The Remnant of SN1987A

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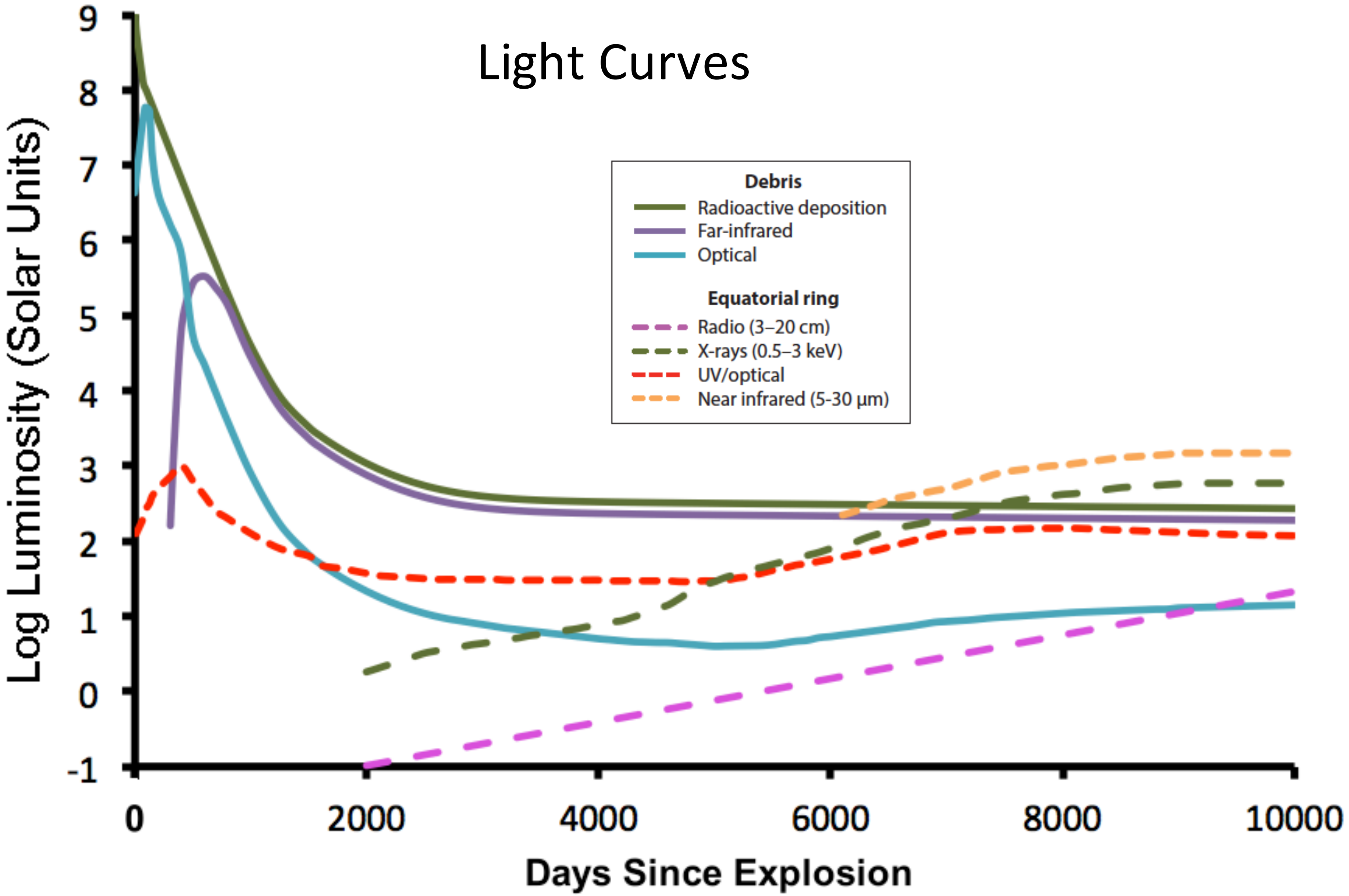
Chania,
10 June 2016

Topics

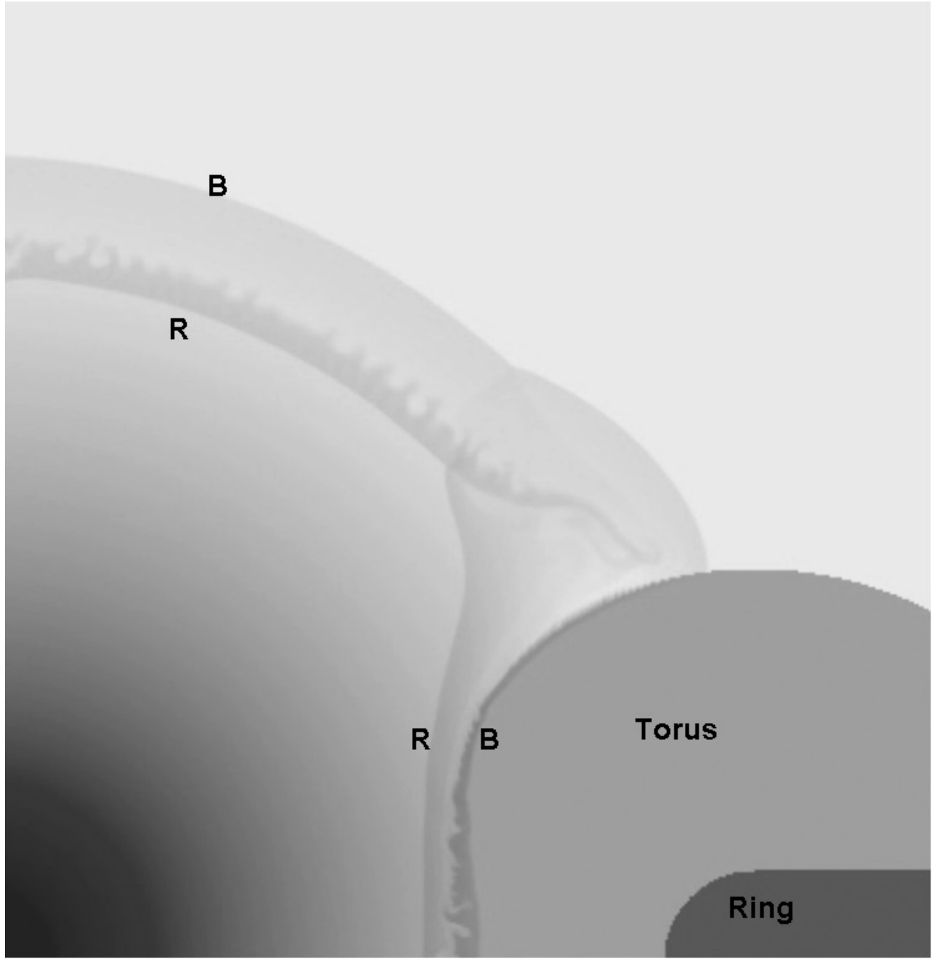
- Light Curves
- Reverse shock
- Hotspots
- ALMA: CO and SiO


Light Curves
Log Luminosity (Solar Units)
Days Since Explosion
Debris
Radioactive deposition
Far-infrared
Optical
Equatorial ring
Radio (3–20 cm)
X-rays (0.5–3 keV)
UV/optical
Near infrared (5-30 μm)
9
8
7
6
5
4
3
2
1
0
-1
0
2000
4000
6000
8000
10000

Comments about light curves:

- Optical light from interior has faded by factor $\sim 10^{-7}$
- Luminosity of interior is dominated by Far-IR: $\sim 220\ L_\odot$
- Far-IR is $\sim$ 90% of energy deposited by ^{44}Ti decay.
- Upper limit of energy input from compact object is $\sim 30\ L_\odot$
- Today, luminosity is dominated by near-IR and X-ray emission from shocked ring
- Optical/UV emission from ring reached a maximum at t = 400 days, then faded.
- Ring began to brighten again when hotspots appeared @ t $\sim$ 5000 days. Now leveling off. Not as bright as initial maximum.

Reverse Shock

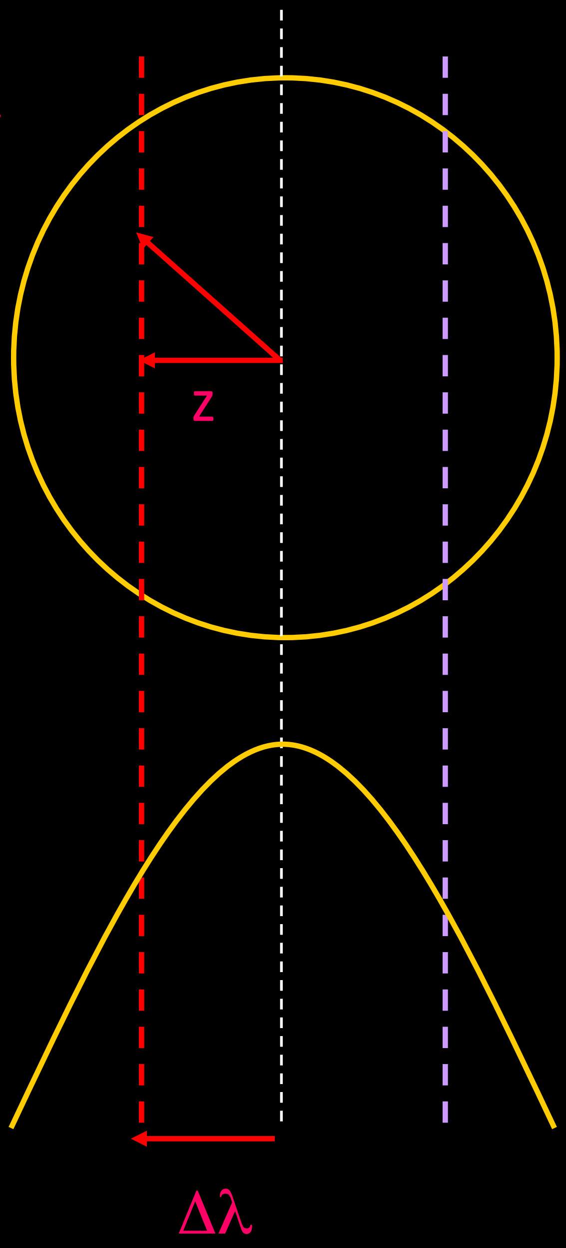


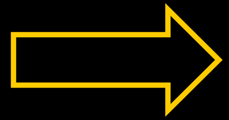
Doppler Tomography

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

(Flat: $\Delta z/z < 1$ month/27 yr)

Thin: $\delta z/z < 10^{-3}$





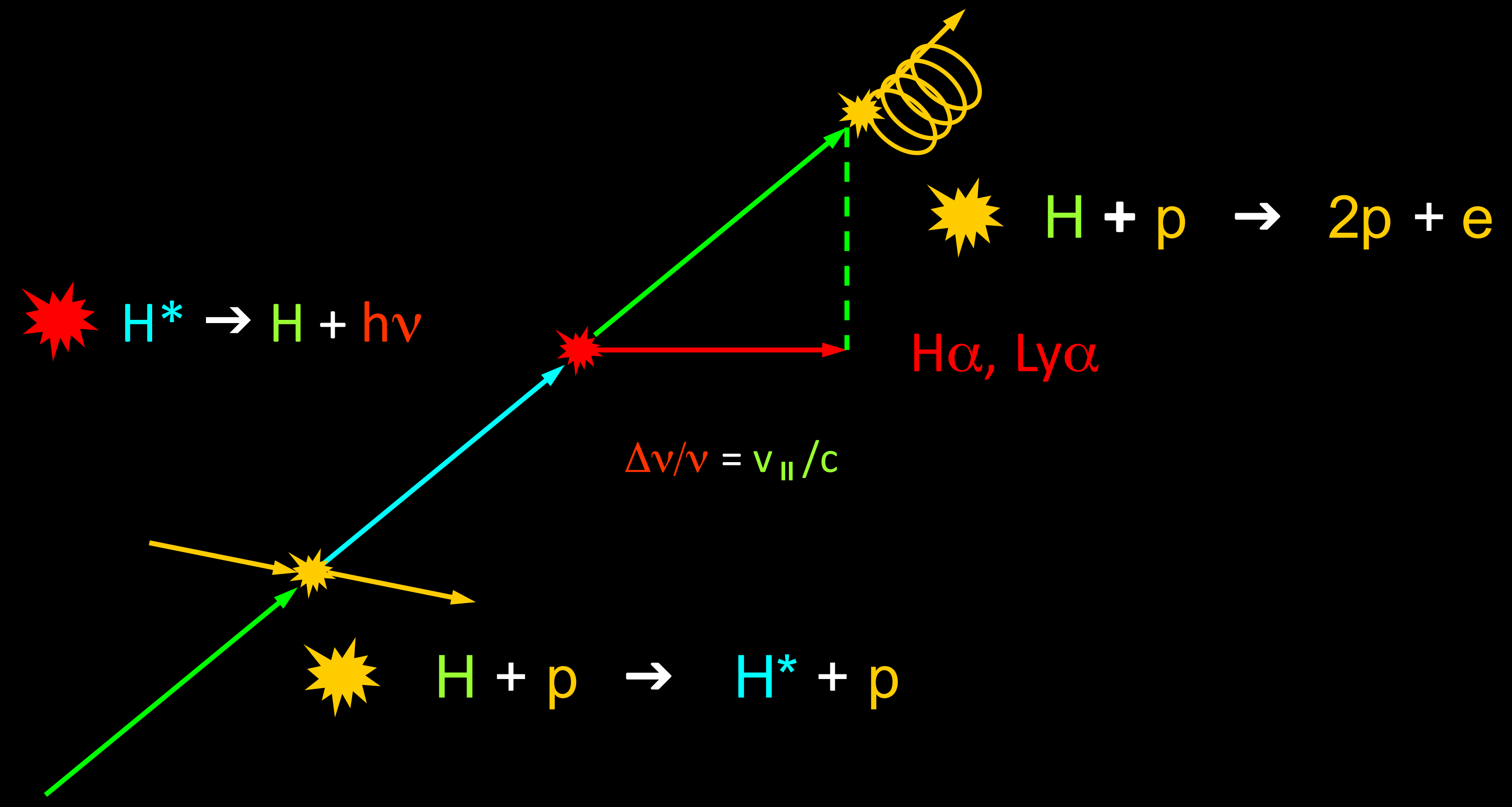
To observer

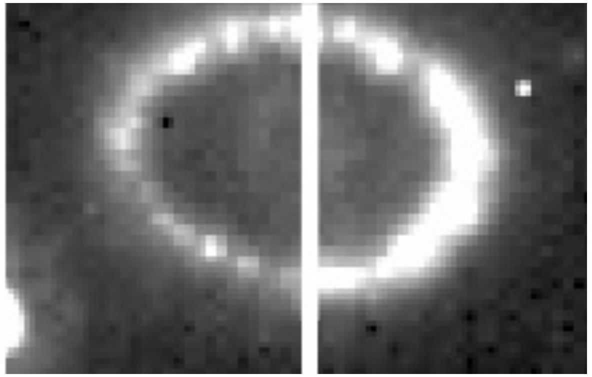
$\Delta\lambda/\lambda_o = v/c$

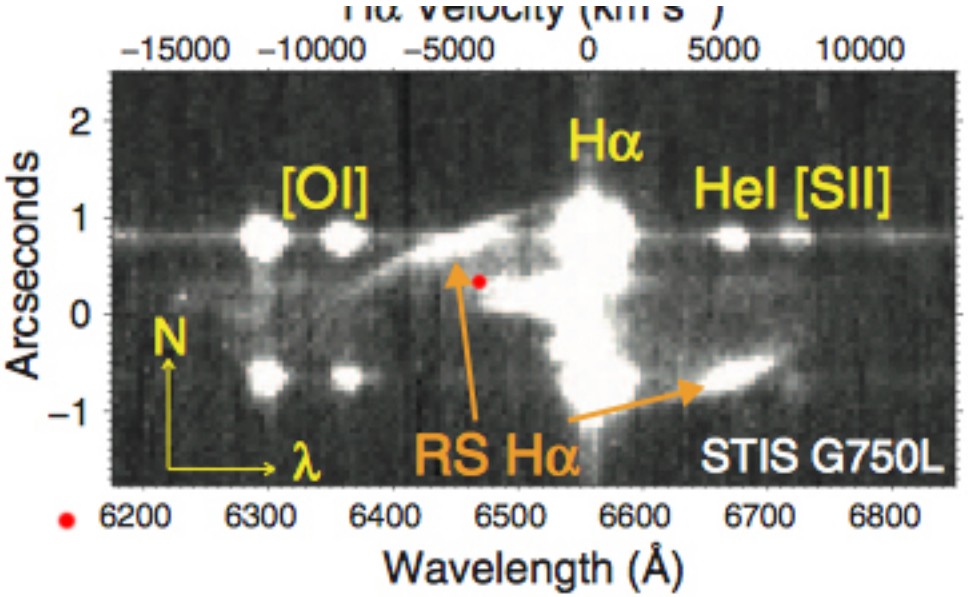
where $v = H_0 z$

and $H_0 = 1/t$

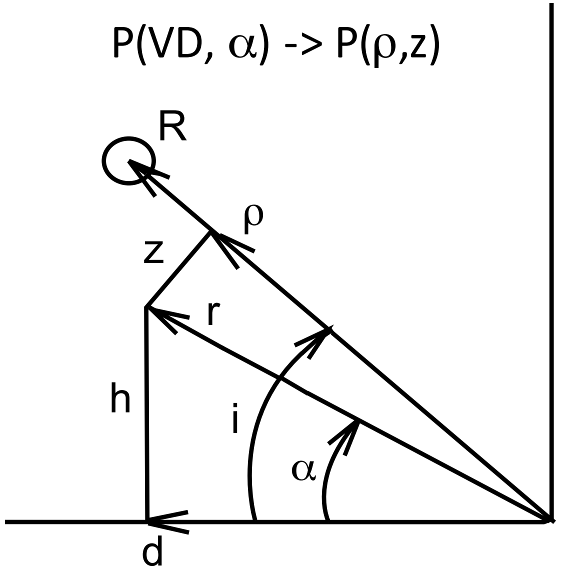
Line emission and impact ionization at reverse shock surface



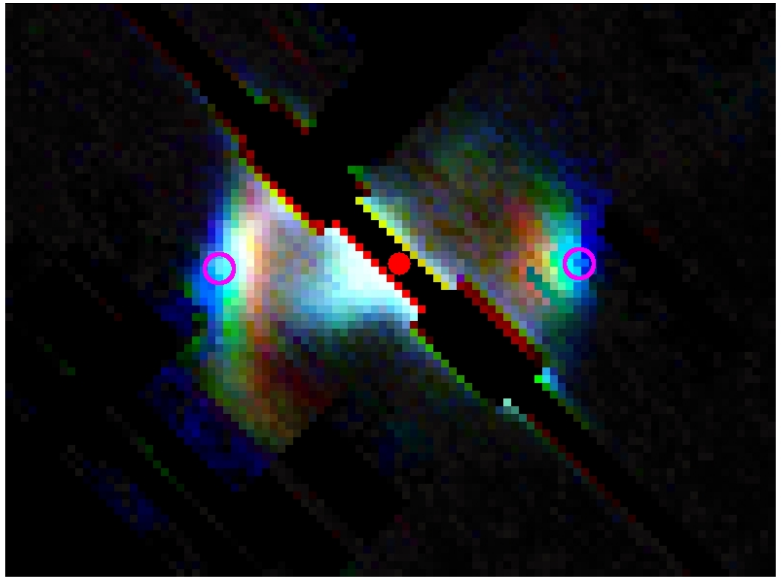




Hα Velocity (km s⁻¹)
−15000
−10000
−5000
0
5000
10000
Arcseconds
2
1
0
−1
[OI]
Hα
HeI [SII]
N
λ
RS Hα
STIS G750L
6200
6300
6400
6500
6600
6700
6800
Wavelength (Å)



P(VD, α) -> P(ρ,z)
R
ρ
z
r
h
i
α
d

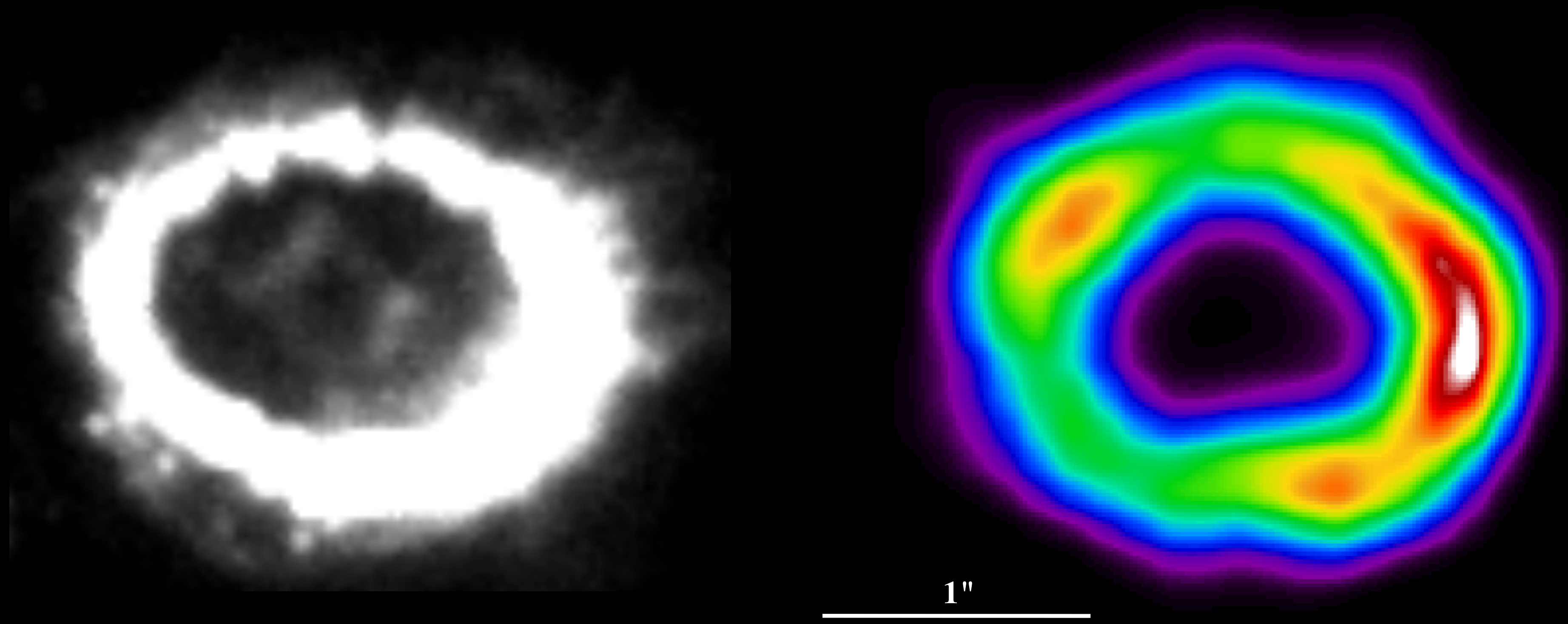


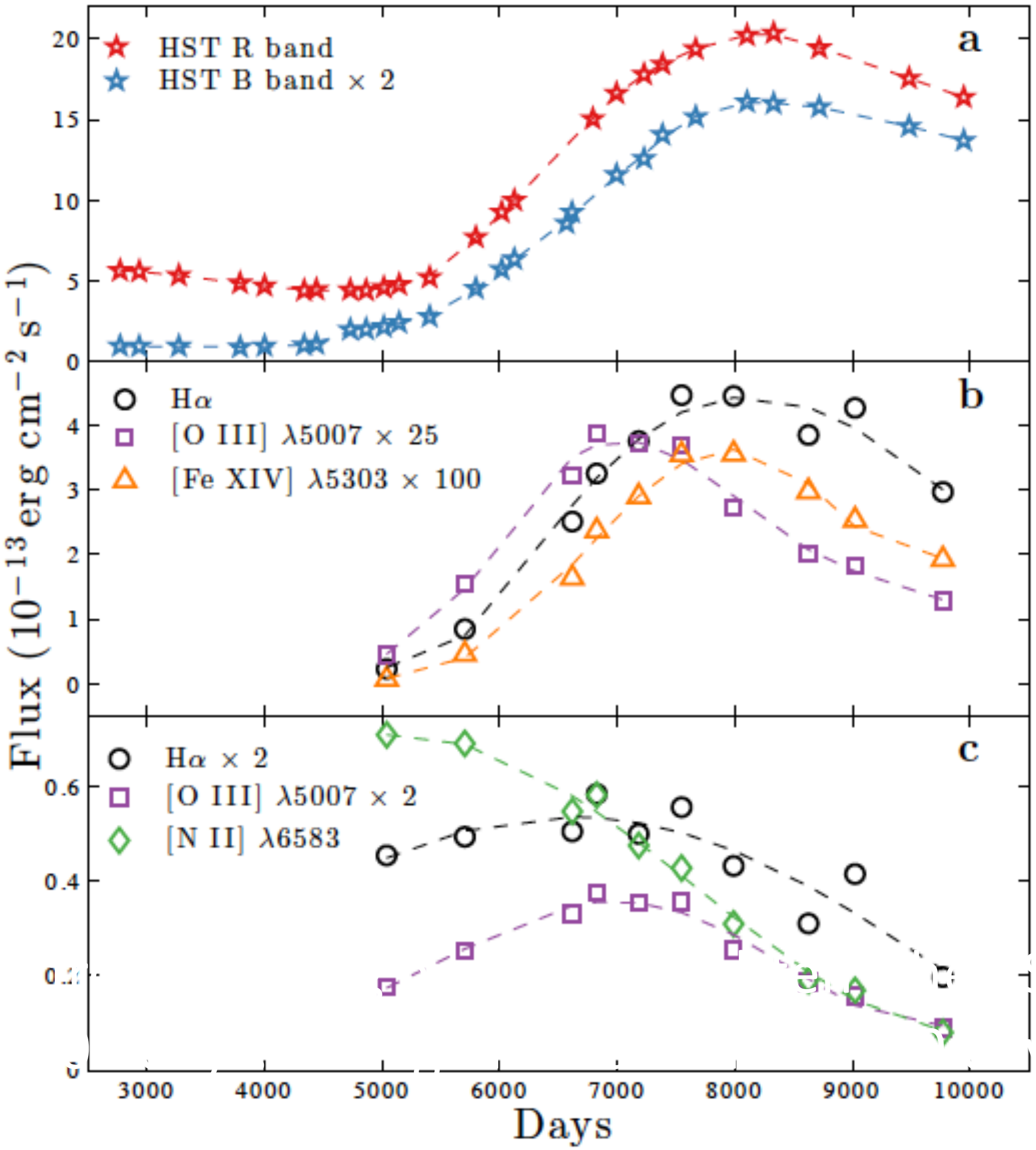
What we have learned from STIS

- Reverse shock has entered equatorial ring
- RS is expanding with radial velocity $\sim$ 1400 km/s
- Can map Hα emission from near side of internal debris, expanding with velocity $\sim$ 6000 km/s
- Can't see much Hα from far side because of internal dust

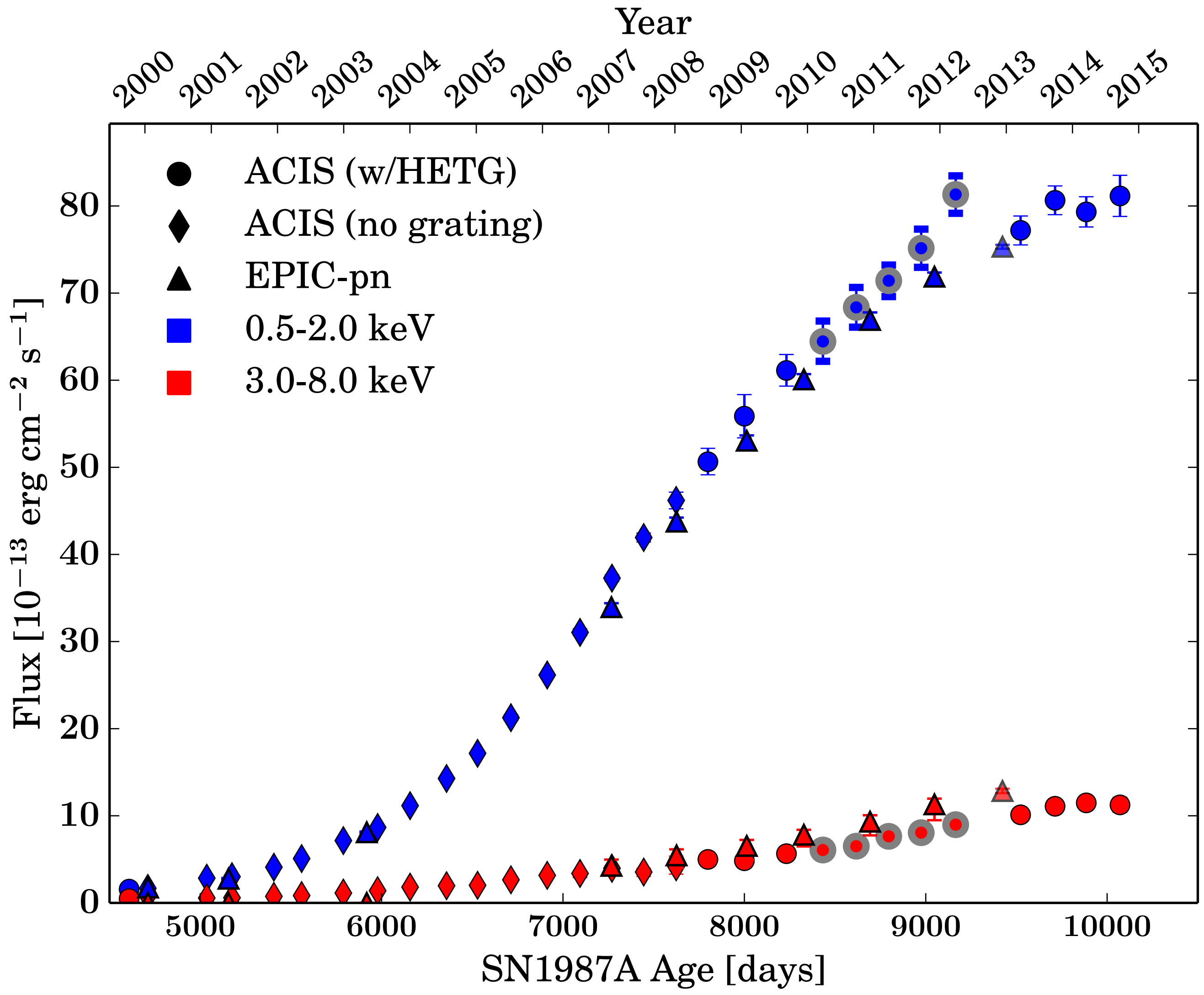
Hotspots


Sep, 1994
Mar, 1995
Feb, 1996
Jul, 1997
Feb, 1998
Apr, 1999
Nov, 2000
Dec, 2001
Jan, 2003
Nov, 2003
Sep, 2005
Apr, 2006
Dec, 2006
May, 2007
Feb, 2008
Apr, 2009
Dec, 2009
Jan, 2011
Feb, 2013
Jun, 2014

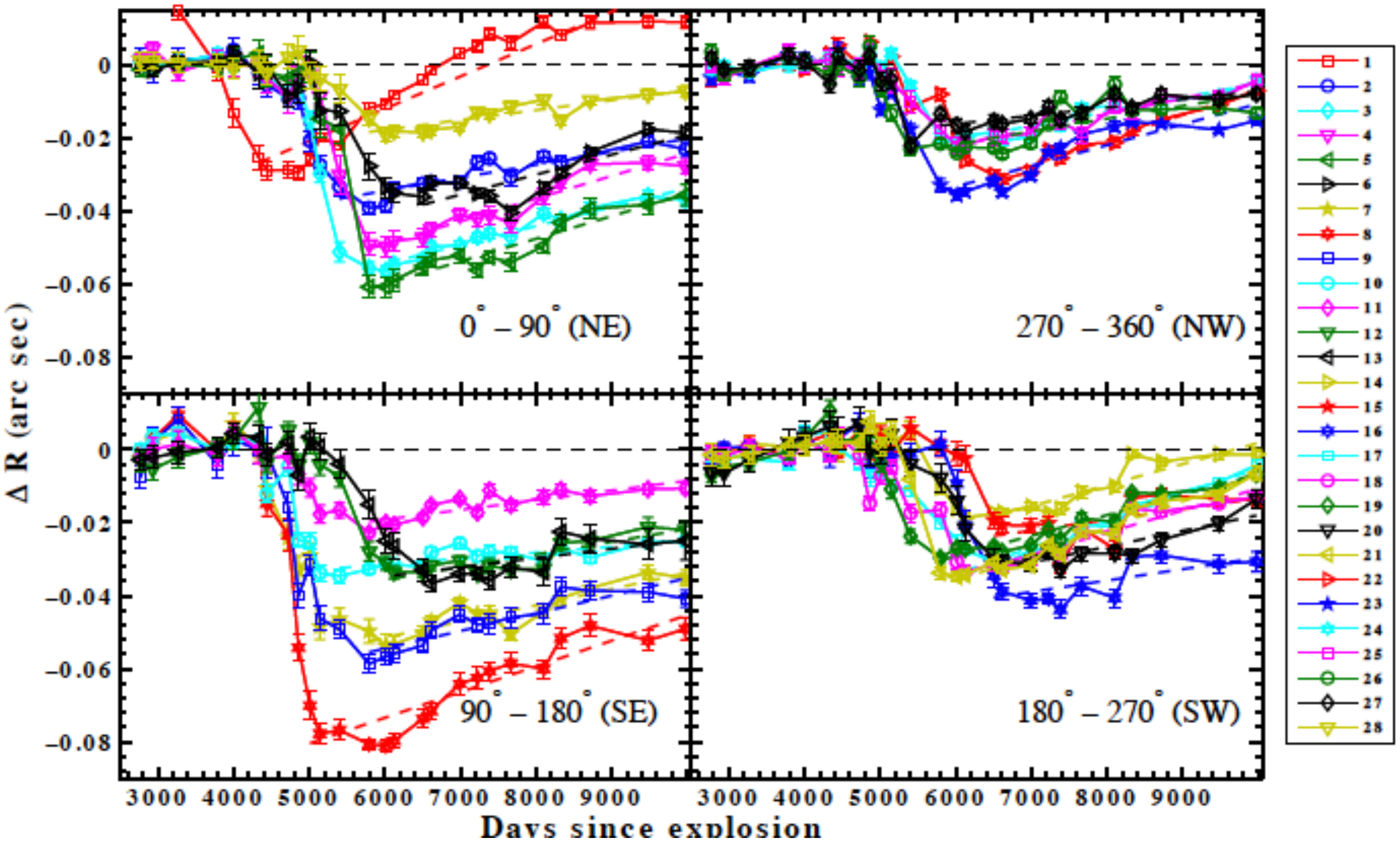

1"



HST R band
HST B band × 2
a
Hα
[O III] λ5007 × 25
[Fe XIV] λ5303 × 100
b
Hα × 2
[O III] λ5007 × 2
[N II] λ6583
c
Flux (10^{-13} erg cm^{-2} s^{-1})
Days



Year
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
ACIS (w/HETG)
ACIS (no grating)
EPIC-pn
0.5-2.0 keV
3.0-8.0 keV
Flux [10^{-13} erg cm^{-2} s^{-1}]
0
10
20
30
40
50
60
70
80
5000
6000
7000
8000
9000
10000
SN1987A Age [days]



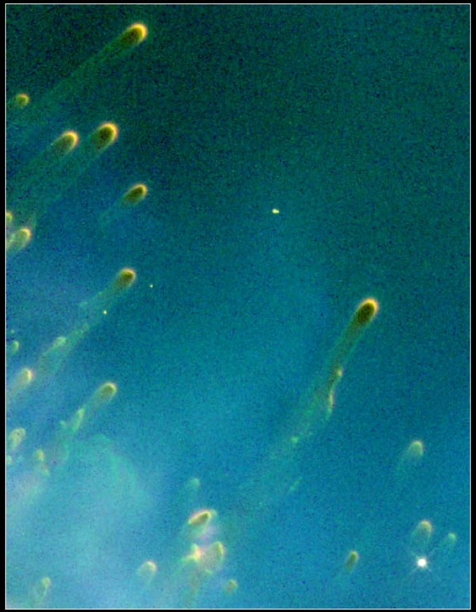
0° – 90° (NE)
270° – 360° (NW)
90° – 180° (SE)
180° – 270° (SW)
Δ R (arc sec)
Days since explosion

Distance of SN1987A

$D = d/\theta$, where:
d = line of sight diameter (from IUE light curves of narrow lines)
θ = angular diameter (from Hubble image)

The mistake:
Hubble image (pre-hotspots) was low density ring
IUE light curves were dominated by ring of hotspots

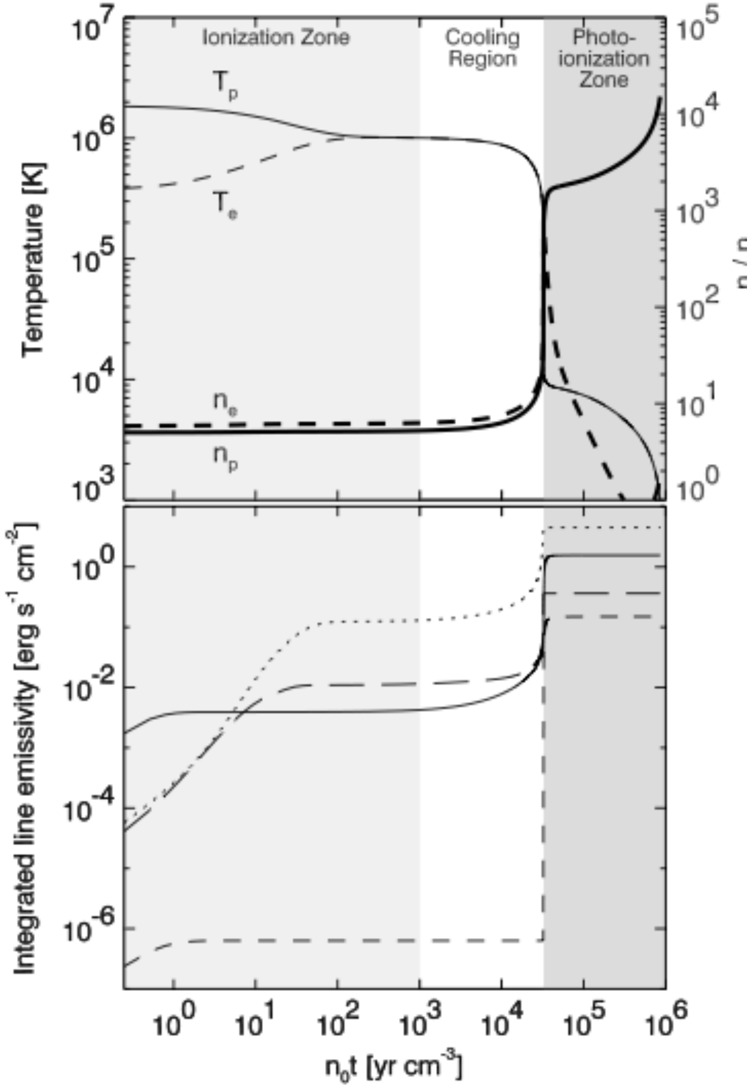
Should use Hubble image of hotspots: reduce θ by 5%.
a D should be increased by 5%, from 51.2 ± 3 to 53.7 ± 3 kpc



Helix Nebula Detail HST • WFPC2

PRC96-13b • ST ScI OPO • April 15, 1996 • C.R. O'Dell (Rice Univ.), NASA

Structure of a "radiative" shock



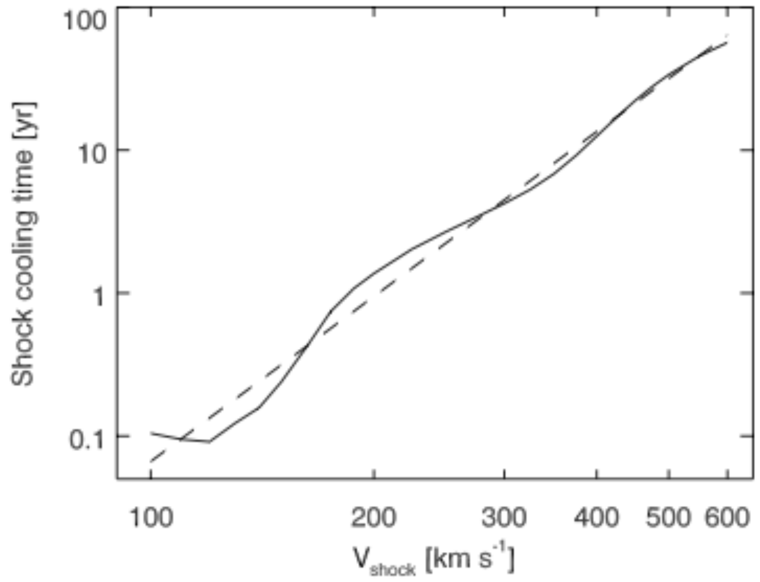


FIG. 12.—Model shock cooling time t_{cool} vs. shock velocity V_{shock} for initial obstacle density $\rho_0 = 2 \times 10^4$ amu cm^{-3} (*solid line*). The power-law fit $t_{cool} \propto V_s^{3.8}$ (*dashed line*) is also shown.

Cooling timescale is a sensitive function of shock velocity:
$n_0\ t_{cool} \propto V_{shock}^{3.8}$

Such "radiative shocks" are subject to violent instabilities

- $n_0 t \sim V^{3.8}$
- $p \sim n_0 V^2$
- $V \sim [p/n_0]^{1/2}$
- $n_0 t \sim p^{1.9} n_0^{-1.9}$
- $n_0 \sim p^{0.5} t^{-0.3}$

The Velocity of shocks entering clumps is determined by driving pressure of outer SN debris across the reverse shock:

p = ρ_{debris} V_{debris}^2, increases *fast*: p $\propto t^{3.5}$.

If shock is radiative, optical luminosity increases rapidly with time, L(t) $\propto t^{5.25}$ to maximum value $L_{max} \propto n^2$.

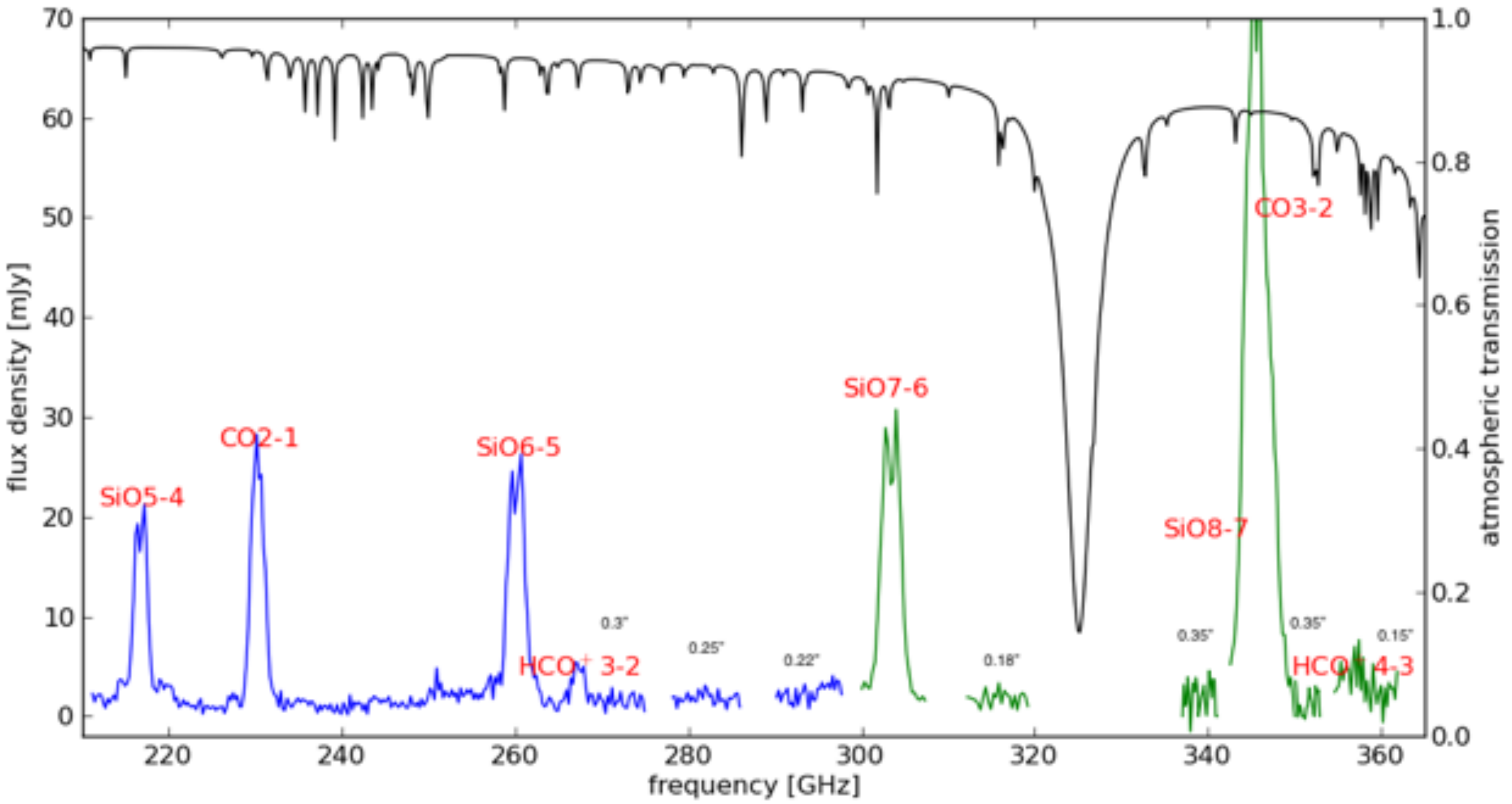
There is a critical density, $n_{crit} \approx 10^4$ cm^{-3}, below which the shocks will be non-radiative. The shocked gas will radiate soft X-rays and very little optical radiation. The shocks will erase optical narrow line emission.

Conclusions

- The early (t< 3 year) light curve (IUE) of the ring was dominated by dense ($n > 3 \times 10^4$ cm^{-3}) hotspots.
- The ring imaged by Hubble (before hotspots appeared) was dominated by less dense ($n < 3 \times 10^3$ cm^{-3}) gas.
- The ring that IUE measured is smaller than the Hubble ring. Allowing for this increases SN1987A distance estimate by $\sim$ 5%.
- Hotspots manifest radiative shocks entering dense clumps.
- Hotspots are fading now, as instabilities dissolve dense gas formed by radiative shocks.
- X-ray emission is dominated by non-radiative shocks in lower density gas. X-rays continued to rise as hotspots faded.
- New hotspots are appearing outside ring in SE quadrant.
- This scenario begs for 2- or 3-d hydro simulations.

Mapping of Internal Debris with ALMA

ALMA Spectra



Inferring properties of molecular zones from emission lines

e.g. CO 2-1, L_{21} = 1.05 e32 ergs/s;

If optically thin, uniform density:

$L_{2\text{-}1} = N_{CO}\, f_2 A_{21} h\nu_{21}$; ν_{21} = 230 GHz; A_{21} = 6.9 e-7 s^{-1}

If LTE: f_2 = 5G(T)$^{-1}$ \exp(-E_2/kT)

N_{CO} = 3.3 e53; M_{CO} = 7.9e-3 $M_\odot$

Filling factor: $f_{CO} = V_{CO}/V_{1200}$

$V_{1200} = 4\pi/3$ [1200 km/s *28 years]^3

$n_{CO} \approx 60\ cm^{-3}/f_{CO}$

SiO, ν_{54} = 217 GHz : A_{54} = 5.2e-4 $s^{-1} \approx$ 700 A_{CO}

Sobolev appoximation

L = L_{thin} $P_{esc}(\tau_S)$, where $P_{esc}(\tau_S)$ = $[1 - e^{-\tau_S}]/\tau_S$,

and, for freely expanding debris,

$$\tau_S(J, J-1) = \frac{\lambda_0^3 t g_J A_{J,J-1} n_{J-1}}{8\pi g_{J-1}} \left(1 - \frac{g_{J-1} n_J}{g_J n_{J-1}}\right)$$

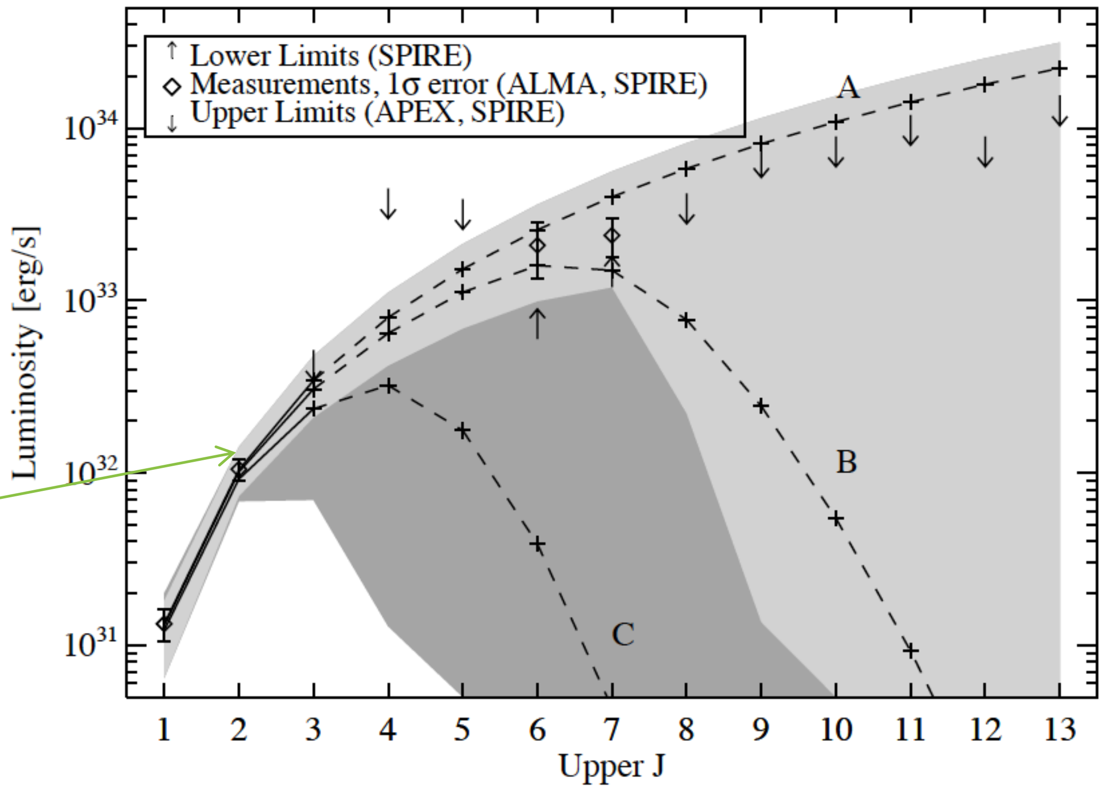
$\tau_S \propto n_0/T$

A sequence of models for line emission

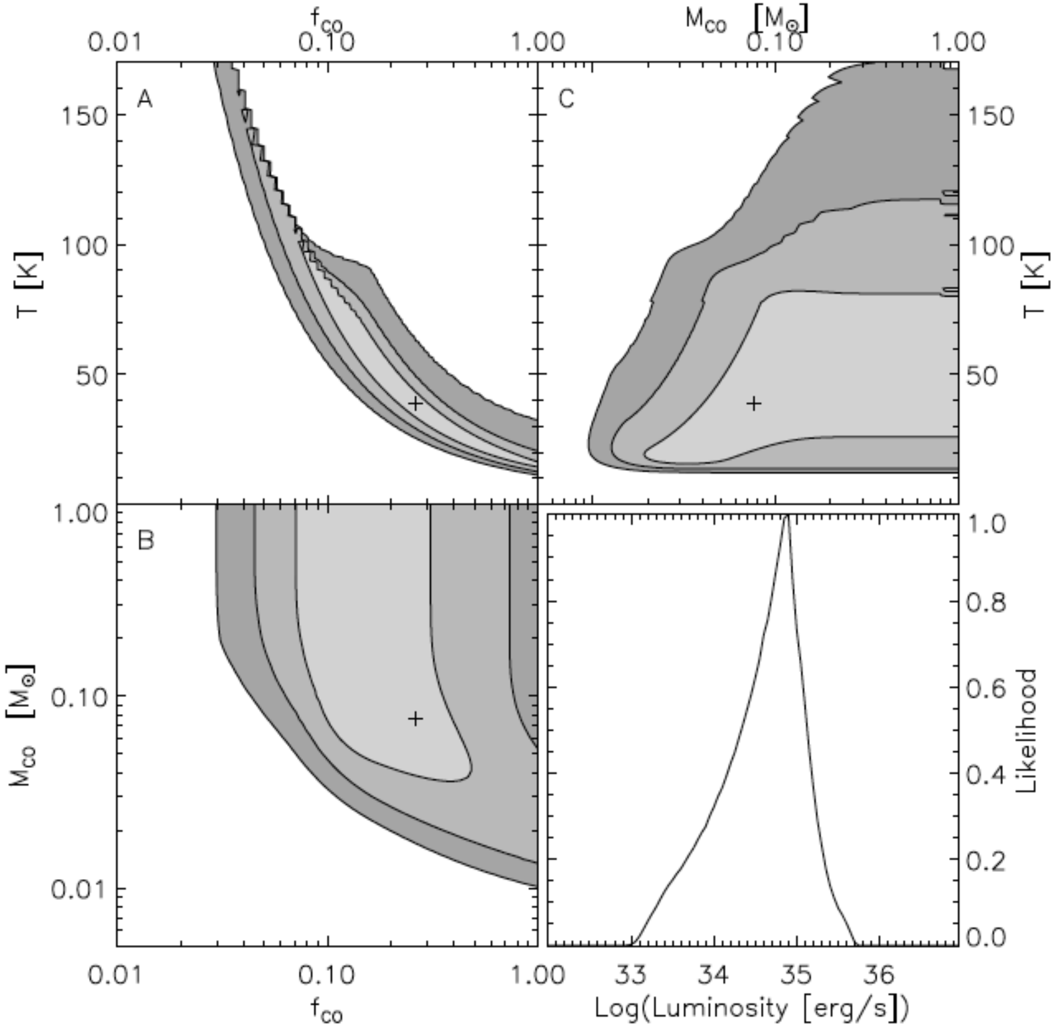
4. The RADEX Code

- Accurate in general: calculates level populations using Sobolev approximation
- Line luminosities depend on M_{CO}, f_{CO}, $T_{kinetic}$, collision rates (??)

LTE approx is OK for J < 4



Allowable CO parameter space determined from ALMA + SPIRE Observations



$M_{CO} > 0.01\ M_{\odot}$

$T_{CO} \approx 10 – 80$ K

$f_{CO} \approx 0.05 – 1$

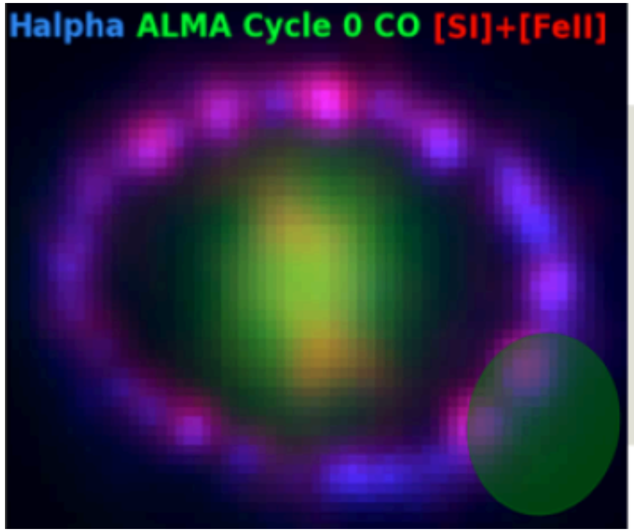
$L_{CO} \approx 1 – 40\ L_{\odot}$

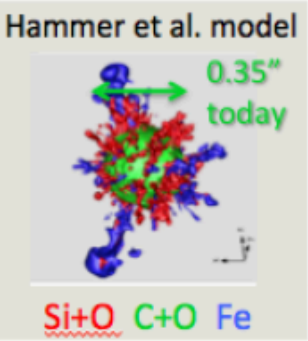
Isotopologues

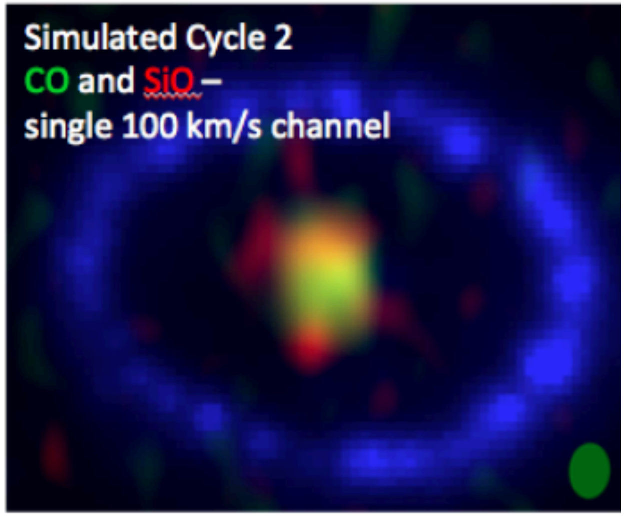
e.g. ^{13}CO: ν_{21} = 220.4 GHz, not seen!

$L_{21}(^{13}CO)/L_{21}(^{12}CO) < 0.07$
But $L_{21}(^{13}CO)/L_{21}(^{12}CO) = [A_{13}/A_{12}][P_{esc}(^{13}CO)/P_{esc}(^{12}CO)]$
$A_{13}/A_{12} = 1.09e\text{-}2$
$P_{esc}(^{13}CO) \approx 1$; $P_{esc}(^{12}CO) \approx 1/\tau_S$
no ^{13}CO implies $\tau_S < 7$, $n_{CO}/T < 3.8$

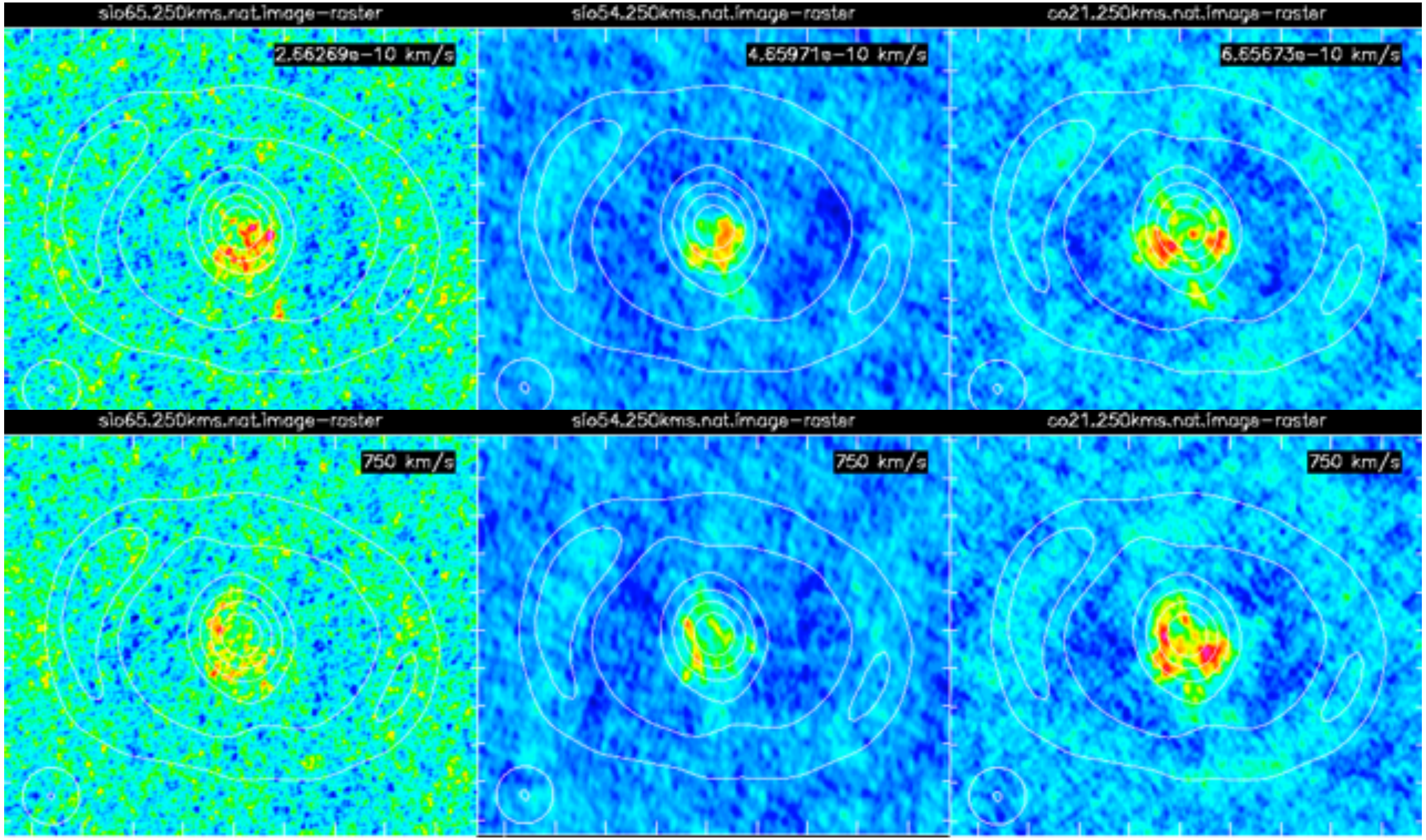
Cycle 2 Angular Resolution (Band 7, 1.5 km baseline)







ALMA Imaging



Findings from ALMA

- $M_{CO} > 0.01\ M_{\odot}$ – at least 10 times more than seen at 18 months
- $T_{CO} \approx 10 – 80$ K
- CO J = 3-2 line is brighter than J = 2-1 by factor 3.4
- Can map CO and SiO at resolution ~ 0.03 “

$$\tau_S(J, J-1) = \frac{\lambda_0^3 t g_J A_{J,J-1} n_{J-1}}{8\pi g_{J-1}} \left(1 - \frac{g_{J-1} n_J}{g_J n_{J-1}}\right)$$

τ_{21} = .13^3 *30*3.11e7*5*6.9e-7*3n0*/\exp(-E1/kT)[1-\exp(-E2+E1)/kT]/[8*3\piG(T)]
E2-E1/k = (5-3)E0k = h*2.30e9/k =11/T
1.3^3*3*3.11*5*6.9*3 e(-3+1+7-7) = 102.47