Current Models of Type Ia Supernovae

(and their observable predictions)

Wolfgang Hillebrandt
MPI für Astrophysik
Garching

Paths to Exploding Stars
KITP, UCSB,
March 19 - 23, 2007

In collaboration with ….

Friedrich Röpke (MPA),

Martin Reinecke (MPA),

Paolo Mazzali (MPA),

Stuart Sim (MPA),

Jens Niemeyer (U. Würzburg),

Wolfram Schmidt (U. Würzburg),

Claudia Travaglio (Obs. Torino),

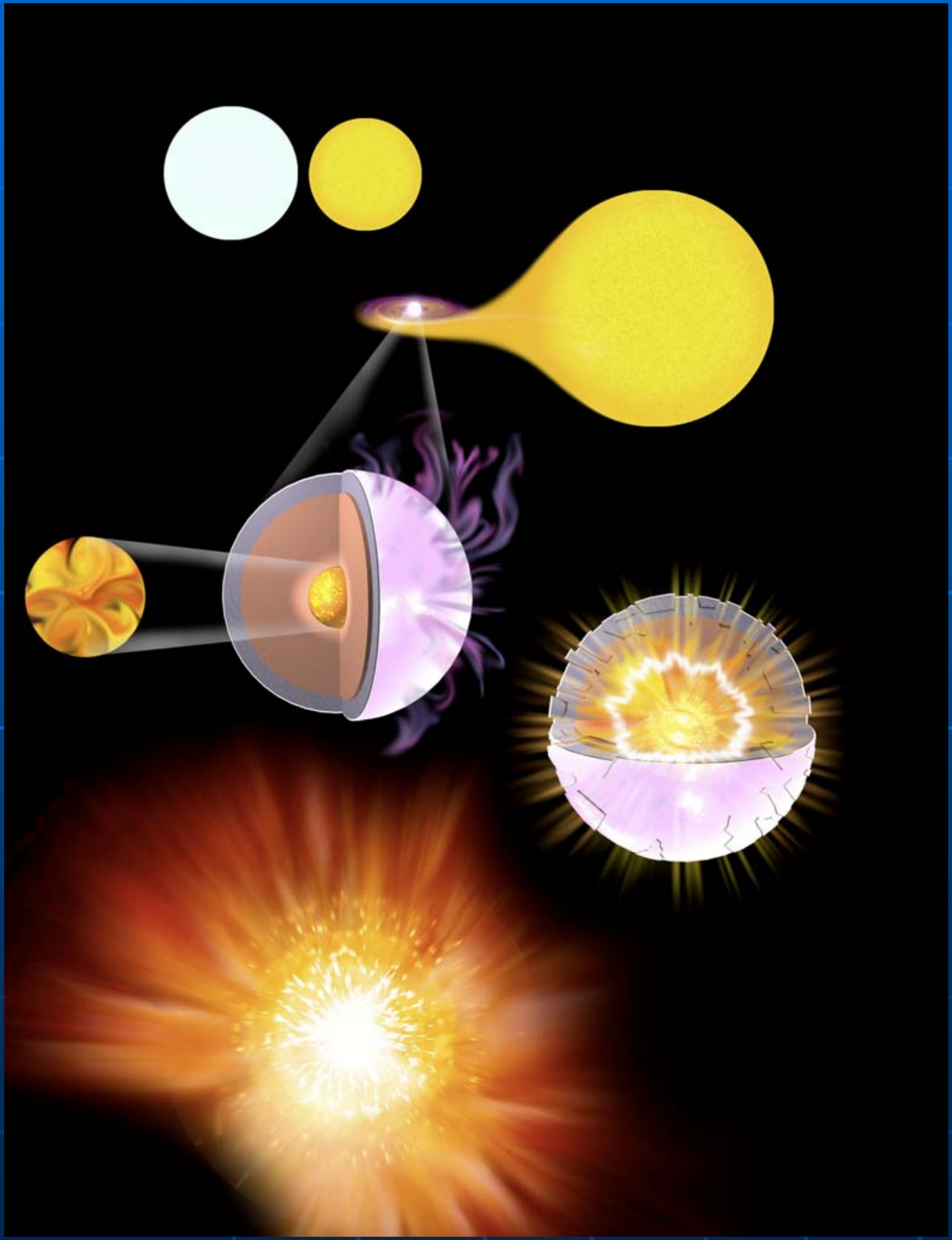
Sergei Blinnikov (ITEP Moscow),

Elena Sorokina (ITEP Moscow),

Stan Woosley (UC Santa Cruz),

………………

The "standard model" of a SN Ia



- White dwarf in a binary system
- Growing to M_{Chan} by mass transfer
- Disrupted by a thermonuclear explosion

Here, I will mainly discuss deflagration models!

Questions to be addressed:

- Can we model (pure) deflagrations ‘ab initio’?

  (Nomoto, Sugimoto & Neo 1976;

  Nomoto, Thielemann & Yokoi 1984)
- How well do they reproduce observations?

  (Thielemann, Nomoto & Yokoi 1986;

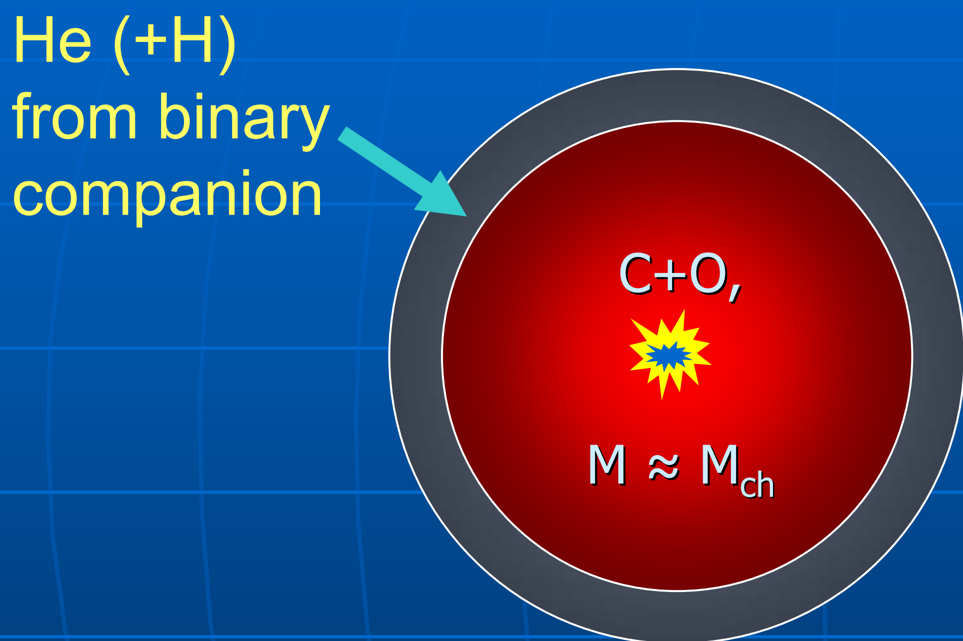
  Iwamoto et al. 1999; ….)
- What is still missing?

  (several talks tomorrow!)

How it all started: the years of W7 …

How it all started: the years of W7 …

How does the model work in more detail?



Density ~ 10^9 - 10^{10} g/cm

Temperature: a few 10^9 K

Radii: a few 1000 km

Explosion energy:

Fusion C+C, C+O, O+O → "Fe"

Laminar burning velocity:

$U_L \sim 100$ km/s $<< U_S$

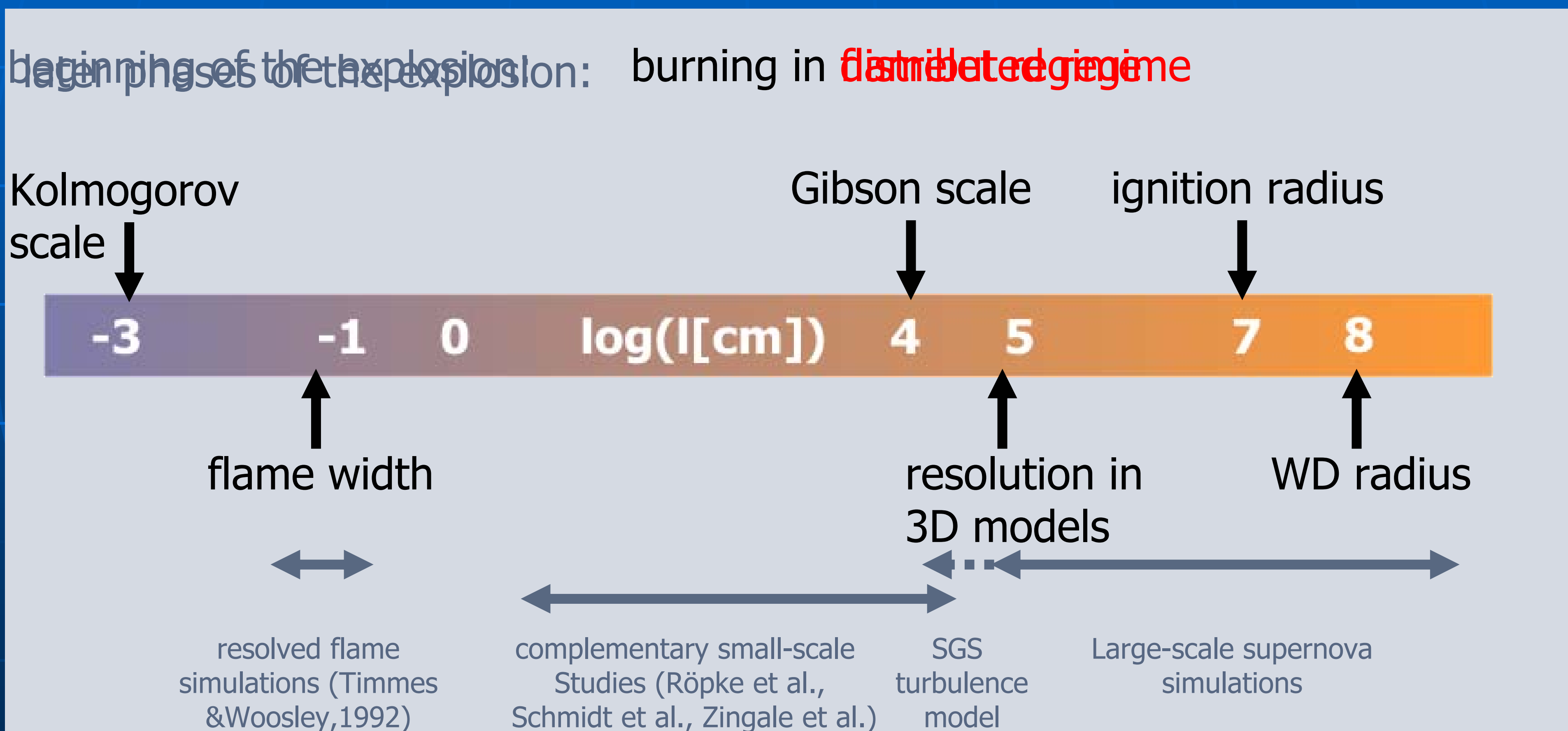
Too little is burned!

The physics of turbulent combustion

- In a star: Reynoldsnumber ~ 10^{14} !
- In the limit of strong turbulence: $U_B \sim V_T$!
- Everydays experience: *Turbulence increases the burning velocity.*
- Physics of thermonuclear burning is very similar to premixed chemical flames.

Simulating the relevant scales

- Gibson scale $s_L = v'$: below turbulence does not affect flame propagation



When the next generation of models began to emerge …

… and somewhat later …

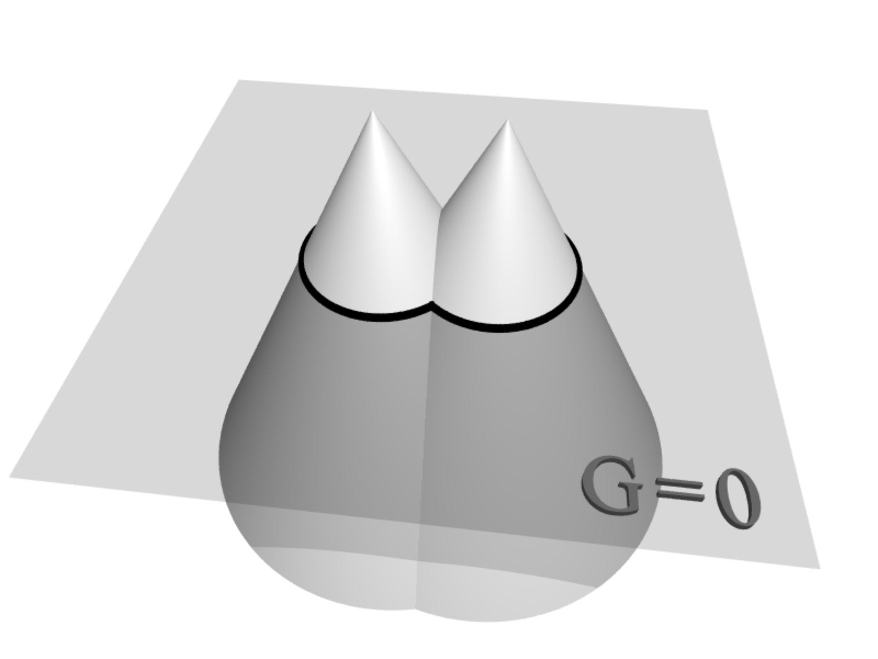
… and still later …

How to model thermonuclear flames?

- The "flames" cannot be resolved numerically.
- The amplitutes of turbulent velocity fluctuations in the length scale of the flame are determined on the integral scale.

→

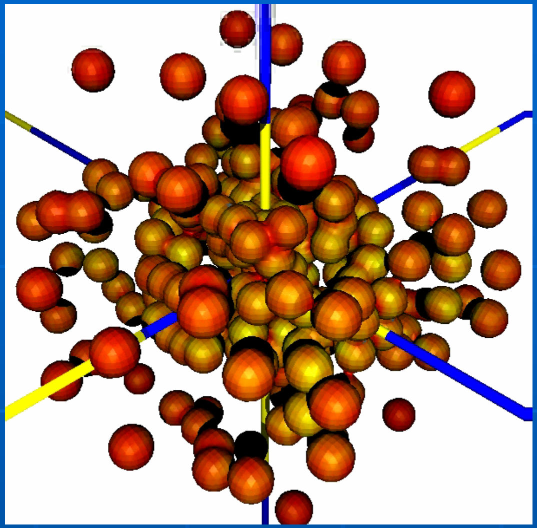
"LES" + "Level Set"

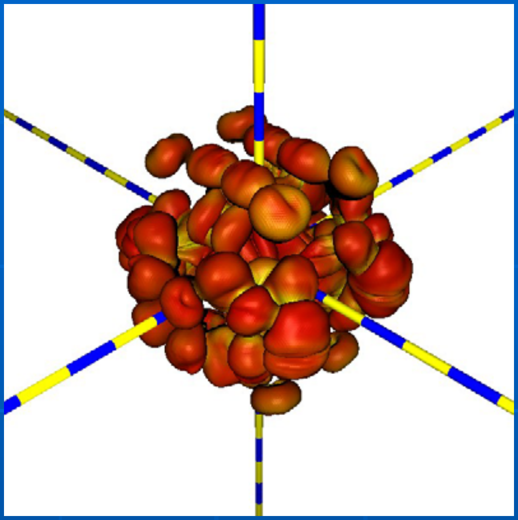


$$\partial G/\partial t = -\mathcal{D}_f \nabla G$$

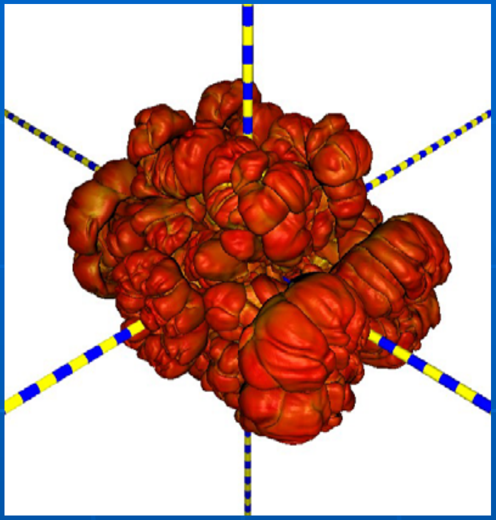
$$\mathcal{D}_f = \mathbf{v}_u + s_{tur}\,\mathbf{n}; \quad |\nabla G| = 1$$

The 'early' 3D models (and their predictions)

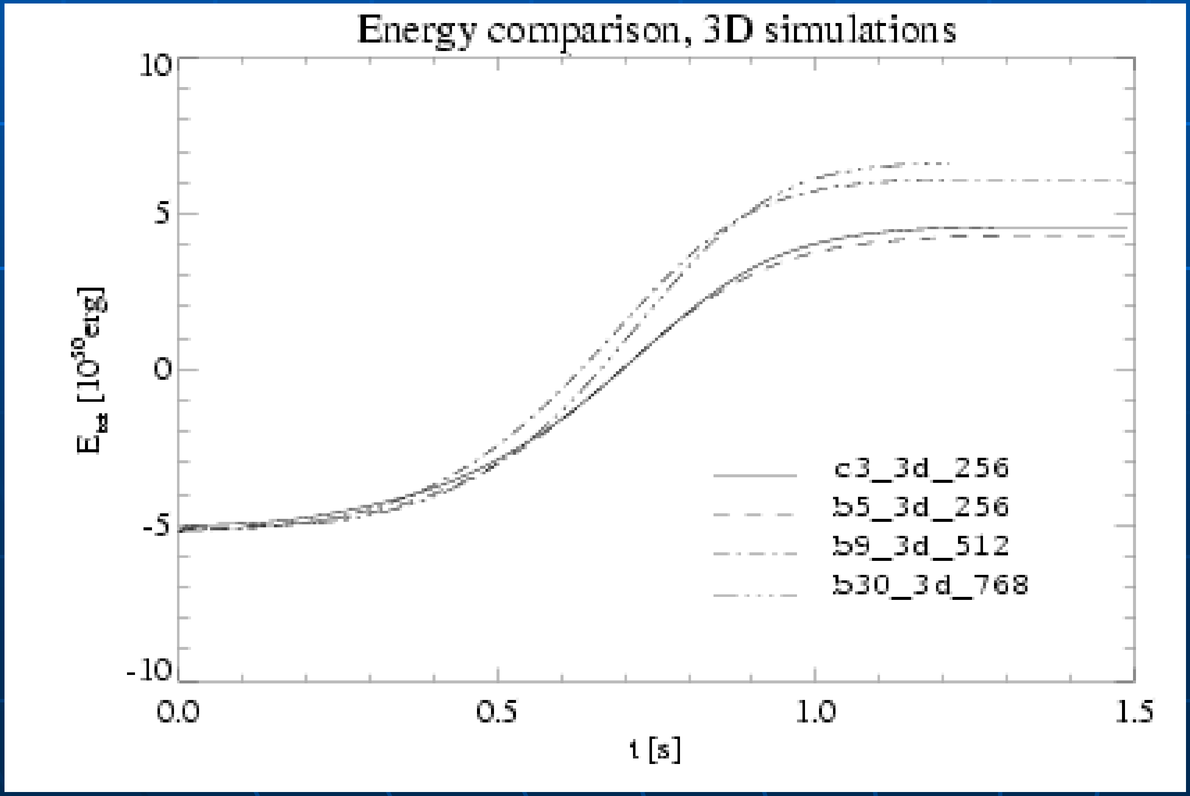




0.25s



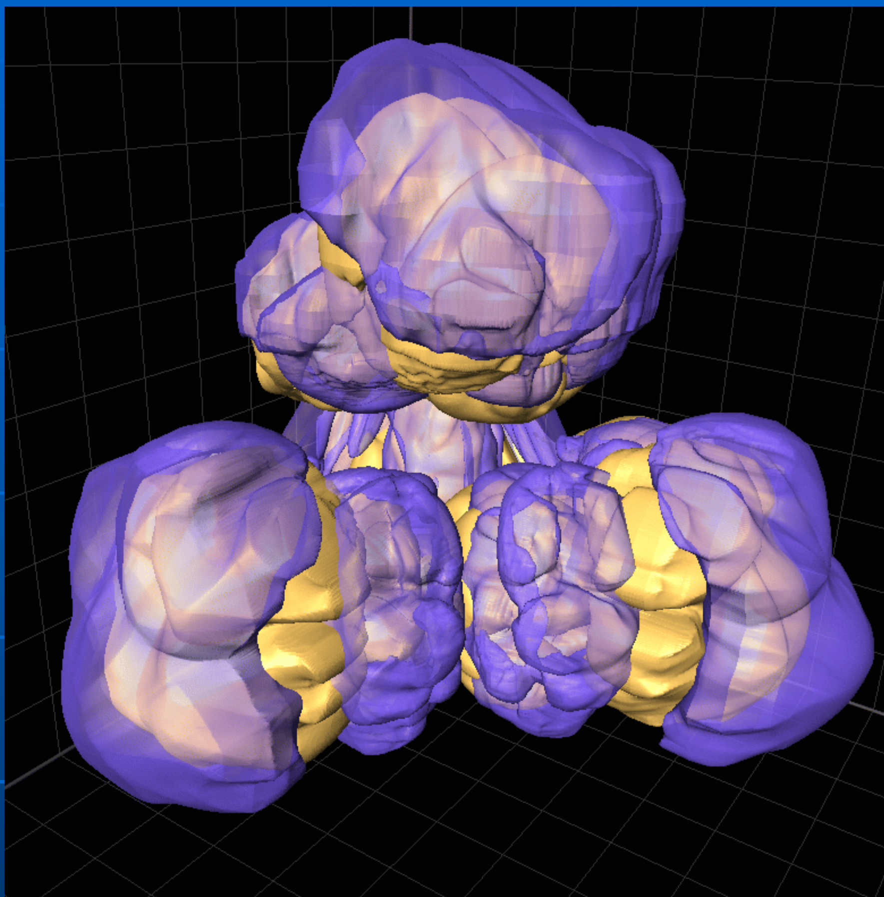
0.6s



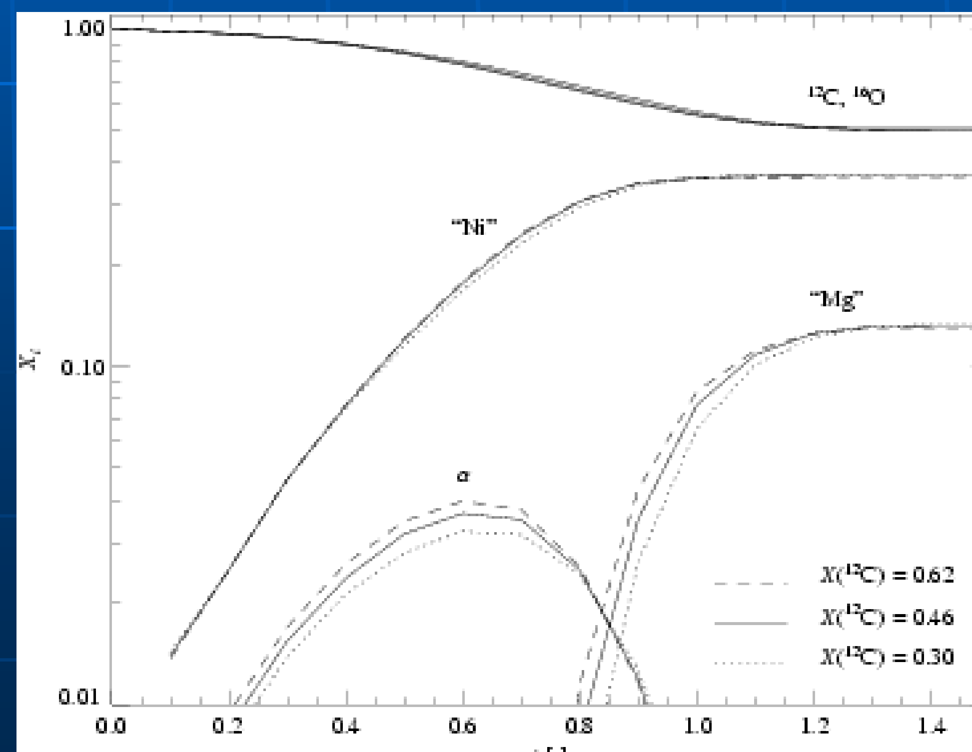
Mod b30_3d

(Reinecke et al., 2002, 2003; also Gamezo et al. 2003, Garcia-Senz & Bravo, 2005)

Dependence on the initial C/O ratio?



$X(^{12}C)$	E_{nuc} (10^{50}erg)	$M(Ni)$ ($M_\odot$)	M_α^{max} ($M_\odot$)
0.30	8.85	0.5178	0.0458
0.46	9.46	0.5165	0.0518
0.62	9.97	0.5104	0.0564

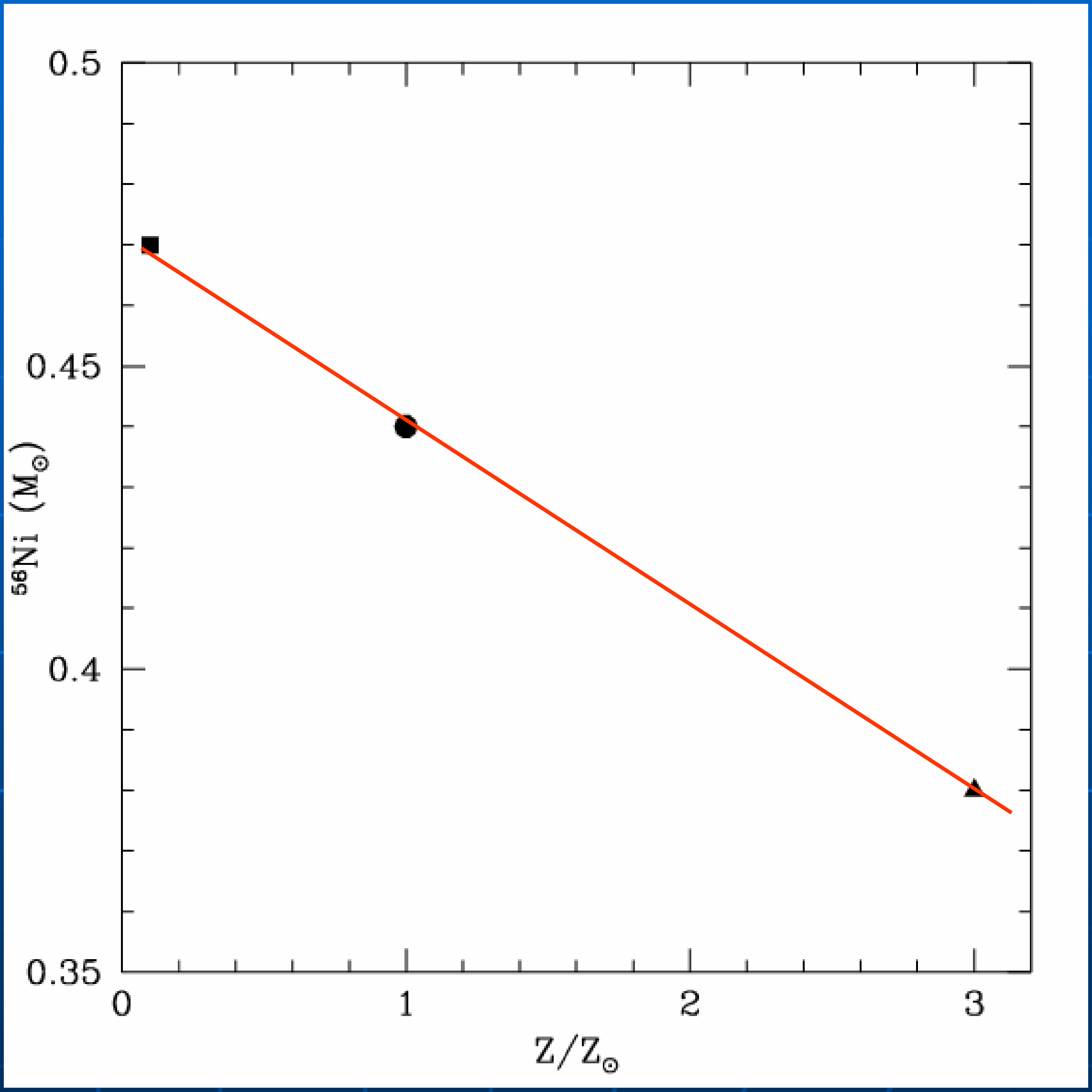


Ni-mass (luminosity) independent of initial C/O!

(Röpke & Hillebrandt, 2004)

Metallicity dependence?

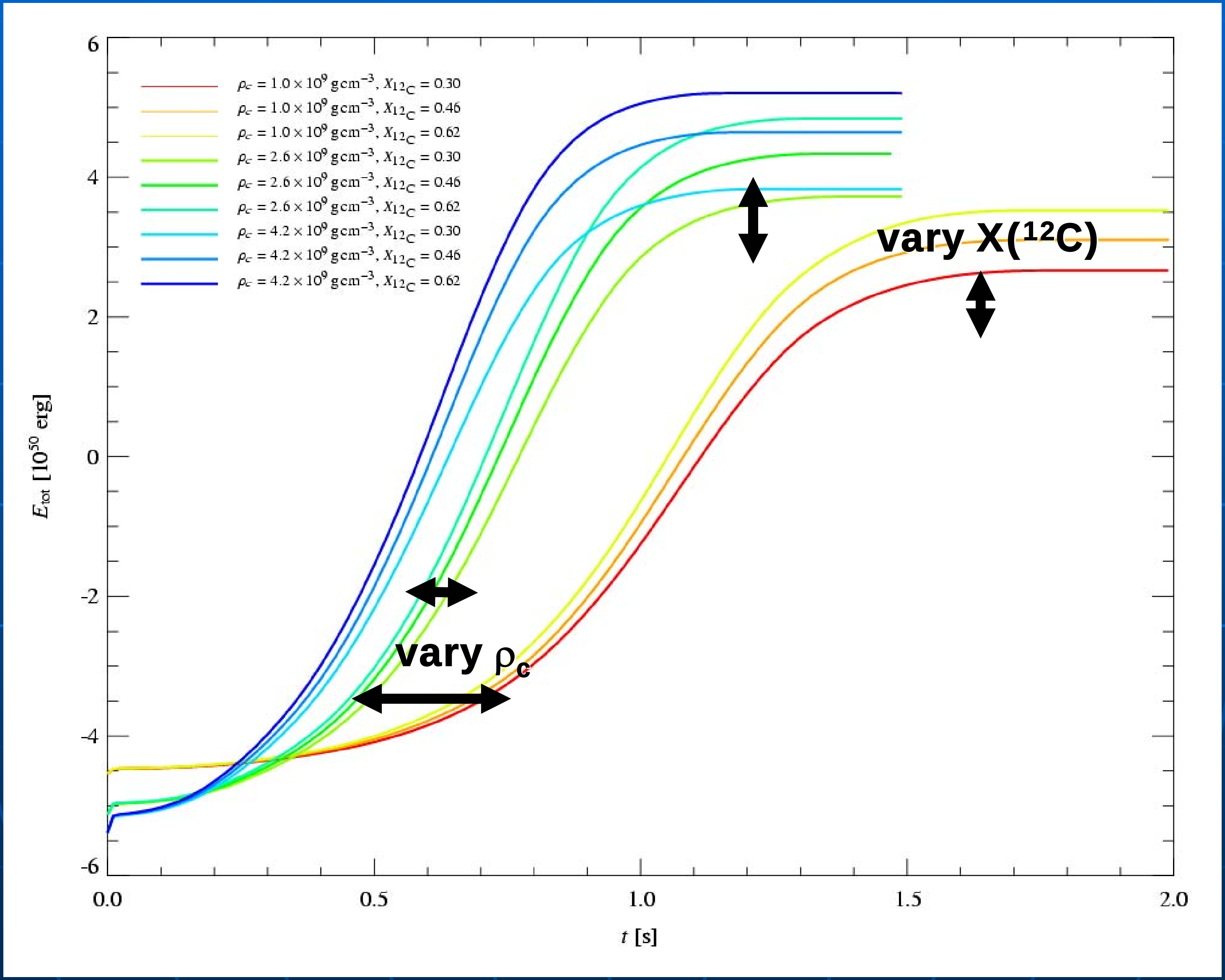
(Model “b30_3d”)



Weak metallicity dependence (in agreement with Timmes et al. 2003)

(Travaglio et al. 2005)

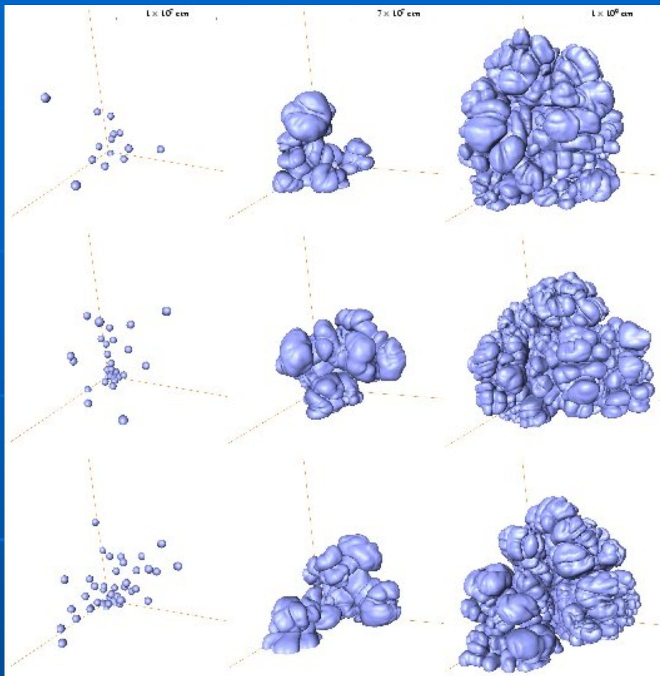
Dependence on initial conditions?

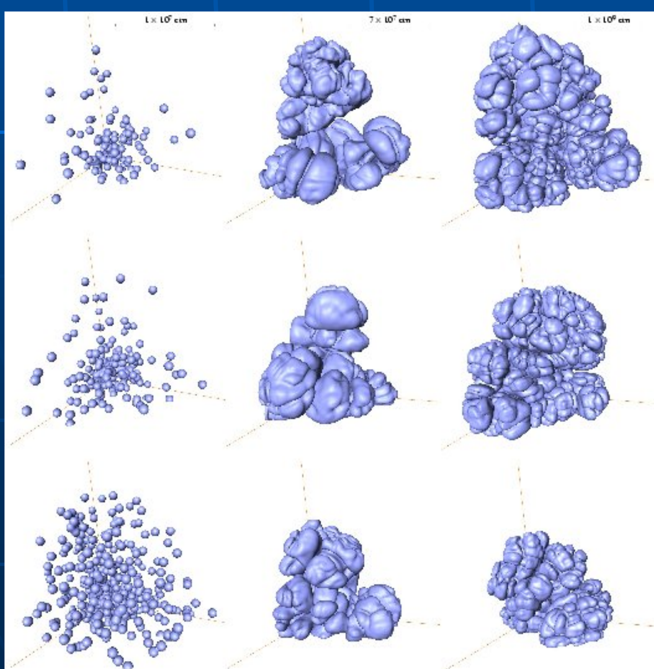


Moderate dependence on initial conditions!

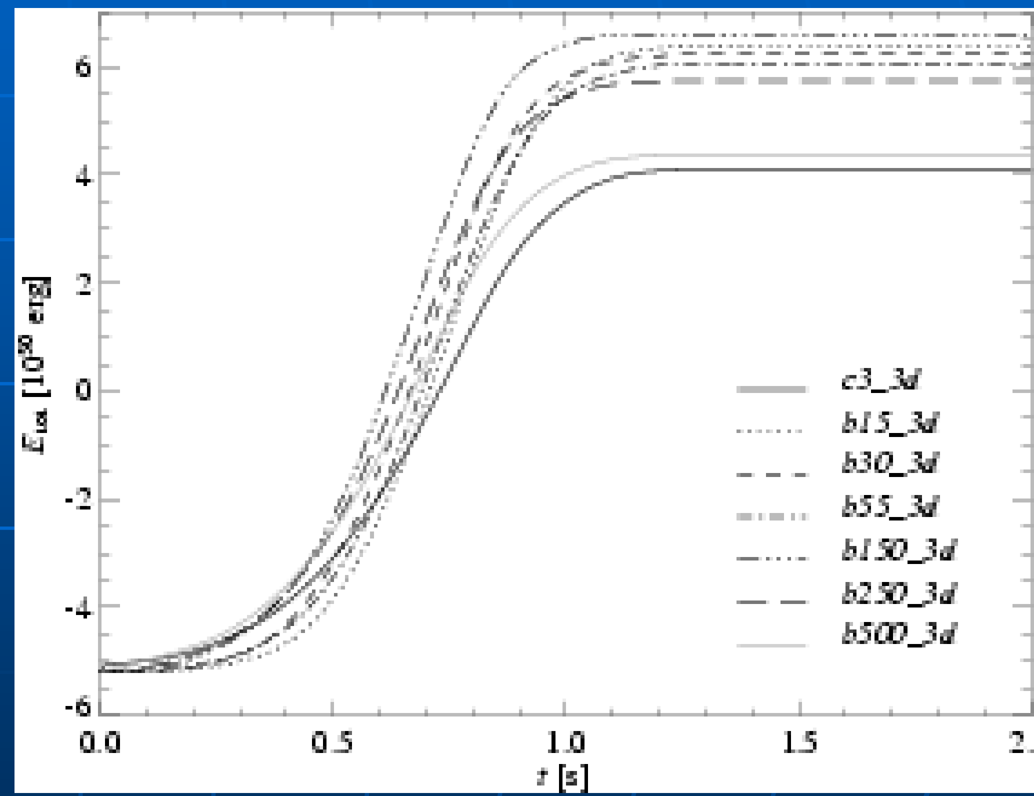
(Röpke et al., 2004)

Ignition conditions: another reason for the diversity?



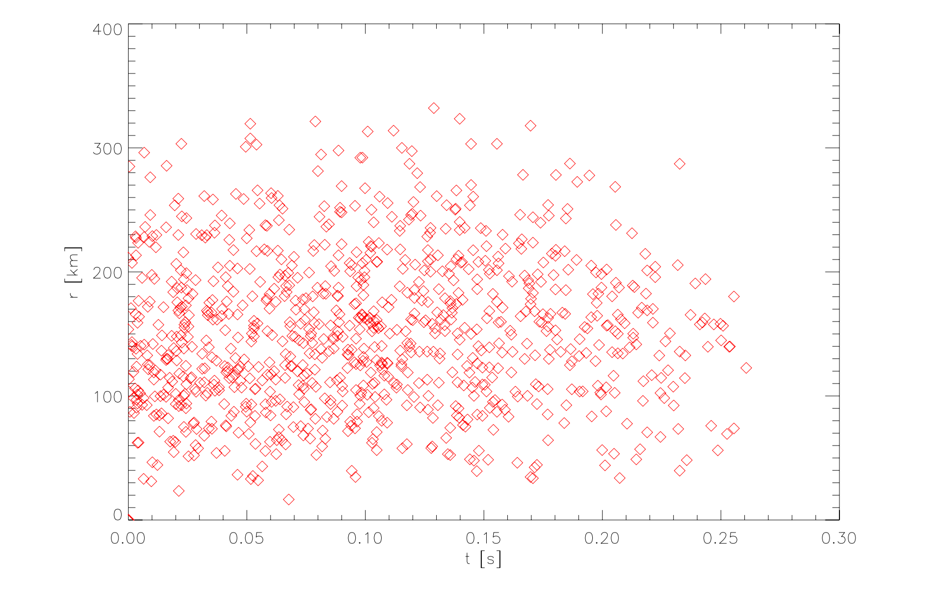


"Multi-spot"

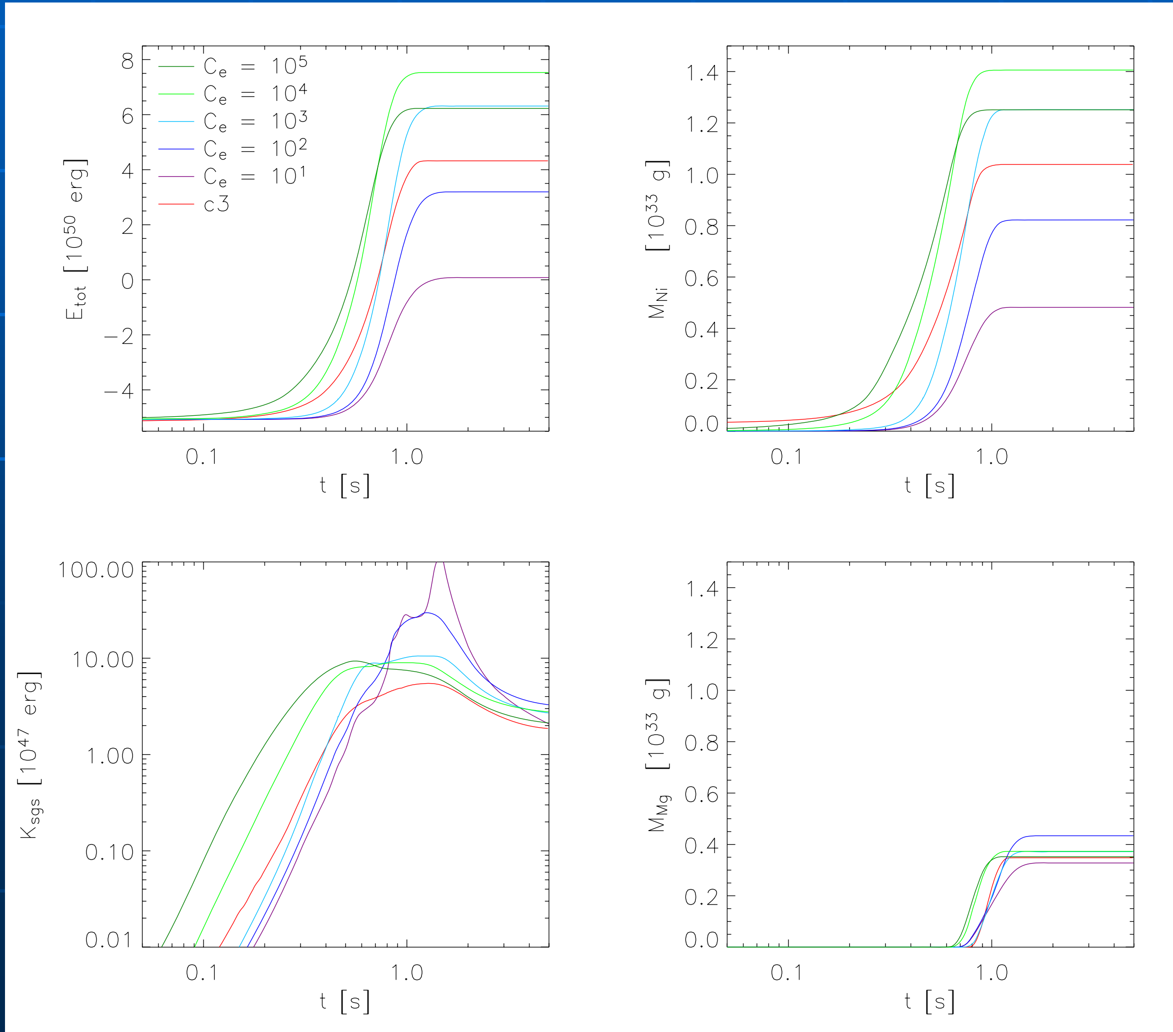


Röpke et al. (2005)

Ignition conditions (cont.):

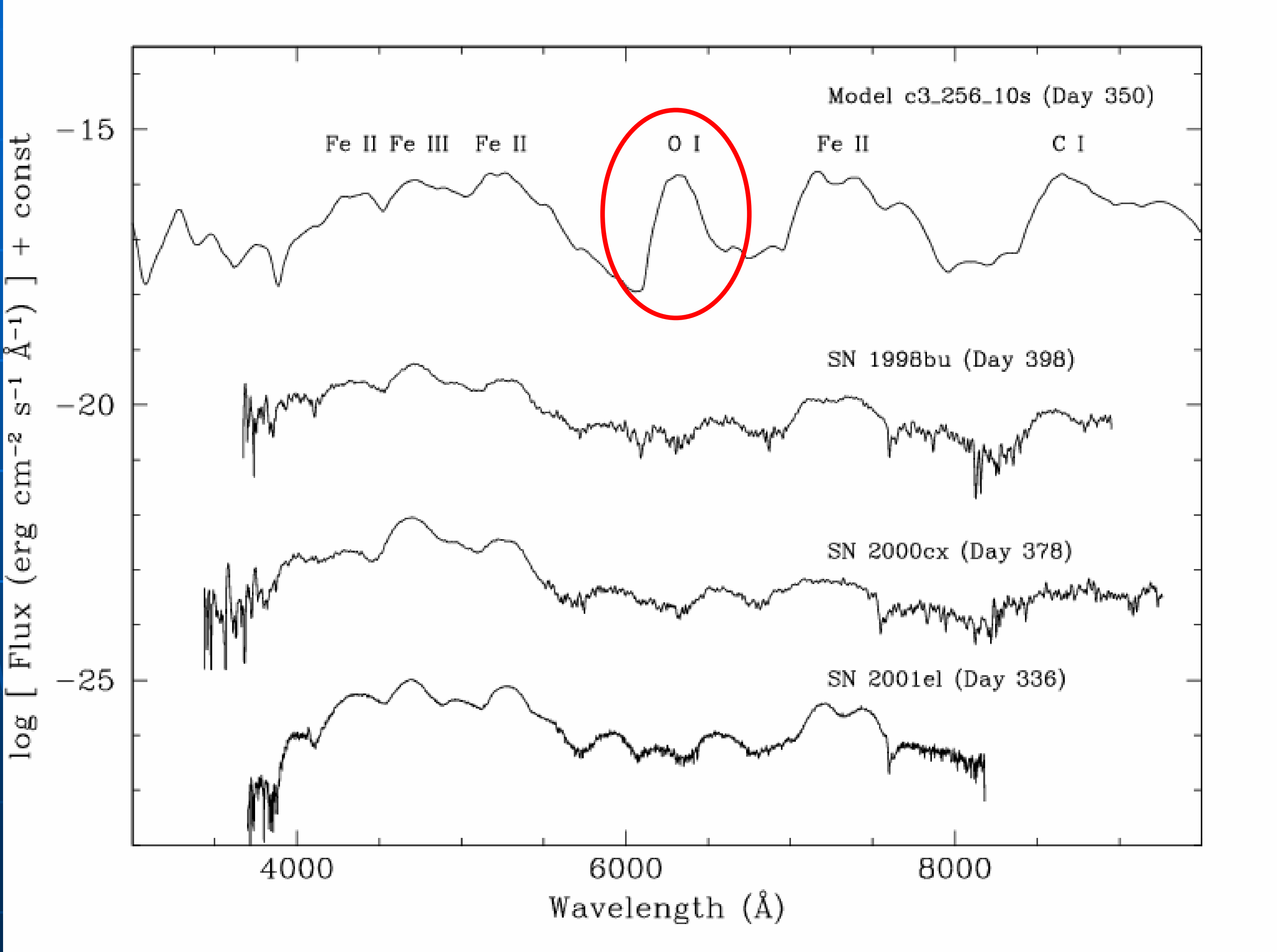


"Stochastic ignition"



Schmidt & Niemeyer. (2005)

But: Nebular spectra? (3D Monte Carlo; Kozma et al. 2005)



Too much oxygen at low velocities?!

So, where are we today?

Extra ingredients to the present MPA code

(Supernova Combustion Code for Explosion Simulations, SuCCESs)

1. Subgrid-scale modeling

(from technical combustion; Schmidt et al. 2005, 2006)

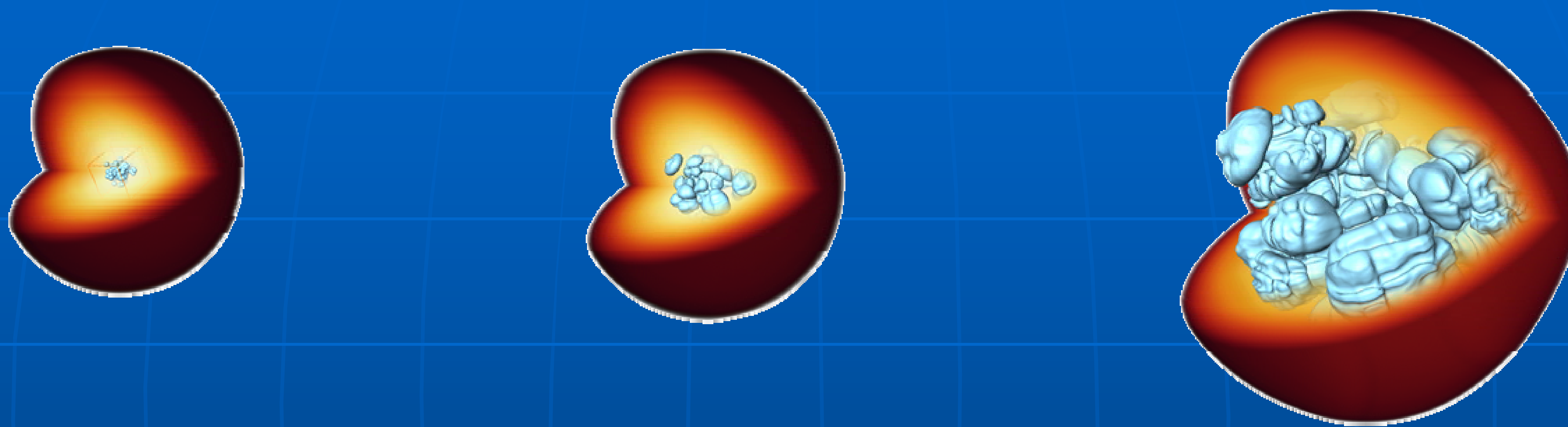
$s_{tur} = s_{lam}[1 + C_{tur}(q_{sgs}/s_{lam})^2]^{1/2}$, $C_{tur} = 4/3$;

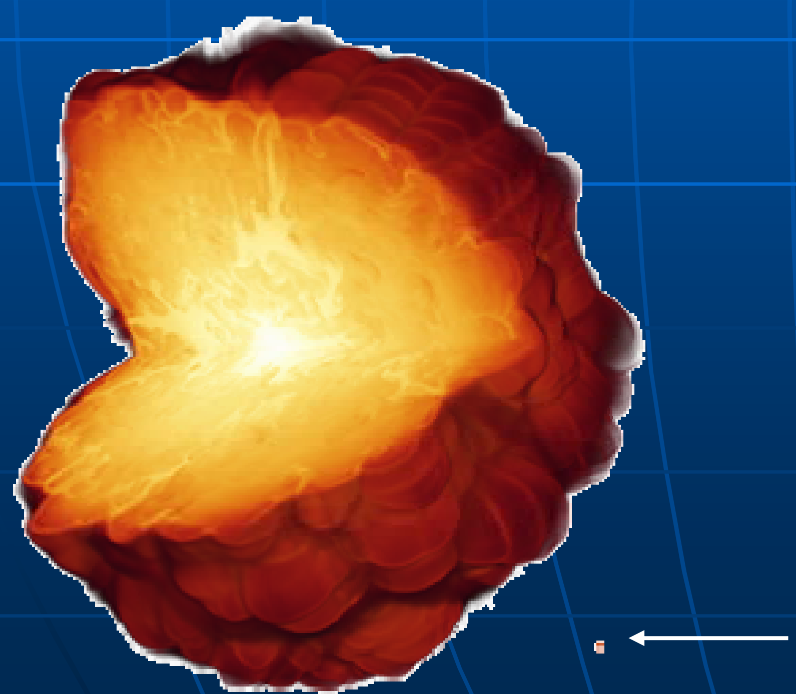
$s_{tur} \approx 2q_{sgs}/\sqrt{3}$ in the asymptotic regime $s_{tur} \gg s_{lam}$

(Pocheau ’94, Peters ’99)

Problem: To compute q_{sgs} !

2. Full star (“4π”) models with a moving grid





White
dwarf!

Röpke &
Hillebrandt (2004)

A high-resolution model ("the SNOB run")

Röpke et al. (2007)

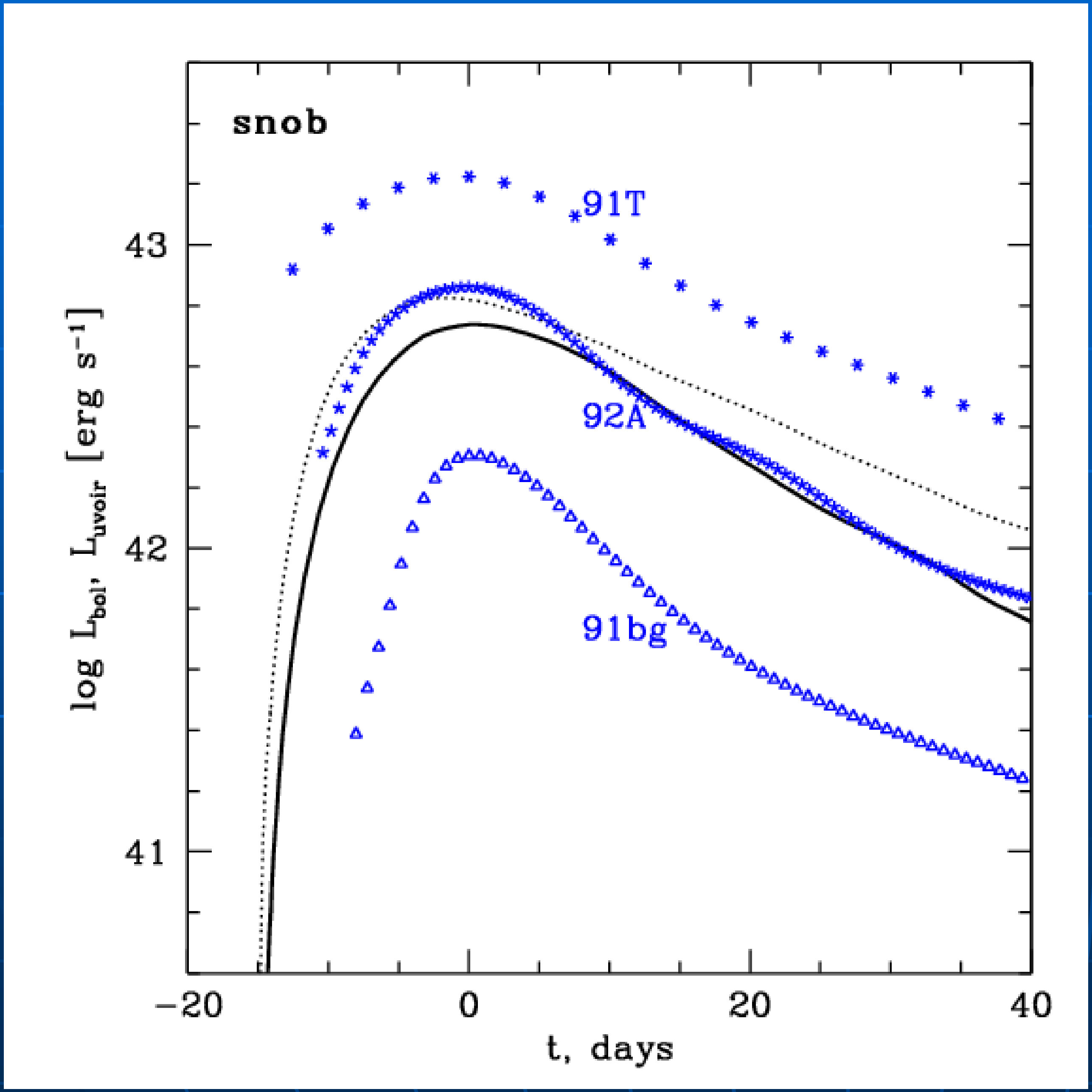
The main results:

- $E_{kin} = 8.1 \cdot 10^{50}$ erg
- Iron-group nuclei: 0.61 M_{sun}
  (“post processing”: 0.56 M_{sun} “Fe”, 0.33 M_{sun} ^{56}Ni)
- Intermediate-mass nuclei: 0.43 M_{sun} (from hydro)
- Unburned C+O: 0.37 M_{sun} (from hydro)
  (less than 0.08 M_{sun} at $v<8000$km/s)
- Vmax ≈ 17,000 km/s

Good agreement with some SNe Ia!

Röpke et al. (2007)

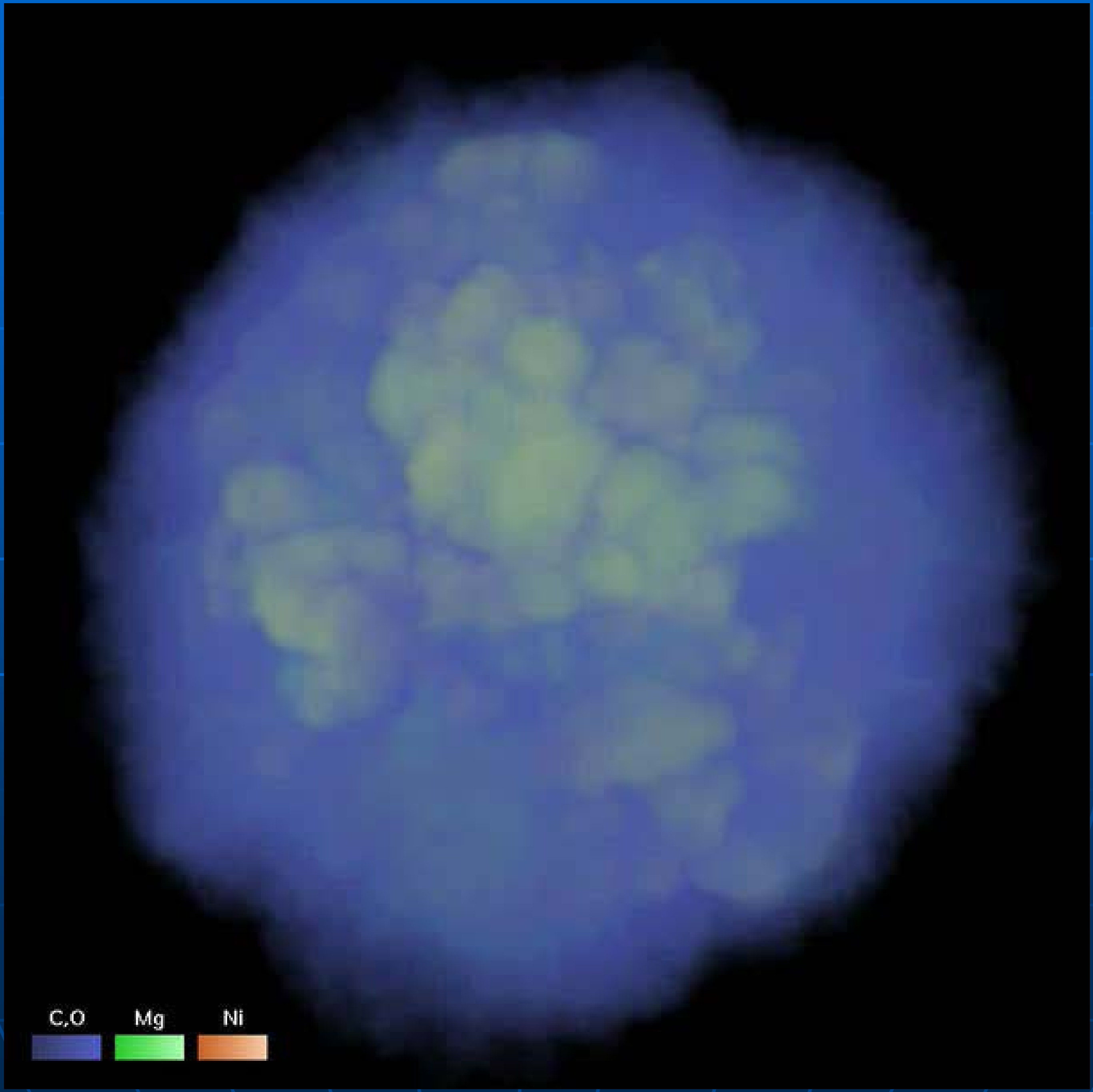
Example: Bolometric light curves from SNOB



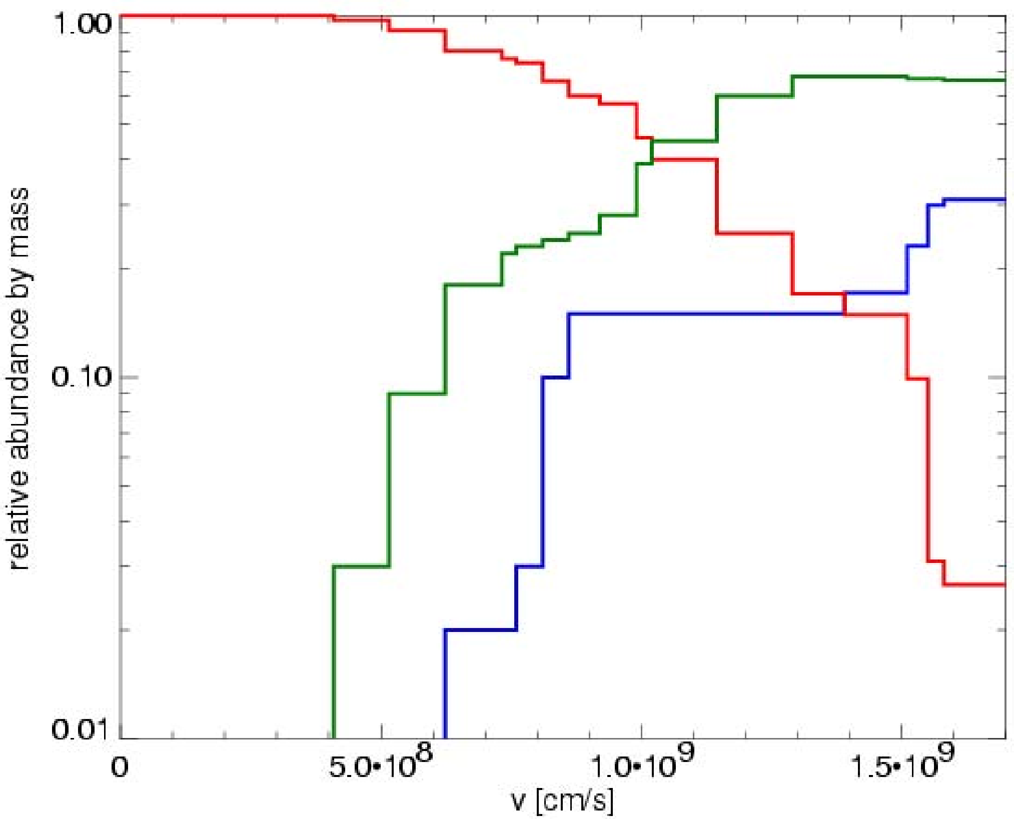
Note:
These are predictions, not fits!

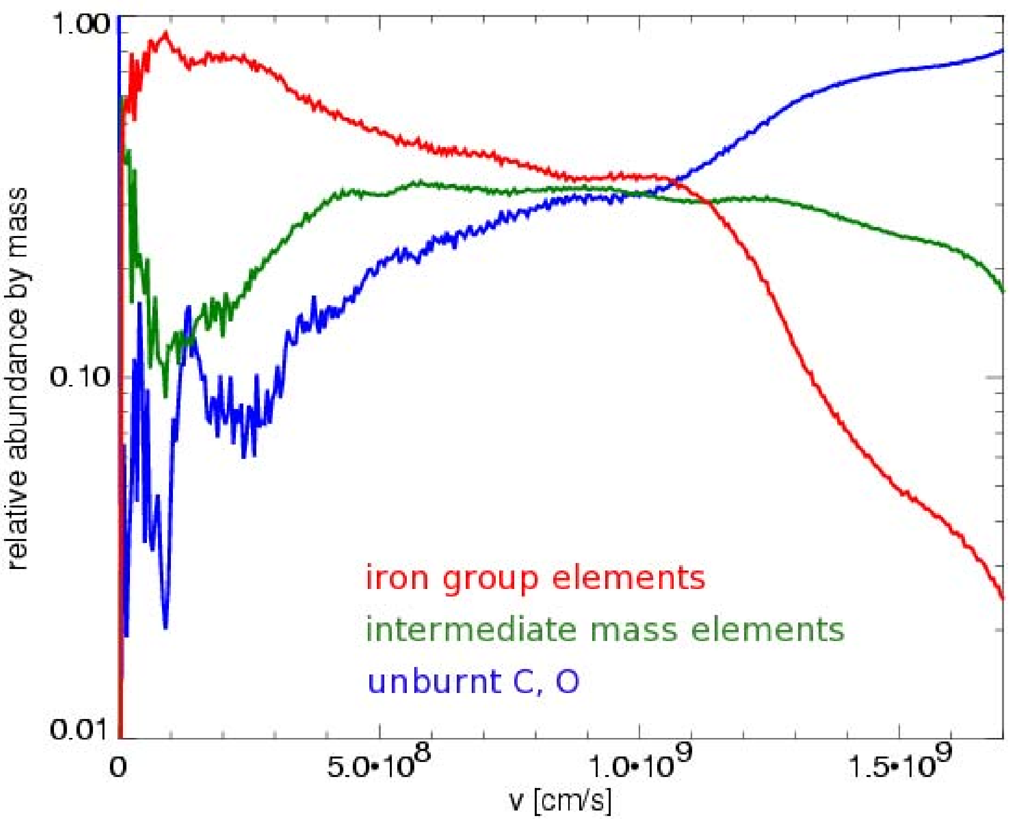
Röpke et al. (2007)

Example: Abundances of the SNOB run…



…. and "abundance tomography"





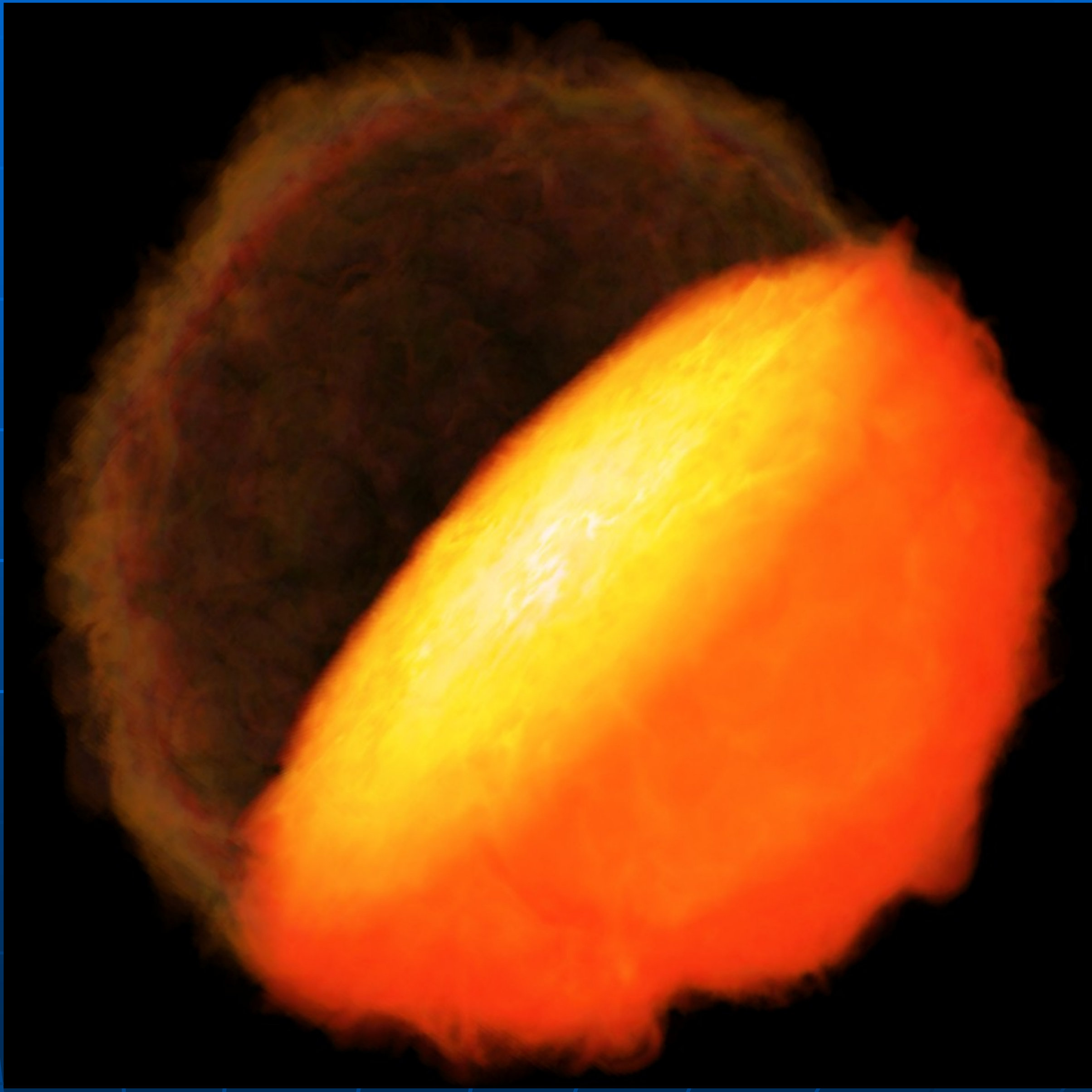
SN 2002bo

SNOB-run

Röpke et al. (2007)

Changing physical parameters: ignition density

- "4π"
- 640^3 grid
- initial resolution near the center ≈ 1000m
- moving grid
- Local & dynamical sgs-model
- ~ 200,000 CPUh on IBM/Power5, at EPCC



Röpke et al. (in preparation)

Very preliminary results:

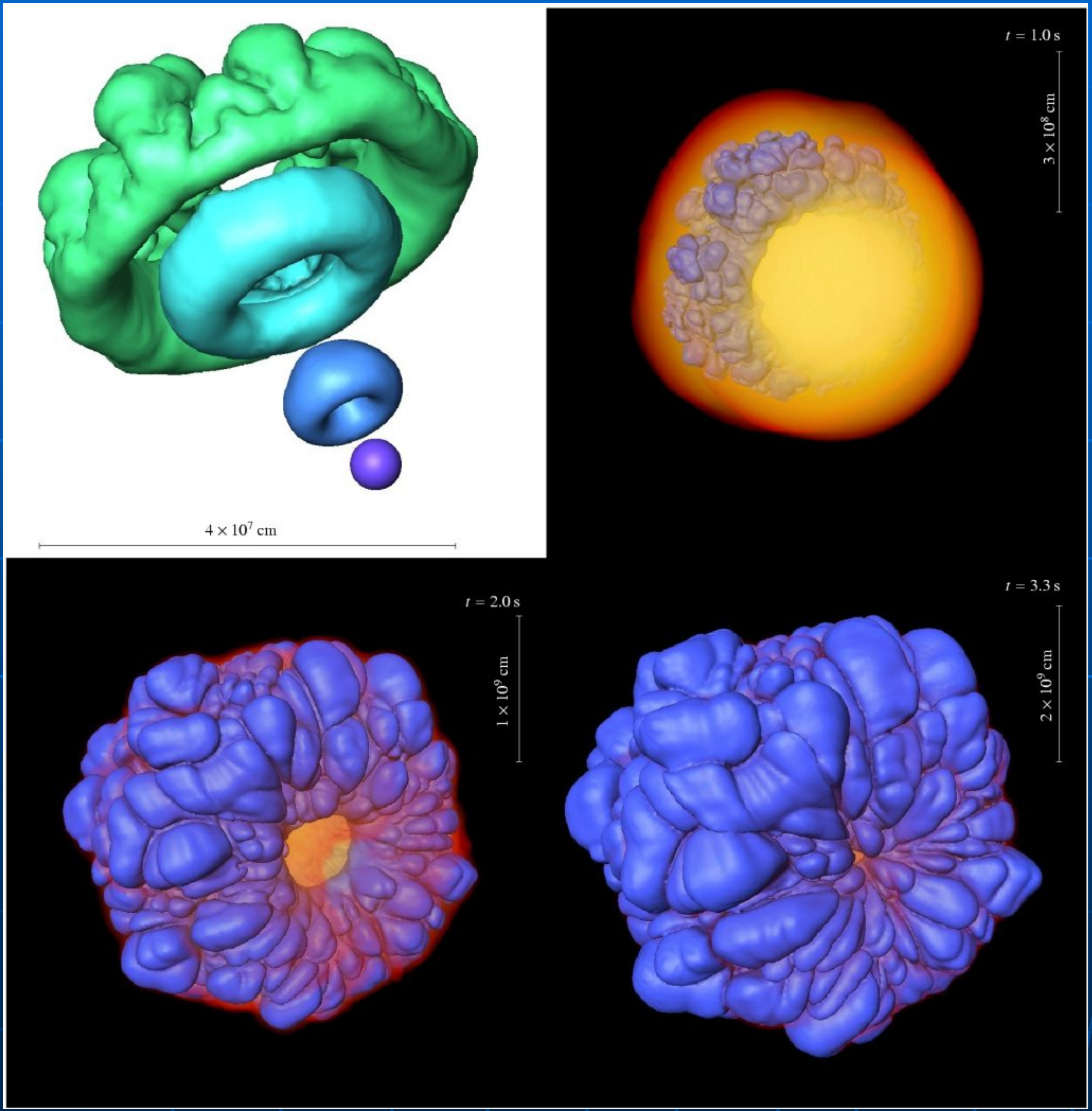
- $E_{kin} = 7.7 \cdot 10^{50}$ erg
- Iron-group nuclei: 0.55 M_{sun} (mostly ^{56}Ni !)
- Intermediate-mass nuclei: 0.47 M_{sun}
- Unburnt C+O: 0.38 M_{sun}
- Vmax ≈ 16,000 km/s

Lower ignition density makes a supernova a bit less energetic, but brighter!

Observations?

Röpke et al. (in preparation)

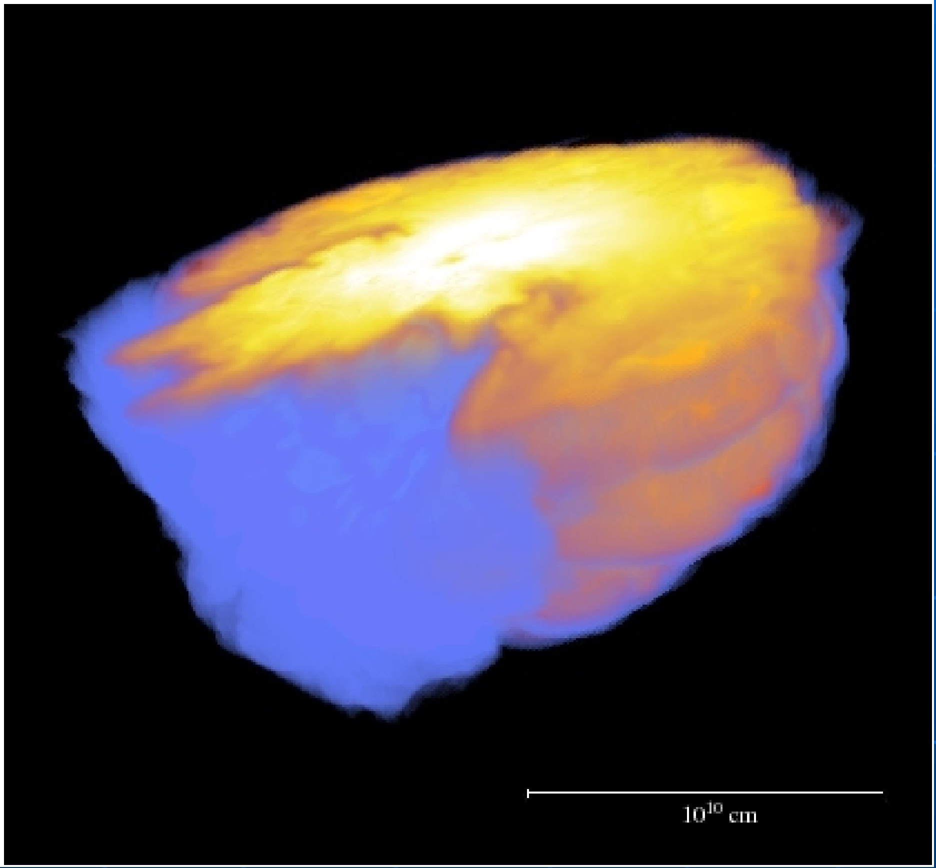
Off-center explosions ….

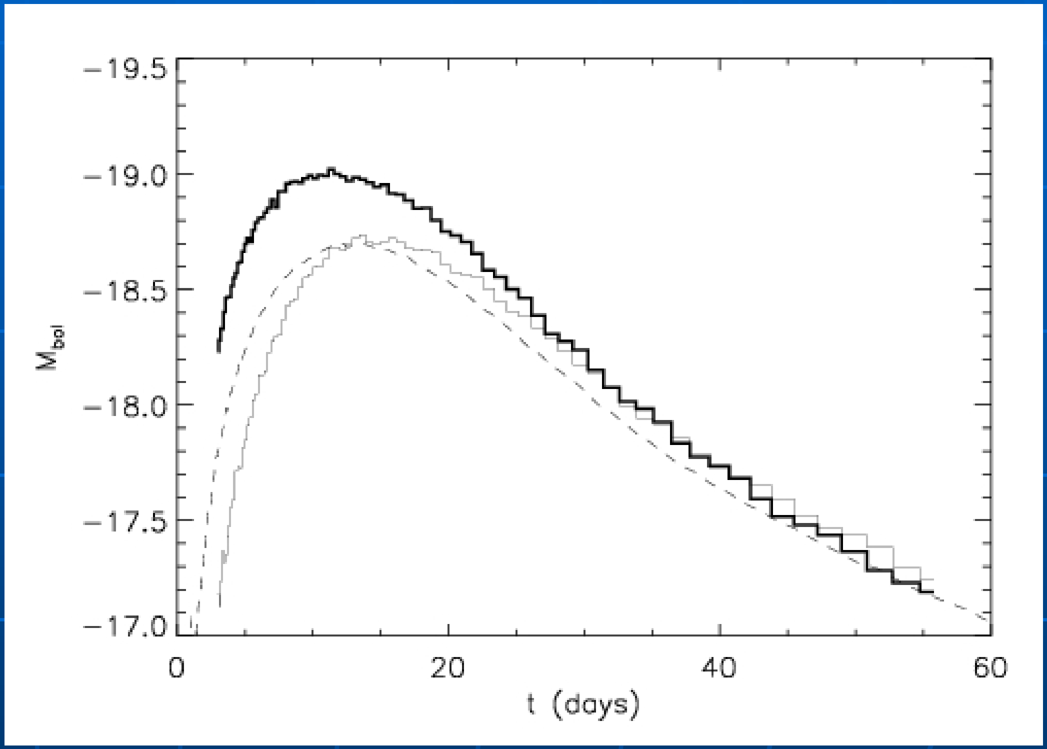


Röpke et al. (2006)

…. and their predictions

Sim et al. (2007)

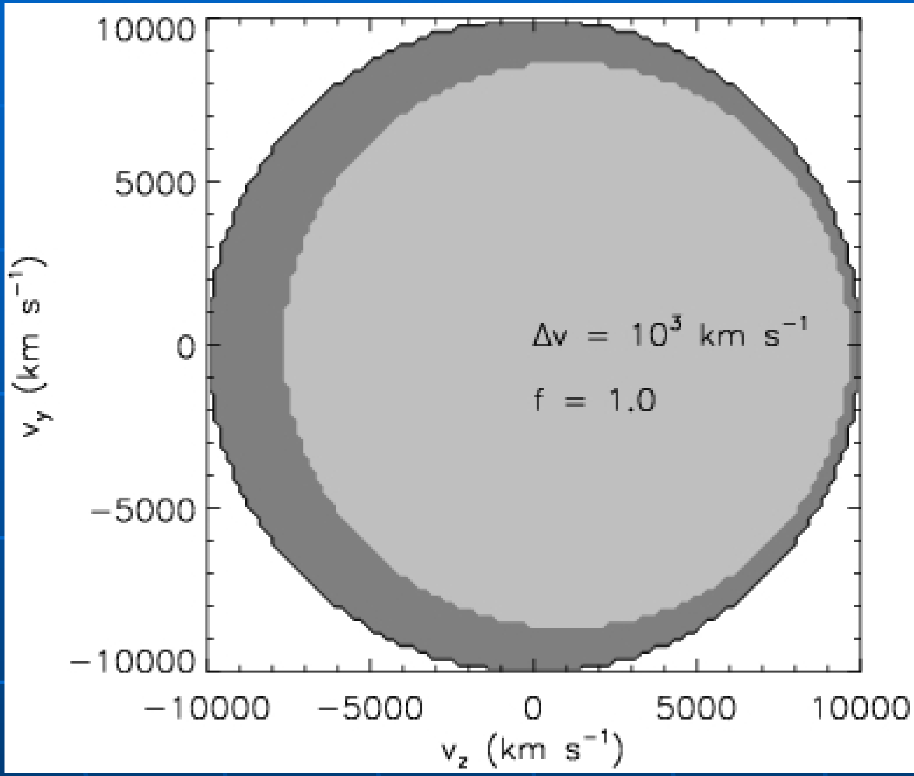


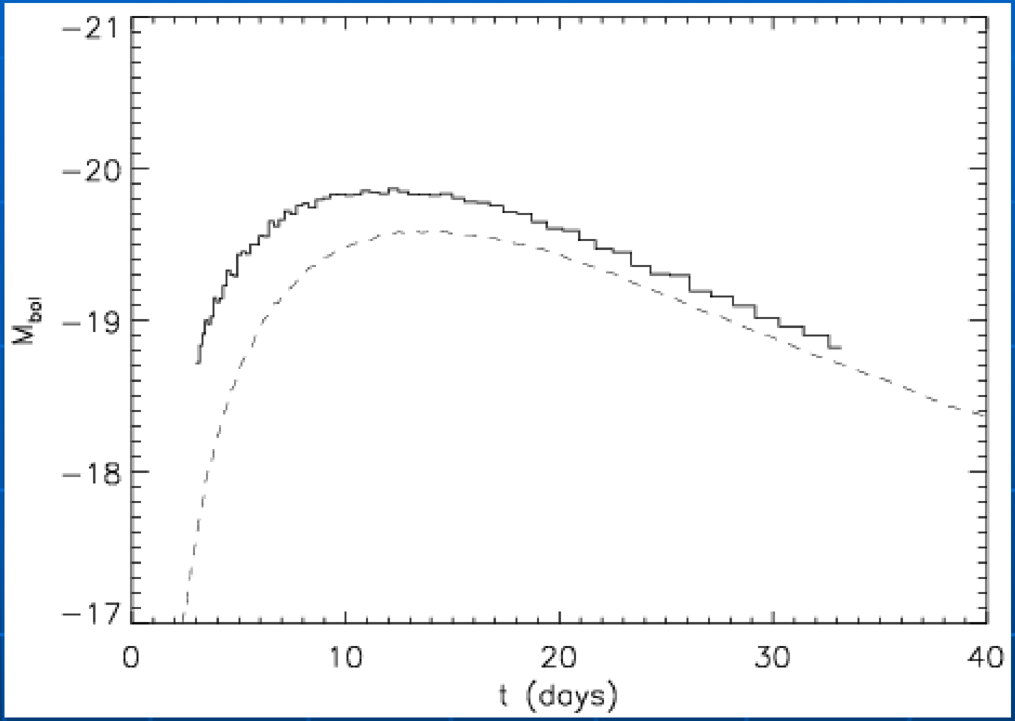


Note: This is a model that has ~ 0.4 M_{sun} of Ni only!

How far up can we go in luminosity?

Hillebrandt et al. (2007)



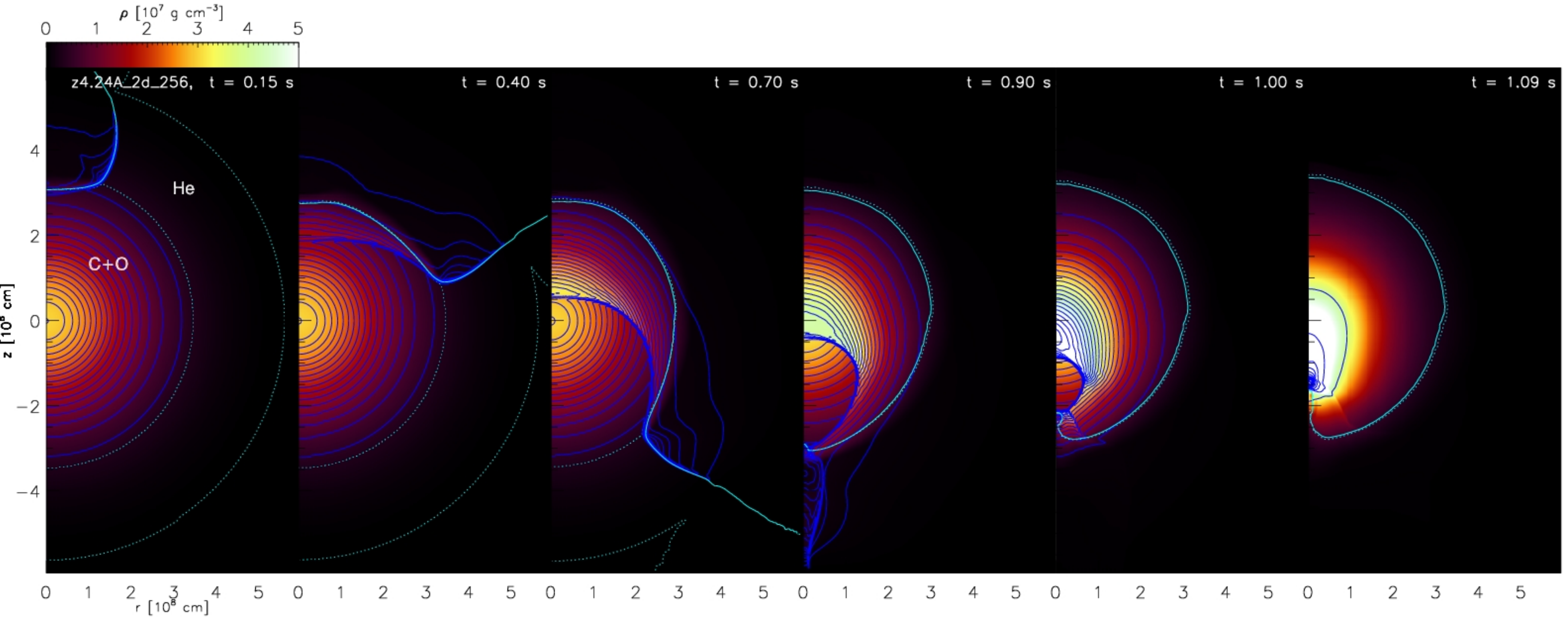


$M_{bol} \approx -20$ is possible with ~ 0.9 M_{sun} of Ni.

This could be a model for SN 2003gf .

A few remarks on sub-Chandra double detonations

Fink et al. (in preparation 2007)



- *The He-triggered double detonation is a robust explosion mechanism, provided one can accumulate ≥ 0.1 M_{sun} of He.*
- *These explosions would be bright (≥0.4 M_{sun} of Ni), but velocity too high: They would no look like any of the observed SNe Ia.*

Summary and conclusions

- "Parameter-free" thermonuclear models of SNe Ia, based on Chandrasekhar-mass white dwarfs explode with about the right energy.
- They allow to predict light curves and spectra, depending on physical parameters!
- The diversity may be due to:
  → Ignition conditions (or other physical parameters, i.e., metallicity, …).
  → Or different progenitors, i.e., mergers ?
  → Or deflagration-detonation transitions?
  → Or 3D effects?

Summary and conclusions (cont.)

- Double-detonation sub-M_{chan} explode if enough He is accumulated on the C+O core.
- They would have "normal" luminosity, but "wrong" spectra.
- Rapidly spinning C+O white dwarfs ("mergers") produce less Ni in the deflagration mode than non-rotating models (Jan Pfannes, PhD thesis)

  → Are they the faint SNe Ia?

Dear Ken, Happy Birthday!

"Forced" turbulent combustion:

3-D "direct" numerical simulations of flames moving in WD matter.

Subgrid-scale velocity

$\rho = 2.9 \cdot 10^9 \, gcm^{-3}$

$V_f/s_{lam} = 4$

$V_f/c_s = 0.043$

(Schmidt et al., 2005)