Constraining supernova ejecta from ^{56}Ni/ ^{56}Co decay lines and Fe optical/IR lines

Anders Jerkstrand, in collaboration with T. Janka, A. Wongwathanarat, M. Gabler, R. Diehl, K. Maeda, K. Kawabata and more

MARIE CURIE ACTIONS
SEVENTH FRAMEWORK PROGRAMME
erc Starting Grant

Papers

1 *"Properties of gamma-ray decay lines in 3D core-collapse supernova models, with application to SN 1987A and Cas A"*

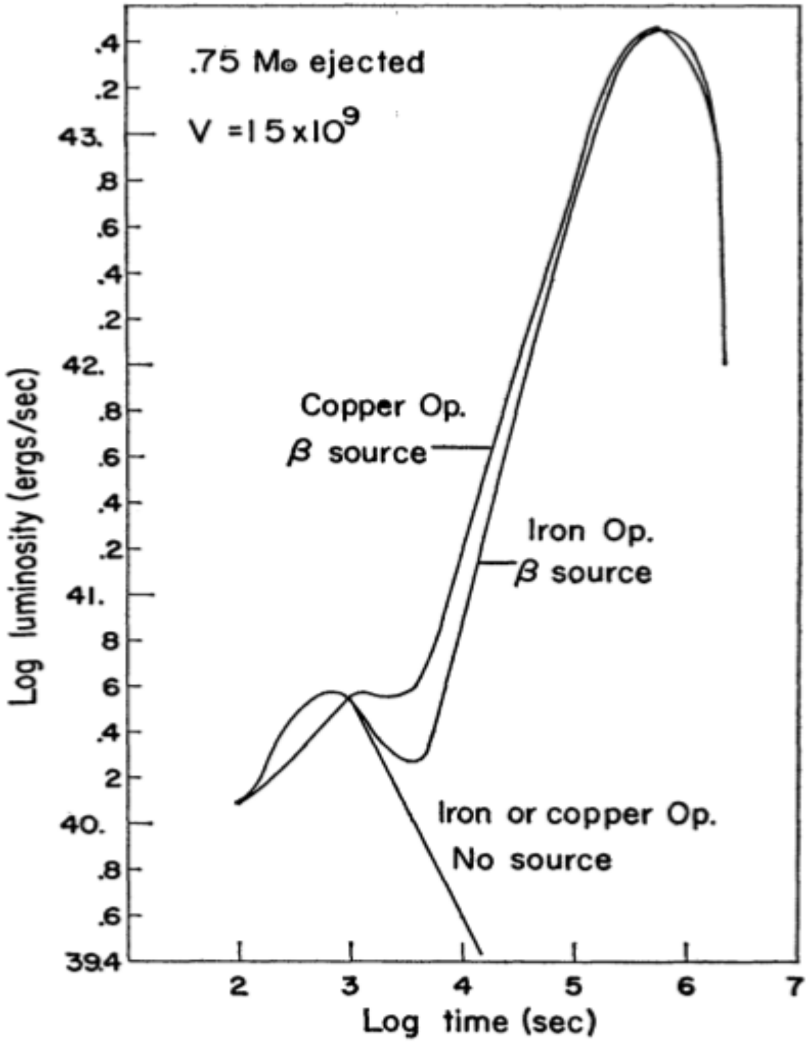
Jerkstrand, Wongwathanarat, Janka, Gabler, Alp, Diehl, Maeda, Larsson, Fransson, Menon, Heger MNRAS, submitted

2 *"A Type Ia supernova at the heart of superluminous transient SN 2006gy"*

Jerkstrand, Maeda, Kawabata Science, last stages of editing

Background: the key role of ^{56}Ni in supernovae

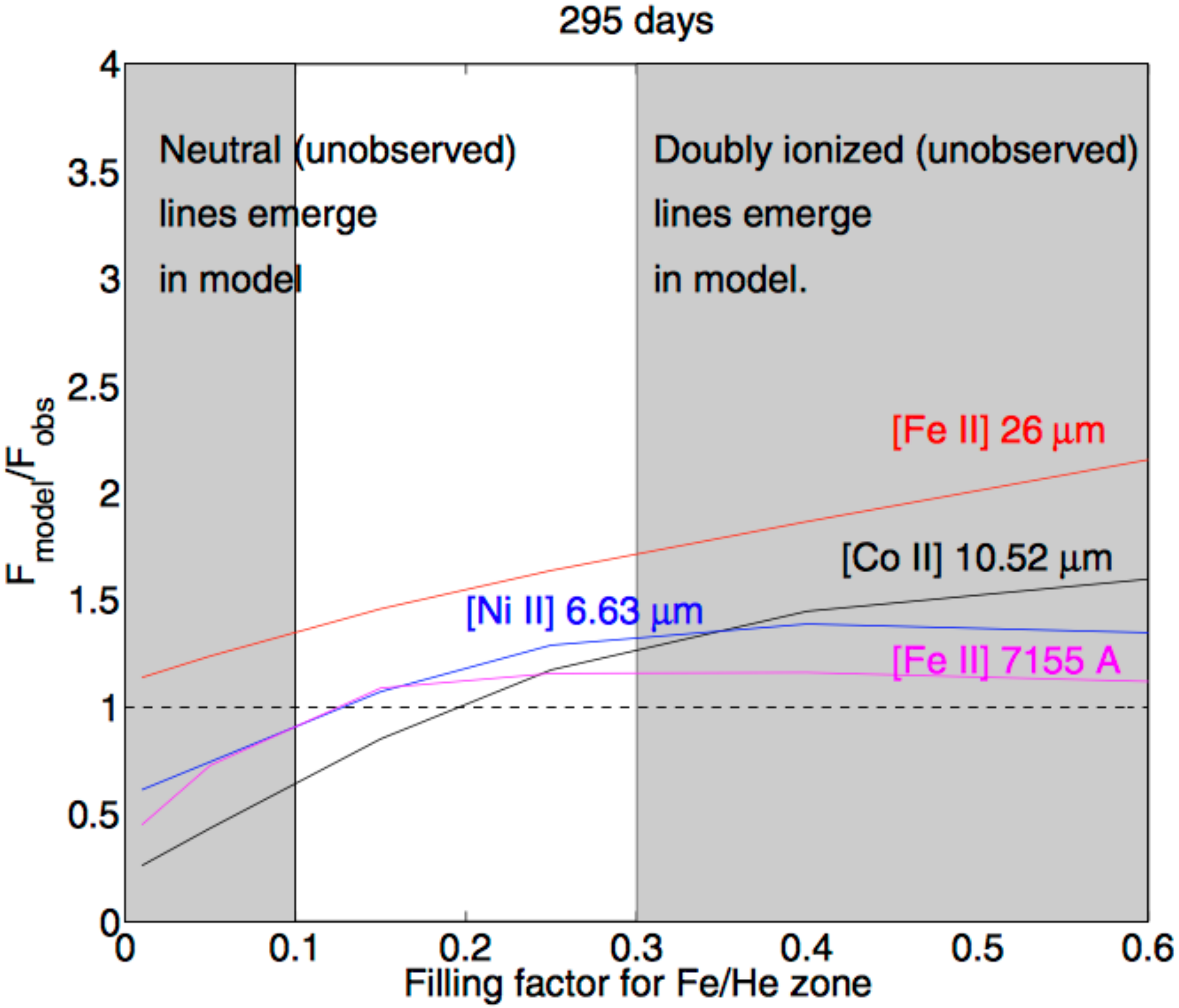
- Colgate & McKee 1969: The ^{56}Ni → ^{56}Co → ^{56}Fe radioactive decay chain is the reason we see SNe at all. At the same time the main source of iron in the universe was identified.
- This ^{56}Ni is produced in the innermost region of the collapsing star, just outside newly formed neutron star → <u>direct diagnostic of explosion physics and innermost stellar layers of progenitor</u>.
- We can probe this Ni/Co/Fe in multiple ways:
  - Light curves Utrobin, Kozyreva, …
  - Decay lines of ^{56}Ni and ^{56}Co Churazov, Diehl, Siegert..
  - Optical/IR lines of
    - Fe Spyromilio, Mazzali, Jerkstrand, Taubenberger,..
    - Co Axelrod, Childress
    - Ni Maeda, Jerkstrand, Flörs,..



Colgaete & McKee 1969

Some previous results from Ni/Co/Fe line modelling

Filling factor of ^{56}Ni bubble in CCSNe
Jerkstrand+2012



Ni/Fe ratios CCSNe
Jerkstrand+2015ab

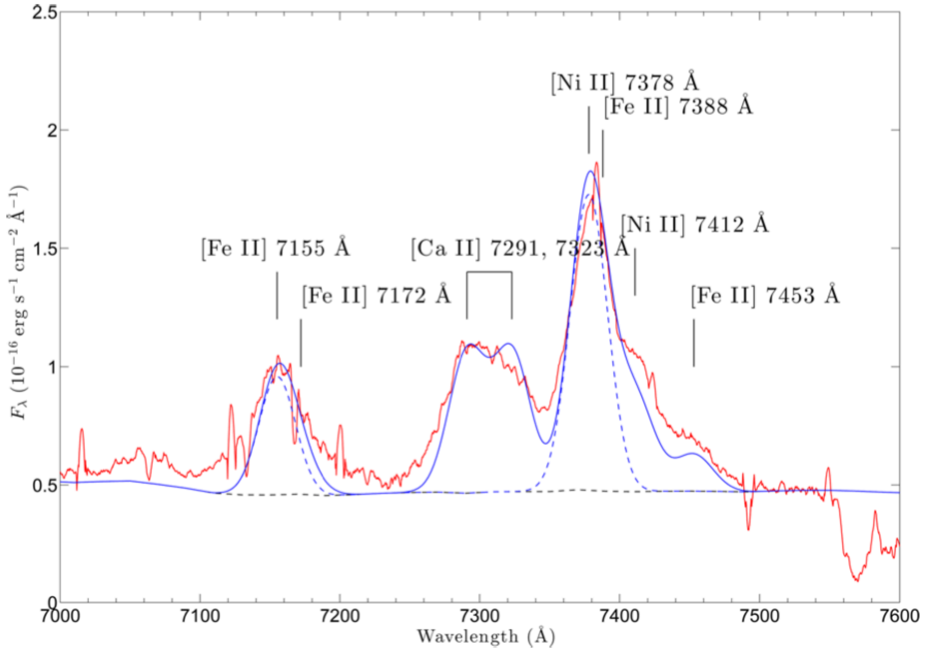
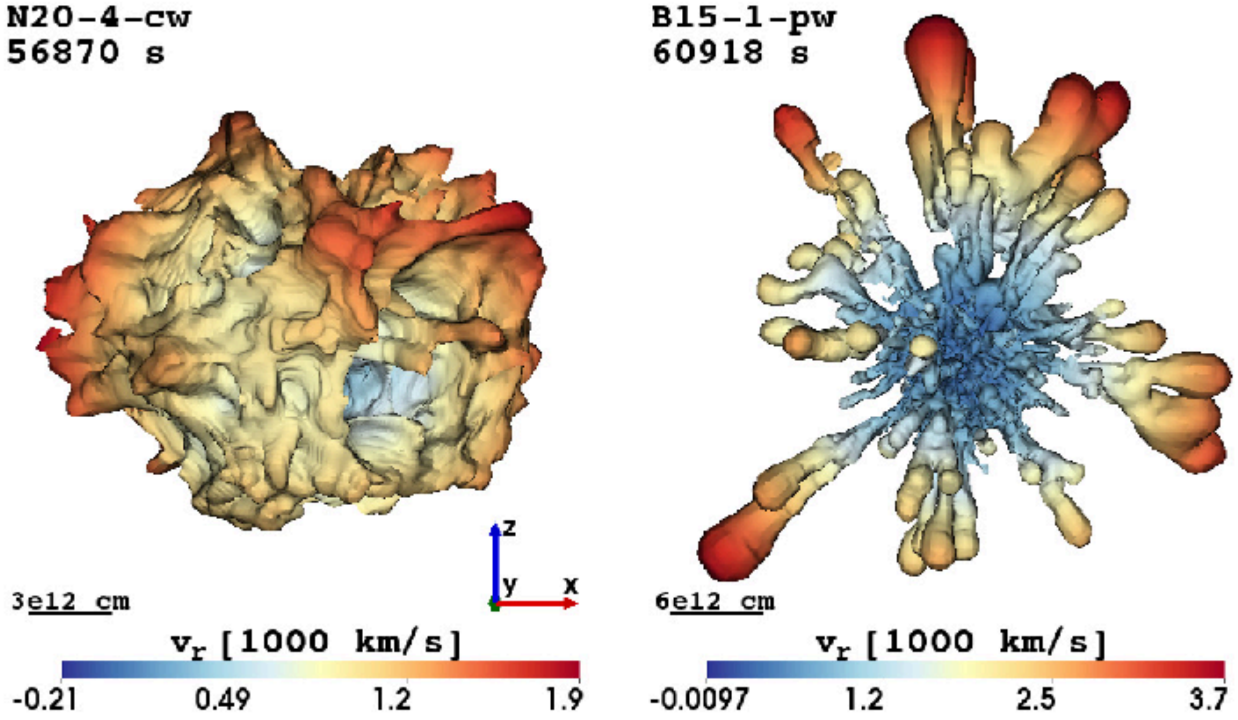


Table 4. Measurements of the Ni/Fe ratio in core-collapse SNe.

SN	Ni/Fe (times solar)	Reference
Crab	60–75	MacAlpine et al. (1989, 2007)
SN 1987A	0.5–1.5	Rank et al. (1988), Wooden et al. (1993), this work
SN 2004et	∼1	J12
SN 2006aj	2–5	Maeda et al. (2007), Mazzali et al. (2007)
SN 2012A	∼0.5	This work
SN 2012aw	∼1.5	This work
SN 2012ec	2.2–4.6	This work

3D modelling of decay lines: context

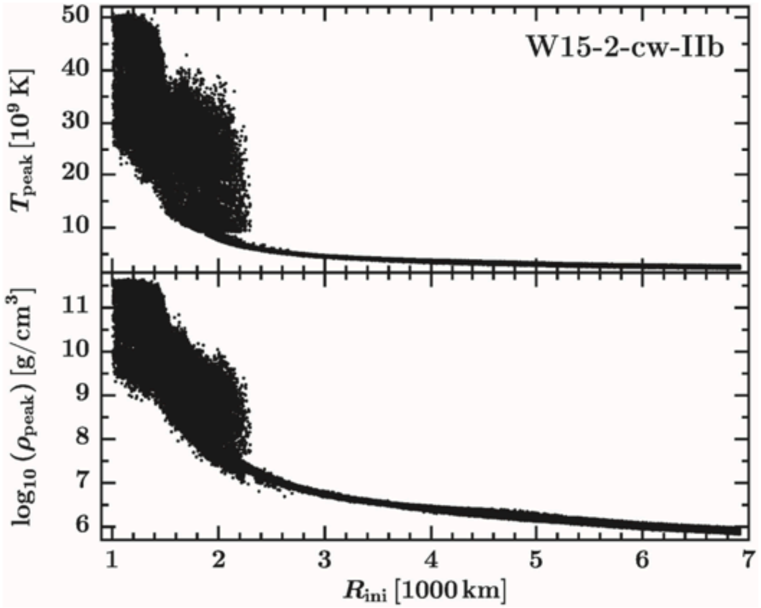
- First 3D models with realistic explosion physics and evolved to late times produced by Garching group Wongwathanarat+2013,2015,2017, Gabler in prep., Stockinger in prep.



3% ^{56}Ni isosurfaces

Wongwathanarat+2015

- Opportunity to put explosion models to the test.
  - Fastest ^{56}Ni?
  - Bulk velocity of ^{56}Ni?
  - Degree of asymmetry?
  - Composition of Si-burn ashes?



Wongwathanarat+2017

Hydrodynamic model set

Degree of asymmetry varies ~100-1000 km/s

	Explosion energy (Bethe)	Ejecta mass ($M_\odot$)	^{56}Ni shift (km/s)	X* shift (km/s)	^{44}Ti shift (km/s)	Bulk speed (km/s)
B15	1.4	14.1	145	288	216	1130
L15-1	1.7	13.6	398	388	414	1160
W15-2	1.5	13.9	517	584	521	1170
M15	1.4	19.4	473	787	633	1490

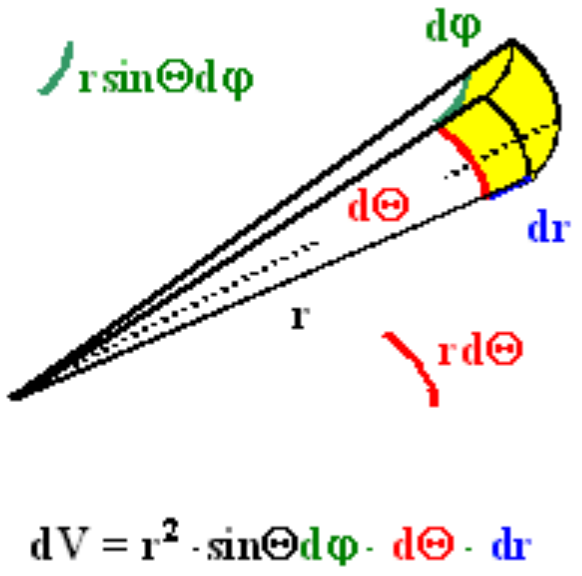
**X is ^{56}Ni or other iron-group nucleus*

Models from Wongwathanarat+2015, 2017 (L15-2,W15-1,M15-7b1,W15-IIb, evolved to ~1d) , and Gabler+ in prep. (B15-1L, L15-1L, W15-2L, evolved to 150d)

M_{ZAMS}=15-20 $M_\odot$ progenitors exploded with 1.4-2.8 Bethe (10^{51} erg).

3D modelling: method

- **Upgrade of SUMO spectral synthesis (Jerkstrand+2011/2012) code to 3D**. Decay lines are first "simplest possible" application (because emission and absorption/scattering do not depend on gas state).
- Full version (under development/testing) solves for **NLTE gas state, line (Sobolev) and continuum UVOIR transfer**.
- **Monte Carlo transport in spherical coordinate system**.
  - Avoid remapping
  - Avoid expensive small-cell transport in outer regions
  - Allow resolution of small-scale structure in metal core
- Time-dependence incorporated (except "live expansion" which has only a v/c~0.01 effect) by modulation factors in otherwise **snapshot simulation**.



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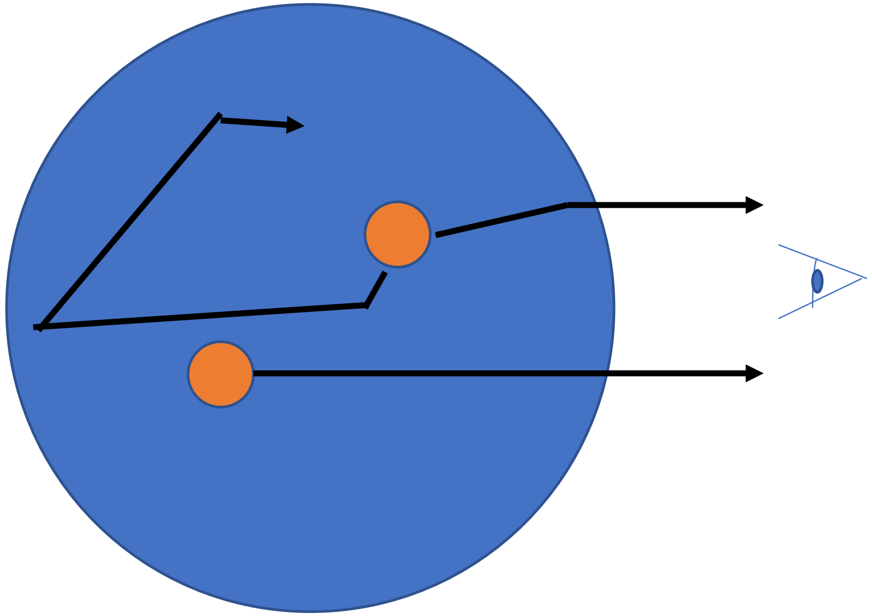
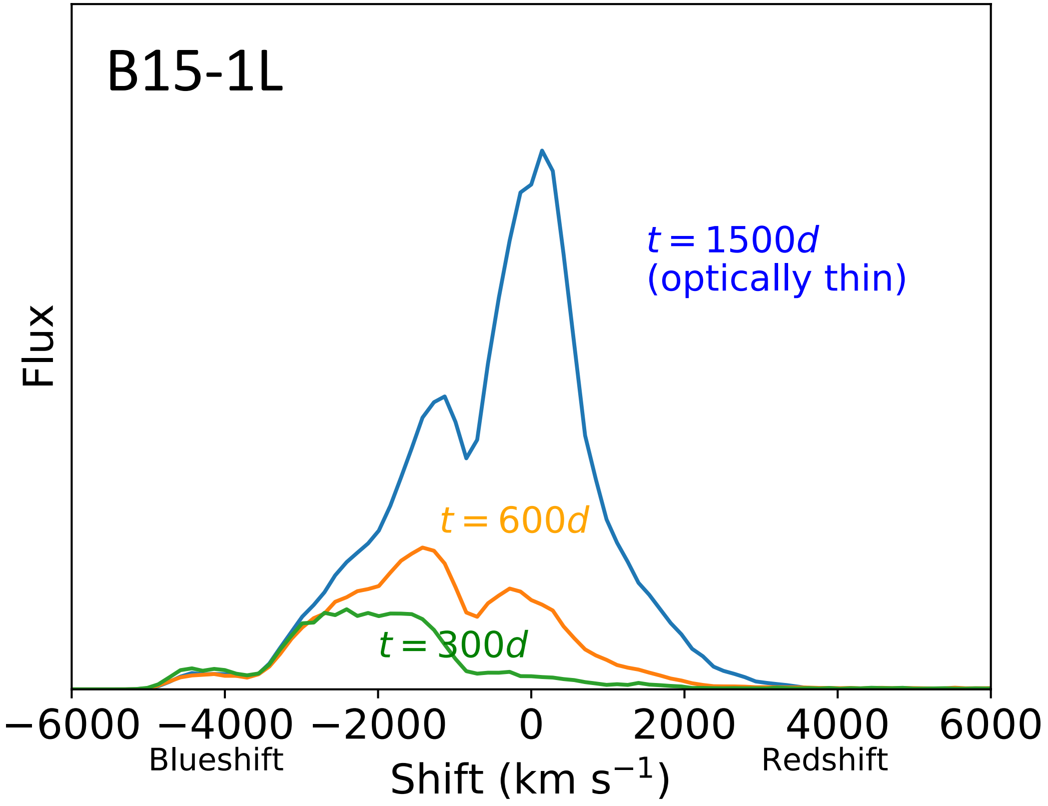


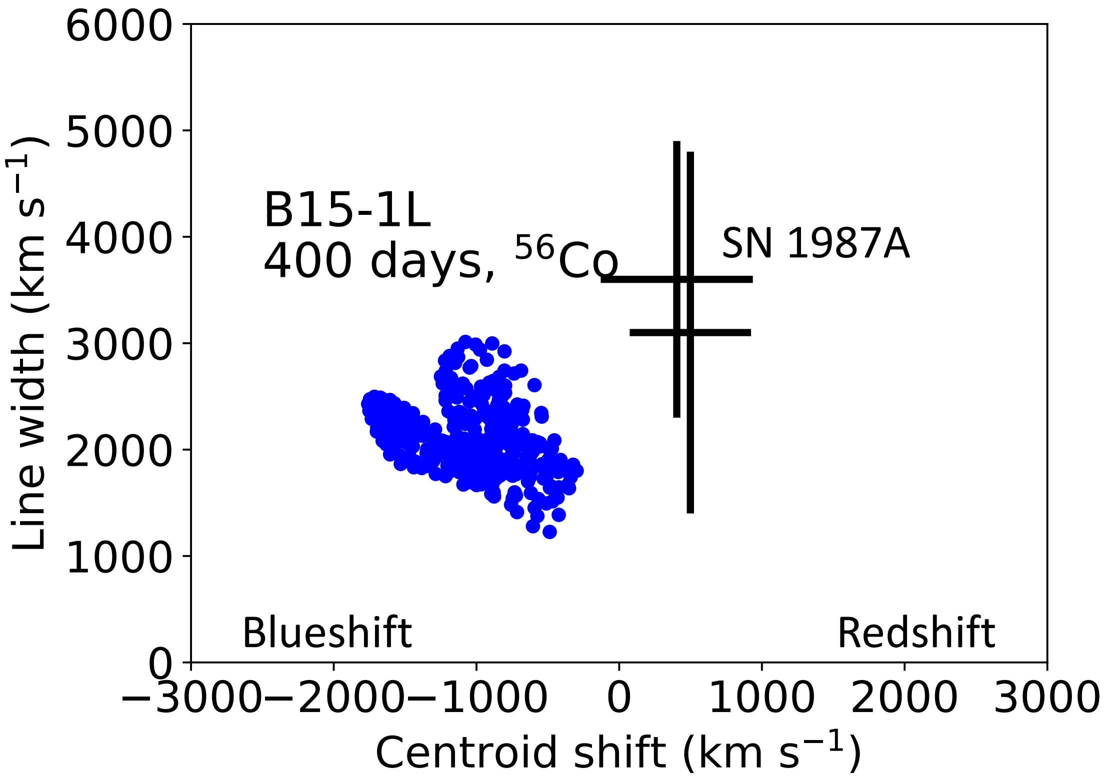
Example line profiles



Define **shift** and **width** of line:

$$V_{\rm shift}^{\rm direct} = \frac{\int C_{\rm E} V(E) dE}{\int C_{\rm E} dE}.$$

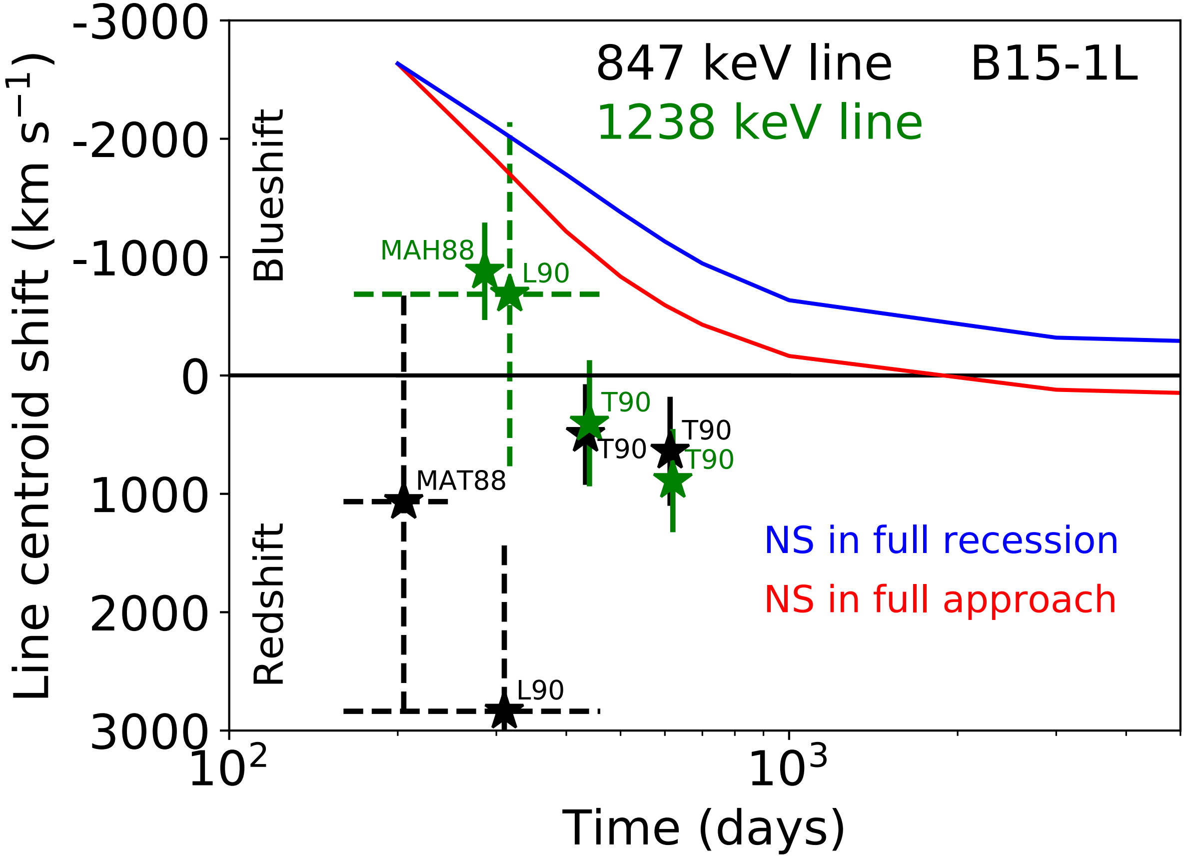
$$\Delta V^{\rm direct} = 2.35 \left(\frac{\int (V(E) - V_{\rm shift}^{\rm direct})^2 C_{\rm E} dE}{\int C_{\rm E} dE} \right)^{1/2}$$

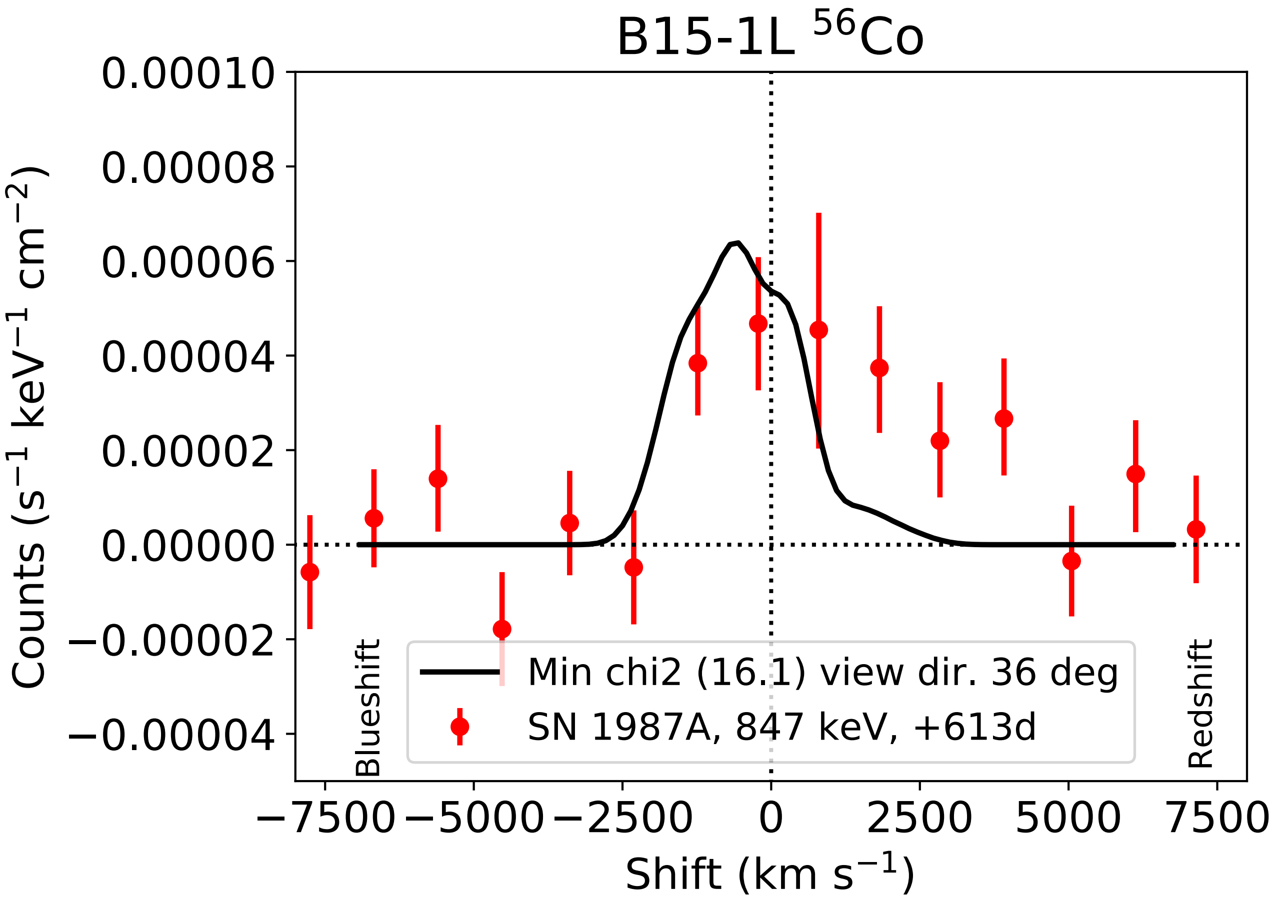


- Lines can have multiple peaks and are generally not "Gaussian".
- Compton scattering removes ~70% at 600d, ~90% at 300d, and blueshifts line.

Comparison to SN 1987A

B15: Too small ^{56}Ni asymmetry (~150 km/s)





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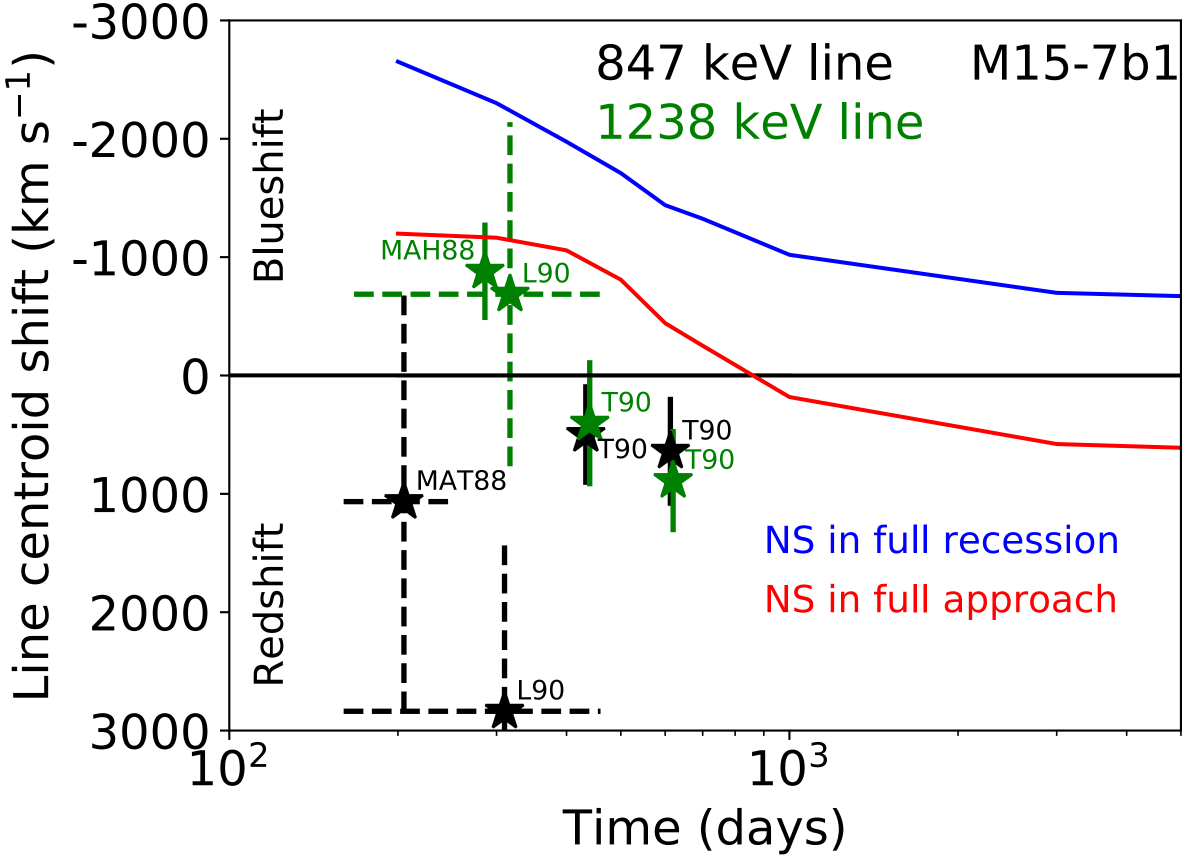

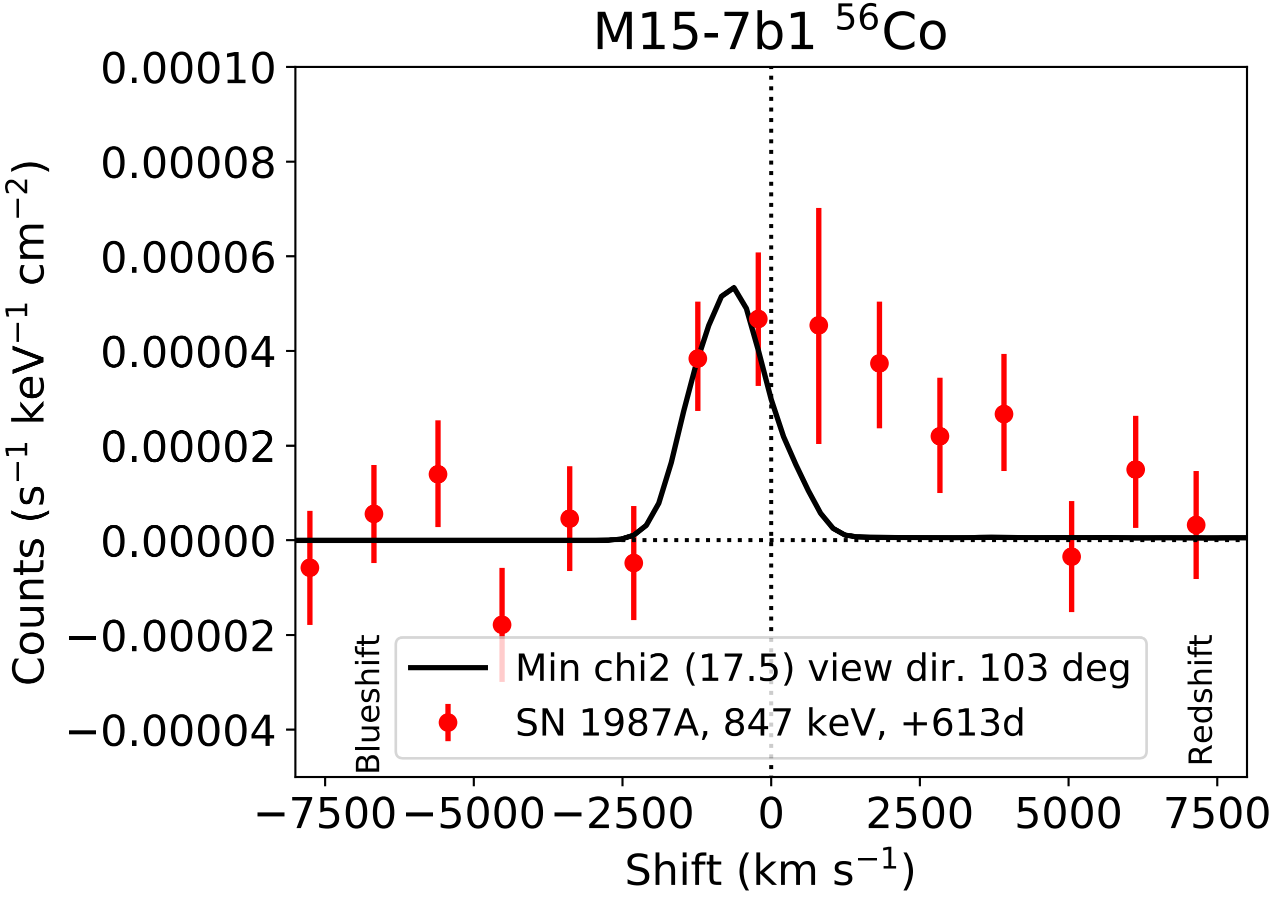

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Comparison to SN 1987A

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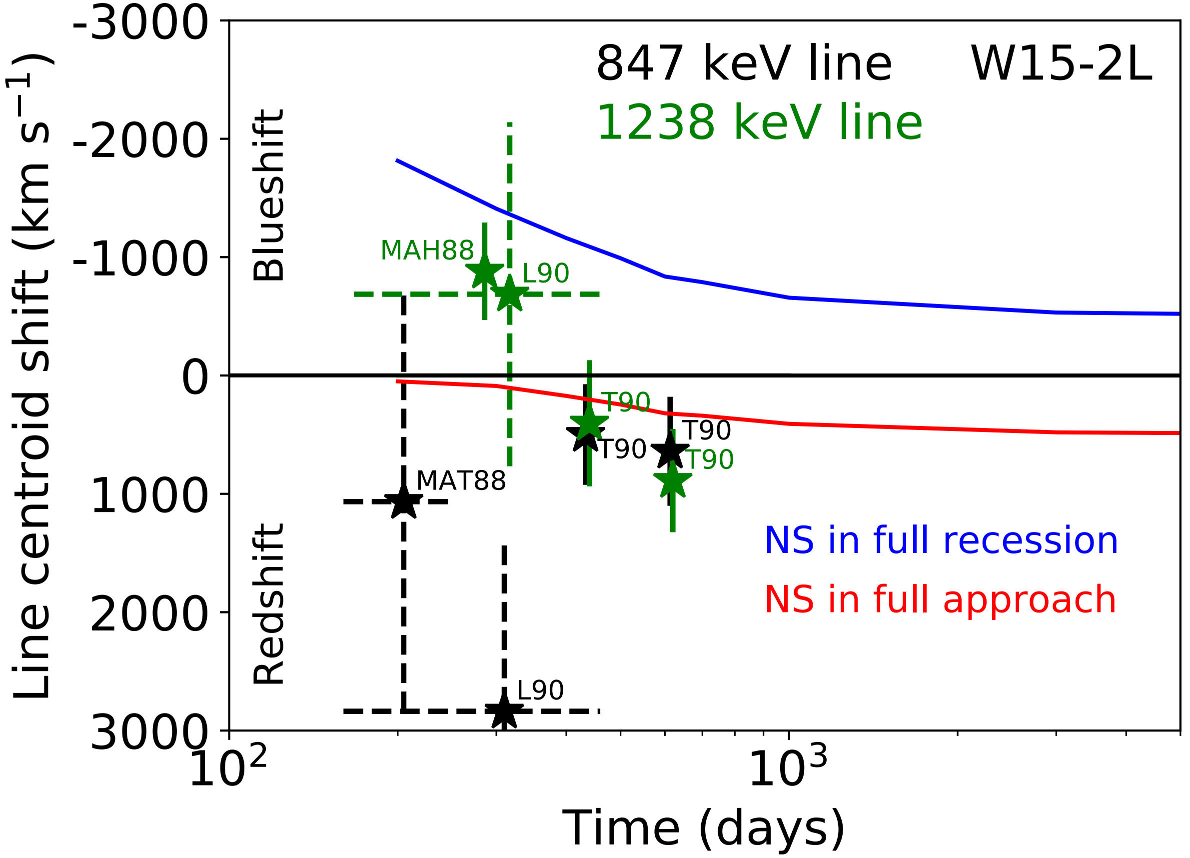

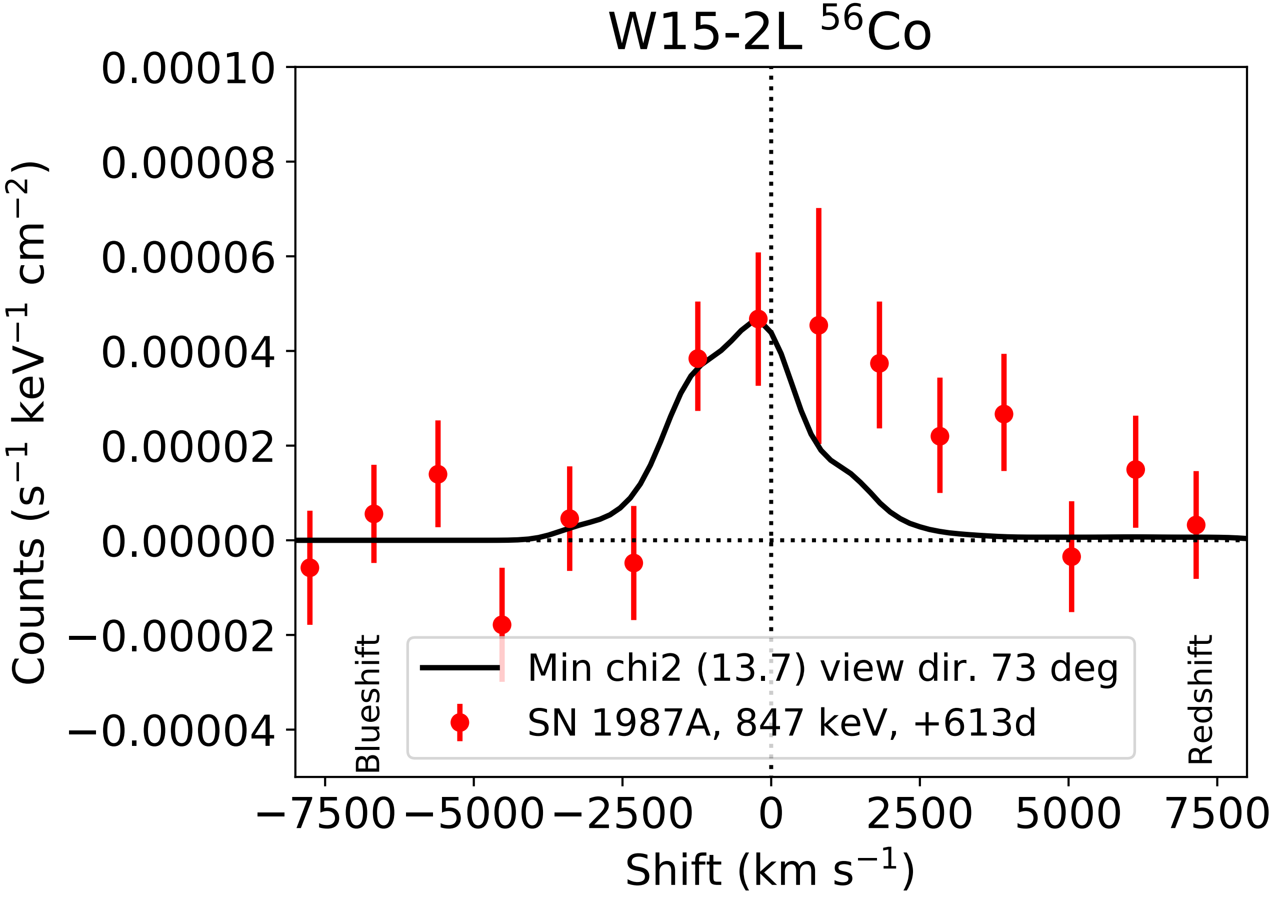

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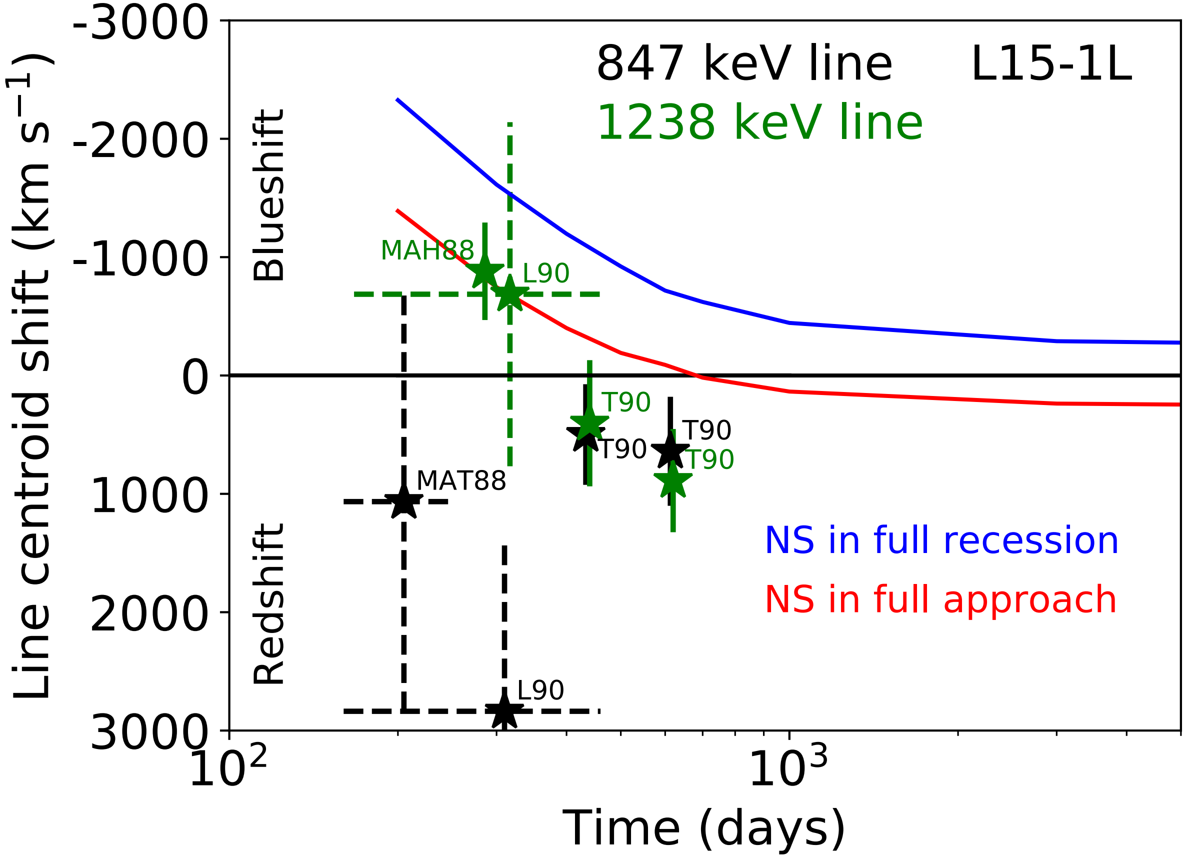
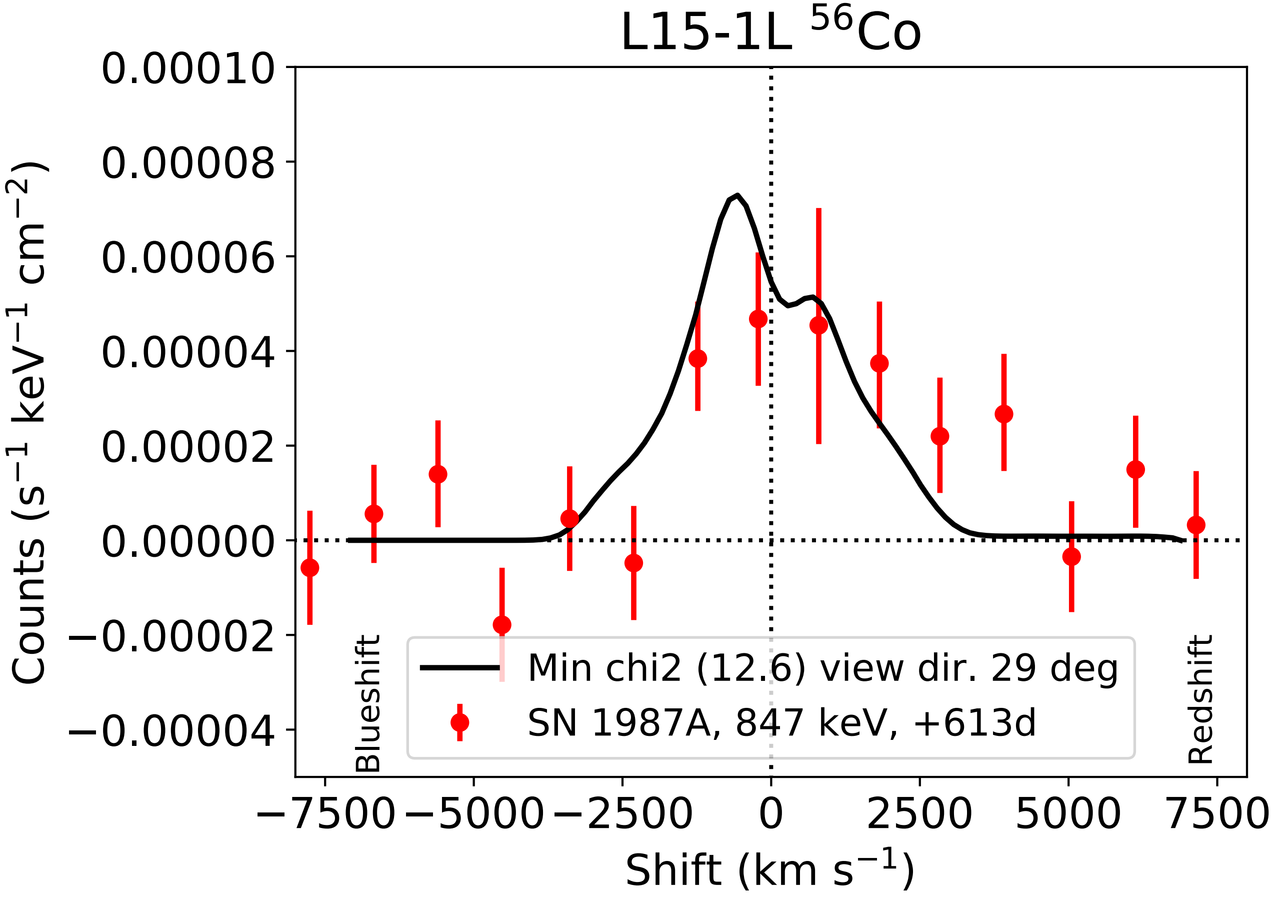


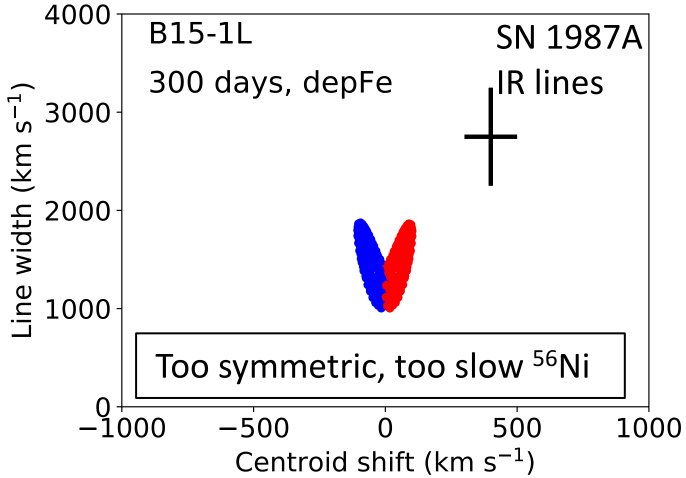


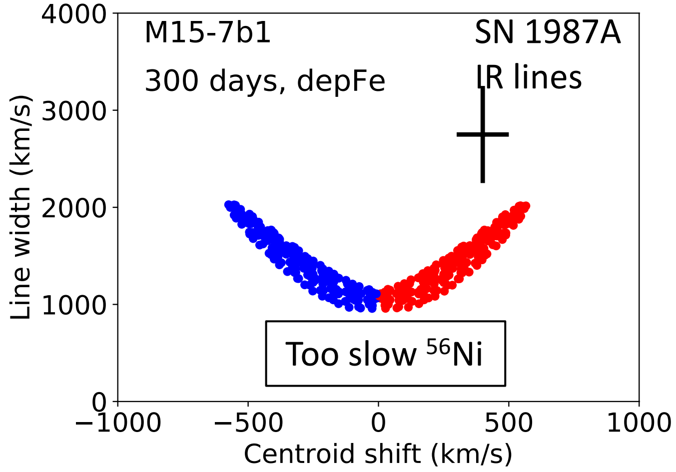
Highest explosion energy in set (1.7 B)

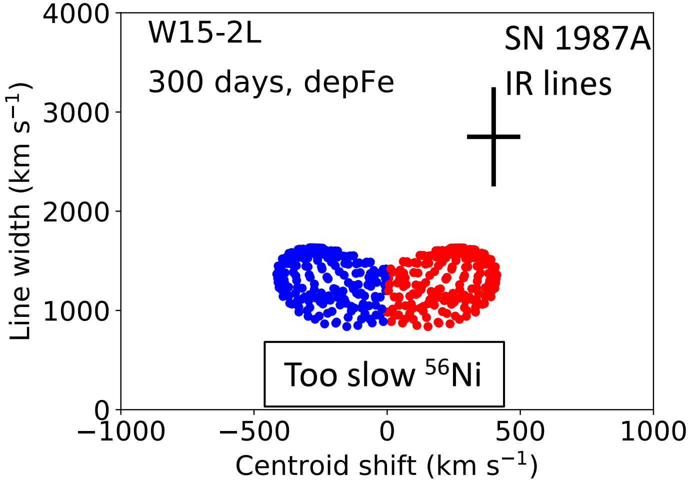
Data: Matz+1988 (M88), Mahoney+1988 (MAH88), Leising&Share 1990 (L90), Tueller+1990 (T90)

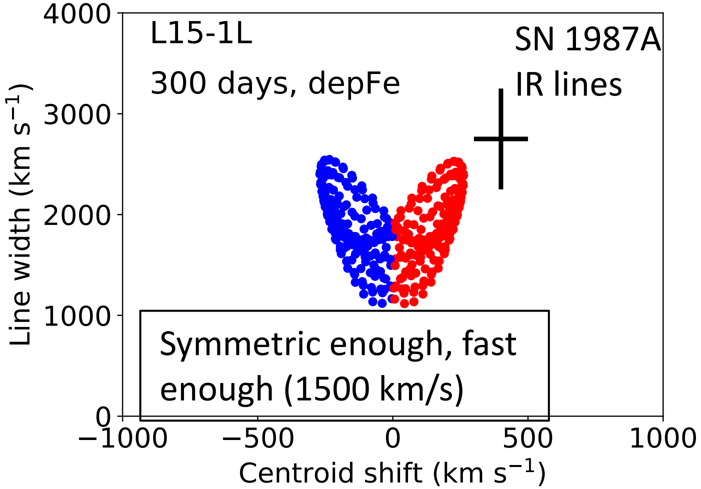
Infrared iron lines

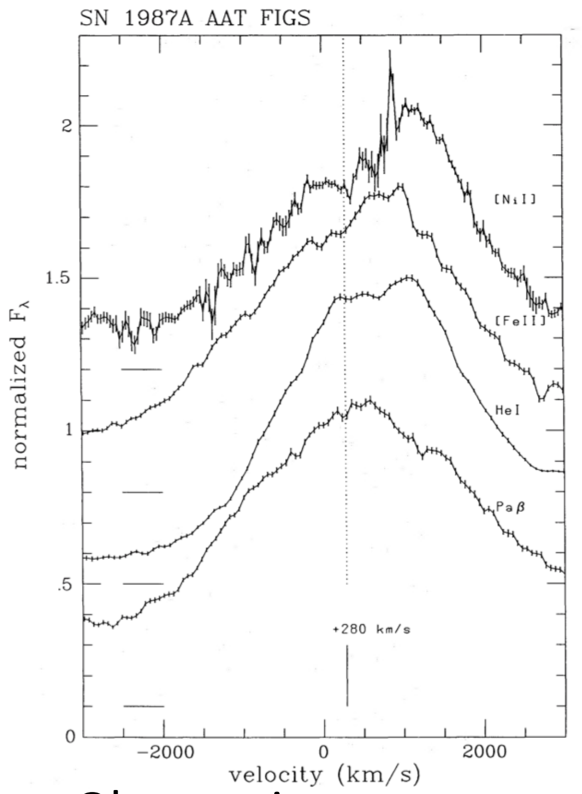
- Compared to decay lines: **Better data** and **less transfer-sensitivity** but **more approximate emissivity model** (here gamma deposition times the iron number fraction).
- Important confirmation of net recession of the ^{56}Ni, and degree of asymmetry.





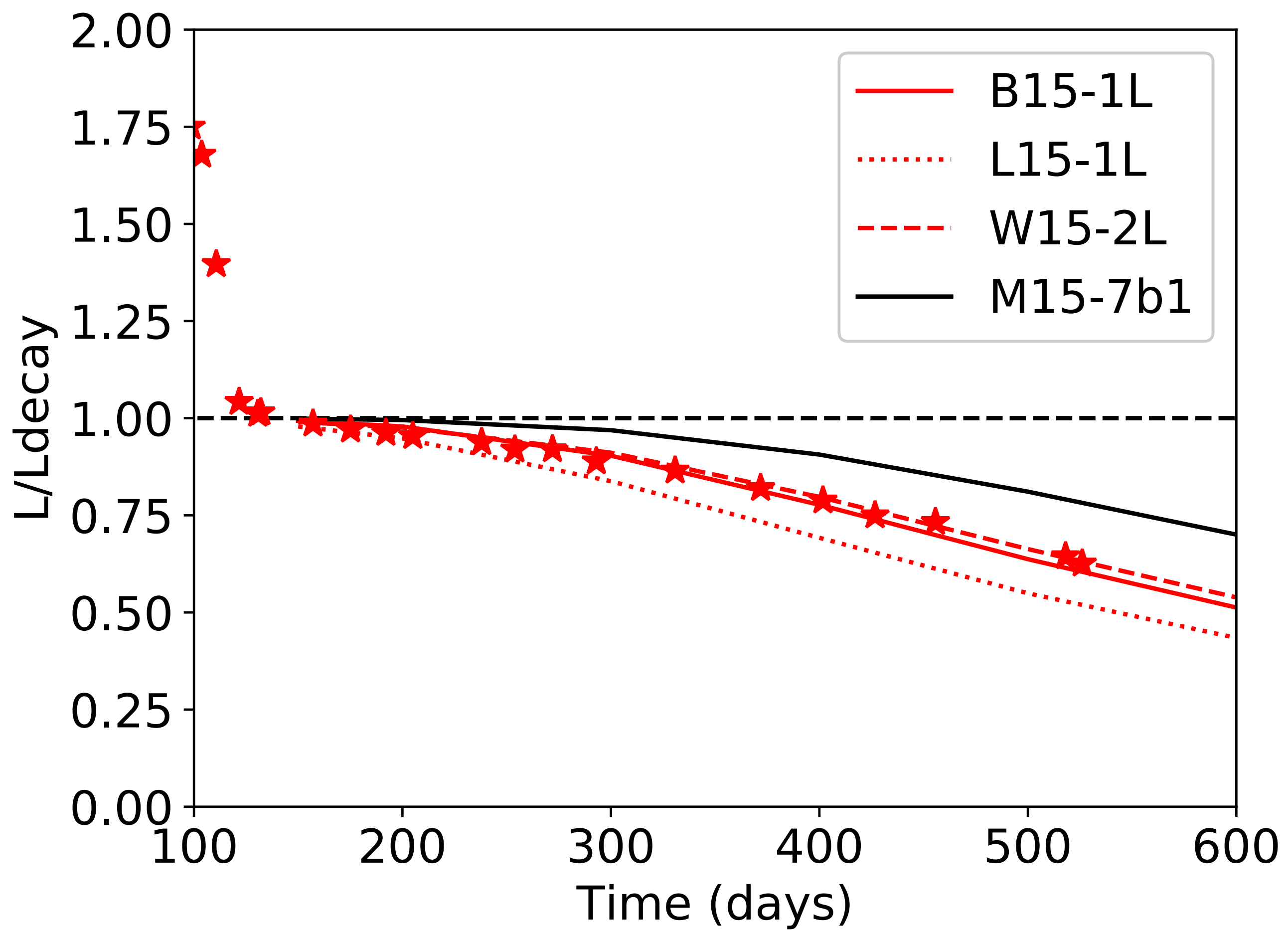






Observations:
Witteborn+1989,
Haas+1990,
Spyromilio+1990

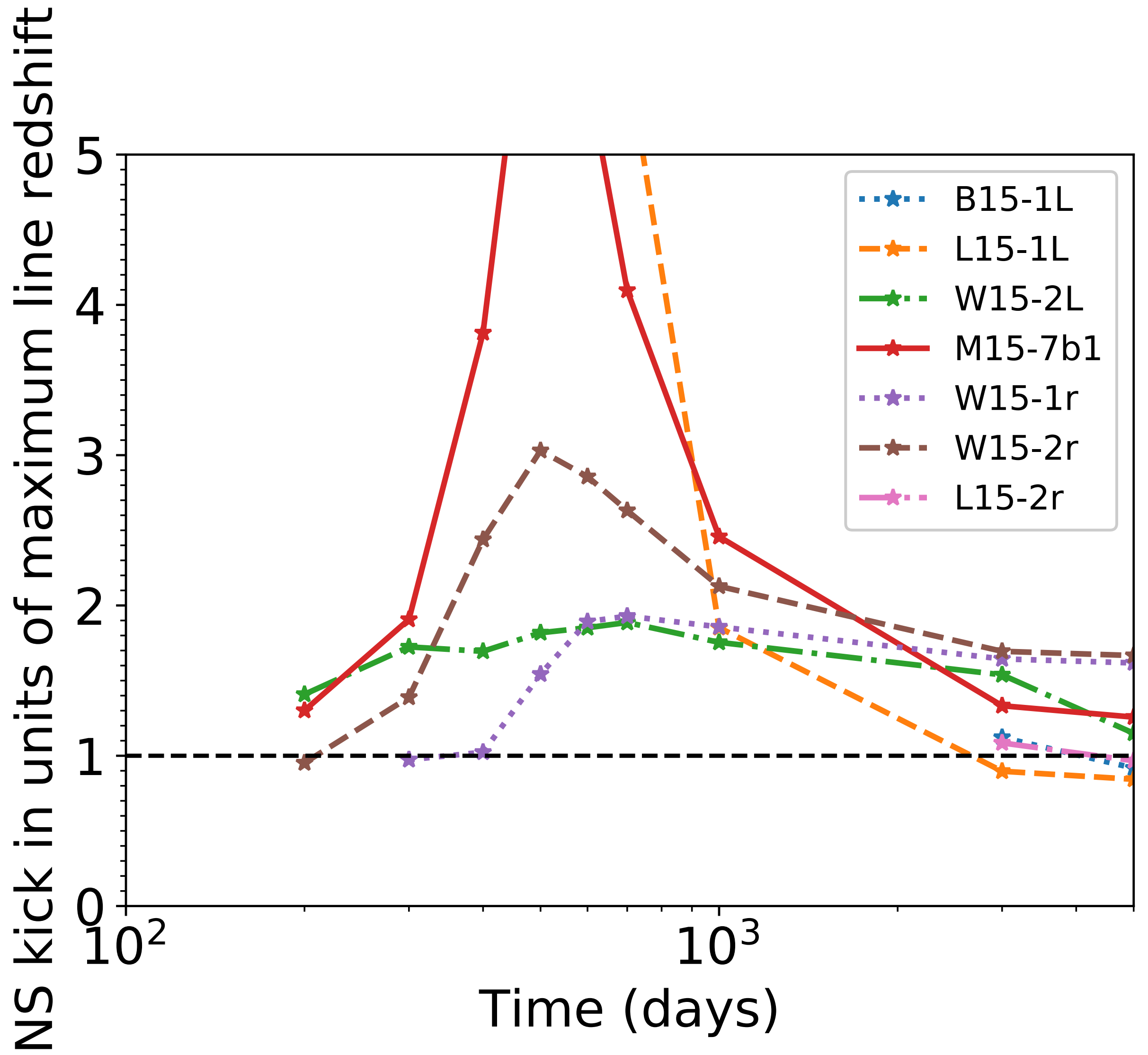
UVOIR light-curve fit: First test of 3D models for key observable



Data: Suntzeff+1990

- Models with ejecta mass of 13-14 $M_\odot$ do ok (assuming E ~ 1.5E51 erg)
- The model with ejecta mass 19 $M_\odot$ traps the gamma rays for too long.
- Trapping scales with M_{ejecta}^2 → good constraints on M_{ejecta}.

Neutron star kick constraint

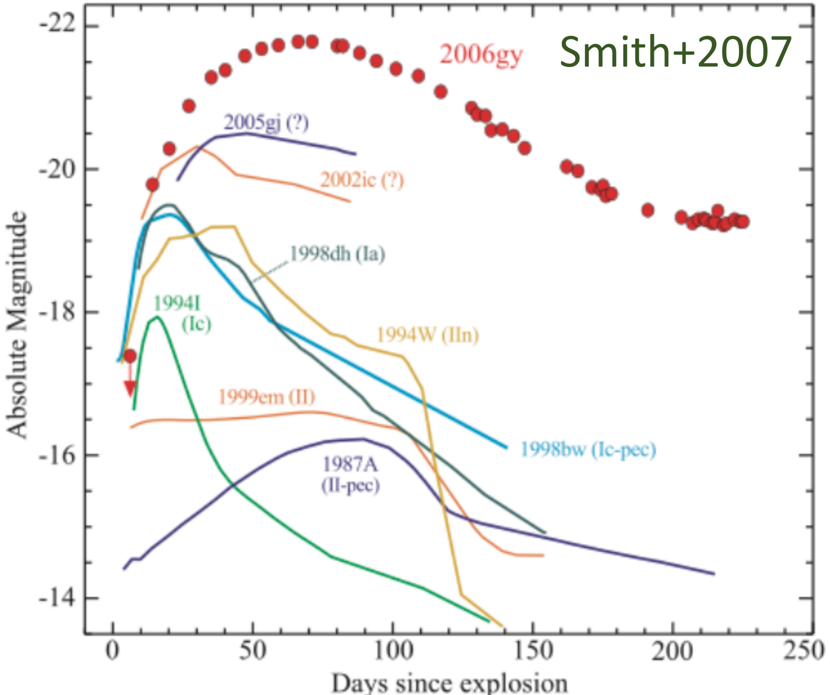


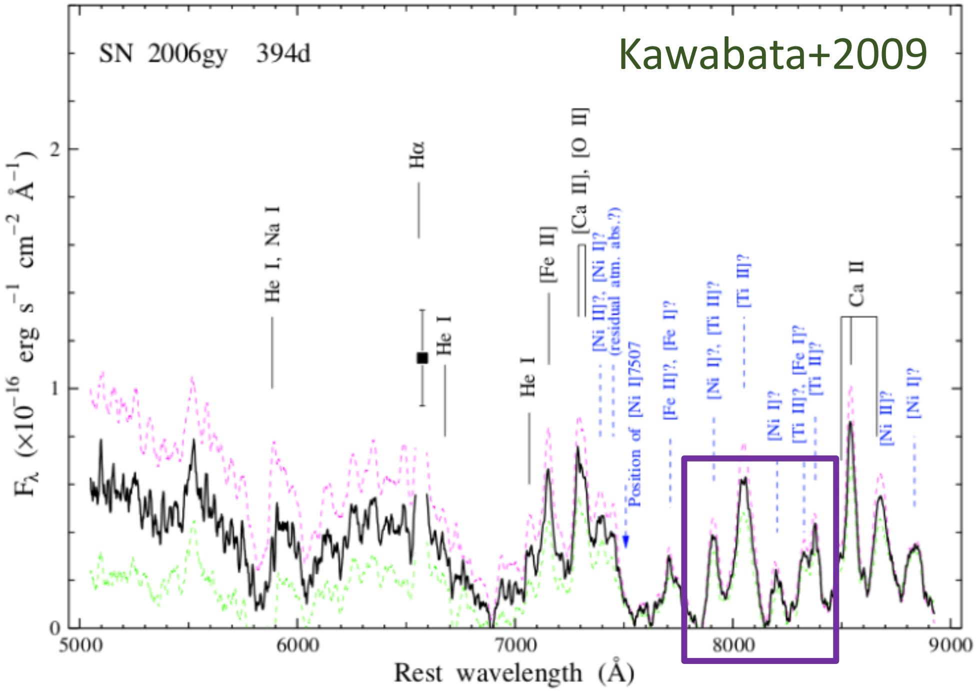
- All models produce a line redshift smaller than the (3D speed) NS kick.
- Observed line redshift in SN 1987A is ~500 km/s → **NS kick speed >~500 km/s.** Would place it in upper half of known distribution 10-1000 km/s.
- No direct constraint on angle to observer.

PAPER 2

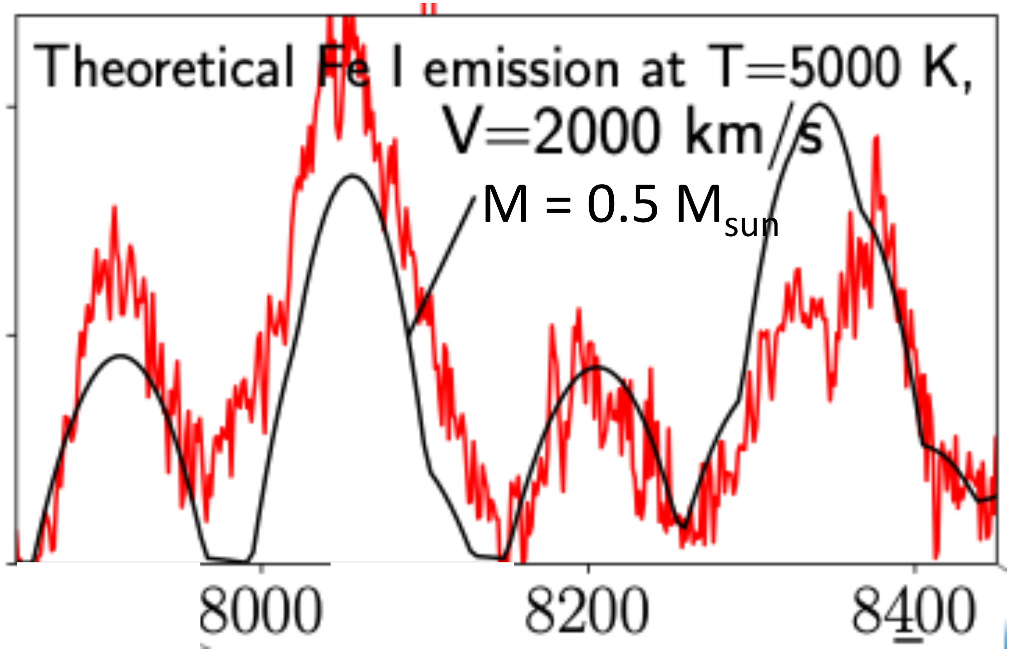
Superluminous SNe : background and context

- The brightest tail of (rare) events start to be discovered with automated surveys mid-2000s. Named “superluminous”.
- Most events either **Type IIn** (interaction with CSM) or **Type Ic** (no He or H lines seen at all).
- Radiated energies up to around 10^{51} erg (100 times more than a typical SN).
- **SN 2006gy**: One of the first discovered events (Type IIn). A broad light curve, a spectrum with unidentified emission lines at 400d.

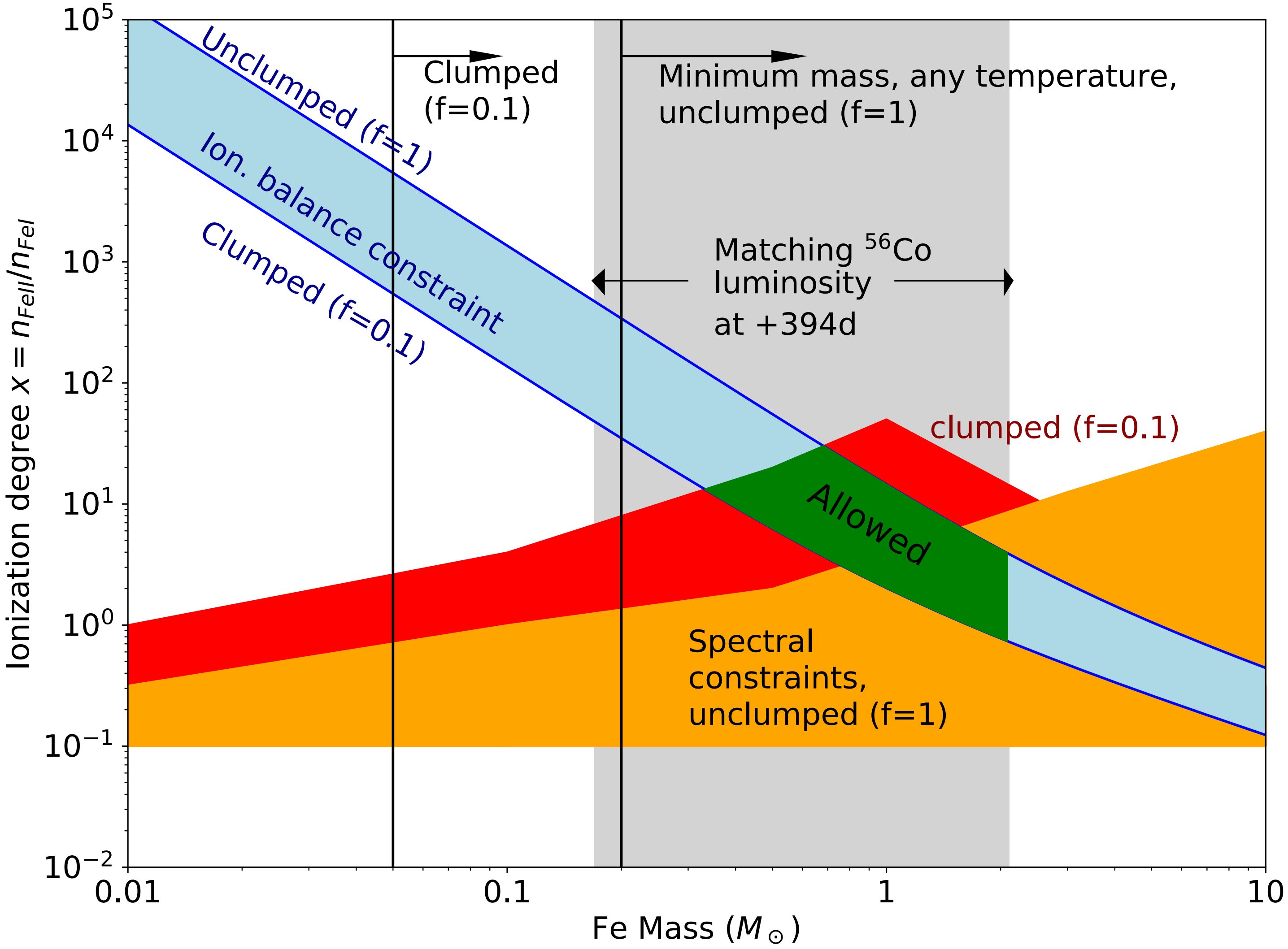




Identification of neutral iron lines in SN 2006gy and a large iron mass

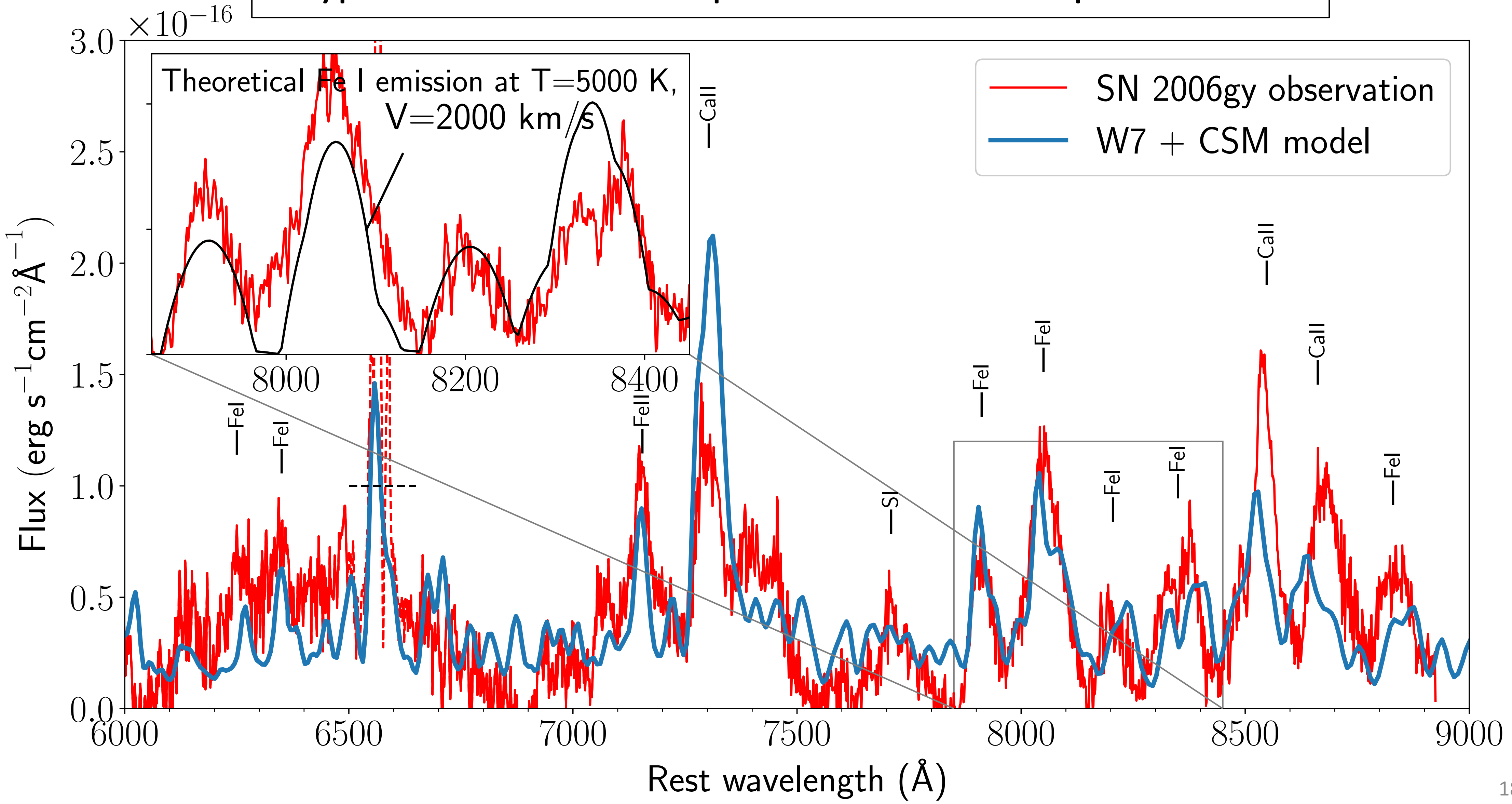


Iron mass limit: >0.3 M$_\odot$

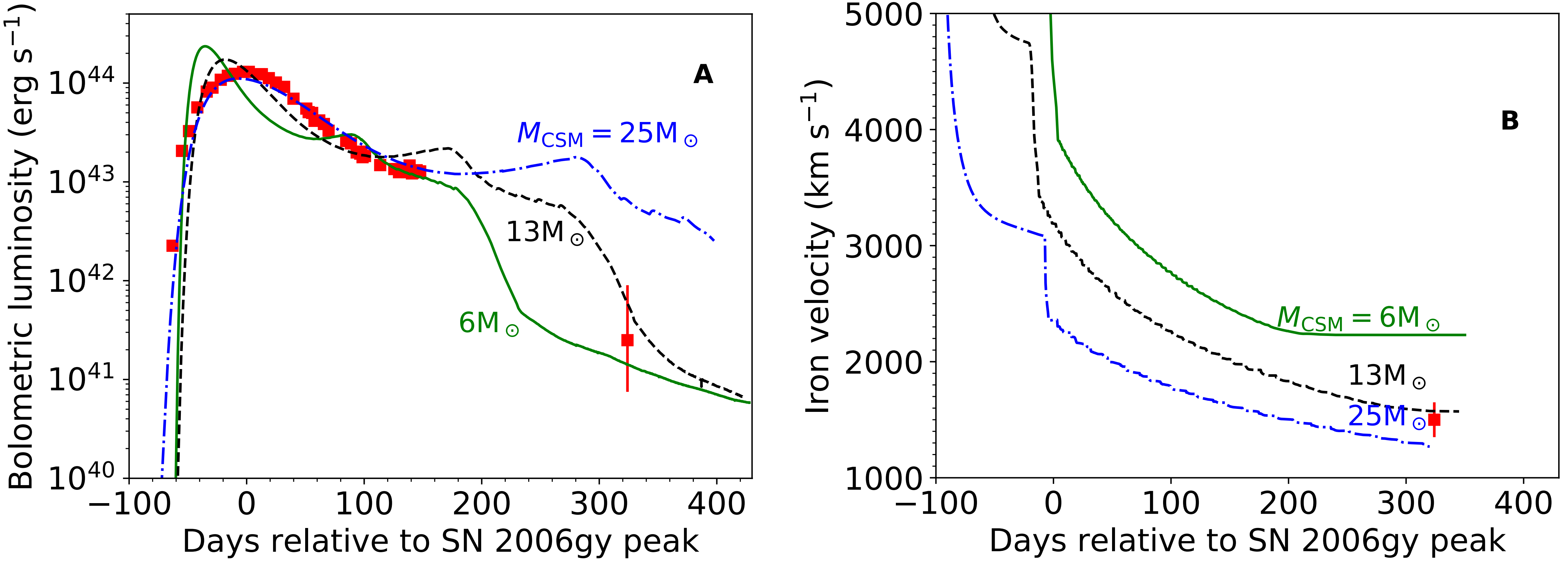


Identification of neutral iron lines in SN 2006gy and a large iron mass

A Type Ia + CSM model reproduces observed spectrum well



The CSM mass controls both light curve duration and iron deceleration. M_{CSM} ~10-15 $M_{\odot}$ gives a consistent fit to both.



Common envelope evolution holds promise to explain the *synchronization* of CSM ejection and SN explosion (separated by ~100y)

Terman 1995

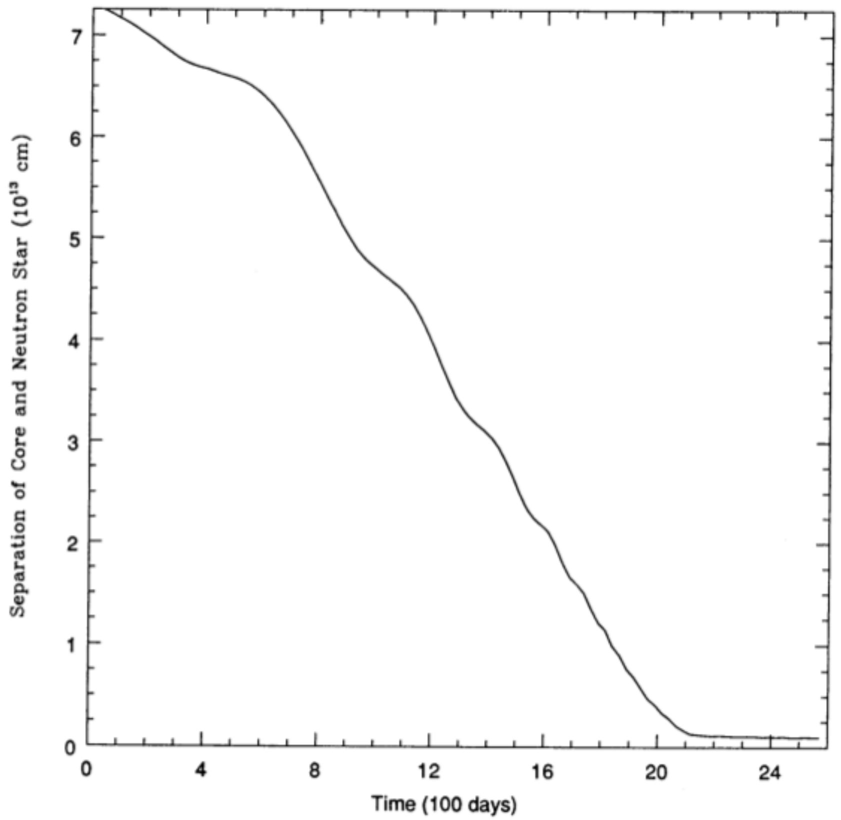


FIG. 12.—Time variation of the separation between the core of the red supergiant and the neutron star companion in sequence 3. The separation is expressed in units of 10^{13} cm and the evolution time is expressed in units of 100 days.

E_{orb} = 4E48 erg ($M_{core}/M_\odot$) (M_{WD}/1.4 M_{sun}) ($R/R_\odot)^{-1}$

$E_{bind,env}$ = 4E48 erg (M_{env}/10 $M_\odot$) (R/100 $R_\odot$)

$tau_{inspiral}$ = 1-200y

Formation of Cataclysmic Binaries through Common Envelope Evolution

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Received August 23, revised November 11, 1978

Summary. We follow the common envelope evolution for a 5 $M_\odot$ evolved red giant in wide orbit with a 1 $M_\odot$ main sequence star. Contact is assumed to occur when the degenerate core of the red giant has grown to 1 $M_\odot$. The main sequence star and the degenerate core of the red giant form a binary surrounded by a common envelope. We follow the dynamical evolution of the internal binary in this envelope. The interaction between binary and common envelope is modeled by a corotating region around the binary, where tidal effects dominate, coupled to a differentially rotating envelope, where turbulent convective transport of angular momentum dominates.

The resulting evolution leads to a rapid shrinking of the inner binary in an extended envelope of near constant high luminosity $L \approx 10^5 L_\odot$. The braking time is inversely proportional to the binary separation and grows from about a year at 10^{13} cm to about a 100 yr at 10^{11} cm. The evolution is fairly independent of the assumed nuclear and accretion luminosities of the two "cores". A closed circuit coupling between the luminosity generated by friction and the frictional coefficient stabilizes the total luminosity and allows generalization of our results to other binary masses.

We thus conclude that common envelope evolution of a main sequence star with a degenerate core will normally reduce an initial wide separation to distances of a few solar radii within less than 1000 yr. We argue that rapid mass transfer from the main sequence star into the common envelope ends the evolution at this stage and leads to the loss of the envelope, leaving a system characteristic of cataclysmic variables or their immediate progenitors.

The question arises by what method did such systems decrease their separation to their present few solar radii (Ritter, 1976).

One suggestion is that the double star system might have formed a common corotating envelope extending to the outer Lagrangean point L_2. Mass loss through L_2 then would lead to a loss of average specific angular momentum and result in continuous decrease of orbital separation as discussed by Nariai and Sugimoto (1976) and Flannery (1977). Essential for this process is the assumption of corotation up to the Lagrangean point L_2. However in many cases corotation will be lost before a common envelope would extend that far. The separation of the two dense stellar cores then decreases due to angular momentum transfer from the rapidly revolving inner cores to the slowly rotating outer layers (Paczyński, 1976 and references therein). We show that as soon as synchronism is lost, the friction generated luminosity expands the envelope and makes it improbable that corotation can be achieved. The processes leading to the formation of the common envelope are discussed in Sect. II.

We investigate the further evolution of the binary system consisting of the main sequence star and the red giant core in the common envelope. Essential for the spiralling in is the process of tidal and frictional transfer of angular momentum between the internal binary and the common envelope (Sect. III). The mechanism of angular momentum transfer proposed here differs from earlier considerations by Paczyński (1976). It depends on the structure of the surrounding envelope which itself depends sensitively on the frictional luminosity generated in this process

Summary

- The study of lines from ^{56}Ni and its decay products (^{56}Co, ^{56}Fe) – across the EM spectrum - provide one of the cornerstones of supernova analysis.

Paper 1

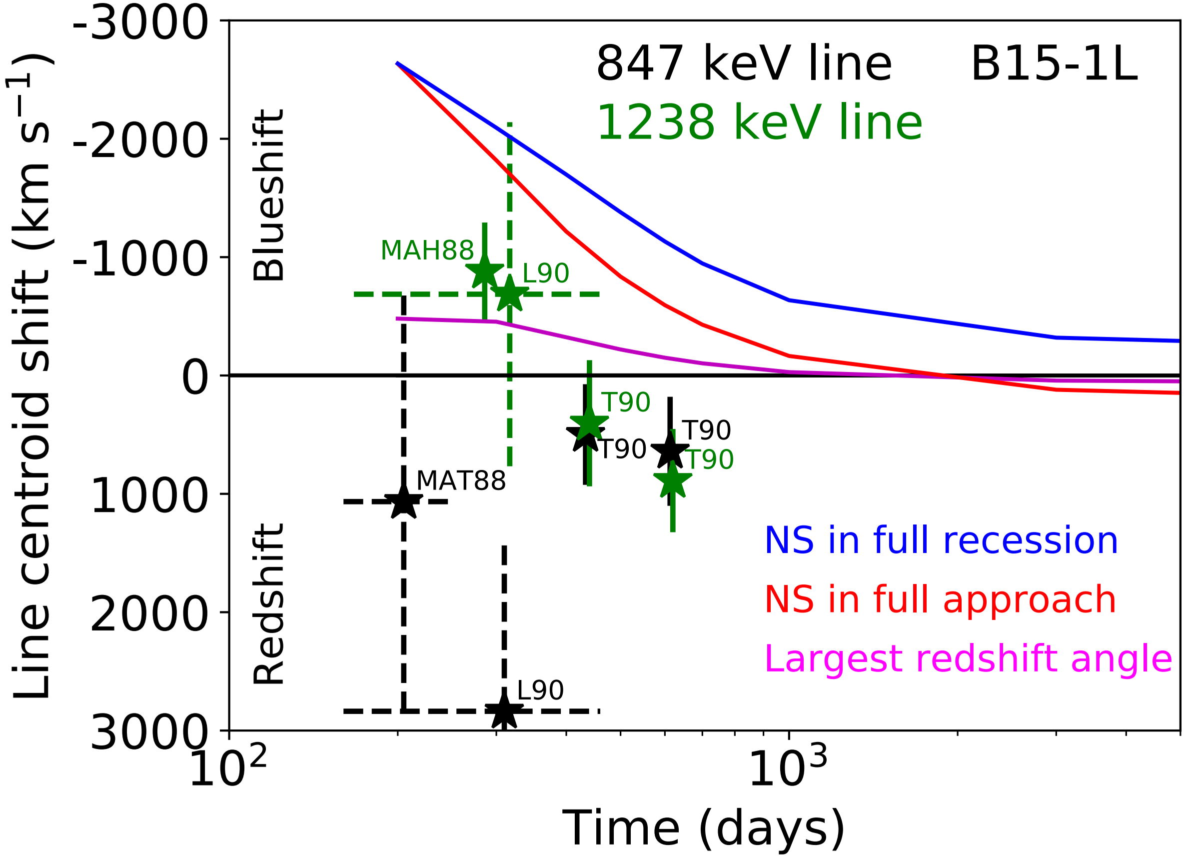
- First prediction of line profiles from ^{56}Ni/ ^{56}Co decay lines and Fe IR lines using realistic 3D models. Severe viewing angle effects both for shifts and widths.
- To reproduce observed lines in SN 1987A a model need
  - A) A ^{56}Ni asymmetry of >~ 400 km/s.
  - B) A ^{56}Ni bulk speed >~ 1500 km/s.
  - C) Ejecta mass ~ 13-14 $M_{\odot}$.

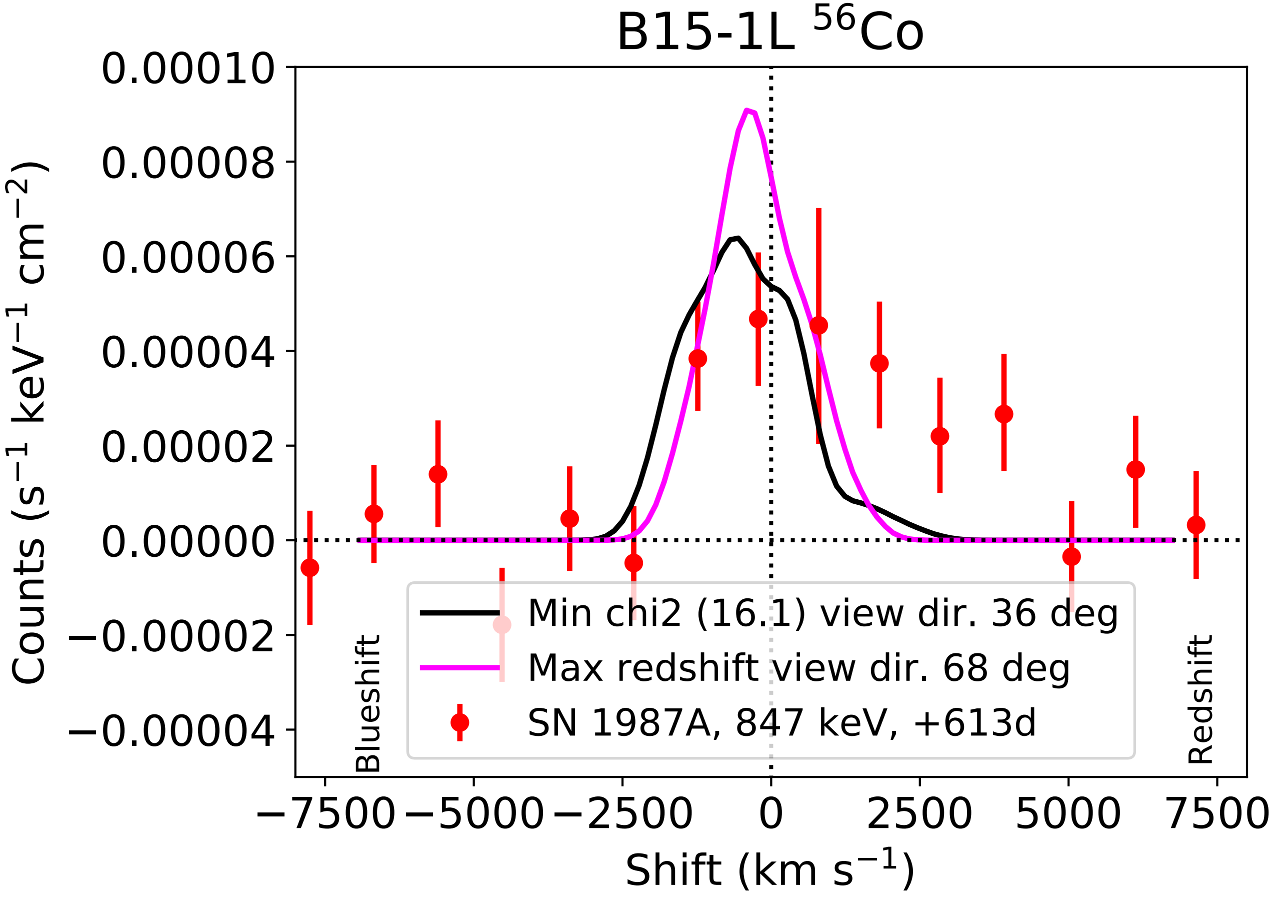
Paper 2

- Current set of neutrino-driven 3D models have *marginal success*.
- Identification of lines at 400d in SLSN SN with Fe I. Inferred Fe mass >~ 0.3 $M_{\odot}$.
- A "Ia-CSM" model (with $M_{CSM} >> M_{ejecta}$) reproduces both spectrum, light curve and Fe deceleration.

Comparison to SN 1987A

B15: Too small ^{56}Ni asymmetry (~150 km/s)





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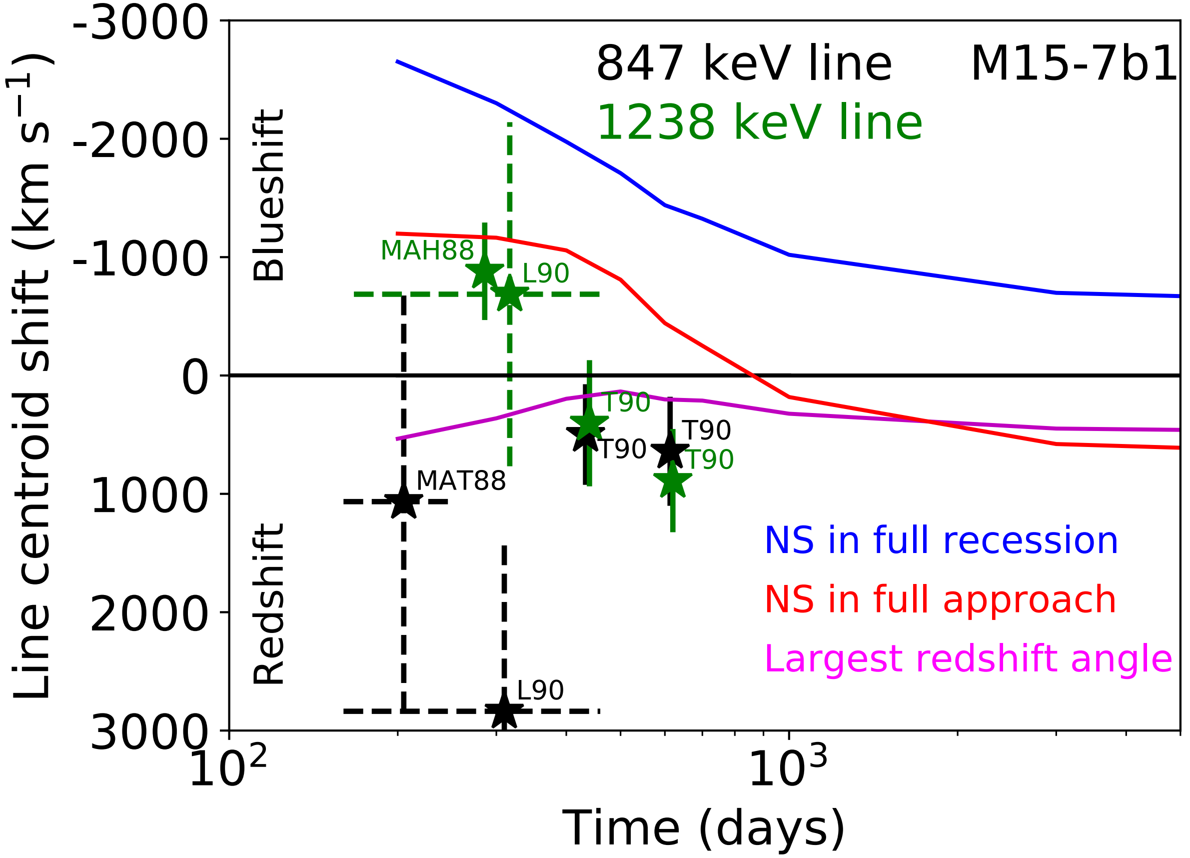

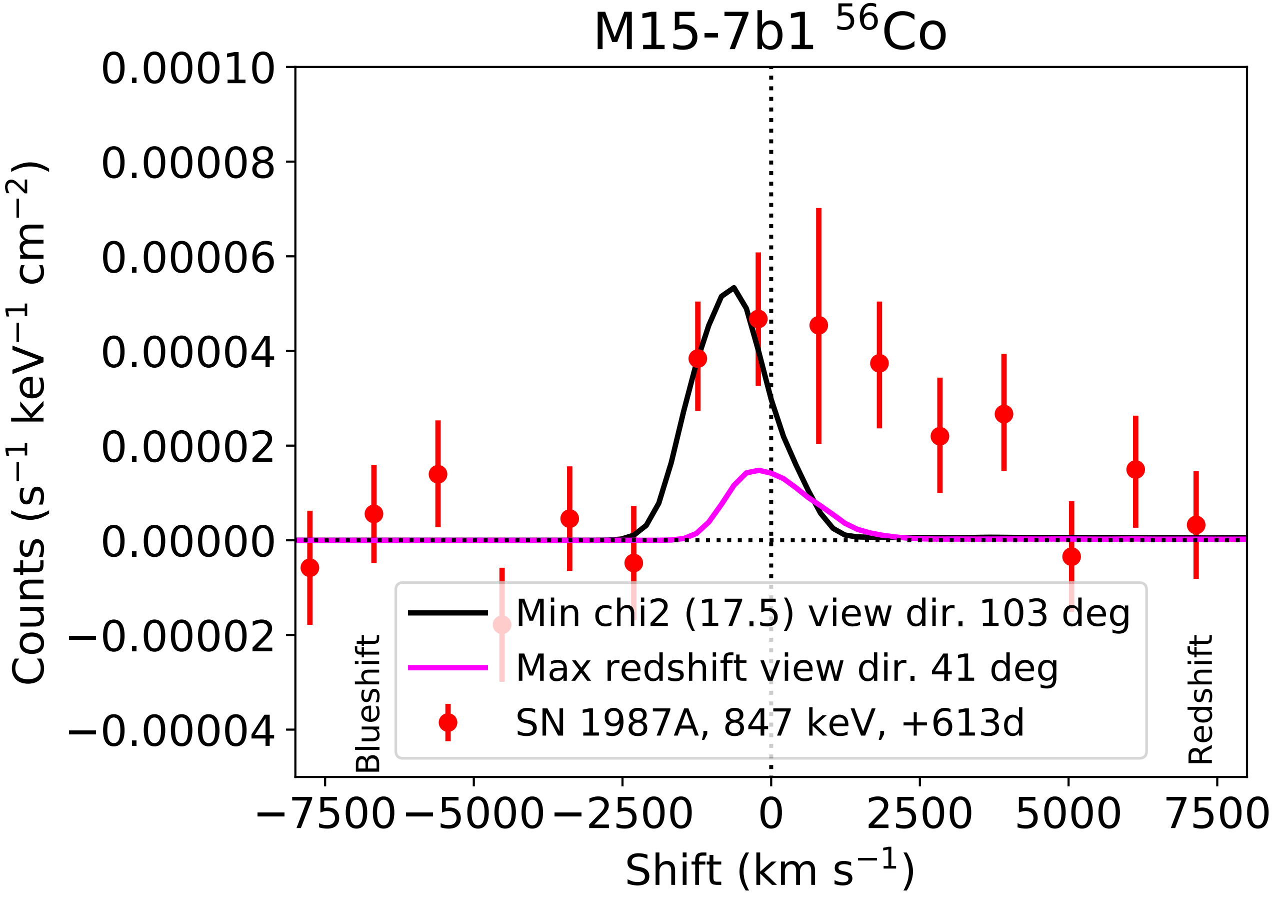

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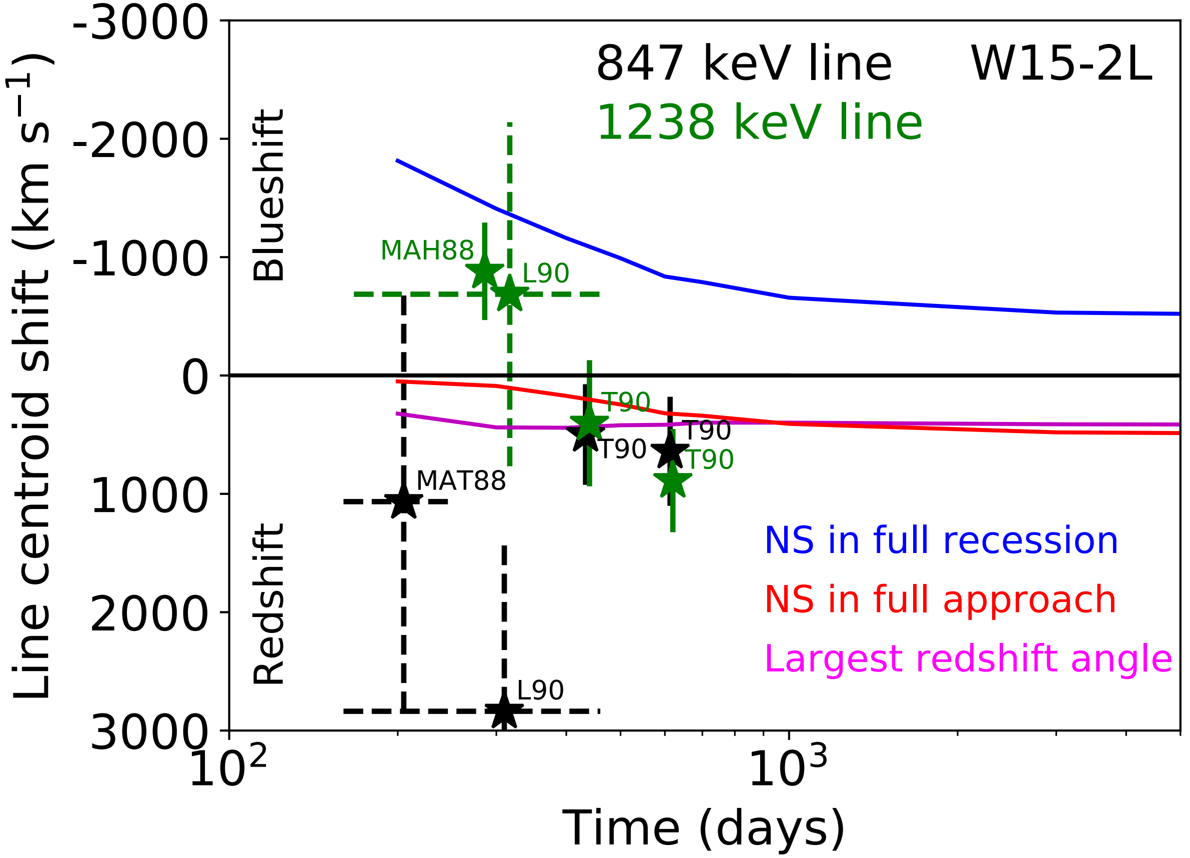

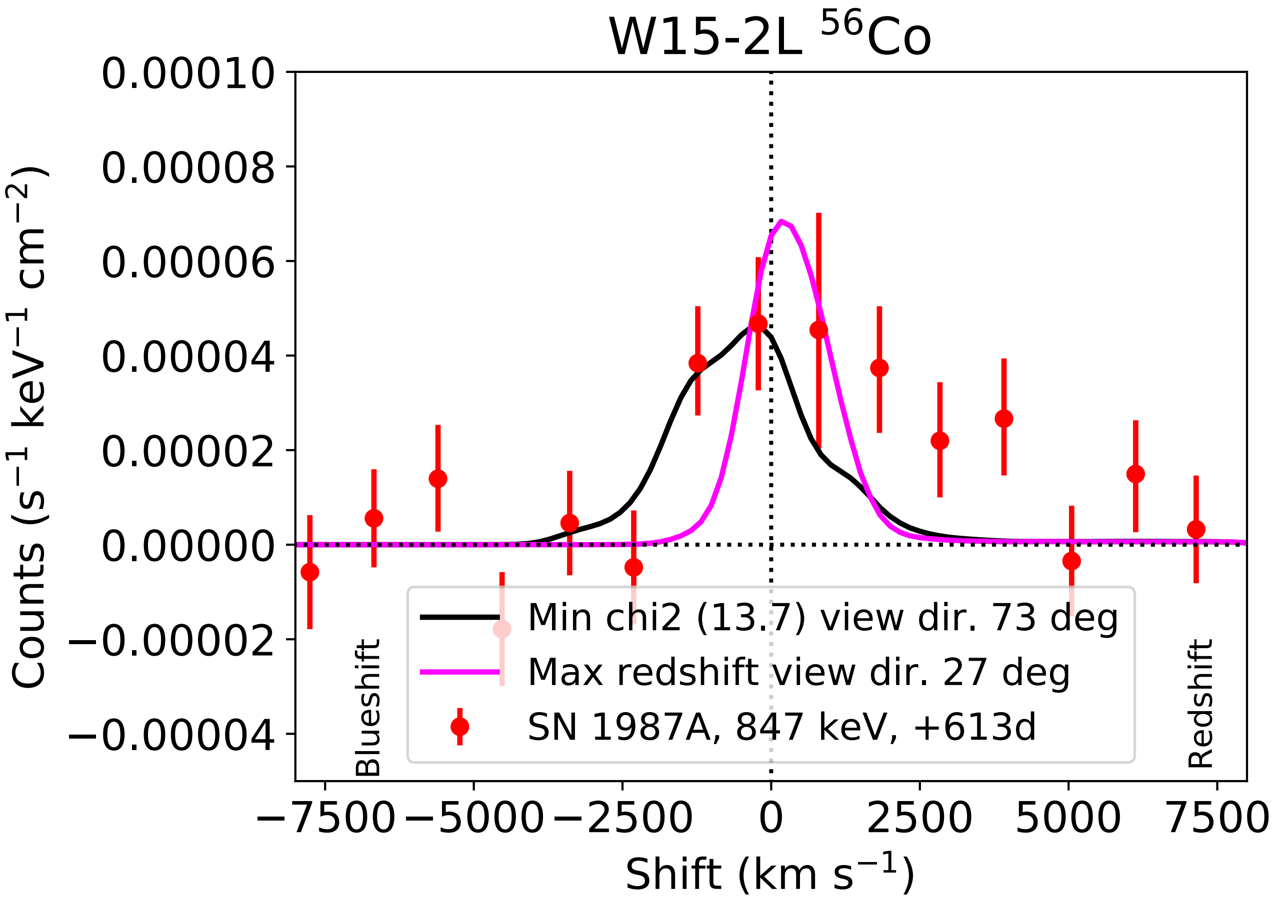

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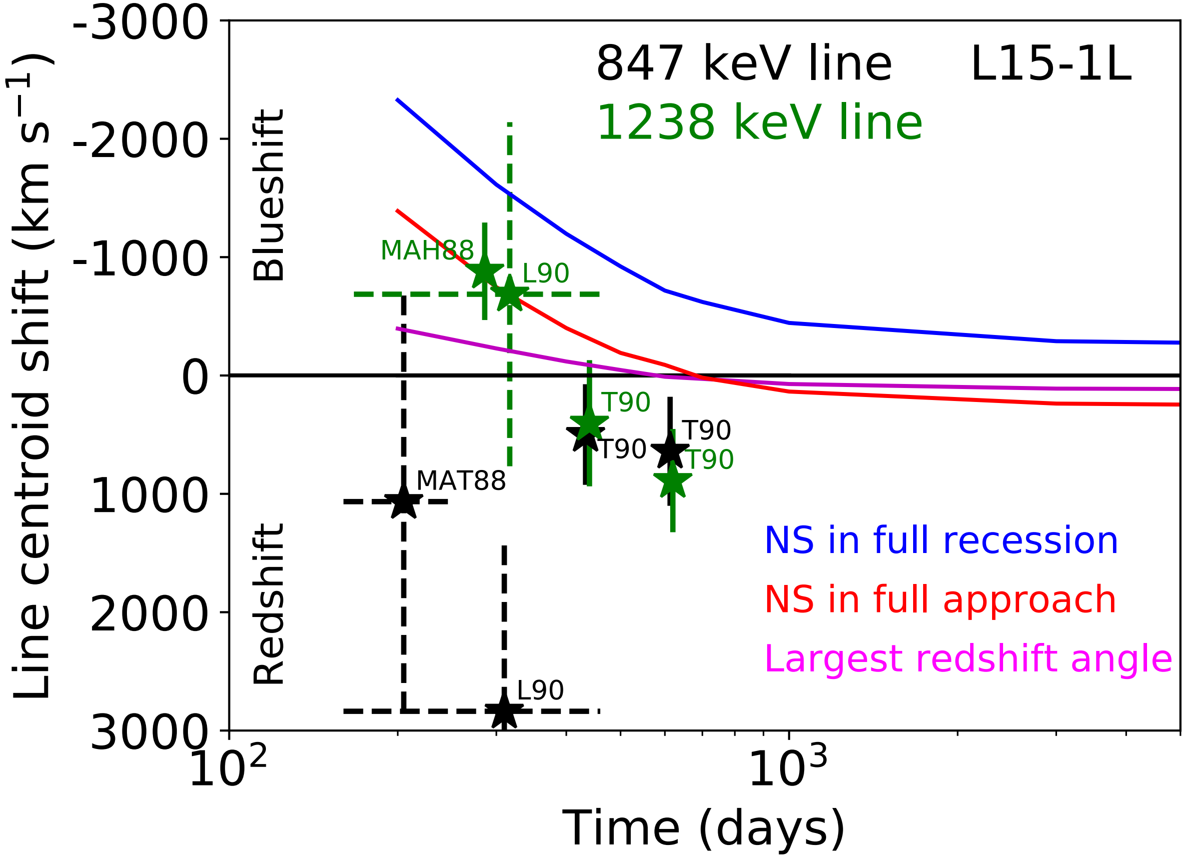

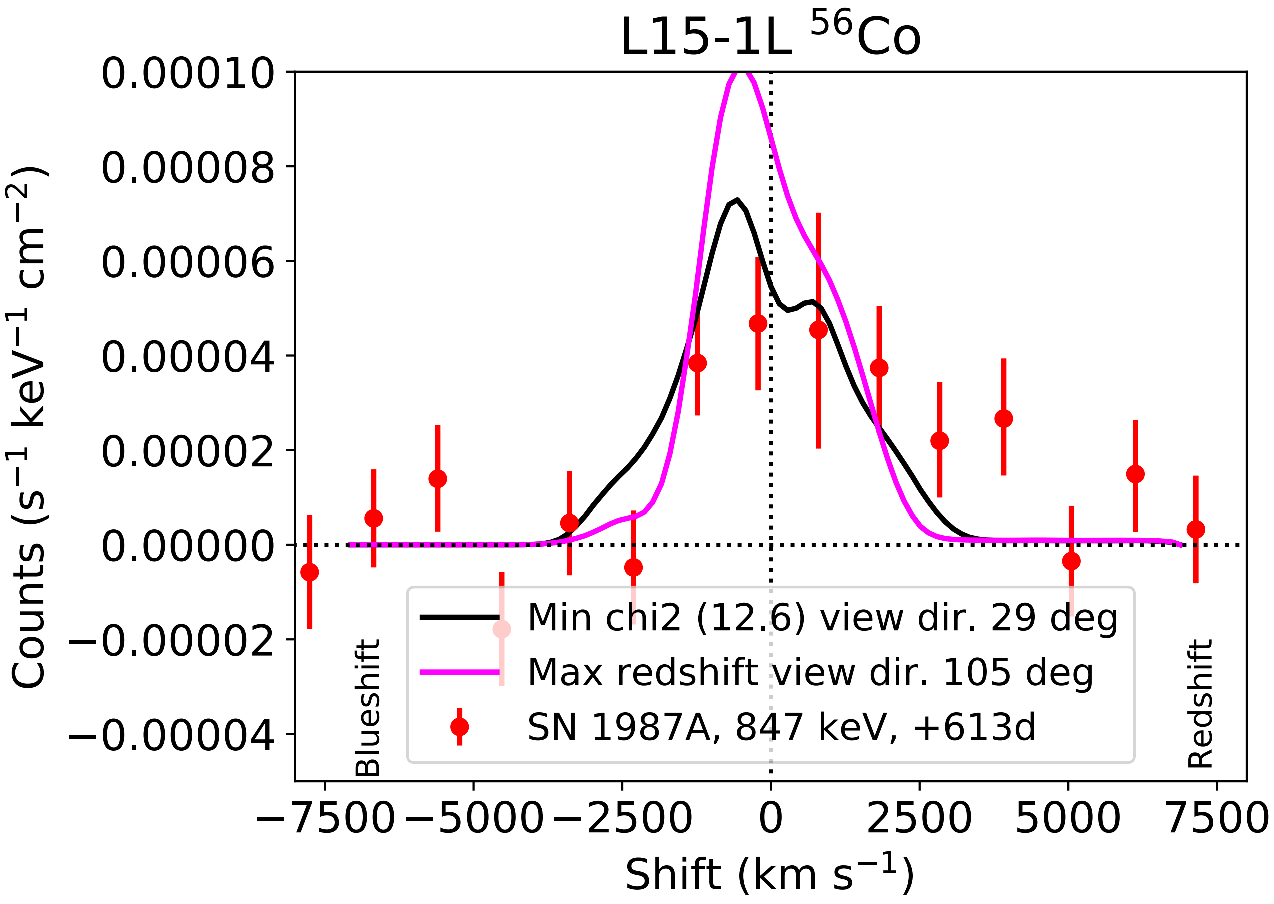

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