Clues on supernova explosion physics from nebular iron lines

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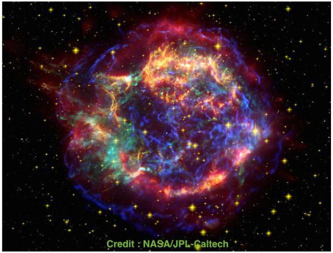

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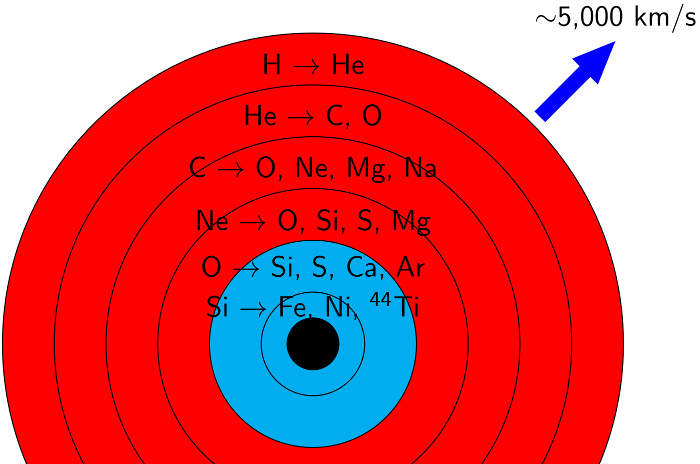
Outline

- Supernova explosive nucleosynthesis
- Spectral synthesis modelling and the SUMO code
- Application 1: Superluminous SN 2006gy - detection of a massive iron reservoir suggests a new model scenario
- Application 2: Ni/Fe ratios in core-collapse supernovae
- Application 3: ^{56}Ni decay lines and Fe IR lines in 3D core-collapse models
- Outlook and summary

Nucleosynthesis in massive stars and their supernovae

- 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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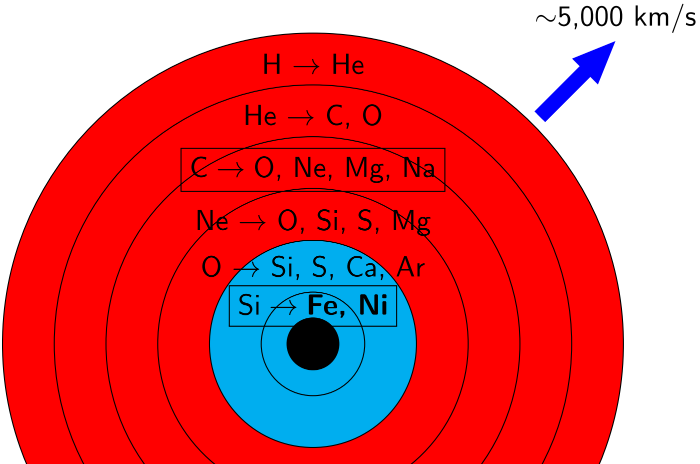
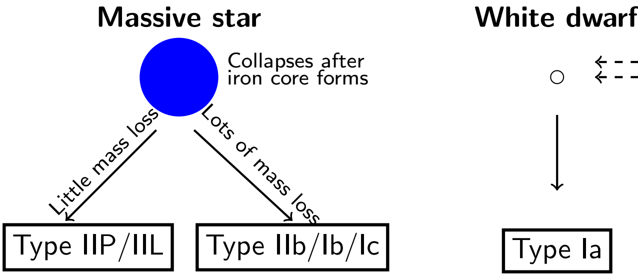
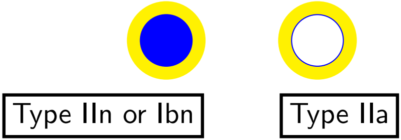


The supernova landscape



• $E \sim 10^{51}$ erg • $M_{ej} = 2 - 20\ M_\odot$ • $M(^{56}\mathrm{Ni}) = 0.01 - 0.2\ M_\odot$	• $E \sim 10^{51}$ erg • $M_{ej} \approx 1\ M_\odot$ • $M(^{56}\mathrm{Ni}) = 0.3 - 0.7\ M_\odot$

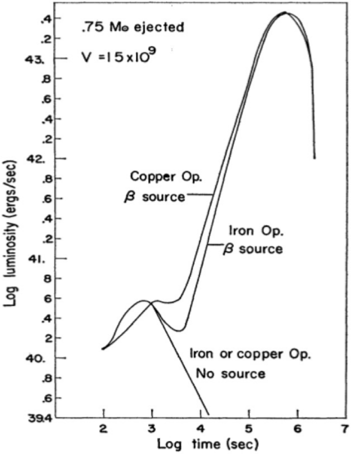
Sometimes : CSM interaction



Disc

The key role of ^{56}Ni in supernovae

- Colgate & McKee 1969: the ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe decay chain is the reason we see (most) SNe at all.
- This ^{56}Ni is produced in the innermost region of the collapsing star, just outside newly formed NS $\rightarrow$ **direct diagnostic of explosion physics and innermost stellar layer of progenitor.**
- We can probe this Ni/Co/Fe in multiple ways
    - Light curves
    - Gamma decay lines of ^{56}Ni and ^{56}Co
    - Optical/IR emission lines



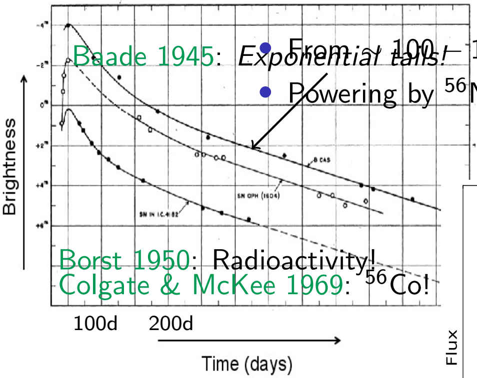
The nebular phase: an opportunity to see the inner parts of supernovae

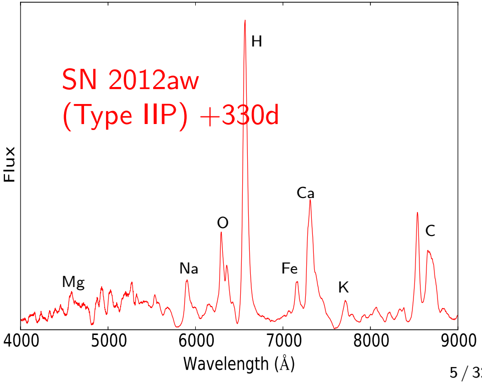
- From $\sim 100 - 1000$d post explosion.
- Powering by ^{56}Ni$\rightarrow$^{56}Co$\rightarrow$^{56}Fe.

Baade 1945: *Exponential tails!*

Borst 1950: Radioactivity!

Colgate & McKee 1969: ^{56}Co!





Forward modelling: the SUMO code

Radioactive decay and γ-ray transport

Distribution of Compton electrons

- Spencer-Fano equation

Radiative transfer

- 300,000 atomic lines, 3,000 bound-free continua, free-free, electron scattering

Temperature

- Heating = cooling

NLTE statistical equilibrium

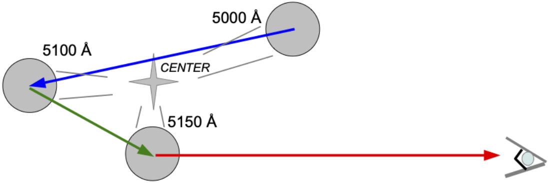
- 22 of 28 elements from H to Ni, 3 ion. stages, ∼100 exc. states each

Jerkstrand 2011, PhD thesis, Jerkstrand+2011,2012

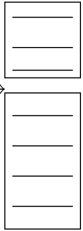
- 1-D version of code allows for macroscopic mixing and clumping by 'virtual grid' option.

Radiative transfer

- Homologous flow (=Hubble flow) → lines "cooperate" to provide line opacity for years.
- Treat line interactions one-by-one with Sobolev approximation (Monte Carlo method).
- Flexible degree of radiation-matter interaction (balance run-time and convergence with accuracy).



Split typically at 200-300 levels →

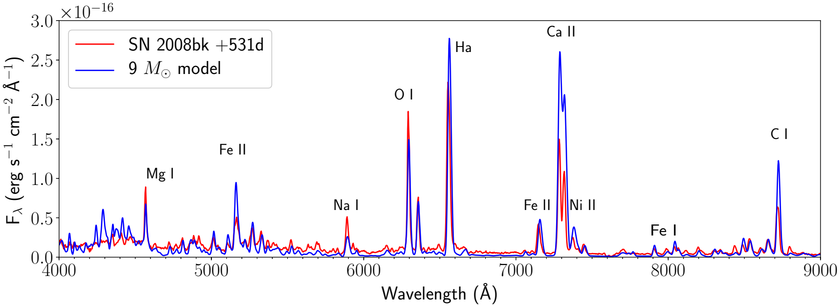


High levels: uncoupled to rad. field. Dont solve NLTE equations. Scatter/fluoresce on the fly.

Low/mid levels: coupled to rad. field. Attenuate packet and accrue photoexc. rate to be used in next NLTE solution.

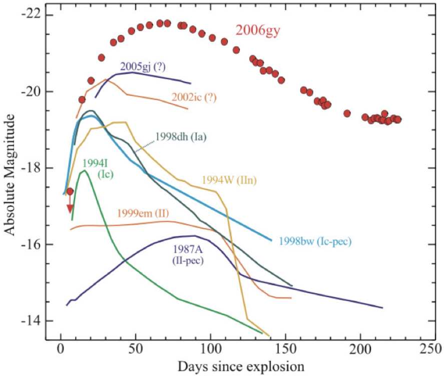
Example

A $M_{ZAMS} = 9\ M_\odot$ 1D neutrino-driven simulation compared to a weak IIP explosion (Jerkstrand, Ertl, Janka+2018)



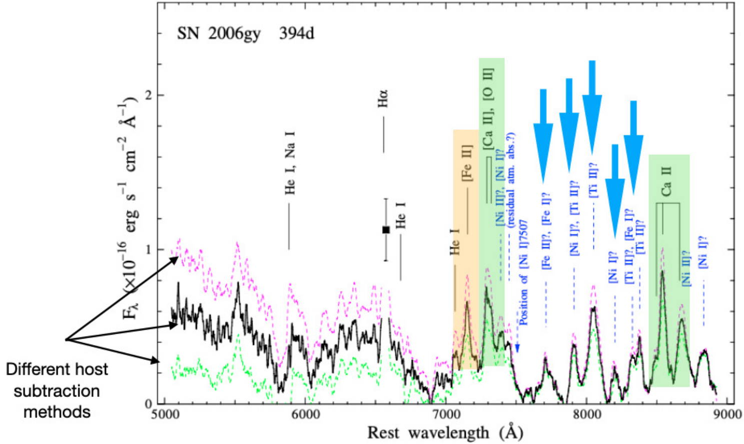
Application 1: Iron in superluminous SN 2006gy

- 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**.



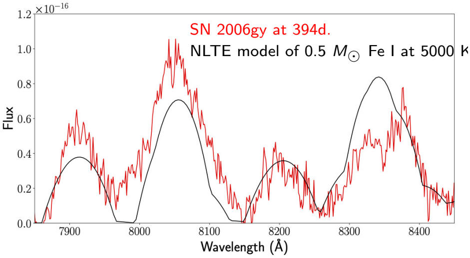
Smith et al. 2007

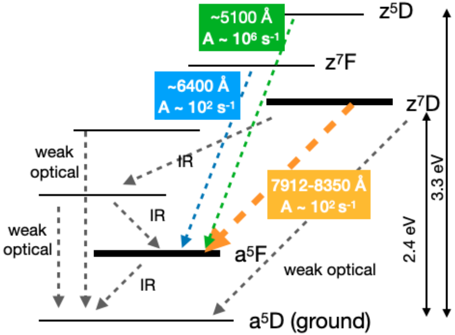
Strange, unknown lines seen at 400d *Kawabata et al 2009*



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

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





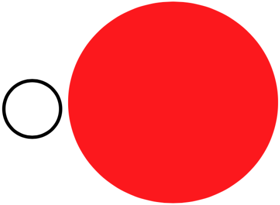
Modelling of the line emission constrains the iron mass to

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

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?

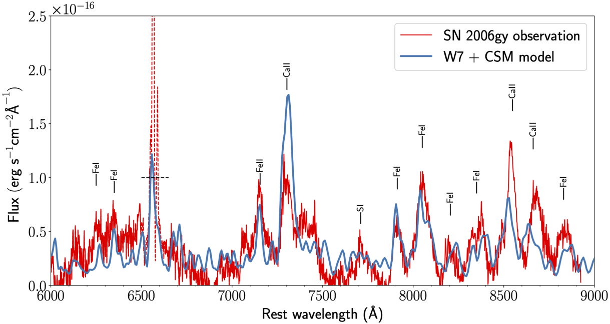
Could SN 2006gy be the result of a merger of a white dwarf with a massive star?

- **Causally connects a massive CSM ejection with a SN explosion** (inspiral $\rightarrow$ 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).

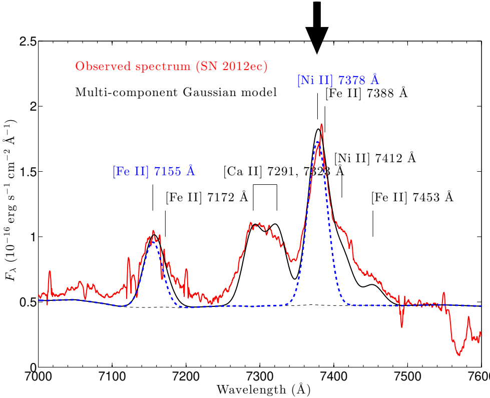
Questions raised if WD-RSG merger is the right explanation

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?

Strong support in the binary stellar evolution literature for (1) and (2) to work out, (3) unclear.

Application 2: Ni/Fe ratios in CCSN

- 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

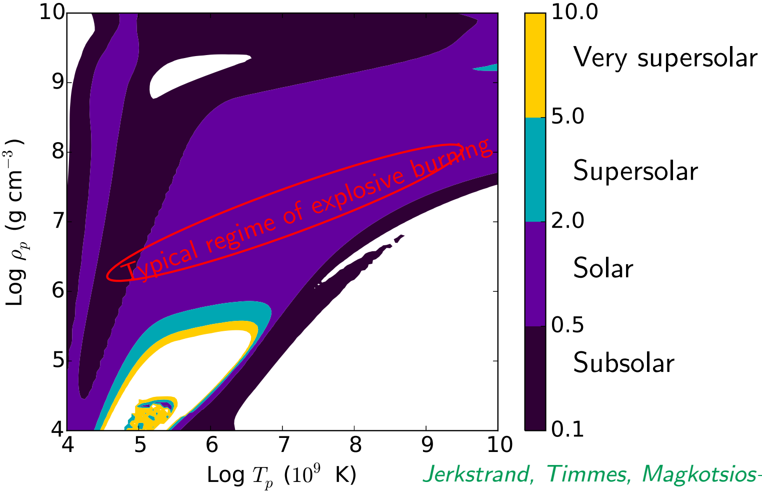
SN	Ni/Fe times solar	Reference
SN 1987A	0.5 – 1.5	Rank+1988, Wooden+1993, AJ+2015
SN 2004et	$\sim$1	AJ+2012
SN 2012A	$\sim$ 0.5	AJ+2015
SN 2012aw	$\sim$ 1.5	AJ+2015
SN 2012ec	2.2 – 4.6	AJ+2015
SN 2006aj	2 – 5	Maeda+2007, Mazzali+2007
Crab	60 – 75	MacAlpine+1989, MacAlpine+2007

- Average ratio $\geq$ solar.
- 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 $\sim$ solar produced for typical burning conditions

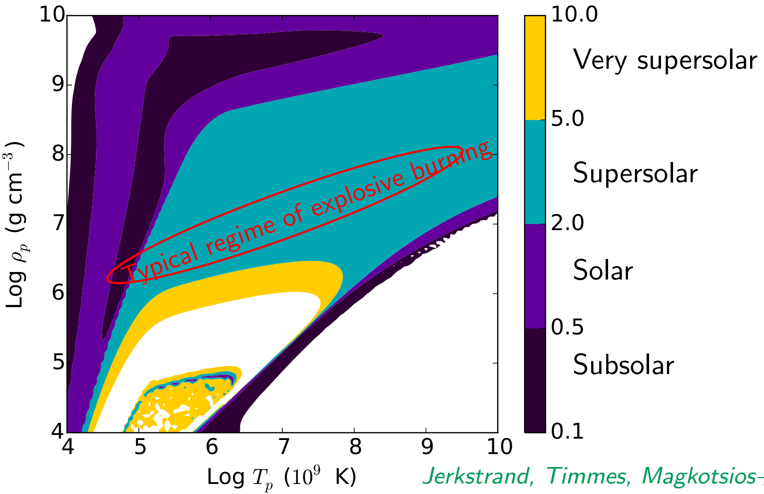


Jerkstrand, Timmes, Magkotsios+2015, ApJ

What is Ni/Fe ratio diagnostic of?

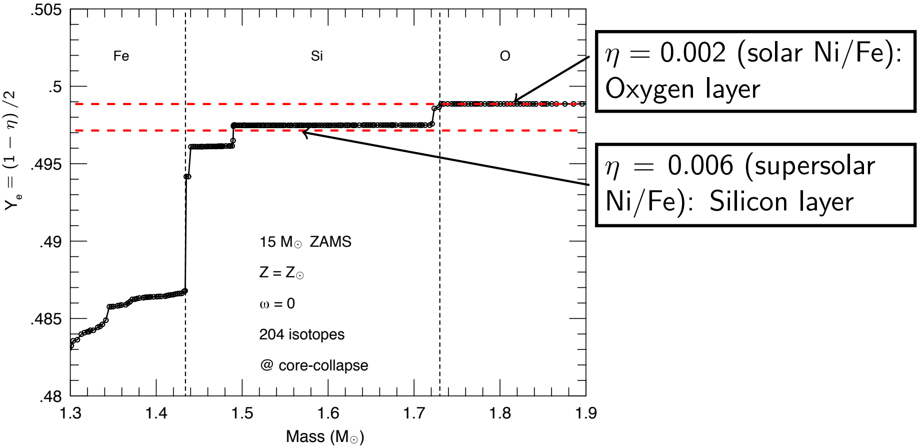
The **neutron-richness of the fuel** ($\eta = \frac{N_n - N_p}{N_n + N_p}$) sets the Ni/Fe ratio.

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



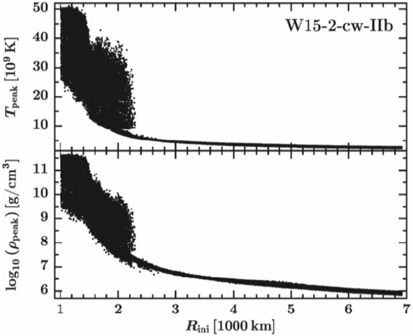
Jerkstrand, Timmes, Magkotsios+2015, ApJ

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



- 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?



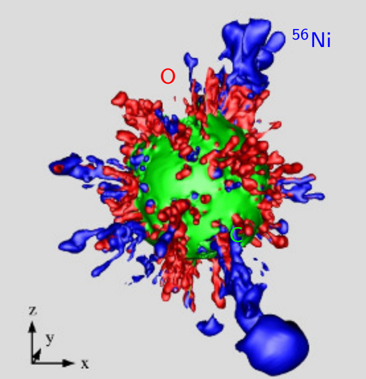
Wongwathanarat et al. 2017

- 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.

Application 3: Gamma decay lines and Fe lines in 3D models

Jerkstrand, Wongwathanarat, Janka et al., MNRAS 2020

- New **3D version of SUMO**, as of now with highly simplified microphysics.
- Motivation for 3D modelling:
  - Allow tests of 3D explosion simulations.
  - Understand degree of validity of 1D models, and how to best use them.
  - Which microphysics to trade off?

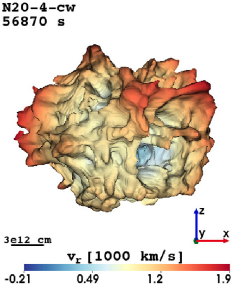


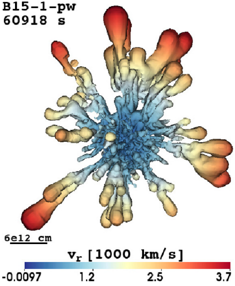
Hammer et al, 2010, ApJ

3D explosion simulations

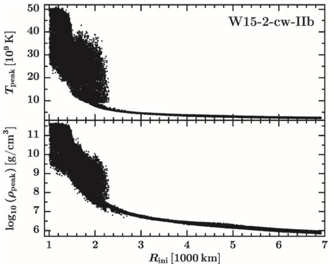
- First 3D models with realistic explosion physics, evolved to late times, produced by the Garching group Wongwathanarat+2013,2015,2017, Gabler+2021 MNRAS, Stockinger+2020, ApJ

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





Wongwatharanat+2015



Wongwatharanat+2017

3D hydrodynamic model set

$M_{ZAMS} = 15 - 20\ M_\odot$ progenitors exploded with ∼1.5 Bethe.

Model	E (10^{51} erg)	Ejecta mass ($M_\odot$)	^{56}Ni bulk speed (km/s)	^{56}Ni asymmetry (km/s)
B15	1.4	14	1130	145
L15	1.7	14	1160	398
M15	1.4	19	1490	473
W15	1.5	14	1170	517

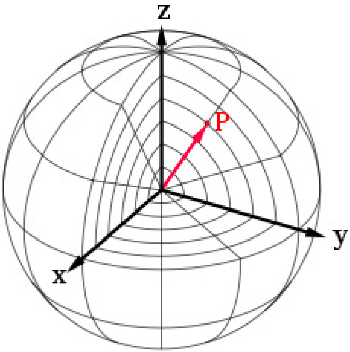
Wongwatharanat+2015, 2017, Gabler+2021

↑ Imprint on **line widths**

↑ Imprint on **line asymmetries**

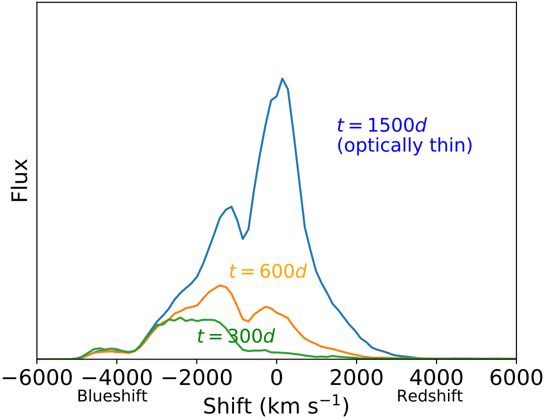
3D modelling: radiative transfer method

- **Monte Carlo transport in spherical coordinate system** (all previous 3D radiative transfer codes in Cartesian)
  - Avoid remapping
  - Avoid expensive small-cell transport in outer regions, while resolving the small-scale structure in the metal core.
  - Cost: More expensive geometry calculations to zone boundaries. Tests show factor few penalty but can be offset by more efficient gridding.



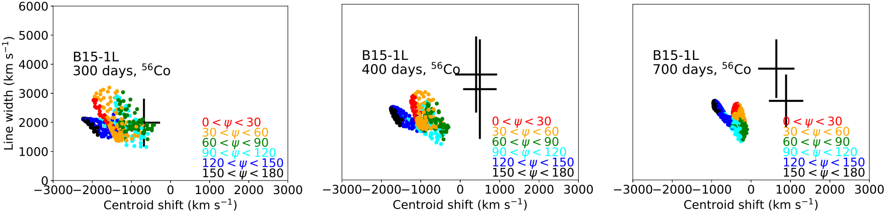
Gamma-ray line formation

- Only Compton scattering important → don't need to compute gas state → simplest possible application.
- First emission line predictions from a 3D CCSN hydromodel.



Gamma ray lines in SN 1987A

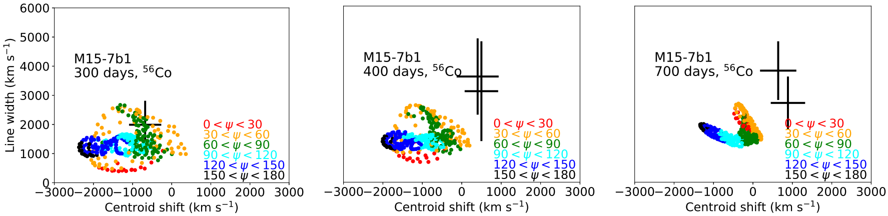
Model B15



- Line width and shift (degree of asymmetry) can vary with several 1000 km/s depending on viewing angle.
- B15 fails to achieve the observed redshifts at $\gtrsim$ 400d: all emission paths are too heavily blocked giving blueshifts only. But even in optically thin limit the ^{56}Ni is not asymmetric enough.

Gamma ray lines in SN 1987A

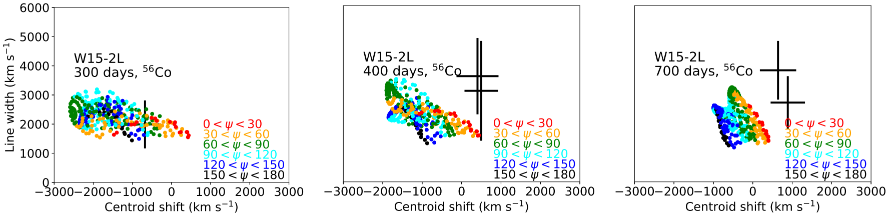
Model M15



- Line width and shift (degree of asymmetry) can vary with several 1000 km/s depending on viewing angle.
- M15 has more asymmetric ^{56}Ni, but the degree of Compton scattering is too large due to the large ejecta mass ($19\ M_{\odot}, \tau \propto M^2$).

Gamma ray lines in SN 1987A

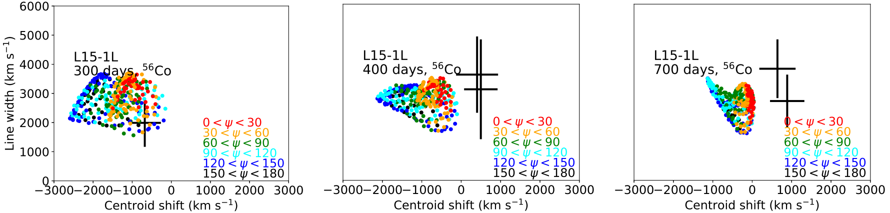
Model W15



- Line width and shift (degree of asymmetry) can vary with several 1000 km/s depending on viewing angle.
- W15 has similar degree of asymmetry as M15, but less mass, and gives redshifted lines for certain viewing angles.

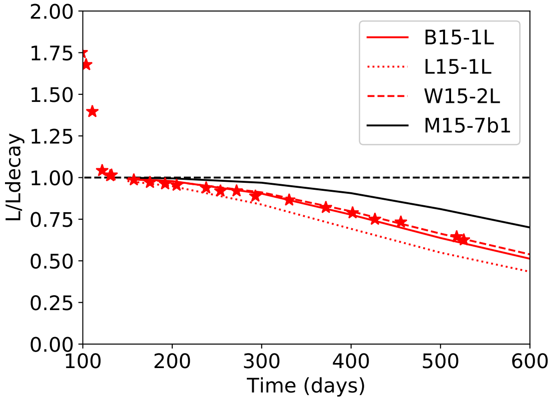
Gamma ray lines in SN 1987A

Model L15



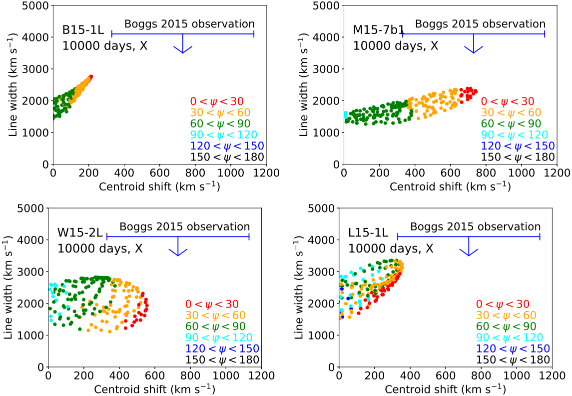
- Line width and shift (degree of asymmetry) can vary with several 1000 km/s depending on viewing angle.
- L15 has highest ^{56}Ni bulk velocity and gives best match for line widths.

Testing the degree of gamma-ray trapping by UVOIR bolometric luminosity



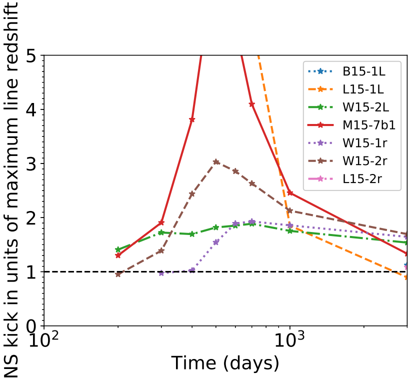
- Big advantage over comparing to gamma lines : UVOIR luminosity is **independent of viewing angle**. Models are quite successful.

^{44}Ti lines - from a partially different region than ^{56}Ni



- **B15** (290 km/s asymmetry for ^{44}Ti) and **L15** (390 km/s) too little asymmetry.
- **M15** (790 km/s) and **W15** (580 km/s) sufficiently asymmetric. Viewing angles where NS is moving away from is is required.

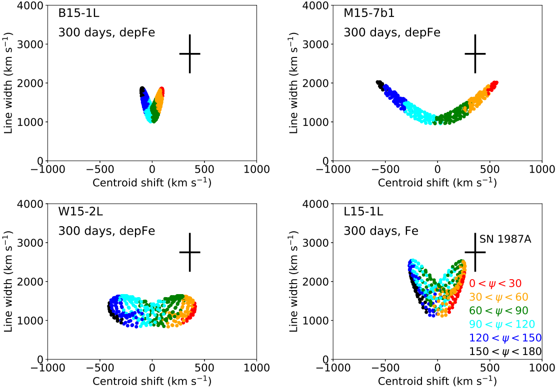
Constraints on the neutron star kick

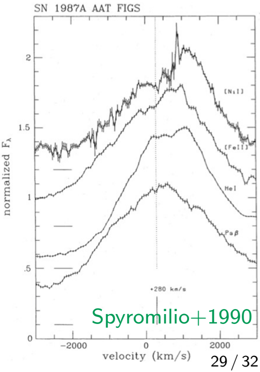


- Element momentum vectors strongly anti-aligned with the NS kick vector : *the 3D models predict a certain relation between line shifts and NS kick*.
- For the whole model grid here $V_{NS} > V_{line-shift,^{56}Co} \approx 500$ km s^{-1} for SN 1987A.

Infrared iron lines

- Infrared lines of Fe, Co, Ni also show redshifts (Witteborn+1989,Haas+1990,Spyromilio+1990).
- Compared to decay line analysis: better data and optically thin, but more uncertainty for the emissivity.
- Only one of the four models (L15) gives enough width and asymmetry of the iron-group lines. It has a bulk ^{56}Ni speed of 1500 km s^{-1}.





Summary of 1987A analysis with 3D models

- No models are completely successful : SN 1987A has **yet faster** and **yet more asymmetric** ^{56}Ni than current 3D explosion simulations achieve.
- The best models (with $v_{bulk} \sim 1500$ km/s, $v_{shift} \sim 500$ km/s, $M_{ej} \sim 14\ M_{\odot}$, $E \sim 1.5$ B) are, however, on the right track and marginally reproduce some of the observables.
- The NS has likely received a kick of at least 500 km s^{-1}, from the strong asymmetries seen in Ni/Co/Fe lines.

Outlook : element diagnostic situation

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

- Modelling iron-group lines in the nebular phase **probes supernova explosive nucleosynthesis**.
- **A large iron reservoir** ($\sim 0.5\ M_{\odot}$) identified in the superluminous IIn SN 2006gy. New model scenario of a white dwarf exploding when merging with a massive companion star looks promising.
- The **Ni/Fe ratio** can be used to constrain the explosive burning process. 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 first 3D radiative transfer code version is now available and has been used to **test 3D explosion models**. First application to gamma-ray decay lines and IR iron lines in SN 1987A show current models give (marginally) too slow and too symmetric ^{56}Ni.