Recent Progress in Type Ia Supernova Modeling and its Implication for Cosmology

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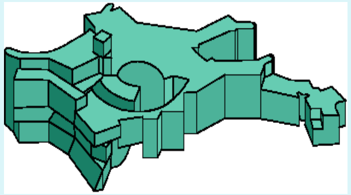

RESCUE Symp. on Astroparticle Physics and Cosmology
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In collaboration with ….

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Martin Reinecke (MPA),

Stuart Sim (MPA),

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Rüdiger Pakmor (MPA),

Paolo Mazzali (MPA & Obs. Padova),

Jens Niemeyer (U. Würzburg),

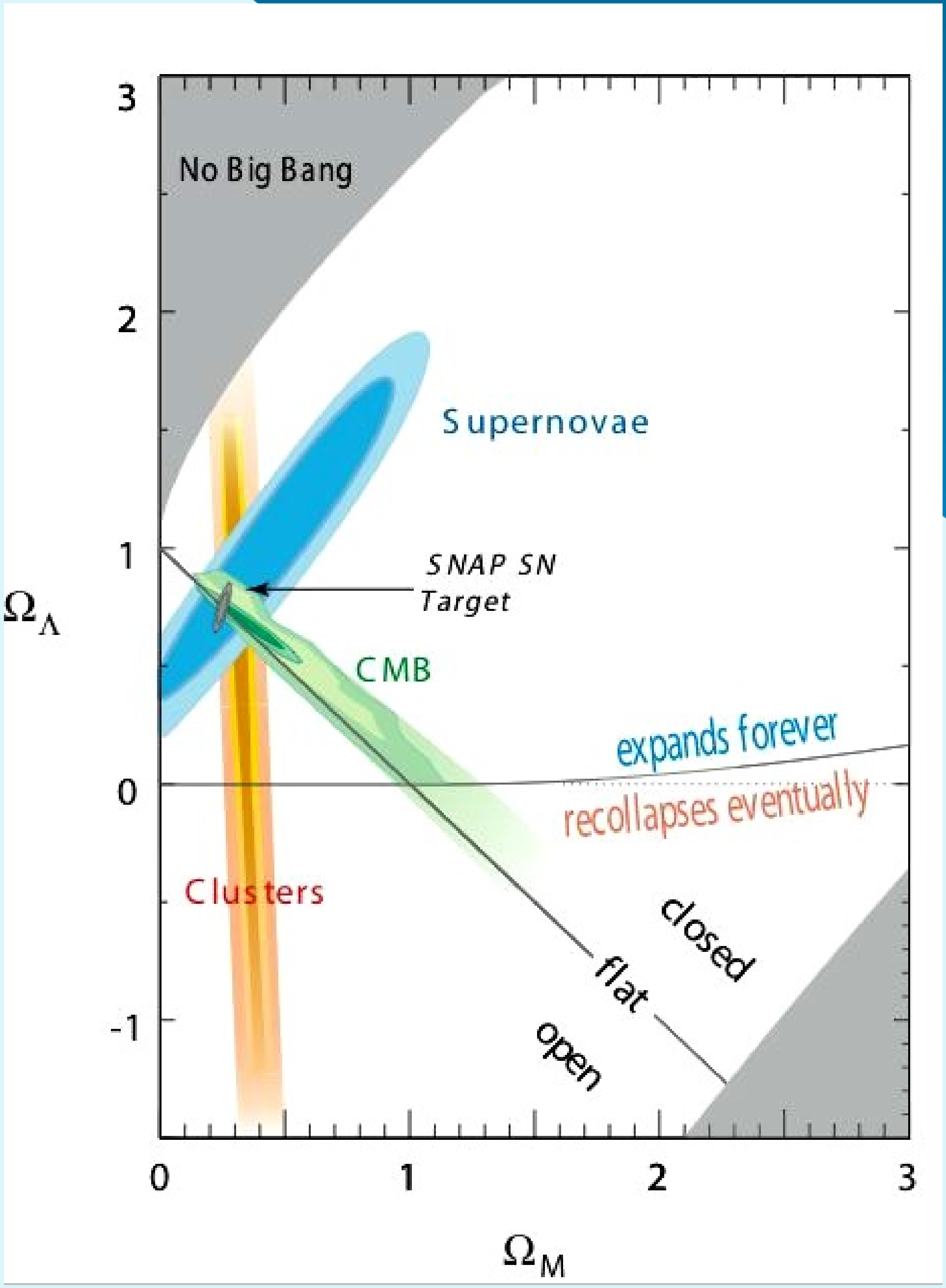
Wolfram Schmidt (U. Würzburg),

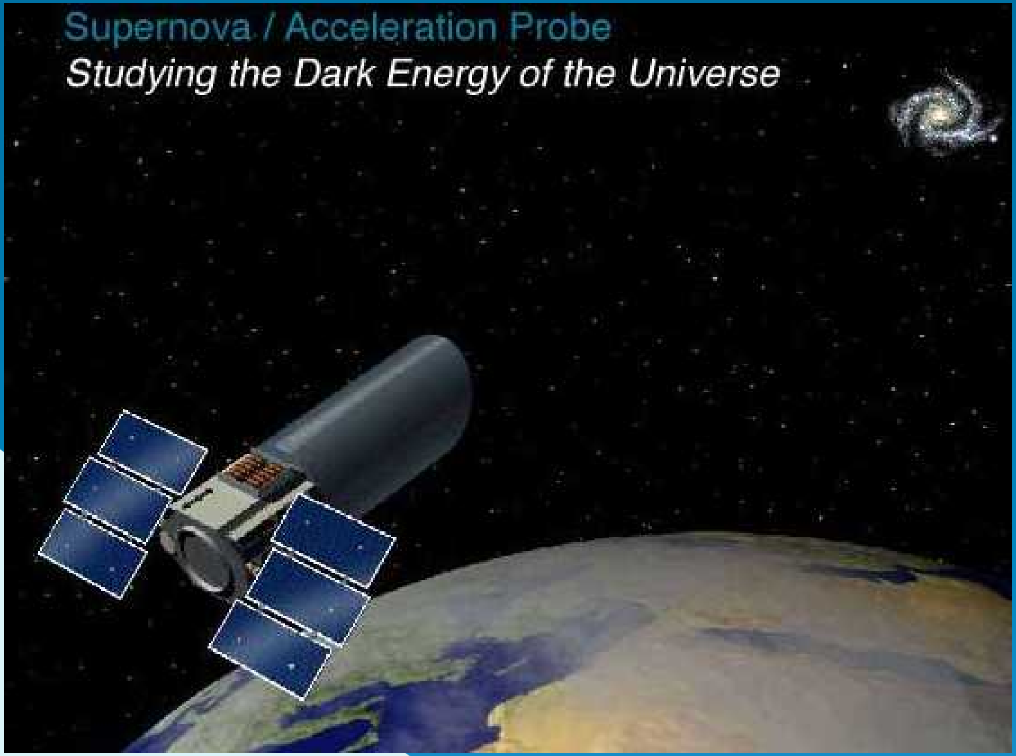
Sergei Blinnikov (ITEP Moscow),

Stan Woosley (UC Santa Cruz),

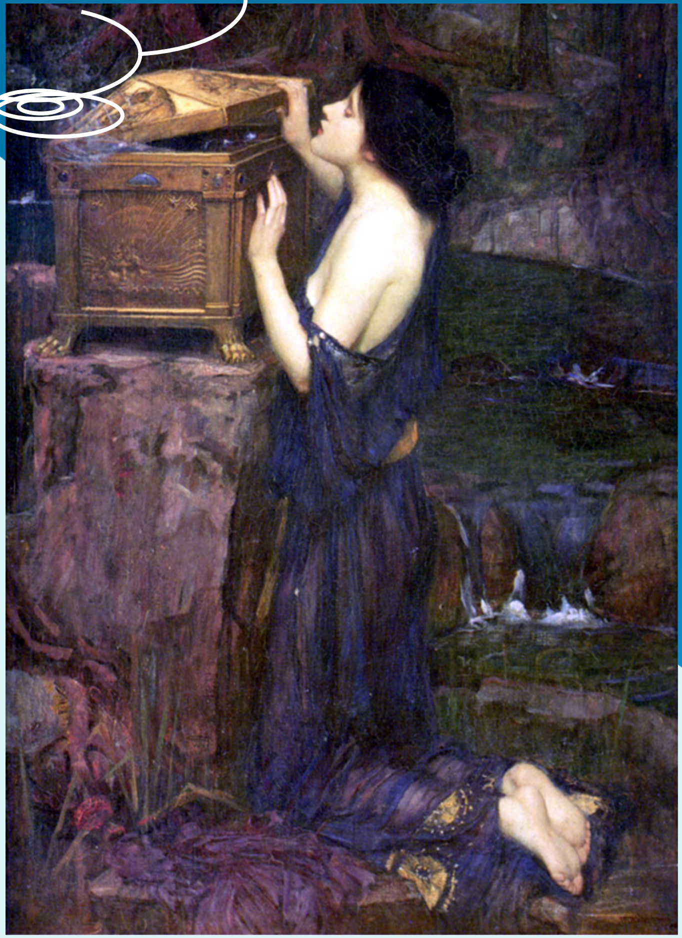
……………..

The promise of supernova cosmology:





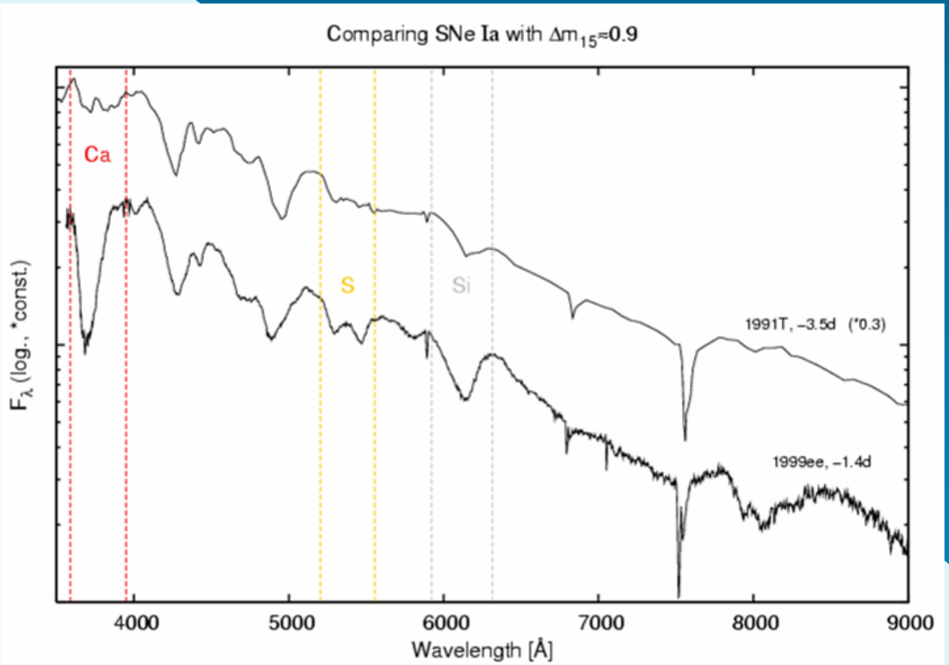
But …

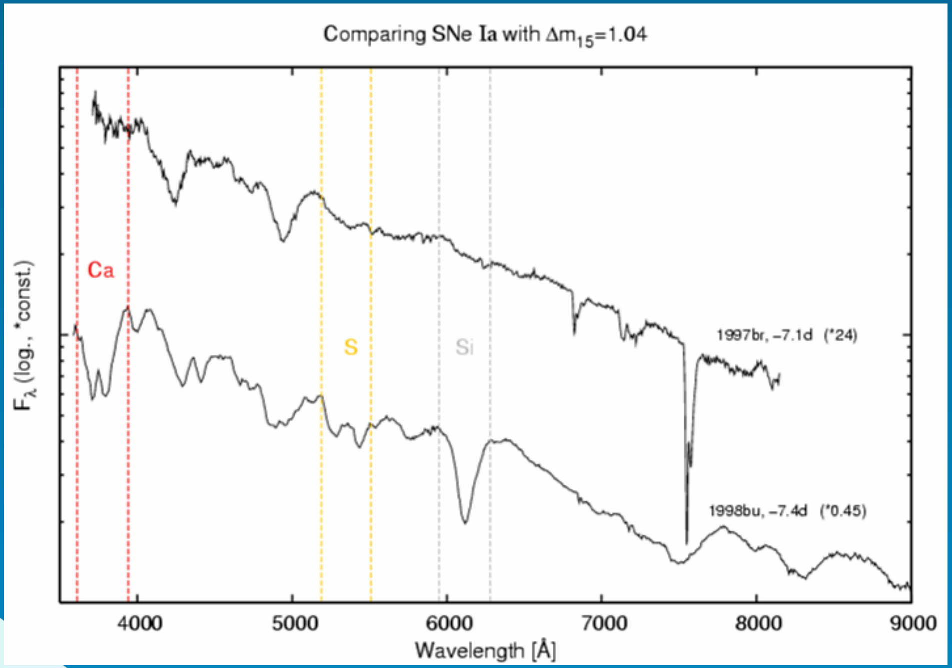


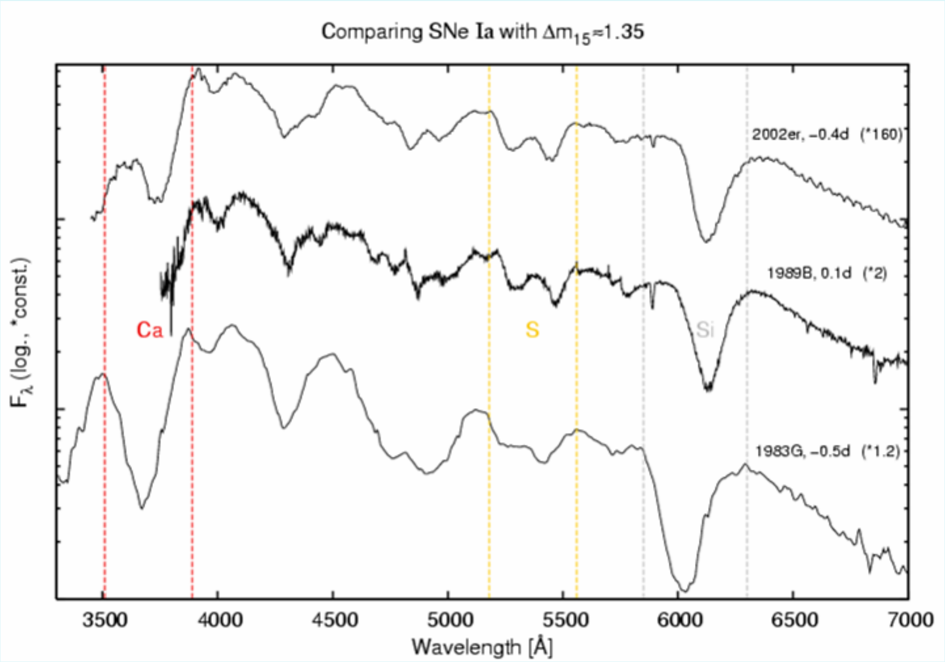
Is Hope left in Pandora's box ?

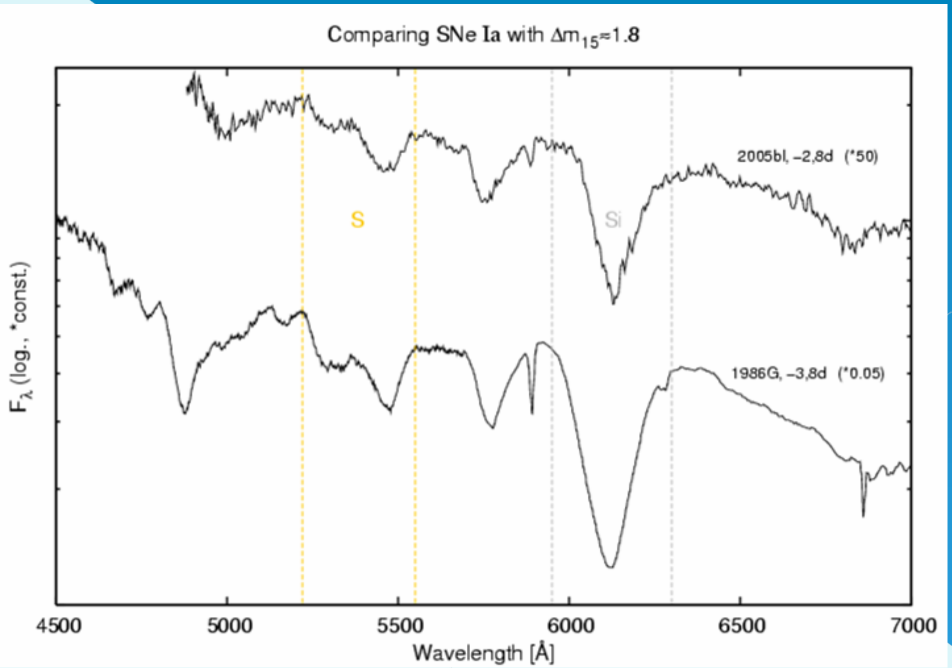
How “different” are SNe Ia?

Example: Early time spectra (court. Stephan Hachinger)



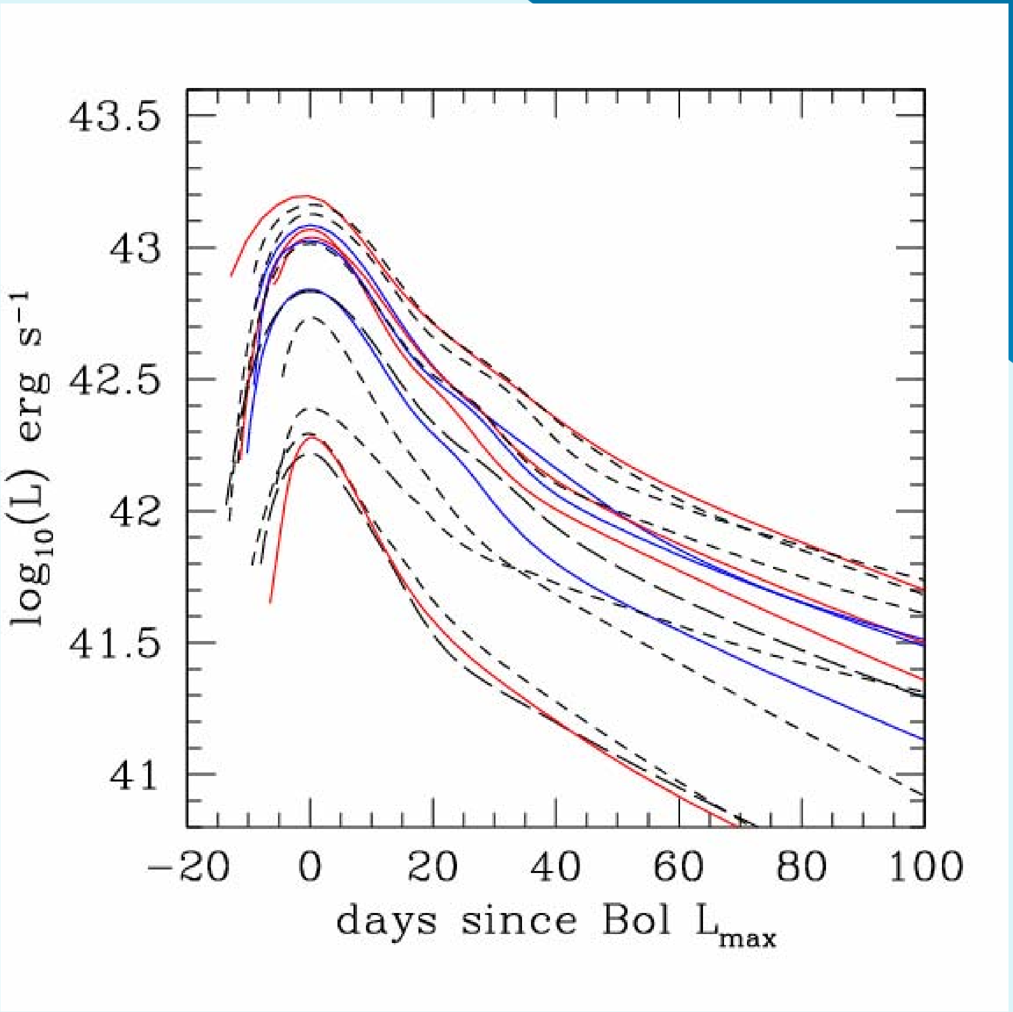


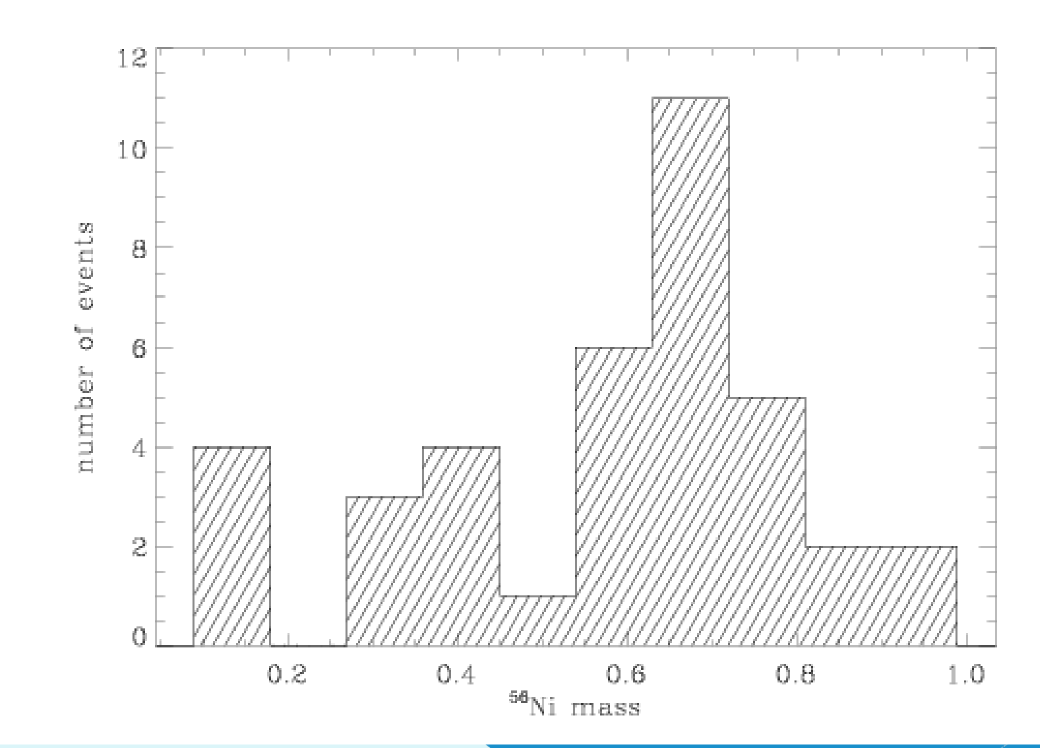




Example: Bolometric LCs and Ni-masses

(mostly RTN/ESC data)





(Court. M. Stritzinger;

also: Stritzinger et al. 2006)

Is evolution a problem?

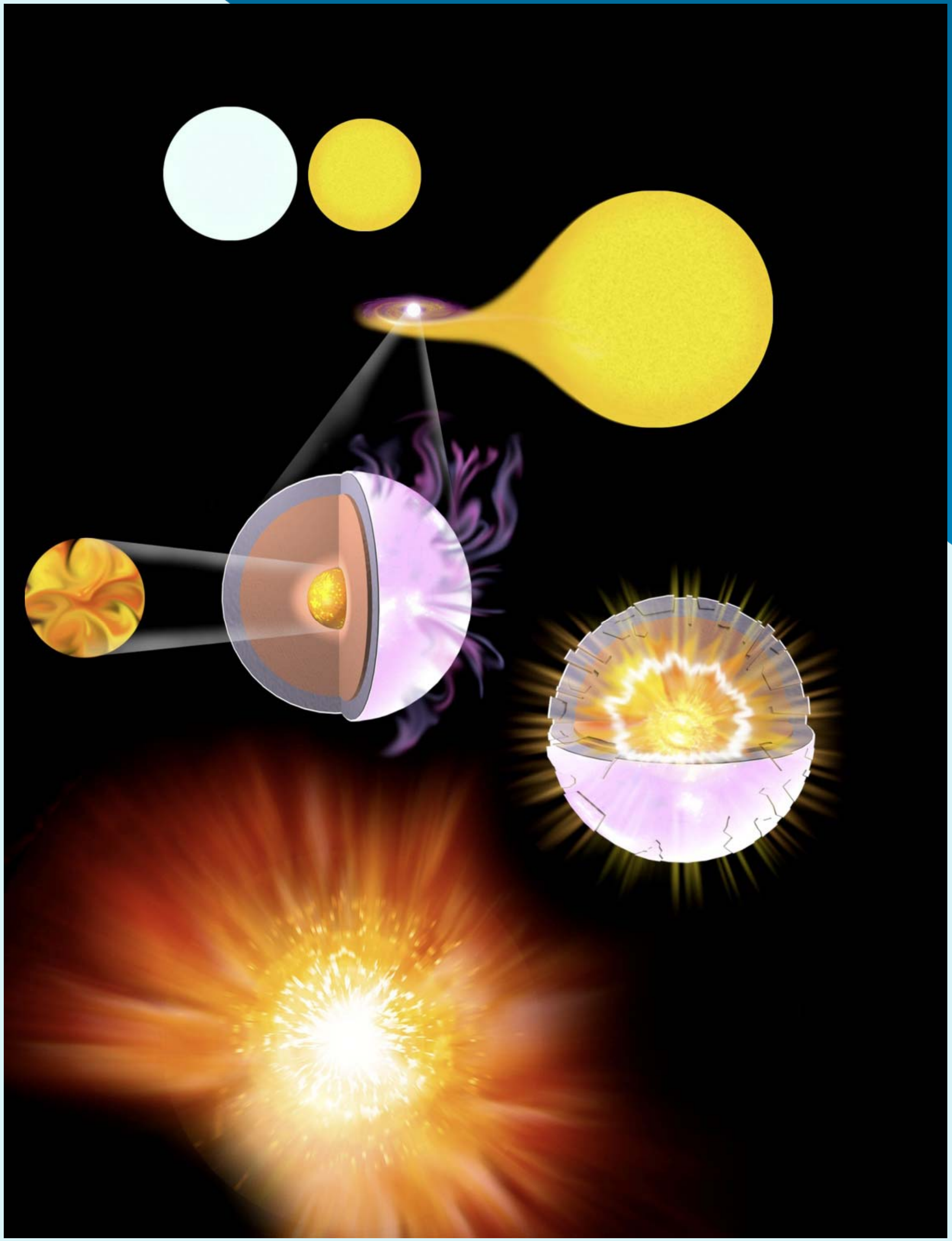
Or extiction?

Or ……. ?

Ask theory also!

The “standard” model of type Ia supernovae

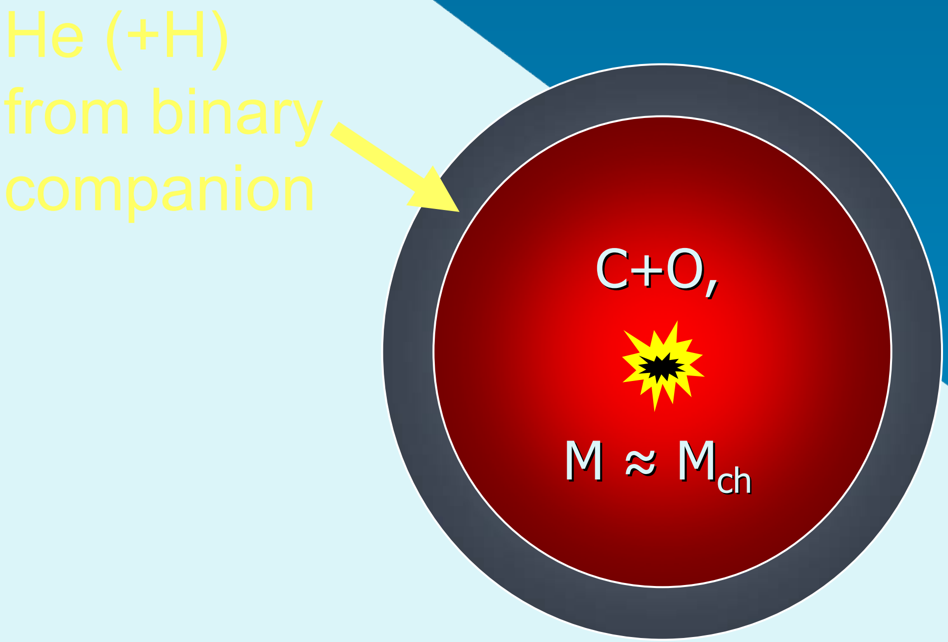
The "standard" model of type Ia supernovae



- 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!

How does the model work?



Explosion energy:

Fusion C+C, C+O, O+O → "Fe"

Laminar burning velocity:

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

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

Temperature: a few 10^9 K

Radii: a few 1000 km

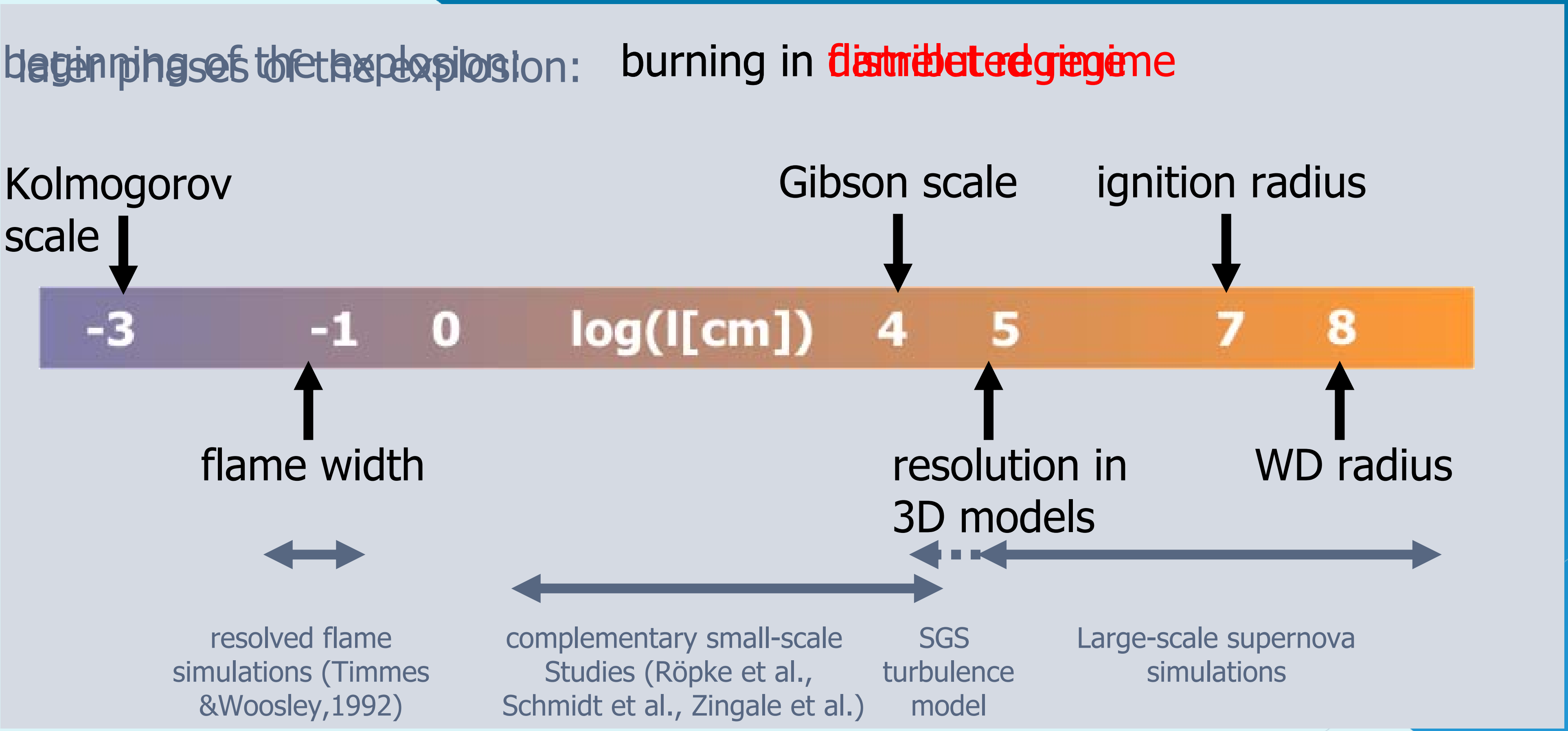
Too little is burned!

The physics of turbulent combustion

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

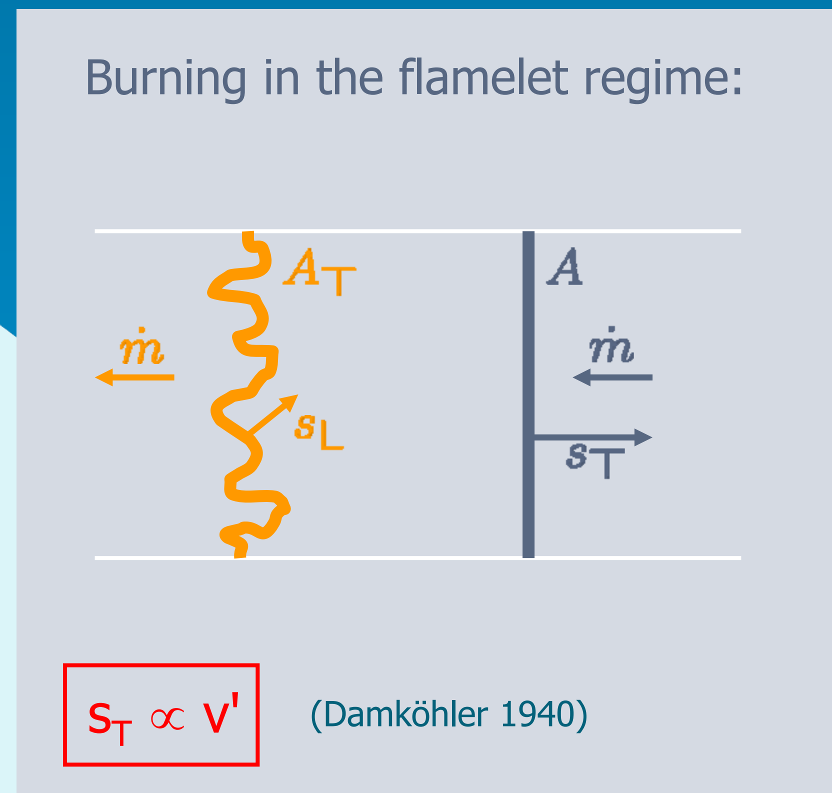
Relevant length scales in simulations of SN Ia explosions

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



The basic principles of modeling turbulent combustion:

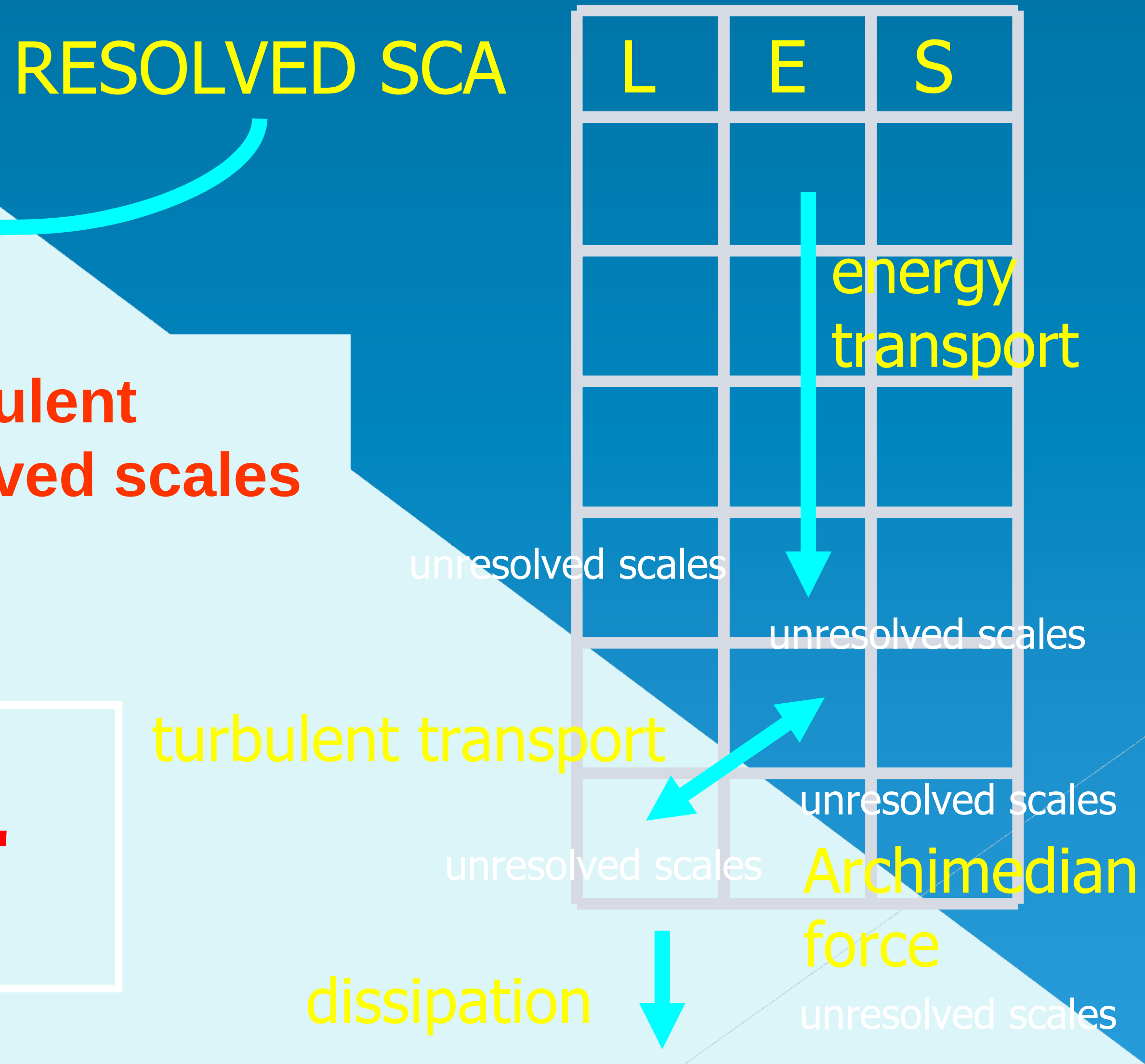
- During most parts of the SN Ia explosion: turbulence does not penetrate internal flame structure; flamelet regime of turbulent combustion



In very late stages: turbulence may affect burning microphysics $\rightarrow$ onset of distributed burning regime

Numerical implementation (I)

- Large Eddy Simulation (LES) approach
- Subgrid-scale turbulence model (Niemeyer & WH, 1995; Schmidt et al., 2005, 2006)



Balance equation for turbulent kinetic energy on unresolved scales

→ determines turbulent velocity fluctuations v' (and s_T)

Numerical implementation (II)

- seen from scales of WD: flame is a discontinuity between fuel and ash; flame propagation via Level Set Method:

  associate flame front with

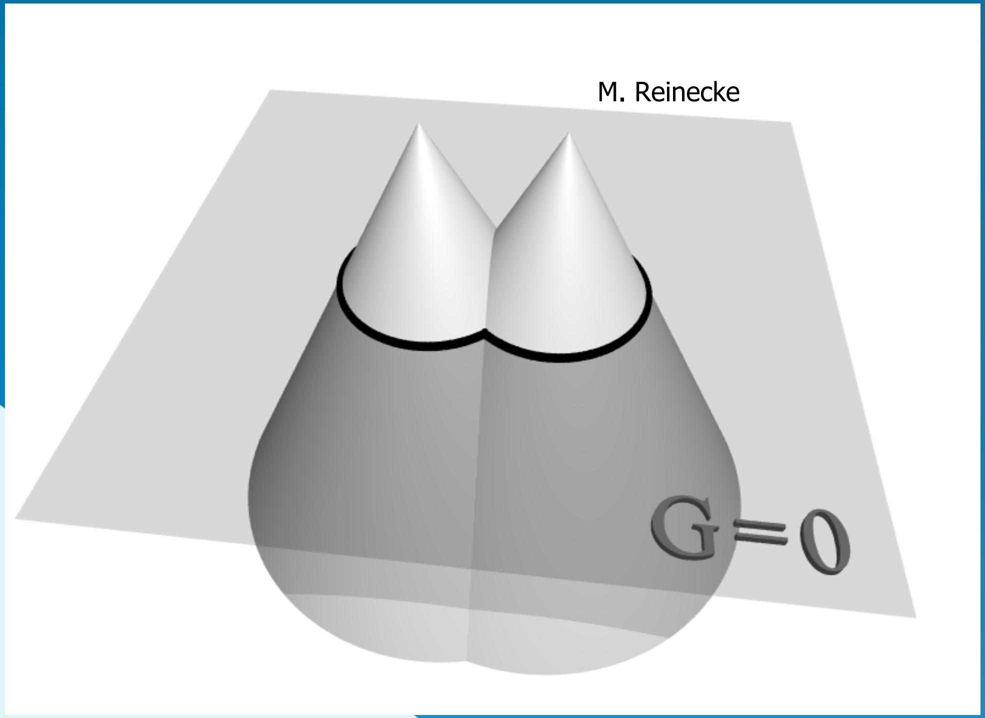
  $$\Gamma = \{\vec{r} \mid G(\vec{r},t) = 0\}$$

- distance function G, G<0 in fuel,

  G>0 in ashes,

  equation of motion:

  $$\frac{\partial G}{\partial t} = (\mathbf{v}_{\mathrm{u}}\mathbf{n} + s_{\mathrm{T}}) \mid \nabla G \mid$$



- simplified description of burning: everything behind G=0 isosurface is nuclear ash; depending on fuel density at burning: intermediate mass elements (“Mg”) or NSE (mixture of “Ni” and ^{4}He)

Note:

- *This has become the preferred method in many recent technical applications involving premixed turbulent chemical flames!*
(e.g., Smiljanowski et al. 1997, Peters 2000, Angelberger et al. 2002, Kraus 2007, ...)

- *It is free of adjustable parameters once the subgrid-scale model has been fixed!*

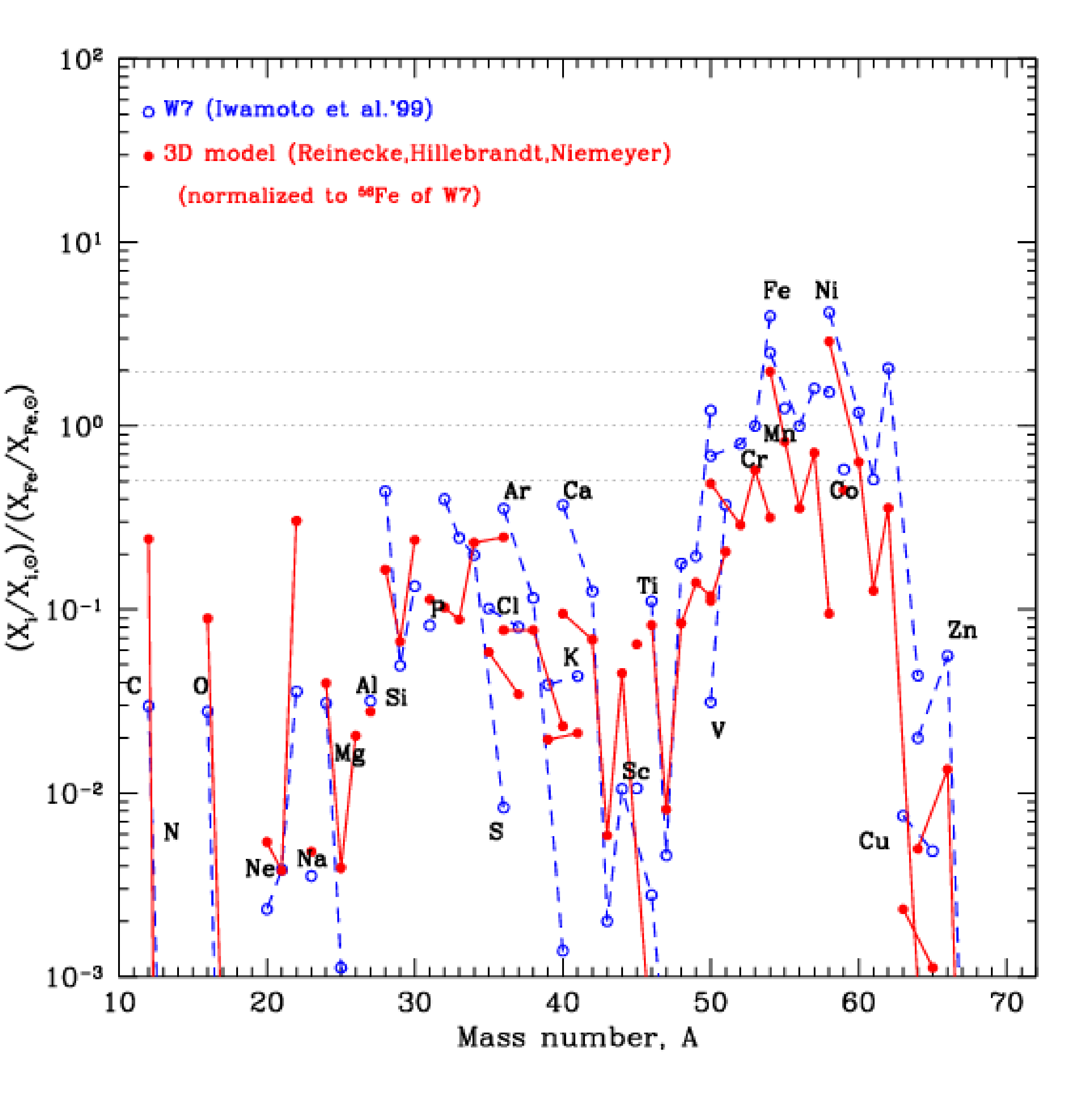
A few 'generic' results

('low-resolution' 3D parameter study)

Nuclear Abundances

(Travaglio et al. 2004,

also Röpke et al. 2006)

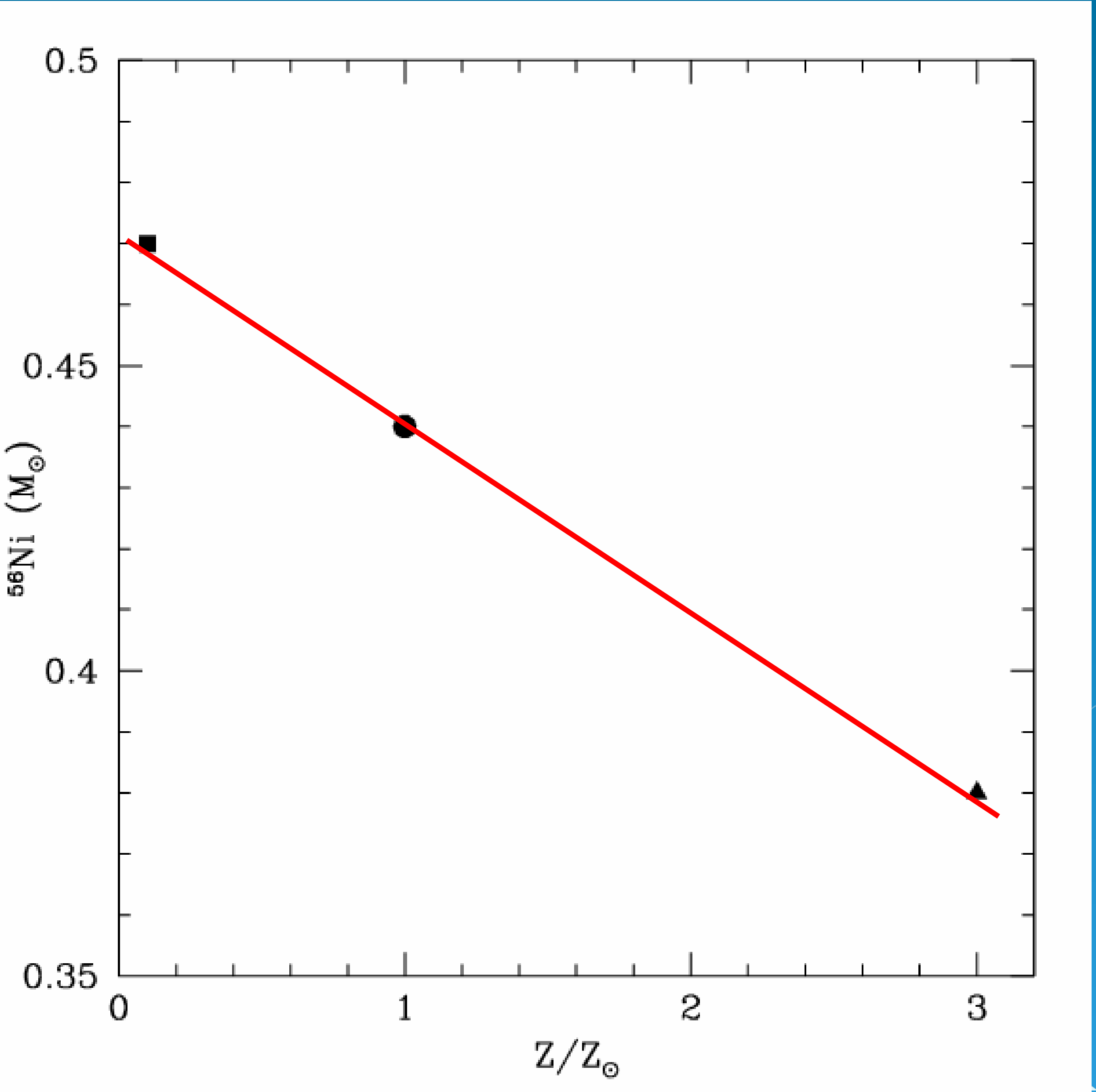


Effects of metallicity

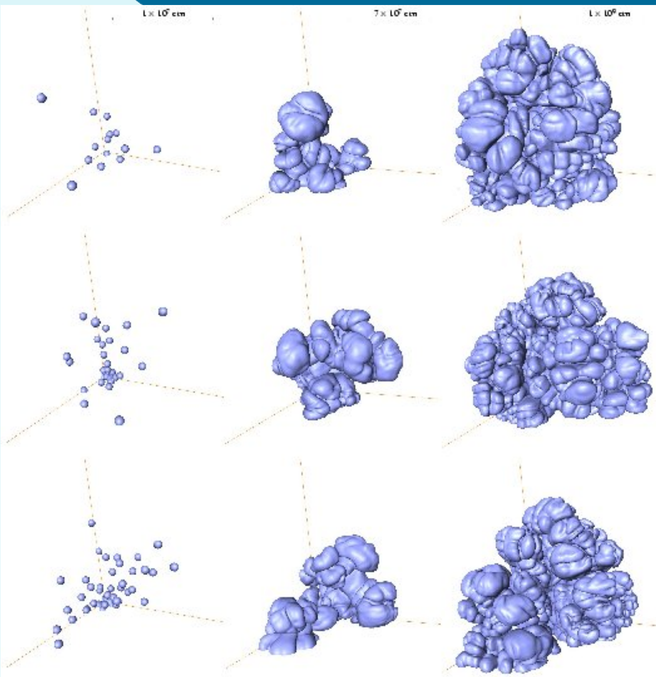
(Travaglio et al. 2005,

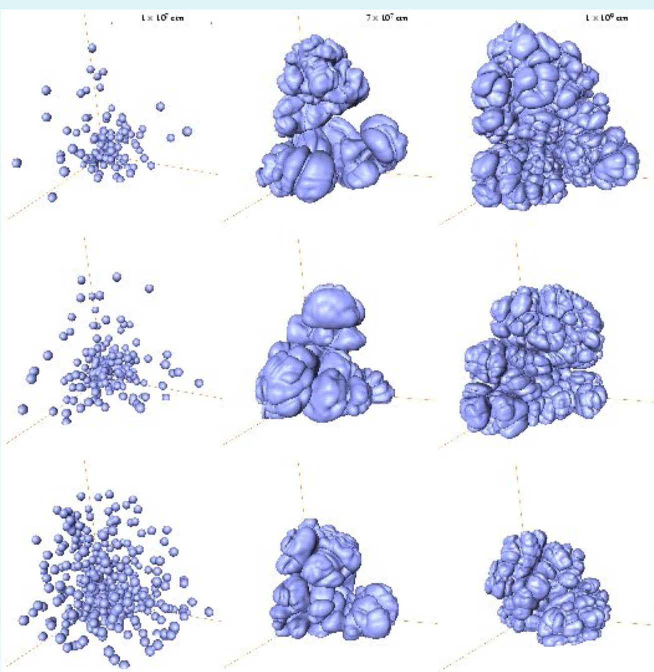
Röpke et al. 2006)

(also Timmes et al. 2003)

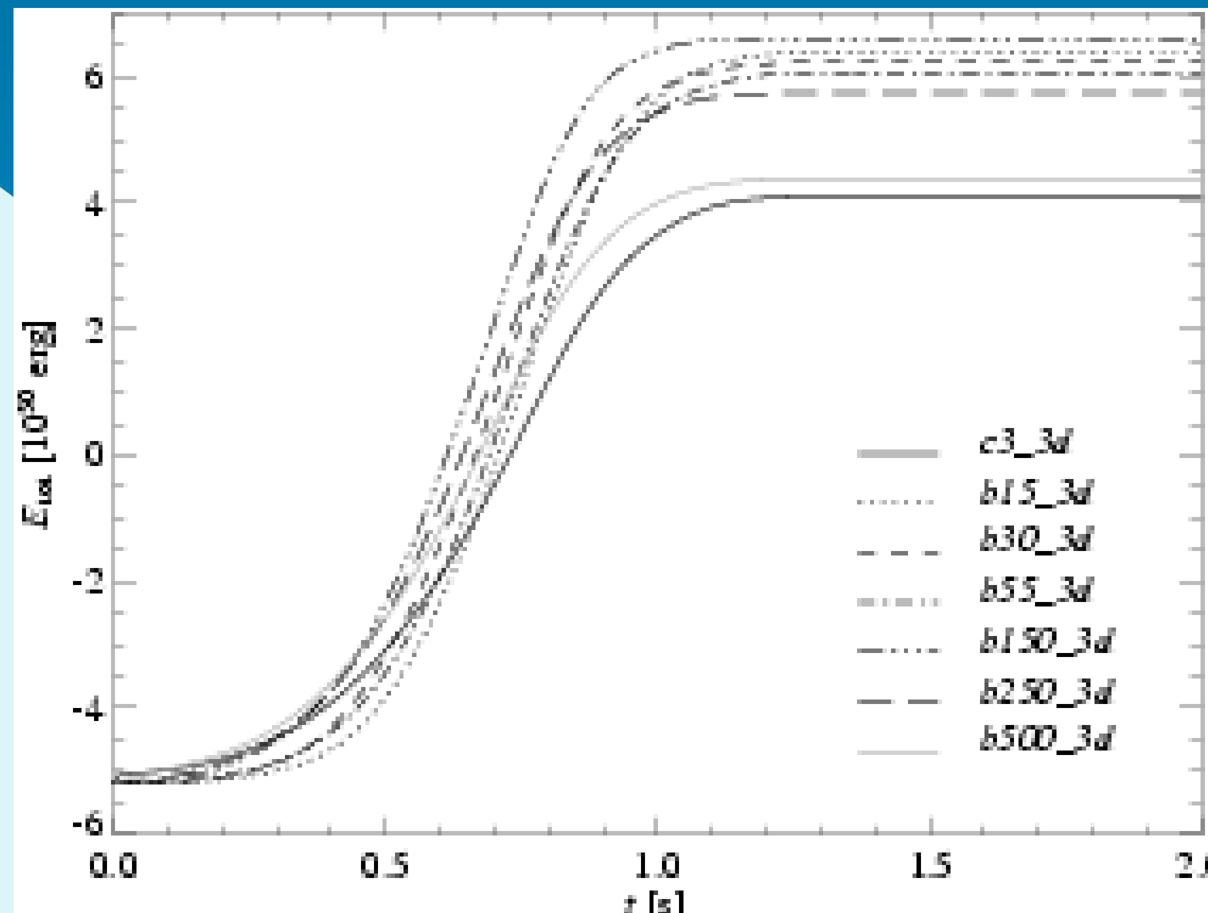


Ignition conditions: a reason for diversity?





“Multi-spot”

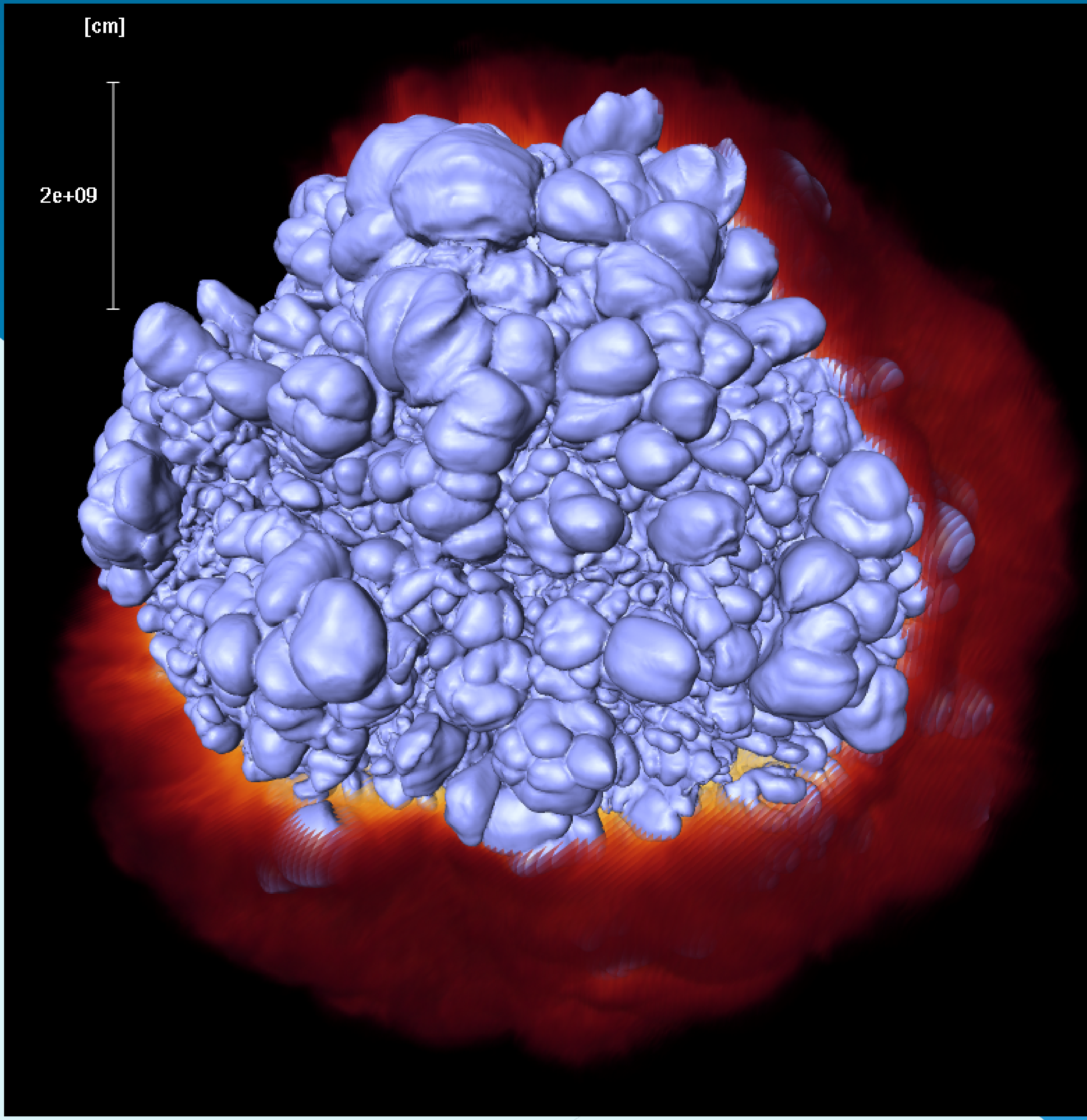


Röpke et al. (2005)

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

- "4π"
- 1024^3 grid
- initial resolution near the center ≈ 800m
- moving grid
- Local & dynamical sgs-model
- ~ 1,000 h on 512 processors, IBM/Power4, at RZG

(Röpke et al., 2007)



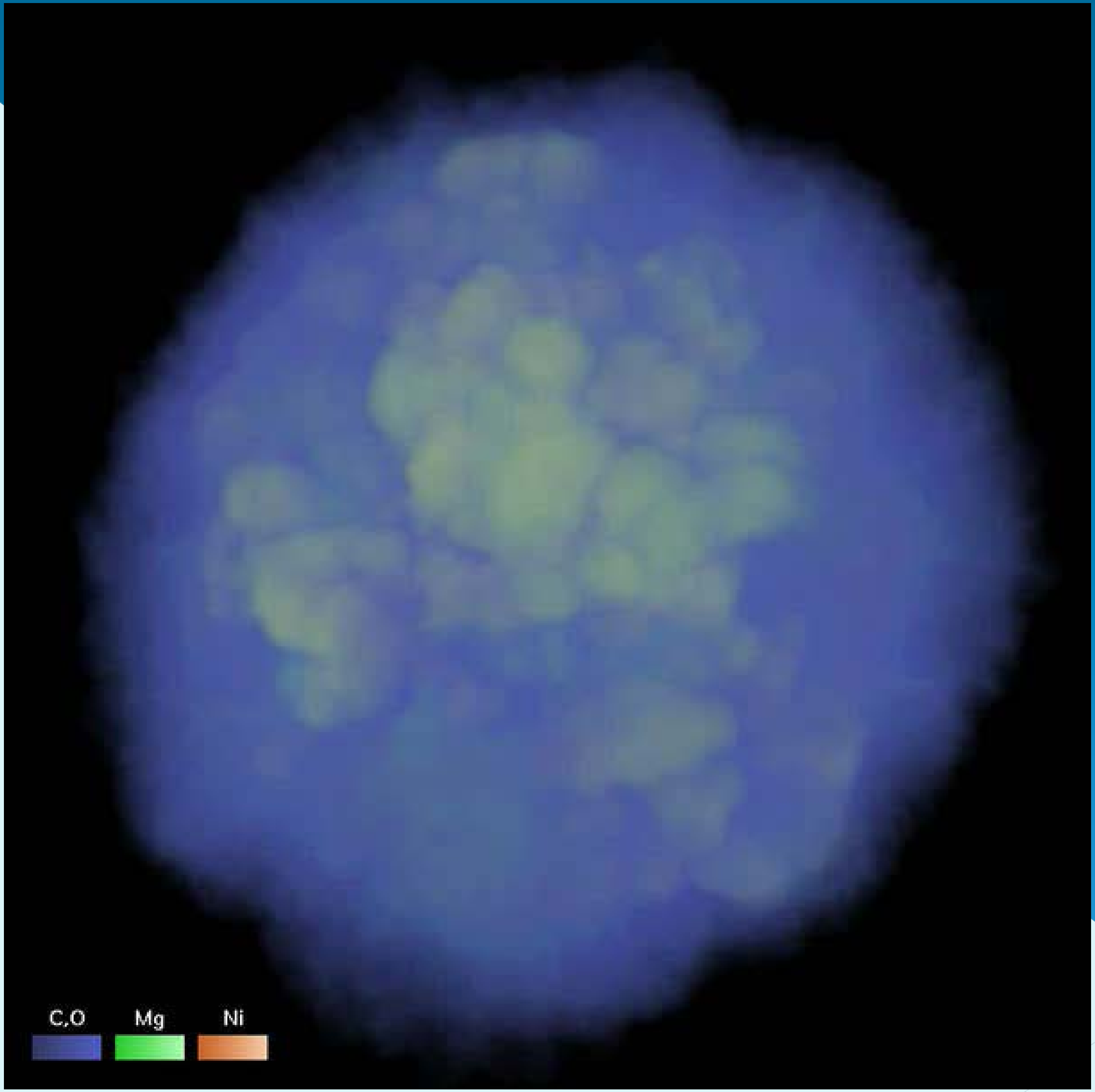
Some important results

- $E_{kin} = 8.1 \cdot 10^{50}$ erg (= 0.81 B)
- Iron-group nuclei: 0.61 M_{sun} (~ 0.33 M_{sun} ^{56}Ni)
- Intermediate-mass nuclei: 0.43 M_{sun} (from hydro)
- Unburnt C+O: 0.37 M_{sun} (from hydro)
  (less than 0.08 M_{sun} at v<8000km/s)
- Vmax ≈ 17,000 km/s

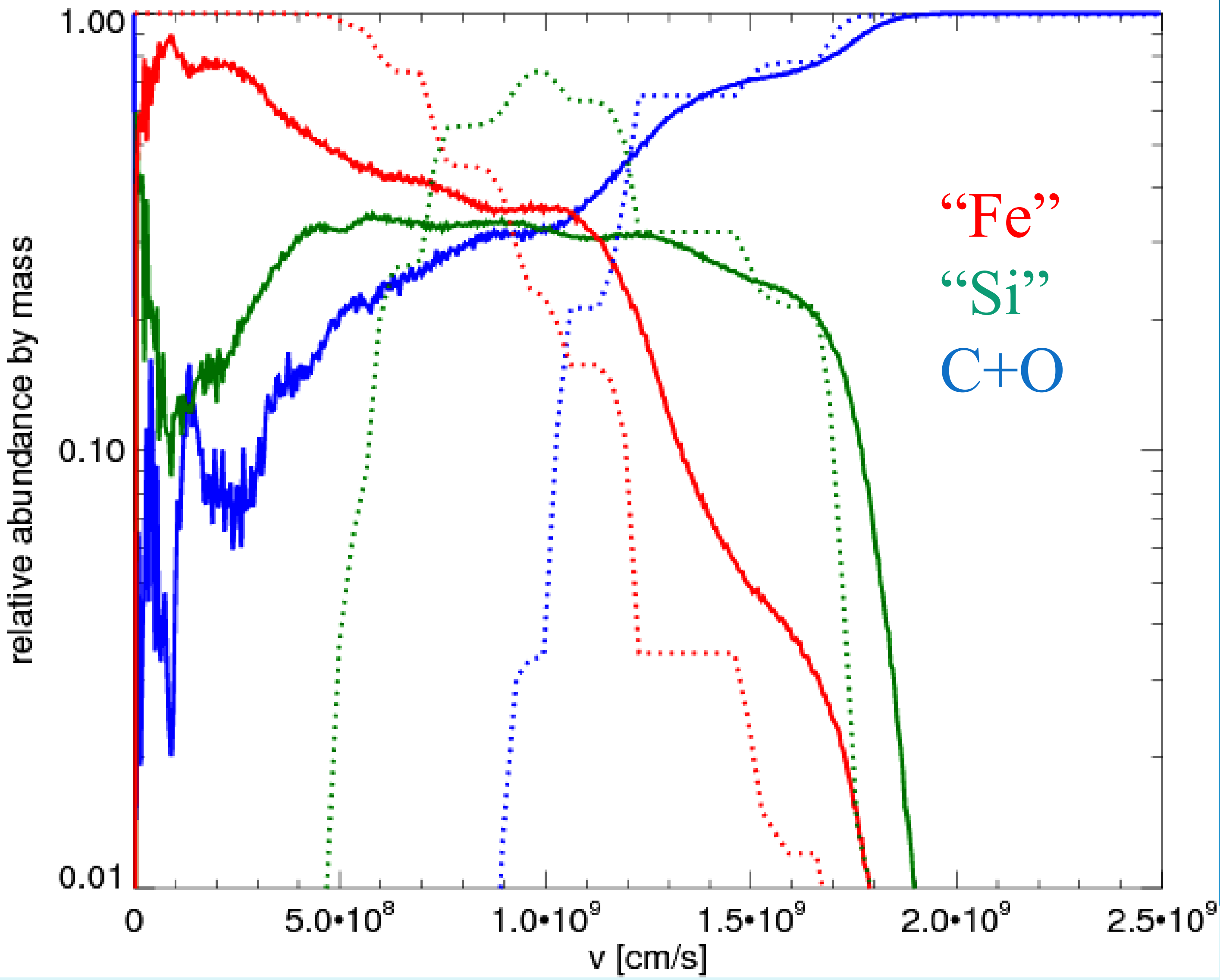
Good agreement with observations of some "normal" SNe Ia!

Röpke et al. (2007)

Example 1: Abundances ……..

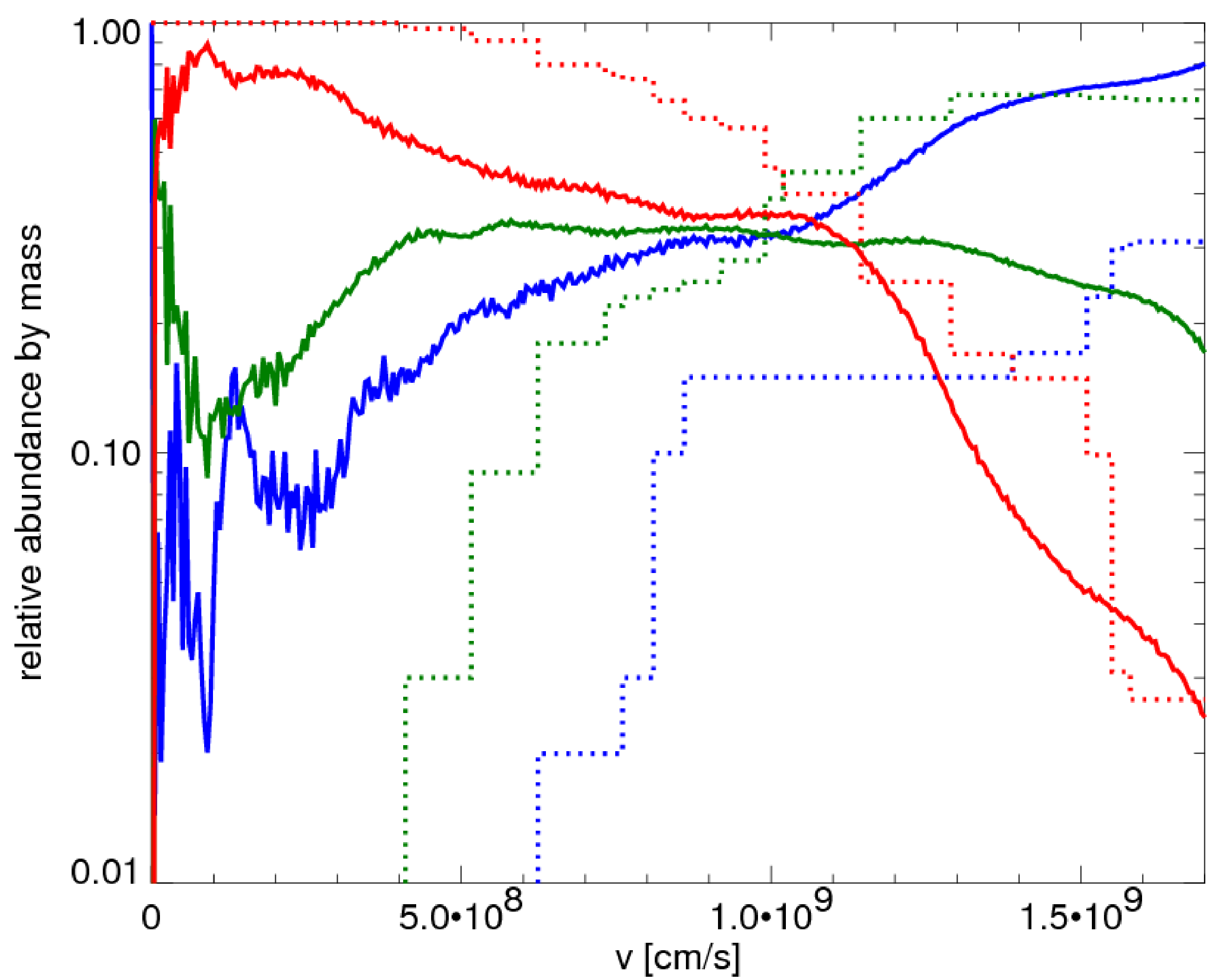


…. and “abundance tomography”



SN 2004eo (Mazzali et al., 2008)

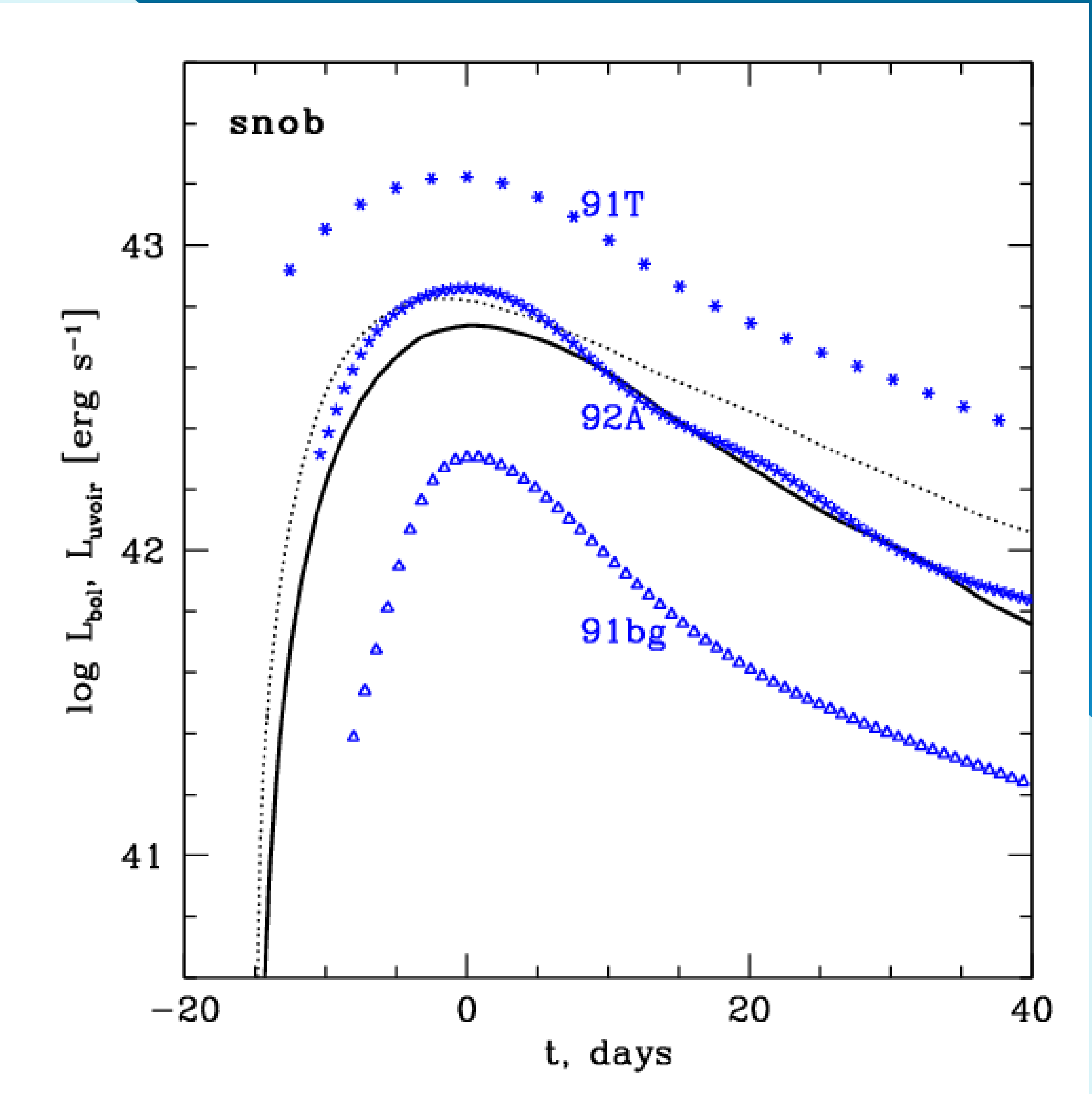
…. and "abundance tomography"



SN 2002bo vs. SNOB

Röpke et al. (2007)

Example 2: Bolometric light curve



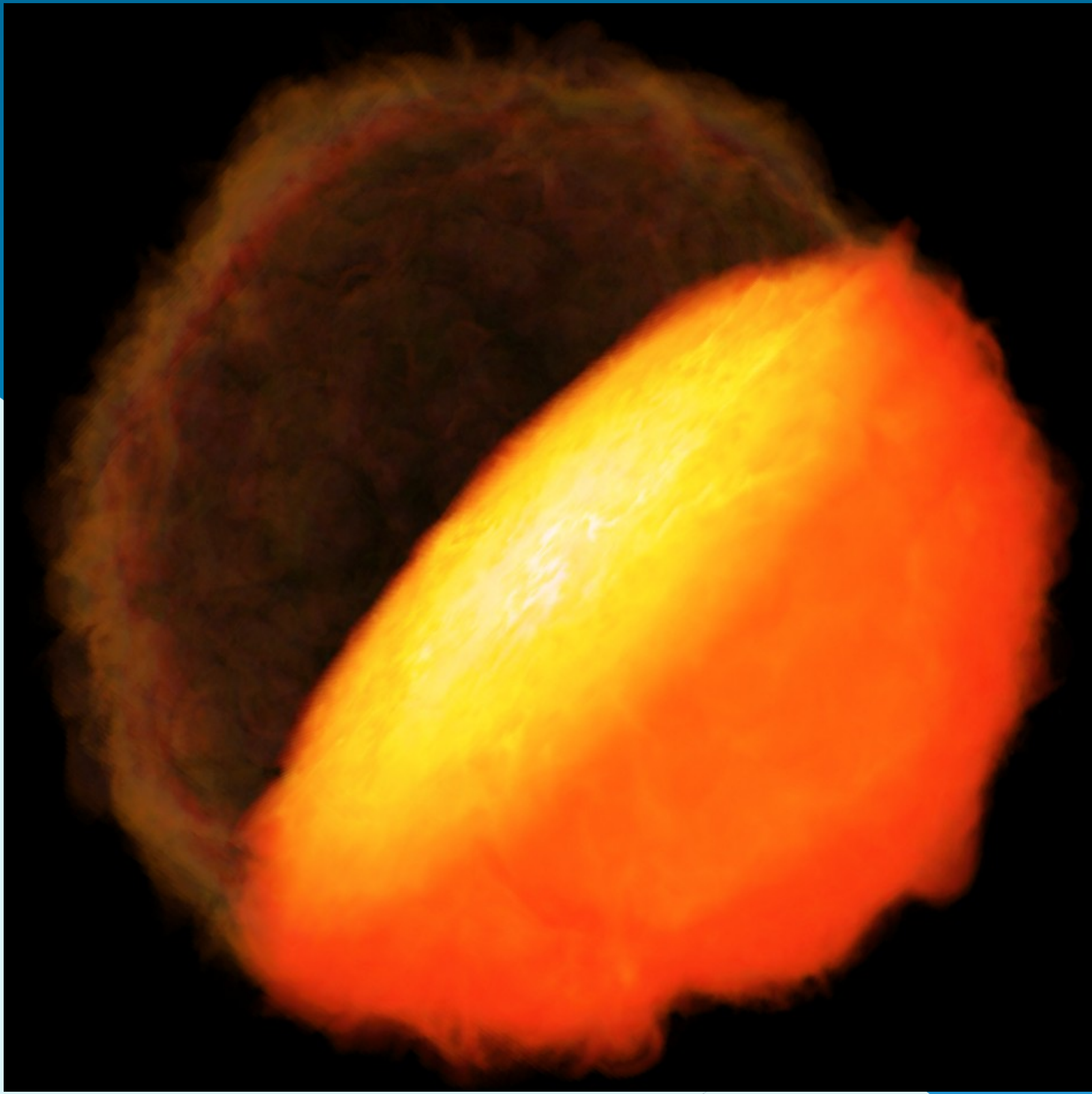
Note:

These are predictions, not fits!

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)

Preliminary results:

- $E_{kin} = 7.7 \cdot 10^{50}$ erg (= 0.77 B)
- 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

ova less

Observations?

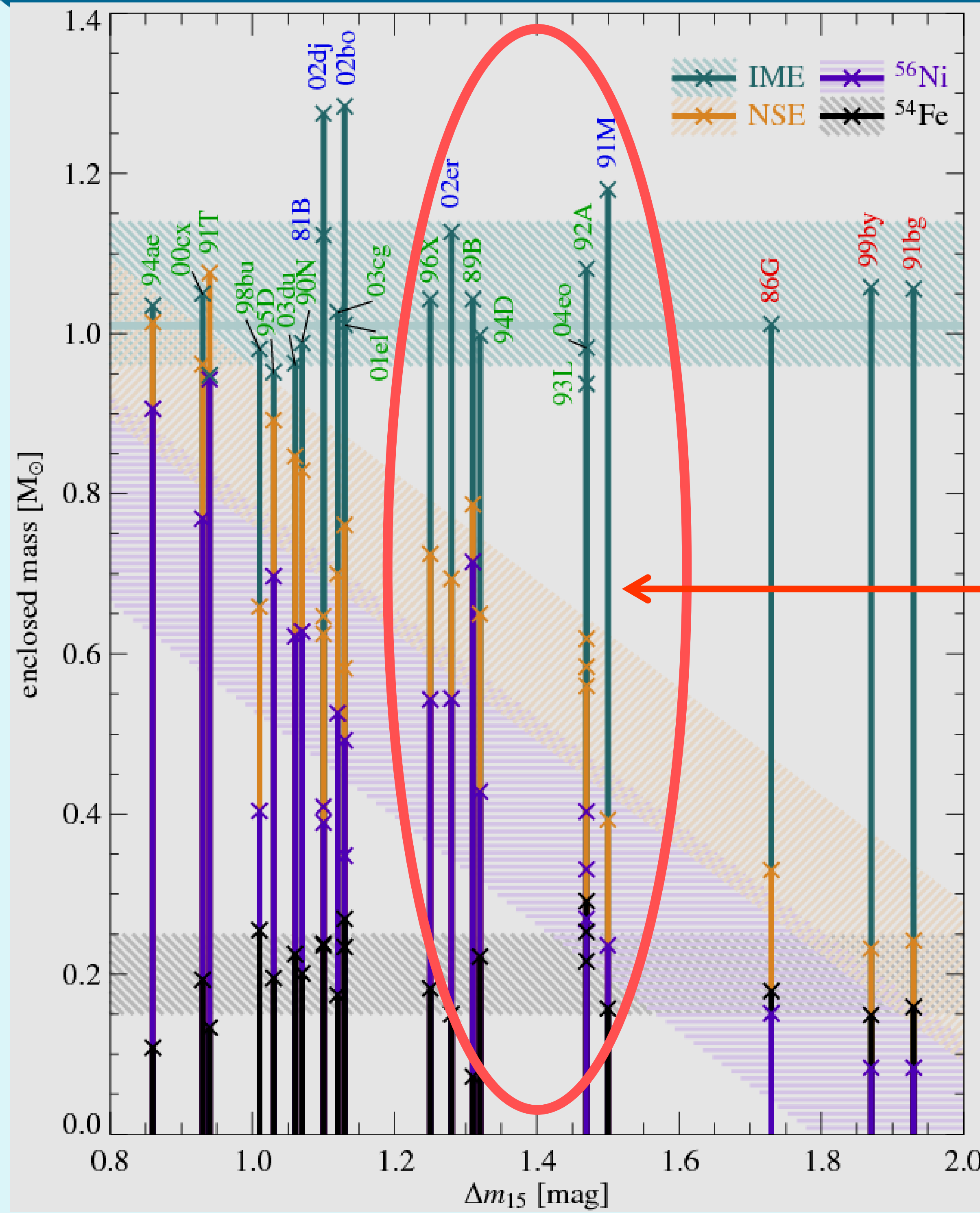
Röpke et al. (in preparation)

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).
  → Or deflagration-to-detonation transitions?

(Gamezo et al. 2004, 2005; Röpke & Niemeyer 2006, Woosley 2007, Röpke 2007)

The ‘Zorro’ diagramme



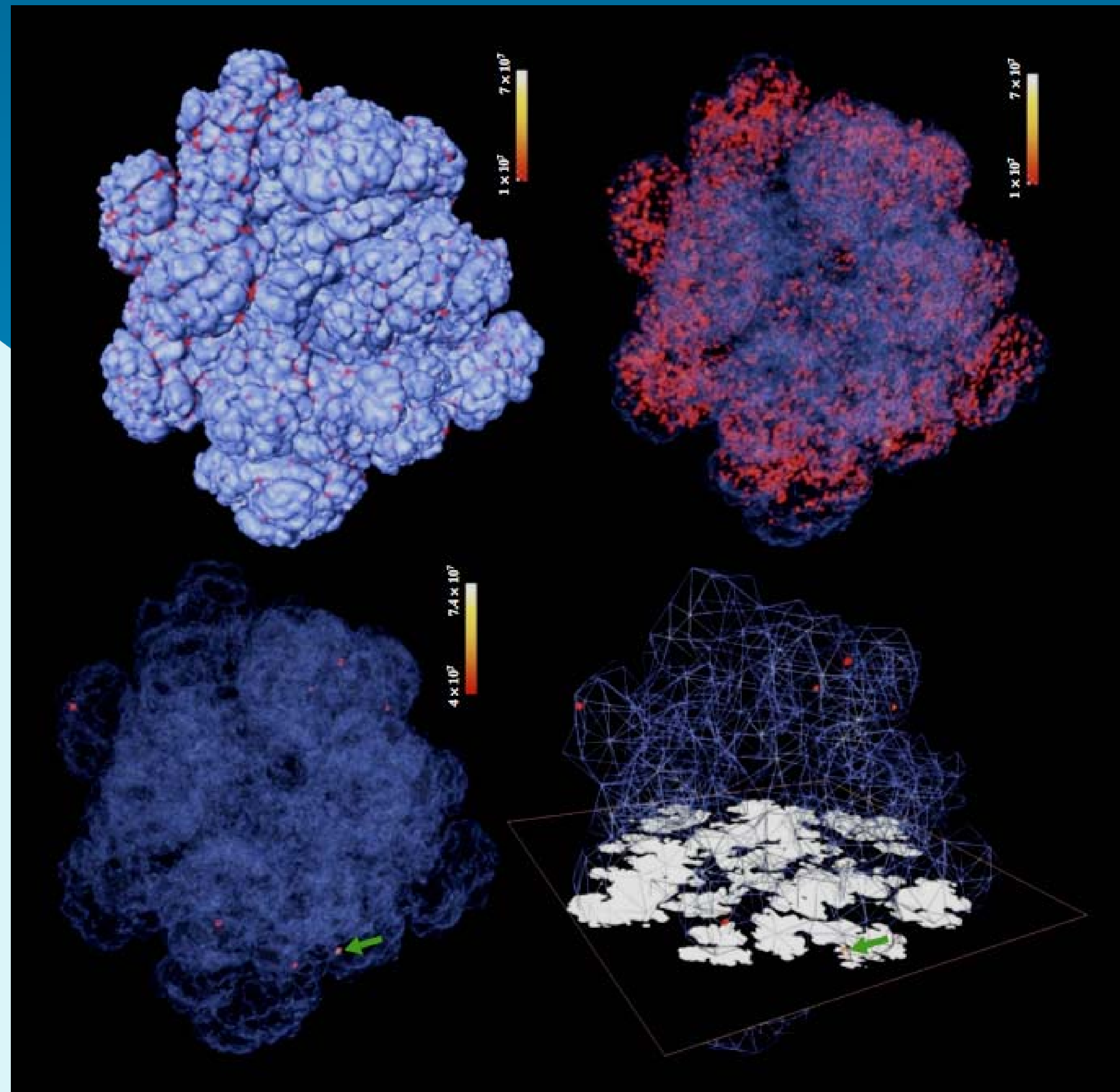
Pure deflagrations!

Mazzali et al. (2007)

Deflagration-to-detonation transitions?

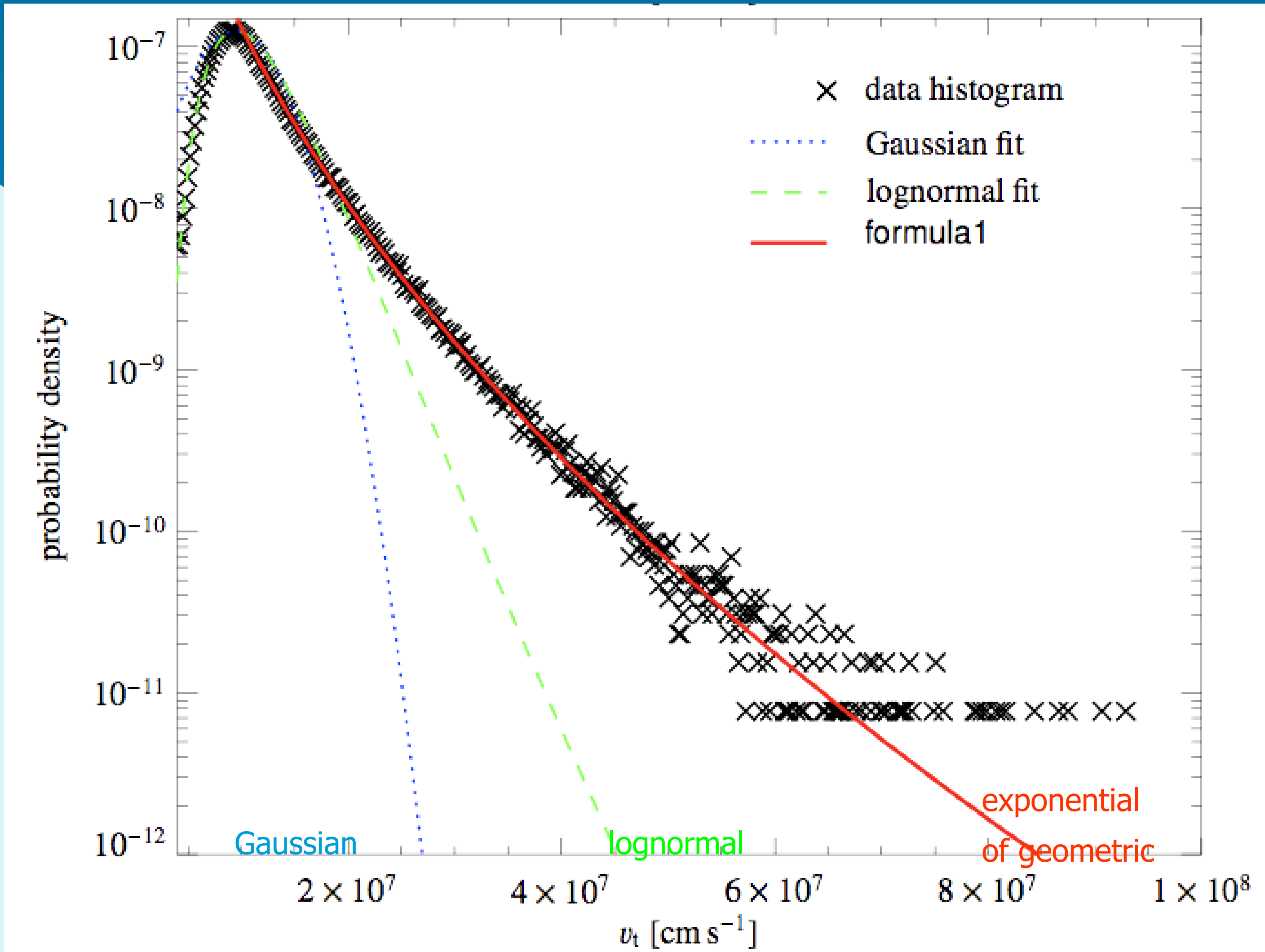
Analysis of turbulent velocity flucutations (as predicted by sub-grid scale model at the flame front for densities $1 \ldots 3 \cdot 10^7$ g cm^{-3})

(Röpke 2007)



Deflagration-to-detonation transitions?

High-amplitude turbulent velocity fluctuations ($\sim 10^8$ cm s^{-1}) occur at the onset of distributed burning regime on sufficiently large area of flame ($\sim 10^{12}$ cm^2)



(Röpke 2007)

More questions and challenges

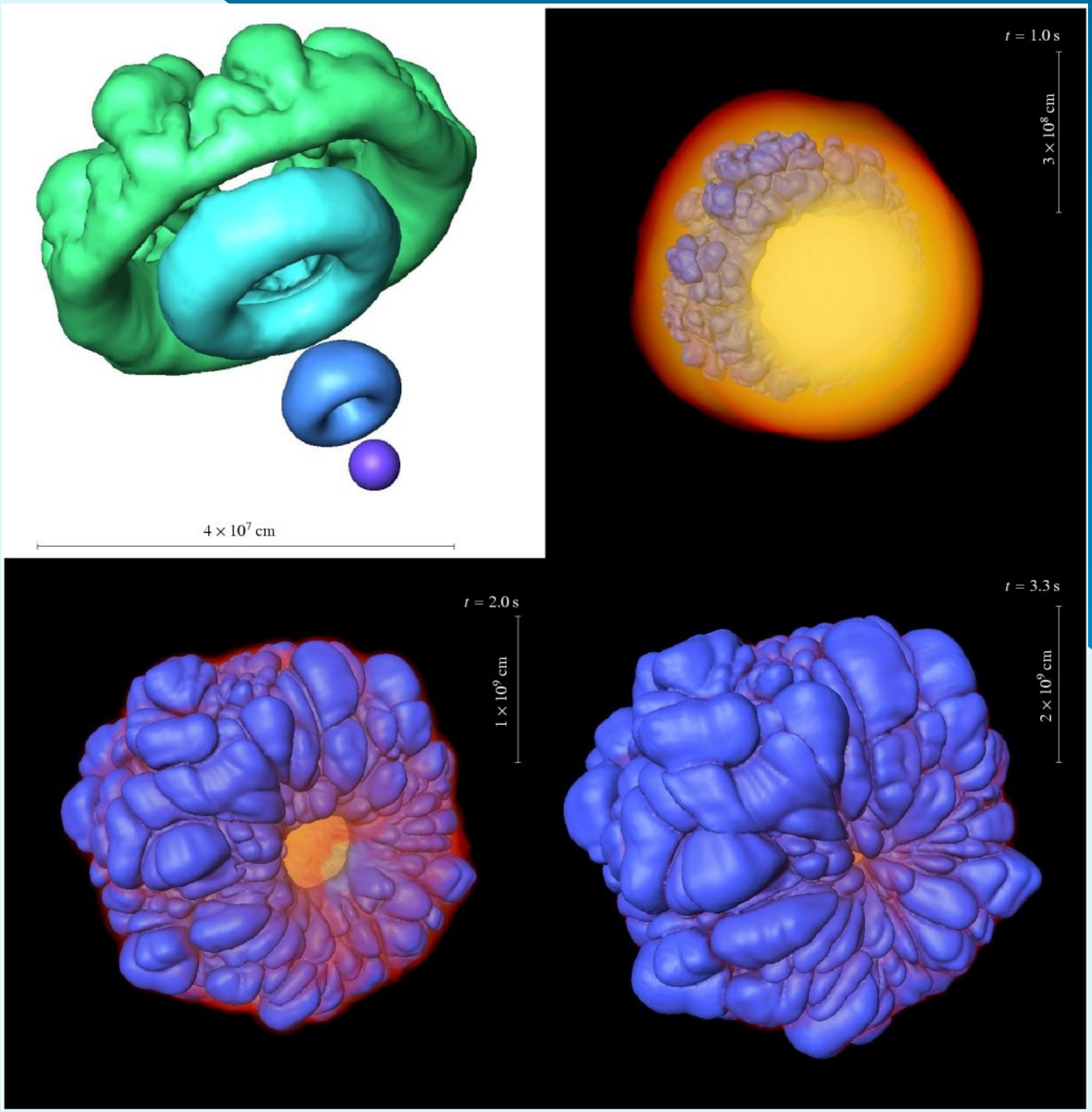
- Ignition conditions:

  How do WDs reach the critical mass?

  Center/off-center ignition?

  One/multiple ‘points’?

Off-center explosions ….



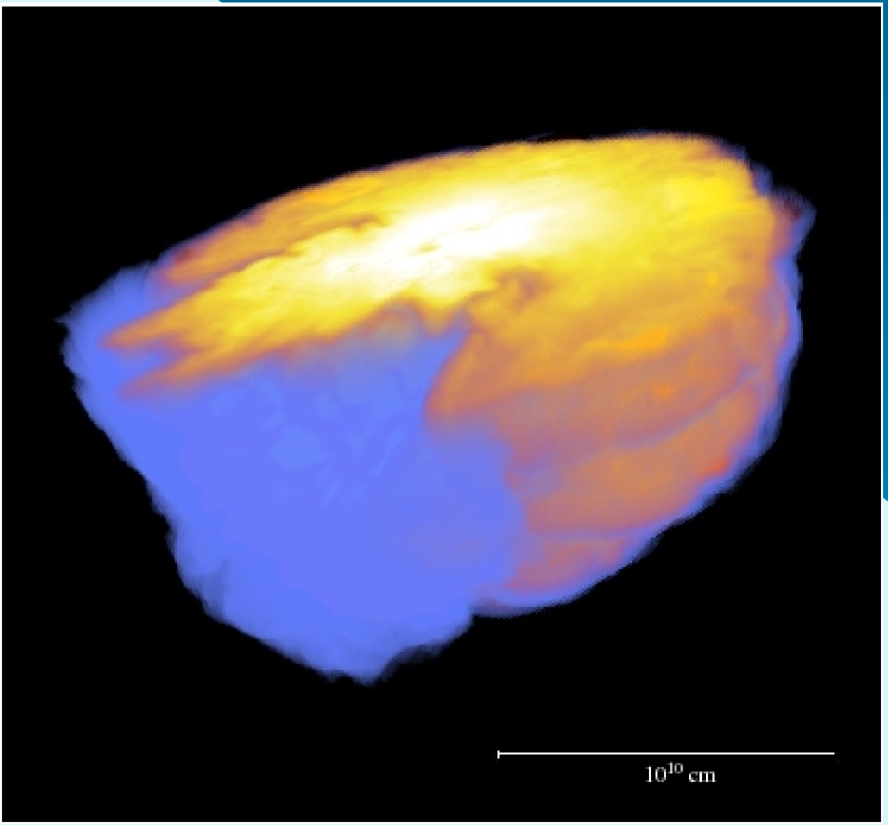
Röpke et al. (2006)

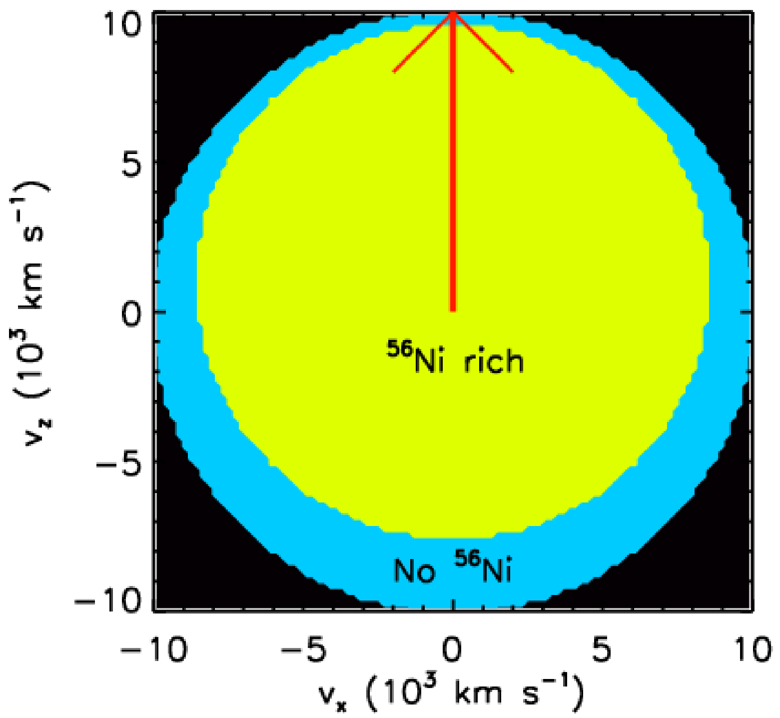
(also Jordan et al., 2008;

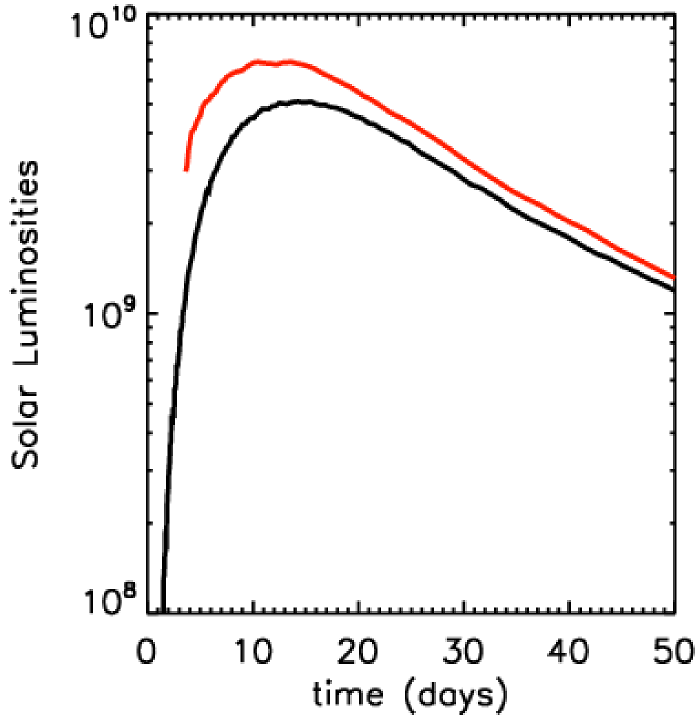
Meakin et al., 2008;

Townsley et al., 2007; …)

…. and their predictions





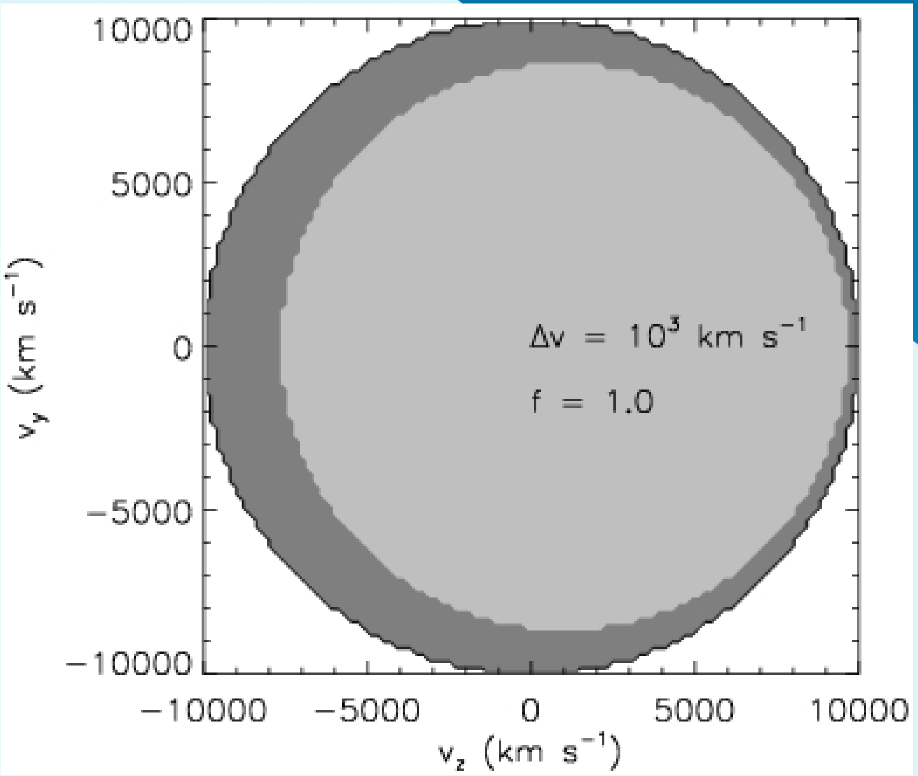


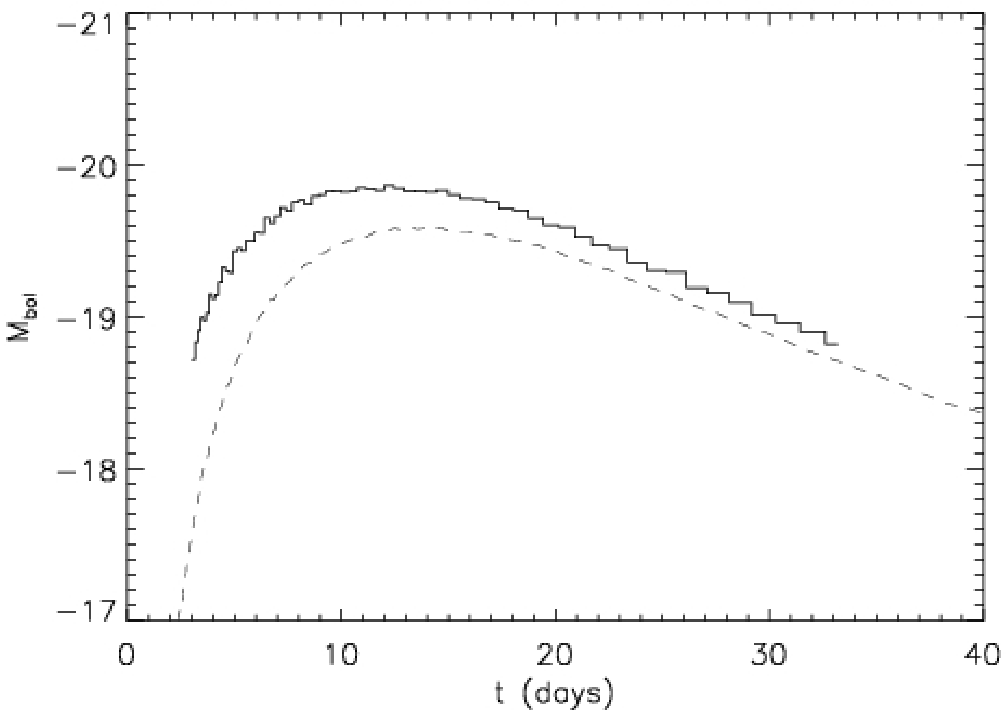
***Note:* This is a model that has ~ 0.4 M_{sun} of Ni only!**

Sim et al. (2007)

How far up can we go in luminosity?

Hillebrandt et al. (2007)

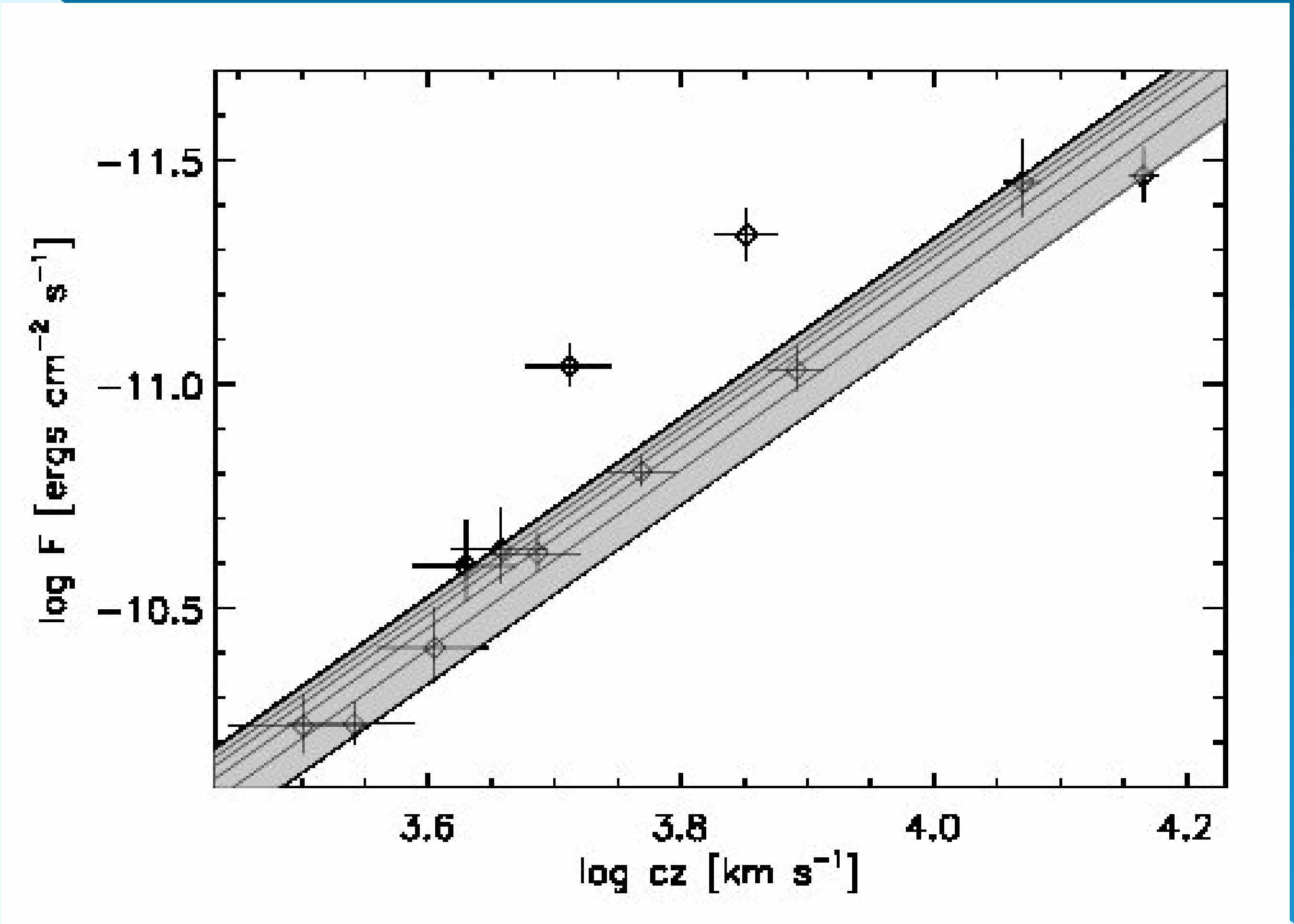




$M_{bol} \approx -20$ is possible with ~ 0.9 M_{sun} of Ni!

And what does this mean for cosmology?

Sim et al. (2007)

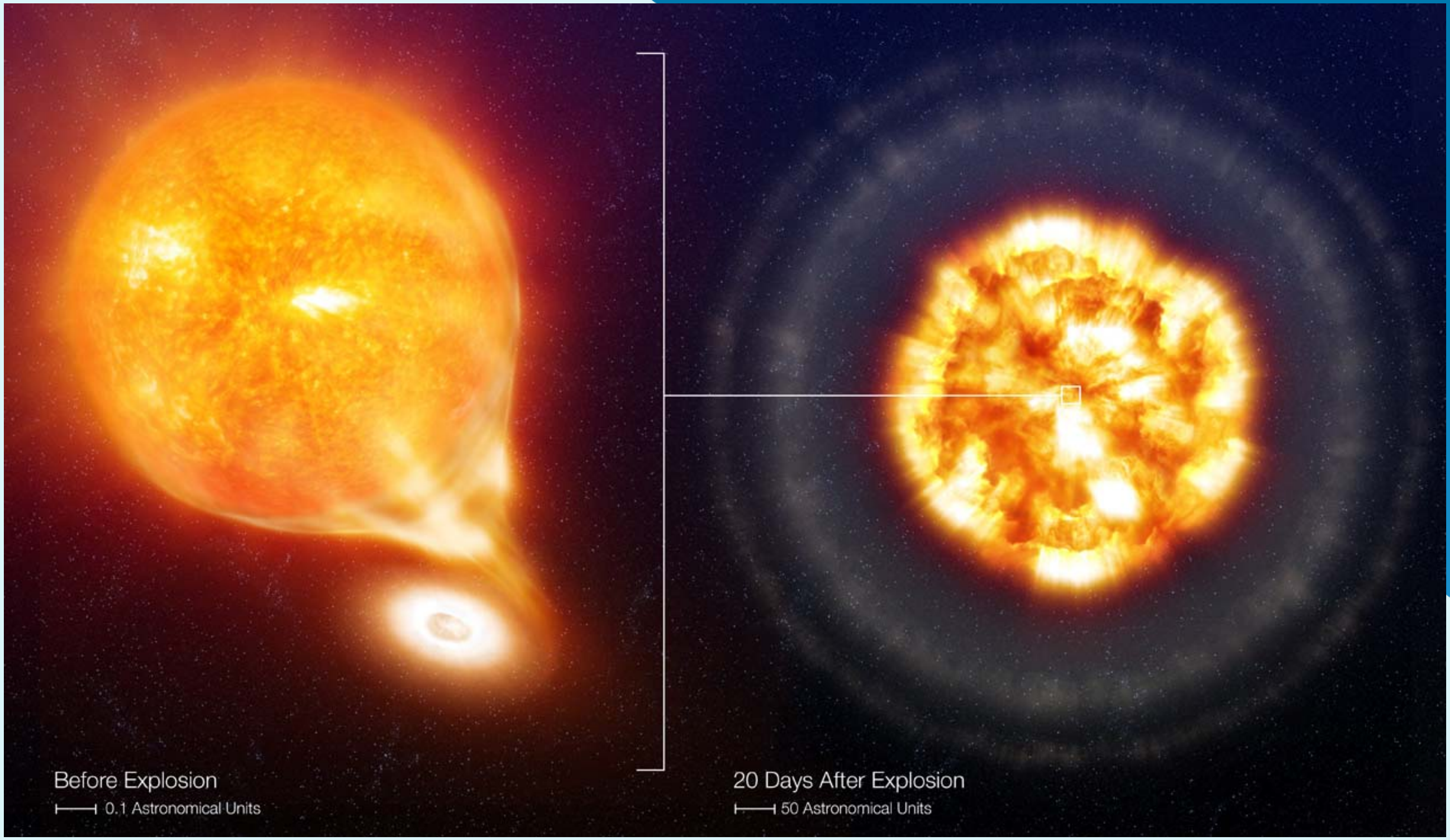


Viewing-angle effects can (in principle) explain the observed scatter in the SN Ia Hubble diagram!

More questions and challenges (cont.)

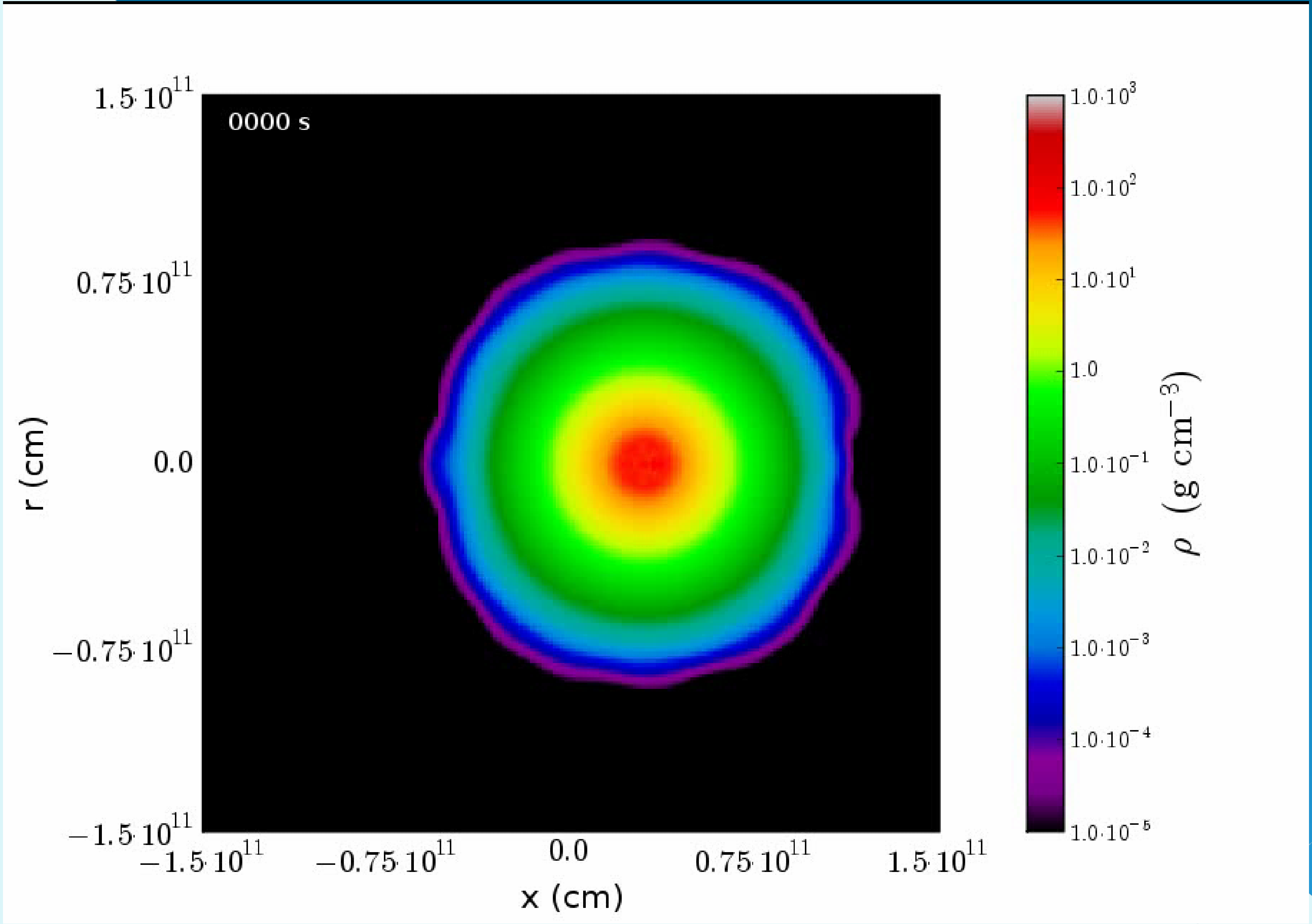
- The progenitor question:

  Single degenerates? Double degenerates? Sub-M_{ch} explosions?



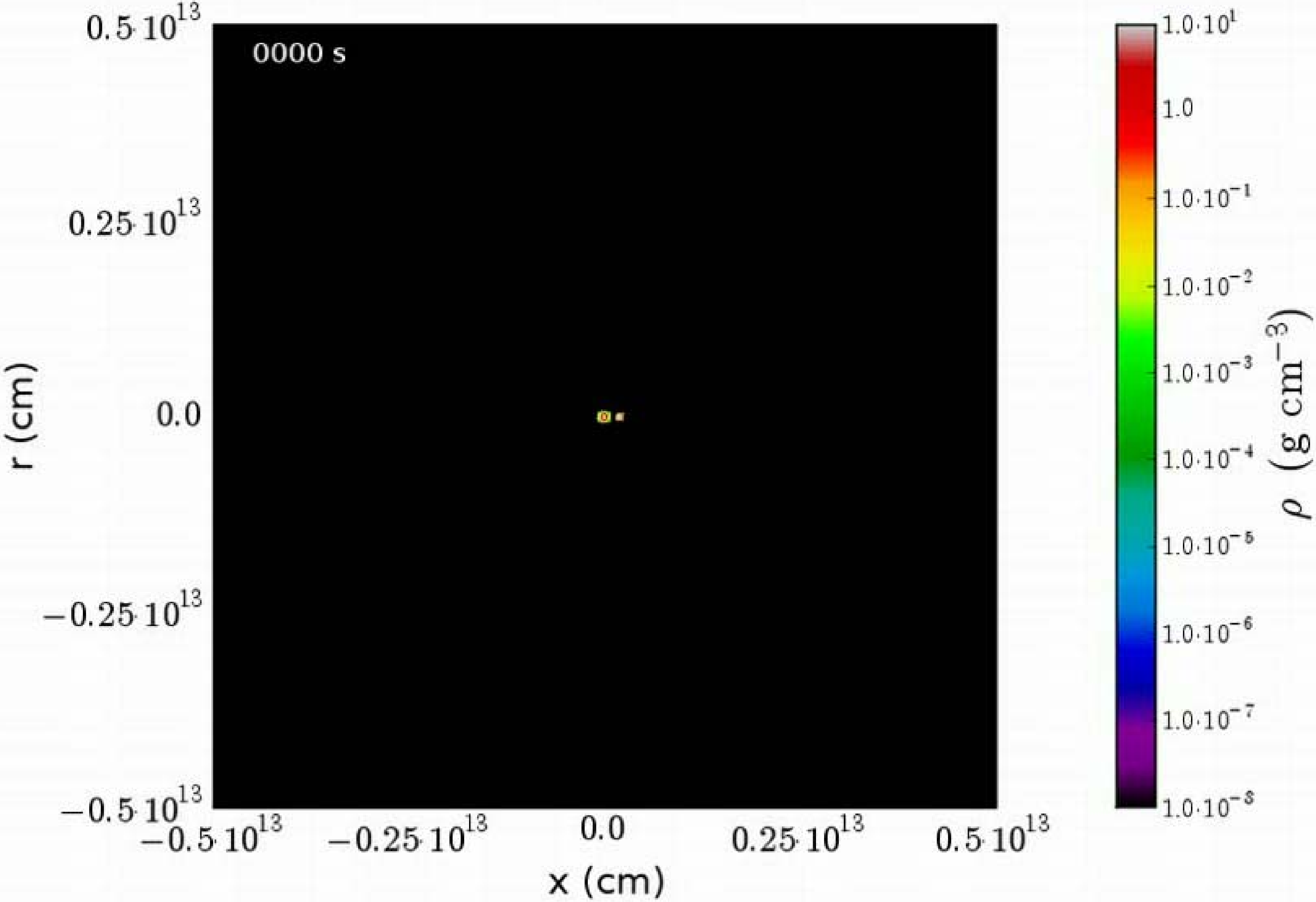
SN 2006X
(Patat et al. 2007)

➢ Should one see the hydrogen?

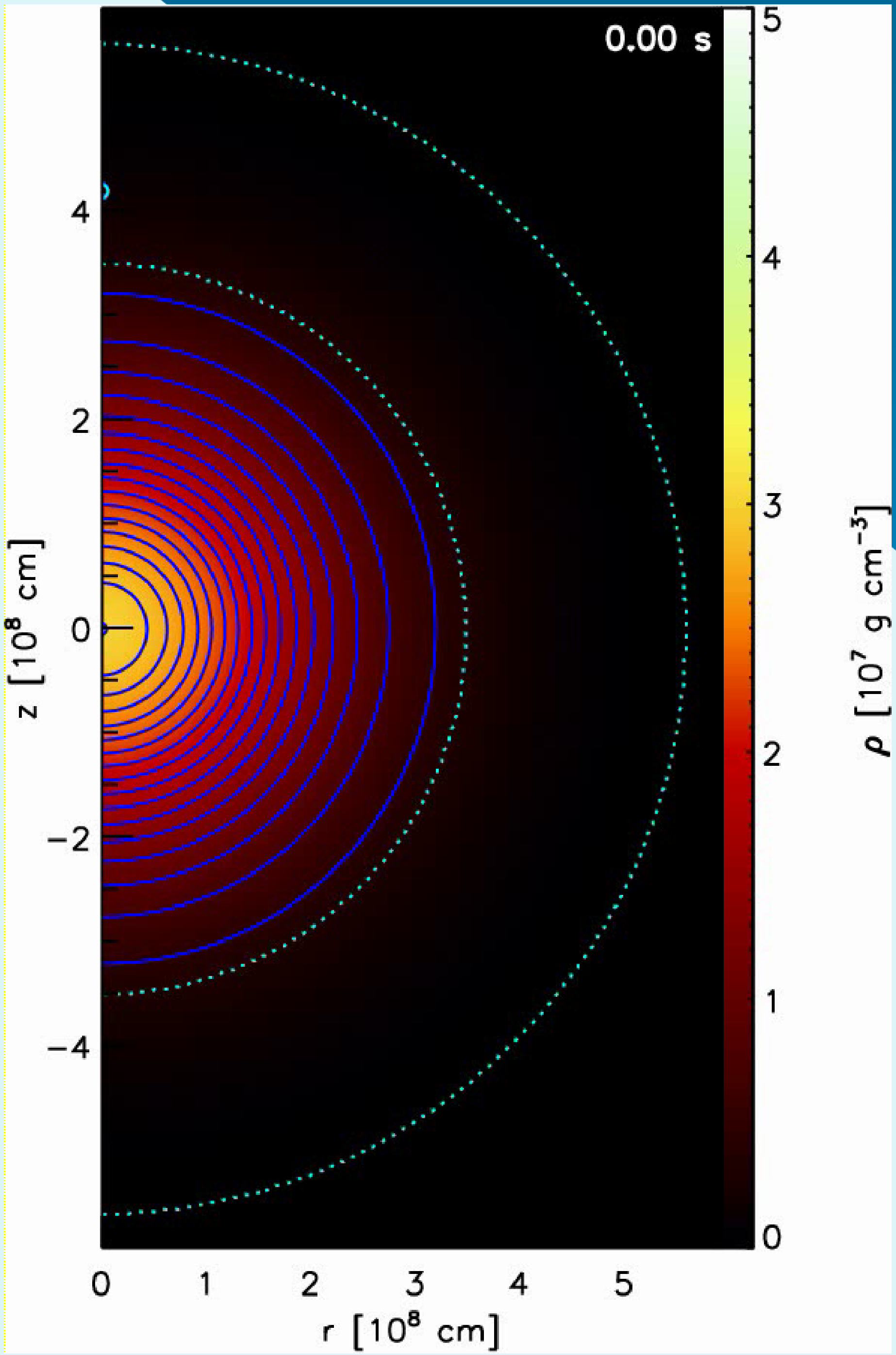


No, not necessarily !

(Pakmor et al., 2008)


0000 s
r (cm)
x (cm)
0.5·10^13
0.25·10^13
0.0
−0.25·10^13
−0.5·10^13
1.0·10^1
1.0
1.0·10^-1
1.0·10^-2
1.0·10^-3
1.0·10^-4
1.0·10^-5
1.0·10^-6
1.0·10^-7
1.0·10^-8
ρ (g cm^-3)

A few remarks on sub-Chandra double detonations



(Fink et al., 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 the velocity too high: they would **not** look like any of the observed SNe Ia.*

More questions and challenges (cont.)

- New generation of 'full-star' models:

  Light curves?

  Spectra?

  Luminosity calibration?

Key question for supernova cosmology:

There are potential sources of systematic errors.

But: *they can be controlled by better models.*

Hope has left Pandora's box!