spectropolarimetry (e.g. Wang et al., 2004)

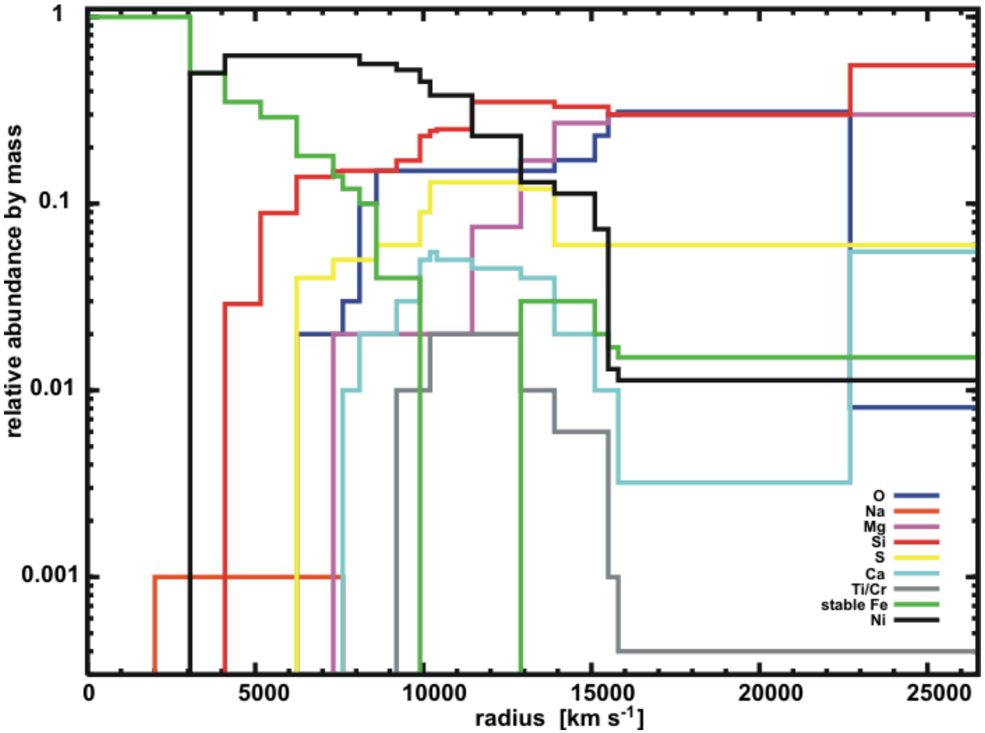
- provide information on multi-dimensional structure of explosion

The challenge: nearby observations

Example 3: Abundance tomography of SN 2002bo (M. Stehle et al., 2004)



Benetti et al., 2004



spectral modeling

Astrophysical Scenario

- no hydrogen in the spectra
- huge energy release ($\sim$ 1 foe)
- uniform properties → standard candles?
- no compact remnant, occur in young and old populations

→ thermonuclear explosion of white dwarf star

- How can WD reach state to trigger thermonuclear explosion?

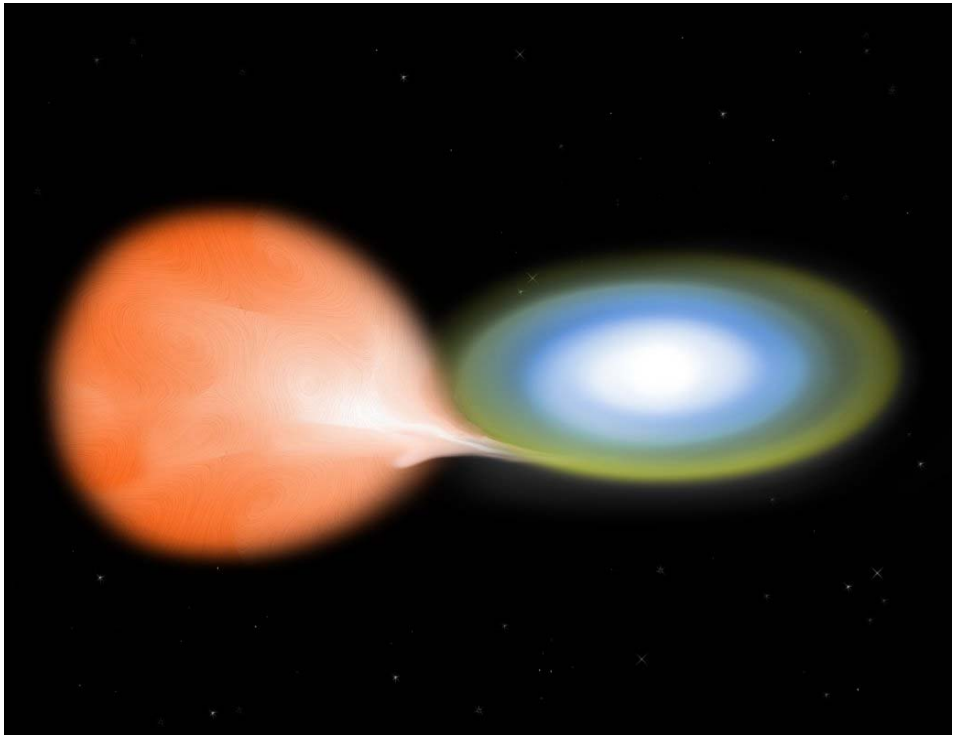
scenarios:

- double degenerate (DD): 2 WDs merge, smaller is disrupted and accreted onto more massive companion, high rate expected, natural way to aviod hydrogen in spectra

  problem: too high accretion rate → C-shell flash → ONeMg WD → collapse

Astrophysical scenario

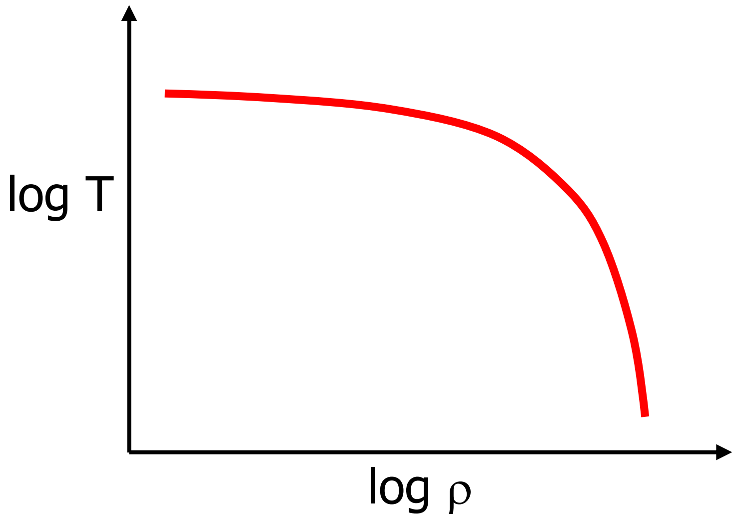
- single degenerate (SD): C/O WD accretes matter from non-degenerate binary companion (MS or AGB?)
  - sub-Chandrasekhar: WD composed of C/O center and He-shell, He-shell detonation converges in center, triggers detonation, high rate expected
    multi-d problem, nucleosynthesis not consistent with main channel
  - Chandrasekhar: accretion until WD reaches Chandrasekhar mass, candidates: supersoft sources (U Sco), cataclysmic binaries
    problem: too low rate



Astrophysical scenario

ignition

- accretion until close to M_{Ch}
- densities reach values of carbon ignition



- convective burning until energy generation exceeds convective cooling
- thermonuclear runaway in small spatial region
- flame formation (central, multi-spot???)

Astrophysical scenario

flame propagation

- hydrodynamics: 2 modes:

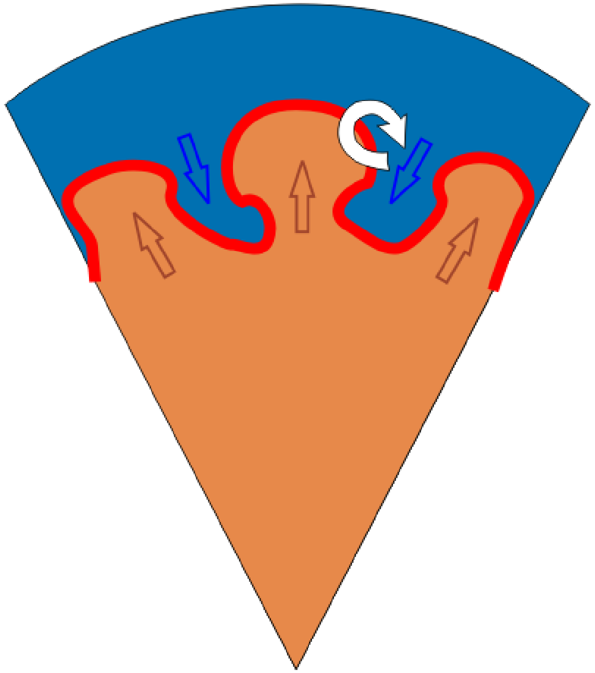
deflagration
subsonic
flame mediated by thermal conduction of e^-

detonation
(super)sonic
flame driven by shock waves

- pure detonation would produce wrong composition of explosion products (Arnett, 1969)
- flame starts out as deflagration
- problem: laminar deflagration flame too slow

Astrophysical scenario

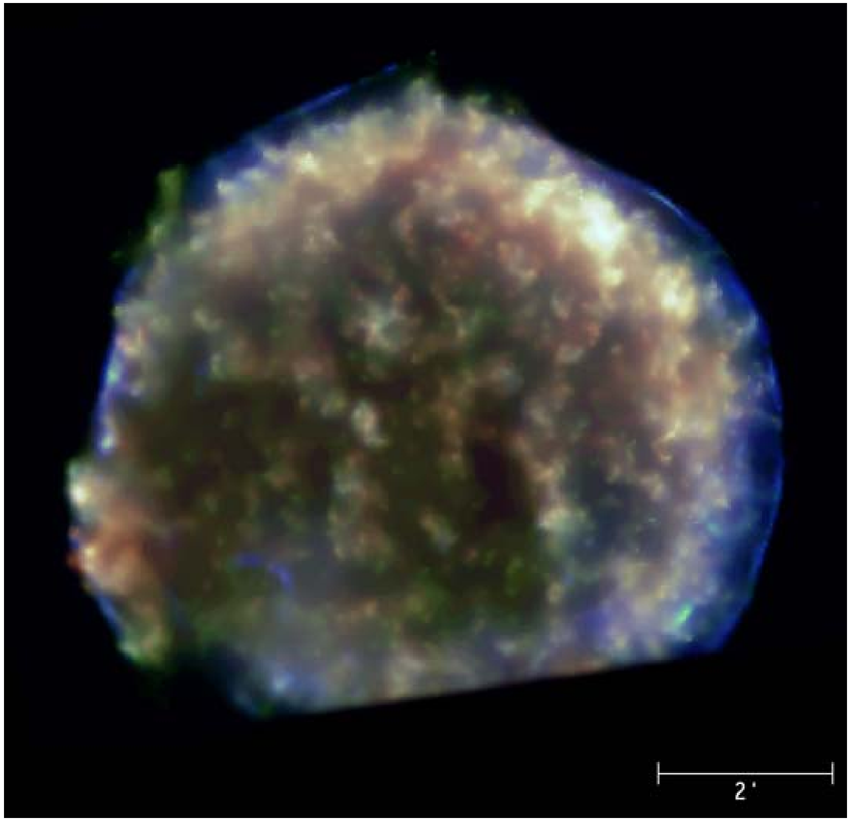
- interaction of flame with turbulence → turbulent combustion
- Re $\sim 10^{14}$ → instabilities generate turbulence

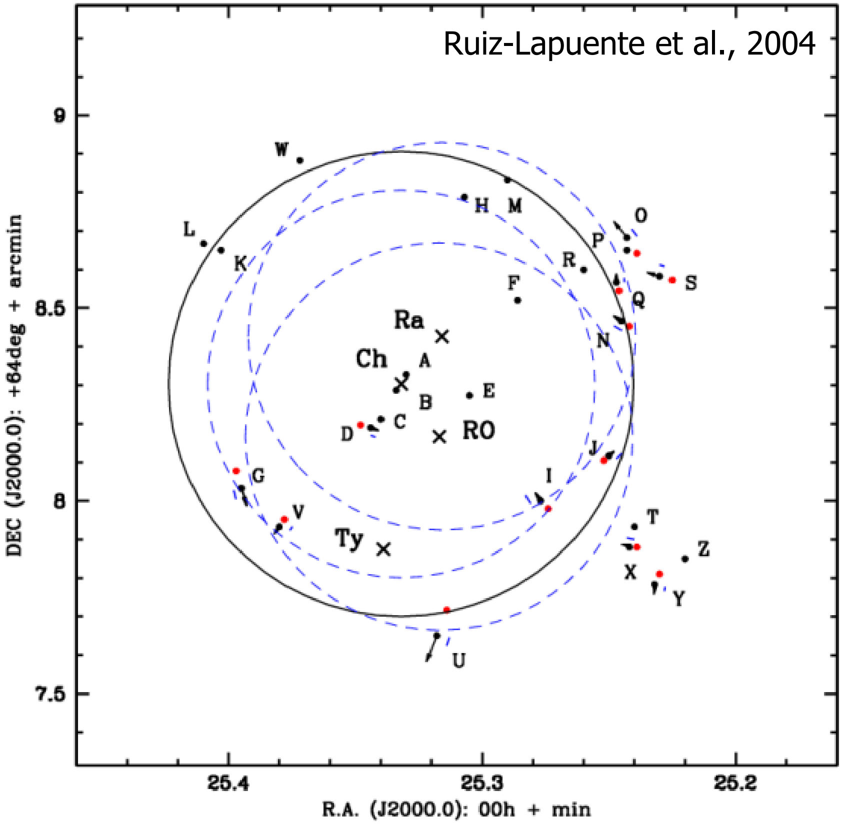


- wrinkling of the flame front → flame surface ↑ → net burning rate ↑ → flame propagation strongly accelerated
- later transition to (supersonic) detonation?

Astrophysical scenario

- thermonuclear burning disrupts WD
- diffuse cloud of ejecta but no compact remnant → remnant of Tycho's supernova (1572)

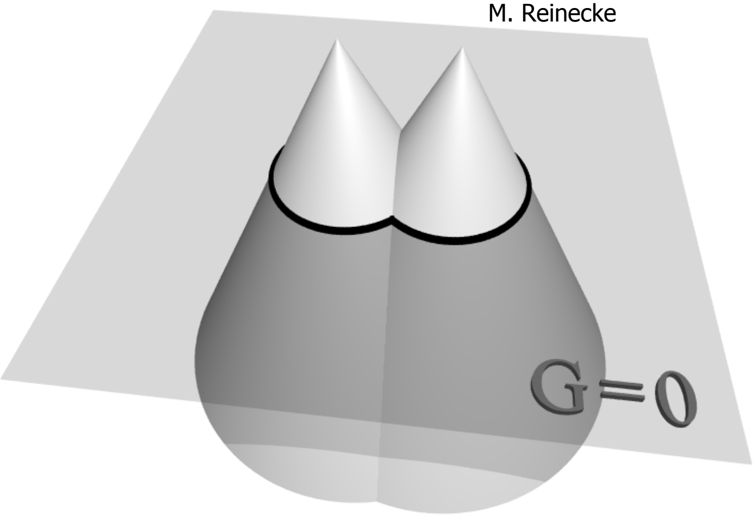



Ruiz-Lapuente et al., 2004

Numerical techniques

explosion model (Reinecke et al., 1999, 2002)

- hydrodynamics: finite volume approach → PROMETHEUS (Fryxell et al., 1989) implementation of PPM (Colella & Woodward, 1984)
- turbulence on unresolves scales implemented via sub-grid scale model
- flame model: WD ~ 10^8 cm structure of flame ~ 1mm → not resolvable → modeled as discontinuity between fuel and ashes
- level set method


M. Reinecke

- "flamelet regime" of combustion: turbulent flame propagation velocity determined from sub-grid scale model

Numerical techniques

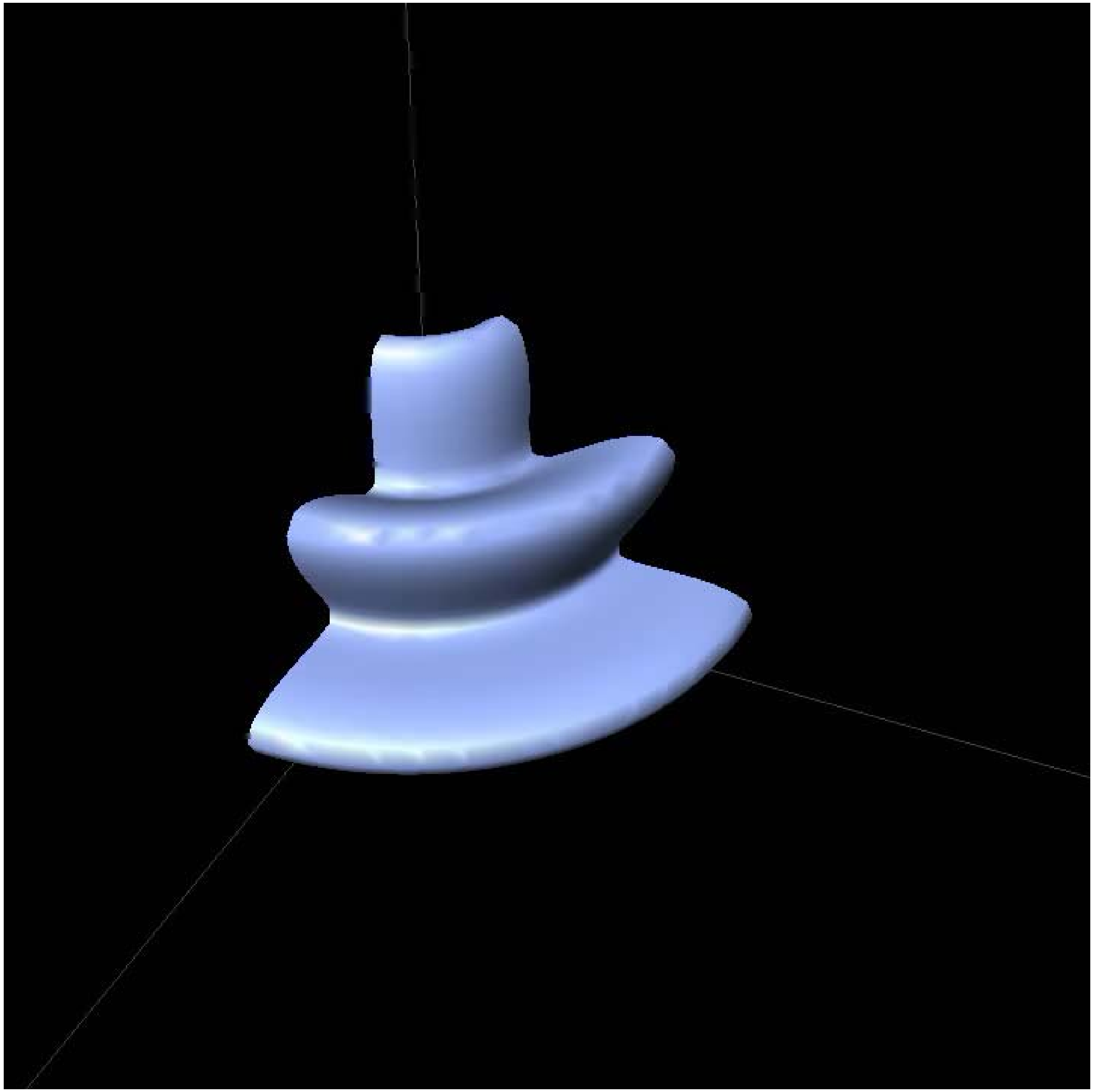
- simplified description of nuclear burning (Reinecke, 2002):
  - include 5 species: ^{12}C, ^{16}O, "Mg" → intermediate mass elements, "Ni" → iron group elements, α-particles
  - at high ρ_{fuel} burn to NSE consisting of "Ni" and α
  - for $\rho_{\mathrm{fuel}} < 5.25 \times 10^7$ g cm^{-3} burn to "Mg"
  - for $\rho_{\mathrm{fuel}} < 1 \times 10^7$ g cm^{-3} burning is no longer followed

nucleosynthesis postprocessing (C.Travaglio, 2004, M. Gieseler)

- record evolution of density, energy, temperature by tracer particles equally distributed in mass shells (Lagrangian component in Eulerian explosion code)
- use tracer information to perform nuclear postprocessing with nuclear reaction network (384 isotopes) provided by F.K. Thielemann

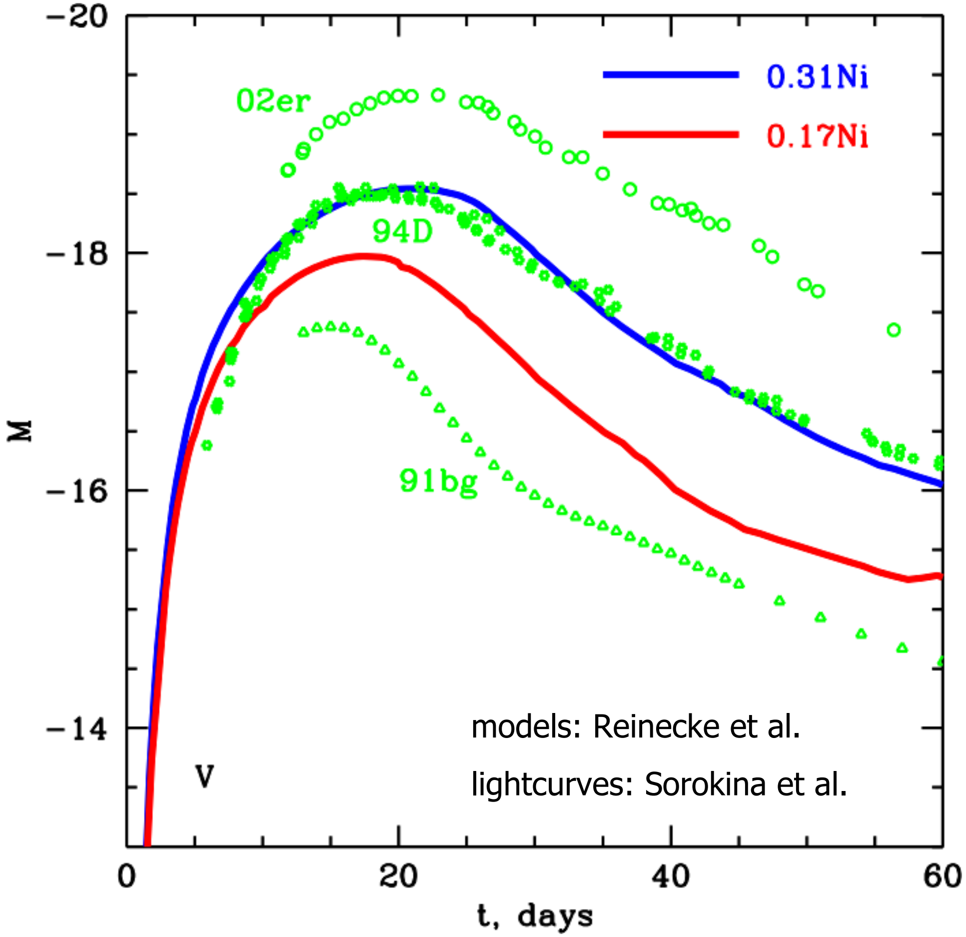
Simulation

- isosurface represents flame front



Status of modeling

- synthetic light curves:



models: Reinecke et al.

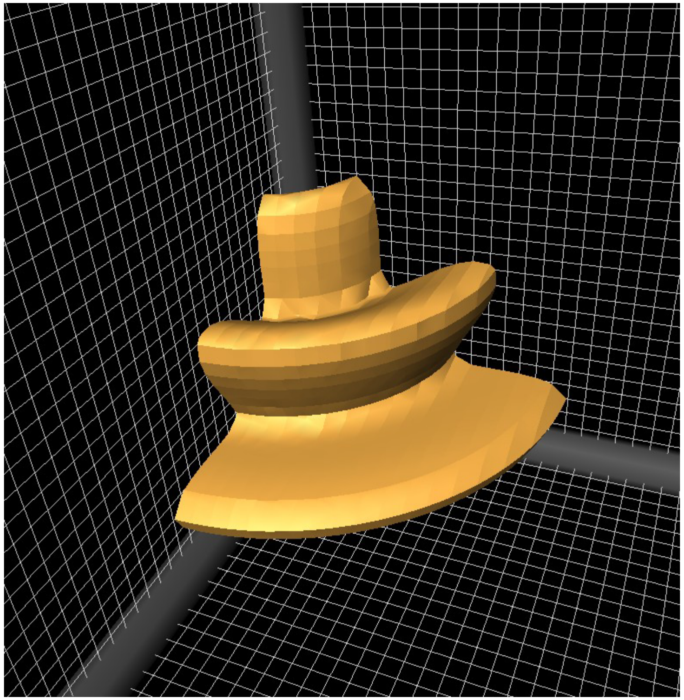
lightcurves: Sorokina et al.

- "best model" (b30, M. Reinecke, 2003): 0.4 $M_\odot$ of ^{56}Ni, 0.7 foe

Simulations

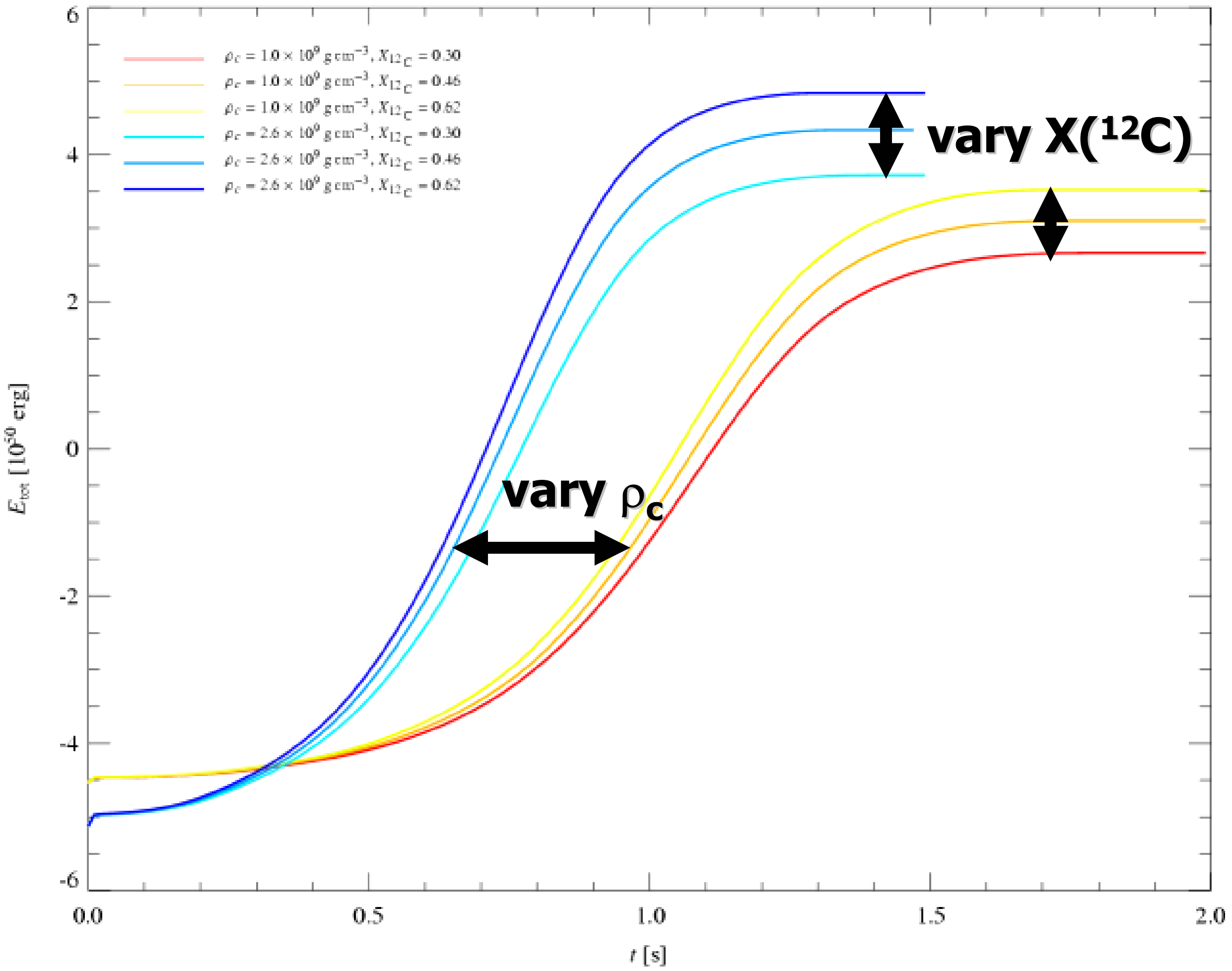
parameter study with 3D models (Röpke et al., 2004 and in prep.)

- Which parameters can account for SN Ia diversity?
  1. progenitor's carbon-to-oxygen ratio → $X(^{12}C) = 0.3, 0.46, 0.62$
  2. central density at ignition → $\rho_c = [1.0, 2.6] \times 10^9$ g cm^{-3}
  3. progenitor's metallicity (Timmes et al. 2003) → $Z = 0.5, 1.0, 3.0\, Z_\odot$
     → ^{22}Ne fraction
  4. rotation
  5. flame ignition ...
- change parameters independently to study effects (but of course in a realistic scenario interrelated → here: not based on stellar evolution of progenitor)
- simplified setup



Results

- temporal evolution of explosion energy

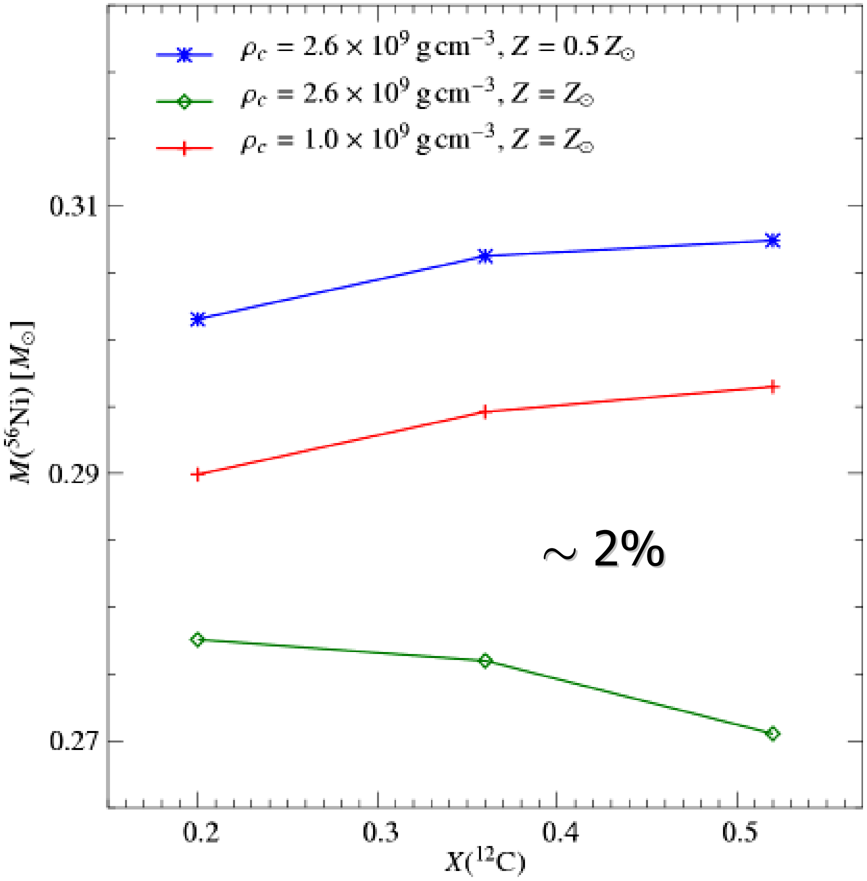


vary X(^{12}C)

vary ρ_c

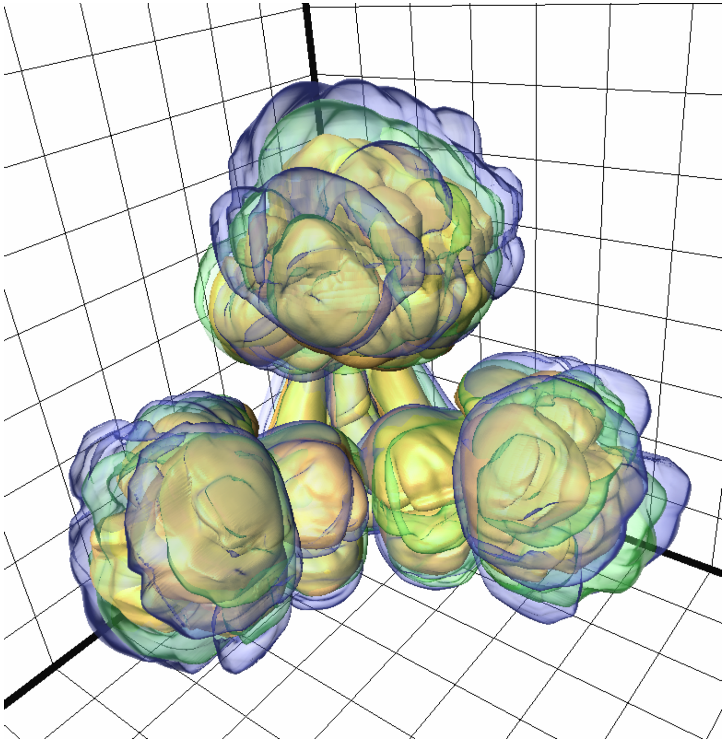
Progenitor's C/O Ratio

- produced ^{56}Ni mass



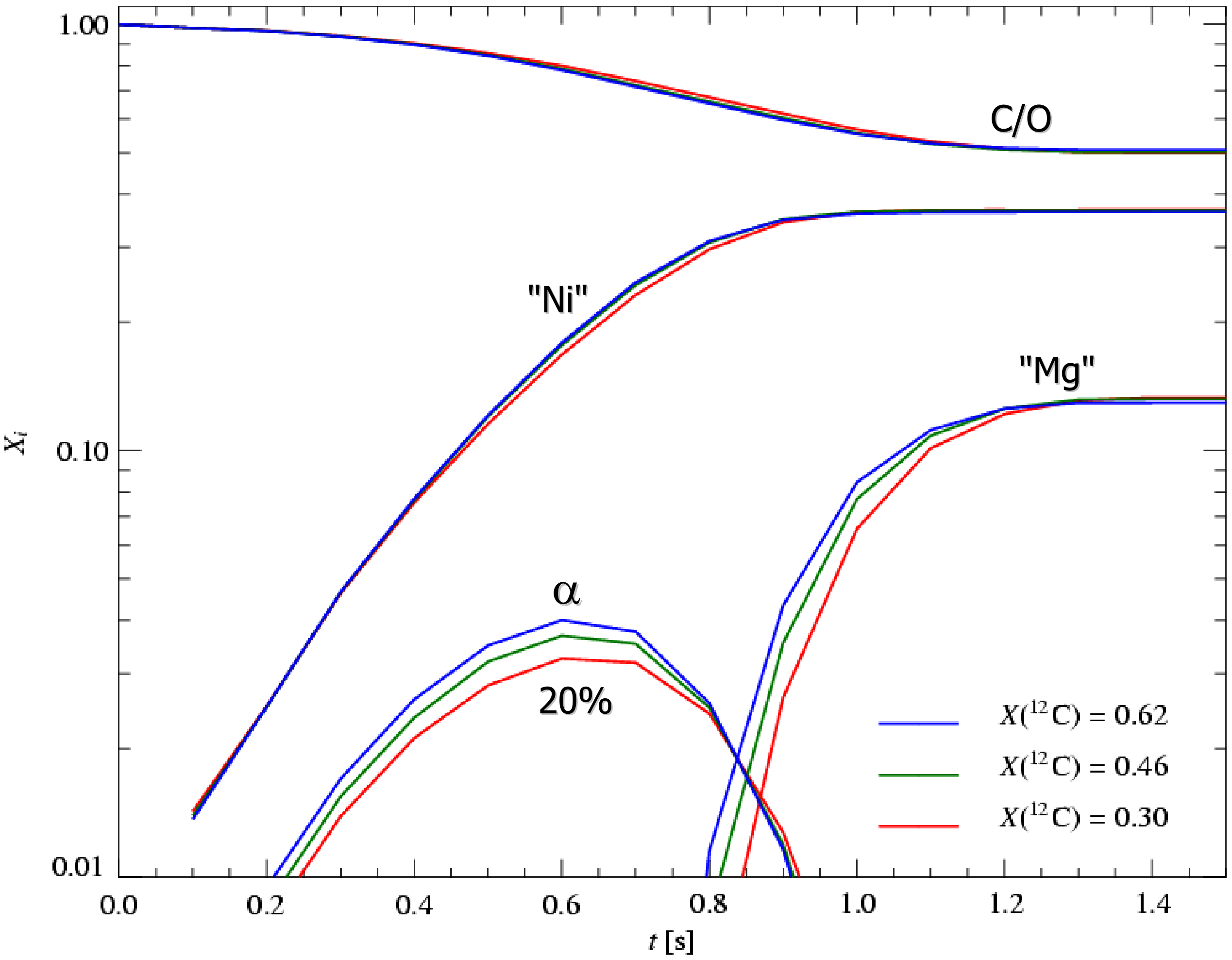
$\sim$ 2%

- flame front at t=1s



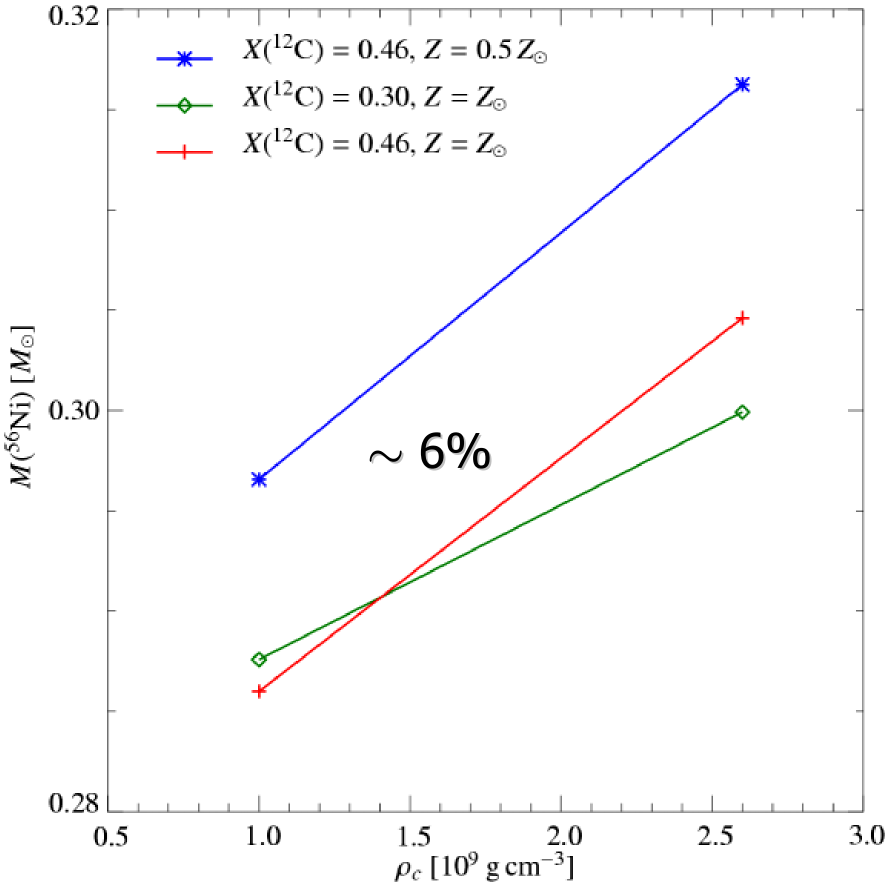
Progenitor's C/O Ratio

- chemical evolution of the explosion models

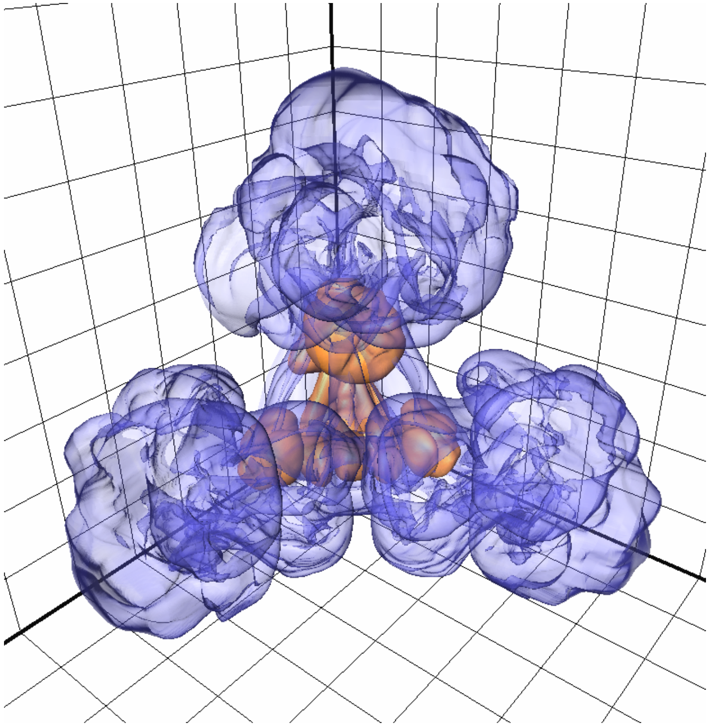


Central Density

- produced ^{56}Ni mass

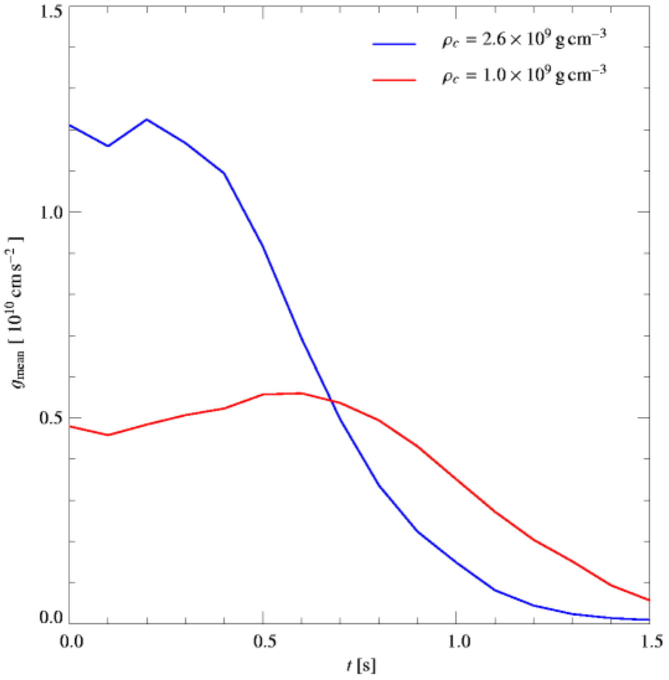


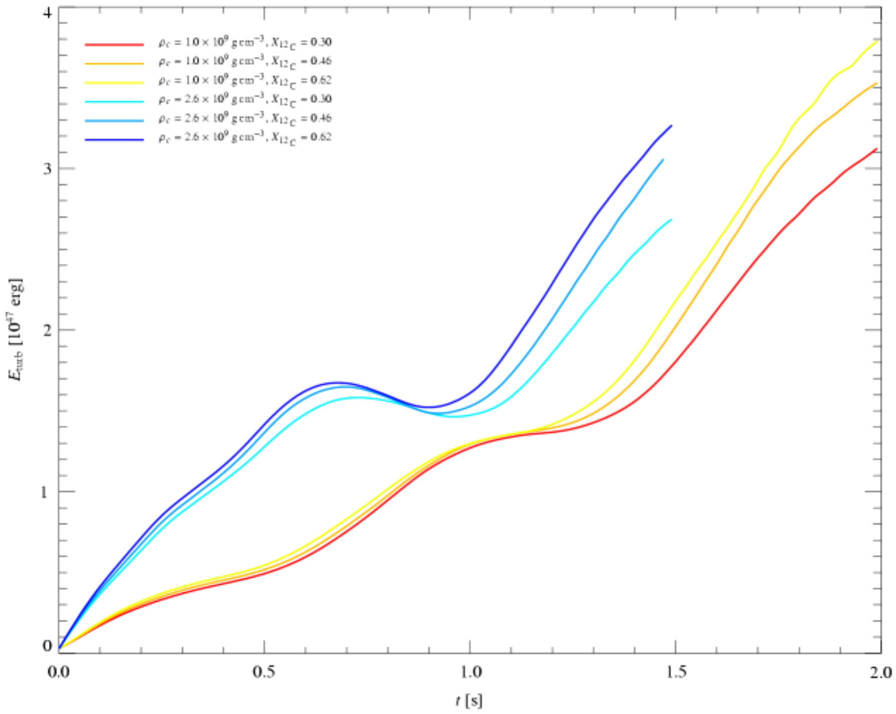
- flame fronts at t=1s



Central Density

- gravitational acceleration at mean flame position, turbulent energy

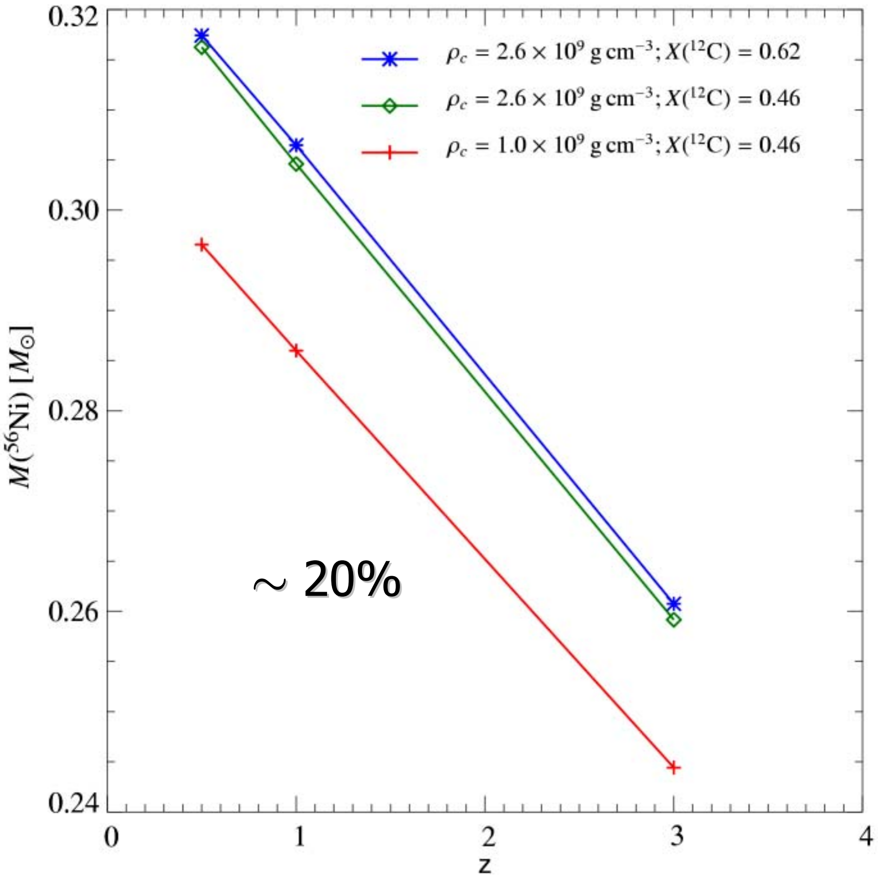




- two competing effects
  - with higher ρ_c increased flame propagation velocities → more material burnt at high densities
  - at higher densities increased electron capture rates → less ^{56}Ni

Metallicity

- produced ^{56}Ni mass



$\sim$ 20%

- linear relation as analytically predicted by Timmes et al. (2003)

Results

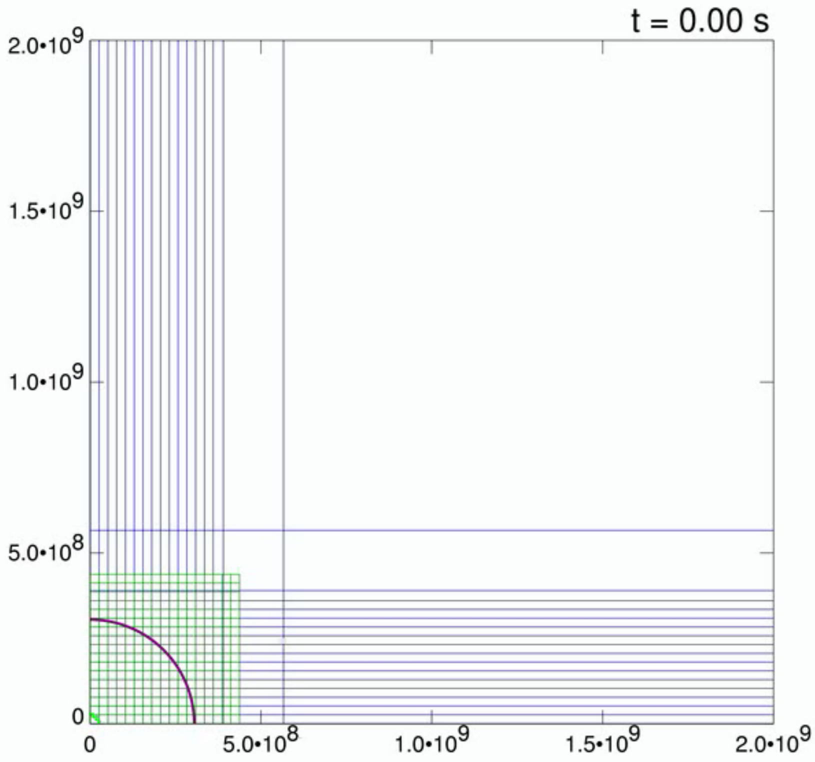
- variations of the models due to initial parameters:

parameter	variation of ^{56}Ni mass (→ peak luminosity)	variation of explosion energy (light curve shape)
C/O ratio	a few percent	$\sim$ 14%
central desnity (preliminary result!)	$\sim$ 6%	$\sim$ 17%
metallicity	$\sim$ 20%	none

- can account partially for observed diversity
- no single parameter reproduces the empirically established peak luminosity-light curve shape relation
- probably combination of parameters (stellar evolution)
- synthetic light curves from explosion models needed!

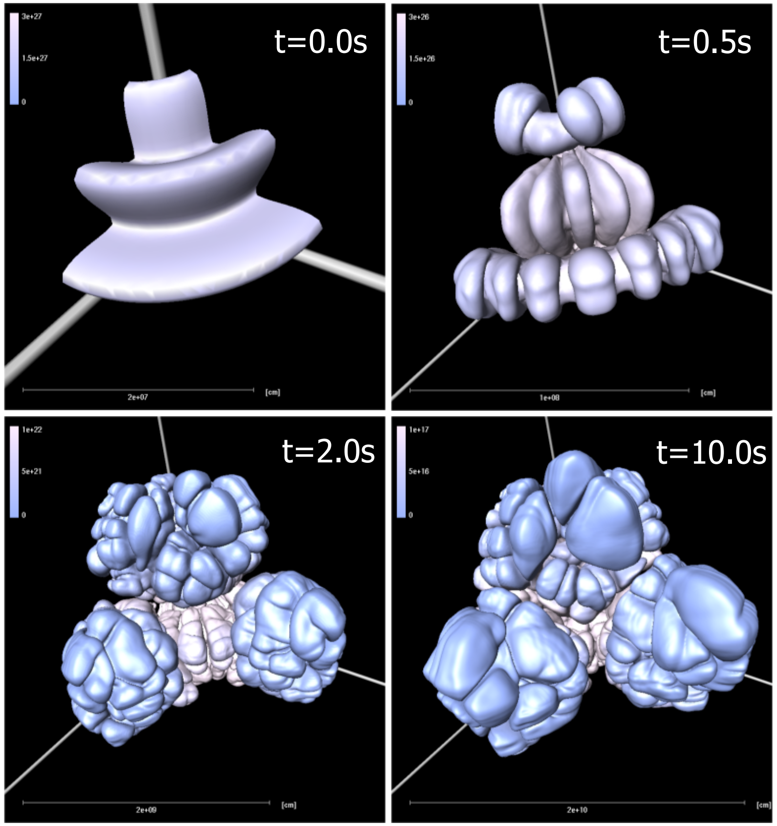
Homologous expansion

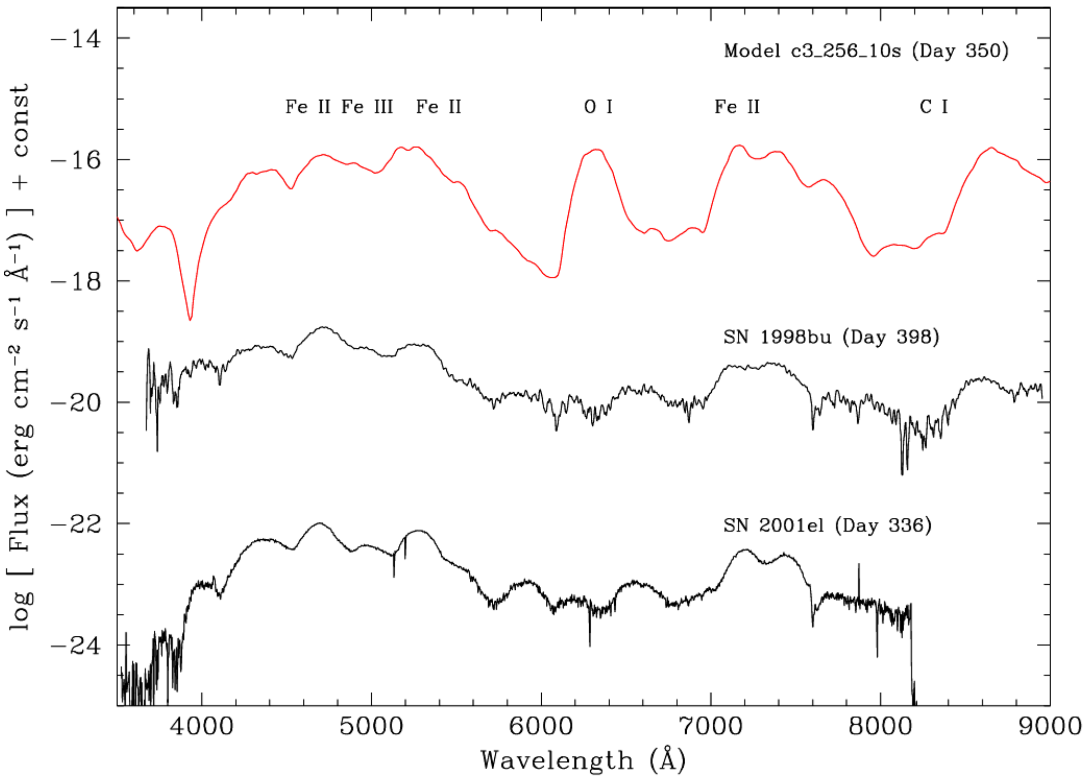
- for derivation of synthetic light curves, spectra models must be close to homologous expansion
- previous multi-dimensional explosion models reached to $\sim$ 2 s
- goal: evolve models to $\sim$ 10 s to reach homologous expansion (F.R., 2004)
- co-expanding computational grid, tracking outer mass shell of WD instead of static non-uniform grid used so far
- model meets criteria for homologous expansion after $\sim$ 10 s:
  - $v(r) \propto r$ (deviation below 5%)
  - $|\nabla p|$, $|\nabla \Phi|$ small
  - $E_{kin} \gg E_{int}, E_{grav}$



Nebular spectra

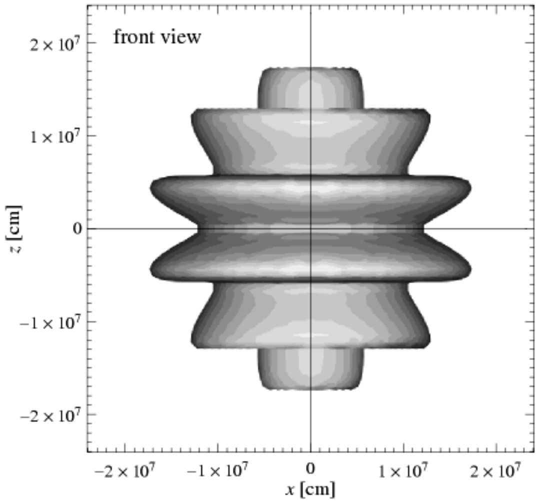
- 3d example → spectrum at day ~350 (Kozma et al., in prep.)

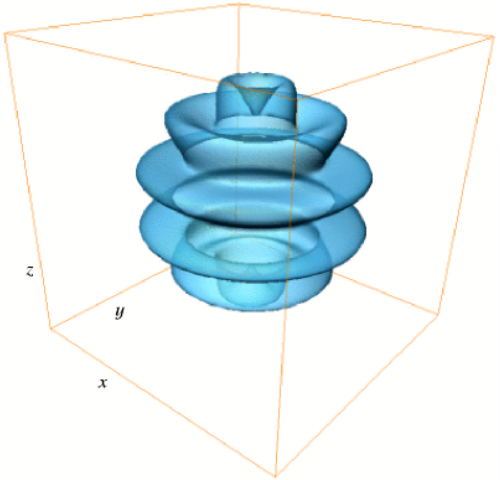




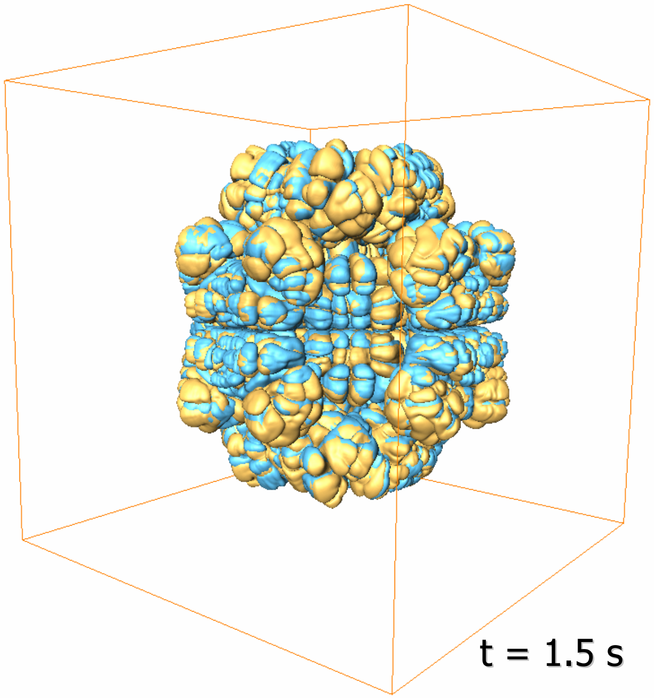
Full-star models

- purpose: assess octant-symmetry in previous simulaitons by comparison with full-star model
- initial condition corresponds to mirrored c3-model (Reinecke, 1999,2002)



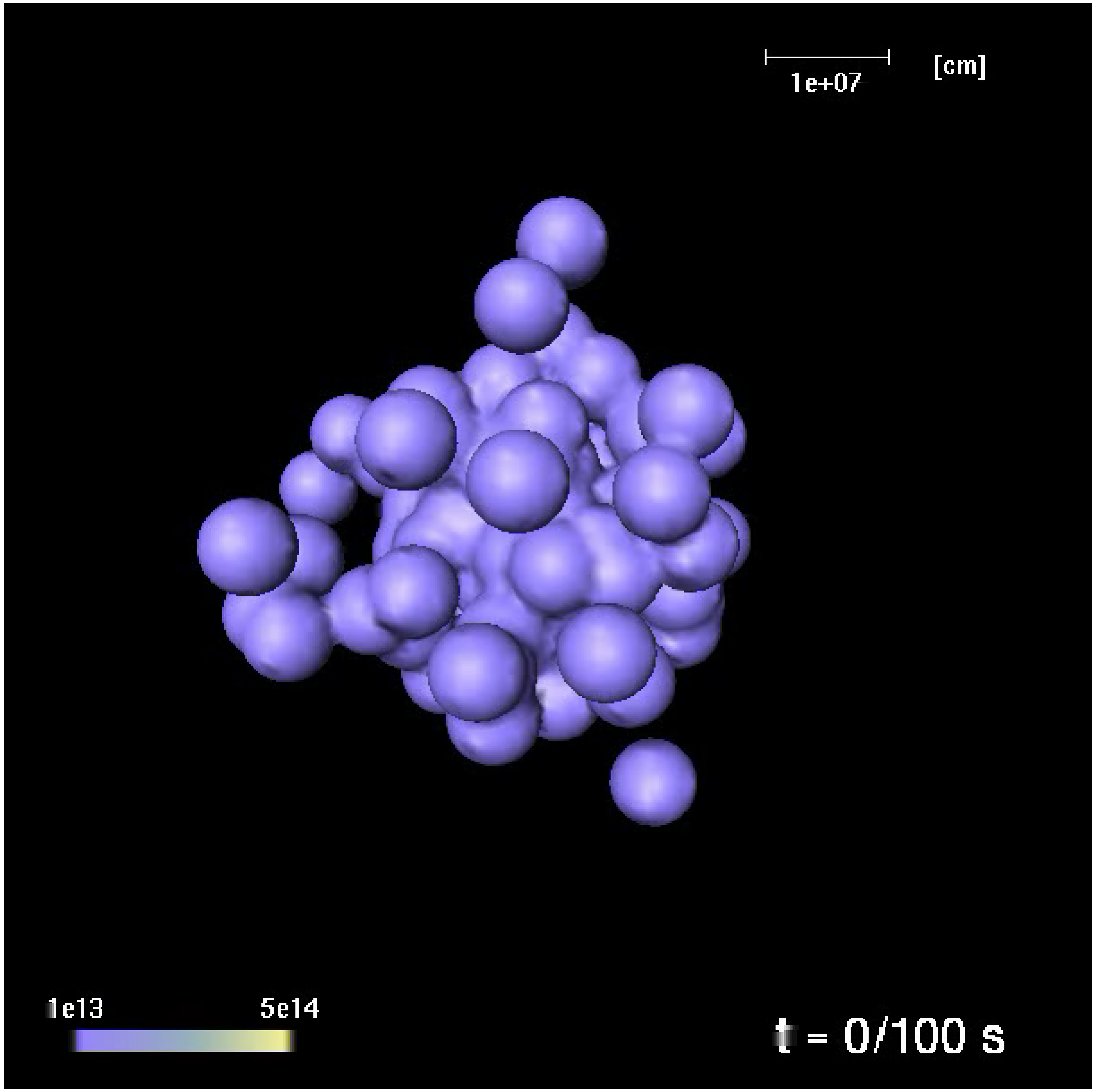


- only small differences between single-octant (yellow) and full-star (blue) model
- no surprizing features by abolishing artificial mirror-symmetry



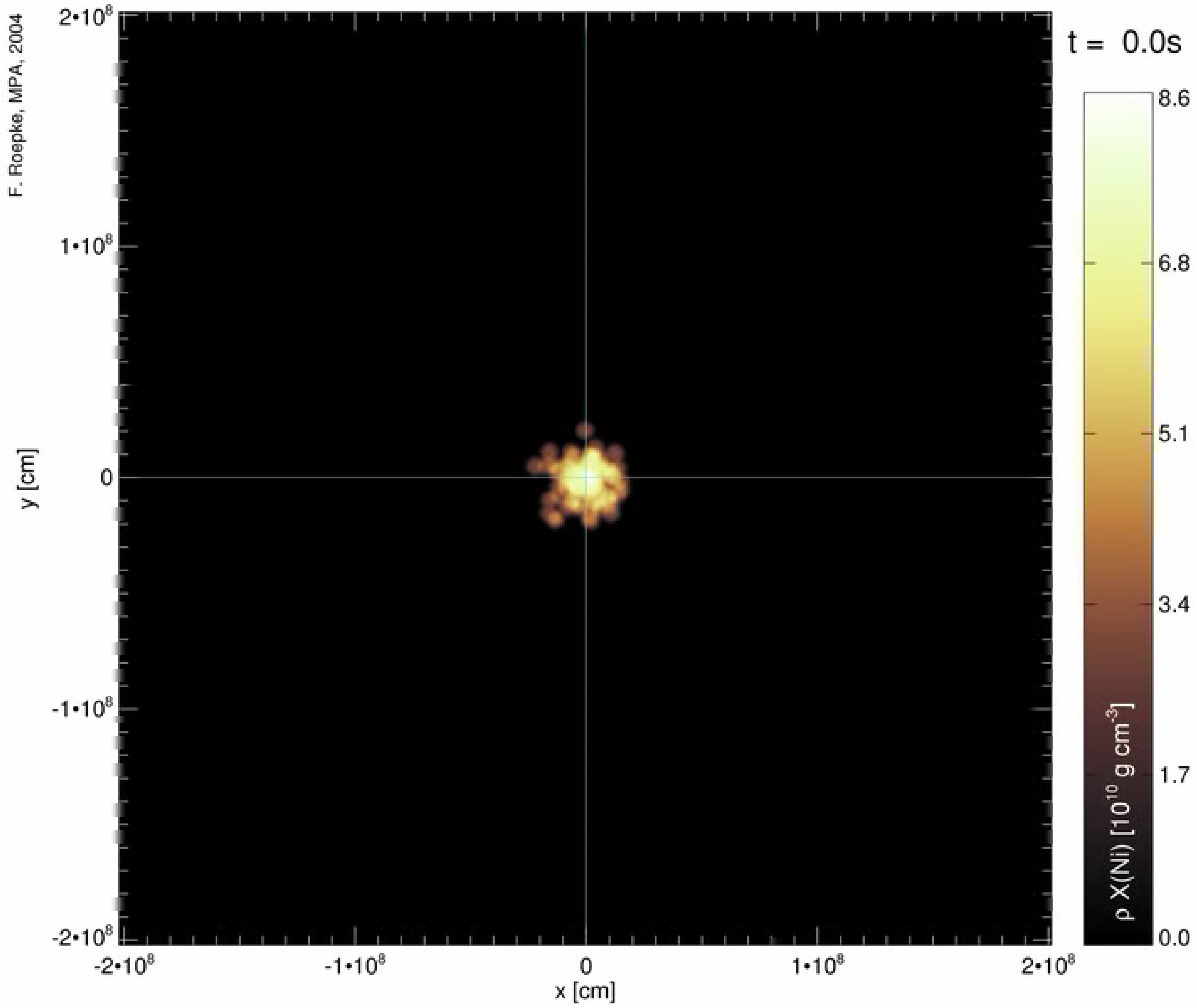
Full star models

- "foamy" initial flame configuration
- anisotropic, asymmetric flame shape
- center of initial flame ~13 km misaligned with WD center



Asymmetries

- distribution of "nickel"



Future directions

deflagration models can explain many observational features but need improvements

- large simulation in preparation
- cure low velocity unburnt material problem:
  - improve sub-grid scale model (W. Schmidt, U Würzburg)
  - test initial flame configurations
  - distributed burning in late phases
  - delayed detonation?
  - ...
- implement electron captures → study variation of central density
- improve initial models
- improve description of nuclear burning in explosion models
- (...)