Constraining the progenitor system and environs of the Type Ia SN 2014J with the EVN and eMERLIN

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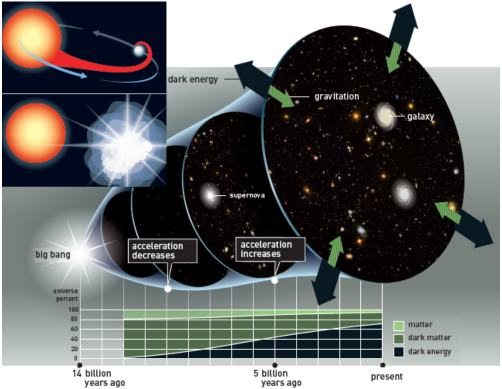
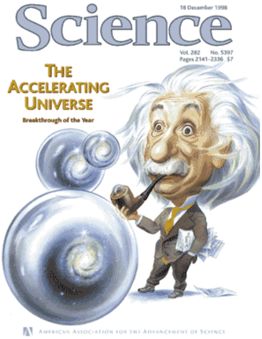
(See Pérez-Torres, Lundqvist, Beswick, Björnsson, Muxlow, Paragi, Ryder, Alberdi, Fransson, Marcaide, Marti-Vidal, Ros, Argo, and Guirado **2014, ApJ, 792, 38**)

12$^{\text{th}}$EVN Symposium, 2014 October 9

SNe Ia - used in cosmology and galaxy evolution

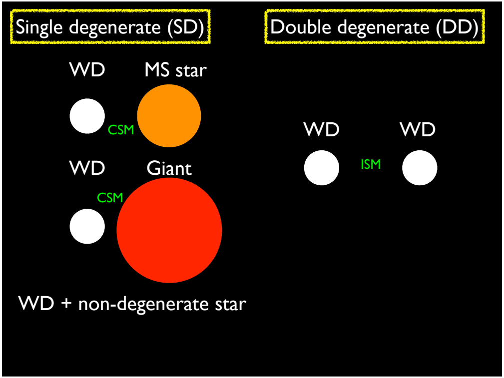




Type Ia SNe play a crucial role

- Primary cosmological distance indicators
- Major contributors to the chemical evolution of galaxies

What are the progenitors of Type Ia SNe?



Yet we don't know what makes a Type Ia SN (embarrassing)

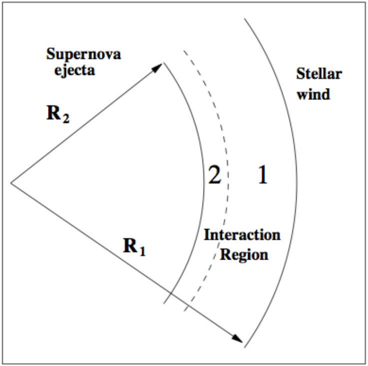
- Plethora of Single Degenerate (SD) scenarios + DD scenario
- Observationally is tough to distinguish between them

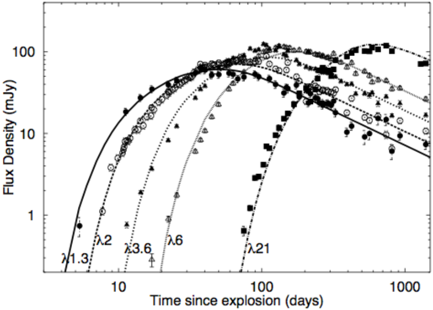
Radio observations to unveil long-standing mystery

Radio (and X-rays) is probably the most powerful observational tool to unveil the progenitor system of Type Ia SNe

- Single-degenerate scenario (WD + non-degenerate star)
  ⇒ measurable prompt radio emission
- Double-degenerate scenario (WD + WD)
  ⇒ no prompt radio emission

Synchrotron radio emission from CCSNe

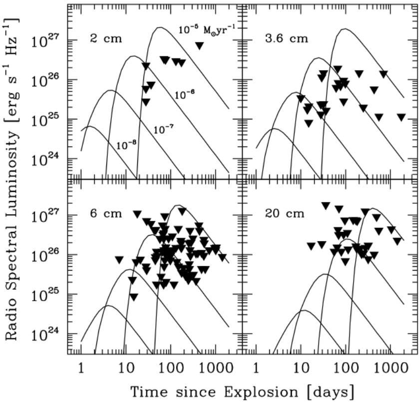




Radio measurements directly tell us the mass-loss rate of SNe

$$L_{\nu,\mathrm{radio}} \propto \nu^{\alpha}\, t^{\beta} \propto \left(\dot{M}/v_w\right)$$

Radio observations of SNe Ia



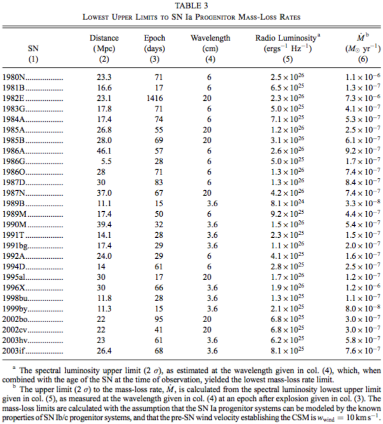


TABLE 3

LOWEST UPPER LIMITS TO SN Ia PROGENITOR MASS-LOSS RATES

SN (1)	Distance (Mpc) (2)	Epoch (days) (3)	Wavelength (cm) (4)	Radio Luminosity[a] (ergs^{-1} Hz^{-1}) (5)	$\dot{M}$[b] ($M_{\odot}$ yr^{-1}) (6)
1980N	23.3	71	6	2.5×10^{26}	1.1×10^{-6}
1981B	16.6	17	6	6.5×10^{25}	1.3×10^{-7}
1982E	23.1	1416	20	2.3×10^{26}	7.3×10^{-6}
1983G	17.8	71	6	5.0×10^{25}	4.1×10^{-7}
1984A	17.4	74	6	7.1×10^{25}	5.3×10^{-7}
1985A	26.8	55	20	1.2×10^{26}	2.5×10^{-7}
1985B	28.0	69	20	3.1×10^{26}	6.1×10^{-7}
1986A	46.1	57	6	2.6×10^{26}	9.2×10^{-7}
1986G	5.5	28	6	5.0×10^{25}	1.7×10^{-7}
1986O	28	71	6	1.3×10^{26}	7.4×10^{-7}
1987D	30	83	6	1.3×10^{26}	8.4×10^{-7}
1987N	37.0	67	20	4.2×10^{26}	7.4×10^{-7}
1989B	11.1	15	3.6	8.1×10^{24}	3.3×10^{-8}
1989M	17.4	50	6	9.2×10^{25}	4.4×10^{-7}
1990M	39.4	32	3.6	1.5×10^{26}	5.4×10^{-7}
1991T	14.1	28	3.6	2.3×10^{25}	1.5×10^{-7}
1991bg	17.4	29	3.6	1.1×10^{26}	2.0×10^{-7}
1992A	24.0	29	6	4.1×10^{25}	1.6×10^{-7}
1994D	14	61	6	2.8×10^{25}	2.5×10^{-7}
1995al	30	17	20	1.7×10^{26}	1.2×10^{-7}
1996X	30	66	3.6	1.9×10^{26}	1.2×10^{-6}
1998bu	11.8	28	3.6	1.3×10^{25}	1.1×10^{-7}
1999by	11.3	15	3.6	2.1×10^{25}	8.0×10^{-8}
2002bo	22	95	20	6.8×10^{25}	3.0×10^{-7}
2002cv	22	41	20	6.8×10^{25}	3.0×10^{-7}
2003hv	23	61	3.6	6.2×10^{25}	5.8×10^{-7}
2003if	26.4	68	3.6	8.1×10^{25}	7.6×10^{-7}

[a] The spectral luminosity upper limit (2 σ), as estimated at the wavelength given in col. (4), which, when combined with the age of the SN at the time of observation, yielded the lowest mass-loss rate limit.

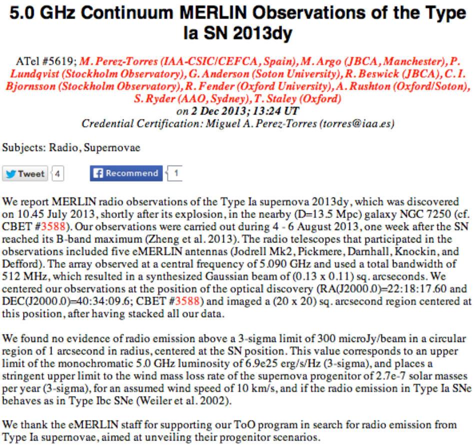
[b] The upper limit (2 σ) to the mass-loss rate, $\dot{M}$, is calculated from the spectral luminosity lowest upper limit given in col. (5), as measured at the wavelength given in col. (4) at an epoch after explosion given in col. (3). The mass-loss limits are calculated with the assumption that the SN Ia progenitor systems can be modeled by the known properties of SN Ib/c progenitor systems, and that the pre-SN wind velocity establishing the CSM is $w_{\rm wind} = 10\ {\rm km\ s^{-1}}$.

Panagia et al. (2006)

- Chevalier (1982) model + scaling of emission from SNe Ib/c

SN 1999by: $L_{\nu} \approx 2.0 \times 10^{25}$ erg s^{-1} Hz^{-1}; $\dot{M} \approx 1.2 \times 10^{-7}\, {\rm M_{\odot}\, yr^{-1}}$(3-$\sigma$)

Upper limits to the radio emission of SN 2013dy



5.0 GHz Continuum MERLIN Observations of the Type Ia SN 2013dy

ATel #5619; *M. Perez-Torres (IAA-CSIC/CEFCA, Spain), M. Argo (JBCA, Manchester), P. Lundqvist (Stockholm Observatory), G. Anderson (Soton University), R. Beswick (JBCA), C. I. Bjornsson (Stockholm Observatory), R. Fender (Oxford University), A. Rushton (Oxford/Soton), S. Ryder (AAO, Sydney), T. Staley (Oxford)*
on ***2 Dec 2013; 13:24 UT***
Credential Certification: Miguel A. Perez-Torres (torres@iaa.es)

Subjects: Radio, Supernovae

We report MERLIN radio observations of the Type Ia supernova 2013dy, which was discovered on 10.45 July 2013, shortly after its explosion, in the nearby (D=13.5 Mpc) galaxy NGC 7250 (cf. CBET #3588). Our observations were carried out during 4 - 6 August 2013, one week after the SN reached its B-band maximum (Zheng et al. 2013). The radio telescopes that participated in the observations included five eMERLIN antennas (Jodrell Mk2, Pickmere, Darnhall, Knockin, and Defford). The array observed at a central frequency of 5.090 GHz and used a total bandwidth of 512 MHz, which resulted in a synthesized Gaussian beam of (0.13 x 0.11) sq. arcseconds. We centered our observations at the position of the optical discovery (RA(J2000.0)=22:18:17.60 and DEC(J2000.0)=40:34:09.6; CBET #3588) and imaged a (20 x 20) sq. arcsecond region centered at this position, after having stacked all our data.

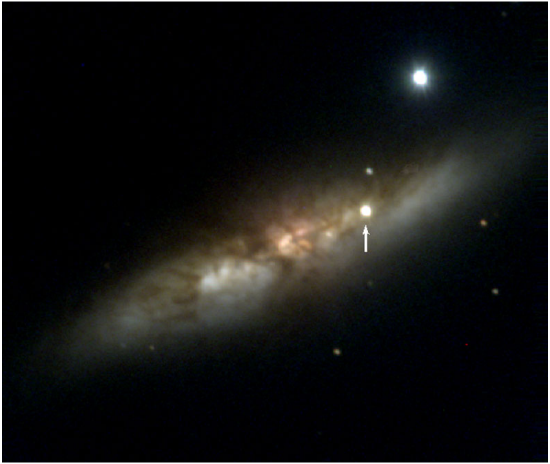
We found no evidence of radio emission above a 3-sigma limit of 300 microJy/beam in a circular region of 1 arcsecond in radius, centered at the SN position. This value corresponds to an upper limit of the monochromatic 5.0 GHz luminosity of 6.9e25 erg/s/Hz (3-sigma), and places a stringent upper limit to the wind mass loss rate of the supernova progenitor of 2.7e-7 solar masses per year (3-sigma), for an assumed wind speed of 10 km/s, and if the radio emission in Type Ia SNe behaves as in Type Ibc SNe (Weiler et al. 2002).

We thank the eMERLIN staff for supporting our ToO program in search for radio emission from Type Ia supernovae, aimed at unveiling their progenitor scenarios.

From Pérez-Torres et al. 2013, ATel No. 5619

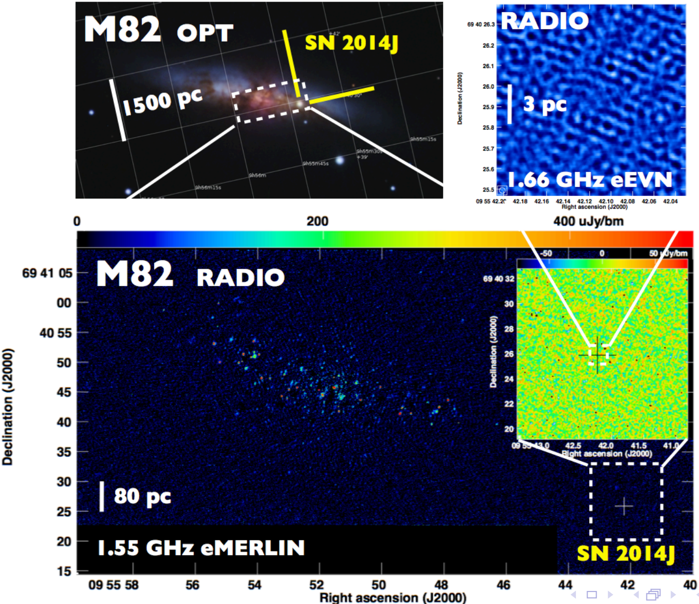
$$L_\nu \approx 6.9\times10^{25}\ \mathrm{erg\ s^{-1}\ Hz^{-1}};\ \dot{M}\approx 2.7\times10^{-7}\,\mathrm{M_\odot\,yr^{-1}}(3\text{-}\sigma)$$

The Type Ia SN 2014J in M 82 (D = 3.5 Mpc)



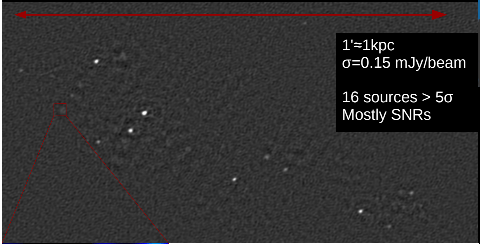
Serendipitous discovery by Fossey et al. (2014)
Imaging by Itagaki $\Rightarrow t_{\mathrm{expl}} \approx$ 15.0 Jan 2014

EVN and eMERLIN obs-ns (Pérez-Torres et al. 2014)



(Unrelated to this talk)LOFAR imaging of M 82

M82 with LOFAR: “Meter-VLBI”
0.3" resolution at 154 MHz



1'≈1kpc
σ=0.15 mJy/beam

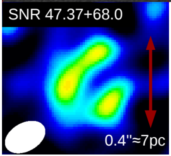
16 sources > 5σ
Mostly SNRs

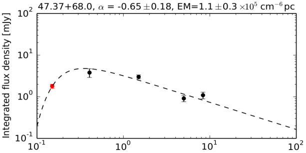
Calibration “EVN-style”:

AIPS

“MFS”-imaging:

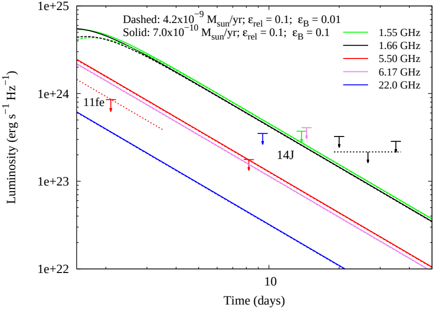
CASA





Varenius et al., submitted to A&A

Severe constraints on the radio luminosity of SN 2014



Starting UT	T day	$t_{\rm int}$ hours	Array	ν GHz	S_ν μJy	L$_{\nu,22}$	$\dot{M}_{-9}$
Jan 23.2	8.2	–	JVLA	5.50	4.0	5.9	0.70
Jan 24.4	9.4	–	JVLA	22.0	8.0	11.7	3.7
Jan 28.8	13.8	13.6	eMERLIN	1.55	12.4	18.2	0.85
Jan 29.5	14.5	14.0	eMERLIN	6.17	13.6	19.9	2.7
Feb 4.0	20.0	11.0	eEVN	1.66	10.8	15.8	1.3
Feb 19.1	35.0	10.0	eEVN	1.66	9.5	13.9	2.2

Pérez-Torres et al. (2014)

Most constraining upper limits to radio emission of SNe Ia, together with those on SN2011fe

- $L_\nu \lesssim 2 \times 10^{23}$ erg s^{-1} Hz^{-1}

Modelling the radio emission from Type Ia SNe

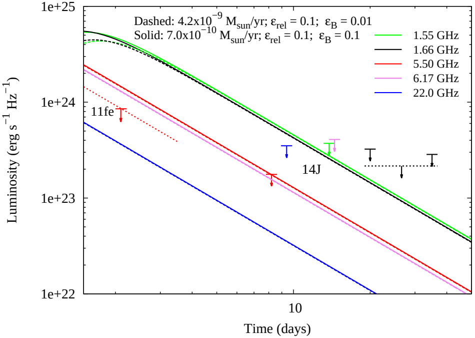
- Chevalier's model
- Shock-CSM interaction: $r_{\rm shock} \propto t^m$; $\rho_{\rm wind} \propto r^{-2}$
- Shock energetics: $\epsilon_{\rm B} = u_{\rm B}/u_{\rm th}$

Radio luminosity traces the mass-loss rate of SNe

$$L_{\nu,\rm thin} \propto \epsilon_{\rm B}^{1.1} \left(\dot{M}/v_w\right)^{1.4} \; t^{-1.6}$$

- Time dependence ⇒ Early radio observations are crucial!

Radio evolution of SN 2014J - CSM wind scenario

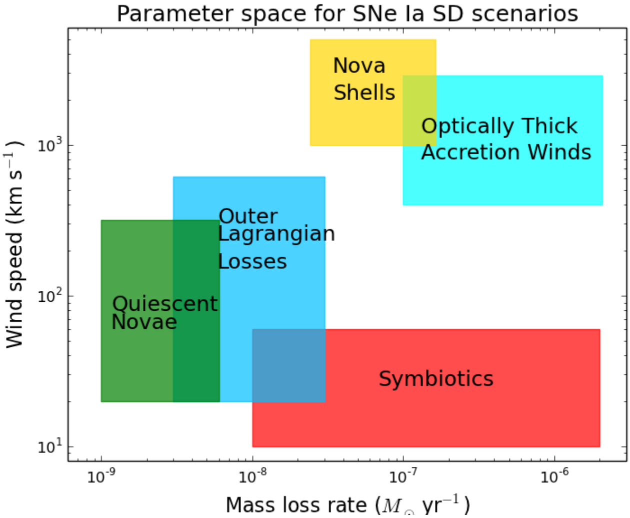


$$L_{\nu,\mathrm{thin}} \propto \epsilon_{\mathrm{B}}^{1.1} \left(\dot{M}/v_w\right)^{1.4} \; t^{-1.6}$$

Most constraining $\dot{M}$ for SNe Ia, together with those for SN2011fe

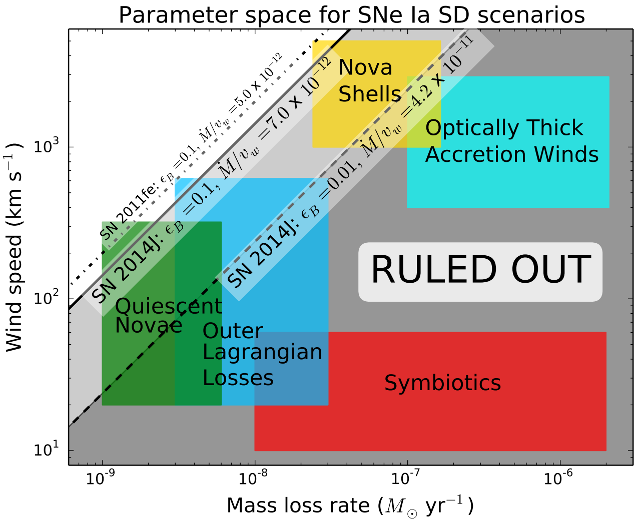
- $\dot{M} \lesssim 7.0 \times 10^{-10}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ ($\epsilon_{\mathrm{B}} = 0.1$); v_w=100 km s^{-1}

Mass-loss rate – wind-speed parameter space for SNe

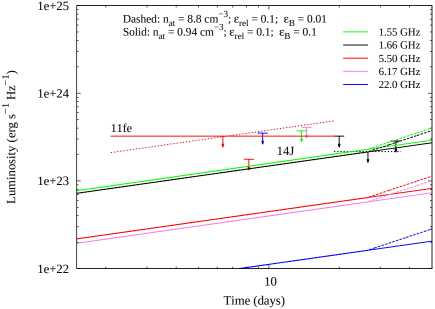


Constraints on the progenitor system of SN 2014J

Pérez-Torres et al. (2014)



Radio obs-ns of SN 2014J - ISM constraints



$n_{\rm ISM} = \mu \, N_{\rm H\,I}/l$

$N_{\rm H\,I} \sim 2 \times 10^{20}$ cm^{-2}

Path length, $l \sim 100$ pc

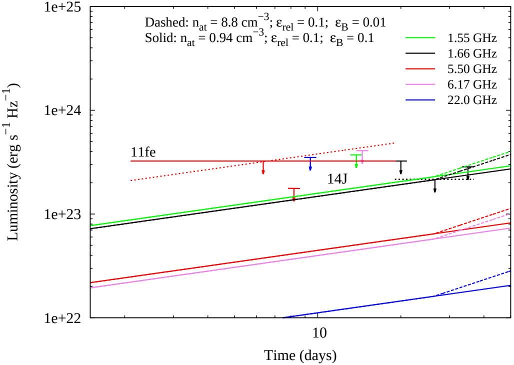
Solar abundances, $\mu \approx 1.4$

$\Rightarrow n_{\rm ISM} \lesssim 1$ cm^{-3} $(\epsilon_B = 0.1)$

Most constraining upper limits to the ISM around the progenitor star of SNe Ia (in the DD scenario)

- $n_{\rm ISM} \lesssim 1$ cm^{-3} $(\epsilon_B = 0.1)$

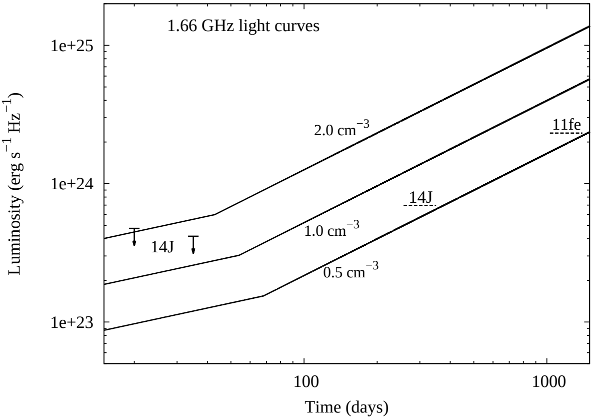
Late radio emission as a probe of the DD scenario



$$L_{\nu,\mathrm{thin}} \propto \epsilon_{\mathrm{B}}^{1.1}\; n_{\mathrm{ISM}}^{1.3}\; t^{0.9}$$

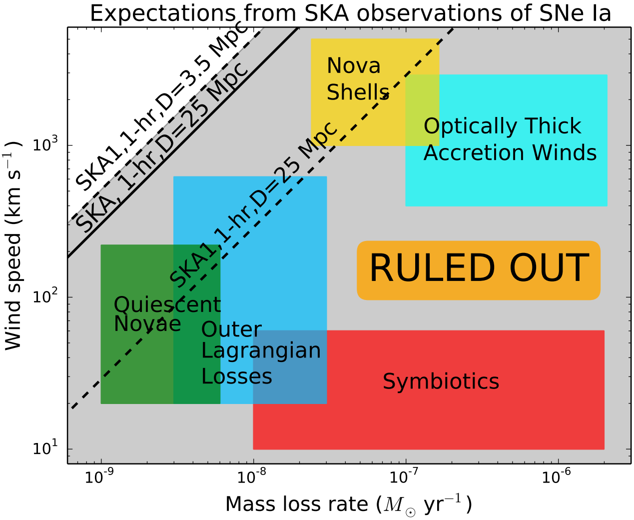
- The DD scenario predicts a steady increase of radio emission (!)

Probing the late time radio emission of SNe Ia



Granted EVN observations to probe the double-degenerate scenario in SN2011fe and SN2014J

A promising future: SKA



Take-away messages

EVN and eMERLIN are incredible machines

- Enormous contribution to the field of stellar evolution, thanks to their sensitivity and high-angular resolution.

Most single degenerate scenarios ruled out for SN 2014J

- There is little room for SD scenarios, which favors the DD scenario.
- If the medium is uniform (i.e., the ISM) $\Rightarrow n_{\mathrm{ISM}} \lesssim 1\ \mathrm{cm}^{-3}$
- Late radio observations to test the DD scenario (!) (very clean environment!)

$\Re \sim 3 \times 10^{-5}$ SN/yr/Mpc^{-3} (Dilday et al. 2010)
Very few nearby SNe per decade $\Rightarrow$ should be observed

- Prompt (and late!) radio observations key to unveil true progenitors
- SKA to unambiguously solve the issue.