Deciphering the Encoded Debris of *SUPERNOVAE*

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Harvard-Smithsonian Center for Astrophysics

SNR: Odyssey in Space After Stellar Death

Chania, Greece, June 10, 2016

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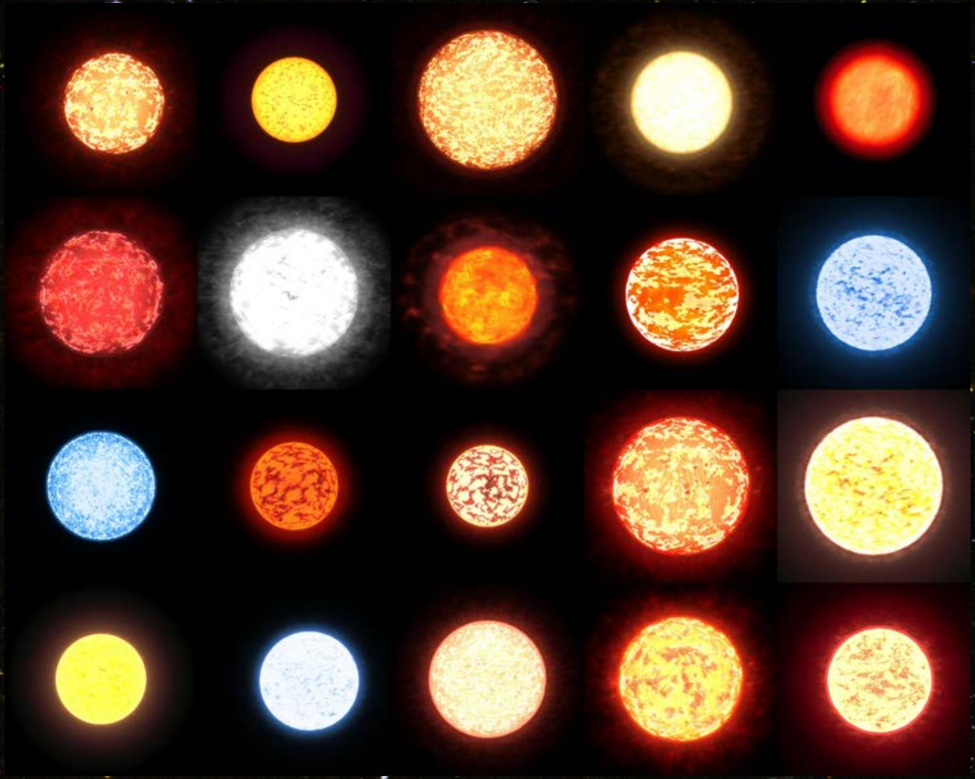
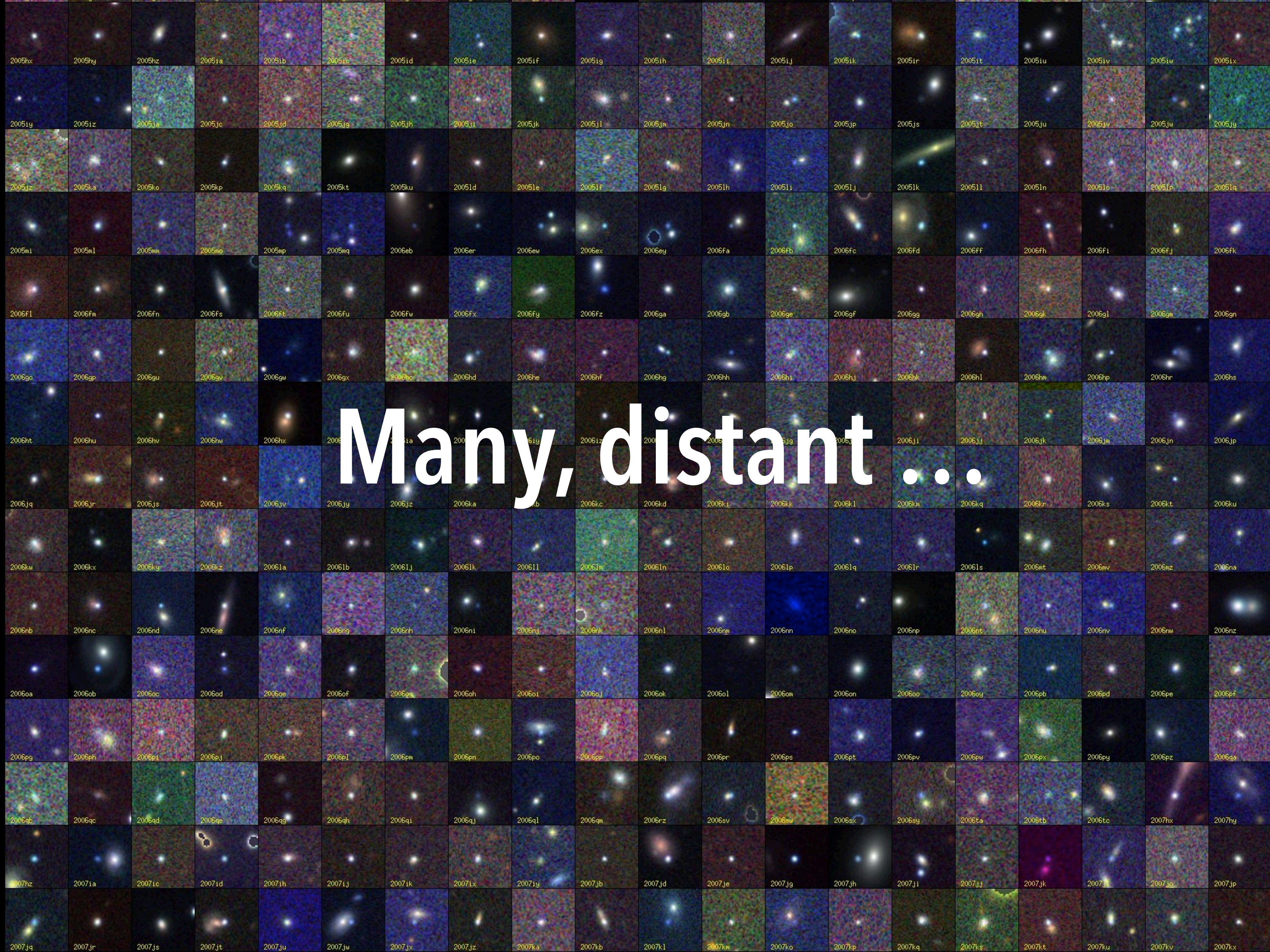
What types of stars explode?



How do stars explode?


Many, distant …


… or a few, up close.

Supernova remnant shown…

The Ninth Harvard-Smithsonian Conference on Theoretical Astrophysics

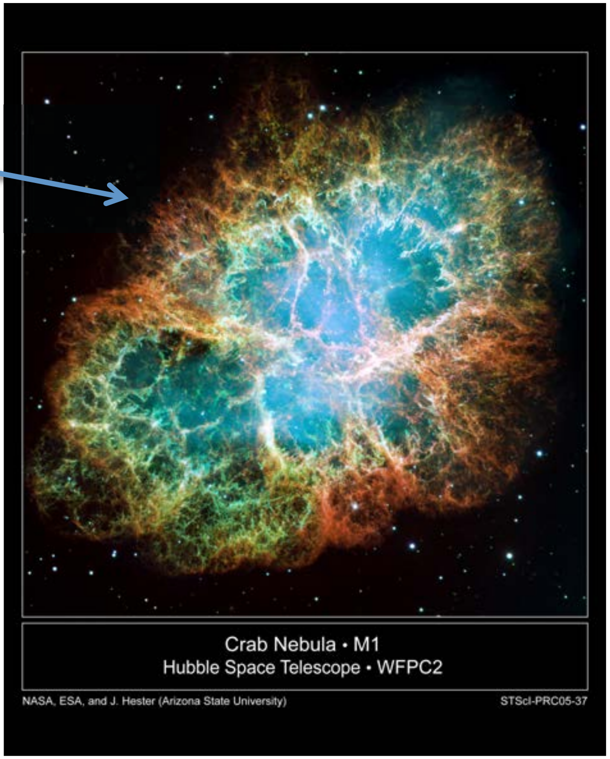
The Transient Sky

Sponsored by Raymond and Beverly Sackler and Irwin Shapiro

Monday, May 16 through Thursday, May 19, 2016

Sheraton Commander Hotel, 16 Garden Street, Cambridge, MA

Hosted by the Institute for Theory and Computation, Harvard University



Crab Nebula • M1
Hubble Space Telescope • WFPC2
NASA, ESA, and J. Hester (Arizona State University) STScI-PRC05-37

Scientific Organizing Committee: Avi Loeb (chair), Edo Berger, Mansi Kasliwal
Local Organizing Committee: Avi Loeb, Uma Mirani, Mark Palmer, Nina Zonnevylle

http://www.cfa.harvard.edu/events/2016/sackler

…but no supernova remnant talks!


GRB 130427
Fantasy

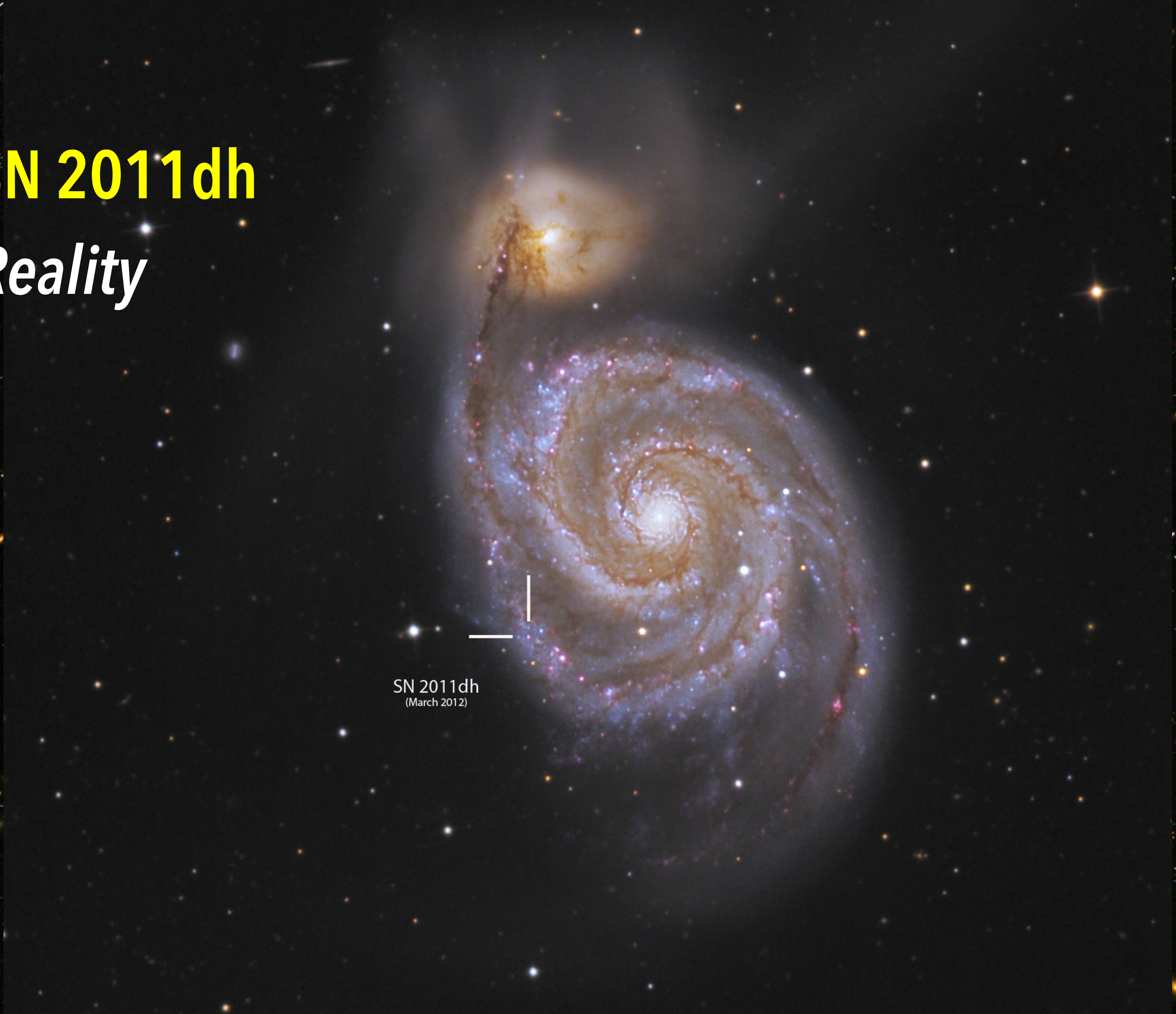

GRB 130427
Reality

SN 2011dh

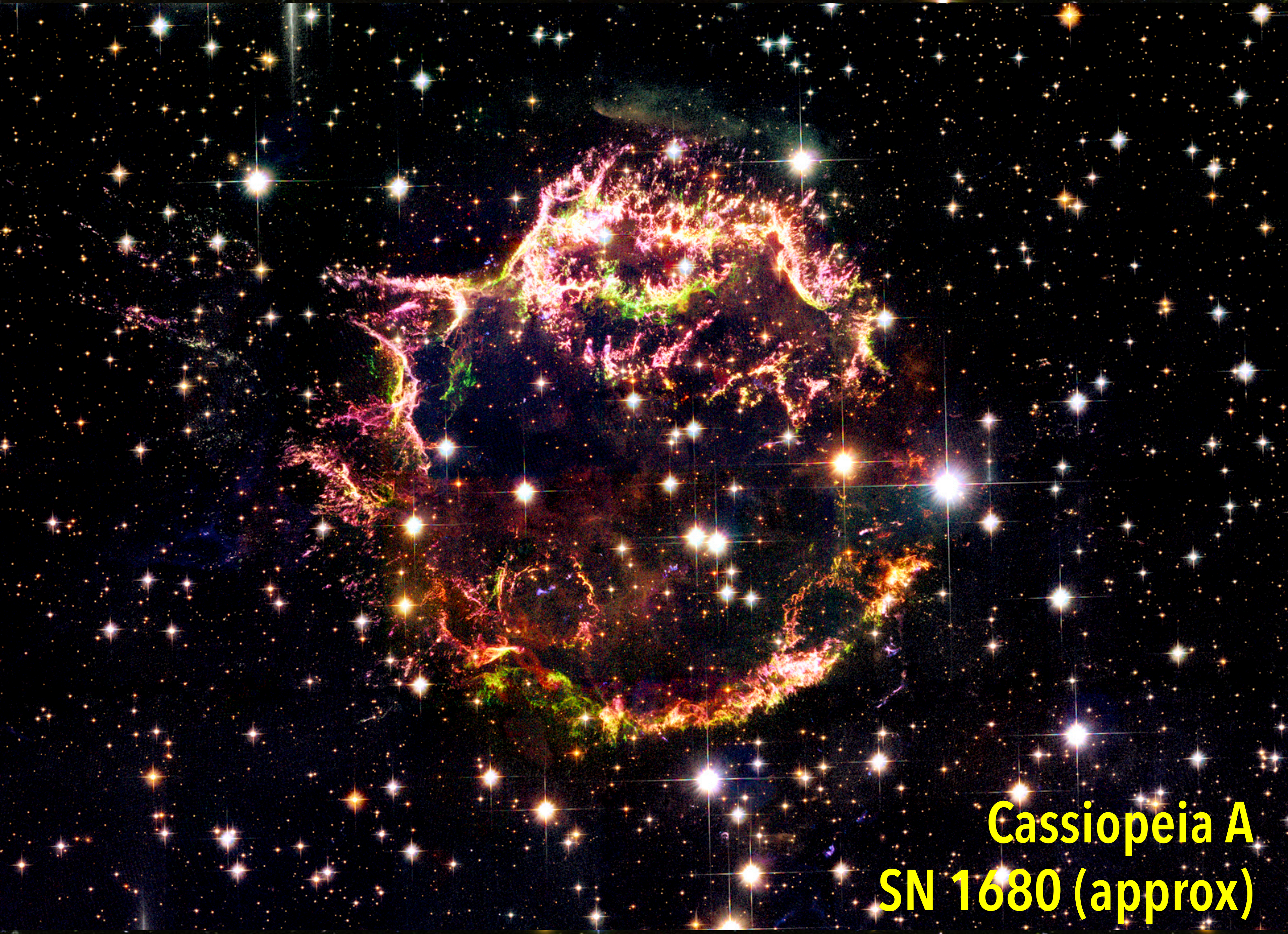
Fantasy

SN 2011dh

Reality




REALITY!
Cassiopeia A
SN 1680 (approx)

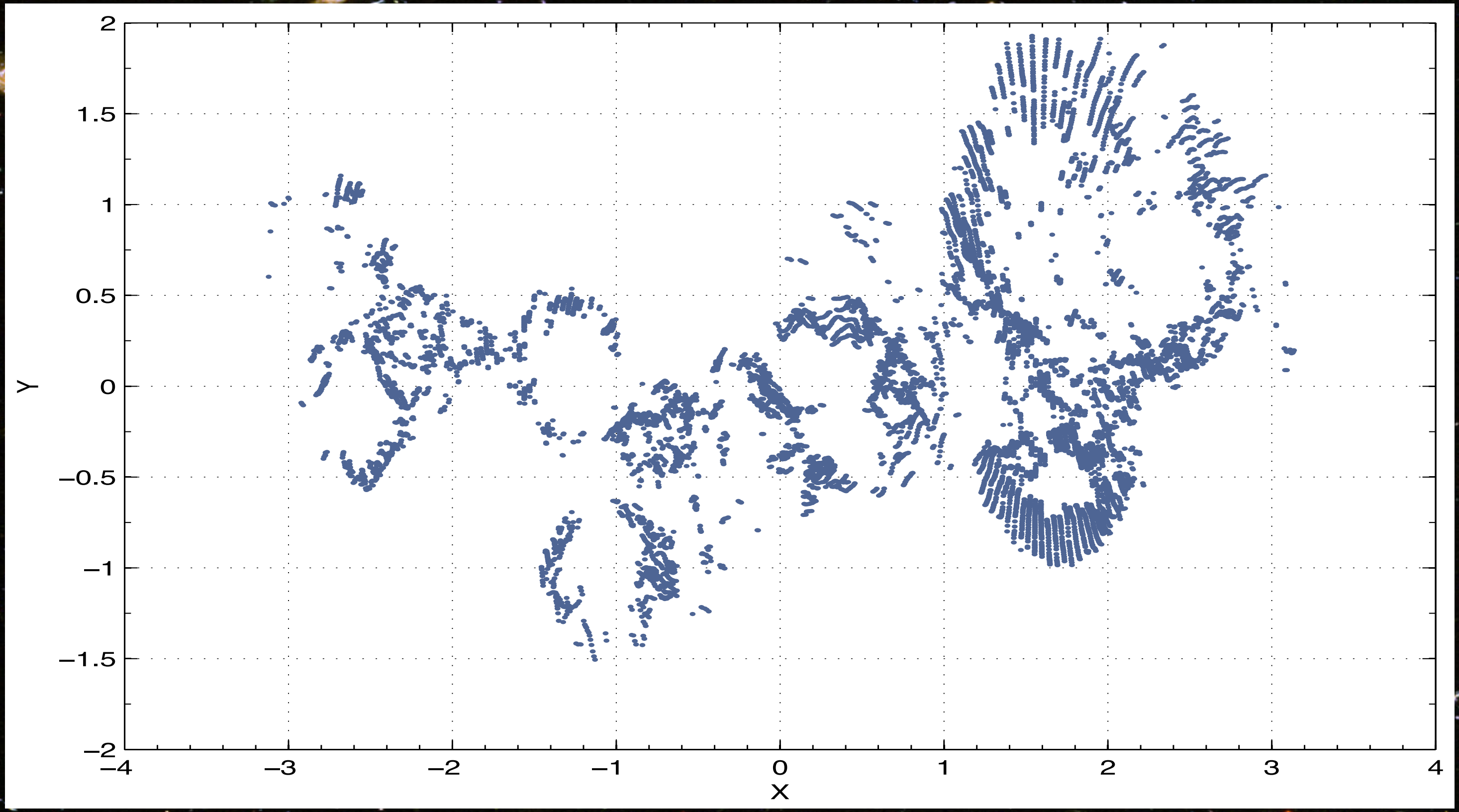

Cassiopeia A
SN 1680 (approx)

www.cfa.harvard.edu/~dmilisav/casa-webapp

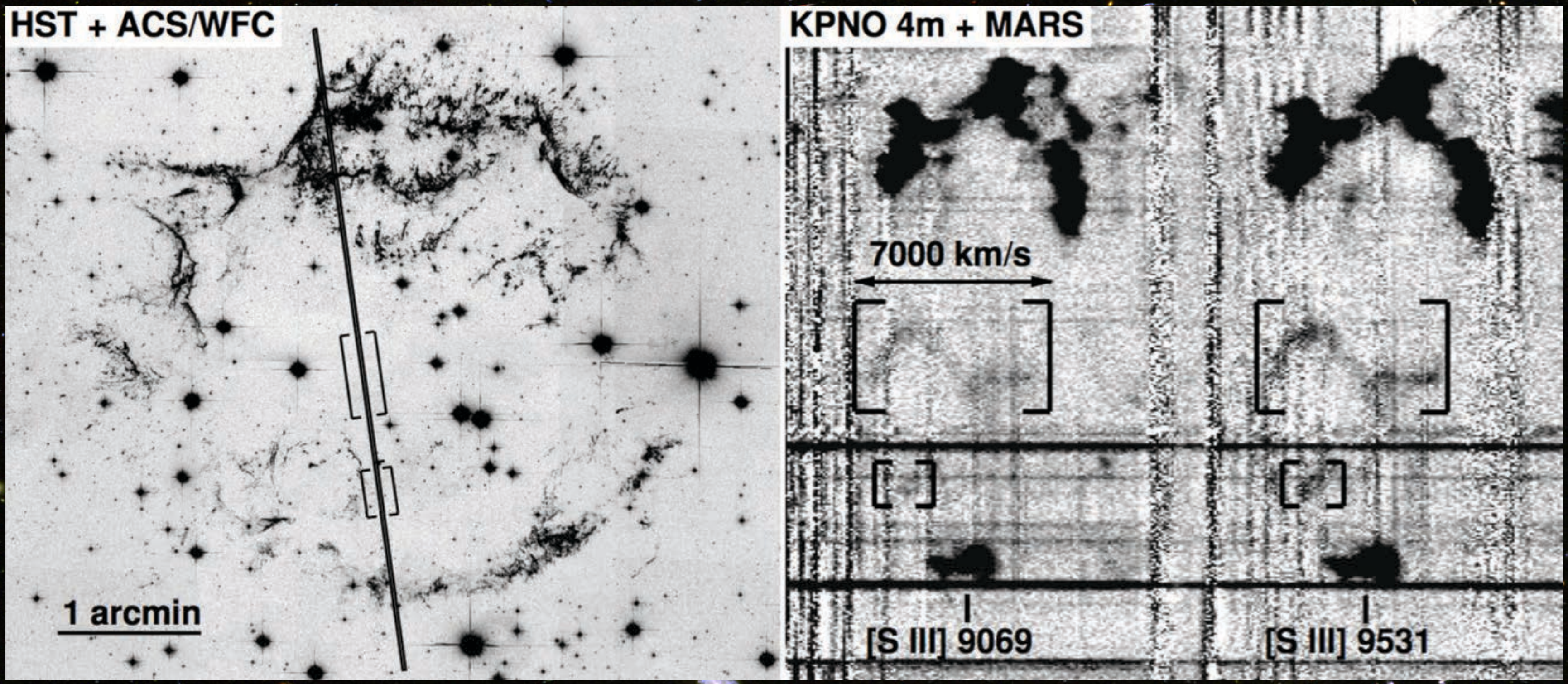
See also Reed et al. (1995), Lawrence et al. (1995), DeLaney et al. (2010), Alarie et al. (2014).

Ejecta Rings!

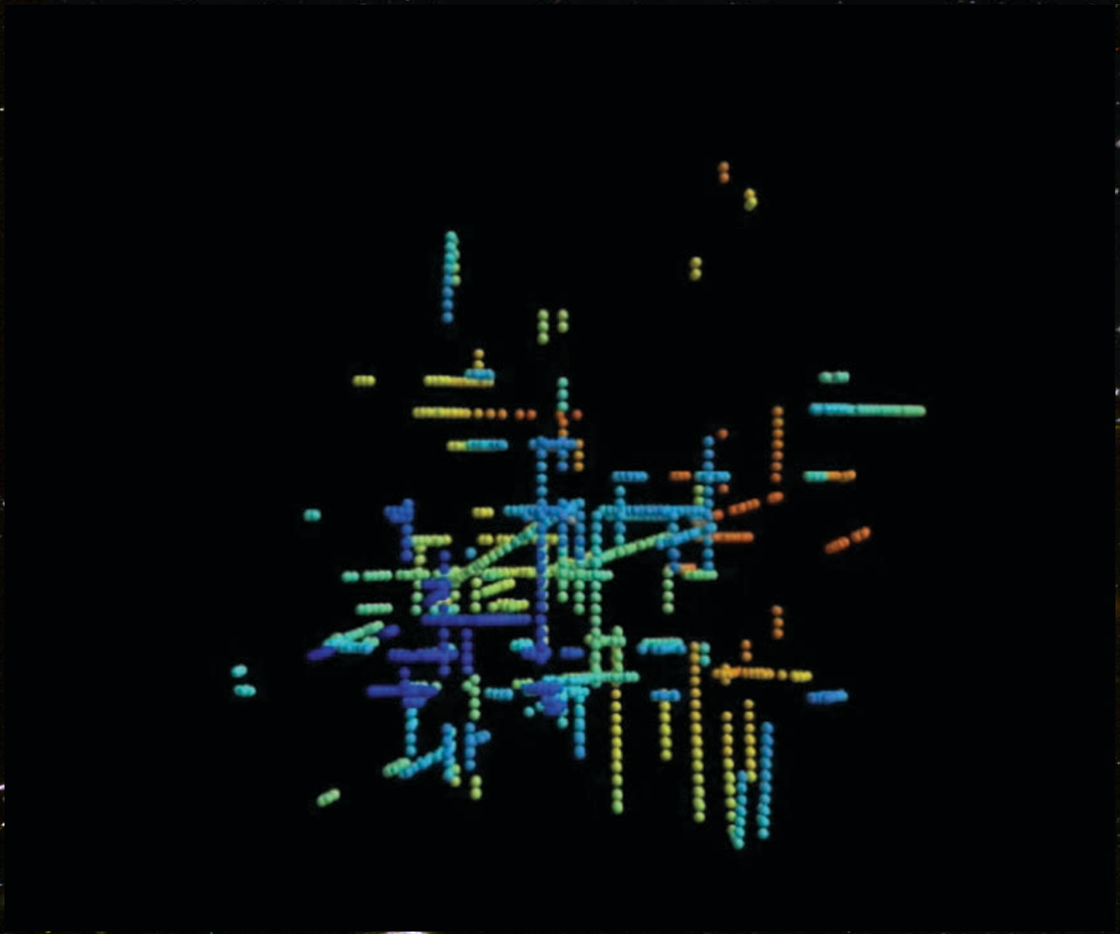
The main shell of Cas A's optically-emitting ejecta as represented in a Mercator projection.



Rings → Bubbles?   Blondin, Borkowski, Reynolds (2001)


HST + ACS/WFC
1 arcmin
KPNO 4m + MARS
7000 km/s
[S III] 9069
[S III] 9531

3D Reconstruction of a SN Debris Field

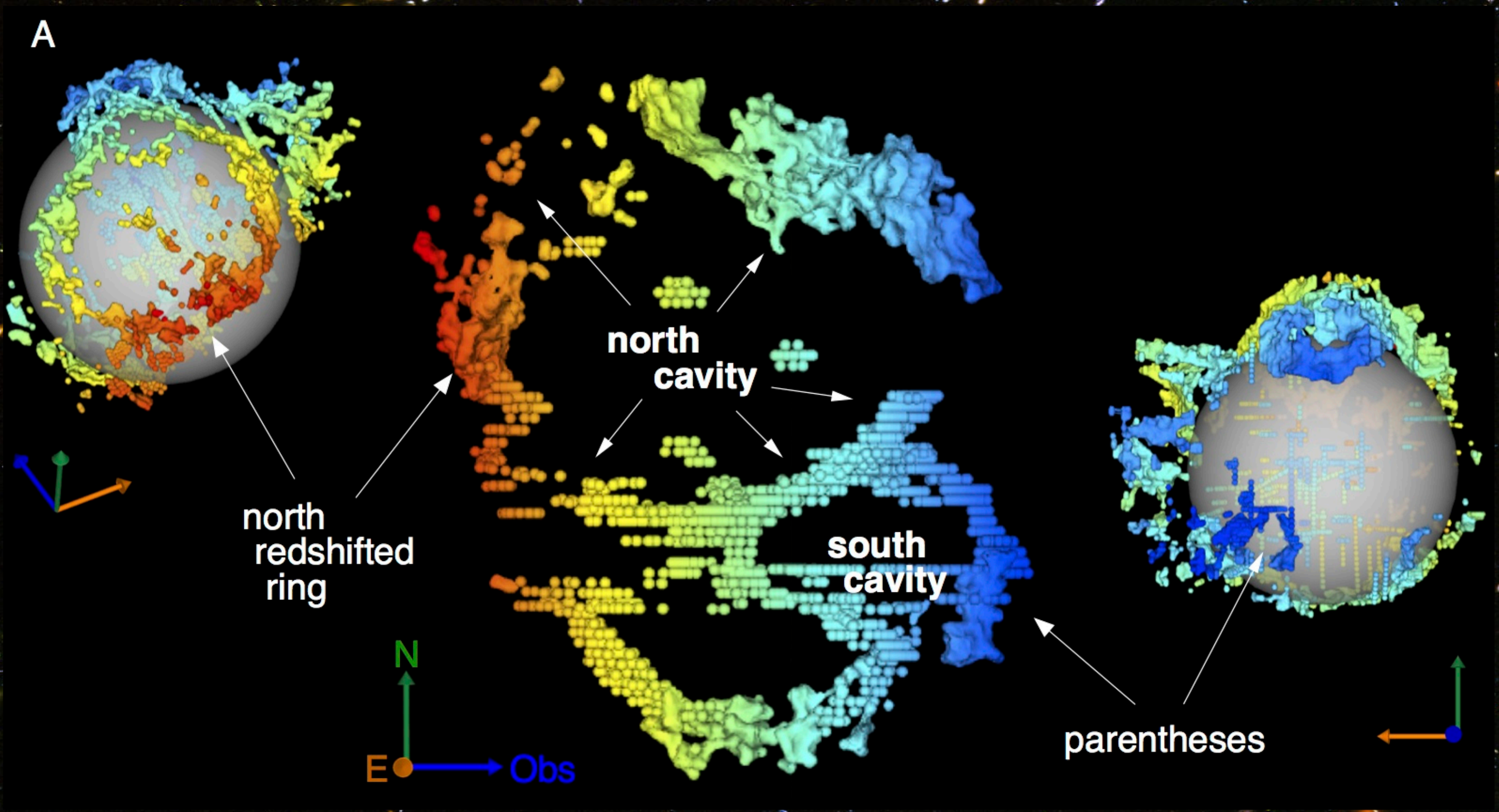


Ejecta distribution exhibits large-scale coherent structure that was imprinted early in the explosion

Milisavljevic & Fesen (2015, *Science*)

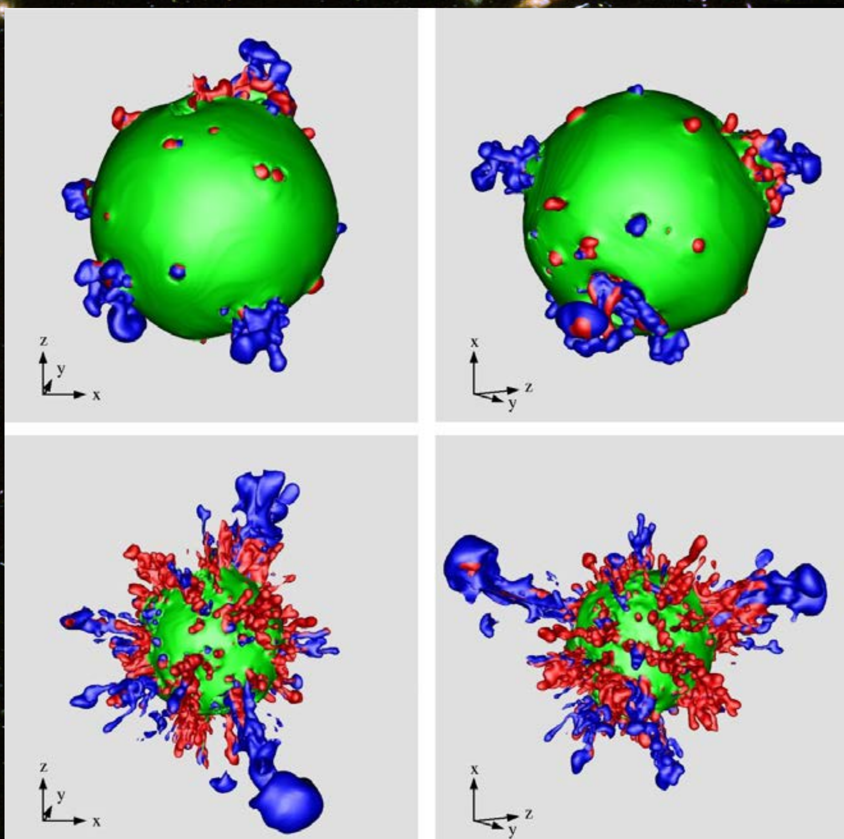
Radioactive Bubbles May Have Punched Holes in Supernova's Heart

by Calla Cofield, Space.com Staff Writer | January 29, 2015 02:01pm ET



Simulation

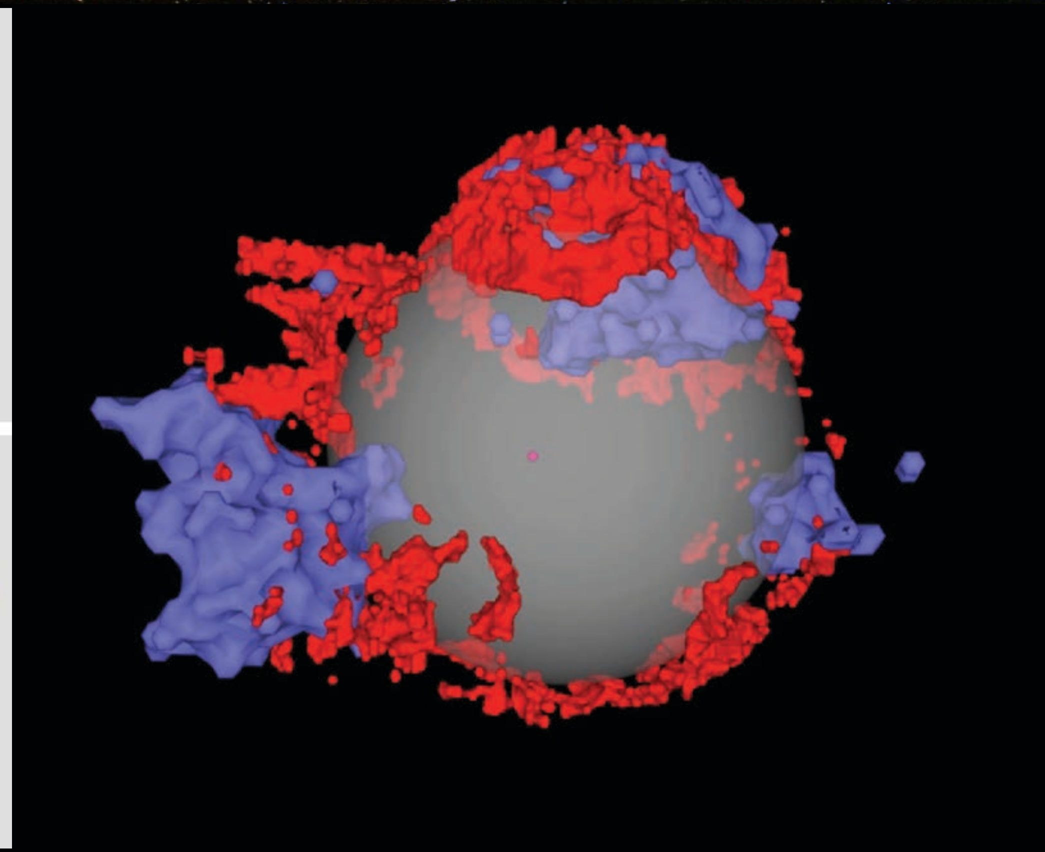
Carbon Nickel Oxygen



Hammer, Janka, Müller (2010)

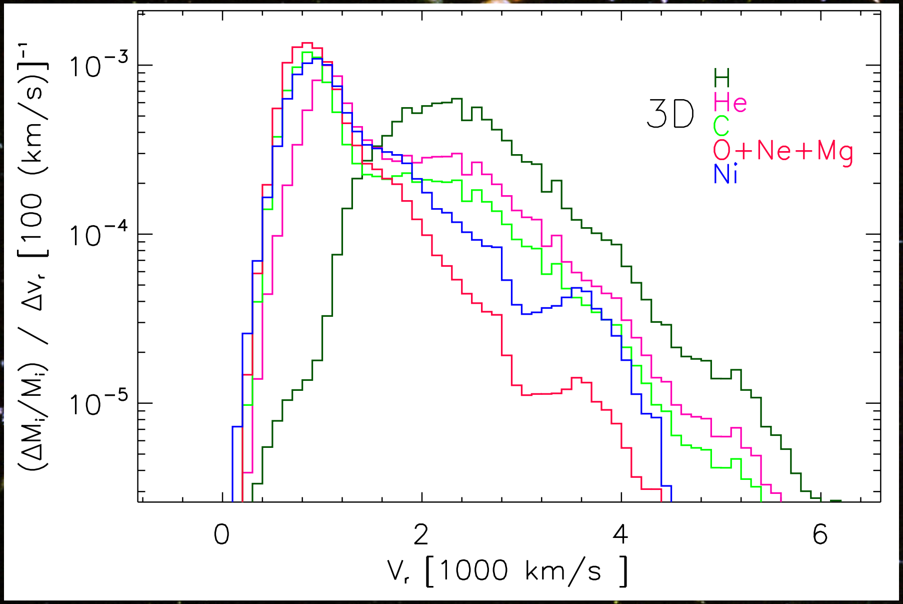
Observation

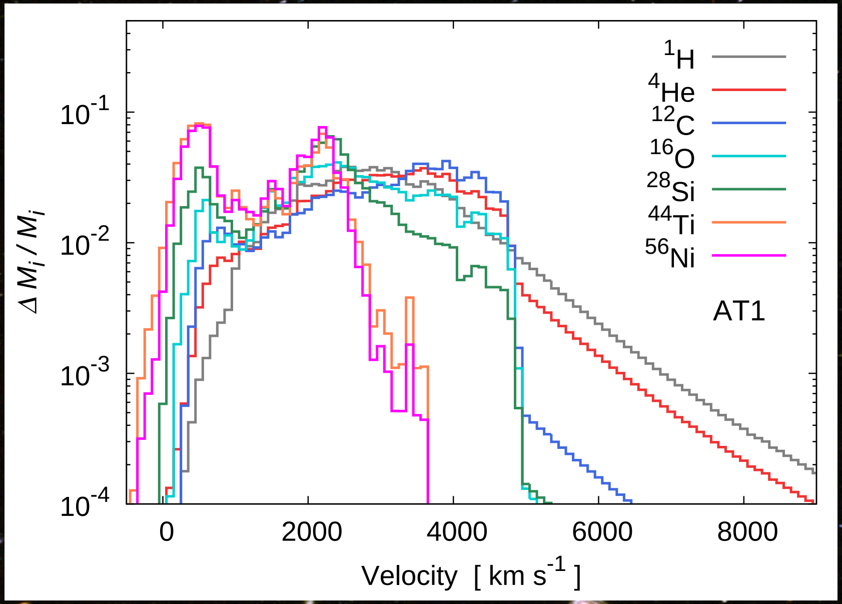
Optical (Sulfur+Oxygen) X-ray (Iron)



Milisavljevic & Fesen (2013)

Ni is being mixed to much higher velocities than those predicted by simulations

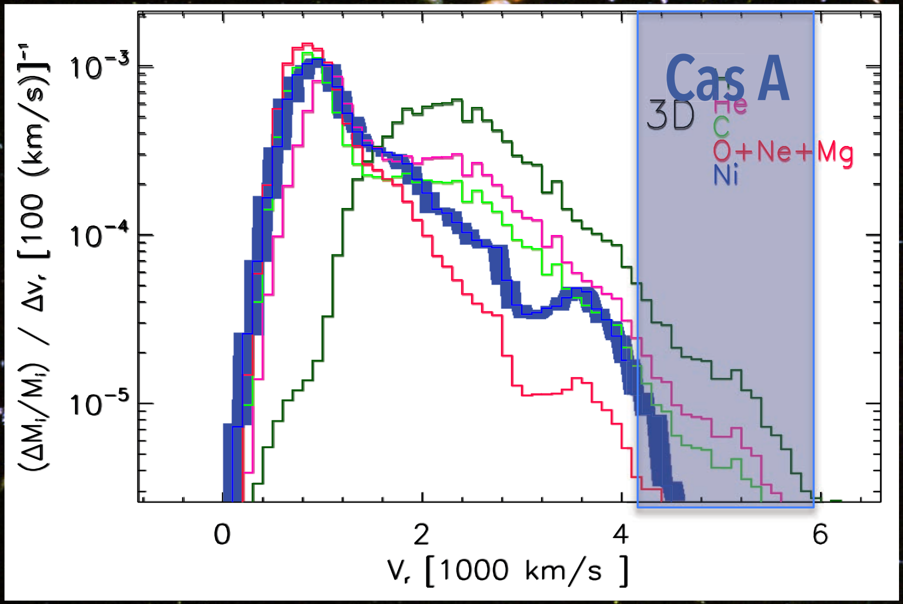




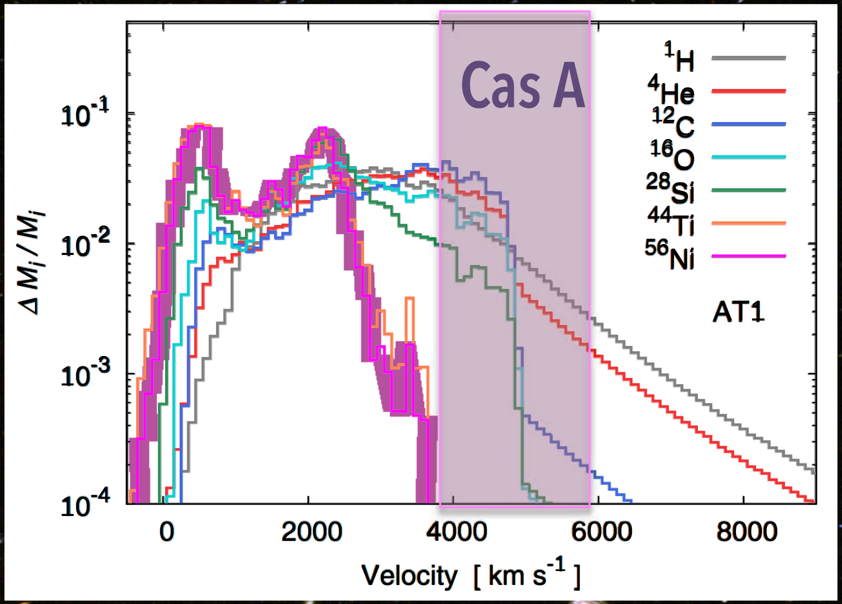
Hammer et al. 2010

Ono, Nagataki et al. 2011

Ni is being mixed to much higher velocities than those predicted by simulations



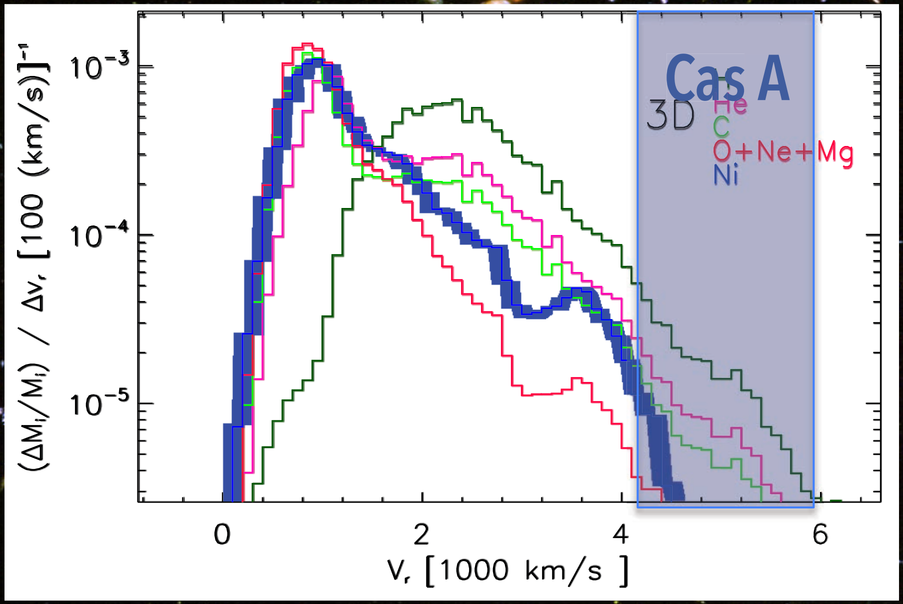
Hammer et al. 2010

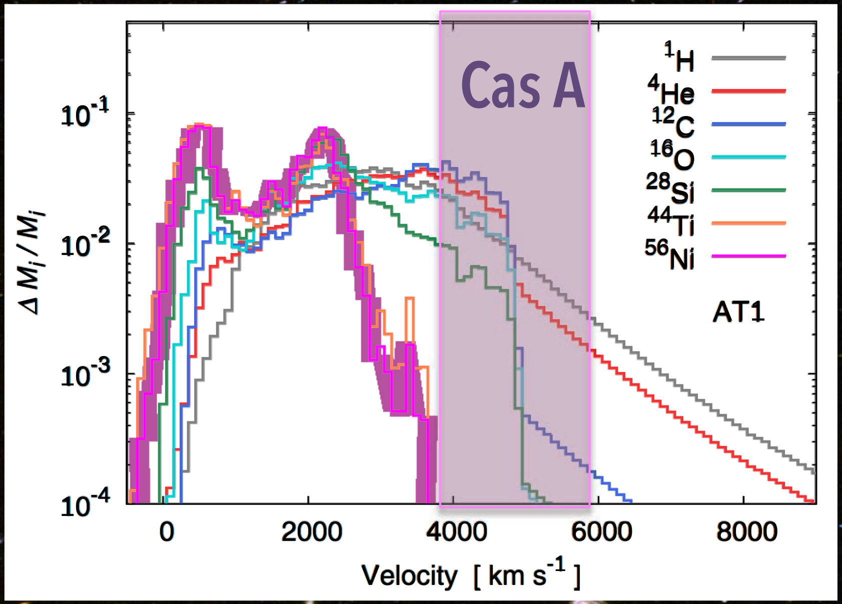


Ono, Nagataki et al. 2011

"Missing iron"

Ni is being mixed to much higher velocities than those predicted by simulations





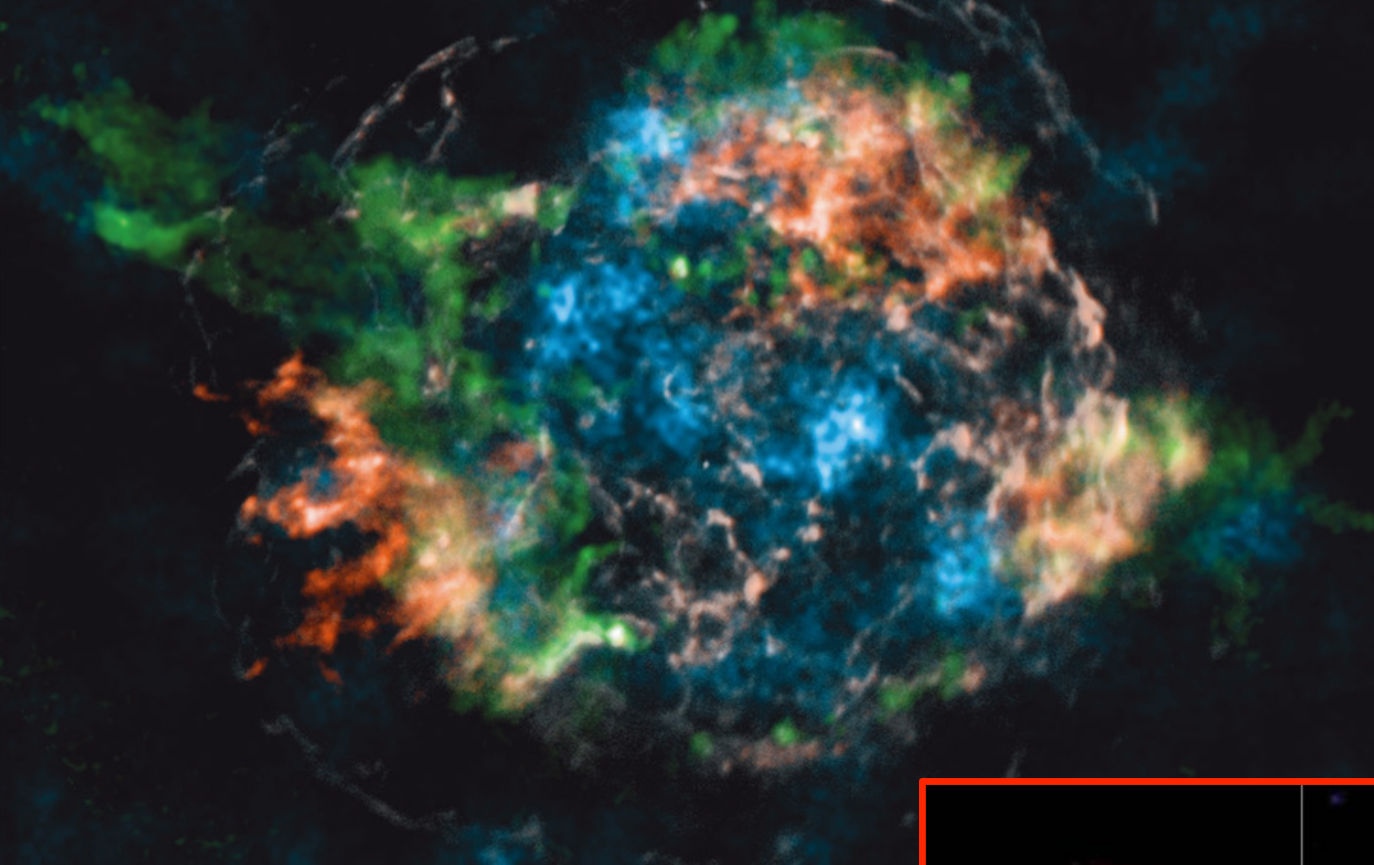
Hammer et al. 2010

Ono, Nagataki et al. 2011

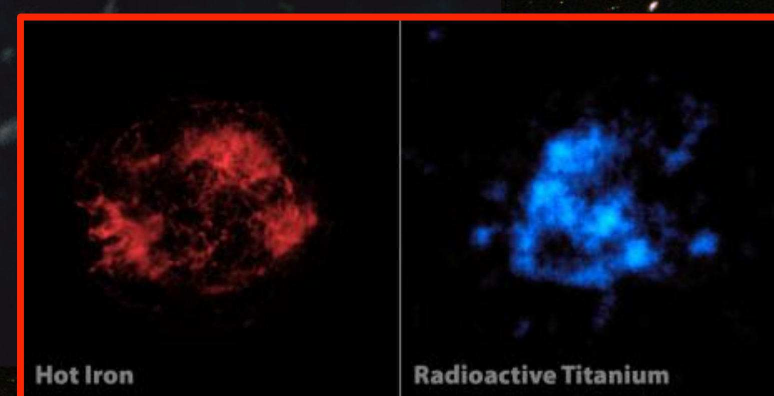
This is a problem!

NuSTAR

Radioactive 44Ti

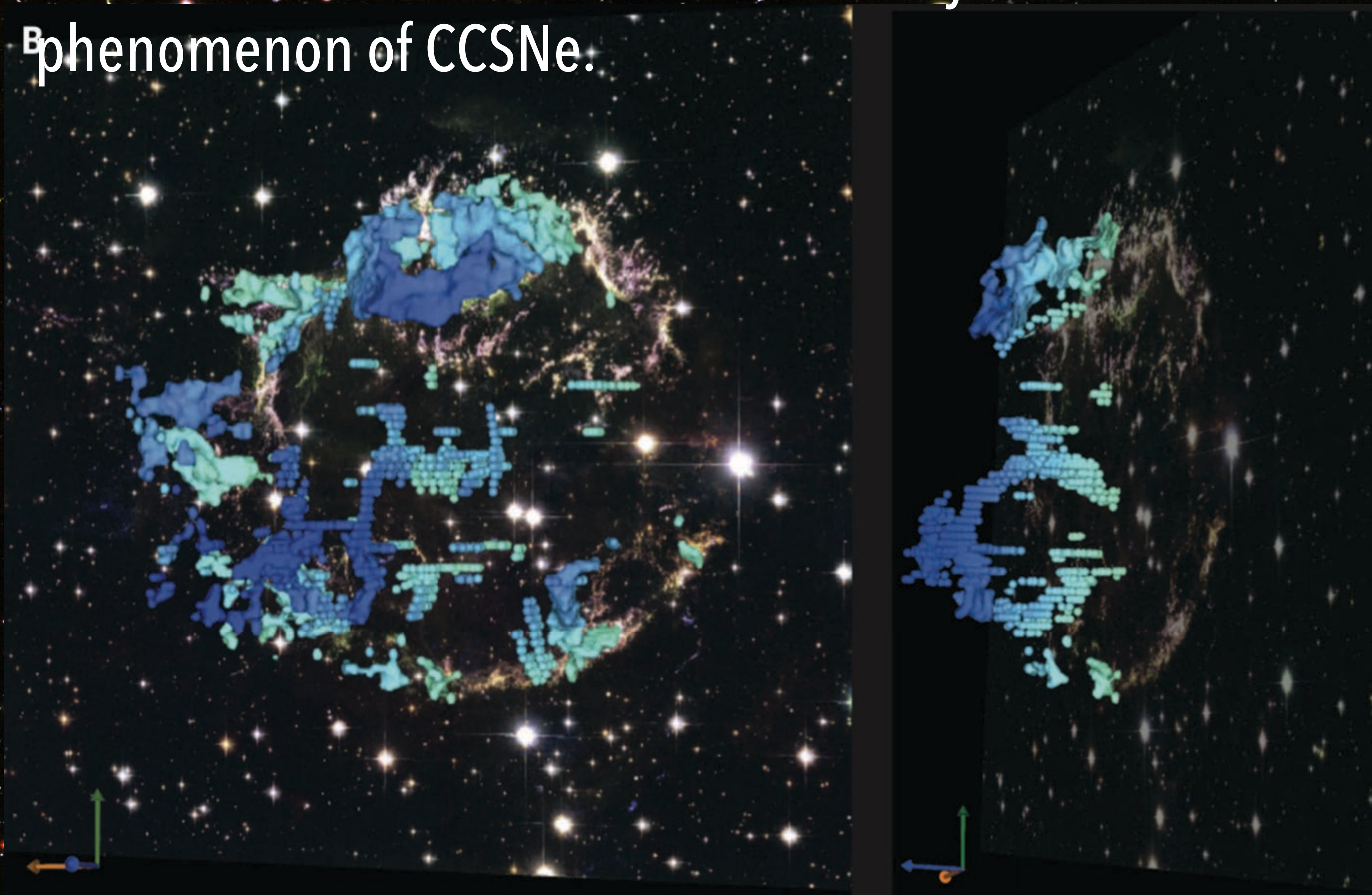


Grefenstette et al. (2014)

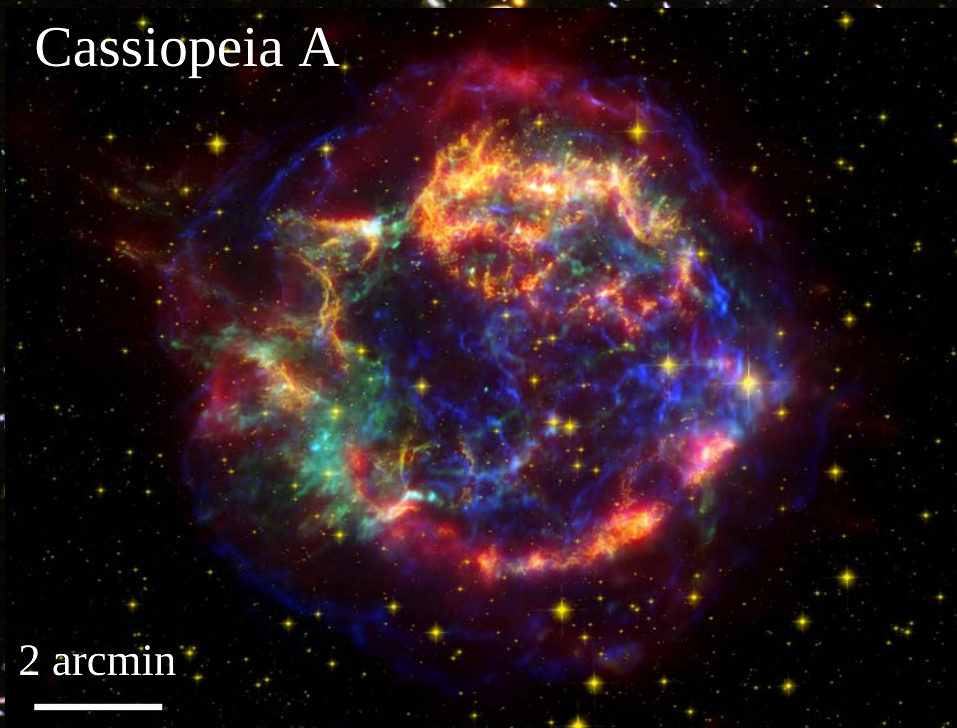


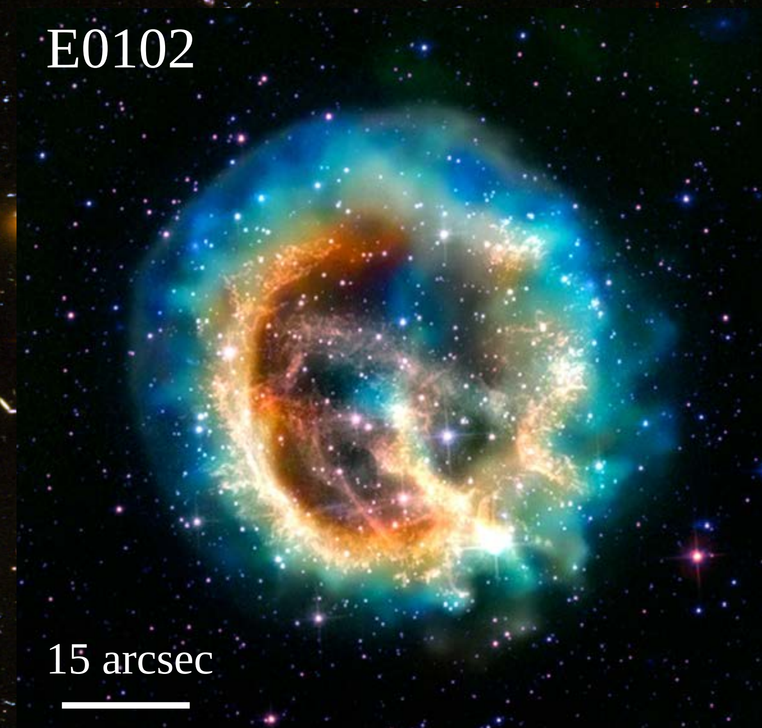
The SN – SNR Connection

The bubble-like interior of Cas A is likely a common phenomenon of CCSNe.



Cas A has an older brother that grew up in a different neighborhood…





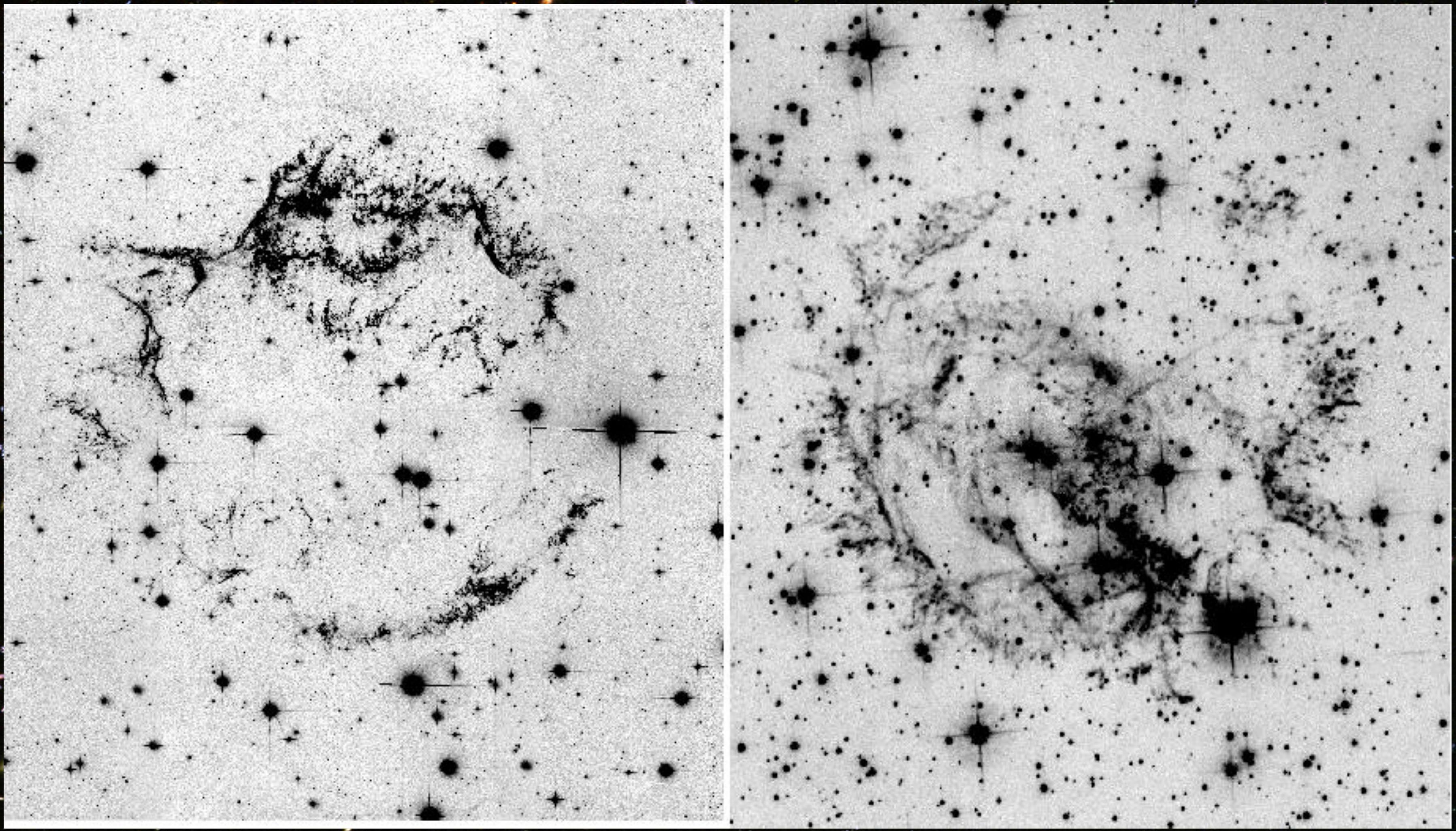
~330 yr

Galactic

~2000 yr

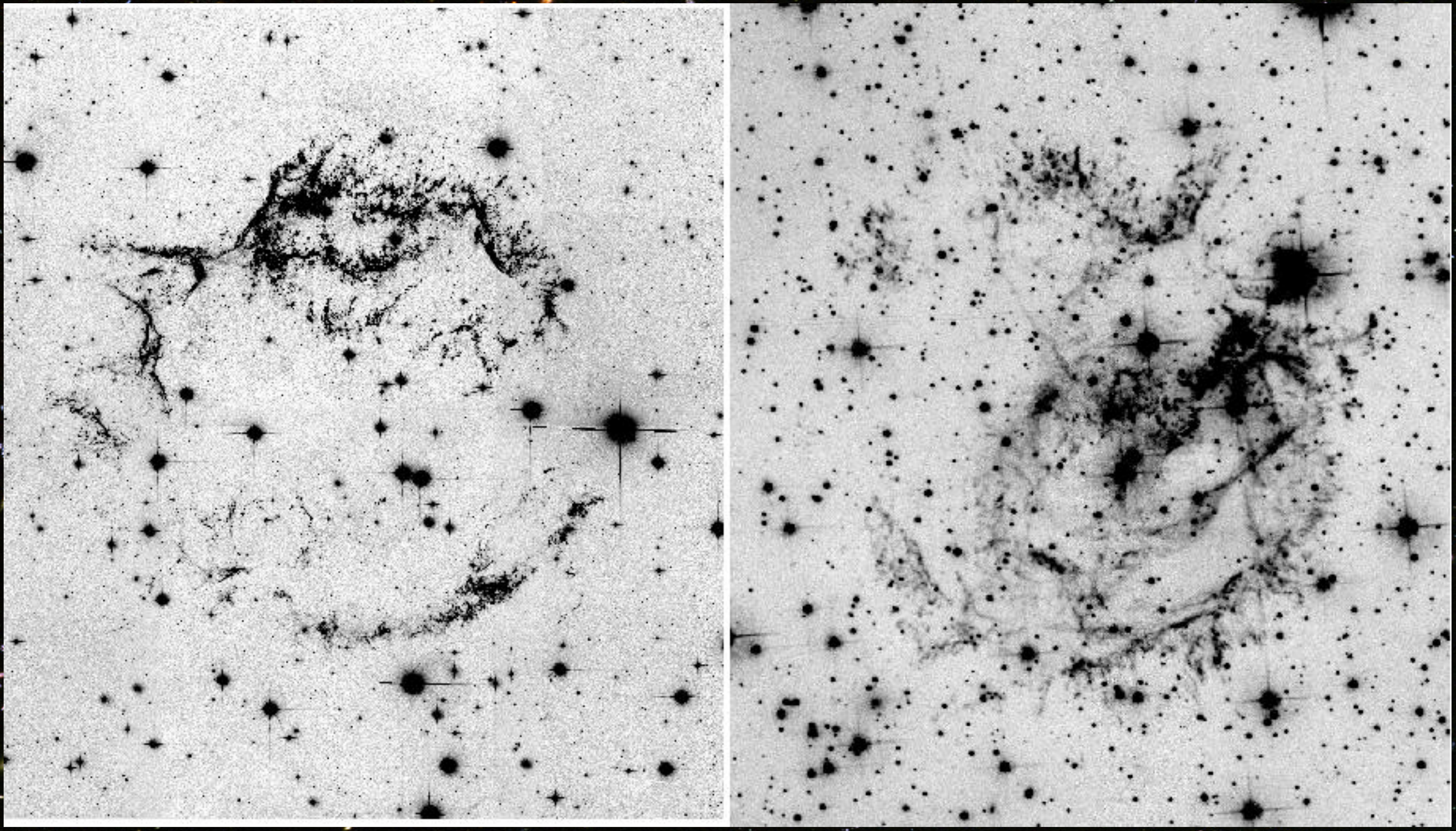
Small Magellanic Cloud

Shared morphology but different ejecta composition



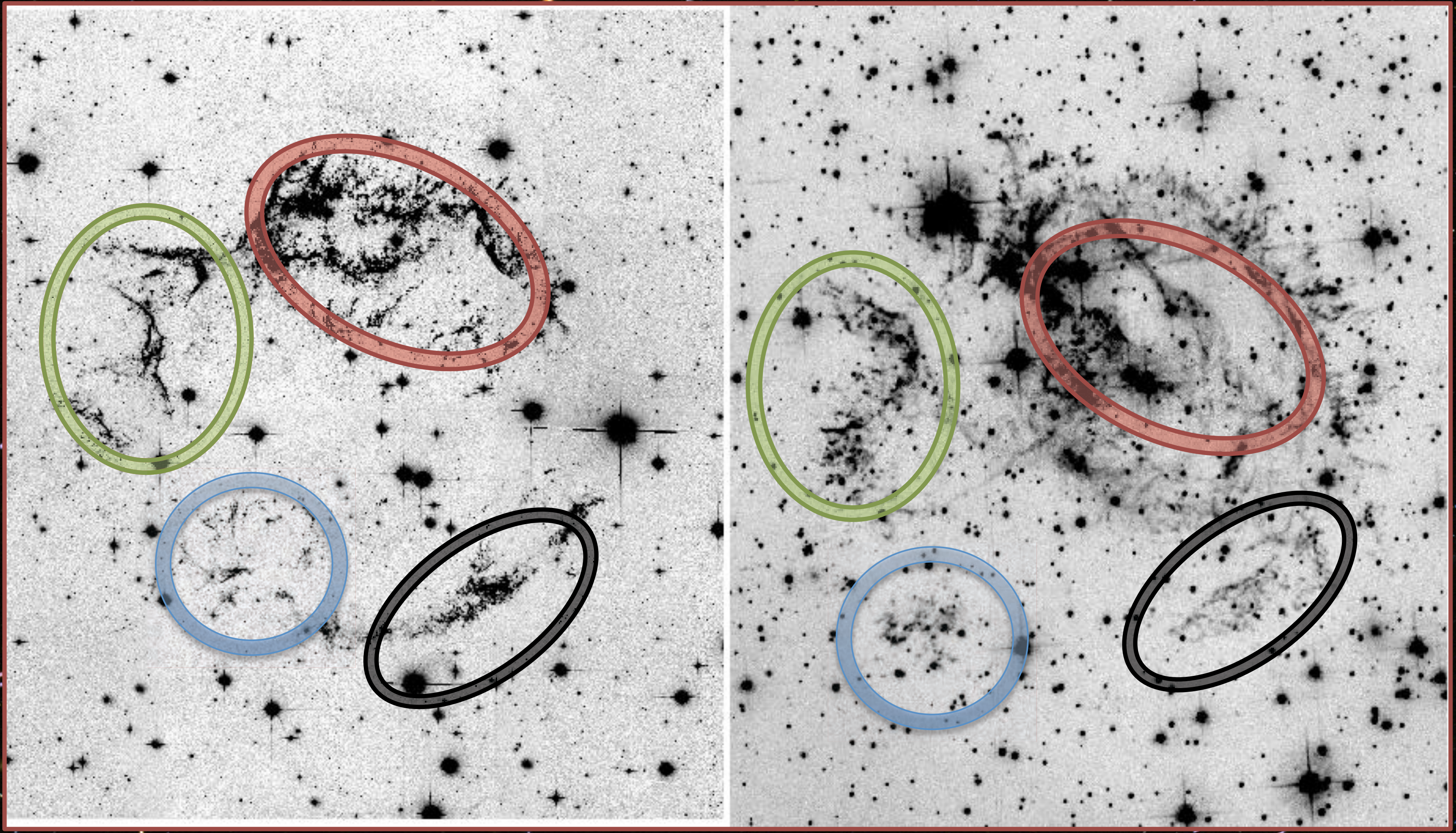
Milisavljevic et al. (2016)

Shared morphology but different ejecta composition



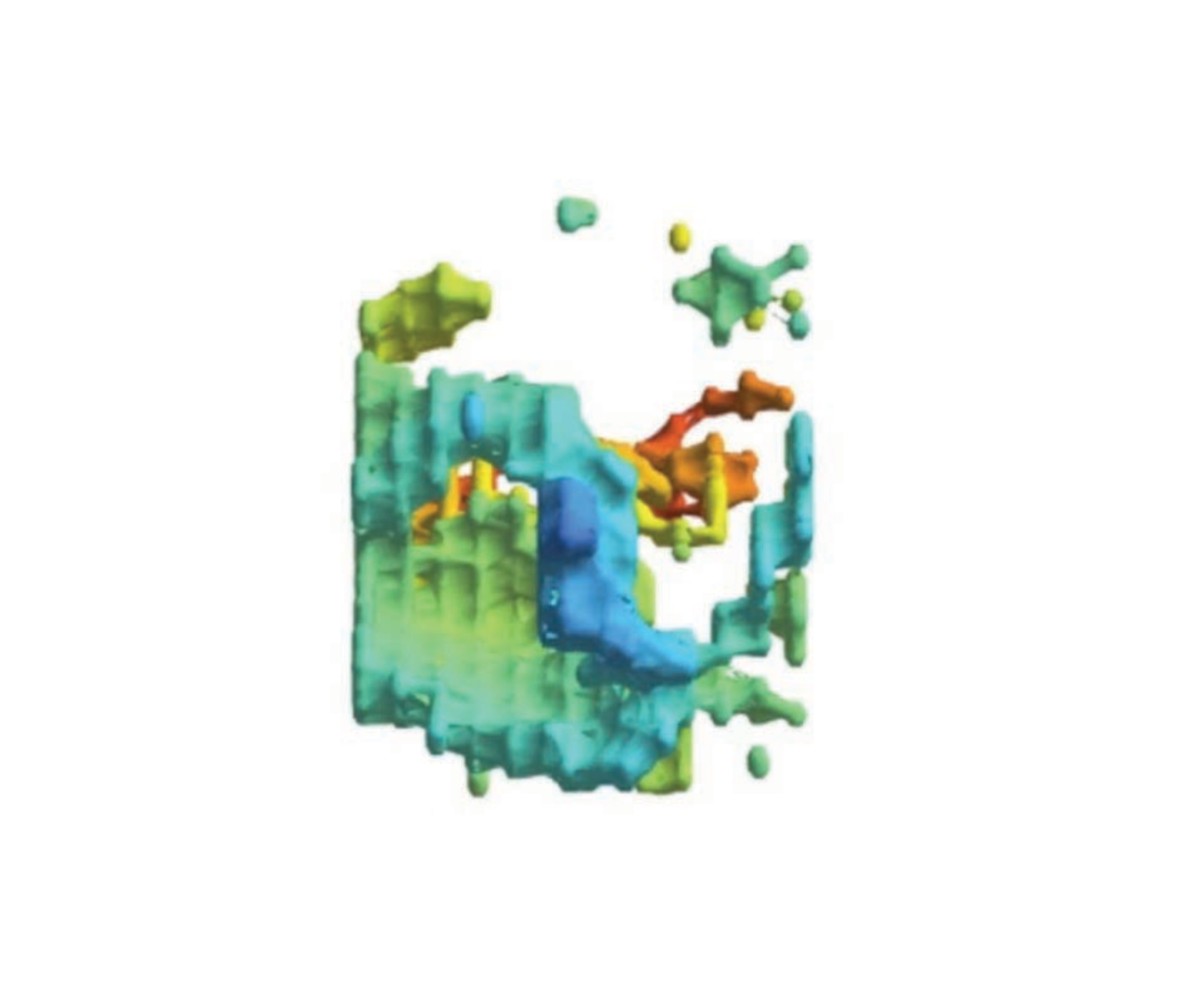
Milisavljevic et al. (2016)

Shared morphology but different ejecta composition



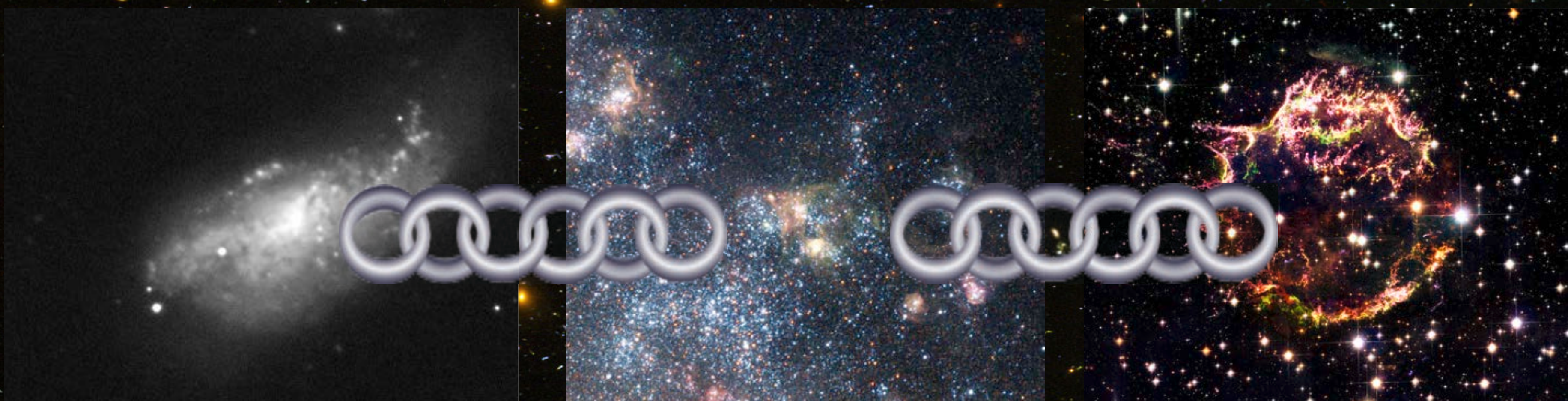
Milisavljevic et al. (2016)

E0102 also has a bubble-like interior



Milisavljevic et al. (2016)

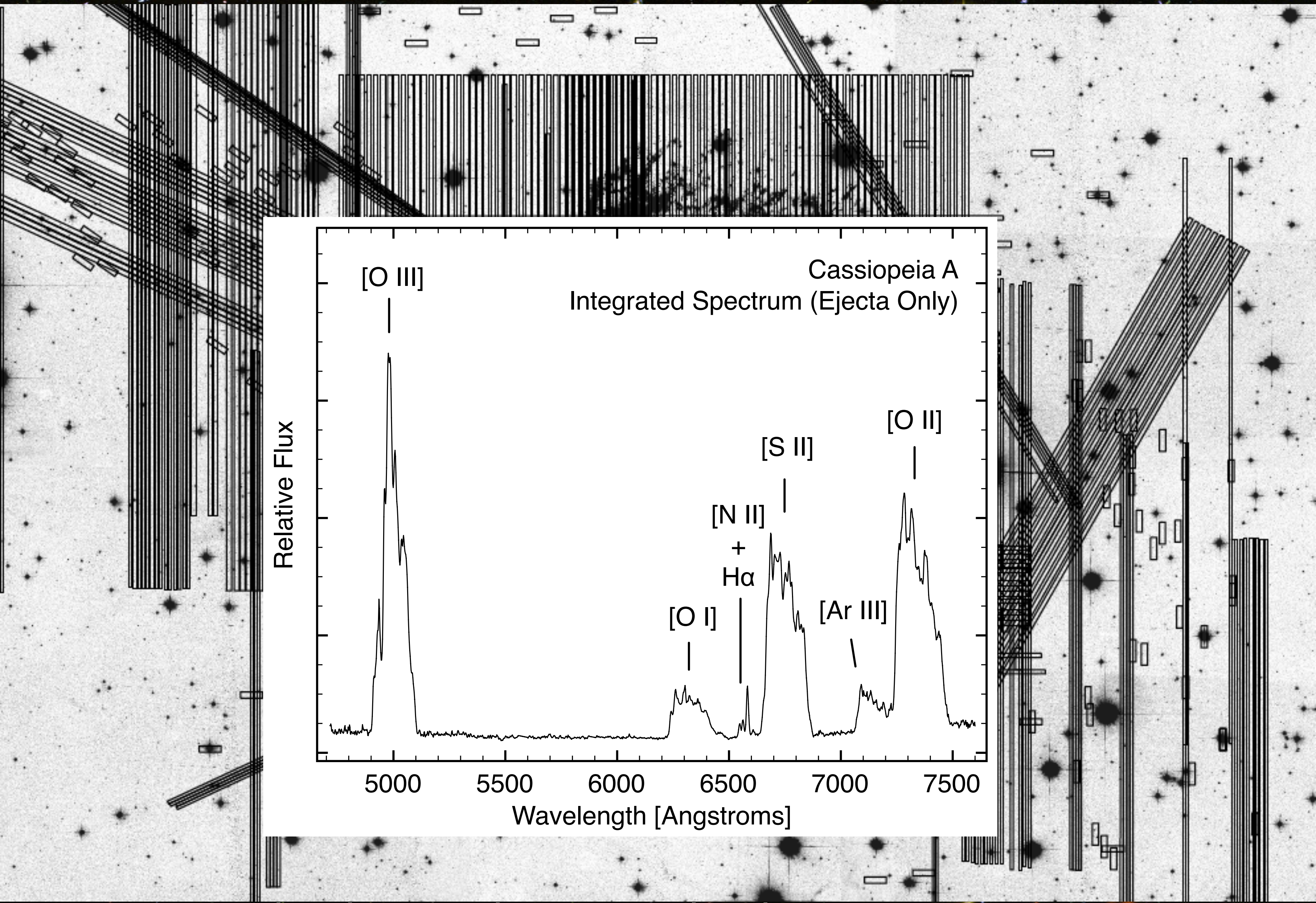
The SN-SNR Connection



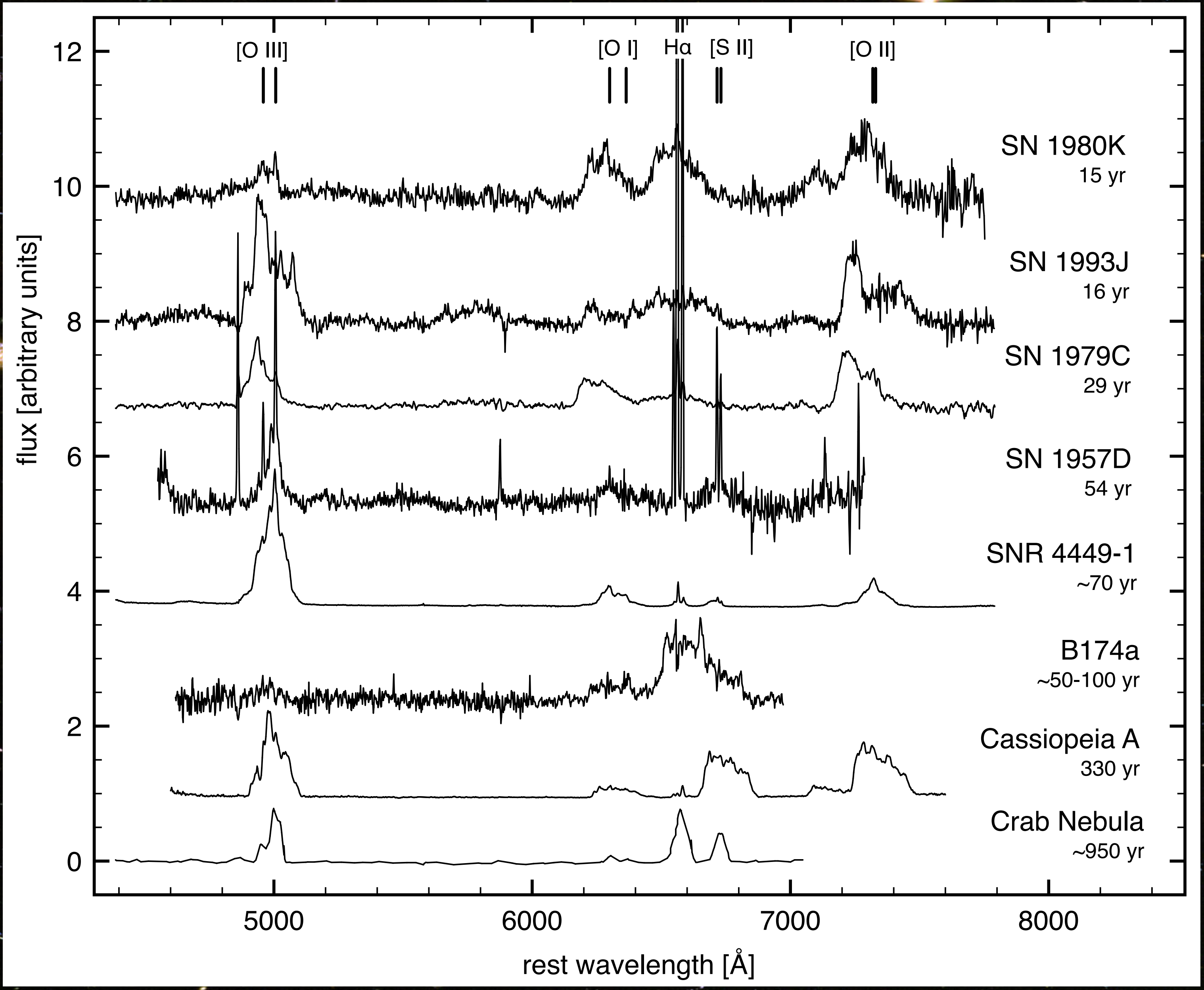
Supernovae
(t < 14 months)

Intermediate-Aged
Supernovae
(2 < t < 100 yr)

Young Supernova
Remnants
(100 < t < 1000 yr)

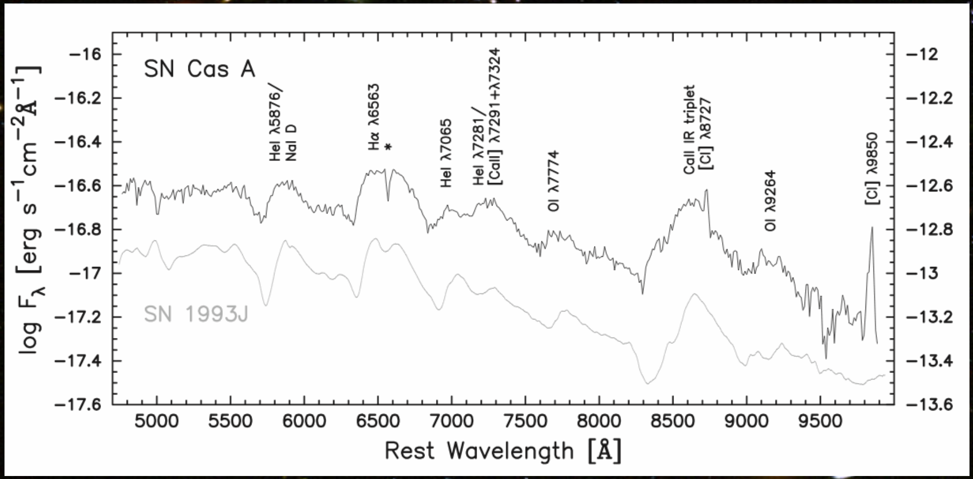


Milisavljevic et al. (2012), Milisavljevic & Fesen (2013)

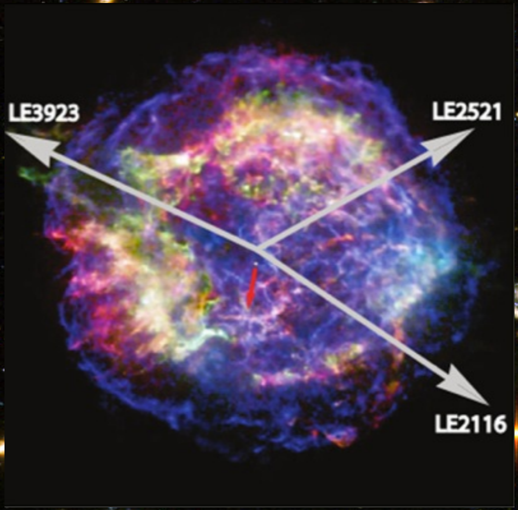


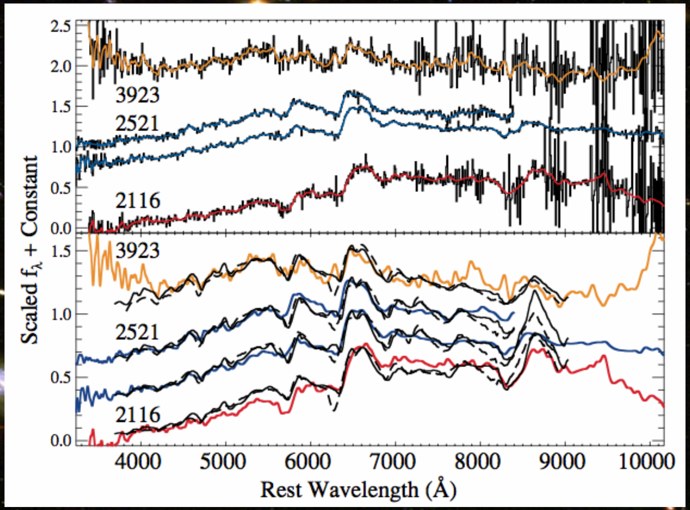
Milisavljevic & Fesen (2017?)

Cas A was a Type IIb explosion…



Krause et al. (2008)



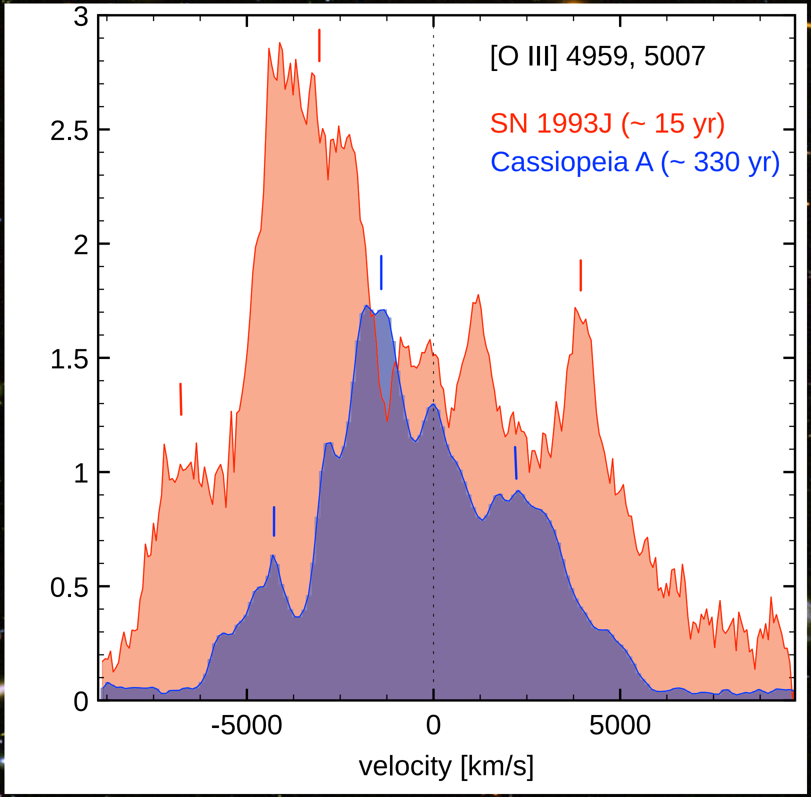


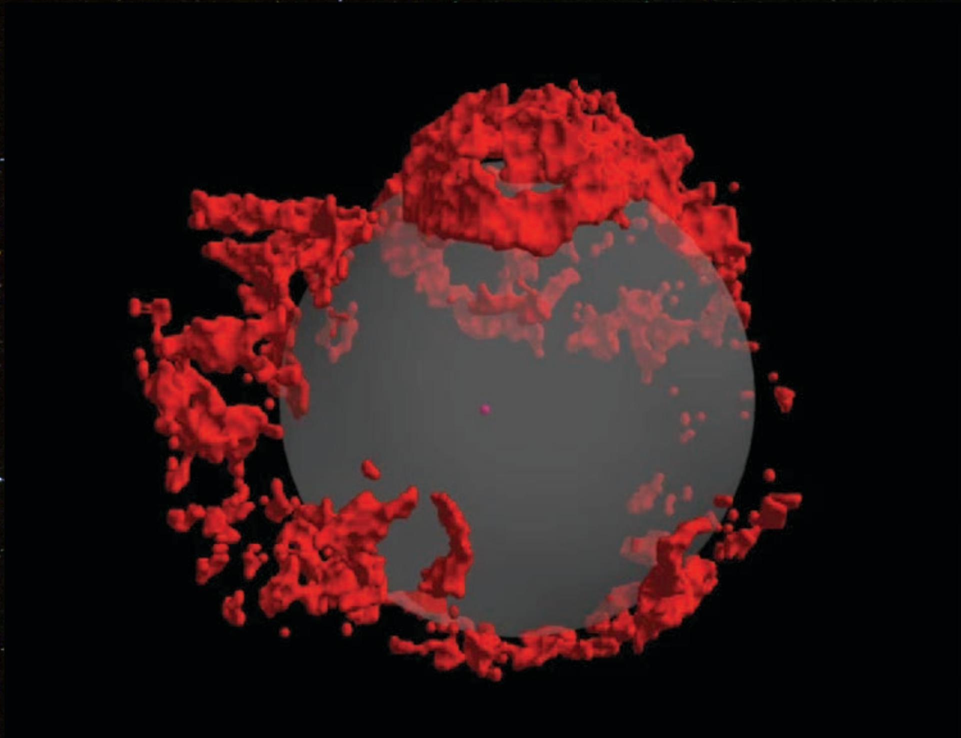
Rest et al. (2011)

… with evidence of asymmetry.

The SN – SNR Connection

Emission line profiles of SN 1993J and Cas A are similar and consistent with shared morphology.

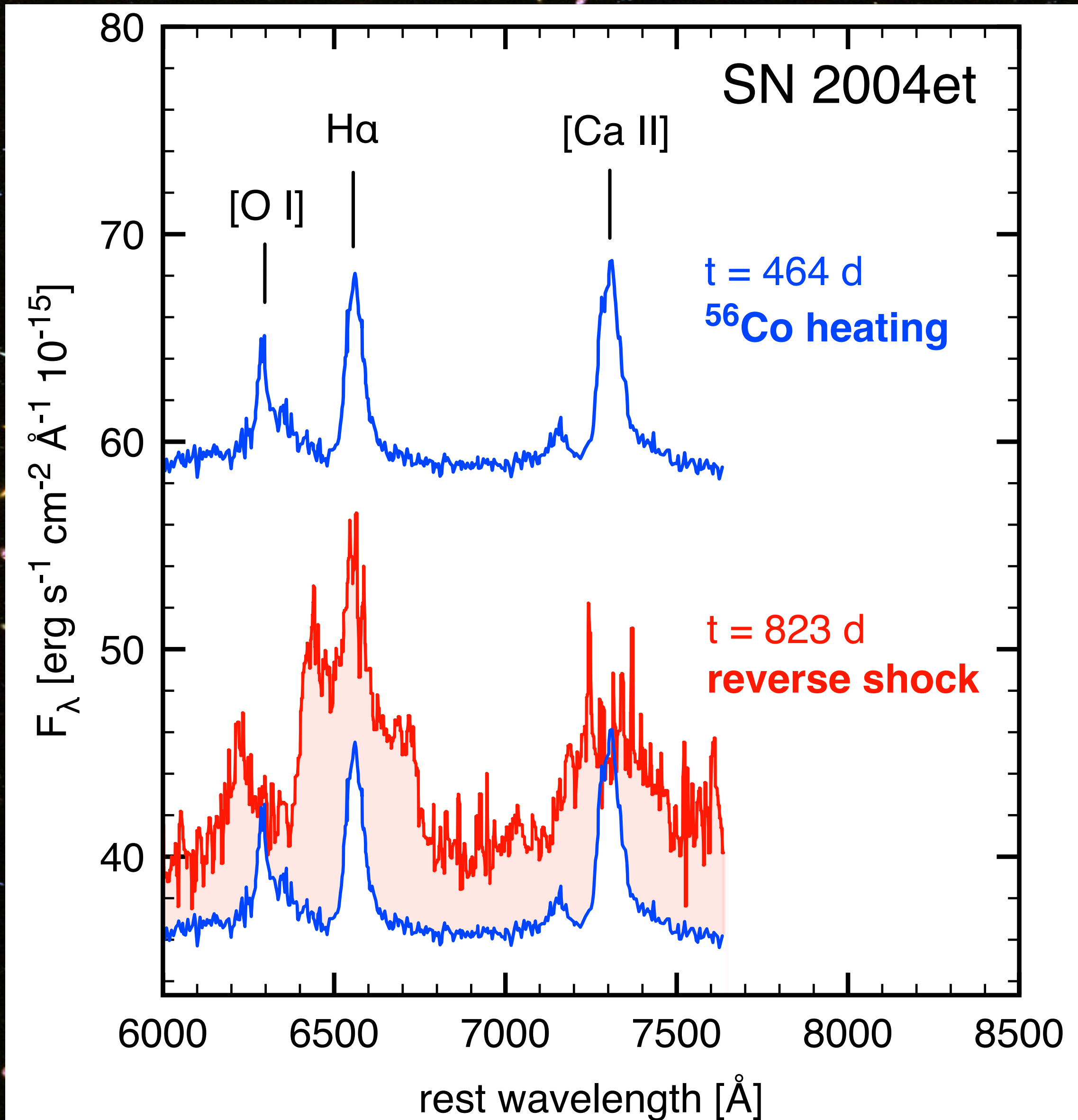




Cassiopeia A

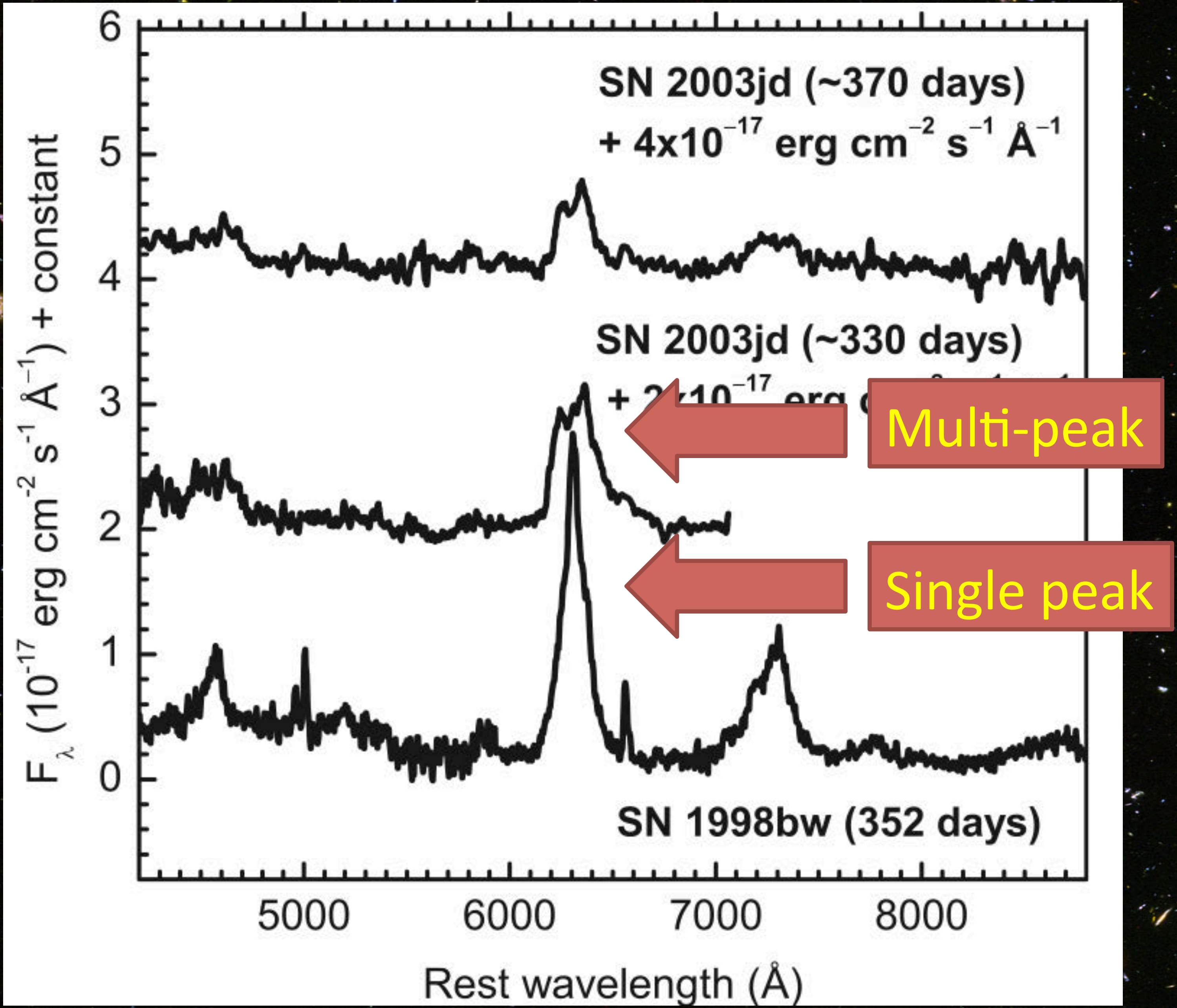
Flying Donuts?!

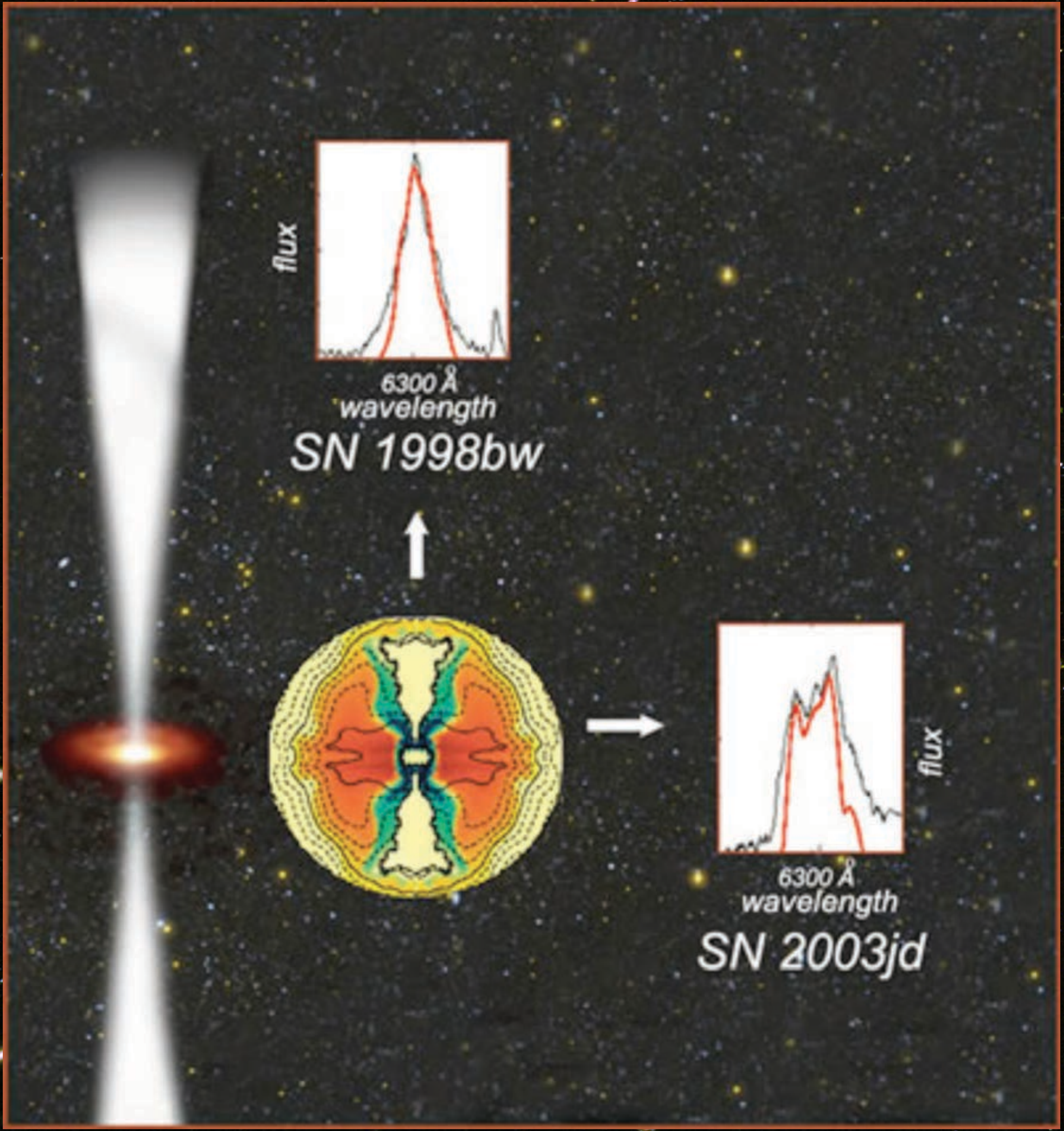
Understanding late-time emissions from supernovae



SN to SNR transition

Milisavljevic & Fesen (2017?)
Data from Kotak et al. (2007)


SN 2003jd (~370 days)
+ 4x10^{-17} erg cm^{-2} s^{-1} Å^{-1}
SN 2003jd (~330 days)
SN 1998bw (352 days)
Multi-peak
Single peak
F_λ (10^{-17} erg cm^{-2} s^{-1} Å^{-1}) + constant
Rest wavelength (Å)
0
1
2
3
4
5
6
5000
6000
7000
8000

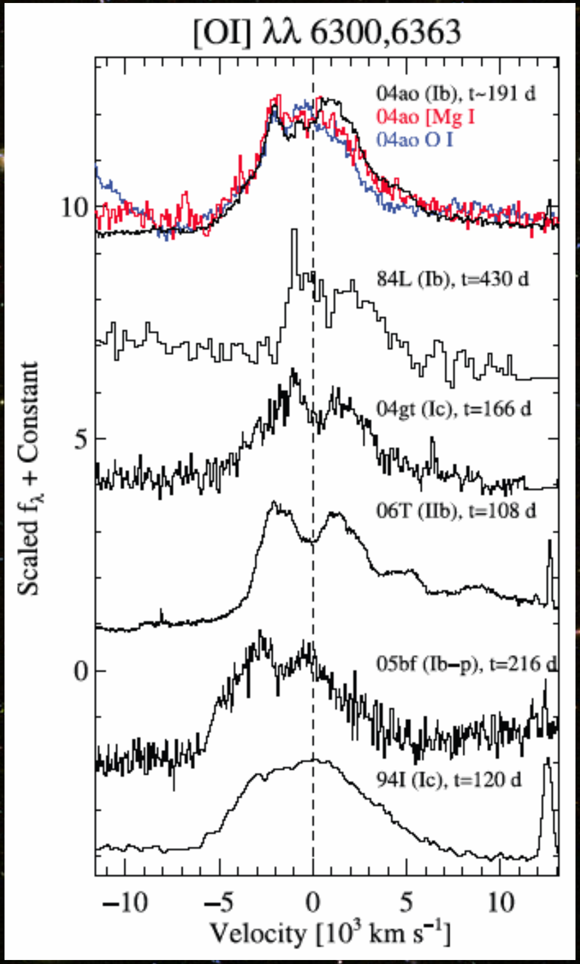


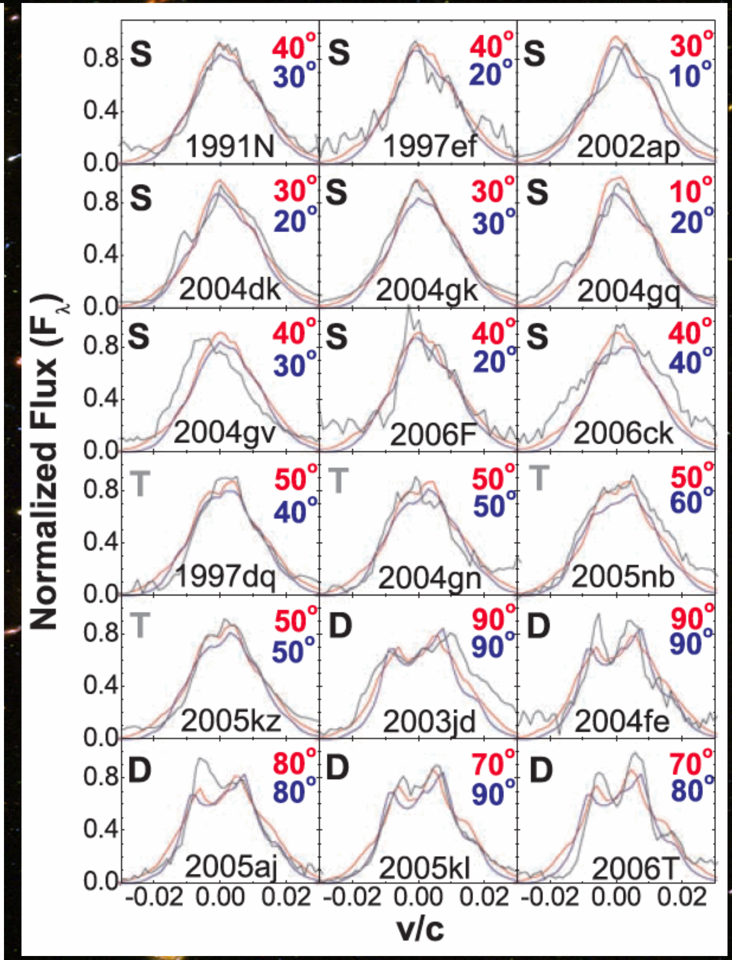
Adapted from Mazzali et al. (2005)

Mazzali et al. (2005) interpreted this as emission originating from an O-rich ejecta torus developed from a GRB directed perpendicular to the line of sight.

This was a nice framework to understand the diversity of their late-time emission profiles and why only a subset of broad-lined supernovae are associated with GRBs and.

Double peaks everywhere!

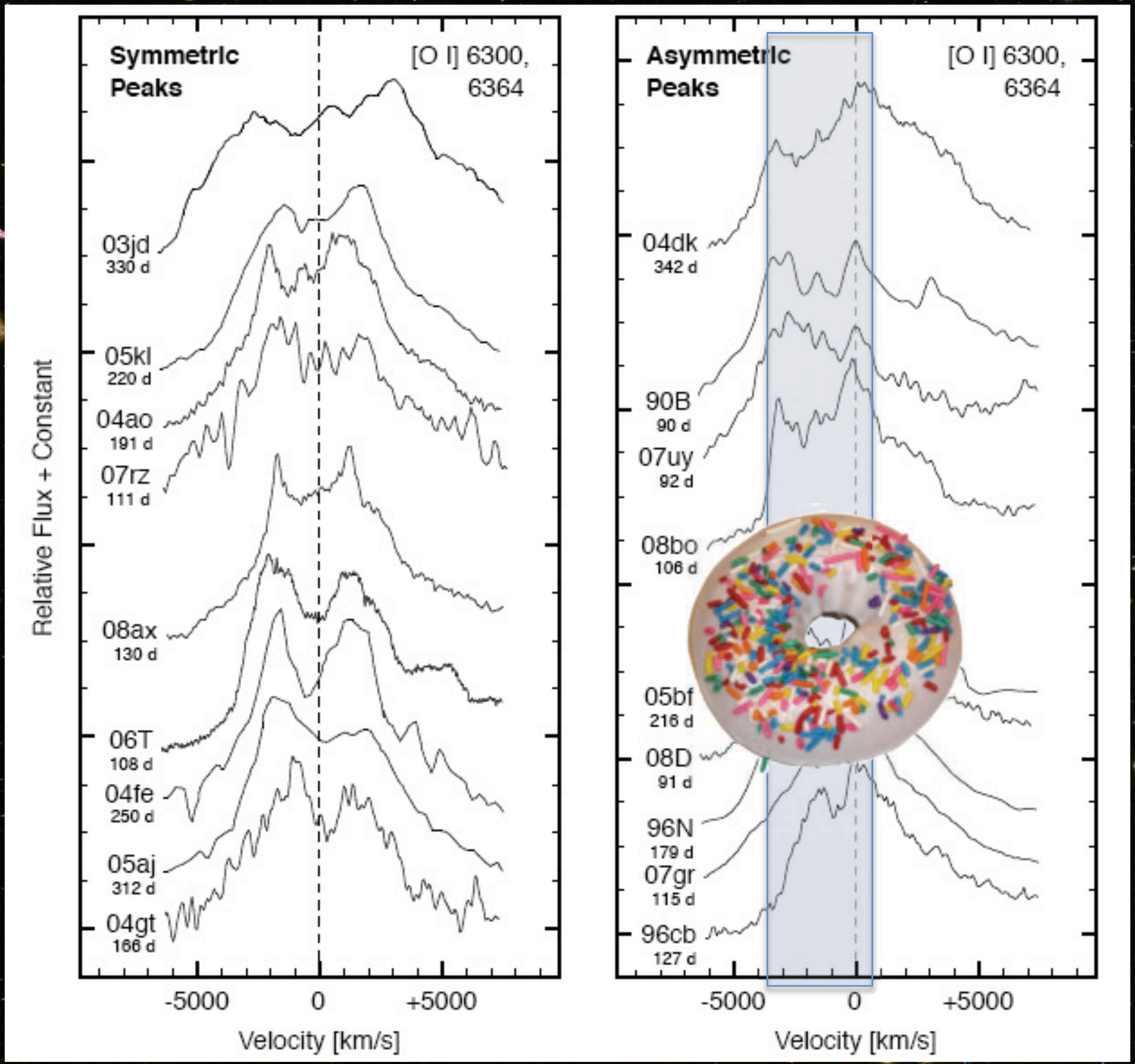




Modjaz et al. (2008)

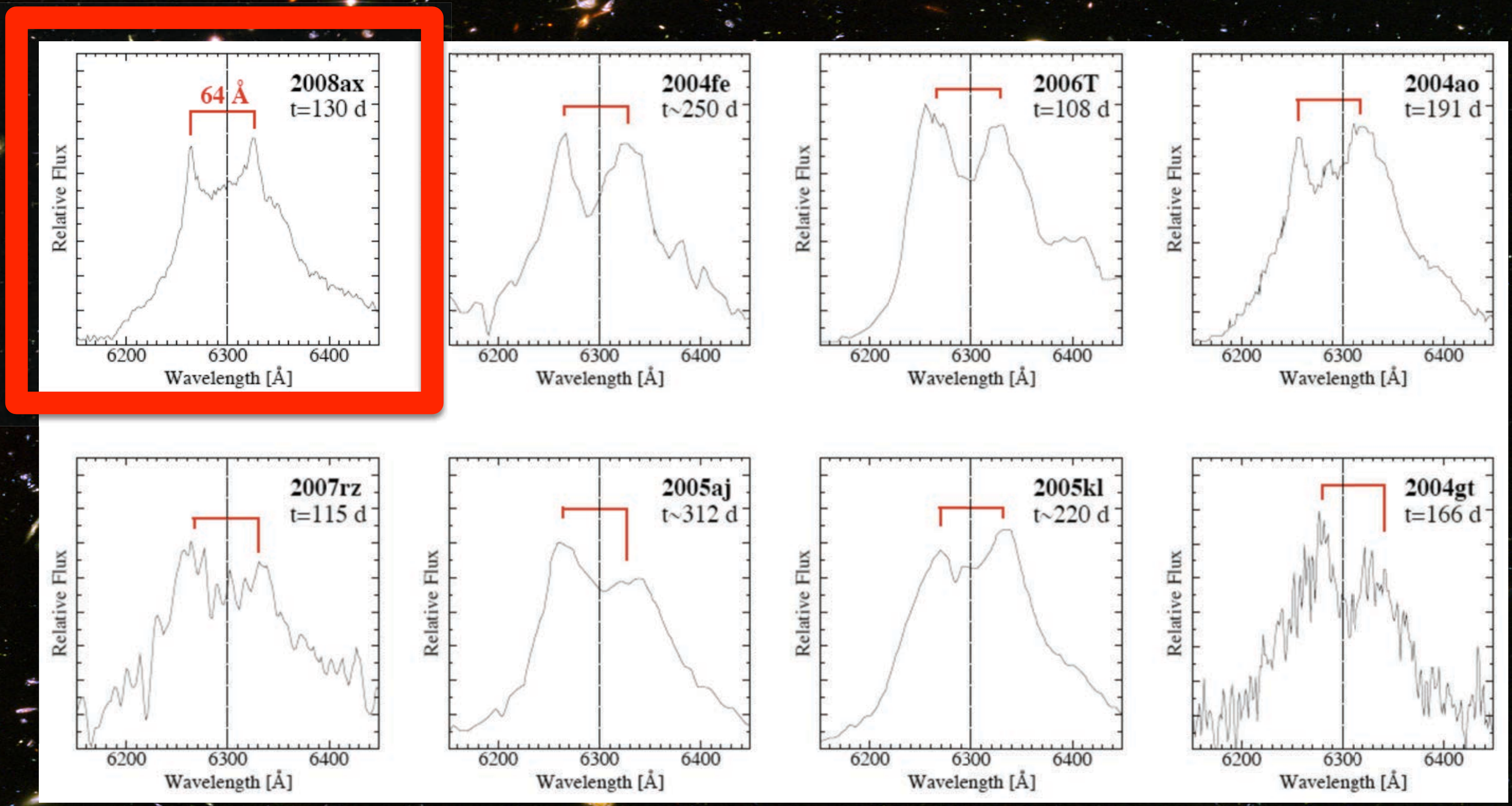
Maeda et al. (2008)

Double-peaked [O I] 6300, 6364 profiles were observed in other stripped-envelope CCSNe (Type Ib/c, IIb) and asymmetry due to jets was implied.

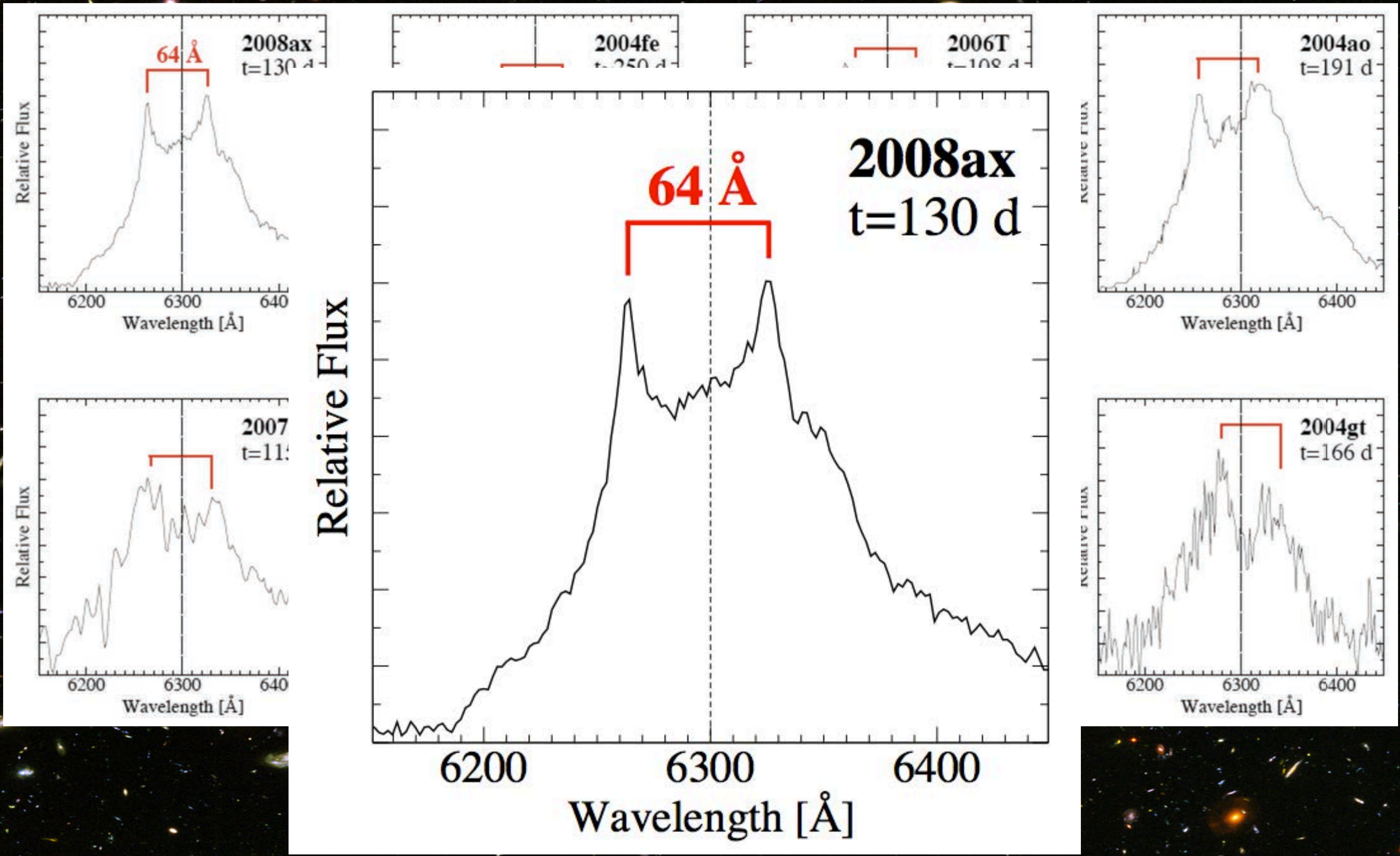


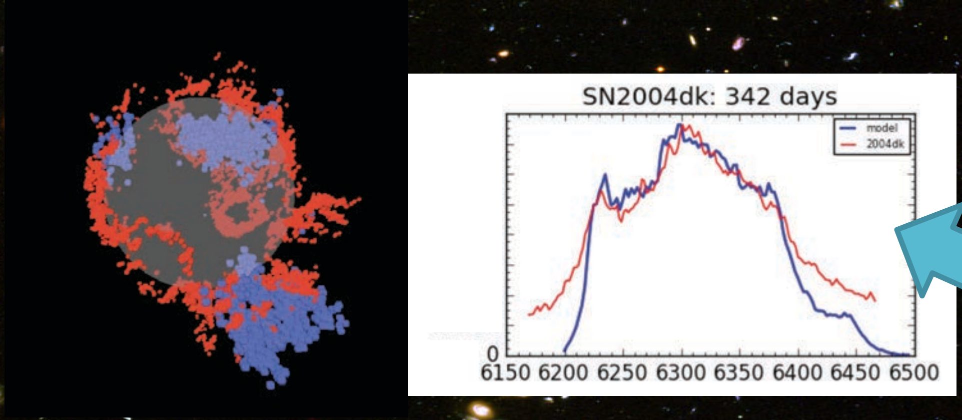
Milisavljevic et al. (2010)

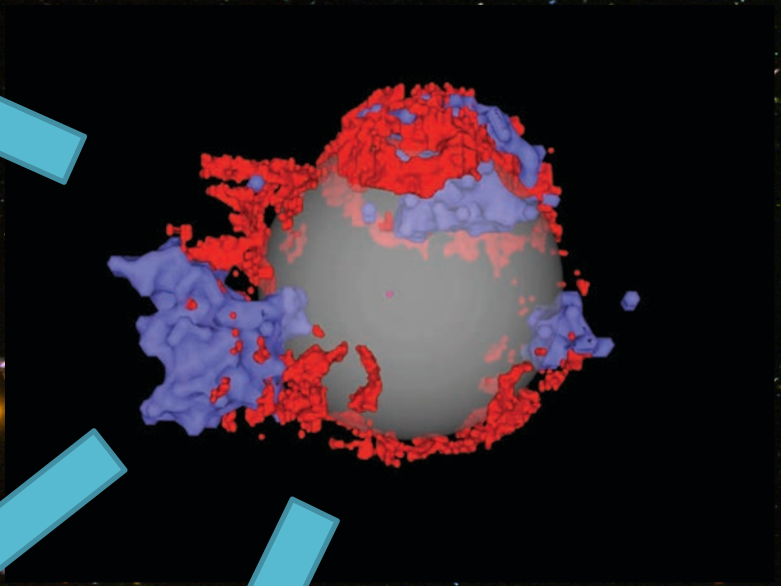
“Symmetric” double peaks have 64 Angstrom separation



Recall: 6364 – 6300 = 64

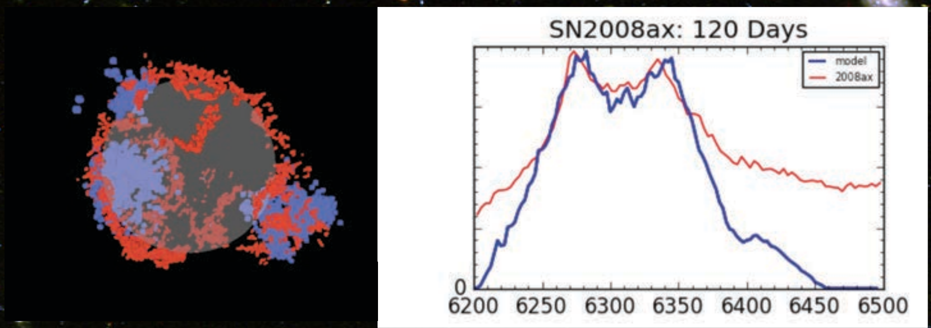

2008ax
t=130 d
64 Å
Relative Flux
6200
6300
6400
Wavelength [Å]
2004fe
2006T
2004ao
t=191 d
2007
2004gt
t=166 d

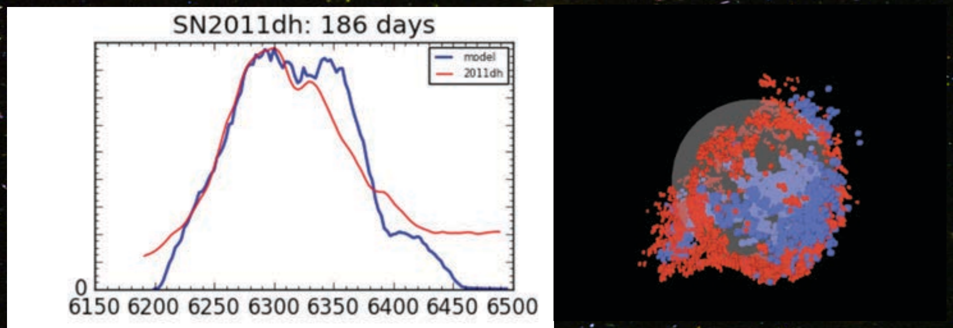


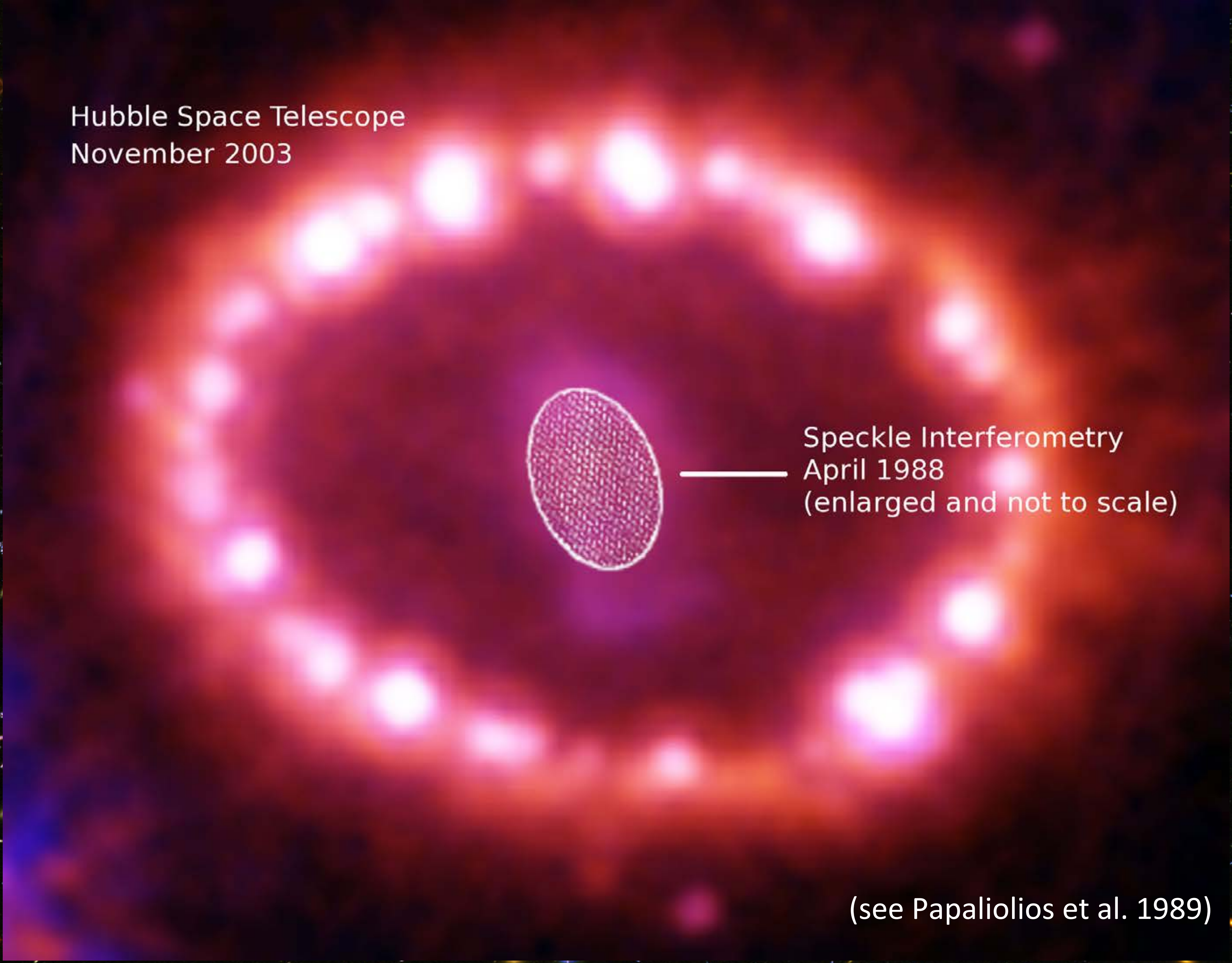


Viewing angle changes line-of-sight ejecta geometry and, consequently, the observed emission line profile.

Milisavljevic, Law & Patnaude (2016)

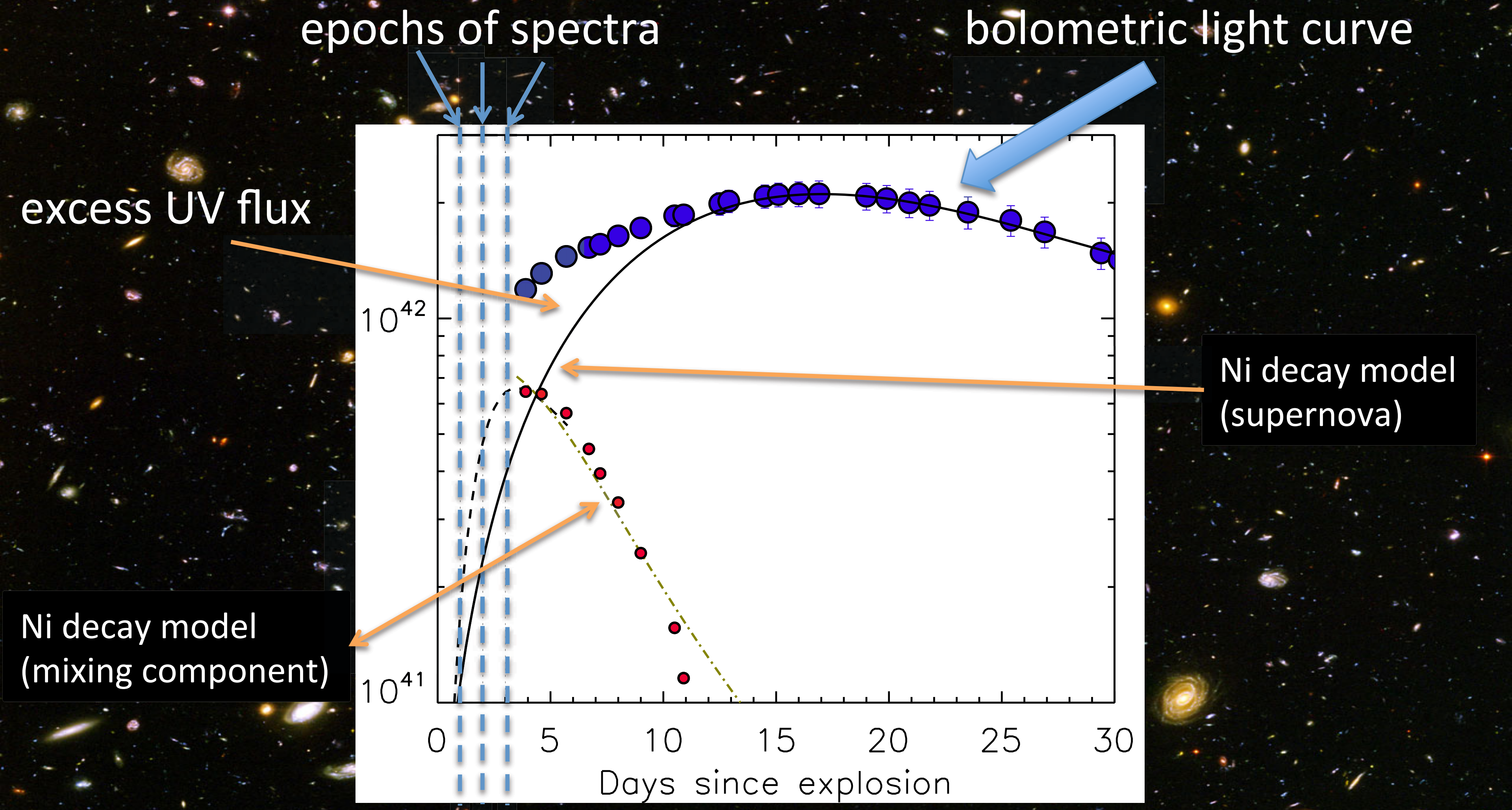






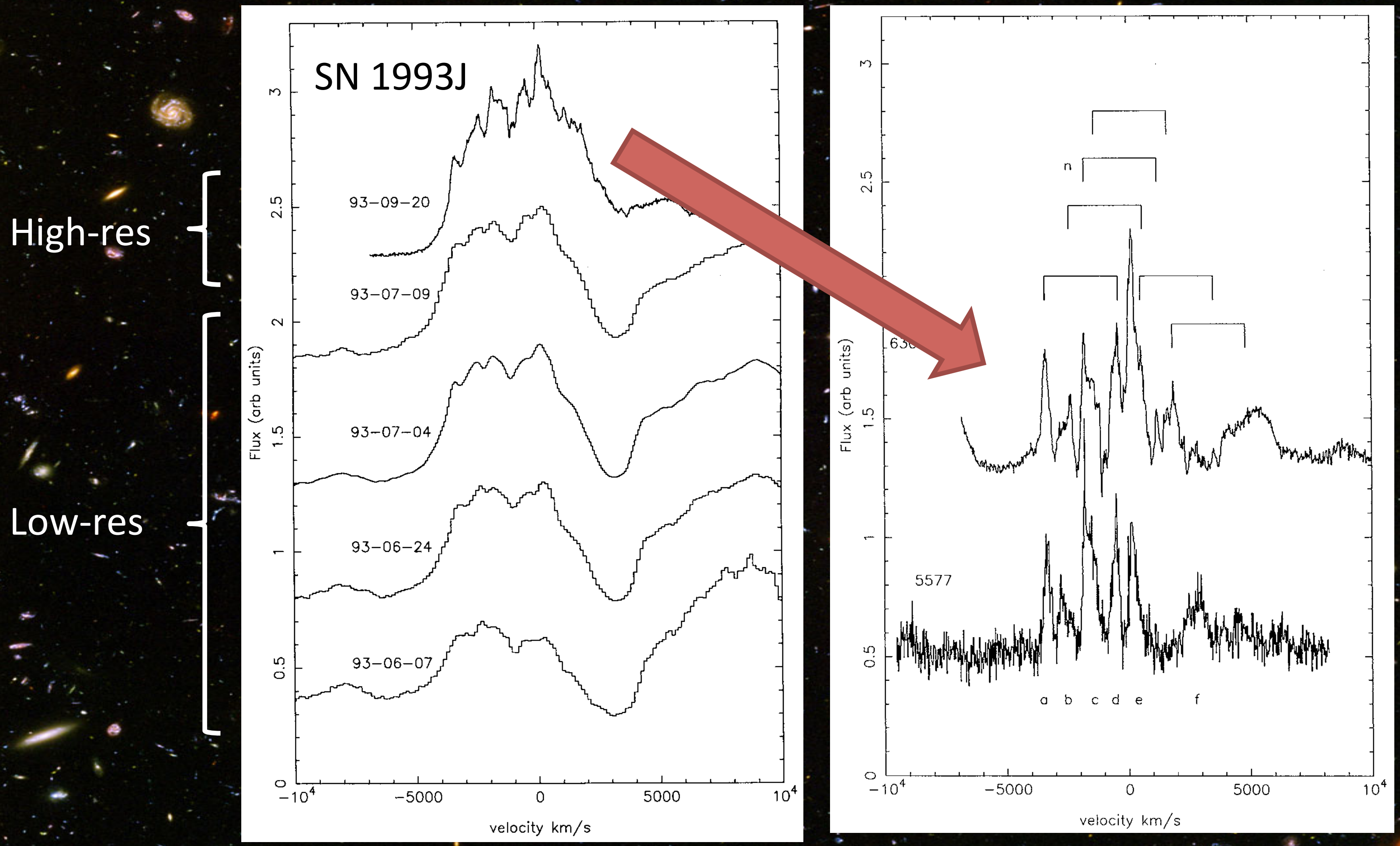
(see Papaliolios et al. 1989)

Light curves of stripped-envelope supernovae near the time of explosion show excess UV flux consistent with mixing.



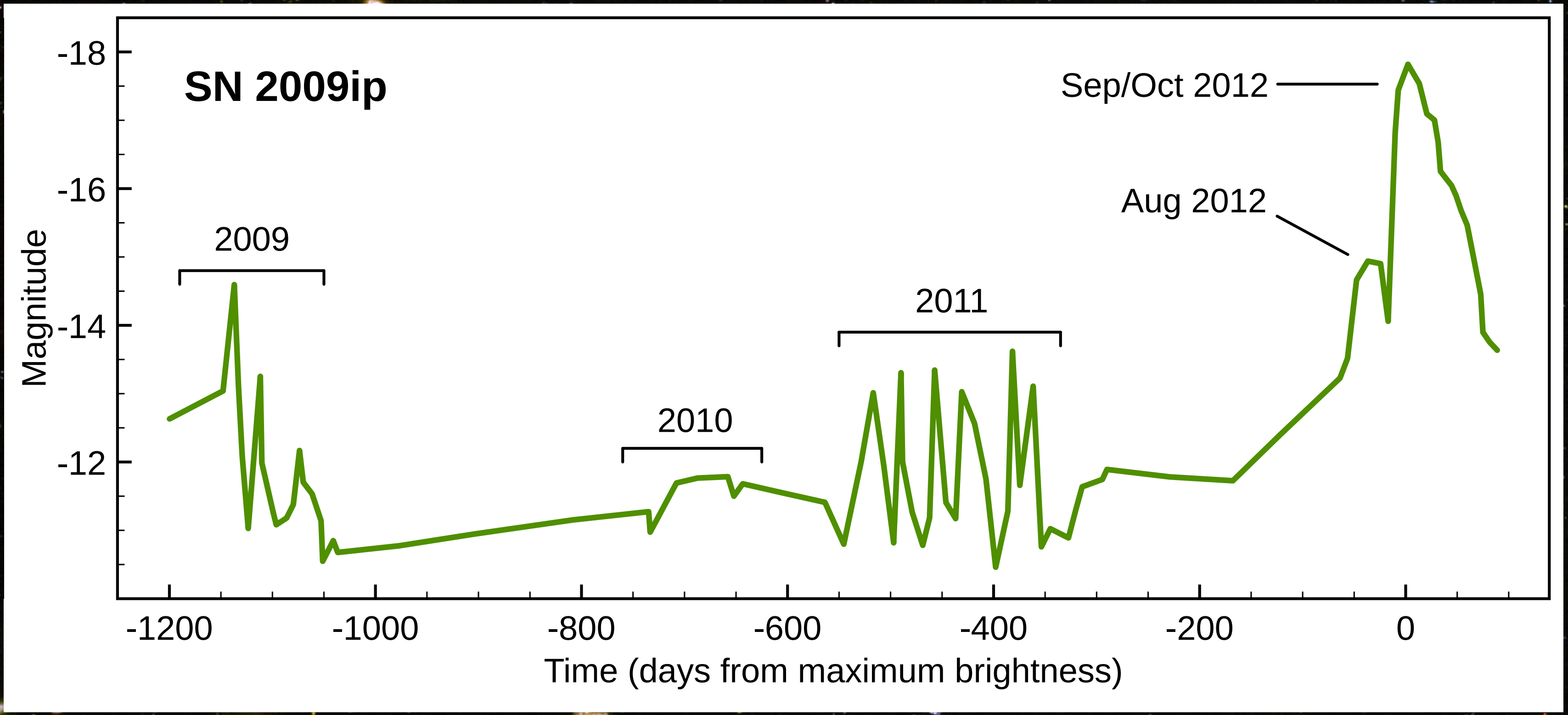
Drout, Milisavljevic, et al. (2016)

The extent of fine structure clumping is poorly constrained. It has been observed when observations are of high enough resolution. Presently not known whether extent of clumping is function of supernova type.



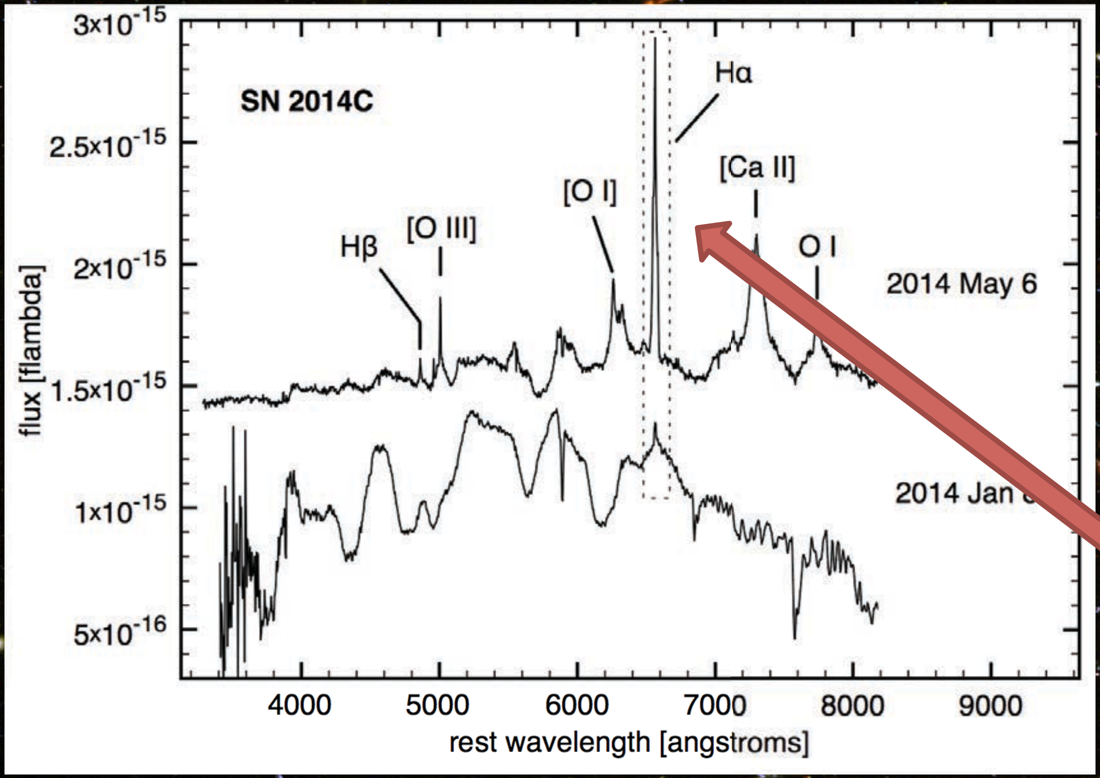
Spyromilio (1994)

We've observed stars that undergo eruptions shortly before a supernova explosion

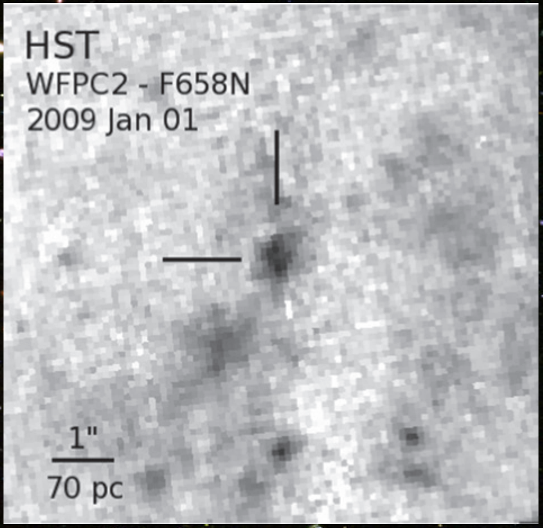


Data from Pastorello et al. (2013) and Margutti, Milisavljevic, et al. (2014)

Supernova Metamorphosis: Type Ib → IIn



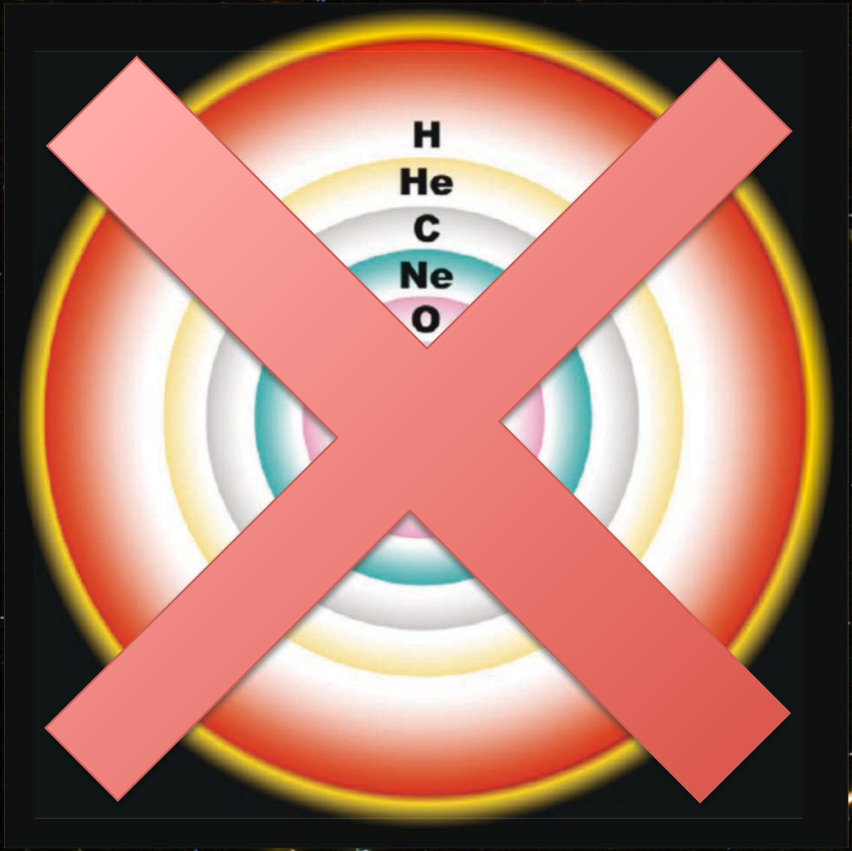
Milisavljevic et al. (2015)



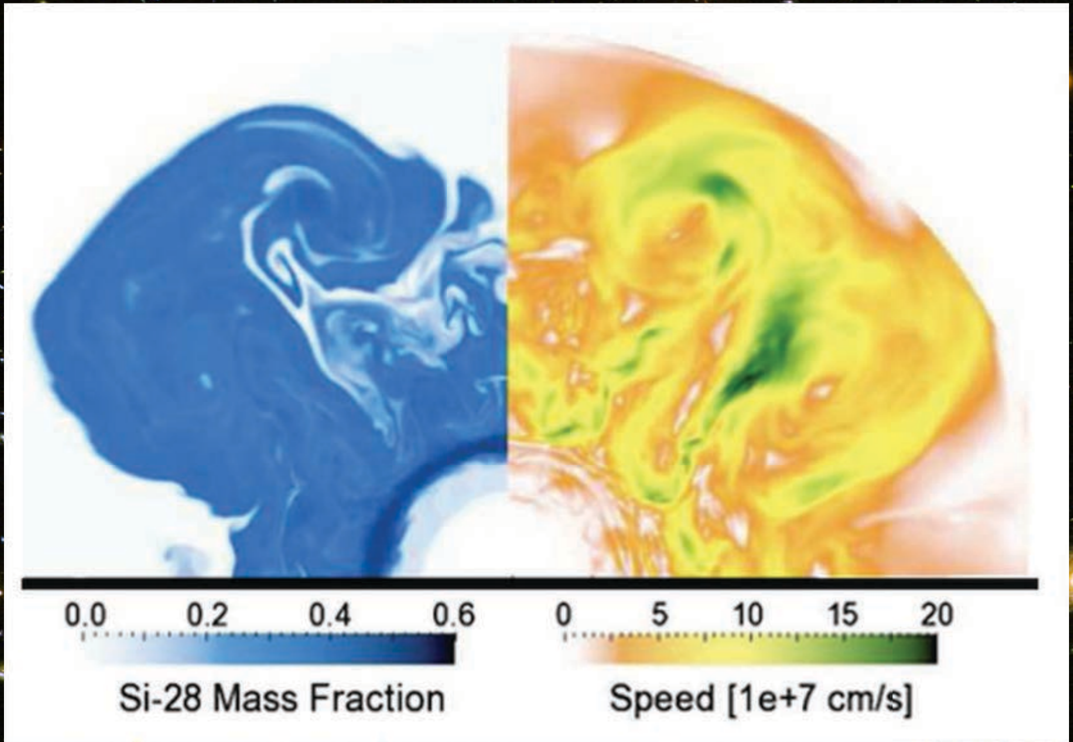
H-poor supernova explosion started to interact with dense H-rich material months after explosion.

Best explanation: SN encountered a massive H-rich shell, presumably made from material gradually stripped or violently ejected from the progenitor star 100-1000 years earlier.

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



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



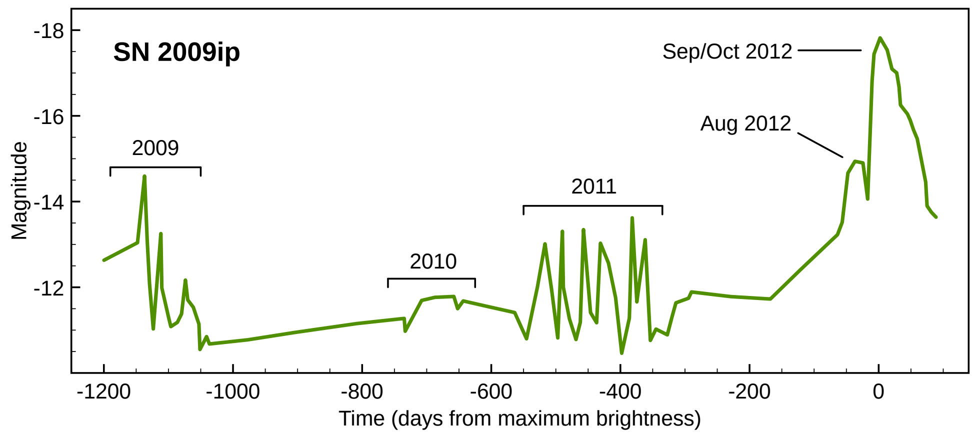
Arnett & Meakin (2011)

How can we unravel asymmetry in the explosion from asymmetry in the progenitor?

LSST may find 100 000 supernovae per year …

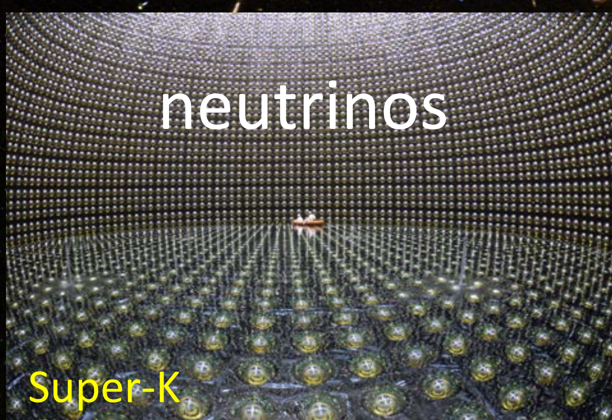
… but it's real strength will come from photometry accumulated after several years of operation.

These complete "before-and-after" SN light curves will offer a trove of information about precursor activity.



A direct and live view inside a supernova will require a *multi-messenger* investigation

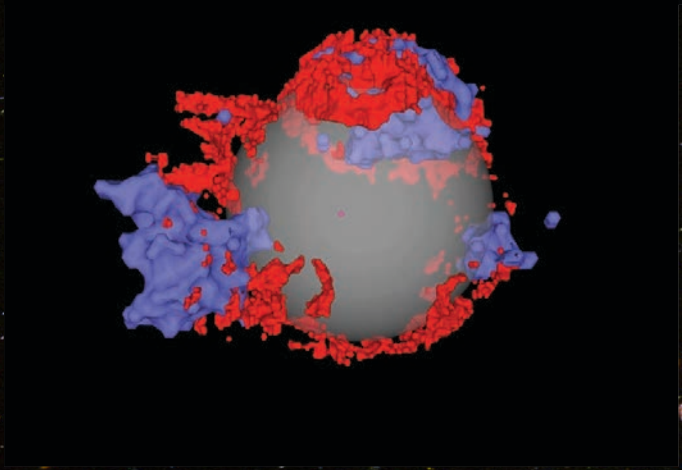
fluid instabilities, rotation, the structure of the protoneutron star, and the nuclear EOS

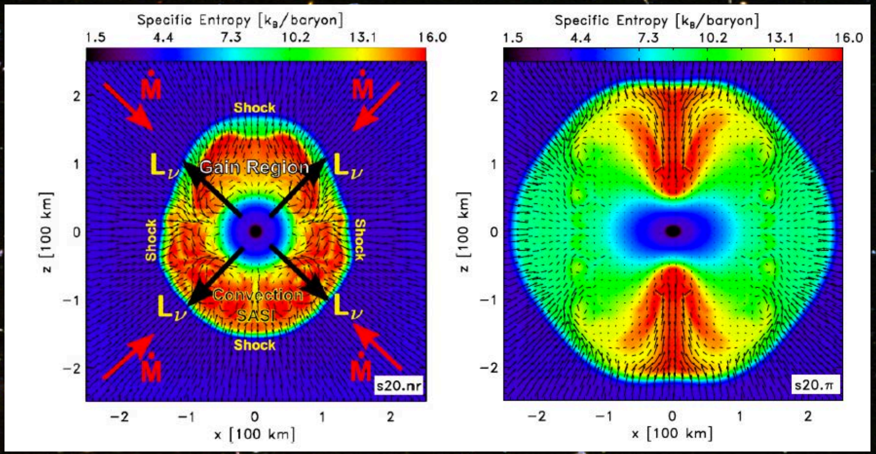


shock waves, accretion, cooling, possible formation of exotic matter, and further collapse to a black hole

We know that a galactic supernova will be an epic achievement of *multi-messenger* astronomy …

… but interpretations of multi-messenger signals made from core-collapse simulations must be rigorously tested with detailed observations to be considered realistic.



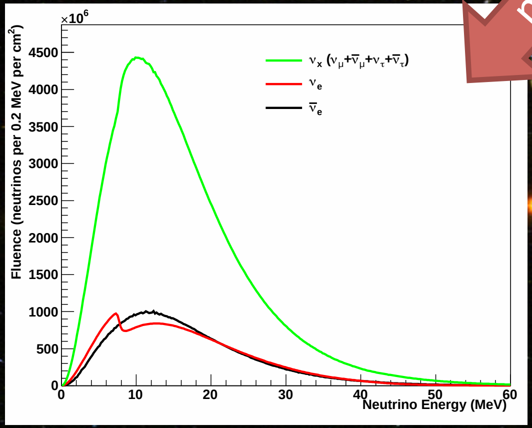


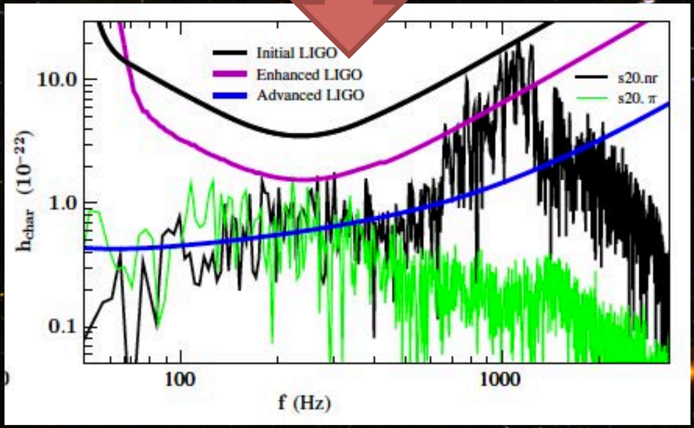
Observation

neutrino

GW

Simulation



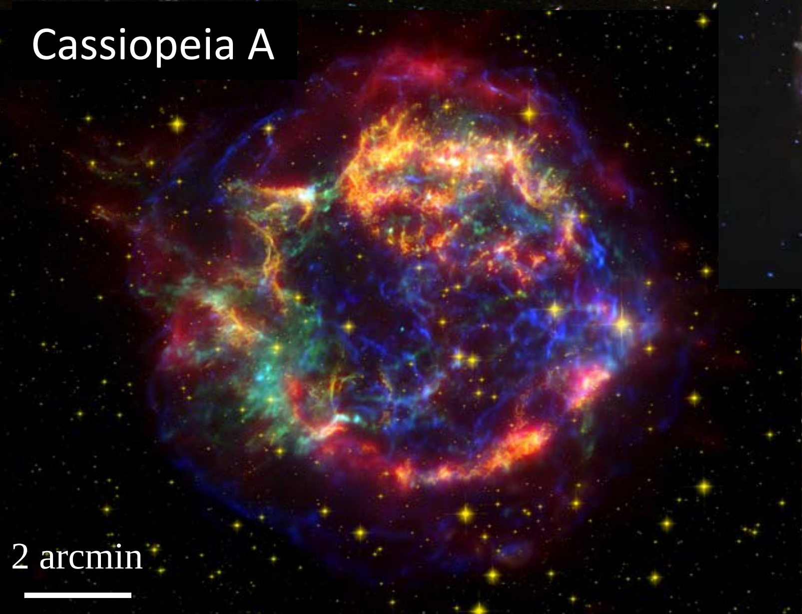


Gava et al. (2009)

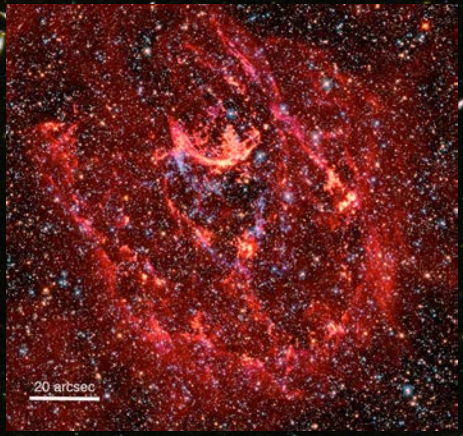
Prediction

Ott (2009)

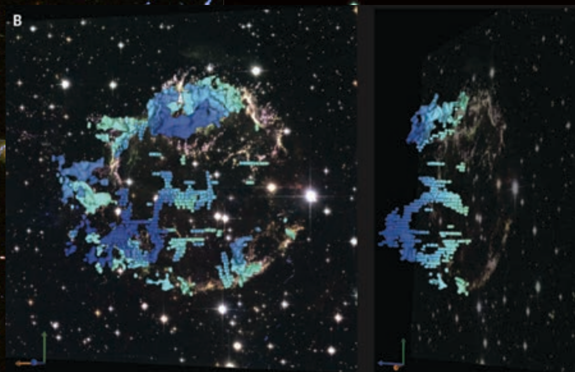
First-order tests can come from *precision supernova tomography* that can be performed on the diverse family of young SNRs

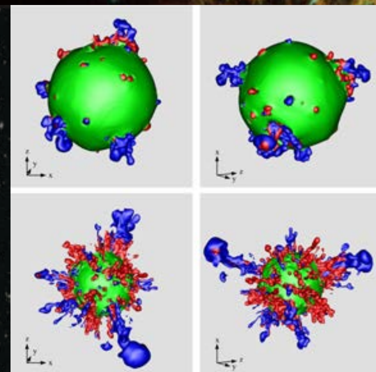


N132D



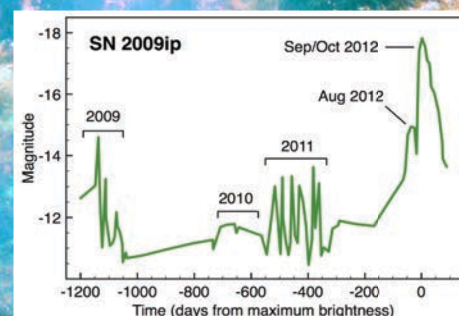
Take away points

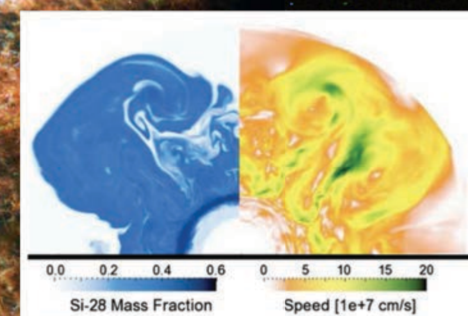


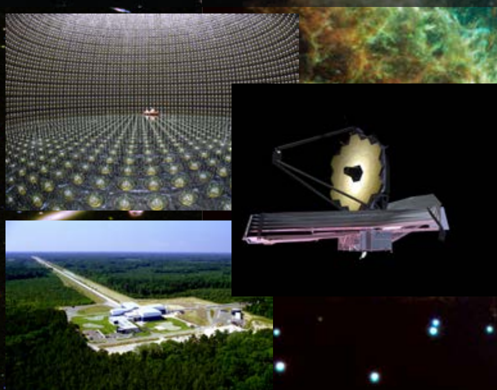


Massive star explosions involve turbulent mixing that we're only beginning to understand.

Varying degrees of eruptive mass loss that prelude SNe likely reflect perturbed progenitor interior structure







Multi-messenger astronomy has breakthrough potential but interpretation can be crucially dependent on simulations that need cold hard observational facts for guidance.

Thank You!