# SUPERNOVA 1987A: THE BIRTH OF A SUPERNOVA REMNANT

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- Introduction
- Circumstellar rings
- 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 |

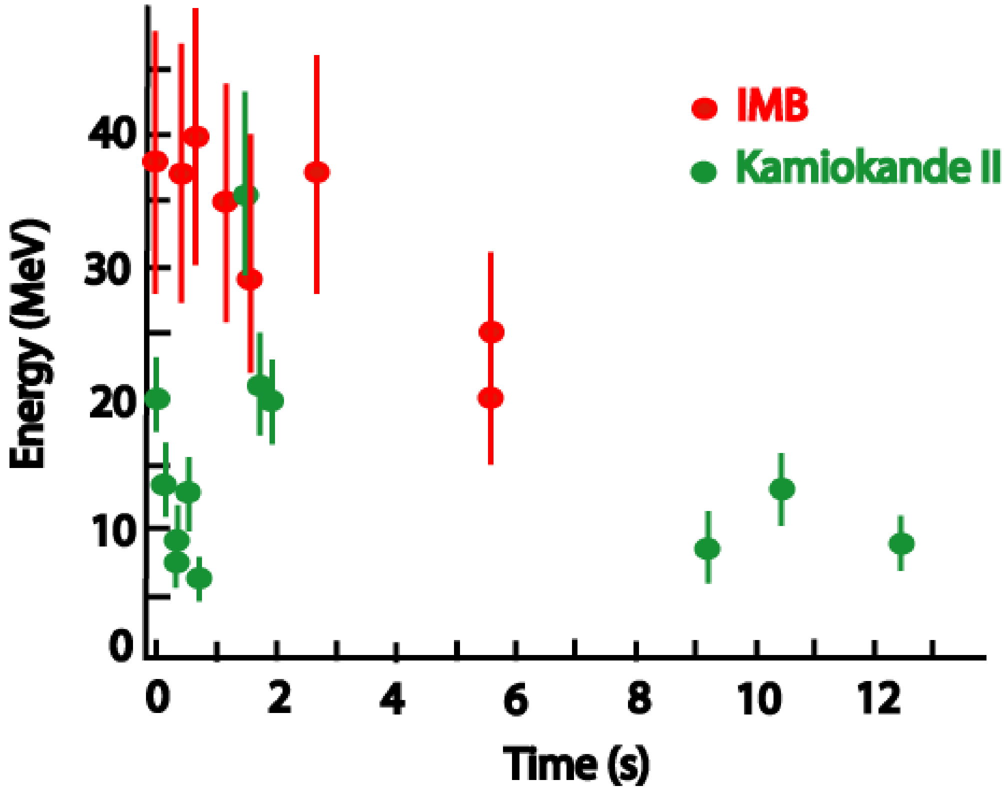
# Supernova Energy Sources

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

Core collapse:

$E \sim GM^2/R \sim 0.1\ Mc^2 \sim 10^{53}$ ergs

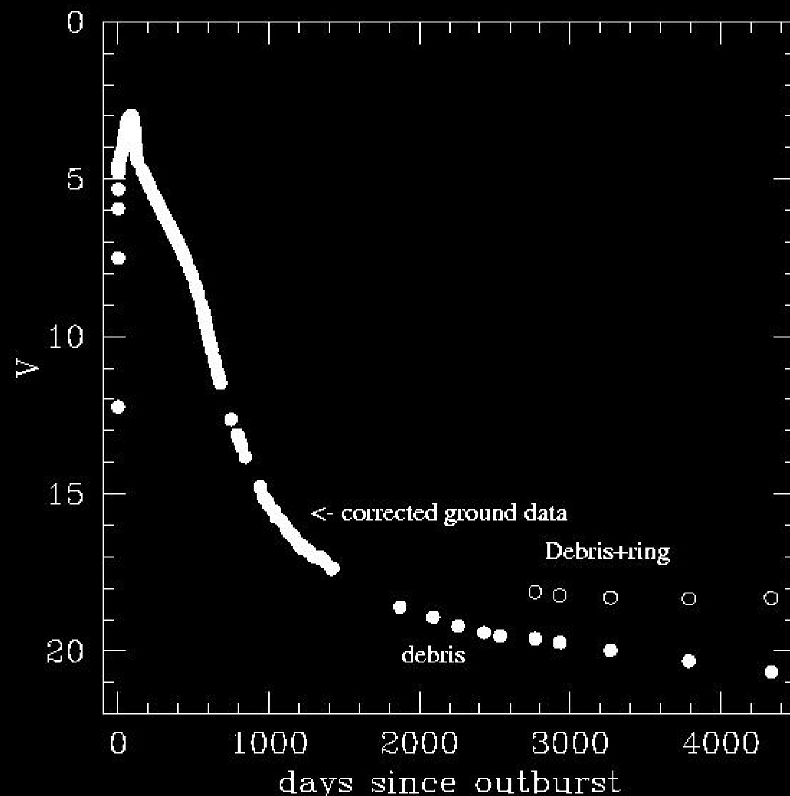
**Neutrinos: t ~ 10s**



•Radioactivity:

$0.07\ M_{\odot}[^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe] \sim 10^{49}$ ergs.

Light: t ~ 3 months

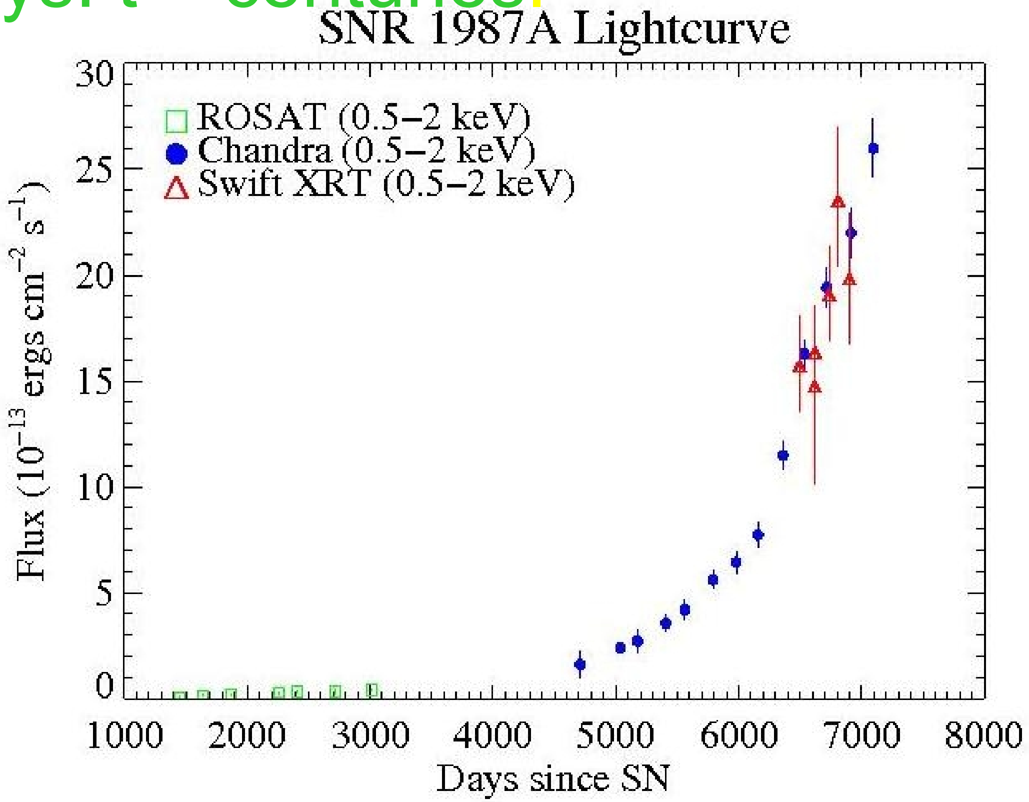

SN: light comes from interior of debris

SNR: light from crash

Kinetic energy:

~ 10 $M_{\odot}$, $V_{expansion}$ ~ 3000 km/s ~ $10^{51}$ ergs ~ 1% core collapse.

X-rays: t ~ centuries.



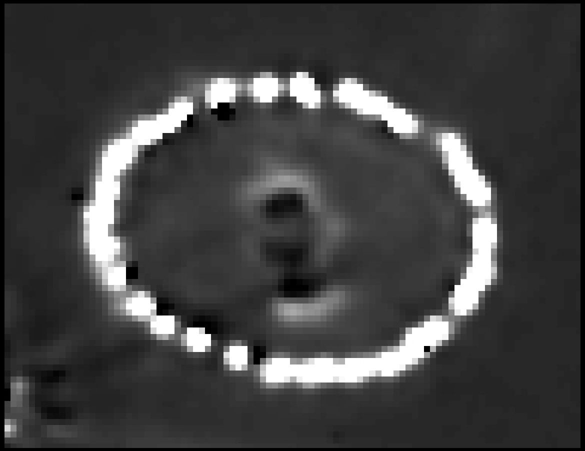
# Circumstellar Rings

# What we know about the rings

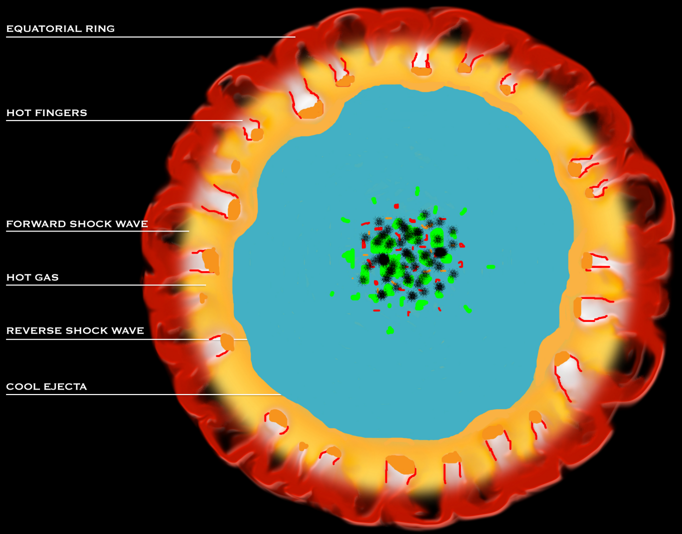
- were ejected 20,000 years before explosion
- density ~ $10^4$ $cm^{-3}$
- ionized mass ~ 0.07 $M_{\odot}$
- were photoionized by initial X-ray flash (~ 1 day)
- they are only the inner surfaces of a much greater mass, ~ several $M_{\odot}$

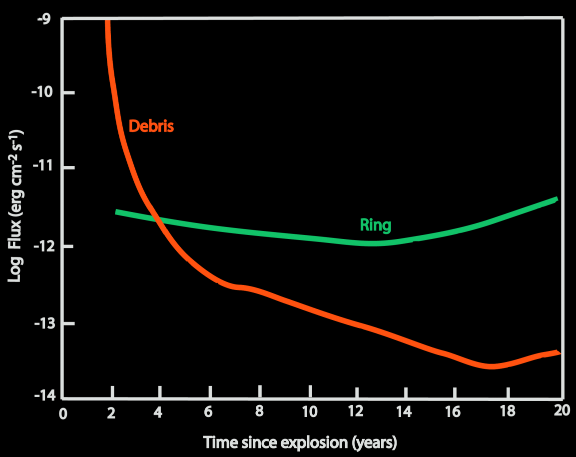
# CRASH!

# Optical Hotspots!



2006 – 2003 difference

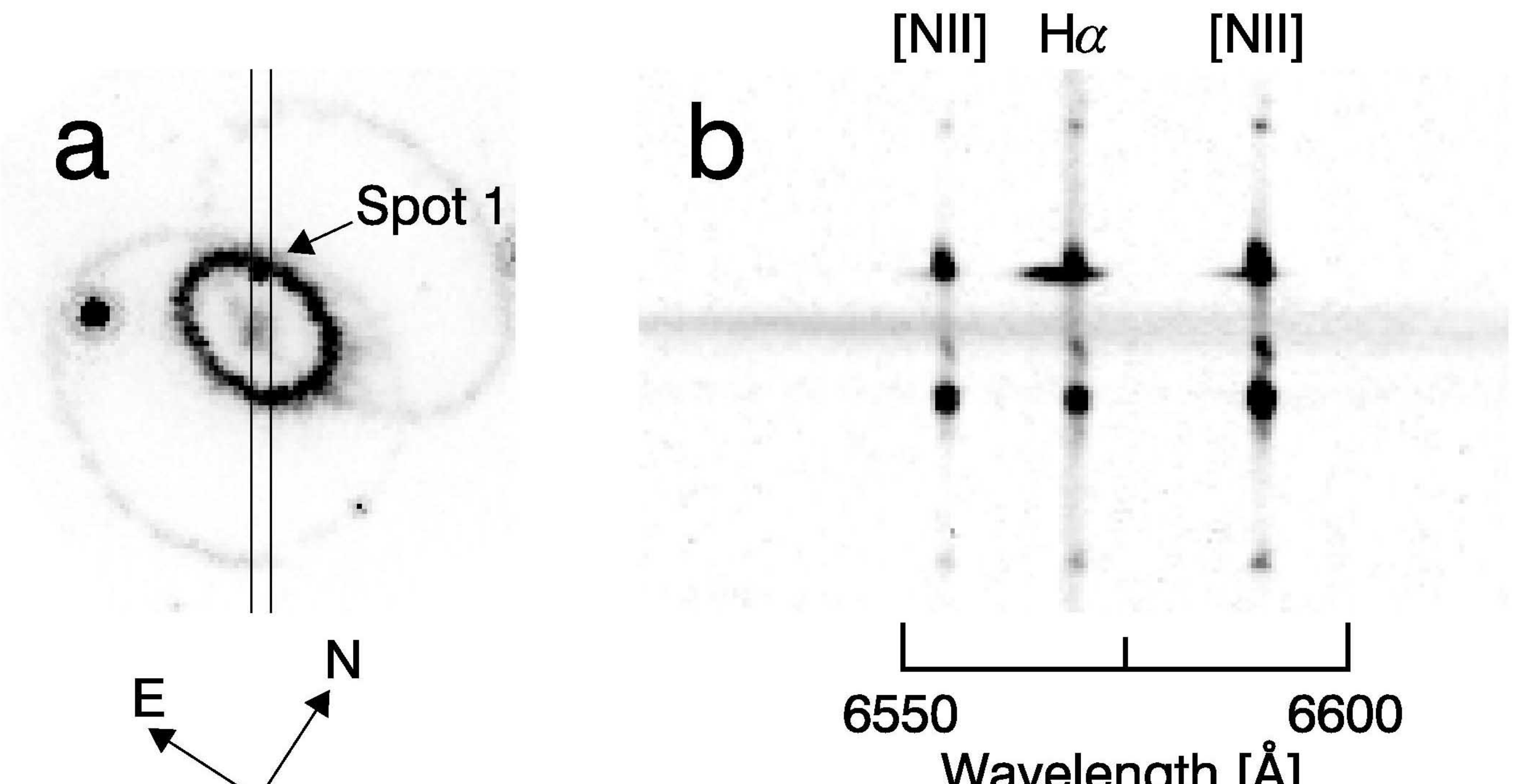


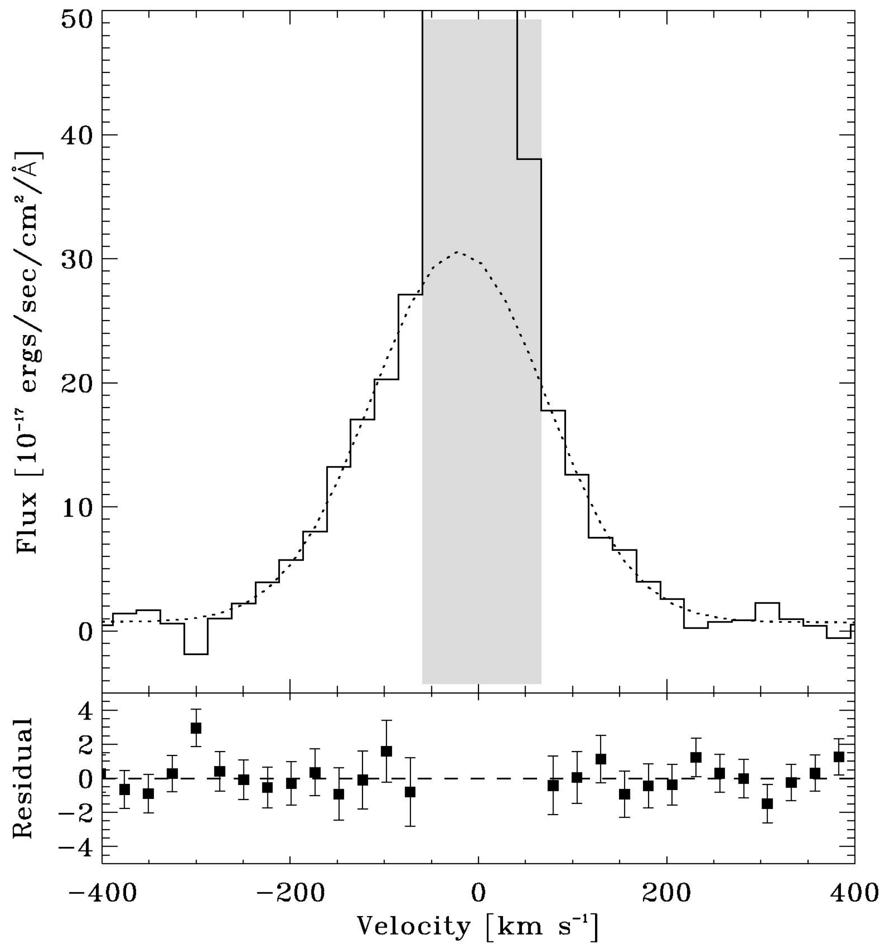




- Ring brightened by factor ~ 3
- Hotspots still unresolved
- Have not fully merged

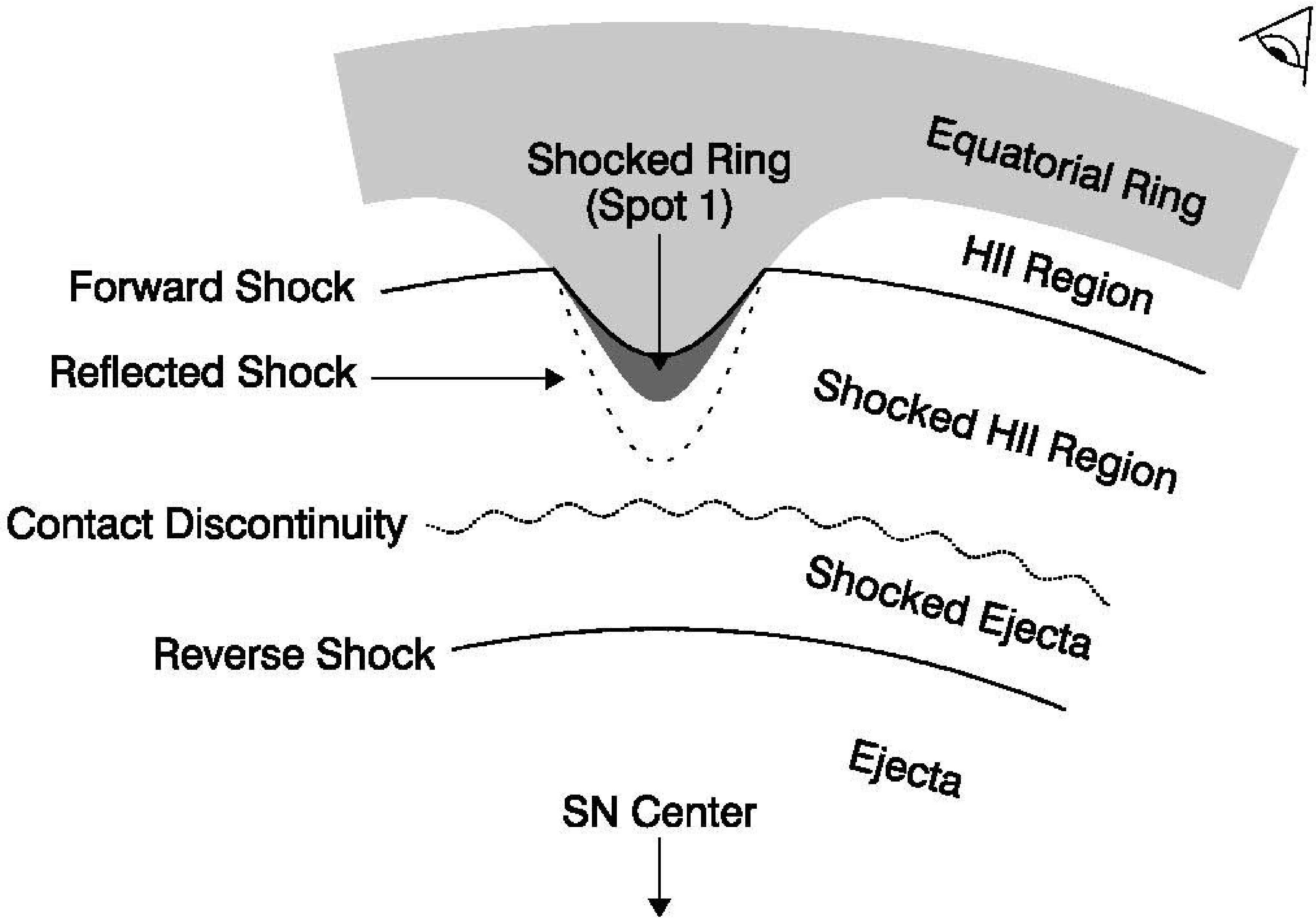
What caused fingers?
Why so regularly spaced?

# HST-STIS Spectroscopy of Spot 1



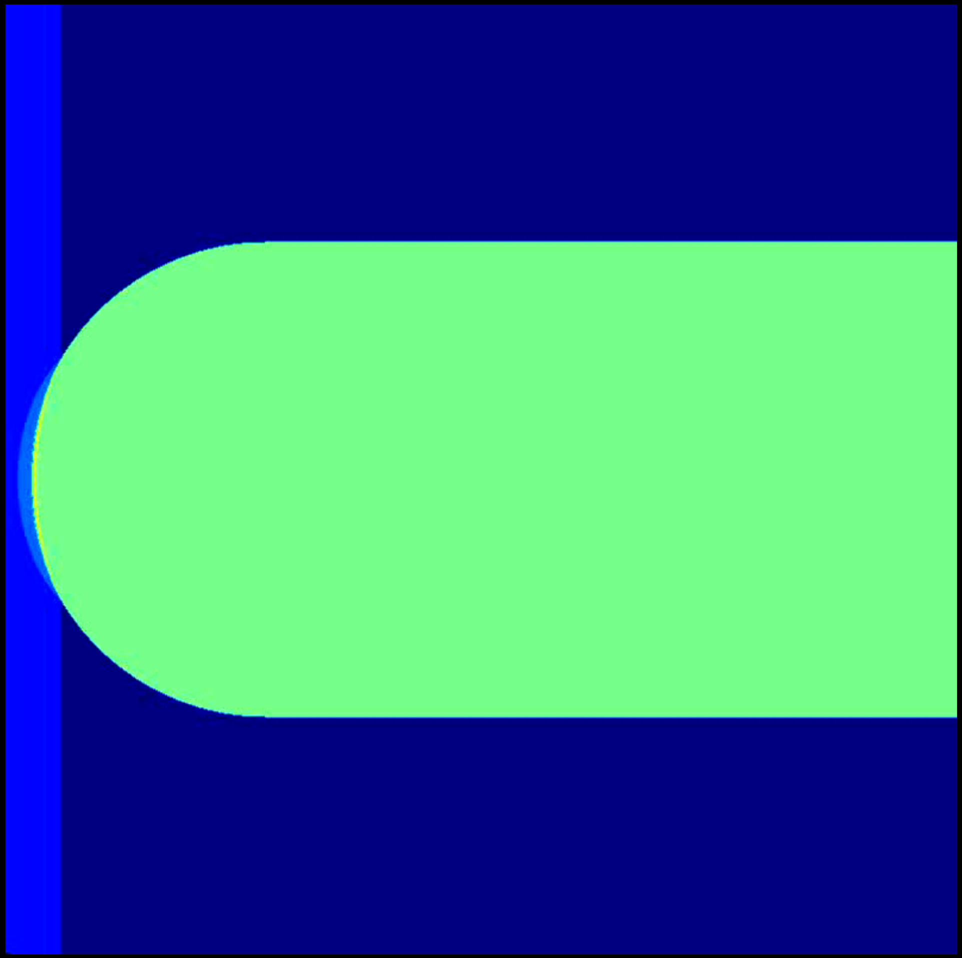


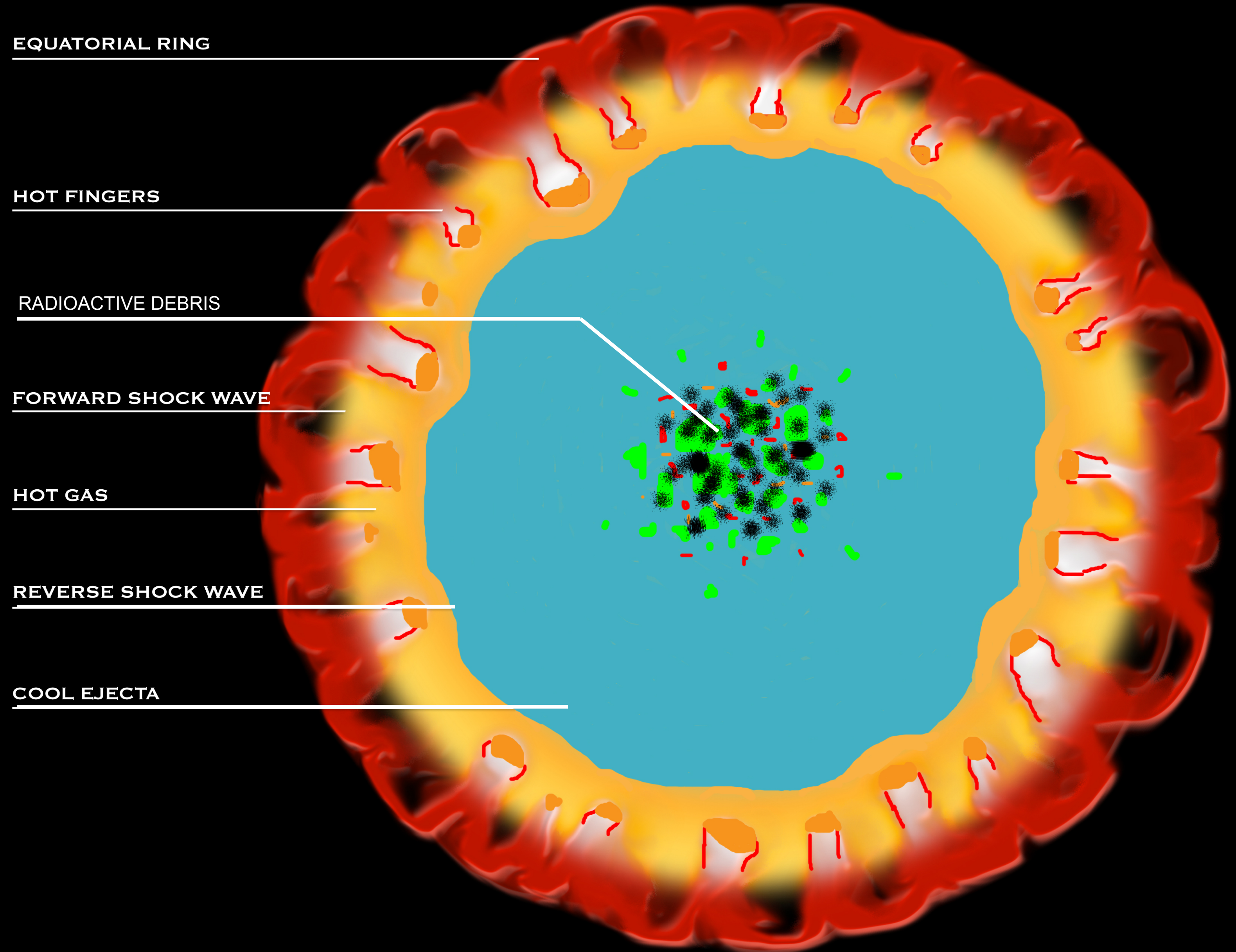

# Hα : FWHM ~ 300 km s$^{-1}$



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

# Hydro Simulation of Blast Wave Overtaking Protrusion



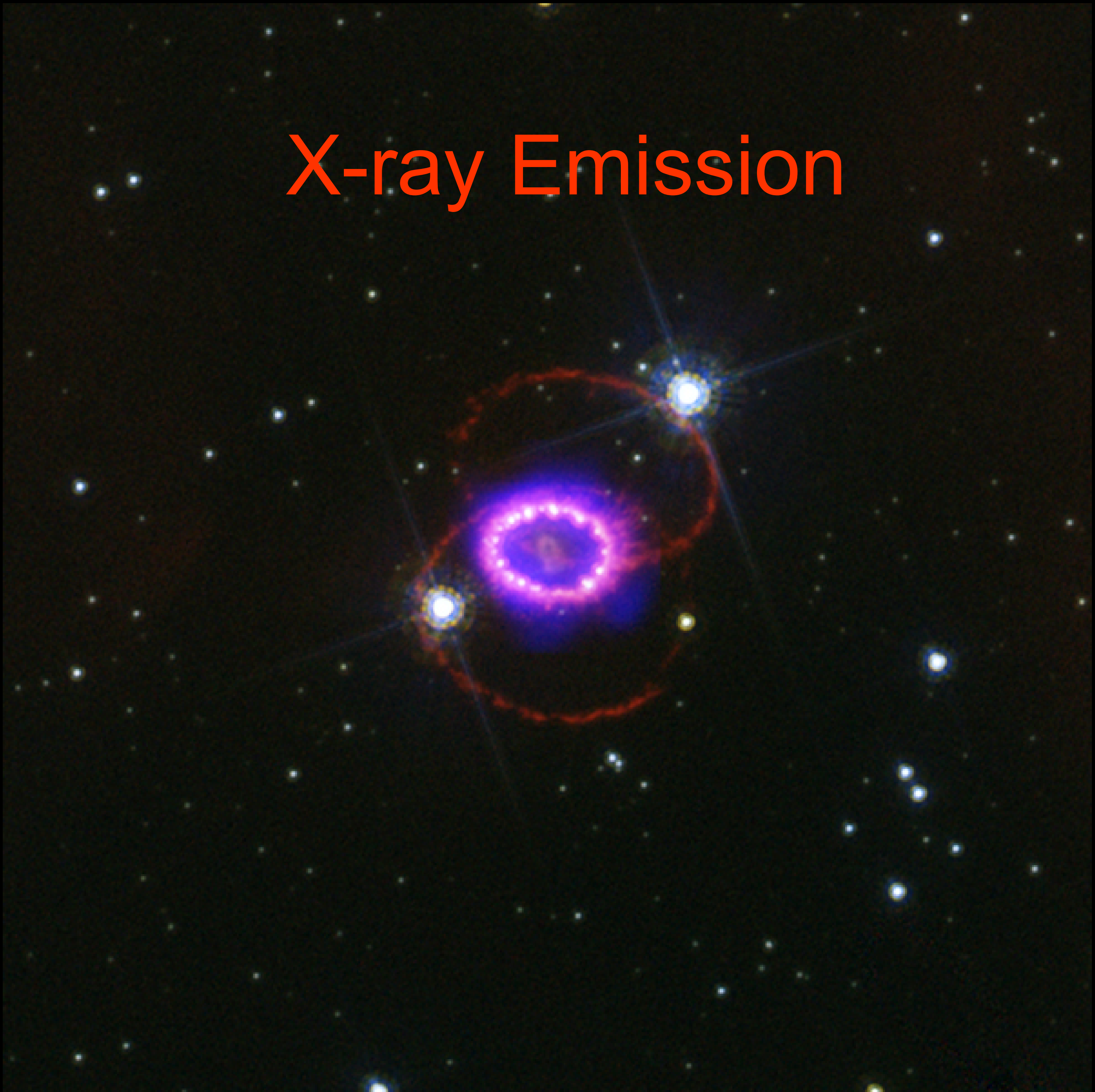


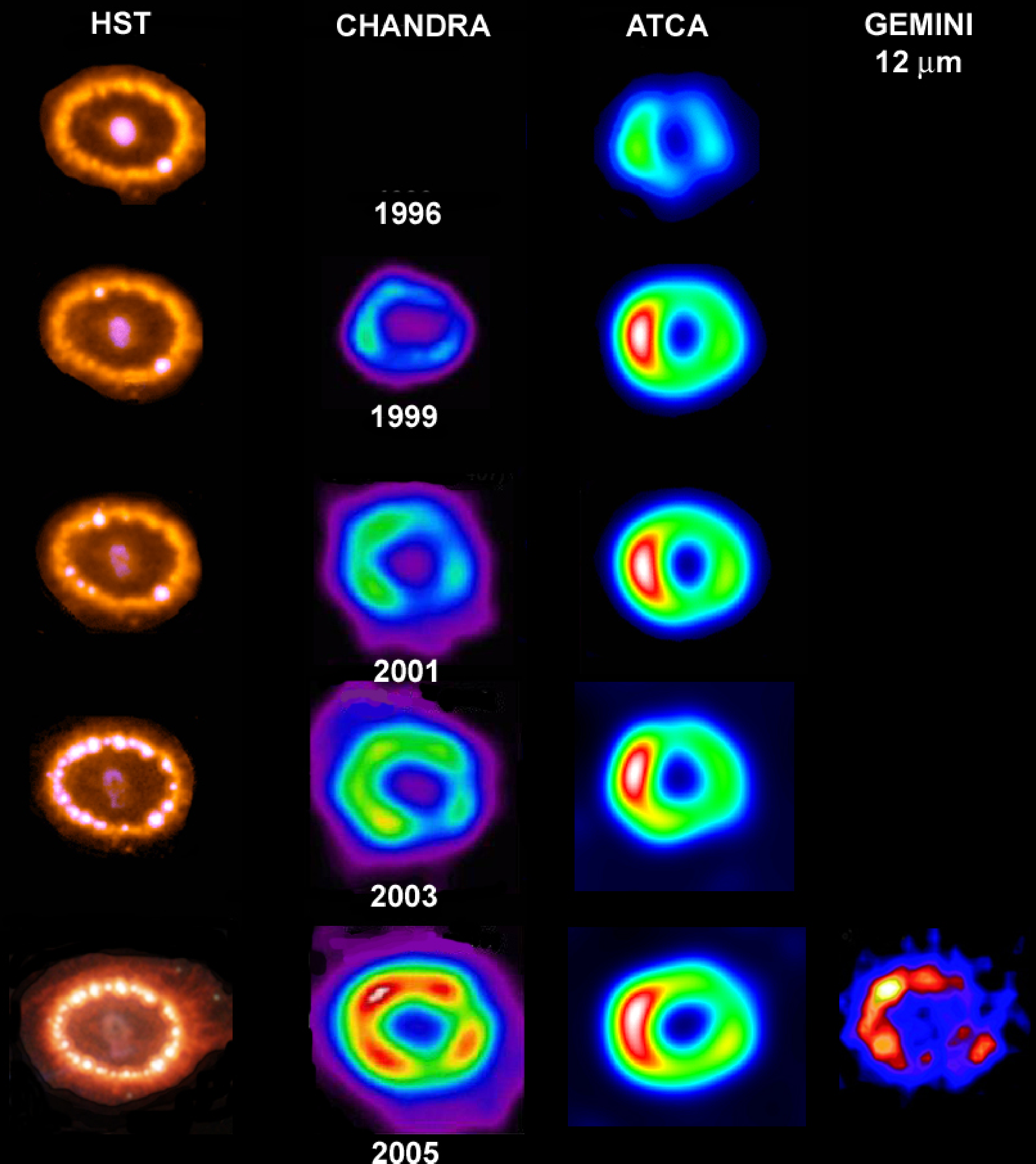
EQUATORIAL RING
HOT FINGERS
RADIOACTIVE DEBRIS
FORWARD SHOCK WAVE
HOT GAS
REVERSE SHOCK WAVE
COOL EJECTA

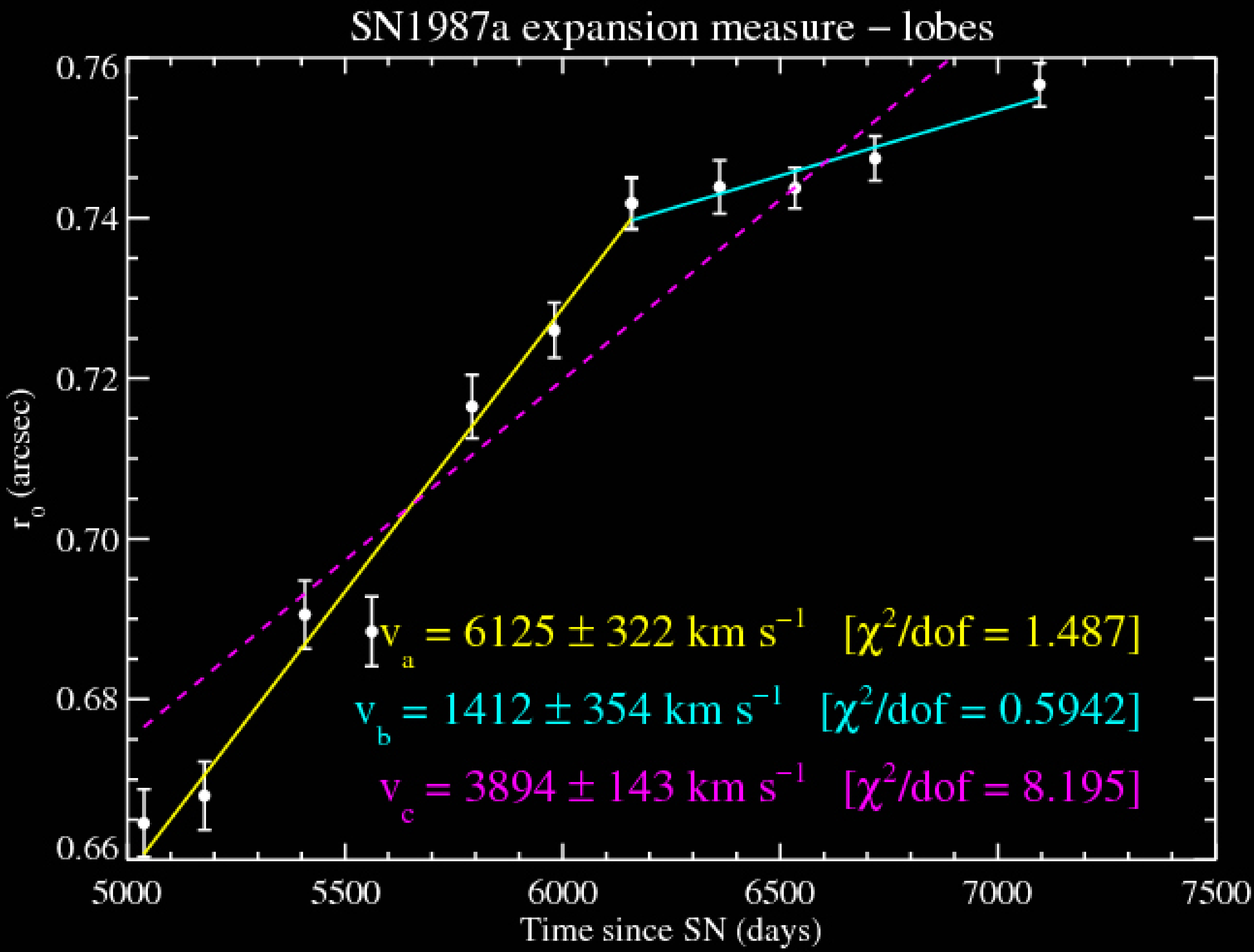
# What we know about the hot spots

- Most spots appeared first on NE and SE quadrants of ring
- Spots now encircle entire ring
- Densities ~ $10^6$ $cm^{-3}$ (from forbidden line ratios)
- 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



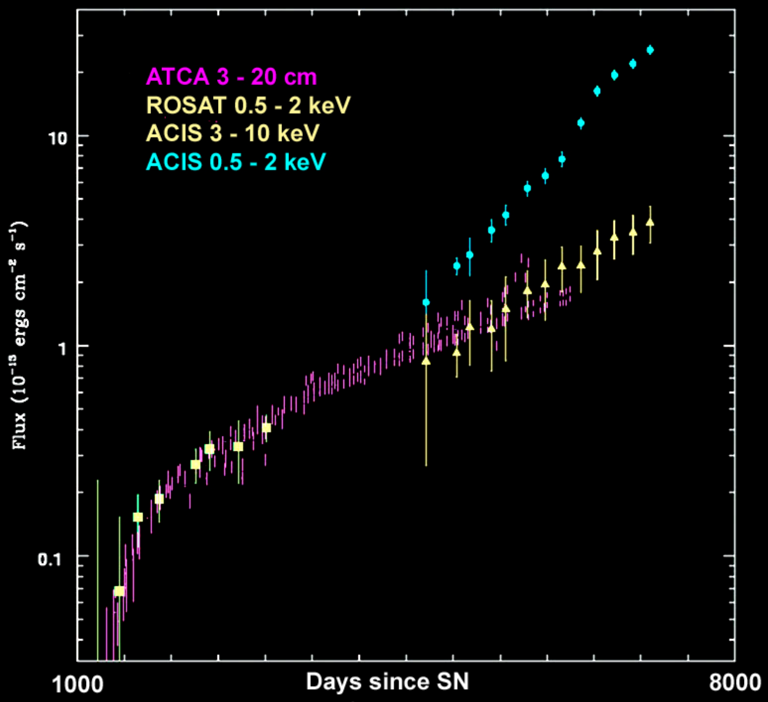

HST
CHANDRA
ATCA
GEMINI
12 μm
1996
1999
2001
2003
2005



SN1987a expansion measure – lobes
r0 (arcsec)
Time since SN (days)
0.76
0.74
0.72
0.70
0.68
0.66
5000
5500
6000
6500
7000
7500
va = 6125 ± 322 km s−1 [χ2/dof = 1.487]
vb = 1412 ± 354 km s−1 [χ2/dof = 0.5942]
vc = 3894 ± 143 km s−1 [χ2/dof = 8.195]

# Radio & X-ray Emission

## (Gaensler, Staveley-Smith, Aschenbach, Park)

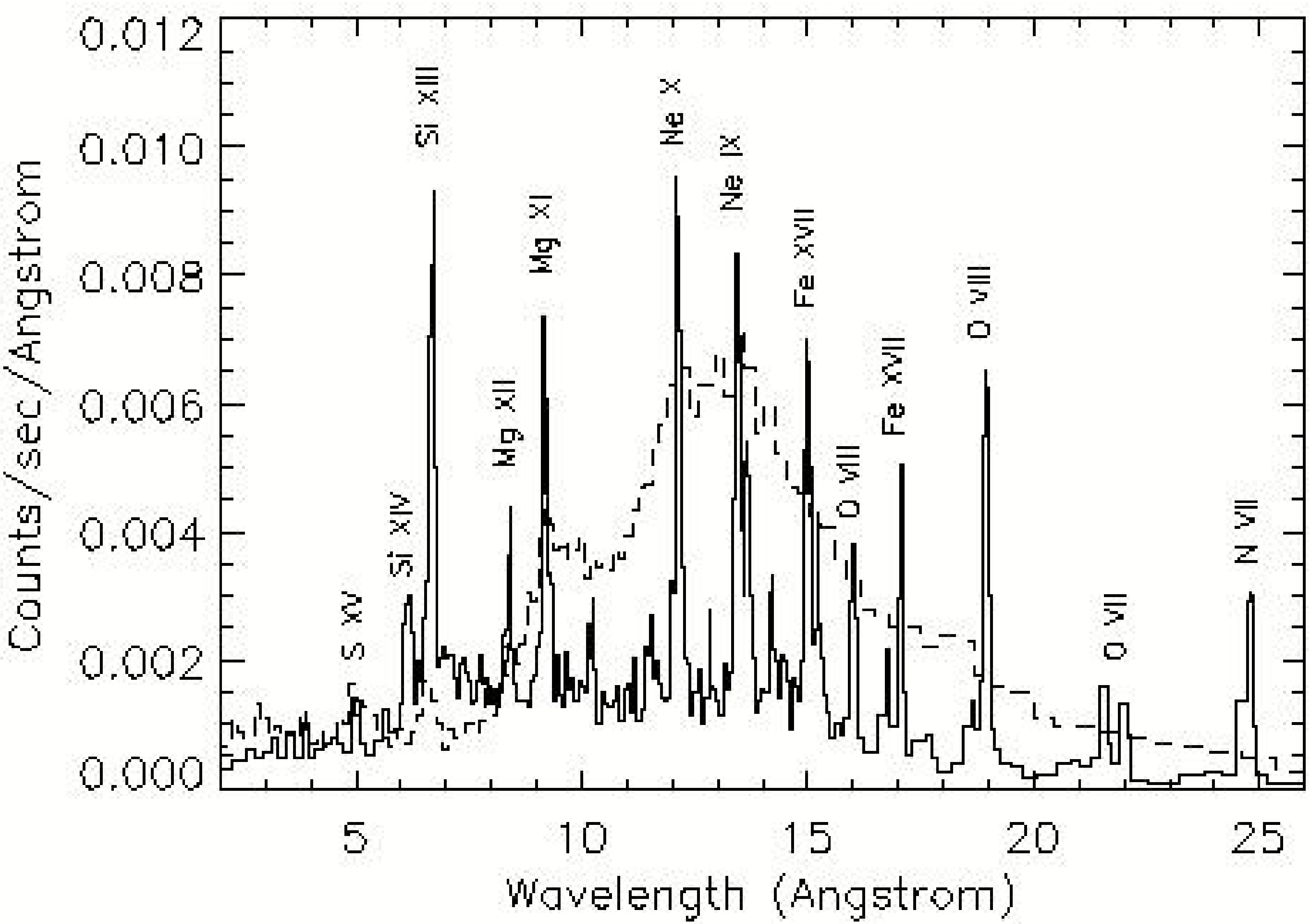



• X-rays and radio turned on at 1200 d
•ratio [hard (> 3keV) X/Radio] remains nearly constant
• Soft (~0.5 – 2 keV) X-rays increased rapidly after hotspots appeared)
•Soft X-ray image resembles optical image

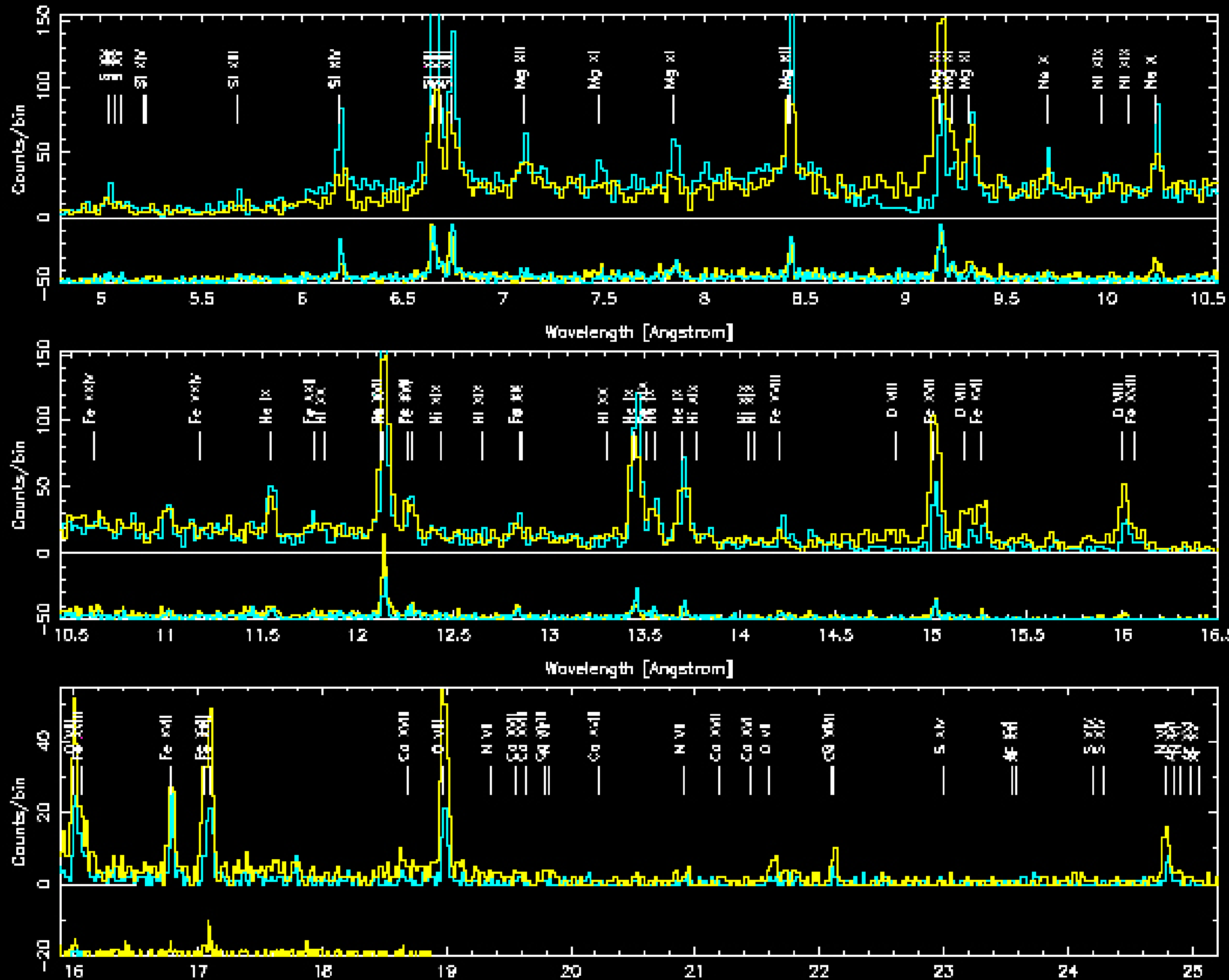
9 Radio and hard X-rays come from relatively low density gas between blast wave and reverse shock

□Optical and soft X-rays come from blast waves overtaking hotspots

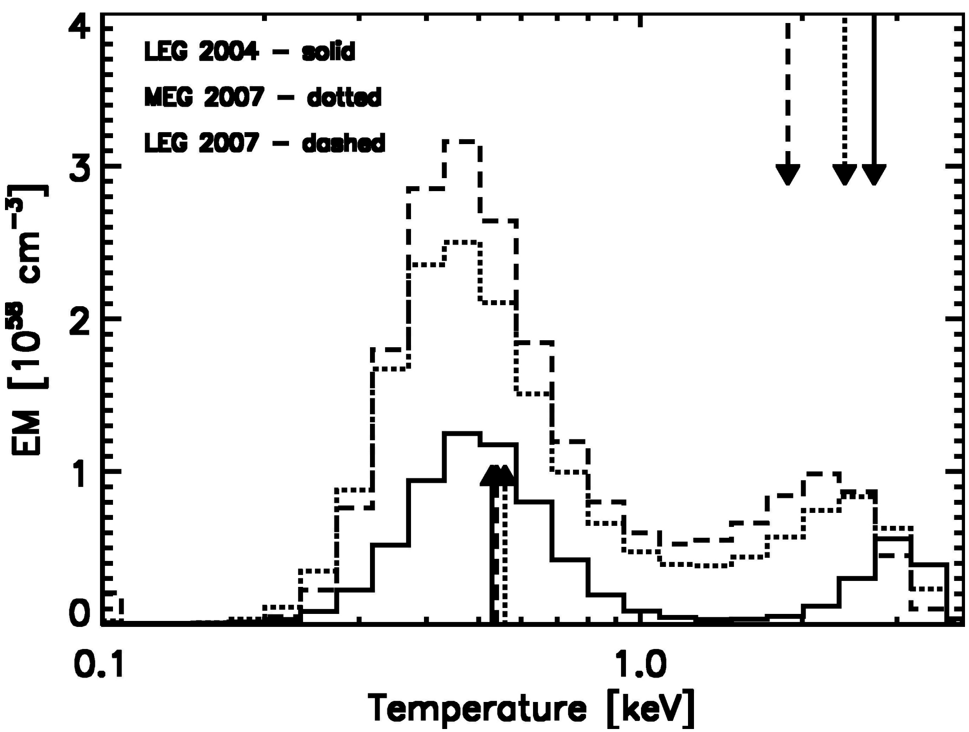
# Chandra LETG Spectra Sept. 2004 (Zhekov et al)



# Chandra HETG Spectrum April 2007 (Dewey et al.)

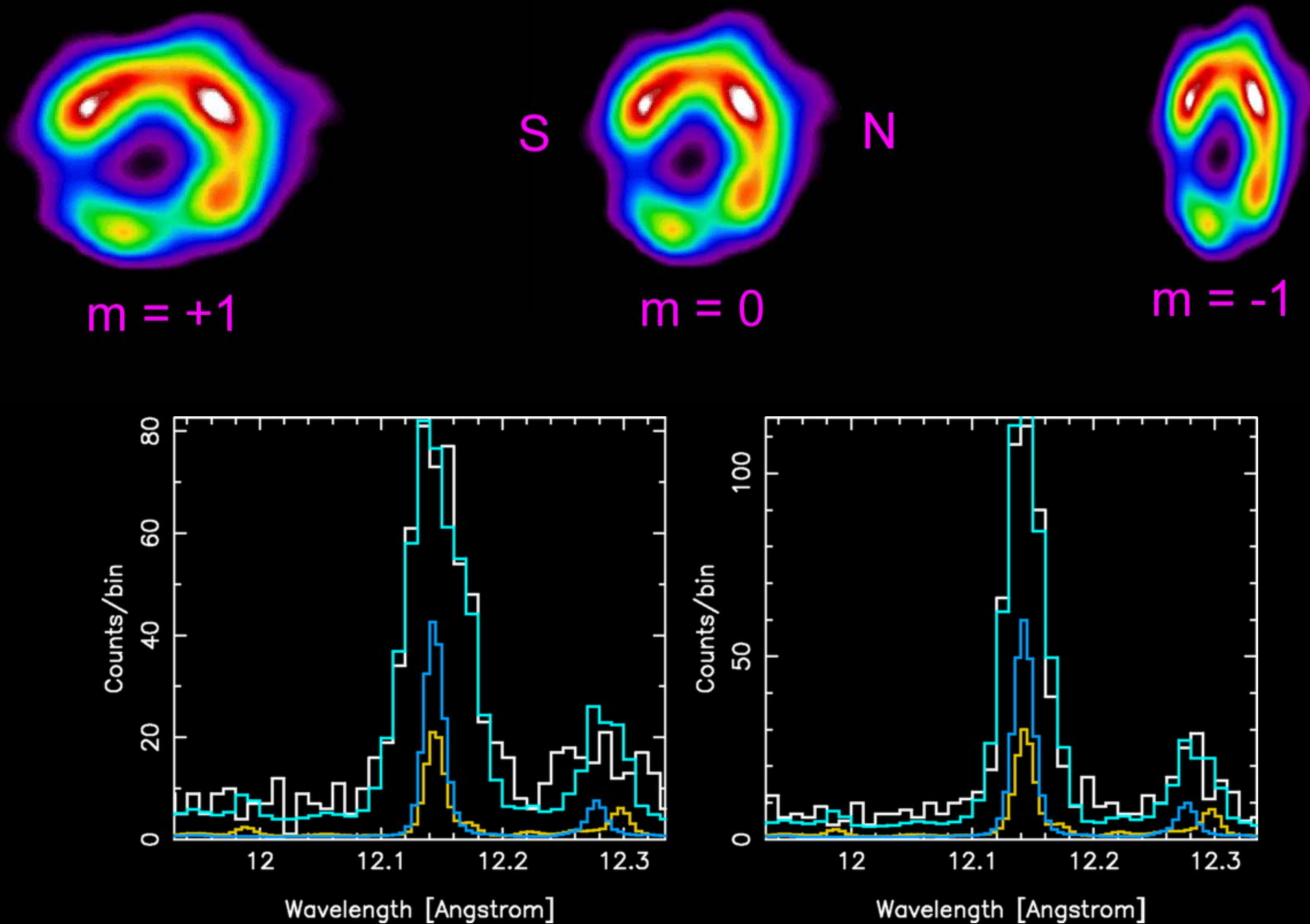


# Global fits of NIE models to Chandra grating spectra

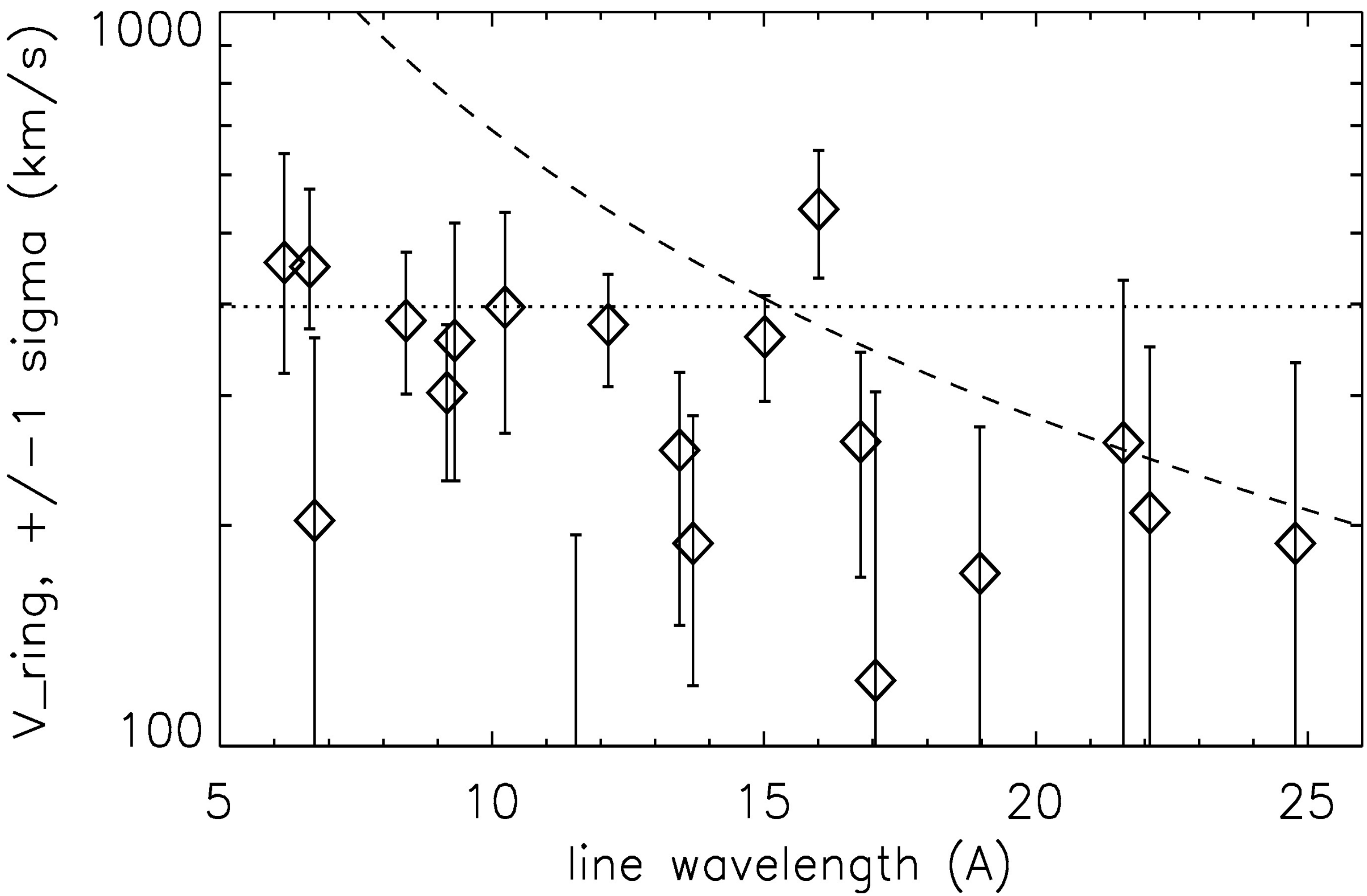



- Bimodal temperature distribution: ~ 2 keV and 0.5 keV
- Hard component cooled, intermediate temperatures filled in

# Shock Kinematics from X-ray Line Profiles



# Radial expansion velocities inferred from X-ray emission line profiles



# Puzzle #1

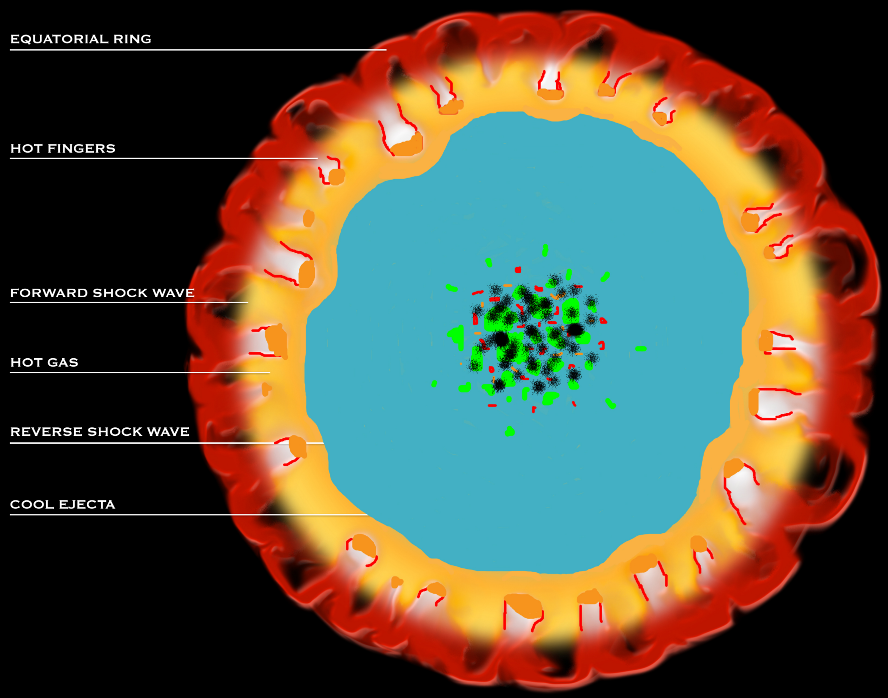
•Radial expansion velocity of ring inferred from line profiles (Doppler shifts) ~ 300 km s-1.

•Radial expansion velocity inferred from proper motion of image ~ 1400 km s-1.

But ring is tilted at ~45$^{o}$. If X-ray source is the same in both cases, transverse velocity should be the same as Doppler velocity. Discrepancy = factor ~ 4.6!

???

# Solution to Puzzle #1




- When we look at line profiles, we are measuring actual fluid motion
- When we look at transverse expansion, we are measuring barycenter of X-ray emission, caused by overtaking blast wave.

# Puzzle #2

•Velocity of shocked gas inferred from X-ray line profiles (Doppler shifts) ~ 300 km $s^{-1}$.

•Temperature of X-ray emitting gas inferred from line ratios ~ 0.5 – 2 keV

But, shock jump conditions $kT = 3/16\, mV_S^2$, and post-shock gas should be moving with velocity $V_R = ¾\, V_S$. Taking $V_R$ ~ 400 km $s^{-1}$, jump conditions imply kT = 0.14 keV. Discrepancy = factor ~ 3.5 - 14.

The shocked X-ray emitting gas is not moving fast enough to account for its temperature.

???

# Solution to Puzzle #2

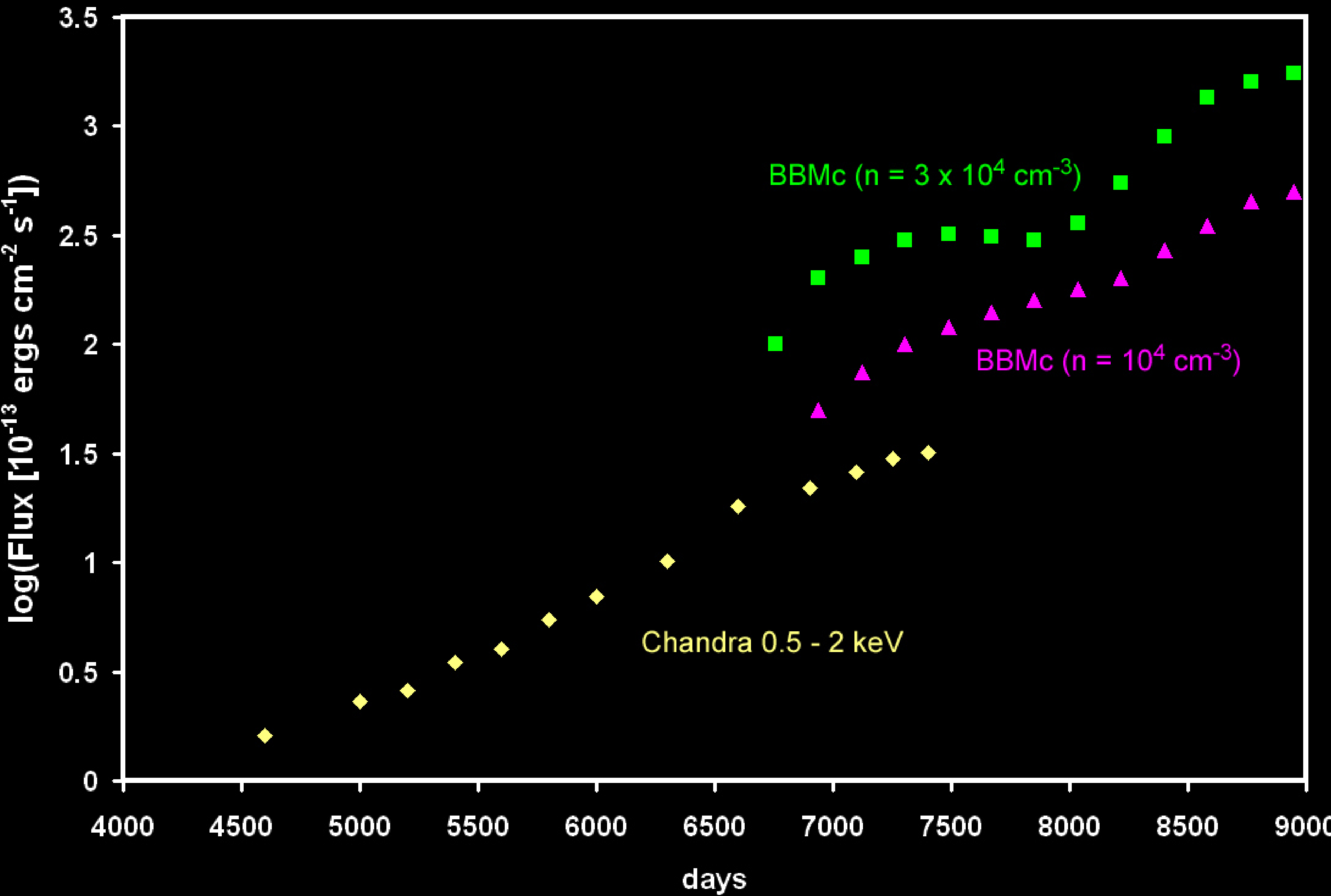
Blast wave strikes high density ring, a reflected shock goes backwards, slowing the X-ray emitting gas to the velocity of the transmitted shock. The twice-shocked gas has density ~2.5 times greater than the gas behind the blast wave, and temperature ~2.4 times greater. It dominates the X-ray emissivity.

# 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: 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.
- 25 year forecast: will see newly synthesized material cross reverse shock
- Long range forecast: Will remain bright for decades - centuries



BBMc (n = 3 x 10^4 cm^-3)
BBMc (n = 10^4 cm^-3)
Chandra 0.5 - 2 keV
log(Flux [10^-13 ergs cm^-2 s^-1])
days
3.5
3
2.5
2
1.5
1
0.5
0
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000

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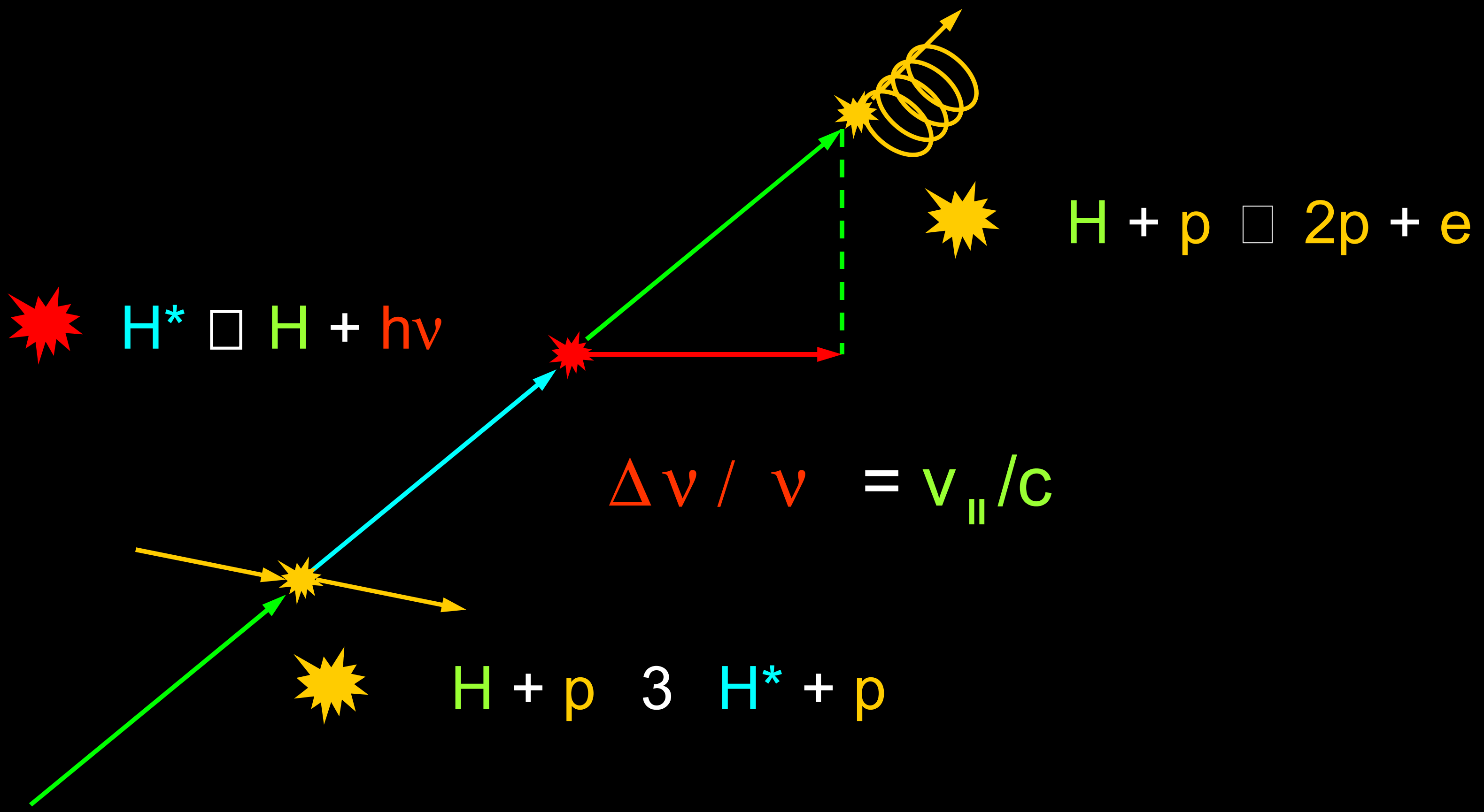
Kevin Heng
Svet Zhekov
Nathan Smith
Dave Burrows
Sangwook Park

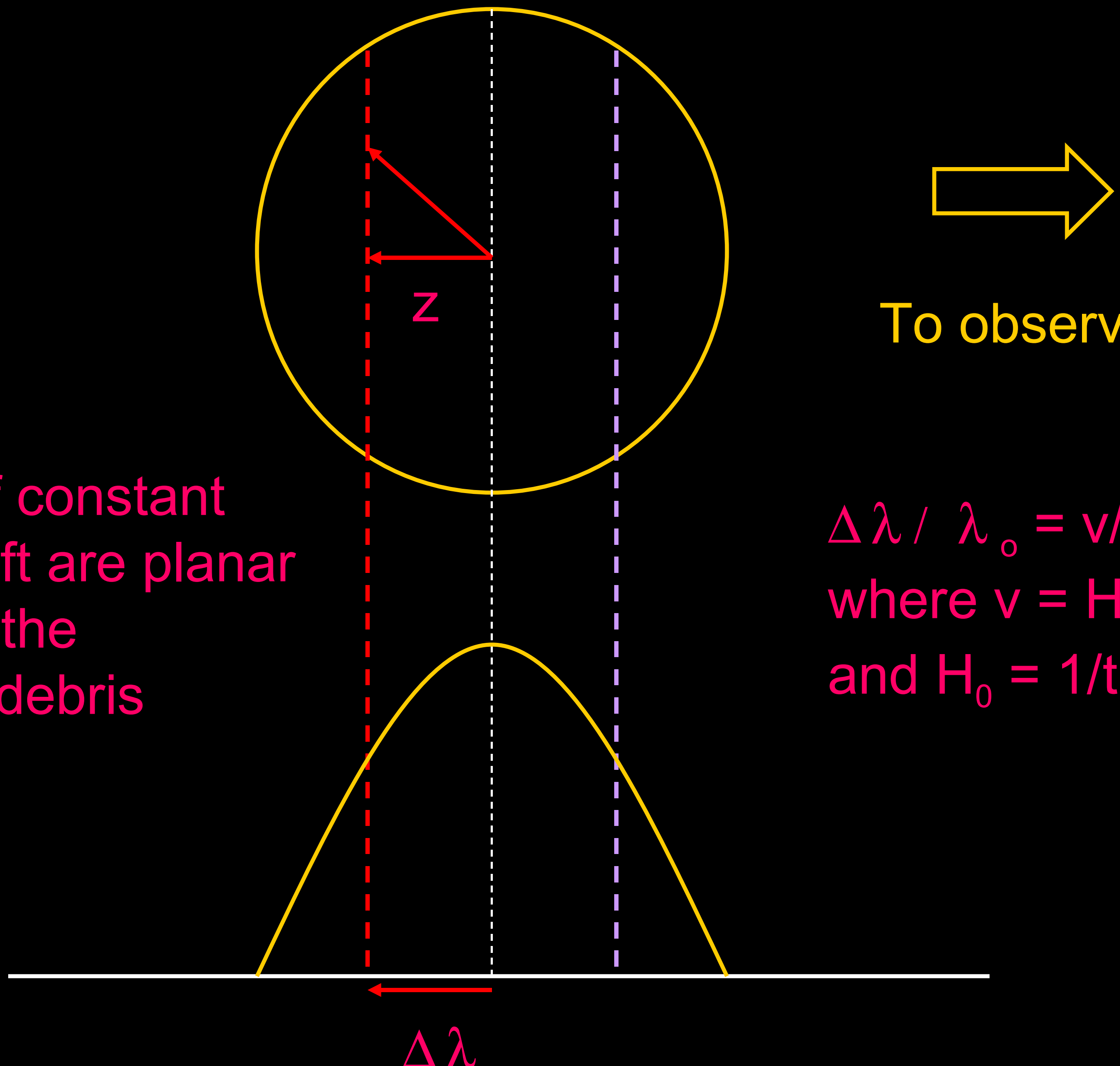
Bob Kirshner and SINS team
Dick Manchester
Bryan Gaensler
Kazik Borkowski
John Blondin

… and many others

# Reverse Shock

# Line emission and impact ionization at reverse shock surface



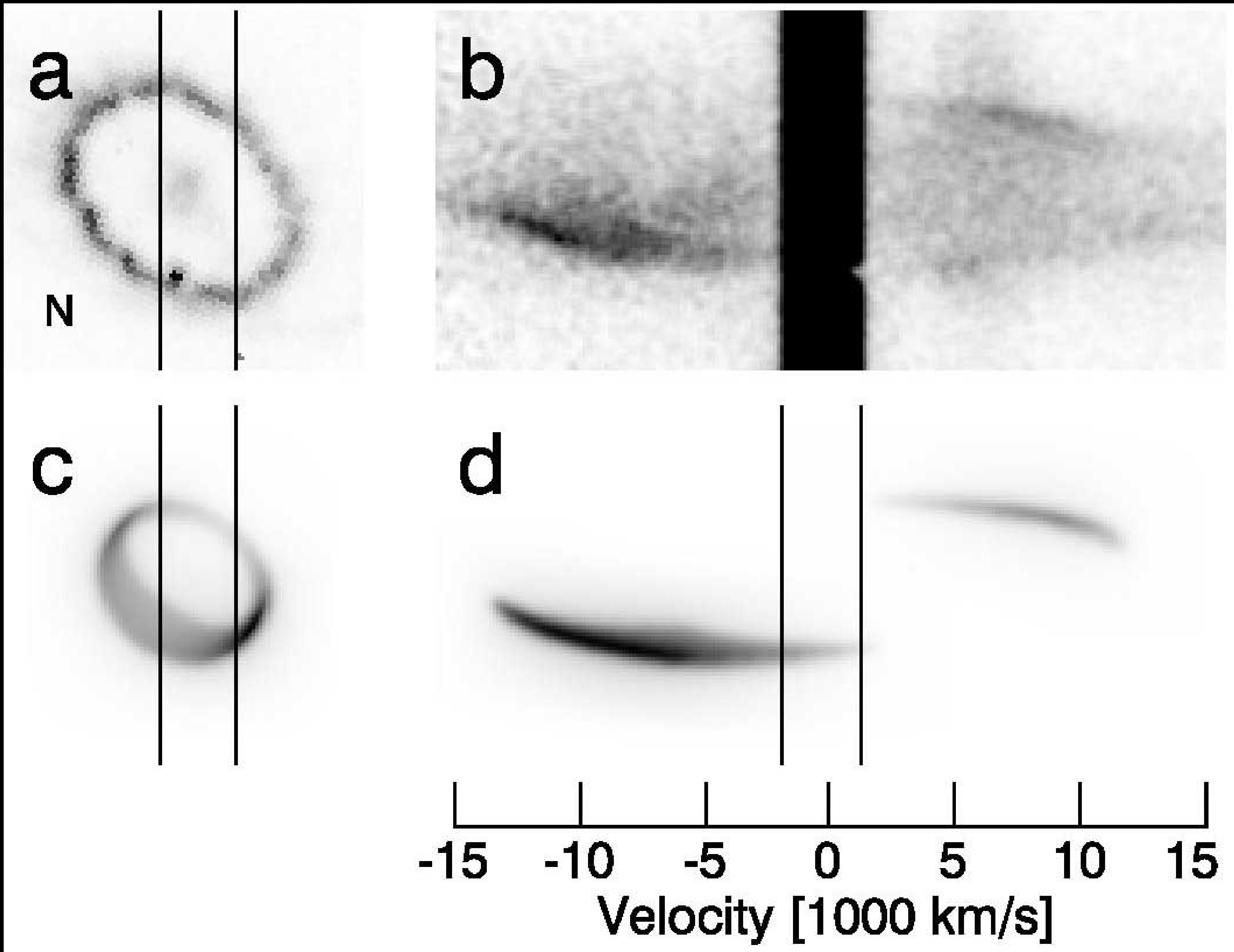


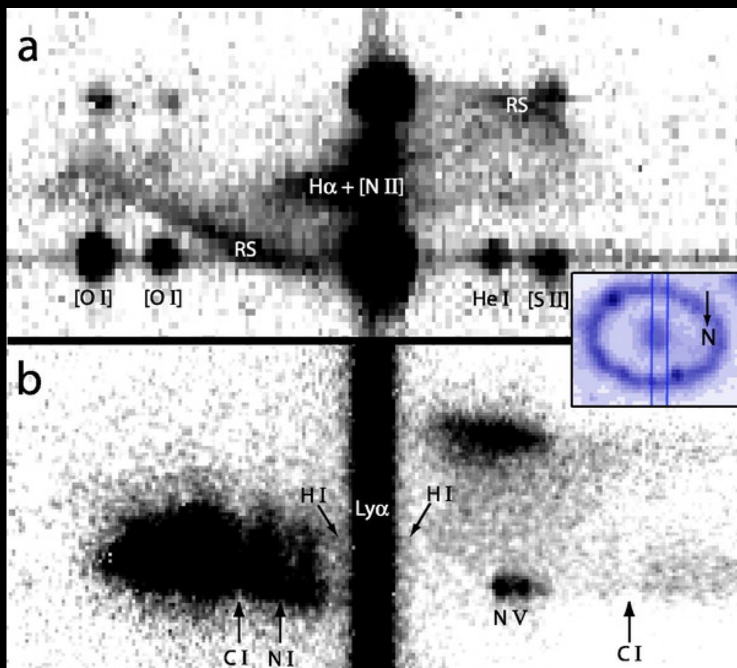

Surfaces of constant Doppler shift are planar sections of the supernova debris

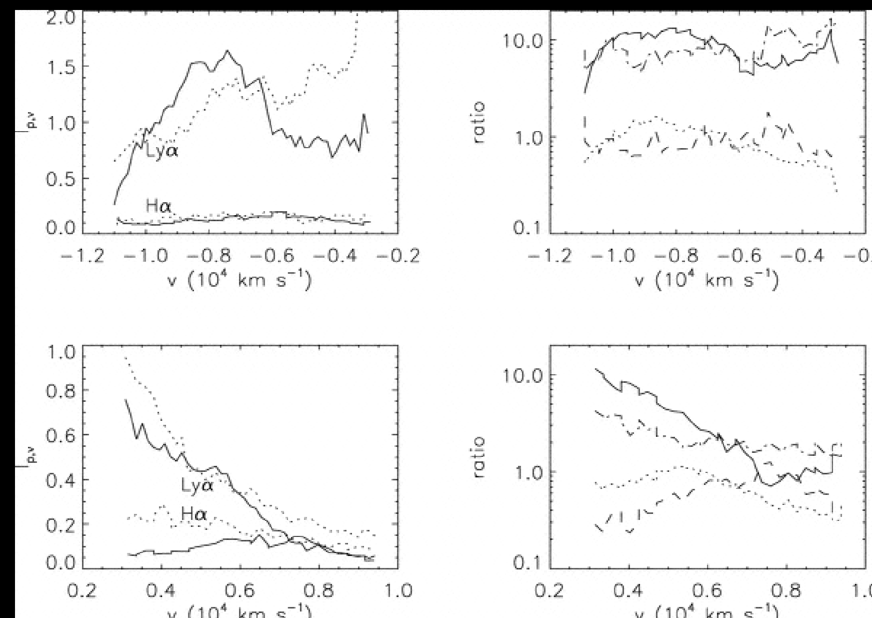
$\Delta\lambda / \lambda_o = v/c$

where $v = H_0 z$

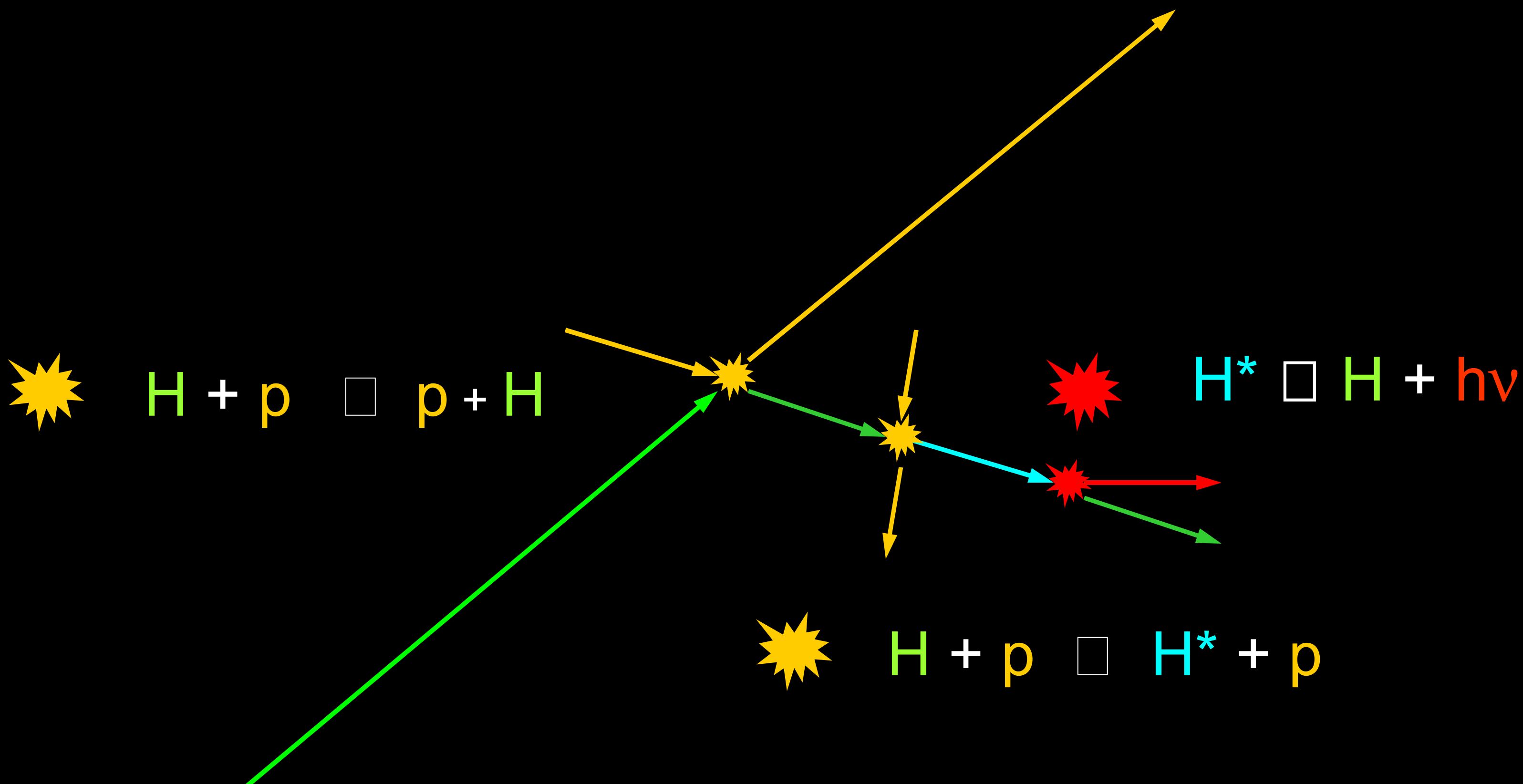
and $H_0 = 1/t$


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

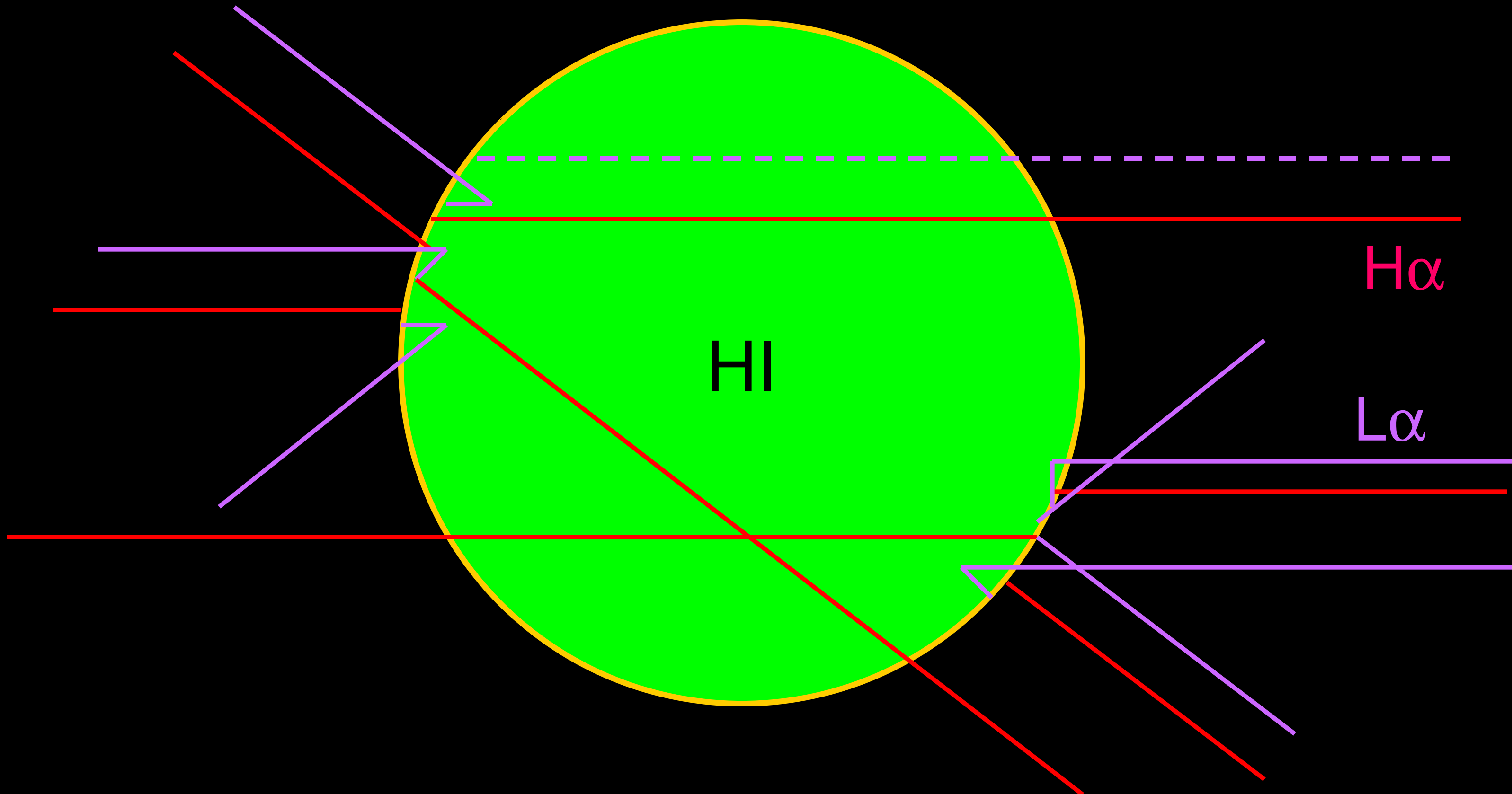

a
RS
Hα + [N II]
RS
[O I]
[O I]
He I
[S II]
N
b
H I
Lyα
H I
C I
N I
N V
C I

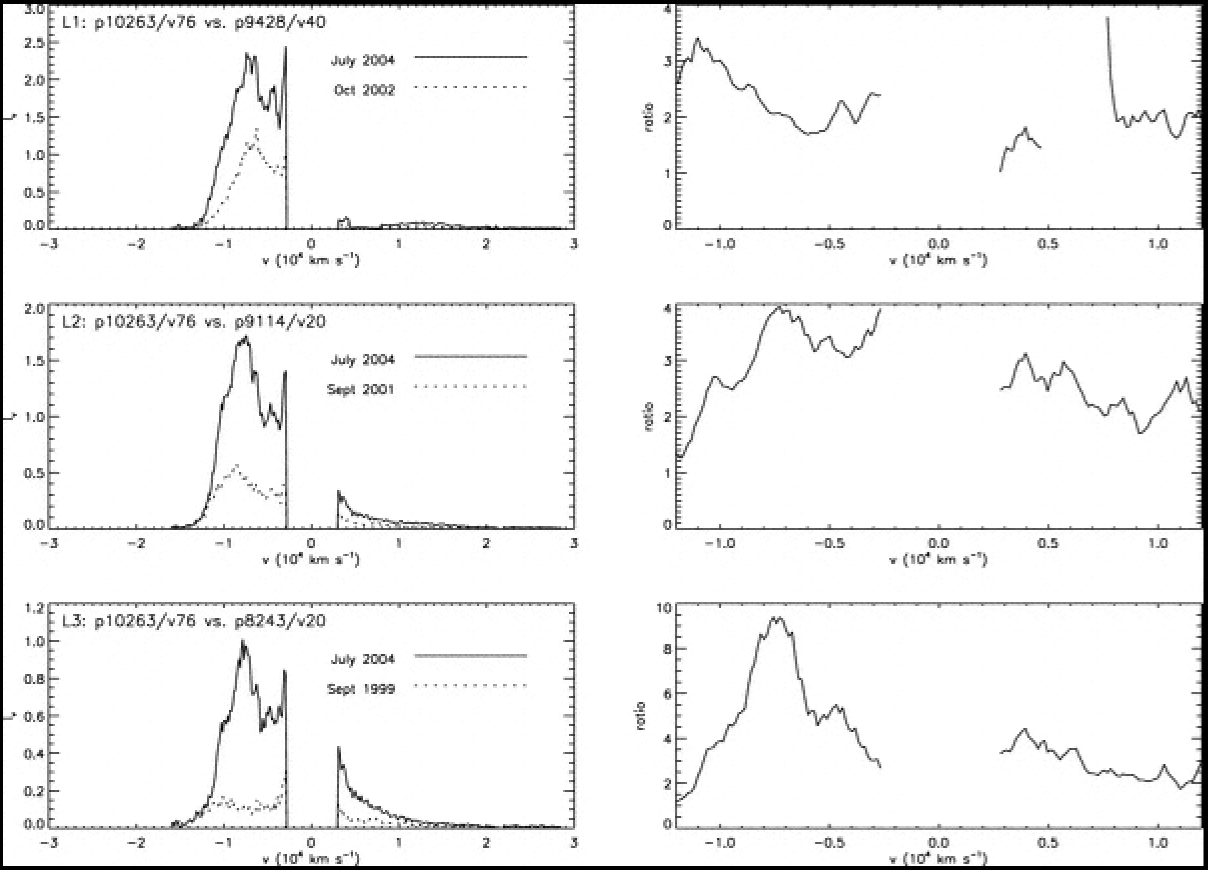

Lyα
Hα
v (10^4 km s^-1)
ratio
v (10^4 km s^-1)
Lyα
Hα
v (10^4 km s^-1)
ratio
v (10^4 km s^-1)

# Charge Transfer at Reverse Shock Surface



# Lα Resonance Scattering

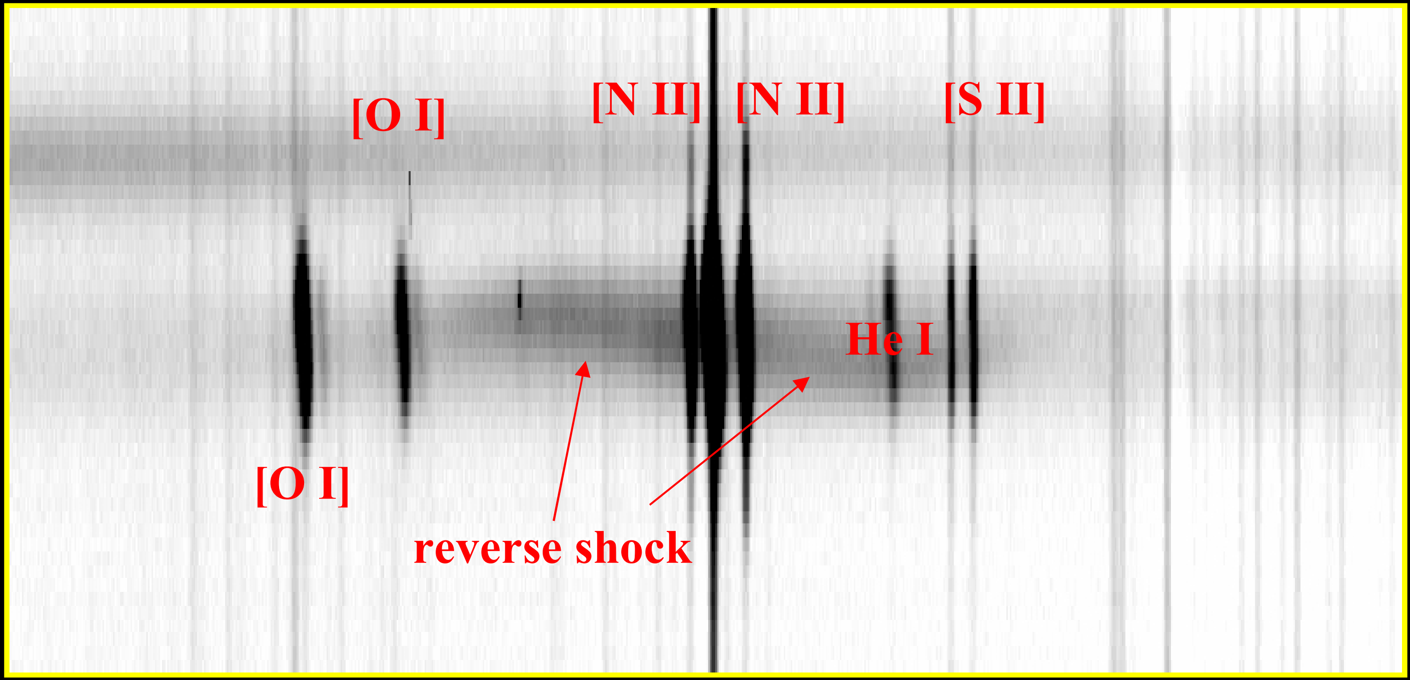




L1: p10263/v76 vs. p9428/v40
July 2004
Oct 2002
L2: p10263/v76 vs. p9114/v20
July 2004
Sept 2001
L3: p10263/v76 vs. p8243/v20
July 2004
Sept 1999
ratio
v (10⁴ km s⁻¹)

# Magellan/LDSS Hα Observation

(Nathan Smith)




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

# Bleaching of Reverse Shock Emission by Preionization