Shocks in SN 1987A

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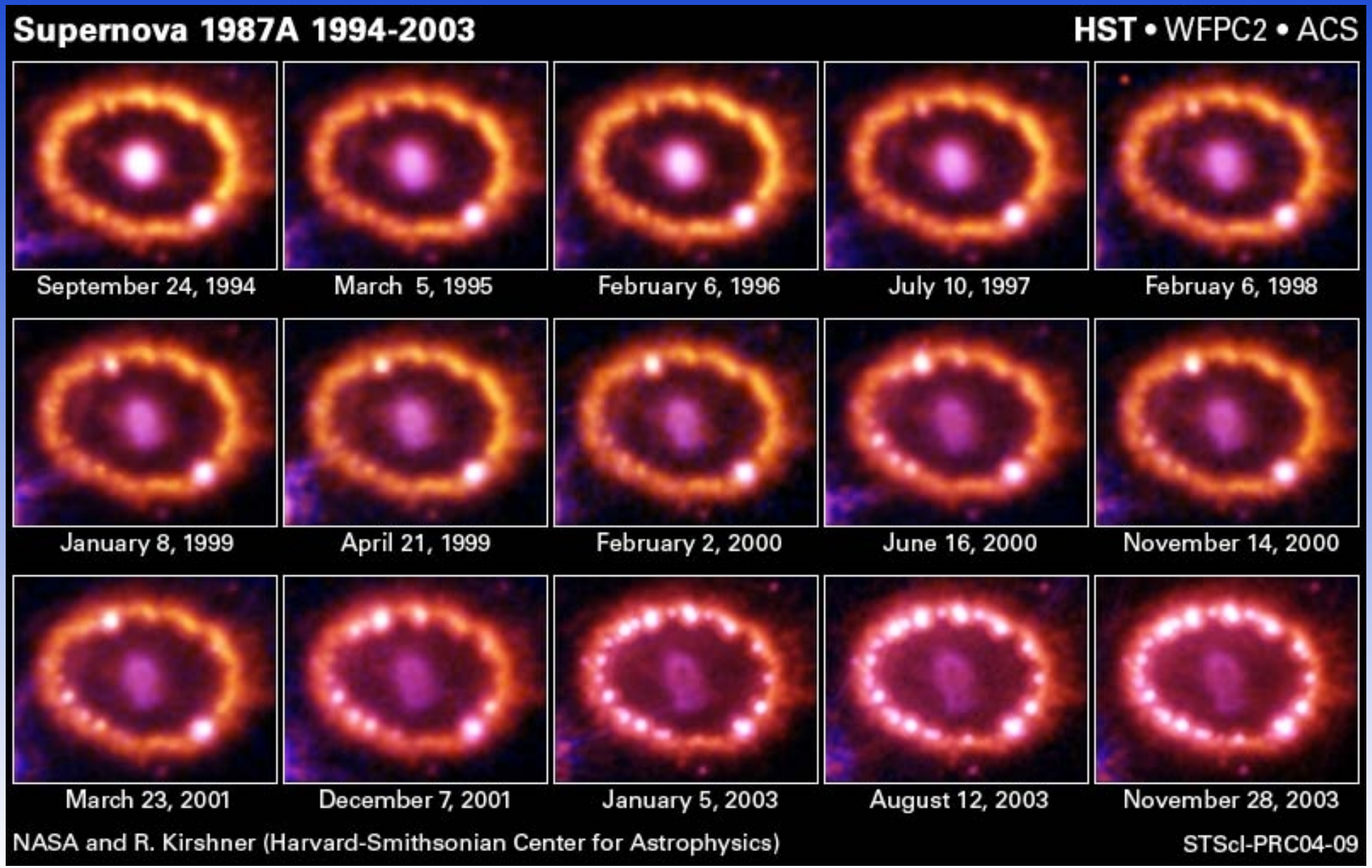
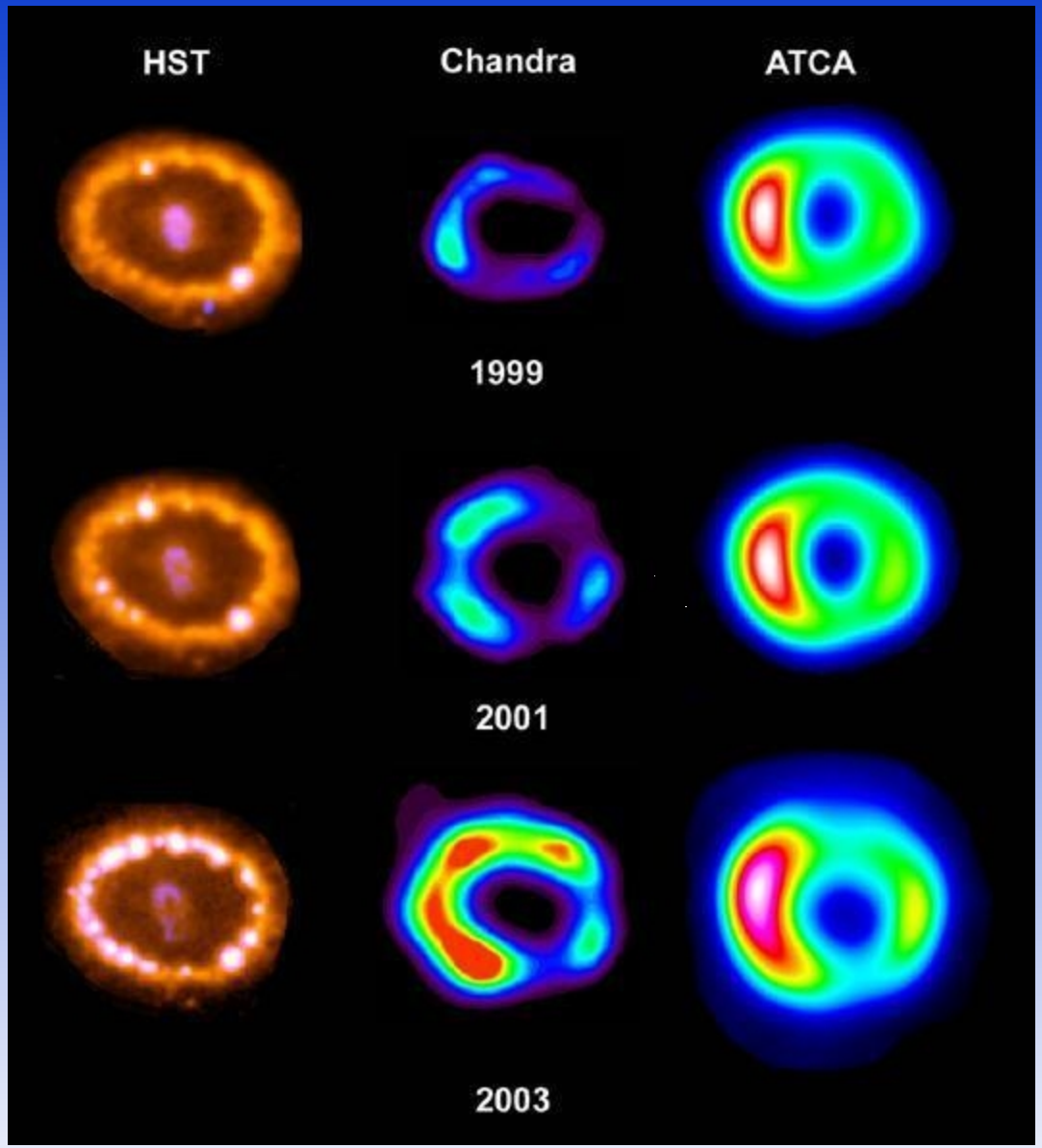
SN 1987A ring collision

SAINTS collab.



Chandra & ATCA

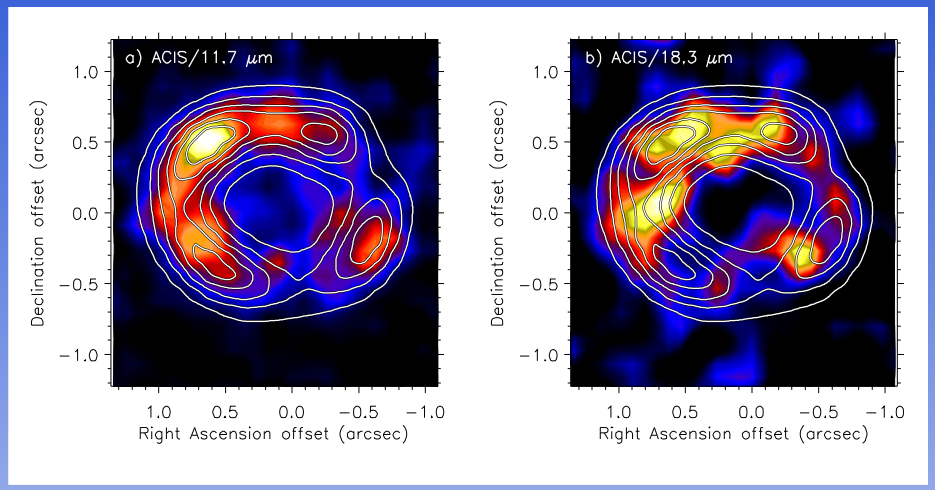


Park et al
Manchester et al

Dust emission

Gemini S + Spitzer

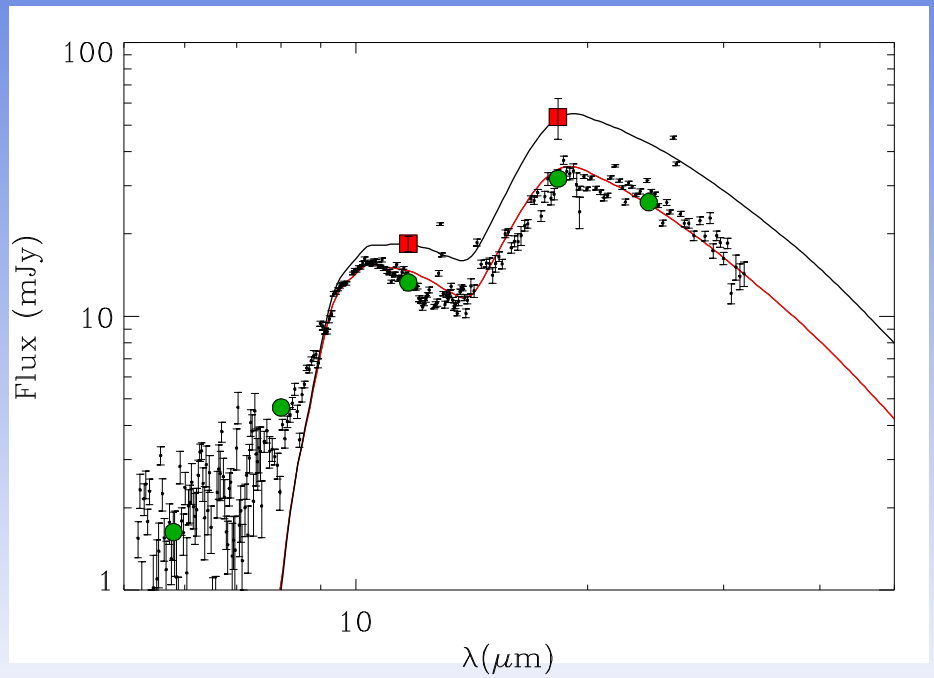
Bouchet et al 2006



11.7 μ

18.3 μ

Spitzer



T ~ 166 K
Si feature
collisionally heated

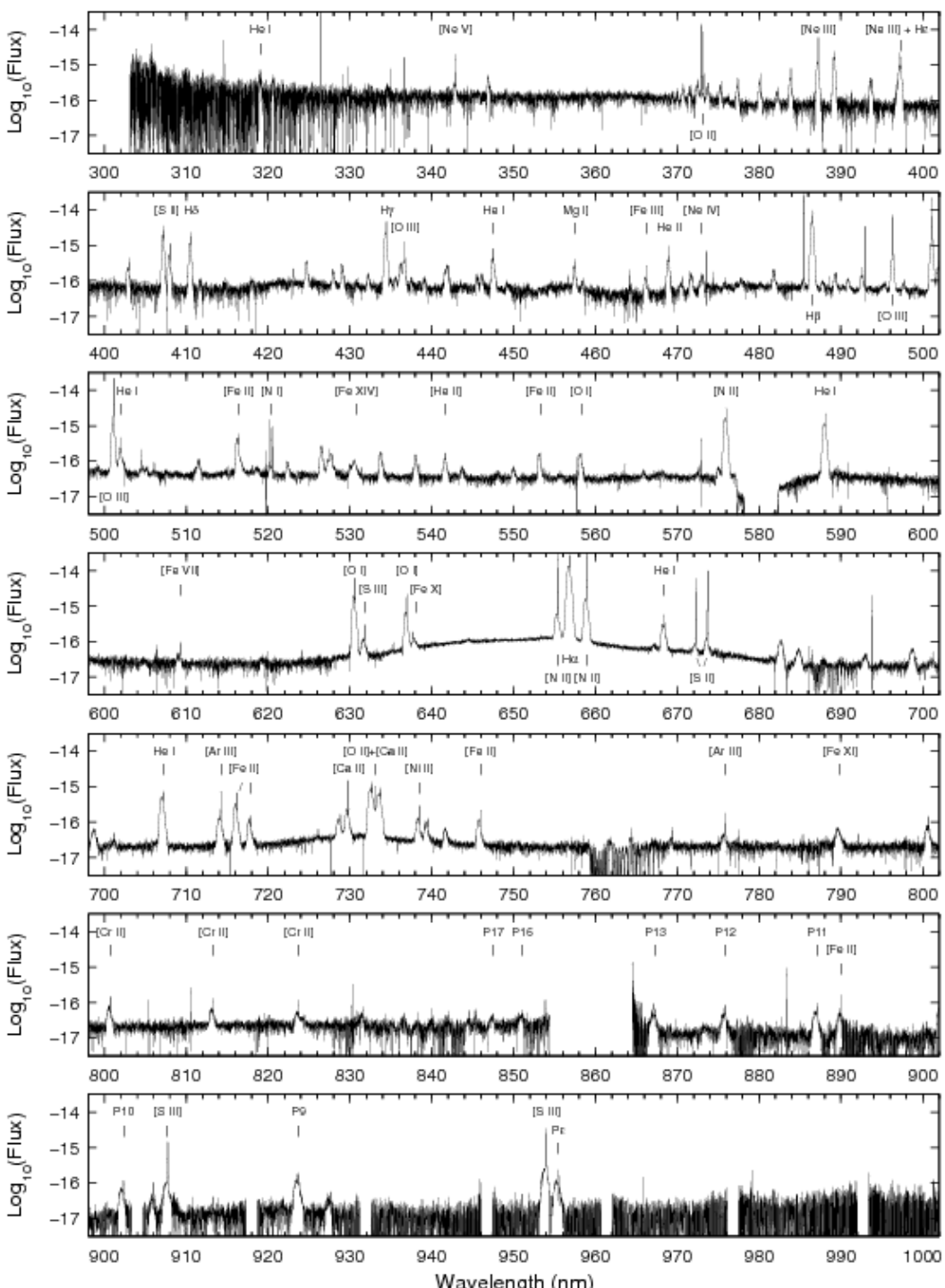
VLT/UVES

FWHM ~ 6 km s^{-1}

Seeing 0.5-0.8"

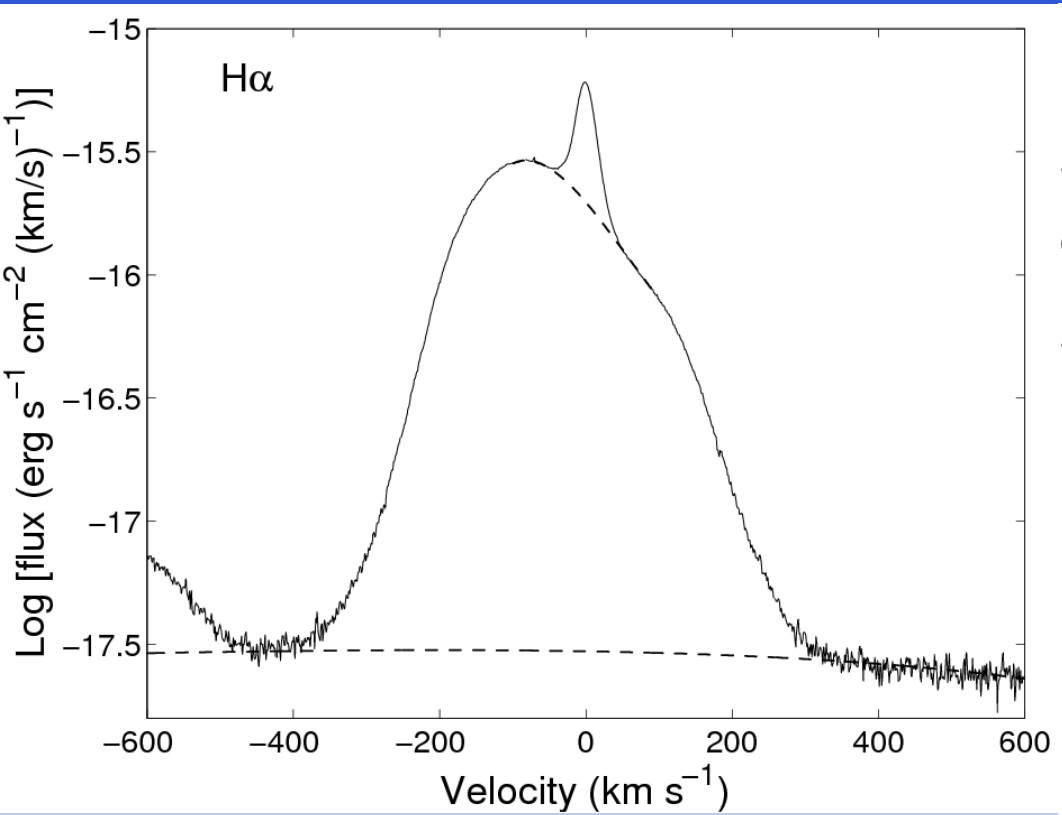
Resolves N/S

Gröningsson et al 2006

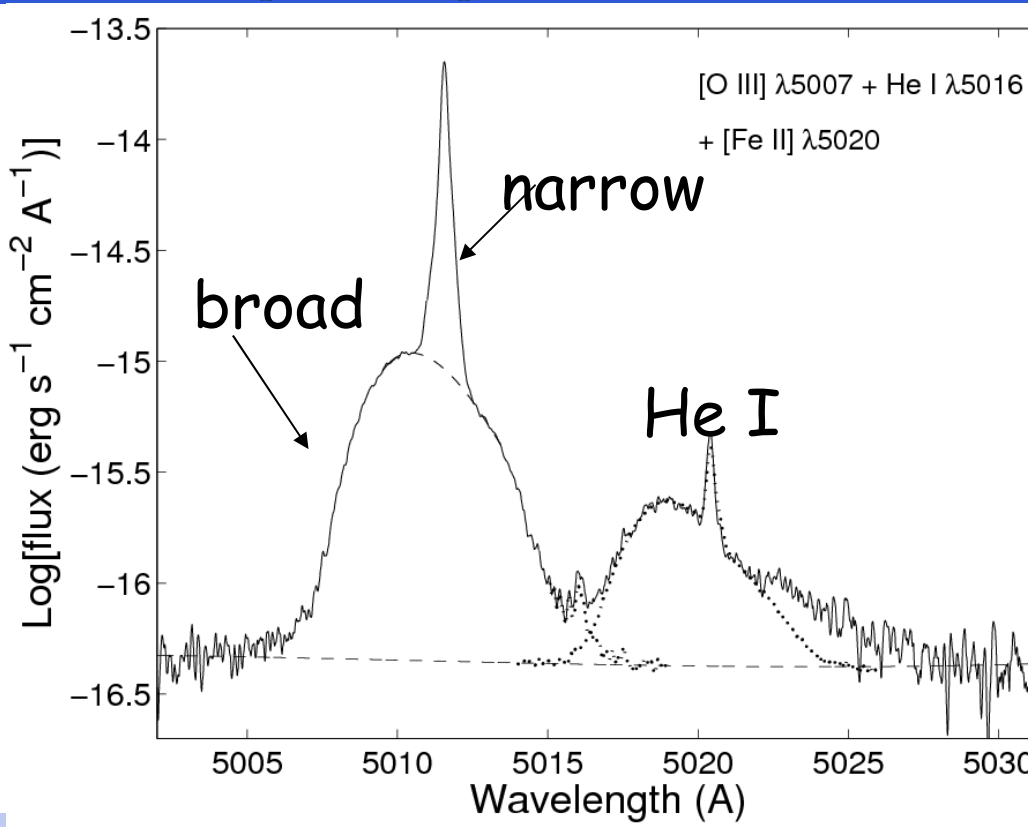


Gröningsson et al 2006

Hα



[O III] 5007

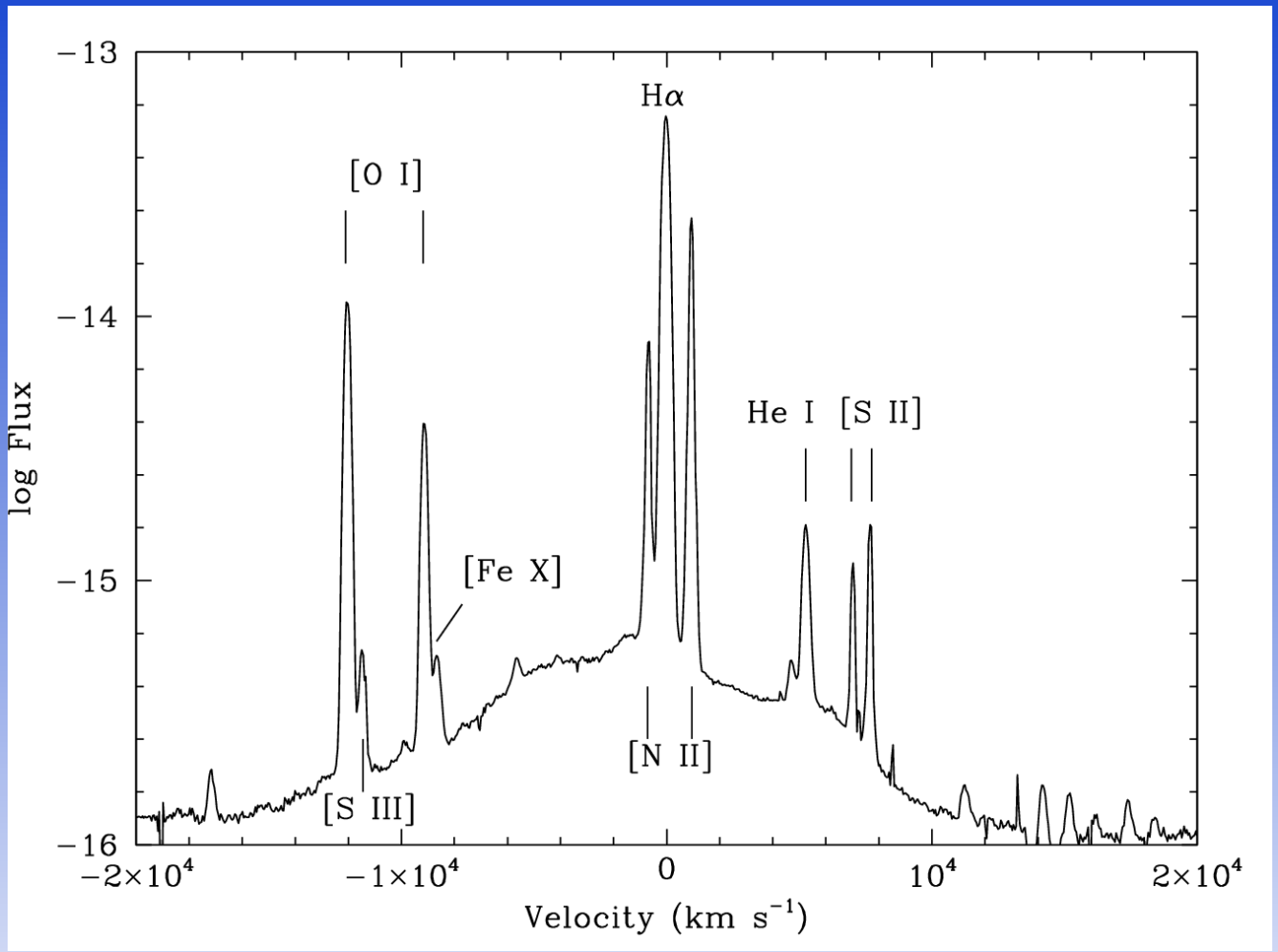


Narrow FWHM ~ 10 km s^{-1} from unshocked ring

Broad V_{max} 300-400 km s^{-1} from shocked ring (Pun et al 2002)

Reverse shock

Gröningsson et al (2006)
Smith et al (2006),
Heng et al (2006)



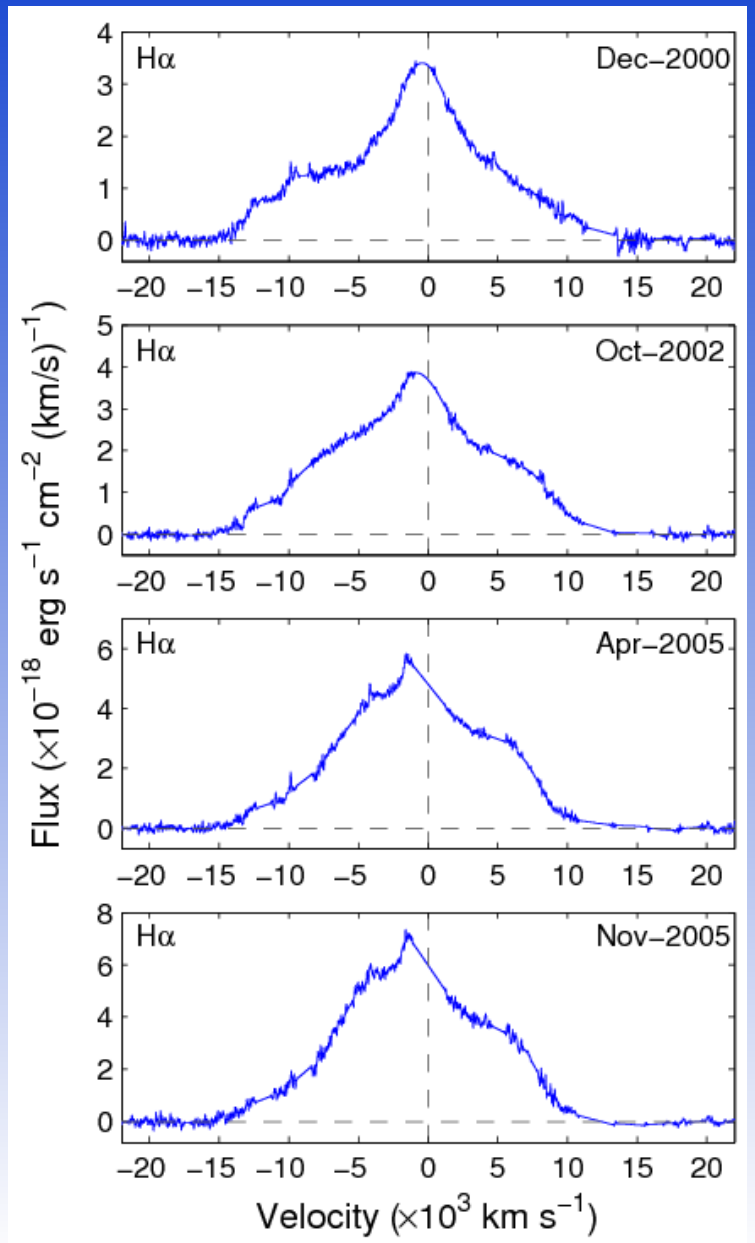
VLT/FORS
Dec 2006

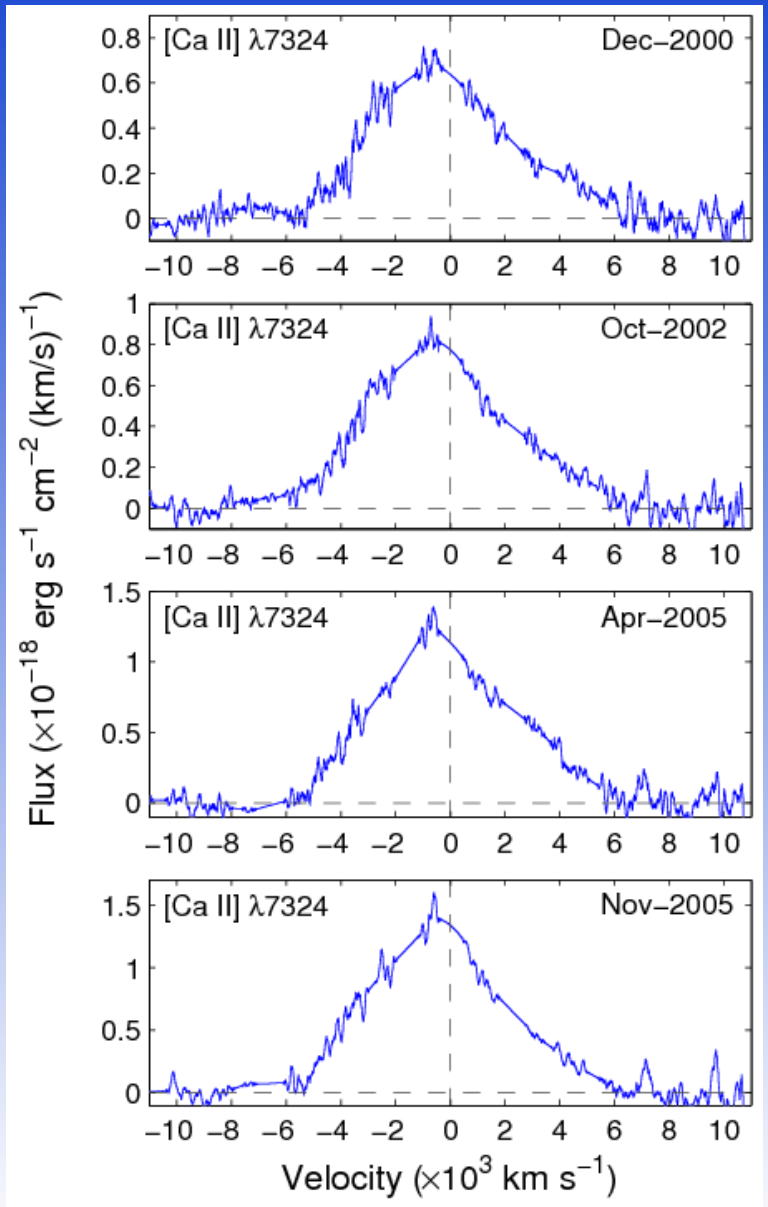
Velocity (10^4 km/s)

Broad ~16,000 km/s emission from reverse shock going back into ejecta

Reverse shock evolution

Hα





Ca II

What is causing the reverse shock emission?

Broad ~16,000 km/s emission from reverse shock going back into ejecta

1. Lyα and Hα from charge exchange of neutral ejecta?
   Probably not (Heng & McCray 2007)

2. X-ray excitation by reverse shock + blobs more likely?

   Recombination time in ejecta long,

   non-thermal excitation, ….

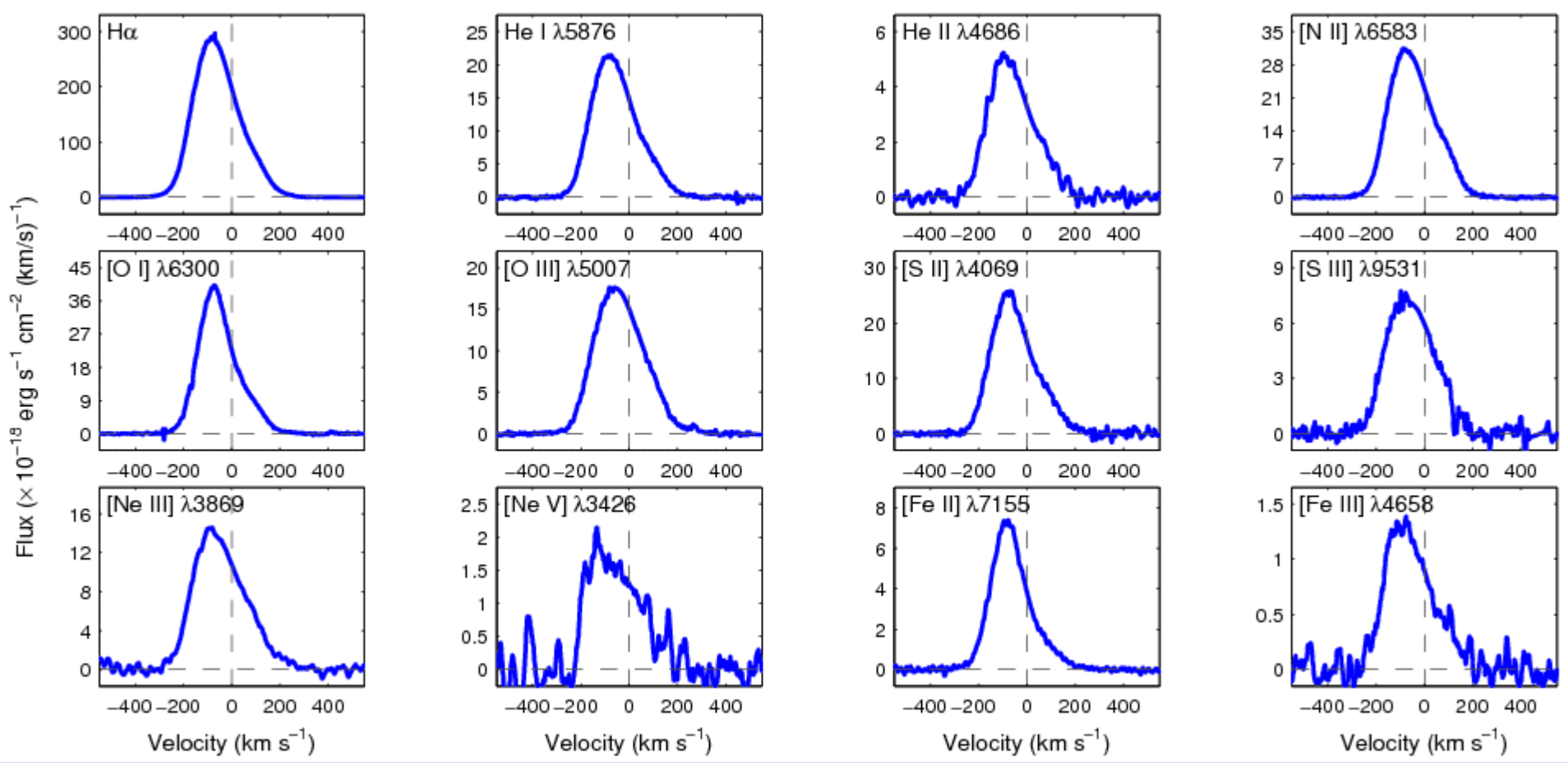
   non-spherical

Similar to freeze-out phase for radioactive excitation and to Type IIb/IIn CS interaction (cf SN 1993J)

3. Cosmic ray excitation?

Intermediate velocity lines from shocked ring protrusions

Oct 2002



N part of ring ~ 'Spot 1'. Peak velocity ~ 120 km s^{-1}.

Max extension ~ 300 km s^{-1}

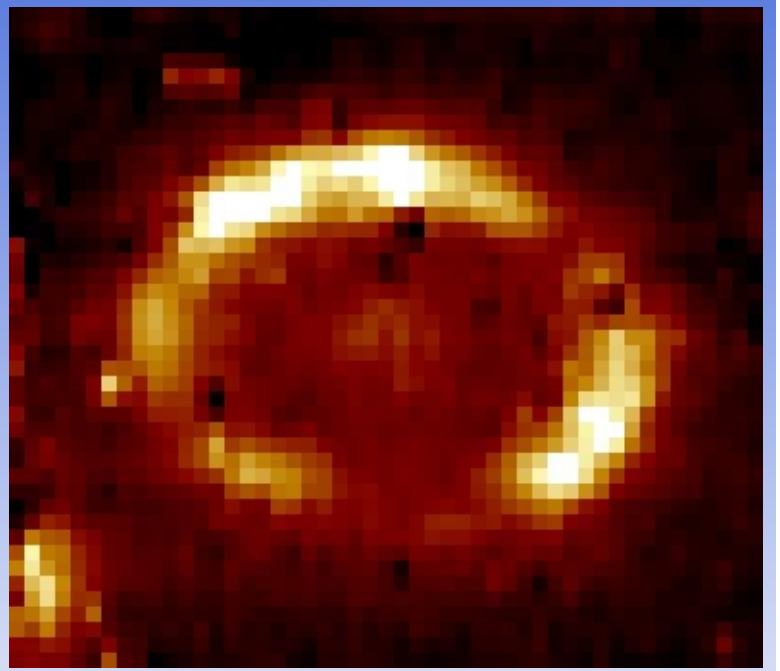
VLT/SINFONI

Adaptive optics integral field unit for J, H, K

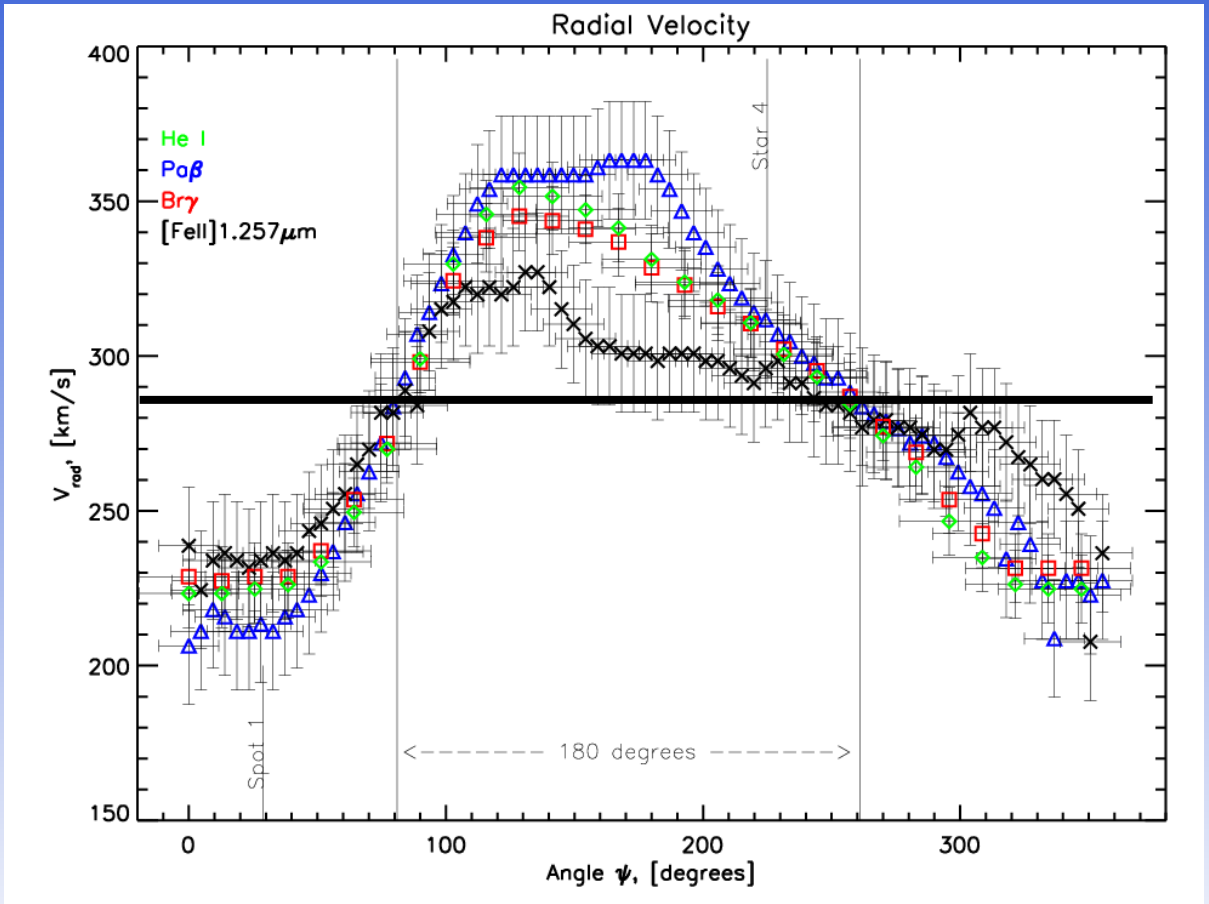
March 2005

He I 2.06 μ

Kjaer et al 2007

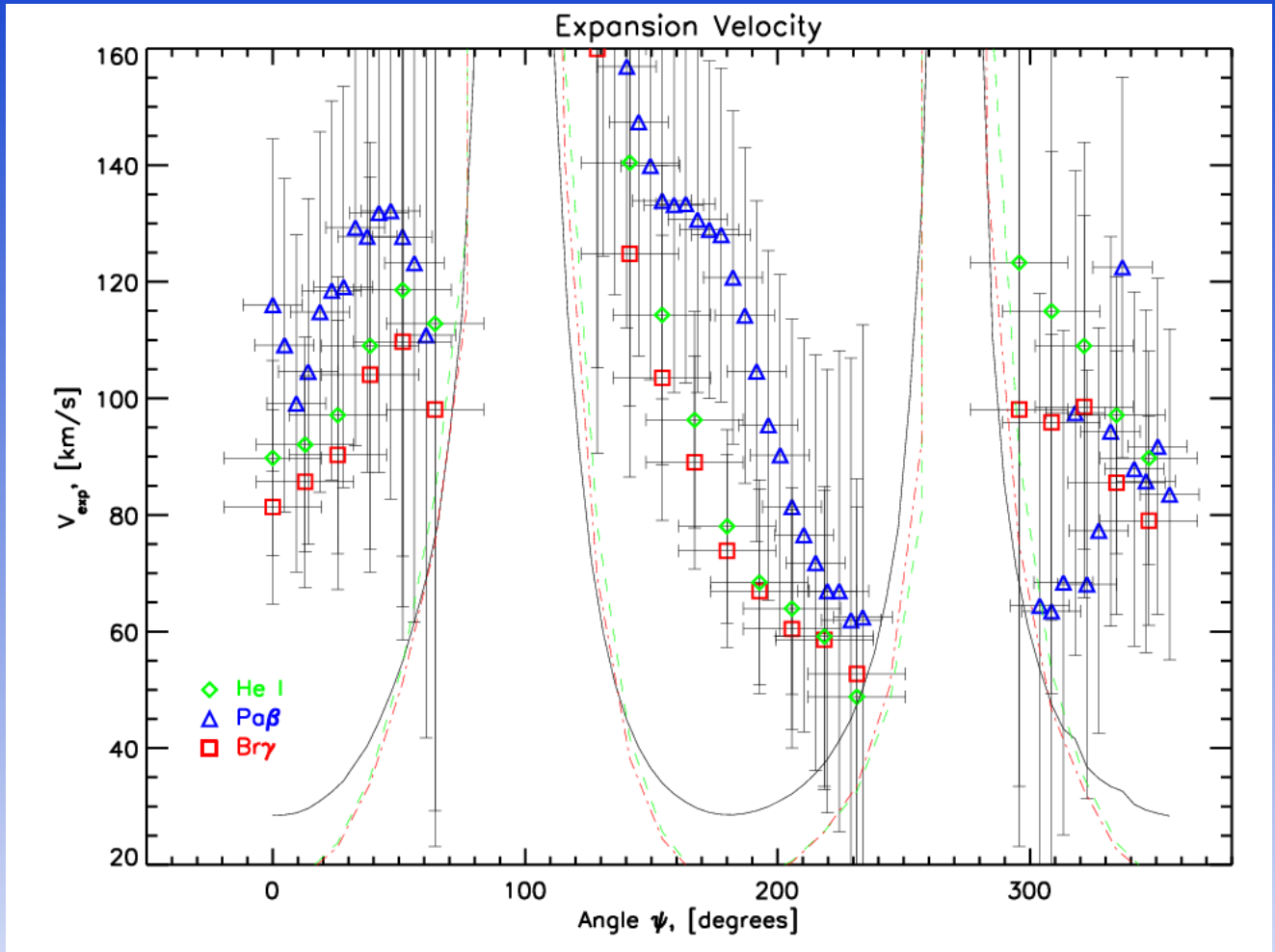


J-band



Expansion velocities along ring

Deprojected velocities



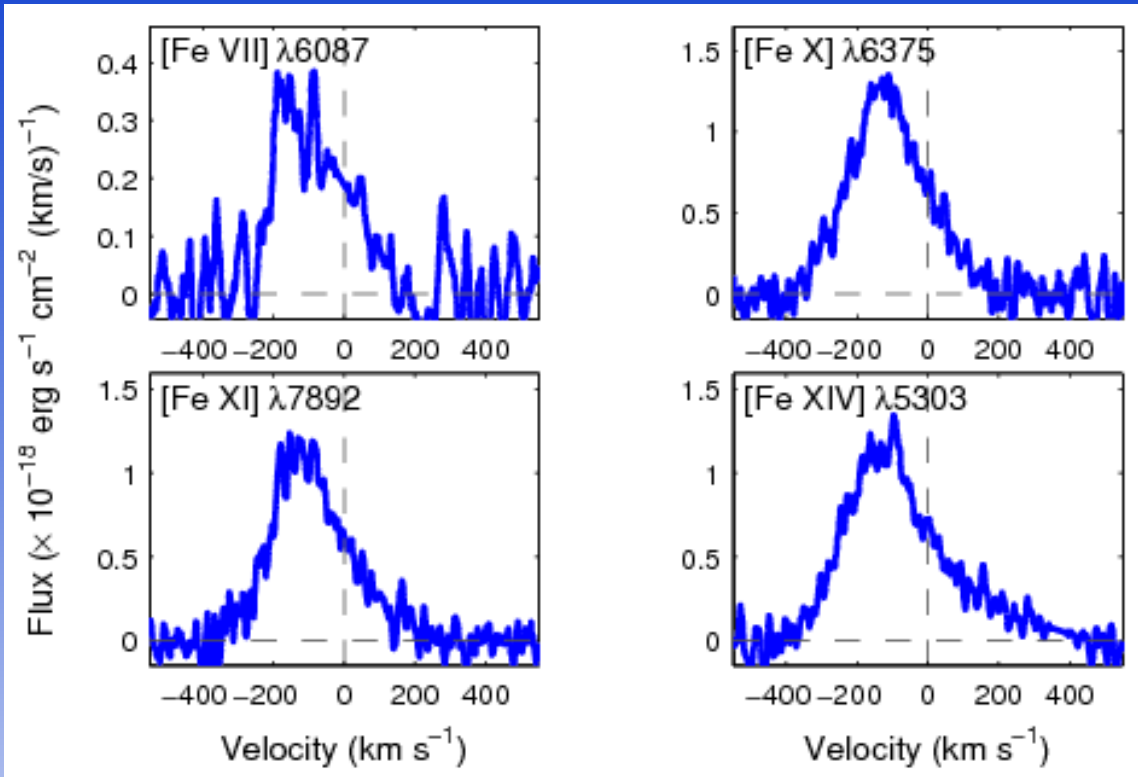
Average velocity over the ring ~ 120 km s^{-1}

UVES gives high and low velocity tails

Coronal lines

Gröningsson et al 2006

VLT/UVES spectrum

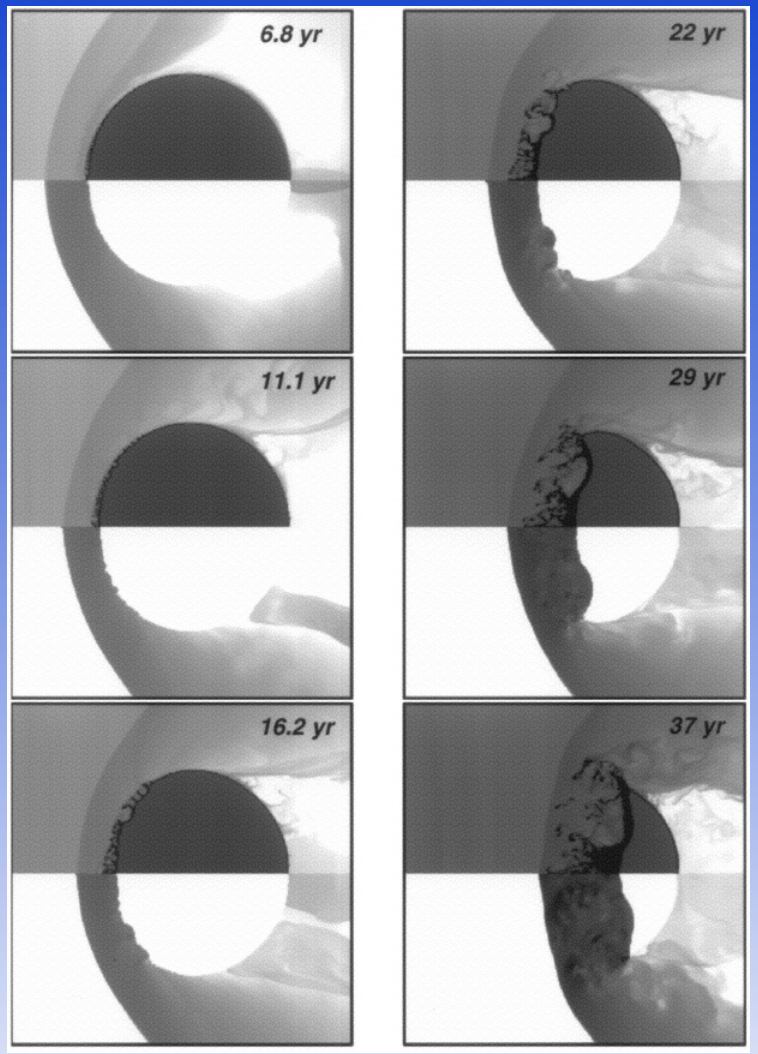


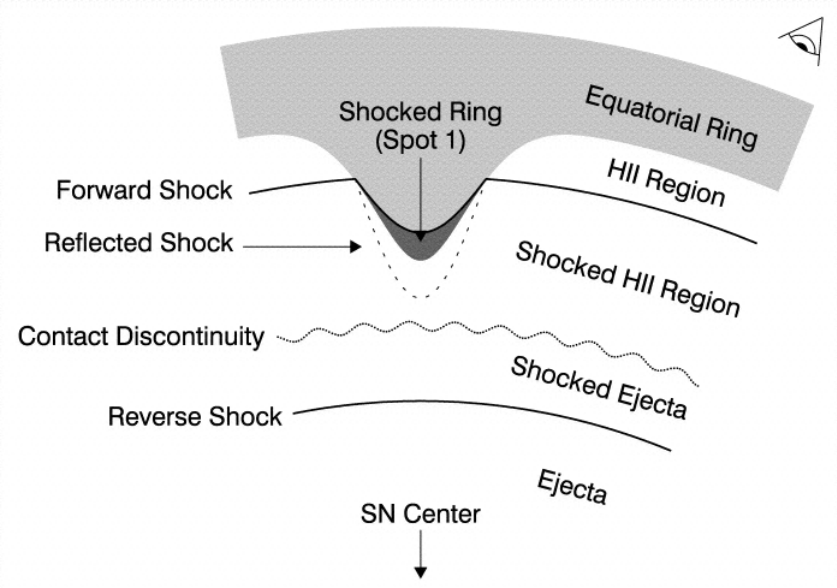
Max. velocity ~ shock velocity ~ 300-400 km/s

Fe XIV λ 5303 $\Rightarrow$ $T_s \sim 2\times10^6$ K

H I, He I, N II, O I-III, Fe II, Ne III-V.....
Cooling, photoionized gas behind radiative shock into ring protrusions

Hydrodynamics of ring collision



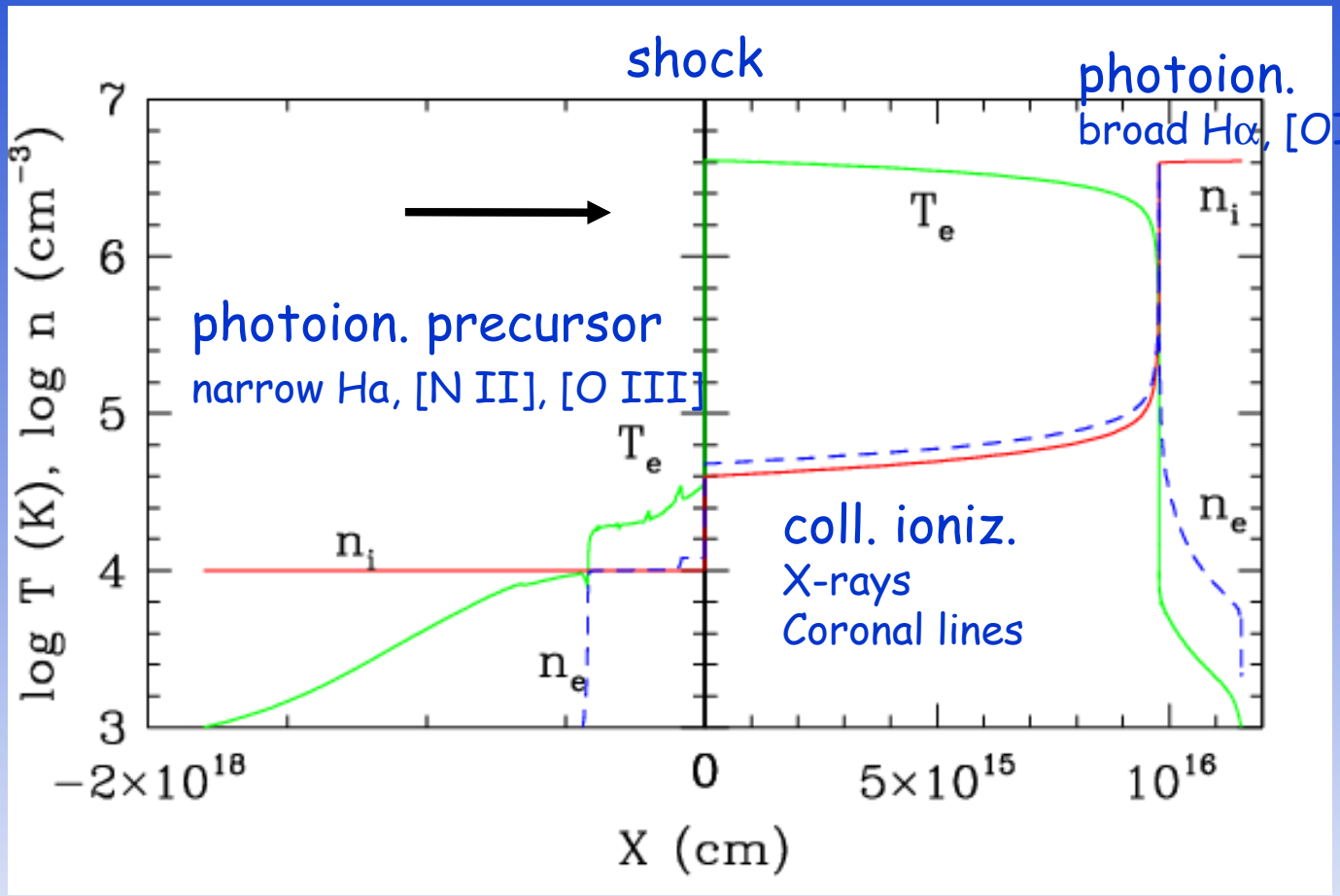


Optical emission from radiative shocks into the ring material
Radio and hard X-rays from reverse shock

Borkowski et al 1997
Pun et al 2002

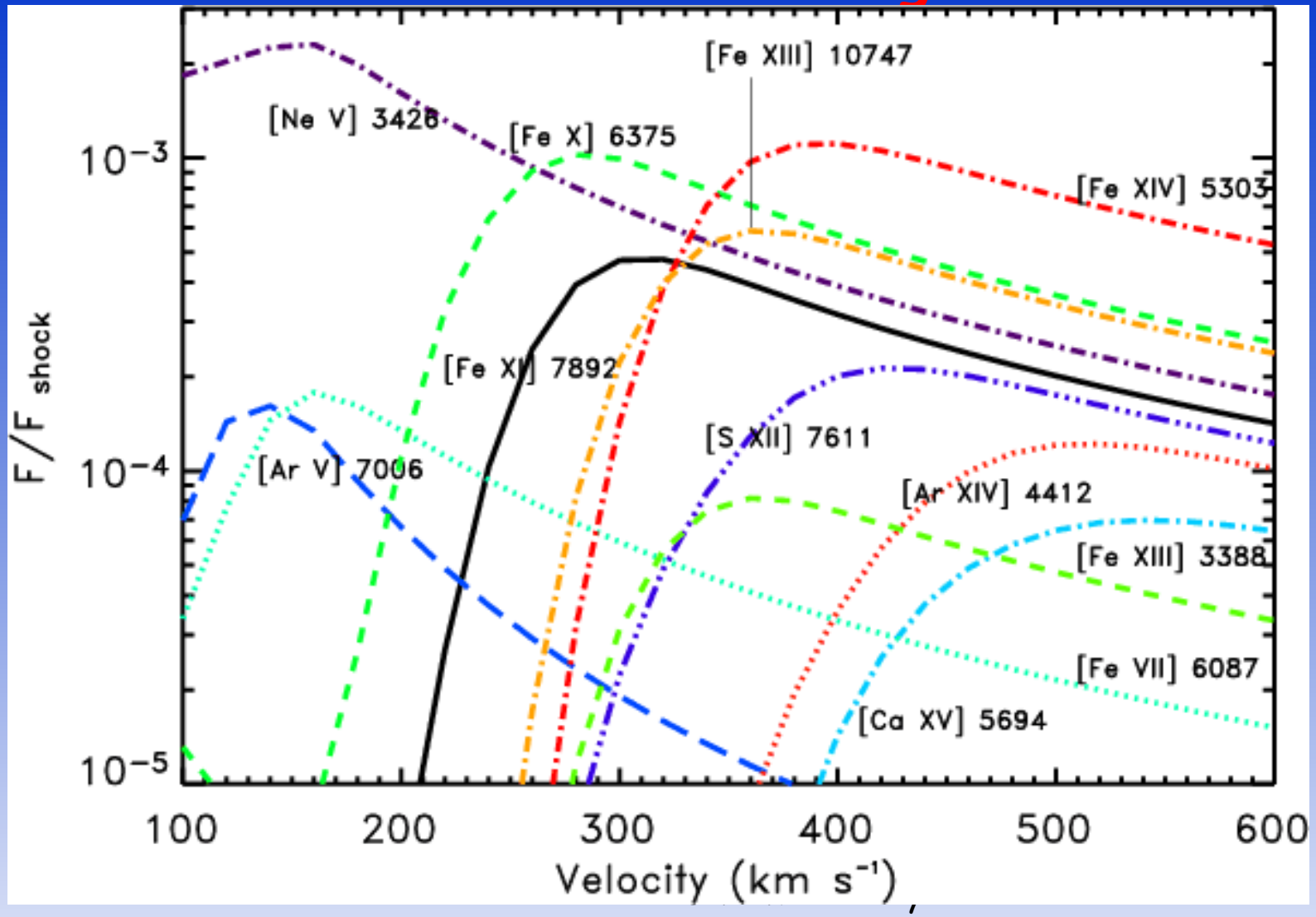
Radiative shock structure

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



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

Coronal line diagnostics

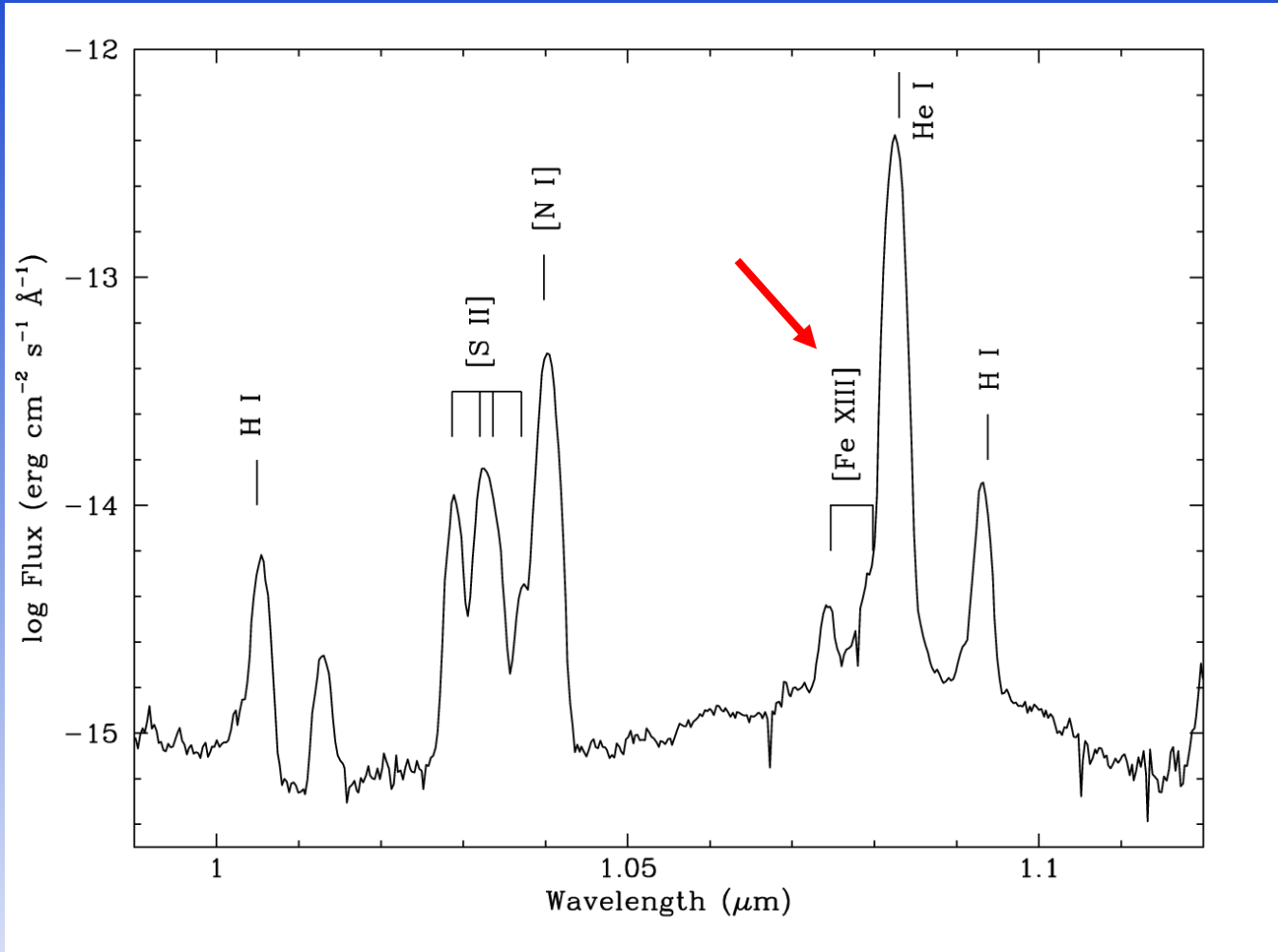


Gröningsson, Nymark…

Shock velocity into hot-spots 300 – 400 km s^{-1} $\Rightarrow T_s \sim 2\times10^6$ K

Coronal lines complement the X-rays to probe whole temp. range

Near-IR



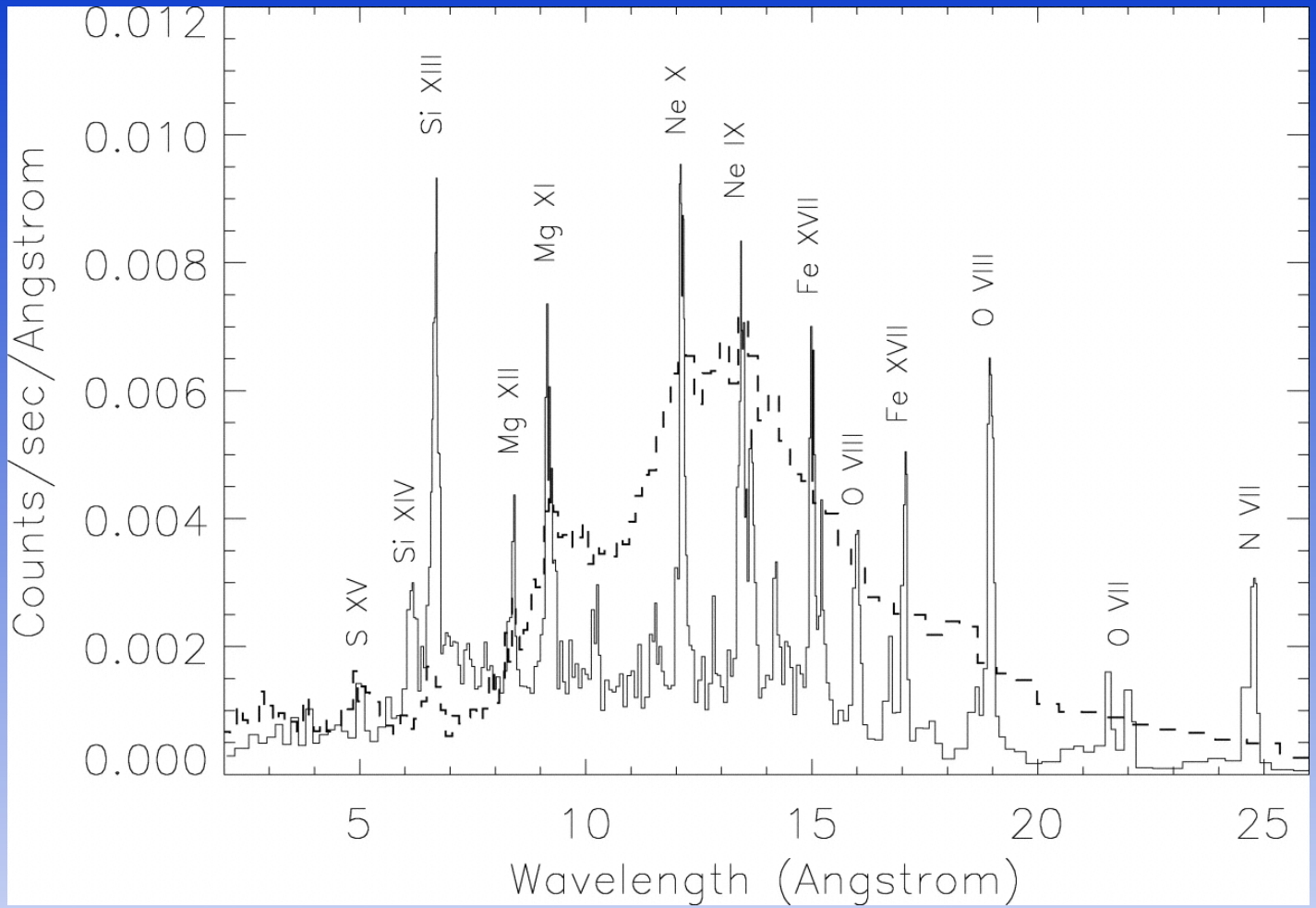
[Fe XIII] 1.0747-1.0798 μ

VLT/ISAAC

X-rays

Chandra: Zhekov et al (2005, 2006)

also XMM by Haberl et al



N VII, O VII-VIII, Ne IX-X, Mg XI-XII, Si XIII, Fe XVII.....

Two components: High density (10^4 cm^{-3}) kT ~ 0.5 keV +
Low density (10^2 cm^{-3}) kT ~ 3.0 keV

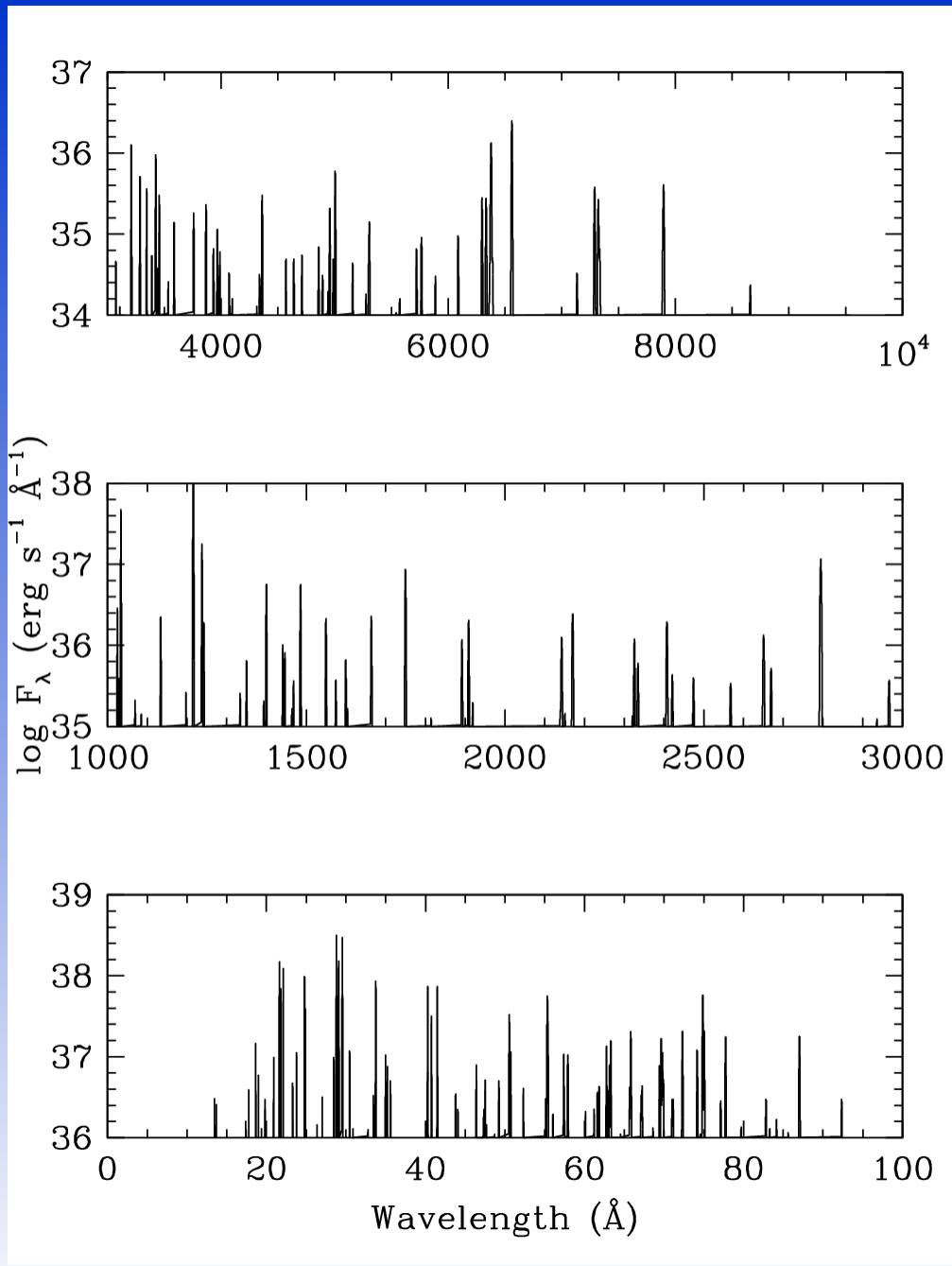
Optical/UV from radiative shocks

Soft X-rays from radiative + adiabatic shocked ring blobs

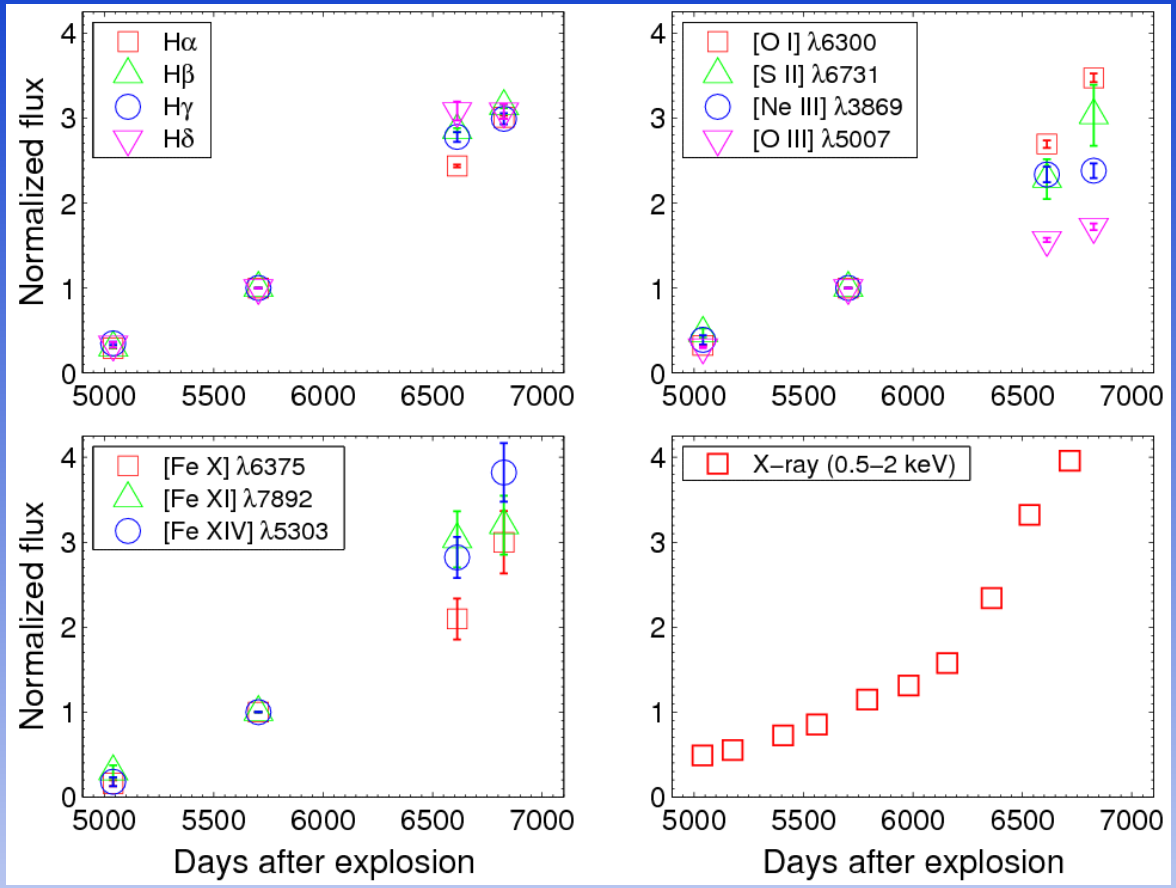
Hard X-rays and radio from adiabatic reverse shock

A radiative shock gives X-rays, UV, optical, IR

Expect correlation between optical/UV and soft X-rays, but not with hard and radio



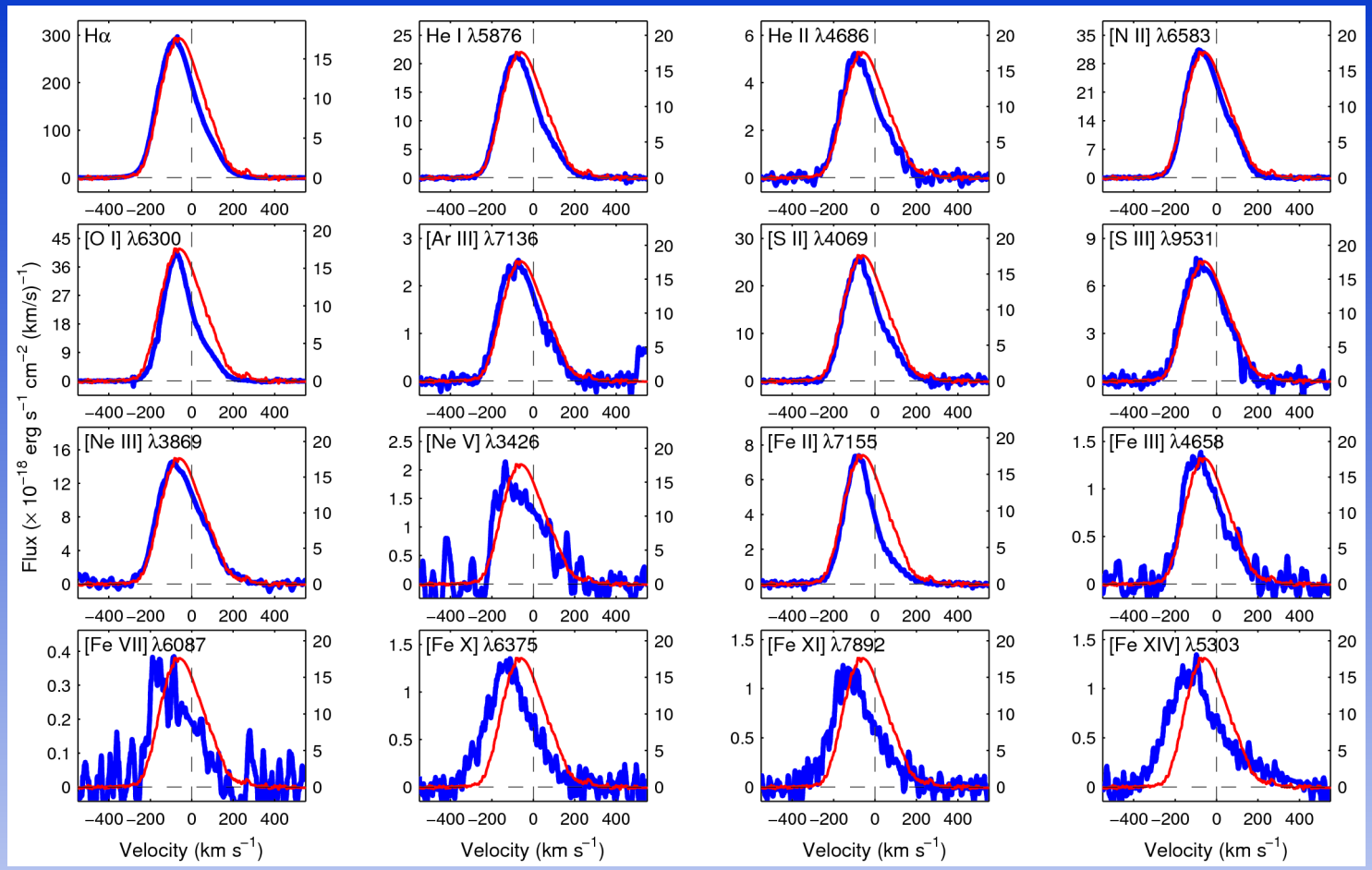
Time evolution



Optical: Gröningsson et al
X-rays: Park et al 2005

Coronal lines and soft X-rays correlate. Soft X-rays from hot-spots. Hard from reverse shock & blast wave

Gröningsson et al 2007



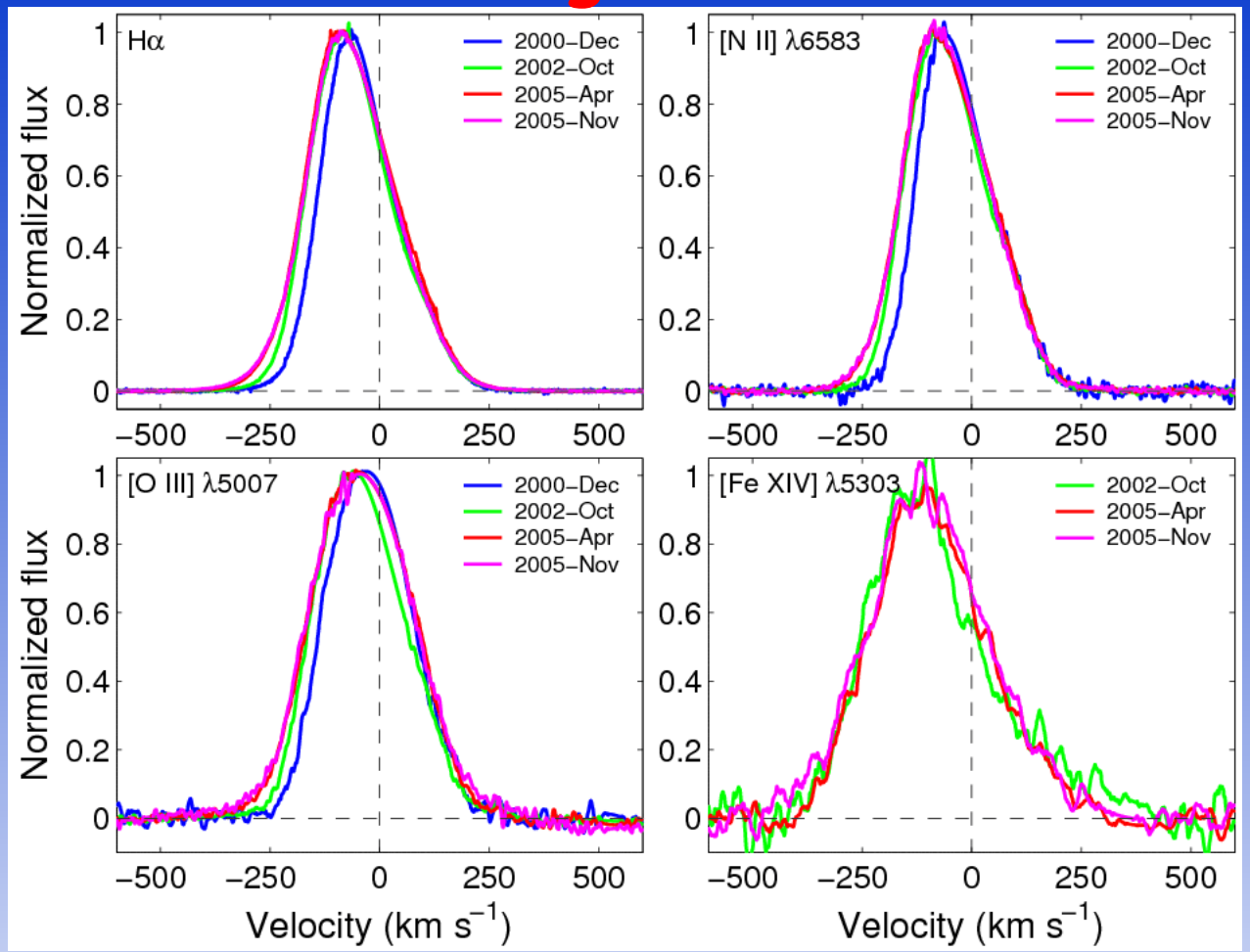
Oct 2002

Low ionization lines (up to [O III]) have V_{max} ~ 250 km s^{-1}

Coronal lines V_{max} ~ 400 km s^{-1}

Highest vel. shocks may have been adiabatic in 2002

Cooling shocks



Line widths of low ionization ions increase with time

2000: ~ 250 km s^{-1} -> 2006: ~ 450 km s^{-1} .

Coronal lines ~ constant ~ 450 km s^{-1}

Cooling shocks

$$t_{cool} \approx 8 \left(\frac{V_s}{300\ km\ s^{-1}} \right)^{3.4} \left(\frac{n_e}{10^4\ cm^{-3}} \right)^{-1} \text{yrs}$$

High velocity shocks seen in soft X-rays gradually become radiative

Now, Hα up to ~ 450 km s^{-1} $\Rightarrow$

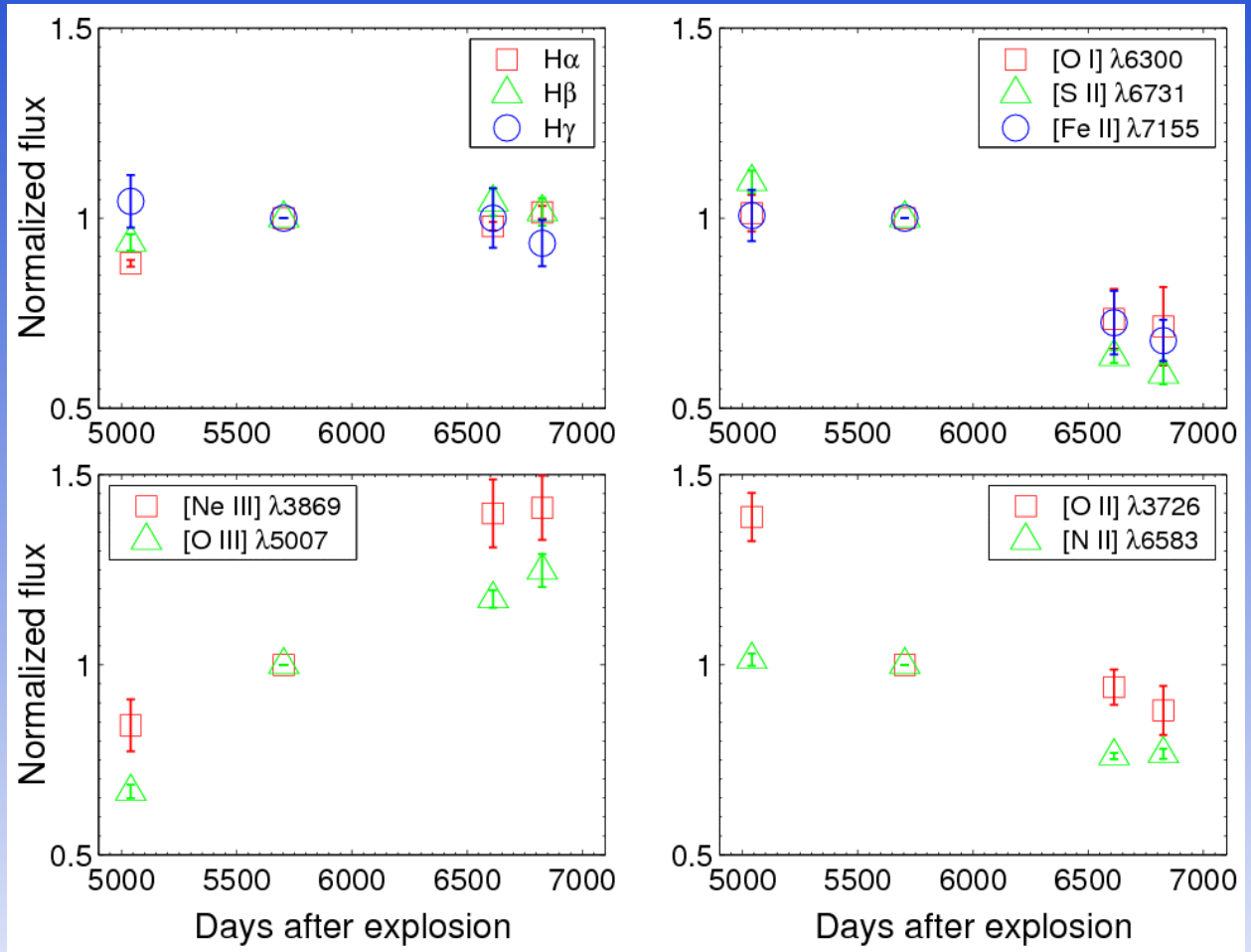
n_e up to ~ 4×10^4 cm^{-3} ~ ring density (Lundqvist & CF 96)

Expect this to continue to higher shock velocities

Narrow, unshocked lines

Unshocked ring ionized by SN shock breakout, then recombining
Ring is now ionized by X-rays from shocks. Come-back of narrow lines

Pre-ionized region
~ 5×10^{17} $(n/10^4\ cm^{-3})^{-1}$ cm



Shock models:
Most of absorbed X-rays in pre-shock gas are re-emitted as [O III]

We are now starting to see the re-ionization of the ring!

Conclusions

- SN 1987A excellent case of CSI, with both thermal and non-thermal processes.

- Line profiles probe shock distribution + dynamics
- UV/optical/IR from radiative shocks
- Strong correlation between increase in optical and soft X-rays
- Coronal lines complement soft X-rays as shock diagnostics
- Higher velocity shocks gradually cooling. Now up to ~ 450 km s^{-1}
- Unshocked CSM is now becoming ionized.

  Bright future!