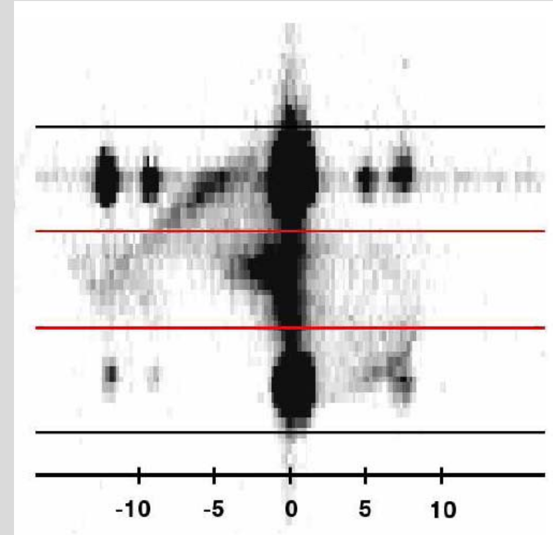
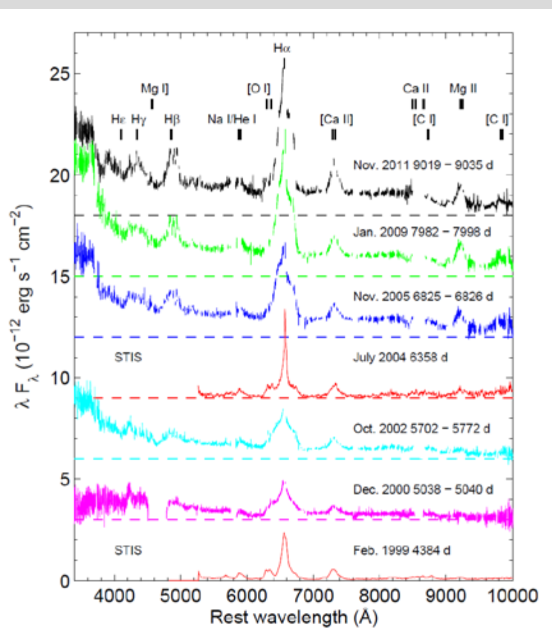


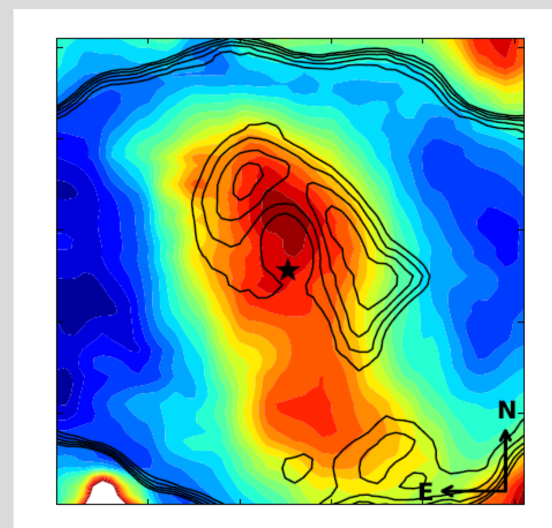
SN 1987A

spectacular physics

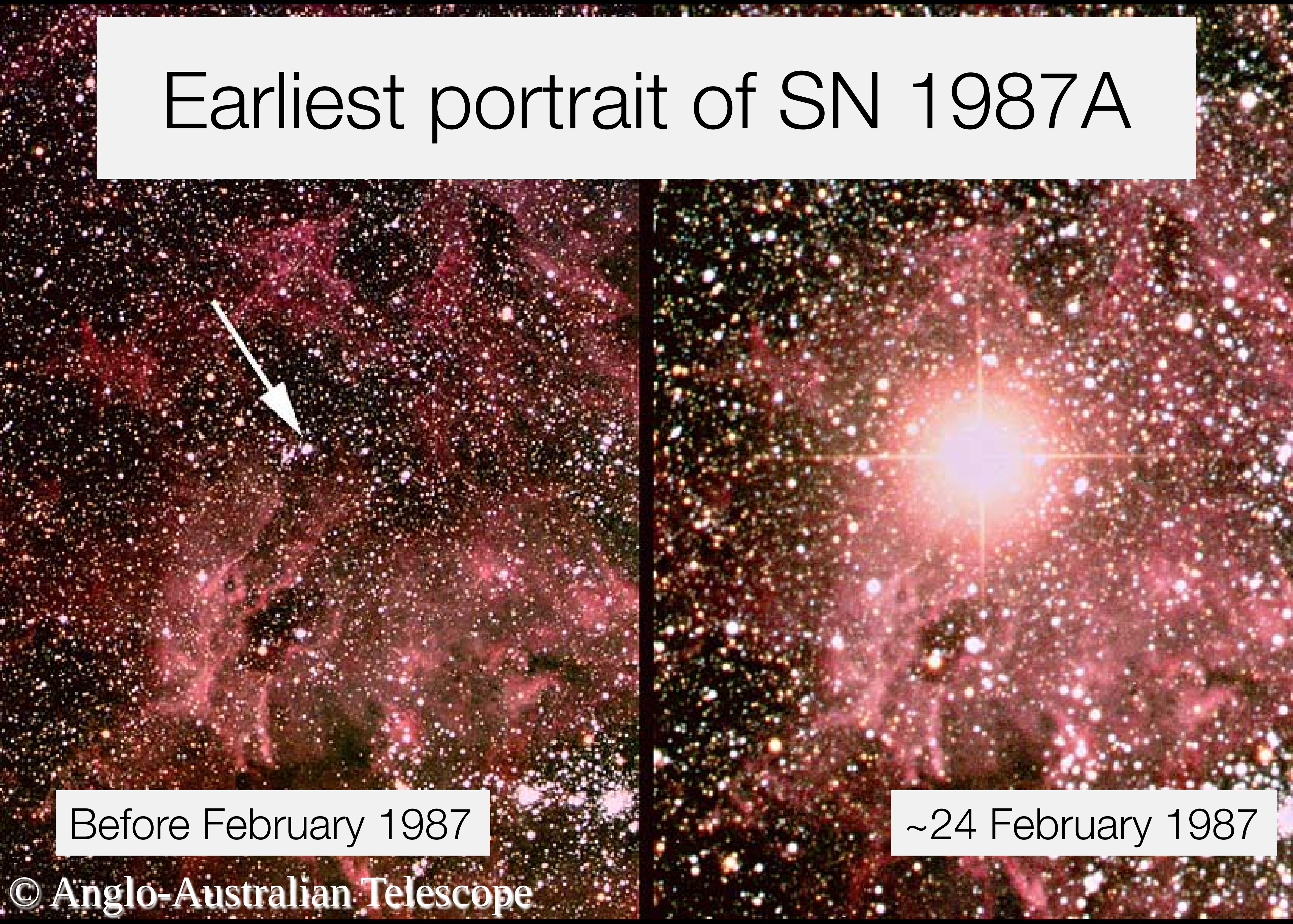


Bruno Leibundgut

ESO



Earliest portrait of SN 1987A



Uniqueness of SN 1987A

Neutrino detection

- direct evidence of core collapse and formation of a neutron star (or black hole)

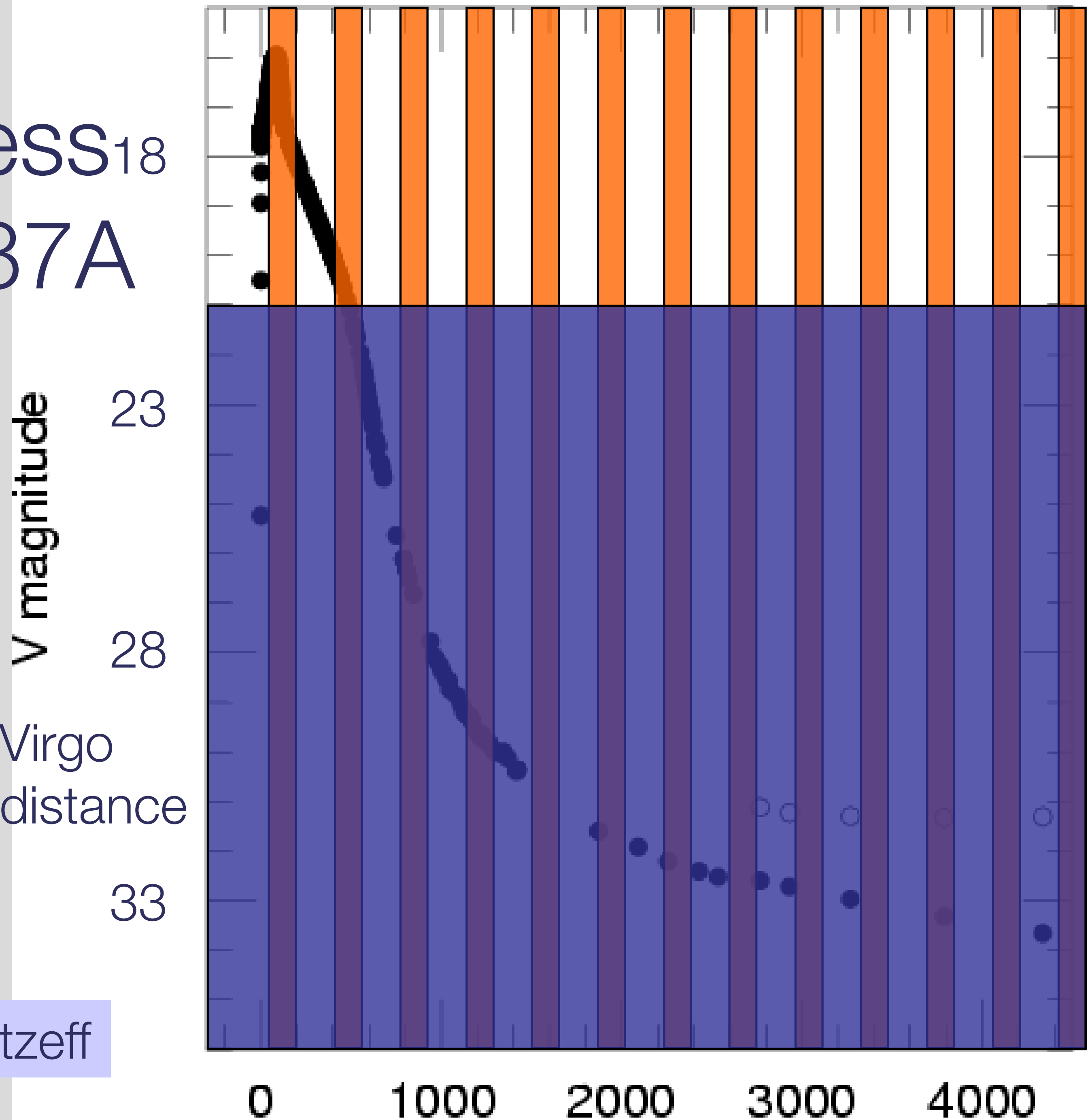
Naked-eye supernova after >350 years

- detection of X-rays and γ-rays very early
  - mixing and direct nucleosynthetic products
- monitoring with HST, VLT, Gemini, Chandra, XMM, ATCA, Herschel, Spitzer, ALMA

Progenitor star observed before explosion

- insight into stellar evolutionary channel leading to a supernova   surprise → blue supergiant!

Uniqueness of SN 1987A



Suntzeff

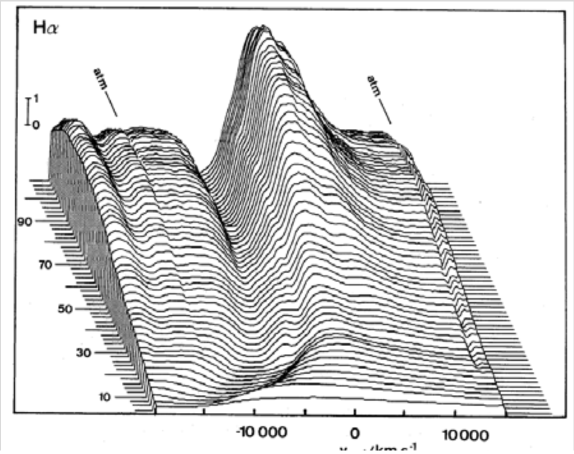
Uniqueness of SN 1987A

Spatially resolved

- separate circumstellar environment (rings) from the ashes of the explosion (ejecta)

Signatures of an asymmetric explosion

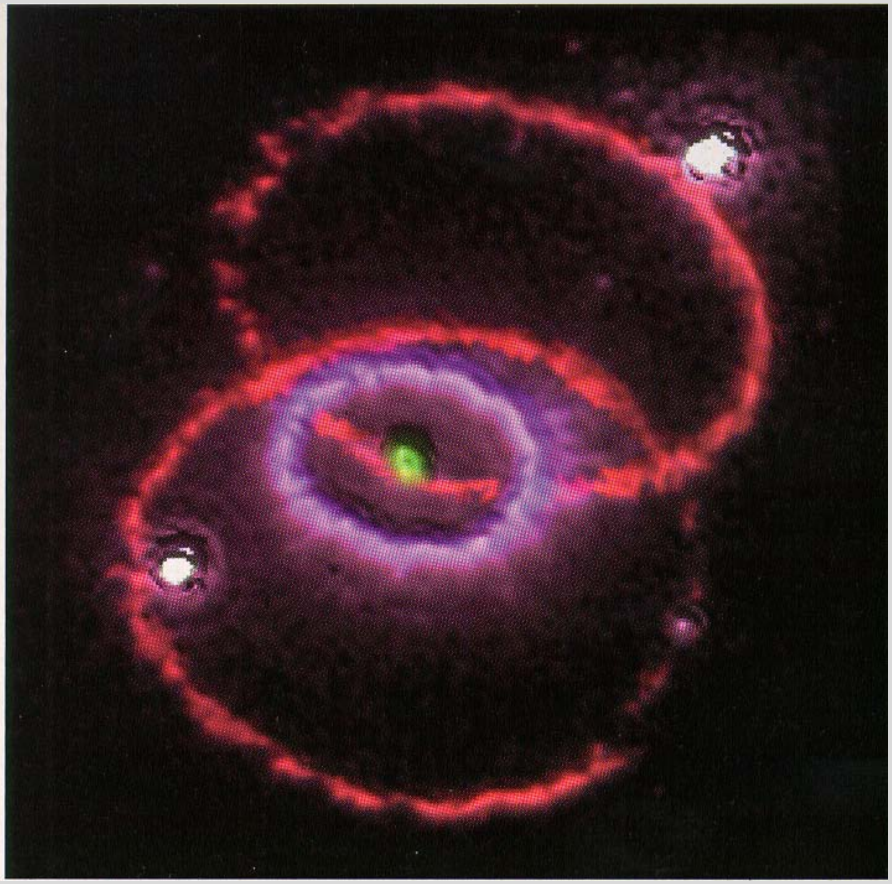
- polarimetry, 'mystery spot', spectral line evolution ('Bochum event')



Hanuschik & Thimm 1988

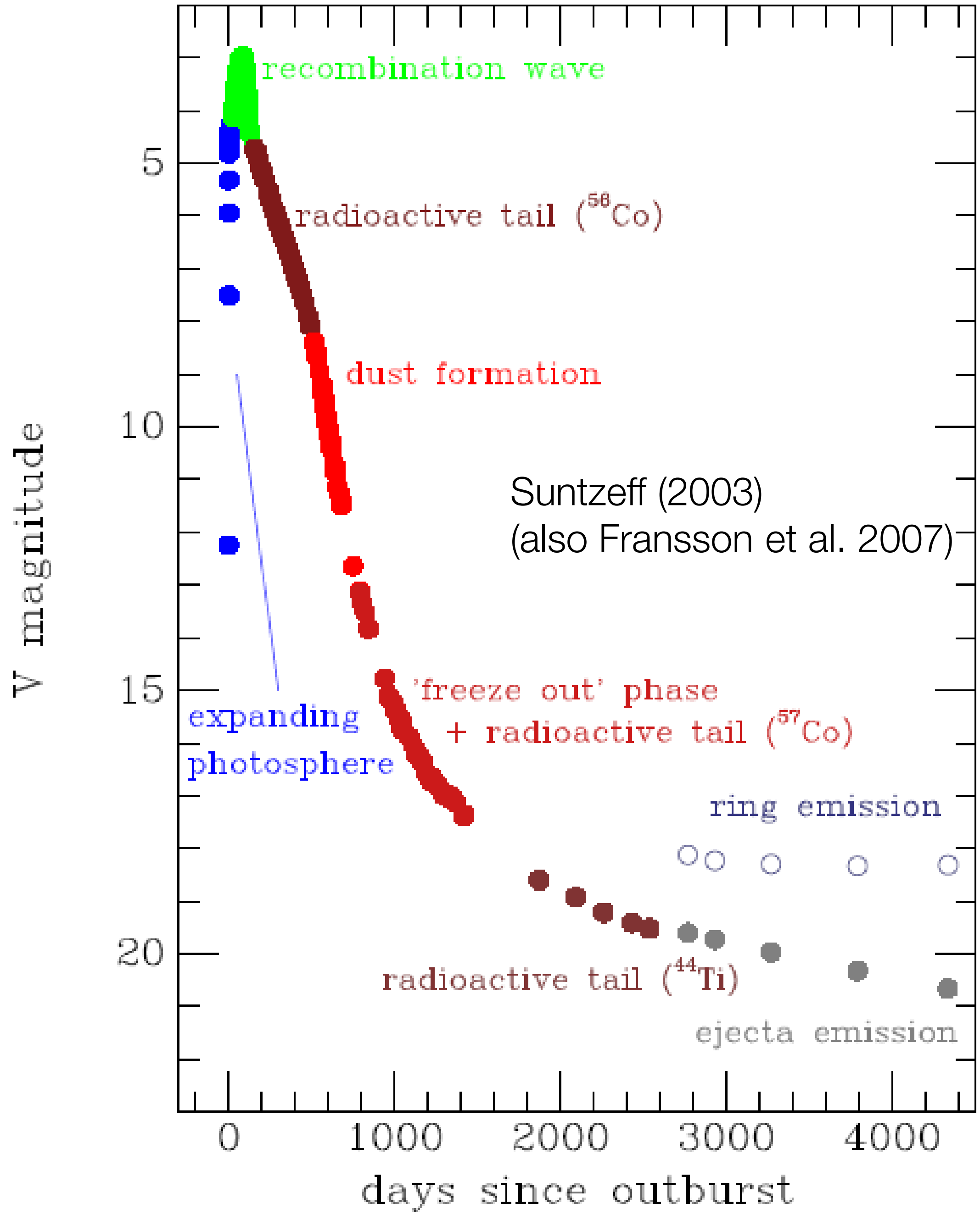
The exciting SN 1987A today

(9606 days since explosion – 26 years old)

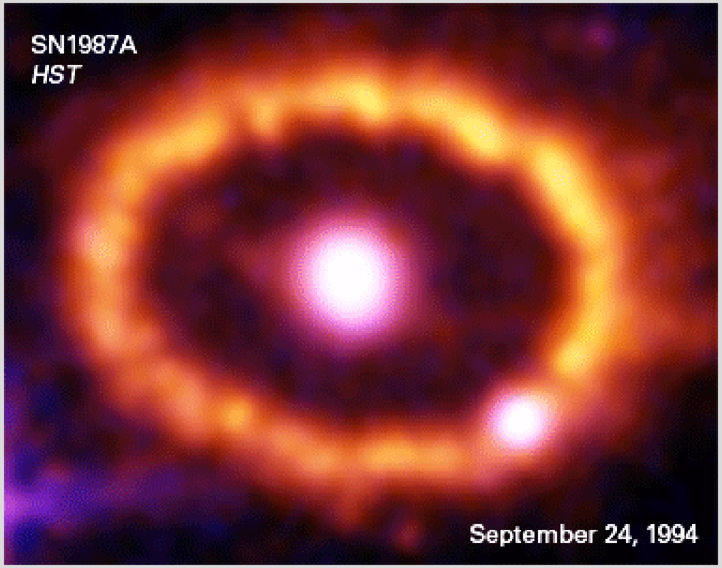


- Fluorescing rings
- Shocks
  - outer ejecta reached the inner ring
- Radioactively heated material
  - inner ejecta
- Dust
  - in and around the supernova

Energy escape from a (core-collapse) supernova



SN 1987A
the best observed supernova ever



Energy sources

Gravity →Type II supernovae

– collapse of a solar mass or more to a neutron star

Gamow's picture of
a core collapse supernova

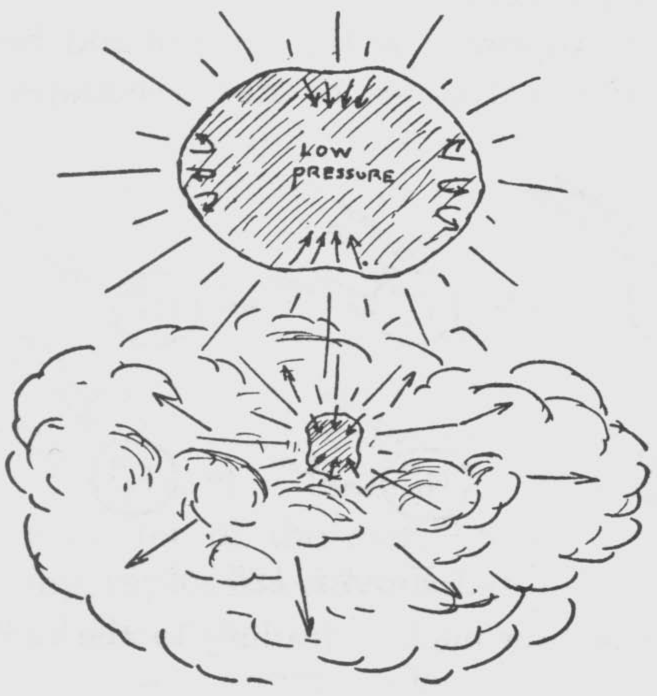


FIGURE 126
An early and a late stage of a supernova explosion.

Energy sources

Shock

- breakout
- kinetic energy

Cooling

- due to expansion of the ejecta

Radioactivity

- nucleosynthesis

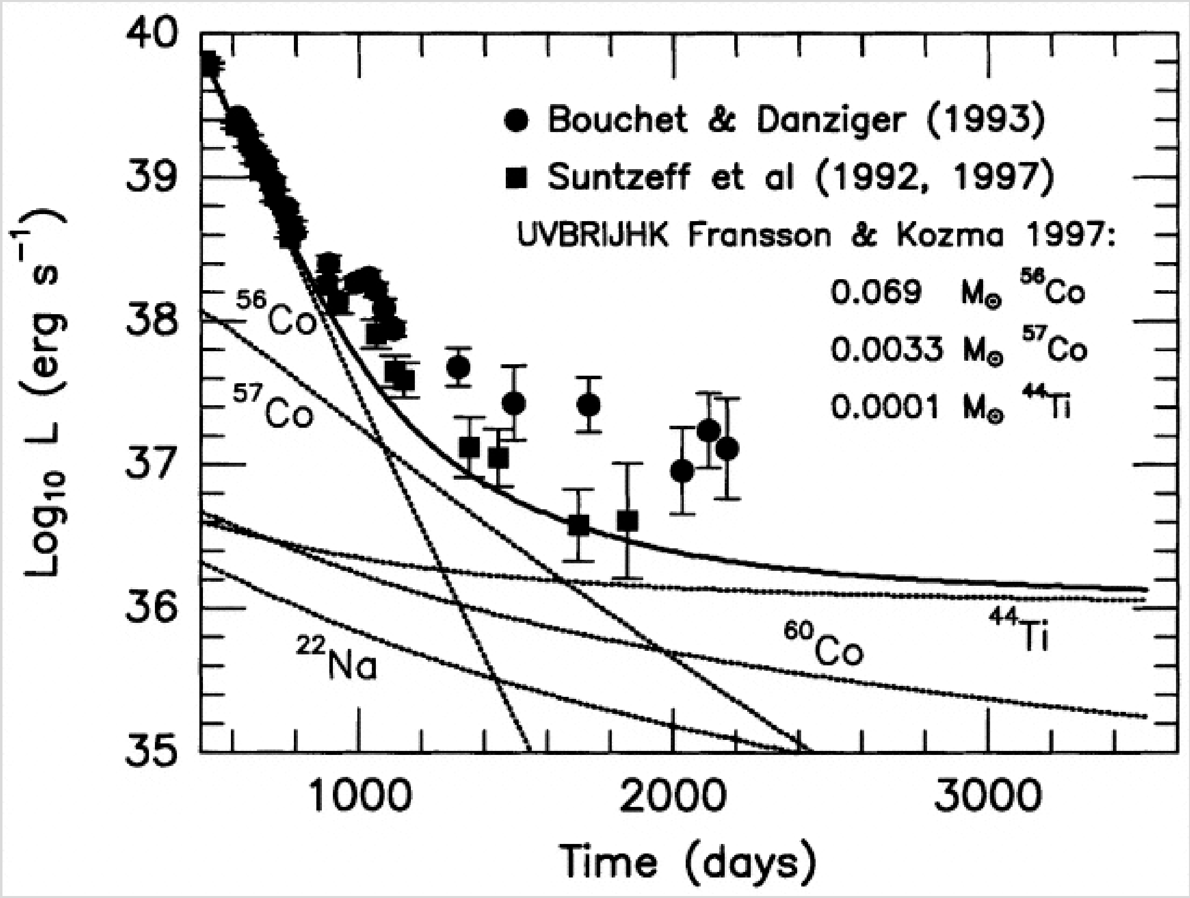
Recombination

- of the shock-ionised material

What can drive SN emission at late phases?

Freeze-out

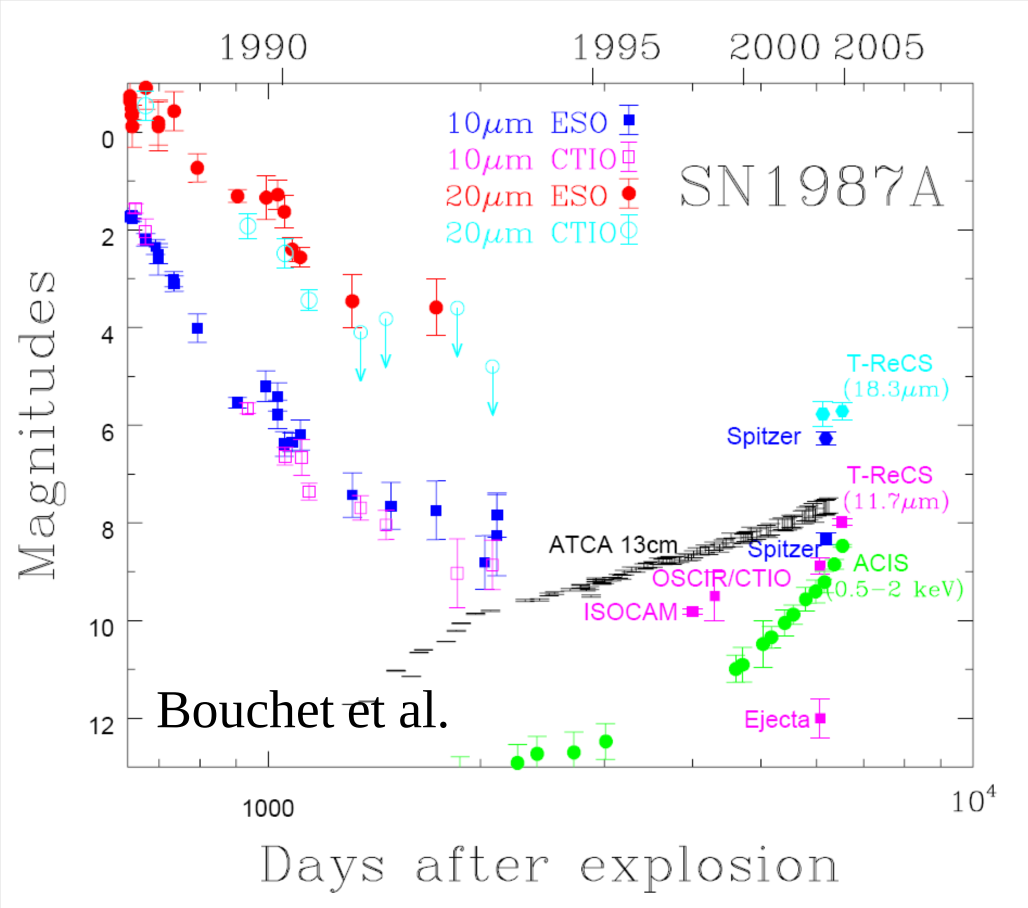
recombination of atoms at long time-scales



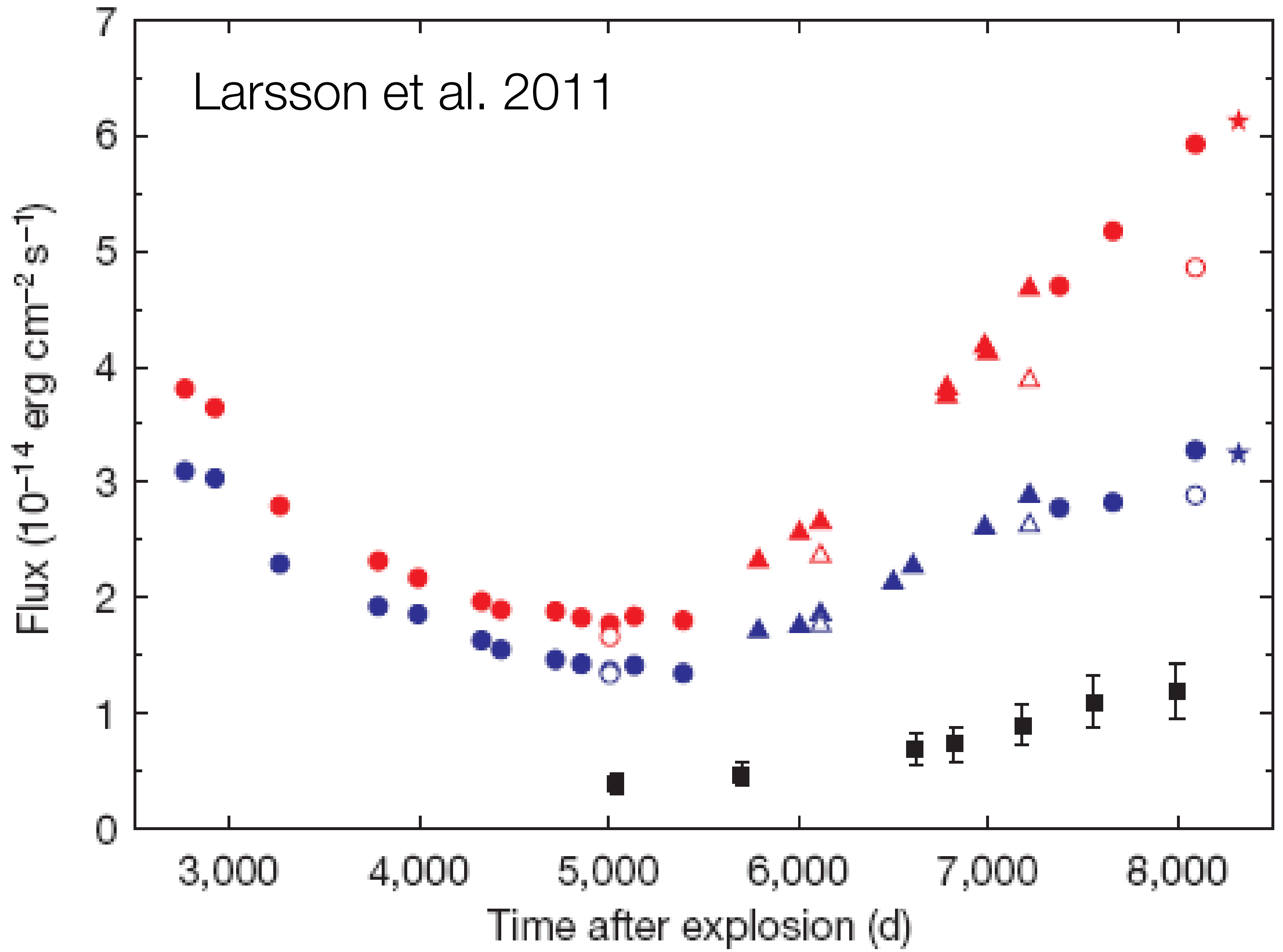
The excitement is back

increase observed in

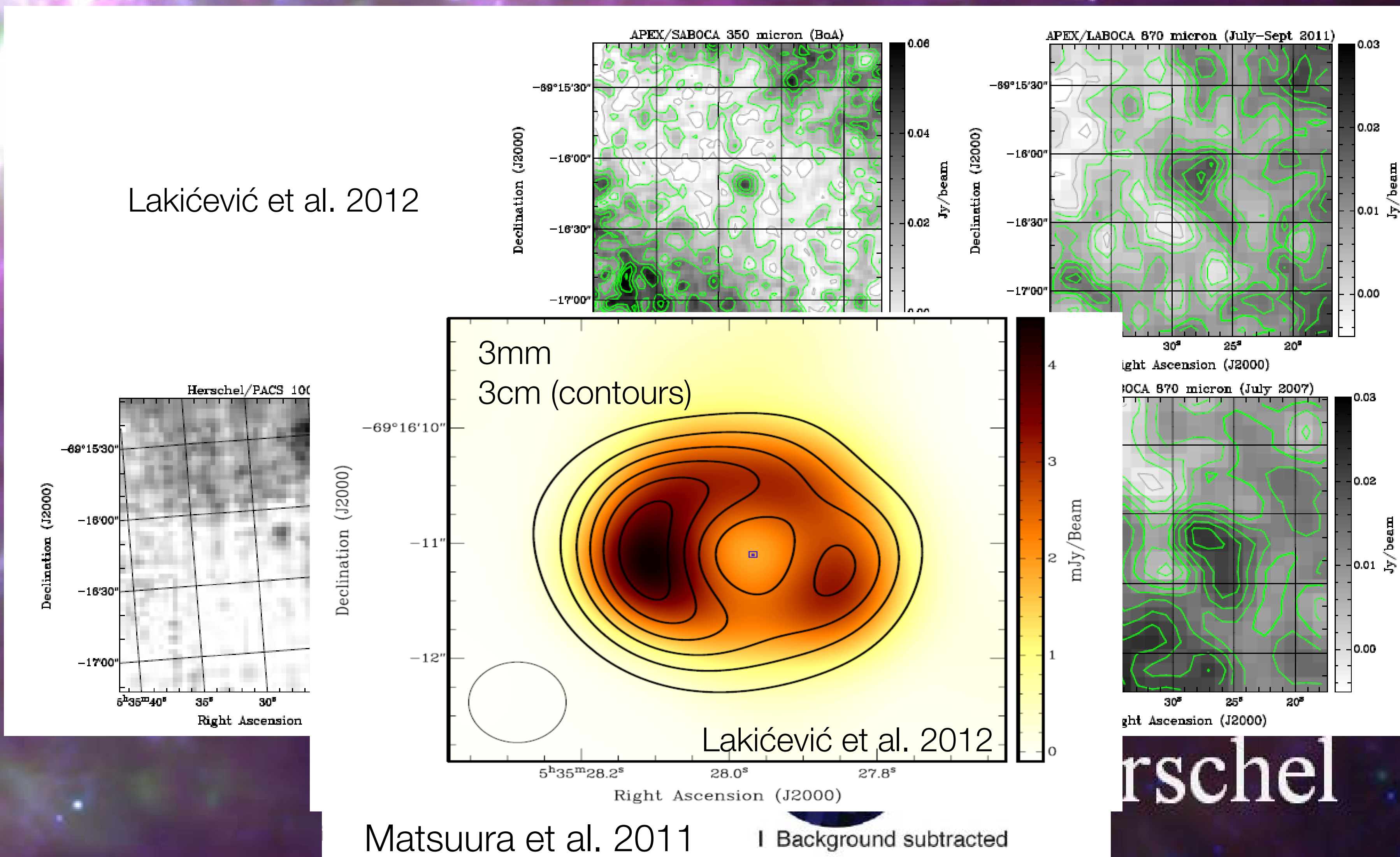
- X-rays
- optical
- IR
- radio



SN 1987A is brightening at all wavelengths



Exciting developments



Dust - where is it?

Dust formed early

~500 days after e

Herschel fluxes in

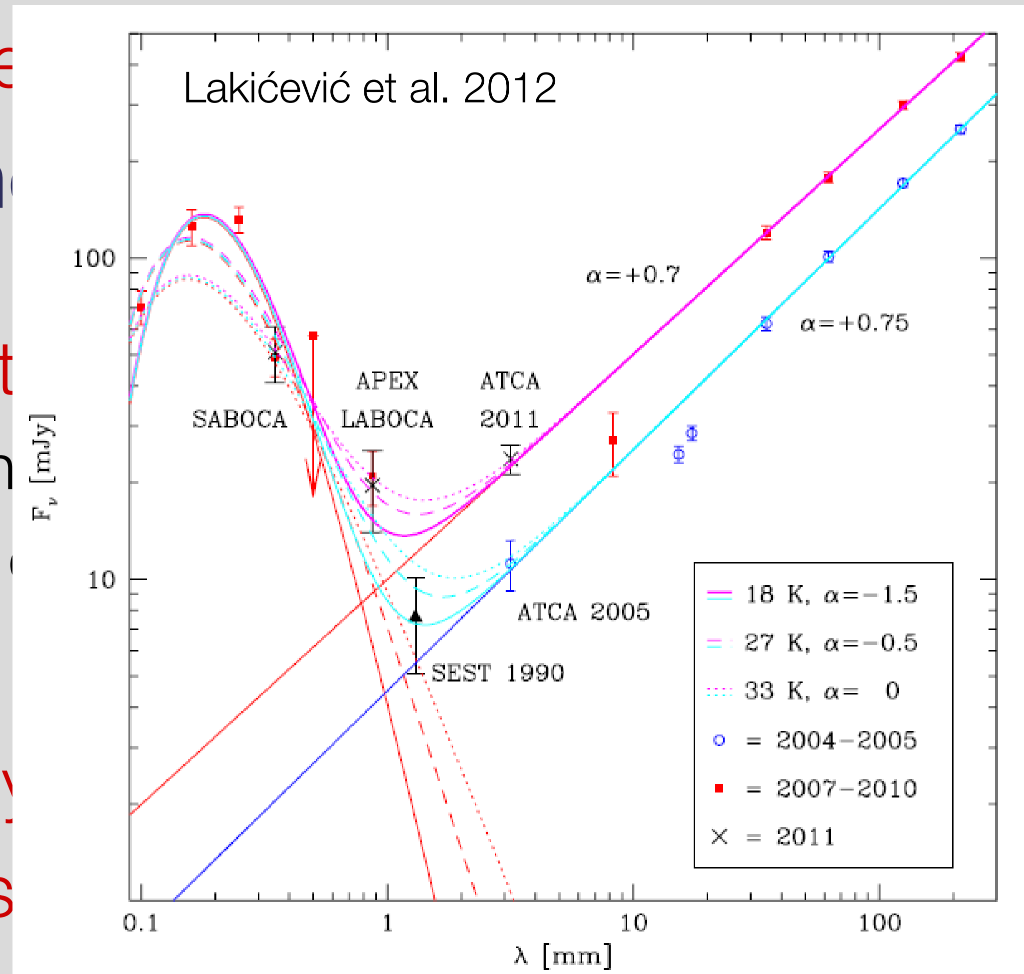
~0.5 $M_\odot$ dust in t

- strongly depen
- location in the

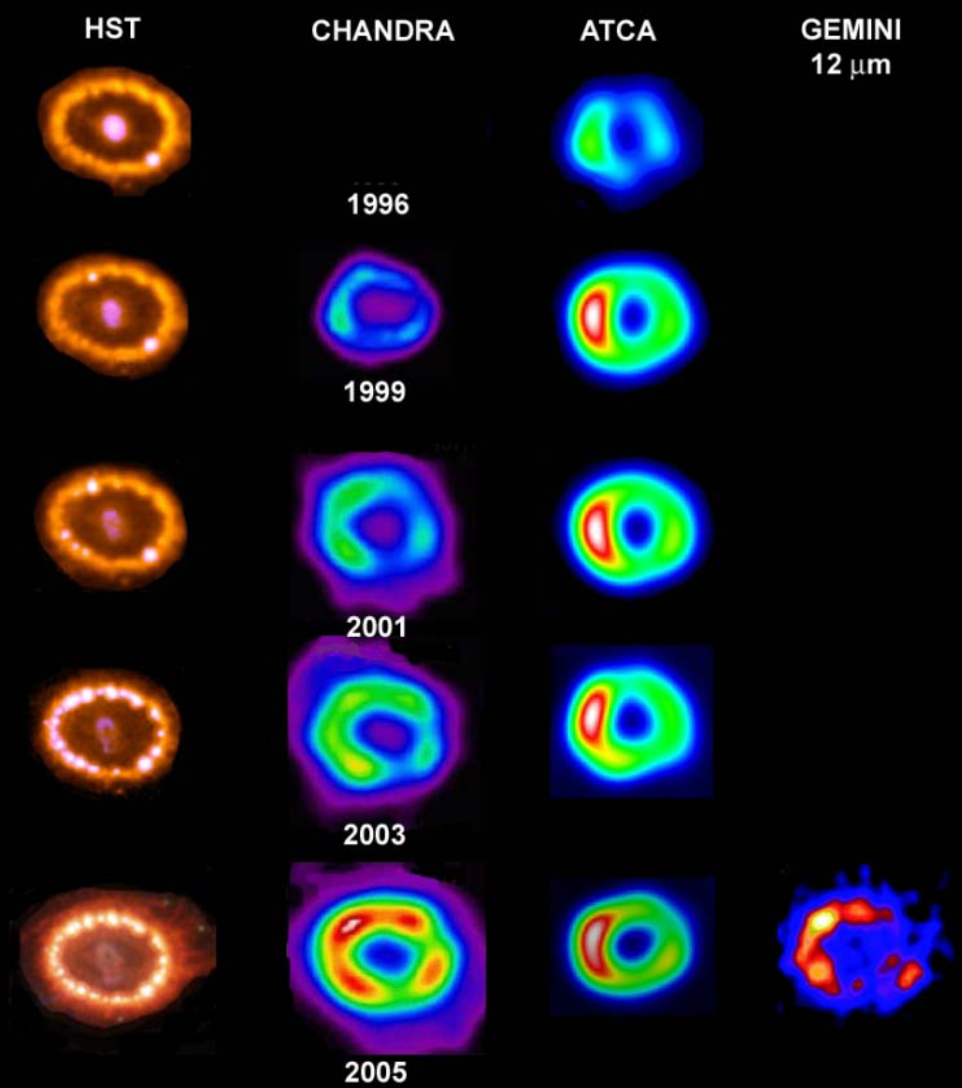
IR/radio SED

dust – black body

synchrotron emis



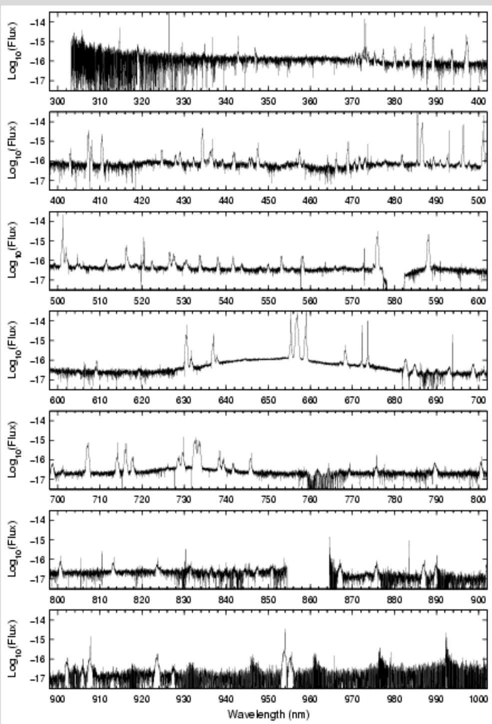
Optical, X-rays and Radio



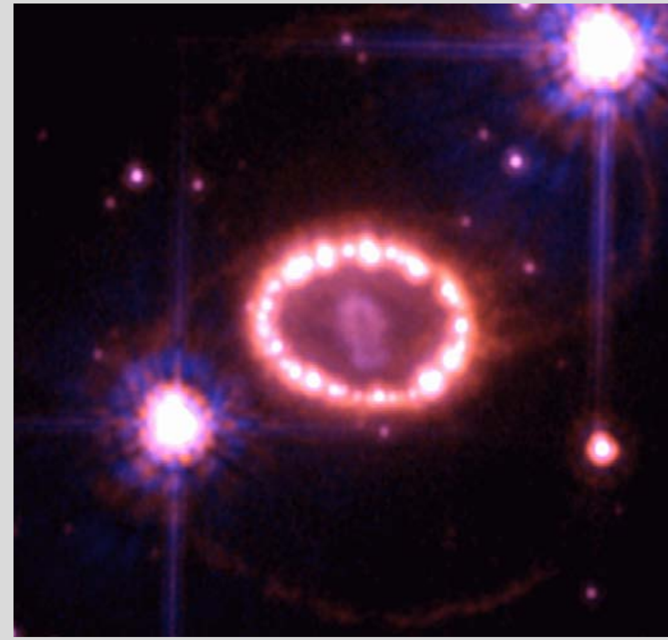
Park et al
Manchester et al

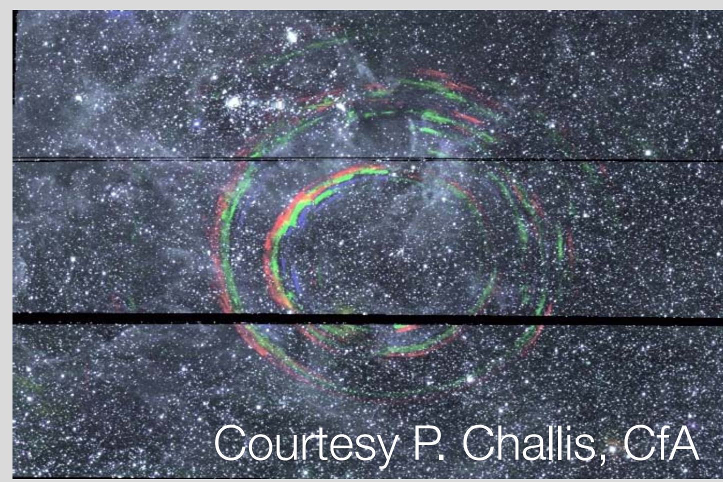
The complex SN 1987A @ 26 years

Combination of several emission sites

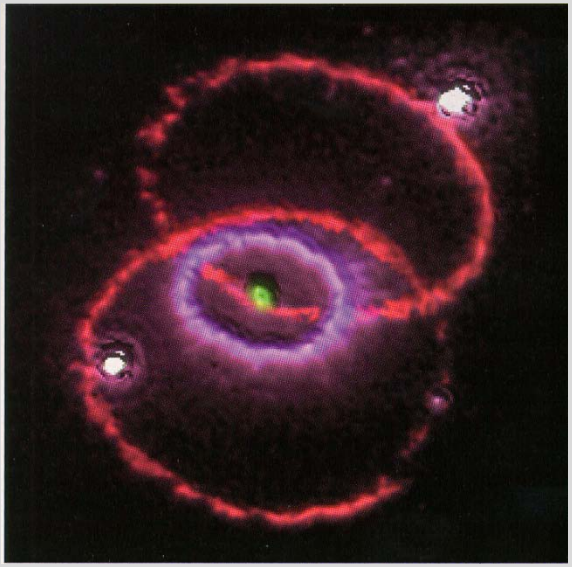


- inner ejecta
- shocked ejecta
- shocked inner ring
- ionised inner ring
- outer rings
- light echoes



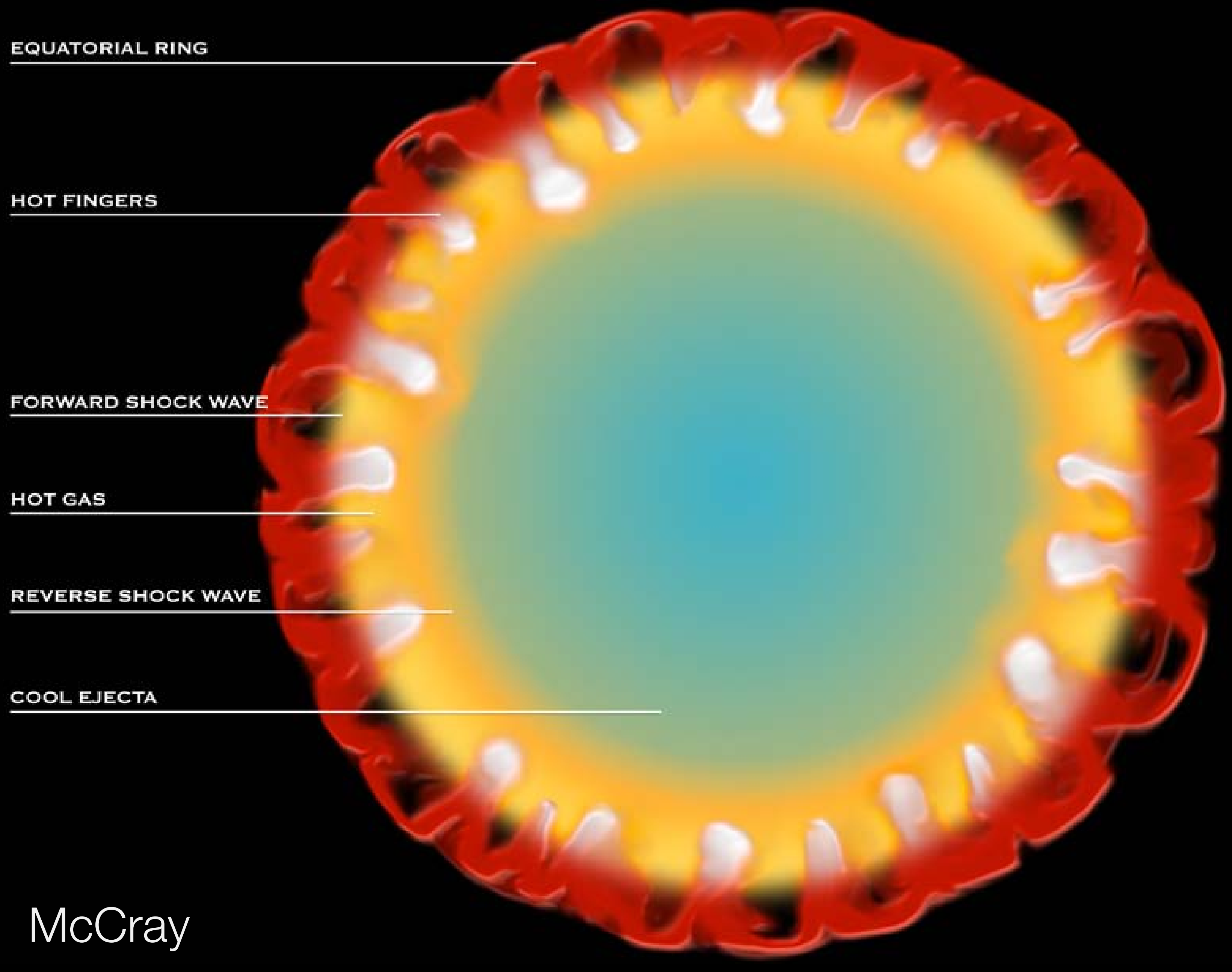


The different emission sites in SN 1987A



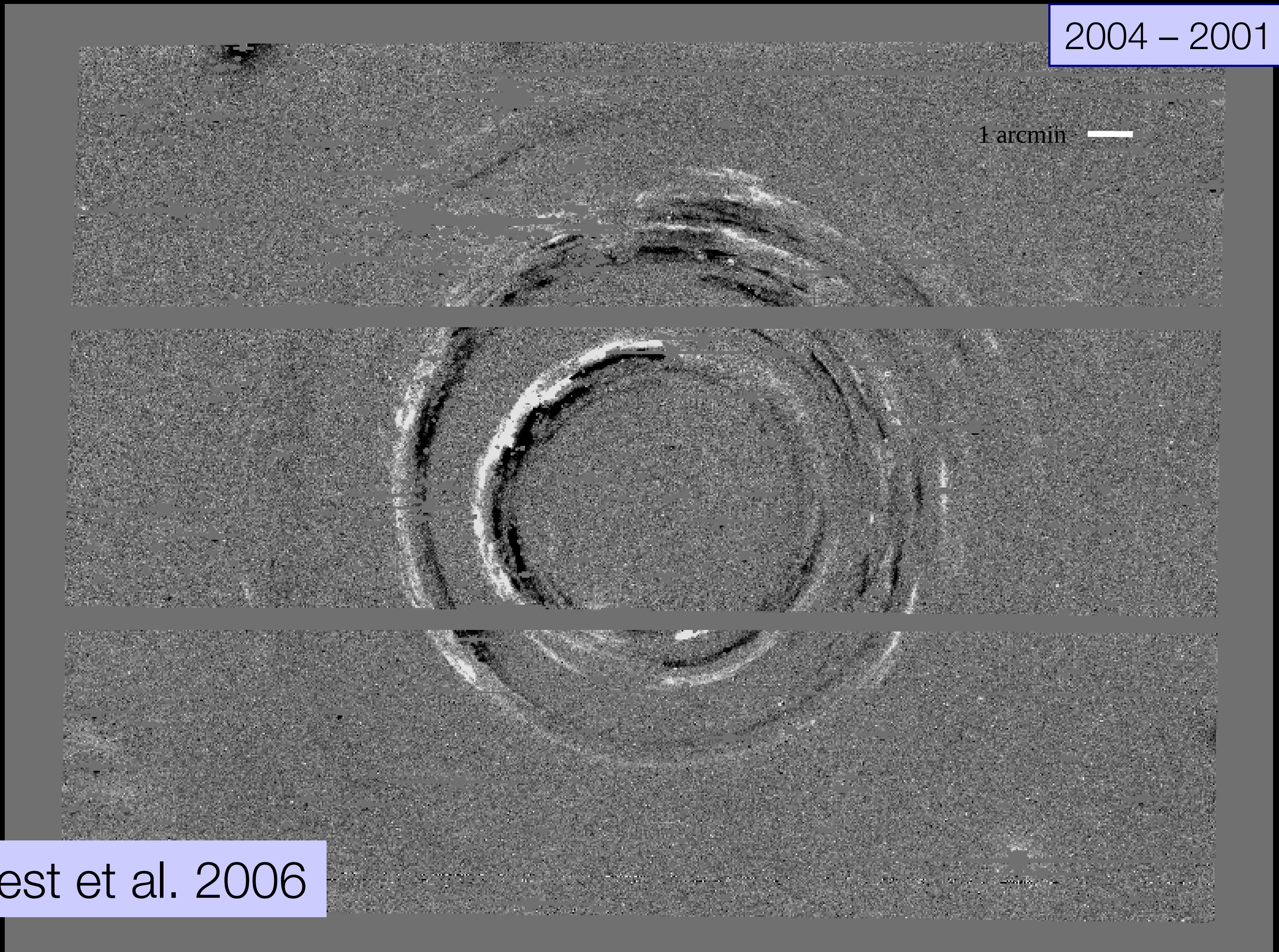
SN ejecta
- radioactively heated material (‘inner ejecta’)
- X-ray heated ejecta
- dust?

Rings
- density enhancements in equatorial (?) plane
- shock physics
  - forward shock (into the ring)
  - reverse shock (into the ejecta)
- dust?


EQUATORIAL RING
HOT FINGERS
FORWARD SHOCK WAVE
HOT GAS
REVERSE SHOCK WAVE
COOL EJECTA

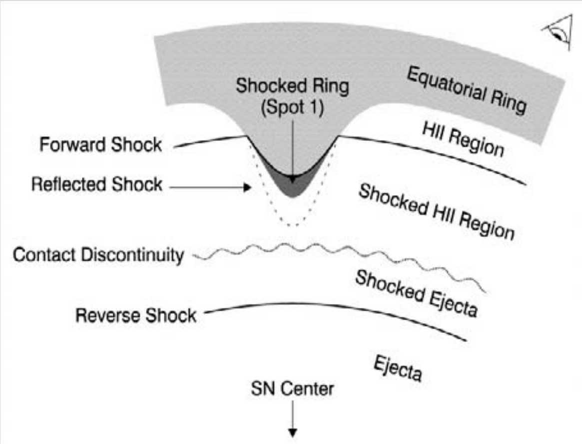
McCray

The hidden SN 1987A



Rest et al. 2006

The ring collision



Dominating at all wavelengths

- shock emission increasing for the past 13 years

Emission from the stationary ring

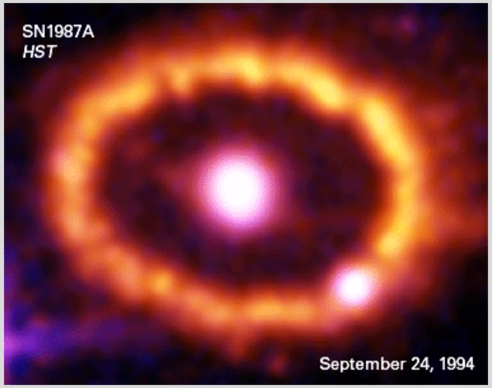
- narrow lines (FWHM ≈ 10 km/s)
- known since 1987 - fading

Shocked ring region (forward shock)

- intermediate lines (~300 km/s)

Reverse shock

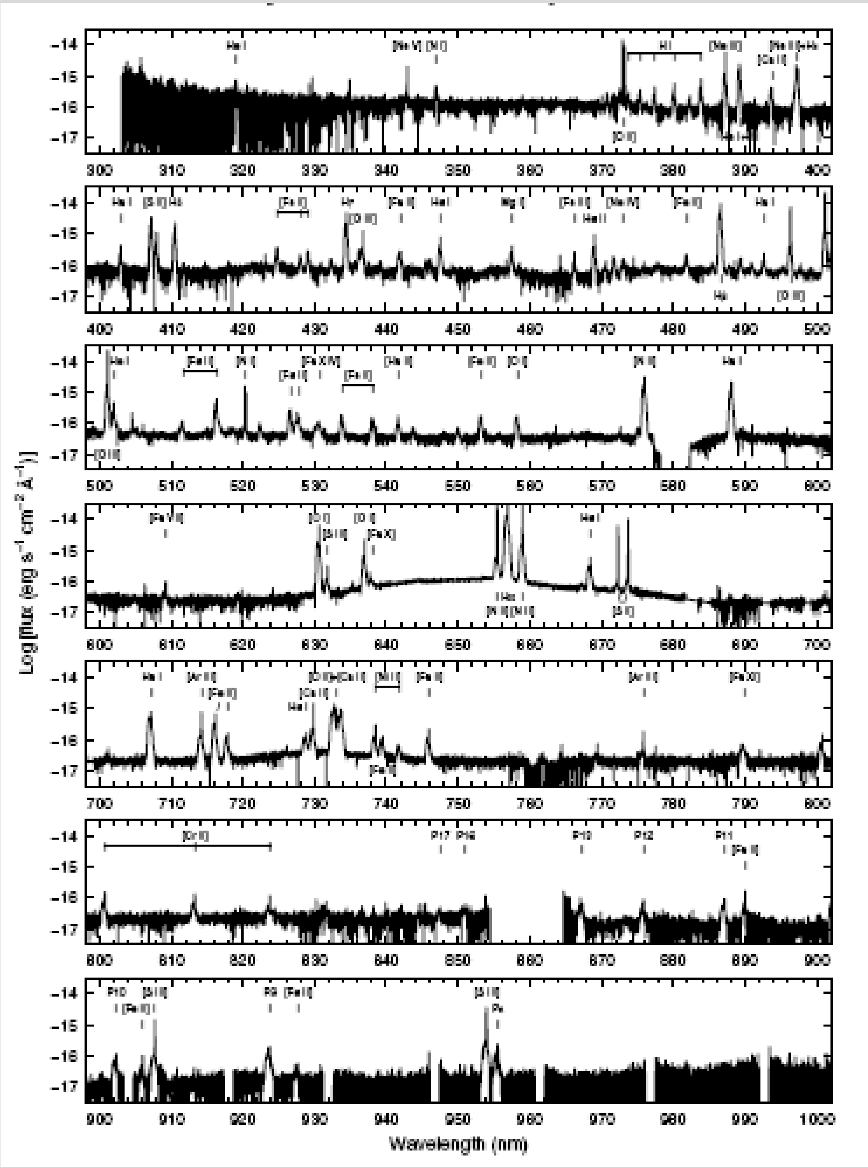
- ejecta (~15000 km/s)



High-resolution spectroscopy

VLT/UVES

- 310-1000nm, Δv≈6 km/s
- ~170 intermediate (~300 km/s) velocity lines
- (half of these are Fe II)
- ring lines (~10 km/s) easily detected
- broad lines from the reverse shock (Hα)

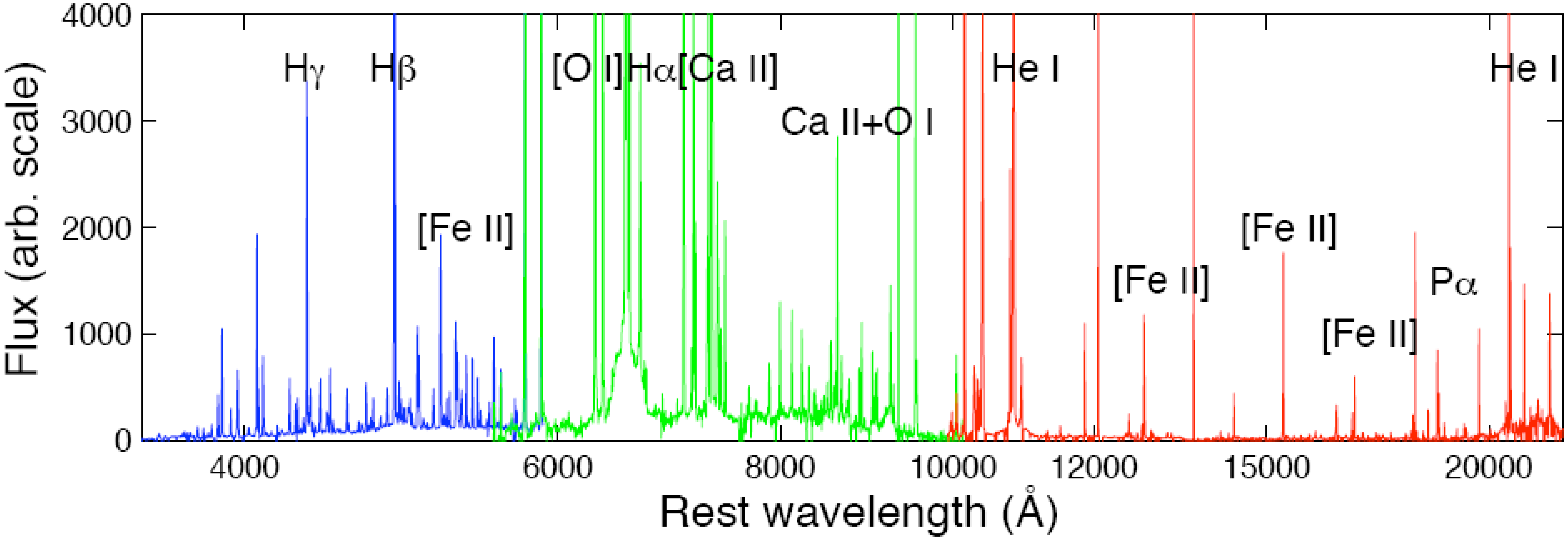


Gröningsson et al. 2008

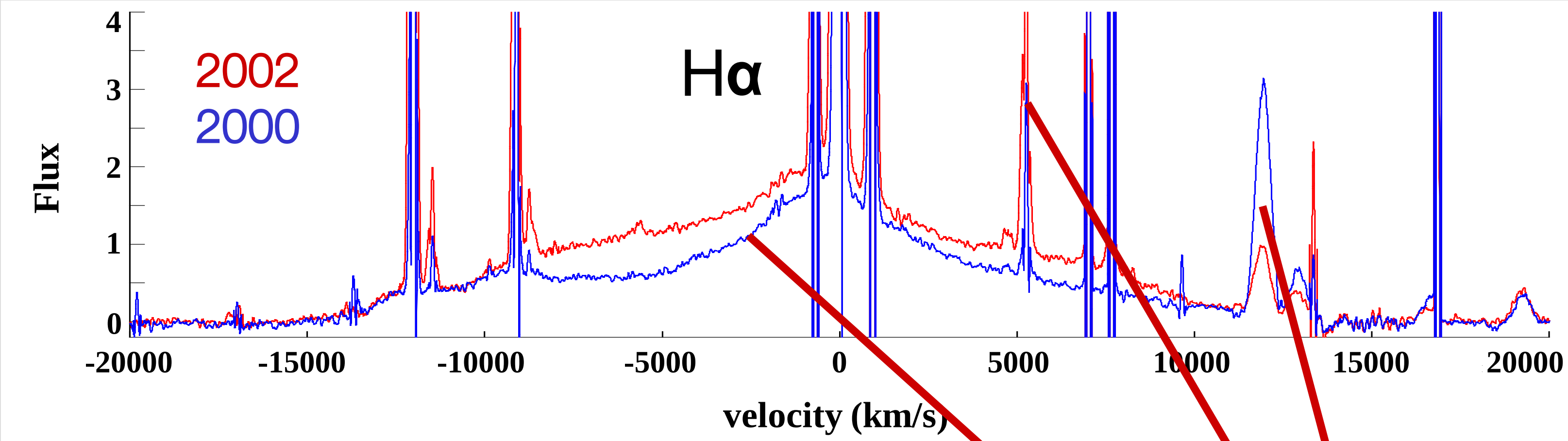
Emission line components

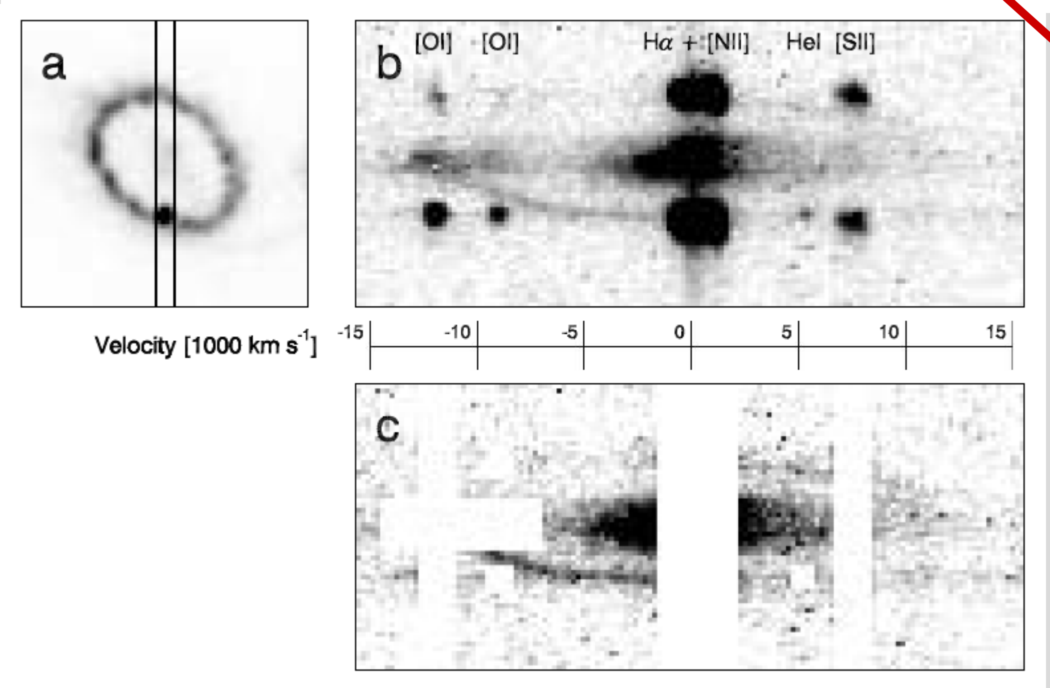
SN 1987A in Dec 2010

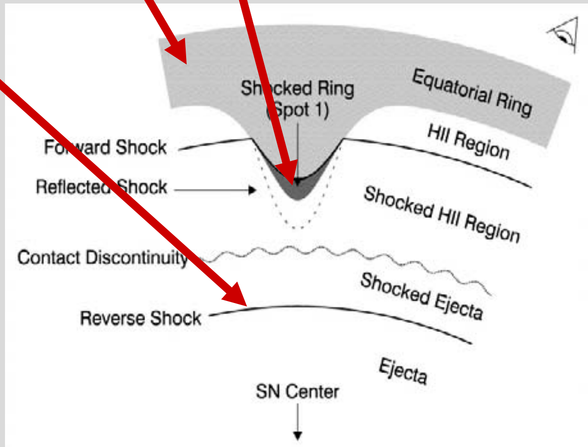
Xshooter



The emission line components





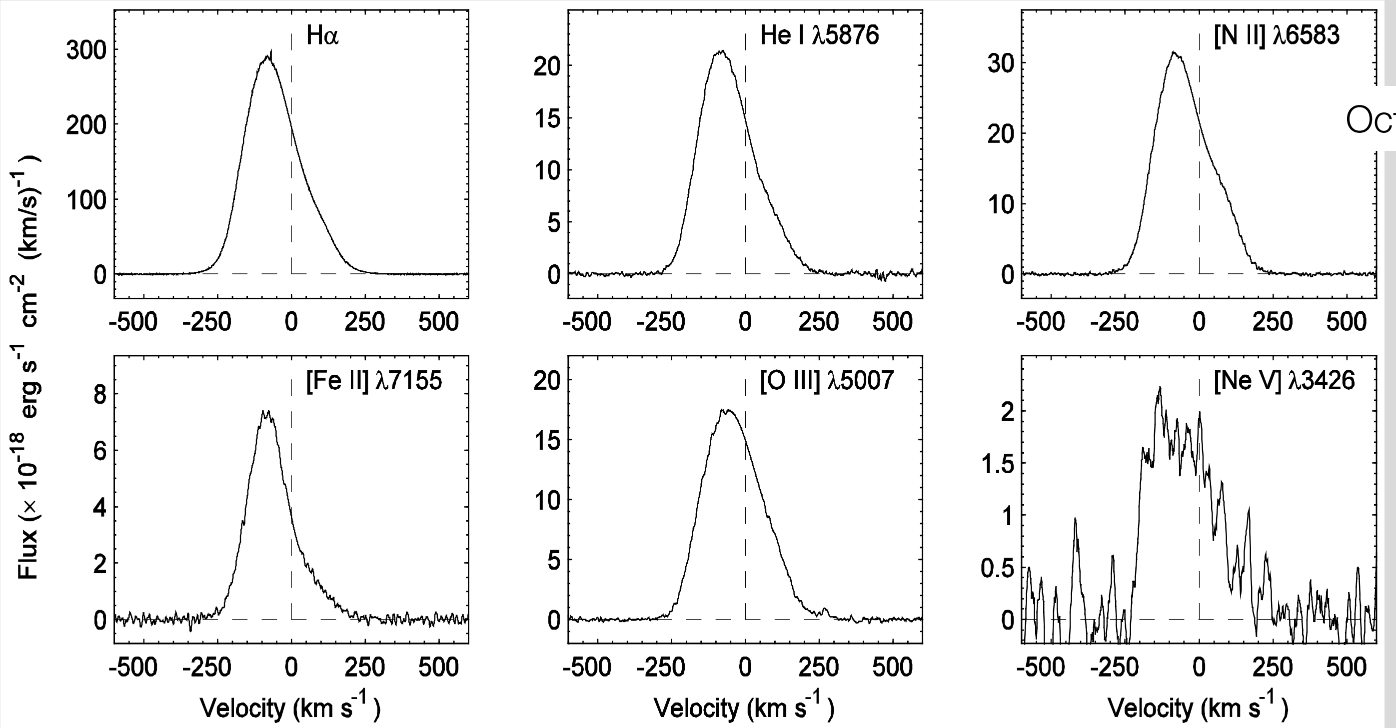


Michael et al. HST/STIS 1999

Intermediate lines – shocked material in the ring

HI, He I, N II, O I-III, Fe II, Ne III-V…..

Cooling, photoionized gas behind radiative shock into ring protrusions

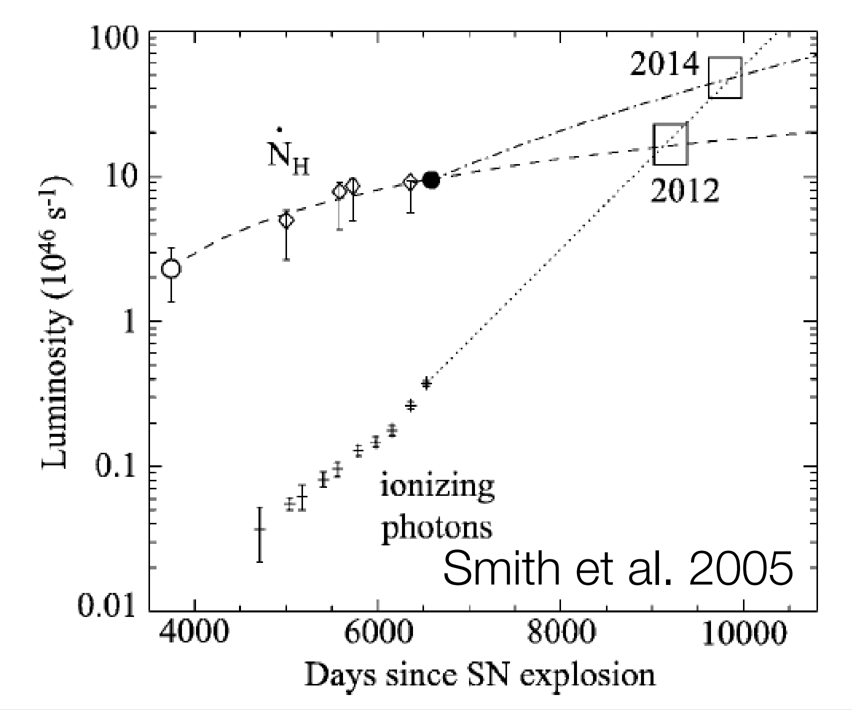


Oct 2002

Reverse shock

Forward shock is ionizing the ejecta

- At some point all H atoms will be ionized before they reach the reverse shock and the emission will turn off
- X-rays give the amount of ionizing photons
- Monitoring the Hα emission will tell



Hydrogen in SN 1987A

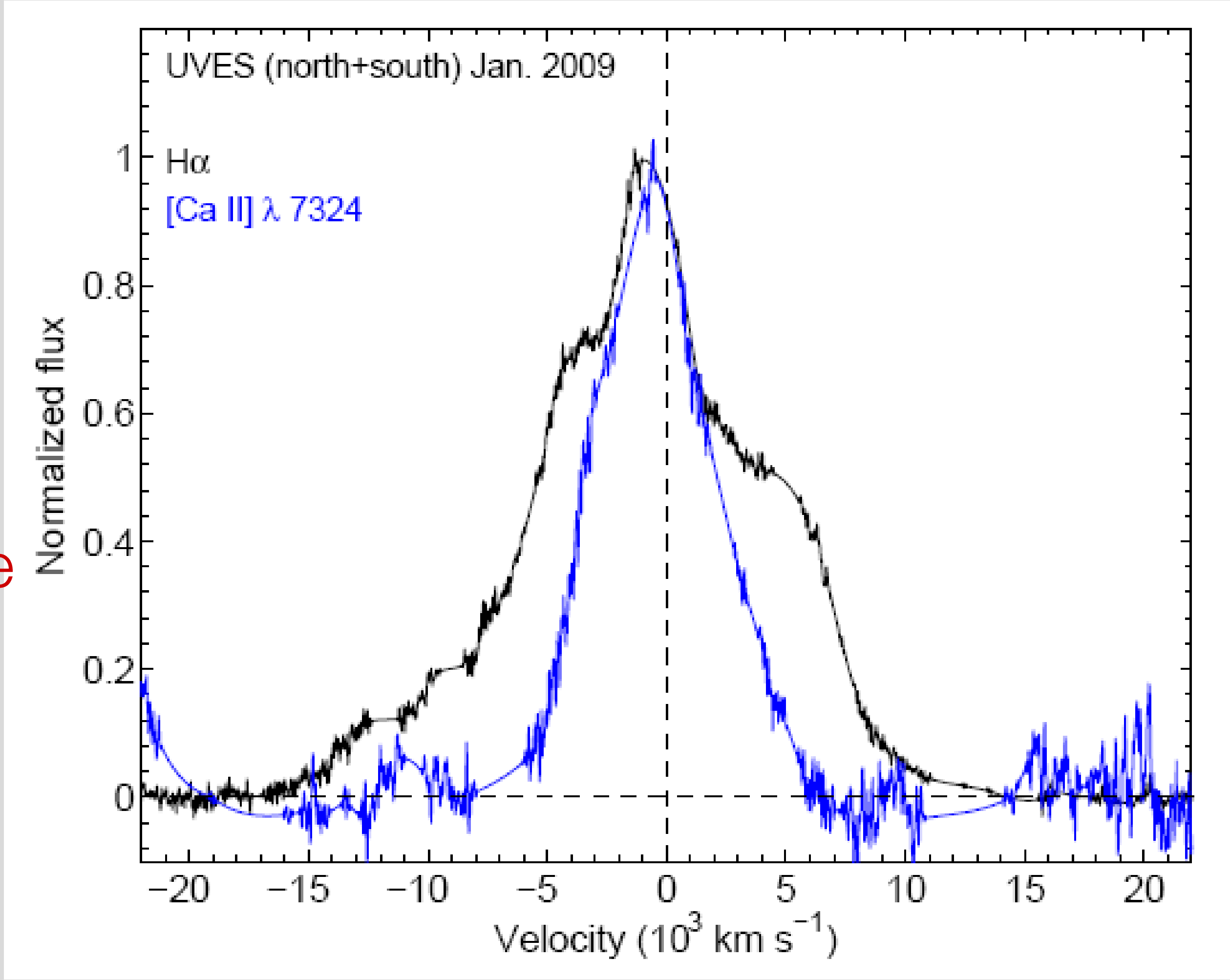
'Clean Hα'

Flux increase by 4 to 6 from 2000 to 2007

v_{max}>11000 km/s

larger than possible in equatorial ring

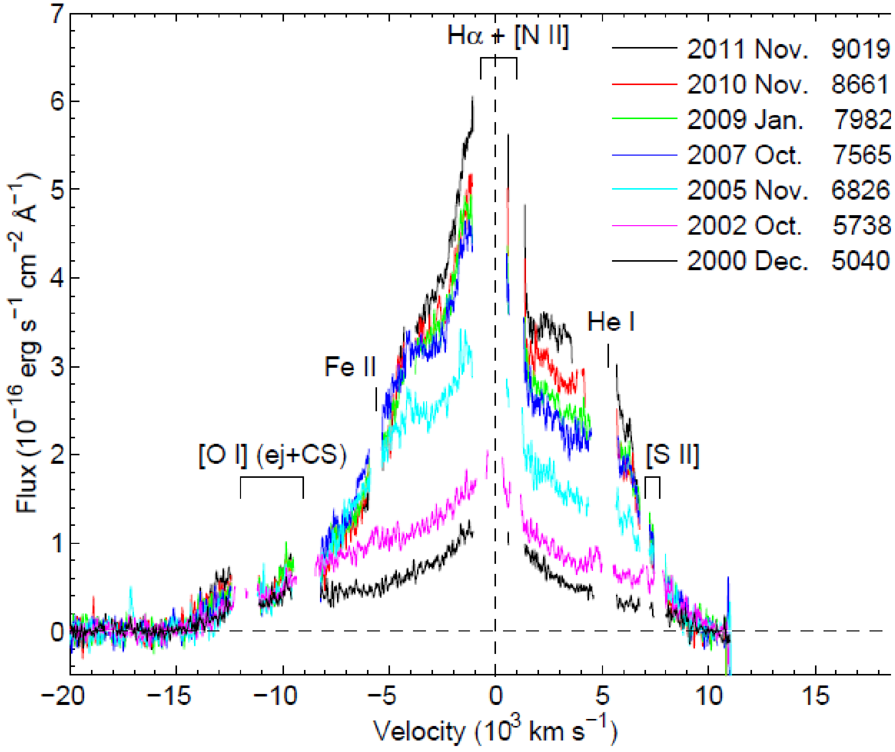
anisotropic expansion

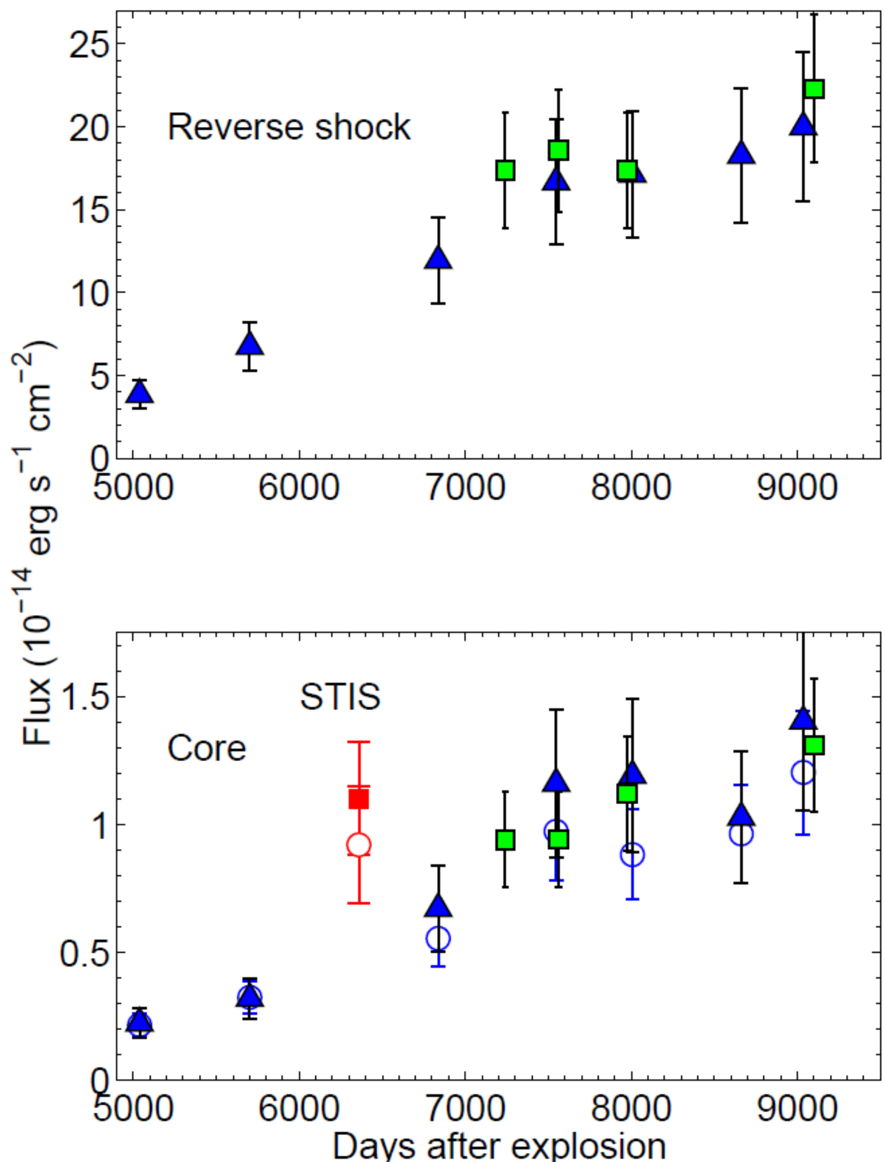


Fransson et al. 2013

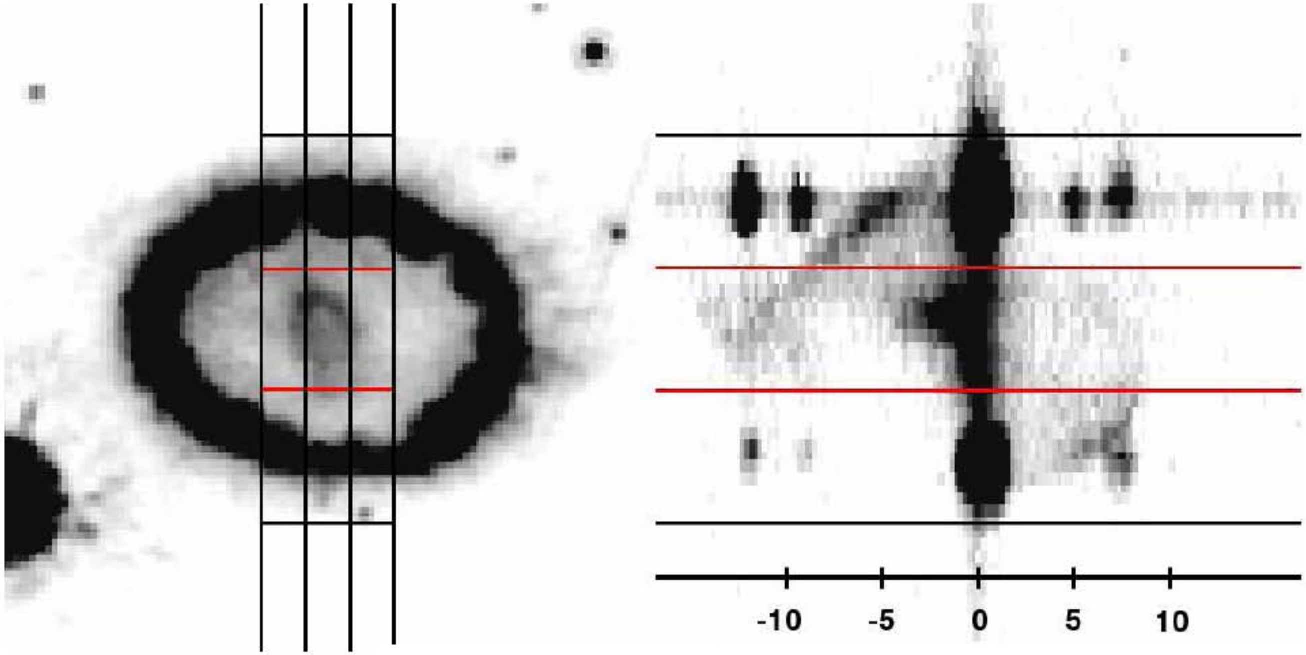
Evolution of Hα

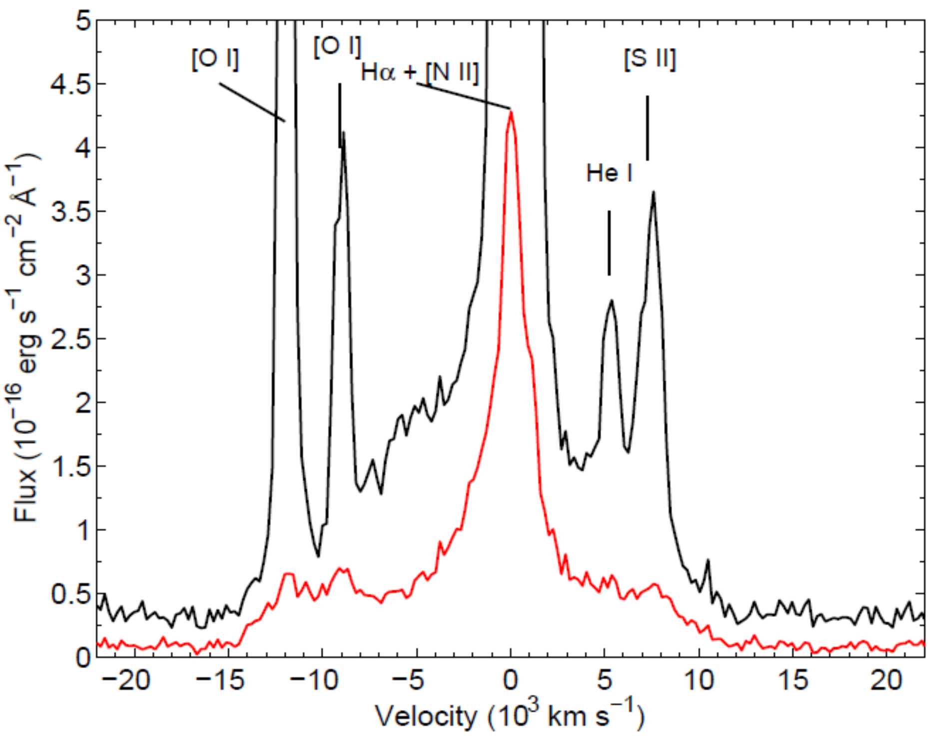
Combination of FORS, UVES and STIS data





Complex emission



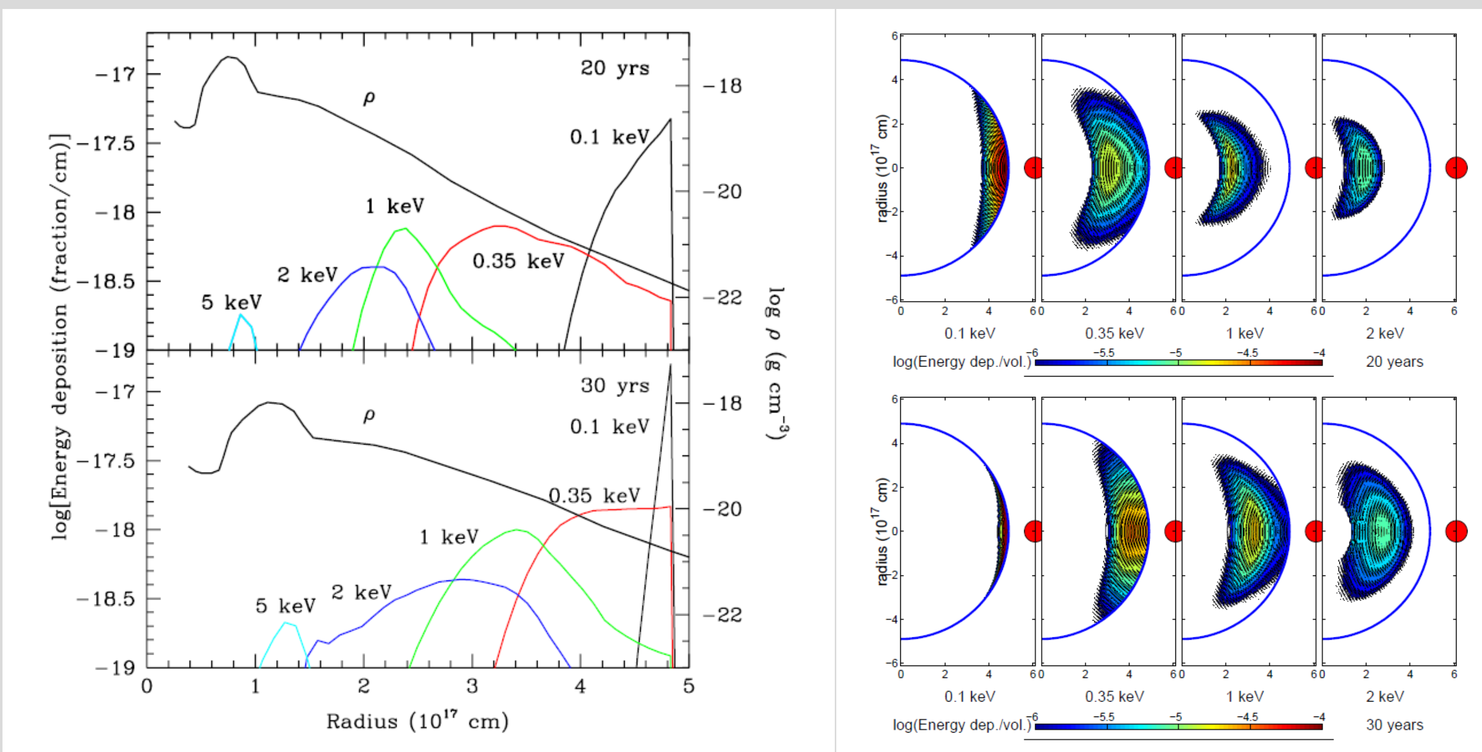


Disentangle the ring from reverse shock from inner ejecta

Reverse shock

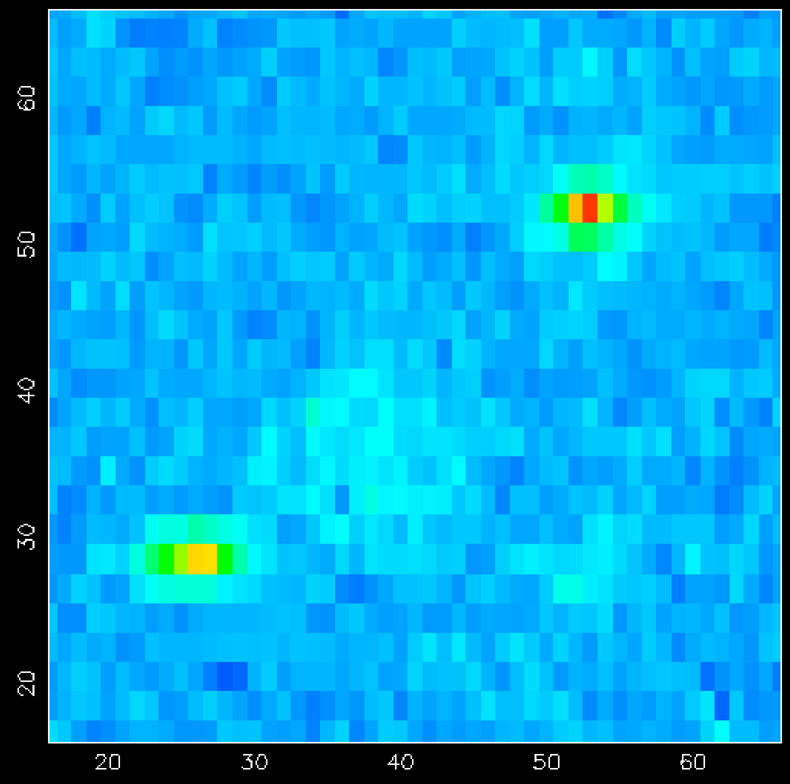
Only seen in hydrogen lines Hα and Hβ

- Lower velocity ‘core’ (<4500 km s^{-1}) from unshocked ejecta heated by X-rays



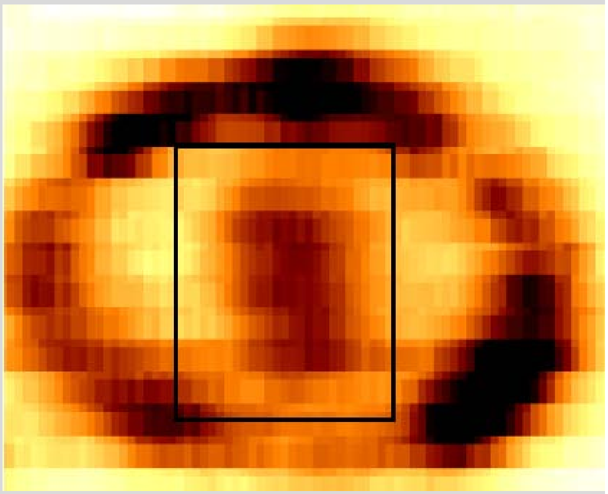
Spatially resolved infrared spectroscopy

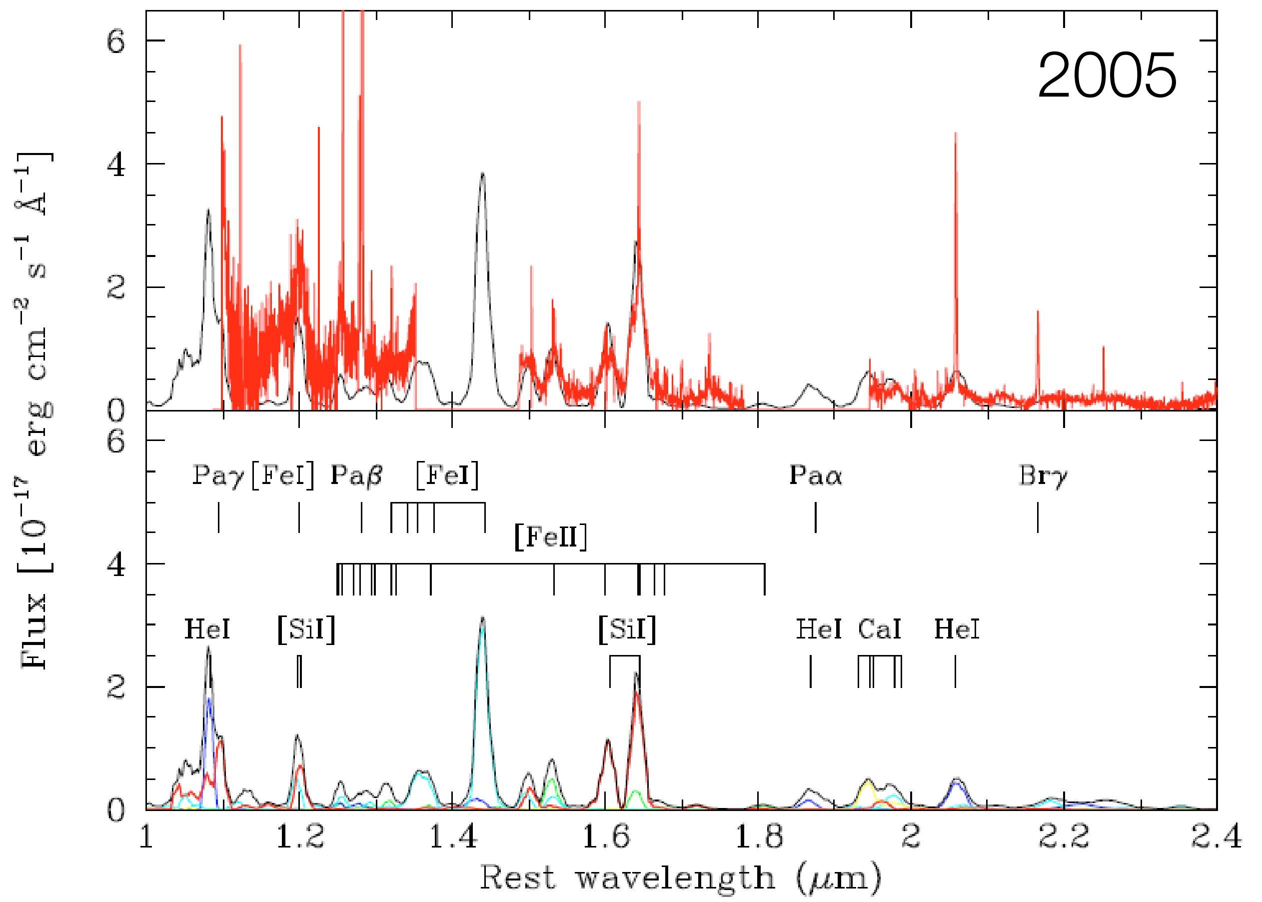
- separate ring from ejecta
- trace the ring in individual lines
- get spectra from separate regions
- photometry of selected regions



Ejecta resolved

- Ground-based near-IR data show spatially resolved ejecta

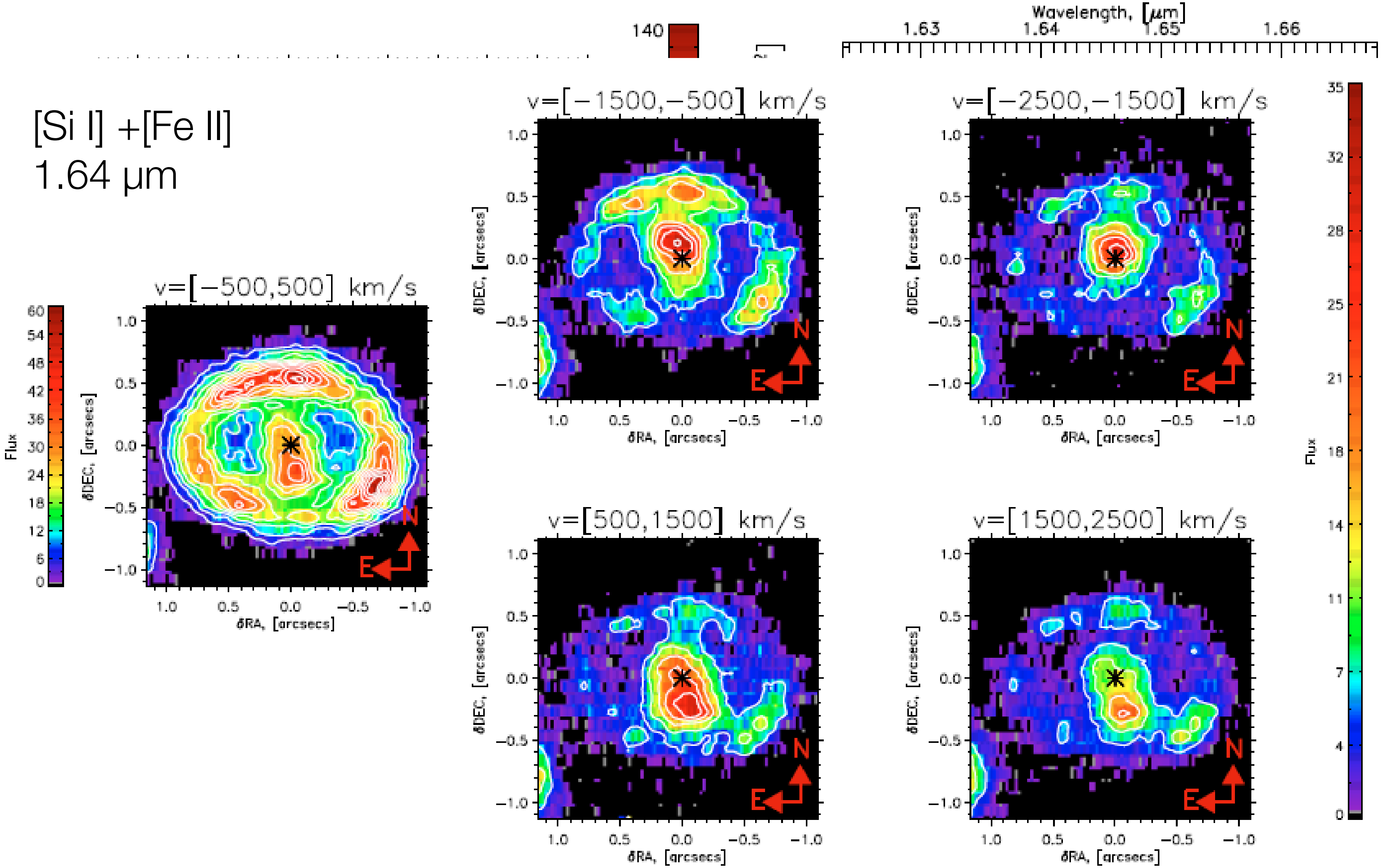




Kjær et al. 2010

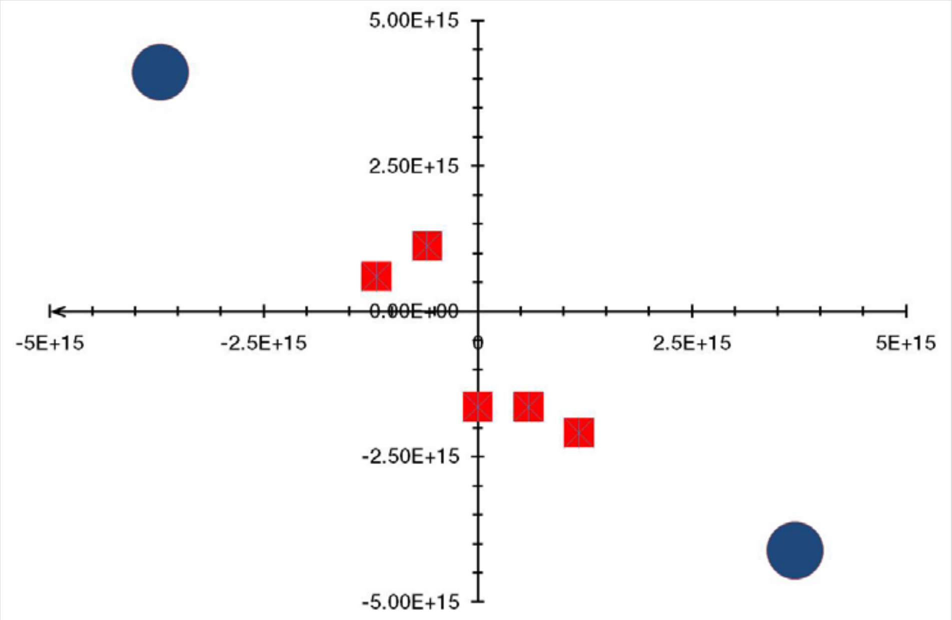
Asymmetry in the ejecta

[Si I] +[Fe II]
1.64 µm

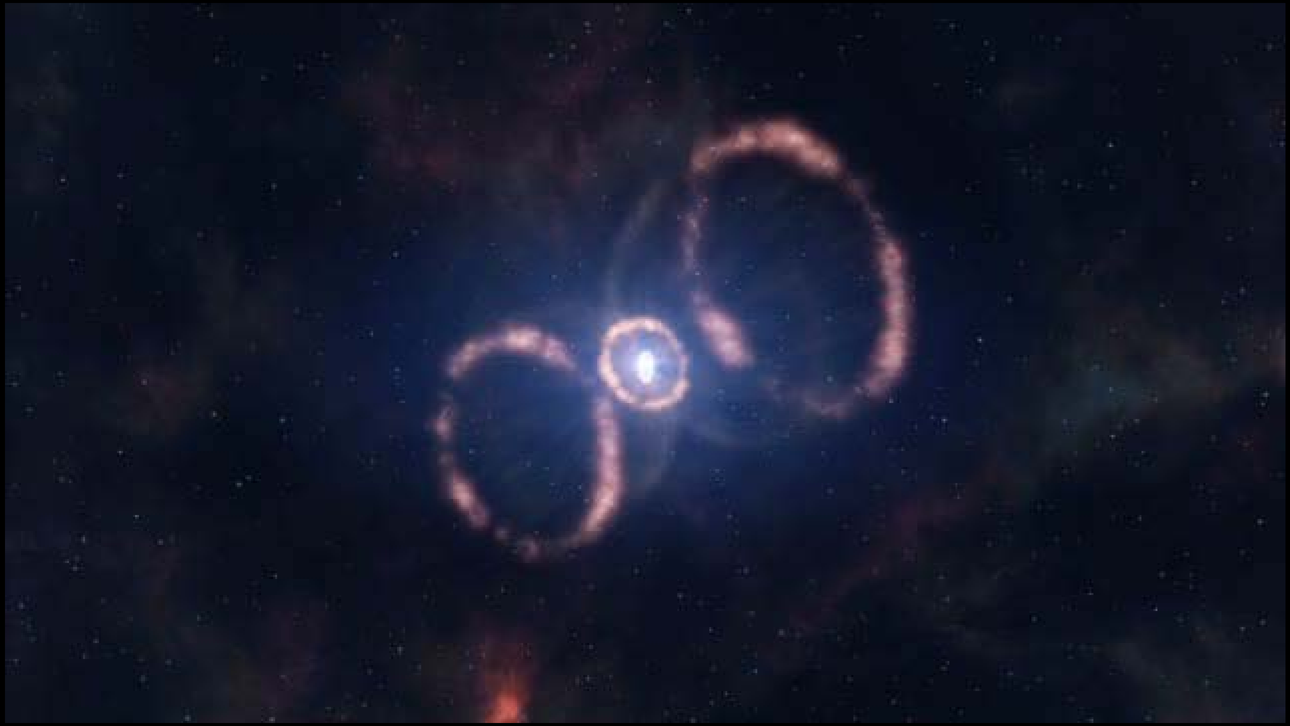


Ejecta kinematics

- Southern part is redshifted, northern ejecta are blueshifted
- Expansion velocity roughly 3000 to 4000 km/s
- This is the same orientation as the inner ring!
- Ejecta lies in the same plane as the ring!

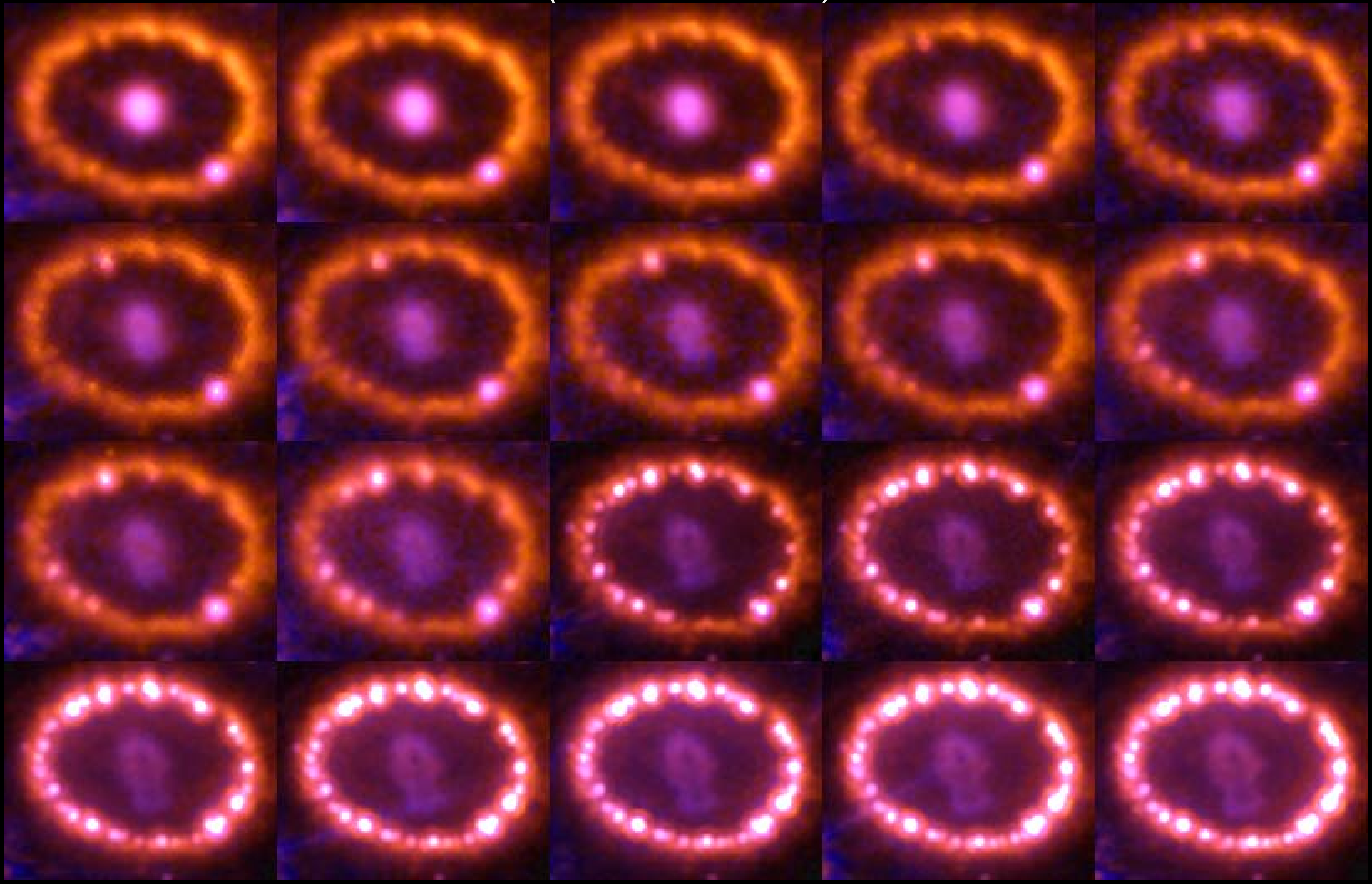


How this could look like



SN 1987A evolution

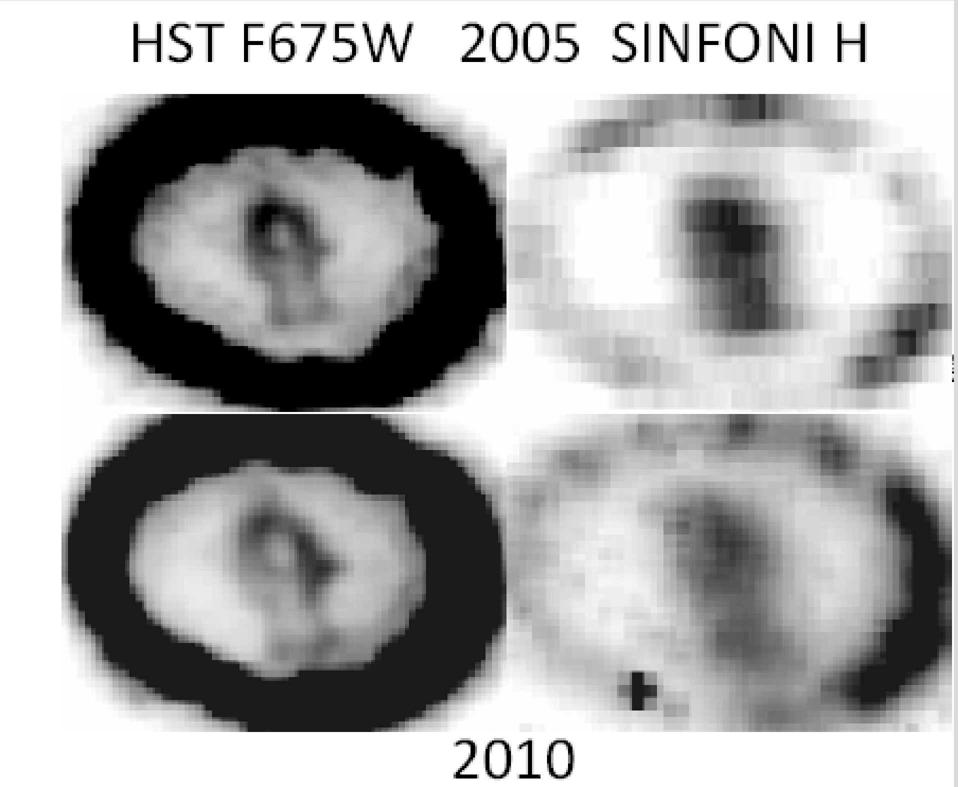
(1994-2010)



The inner ejecta

Comparison optical vs. IR

- optical
  - heated by X-rays
- IR
  - radioactive heating



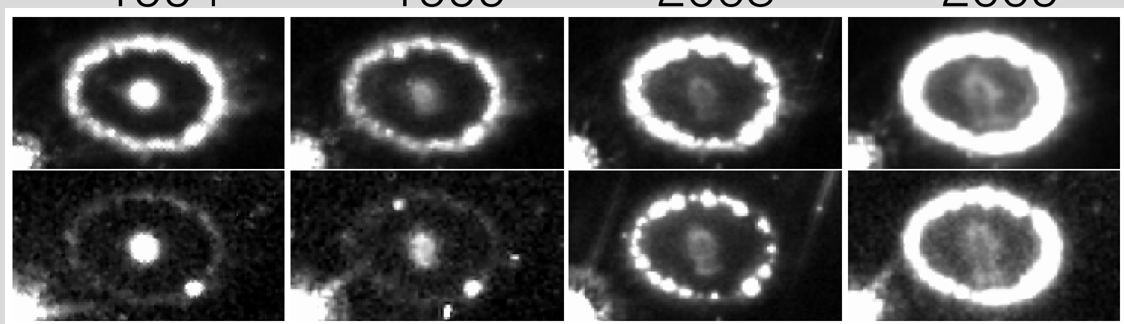
The next surprise

X-raying the ejecta of SN 1987A

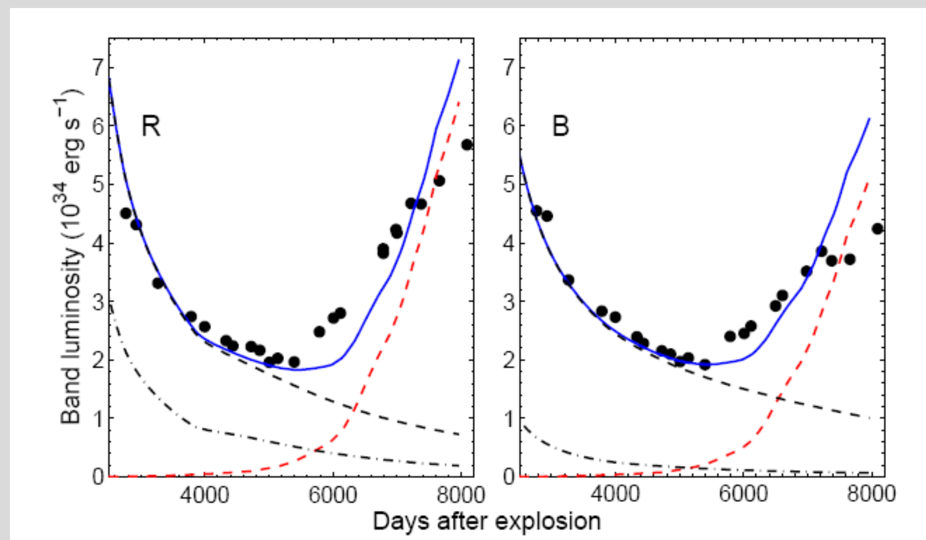
1994 1999 2003 2009

R

B



Larsson et al. 2011



- flux of the inner ejecta has increased again (starting at about 13.5 years)
- sign of additional energy input

What's happening?

The outer ejecta has reached the equatorial ring and creates shocks in the dense material

X-rays are emitted in all directions

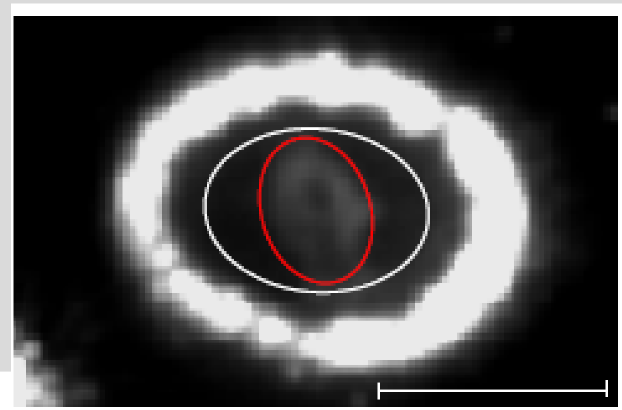
heat the inner ejecta

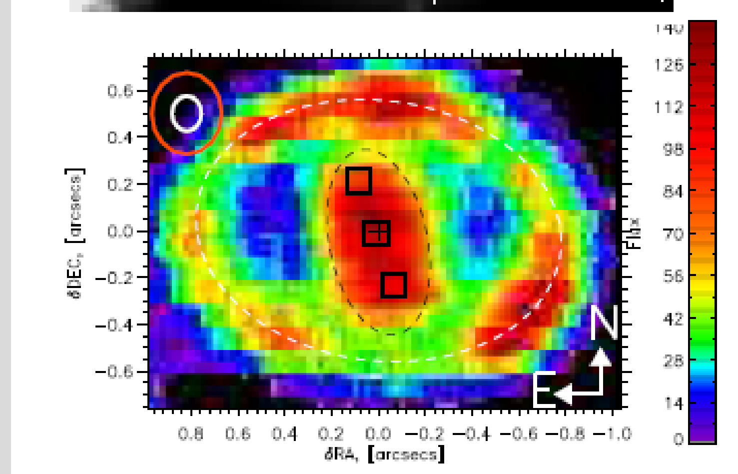
Other possibilities excluded

- reverse shock in HII region → no increase in (broad) Lyα or Hα observed
- pulsar → no trace so far (e.g. in radio or X-rays)
- transition from optically thick to optically thin dust → unlikely to occur at this point

Transition to SN remnant

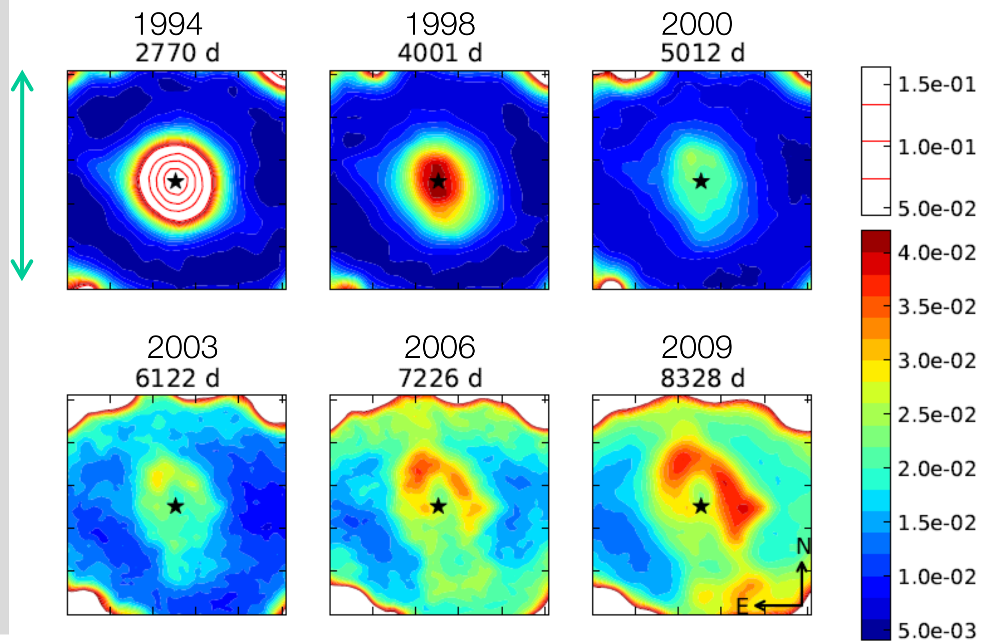
- SN 1987A no longer powered by radioactive decays, but the kinetic energy from the shocks
- Heating on the outskirts → shell-like structure
- Different from the Fe-core still heated by ^{44}Ti
  - – Kjær et al. (2010);
  - – SINFONI observations



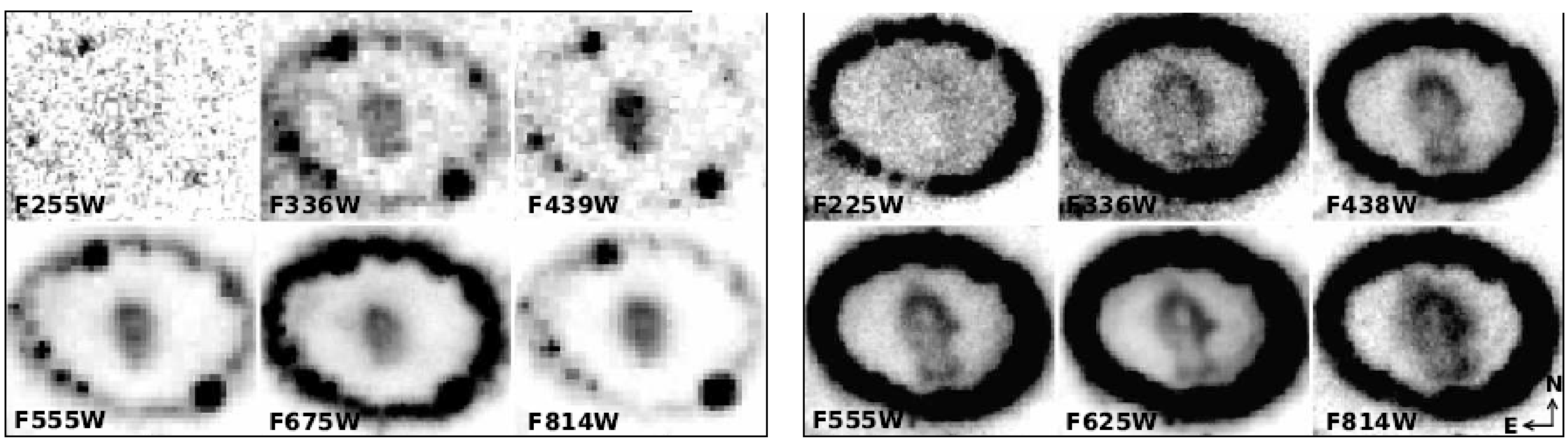


Evolution of the inner ejecta

Clear change in morphology at optical wavelengths



Larsson et al. 2013

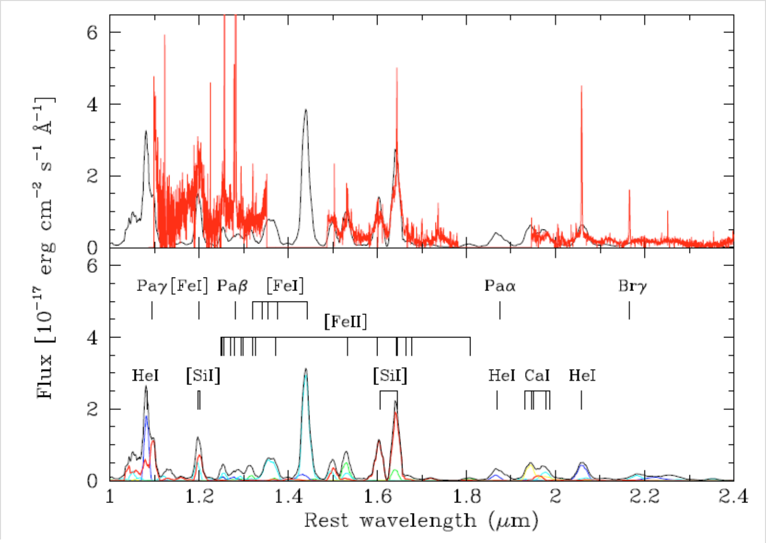


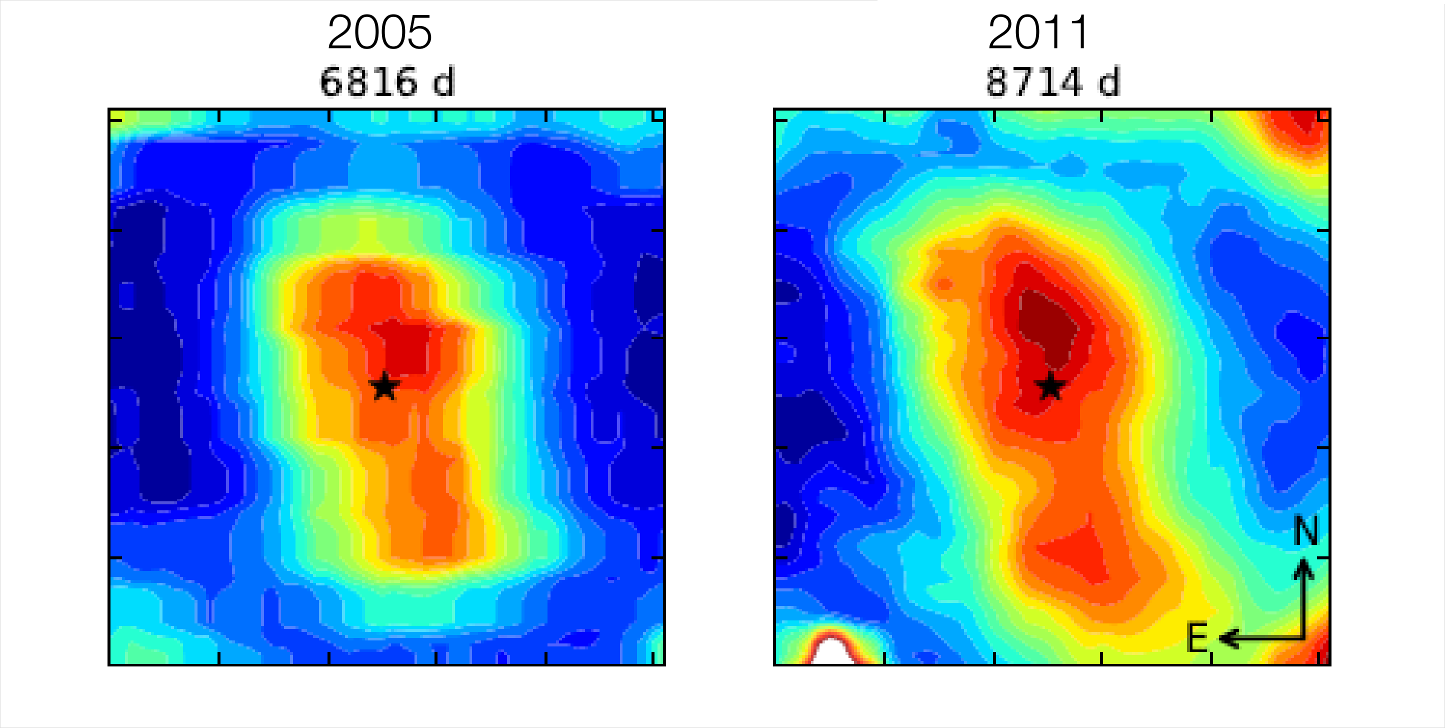
13 Nov 2000

12 Dec 2009

IR observations

[Si I]/[Fe II] 1.644μm emission



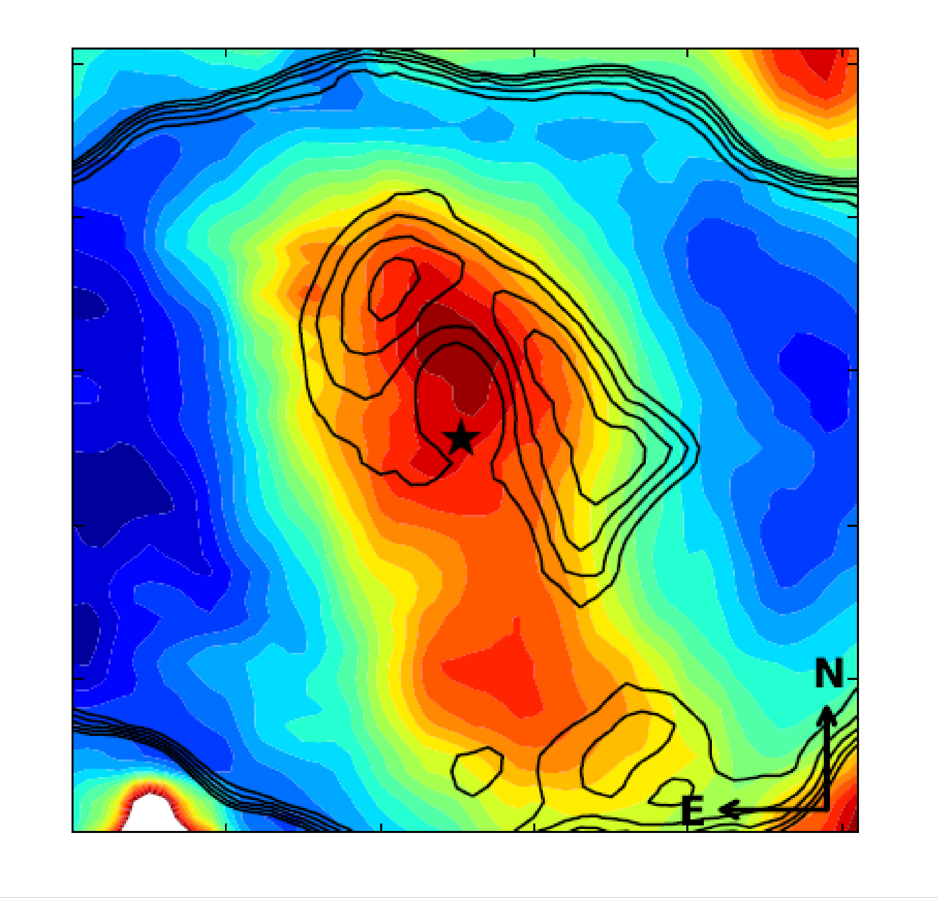


Complementary optical and IR observations

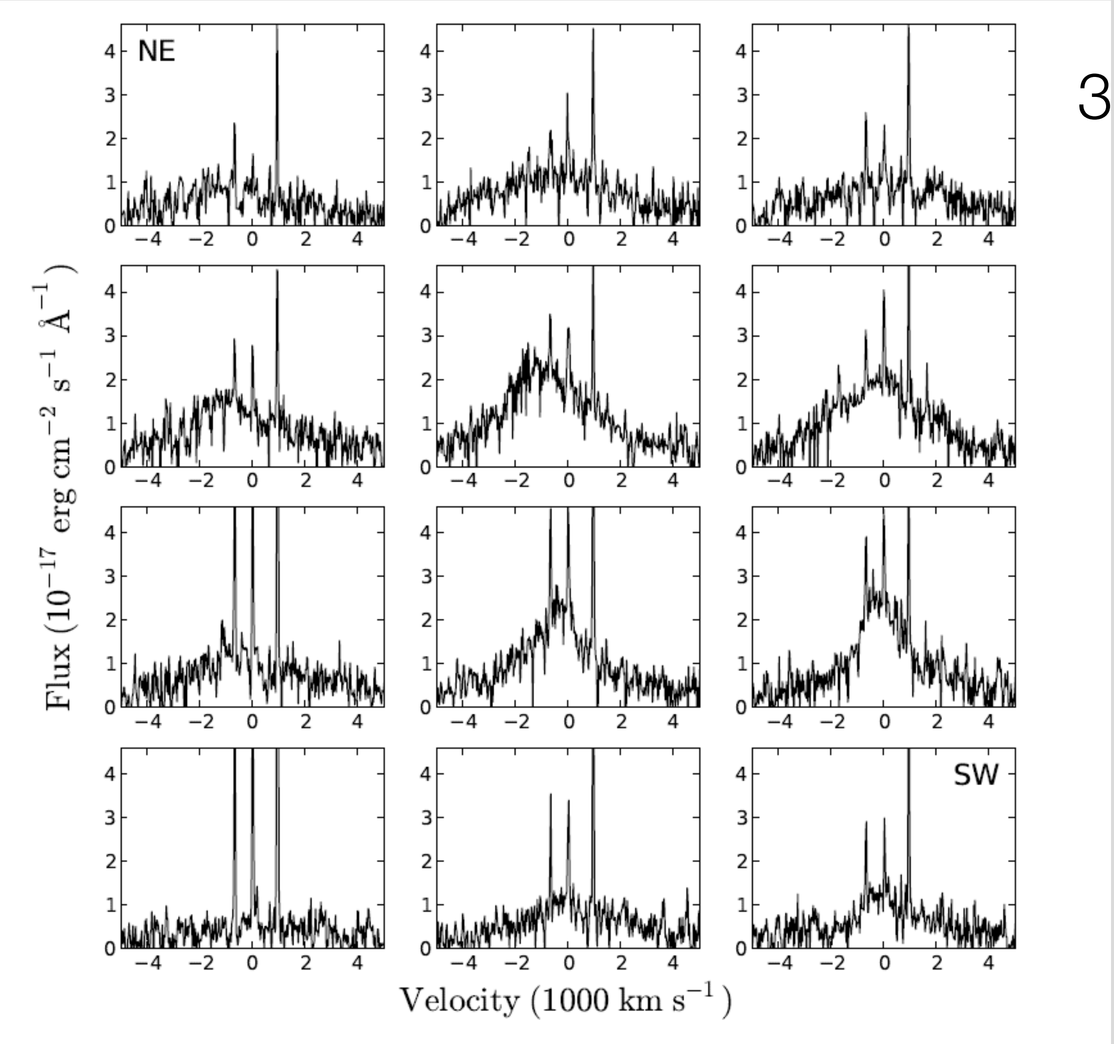
Optical emission clearly different from the IR

- [Si I]+[Fe II] concentrated towards the center
- Optical ($H\alpha$) in a 'shell'

➢ Different energy sources

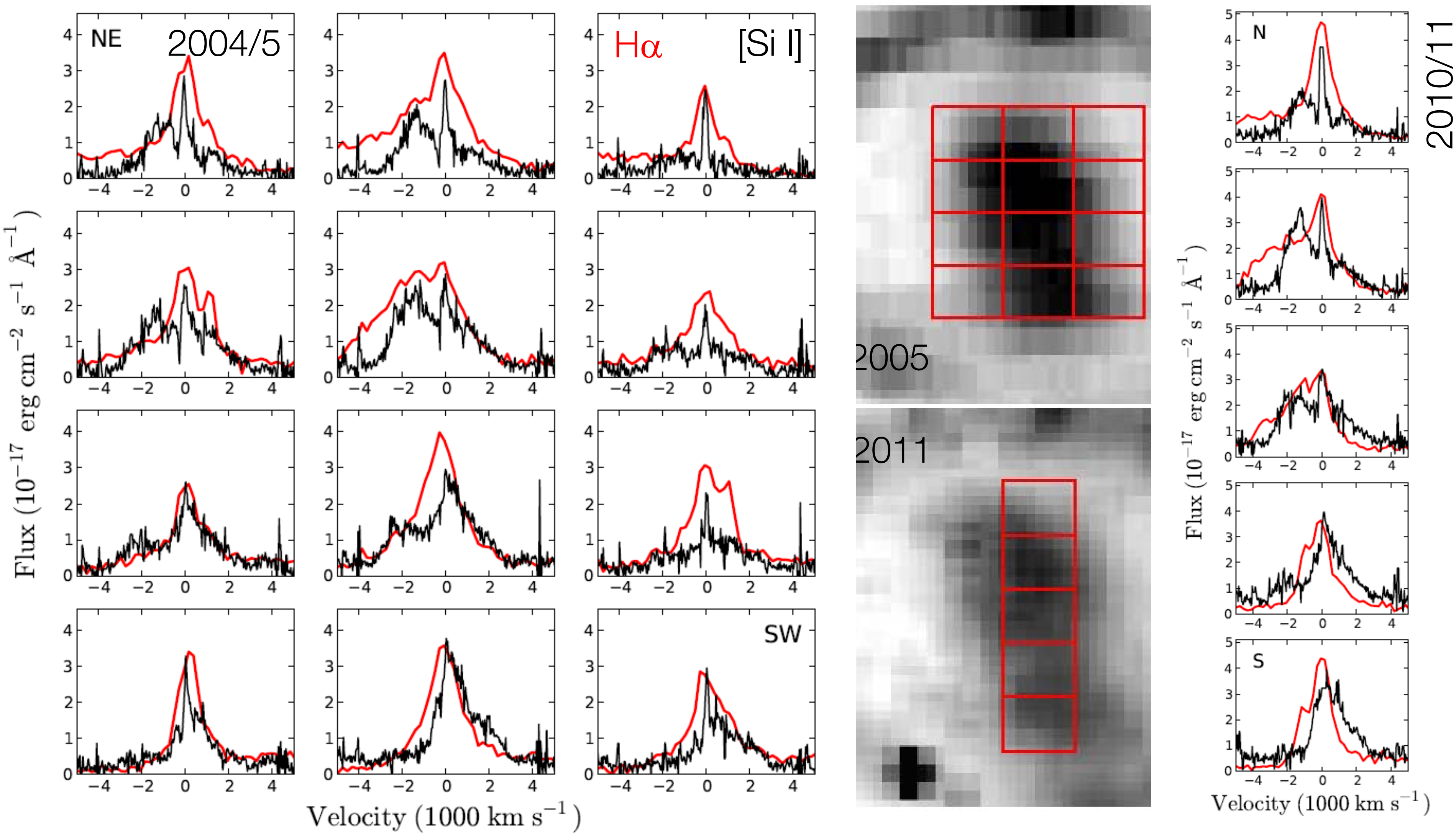


‘Integral field’ spectroscopy



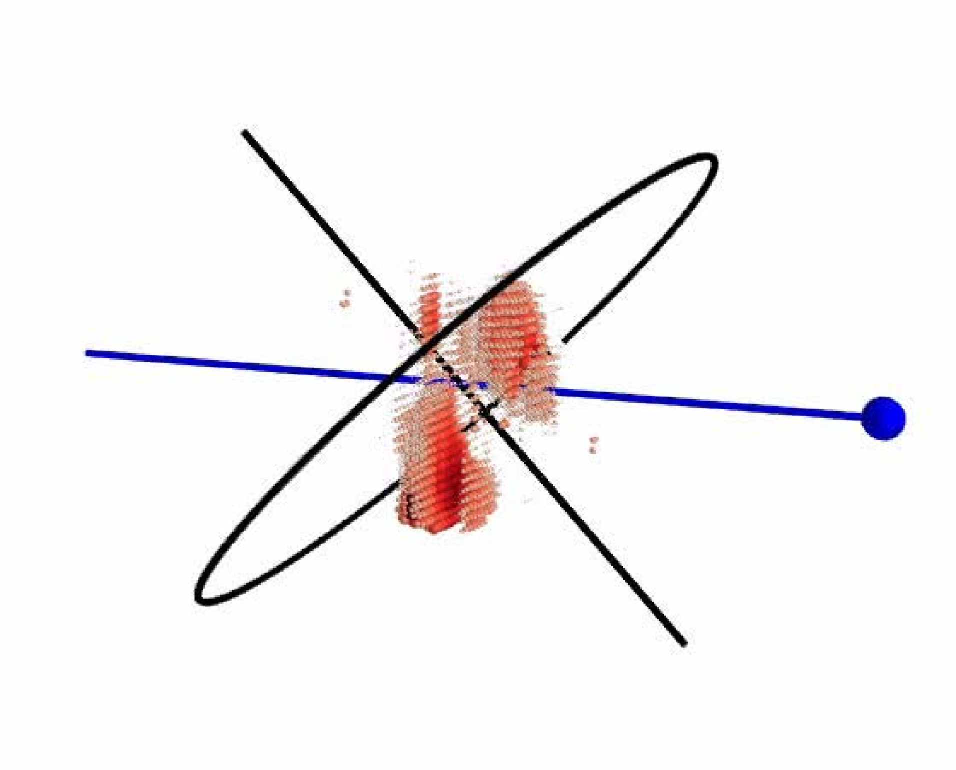
30 Aug 1999

Comparison optical and IR



3-dimensional picture

- Derived from [Si I]+[Fe II] 1.644μm emission
- Emission in the plane of the equatorial ring
- Clumpy distribution
- Extending out to ~3500 km s^{-1}



Larsson et al. 2013


No sign yet of a neutron star
Collapse to a black hole?

Summary

SN 1987A is as interesting as ever

- ring collision is in full swing
  - forward shocks in the ring
  - reverse shock in the debris (outer ejecta)
- shocked material can be analyzed through the X-rays and the coronal lines
  - now heating the inner ejecta as well
- first direct look at an explosion
  - resolved inner ejecta (iron core) are the immediate reflection of the explosion mechanism
  - confirmation of the standing accretion shock instability (SASI) → neutrino convection in the explosion

More to come

- Complete destruction of the ring
- Illuminating the outside
    - beyond the inner ring
- Detailed mapping of the inner ejecta
    - details on explosion mechanics and distribution of synthesized material
    - dust formation
        - where is the dust that formed early on?
        - what is the dust composition?
    - what will be lost due to the external illumination?
- Where is the neutron star?
    - limits uncomfortable for the theory

SN 1987A will be the first supernova that we can observe forever.

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