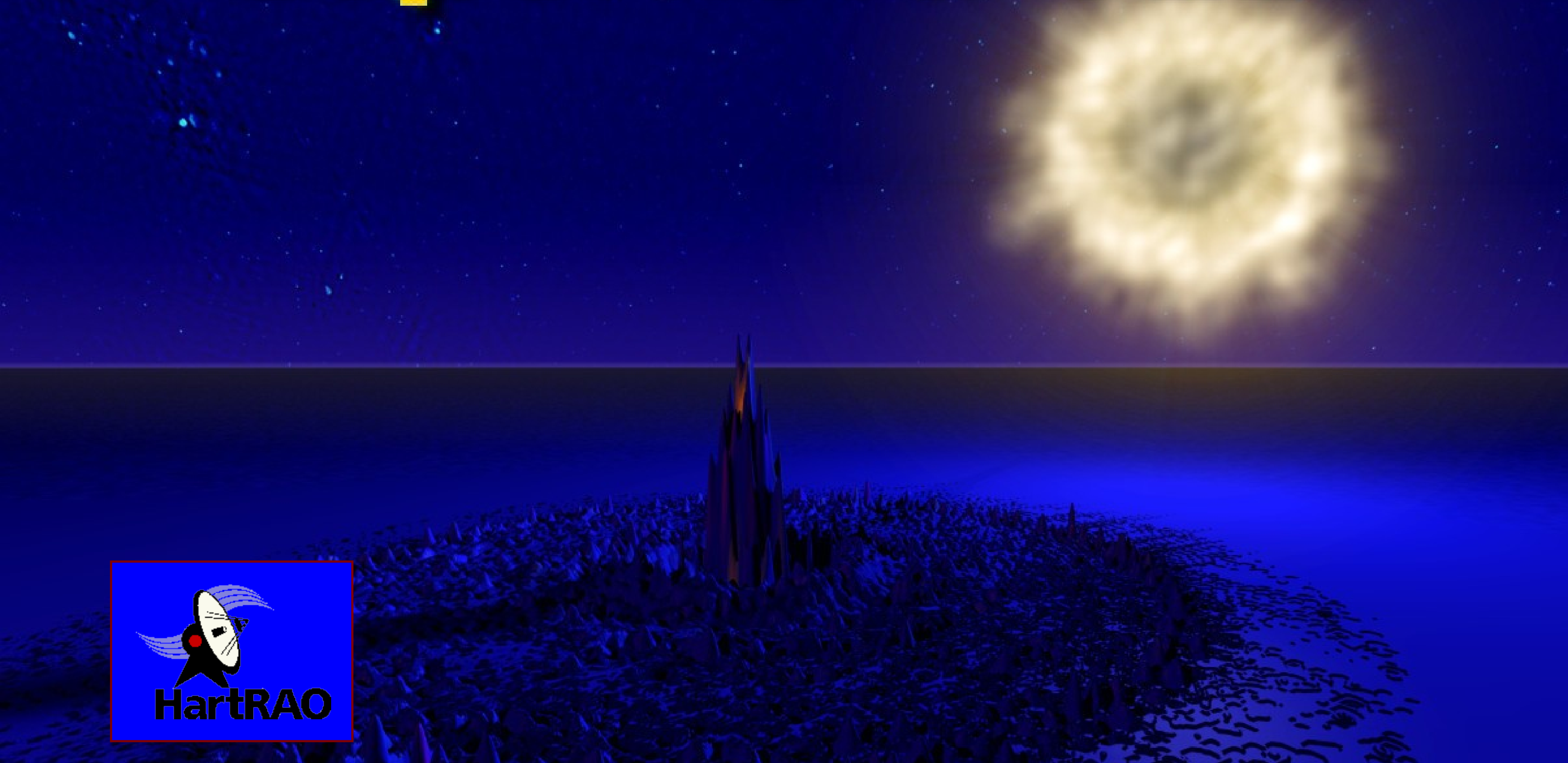
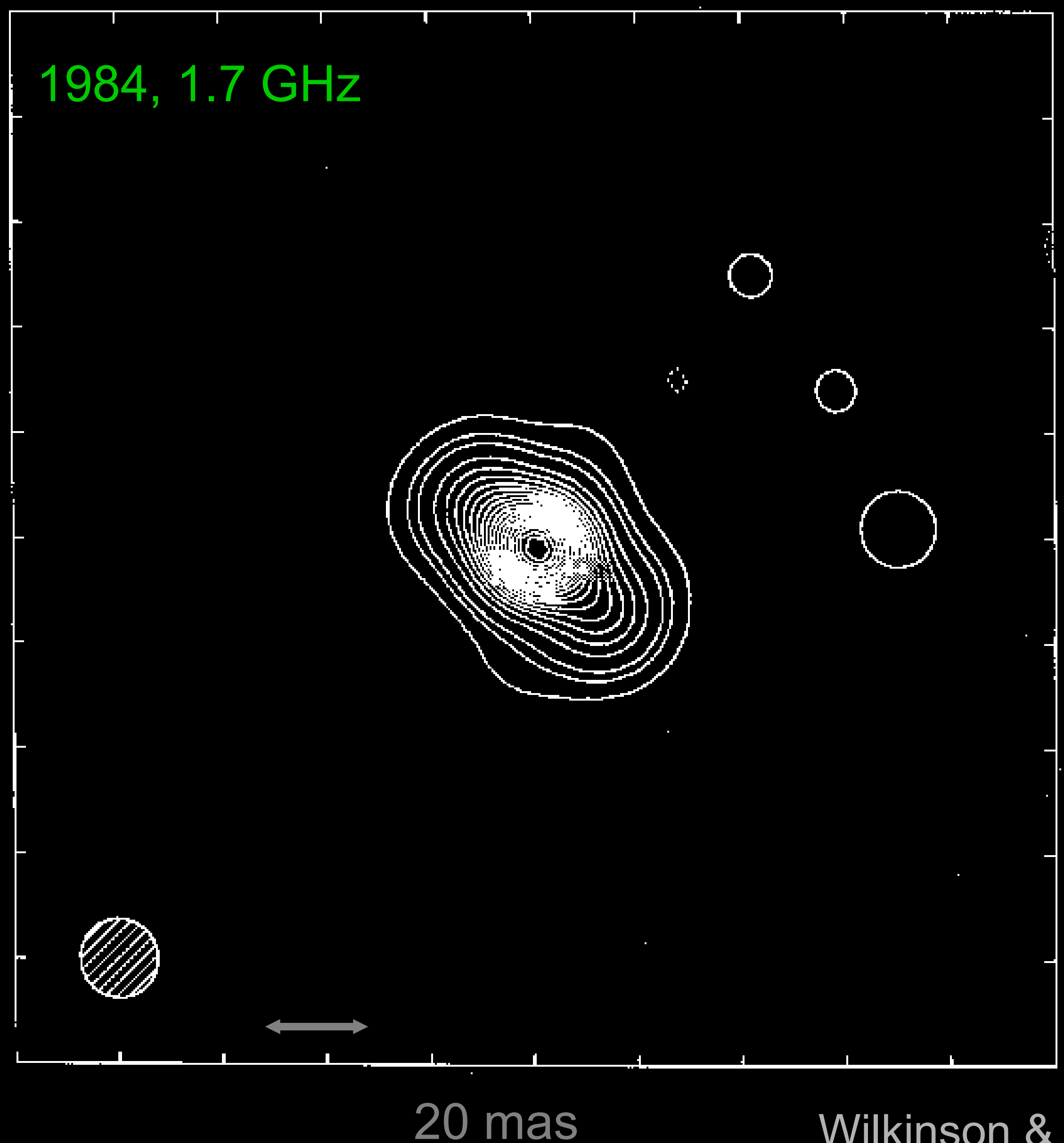
Supernova VLBI



Michael Bietenholz, Hartebeesthoek Radio Observatory, South Africa

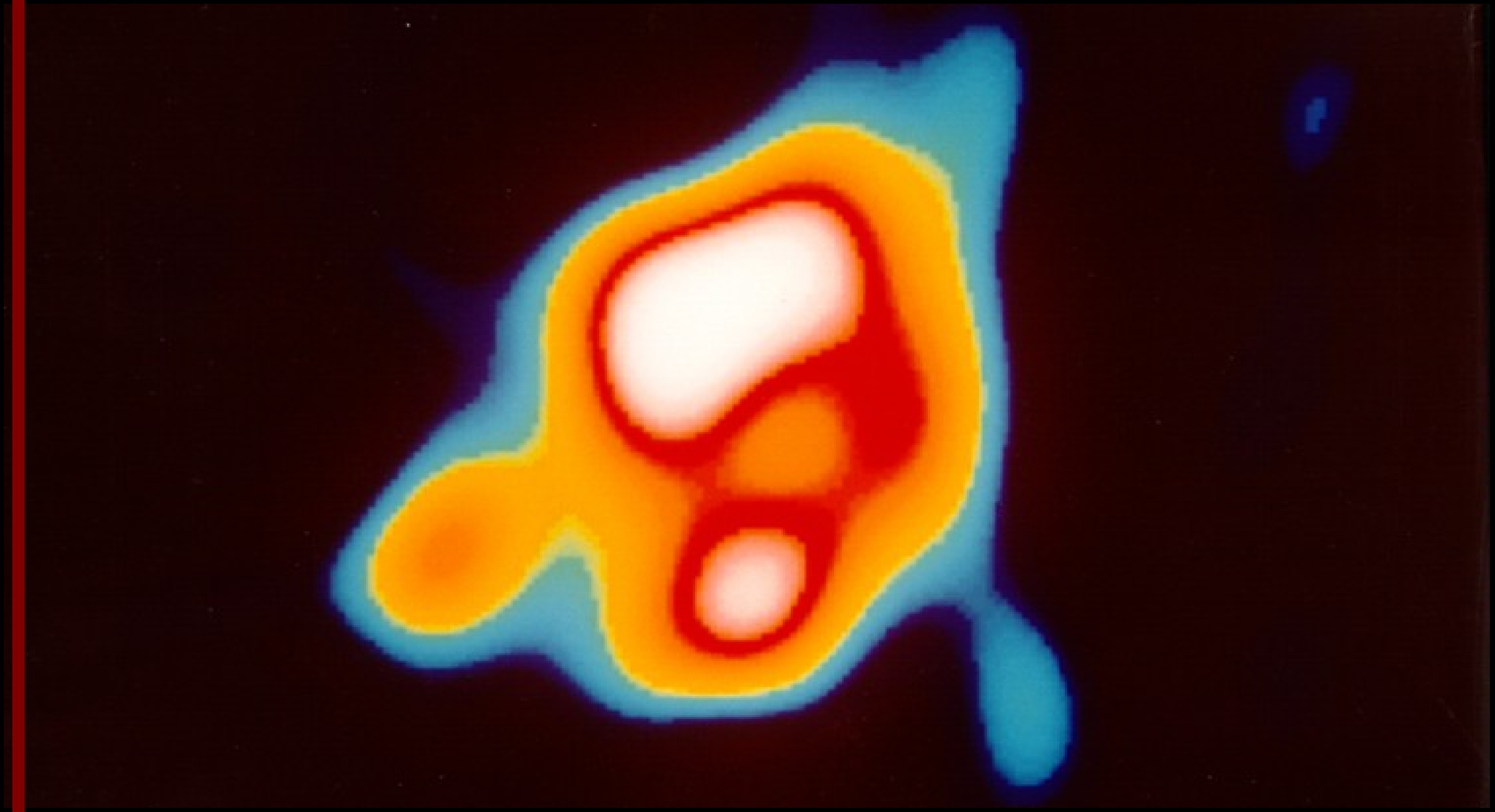
41.95+575



Wilkinson & de Bruyn, 1984

SN 1986J

1988.8, 8 GHz



1 mas

Bartel et al., 1990

Introduction and History

- Radio emission from a supernova was first detected in the 1972 (SN 1970G; Gottesman et al., Goss et al.)
- First paper about supernova and VLBI was in 1974 – Cass A at meter wavelengths
- First determination of the size of a supernova in 1983: SN 1979C (Bartel et al.)
- First image of a radio supernova in 1984: 41.95+575 in M82 (Wilkinson & de Bruyn)

Radio Emission from Supernovae

- Thermonuclear:
  - Type Ia: no detections to radio date (see Panagia et al 2006)

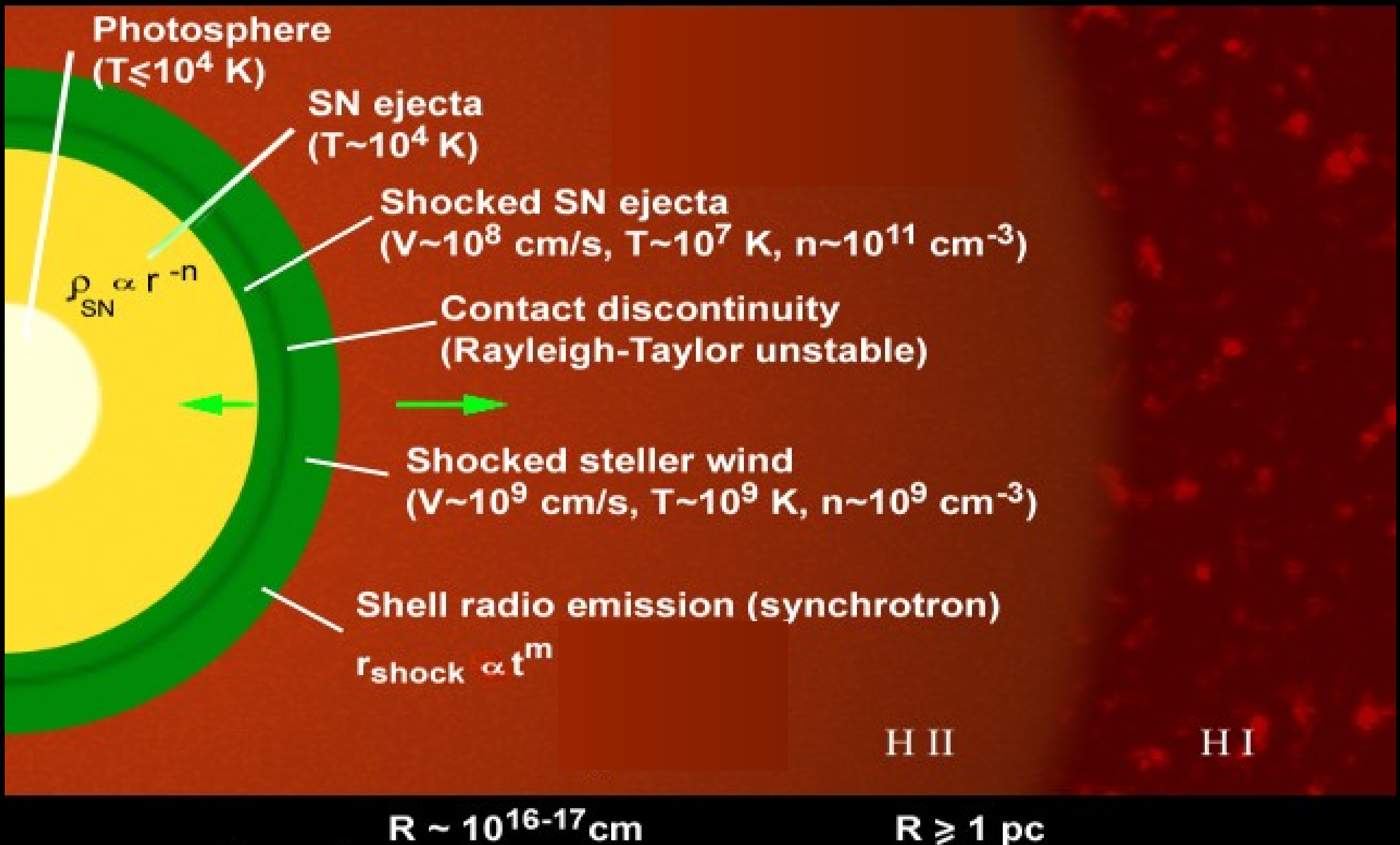
- Core Collapse:
  - Type Ib/c (no Hydrogen in spectrum; stripped envelope stars)
    - Generally have steep spectra: α <~ −1 ($S \propto \nu^{\alpha}$)
    - Fast turn-on/turn-off, peak at 5 GHz near optical maximum
  - Type II: (Hydrogen in spectrum; supergiant progenitors) large range in radio luminosities
    - Relatively slow turn-on/turn-off, radio peak often significantly after optical peak.

- Approximately 30 RSNe (all core-collapse) with flux densities > 1 mJy have been detected, and >100 have upper limits (Weiler et al.) Most are at <30 Mpc

Radio Detection of SNe

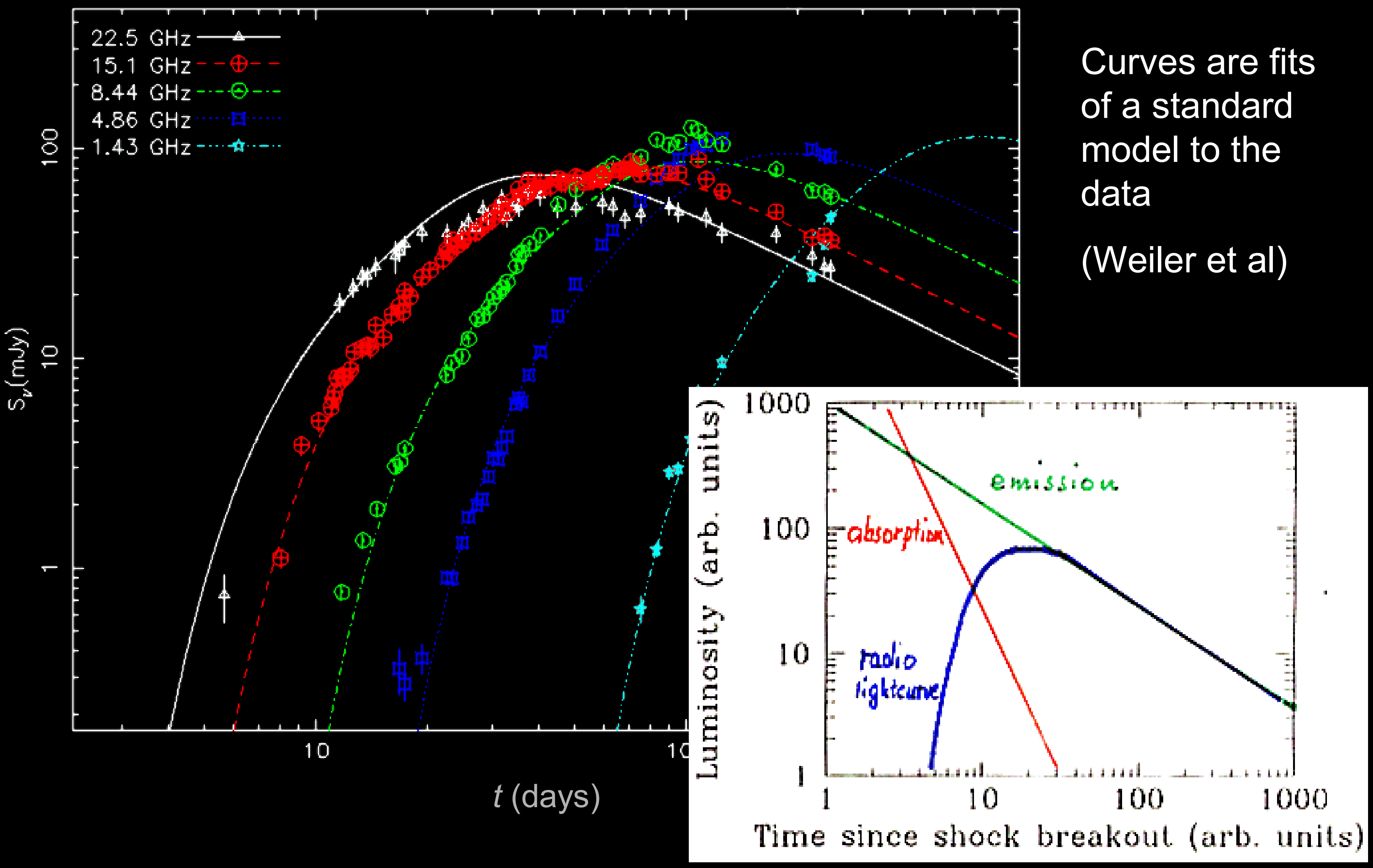
- Several hundred SNe are detected each year in optical
- Only a few SNe detected each year in radio
  - Total radio SNe detections: a few dozen
  - 'All' radio detected SNe are core collapse (Type II, Type Ib/c etc)
- Even fewer have been resolved by radio observations (so every VLBI observation is of great value)….
- A few SNe detected in radio but NOT in optical (e.g. a supernova in NGC7469 – Colina et al 2001; several SNe in Arp220 – Smith et al., Lonsdale et al, Parra et al.)

Standard Model of SN Radio Emission



Chevalier, 1982

Early Radio Lightcurve of SN1993J



Curves are fits of a standard model to the data

(Weiler et al)

Why Image Supernovae with VLBI?

- Interaction of the expanding ejecta with the circumstellar medium (CSM) – usually the wind of the SN progenitor
- Stellar wind history of star: supernova shock front overruns CSM wind with 1000× wind speed

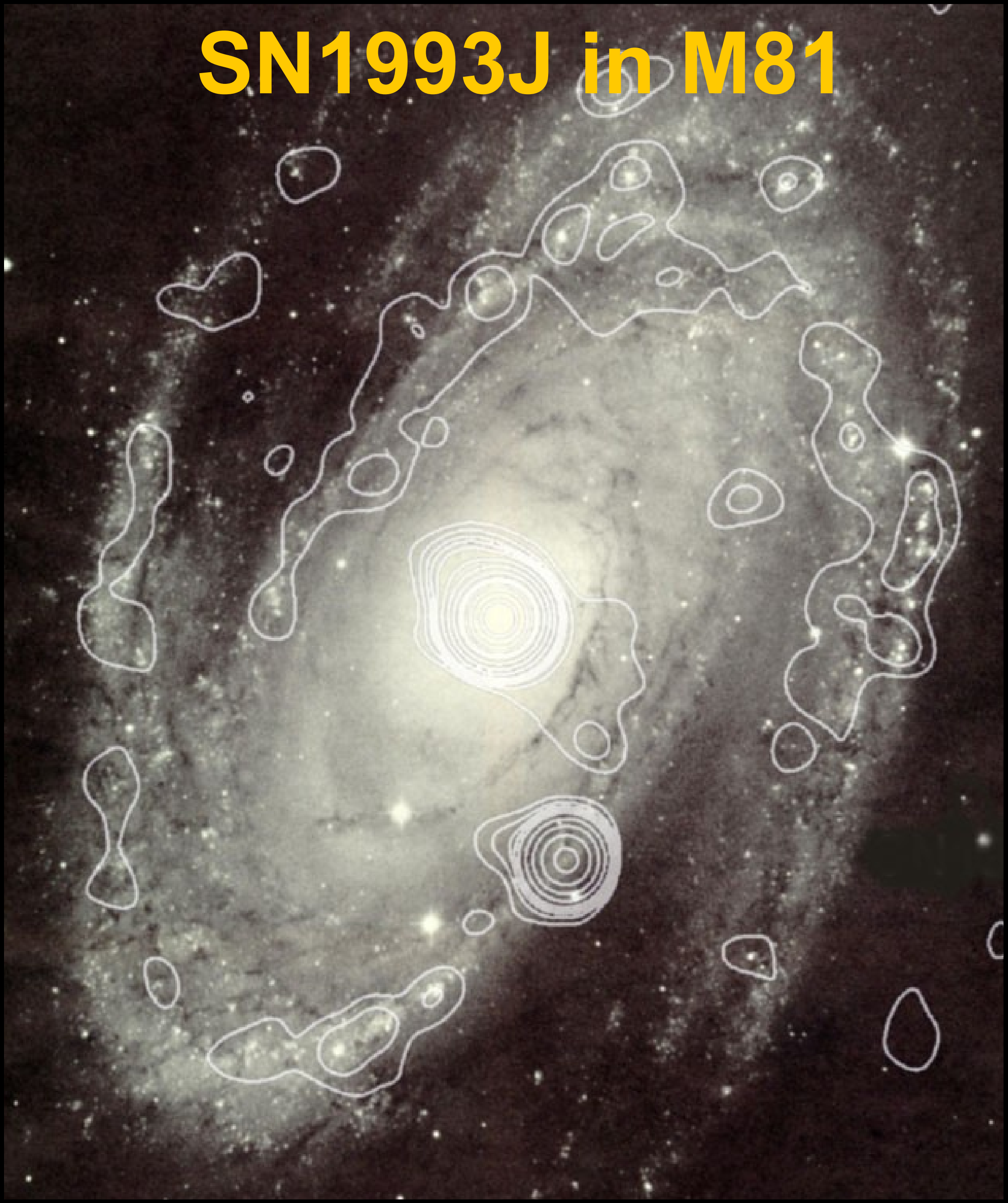
  → time machine that records progenitor wind history in reverse
- Evolution of SN shells, shock acceleration, eventual merging with ISM
- Compact remnant of a core-collapse SN?
- Supernova rates, especially in dusty environments
- Direct distances with the expanding shock front method – out to Virgo cluster
- Imaging jets of nearby GRB events

RSNe Observed with VLBI

Name	***Type***	***Host galaxy***	***Distance*** (Mpc)	***Peak*** (mJy at 8 GHz)	Reference
Several SN/SNR	?	M82	3.2		Beswick et al 2006
Several SN/SNR	?	Arp 299	40		Neff et al 2004
Several SN/SNR	?	Arp 220	77		Lonsdale et al 2006
SN1978K	II	NGC 1313	4	>100?	Smith et al 2007.
SN1979C	II	M100	16	6	Bartel & Bietenholz 2008
SN1980K	II	NGC6946	6	2	Bartel 1985
SN1986J	II	NGC891	10	100	Bietenholz et al 2004
SN1987A	II	LMC	0.05	80	Jauncey, Gaensler, Manchester
SN1993J	II	M81	4	100	Bietenholz, Bartel, Marcaide
SN1994I	Ic	M51	8	20	Bietenholz & Bartel, unpublished
SN1996cr	II	Circinus	3.6	~100	Bauer et al 2008.
SN2001em	Ib/c	NGC 7112	80	4	Bietenholz, Paragi, Schinzel
SN2001gd	II	NGC 5033	13	4	Pérez-Torres et al 2008
SN2003L	Ib/c	NGC 3506	92	3	Soderberg et al 2005
SN2004et	II	NGC 6946	6	2	Martí-Vidal et al
SN2007gr	Ib/c	NGC 1058	10	<~ 1	Paragi et al 2007
SN2008D	Ib/c	NGC 2770	27	3	Soderberg, Bietenholz Paragi

Approximately 30 RSNe with flux densities > 1 mJy have been detected, and >100 have upper limits (Weiler et al.)

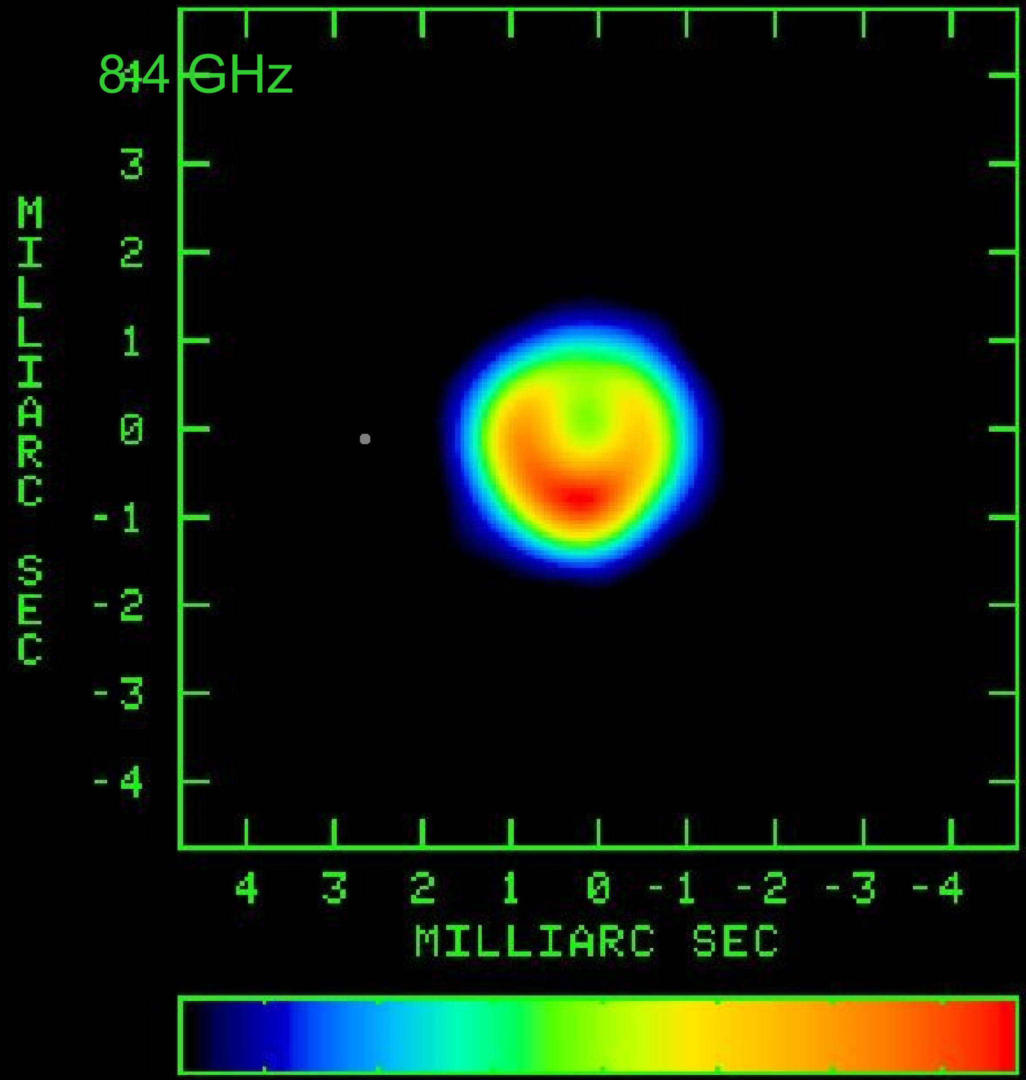
SN1993J in M81



Contours: 5 GHz VLA Radio observations of M81 (Nov. 1997)

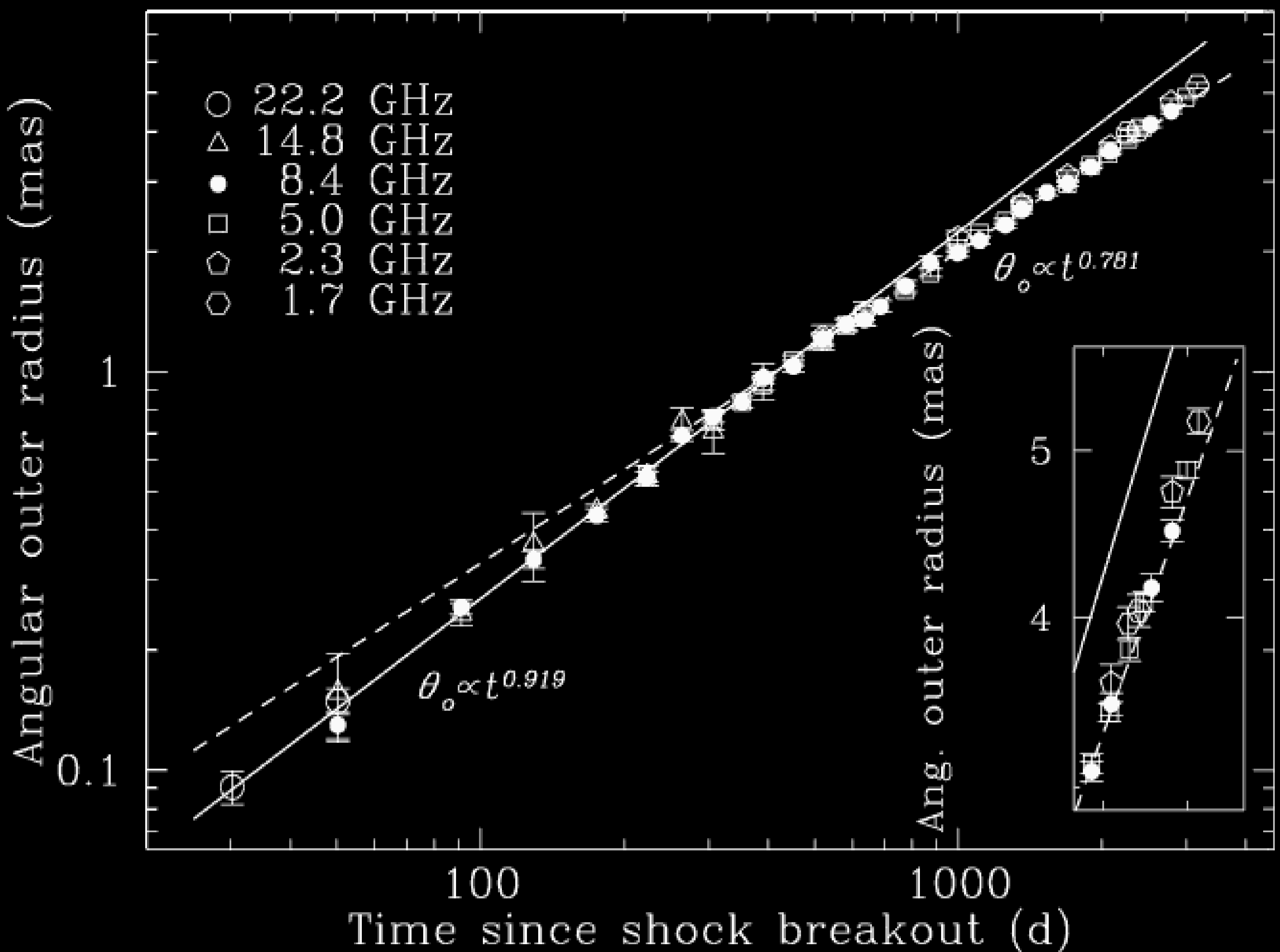
Optical image from A. Sandage, *The Hubble Atlas of Galaxies*

VLBI Image of SN 1993J



22 Jun 1994; day 451 ~ 1.5 years after the explosion.
Shell clearly visible with some asymmetry: a hot-spot to the south and a gap to the North

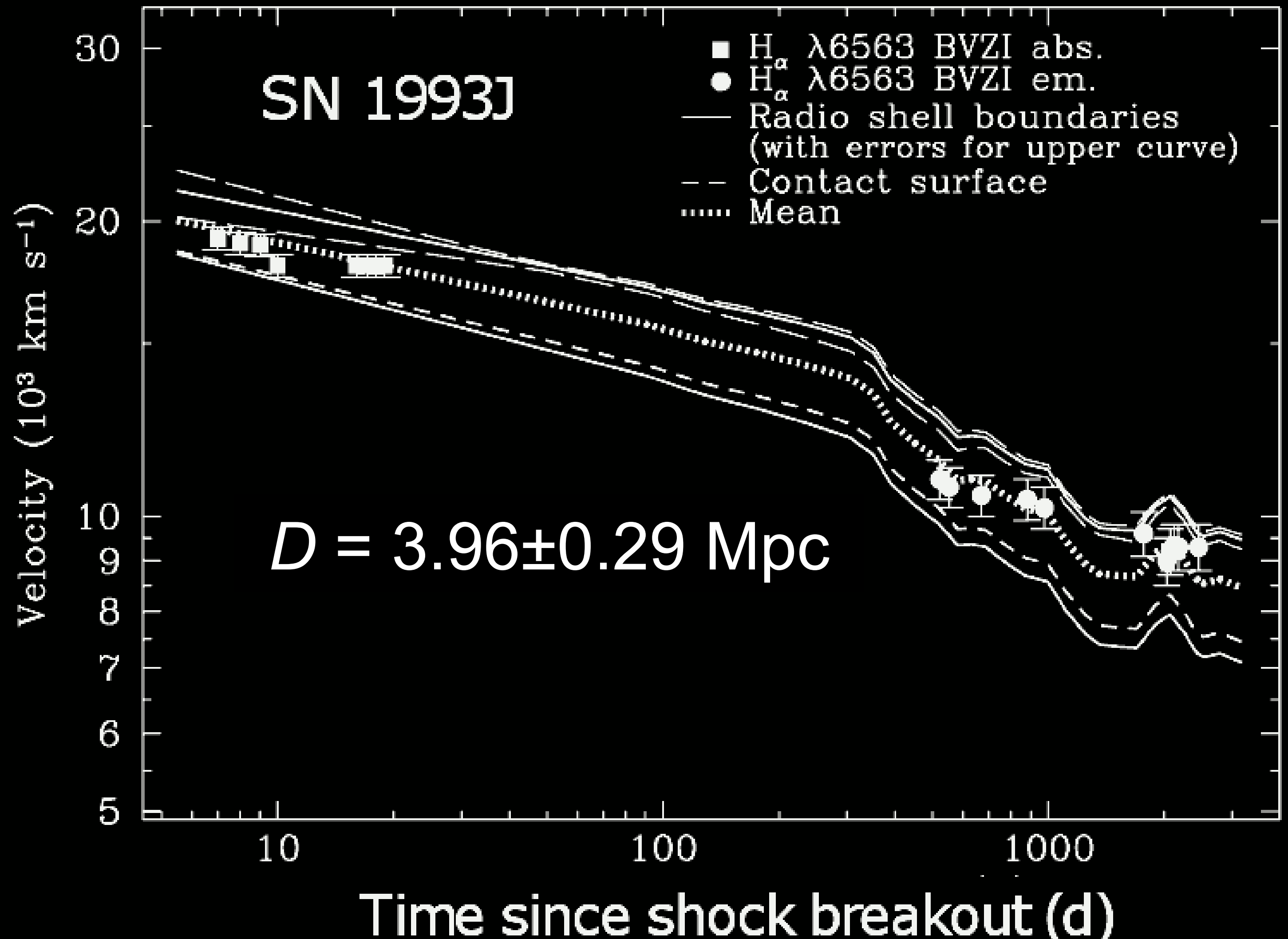
Expansion of SN1993J



Expansion velocity depends on density profiles of both ejecta and circum-stellar (pre-SN wind)

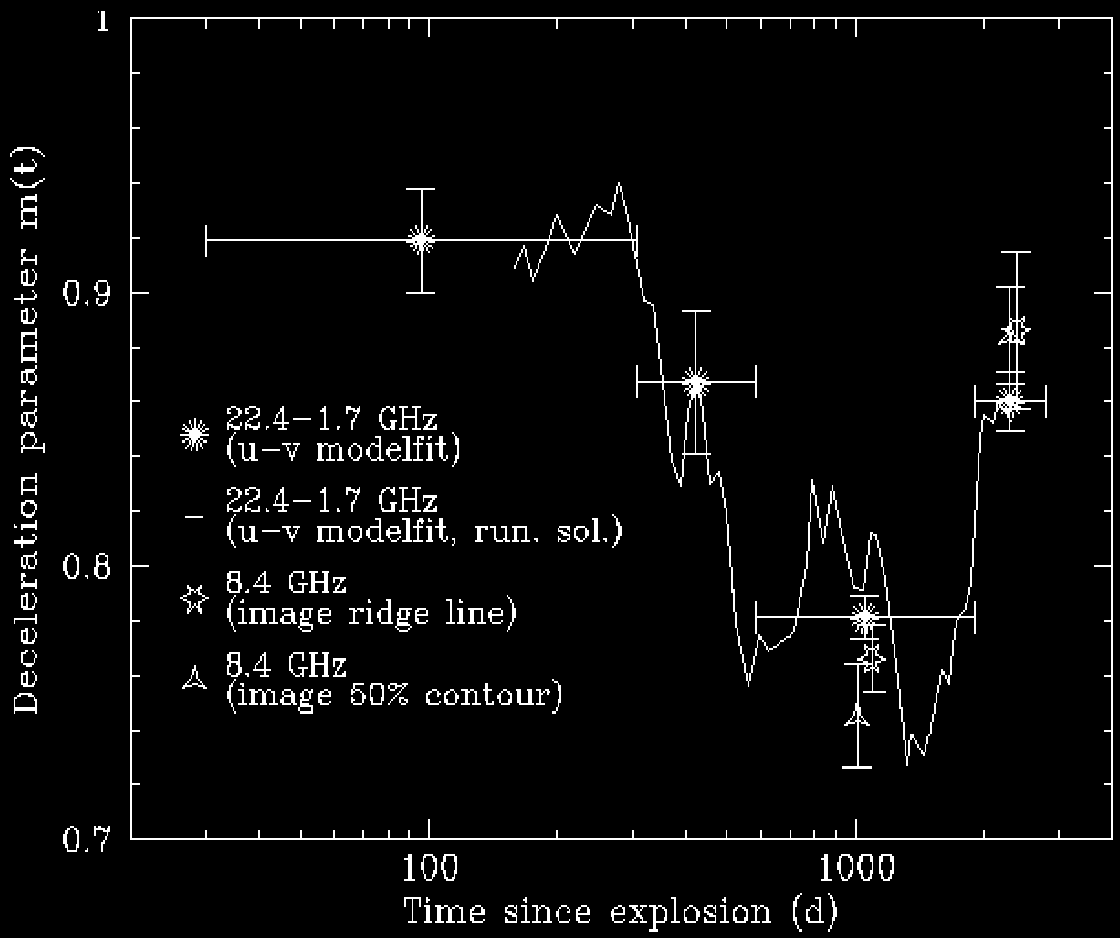
Bartel et al, 2002; see also Marcaide et al

Geometrical Distance to SN 1993J in M81



Bartel et al 2007

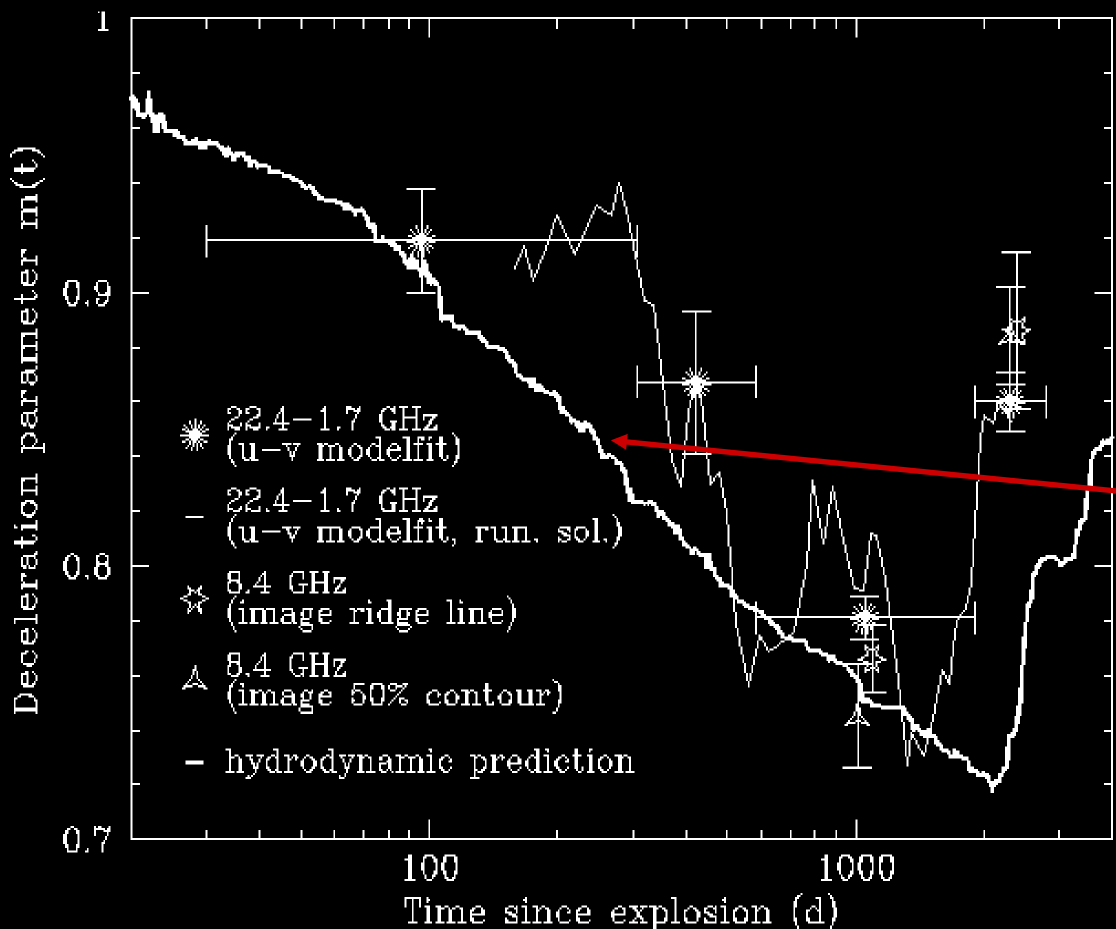
Deceleration of SN1993J



Deceleration parameter, *m*:

$\theta \propto t^{m(t)}$

Deceleration of SN1993J

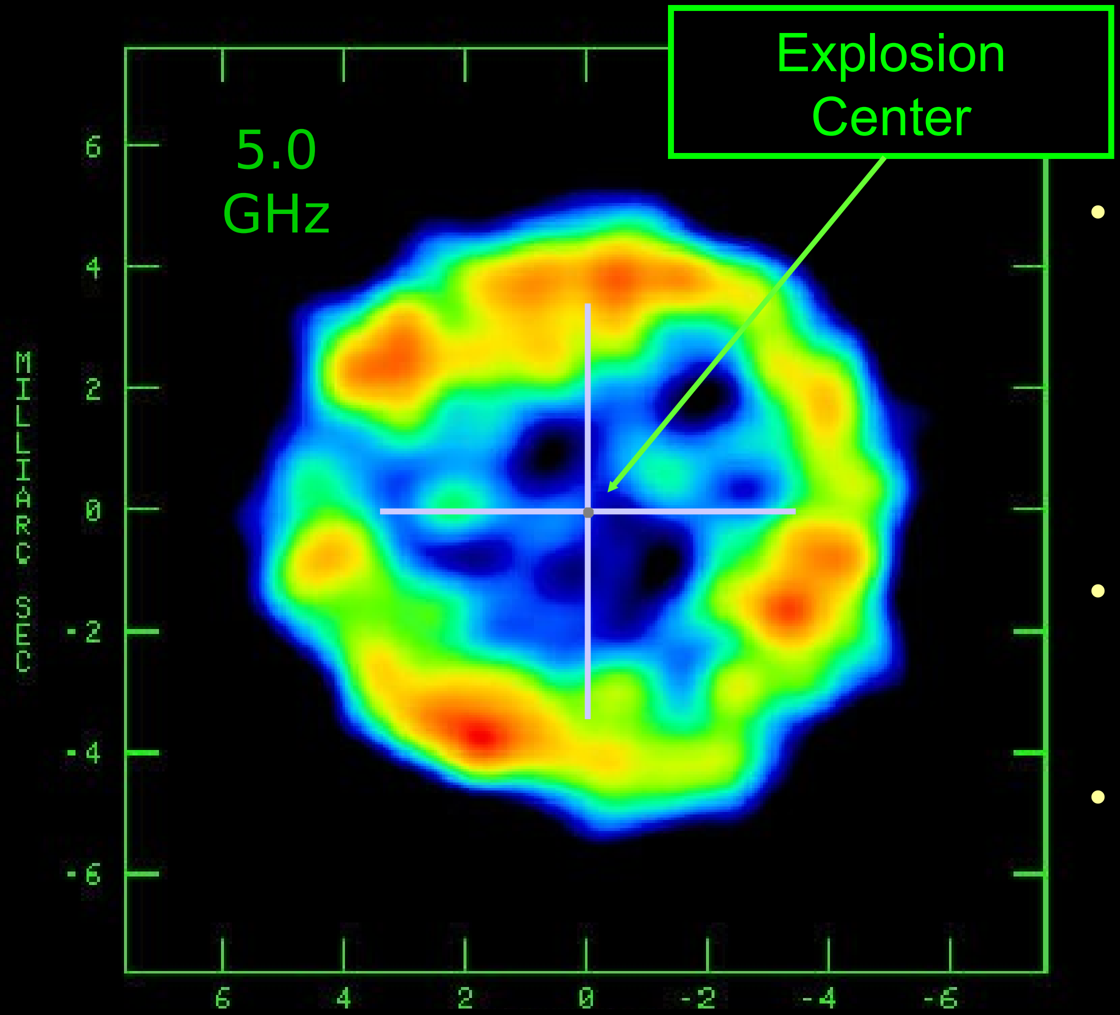


Deceleration parameter, *m*:

$\theta \propto t^{m(t)}$

Hydrodynamical modelling (Mioduszewski, Dwarkadas, & Ball 2001)

SN 1993J

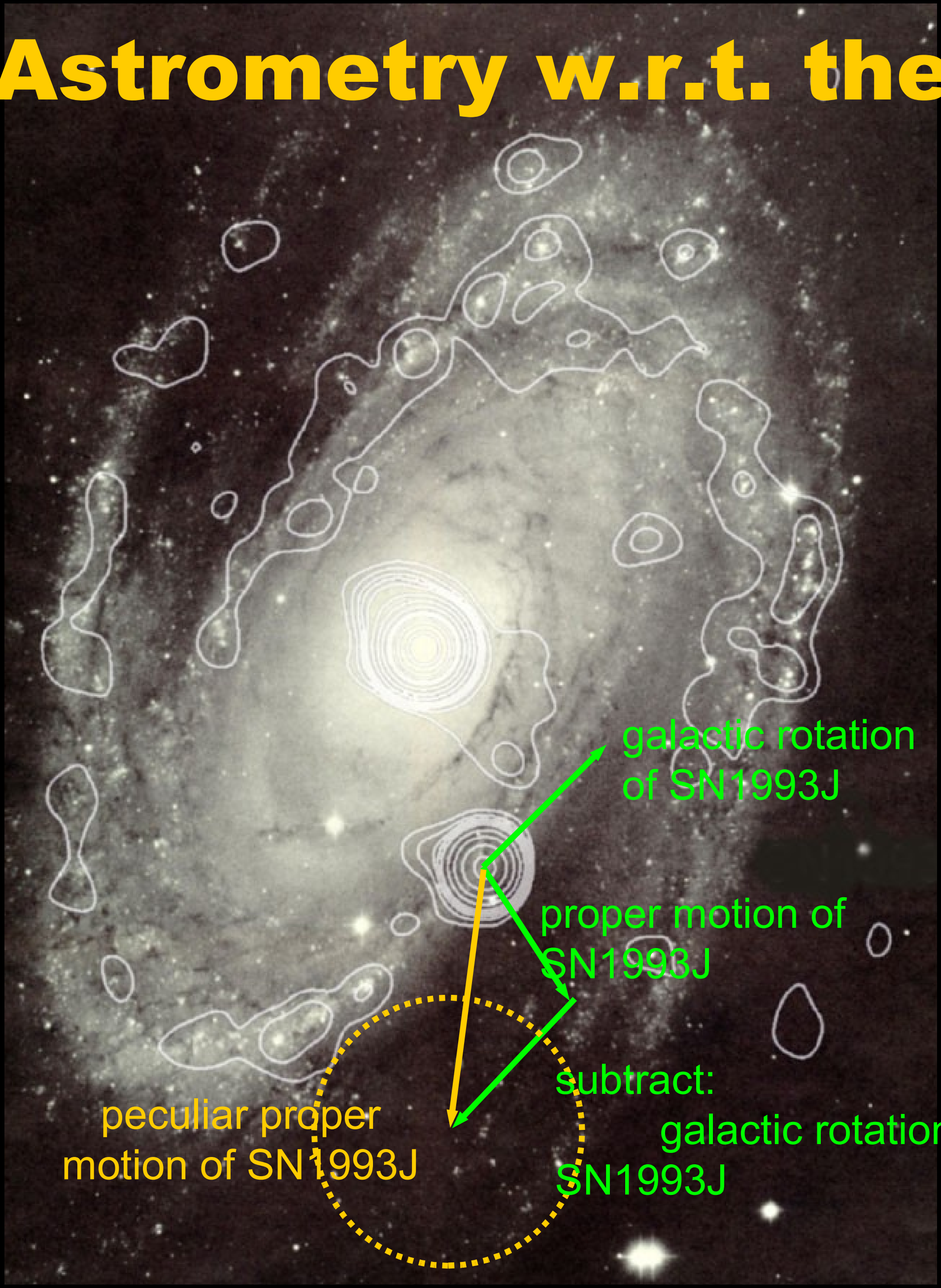


- Spherical shell of material thrown off in the explosion
- Expanding at 8,000 km/sec
- Size: 32,000 AU, 0.15 parsec = 4.8×10^{17} cm

24 May 2002, day 3345 ~ 9 years after the explosion

Global array VLBI: Bietenholz et al, Bartel et al 1993-2008; See also Marcaide et al

Astrometry w.r.t. the Core of M81

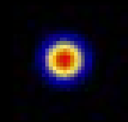


Bietenholz et al 2002

Location of
explosion center
determined to
45 μas or 160 AU

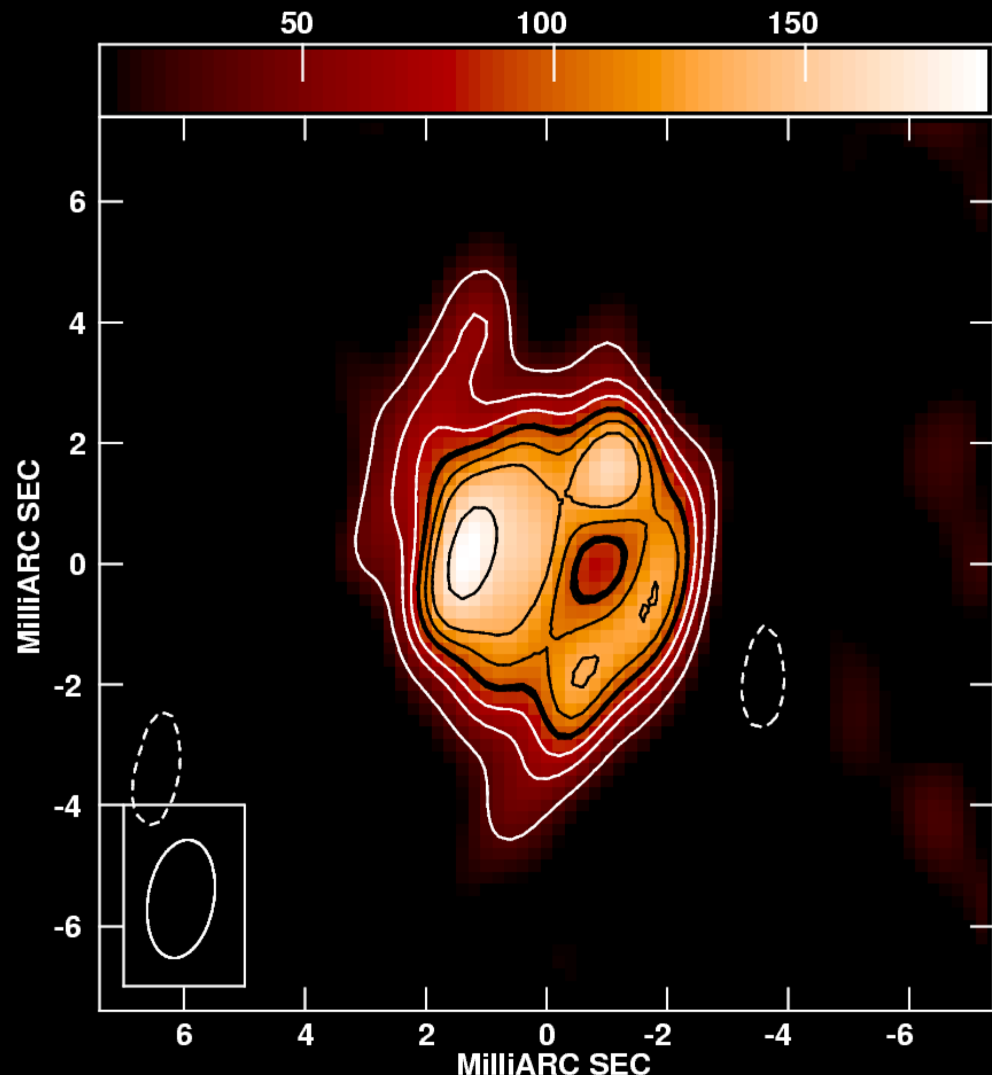
Peculiar proper
motion:
320 ±160 km/s to
south
(2 ~ 3% of
expansion velocity)

VLBI Movie of SN 1993J



- Global Array VLBI at 8.4 GHz and 5 GHz for last few epochs
- 33 Epochs of VLBI from 1993 to 2006 (and continuing!)

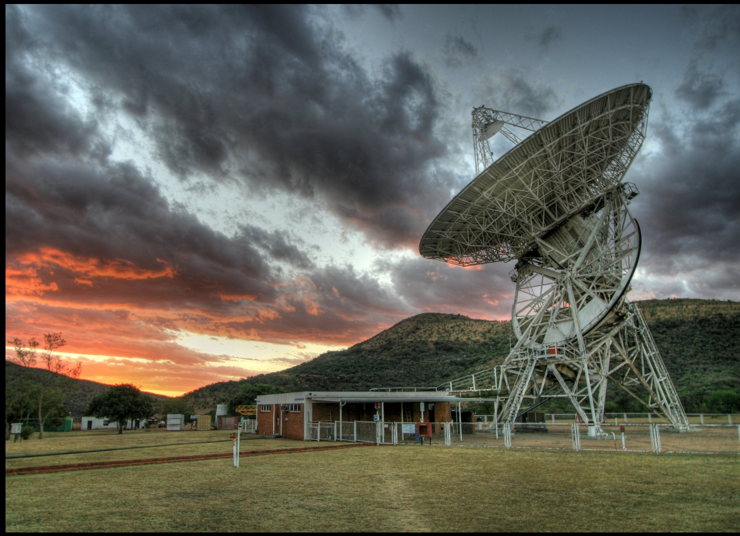
SN 1979C



Bartel & Bietenholz 2008

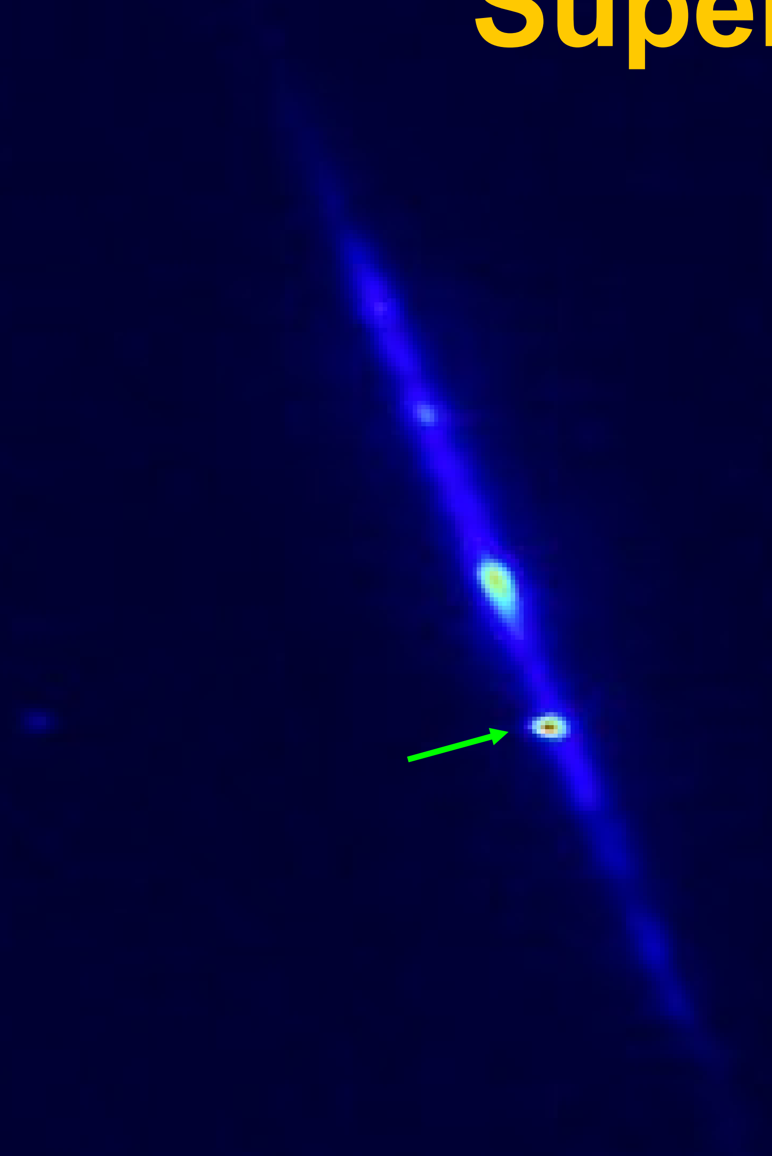
- Galaxy M100
- 15 Mpc
- SN 1979C discovered 19 Apr. 1979
- Age = 26 yrs
- Peak = 7 mJy

- 5 GHz observations in Feb 2005 using a global array
- 50% contour is circular to <= 8%



Thomas Abbott

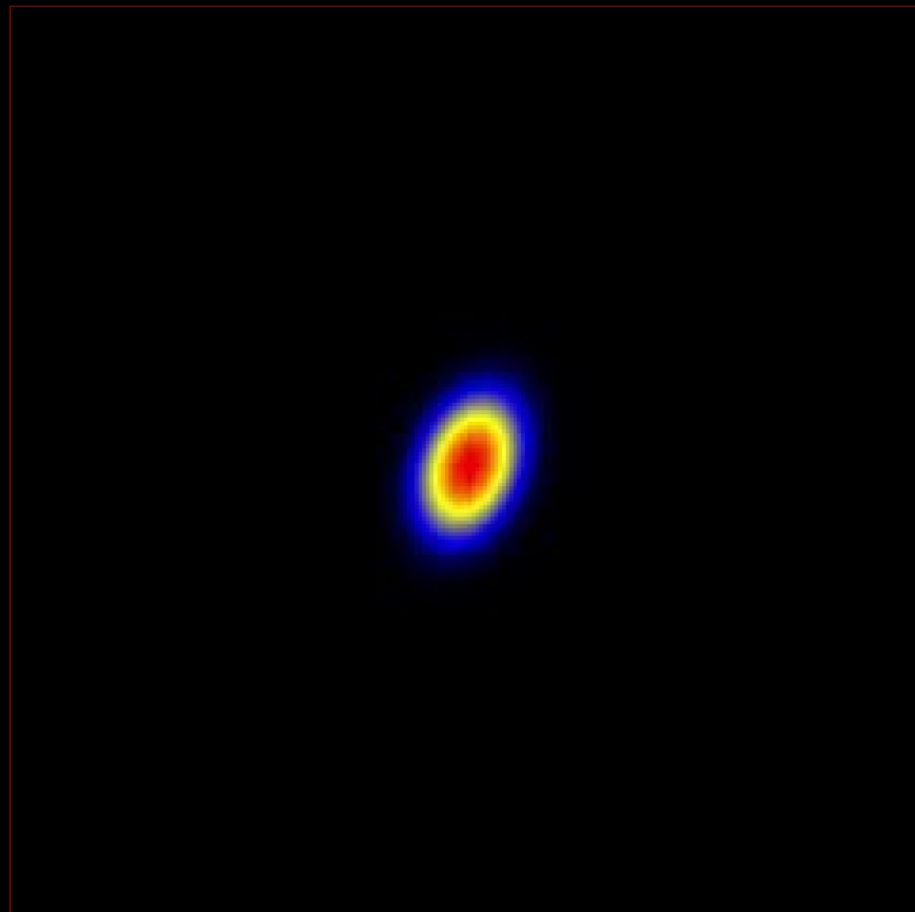
Supernova 1986J



VLA 5 GHz

- Supernova 1986J discovered in August 1986 in NGC 891
- Distance: ~10 Mpc
- Explosion date: 1983.2 ± 1.1 yr
- Among the most luminous radio supernovae ever
- Models suggest that the progenitor was a red supergiant, with mass > 20 $M_{\odot}$

S N 1 9 8 6 J



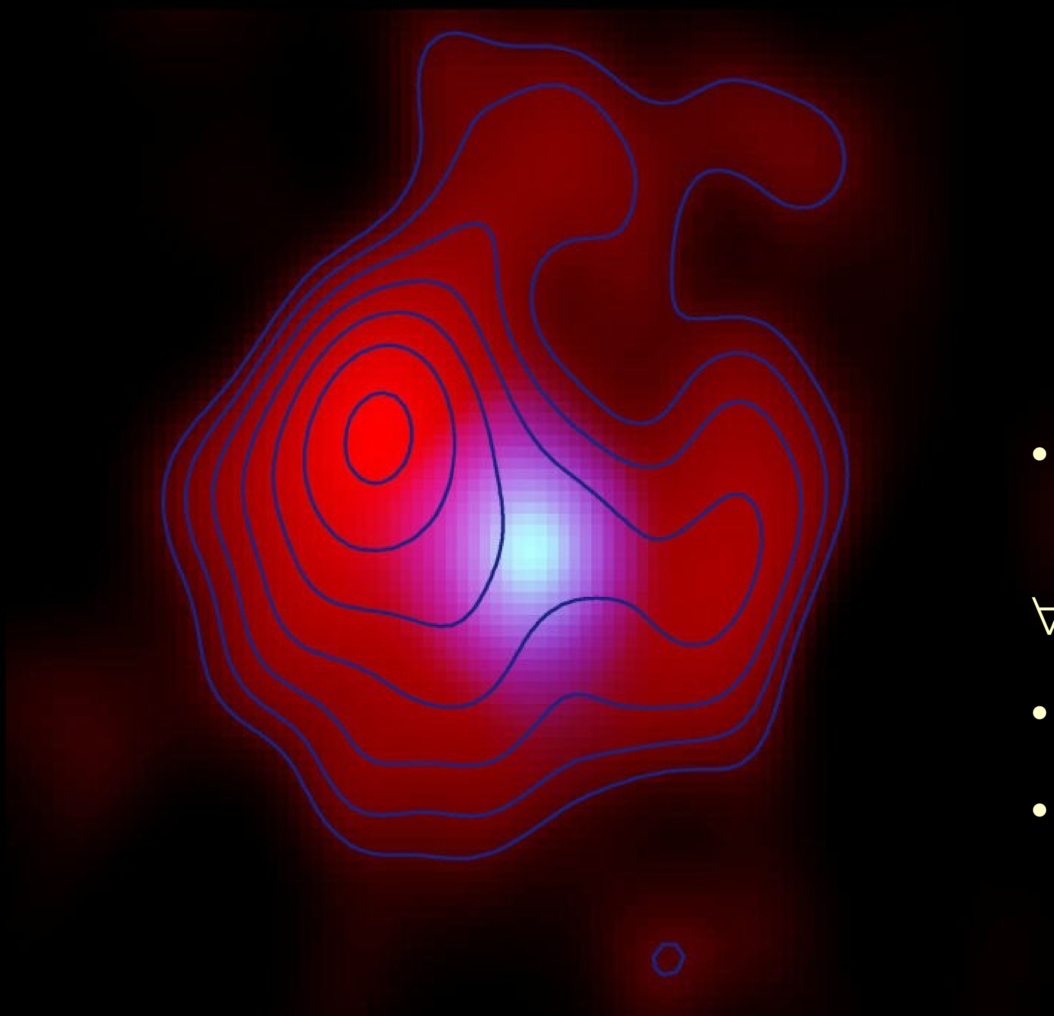
VLBI Images:
1987 to 2005

(and continuing_

1 mas

Bietenholz & Bartel 2007

Central Component in SN1986J



Multi-frequency VLBI Image:

Contours, red: 5 GHz

Blue → white: 15 GHz

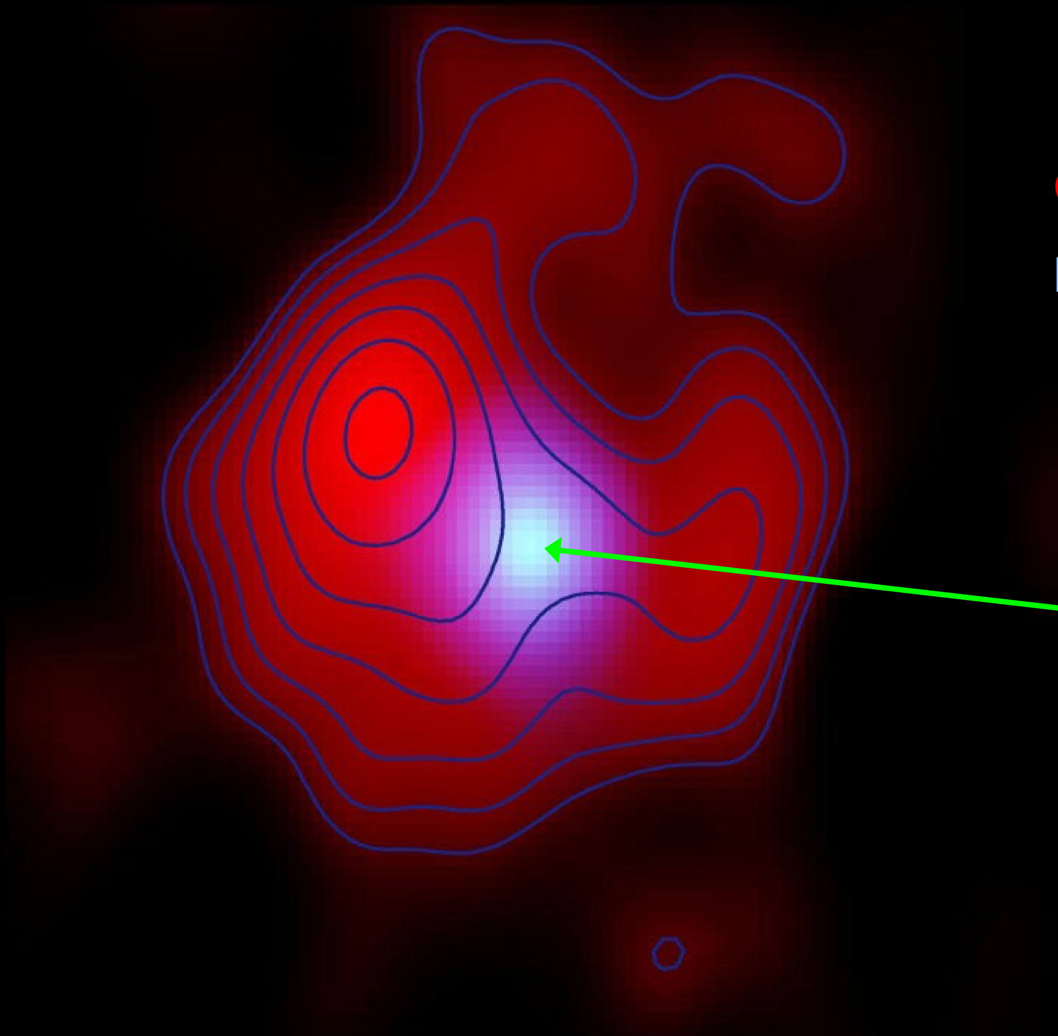
- Not visible in any earlier image

∀ ≤ 0.8 milli-arcsec (10^{17} cm)

- Too bright to be an HII region
- 200 × the current radio luminosity of the Crab Nebula at 15 GHz

Bietenholz, Bartel & Rupen 2004

Central Component in SN1986J



Multi-frequency VLBI Image:

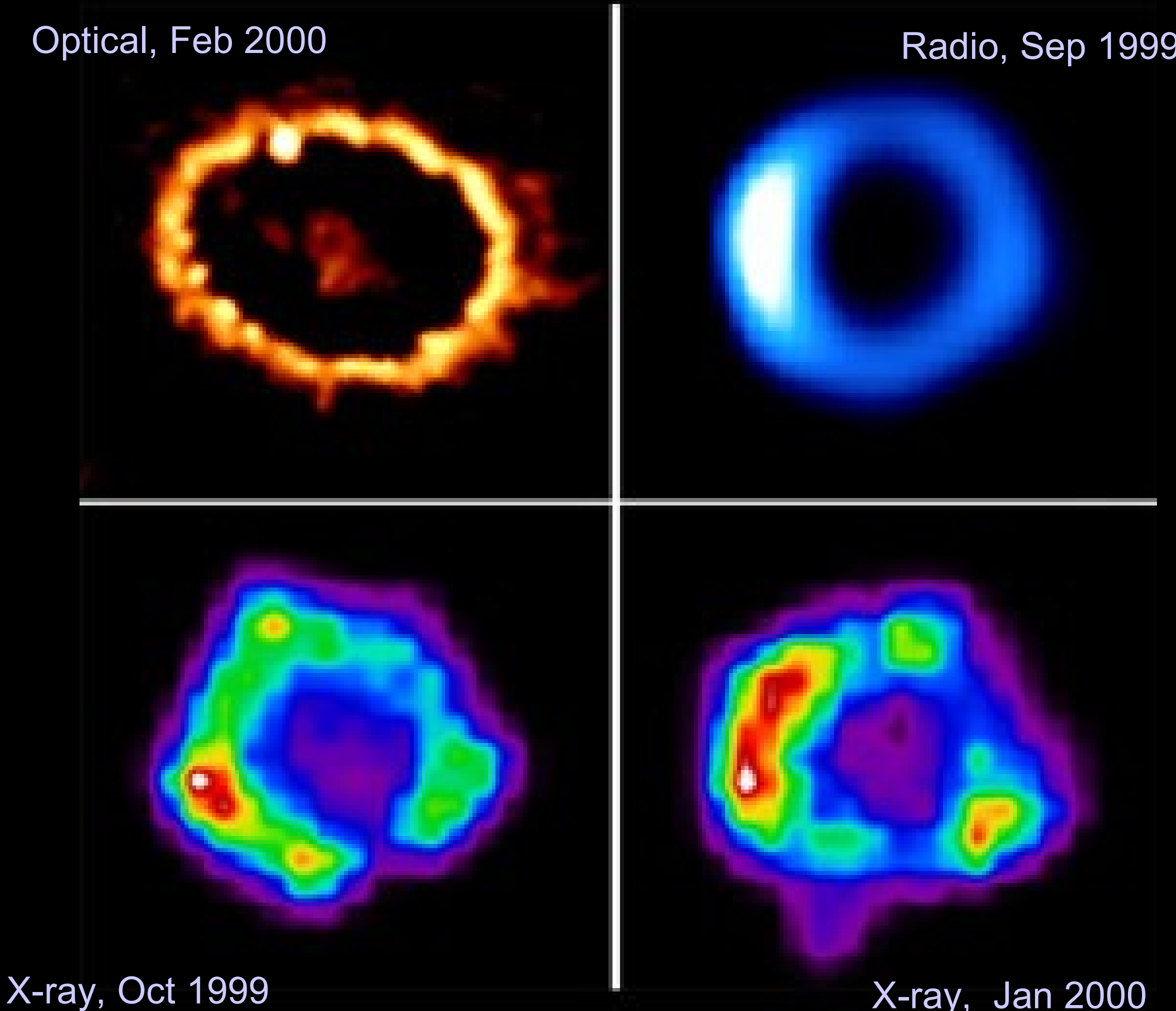
Contours, red: 5 GHz

Blue → white: 15 GHz

Youngest Neutron Star or Black Hole?

Bietenholz, Bartel & Rupen 2004

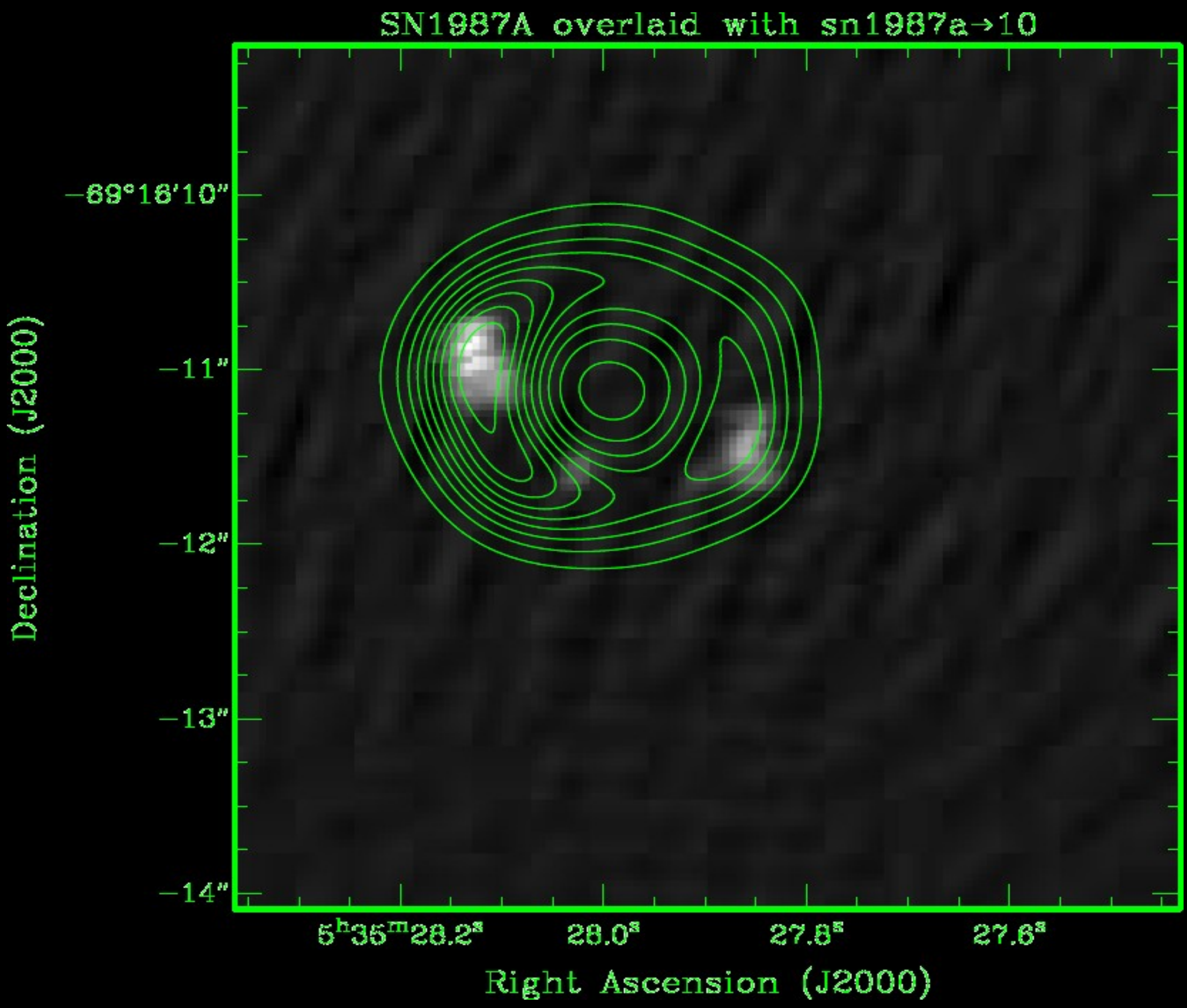
SN 1987A



Optical ring, enhancement of radio and X-ray brightness at same position angle

Optical: NASA/CfA/P. Challis et al; Radio: MIT/ATN/Gaensler & Manchester; X-ray: NASA/PSU/D. Burrows et al

SN 1987A VLBI (2nd Epoch)

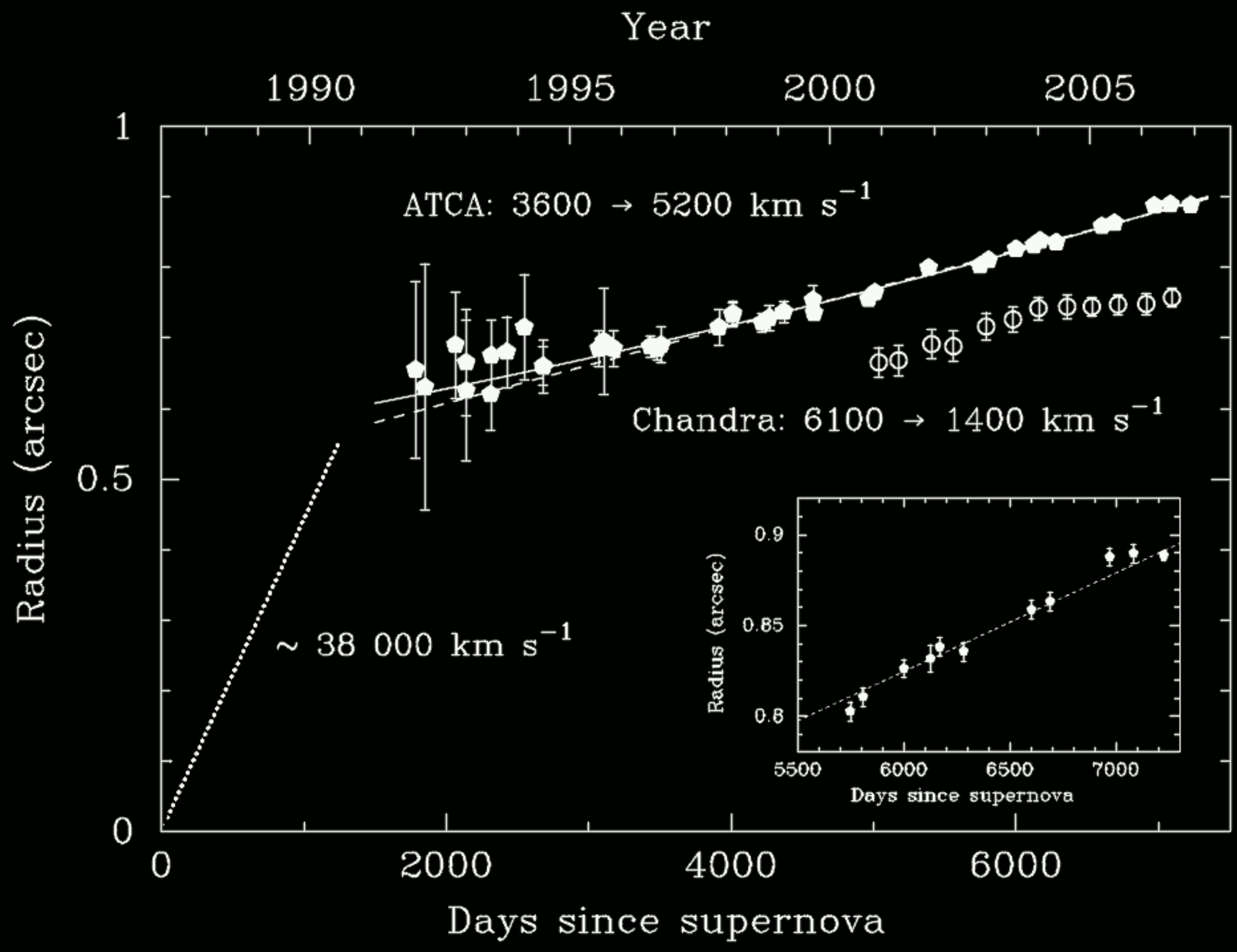


Greyscale: Australian Long Baseline Array, 1.3 GHz, Oct. 2007

Contours: ATCA 9 GHz

Tzioumis et al

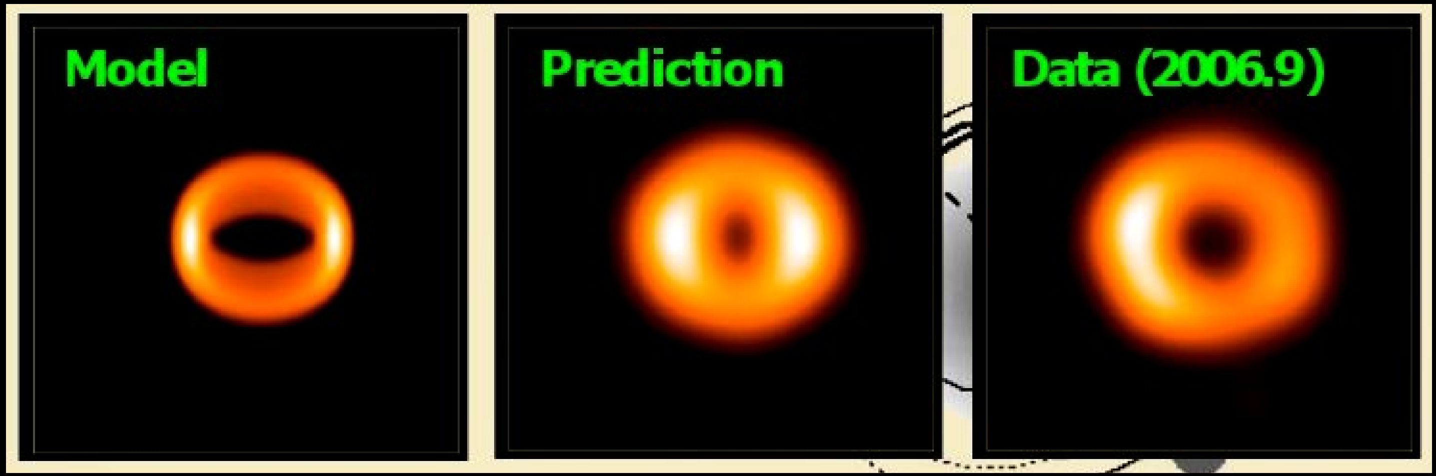
Expansion of SN1987A



Gaensler et al 2007

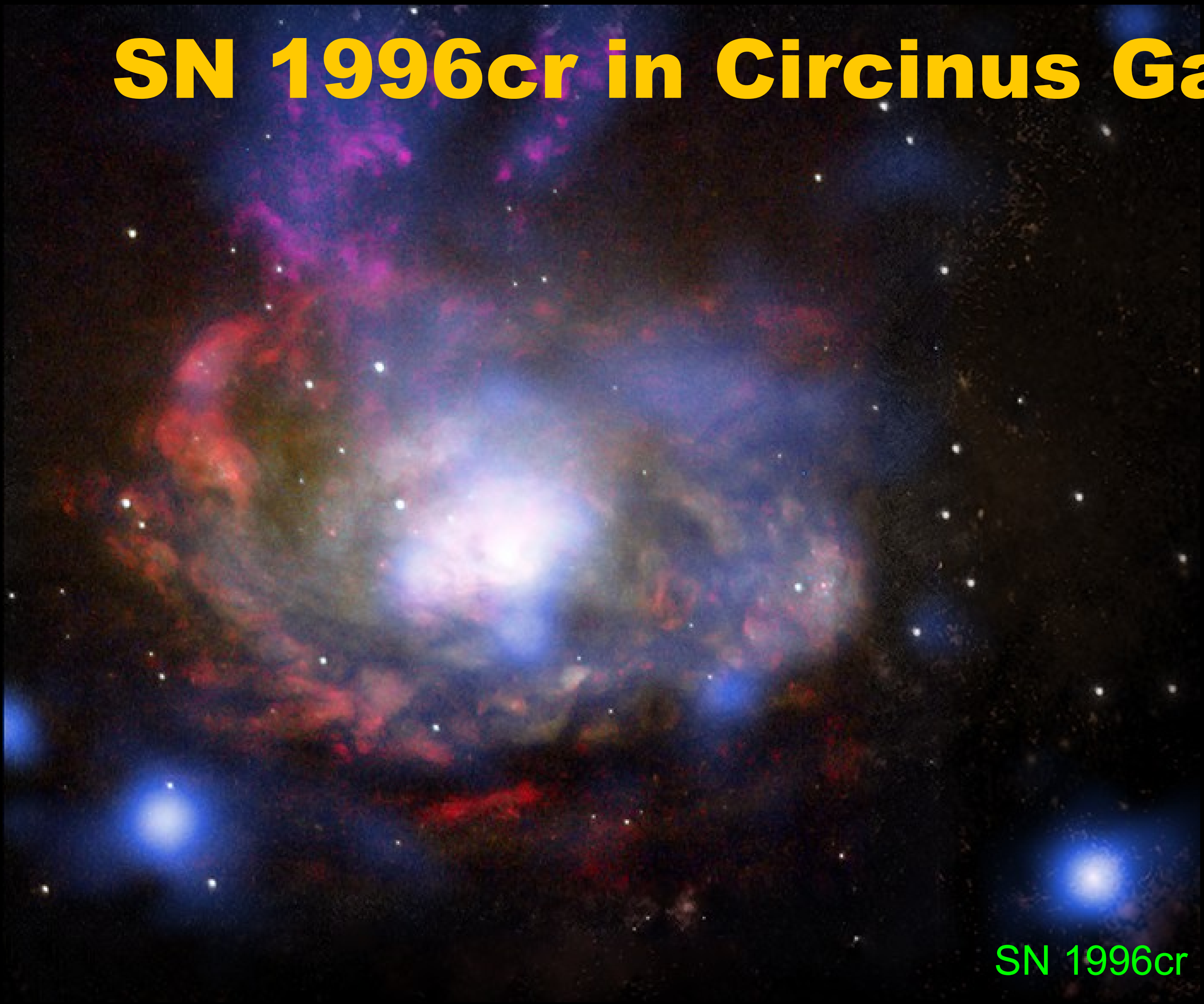
Supernova 1987A: Equatorial Ring?

- Two-lobed structure in radio, X-ray
- Lobes aligned with optical ring
- Brighter lobe is at larger radius
- True geometry: likely a tilted torus



Michael et al 2003

SN 1996cr in Circinus Galaxy

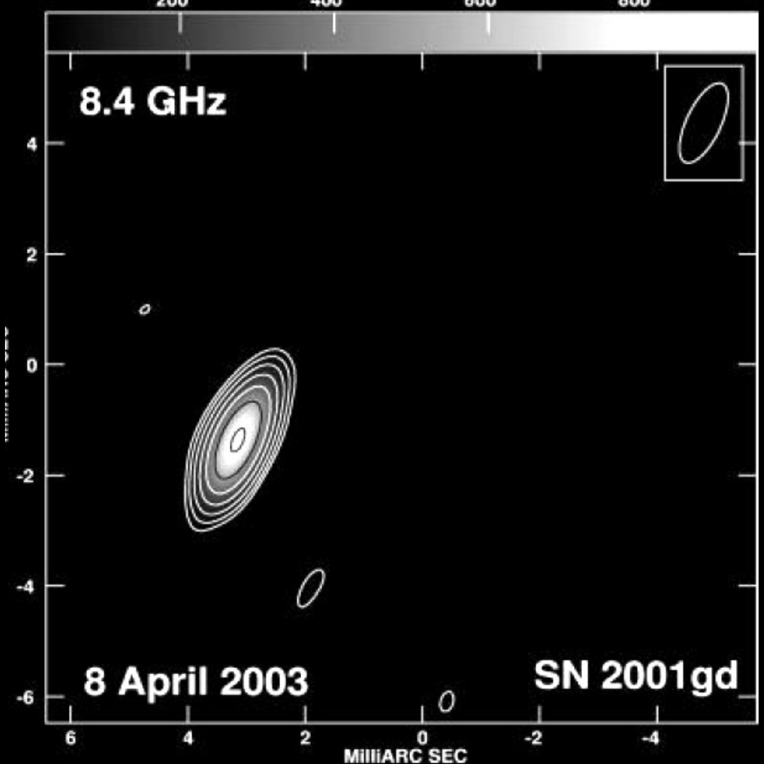


- VLBI (LBA): source radius ~5mas
- Dense CSM shell

Bauer et al 2008; Bartel et al in prep.

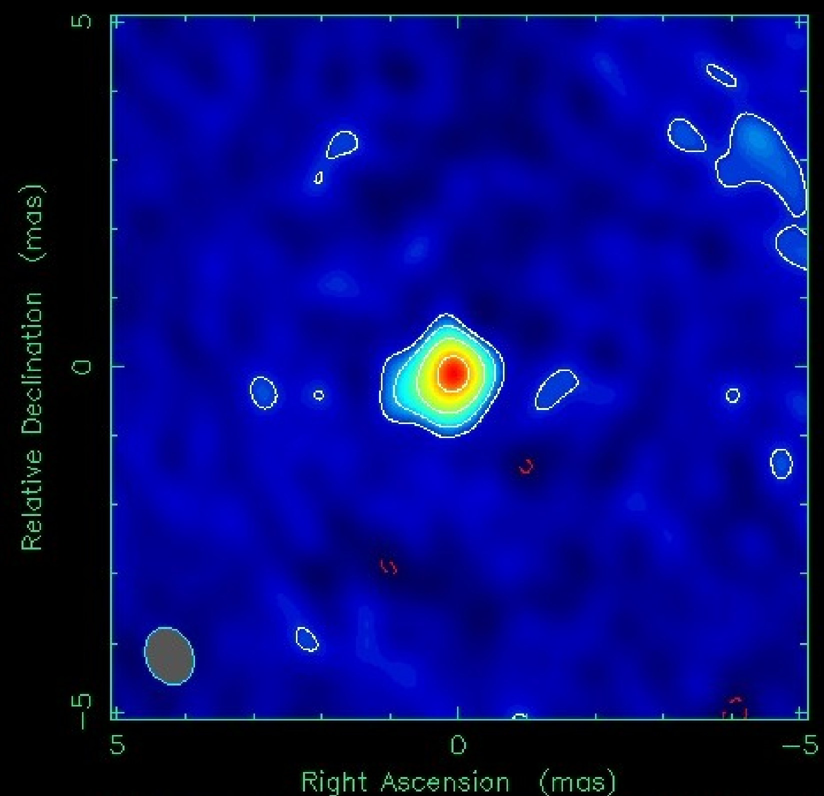
Other Radio Supernovae

SN 2001gd



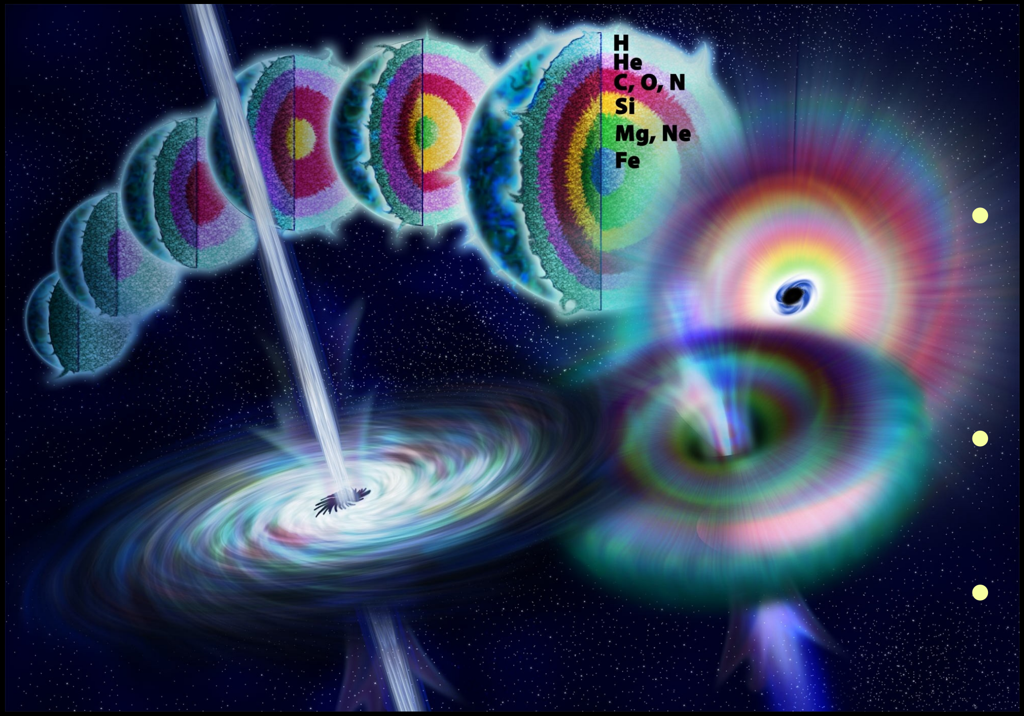
Type II
Θ = 0.37 ± 0.08
(Pérez-Torres et al)

SN 2004et



Type II
V_{exp} 15000 ± 2000 km/s
(Martí-Vidal et al)

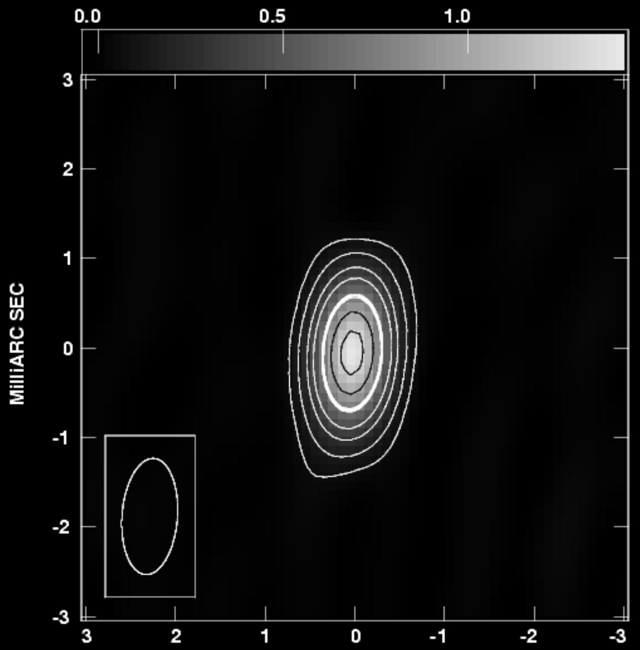
Relativistic Expansion: SNe and GRBs



- Long Duration GRB's associated with Type Ibc supernovae
- Collapse of massive star into a black hole powers highly relativistic jet
- GRB's are jets oriented near the line of sight
- The jets *not* near the line of sight may be visible in radio

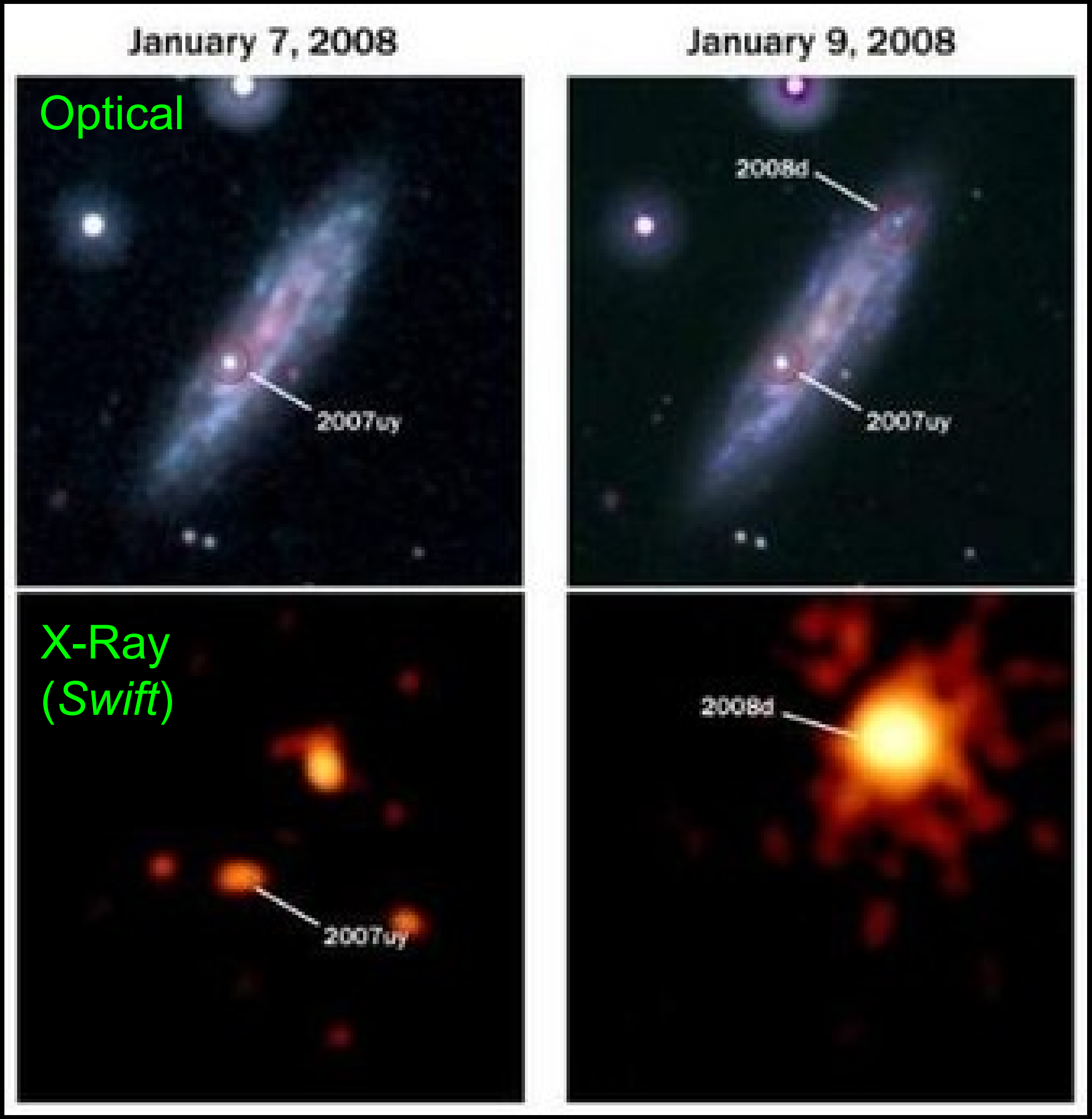
SN 2001em

Nov 2004. 8.4 GHz



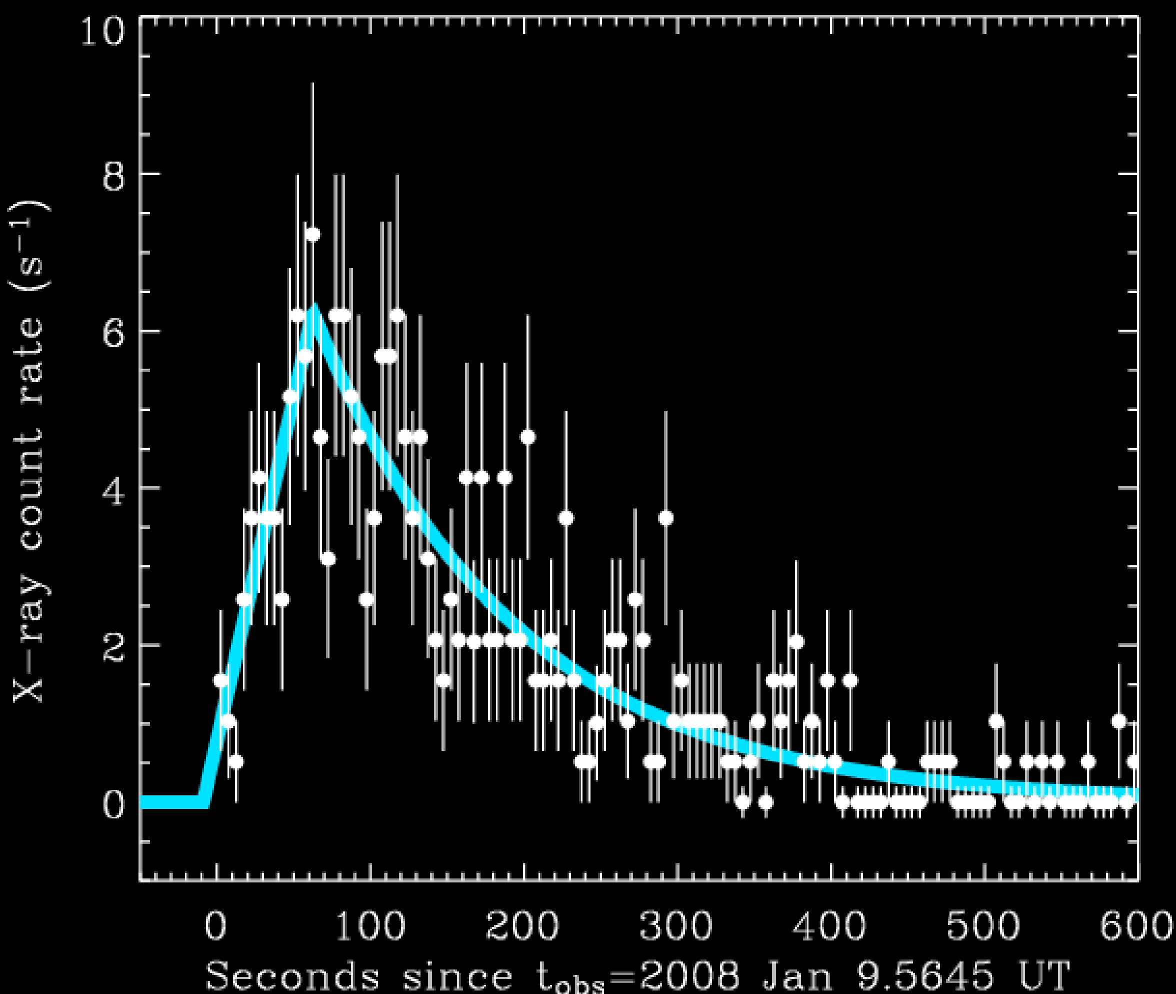
- SN2001em was discovered on 15 Sep. 2001 in UGC11794 (Papenkova 2001).
- 80 Mpc.
- Type Ib/c, most likely Ic.
- Exceptional radio and X-ray luminosities
- Late turn on of radio and X-ray emission
- Possible off-axis GRB event (Granot & Ramirez-Ruiz 2004)
- Several different VLBI experiments: non-relativistic upper limits on expansion velocity (5800 ± 10000 km/s) and on the proper motion (corresponding to 33000 ± 34000 km/s)
- First faint target detected (4.5 σ) with EVN e-VLBI (Paragi et al 2005).
- See poster #28 by Schinzel

SN 2008D: Caught in the Act!



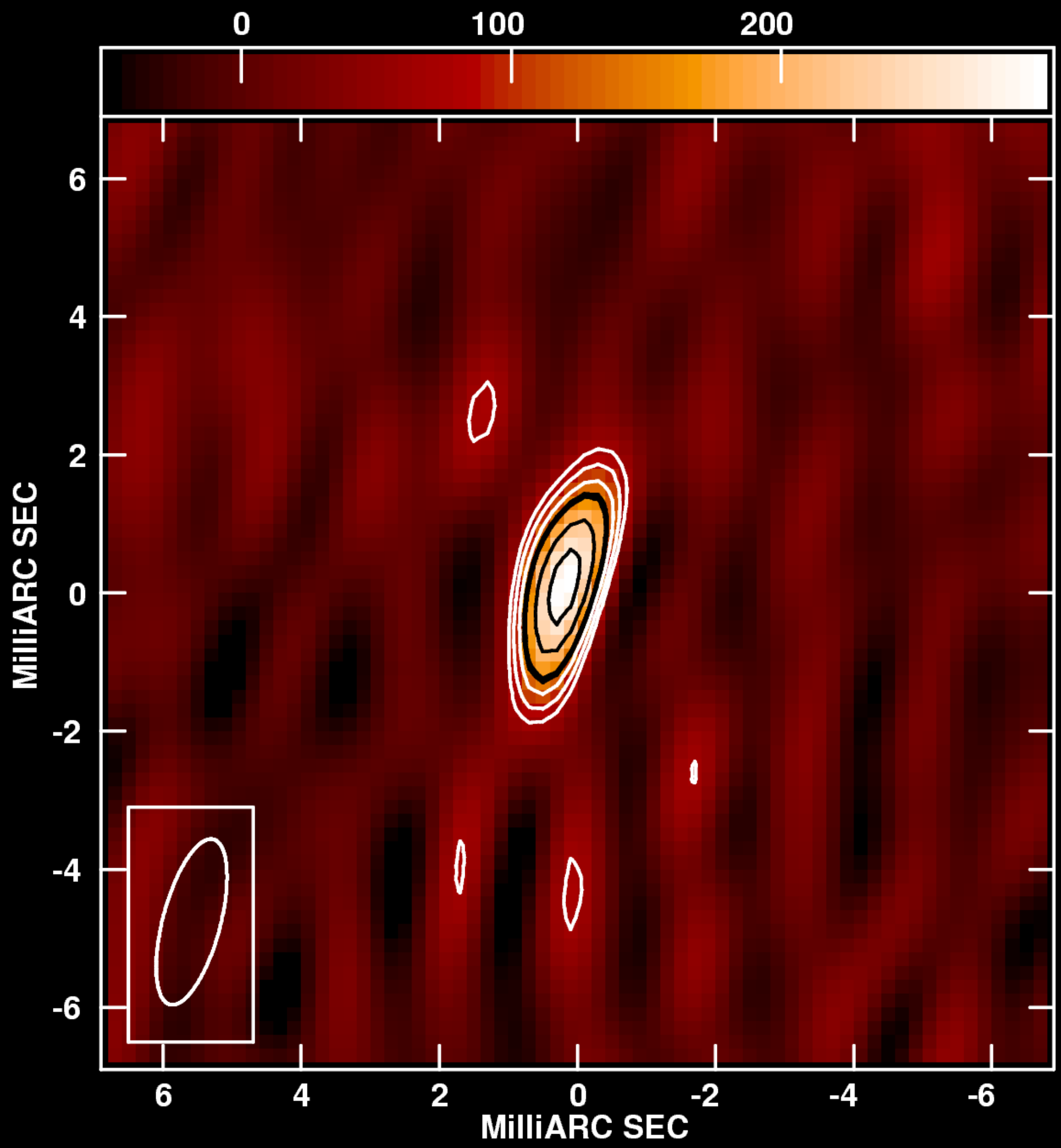
- Normally, super-novae detected in optical
- Light comes chiefly from decay of ^{56}Ni - doesn't start till a few days after shock breakout
- Shock breakout has been thought to produce a brief, bright flash in X-rays
- Flash from SN 2008D was seen during observations of SN 2007uy (NGC 2770; 27 Mpc)
- Duration ~5 minutes!
- Subsequent optical spectra confirmed a supernova (Type I bc)

SN 2008D: Caught in the Act!



- Normally, super-novae detected in optical
- Light comes chiefly from decay of ^{56}Ni - doesn't start till a few days after shock breakout
- Shock breakout has been thought to produce a brief, bright flash in X-rays
- Flash from SN 2008D was seen during observations of SN 2007uy (NGC 2770; 27 Mpc)
- Duration ~5 minutes!
- Subsequent optical spectra confirmed a supernova (Type I bc)

SN 2008D VLBI

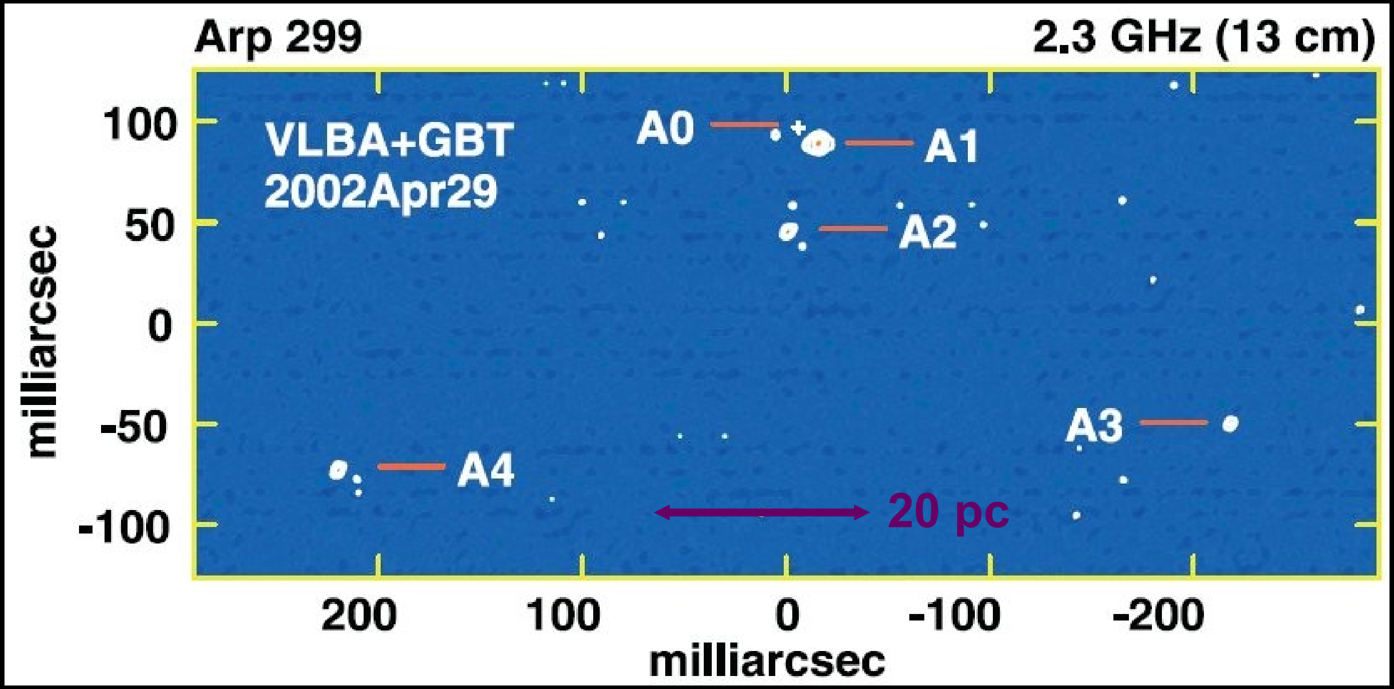


- Epoch May 2008
- VLBA + Ef + Y27
- 5 GHz
- Total flux density: ~200 μJy
- Preliminary result on angular size: 3σ limits on apparent expansion speed: <1.0 *c* for isotropic expansion

Bietenholz et al, in prep

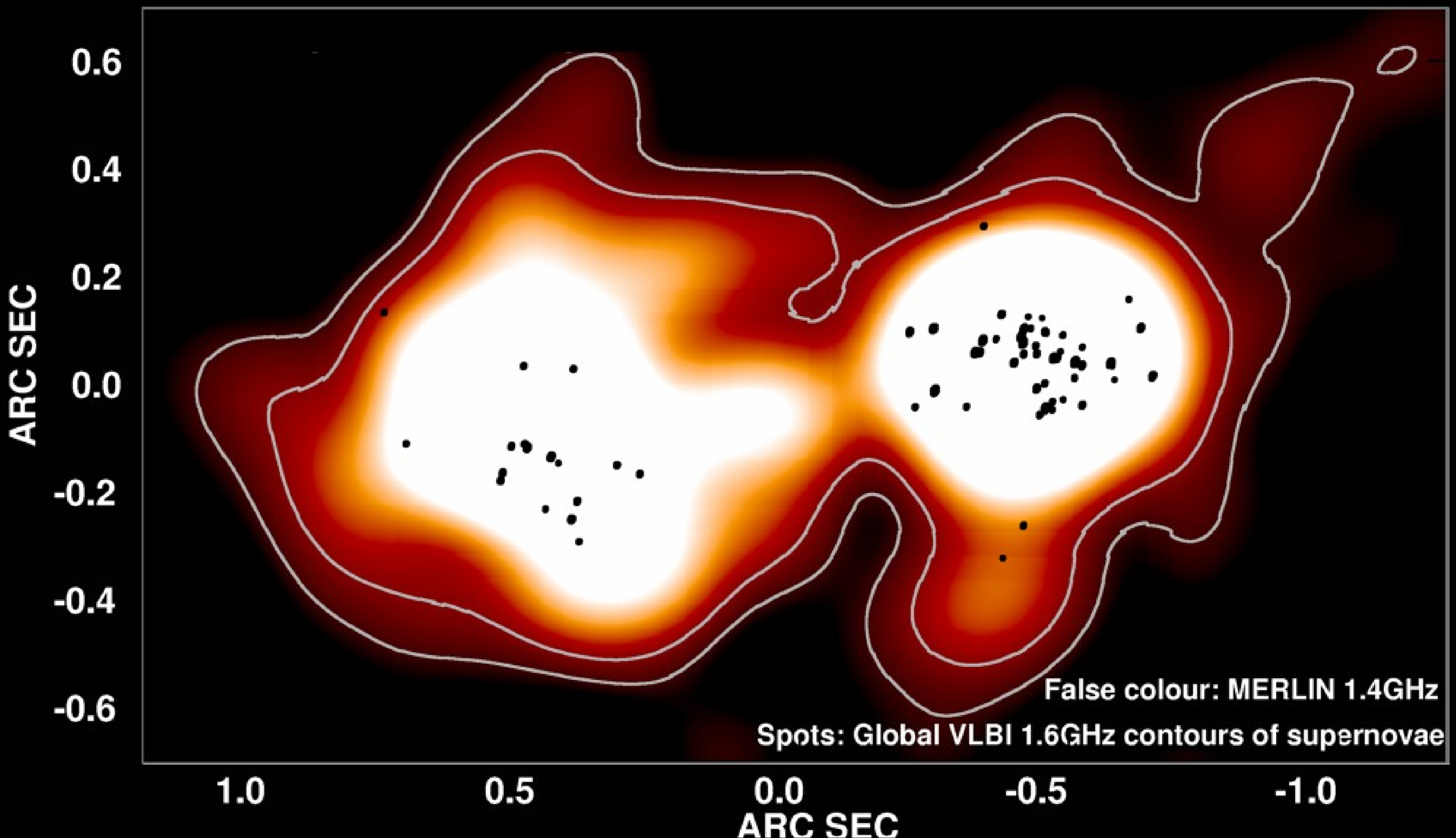
ULIRGS: Supernova Factories

- Arp 220 (Parra, Lonsdale, Conway) SN rate 4±2/yr
  - different IMF for ULIRGs?
- Arp 229 (Neff, Ulvestad & Teng) – LIRG; original starburst; 41 Mpc; several optical supernovae;
  - VLBI sources probably SNe/SNR: 100 to 1000×Cas A
  - Supernova rate of 0.1 – 1/yr

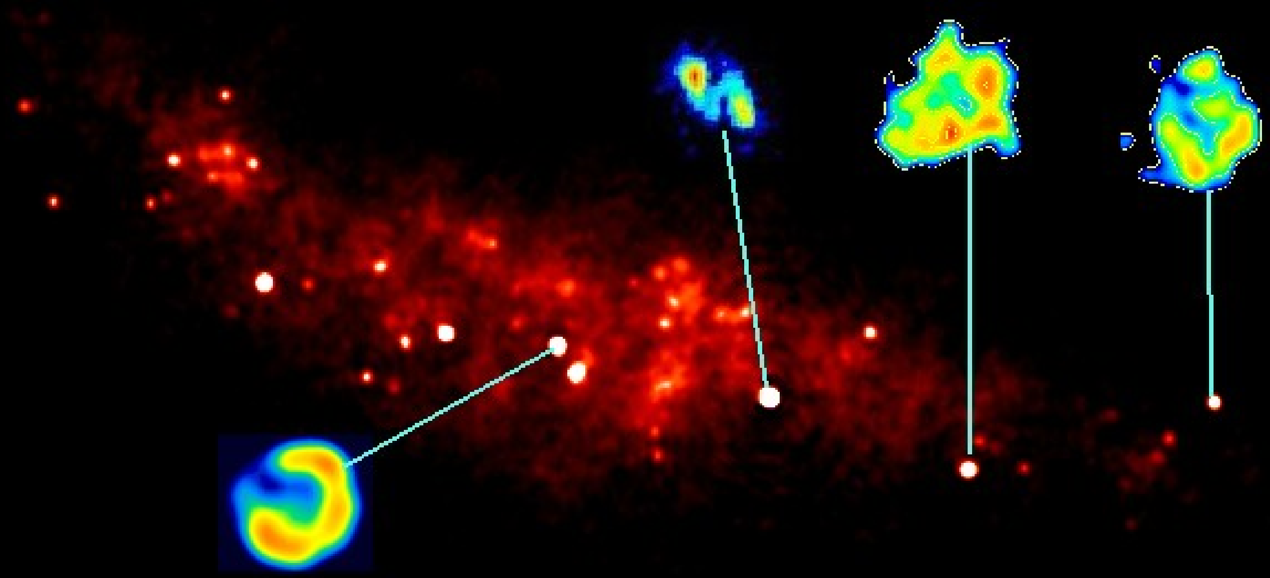


See also poster by Romero-Cañizales: EVN-Merlin observations of IRAS 23365+3604

Supernovae in Arp 220

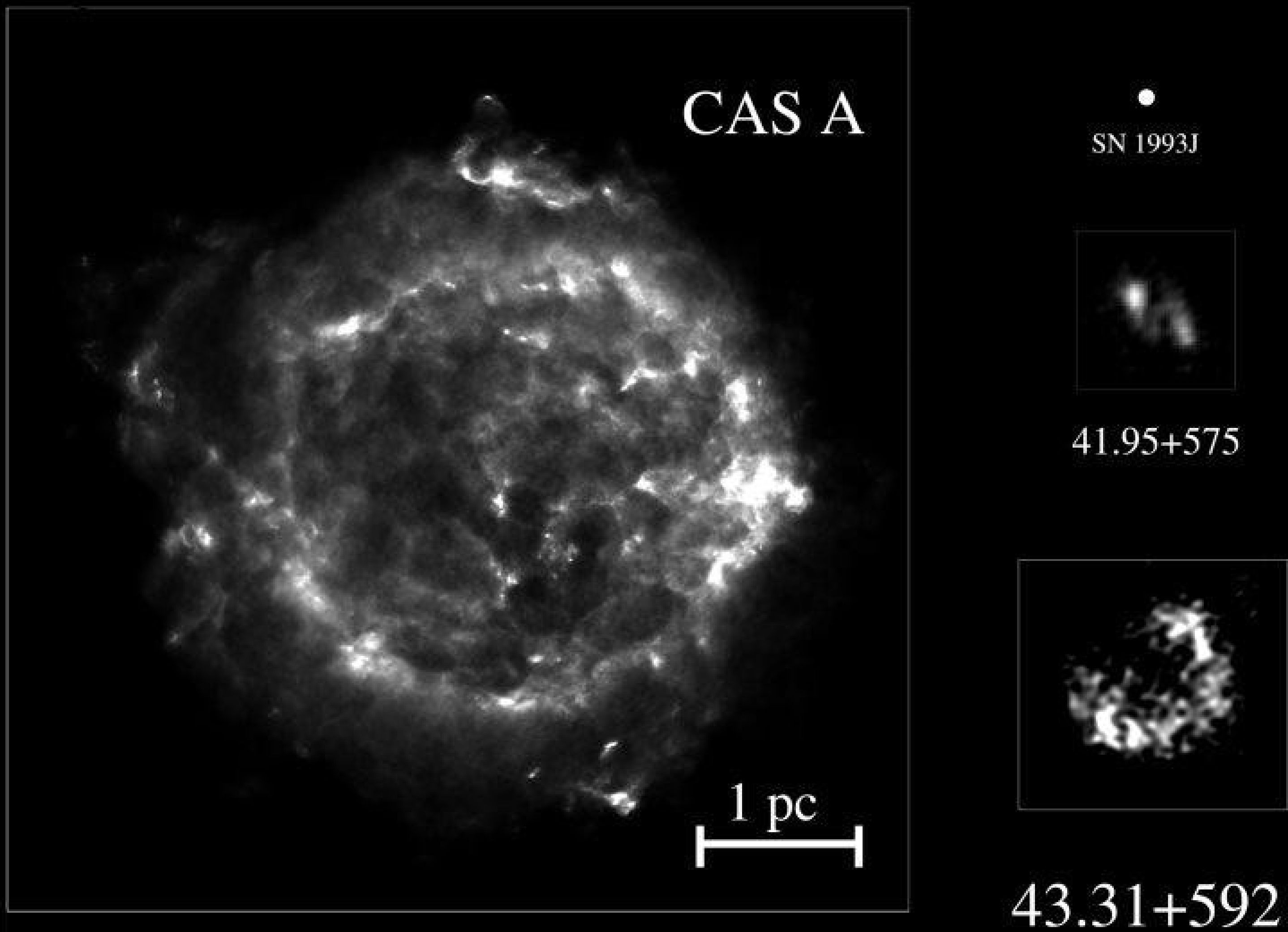


Radio Supernovae in M82



- Over 50 compact sources discovered in M82, most are supernovae/supernova remnants
- Rob Beswick will tell you more!

Comparison of RSNe & SNRs



McDonald et al., 2001

The Future of Supernova VLBI

- More sensitivity – follow supernova for longer
- Resolve older, more distant supernovae: Cas A is 1 μJy and 6 mas at 170 Mpc
- Fill in the gap between supernovae and supernova remnants
- Census of supernova remnants of nearby galaxies
- Supernova rates → star formation rates
- Type Ia?