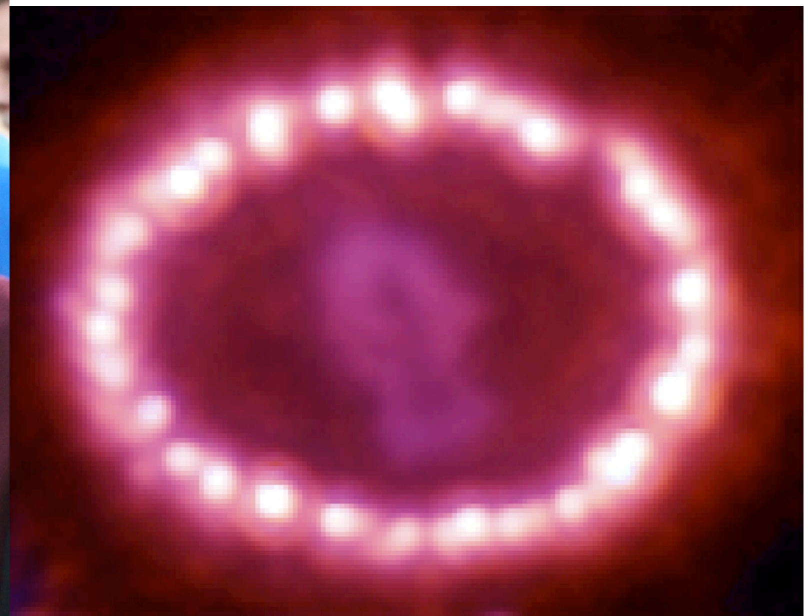
SN 1987A:
From Supernova to Supernova Remnant

Claes Fransson
Stockholm University





Plan

Ejecta structure

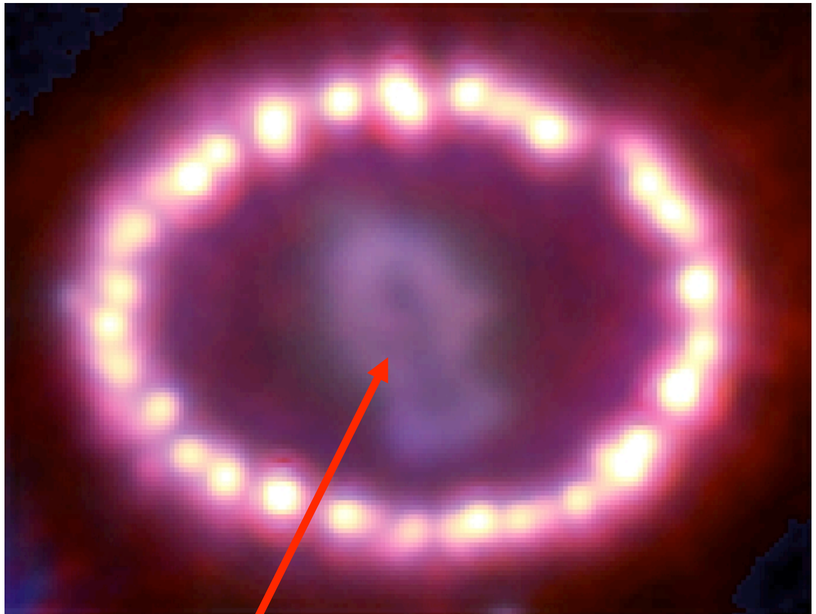
Nucleosynthesis

Ring collision

Compact object?

Collaborators: **A. Jerkstrand**, **P. Gröningsson**, P. Lundqvist, (SU)
B. Leibundgut, J. Spyromilio (ESO), **K. Kjaer**(Belfast)
SAINTS/SINS team: **R. Kirshner**, **P. Challis**,
R. Chevalier, D.McCray, K. Heng, N. Suntzeff,
A Filippenko, C. Wheeler……

Ejecta structure



SN ejecta

Now powered by ^{44}Ti

+ hard X-rays (?)

HST/SAINTS collab.

see also Wang et al 2001

Ejecta kinematics

VLT/SINFONI AO/IFU

K. Kjaer et al 2009

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

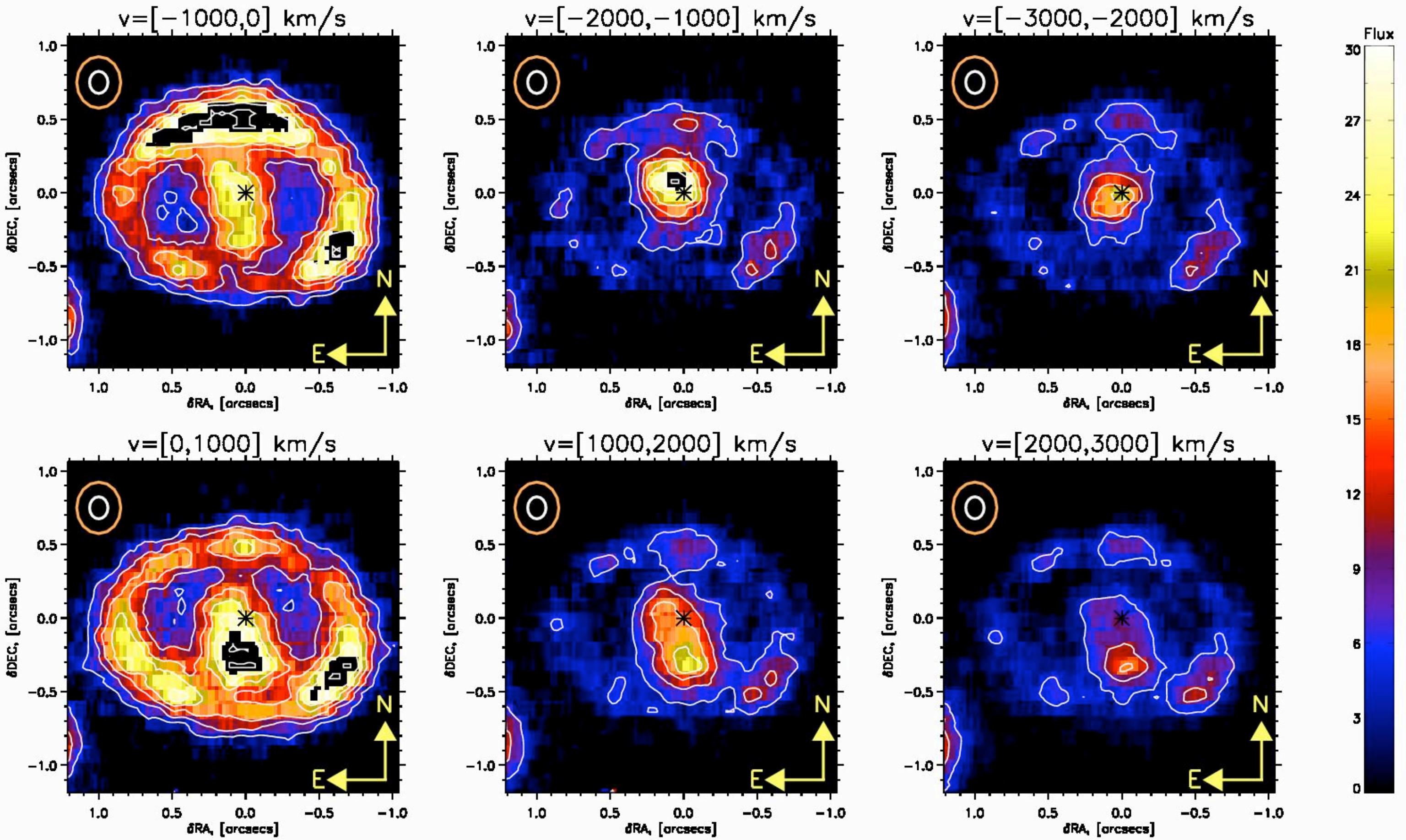
Si I/Fe II

1.64 μ

N blue shifted

S red

(same as ring)

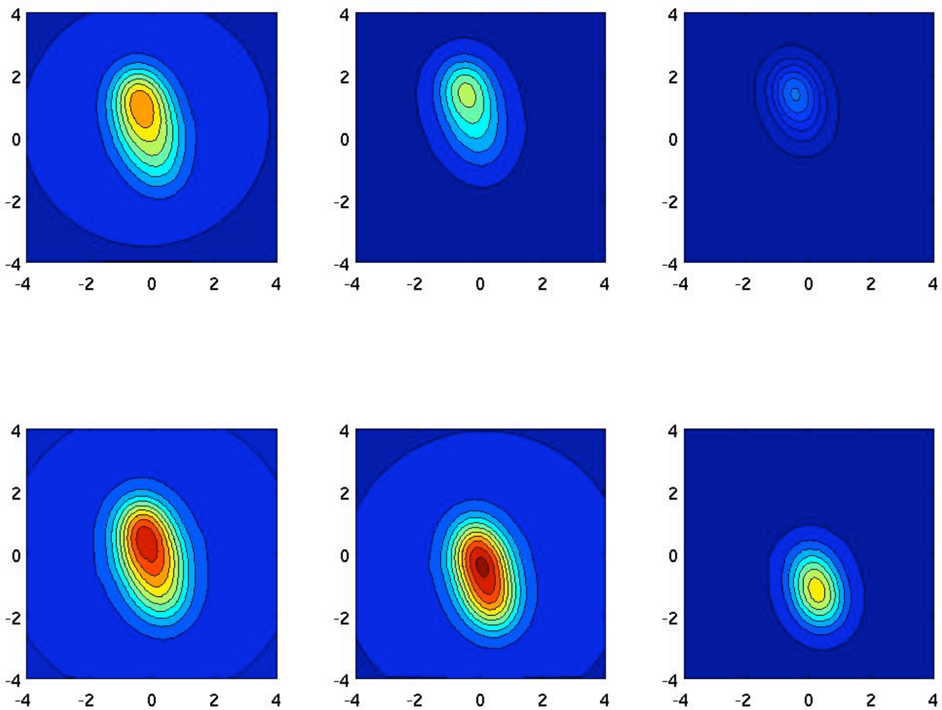


0 - 1000   1000 - 2000   2000 - 3000 km/s

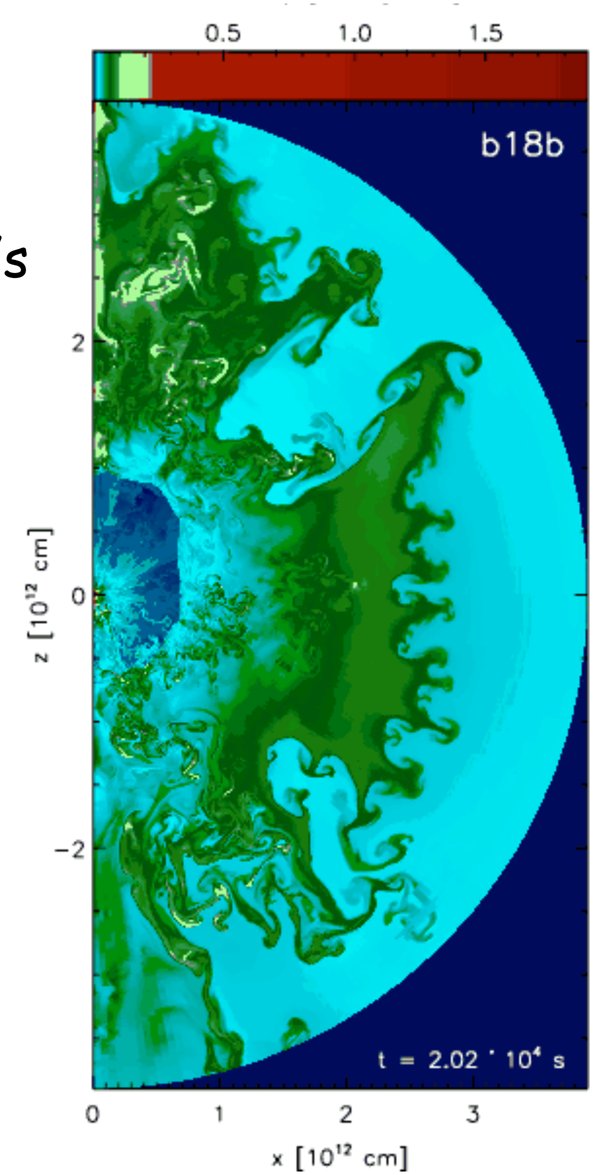
Ejecta asymmetry

Model

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



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

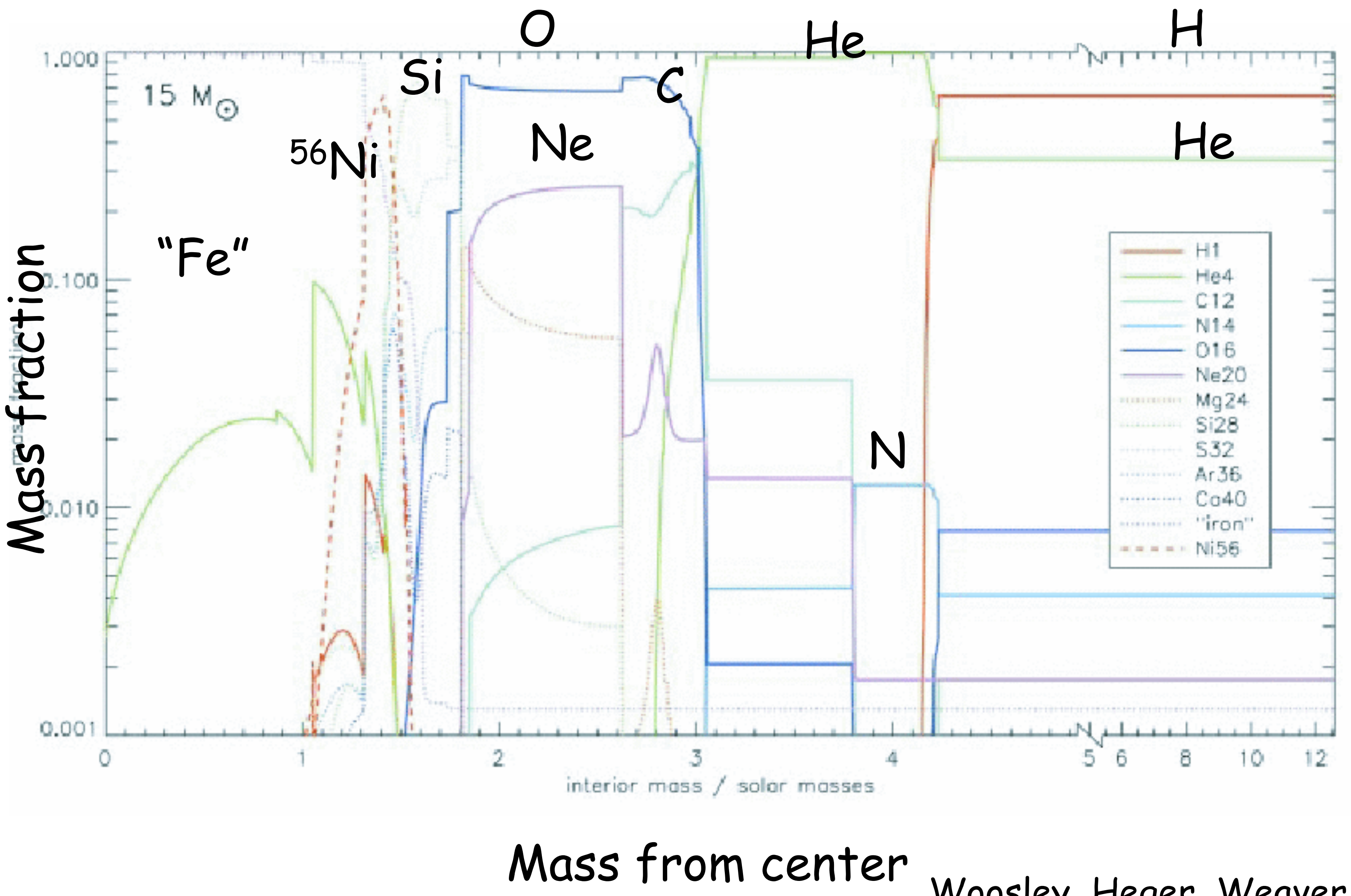


Ellipsoid with axis ratios 1.5 : 2 : 3

Not jet along ring axis! SASI?

Kifonidis et al 2006

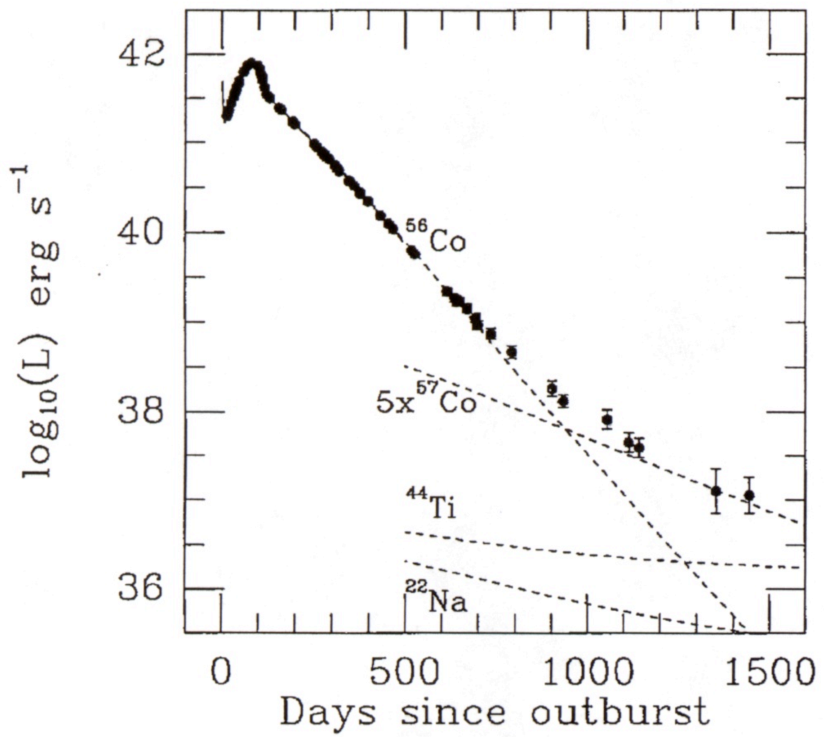
Nucleosynthesis



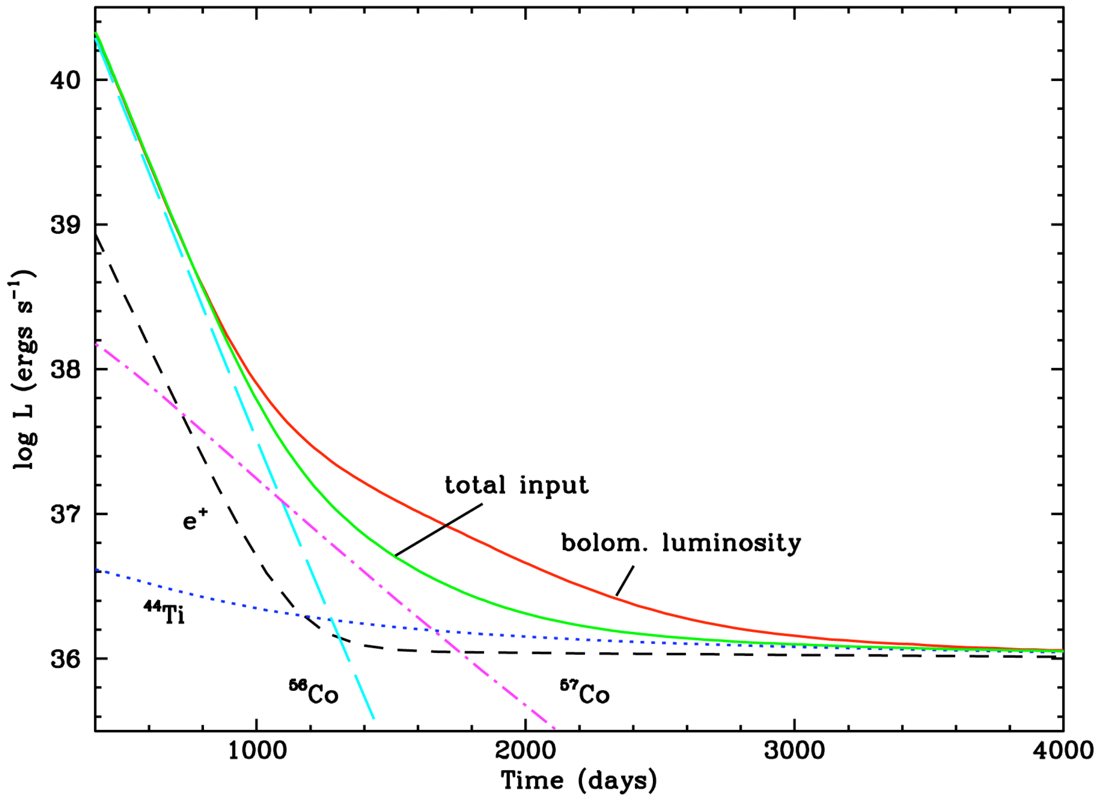
Woosley, Heger, Weaver 2002

Late light curve

C. Kozma + CF



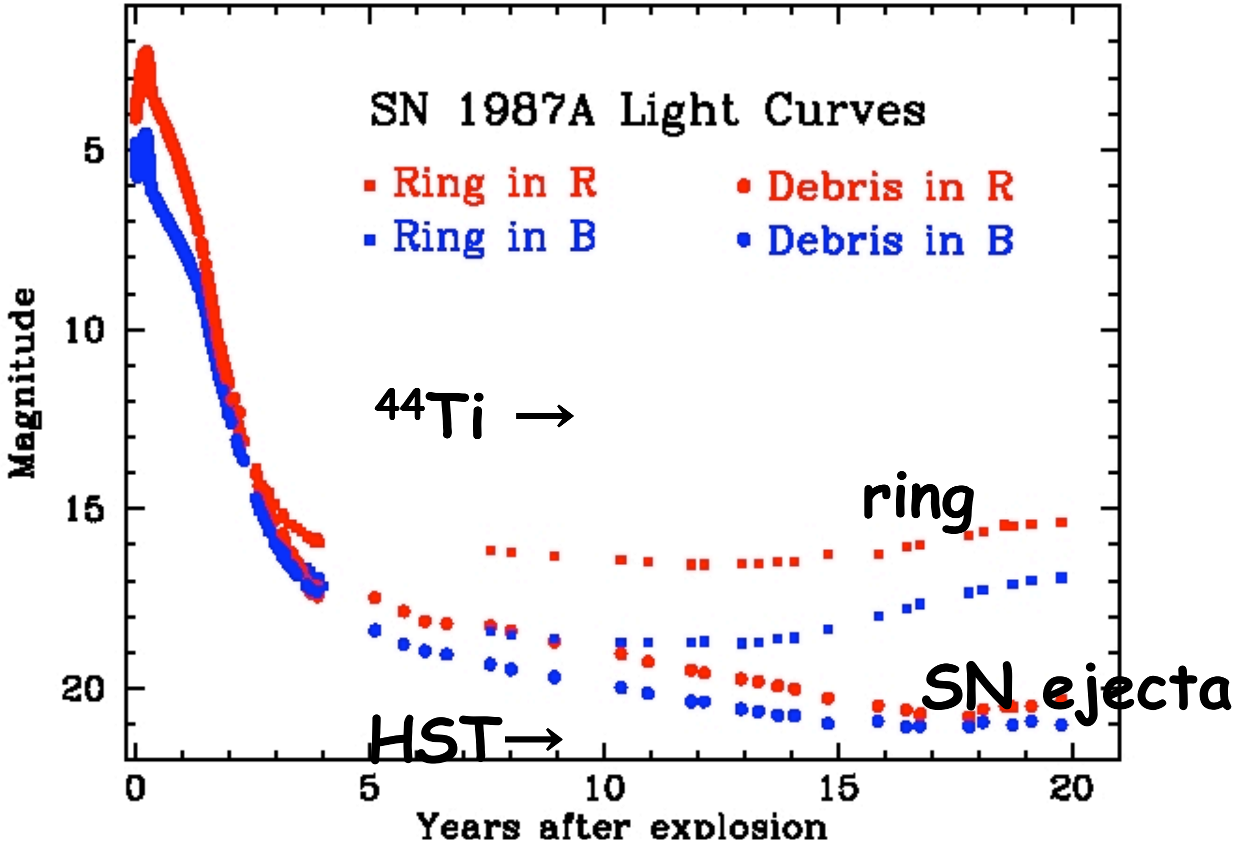
Suntzeff et al 1991



$$M(^{56}Ni) = 0.07\ M_O\ ,\ M(^{57}Ni) = 3\times10^{-3}\ M_{O,}$$

^{44}Ti epoch

SAINTS/Suntzeff, Challis...



Ejecta cold (fewx100 K) + dust ⇒ Most emission in mid- & far-IR

Modeling of spectrum

A. Jerkstrand,
C. Kozma, CF

Input

Gamma-ray & positron thermalization (Boltzmann eqn.)

NLTE treatment of all abundant elements

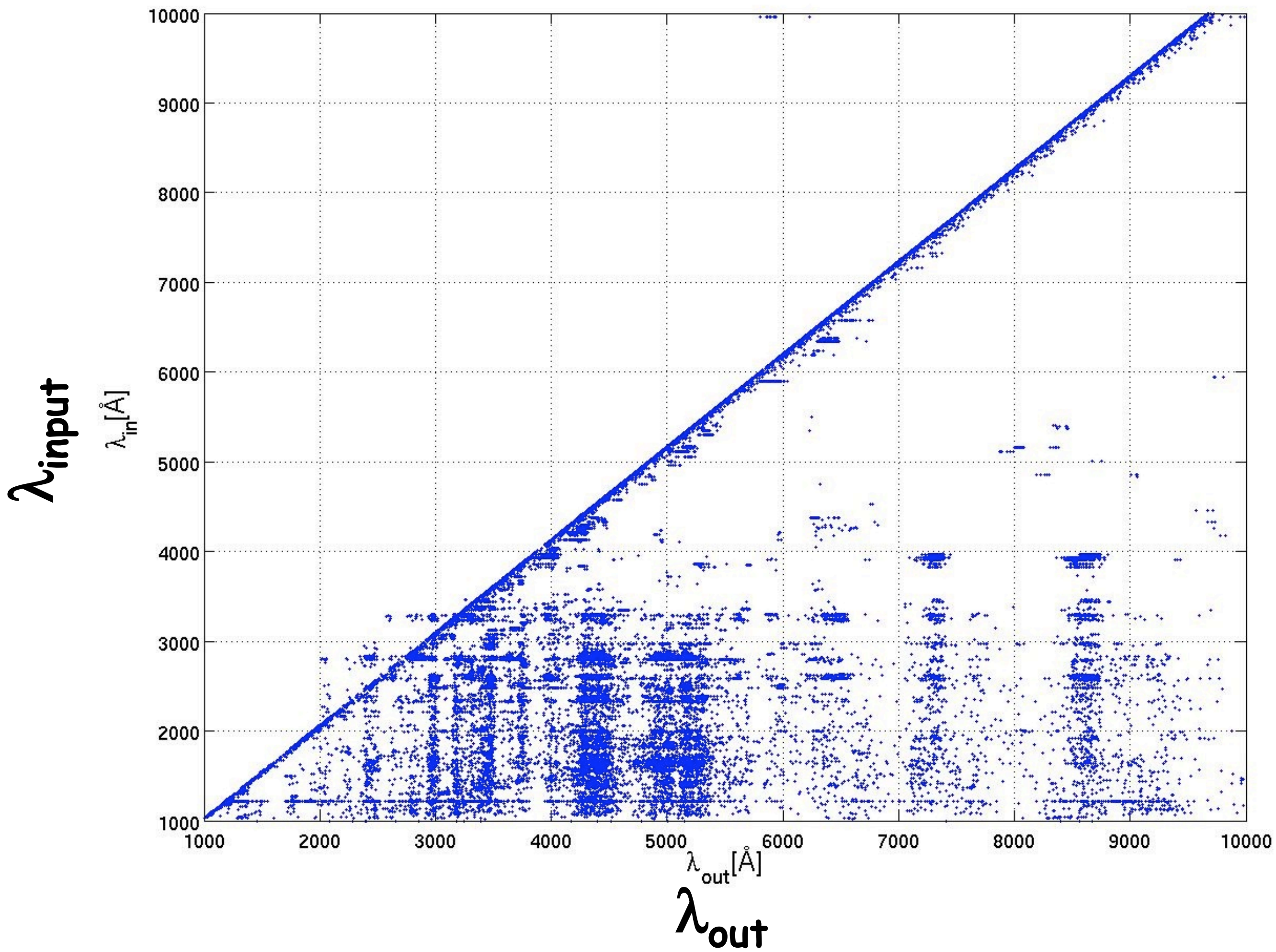
Time dependent effects (freeze out) included

Monte Carlo radiative transfer (Lucy)

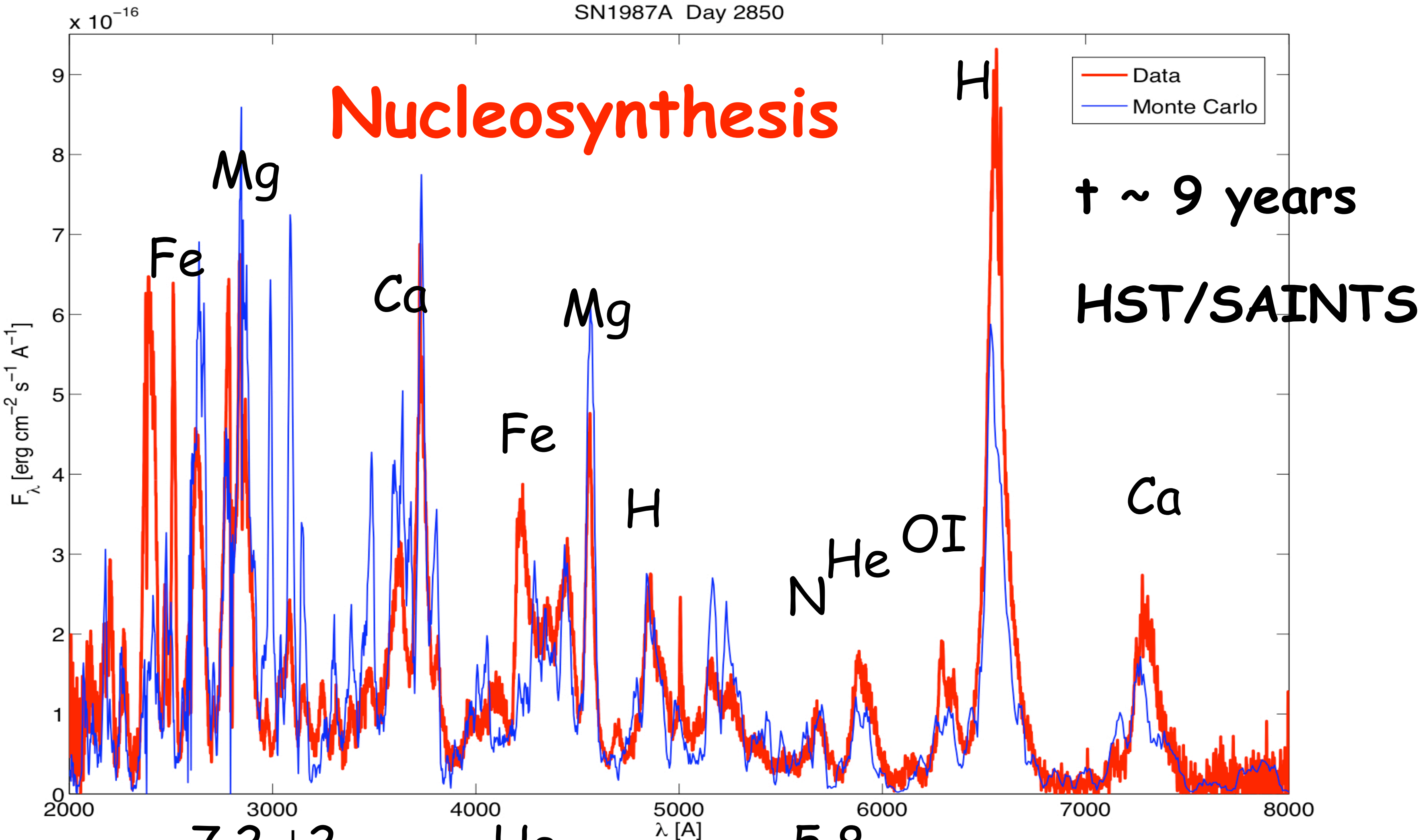
Dust absorption

Macroscopic mixing of the different zones

Resonance scattering & fluoresence important even at several years
Redistribution of UV to optical lines



Nucleosynthesis



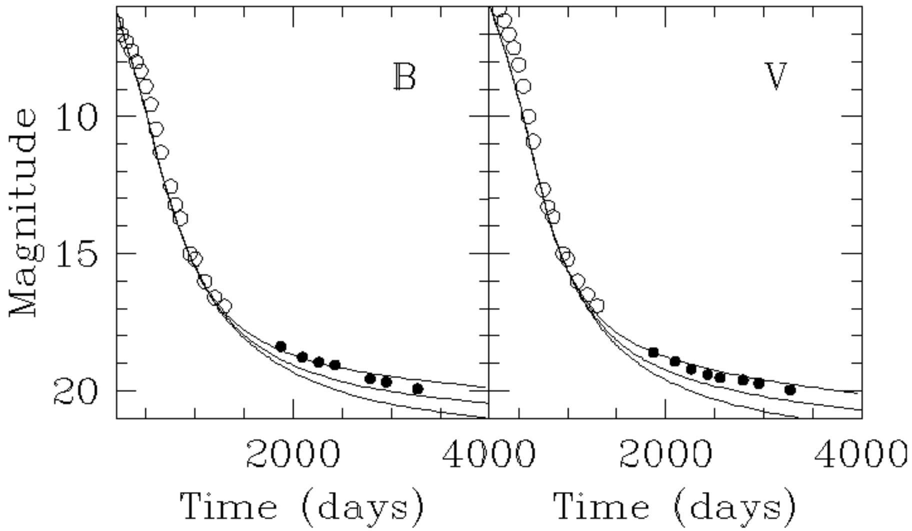
H	7.2 ±2	He	5.8
N	3.4×10^{-2}	O	1.9 ±1
Ne	6.0×10^{-2}	Mg	2.2×10^{-2}
^{44}Ti ($\Rightarrow ^{44}Ca$)	$(1\text{-}2) \times 10^{-4}$	^{56}Ni($\Rightarrow ^{56}Fe$)	0.07
^{57}Ni ($\Rightarrow ^{57}Fe$)	$3 \mathrm{X} 10^{-3}$	$^{58}Ni + ^{60}Ni$	6.0×10^{-3}

$M_{initial} \sim 20\ M_{O}$

A. Jerkstand, C. Kozma + CF 2009

Photometry

Jerkstrand, Kozma + CF



, $M(^{44}Ti) = (1\text{-}2) \times 10^{-4}\ M_{O}$

Probes the explosion during first seconds

^{44}Ti mass may need asymmetric explosion

Good general agreement with 20 M model

O mass 2.0 +/- 0.5 M_O

Freeze out effects dominates H lines

Metal lines in steady state

^{44}Ti mass (1-2)x10^{-4} M_O (probably 1x10^{-4})

^{44}Ti positrons dominate energy input to ejecta

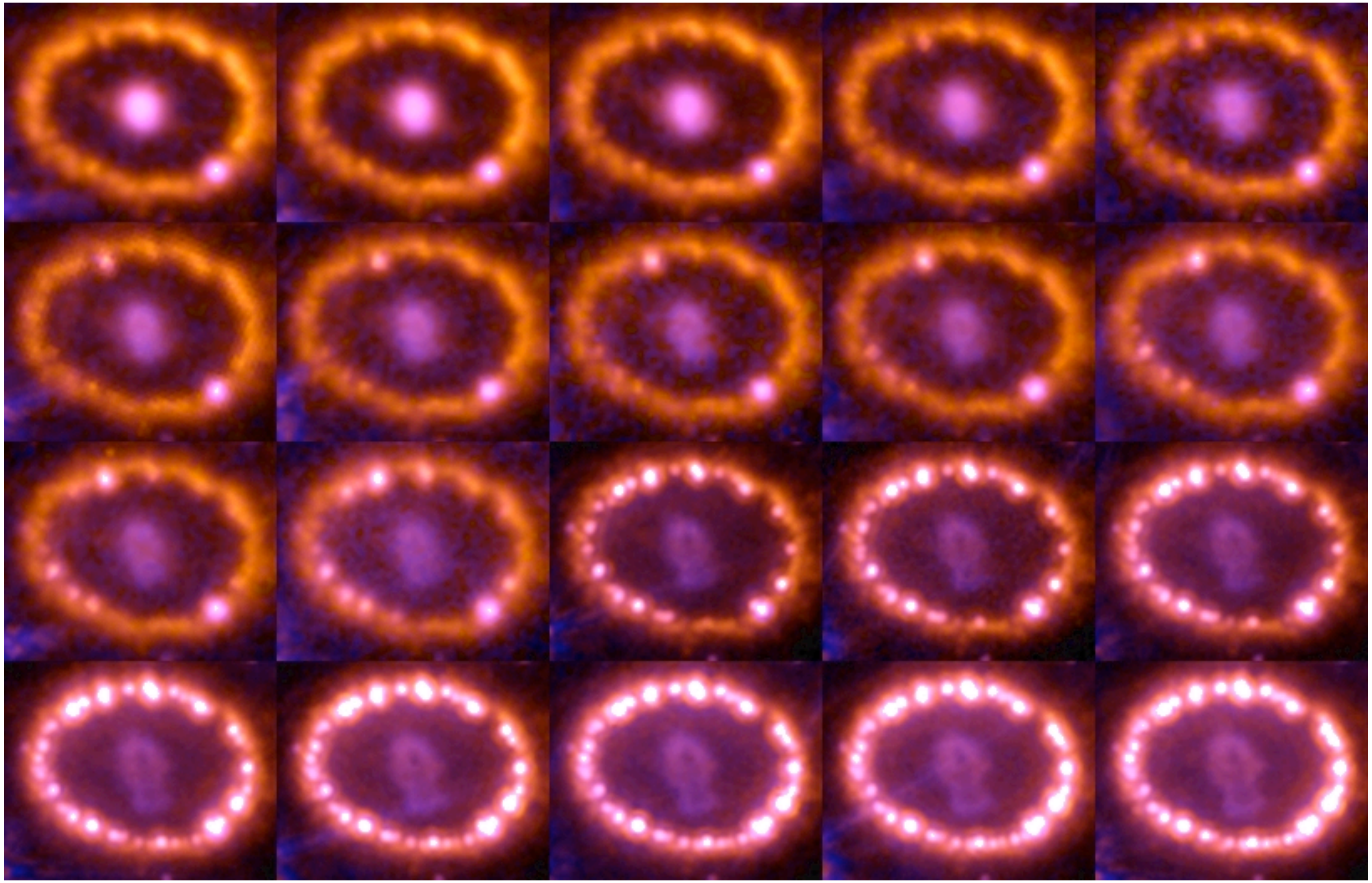
Leakage from ^{44}Ti regions to O/Si regions

needed for t > 1500 days

SN 1987A ring collision

SAINTS/
R. Kirshner, P. Challis

Sep 24 1994



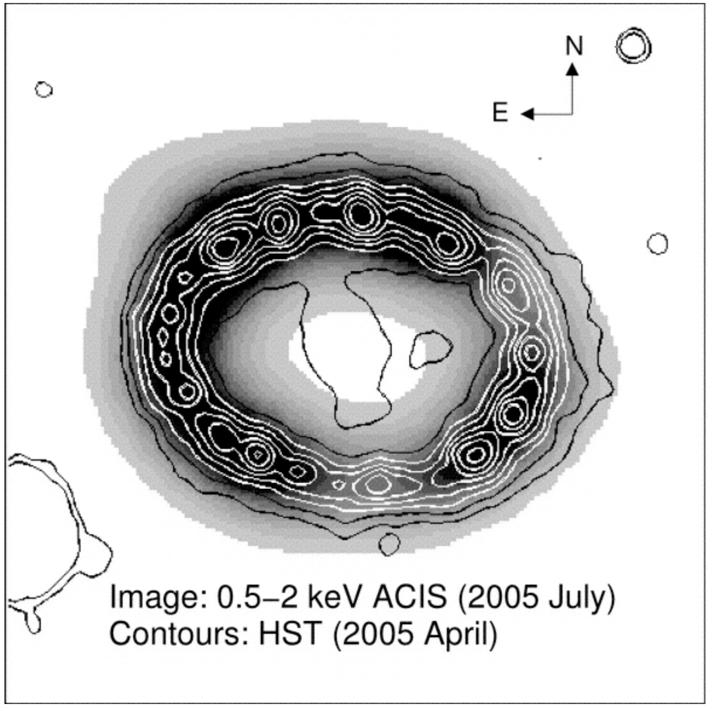
Feb 6 1998

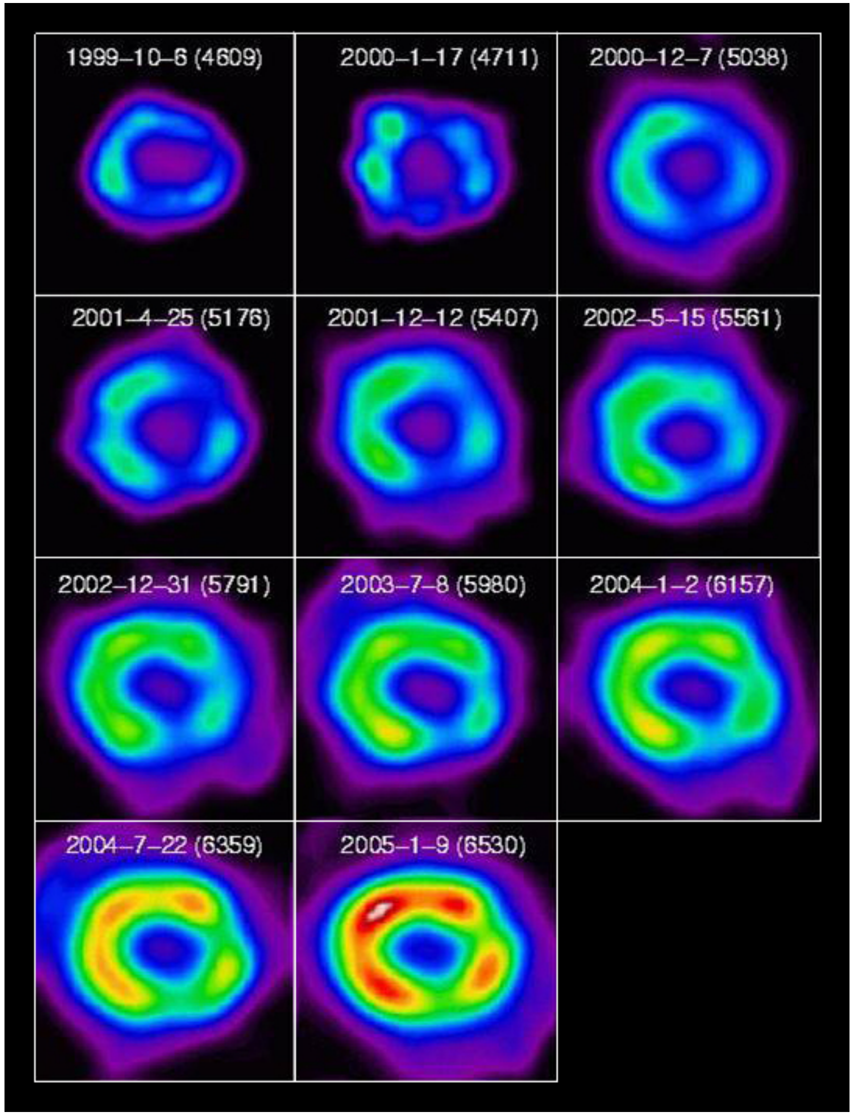
Nov 14 2000

Nov 28 2003

Dec 6 2006

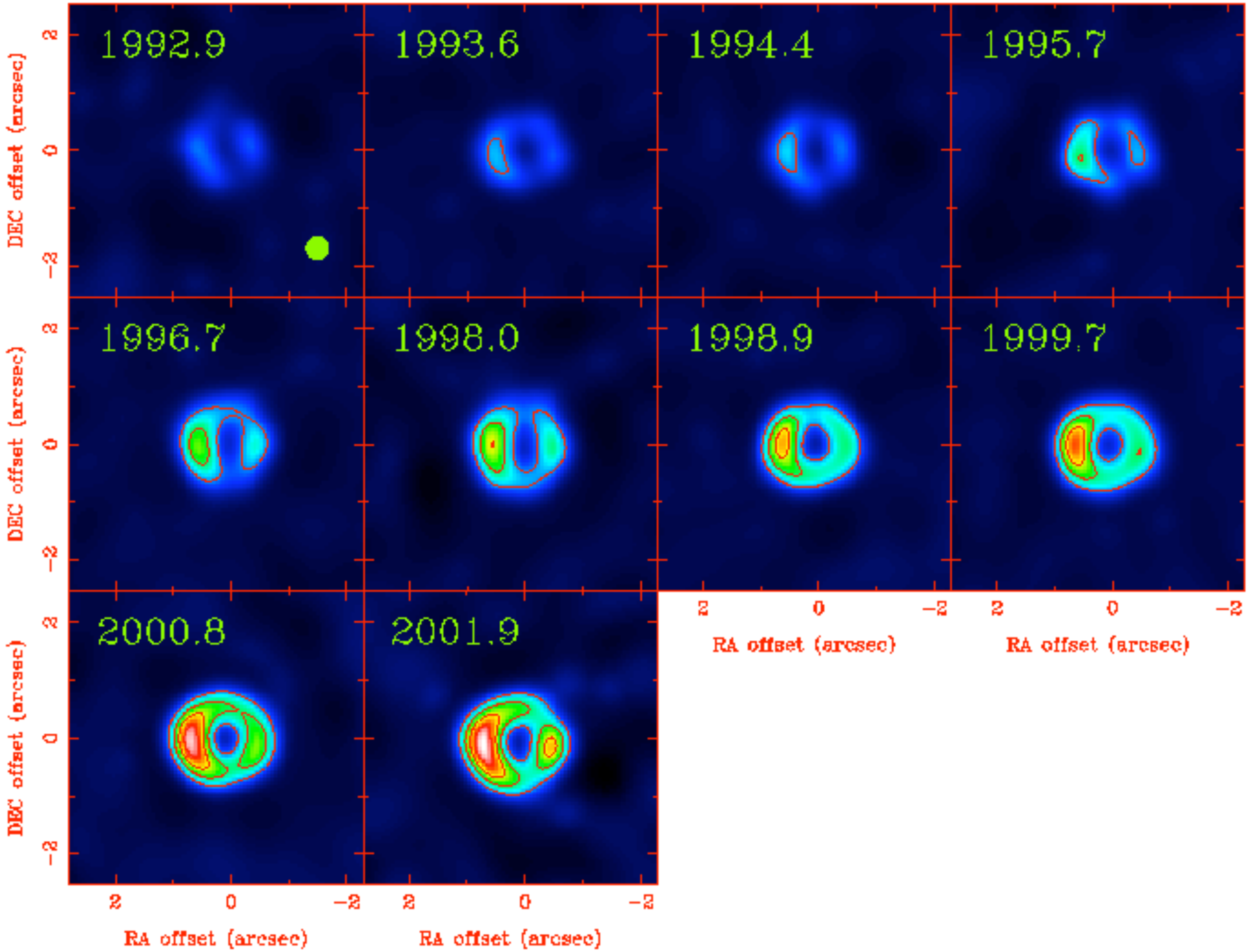
X-rays with Chandra





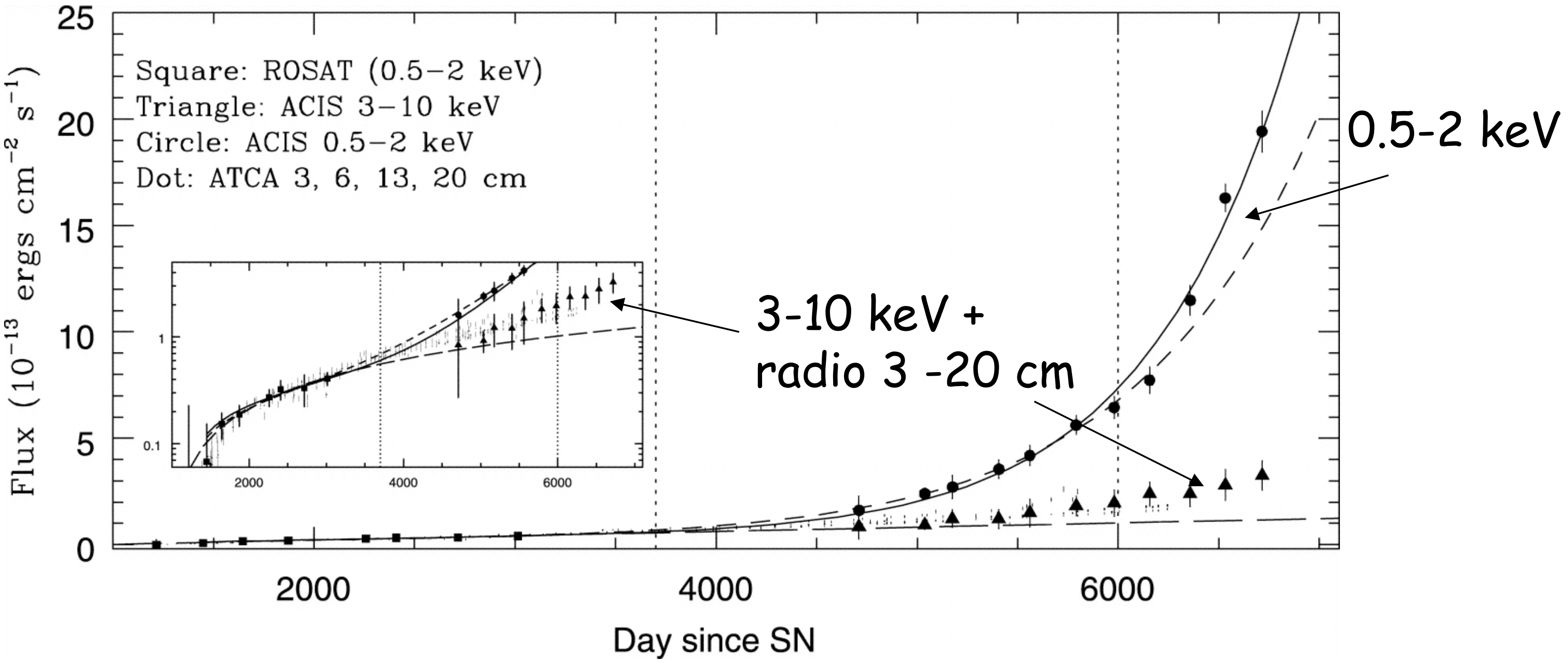
Park et al

Radio with ATCA



Manchester et al

Radio and X-ray brightening

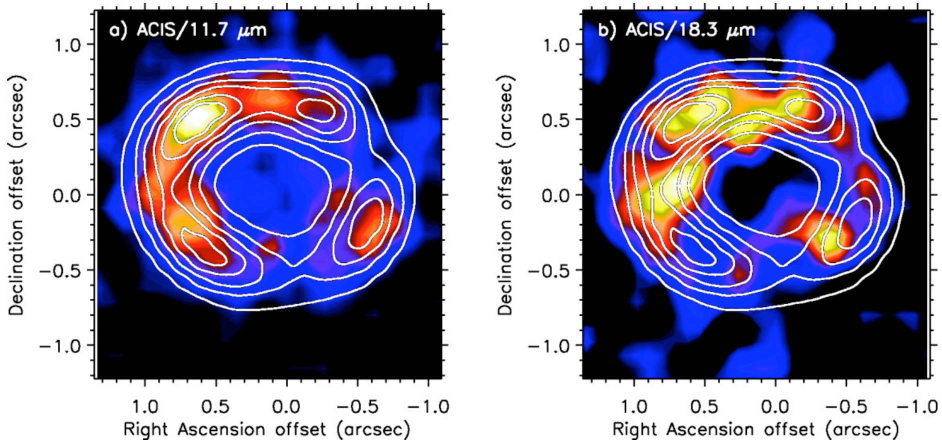


Park et al 2005
Manchester et al

Correlation of hard X-rays and radio probably close to reverse shock

Dust emission

Gemini S

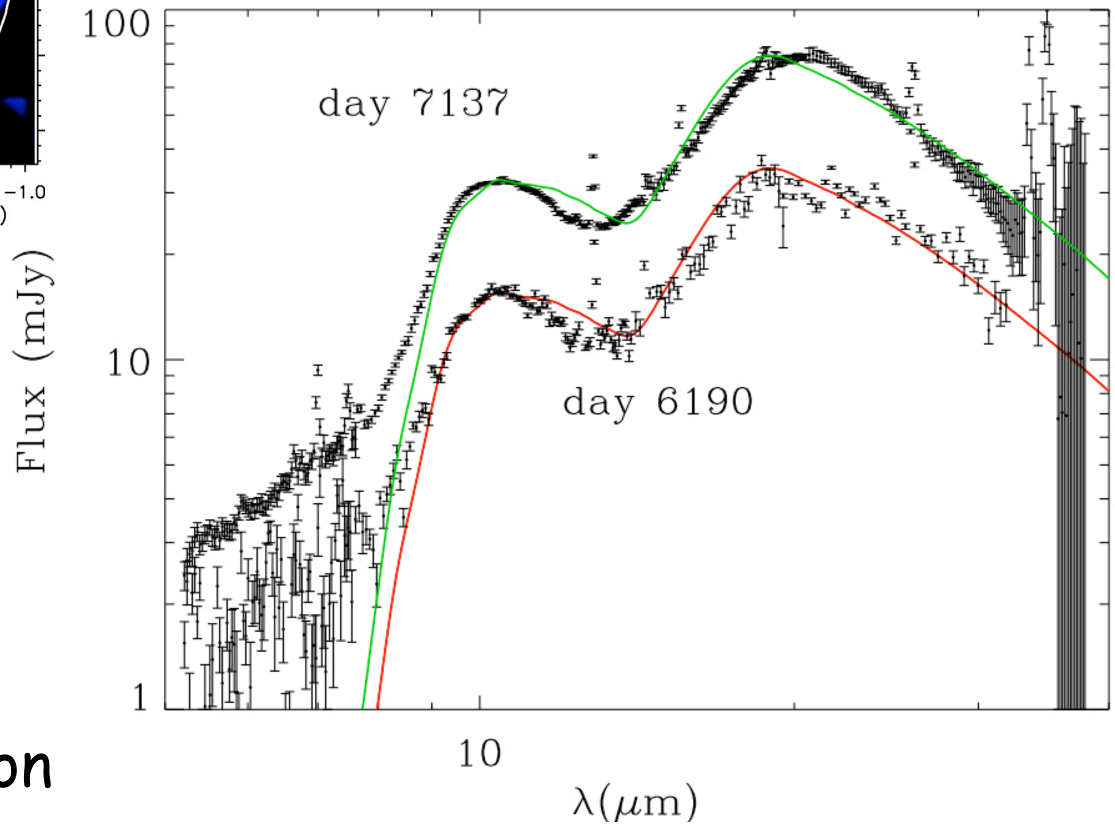


11.7 μ

18.3 μ

Bouchet et al 2006
Dwek et al 2008

Spitzer



T ~ 180 K
Si feature
collisionally heated
Evidence for dust destruction

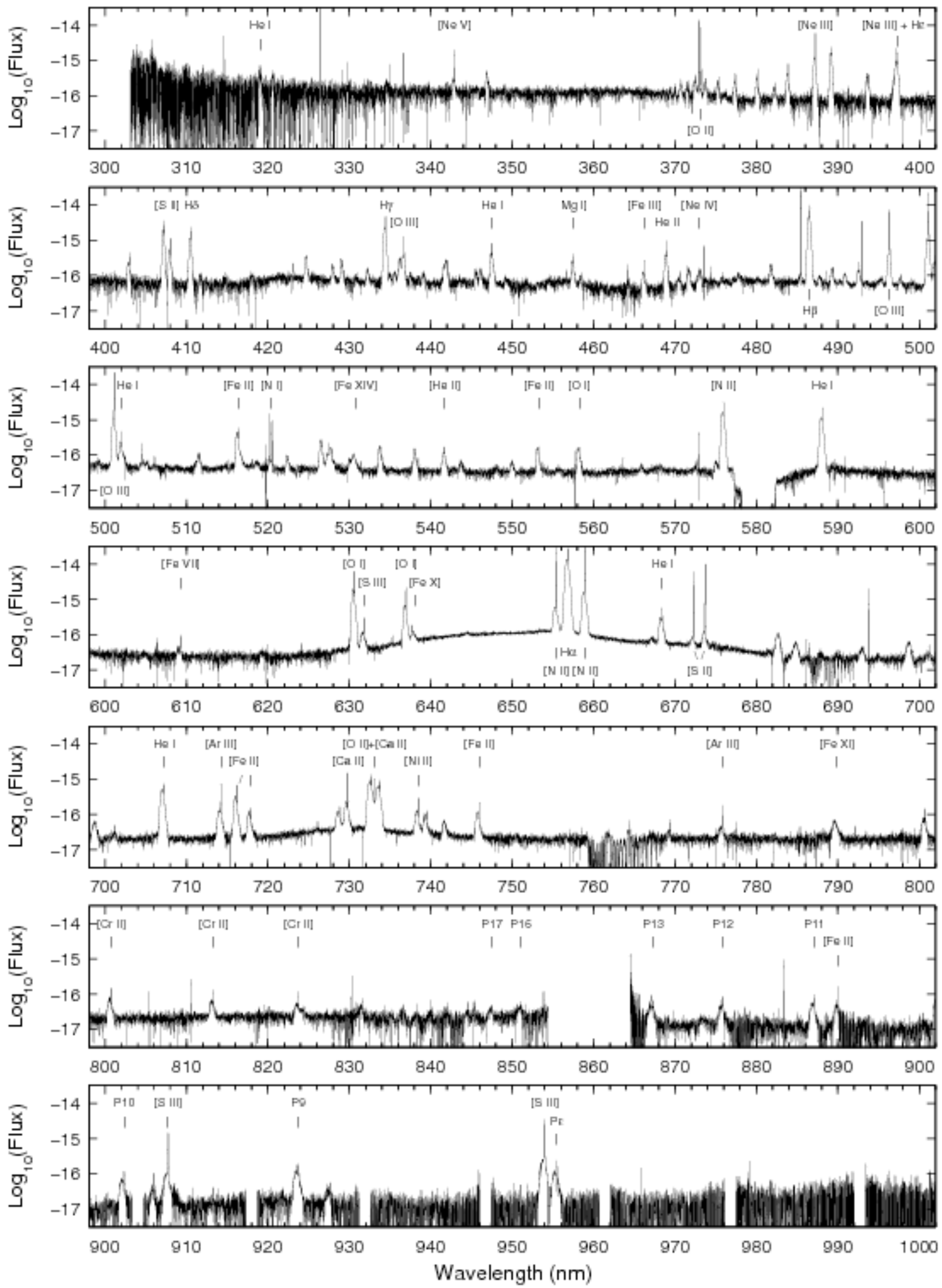
VLT/UVES

FWHM ~ 6 km s^{-1}

Seeing 0.5-0.8"

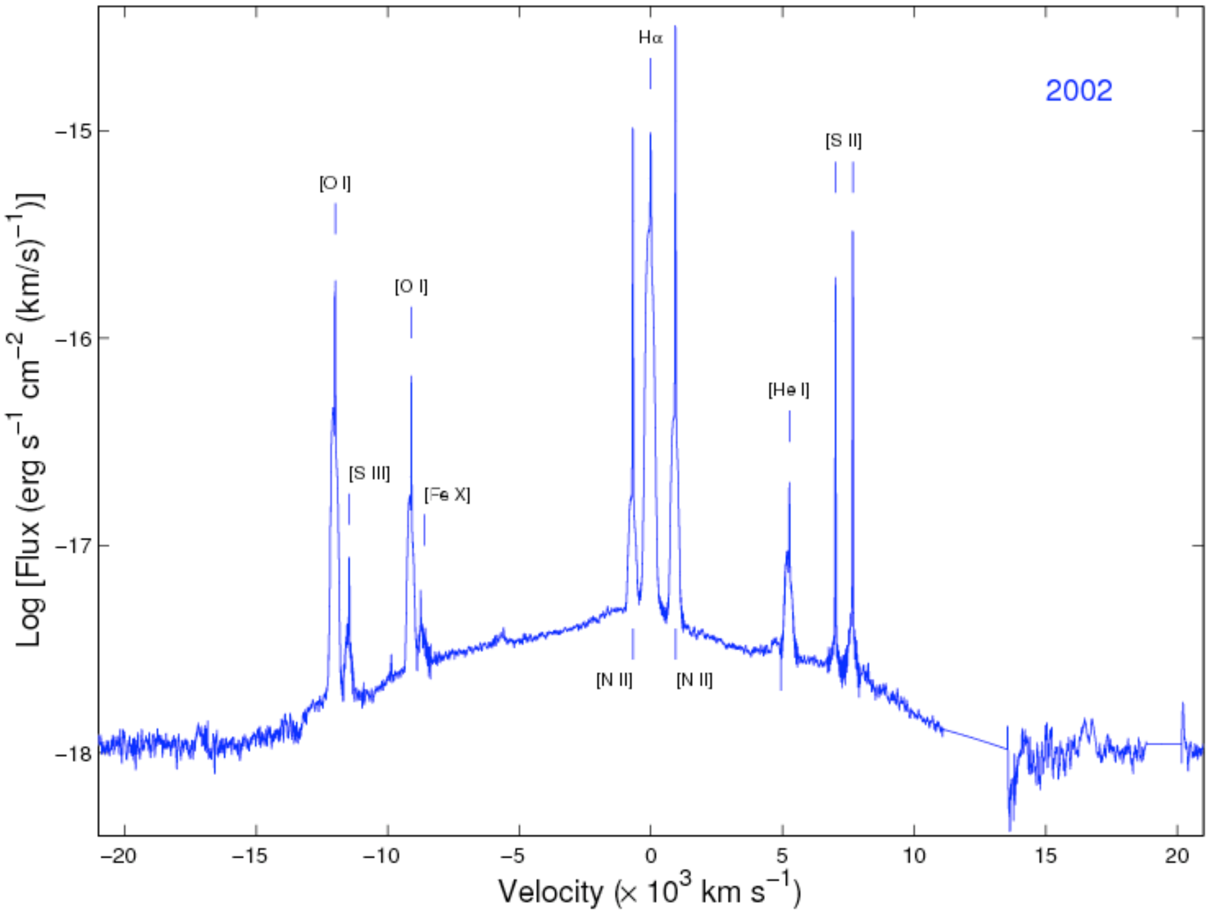
Resolves N/S

Gröningsson et al 2006



Three velocity components

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



VLT/UVES

2002

Velocity (10^4 km/s)

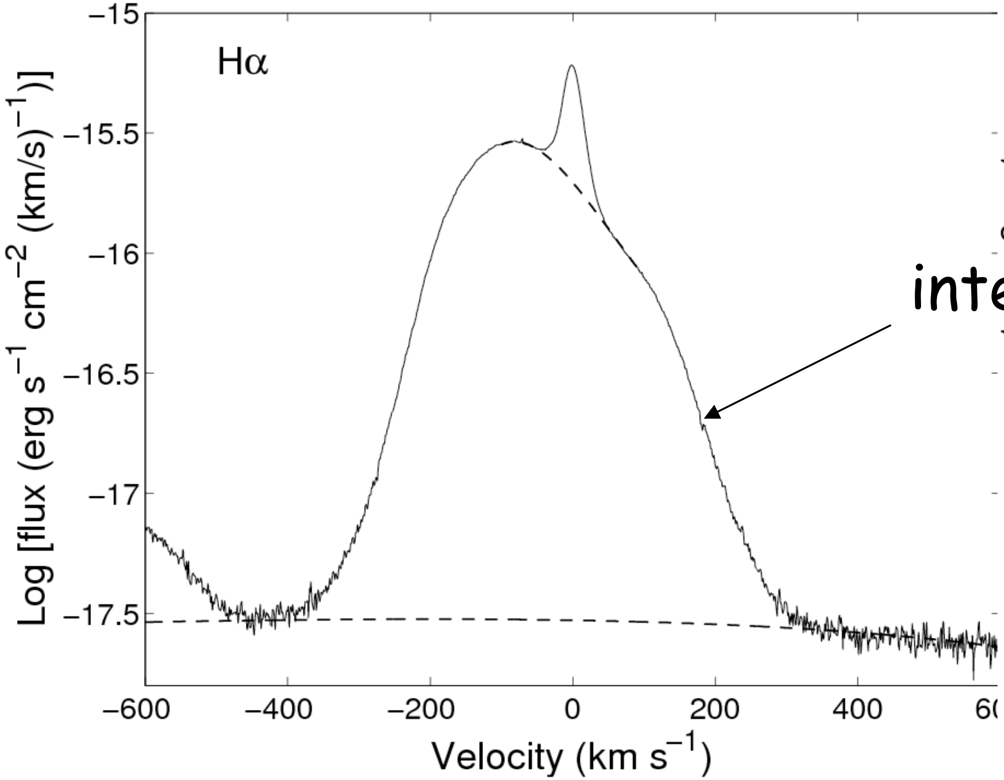
Broad ~16,000 km/s emission

Intermediate velocity 200 – 500 km s^{-1}

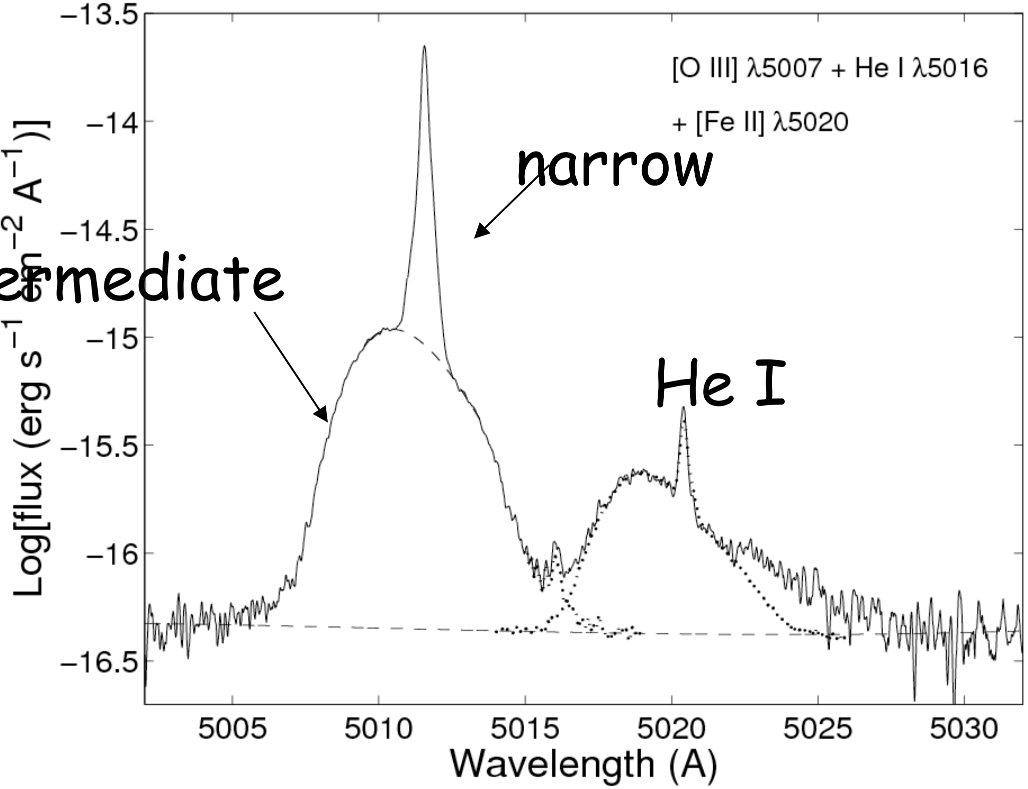
Narrow ~ 10 km s^{-1} from unshocked ring

Gröningsson et al 2006

Hα



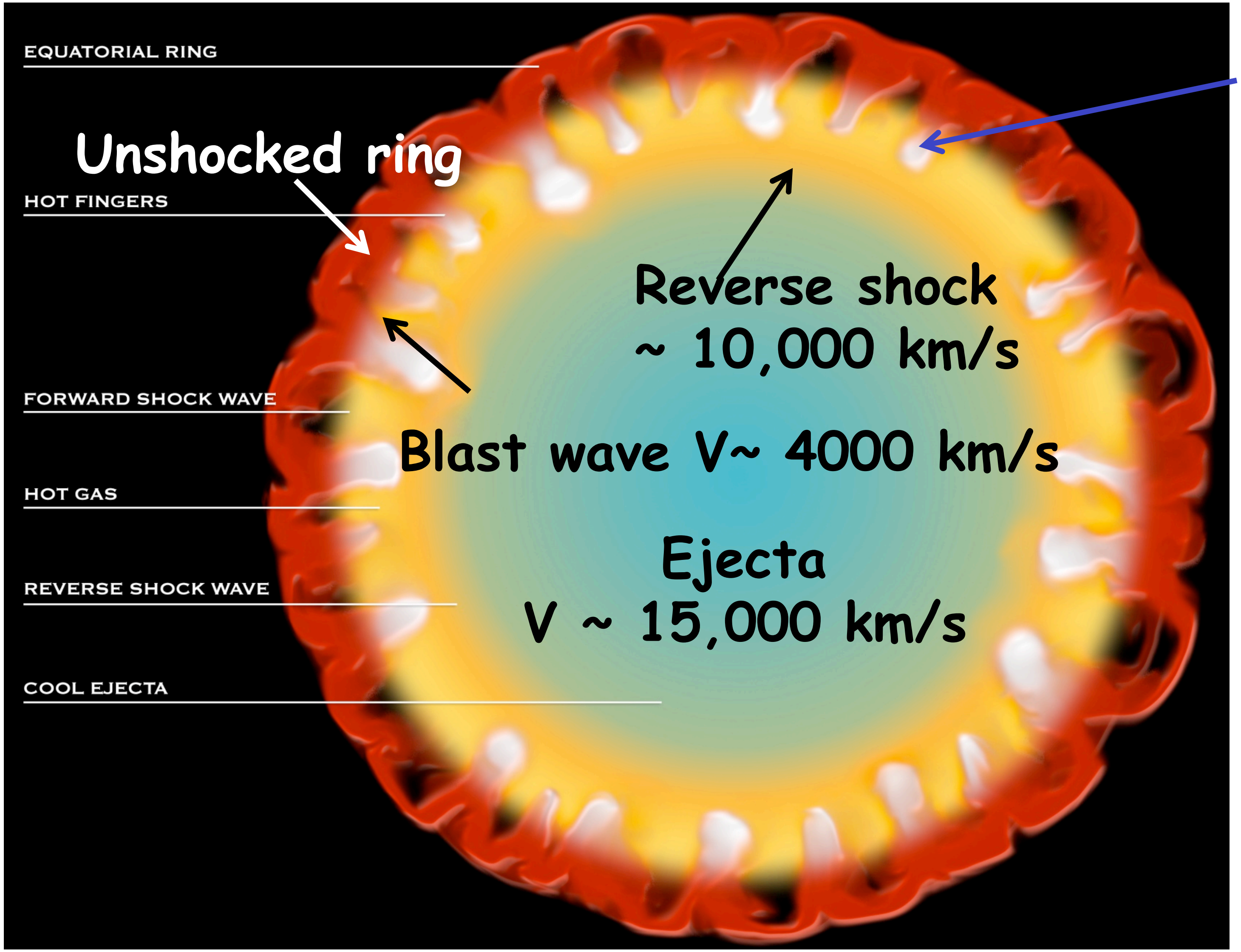
[O III] 5007



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

Intermediate V_{max} = 200-500 km s^{-1} from shocked ring

seen in Hα, He I, N II, O I-III, Fe II-XIV, Ne III-V, ...



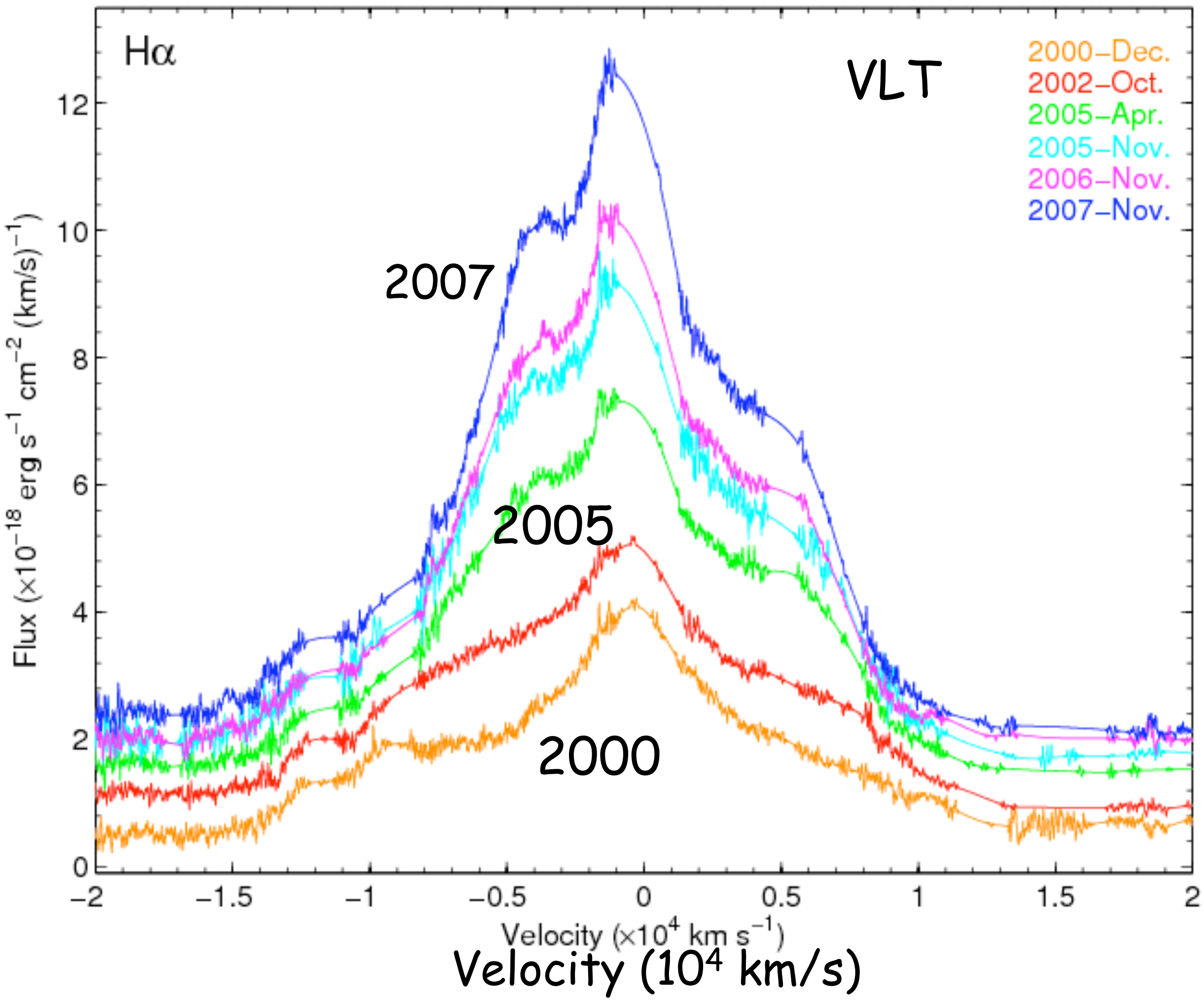
Ring shocks
200-500 km/s

Ejecta: ~10^2 cm^{-3}
Ring: ~10^4 cm^{-3}
$V_{rev} >> V_{forward}$

Coutesey: Dick McCray

Reverse shock

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



H I from ejecta unaffected by shock + coll. excit. and ion. by shocked el. $\Rightarrow$ Broad Hα

Broad ~16,000 km/s emission from reverse shock going back into ejecta
Ring interaction at R/t~11,000 km/s $\Rightarrow$ High velocity wing from high latitudes

Red side to ~11,000 km/s: dust absorption of red wing by ejecta?

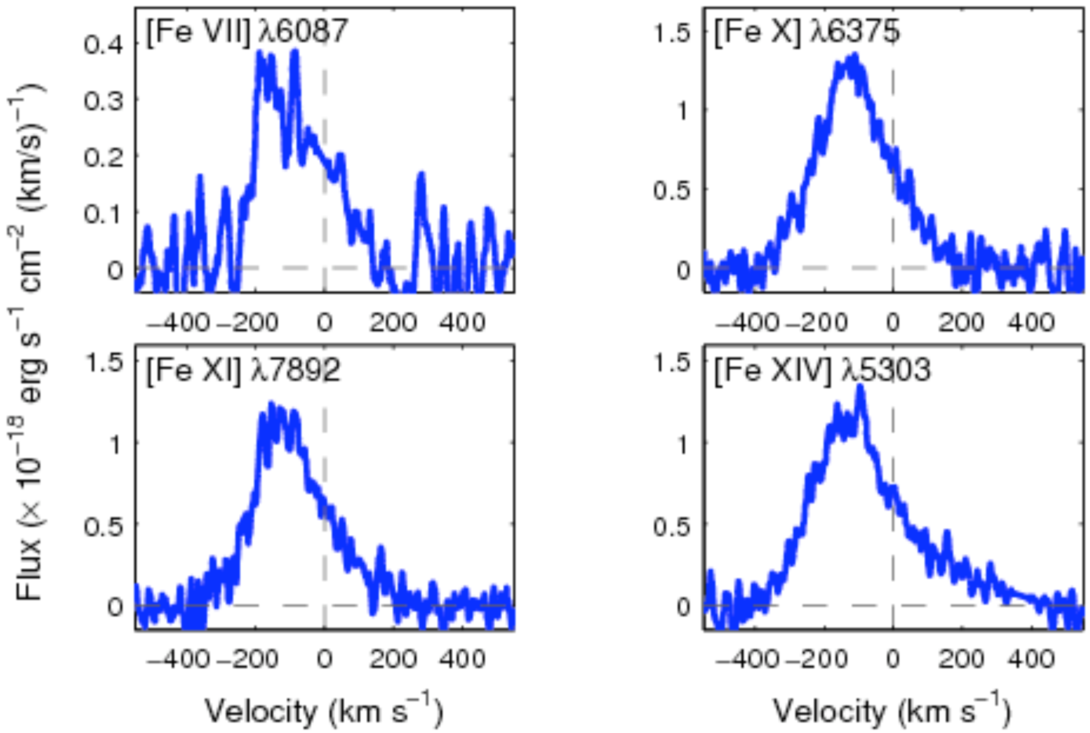
Coronal lines

Gröningsson et al 2006

VLT/UVES spectrum
[Fe VII], [Fe X], [Fe XI],
[Fe XIV]

VLT/ISAAC
[Fe XIII] 1.0747-1.0798 μ

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



Fe XIV λ 5303 ⇒ $T_s \sim 2 \times 10^6$ K

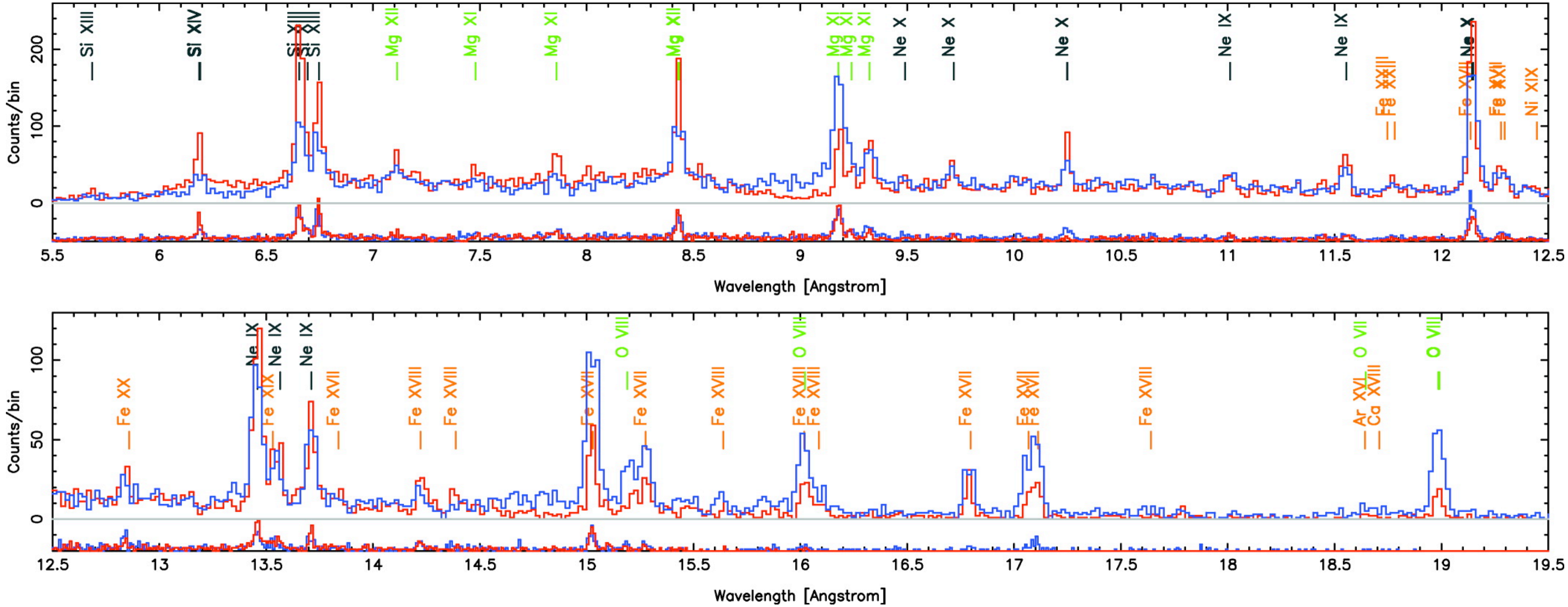
Hα, He I, N II, O I-III, Fe II, Ne III-V.....
Cooling, photoionized gas behind radiative shock into ring protrusions

X-rays

Chandra: Zhekov et al (2005, 2006)

Dewey et al (2008)

also XMM by Haberl et al and Heng et al

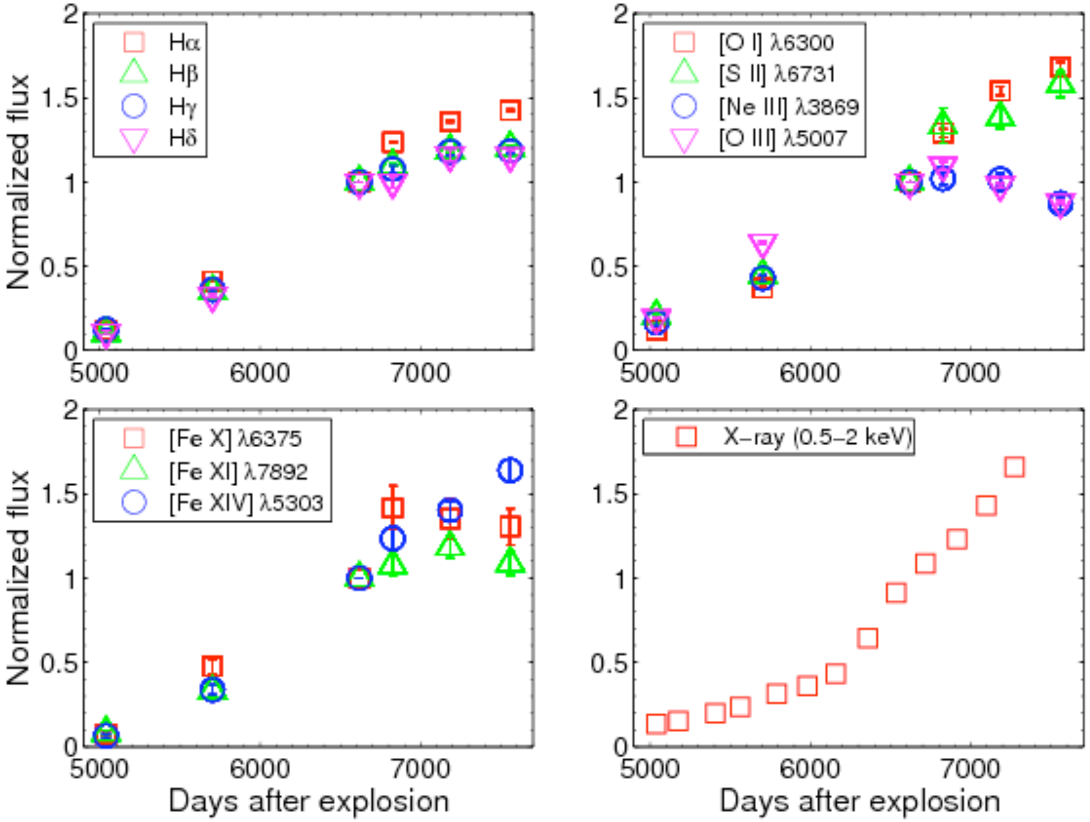


N VII, O VII-VIII, Ne IX-X, Mg XI-XII, Si XIII, Fe XVII.....

Similar N/O ratio as from unshocked ring

Two components: kT ~ 0.5 keV + kT ~ 3.0 keV

Time evolution



Optical: Gröningsson et al 2008

X-rays: Park et al 2005

Coronal lines, low ionization lines and soft X-rays correlate.

Soft X-rays & optical lines from same component

Hard from reverse shock & blast wave

Narrow, unshocked lines

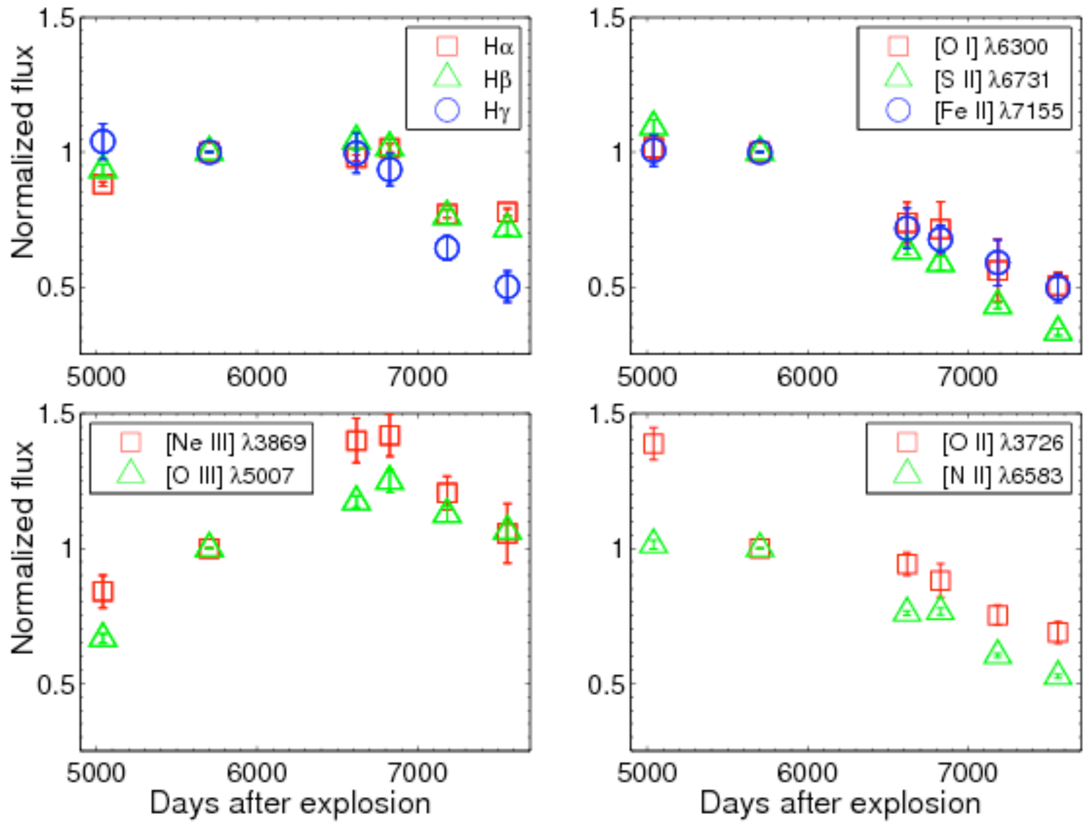
Unshocked ring ionized by SN shock breakout, then recombining

Lines have been fading during last decade

Most lines decrease, but [O III] and [Ne III] have been increasing!

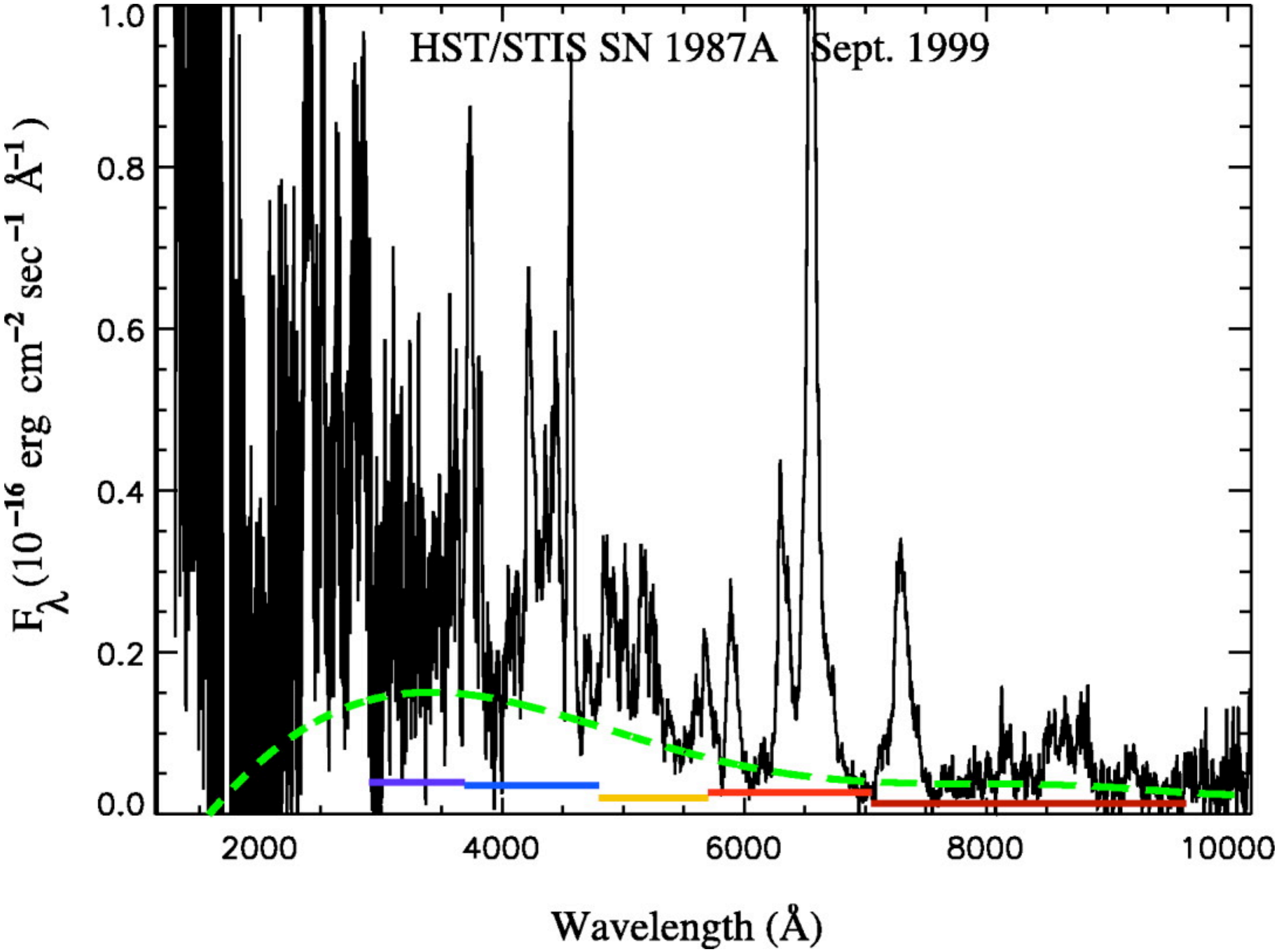
Predicted from shock models

Ring and neutral CSM will become ionized



The compact object: Optical

Graves et al. 2005 /SAINTS



Resonance scattering important for $\lambda <$ 5000 Å, transparent in red & IR

$L < 8 \times 10^{33}$ erg s^{-1}

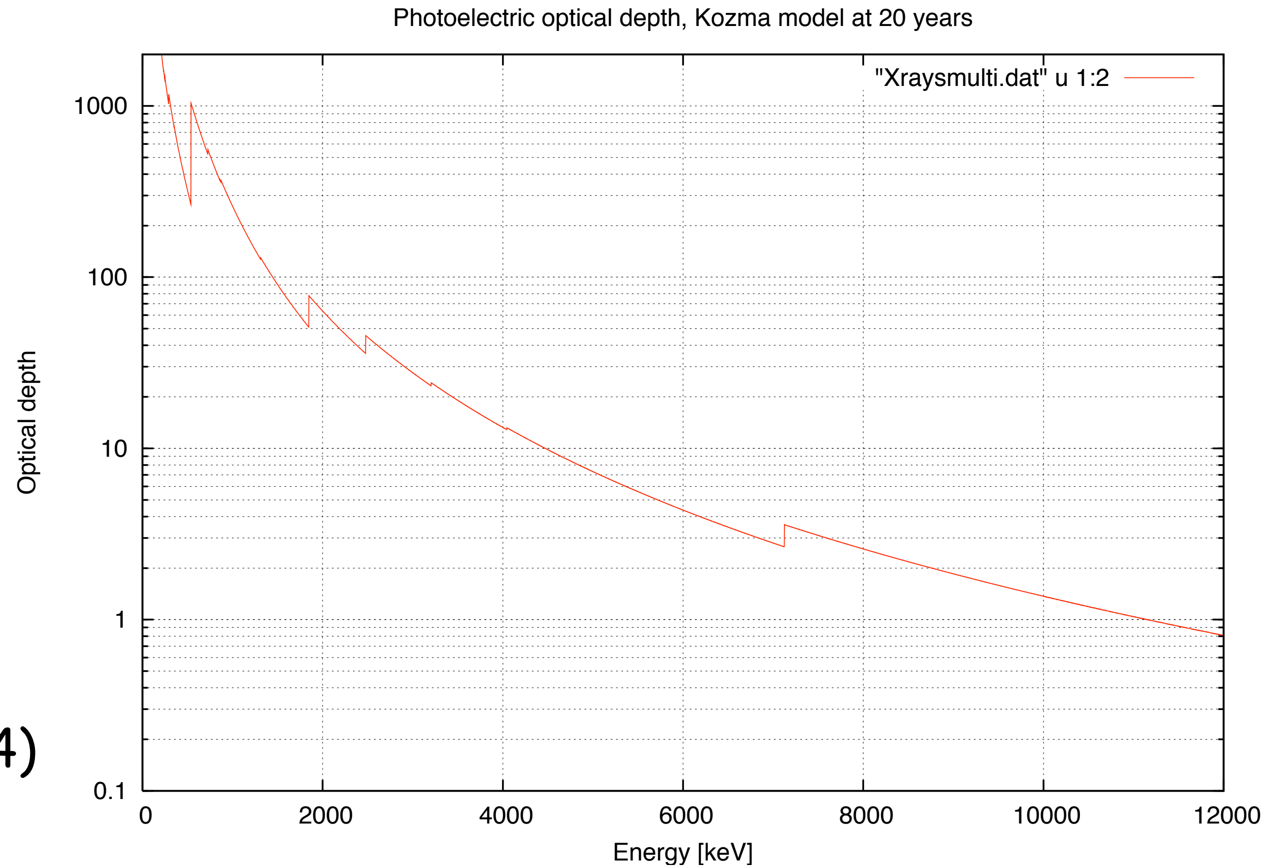
X-ray transparency of ejecta

Jerkstrand, Kozma +CF

Spherically symmetric. Density and abundance distribution by fitting optical spectra.

Chandra:

$L < 1.5 \times 10^{34}$ erg/s at 2-10 keV (Park et al 2004)



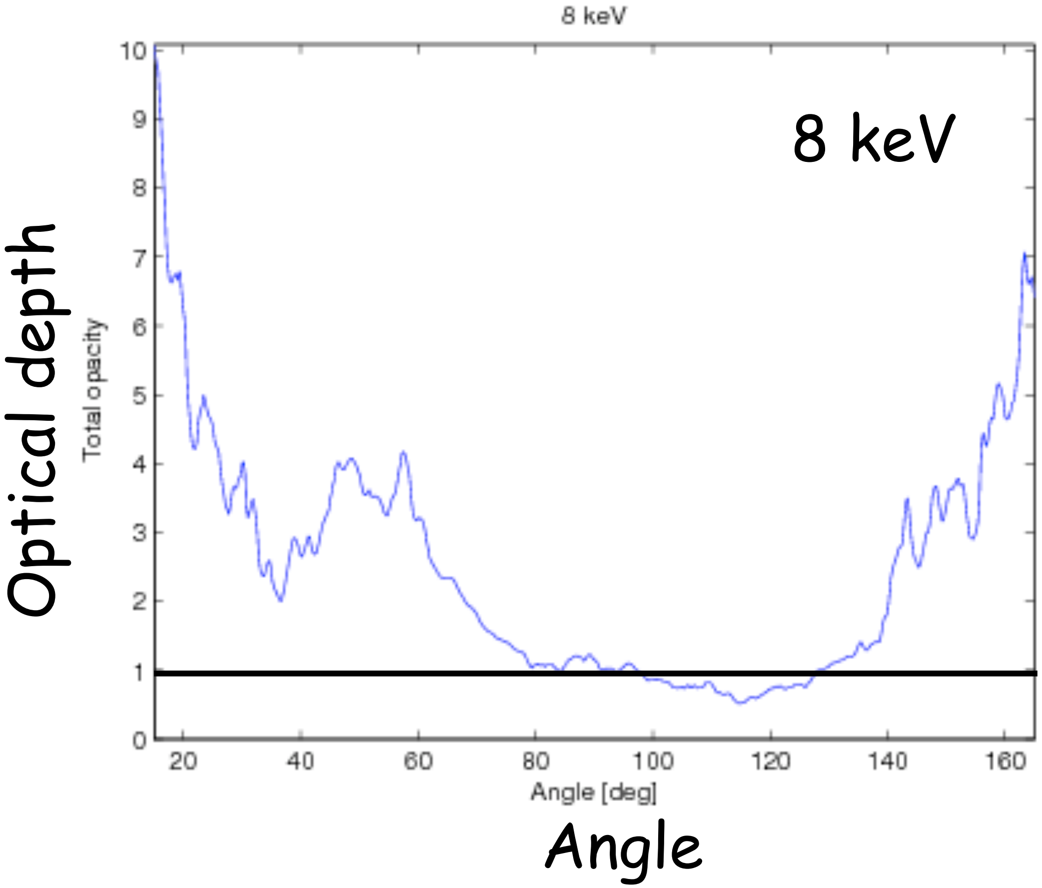
$\tau > 1$ below 10 keV at 20 years. Ejecta probably clumpy!

1. Can probably hide compact X-ray source in center
2. X-rays from the shock can ionize large fraction of the ejecta

Effects of instabilities

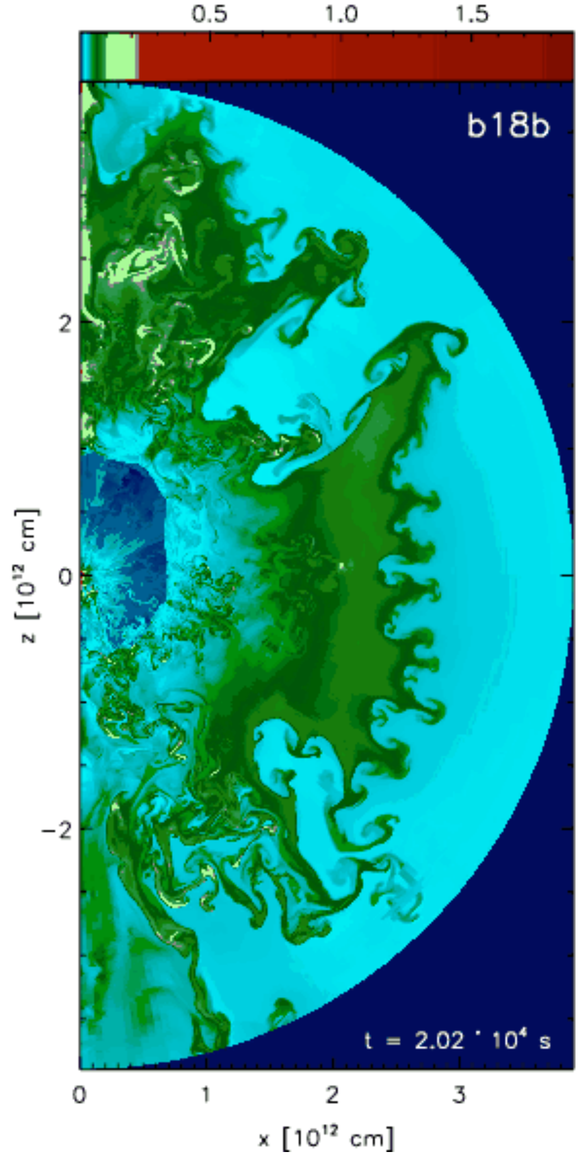
Jerkstrand, Kifonidis +CF

15 M_O model



Clumpiness important

Transparency may vary with direction



Kifonidis et al 2006

Where is the remnant?

Radio: No pulses! (Except for TV interference!!)

Optical: $L < 10^{-4}$ x Crab pulsar ($L_{crab} \sim 5\times10^{38}$ erg/s)

X-ray: $L < 10^{-3}$ x Crab

Problems: Radio: Pulses smeared, free-free absorption

Optical: Line scattering

X-ray: Soft X-rays still absorbed by ejecta

(Possible) solutions:

1. Neutron star: Rotation slow $P \sim 0.5$ s (Crab 0.033 s)

   B-field low (Crab $B \sim 3\times10^{12}$ G)

   $L \propto B^2 P^{-4}$

2. Black hole: Little accretion after first months

Future

Collision continues. Will get even brighter.

Structure of the ring: Several density components

Ejecta and CSM illuminated by shock radiation from ring

ALMA ~ 2012 will give resolution far better than HST

shock structure, particle acceleration, pulsar

PTS/Pan-STARRS will find many more 87A like objects

X-rays from compact object?

Next Galactic SN overdue!

Conclusions

- Ejecta clearly asymmetric. Not jet! (SASI?)
- Reliable masses for most abundant elements.

  Consistent with 20 $M_{\odot}$ progenitor
- $M(^{44}Ti) = (1\text{-}2) \times 10^{-4}\ M_{\odot}$
- Ring collision getting more and more intense.
- Excellent example of shock physics laboratory
- Compact object not yet seen but may be there