Radio supernovae in LIRGs/ULIRGs

Miguel Pérez-Torres
(IAA-CSIC, Granada)

SAAO workshop, Nov 2017, Cape Town

(U)LIRGs - Definitions & Intro

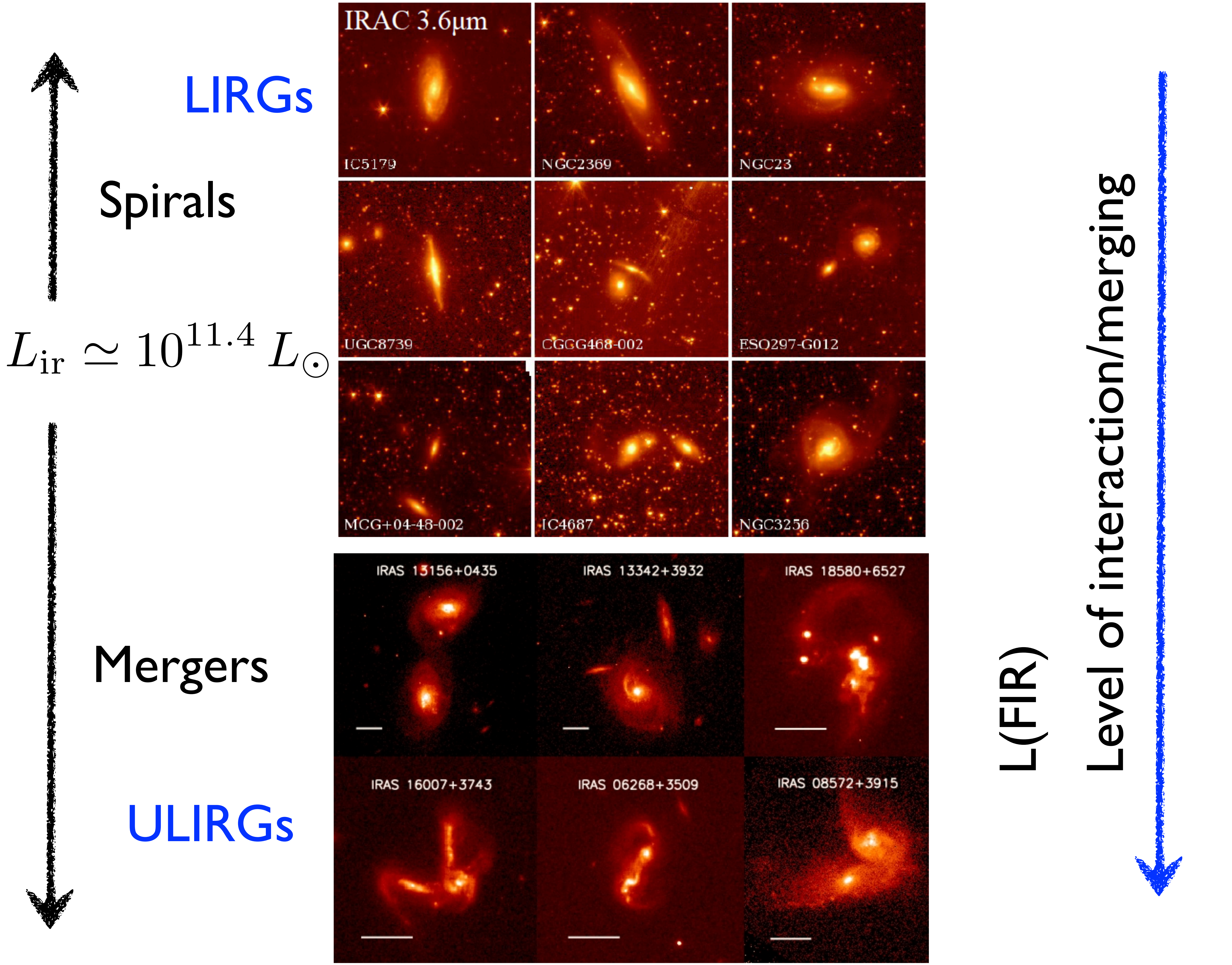
LIRGs: $$10^{11} \leq \frac{\mathrm{L_{ir}}}{\mathrm{L_\odot}} \leq 10^{12}$$

ULIRGs: $$\frac{\mathrm{L_{ir}}}{\mathrm{L_\odot}} \geq 10^{12}$$

$$\mathrm{SFR} \approx 17.2 \left(\frac{\mathrm{L_{FIR}}}{10^{11}\,\mathrm{L_\odot}} \right) \mathrm{M_\odot\,yr^{-1}}$$

$$\mathrm{CCSN\,rate} \approx 0.3 \left(\frac{L_{\mathrm{IR}}}{10^{11}\,\mathrm{L_\odot}} \right) \mathrm{yr^{-1}}$$

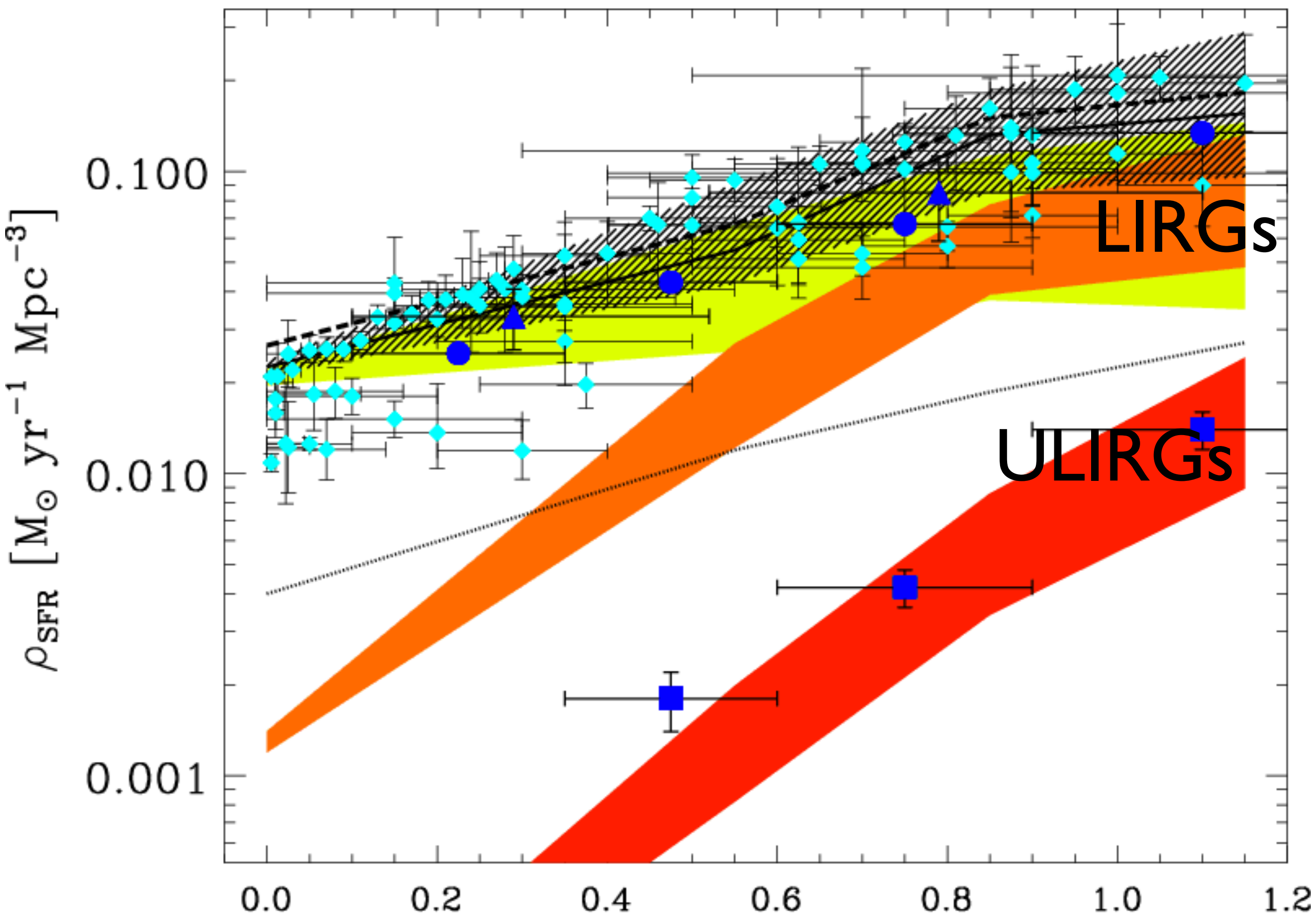
- Provide ~10% of radiant energy production in the local universe
- Provide ~ 20% of all the high-mass SF in the local universe
- Contain millions of OB stars: test massive star evolution, IMFs,...


LIRGs
Spirals
$L_{\rm ir} \simeq 10^{11.4}\, L_{\odot}$
Mergers
ULIRGs
IRAC 3.6μm
IC5179
NGC2369
NGC23
UGC8739
CGCG468-002
ESO297-G012
MCG+04-48-002
IC4687
NGC3256
IRAS 13156+0435
IRAS 13342+3932
IRAS 18580+6527
IRAS 16007+3743
IRAS 06268+3509
IRAS 08572+3915
L(FIR)
Level of interaction/merging

(U)LIRGs & the SFR history of the universe

- Typical SFRs are a few x(10-100) M_{sun}/yr => CCSN rates a few x (0.1-1) SNe/yr
- Significant fraction of the SF at high-z took place in LIRGs/ ULIRGs

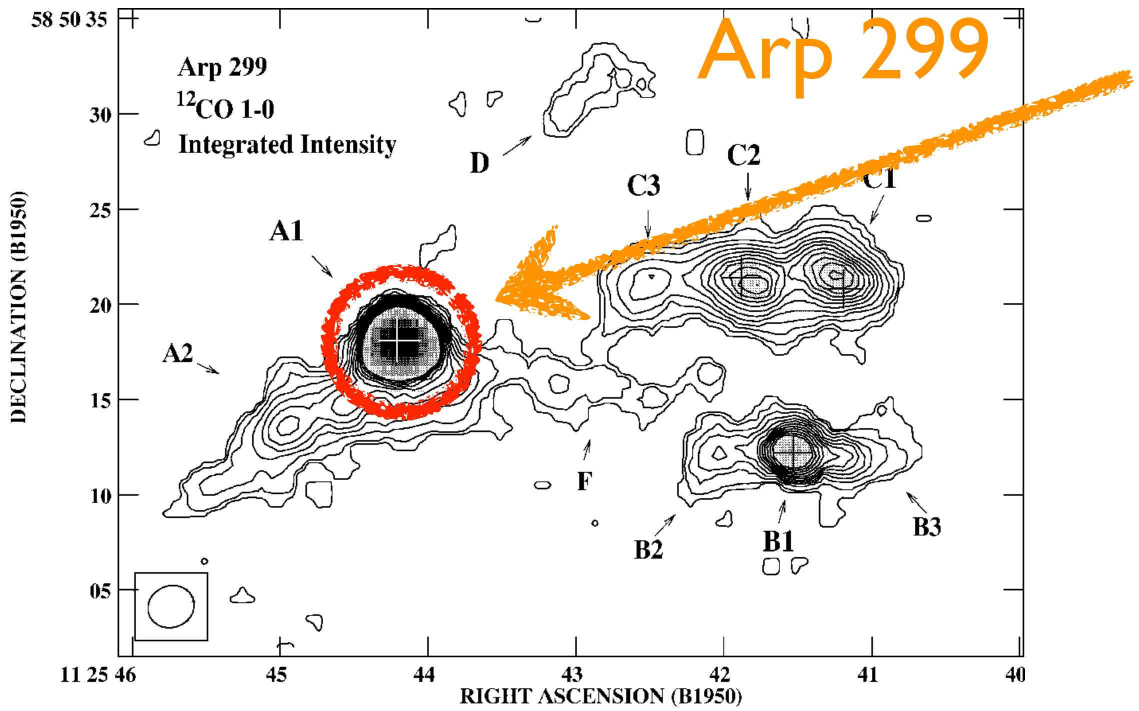
SFR density vs. redshift



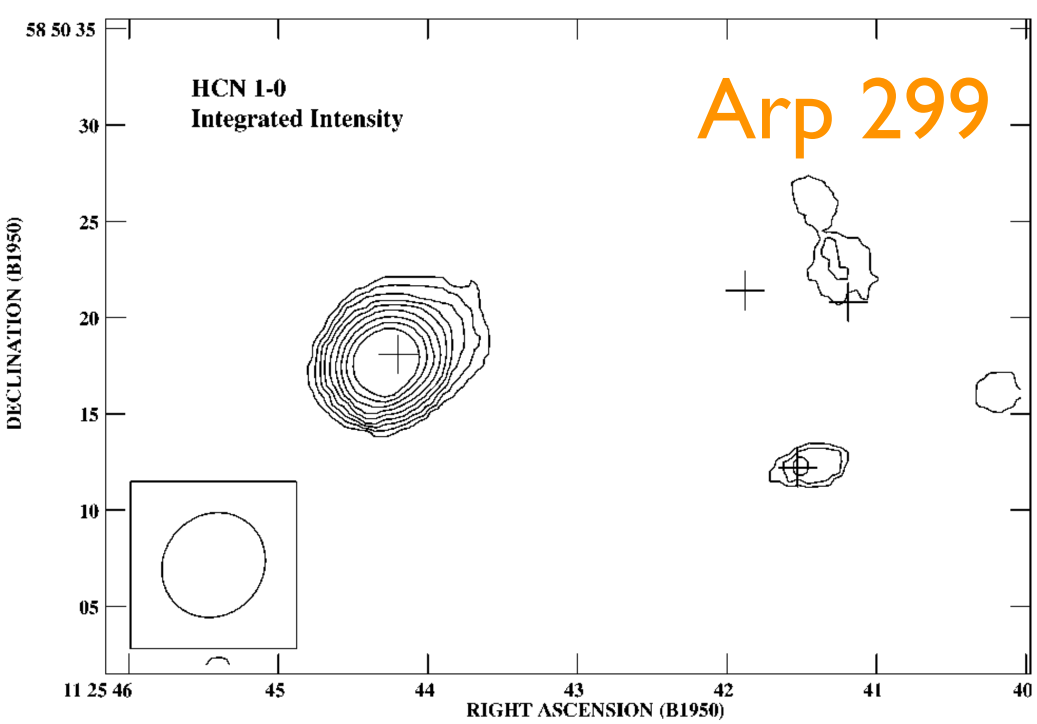
Magnelli +09, +11

(U)LIRGs - Extreme environments

CO(1-0) image



HCN(1-0) image



Aalto+ 1997

$$\mathrm{M}_{H_2} \approx 7.5 \times 10^9 \mathrm{M}_\odot$$

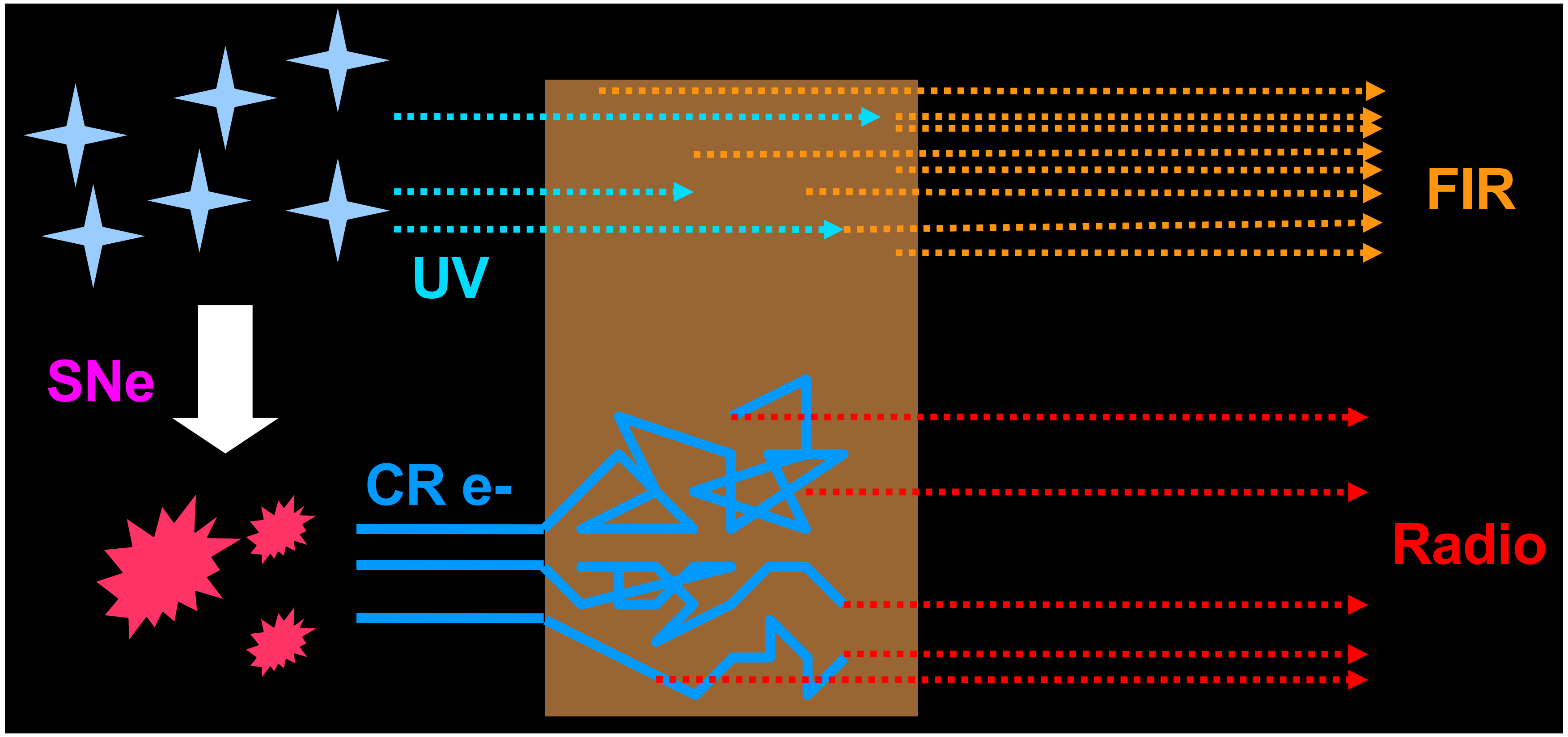
$$N(H_2)/I(^{12}\mathrm{CO}) = 3 \times 10^{20} \mathrm{cm}^{-2}$$

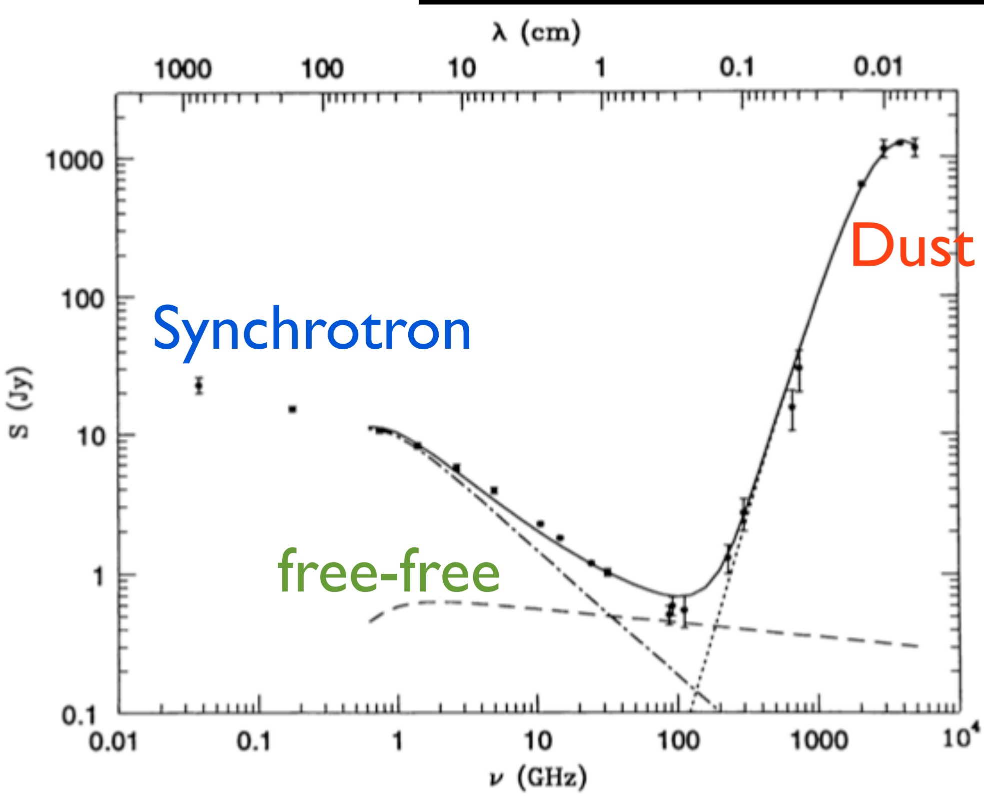
$$\Sigma_\mathrm{g} \approx 1.0 \times 10^5 \,\mathrm{M}_\odot \mathrm{pc}^{-2}$$

$$\mathrm{n}_\mathrm{ISM} \sim 10^4 \mathrm{cm}^{-3}$$

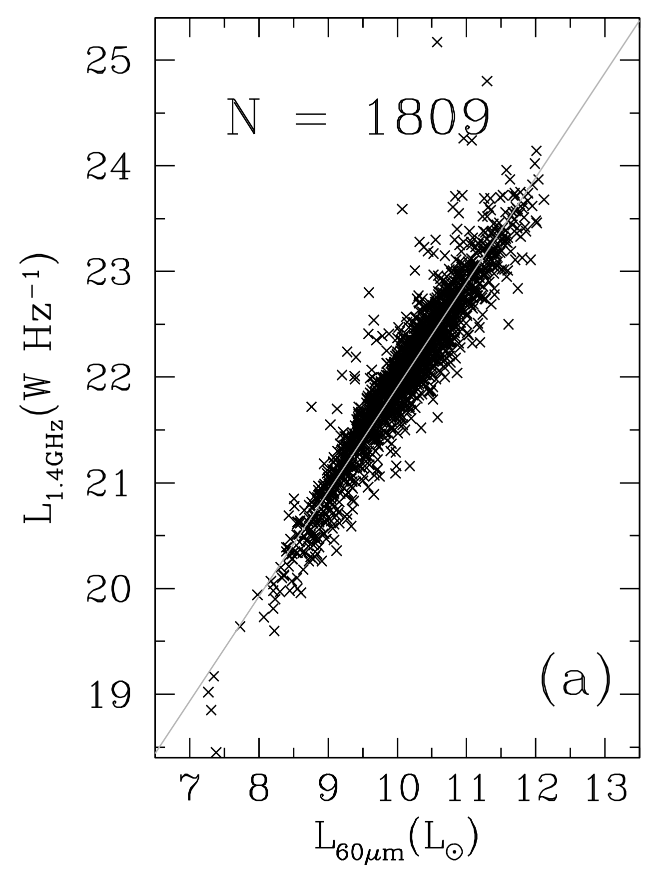
- Huge amounts of molecular gas in their central regions
- Very large surface densities
- Very dense ISM

Far-Infrared Radio Correlation (FRC)





Observed FIR/radio spectrum of M82

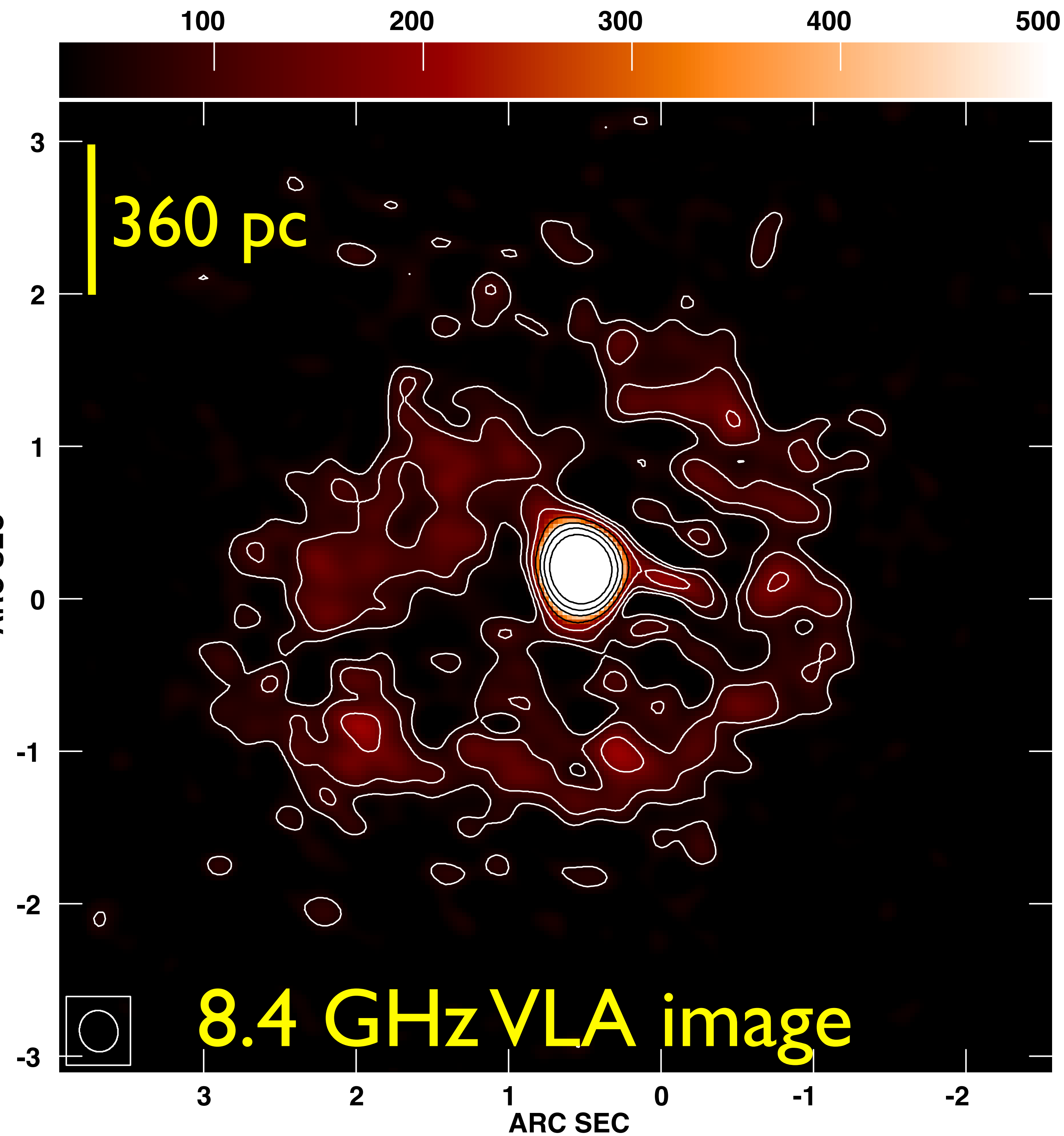


$$\log (L_{1.4\ \mathrm{GHz}}) = (0.99 \pm 0.01) \log (L_{60\ \mu\mathrm{m}}/L_\odot) + (12.07 \pm 0.08)\ .$$

Yun, Reddy & Condon (2001)

(U)LIRGs - High-angular radio obs-ns

Mrk 331 @ 75 Mpc

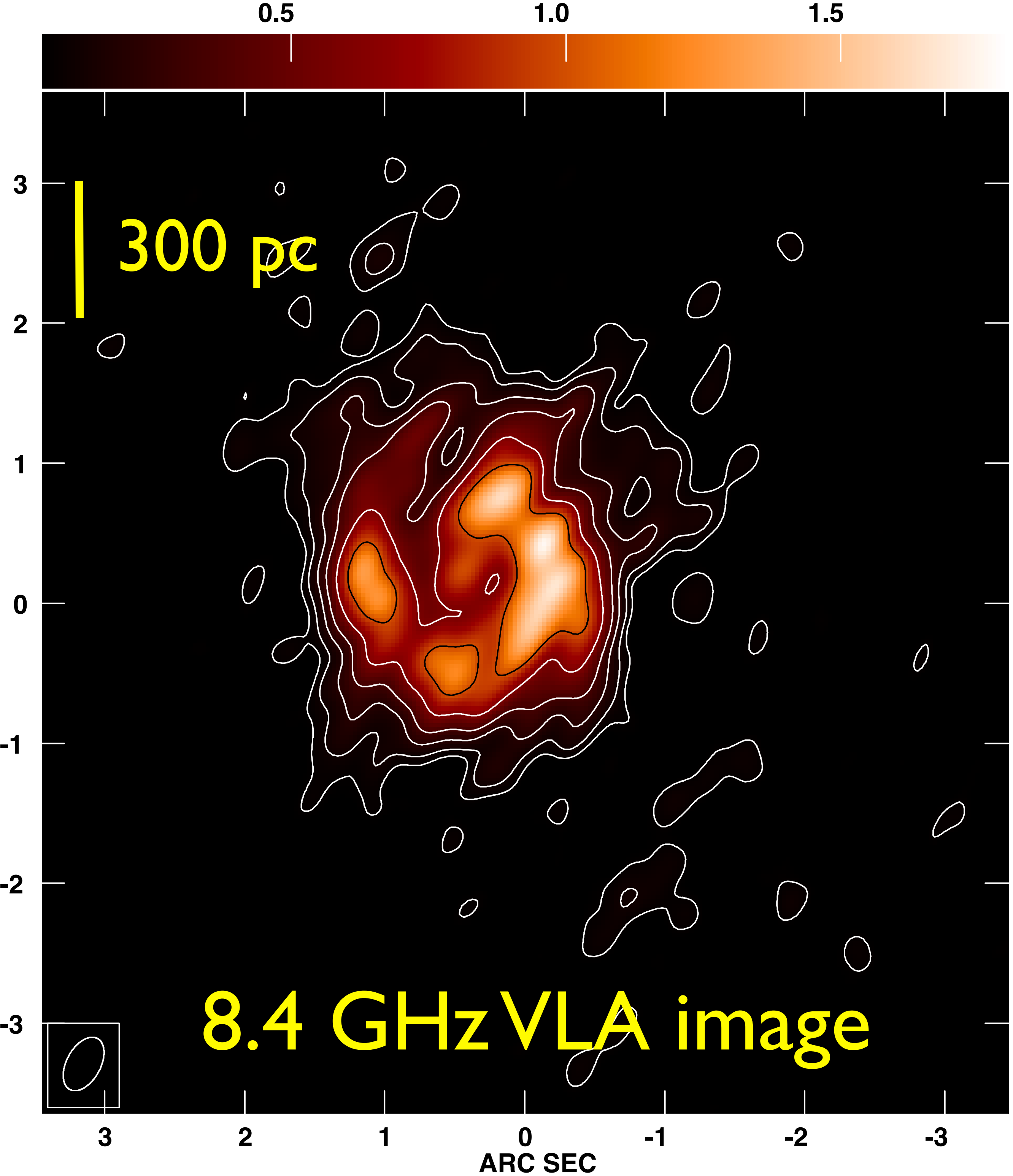


Typical radio structure

- Compact (<=200 pc), high-surface brightness central radio source (42% of total) T => non-thermal
- Extended (>= 1kpc), low-surface brightness circumnuclear region (58% of total)
- Hot question: What is powering the radio emission in each region?

(U)LIRGs - High-angular radio obs-ns

NGC 1614 @ 65 Mpc



Less typical, but often encountered

- Compact (<=200 pc), low-surface brightness central radio source (~10% of total)
- Extended (>= 1kpc), bright-surface brightness circumnuclear region (~90% of total) T => non-thermal
- Question: What is powering the radio emission in each region?

High-angular radio as a tool to pinpoint AGNs

- VLBI provides precise location of AGN (milliarcsecond resolution).

- Accurate quantification of AGN/SB contribution to total radio emission.

- AGNs show flat, or even inverted spectral index at radio wavelengths

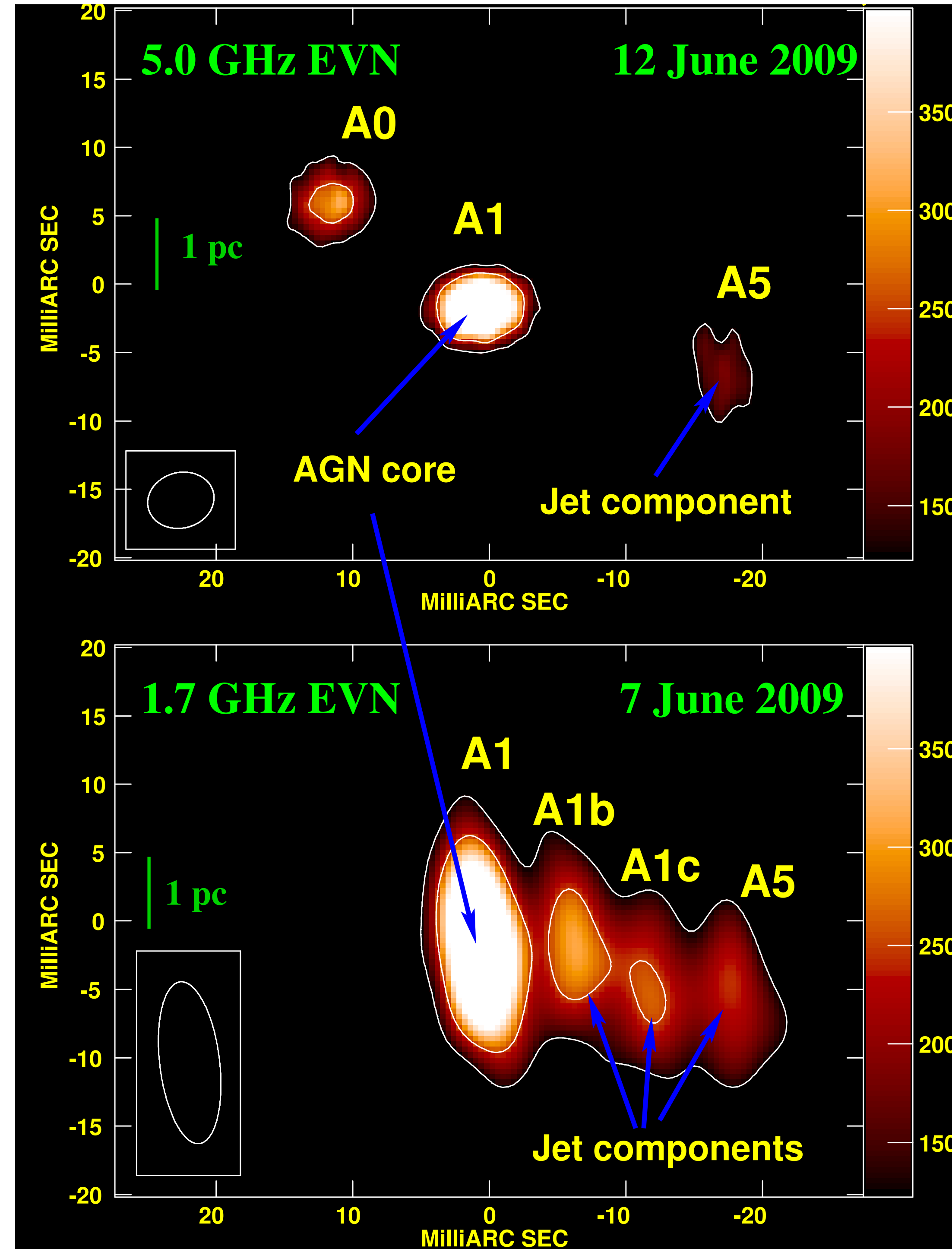
$$S_\nu \propto \nu^\alpha$$

$$\alpha \simeq 0.0\,(\text{flat})$$

$$\alpha > 0.0\,(\text{inverted})$$

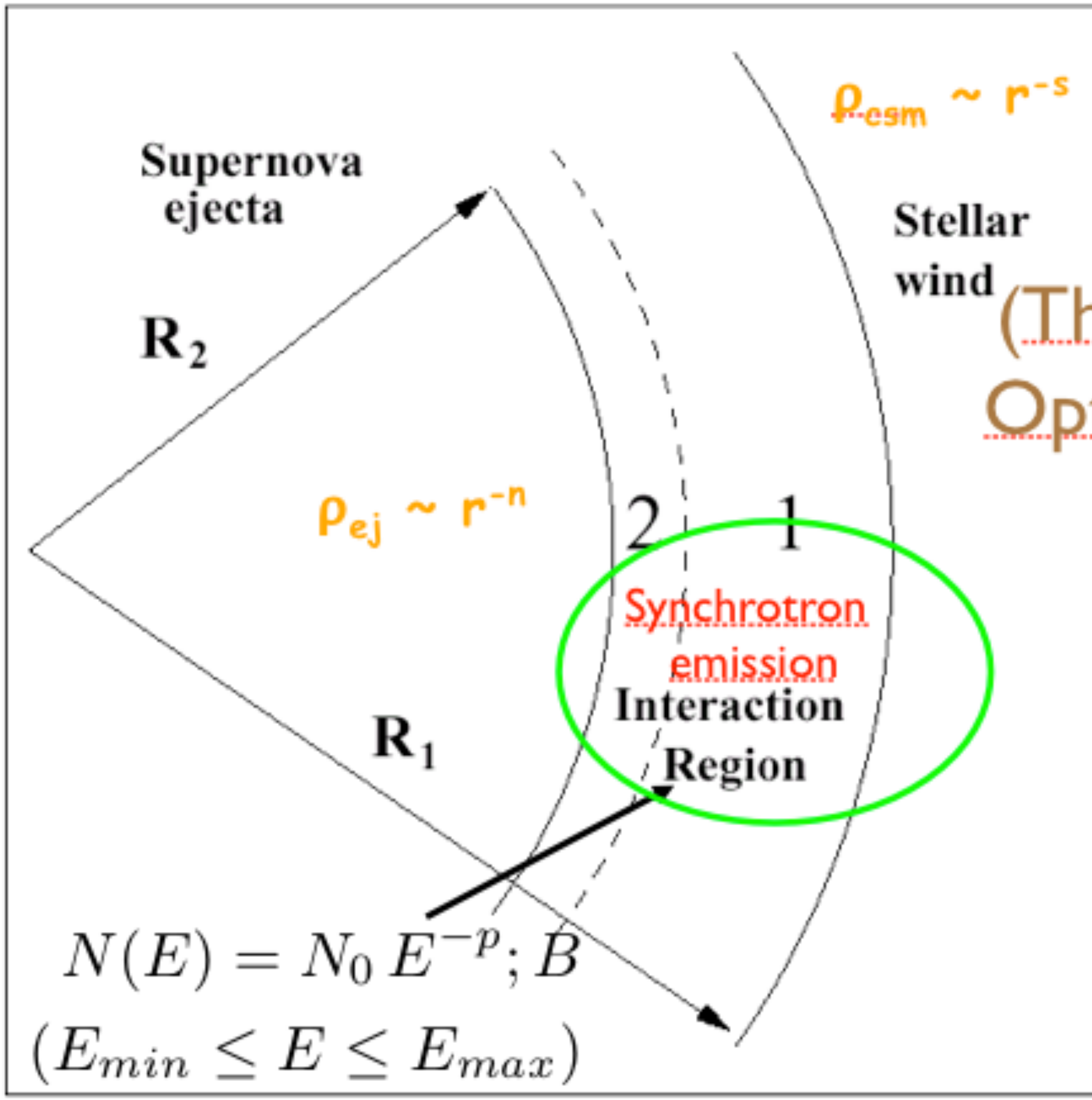
- AGNs show core-jet structure

Arp 299A at cm wavelengths



Pérez-Torres+2009 (Letters to A&A)

Radio emission from CCSNe



(Thermal absorber)

Optical depth ~ $\nu^{-2.1}$

Self-similar expansion

$R \sim t^m$

$m = (n - 3) / (n-s)$

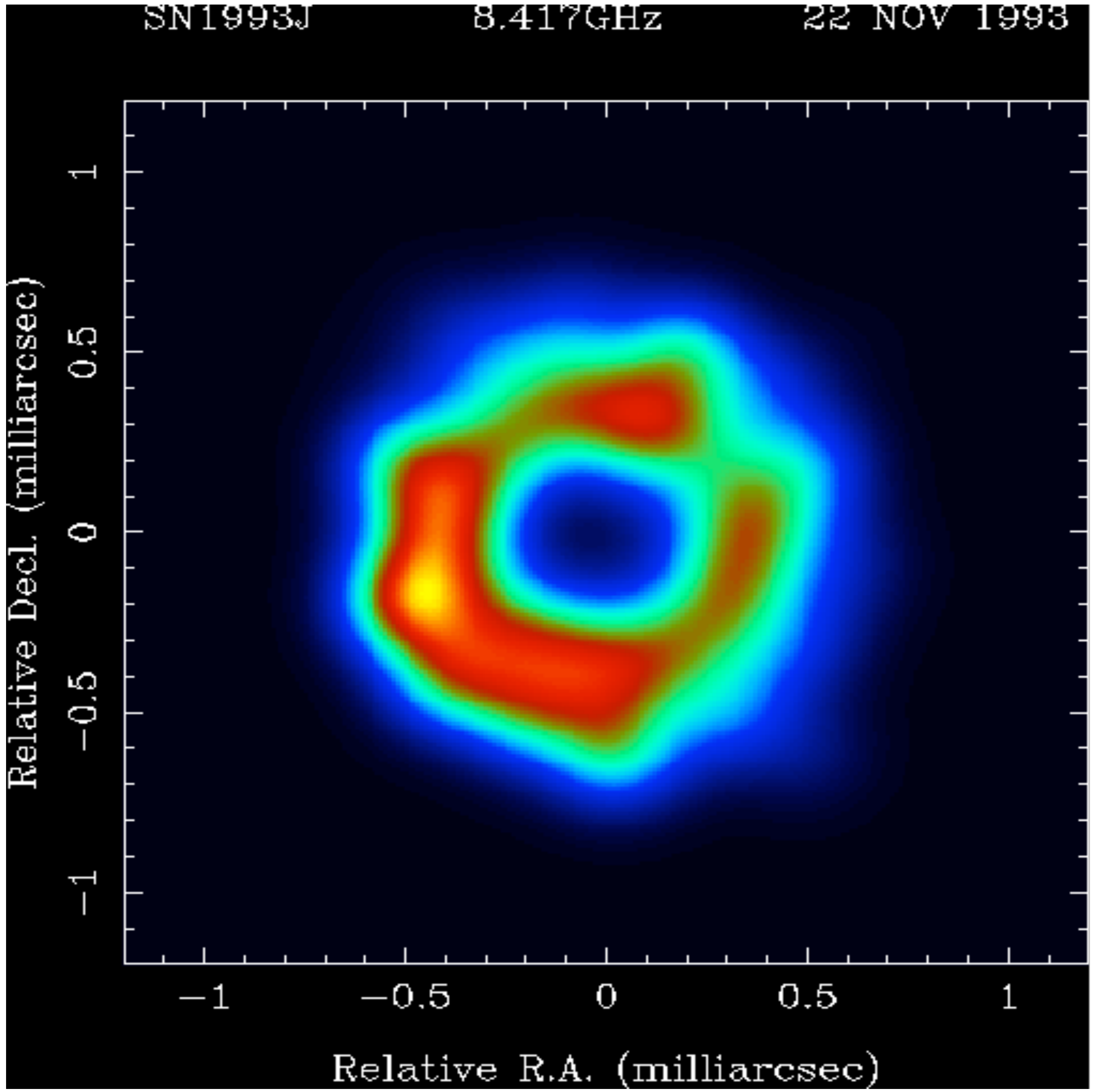
$p = 1 - 2\alpha$

$(S_\nu \propto \nu^\alpha)$

(Chevalier 1982)

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

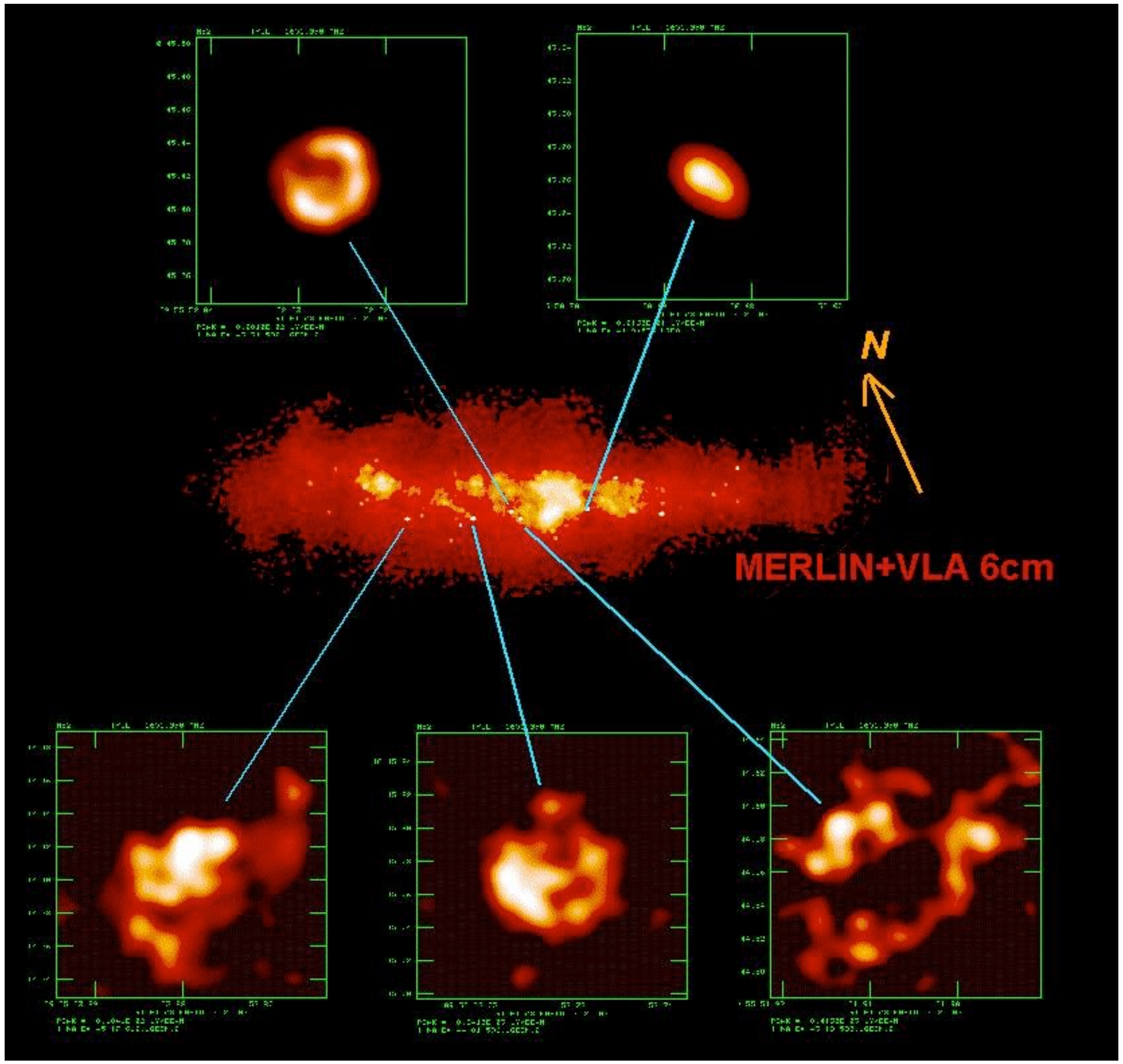
Discovery of a shell structure in SN 1993J



Marcaide+1993, Nature

CCSNe as a direct SFR tracer in (U)LIRGs

M82 at cm wavelengths



- Optical searches are deemed to fail due to severe dust extinction.
- Radio emission is free from extinction effects => searches in radio for CCSNe more promising to yield true estimate of CCSN rates.
- Observed CCSNe rate + IMF => direct measurement of current SFR

$$\nu_{\rm ccsn} = \int_{m_{\rm SN}}^{m_u} \Phi(m)\, dm = SFR \left(\frac{\alpha - 2}{\alpha - 1}\right) \left(\frac{m_{\rm SN}^{1-\alpha} - m_u^{1-\alpha}}{m_l^{2-\alpha} - m_u^{2-\alpha}}\right)$$

Pérez-Torres+2009 (MNRAS)

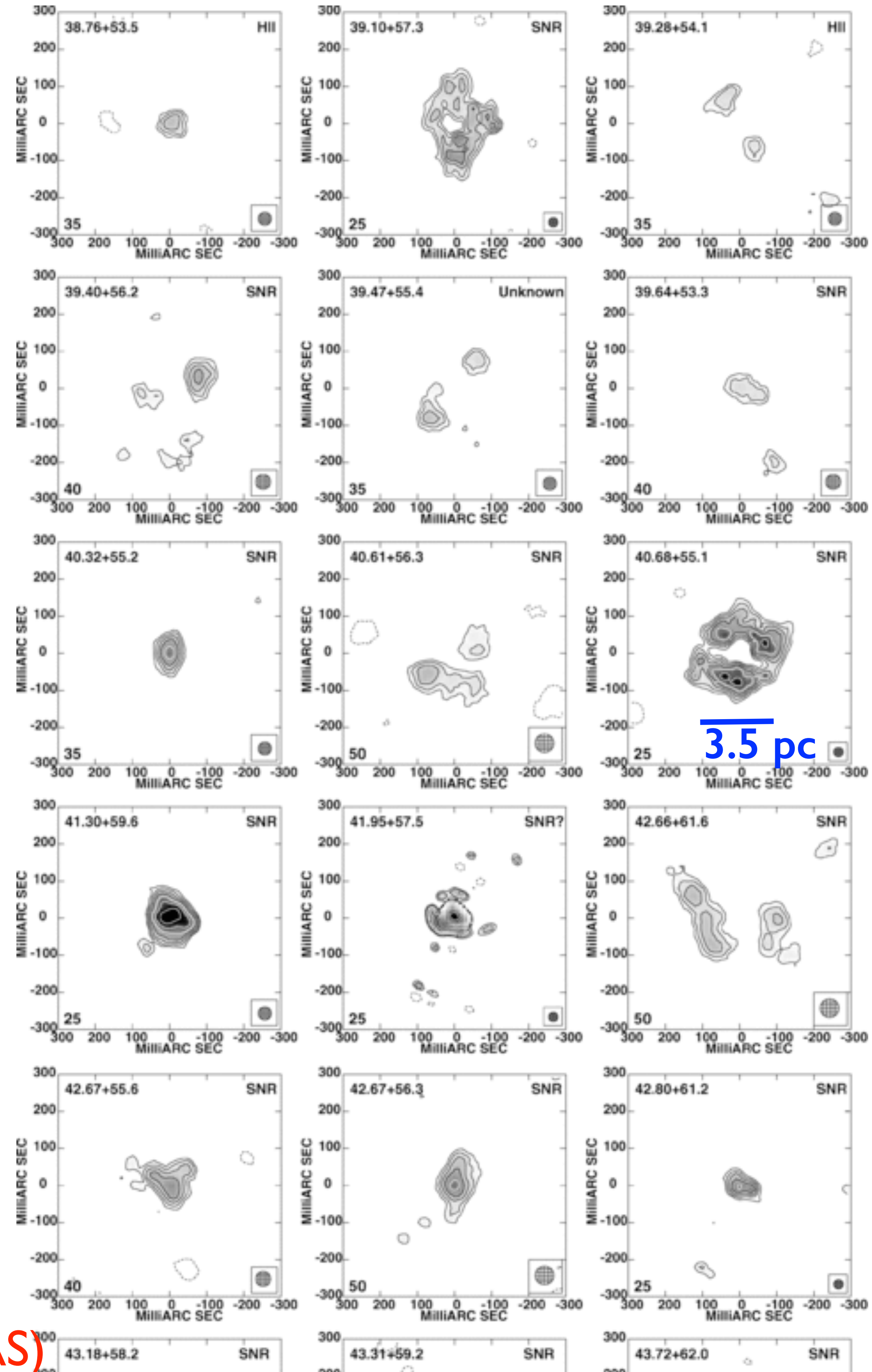
M82 - A Supernova Remnant Lab

D = 3.5 Mpc

1” ~ 17 pc

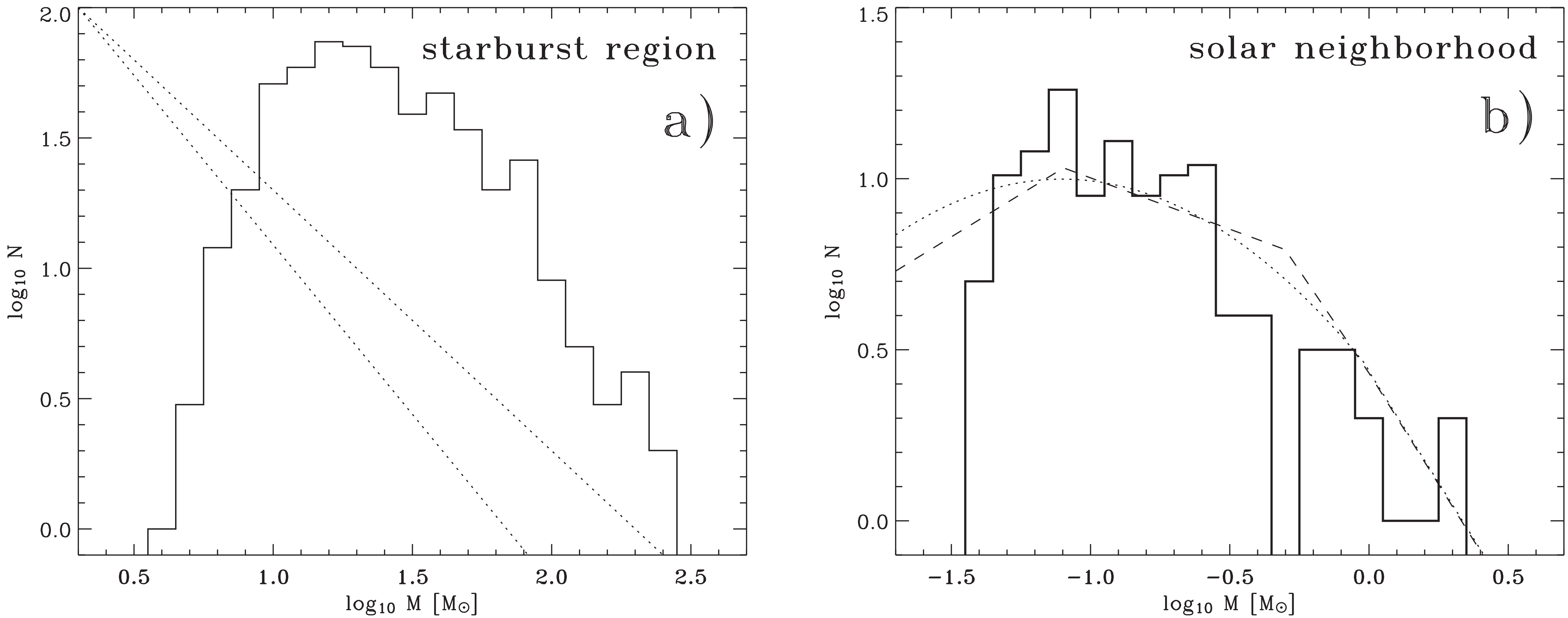
L_{fir} = 5.9 x10^{10} L_{sol}

- If CCSN rate ~ 2.7 x 10^{-12} (L_{fir} / L_{sol}) => SN rate = 0.16 SN/yr
- Radio observations yield SN rate = 0.1 SN/yr (Beswick+06, Fenech +08,+10)
- >60 compact sources. Resolved with MERLIN+VLBI (0.05 pc - 1.7 pc resolution)
- 30 confirmed SNRs; 16 H II regions; 15 unclass. sources



Fenech+2010 (MNRAS)

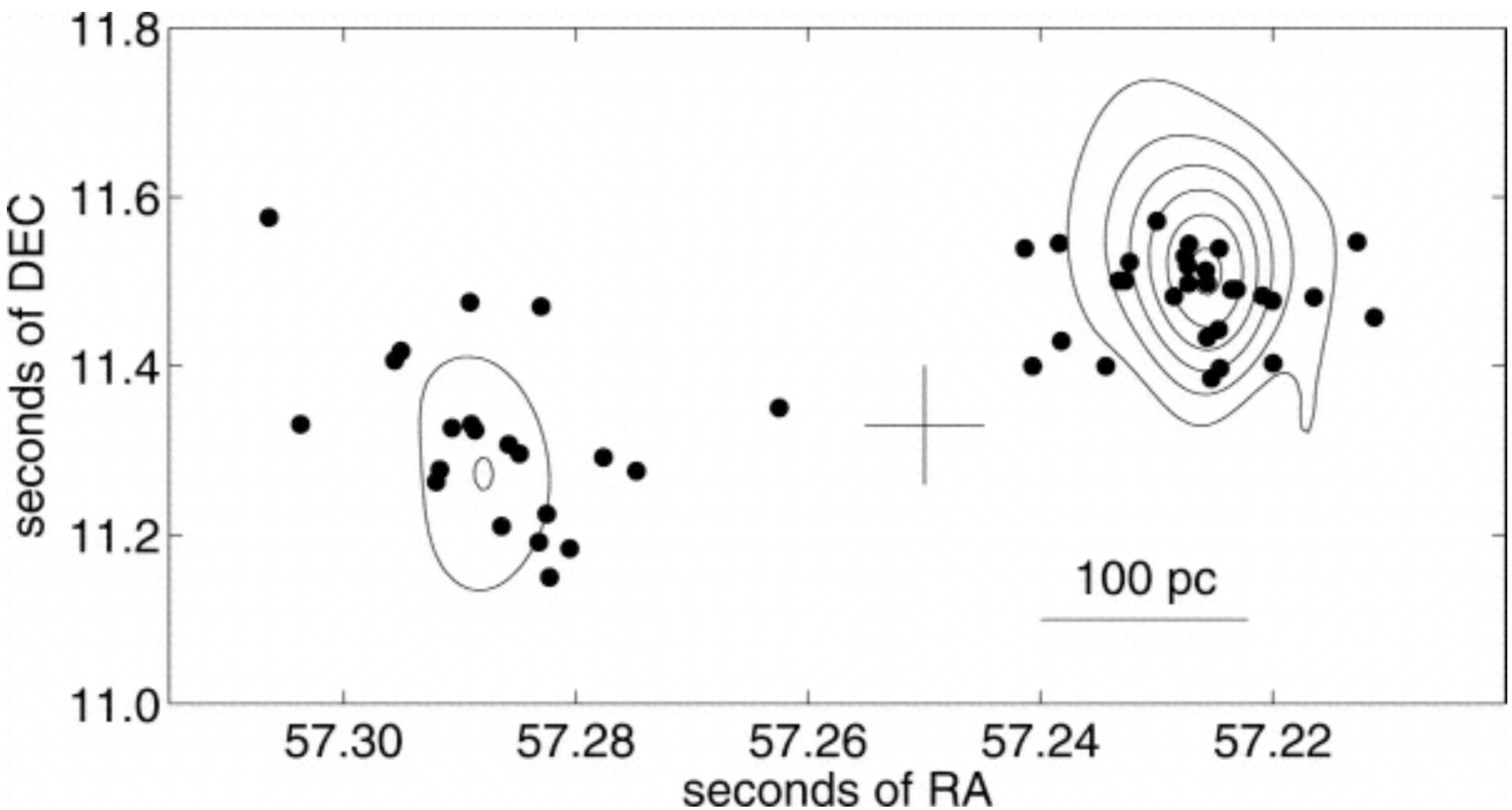
IMF in starburst regions: Top heavy?



Klessen+ 2007 (MNRAS)

- ☑ Broad peak in the (10-25) Msolar range
- ☑ Sharp turn-down around ~7 Msolar
- ☑ Top-heavy as compared with the IMF in the solar neighborhood

The RSN factory in Arp 220



Lonsdale+2006 (ApJ)

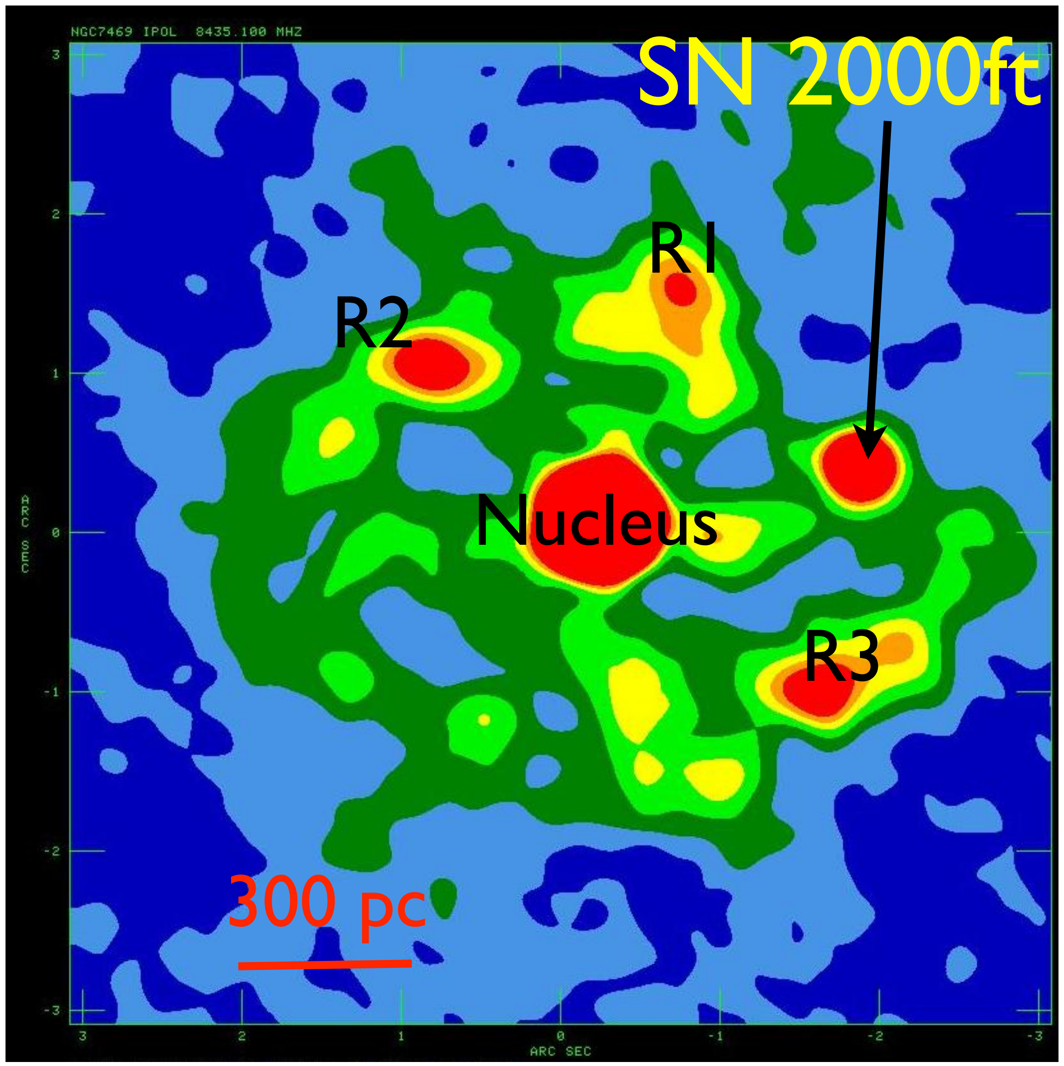
Parra +2007 (ApJ)

- Large numbers of SNe and SNRs detected.
- All Radio SNe are very bright => Type IIn SNe => very massive progenitors
- Radio SN rate = 4 +/- 2 RSN/yr = Expected total CCSN rate!!

Large number of bright, Type IIn-like SNe => Top-heavy IMF... or recent SB (!?)

SNe in circumnuclear SBs

4cm VLA image of NGC 7469 (Sy 1.5)



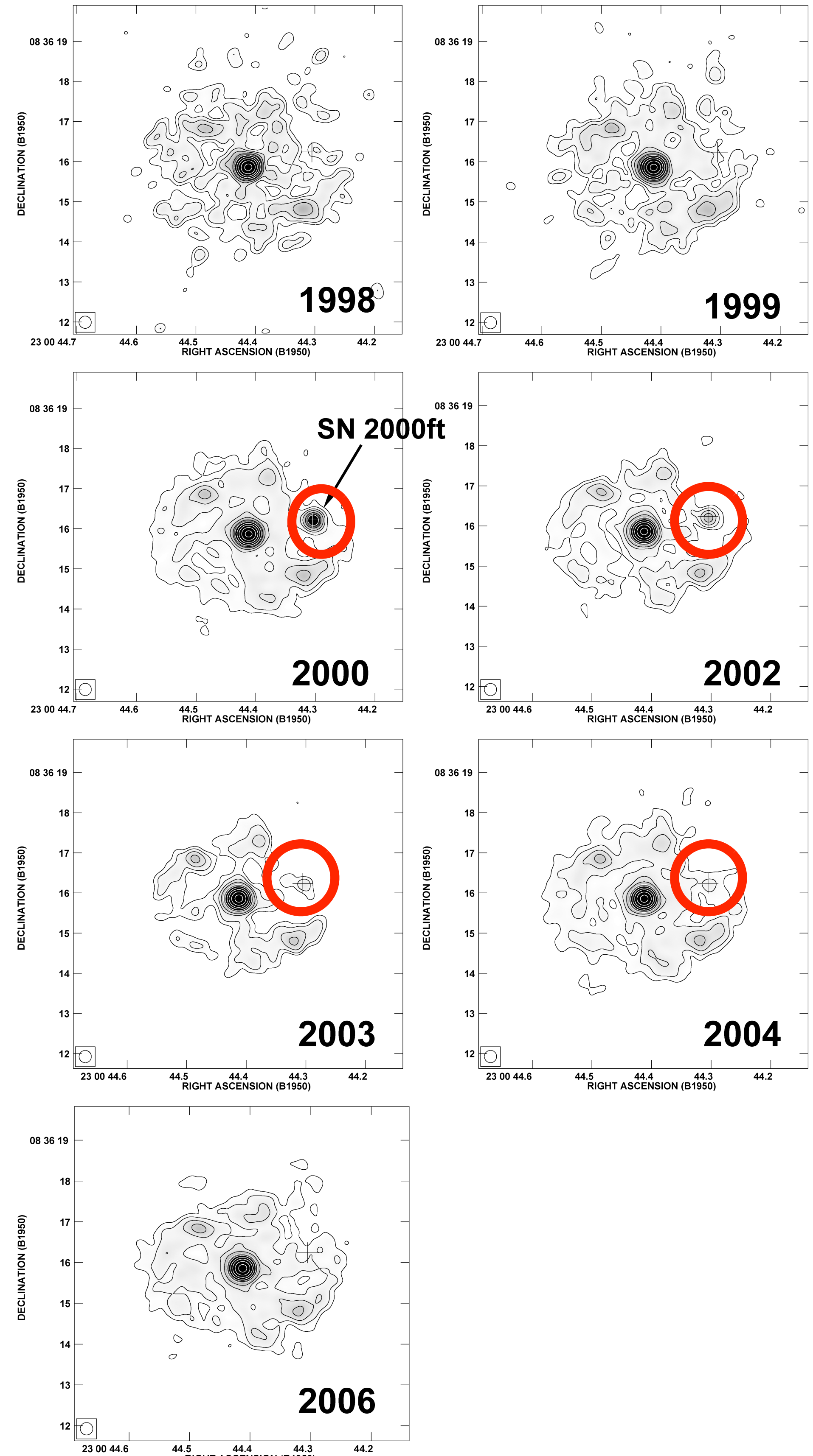
Colina+2001 (ApJL), Alberdi+2006 (ApJ)

D = 70 Mpc; $L_{IR} \sim 5 \times 10^{11} L_{sun}$

=> SN rate ~ 1.4 SN/yr

$L_{SN2000ft} = 1.1 \times 10^{28}$ erg/s/Hz

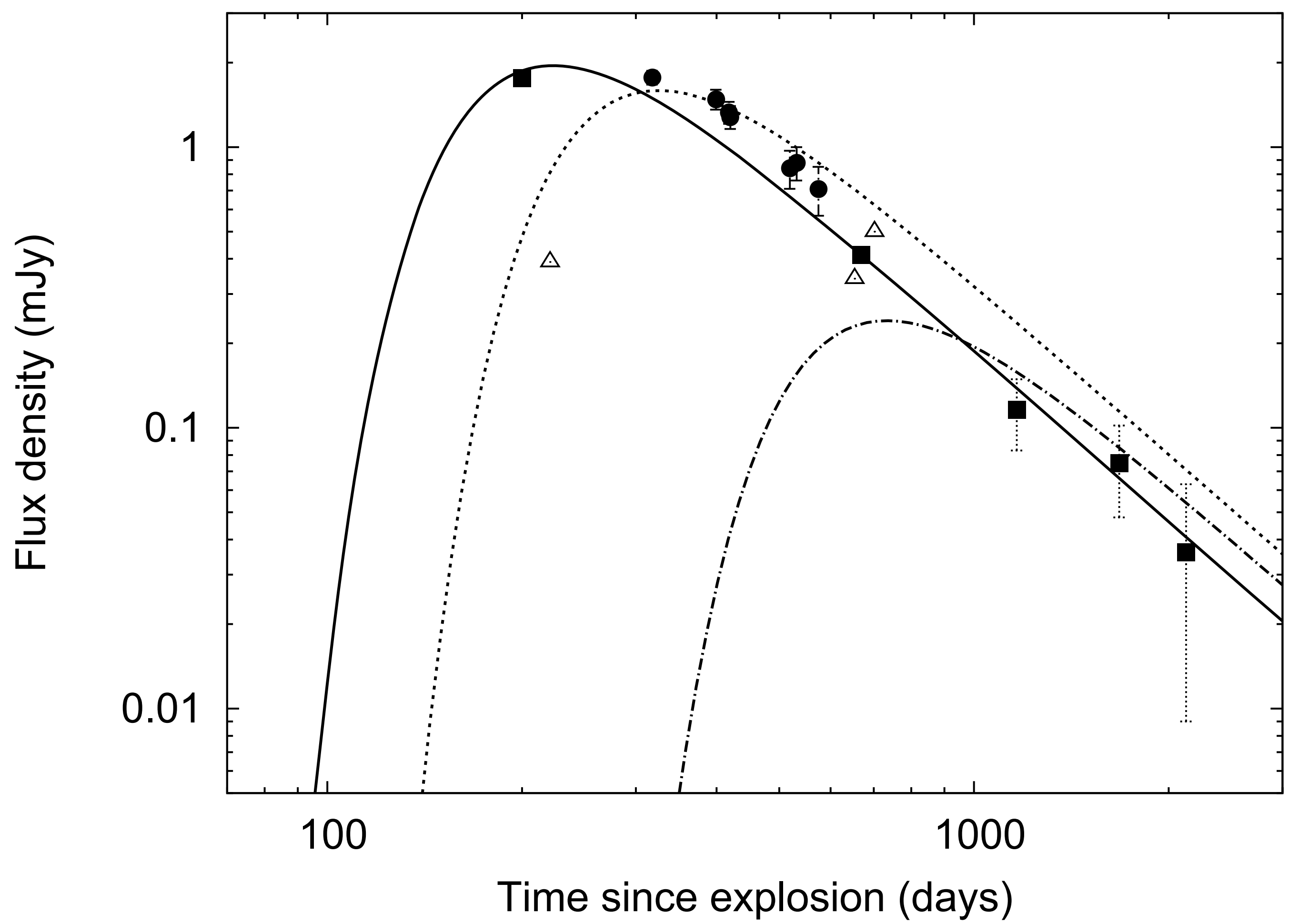
2/3 radio emission in circumnuclear SB



Pérez-Torres+2009 (MNRAS)

No other SN2000ft-like SN in 8 yr

Are SNe in (U)LIRGs intrinsically different?



Pérez-Torres+2009 (MNRAS)

- Rather standard behaviour
- No detection at low freqs => foreground absorber (H II region)
- n ~ 1E4 #/cm^3

$$\dot{\rm M} \approx 5 \times 10^{-5} {\rm M}_\odot\,{\rm yr}^{-1}$$

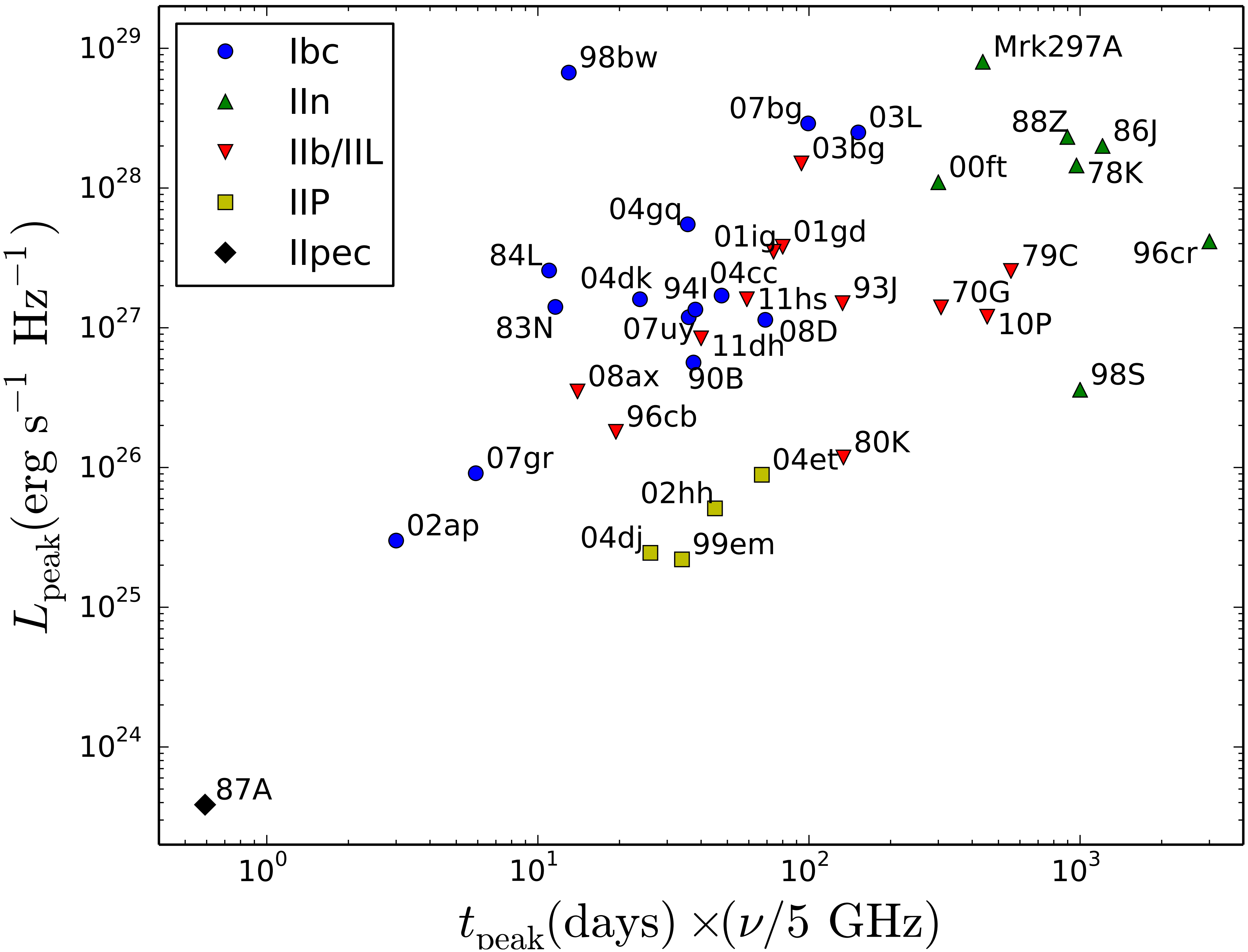
$$\rm M_{swept} \approx 0.29 M_\odot$$

$$\rm P_{ISM} < \rho_w\, v_w^2$$

- SN radio emission due to CSM interaction, not to interaction with the ISM

- B field necessary to explain radio emission (~ few mG) cannot be explained solely by compression from the ISM magnetic field => SN shell (turbulent eddies?)

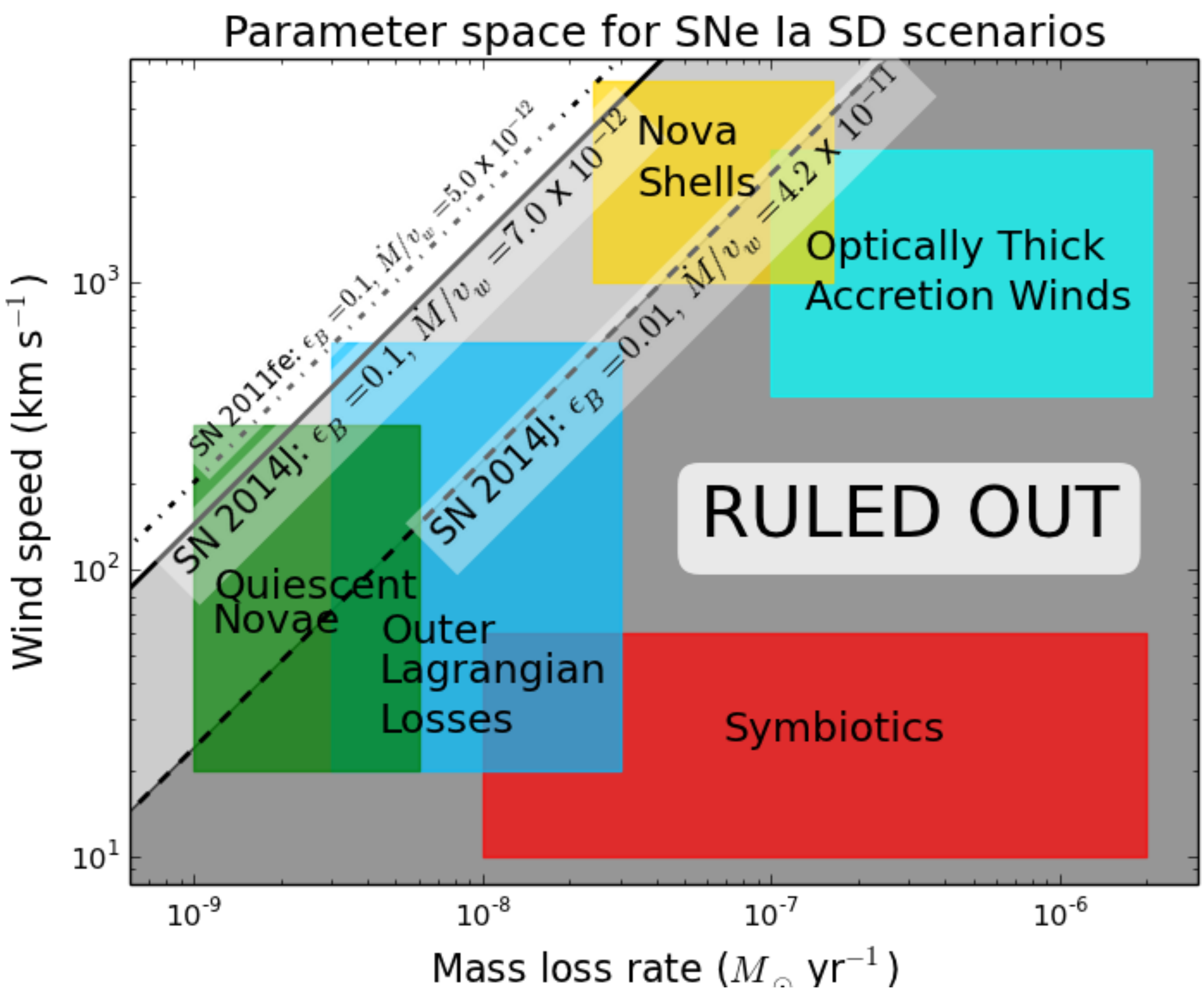
Radio detection of SNe confirm their CCSN nature



Pérez-Torres+2015 (SKA book chapter)

- Observational fact: CCSNe live longer in radio than in the optical.
- The more time takes an RSN to reach the peak, the more luminous is.
- The brighter the RSN, the more massive tends to be its progenitor.

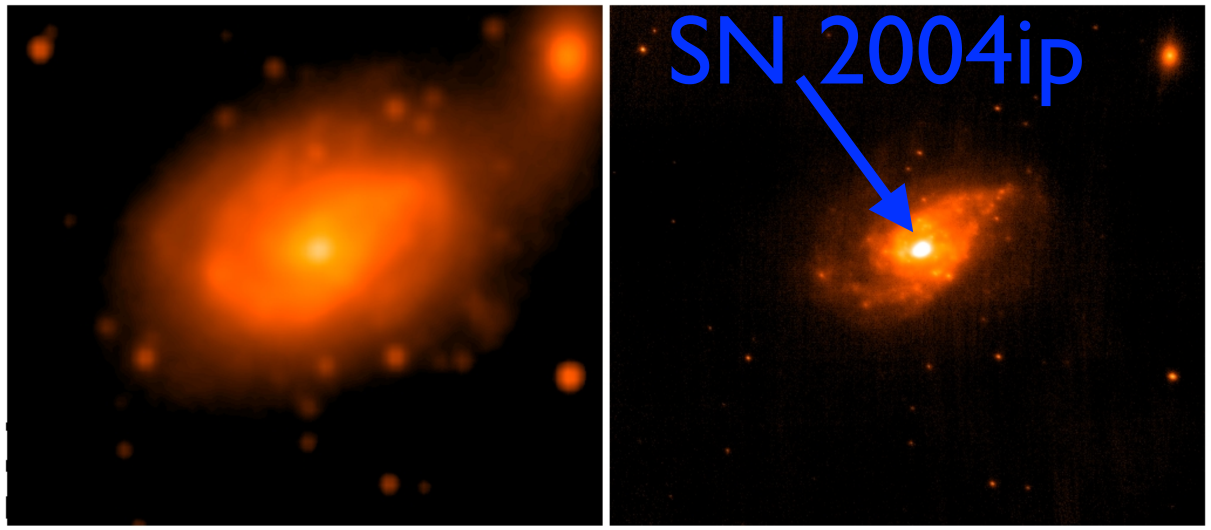
Radio emission from SNe Ia negligible



(Pérez-Torres, Lundqvist +2014, ApJ Letters)

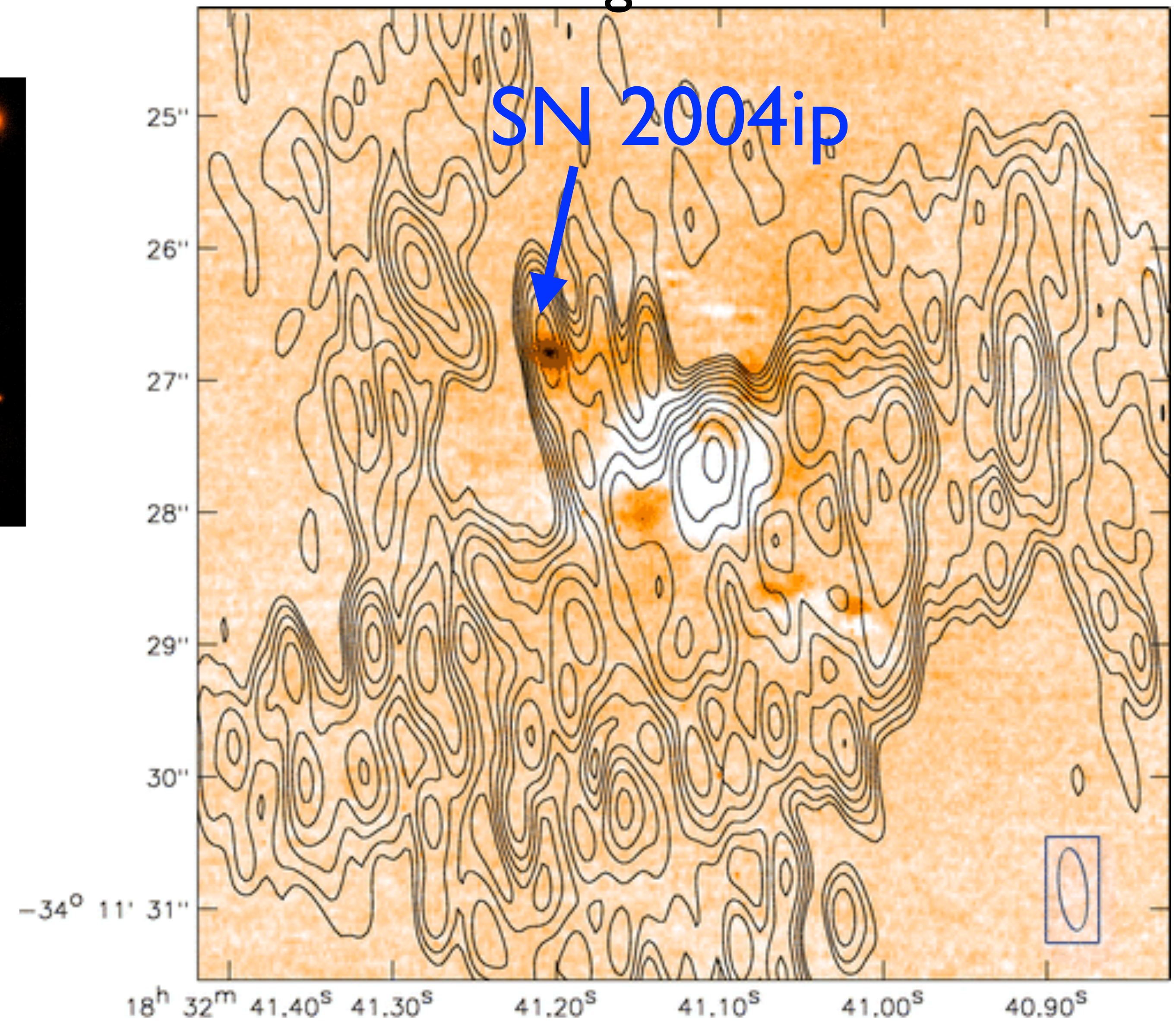
Radio detection of SN 2004ip in IRAS18293-3413

Non-AO (1”) AO (0.1”)



Mattila+2007 (ApJL)

3.6 cm VLA image overlaid on NACO



Pérez-Torres+2007 (ApJL)

VLA detection of the NIR-discovered SN 2004ip in IRAS 18293-3413

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

D = 79 Mpc
$L_{IR} \sim 7 \times 10^{11}\ L_{sun}$
=> SN rate ~ 2.0 SN/yr

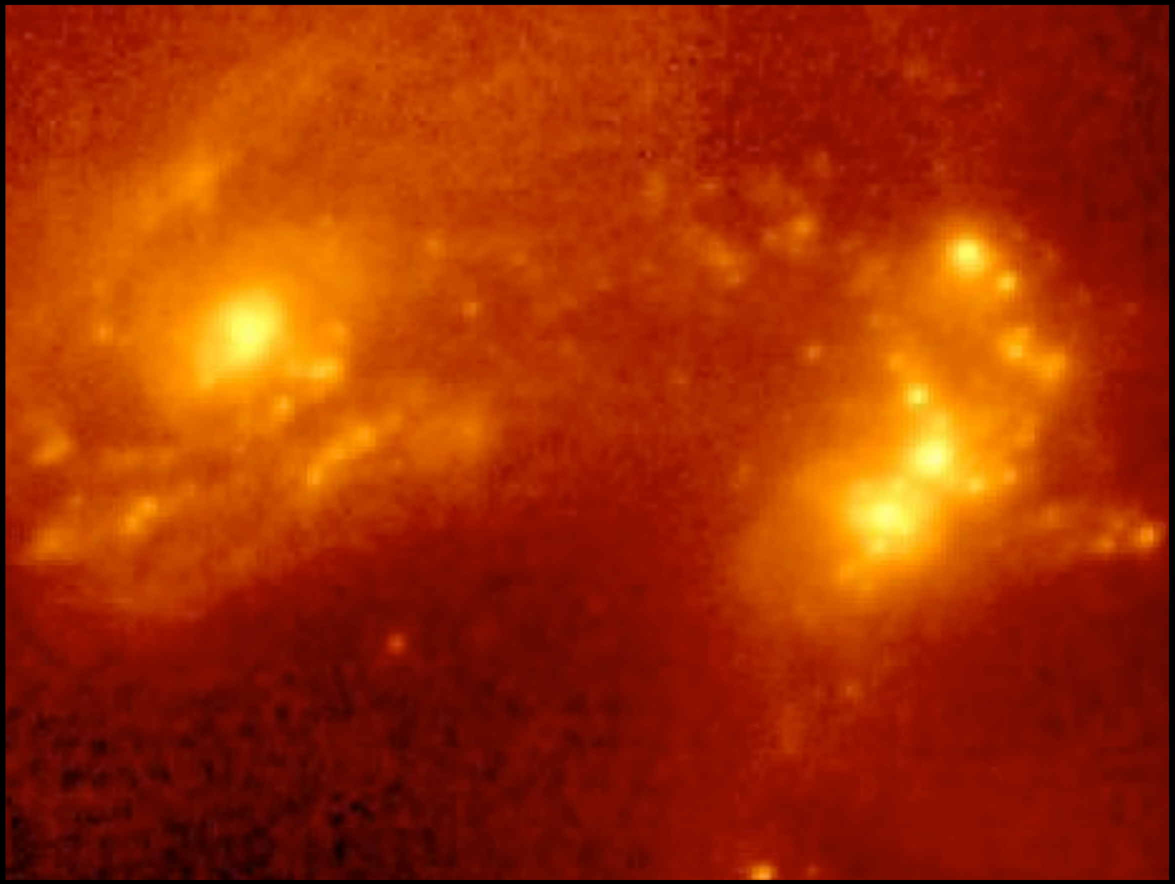
Radio detection => SN 2004ip was a CCSN

Combination of Radio+NIR very promising

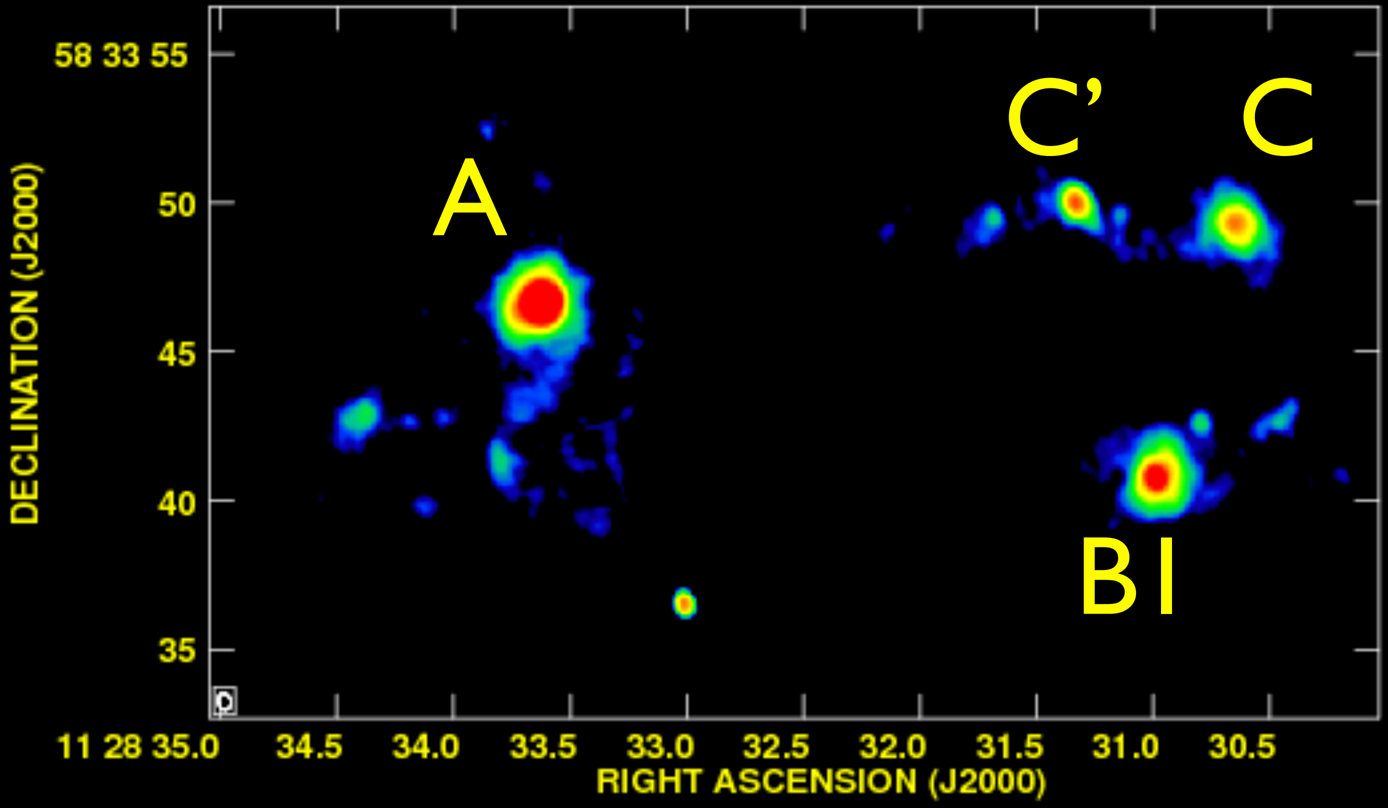
D ~ 45 Mpc

L_{IR} ~ 6.5 x 10^{11} L_{sol}

SFR ~ (150-200) M_{sol}



Arp 299 @ near-IR

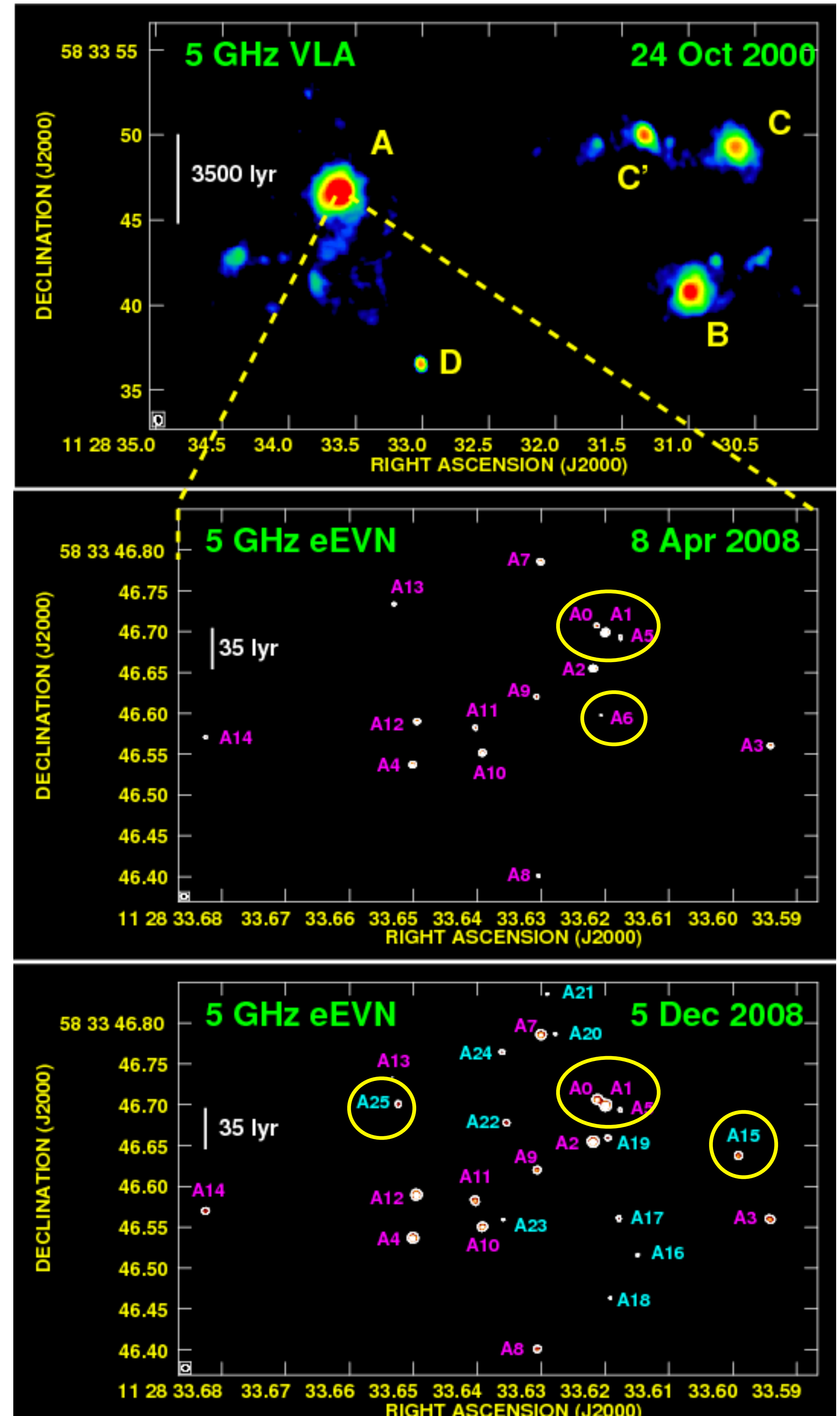


Arp 299 @ radio

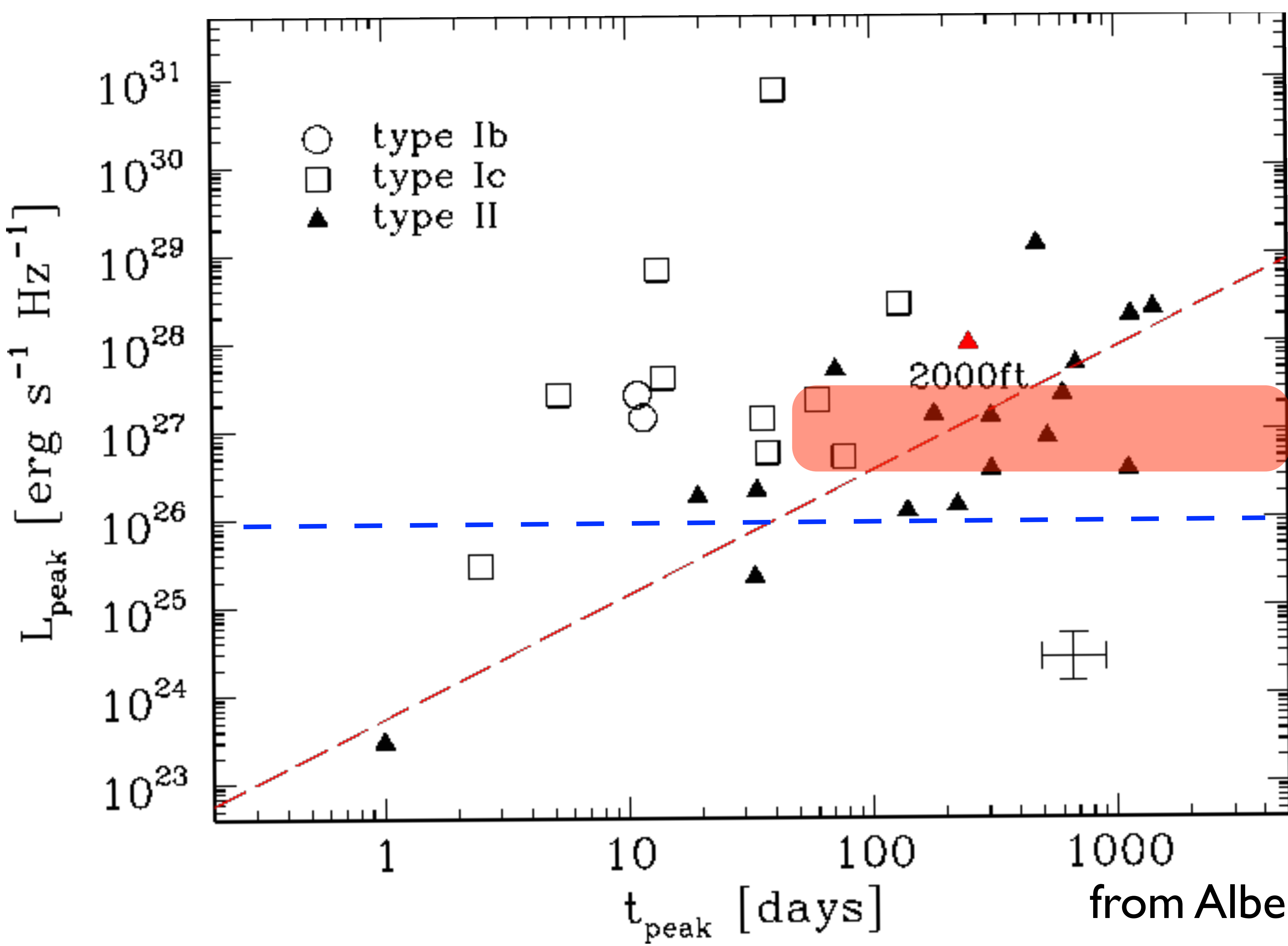
An extremely prolific SN factory in Arp 299-A revealed with the eEVN

(MPT+2009, A&A Letters)

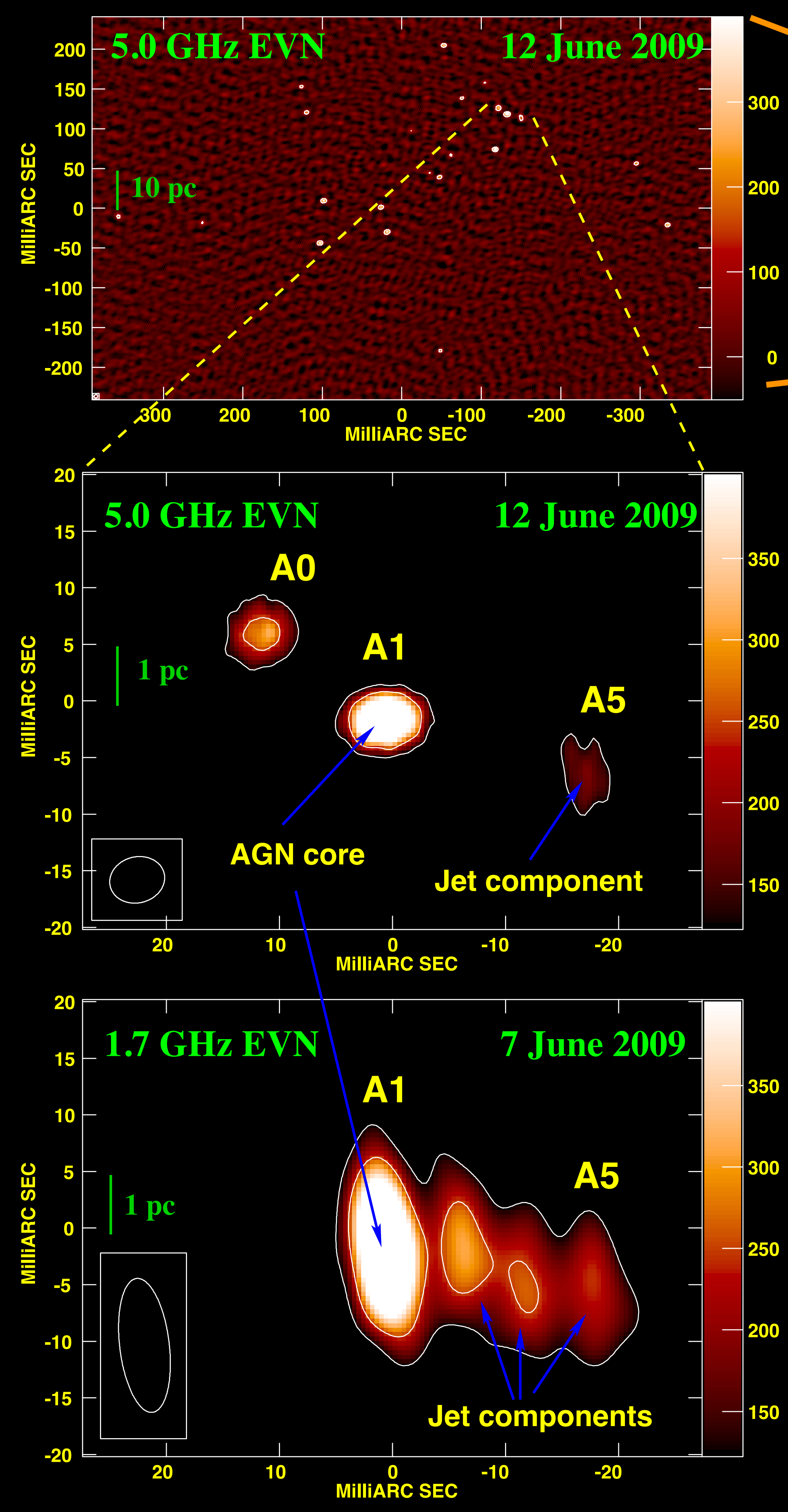
- Rich cluster of compact radio sources in the nuclear region of Arp299A
- SNe and/or SNRs, likely embedded in SSCs.
- Evidence of recent RSNe
- Radio emission levels typical of Type II SNe

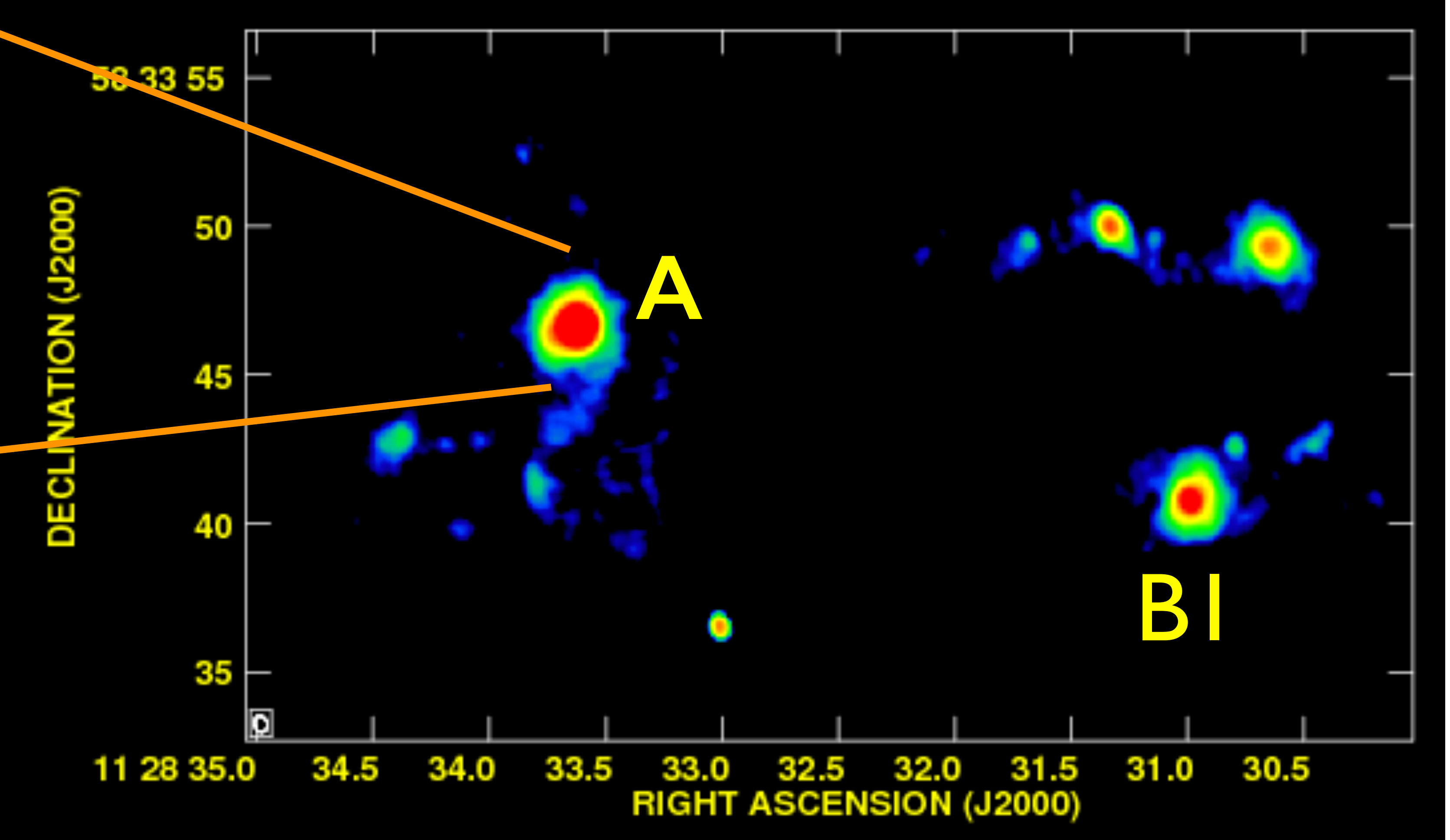


L_peak vs. t_peak => Type II SNe



from Alberdi+ 2006





Discovery of the long-sought AGN in Arp 299-A with the EVN

(MPT+2010)

- Core-jet structure
- A1 - Flat spectrum index
- LLAGN

- Supernova A0 just 2 pc away from AGN

An extremely prolific SN factory in Arp 299A: The movie

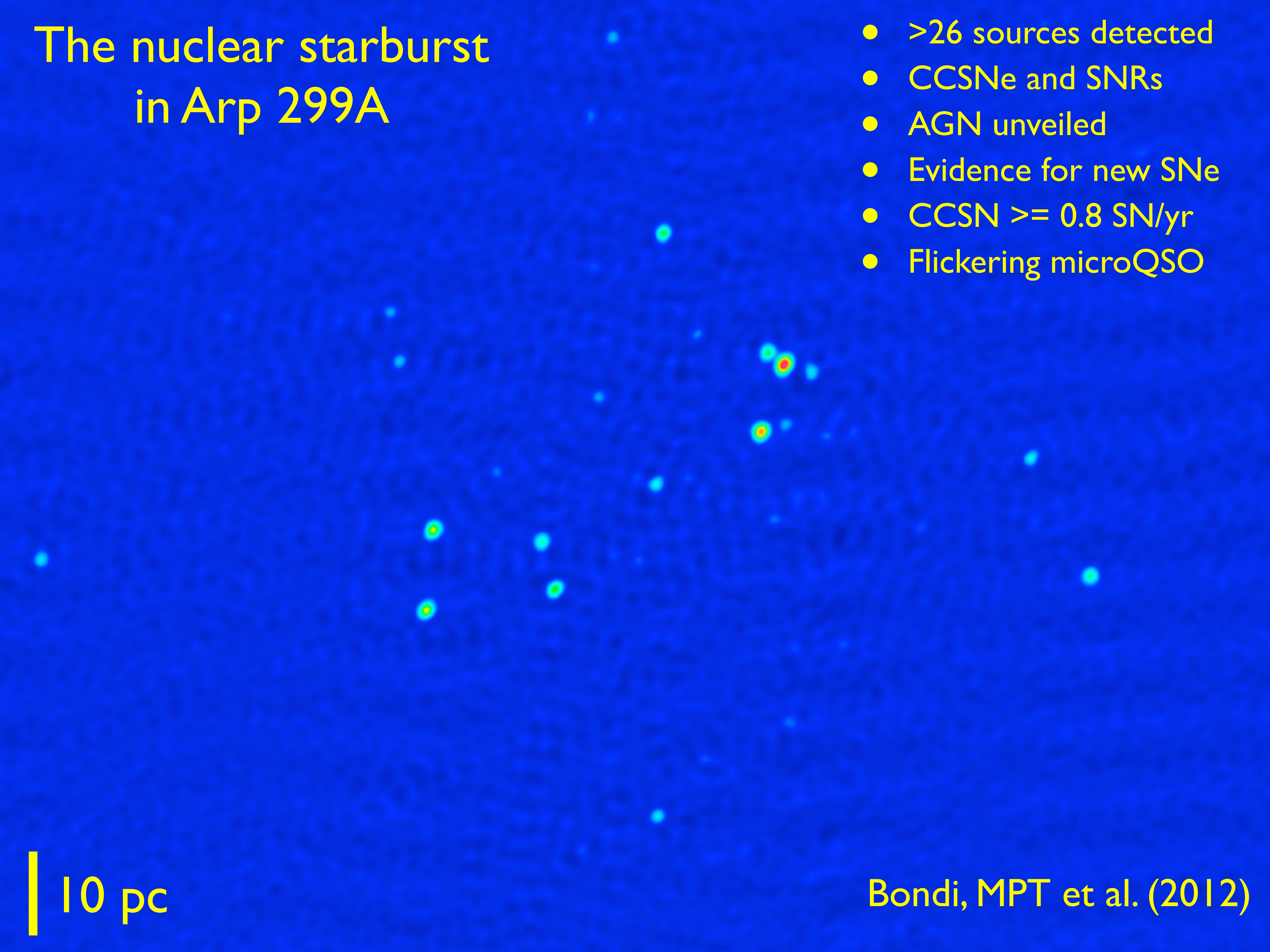
Based on EVN & eEVN obs-ns @ 5 GHz

© Miguel Pérez-Torres (IAA-CSIC, Granada)
Rubén Herrero-Illana (IAA-CSIC, Granada)
Antxon Alberdi (IAA-CSIC, Granada)
Marco Bondi (IRA-INAF, Bologna)

Pérez-Torres et al. (2009, A&A Letters)
Pérez-Torres et al. (2010, A&A Letters)
Bondi, Pérez-Torres et al. (2012, A&A)
Pérez-Torres et al. (tbs to A&A)

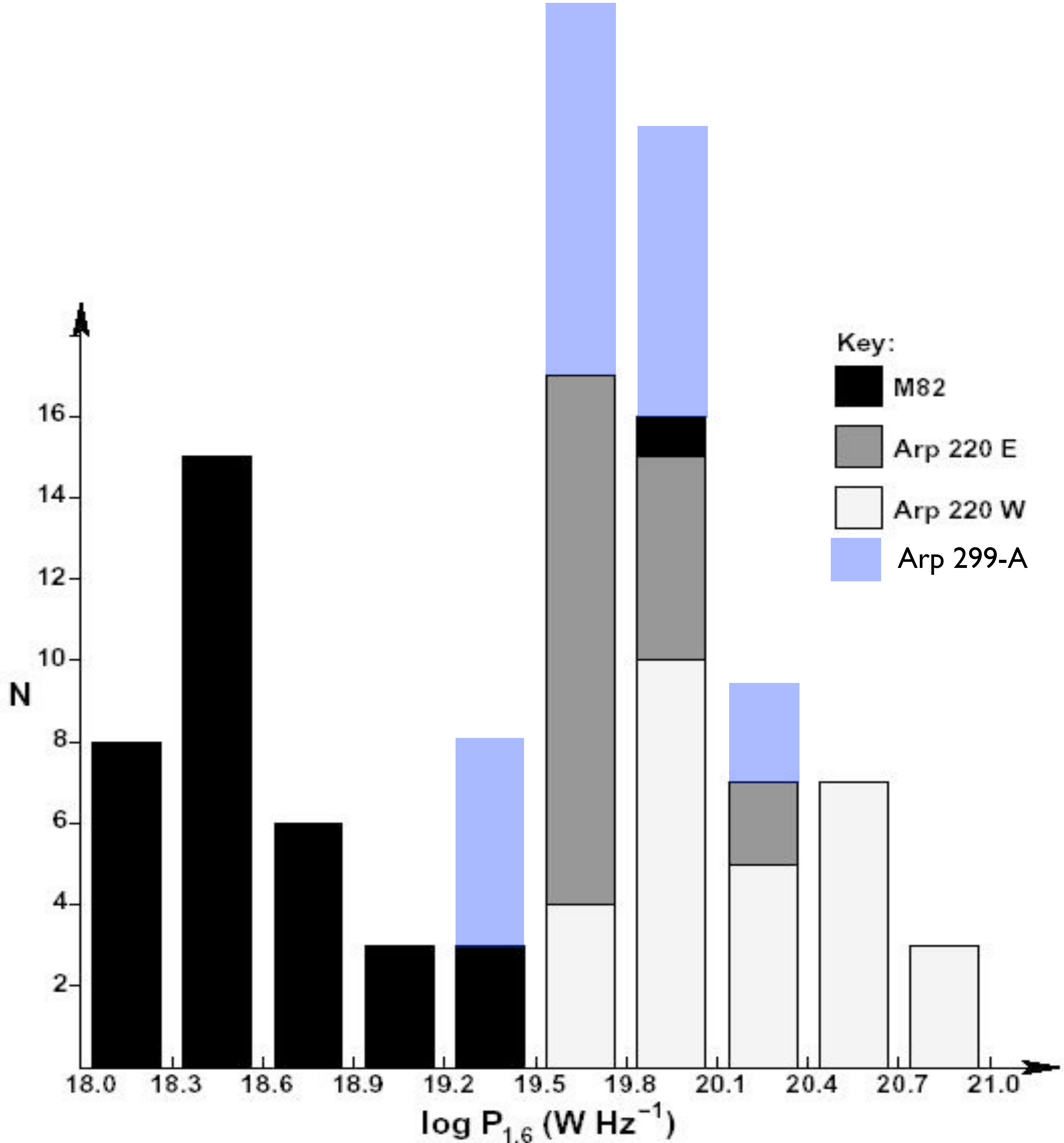
The nuclear starburst in Arp 299A

- >26 sources detected
- CCSNe and SNRs
- AGN unveiled
- Evidence for new SNe
- CCSN >= 0.8 SN/yr
- Flickering microQSO

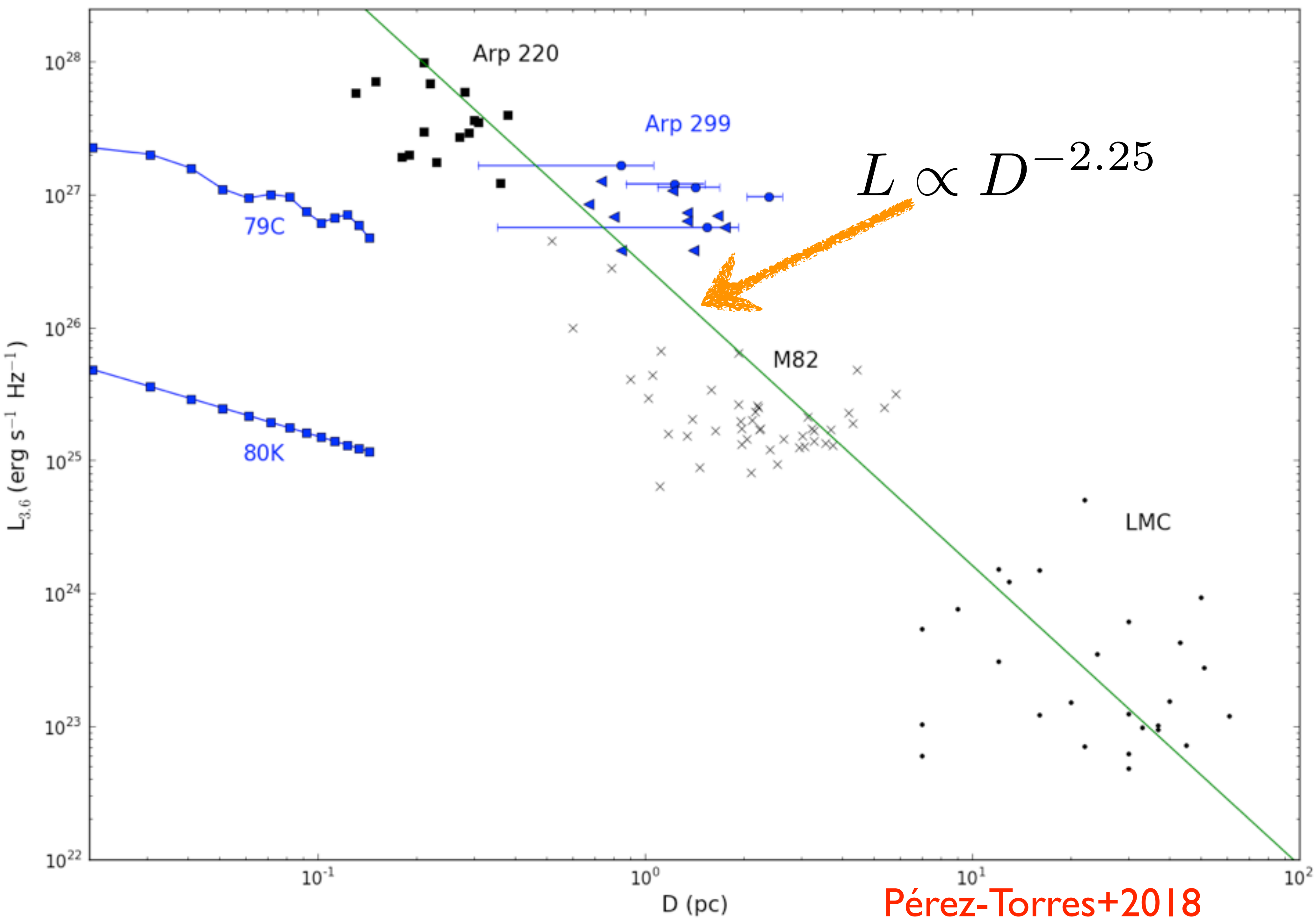


Bondi, MPT et al. (2012)

The Arp 299-A starburst in context - Filling the gap between M82-like and Arp 220-like SBs



Luminosity - size relationship for Arp 299A



Arp 299-A nicely fills the gap between M82 and Arp 220-like objects

Compact sources in Arp 299-A: The movie

Based on EVN & eEVN obs-ns @ 5 GHz

© Miguel Pérez-Torres (IAA-CSIC, Granada)
Rubén Herrero-Illana (IAA-CSIC, Granada)
Marco Bondi (IRA-INAF, Bologna)
Antxon Alberdi (IAA-CSIC, Granada)

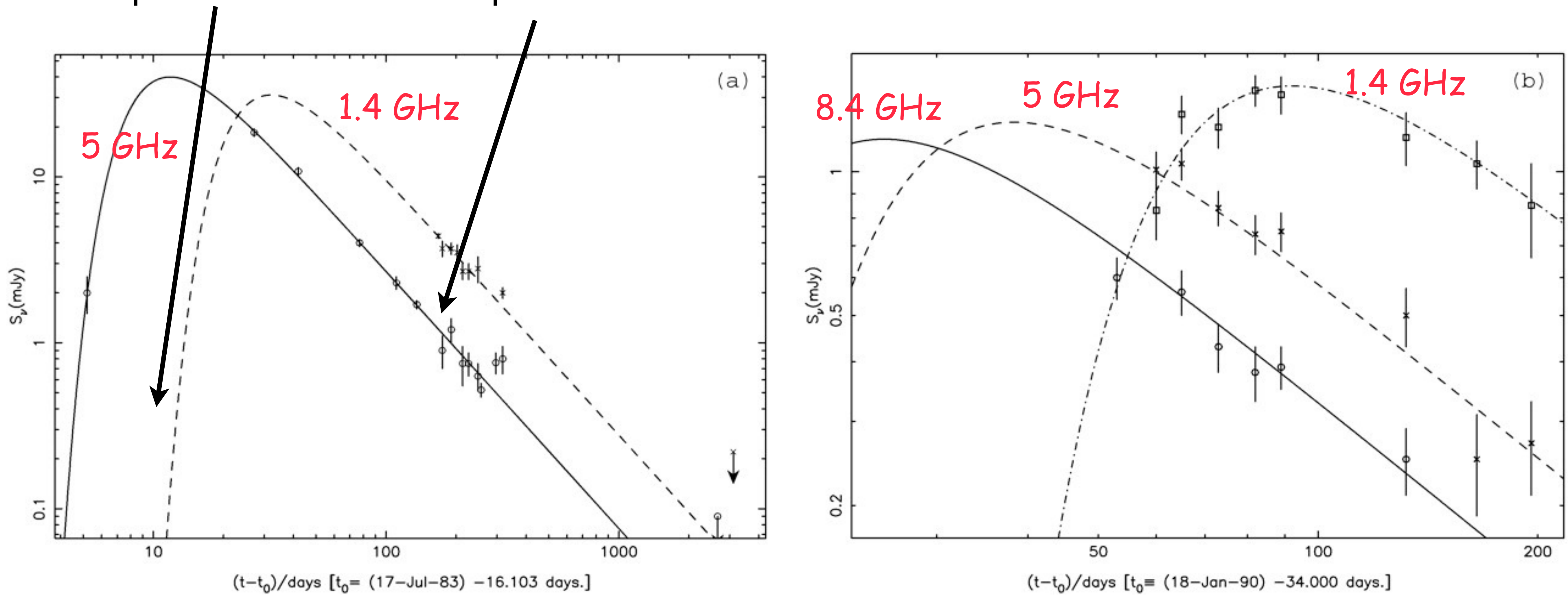
Pérez-Torres et al. (2009, A&A Letters)
Pérez-Torres et al. (2010, A&A Letters)
Bondi, Pérez-Torres et al. (2012, A&A)

Radio light curves & spectra from SNe

Optically thick phase: alpha >> 0.0

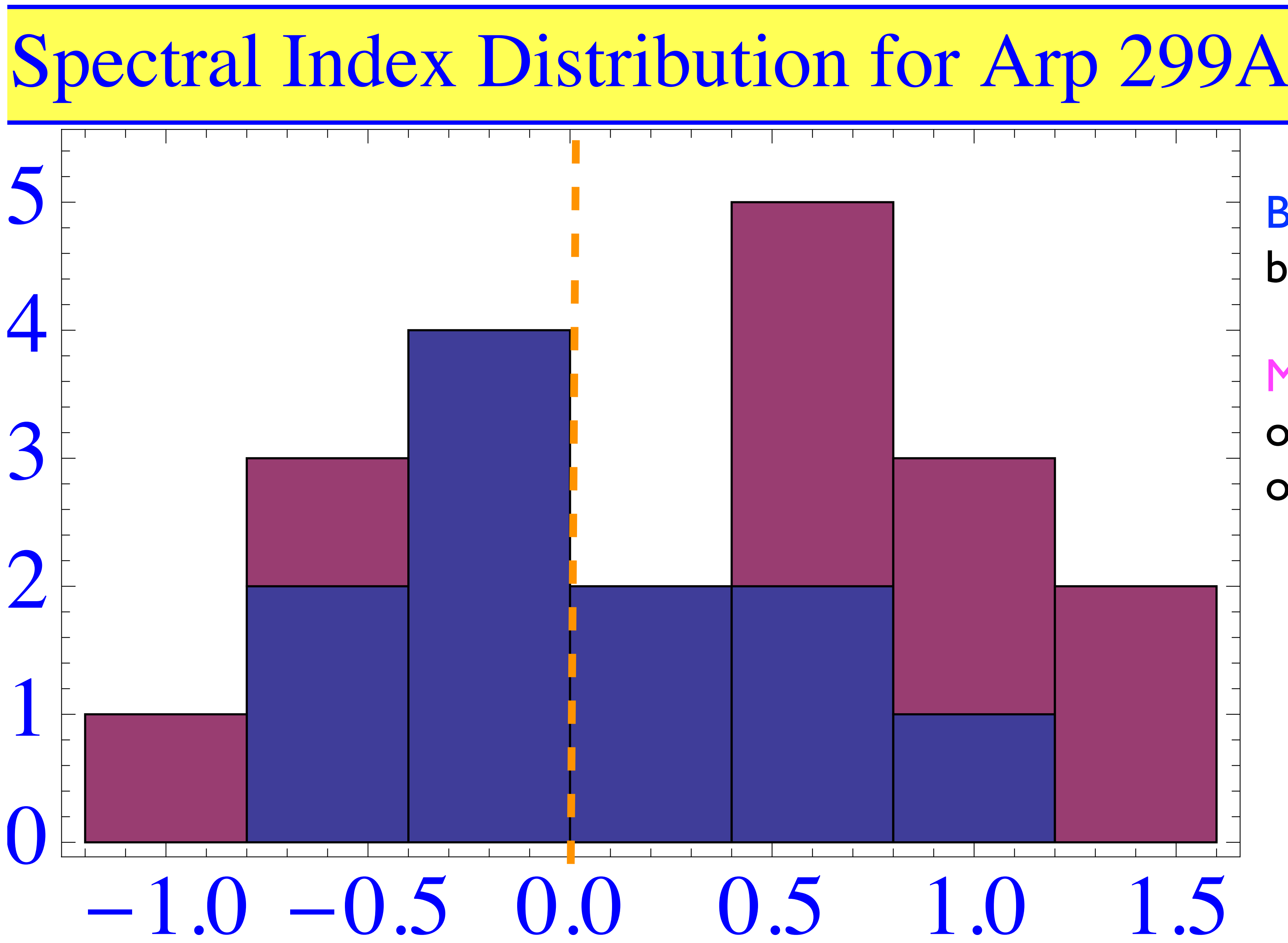
Optically thin phase alpha << 0.0

$$S_\nu \propto \nu^\alpha$$



Very inverted spectra (alpha >> 0.0) suggest very recently exploded CCSNe.
Very steep (alpha << 0.0) suggest RSNe in their optically thin phase.

Source Spectra in Arp 299A



Blue - sources detected at both 1.7 and 5.0 GHz

Magenta - sources detected only at 1.7 GHz (alpha < 0.0), or at 5.0 GHz (alpha > 0.0)

Evidence for RSNe in their optically thick phase (VERY YOUNG), as well as in their opt. thin phase (RELATIVELY YOUNG).

EVN obs-ns of ULIRGs

(PI: Pérez-Torres)

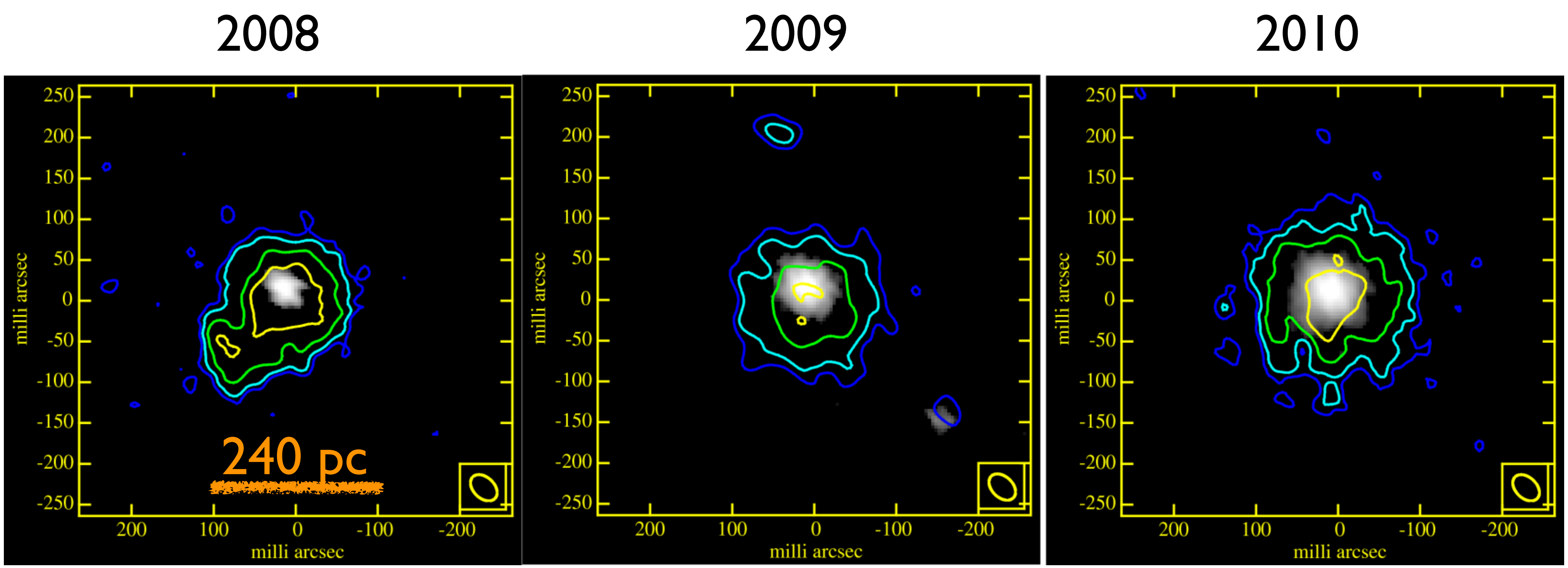
	D (Mpc)	Log(L_ir/L_sun)	CCSN/yr
IRAS 07251-0248	344	12,32	6
IRAS 19295-0406	338	12,37	6
IRAS 19542+1110	257	12,04	3
IRAS 23365+3604	252	12,13	3

- Brightest and farthest ULIRGs in the local universe ever imaged with VLBI
- Resolution ranging from 1-3 mas (EVN@ 6cm), up to 150 mas (MERLIN @ 18 cm), or 4 pc up to 200 pc @ 250 Mpc.

EVN observations of IRAS 23365+3604

D= 250 Mpc; merger in intermediate/advanced state

$L_{IR} \sim 1.4 \times 10^{12} L_{sun}$; CCSN rate = 3 SN/yr

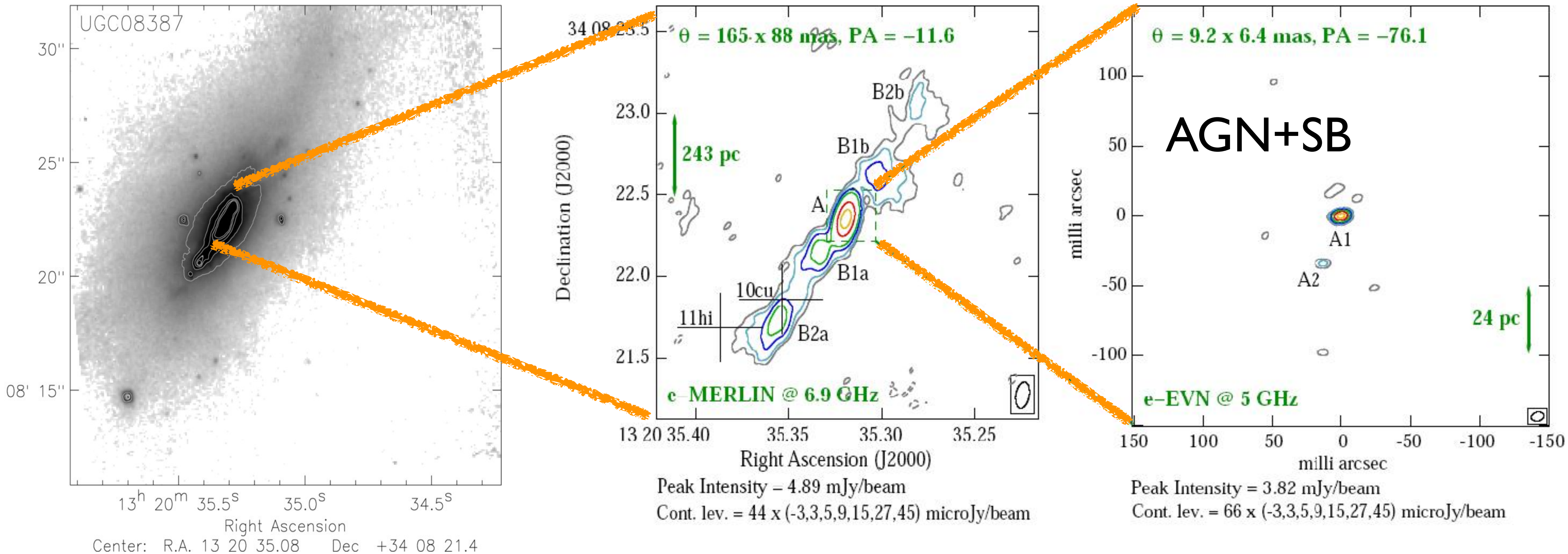


Romero-Cañizales, Pérez-Torres & Alberdi (MNRAS, 2012)

- Evidence for AGN + SB activity - morphological changes, flux variability
- IC losses dominate over synchrotron => reacceleration is needed
- Magnetic field ~200 muG (typical of intermediate/advanced mergers)

The ULIRG IC883

Romero-Cañizales, Pérez-Torres, Alberdi + (2012, A&A)



D= 100 Mpc

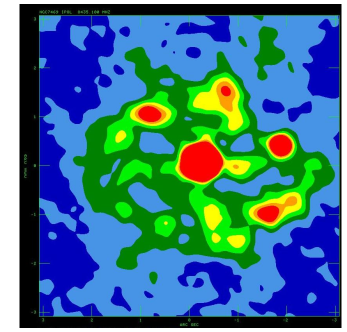
Advanced-stage merger

$L_{IR} \sim 4.7 \times 10^{11}$ L_{sun}; CCSN rate ~ 1.3 SN/yr

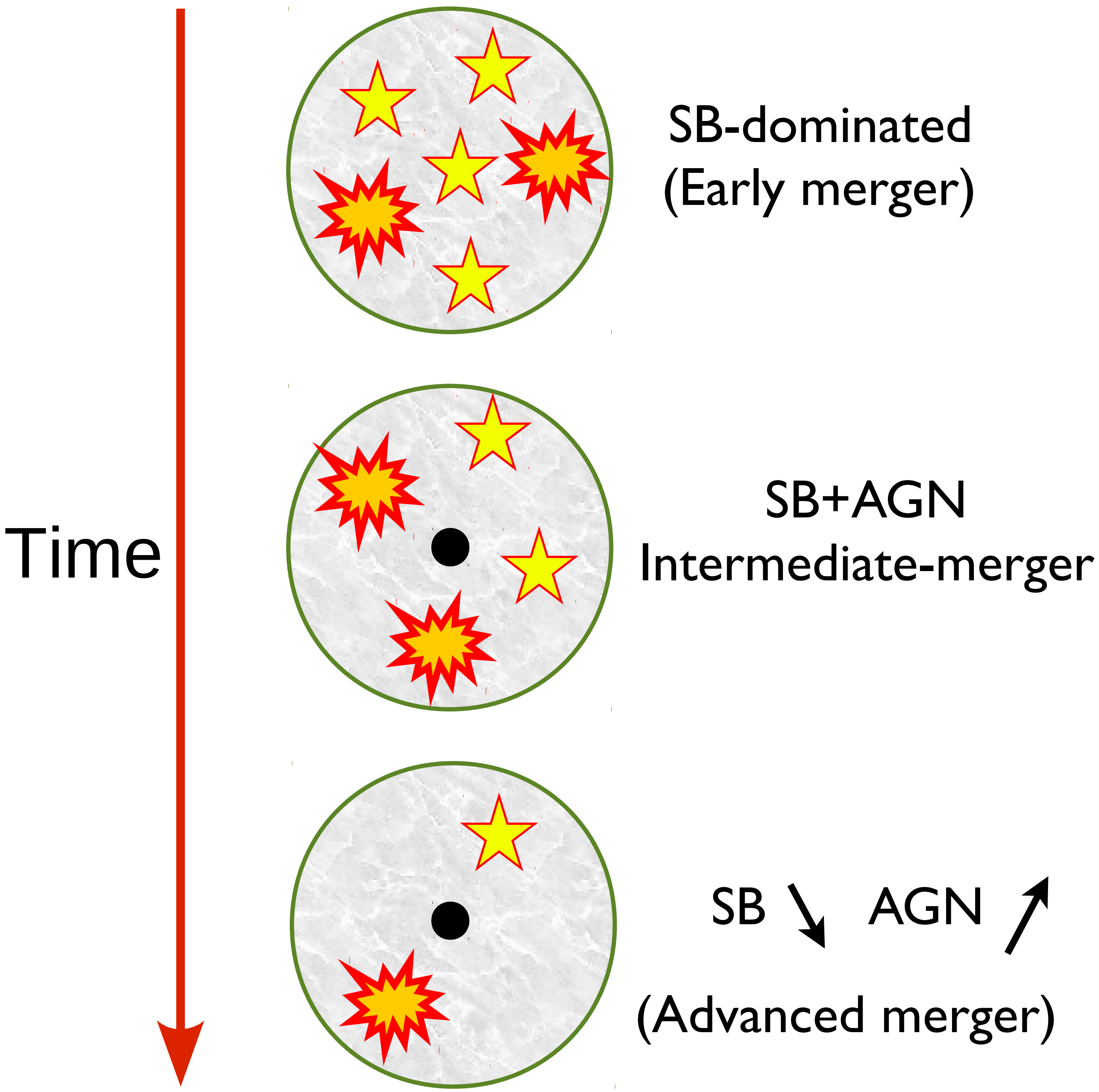
Evidence for AGN + SB activity

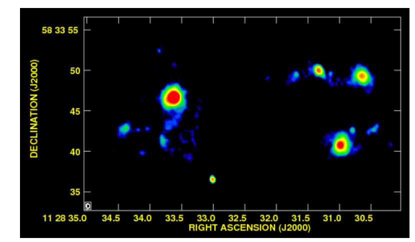
(U)LIRG/QSO evolutionary path

Yuan, Kewley & Sanders (2010)



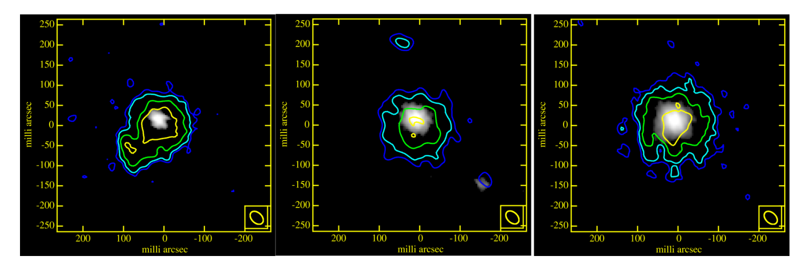
NGC 7469

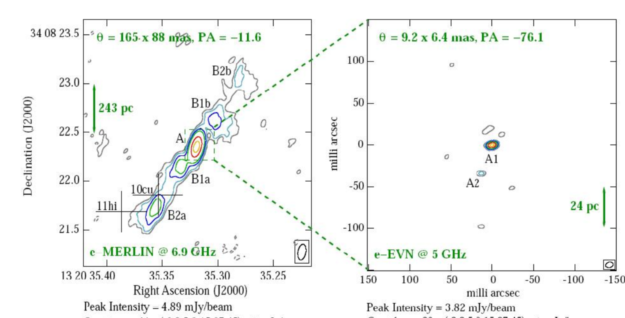




Arp 299

IRAS 23365+3604

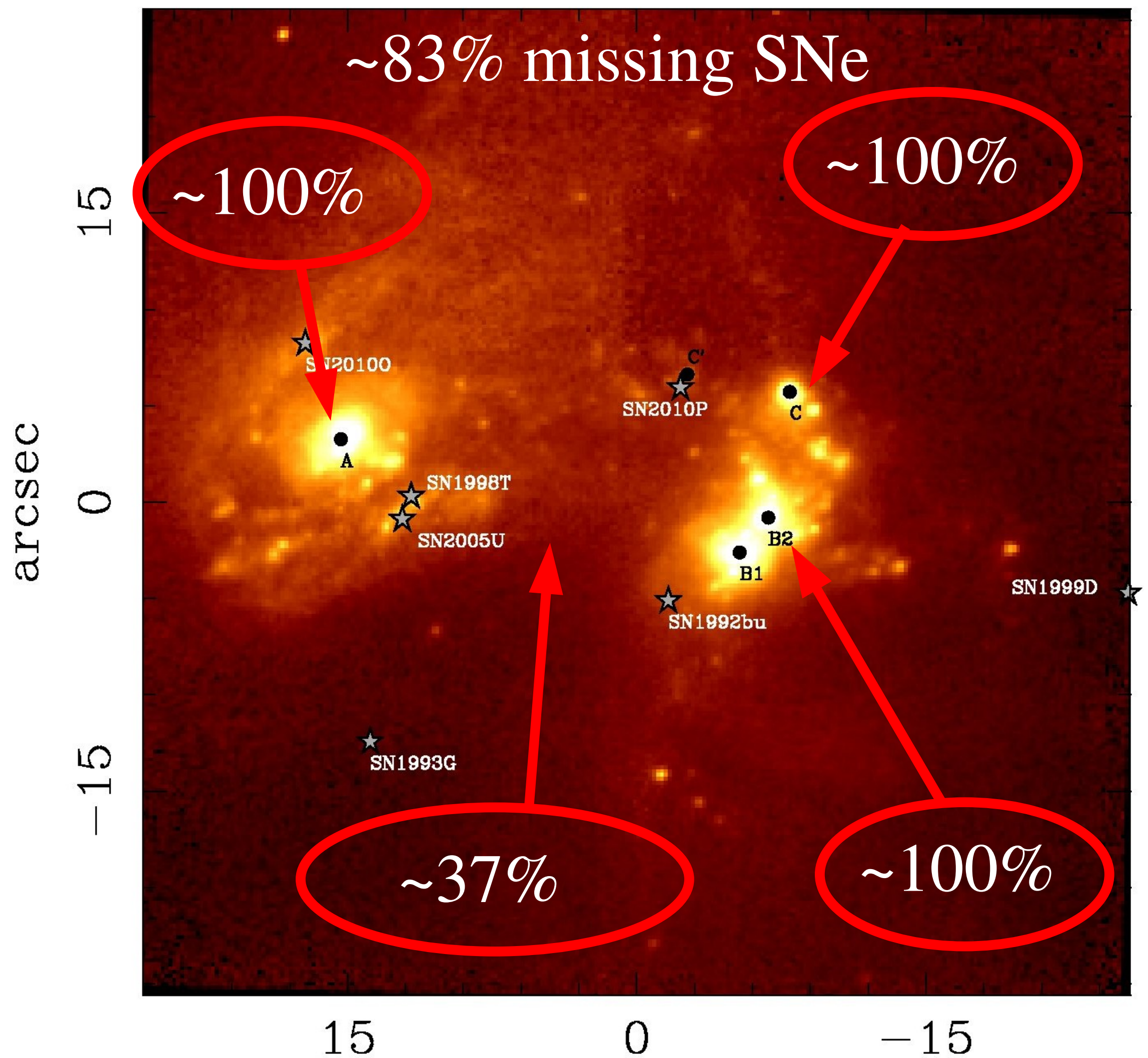


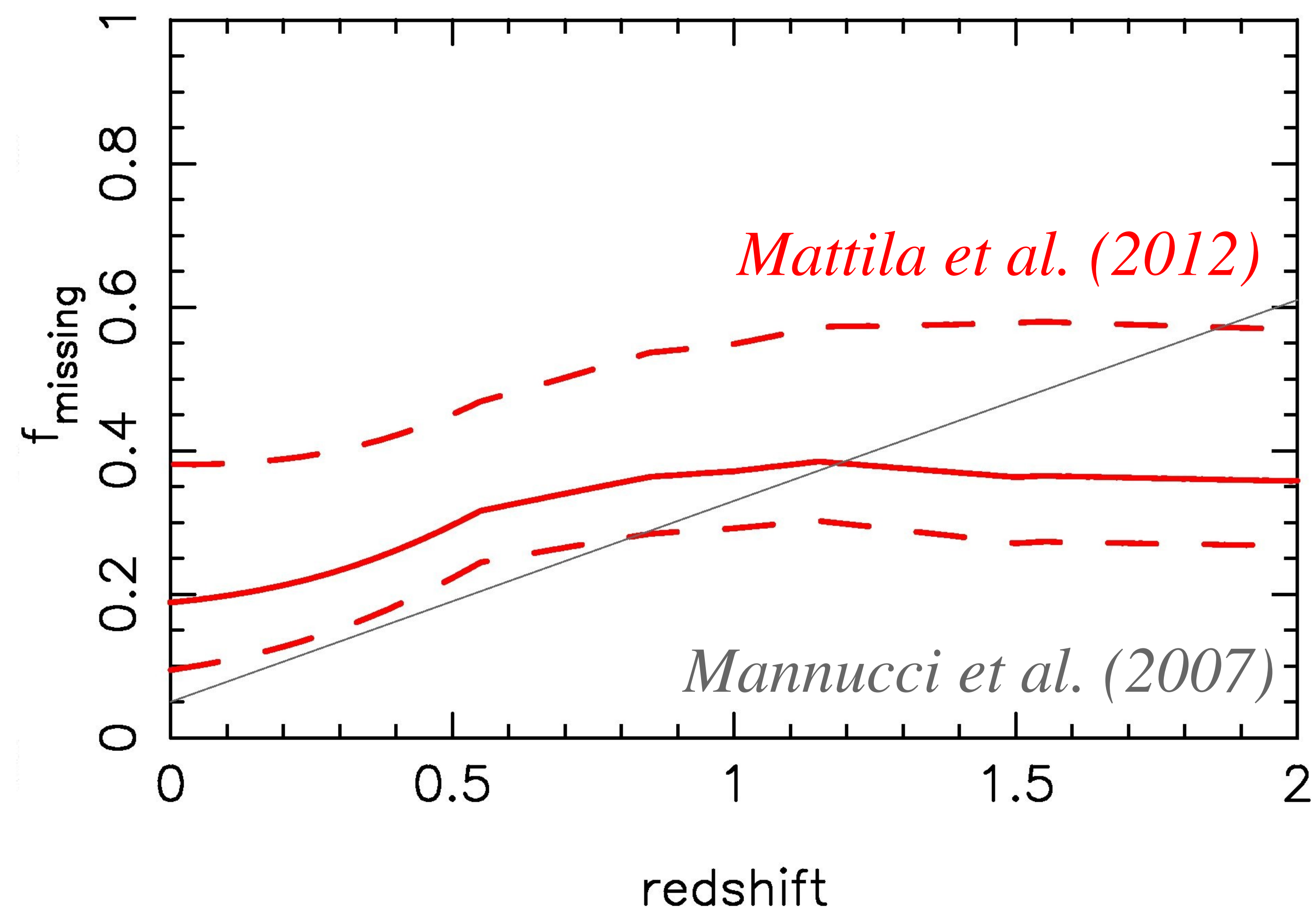


IC883

VLBI observations of local ULIRGs support this scenario

Fraction of (optically) missed SNe in Arp 299



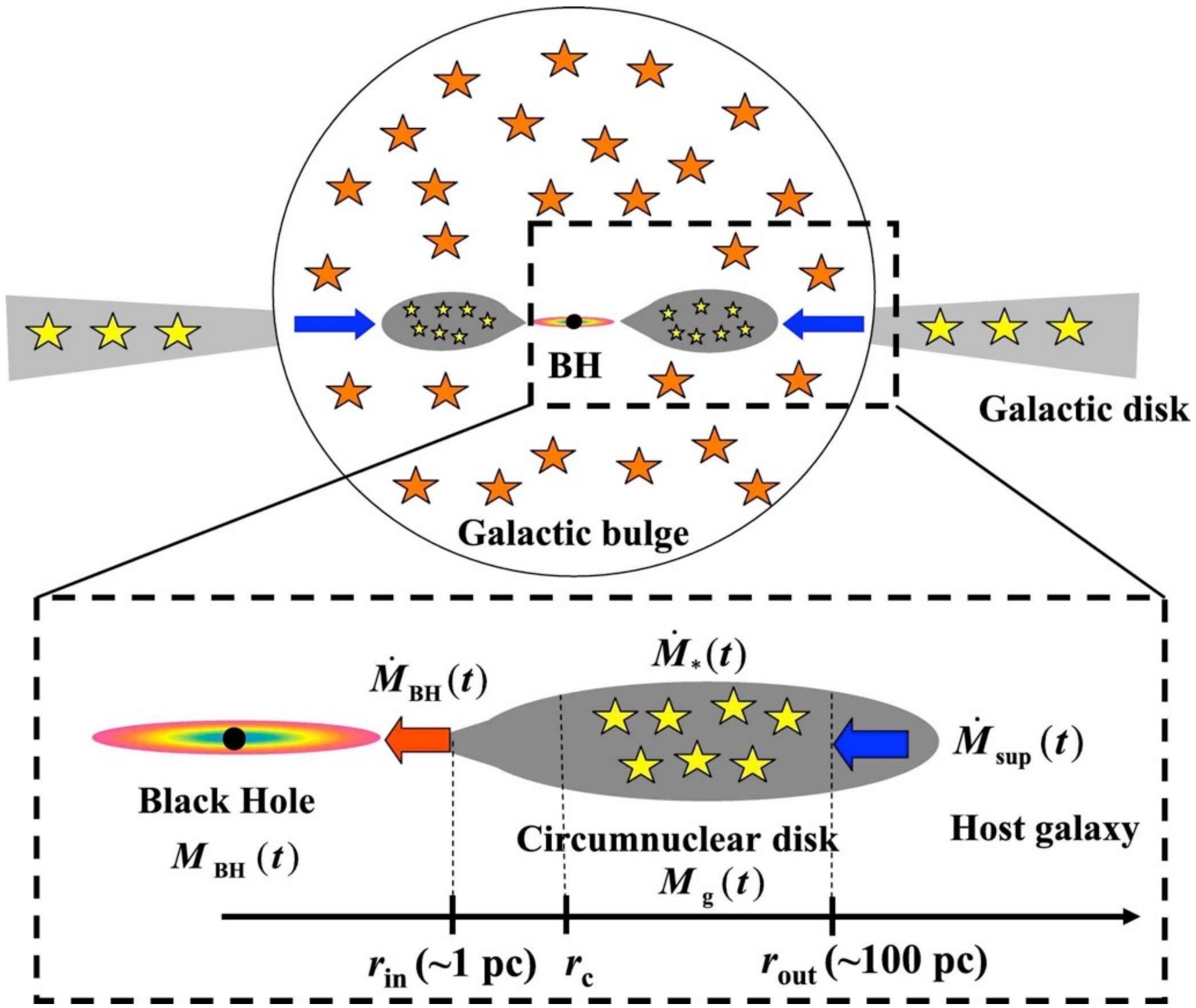


Mattila et al. (2012, ApJ)

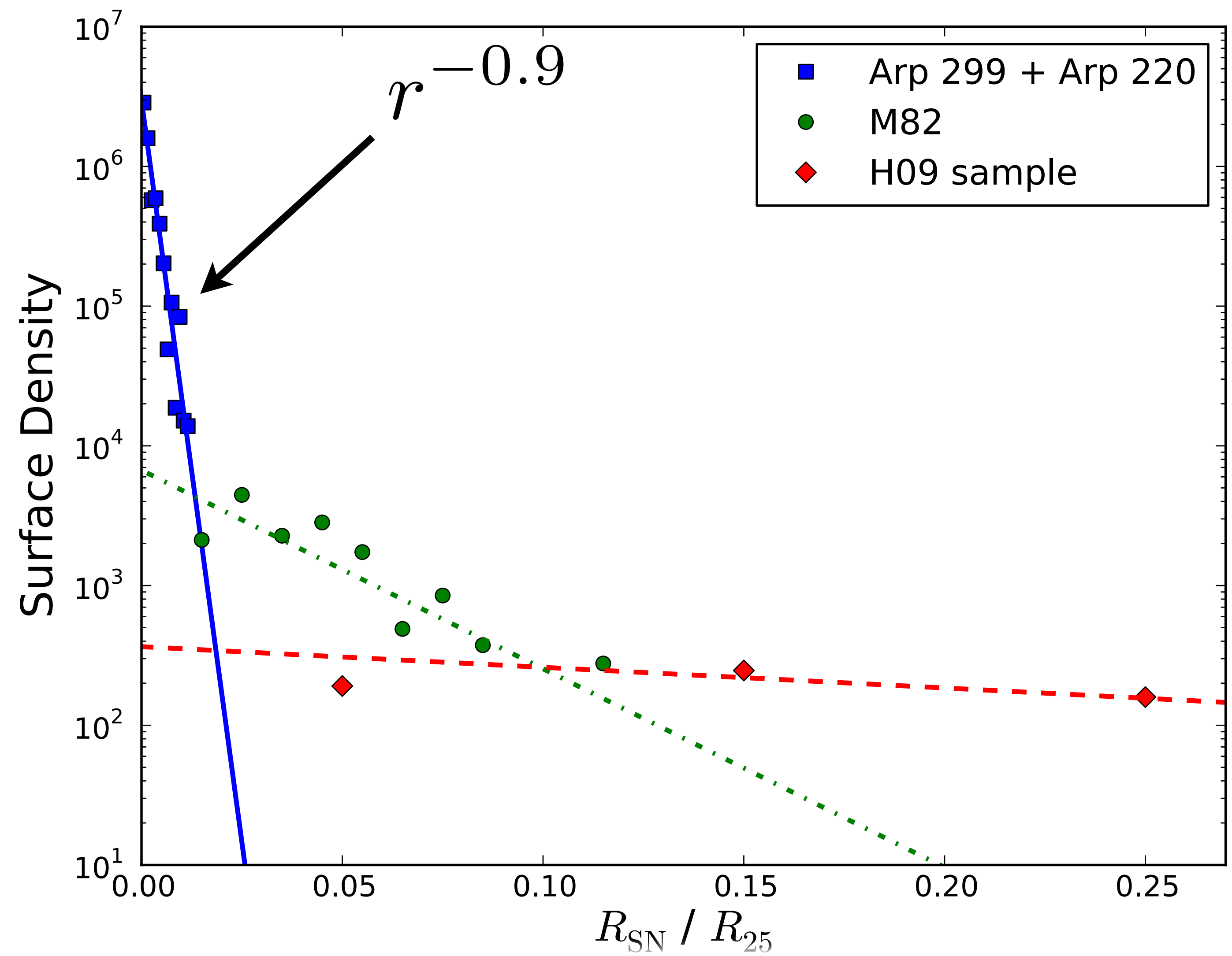
VLBI observations allow to correct for the missing fraction of CCSNe in LIRGs/ ULIRGs

Arp 299 used as template for correct for missing fraction of SNe accross SF history

Evidence of nuclear disks in starburst galaxies from their radial distribution of SNe



Kawakatu & Wada (2008, ApJ)



Herrero-Illana, Pérez-Torres & Alberdi (2012, Letters to A&A)

Theory predicted

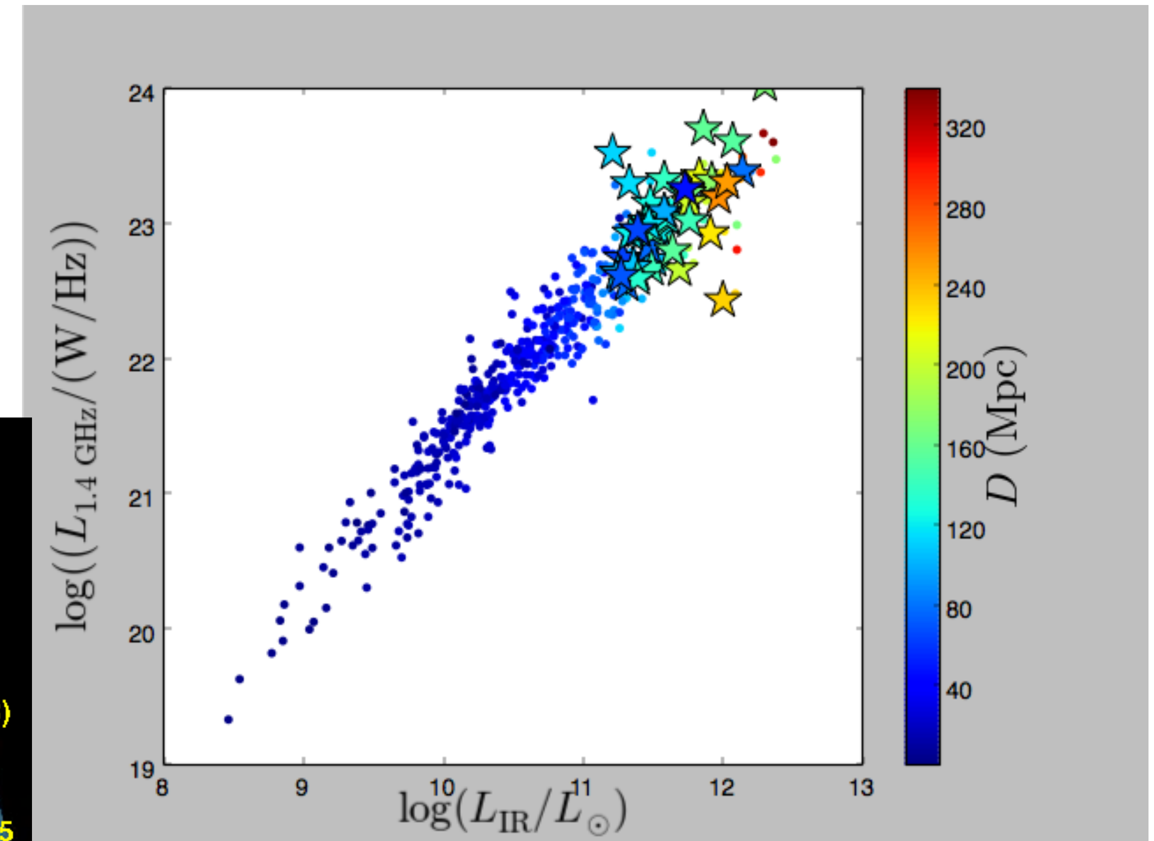
$$\Sigma_{SN} \propto r^{-1}$$

We find

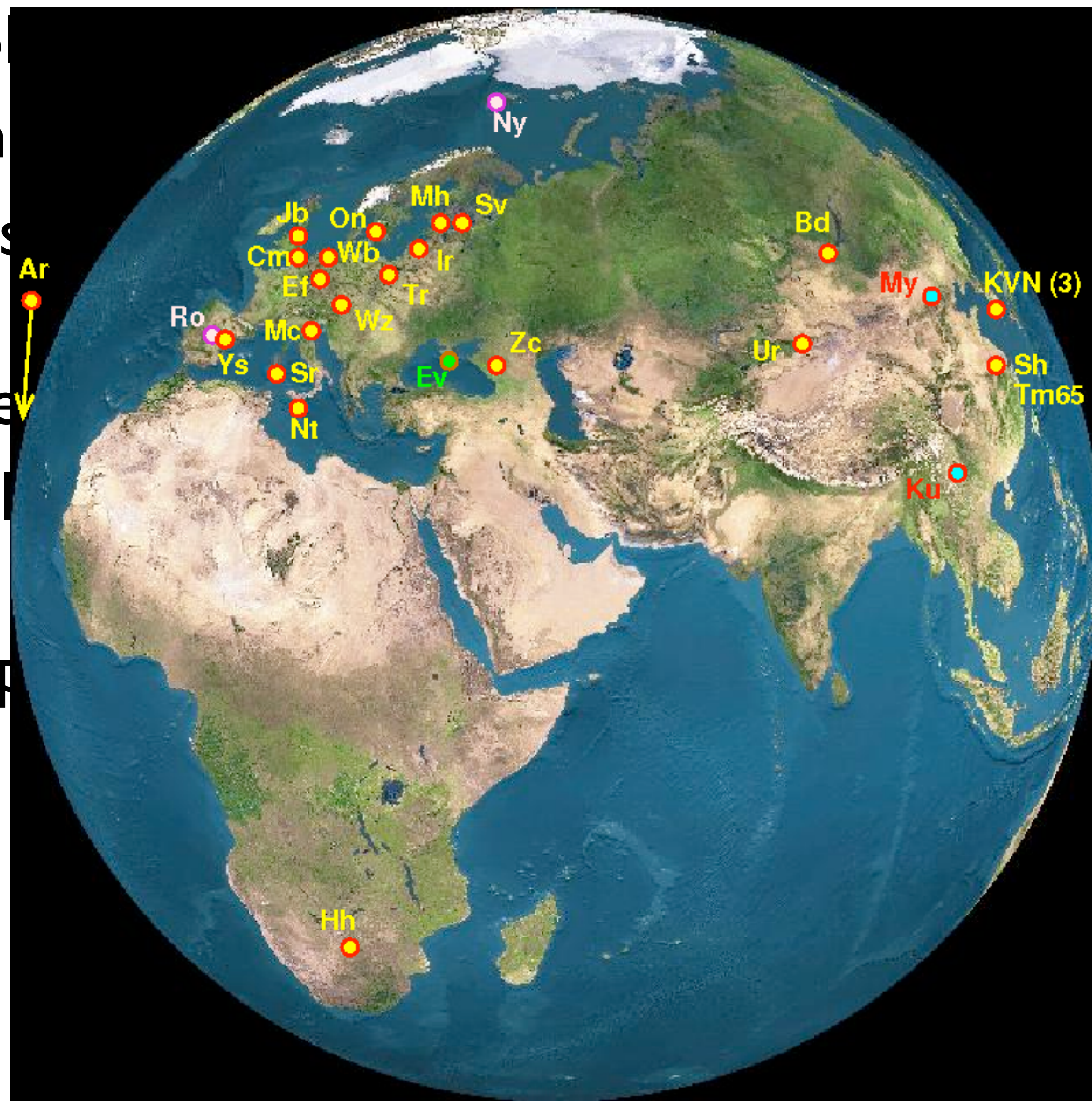
$$\Sigma_{SN} \propto r^{-0.9\pm0.1}$$

LIRGI: Luminous InfraRed Galaxy Inventory
(PIs: John Conway & Miguel Pérez-Torres)

- Legacy survey observations of 42 of the most luminous northern LIRGs selected from IRAS (Sanders+ 2003)

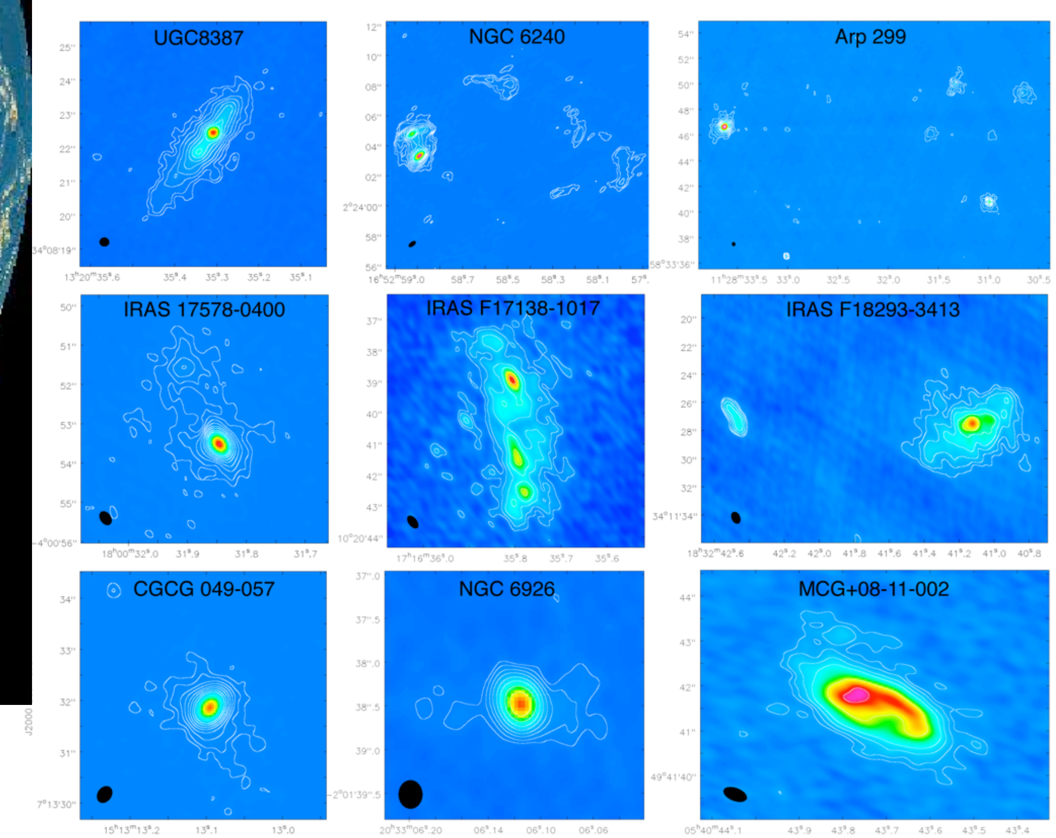


- Sampl
  lumin
  LIRGs



- Prope
  SF-gal

- Comp



EVN-LIRGI

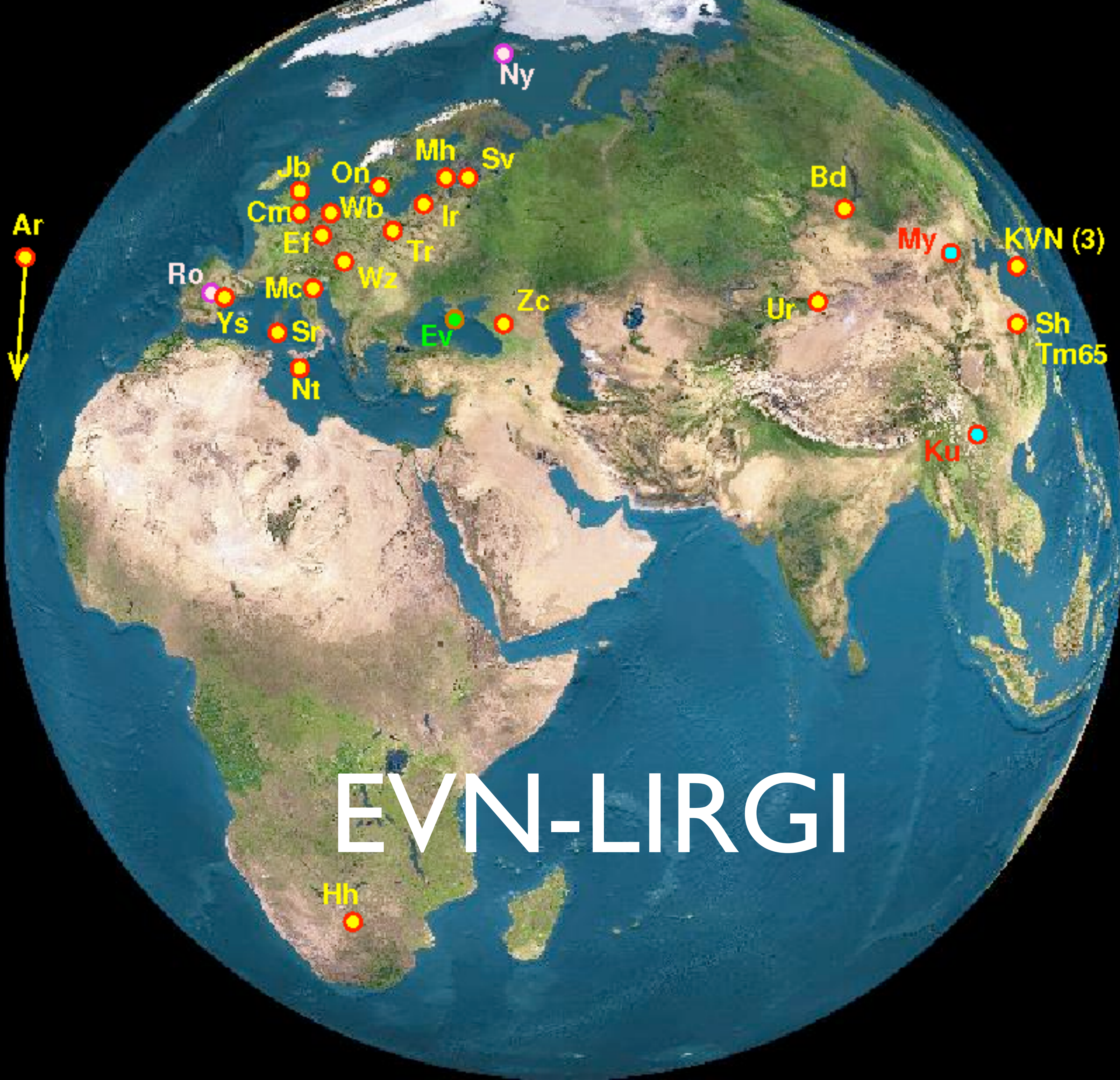

Ny
Mh
Sv
Jb
On
Bd
Cm
Wb
Ir
Ar
Ef
Tr
My
KVN (3)
Ro
Mc
Wz
Zc
Ys
Sr
Ev
Ur
Sh
Tm65
Nt
Ku
Hh

Table 2: Relevant observational parameters for the proposed SKA1 designs and comparable telescopes

	eMERLIN	VLA†	MeerKAT	ASKAP	SKA1-SUR	SKA1-LOW	SKA1-MID
FoV (deg^2)	0.25	0.25	0.86	30	18	27	0.49
Fiducial Freq. (GHz)	1.4	1.4	1.4	1.4	1.67	0.11	1.67
Resolution (arcsec)	0.15	1.4	11	7	0.9	11	0.22
Baseline/size (km)	220	35	4	6	50	50	200
Bandwidth (MHz)	400	1000	1000	300	500	250	770
Sensitivity (μJy-hr$^{-1/2}$)	27.1	3.9	3.2	28.9	3.7	2.1	0.7

†The VLASS 1-σ figure is $\gtrsim$ 10 times worse than obtained with one hr of VLA observing time.

Commensalism and CCSNe in the SKA era

Table 3: Expectations for CCSN detections in the local Universe from commensal radio surveys from the VLASS (5-σ = 500 μJy/beam), SKA1-SUR (5-σ = 46.5 μJy/beam), SKA1-50% (5-σ = 66.4 μJy/beam), and SKA (5-σ = 4.65 μJy/beam) assuming each survey observes at a nominal frequency of 1.7 GHz and covers an area of 10,000 deg^2 in one year. $L_{\nu,26} = L_{\nu,\mathrm{peak}}/10^{26}$ erg/s/Hz; $\nu_5^{-1} = \nu/5$ GHz

SN Type	$\Delta t_{\mathrm{peak}}\, \nu_5^{-1}$ [days]	$L_{\nu,26}$	VLASS		SKA1-SUR		SKA1-50%		SKA	
			D_{max}	N_{det}	D_{max}	N_{det}	D_{max}	N_{det}	D_{max}	N_{det}
Ib/c	30	20	58	5.1	189	177	159	106	596	5618
IIb, IIL	∼150	10	41	0.8	133	29	112.2	17.4	422	924
IIP	40	0.5	9	0.04	30	1.5	25	0.9	94	47
IIn	1000	100	129	6.6	422	104	355	80	1334	7247
87A	2	0.04	2.6	$\sim 10^{-5}$	8.4	$\sim 10^{-3}$	9	$\sim 10^{-3}$	26.7	0.05
Total				∼13		∼311		∼204		∼13800

Pérez-Torres+2015 (SKA book chapter)

Summary

- High-angular, sensitive radio observations in compact U/LIRGs are extremely useful to

  - Determine CCSNe rates in compact U/LIRGs
  - Probe interacion SNe-CSM, SNe-ISM in U/LIRGs
  - Unveil existence of AGN and/or other nuclear transients

- Near-IR searches of CCSNe and radio interferometry very complementary

- Upcoming radio interferometric facilities (MeerKAT, ASKAP, SKA) expected to unveil large numbers of CCSNe (commensal mode)