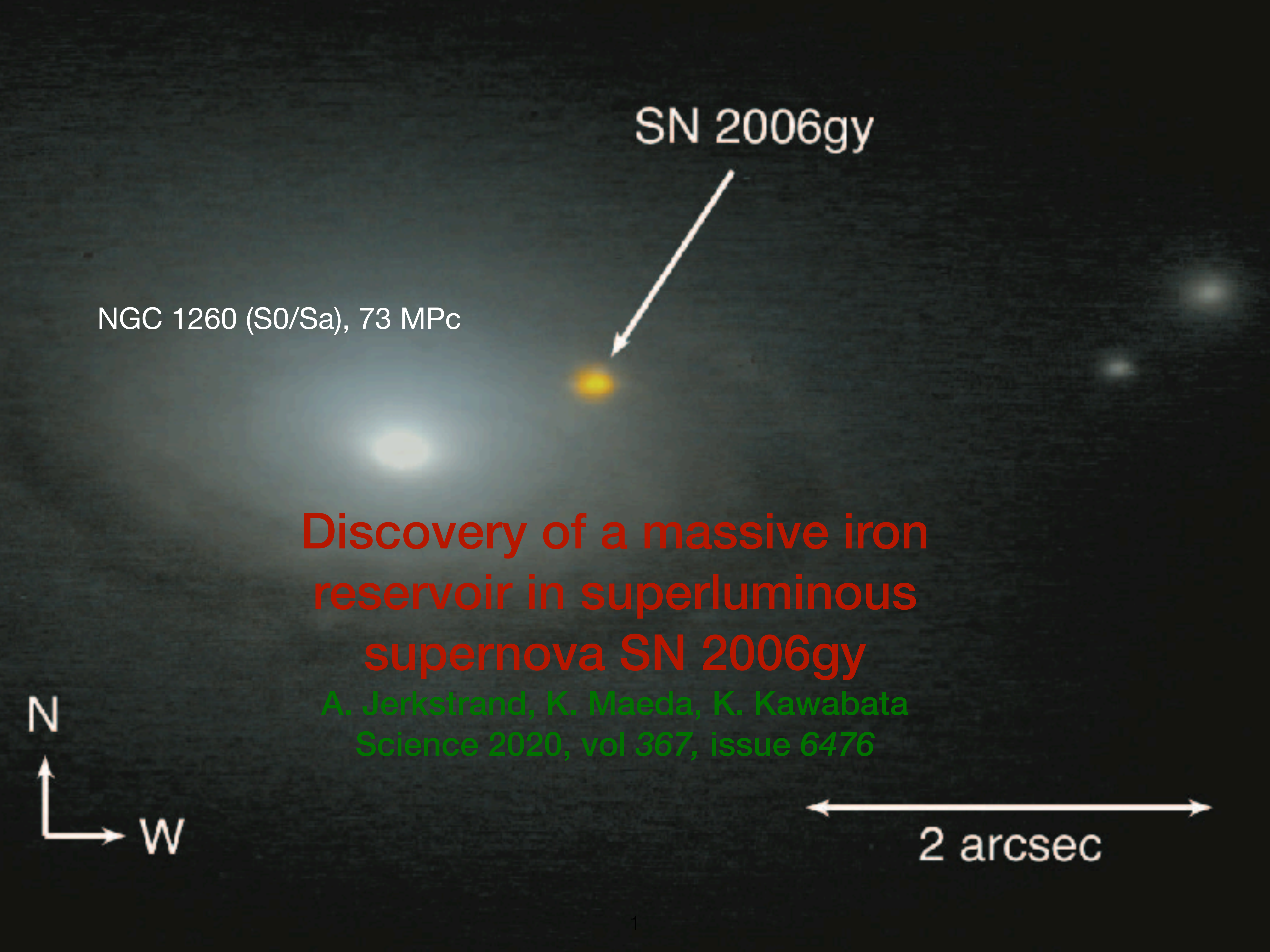
Discovery of a massive iron reservoir in superluminous supernova SN 2006gy

A. Jerkstrand, K. Maeda, K. Kawabata

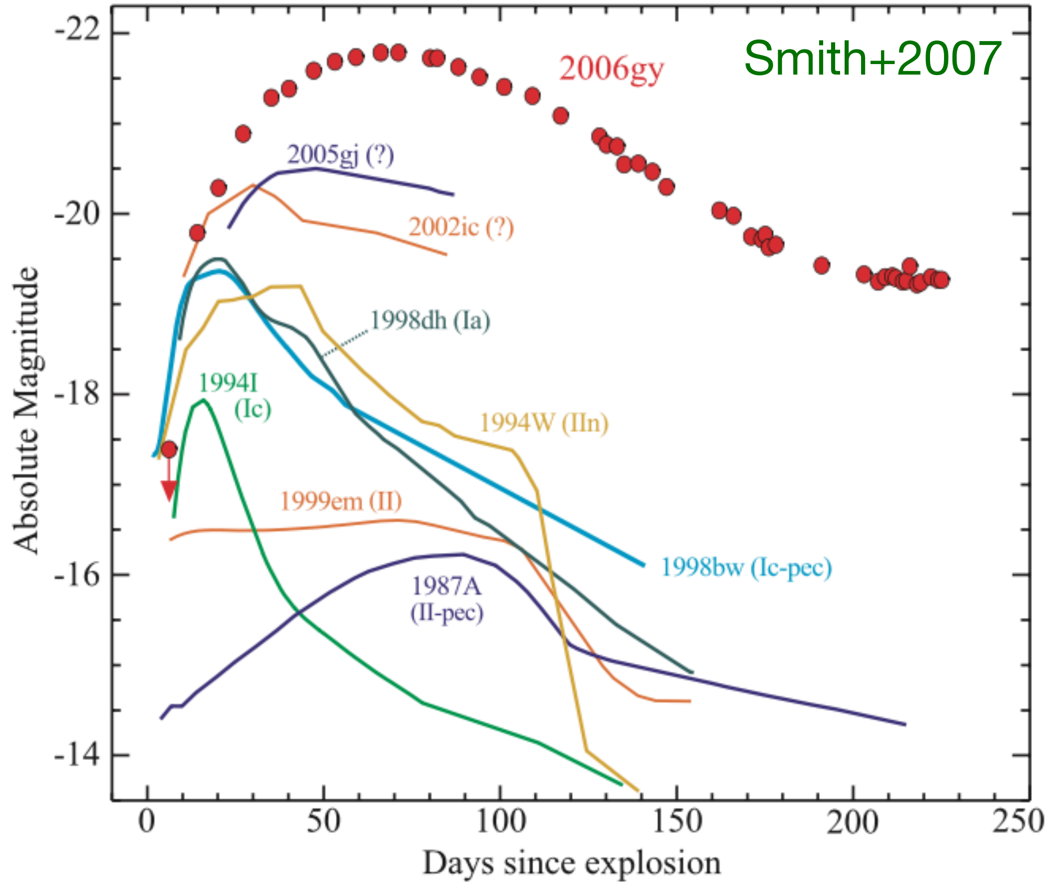
Science 2020, vol *367,* issue *6476*

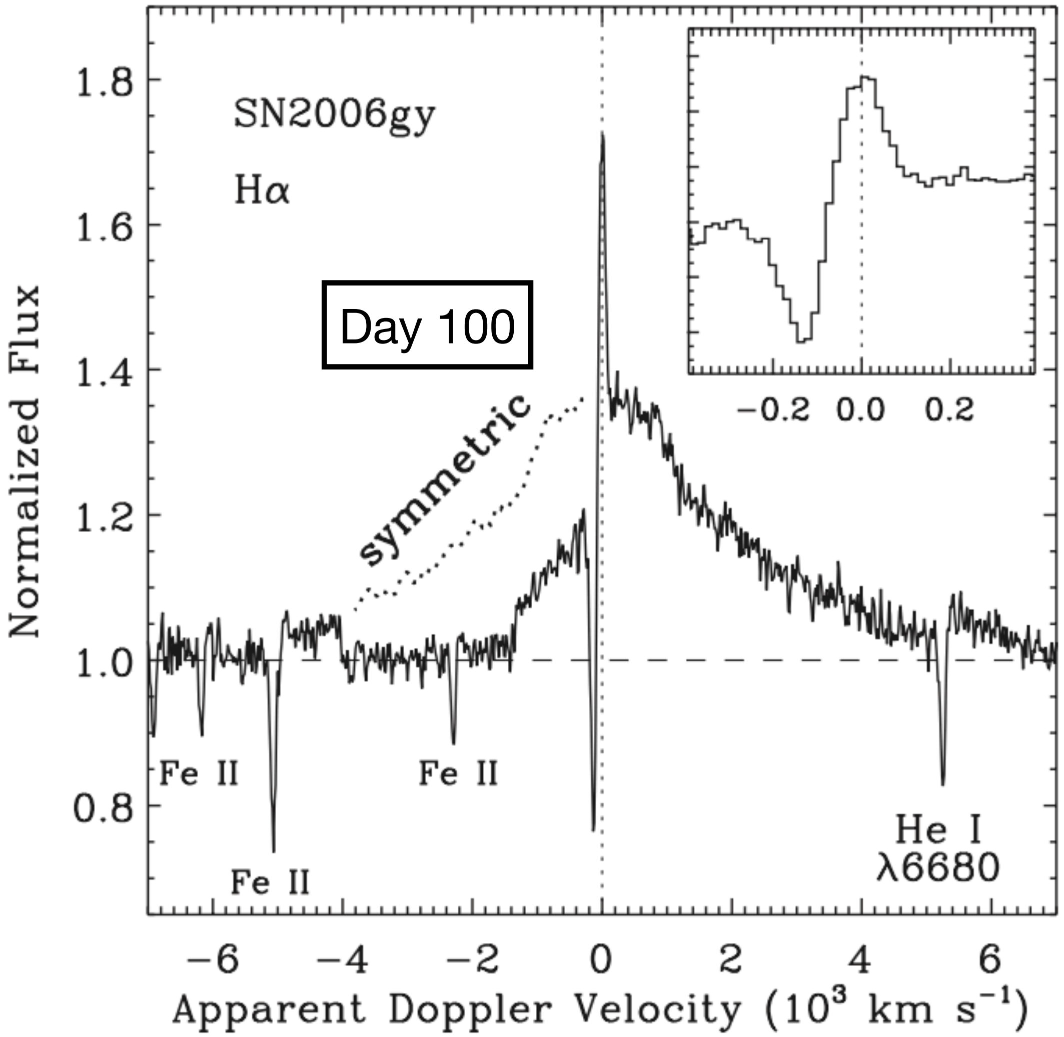


NGC 1260 (S0/Sa), 73 MPc

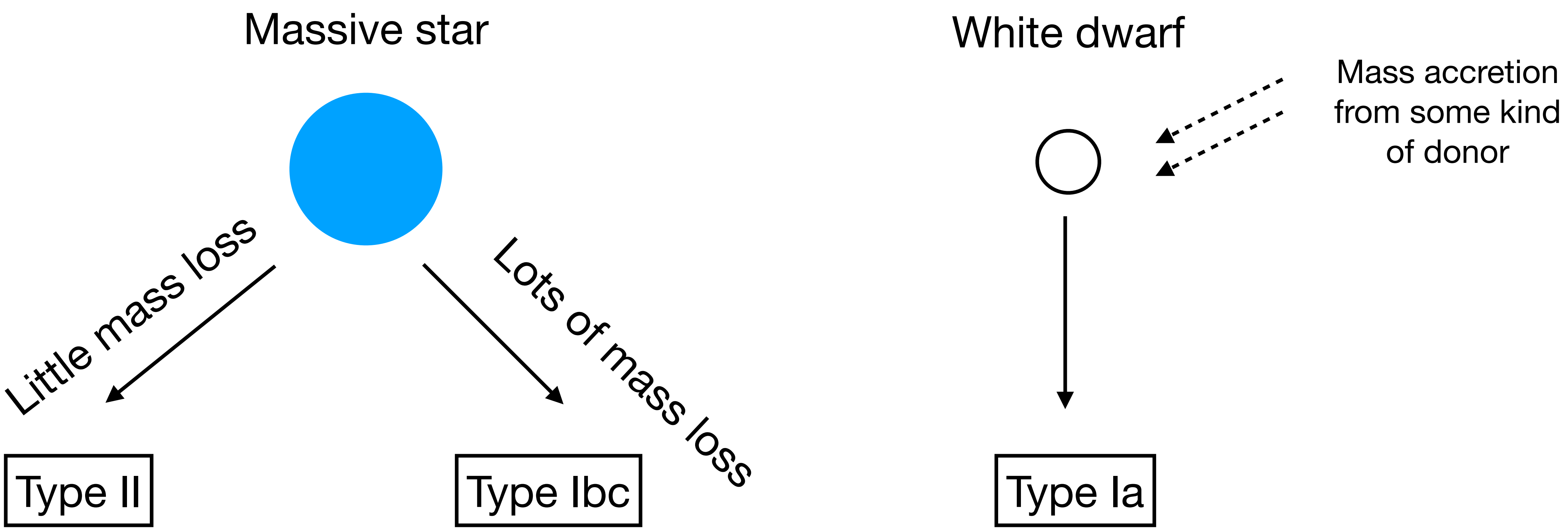
SN 2006gy : one of the brightest SNe ever seen

- Rise time 70d, peak magnitude -22.
- Radiated energy ~10^{51} erg (factor 2 uncertain due to extinction uncertainties).
- Type IIn, narrow (100 km/s) P-Cygni Balmer lines.
- Broad asymmetric Balmer lines. Hα red wing to ~4000 km/s, unusual damped blue side.
- No significant radio or X-ray emission.
- General consensus: a large CSM shell ($\gtrsim$10 $M_\odot$) was ejected $\lesssim$100y before the supernova.





The supernova landscape



Massive star

Little mass loss

Lots of mass loss

Type II

Type Ibc

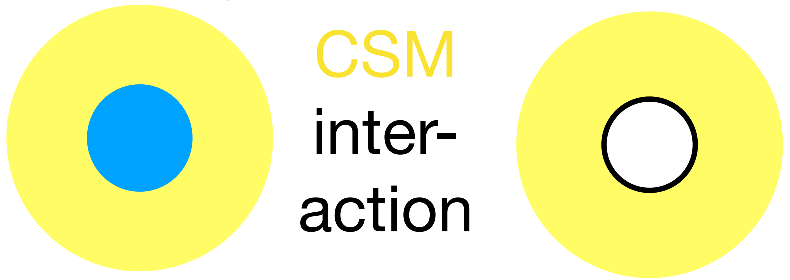
White dwarf

Mass accretion
from some kind
of donor

Type Ia

E ~10^{51} erg = 1 B
$M_{ej} = 2\text{-}20\ M_\odot$
M(^{56}Ni) = 0.01-0.3 $M_\odot$

E ~10^{51} erg = 1 B
$M_{ej} \sim 1\ M_\odot$
M(^{56}Ni) ~ 0.5 $M_\odot$



Sometimes..
CSM
inter-
action

Type IIn
or Ibn

Type IIa

Interaction often masks
the central supernova

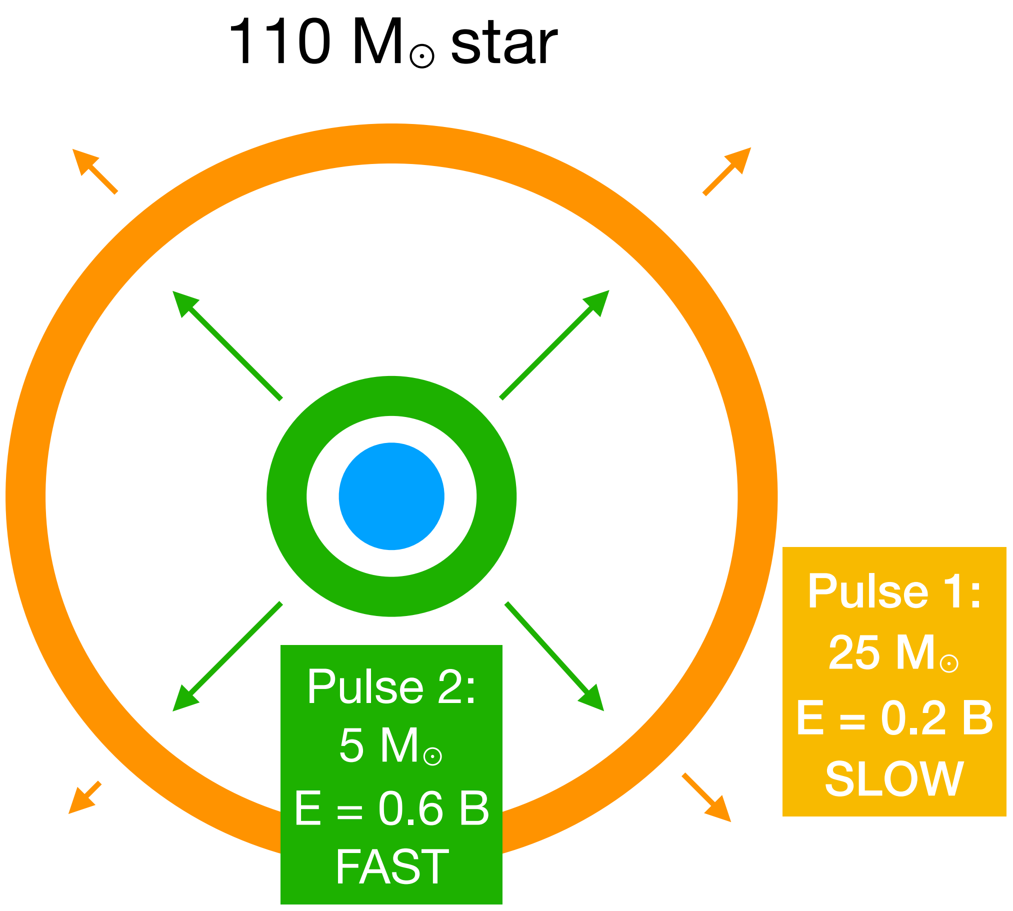
Discovered 2003
(Hamuy et al.)

nature Vol 450|15 November 2007|doi:10.1038/nature06333

LETTERS

Pulsational pair instability as an explanation for the most luminous supernovae

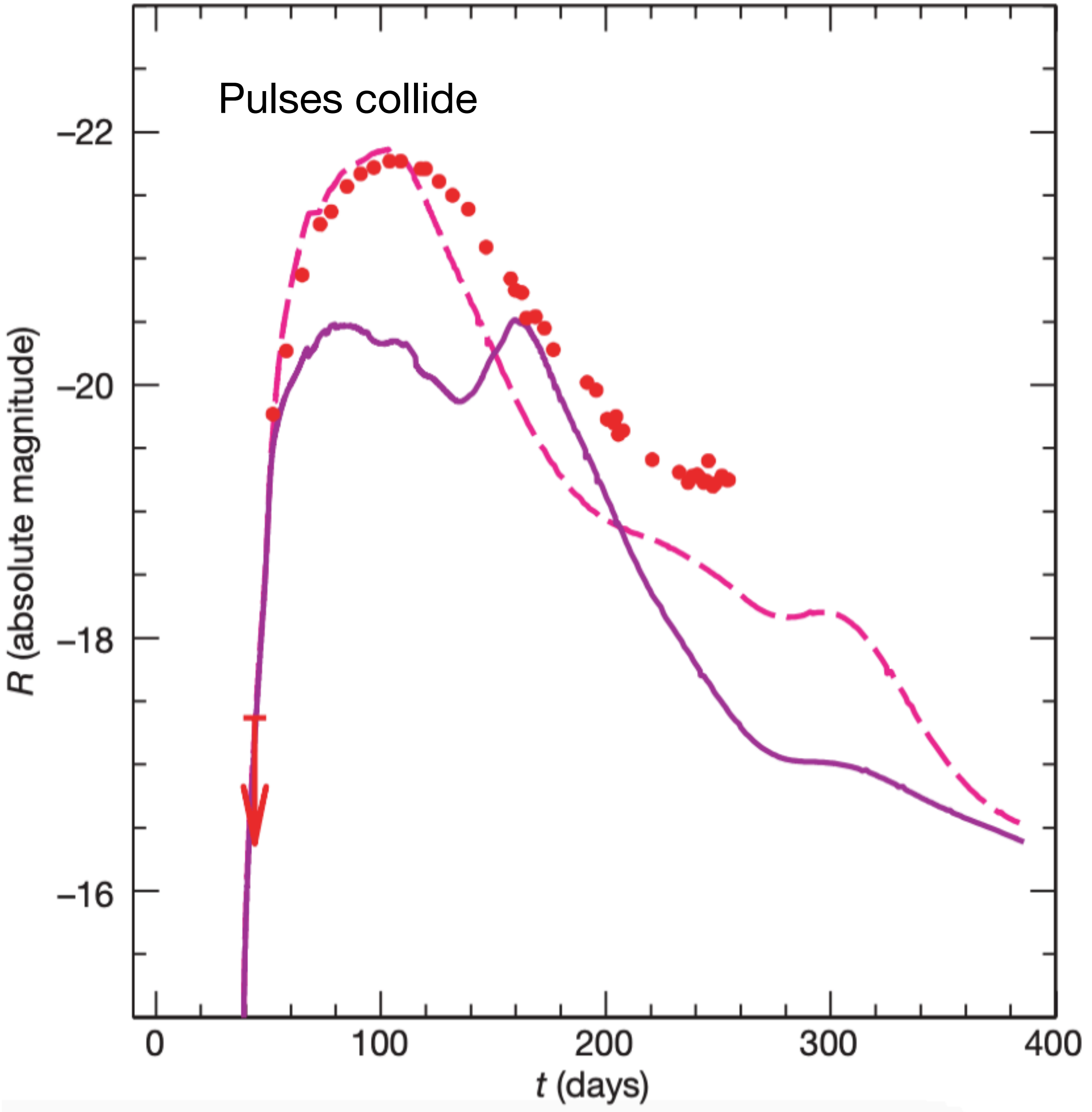
S. E. Woosley[1], S. Blinnikov[1,2,3] & Alexander Heger[1,4]



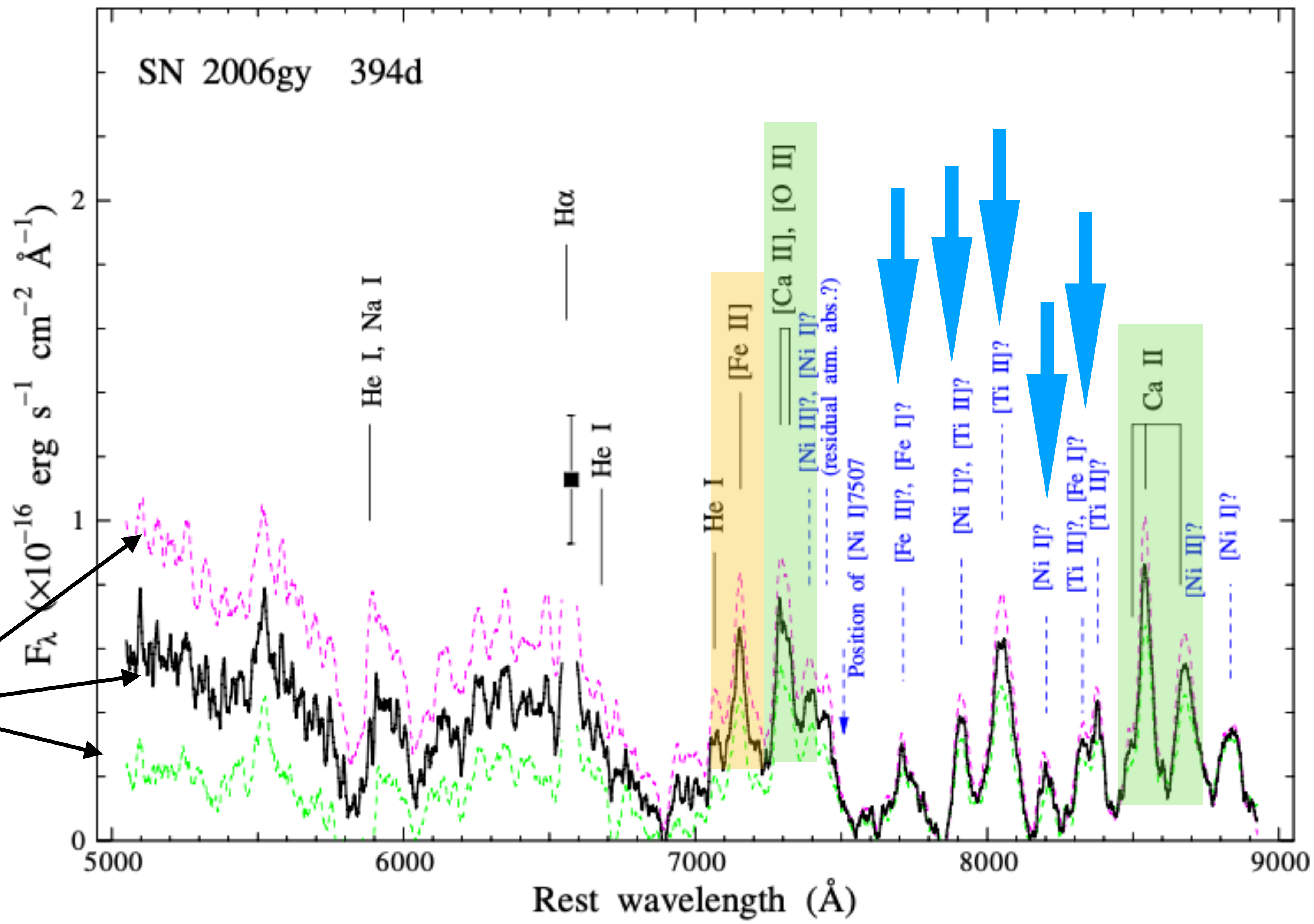
110 $M_\odot$ star

Pulse 1:
25 $M_\odot$
E = 0.2 B
SLOW

Pulse 2:
5 $M_\odot$
E = 0.6 B
FAST



Kawabata+2009: Strange, unknown lines seen in the last obtained spectrum at 394 days

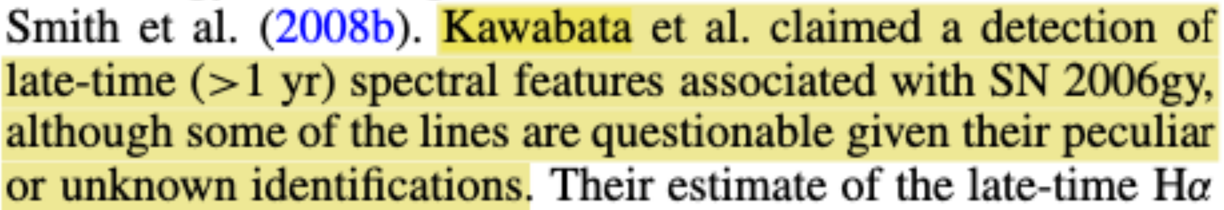


Different host subtraction methods

Only other secure identifications: Fe II and Ca II

Line widths: ~1500 km/s

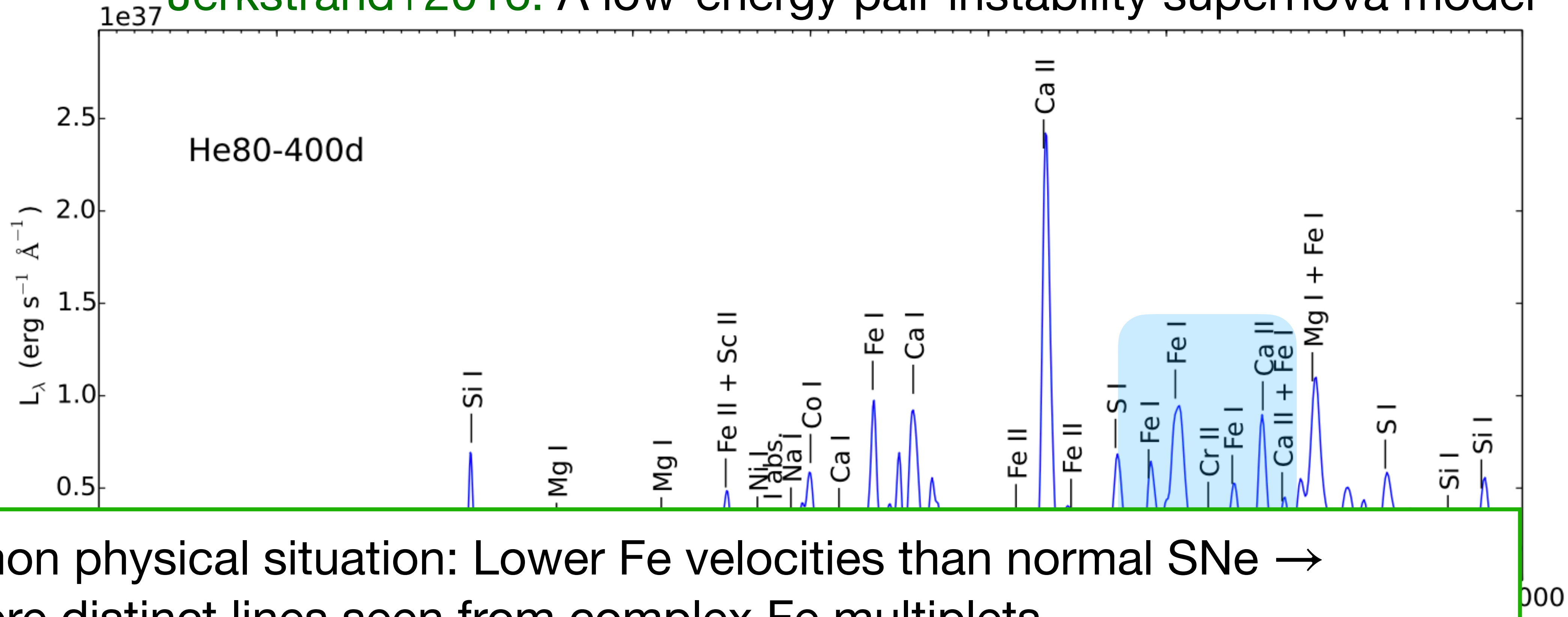
Community not initially convinced:



Smith et al. (2008b). Kawabata et al. claimed a detection of late-time (>1 yr) spectral features associated with SN 2006gy, although some of the lines are questionable given their peculiar or unknown identifications. Their estimate of the late-time Hα

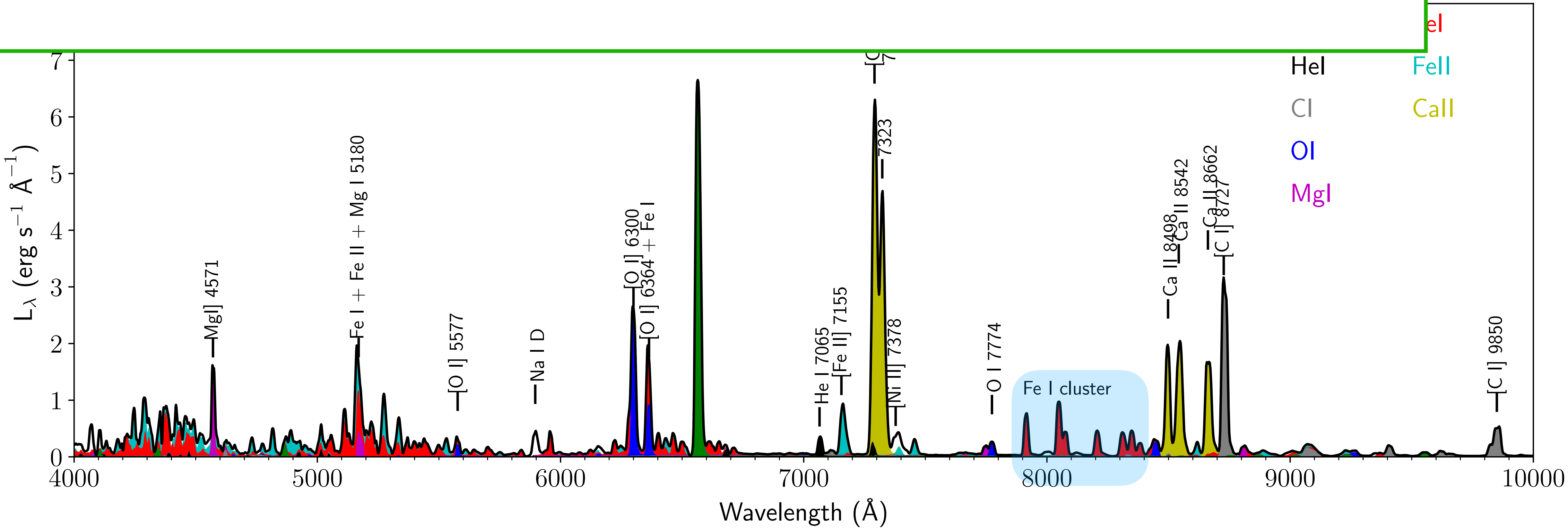
Identification of the lines : Fe I

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

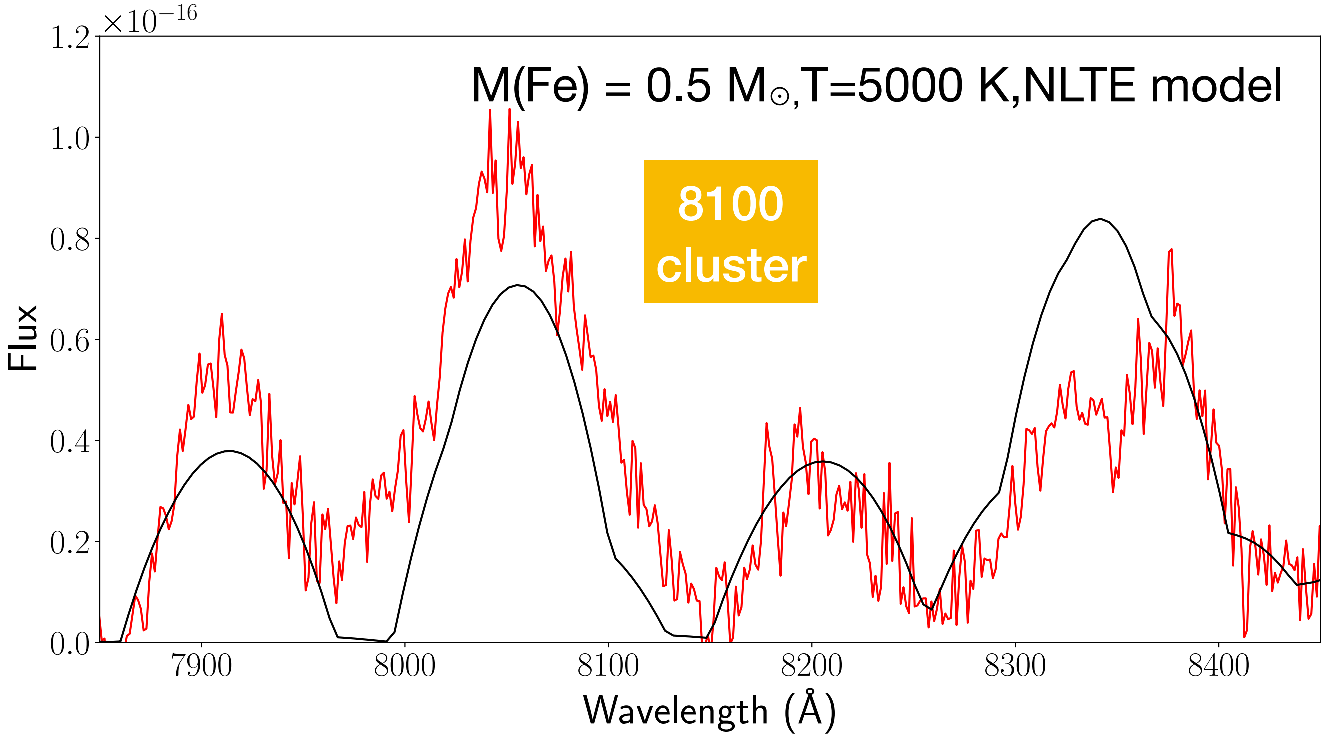


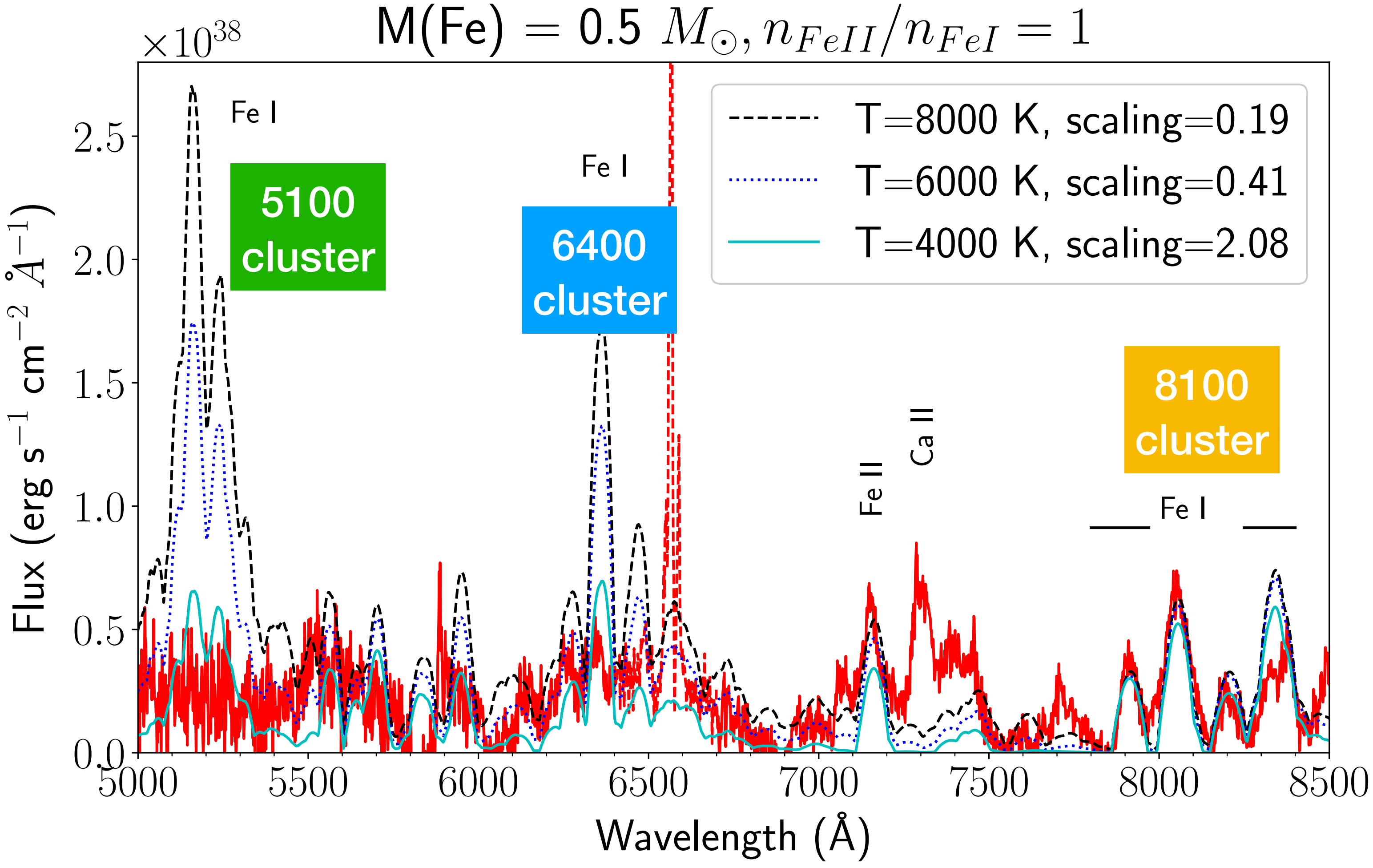
Common physical situation: Lower Fe velocities than normal SNe →

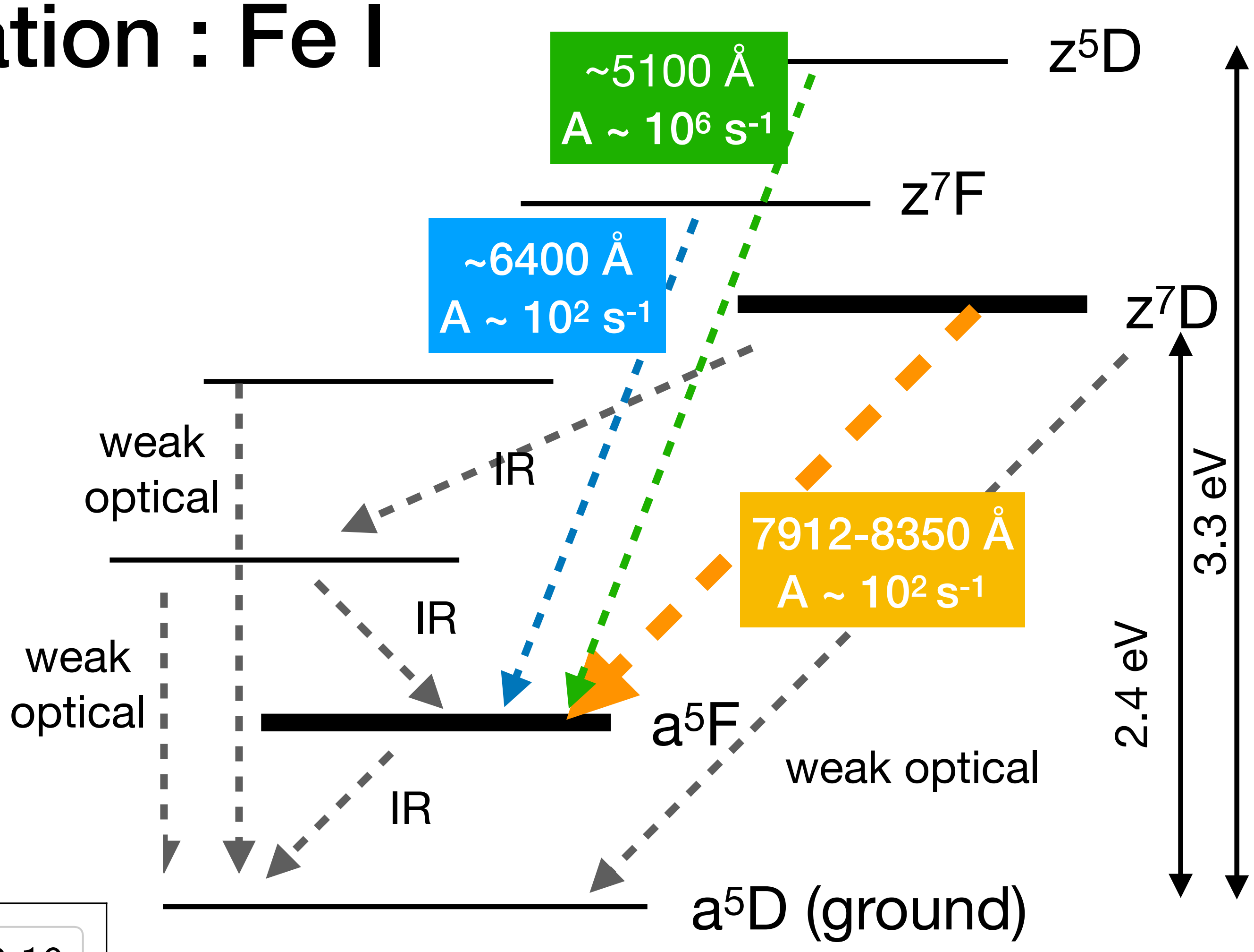
1. More distinct lines seen from complex Fe multiplets
2. Higher density → more neutral gas state → Fe I instead of Fe II and Fe III



Identification : Fe I







- At a few thousand degrees, optical Fe I emission is dominated by three clusters around 8100 Å , 5100 Å, and 6400 Å.
- Since each parent multiplet has different excitation energies, one can put limits to T to get right ratios : **3000 - 7000 K.**

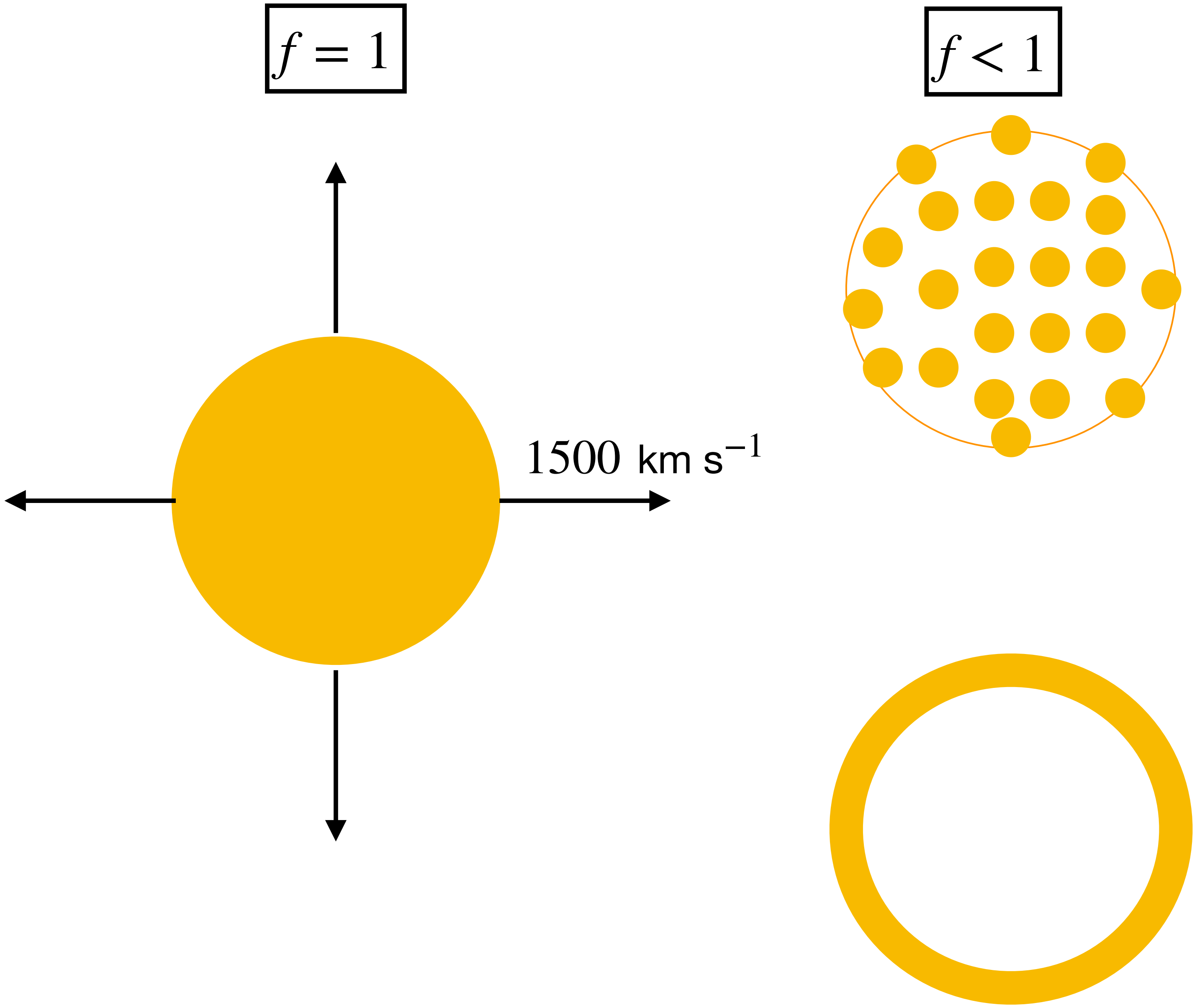
How much iron is there?

Approach 1: Search constraints for any temperature and density.

Parameters:

- M_{Fe}
- T
- $x = n_e / n_{FeI}$
- Density, as expressed by a filling factor f

Solve NLTE emissivities including optical depth with Sobolev self-absorption (SUMO code, Jerkstrand, Fransson & Kozma 2011).



How much iron is there?

Result:

$f = 1 : M_{\rm Fe} \gtrsim 0.25\ M_\odot$

$f = 0.1 : M_{\rm Fe} \gtrsim 0.08\ M_\odot$

$f = 0.01 : M_{\rm Fe} \gtrsim 0.03\ M_\odot$

$f < 0.01$: **No solutions!**

Optically thin, NLTE:

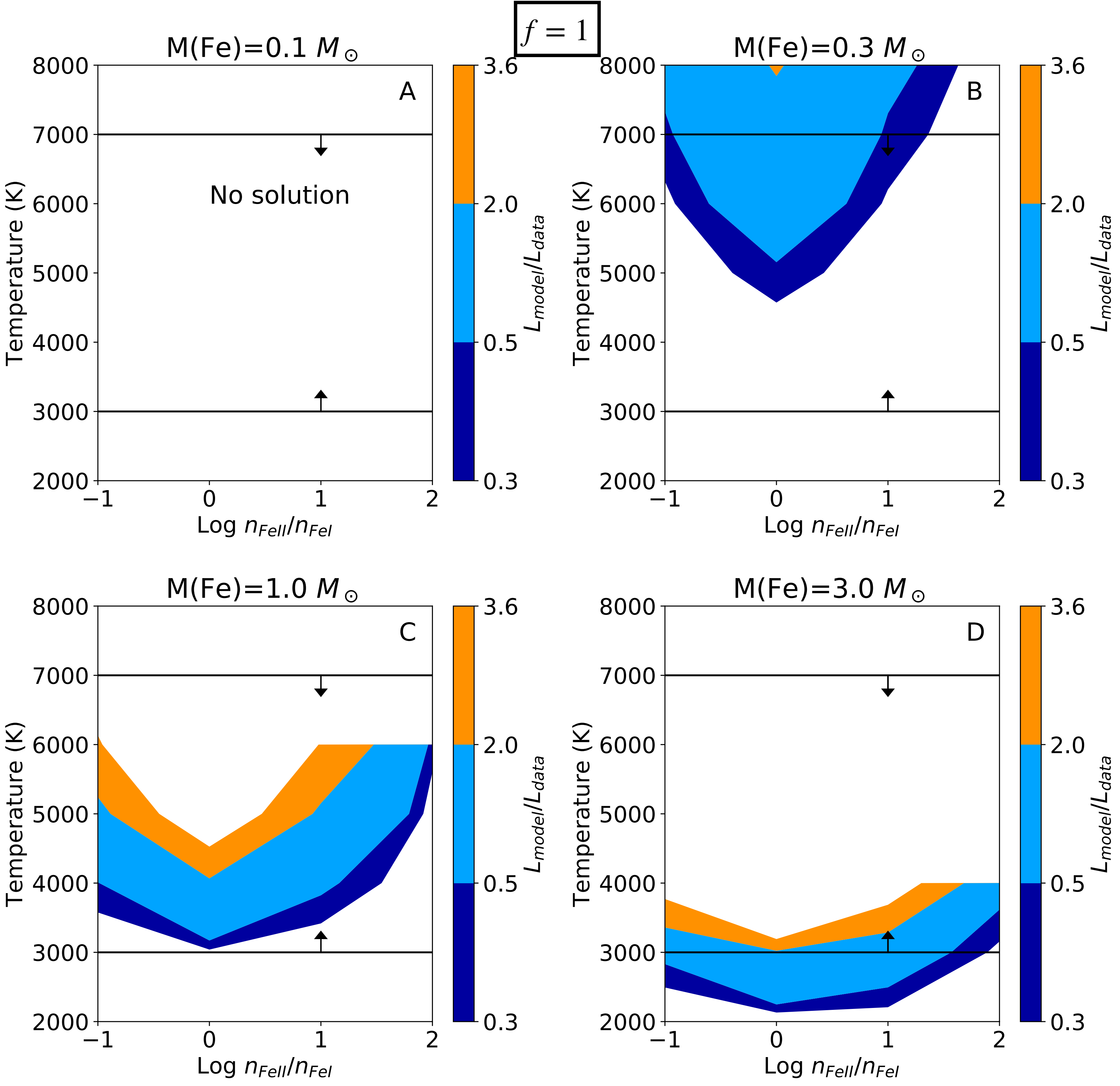
$$L = V \times n_{FeI} n_e f(T)$$

Optically thick, LTE:

$$L = V \times n_{Fe} \beta_S g(T) = const \times V g(T)$$

independent on M_{Fe}

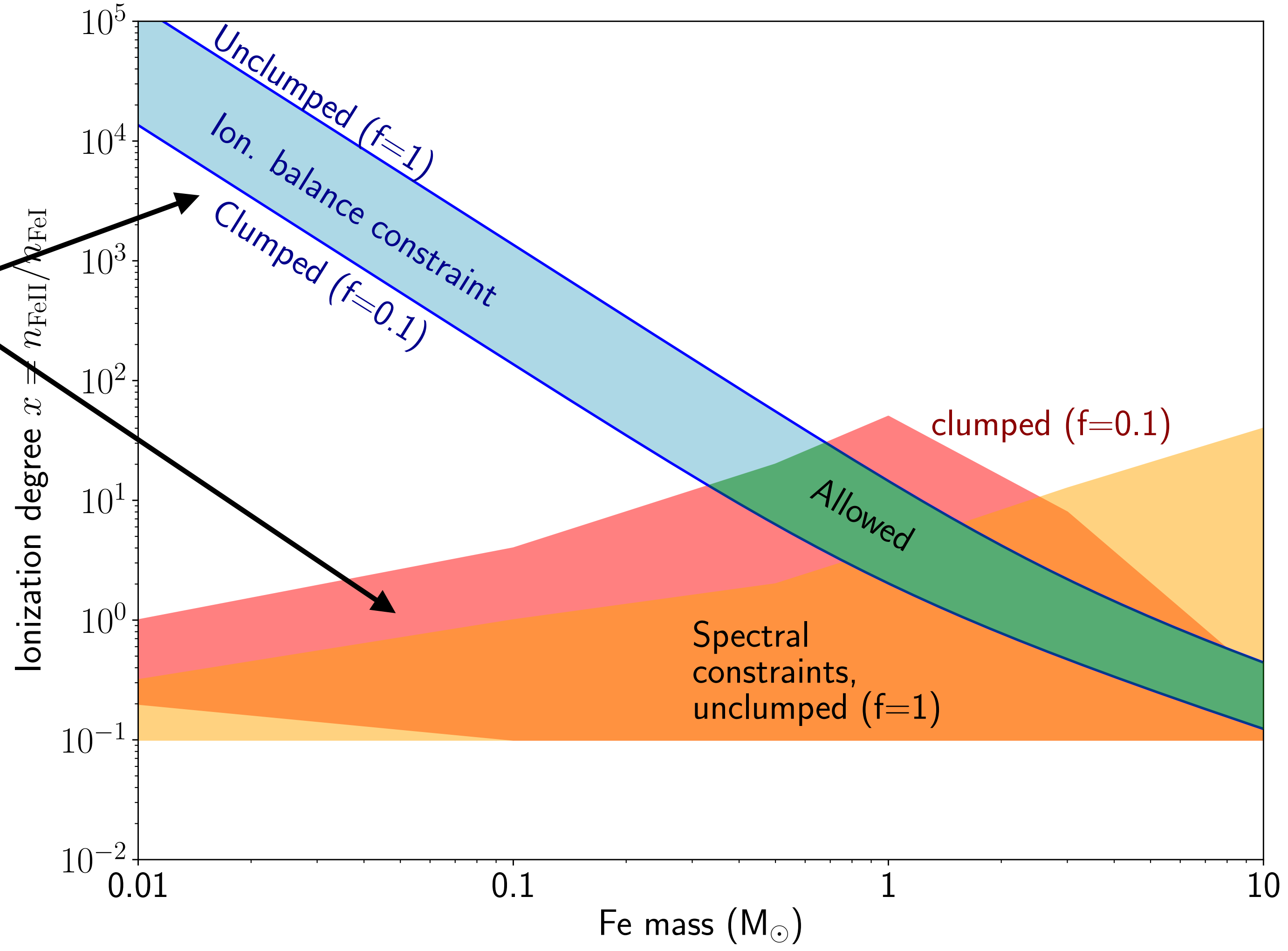
Luminosity in Fe I 7900-8300 Å cluster, model relative to observed:


$\boxed{f = 1}$

How much iron is there?

Approach 2: Spectral constraints.

- Correct ratio of Fe II and Fe I lines in spectral models.
- Ionization degree constrained by power input (=observed luminosity).



Result:

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

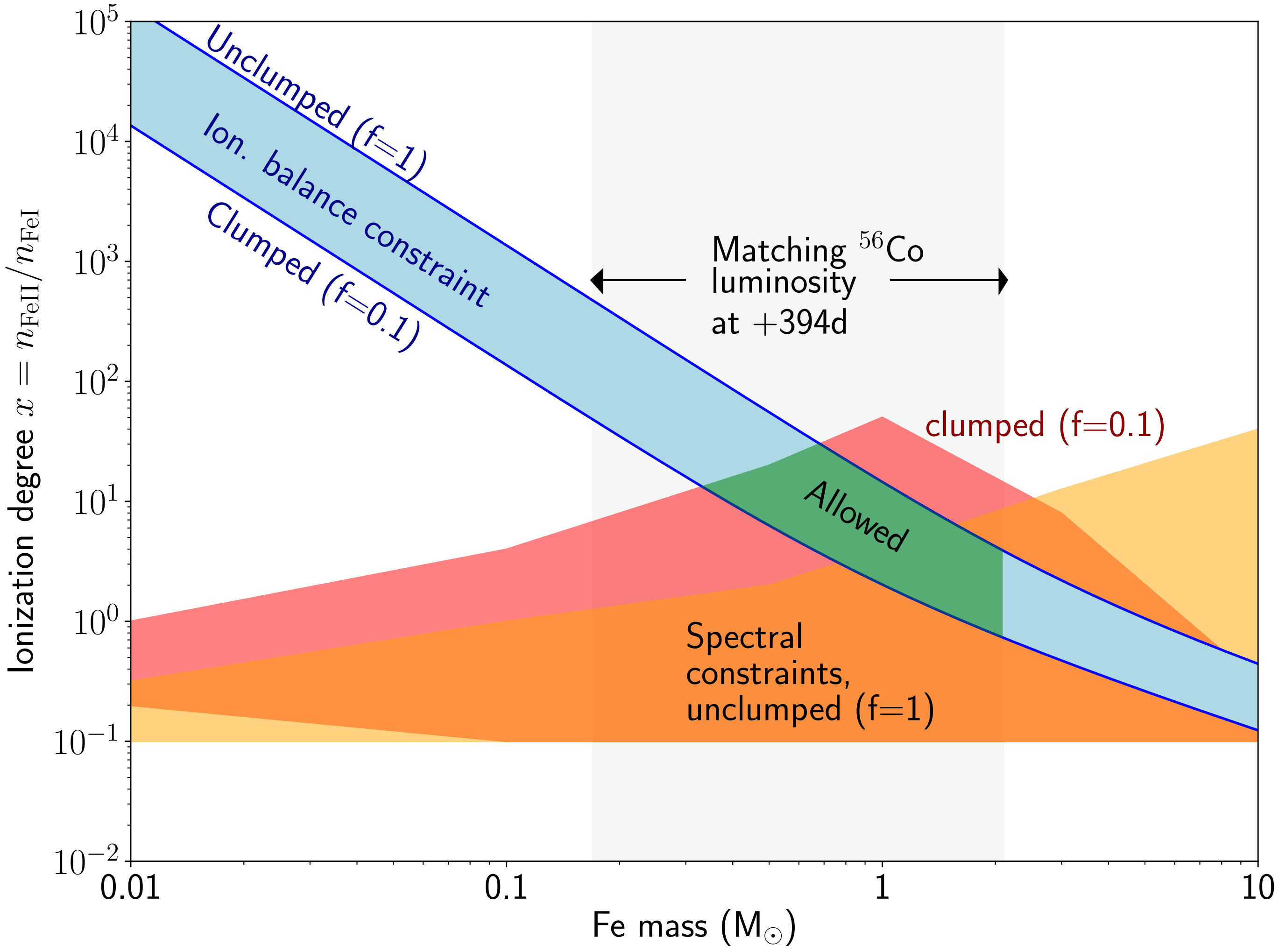
How much iron is there?

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

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

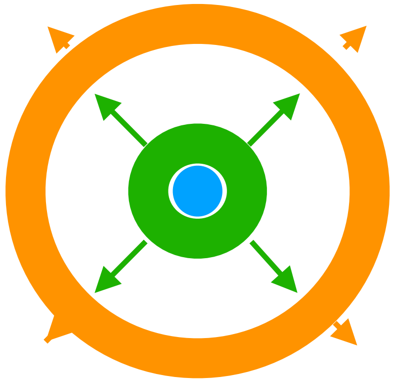
All constraints together:

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



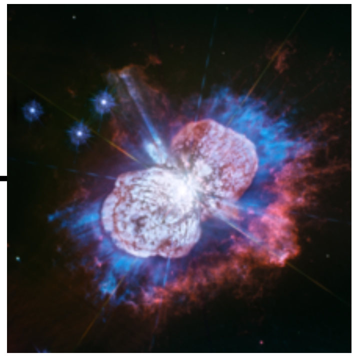
How can one get an interacting supernova with $\gtrsim 0.3\ M_\odot$ of ^{56}Ni and a $\gtrsim 10\ M_\odot$ H-rich CSM ejected $\lesssim$ 100y ago?

Massive star candidates:



1) Pulsational PISN?

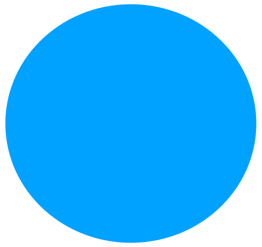
- Can be ruled out: No ^{56}Ni production so no iron lines



2) CCSN with a major LBV outburst just prior to collapse?

- Vast majority of CCSNe make $M_{Fe} < 0.2\ M_\odot$, and those who make more would have $E_{\rm kin} \gtrsim 10^{52}$ erg.
- CCSNe are O-rich but in SN 2006gy no O lines seen

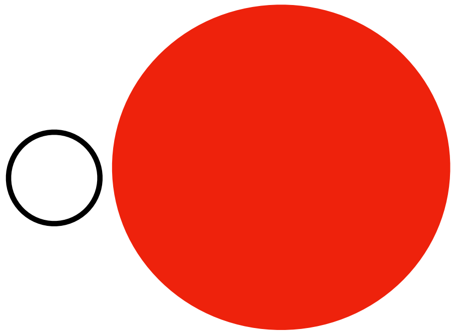
Coincidence problem



3) A M(He-core) ~90 M_{sun} pair instability supernova?

- Fails to reproduce light curve including 394d drop
- No pulsations predicted, and low-metallicity expected whereas SN 2006gy ~ solar

White dwarfs to the rescue?



4) A white dwarf spiralling into a red giant, ejects its envelope and explodes as a Ia supernova?

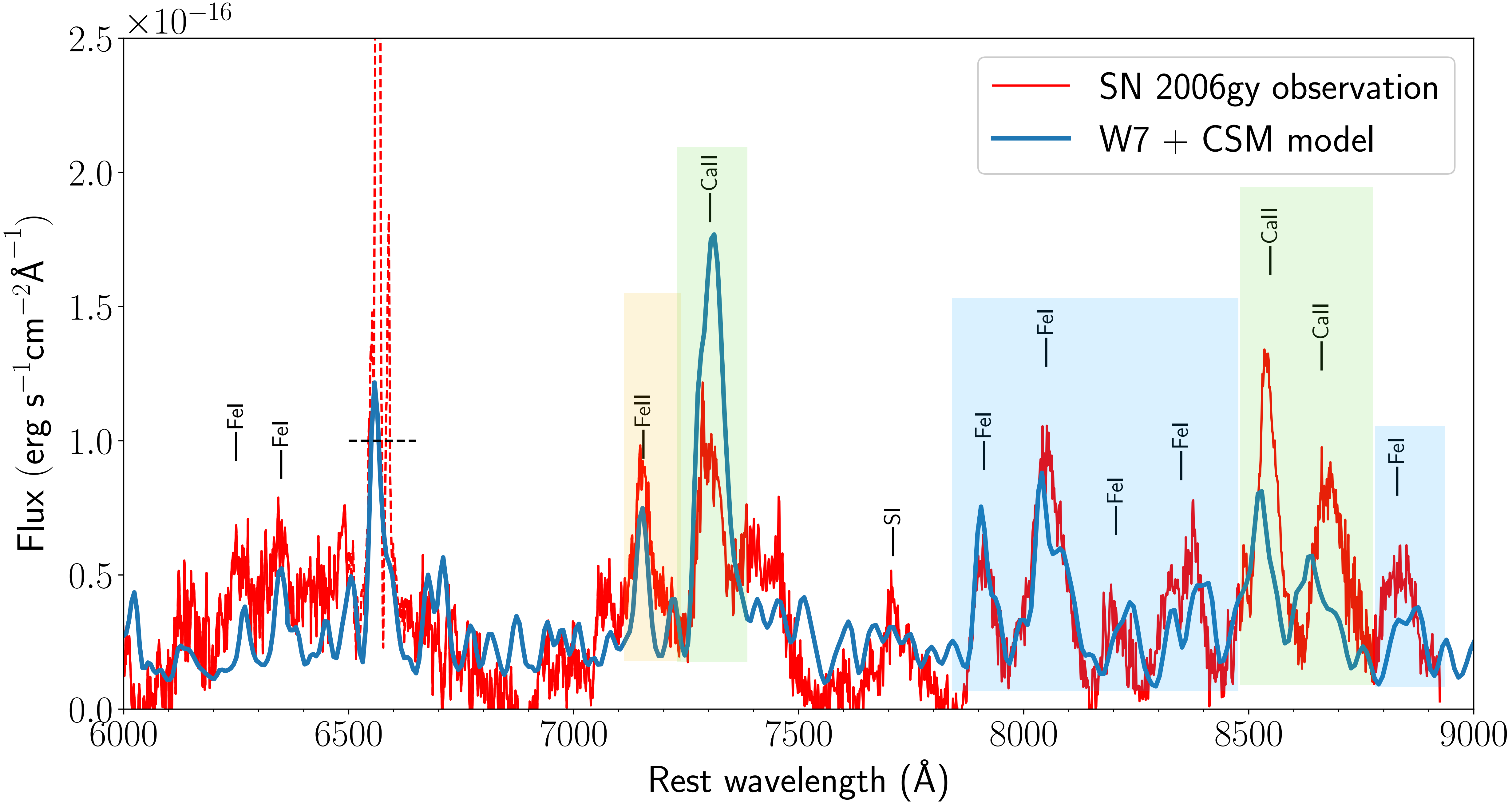
✓Causally links mass ejection - SN

✓Common envelope ejection a well established process - entire stellar envelopes can be ejected on timescale of few years/decades

✓Ia SNe make just the right amount of ^{56}Ni (0.3-0.7 $M_\odot$)

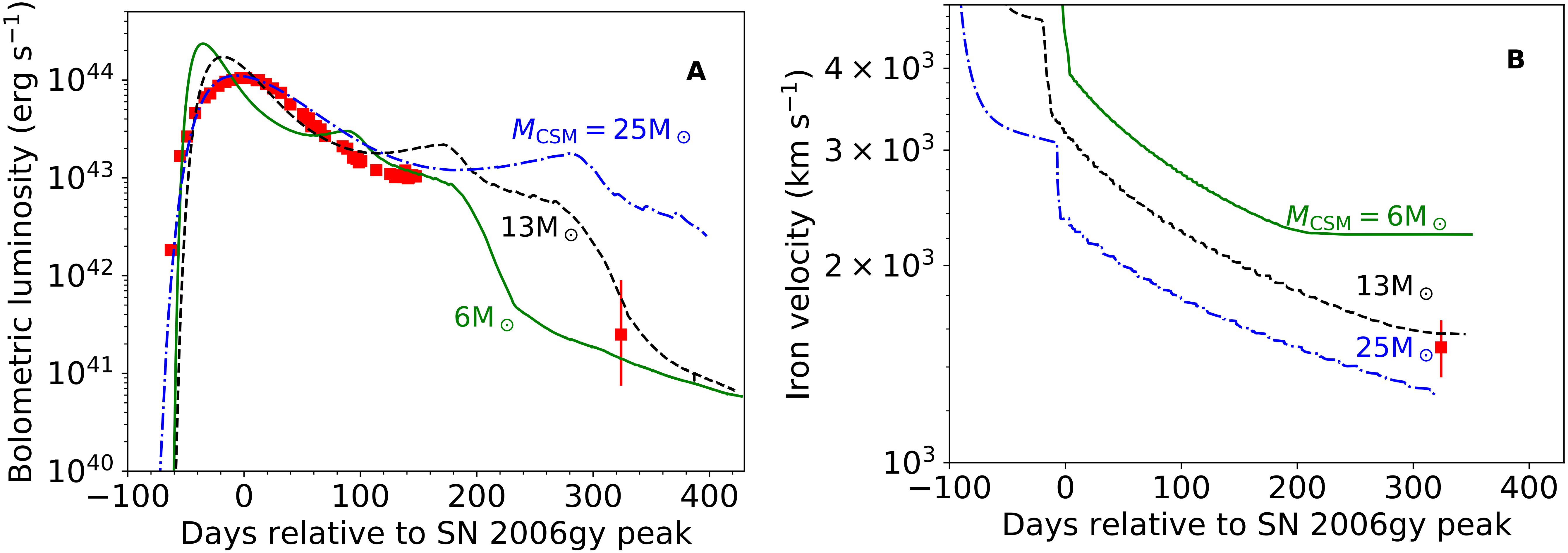
Spectrum of a decelerated Ia SN fits well

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



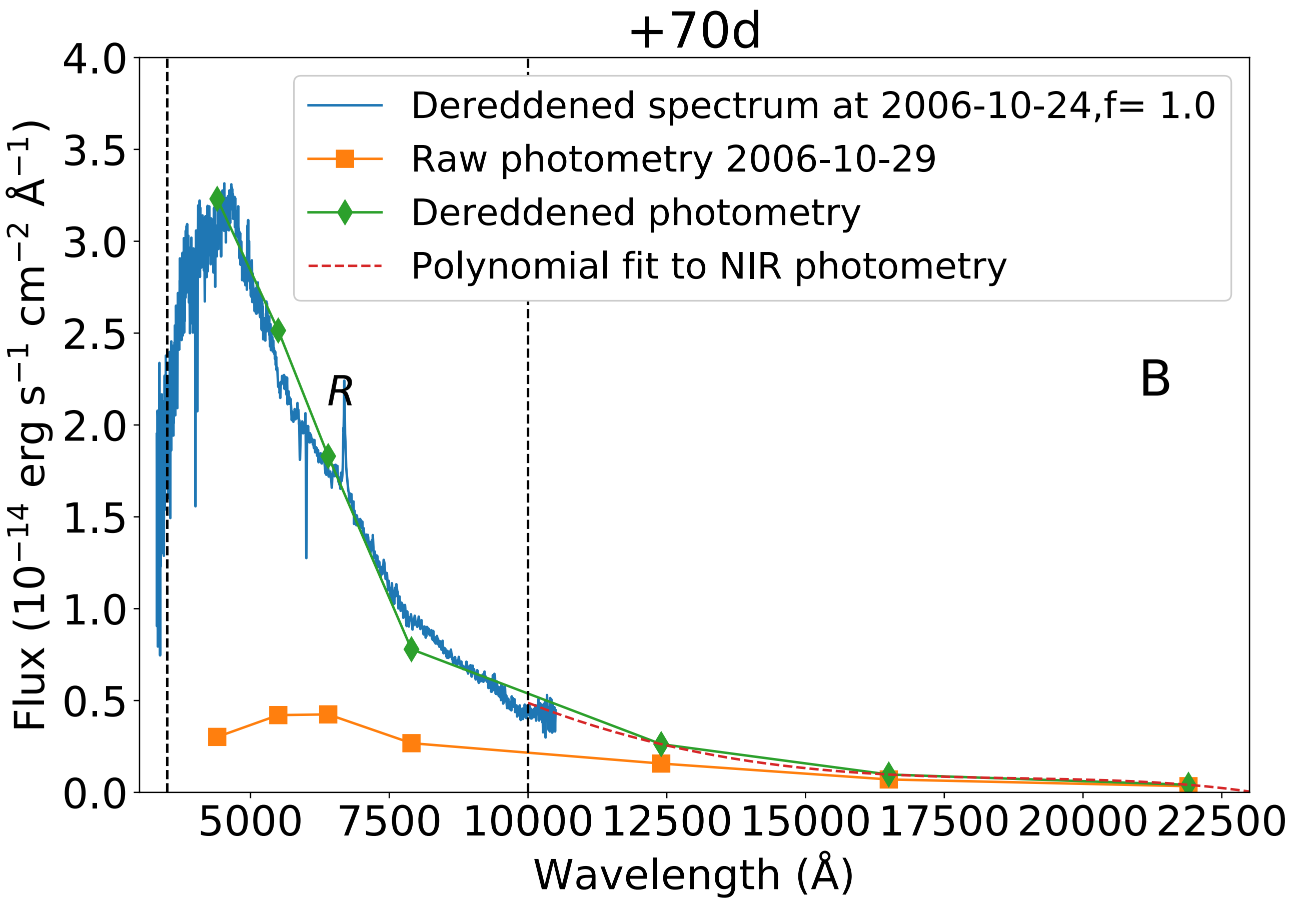
Light curve and final iron velocities for Ia-CSM model also consistent

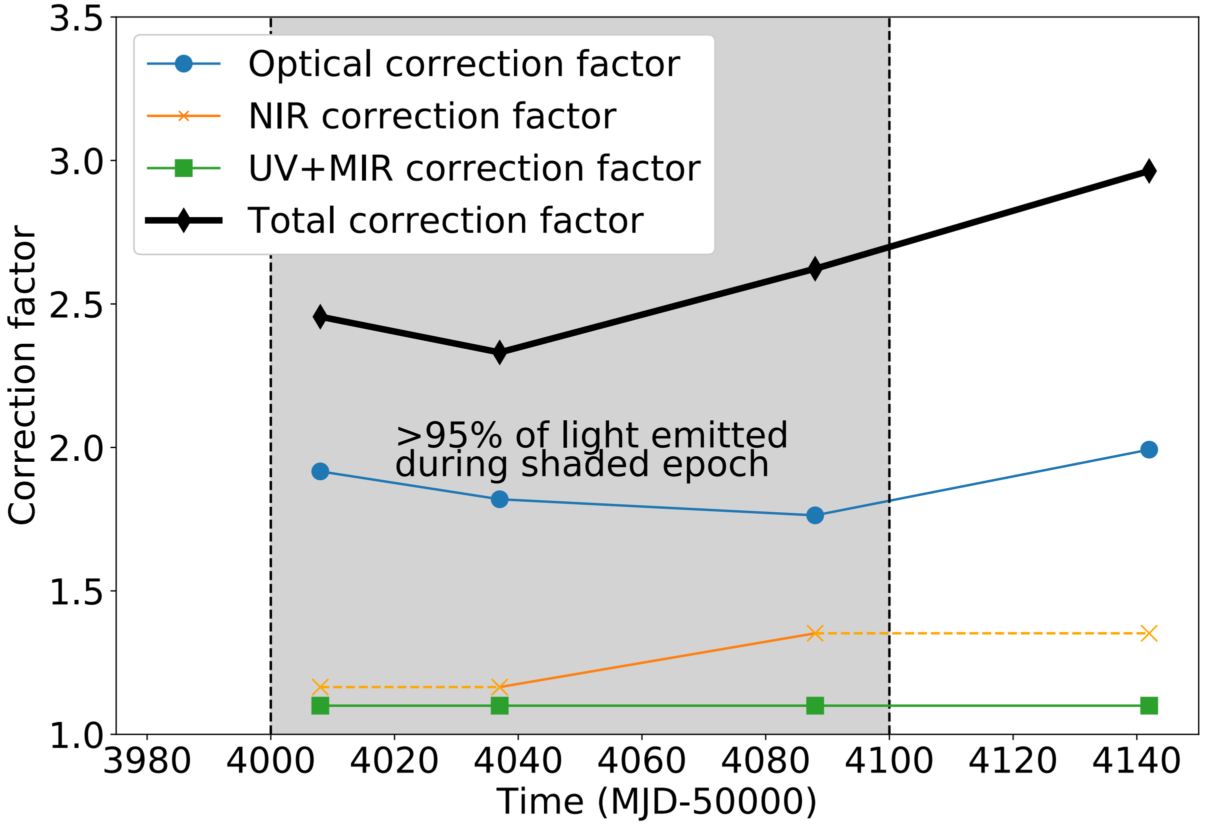
Code : SNEC (Morozova+2015)



- 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 $M_{\rm CSM} \sim 13\ M_\odot$ all properties roughly correct.

Energy budget



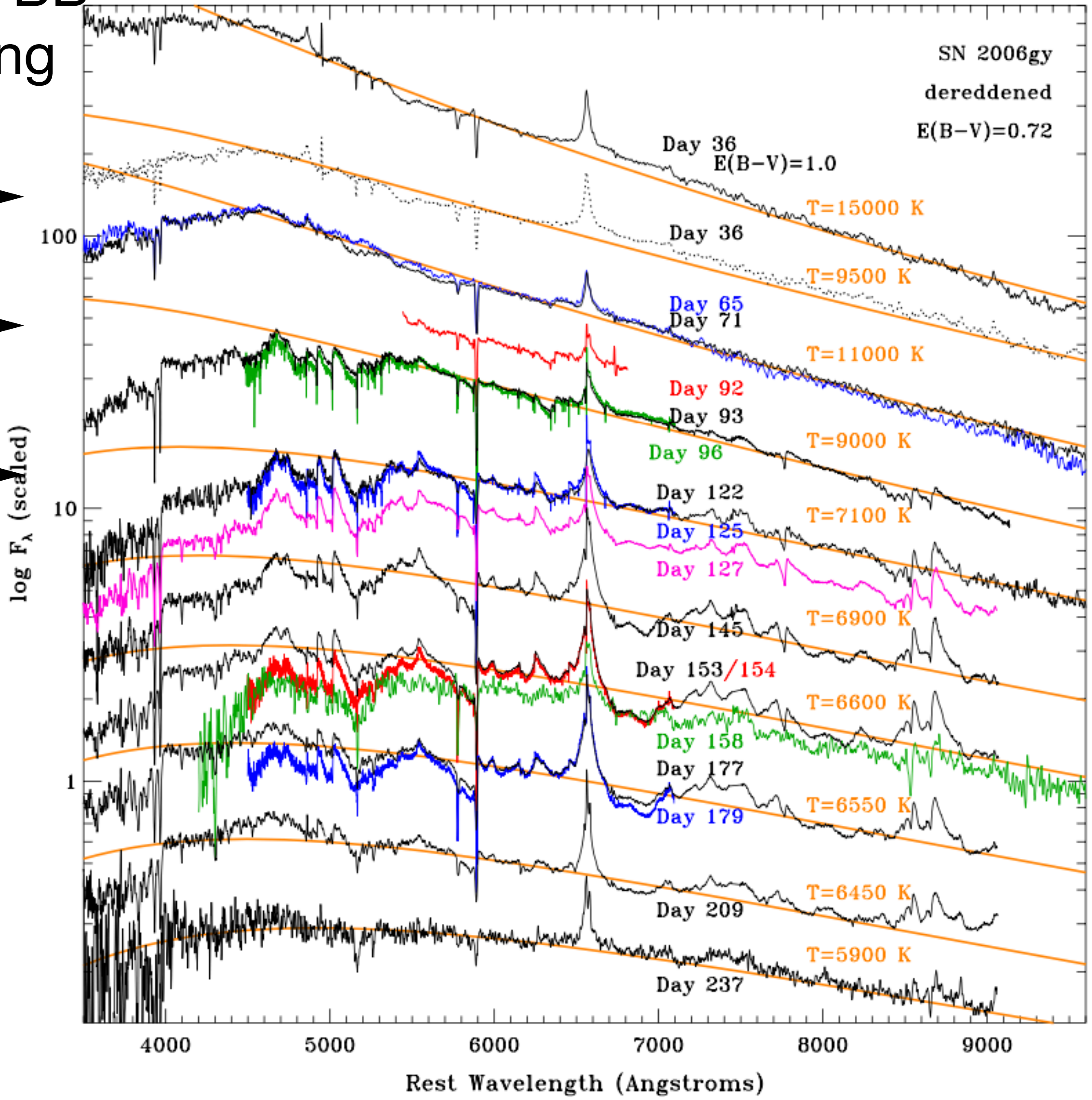


Best estimate : $E_{\rm radiated} = 9 \times 10^{50}$ erg
—> Normal Ia SNe ($E^0_{\rm kin} \sim 1.3 \times 10^{51}$ erg) are within budget

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

Energy budget

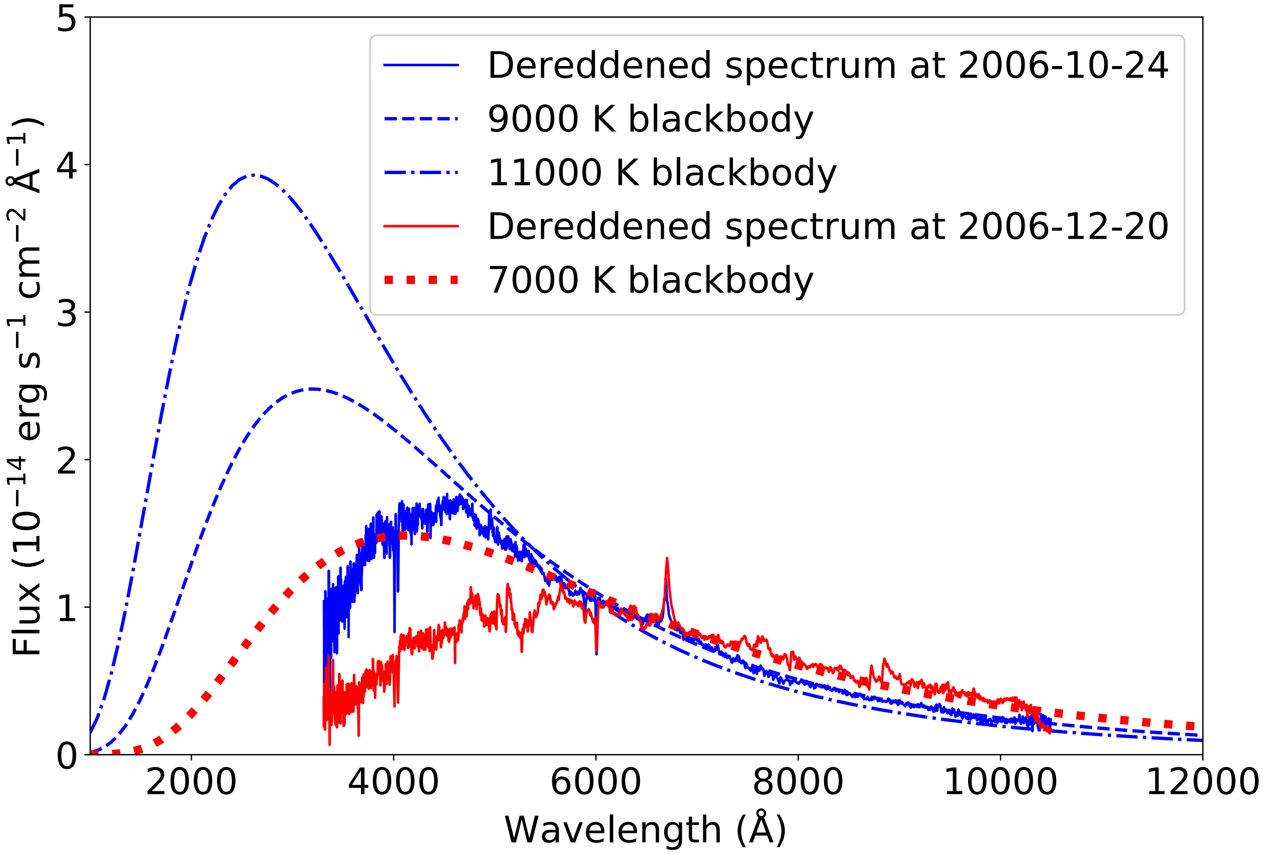
Excesses
from BB
fitting



Smith+2010:

$E_{\rm radiated} = (2-3)\times 10^{51}$ erg,
“too much for a Ia”

Based on fitting blackbodies:
this likely overestimates the
UV contribution.



Questions raised if WD-RSG merger is the right explanation

1. How do you get a WD close to a RG/RSG star?

2. How do you get it to spiral in, eject virtually all of the RG/RSG envelope, and merge with the core?

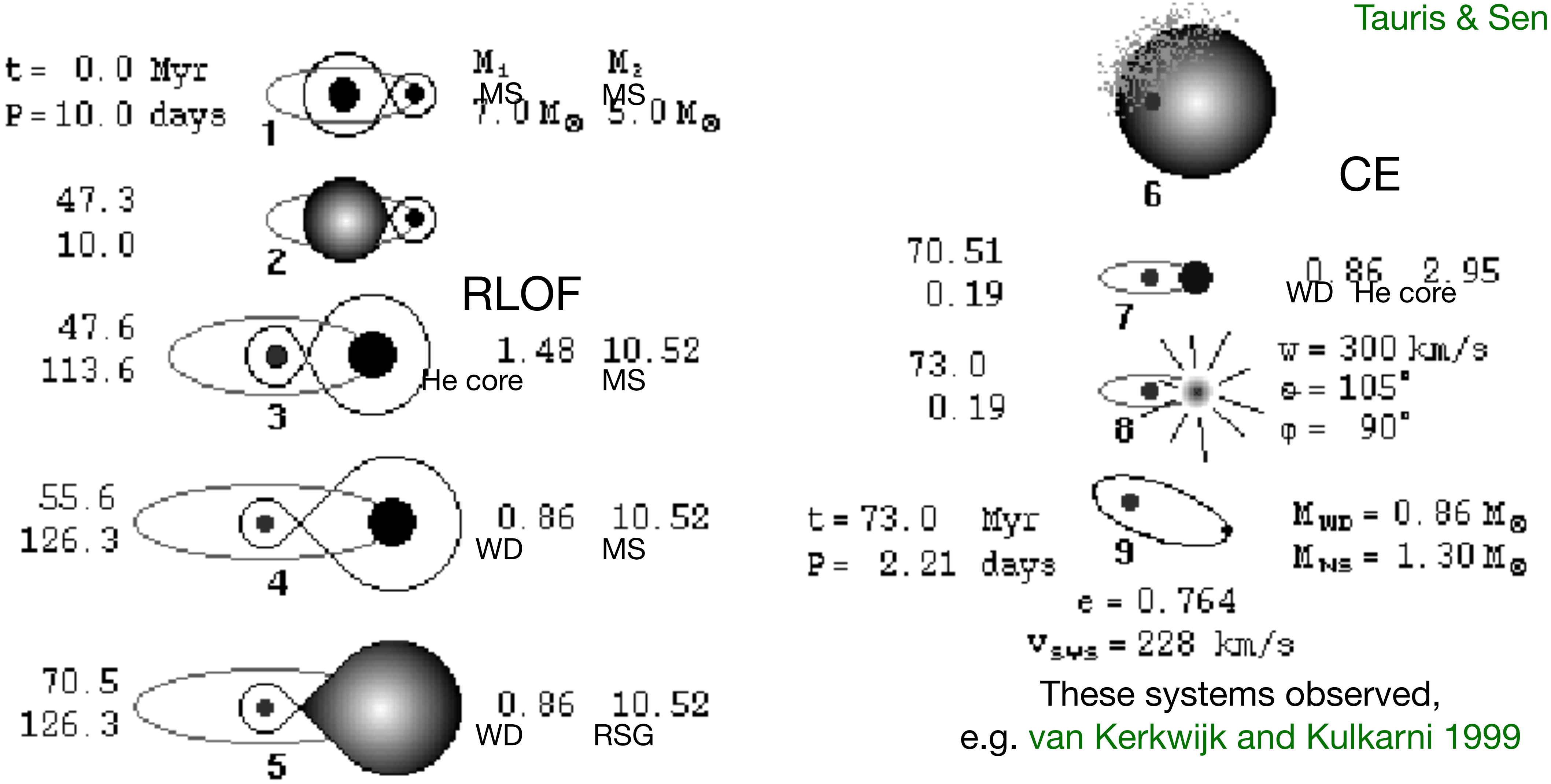
3. How do you get it to explode?

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.
- First mass transfer by Roche lobe overflow: can move more mass than CE (too short, $\lesssim 10^4$ y). Require similar initial masses $M_1/M_2 \gtrsim 0.4$.

Tauris & Sennels 2000



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

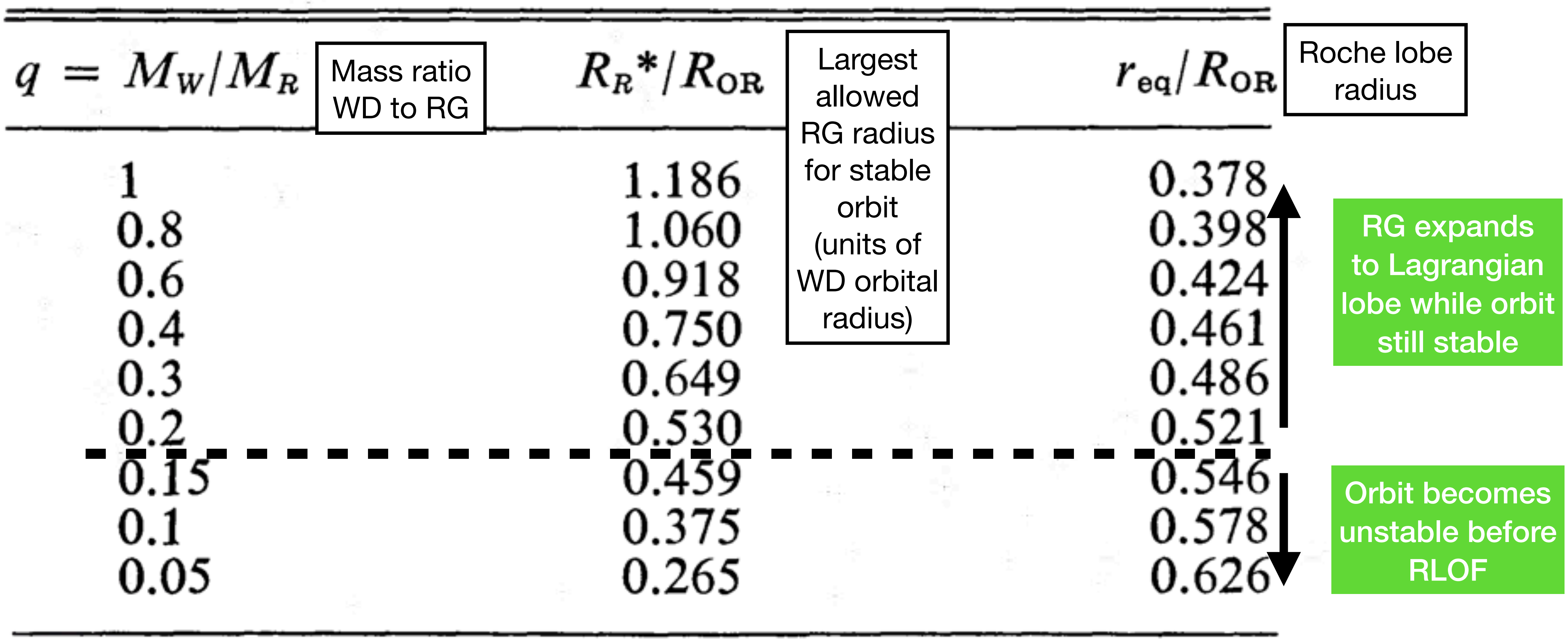
Population studies: $M^{max,final}_{companion} \sim 20\ M_\odot$ e.g. Willems & Kolb 2004

2

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

WARREN M. SPARKS AND THEODORE P. STECHER
Goddard Space Flight Center, Greenbelt, Maryland
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 ,starting typically when $R_{OR} \sim (2-4)\,R_G$.

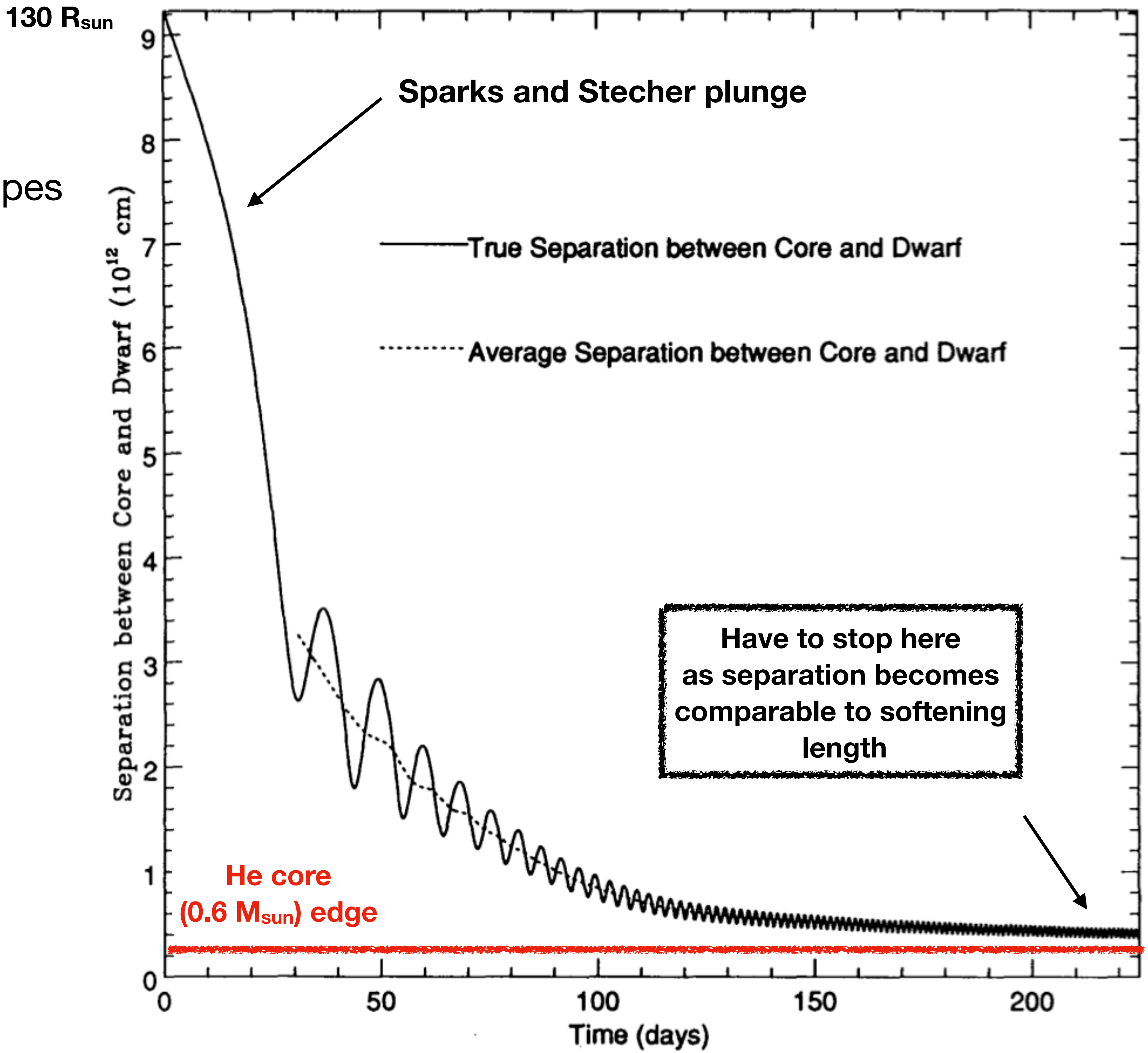
Simulating the in-spiral and common envelope phase with SPH

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



Sparks and Stecher plunge

Have to stop here as separation becomes comparable to softening length

He core (0.6 M_{sun}) edge

3

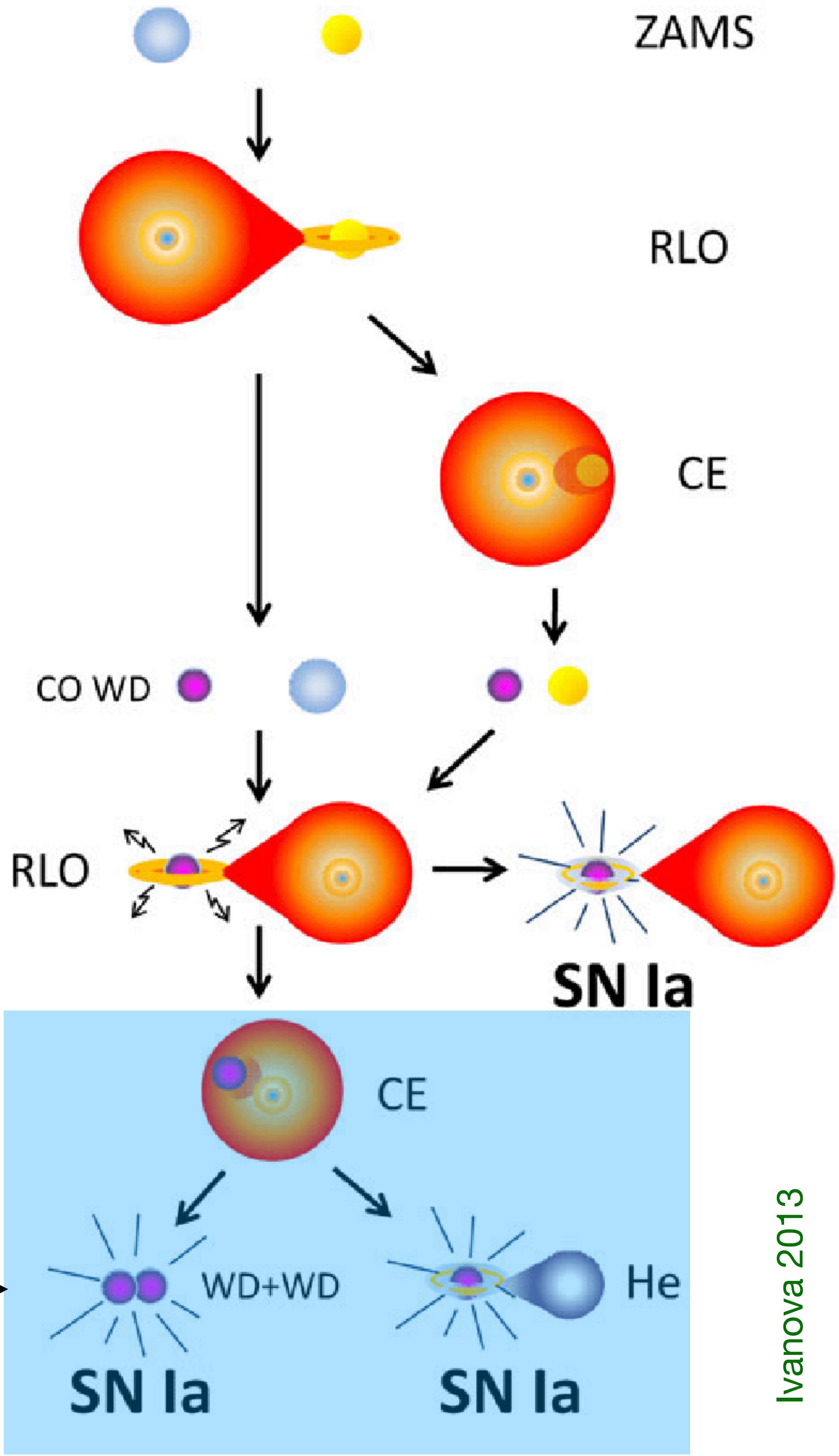
Explosion

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.

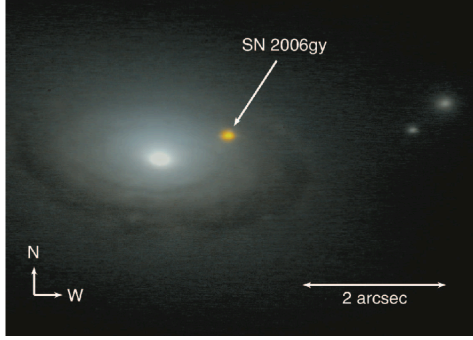
2. Merger with a RSG.
Sub-Chandra double detonation explosion as WD merges with He core. No tension with estimated CSM mass.

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



Ivanova 2013

Summary



- Lines in the emission spectrum of bright IIn supernova SN 2006gy have been identified as Fe I : new emission line diagnostic.
- The luminosity in these iron lines indicate a large iron mass, $\gtrsim 0.3\ M_\odot$.
- We propose a model scenario where a white dwarf merges with a massive companion as it enters its RG/RSG phase.
  - Explains ~**10 $M_\odot$ CSM** close to the SN (common envelope evolution can eject entire stellar envelopes in a short time).
  - Explains the **synchronisation** between CSM creation and SN explosion
    - The WD drops to the core on a time-scale of ~years in the inspiral.
    - Being degenerate it can explode upon high mass accretion.
  - Explains the **large iron mass** (WD SNe make ~0.5 $M_\odot$, CCSNe ~0.1 $M_\odot$)
  - Explains why **E_{rad} ~10^{51} erg** ($M_{ejecta} >> M_{CSM}$, in this limit is most of the SN kinetic energy converted to radiation).
  - Light curve and spectral models show good agreement.

Thank you for listening!