SN 1987A at 30 years

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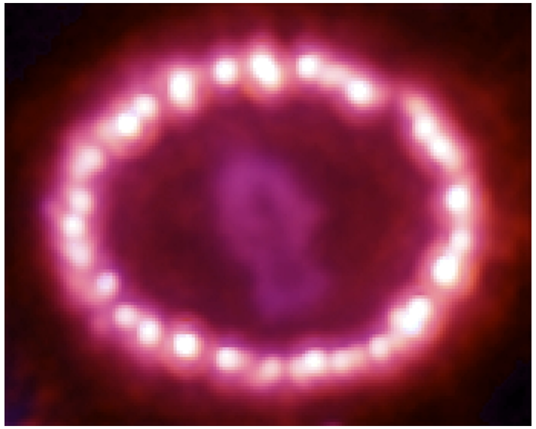
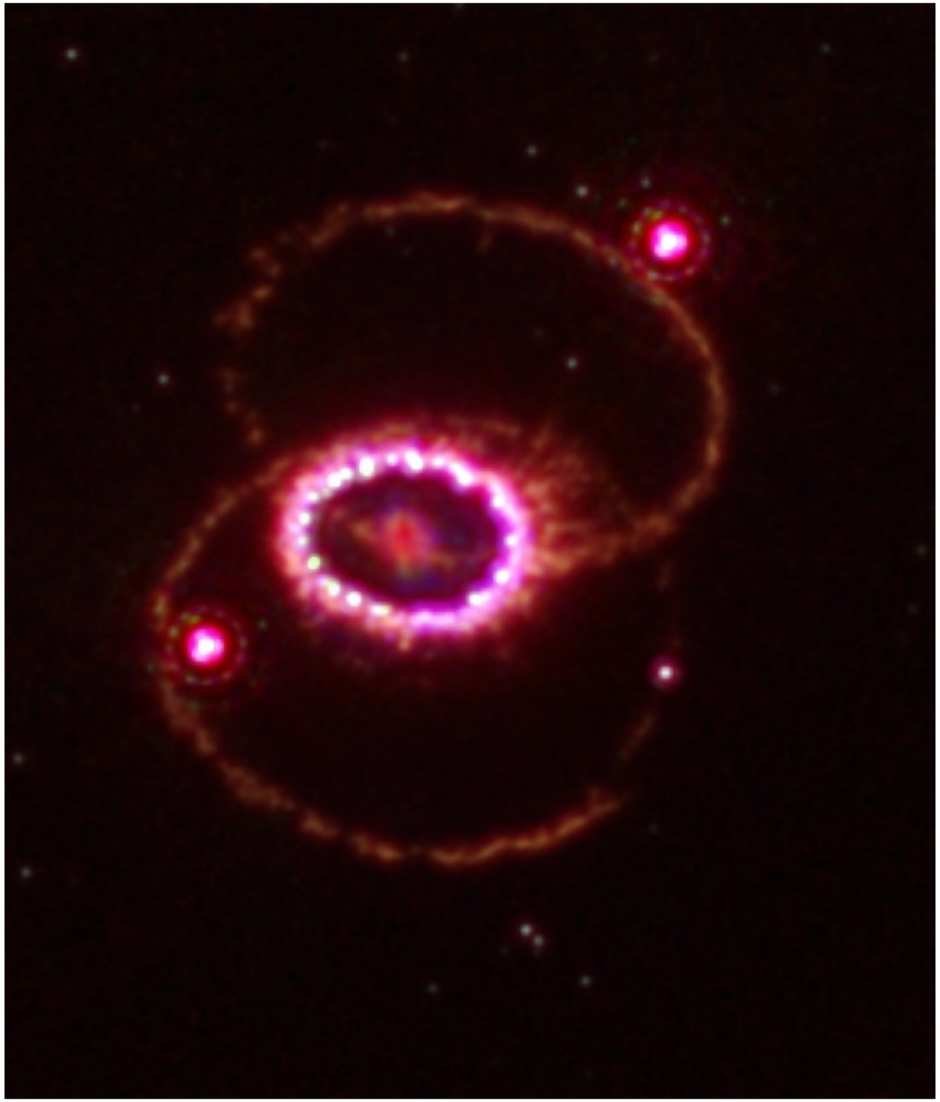
87A review in Ann. Rev. Astr. & Astroph. 2016
R. McCray & CF



- Ring collision: Progenitor environment. Shock physics
- Ejecta: morphology, nucleosynthesis –> Explosion mechanism

Mainly optical/NIR

Earlier ‘historical’ by Bob Kirshner



First SN conf.?
Paris 1939

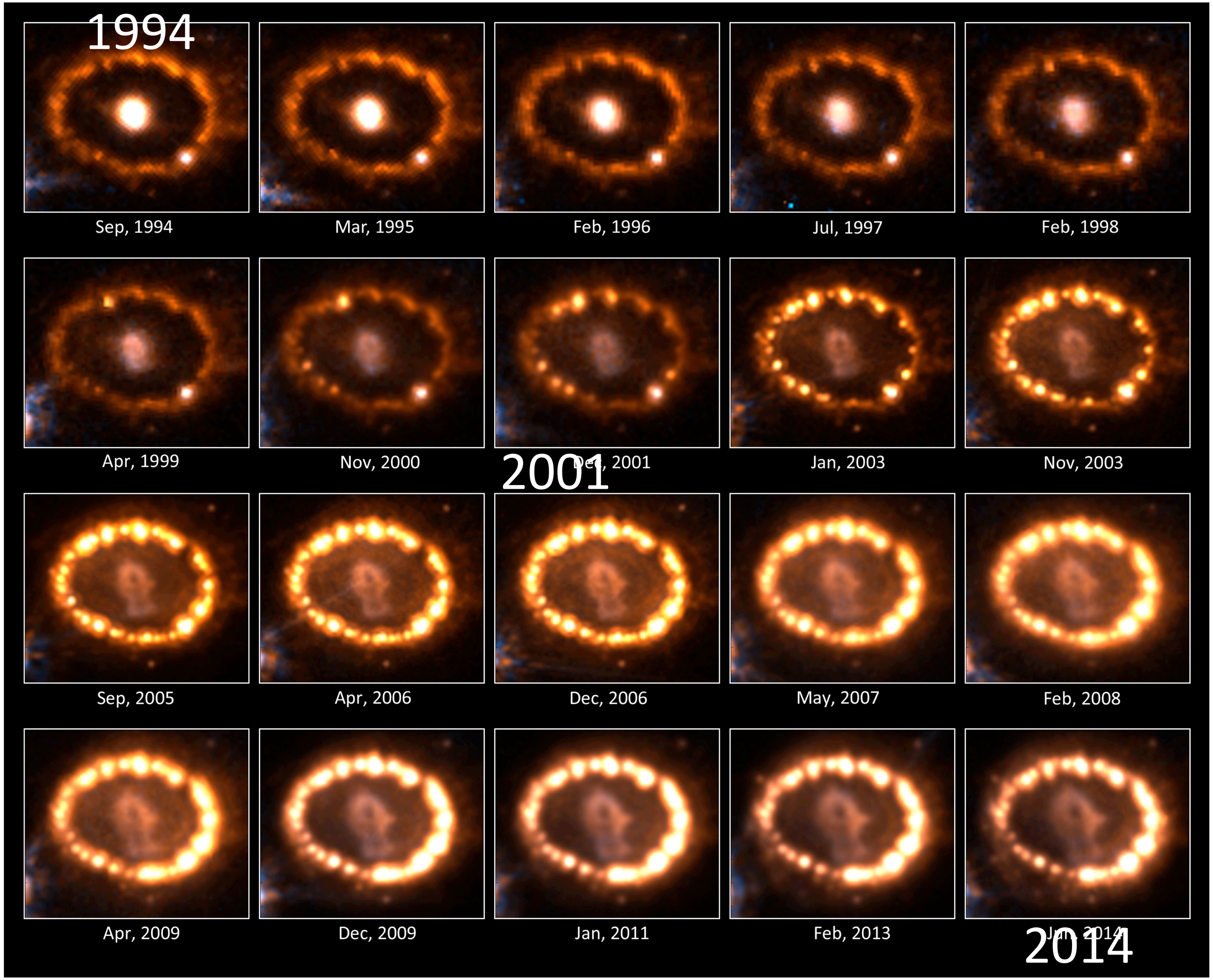
Figure 39 Conference on Novae, Supernovae, and White Dwarfs, Paris (1939) In front row Cecilia Payne-Gaposchkin is second from left, Henry Norris Russell third, Arthur S. Eddington fifth; in second row Pol Swings is third from left, then Gerard P. Kuiper, Bengt Strömgren, Subrahmanyan Chandrasekhar, and Walter Baade. Knut Lundmark is standing in front of Chandrasekhar. Courtesy of Yerkes Observatory.

Canberra 1988

Similarities??

SN 1987A ring evolution

CF, Larsson, Migotto + 2015

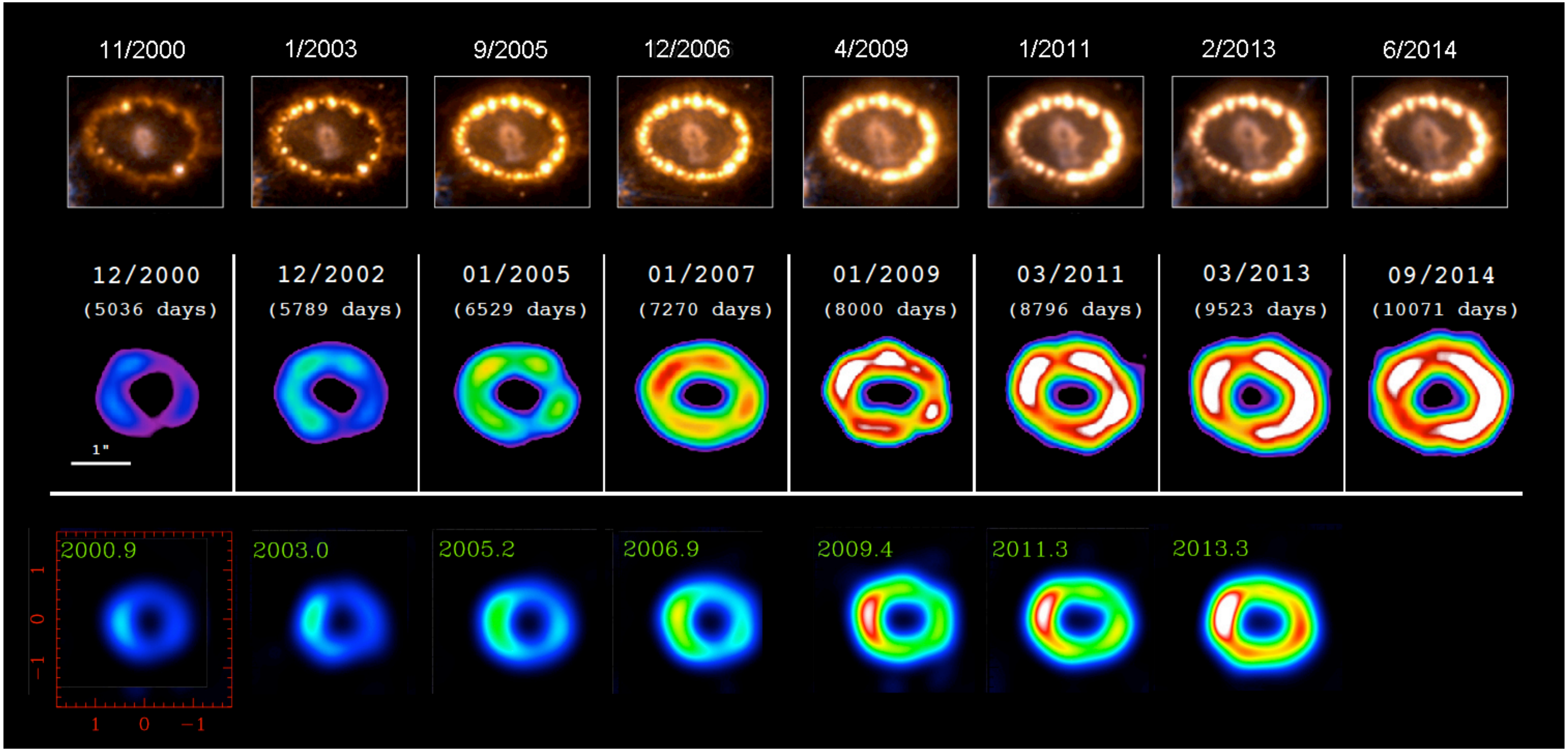


Ring:
First decay until 2000, increase until 2007, then decay

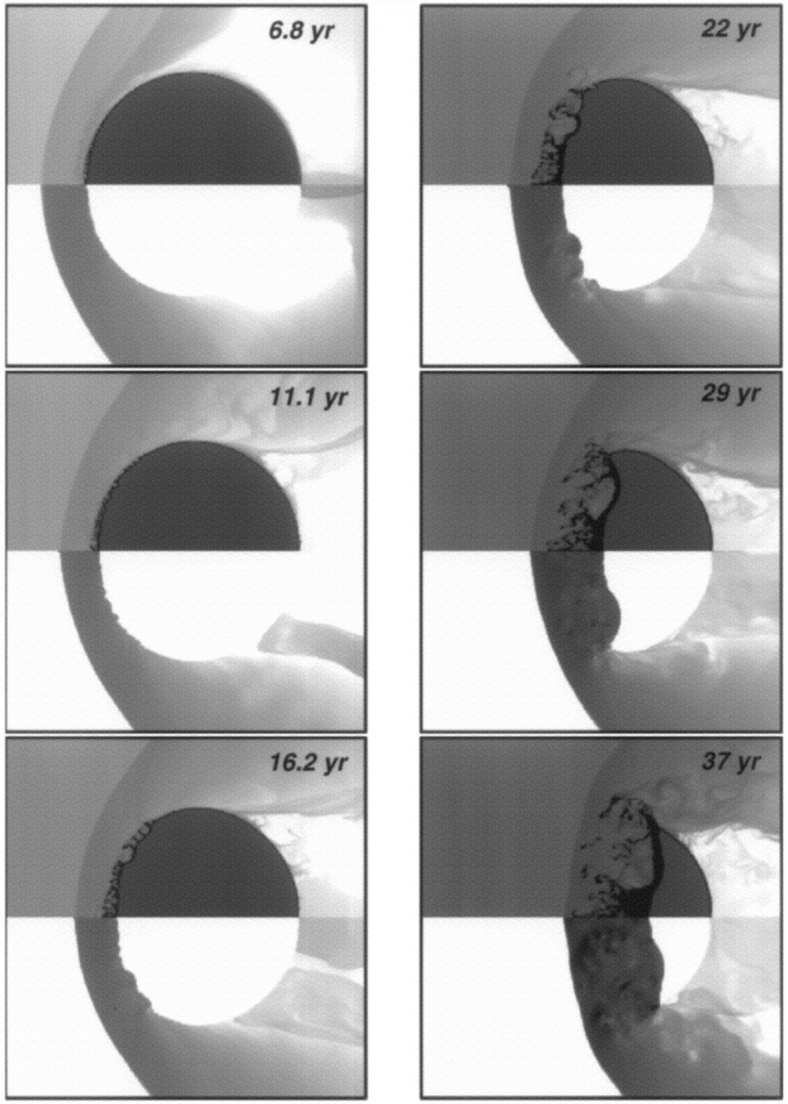
I. Recombination after initial UV/soft X-ray flash
II. Collision with ejecta

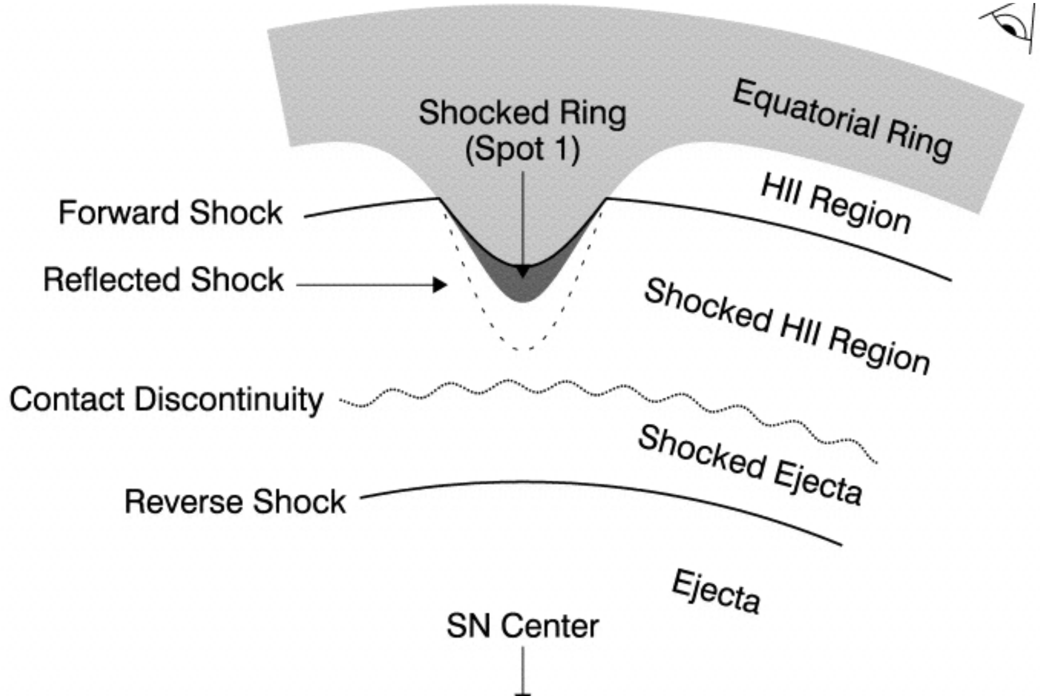
Optical, X-ray and radio evolution

HST, Chandra, ATCA
CF+ 2015, Frank+ 2016, Ng+ 2013



Borkowski. Blondin & McCray 1997





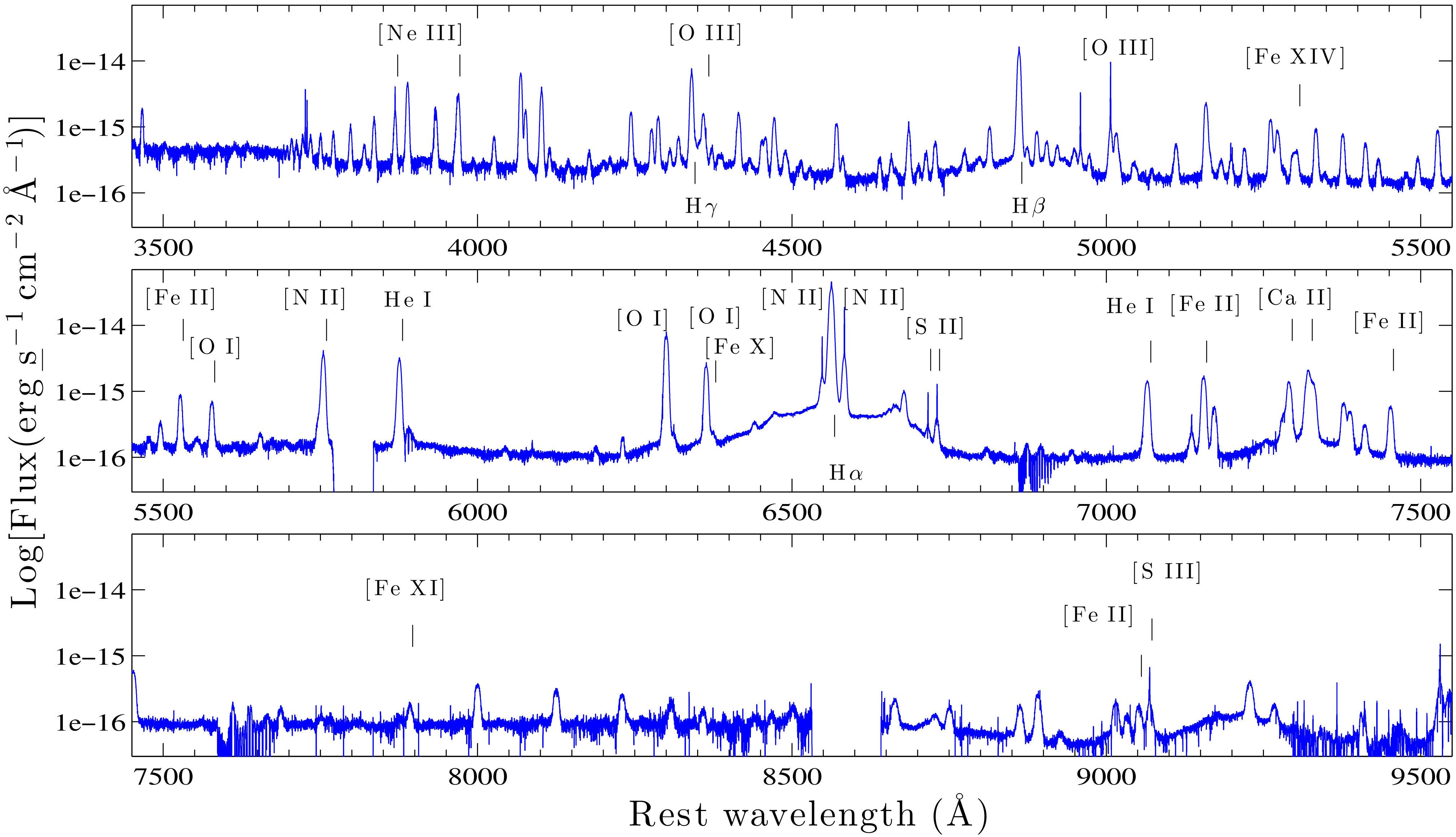
Reverse shock velocity
$V_{rev} \approx 10{,}000$ km/s

Blast wave velocity in H II region
$V_{forward} \approx 2000 - 4000$ km/s

Shock velocity into ring ≈
$\left(\frac{n_{HII}}{n_{ring}}\right)^{\frac{1}{2}} V_{forward} \approx 200 - 400\ km/s$

SN 1987A with UVES/VLT in Dec. 2013

K. Migotto+ in prep.

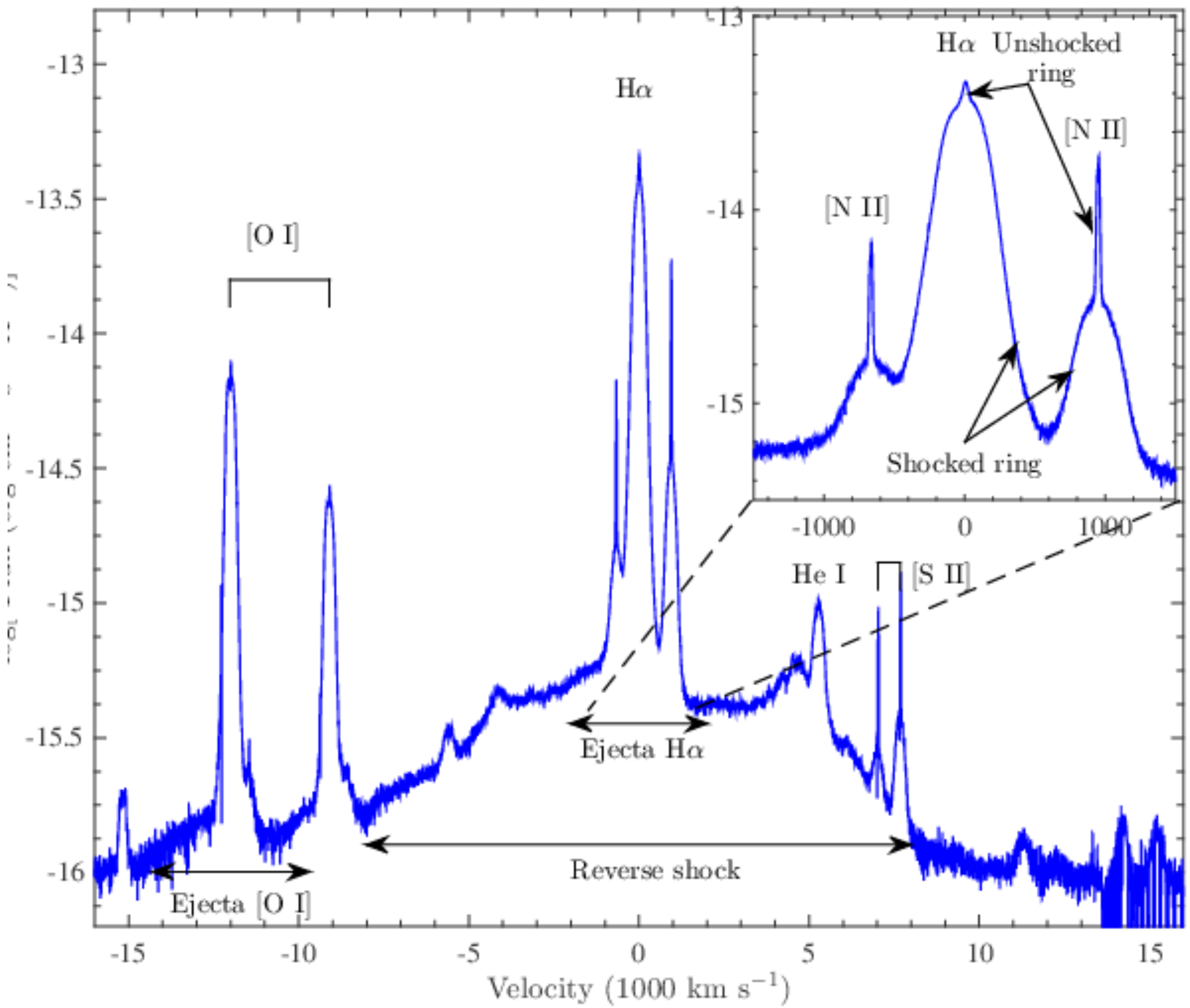


[O I] to [Fe XIV]

Velocity components in Hα

UVES / VLT

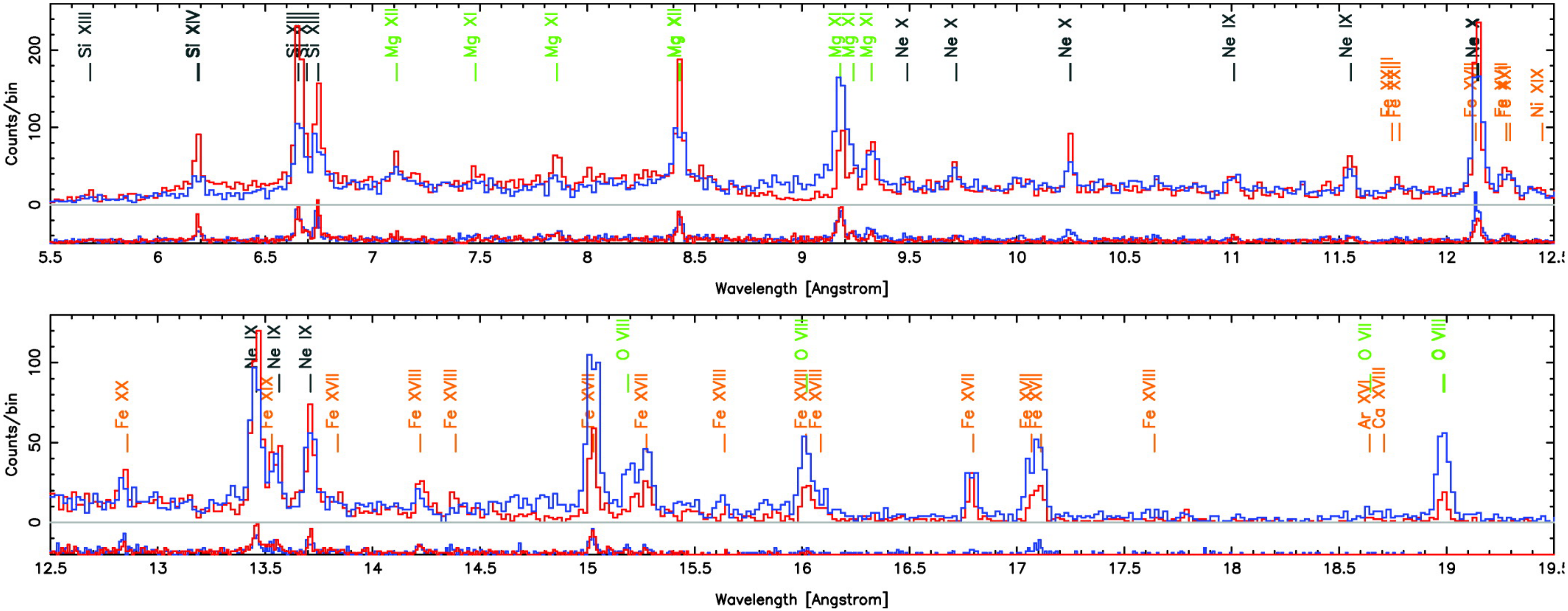
K. Migotto+ in prep.



- Un-shocked ring V~10 km/s
- Shocked ring V ~ 300-700 km/s
- SN ejecta (inner core) V~2000 -3000 km/s
- Reverse shock V~ 11,000 km/s

Dewey+ 2010

Chandra grating spectrum

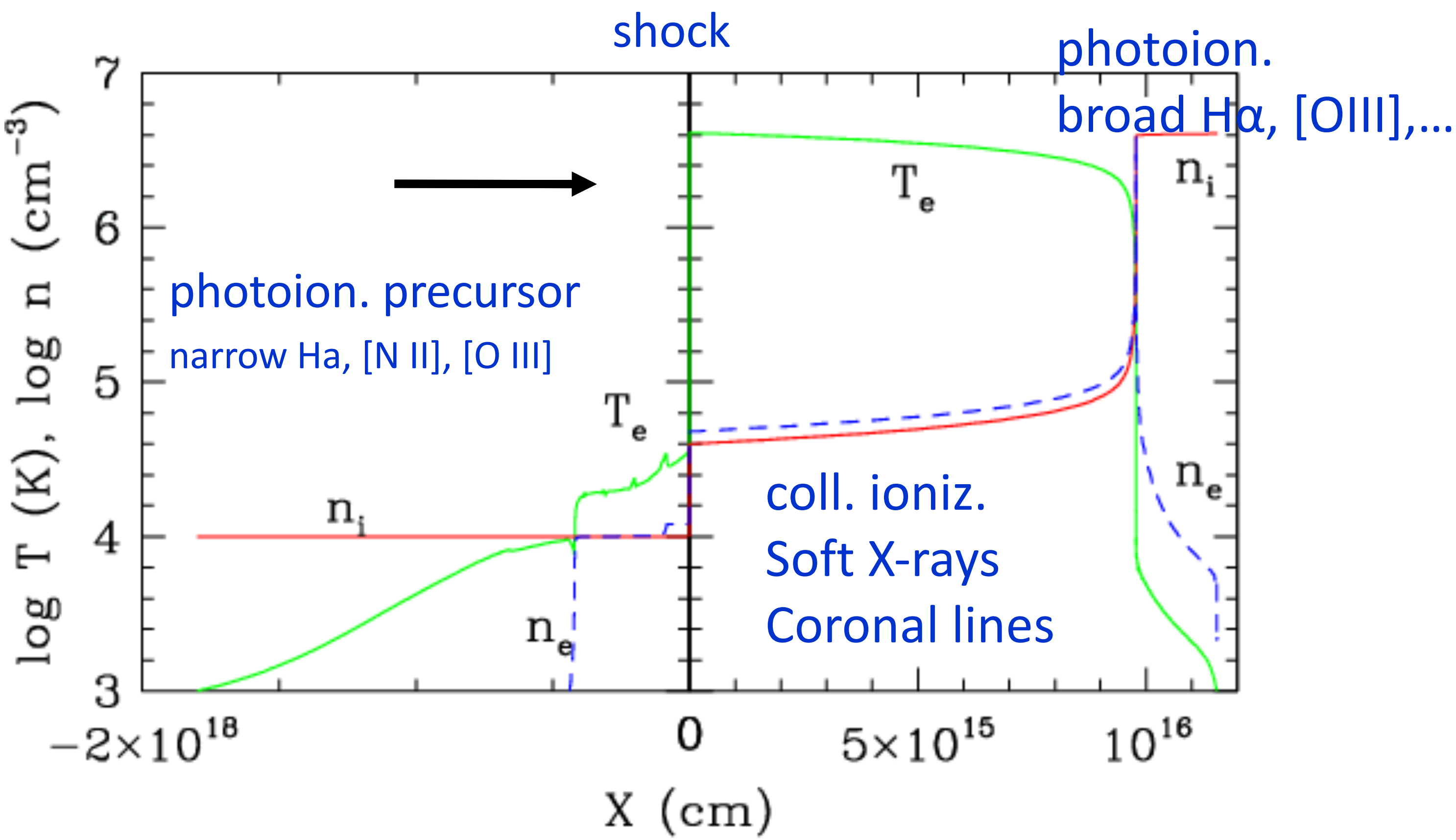


Probes the highest temperatures and shock velocities: Si XIV, Fe XXII…..

Complementarity of optical and X-ray from cooling shocks

Radiative shock structure

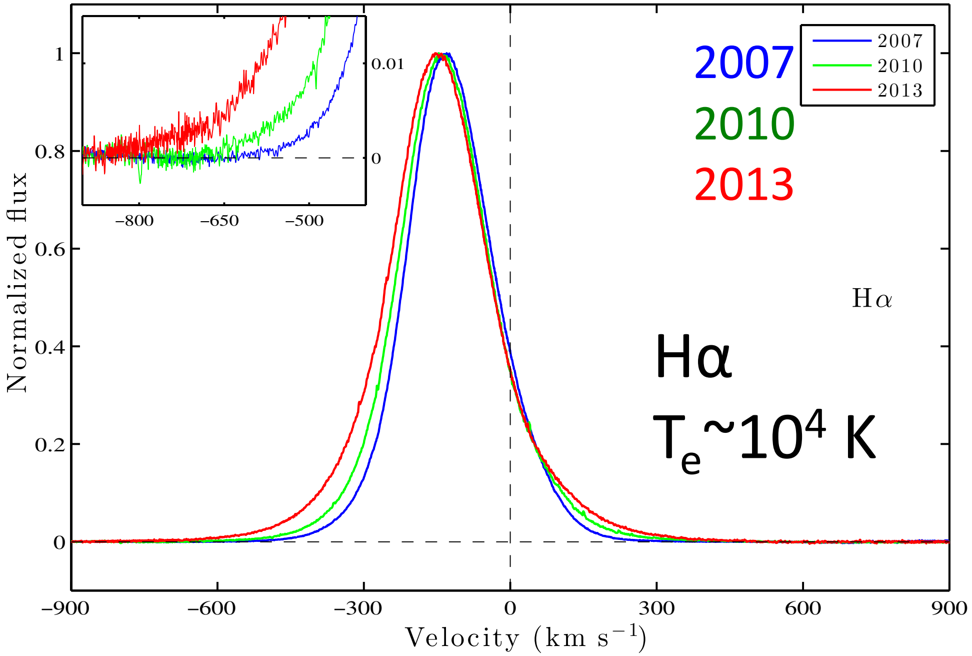
V_s = 350 km/s $n_o = 10^4$ cm^{-3}

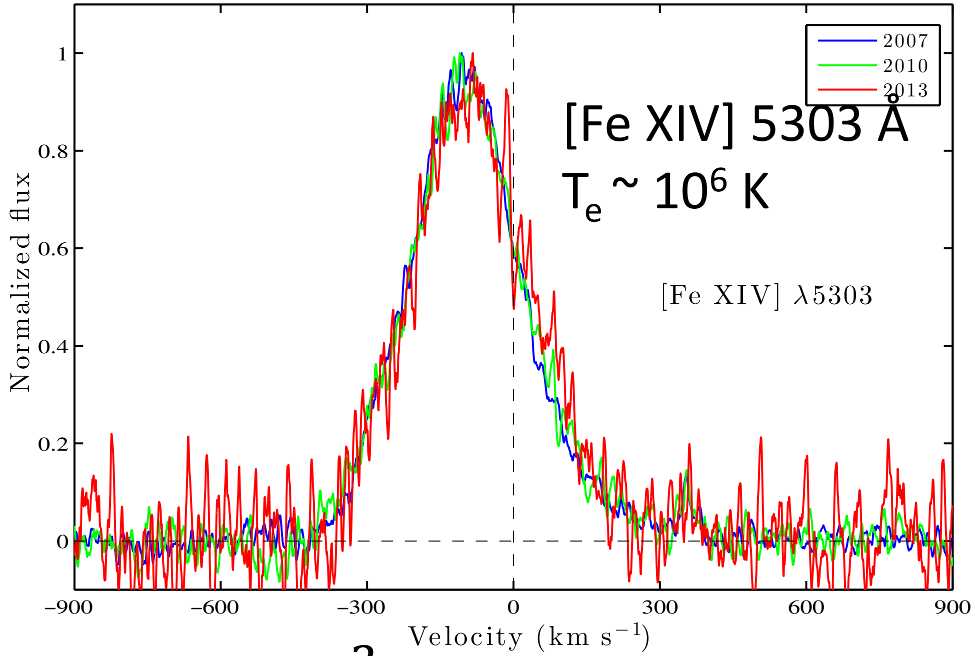


Post-shock densities ~5×10^6 - 10^7 cm^{-3}.

Shock laboratory: Cooling shocks in real time

K. Migotto+ 2016





$$T_s = 3.4\times10^6 \left(\frac{V_s}{500\ \mathrm{km/s}}\right)^2 \ \mathrm{K}$$

$$t_{cool}=38 \left(\frac{V_s}{500\ \mathrm{km/s}}\right)^{3.4} \left(\frac{n}{10^4\ \mathrm{cm}^{-3}}\right)^{-1} \ \mathrm{years} \ \Rightarrow$$

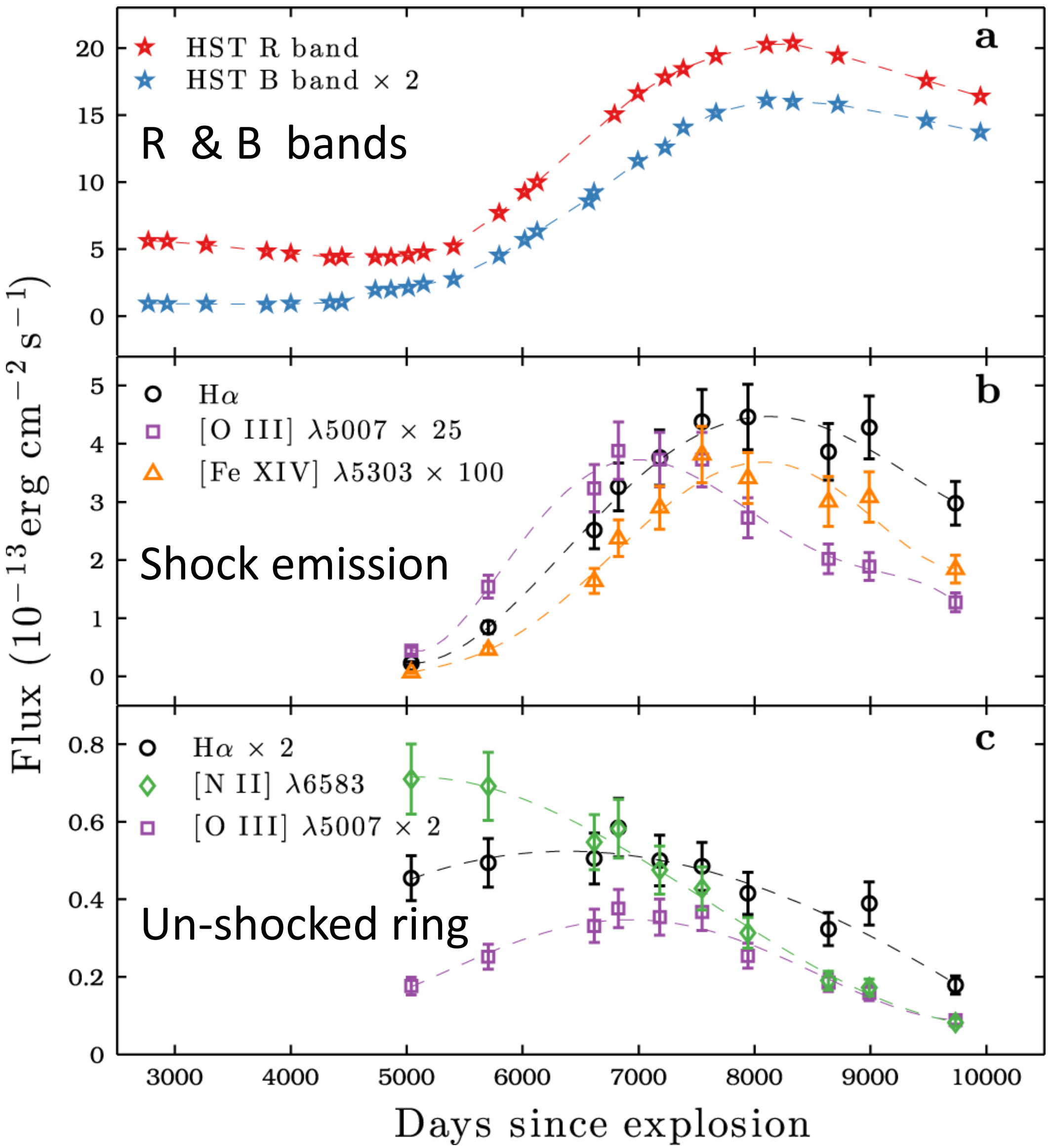
$$V_{cool} = 450 \ \left(\frac{n}{10^4\ \mathrm{cm}^{-3}}\right)^{0.29} \left(\frac{t}{27\ \mathrm{yrs}}\right)^{0.29} \ \mathrm{km/s}$$

Faster and faster shocks become radiative.

Radio: Testing relativistic particle acceleration

CF, Larsson, Migotto+ 2015

Transition to SN remnant



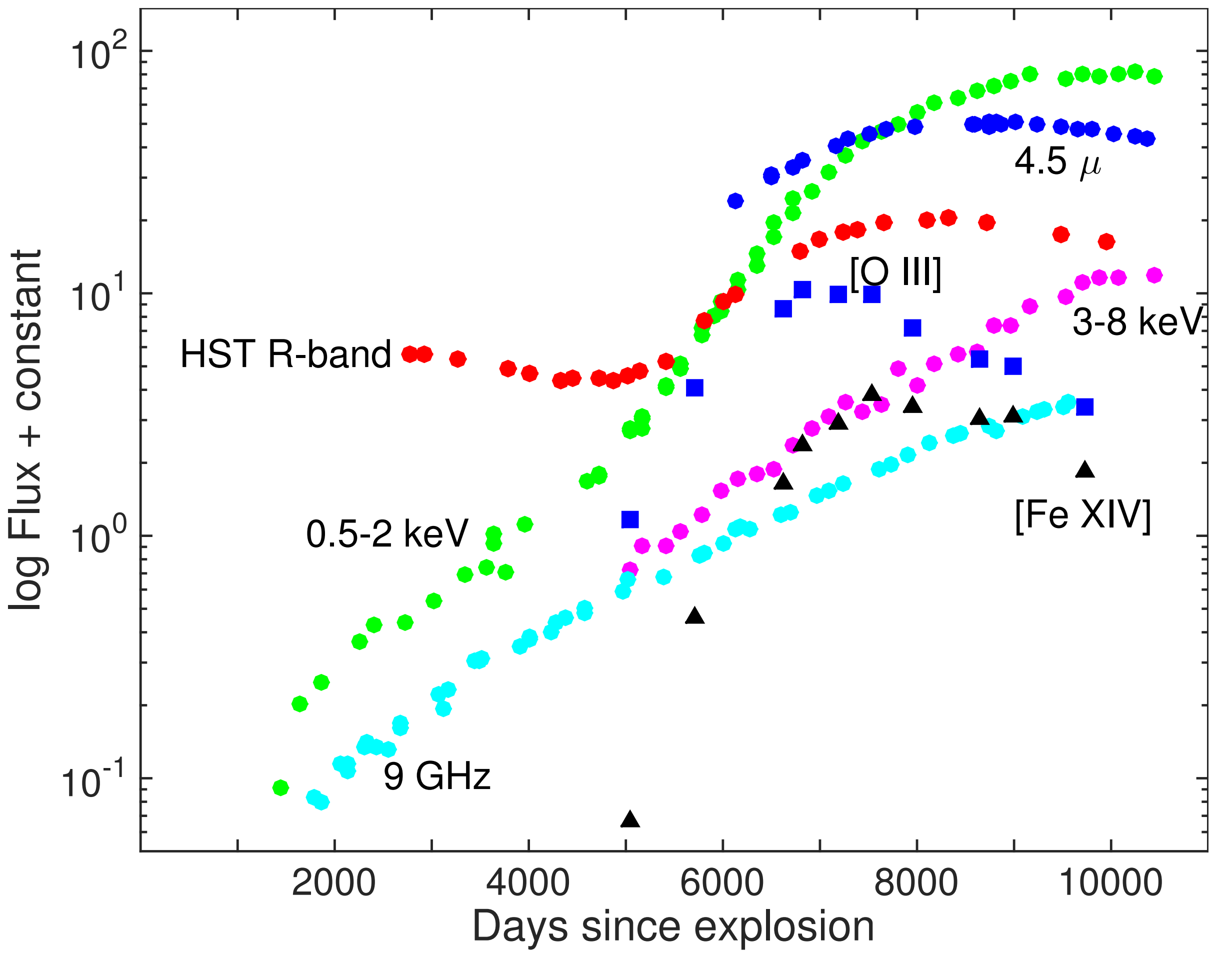
Flux from both shocks into hotspots and the un-shocked ring decrease since day 7000

Marks destruction of ring. Extrapolation → dissolved by ~ 2025

SNR 1987A increasingly X-ray dominated

Reverse shock heating the ejecta

The ring at different wavelengths



Optical and mid-IR peaked at day ~ 8000 and are now decaying (CF+2015, Arendt+2016)

Soft X-rays levelling off (Frank+2016)

Radio and hard X-rays still increasing (Ng+2013)

Consistent with most of optical, soft X-rays and mid-IR from the shocked clumps in the ring.

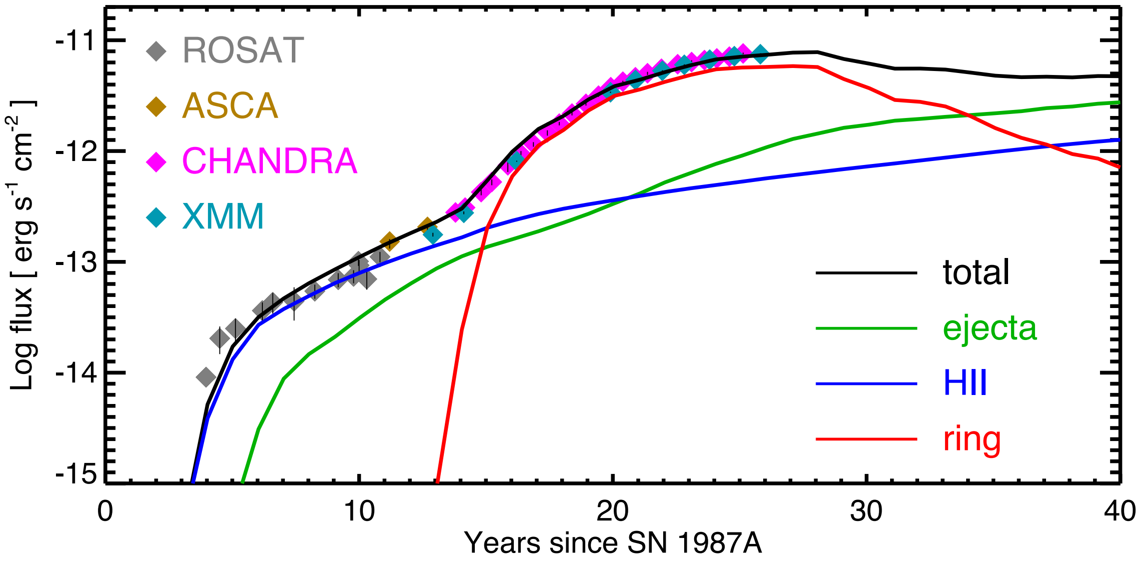
Hard X-rays and radio from blast wave and reverse shock

Modeling of X-rays

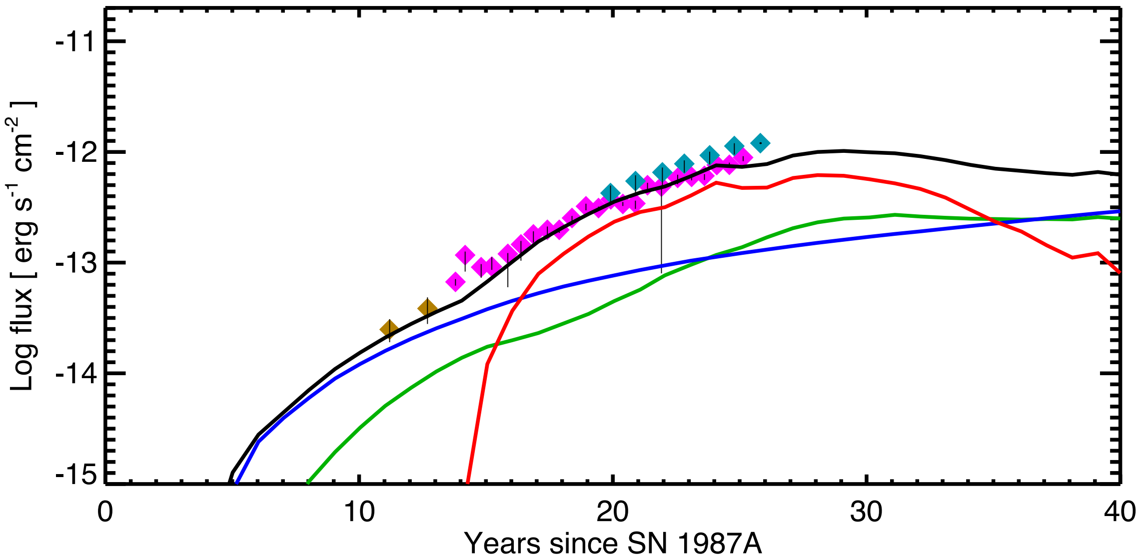
Orlando+ 2015

Talk by Orlando

(b) [0.5, 2.0] keV



(c) [3.0, 10] keV



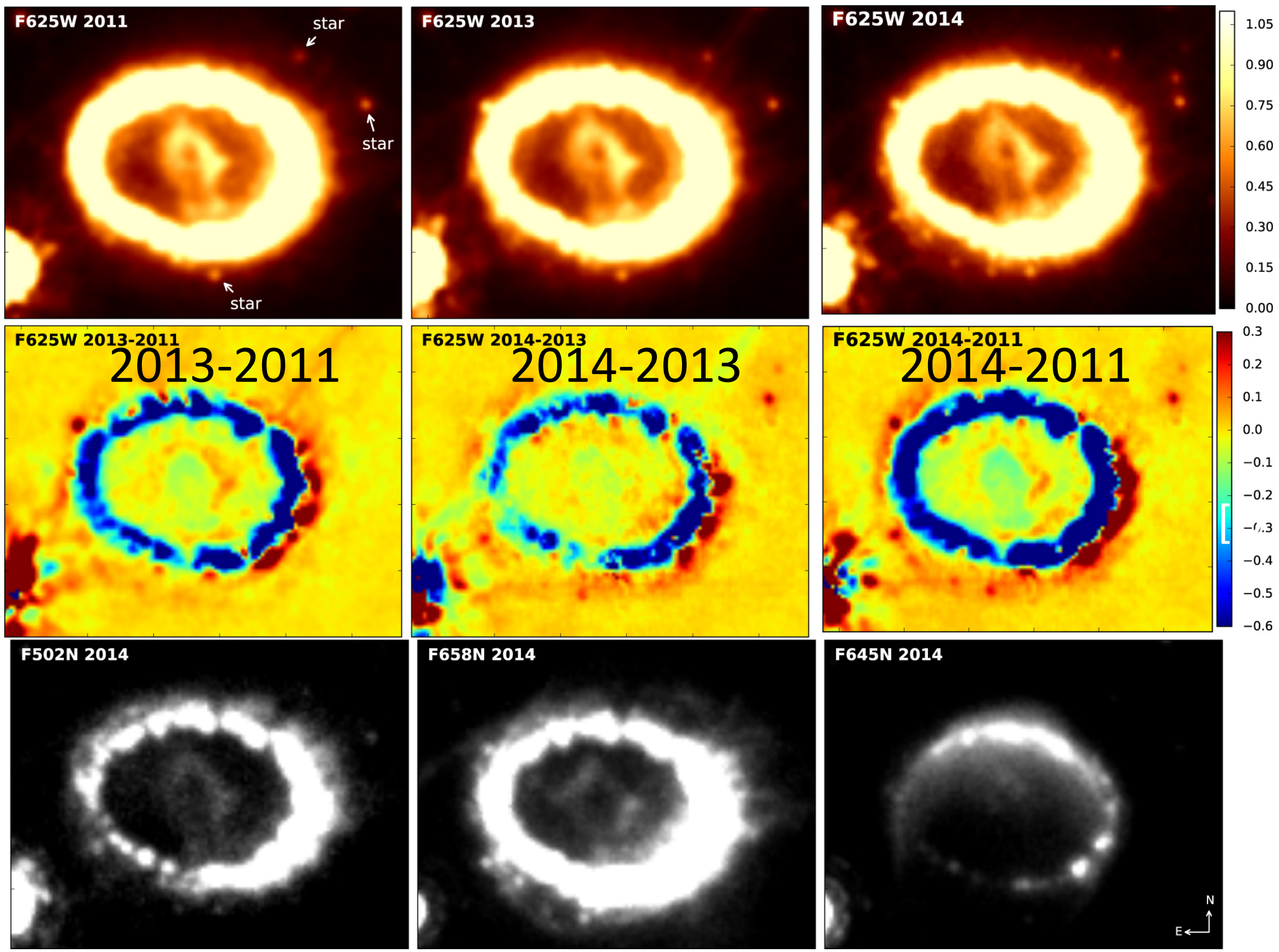
CSM similar to Chevalier & Dwarkadas '95 + clumpy ejecta and ring

Similar simulations of the radio emission by Potter et al 2014

Transition to SN remnant

CF, Larsson, Migotto+ 2015

2011 2013 2014

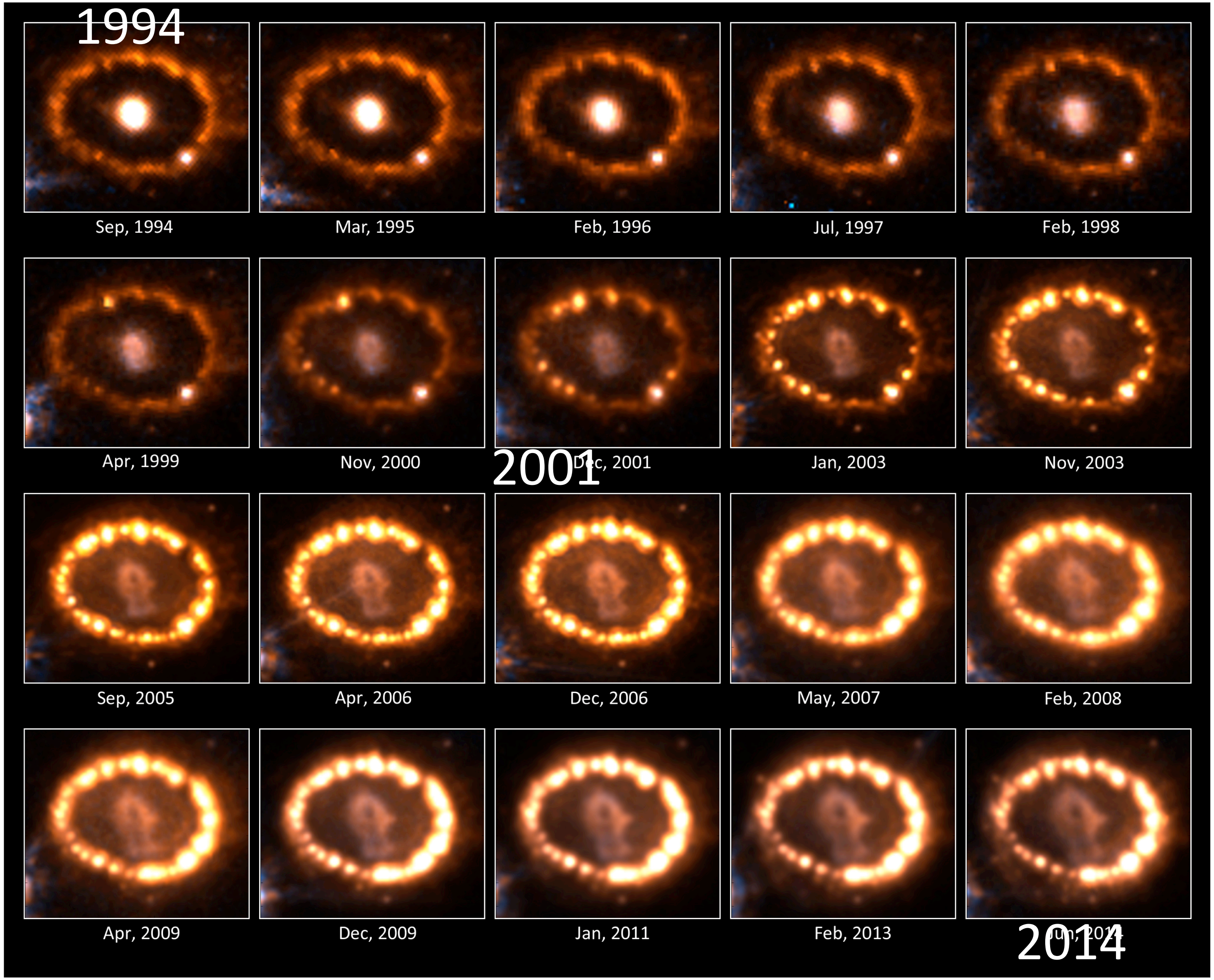


New spots outside of ring.

Blast wave now probes the unseen CSM

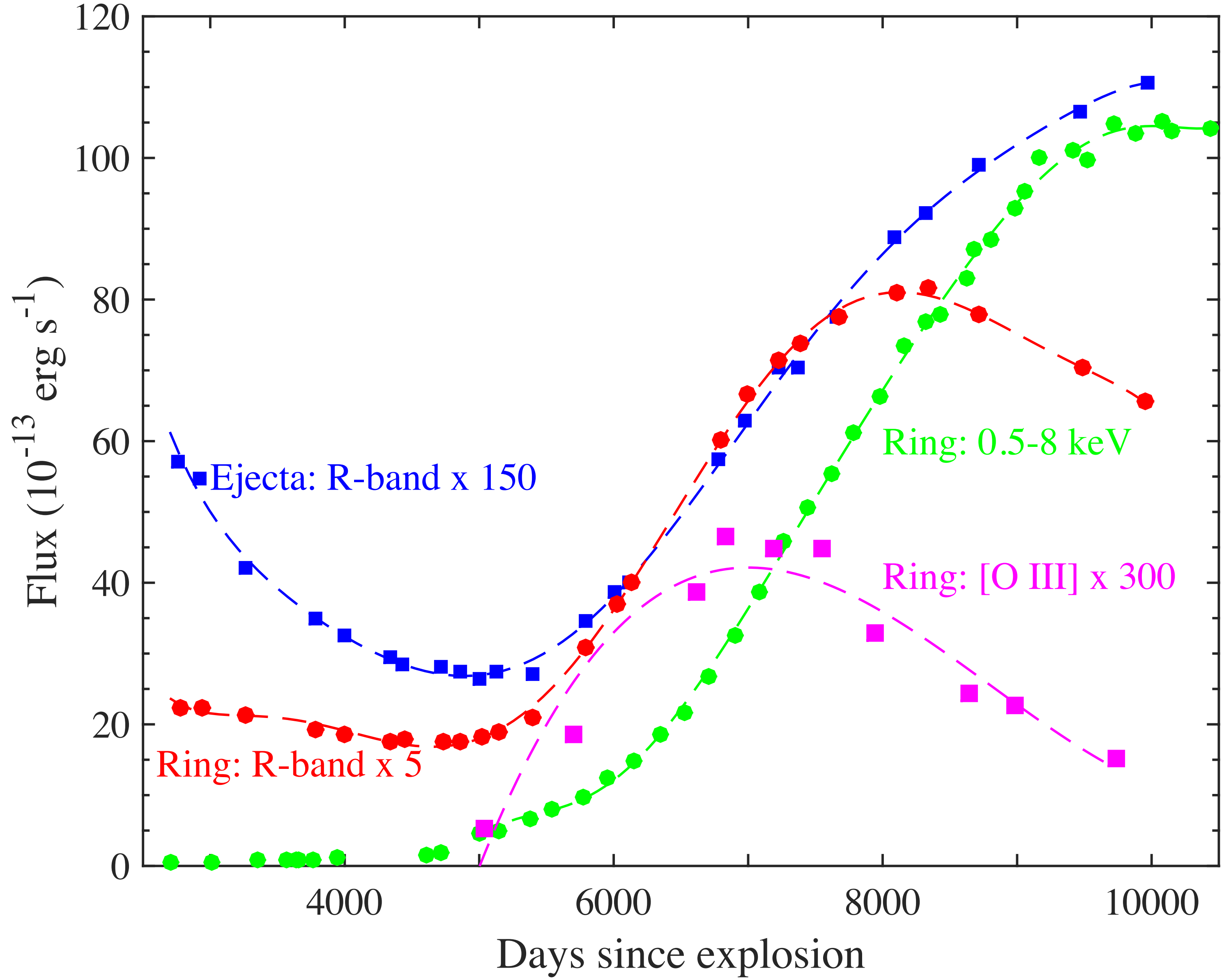
The ejecta

Also the ejecta are getting brighter



Ejecta: Decaying until 2001, then increasing

Ejecta – ring evolution

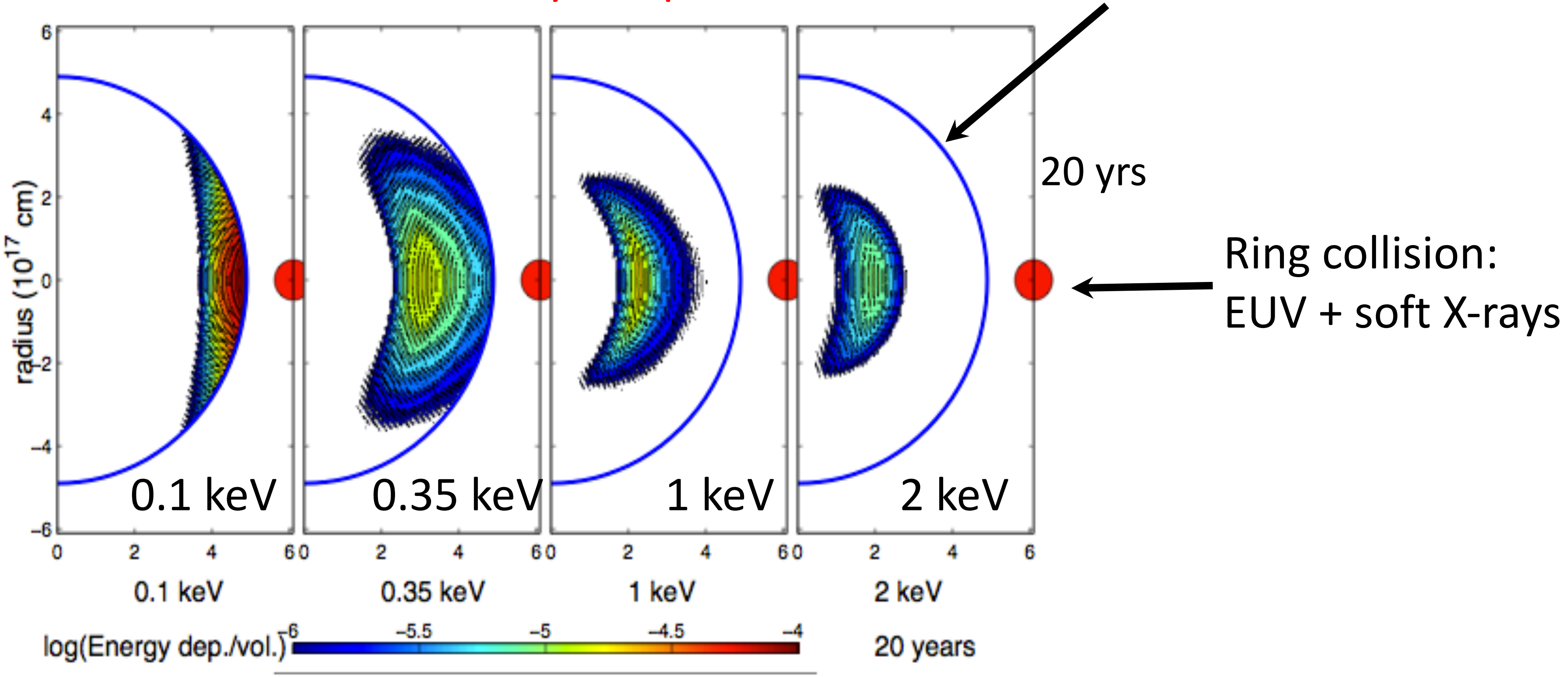


Ejecta: Larsson et al. 2011 updated

Ring: Optical Migotto+, in prep.   X-rays: Frank+2016

(CF et al. 2013)

X-ray deposition



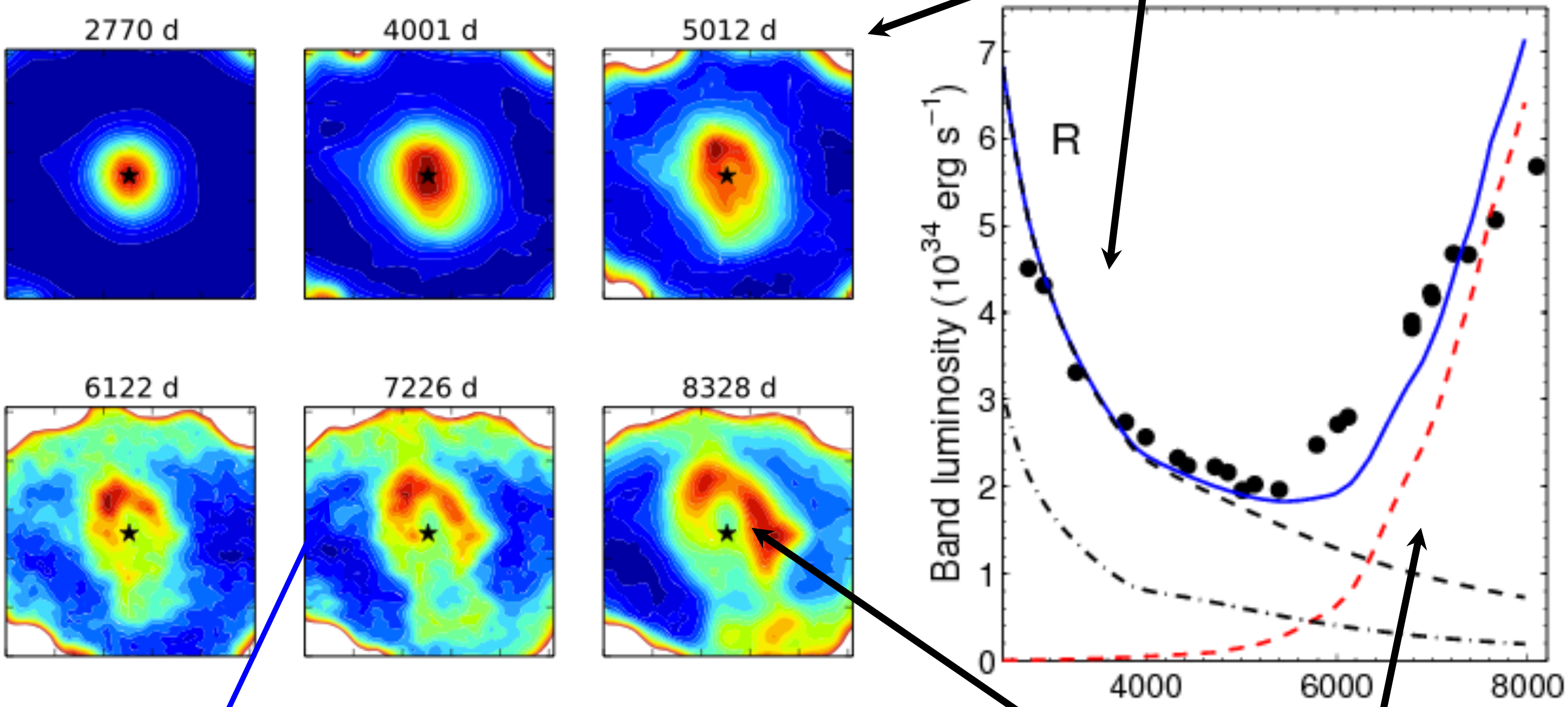
Soft X-rays from transmitted shocks have kT ~ 0.3-0.5 keV $\Rightarrow$ deposition in outer parts of ejecta = H/He rich regions

Hard X-rays with > 2 keV penetrate to but not into the O-core unless very asymmetric and clumpy

Explains horse-shoe-like morphology in Hα

Ejecta morphology in Hα

Radioactivity dominates, centrally peaked



X-ray input dominates

‘Hole’. Only in X-ray dominated phase

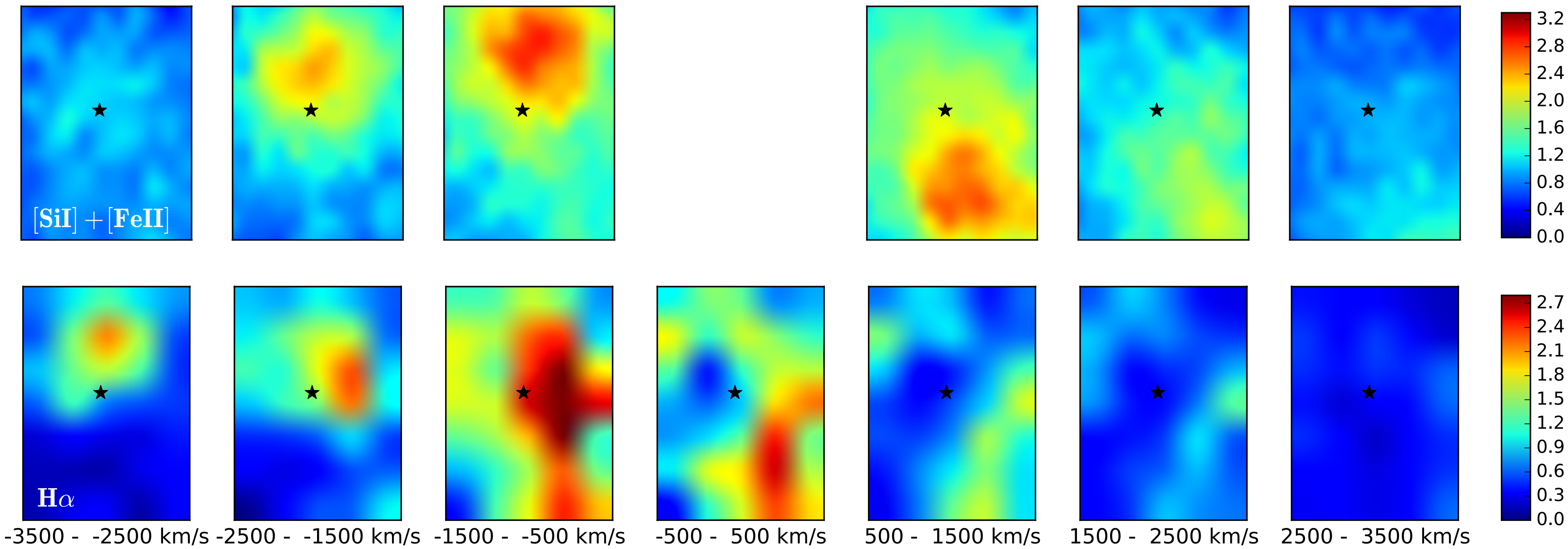
Larsson et al. 2011, 2013

Ejecta tomography of SN 1987A

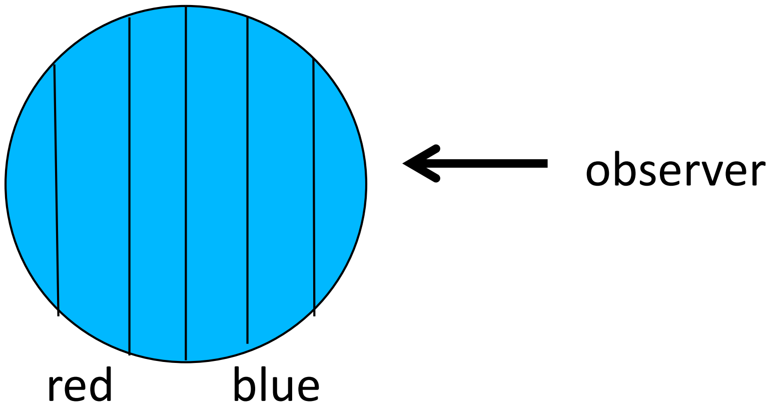
Larsson+ 2016

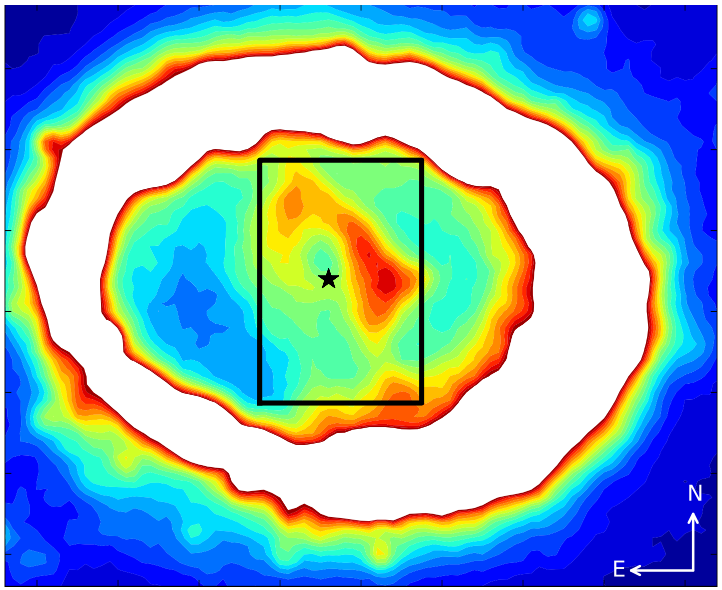
Si I+Fe II
1.644μm
VLT/SINFON

Hα
HST/STIS



-3000 -2000 -1000 0 1000 2000 3000 km/s





V ∝ r ⇒ constant wavelength =
constant LOS velocity =
surfaces perpendicular to LOS

3D distribution of ^{44}Ti

Larsson+ 2016

VLT/SINFONI: [Si I]+[Fe II] 1.644 μ

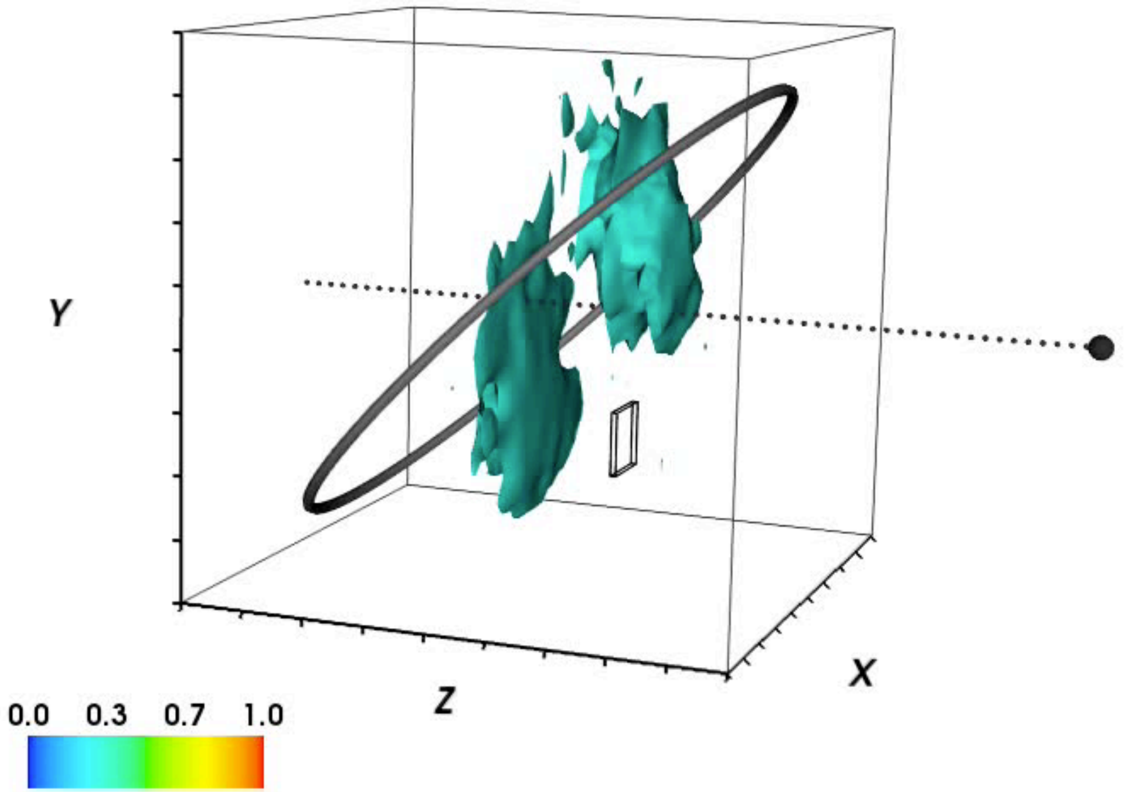
Maps ^{44}Ti input to Si/Fe and

therefore the ^{44}Ti distribution

Mainly in ring plane. NOT jet.

V ~ 2300 km/s

Less sensitive to chemistry, photodissociation, excitation than the molecular lines

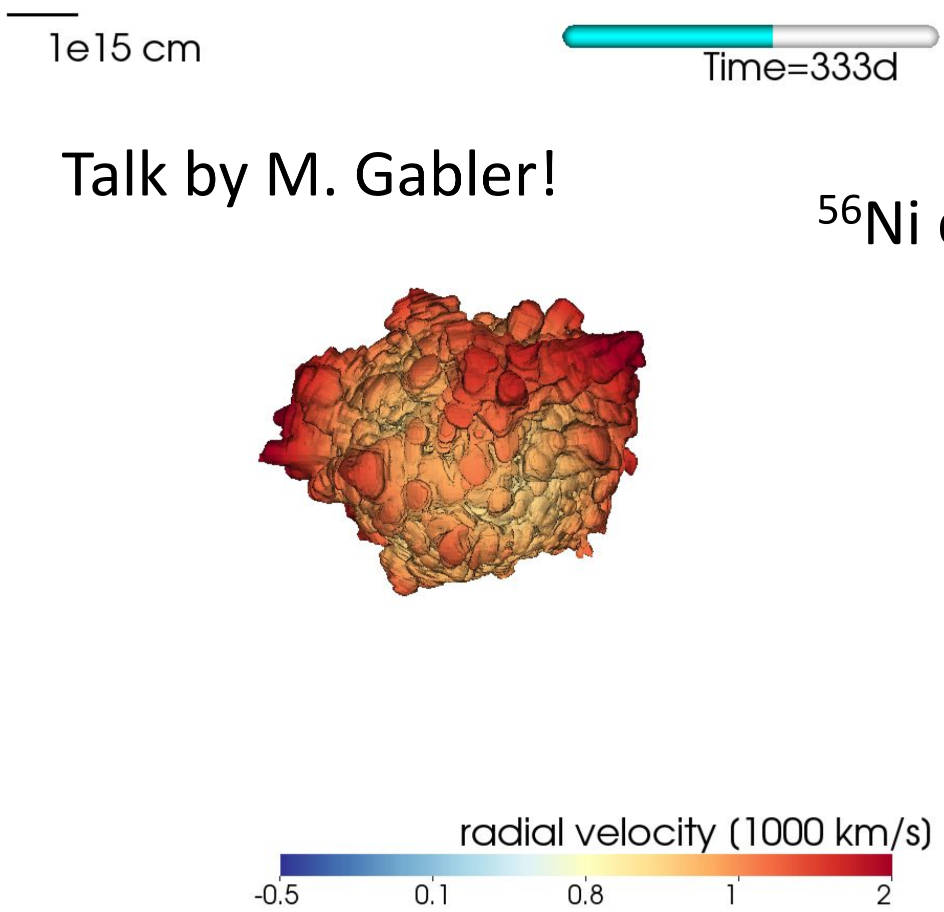


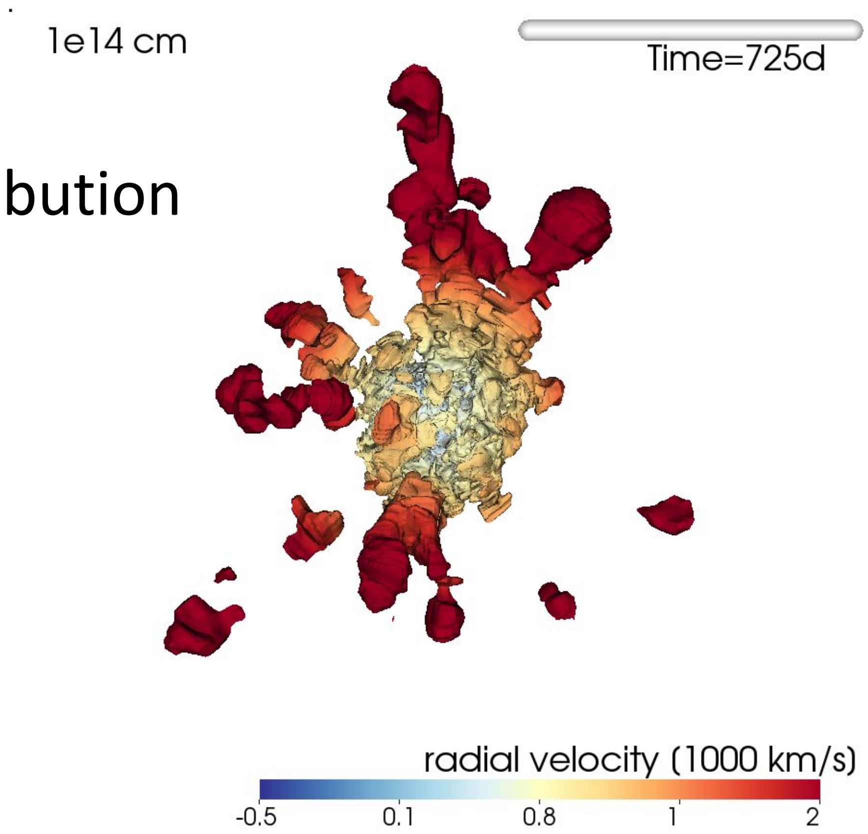
3D simulations of the ejecta structure

M. Gabler et al, in prep.
Wongwathanarat+ 2015
See also Hammer et al. 2010.

Talk by M. Gabler!

^{56}Ni distribution





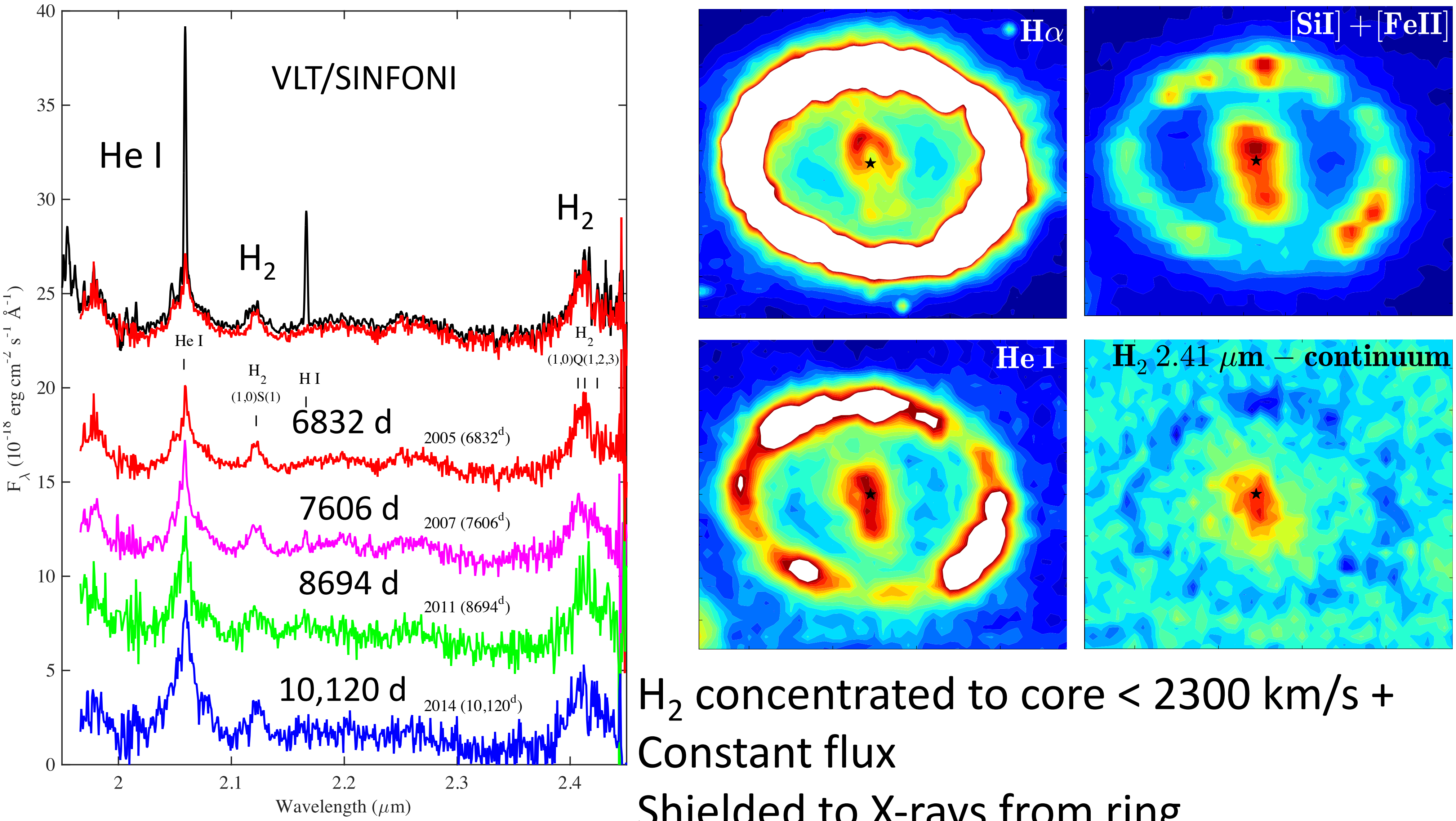
20 M BSG
3 % ^{56}Ni contours

15 M BSG
10 % ^{56}Ni contours

From core collapse to homologous expansion, including ^{56}Ni heating
1 sec to ~2 years

Molecular hydrogen in 87A

CF, Larsson, Spyromilio+ 2016



H_2 concentrated to core < 2300 km/s +

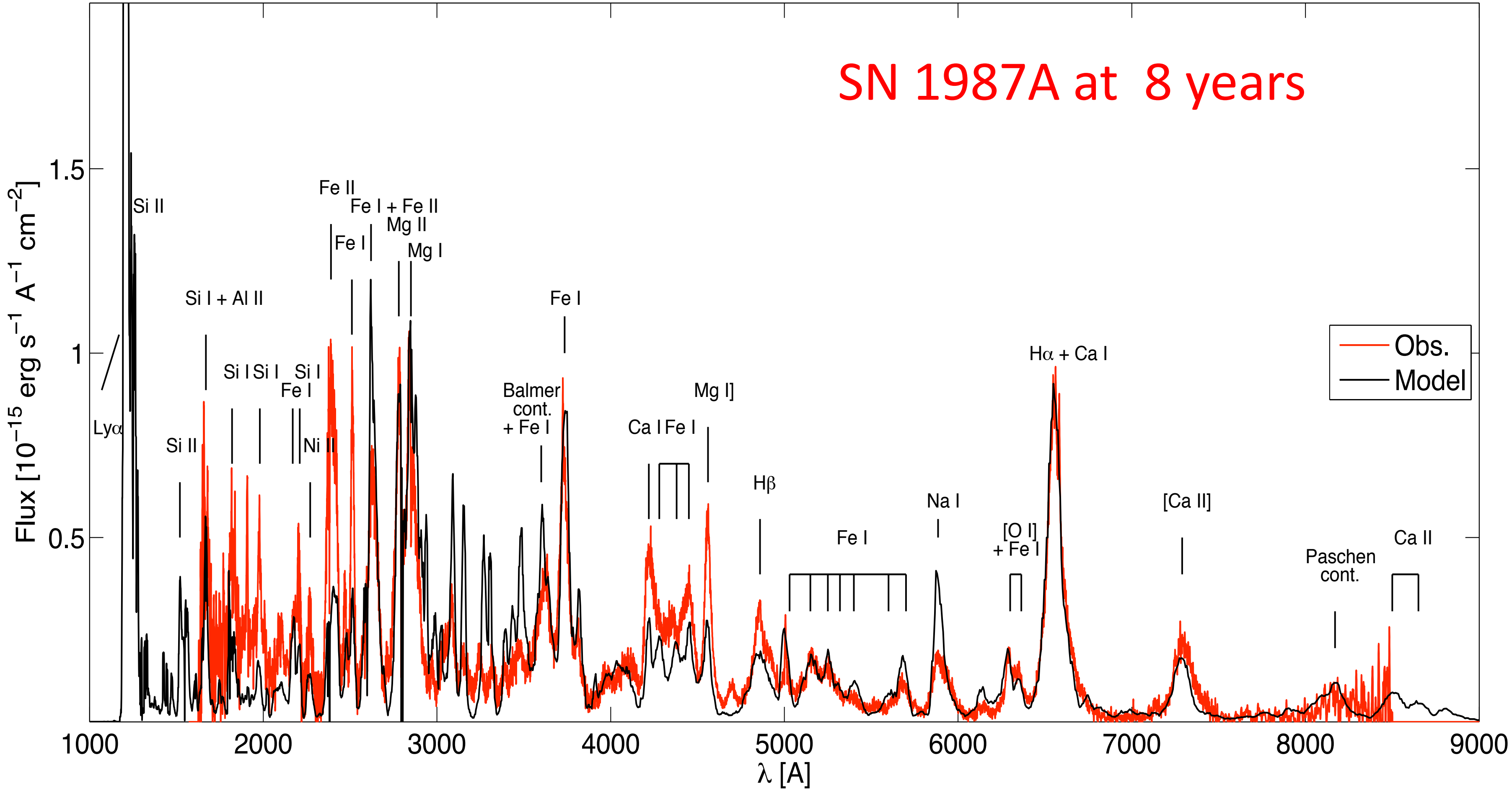
Constant flux

Shielded to X-rays from ring

Mixing of H with metal core to < 400 km/s

^{44}Ti mass

Dominates for > 1500 days. Most emission in mid- and far-IR -> spectral modeling of UV/optical/NIR required for ^{44}Ti mass



$M(^{44}Ti) = (1.5 \pm 0.5) \times 10^{-4}\ M_{\odot}$

τ_{dust} ~ 1 or covering factor ~0.65

non-thermal excit., strong UV, mainly Fe I emission from SN core

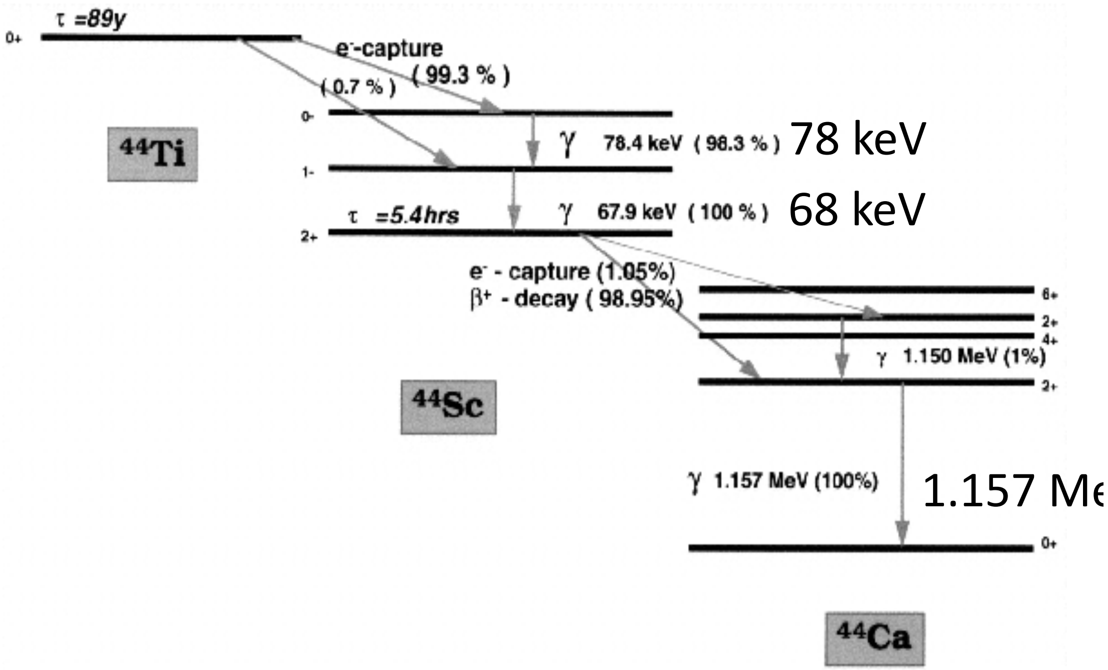
Jerkstrand, CF, Kozma. 2011

Obs. SINS/HST (Chugai et al 1996)

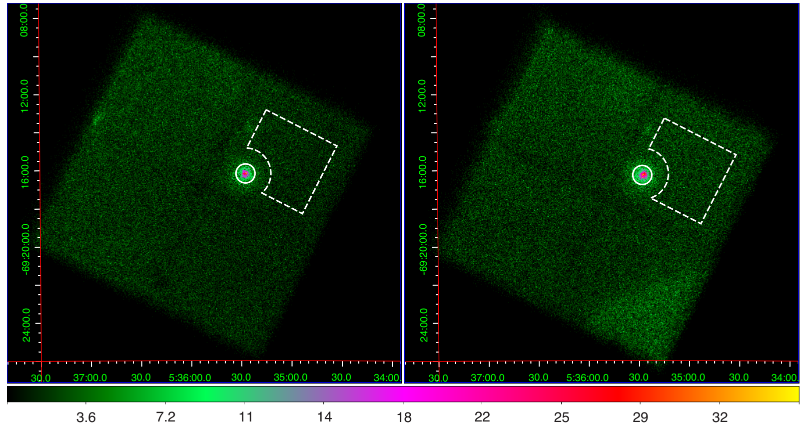
^{44}Ti mass from hard X-rays

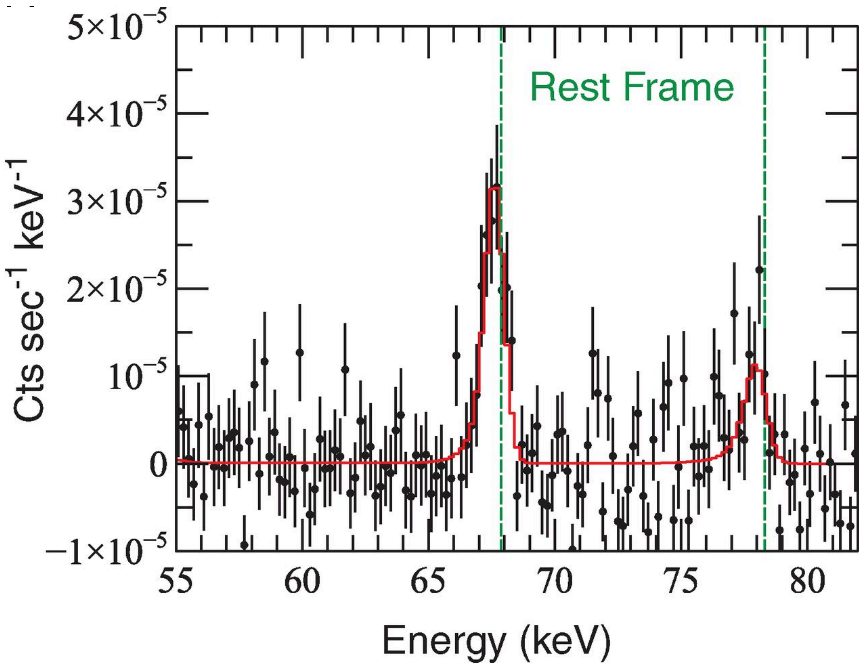
Boggs et al Science May 8 2015

Talk by Grefenstette



NUSTAR





$M(^{44}Ti) \approx (1.5 \pm 0.3) \times 10^{-4}\ M_O$

Line redshifted

INTEGRAL Grebenev et al. 2012

$M(^{44}Ti) \approx (3.1 \pm 0.8) \times 10^{-4}\ M_O$

Energy budget at 30 years for the inner ejecta

Energy input from ^{44}Ti positrons ~278 $L_\odot$. (gamma rays escape freely)

~40% into UV/optical/NIR (UVONIR) emission by non-thermal excitation & ionization of which ~65% is absorbed by the dust, or ~0.4 × 0.65 × 278 $L_\odot$ = 72 $L_\odot$.

UVONIR luminosity only ~15 % of the total!

~60% goes to heating, balanced by the [FeII] 26-μm line. ~0.6 × 278 $L_\odot$ = 167 $L_\odot$. Spitzer limit at least factor 10 lower!

Dust-absorbed energy: 167 + 72 = 239 $L_\odot$

Herschel 100-500μm ~220 $L_\odot$ (Matsuura et al. 2011). Agreement!

So, everything is fine, EXCEPT for understanding the very weak [Fe II] line

What weakens the [Fe II] 26 μm line?

Cooling by dust?

Requires the dust and iron to be co-existing. Fe – grains? Problem: Fe mass << dust mass .....

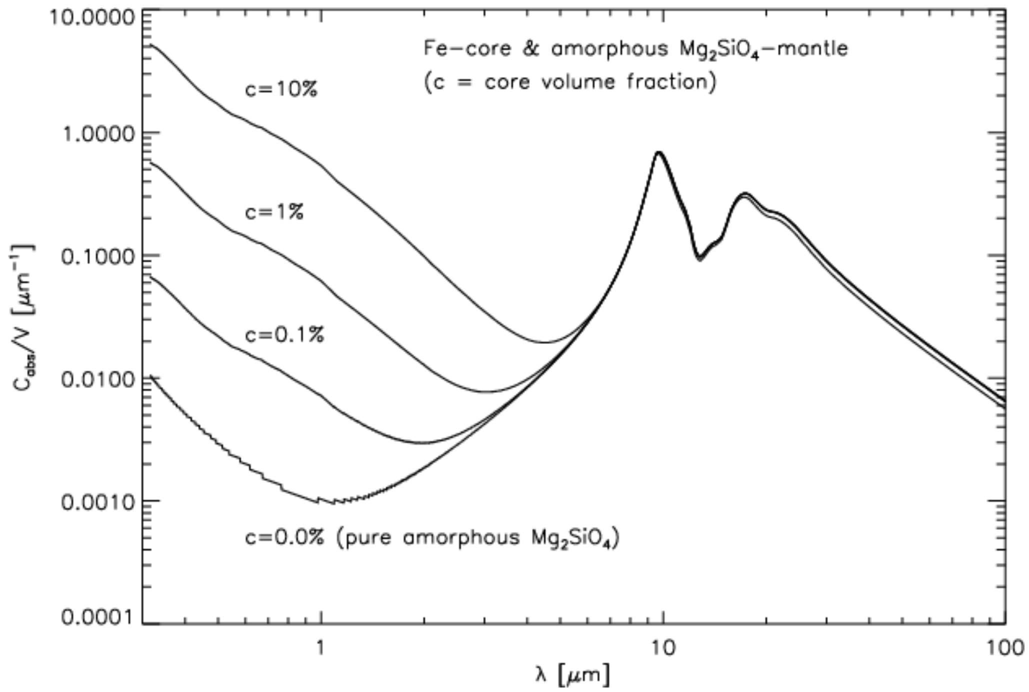
Dust absorption

Require the dust to absorb nearly all radiation in the 10–100-μm band but NOT in the optical

Pure $MgSiO_3$ and $MgSiO_4$ and Al_2O_3 , have an opacity in the 10–30μm range, which is a factor of ~10^2 –10^3 greater than that at optical wavelengths (Jäger et al. 2003).

May be tested with JWST

Jäger+ 2003



What's next?

Reverse shock moves deeper into ejecta

Ring at $V = 6.1\times10^{17}$ cm / t = 7800 $(t/10^4\ \text{days})^{-1}$ km/s. Reverse shock at ~80% of ring + 45° inclination → V_{ejecta}~ 4000 km/s at ring now

O-core at 2000-3000 km/s. [Fe II] wings to ~ 4000 km/s at ~ 1000 days. Mixing, instabilities likely to cause metal blobs to be present at higher velocities.

May soon give stronger He I and O I emission from He/O core at reverse shock, perhaps also Fe. Ejecta increasingly ionized by X-rays.

Forward shock continues into RSG CSM

Compact object: Maximum extra input on top of ^{44}Ti ~ 10^{35} erg $^{s-1}$
X-ray optical depth ~ 1 at 10 keV now, but sensitive to clumping close to compact object. $\tau \propto 1/t^2$ (CF&RAC 1987, Orlando+2015)

‘Old’ facilities – continued monitoring

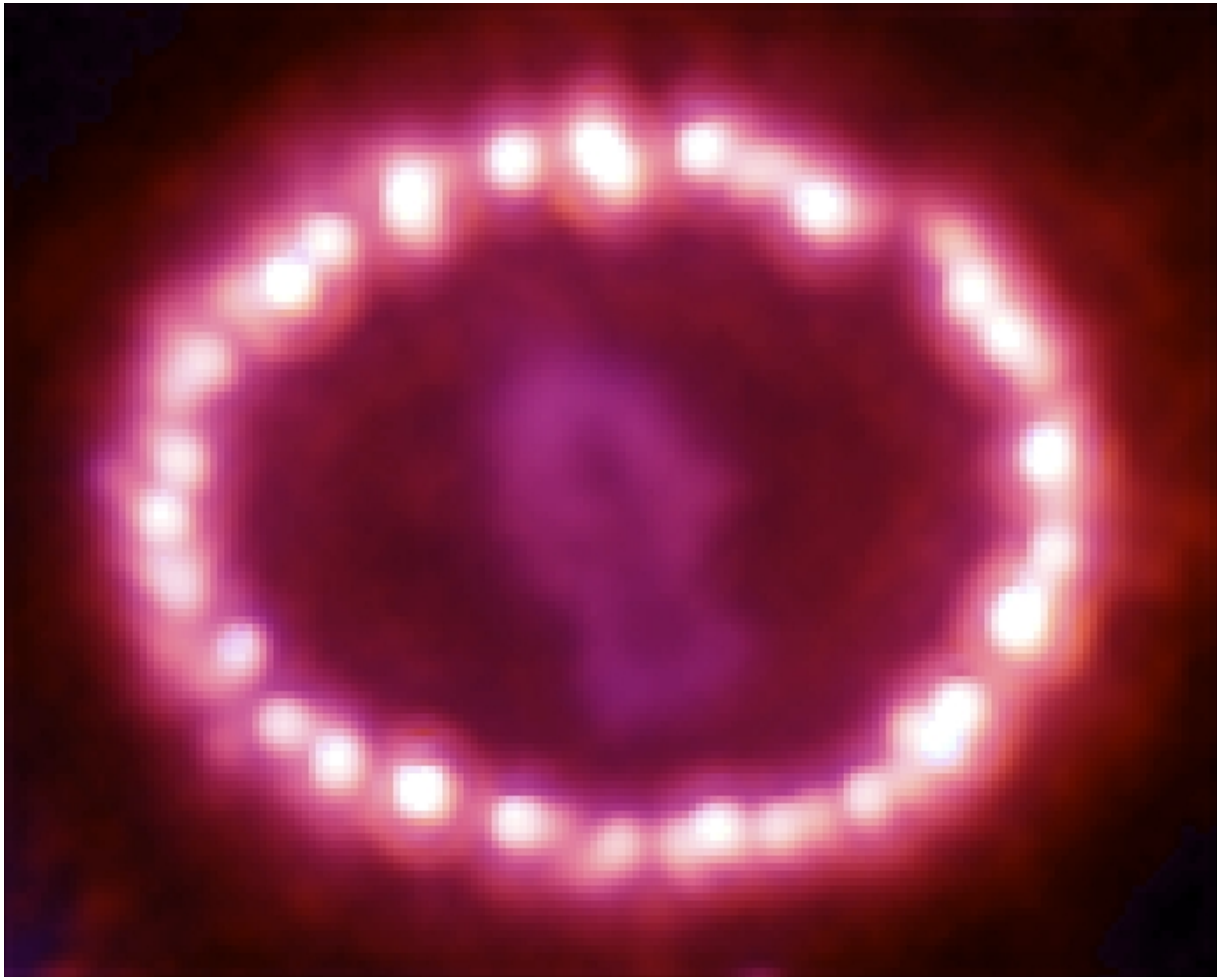
- ❑ HST
  - Follow the changing morphology of the ejecta due to the X-ray input
  - Optical/UV emission outside the ring

    New UV-spectrum with HST today or tomorrow!
- ❑ Chandra/NuSTAR
  - Continued shock evolution
  - Compact source?
- ❑ ALMA
  - Other molecules and isotopologues
  - Pulsar wind nebula?

New facilities – new opportunities

- ❑ JWST Oct 2018:
- Mid-IR lines. [Fe II] 26 μm. Dust absorption / cooling?
- Dust destruction in ring collision
- ❑ E-ELT, GMT + AO 2024+:
- Much higher 3D spatial resolution of the NIR lines → probing the explosion dynamics in detail
- Shock dynamics & ring destruction at better than HST resolution
- ❑ CTA ~2020
- Particle acceleration, cosmic-ray production
- Pulsar?

Happy birthday 87A!



And let's hope for a new Galactic cousin very soon

Peculiar or not? (IIpec)

Yes: Some properties were unexpected

- Compact BSG progenitor (Metallicity? Rotation? Binarity?)
- Light curve faint (consequence of compact BSG)
- CSM (consequence of rotation and/or binarity?)

No: Most properties 'normal' for a Type II CC

- Explosion energy ~10^{51} ergs
- ^{56}Ni mass ~0.07 $M_{\odot}$
- Core mass and core velocity ~ 2000 km/s
- H envelope mass ~ 7 $M_{\odot}$
- Mass 18 +/- 2 $M_{\odot}$
- Nucleosynthesis normal
- Neutrino burst consistent with predictions from normal core collapse (statistics small!)

- What is 'normal'? Crab (EC), Cas A (IIb), 87A (IIp). No IIP! 87A the most 'normal'?