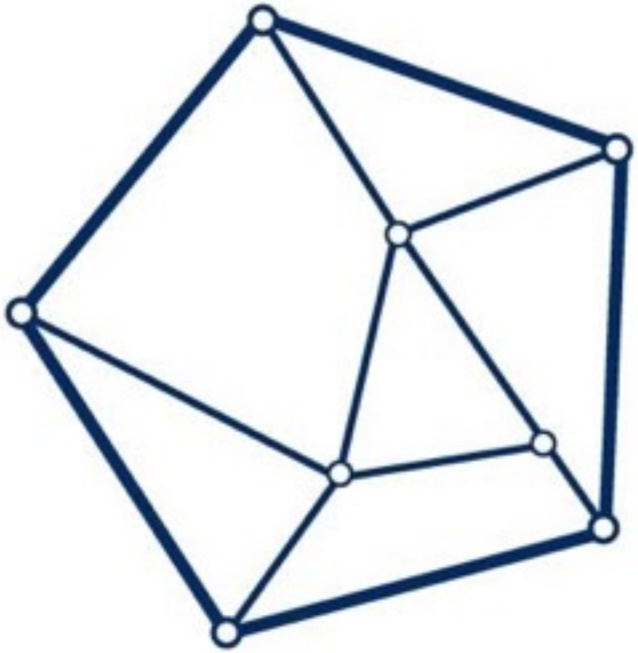
CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Modelling thermonuclear SNe from different progenitor systems

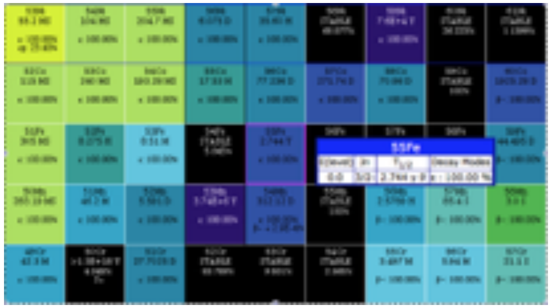
Australian National University

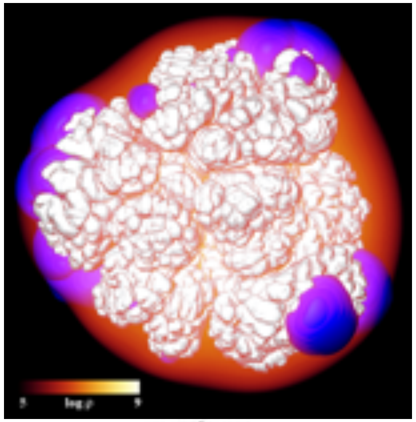


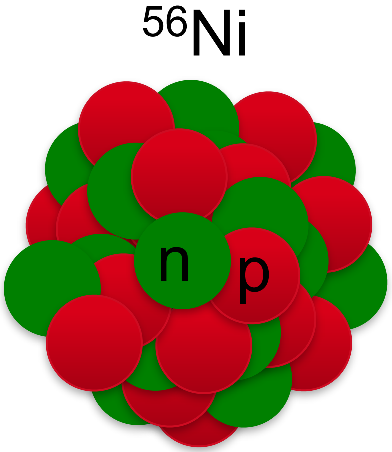
explosion simulations, nucleosynthesis, observables

Ivo Seitenzahl

ANU / CAASTRO







Australian Government
Australian Research Council

What's it like down-under

Ruitenzahl Residence

Canberra

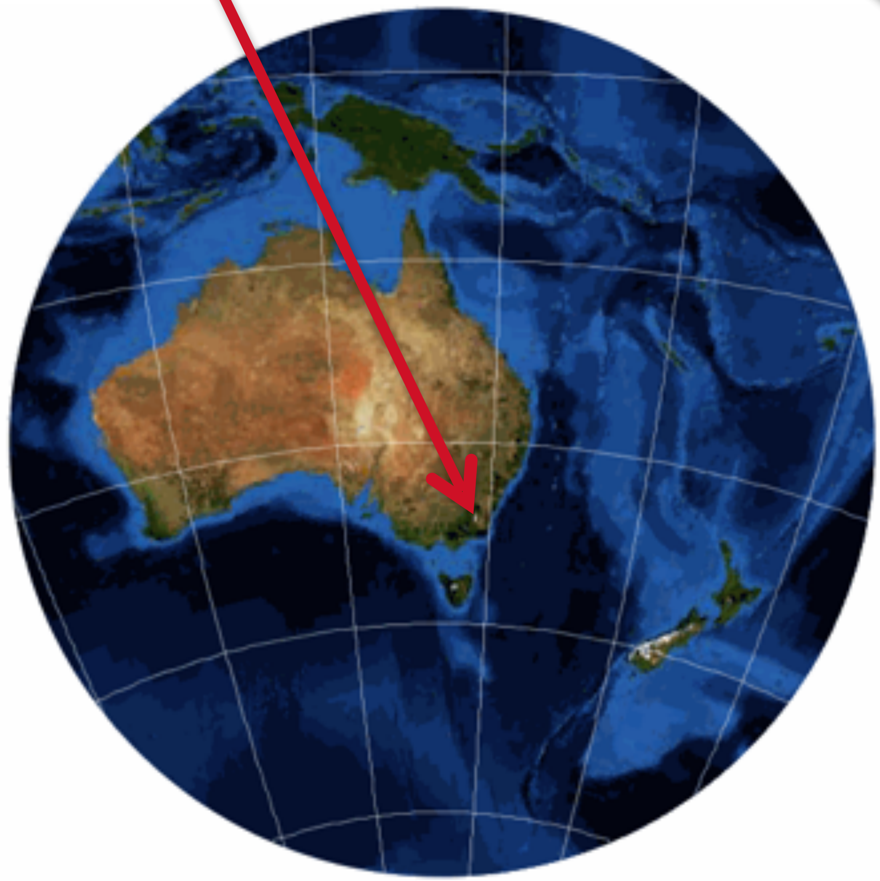


Image: http://www.icsm.gov.au

“Wombat Wandering Warning”

email urging us to drive carefully

SNe Ia

What is a Type Ia supernova?

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Thermonuclear incineration of (at least) one white dwarf.

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Open questions:

- What is/are the progenitor channel(s)?
- What is/are the explosion mechanism(s)?
- What drives the width-luminosity relation?
- What is/are the WD mass(es) (and composition)?
- What elements/isotopes are produced?

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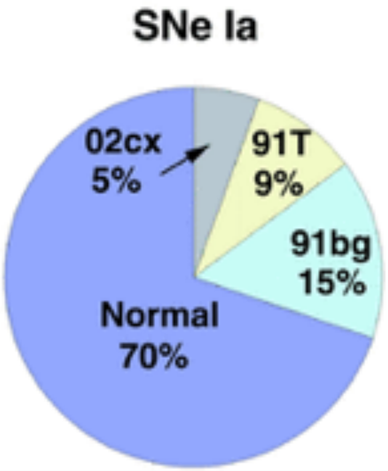

Complication: sub-classes

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

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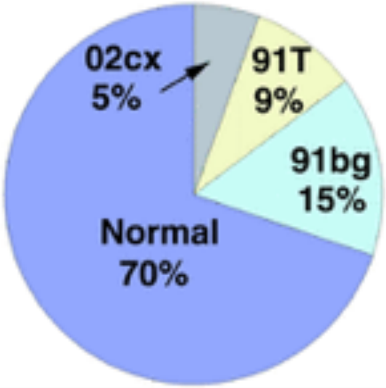
Approach:
explosion simulations



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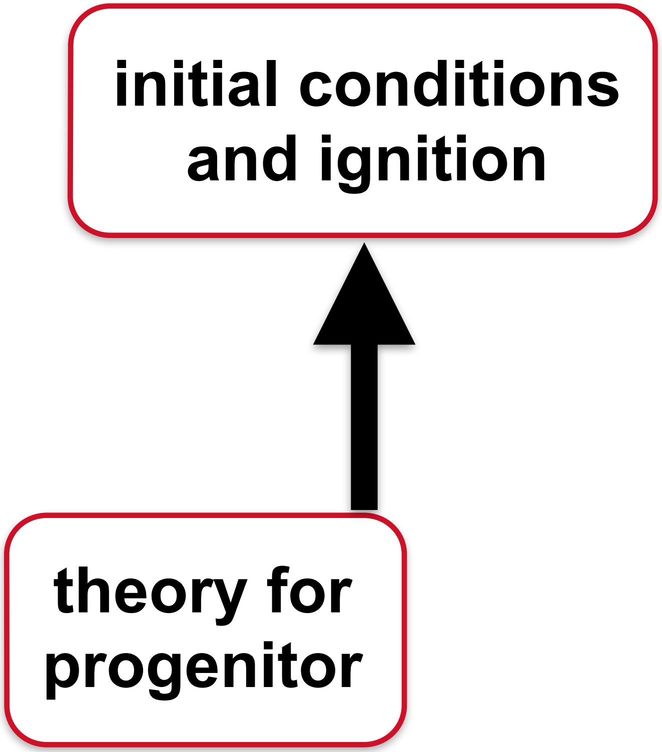
Complication: sub-classes

modelling pipeline

theory for progenitor

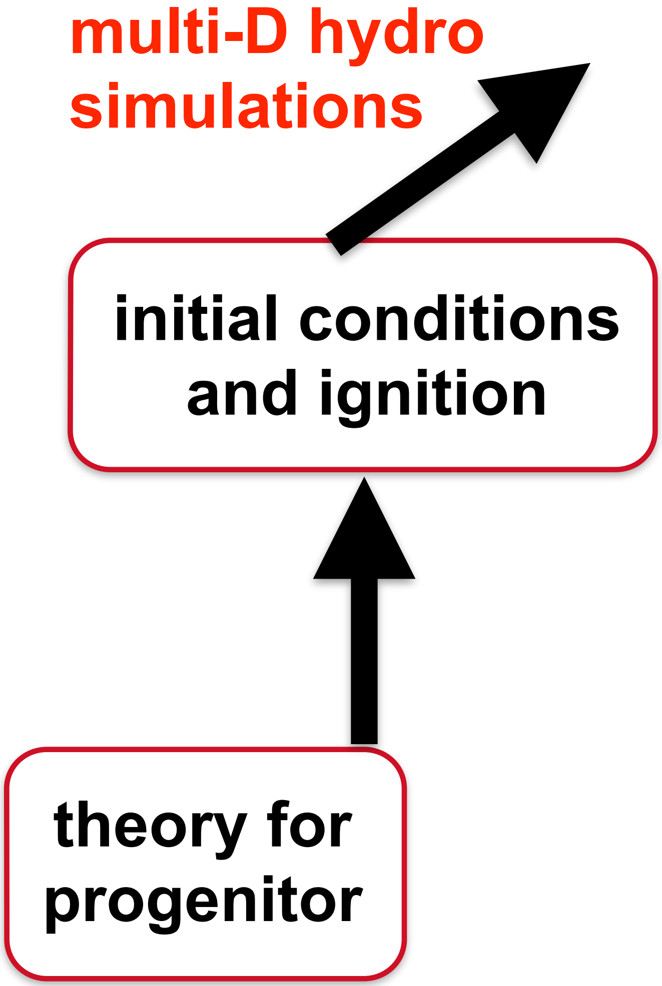
modelling pipeline



initial conditions and ignition

theory for progenitor

modelling pipeline



multi-D hydro simulations

initial conditions and ignition

theory for progenitor

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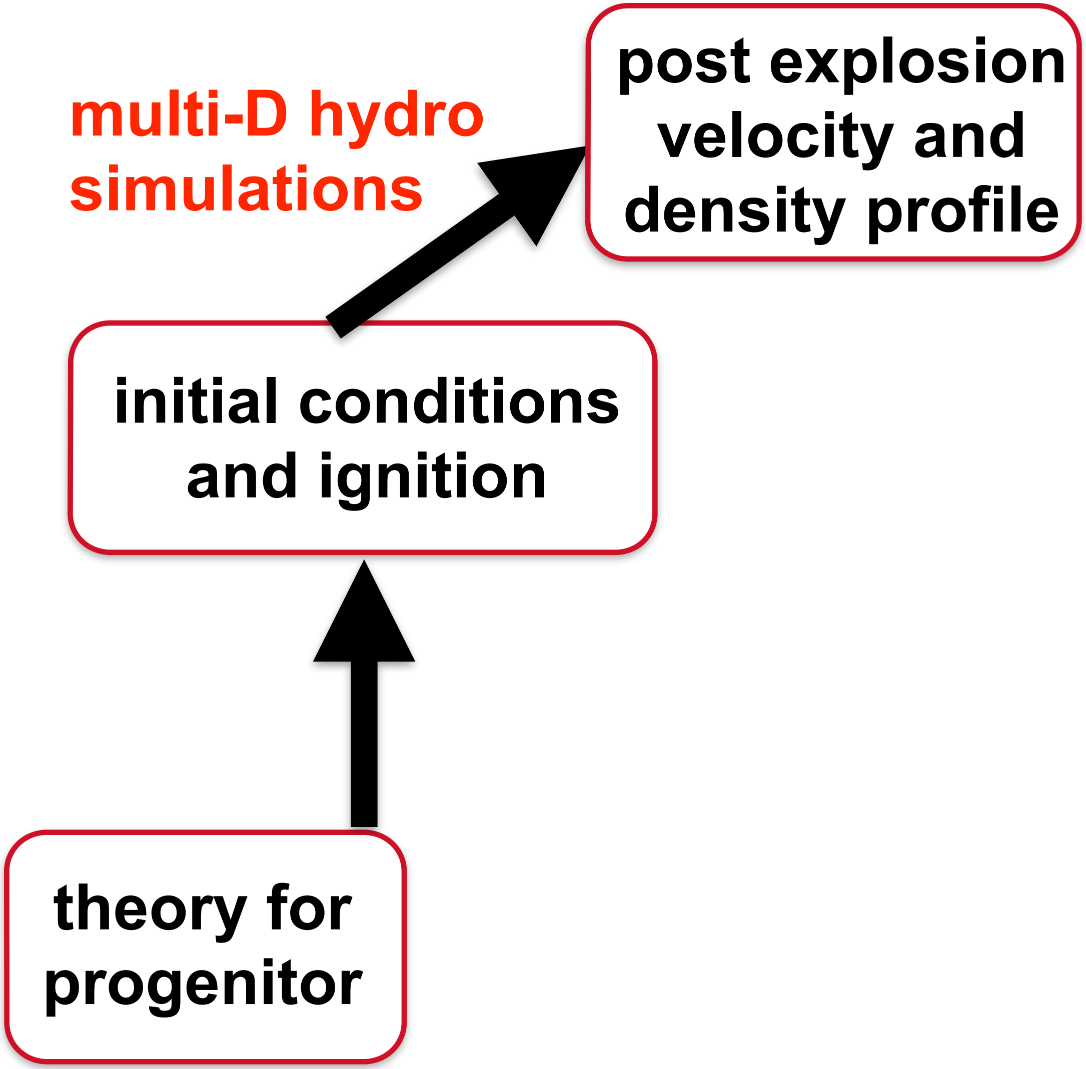

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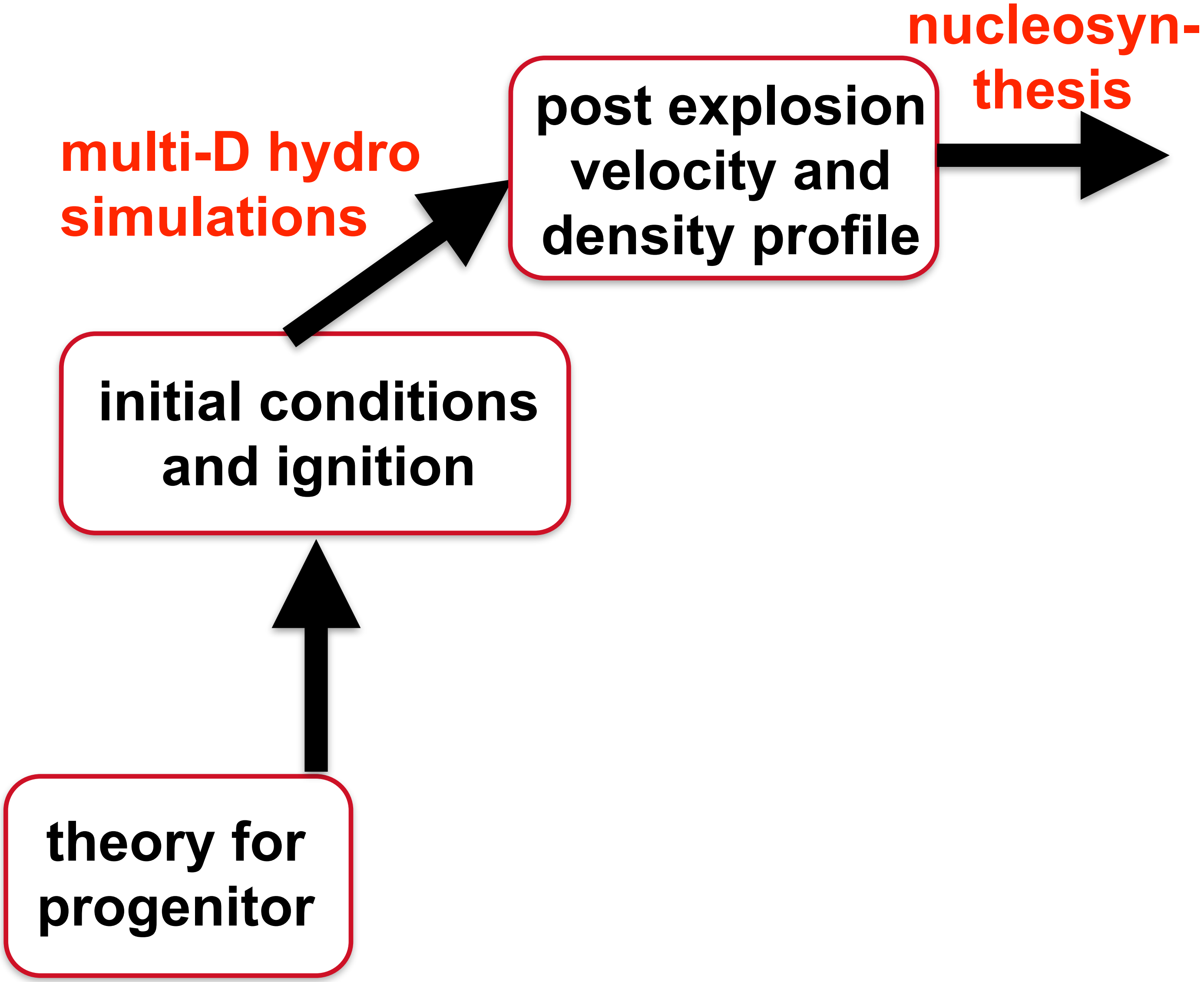
post explosion velocity and density profile

modelling pipeline



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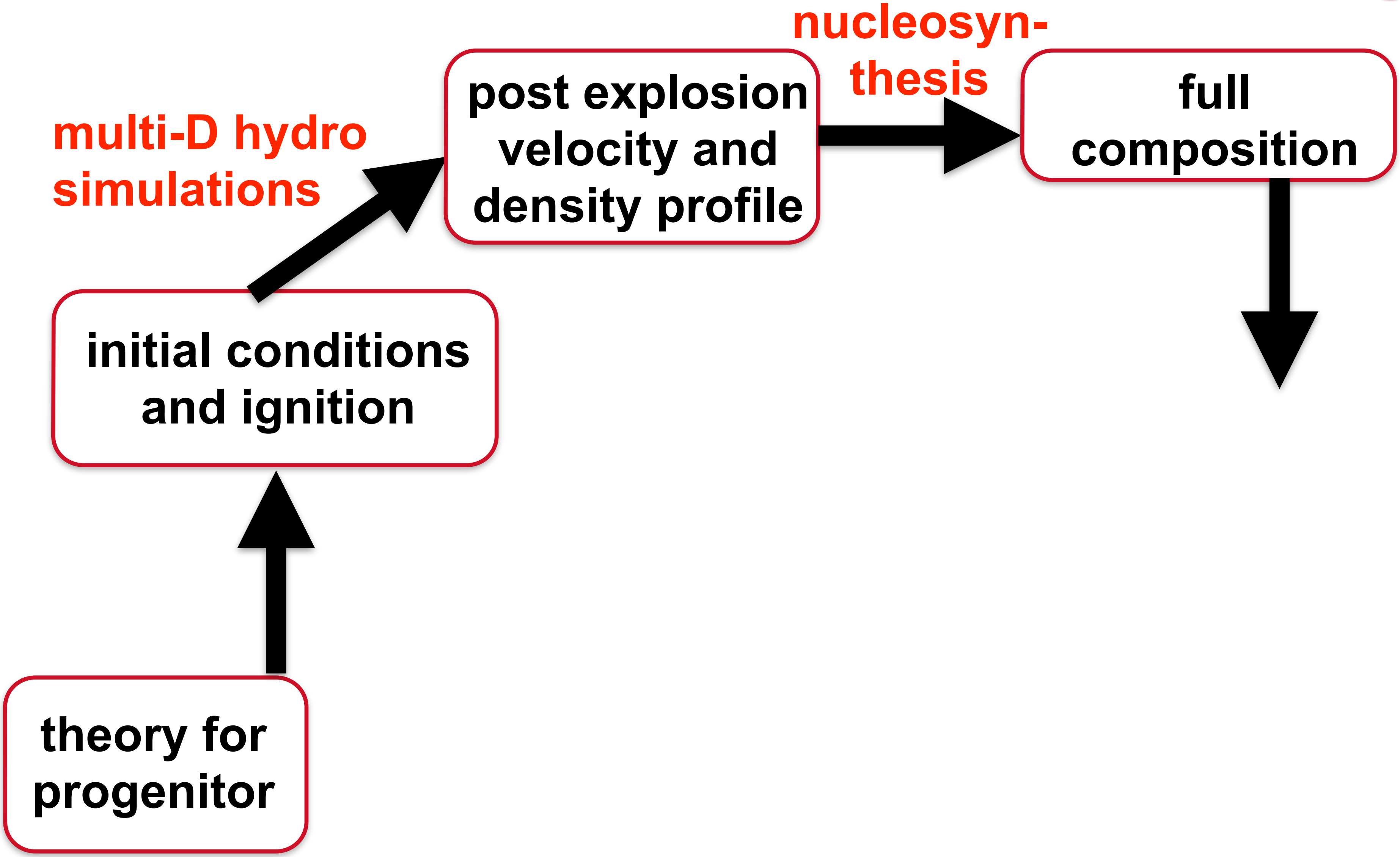

theory for progenitor

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full composition

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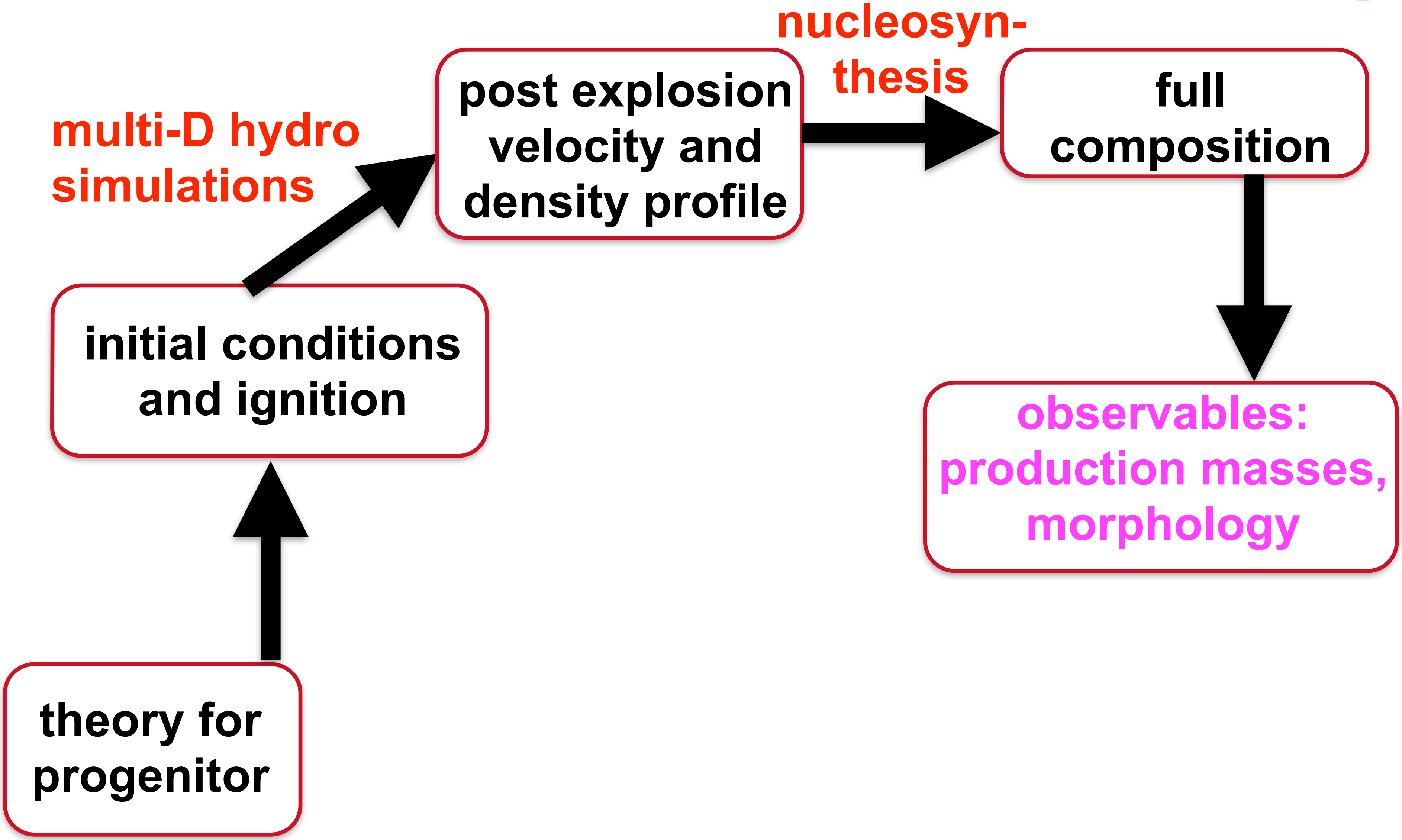

theory for progenitor

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multi-D hydro simulations

post explosion velocity and density profile

nucleosyn-thesis

full composition

observables: production masses, morphology

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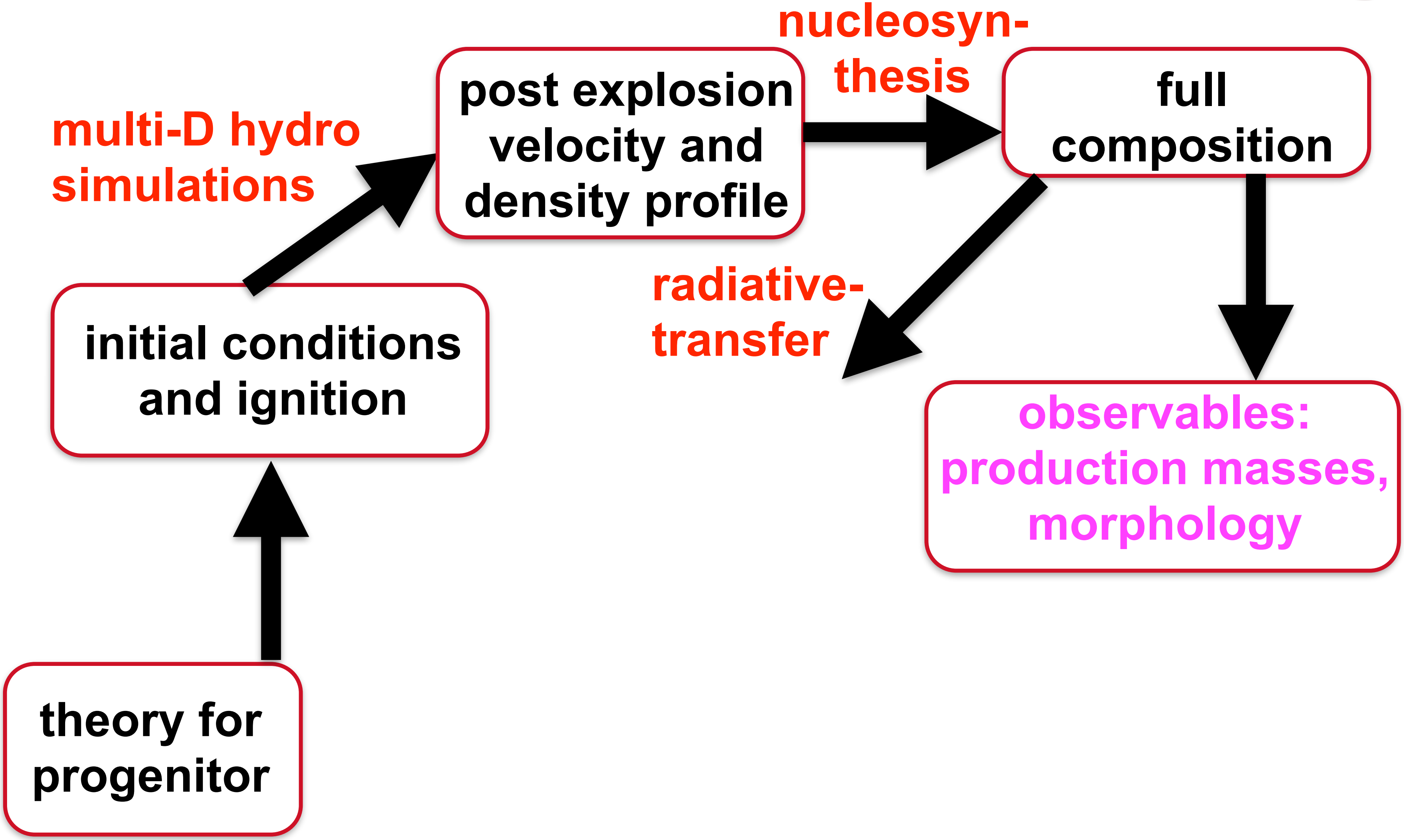
modelling pipeline

Australian National University



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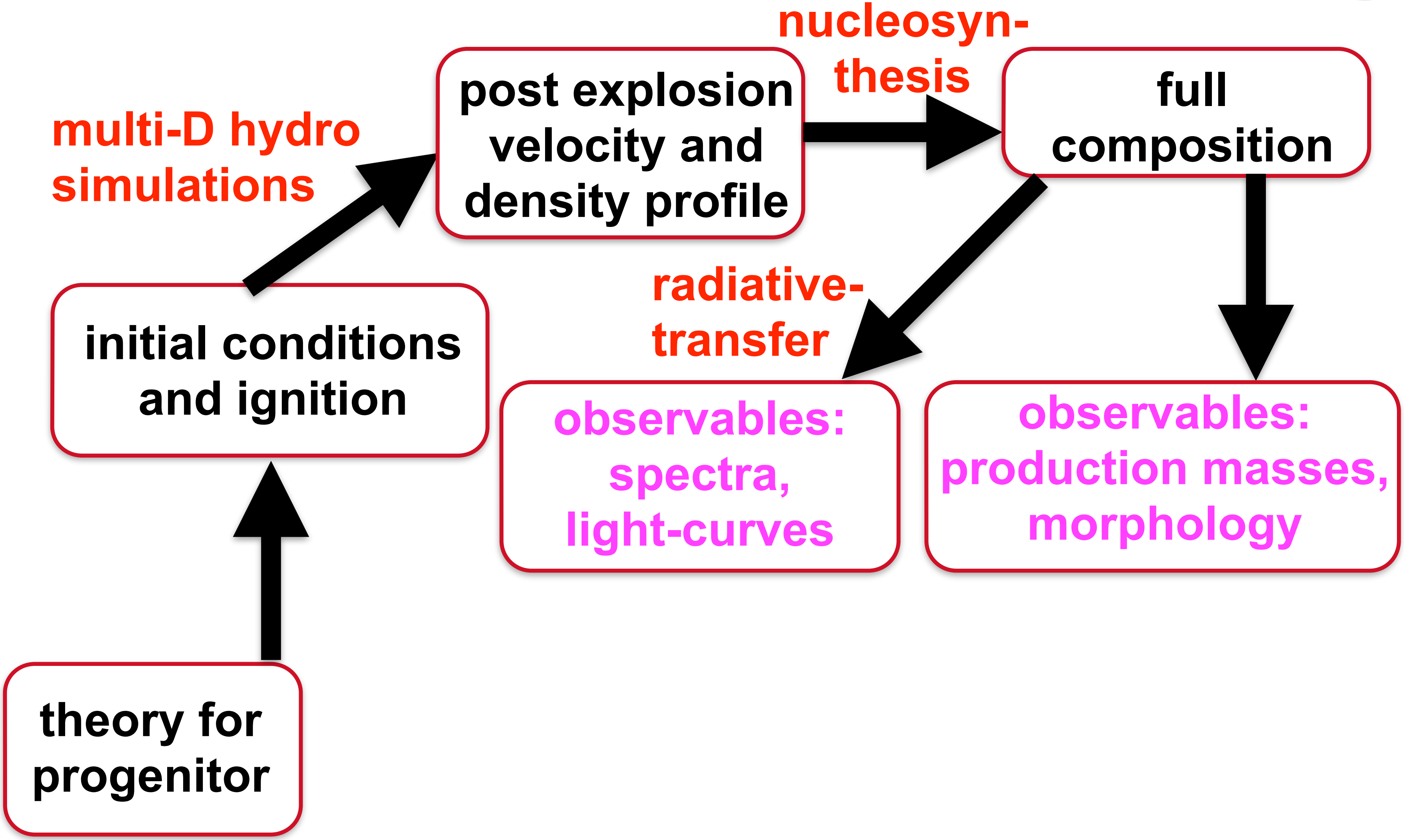

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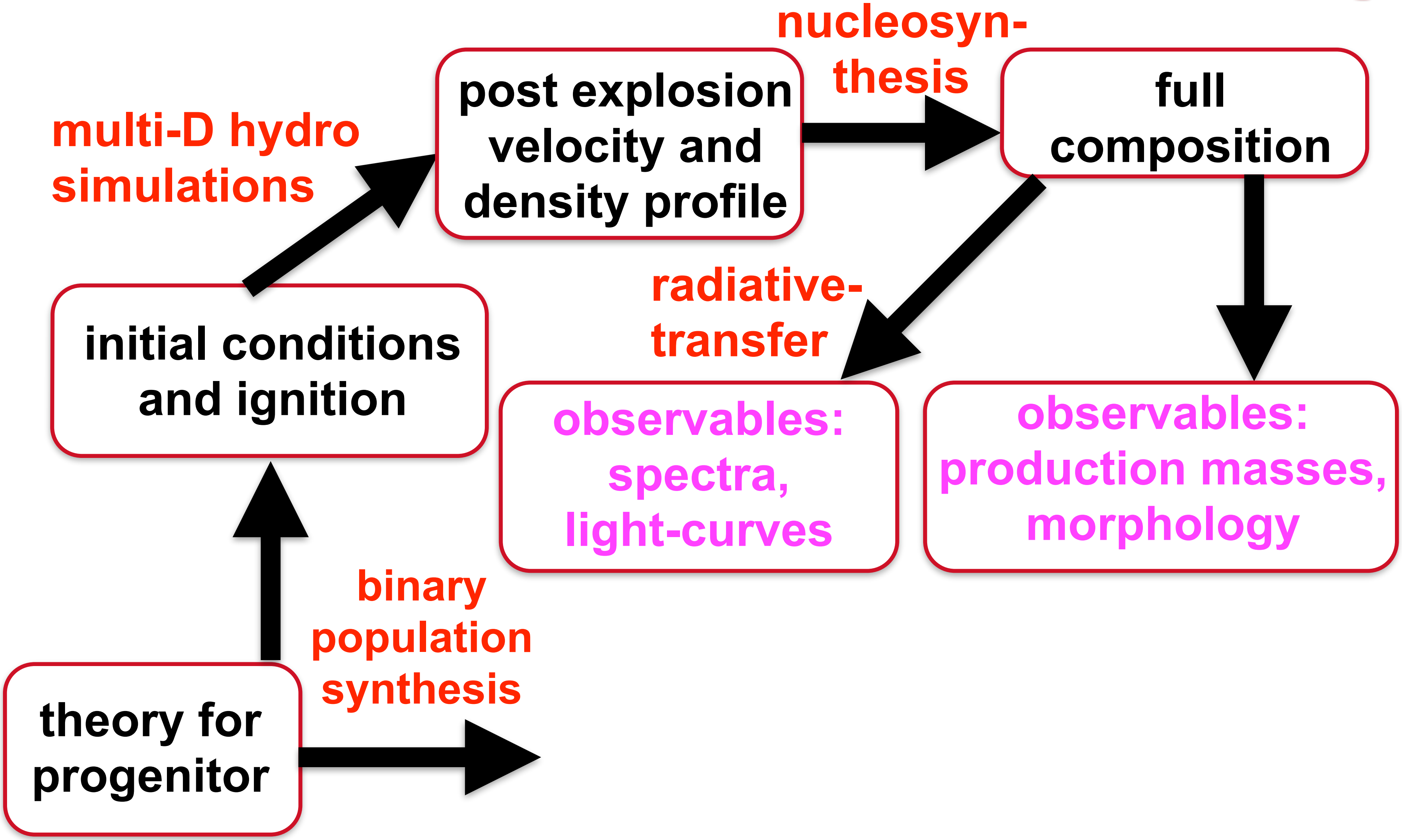

nucleosyn-thesis

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binary population synthesis

theory for progenitor

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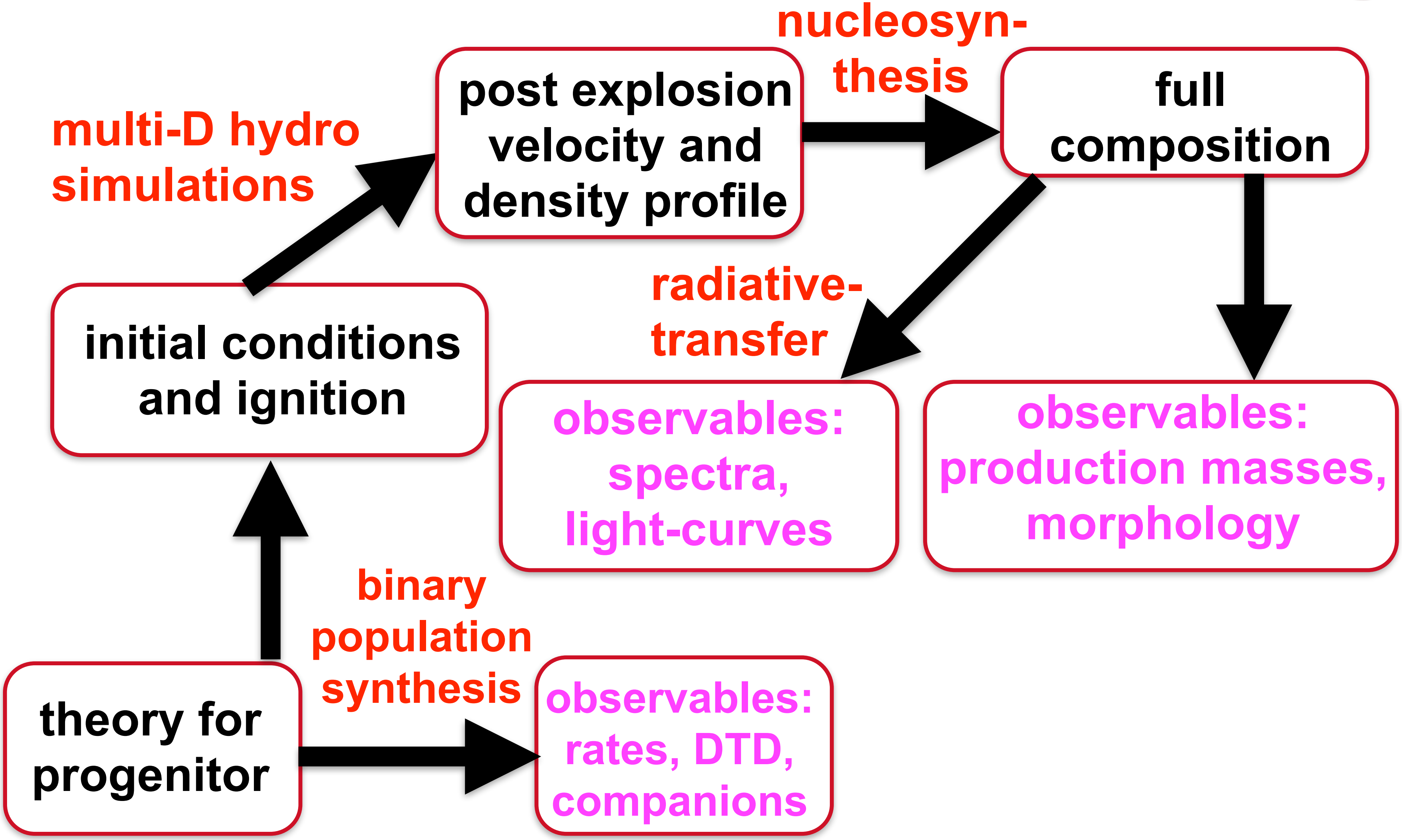

theory for progenitor

binary population synthesis

observables: rates, DTD, companions

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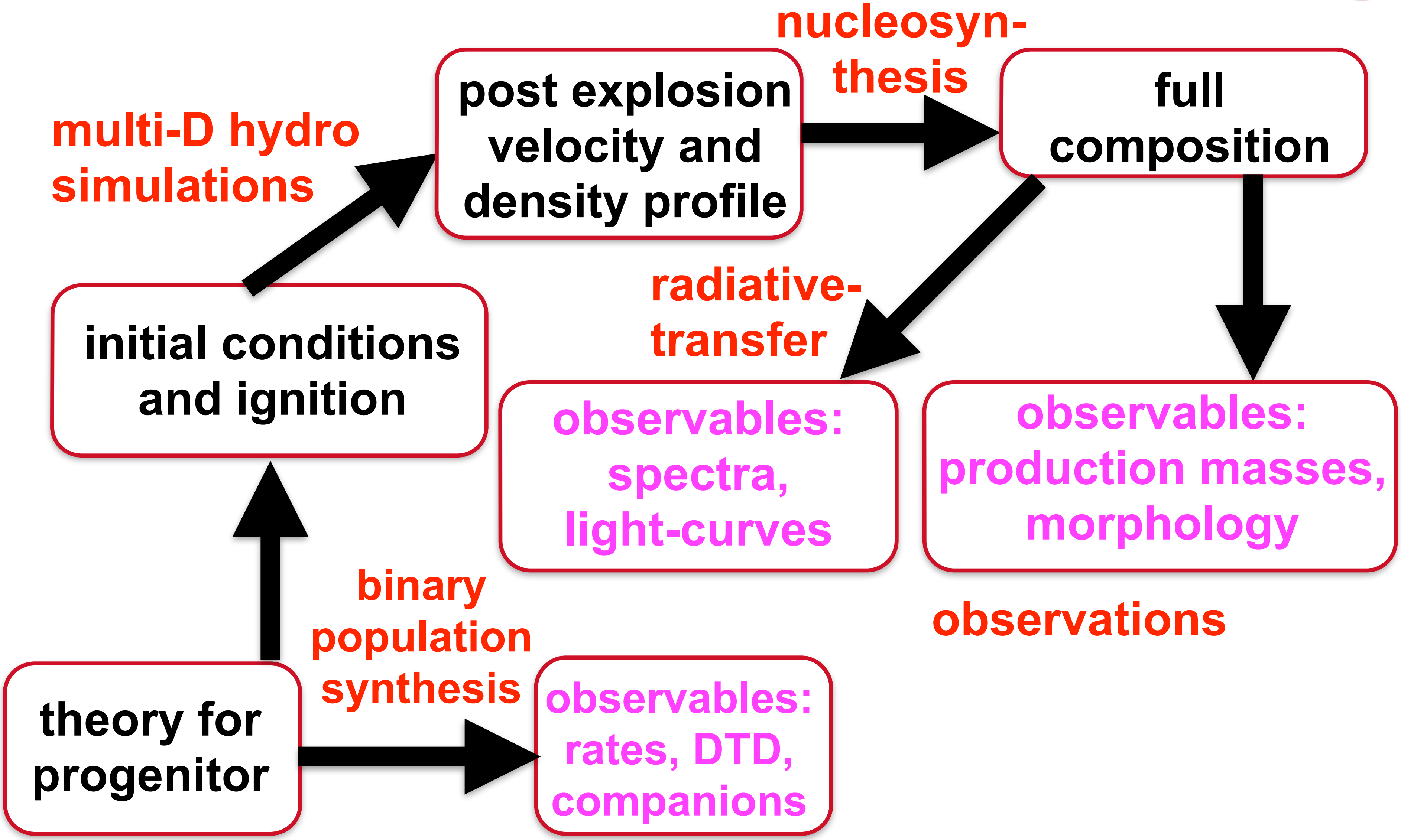

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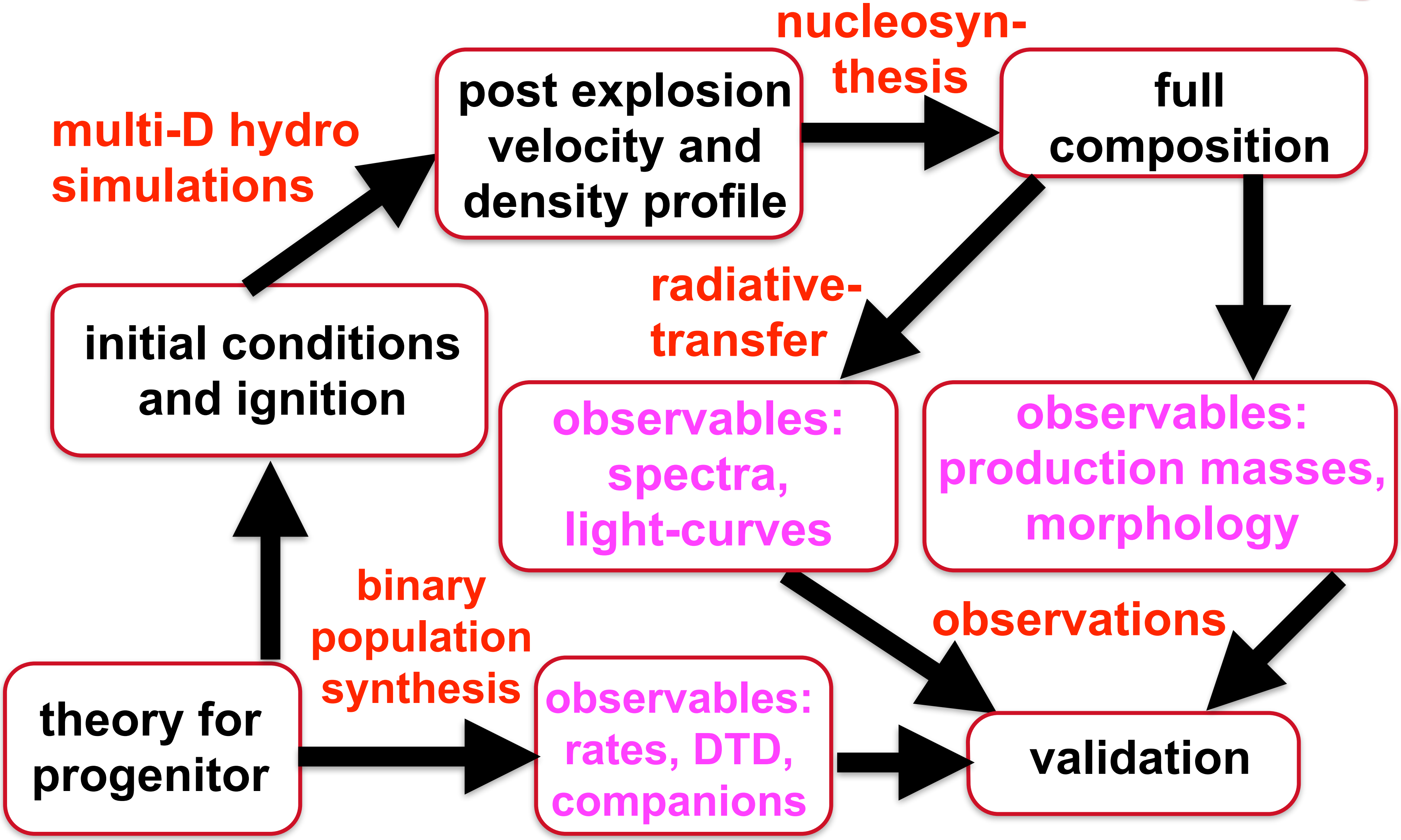

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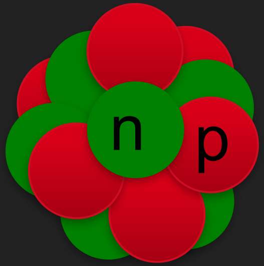
validation

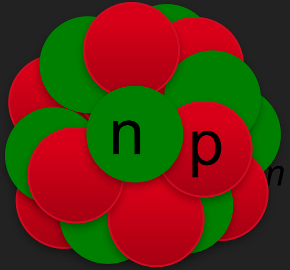
SN Ia energetics
Why FOE?

initial composition

^{12}C



^{16}O



p

SN Ia energetics
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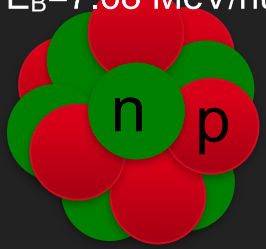
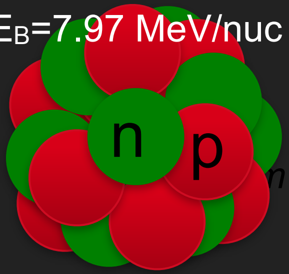
E_B=7.68 MeV/nuc



^{16}O

E_B=7.97 MeV/nuc



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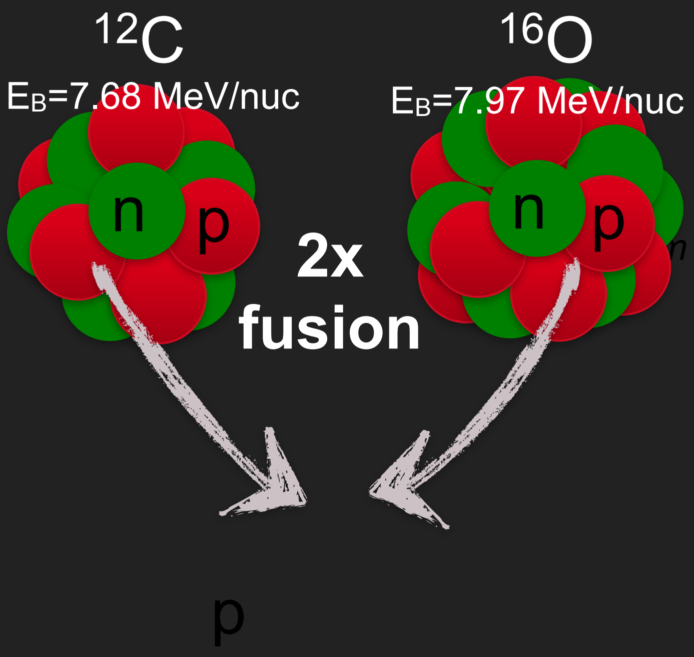

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2x fusion

SN Ia energetics
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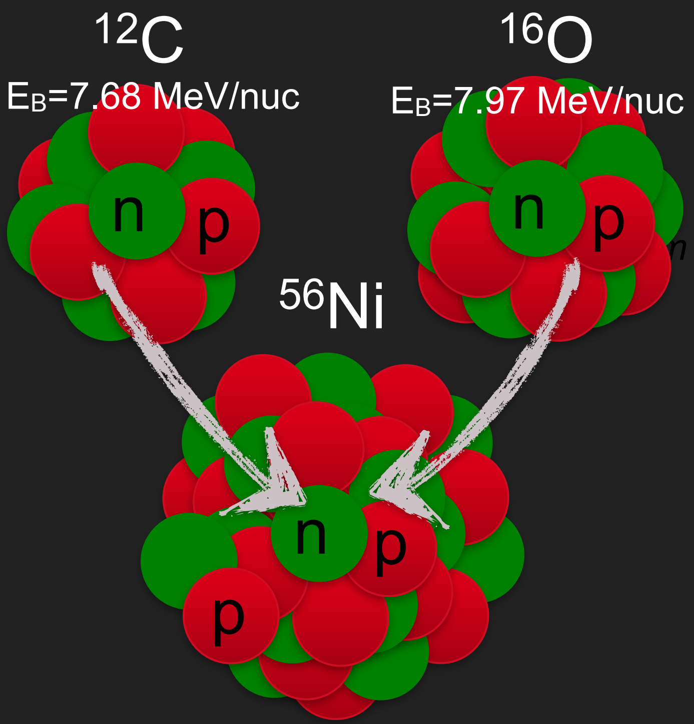

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^{56}Ni

SN Ia energetics
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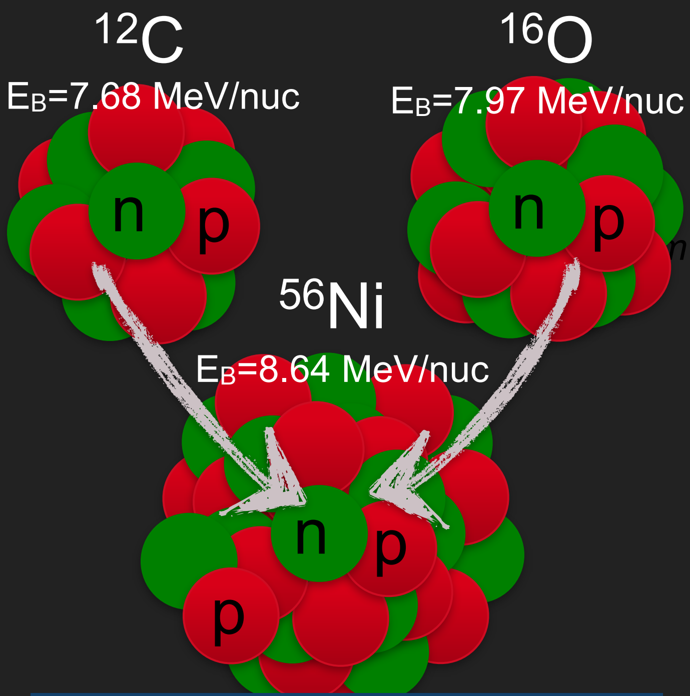


^{12}C

E_B=7.68 MeV/nuc

^{16}O

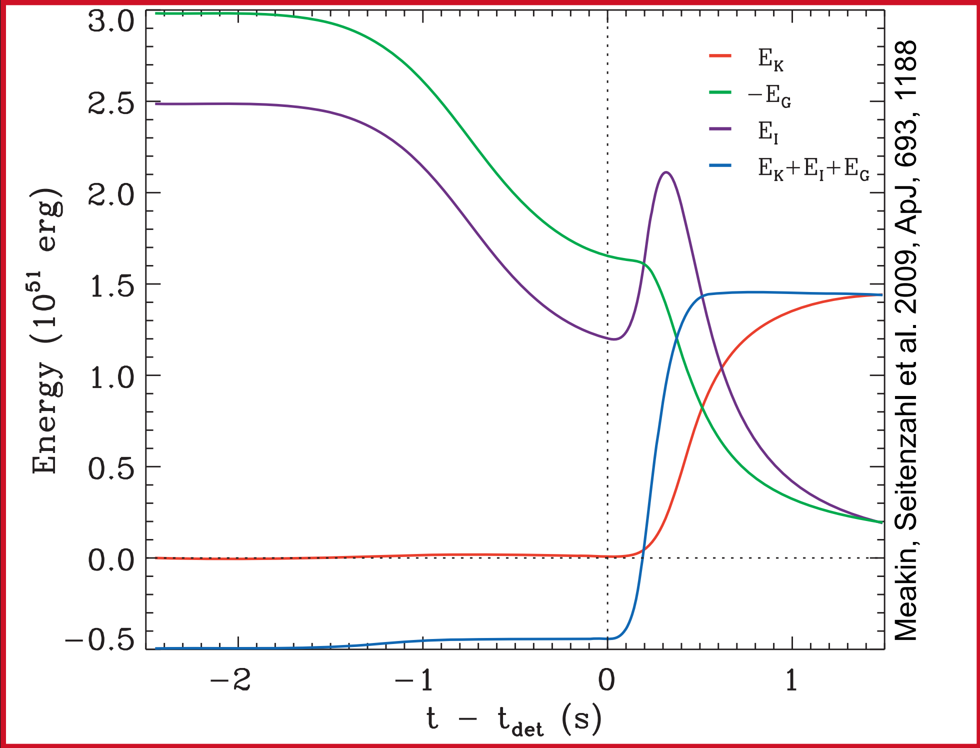
E_B=7.97 MeV/nuc

^{56}Ni

E_B=8.64 MeV/nuc

~10^{51} erg released during ~1 sec of explosive burning transformed into E_{kin} and work against gravity.

0.8 MeV/nuc *
$6x10^{23}$ nuc/g *
$2x10^{33}$ g *
$1.6x10^{-6}$ erg/MeV
= $1.5x10^{51}$ erg



Meakin, Seitenzahl et al. 2009, ApJ, 693, 1188

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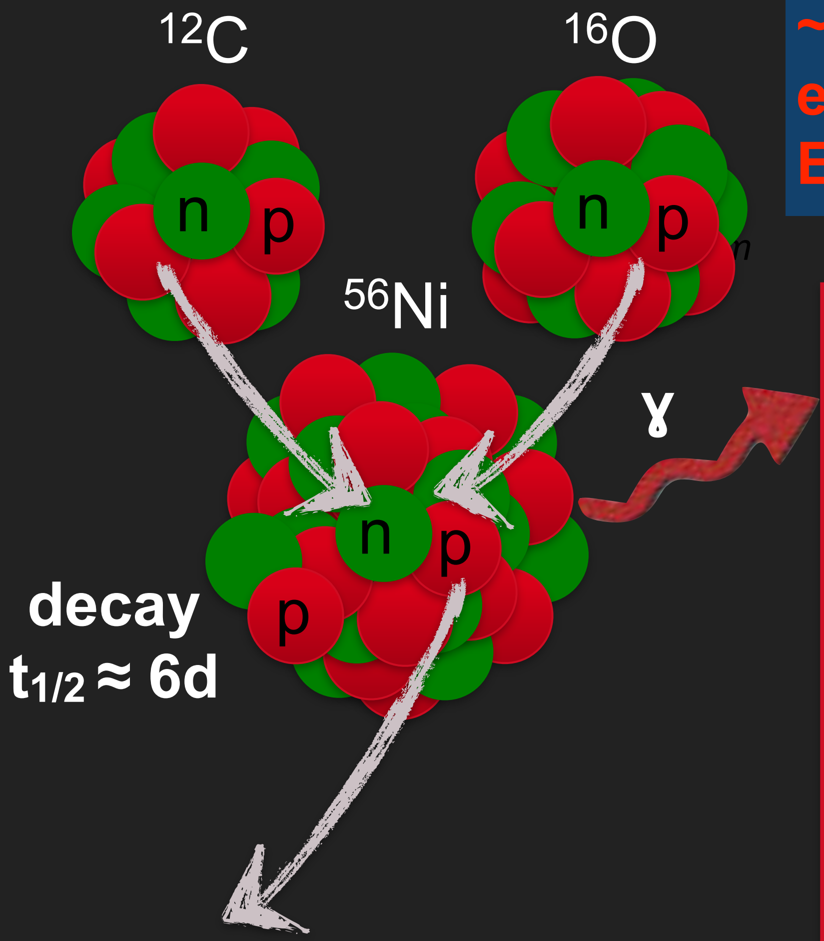

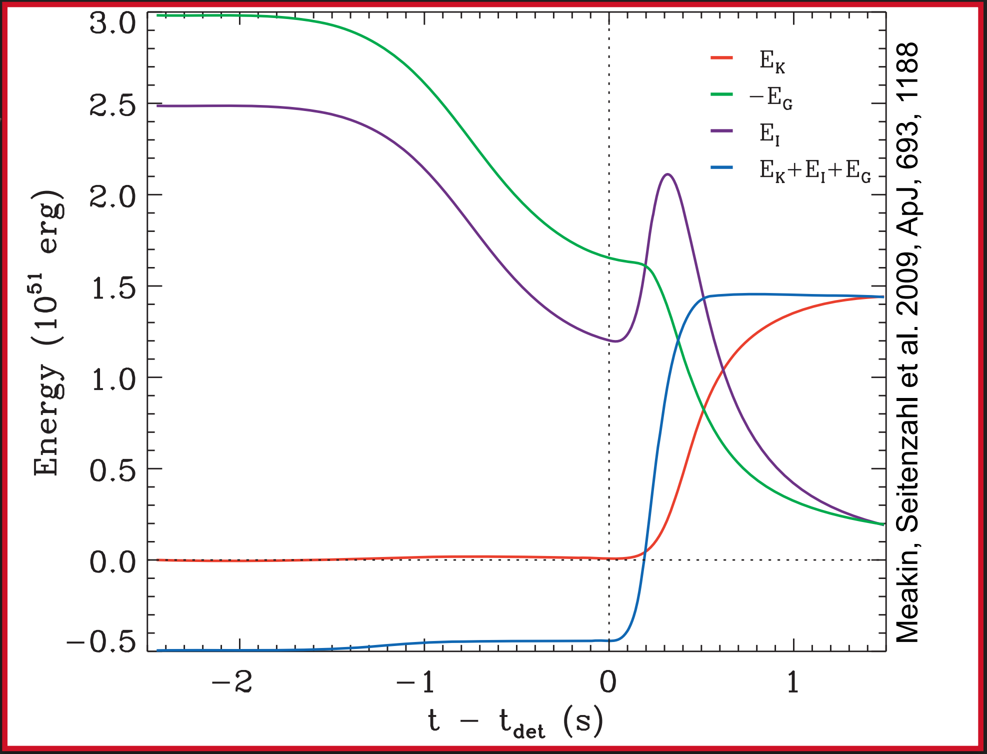

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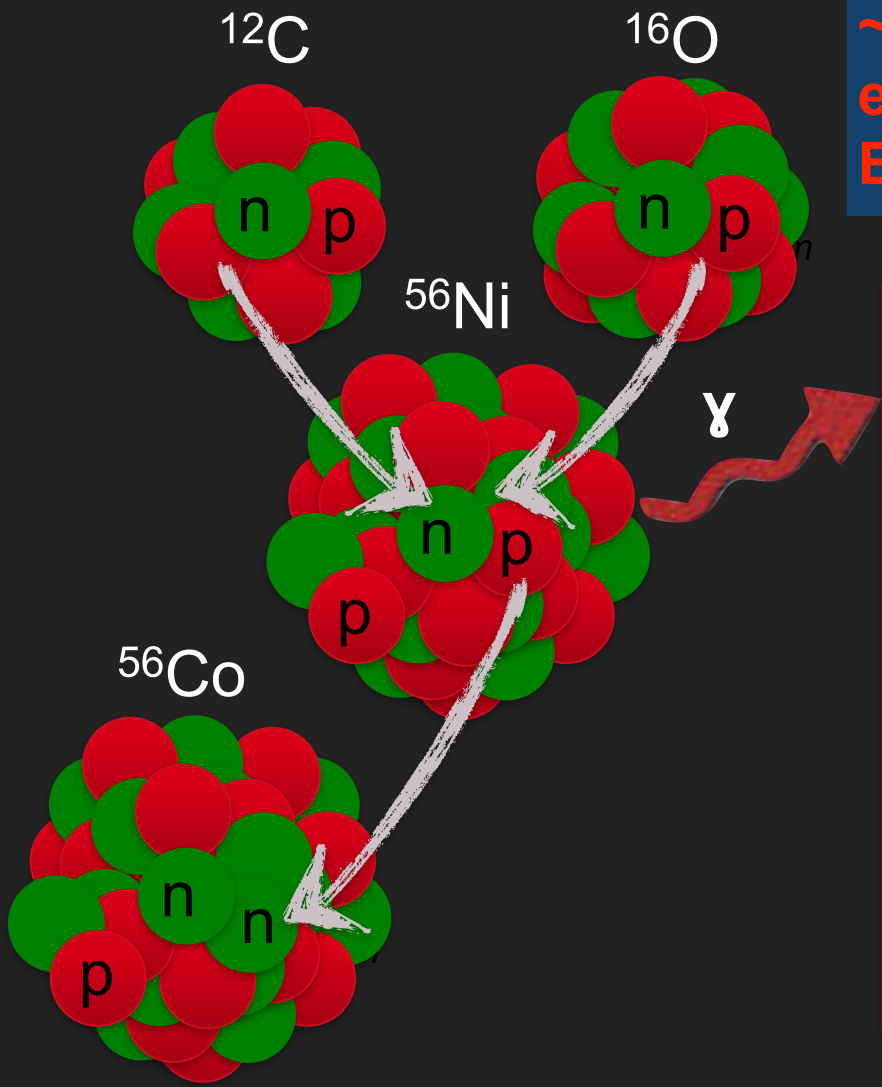

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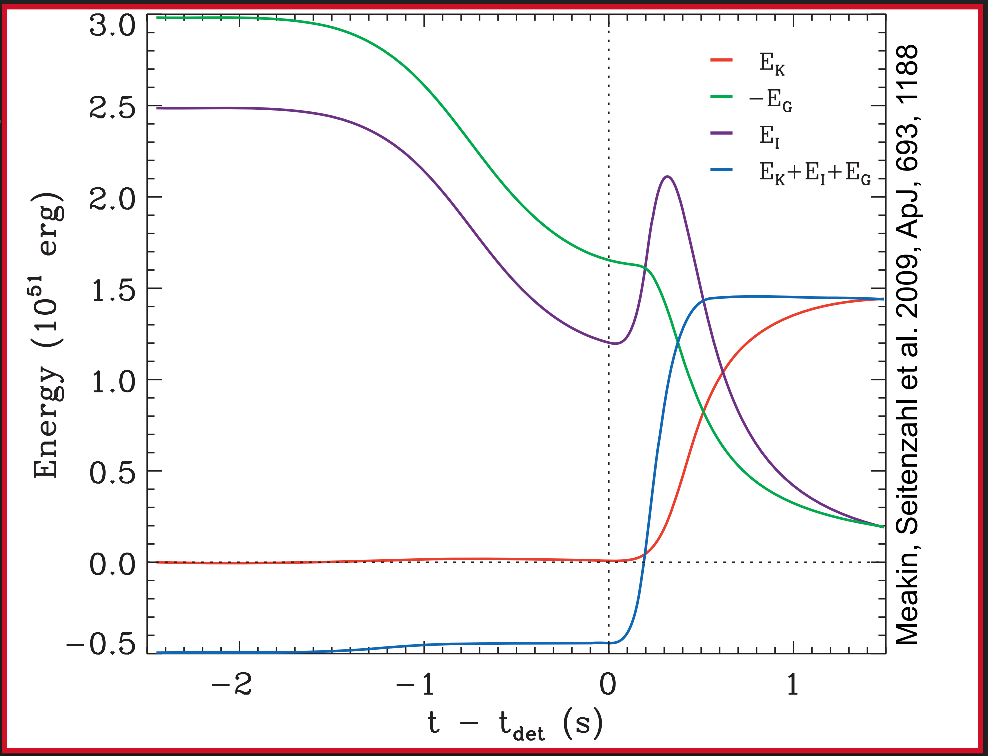

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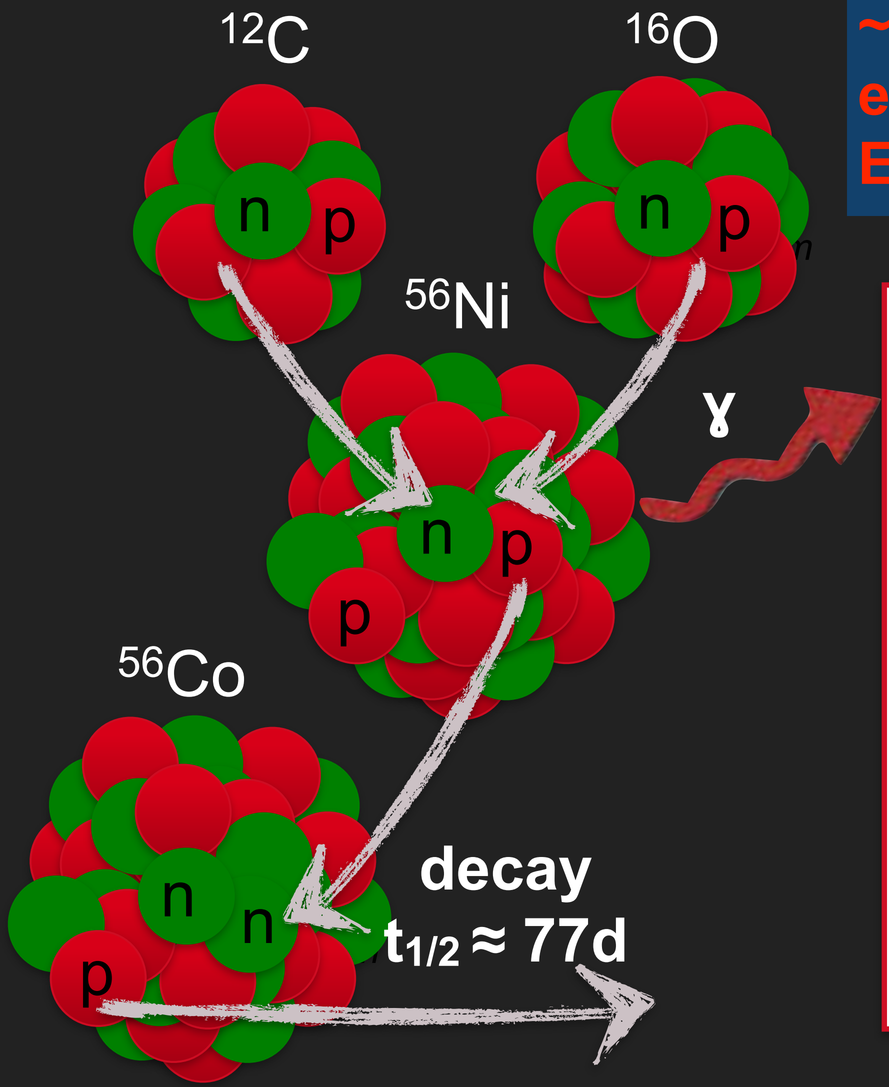

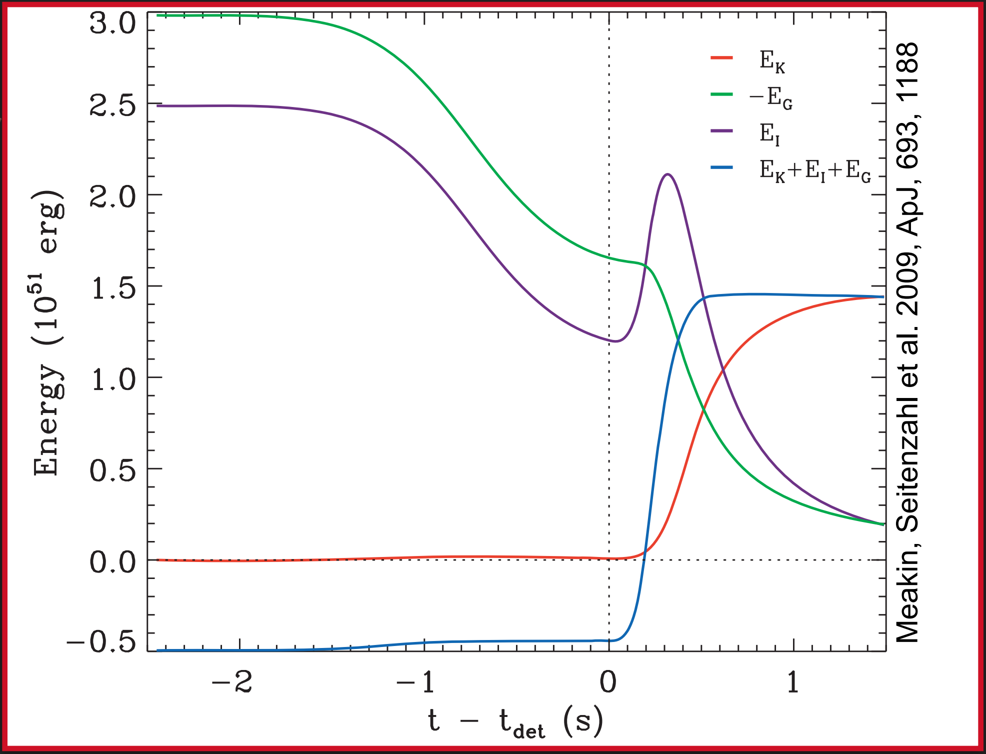

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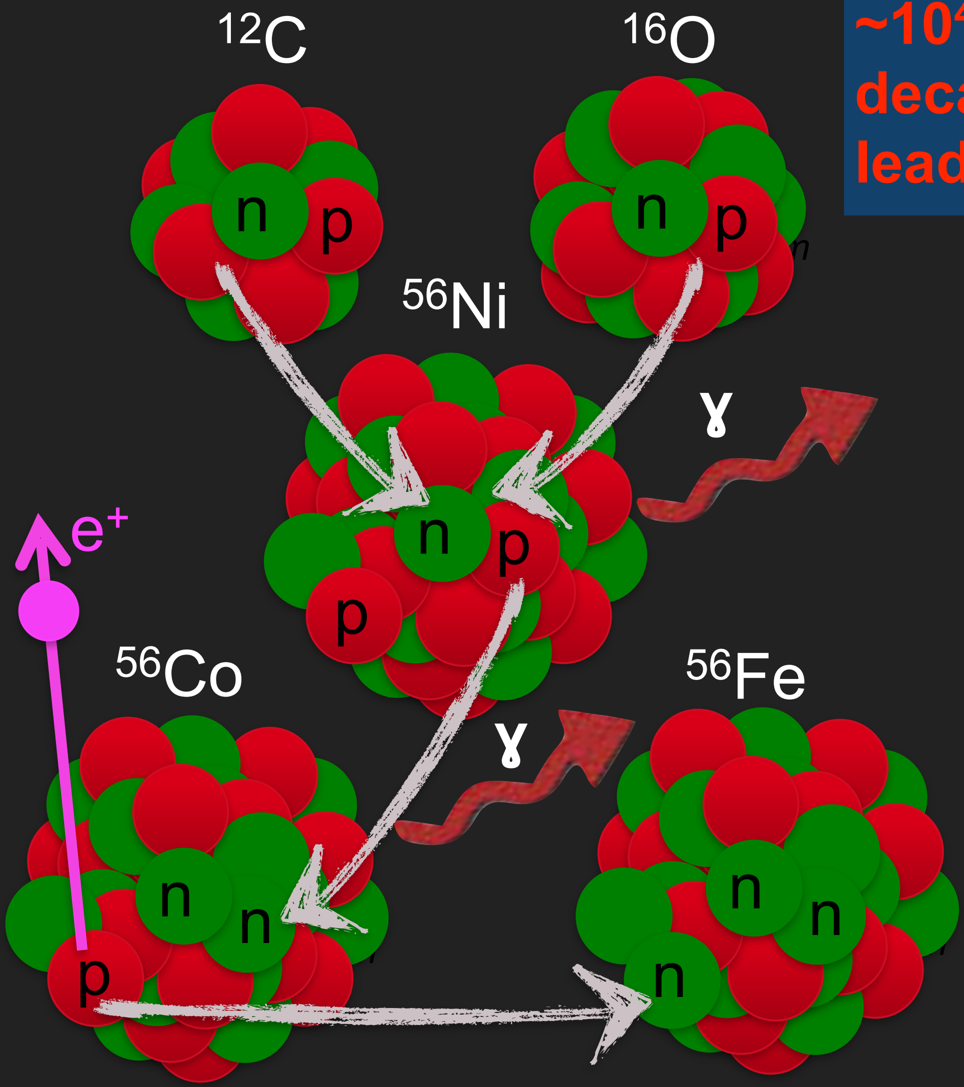
SN Ia energetics
Why FOE?

~10^{49} erg released by radioactive decays reheats the ejecta and leads to observed optical emission



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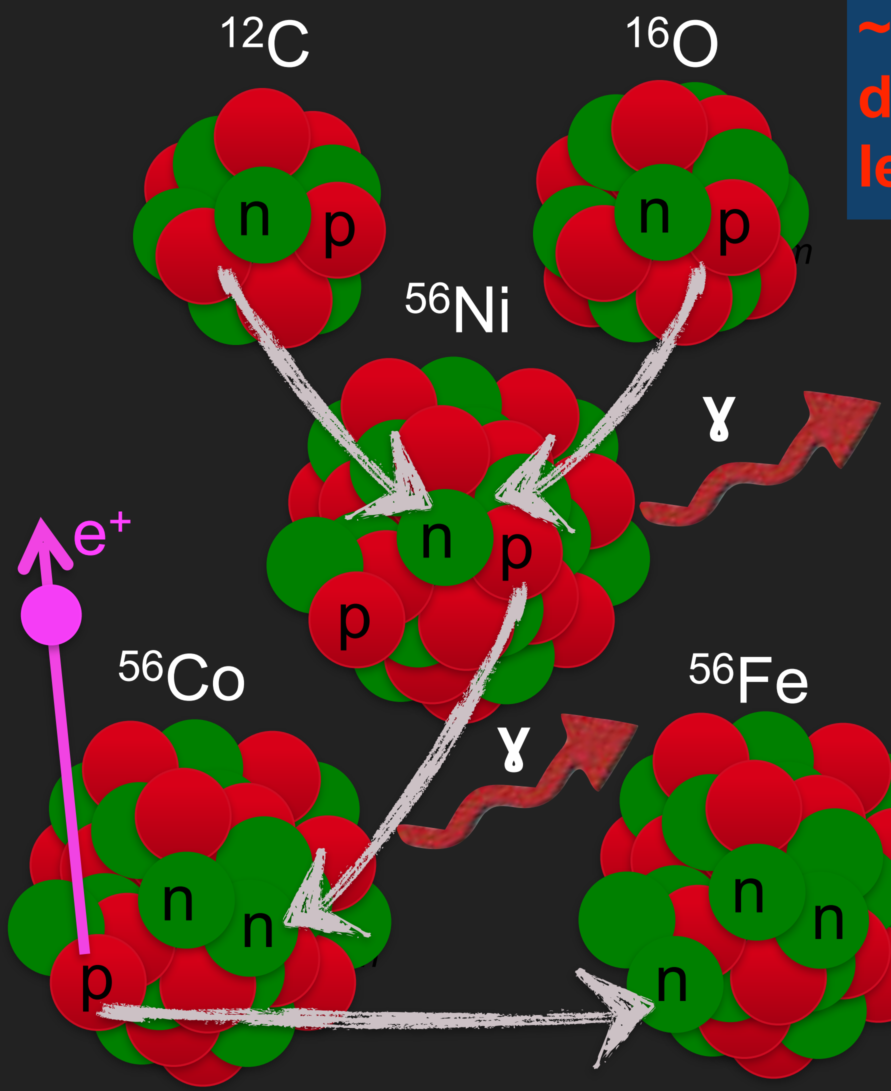
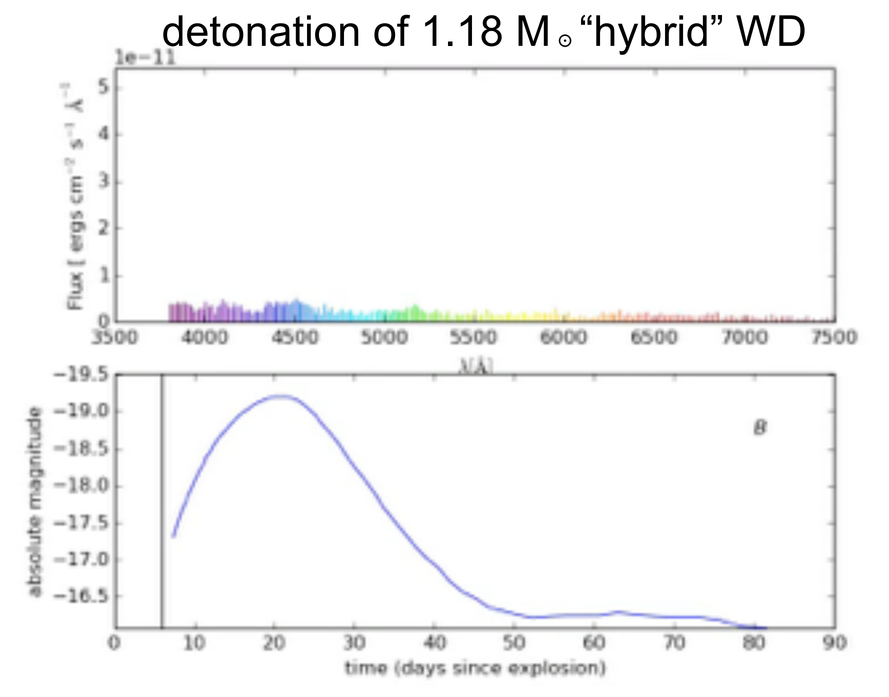


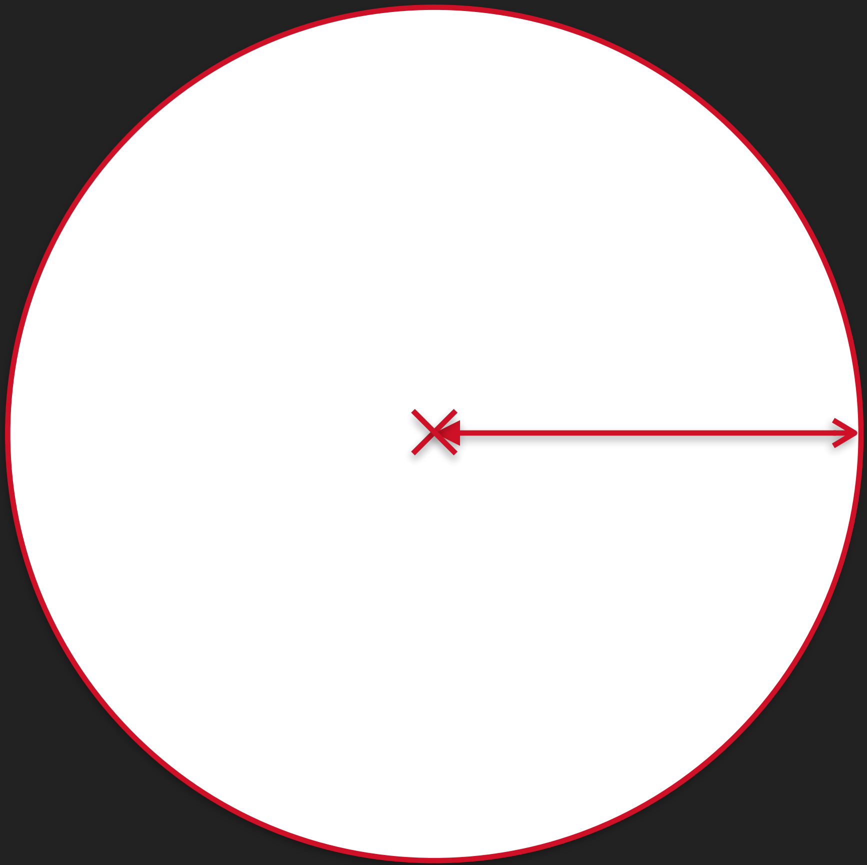
detonation of 1.18 M⊙ “hybrid” WD



Movie Credit: Kai Marquardt

SNe IA
WD physics (simplified)

white dwarf star



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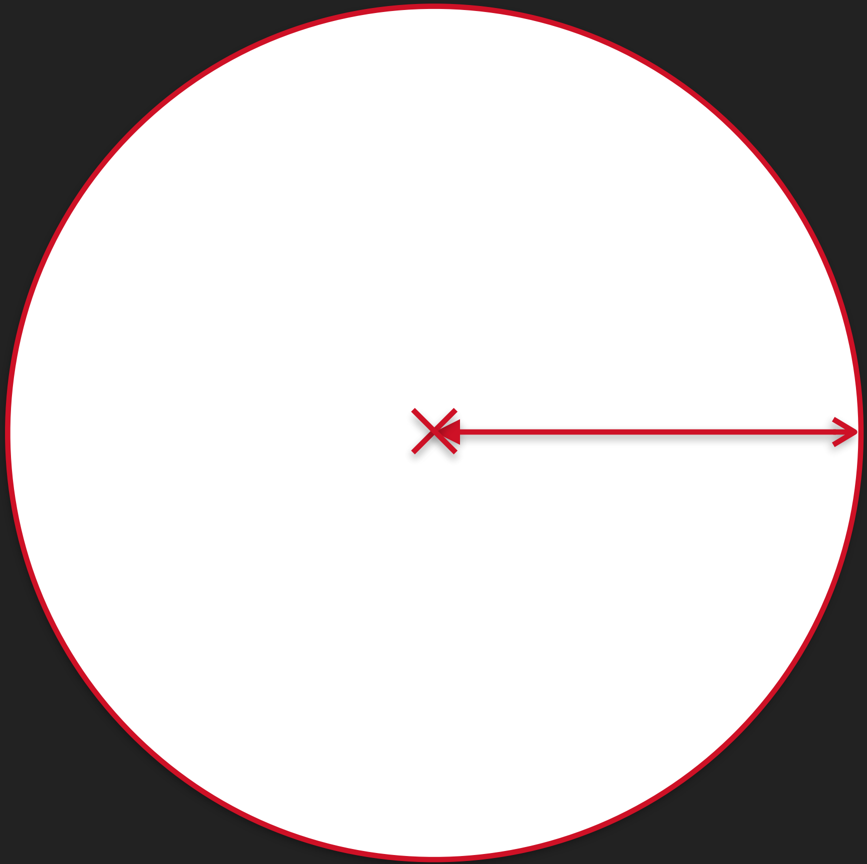

hydrostatic equilibrium:

$dP/dr = - \rho(r)\, g(r)$

SNe IA
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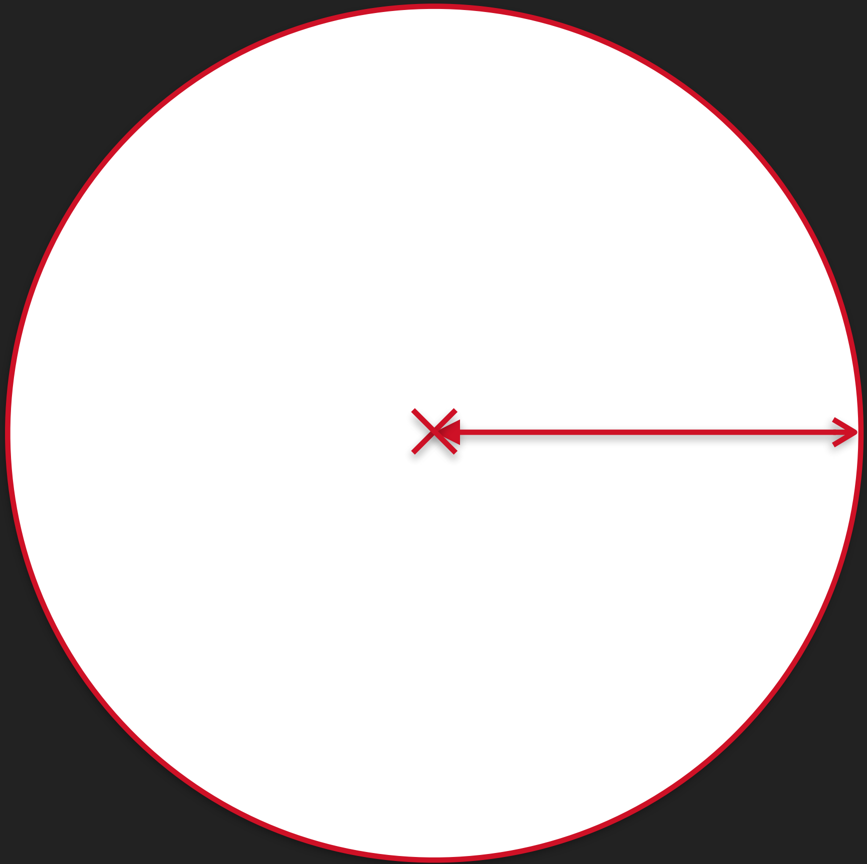

hydrostatic equilibrium:

$dP/dr = -\rho(r)\,g(r)$

equation of state:

relativistic, degenerate e^-

$P = K\rho^{4/3}$

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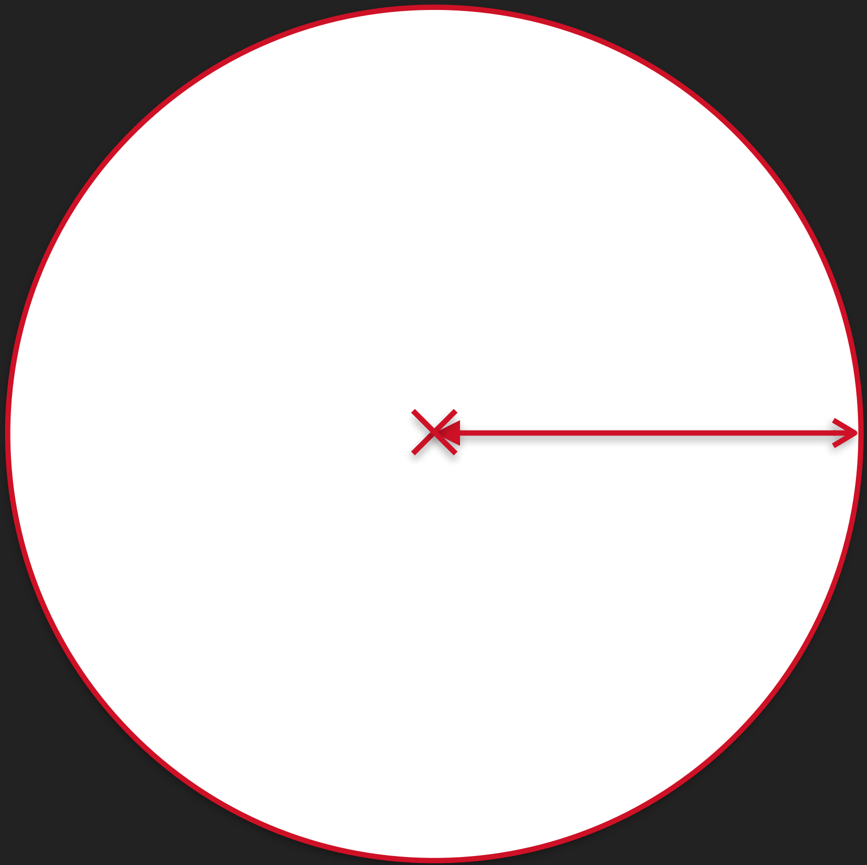

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gravity:

$g(r) = G\, M(r) / r^2$

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WD physics (simplified)

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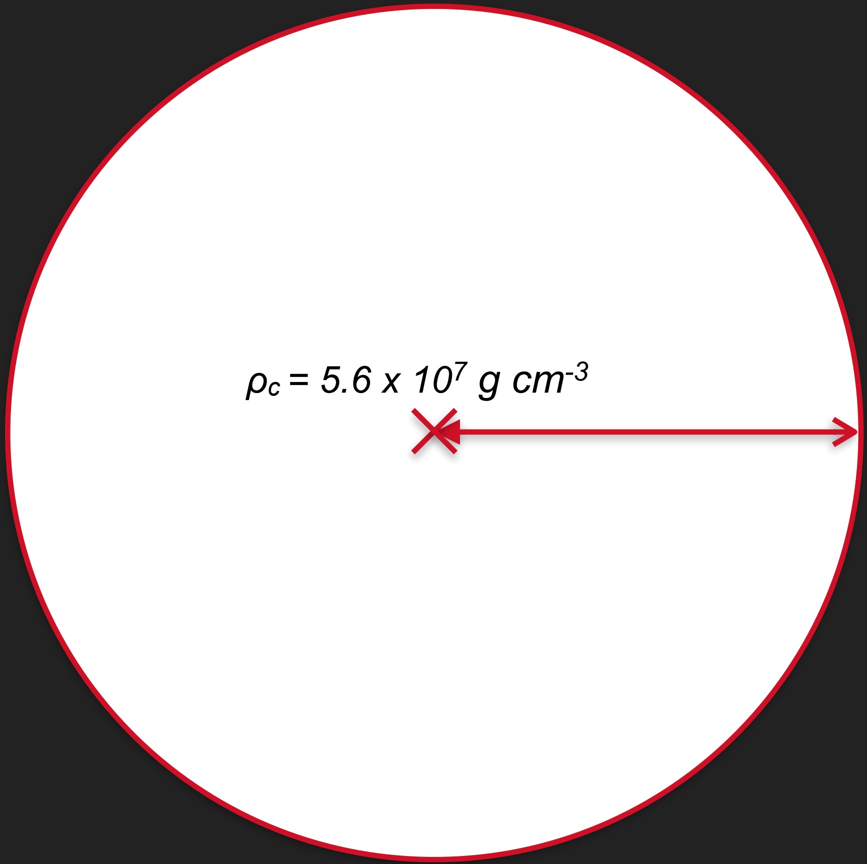

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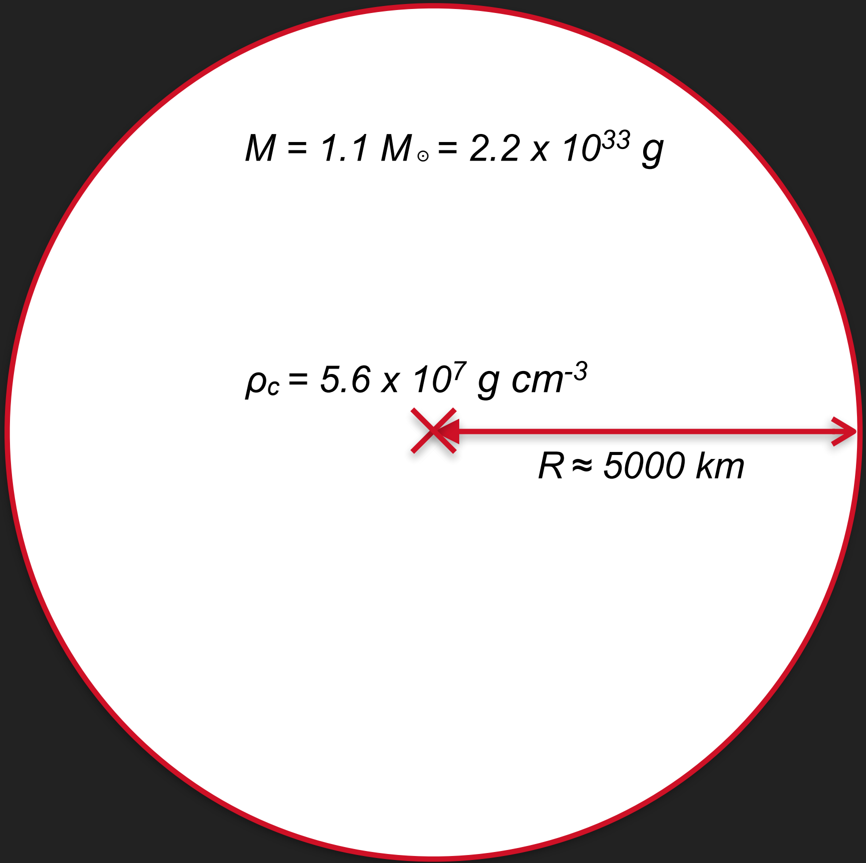
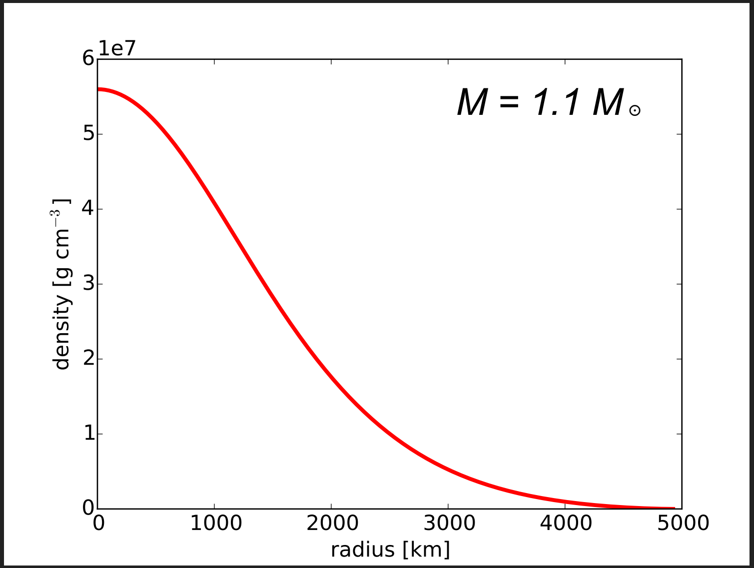


$M = 1.1\ M_\odot = 2.2 \times 10^{33}$ g

$\rho_c = 5.6 \times 10^{7}$ g cm^{-3}

$R \approx 5000$ km



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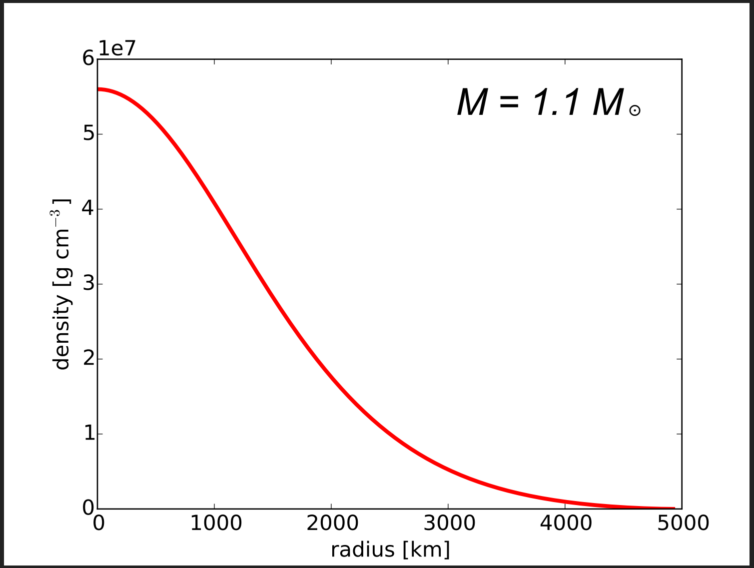

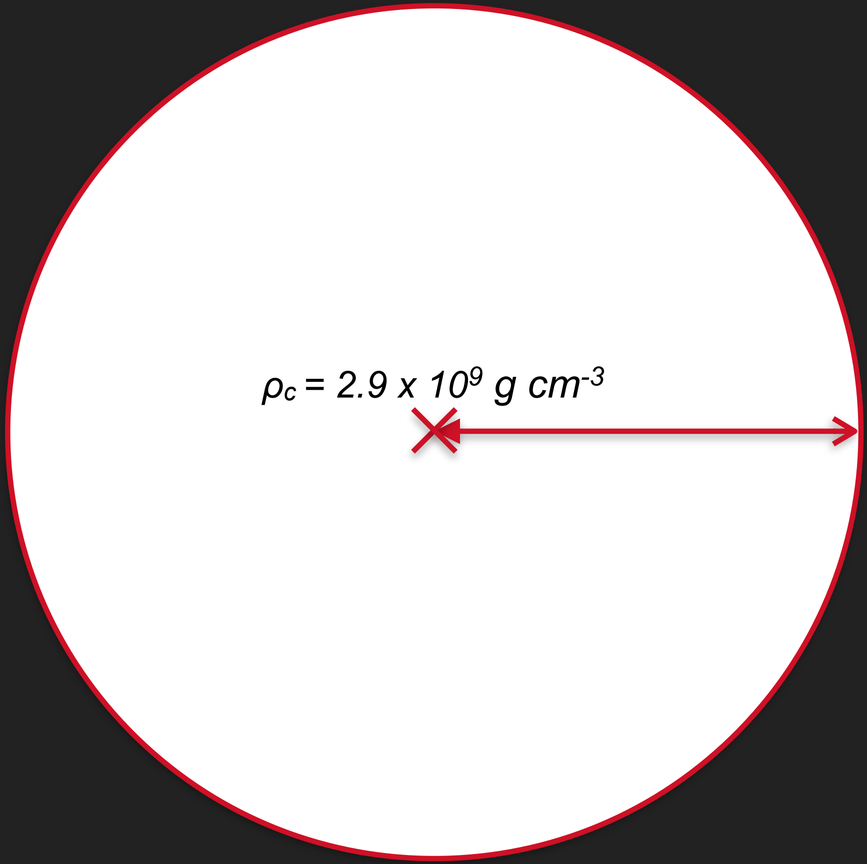

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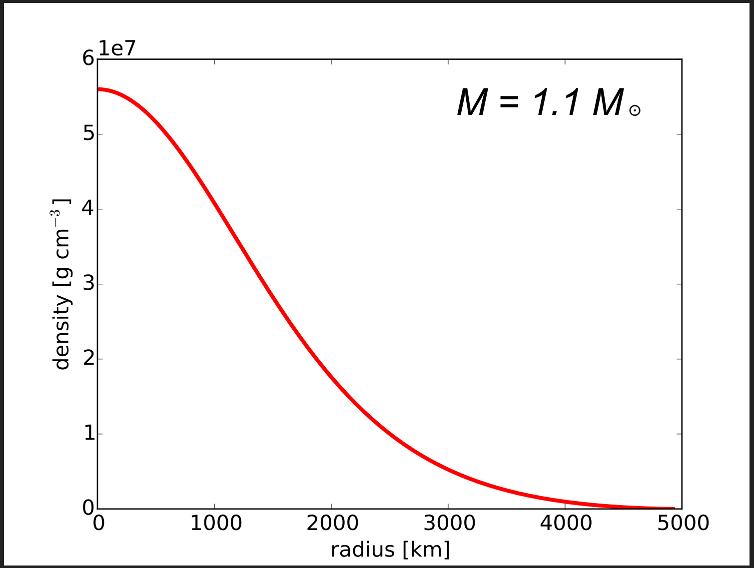

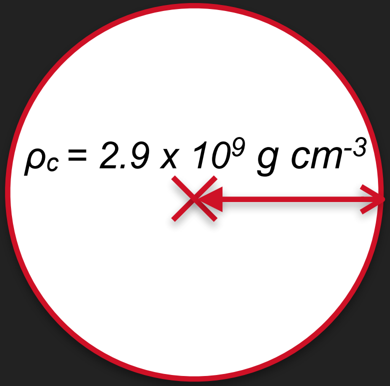

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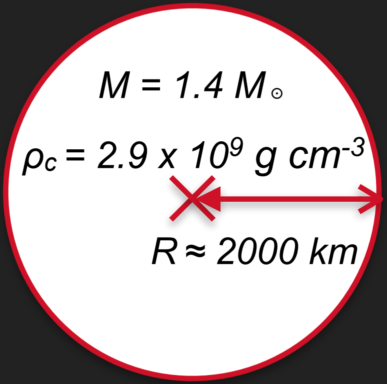
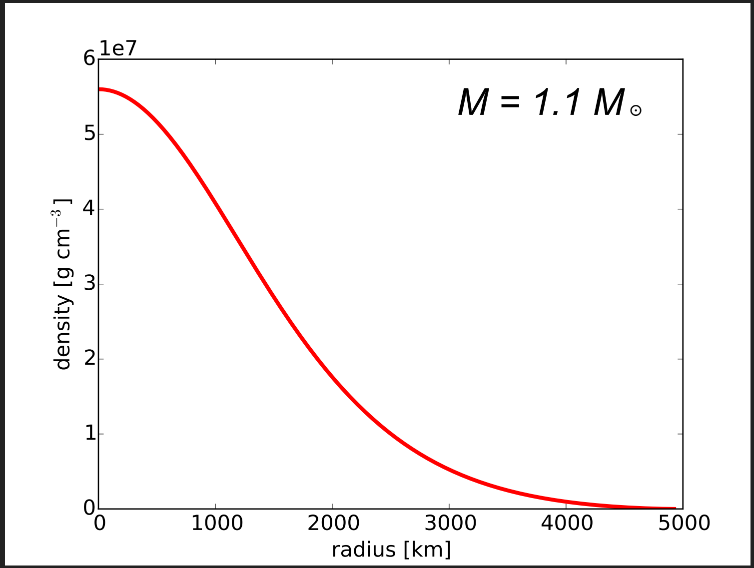
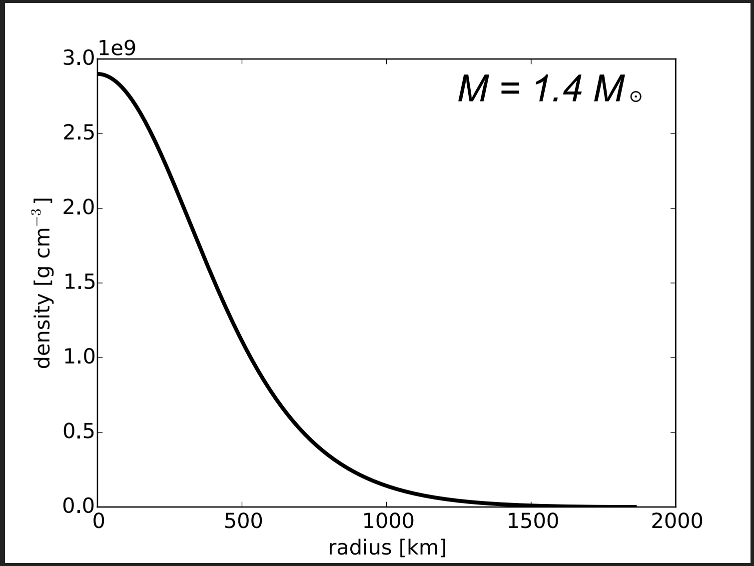


$M = 1.4\,M_\odot$

$\rho_c = 2.9 \times 10^9$ g cm^{-3}

$R \approx 2000$ km





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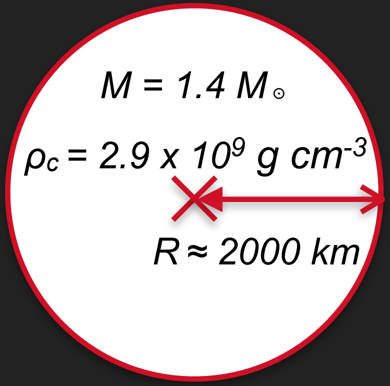

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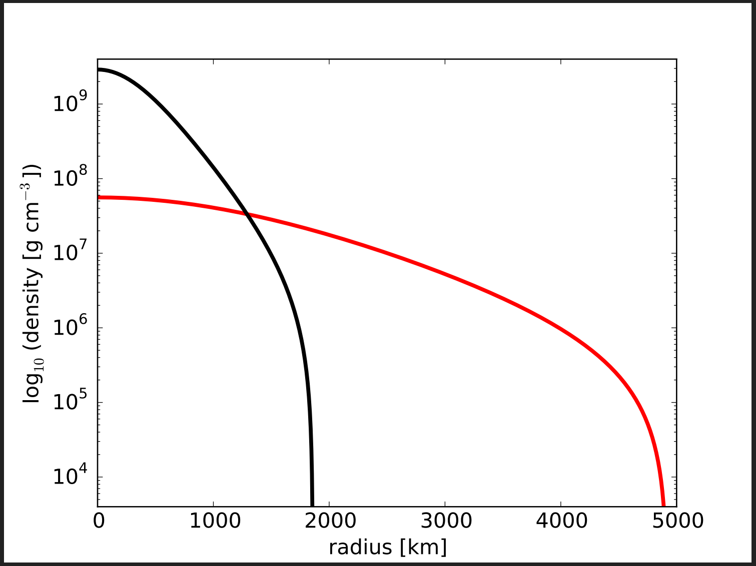

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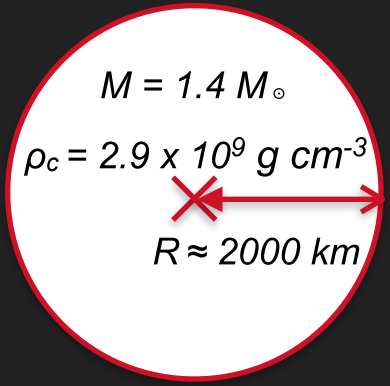

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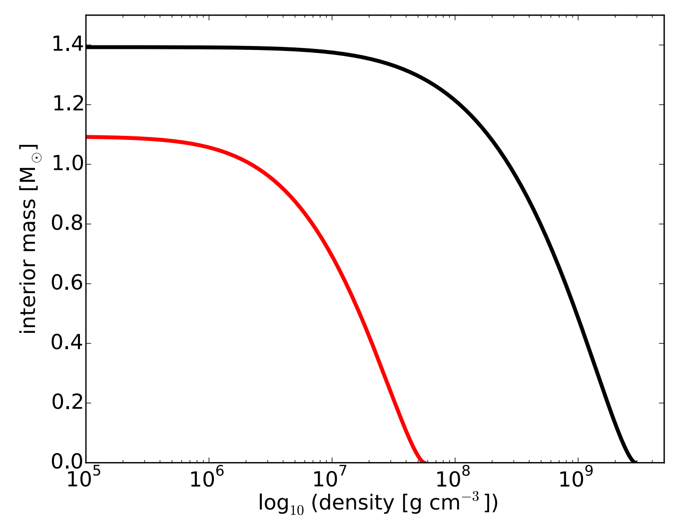
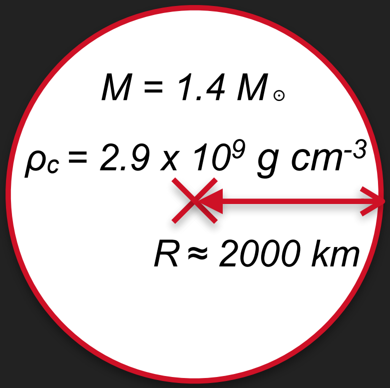


SNe IA
WD physics (simplified)

white dwarf star



$M = 1.4\ M_\odot$

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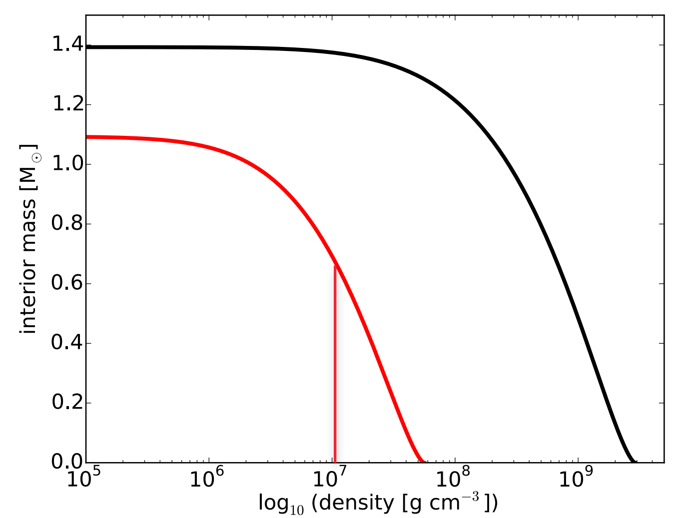

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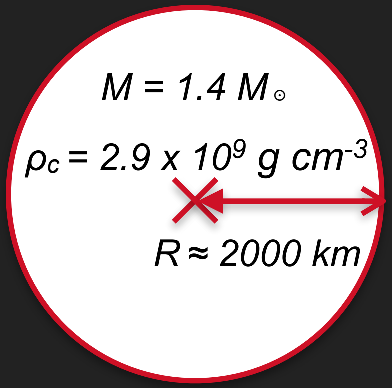

M = 1.4 $M_\odot$

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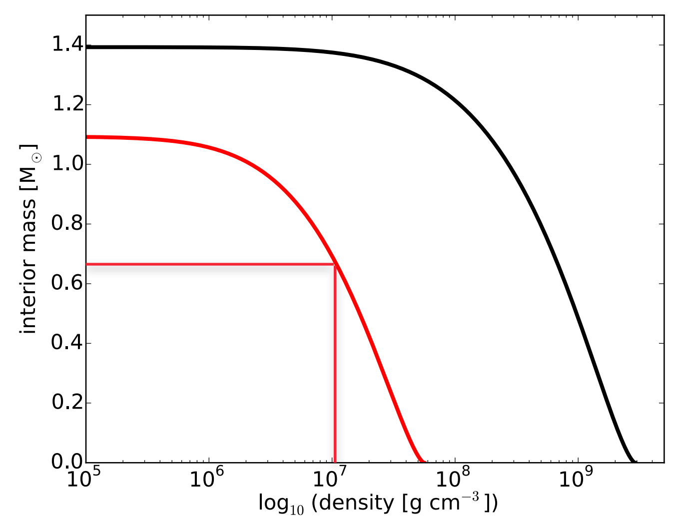
R ≈ 2000 km



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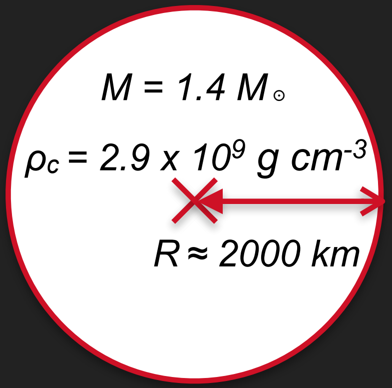

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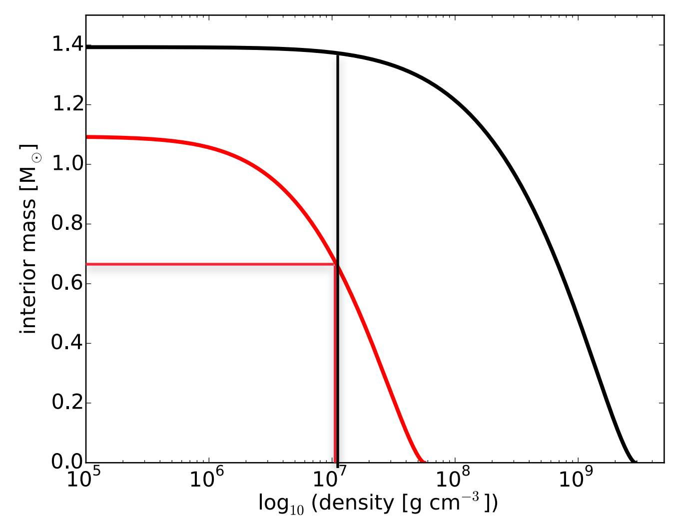

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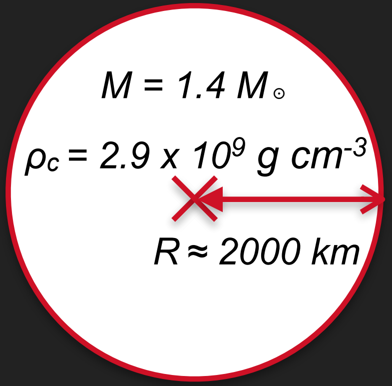

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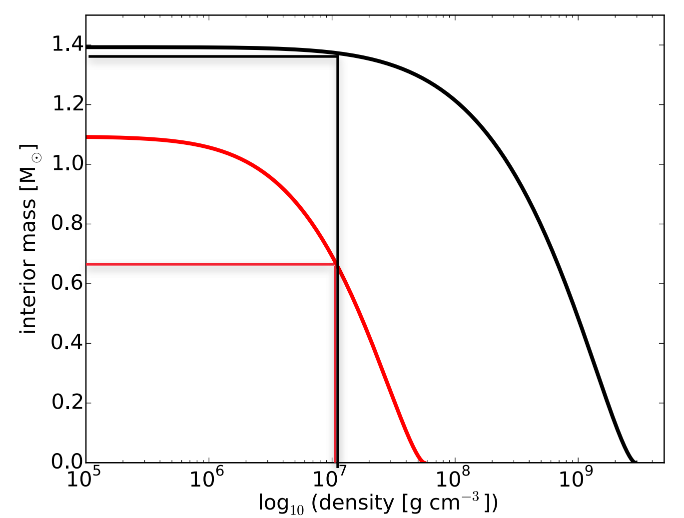


hydrodynamics of nuclear burning front propagation

hydrodynamics of nuclear burning front propagation

subsonic
deflagration
flame mediated by e^- conduction & turbulence:

subsonic nature allows for expansion ahead of flame

interlude: deflagrations and detonations

hydrodynamics of nuclear burning front propagation

subsonic
deflagration
flame mediated by e^- conduction & turbulence:

subsonic nature allows for expansion ahead of flame

supersonic
detonation
front driven by shock wave:

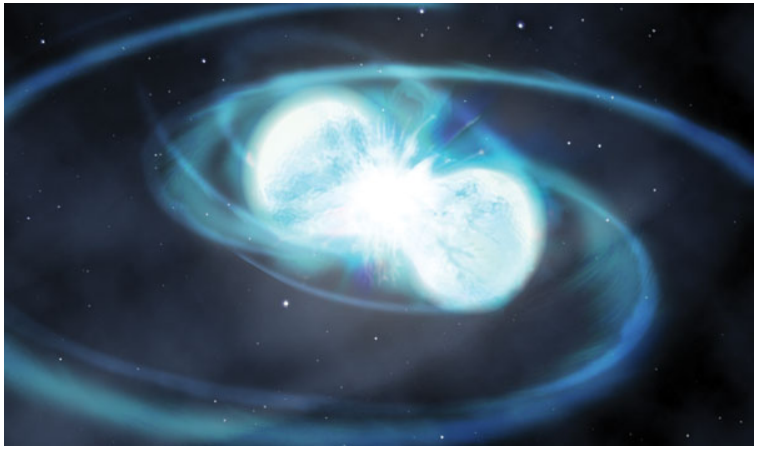
supersonic nature means unburned material unperturbed

2 major categories
near-M_{Ch} vs sub-M_{Ch}

delayed detonations
pure turbulent deflagrations

D. A. Hardy

violent mergers
He double-detonations



Nature

2 major categories near-M_{Ch} vs sub-M_{Ch}

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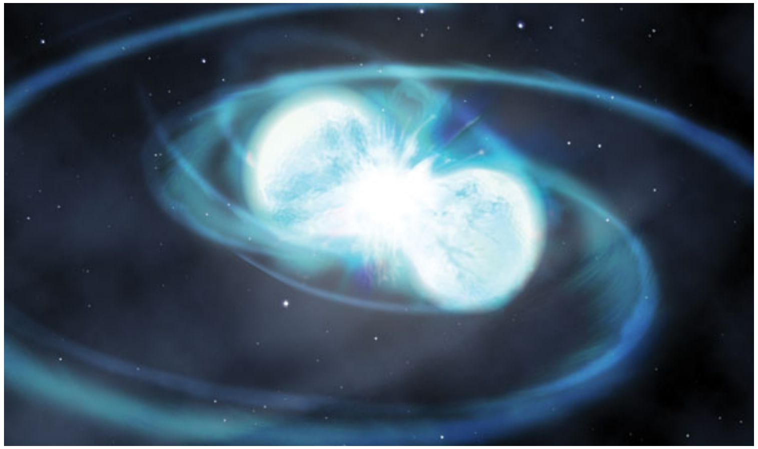

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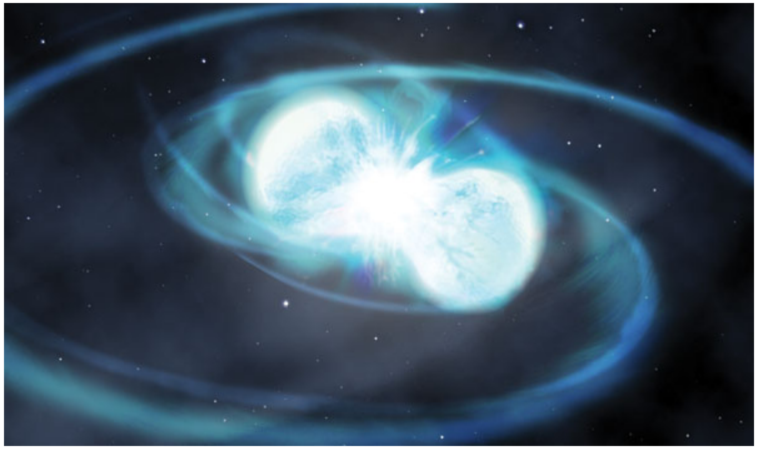

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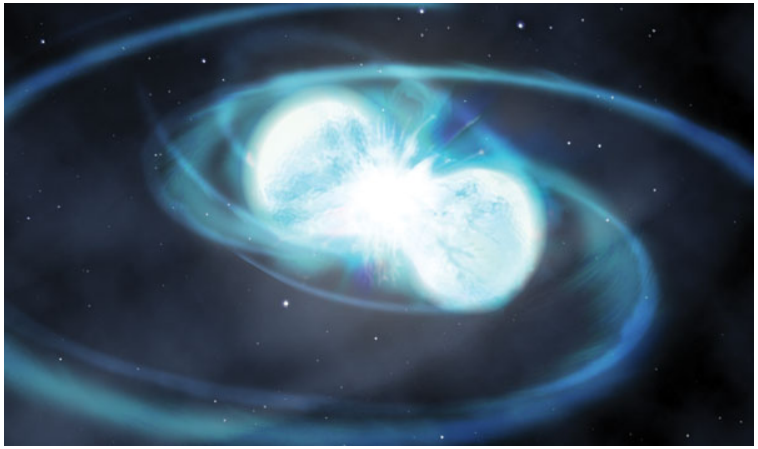

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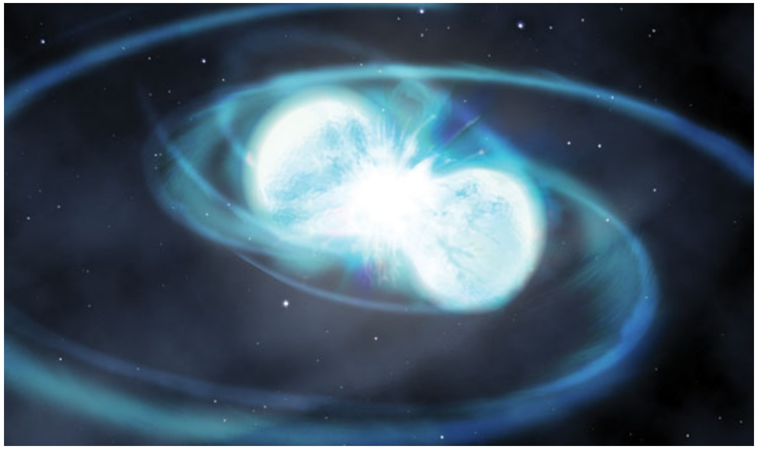

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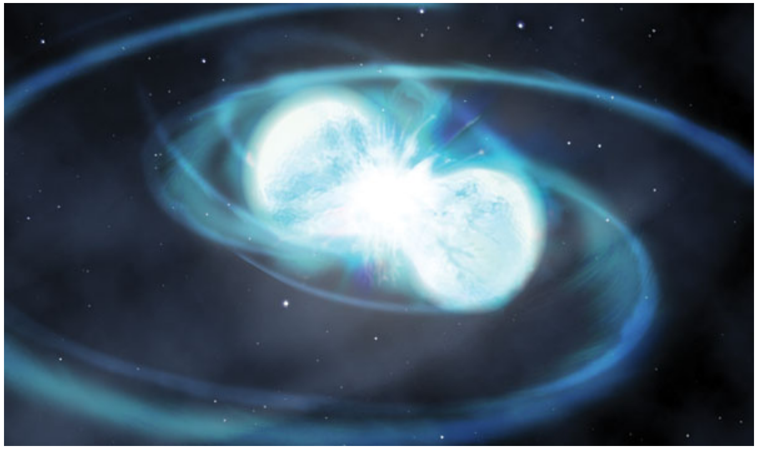

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- ➡ possible DDT

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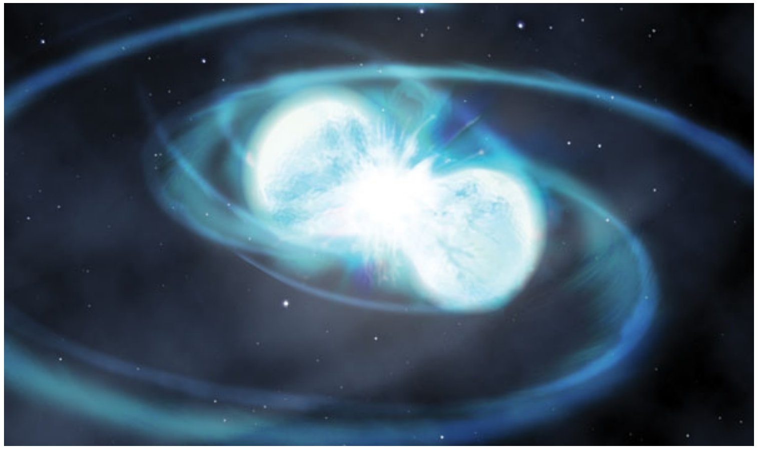

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- ➡ possible progenitor systems known (U Sco, RS Oph, V445 Pup)

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D. A. Hardy

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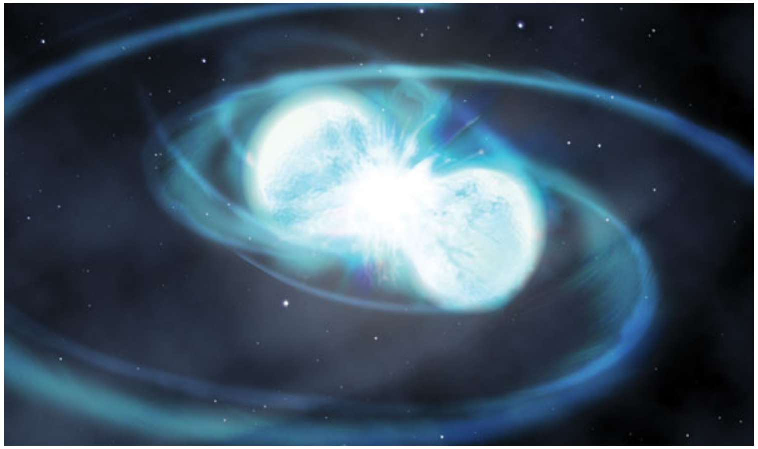

Nature

- ➡ $M_{primary} \approx 1.1$ solar masses

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D. A. Hardy

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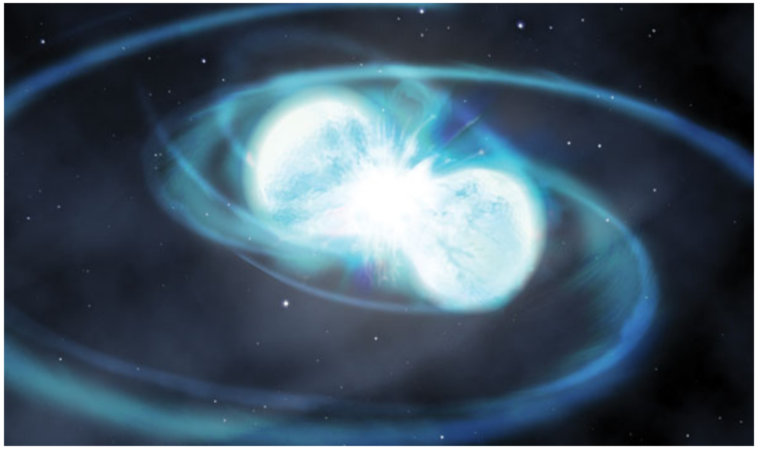

Nature

- ➡ $M_{primary} \approx 1.1$ solar masses
- ➡ ignition occurs as

2 major categories near-M_{Ch} vs sub-M_{Ch}

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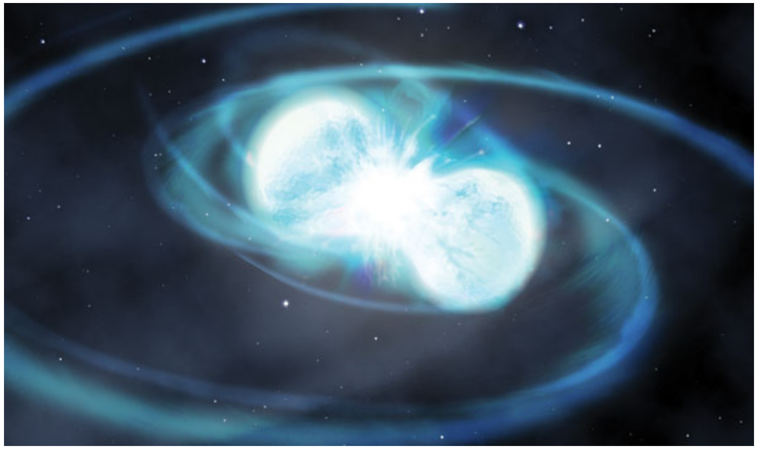

Nature

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- ➡ ignition occurs as
  - ★ violent accretion stream triggers detonation

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pure turbulent deflagrations

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violent mergers
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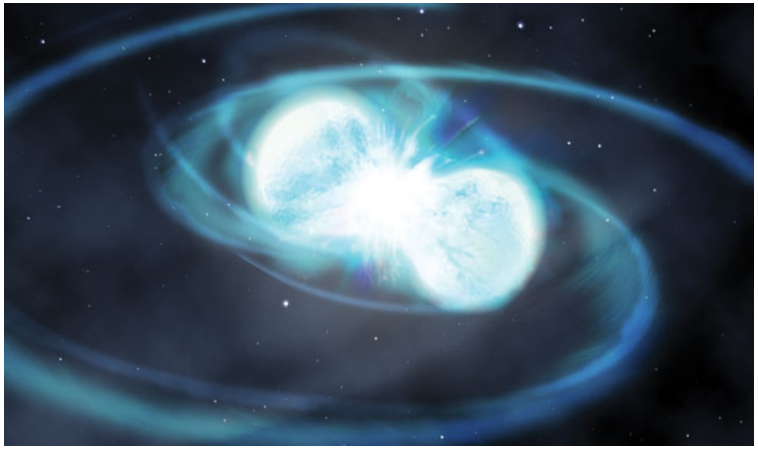

Nature

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  - ★ He-layer detonates

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pure turbulent deflagrations

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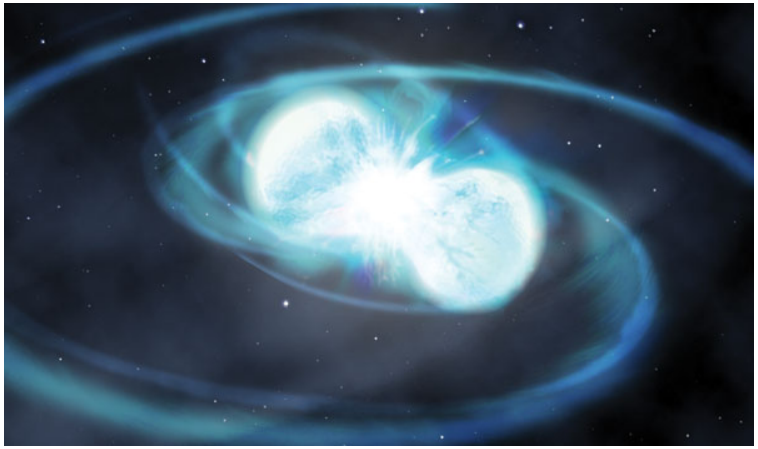
- possible progenitor systems known (U Sco, RS Oph, V445 Pup)

violent mergers
He double-detonations



Nature

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- detonate hydrostatic profile

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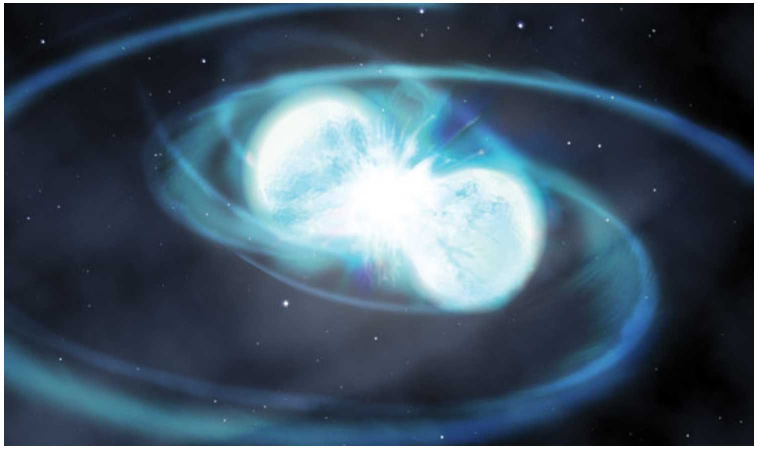

Nature

- $M_{primary} \approx 1.1$ solar masses
- ignition occurs as
  - violent accretion stream triggers detonation
  - He-layer detonates
- detonate hydrostatic profile
- theoretical calculated rates more favourable

Simulation code in 25 seconds

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- Finite volume, grid based hydro: LEAFS (Reinecke+ 1999, 2002)

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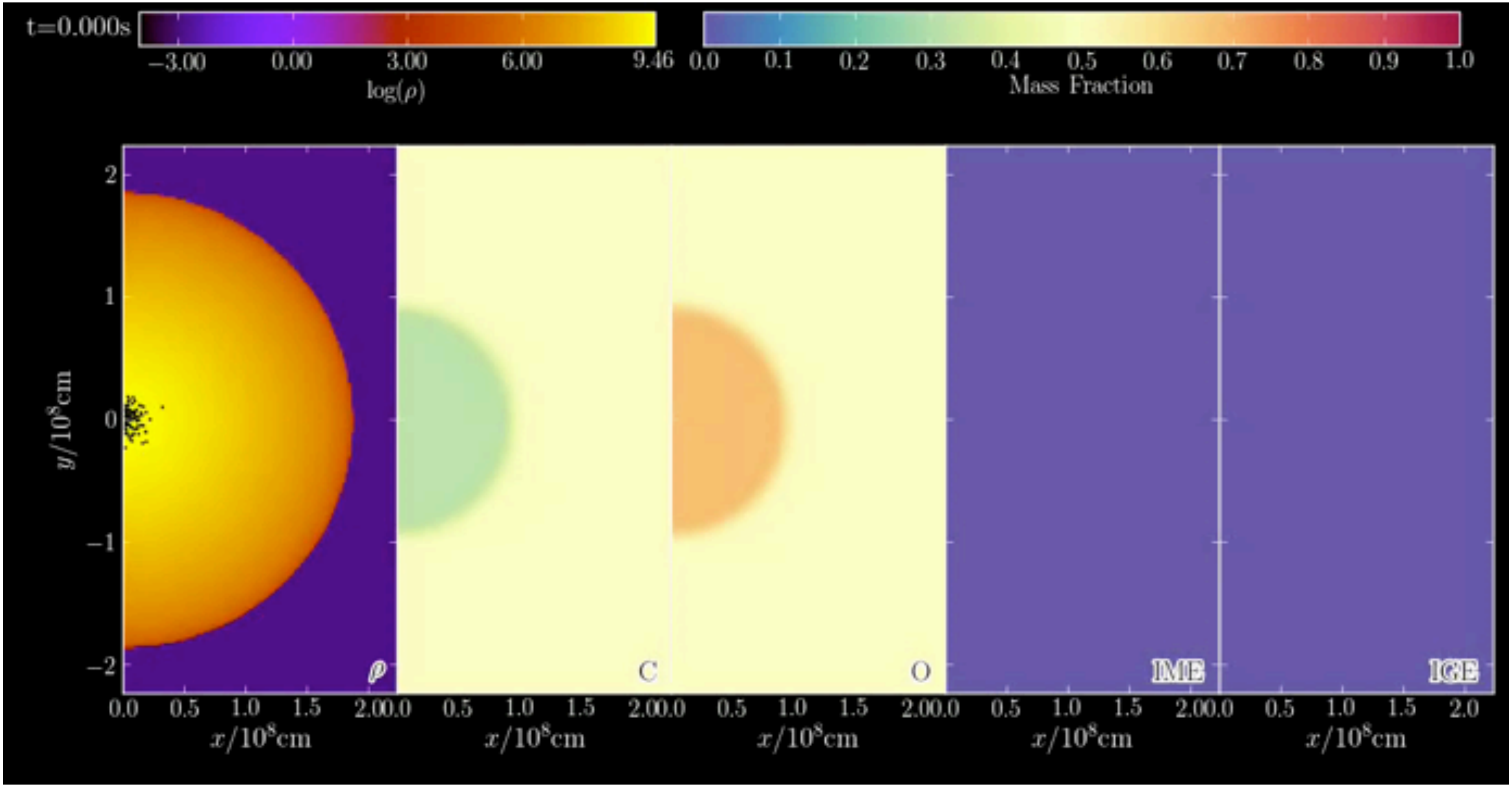
- RT w/ ARTIS (Monte-Carlo, Sim 2007, Kromer & Sim 2009)

N100 delayed-detonation

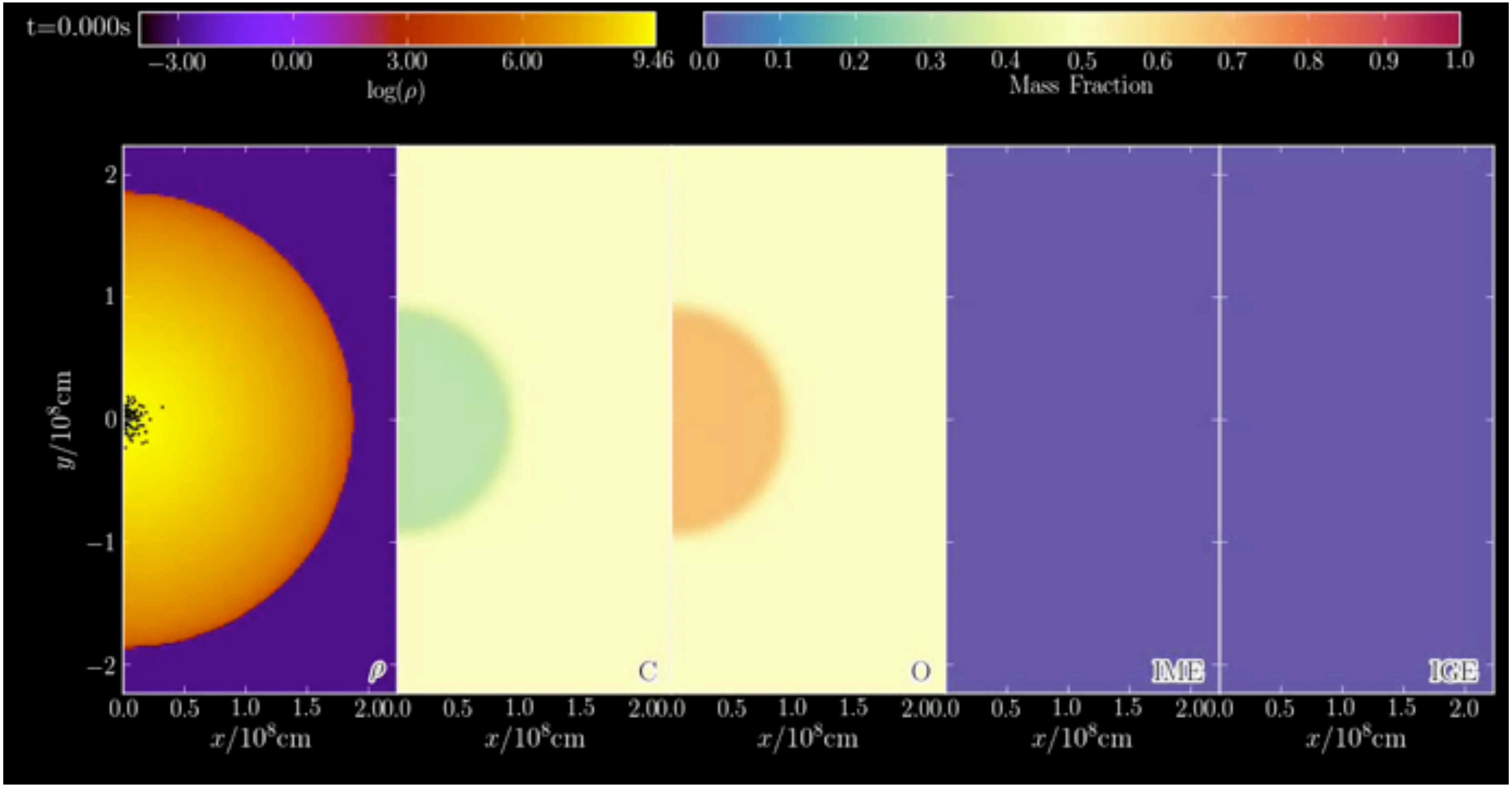


Seitenzahl+ (2013), MNRAS, 429, 1156

Ohlmann+ (2014), A&A, 572, 57

Movie by S. Ohlmann, Univ. Würzburg

N100 delayed-detonation



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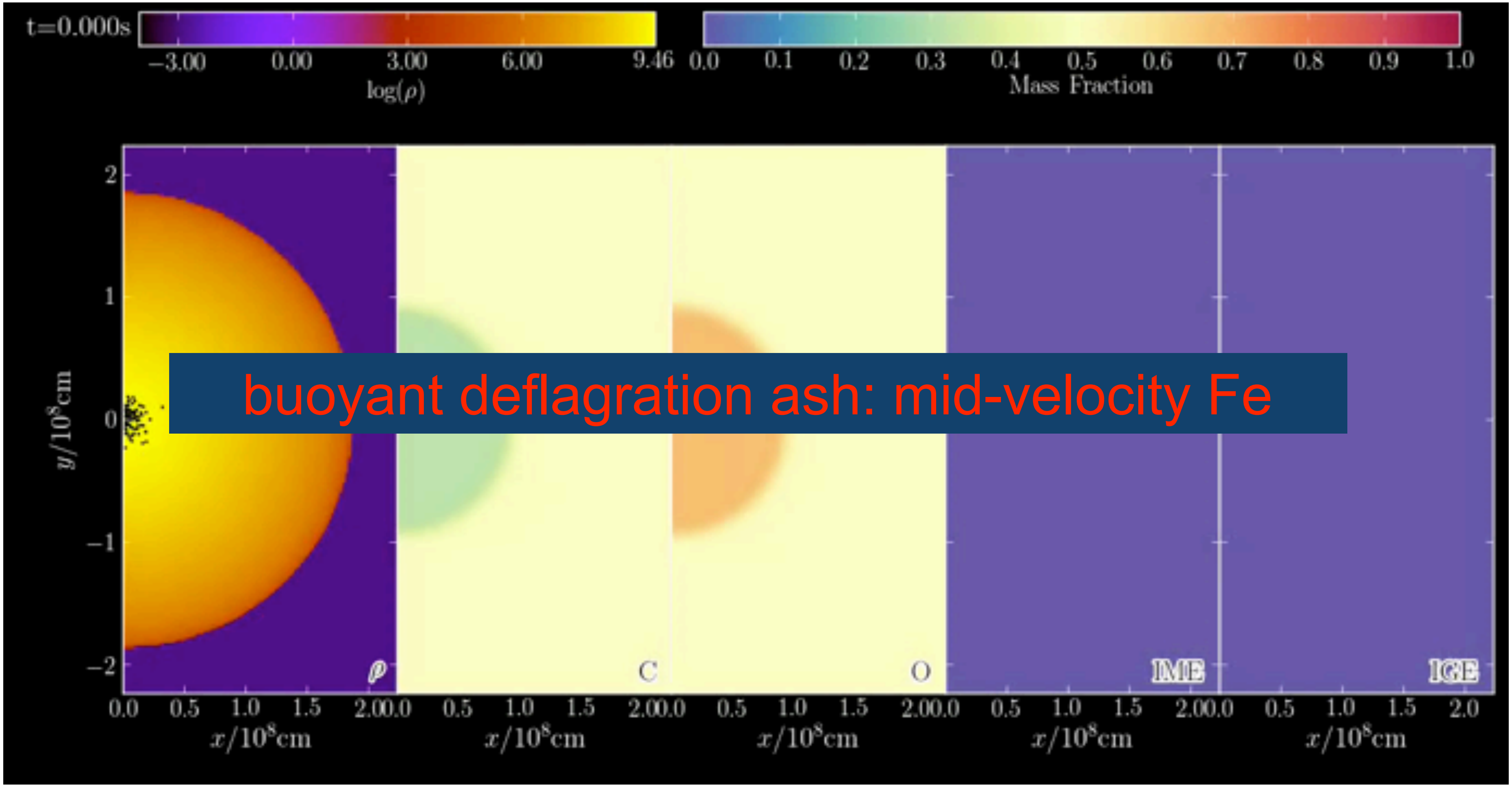


buoyant deflagration ash: mid-velocity Fe

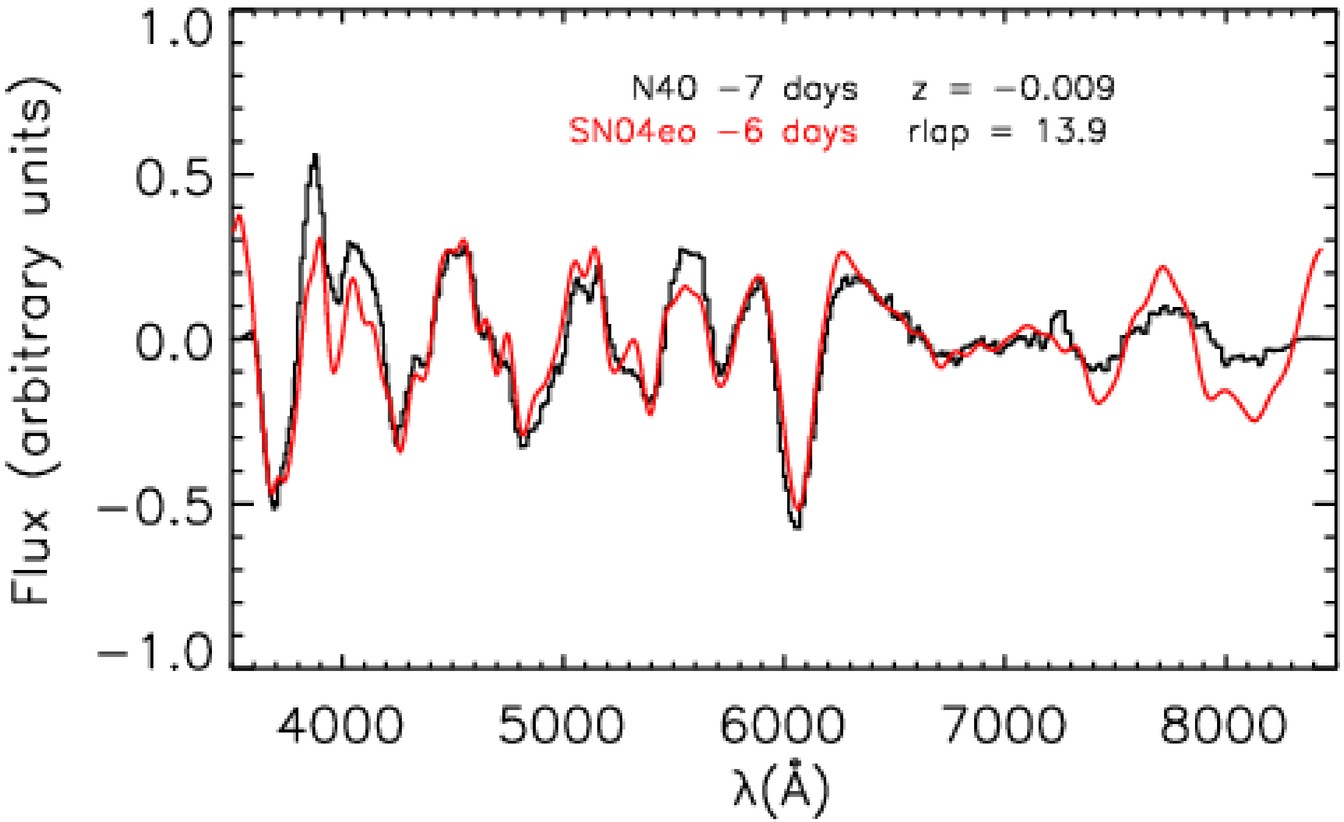
Seitenzahl+ (2013), MNRAS, 429, 1156

Ohlmann+ (2014), A&A, 572, 57

Movie by S. Ohlmann, Univ. Würzburg

delayed-detonations

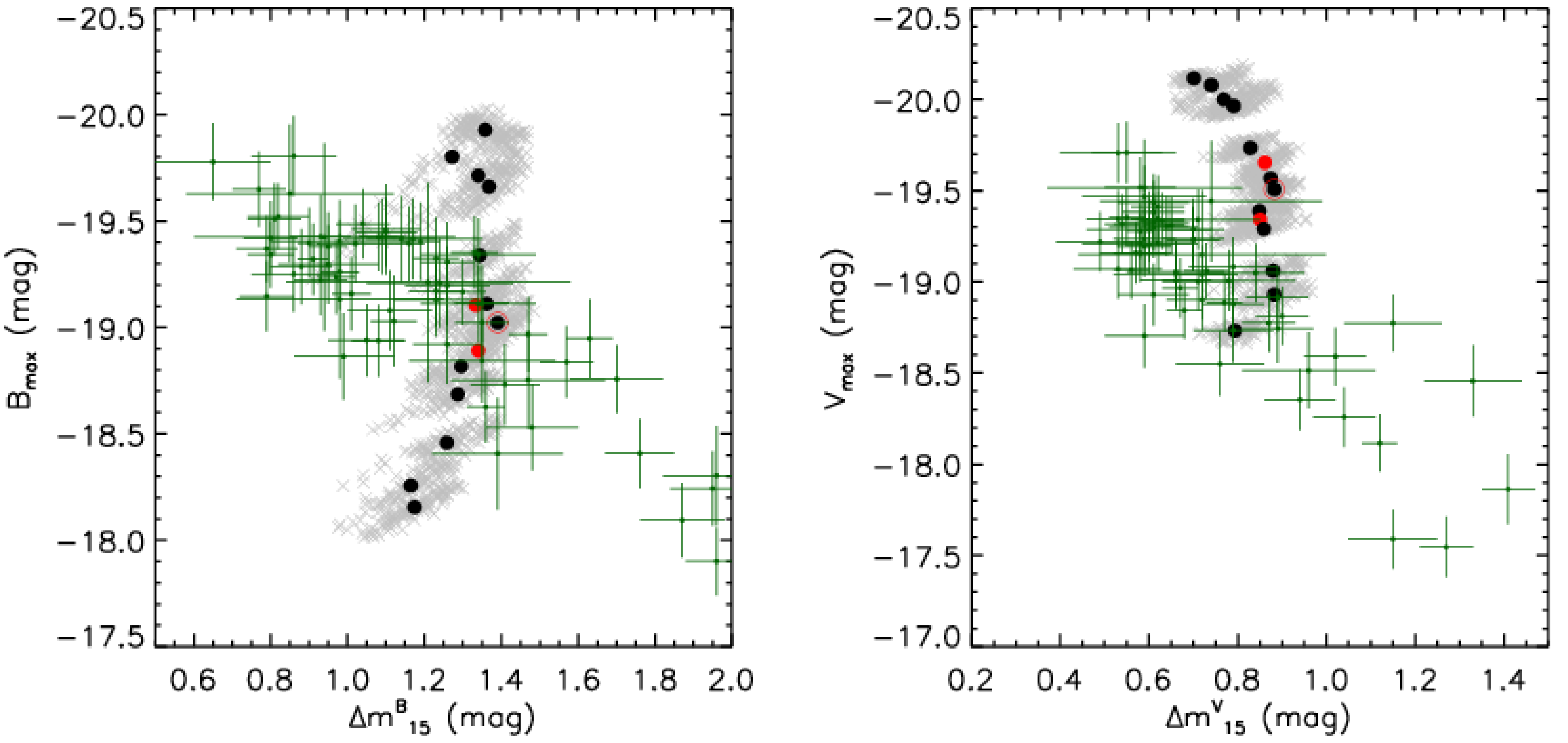
SNID IDs e.g. N40 as normal SN Ia



Sim+ (2013), MNRAS, 436, 333

delayed-detonations

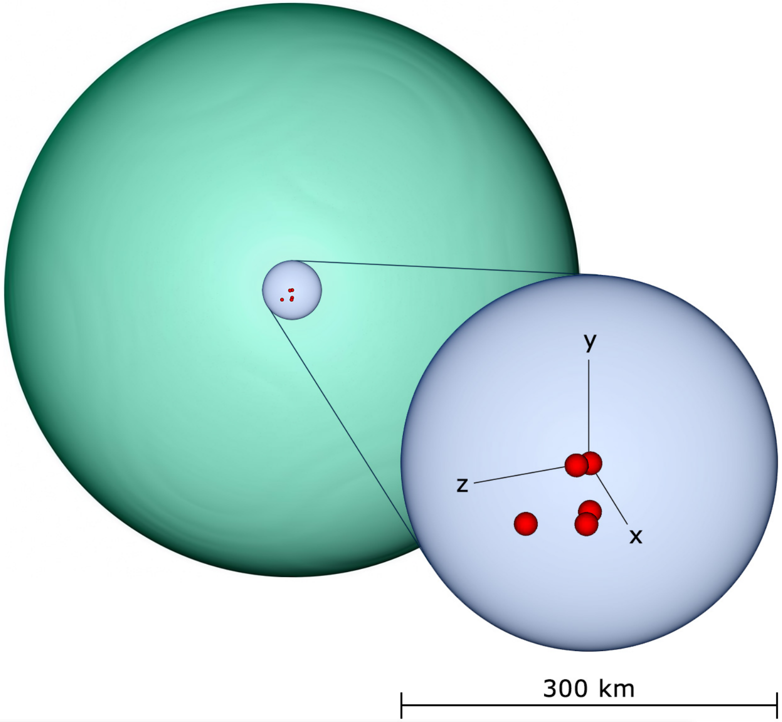
But we don't recover the WLR

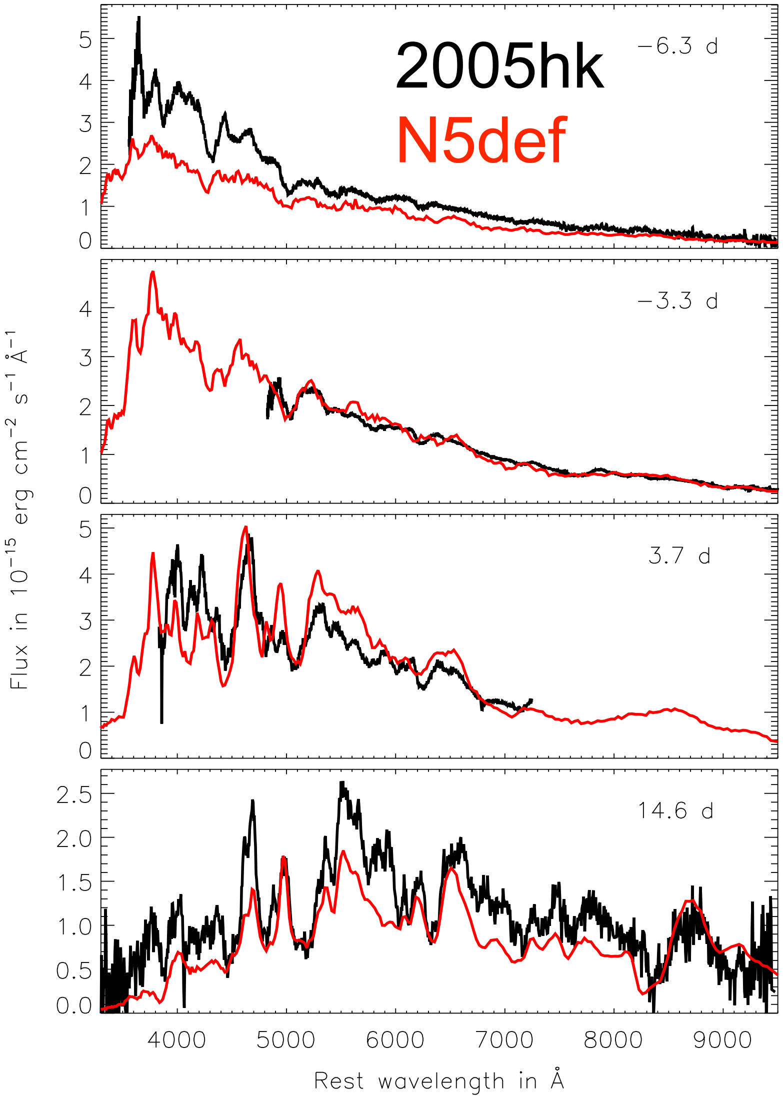


Sim+ (2013), MNRAS, 436, 333

model N5def deflagration leaving bound remnant behind

Deflagrations in $M_{\rm Ch}$ WDs that fail to unbind the whole star provide an excellent model for 2002cx-like SNe Ia





Kromer+ (2013), MNRAS, 429, 2287

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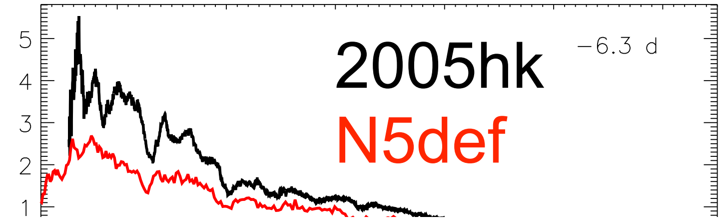
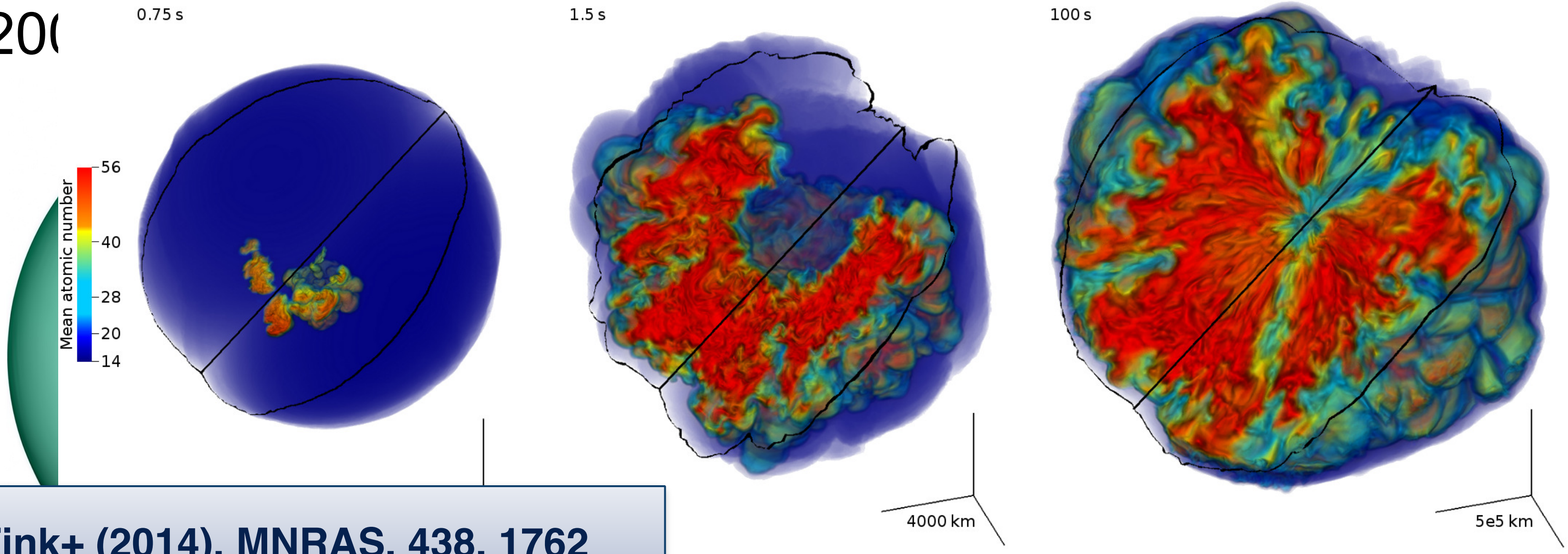
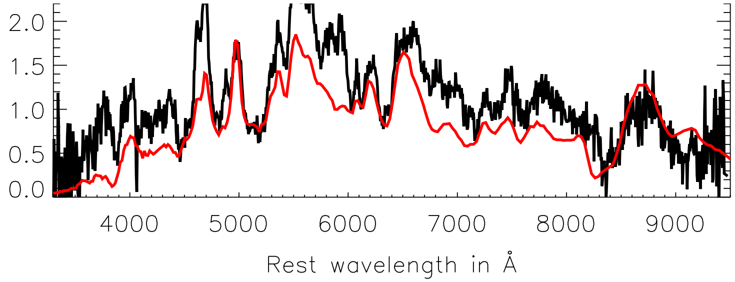
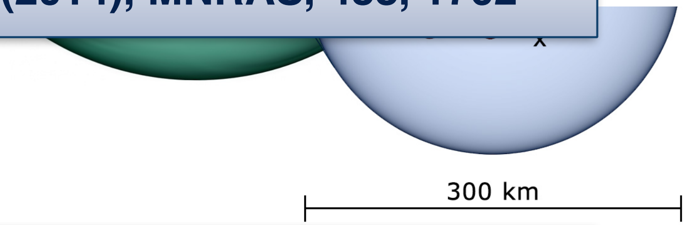
Deflagrations in M_{Ch} WDs that fail to unbind the whole star provide an excellent model for 20





Fink+ (2014), MNRAS, 438, 1762





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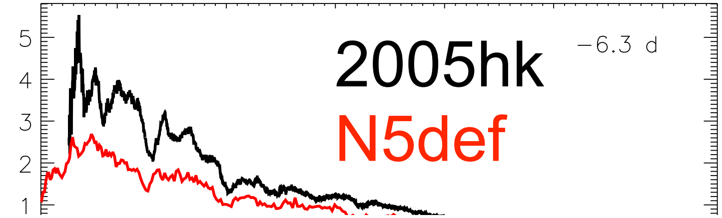
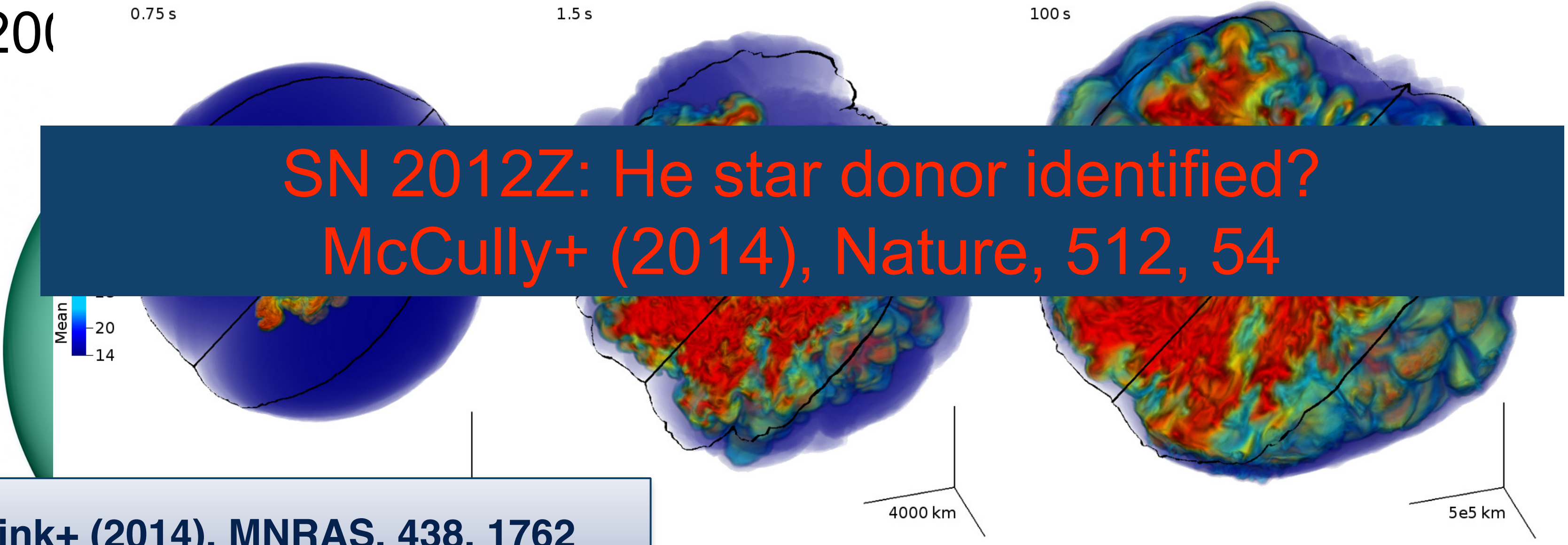
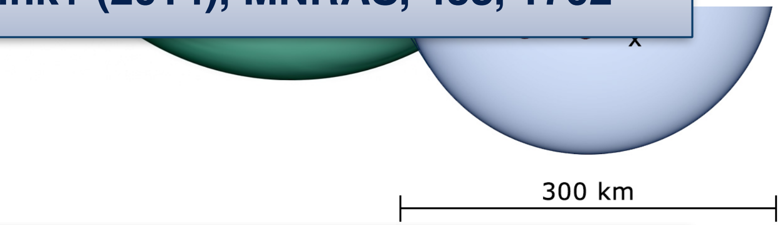




SN 2012Z: He star donor identified?
McCully+ (2014), Nature, 512, 54

Fink+ (2014), MNRAS, 438, 1762



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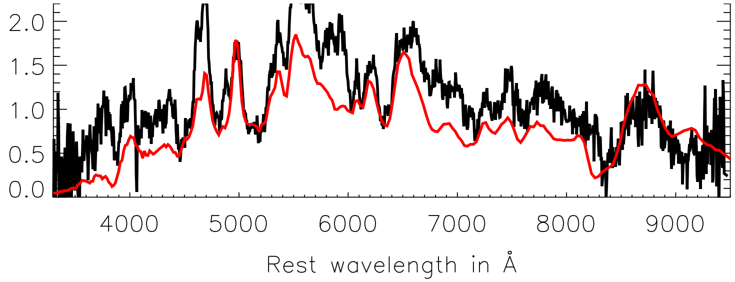

A model for 2008ha (M_V = -14.2) deflagrations in hybrid WDs

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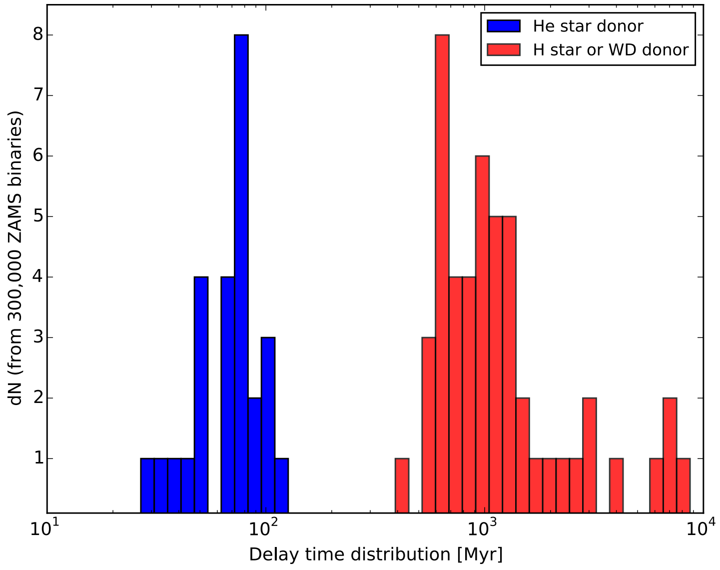

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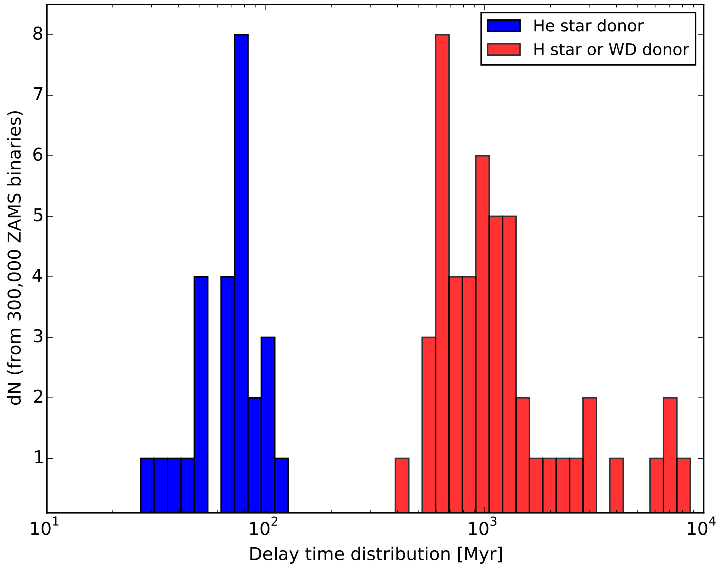

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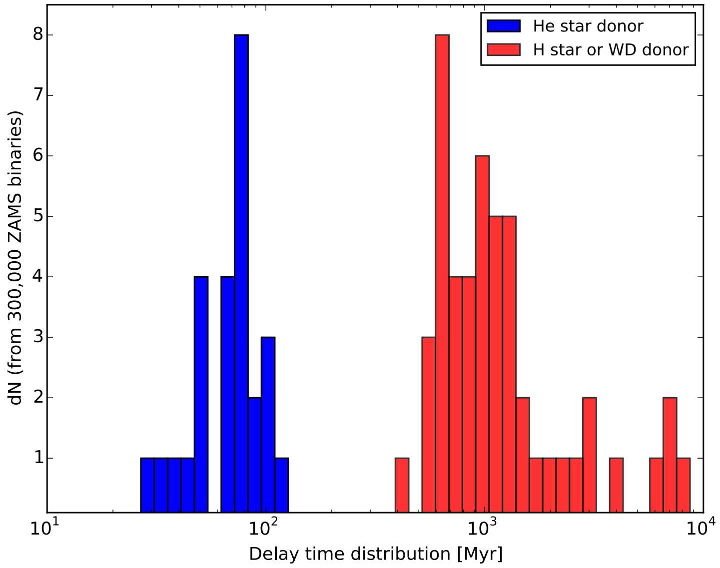

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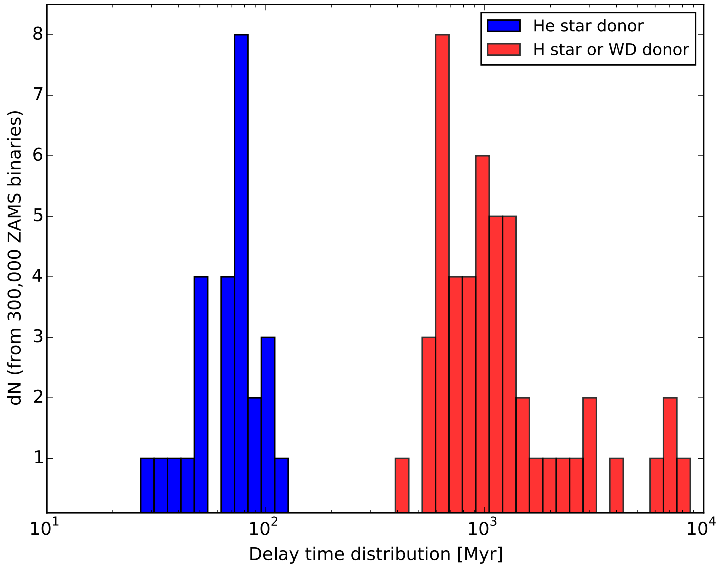

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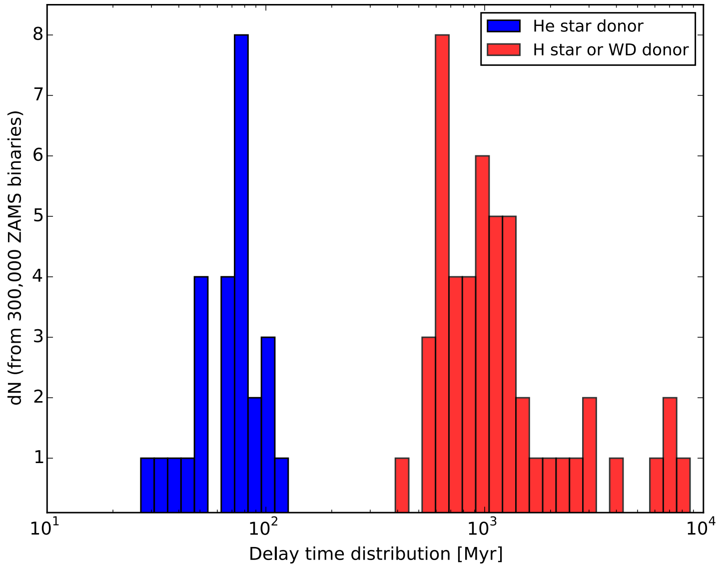

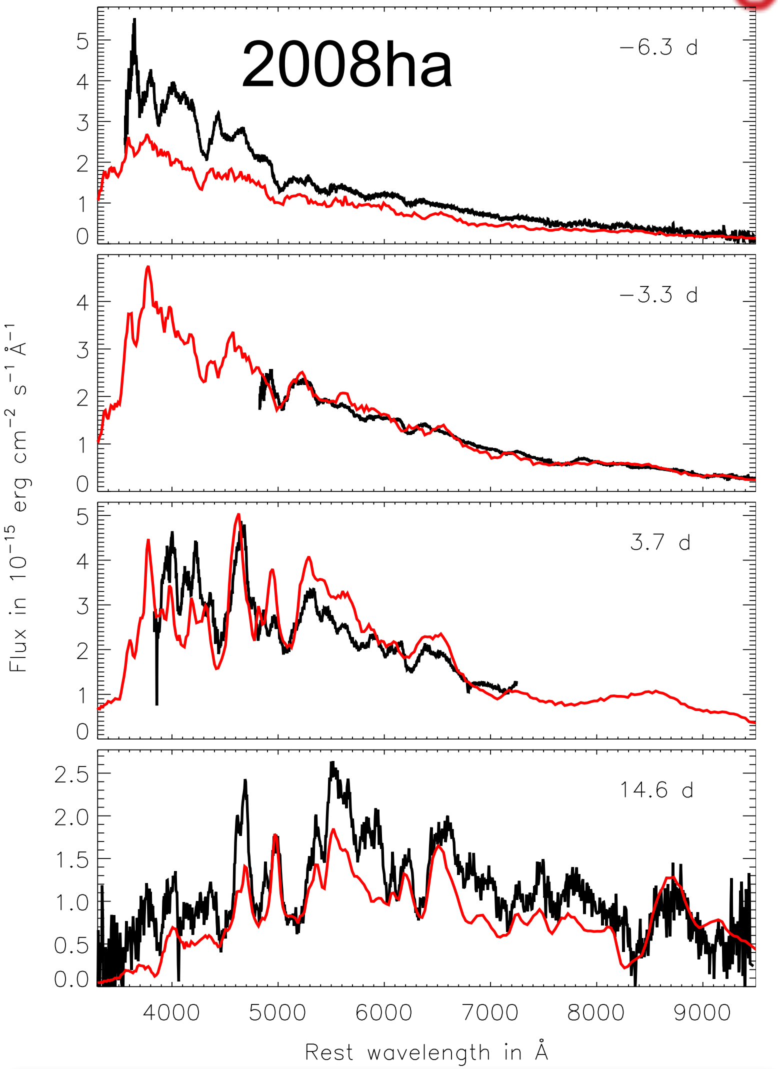

Kromer+ (2015), MNRAS, 450, 3045

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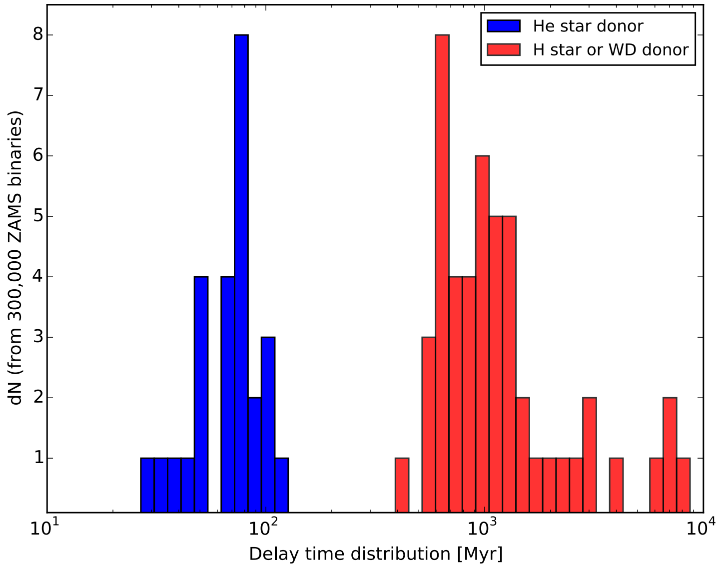

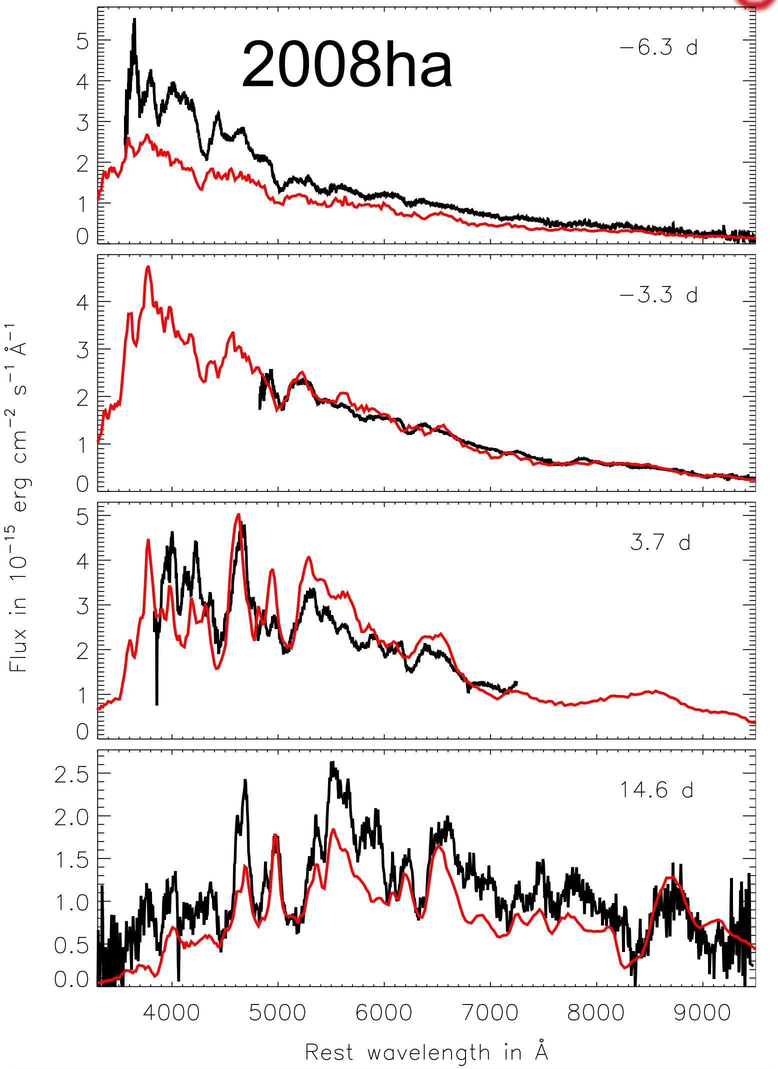

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CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

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Australian National University

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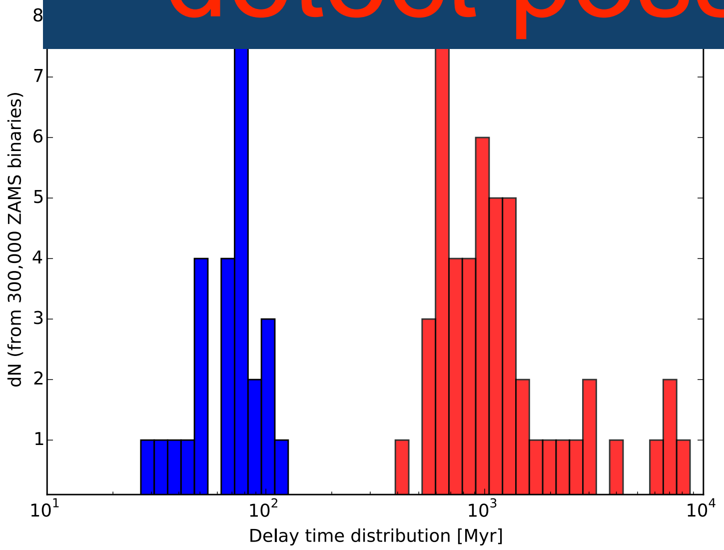
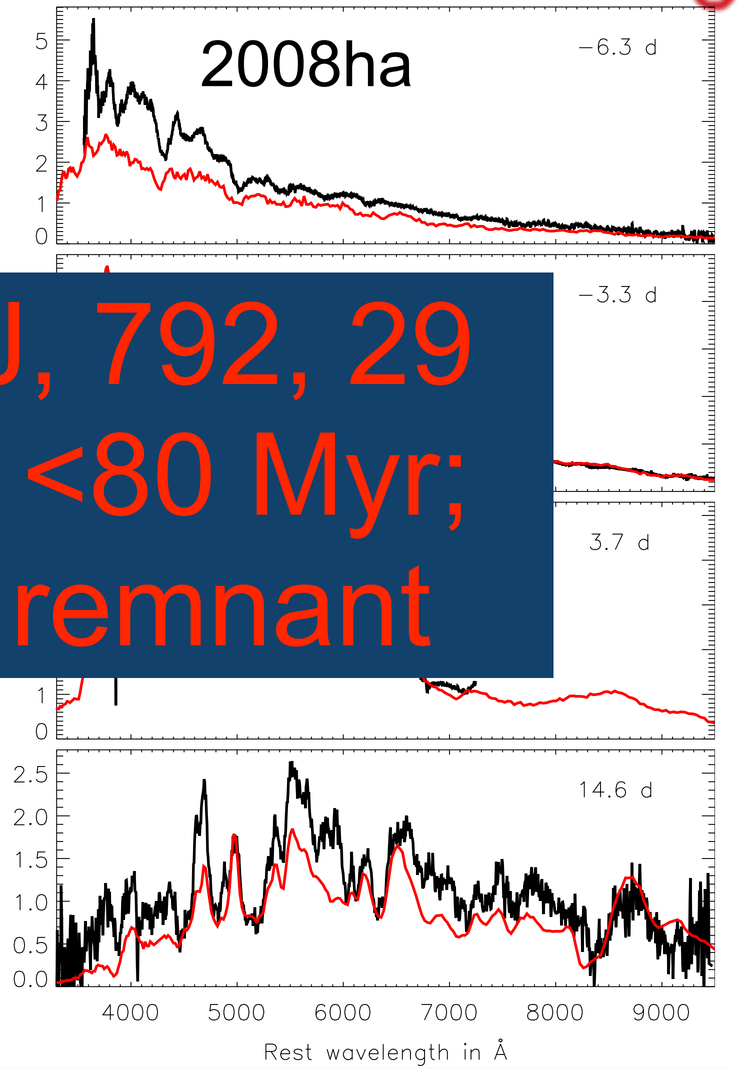
  - accrete to M short delay times
- 3D d
  - ✓ defl
  - ✓ 3.4
  - ✓ 1.3

Foley+2014, ApJ, 792, 29 constrain age to <80 Myr; detect possible remnant



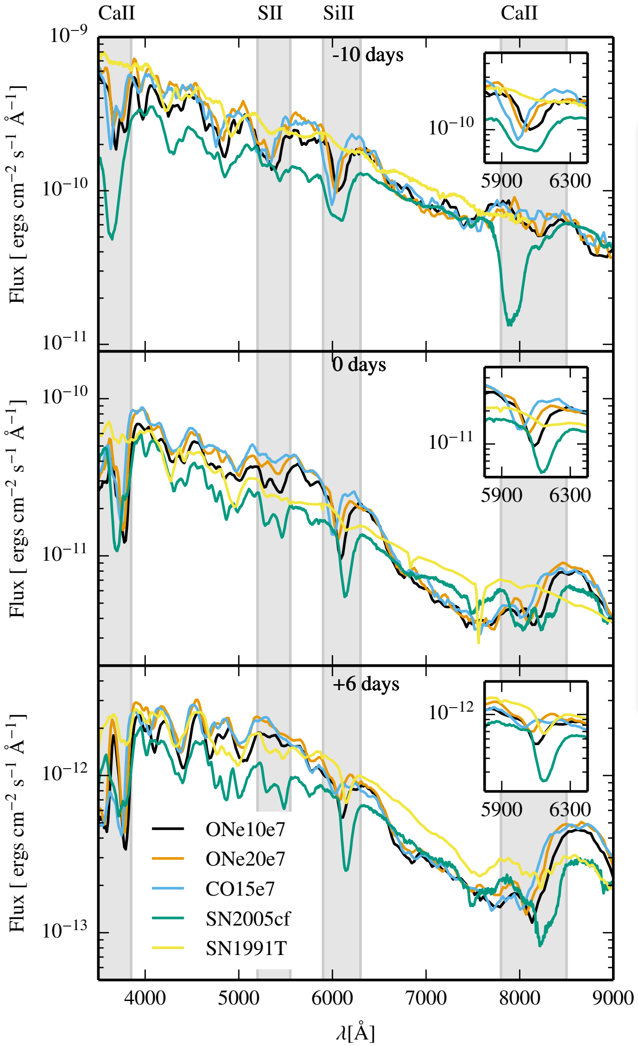


Kromer+ (2015), MNRAS, 450, 3045

What about 1991T?

Detonations of 1.18 - 1.25 $M_\odot$ CO & ONe WDs

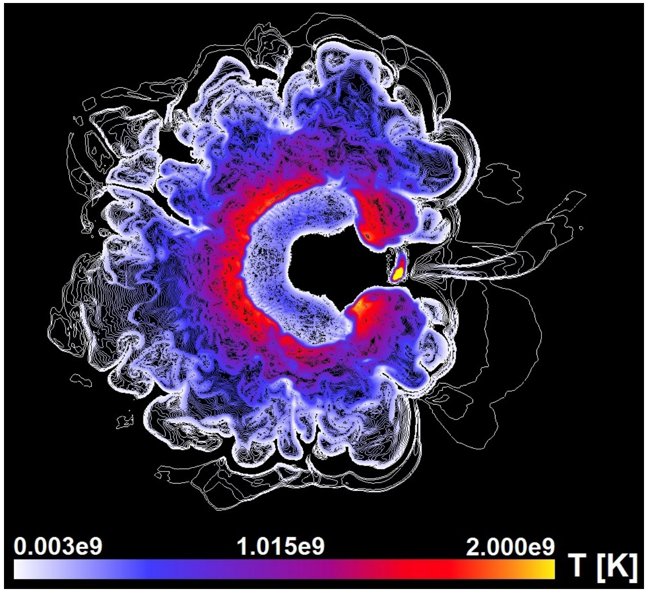
ONe lowers v(Si II)
~12,500 km/s for 1991T (Sasdelli+2014)



Marquardt+ (2015), A&A, in press

GCD-model of 1.4 $M_\odot$ CO WD

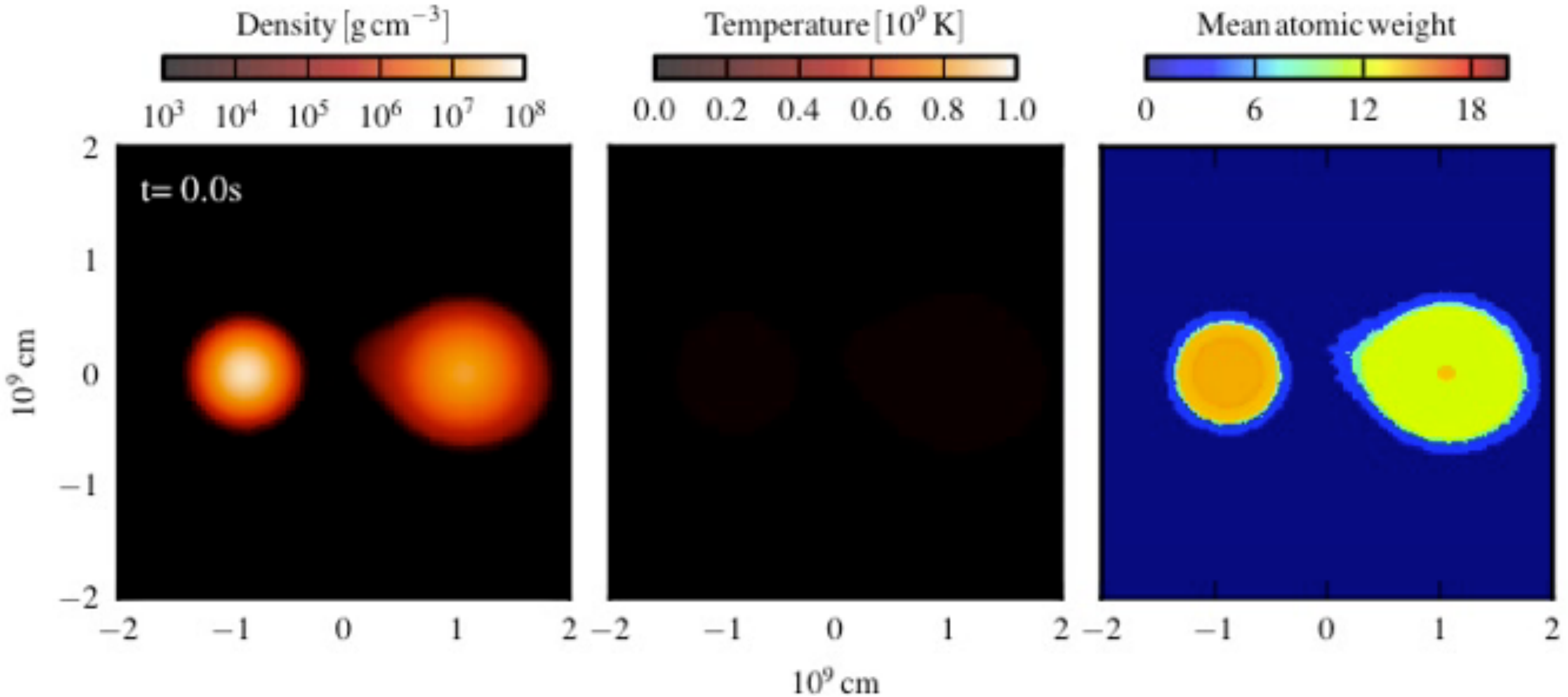
Suggested for 1991T SNe (e.g. Fisher & Jumper 2015)



Total IGE [$M_\odot$]	^{56}Ni [$M_\odot$]	Total IME [$M_\odot$]	^{28}Si [$M_\odot$]	^{16}O [$M_\odot$]	^{12}C [$M_\odot$]
1.0517	0.9367	0.2629	0.1574	0.0686	0.0113

Seitenzahl+ (in prep)

violent merger of two WDs AREPO code



- CO WD in binary system with other WD after common envelope phase
- For right mass ratio, accretion stream triggers He-shell and C/O core detonations
  - primary WD burns almost hydrostatically
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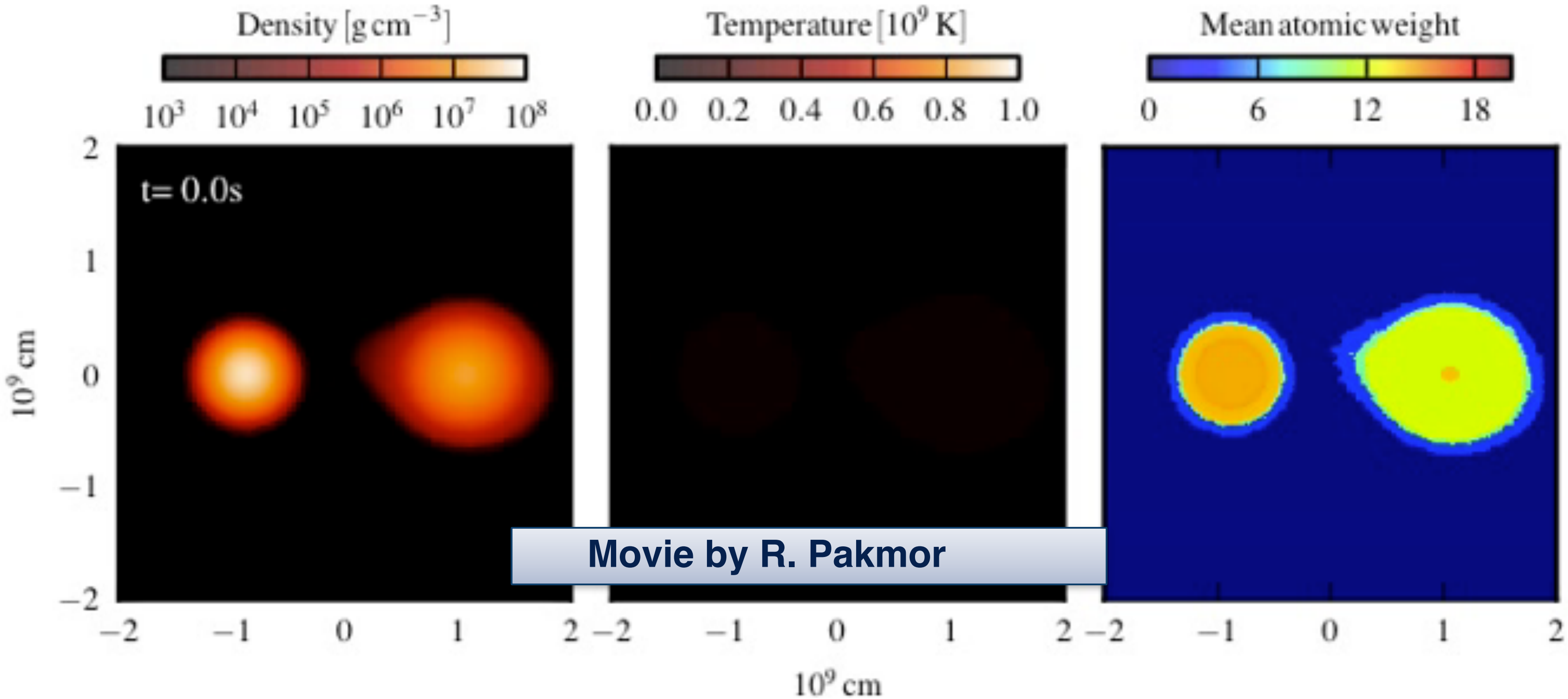

Movie by R. Pakmor

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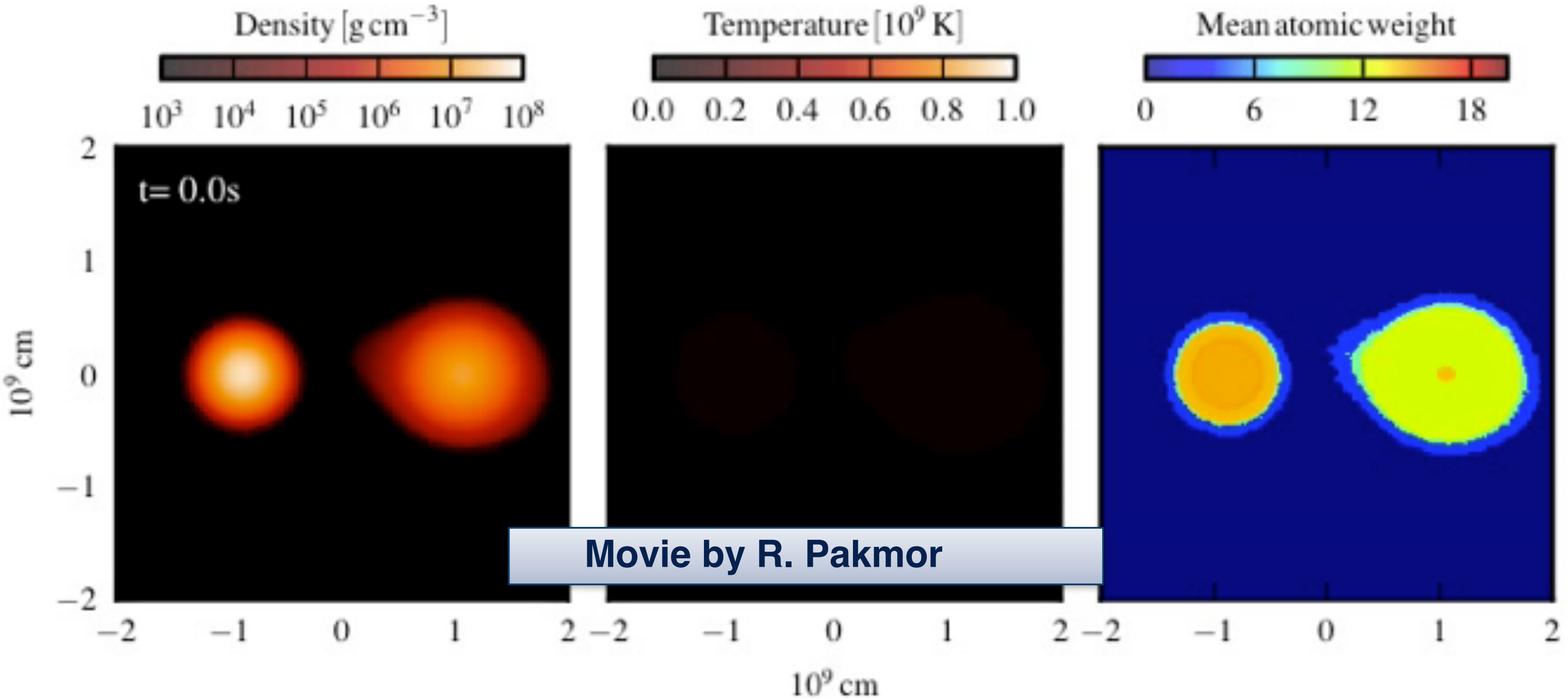

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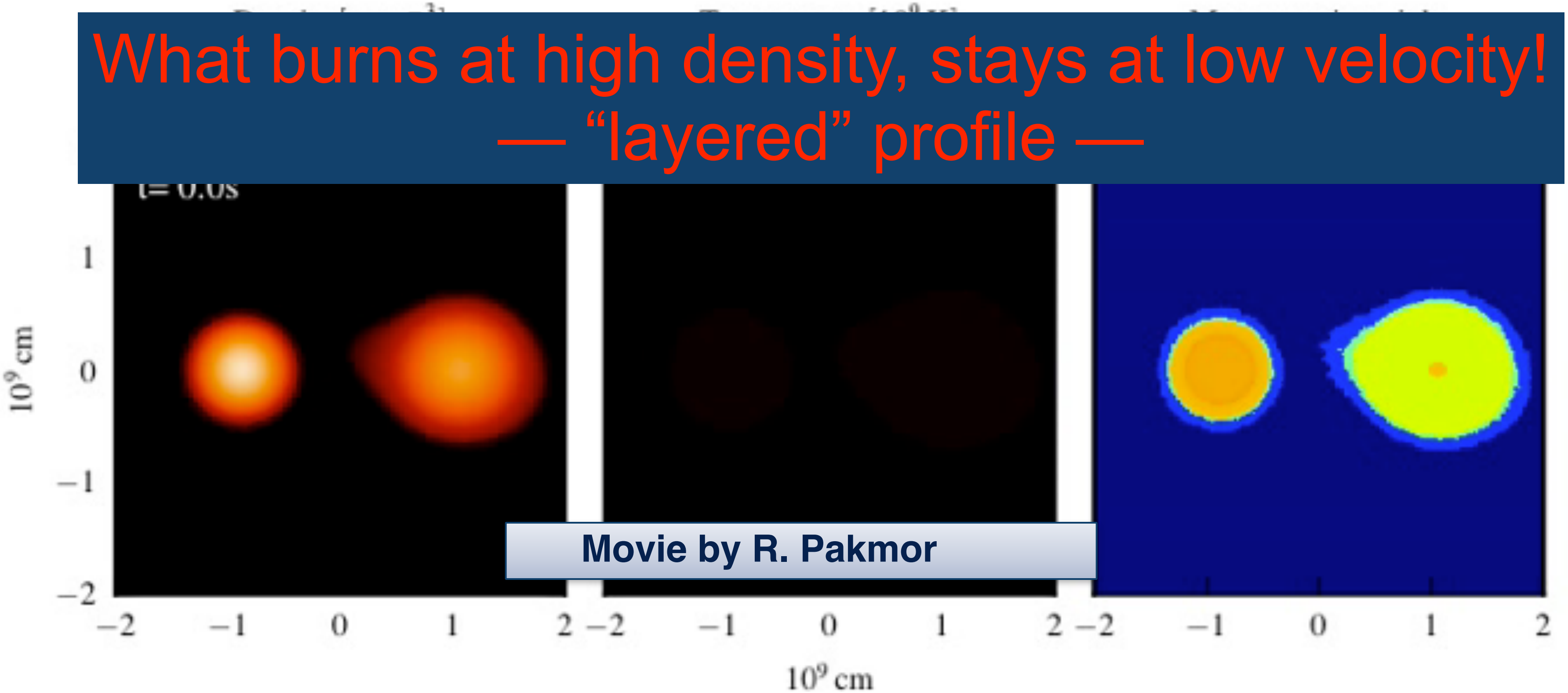
What burns at high density, stays at low velocity!
— “layered” profile —



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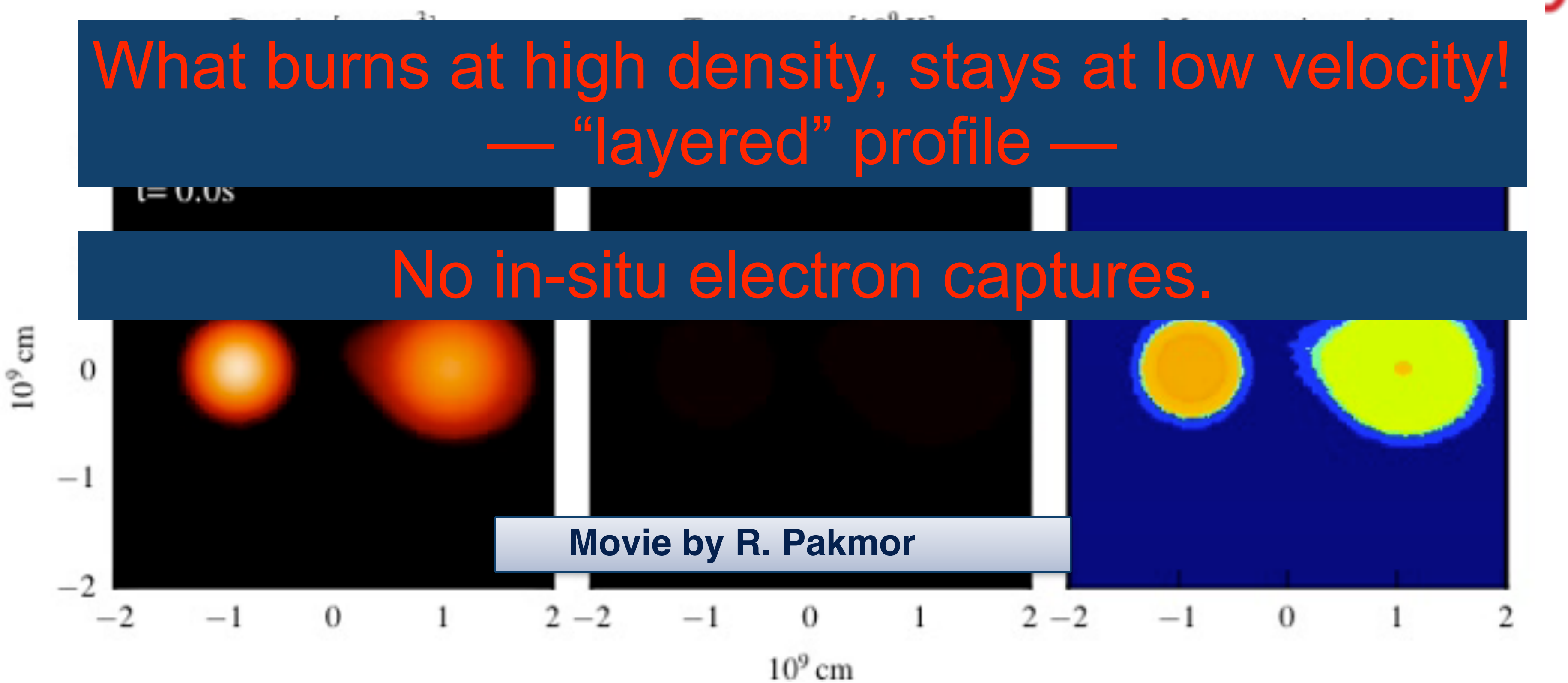

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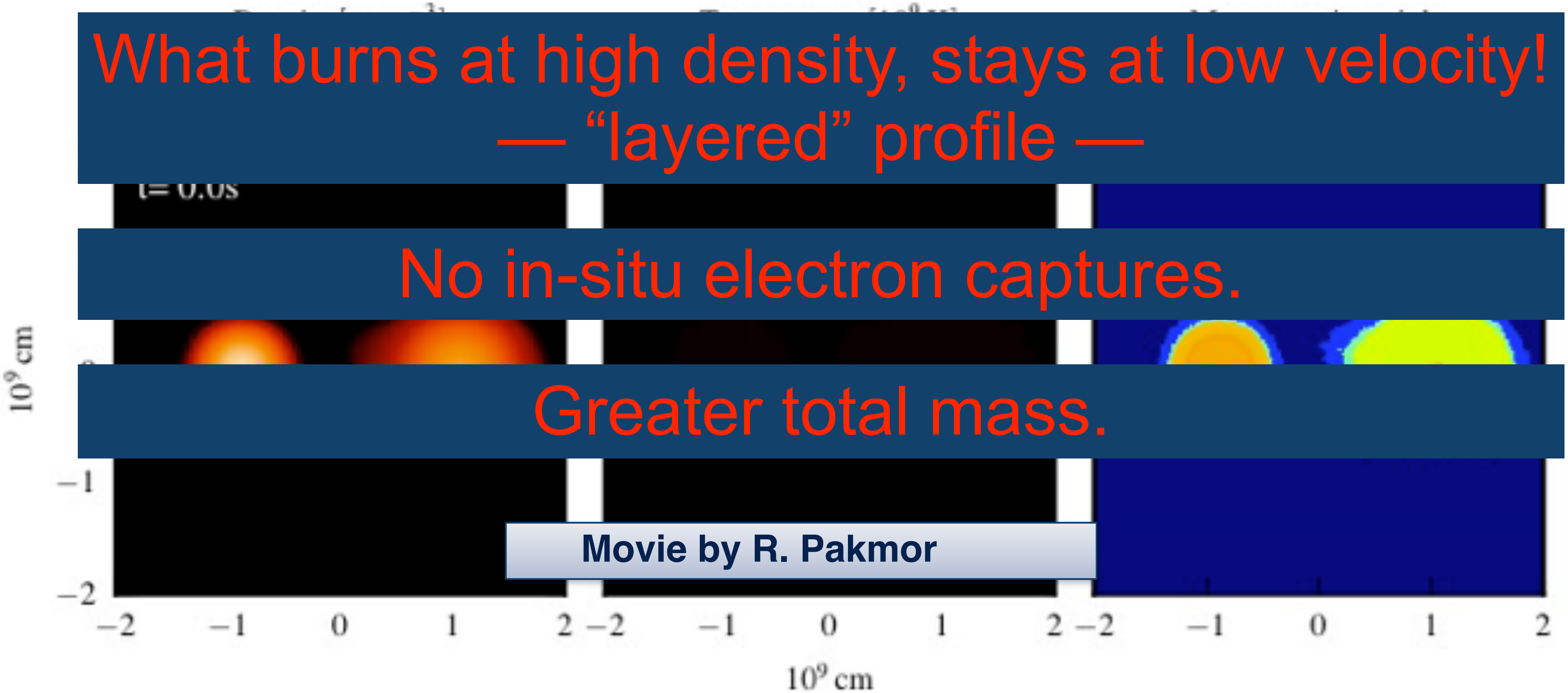

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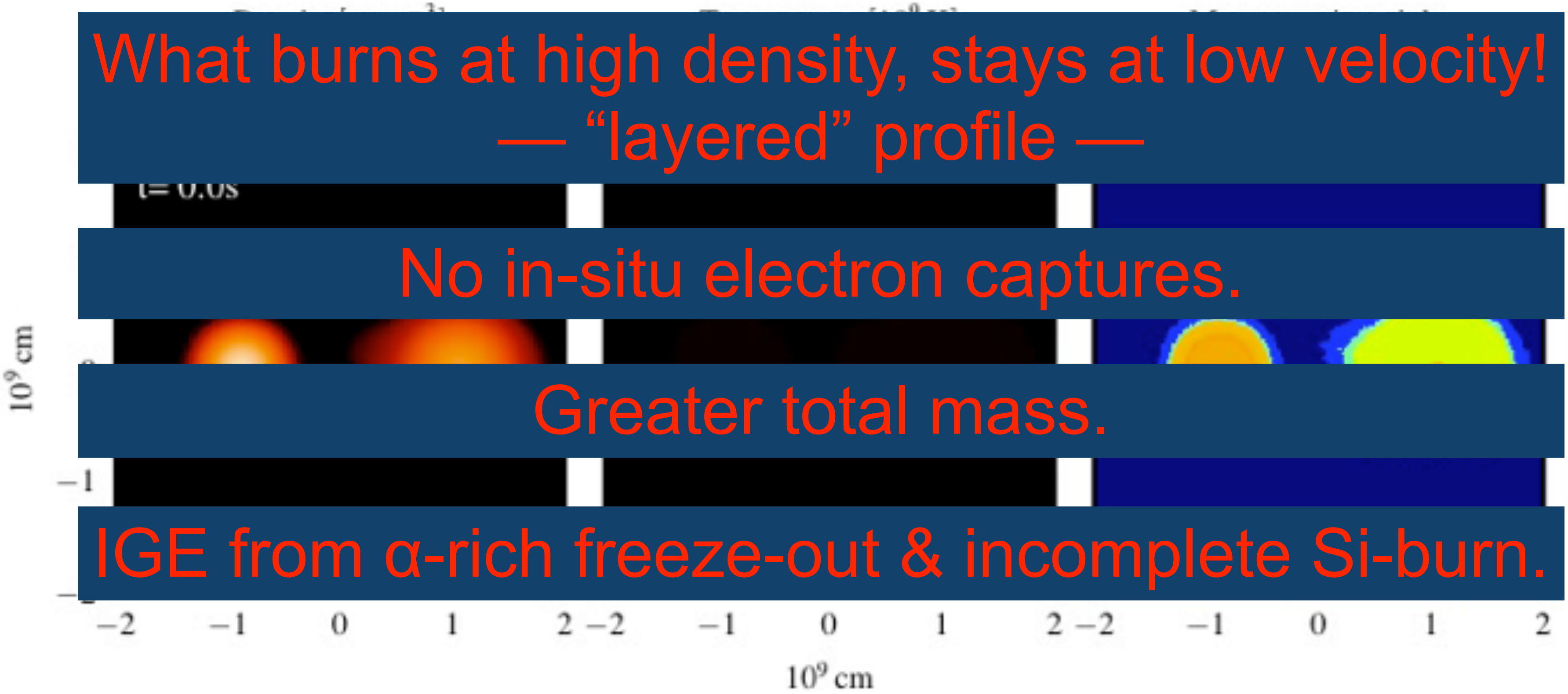

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IGE from α-rich freeze-out & incomplete Si-burn.

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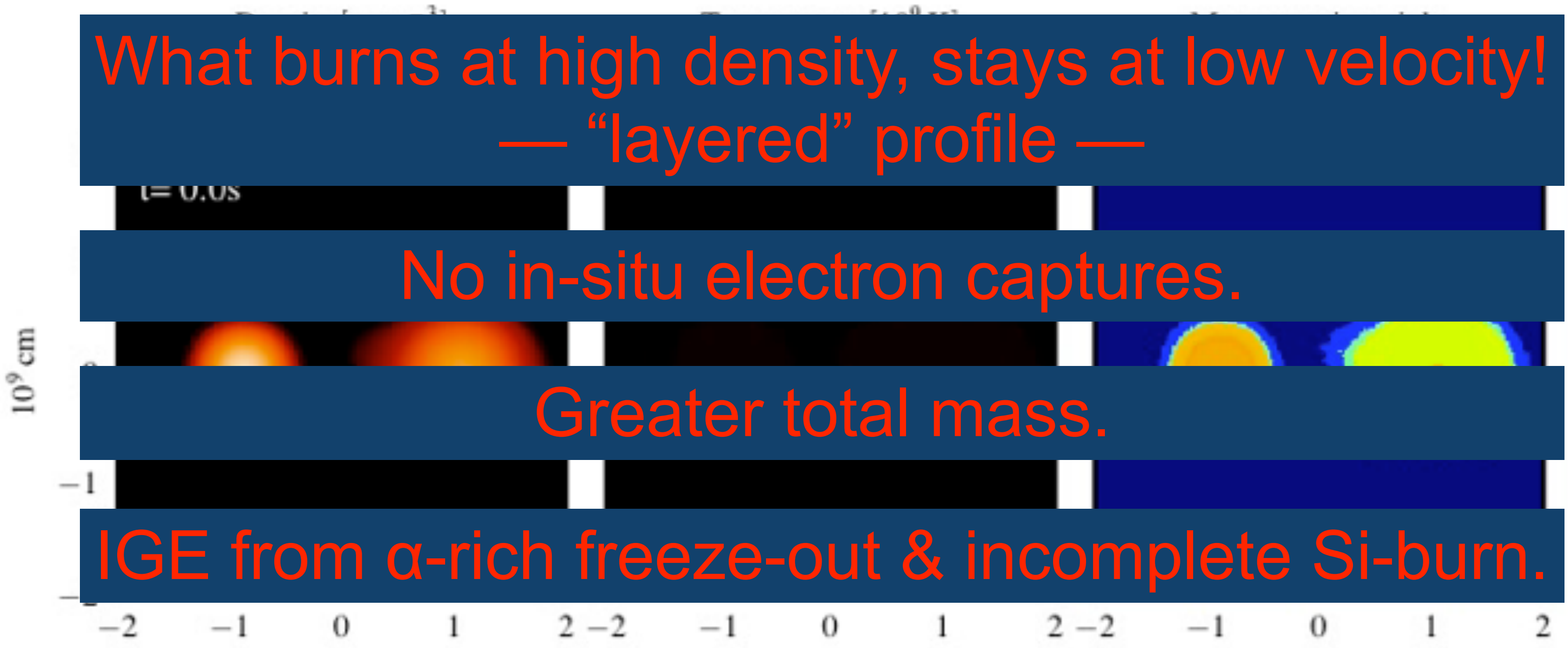

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Low mass mergers excellent models for 1991bg:
Pakmor+ 2010, Nature, 463, 61

- C
- F
  detonations
  - primary WD burns almost hydrostatically
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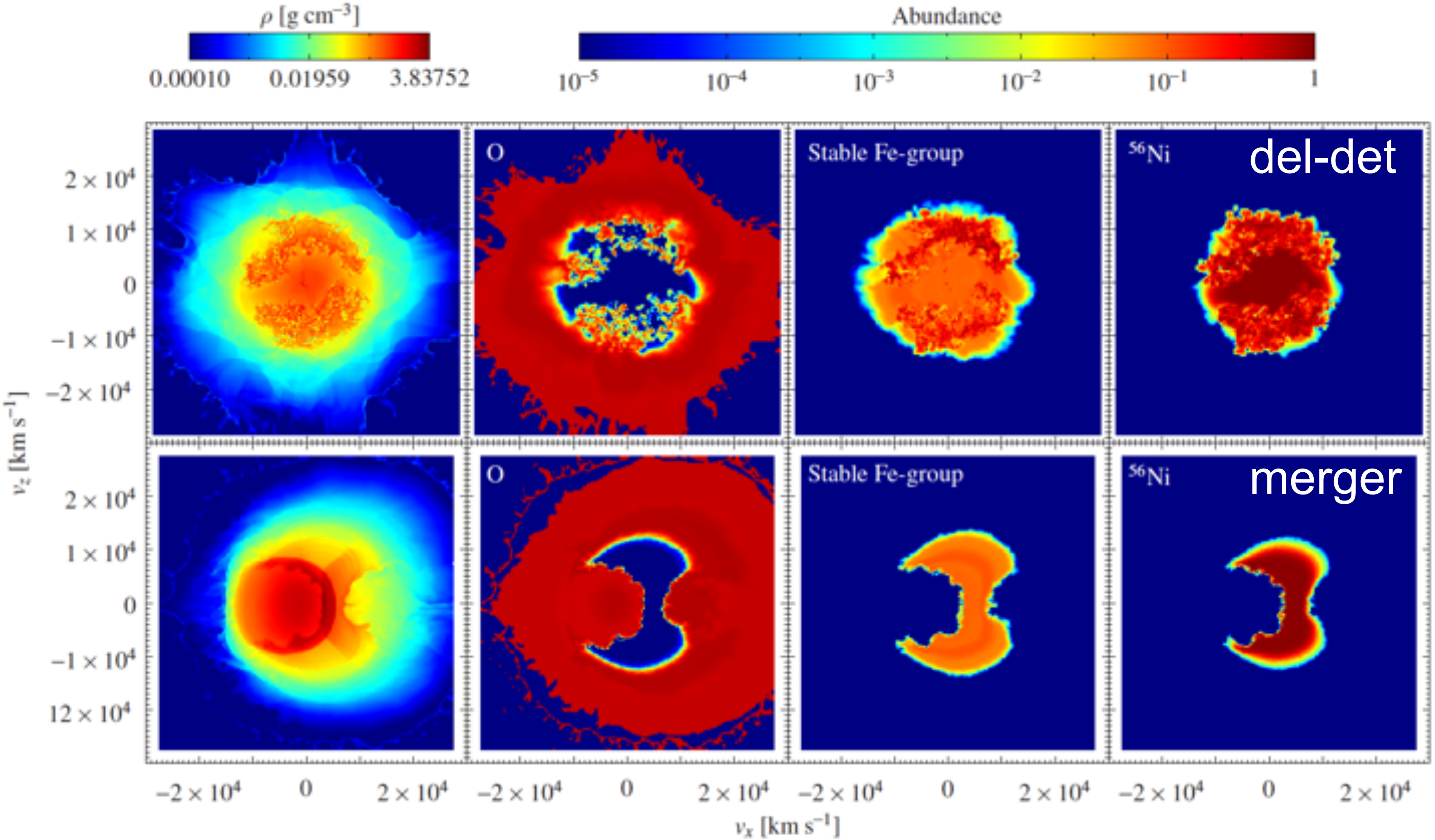
N100 delayed-detonation (Seitenzahl+2013)
1.1+0.9 Msun violent merger (Pakmor+2012)

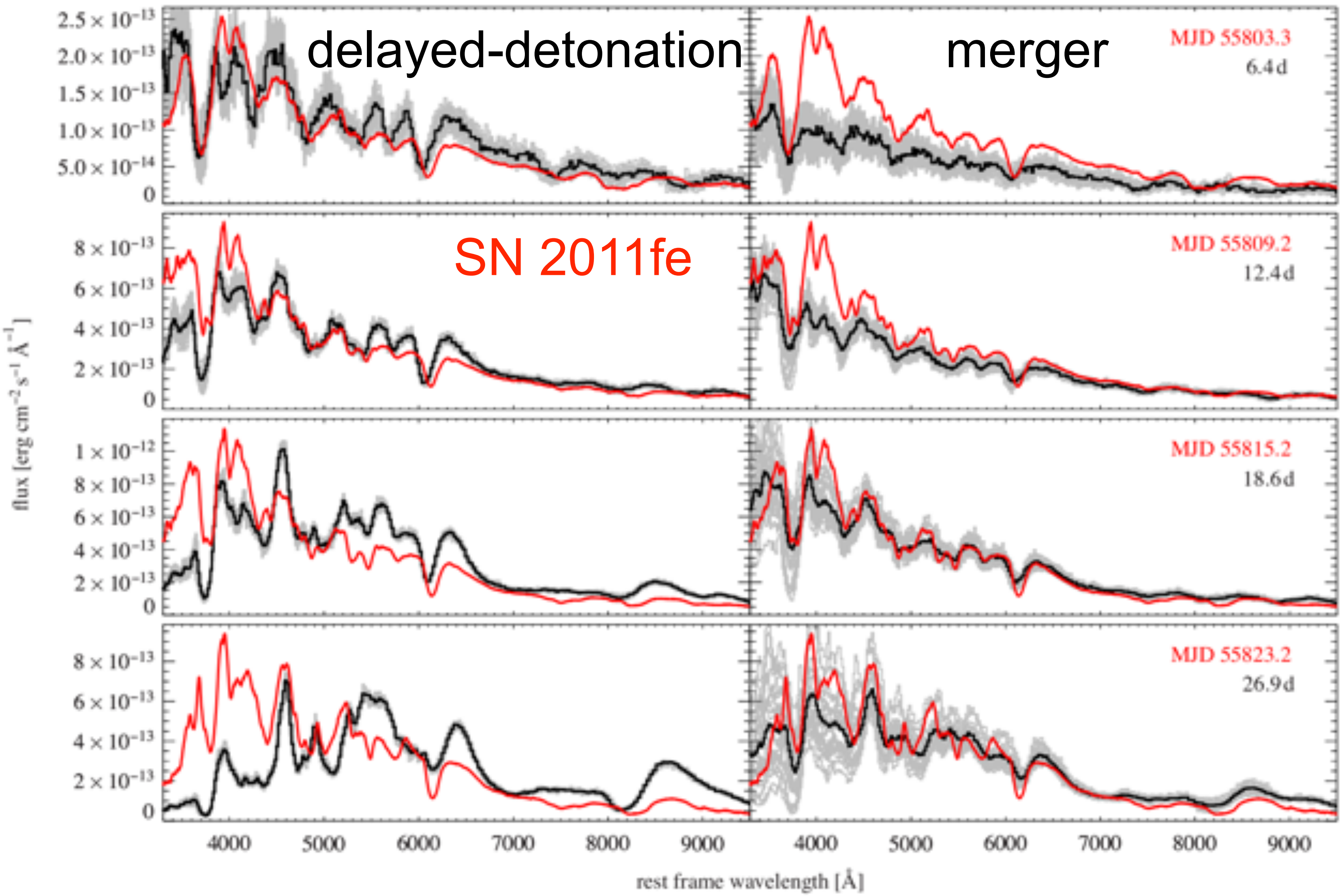
Same ^{56}Ni mass, morphology different



CAASTRO ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

Spectral comparison inconclusive

Australian National University



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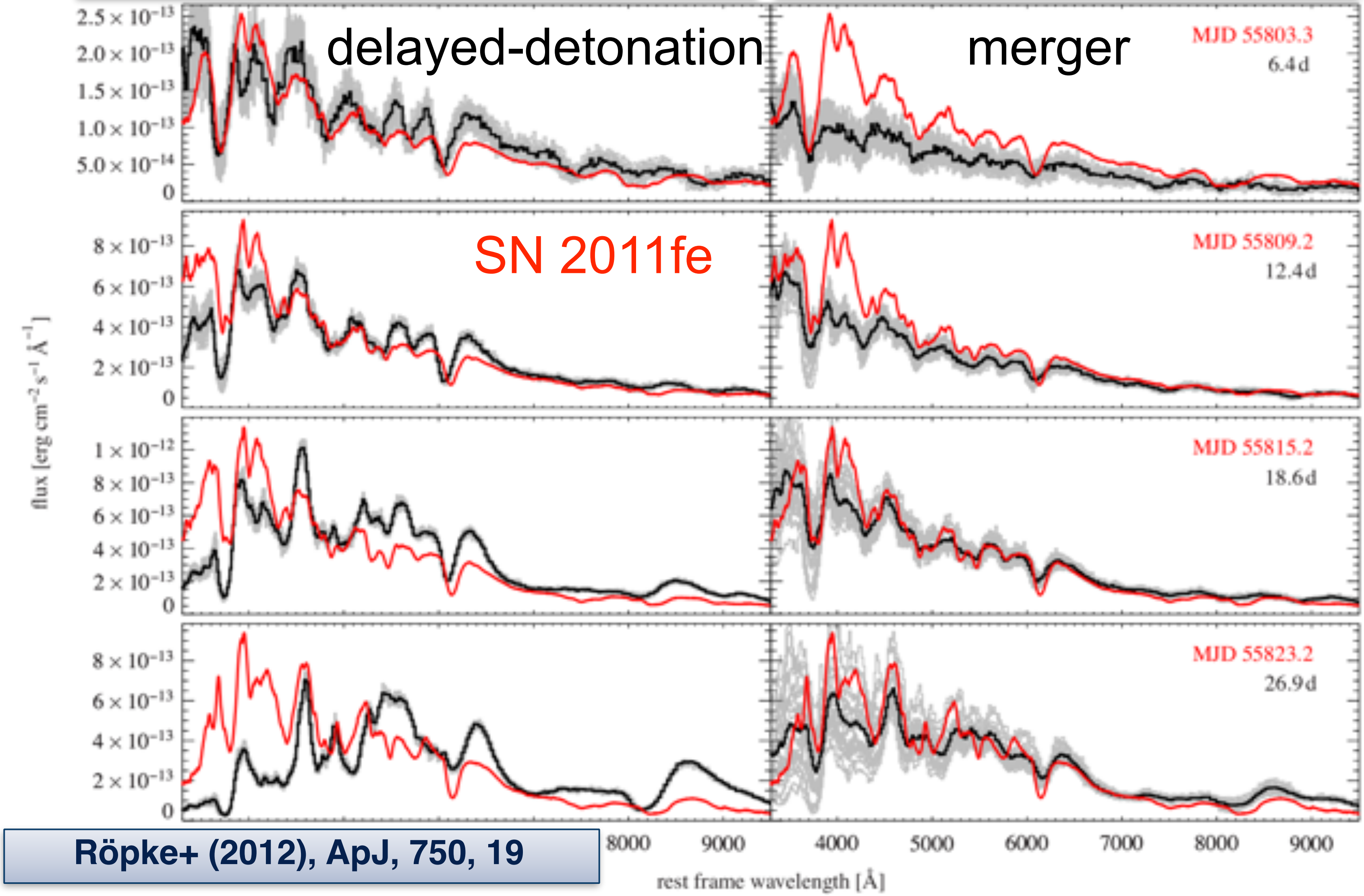

Röpke+ (2012), ApJ, 750, 19

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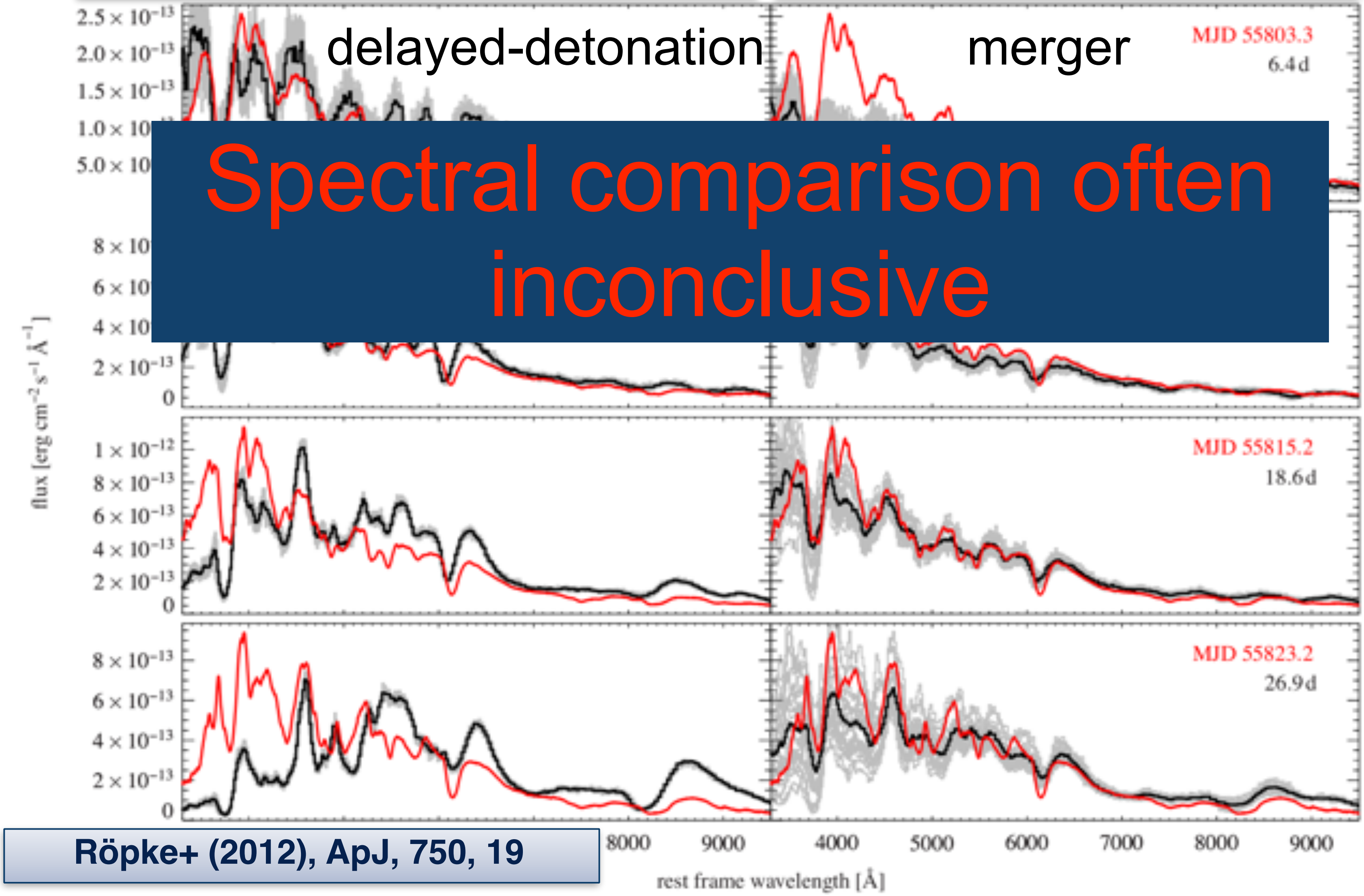

Spectral comparison often inconclusive

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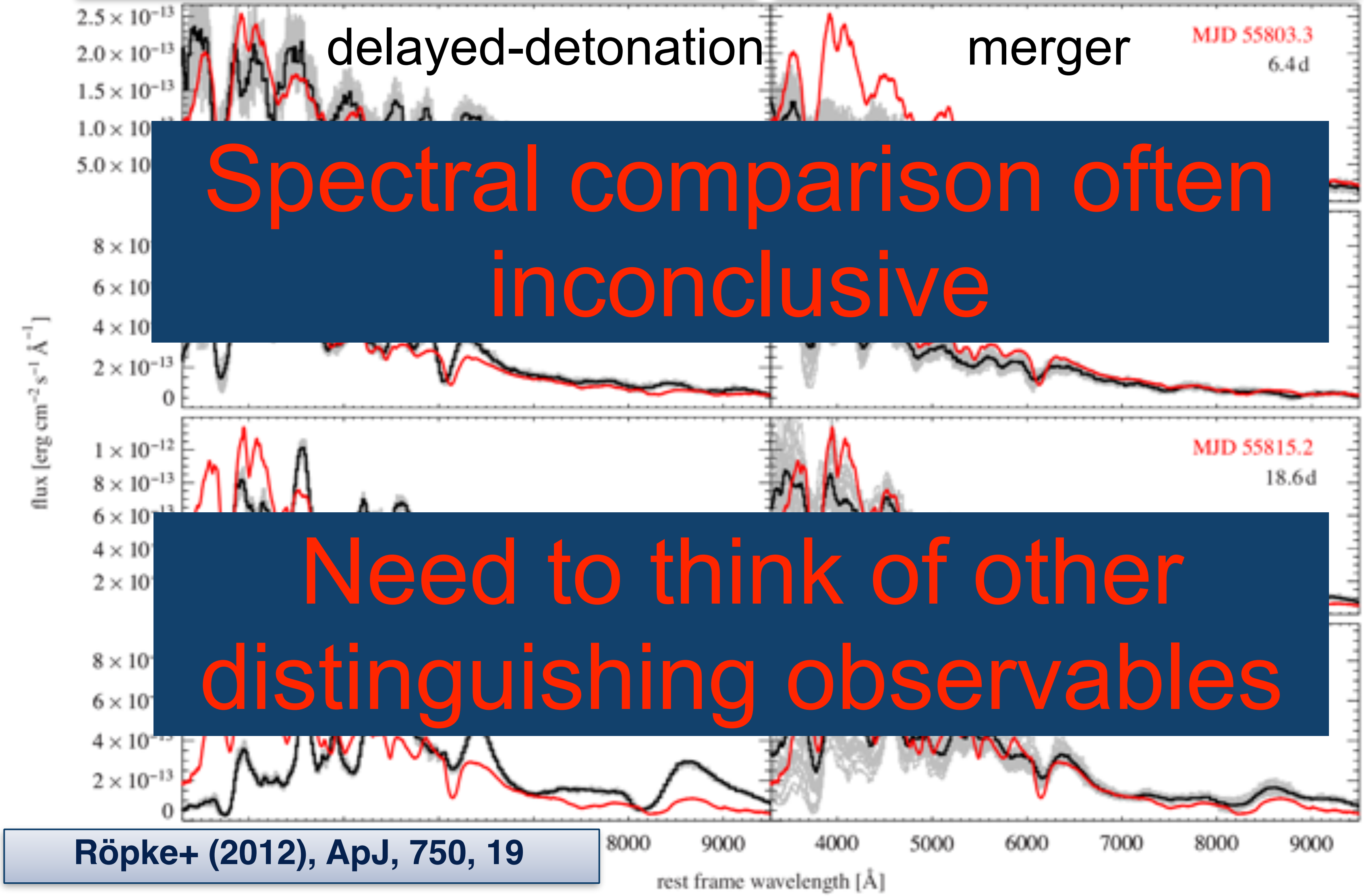


Spectral comparison often inconclusive

Need to think of other distinguishing observables

Röpke+ (2012), ApJ, 750, 19

Nucleosynthesis constraints
Mn from SNe Ia

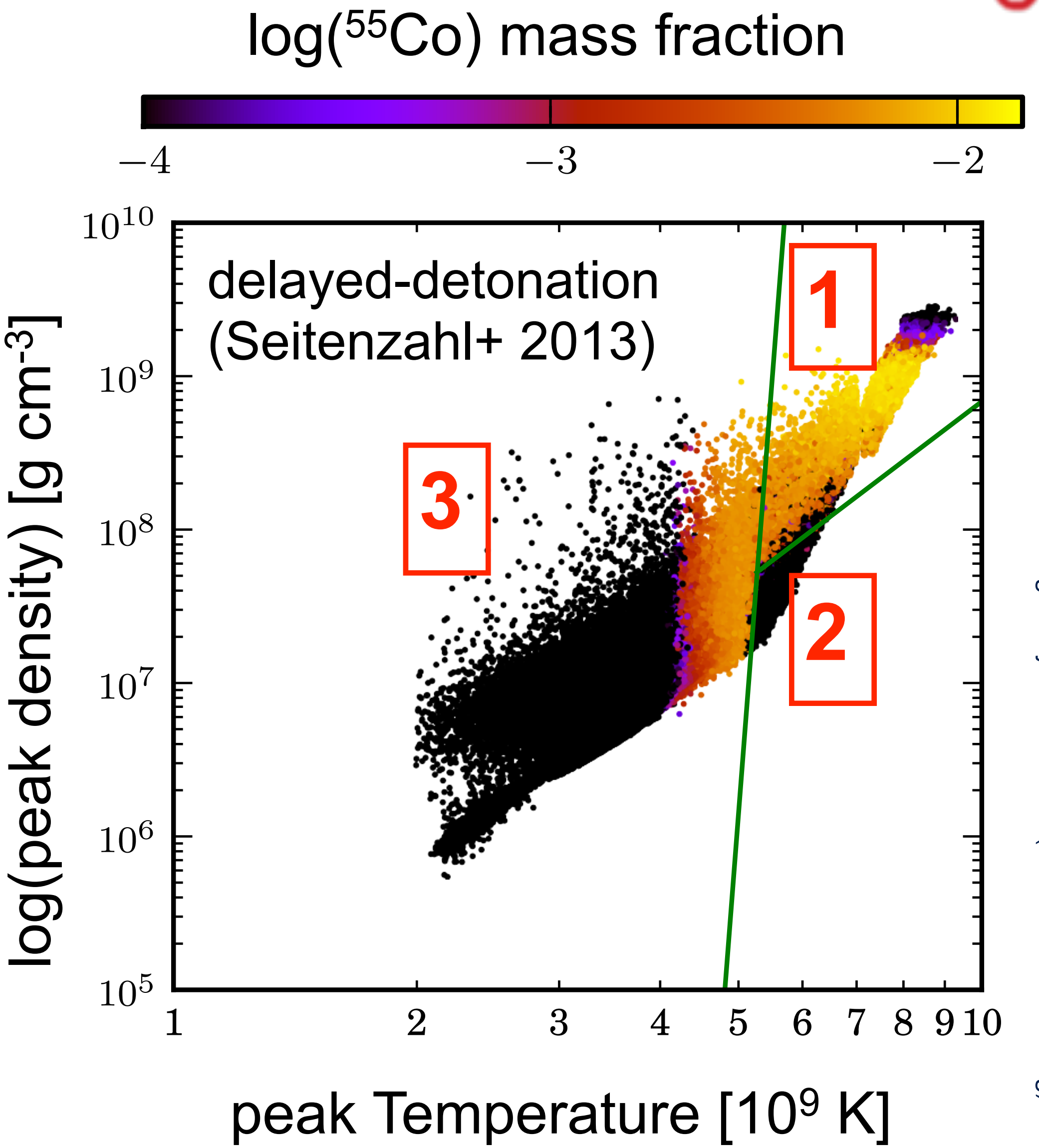
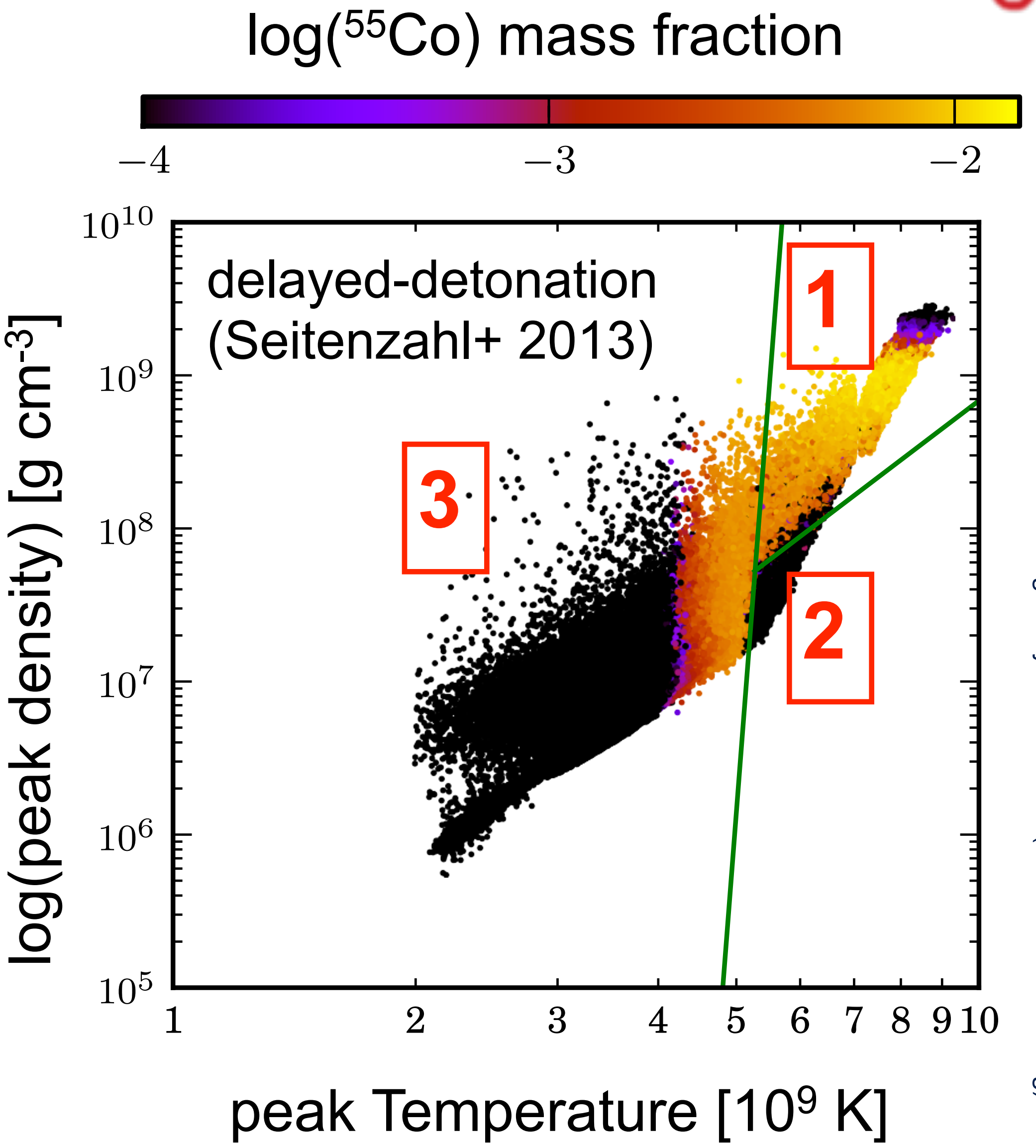


Figure by Florian Lach (Universität Würzburg)

Nucleosynthesis constraints Mn from SNe Ia

- $^{55}Co \rightarrow {}^{55}Fe \rightarrow {}^{55}Mn$



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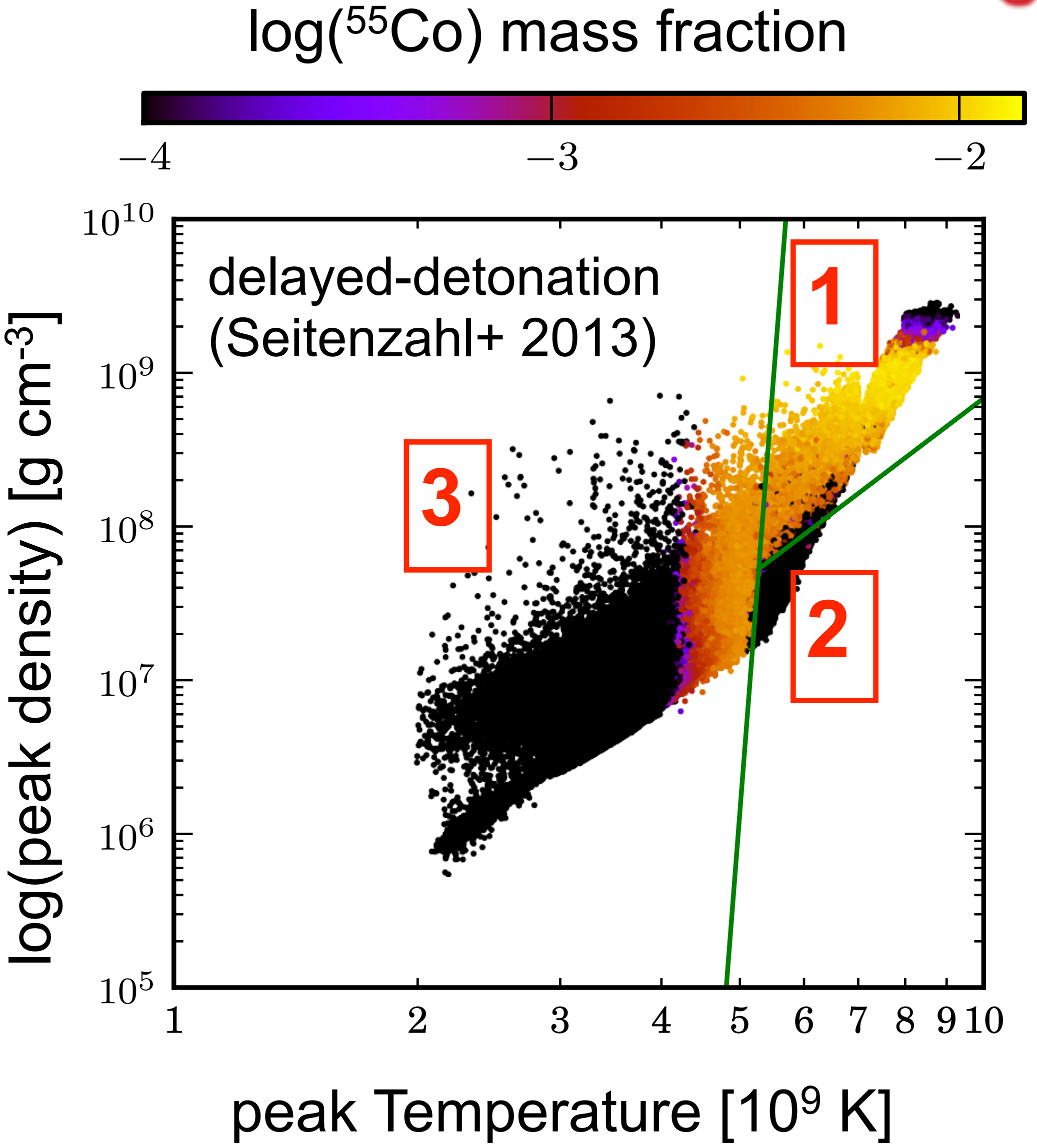

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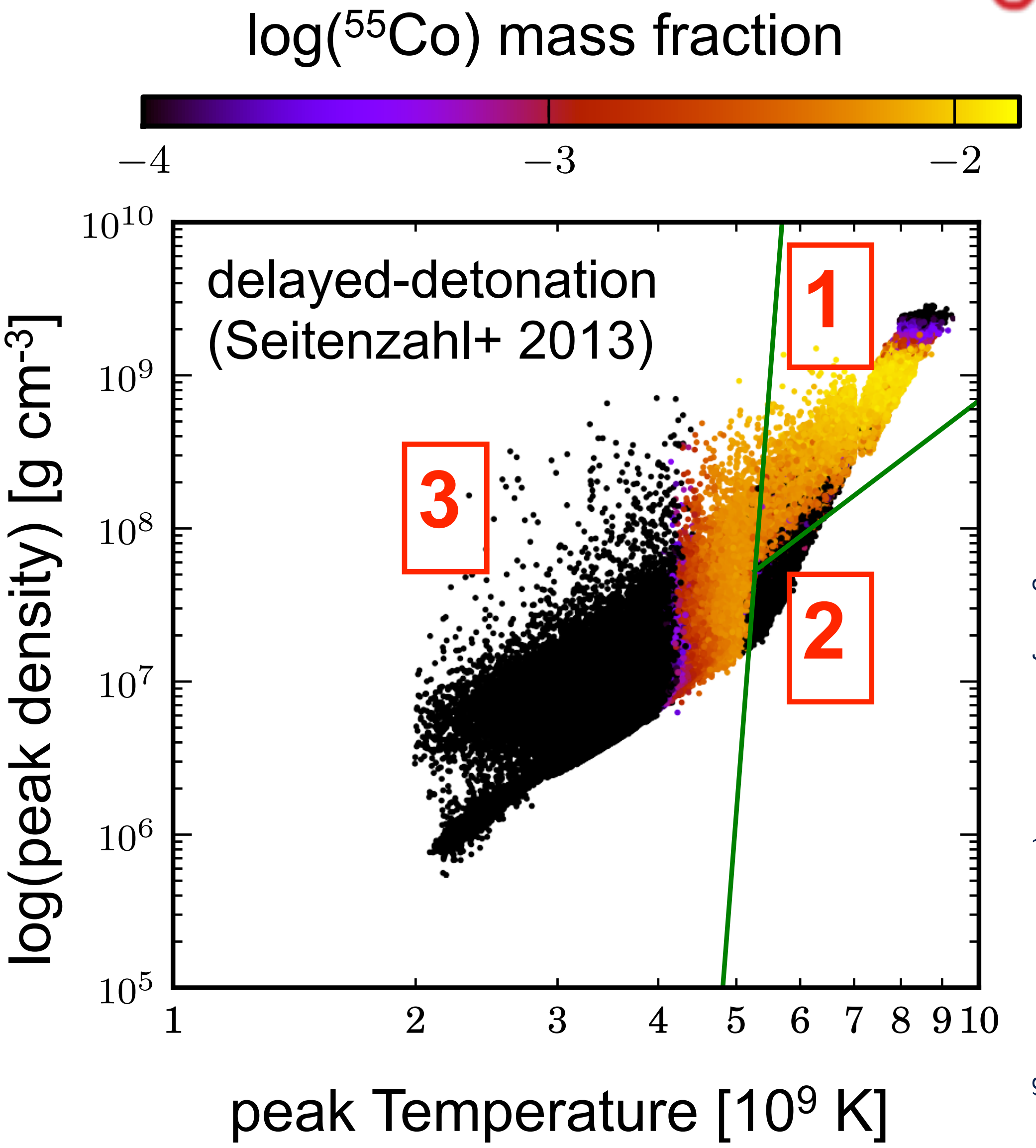

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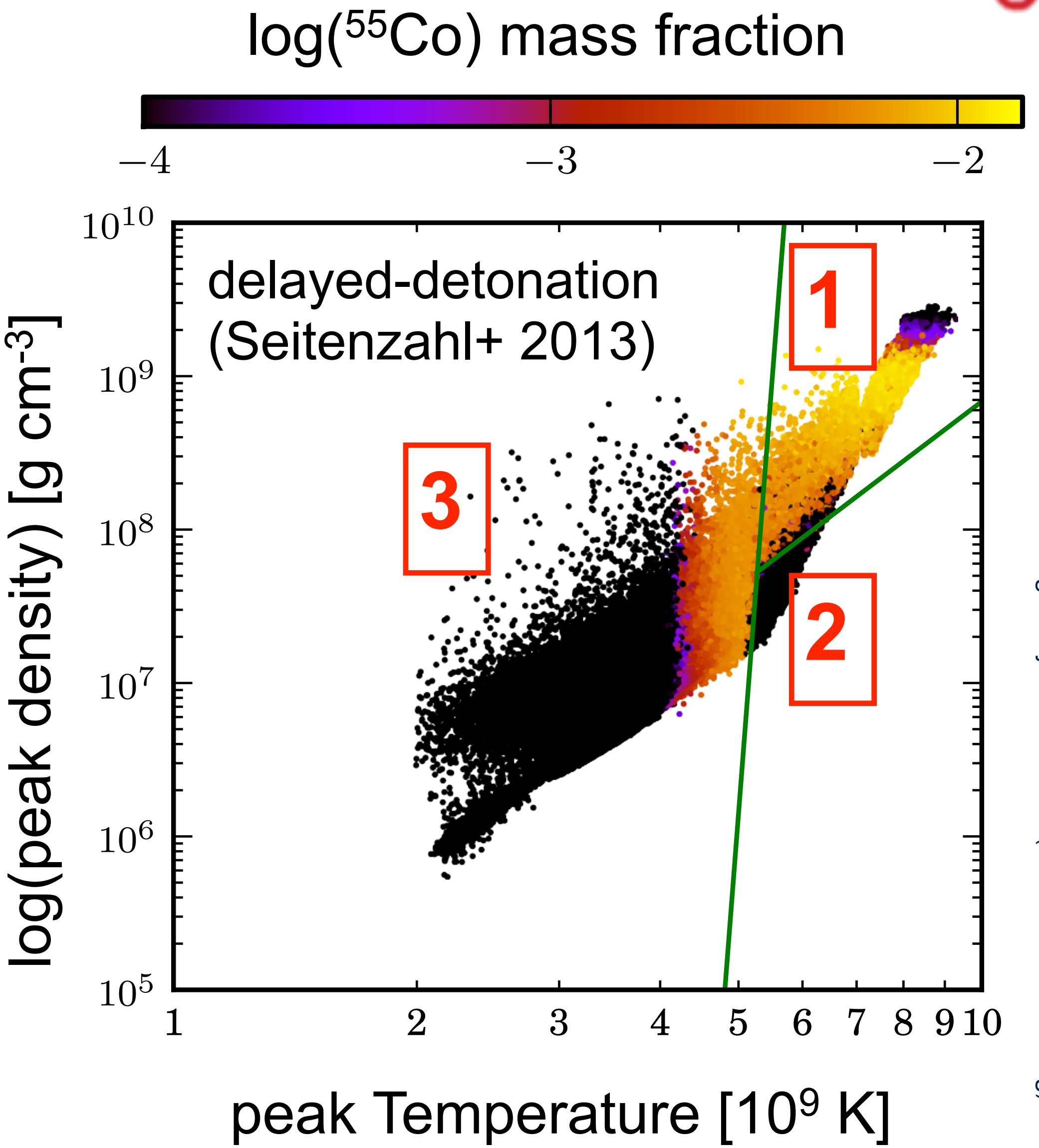

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- 3: incomplete Si-burning
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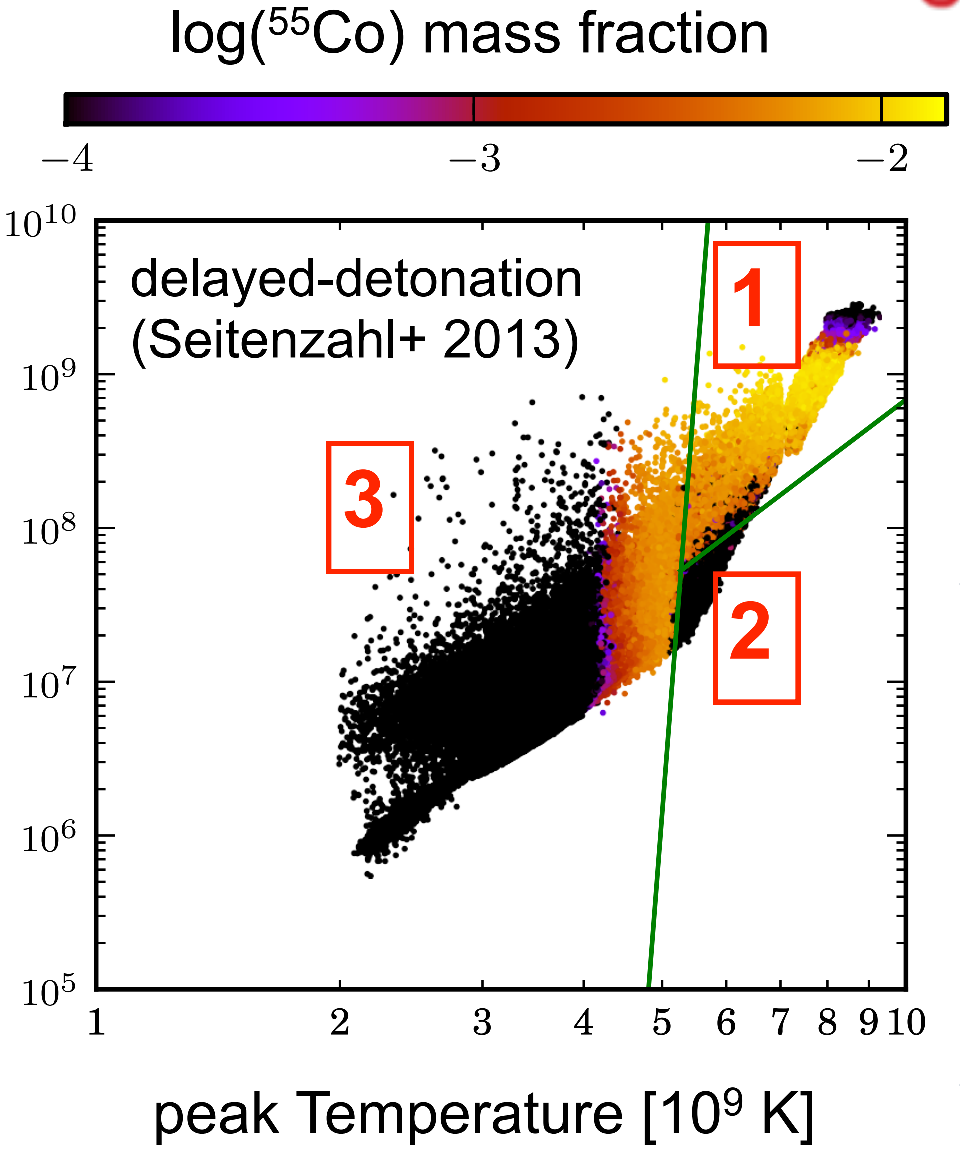

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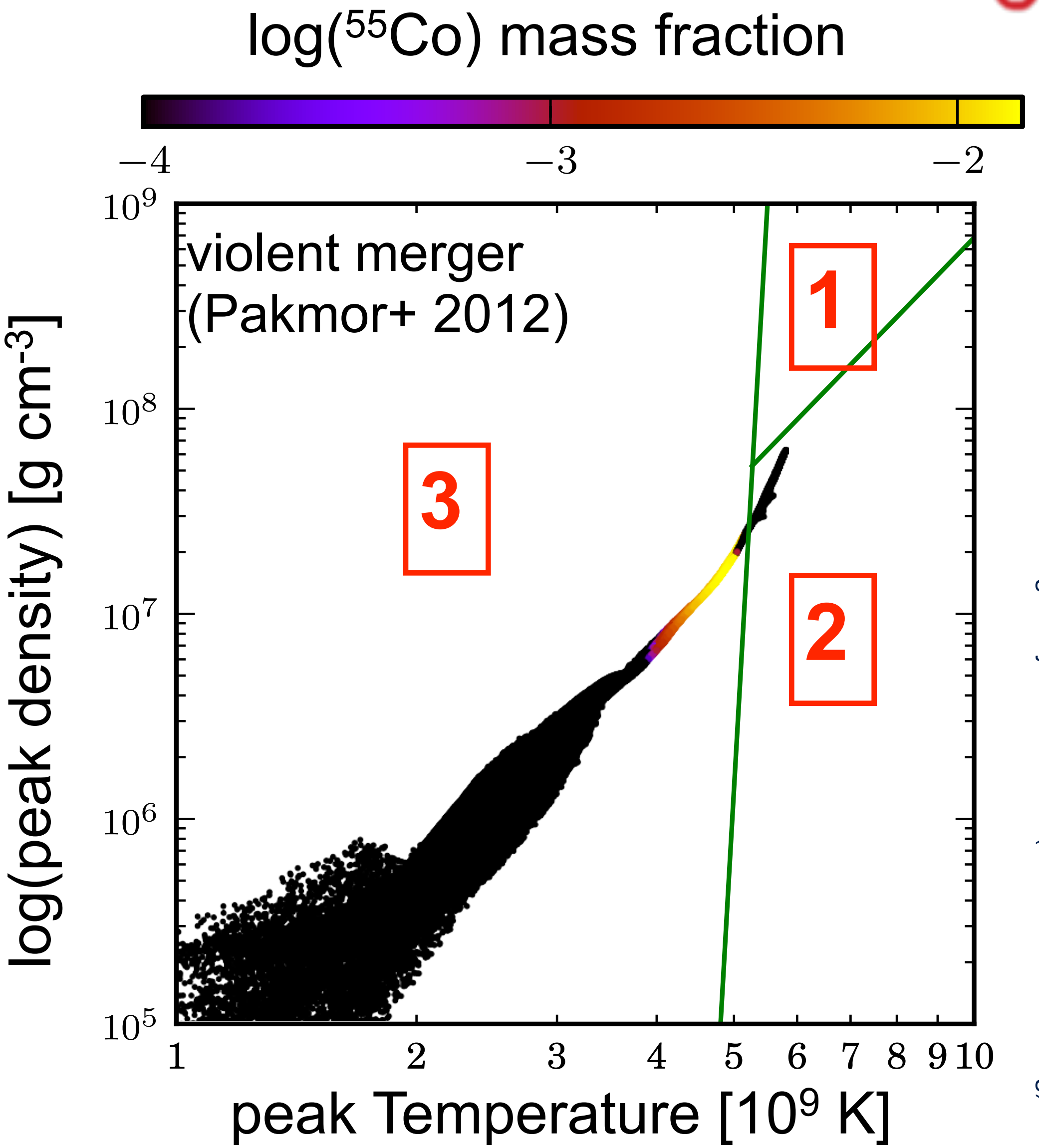
- Densities in merger model too low to enter [1]



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- Densities in merger model too low to enter [1]

- Merger model produces less ^{55}Co for same ^{56}Ni

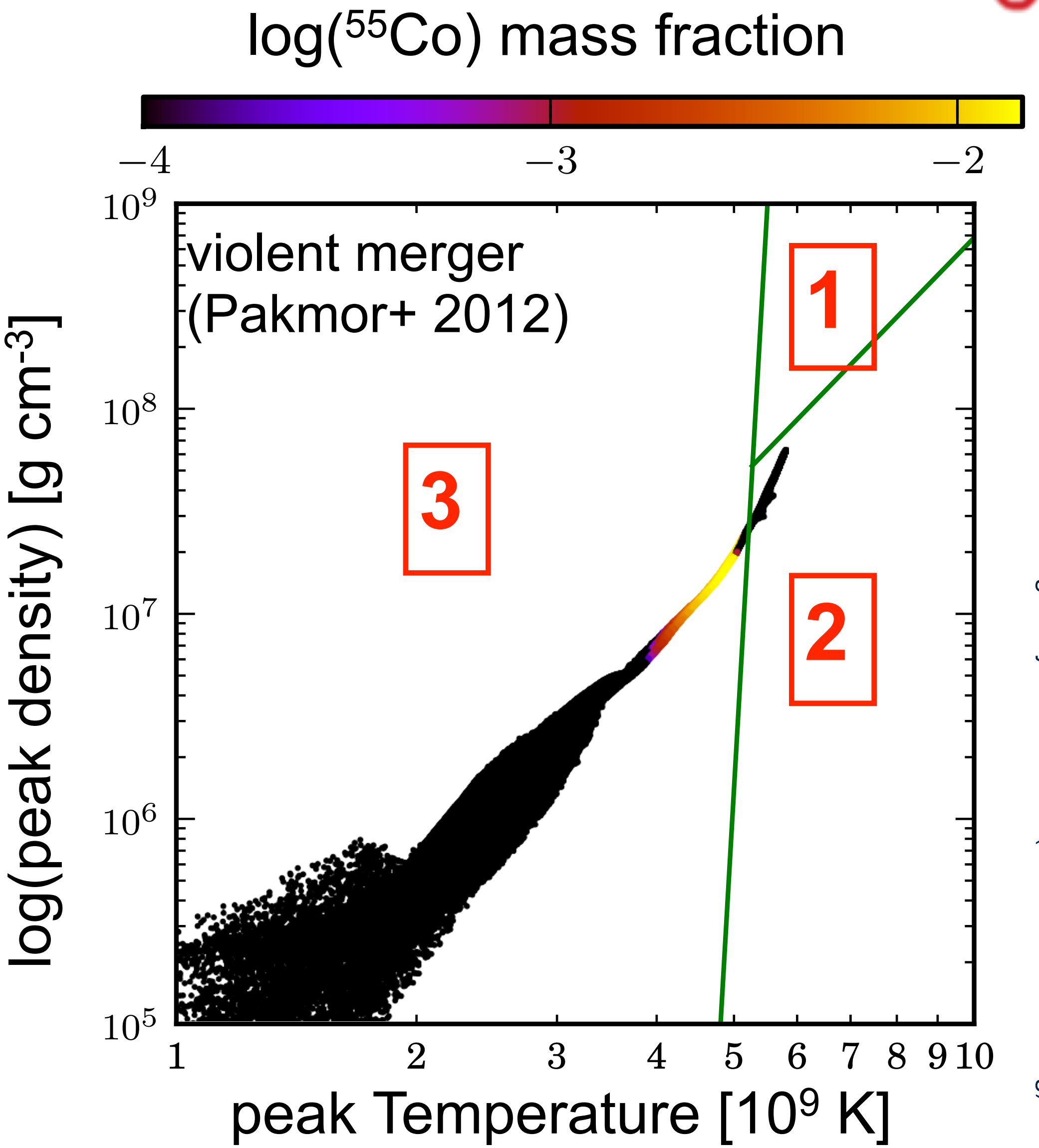

Figure by Florian Lach (Universität Würzburg)

[Mn/Fe] for different sites

$$[\mathrm{Mn/Fe}] \coloneqq \log(N(\mathrm{Mn}) / N(\mathrm{Fe}))_{\star} - \log(N(\mathrm{Mn}) / N(\mathrm{Fe}))_{\odot}$$

model name	SN type	masses	[Mn/Fe]
N100	Ia	near-M_{Ch}	0.33
N5def	Ia	near-M_{Ch}	0.36
N150def	Ia	near-M_{Ch}	0.42
W7	Ia	near-M_{Ch}	0.15
W7	Ia	near-M_{Ch}	0.02
1.1_0.9	Ia	sub-M_{Ch}	-0.15[a]
1.06 $\mathrm{M}_\odot$	Ia	sub-M_{Ch}	-0.13[a]
WW95B[b]	II	$11 < M/\mathrm{M}_\odot < 40$	-0.15[c]
LC03D[d]	II	$13 < M/\mathrm{M}_\odot < 35$	-0.27[c]
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Seitenzahl et al. (2013), A&A, 559, L5

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GCE simulations give best match to solar neighbourhood for ~50% near-M_{ch}.
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Seitenzahl et al. (2013), A&A, 559, L5

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Australian National University

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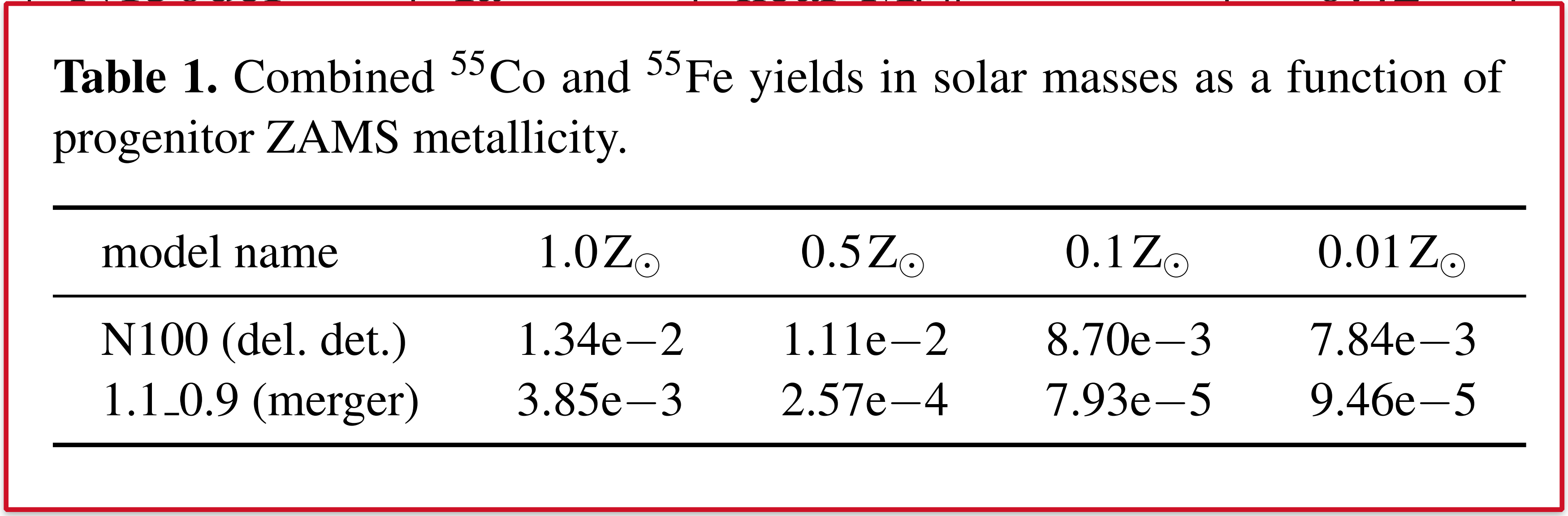
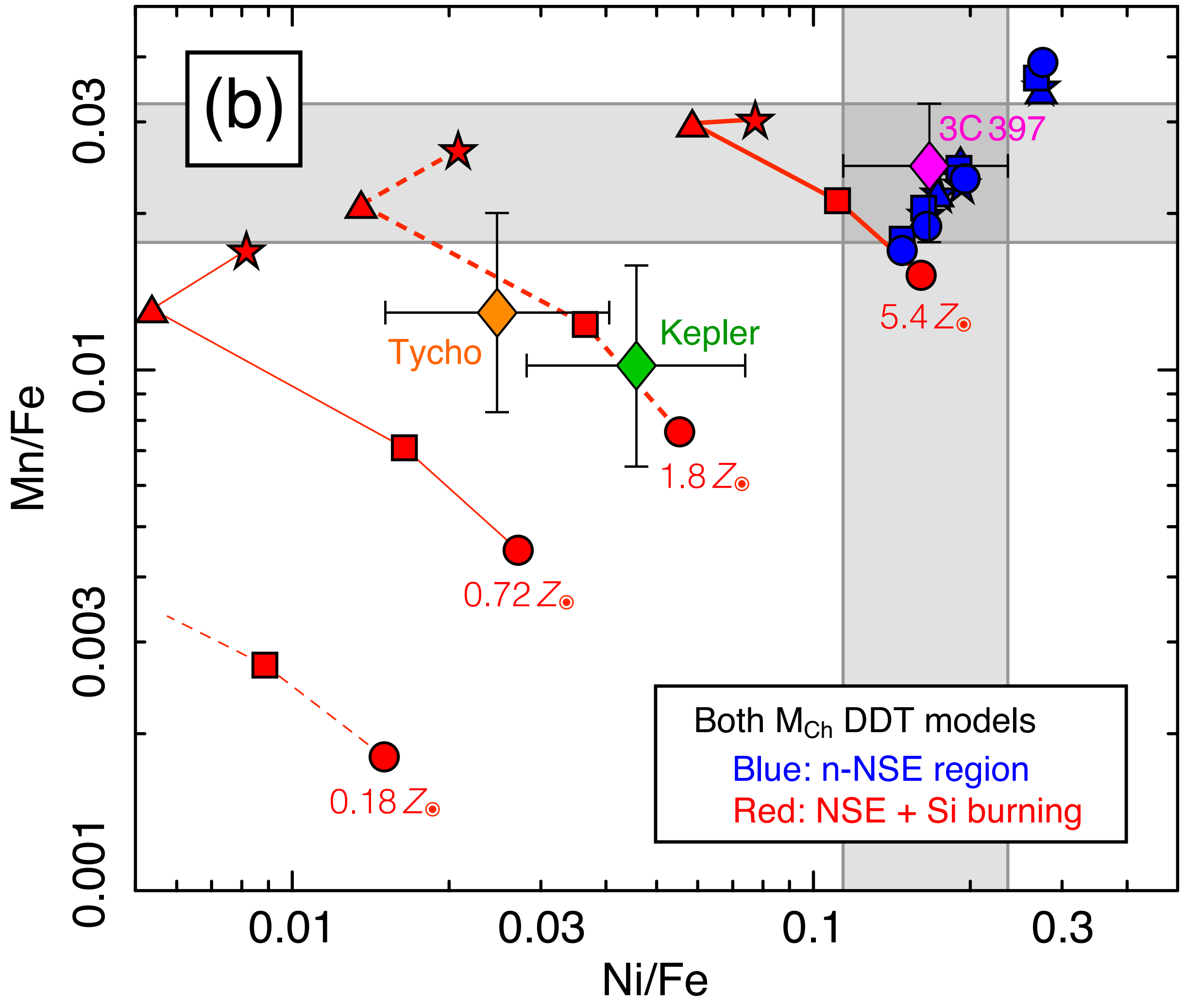


Table 1. Combined ^{55}Co and ^{55}Fe yields in solar masses as a function of progenitor ZAMS metallicity.

model name	$1.0Z_{\odot}$	$0.5Z_{\odot}$	$0.1Z_{\odot}$	$0.01Z_{\odot}$
N100 (del. det.)	1.34e−2	1.11e−2	8.70e−3	7.84e−3
1.1_0.9 (merger)	3.85e−3	2.57e−4	7.93e−5	9.46e−5

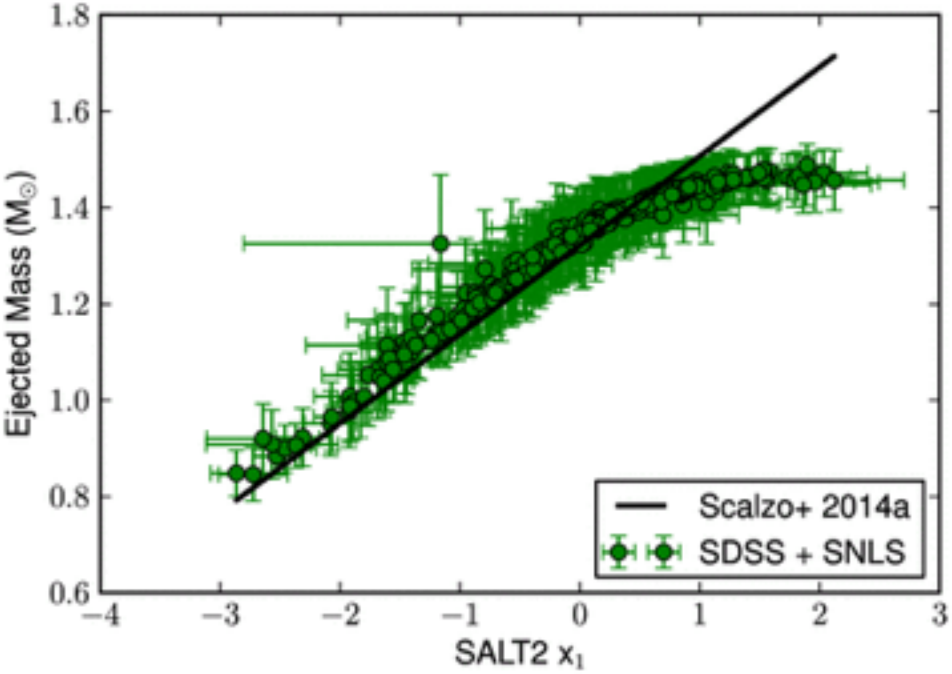
Seitenzahl et al. (2015), MNRAS, 447, 1484

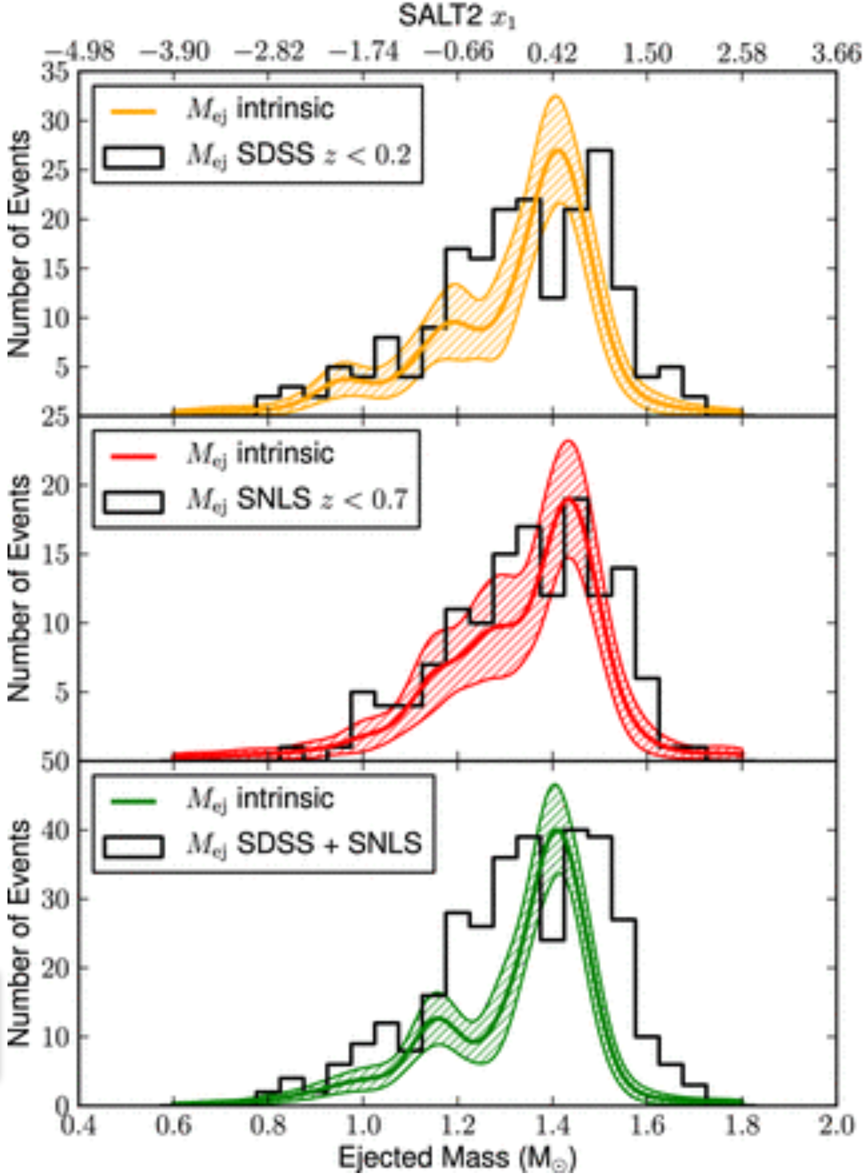


Yamaguchi et al. (2015), ApJL, 801, 31

Ejected masses from bolometric light curves

Bayesian analysis of bolometric light curves:





Scalzo, Ruiter & Sim (2014), MNRAS, 445, 2535

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    - post-explosion companions (SNRs)
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END