A. Alberdi

Radio Supernovae: A Window into the Heart of Starburst Galaxies

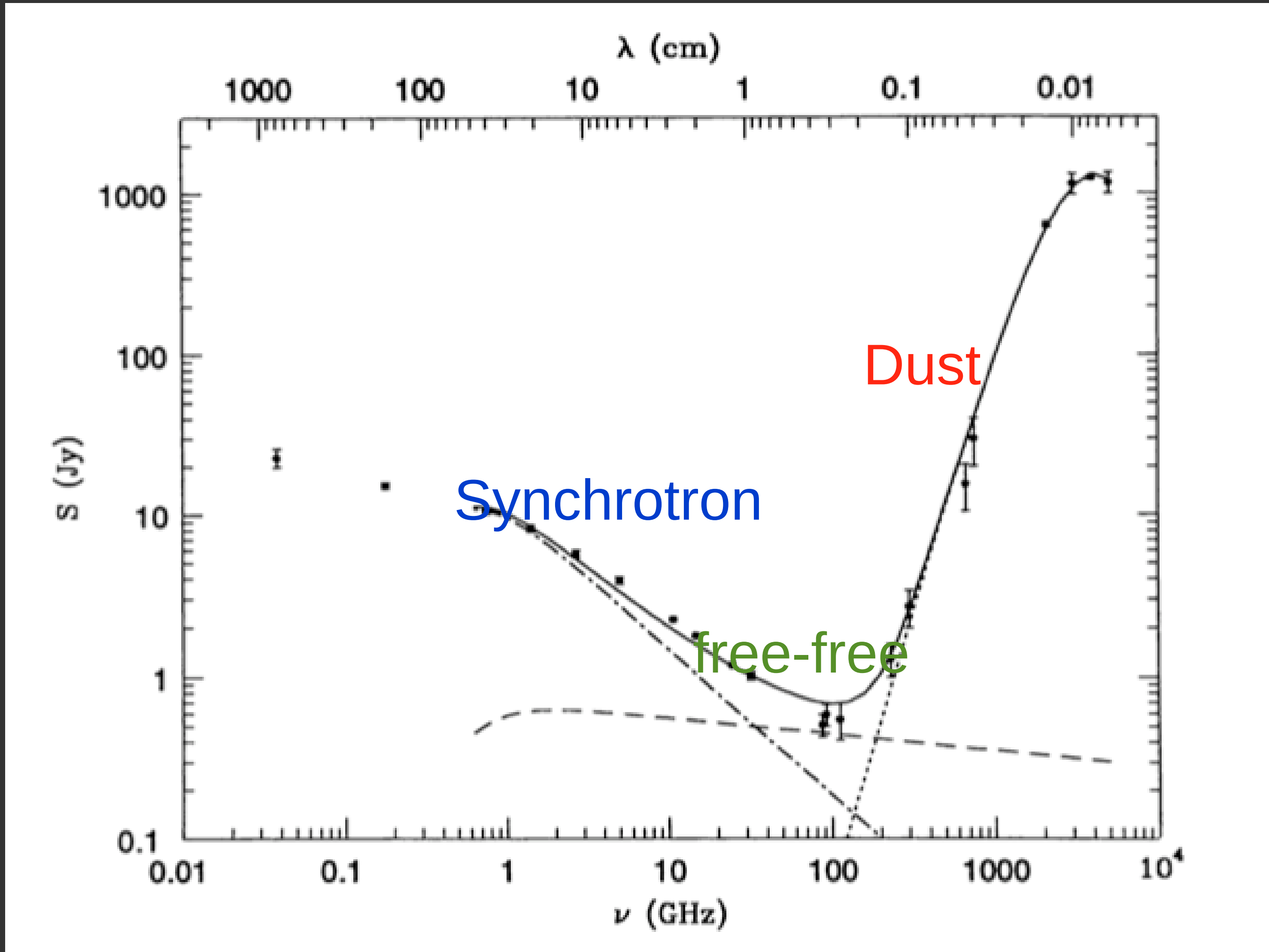
High-resolution radio observations of the nuclear regions of Luminous and Ultraluminous Infrared Galaxies (ULIRGs) have shown that their radio structure consists of a compact high surface-brightness central radio source inmersed in a diffuse low brightness circumnuclear halo. While the central components could be associated with AGNs or compact star-forming regions, where radio supernovae are exploding, it is well known that the circumnuclear regions host bursts of star-formation. Studies of radio supernovae can provide essential information about stellar evolution and CSM/ISM properties in regions hidden by dust at optical and IR wavelengths. High-resolution radio observations of LIRGs can allow us to determine the core-collapse supernova rate in them as well as their star-formation rate.

Radio Supernovae: A Window into the Heart of Starburst Galaxies

Antxon Alberdi (IAA, CSIC)

(+ M.A. Pérez-Torres, C. Romero-Cañizales, L. Colina, J.M. Torrelles, A. Polatidis, S.T. Garrington …)

Starbursts-2010
21 julio 2010



The observed radio/FIR spectrum of M82: steep, the flat, and the inverted

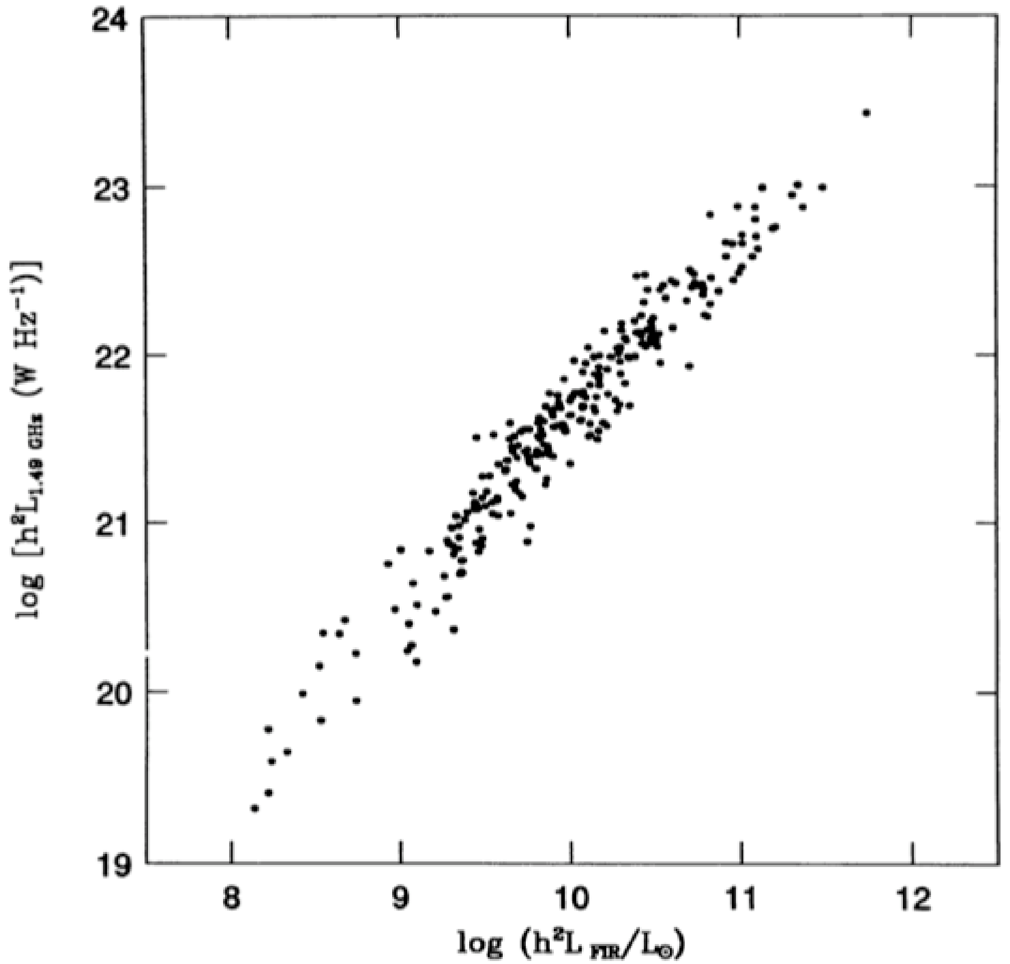
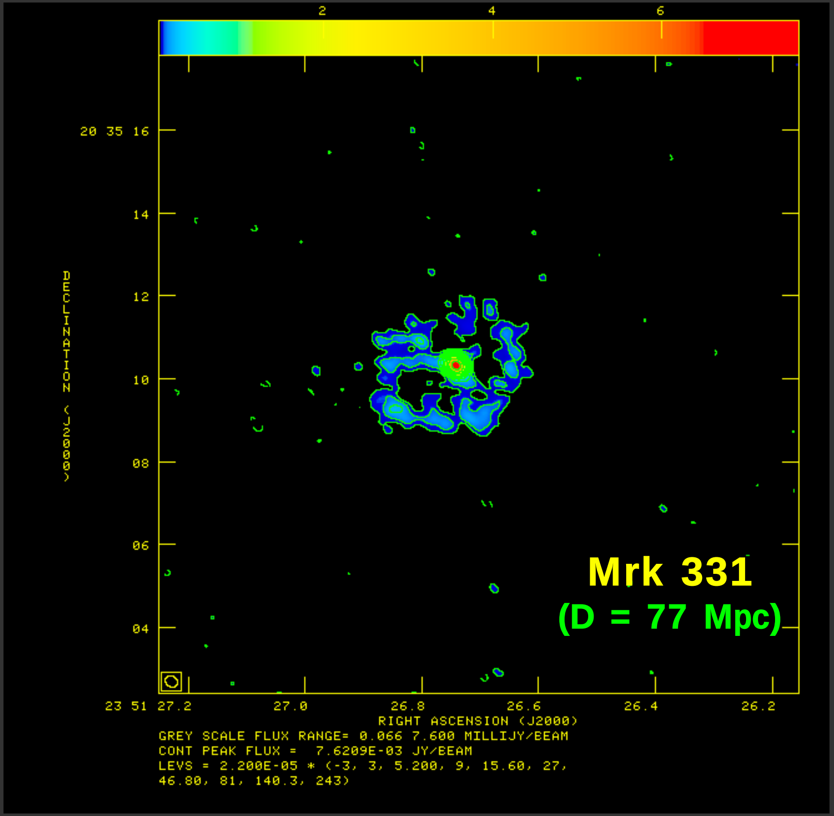


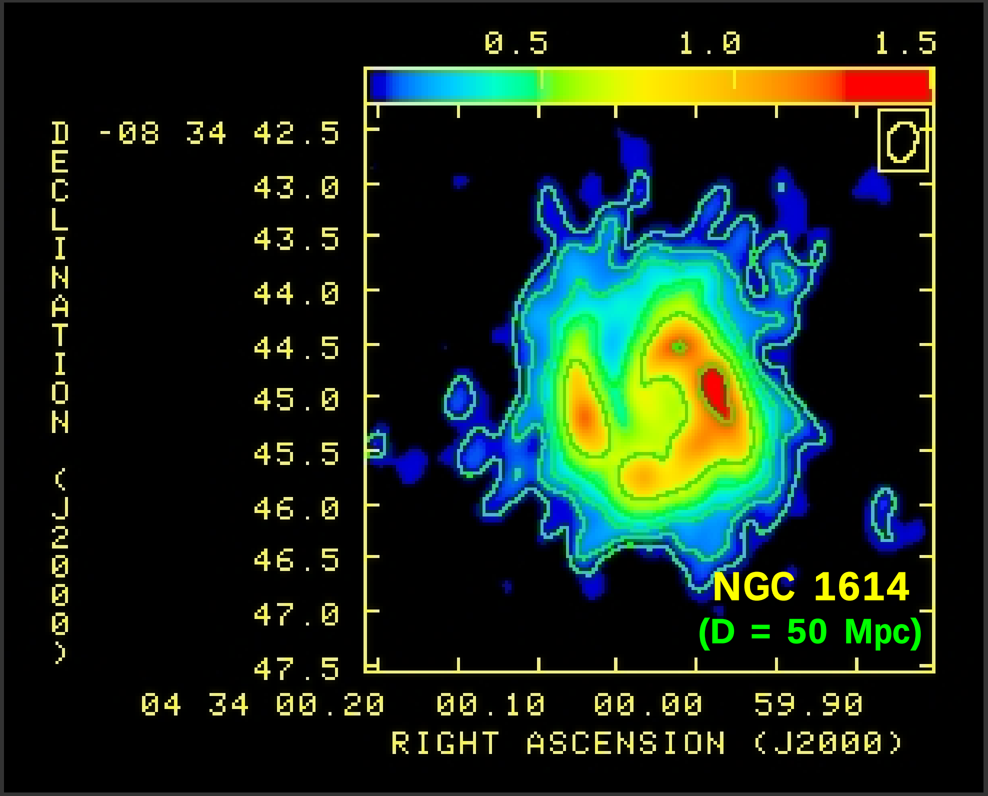
Figure 8 The FIR/radio correlation for strong sources selected at $\lambda = 60\ \mu m$ and not containing known monsters (e.g. Seyfert nuclei) or optically thick to free-free absorption at $\nu = 1.49$ GHz. The measurement errors are smaller than the intrinsic scatter for this sample. Abscissa: log FIR luminosity in solar units. Ordinate: log 1.49 GHz luminosity (W Hz^{-1}).

FIR/radio correlation

Radio Observations of Starburst Galaxies

- Compact (≲150 pc) high surface brightness ($T_b \geq 10^3$ K) central radio source → generated by a point-like source (AGN) or by the combined effect of SNe and RSNe
- Low surface brightness circumnuclear halo → ongoing burst of star formation

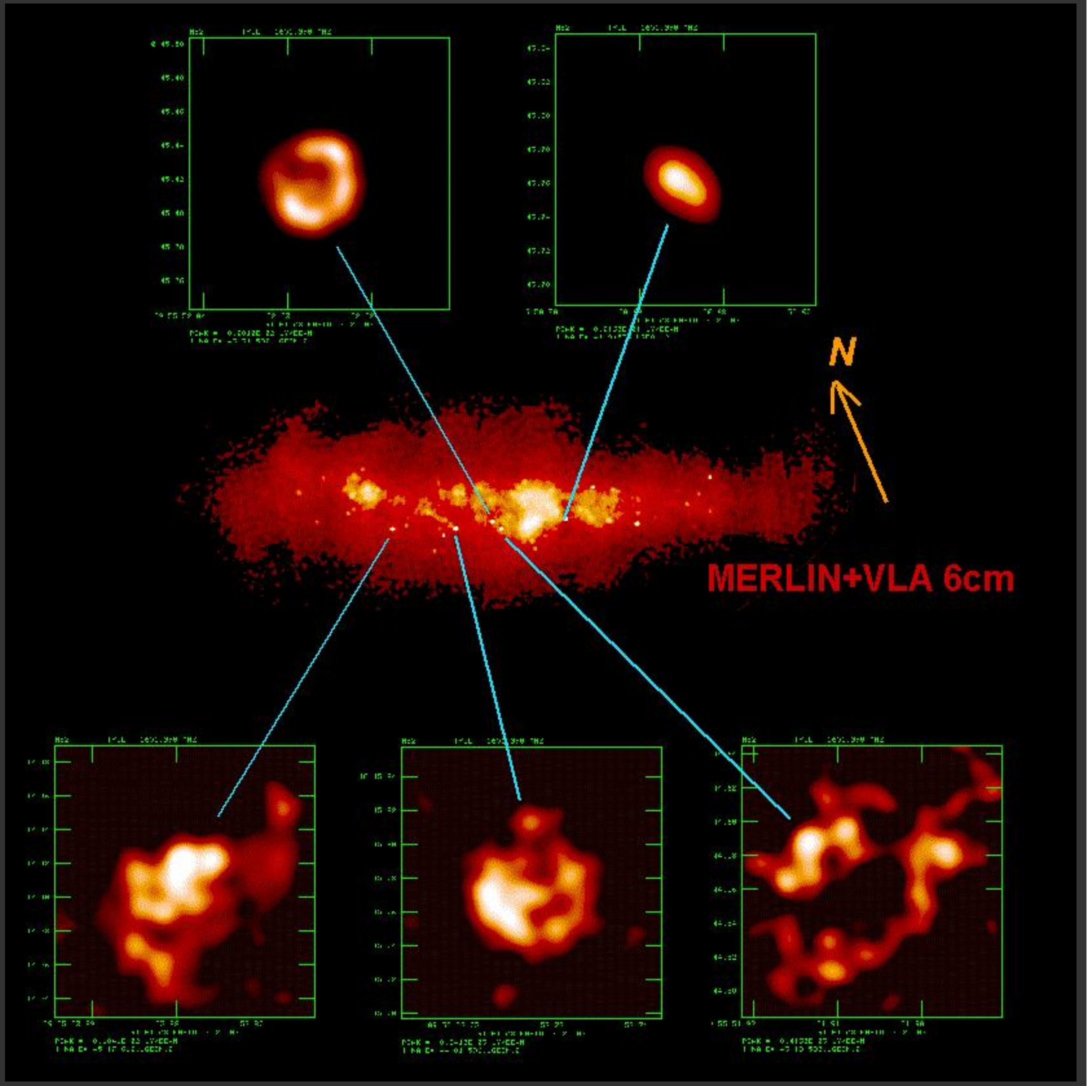




Radio emission and RSNe in LIRGs

- Stars more massive than 8 M_{sun} result in CCSNe (Type Ibc and II)
- Combining observed CCSNe rate and a reasonable IMF (Salpeter, Miller-Scalo,...) yields direct measure of current SFR
- Optical searches only able to discover SNe not severely affected by dust extinction
- Radio emission is free from extinction effects, so searches in radio for CCSNe are more promising to yield a true estimate of the CCSN rate

M82 at cm wavelengths

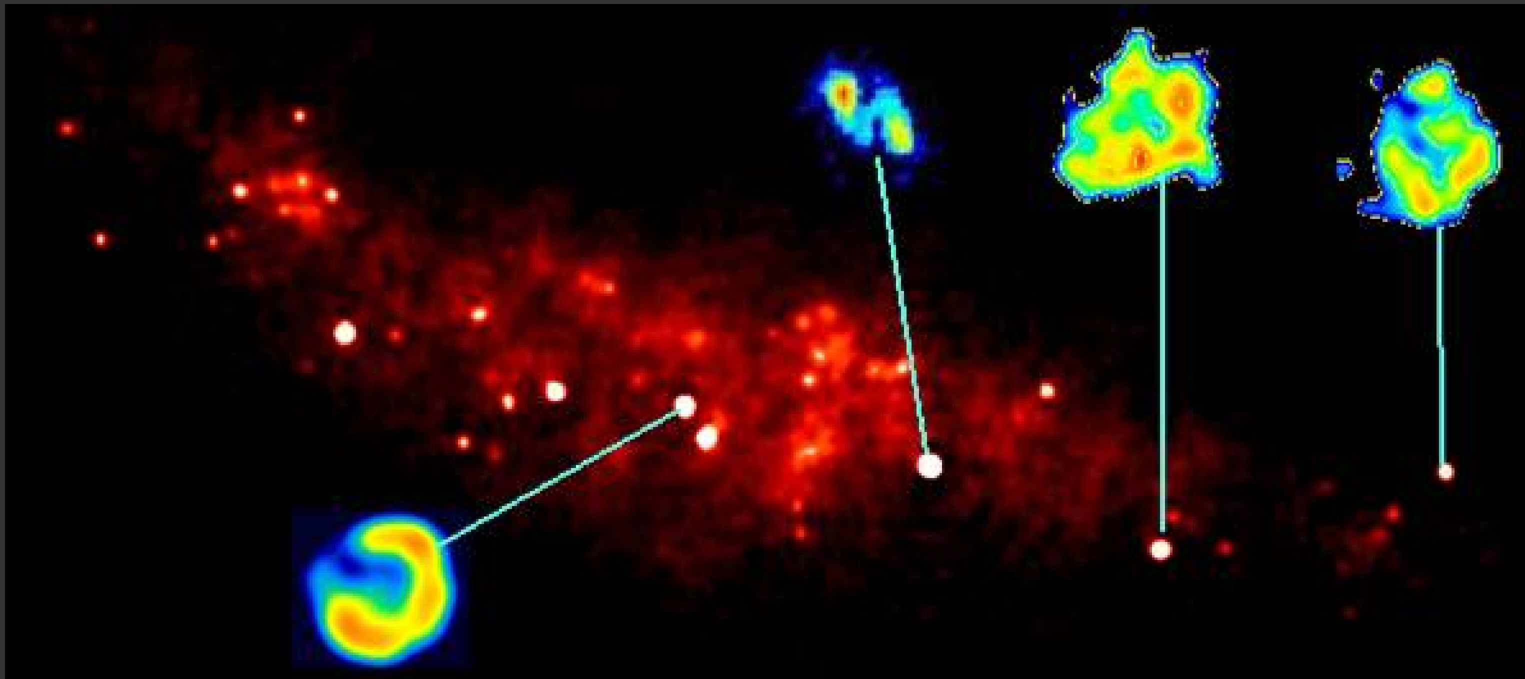


Supernovae and Supernova Remnants in M82

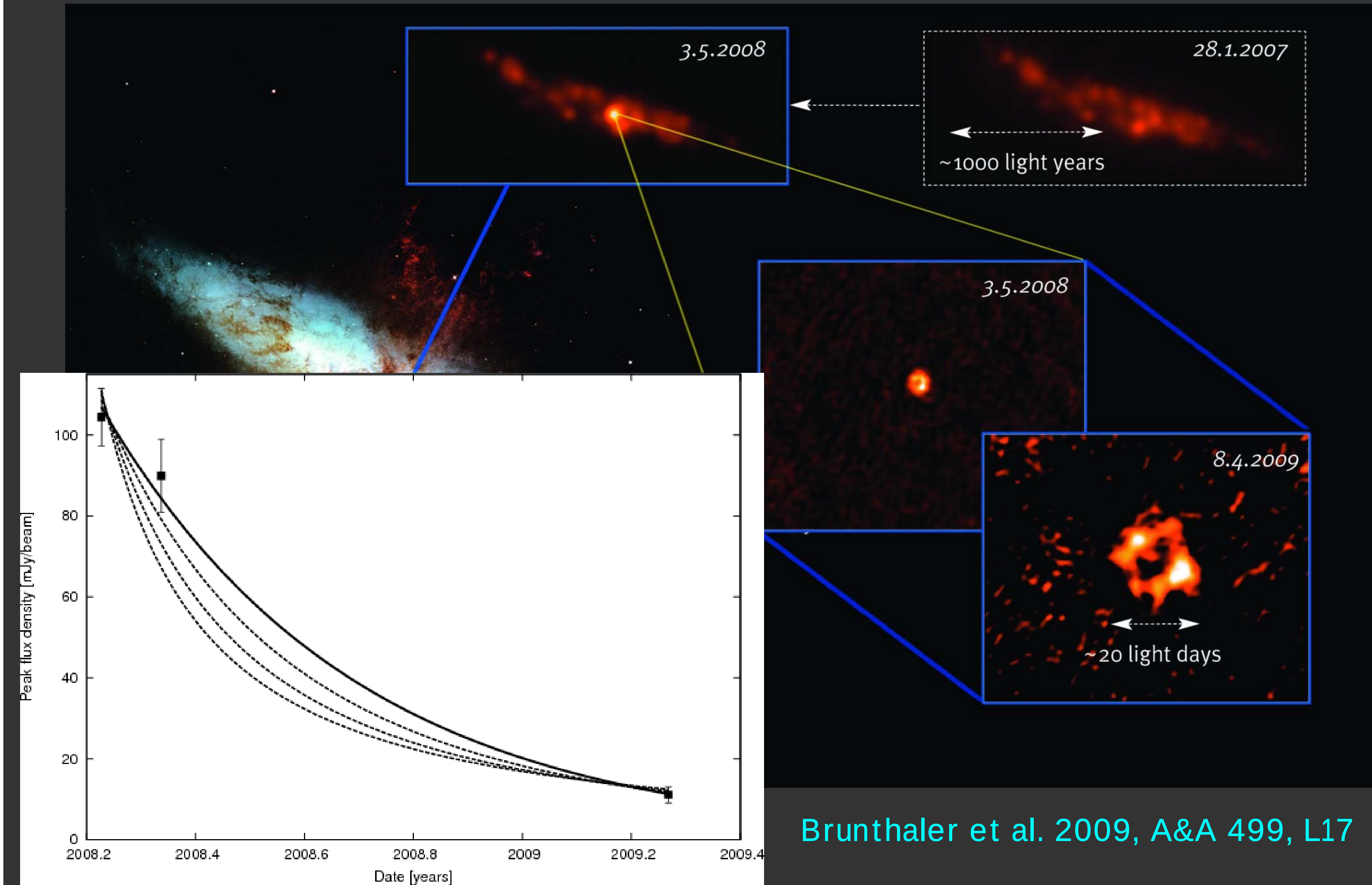
- L_{FIR} ~ 5.9 x 10^{10} L_{sun} ; D = 3.2 Mpc; If CCSN rate ~ 2.7E-12 * L_fir (Mattila & Meikle 2001), then SN rate = 0.16 SN/yr

- > 50 compact sources discovered in M82, most of them SNRs (16 HII regions). All of them are resolved with MERLIN+VLBI (80 mas = 1.2 pc)

- The size of the remnant range from 5pc to 0.3pc



Supernovae and Supernova Remnants in M82



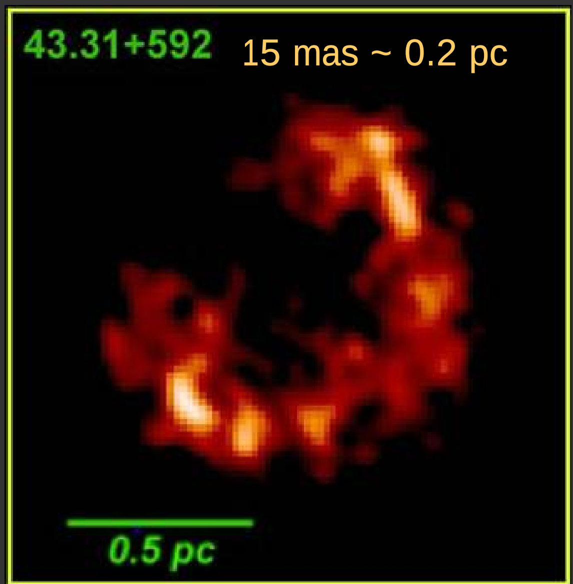
Brunthaler et al. 2009, A&A 499, L17

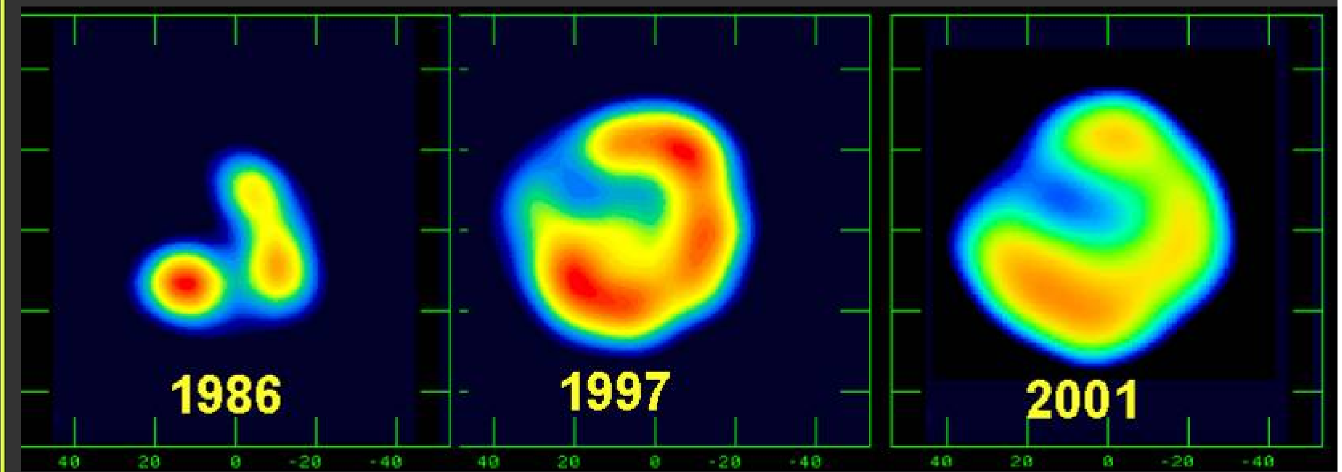
Supernovae and Supernova Remnants in M82:
SNR expansion

→The relatively compact remnants in M82 are found to be expanding over a wide range of velocities, unrelated to their size

- Lower expansion velocities ~2000 km/s, in dense clouds
- Higher expansion velocities ~10000 km/s, outside or in front of dense H1/CO/OH clouds

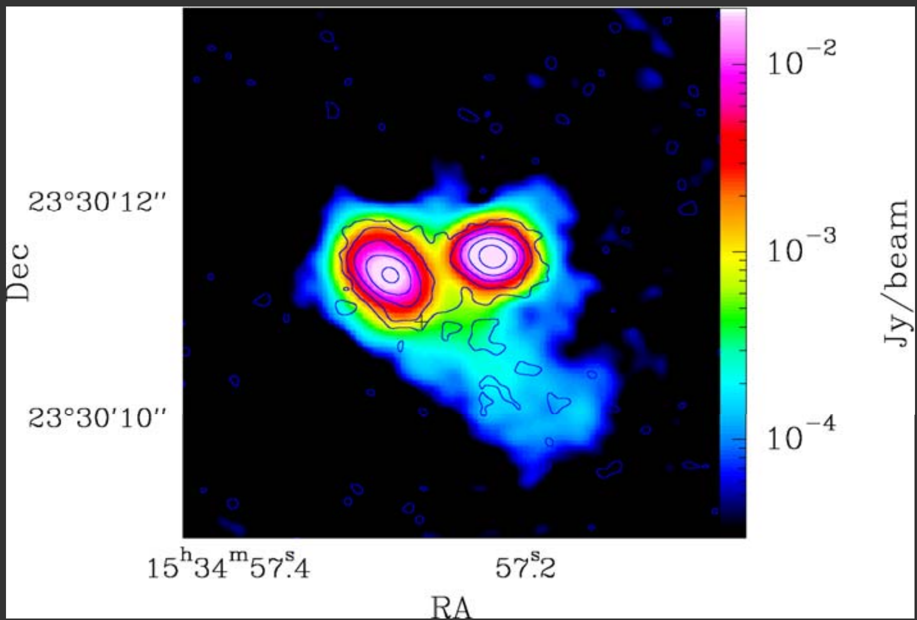
→ 43.31+592 expansion:
- Velocity expansion of 9850 km/s
- In free expansion, possibly exploded in 1966; May be in low pressure regions ?

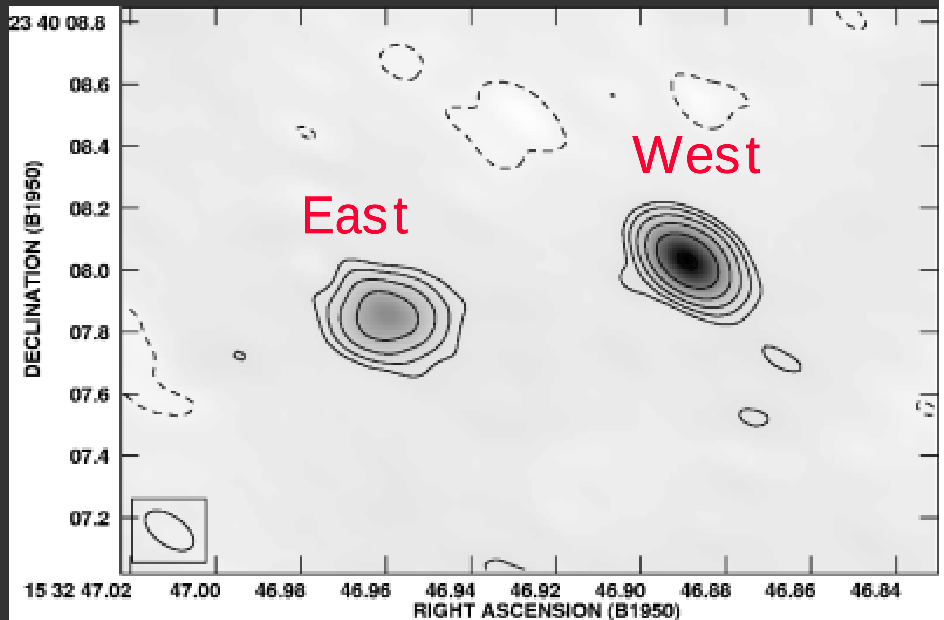




Radio Supernovae in Arp 220

- $L_{IR} \sim 1.3 \times 10^{12} L_{sun}$; D = 77 Mpc
- A pair of Radio Nuclei separated by 370 pc: the Western nucleus is brigther than the eastern one
- Star Formation Rate: 50-100M_{sun}/yr → Luminous SN Rate: 1.75-3.5 yr^{-1}
- Arp 220 is ~ 50 times more luminous than M82 and confined to a smaller volume

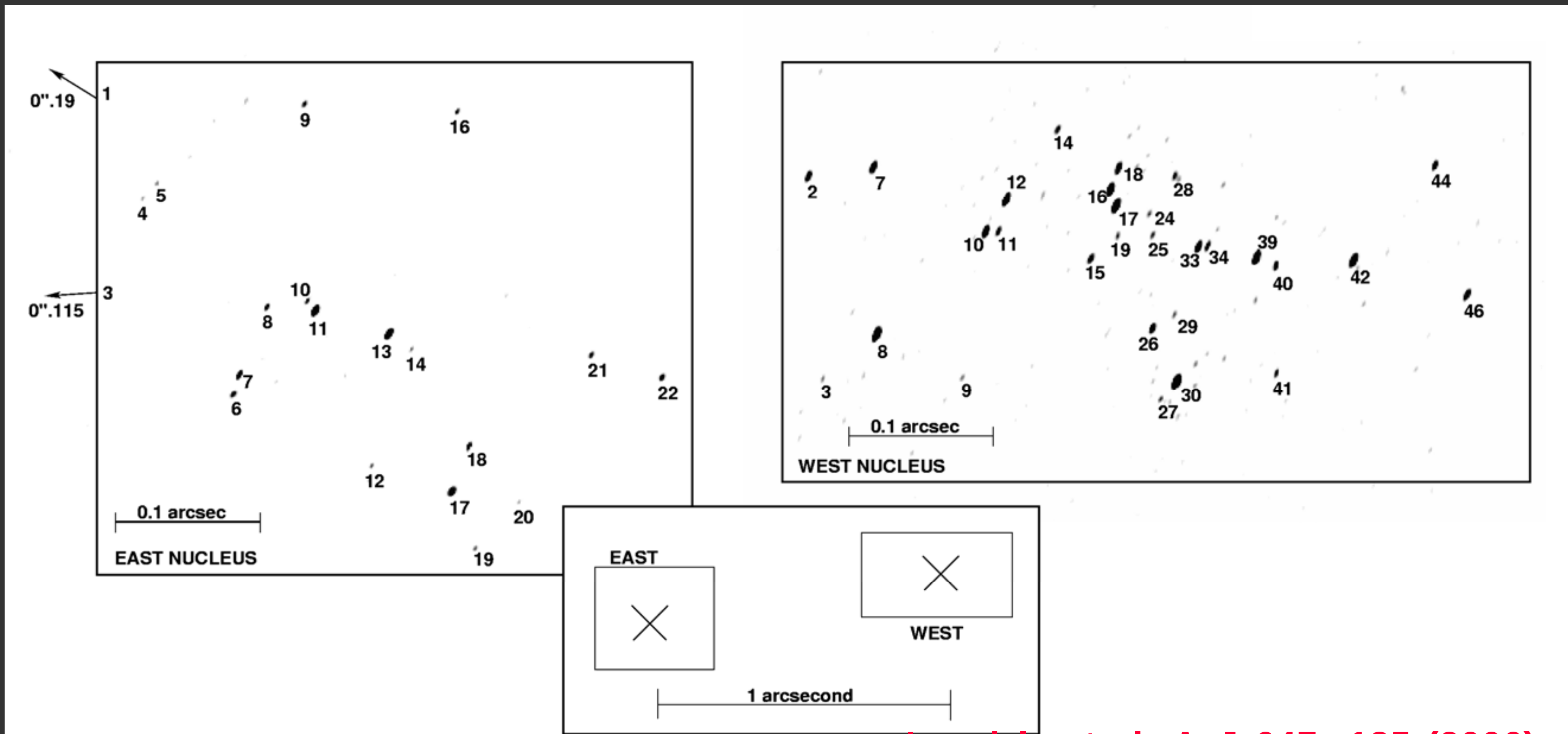




Rovilos et al. MNRAS 342, 373 (2003)

Radio Supernovae in Arp 220

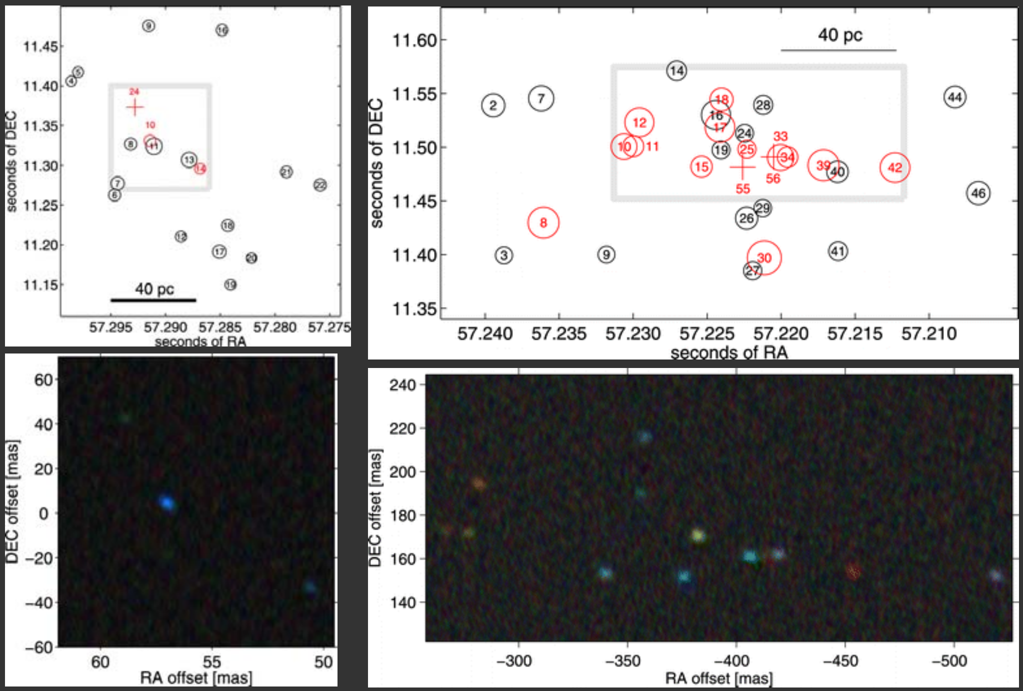
- 20 RSNe in the E-Nucleus; 29 RSNe in the W-Nucleus
- Four new RSNe appeared in one year → SN Rate: 4±2 yr^{-1}
- W-Nucleus more luminous: differential ff-absorption and expansion losses could be the reason
- The light curves are surprisingly stable over a period of more than five years → interaction with a dense ISM

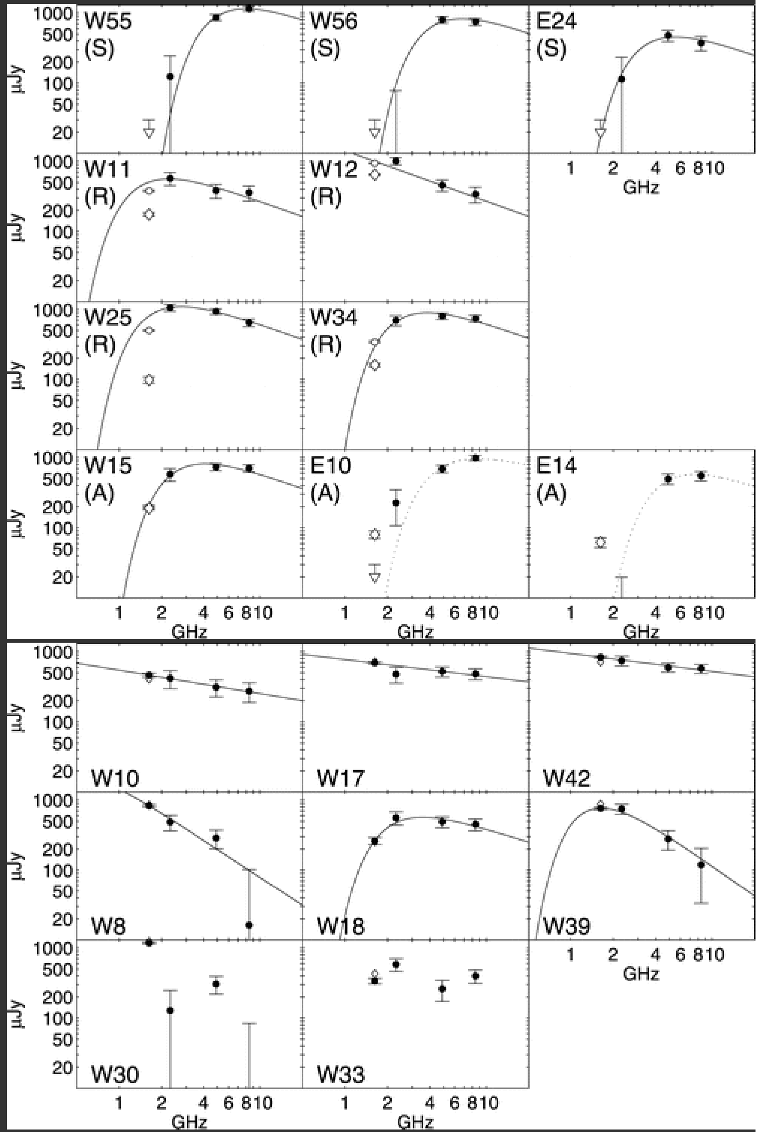


Lonsdale et al. ApJ 647, 185 (2006)

Arp 220: Spectral study of SNe and SNRs

Detection of compact radio sources in Arp 220
at wavelengths shorter than 18 cm





Spectra and models of short-wavelength detected sources (fitted using a power law + free-free absorber)

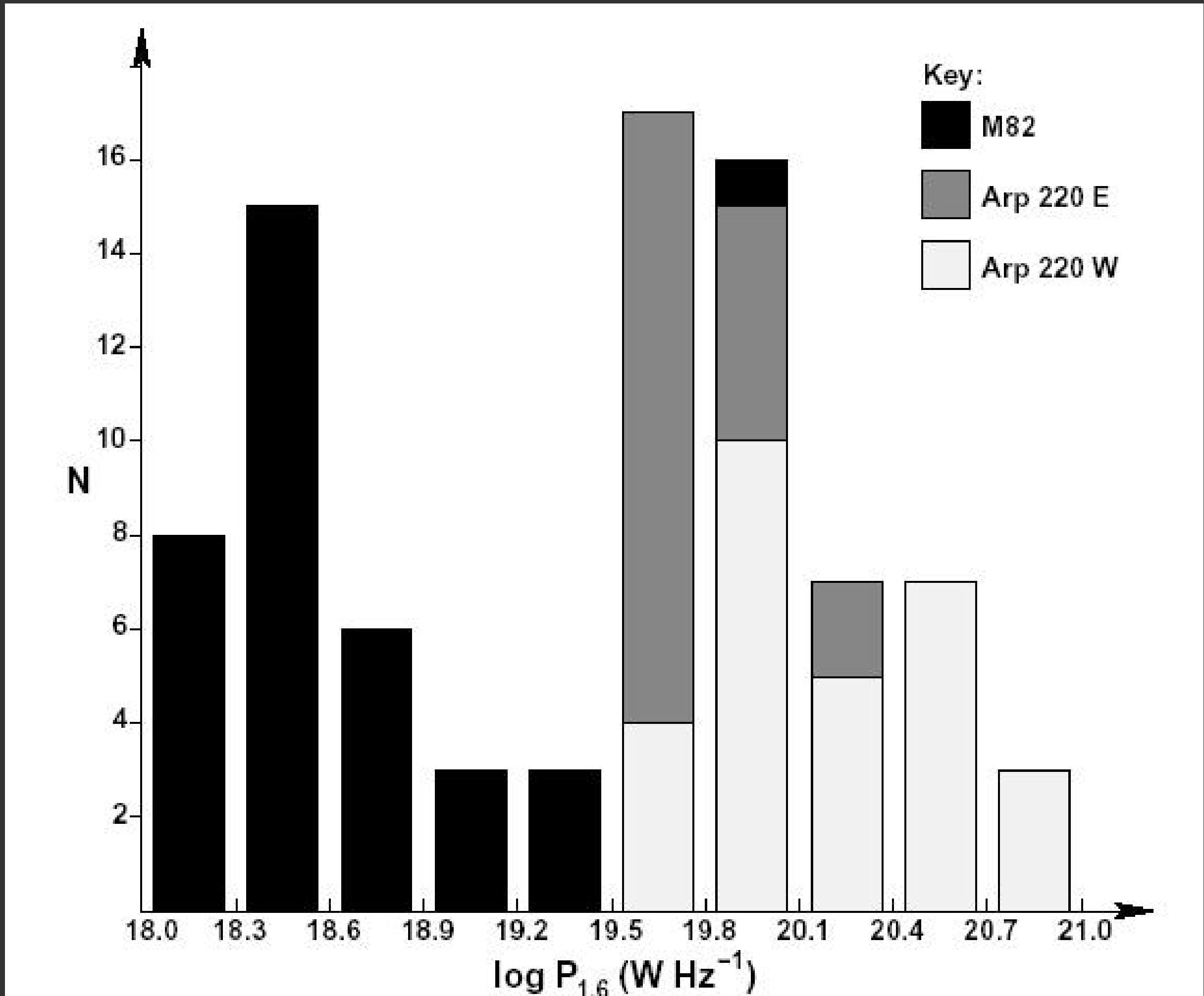
The spectra varied from steep to flat, indicating the presence of both relatively young SN along with SNRs

The large number of bright, Type IIn-like SNe made the authors propose that the IMF of the stars in the nuclei of Arp 220 is a top-heavy one

Parra et al. ApJ, 659, 314 (2007)

Radio Supernovae in Arp 220 & M82

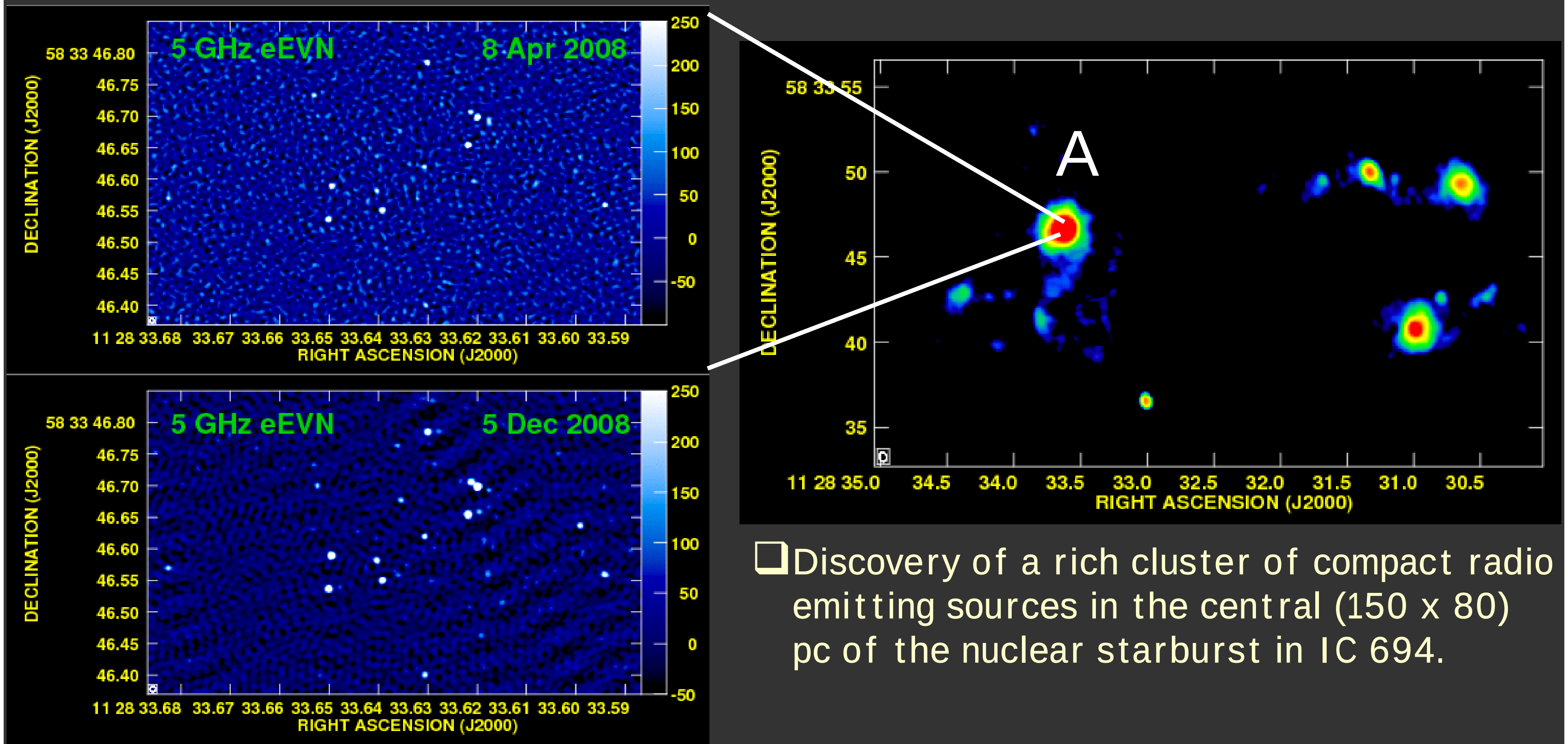
- Arp 220 is ~ 50 times more luminous and is confined to a smaller volume



- The W-Nucleus of Arp 220 is more compact and 3 times more luminous than the E-Nucleus: point sources are systematically stronger in the west

Lonsdale et al. ApJ 647, 185 (2006)

An extremely prolific SN factory in Arp 299-A revealed with the eEVN

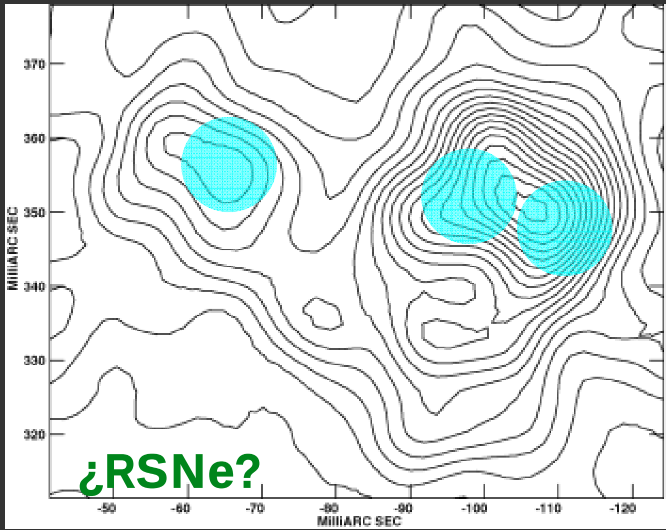


- Discovery of a rich cluster of compact radio emitting sources in the central (150 x 80) pc of the nuclear starburst in IC 694.

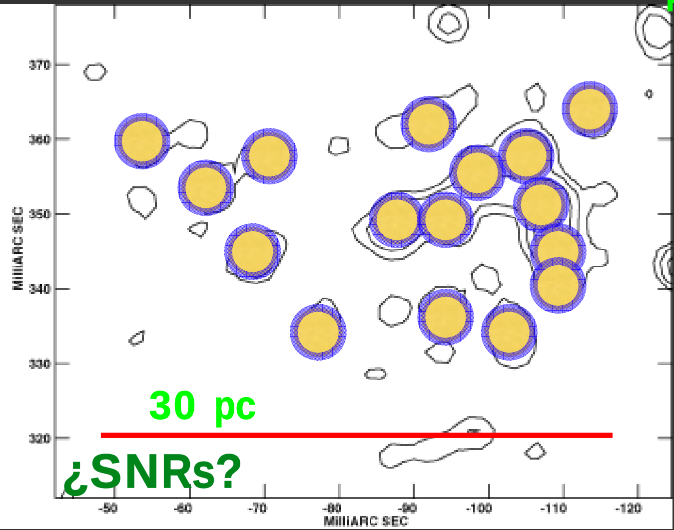
Pérez-Torres et al. 2009, A&A 507, L17

Mrk 273, SN-factory + embedded AGN

D=150 Mpc
$L_{FIR} = 1.2 \times 10^{12}\ L_{sun}$



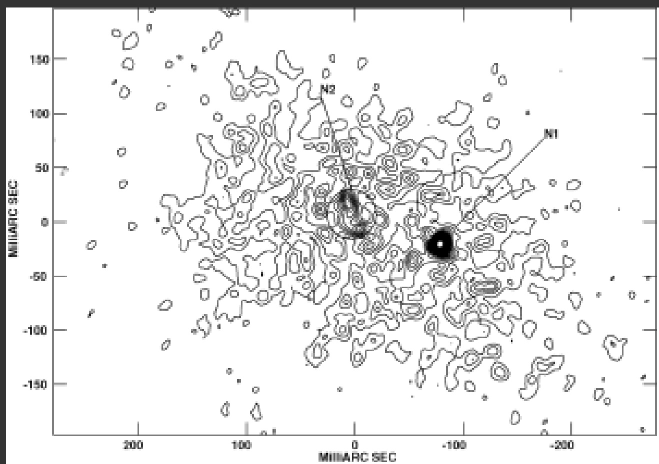
10 mas resolution (7pc)

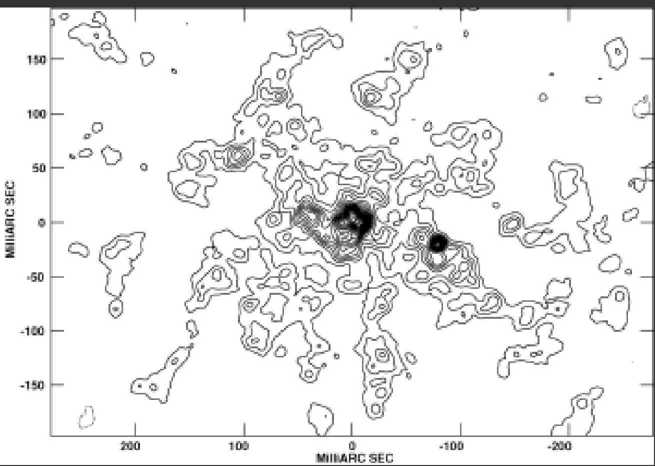


5 mas resolution (3.5 pc)

N2 Region
5 GHz
EVN+MERLIN

Active Star Forming Region with:
- **dM*/dt = 39 M_sun/yr**
- **d(SN)/dt = 1.5 SN/yr**



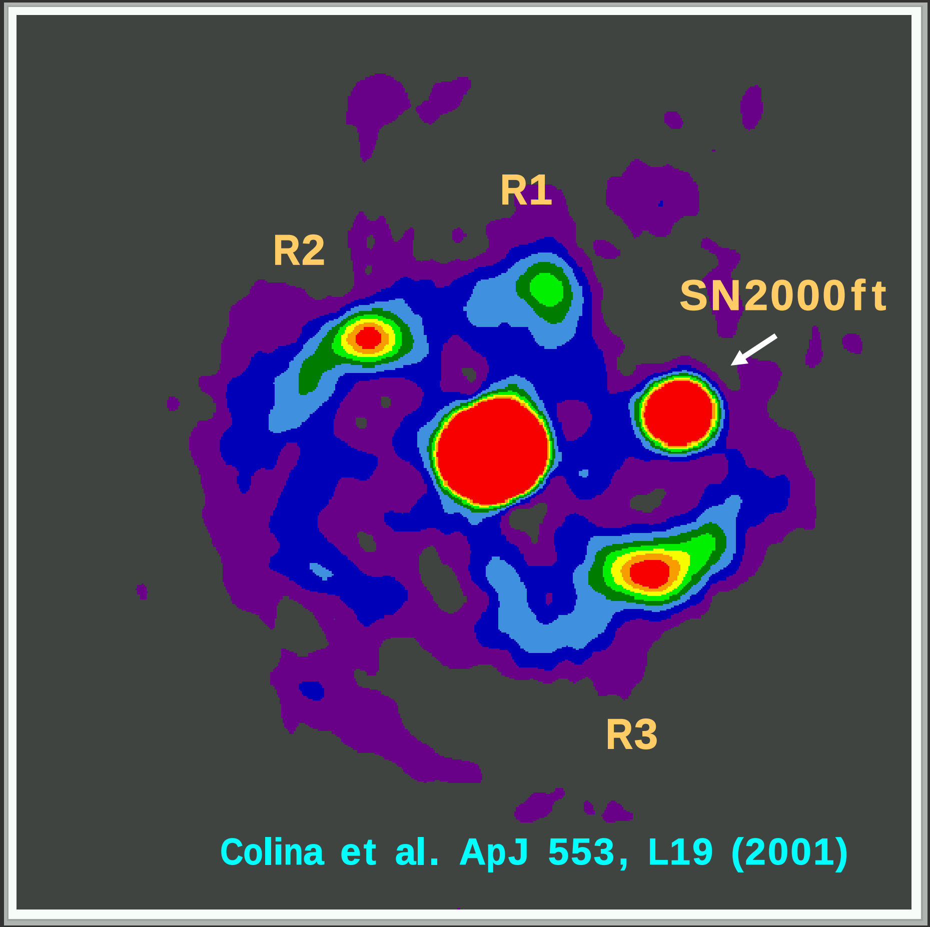


- **Mrk 273 @ 1.6 & 5 GHz, AGN or SNe/RSNe burst?**

(Bondi et al 2005)

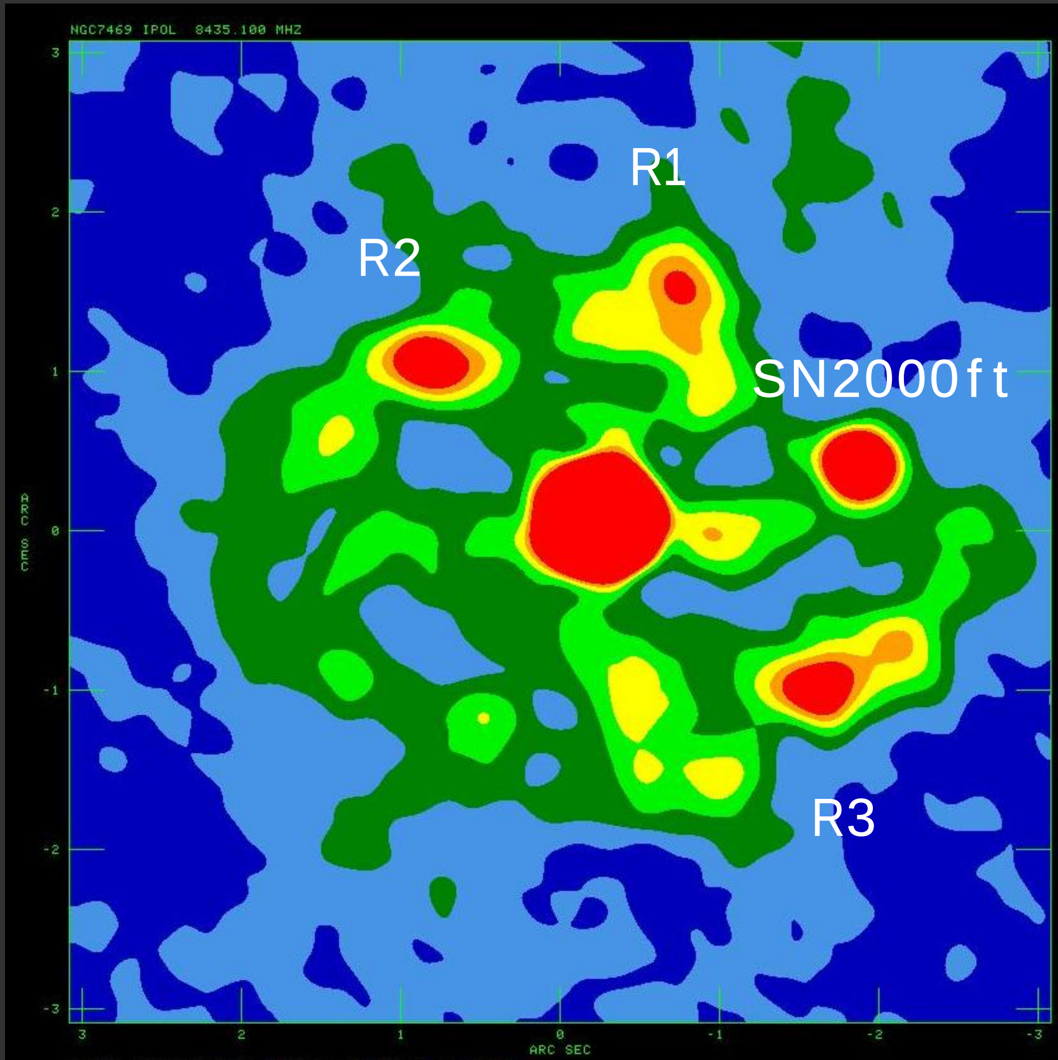
SN 2000ft in NGC 7469

- NGC 7469 is a highly luminous infrared, QSO-like, galaxy.
- There is evidence for a 10^7 M_{sun} BH
- $L_{IR} \sim 5 \times 10^{11}$ L_{sun} ; D: 70 Mpc; 1 mas= 0.32 pc

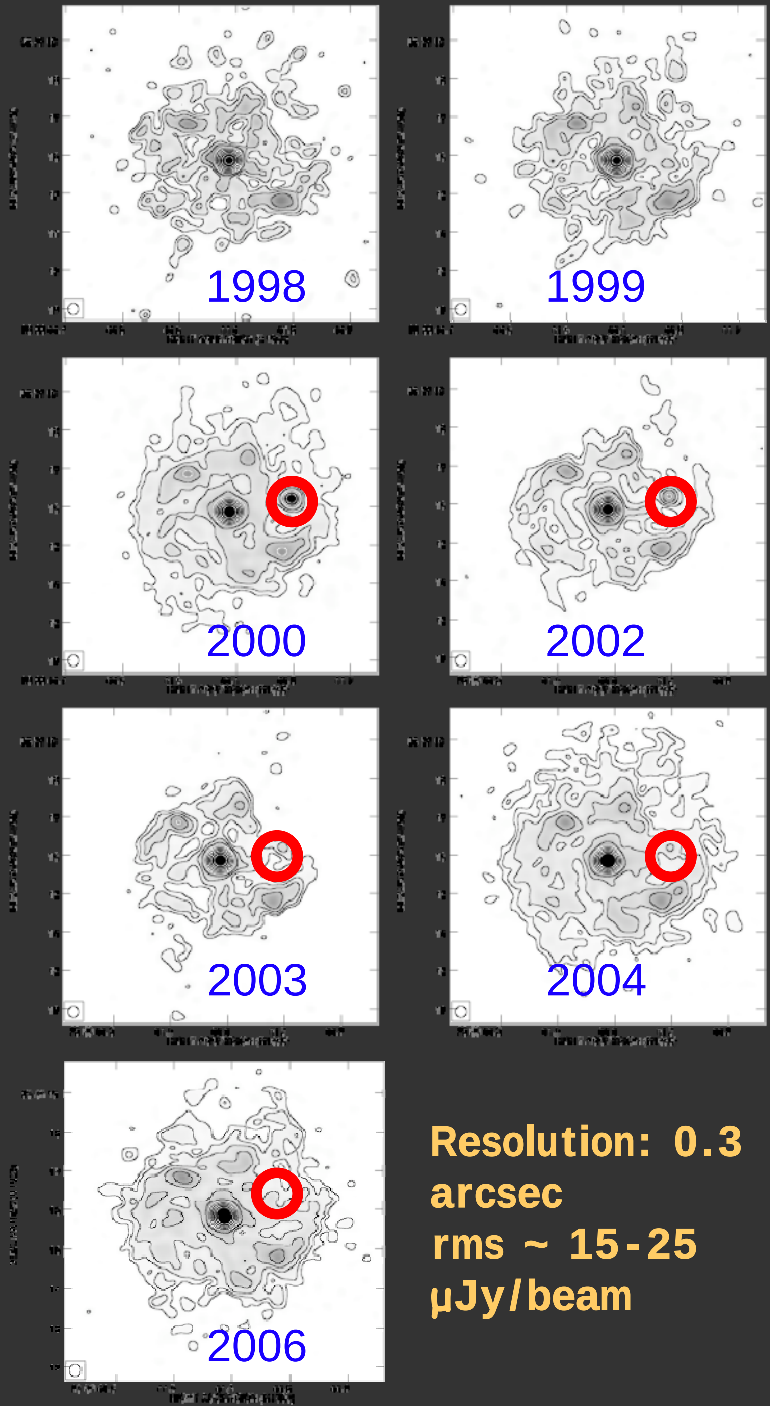


- Ring: 1 Kpc
- SN 2000ft is located in the circumnuclear starburst, at a distance of 600 pc of the nucleus.
- $L_{SN2000ft} = 1.1 \times 10^{21}$ W/Hz, very luminous

SN 2000ft in NGC 7469: X-band evolution (8 years)

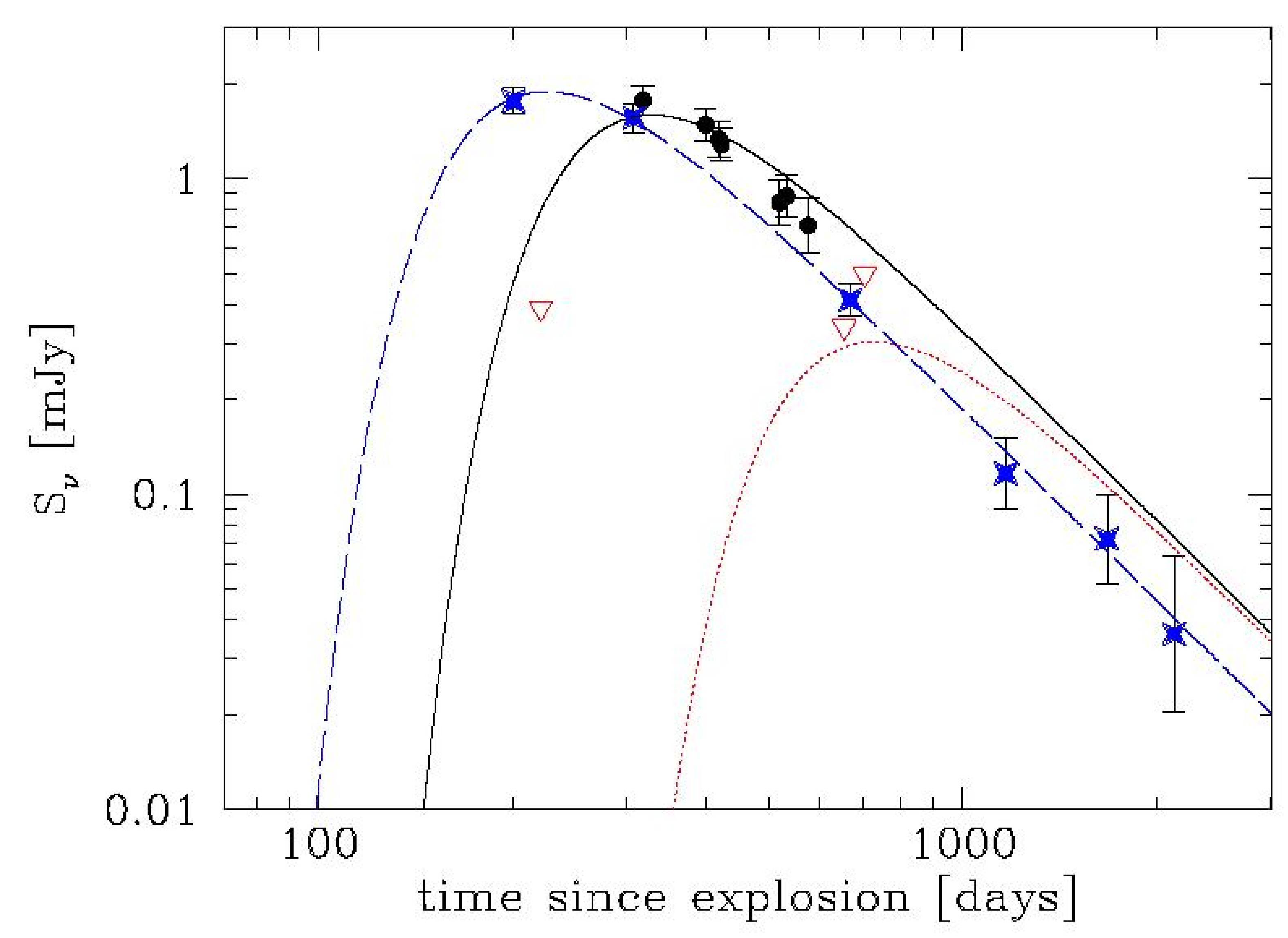


Alberdi et al. ApJ 638, 938 (2006) Pérez-Torres et al. MNRAS 399, 1641 (2009)



Resolution: 0.3 arcsec
rms ~ 15-25 μJy/beam

SN 2000ft in NGC 7469: Radio Light Curve



Alberdi et al. ApJ 638, 938 (2006); Pérez-Torres et al. MNRAS 399, 1641(2009)

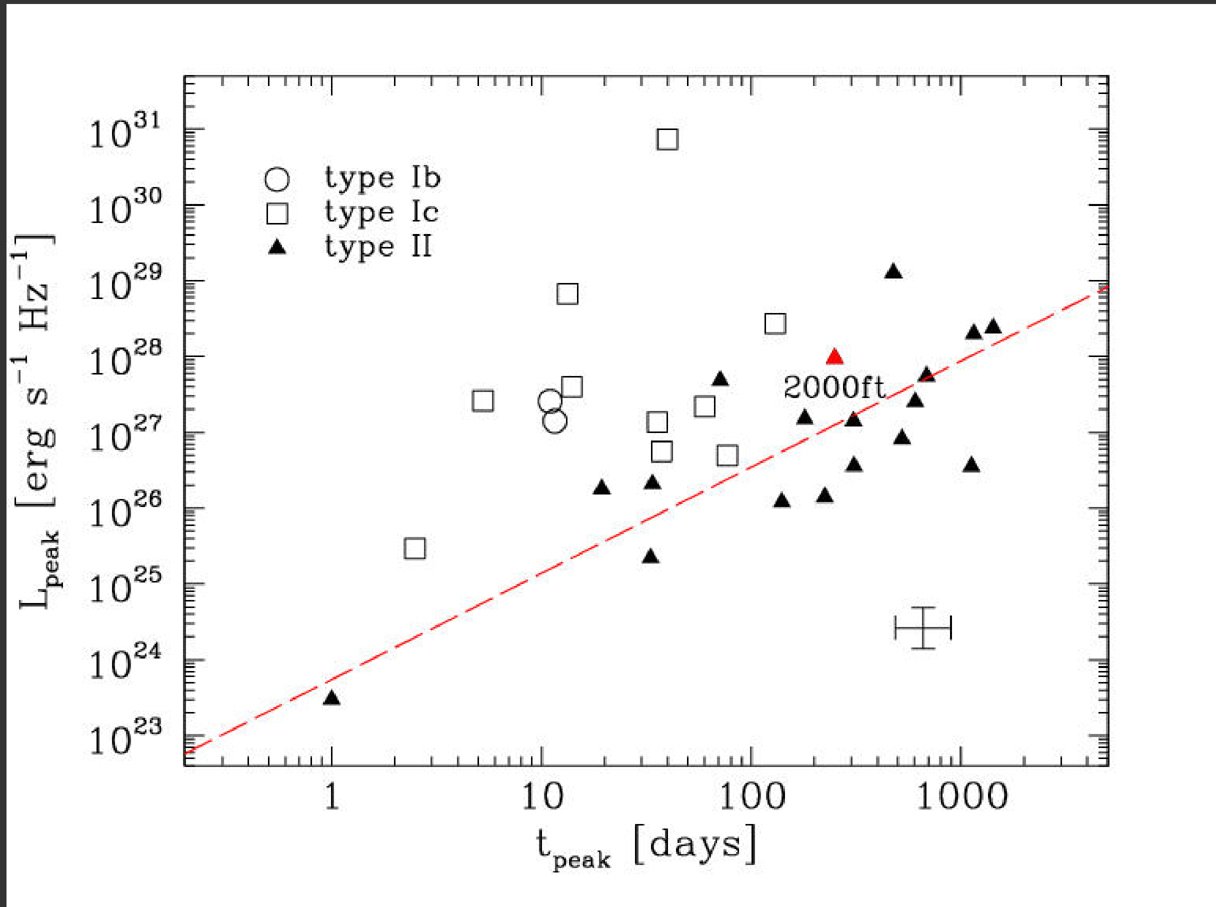
SN 2000ft in NGC 7469: Radio Light Curve

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

- Fitted time of the explosion: 10 May 2000
- Fitted spectral index: $\alpha = -1.27$
- Fitted power-law time decay: ß = -2.02
- Fitted 5 GHz flux at 1 day: K_1 =4.45e5 mJy
- $\tau_{\mathrm{external}} = \tau_{\mathrm{CSM}}$ (fitted 5 GHz RSG stellar wind τ_{ff} at 1 day, K_2 = 1.67e7) + τ_{distant} (associated with a foreground H I I region: $K_4 \geq 0.17$). This value of the opacity implies the presence of an ionized layer along the LOS with an Emission Measure, EM= 1.60 x 10^7 cm^{-6} pc)

Alberdi et al. ApJ 638, 938 (2006); Pérez-Torres et al. MNRAS 399, 1641 (2009)

SN 2000ft in NGC7469: A bright type-II RSN



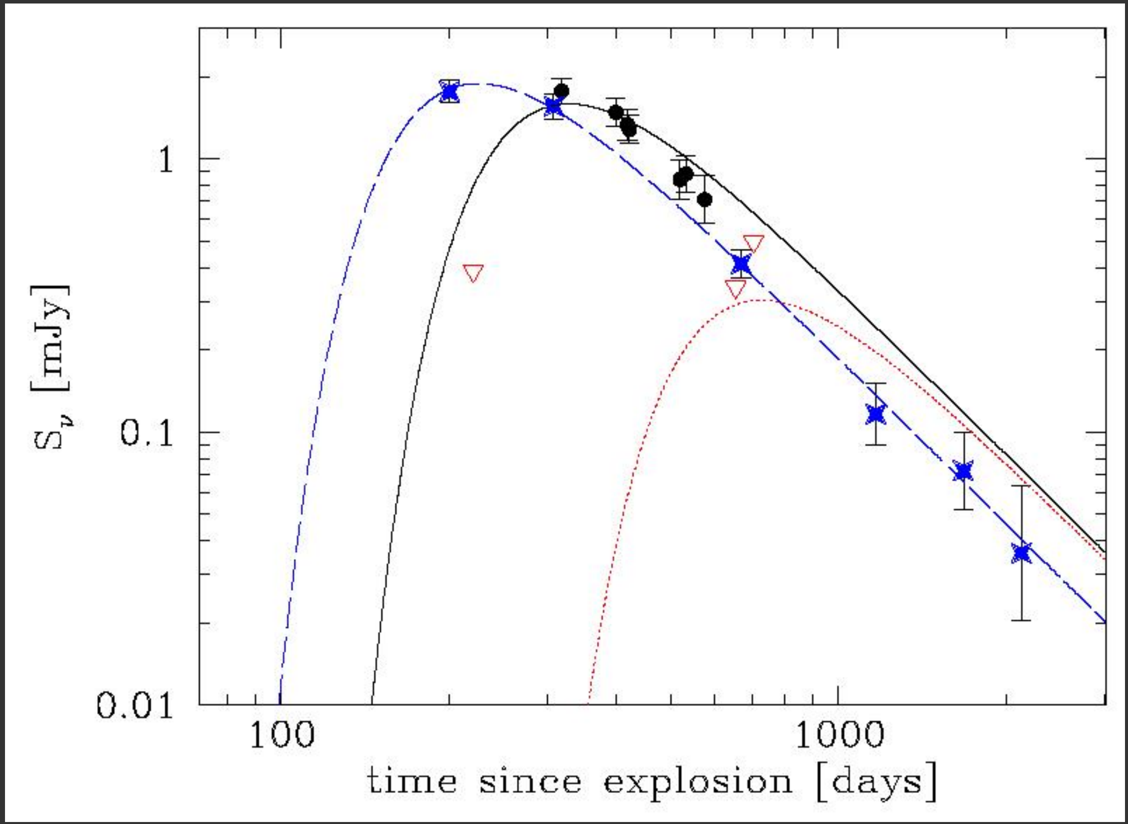
- It is a extremely luminous radio supernova (1.1 × 10^{28} erg s^{-1} Hz^{-1}), like SN79C, SN86J, SN88Z

- Fitting parameters are typical of type-II radio supernovae

- Mass loss rate ≤ (4.7-5.1) x 10^{-5} M_{sun} / yr, typical of a RSG-progenitor

SN2000ft: CSM vs. ISM interaction (I)

First ~2100 days radio emission powered by circumstellar interaction. In the future, departure from standard behaviour will indicate radio emission is being powered by interaction with ISM



ram pressure of wind $\rho_w v_w^2$

radio SN phase ends when

$$P_{\rm ISM} \approx \rho_w v_w^2$$

for a steady, spher. symmetric wind

$$\rho_w \propto r^{-2}$$

$$r_w \approx 0.18 \dot{M}_{-4}^{1/2} v_{w1}^{1/2} p_7^{-1/2}$$

Assuming V_{sh} = 10000 km/s

r ~ 0.06 pc < r_w

Pérez-Torres et al. 2009, MNRAS 399, 1641

SN2000ft: CSM vs. ISM interaction (II)

First ~2100 days radio emission powered by circumstellar interaction. In the future, departure from standard behaviour will indicate radio emission is being powered by interaction with ISM

- The ram pressure of the wind, $\rho_w v_w^2$, is at an age of 2147 days, of the order of 7.6×10^{-9} dyn cm^{-2}, still very high to be overcome by P_{ISM}.

(For comparison, in the central HII regions of M82, $P_{ISM} \sim 4 \times 10^{-9}$ dyn cm^{-2}, while it drops below 4×10^{-9} dyn cm^{-2} at a distance of 540 pc. On the other hand, for the case of Arp 220, $P_{ISM} \geq 4 \times 10^{-9}$ dyn cm^{-2}, which explains the significant flattening in the flux density decay of some of the RSNe).

- The number density of the thermal electrons, 5100 cm^{-3}, at an age of 2147 days, similar to expected values in the dusty, dense environments of Starbursts.

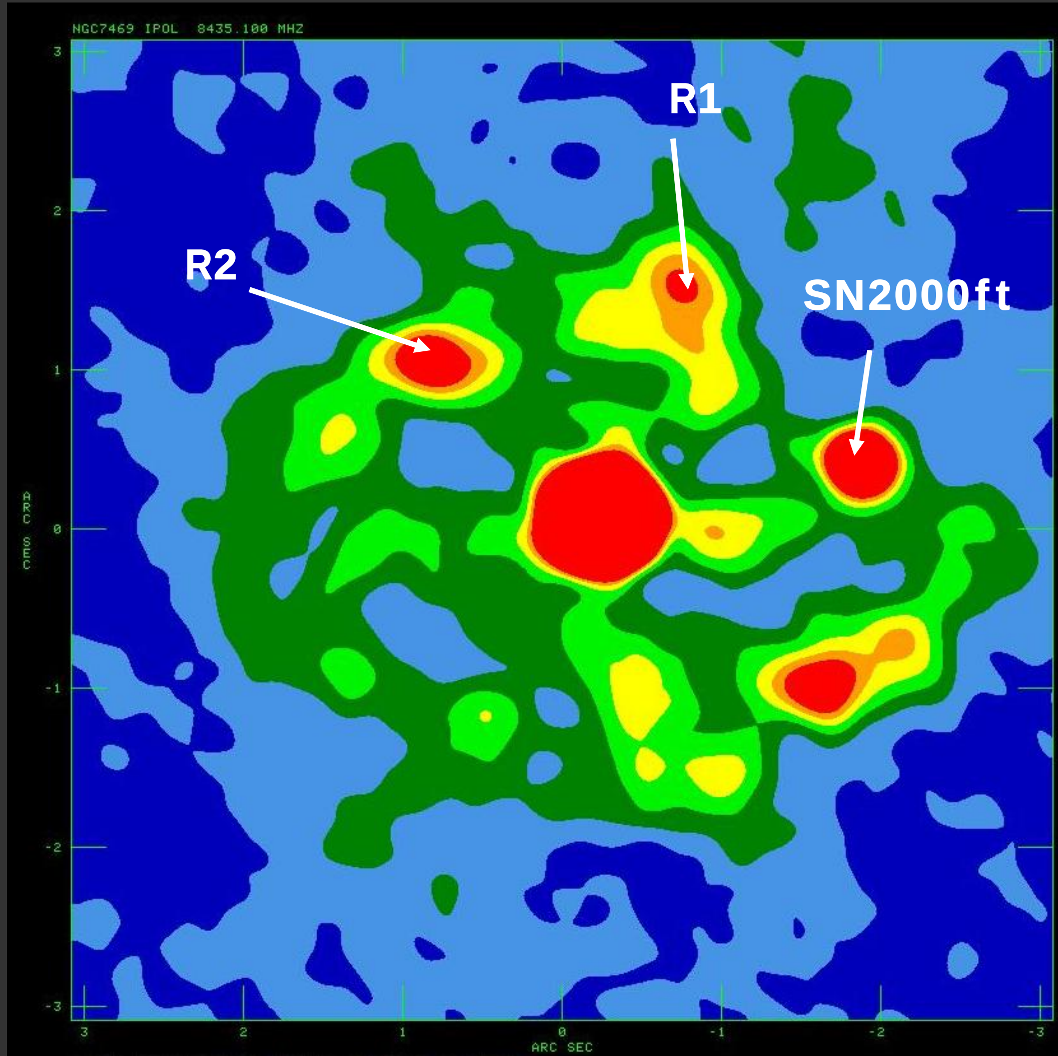
- The swept-up mass by the supernova shock after 2147 days is of the order of 0.29 M_{SUN}, assuming free expansion in a steady spherically-symmetric wind.

Pérez-Torres et al. 2009, MNRAS 399, 1641

The circumnuclear starburst in NGC 7469

Apart from SN 2000ft, there is no evidence for RSNe more luminous than about $L_{peak} \sim 6\times10^{26}$ erg s^{-1} Hz^{-1}, suggesting that no other Type IIn SN has exploded since 2000 in the nuclear starburst of NGC 7469.

CCSN rate is ≲ 0.13 #/yr, in contrast with the CCSN rate = 2.7e-12 * L_fir → 0.81 #/yr



Pérez-Torres et al. 2009, MNRAS 399, 1641

The circumnuclear starburst in NGC 7469

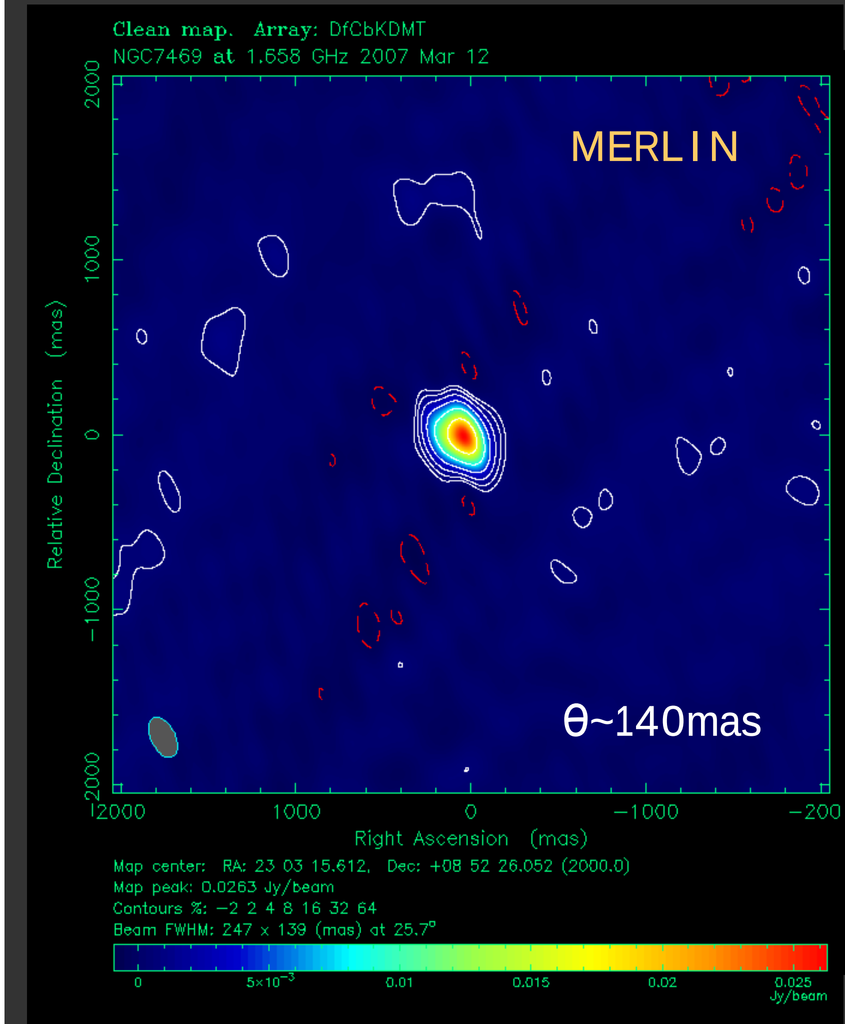
- All of the RSNe with luminosities ranging from a few times 10^{25} to 6×10^{26} erg/s/Hz would go undetected (background emission of the galaxy 100 μJy);

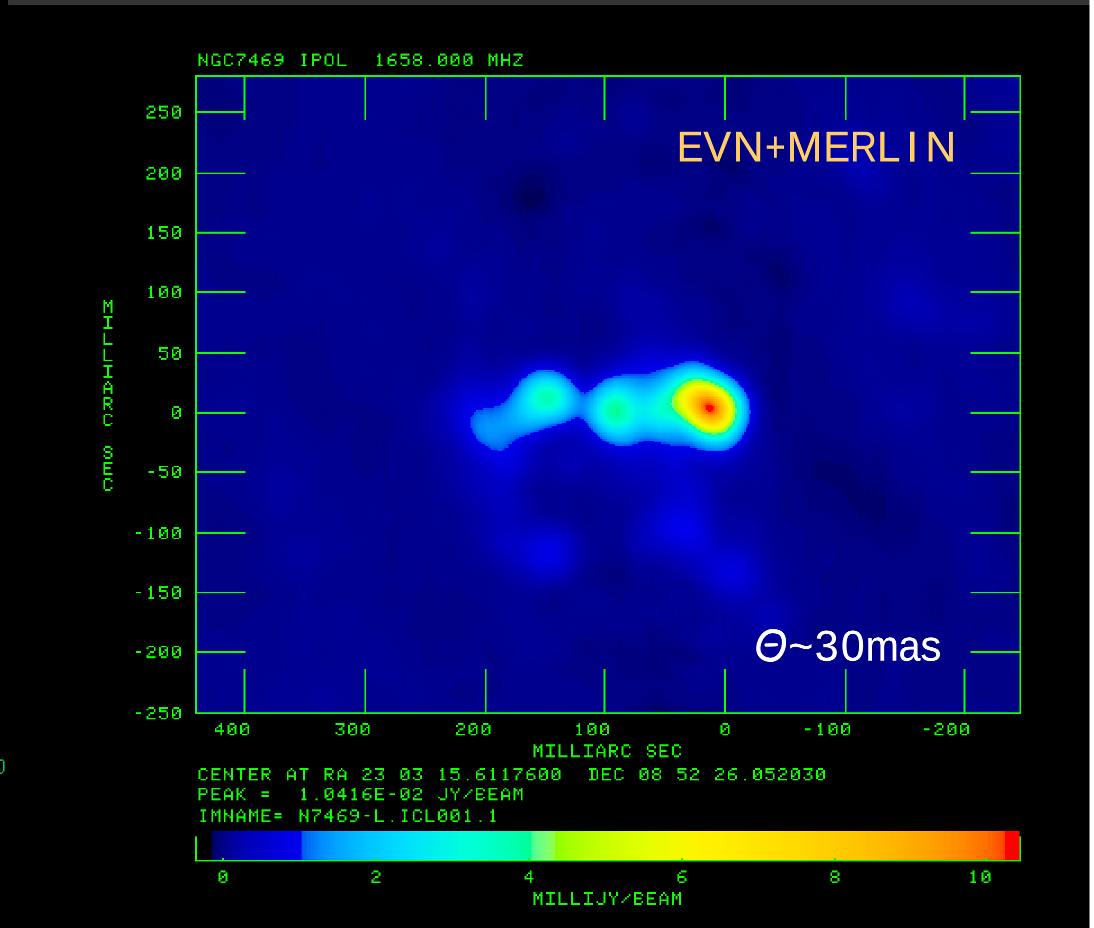
- The bright, long-lived RSNe come from type IIl/IIn SNe (6.4%); the radio faint ones (peak luminosities of $5\text{-}20 \times 10^{25}$ erg/s/Hz) come from type IIP-IIb and are much more numerous (64.1%);

- Assuming the constant star-forming scenario, the radio luminosity function of CCSNe is top-heavy → we would be only witnessing the explosion of very massive stars;

- Alternative scenario: there exists several localized Starbursts in NGC 7469, which started at different times and in different locations of the circumnuclear ring

The nuclear region of NGC 7469 at very high angular resolution





1 mas = 0.32 pc

EVN + MERLIN at λ18cm - March 2007

Alberdi et al. 2010 (in prep.)

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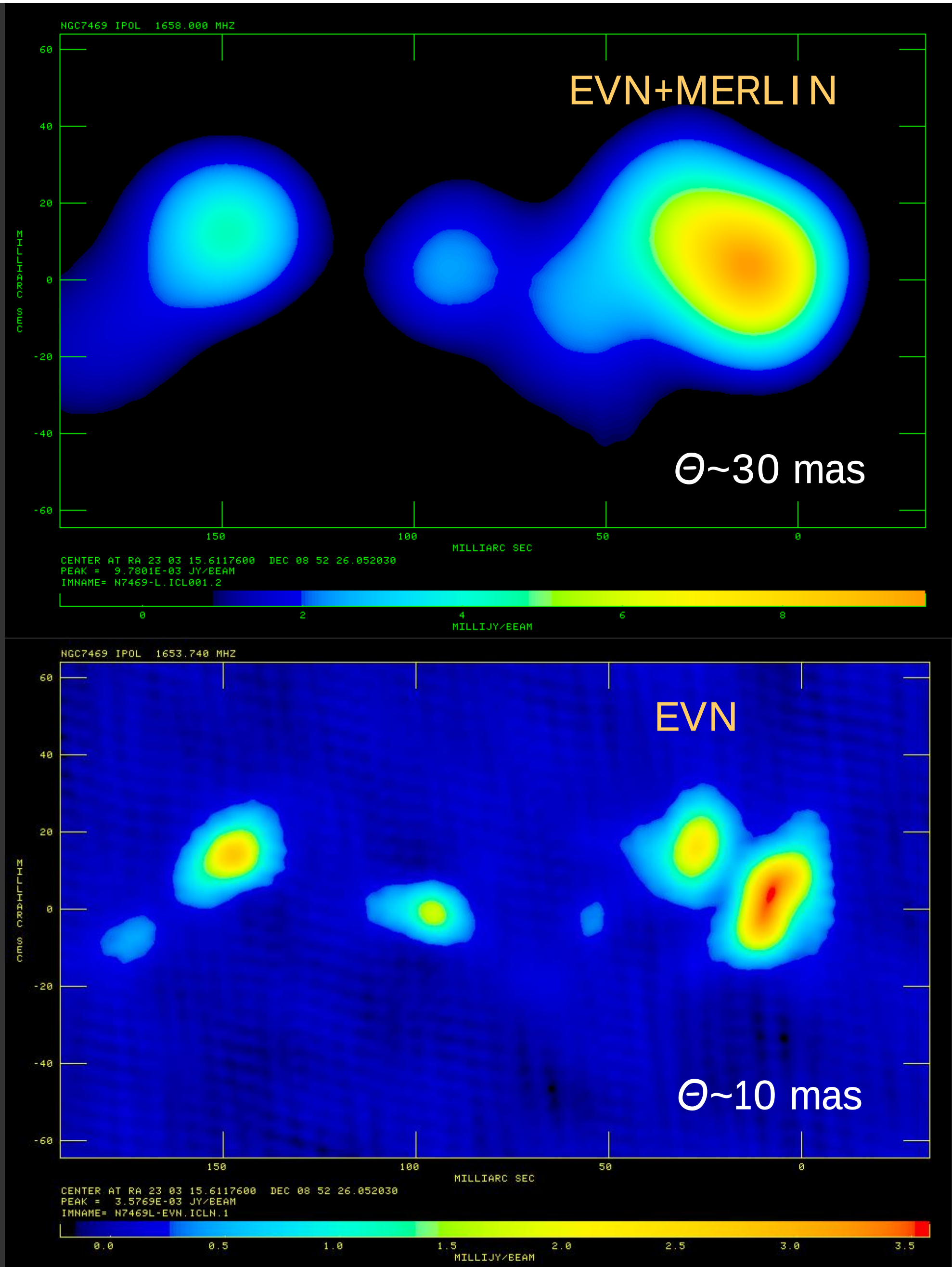

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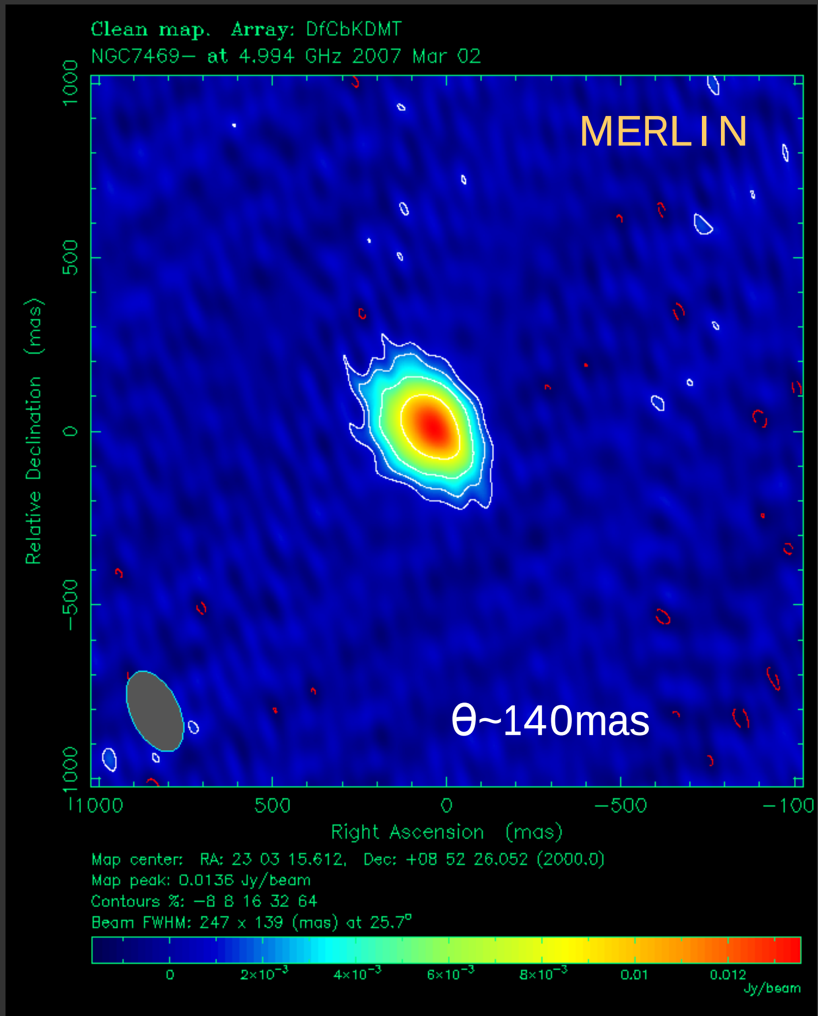

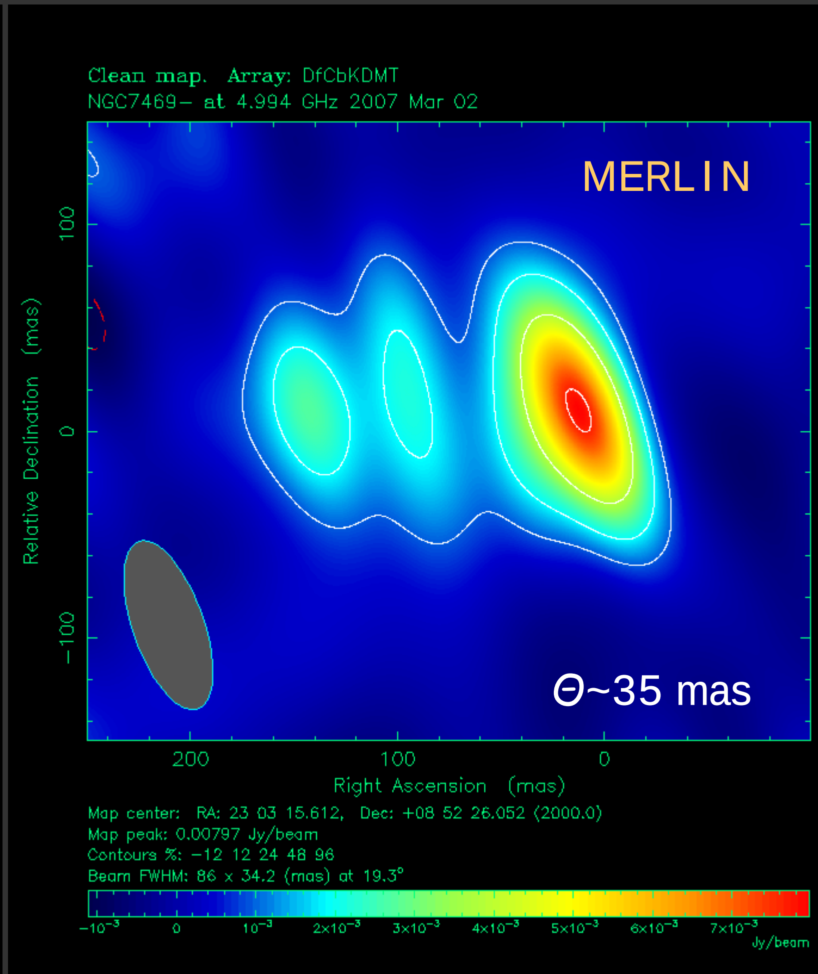

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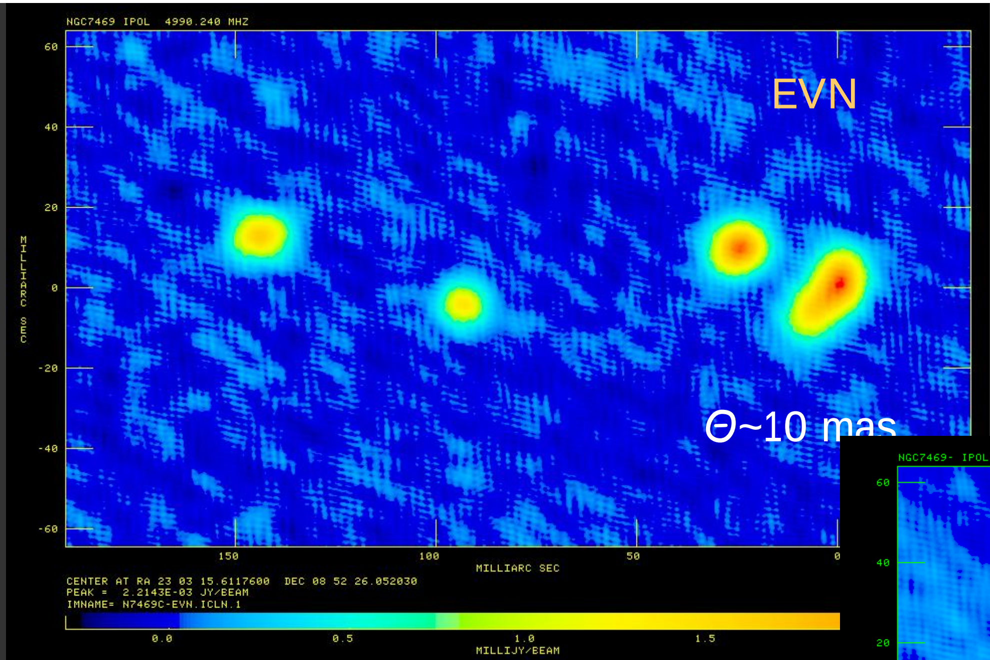
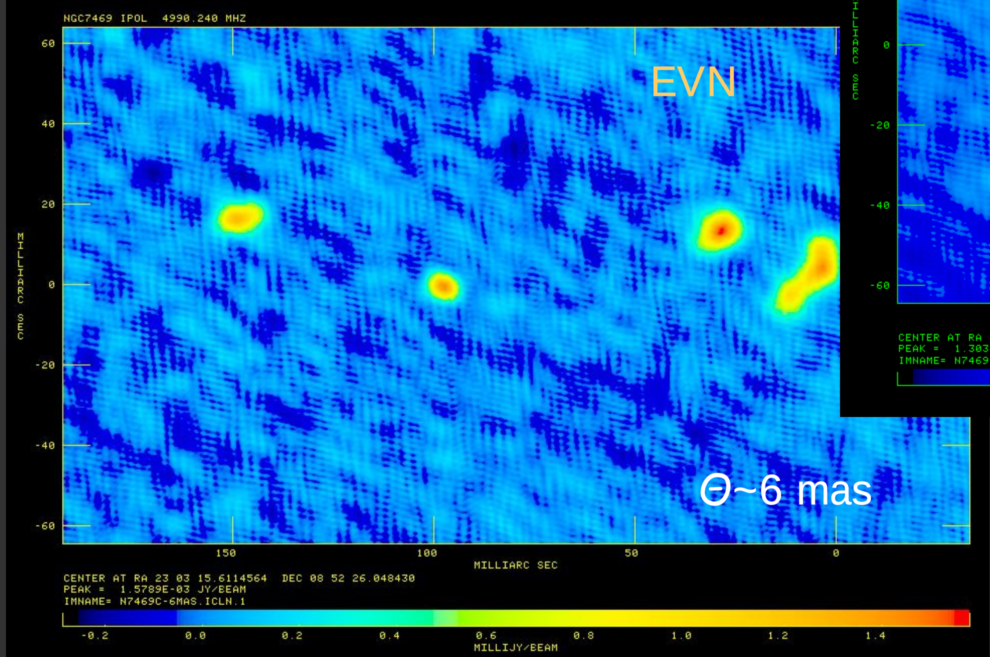
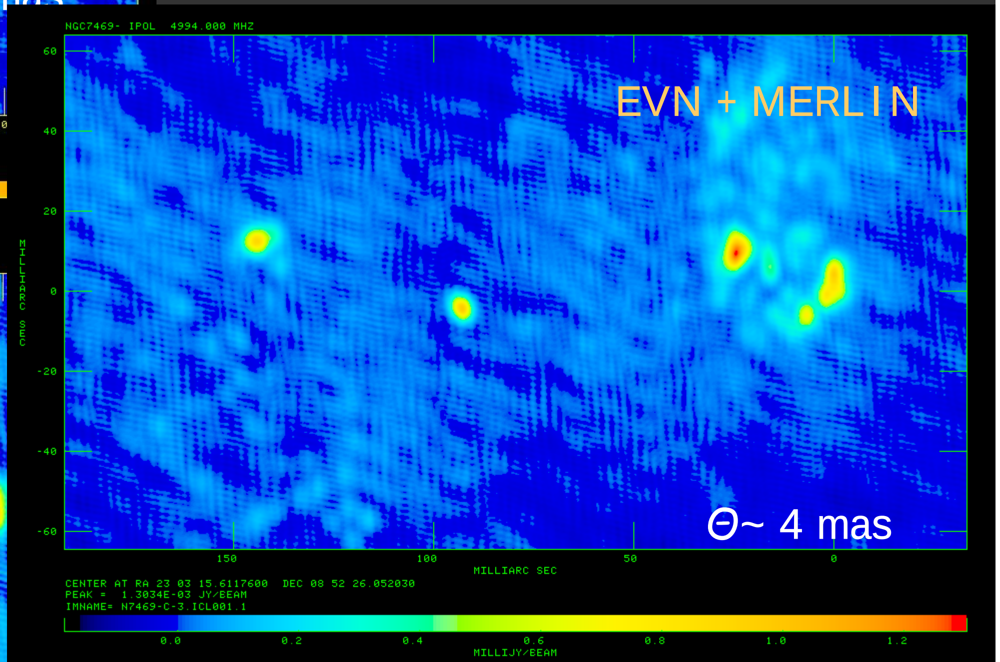
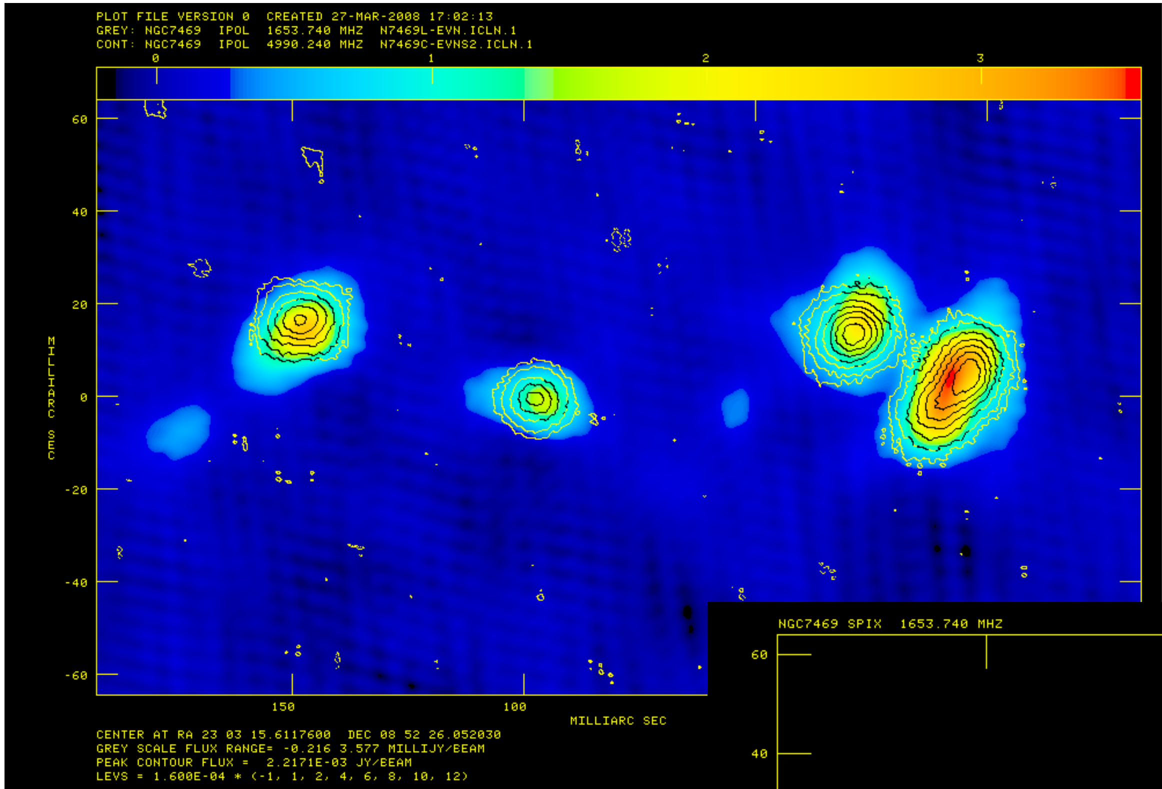


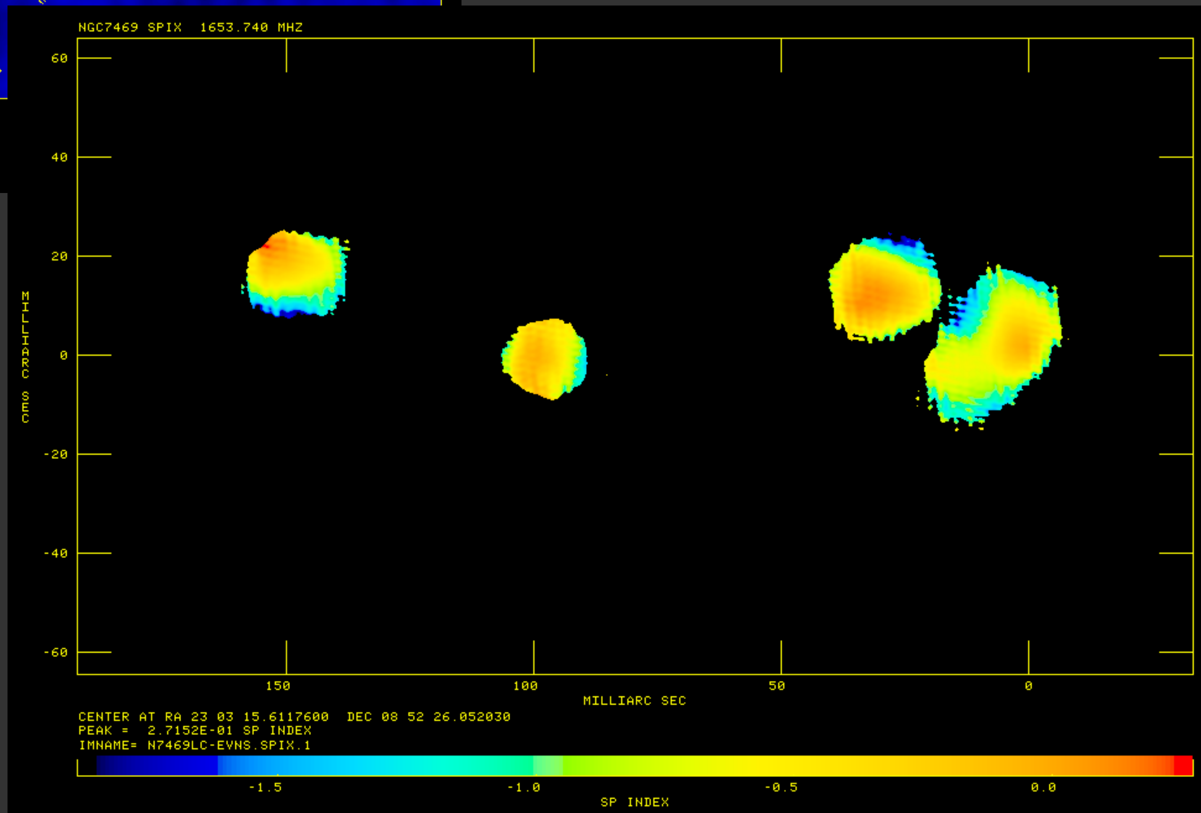




EVN + MERLIN at λ 6cm - March 2007 Alberdi et al. 2010 (in preparation)

Radio spectrum of the nucleus of NGC 7469





Alberdi et al. 2010 (in preparation)

The nuclear region of NGC 7469 at very high angular resolution

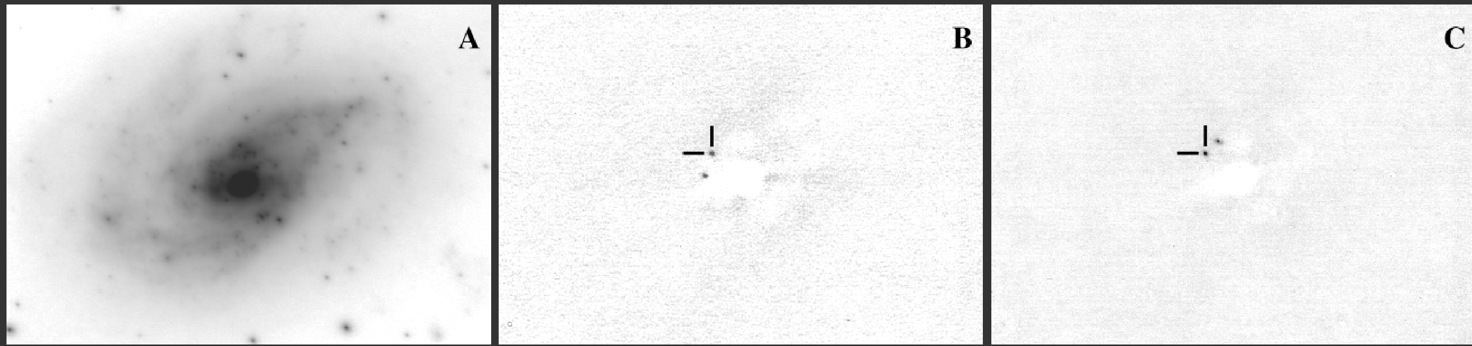
It is still unclear whether these components trace a core-jet structure of an AGN or, alternatively, we are seeing compact starforming regions where individual, or clumps of supernovae, are exploding:

- in favour of an AGN: i) no clear indications of structural and flux density variability; ii) a low supernova rate (based on the infrared luminosity); iii) a kind of jet-like structure in some of the components; iv) there are evidences of a BH from reverb-Mapping.

- in favour of young starforming regions, where core-collapse supernovae are currently exploding: i) all the nuclear components show steep spectra, with values between -1 and -0.3; ii) all the VLBI sources are within an area of 50 pc, which is also the size of the nuclear starburst (Davies et al. 2004; ApJ 602, 148); iii) for all the components, $T_b > 10^6$ K; $L \sim 10^{27}$ erg s^{-1} Hz^{-1}.

Alberdi et al. 2010 (in prep.)

SN 2004ip in IRAS 18293-3413



❑ SN 2004ip detected at NIR (2.2 microns) using NACO adaptive optics system on the ESO VLT

❑ d from nucleus ~ 500 pc (projected), so one of the closest CCSNe to a nucleus

❑ D = 79 Mpc

❑ L_fir = 6.5E11 L_sun; → CCSN rate = 1. 0 # /yr (Mattila et al. (2007))

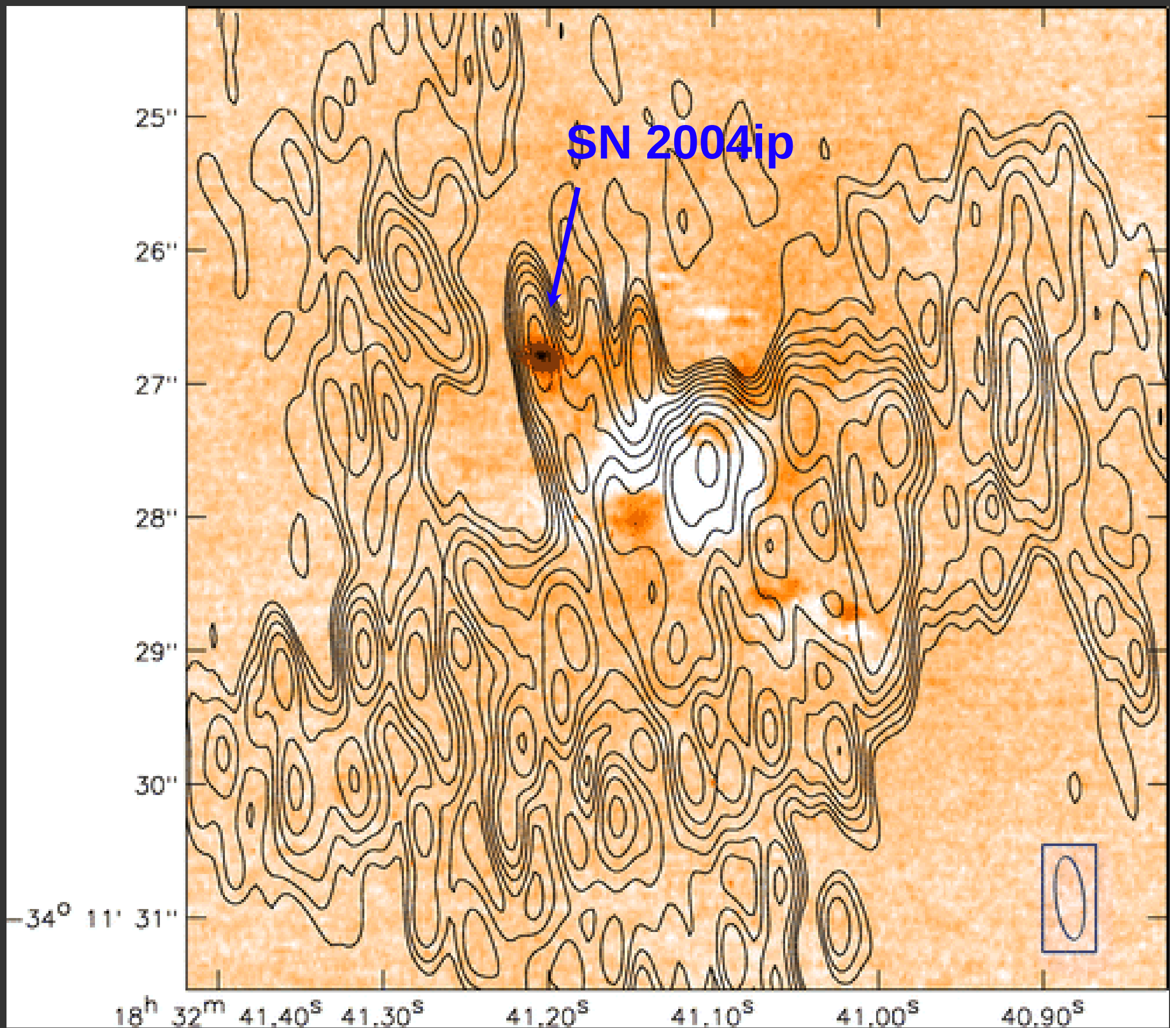
Mattila et al. ApJ, 659, L9 (2007)

Radio detection of SN 2004ip

Contours of 8.4 GHz observations of IRAS 18293–3413 made on 2007 June 11 with the VLA, overlaid on the NACO image (shown with an inverted brightness scale).

Obs-ns on June 2007, about 3 yr after NIR detection.

Confirms SN 2004ip was a CCSN

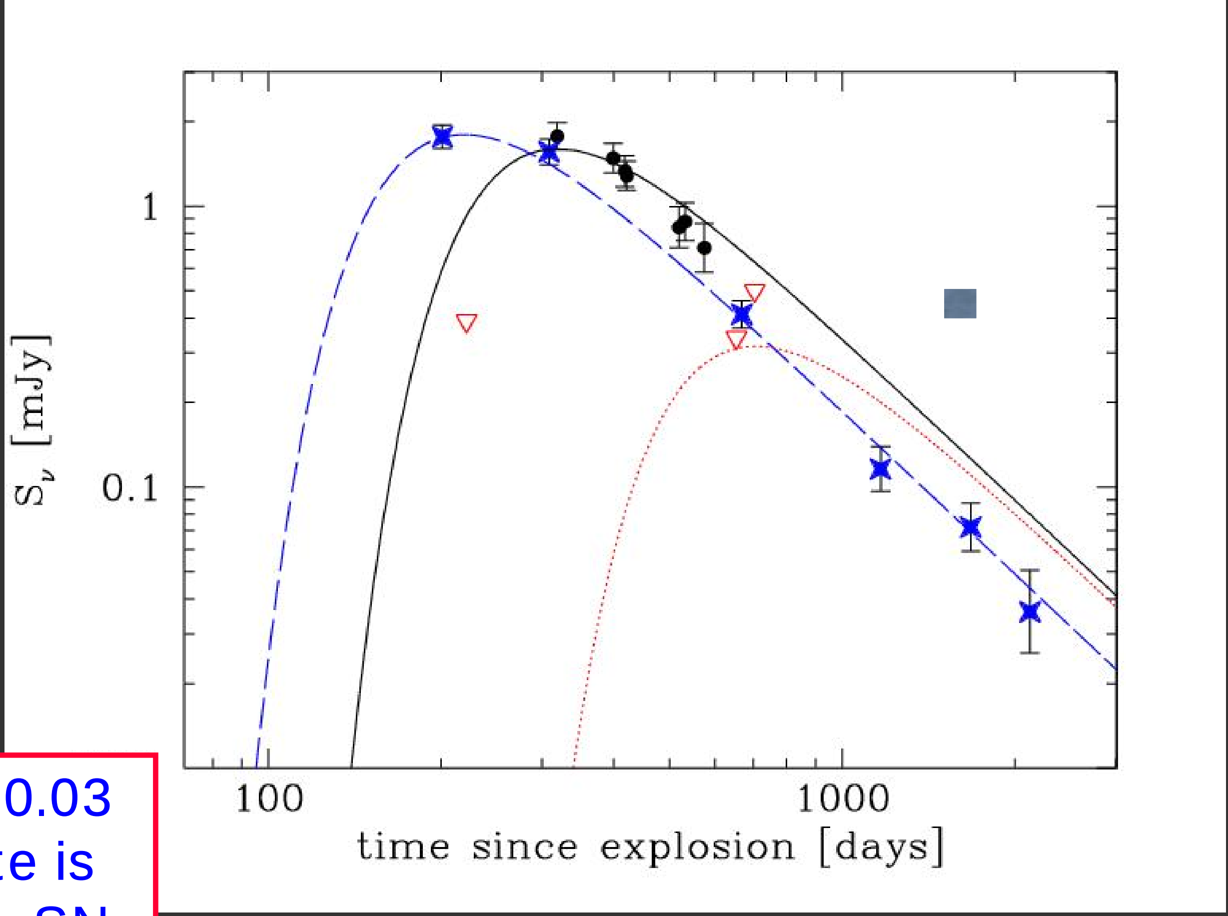


Pérez-Torres et al. ApJ, 671, L21 (2007)

SN 2004ip: a very bright and long lasting SN

Flux ~ 460 microJy, corresponding to L ~ 3.5E27 erg/s/Hz, several times brighter than SN2000ft at such Late epoch.

Consistent with SN 2004ip being a Type IIn CCSN

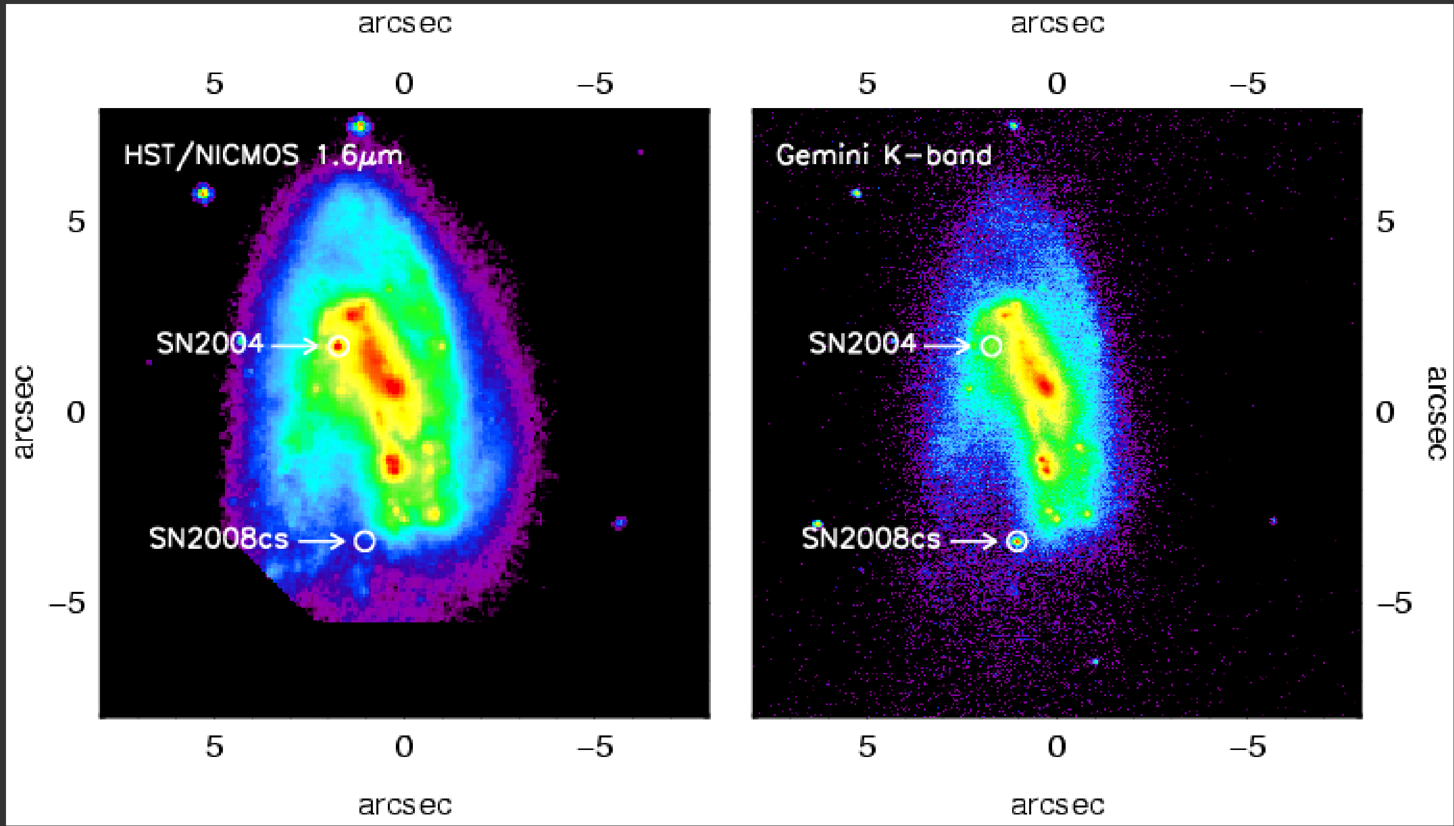


At v_{sh}=10000 km/s, r ~ 0.03 pc. Unless mass loss rate is huge, or P_{ISM} very large, SN 2004ip is still in its radio SN phase, being powered by prominent interaction with the CSM

SN 2000ft light curves and SN 2004ip radio detection datum

Pérez-Torres et al. ApJ, 671, L21 (2007)

SN 2008cs in IRAS 17138-1017



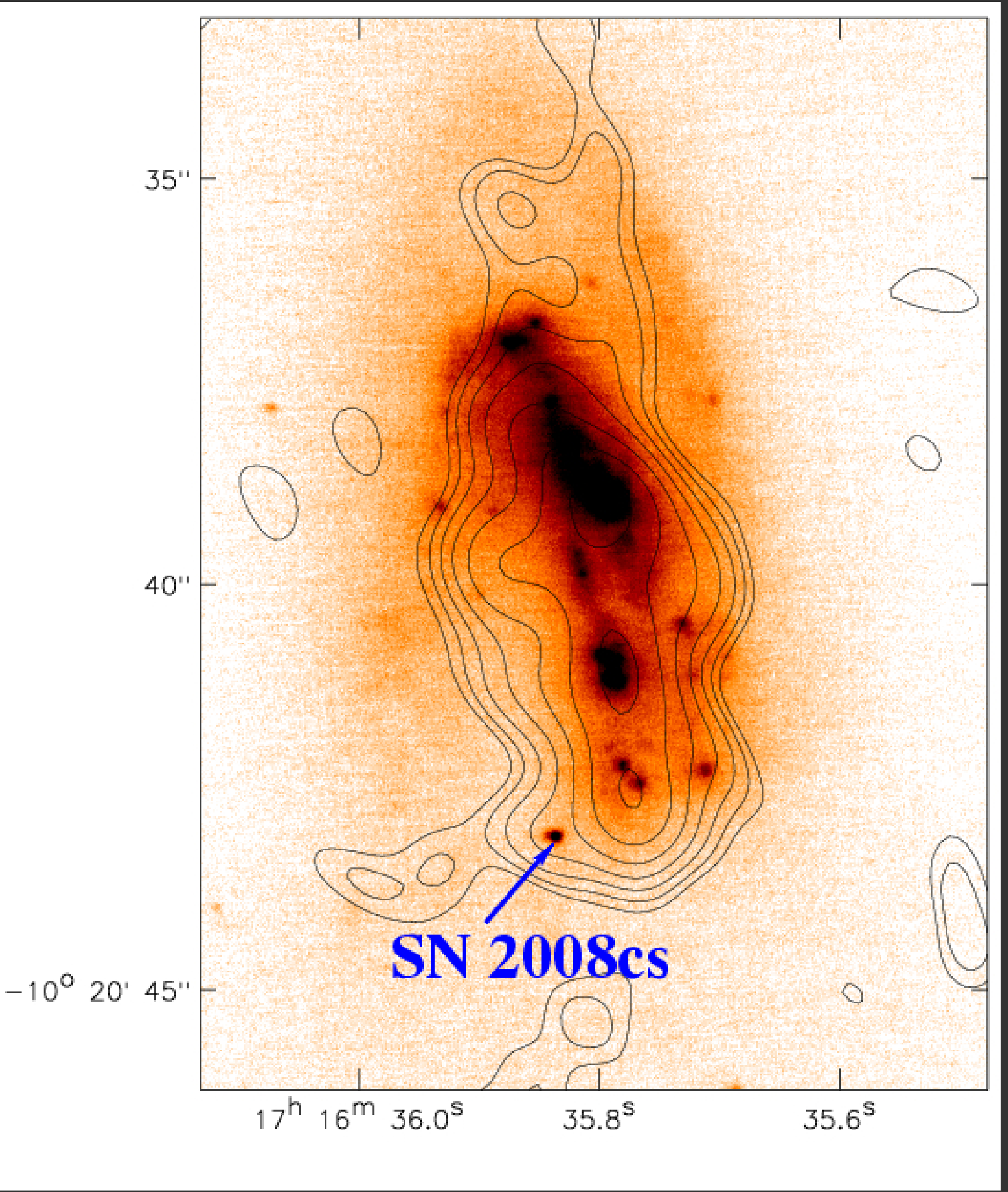
- ❑ SN 2008cs detected using ALTAIR/NIRI adaptive-optics system on GEMINI South (NICMOS:23 Sept 04; ALTAIR: 21 Apr 08)
- ❑ D = 75 Mpc; d from nucleus ~ 1.3 Kpc (projected)
- ❑ L_fir = 3E11 L_sun; Star Formation Rate: 21-46Msun/yr; CCSN rate = 0.7 #/yr

Radio detection of SN 2008cs

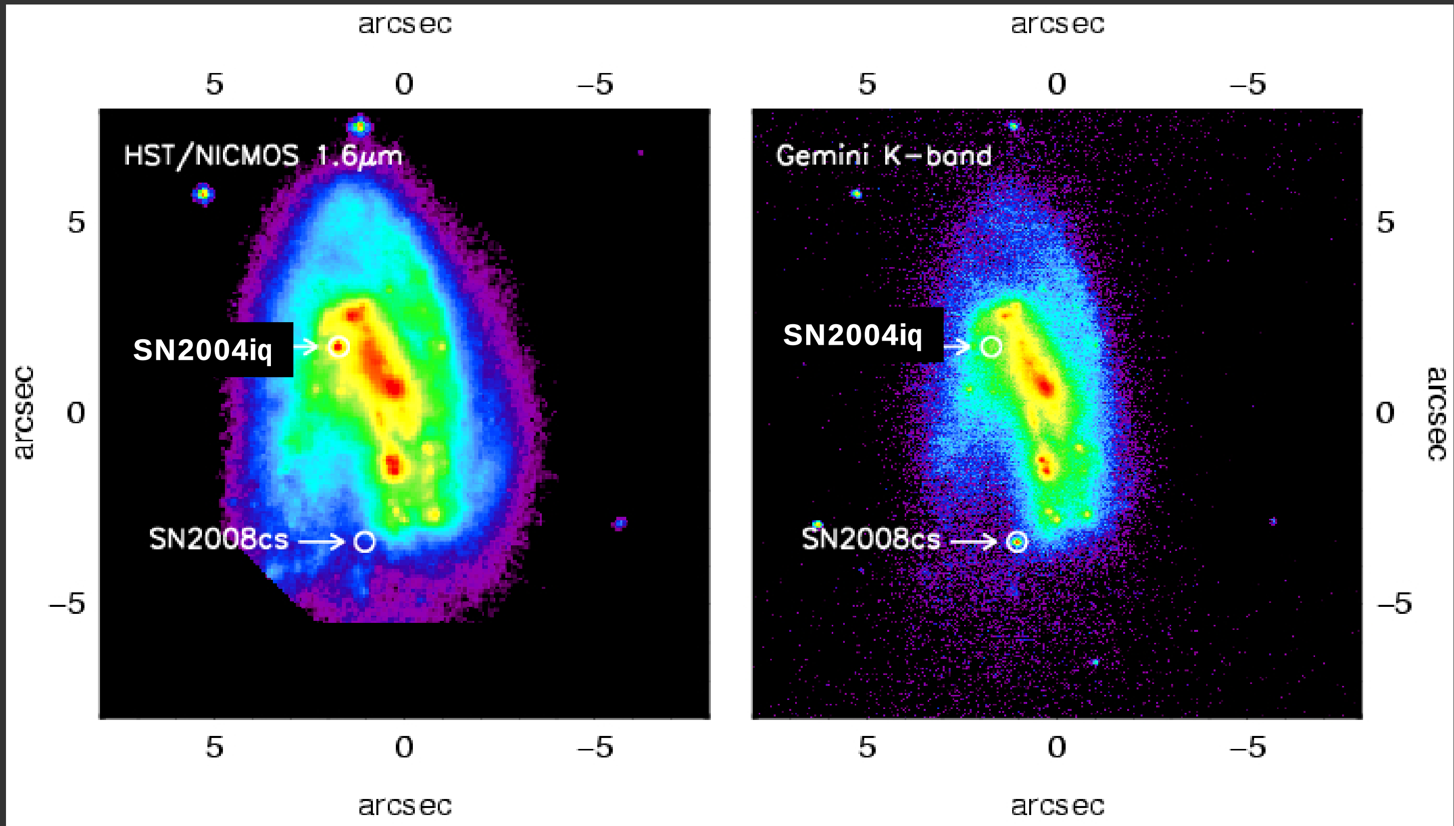
Contours of 22 GHz observations of IRAS 17138-1017 made on 2008 May 10 with the VLA in A configuration, overlaid in the NIR-image

S = 445±75 μJy corresponding to L ~ 3.1E27 erg/s/Hz
(SN 2000ft has 1.76 mJy at its peak, corresponding to L ~ 1E28 erg/s/Hz)

Confirms SN 2008cs was a CCSN



SN 2004iq in IRAS 17138-1017



- ❑ SN 2004iq detected using NICMOS images on 23 Sept 04 (not detected with ALTAIR on 21 Apr 08)
- ❑ D = 75 Mpc; d from nucleus ~ 660 pc(projected)

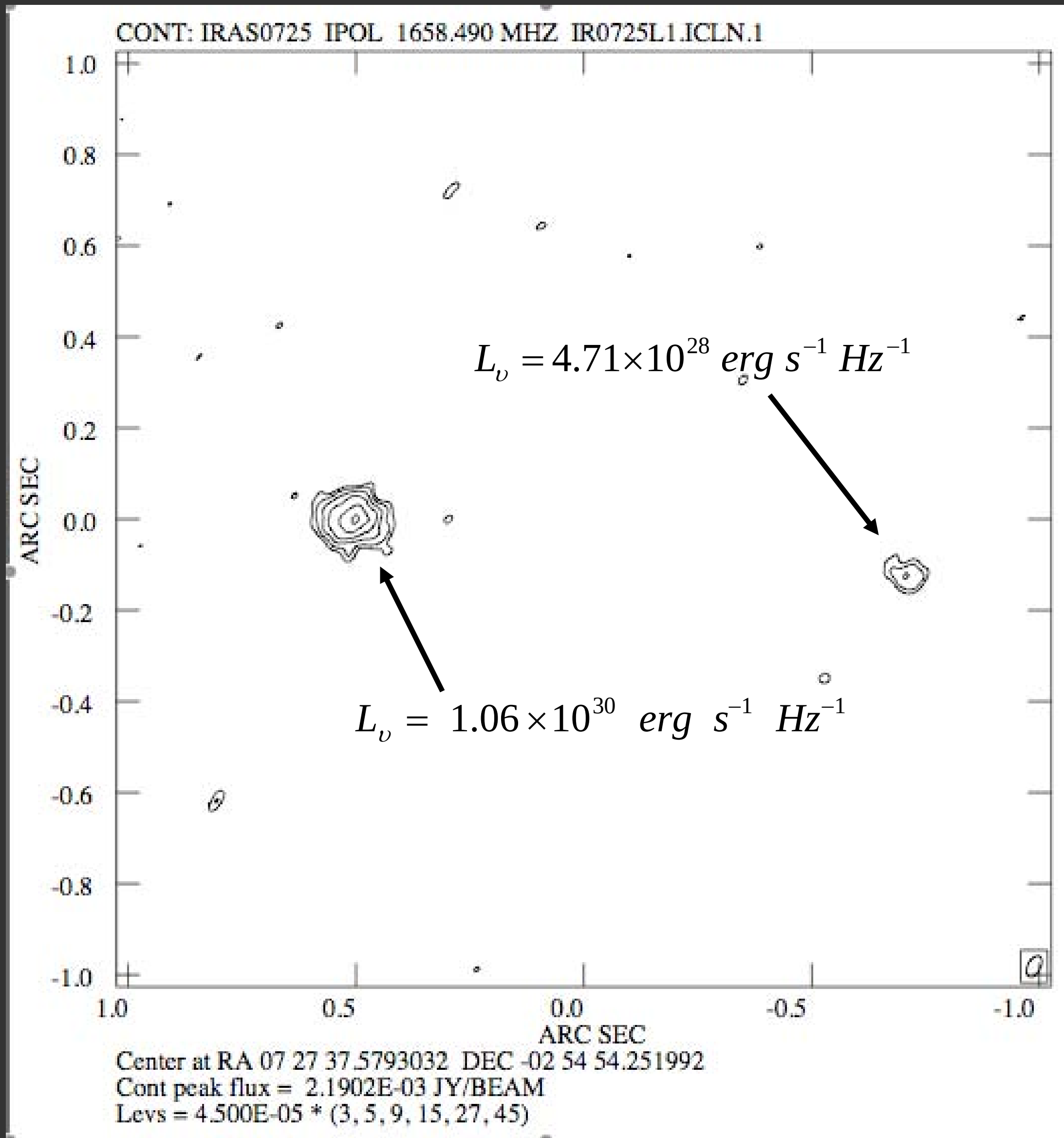
The Farthest and brightest ULIRGs in the local Universe

Preliminary results: taking the EVN to its limit to image faint sources buried in a considerably strong extended emission.

Source	z	log(LFIR/Lsun)
IRAS 07251	0.087	12.32
IRAS 19295	0.088	12.37
IRAS 19542	0.065	12.04
IRAS 23365	0.064	12.13

IRAS 0725 @ 344 Mpc,

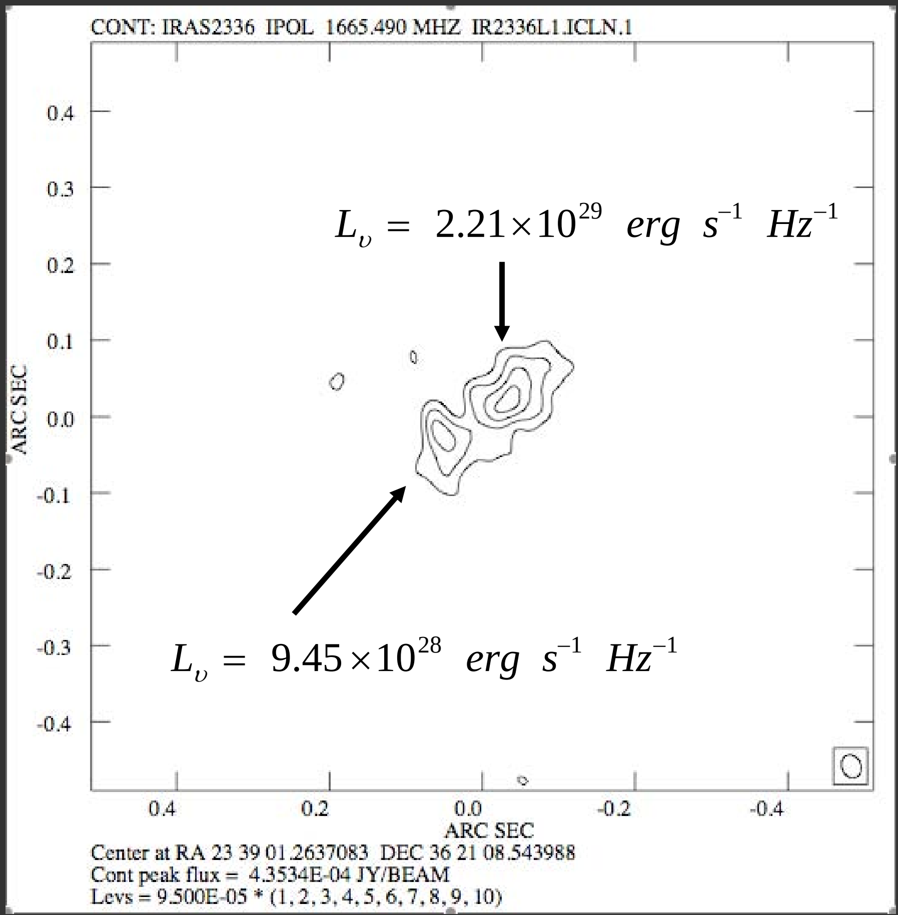
CCSN rate = 8 # /yr

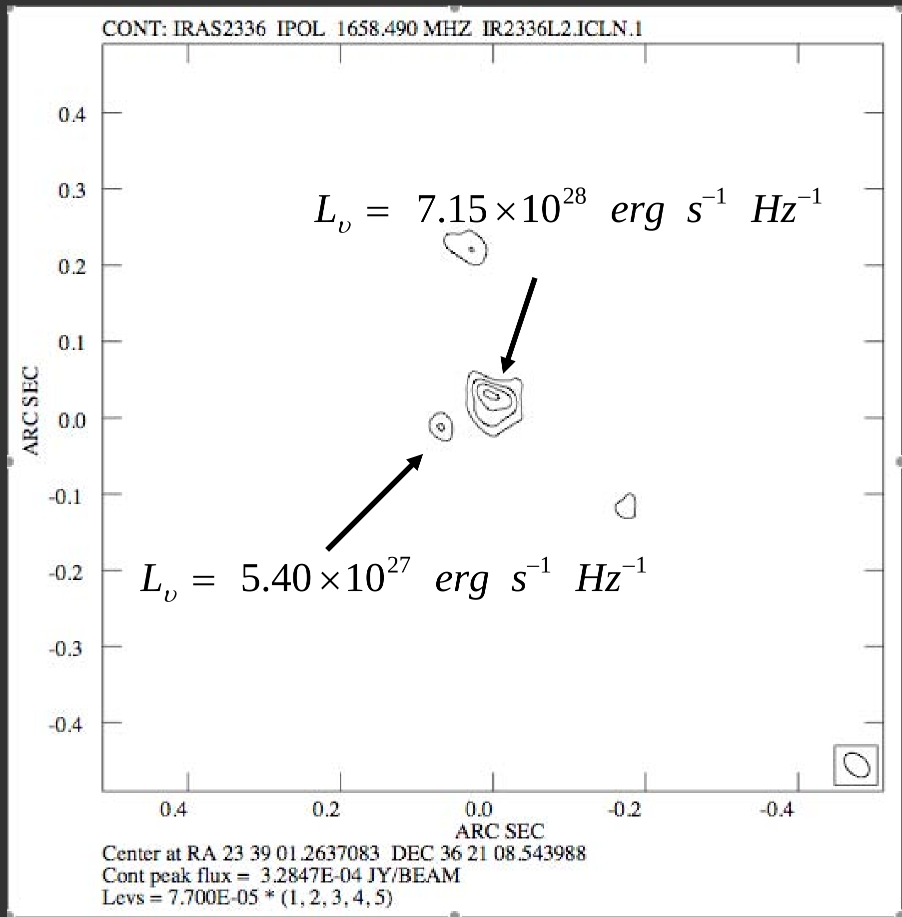


First epoch at 18cm: February 2008

IRAS 2336 @ 252 Mpc,

CCSN rate = 5 # /yr





First epoch at 18cm: February 2008

Second epoch at 18cm: March 2009

Summary

- A direct estimate of the CCSN rate in nearby LIRGs can be obtained by a few-year long radio monitoring of a sample of Starburst Galaxies
- The monitoring of the brightest events will allow to characterize the kind of SNe that occur in starbursts
- Multi-frequency observations discern (young) SNe from SNRs
- The combination of such observations and MC simulations can further shed light on the IMF of those galaxies, and test starburst models
- Very high-resolution radio imaging of LIRGs are able to disentangle AGN from starforming regions up to the most distant ULIRGs in our local Universe