Probing progenitor systems and explosion dynamics of supernovae with UVEX late-time spectroscopy

Dan Milisavljevic

PURDUE UNIVERSITY

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Late-time emission uniquely probes the nature of supernovae and their progenitor systems

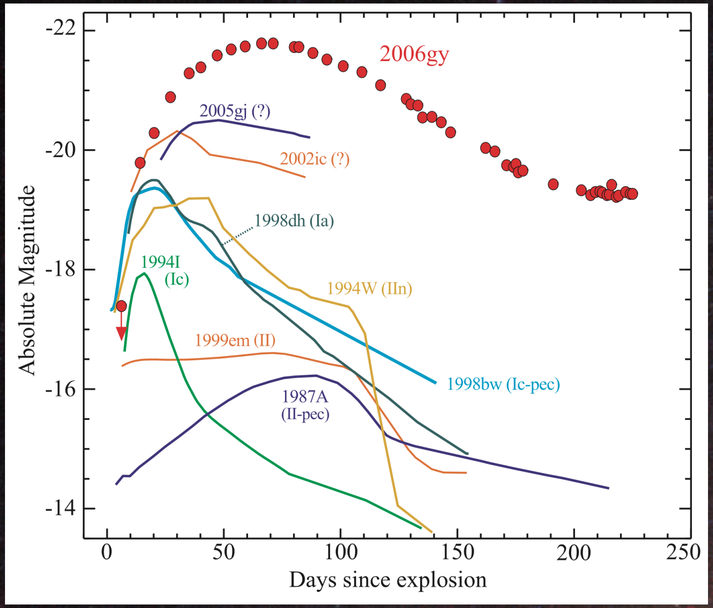
What can we learn?

1. **Probe mass loss hundreds to thousands of years prior to explosion.**
2. **Access abundant emission from layers of metal-rich ejecta. Over time ever-deeper layers will slowly reveal themselves.**

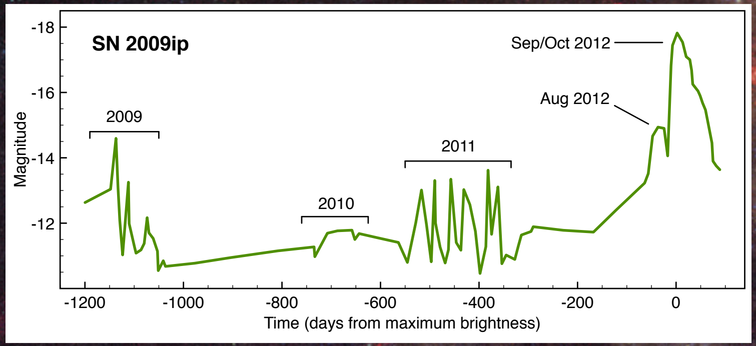
By combining multiwavelength observations, with advanced models capable of predicting emission from various emission processes, it is possible to test both explosion models for the SN ejecta, as well as abundances and densities of the CSM. These observations can also inform about the poorly understood mechanisms of extreme mass loss.

Ultraviolet is key wavelength region yet inadequately utilized.

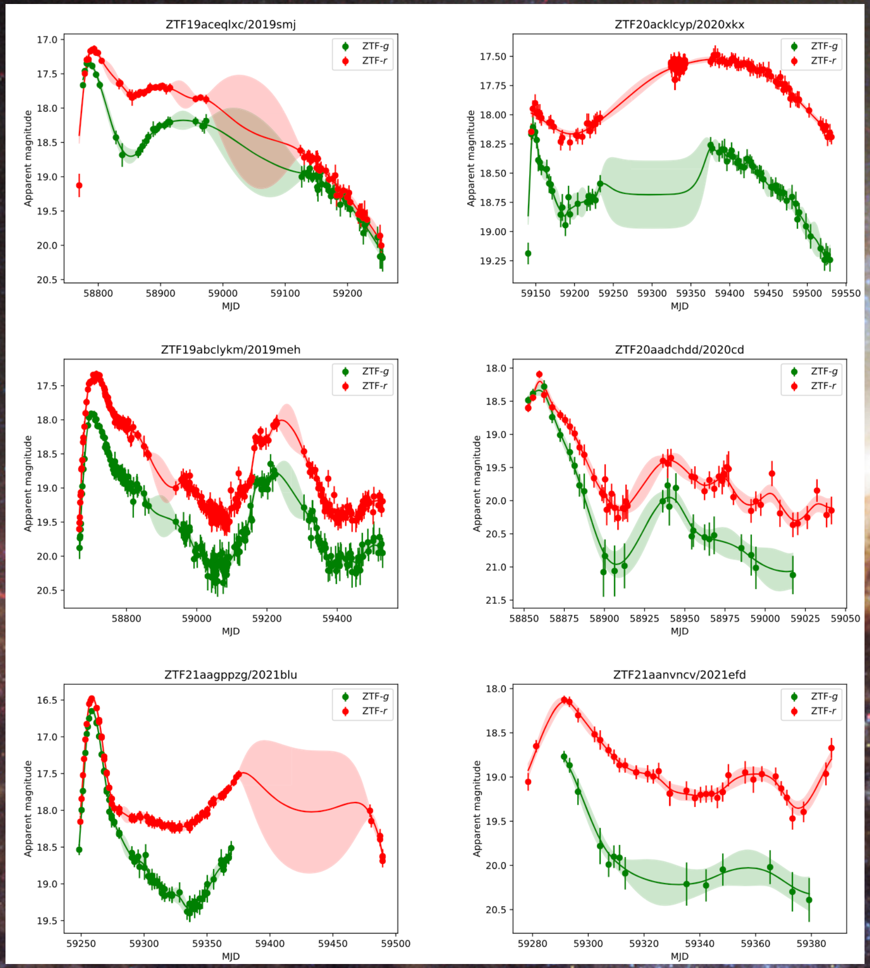
New opportunities to investigate terminal phases of stellar evolution



Smith et al. (2007)



Mauerhan+ 2013, Pastorello+ 2013 and Margutti, DM+2014



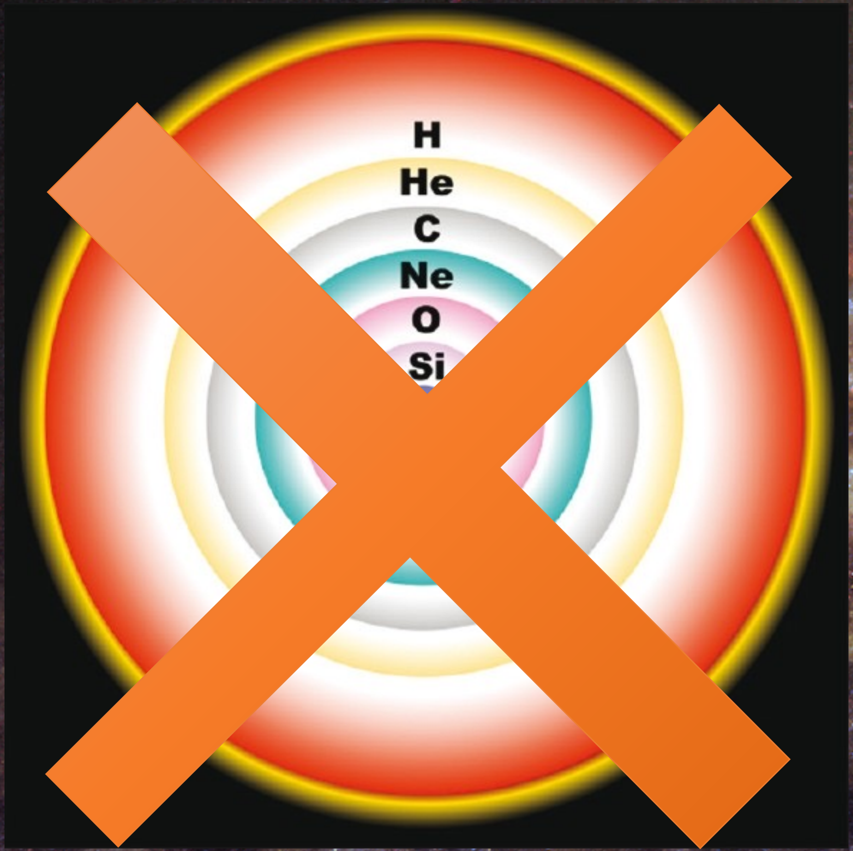
Soraisam et al. (2022)

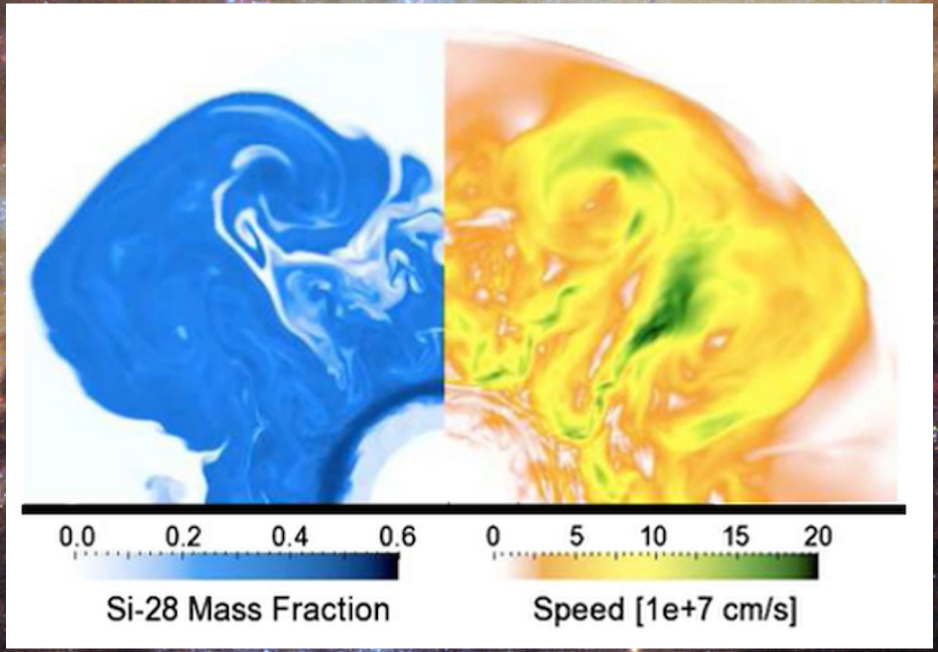
The landscape of SN discovery is changing, bringing new opportunities to investigate stellar evolution in phases leading up to a terminal supernova.

Here, contrast prototypical light curves (left) with some of the many rebrightenings being discovered by ZTF (right). The frequency and timescales of these post-explosion interactions are only beginning to be understood.

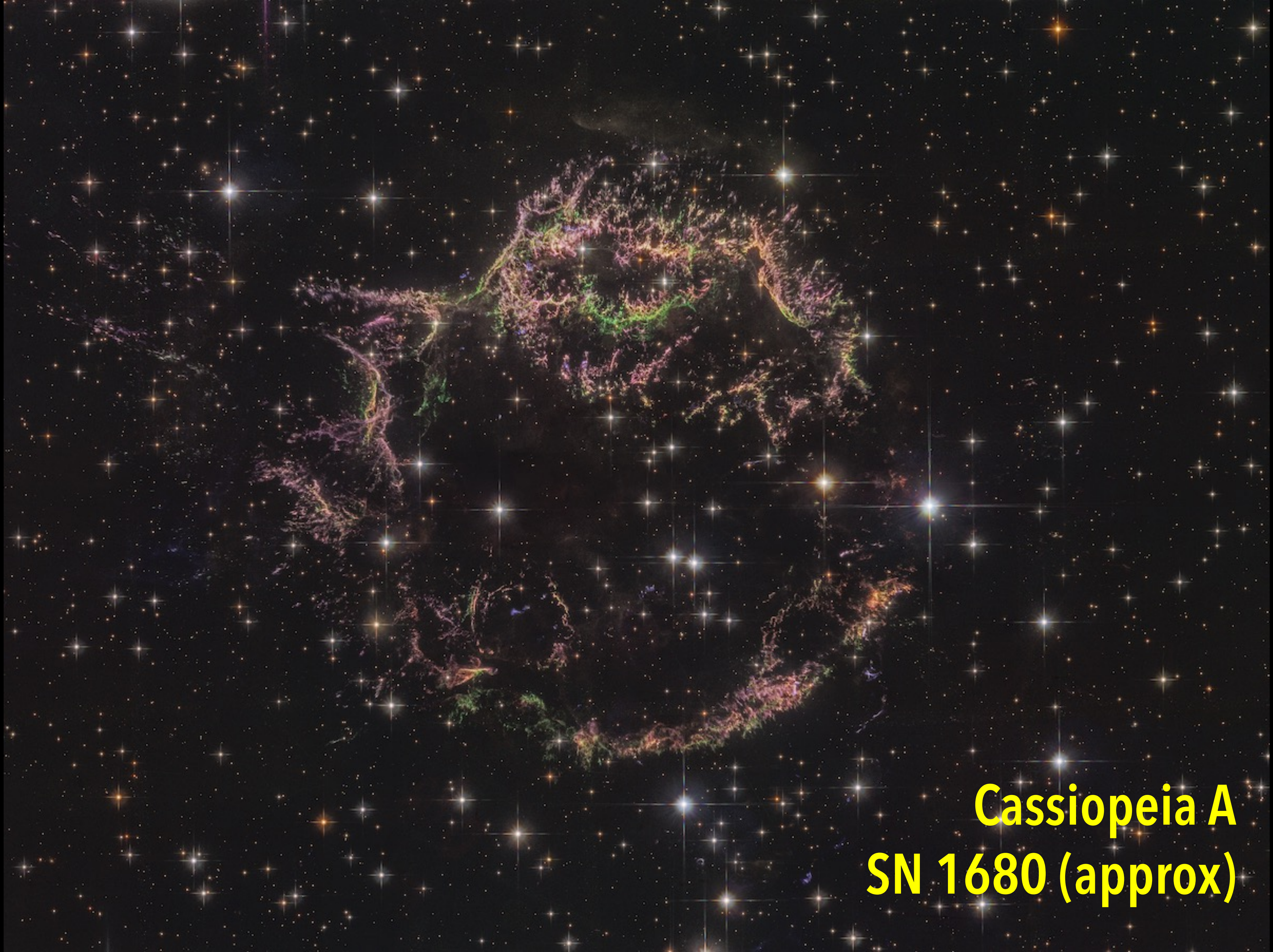
Photometry suggests what may be going on, but spectroscopy needed to accurately interpret.

Interior structure of the progenitor star immediately prior to explosion may be very *turbulent* and *mixed*.

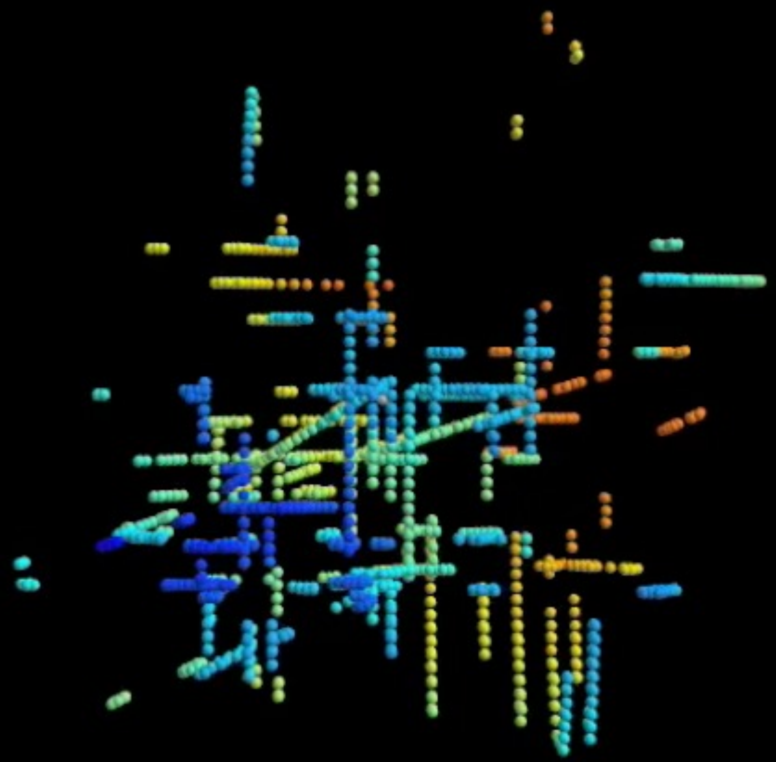




Arnett & Meakin (2011)


Cassiopeia A
SN 1680 (approx)

3D Reconstruction of a SN Debris Field



Cas A's distribution of optically-emitting ejecta exhibits large-scale coherent structure that was imprinted early in the explosion

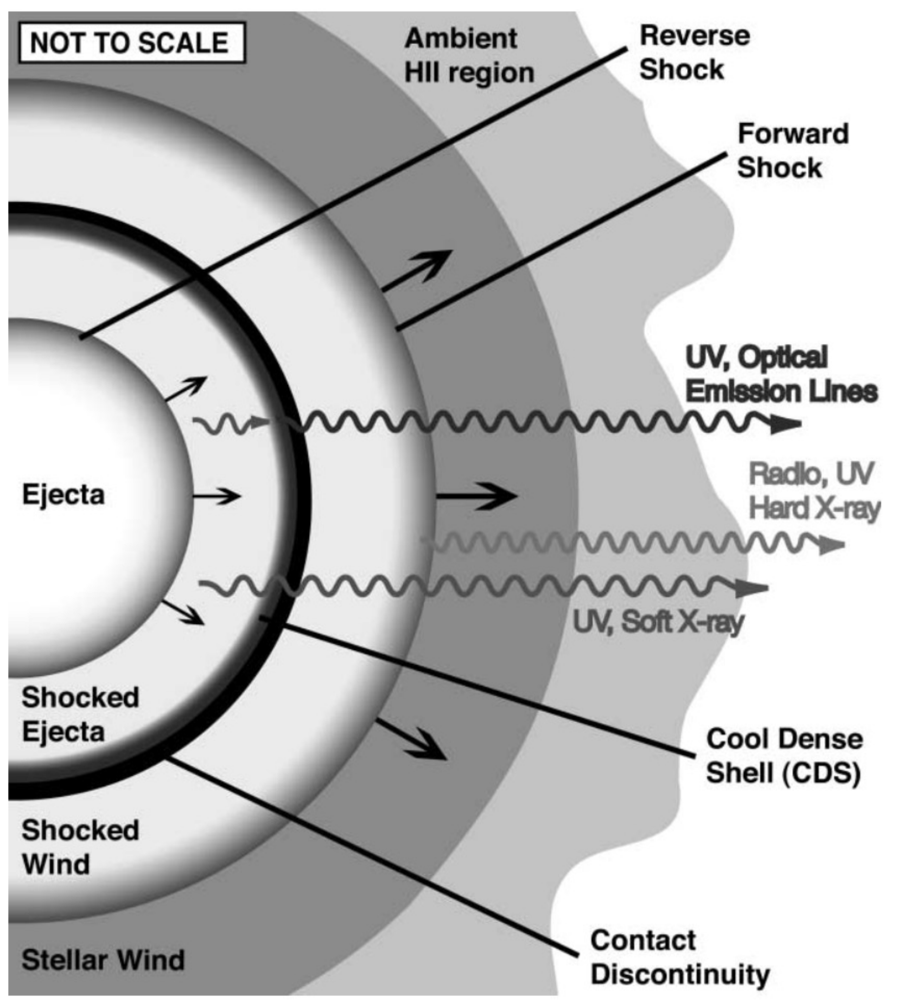
Milisavljevic & Fesen (2015, *Science*)

SN-CSM interaction

SN-CSM interaction is associated with outgoing fast shock and a slow reverse shock. UV and optical emission originates from CSM and the shocked ejecta. The interaction may be with a non-uniform medium with clumps, shells and general asymmetries.

The UV and optical line emission provide an ideal diagnostic of the nucleosynthesis in the SN ejecta, and a probe of the abundances and conditions in the CSM. **The UV is exceptionally informative because of its many strong high and low ionization lines.**

From observing the evolution of the spectrum as the reverse shock is moving into deeper and deeper layers of the ejecta, we can perform a form of tomography of the structure and understand the nucleosynthesis of the SN. We can also map out the history of abundances and mass loss rates during the last few thousand years in connection to the last burning stages of the progenitor star.



Bauer et al. (2008)

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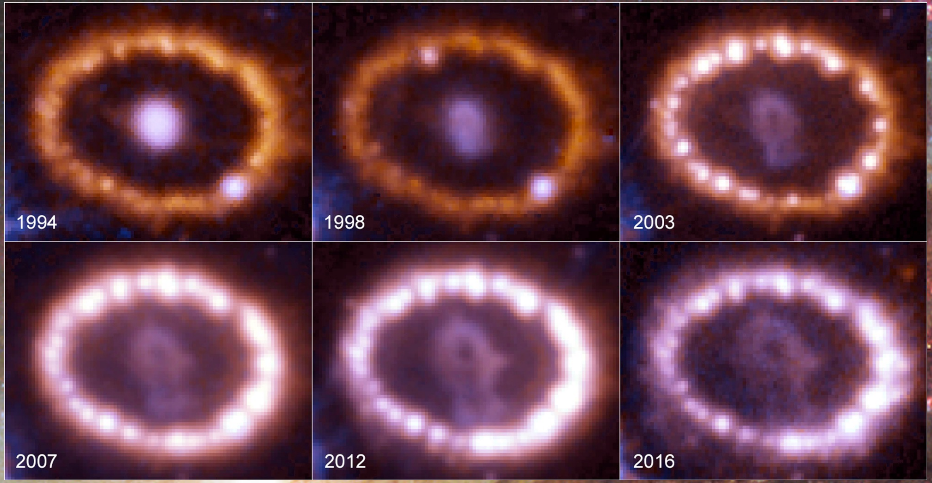
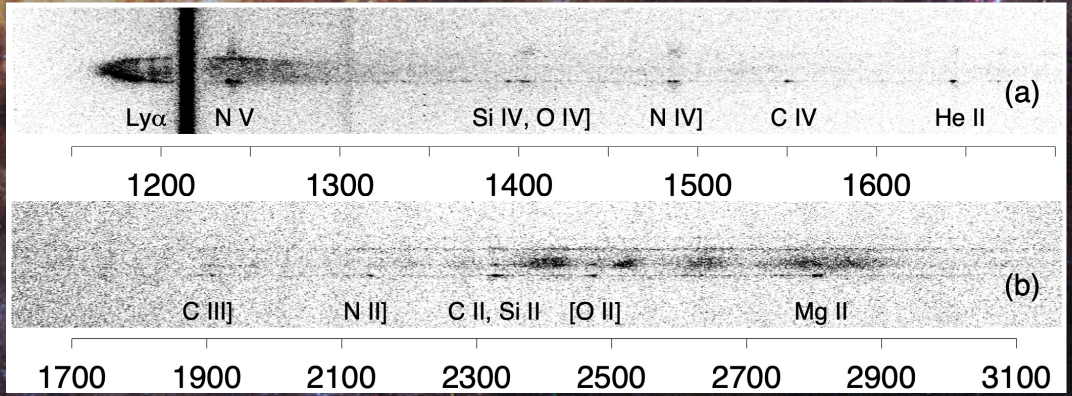


SN 1987A



Pun et al. (2002)

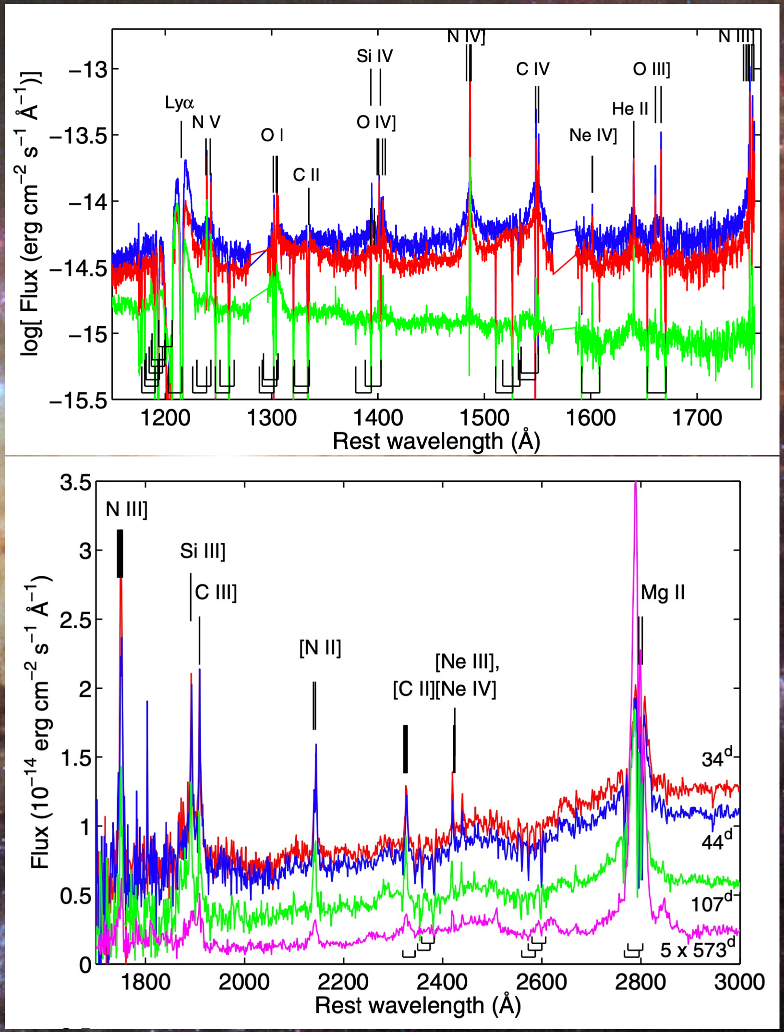
SN-CSM interaction

Models show that most of the radiation excited by the X-rays from the shock interaction with the circumstellar medium (CSM) is re-emitted as high ionization lines in the far- and near UV.

Observations in the near and far UV and of SNe at information-rich epochs t > 1 yr after maximum light are extremely limited.

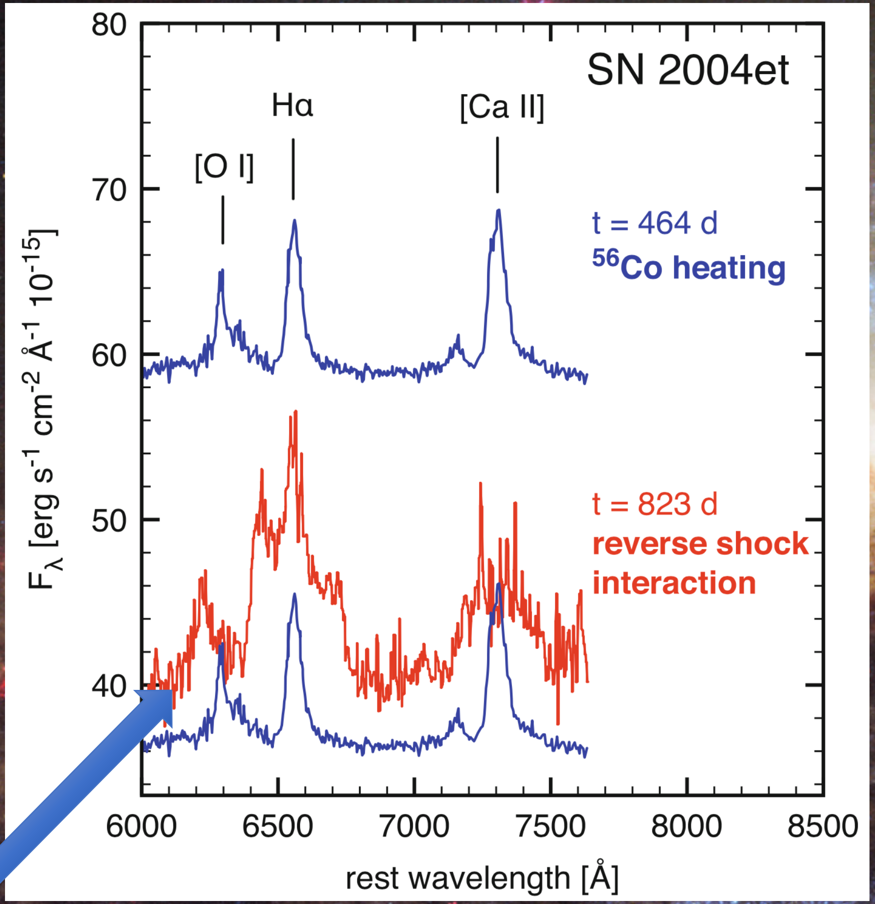
By combining optical and UV observations, and in most cases also X-ray and radio observations, with advanced modeling with combined shock/photoionization code, we can test both explosion models for the SN ejecta and abundancies and densities of the circumstellar media.

SN 2010jl



Fransson et al. (2014)

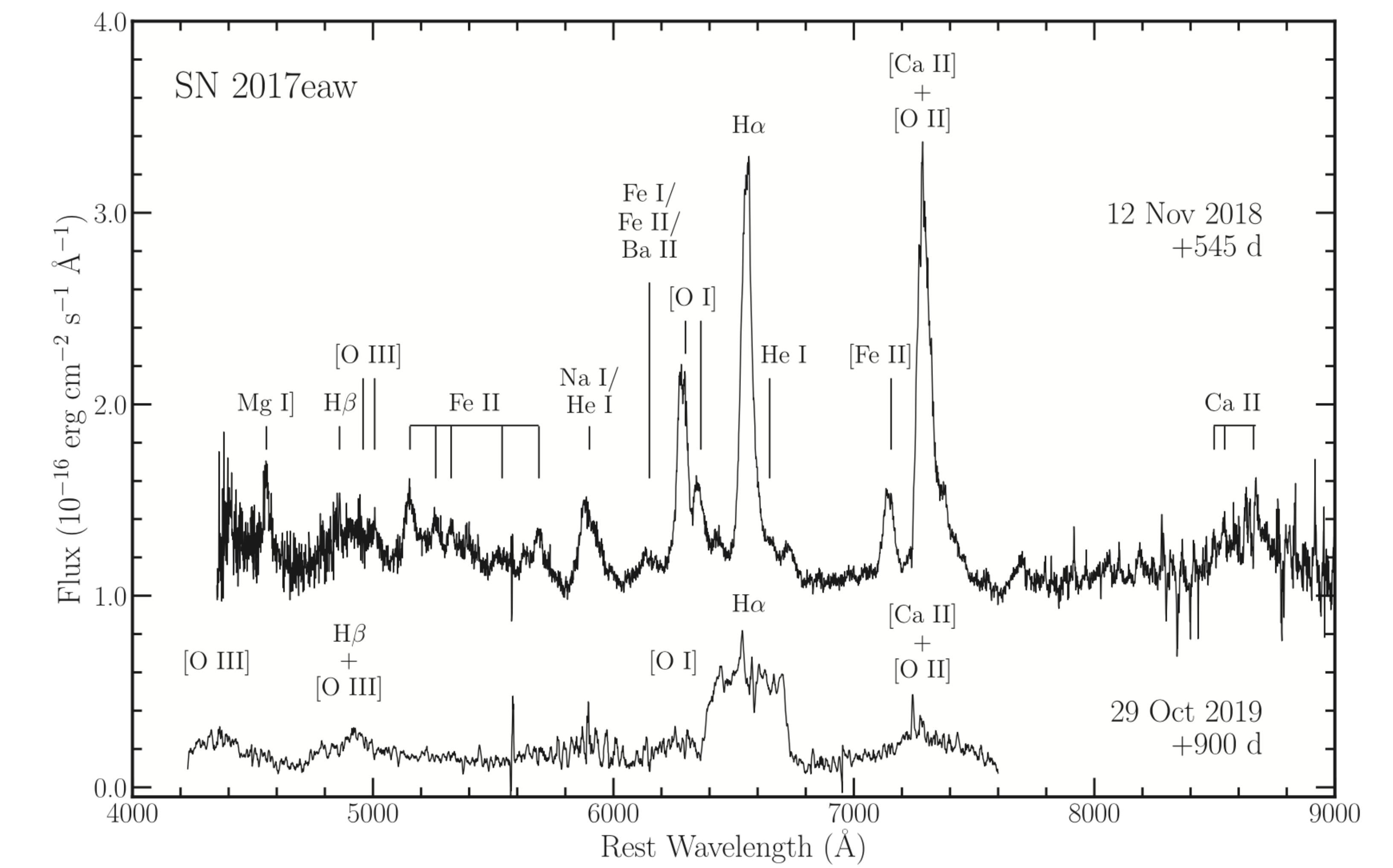
SN-CSM interaction with a smooth wind



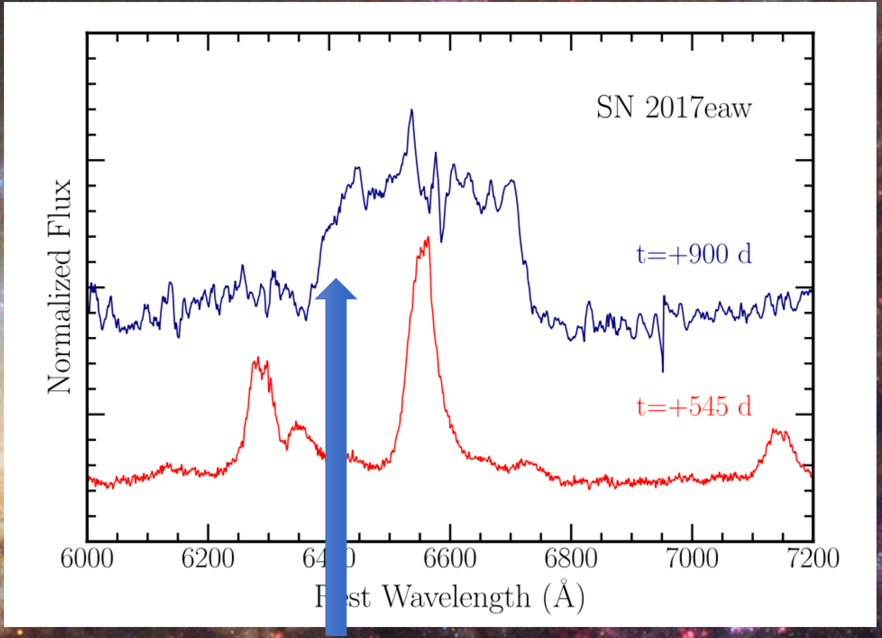
Milisavljevic & Fesen 2017

Reverse shock excites outer high-velocity ejecta

SN-CSM interaction with a smooth wind



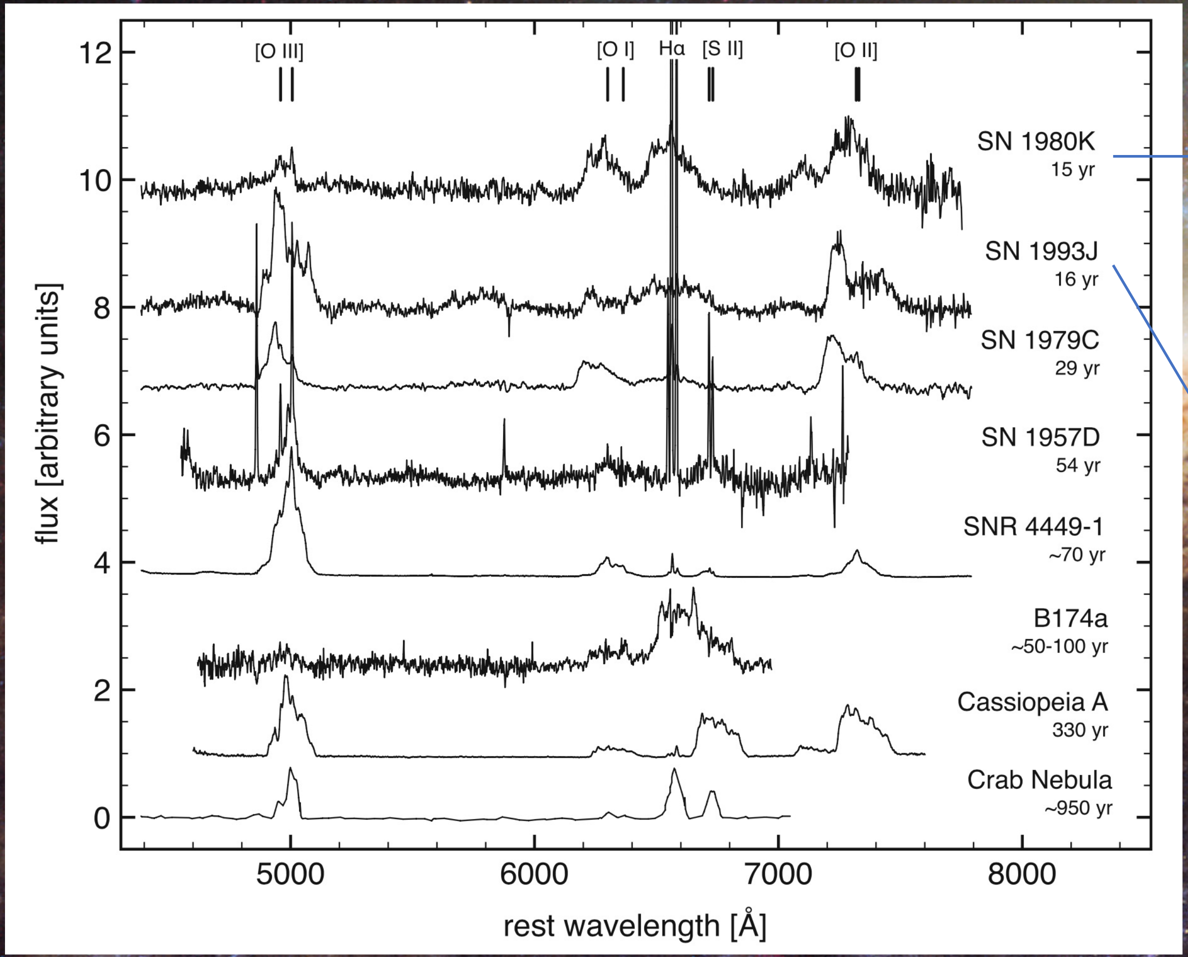
Weil et al. (2020)

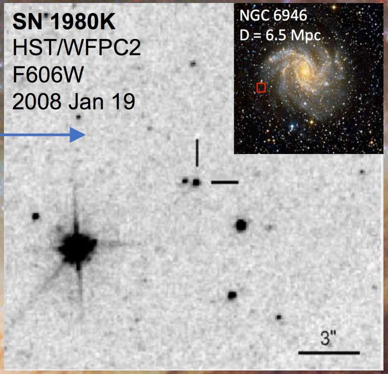


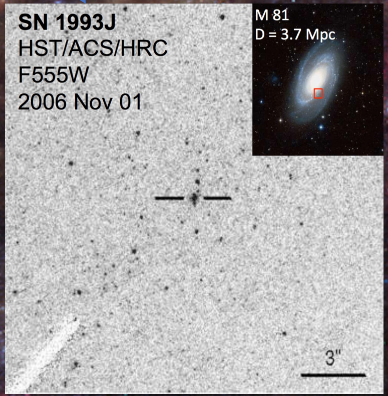
Reverse shock excites outer high-velocity ejecta

Explosions can be monitored for decades via SN-CSM interaction

UV observations are rare and incomplete

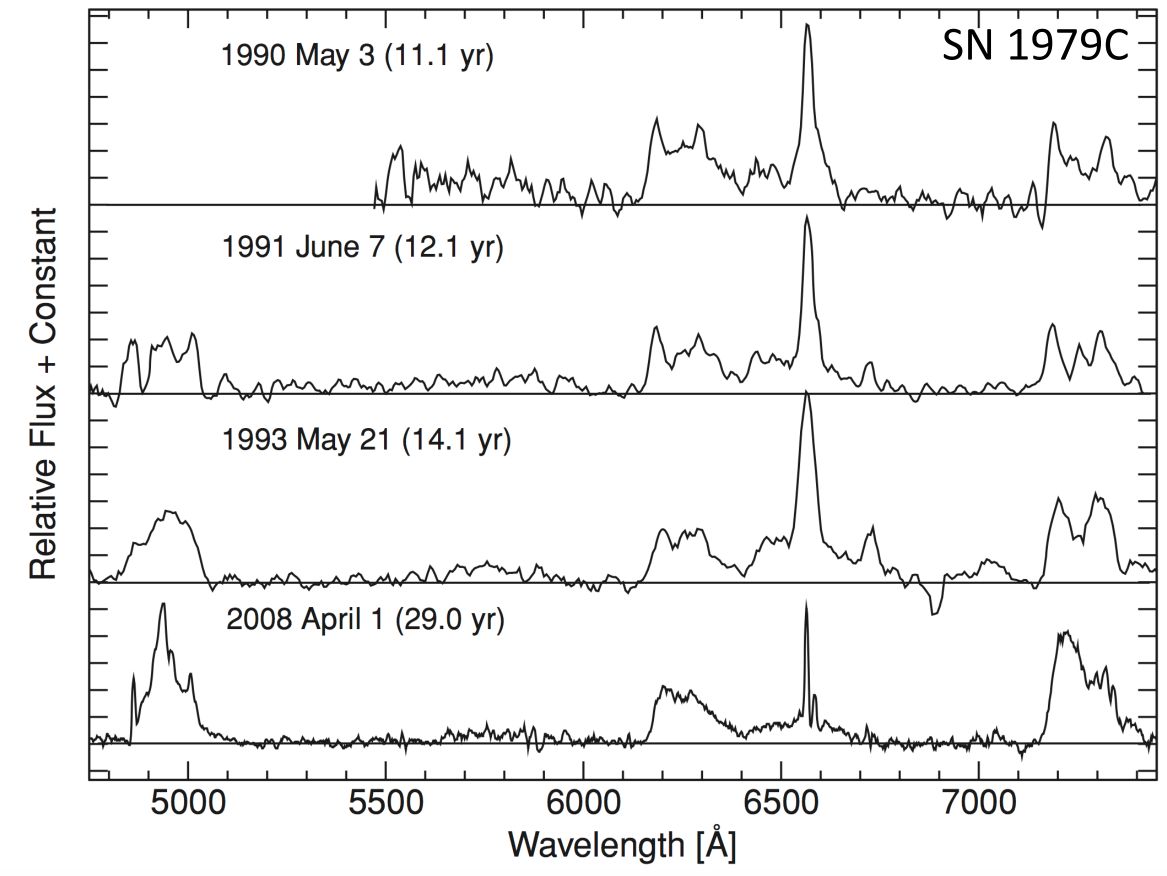


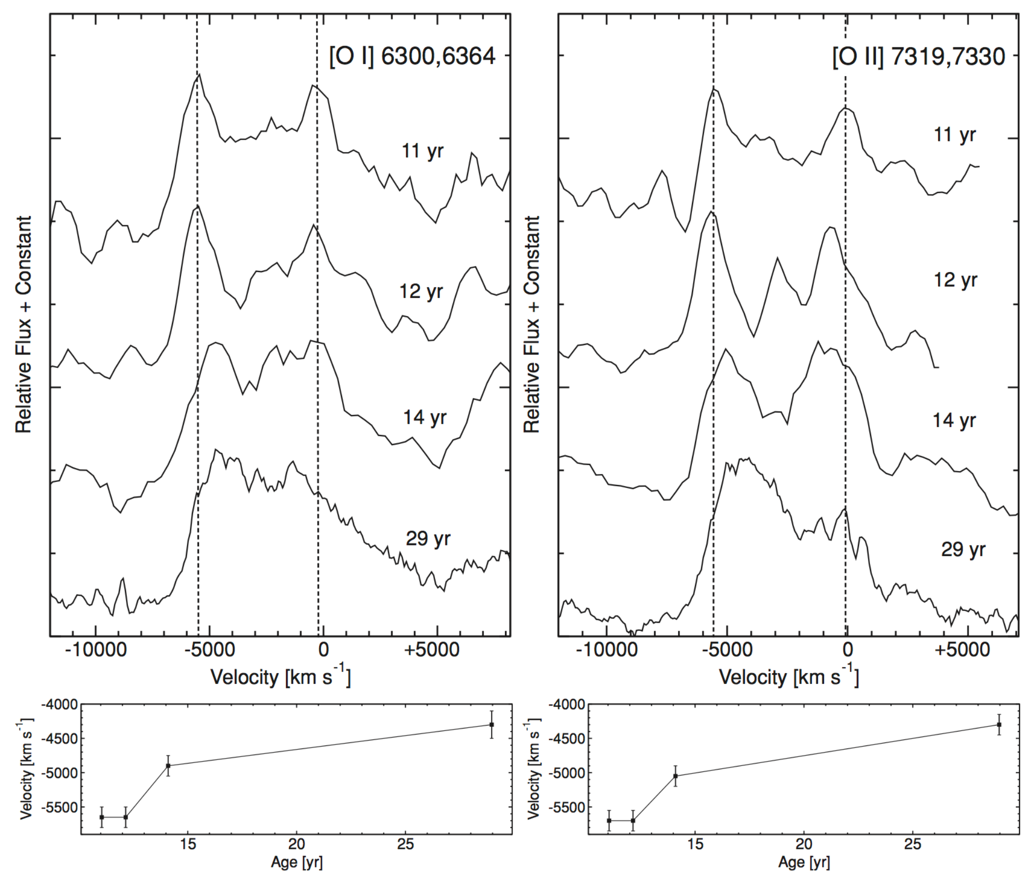




Milisavljevic & Fesen 2017

Changes in features follows progression of reverse shock into inner layers of ejecta



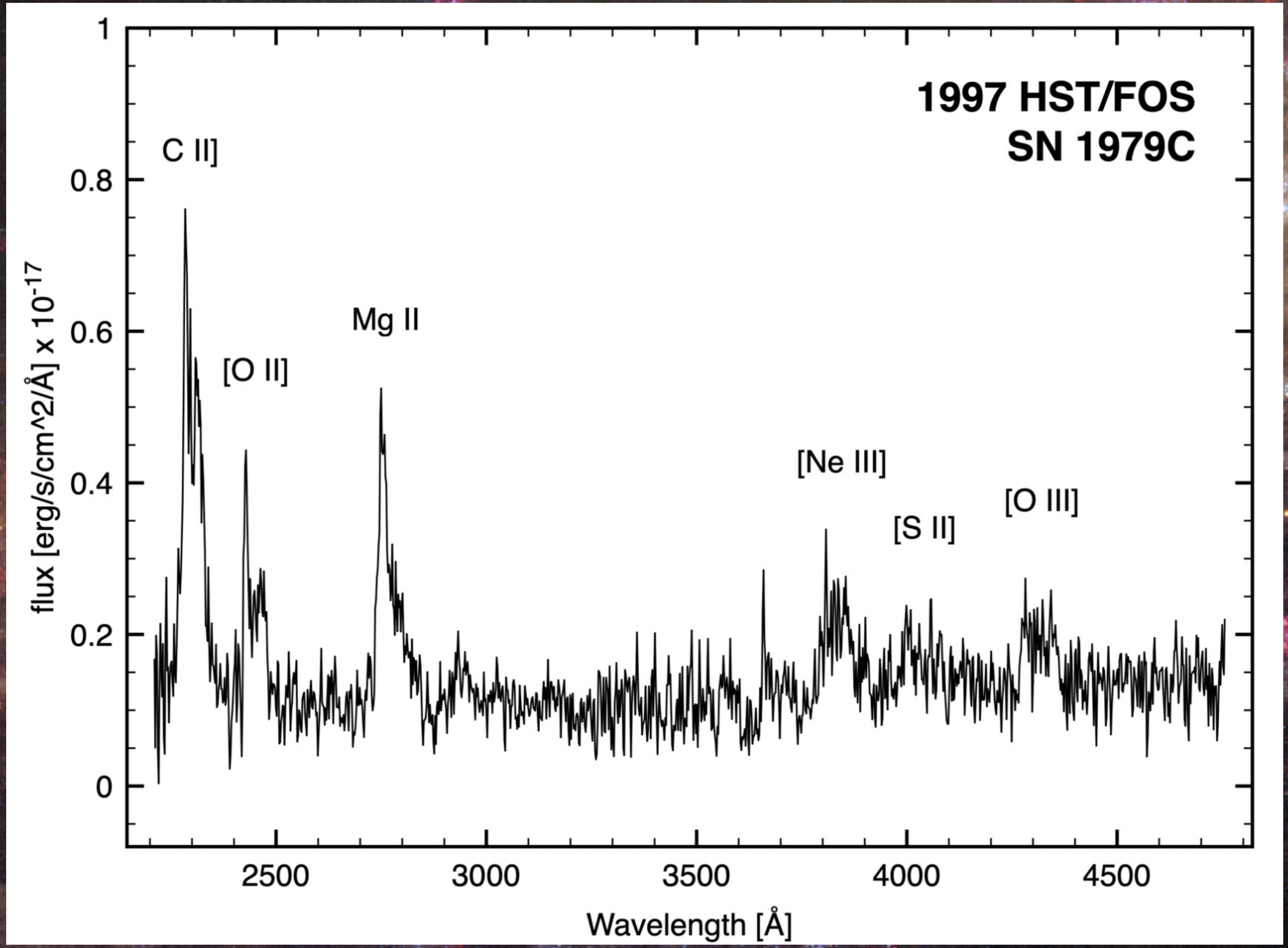


Milisavljevic+ 2009

Need for late-time UV spectroscopy

In the case of SN 1979C the reverse shock has reached the inner oxygen rich layers of the SN core, displaying broad lines from the O core and allowing us to study the nucleosynthesis directly.

The relative strengths of the CNO lines (all present with different ionization stages in the far UV range) provide information of the location and composition at the reverse shock. Asymmetry in the UV emission line profiles can probe the dust grain size distribution in the ejecta, since large or small grains will affect the UV profiles differently from those observed in the optical

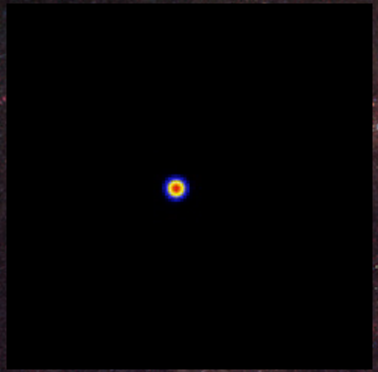


Need for late-time UV spectroscopy

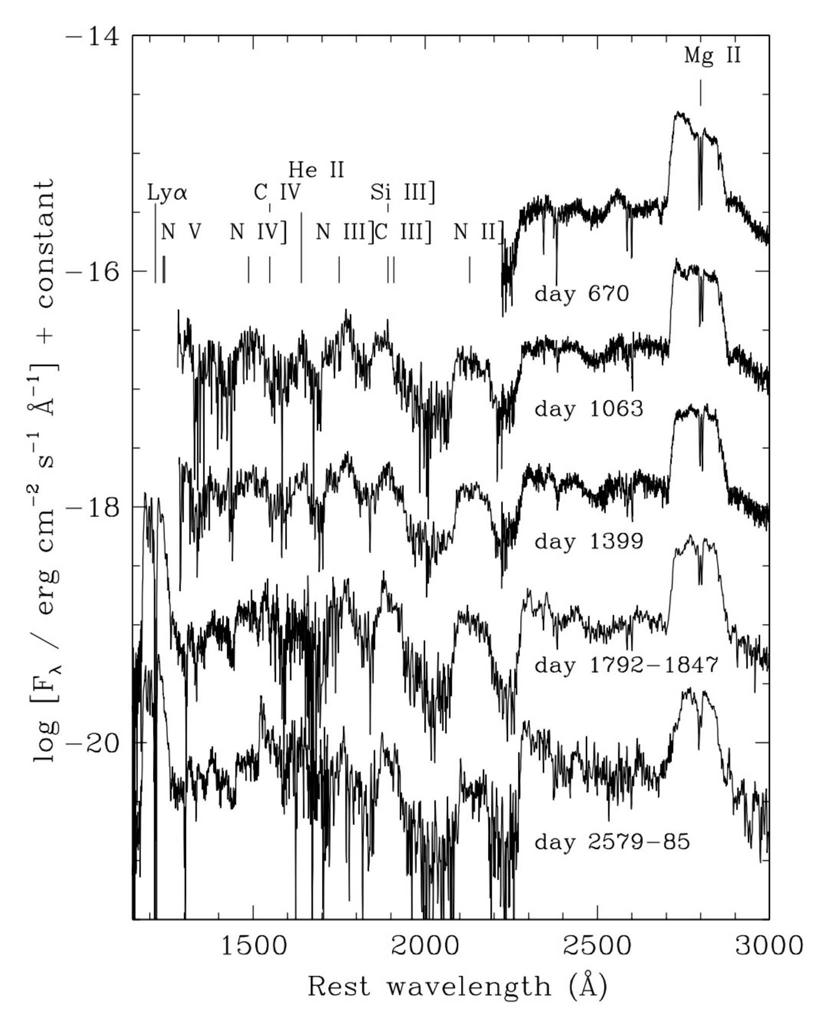
In the case of SN 1993J, after about 1 year, the optical spectrum became dominated by emission lines excited by the circumstellar interaction.

Emission lines in UV provide access to diagnostics not accessible in optical and NIR.

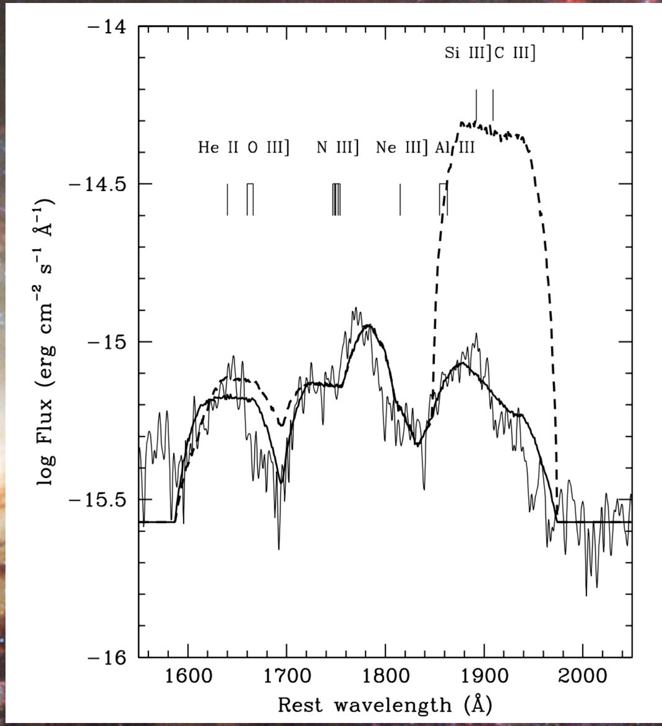
VLBI at 8.4 GHZ



Bietenholz et al. (2003)

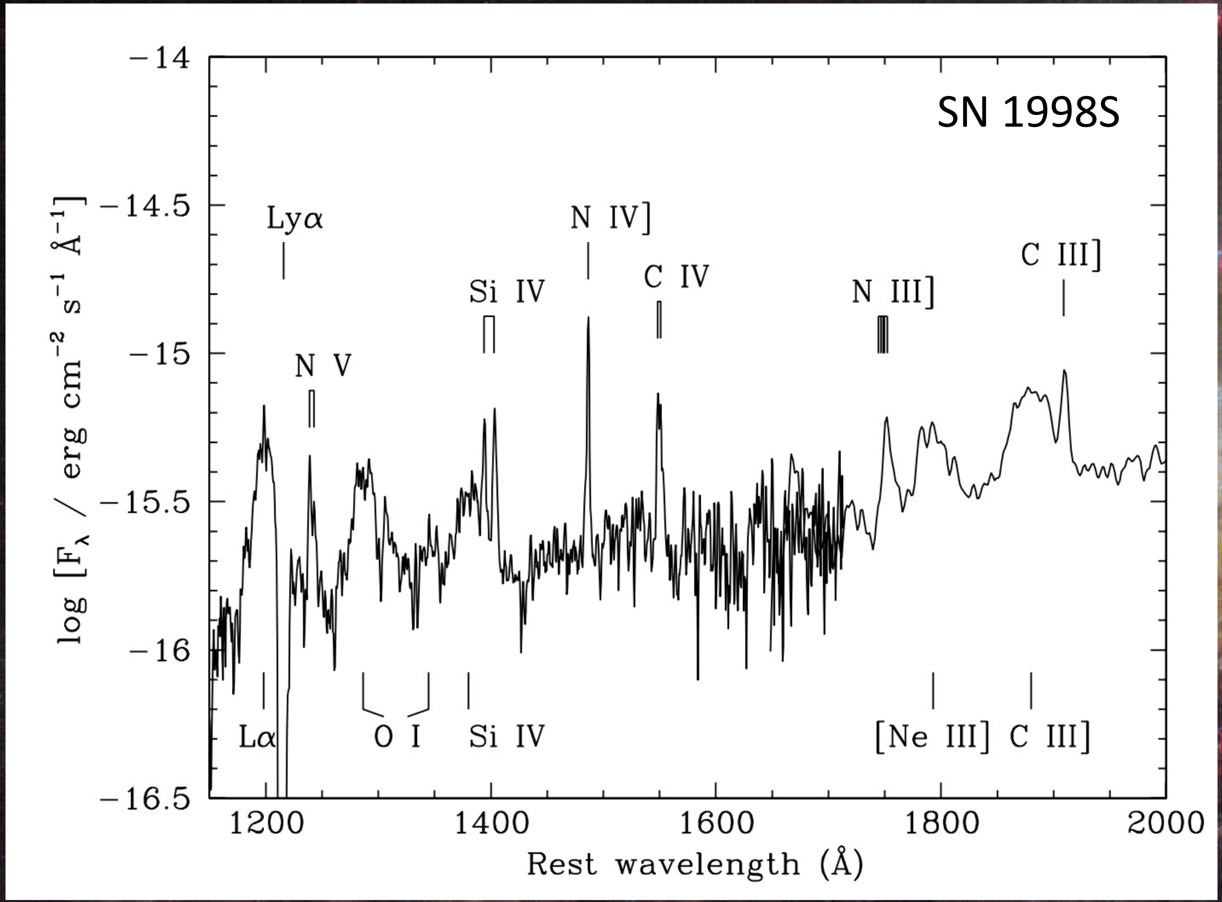


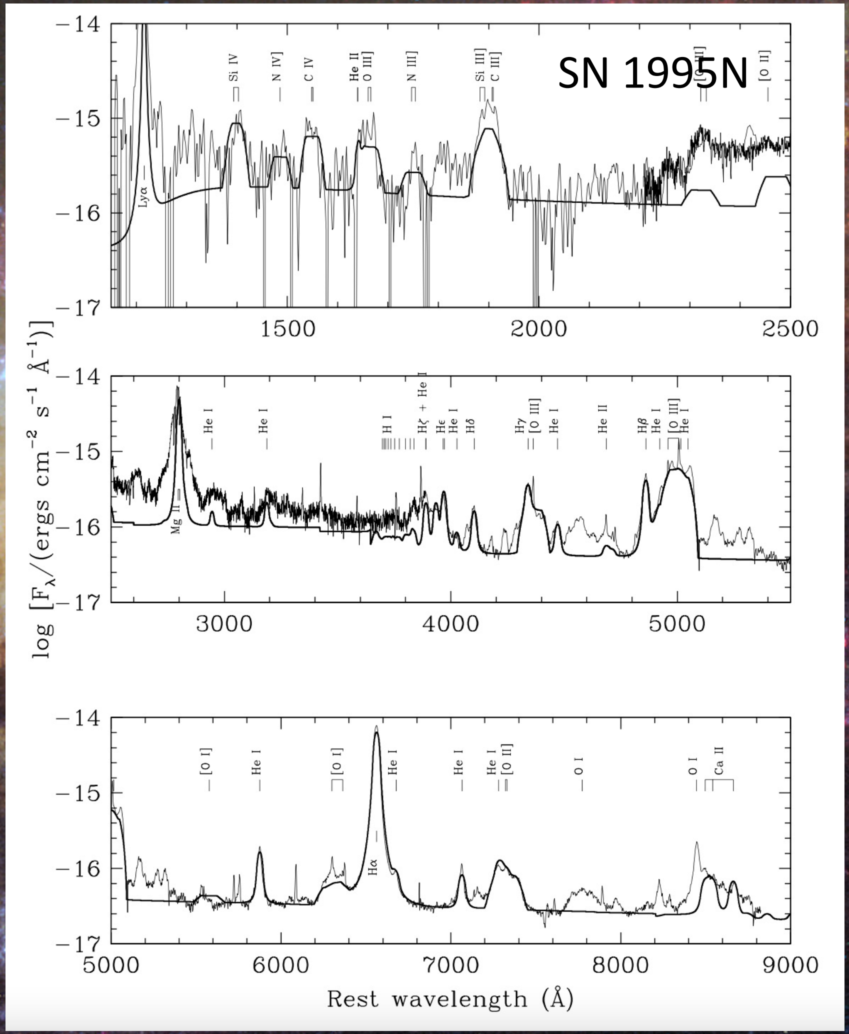
Fransson et al. (2005)



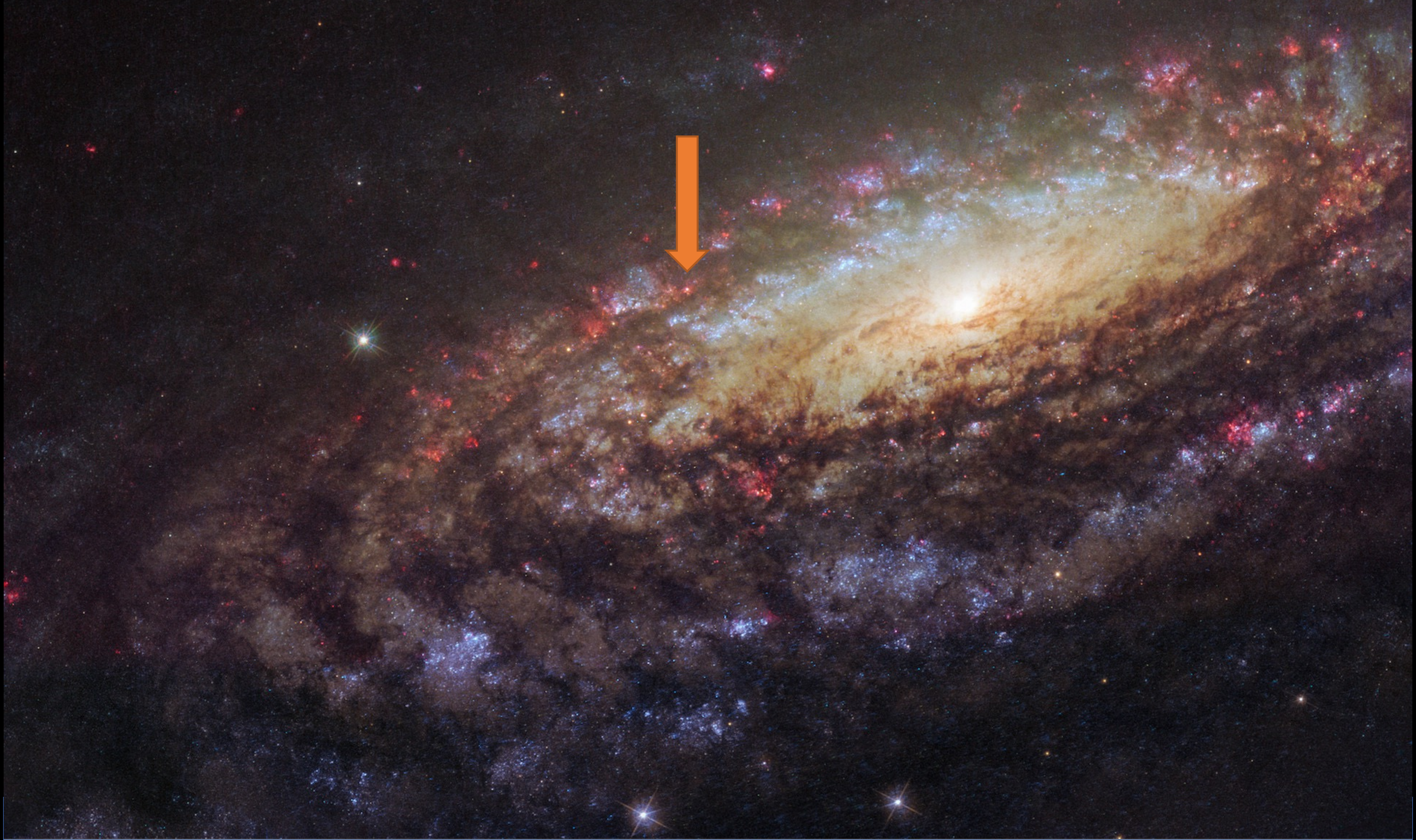
Solid line N/C = 12.4 and N/O = 6
Dashed line N/C = 0.25 and N/0 = 0.12 (solar)

Need for late-time UV spectroscopy



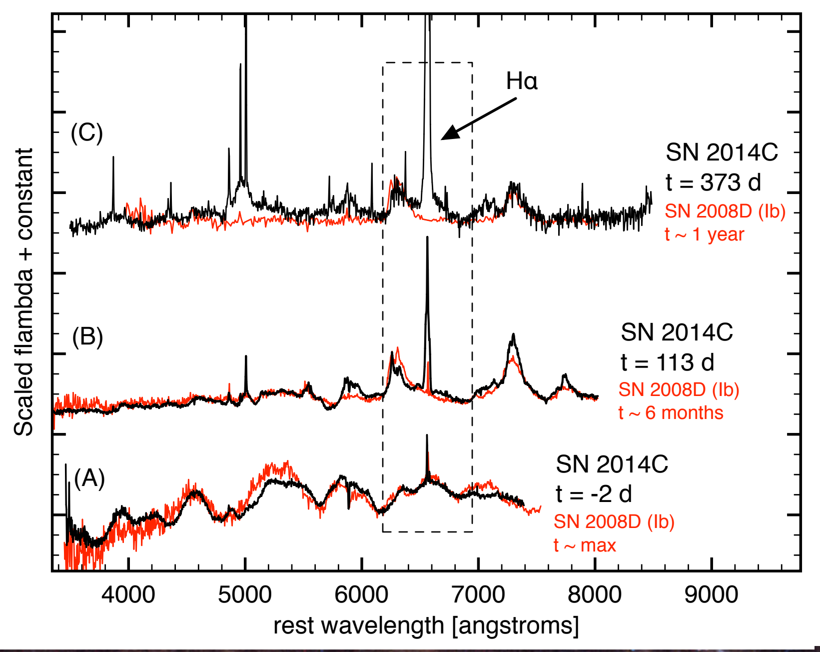


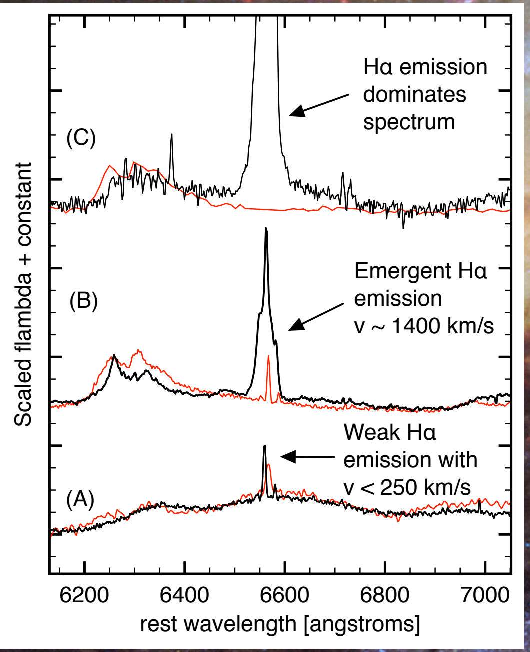
SN 2014C: SN-CSM interaction between a stripped star and eruptive mass loss



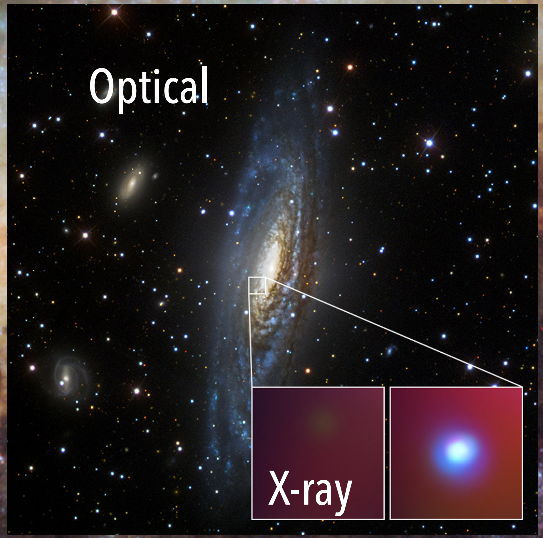
SN 2014C: Supernova Metamorphosis

SN Ib that initially expanded in cavity, then encountered H-rich shell approximately 1 Msun in mass approximately 5 x 10^{16} cm from the explosion site.





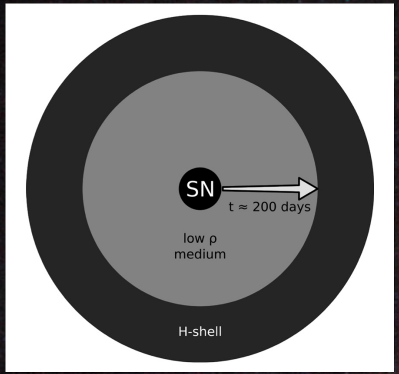
Adapted from Milisavljevic et al. (2015)



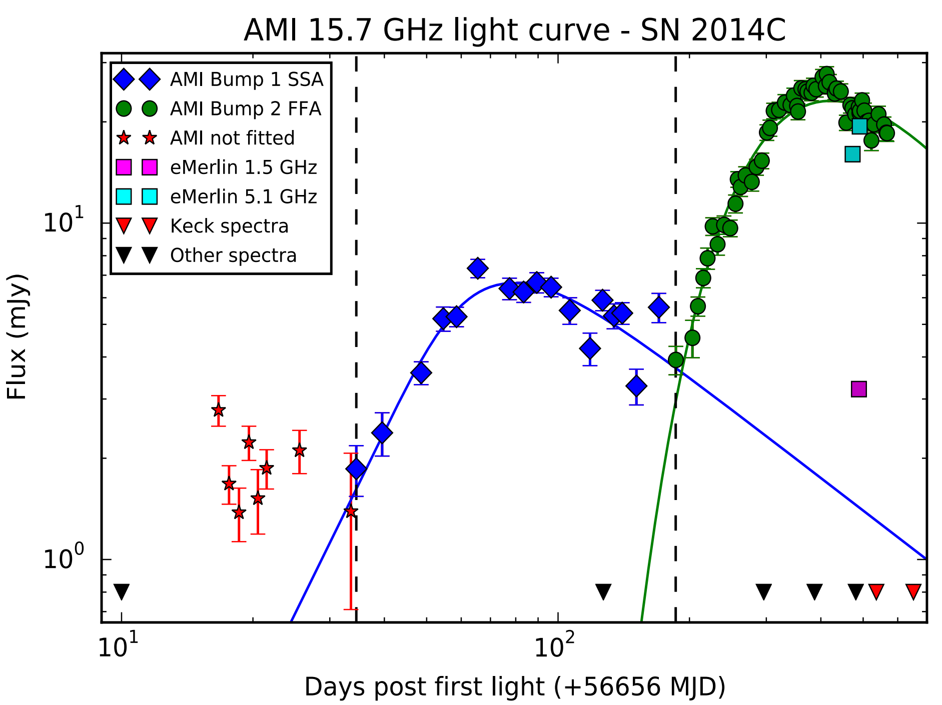
Margutti, Kamble, DM+ 2017

Multi-wavelength characterization

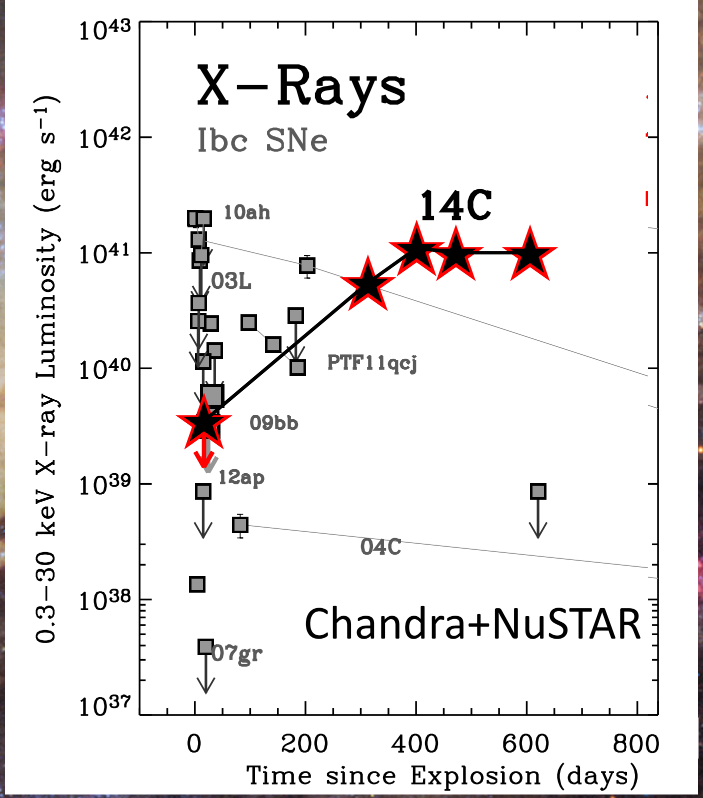
As forward shock plows through circumstellar material, X-ray and radio emission is produced that probes the mass loss environment.



Two distinct regions of mass loss



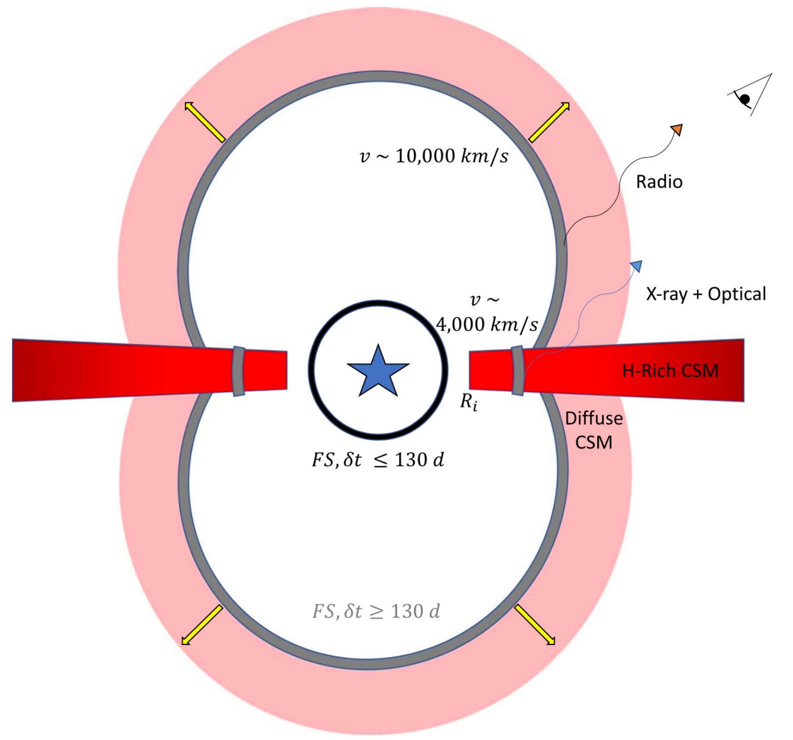
Anderson+ 2017



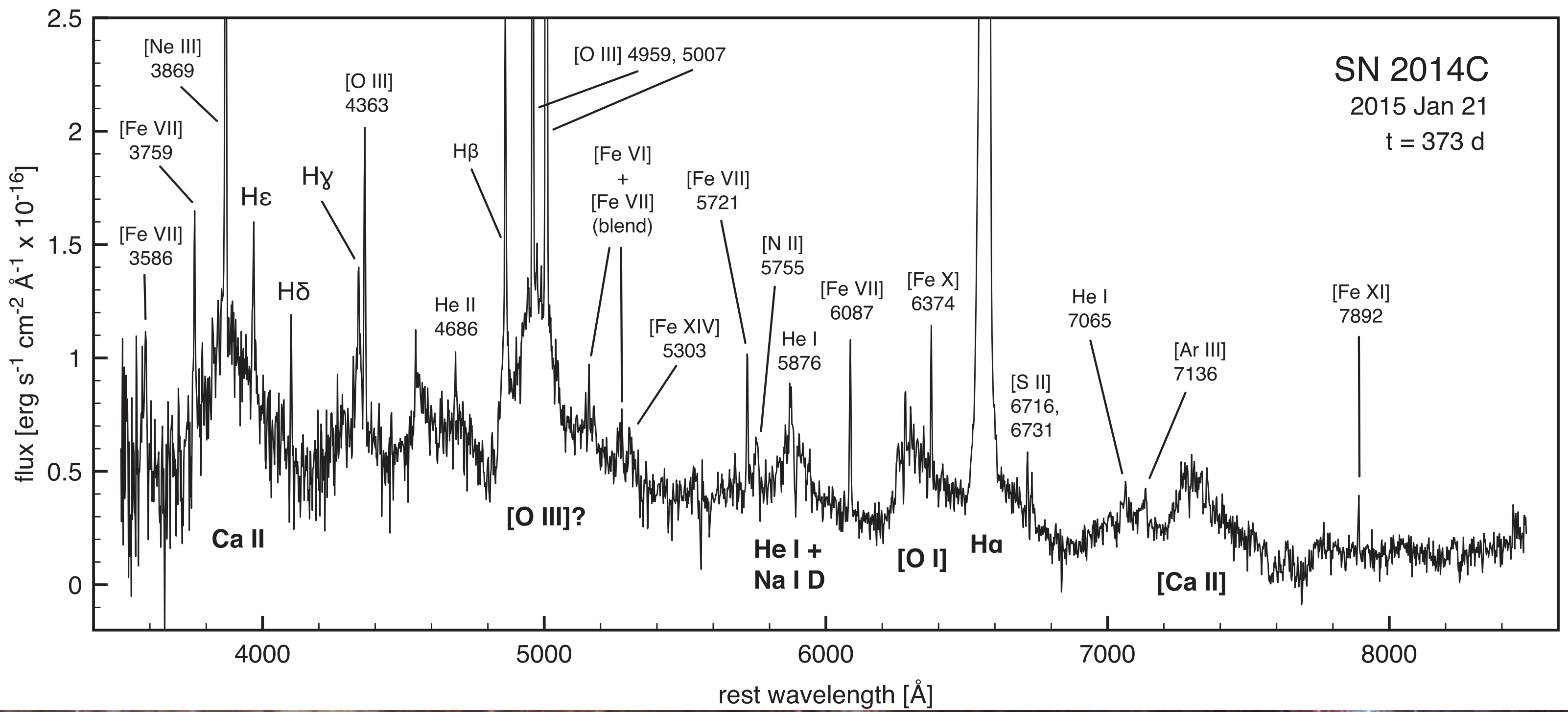
Adapted from Margutti, Kamble, DM+ 2017

See also interesting results by Tinyanont+ 2016 (Spitzer), Vinko et al. (2017), Sun et al. (2020), Thomas et al. (2022)

Accelerated SN-SNR transition



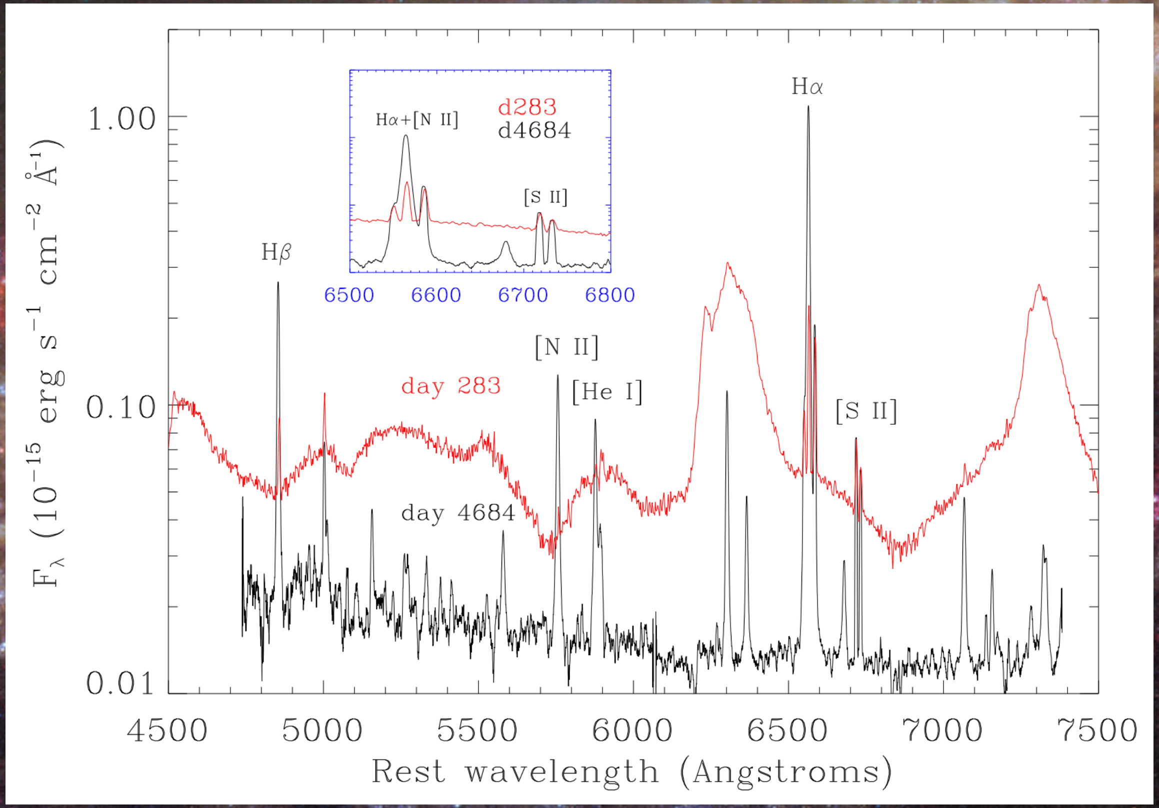
Brethauer, Margutti, DM et al. (2022)



Emission arises from various regions of shocked and photoionized CSM and stellar ejecta. Many coronal lines are observed. Emission from reverse-shock-heated metal-rich ejecta is observed.

Late-time interaction is increasingly recognized across SN types and timescales

SN 2004dk: A Type Ib that evolved into Type IIn 12 years after explosion.

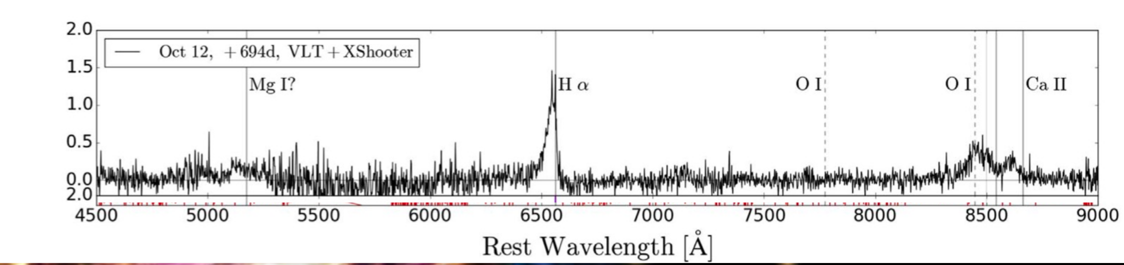


Mauerhan et al. (2018)

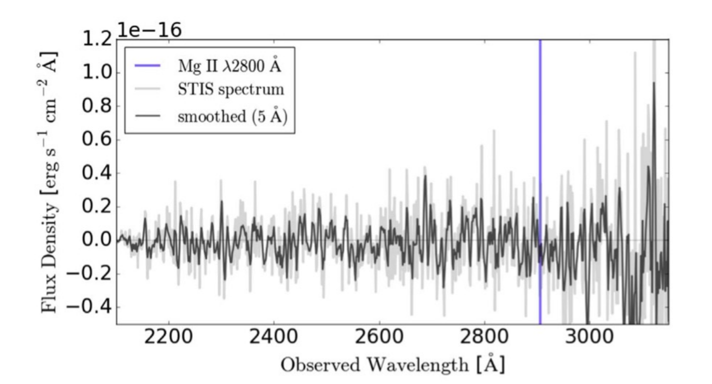
SN Ia – CSM interaction

Graham et al. (2019) In order to constrain the prevalence, location, and quantity of CSM in SN Ia systems, performed a near-ultraviolet (NUV) survey with the Hubble Space Telescope (HST) to look for the high-energy signature of SN Ia ejecta interacting with the CSM. SN 2015cp, an SN 1991T-like overluminous SN Ia, was experienced late-onset interaction between its ejecta and the surrounding CSM 664 days after its light-curve peak.

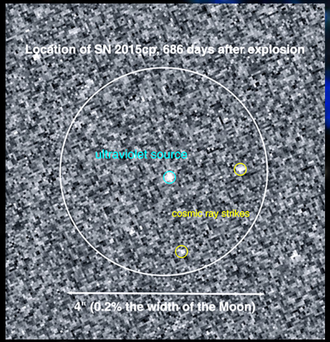
Late-time interaction is rare among SN Ia (< 6%) but provide unique opportunity to probe progenitor system.
Imaging alone was unable to constrain nature of CSM.



Optical spectrum



Attempted UV spectrum was unsuccessful



Conclusions

Ultraviolet light is a powerful probe of supernovae. The UVEX combination of imaging + spectroscopy has the potential to transform our understanding of supernova progenitor systems and explosion dynamics.

Probe mass loss hundreds to thousands of years prior to explosion. Informs about poorly understood mass loss mechanisms.

Access abundant emission from layers of metal-rich ejecta. Over time ever-deeper layers will slowly reveal themselves, mapping out nucleosynthesis.