Looking through the dust in luminous infrared galaxies

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Outline

- Introduction
  - SFR tracers
  - Core collapse supernovae (CCSNe)
  - Starbursts
  - LIRGs and ULIRGs
  - Observations and tools
- Scientific cases
  - Arp 299
  - IC 883

Star formation: tracers (I)

Low and intermediate mass stars

$M_{initial} < 8\ M_{\odot}$

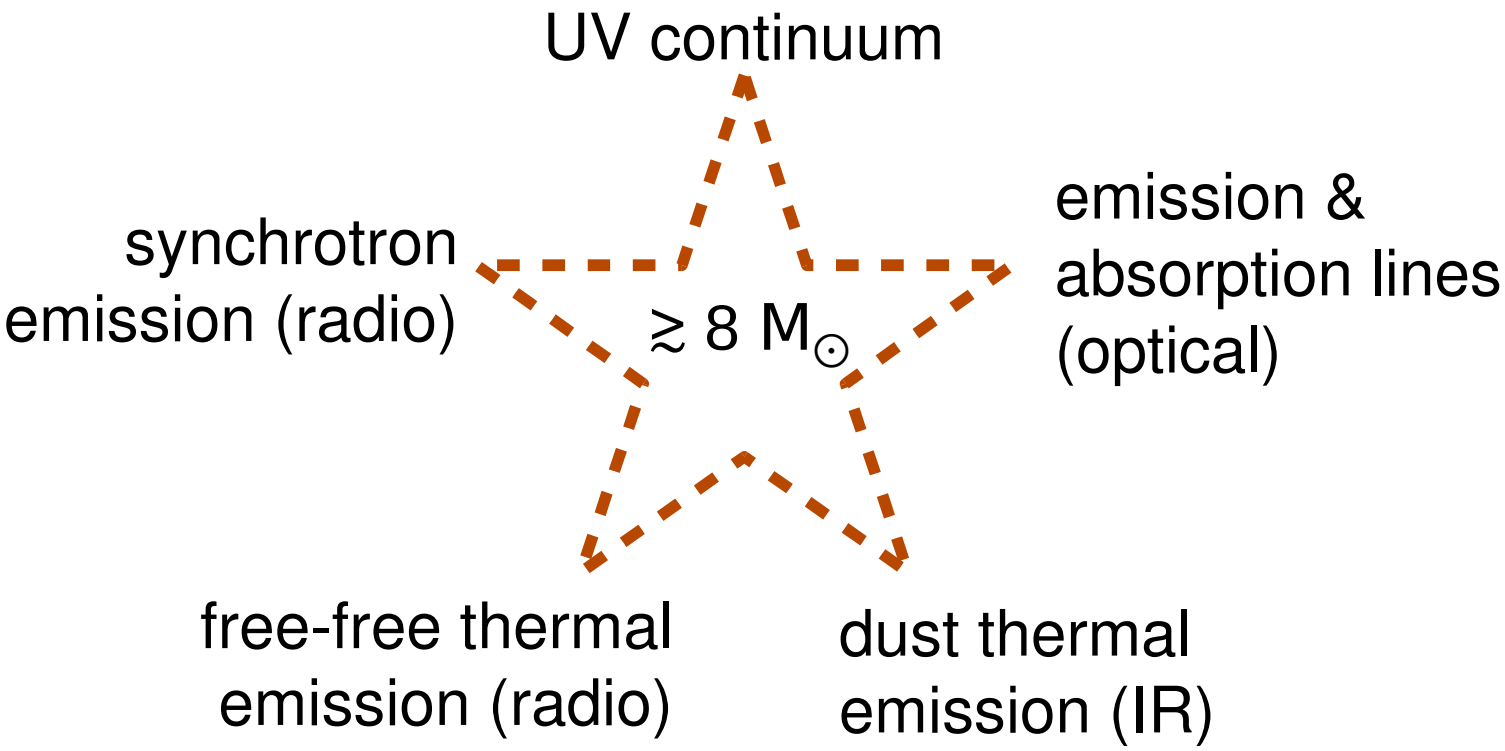
$t \backsim$ Myr - Gyr

Massive stars

$M_{initial} \gtrsim 8\ M_{\odot}$

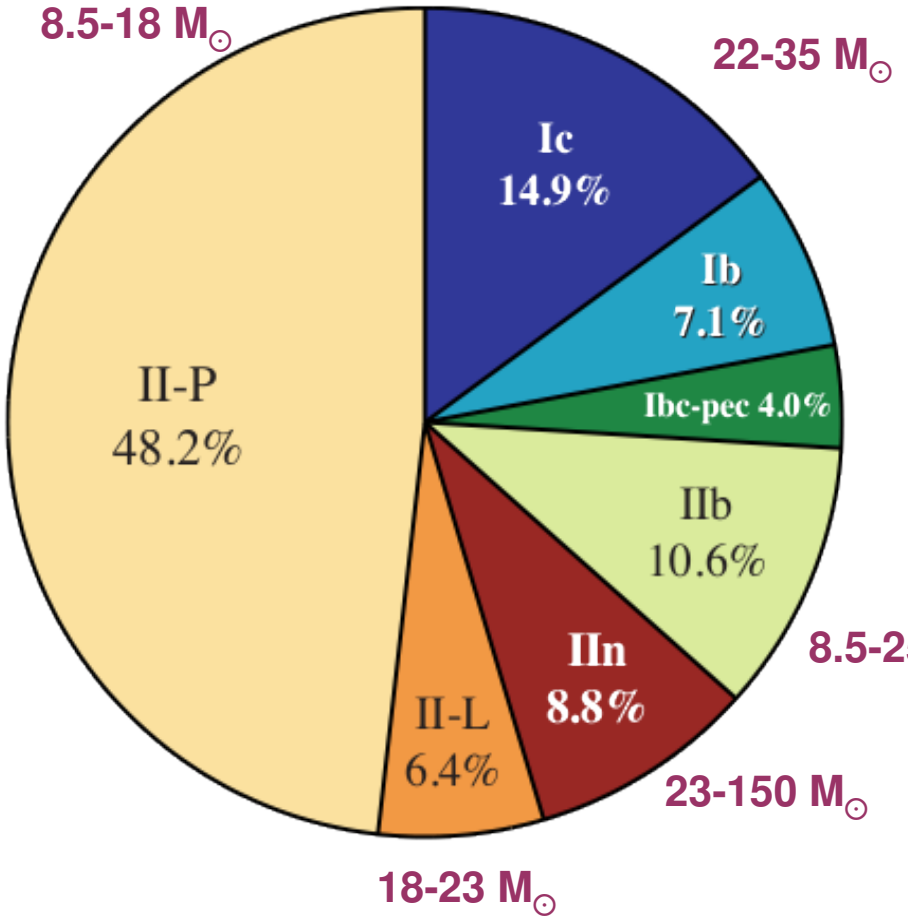
$t \backsim$ Myr

Star formation: tracers (II)

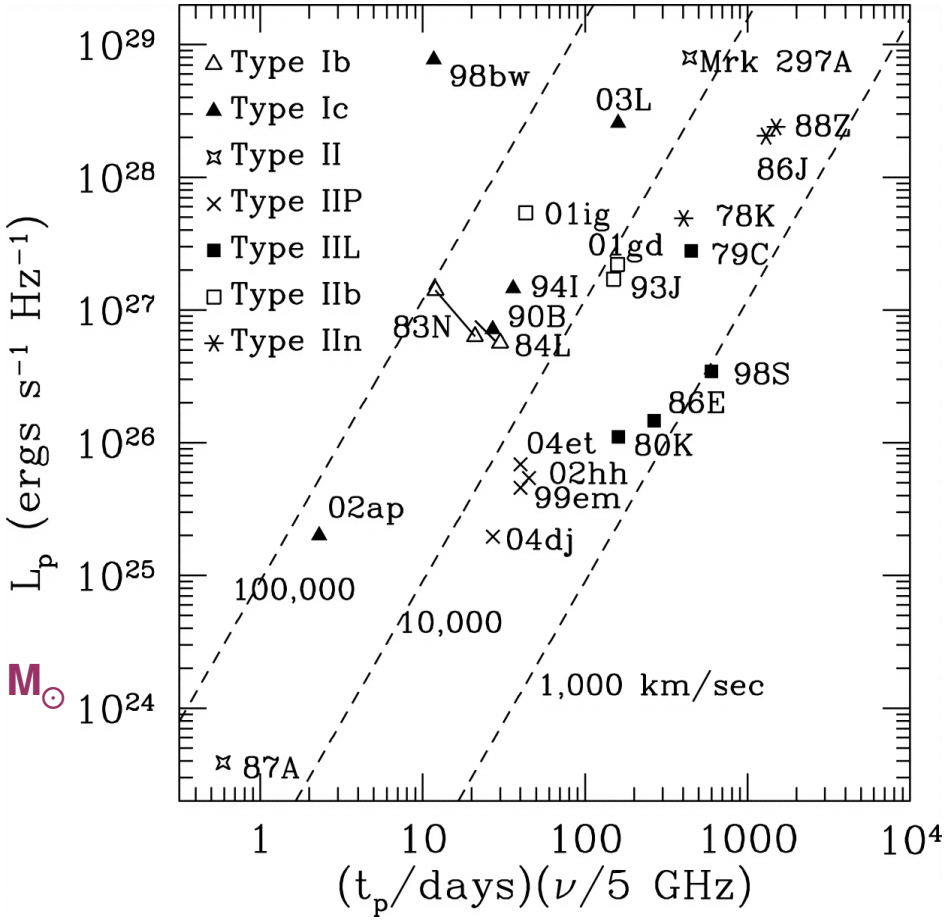


↪ CCSNe as tracers of SFR

CCSNe: relative fractions

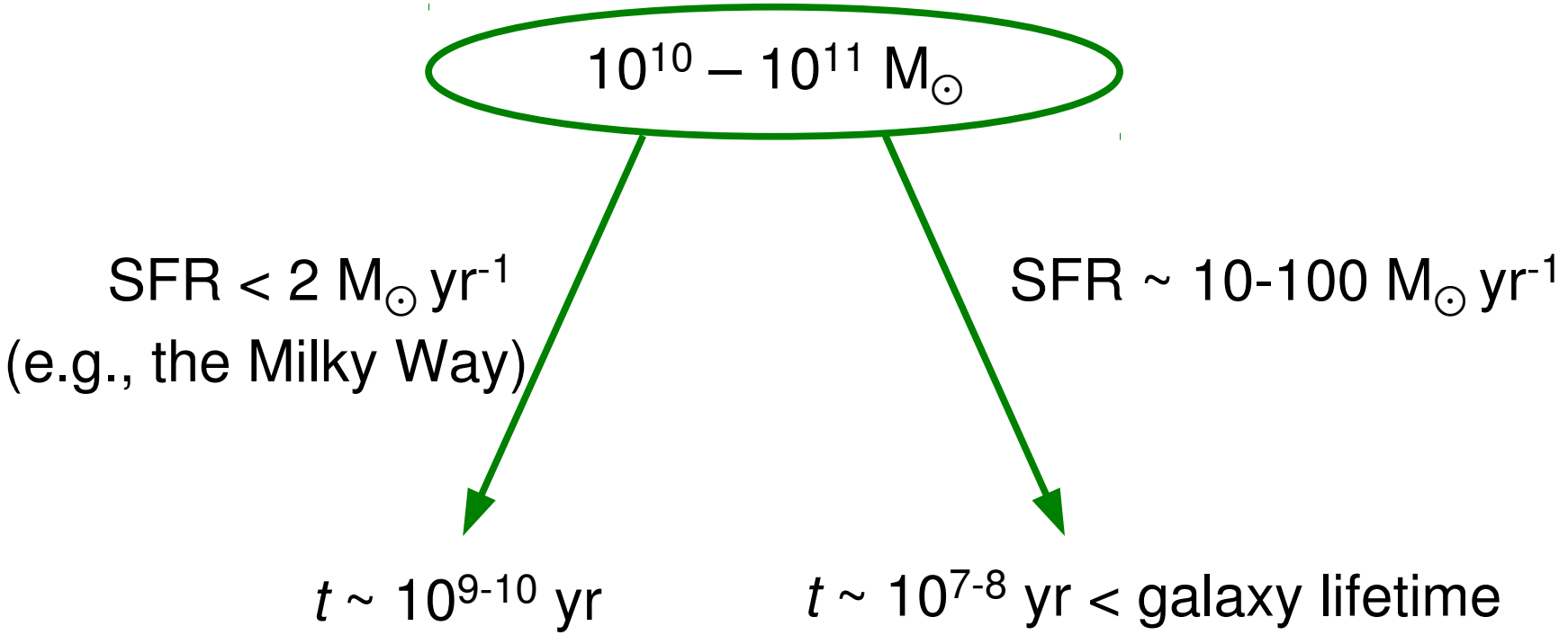


(Smith et al., 2011)

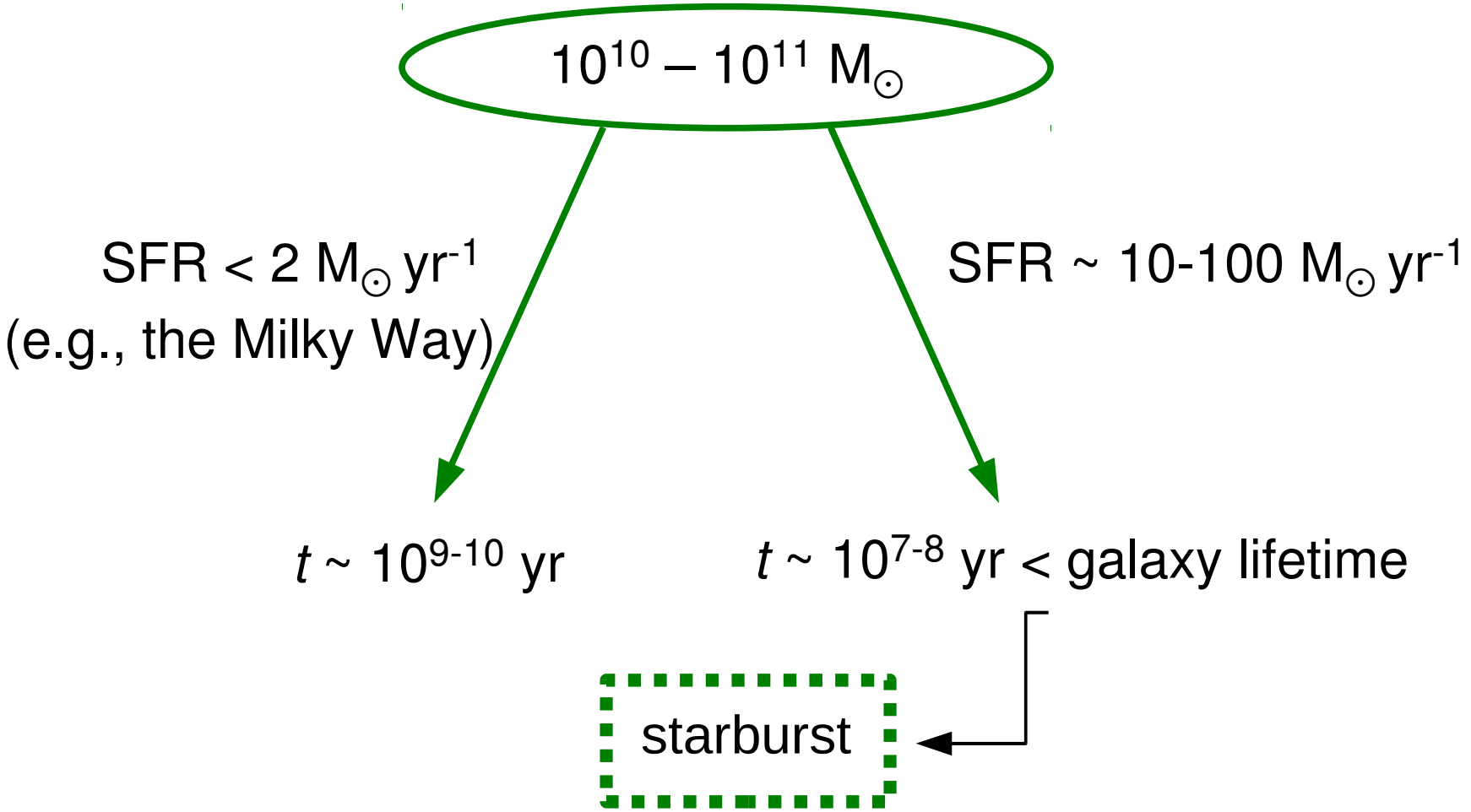


(Chevalier & Franson, 2006)

Starbursts


$10^{10} - 10^{11}$ $M_\odot$
SFR < 2 $M_\odot$ yr^{-1}
(e.g., the Milky Way)
SFR ~ 10-100 $M_\odot$ yr^{-1}
$t \sim 10^{9\text{-}10}$ yr
$t \sim 10^{7\text{-}8}$ yr < galaxy lifetime

Starbursts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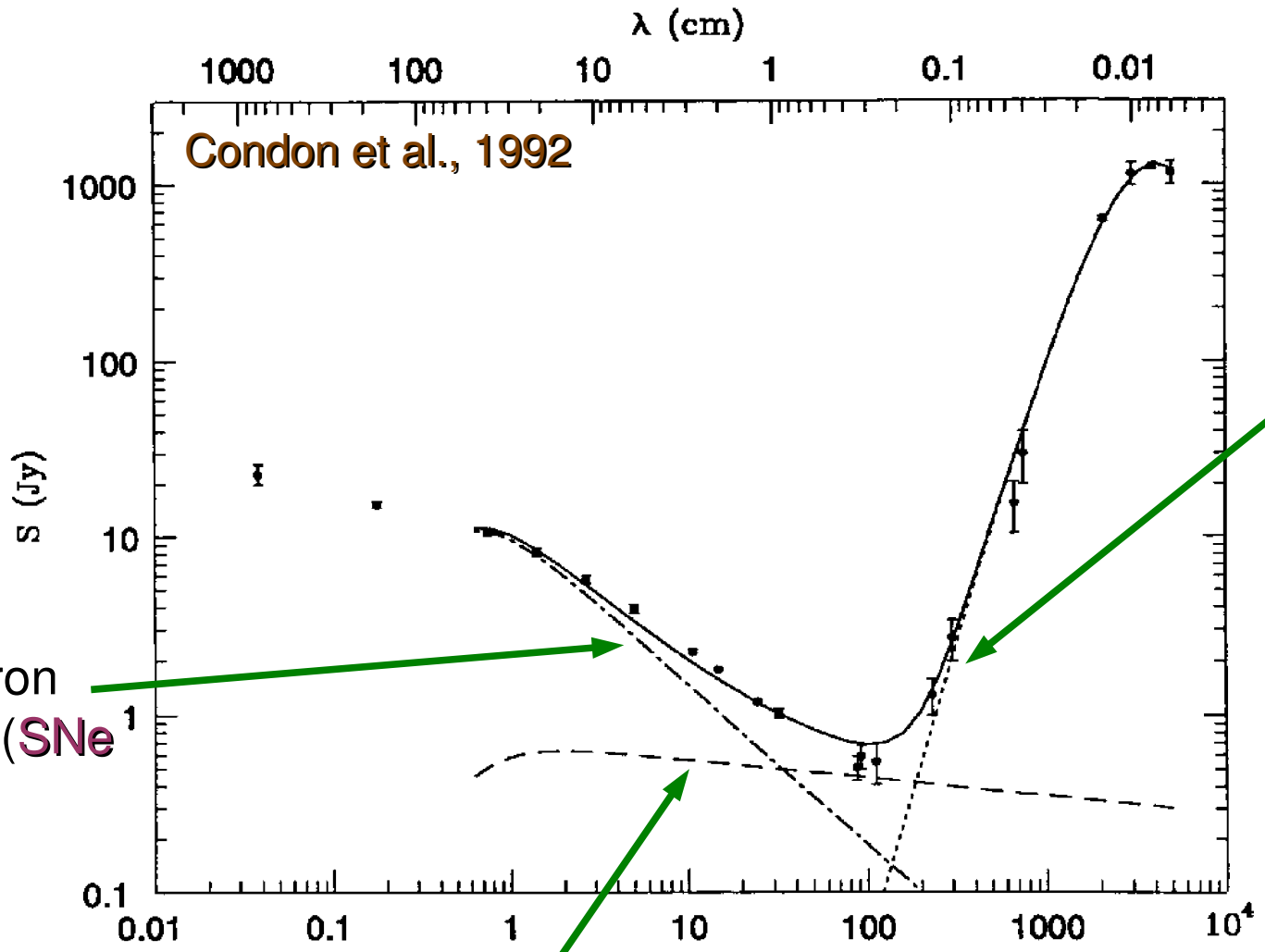
$t \sim 10^{7\text{-}8}$ yr < galaxy lifetime
starburst

Star forming galaxies: SED (radio/FIR)



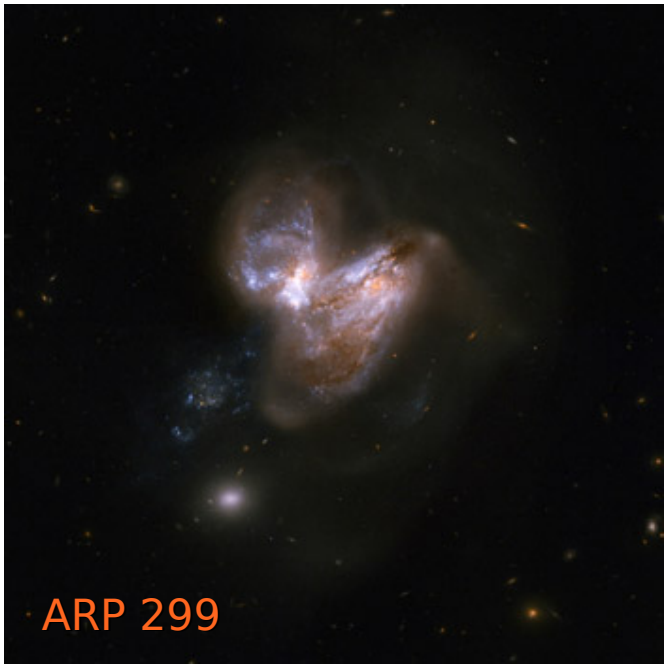
Thermal emission (dust)

Synchrotron emission (SNe & SNRs)

Free-free emission (HII regions)

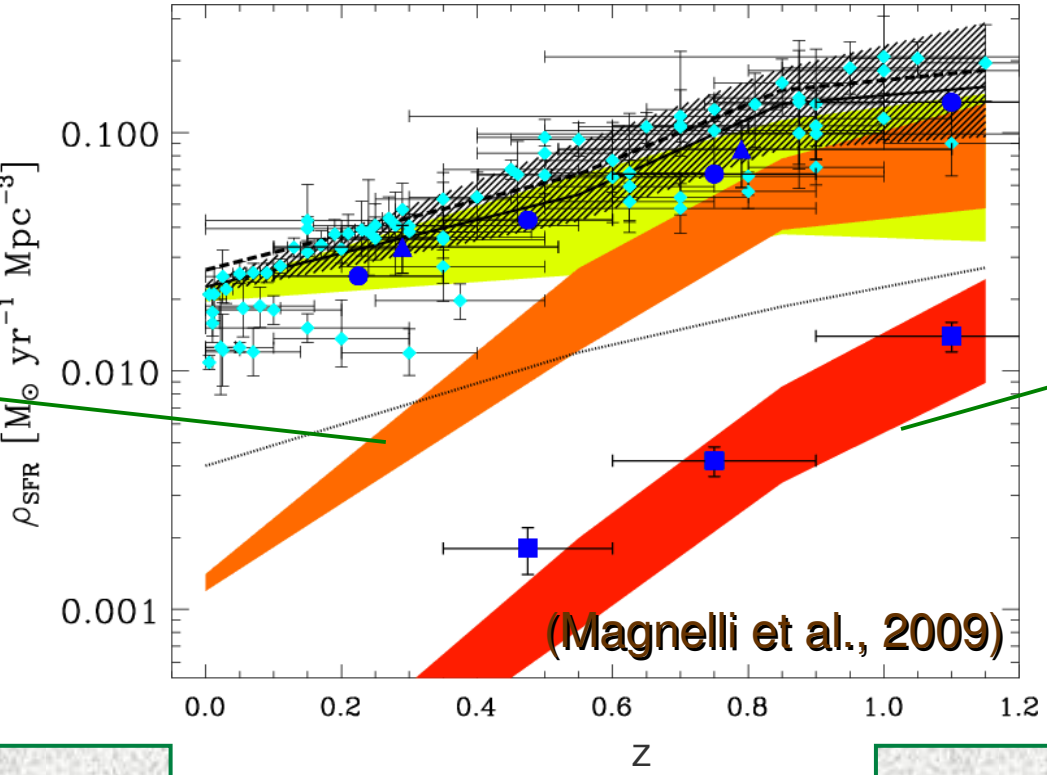
Inducing star formation

Interacting galaxies / Mergers (Sanders & Mirabel 1996)



(U)LIRGs: scaled up starbursts

(Ultra) Luminous Infrared Galaxies



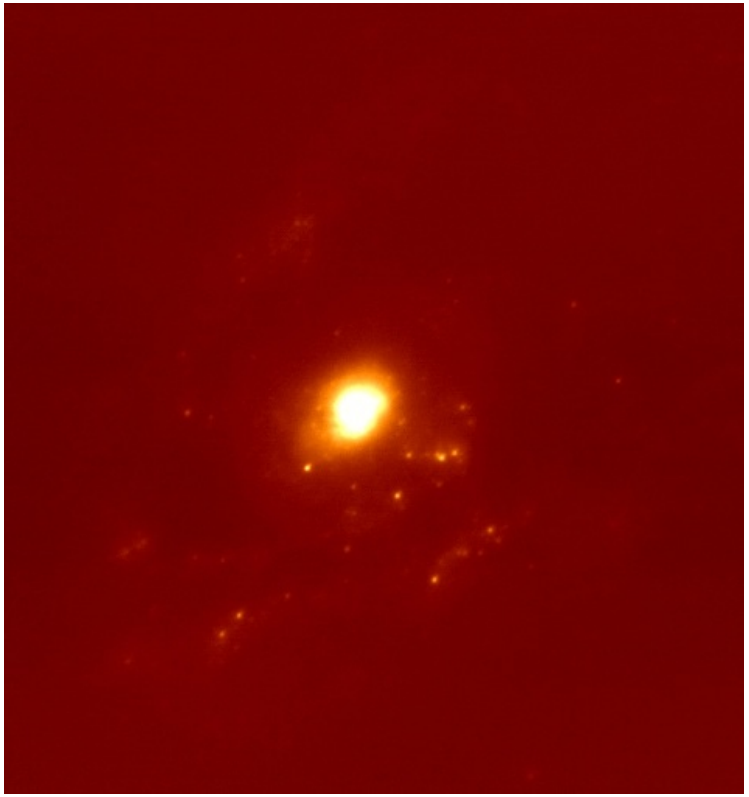
LIRGs

- $L_{IR} > 10^{11}\ L_\odot$
- z~1 (Le Floc'h +05)

ULIRGs

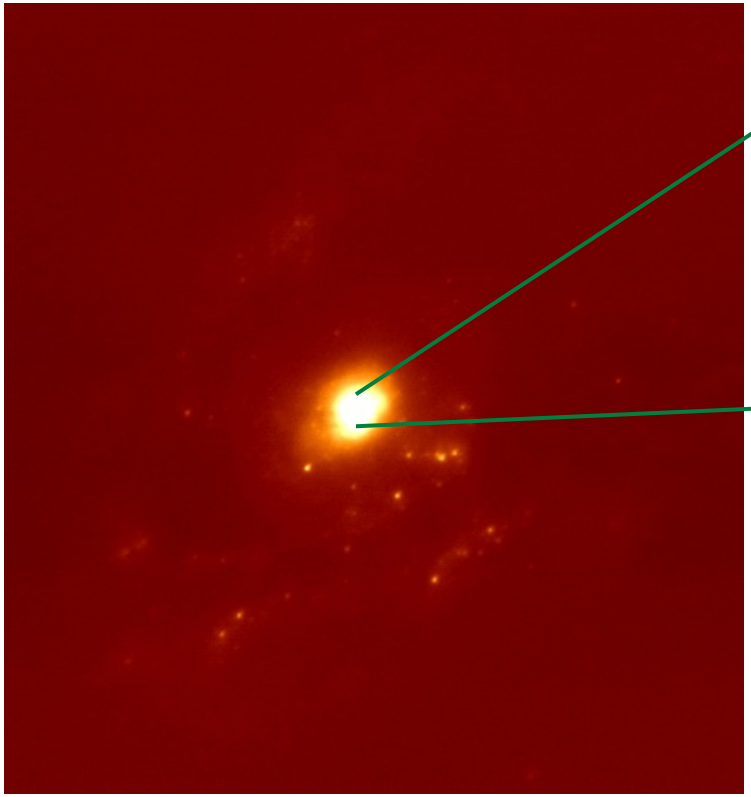
- $L_{IR} > 10^{12}\ L_\odot$
- z~2 (Caputi +07)

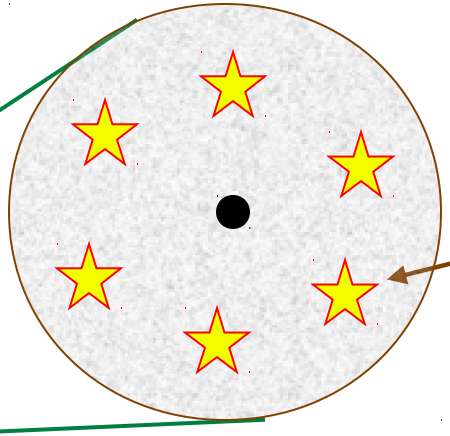
(U)LIRGs: heating mechanism



IC 694 *Gemini*-**NIRI** image @ 2.2 μm

(U)LIRGs: heating mechanism



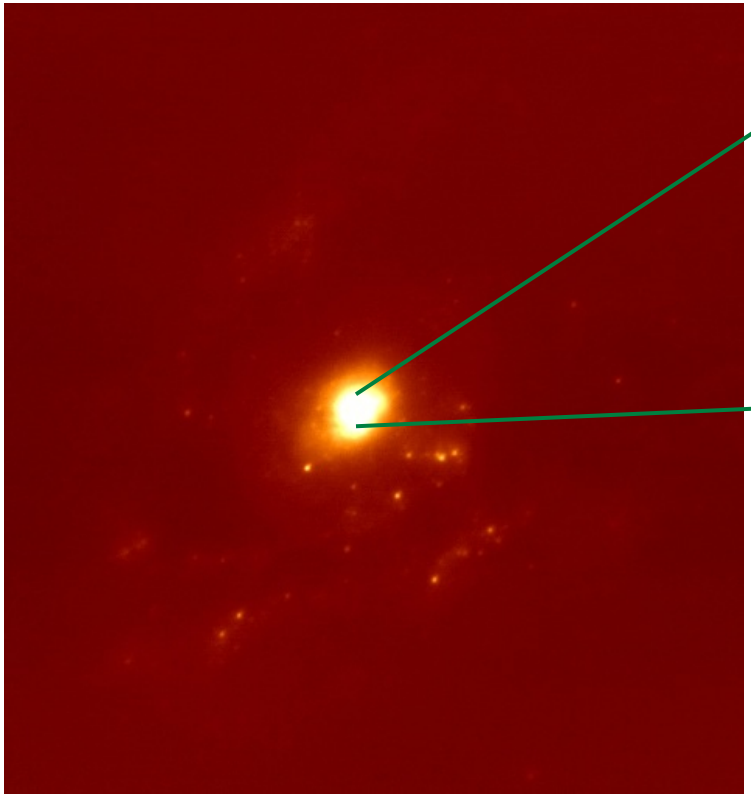


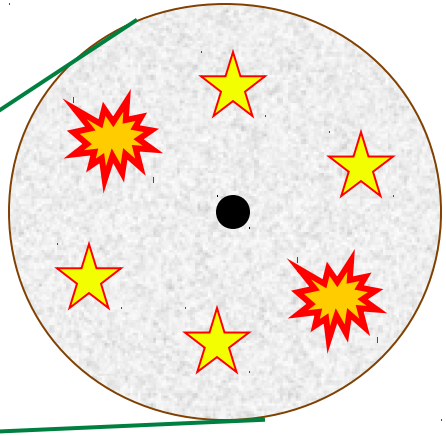
SB and/or AGN

$M > 8M_{\odot}$

IC 694 *Gemini*-**NIRI** image @ 2.2 μm

(U)LIRGs: high SFR





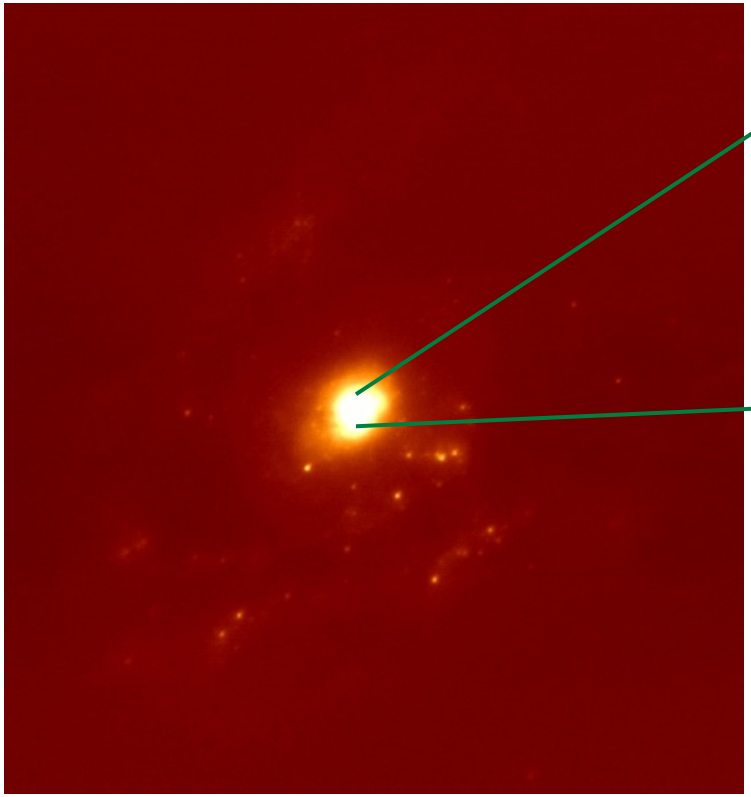
IC 694 *Gemini*-**NIRI** image @ 2.2 μm

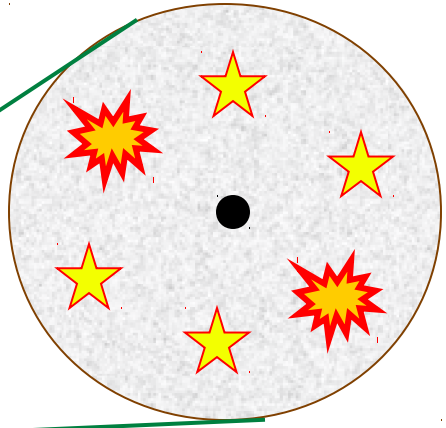
Condon et al., 1992

$$\left(\frac{\nu_{\mathrm{CCSN}}}{\mathrm{yr}^{-1}}\right) \propto \left[\frac{SFR\,(M \geq 8\mathrm{M}_{\odot})}{\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}}\right] \propto \left(\frac{L_{\mathrm{FIR}}}{\mathrm{L}_{\odot}}\right)$$

↑SFRs ⇒ ↑CCSN rates

(U)LIRGs: CCSN rates





IC 694 *Gemini*-**NIRI** image @ 2.2 μm

Mattila & Meikle, 2001

$$\left(\frac{\nu_{\mathrm{CCSN}}}{\mathrm{yr}^{-1}}\right) = 2.7\times10^{-12}\left(\frac{L_{\mathrm{IR}}}{\mathrm{L}_{\odot}}\right)$$

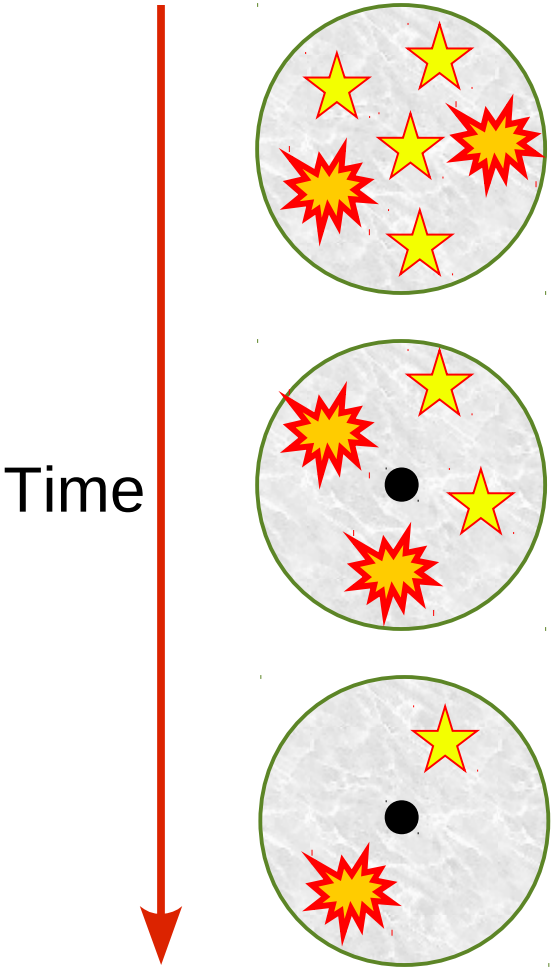
LIRGs → ~0.3-2.6 SN yr^{-1}

ULIRGs → >2.7 SN yr^{-1}

(U)LIRGs: evolution scenario

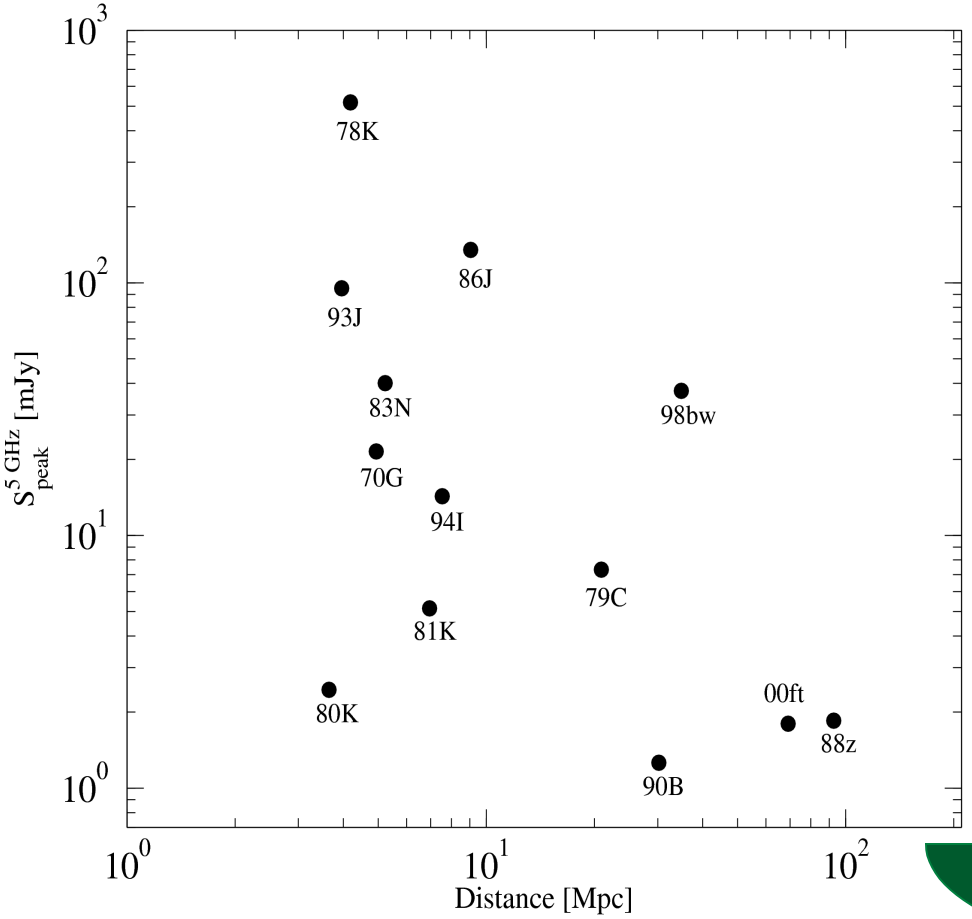
Classification of IR selected galaxies:

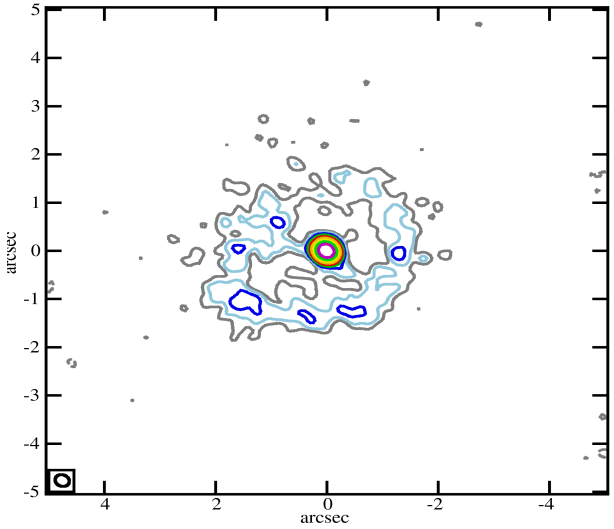
- IR luminosity
- Merger stage



(Yuan et al., 2010)

Observational constraints

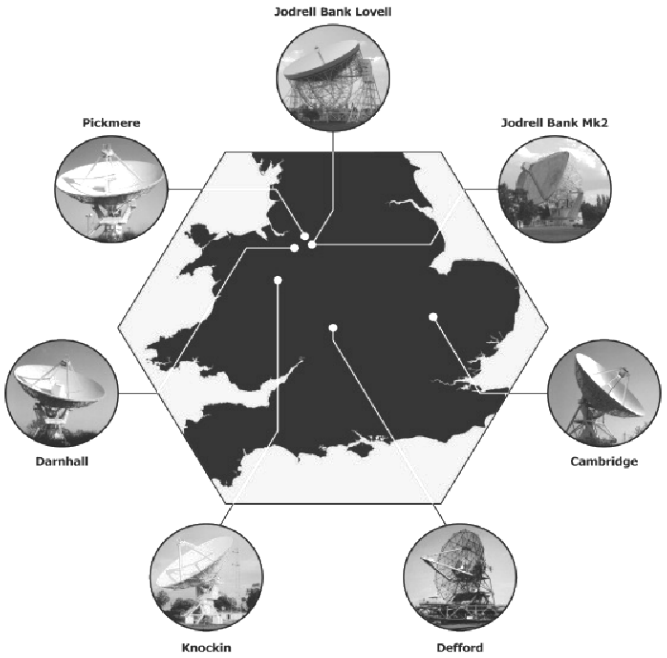




High sensitivity!

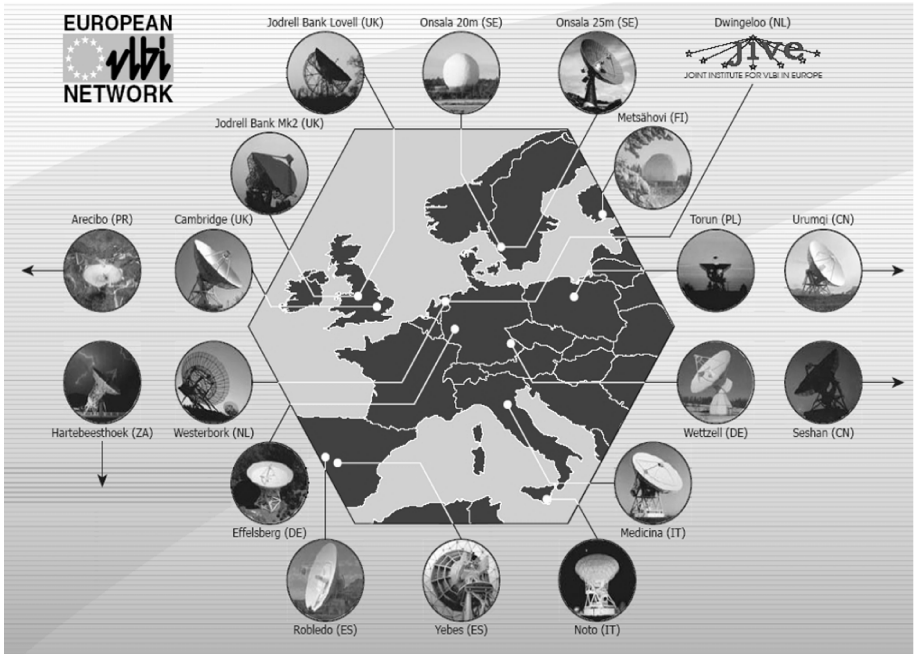
High resolution!

Instruments: radio interferometers



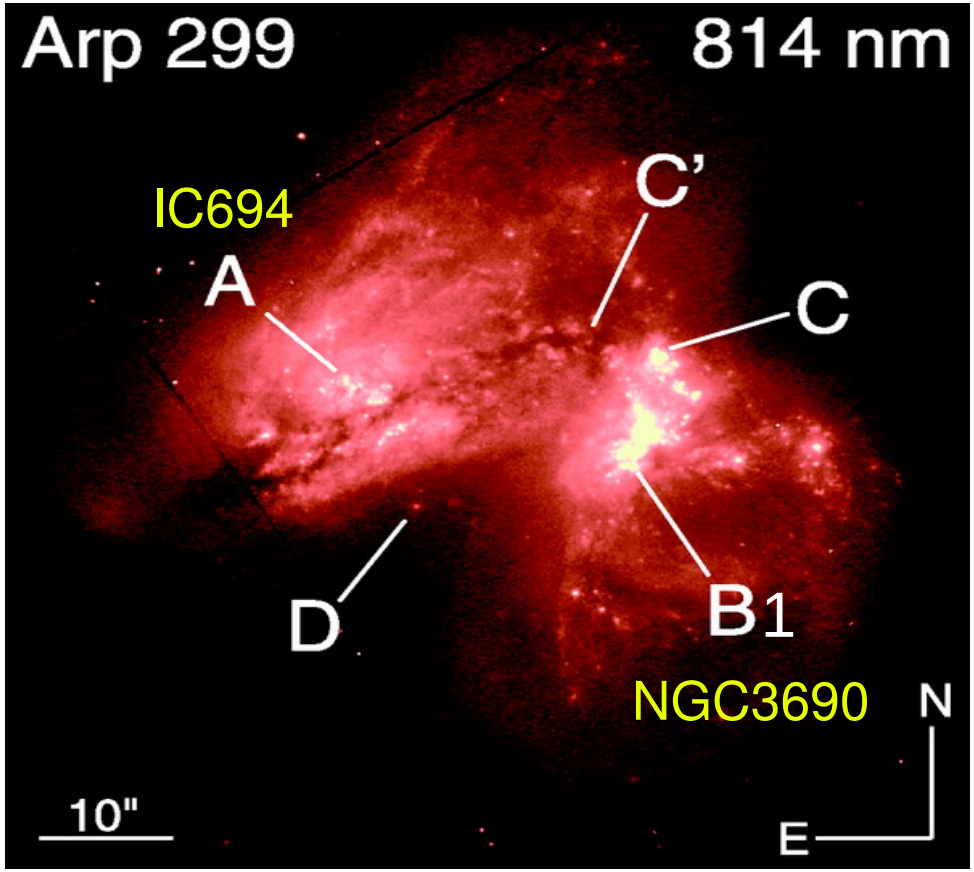
B_{max} ~ 215 km ⇒ 40 mas

B_{max} ~ 36 km ⇒ 400 mas



B_{max} > 8,000 km ⇒ mas

Arp299



HST -**WFPC2** 814nm image (Neff et al., 2004)

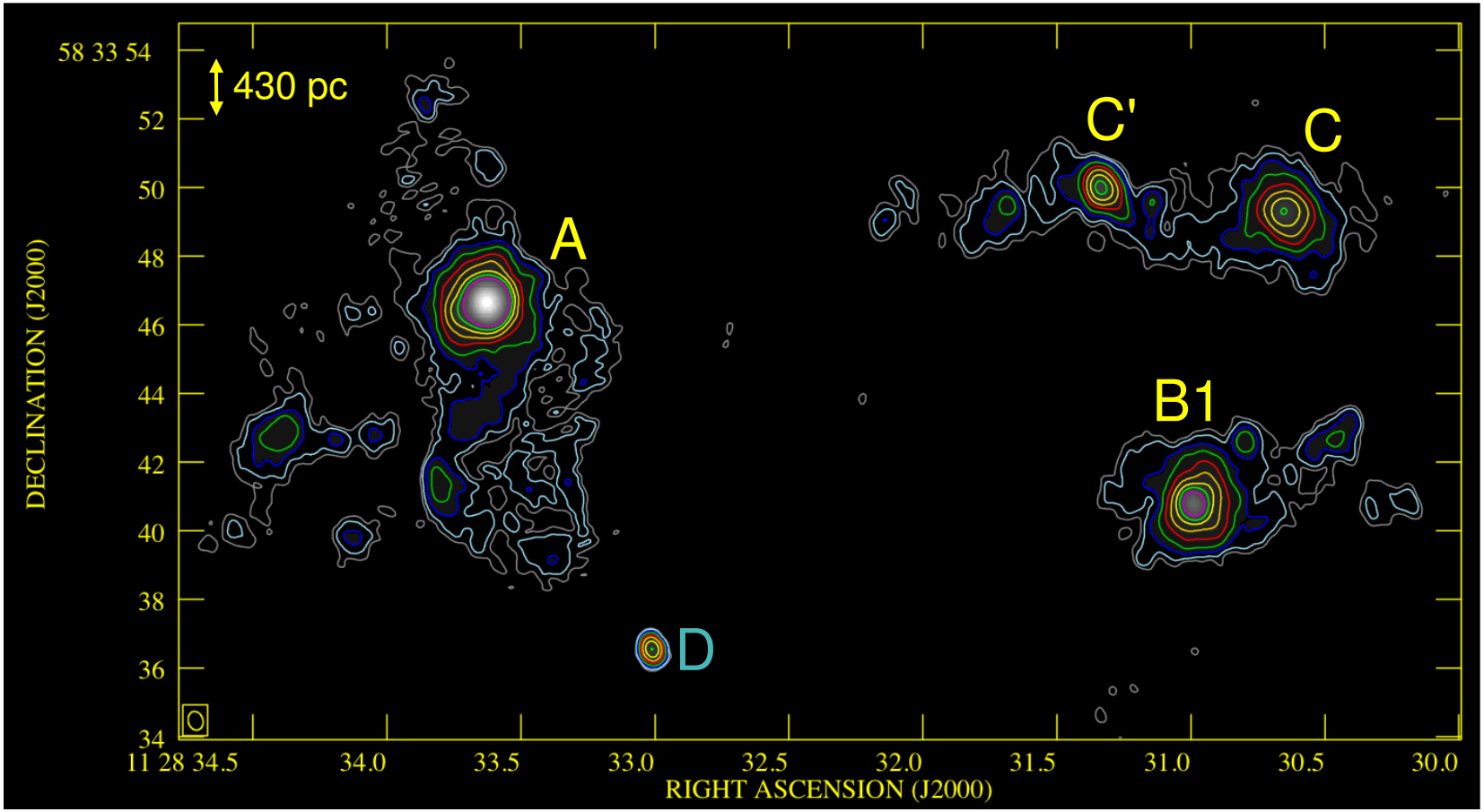
Early stage merger

- D ~ 45 Mpc ⇒ 1 mas ~ 0.2 pc
- L_{IR} ~ 6.7 x 10^{11} $L_{\odot}$

  ~ 40% in A ⇒ $\nu_{CCSN} \approx 0.7\,\mathrm{yr}^{-1}$

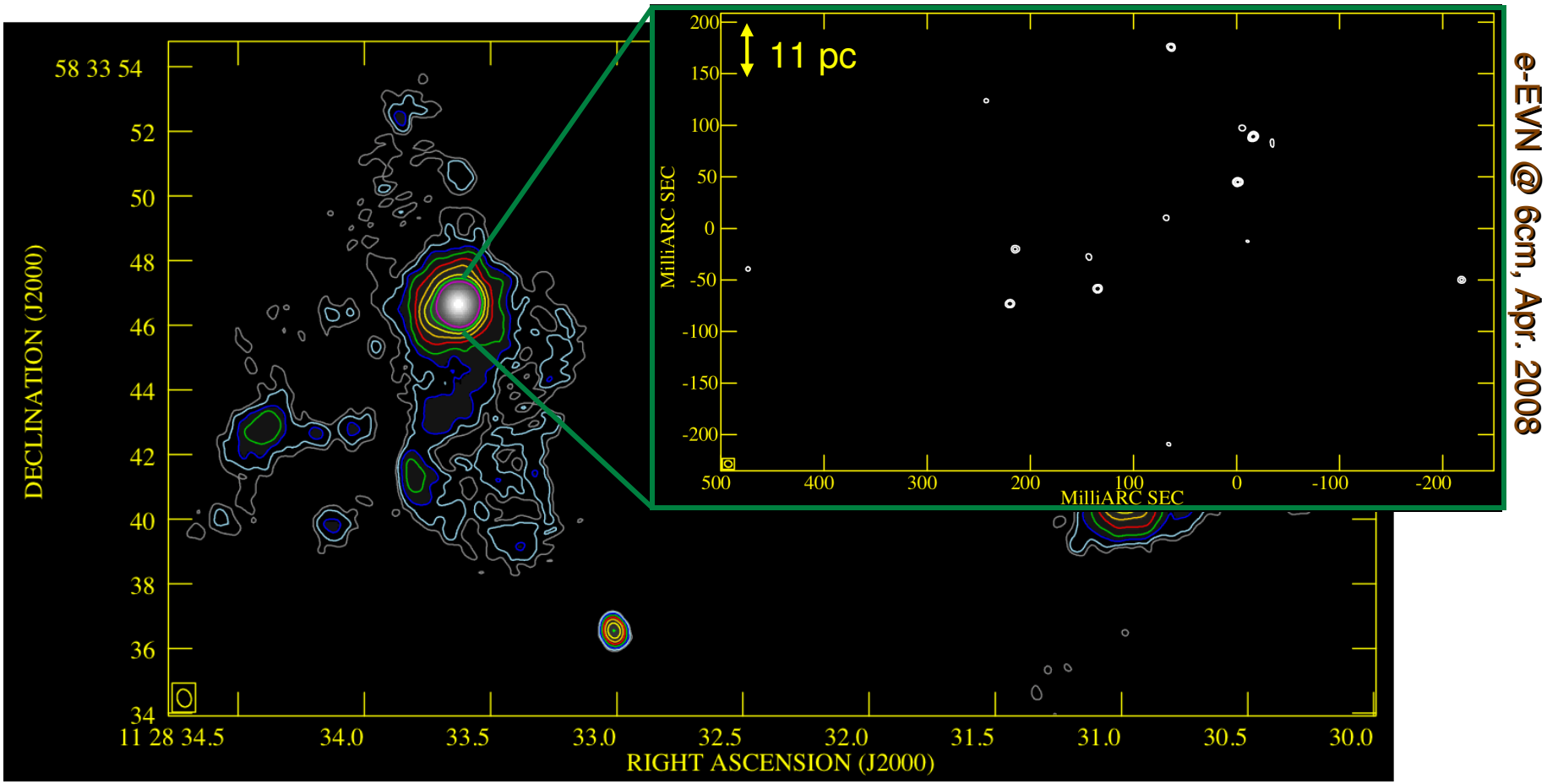
  ~ 20% in B1 ⇒ $\nu_{CCSN} \approx 0.4\,\mathrm{yr}^{-1}$

Arp299: Its radio emission



VLA observations (6cm, Oct 2000)

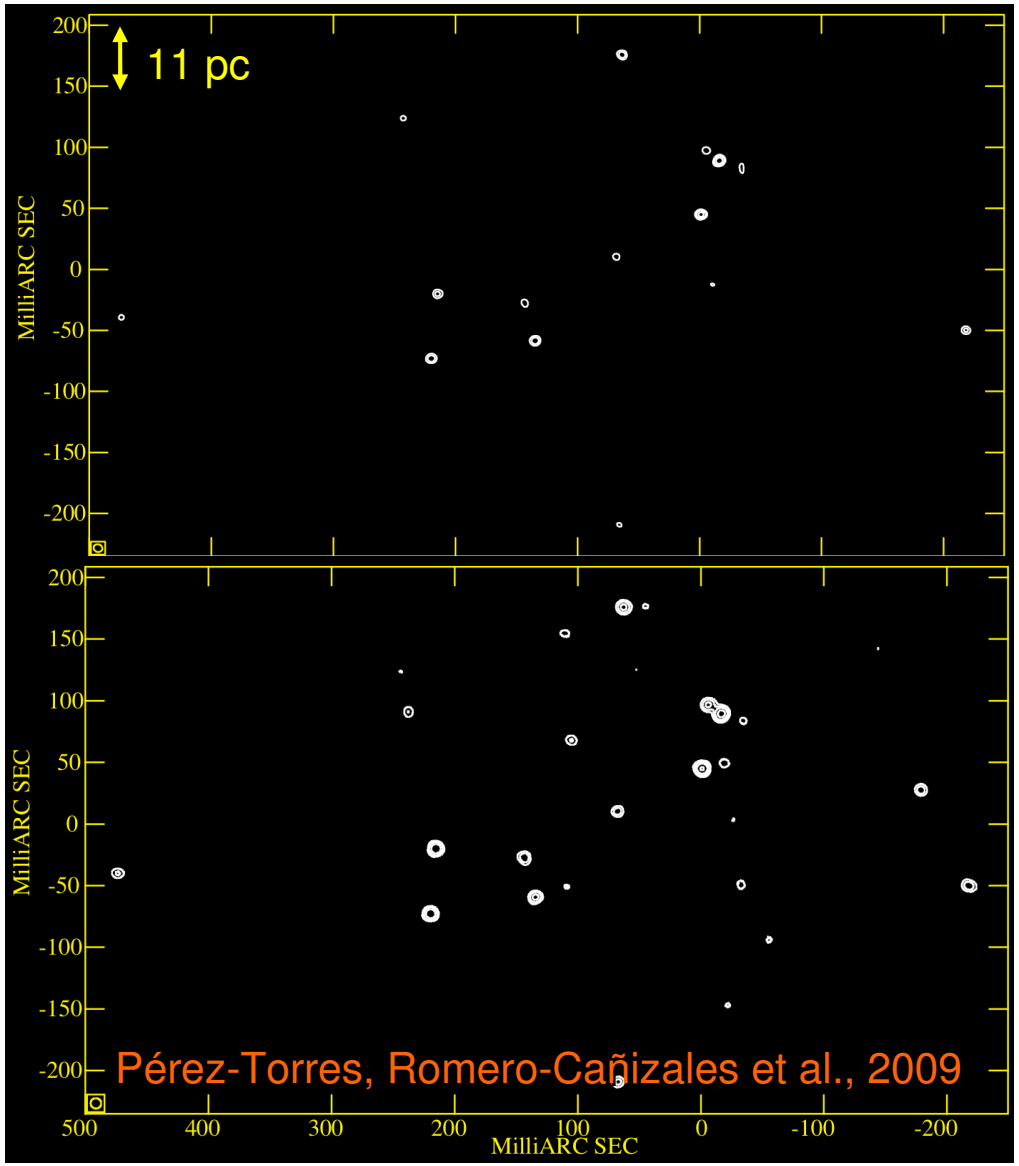
Arp299-A: SN factory (I)



Five of these sources were identified previously with the VLBA by Neff et al., 2004

Arp299-A: SN factory (II)

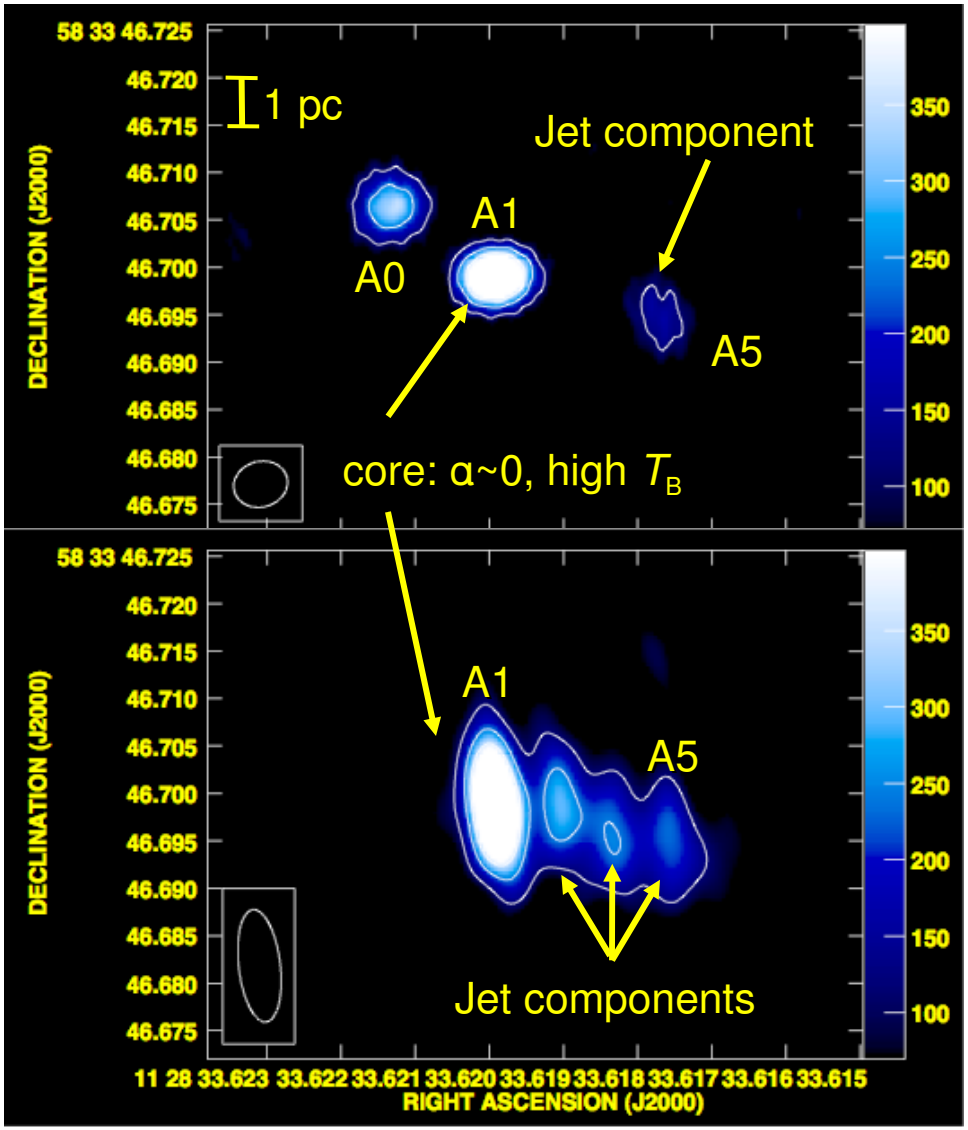
- Rich cluster of compact sources in 150 x 80 pc region
- High $T_B \Rightarrow$ non-thermal origin (SNe and/or SNRs)
- Moderate to high radio emission levels (typical of Type IIb, IIP and IIL SNe): $L_{5GHz} \sim 10^{26}$-10^{27} erg s^{-1} Hz^{-1}
- Three RSNe: young, slowly evolving & long-lasting



Arp299-A: LLAGN and SB coexistence

EVN @ 6cm, Jun. 2009

EVN @ 18cm, Jun. 2009



Discovery of a dusty-buried AGN (Pérez-Torres et al., 2010)

A1-A5 complex

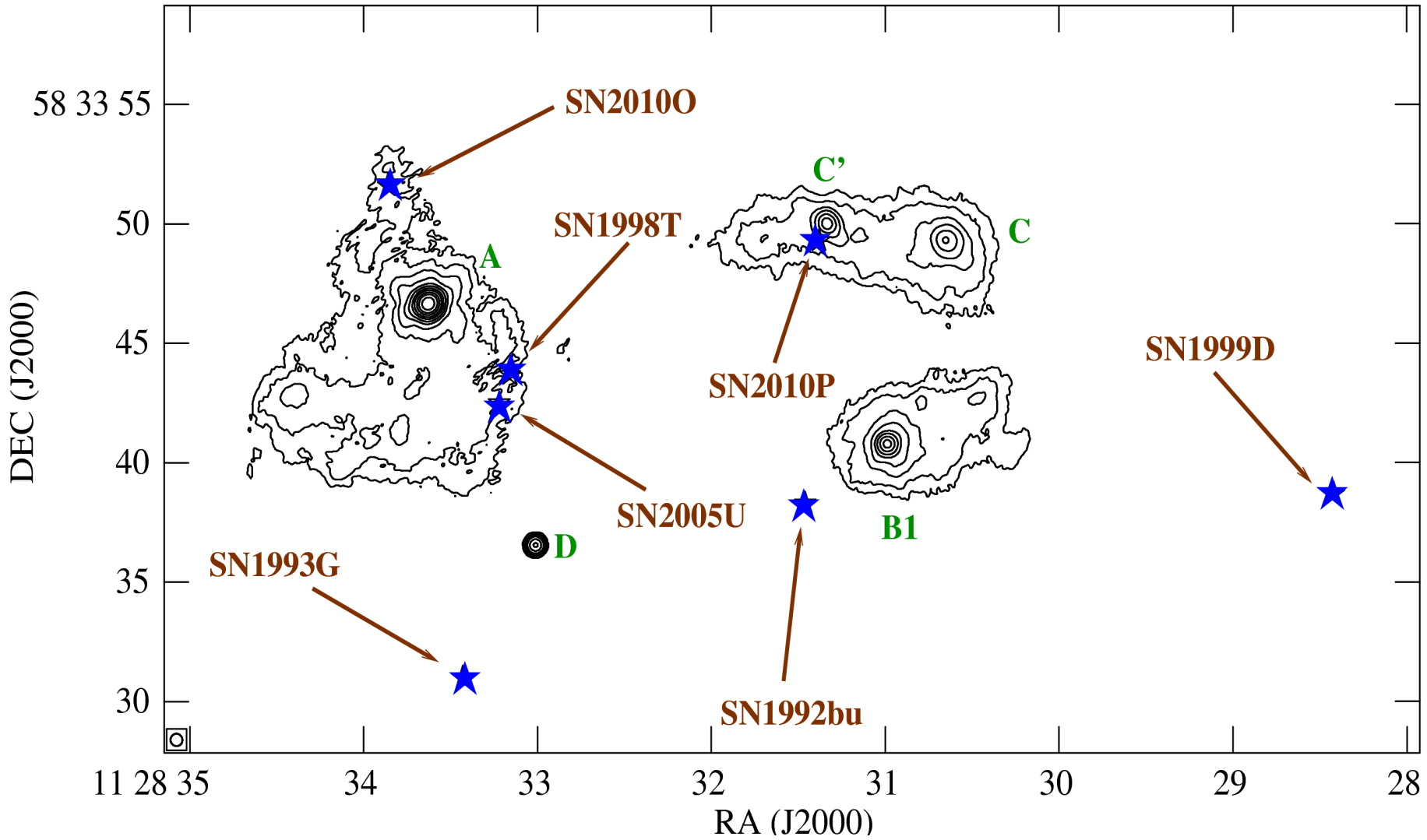
- Core-jet morphology
- $\left(\frac{\nu \times L_\nu}{L_X}\right)_{\nu=5\,\mathrm{GHz}} \sim 10^{-3} \Rightarrow$ LLAGN

A0

- ~~Emission~~ at low freq. by a nearby absorber
- RSN 2 pc away from a SMBH

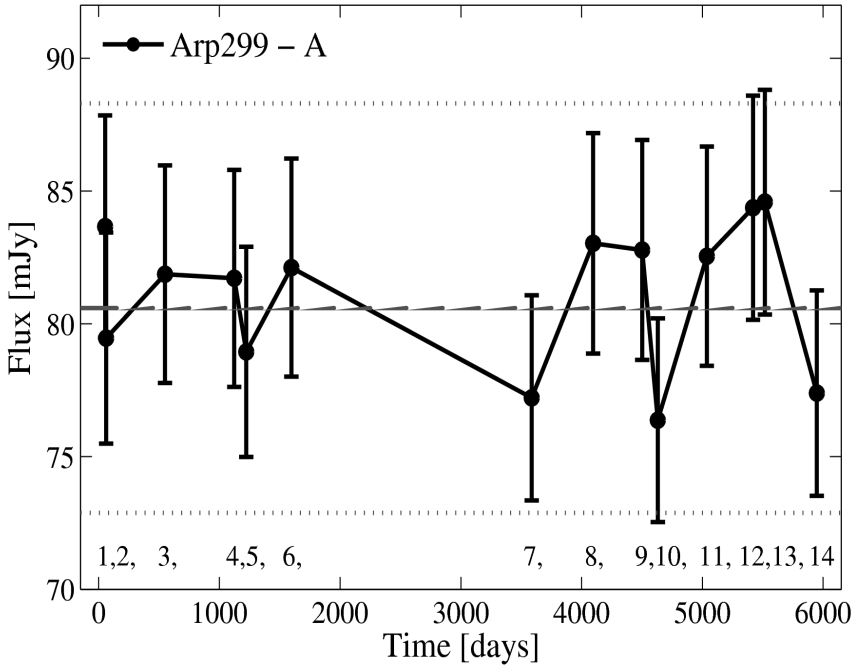
SB & AGN together!!!

Arp299: revisiting the CCSN rate (I)

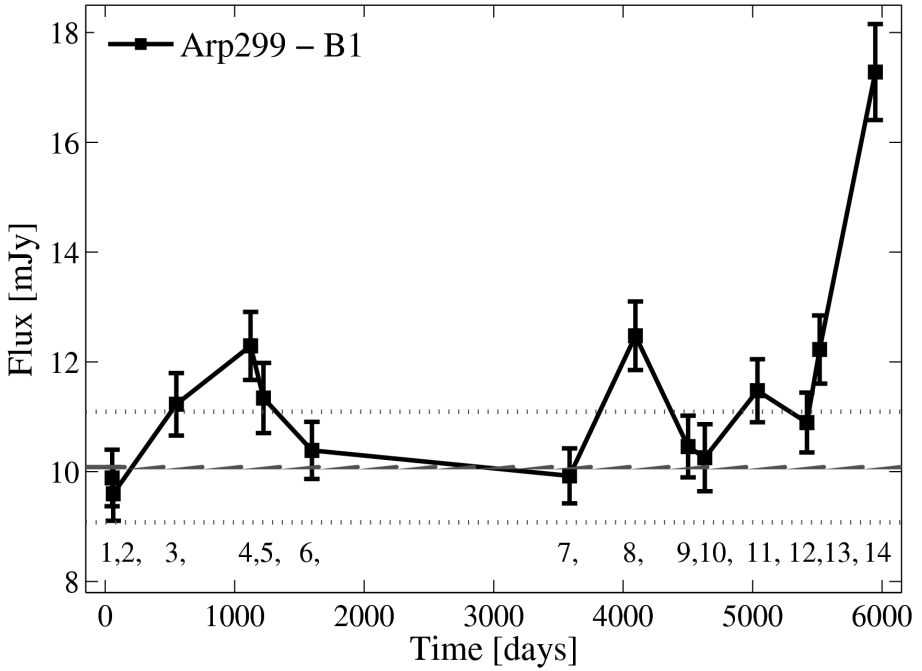


Arp299: revisiting the CCSN rate (II)

σ = 2.57 mJy

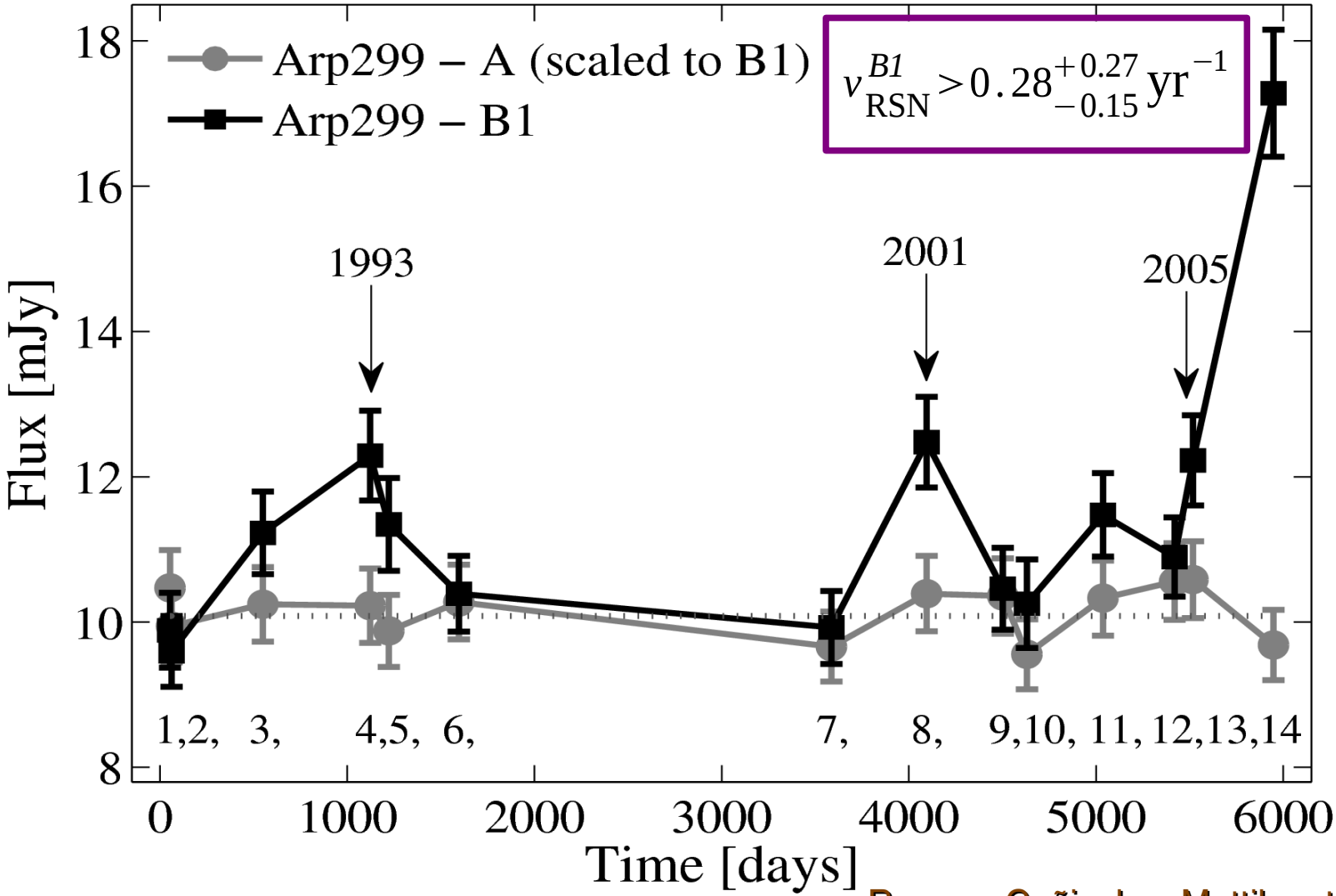


σ = 0.34 mJy



Variability in B1 due to SN activity

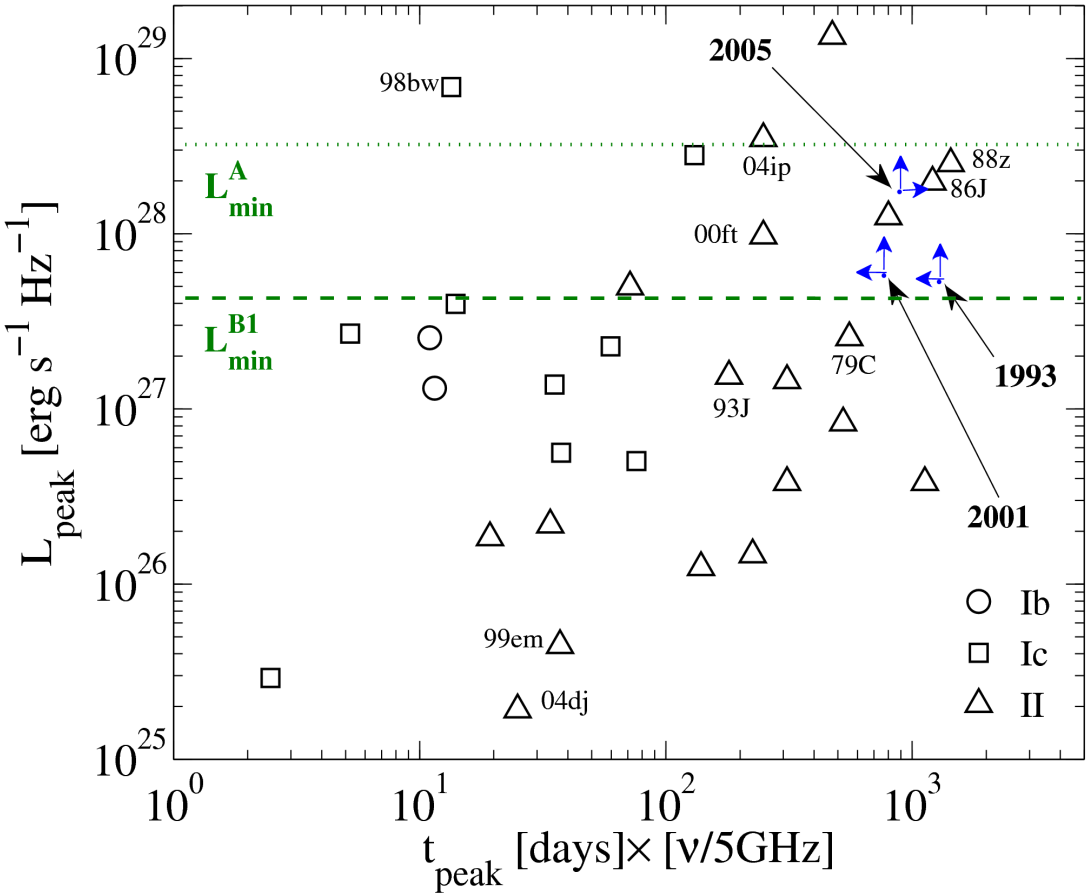
Arp299: revisiting the CCSN rate (III)



Romero-Cañizales, Mattila, et al., 2011

Arp299: revisiting the CCSN rate (IV)

- Three SNe in B1
- Bright & long-lasting SNe



Romero-Cañizales, Mattila, et al., 2011

Arp299: revisiting the CCSN rate (IV)

Before SN explosion:

A

B1

Arp299: revisiting the CCSN rate (IV)

Before SN explosion:

A

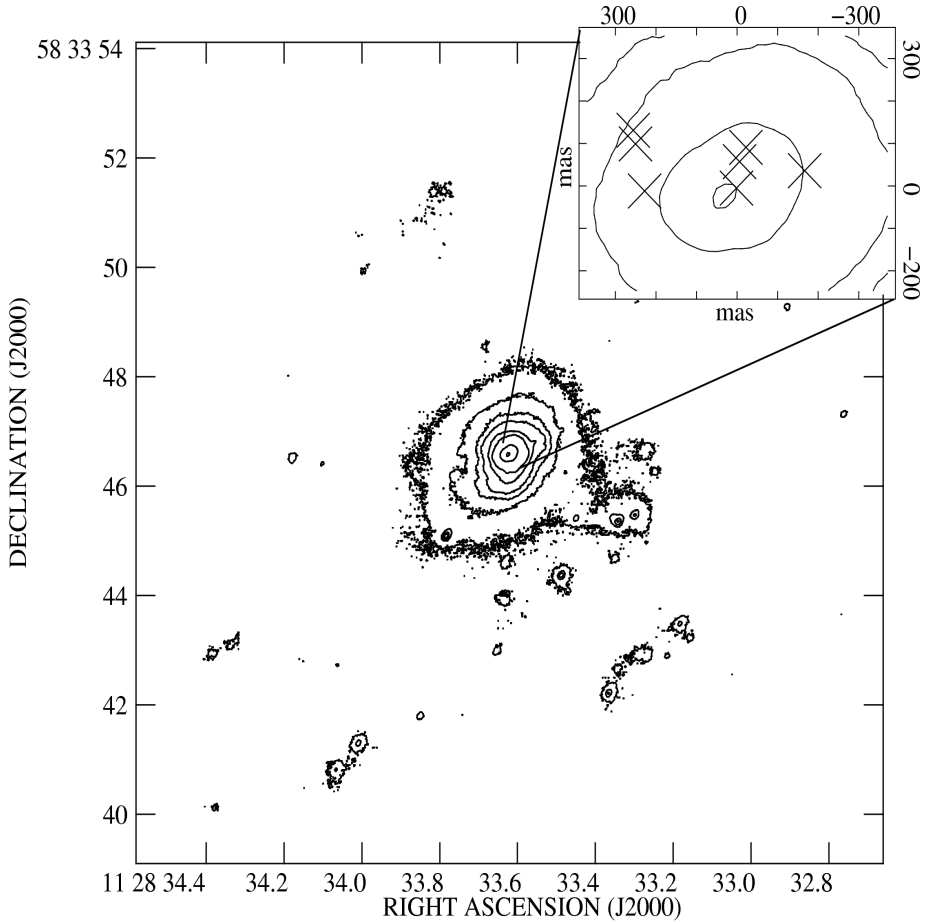
B1

After SN explosion:

A

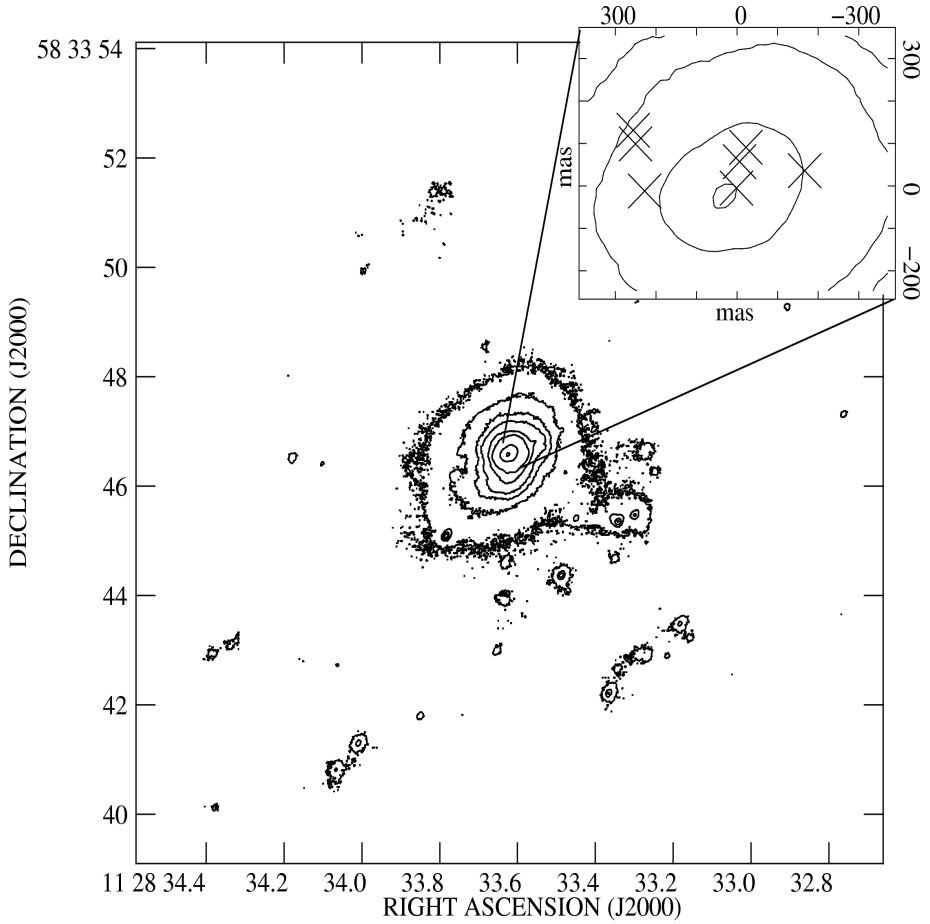
B1

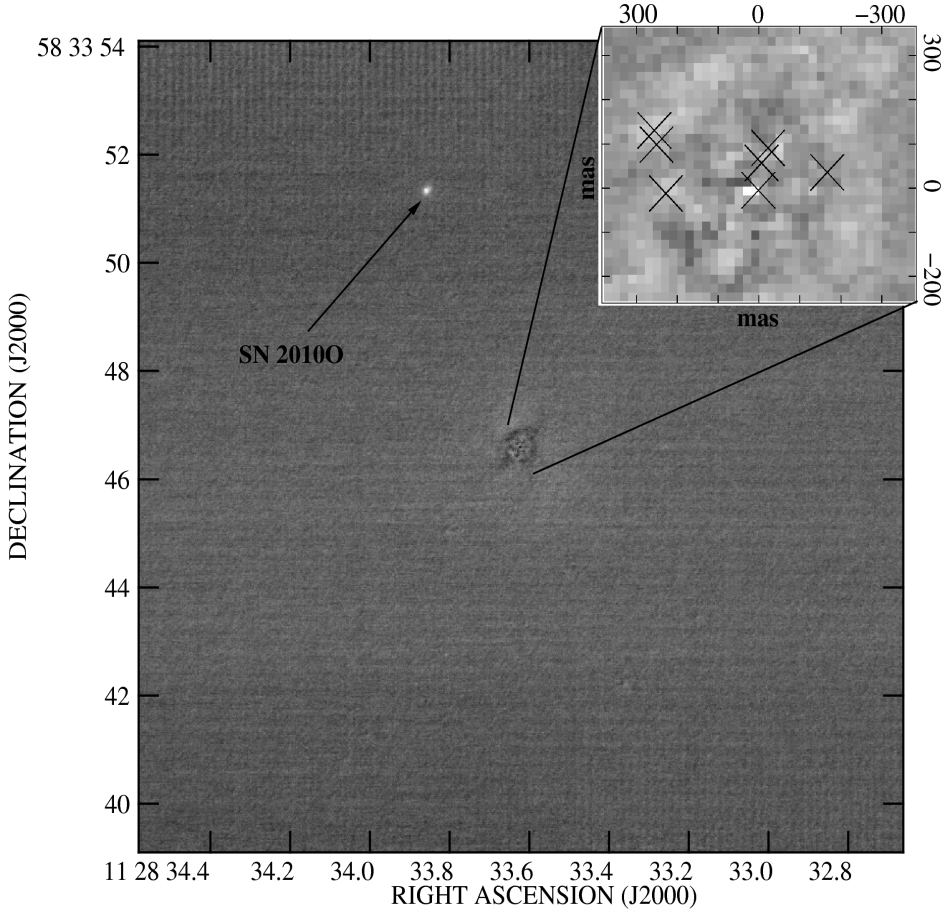
Arp299: searching for radio/NIR SNe (I)



Gemini-**NIRI** image @ 2.2 μm
(FOV=15 x 15 arcsec)

Arp299: searching for radio/NIR SNe (I)





Detection threshold: SN brightness and optical extinctions

Romero-Cañizales, Mattila, et al., 2011

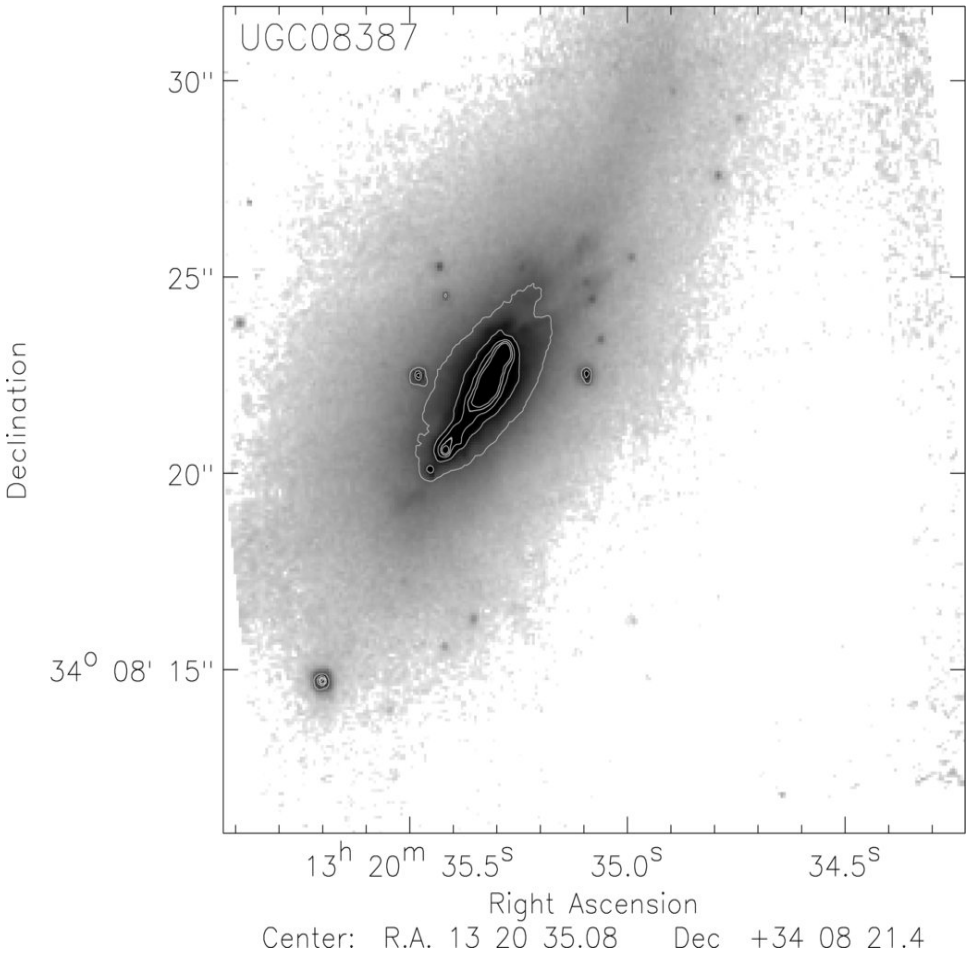
Arp299: results

- **Arp299-A: SN factory** (26 compact sources in a 150x80 pc region, with L_{5GHz}~ 10^{26}-10^{27} erg s^{-1} Hz^{-1}, typical of Type IIb, IIP and IIL SNe, and SNRs)

- Detection only possible through VLBI due to the brightness of the nucleus A

- **CCSN rate in B1 of ~0.28 (+0.27,-0.15) yr^{-1}** from the indirect detection of three SNe

IC883



***HST* -NICMOS 1.6 μm image (Haan et al., 2011)**

Romero-Cañizales et al., 2012
(accepted for pubblication in A&A)

see also: **Kankare et al., 2012**

Advanced stage merger (starburst-AGN composite)

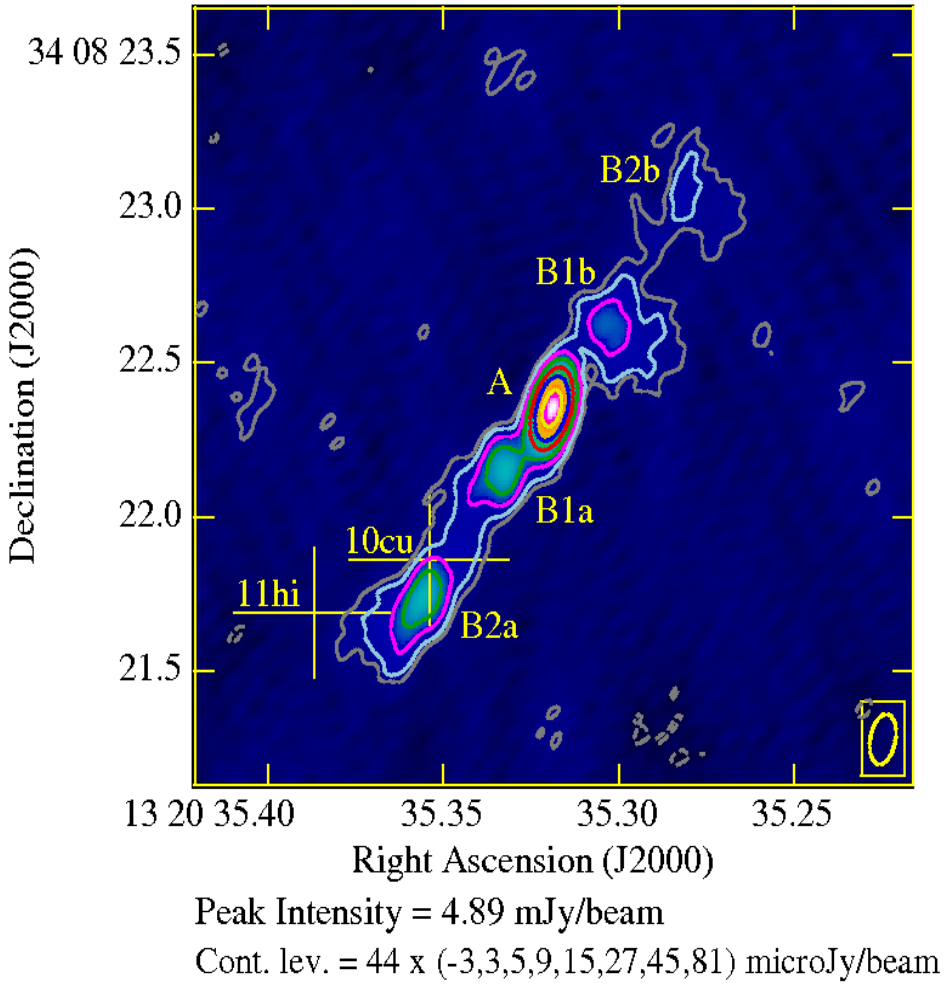
- D ~ 100 Mpc ⇒ 1 mas ~ 0.5 pc
- L_{IR} ~ 4.7 x 10^{11} $L_{\odot}$

$$\nu_{CCSN} \approx 1.3\,\mathrm{yr}^{-1}$$

Two new SNe discovered: SN 2010cu (Ryder et al., 2010) & SN 2011hi (Kankare et al. 2011)

$$\nu_{CCSN} \approx 2^{+2.6}_{-1.3}\,\mathrm{yr}^{-1}$$

IC 883: e-MERLIN observations

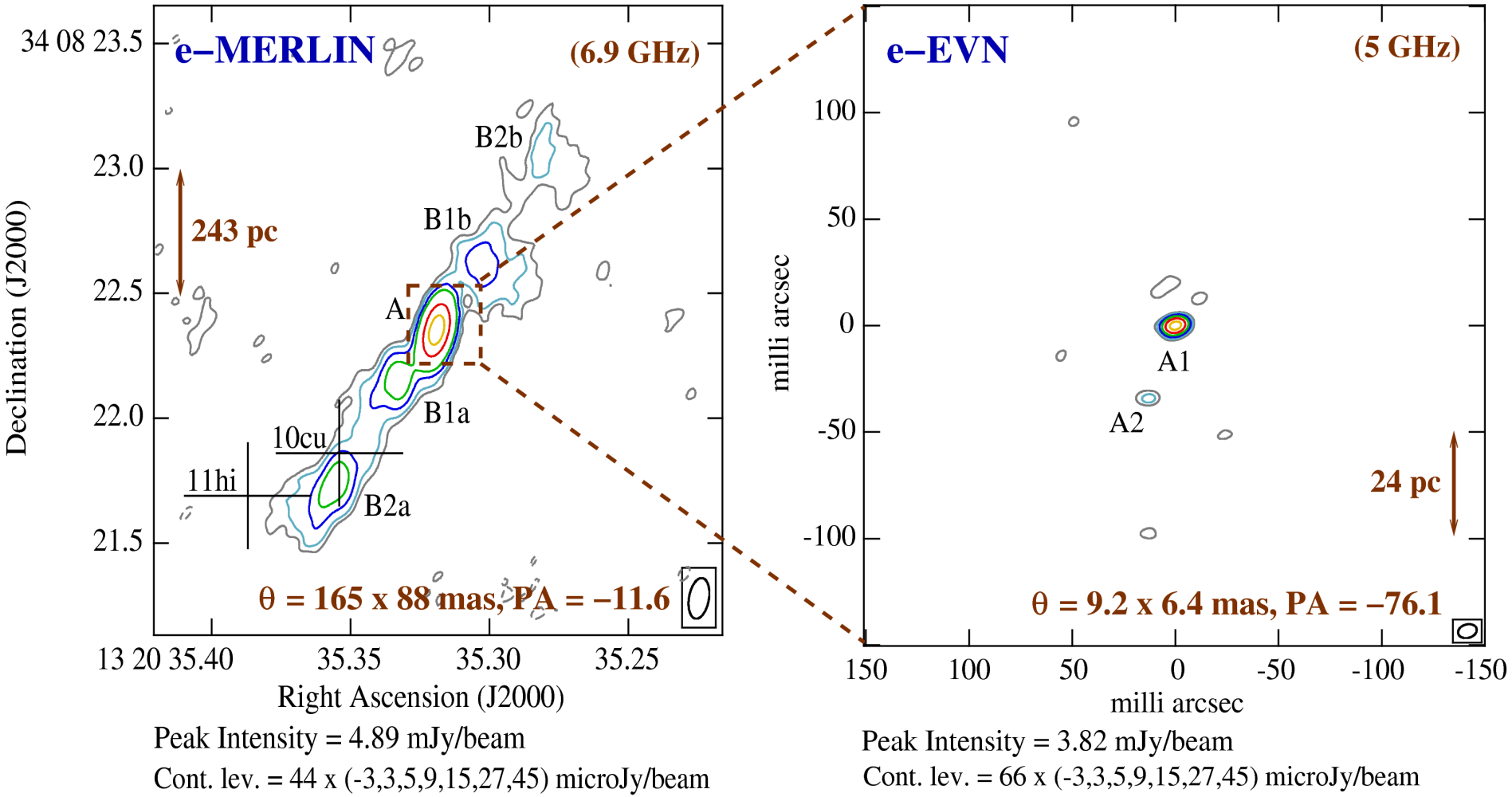


~ 1 kpc structure at 144º

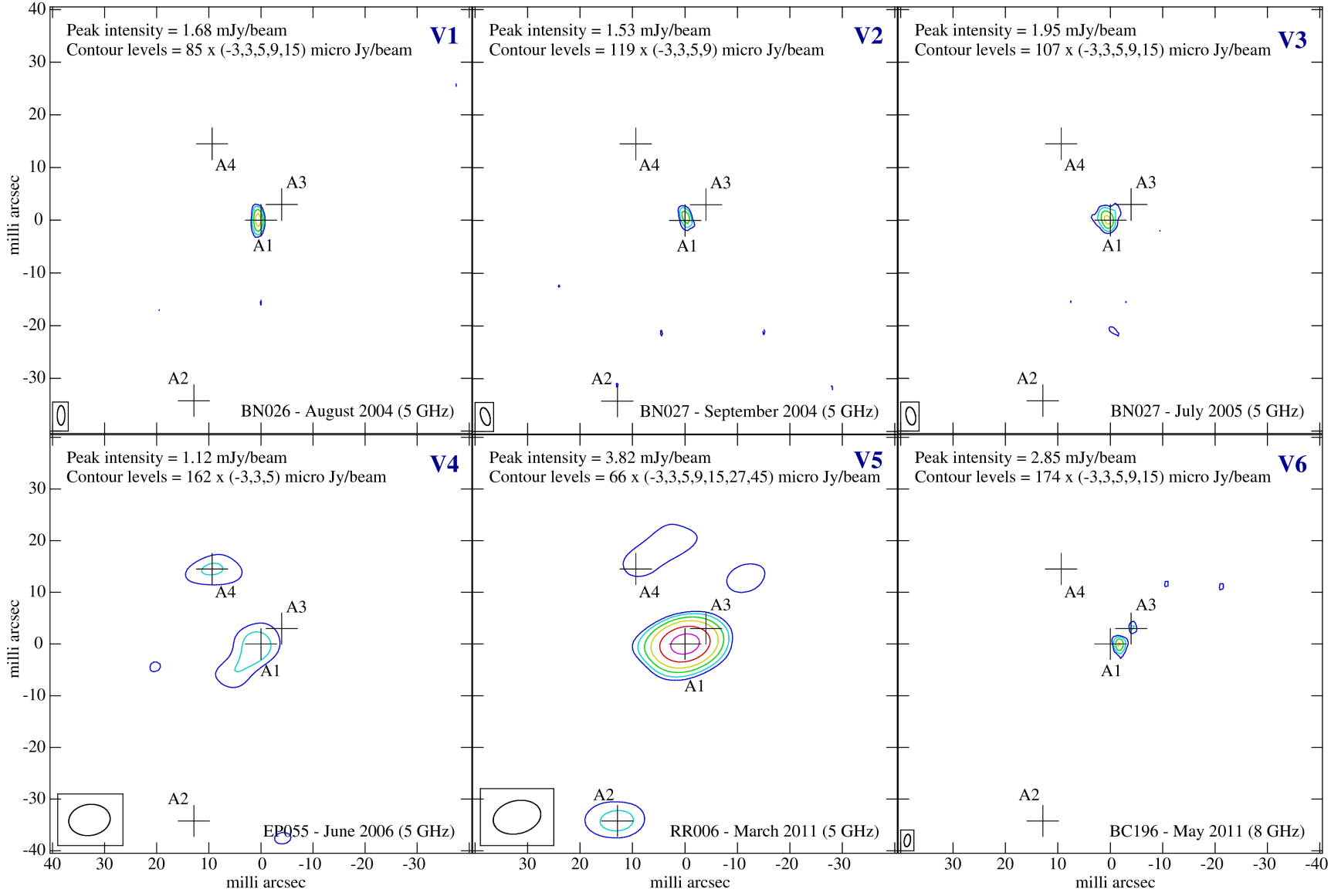
Jet?

Warped ring?

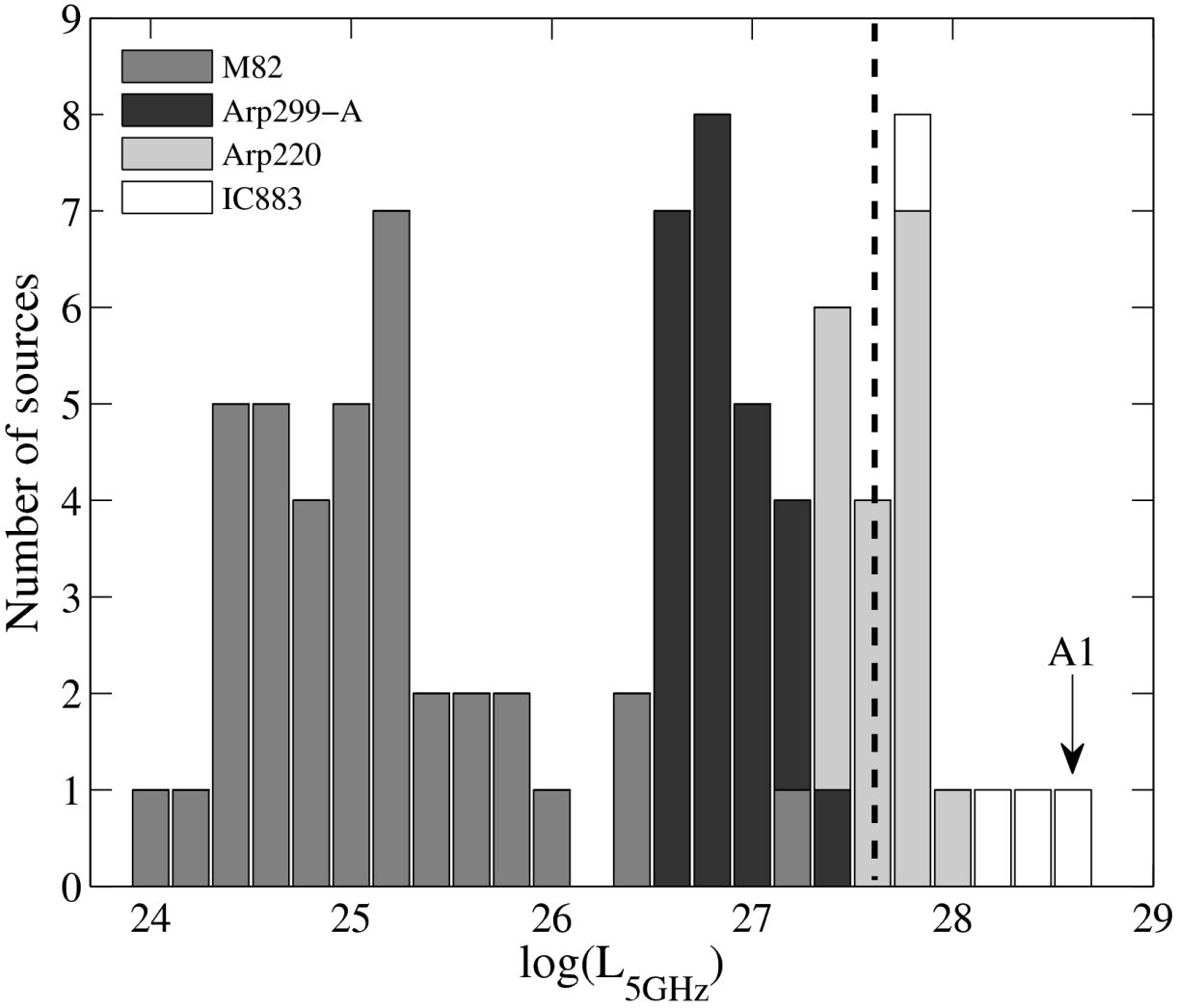
IC 883: e-MERLIN + e-EVN observations



IC 883: VLBI monitoring



IC 883: compact sources (SNe, SNRs, AGN?)



IC 883: results

- A1 (e-EVN) and A (e-MERLIN) ⇒ AGN

$$\left(\frac{\nu \times L_\nu}{L_X}\right)_{\nu=5\mathrm{GHz}} \sim 10^{-3} \Rightarrow \text{LLAGN or normal AGN ?}$$

- Non-thermal compact components in a 100 x 100 pc region ⇒ SB activity in the nucleus

AGN & SB together!!!

Summary

- High resolution studies of (U)LIRGs would allow us to determine the CCSN rate in them, as well as their SFR
- Information of the SFR at both low and high redshifts can be obtained from CCSN surveys, and a new independent measurement of the star formation history of the Universe can be obtained
- Radio observations are an excellent tool, but complementary observations at other wavelengths, which allow us to look through the dust, are strongly recommended.

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