SUPERNOVA 1987A: THE BIRTH OF A SUPERNOVA REMNANT

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- Introduction
- Circumstellar rings
- Reverse shock
- Hotspots
- X-ray emission
- The future

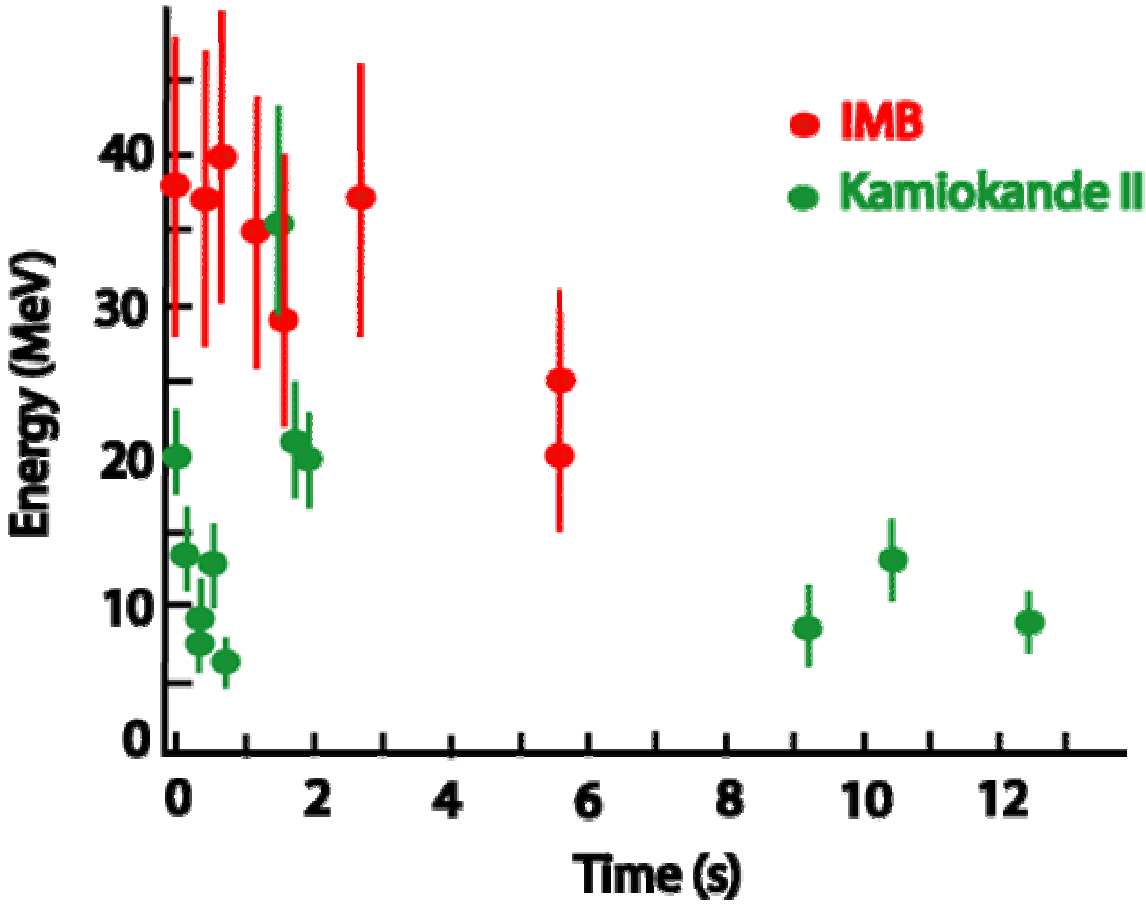
HISTORICAL SUPERNOVAE

Date (AD)	Type	Magnitude at Max	Discovered by	Remnant
1006	I	-10	Chinese/Arabs	SN1006
1054	II	-5	China/Japan	Crab
1181	II	-1	China/Japan	3C58
1572	I	-4	Tycho Brahe	Tycho
1604	I	-3	Kepler	Kepler
ca. 1680	II	5 ?	Flamsteed	Cas A
1987	II	+2.9	Ian Shelton	SN1987A

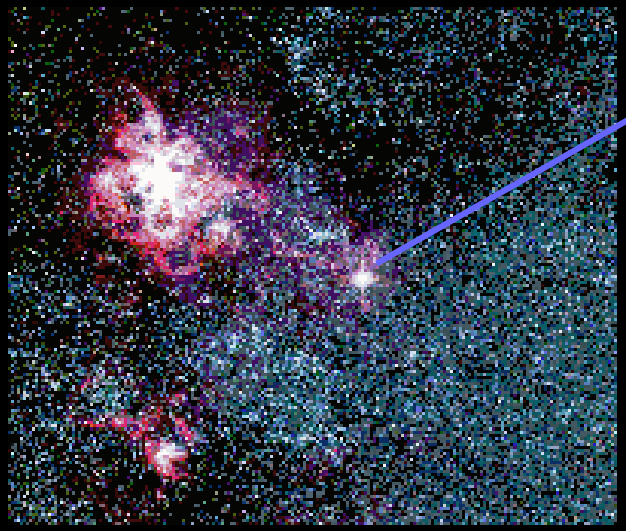
Supernova Energy Sources

- Core collapse:
  $E \sim GM^2/R \sim 0.1\ Mc^2 \sim 10^{53}$ ergs
  Neutrinos: t ~ 10s
- Radioactivity:
  $0.07\ M_\odot[^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe] \sim 10^{49}$ ergs.
  Light: t ~ 3 months
- Kinetic energy:
  $\sim 10\ M_\odot$, $V_{expansion} \sim 3000$ km/s $\sim 10^{51}$ ergs
  ~ 1% core collapse.
  X-rays: t ~ centuries.

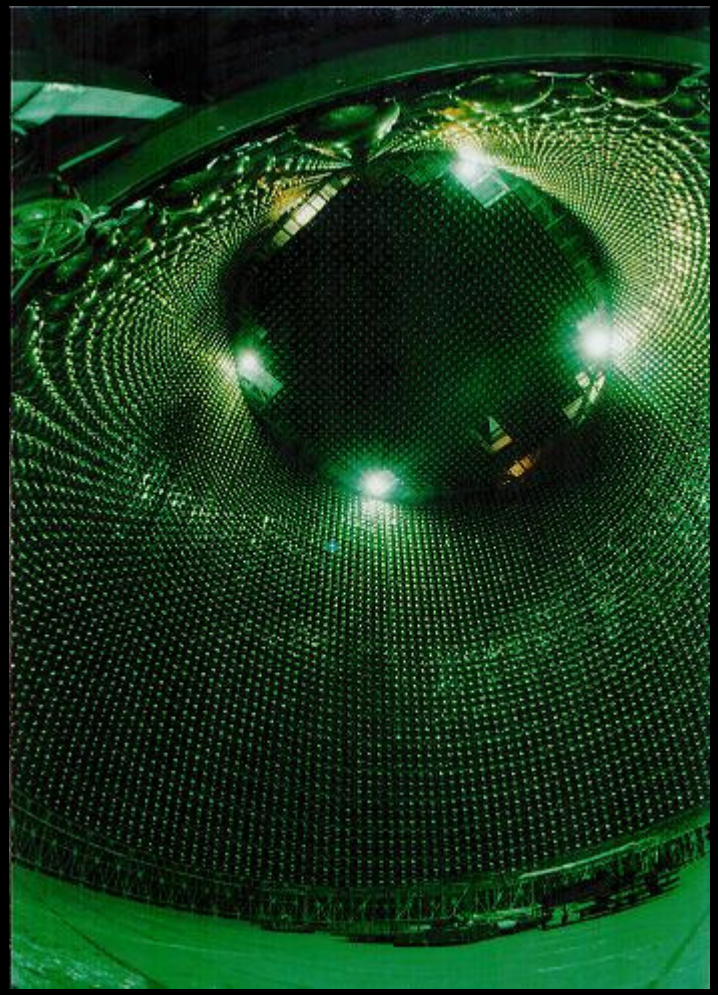
SN1987A neutrinos: 10^{53} ergs

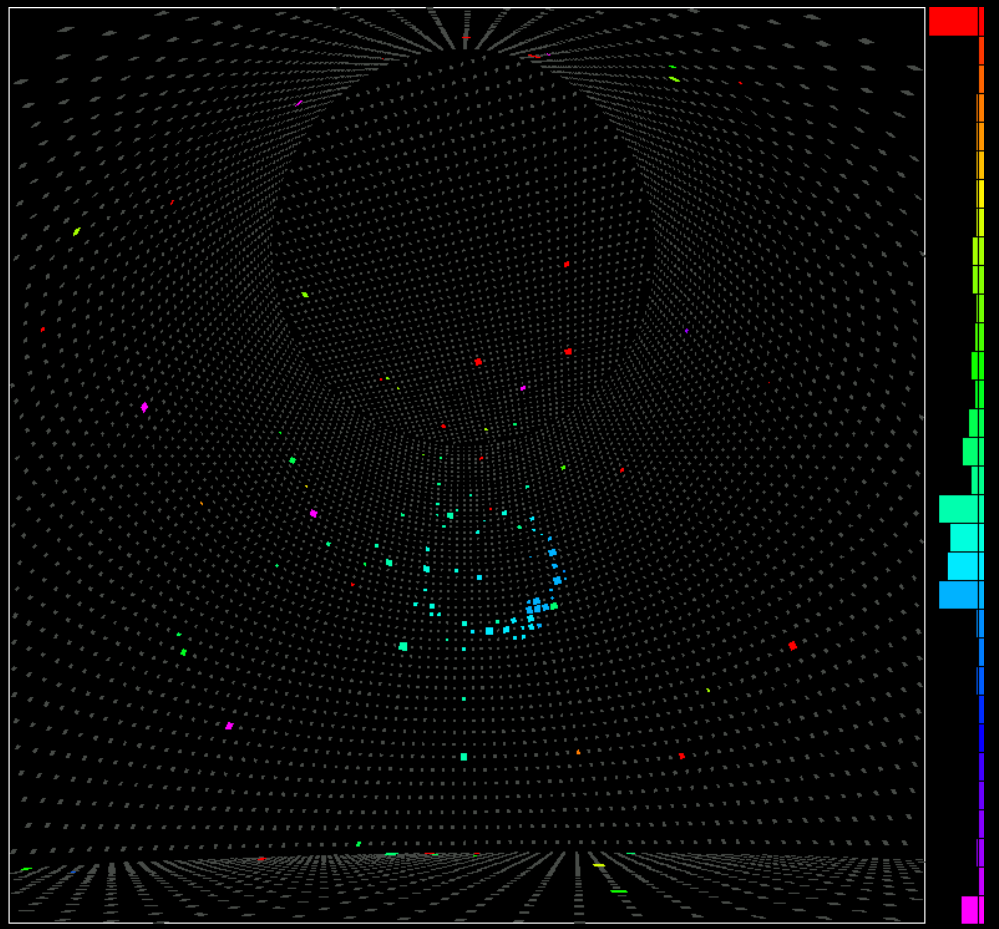


Detecting neutrinos from SN1987A



Kamiokande neutrino detector





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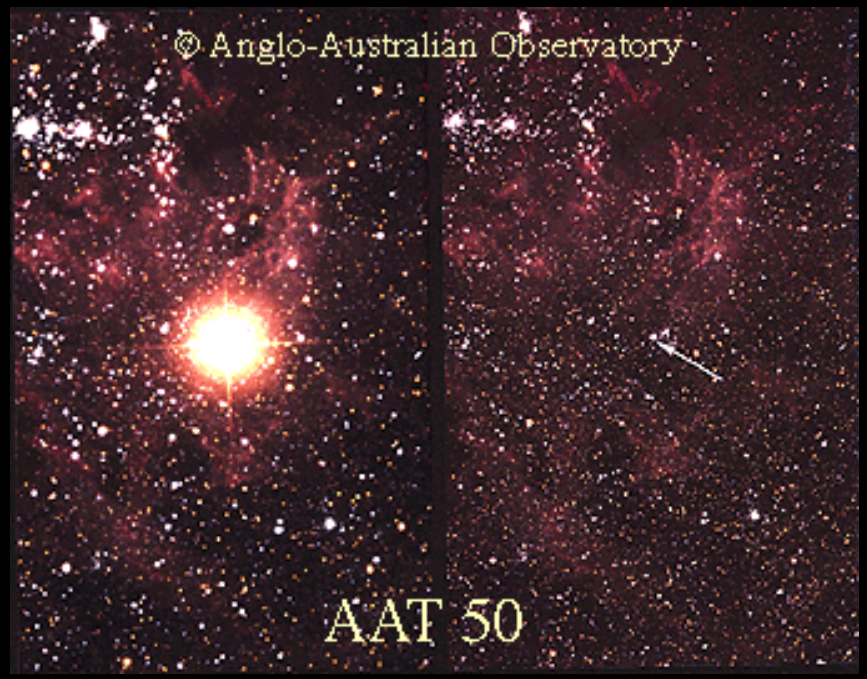
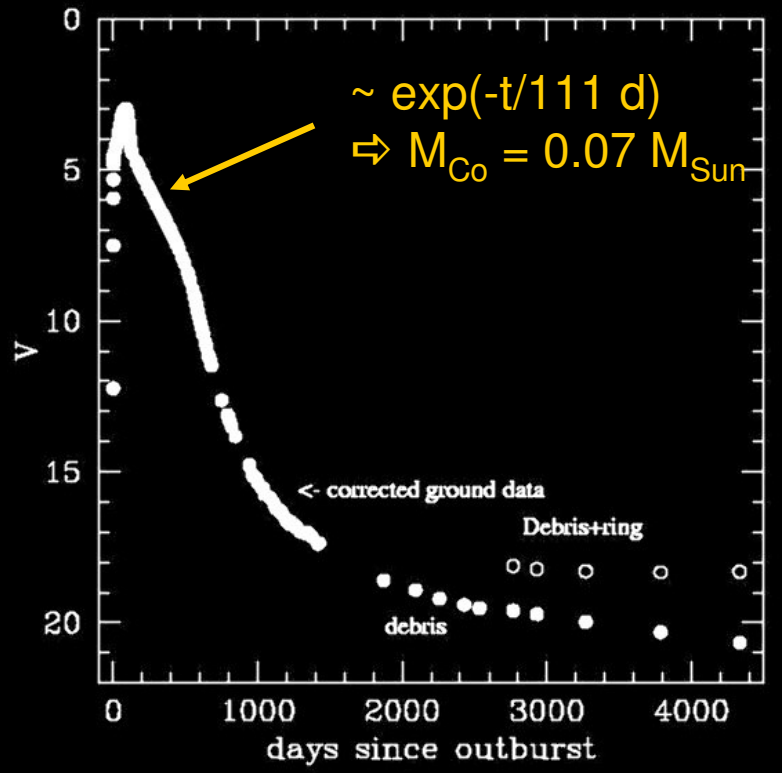
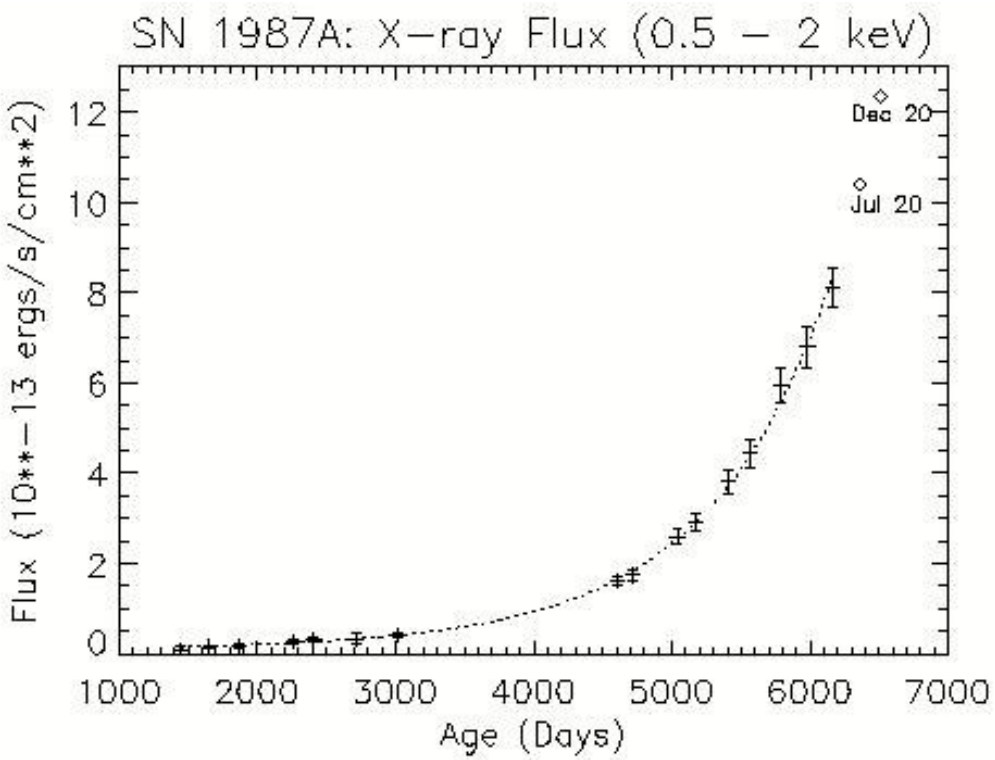




X-Rays: 10^{51} ergs

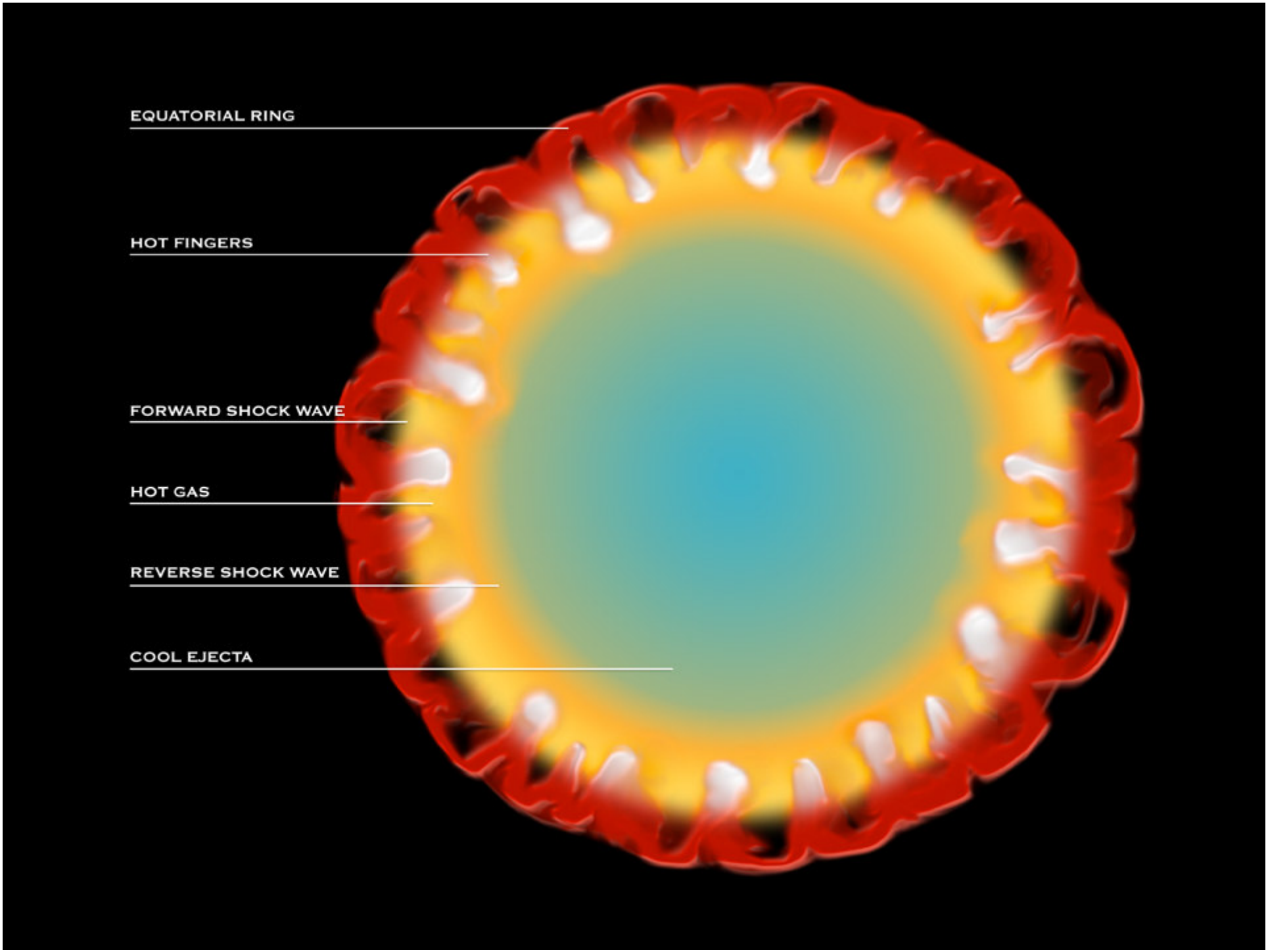


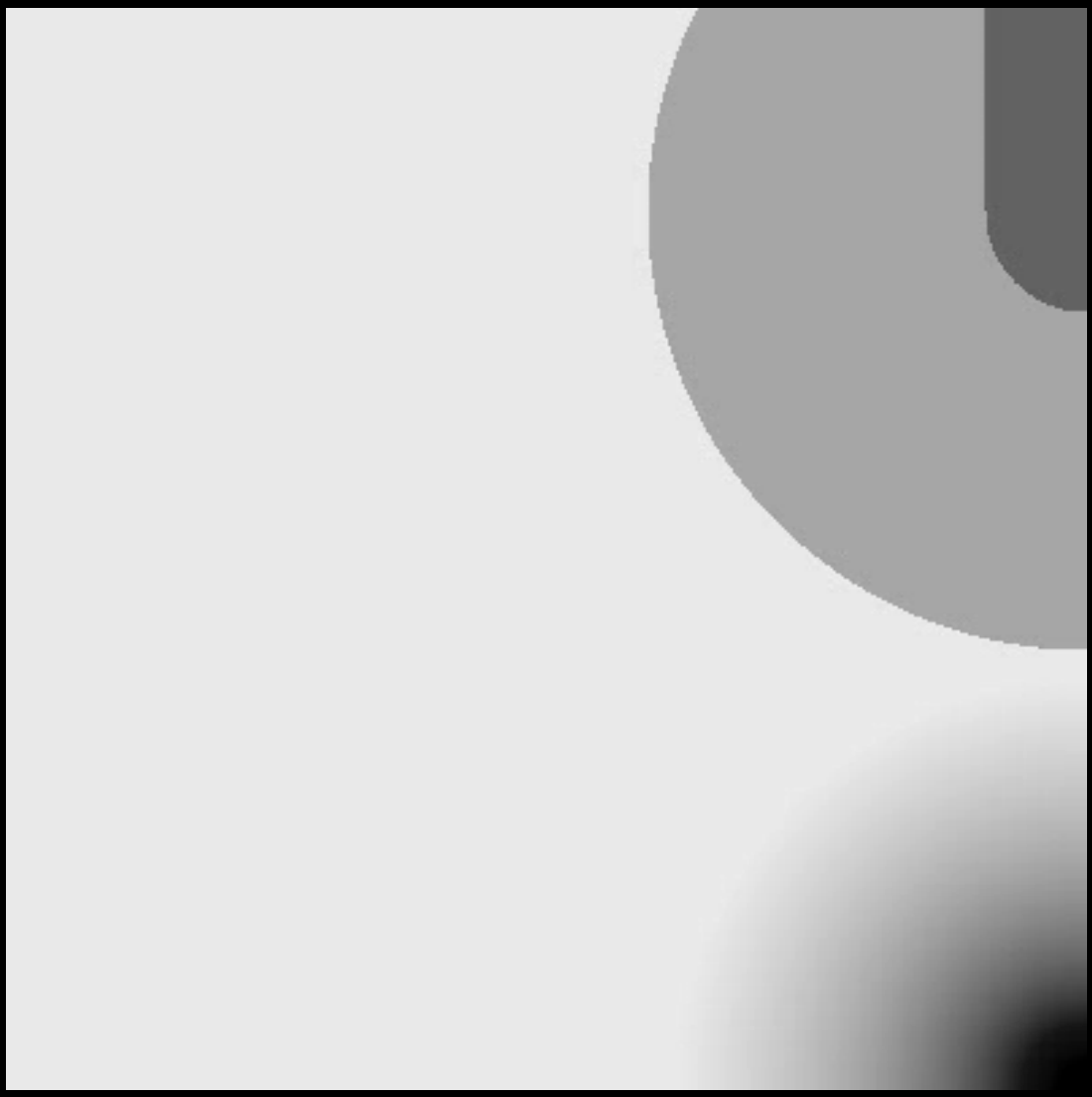
Circumstellar Rings

What we know about the rings

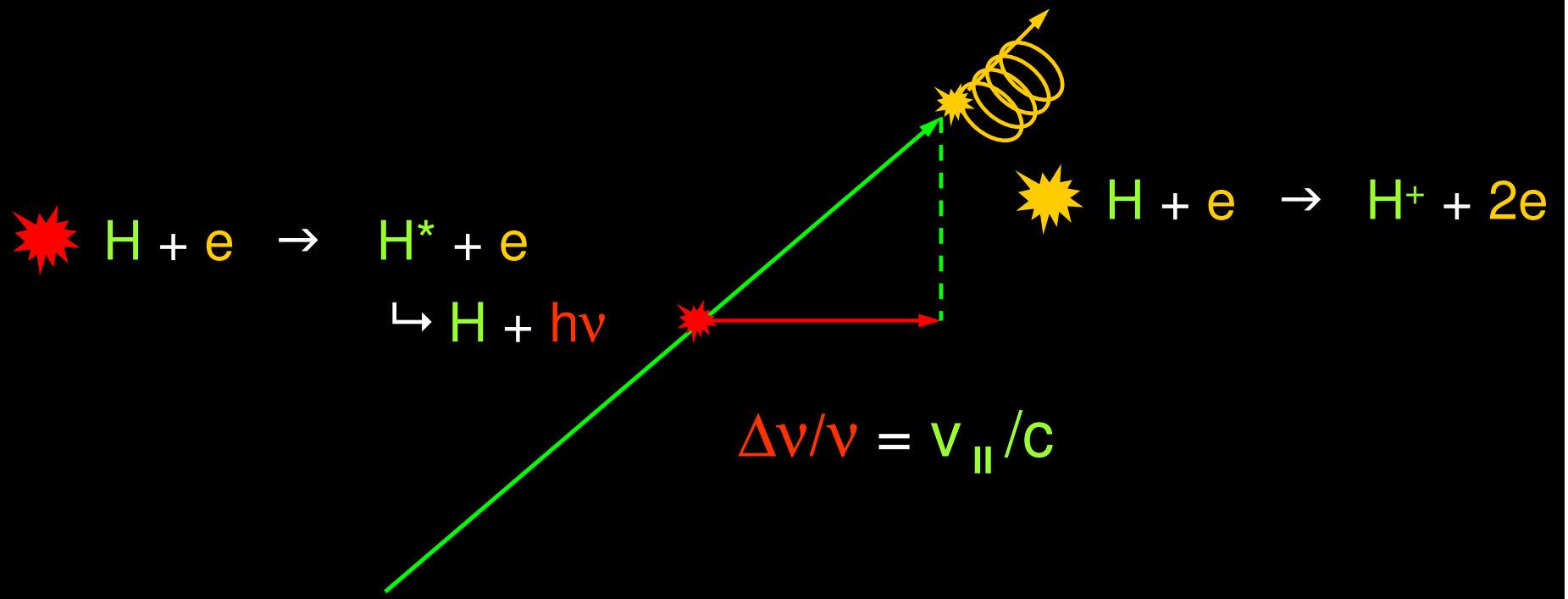
- were ejected 20,000 years before explosion
- density ~ 10^4 cm^{-3}
- ionized mass ~ 0.07 $M_\odot$
- were photoionized by initial X-ray flash (~ 1 day)
- they are only the inner surfaces of a much greater mass, ~ several $M_\odot$

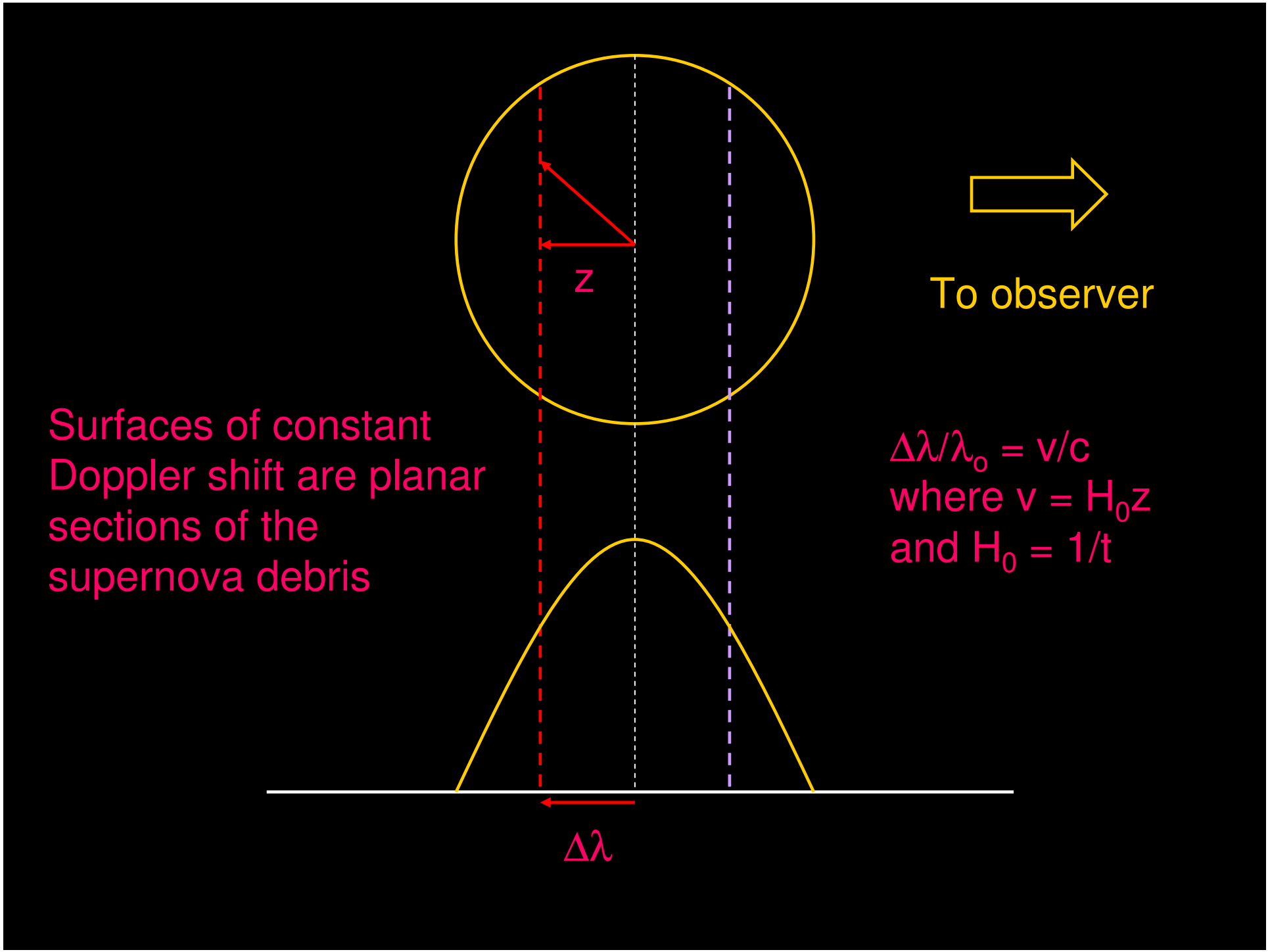
Reverse Shock

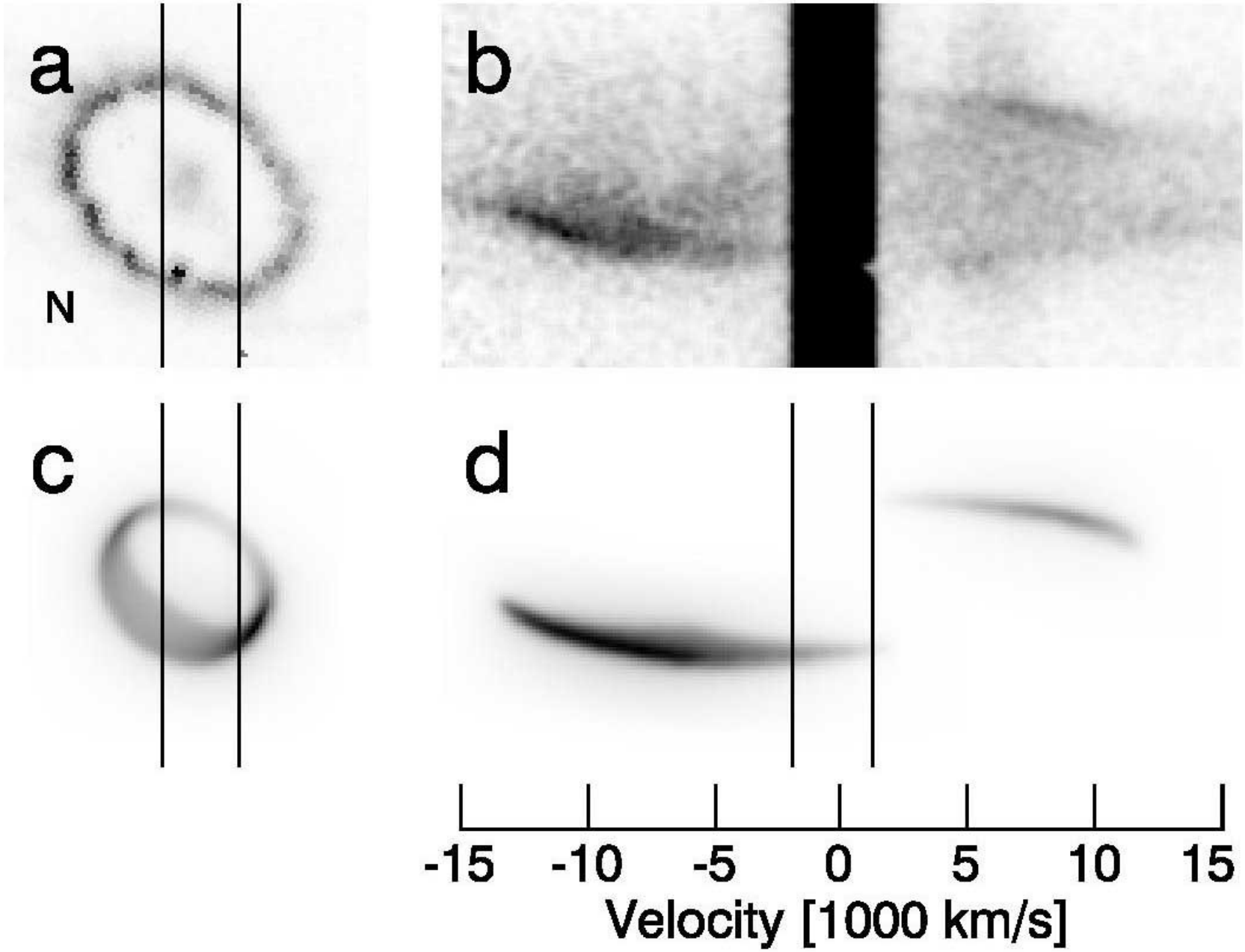

EQUATORIAL RING
HOT FINGERS
FORWARD SHOCK WAVE
HOT GAS
REVERSE SHOCK WAVE
COOL EJECTA



Line emission and electron impact ionization at reverse shock surface

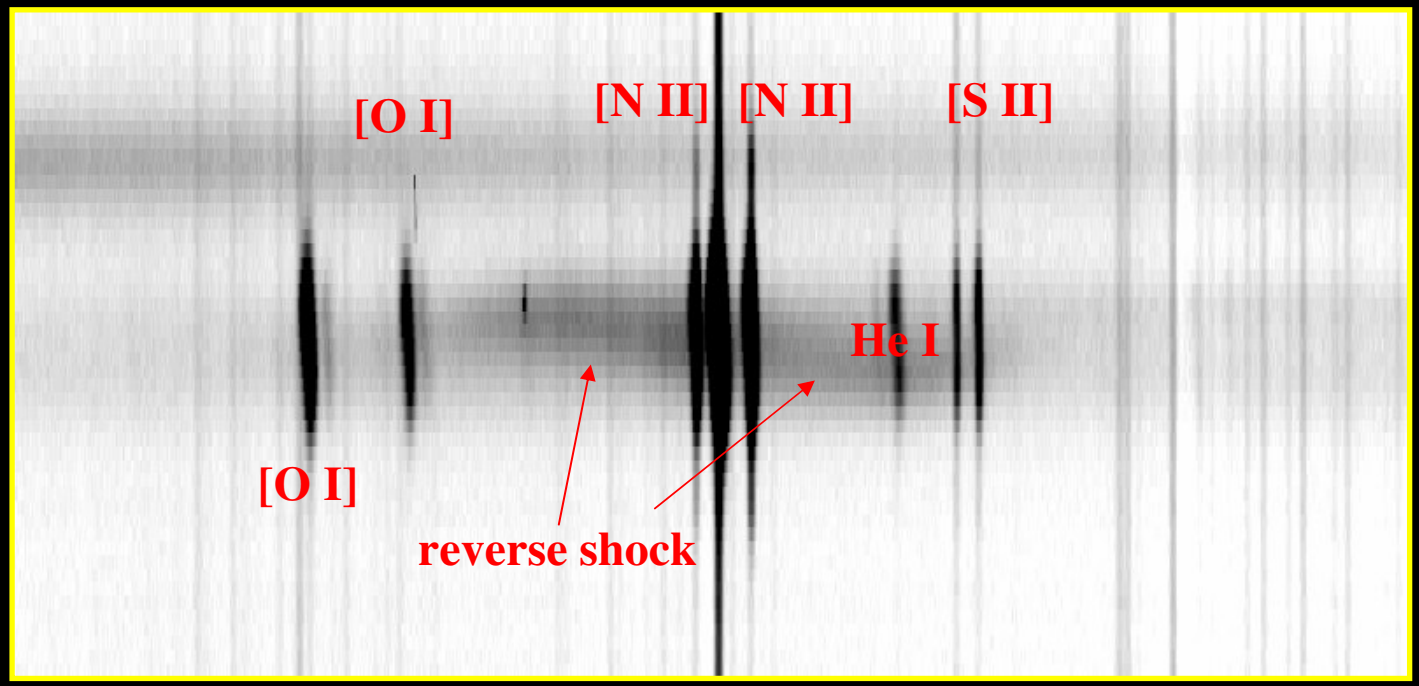



z
To observer
Surfaces of constant
Doppler shift are planar
sections of the
supernova debris
$\Delta\lambda/\lambda_o = v/c$
where $v = H_0 z$
and $H_0 = 1/t$
$\Delta\lambda$


a
N
b
c
d
-15
-10
-5
0
5
10
15
Velocity [1000 km/s]

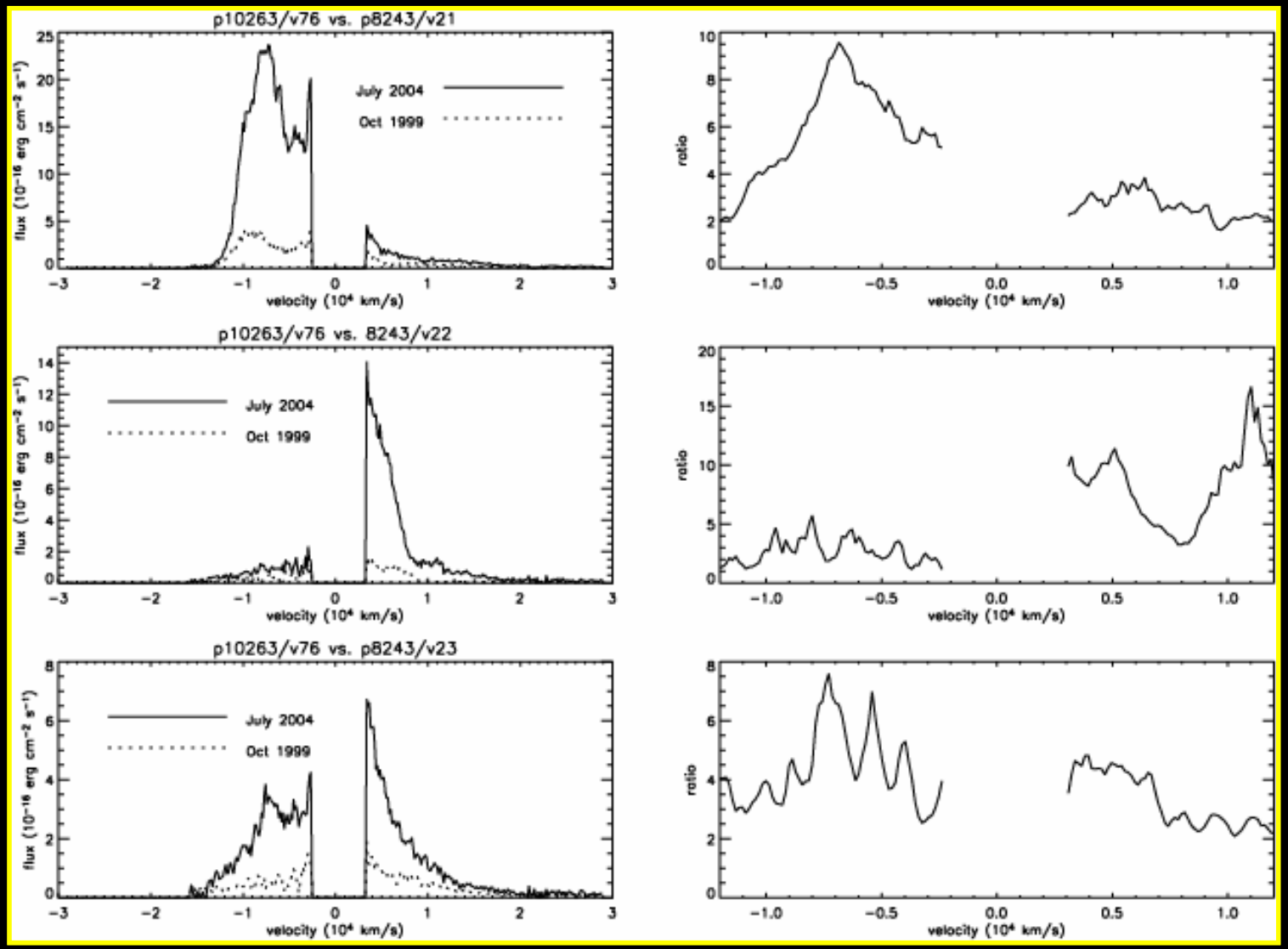
Magellan/LDSS Hα Observation

(Nathan Smith)



- Does not have HST spatial resolution, but can still monitor the time evolution of Hα from the ground.

Evolution of Lyα from Reverse Shock



What we know about reverse shock

- Radius ~ 0.8 R_{ring}
- Much brighter near equatorial plane
- Brightness ⇨ mass flux across shock
- Observed brightness evolution agrees with that predicted by SN atmosphere model
- Not cylindrically symmetric: much brighter on E side

Why is reverse shock (and radio and X-rays) brighter on E side?

(A) Circumstellar matter; or

(B) Supernova debris is more dense on E.

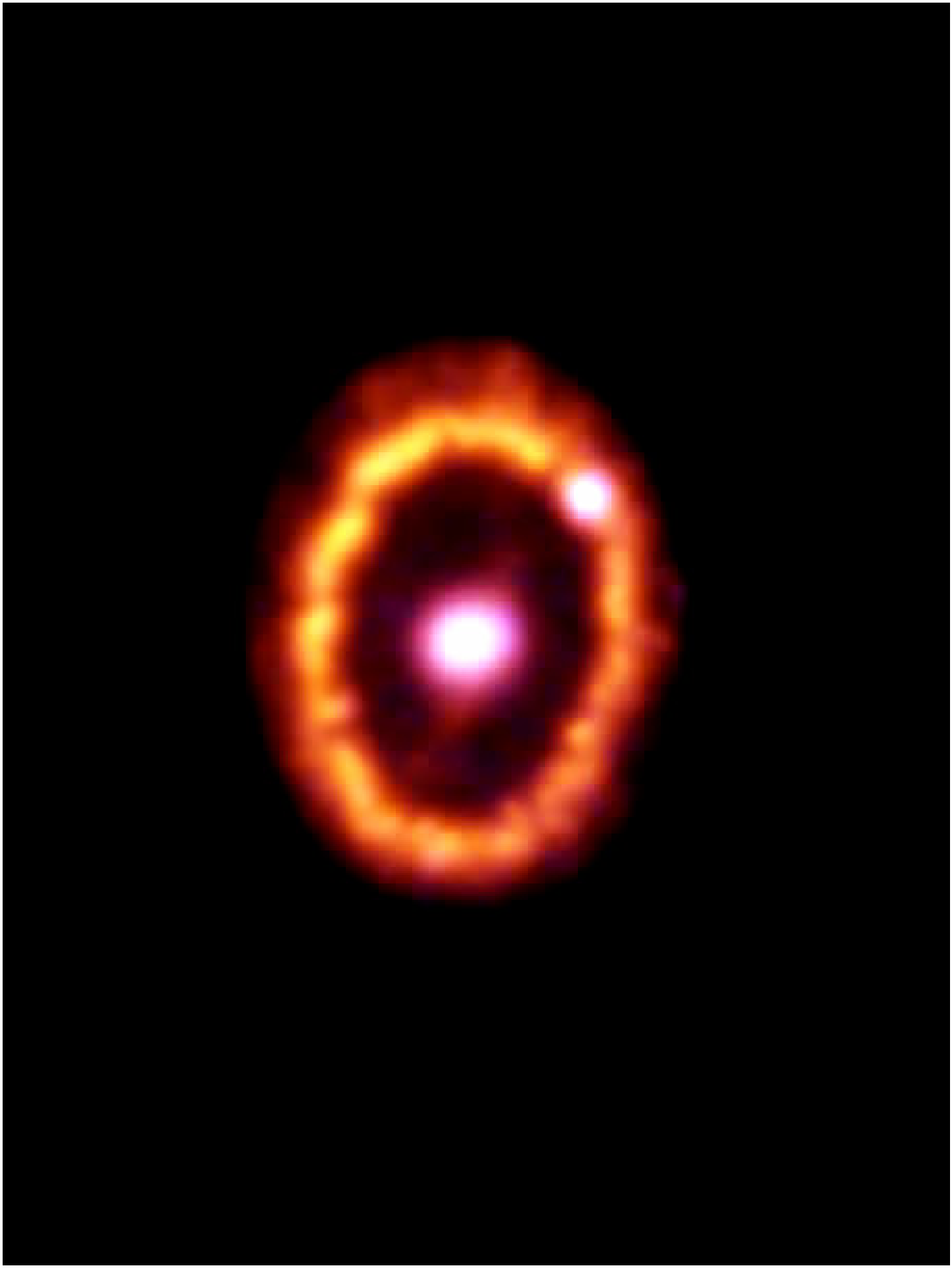
If (A), blast wave wouldn't travel so far to E.

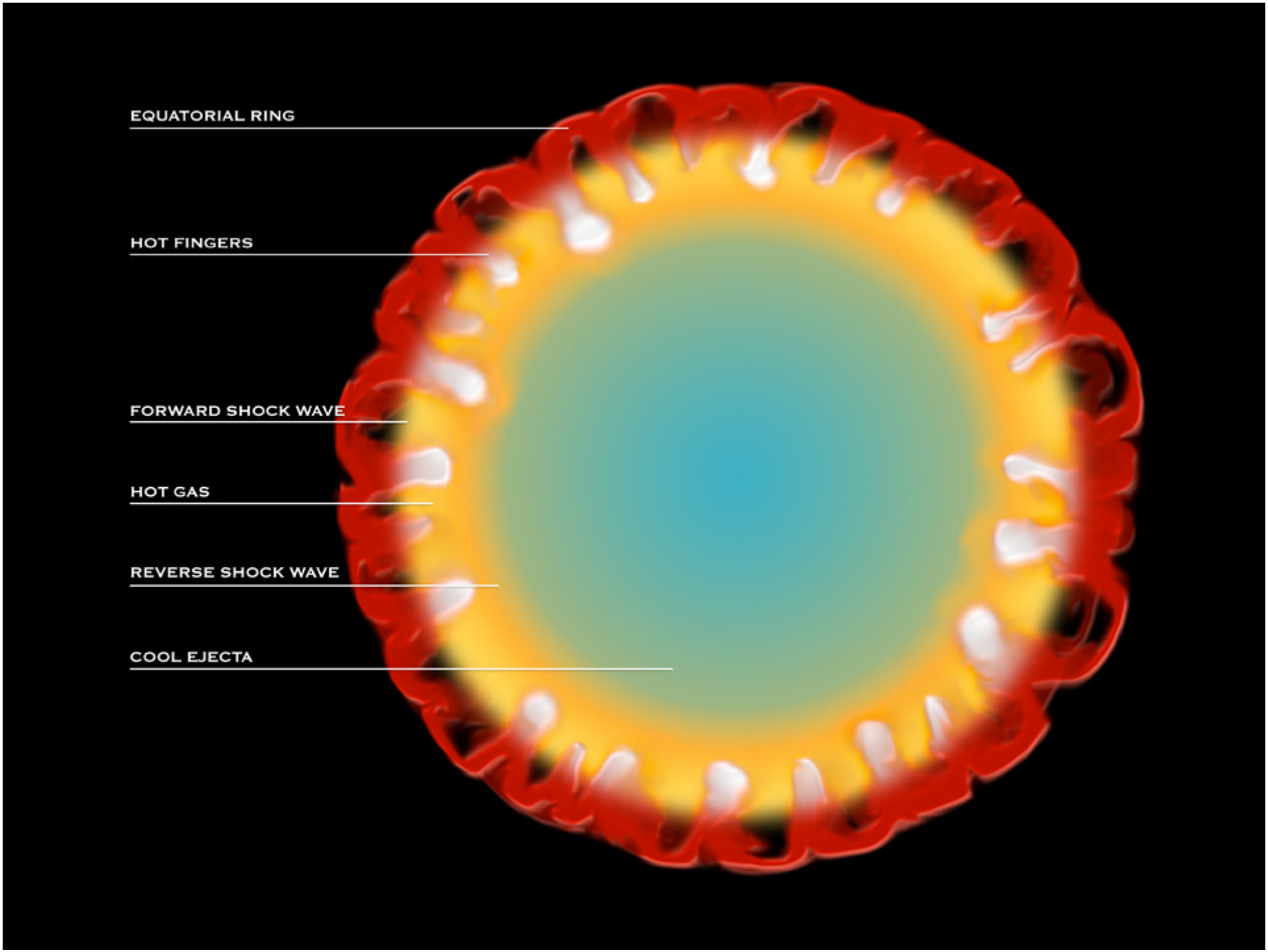
But hotspots appeared first on E side.

Therefore (B): ⇨ SN debris is triaxial!

(unless inner ring is not concentric on SN)

Optical Hotspots




EQUATORIAL RING
HOT FINGERS
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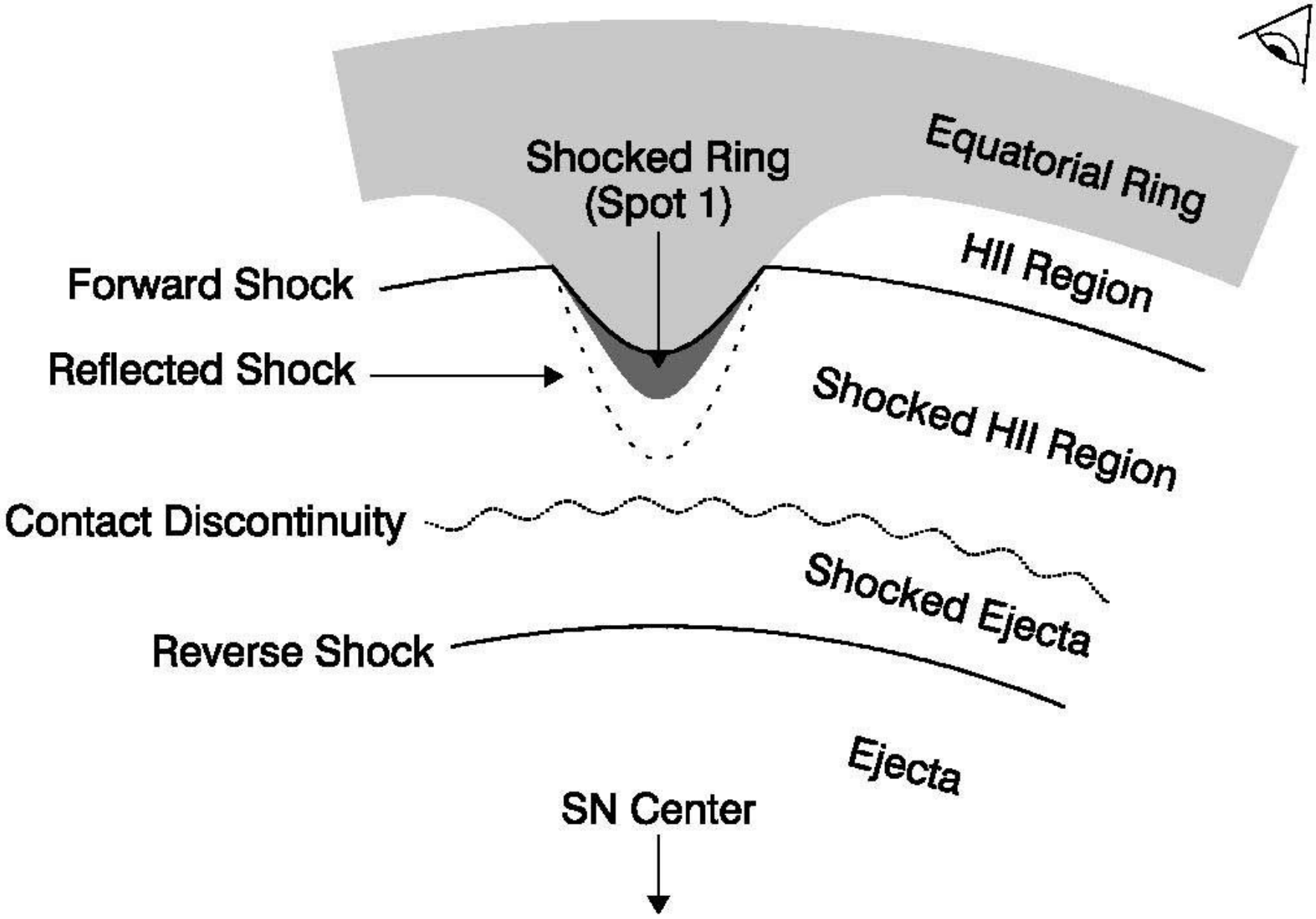
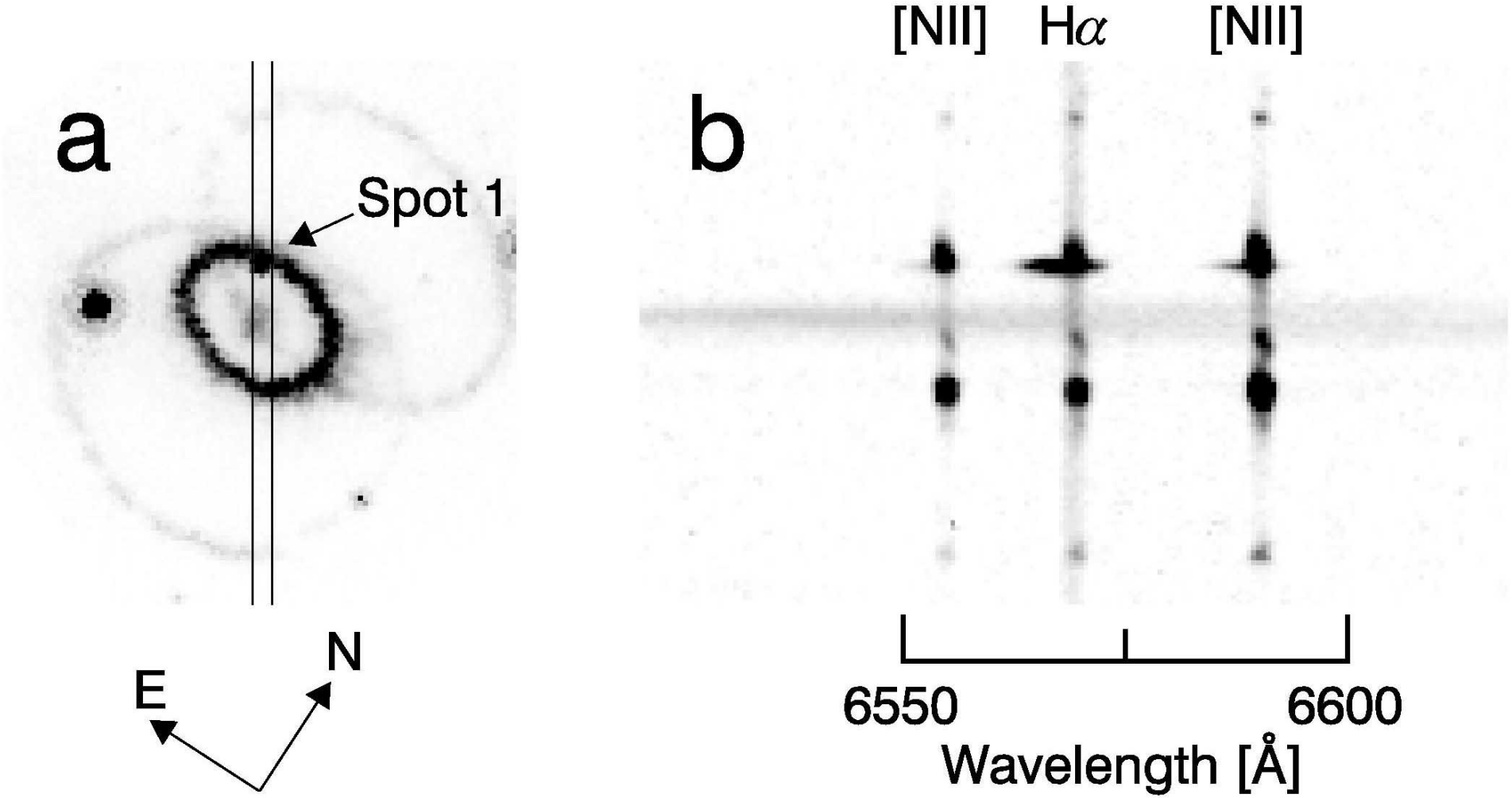
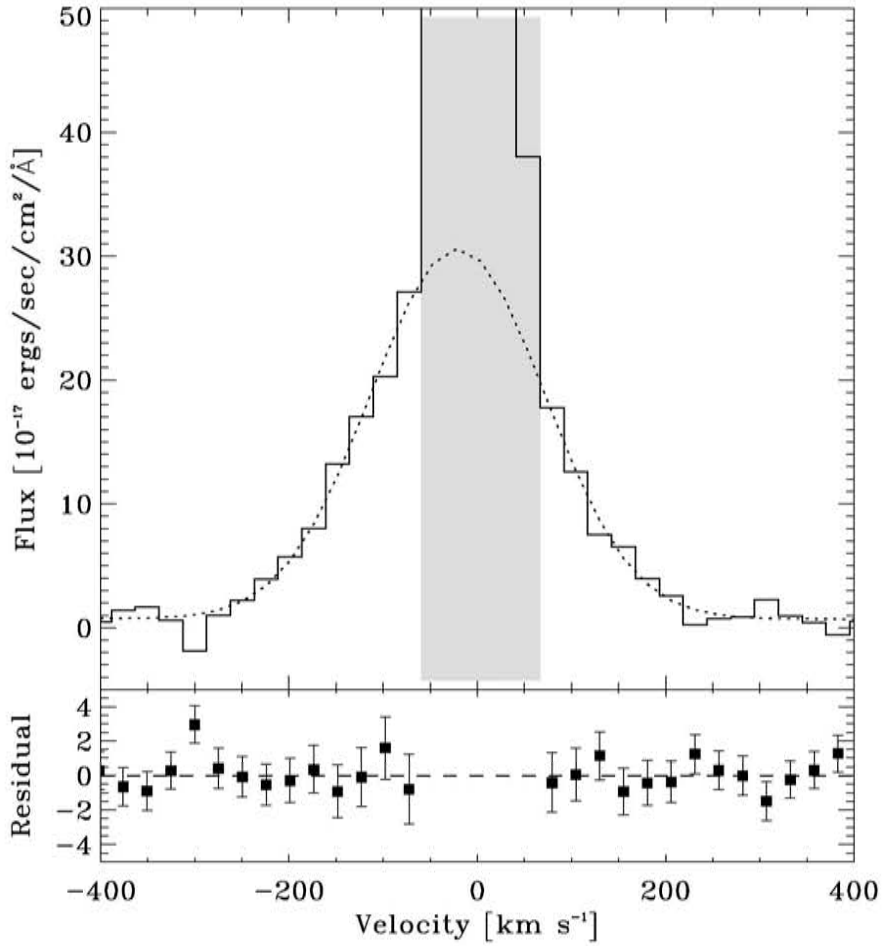
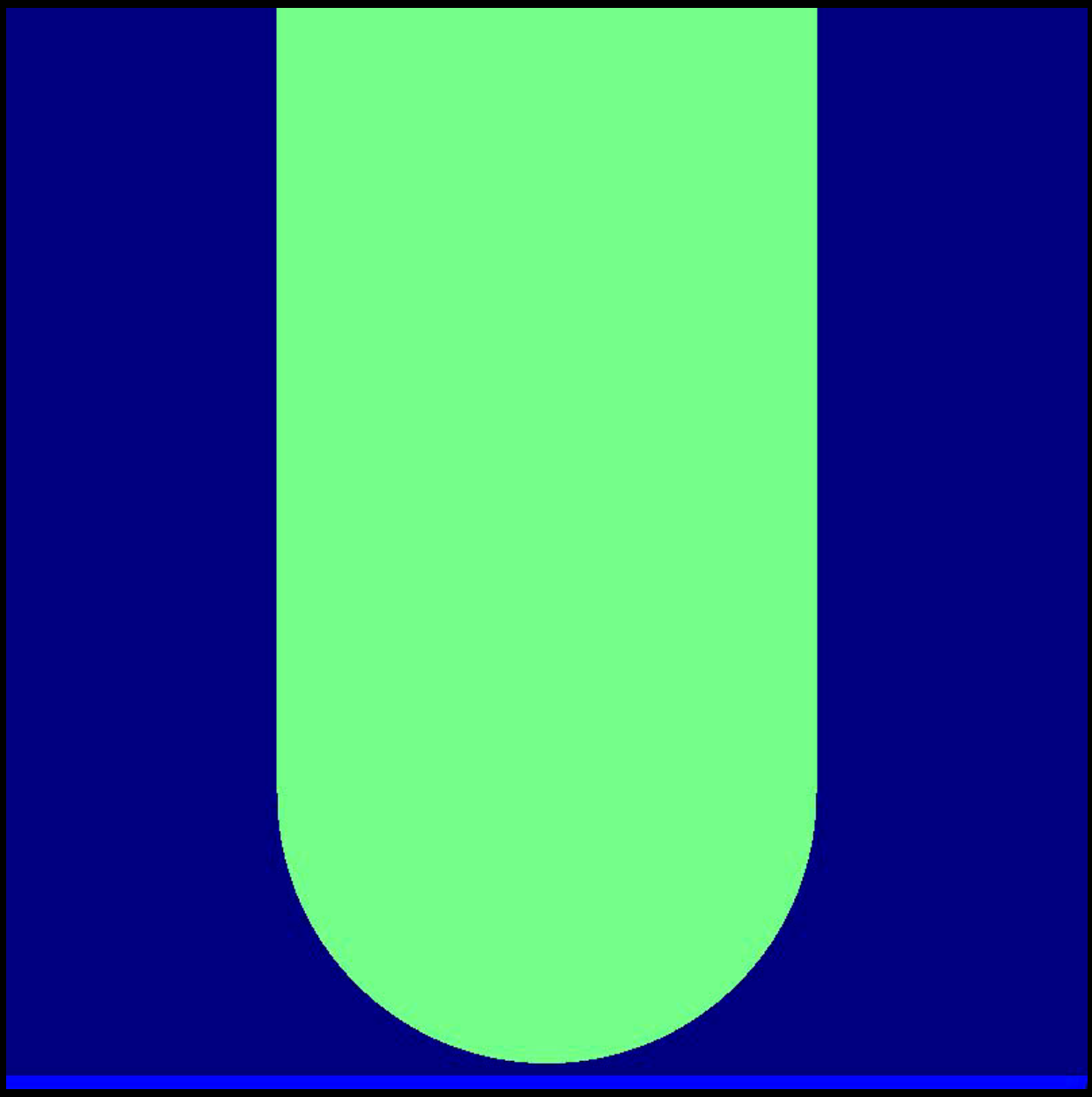

Shocked Ring
(Spot 1)
Equatorial Ring
HII Region
Forward Shock
Reflected Shock
Shocked HII Region
Contact Discontinuity
Shocked Ejecta
Reverse Shock
Ejecta
SN Center


a
Spot 1
N
E
b
[NII]
Hα
[NII]
6550
6600
Wavelength [Å]

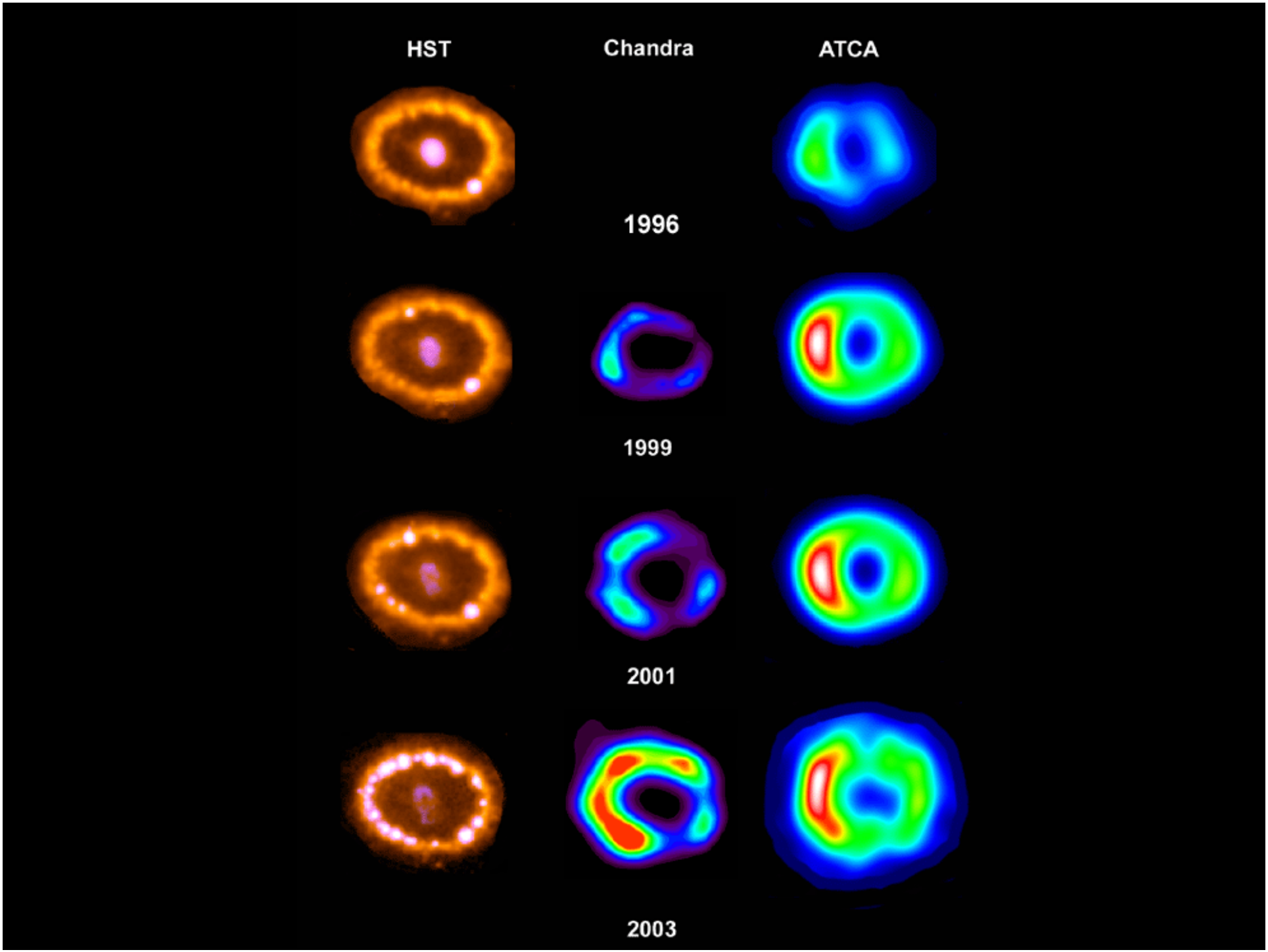

Flux [10⁻¹⁷ ergs/sec/cm²/Å]
50
40
30
20
10
0
Residual
4
2
0
−2
−4
−400
−200
0
200
400
Velocity [km s⁻¹]

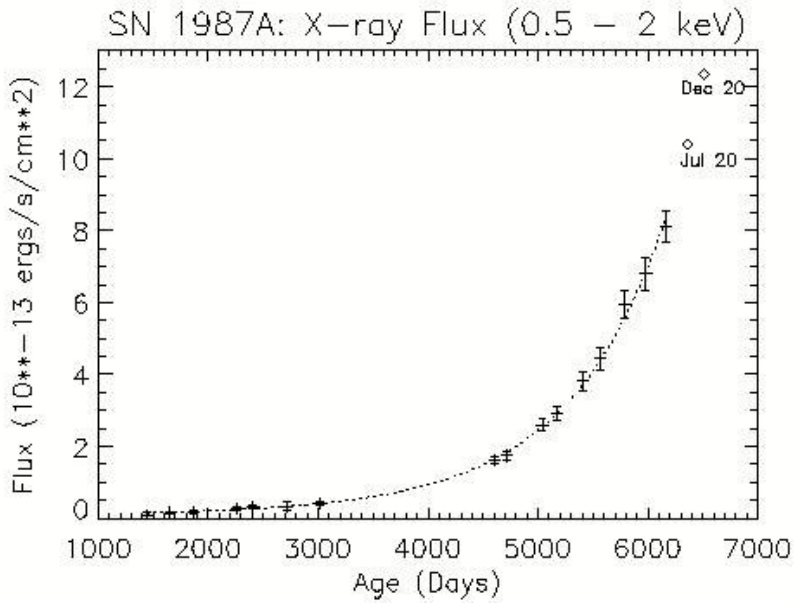


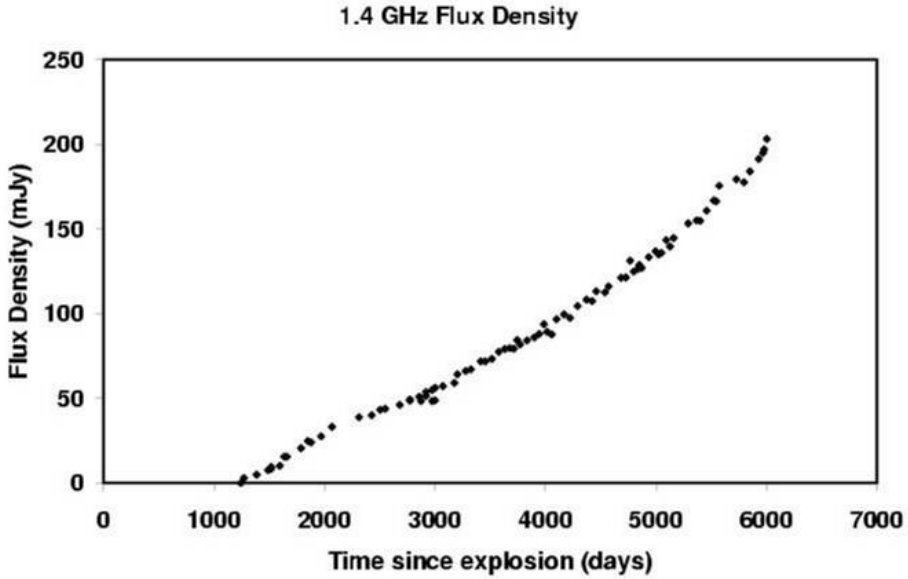
What we know about the hot spots

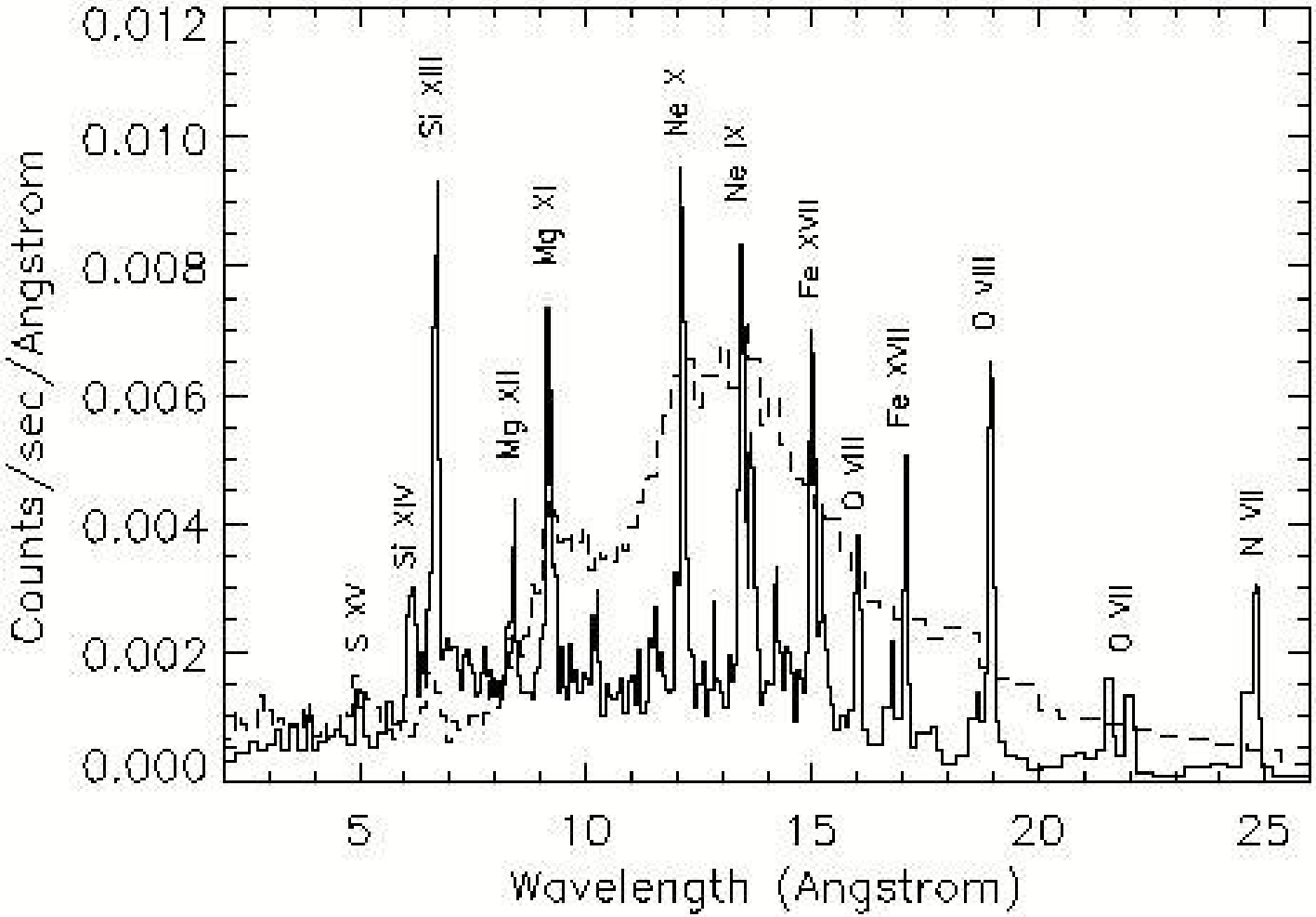
- Most spots appeared first on NE and SE quadrants of ring
- Spots now encircle entire ring
- Densities ~ 10^6 cm^{-3}
- Most are unresolved: < 1 WFPC pixel
- Optical emission lines caused by radiative shocks
- Faster non-radiative shocks must be present but are invisible in optical & UV

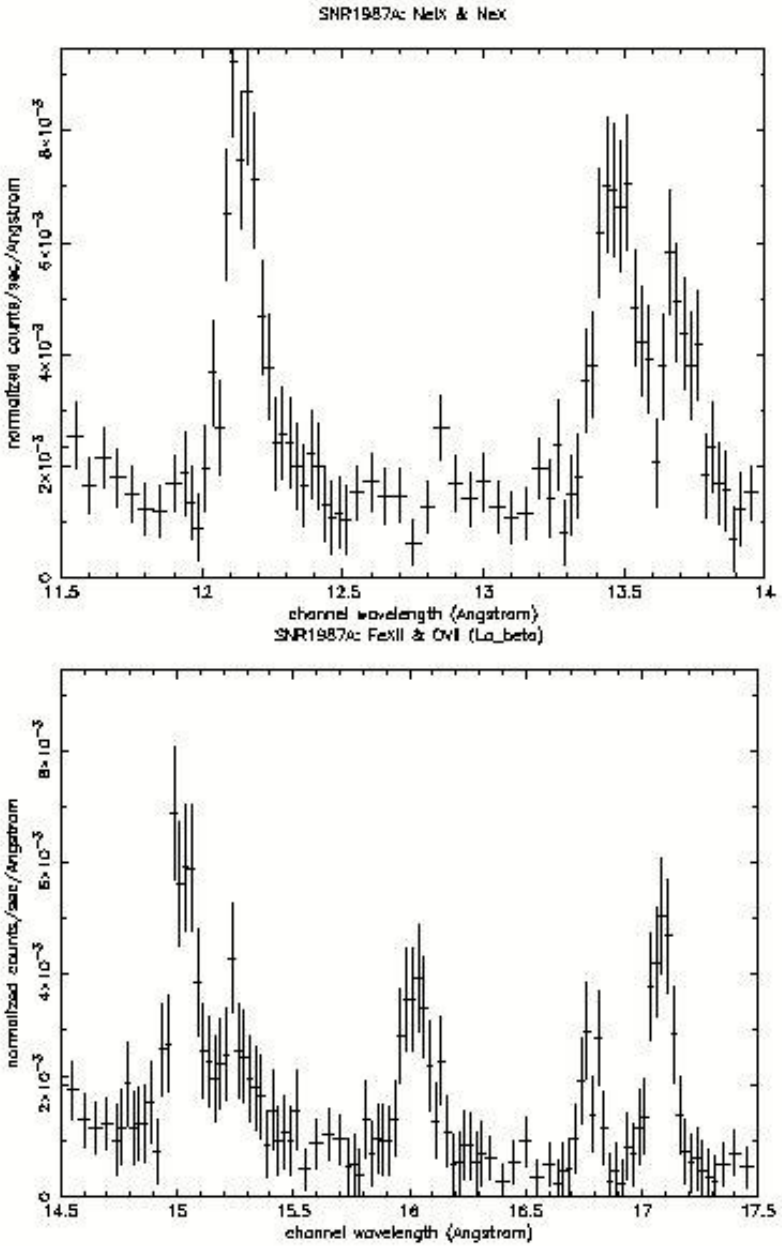
X-ray Emission

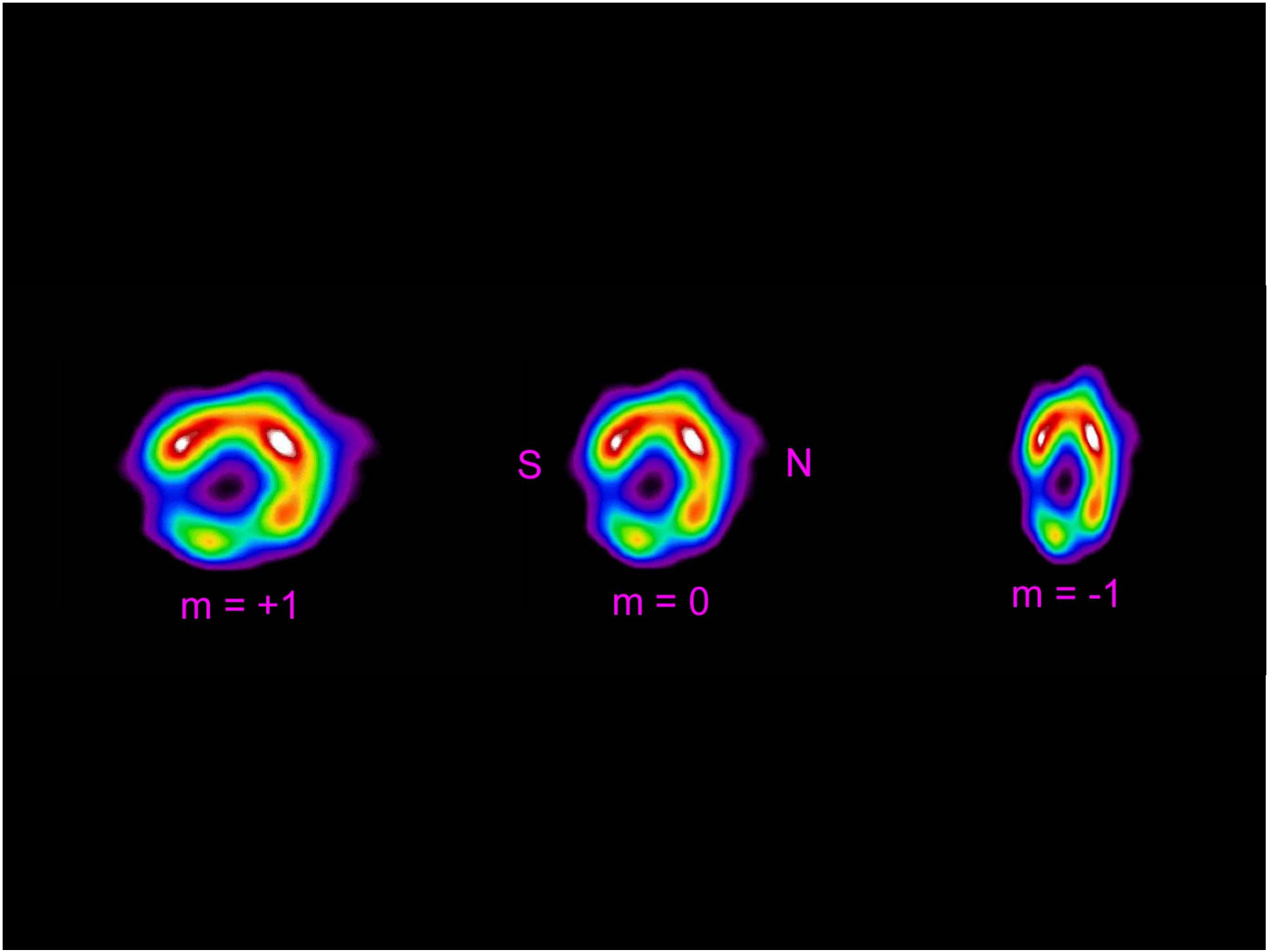

HST
Chandra
ATCA
1996
1999
2001
2003

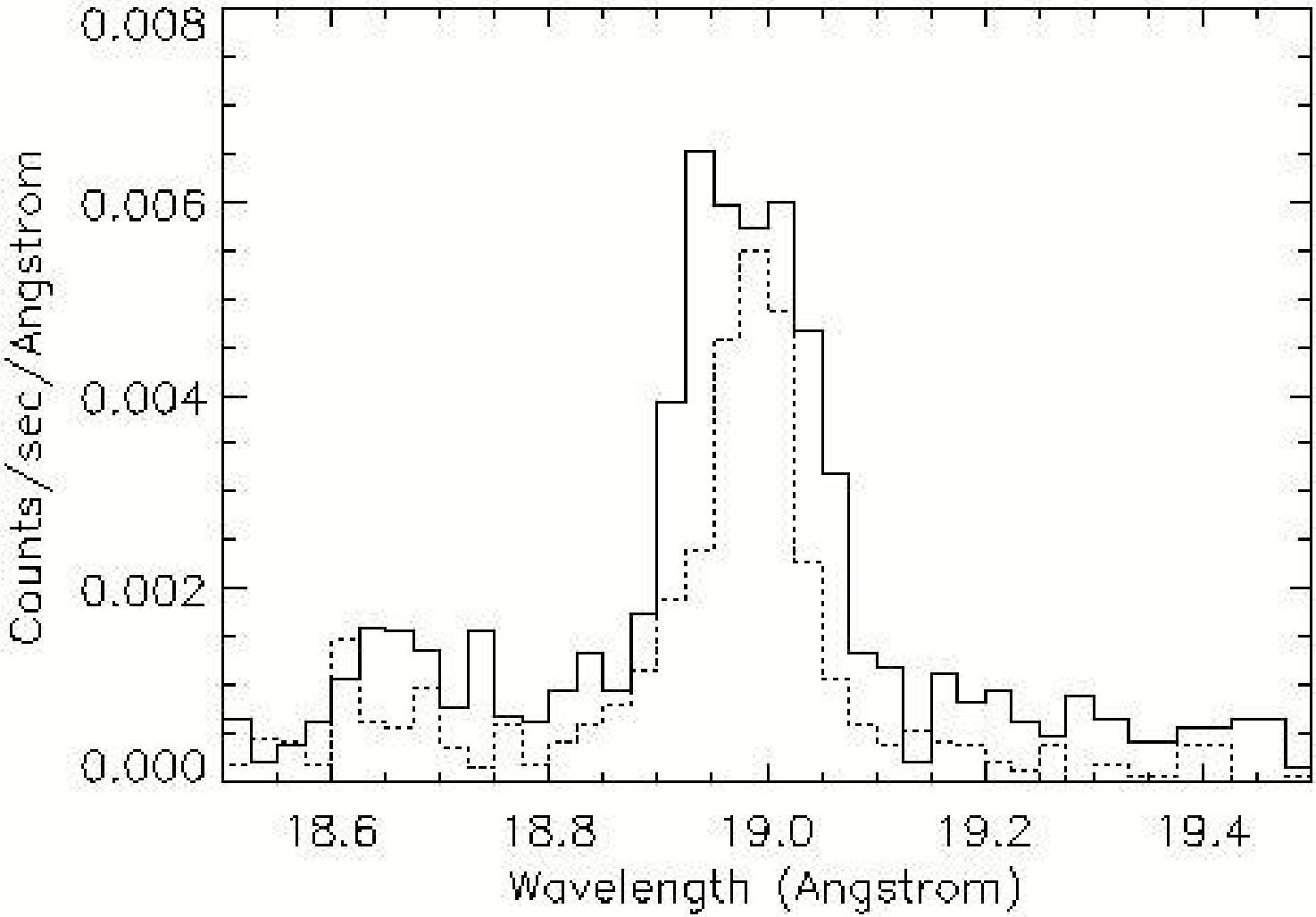

SN 1987A: X-ray Flux (0.5 – 2 keV)
Flux (10**-13 ergs/s/cm**2)
Age (Days)
Dec 20
Jul 20
0
2
4
6
8
10
12
1000
2000
3000
4000
5000
6000
7000

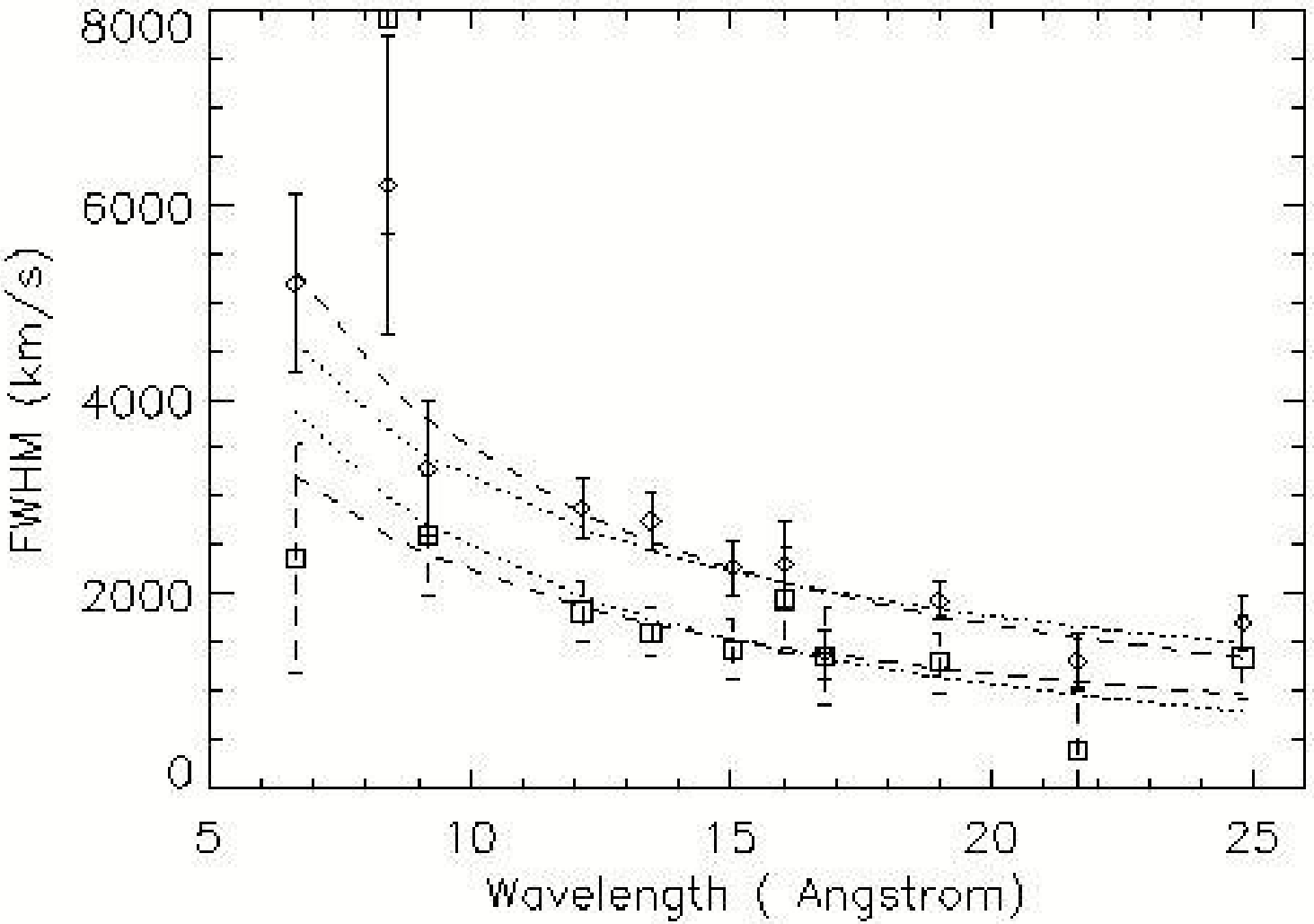

1.4 GHz Flux Density
Flux Density (mJy)
Time since explosion (days)
0
50
100
150
200
250
0
1000
2000
3000
4000
5000
6000
7000


0.012
0.010
0.008
0.006
0.004
0.002
0.000
Counts/sec/Angstrom
5
10
15
20
25
Wavelength (Angstrom)
S xv
Si xiv
Si xiii
Mg xii
Mg xi
Ne x
Ne ix
Fe xvii
O viii
Fe xvii
O viii
O vii
N vii


SNR1987a: NeIX & NeX
normalized counts/sec/Angstrom
channel wavelength (Angstrom)
SNR1987a: FeXII & OVII (Lo_beta)
normalized counts/sec/Angstrom
channel wavelength (Angstrom)

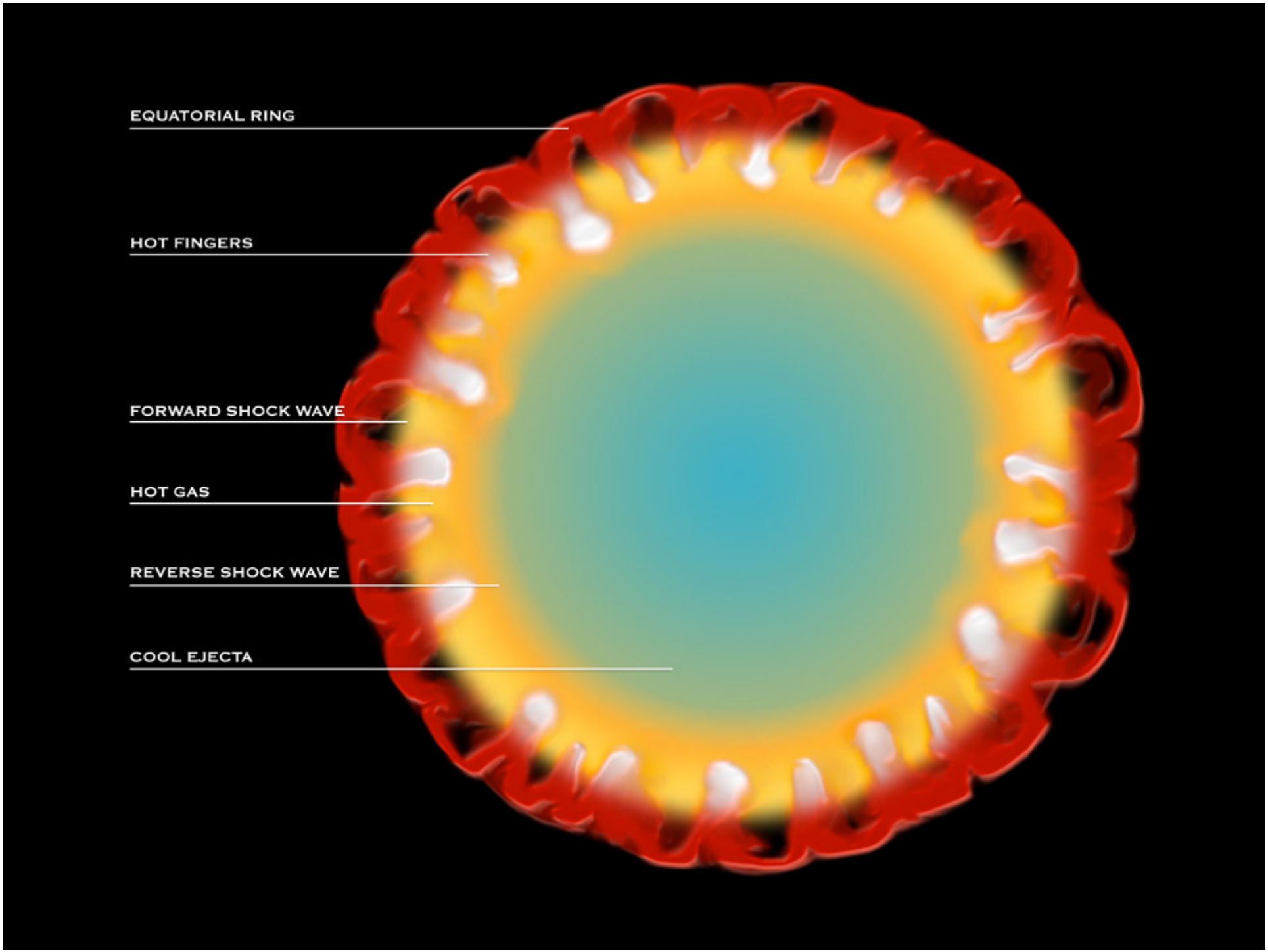

S
N
m = +1
m = 0
m = -1


0.008
0.006
0.004
0.002
0.000
Counts/sec/Angstrom
18.6
18.8
19.0
19.2
19.4
Wavelength (Angstrom)


8000
6000
4000
2000
0
FWHM (km/s)
5
10
15
20
25
Wavelength (Angstrom)

What we know about the X-rays

- Brightening fast: ~ exp(t/2 yr)
- Soft X-ray bright spots correlate fairly well with optical/UV hot spots.
- Like radio emission, X-rays are much brighter toward East, where most hotspots first appeared
- In 1999 X-ray line *profiles* had FWHM ~ 2500 km s^{-1}, ⇨ kT_i ~ 15 keV
- In 2004, line profiles narrowed to FWHM < 800 km s^{-1}


EQUATORIAL RING
HOT FINGERS
FORWARD SHOCK WAVE
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COOL EJECTA

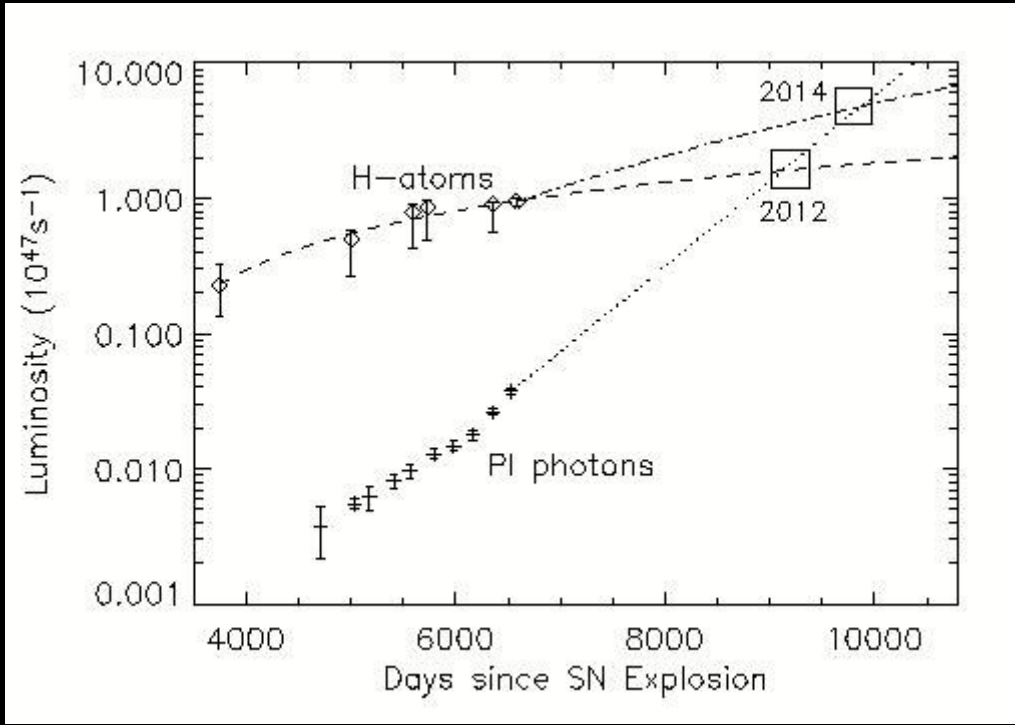
What we don't know

- What accounts for the morphology of the circumstellar rings? Merged binary?
- What accounts for the protrusions on the ring?
- What accounts for the EW asymmetry? Asymmetric explosion?
- Where is the compact object?

The Future

- 5 year forecast: X-rays, infrared, optical, UV will brighten by another factor ~ 10
- 10 year forecast: Reverse shock emission will vanish
- Illumination by X-rays and EUV from inner ring will cause exterior matter to glow in narrow emission lines
- ALMA will give us a spectacular (~10 mas) view of the non-thermal radio source.
- 30 year forecast: will see newly synthesized material cross reverse shock
- Long range forecast: Will remain bright for decades - centuries

Bleaching of Reverse Shock Emission by Preionization

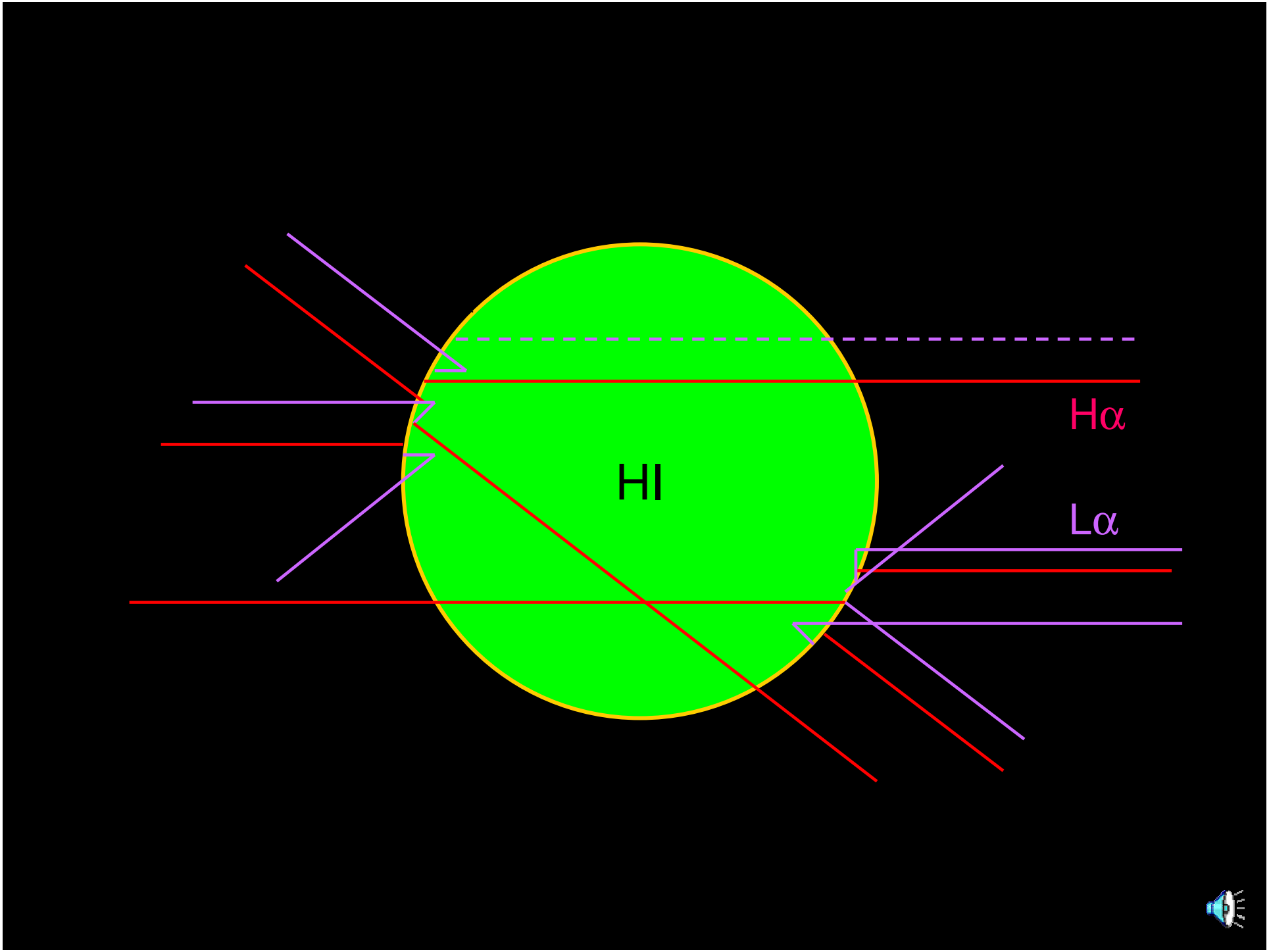


Thanks to:

Kevin Heng
Svet Zhekov
Nathan Smith
Dave Burrows
Sangwook Park

Bob Kirshner and SINS team
Dick Manchester
Bryan Gaensler
Kazik Borkowski
John Blondin

… and many others


Hα
HI
Lα