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ADVANCED COMPUTING  
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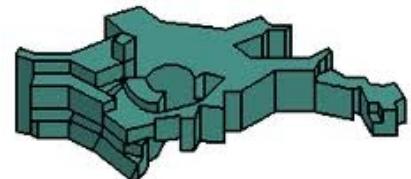
# 3D Simulations of Thermonuclear Supernova Explosions

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ASTROPHYSIK

# Overview

## Part 0: PRACE

## Part I: Some background on Thermonuclear Supernovae

## Part II: Explosion Models

- ▶ Introduction
- ▶ Deflagrations and Detonations
- ▶ Hydrodynamical Explosion Simulations

## Part III: Predicting Observables

- ▶ Nucleosynthesis
- ▶ Radiative Transfer
- ▶ Comparing Simulations with Observations
  - ▶ Nucleosynthetic yields
  - ▶ Optical spectra
  - ▶ High energy photons (Gamma and X-rays)
  - ▶ Late-time light curves

## Part IV: Summary

# Part 0: Thank you, PRACE!

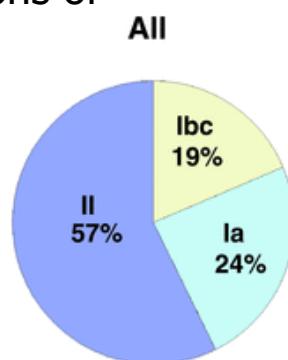
For the PRACE early access call we were awarded 23.600.000 core-hours for “**Type Ia supernovae from Chandrasekhar-mass white dwarf explosions**” (PI: Röpke).

For the follow-up project “**Diversity of Type Ia supernovae from initial conditions of the exploding white dwarf star**” (PRA042, PI: Seitenzahl) we were subsequently awarded 21.600.000 core-hours (220 RD, roughly 14 RD / month) on JUGENE. The project duration was May 1<sup>st</sup> 2011 – April 30<sup>th</sup> 2012.

The data generated in the project resulted in four publications in scientific journals (Astronomy & Astrophysics, Monthly Notices of the Royal Astronomical Society, The Astrophysical Journal Letters) and four more publications have been submitted/are being prepared. The project was featured as a “Success Story” in the PRACE Annual Report 2012.

# Part I: Thermonuclear Supernovae

- ▶ SN Ia spectroscopically defined by absence of hydrogen and presence of strong silicon absorption in spectra
- ▶ Unlike SN II and SN Ib/c, SN Ia occur also in apparent absence of recent star formation (e.g. elliptical galaxies)
- ▶ Connection to old stellar population excludes gravitational collapse of massive stellar cores
- ▶ No progenitor or compact remnant has ever been identified, leaving thermonuclear incinerations of compact white dwarf stars as the only explosion mechanism
- ▶ Details of explosion mechanism remain unknown and debated



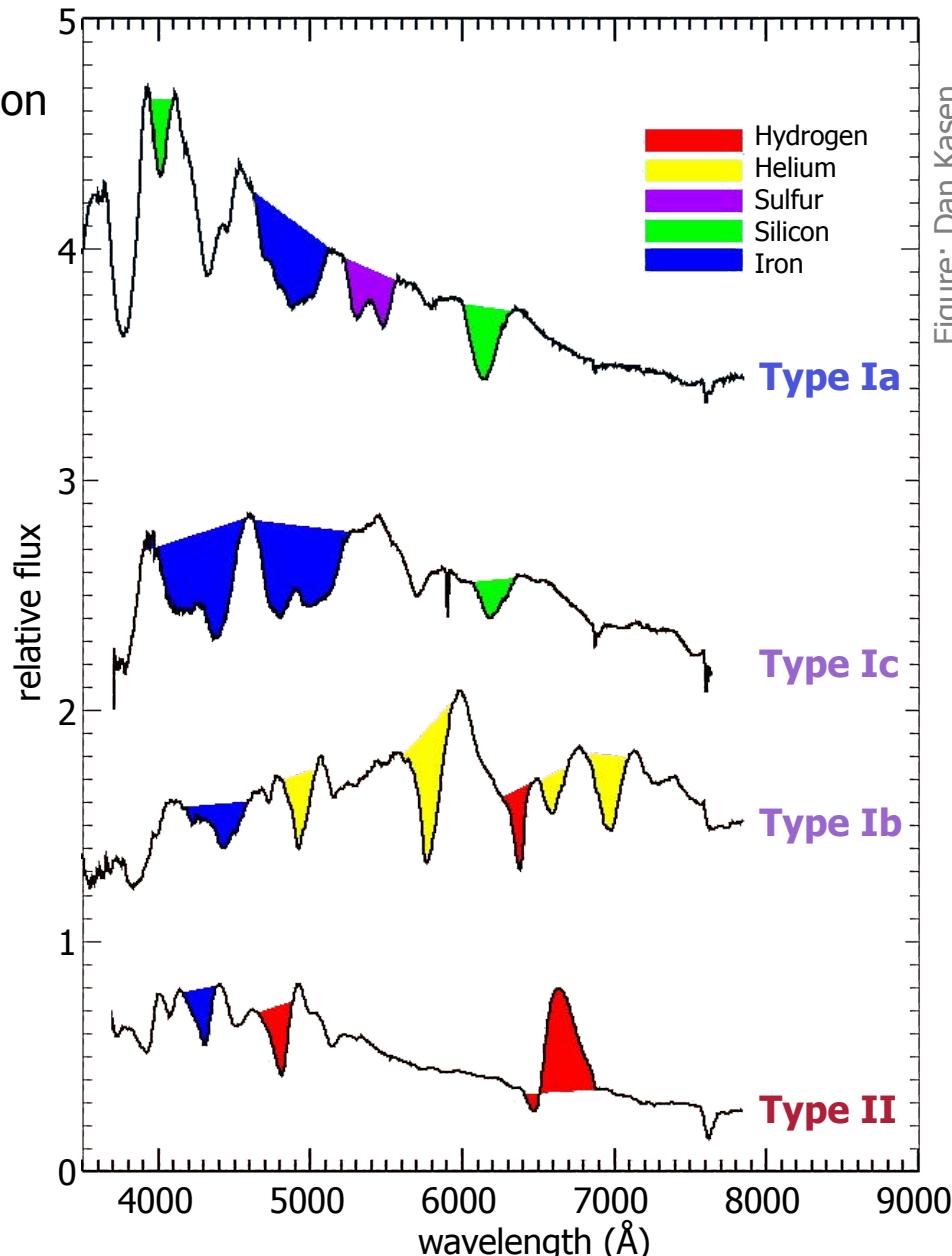
Li et al. (2011), MNRAS 412, 441



SN 2011fe, Imagecredit: Thunderf00t

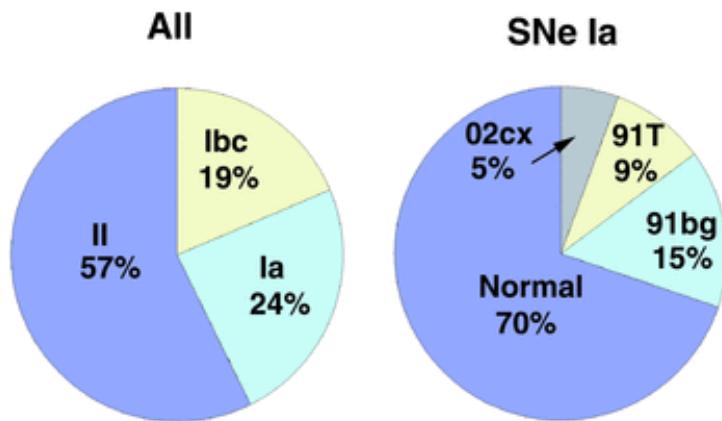
# Classification of supernovae

- ▶ astronomical classification according to spectral features



# Classification of supernovae

- ▶ physical classification according to energy source
- ▶ thermonuclear (SNe Ia) are further divided into sub-categories based on observational characteristics



Li et al. (2011), MNRAS 412, 441

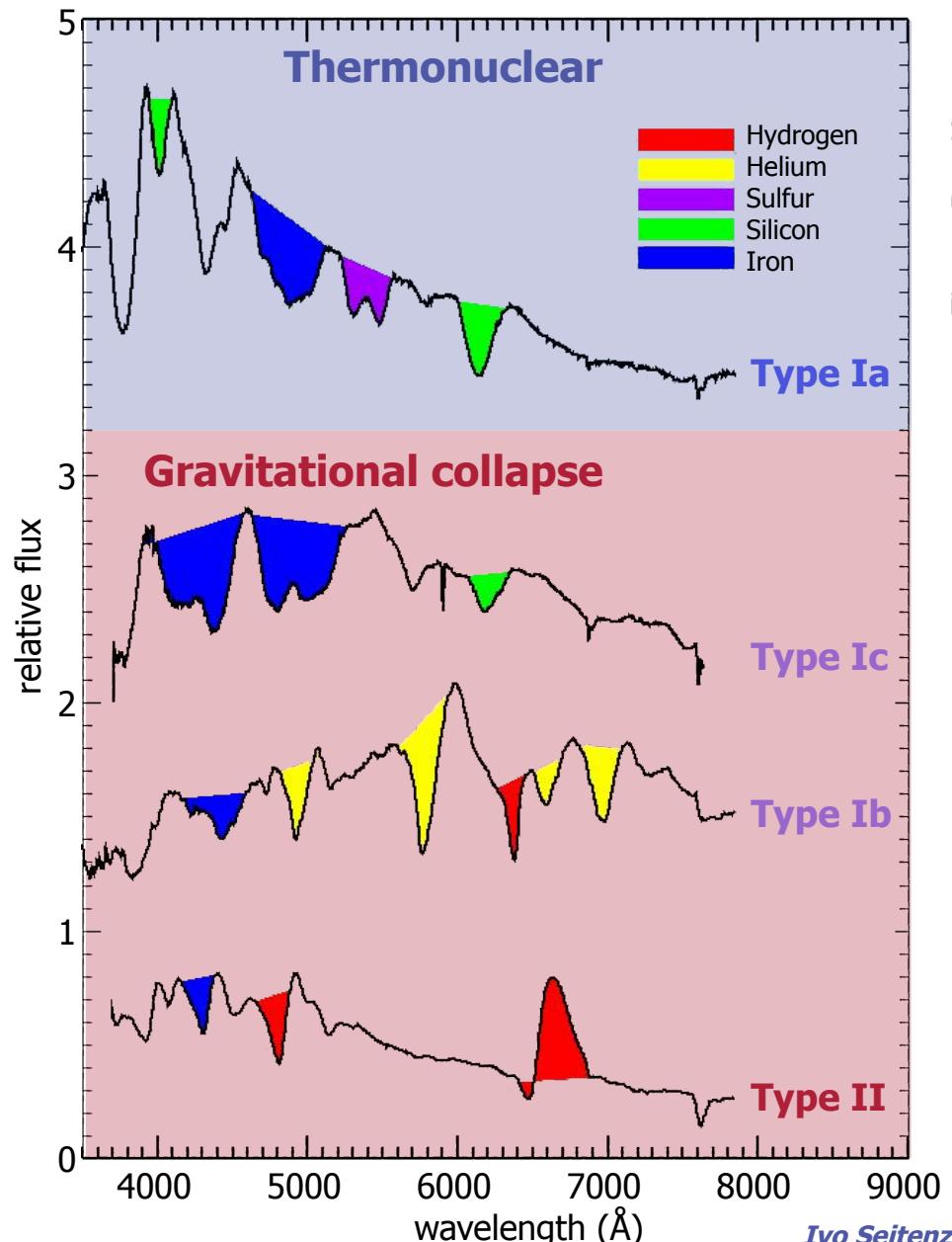


Figure: Dan Kasen

# Nobel Prize in Physics 2011

- ▶ Nobel Prize 2011 was awarded for the discovery of the acceleration of the expansion of the Universe
- ▶ SN Ia were used by Supernova Cosmology Project (Perlmutter) and High-Z SN search team (Schmidt, Riess) as standard candles
- ▶ High-redshift SNe were fainter than expected  
→ Universe very close to flat, but expansion is accelerating



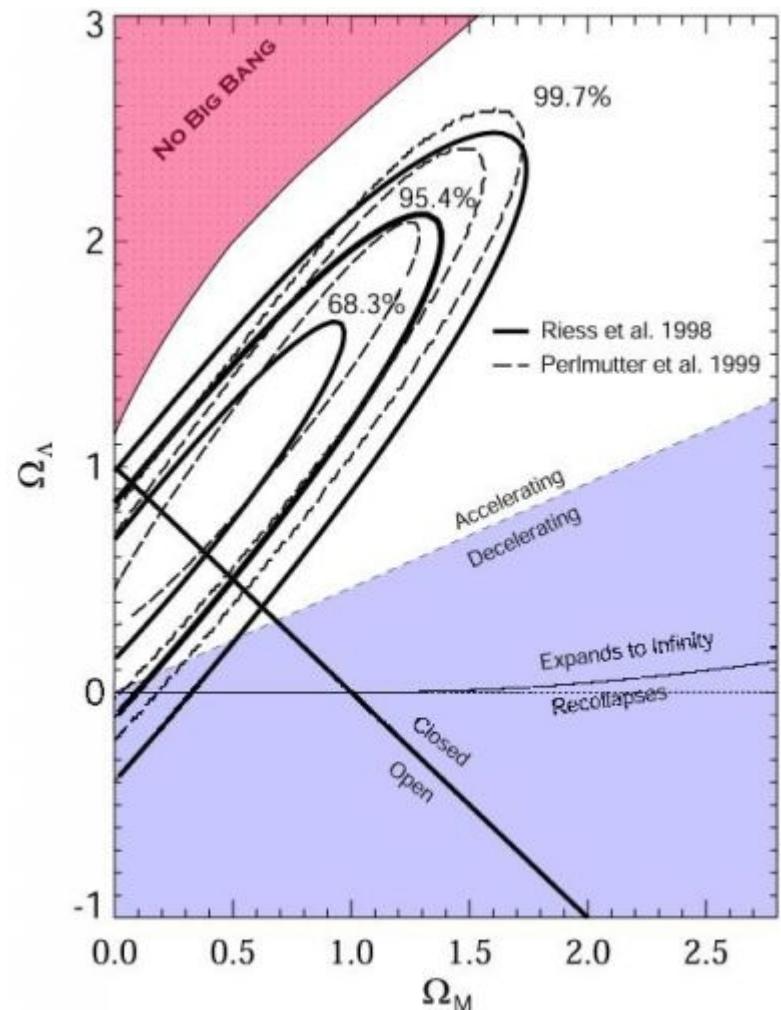
Saul Perlmutter



Brian P. Schmidt

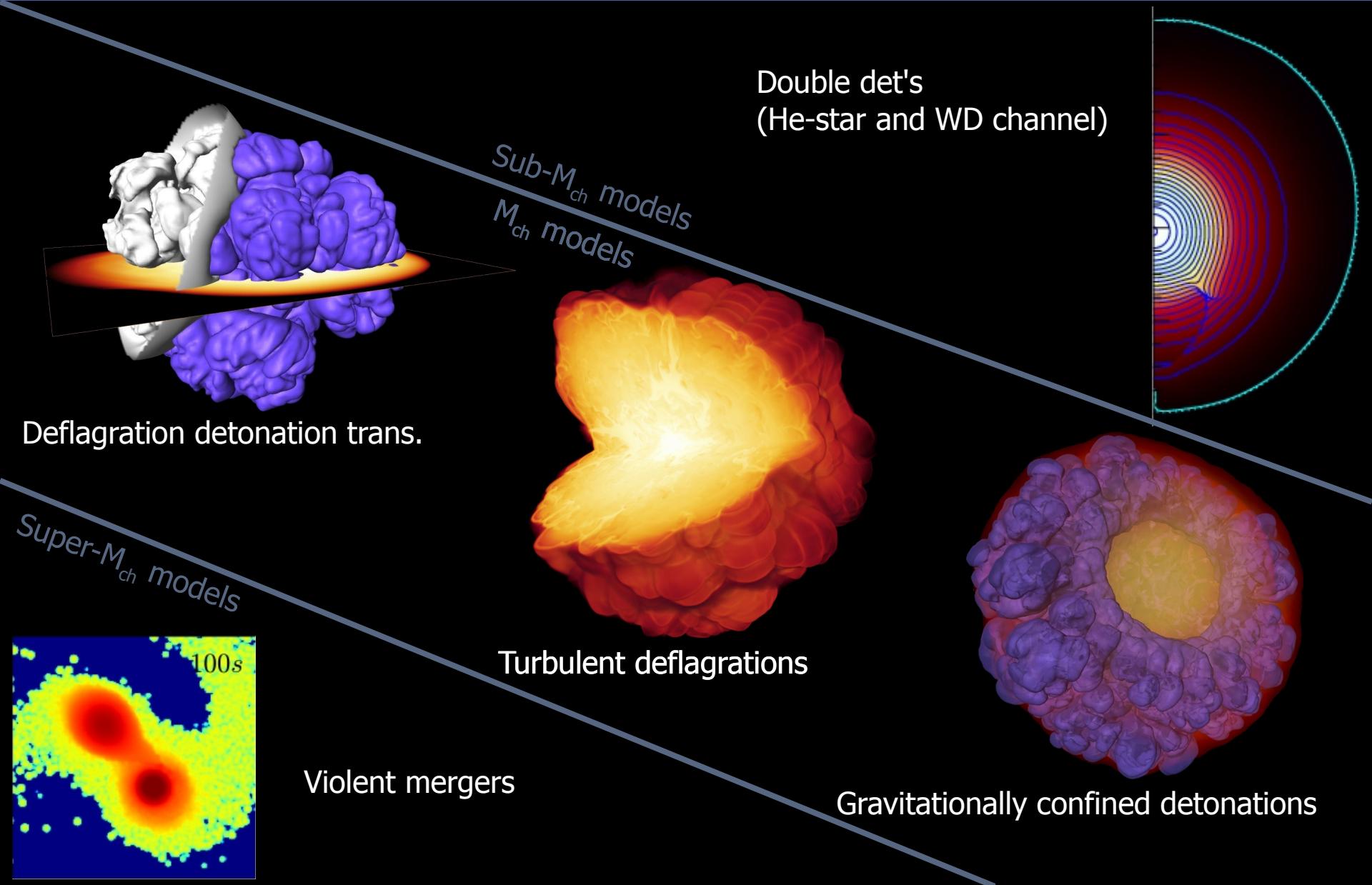


Adam G. Riess

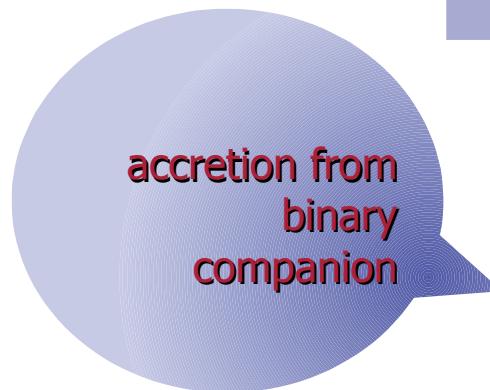


"The Nobel Prize in Physics 2011". Nobelprize.org. 4 Nov 2011  
[http://www.nobelprize.org/nobel\\_prizes/physics/laureates/2011/](http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/)

## Part II: some popular explosion scenarios



# Chandrasekhar-mass scenario



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

- ▶ 1 century of convective carbon burning

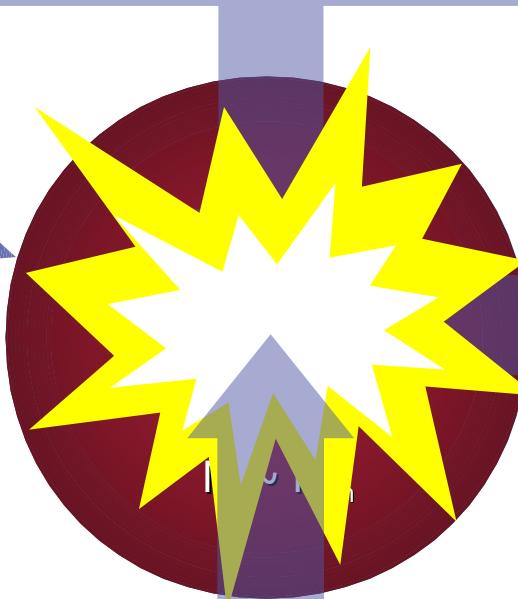


Figure: F. Röpke

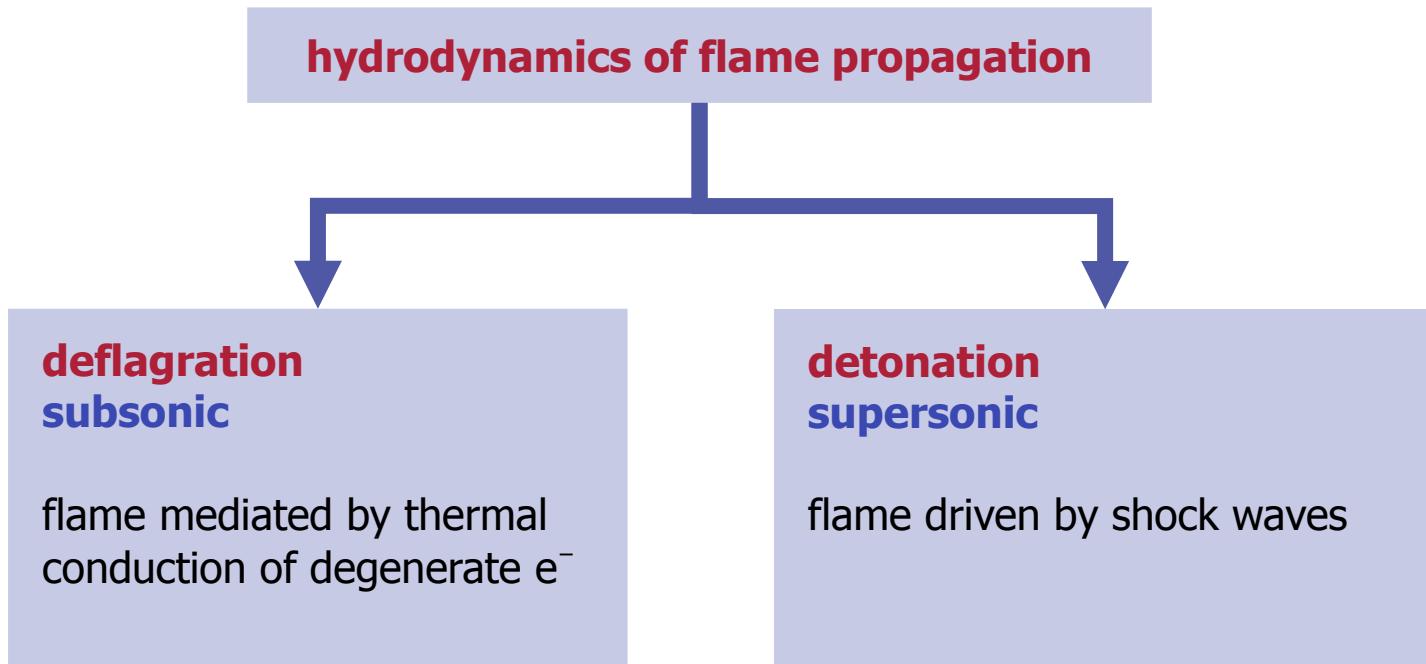
flame ignition due to  
thermonuclear runaway

- ▶ number/distribution of ignition sparks?

explosion due to flame propagation

- ▶ produced  $^{56}\text{Ni}$  makes event bright

# Flame propagation and burning



# $M_{\text{Ch}}$ model: turbulent combustion

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

- ▶ buoyancy instabilities lead to turbulent combustion

inherently three-dimensional problem

→ need for HPC

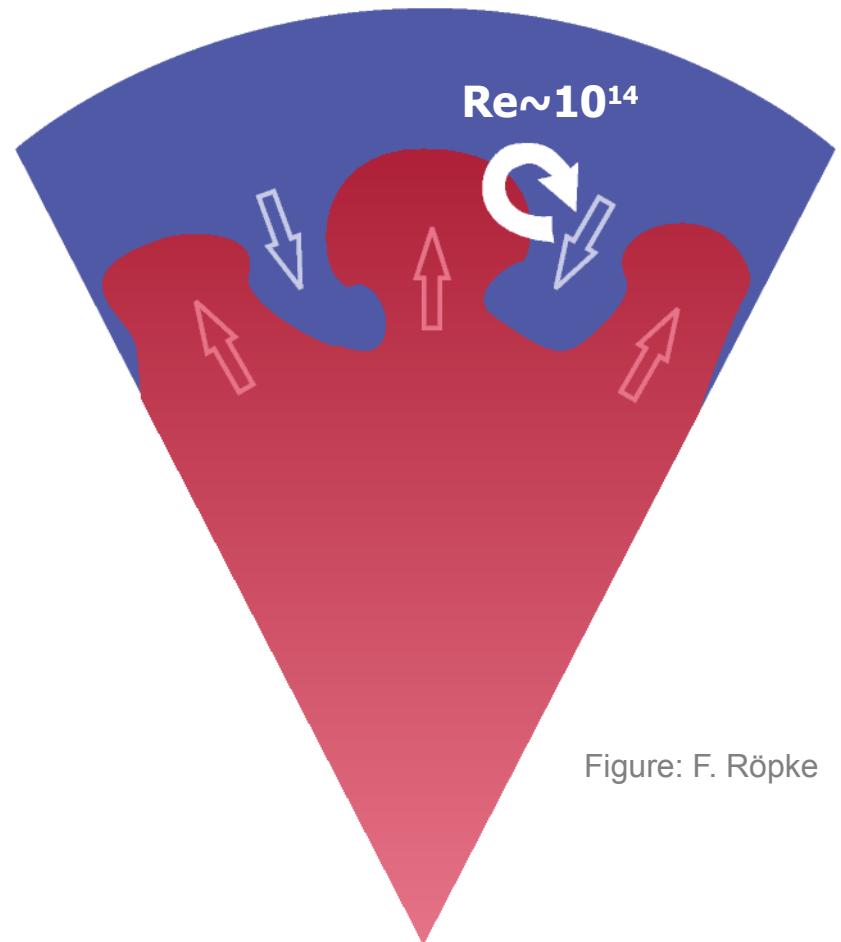
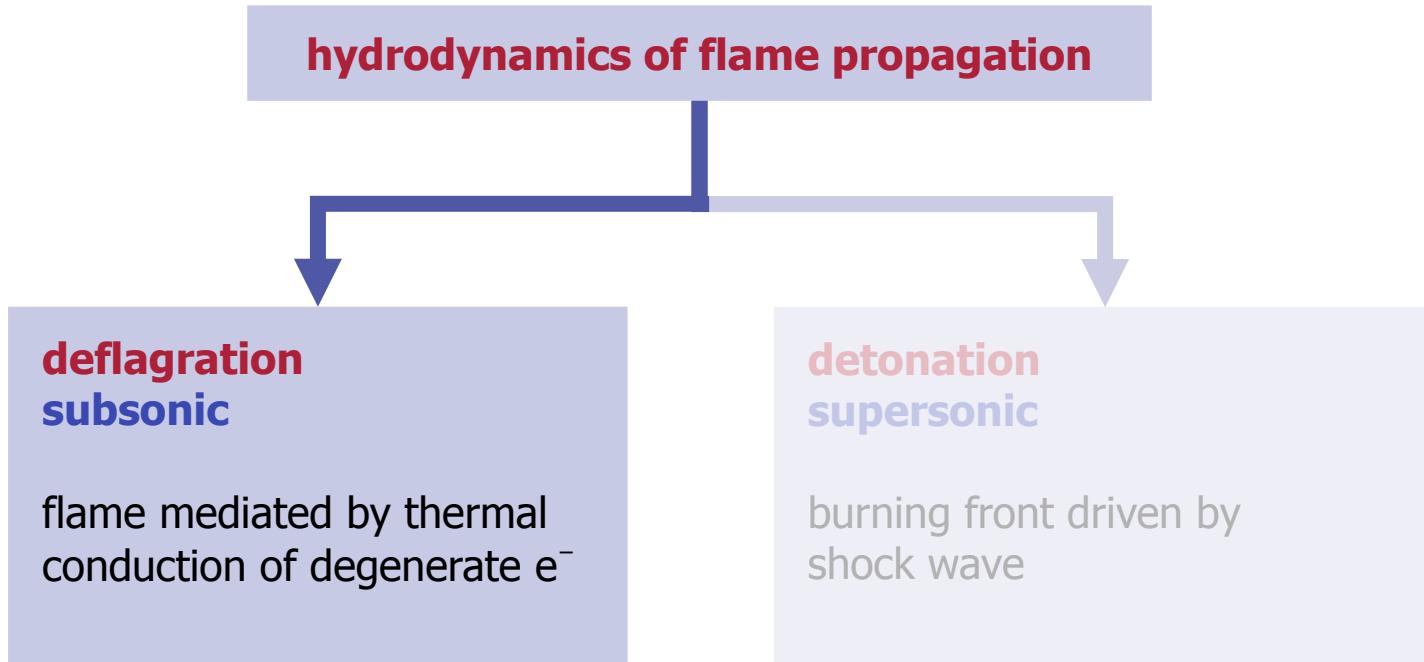


Figure: F. Röpke

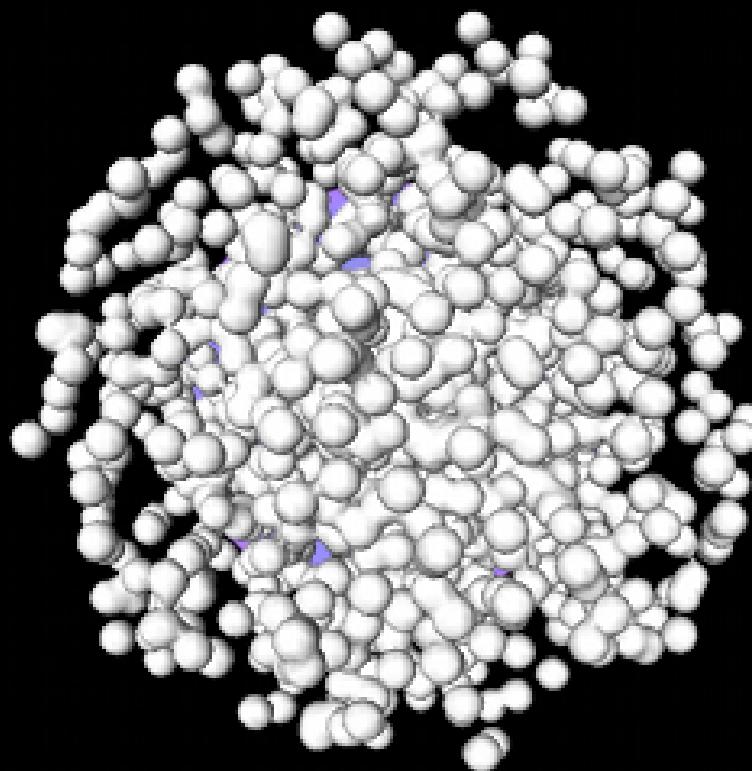
# Burning starts with deflagration



# $M_{\text{Ch}}$ model: turbulent deflagrations

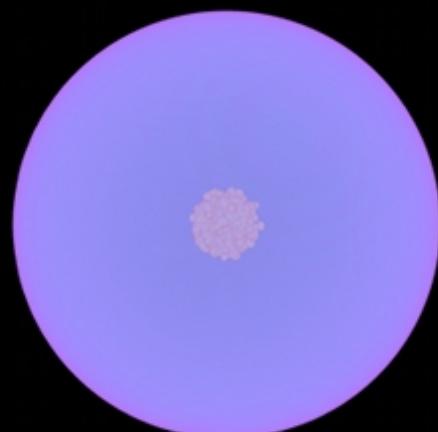
## PRACE early access

$t = 0.025 \text{ sec}$



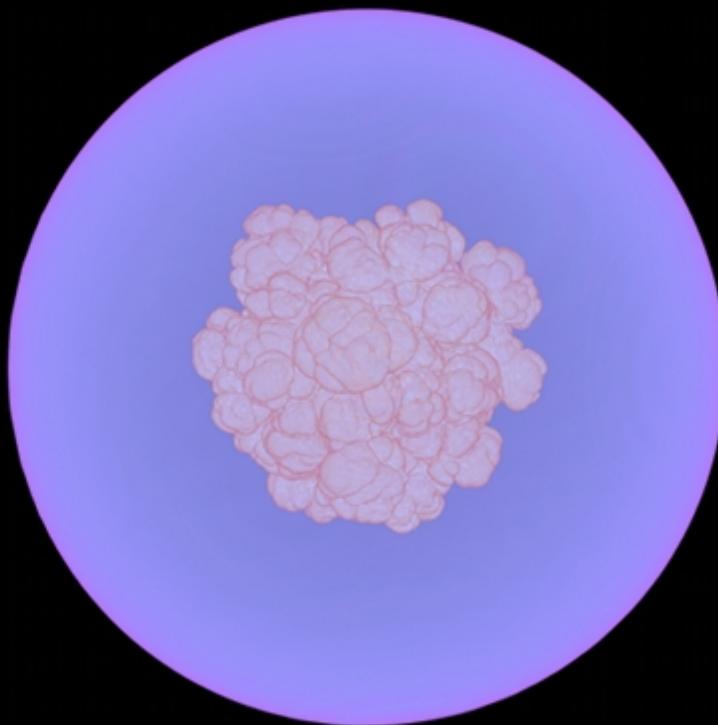
# $M_{Ch}$ model: turbulent deflagrations

$t = 0.200 \text{ sec}$



# $M_{\text{Ch}}$ model: turbulent deflagrations

$t = 0.600 \text{ sec}$



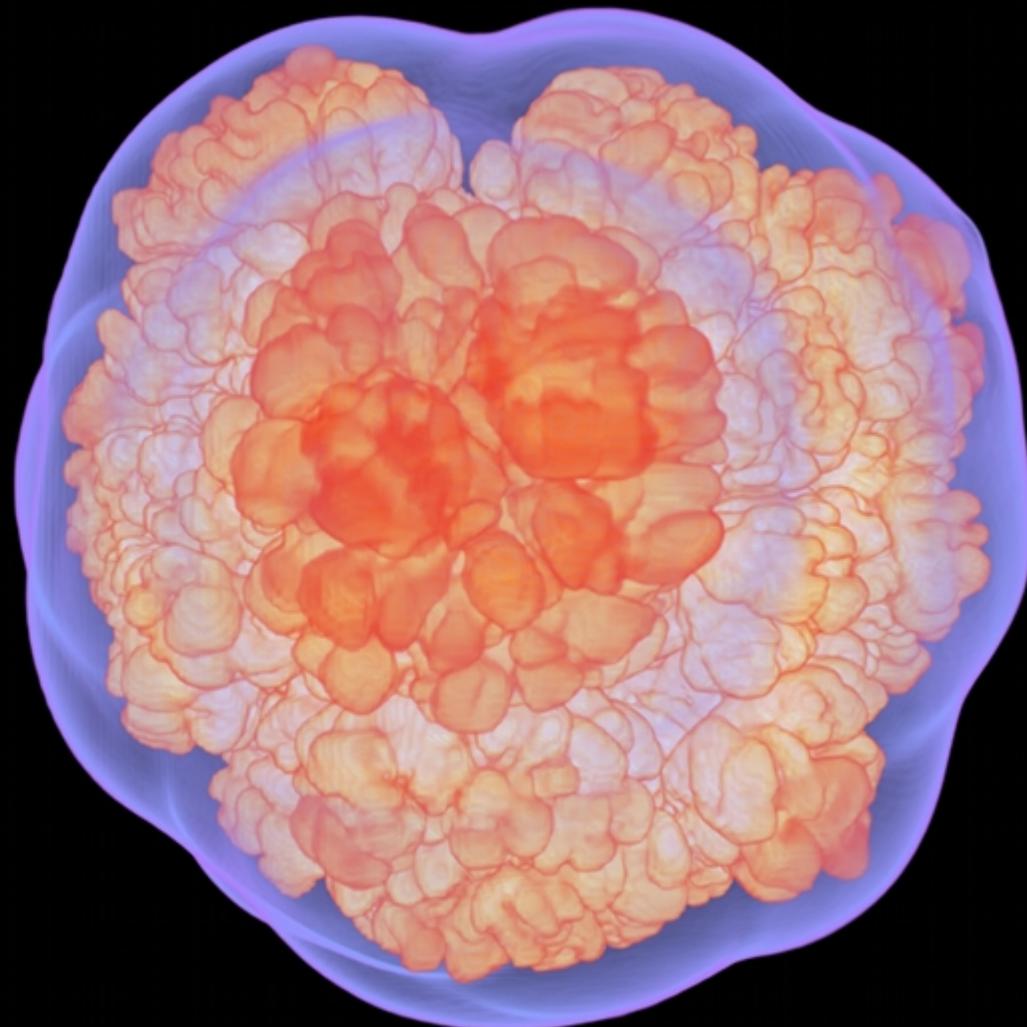
# $M_{\text{Ch}}$ model: turbulent deflagrations

$t = 1.000 \text{ sec}$



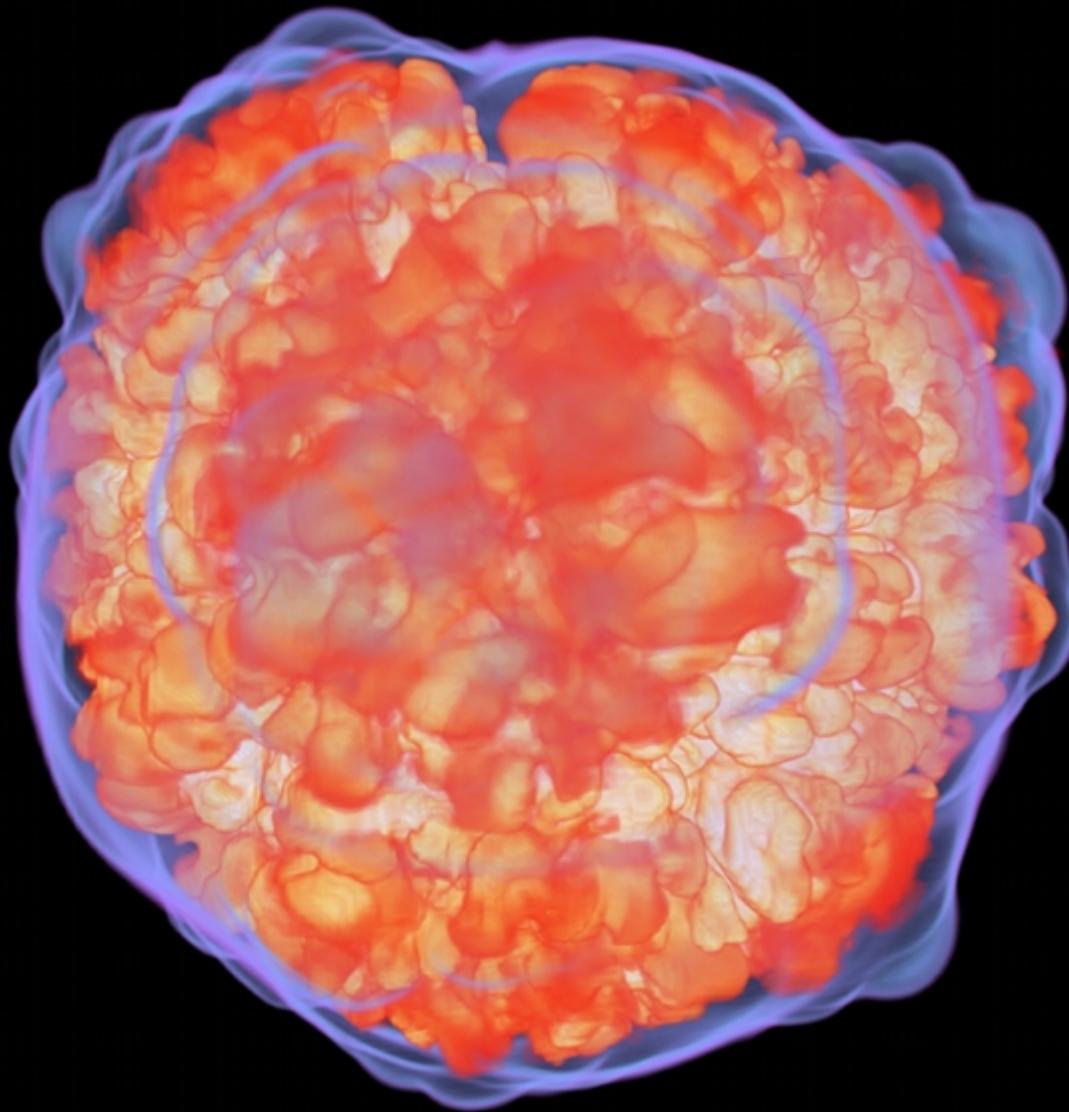
# $M_{\text{Ch}}$ model: turbulent deflagrations

$t = 1.600 \text{ sec}$

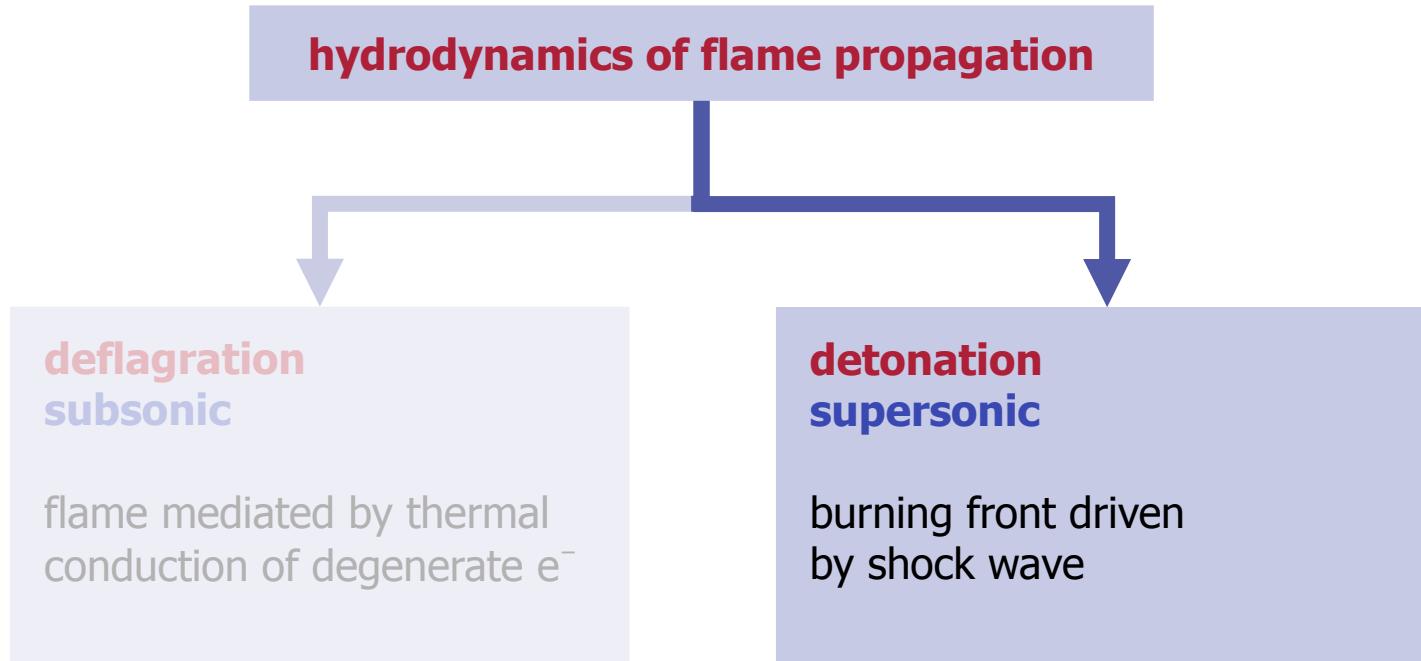


# $M_{\text{Ch}}$ model: turbulent deflagrations

$t = 3.000 \text{ sec}$

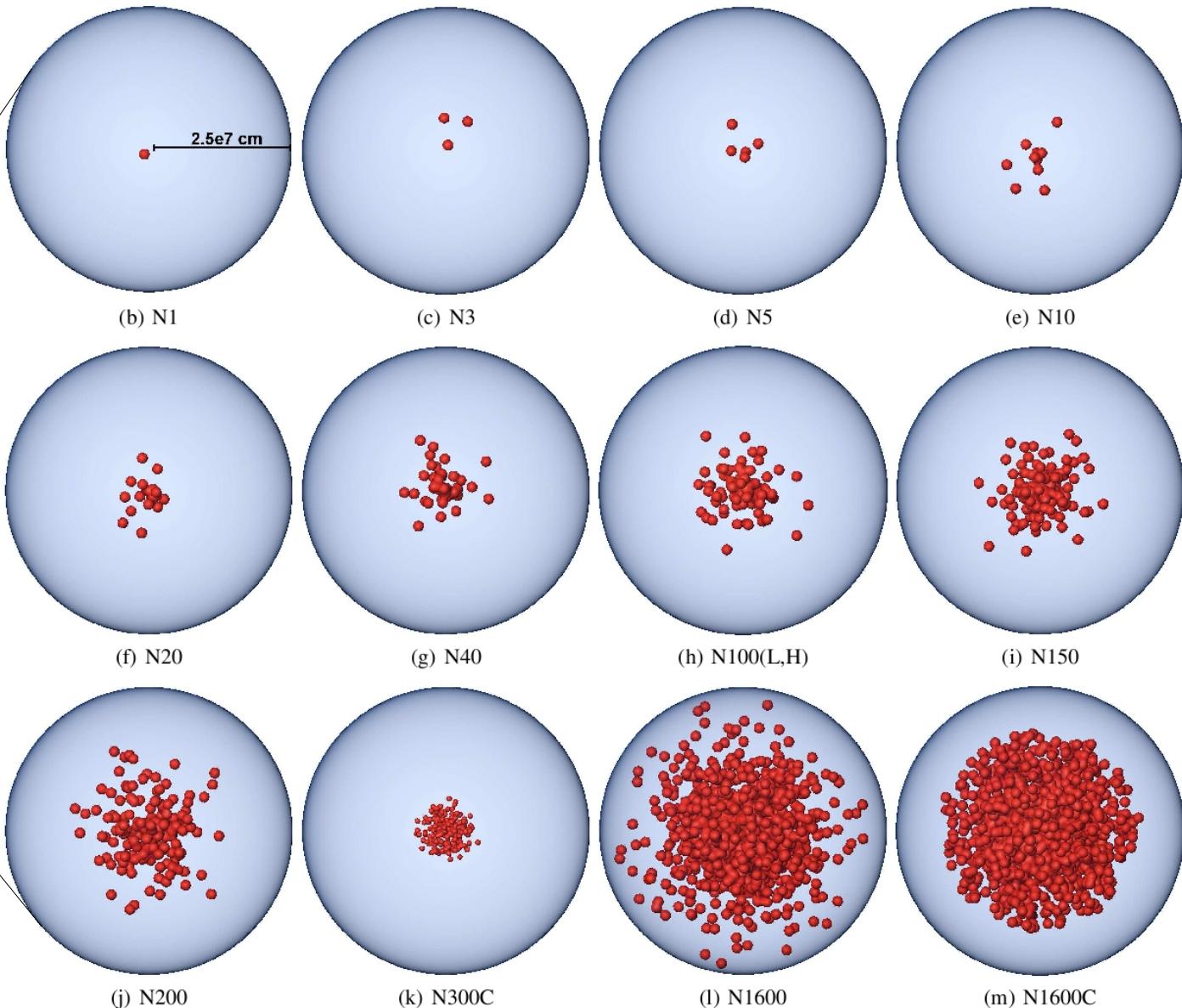
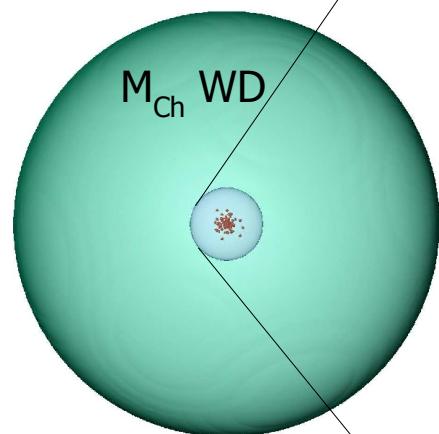


# Deflagration to detonation transition may occur

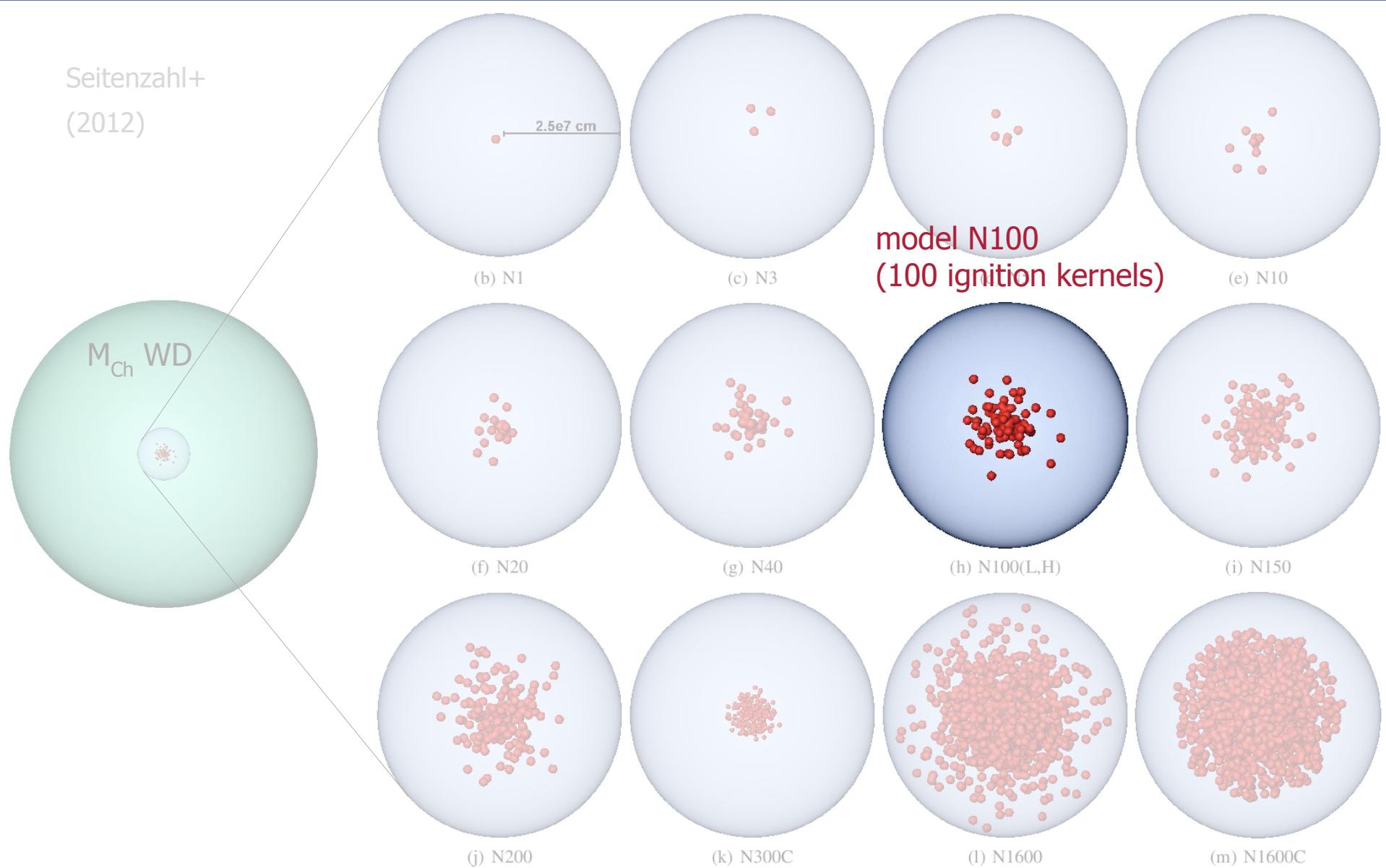


# Suite of 3D delayed detonation models

Seitenzahl+  
(2013)



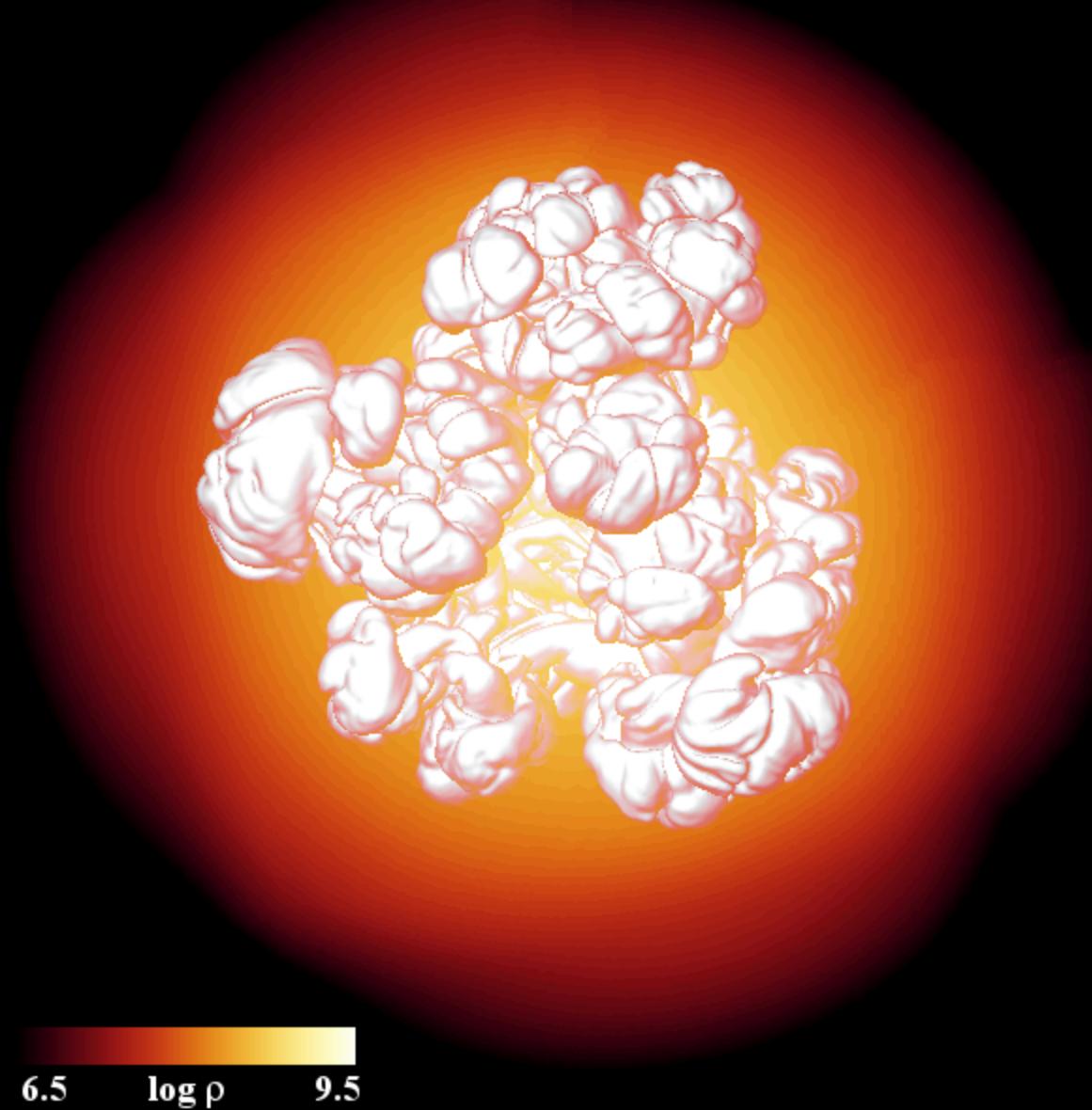
# Suite of 3D delayed detonation models



# Delayed detonation model N100

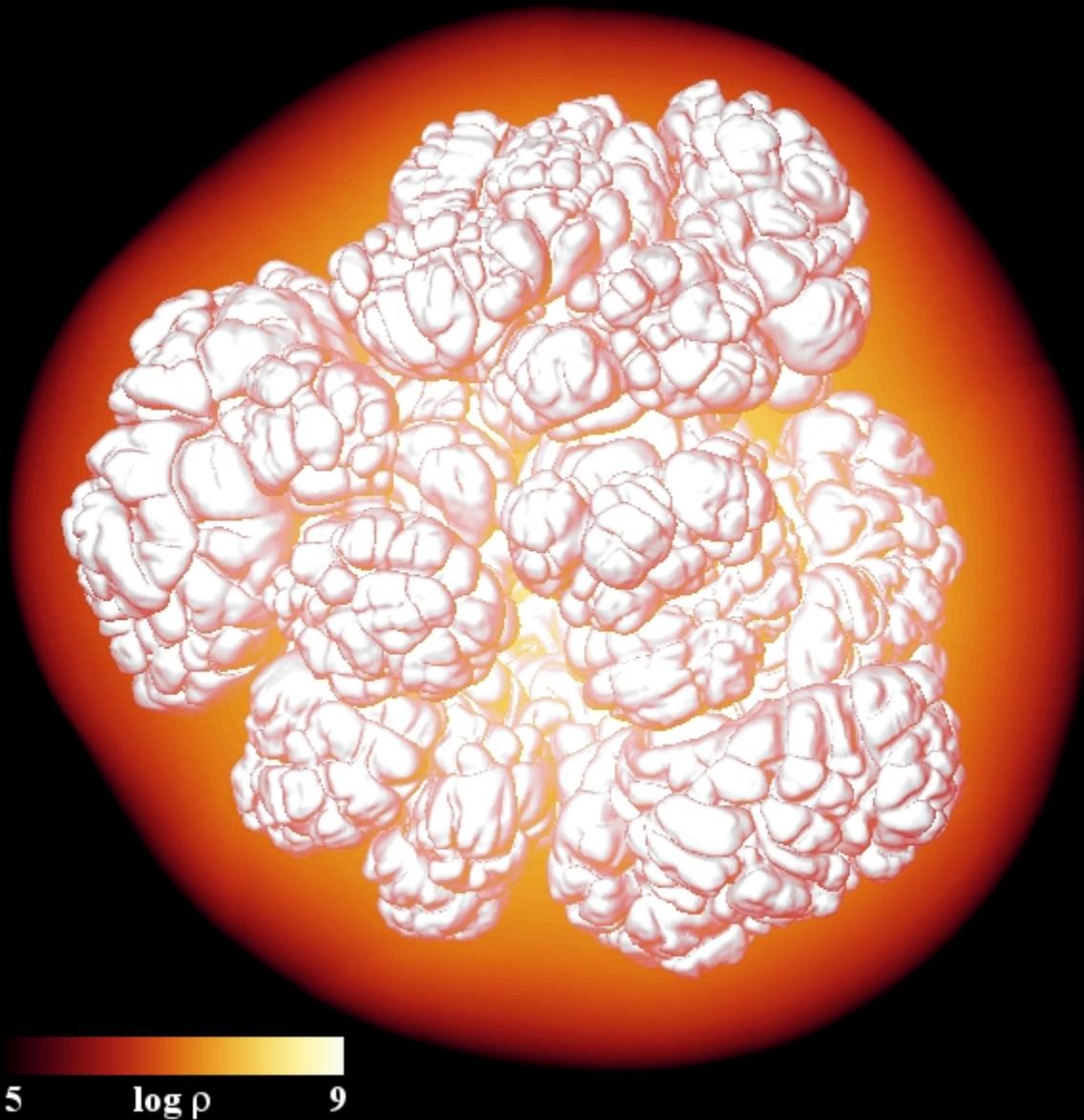
## Current PRACE project

- ▶  $t = 0.70 \text{ s}$



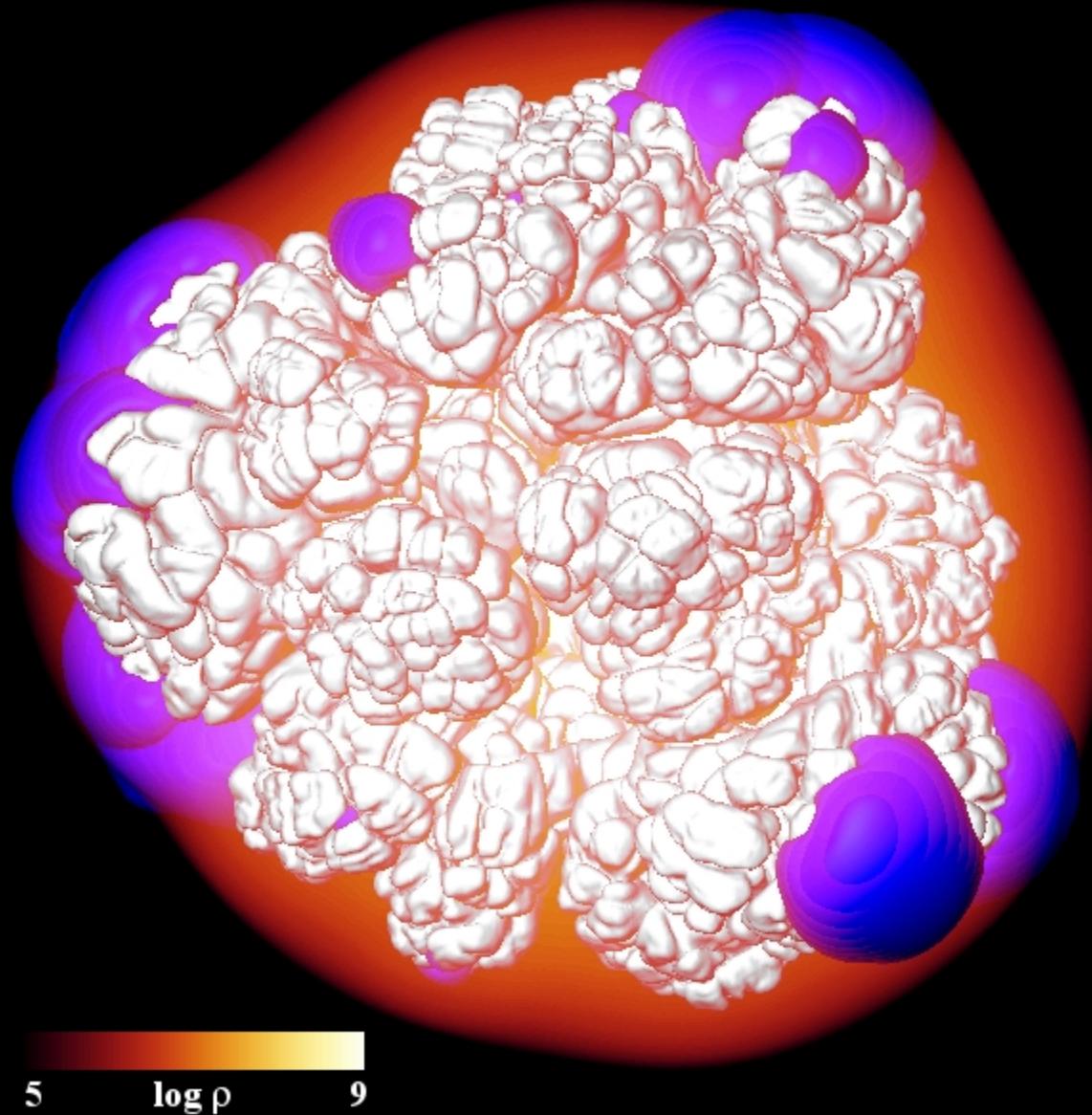
# Delayed detonation model N100

- ▶  $t = 0.93 \text{ s}$



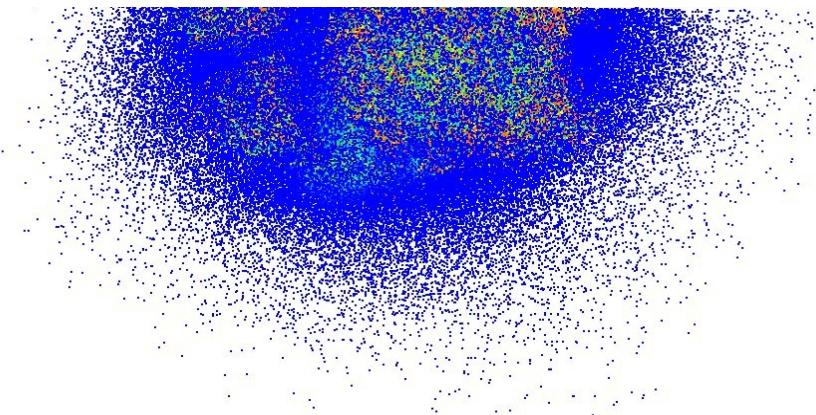
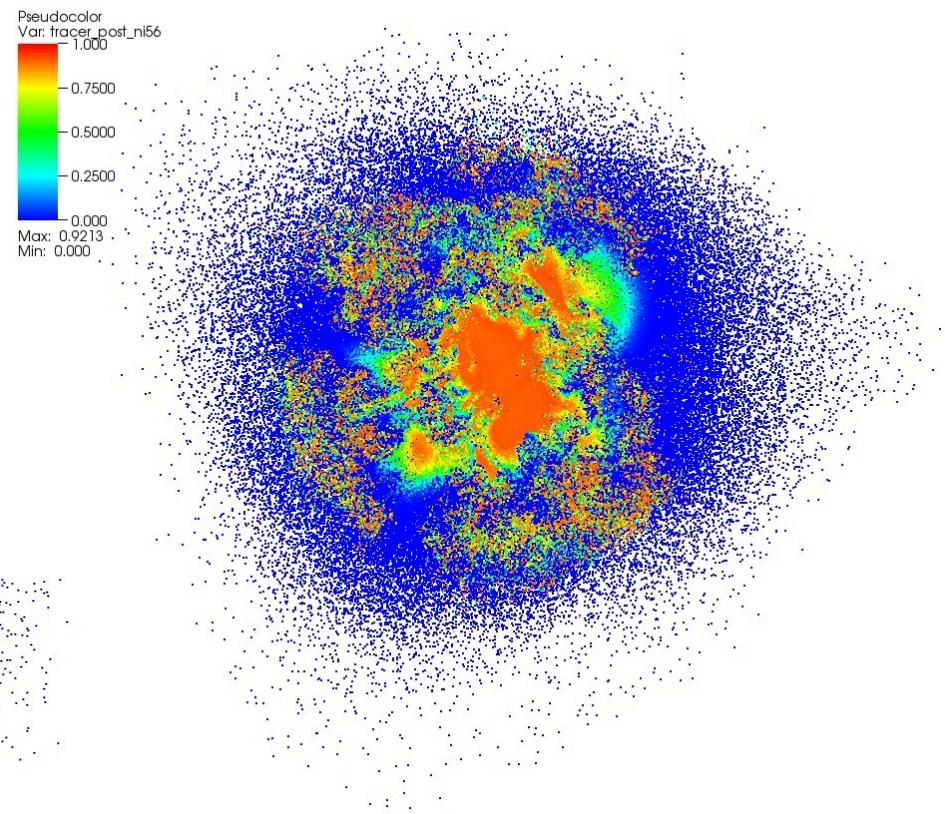
# Delayed detonation model N100

►  $t = 1.00 \text{ s}$



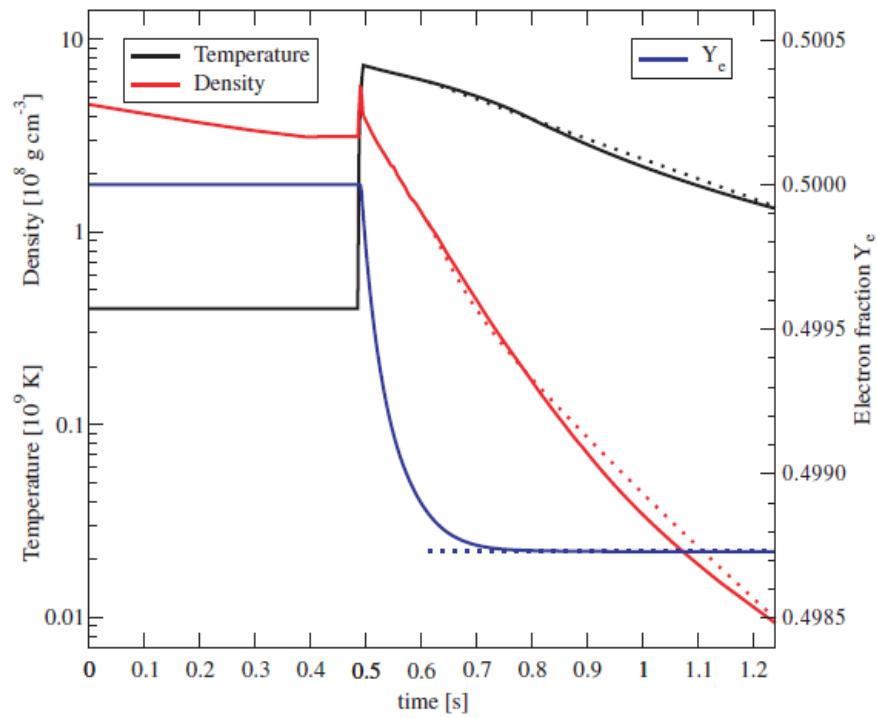
# Part III: tracer particle distributions

- ▶ Tracer particle positions 100s after the explosion colored by  $^{56}\text{Ni}$  mass fraction
- ▶ Spherical cloud of tracers was cut in half (bottom) and then rotated 90 degrees (right) to allow view deep into the core

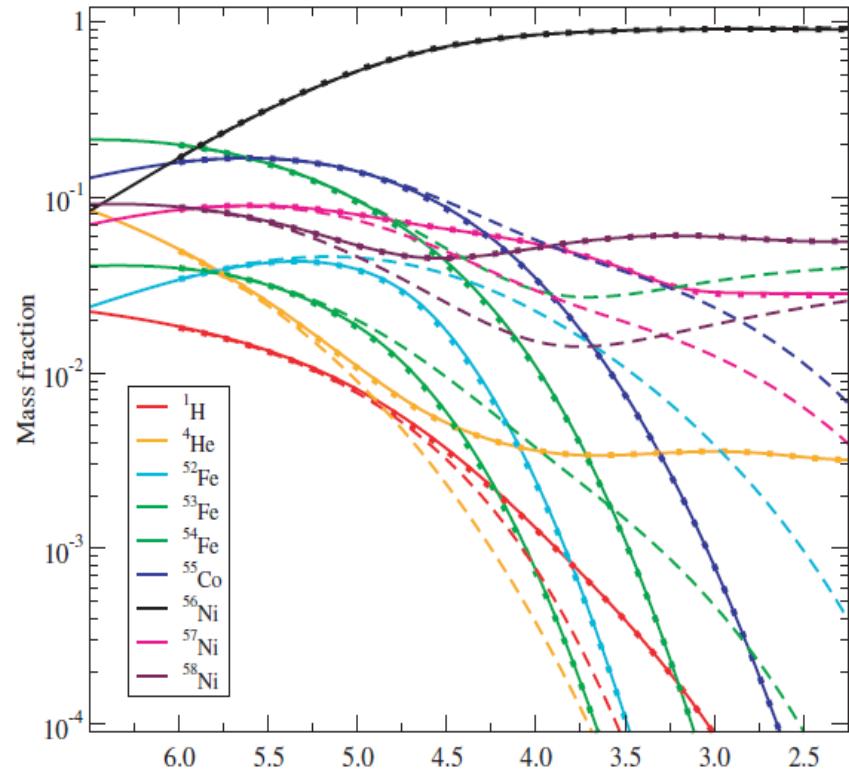


# Abundance evolution along tracer trajectory

- ▶ Contrary to nuclear fusion in the Sun, the burning is not hydrostatic, but rather “explosive” → temperature rises due to nuclear burn, but then decreases exponentially due to subsequent expansion
- ▶ Important to follow isotopic evolution throughout freeze-out phase, when reaction rates become too slow to keep abundances in equilibrium corresponding to thermodynamic state



Meakin, Seitzenzahl et al. (2011) ApJ 693, 1188



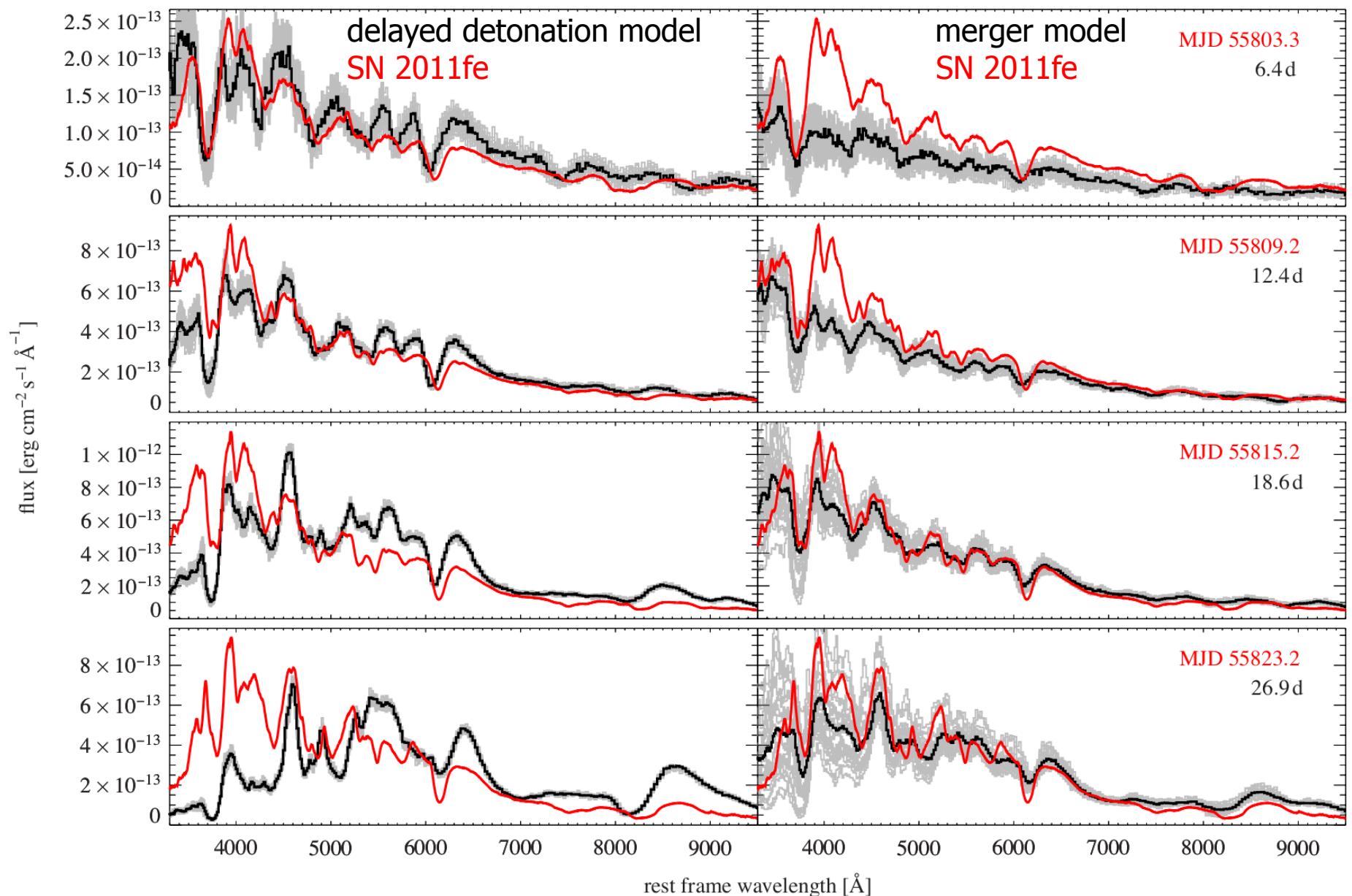
Ivo Seitzenzahl

# New 3D delayed detonation SNe Ia yield tables

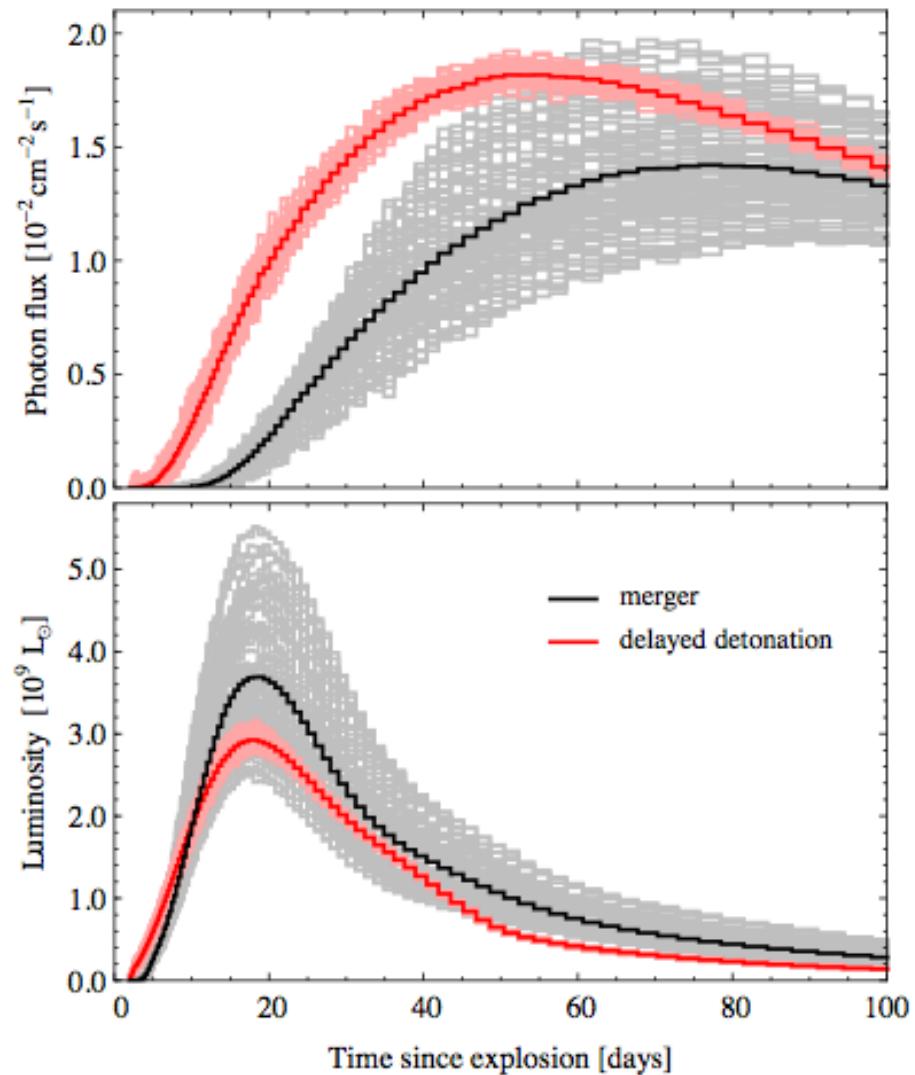
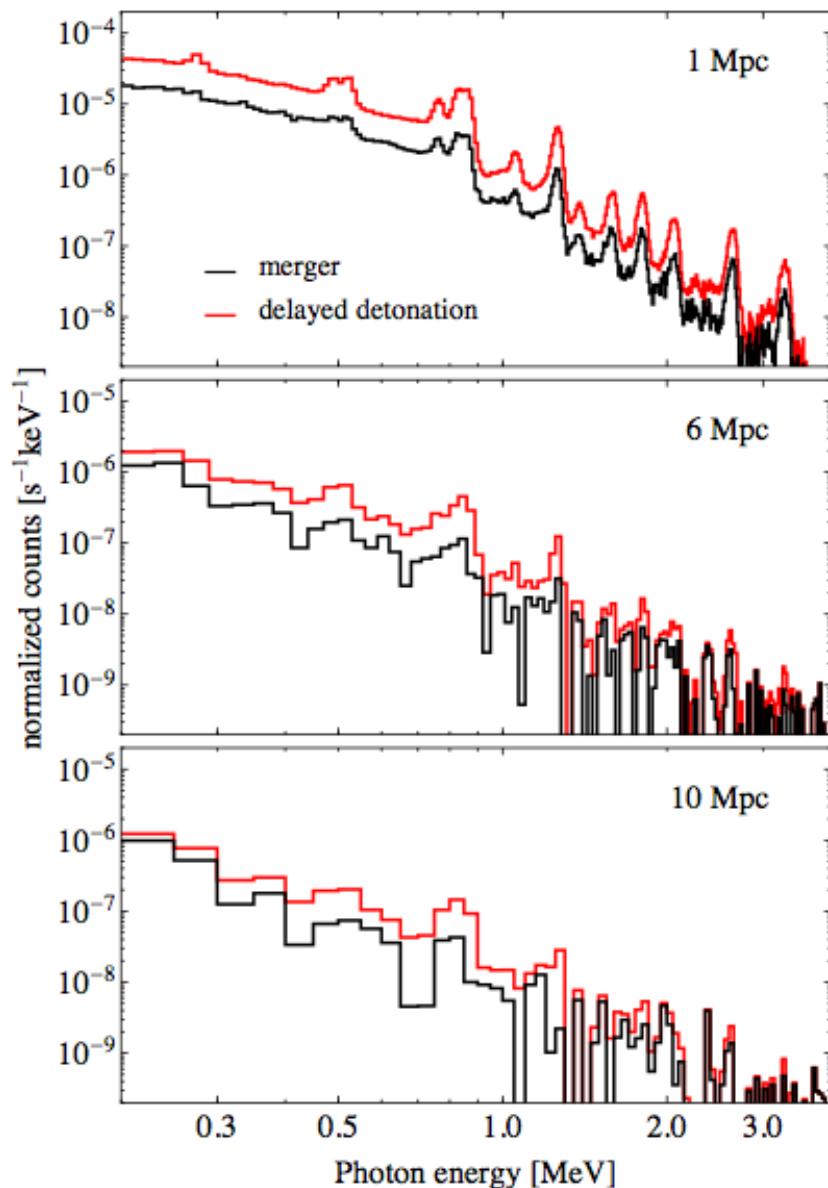
**Table 2.** Asymptotic nucleosynthetic yields (in solar masses) of stable nuclides.

|                  | N1       | N3       | N5       | N10      | N20      | N40      | N100H    | N100     | N100L    | N150     | N200     | N300C    | N1600    | N1600C   | N100_Z0.5 | N100_Z0.1 | N100_Z0.01 |
|------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|------------|
| <sup>12</sup> C  | 2.61E-03 | 9.90E-03 | 9.05E-03 | 4.43E-03 | 9.20E-03 | 3.90E-03 | 3.87E-03 | 3.04E-03 | 3.85E-03 | 1.72E-02 | 1.21E-02 | 8.86E-03 | 1.06E-02 | 1.68E-02 | 3.10e-03  | 3.15e-03  | 3.16e-03   |
| <sup>13</sup> C  | 1.84E-08 | 6.15E-08 | 5.05E-08 | 2.57E-08 | 4.52E-08 | 2.18E-08 | 2.28E-08 | 1.74E-08 | 2.17E-08 | 1.00E-07 | 6.57E-08 | 4.95E-08 | 5.57E-08 | 8.44E-08 | 8.47e-09  | 1.91e-09  | 2.72e-10   |
| <sup>14</sup> N  | 2.92E-06 | 9.93E-06 | 8.46E-06 | 3.85E-06 | 8.34E-06 | 4.30E-06 | 4.25E-06 | 3.21E-06 | 3.98E-06 | 1.84E-05 | 1.33E-05 | 9.16E-06 | 1.04E-05 | 1.88E-05 | 1.80e-06  | 4.71e-07  | 7.22e-08   |
| <sup>15</sup> N  | 3.36E-09 | 1.22E-08 | 1.03E-08 | 4.47E-09 | 1.03E-08 | 5.16E-09 | 5.24E-09 | 3.67E-09 | 4.66E-09 | 2.29E-08 | 1.71E-08 | 1.14E-08 | 1.29E-08 | 2.41E-08 | 2.07e-09  | 2.98e-09  | 8.73e-08   |
| <sup>16</sup> O  | 2.63E-02 | 4.74E-02 | 5.63E-02 | 5.16E-02 | 9.04E-02 | 9.89E-02 | 7.30E-02 | 1.01E-01 | 1.24E-01 | 1.24E-01 | 1.96E-01 | 1.21E-01 | 1.91E-01 | 2.72E-01 | 9.87e-02  | 9.64e-02  | 9.47e-02   |
| <sup>17</sup> O  | 3.96E-07 | 1.37E-06 | 1.16E-06 | 5.34E-07 | 1.12E-06 | 5.54E-07 | 5.61E-07 | 4.13E-07 | 5.14E-07 | 2.48E-06 | 1.74E-06 | 1.22E-06 | 1.36E-06 | 2.42E-06 | 2.84e-07  | 9.32e-08  | 5.43e-09   |
| <sup>18</sup> O  | 3.32E-09 | 1.33E-08 | 1.11E-08 | 4.54E-09 | 1.12E-08 | 5.29E-09 | 5.59E-09 | 3.53E-09 | 4.61E-09 | 2.52E-08 | 1.98E-08 | 1.25E-08 | 1.44E-08 | 2.73E-08 | 2.23e-09  | 1.21e-09  | 9.93e-10   |
| <sup>19</sup> F  | 3.73E-11 | 1.35E-10 | 1.17E-10 | 5.05E-11 | 1.22E-10 | 6.22E-11 | 6.32E-11 | 4.39E-11 | 5.68E-11 | 2.64E-10 | 2.13E-10 | 1.36E-10 | 1.58E-10 | 2.97E-10 | 2.20e-11  | 1.48e-11  | 4.79e-11   |
| <sup>20</sup> Ne | 1.47E-03 | 3.37E-03 | 3.75E-03 | 2.40E-03 | 5.41E-03 | 4.15E-03 | 3.66E-03 | 3.53E-03 | 4.33E-03 | 8.72E-03 | 1.15E-02 | 6.76E-03 | 9.40E-03 | 1.73E-02 | 3.60e-03  | 3.19e-03  | 3.74e-03   |
| <sup>21</sup> Ne | 3.08E-07 | 9.79E-07 | 8.81E-07 | 4.16E-07 | 9.63E-07 | 5.43E-07 | 5.20E-07 | 4.11E-07 | 5.17E-07 | 1.98E-06 | 1.68E-06 | 1.08E-06 | 1.29E-06 | 2.39E-06 | 1.97e-07  | 4.47e-08  | 6.93e-09   |
| <sup>22</sup> Ne | 6.40E-05 | 3.26E-04 | 2.87E-04 | 1.31E-04 | 2.58E-04 | 5.77E-05 | 7.62E-05 | 4.07E-05 | 5.51E-05 | 4.83E-04 | 2.34E-04 | 2.11E-04 | 2.32E-04 | 2.97E-04 | 1.65e-0   | 2.30e-06  | 1.71e-07   |
| <sup>23</sup> Na | 2.20E-05 | 6.41E-05 | 6.09E-05 | 3.22E-05 | 7.30E-05 | 4.66E-05 | 4.25E-05 | 3.74E-05 | 4.68E-05 | 1.38E-04 | 1.38E-04 | 8.53E-05 | 1.09E-04 | 2.01E-04 | 2.63e-05  | 1.96e-05  | 1.72e-05   |
| <sup>24</sup> Mg | 3.93E-03 | 7.13E-03 | 8.53E-03 | 7.77E-03 | 1.46E-02 | 1.54E-02 | 1.15E-02 | 1.52E-02 | 1.83E-02 | 1.93E-02 | 3.32E-02 | 1.97E-02 | 3.08E-02 | 4.6E-02  | 2.02e-02  | 2.69e-02  | 2.90e-02   |
| <sup>25</sup> Mg | 3.35E-05 | 9.26E-05 | 8.92E-05 | 5.07E-05 | 1.11E-04 | 7.70E-05 | 6.86E-05 | 6.49E-05 | 8.02E-05 | 2.02E-04 | 2.14E-04 | 1.33E-04 | 1.75E-04 | 2.12E-04 | 3.09e-05  | 1.06e-05  | 8.99e-07   |
| <sup>26</sup> Mg | 5.15E-05 | 1.36E-04 | 1.34E-04 | 7.55E-05 | 1.71E-04 | 1.17E-04 | 1.04E-04 | 9.66E-05 | 1.19E-04 | 3.07E-04 | 3.27E-04 | 2.01E-04 | 2.6E-04  | 4.82E-04 | 4.44e-05  | 7.36e-06  | 1.04e-06   |
| <sup>27</sup> Al | 1.98E-04 | 3.95E-04 | 4.56E-04 | 3.71E-04 | 7.32E-04 | 7.05E-04 | 5.47E-04 | 6.74E-04 | 8.32E-04 | 1.04E-03 | 1.14E-13 | 6.68E-04 | 1.48E-03 | 2.37E-03 | 5.88e-04  | 2.68e-04  | 8.71e-05   |
| <sup>28</sup> Si | 6.32E-02 | 8.99E-02 | 1.19E-01 | 1.38E-01 | 1.98E-01 | 2.59E-01 | 2.12E-01 | 2.84E-01 | 3.55E-01 | 2.71E-01 | 1.2E-01  | 3.19E-01 | 3.61E-01 | 3.44E-01 | 2.90e-01  | 2.94e-01  | 2.89e-01   |
| <sup>29</sup> Si | 2.69E-04 | 4.64E-04 | 5.68E-04 | 5.17E-04 | 9.49E-04 | 1.03E-03 | 7.73E-04 | 1.03E-03 | 1.25E-03 | 1.30E-03 | 2.18E-03 | 1.29E-03 | 1.97E-03 | 2.86E-03 | 7.28e-04  | 4.30e-04  | 1.35e-04   |
| <sup>30</sup> Si | 5.96E-04 | 1.00E-03 | 1.23E-03 | 1.18E-03 | 2.12E-03 | 2.35E-03 | 1.72E-03 | 2.36E-03 | 2.86E-03 | 2.77E-03 | 4.76E-03 | 2.87E-03 | 4.53E-03 | 6.55E-03 | 1.19e-03  | 1.44e-04  | 1.84e-05   |
| <sup>31</sup> P  | 1.40E-04 | 2.28E-04 | 2.87E-04 | 2.78E-04 | 4.87E-04 | 5.60E-04 | 4.20E-04 | 5.77E-04 | 7.04E-04 | 6.59E-04 | 1.08E-03 | 6.85E-04 | 1.05E-03 | 1.47E-03 | 3.58e-04  | 1.05e-04  | 3.54e-05   |
| <sup>32</sup> S  | 2.62E-02 | 3.70E-02 | 4.79E-02 | 5.74E-02 | 7.74E-02 | 1.01E-01 | 8.55E-02 | 1.11E-01 | 1.38E-01 | 1.07E-01 | 1.10E-01 | 1.27E-01 | 1.22E-01 | 1.03E-01 | 1.12e-01  | 1.12e-01  | 1.15e-01   |
| <sup>33</sup> S  | 7.51E-05 | 1.06E-04 | 1.42E-04 | 1.53E-04 | 2.43E-04 | 3.14E-04 | 2.37E-04 | 3.39E-04 | 4.21E-04 | 3.27E-04 | 5.23E-04 | 3.65E-04 | 5.47E-04 | 6.79E-04 | 2.39e-04  | 1.04e-04  | 4.57e-05   |
| <sup>34</sup> S  | 8.26E-04 | 1.16E-03 | 1.57E-03 | 1.75E-03 | 2.84E-03 | 3.73E-03 | 2.7E-03  | 4.04E-03 | 5.02E-03 | 3.68E-03 | 6.22E-03 | 4.22E-03 | 6.56E-03 | 8.06E-03 | 1.86e-03  | 2.60e-04  | 7.14e-06   |
| <sup>36</sup> S  | 8.12E-08 | 1.35E-07 | 1.65E-07 | 1.41E-07 | 2.54E-07 | 2.57E-07 | 1.82E-07 | 2.47E-07 | 3.05E-07 | 3.59E-07 | 5.42E-07 | 3.23E-07 | 4.97E-07 | 7.68E-07 | 3.86e-08  | 1.64e-09  | 1.73e-11   |
| <sup>35</sup> Cl | 4.29E-05 | 6.20E-05 | 8.27E-05 | 8.37E-05 | 1.35E-04 | 1.67E-04 | 1.27E-04 | 1.78E-04 | 2.27E-04 | 1.89E-04 | 2.89E-04 | 2.00E-04 | 2.98E-04 | 3.84E-04 | 9.91e-05  | 2.64e-05  | 5.65e-06   |
| <sup>37</sup> Cl | 7.32E-06 | 9.62E-06 | 1.34E-05 | 1.53E-05 | 2.26E-05 | 3.14E-05 | 2.44E-05 | 3.51E-05 | 4.49E-05 | 3.14E-05 | 4.66E-05 | 3.63E-05 | 5.22E-05 | 5.75E-05 | 2.27e-05  | 9.14e-06  | 3.52e-06   |
| <sup>36</sup> Ar | 4.52E-03 | 6.36E-03 | 8.03E-03 | 9.89E-03 | 1.28E-02 | 1.61E-02 | 1.43E-02 | 1.77E-02 | 2.17E-02 | 1.76E-02 | 1.50E-02 | 2.08E-02 | 1.64E-02 | 1.23E-02 | 1.85e-02  | 1.92e-02  | 2.04e-02   |
| <sup>38</sup> Ar | 3.77E-04 | 5.15E-04 | 7.18E-04 | 8.01E-04 | 1.25E-03 | 1.72E-03 | 1.29E-03 | 1.91E-03 | 2.48E-03 | 1.69E-03 | 2.69E-03 | 1.96E-03 | 2.98E-03 | 3.42E-03 | 8.31e-04  | 1.19e-04  | 5.40e-06   |
| <sup>40</sup> Ar | 1.68E-09 | 2.45E-09 | 3.15E-09 | 2.90E-09 | 4.79E-09 | 5.27E-09 | 3.81E-09 | 5.21E-09 | 6.60E-09 | 6.64E-09 | 1.04E-08 | 6.29E-09 | 9.87E-09 | 1.48E-08 | 4.66e-10  | 9.87e-12  | 5.11e-14   |
| <sup>39</sup> K  | 2.26E-05 | 2.98E-05 | 4.42E-05 | 4.65E-05 | 6.80E-05 | 9.52E-05 | 7.40E-05 | 1.07E-04 | 1.39E-04 | 9.53E-05 | 1.42E-04 | 1.10E-04 | 1.60E-04 | 1.75E-04 | 6.25e-05  | 1.89e-05  | 3.57e-06   |
| <sup>41</sup> K  | 1.29E-06 | 1.65E-06 | 2.30E-06 | 2.66E-06 | 3.80E-06 | 5.38E-06 | 4.22E-06 | 6.08E-06 | 7.87E-06 | 5.36E-06 | 7.81E-06 | 6.21E-06 | 8.93E-06 | 9.65E-06 | 3.85e-06  | 1.42e-06  | 4.92e-07   |
| <sup>40</sup> Ca | 4.05E-03 | 5.74E-03 | 7.09E-03 | 8.82E-03 | 1.13E-02 | 1.35E-02 | 1.24E-02 | 1.47E-02 | 1.75E-02 | 1.50E-02 | 1.07E-02 | 1.78E-02 | 1.10E-02 | 7.50E-03 | 1.57e-02  | 1.66e-02  | 1.77e-02   |

# Radiative transfer: synthetic optical spectra



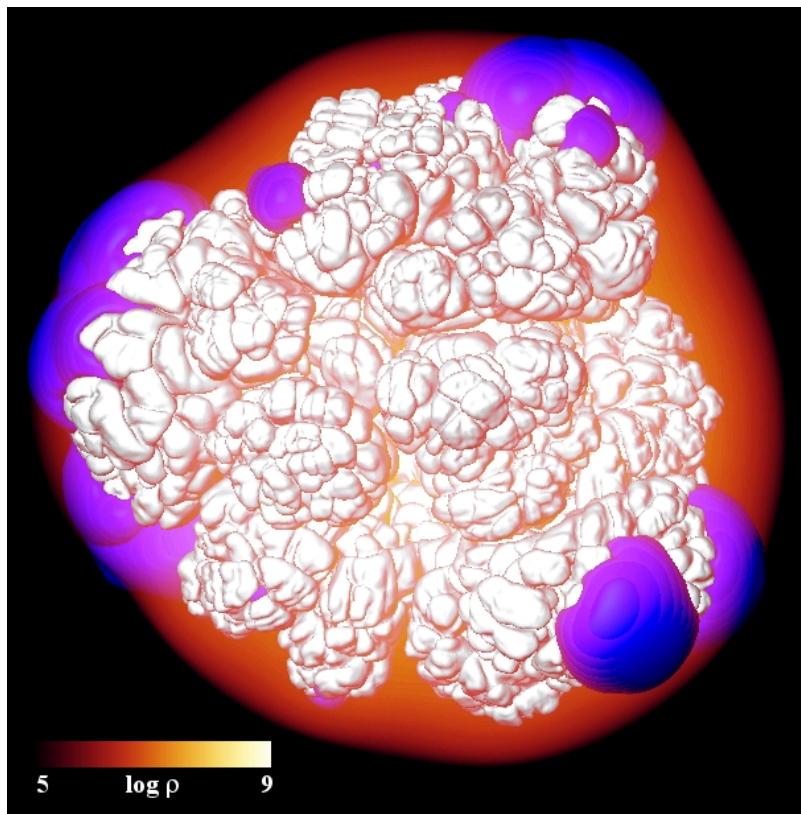
# Gamma ray light curves and spectra



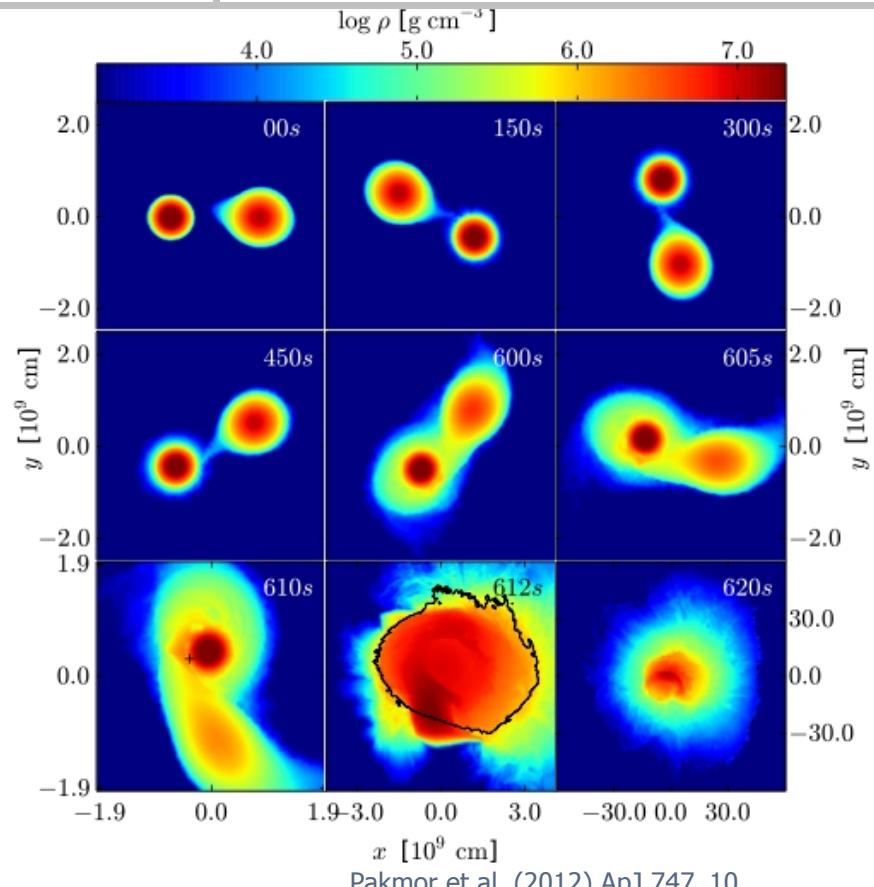
(Summa et al. 2013, A&A 554, 67)

# $M_{\text{ch}}$ delayed detonation vs. violent merger

|   | delayed detonation $M_{\text{Ch}}$ WD | violent merger ( $1.1+0.9 M_{\odot}$ WD) |
|---|---------------------------------------|--|
| $^{56}\text{Ni}$ mass [ $M_{\odot}$ ]                         | 0.604                                 | 0.616                                    |
| mass of $^{57}\text{Ni}$ and $^{57}\text{Co}$ [ $M_{\odot}$ ] | $1.88 \times 10^{-2}$                 | $1.49 \times 10^{-2}$                    |
| mass of $^{55}\text{Fe}$ and $^{55}\text{Co}$ [ $M_{\odot}$ ] | $1.33 \times 10^{-2}$                 | $3.73 \times 10^{-3}$                    |



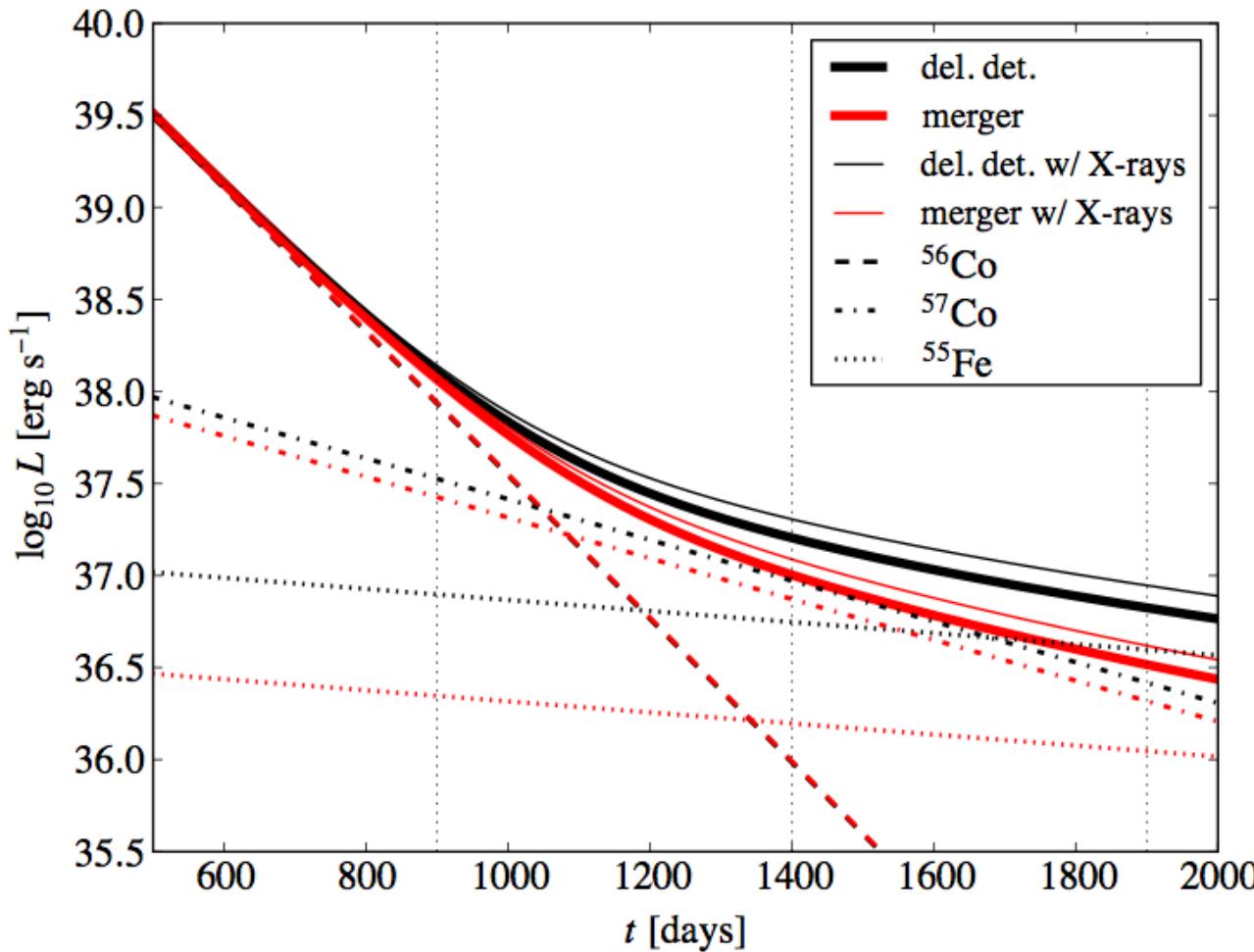
(Seitenzahl, Ciaraldi-Schoolmann, Röpke et al. 2013, MNRAS 429, 1156)



Pakmor et al. (2012) ApJ 747, 10

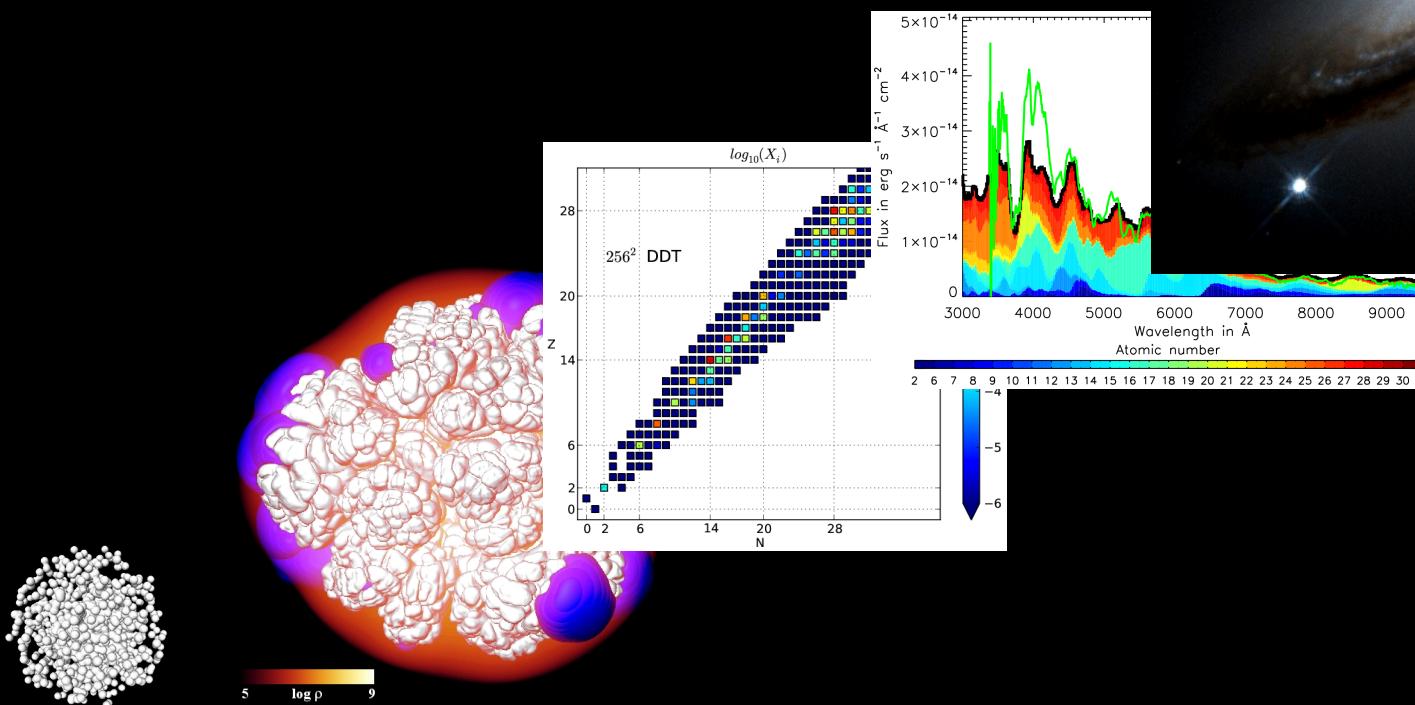
# Possible late light curves for SN 2011fe

- ▶ Merger and delayed-detonation models produce at equal  $^{56}\text{Ni}$  yields somewhat different  $^{57}\text{Ni}$  and very different amounts of  $^{55}\text{Co}$  (due to different central densities). This provides an additional, independent way to distinguish the models.



(Röpke, Kromer, Seitenzahl et al. 2011, ApJL, 750, 19)

# Part IV: Summary of modeling pipeline



# Summary

- ▶ SNe Ia are thermonuclear explosions of white dwarfs
- ▶ interesting for galactic chemical evolution, 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  $M_{\text{Ch}}$  WDs, mergers of WDs (other models studied but not discussed here may also contribute)
- ▶ three-dimensional simulations of explosions and subsequent nucleosynthesis and radiative transfer calculations allow us to predict observable differences between competing theoretical models