Search for Radio Emission in Type Ia Supernovae

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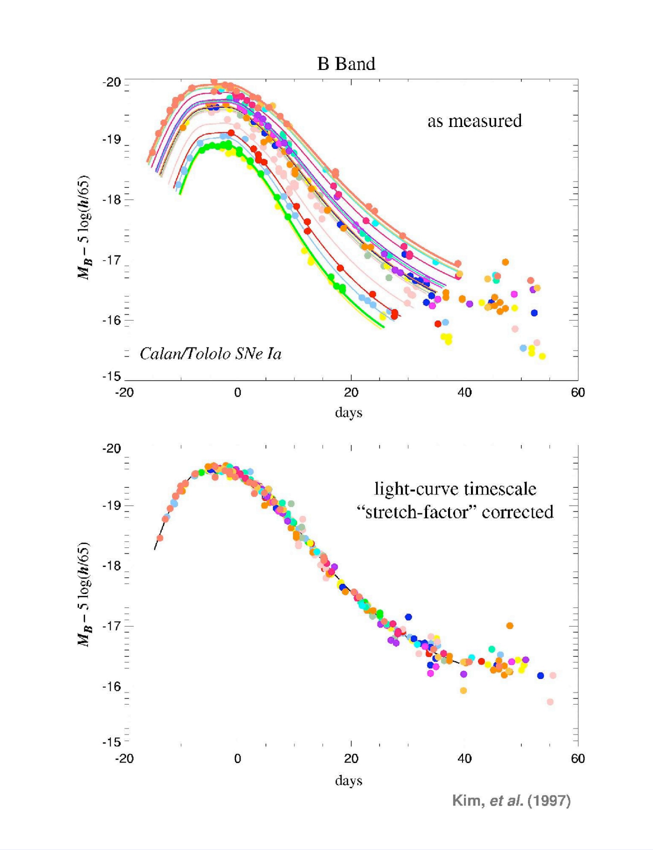
(January 9, 2014)

The Origin of Type Ia Supernovae...

Why are SNe Ia interesting?

astrophysical relevance: cosmology

- tool for geometrical survey of the universe
  - brightness
  - uniformity
  - empirical calibration
- content of the universe:
  - 70% dark energy
  - 30% matter (dark and visible)

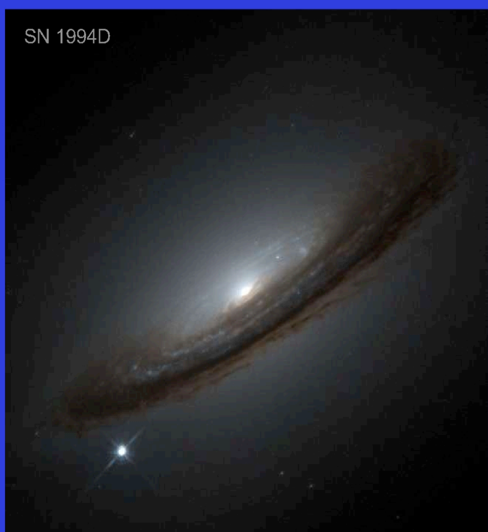


The small spread in the corrected light curve could be systematic – do we have more than one route to produce Type Ia:s?

The Origin of Type Ia Supernovae...

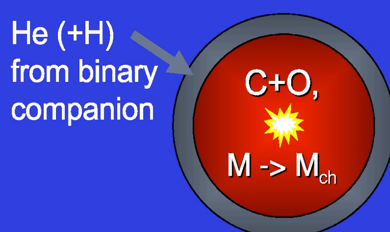
What are SNe Ia?

astrophysical events of enormous energy release and brightness

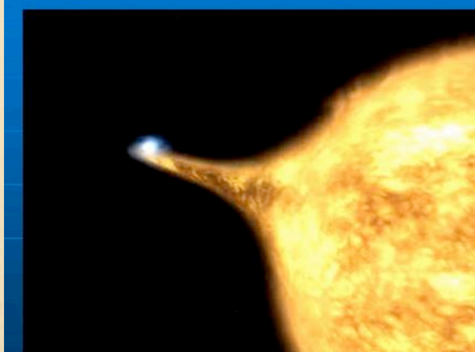


Favored astrophysical model:

thermonuclear explosion of a white dwarf star



The "standard model"

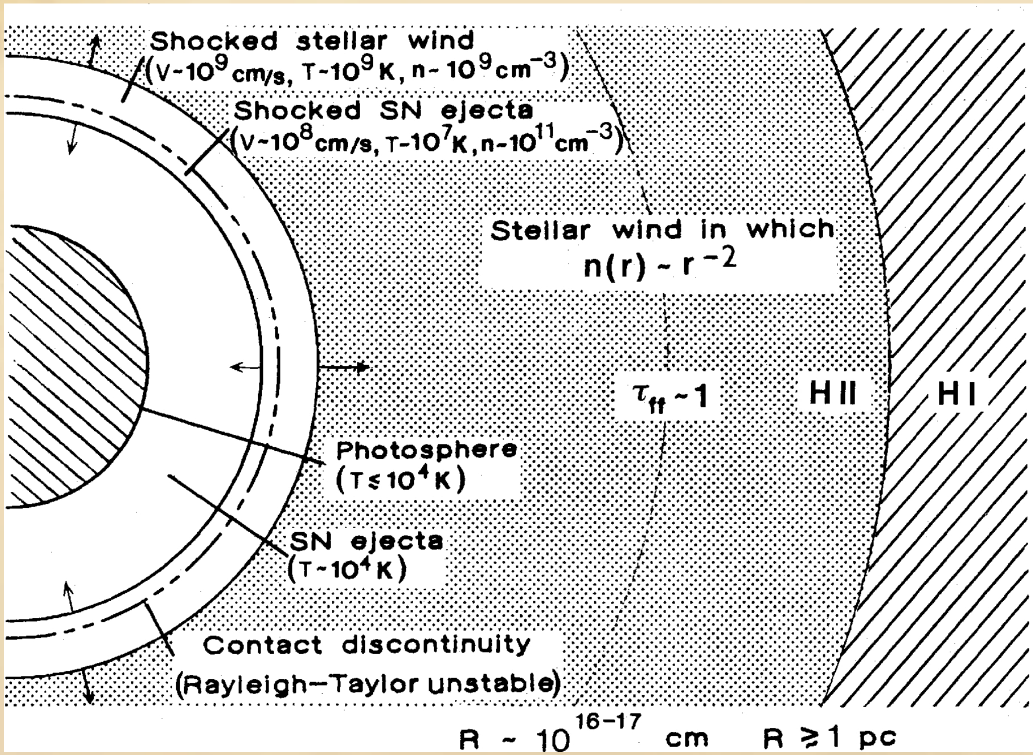


- White dwarf in a binary system
- Growing to the Chandrasekhar mass by mass transfer

Another possibility is two merging white dwarfs. Which is the correct one?

Testing non-conservative mass loss

Some of the mass might escape from the binary system.



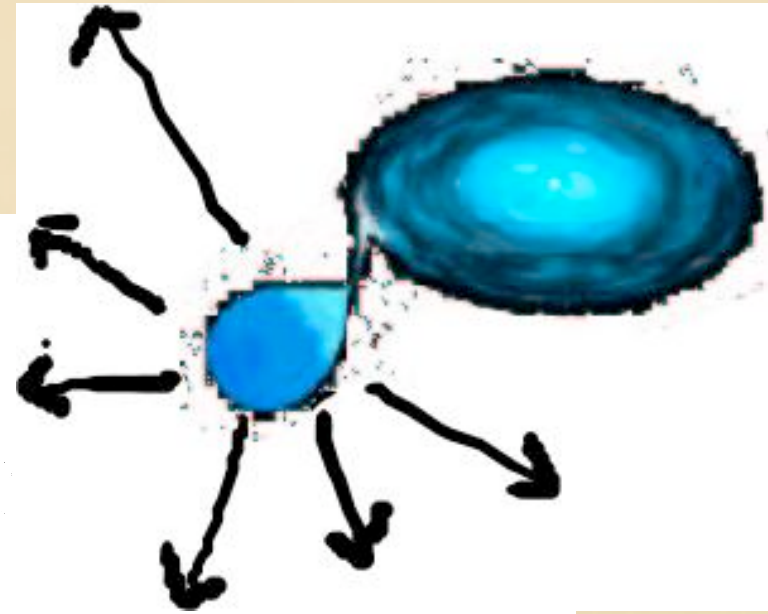


Fig. 1. Schematic picture (not to scale) of a young Type II supernova interacting with a dense circumstellar medium, originating from presupernova mass loss. Typical values of the important physical parameters are shown, as well as the boundary of the region where the free-free optical depth to the radio emission is unity and the boundary of the ionized region

We might use the same model as for young core-collapse SNe. (The companion is overtaken in just a few hours and the system quickly becomes point-symmetric.)

Model for the circumstellar interaction

SELF-SIMILAR SOLUTIONS FOR THE INTERACTION OF STELLAR EJECTA WITH AN EXTERNAL MEDIUM

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Received 1981 October 26; accepted 1982 February 8

CIRCUMSTELLAR INTERACTION IN SN 1993J

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Received 1994 May 17; accepted 1995 July 14

Assume power-law dependencies on density for the ejecta, $\rho \propto r^{-n}$ and the CS gas, $\rho \propto r^{-s}$. The W7 model has roughly n=7, and the wind has s=2.

PROPERTIES OF THE SELF-SIMILAR SOLUTIONS

s	n	R_1/R_c	R_2/R_c	A	ρ_2/ρ_1	p_2/p_1	u_2/u_1	M_2/M_1
2	7	1.299	0.970	0.27	7.8	0.27	1.058	0.82
2	12	1.226	0.987	0.038	46	0.37	1.104	2.7

Numerical solution of shock structure
for 3×10^{-5} M_o/yr, v_{wind}=10 km/s

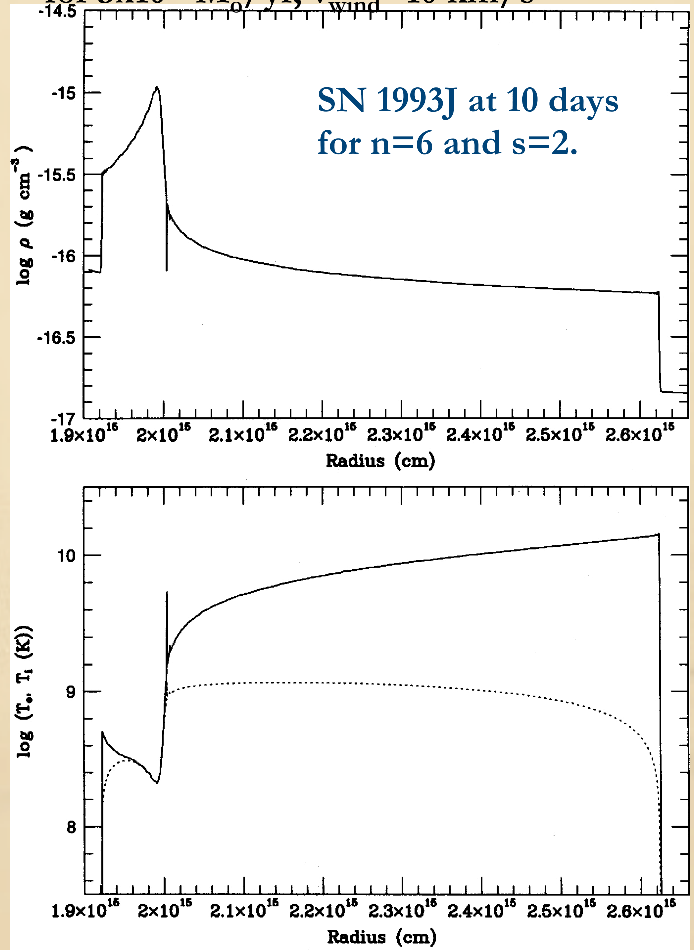

FIG. 3.—Density, electron temperature, and ion temperature for the $s = 2$, $n = 6$, $\dot{M}_{-5}/v_{w1} = 3$ model at 10 days. Only Coulomb heating of the electrons is assumed, leading to $T_e \ll T_{ion}$ for the circumstellar shock.

Constraints on the models

Maximum velocity of the ejecta must exceed observed ones

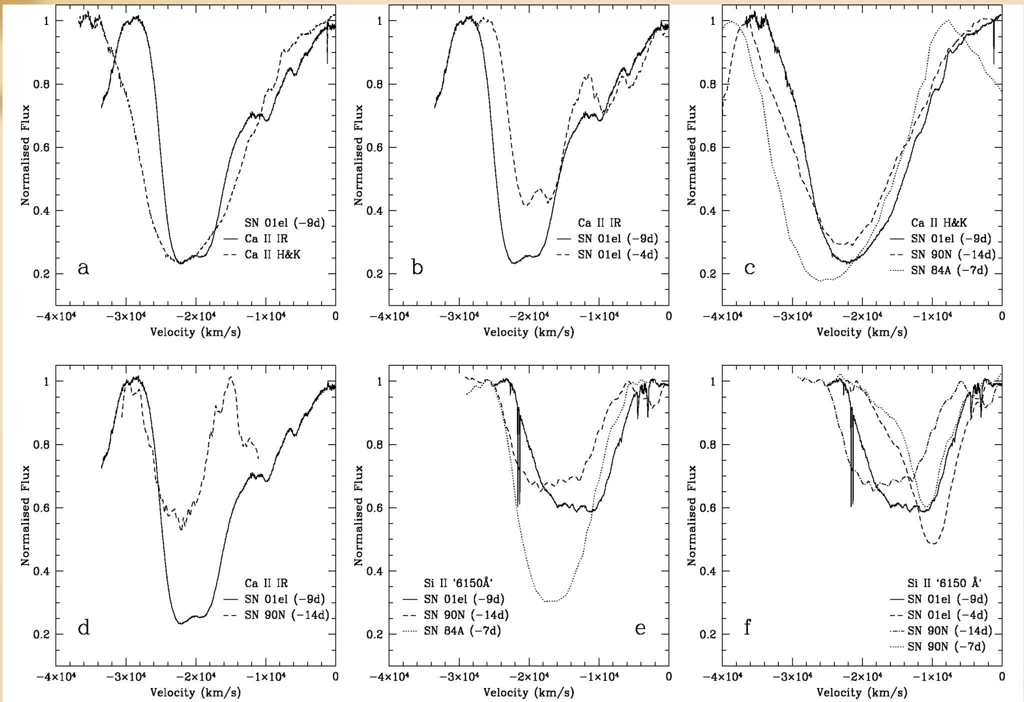

Fig. 8. a) Comparison between the Ca II IR triplet (solid line) and the Ca II H&K velocity profiles (dashed line) at −9 days. **b)** Spectral evolution of the Ca II IR triplet from −9 days (solid line) to −4 days (dashed line). **c)** The Ca II H&K profiles in SNe 2001el at −9 days (solid line), 1984A at −7 days (dotted line), and SN 1990N at −14 days (dashed line). **d)** Comparison between the Ca II IR triplet profiles of SNe 2001el (solid line) and 1990N (dashed line). Note that due to the limited wavelength coverage in SN 1990N spectrum the normalisation of its Ca II IR profile is unreliable in the red part. **e)** Comparisons between the Si II "6150 Å" profiles in SNe 2001el at −9 days (solid line), 1984A at −7 days (dotted line), and SN 1990N at −14 days (dashed line). **f)** Spectral evolution of the Si II "6150 Å" profile in SNe 2001el (solid and dashed lines) and 1990N (dotted and dotted-dashed lines). The flux calibrated (f_λ) spectral features have been normalised and converted to velocity space w.r.t. to the rest wavelengths assuming V_{rec} = 1180, 1010, and −261 km s^{-1} for SNe 2001el, 1990N, and 1984A, respectively. For this we used the rest wavelengths of the bluest components of the Ca II triplet/doublet lines viz. 8498 Å and 3934 Å, and the Si II "6150 Å" profile of 6347 Å.

Table 4. Maximum velocities for SNe 1984A, 1990N, and 2001el as indicated by the blue edges of the Ca II H&K and IR triplet and Si II "6150 Å" profiles (see Fig. 8).

SN	Epoch (days)	$V_{\mathrm{Ca\ II,H\&K}}$ (km s^{-1})	$V_{\mathrm{Ca\ II,IR}}$ (km s^{-1})	$V_{\mathrm{Si\ II}}$ (km s^{-1})
1984A	-7^a	38 000	–	26 000
1990N	-14^b	36 000	~28 000	26 000
2001el	−9	34 000	28 000	23 000

[a] Date of observation 1984 Jan. 10 (Wegner & McMahan (1987). The epoch adopting Jan. 17 for the *B*-band maximum light (Barbon et al. 1989).
[b] Date of observation 1990 June 26.2 UT (Leibundgut et al. 1991).

We require: $V_{ej,max} \geq 4.5\text{x}10^4$ km/s at 1 day (decays with time as $\propto t^{-0.2}$)

Early and late time VLT spectroscopy of SN 2001el – progenitor constraints for a type Ia supernova★

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Modeling:

- Calculating the ionizing radiation from the reverse shock in detail, and in some models including the photospheric emission (from Blinnikov & Sorokina). Other contributions omitted. Models for $T_e = T_i$ and $T_e \neq T_i$ of the reverse shock have been made.
- Calculating the temperature and ionization structure of the unshocked circumstellar gas time dependently. (Elements included are H, He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca and Fe. Most of the ions are treated as multilievel atoms.)
- Calculating the emission of the escaping line photons.

X-ray emission and absorption

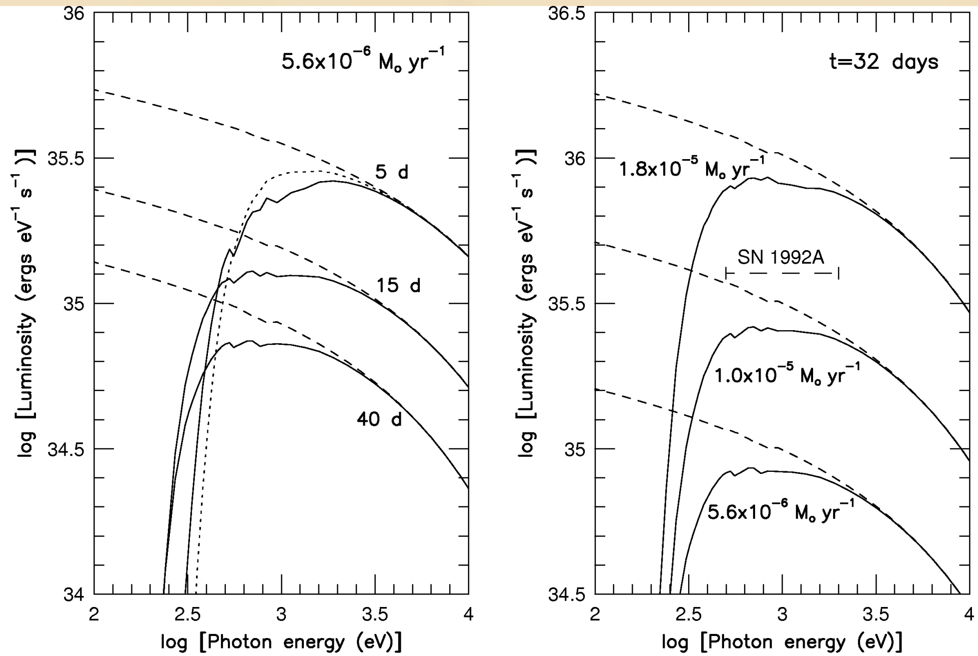
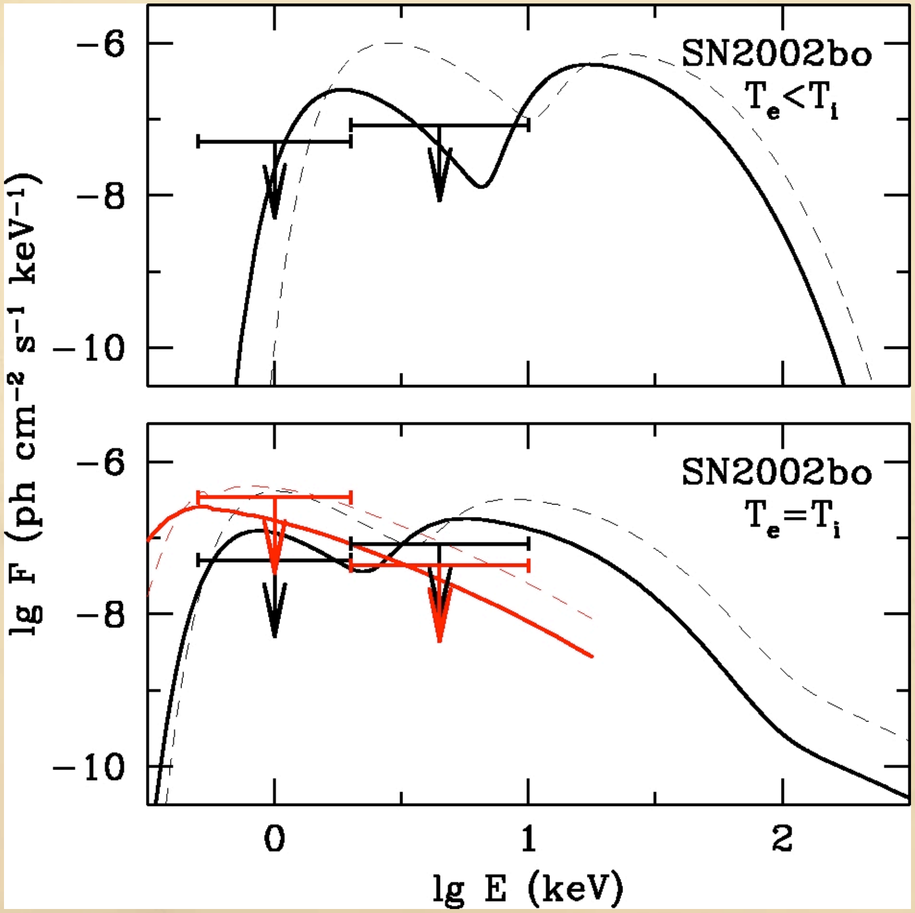


Fig. 9. Left: Ionizing spectrum at 5, 15 and 40 days for a model with a wind density described by the mass loss rate 5.6×10^{-6} M$_\odot$ yr^{-1} and wind speed 10 km s^{-1}. Ion and electrons in the shocked supernova ejecta are assumed to have the same temperature. Dashed lines show the unattenuated spectrum, while solid lines show the spectrum after absorption in the wind. (Dotted line shows a case for 5 days assuming He/H = 1.0. The other models have He/H = 0.085.) **Right:** Ionizing spectrum at 32 days for three mass loss rates (using the same representations as in the figure to the left). The vertical long-dashed bar shows the upper limit on the luminosity within $0.5 - 2.0$ keV estimated by Schlegel & Petre (1993) for SN 1992A at ~ 16 days after maximum. (For simplicity, we have assumed a constant flux within the passband used by Schlegel & Petre.)

Revised limit on mass loss rate for SN 1992A: <1.3x10^{-5} M$_o$/yr (for 10 km/s) (Lundqvist et al. 2013)

Chandra X-ray observations of SN 2002bo
(Hughes et al., 2007)



"Red" models are the same as in Lundqvist et al. (2013). Other models are described In Hughes et al. (2007). Mass loss rate limit is the same as the revised one for SN 1992A.

Optical campaigns were launched in 2000 using echelle spectrographs at VLT and Subaru.

Early Evolution of Nearby Type Ia Supernovae

(Probing the nature of the progenitors of thermonuclear supernovae)

ESO runs

(ESO Period 65 run: April 1, 2000 - September 30, 2000)
(ESO Period 66 run: October 1, 2000 - March 31, 2001)
(ESO Period 67 run: April 1, 2001 - September 30, 2001)
(ESO Period 68 run: October 1, 2001 - March 31, 2002)
(ESO Period 69 run: April 1, 2002 - September 30, 2002)
(ESO Period 70 run: October 1, 2002 - March 31, 2003)
(ESO Period 71 run: April 1, 2003 - September 30, 2003)
(ESO Period 72 run: October 1, 2003 - March 31, 2004)
(ESO Period 73 run: April 1, 2004 - September 30, 2004)
(ESO Period 75 run: April 1, 2005 - September 30, 2005)

Investigators: P. Lundqvist (PI), S. Mattila, J. Sollerman, E. Baron, P. Ehrenfreund, C. Fransson, B. Leibundgut, K. Nomoto & The SN Ia RTN team

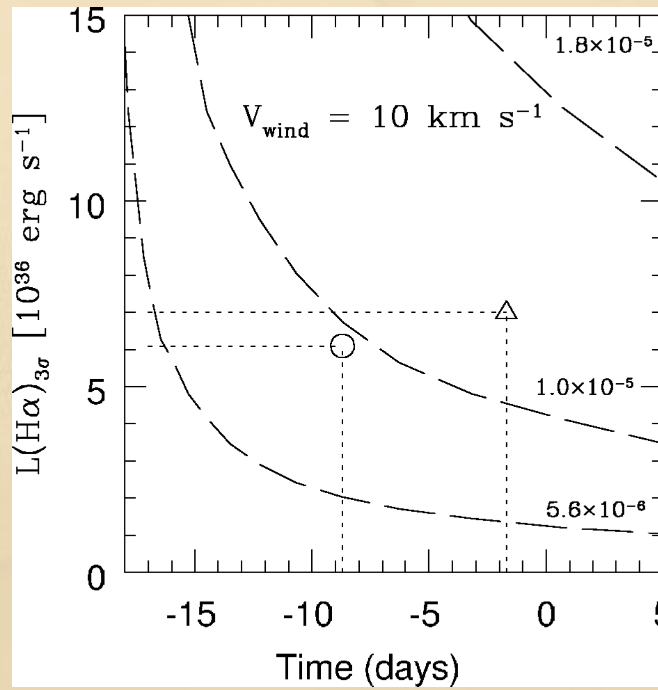
Subaru runs

(Subaru Semester S04A run: April 1, 2004 - September 30, 2004)
(Subaru Semester S04B run: October 1, 2004 - March 31, 2005)
(Subaru Semester S05A run: April 1, 2004 - August 31, 2005)

Investigators: P. Lundqvist (PI), S. Mattila, K. Nomoto, J. Sollerman, H. Ando, J. Deng, P. Ehrenfreund, C. Fransson, R. Kotak, K. Maeda, A. Tajitsu, H. Terada

Last updated - June11, 2005
by Peter Lundqvist, peter@astro.su.se

For a smooth r^{-2} wind it is important to do very early observations. One could then reach down to a few x 10^{-6} M_o/yr for a supernova within 20 Mpc.



(Mattila et al. 2005)

SN 2001el

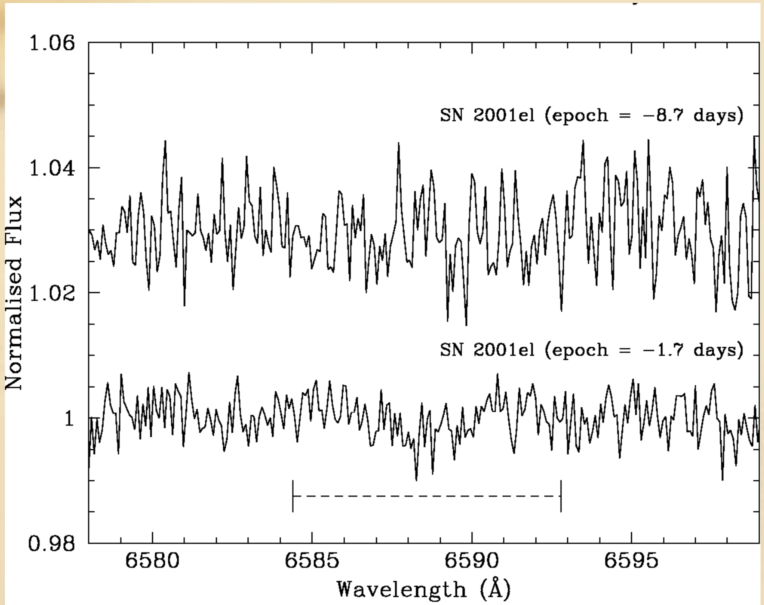


Fig. 3. Normalised and rebinned (~4 km s^{-1} pixel^{-1}) UVES spectra in the expected spectral region around Hα for SN 2001el on two epochs, September 21.3 and 28.3 (UT) 2001, i.e., 8.7 and 1.7 days before the SN maximum light, respectively. The expected wavelength range of Hα is marked with a horizontal dashed line, and the upper spectrum has been shifted vertically for clarity. No significant emission or absorption lines are visible.

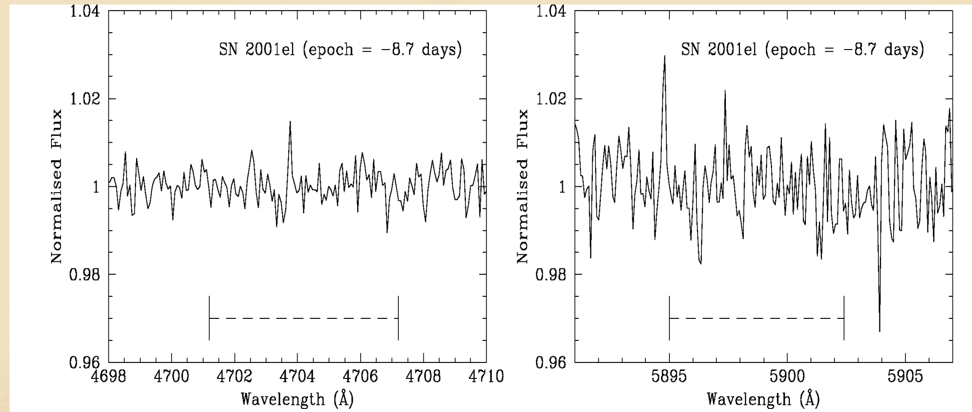


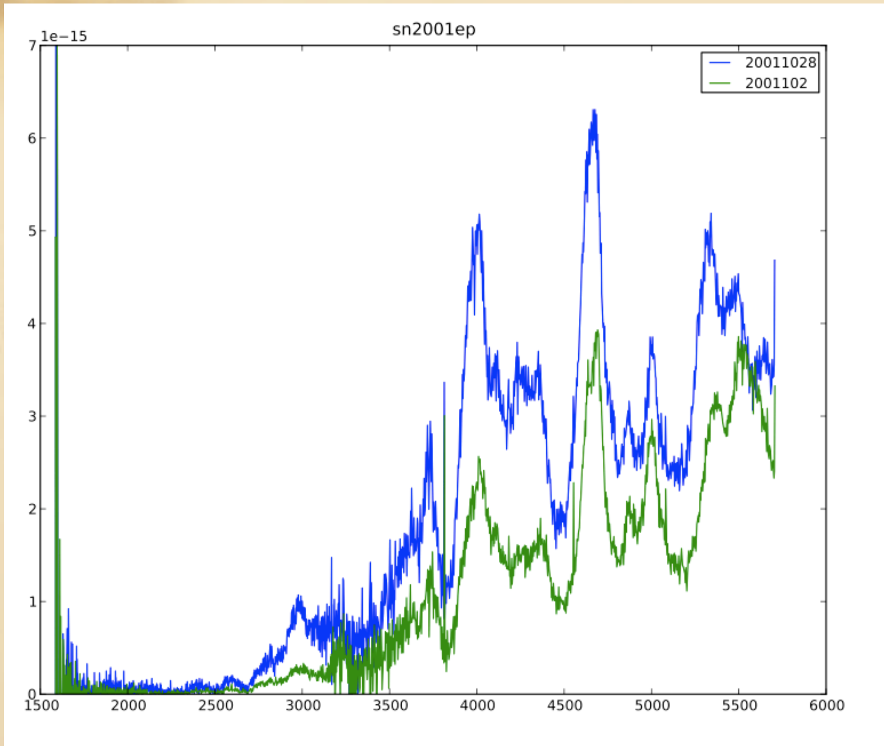
Fig. 4. Normalised and rebinned (~4 km s^{-1} pixel^{-1}) UVES spectra in the expected spectral regions around He II (4686 Å) and He I (5876 Å) for SN 2001el on September 21.3 (UT) 2001, i.e., 8.7 days before the maximum light. The expected wavelength range of the CSM lines is marked with a horizontal dashed line. No significant emission or absorption lines are visible.

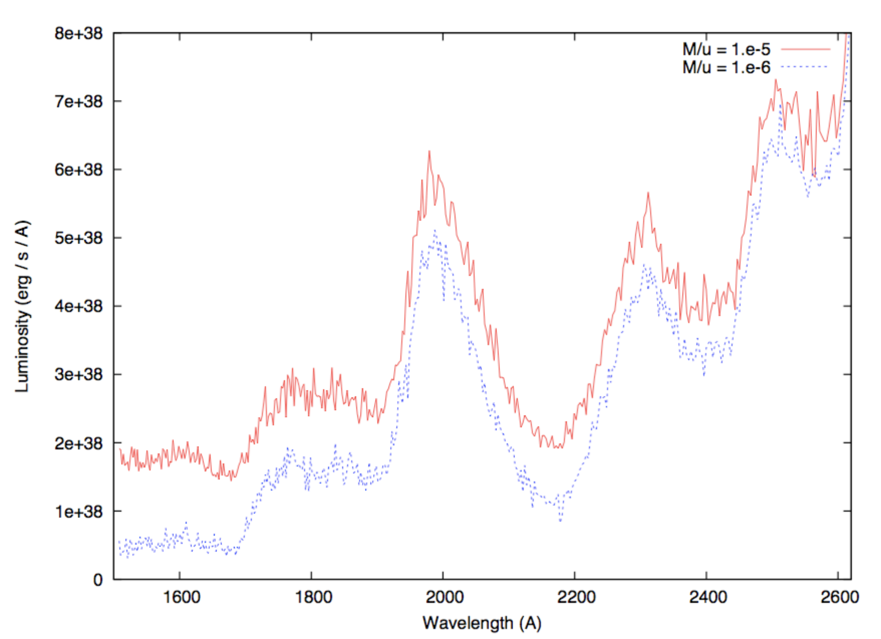
Limit on mass loss rate: 9x10^{-6} M$_o$/yr (for a 10 km/s wind)

(Mattila et al. 2005; Lundqvist et al. 2013)

SN 2001ep: Ultraviolet tail due to inverse Compton scattering (conservative case with $T_e = T_{Coul}$)

HST observations (29 days after explosion)





Limit on mass loss rate could be down to < a few x 10^{-6} M_o/yr (for a 10 km/s wind) for an earlier event.

(Lundqvist et al., in prep.)

Radio observations of SNe Ia

THE ASTROPHYSICAL JOURNAL, 646:369–377, 2006 July 20

A SEARCH FOR RADIO EMISSION FROM TYPE Ia SUPERNOVAE

NINO PANAGIA,[1,2] SCHUYLER D. VAN DYK,[3] KURT W. WEILER,[4] RICHARD A. SRAMEK,[5]
CHRISTOPHER J. STOCKDALE,[6] AND KIMBERLY P. MURATA[7]
Received 2006 February 21; accepted 2006 March 29

Using Chevalier's model From 1983 and adopting scaling of emission from SNe Ib and Ic, **Panagia et al. (2006)** obtain very low upper limits on the wind density.

TABLE 3

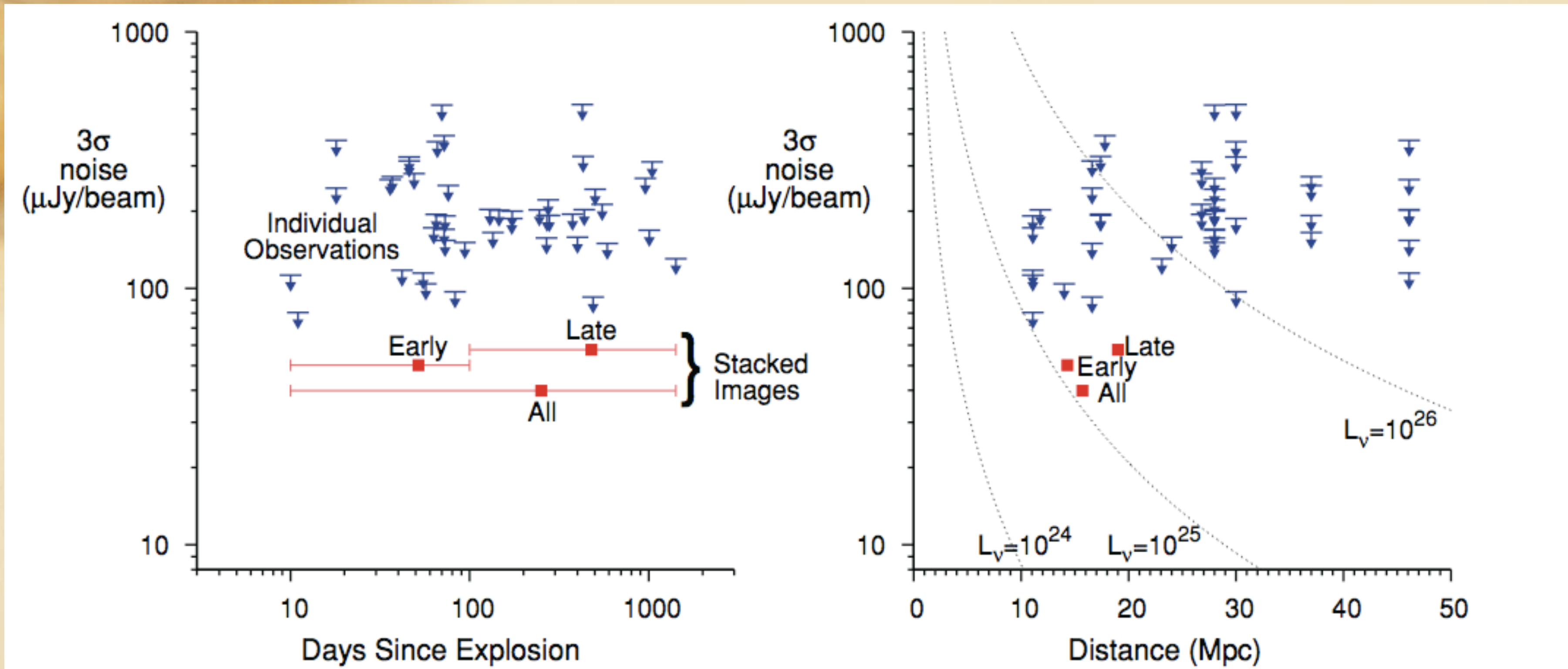
LOWEST UPPER LIMITS TO SN Ia PROGENITOR MASS-LOSS RATES

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 $w_{\rm wind} = 10$ km s^{-1}.

Radio observations of SNe Ia



(Hancock et al., 2011)

Parameters for the Stacked Images

Parameter	Image Stack		
	Early	Late	All
d_o (Mpc)	14.3	19.0	15.7
Effective age (days)	51.9	478	251
Effective integration at 50 MHz b/w (hr)	22.5	19.6	42.1
1σ (μJy beam^{-1})	16.7	19.2	13.3
Synthesized beam (arcsec^2)	21 × 18	22 × 15	21 × 17
L_o(erg s^{-1} Hz^{-1})	1.2×10^{25}	2.5×10^{25}	1.2×10^{25}
$\dot{M}$($M_\odot$ yr^{-1})	1.3×10^{-7}	1.5×10^{-6}	5.4×10^{-7}

Note. Radio luminosity and inferred mass-loss rates are 3σ upper limits.

Radio program at ATCA

Australia Telescope Compact Array — **2006OCTS / C1303**

Probing the radio emission from a young Type Ia supernova

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Brian Schmidt	brian@mso.anu.edu.au	Australia National University	Australia	No	No
Miguel Angel Perez-Torres	torres@iaa.es	IAA - C SIC / Instituto de Astrofisica de Andalucia	Spain	No	No
Stuart Ryder	sdr@aao.gov.au	Anglo-Australian Observatory	Australia	No	No

As radio observations do appear to be the most sensitive to detect smooth mass loss, we have since 2004 been using ATCA.

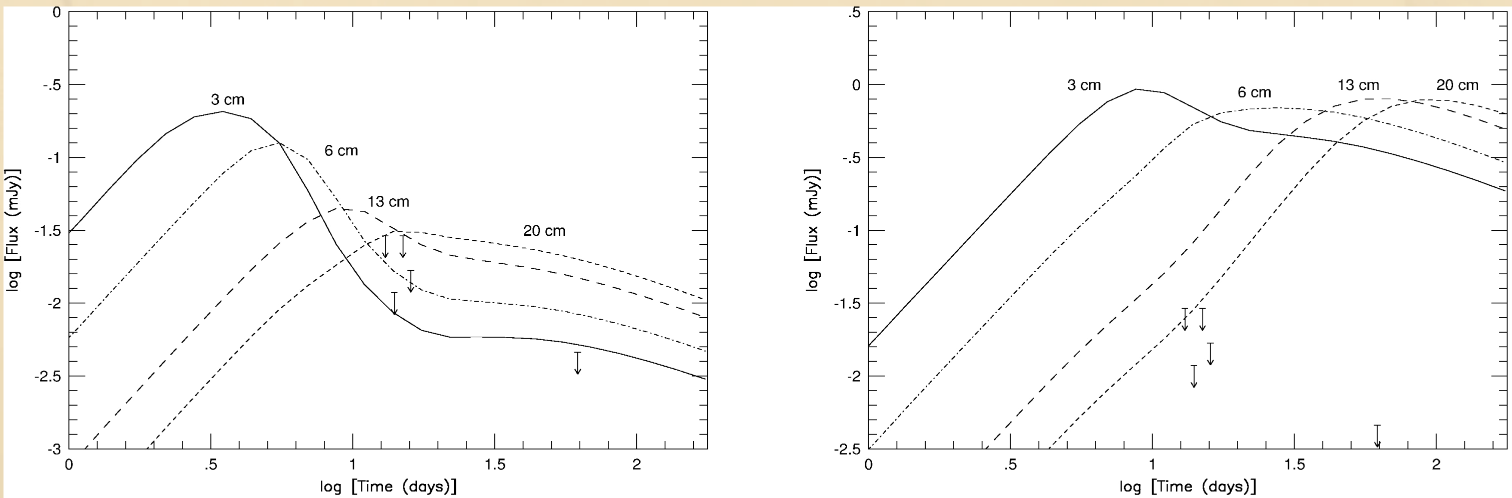


Figure 1: Radio light curves for a mass loss rate of 10^{-7} M$_\odot$ yr^{-1} (for $V_{\rm wind} = 10$ km s^{-1}) and two assumptions about the ratio of the energy densities of the magnetic field and relativistic electron density: 1% (left) and 10% (right). The expansion velocity on day 1 after explosion is $50,000$ km s^{-1}, and the ejecta density decreases as r^{-7} (e.g., Chevalier 1982). All cooling processes, like synchrotron and Compton cooling, are included. Note the earlier turn on of the flux for the lower efficiency case. The depression of the emission around 20 days at mainly high frequencies is due to Compton cooling. The distance to the modeled event is 20 Mpc. 3σ upper limits of observed events have also been included, after scaling for their actual distances: 1986G ($t = 13$ days, $\lambda = 2$ cm), 1998bu ($t = 14$ days, $\lambda = 3.6$ cm), 1989B ($t = 15$ days, $\lambda = 3.6$ cm), 1999by ($t = 16$ days, $\lambda = 3.6$ cm), and 1994D ($t = 62$ days, $\lambda = 6$ cm).

Radio observations 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

Tweet 4 Recommend 1

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.

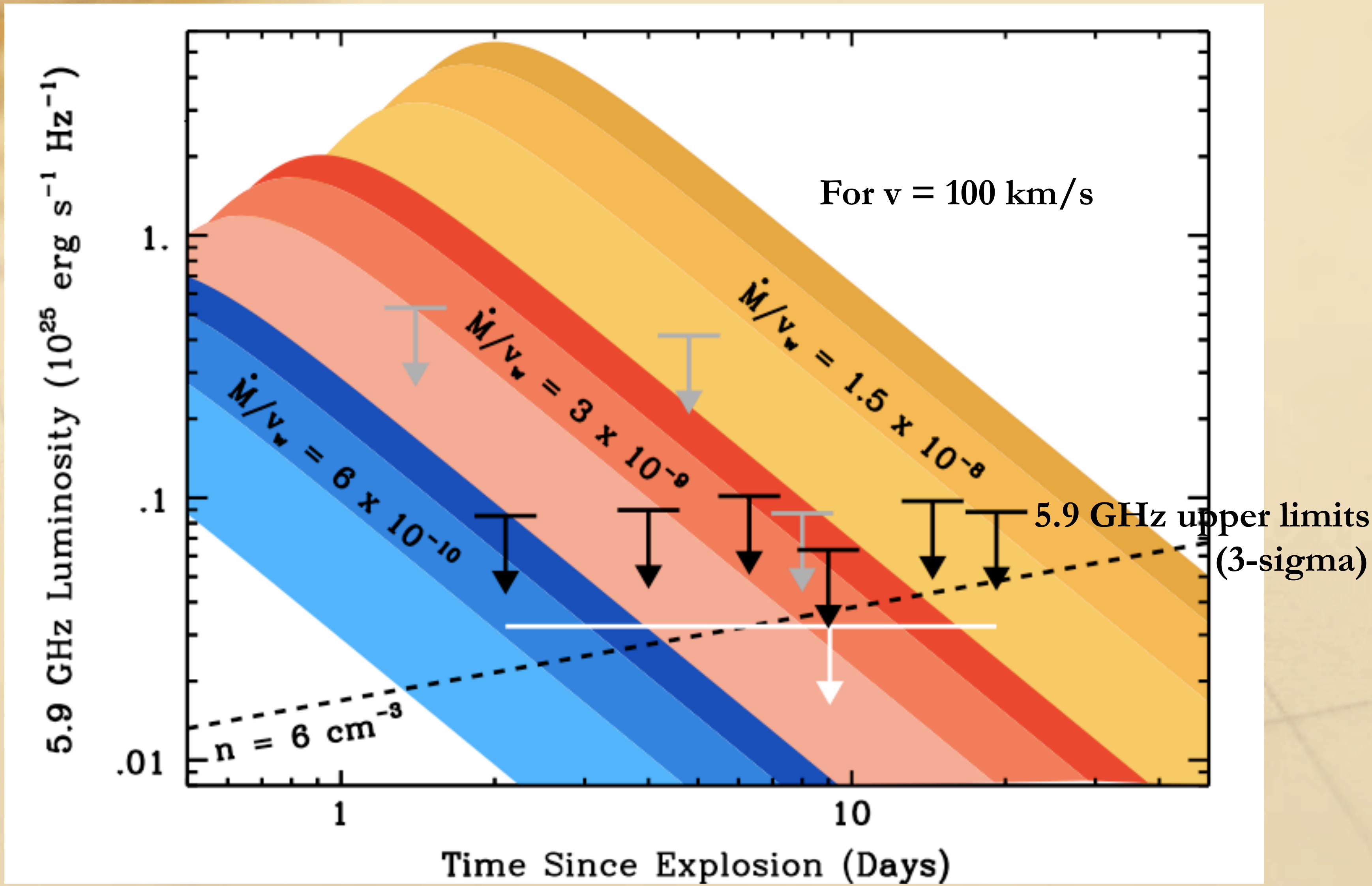
We found no evidence of radio emission above a 3-sigma limit of 300 microJy/beam in a circular region of 1 arcsecond in radius, centered at the SN position. This value corresponds to an upper limit of the monochromatic 5.0 GHz luminosity of 6.9e25 erg/s/Hz (3-sigma), and places a stringent upper limit 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.

(Perez-Torres, Argo, Lundqvist et al., 2013)

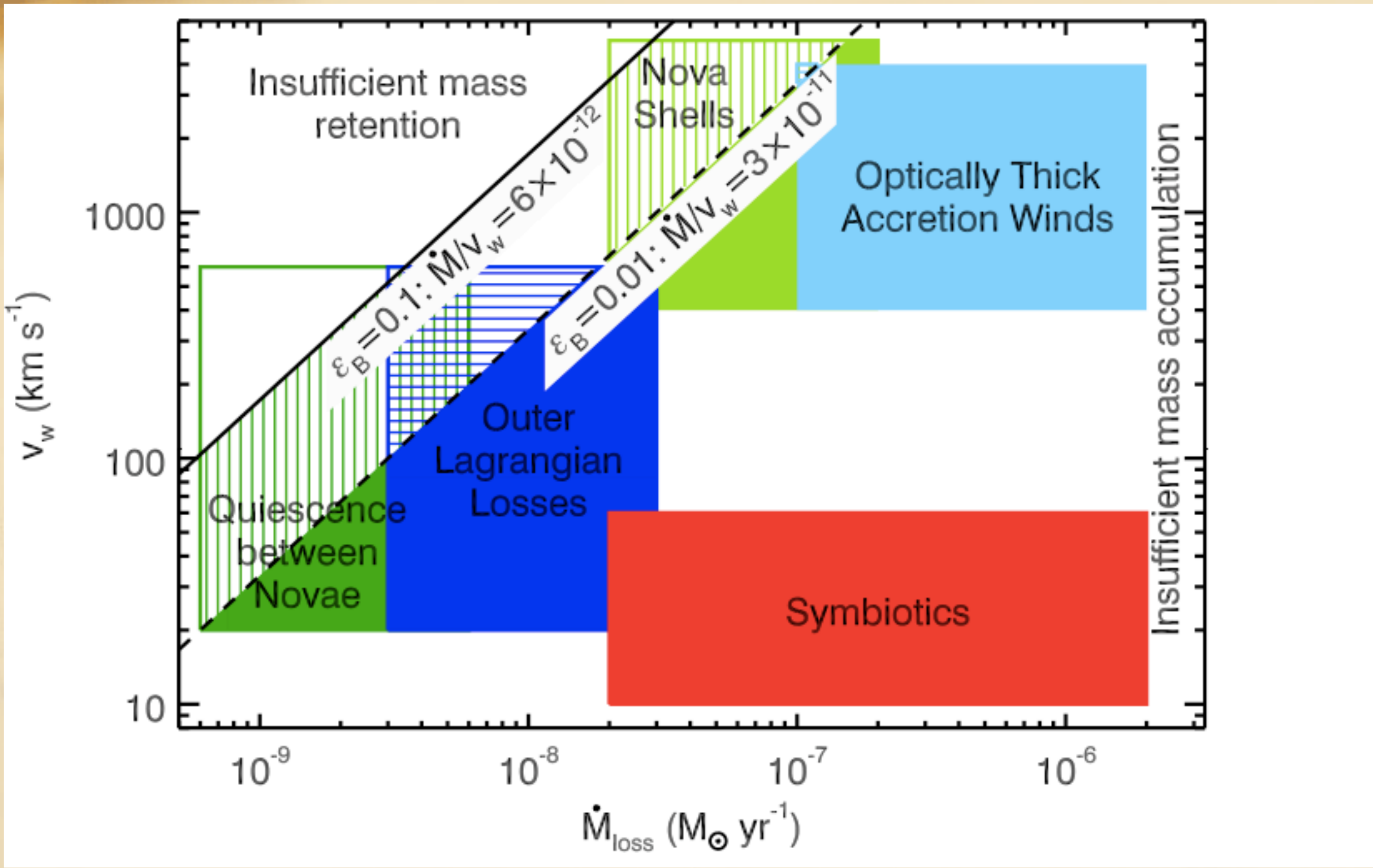
$< 2.7 \times 10^{-7}\ M_{o}\ yr^{-1}$

EVLA radio observations of SN 2011fe (D=6.4 Mpc)



(Chomiuk et al., 2013)

EVLA radio observations of SN 2011fe (D=6.4 Mpc)



(Chomiuk et al., 2013)

SKA vs. present facilities

- EVLA upper limit (1-sigma) of SN 2011fe was ~6 micro-Jy (5 GHz)

  (spatial resolution of SN 2011fe observations: 0.56 arcsec x 0.39 arcsec)

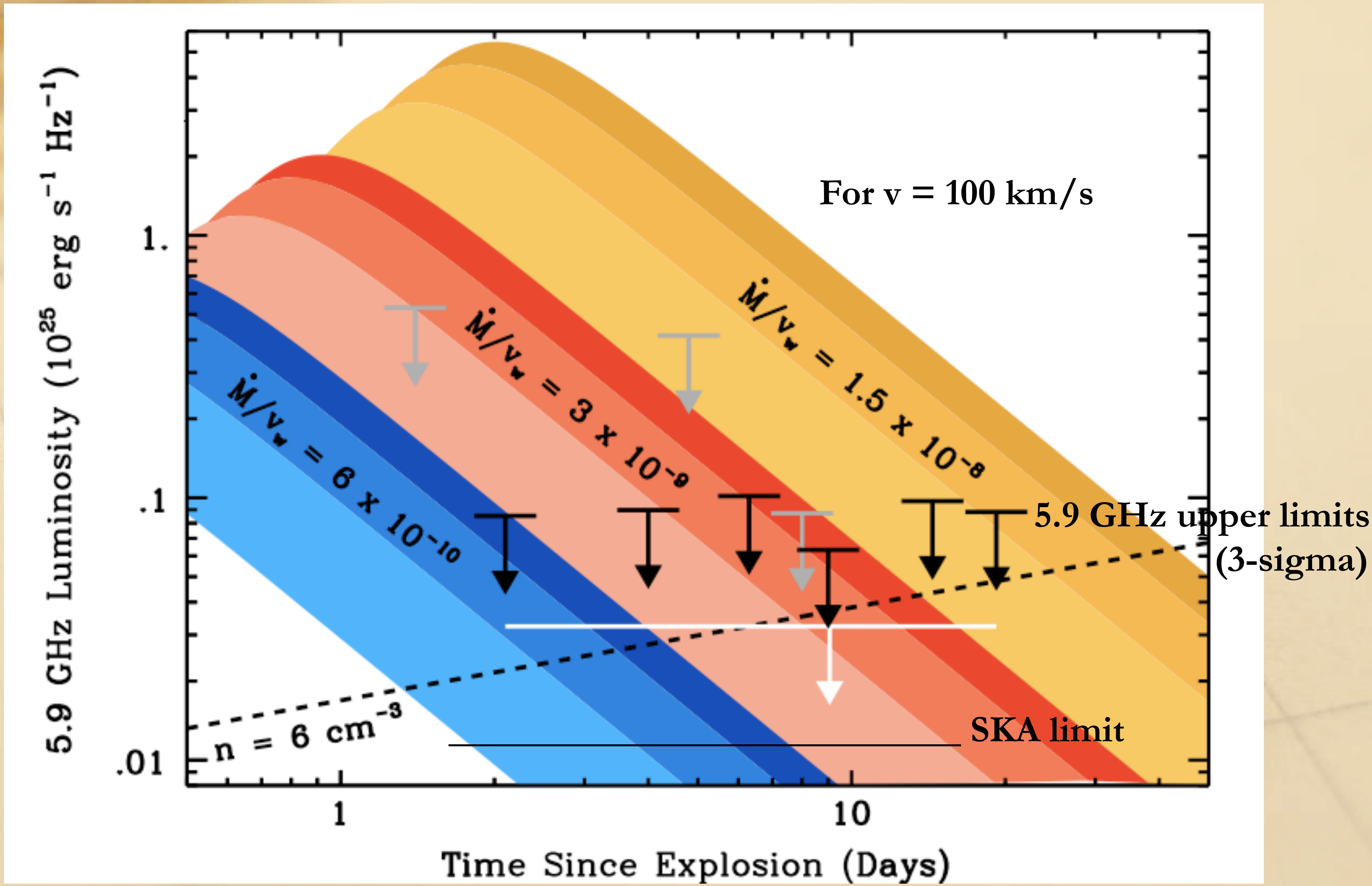
- SKA-mid (in the range 0.35-14 GHz) can obtain 0.72 micro-Jy (1 hour)

  (spatial resolution: 0.3 arcsec x 0.3 arcsec)

  → We can probe similar limits as for SN 2011fe out to ~20 Mpc (typically 1 Type Ia per year.)

  → For the same distance (if early) we can go much deeper in circumstellar density to test more (all possible?) progenitor scenarios.

EVLA radio observations of SN 2011fe (D=6.4 Mpc)



(Chomiuk et al., 2013) + SKA upper limits (1 hr)

Absorption features in SN 2006X.

(Patat et al., 2007)

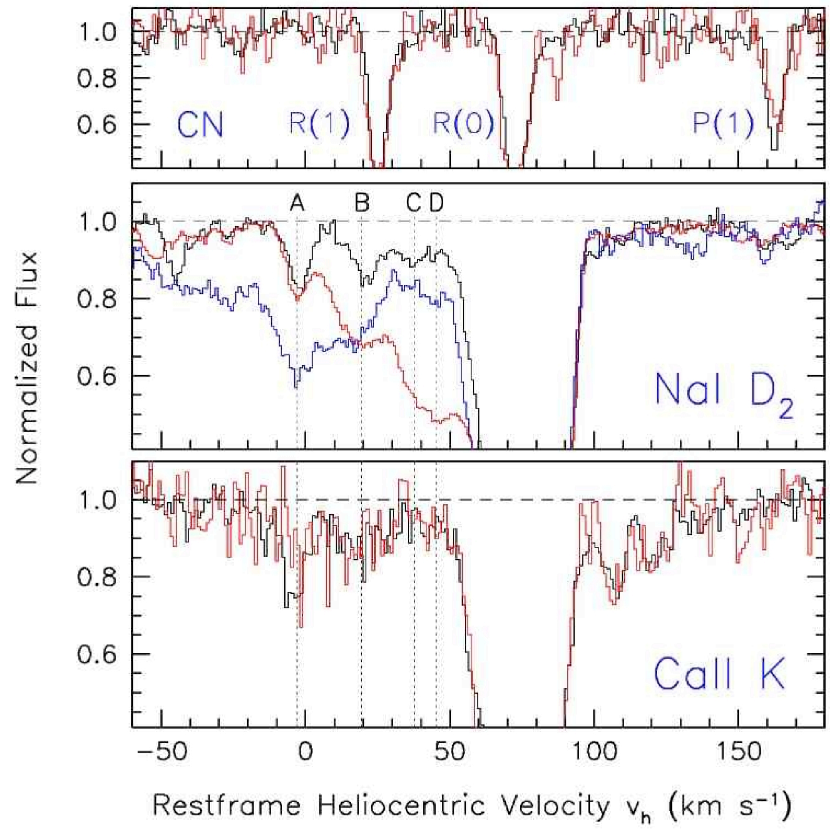
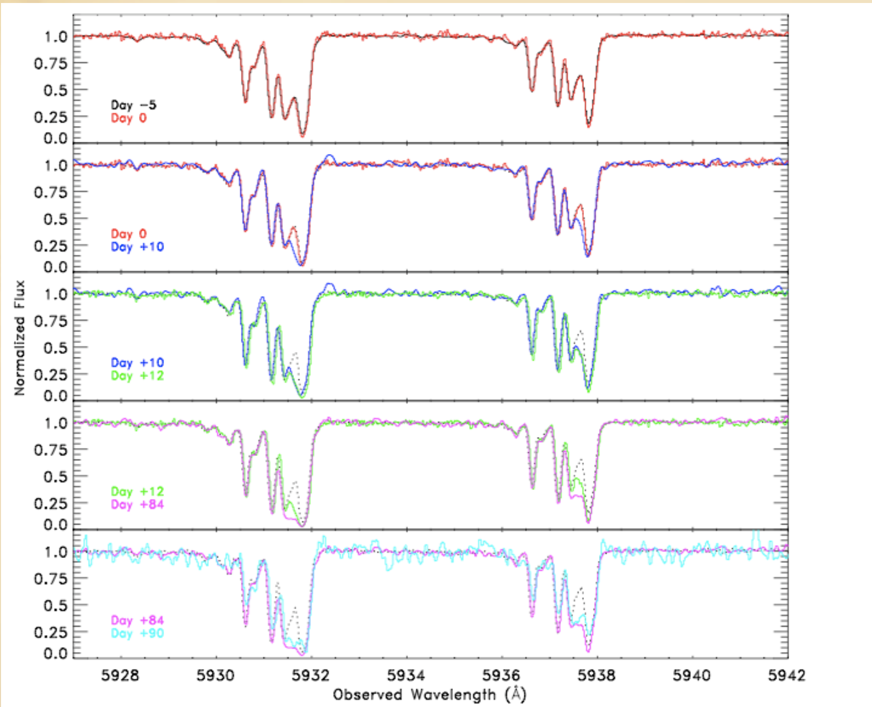


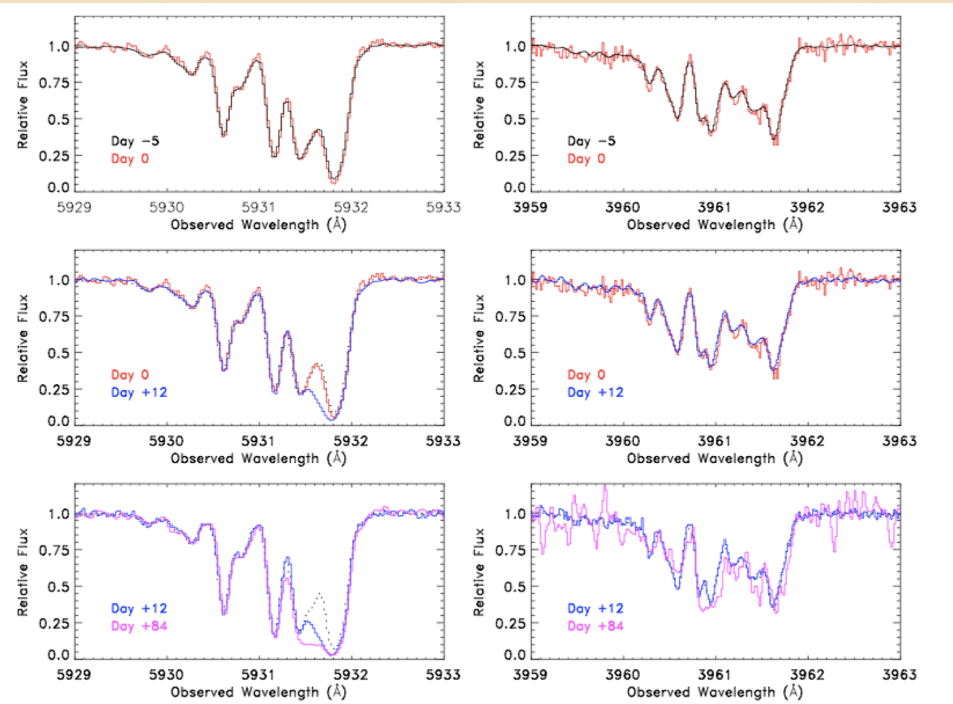
Figure 2: Evolution of the Na I D_2 and Ca II K line profiles between day -2 (black), day +14 (red) and day +61 (blue, Na I D_2 only). The vertical dotted lines mark the four main variable components at -3 (A), +20 (B), +38 (C) and +45 (D) km s^{-1}. For comparison, the upper panel shows the $R(0)$, $R(1)$ and $P(1)$ line profiles of the (0-0) vibrational band of the CN $B^2\Sigma - X^2\Sigma$. The velocity scale refers to the $R(0)$ transition (3874.608 Å). Color coding is as for the other two panels.

Absorption features in SN 2007le.

(Simon et al., 2009)



Na I



Ca II

Shells and continuous mass loss

- Patat et al.(2007) claim that the Na I variability is due to recombination in a shell at radius of about 10^{16} cm. The shell is then most likely circumstellar, and the mass loss rate is of order a few x 10^{-8} M_o/yr.
- Chugai (2008) has disputed this, and claims that the absence of Ca II 3934 Å gives <u>an upper limit</u> to the mass loss rate of 10^{-8} M_o/yr as (for $v_{wind} = 30$ km/s). The variable Na I lines do not come from gas closer to the star than 10^{17} cm.
- **<u>Note:</u>** A shell around SN 2006X as discussed by Patat et al. should have given rise to an X-ray/radio flash within a few months after the explosion. Radio was not seen half a year after.
- <u>Radio observations should not be limited to early time studies!</u>

Conclusions

- No detection of circumstellar *emission* from a ”normal” Type Ia SN has ever been seen in any wavelength region. Deep limits are obtained in the radio and indicate $<6\text{x}10^{-10}$ M_o yr^{-1} (for SN 2011fe). *Optical Absorption* features in SNe 2006X and 2007le could indicate $<10^{-8}$ M_o yr^{-1}. Discrete shells?
- SKA should be able to probe one order of magnitude deeper than EVLA. As deep limits as for SN 2011fe will be obtained for events out to 20 Mpc, which means for about one Type Ia SN per year. (Statistically useful limits may be obtained for more Type Ia:s.)