Modeling the diversity of Type Ia supernova explosions

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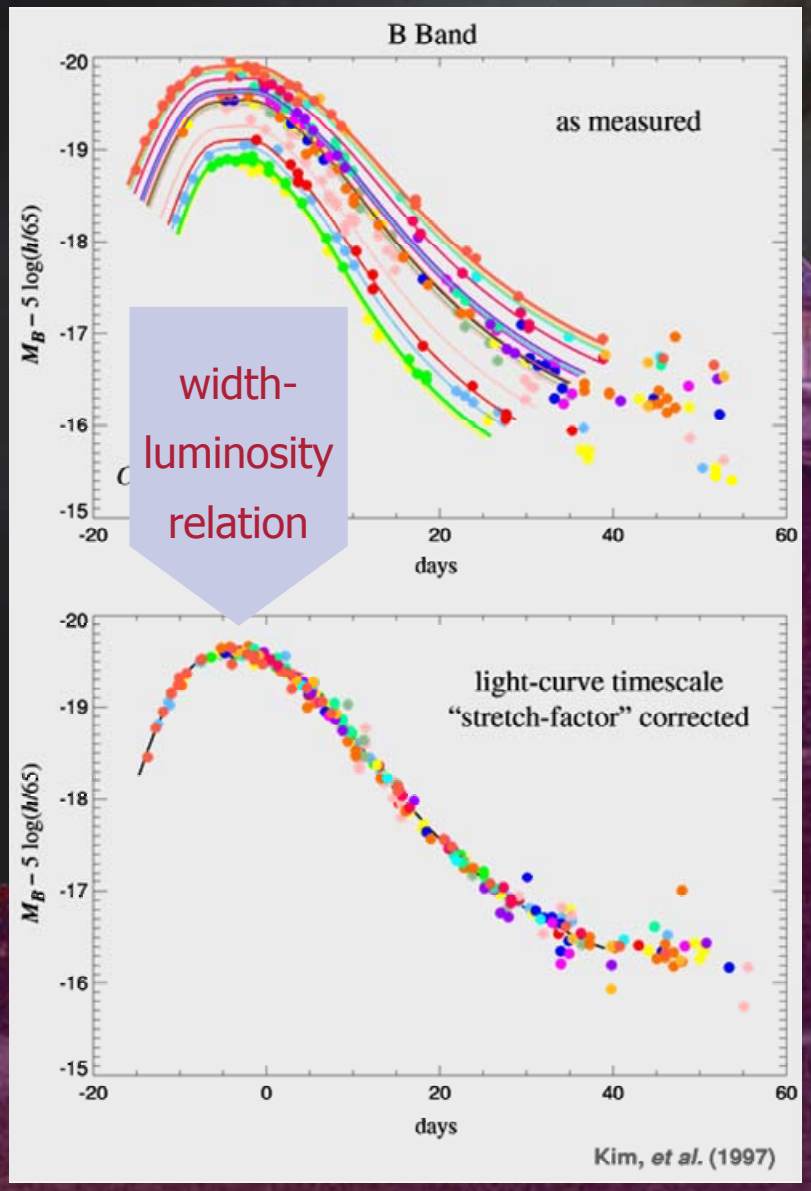
SN Ia cosmology

- best distance indicators out to z~1



- empirical calibration
- systematics?
- evolutionary effects?

Theoretical approach

SN Ia model

- build a self-consistent astrophysical model
- avoid tunable parameters
- simulate the explosion

Comparison with observations

- via synthetic light curves and spectra

SN Ia cosmology/nucleosynthesis

- origin of observed SN Ia diversity
- theoretical reasoning for calibration techniques
- predict nucleosynthetic yields

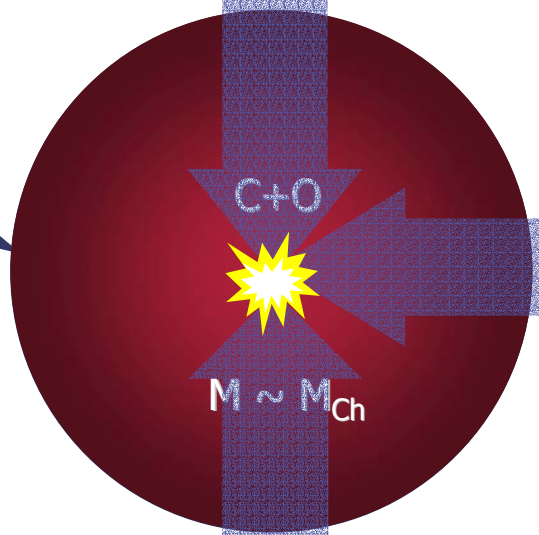
Favored scenario

Chandrasekhar-mass single degenerate scenario

ignition of carbon burning due to increase in $\rho_{central}$

- 1 century of convective carbon burning

H (+He) from binary companion



flame ignition: due to thermonuclear runaway

- geometrical shape of ignition?

explosion due to flame propagation

- produced ^{56}Ni makes event bright

Flame propagation

...from ignition near center outwards

hydrodynamics of flame propagation

deflagration
subsonic

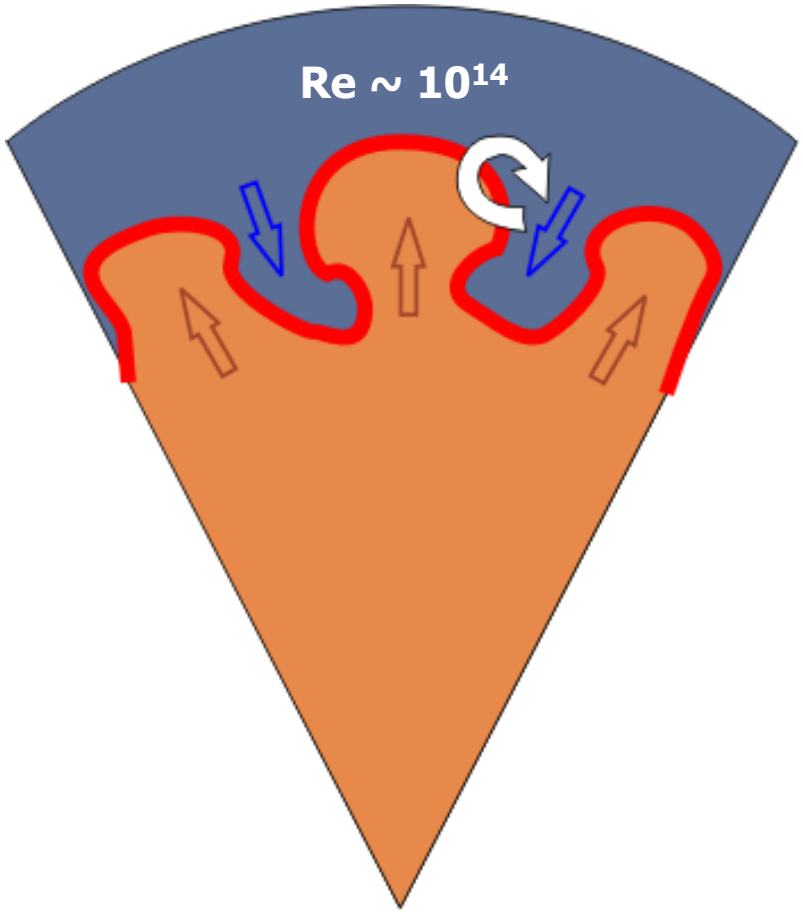
flame mediated by thermal conduction of degenerate e^-

detonation
supersonic

flame driven by shock waves

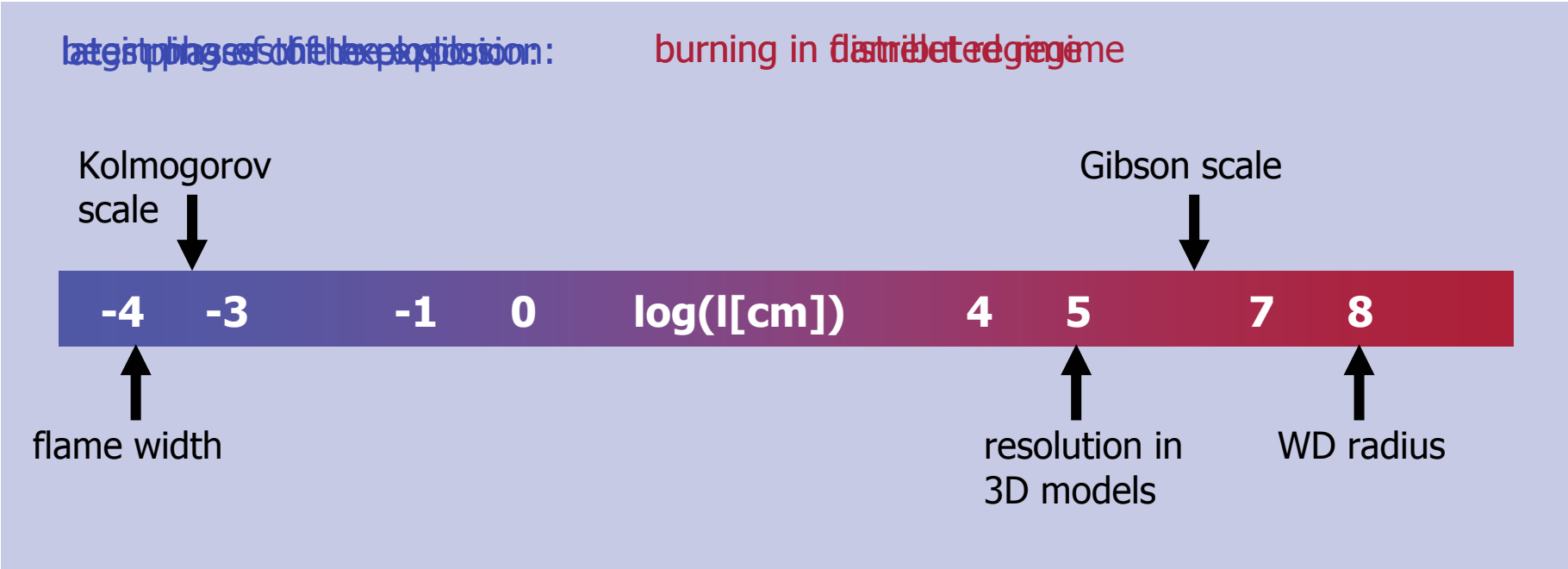
- prompt detonation ruled out (Arnett 1969)

Turbulent combustion in SNe Ia



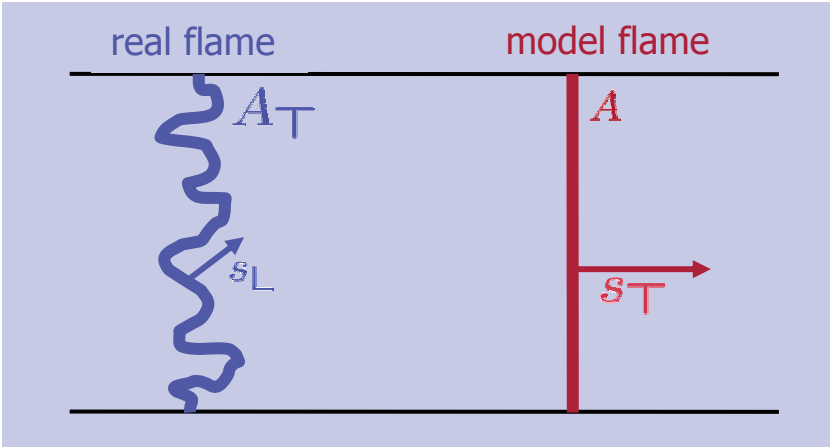
Relevant scales

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



Turbulent deflagration

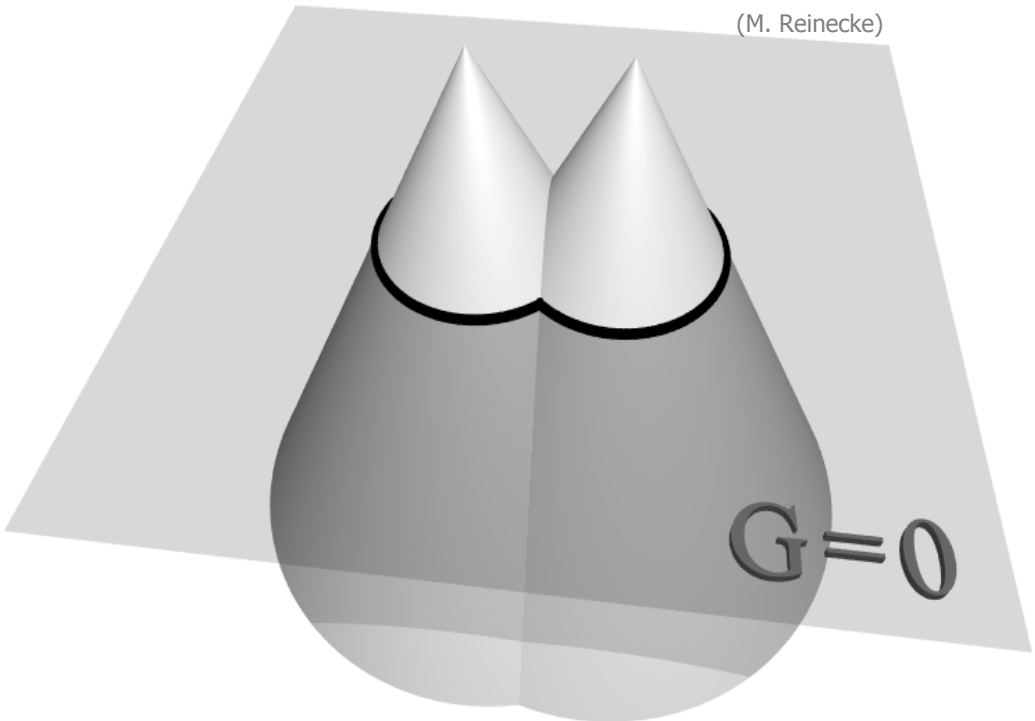
- most parts of the SN Ia explosion: turbulence does not penetrate internal flame structure: flamelet regime of turbulent combustion



- $s_T \propto$ turbulent velocity fluctuations (Damköhler 1940)

Numerical Implementation

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

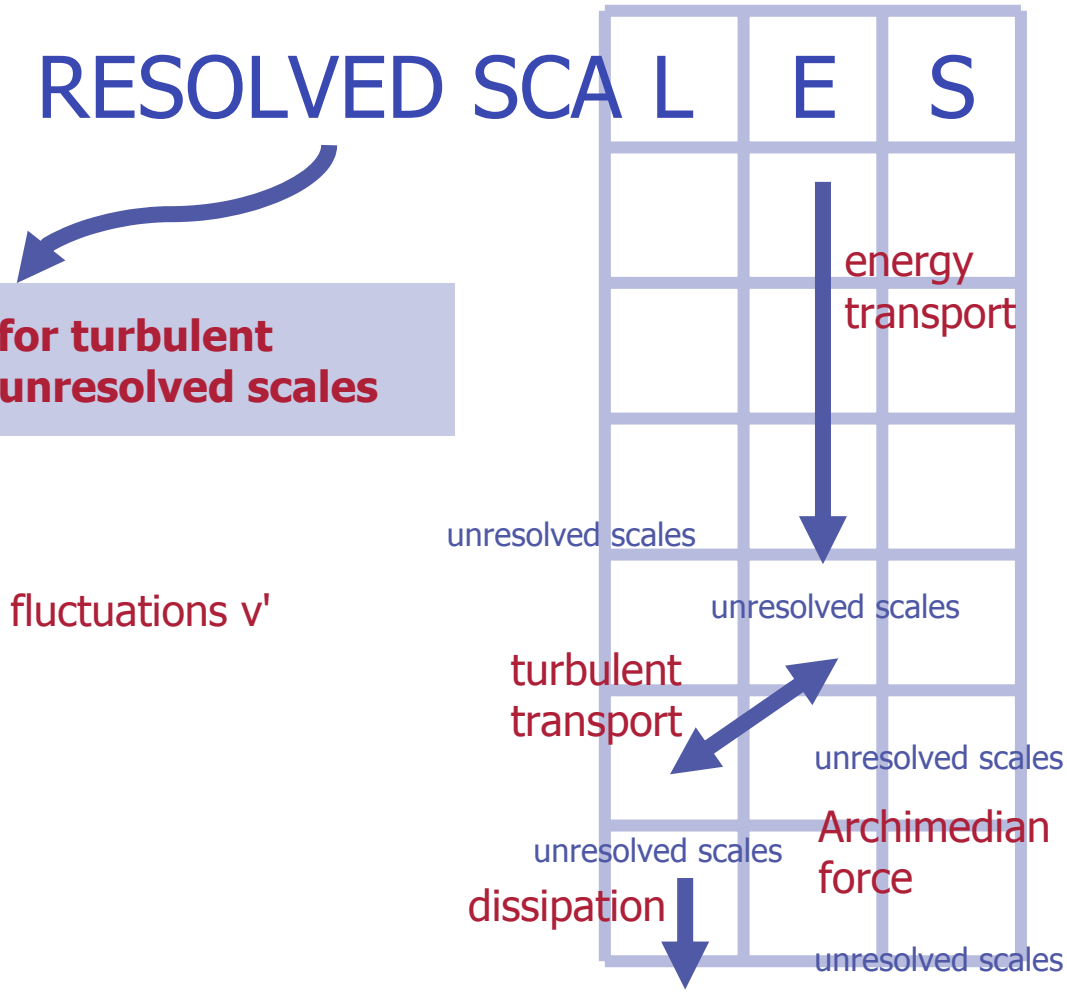


- equation of motion:

$$\frac{\partial G}{\partial t} = (\vec{v}_{\mathrm{u}}\vec{n} + s_{\mathrm{u}})\ |\nabla G|$$

Numerical Implementation

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



Balance equation for turbulent kinetic energy on unresolved scales

→ determines turbulent velocity fluctuations v'

High-resolution simulation

- 1024^3 computational cells, 500.000 CPU hours on IBM regatta (FR et al., 2007)

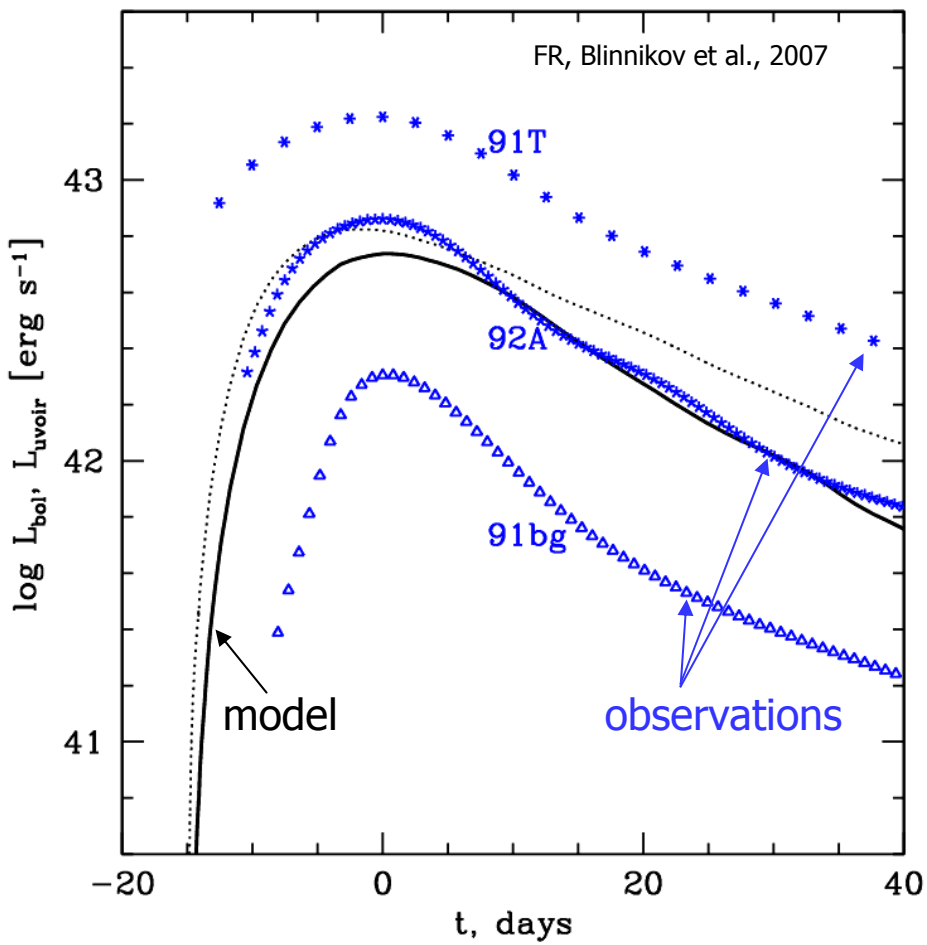
Deflagration model vs. observations

light curves

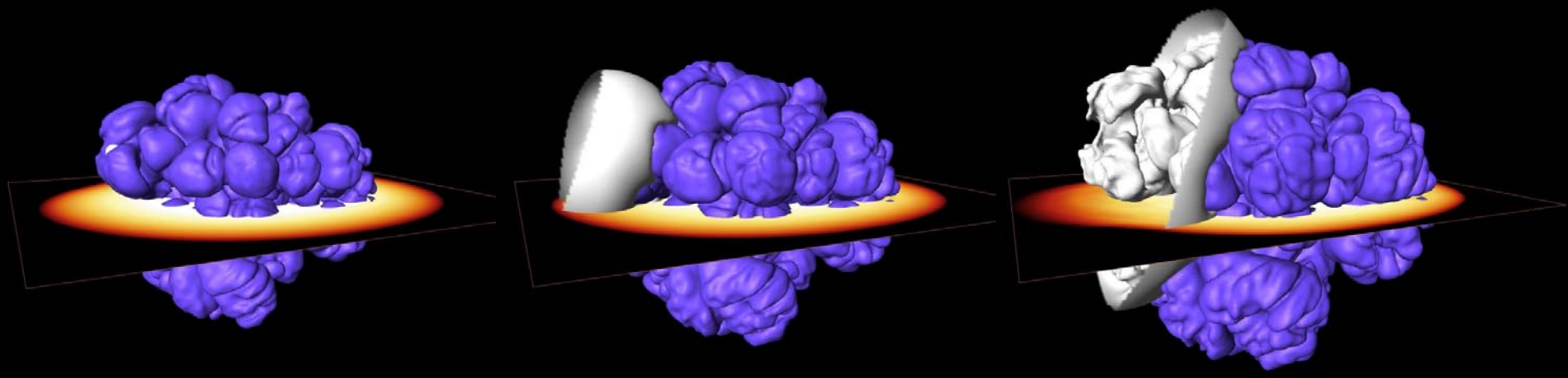
- reasonable agreement with dimmer examples of normal SNe Ia

- ^{56}Ni masses $\lesssim 0.4\ M_\odot$

  $\rightarrow$ generally not very bright



Delayed detonation models



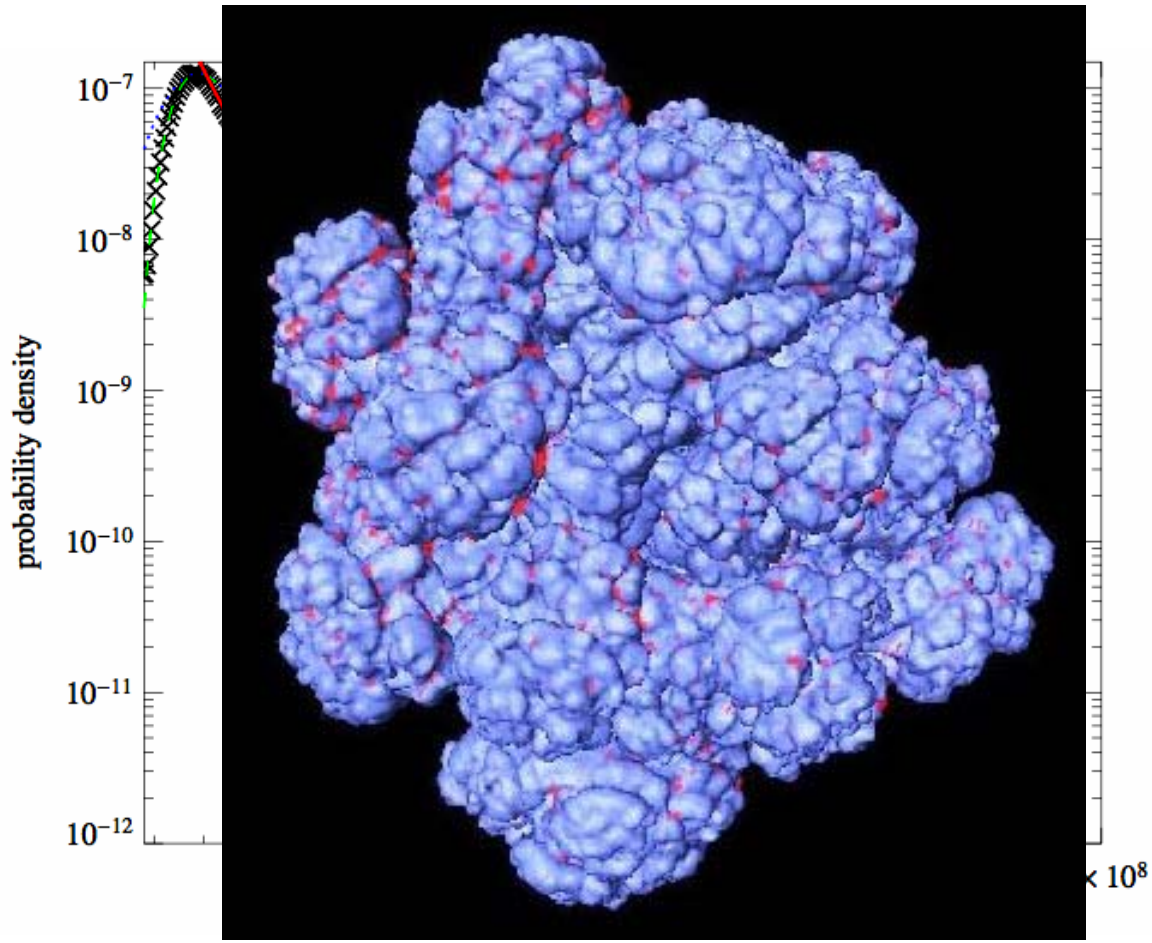
FR & Niemeyer, 2007
Mazzali et al., 2007

preliminary test calculations:

- promising candidate for explaining normal to bright SNe Ia

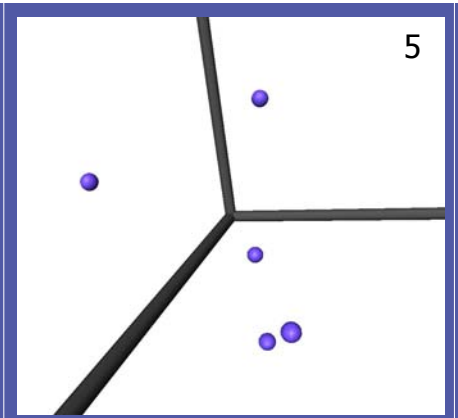
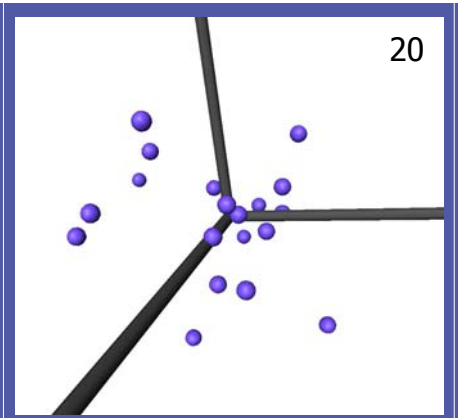
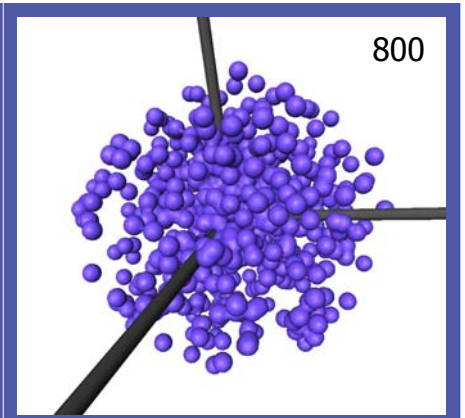
Deflagration-Detonation Transitions?

- DDT at late stages of the explosion process (onset of distributed burning regime, Niemeyer & Woosley, 1997)?
- high turbulent velocities (~1000 km/s) required
  (Lisewski et al., 2000;
  Woosley, 2007,
  Woosley et al., subm.)
- Analysis of turbulent velocity flucutations in simulations
  (FR 2007)
- intermittency effects
  (analytic treatment:
  Pan et al., 2008
  analysis from simulation data:
  Schmidt et al., subm.)



Variability of 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 (FR & Niemeyer, 2007)

			
$E_{kin,asympt}$ [Bethe]	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

A 2D pilot study

~40 2D models (with D. Kasen, S. Woosley)

explored parameter space:

fixed parameters

- central density (2.9×10^9 g/ccm)
- metallicity (solar)
- C/O ratio (50%)

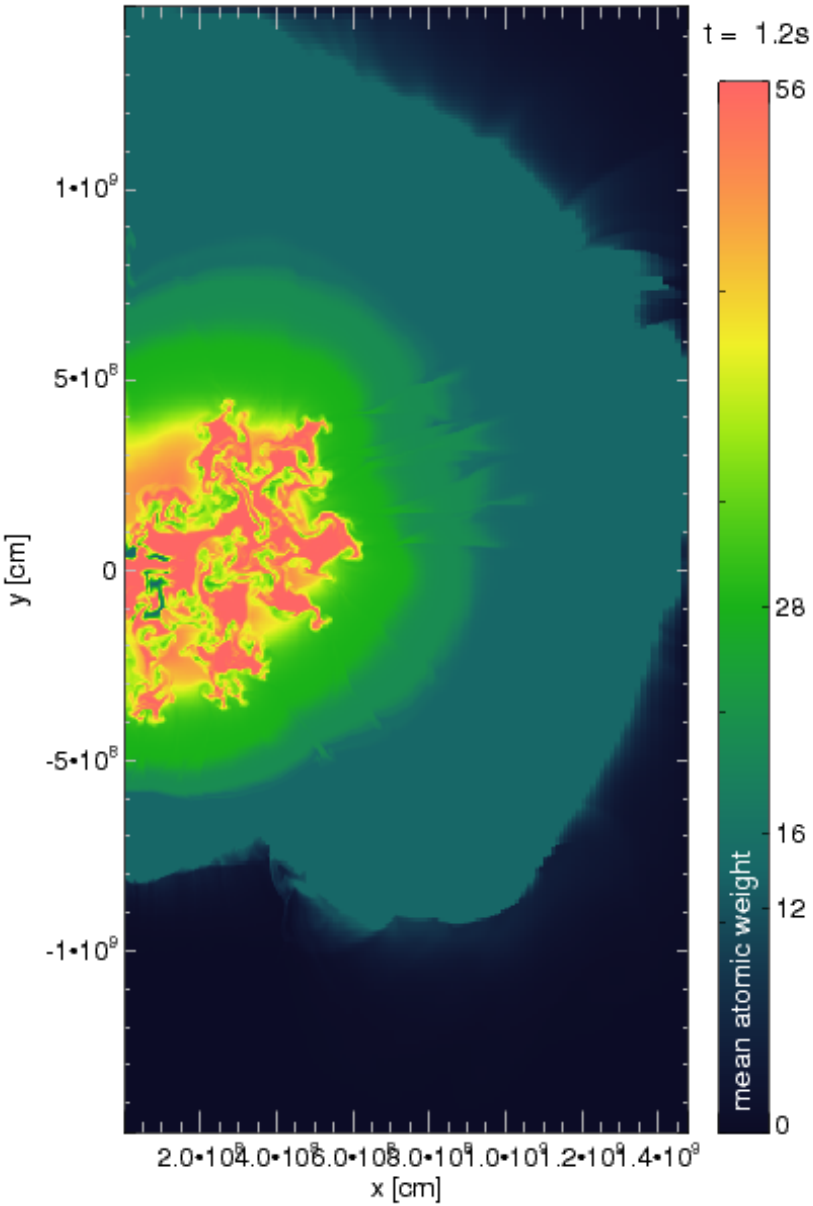
variable parameters

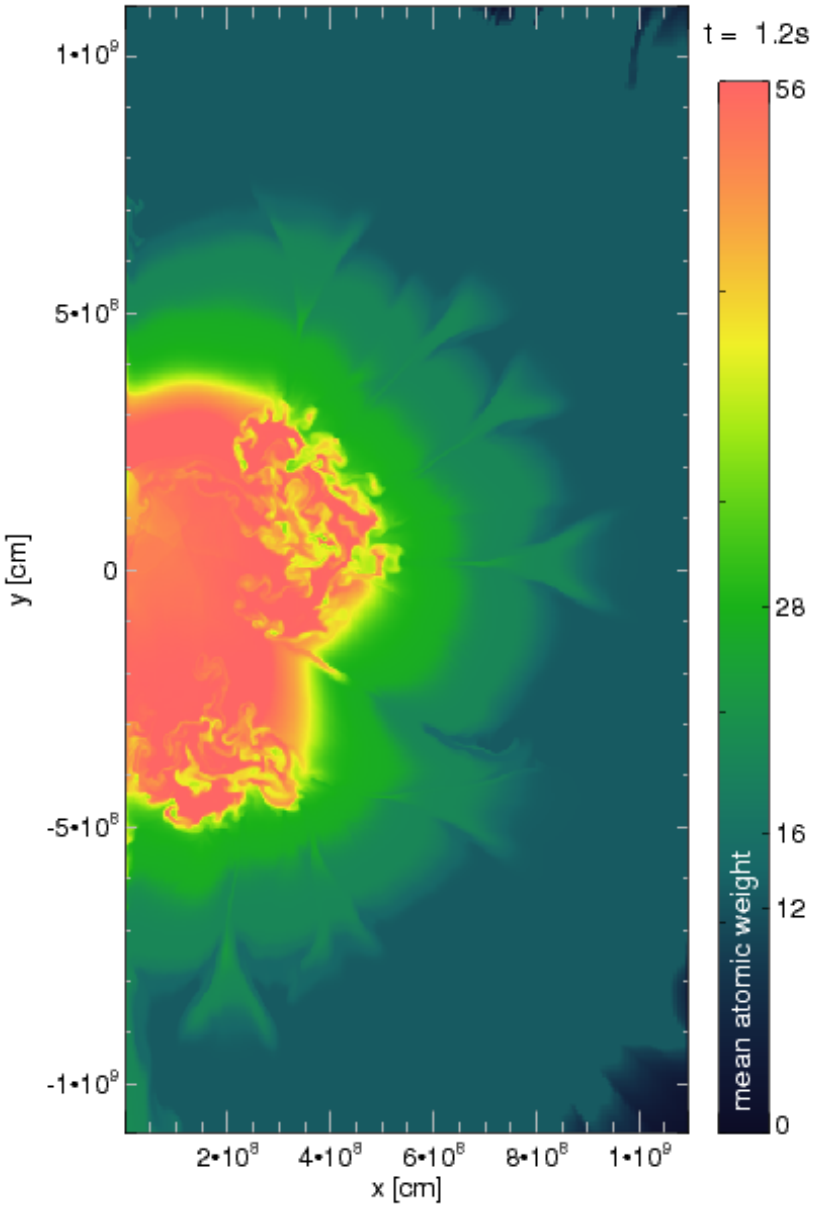
- ignition spark distribution
- turbulence criterion for DDT

results:

- ^{56}Ni masses: 0.44 to 1.1 $M_\odot$
- kinetic energies: 1.2 to 1.6 B

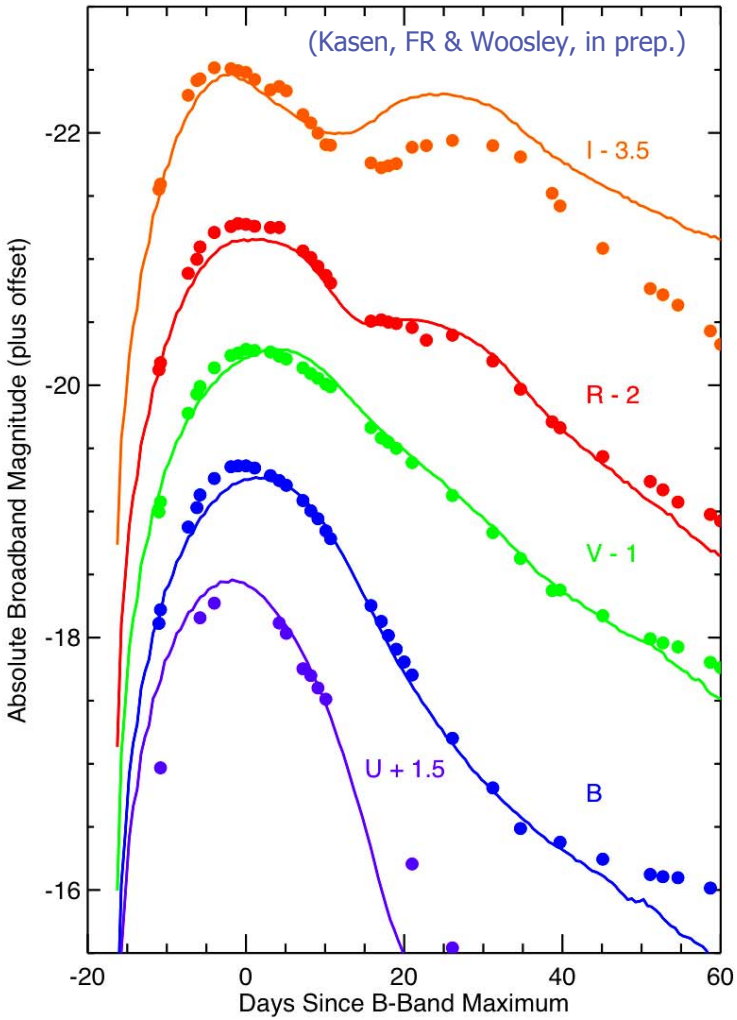
Strong vs. weak deflagration phase

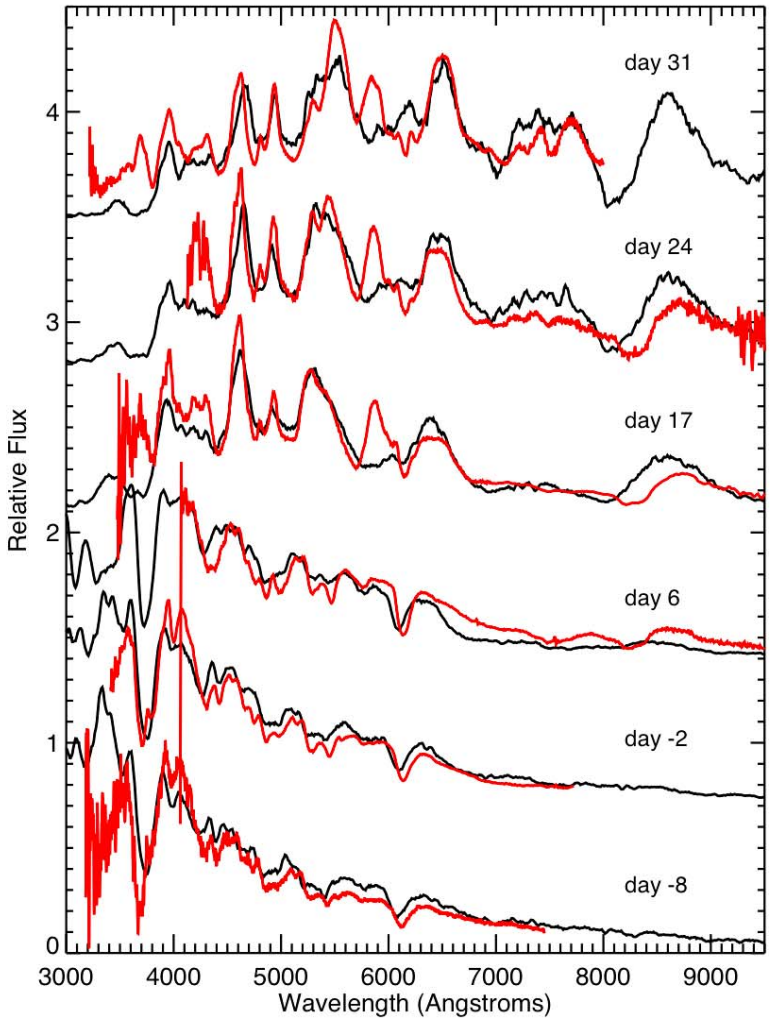




Synthetic observables

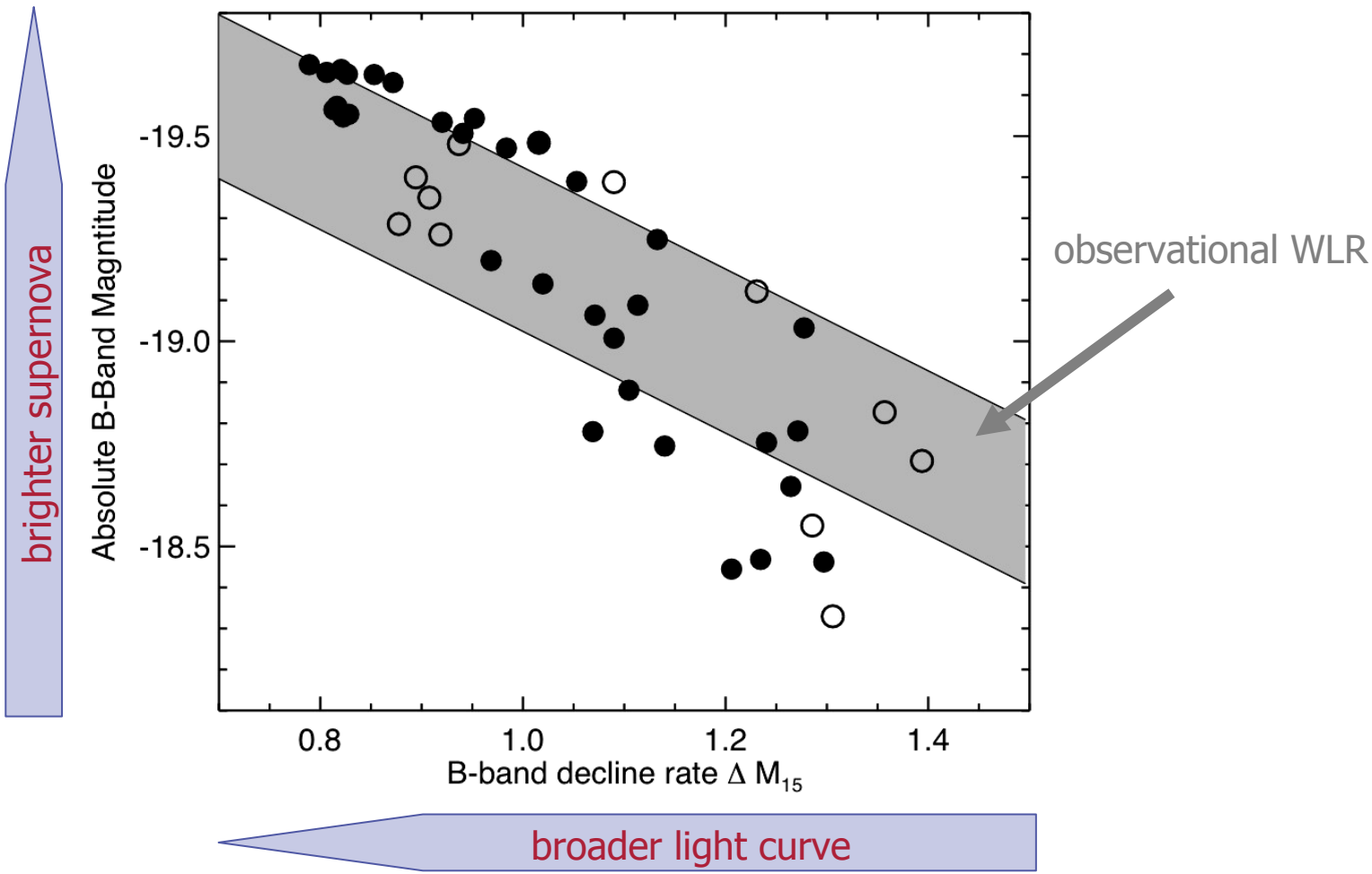
- model with emphasis on detonation phase compared with SN 2003du





Width-luminosity relation

- 44 models angle averaged light curves (Kasen, FR & Woosley, in prep.)



Summary

- standard Chandrasekhar-mass explosion model can account for bulk of SNe Ia
- detonation must follow initial deflagration stage

- pre-expansion and burning in the deflagration controls overall energy release and brightness
- varies with ignition spark distribution

- models reproduce normal to bright SNe Ia and follow the with-luminosity relation