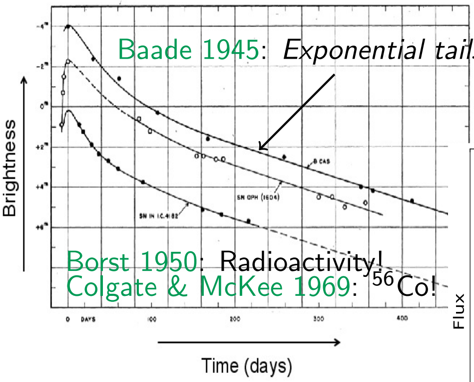
# Nebular-phase spectral modelling of the Garching 3D explosion simulations

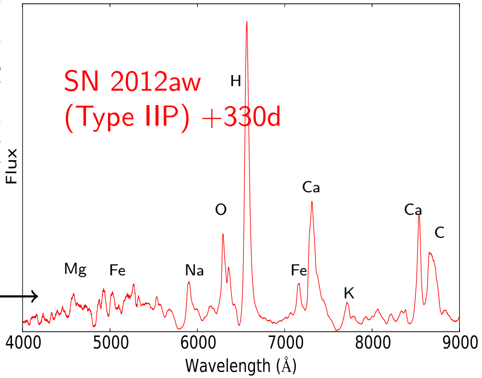
Anders Jerkstrand

Department of Astronomy, Stockholm University

# The nebular phase: an opportunity to see what exploded stars are made of




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




Emission lines tell us about the **nucleosynthesis** and the **morphology**.

# Intermediate densities : Both NLTE and radiative transfer needed

*The SUMO code: Jerkstrand 2011, PhD thesis, Jerkstrand, Fransson & Kozma 2011, Jerkstrand+2012*

**Radioactive decay and $\gamma$-ray transport**

**NLTE statistical equilibrium**

- 22 of 28 elements from H to Ni,
- Some r-process
- ∼100 exc. states each

**Compton electron degradation**

- Spencer-Fano equation

**Temperature**

- Heating = cooling

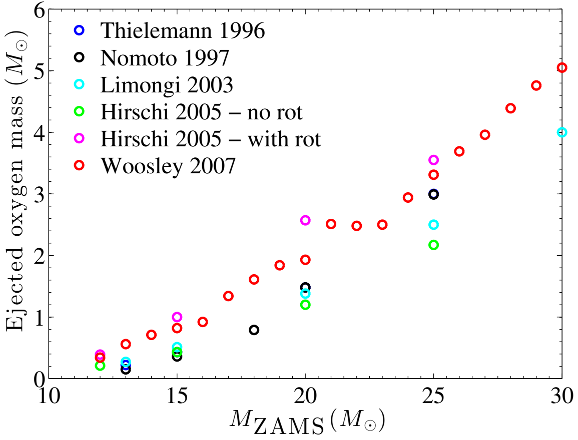
**Radiative transfer**

- Monte Carlo with Sobolev approximation
- $\sim 10^6$ atomic lines, $\sim 10^3$ bound-free continua, free-free, electron scattering

- Code is 1D but allows for 3D-informed artificial mixing by **virtual grid** method.

# Example : Progenitors and nucleosynthesis of Type IIP SNe

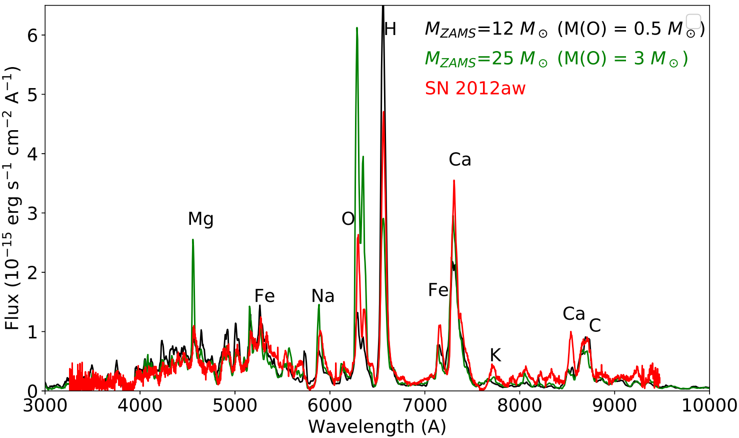
AJ+2012,2014




If we can measure the amount of O, we should be able to determine $M_{ZAMS}$.

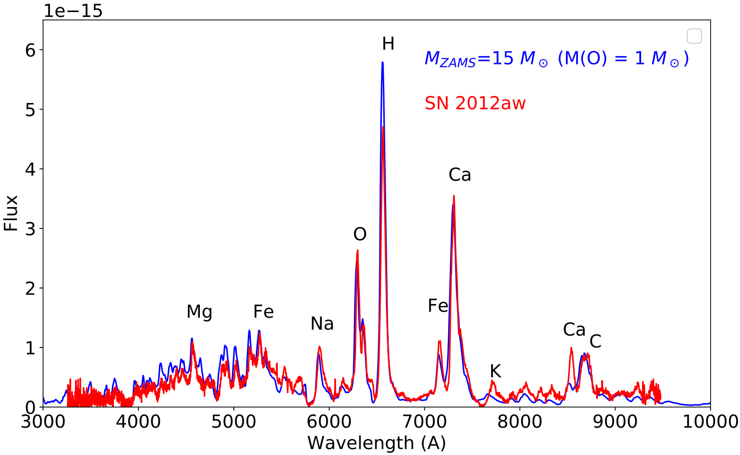
# Example : Progenitors and nucleosynthesis of Type IIP SNe

AJ+2012,2014



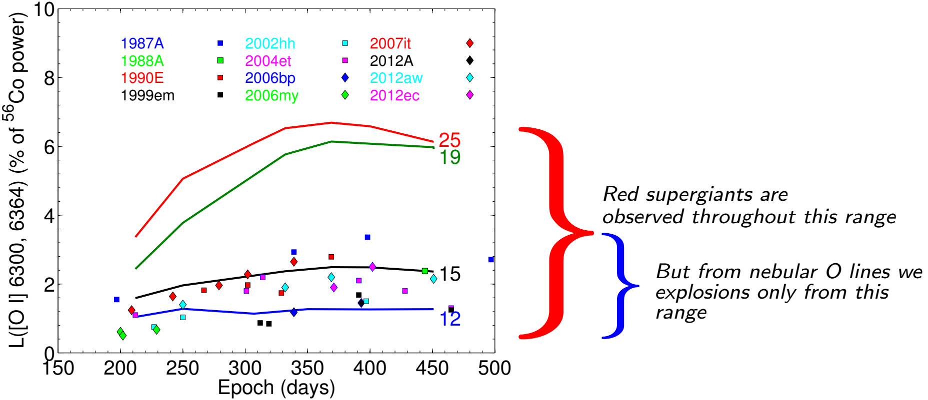
# Example : Progenitors and nucleosynthesis of Type IIP SNe

AJ+2012,2014



# Example : Progenitors and nucleosynthesis of Type IIP SNe

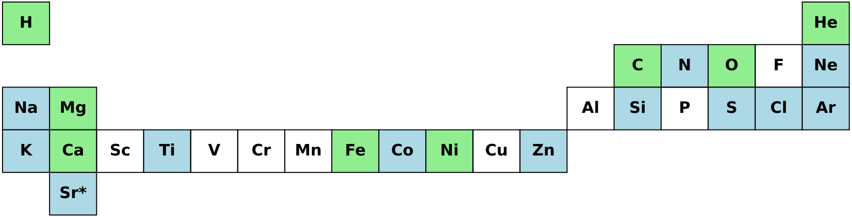
Highest mass RSGs missing : Direct black holes? IIL/IIn SNe? Late evolution to Ibc SNe?




*Jerkstrand, Smartt, Sollerman+2015, MNRAS*

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

# Direct determination of the origin of the elements, source by source

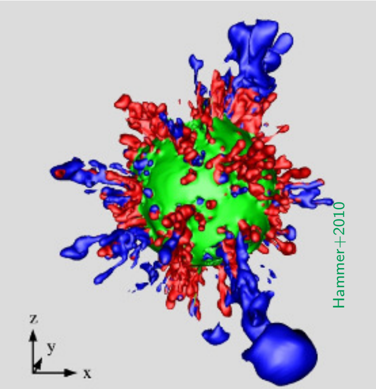


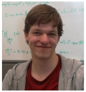

**Good diagnostic situation**

**Moderate diagnostic situation**

**Challenging to diagnose**

# Going to 3D



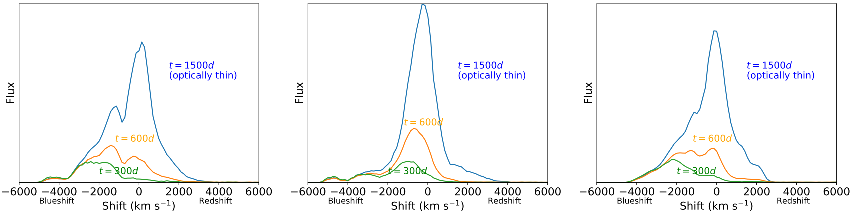

- Initial framework completed in 2020 (Jerkstrand+2020).
- Code currently being developed by PhD student Bart van Baal .

# First application : Gamma decay lines in SN 1987A

Jerkstrand et al (incl. Wongwathanarat, Janka, Gabler, Diehl) 2020

- Clearly difficult to make any sense of observed line profiles with 1D models.

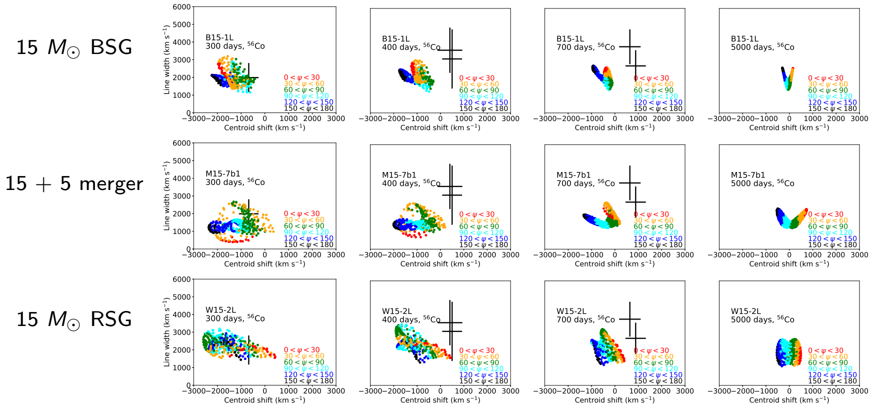
15 $M_\odot$ BSG model, 3 different viewing angles.



# First application : Gamma decay lines in SN 1987A

Jerkstrand et al (incl. Wongwathanarat, Janka, Gabler, Diehl) 2020

Time →

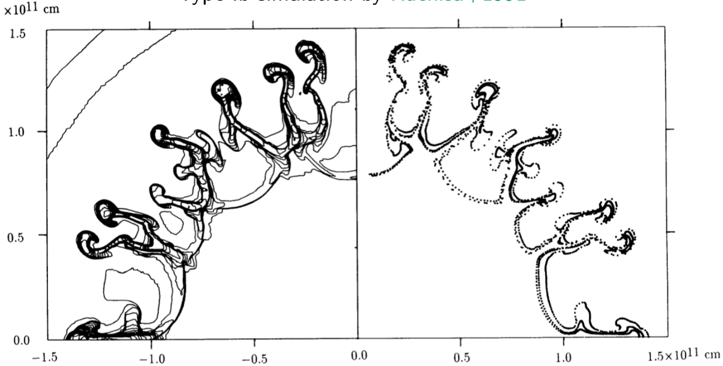



- Current 3D models give (marginally) **insufficient asymmetry** of the $^{56}$Ni.

# He-core models in 3D : Motivation

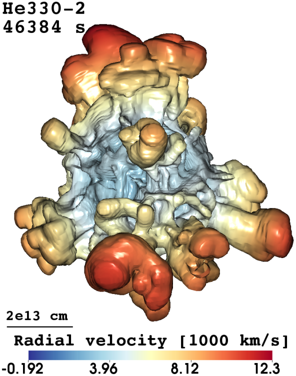
- 2D hydrosimulations in 1990s : also H-free explosions experience significant mixing. Shigeyama+1990,Hachisu+1991,1994,Nomoto1995.
- Strong mixing was soon also inferred from light-curve fitting of Ibc SNe.

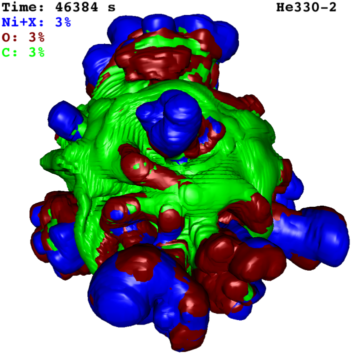
Type Ib simulation by Hachisu+1991



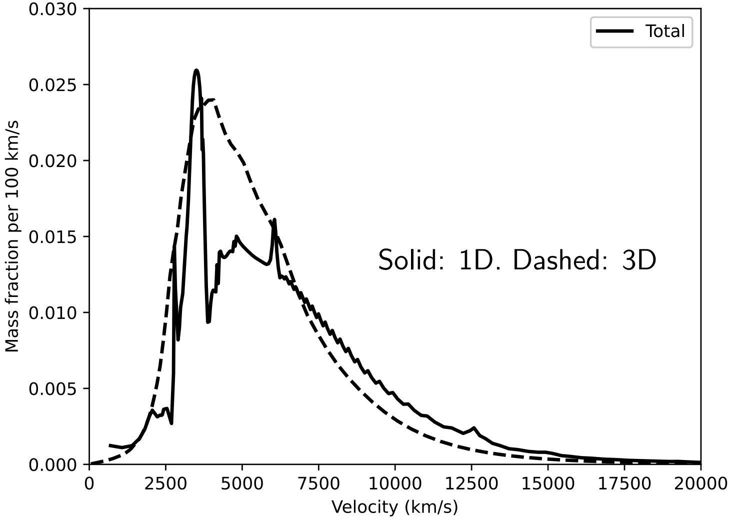
# He-core models in 3D : Method

- Progenitor models from Woosley 2019 : Instantaneous removal of the H envelope at He ignition.
- Annop Wongwathanarat  is running long-term simulation grid covering He core masses and explosion energies. First model (He 3.3) finished.

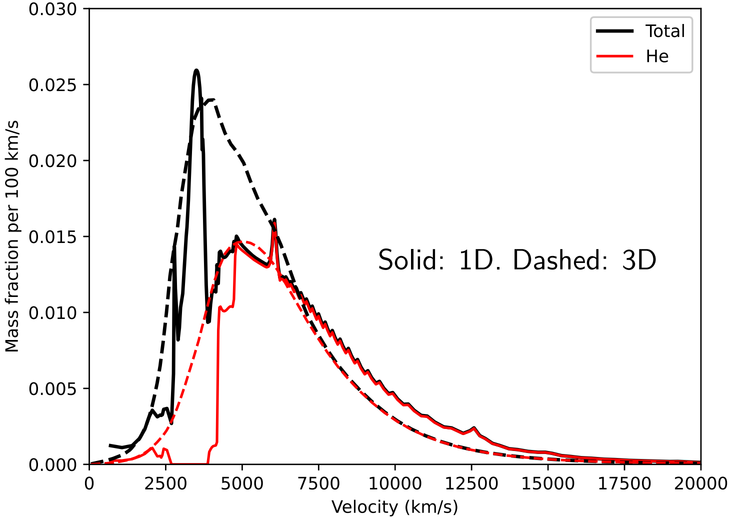


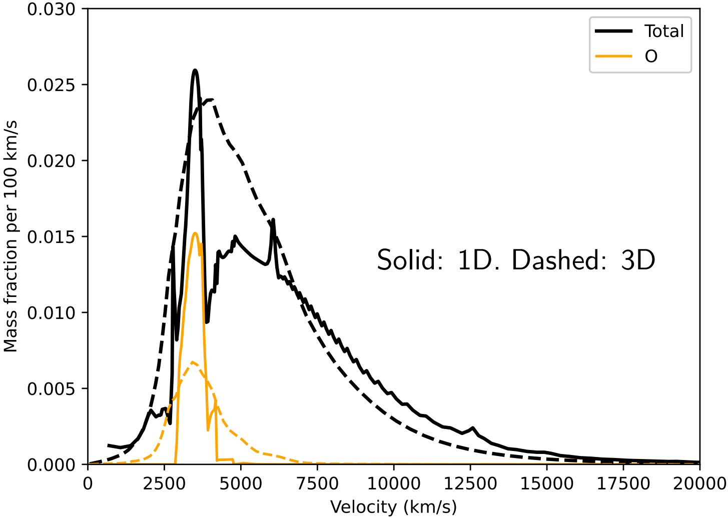
# Angle-averaged profiles



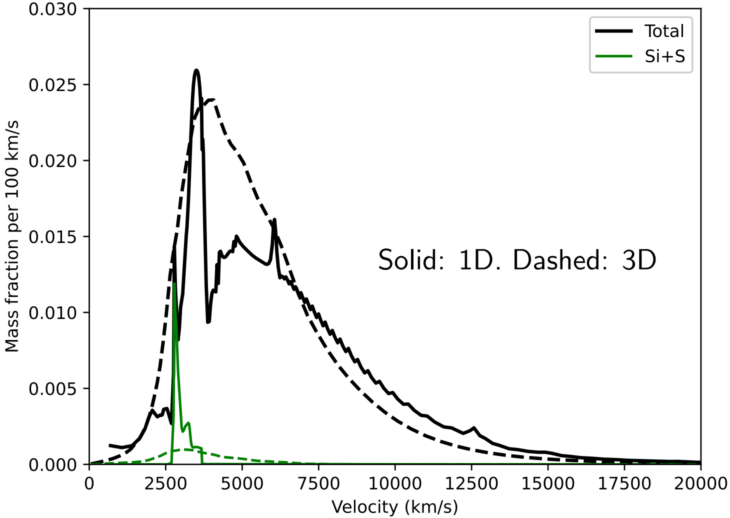
# Angle-averaged profiles



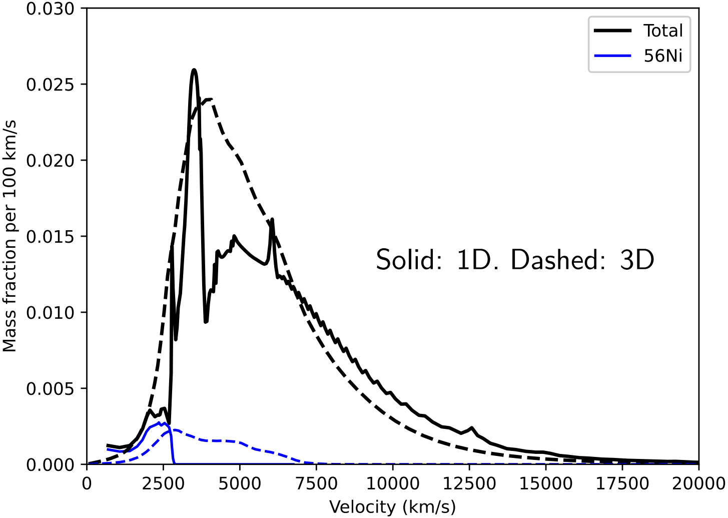
# Angle-averaged profiles



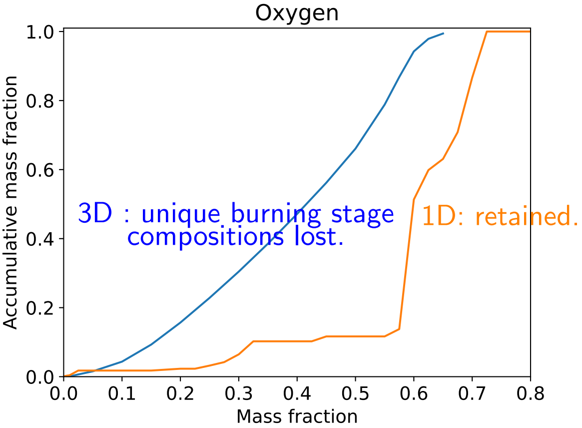
# Angle-averaged profiles



# Angle-averaged profiles



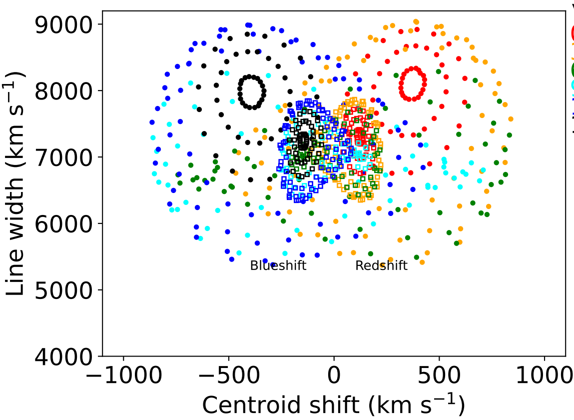
# Compositional mixing : physical or numeric?

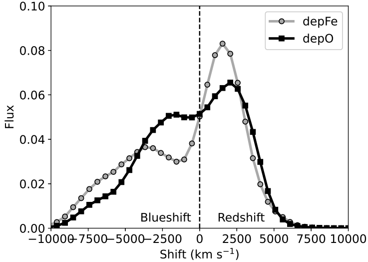



- Nebular spectra are sensitive to the degree elements are **microscopically** mixed.

# O and Fe lines in 3D under the $j_{el}(\mathbf{x}) = dep(\mathbf{x}) \times ab_{el}(\mathbf{x})$ approximation

- Iron lines (○) show more asymmetry and diversity than oxygen lines (□).

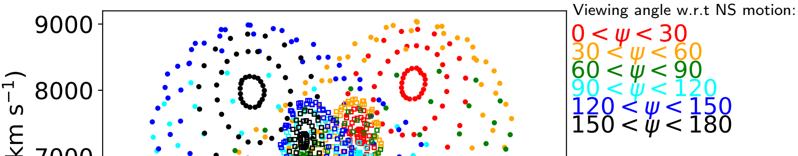


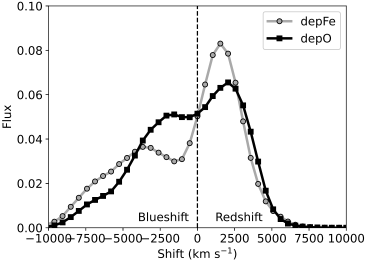




- Work ongoing to improve the emissivity calculations.

# O and Fe lines in 3D under the $j_{el}(\mathbf{x}) = dep(\mathbf{x}) \times ab_{el}(\mathbf{x})$ approximation

- Iron lines (○) show more asymmetry and diversity than oxygen lines (□).




- Work ongoing to improve the emissivity calculations.

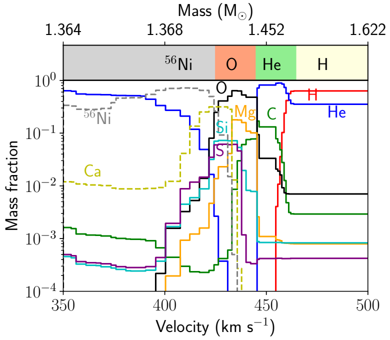
# The most common type of SNe : $M_{ZAMS}$ = 8-12 $M_\odot$ stars

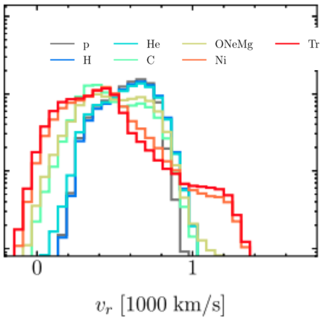
Ertl+2018, Jerkstrand+2018 :

First spectral predictions (1D)

..but..Stockinger+2020:

Ejecta mixes strongly also at low mass.




- The hunt for the first clear detection of an **electron-capture supernova** is ongoing but our (toy) 1D prediction needs replacement by 3D models.

# Higher-mass Type II SNe

- Large set of models by Michael Gabler .
- Test accuracy of the (significant) set of 1D SUMO models.
- Make progress on the "Red Supergiant" and "Missing Oxygen" problems.

# Summary

- In the nebular phase we see the interior of the whole exploded star and can learn about **nucleosynthesis** and **ejecta morphology**.
- **Non-thermally powered** gas at **intermediate densities** → Modelling is complex, needing 3D, NLTE, and radiative transfer.
- We currently have results or **diagnostic potential for 20 elements** : H, He, C, N, O, Ne, Na, Mg, Si, S, Cl, Ar, K, Ca, Ti, Fe, Co, Ni, Zn, Sr.
- **3D modelling** of both Type IIP and Type Ibc SNe in progress.
- **Gamma decay line** analysis of SN 1987A shows that current models still don't quite capture enough $^{56}$Ni asymmetry.