Determining the nucleosynthesis of supernovae by nebular spectral modelling

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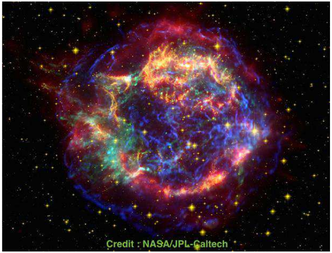

Credit : NASA/JPL-Caltech

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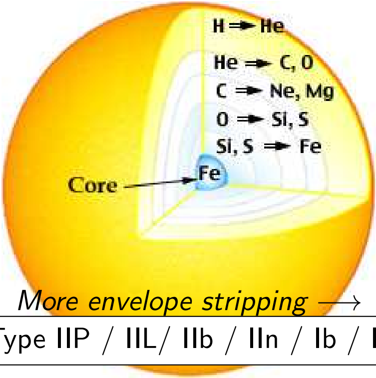
Outline

1. Introduction to supernovae and their nucleosynthesis
2. Spectral synthesis modelling and the SUMO code
3. Application 1: Type II SNe and the origin of oxygen
4. Application 2: The Ni/Fe ratio as a diagnostic of the explosion
5. Application 3: Superluminous SN 2006gy - detection of a massive iron reservoir upends old ideas
6. Outlook and summary

Supernovae - the deaths of stars

$\boxed{1}$ Core-collapse of a **massive star** ($M \gtrsim 8\ M_{\odot}$) as it runs out of fuel at the end of its life.

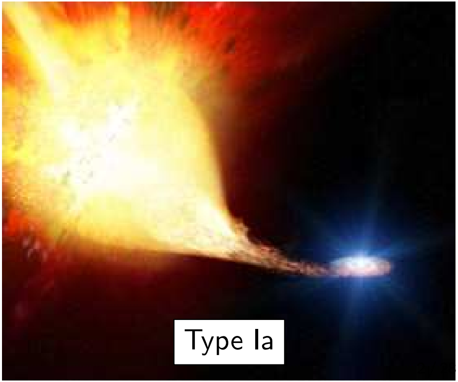


More envelope stripping ⟶

Type IIP / IIL/ IIb / IIn / Ib / Ic

Credit: www.phys.olemiss.edu

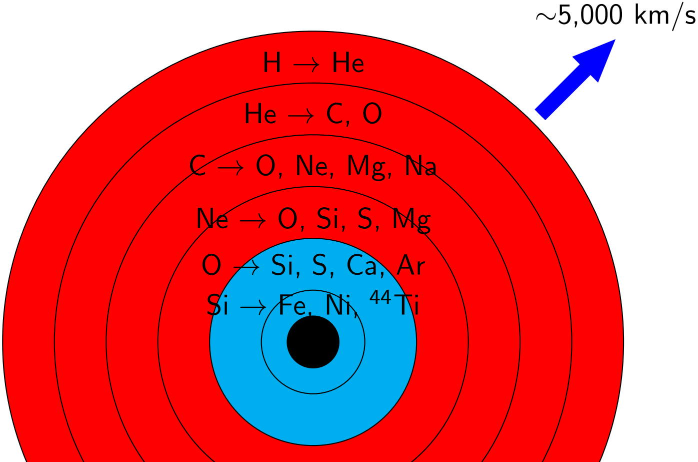
$\boxed{2}$ Thermonuclear explosion of a **white dwarf** as some accretion process ignites runaway burning of the C and O.



Type Ia

Nucleosynthesis in massive stars

- Hydrostatic (pre-SN) burning: main source of C, O, F, Ne, Na, Mg, Al, P in Universe.
- Explosive SN burning: main source of Si, S, Ar, Ca, Fe, Ni in the Universe.



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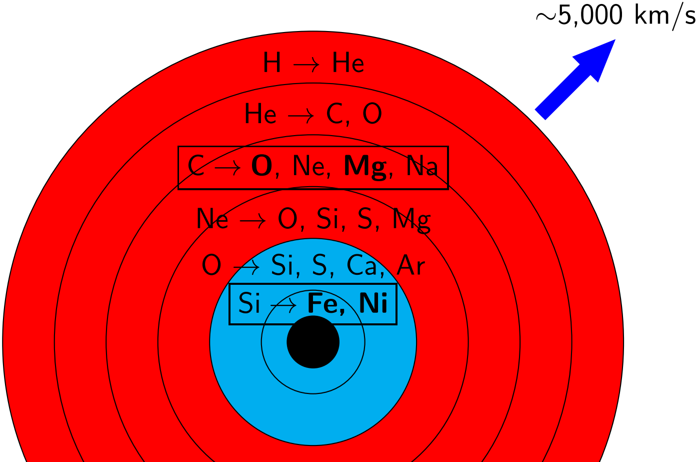
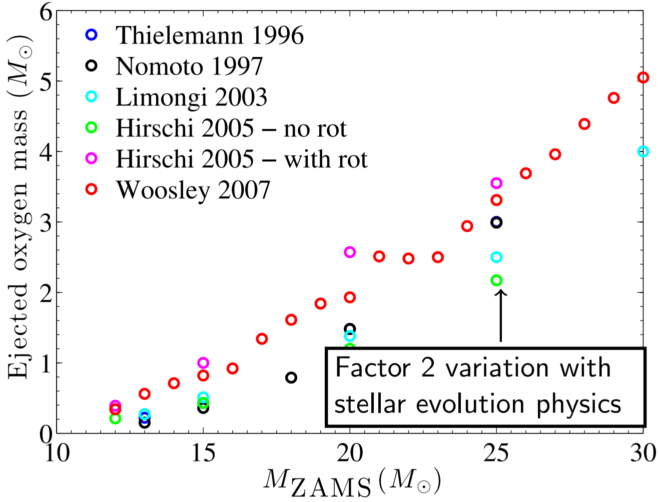


The origin of the elements

Ab.	El.	Main source	Direct emission seen in SNe
1	H	Big Bang	Many
2	He	Big Bang	He I 5016, 7065, 1.08 μm, 2.06 μm
3	O	CCSN	[O I] 5577, **[O I] 6300, 6364**, O I 7774, O I 9263 + ..
4	C	AGB stars+CCSN	[C I] 8727, 9824/9850, 1.44 μm, CO lines
5	Fe	CCSN+TNSN	[Fe II] 7155, 1.26 μm, 1.64 μm, 18 μm, **Fe I 8000 cluster**
6	Ne	CCSN	[Ne II] 12.8 μm
7	Si	CCSN+TNSN	[Si I] 1.10 μm, 1.20 μm, 1.60/1.64 μm, SiO lines
8	N	AGB stars	[N II] 6548, 6583
9	Mg	CCSN	**Mg I] 4571, 1.50 μm**
10	S	CCSN	[S I] 1.082 μm, 1.13 μm
11	Ar	CCSN	[Ar II] 6.99 μm
12	Ni	CCSN+TNSN	**[Ni II] 7378**, 1.93 μm, 6.6 μm, 10.7 μm, [Ni I] 3.1 μm
13	Ca	CCSN	[Ca II] 7300, NIR triplet, Ca I 4200
14	Al	CCSN	-
15	Na	CCSN	Na I 5890, 5896, 1.14 μm

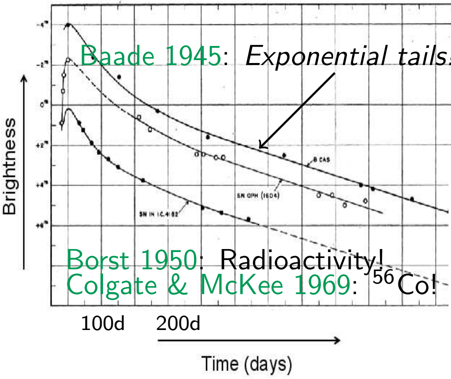
Still few quantitative results by SN spectral analysis

Oxygen nucleosynthesis : theoretical $M(O)$ vs M_{ZAMS}



Factor 2 variation with stellar evolution physics

The nebular phase: an opportunity to see what massive stars are made of and determine nucleosynthesis yields

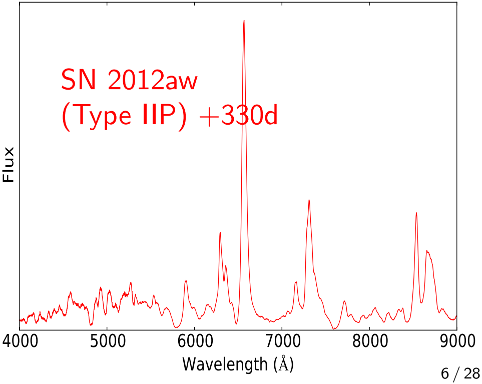


Baade 1945: *Exponential tails!*

Borst 1950: Radioactivity!

Colgate & McKee 1969: ^{56}Co!

From ∼100 days (optically thick earlier) to ∼1000 days (too dim and/or complex physics after) post explosion.

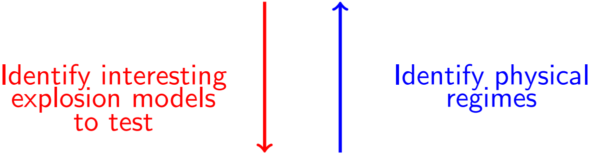


Data collection rate: a few per year.

Total number of SNe with good data sets:∼50.

How can we determine element masses in SN ejecta from their nebular spectra?

1. **Inverse modelling**: Measure line luminosities, assume uniform conditions and use analytic forms valid in certain limiting physical regimes (e.g. LTE, optically thin,..).



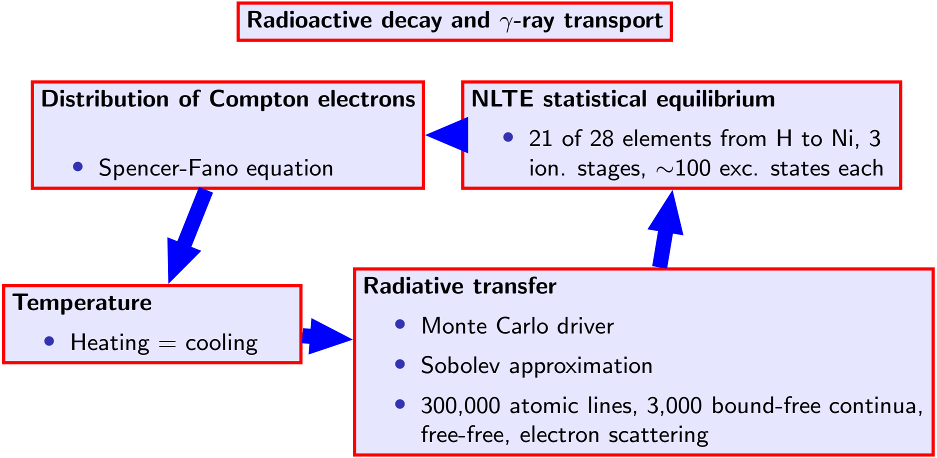
Identify interesting explosion models to test

Identify physical regimes

2. **Forward modelling**: Radiative transfer modelling of multi-zone explosion models with self-consistent nucleosynthesis.

Forward modelling: the SUMO code

Jerkstrand 2011, PhD thesis, Jerkstrand, Fransson & Kozma 2011, Jerkstrand+2012



Radioactive decay and γ-ray transport

Distribution of Compton electrons

- Spencer-Fano equation

NLTE statistical equilibrium

- 21 of 28 elements from H to Ni, 3 ion. stages, ∼100 exc. states each

Temperature

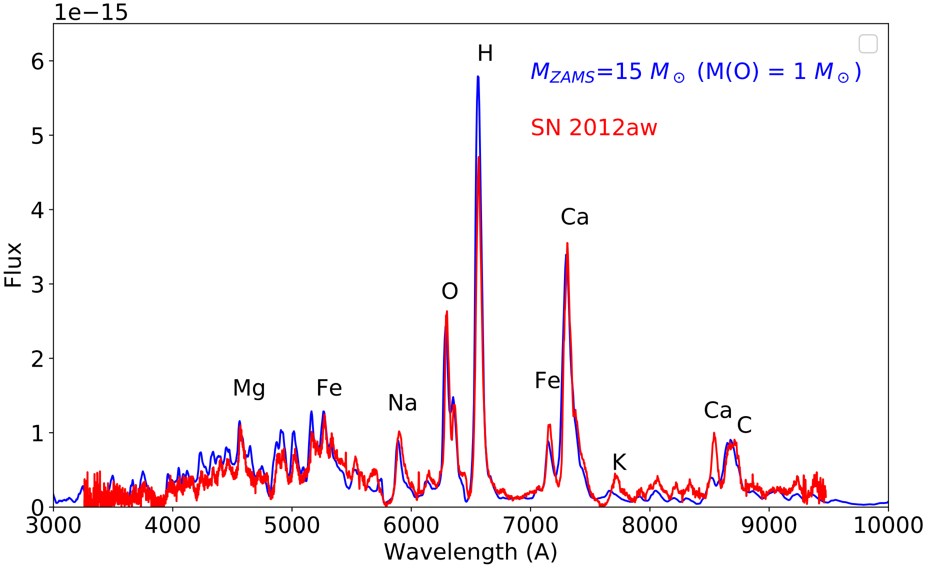
- Heating = cooling

Radiative transfer

- Monte Carlo driver
- Sobolev approximation
- 300,000 atomic lines, 3,000 bound-free continua, free-free, electron scattering

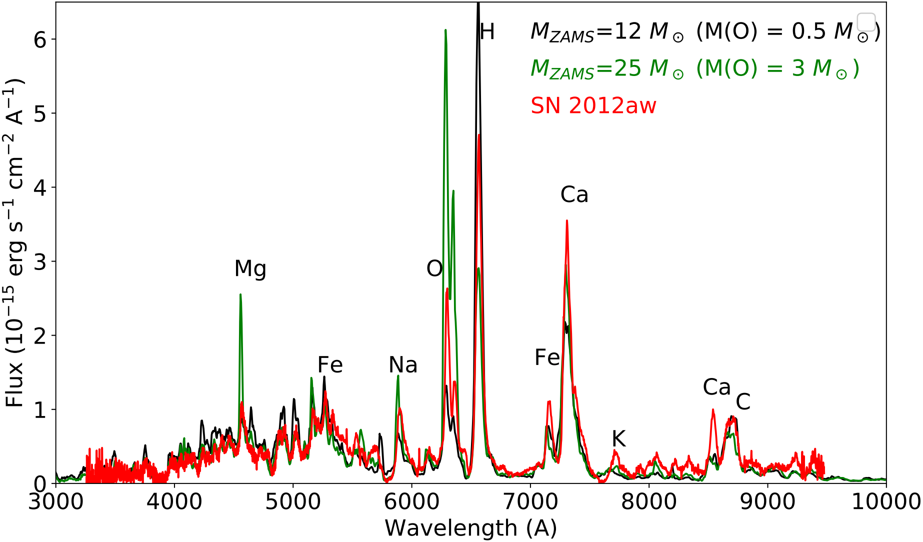
- Code is 1D but allows for mixing by 'virtual grid' option.

Type IIP model spectra



AJ+2012,2014

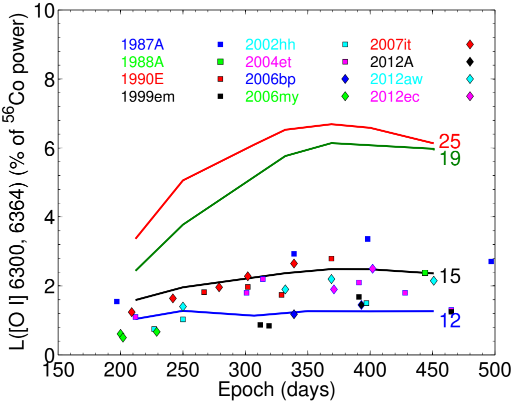
Type IIP model spectra



AJ+2012,2014

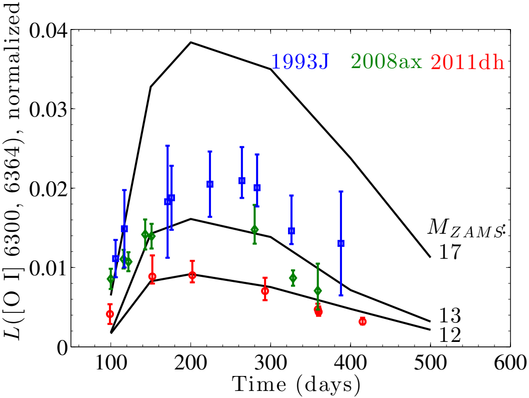
Type IIP model spectra *Jerkstrand, Smartt, Sollerman+2015, MNRAS*

Highest mass stars missing : are they collapsing directly to black holes? Or maybe become stripped-envelope SNe?



- True also in larger samples (e.g. *Silverman+2017*).

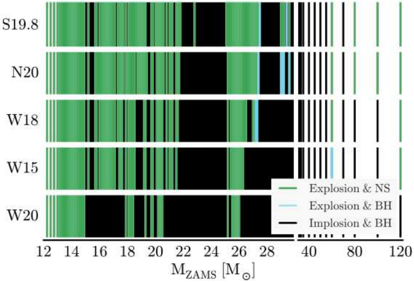
Stripped-envelope supernovae: also here small amounts of oxygen and low-mass progenitors



Jerkstrand, Ergon, Smartt+2015, A&A

- Most IIb-Ib-Ic SNe seem to come from stars stripped by binary interaction.

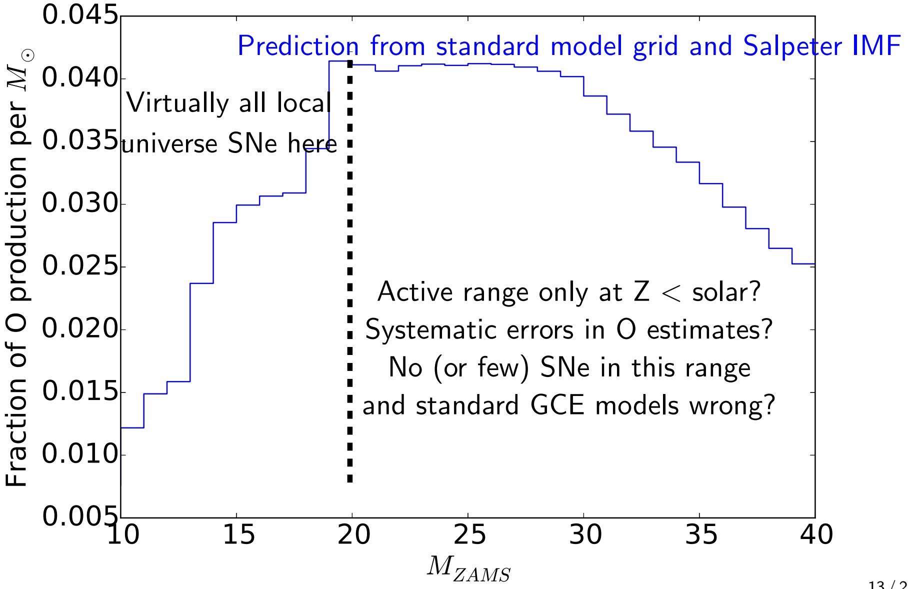
Fate of $M_{ZAMS} \gtrsim 20 M_\odot$ stars?



Sukhbold+2016

- Growing consensus that many stars at $M_{ZAMS} \gtrsim 20\ M_\odot$ fail to explode with neutrino mechanism : cores too compact (e.g. *O'Connor & Ott 2011*)
- No massive stars detected in progenitors imaging (e.g. *Smartt 2009, 2015*).
- Some candidates emerging for disappearing stars (*Kochanek+2008, Adams+2017,Reynolds+2015*).

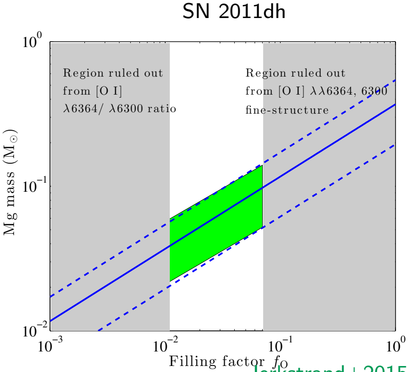
Which stars actually make most of our oxygen?



Relative abundances: example of magnesium

- Most stellar evolution models underpredict Mg/O compared to the solar value (factor 2-3)...why?
- Two main diagnostics : Mg I] 4571 and Mg I 1.50 μm.
- Mg I] 4571 : Relatively sensitive to model detail → large error bars
- Mg I 1.50 μm : Simpler formation, but less often observed

- Oxygen : $n_{OII} \approx n_e \rightarrow$ $\boxed{L_{O-rec} \propto f_O \times n_e^2}$ where f_O is the oxygen filling factor (constrained from [O I]).
- Magnesium : $n_{MgII} \approx n_{Mg}$ $\rightarrow \boxed{L_{Mg-rec} \propto M_{Mg} \times n_e}$
- O and Mg recombination lines together gives Mg mass.



Jerkstrand+2015,A&A

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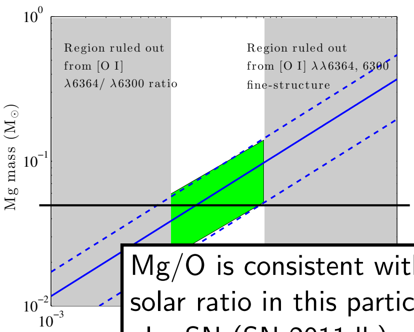
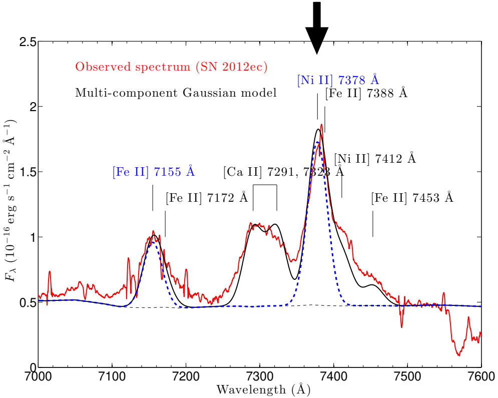
SN 2011dh



Mg/O is consistent with solar ratio in this particular SN (SN 2011dh)

Stable nickel

- Main diagnostic line: **[Ni II] 7378**



Jerkstrand, Smartt, Sollerman et al. 2015, MNRAS

- Use forward models to identify lines present between 7000-7600 Å.
- 4-component fit gives $L_{\text{[Ni II] 7378}}$ and $L_{\text{[Fe II] 7155}}$.
- This luminosity ratio robustly links to the Ni/Fe abundance ratio.
- Fe emission comes from decayed ^{56}Ni, so this ratio probes the $^{58-60}$Ni/^{56}Ni production.

Ni/Fe ratios in CCSNe

Jerkstrand, Smartt, Sollerman et al 2015, MNRAS

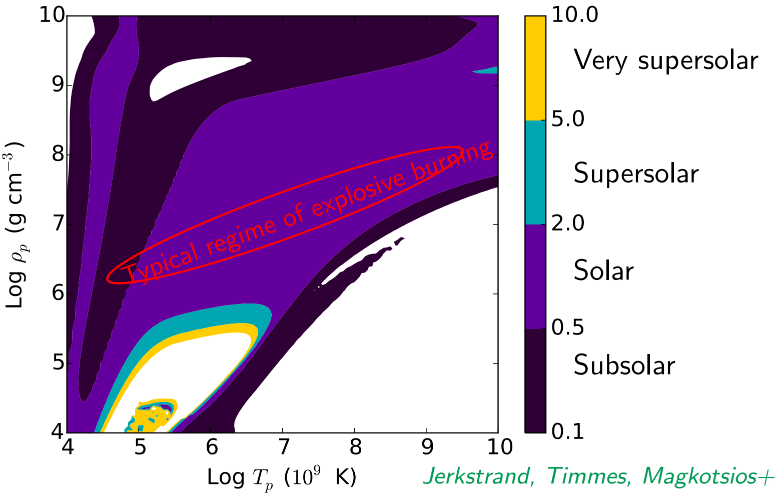
SN	Ni/Fe times solar	Reference
SN 1987A	0.5 – 1.5	Rank+1988, Wooden+1993, AJ+2015
SN 2004et	∼1	AJ+2012
SN 2012A	∼ 0.5	AJ+2015
SN 2012aw	∼ 1.5	AJ+2015
SN 2012ec	2.2 – 4.6	AJ+2015
SN 2006aj	2 – 5	Maeda+2007, Mazzali+2007
Crab	60 – 75	MacAlpine+1989, MacAlpine+2007

- Average ratio $\geq$ solar.
- If true in larger sample, Type Ia SNe must make Ni/Fe $\leq$ solar → constraints on Ia explosions models.
- Sometimes ratio is significantly larger..what does it mean?

What is Ni/Fe ratio diagnostic of?

The **neutron-richness of the fuel** ($\eta = \frac{N_n - N_p}{N_n + N_p}$) sets the Ni/Fe ratio.

$\boxed{\eta = 0.002}$: Ni/Fe ∼ solar produced for typical burning conditions

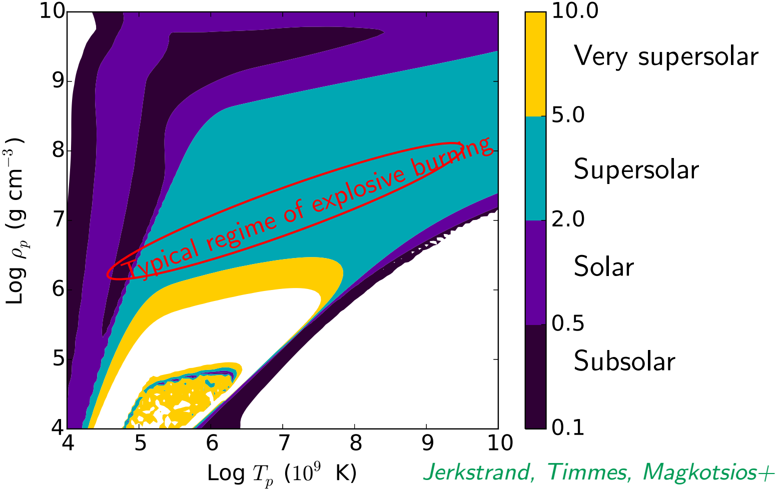


Jerkstrand, Timmes, Magkotsios+2015, ApJ

What is Ni/Fe ratio diagnostic of?

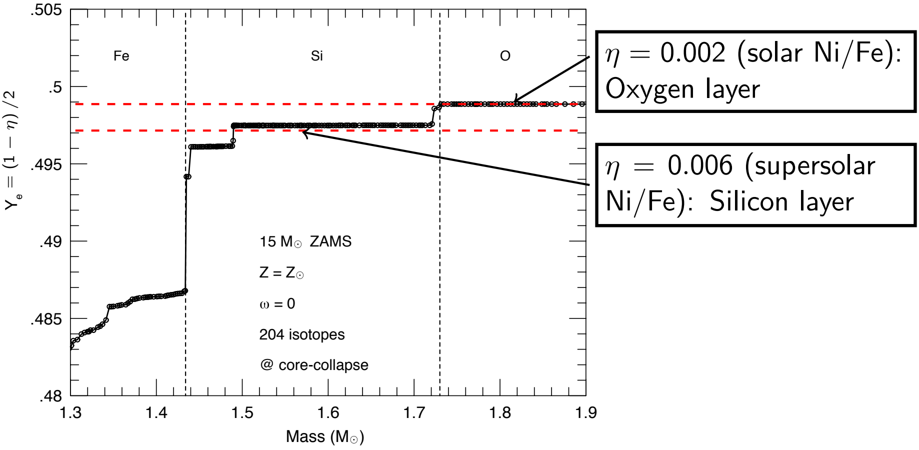
The **neutron-richness of the fuel** ($\eta = \frac{N_n - N_p}{N_n + N_p}$) sets the Ni/Fe ratio.

$\boxed{\eta = 0.006}$: Ni/Fe 2-5 times solar produced for typical burning conditions



Jerkstrand, Timmes, Magkotsios+2015, ApJ

The Ne/Fe ratio is a tracer of which progenitor layer was explosively burnt *Jerkstrand, Timmes, Magkotsios+2015, ApJ*

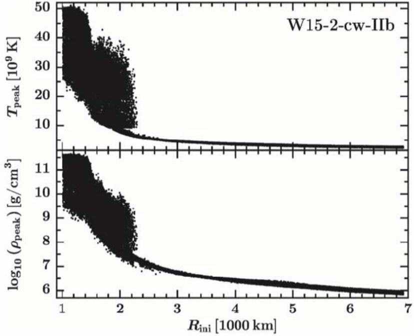


$\eta = 0.002$ (solar Ni/Fe): Oxygen layer

$\eta = 0.006$ (supersolar Ni/Fe): Silicon layer

- If this interpretation is correct, SNe mostly burn and eject oxygen shell material, but sometimes silicon shell material.

Does the picture hold considering 3D effects with neutrino-induced η changes?

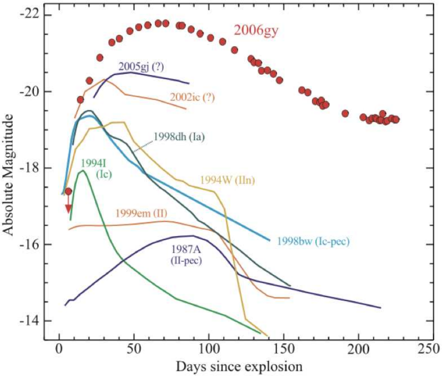


Wongwathanarat et al. 2017

- Ongoing work in several groups to determine explosive nucleosynthesis η in better detail (Garching, NC State, Princeton, Oak Ridge..).
- Uncertain neutrino physics limits accuracy of η predictions for those layers cycled close to NS.

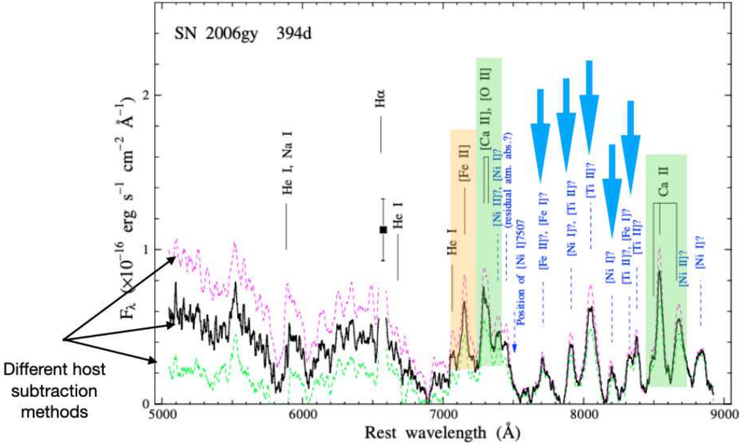
Iron in SN 2006gy : one of the brightest SNe ever seen

- Radiated energy $\sim 10^{51}$ erg (compare 10^{49} erg normal SNe).
- Type IIn : interaction with a massive slow-moving CSM indicated from narrow H lines. This CSM ($\sim 10 M_\odot$) ejected $\lesssim$ 100y before the SN.
- A vast and diverse set of models proposed over the years: pair-instability SN, pulsational pair instability SN, an LBV exploding into an Eta-Carina like eruption. All of them involve the explosion of a **massive star**.



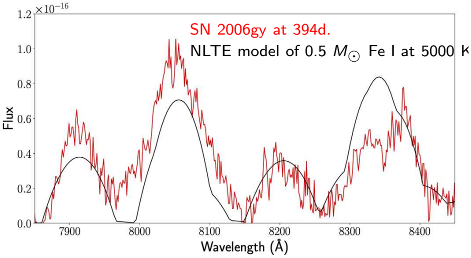
Smith et al. 2007

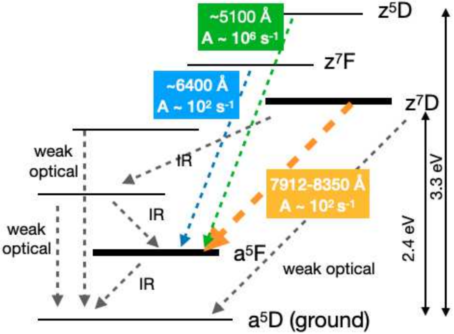
Strange, unknown lines seen at 400d *Kawabata et al 2009*



- Only clearly identified elements : Fe II and Ca II. Explosive burning products suggested.
- Line widths indicate $\sim$ 1500 km s^{-1} expansion.

Identification : Fe I! *Jerkstrand, Maeda & Kawabata 2020, Science*





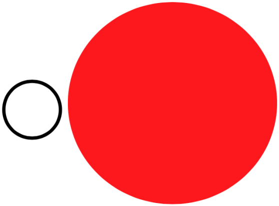
Modelling of the line emission constrains the iron mass to

$$\boxed{0.3 < M_{Fe} < 2.1\ M_\odot}$$

CCSNe : $M_{Fe} \lesssim 0.2\ M_\odot$. Problematic.
Pulsational PISNe: $M_{Fe} = 0$. Ruled out.
Ia SNe: $M_{Fe} \sim 0.5\ M_\odot$. Could it be?

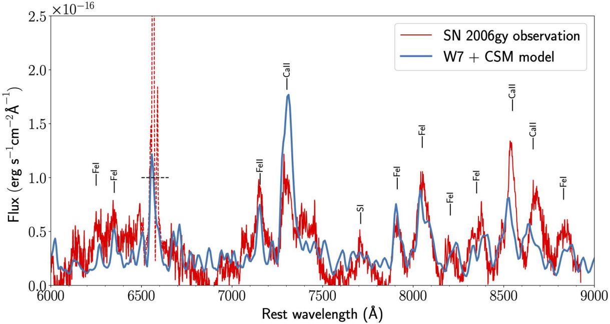
Could SN 2006gy be the result of a merger of a white dwarf with a massive star?

- **Causally connects the massive CSM ejection and the SN** (inspiral → common envelope ejection followed by explosion when WD reaches the centre of the other star).
- **Common envelope ejection a well established process** - entire stellar envelope expected to be ejected on timescales of years/decades.
- **Ia SNe make the right amounts of ^{56}Ni** ($0.3 - 0.7\ M_\odot$).



Spectrum of a decelerated Ia SN fits well

Standard Ia explosion model (W7) with velocities reduced factor 7 to mimic a deceleration due to strong interaction with a massive CSM.



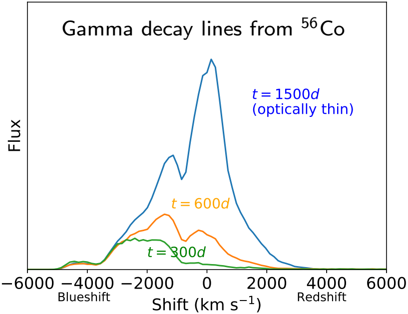
- No flux scaling - a major strength of the model.
- Physical conditions (temperature which sets the SED, and ionization which sets the line ratios), and the amounts of Fe and Ca seem correct.
- Light curve shown to be well produced by Ia SN hitting a 10-15 $M_\odot$ CSM (see paper).

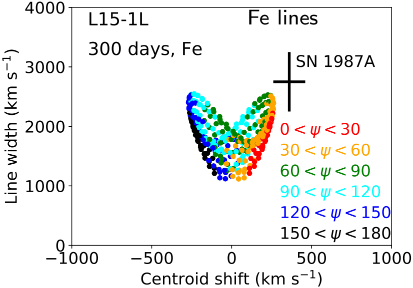
Questions raised if WD-RSG merger is the right explanation

1. How do you get a WD close to a RSG or RG star?
2. How do you get it to spiral in, eject virtually all the envelope, and merge with the core of the other star?
3. How do you get it to explode?

Outlook

Advent of 3D nebular-phase models (*Jerkstrand et al, 2020, MNRAS, see also Botyanszki+2017, 2018 and Shingles+2020 for Ia cases*)

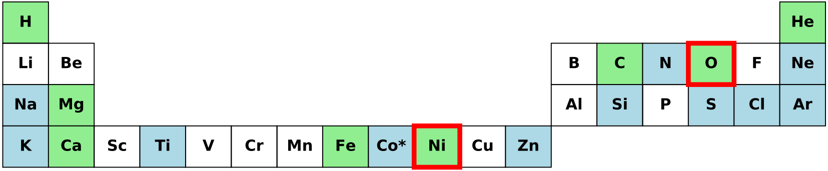




- Allow tests of 3D explosion simulations.
- Understand degree of validity of 1D models, and how to best use 1D models.
- Which microphysics to trade off?

Outlook

Elements currently diagnosed from supernova nebular spectra



H																	**He**
Li	**Be**											**B**	**C**	**N**	**O**	**F**	**Ne**
Na	**Mg**											**Al**	**Si**	**P**	**S**	**Cl**	**Ar**
K	**Ca**	**Sc**	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co***	**Ni**	**Cu**	**Zn**						

Good diagnostic situation

Moderate diagnostic situation

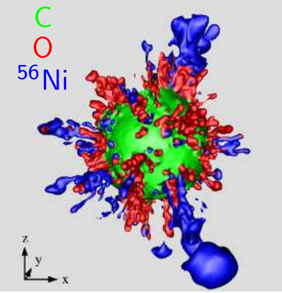
Poor diagnostic potential

Summary

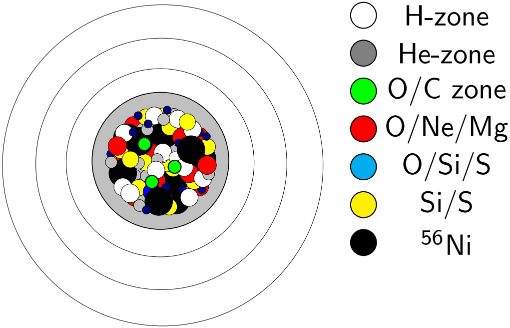
- Supernovae are import element producers, nebular-phase spectral modelling allows direct inferrence of hydrostatic and explosive nucleosynthesis yields.
- Spectral modelling of Type II SNe with SUMO indicate low/moderate amounts of **oxygen** ($\lesssim 1\ M_\odot$), with no clear candidates from the $M_{ZAMS} \gtrsim 20\ M_\odot$ range.
- Some results on **abundance ratios** are becoming available, e.g. Mg/O.
- The [Ni II] 7378 line can be used to determine the **amount of $^{58-60}$Ni** produced in the explosion. A sample of CCSNe show Ni/Fe $\sim$ solar, but in a few cases a higher ratio. A solar value indicates explosive burning of the **oxygen shell**, whereas a supersolar value indicates burning of the **silicon shell** of the progenitor.
- **A large iron reservoir** ($\sim 0.5 M_\odot$) identified in the superluminous IIn SN 2006gy. Model scenario of a Ia SN exploding inside a recently ejected common envelope promising.

Modelling Type IIP SNe *AJ+2012, AJ+2014*

- Stellar evolution/explosion models from KEPLER (Woosley & Heger 2007) → all nucleosynthesis self-consistent
- Consider macroscopic mixing effects of core from 2D/3D models
- Parameterized molecular cooling of O/Si/S and O/C zones



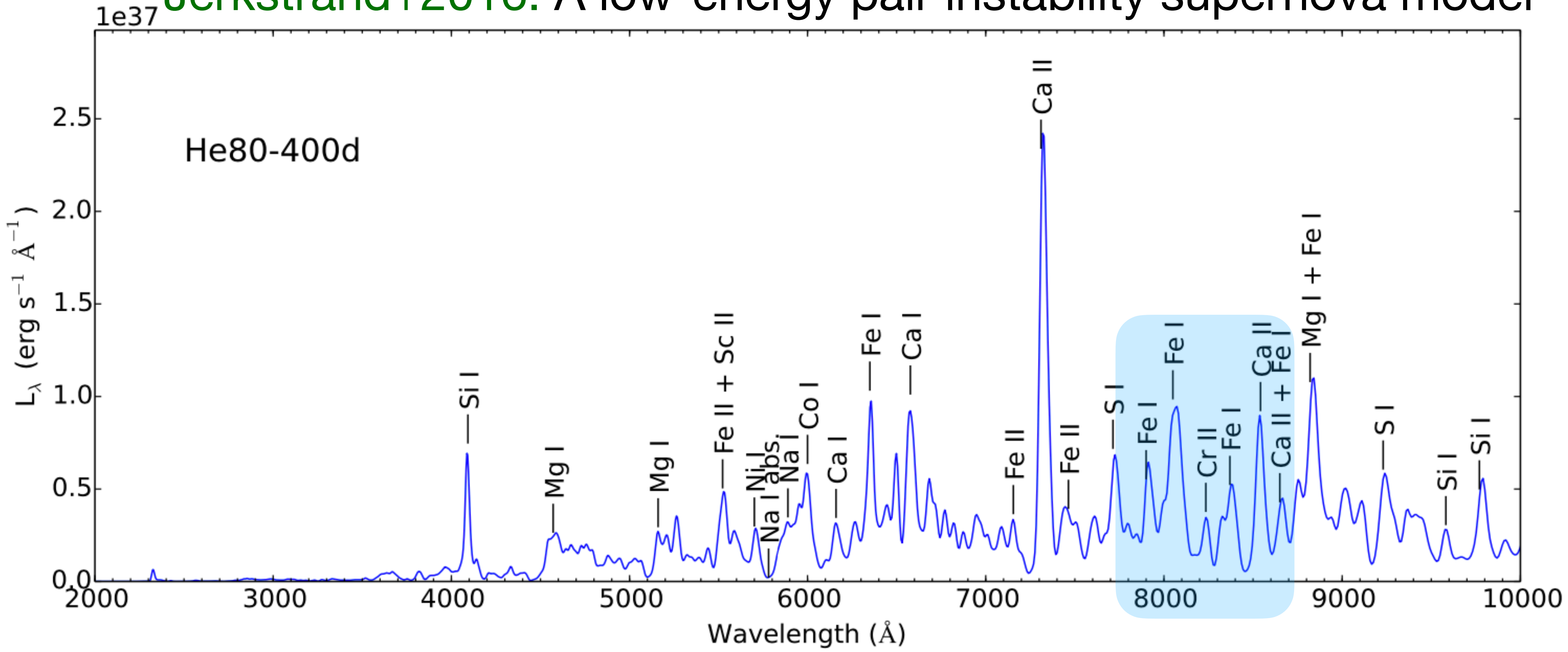
Hammer+2010, 3D model



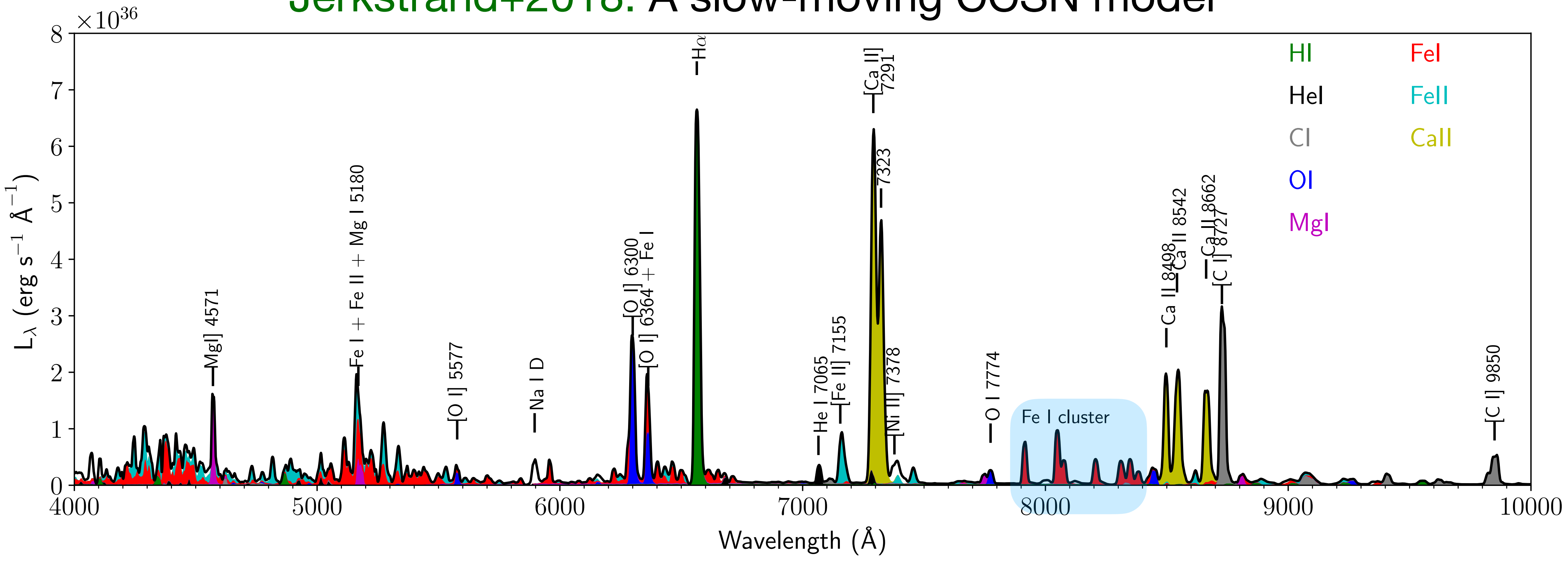
Ejecta setup in SUMO

Identification of the lines : Fe I

Jerkstrand+2016: A low-energy pair instability supernova model



Jerkstrand+2018: A slow-moving CCSN model



How much iron is there?

Approach 1: Search constraints for any temperature and density.

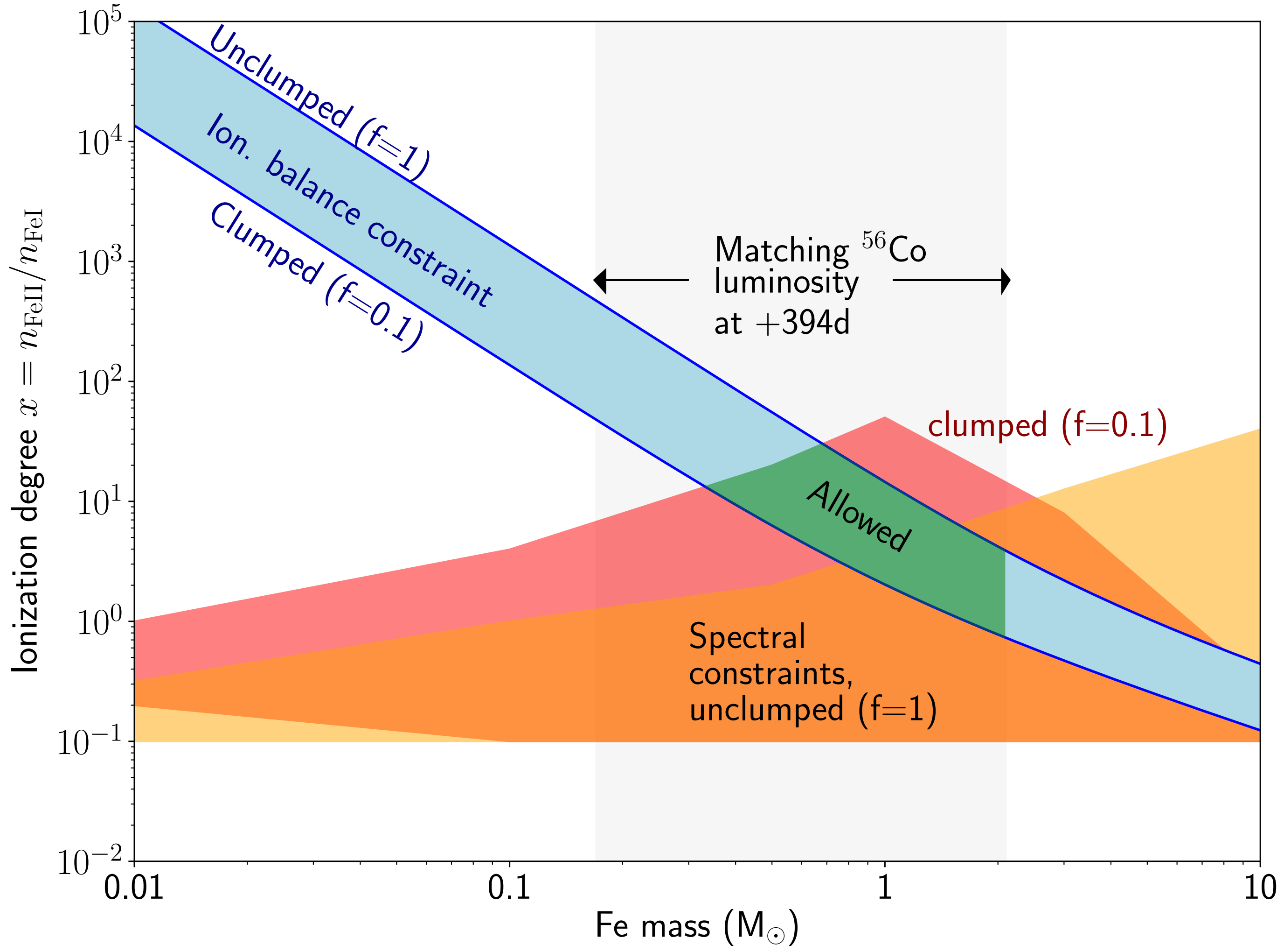
Result:
$M_{\mathrm{Fe}} \gtrsim 0.1\ M_\odot$

Approach 2: Spectral constraints.

Result:
$M_{\mathrm{Fe}} \gtrsim 0.3\ M_\odot$

Approach 3: Luminosity constraints, assume the iron comes from ^{56}Ni and this powers the 394d emission.

Result:
$0.2 < M_{\mathrm{Fe}} < 2.1\ M_\odot$

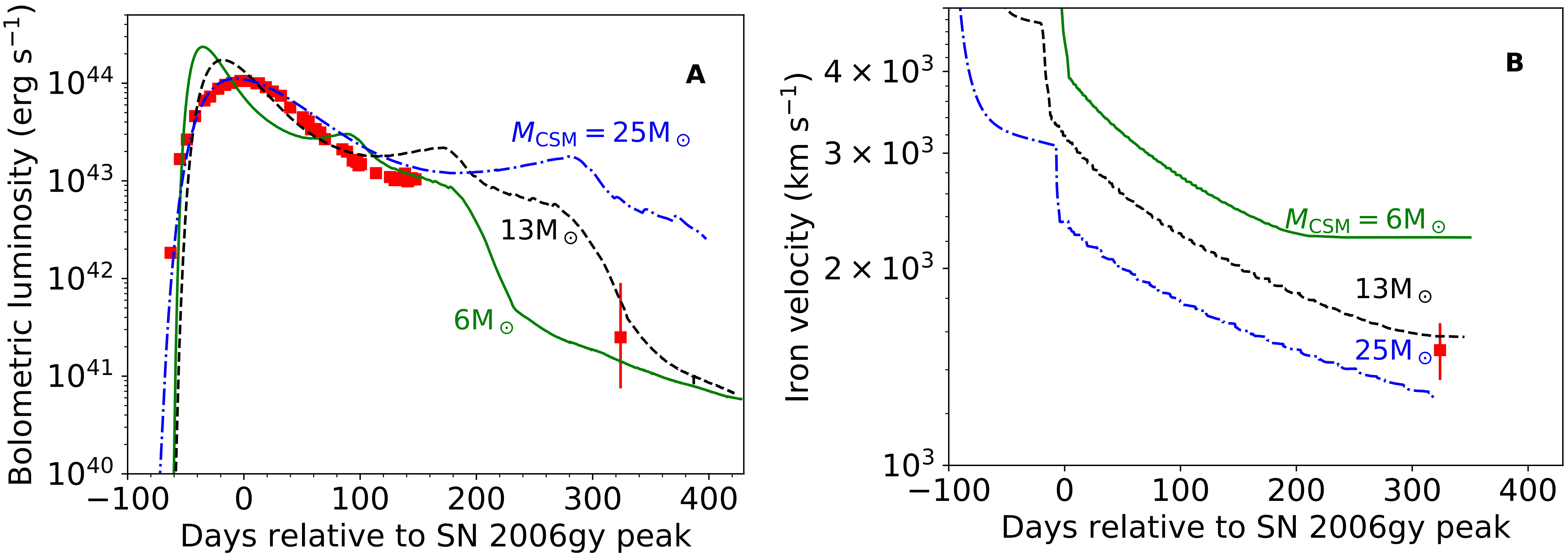


All constraints together:

$0.3 < M_{\mathrm{Fe}} < 2.1\ M_\odot$

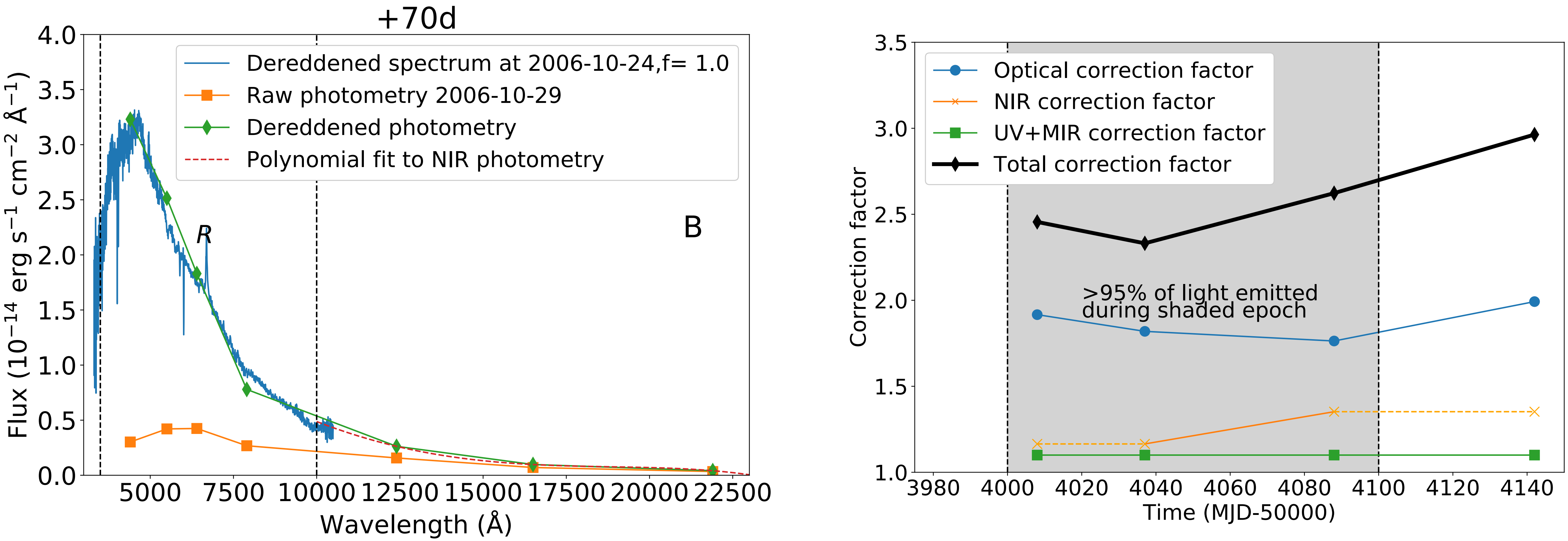
Light curve and final iron velocities for Ia-CSM model also consistent

Code : SNEC (Morozova+2015)



- Too small CSM masses: too narrow light curve and insufficient iron deceleration.
- Too large CSM masses: too long lasting interaction and too strong deceleration.
- At $M_{\mathrm{CSM}} \sim 13\ M_\odot$ all properties roughly correct.

Energy budget



Best estimate : $E_{\rm radiated} = 9 \times 10^{50}$ erg
—> Normal Ia SNe ($E^0_{\rm kin} \sim 1.3 \times 10^{51}$ erg) are within budget

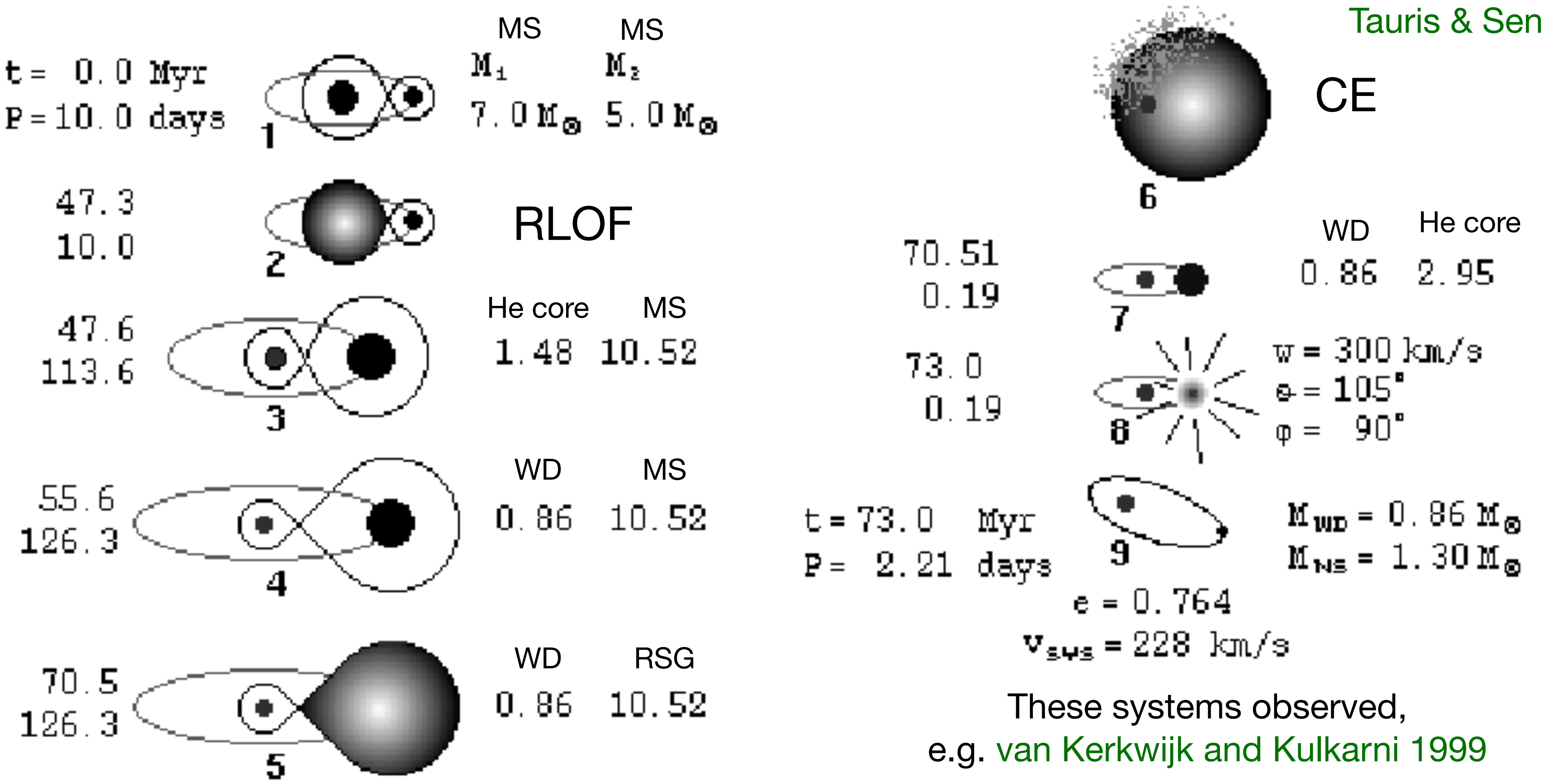
Note: $E_{\rm kin} \sim 10\ M_\odot \times \left(1500\ \text{km s}^{-1}\right)^2 \sim 2 \times 10^{50}$ erg left in kinetic energy at 394d

Can a WD form before a massive (NS-forming) companion ends its evolution?

1

- Binary stellar evolution simulations allow for mass reversals and WD - massive star systems.

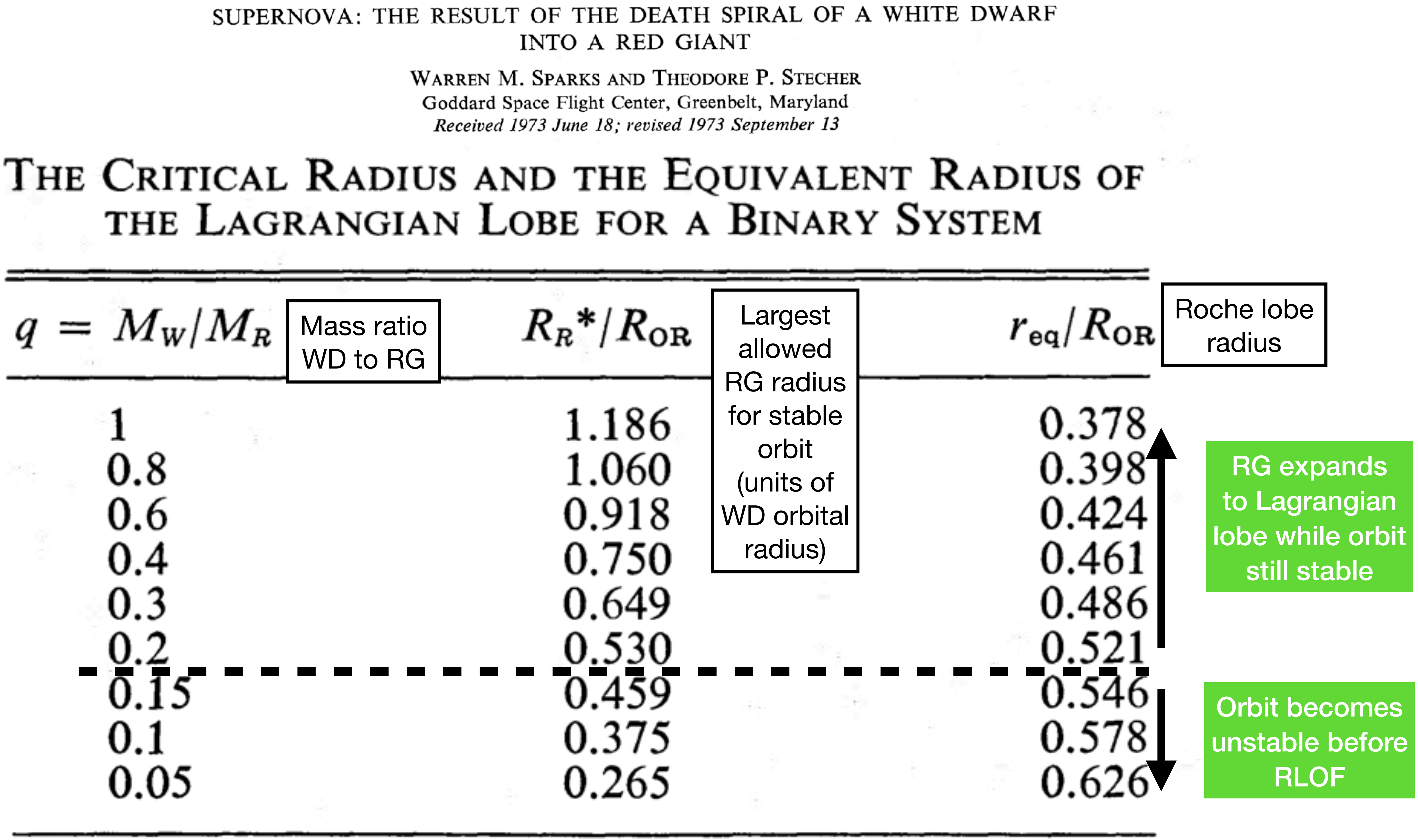
Tauris & Sennels 2000



These systems observed,
e.g. van Kerkwijk and Kulkarni 1999

Population studies: $M^{max,final}_{companion} \sim 20\ M_\odot$ e.g. Willems & Kolb 2004

2



SUPERNOVA: THE RESULT OF THE DEATH SPIRAL OF A WHITE DWARF INTO A RED GIANT

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Received 1973 June 18; revised 1973 September 13

THE CRITICAL RADIUS AND THE EQUIVALENT RADIUS OF THE LAGRANGIAN LOBE FOR A BINARY SYSTEM

$q = M_W/M_R$	R_R^*/R_{OR}	r_{eq}/R_{OR}
1	1.186	0.378
0.8	1.060	0.398
0.6	0.918	0.424
0.4	0.750	0.461
0.3	0.649	0.486
0.2	0.530	0.521
0.15	0.459	0.546
0.1	0.375	0.578
0.05	0.265	0.626

Mass ratio WD to RG

Largest allowed RG radius for stable orbit (units of WD orbital radius)

Roche lobe radius

RG expands to Lagrangian lobe while orbit still stable

Orbit becomes unstable before RLOF

- If the companion is massive enough (>5 times the WD mass), the system will never settle into RLOF accretion but the WD will plunge into the companion.

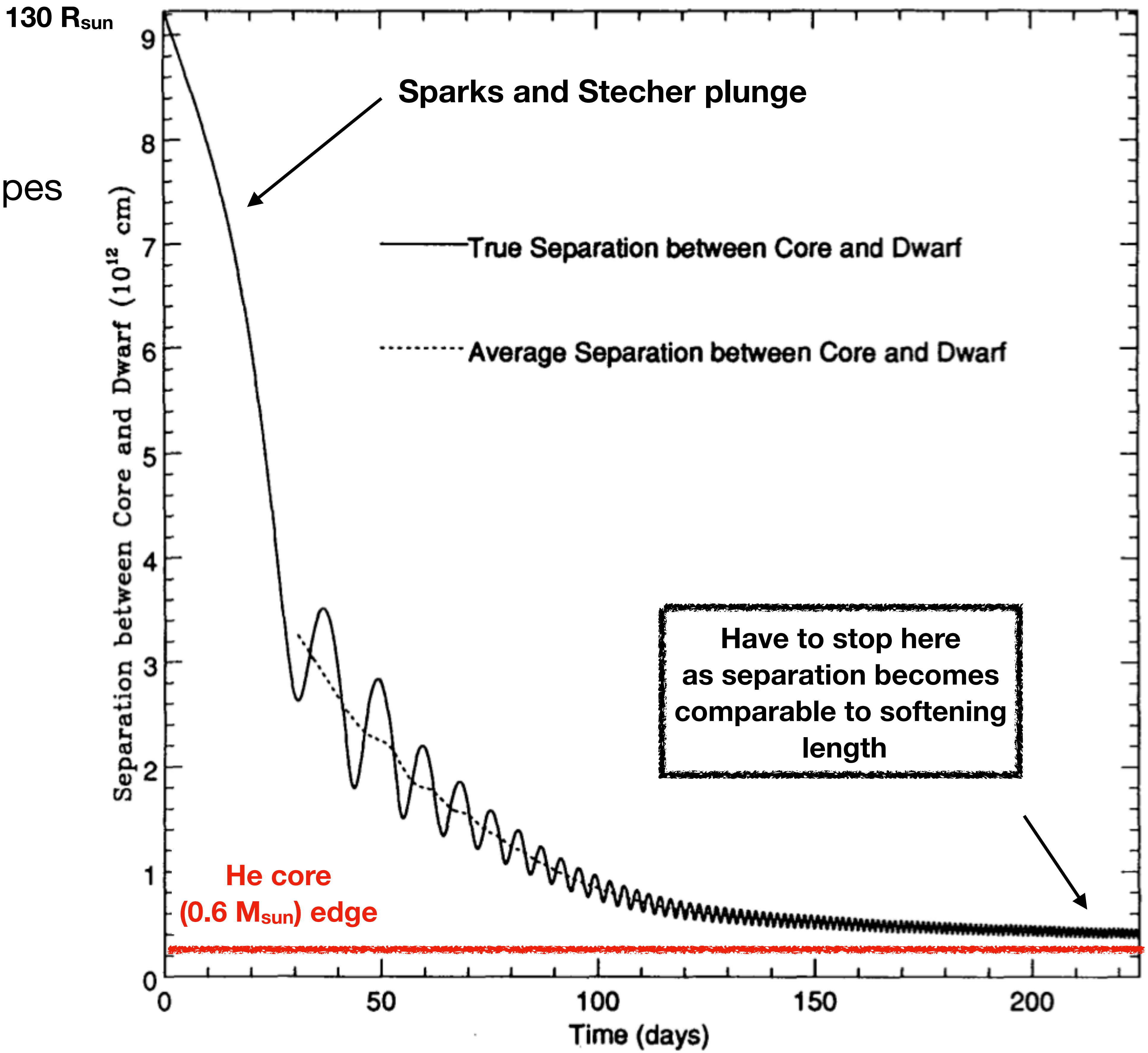
Simulating the in-spiral and common envelope phase with SPH

2

Simulations predict ejection of whole envelopes on time-scales 1-10y.

e.g. Terman+1995, Yorke+1995, Sandquist 1998, Taam and Sandquist 2000

Terman+1994 : 1 M_{sun} WD into a 5 M_{sun} RG



130 R_{sun}

Sparks and Stecher plunge

Have to stop here as separation becomes comparable to softening length

He core (0.6 M_{sun}) edge

3

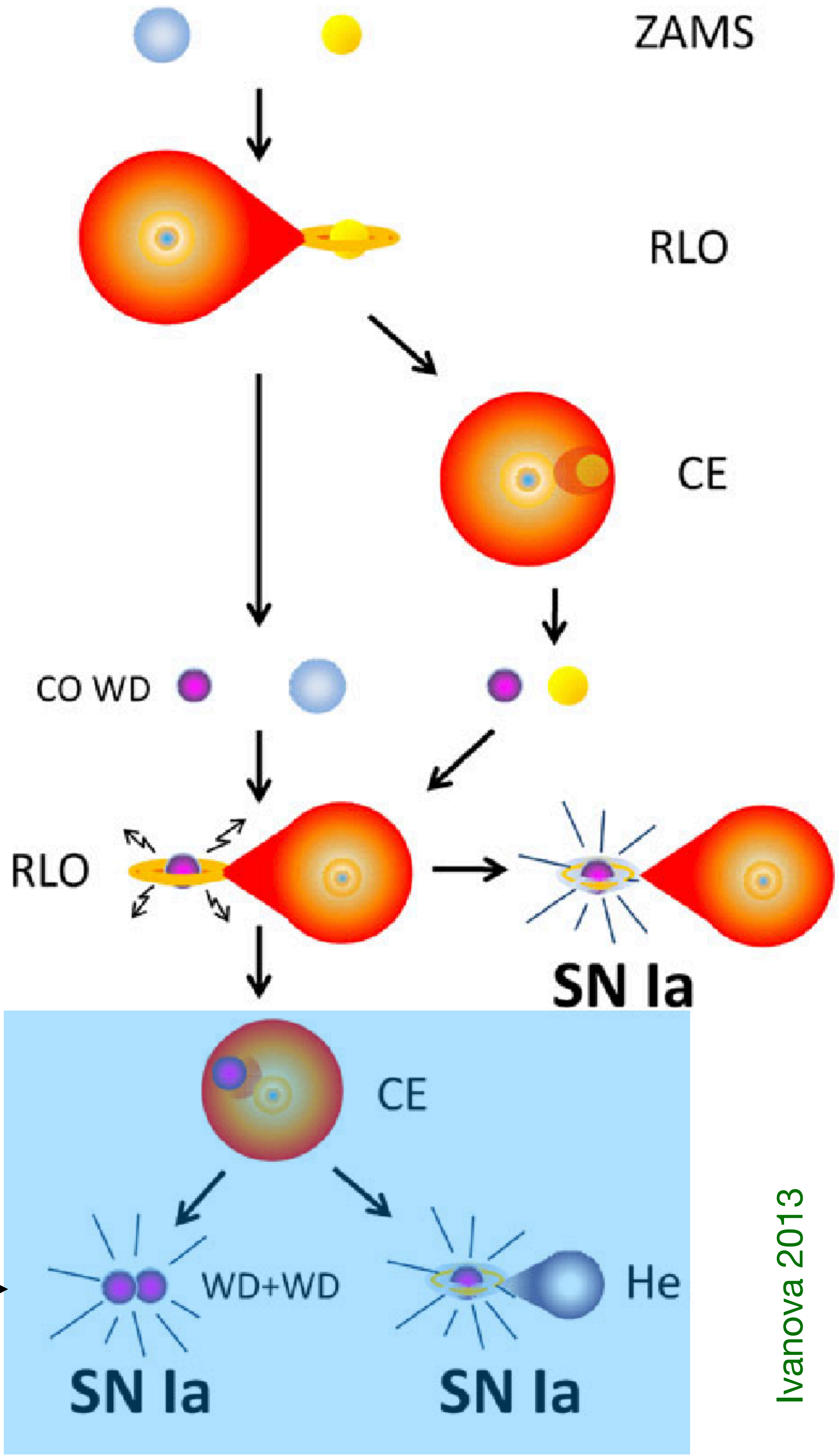
Explosion

1. Merger with a RG (AGB) star.
WD-RG CE merger likely channel to produce WD-WD close binaries (normal Ia progenitors).

With an AGB star companion another WD ready (—>Super-Chandra merger explosion). Some tension with estimated CSM mass in SN 2006gy.

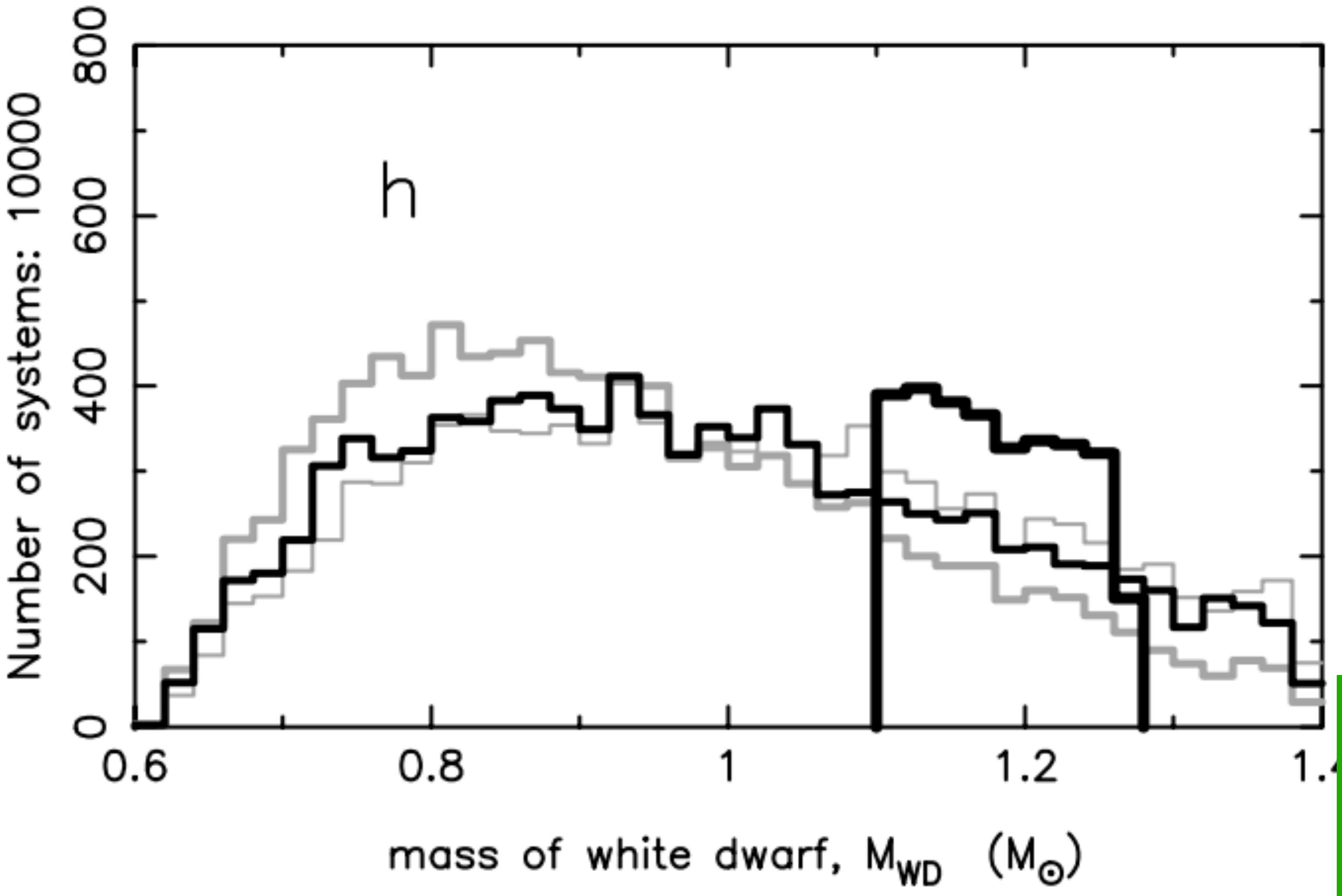
2. Merger with a RSG.
Sub-Chandra double detonation explosion as WD merges with He core. No tension with estimated CSM mass.

Need one of these explosion channels to happen within 100y of the CE ejection.

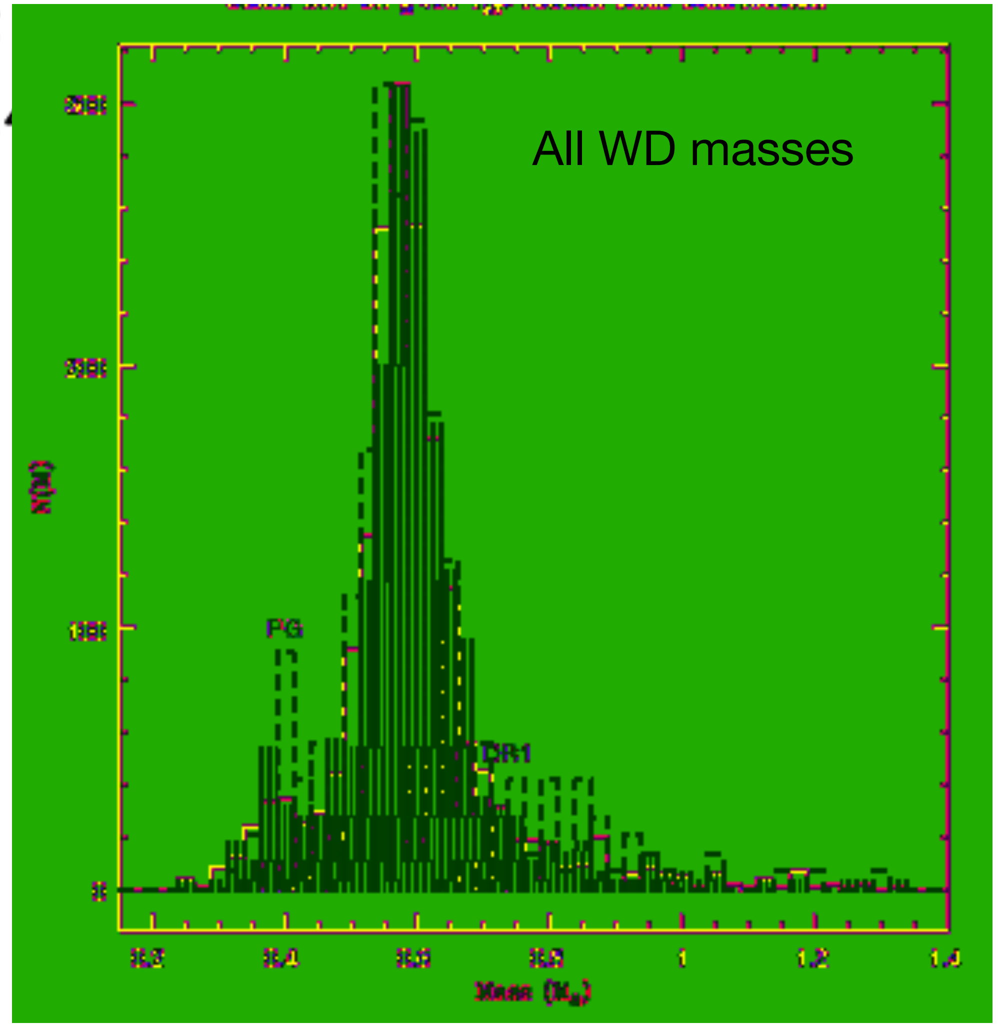


Ivanova 2013

Predicted WD masses



Thin black: standard grid
Thin gray: Enhanced CE efficiency
Thick gray: No ns kicks



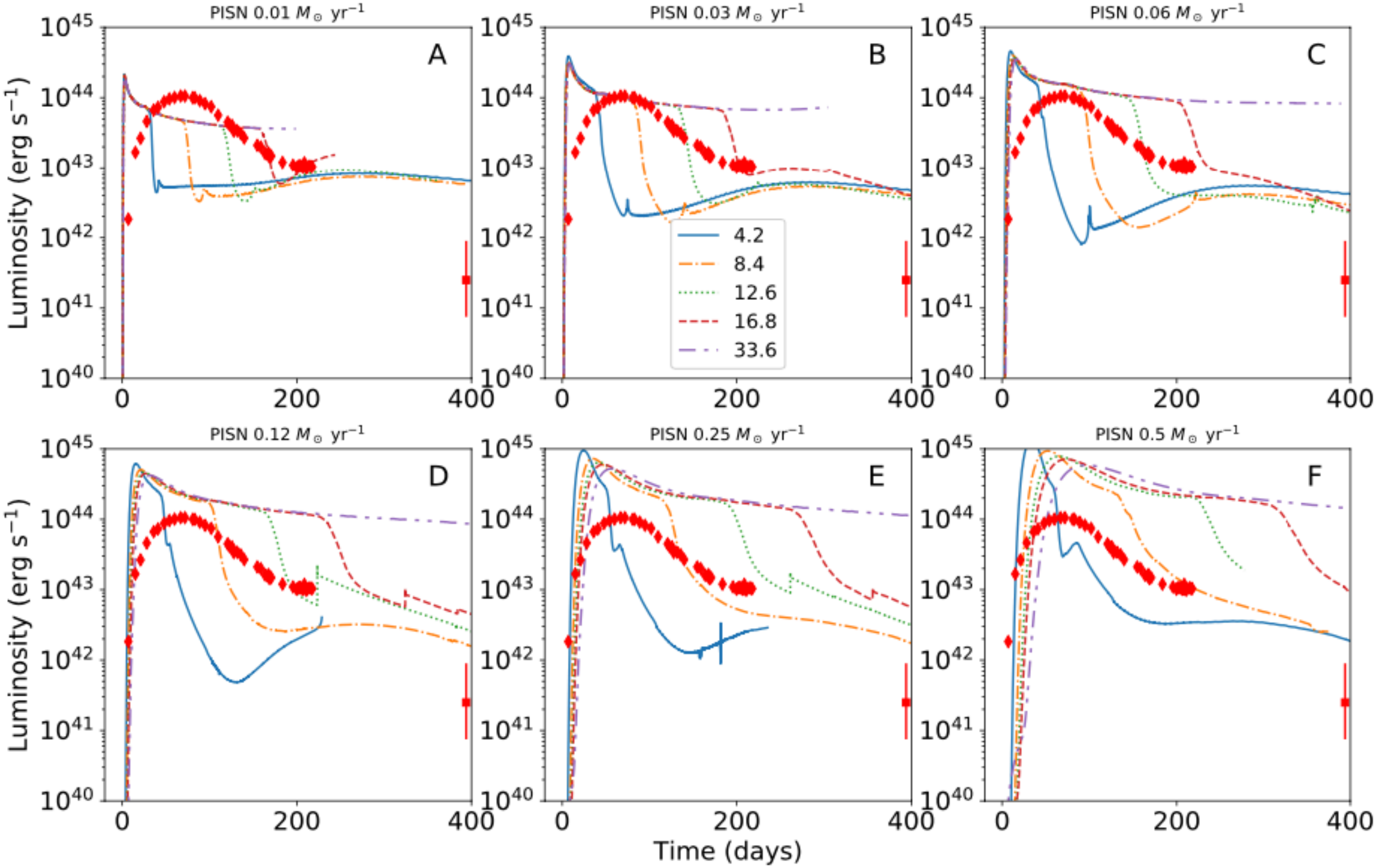
WDs merging with RSGs are unusually massive.

To simulate the formation of WDNS binaries, we assume that the initial system consists of two ZAMS stars in a circular orbit. In our code we used a flat logarithmic initial separation distribution ($\Gamma(a) \propto a^{-1}$) and assumed a Salpeter initial mass function for the ZAMS primary stellar masses of $N(m) \propto m^{-2.35}$ combined with a mass-ratio function: $f(q) = 2/(1+q)^2$ (Kuiper 1935). We adopt the term "primary" to refer to the *initially* more massive star, regardless of the effects of mass transfer or loss as the system evolves.

PISN light curves

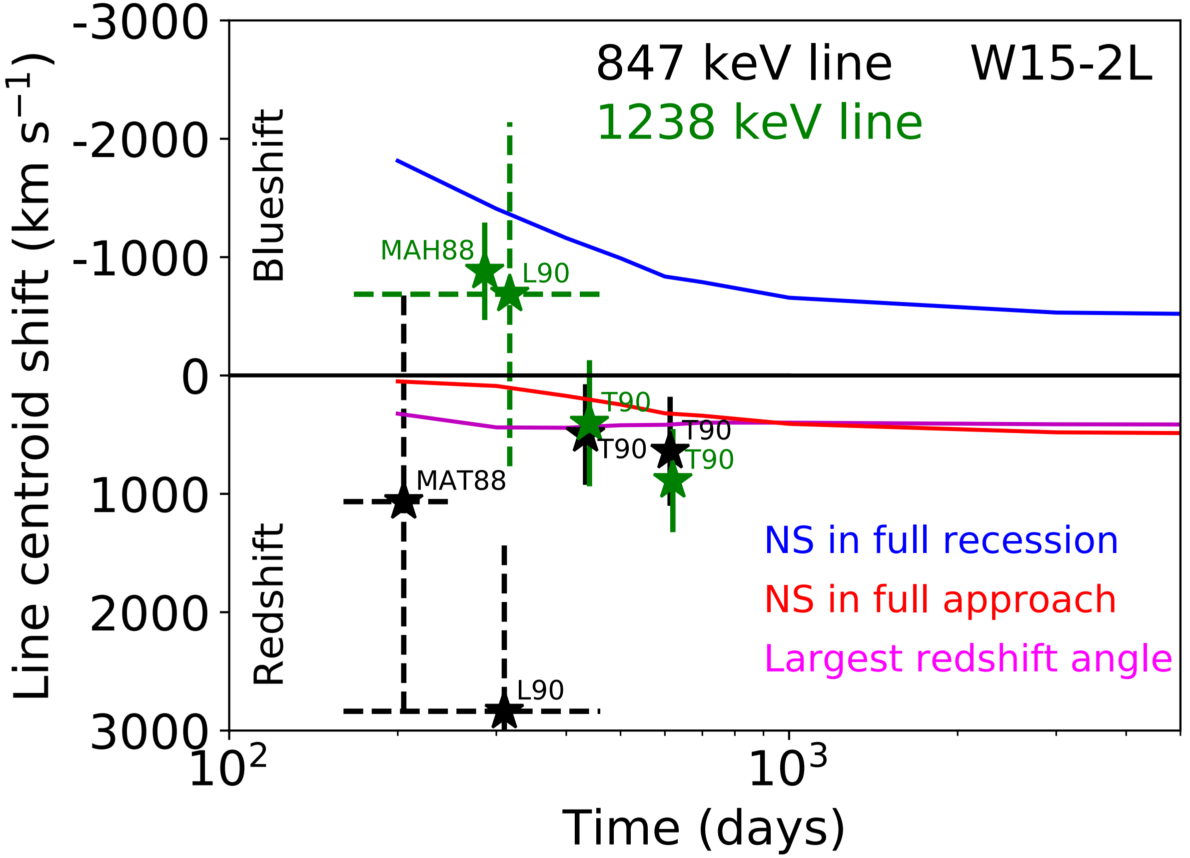
Only a 90 $M_\odot$ He core makes ~0.5 $M_\odot$ of ^{56}Ni. But peak would require 5-10 $M_\odot$ —> must be CSI that powers main light curve.

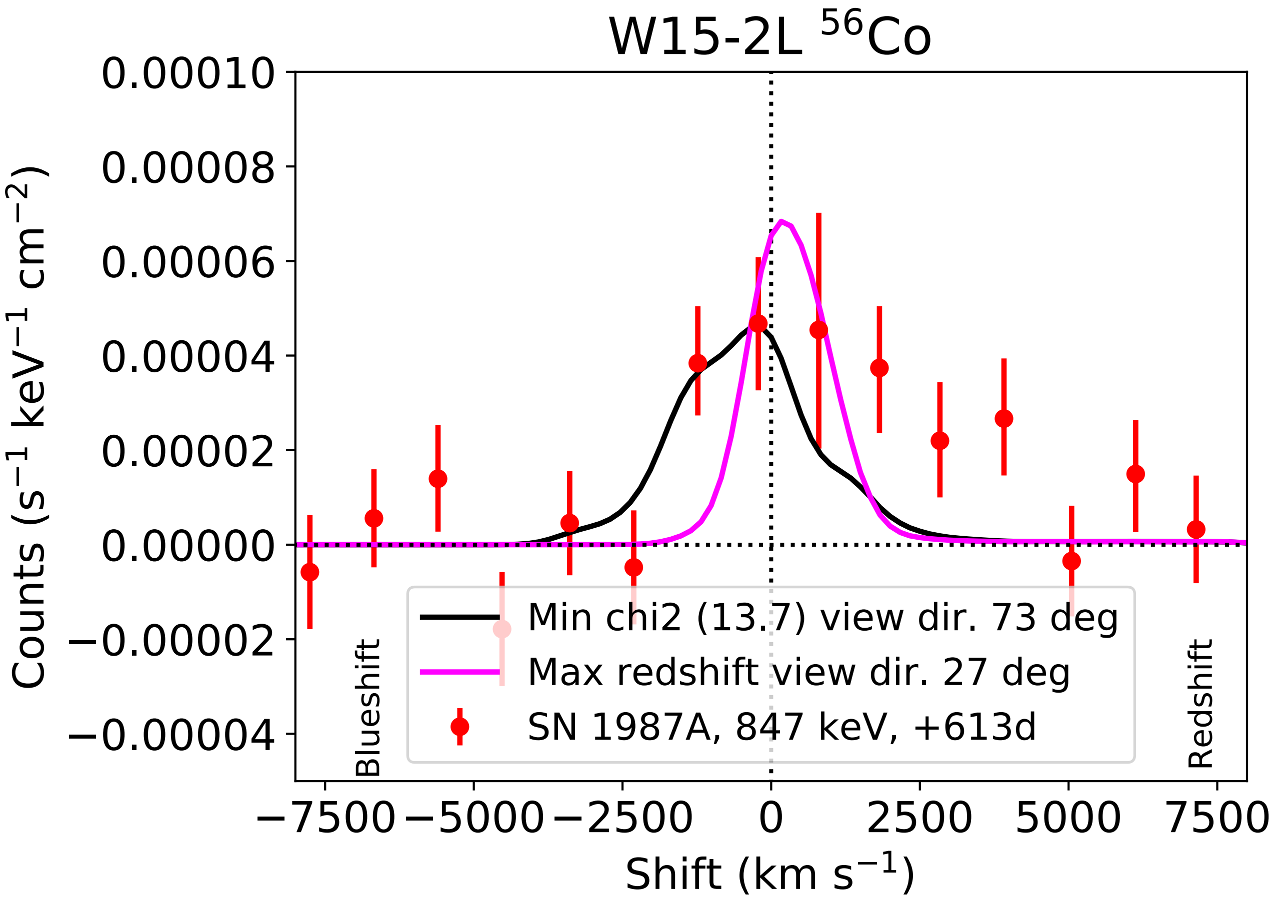
Light curve simulations find no agreement.



Comparison to SN 1987A

W15: Reasonable. Quite large ^{56}Ni asymmetry (550 km/s) and moderate ejecta mass (14 M_{sun})





Data: Matz+1988 (M88), Mahoney+1988 (MAH88), Leising&Share 1990 (L90), Tueller+1990 (T90)