Astrophysics and Nuclear Structure

Hirschegg, January 27, 2013

Type Ia supernovae – observable nuclear astrophysics

Friedrich Röpke

Julius-Maximilians-Universität Würzburg, Germany

W. Hillebrandt, S. Woosley, S. Sim, I. Seitenzahl, D. Kasen, A. Ruiter, P. Mazzali, M. Kromer, R. Pakmor, M. Fink, S. Blondin, C. Travaglio, F. Ciaraldi-Schoolmann

ASTROPHYSIK

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 enrichment with p-nuclei (e.g. Kusakabe+, 2010) → project with C. Travaglio (Travaglio+,2011): SNe Ia can produce both light and heavy p-isotopes with almost equal production factors; could be responsible for 50% of the solar p-process composition

Astrophysical significance of SNe Ia

- observational cosmology
- cosmic cycle of matter
- triggering star formation
- understanding binary stellar evolution
- main driver of current searches for astrophysical transients

- gravitational wave background?
- source of galactic positrons?

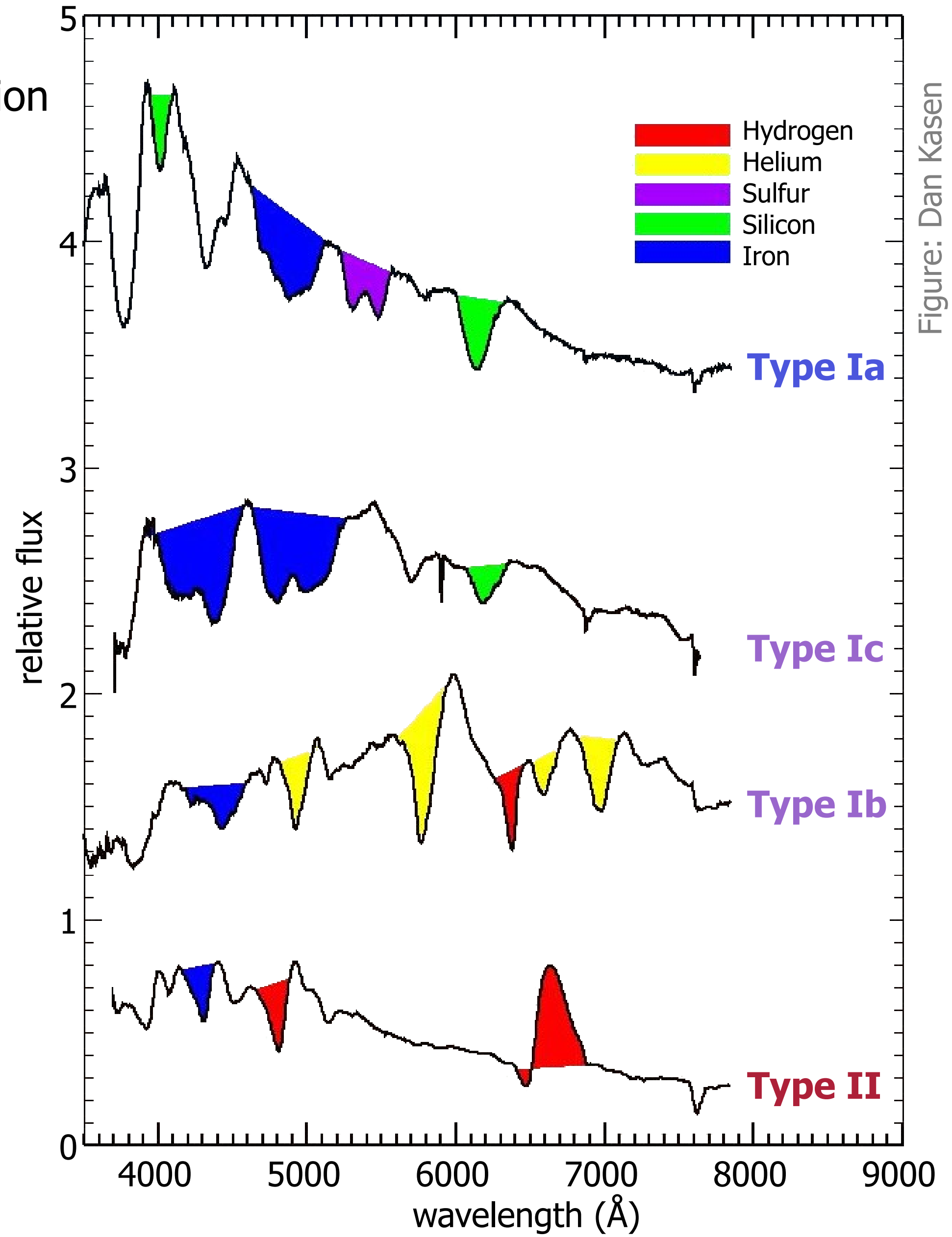
...and they are by themselves fascinating astrophysical objects!

observationally extremely well studied

...only partially understood theoretically

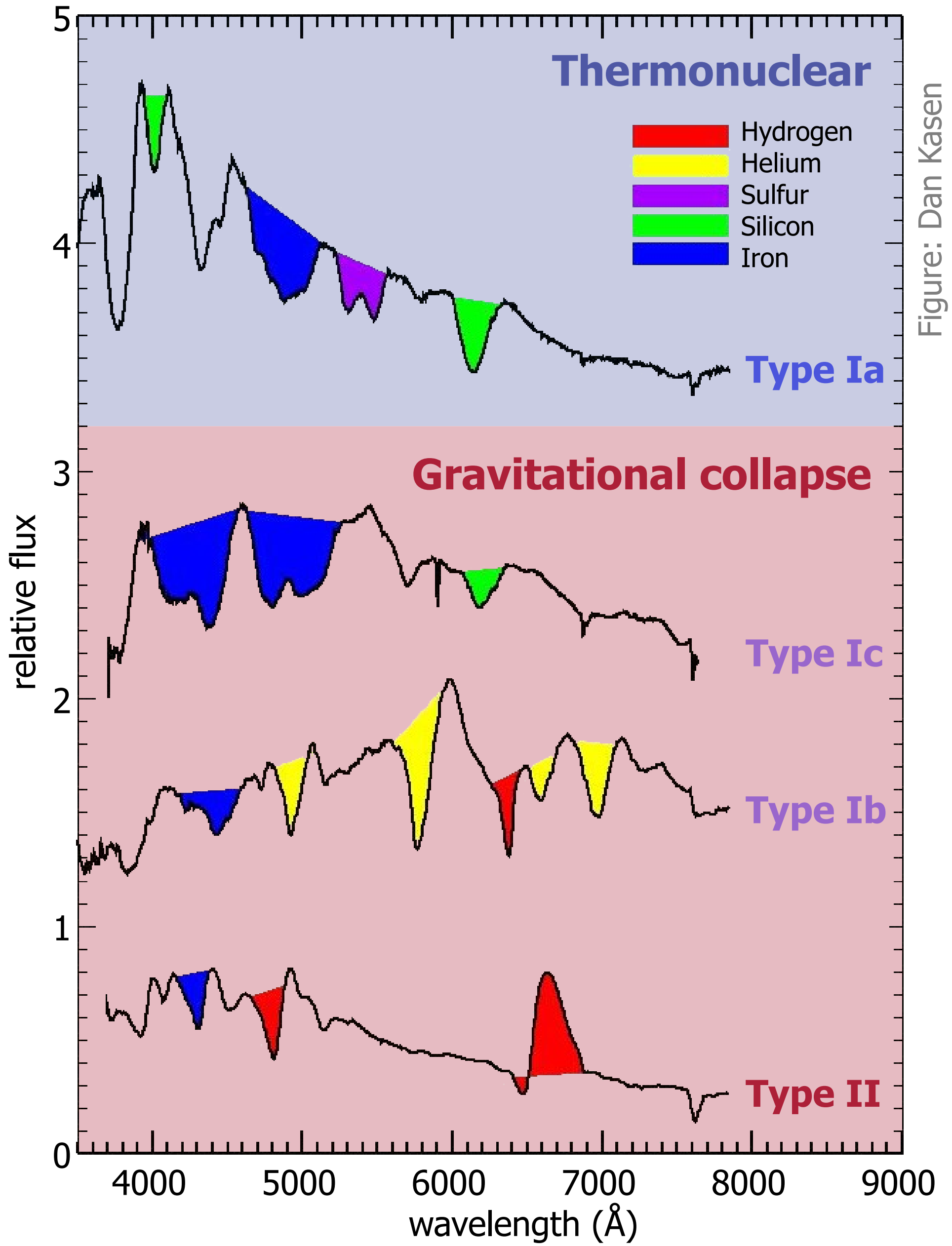
Classification of supernovae

- astronomical classification according to spectral features



Classification of supernovae

- physical classification according to energy source



The progenitor problem

What is it, that explodes?

- no direct observation

- compact star → WD (Nugent+ 2011; Bloom+, 2012)
- no H, He → C+O WD

- Inert object → Why does it explode?

Thermonuclear burning fronts

- $^{12}C + ^{12}C$ reaction rate $\propto T^{20}$

→ burning proceeds in thin fronts (flames, combustion waves)

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

→ described by discontinuity approximation

Flame propagation and burning

hydrodynamics of flame propagation

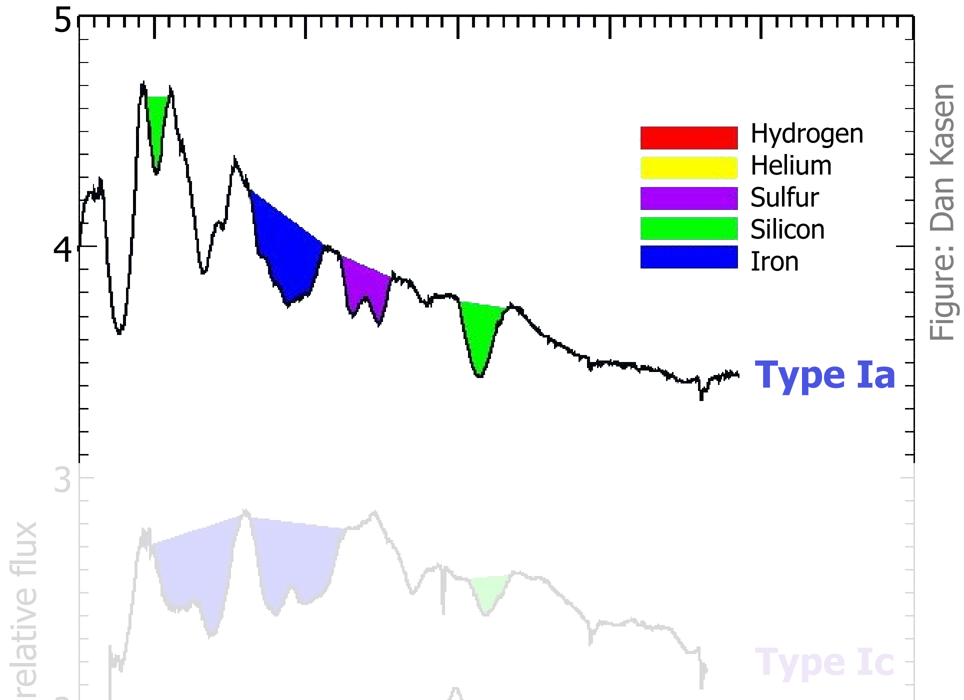
deflagration
subsonic

flame mediated by thermal conduction of degenerate e^-

detonation
supersonic

flame driven by shock waves

Nuclear burning in SNe Ia

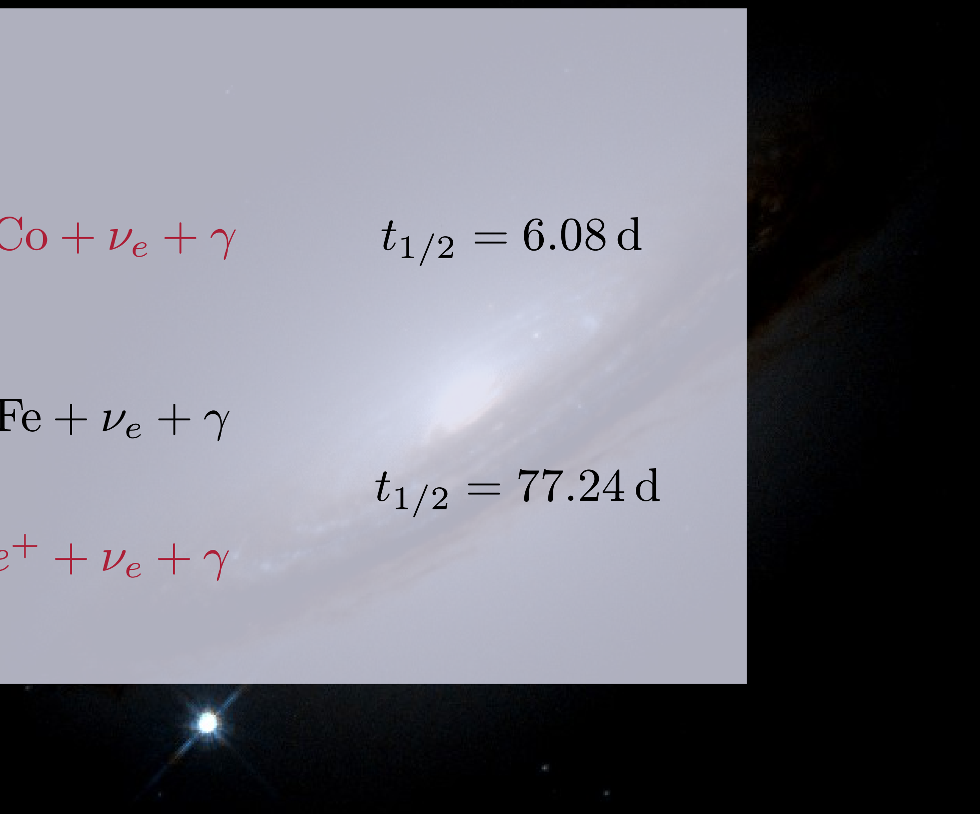


- fuel density ahead of combustion front determines nucleosynthesis:

decreasing fuel density

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

Why are SNe Ia bright?



^{56}Ni decay chain

100%	$^{56}\mathrm{Ni} + e^- \rightarrow {}^{56}\mathrm{Co} + \nu_e + \gamma$	$t_{1/2} = 6.08\,\mathrm{d}$
80%	$^{56}\mathrm{Co} + e^- \rightarrow {}^{56}\mathrm{Fe} + \nu_e + \gamma$	$t_{1/2} = 77.24\,\mathrm{d}$
20%	$^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe} + e^+ + \nu_e + \gamma$	

- γ and e^+ from ^{56}Ni decay chain heat ejecta (Truran 1967, Colgate & McKee, 1969)
  → optical emission (e.g. Kuchner+ 1994)

The progenitor problem

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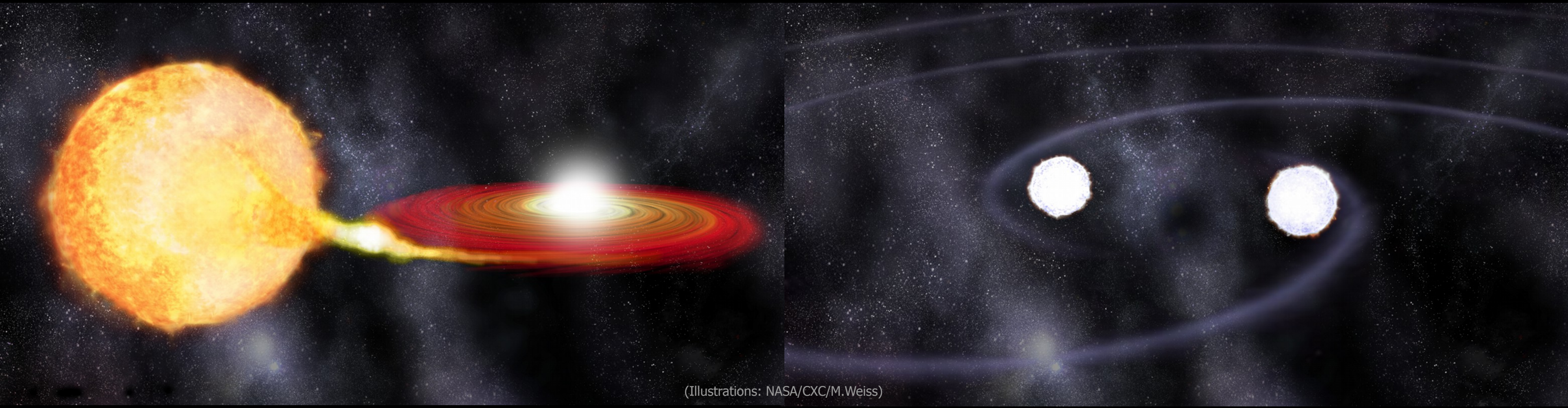
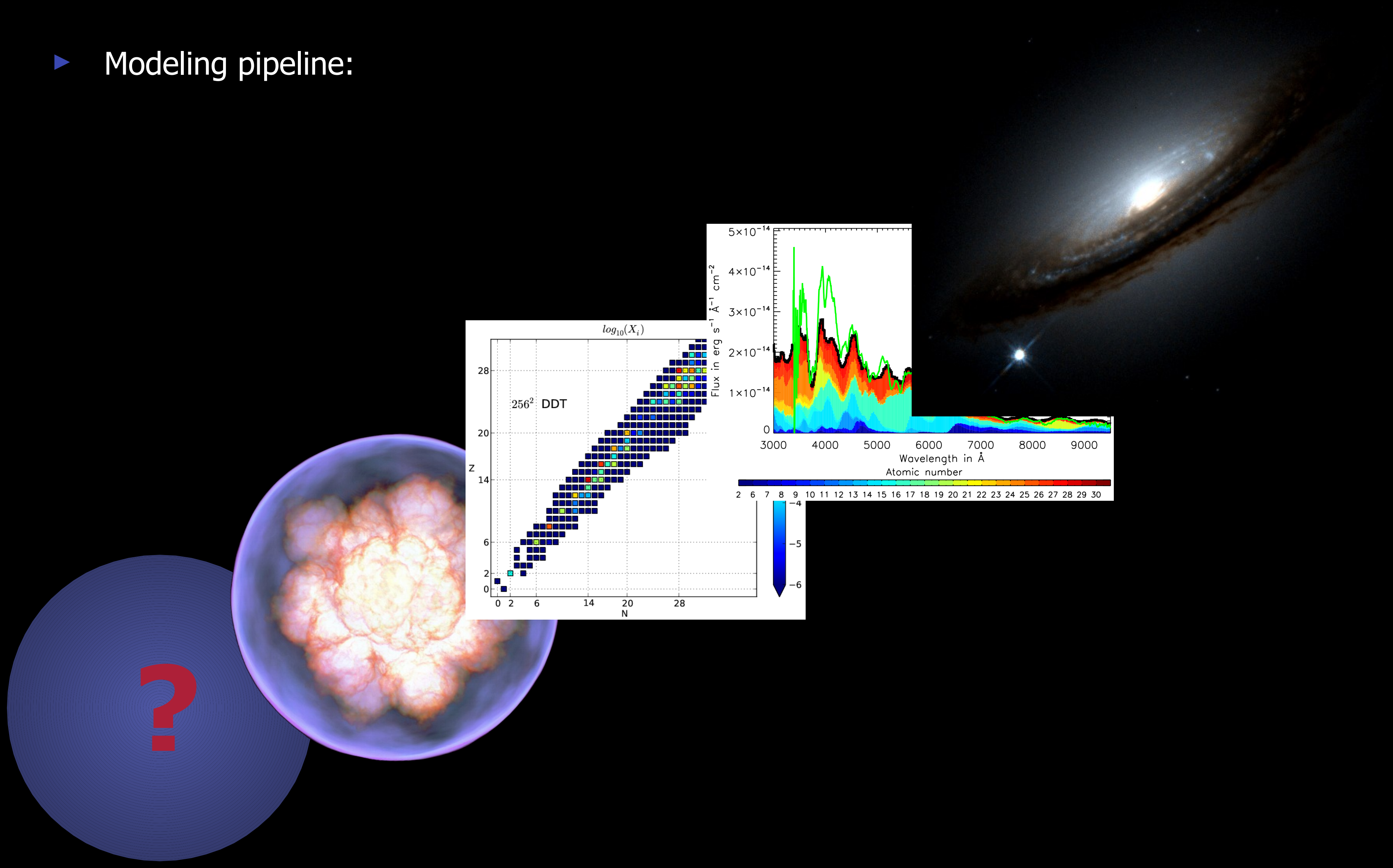


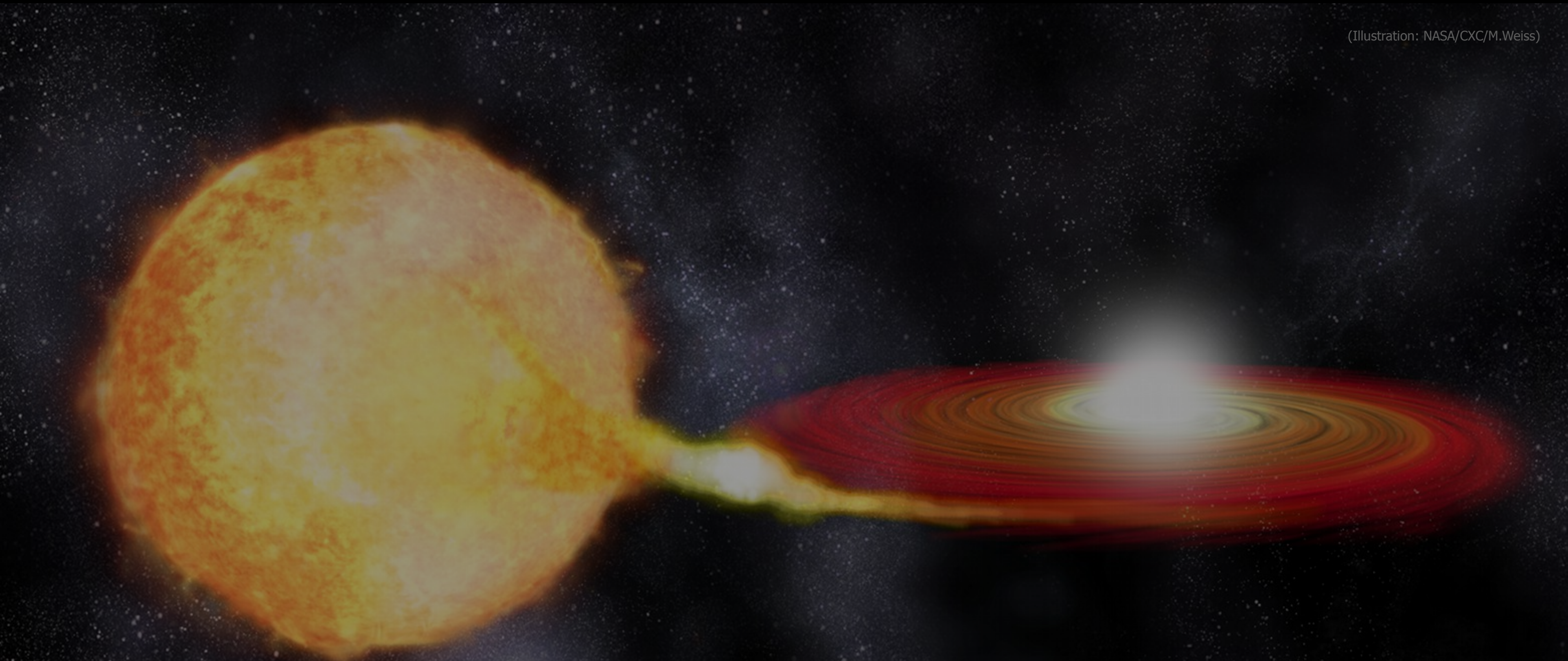
(Illustrations: NASA/CXC/M.Weiss)

Connecting explosion models to observations

- Modeling pipeline:



The Chandrasekhar-mass story



(Illustration: NASA/CXC/M.Weiss)

→ textbook wisdom on SNe Ia

...why?

- provides good reason why thermonuclear burning commences
- seems to explain homogeneity
- 1D parameterized models fit observations well (e.g. W7 model of Nomoto+, 1984)
- potential progenitor systems do exist (U Sco, RS Oph...)

Flame propagation and burning

hydrodynamics of flame propagation

deflagration
subsonic

flame mediated by thermal conduction of degenerate e^-

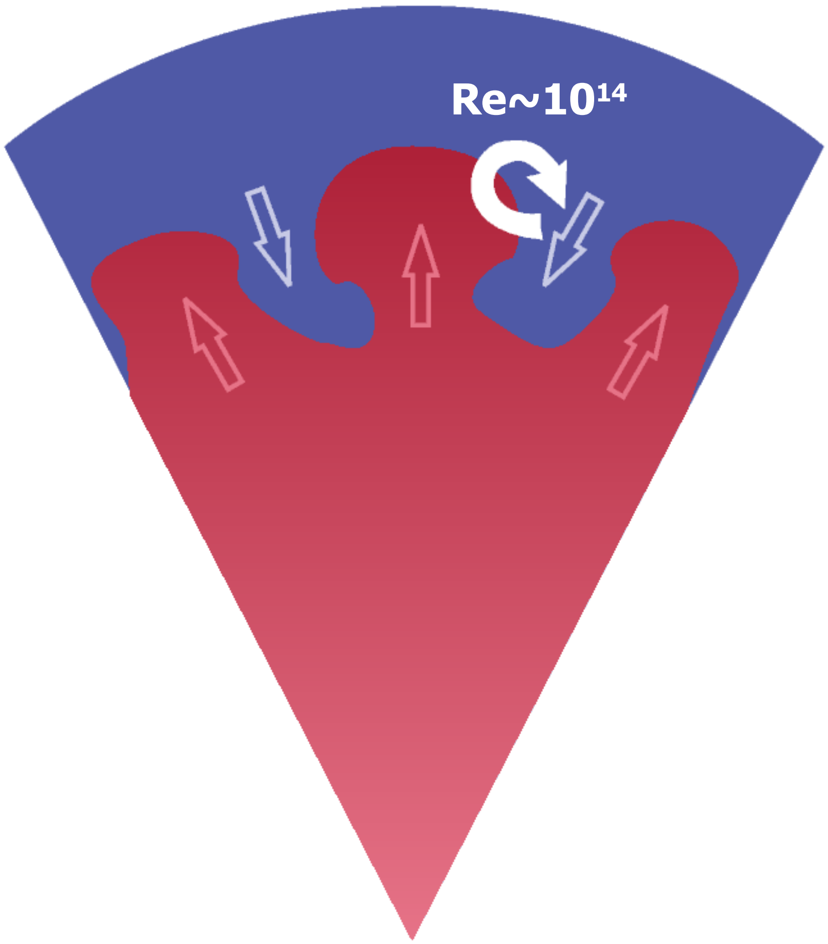
detonation
supersonic

flame driven by shock waves

M_{Ch} model: turbulent combustion

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

- buoyancy instabilities lead to
  turbulent combustion



M_{Ch} model: turbulent deflagrations

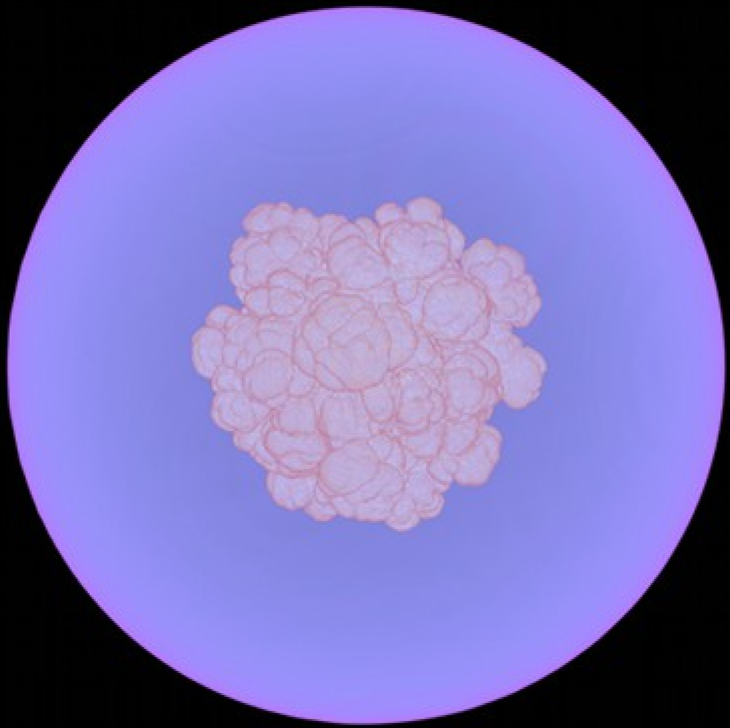
t = 0.025 sec

M_{Ch} model: turbulent deflagrations

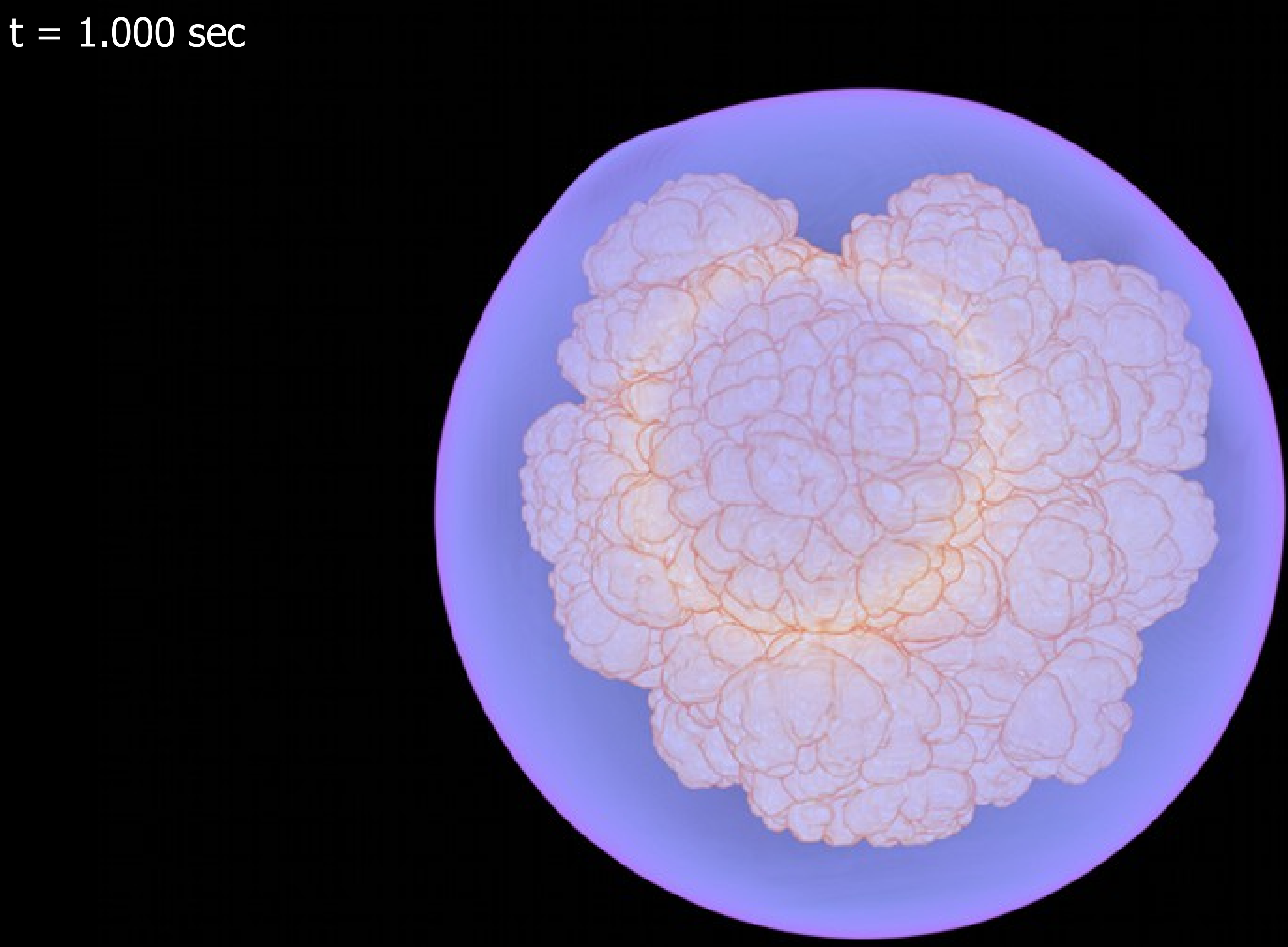
t = 0.200 sec

M_{Ch} model: turbulent deflagrations

t = 0.600 sec

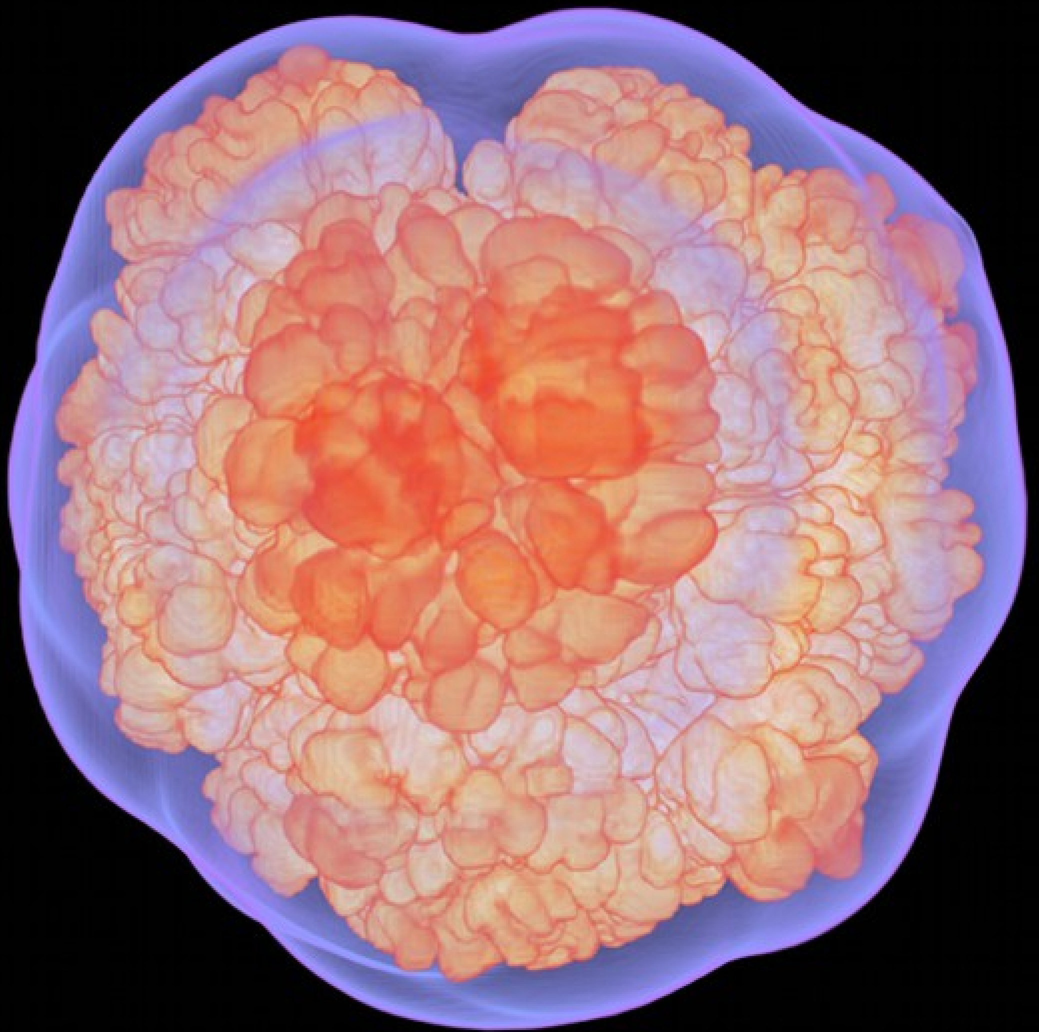


M_{Ch} model: turbulent deflagrations



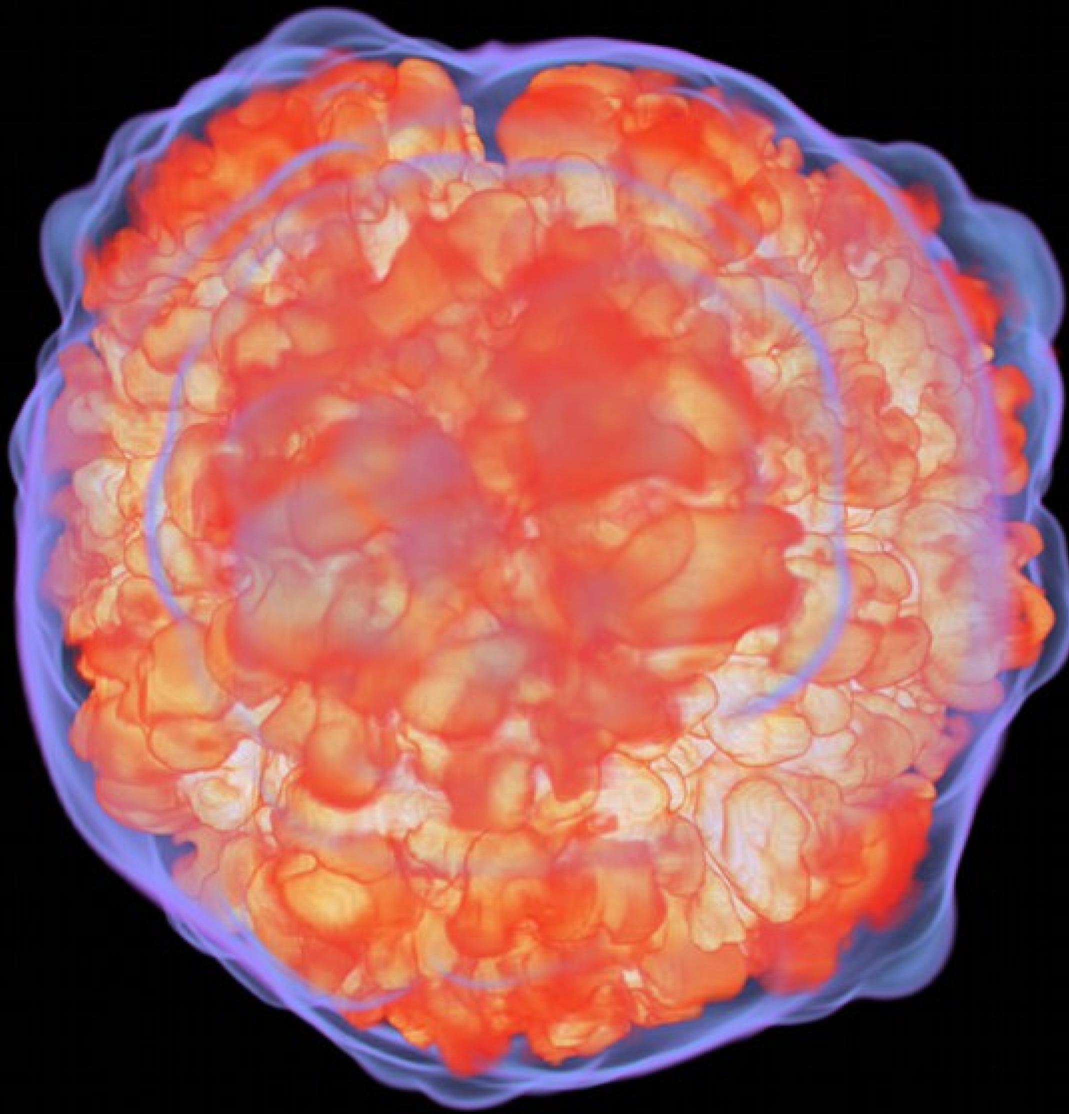
M_{Ch} model: turbulent deflagrations

t = 1.600 sec



M_{Ch} model: turbulent deflagrations

t = 3.000 sec



Treatment of nuclear reactions

- flame modeled as discontinuity → internal structure unresolved → nuclear reactions inside flame not captured directly

simplified burning model:

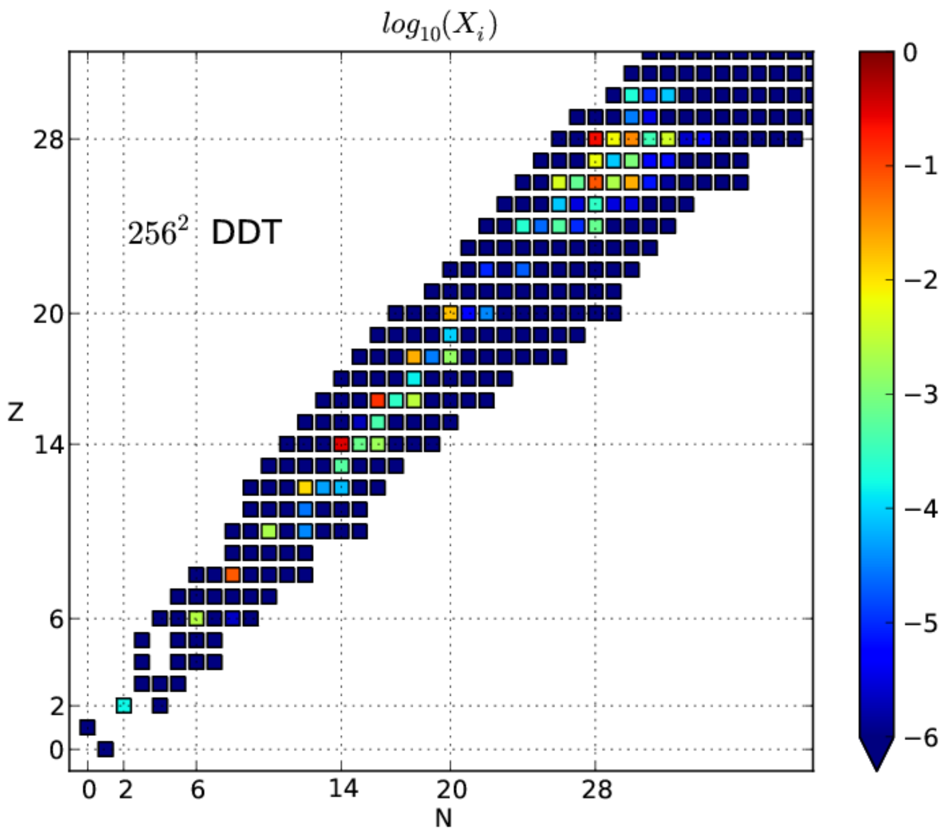
- only five species taken into account (C, O, "representative IME nucleus", α, ^{56}Ni)
- NSE represented by T and ρ-dependend mixture of α and ^{56}Ni

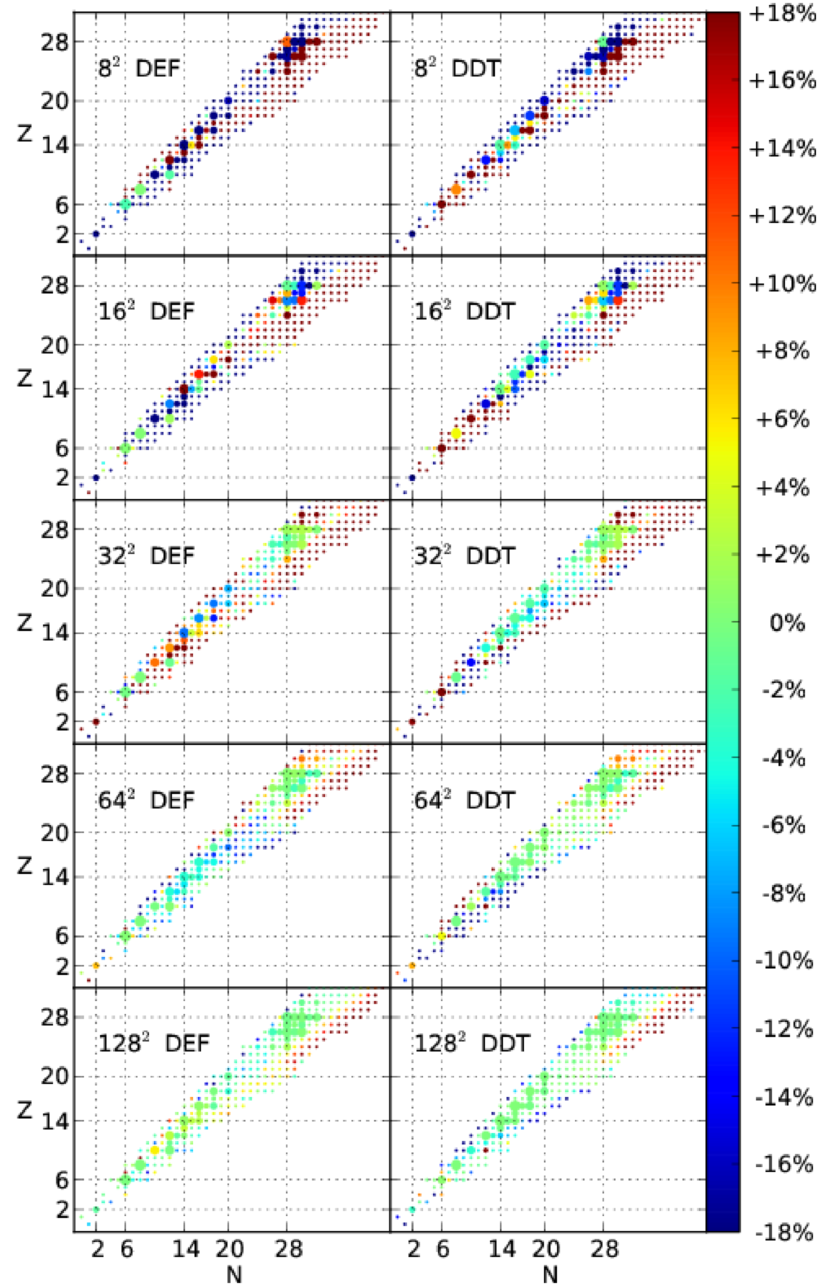
sufficient to model energy release and dynamics, insufficient for deriving synthetic observables (chemical structure of ejecta has to be known) and nucleosynthetic yields

→ nucleosynthesis postprocessing from tracers (C. Travaglio et al., 2004; FR et al., 2006)

Tracers/nucleosynthetic postprocessing

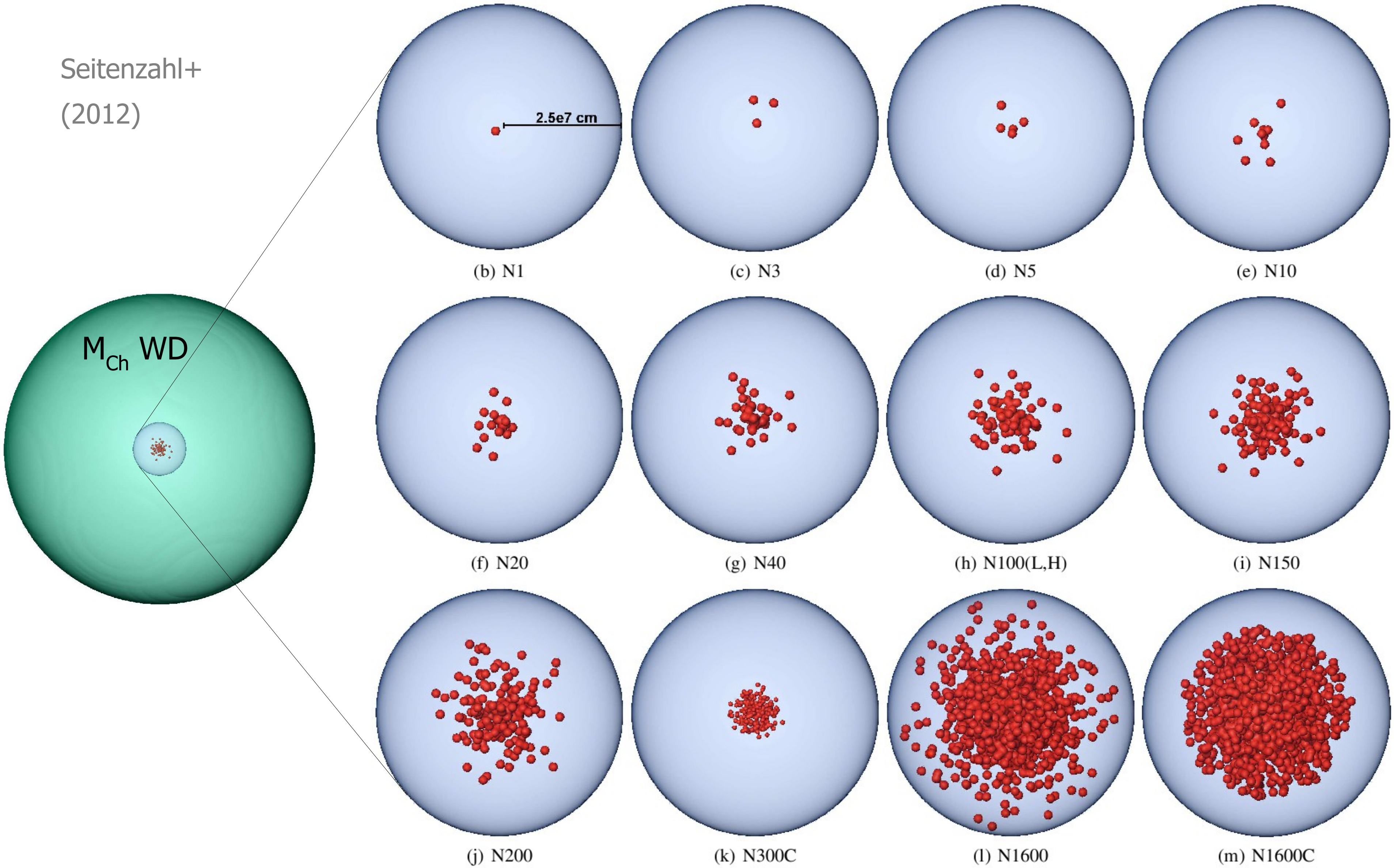
- convergence? (I. Seitenzahl +, 2010)



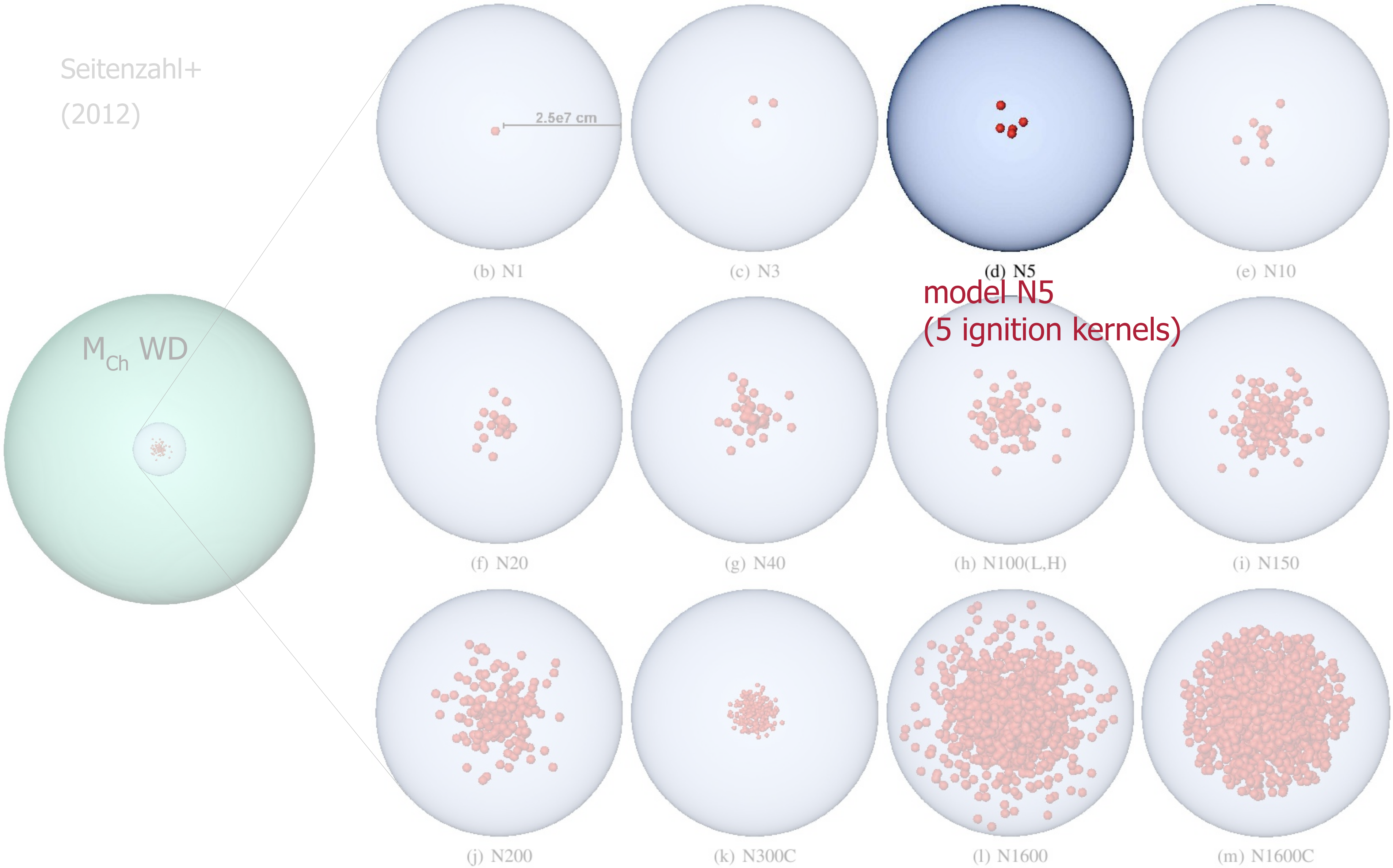


Suite of 3D delayed detonation models

Seitenzahl+ (2012)

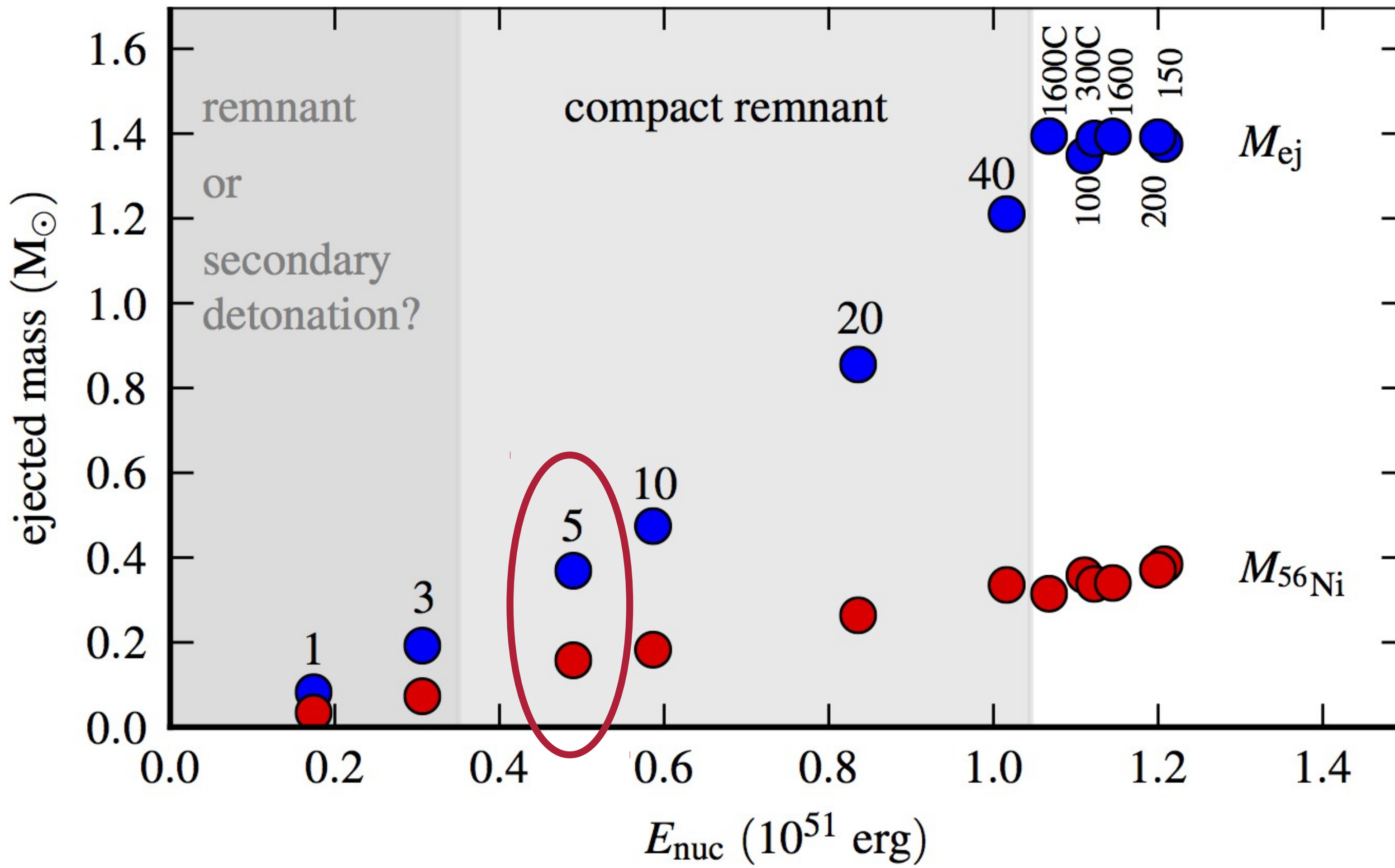


Suite of 3D delayed detonation models



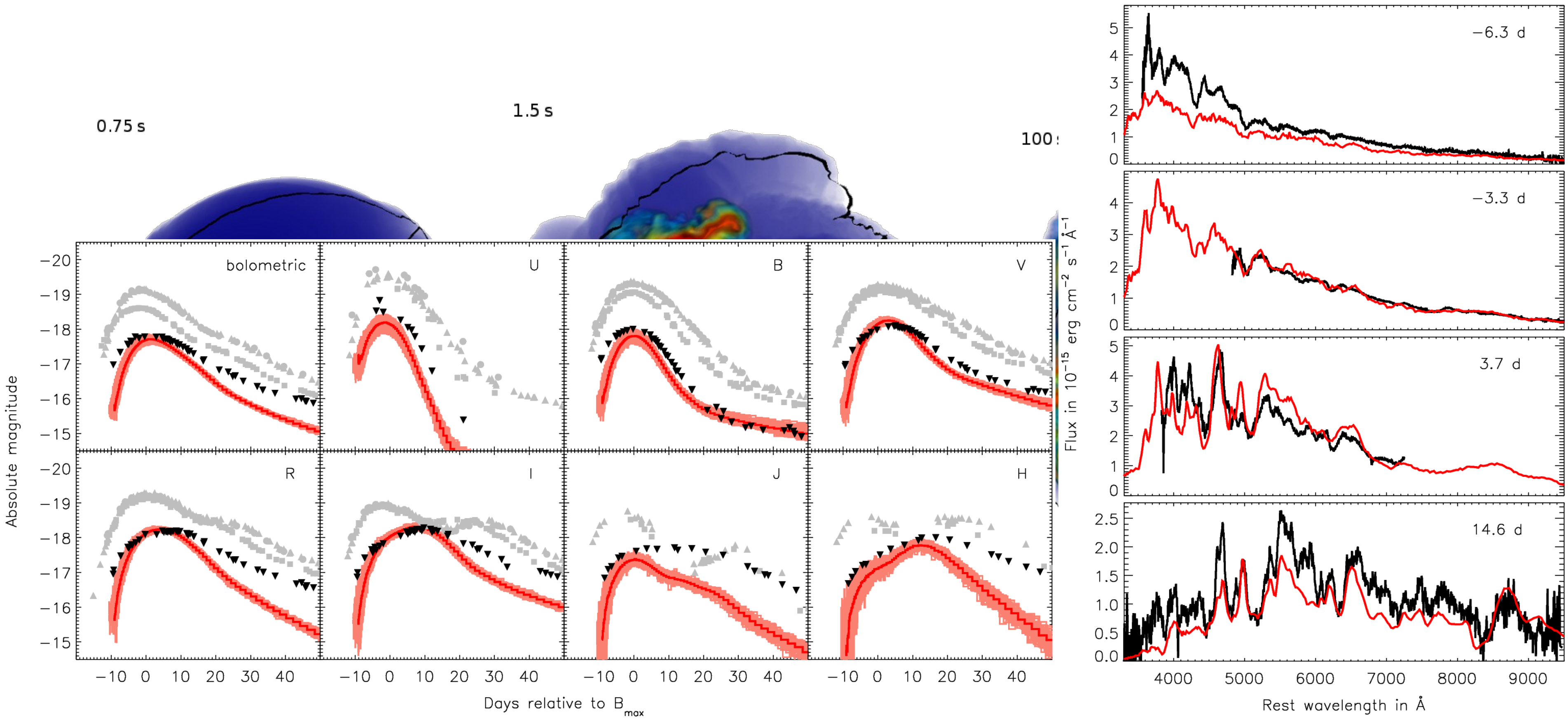
“Failed deflagrations”

- Fink et al. in prep

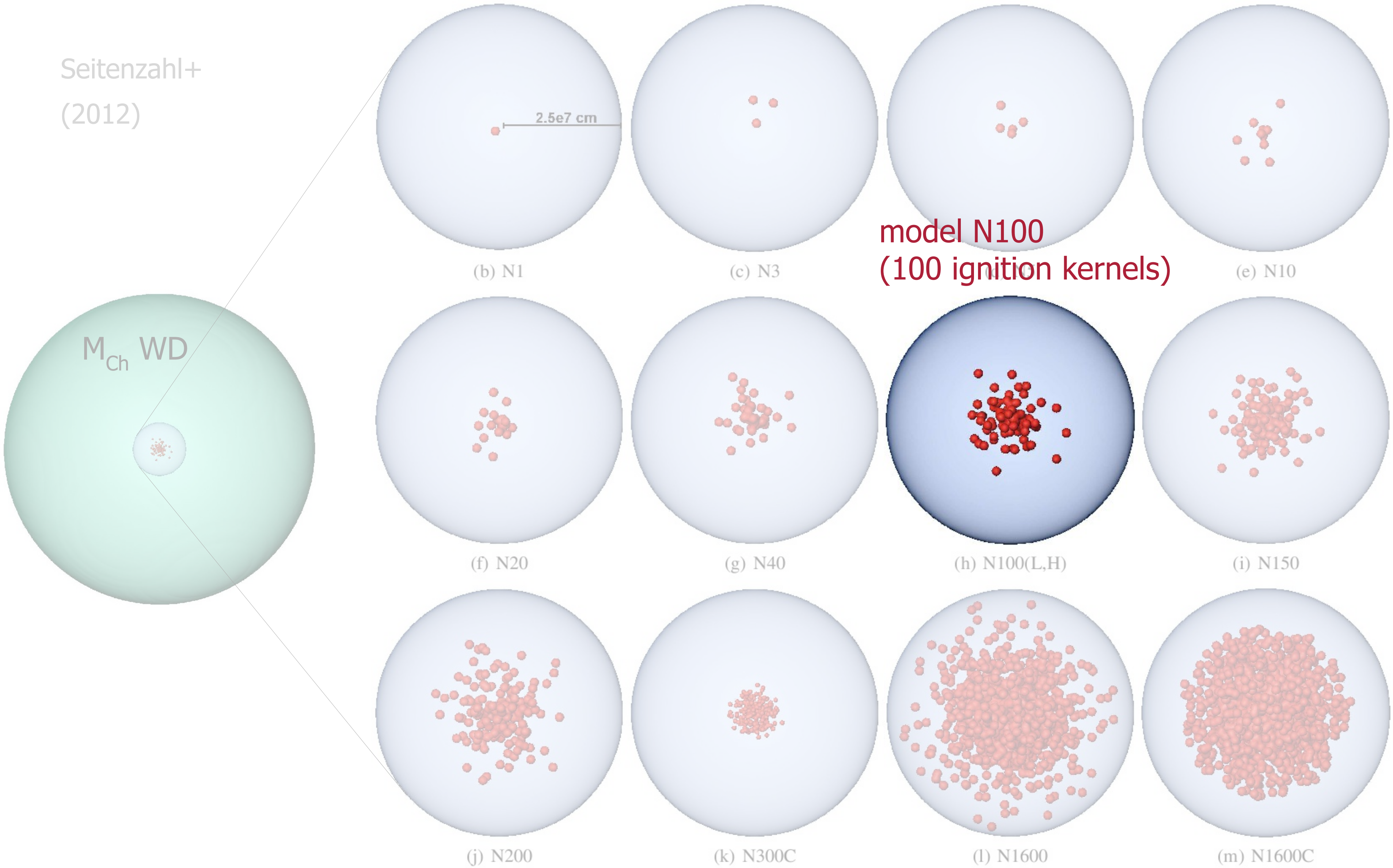


"Failed deflagration"

- good match to SN2002cx-like supernovae (Kromer+, 2012)

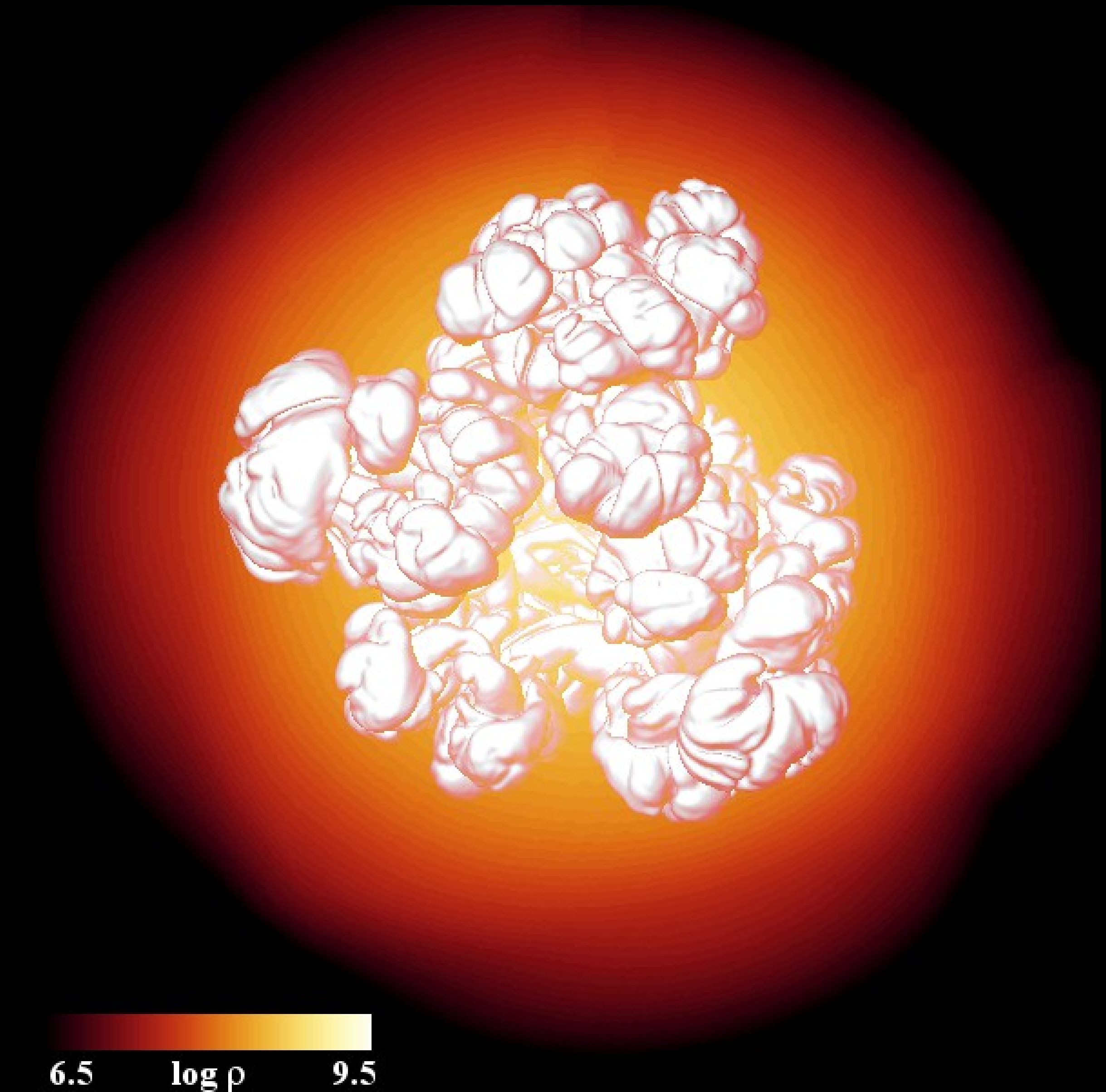


Suite of 3D delayed detonation models



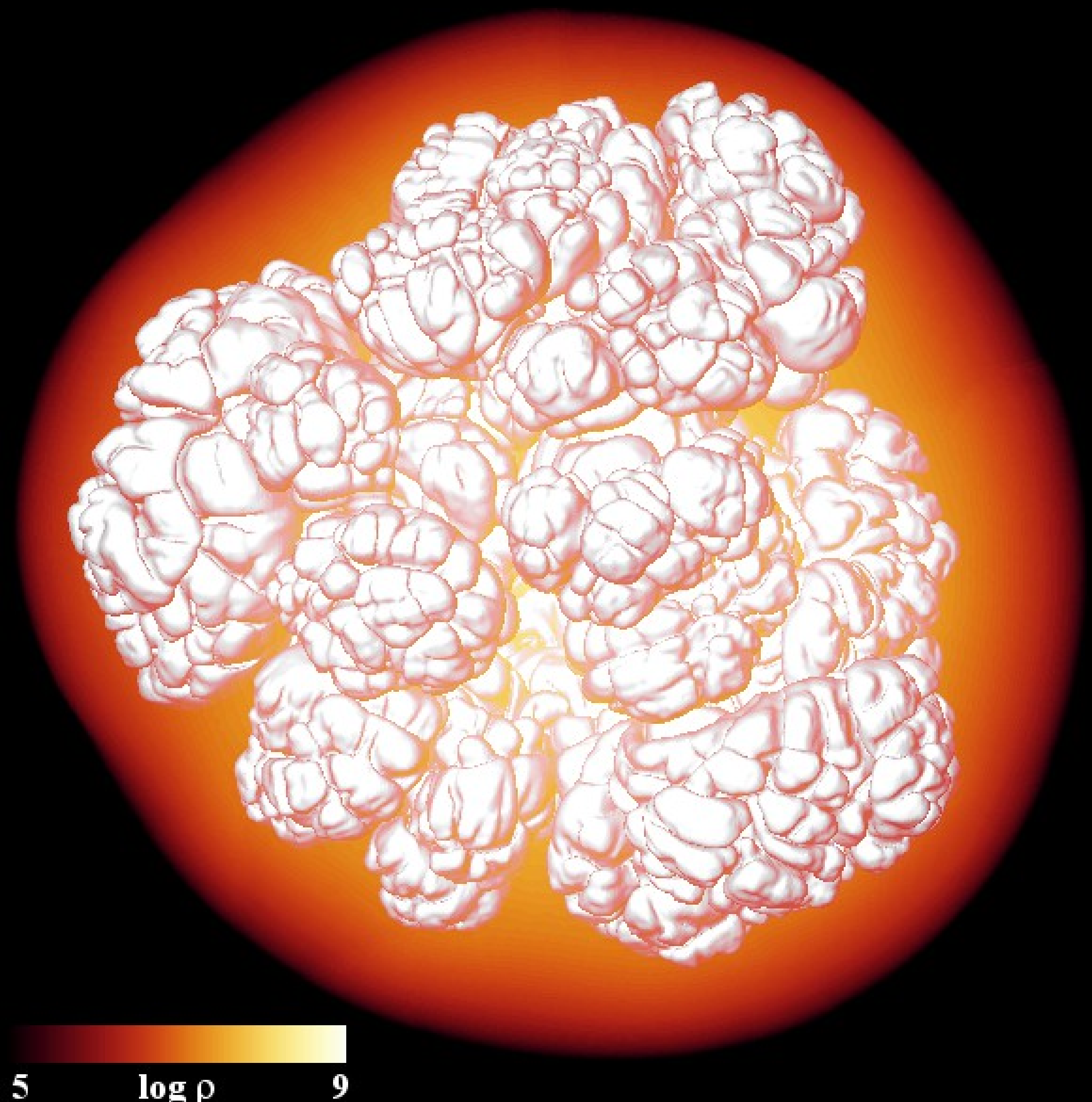
Delayed detonation model N100

- t = 0.70 s



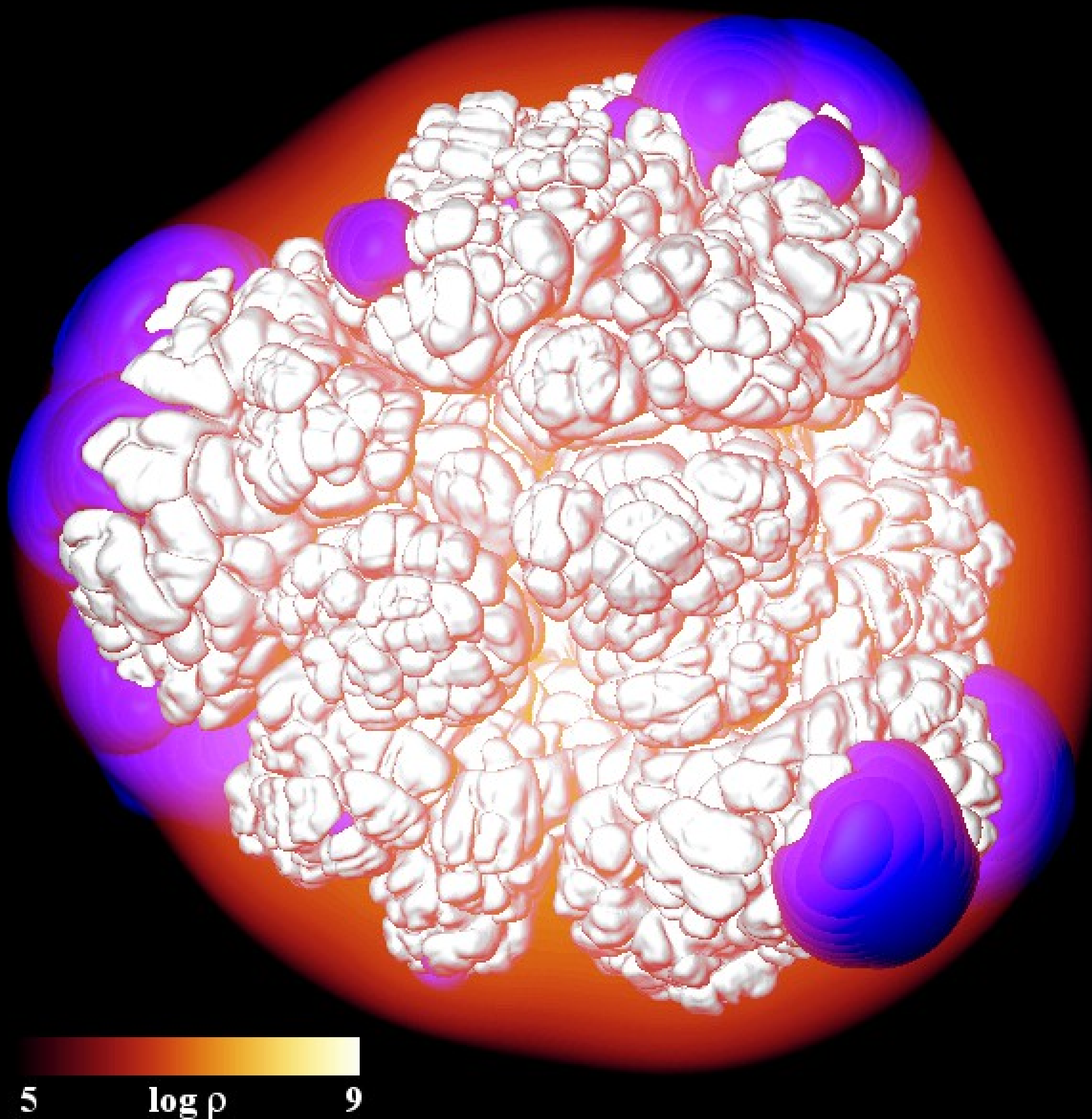
Delayed detonation model N100

- t = 0.93 s



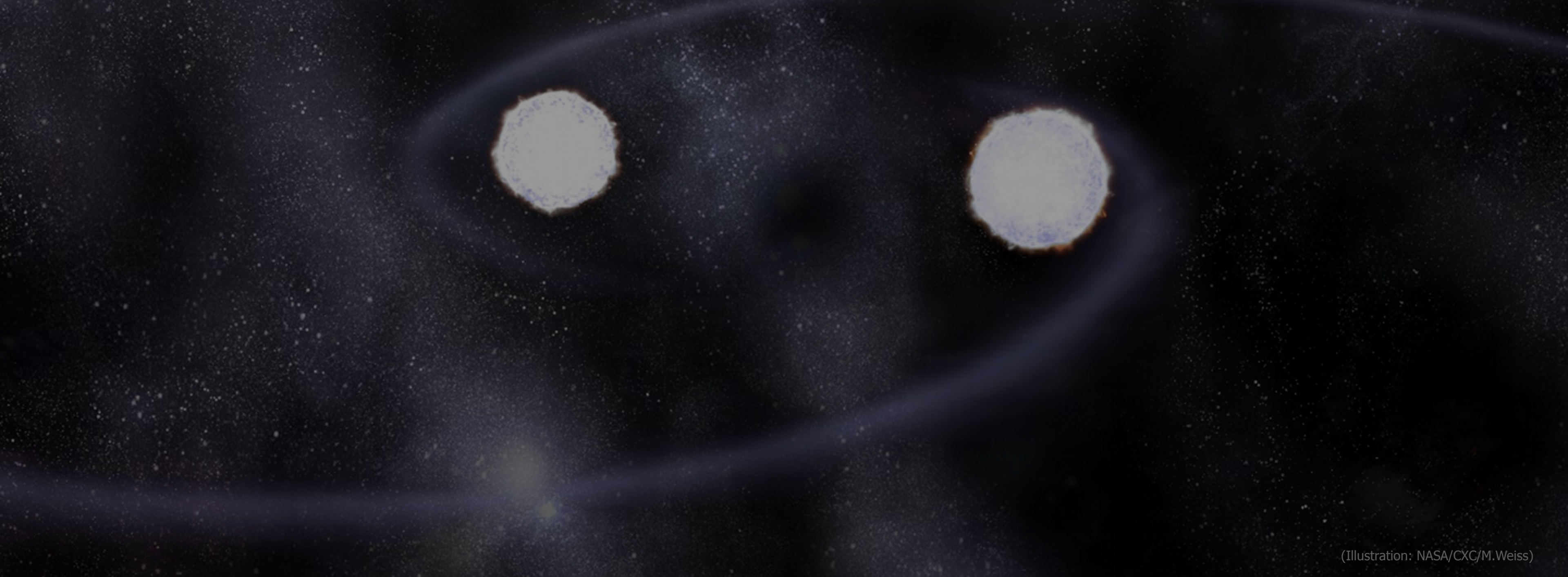
Delayed detonation model N100

- t = 1.00 s



Violent mergers of white dwarfs

- Are there enough systems that can grow WD to M_{Ch}? → Probably not.
- alternatives:
  - detonation in sub-M_{Ch} WD triggered by detonation in He shell ("double detonations, e.g. Fink+ 2007/2010, Kromer+ 2010) or instabilities in the accretion process
  - mergers of white dwarfs (e.g. Pakmor+ 2010/2011/2012)

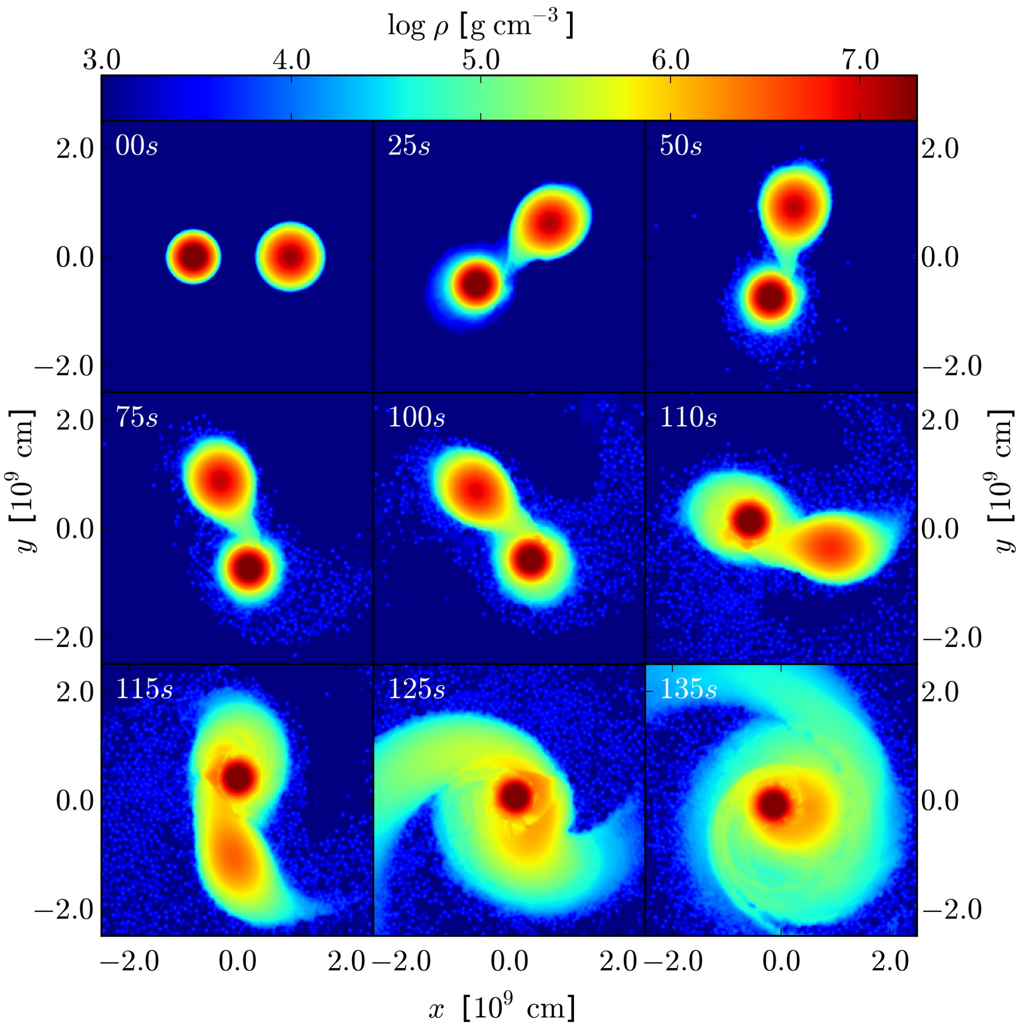


(Illustration: NASA/CXC/M.Weiss)

Violent WD-WD mergers

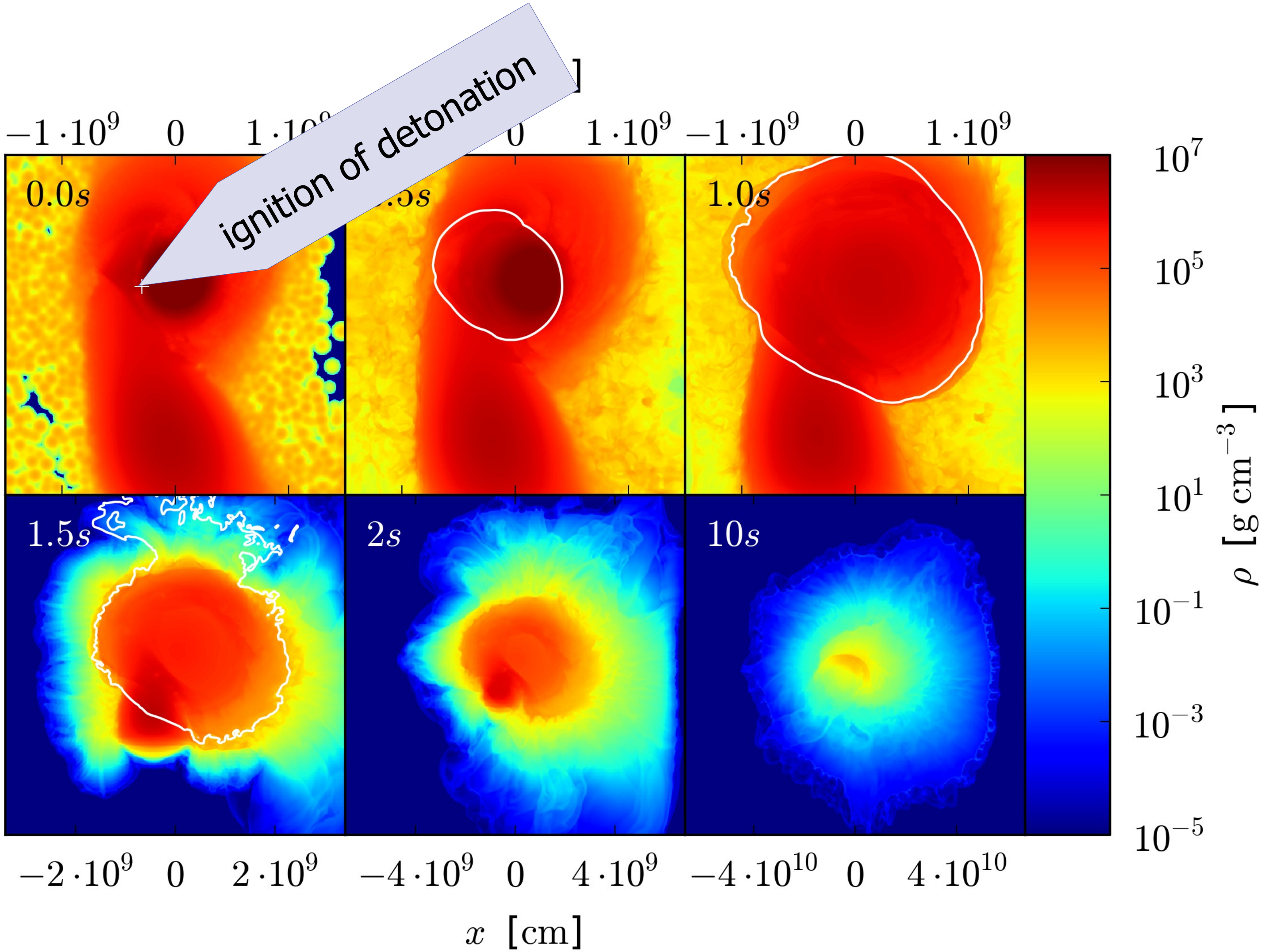
$M_1 = 1.1 M_\odot$ $M_2 = 0.9 M_\odot$ (Pakmor+, 2012)

- inspiral and merger: 3D SPH code (GADGET3)

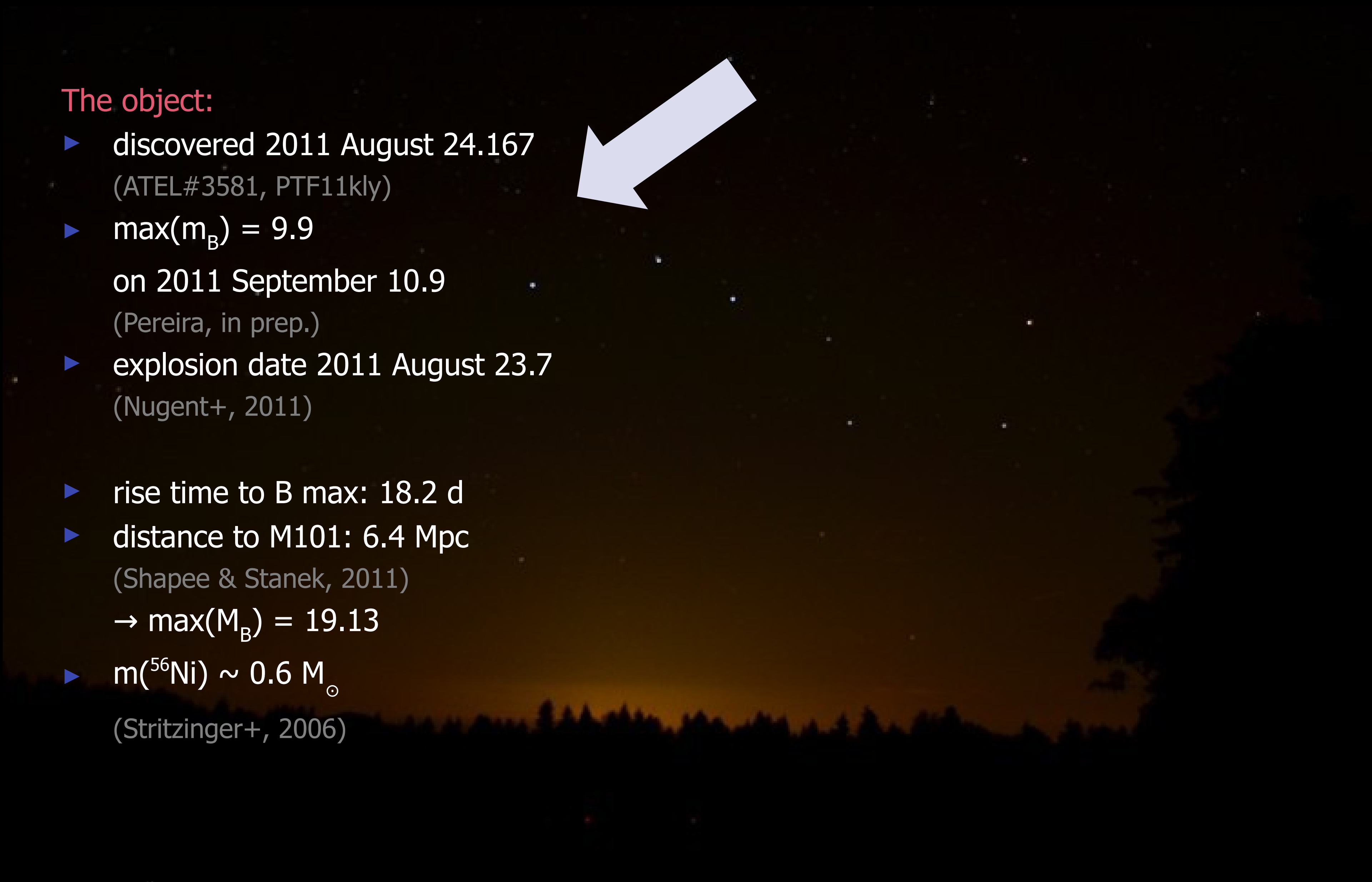


Violent WD-WD mergers

- explosion: 3D MPA SN Ia code (LEAFS)



SN 2011fe in M101

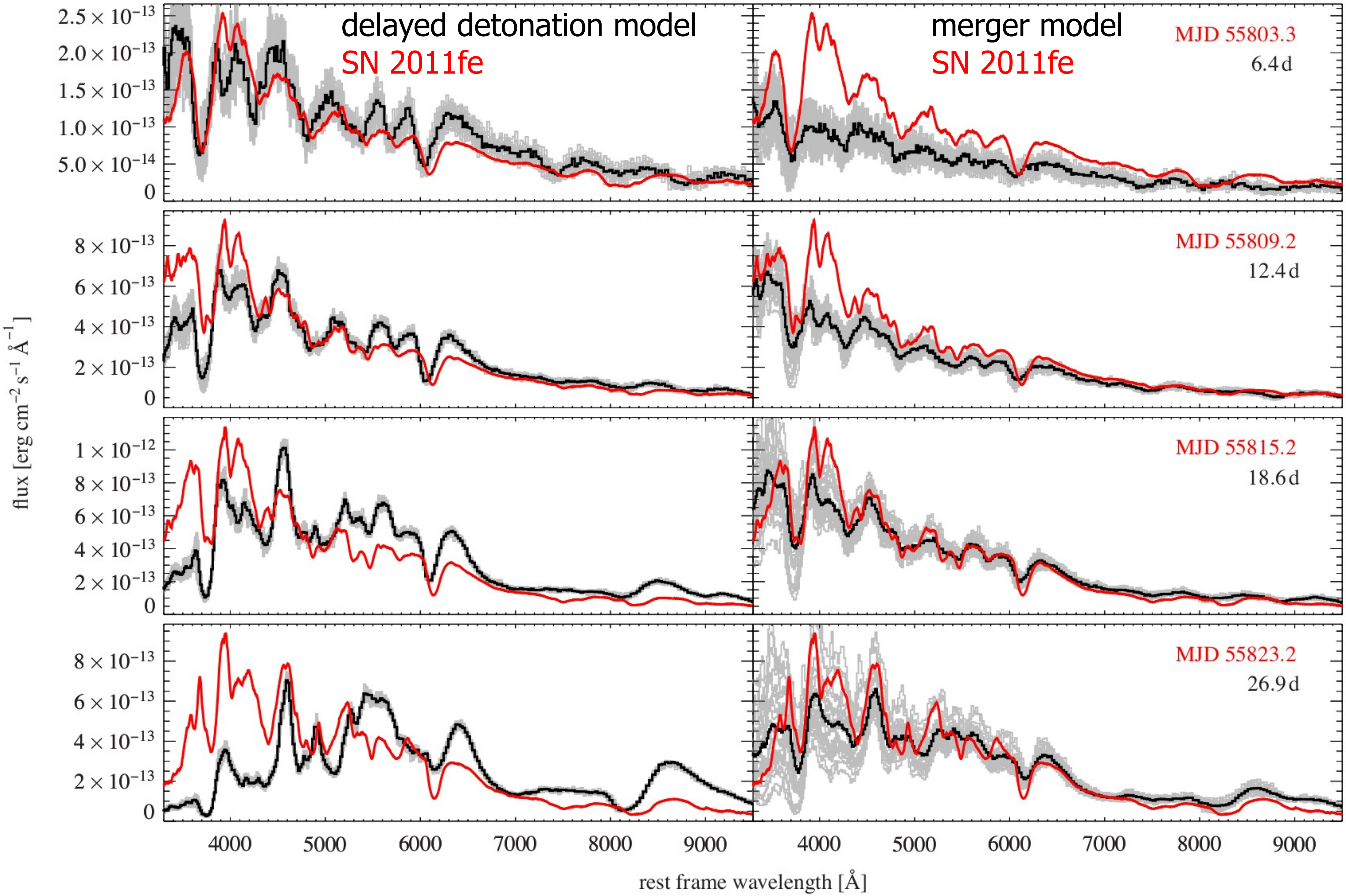


The object:

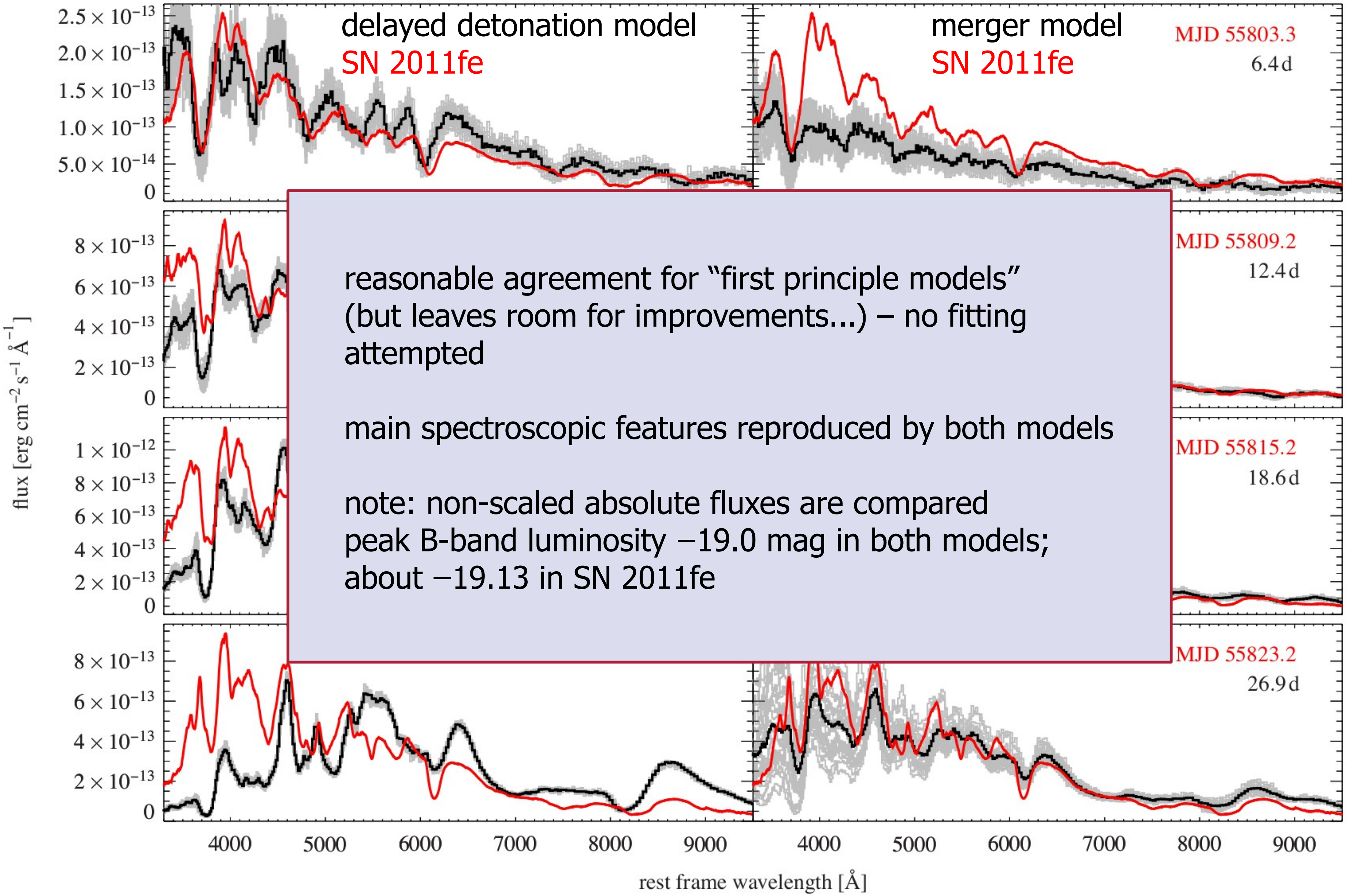
- discovered 2011 August 24.167
  (ATEL#3581, PTF11kly)
- $\max(m_B) = 9.9$
  on 2011 September 10.9
  (Pereira, in prep.)
- explosion date 2011 August 23.7
  (Nugent+, 2011)
- rise time to B max: 18.2 d
- distance to M101: 6.4 Mpc
  (Shapee & Stanek, 2011)
  $\rightarrow \max(M_B) = 19.13$
- $m(^{56}\mathrm{Ni}) \sim 0.6\,M_\odot$
  (Stritzinger+, 2006)

(image: A. Bolaños)

Synthetic optical spectra



Synthetic optical spectra

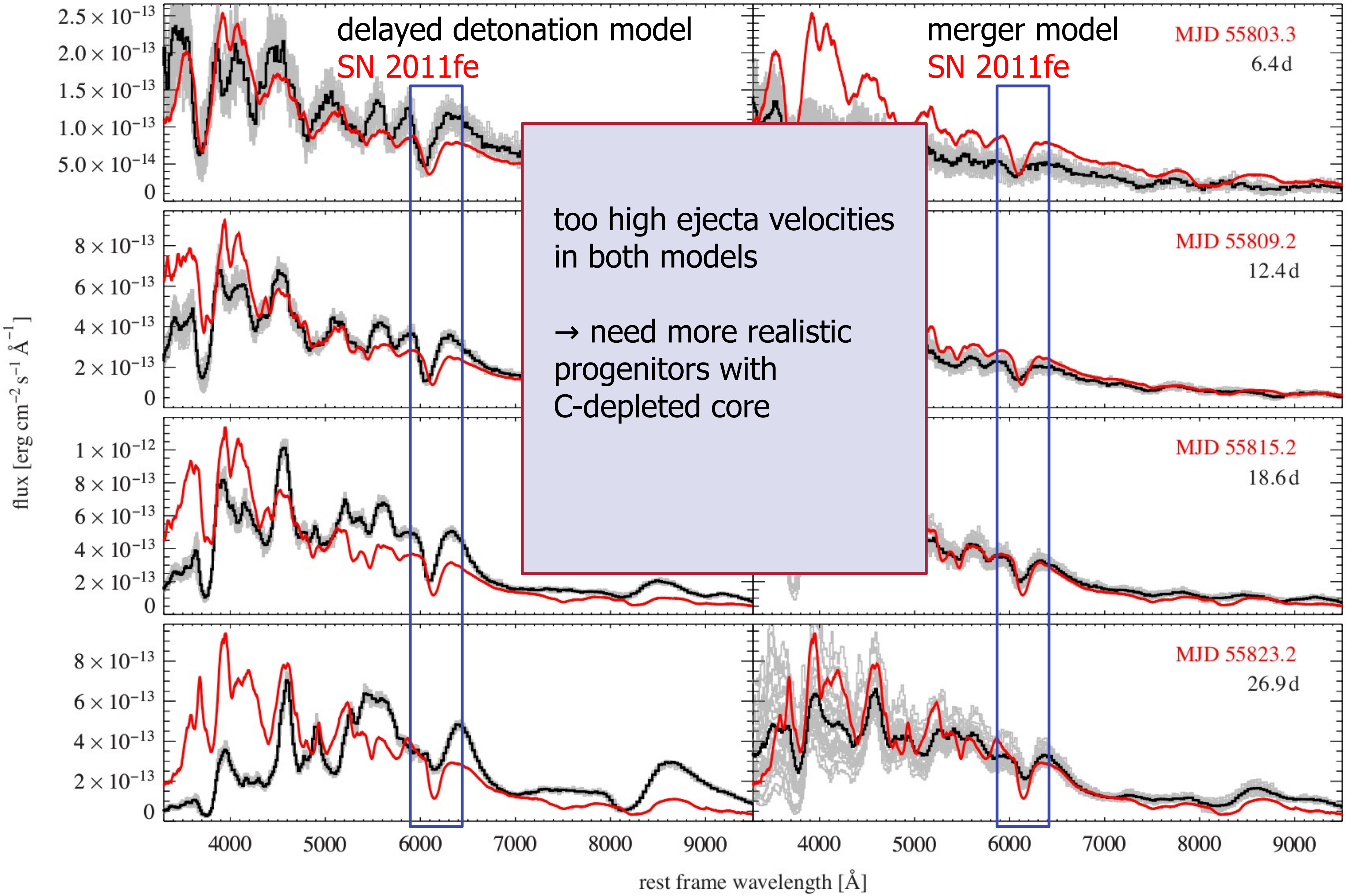


reasonable agreement for “first principle models” (but leaves room for improvements...) – no fitting attempted

main spectroscopic features reproduced by both models

note: non-scaled absolute fluxes are compared
peak B-band luminosity −19.0 mag in both models;
about −19.13 in SN 2011fe

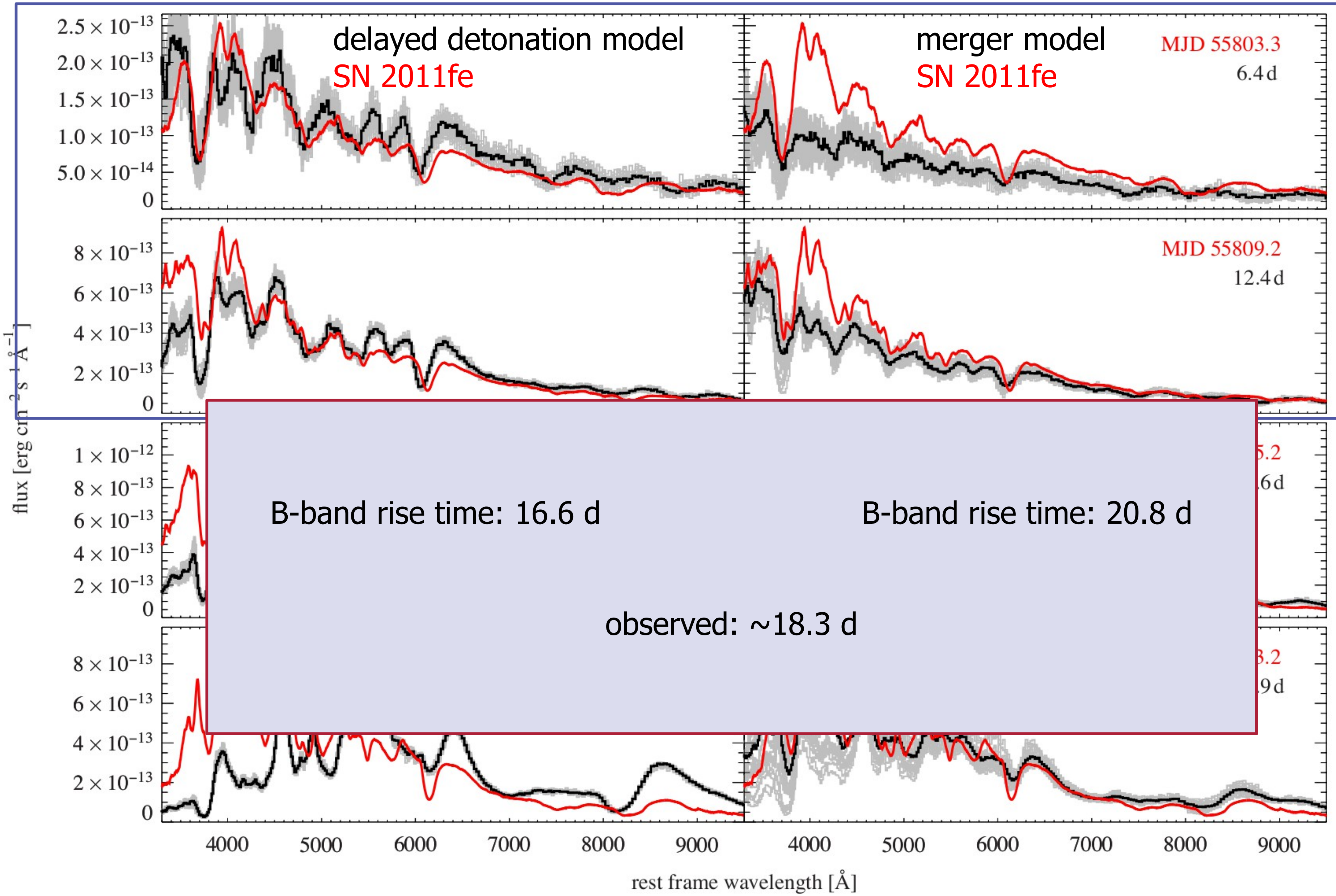
Synthetic optical spectra



too high ejecta velocities in both models

→ need more realistic progenitors with C-depleted core

Synthetic optical spectra



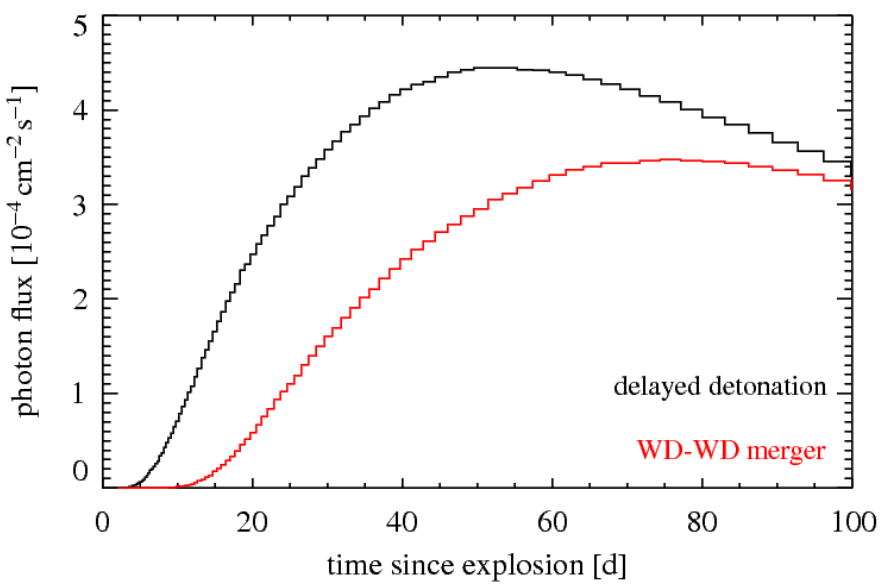
B-band rise time: 16.6 d

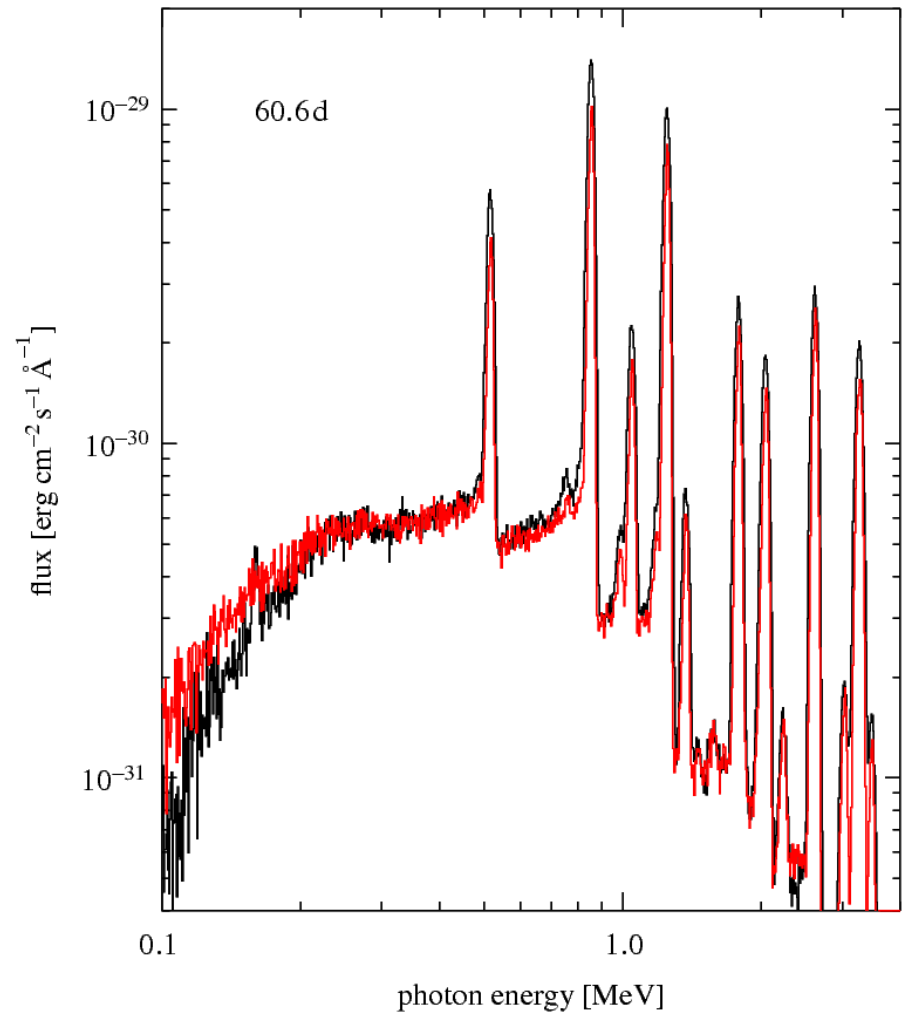
B-band rise time: 20.8 d

observed: ~18.3 d

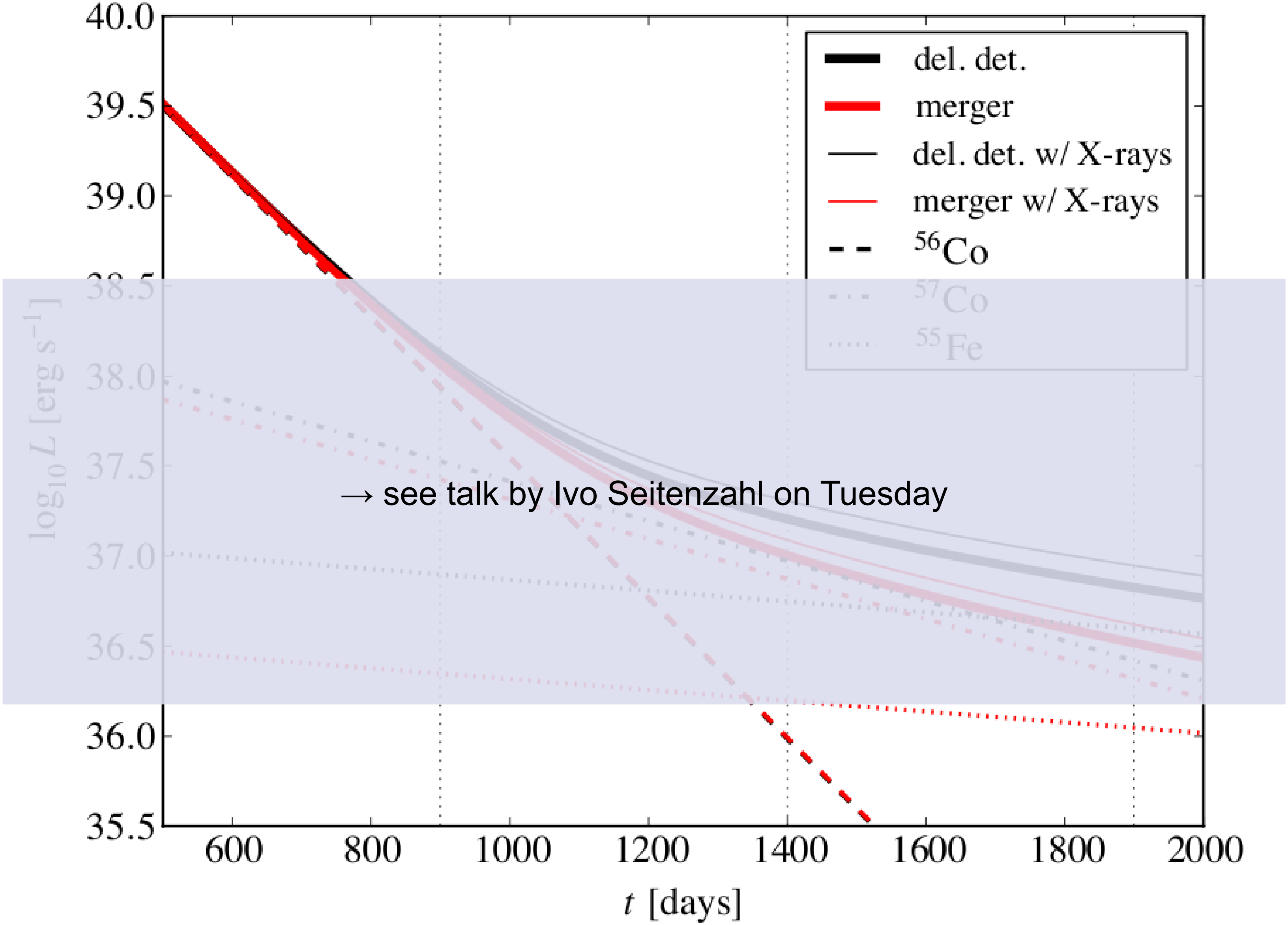
Breaking the degeneracy: gamma-ray observables?

- sensitivity of current gamma-ray observatories is insufficient (even for nearby SN 2011fe...)
  Summa+, subm.





Breaking the degeneracy: late photometry?



→ see talk by Ivo Seitenzahl on Tuesday

Summary

- SNe Ia are thermonuclear explosions of white dwarfs
- interesting for galactic chemical evolution, observational cosmology...
- largest problem in understanding SNe Ia: progenitor system unclear
- may or may not be explosions of Chandrasekhar-mass white dwarfs: leading models are delayed detonations in M_{Ch} WDs, mergers of WDs (other models studied but not discussed here may also contribute)
- hard to distinguish from observables
- elemental (or even better: isotopic) abundances could help to constrain explosion models