Type Ia supernovae

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Outline

1st lecture

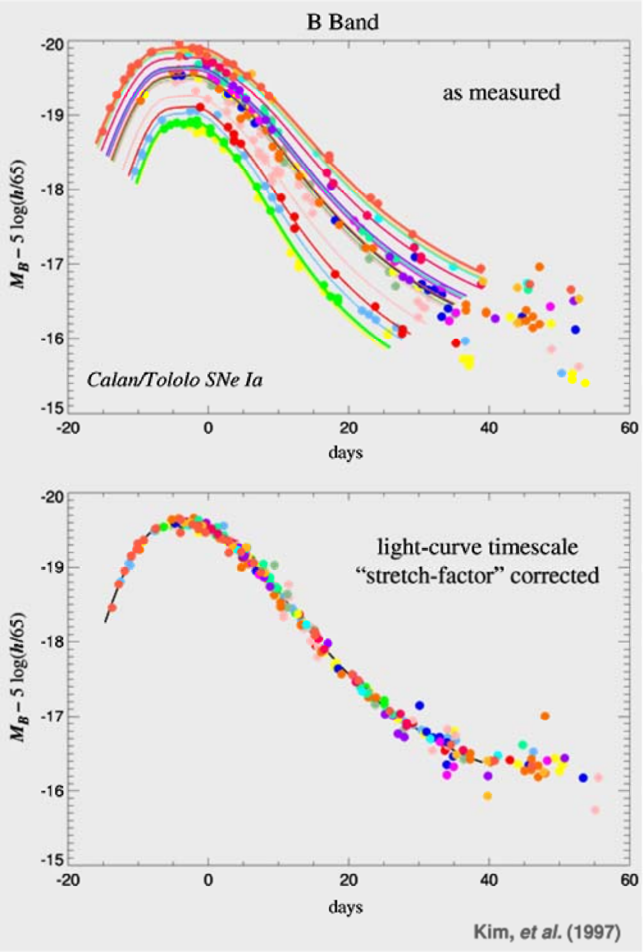
- supernovae in astronomy
- Type Ia supernovae: general scenario
- Modeling Type Ia supernova explosions

2nd lecture

- numerical implementation
- type Ia supernova simulations
- initial parameters
- nucleosynthesis
- reproducing the SN Ia sample
- implications for cosmology

SNe Ia as "cosmological lighthouses"

- very bright objects
- almost uniform peak luminosity
- best distance indicators out to z~1

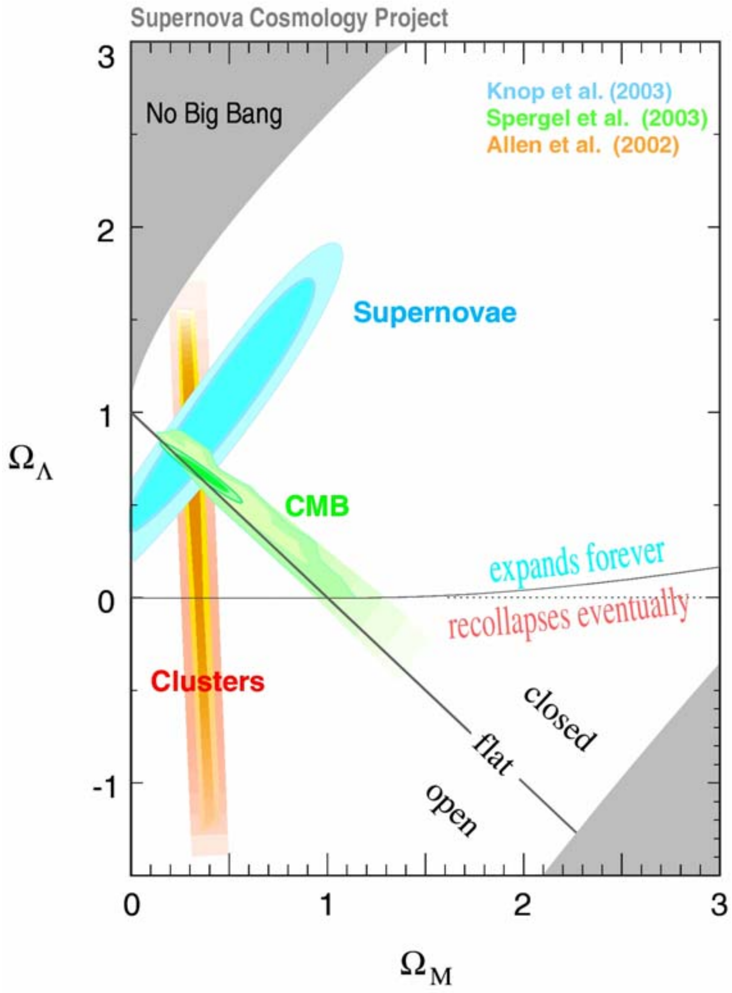


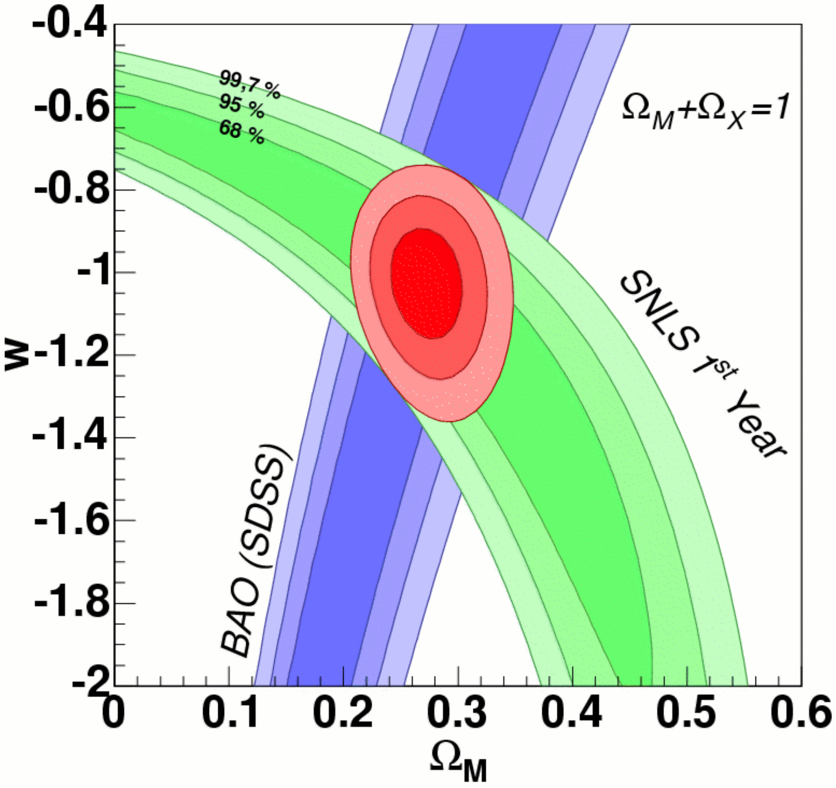
Kim, *et al.* (1997)

- empirical calibration
- systematics?
- evolutionary effects?

SN Ia cosmology

- dominating dark energy form...what is its nature?

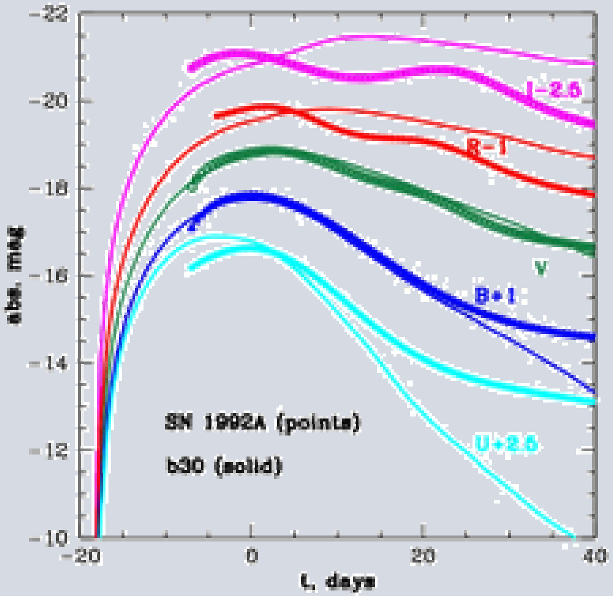




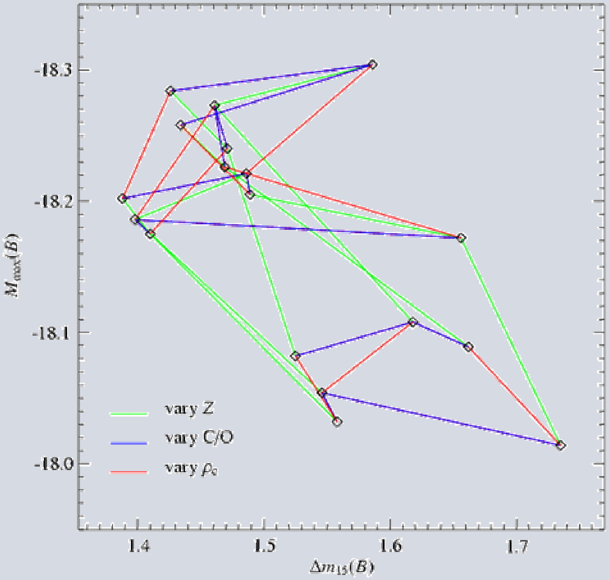
Modeling: objectives and approach

- build a self-consistent astrophysical model
- avoid tunable parameters

- derive observables
- compare with observations



- explore the origin of the observed SN Ia diversity
- give theoretical reasoning for calibration techniques



Numerical implementation

- operator splitting: treat hydrodynamics and nuclear burning separately

Hydrodynamics

- Euler's equations: system of hyperbolic equations

- Eulerian approach: discretized on a computational grid
- finite volume approach: compute fluxes of mass, momentum, energy over interfaces of computational grid cells → update of cell mean values (conservative by construction)

- computation of fluxes requires extrapolation of cell means to boundaries and solution of Riemann's problems there → linear extrapolation: "Godunov scheme"
- PPM "piecewise parabolic method" (Colella & Woodward, 1984) → parabolic extrapolation (high resolution shock capturing method) → here: PROMETHEUS implementation (Fryxell & Müller, 1989)

Numerical implementation

WD matter equation of state

- arbitrarily degenerate and relativistic gas of electrons
- ideal gas (Maxwell-Boltzmann) of nuclei
- radiation following Stefan-Boltzmann law
- electron-positron pair creation/destruction

Nuclear reactions

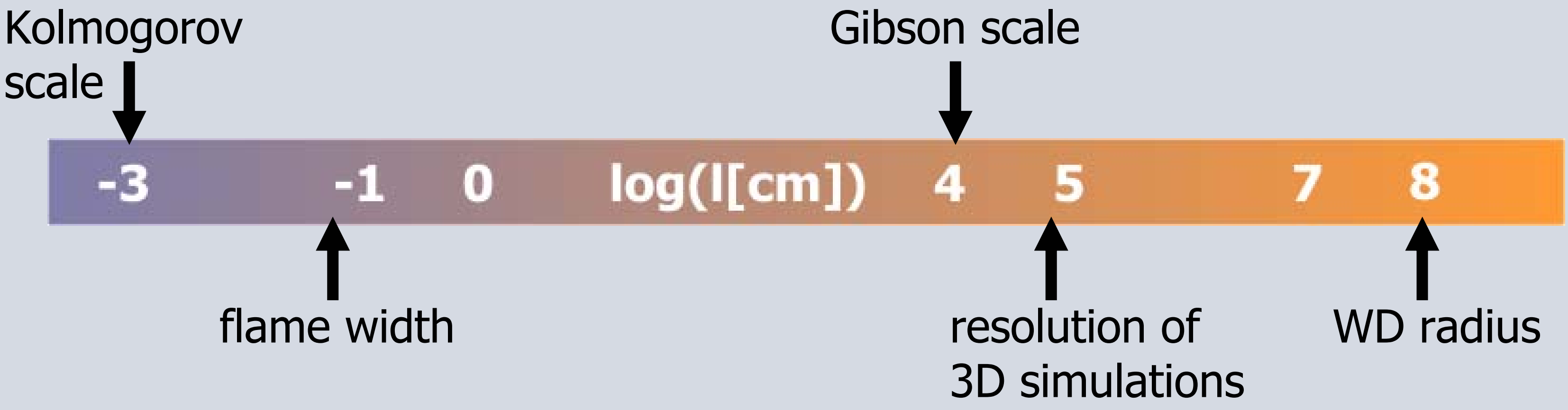
- correct treatment would require large nuclear reaction network but even rather small reduced networks are way too expensive to run concurrently with hydro simulation
- coarse description: include five species only (C, O, Mg, Ni, α)
- material crossed by flame is burned into
  - NSE (here: mixture of Ni and α depending on ρ and T) if $\rho_{\mathrm{fuel}} > 5 \times 10^{7}\ \mathrm{g\ cm^{-3}}$
  - intermediate mass elements (here: Mg) if $\rho_{\mathrm{fuel}} > 1 \times 10^{7}\ \mathrm{g\ cm^{-3}}$
- the corresponding difference of nuclear binding energy is released → sufficient to describe the dynamics
- recently added (with S. Woosley, UCSC): parametrized treatment of electron captures

Simulating the relevant scales

- Gibson scale $s_{lam} = v'$ → below turbulence does not affect flame propagation

beginning of the explosion: burning in flamelet regime

later phases of the explosion: burning in distributed regime

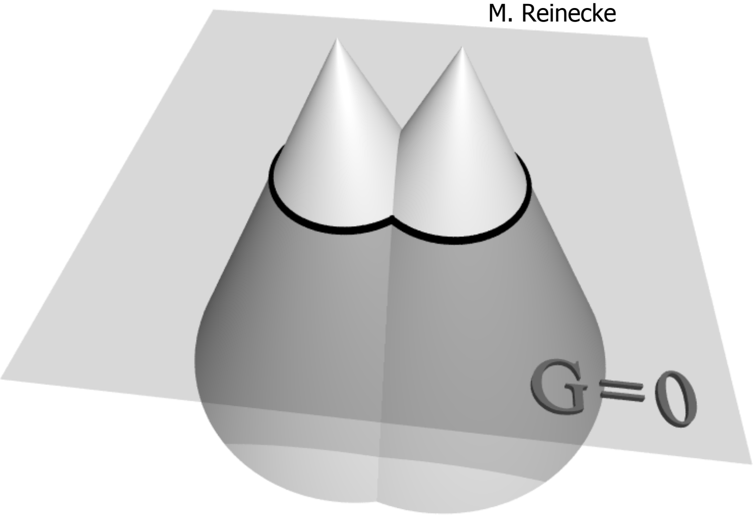


Numerical implementation

explosion model (Reinecke et al., 1999, 2002) → Large Eddy Simulation approach

- flame model: WD ∼ 10^8 cm structure of flame ∼ 1mm → not resolvable → modeled as discontinuity between fuel and ashes
- level set method

M. Reinecke



- flame not resolved → How to prescribe flame propagation velocity?
- Theory of turbulent combustion: in flamelet regime flame speed determined by turbulent motions

Numerical Implementation

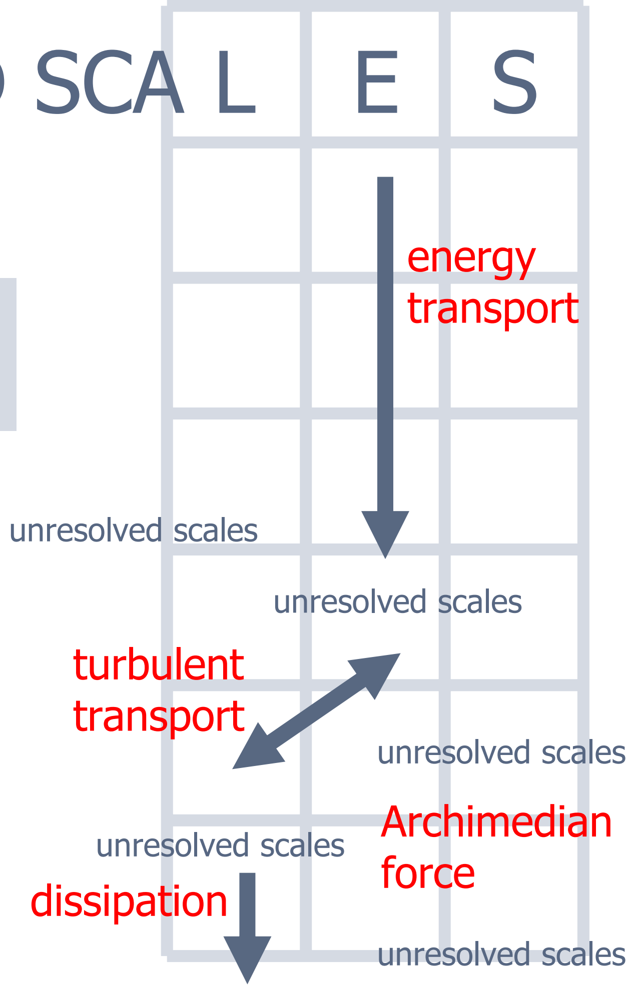
- Large Eddy Simulation (LES) approach
- Subgrid-scale turbulence model (Niemeyer et al., 1995; Schmidt et al., 2005)

RESOLVED SCALES

Balance equation for turbulent kinetic energy on unresolved scales

→ determines turbulent velocity fluctuations v'

self-consistent model: no tunable parameters


energy transport

unresolved scales

unresolved scales

turbulent transport

unresolved scales

Archimedian force

unresolved scales

dissipation

unresolved scales

SN Ia simulation code

- build on the POMETHEUS implementation (Fryxell & Müller, 1989) on a moving computational grid
- subgrid-scale turbulence modeling
- level set flame tracking algorithm
- simplified description of burning
- monopole gravity solver

- efficiently MPI parallelized (benchmarking: scales well up to 4000 processors)

- used on various architectures:
  - IBM Power 4/5 Regatta (Computer Center Garching)
  - IBM Power 5 HPCx (Edinburgh)
  - Cray XT3/4 Jaguar (Oak Ridge Nat'l Lab)
  - MareNostrum (Barcelona)
  - various Linux clusters

SN Ia explosion model

SN Ia model

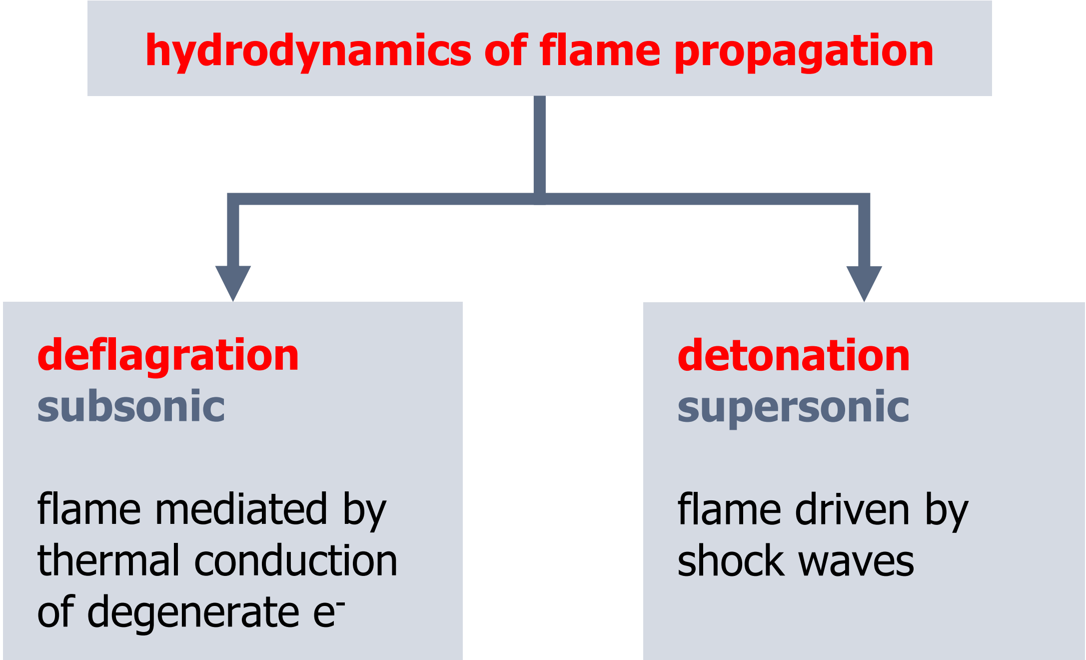
progenitor evolution

pre-ignition phase (initial conditions)

explosion phase

formation of spectra, light curve

- flame burns from ignition near center of WD towards surface



hydrodynamics of flame propagation

deflagration
subsonic

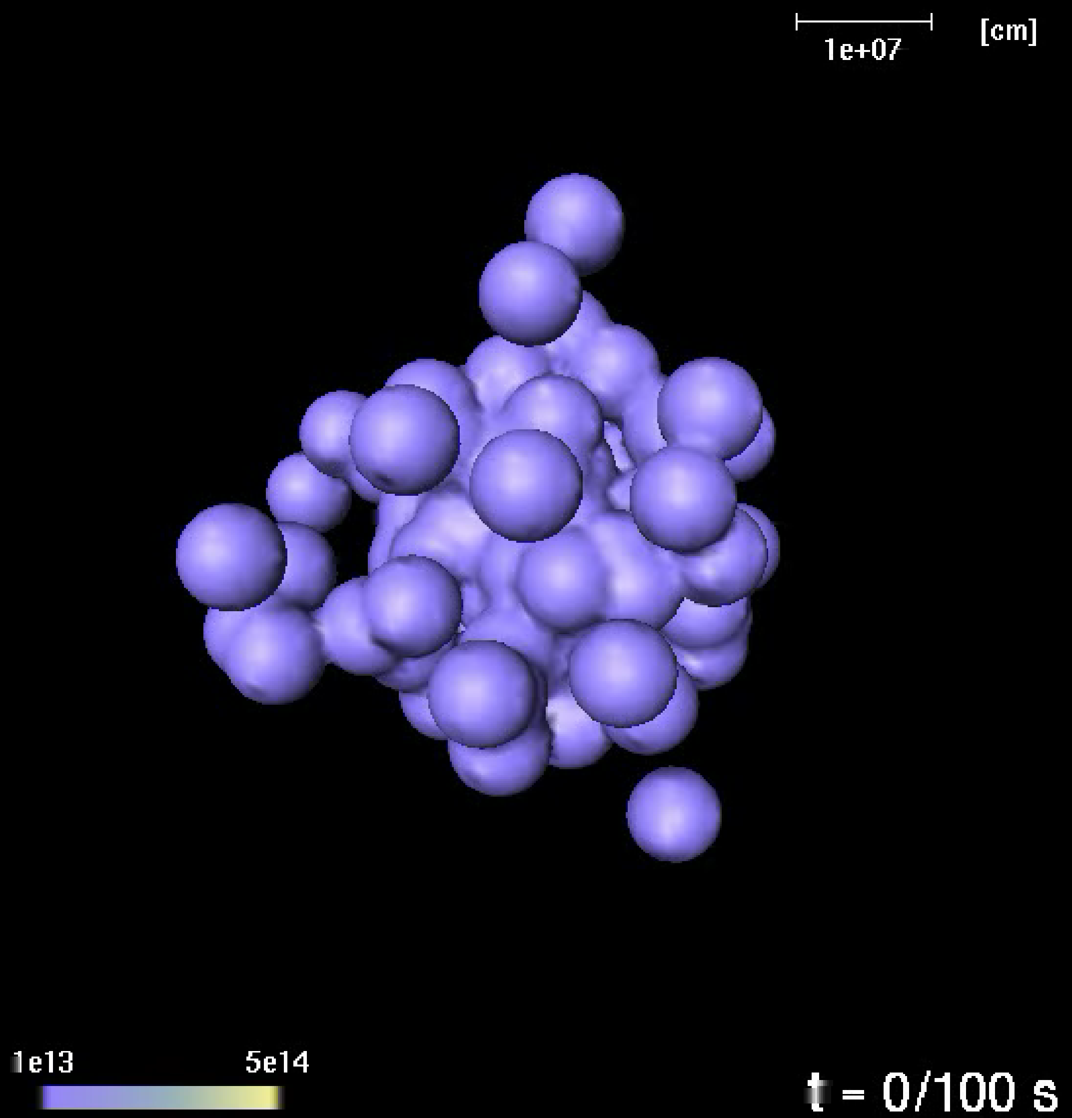
flame mediated by thermal conduction of degenerate e^-

detonation
supersonic

flame driven by shock waves

Deflagration model: example

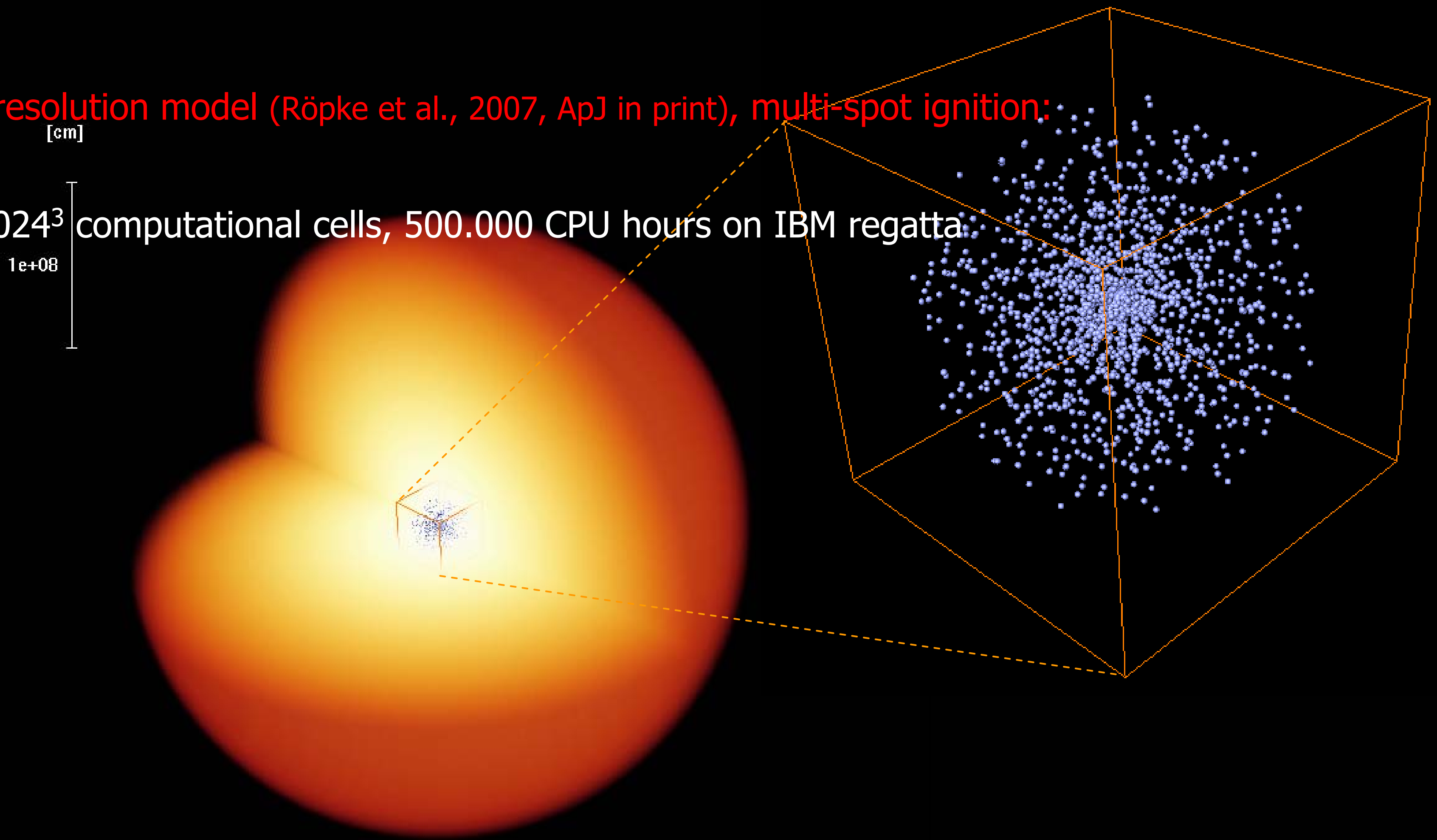
Röpke et al.,
2005



Isotropic ignition

high-resolution model (Röpke et al., 2007, ApJ in print), multi-spot ignition:

- 1024^3 computational cells, 500.000 CPU hours on IBM regatta

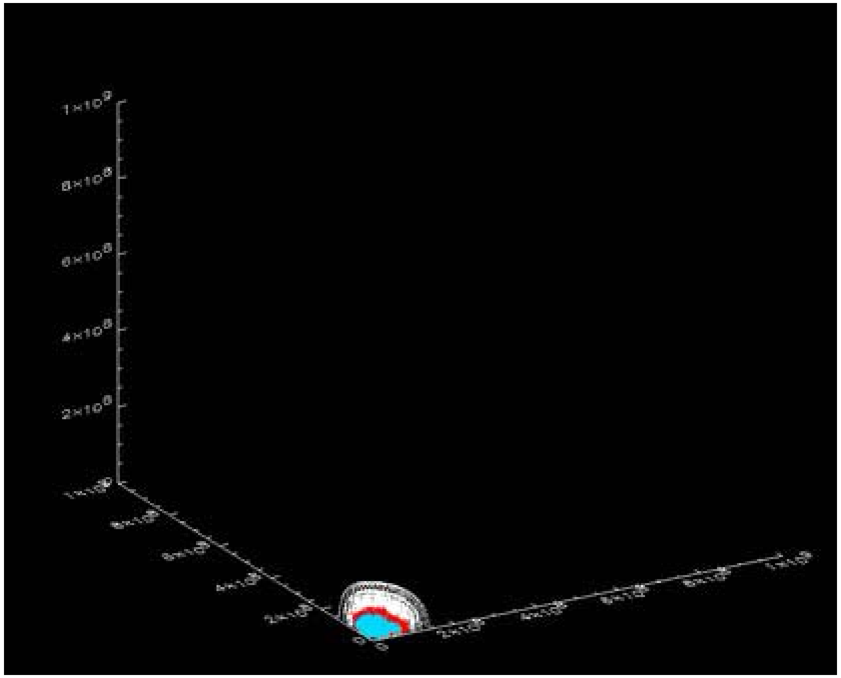


High-resolution simulation

Röpke et al., 2007

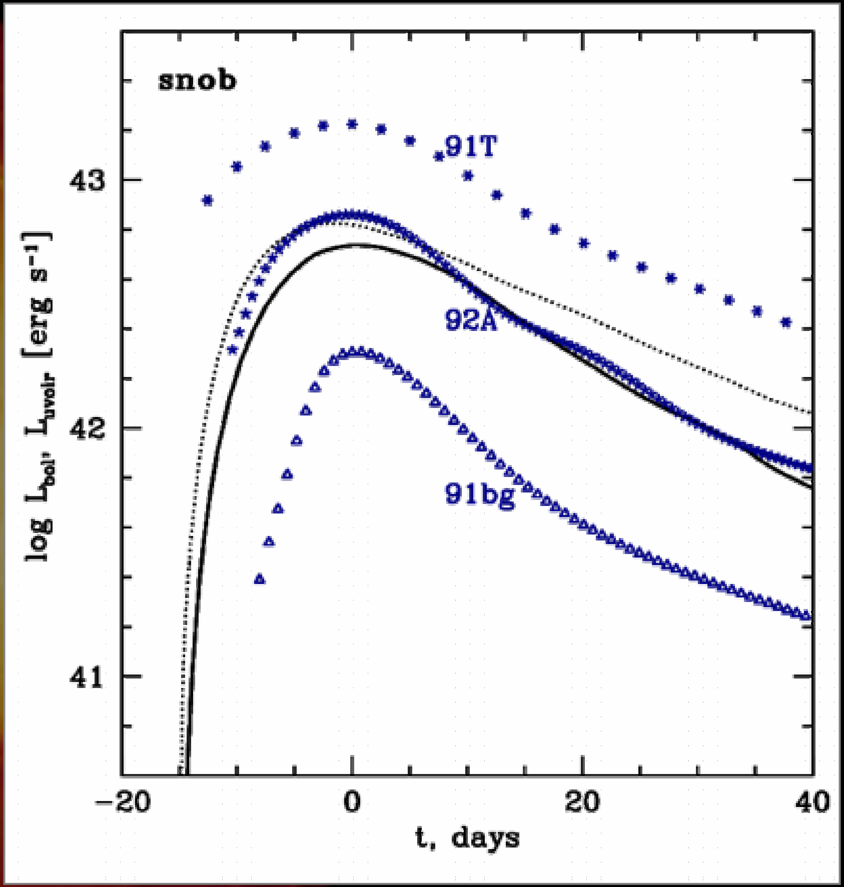
Nuclear Reactions

- simplifed description of nuclear reaction (5 species: C, O, Mg, Ni, α) in explosion dynamics
- postprocessing step (Travaglio et al., 2004) with $\sim$ 150 000 tracer particles in full-star simulations

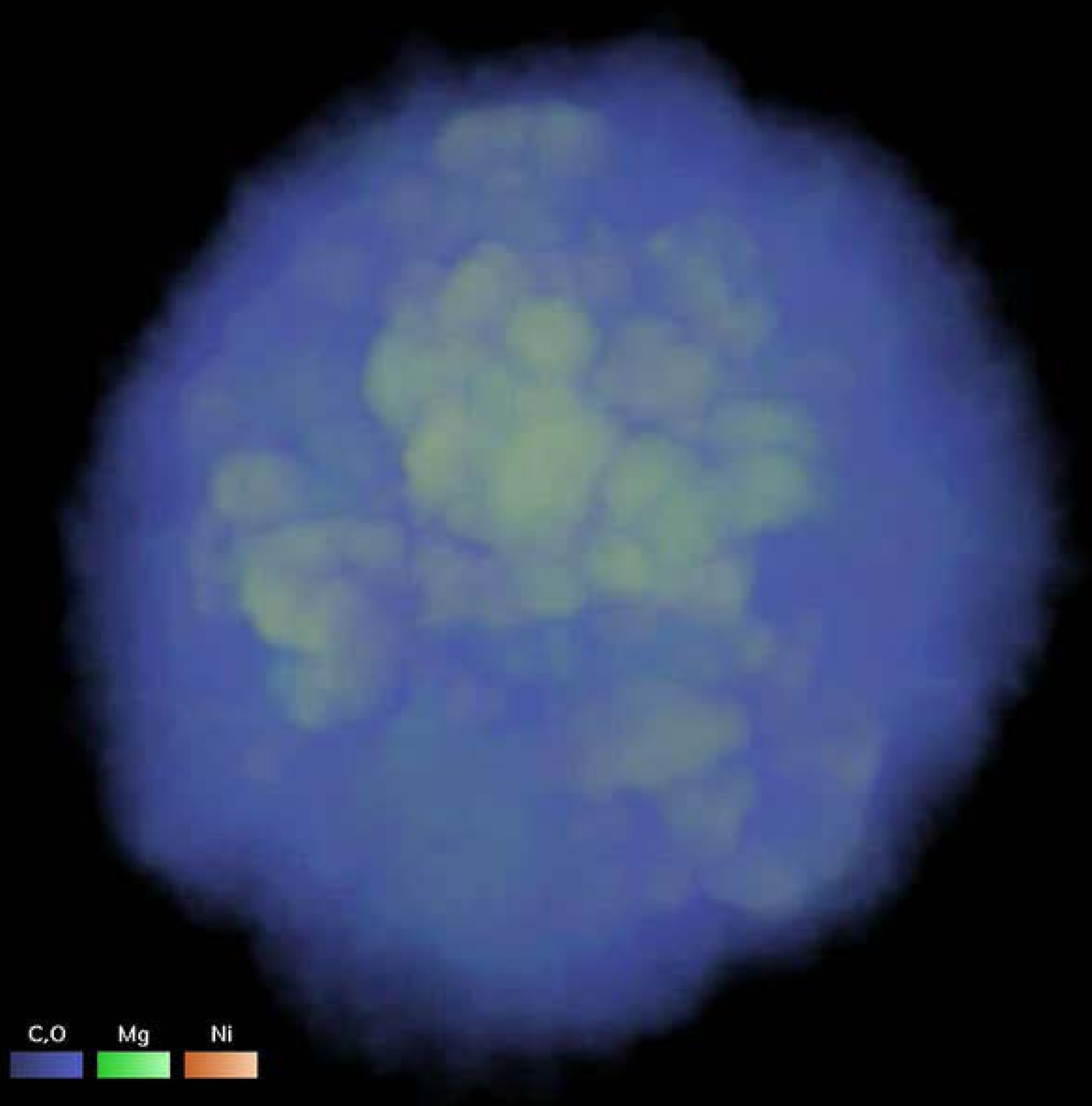


Results

- asymptotic kinetic energy: 0.81 Bethe
- hydro: 0.61 $M_\odot$ of iron group elements, 0.43 $M_\odot$ of intermediate mass elements
- postprocessing step → 0.33 $M_\odot$ of ^{56}Ni
- leads to synthetic light curves consistent with weaker normal SNe Ia



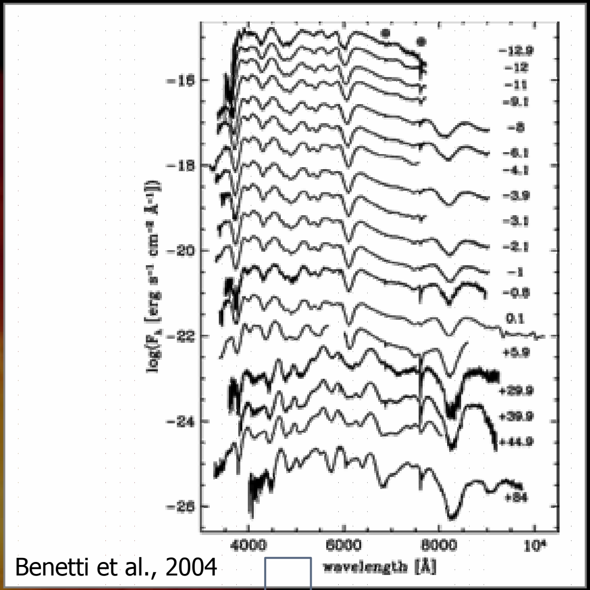
Compositon of explosion ejecta



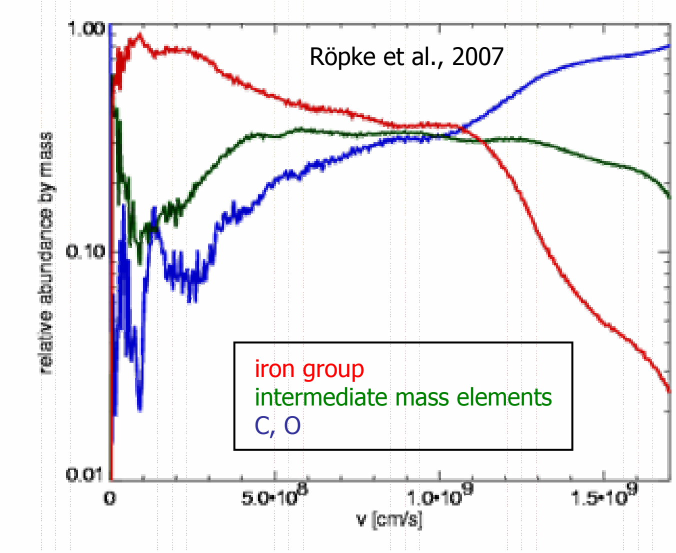
Röpke et al., 2007

Results

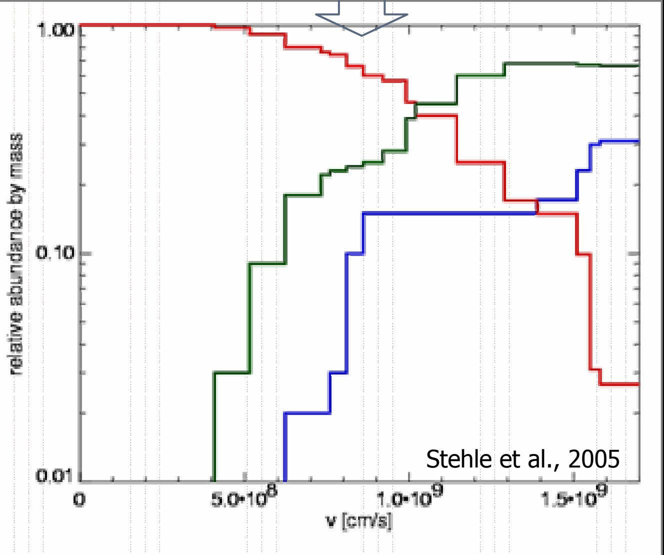
- do the spectra agree with observations?
  → test the chemical structure of the ejecta
- consistent in inner part; discrepancies in outer layers



Benetti et al., 2004

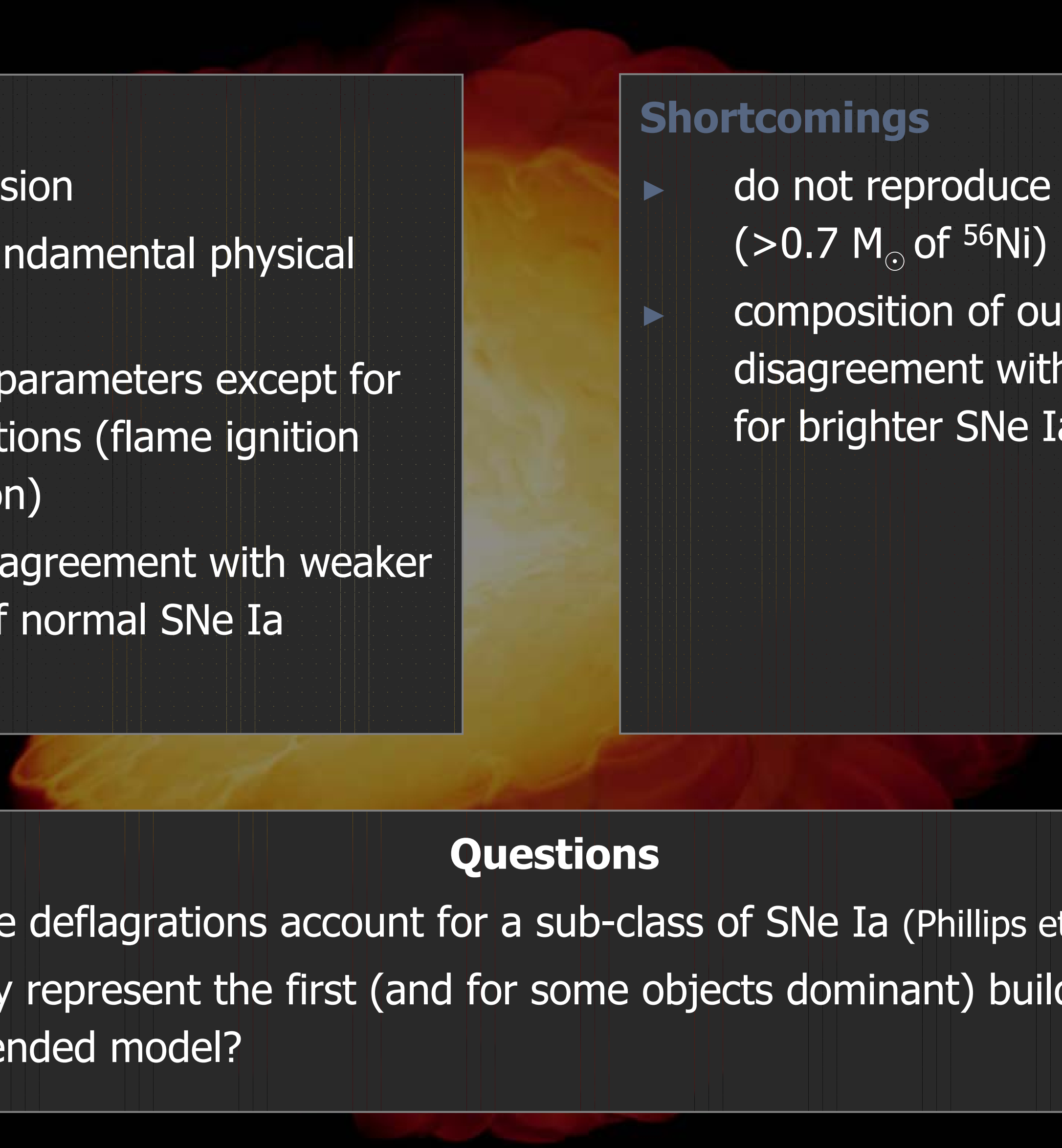


Röpke et al., 2007



Stehle et al., 2005

Deflagration model



Successes

- yields explosion
- based on fundamental physical principles
- no tunable parameters except for initial conditions (flame ignition configuration)
- reasonable agreement with weaker examples of normal SNe Ia

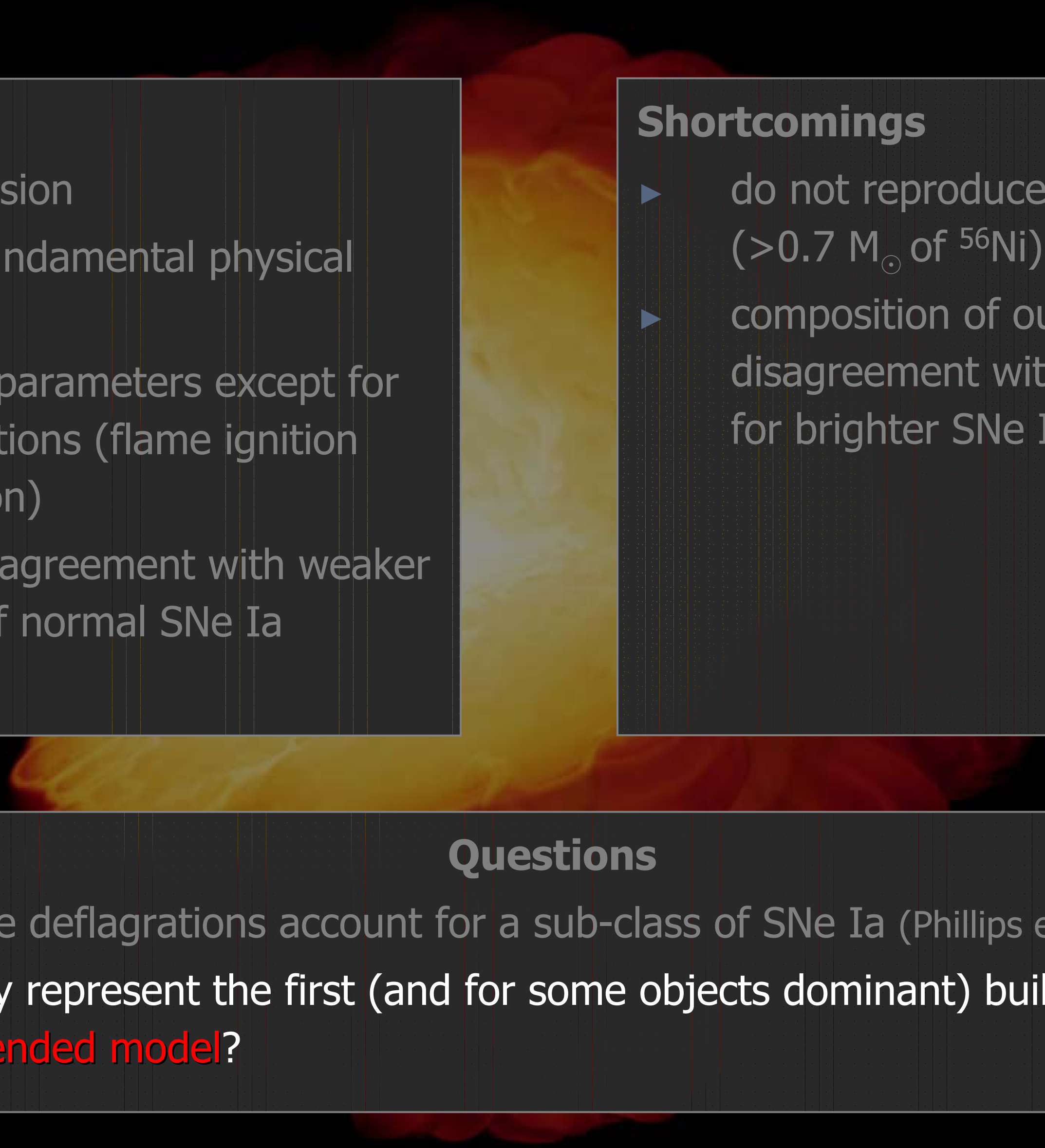
Shortcomings

- do not reproduce brighter SNe Ia (>0.7 $M_\odot$ of ^{56}Ni)
- composition of outer layers in disagreement with those expected for brighter SNe Ia

Questions

- Do pure deflagrations account for a sub-class of SNe Ia (Phillips et al., 2006)?
- Do they represent the first (and for some objects dominant) building block of an extended model?

Deflagration model



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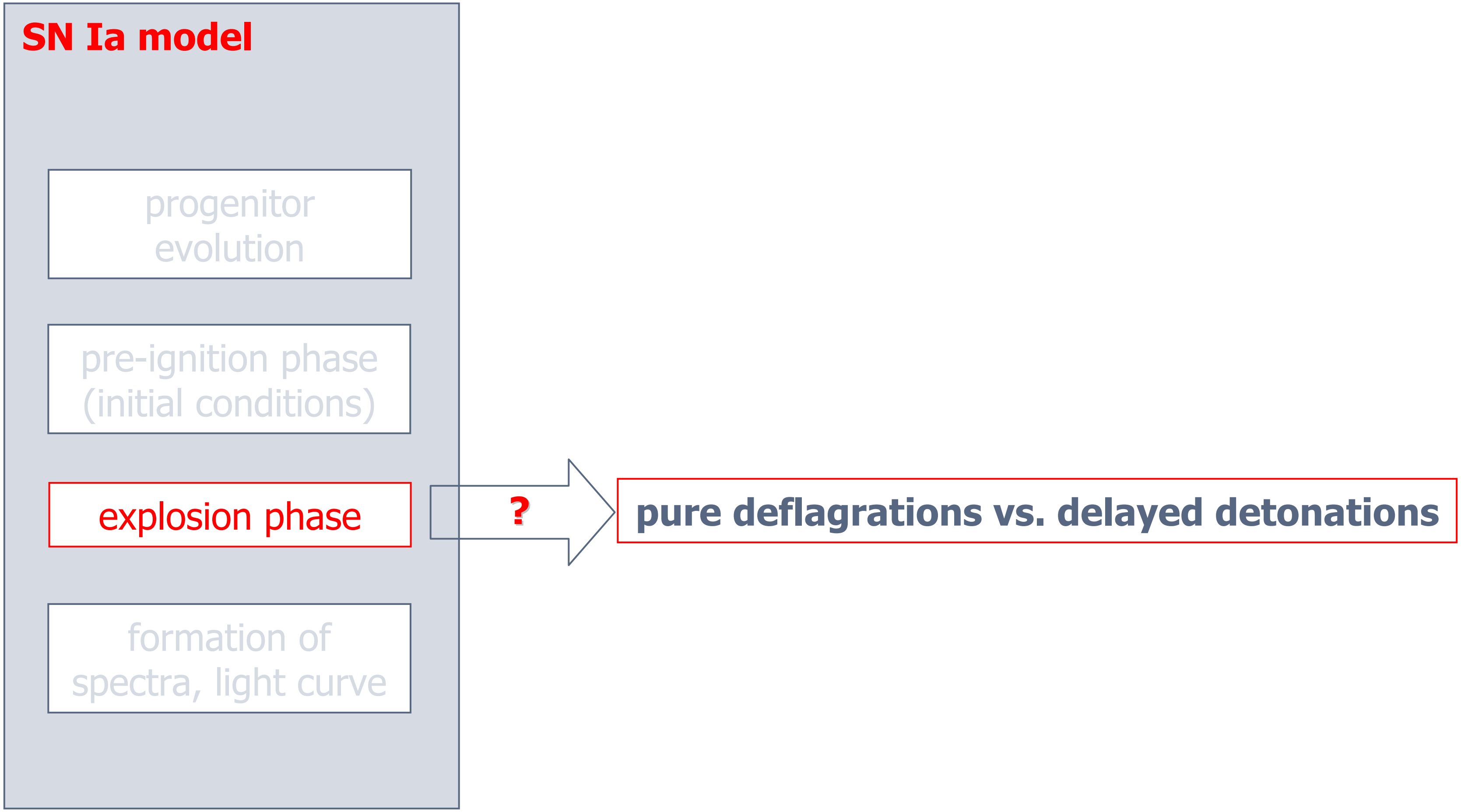
Model uncertainties



SN Ia model

progenitor evolution

pre-ignition phase (initial conditions)

explosion phase

formation of spectra, light curve

?

pure deflagrations vs. delayed detonations

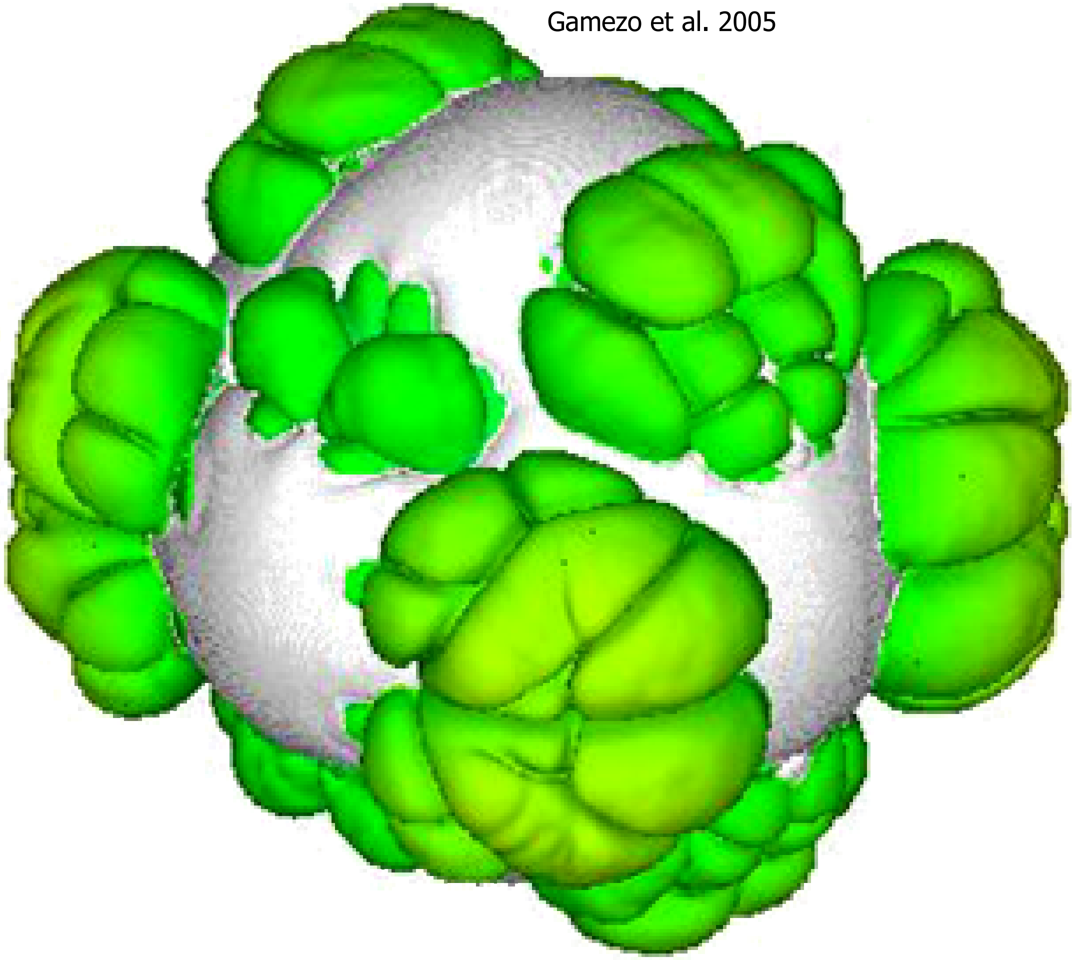
Delayed detonation model

Idea:

- transition (DDT) to detonation after deflagration phase (Khokhlov, 1991)
- supersonic detonation front burns parts of remaining fuel

Problem:

- DDT mechanism unknown in astrophysical context (e.g. Niemeyer 1999, Oran & Gamezo, 2006)



Gamezo et al. 2005

Deflagration-Detonation Transitions?

- Niemeyer & Woosley (1997) hypothesis: DDT at onset of distributed burning regime
- only instance of drastic change in flame properties
- analysis by Lisewski et al.(2000):

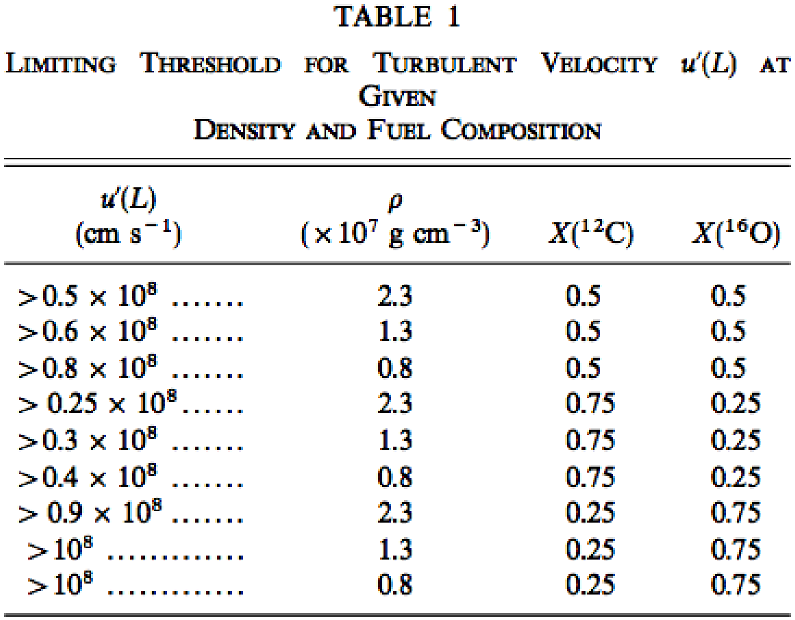


TABLE 1

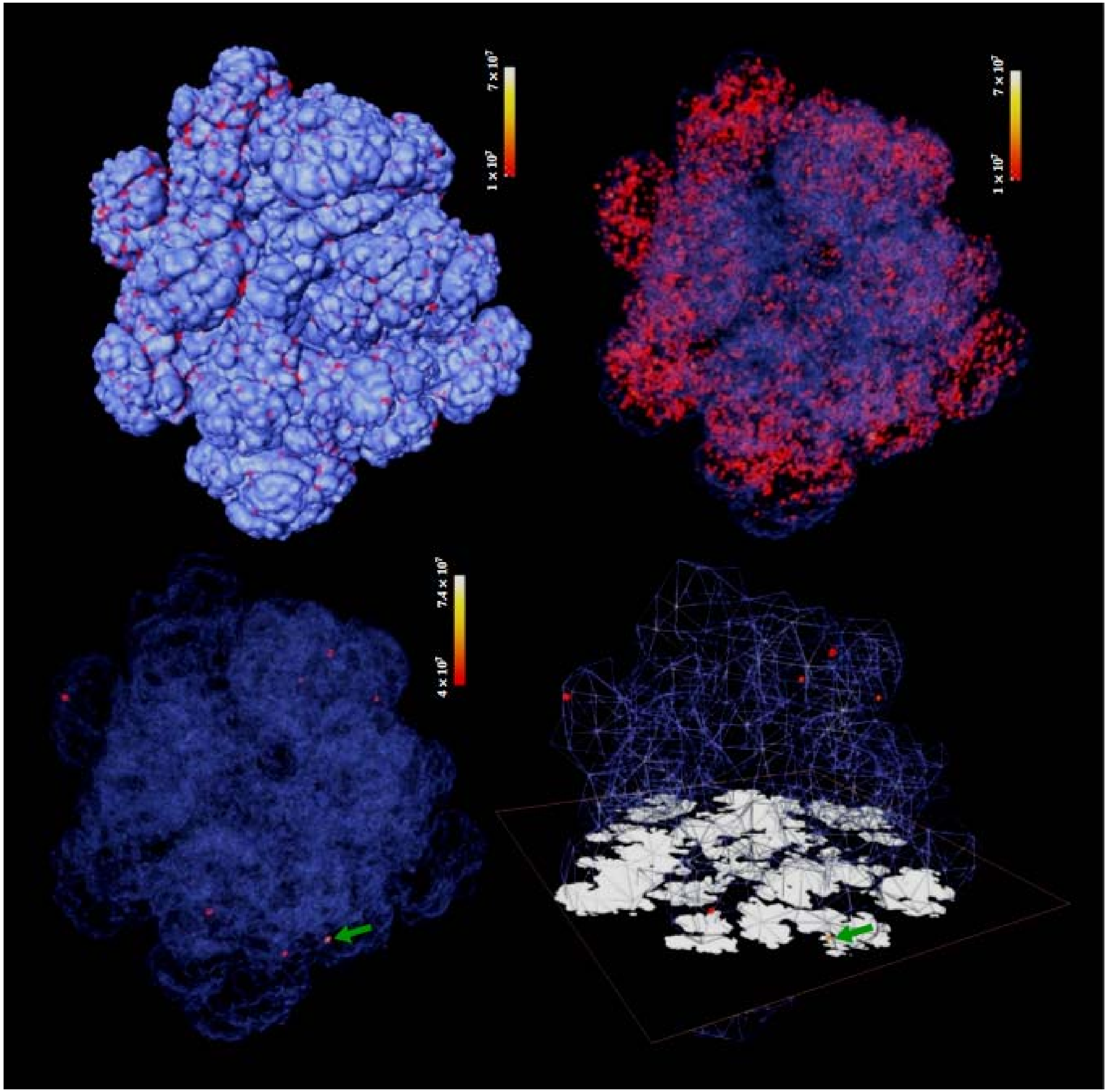
LIMITING THRESHOLD FOR TURBULENT VELOCITY $u'(L)$ AT GIVEN DENSITY AND FUEL COMPOSITION

$u'(L)$ (cm s^{-1})	ρ ($\times 10^7$ g cm^{-3})	$X(^{12}C)$	$X(^{16}O)$
$>0.5 \times 10^8$	2.3	0.5	0.5
$>0.6 \times 10^8$	1.3	0.5	0.5
$>0.8 \times 10^8$	0.8	0.5	0.5
$>0.25 \times 10^8$	2.3	0.75	0.25
$>0.3 \times 10^8$	1.3	0.75	0.25
$>0.4 \times 10^8$	0.8	0.75	0.25
$>0.9 \times 10^8$	2.3	0.25	0.75
$>10^8$	1.3	0.25	0.75
$>10^8$	0.8	0.25	0.75

- updated analysis: Woosley (2007): $\rho_{det} = 0.5 - 1 \times 10^7$ g /cm^3 u' $\sim 10^8$ cm/s
- necessary but not sufficient conditions for DDT → met in SN Ia models?

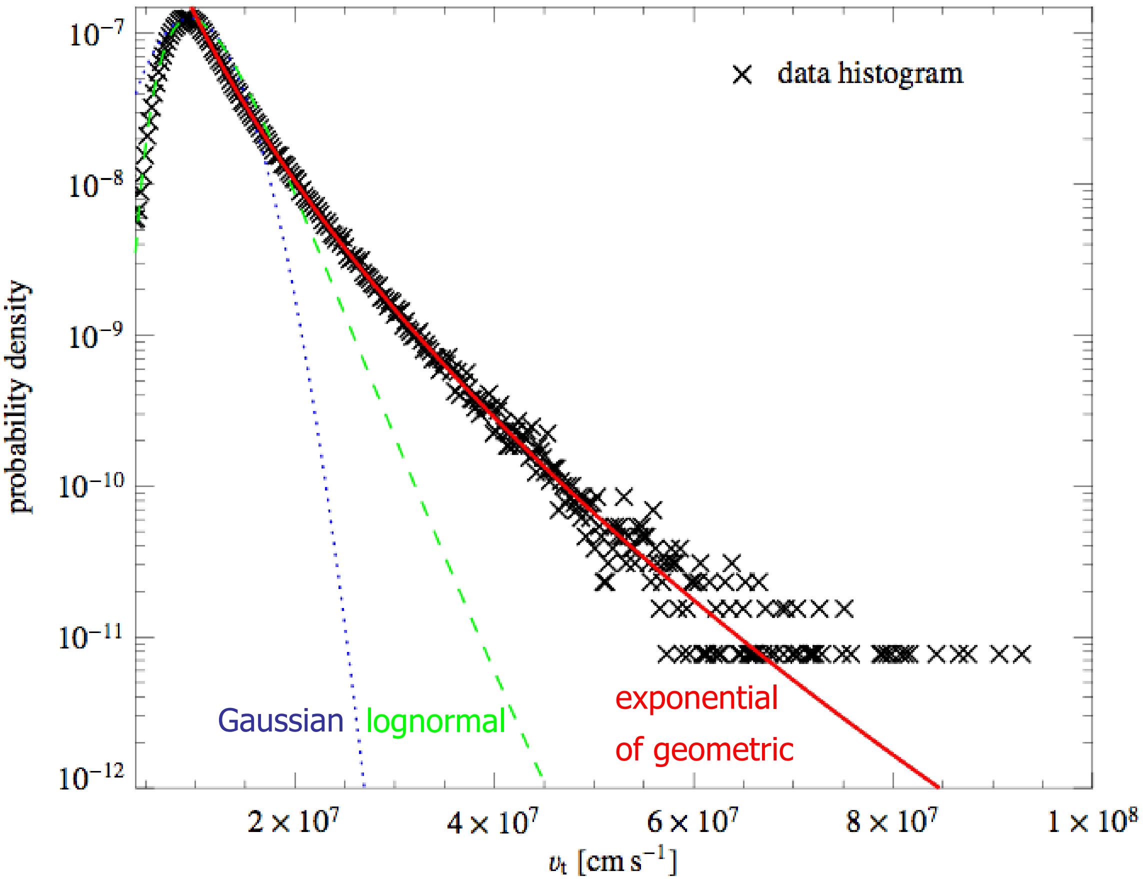
Deflagration-Detonation Transitions?

- Analysis of turbulent velocity flucutations as predicted by sub-grid scale model at the flame front for densities $1...3 \times 10^7$ g cm^{-3} (Röpke 2007, ApJ in print)



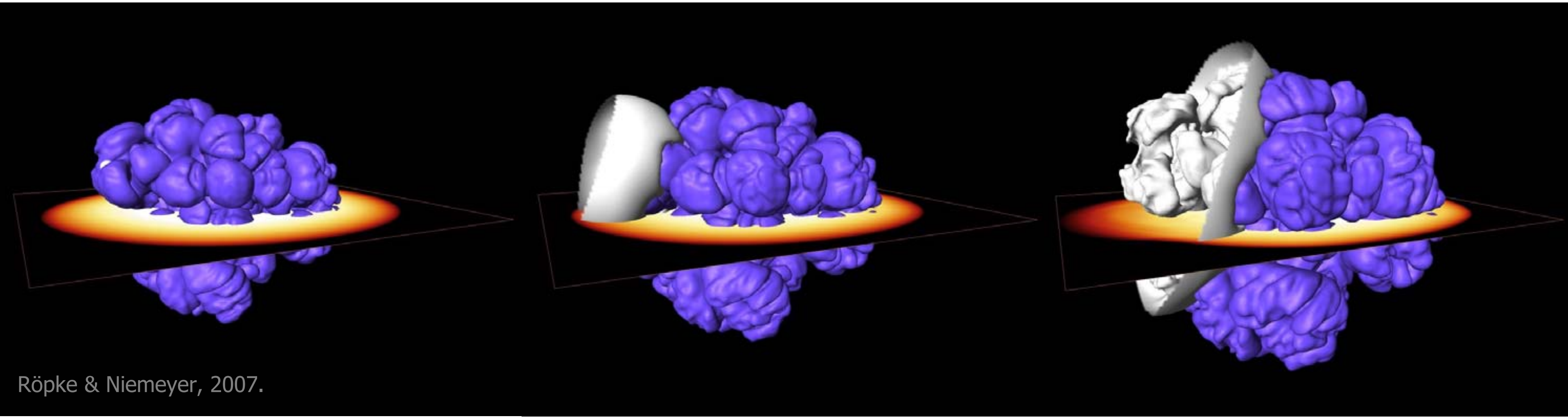
Deflagration-Detonation Transitions?

- High-amplitude turbulent velocity fluctuarions (~10^8 cm s^{-1}) occur at the onset of distributed burning regime on sufficiently large area of flame (~10^{12} cm^2) (Röpke 2007, ApJ in print)



Problems of Delayed Detonations

- no robust DDT mechanism known in astrophysical context (e.g. Niemeyer 1999)
- detonation cannot cross even tiny regions of ash (Maier & Niemeyer 2006) → pockets of unburnt material may remain, needs to burn around complicated deflagration structure
- competition with expansion: does it reach far side when triggered off-center?



Röpke & Niemeyer, 2007.

Parametrizations (in 3D simulations):

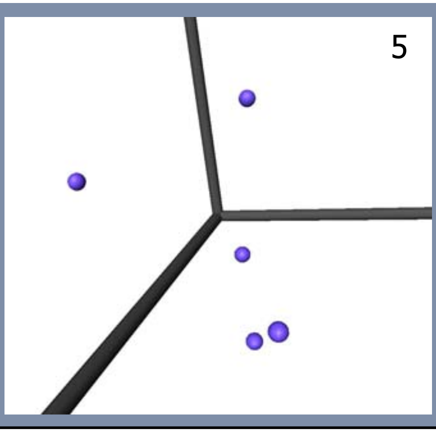
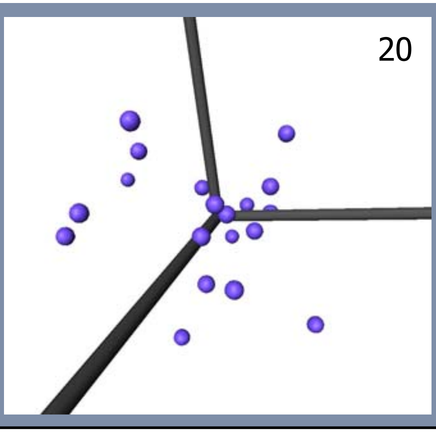
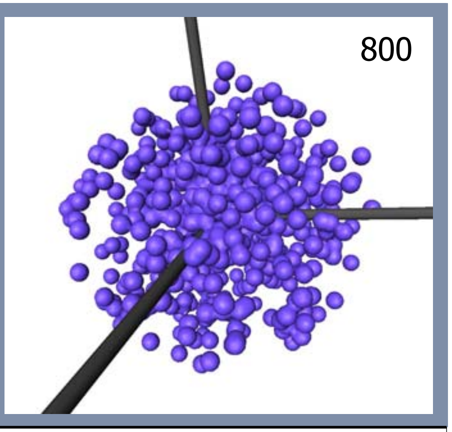
- arbitrarily prescribe position and time for DDT (Gamezo et al. 2005)
- DDT once deflagration flame enters distributed burning regime (Golombeck & Niemeyer 2005)

Delayed detonation model: example

(Röpke & Niemeyer, 2007)

Delayed detonation model

- varying the number of ignition kernels of the deflagration flame shifts emphasis from deflagration to detonation phase
- elegant way to reproduce scatter in SNe Ia (Röpke & Niemeyer, 2007)

			
$E_{kin,asympt}$ [B]	1.5	1.2	1.0
M(NSE) [$M_\odot$]	1.14	0.83	0.64
M(IME) [$M_\odot$]	0.22	0.44	0.55

Speculation on the overall picture

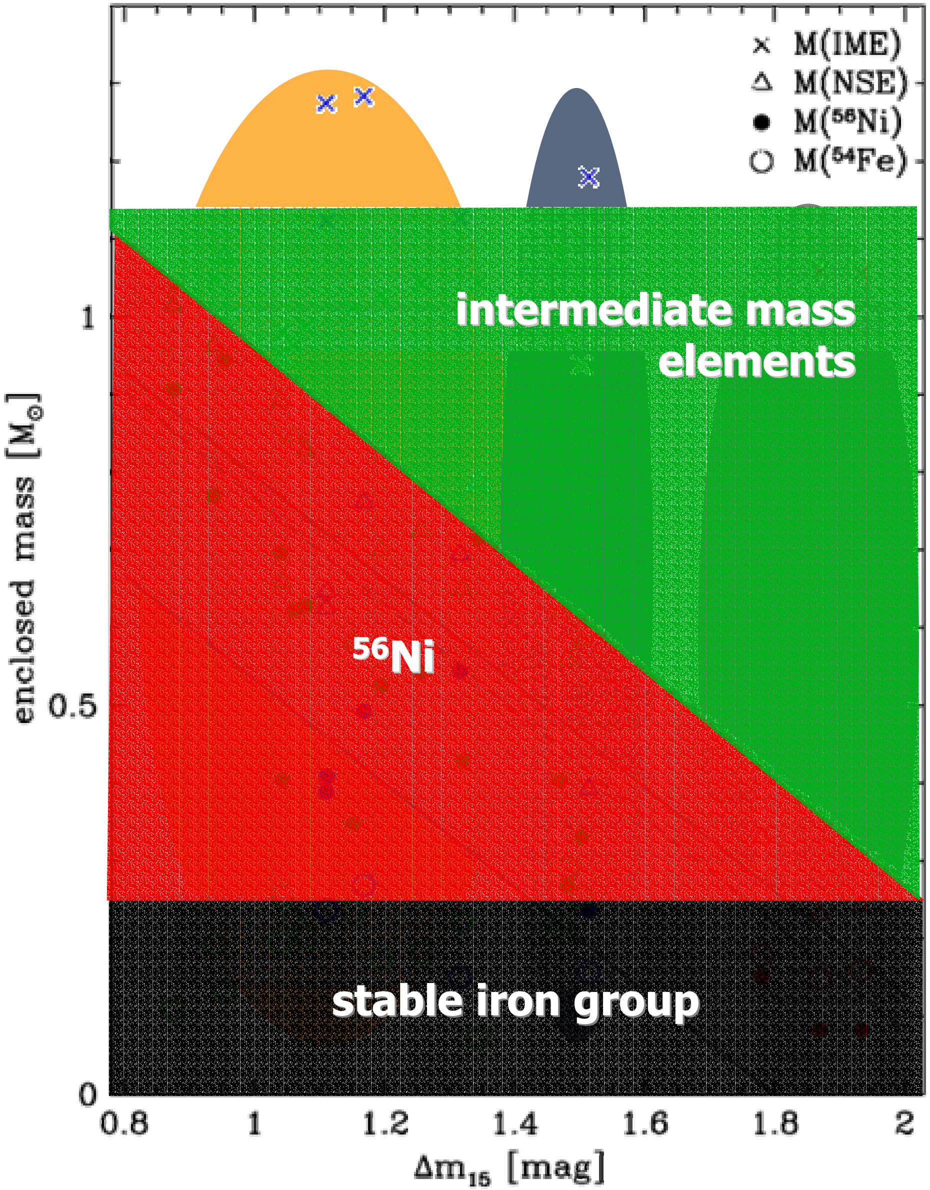
"Zorro diagram"

(Mazzali et al., Science 2007)

- weak normal SNe Ia
  deflagrations or
  deflagration phase dominant

- bright SNe Ia
  delayed detonations
  for brightes examples:
  detonation phase dominant

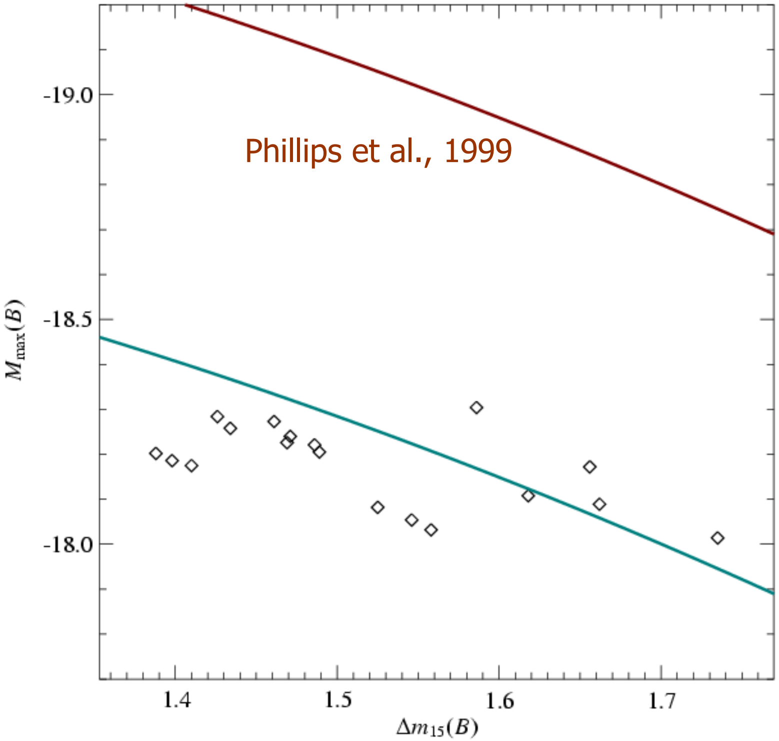
- sub-luminous: ???



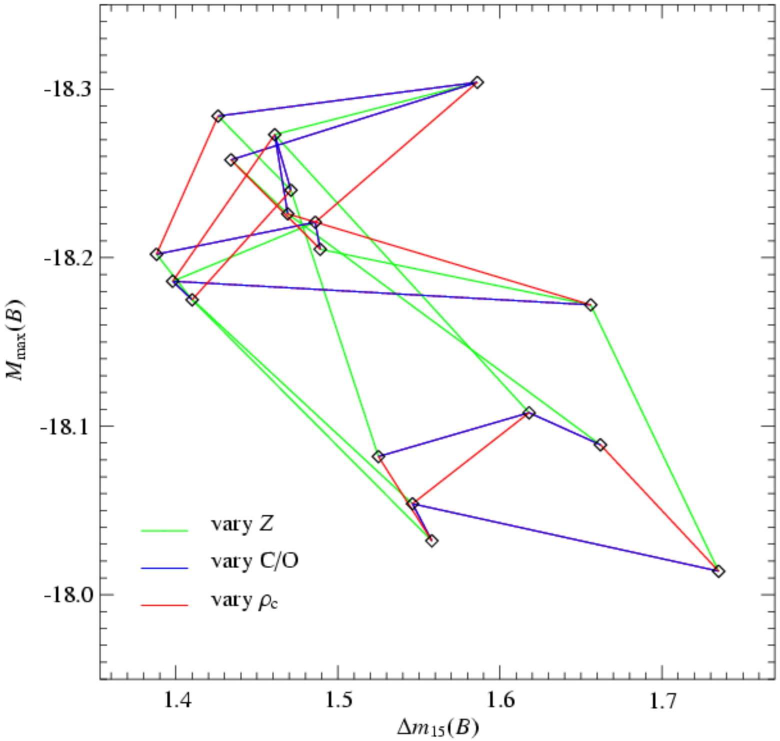
Diversity in 3D models

parameter study with 3d deflagration models (Röpke et al., 2004, 2005)

- Which parameters can account for SN Ia diversity?
  1. progenitor's carbon-to-oxygen ratio
  2. central density at ignition
  3. progenitor's metallicity



Röpke, Hillebrandt & Blinnikov, 2006



Deflagration model: example