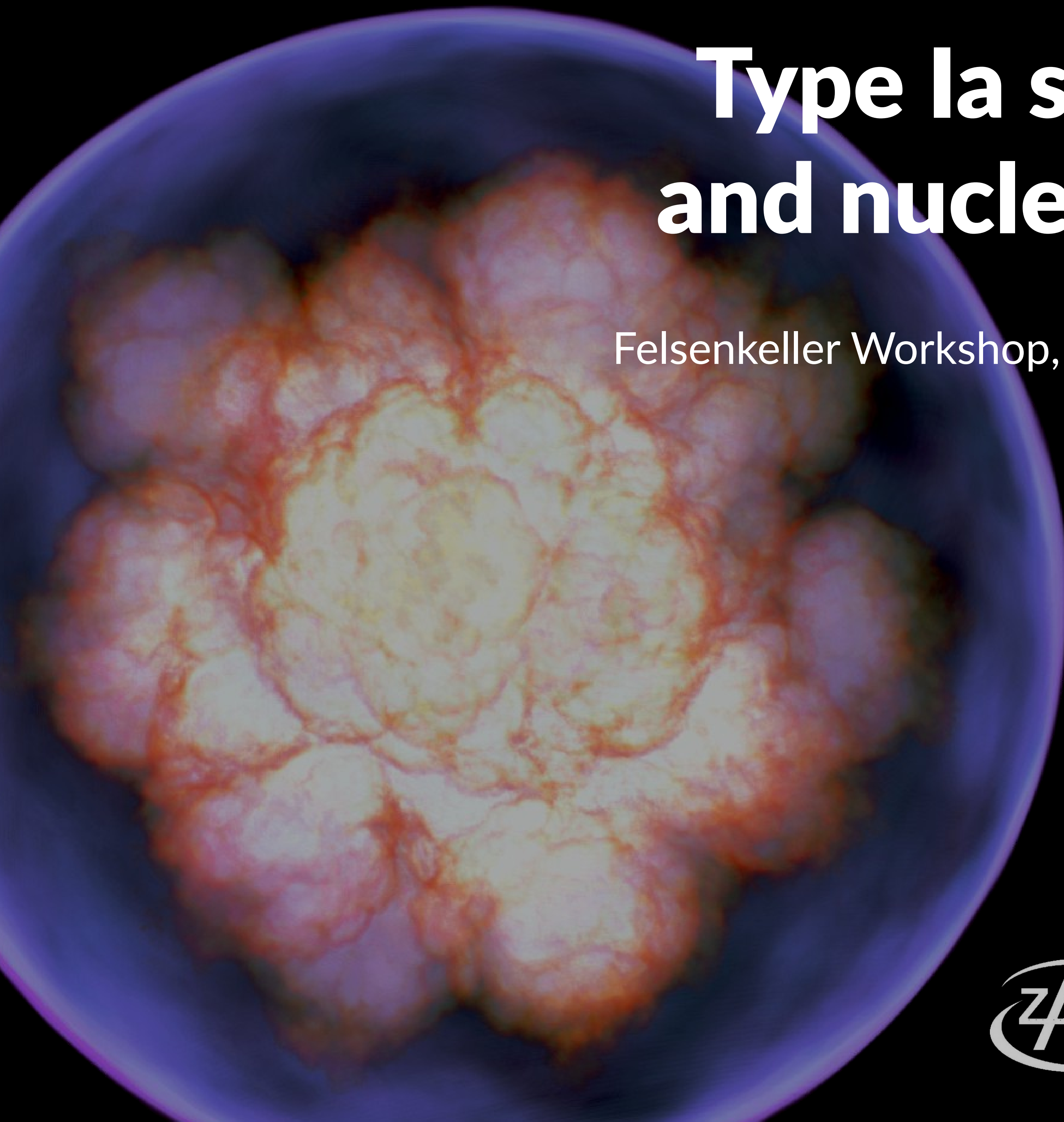


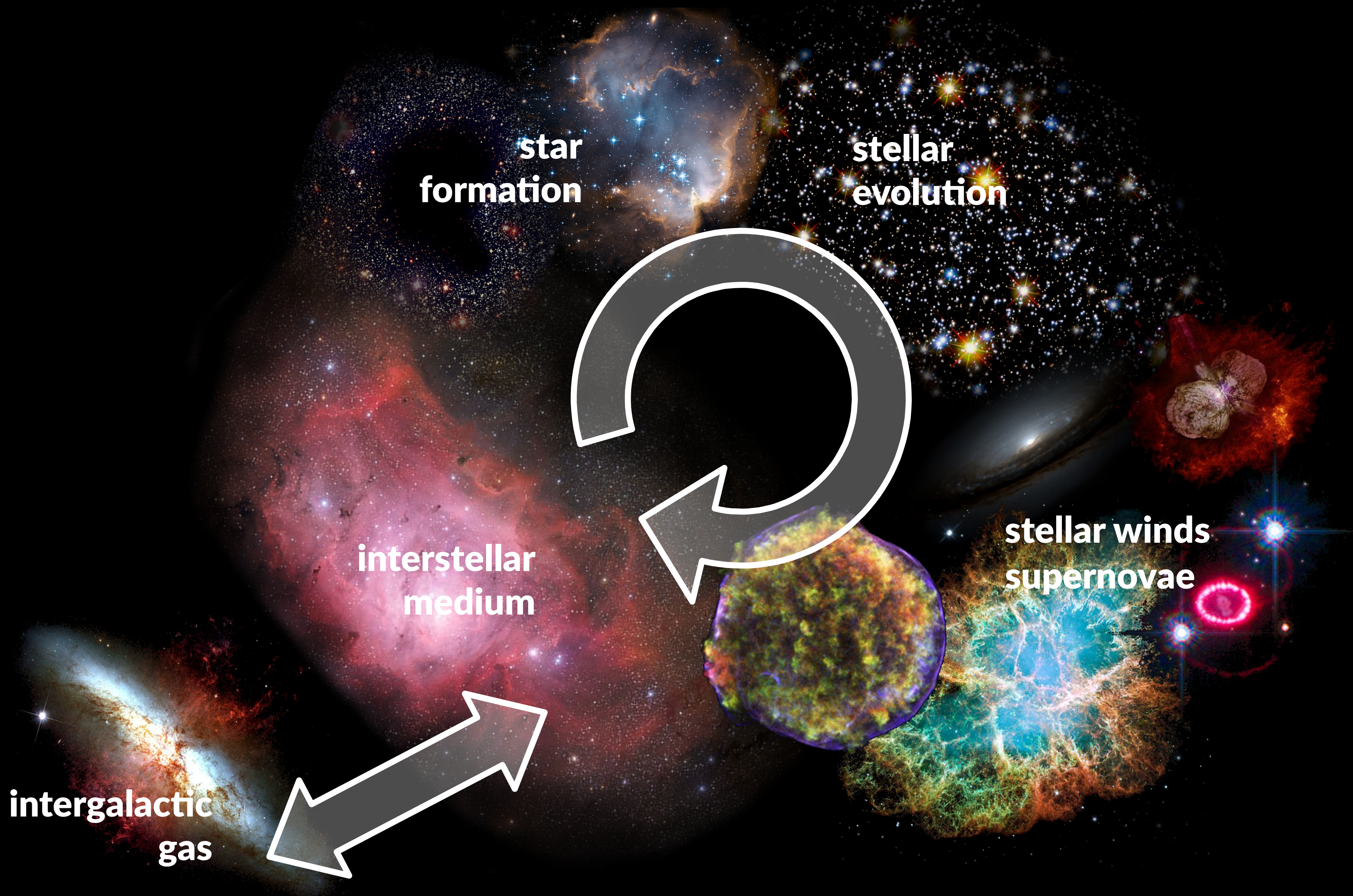
Type Ia supernovae and nucleosynthesis

Felsenkeller Workshop, Dresden, June 27, 2017

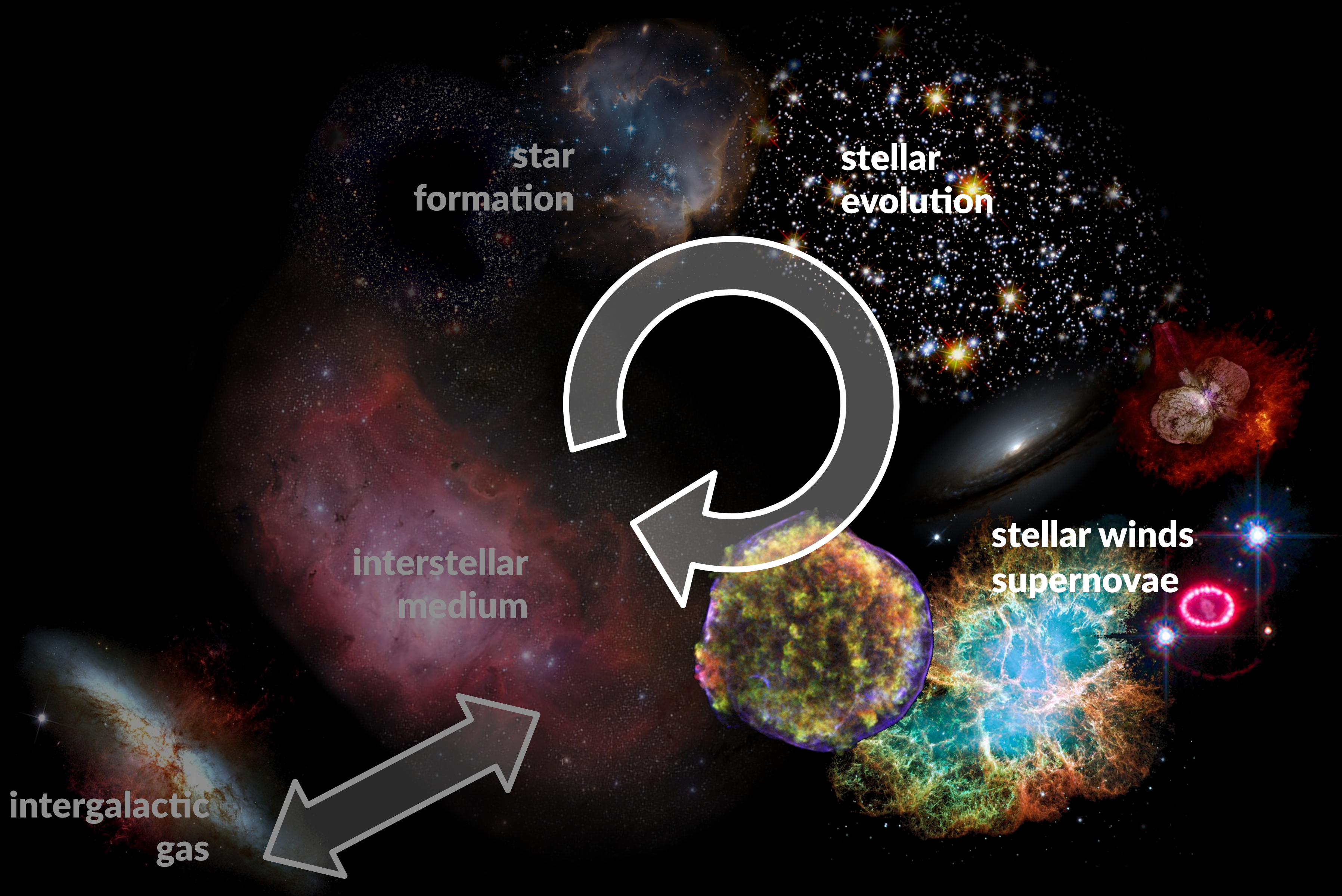
Friedrich Röpke

Heidelberg

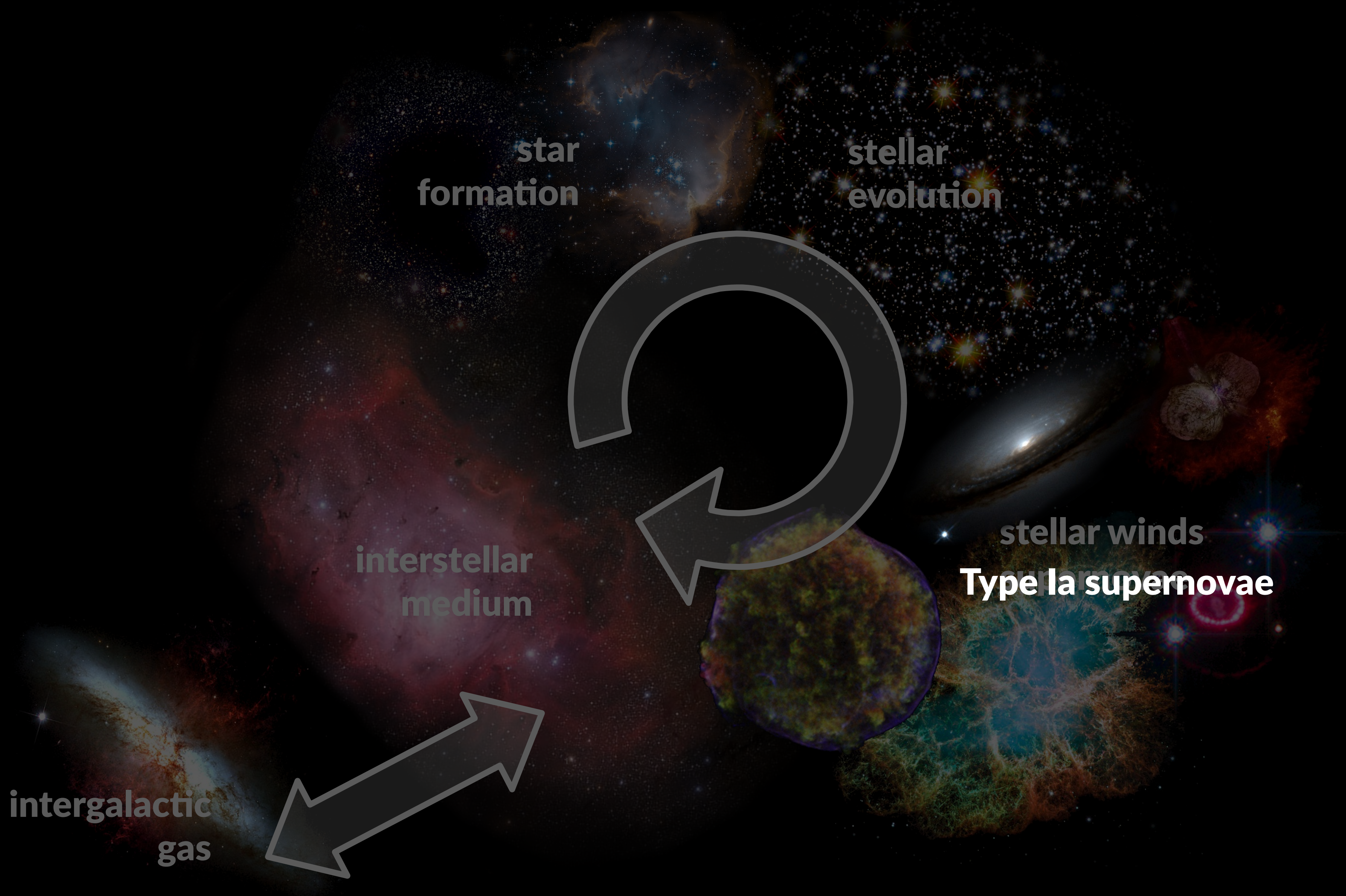
Combustion in the cosmic cycle of matter



Combustion in the cosmic cycle of matter



Combustion in the cosmic cycle of matter



Supernova classification

astronomical classification

- according to observed spectral features

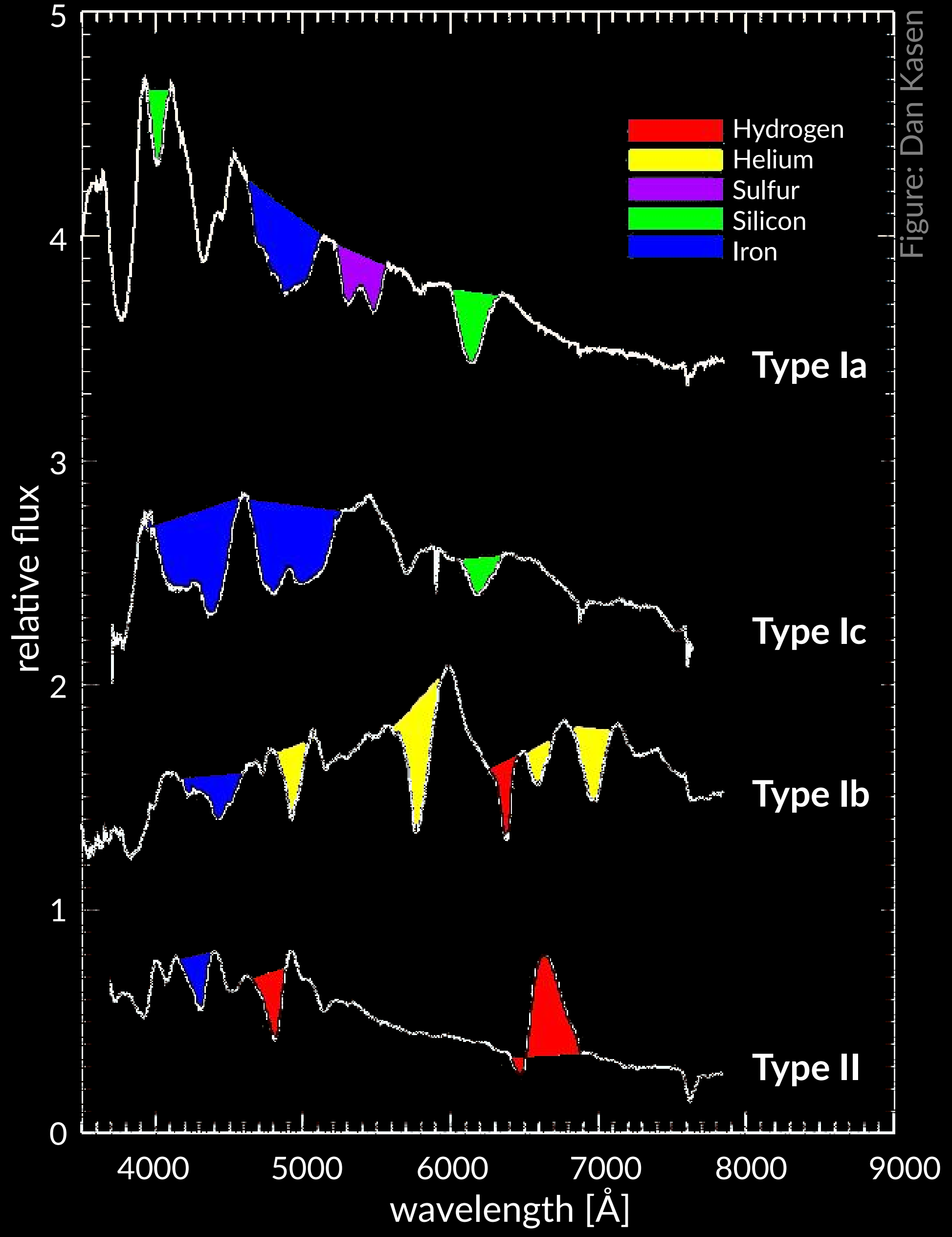
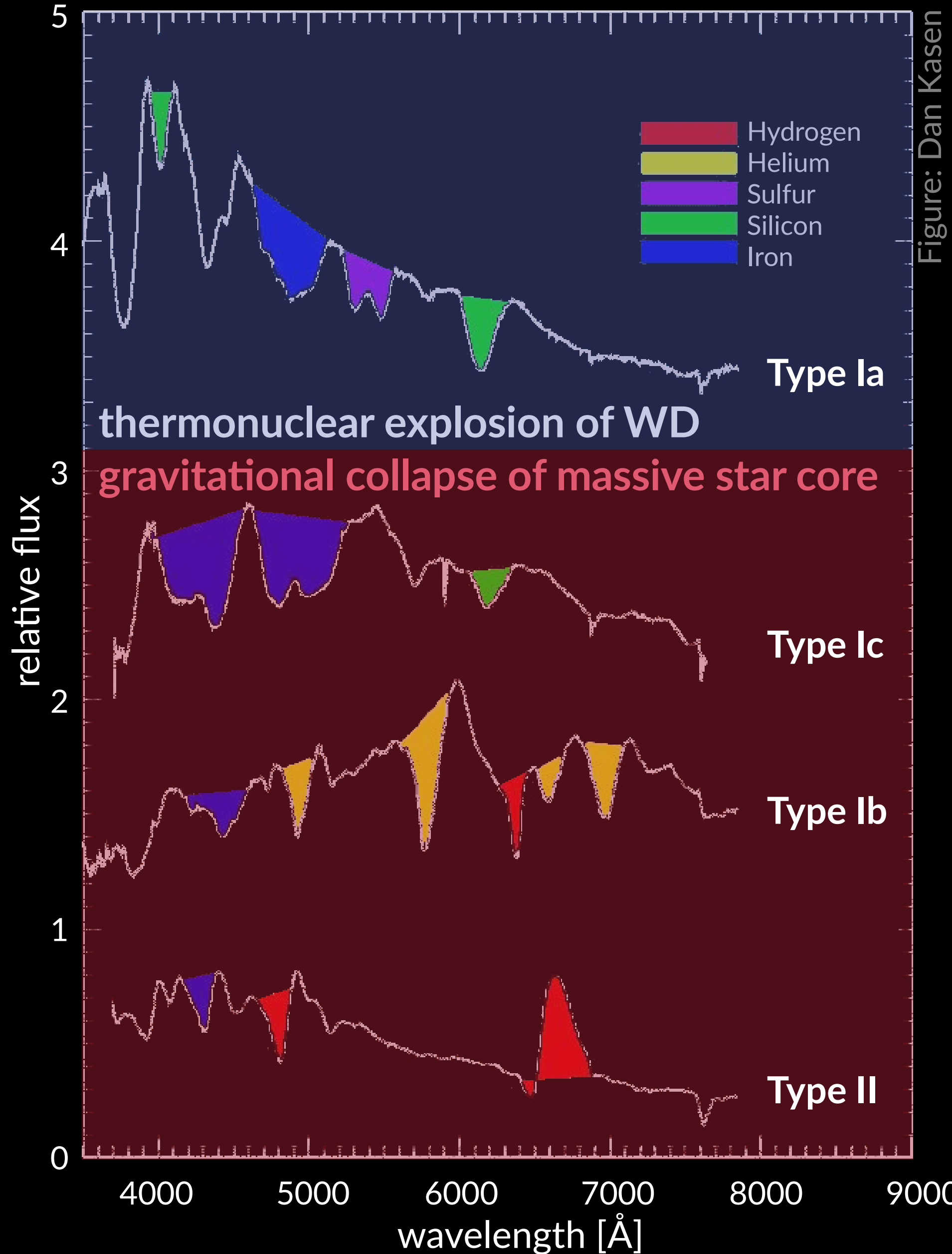


Figure: Dan Kasen

Supernova classification

physical classification

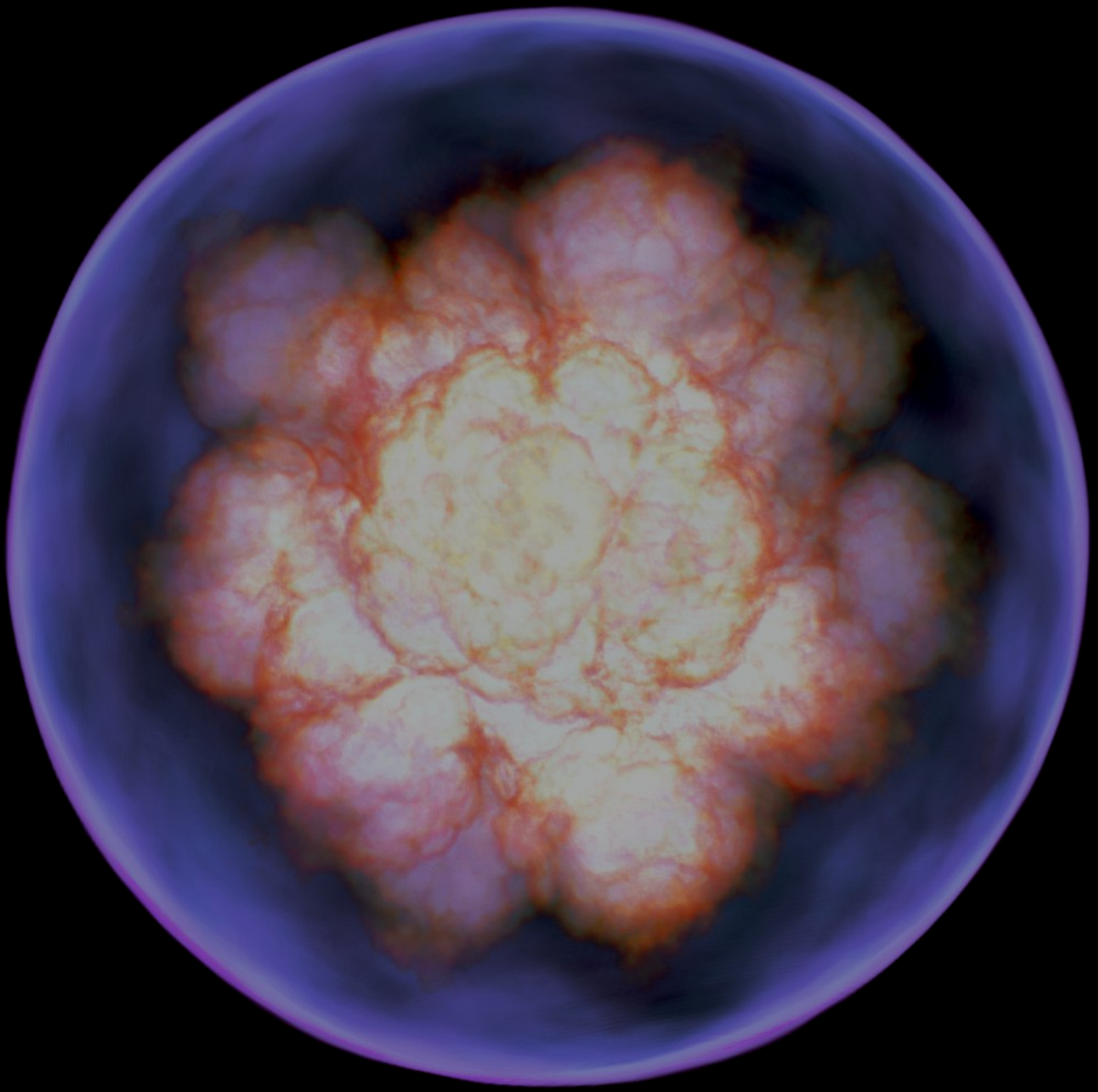
- according to energy source



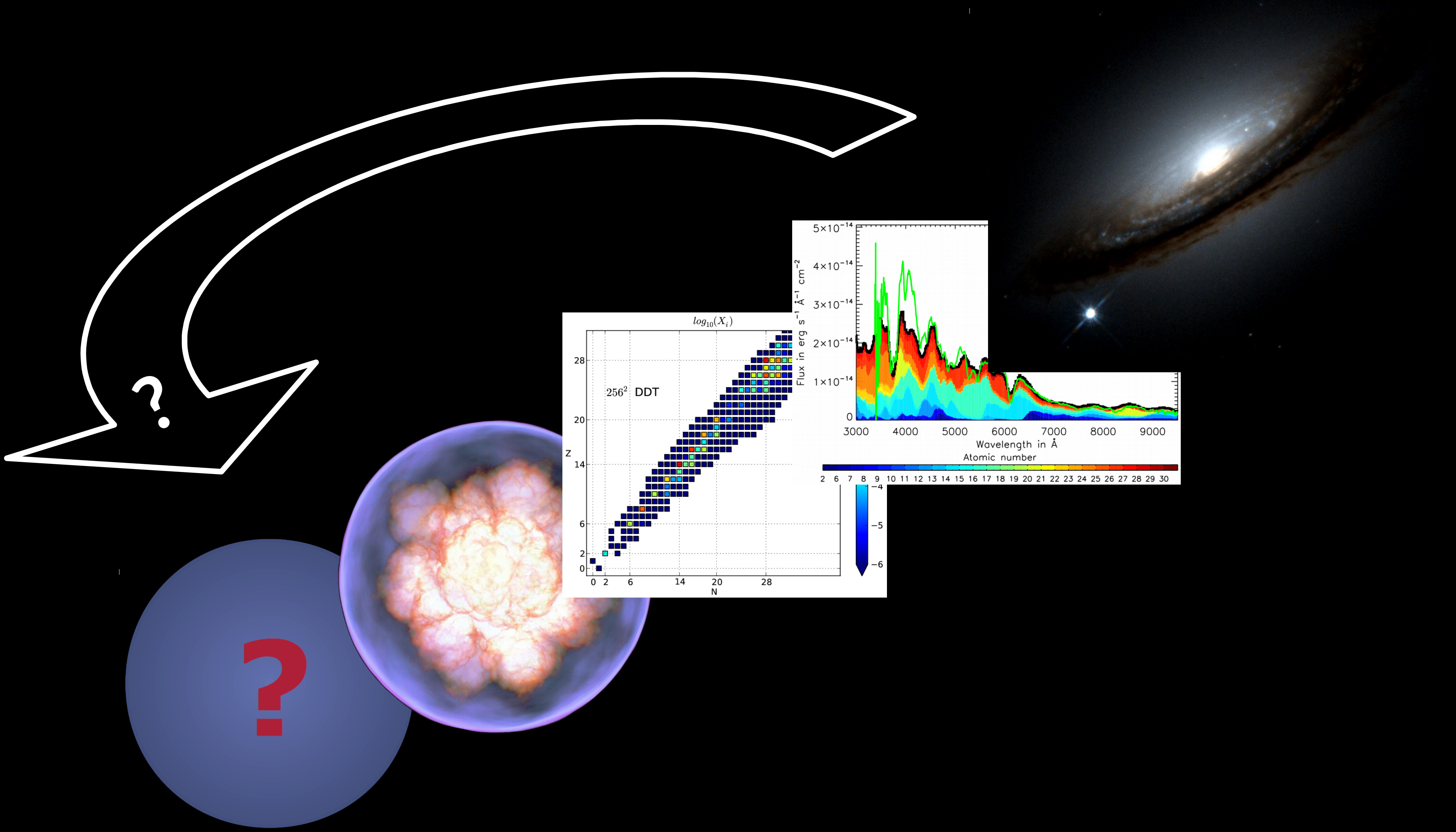
Modeling of thermonuclear supernovae

status:

- main problem: **unknown nature of progenitor system(s)**
- homogeneity of SNe Ia?
- different scenarios at work? → supported by diversity and newly observed astrophysical transients
- a number of explosion scenarios is relatively well explored
- successful connection to observables



Consistent multi-D modeling pipeline



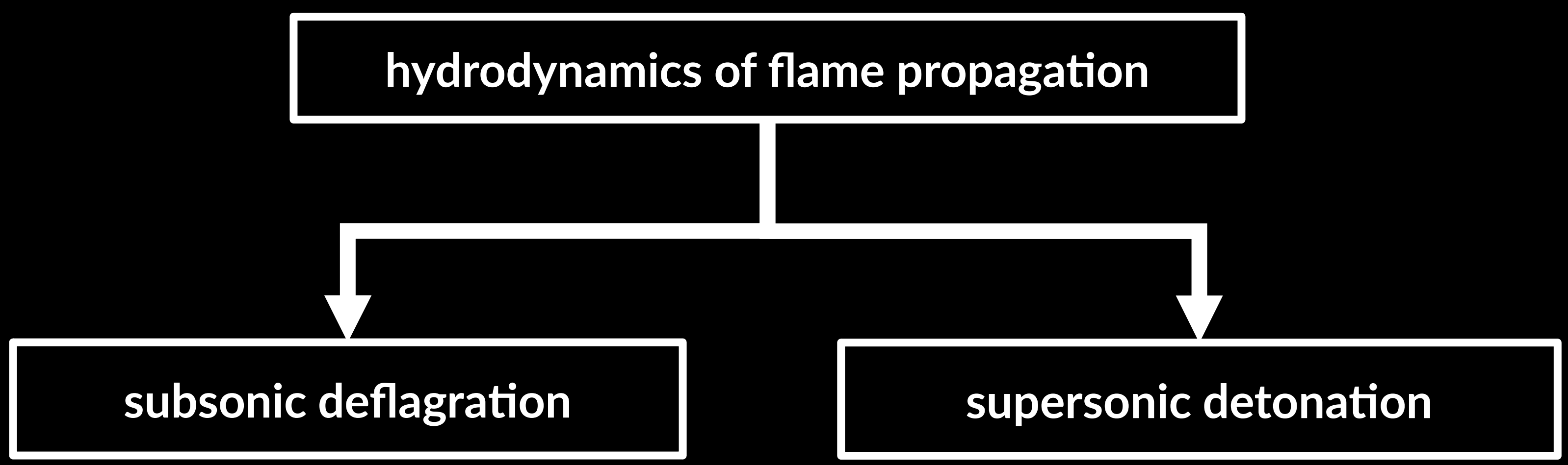
Thermonuclear burning fronts

- extreme temperature sensitivity of reactions (^{12}C + ^{12}C reaction rate $\propto T^{20}$)

  → burning proceeds in **thin fronts**

- internal width (mm to cm) ≪ scales of white dwarf star (~10^3 km)

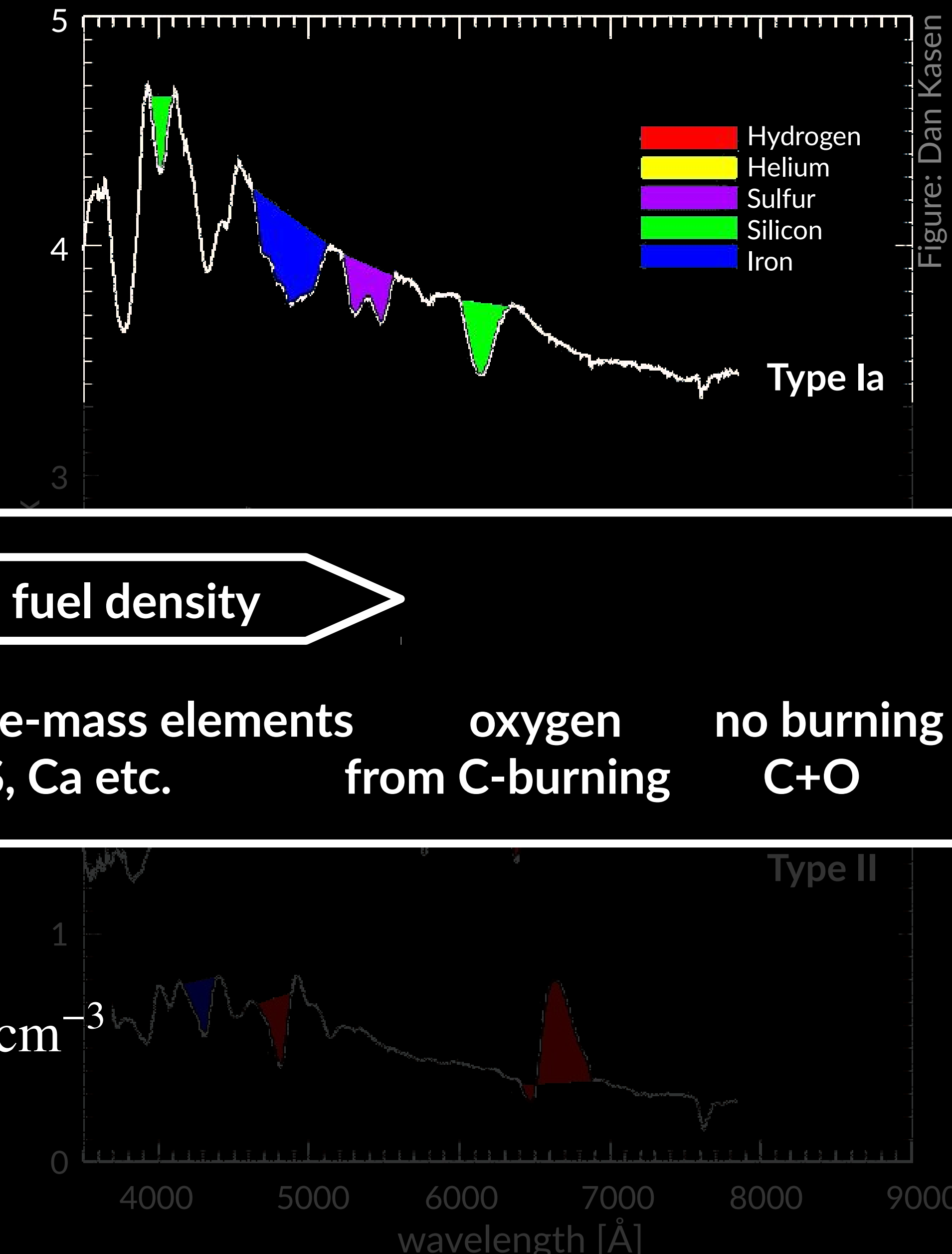
  → described in **discontinuity approximation**



Nuclear burning in SNe Ia

- burning in C+O WD matter:

  fuel density ahead of flame determines ash composition



decreasing fuel density →

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

→ substantial burning below $\rho_{\mathrm{fuel}} \sim 10^7\,\mathrm{g\,cm^{-3}}$ **required**

Why are SNe Ia bright?

^{56}Ni decay chain

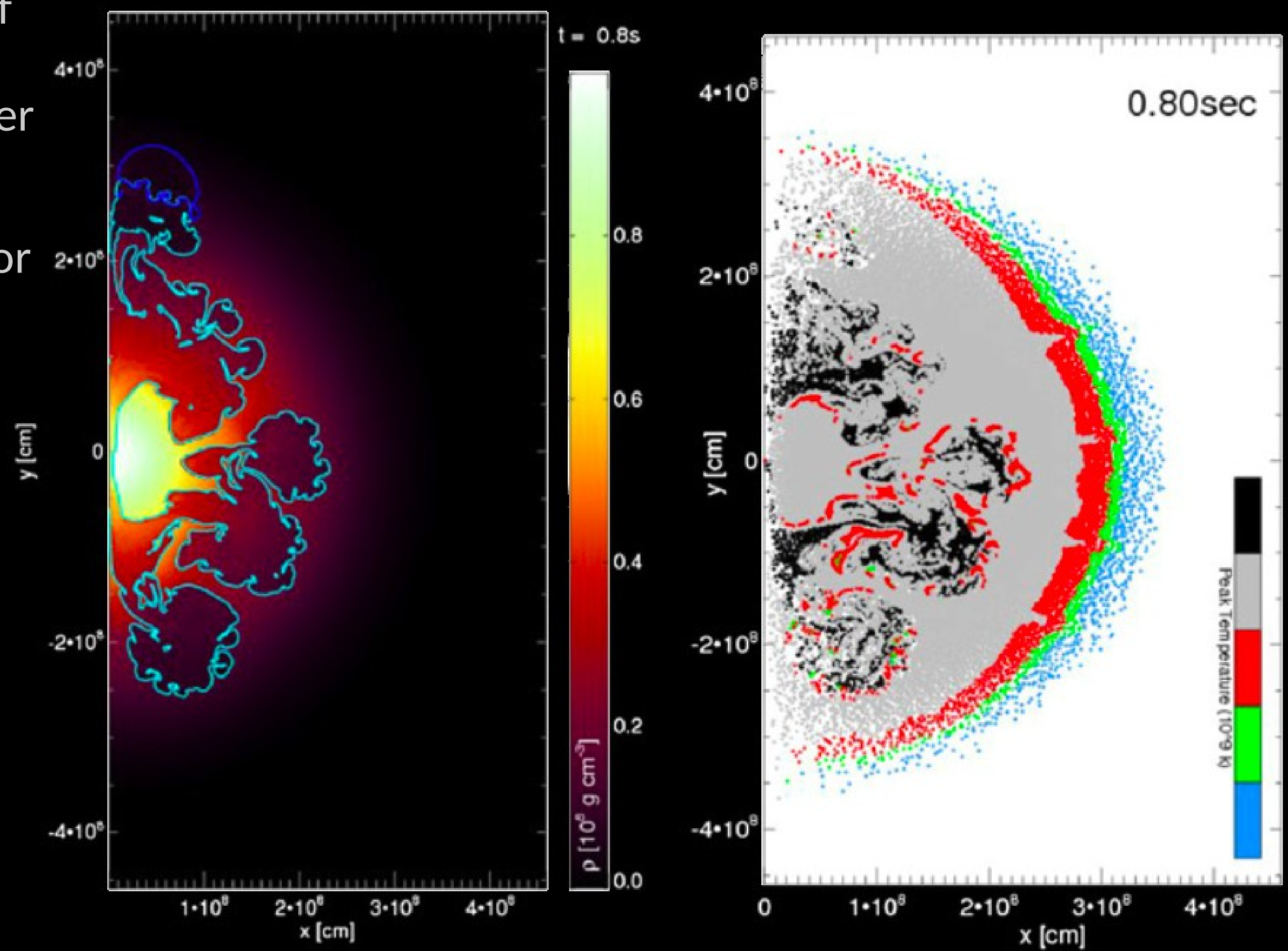
100%	$^{56}\mathrm{Ni} + \mathrm{e}^-$	$\longrightarrow$	$^{56}\mathrm{Co} + \nu_\mathrm{e} + \gamma$	$t_{1/2} = 6.08\,\mathrm{d}$
80%	$^{56}\mathrm{Co} + \mathrm{e}^-$	$\longrightarrow$	$^{56}\mathrm{Fe} + \nu_\mathrm{e} + \gamma$	$t_{1/2} = 77.24\,\mathrm{d}$
10%	$^{56}\mathrm{Co}$	$\longrightarrow$	$^{56}\mathrm{Fe} + \mathrm{e}^+ + \nu_\mathrm{e} + \gamma$	

- γ and e^+ from ^{56}Ni decay chain **heat ejecta** (Truran 1967, Colgate & McKee 1969)

  $\rightarrow$ optical emission (e.g. Kuchner+ 1994), ~ **$0.5M_\odot$ of ^{56}Ni** needed for **normal** SN Ia
- **confirmation:** γ-ray detection from SN 2014J with Integral satellite (Diehl+ 2014, Churazov+ 2014, Diehl+ 2015)
- **main producers of iron in current universe!**

p-process in SNe Ia?

- one specific progenitor/explosion model provides **favorable conditions for production of p-nuclei** → "gamma process" (Travaglio+ 2011, 2014)
- substantial production of both light (A<120) and heavy p-nuclei with rather flat production factors
- potentially responsible for 50% of p-nuclei in solar system (Travaglio+ 2015)

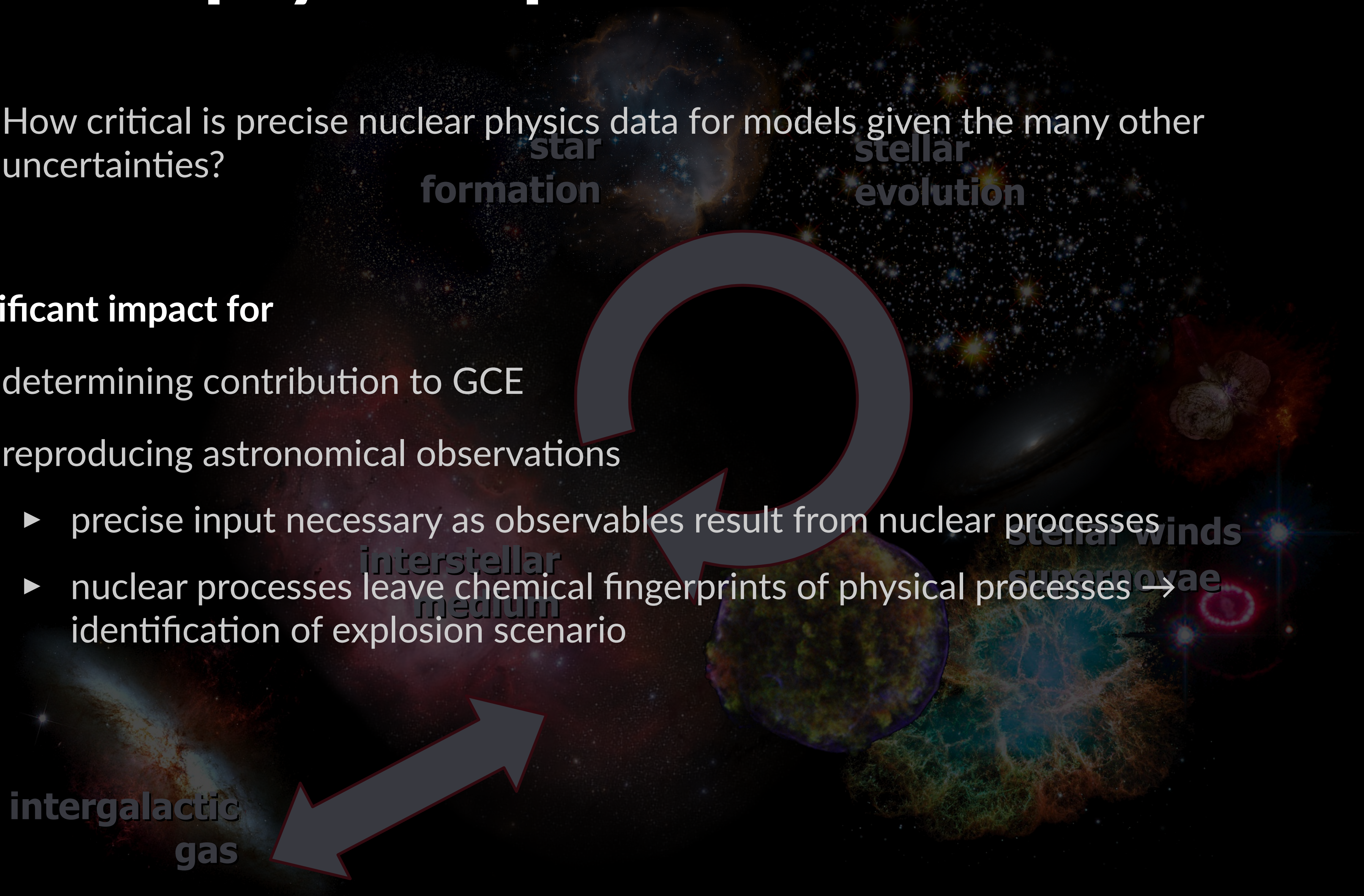


Nuclear physics input

- How critical is precise nuclear physics data for models given the many other uncertainties?

significant impact for

- determining contribution to GCE
- reproducing astronomical observations
  - precise input necessary as observables result from nuclear processes
  - nuclear processes leave chemical fingerprints of physical processes → identification of explosion scenario



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

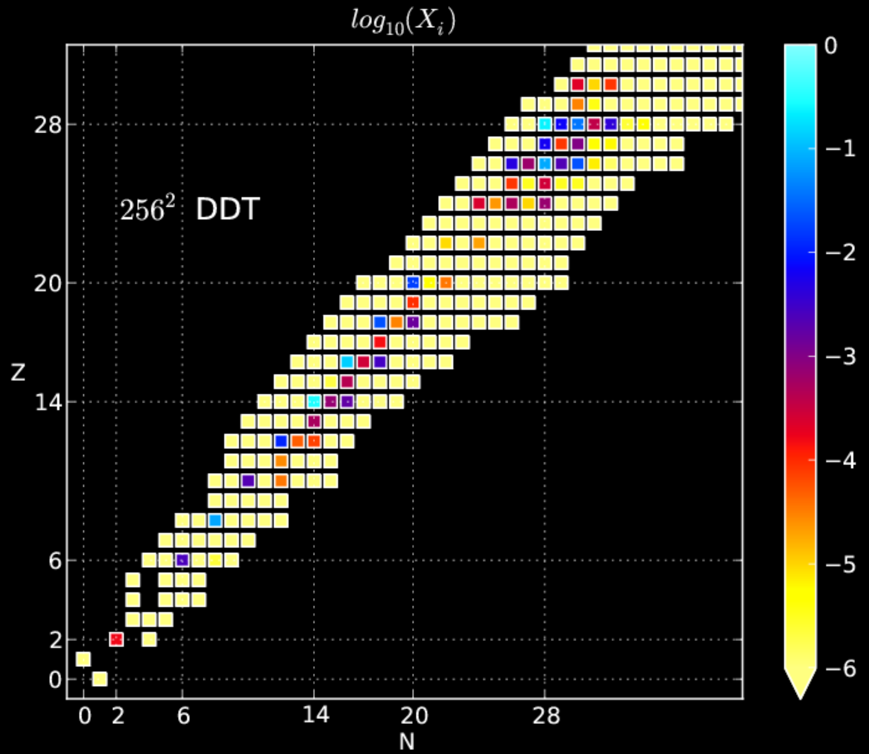
→ **nucleosynthesis postprocessing from tracers** (C. Travaglio+, 2004; FR+, 2006)

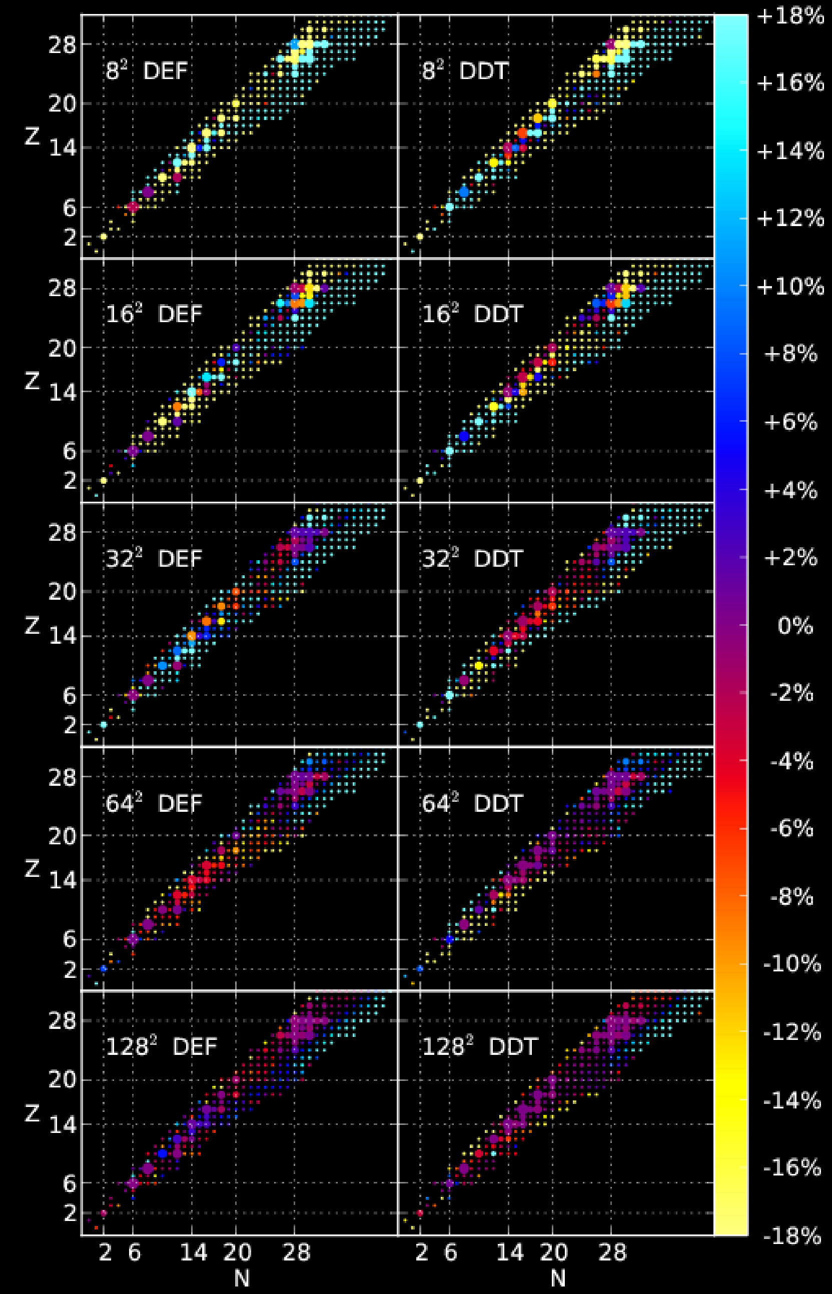
How good is this approach?

Treatment of nuclear reactions

How good is the tracer particle approach?

- convergence in yields (Seitenzahl+ 2010)

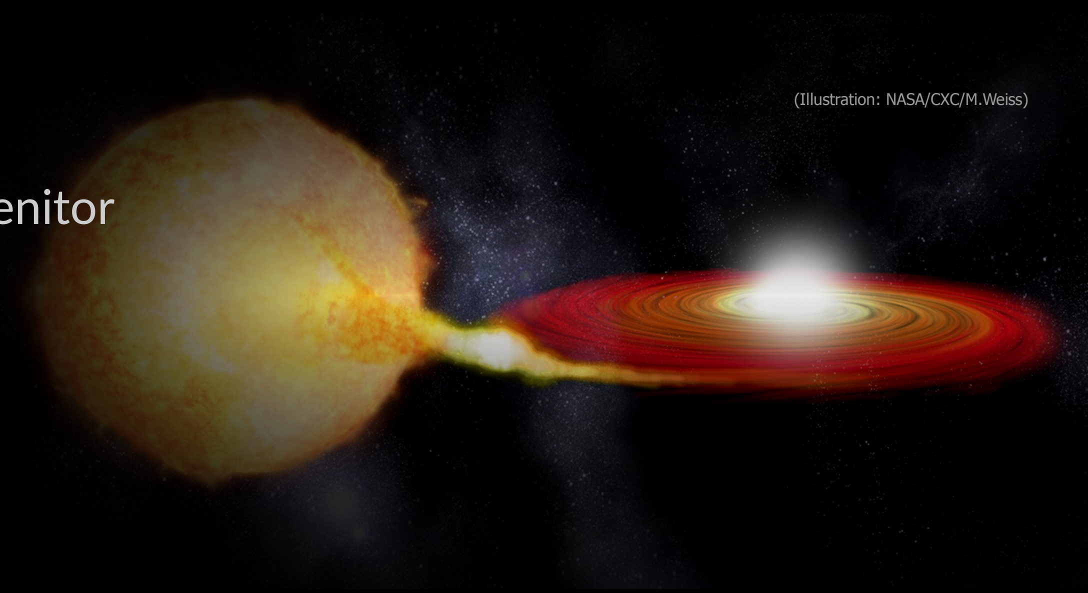




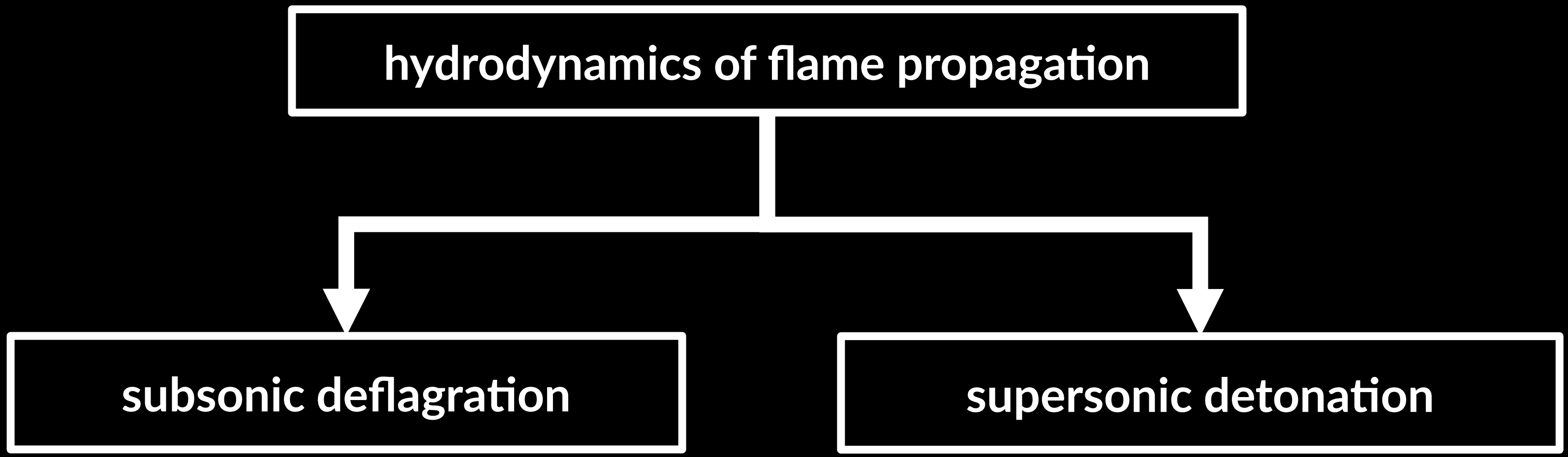
Thermonuclear supernova scenarios

Chandrasekhar mass explosions

- associated with single-degenerate progenitor channel



(Illustration: NASA/CXC/M.Weiss)



Thermonuclear supernova scenarios

Chandrasekhar mass explosions

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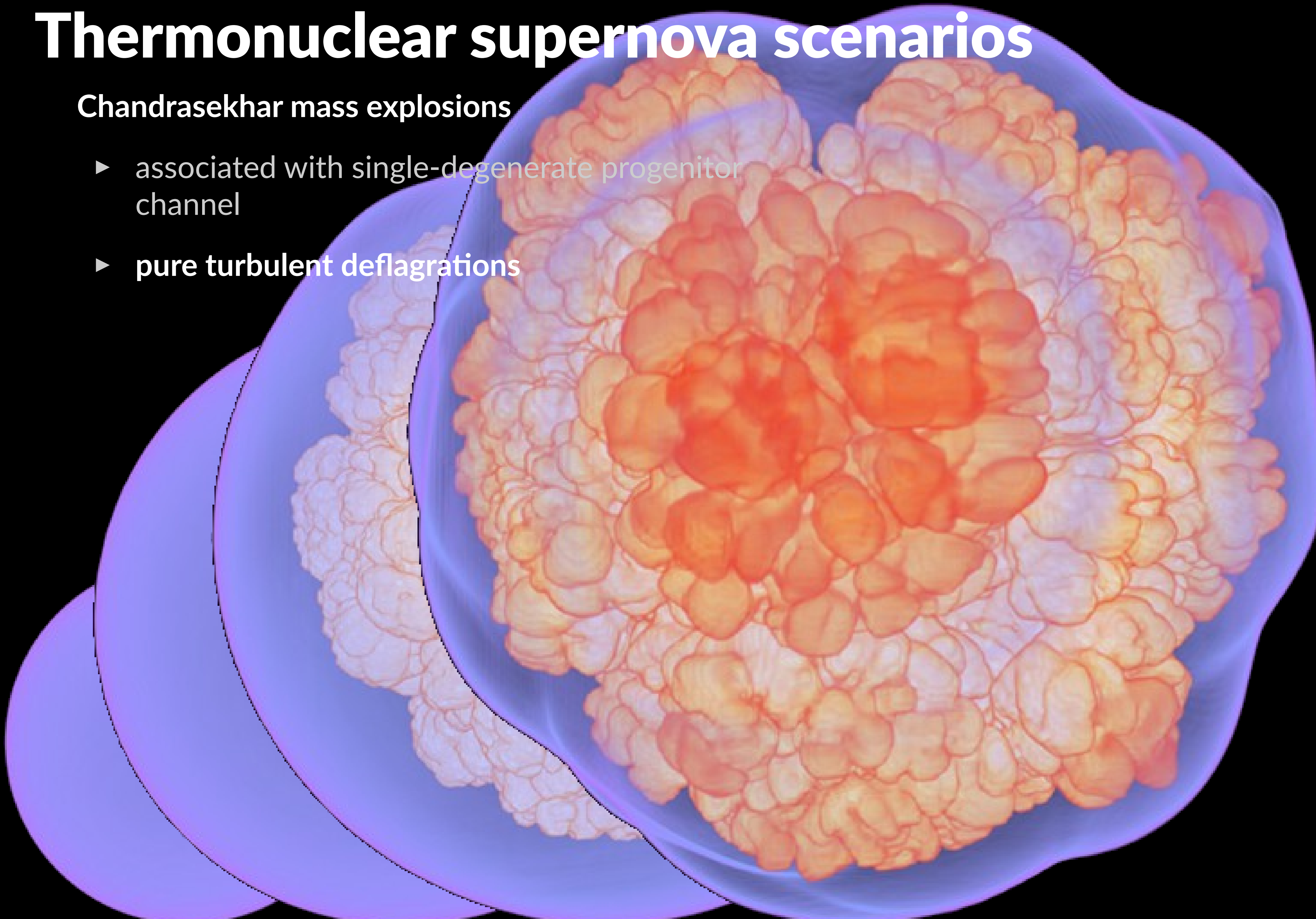
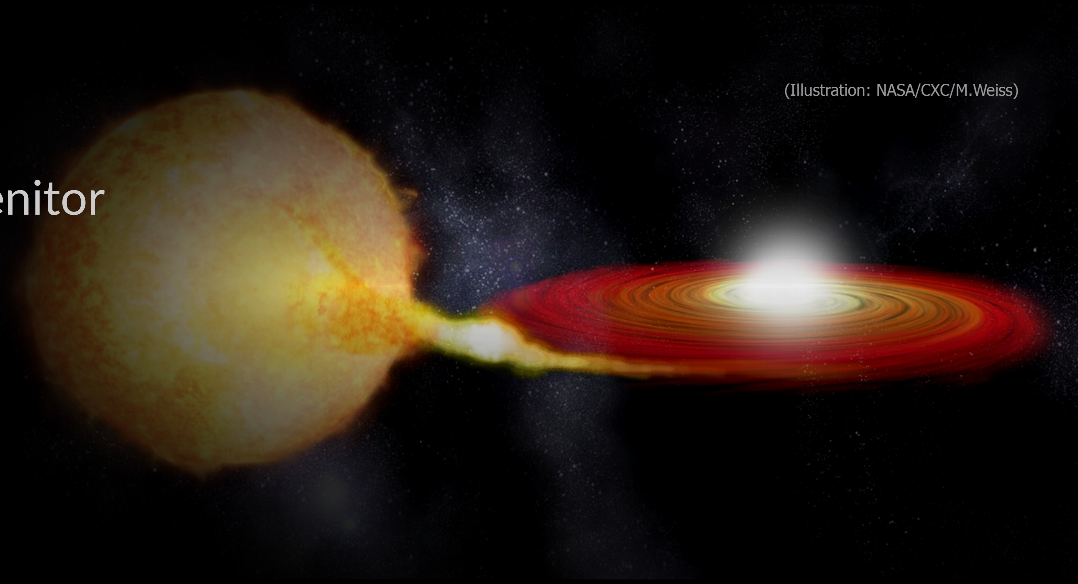
- **pure turbulent deflagrations**



Thermonuclear supernova scenarios

Chandrasekhar mass explosions


(Illustration: NASA/CXC/M.Weiss)

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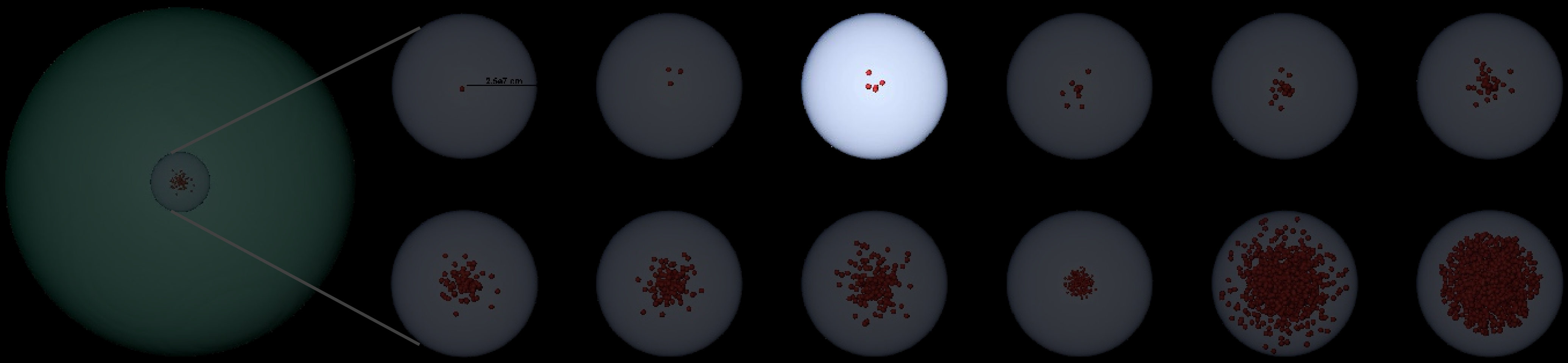
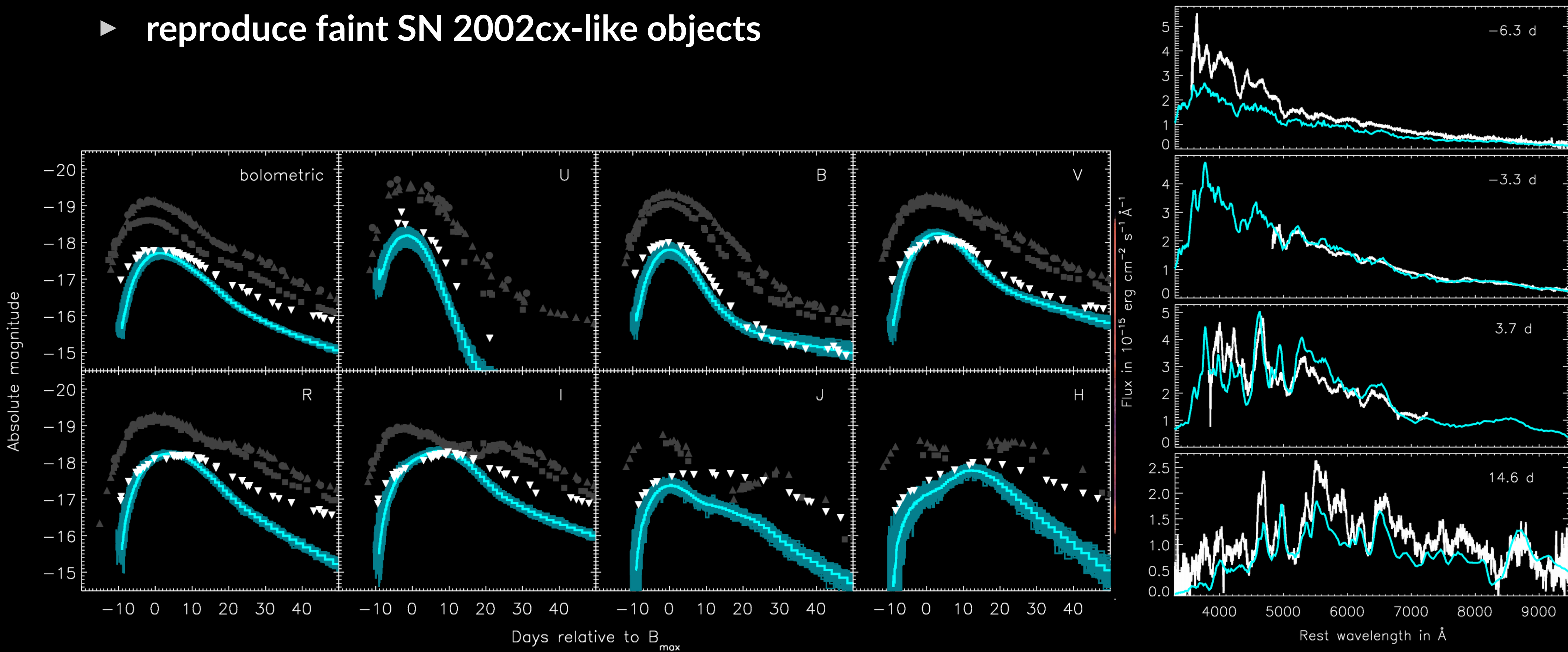


Seitenzahl+, 2012; Fink+, 2014

Thermonuclear supernova scenarios

Chandrasekhar mass explosions

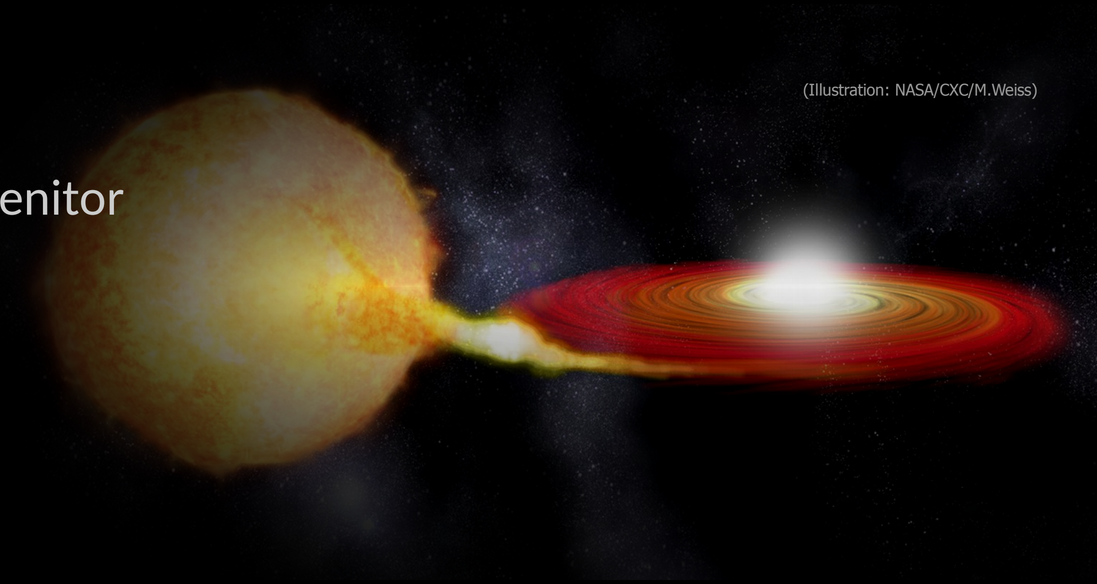
- associated with single-degenerate progenitor channel
- **pure turbulent deflagrations**
- **reproduce faint SN 2002cx-like objects**

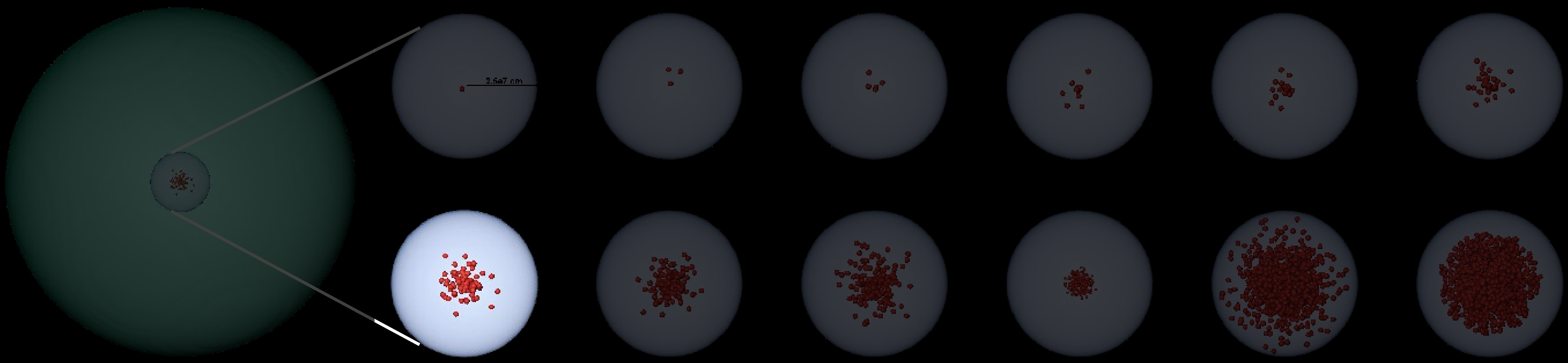


Thermonuclear supernova scenarios

Chandrasekhar mass explosions

- associated with single-degenerate progenitor channel
- **delayed detonations**





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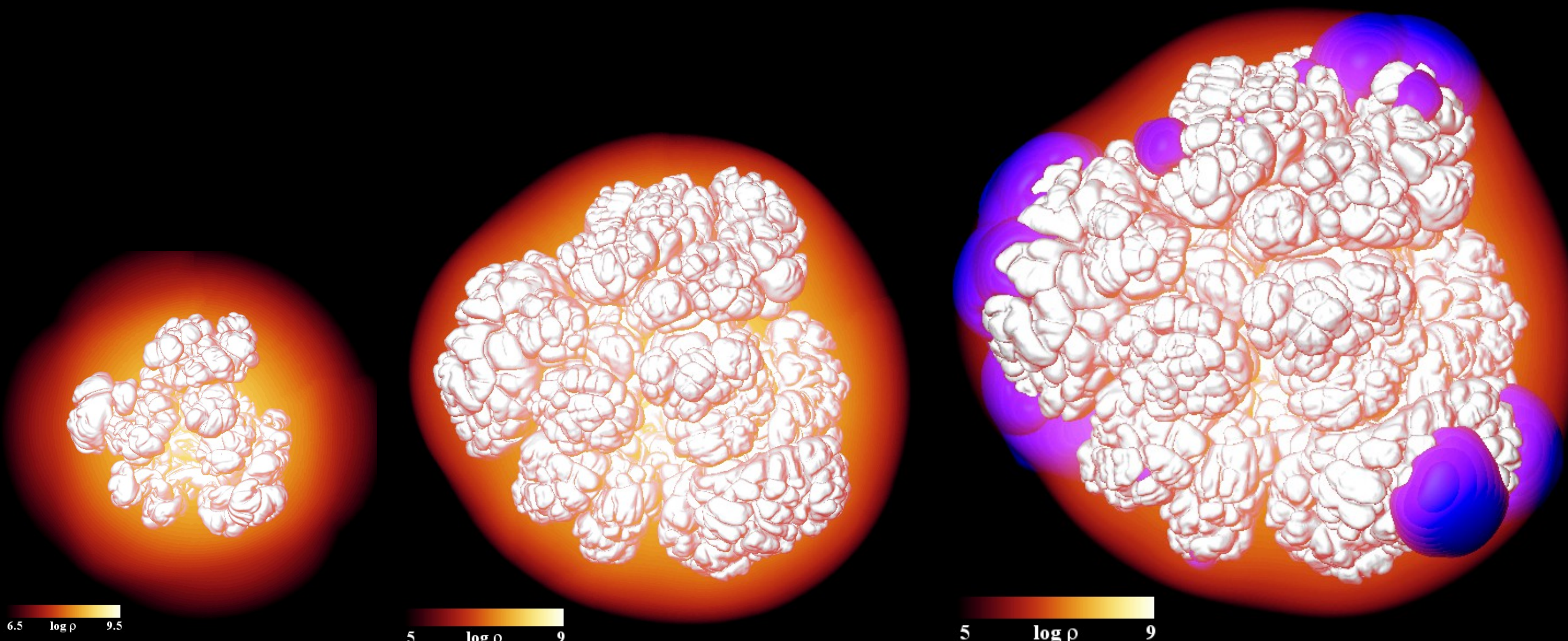


Seitenzahl+, 2012

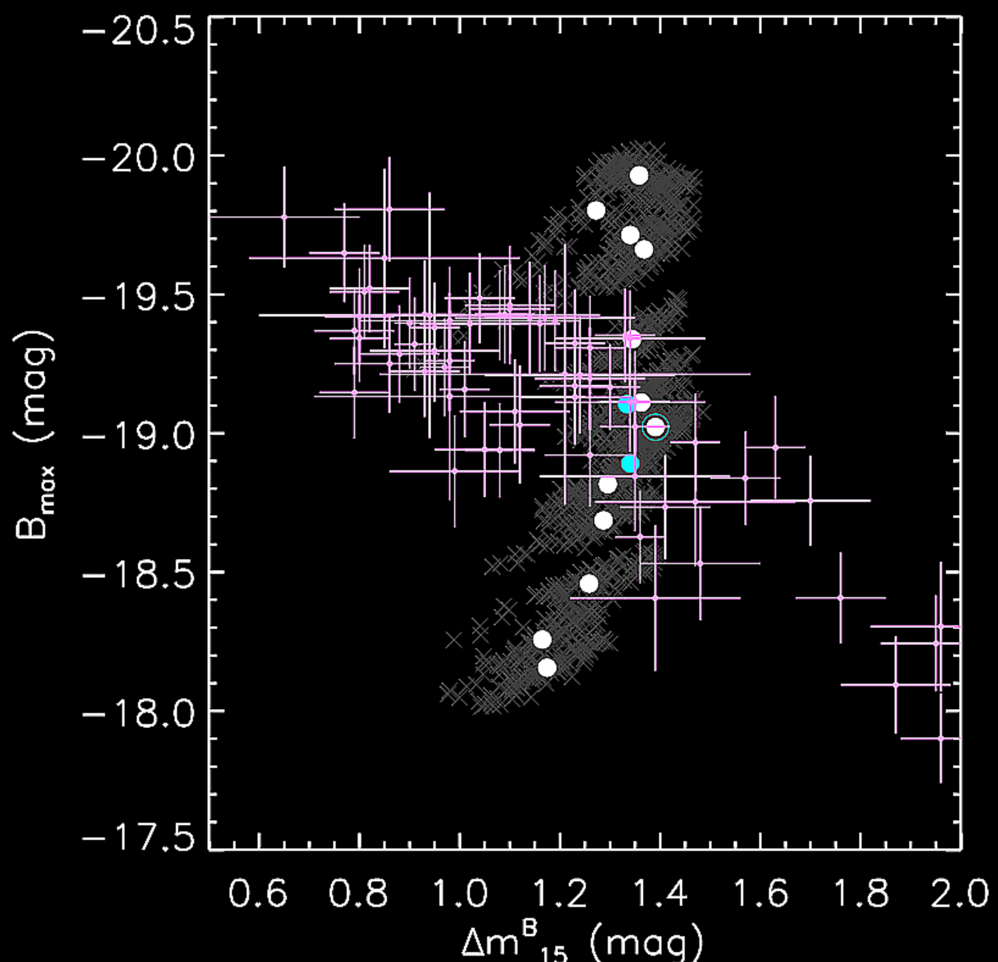
Delayed detonations in M_{Ch} WDs

- Model for normal SN Ia? → reasonable agreement with spectra of normal SNe Ia (Blondin+, 2011)

- **WLT and global trends???** → 2D study (Kasen+ 09) vs. 3D study (Sim+ 13)

- **Main problem:**

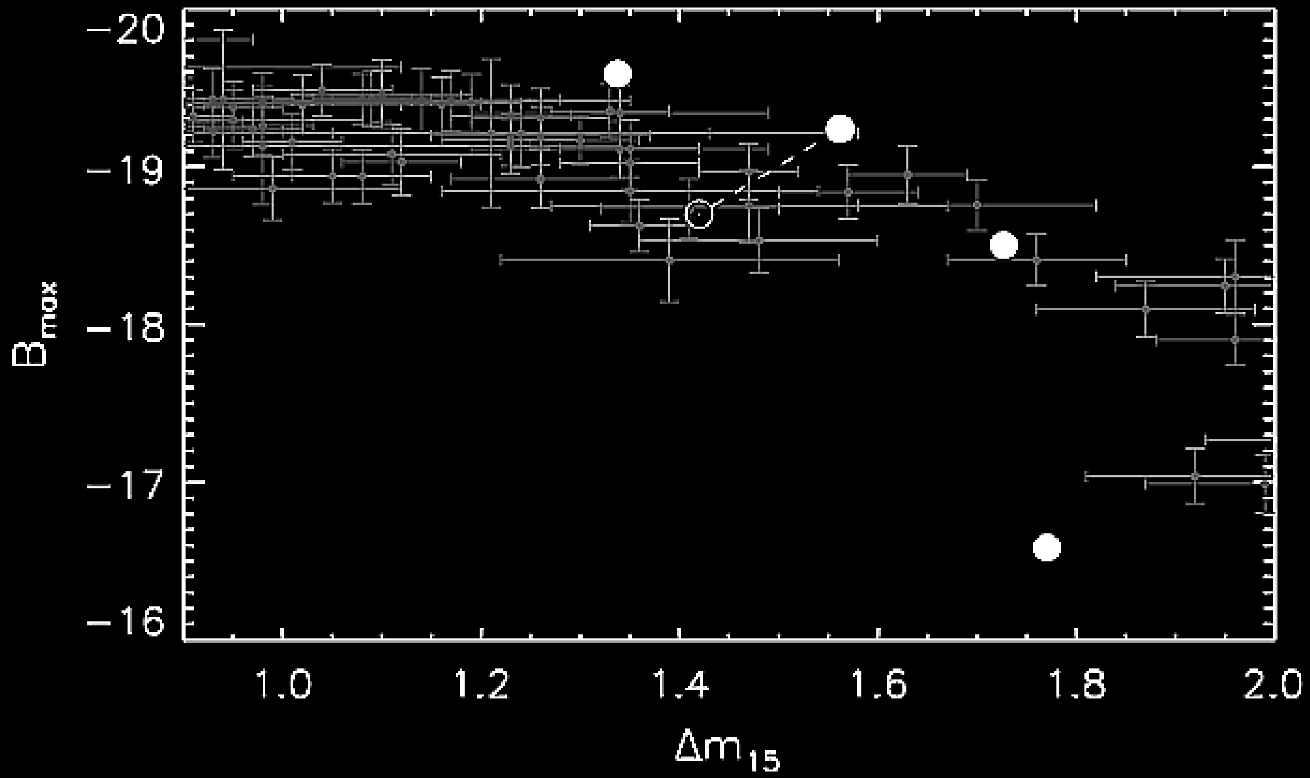
  Fixed mass → not enough fidelity for reproducing range of observables (?)



Thermonuclear supernova scenarios

Sub-Chandrasekhar mass explosions:

- In priciple capable of reproducing normal SNe Ia (Sim+, 2010)



Thermonuclear supernova scenarios

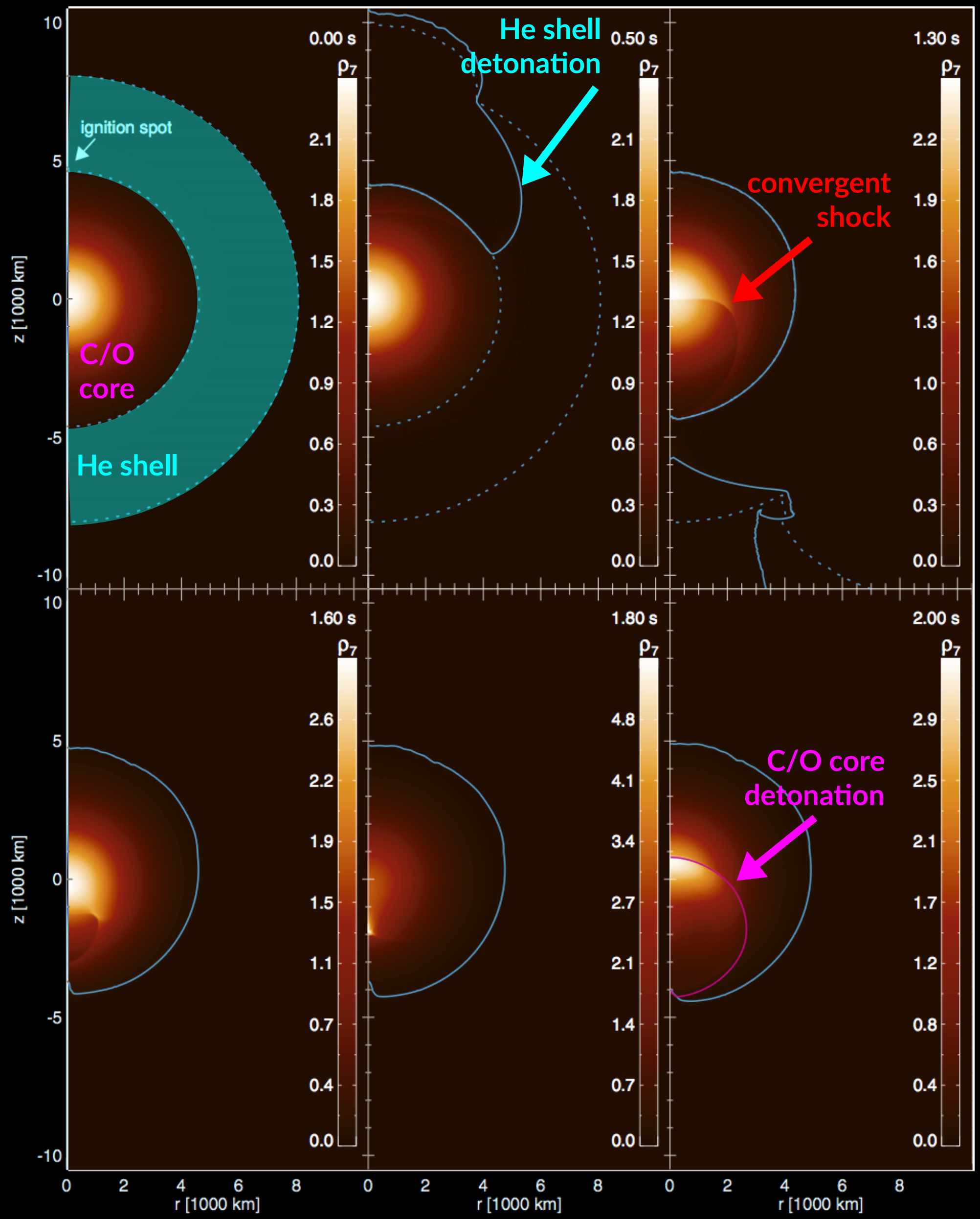
Fink+, 2010

Sub-Chandrasekhar mass explosions:

- In priciple capable of reproducing normal SNe Ia (Sim+, 2010)

double detonations?

- from single or double degenerate progenitor channel



Thermonuclear supernova scenarios

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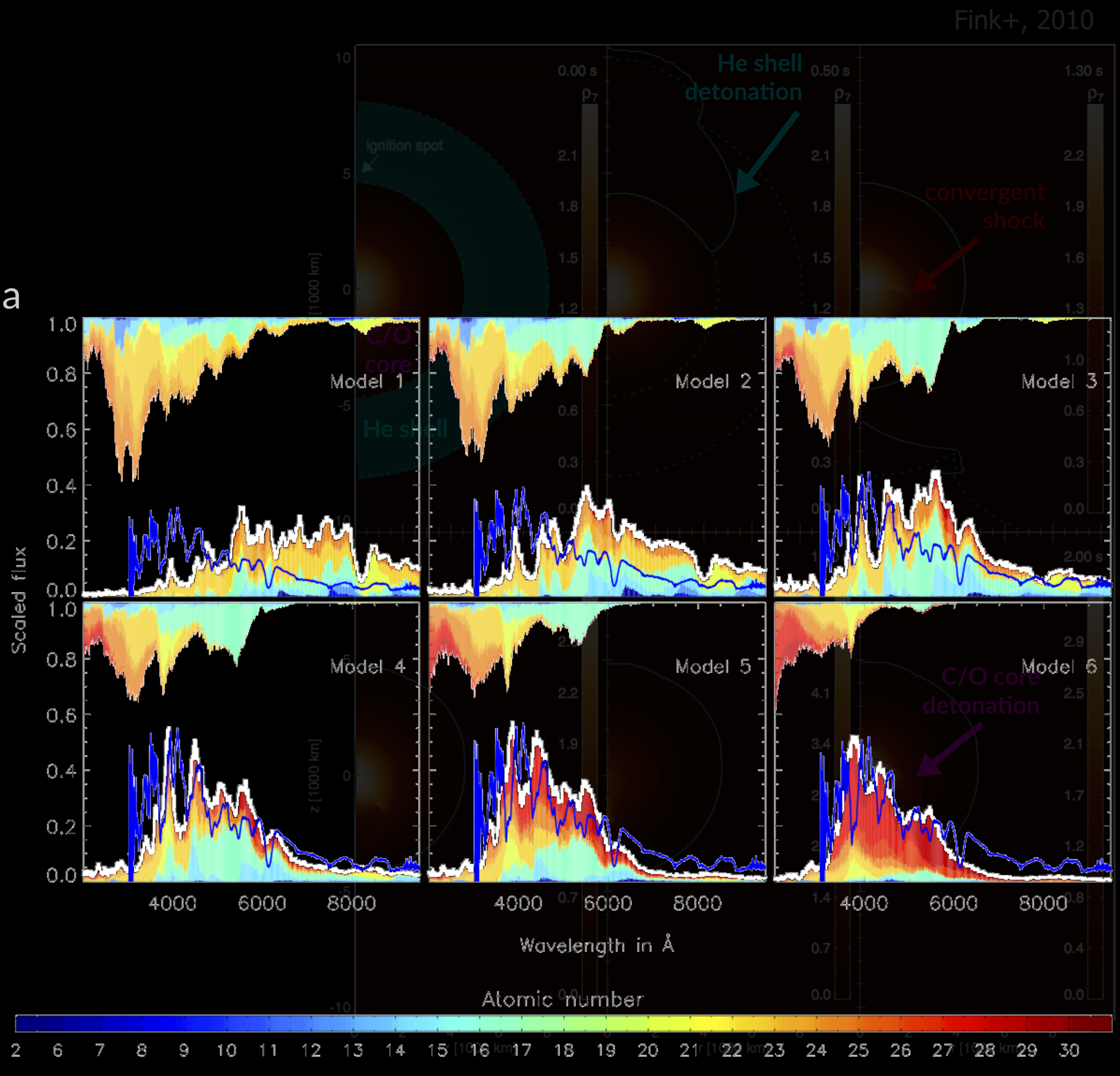
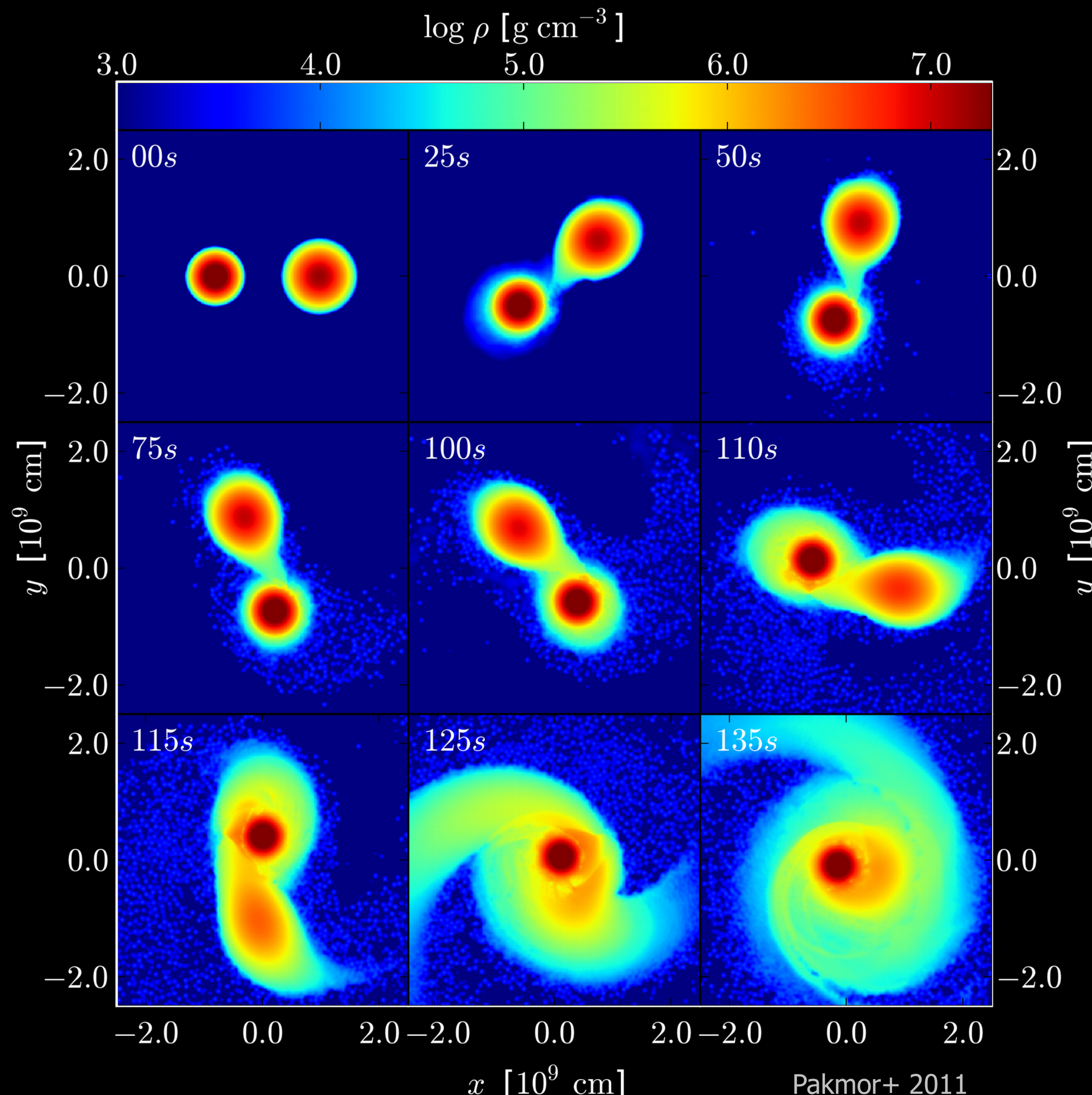


Thermonuclear supernova scenarios

double degenerate channel:

- Violent white dwarf mergers (Pakmor+ 2010, 2011, 2012, 2013)



Pakmor+ 2011

Thermonuclear supernova scenarios

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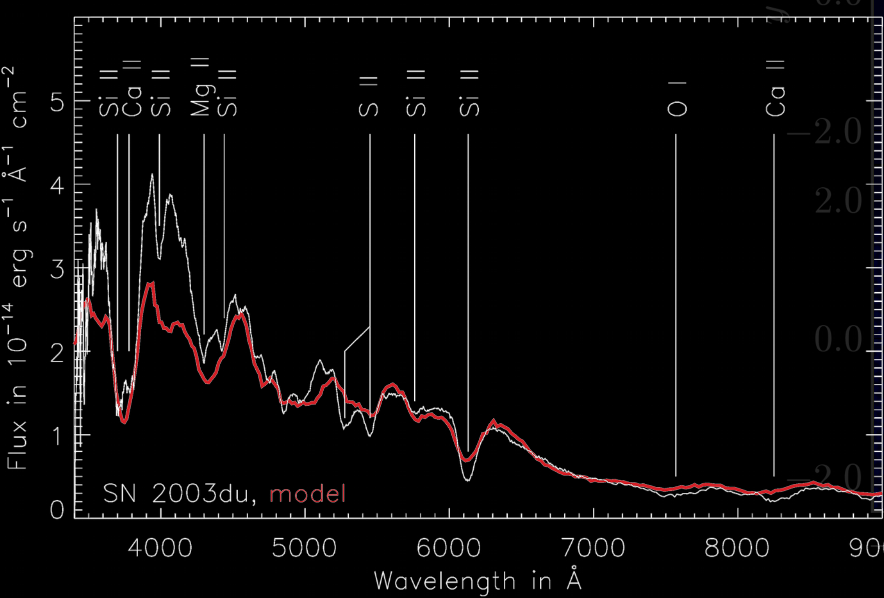
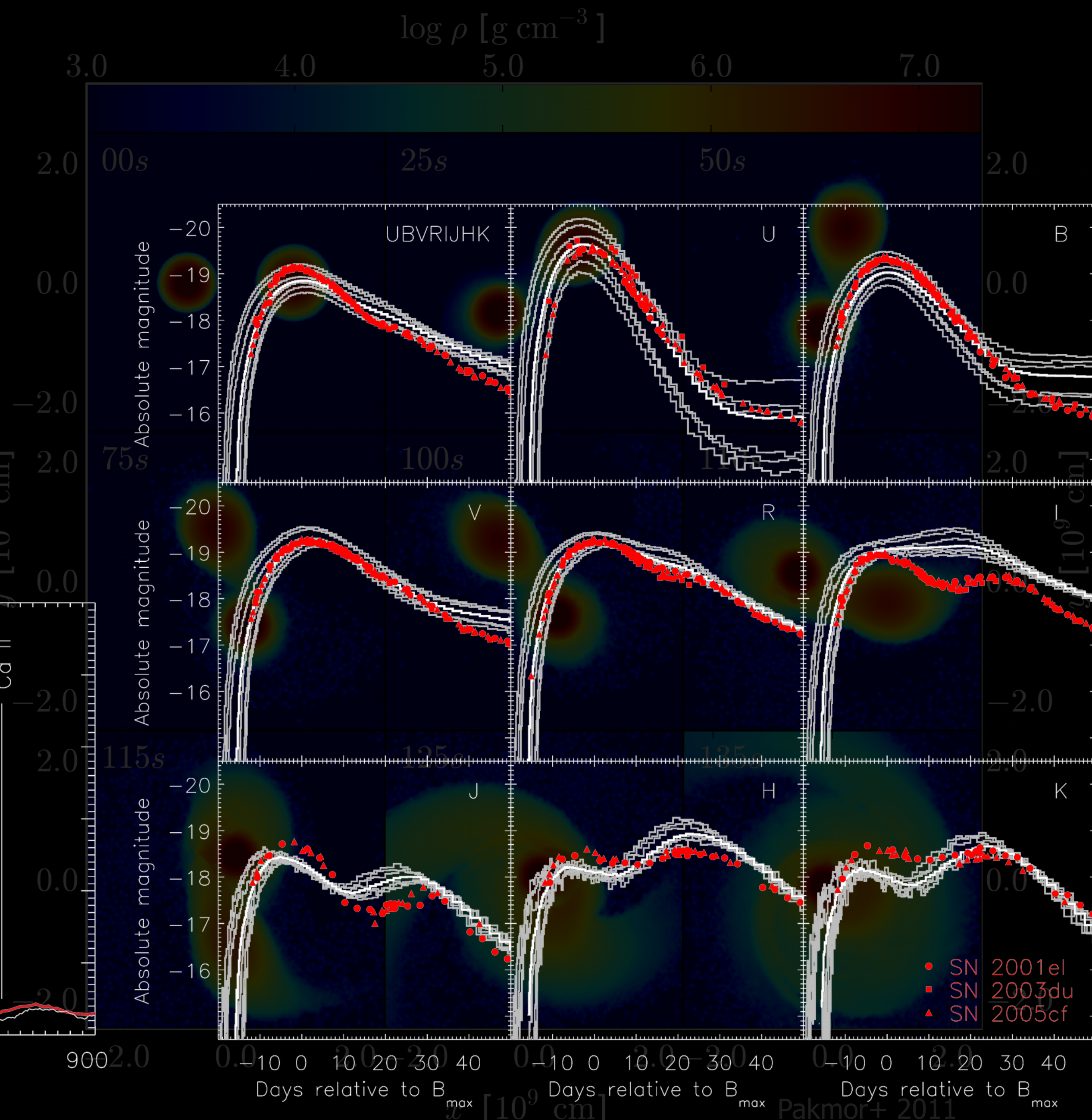
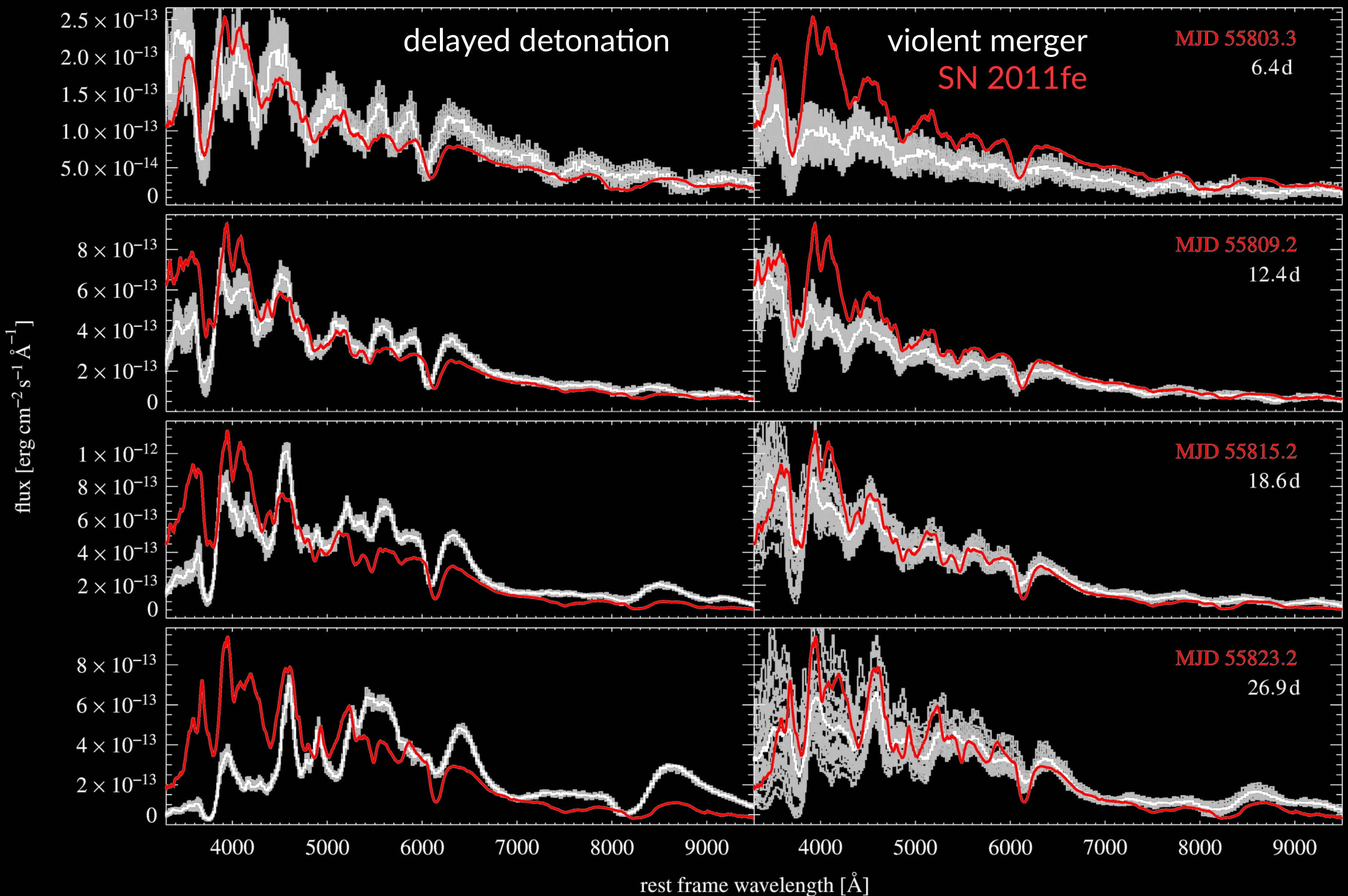




Identify discriminating observables

- Not much difference in optical
- Or not precise enough?

FR+ 2012



^{56}Ni production in different scenarios

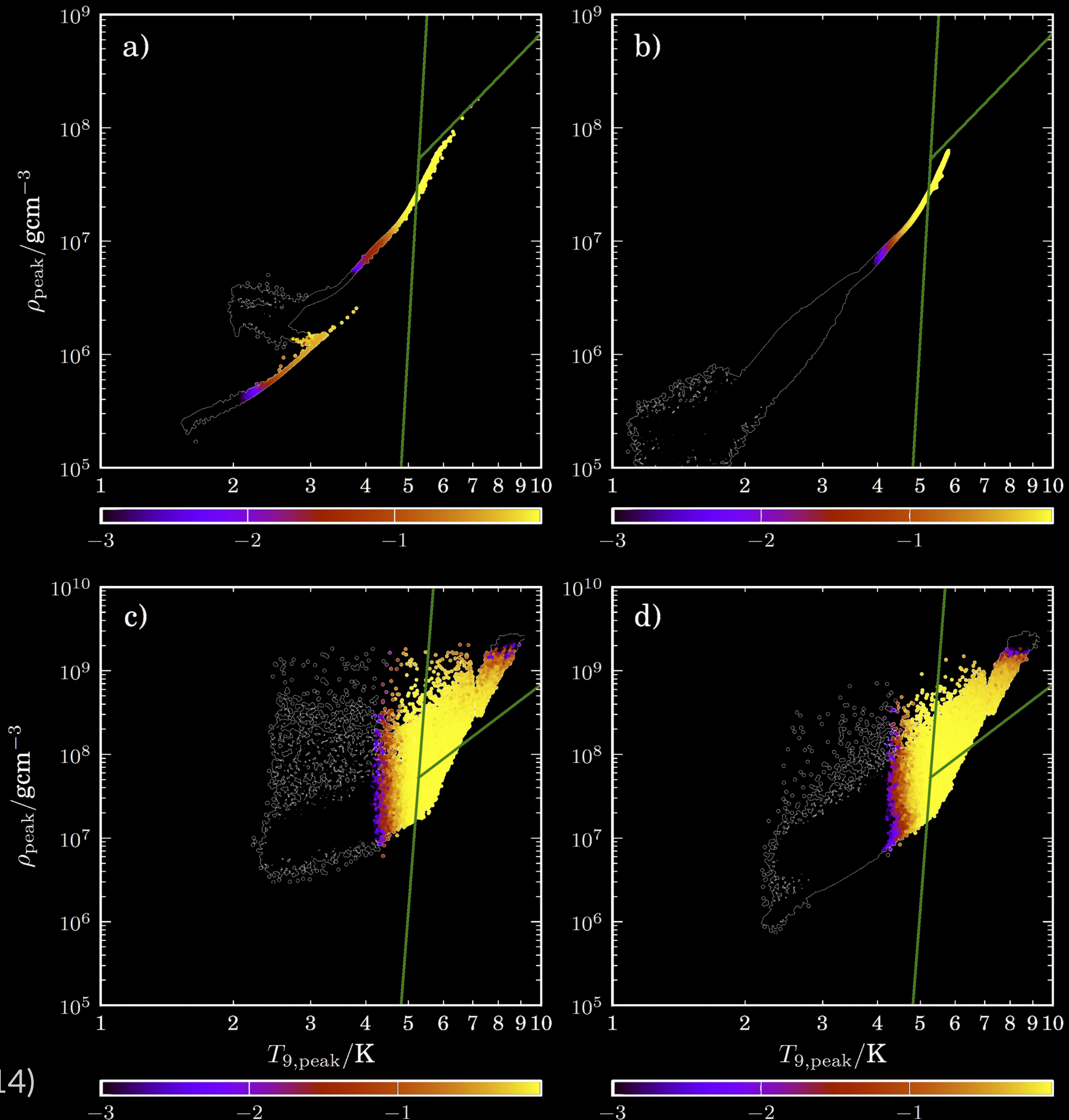
color: X(^{56}Ni)

a) double detonation in sub-M_{Ch} WD

b) violent merger of two WDs

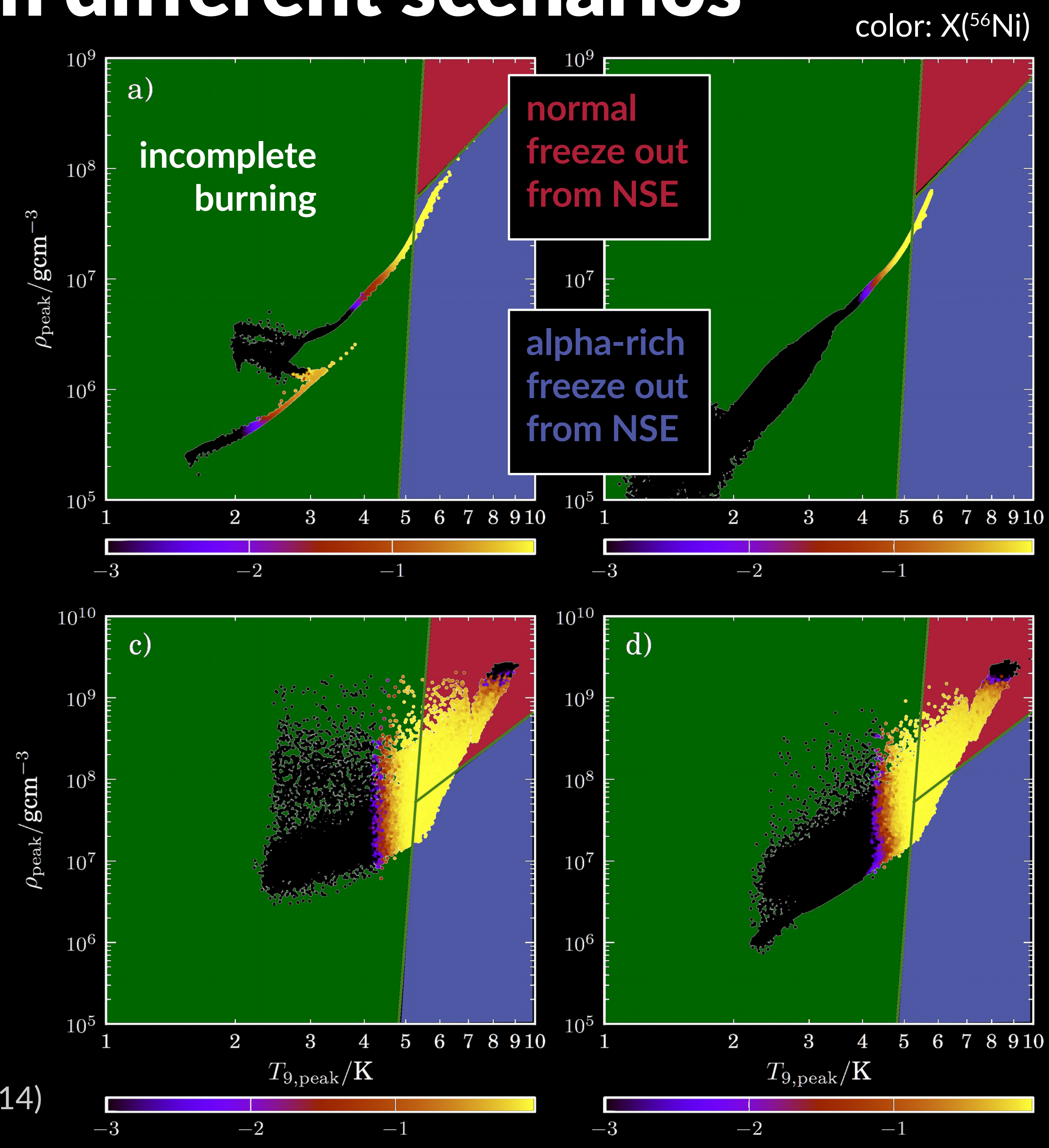
c) turbulent deflagration in M_{Ch} WD

d) delayed detonation in M_{Ch} WD



(F. Lach, bachelor thesis, University of Würzburg 2014)

^{56}Ni production in different scenarios

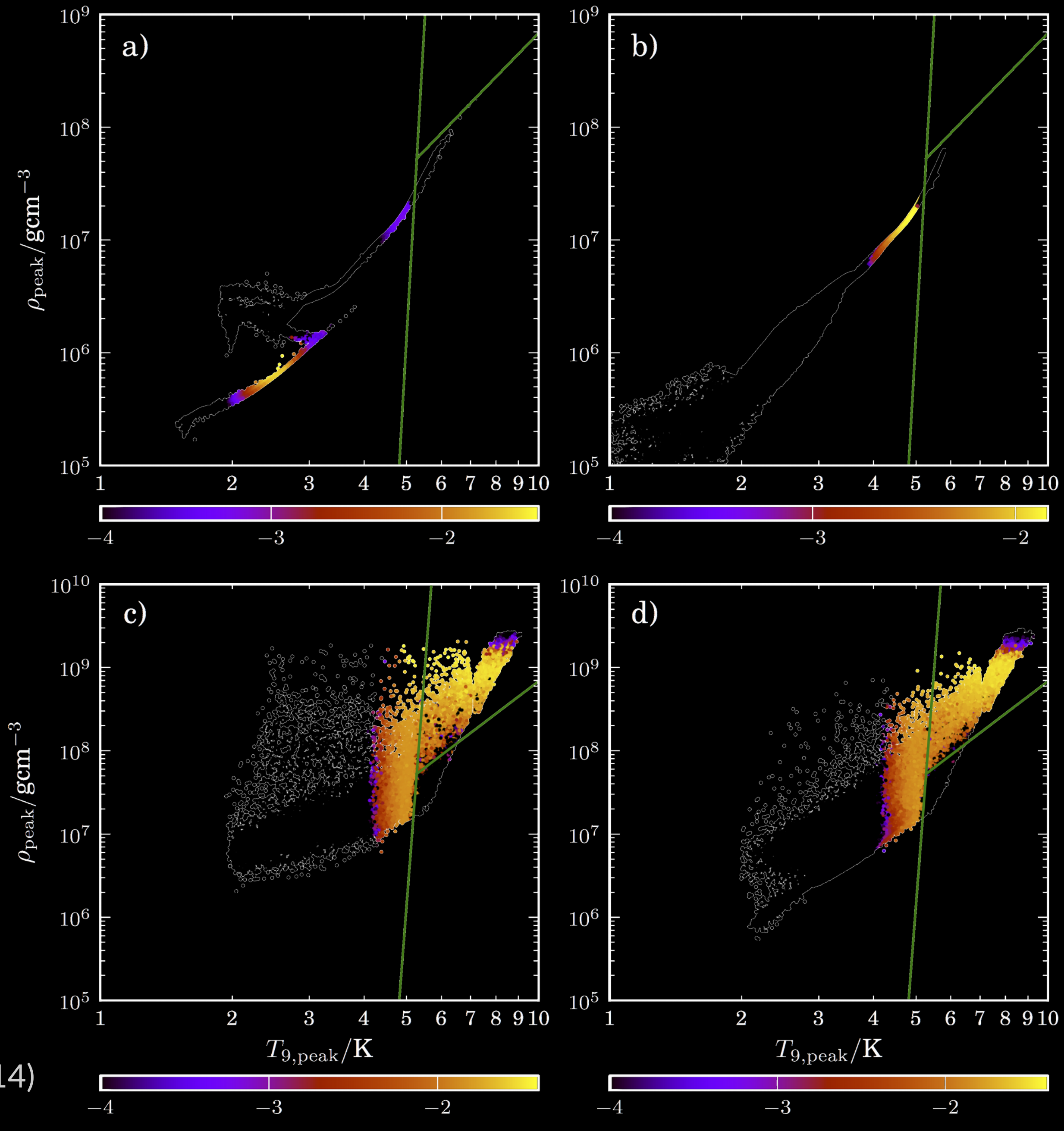


(F. Lach, bachelor thesis, University of Würzburg 2014)

^{55}Co production in different scenarios

color: X(^{55}Co)

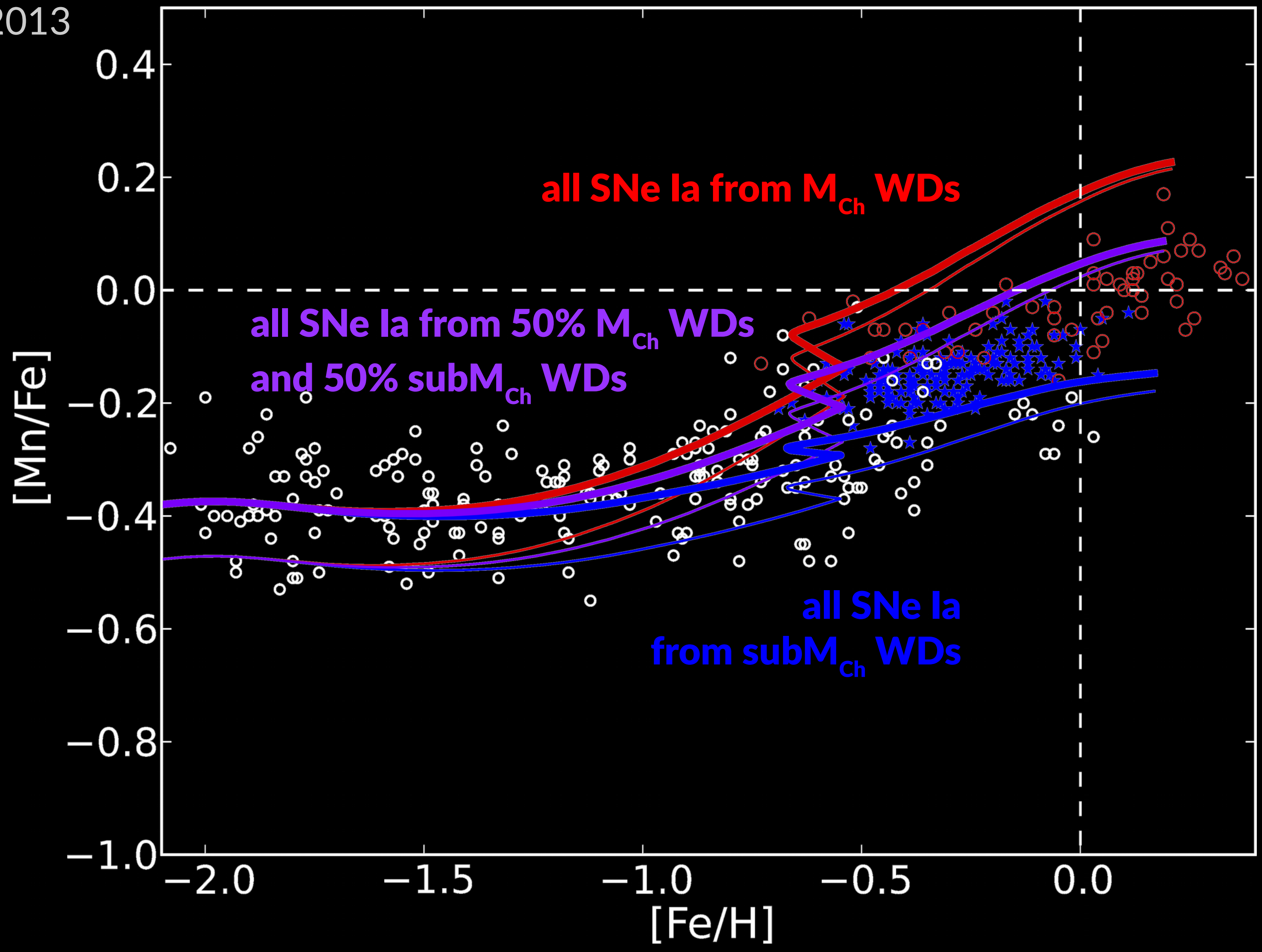
- destroyed during α-rich NSE freeze-out via $^{55}\mathrm{Co}(\mathrm{p},\gamma)^{55}\mathrm{Ni}$



(F. Lach, bachelor thesis, University of Würzburg 2014)

Production of manganese

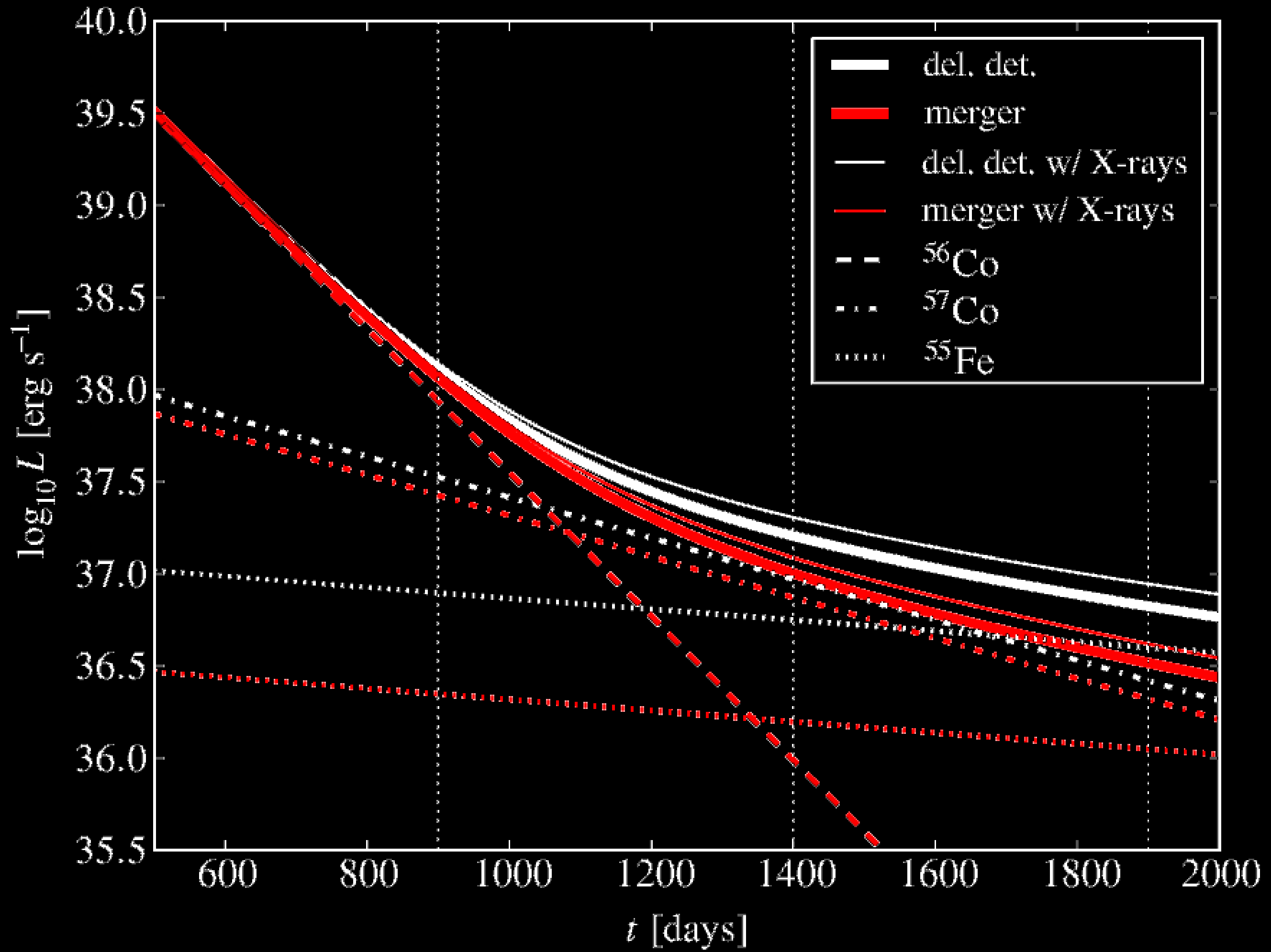
- Seitenzahl+ 2013



Identify discriminating observables

Promising alternatives:

- late observables (FR+ 2012)
- nucleosynthesis (Seitenzahl+ 2013)
- spectrapolarimetry (Bulla+ 2015, 2016)
- nebular spectra (Kozma+ 2005)
- gamma ray observables (Summa+ 2014)
- remnant studies (Badenes+ 2007)



Conclusions

- SNe Ia substantially contribute to GCE

- modeling in successful 3D simulations
- details of the explosion process need further study
- realistic progenitor models are urgently needed

- precise nuclear physics data necessary to pin down explosion mechanism and details of contribution to GCE