International School of Nuclear Physics, 32nd Course

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Description of (Type Ia) Supernova Explosions

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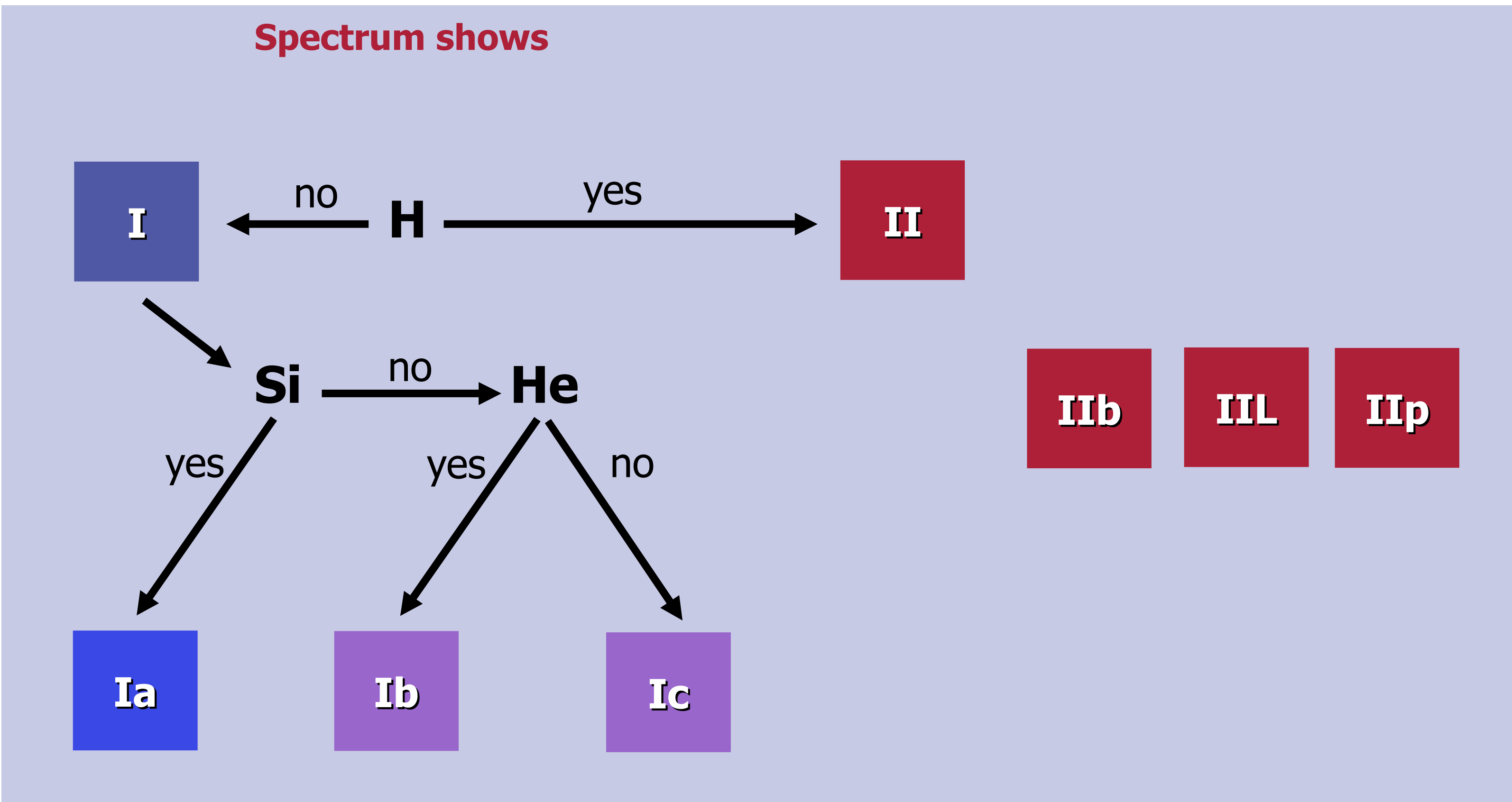
SN Ia

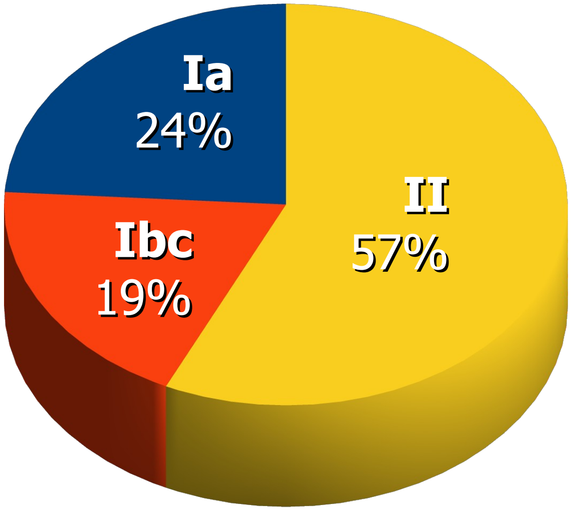
Example: Type Ia supernova explosions

- astronomical (empirical) classification



SN fractions

- volume-limited (Li+, 2010)



Model: energetics

energy release: ~10^{51} erg

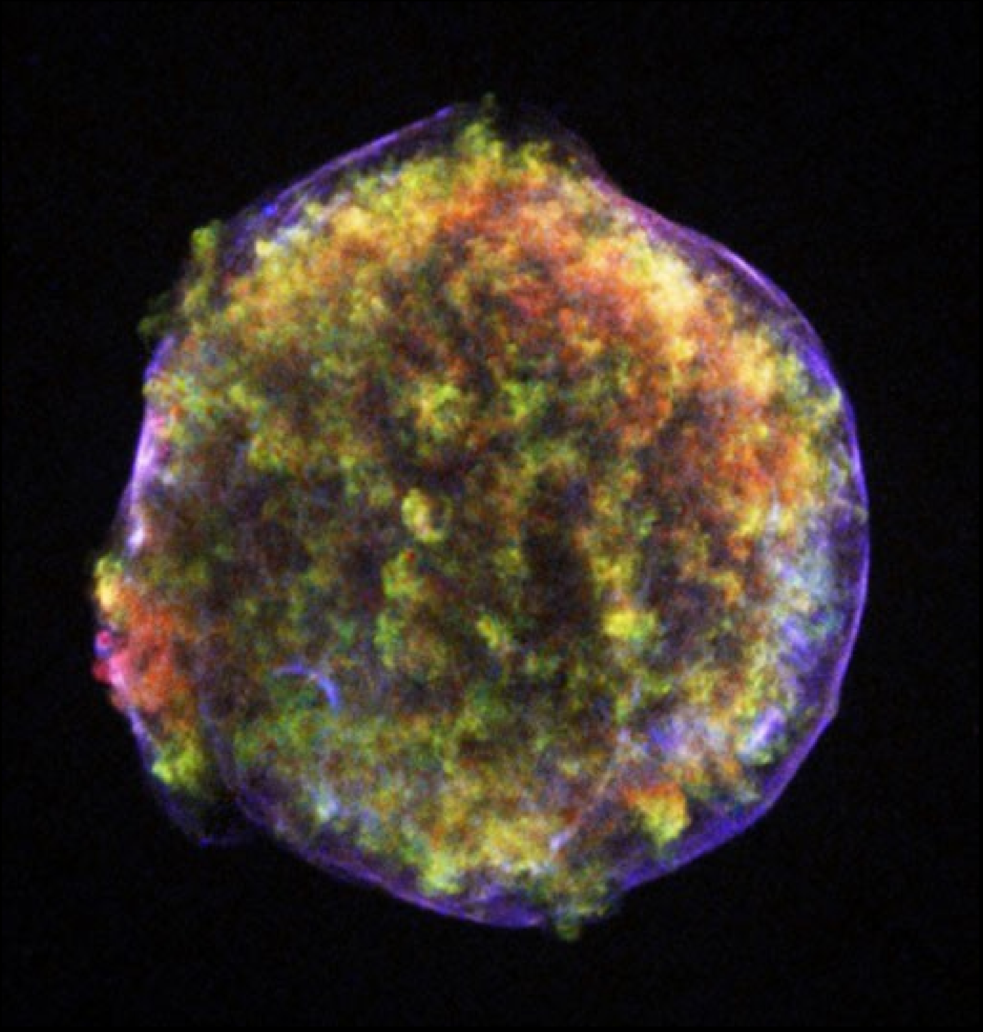
energy source:

- collapse to neutron star?
- release of gravitational binding energy:

$$U_{\mathrm{grav}} \sim -\frac{3}{5}\frac{GM_\odot^2}{10\,\mathrm{km}} \sim -10^{53}\,\mathrm{erg}$$

- sufficient to power supernova!

...but no compact object found in SNe Ia remnants



Model: energetics

energy release: ~10^{51} erg

energy source:

- nuclear energy

- no H, He in SNe Ia spectra
  $\longrightarrow$ exploding star: C+O WD

- energy release due to burning of C+O material to ^{56}Ni: 7.86×10^{17} erg/g

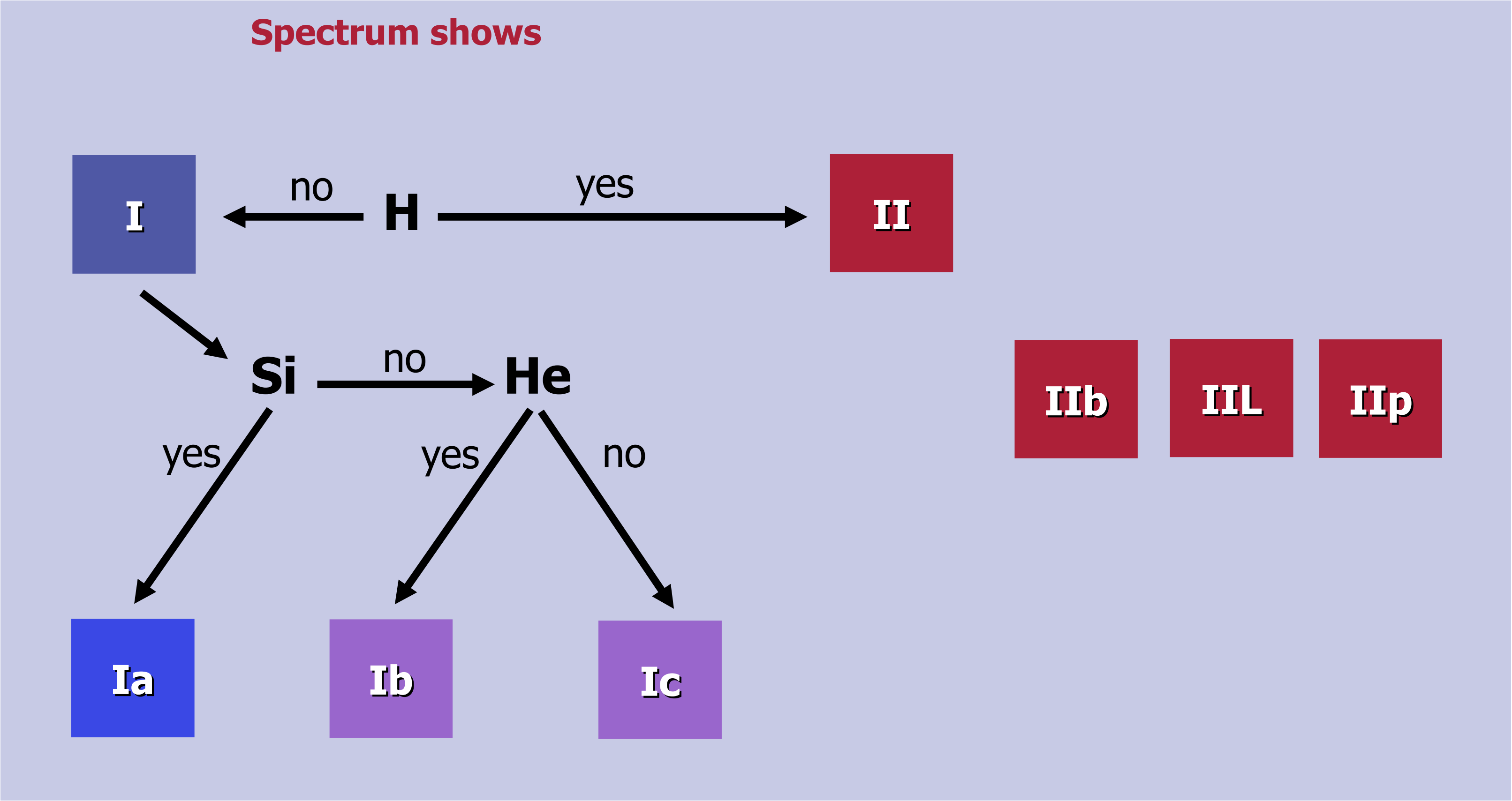
  Chandrasekhar-mass (1.4 $M_\odot$) WD:

  2×10^{51} erg

- radioactive decay of ^{56}Ni leads to bright optical display

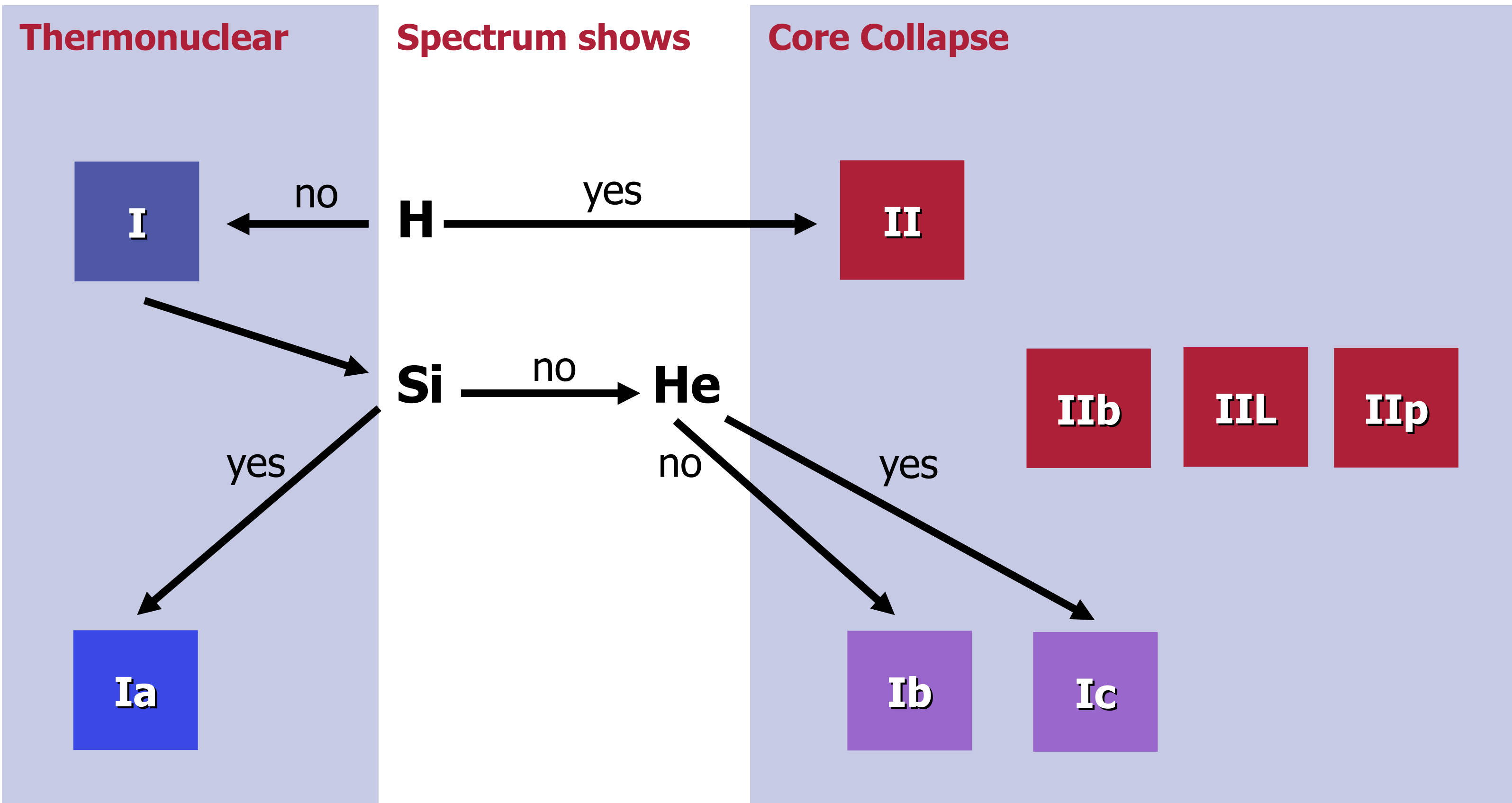
Astronomical classification

- astronomical (empirical) classification



Astrophysical classification

- physical classification



Nucleosynthesis and chemical evolution

SNe Ia significantly contribute to cosmic cycle of matter:

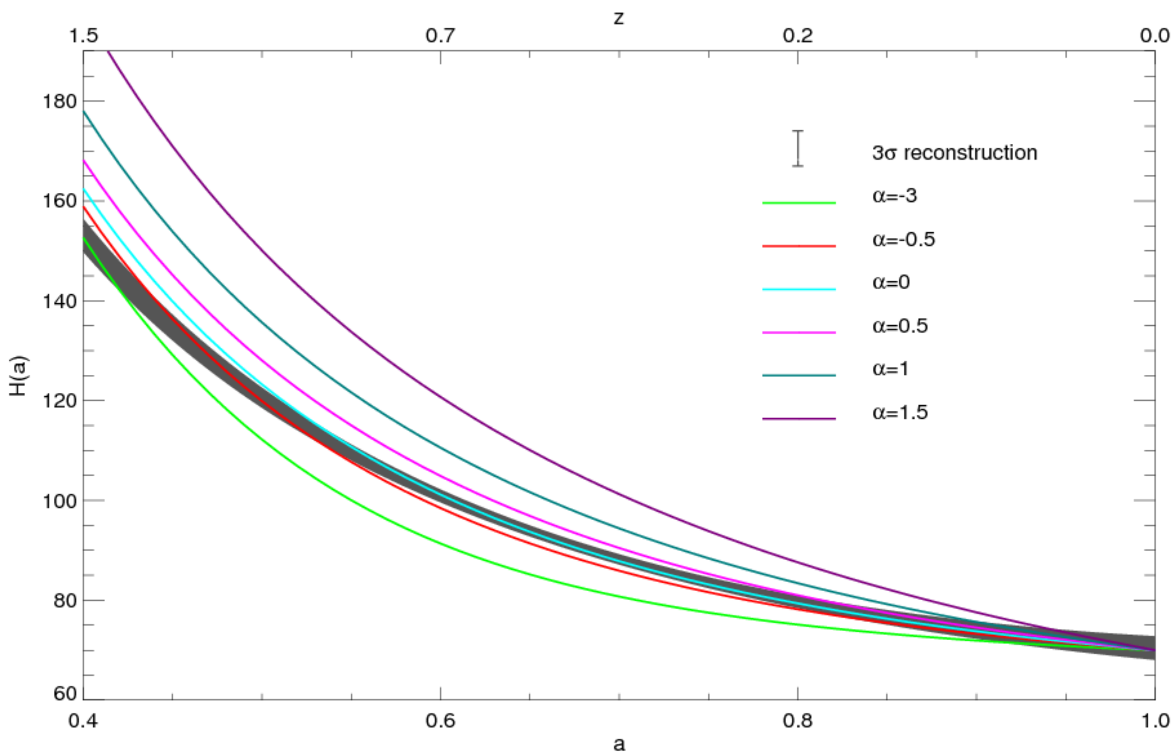
- main contributor to iron group elements in the Universe
- about 1/3 of intermediate mass elements (Si to Ca)
- p-process site? → contribution to the galactic evolution of p-nuclei (e.g. Kusakabe et al., 2006) → project with C. Travaglio (Turin)

SN Ia Cosmology

SNe Ia

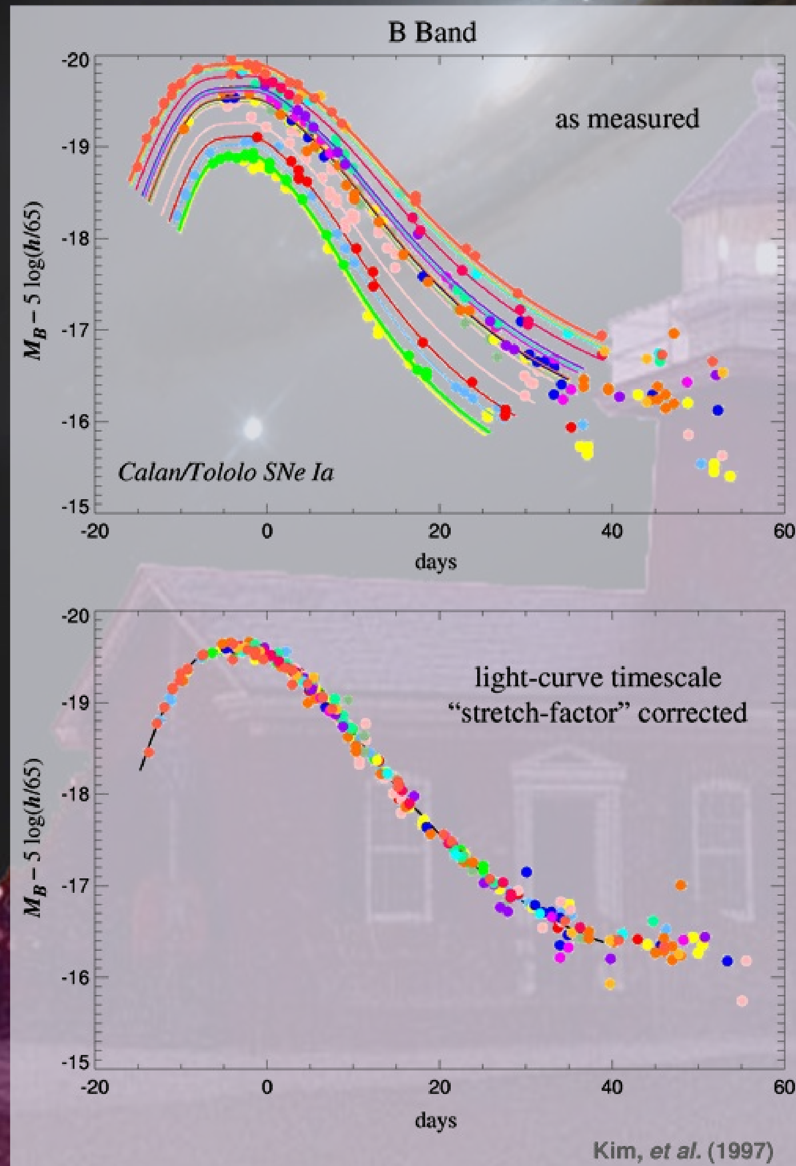
- established accelerated expansion of the present Universe
- probe Dark Energy
- luminosity distance reconstruct H(z) model-independently (Benitez+, in prep.)

Union2 Sample Vs. DGP Models



SN Ia cosmology

standard candles?



standardizable

- systematics?
- evolutionary effects?

SN Ia basics

What we (believe to) know...

- thermonuclear explosion of WD (Hoyle & Fowler 1960) consisting of C+O material
- ^{56}Ni as main product (Truran 1967, Colgate & McKee, 1969) decays radioactively, powers optical display (e.g. Kuchner+ 1994)

(potentially misleading) prejudices...

- homogeneity   fixed mass of exploding star?
- Ni masses necessary to explain brightness of typical SNe Ia?
- consistency of iron group yields with solar abundances?

The great unknowns...

- progenitor system
- single or multiple explosion mechanisms

use explosion models (combined with radiative transfer, population synthesis) to find out

How to explode a WD?

single C+O WD: inert object   trigger explosion by

- spontaneous self-ignition...
  requires particular conditions

- hitting it with a hammer...
  requires external compression

stellar binary companion necessary

How to explode a WD?

single C+O WD: inert object   trigger explosion by

- spontaneous self-ignition...
  requires particular conditions
    - high density at core of WD
    - reached by growing WD to M_{Ch}
    - stable accretion (+hydrostatic burning of accreted material) from RG, MS, WD

  mass fixed to ~1.4 M_{sun}

M_{Ch} models

- hitting it with a hammer...
  requires external compression
    - explosive instabilities in accretion stream or accreted layer of material
    - violent WD-WD merger

  no tight constraints on mass of exploding WD

non-M_{Ch} model

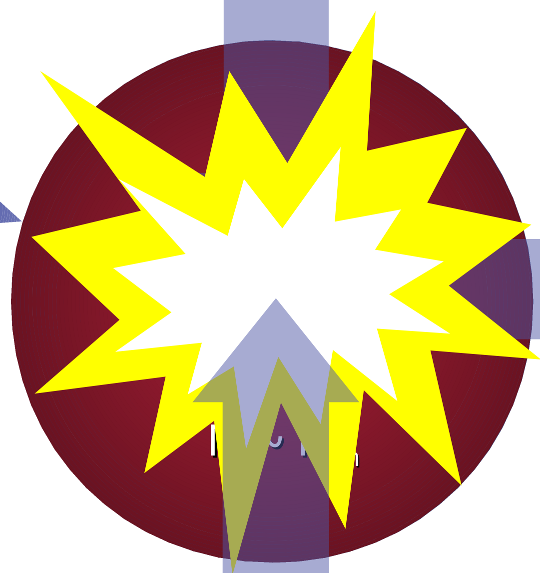
stellar binary companion necessary

M_{Ch} model

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

- 1 century of convective carbon burning

accretion from binary companion



flame ignition due to thermonuclear runaway

- number/distribution of ignition sparks?

explosion due to flame propagation

- produced ^{56}Ni makes event bright

Explosive C+O burning

- fuel density ahead of combustion front determines nucleosynthesis:

decreasing fuel density →

nuclear statist. equilibrium (iron group elements)	intermediate-mass elements Si, S, Ca etc.	oxygen from C-burning	no burning C+O

- $^{12}C+^{12}C$ reaction rate: $\propto T^{20}$
- electron-degenerate material: high thermal conductivity

burning proceeds in thin fronts (flames)

flame width (mm to cm) $\ll$ scales of WD (radius ~ 2000 km)

described by discontinuity approximation

Flame propagation and burning

hydrodynamics of flame propagation

deflagration
subsonic

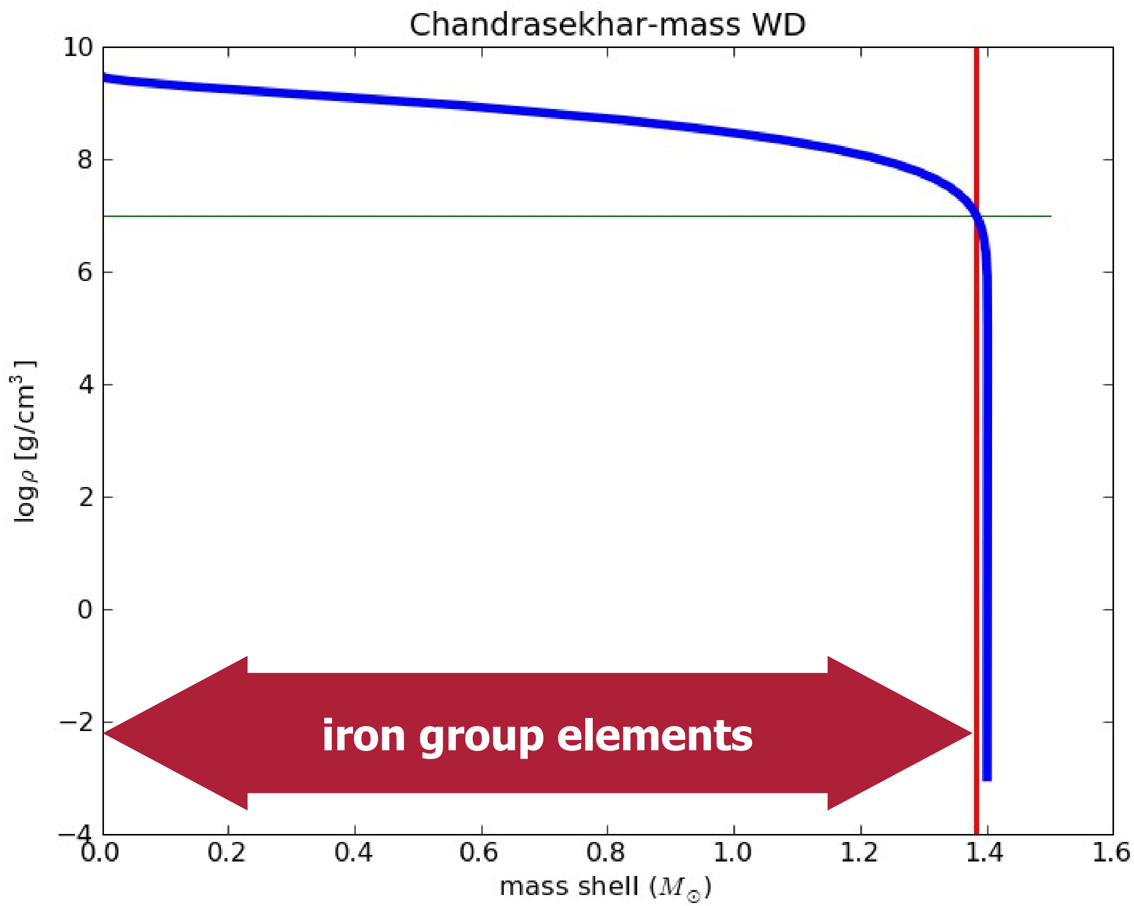
flame mediated by thermal conduction of degenerate e^-

detonation
supersonic

flame driven by shock waves

Detonations

- M_{Ch} WD in hydrostatic equilibrium



Flame propagation and burning

hydrodynamics of flame propagation

deflagration
subsonic

flame mediated by thermal conduction of degenerate e^-

detonation
supersonic

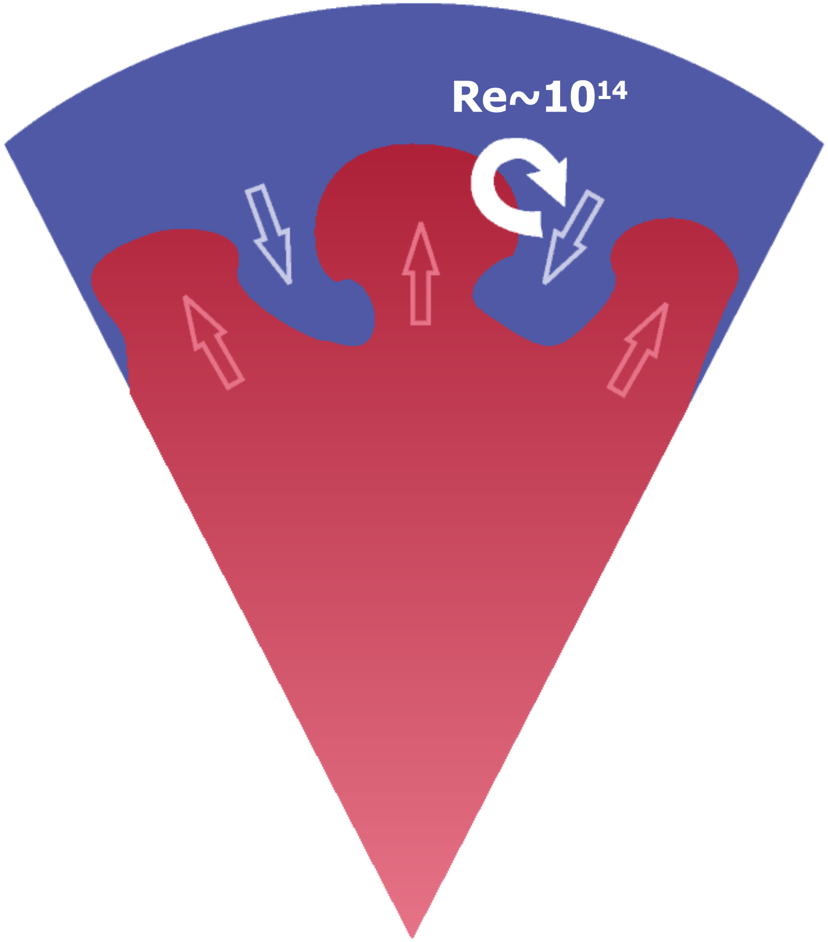
flame driven by shock waves

Turbulent combustion in SNe Ia

- subsonic bring WD material ahead of flame out of equilibrium
  pre-expansion

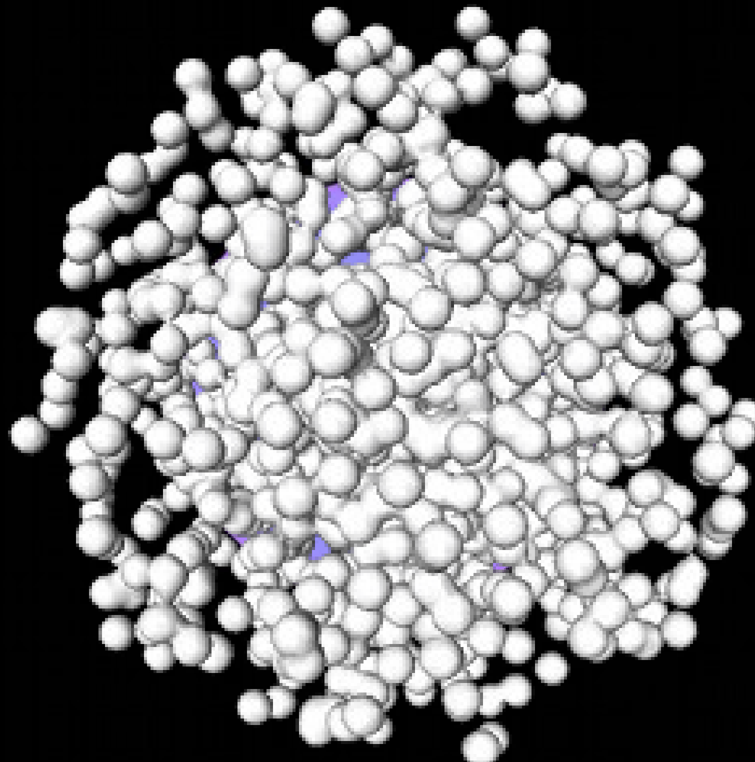
- laminar flames: Mach ~10^{-2}
  cannot catch up with WD expansion
  nuclear energy release insufficient

- buoyancy instabilities lead to
  turbulent combustion



Turbulent deflagrations

t = 0.025 sec

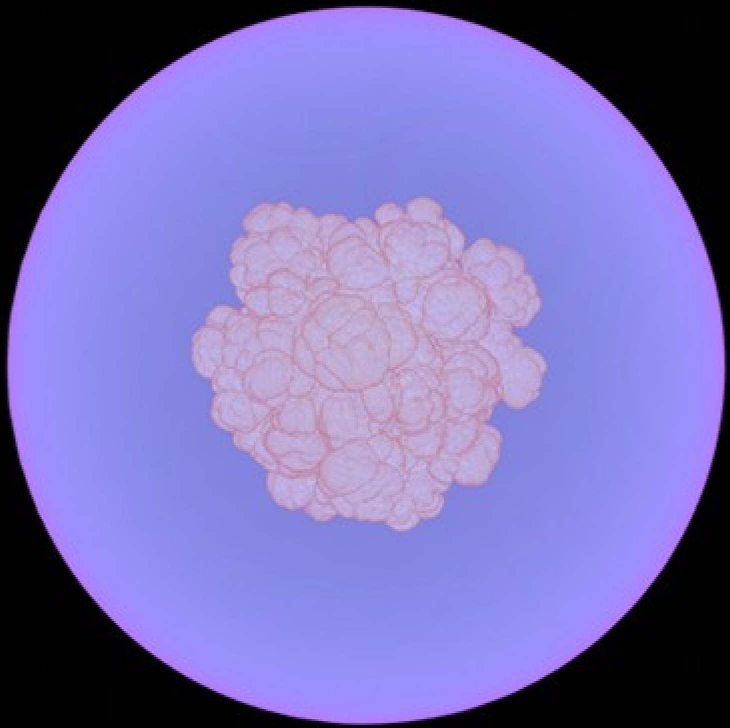


Turbulent deflagrations

t = 0.200 sec

Turbulent deflagrations

t = 0.600 sec

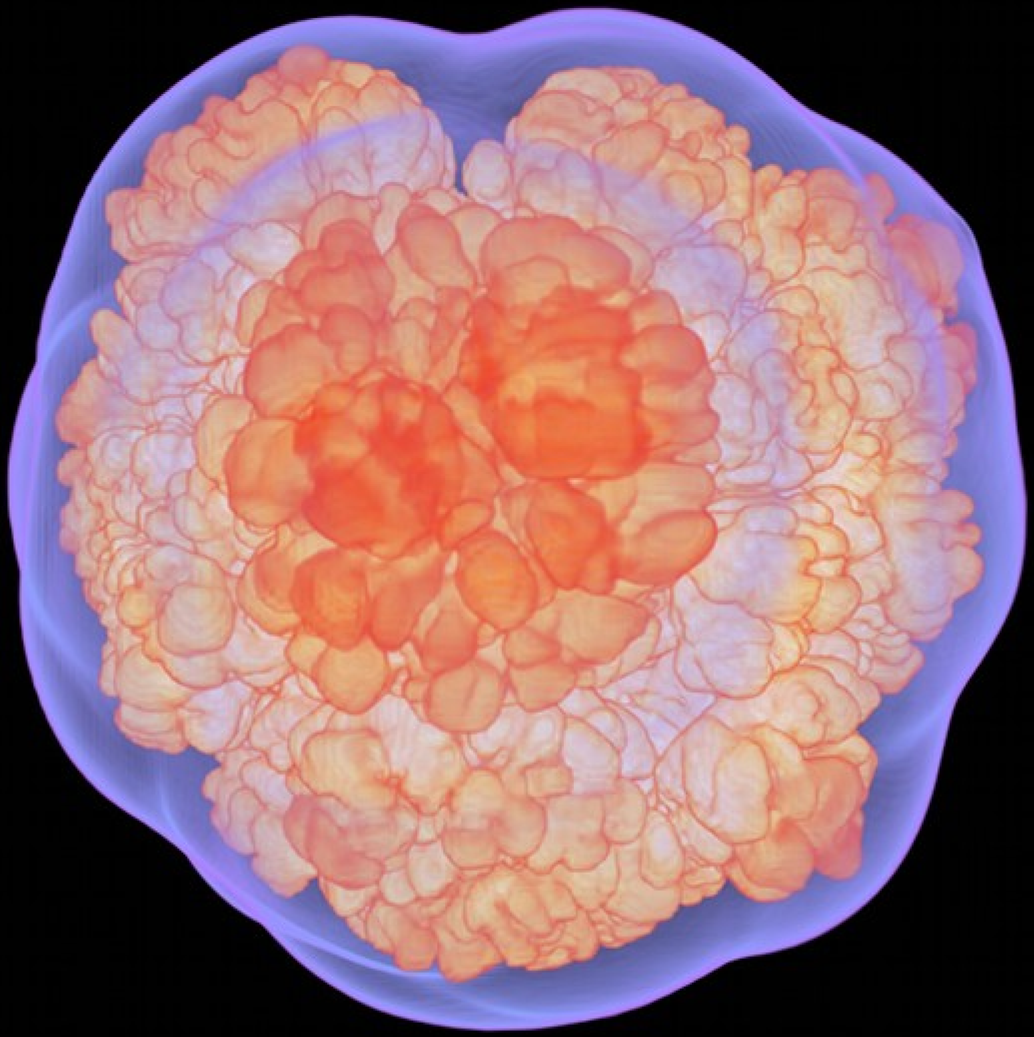


Turbulent deflagrations

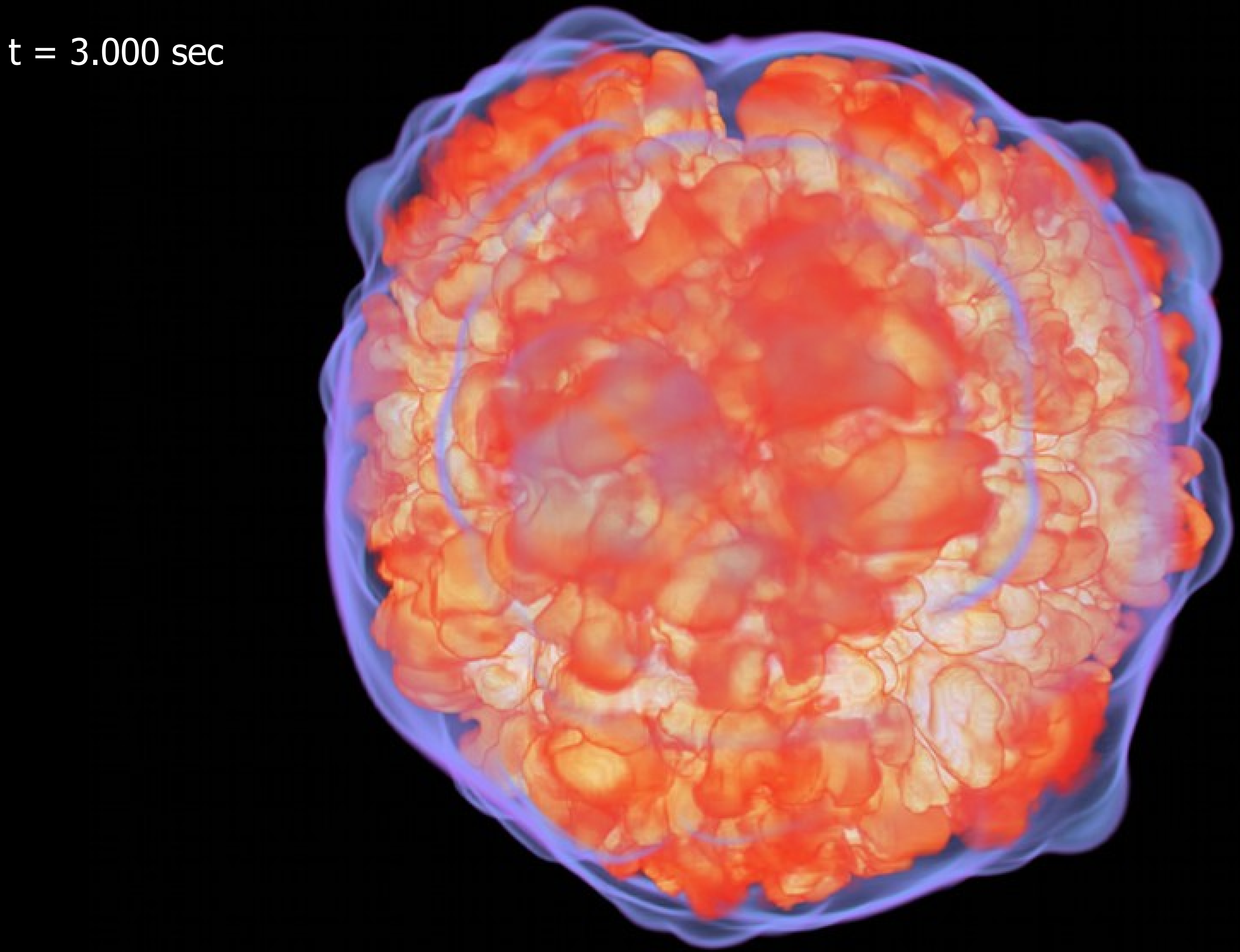
t = 1.000 sec

Turbulent deflagrations

t = 1.600 sec

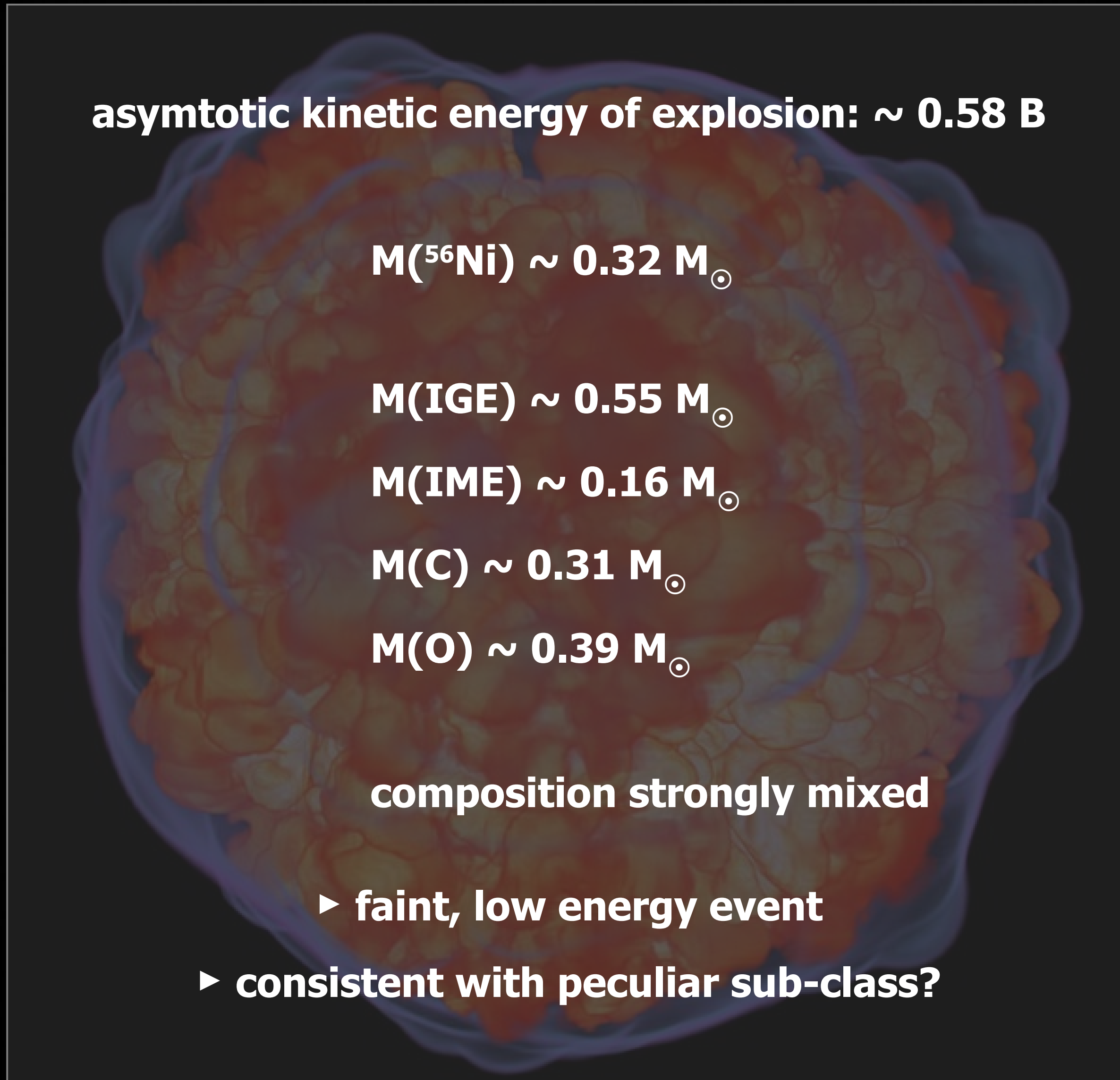


Turbulent deflagrations



Turbulent deflagrations

t = 3.000 sec



asymtotic kinetic energy of explosion: ~ 0.58 B

M(^{56}Ni) ~ 0.32 $M_\odot$

M(IGE) ~ 0.55 $M_\odot$

M(IME) ~ 0.16 $M_\odot$

M(C) ~ 0.31 $M_\odot$

M(O) ~ 0.39 $M_\odot$

composition strongly mixed

- **faint, low energy event**
- **consistent with peculiar sub-class?**

Nucleosynthetic postprocessing

- simplified description of burning in hydro (only 5 species)

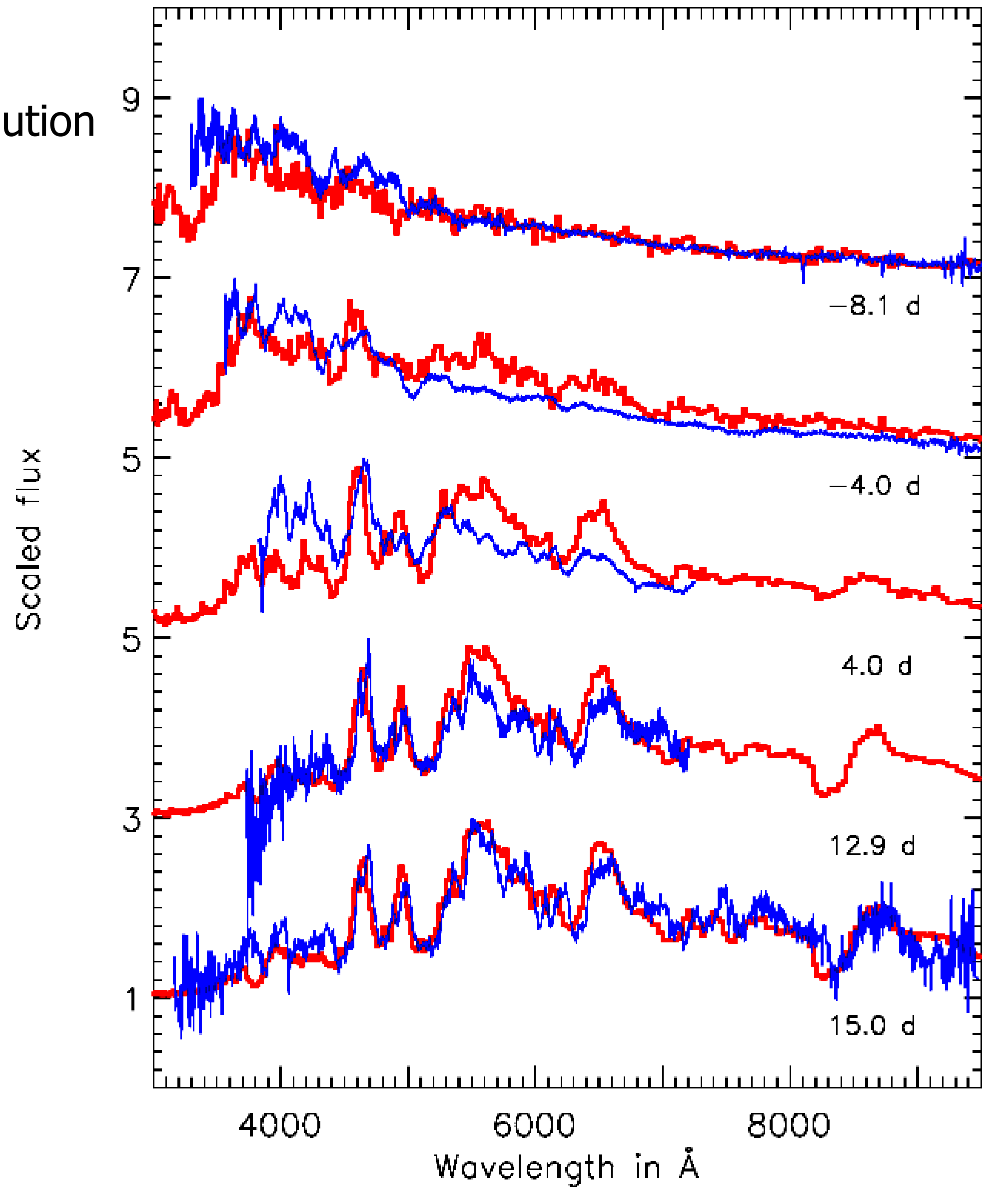
- nucleosynthesis postprocessing from tracers based on large reaction network (C. Travaglio et al., 2004; FR et al., 2006)

Turbulent deflagrations

- radiation transfer:

  preliminary, low resolution

  (Kromer & Sim)

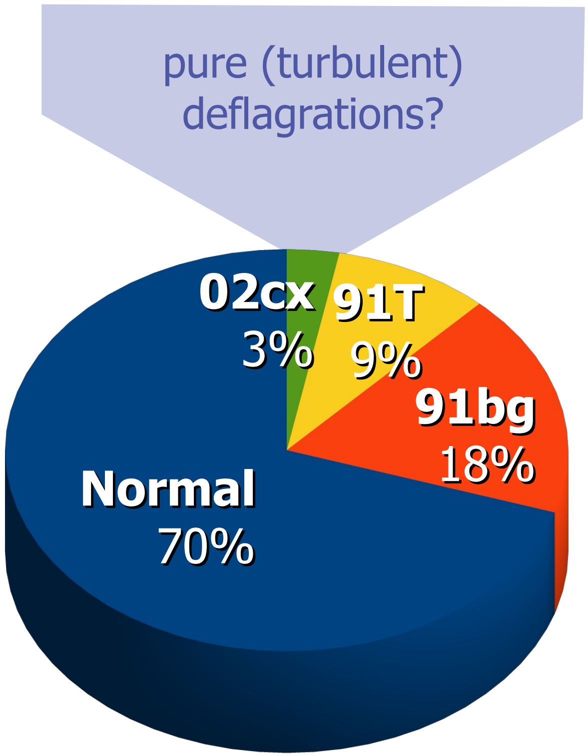


model spectrum (deflagration simulation)

SN 2005hk (observation)

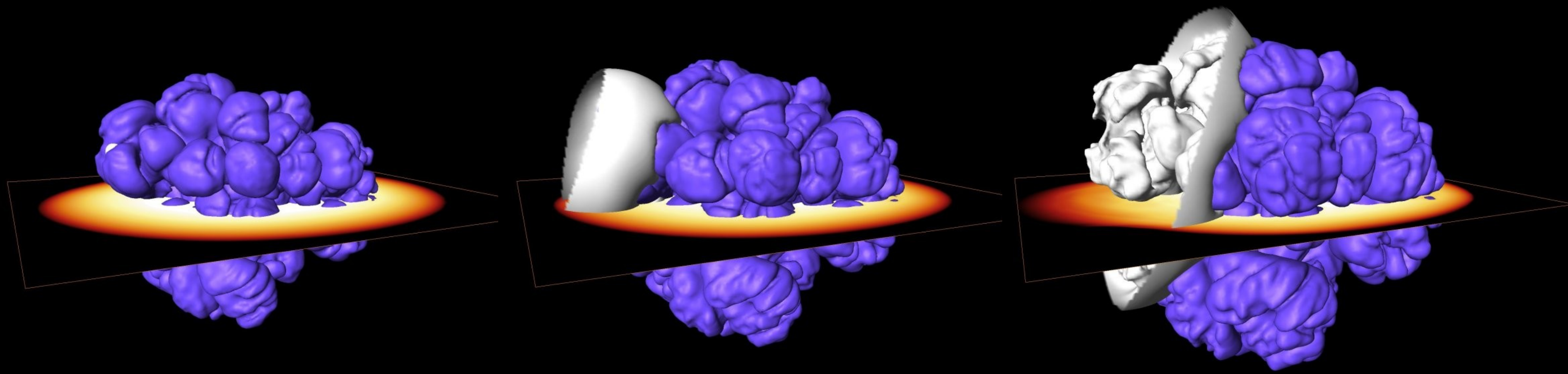
SN Ia sub-classes and fractions

- volume-limited (Li+, 2010)



Delayed detonation model

- detonation of M_{Ch} WD after pre-expansion in initial deflagration phase (Khokhlov 1991)

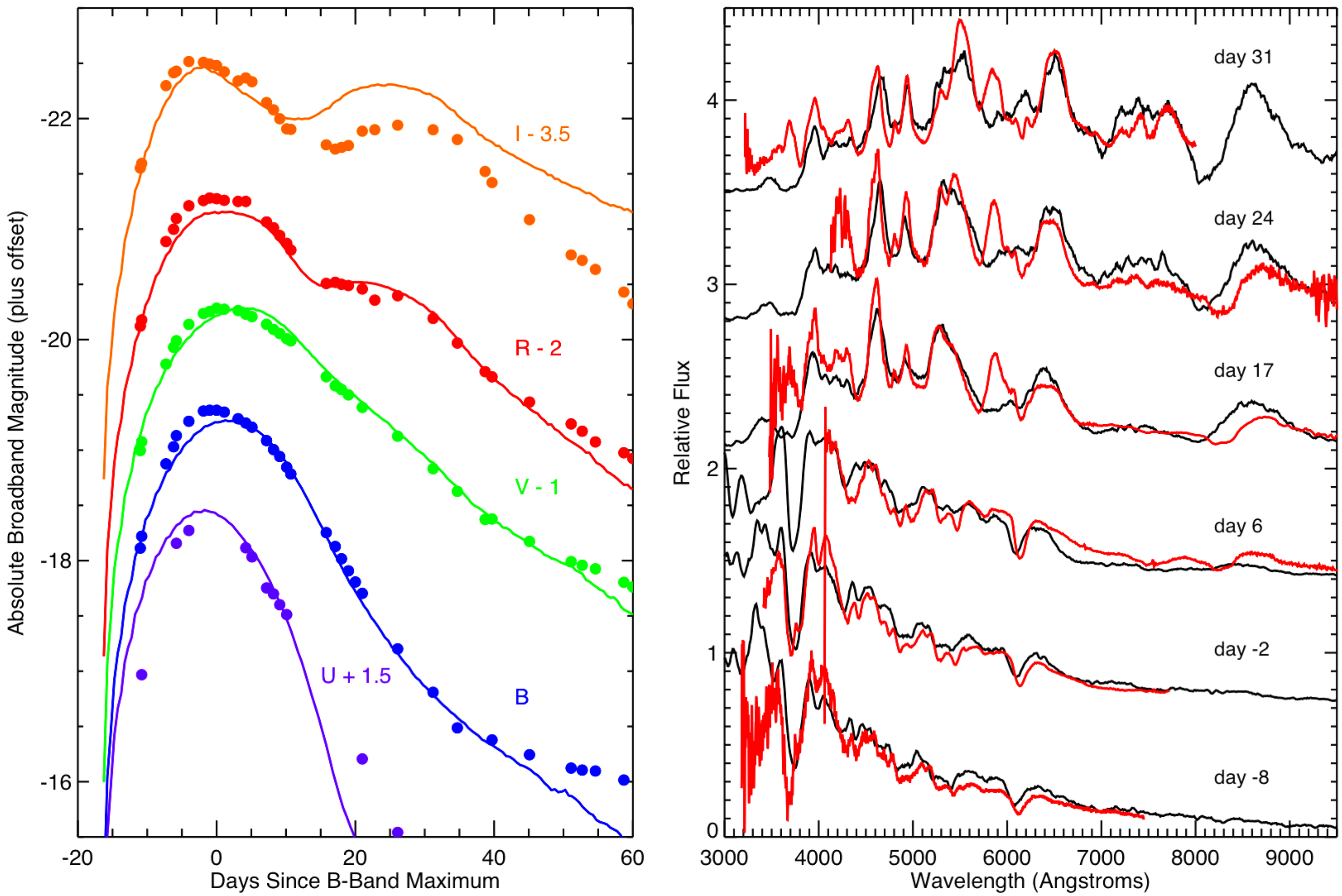


FR & Niemeyer, 2007
Mazzali et al., 2007

- requires deflagration-to-detonation transition (DDT) of flame
- probably possible at low densitites (late phase of explosion) if turbulence still strong enough (FR, 2007; Woosley 2007; Woosley+, 2009)

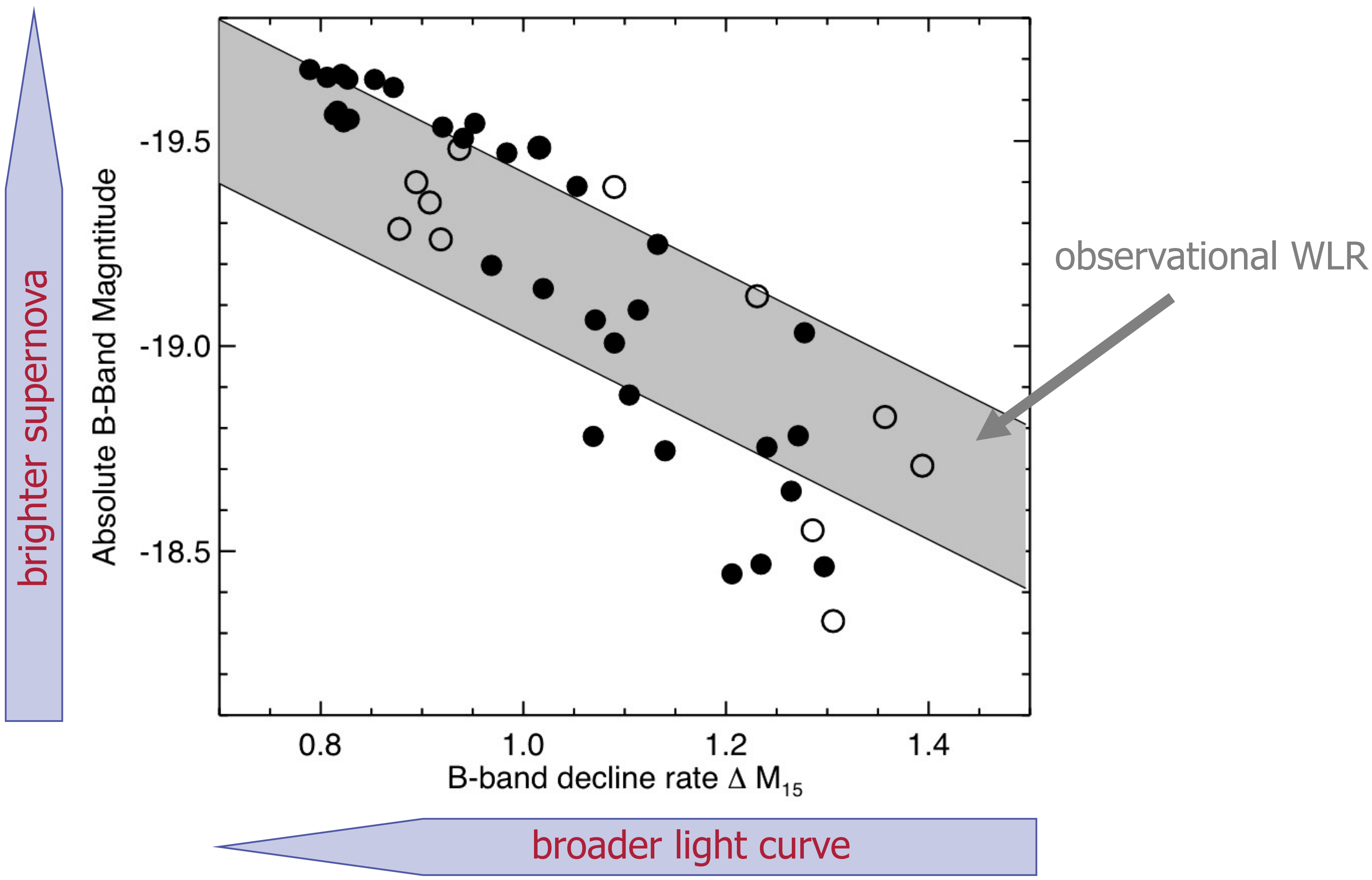
Synthetic observables

- radiation transfer for 44 2D explosion models (Kasen+, 2009) compared with SN 2003du



Width-luminosity relation

- angle averaged light curves (Kasen+, 2009)



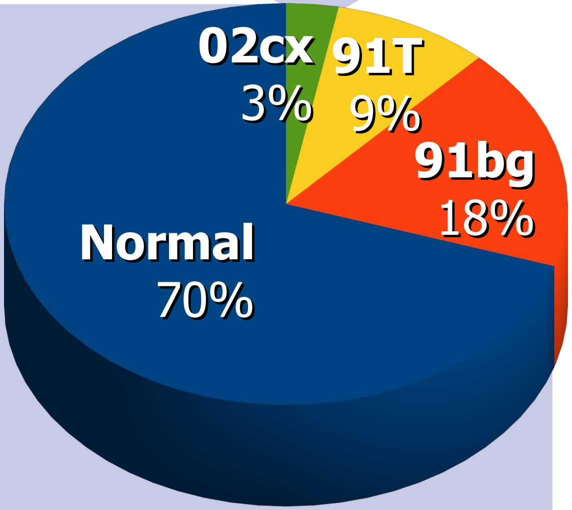
SN Ia sub-classes and fractions

- volume-limited (Li+, 2010)

pure (turbulent) deflagrations?

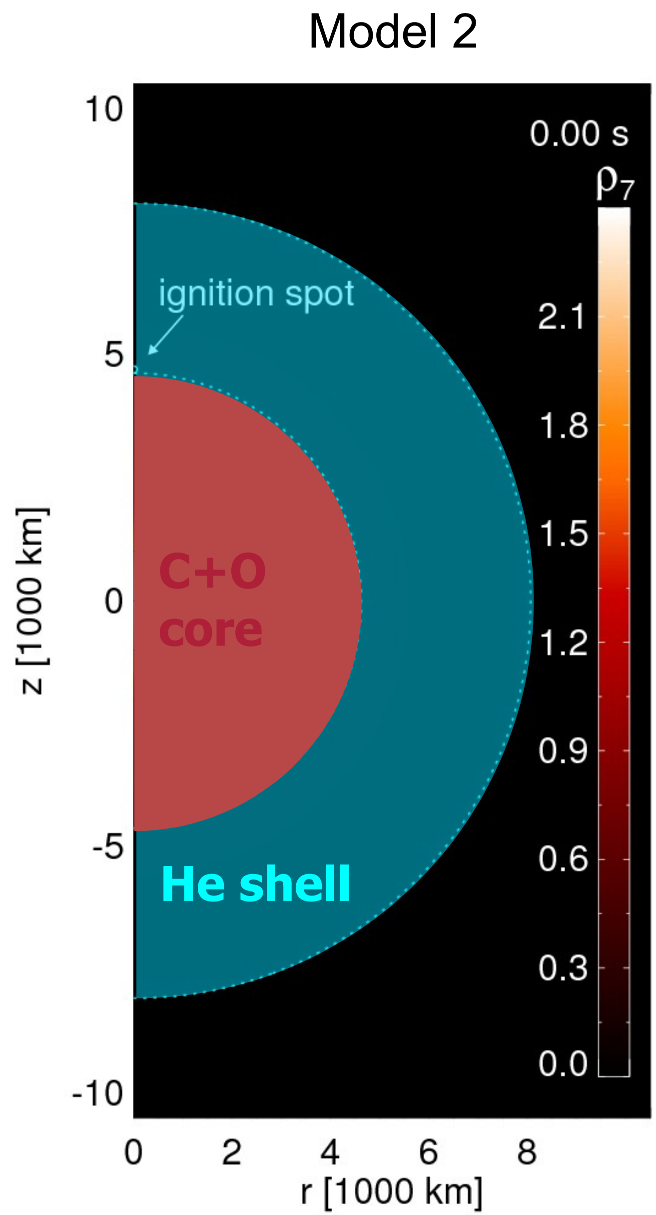
delayed detonations?

not supported by population synthesis



Sub-M_{Ch} explosions

- explosion simulation (Fink+, 2007, 2010)
- minimum He-shell masses (Bildsten+, 2007)

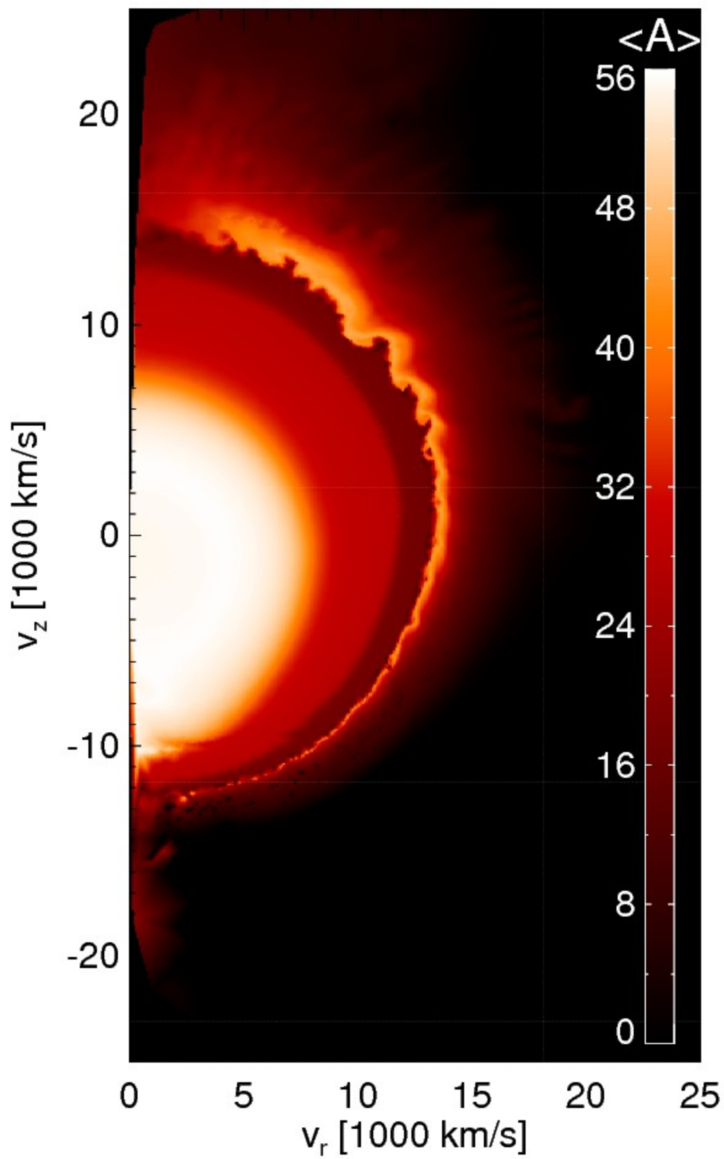


Sub-M_{Ch} explosions

- explosion simulation: (Fink+, 2007, 2010)
- minimum He-shell masses (Bildsten+, 2007)

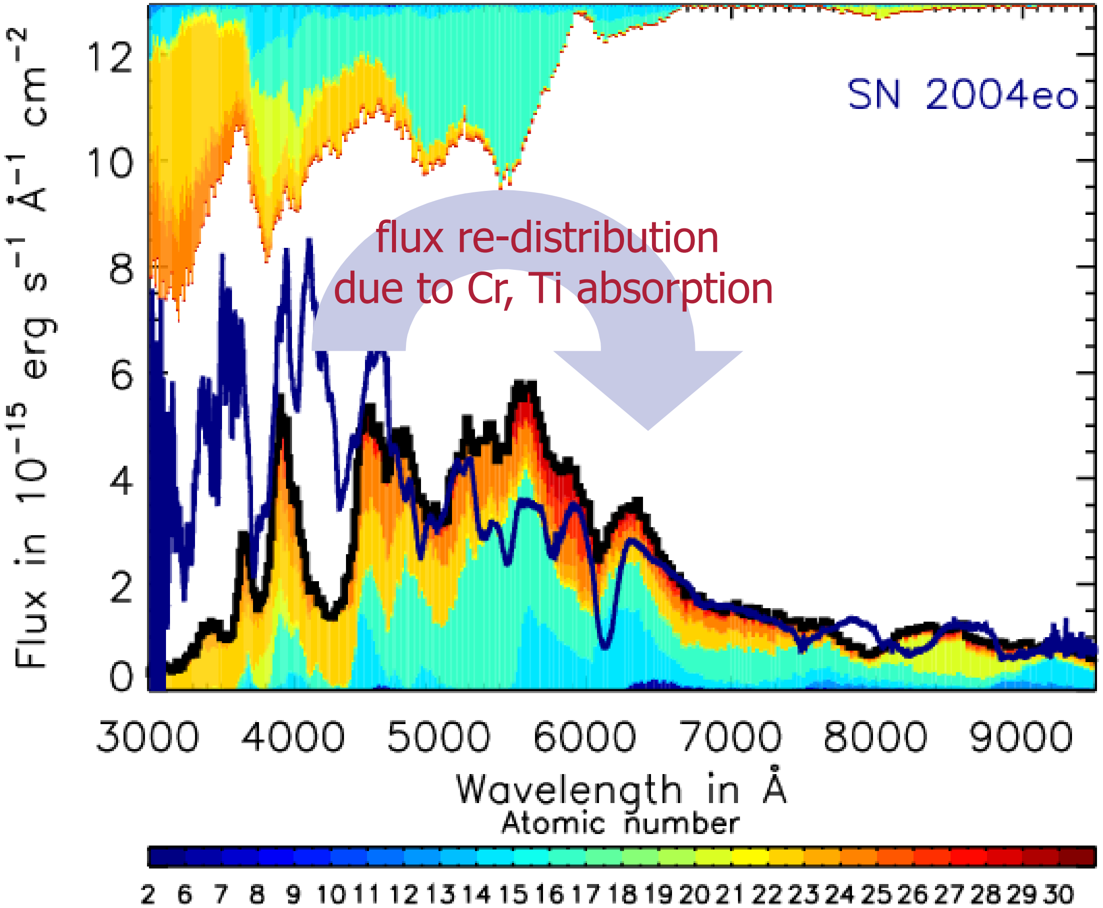
- C+O core detonation triggers robustly

Model 2



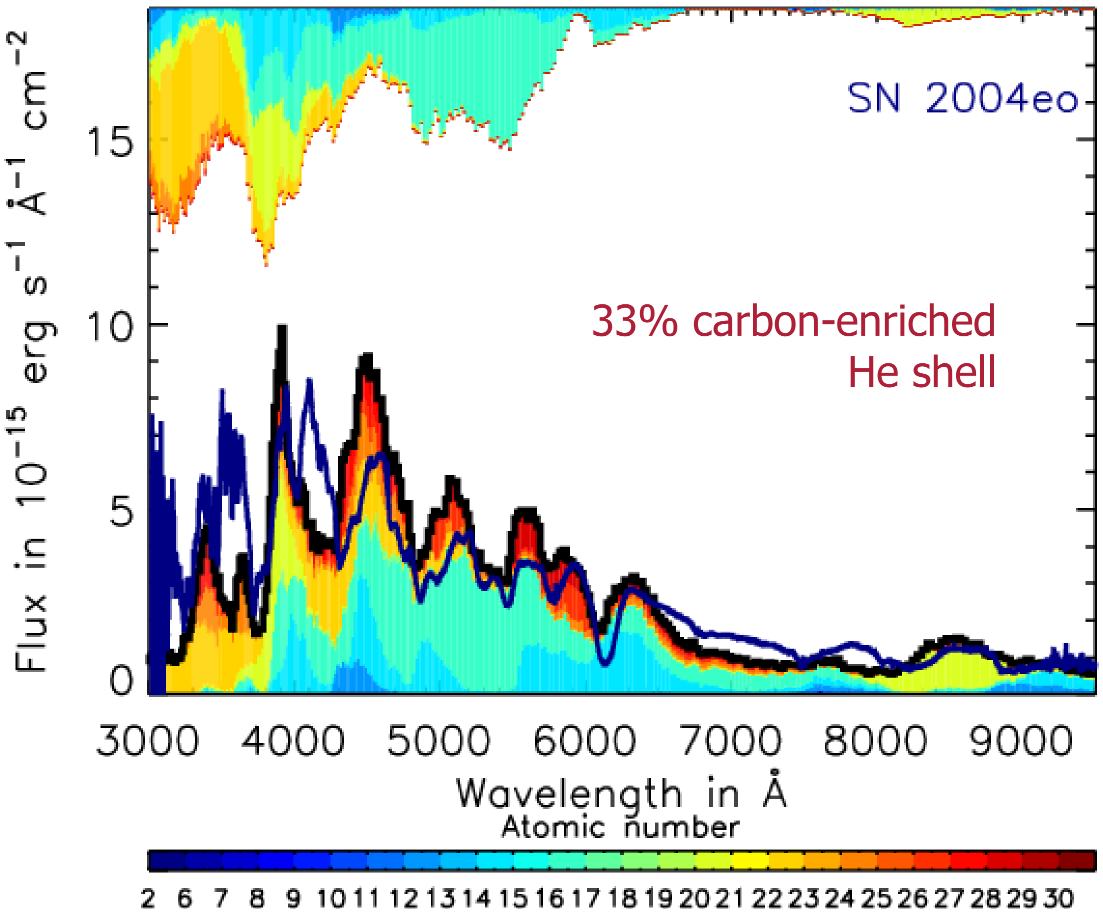
Sub-M_{Ch} explosions

- radiation transfer (Kromer+, 2010)
- iron group elements produced in He shell detonation (Ti, Cr, etc) may be problematic



Sub-M_{Ch} explosions

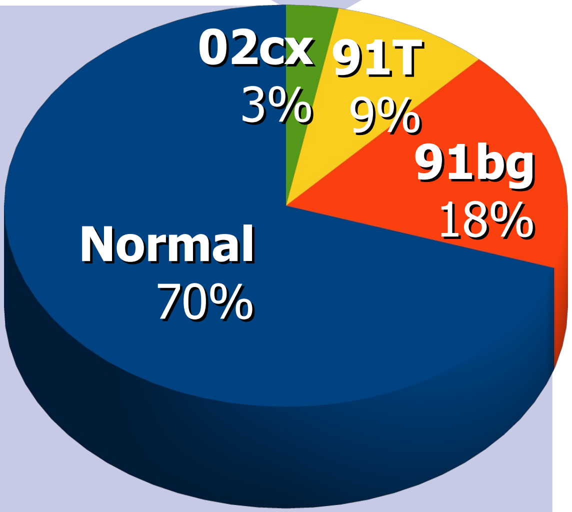
- changing C abundance in He shell may help (Kromer+, 2010)
- bare sub-M_{ch} detonations produce promising results (Sim+, 2010)



SN Ia sub-classes and fractions

- volume-limited (Li+, 2010)

pure (turbulent) deflagrations?



delayed detonations?

or

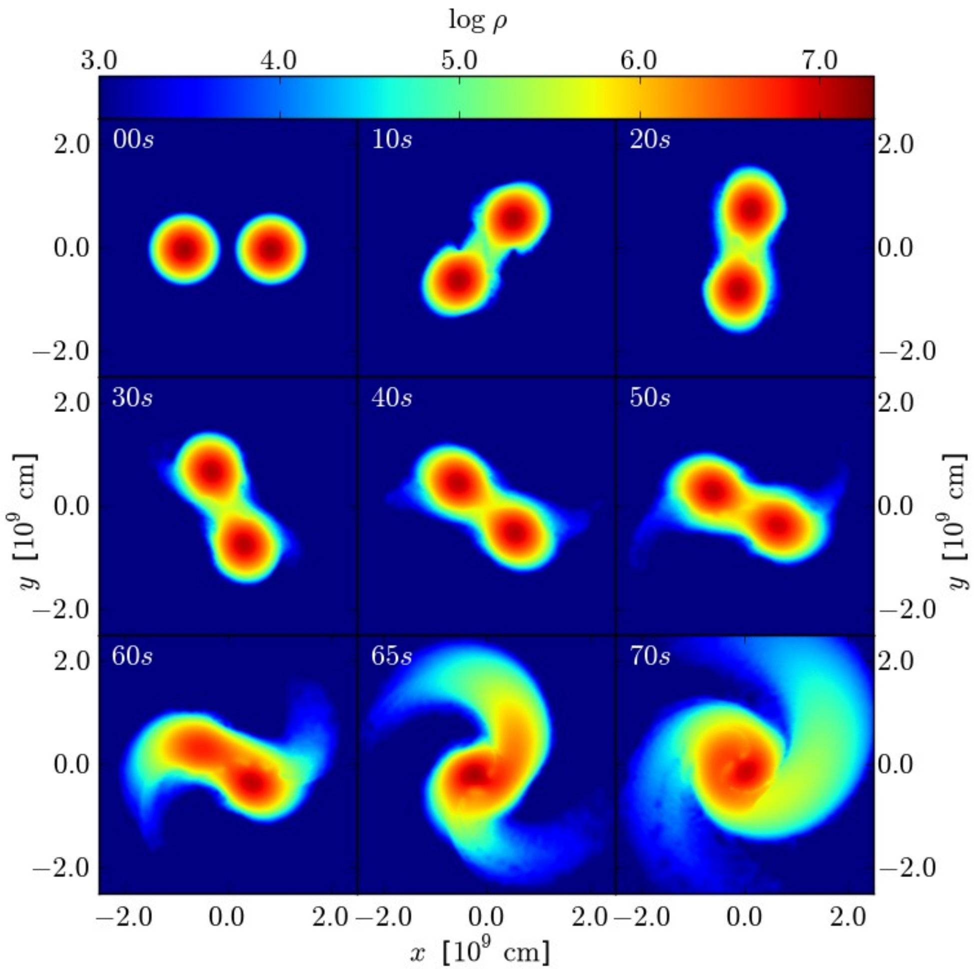
sub-M_{Ch} detonations?

(consistent with population synthesis)

Violent WD-WD mergers

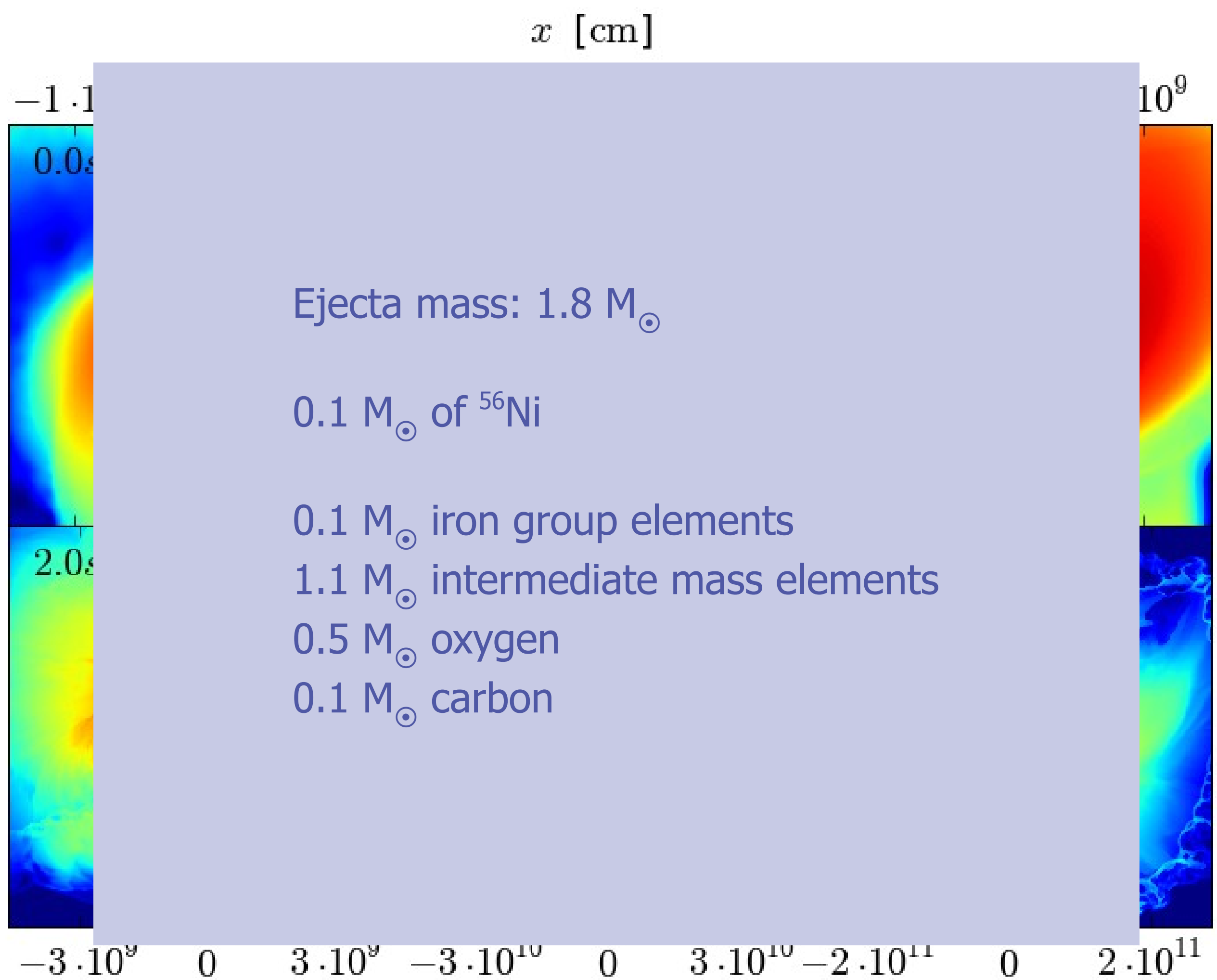
(Pakmor+, 2010)

- inspiral and merger: 3D SPH code (GADGET3)
- 2 WDs: $M_1 = M_2 = 0.9M_\odot$



Violent WD-WD mergers

- explosion: 3D MPA SN Ia code (LEAFS)
- detonation after T>2.8 GK reached @ $\rho = 3.8\ 10^6\ \mathrm{g/cm^3}$



Ejecta mass: 1.8 $M_\odot$

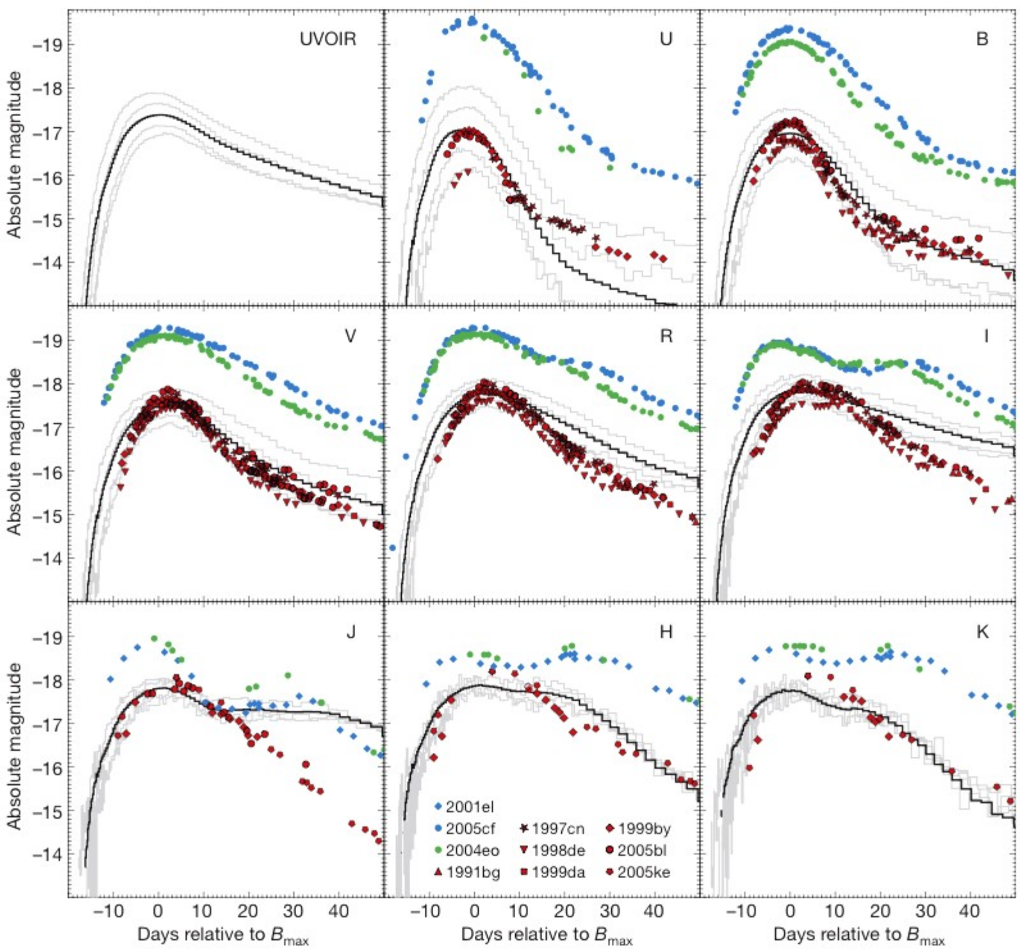
0.1 $M_\odot$ of ^{56}Ni

0.1 $M_\odot$ iron group elements
1.1 $M_\odot$ intermediate mass elements
0.5 $M_\odot$ oxygen
0.1 $M_\odot$ carbon

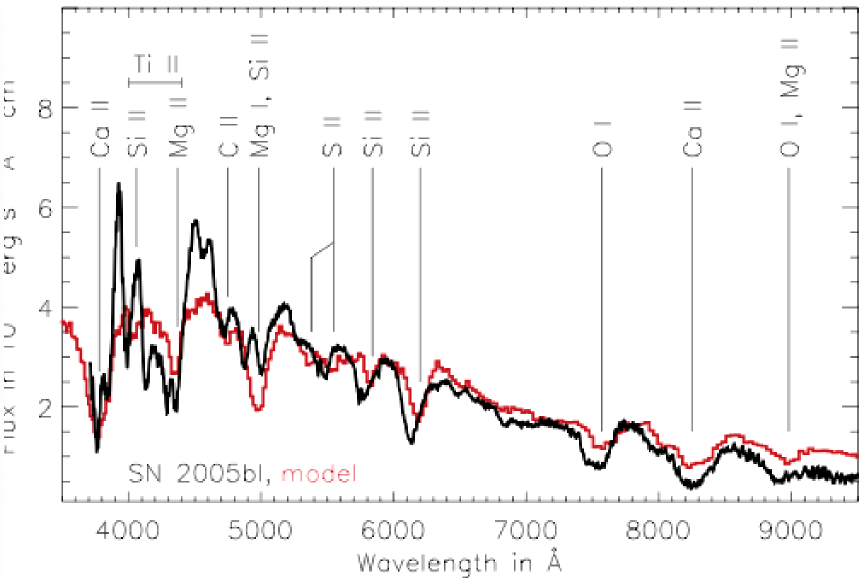
Violent WD-WD mergers

- radiation transfer: 3D monte carlo (ARTIS)

light curves



spectrum



good agreement with observed sub-luminous SNe Ia ("1991bg-like" objects)
also supported by population synthesis

SN Ia sub-classes and fractions

- volume-limited (Li+, 2010)

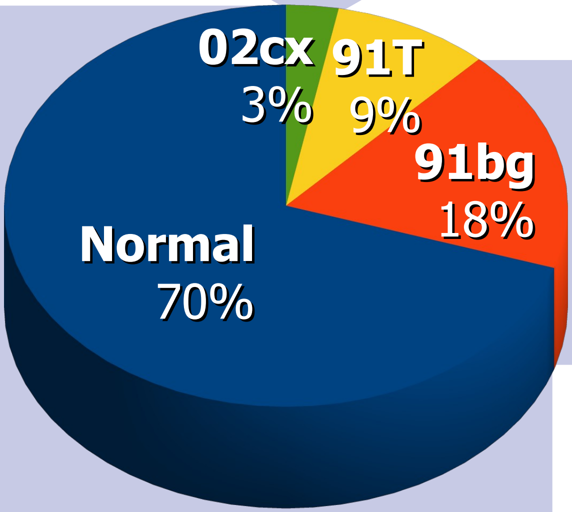
pure (turbulent)
deflagrations?

delayed
detonations?

or

sub-M_{Ch}
detonations?

(consistent with
population synthesis)



violent (q~1)
WD-WD mergers?

Conclusion

Open questions

- Which models do contribute?
- Which explains bulk of SNe Ia?

tools to answer questions have been developed:

population synthesis → 2D/3D hydrodynamic explosion models → nucleosynthesis postprocessing → radiative transfer → SN Ia observations

- perhaps comparison with observations will tell
- uncertainty in nucleosynthesis, radiation transfer
- ...or all goes back to rates/population synthesis for progenitor systems?

- degeneracy in observables?

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