VLBI radio imaging of young type II supernovae

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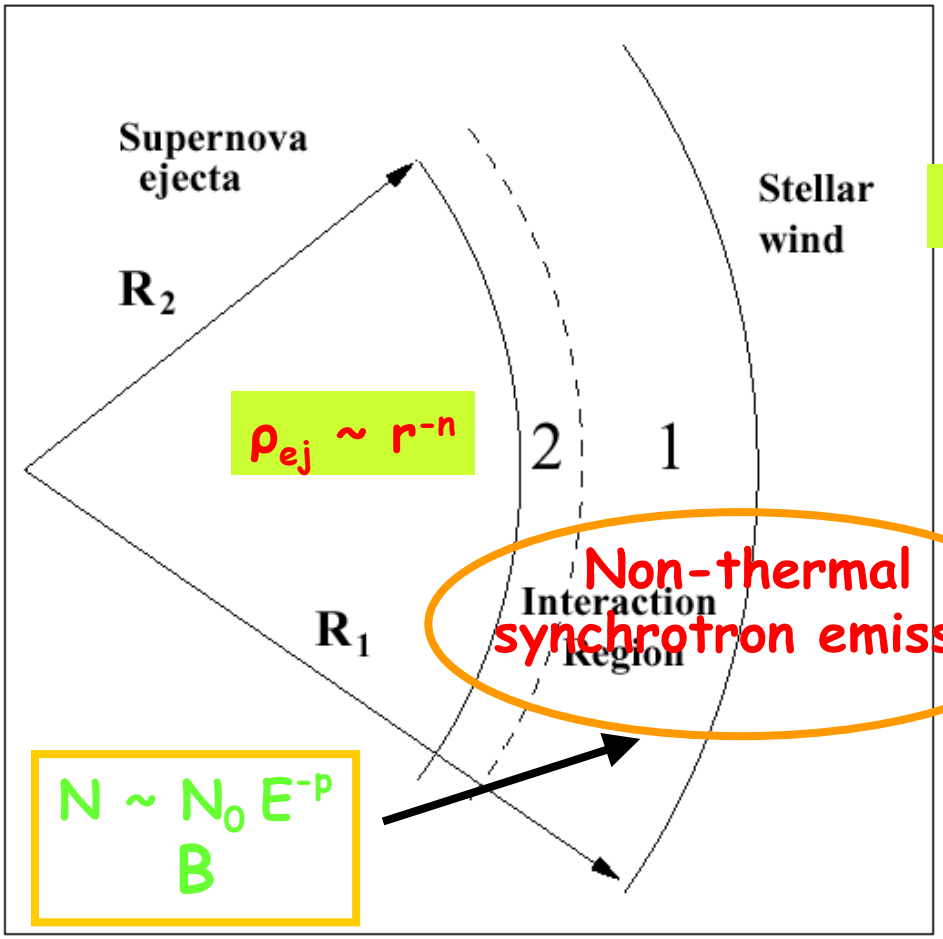
The Standard Interaction Model (Chevalier, 1982)



$\rho_{ej} \sim r^{-n}$

$\rho_{csm} \sim r^{-s}$

(thermal absorber)
opt. depth ~ $v^{-2.1}$

Non-thermal synchrotron emission

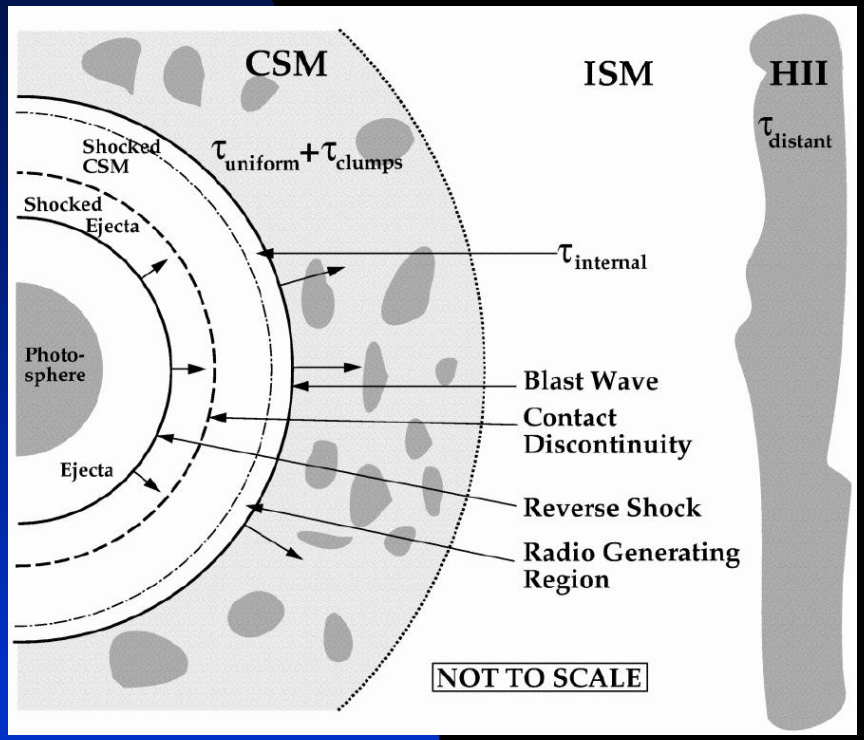
$N \sim N_0 E^{-p}$
B

Self-similar expansion

$R \sim t^m$
$m = (n - 3) / (n-s)$

$n_H \sim 3 \times 10^7 \, (dM/dt)_{-5} \, r_{15}^{-2} \, v_1^{-1} \quad cm^{-3}$

$$S(\mathrm{mJy}) = K_1 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha} \left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\beta} e^{-\tau_{\mathrm{external}}} \left(\frac{1 - e^{-\tau_{\mathrm{CSM_{clumps}}}}}{\tau_{\mathrm{CSM_{clumps}}}}\right) \left(\frac{1 - e^{-\tau_{\mathrm{internal}}}}{\tau_{\mathrm{internal}}}\right) \qquad (1)$$



(Weiler et al. 2002, AR&A, 40, 387)

$S_{syn,\,\nu} \sim \nu^{\alpha}\, t^{\beta}$

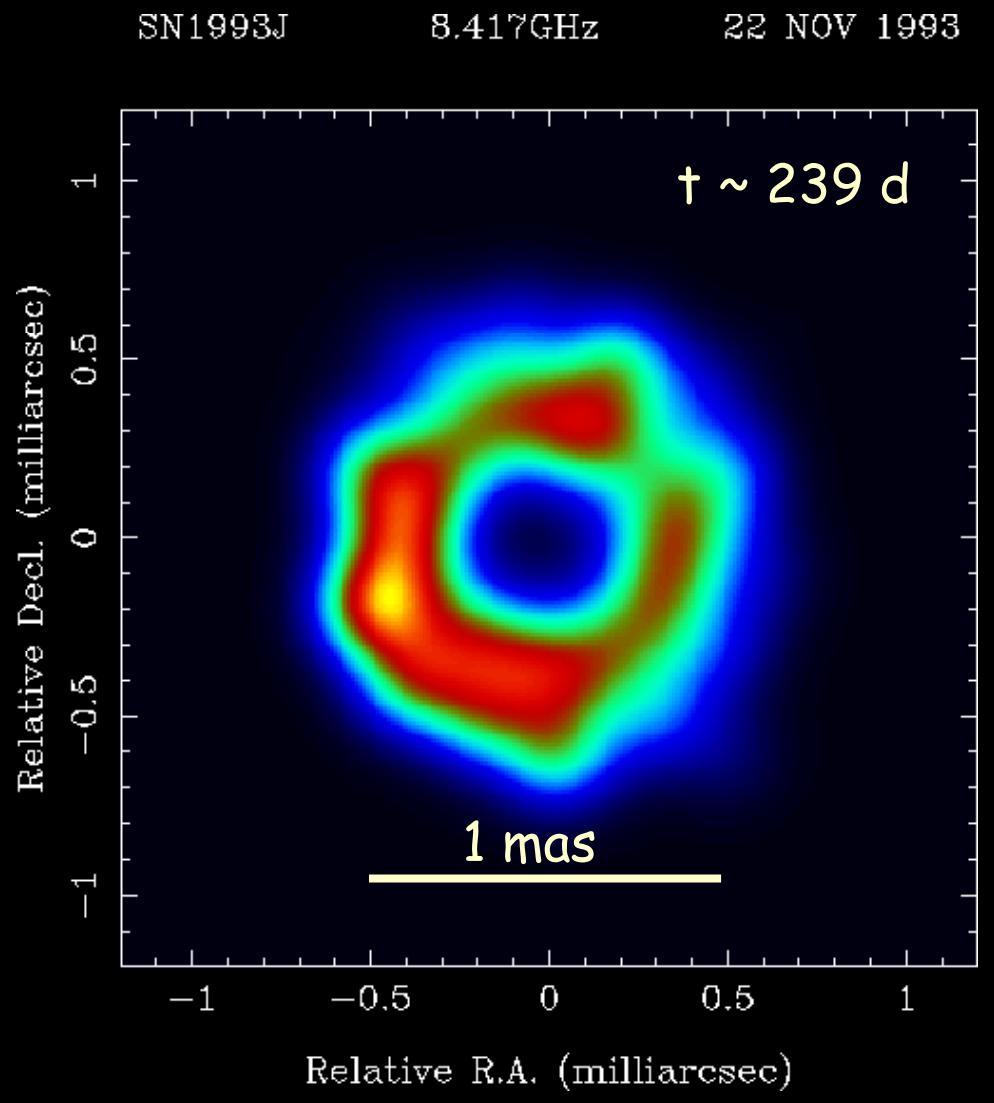
$\alpha = (1 - p)/2$
$\beta = (6m - 5 - p)/2$
$m = (n-3) / (n-2)$

(s=2 assumed)

Discovery of a shell-like structure in an RSN

1 mas at 3.6 Mpc ~ 0.018 pc

Average expansion rate:
2.43 ± 0.15 μas/day
~ 15200 ± 900 km/s

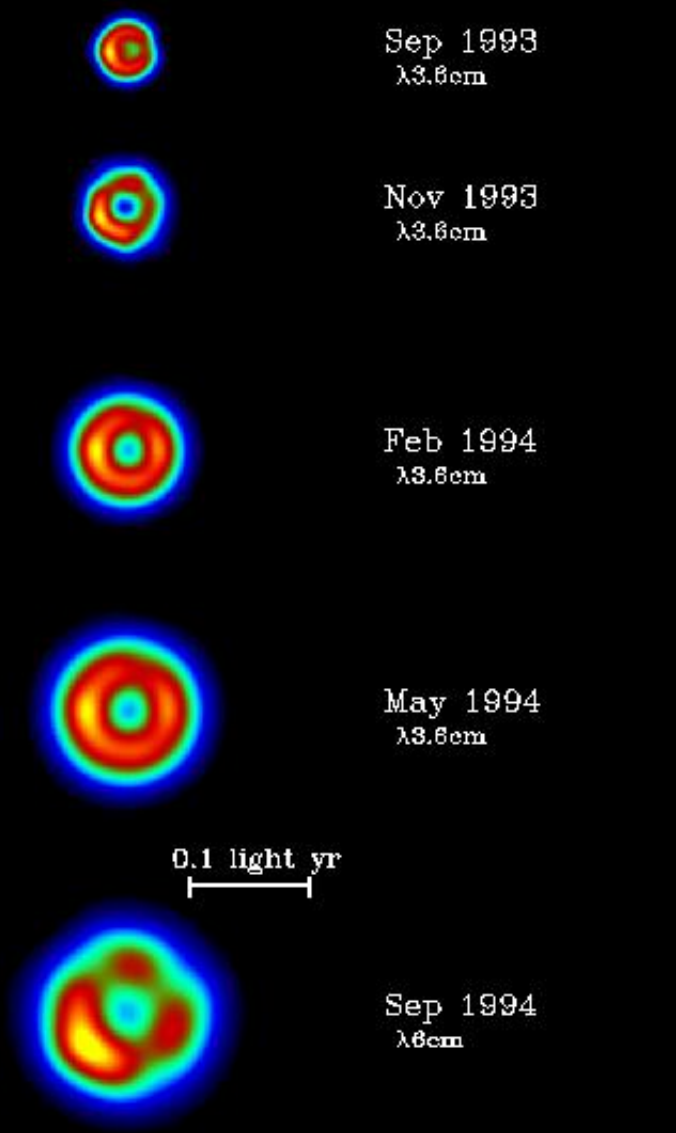


From Marcaide et al. Nature 373, 44-45 (1995)

First movie ever of an expanding radio supernova

Average expansion rate for the first ~ 600 days:

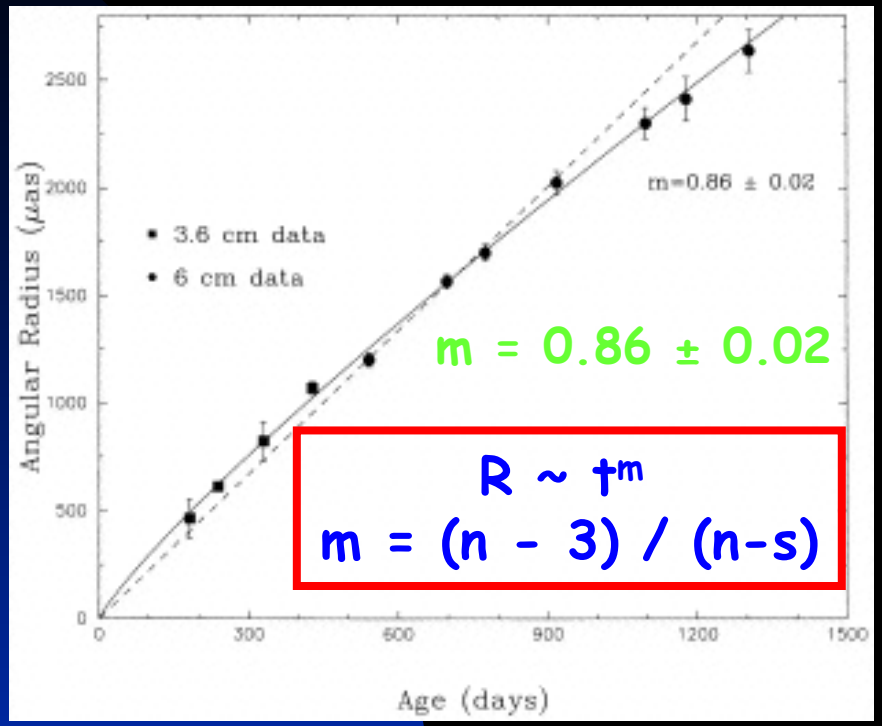
2.39 ± 0.03 μas/day
~ 14900 ± 200 km/s



EXPANSION OF SN 1993J

(Marcaide et al. 1995, Science,270,1475)

Deceleration in the expansion of SN 1993J



V ~ 11400 km/s after ~ 1300 days

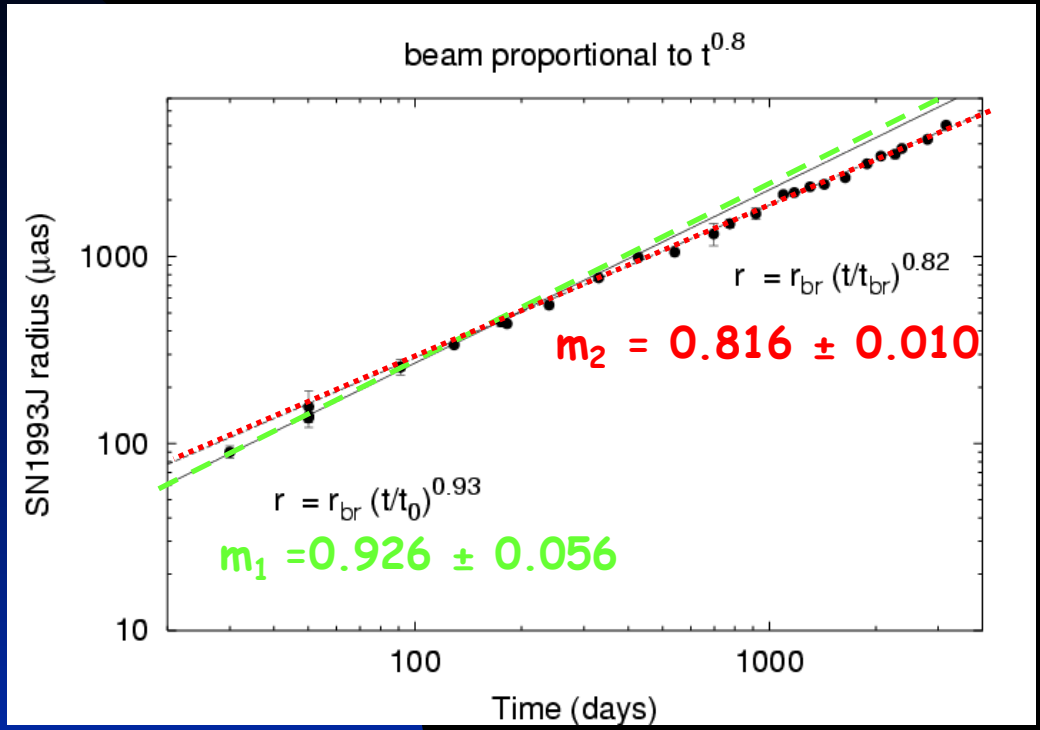
s=1.66 +0.12/-0.25
n=11.2 +3.5/-1.8

Magnetic field amplification

B ~ 170 mG @ r ~ 10^{17} cm

$B_{wind} \leq 0.6$ mG

compression of Bwind not enough
=> turbulent amplification of B?



$r_{break} = 464 \pm 181$ μas

$t_{break} = 180 \pm 85$ days

<V> ~ 9500 km/s at t=3000 days

$M_{swept} = 0.37\ M_{sun}$
$M_{env} \sim 0.6\ M_{sun}$

s=2
$v_w = 10$ km/s
$dM/dt = 5 \times 10^{-5}\ M_{sun}/yr$

SN 1993J in M81

$t_{break} \sim 1$ yr

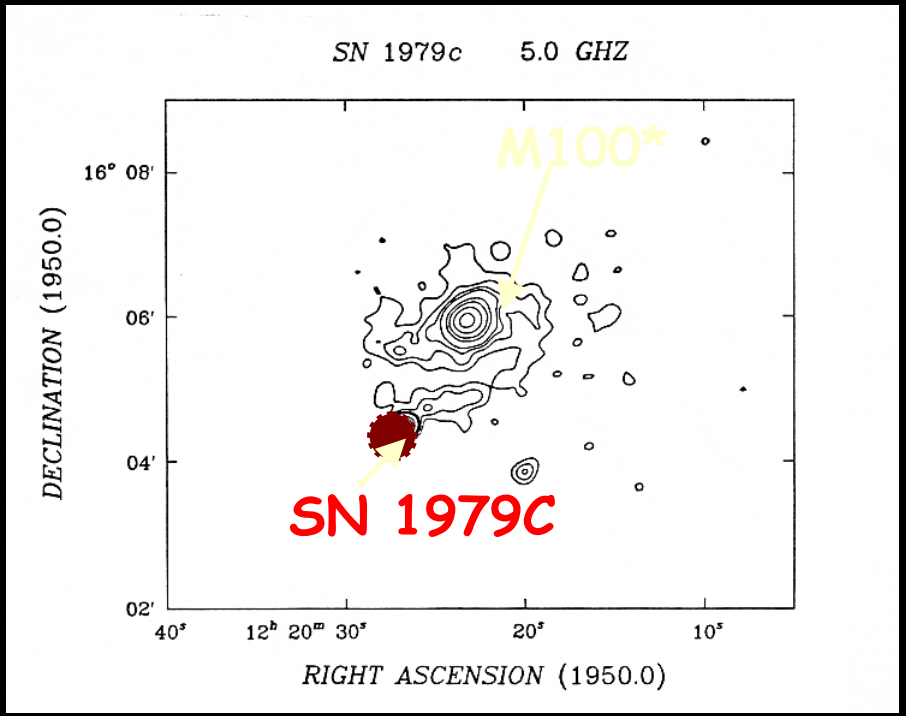
- Strong deceleration -> $M_{swept} \geq M_{env}$
- v_{wind} = 10 km/s
- $dM/dt = 5 \times 10^{-5} M_{sun}/yr$
- $\rho_{csm} \sim r^{-s}$; s = 2
- B ~ 170 mG » B_{wind} ~ 0.6 mG
- Turbulent amplification of B?
- $M_{swept} = 0.37 M_{sun}$
- $M_{env} \leq 0.6 M_{sun}$
- Binary star scenario favoured

SN1979C

- SN1979C in M100 (D= 16.1 Mpc)
- $t_{explosion}$ = April 4, 1979
- $V_{expansion}$ = 9200 km/s at around t = 45 days
- Type II SN-L
- Progenitor: binary system
- M_{progen} ~ 17-18 M_{sun} (Van Dyk et al. 1999)
- Radio emission interpreted within the minishell model

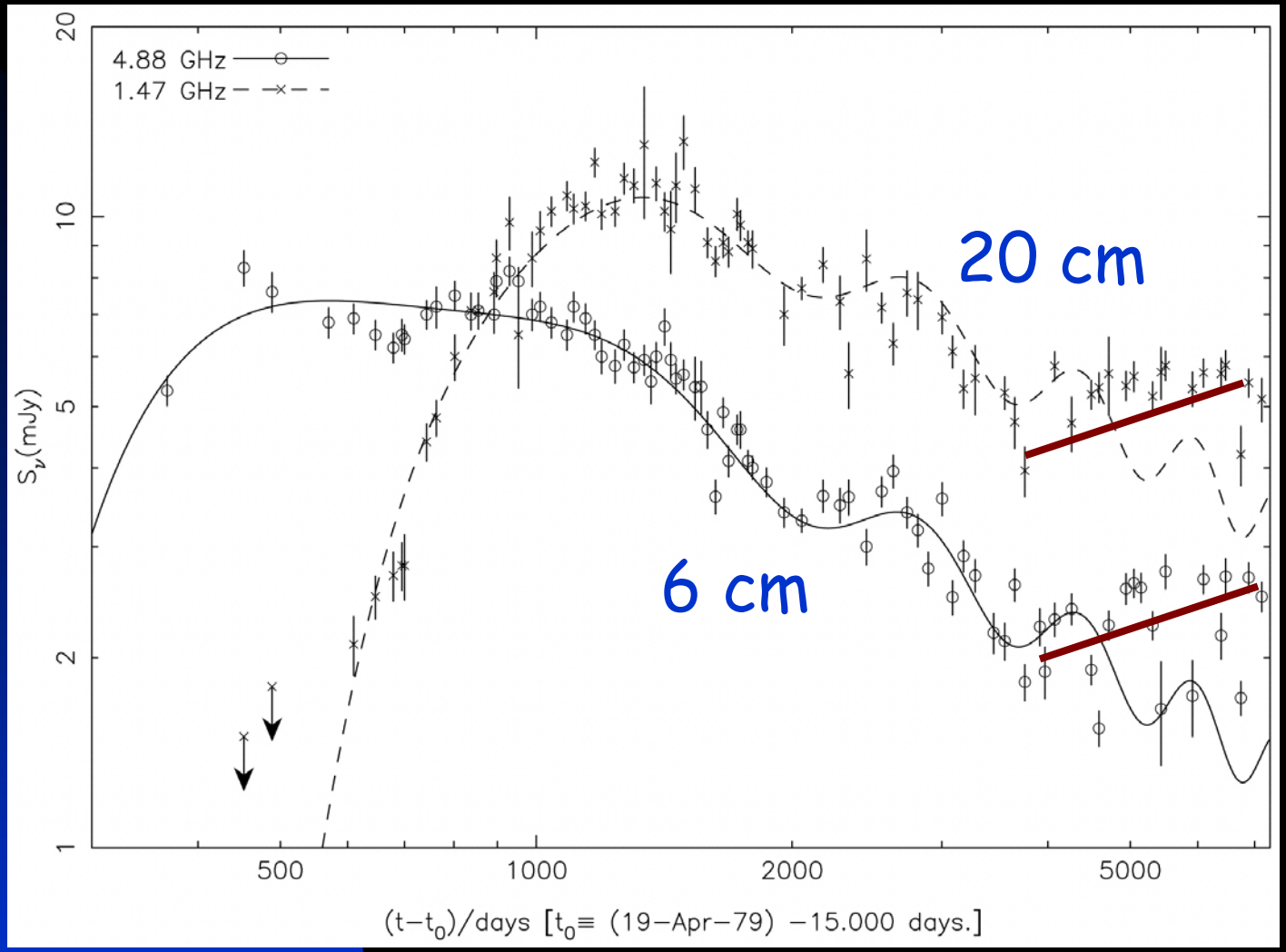
Previous VLBI observations

- VLBI observations 5 years after the explosion (Bartel et al. 1985)
- Source structure was not resolved by VLBI
- Observations consistent undecelerated expansion (m = 1.0; $R \sim t^m$) for the first 5 years!!



VLA image

VLA radio measurements

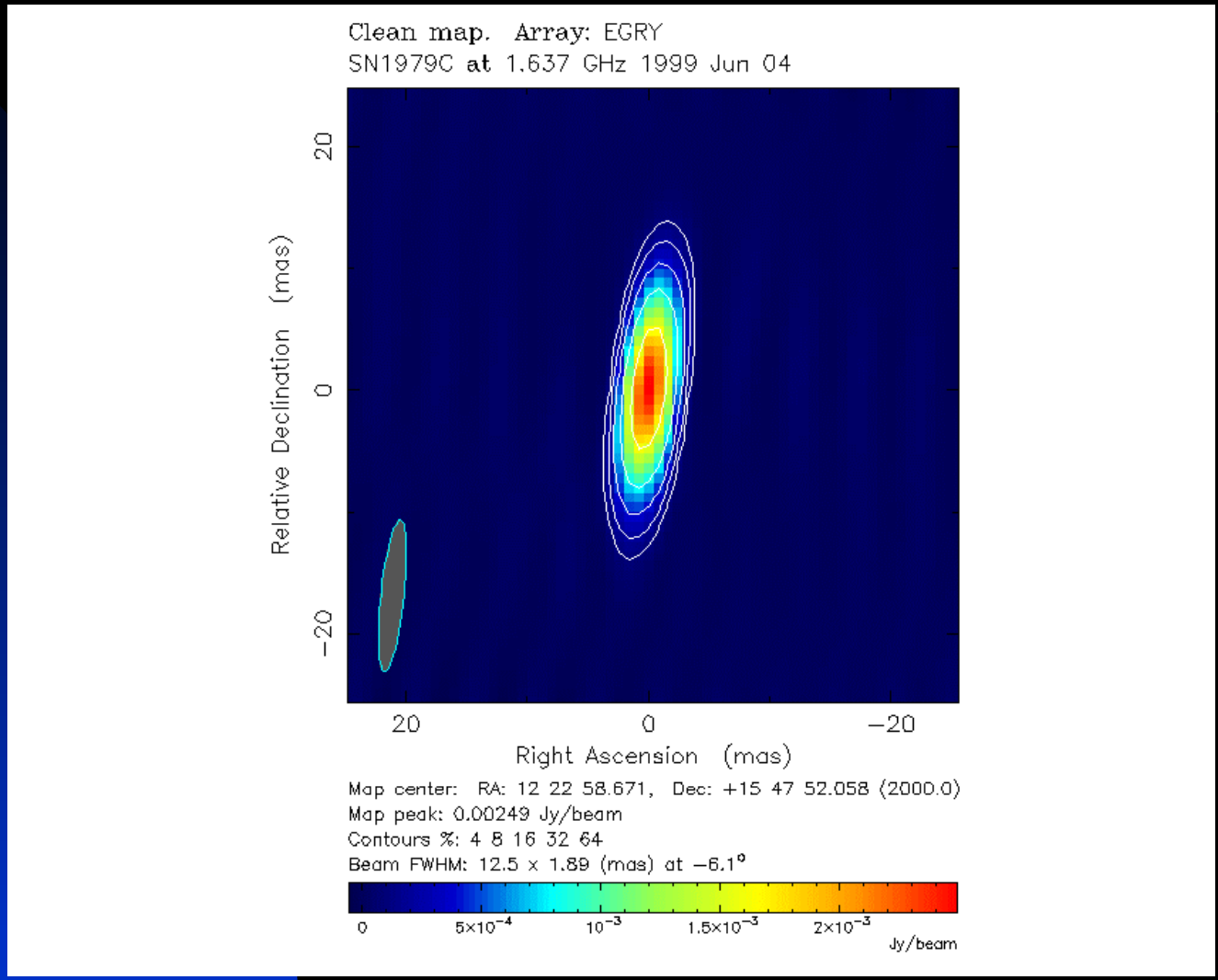


Is flux increasing?

(Montes et al. 2000, ApJ, 532, 1124)

$dM/dt \sim 10^{-4}\ M_{sun}/yr$

VLBI observations at 18 cm, ~20 yr after explosion



4 June 1999

(Marcaide et al. 2002, A&A, 384, 408)

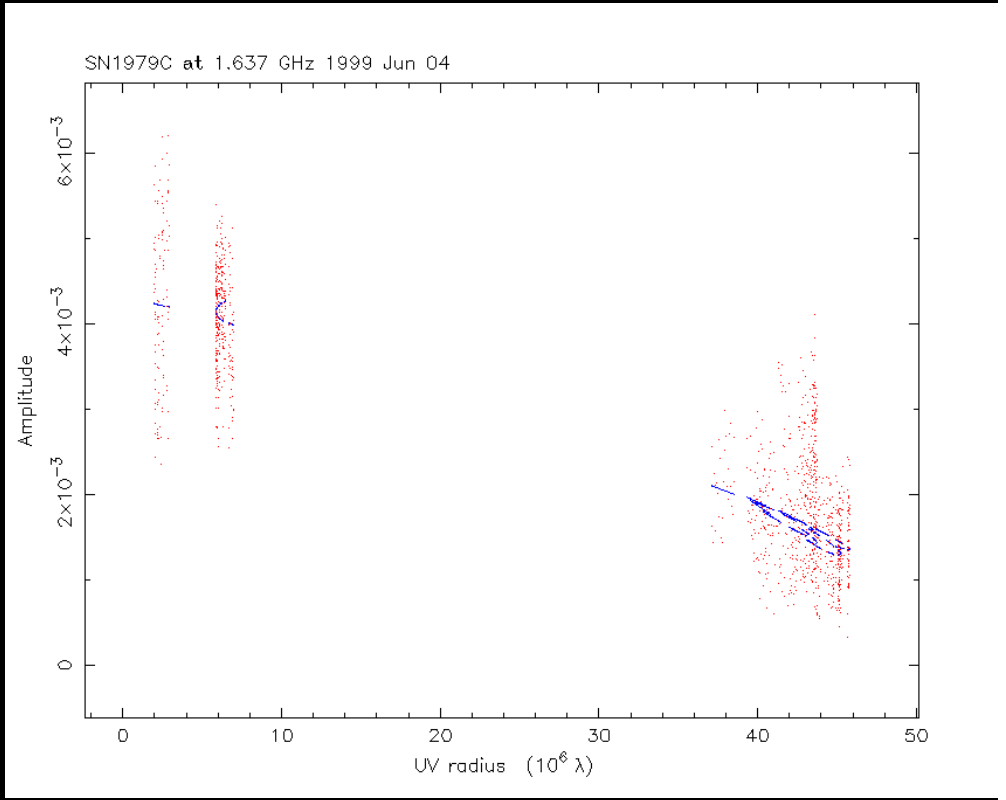
Angular size of SN1979C

Optically thick disk:
4.57 ± 0.25 mas

Optically thin shell of width
0.3 * R_out: 3.60 ± 0.17 mas

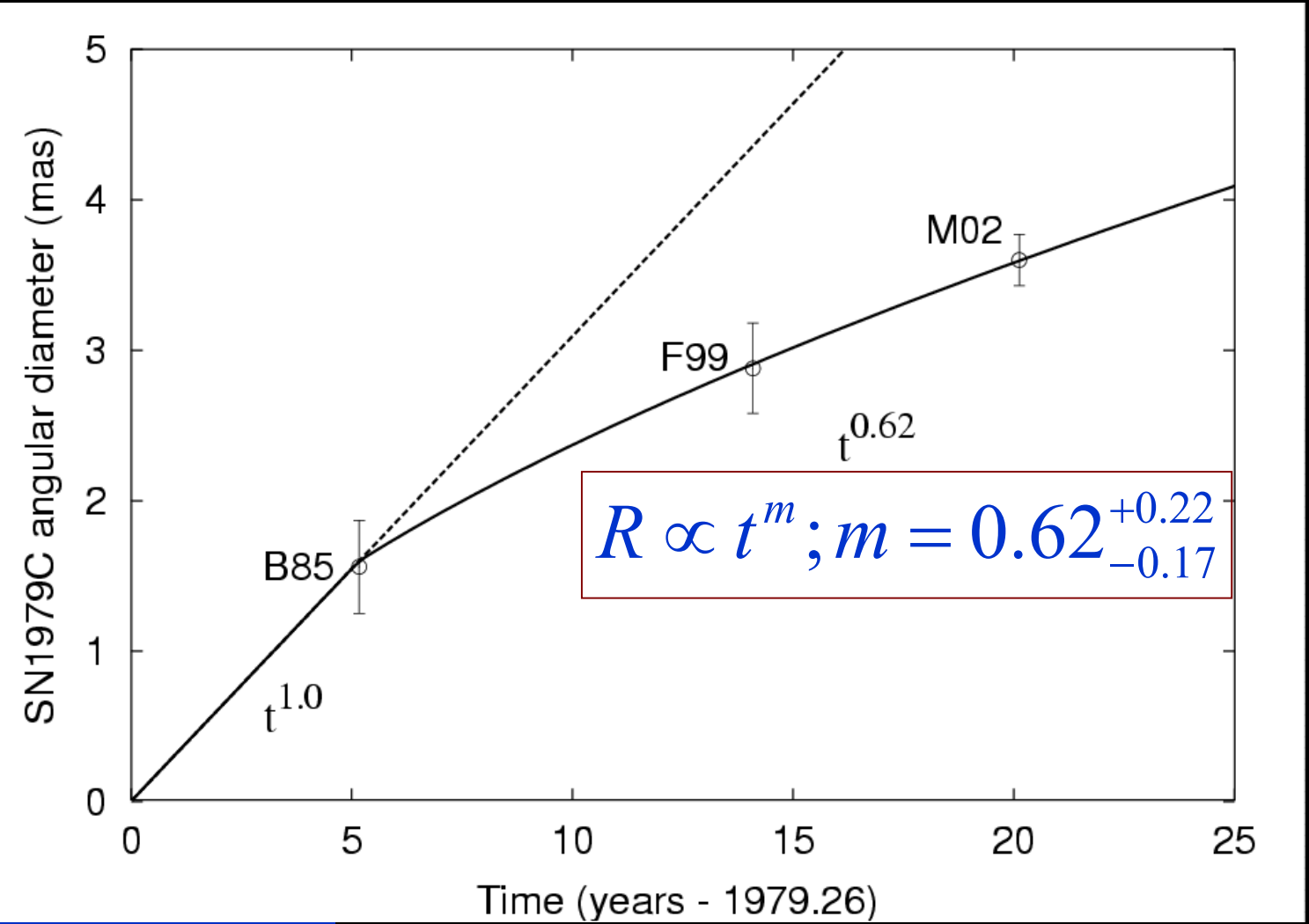
Optically thin ring:
3.10 ± 0.14 mas

Best model: Optically thin shell



1 mas @ 16.1 Mpc ~ 0.08 pc

Strong deceleration of SN1979C



(Marcaide et al. 2002, A&A, 384, 408)

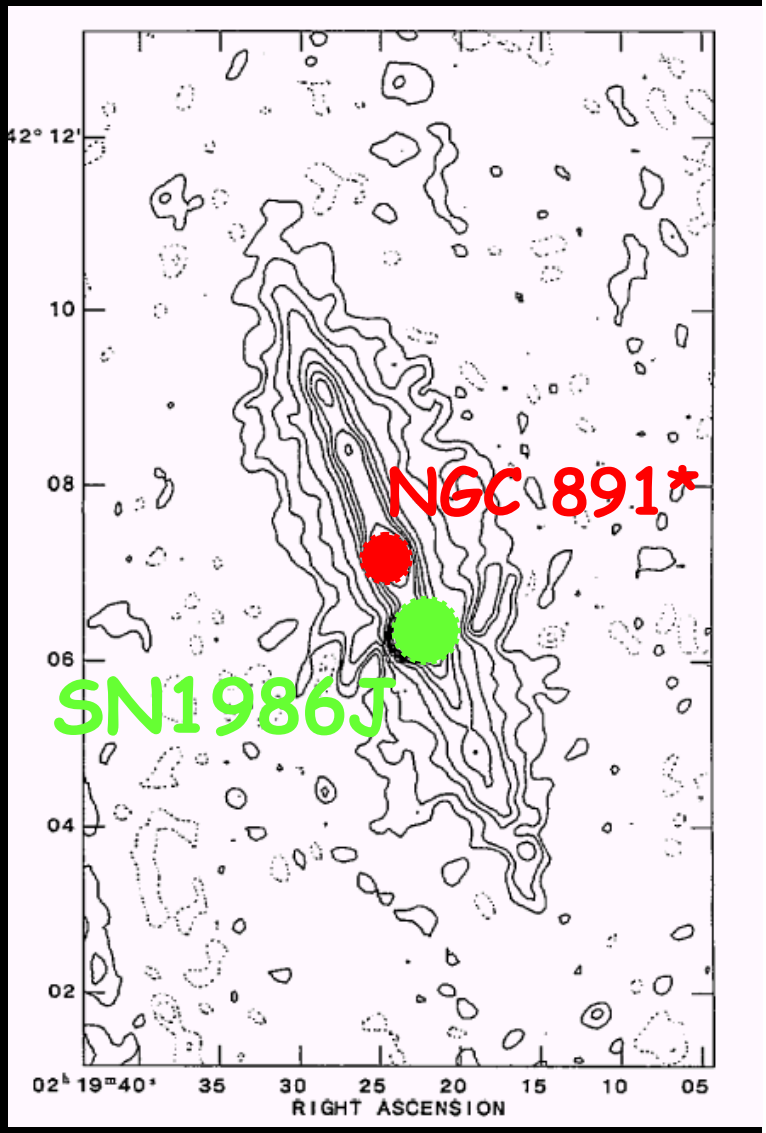
SN 1979C in M100

$m = 0.62$ (strong deceleration)
$t_{break} = 6 \pm 2$ yr

- Strong deceleration -> $M_{swept} \geq M_{env}$
- $v_{wind} = 10$ km/s;
- $dM/dt = 1.2 \times 10^{-4} M_{sun}/yr$
- $\rho_{csm} \sim r^{-s}$; $s = 2$
- $B_{min} \sim (10 - 80)$ mG » $B_{wind} \sim 0.2$ mG
- Turbulent amplification B?
- $M_{swept} = 1.6 M_{sun}$
- $M_{env} \leq 0.9 M_{sun}$
- Binary star scenario favoured

SN 1986J in NGC891

- SN1986J in NGC891 (D ~ 9.6 Mpc)
- Lumin @ 6 cm ~ 8*SN1979C,
  ~13*SN1993J
- It probably exploded at the end of 1982
- MSM of progenitor ~ 20 - 30 M_{sun}
- Type II supernova
- Strong mass loss: $dM/dt \sim 2 \times 10^{-4}\ M_{sun}/yr$

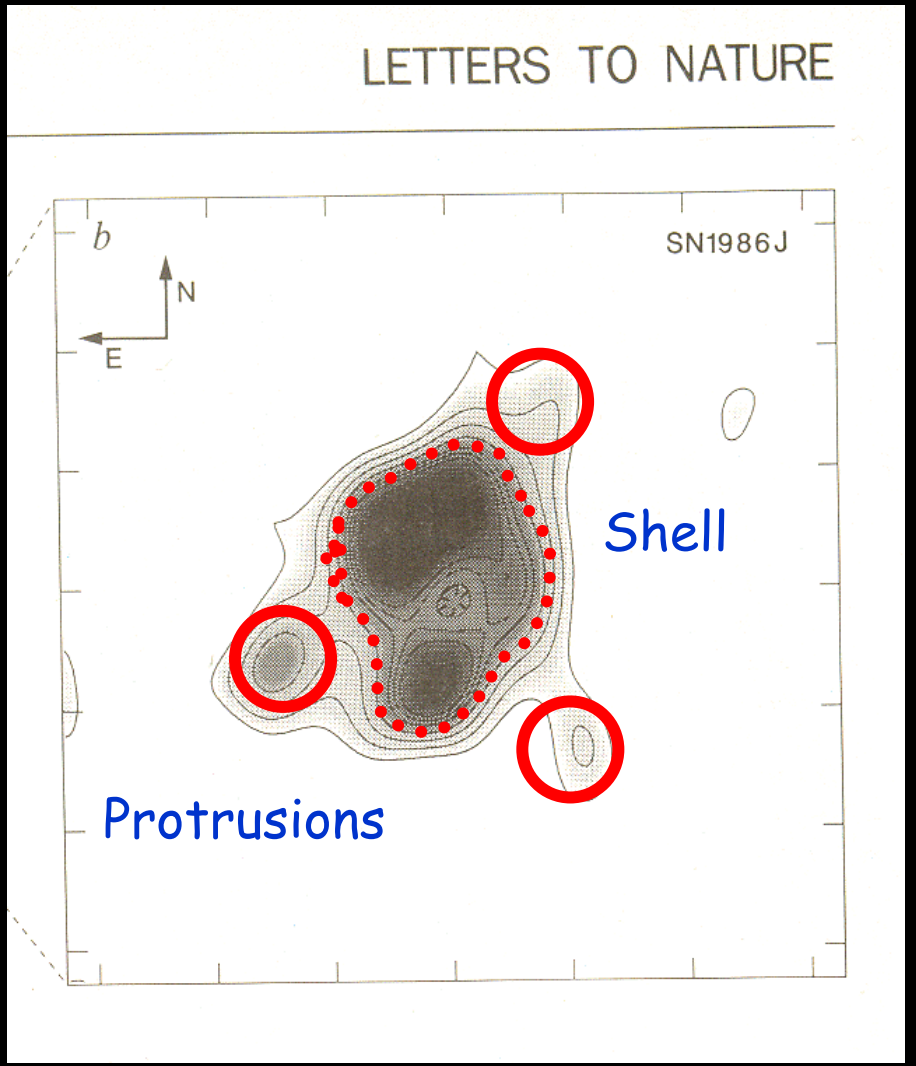


Serendipituous discovery
in the radio

The CSM around SN 1986J

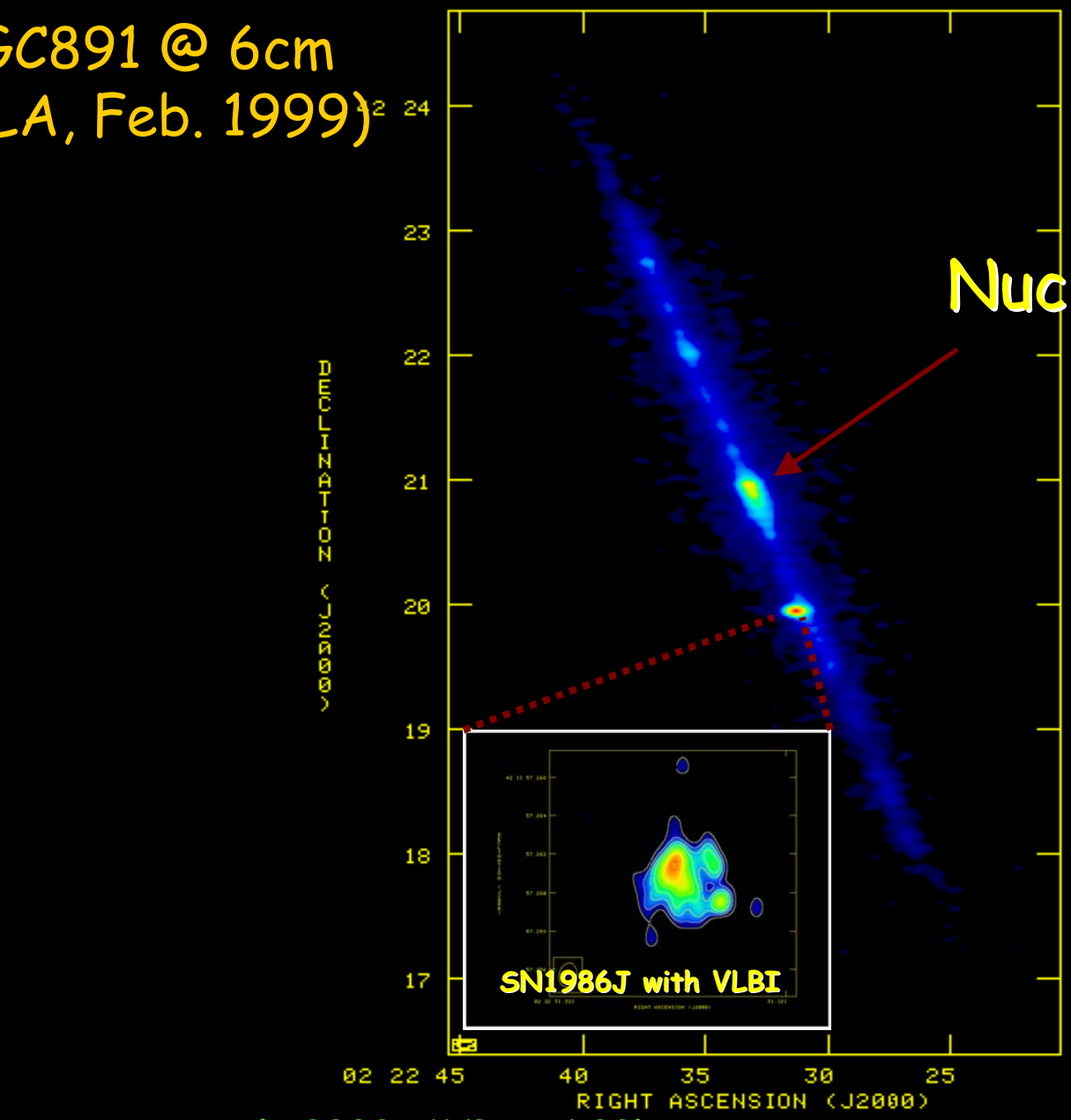
- ✓ Standard scenario (homogeneous free-free absorption medium) predicts optical spectral lines with v~radio speed
- ✓ Optical spectra in 1986 and 1989 showed narrow lines at v ~ 600 km/s
- ✓ Alternative scenario: The CSM is clumpy -> narrow lines are due to shock-excited clumps (Chugai 1993)

VLBI @ 3.6 cm in 1988.74 (t_{exp} ~ 5.7 yr)

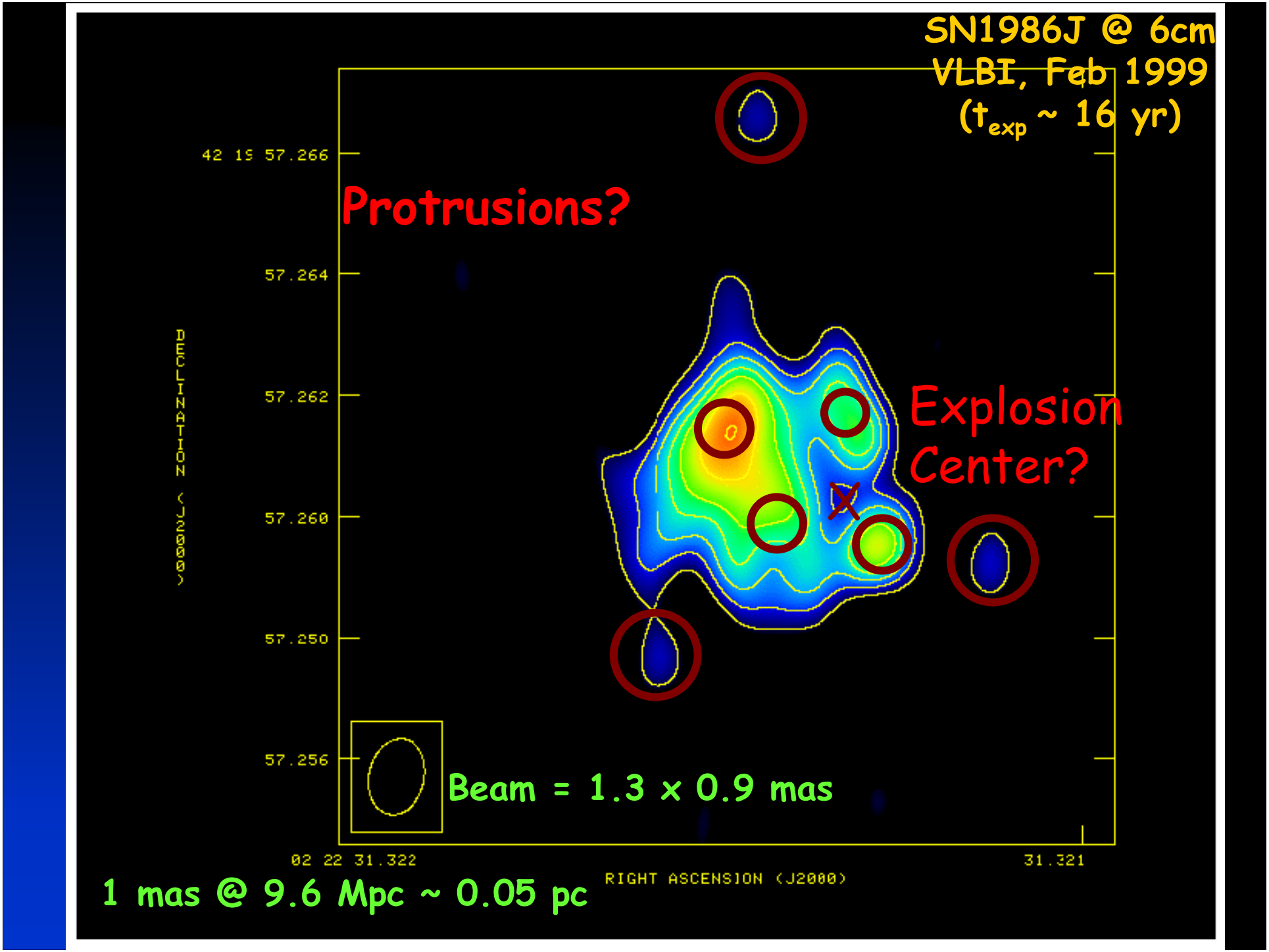


(Bartel et al. 1991, Nature, 350, 212)

NGC891 @ 6cm
(VLA, Feb. 1999)



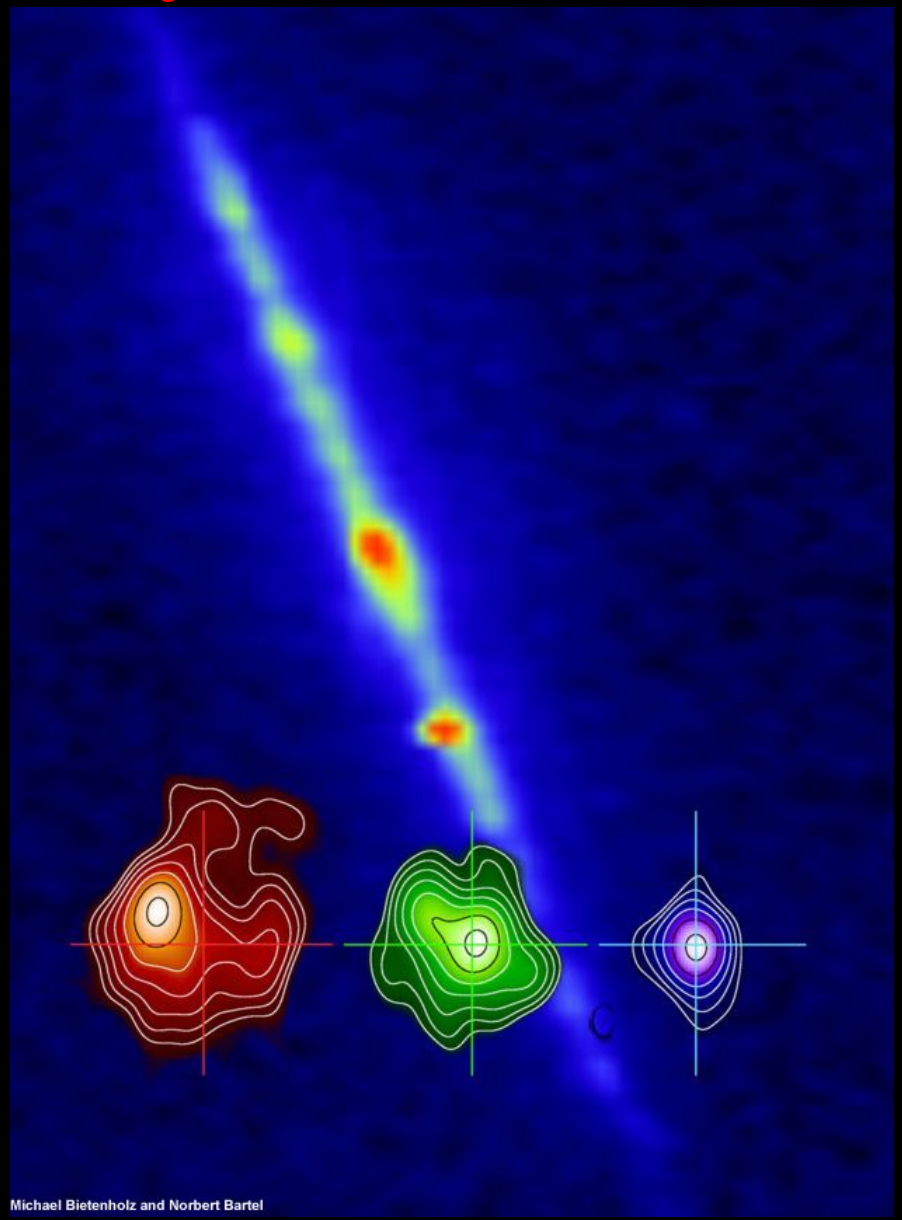
(Pérez-Torres et al. 2002,MNRAS,L23)


SN1986J @ 6cm
VLBI, Feb 1999
(t_{exp} ~ 16 yr)
Protrusions?
Explosion
Center?
42 1S 57.266
57.264
57.262
57.260
57.250
57.256
DECLINATION (J2000)
Beam = 1.3 x 0.9 mas
02 22 31.322
31.321
RIGHT ASCENSION (J2000)
1 mas @ 9.6 Mpc ~ 0.05 pc

SN 1986J in NGC 891

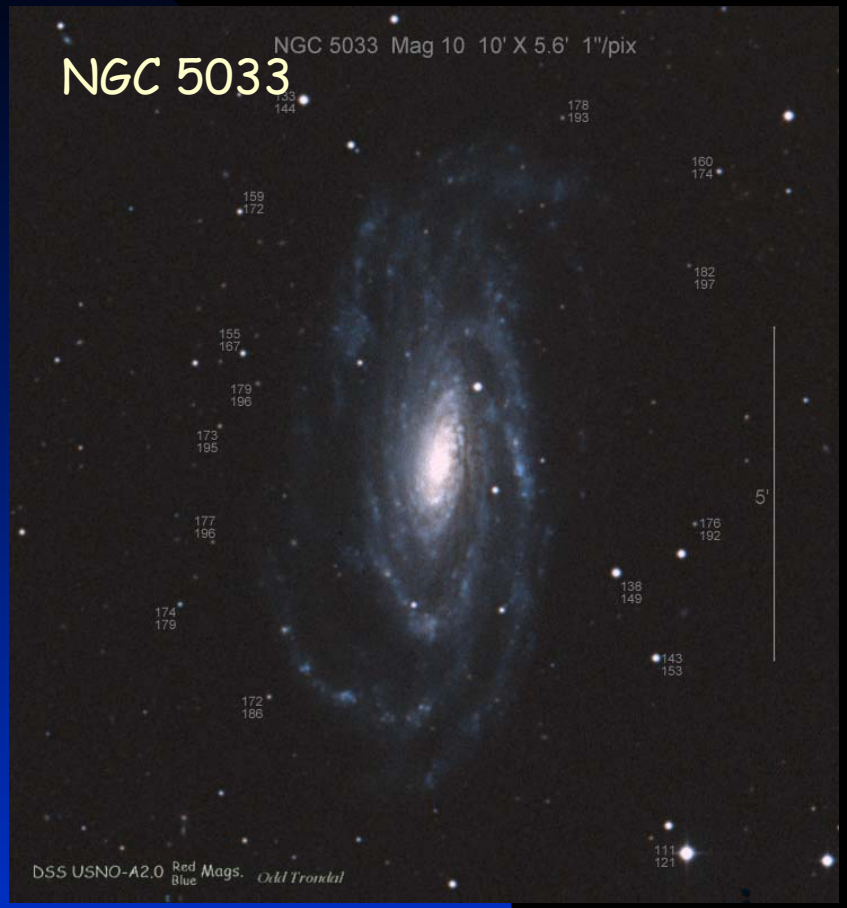
- Mean angular size of ~ 4.7 mas ~ 0.22 pc => v ~ 6300 km/s between 1988.74 and 1999.14
- Anisotropic brightness distribution: shell structure likely due to a collision with a clumpy, or filamentary, wind
- $R \sim t^m$, $m = 0.90 \pm 0.06$ (close to free expansion)
- $v_{wind} = 10$ km/s
- $dM/dt = 1.2 \times 10^{-4} M_{sun}/yr$
- $\rho_{csm} \sim r^{-s}$; $s = 2$
- $r \sim 3.4 \times 10^{17}$ cm
- $B_{min} \sim (13 - 90)$ mG » $B_{wind} \sim 0.3$ mG
- Turbulent amplification B?
- $M_{swept} \sim 2.2 M_{sun}$
- $M_{env} \geq 12 M_{sun}$
- Single star scenario favoured

Compact object in SN 1986J



Bietenholz et al. (2004)

SN2001gd



Prediscovery image

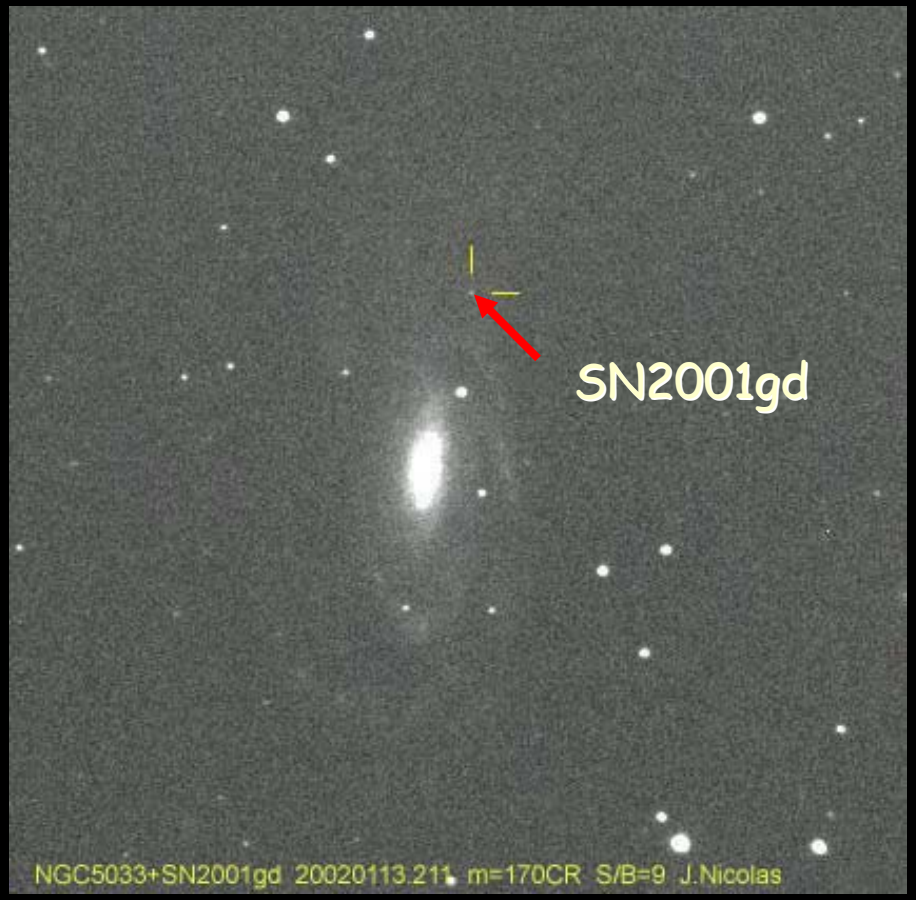
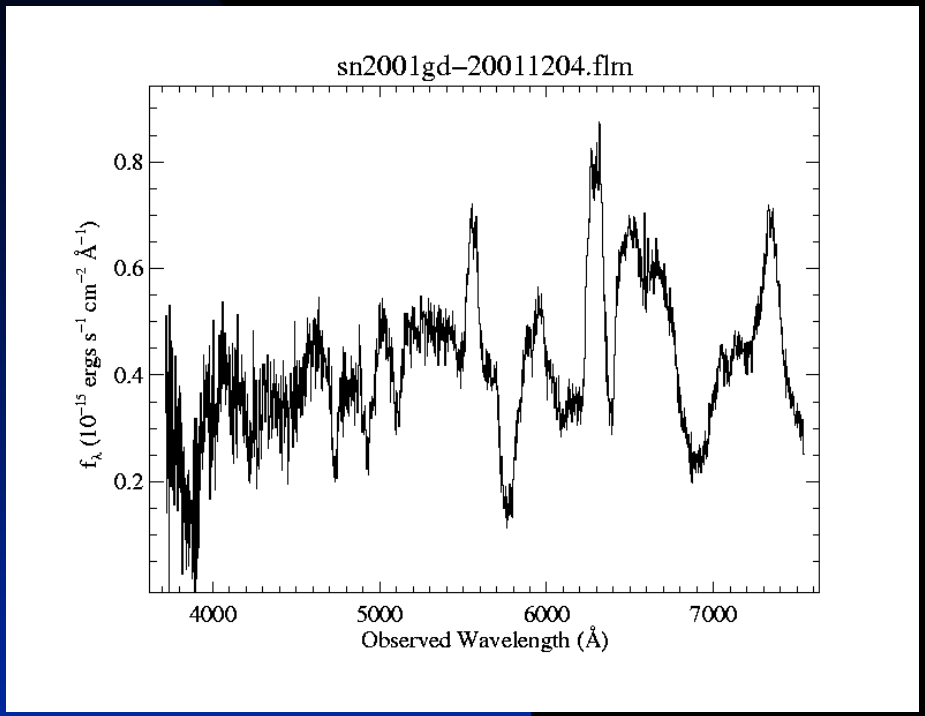
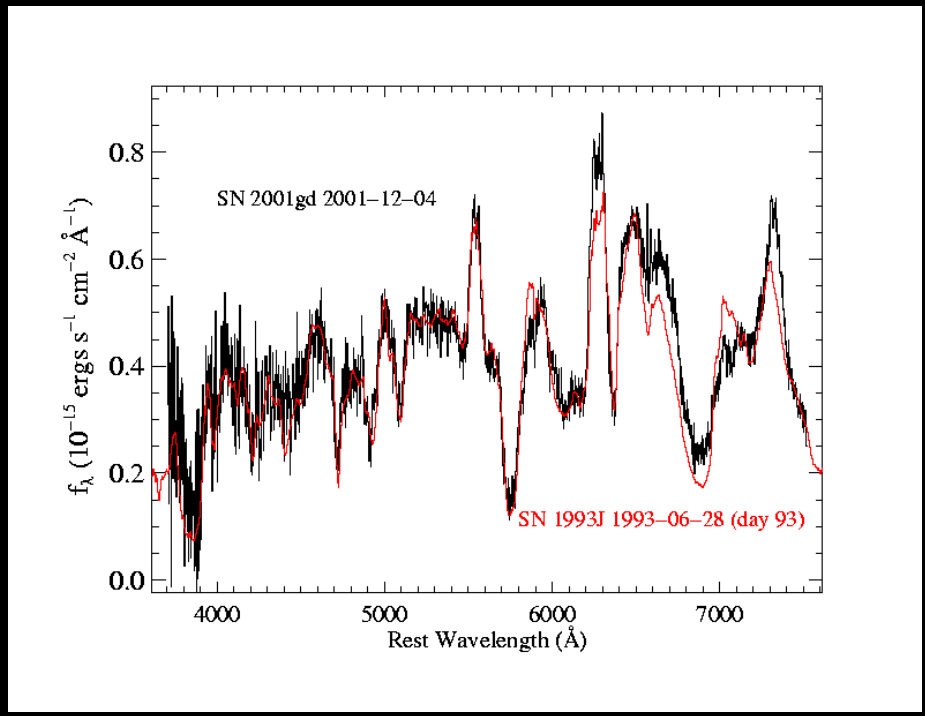


Image taken on 13 Jan 2002

SN2001gd: a SN1993J-like event

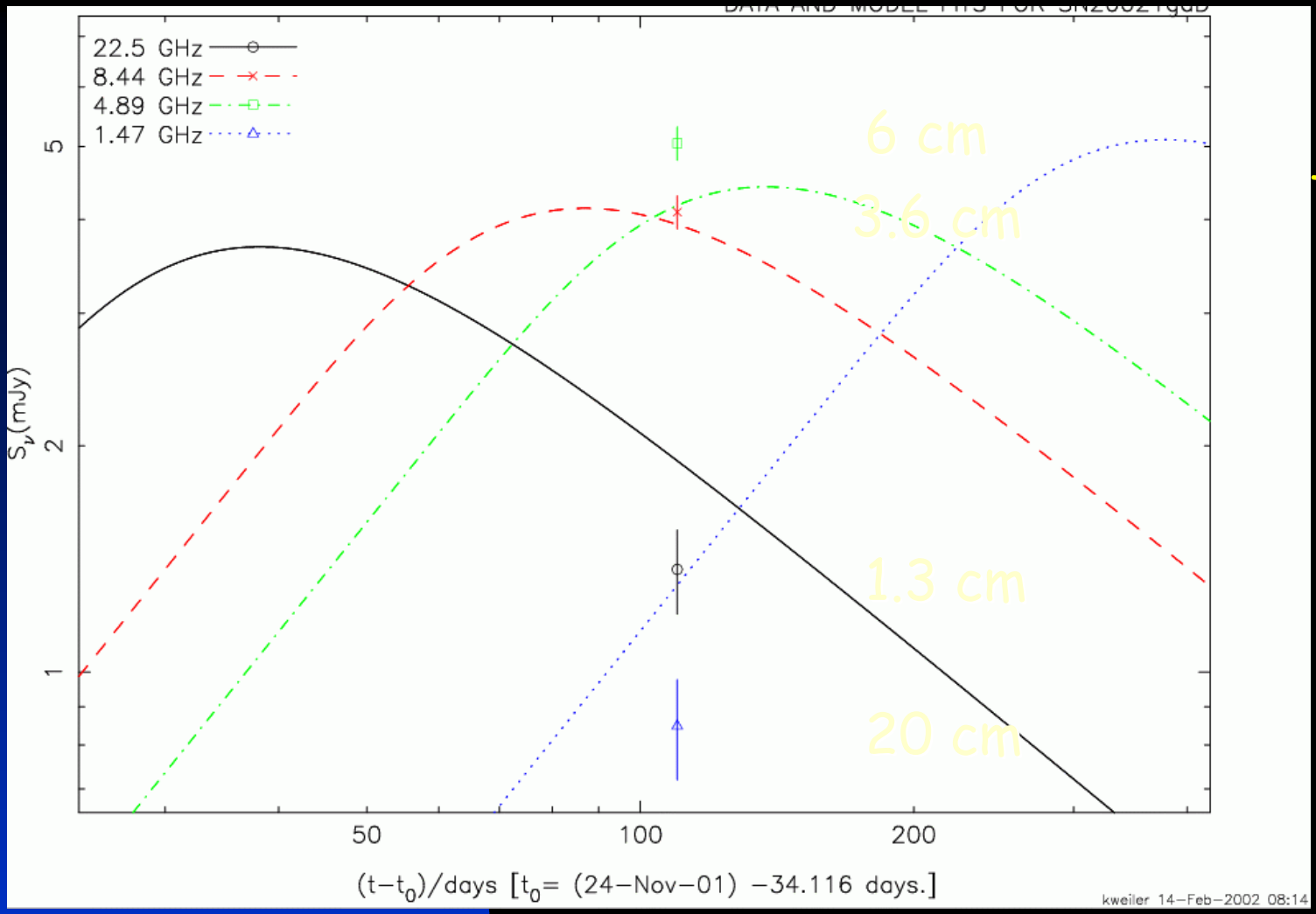


SN2001gd spectrum on 4 Dec 2001
(Matheson et al. 2001)



Comparison spectra SN2001gd/SN1993J
(from Matheson et al. 2001)

First radio detection of SN2001gd



8 Feb 2002

t_{exp} ~ 150 days

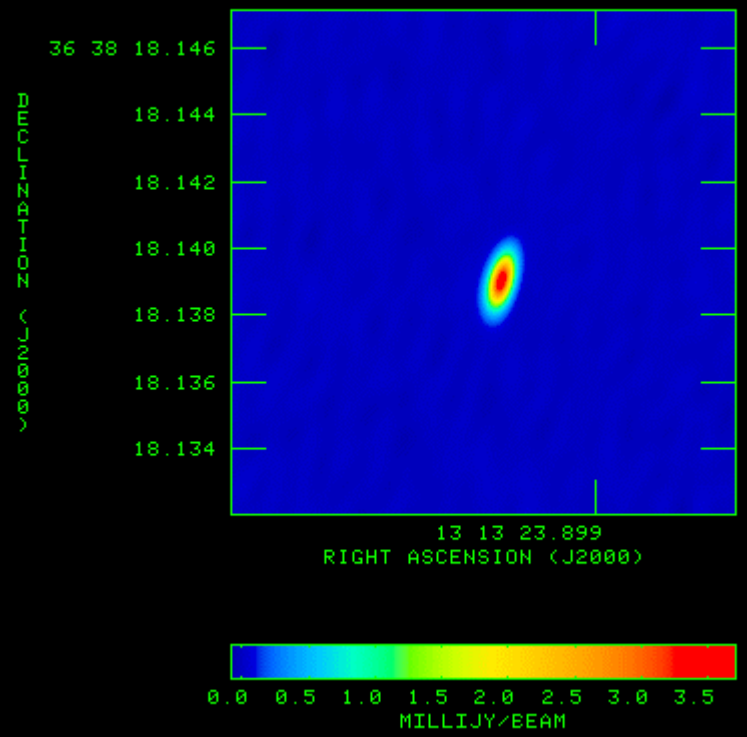
(from Stockdale et al. 2002)

$L_{6\ cm\ peak} \sim 3 \times 10^{27}$ erg/s/Hz

First VLBI detection of SN2001gd

VLBI @ 3.6 cm

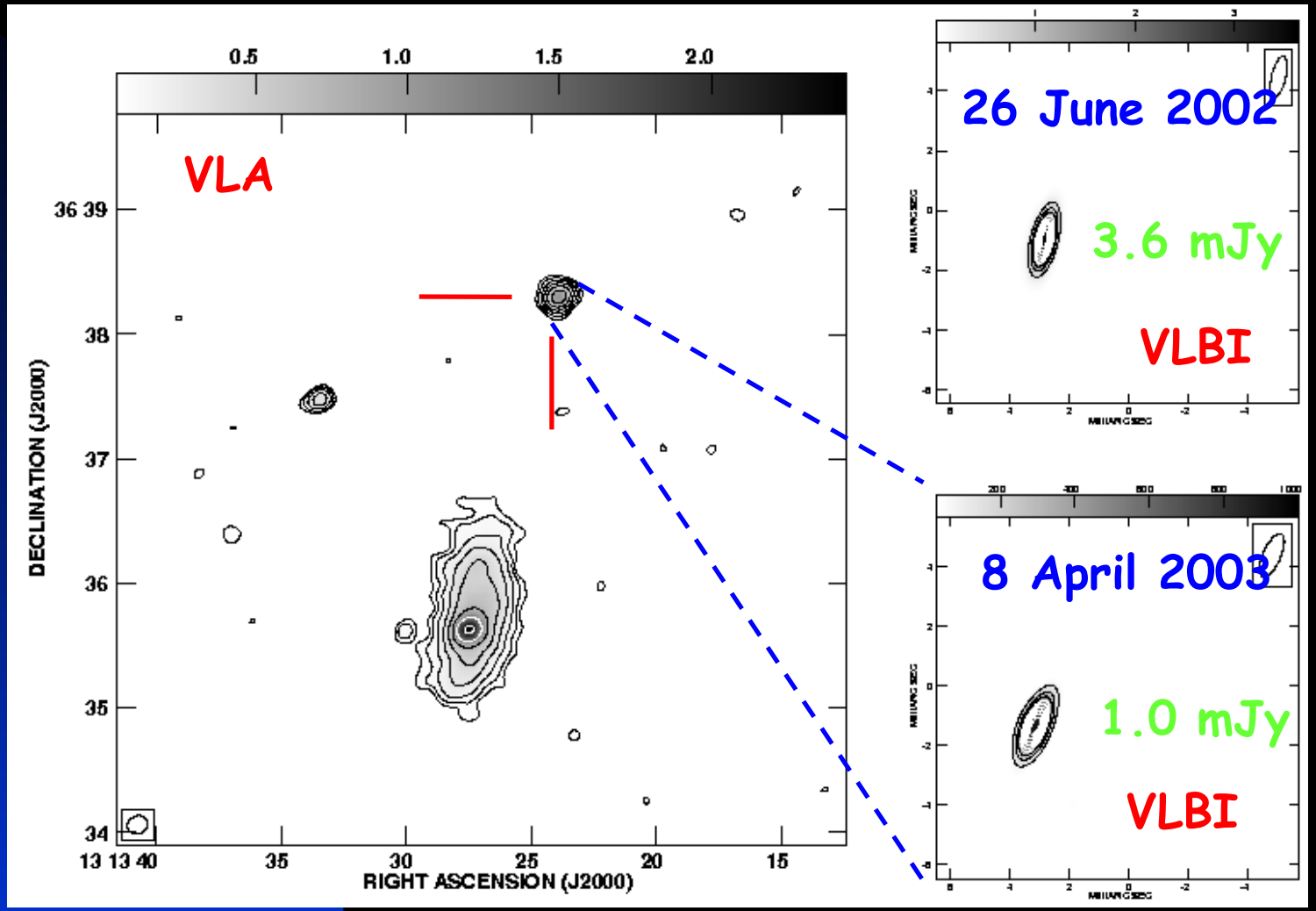
26 June 2002
(t_{exp} ~ 300 days)



Source structure unresolved

(Pérez-Torres et al., in preparation)

Radio images of SN 2001gd at 3.6 cm



MODEL	Angular radius (microarcsec)	
	2002.48	2003.27
Opt. thin sphere	390 +/- 40	440 +/- 50
Opt. thick disk	350 +/- 30	410 +/- 50
Opt. thin shell	330 +/- 30	370 +/- 40

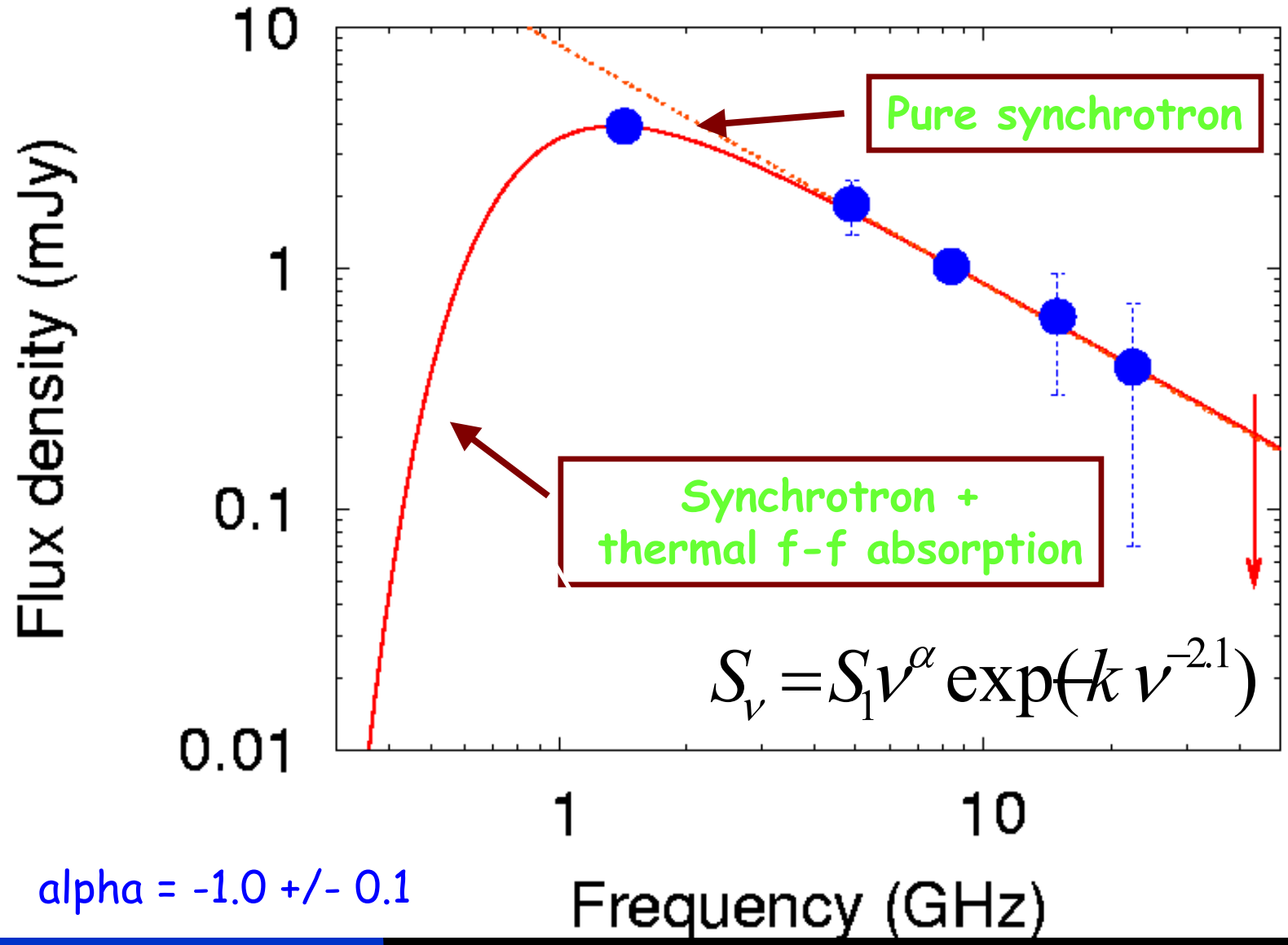
Expected model is the optically thin shell

R ~ 3.6 x 1016 cm on 8 April 2003

Angular diameter change is barely detectable above 1-sigma

100 micro arcsec @ 13.1 Mpc ~ 0.006 pc ~ 1300 AU

VLA Radio spectrum of SN 2001gd on 8 April 2003



alpha = -1.0 +/- 0.1

Free-free optical depth constrains T_e and $(dM/dt)/v_{wind}$

$$S_\nu = S_1 \nu^\alpha \exp(-k\,\nu^{-2.1})$$

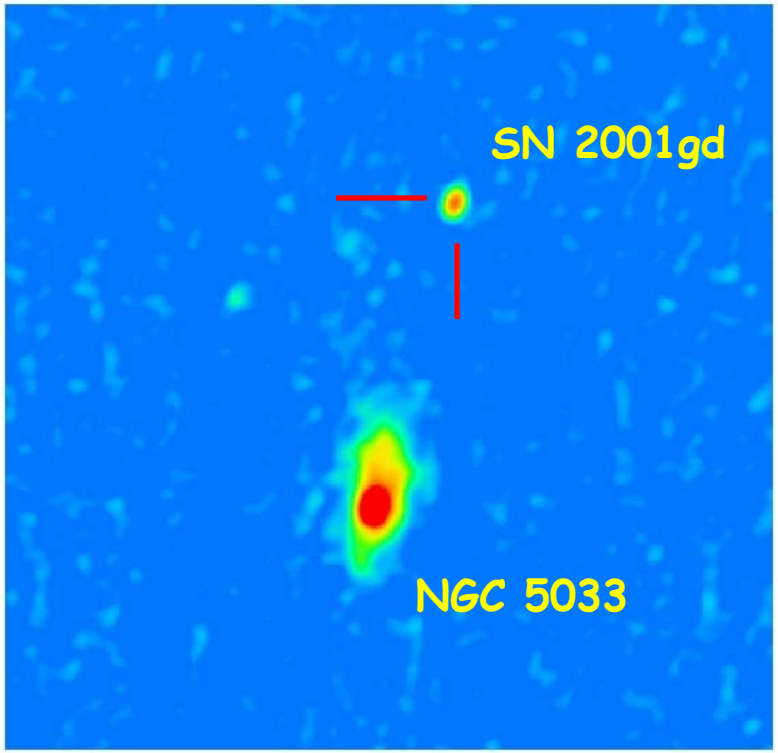
$$\tau_{ff,\nu} = -k\nu^{-2.1}$$

$$\tau_{ff,\nu} \approx 0.17\, g_{ff}\, T_5^{-3/2} \nu_1^{-2}\, (dM/dt)_{-5}^2\, v_{10}^{-2} r_{16}^{-3}$$

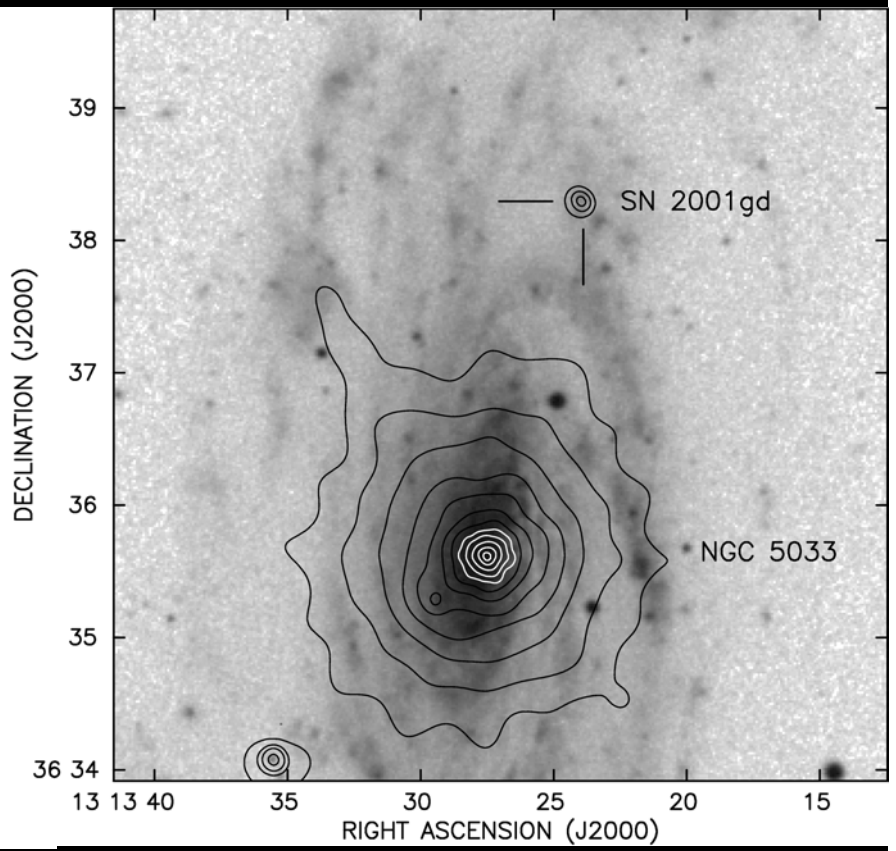
T_e = (8-20) x 10^4 K

(dM/dt) = (5-10) x 10^{-5} M_{sun}/yr

VLA image at 3.6 cm of SN2001gd on 8 April 2003



Contours of soft (0.5-2.5 keV) X-rays on 18 Dec 2002



Most X-ray emission comes from a soft component at T ~ 1.7 keV (reverse shock)

$L_{X\text{-}rays} \sim 4 \times 10^{38}$ erg/s (0.3-5 keV)

SN 2001gd

- $\rho_{csm} \sim r^{-s}$; $s = 2$
- $v_{wind} = 10$ km/s
- $dM/dt = (5\text{-}10) \times 10^{-5} M_{sun}/yr$
- $L_{radio} \sim 6 \times 10^{36}$ erg/s (1-43 GHz)
- $L_{X\text{-}rays} \sim 4 \times 10^{38}$ erg/s (0.3-5 keV)
- $R \sim 3.7 \times 10^{16}$ cm
- $B \sim (50\text{-}380)$ mG » $B_{csm} \sim 2$ mG
- Turbulent amplification of B
- $E_{min} \sim (0.2\text{-}13) \times 10^{47}$ erg

Summary

	SN1979C	SN1986J	SN2001gd	SN1993J
Distance (Mpc)	16.1	9.6	**13.1?**	3.63
Time since explosion (yr)	20.1	~16	**<2**	8.6
$(L_{6cm} / L_{6cm\ SN1993J})_{peak}$	~1.6	~13	**~2**	1
Resolved by VLBI?	Not yet	Yes	**Not yet**	Yes
Optically thin phase?	Yes	Yes	**Yes**	Yes
Radio brightness structure	shell	distorted shell	---	~smooth shell
(dM/dt) / (10^{-5} M_sun/yr)	~10	~20	**5-10**	5
Deceleration parameter (m)	0.62	0.90	1.0?	~0.82
Asymmetric expansion?	No	Yes	?	No (<5%)
Circumstellar medium	---	clumpy	?	~smooth
M_{swept} / M_{sun}	1.6	2.2	?	~0.4
M_{env} / M_{sun}	~0.9	~12	?	~0.6
Explosion scenario	Binary	Single	**Binary?**	Binary
Magnetic field amplification	Turbul.	Turbul.	**Turbul.**	Turbul.
t_{break} (years)	6 ± 2	----	----	~0.5