Observations of SNe Ia that Provide Evidence for Circumstellar Interaction

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Two-pronged Approach: ***"All or nothing"***

All: Hybrid SNe (H-rich Ia's, 2002ic-like, Type IIa)

- Optical spectroscopy (Hα emission) ➔ Alex's talk
- Radio observations
- Host galaxy properties

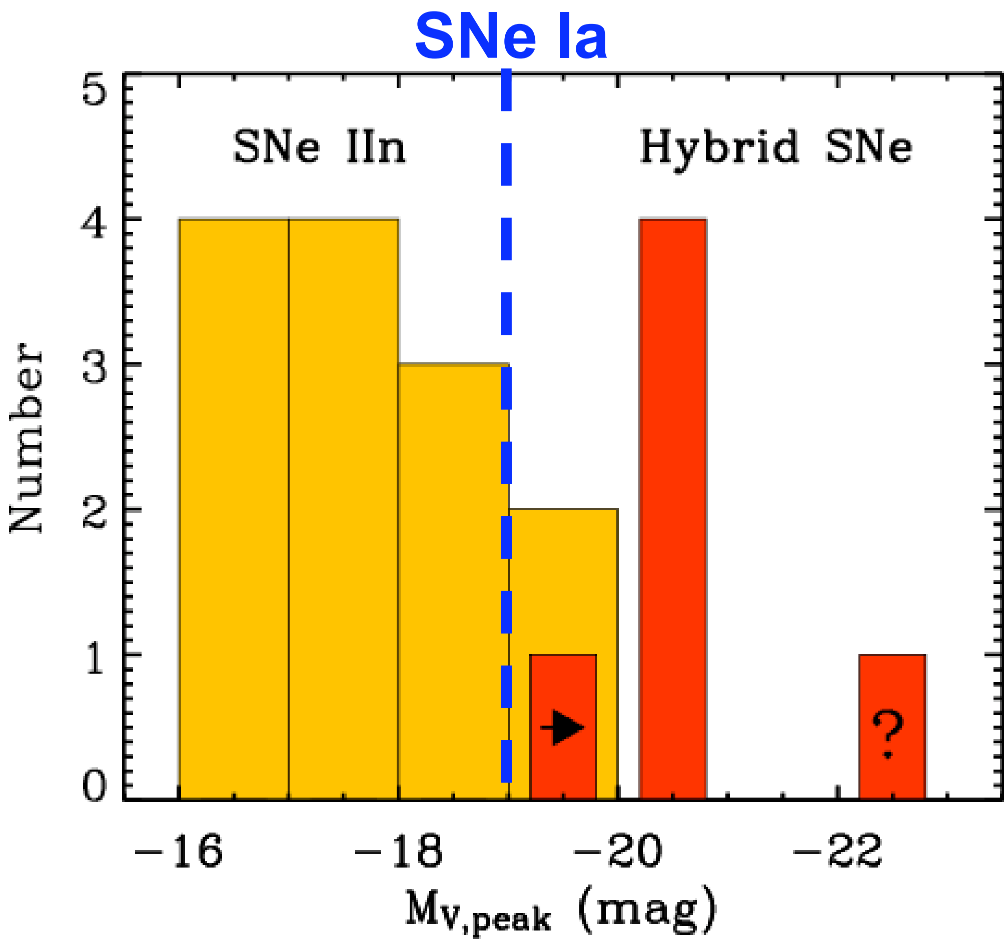
Nothing: CSI in "normal" SNe Ia

- Optical spectroscopy (Hα limits) ➔ Alex's talk
- X-ray observations
- Radio observations

Looking forward

- How do we make progress?

All: Hybrid SNe



1997cy (z=0.064)

(Germany et al., 2000)

1999E (z=0.026)

(Rigon et al., 2003)

2002ic (z=0.067)

(Hamuy et al., 2003)

2005gj (z=0.062)

(Aldering et al., 2006)

SN7017 (z=0.27)

(Prieto, in prep)

2006gy ? (z=73 Mpc)

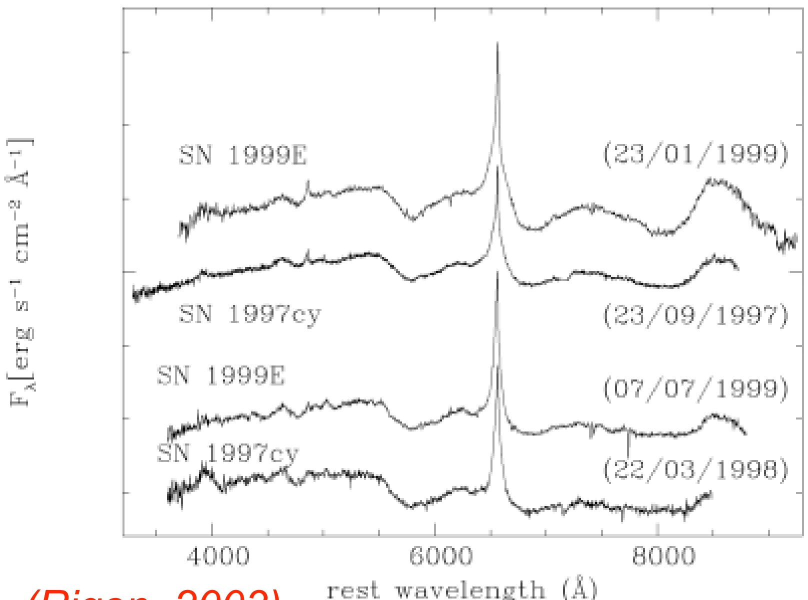
(Ofek et al., 2007)

(SNe IIn data from; van Dyk 1996)

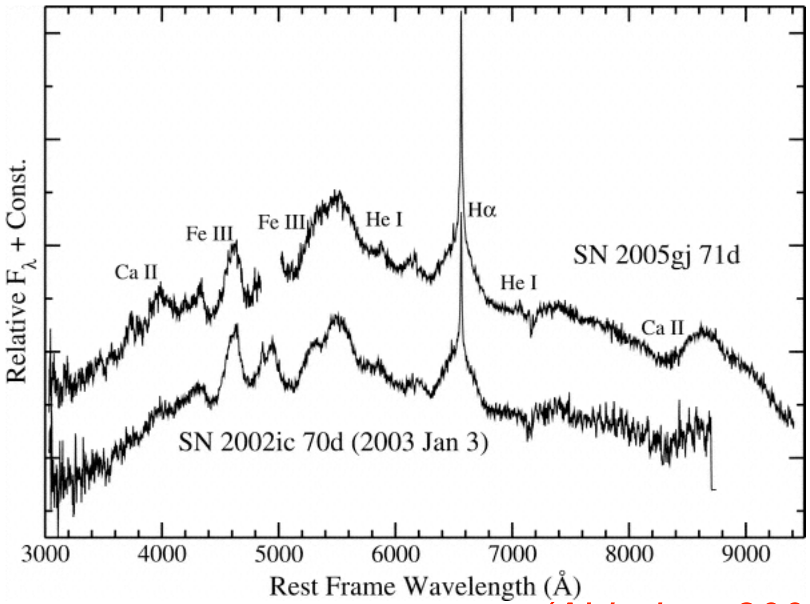
Spectral properties (Alex's talk)

- SN Ia features (91T-like) with broad absorption lines
- Hα emission with broad base and narrow peak
- Hα strength varies with time (*unique* to each SN)
- Inferred mass loss rates are high: ~ 10^{-2} $M_{\odot}$/yr *(Hamuy, 2003)*

➔ 10-100 times higher than SNe IIn, and comparable to Eta Carinae.

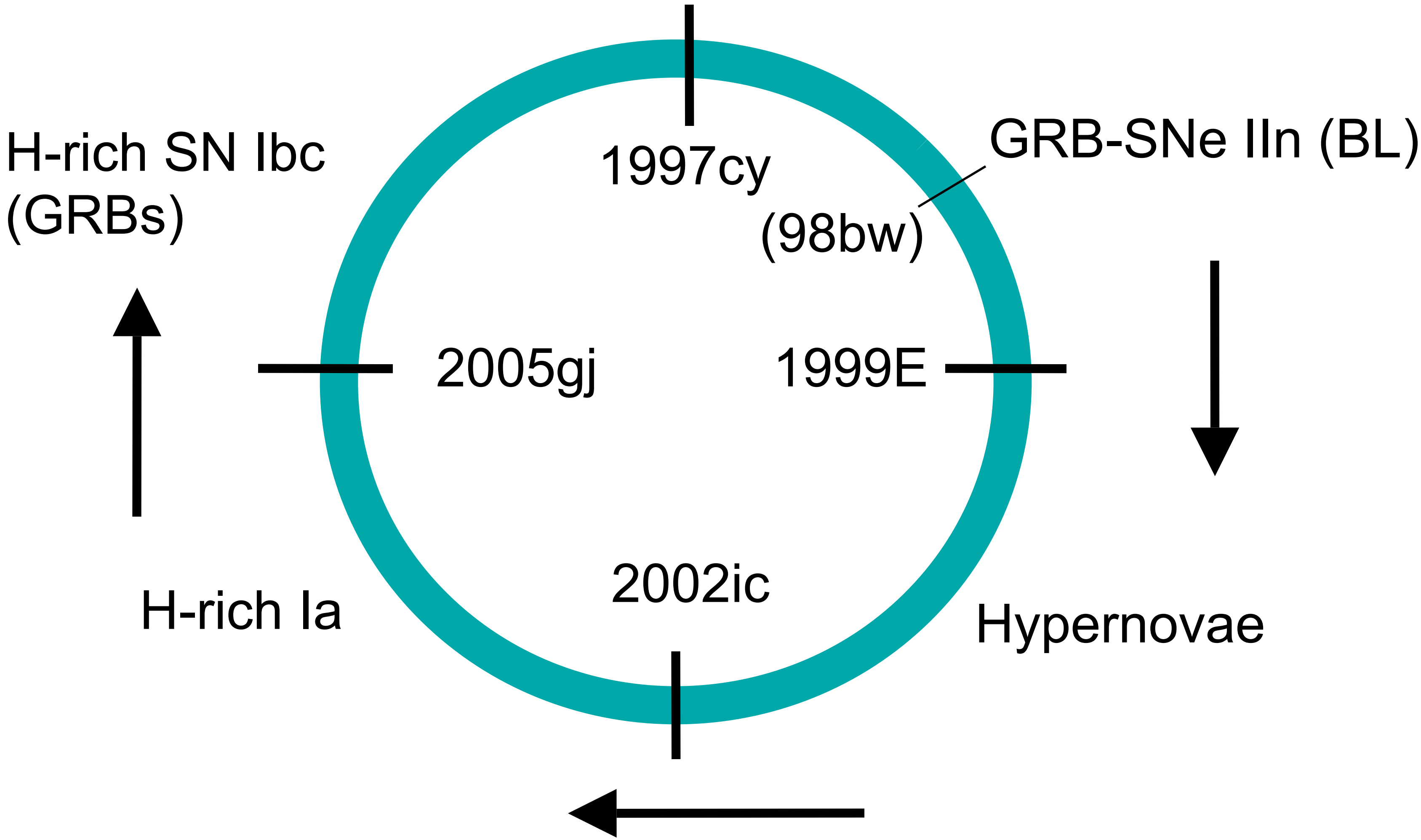


(Rigon, 2003)



(Aldering, 2005)

Ten years later, we've come full circle



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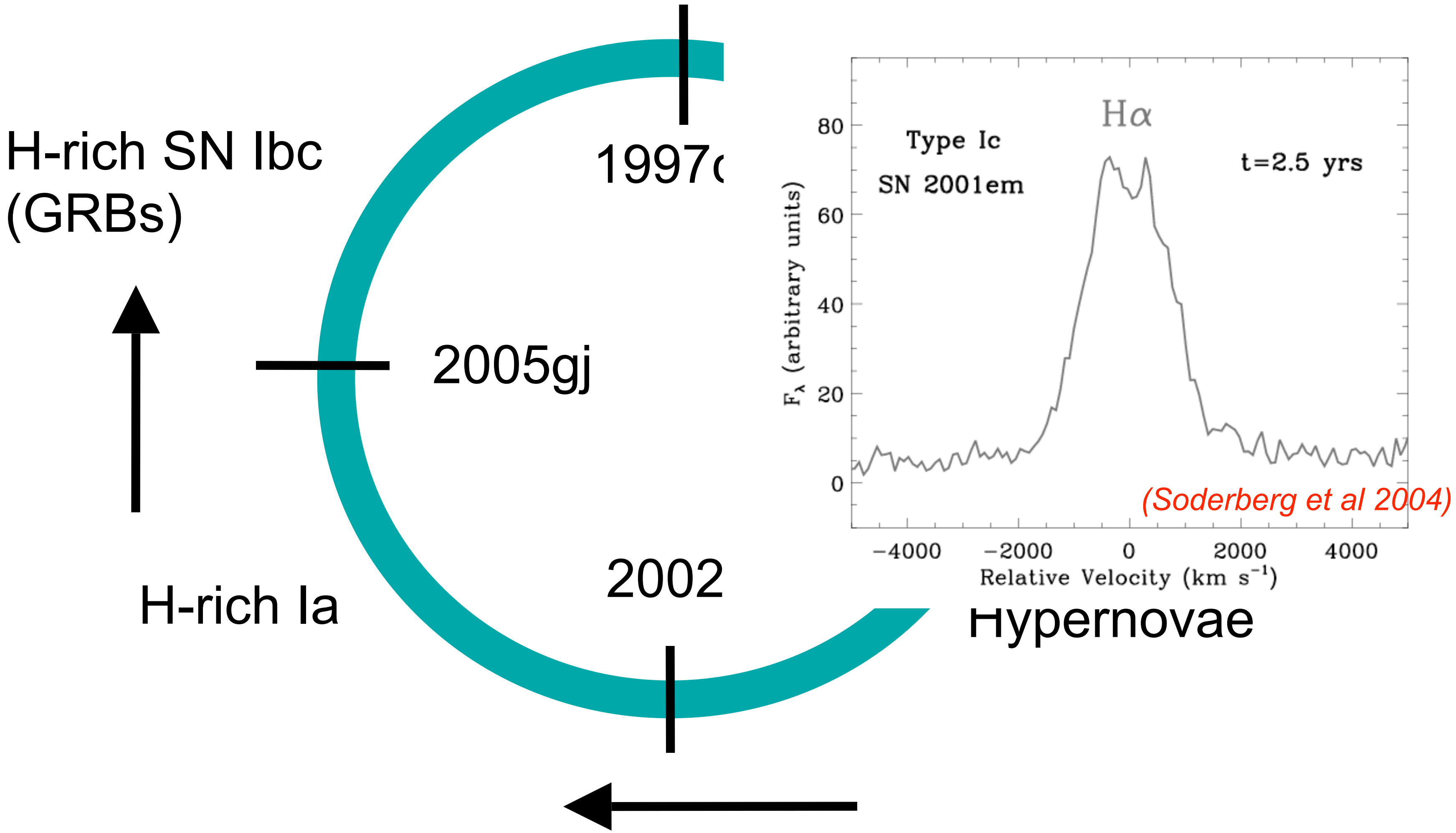

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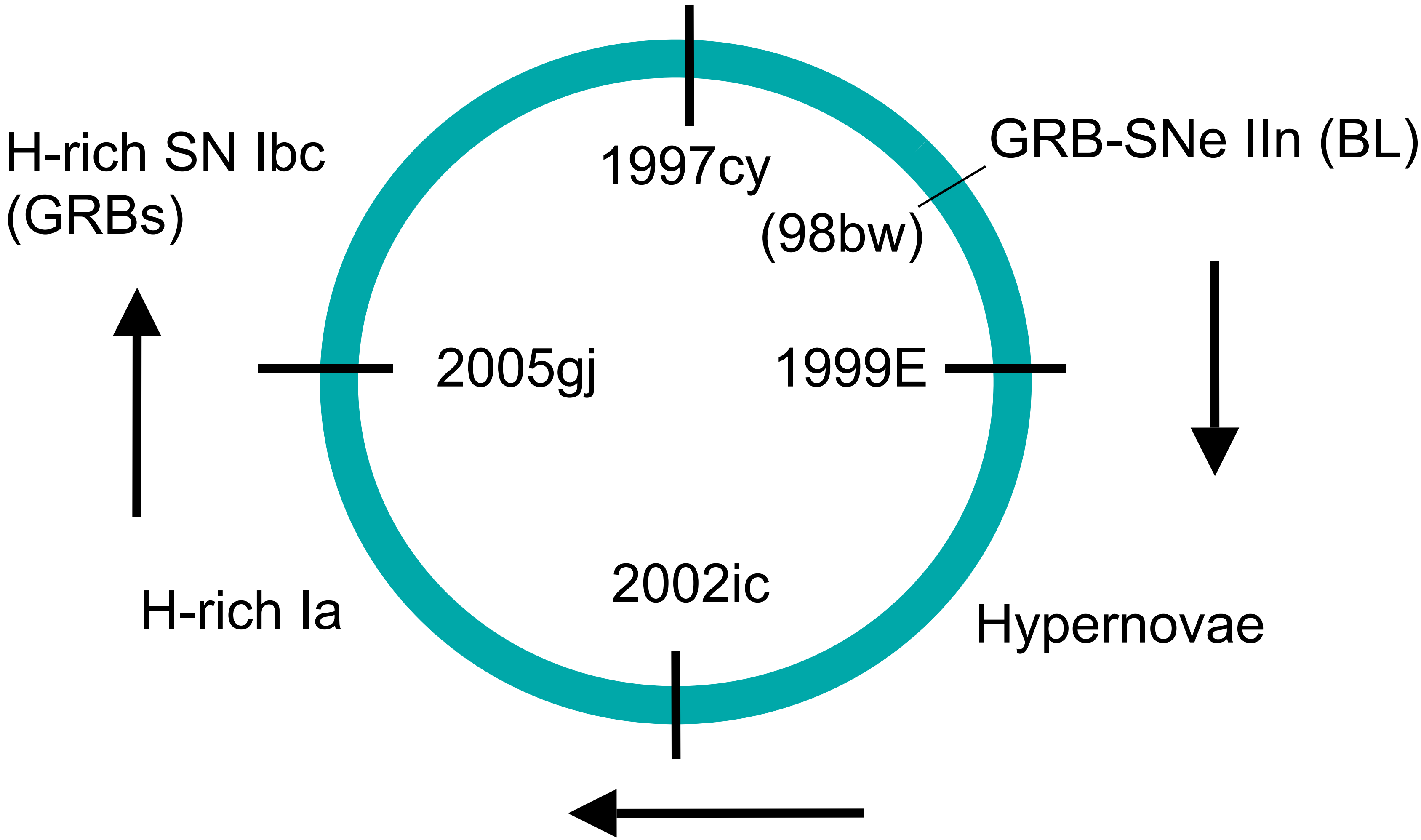
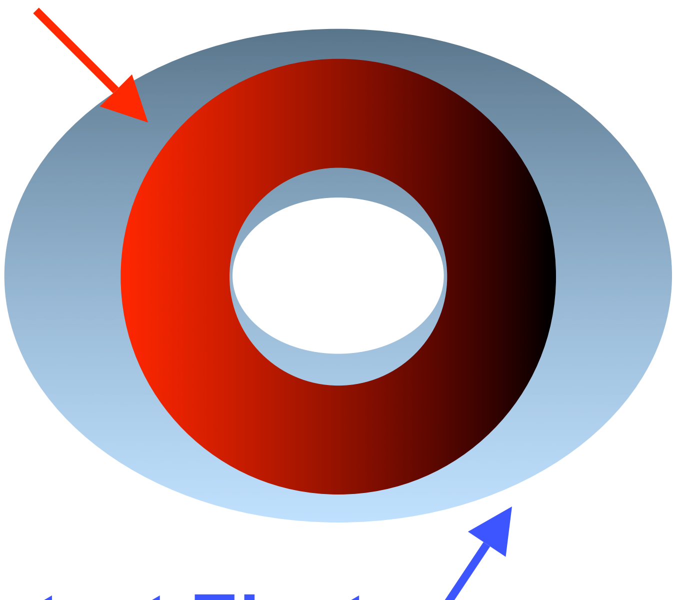


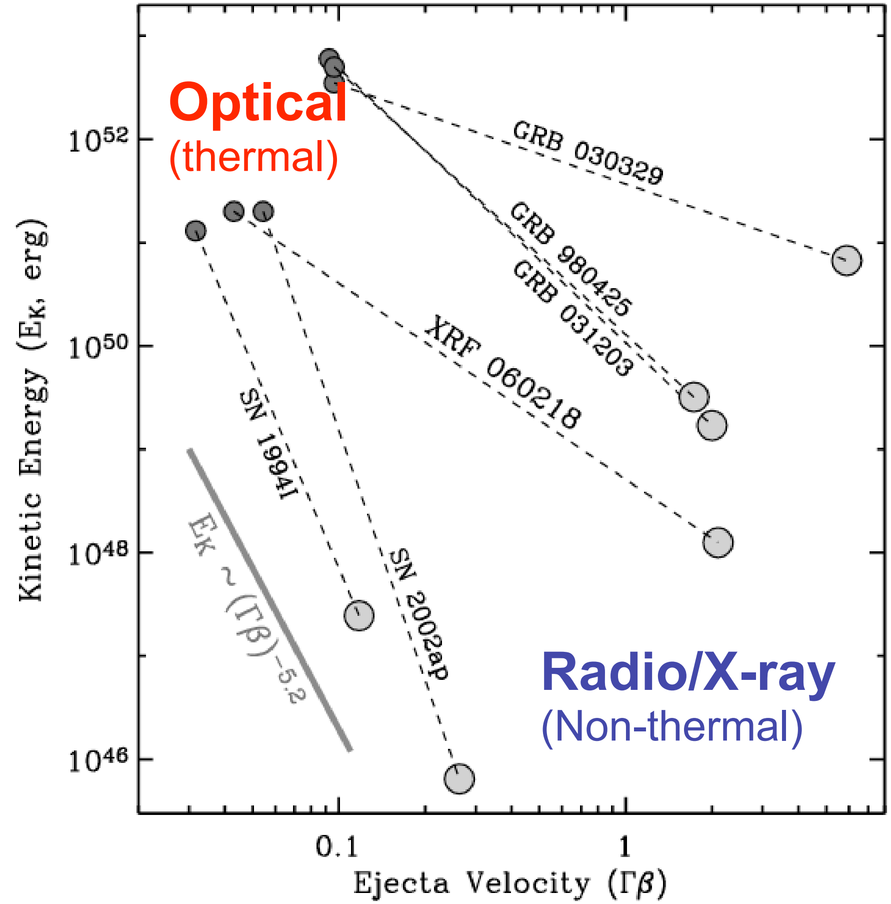
Radio/X-rays Trace the Fastest Ejecta

(Soderberg et al., 2006, Nature)

Photosphere

v ~ 0.03c to 0.1c   E ~10^{51} erg





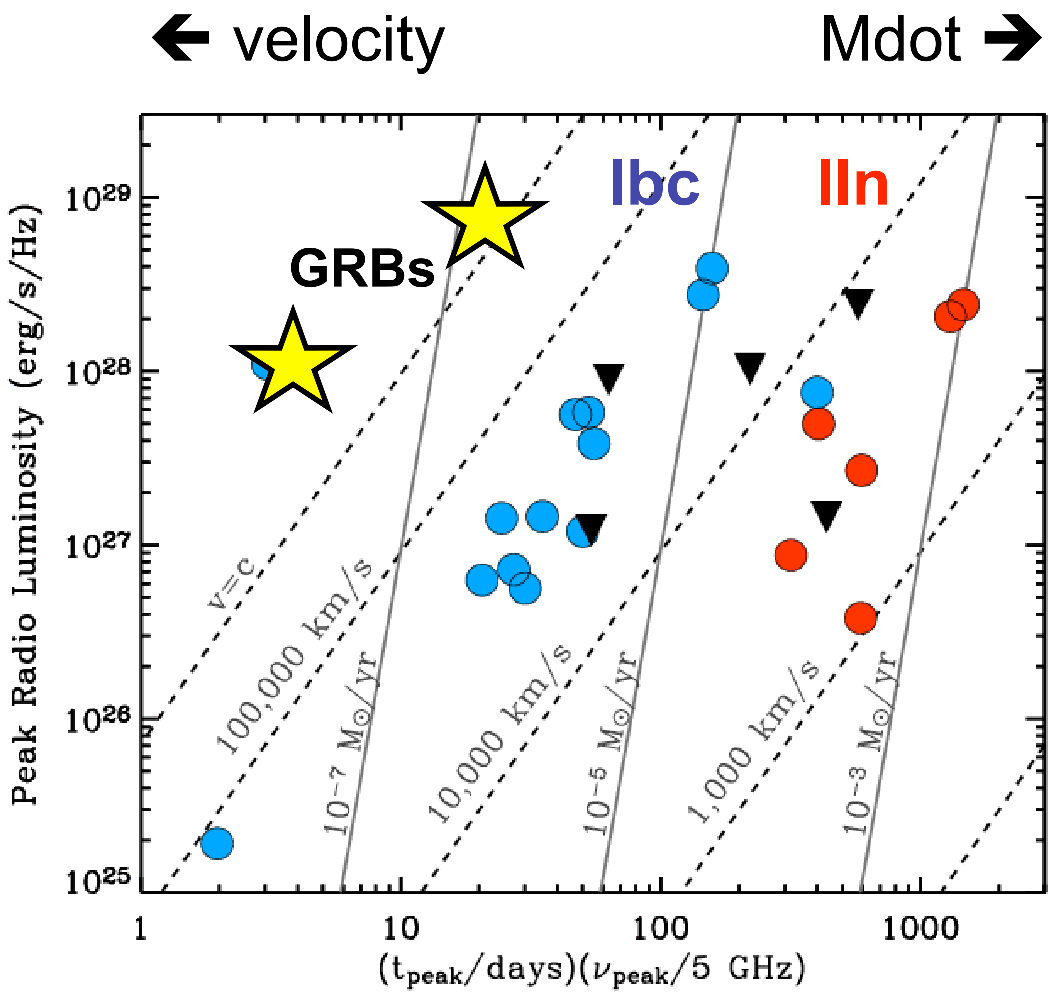
Fastest Ejecta

v ~ 0.1c to **Γ ~ few**

E ~ 10^{45} to **10^{51} erg**

Strong X-ray/radio from: **central engine** (GRBs) and/or **dense CSM** (SNe IIn).

Radio limits on Hybrid SNe



(Soderberg, VLA, A-config)

Radio peak time:

SNe Ibc ~ 30 days
SNe IIn ~ 2 yrs

Hybrid SNe:

Observations are poorly timed, shallow, and sparse

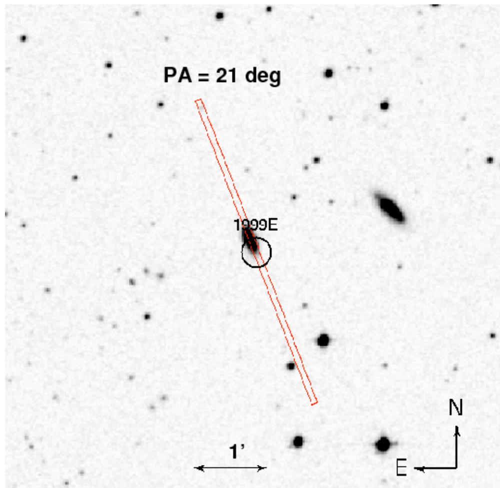
VLA June 1 2007:

Revisit old Hybrids and TOO for new ones *(PI Soderberg)*

Host Galaxies of Hybrid SNe

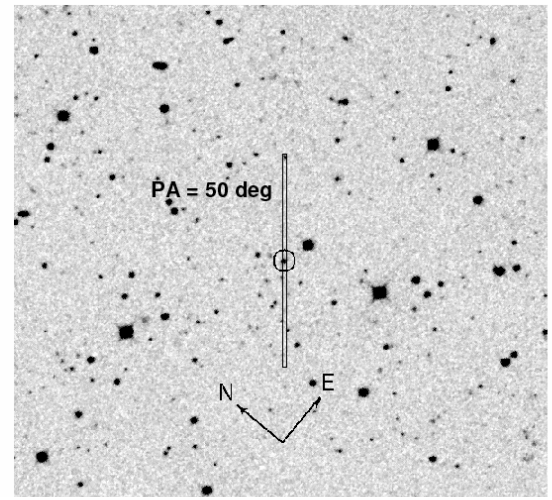
SN 1999E

RA = 13:17:16.37, DEC = −18:33:13.4

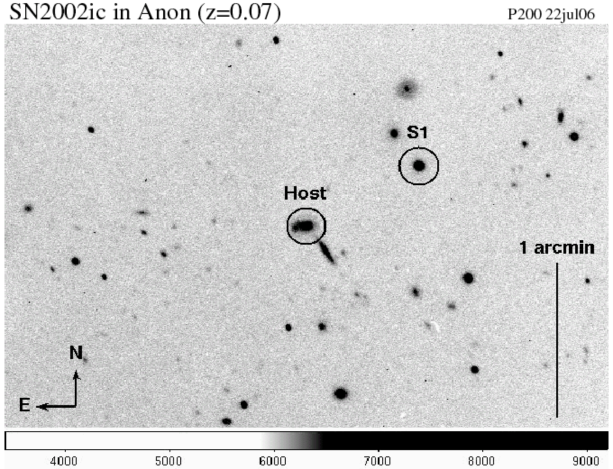


SN 1997cy

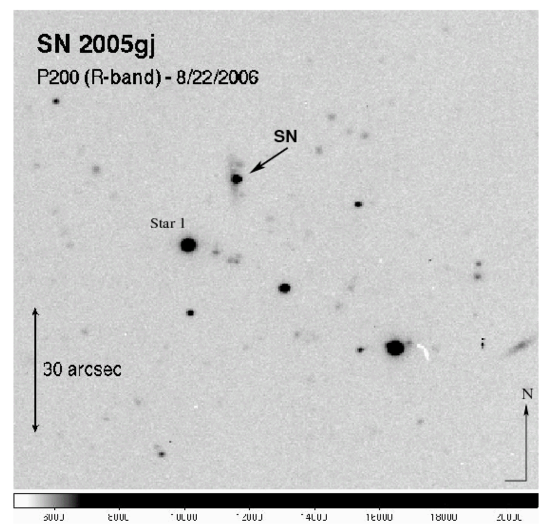
RA = 04:32:54.86, DEC = −61:42:57.5



SN2002ic in Anon (z=0.07) P200 22jul06



Host: 01:30:02.9 +21:53:08.1 J2000 S1: 01:29:59.97 +21:53:31.89 J2000 S1 -> Host: 41.6" E 23.4" S



SN 2005gj
RA: 03:01:11.95
Dec: −00:33:13.9
(J2000)

Star 1 (17 mag)
RA: 03:01:12.68
Dec: −00:33:28.94
(J2000)

Star 1 –> SN
11.43" W, 15.6" N

Host Galaxy Spectroscopy:

all 4 are Anonymous hosts

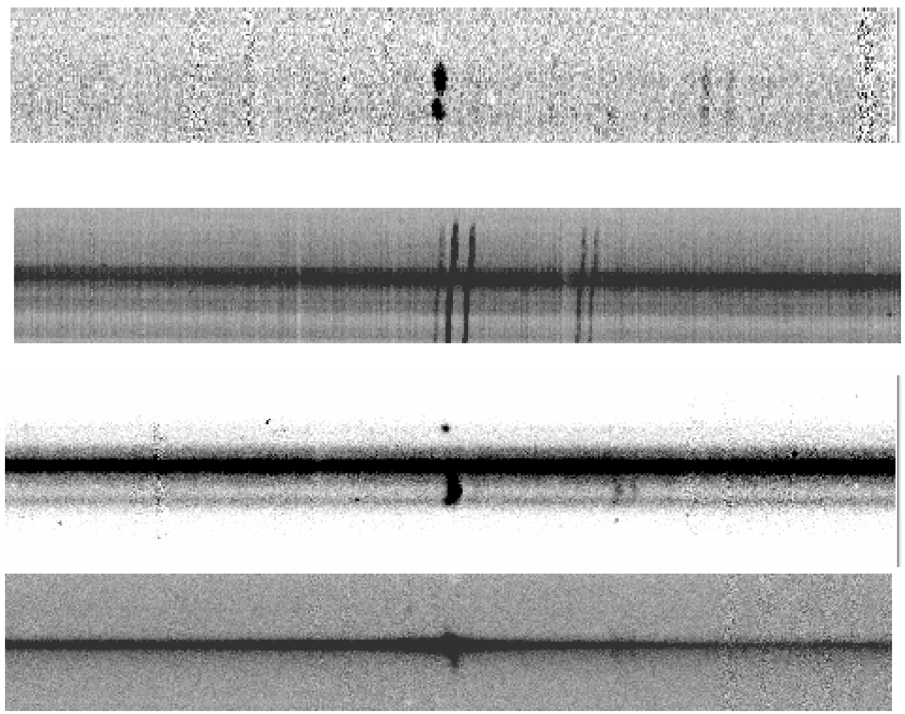
Hα

97cy

99E

02ic

05gj



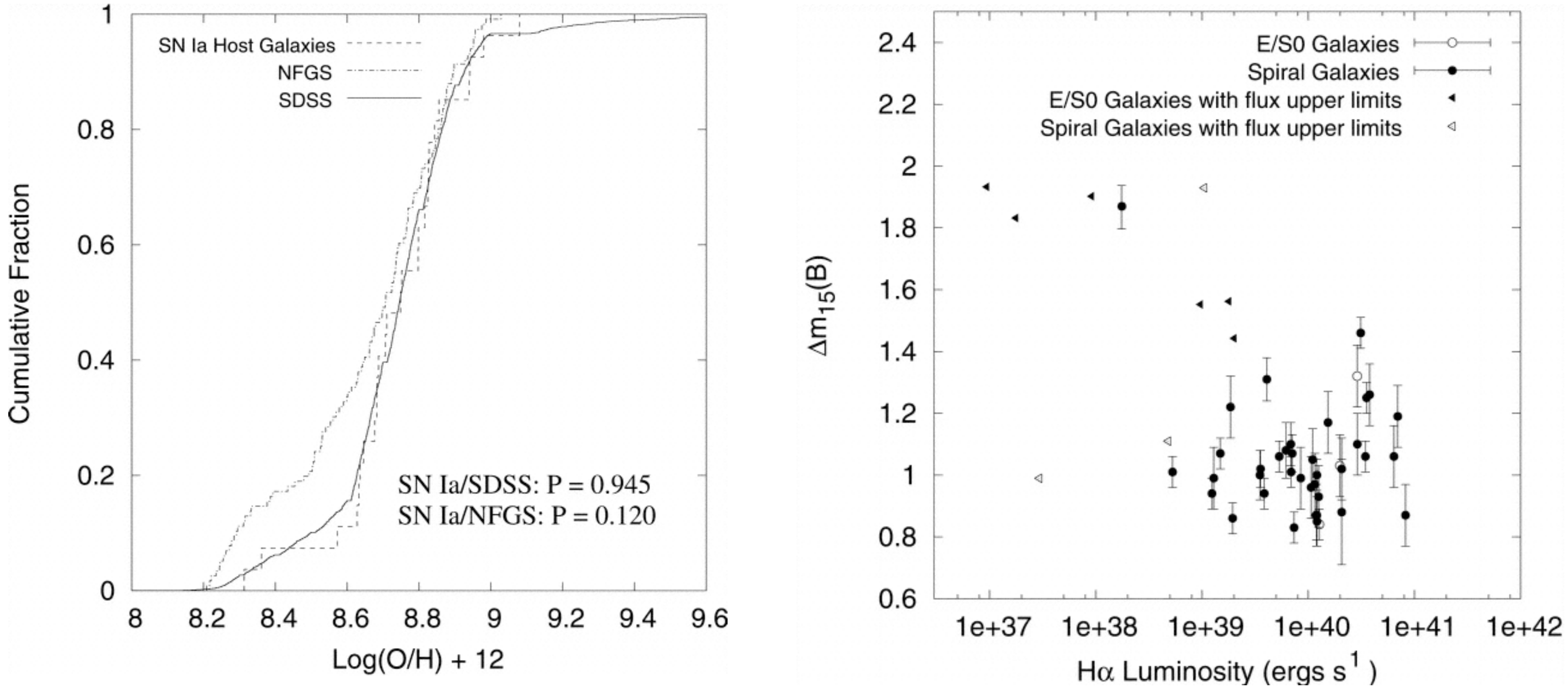
Keck + Magellan

SFR ($M_{\odot}$/yr)	**Z** ($Z_{\odot}$)
0.04	0.3-0.8
0.03	0.4-1.3
0.07	0.3-0.8
>0.002	<0.3

(Soderberg et al., in prep)
(Aldering et al., 2006)

Comparison to SNe Ia Hosts

(Gallagher et al., 2005)



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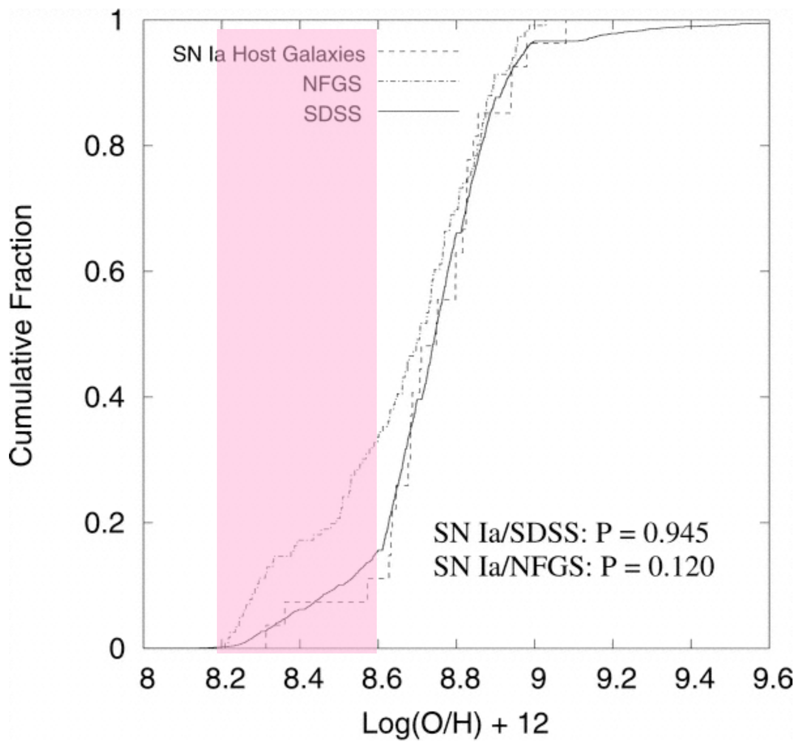

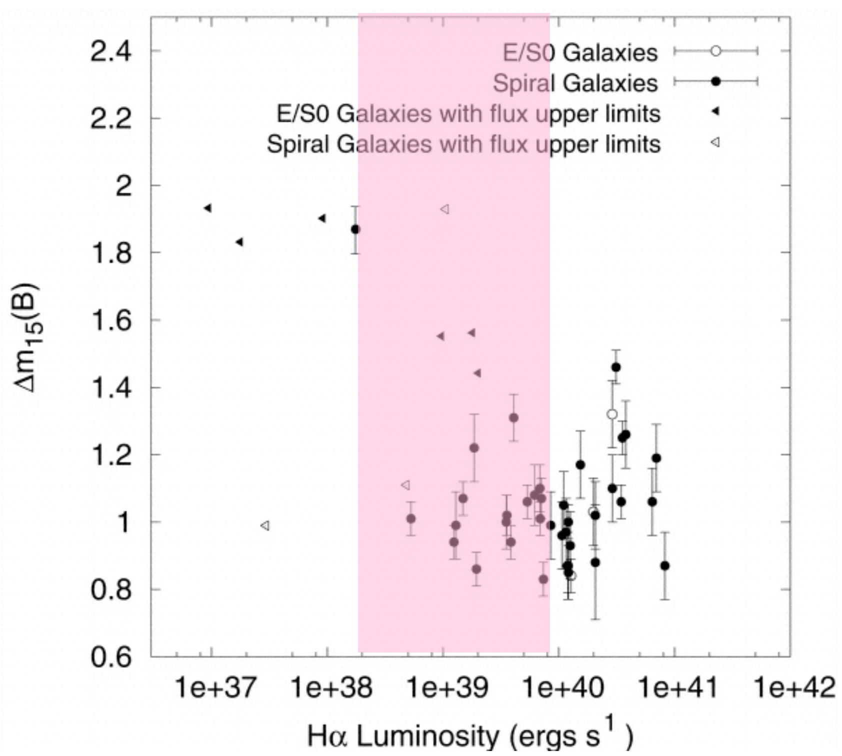

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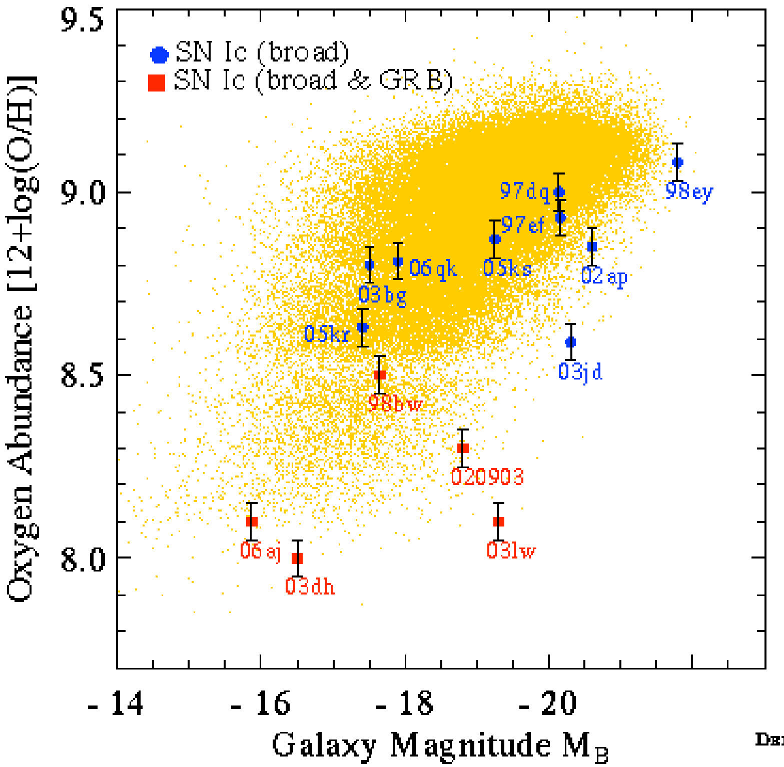

Host metallicity, luminosity **lower** than targeted Ibc,

SFRs **comparable** to Ibc, **lower** than those of GRBs

➔ GRBs? **NO.** (Need to quantify selection bias)

(Modjaz et al., 2007)

TABLE 6
DERIVED PROPERTIES OF HOST GALAXIES OF SN Ic (BROAD) AT SN POSITION IF DIFFERENT FROM NUCLEUS

SN	Host Galaxy	M_B [mag]	log(O/H)+12 KD02[a]	log(O/H)+12 PP04[a]	L(Hα)[b] [10^{40} erg s^{-1}]	SFR[b] [$M_\odot yr^{-1}$]	n_e(SII) [cm^{-3}]	$E(B-V)$ [mag]
SN 1997dq	NGC3810	−20.1	9.0[c]	8.7[c]	...	...	...	...
SN 1997ef	UGC4107	−20.1	8.93	8.69	0.92	0.07	73	0.24
SN 1998ey	NGC7080	−21.8	9.08[d]	8.83[d]	> 0.31	> 0.03	...	0.28
SN 2002ap	M74	−20.6	8.85[e]	8.61[e]	...	...	...	...
SN 2003bg	MCG-05-10-15	−17.5	8.8[c]	8.6[c]	...	...	...	...
SN 2003jd	MCG-01-59-21	−20.3	8.59	8.39	0.83	0.07	119	0.14
SN 2005bf	MCG+00-27-005	−21.6	8.93	8.79	1.03	0.03	< 10	0.34

[a] Extinction-corrected oxygen abundances derived using either the calibrations of Kewley & Dopita (2002, KD02) or of Pettini & Pagel (2004, PP04). See § 4.2 for details.
[b] Extinction-corrected values. Lower limits are indicated if they could not be extinction corrected (when Hβ could not be observed).
[c] Extrapolated using nuclear oxygen abundances from Table 5 and assuming standard metallicity gradient. See text for details.
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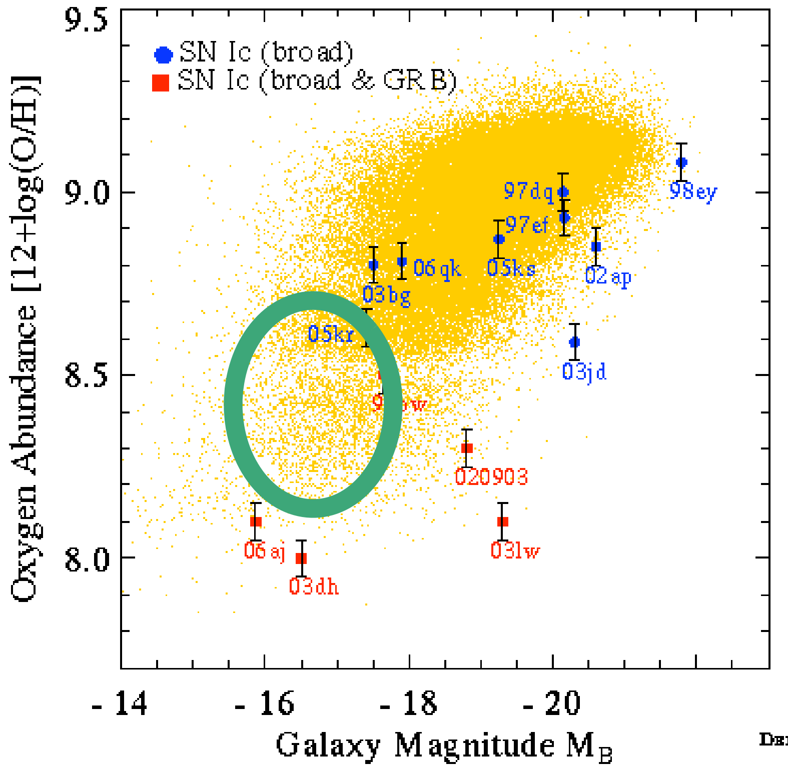

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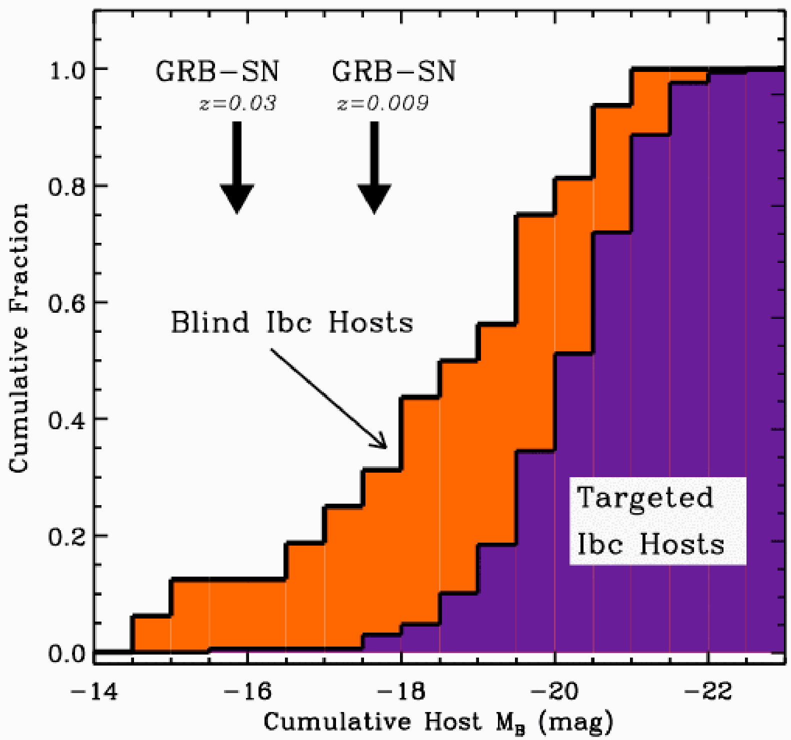
(Soderberg, HST Cycle 16)



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Nothing: X-ray observations of SNe Ia

(Immler et al., 2006)

- Sample of 8 SNe Ia
- Only 2005ke showed a 3-σ X-ray bump (6" PSF) and UV excess
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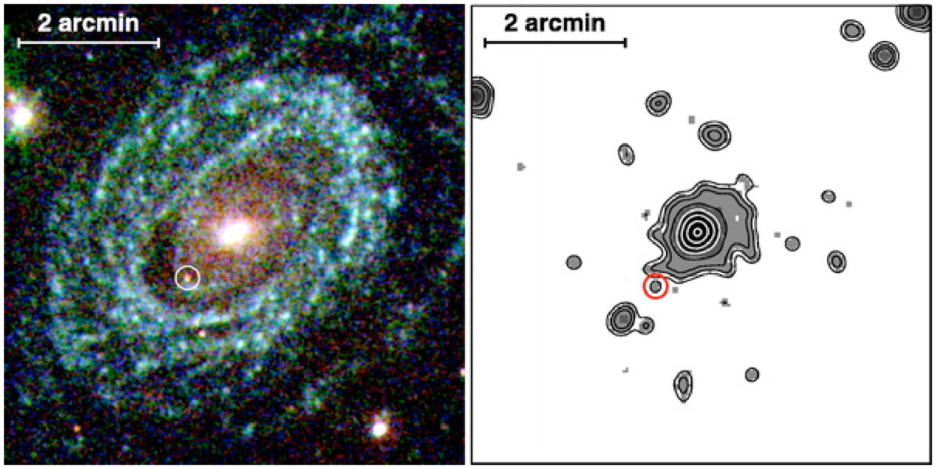
- M_{dot} ~ 3×10^{-6} $M_{\odot}$/yr

UVOT XRT



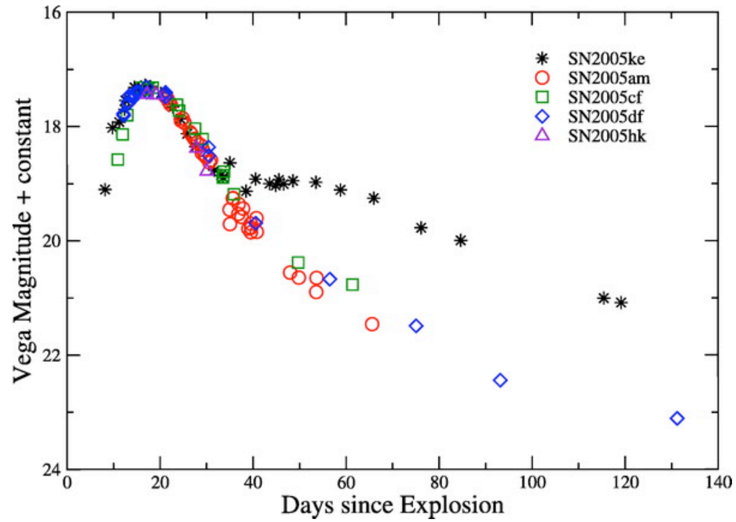
No detection with Chandra

No radio emission *(Soderberg, 2005)*

No Hα emission *(Soderberg, Phillips)*

Other sub-luminous SNe Ia show similar UV excess *(M. Phillips)*

➔ We don't yet understand the UV spectra of SNe Ia



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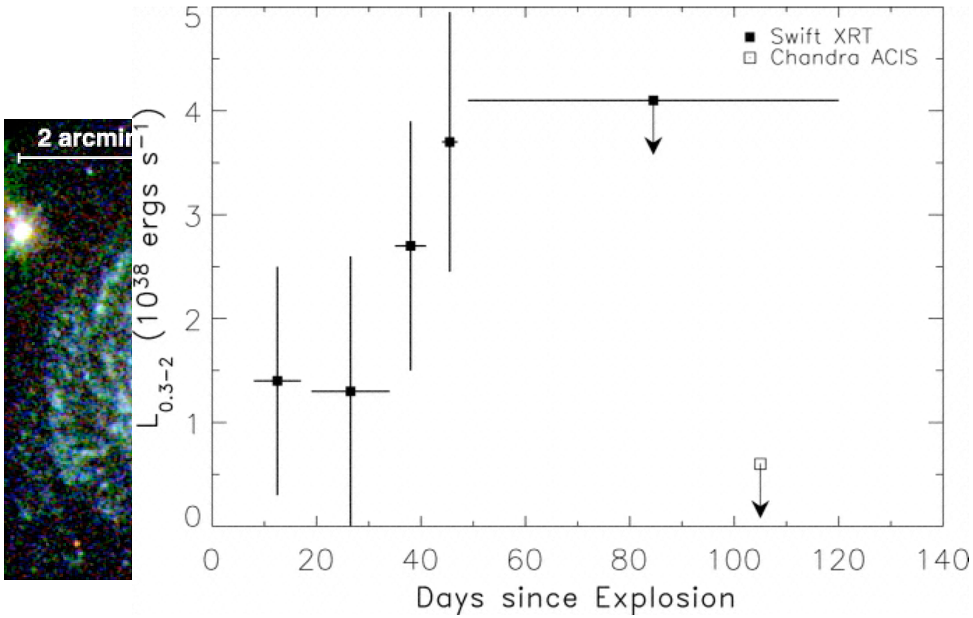

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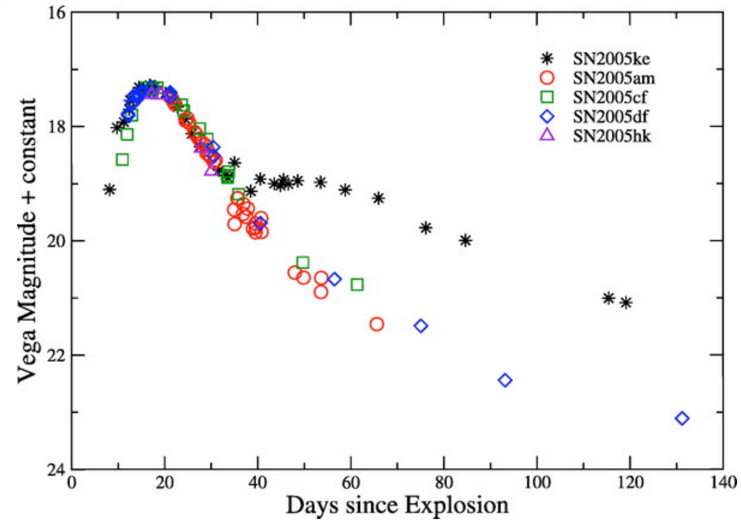
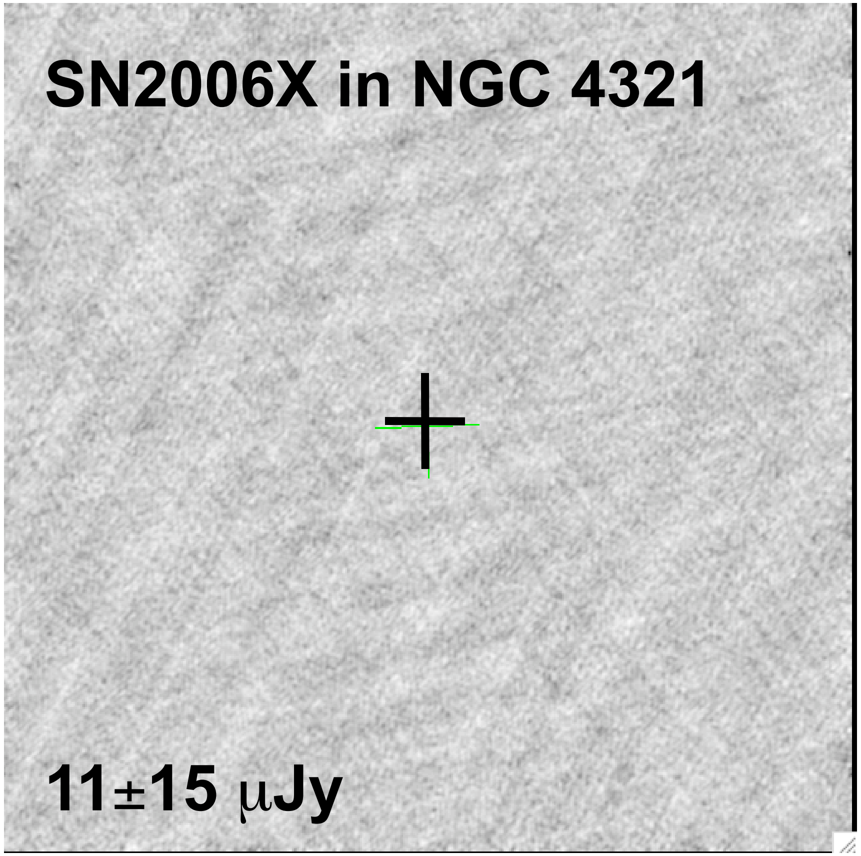


Radio observations of "normal" SNe Ia:

constraints on SDs (massive companions)



Assumptions:

- SN Ibc light-curve (SN1983N)
- Free-free absorption dominates
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- v_w=10 km/s
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(Soderberg, 2006, ATEL 728)

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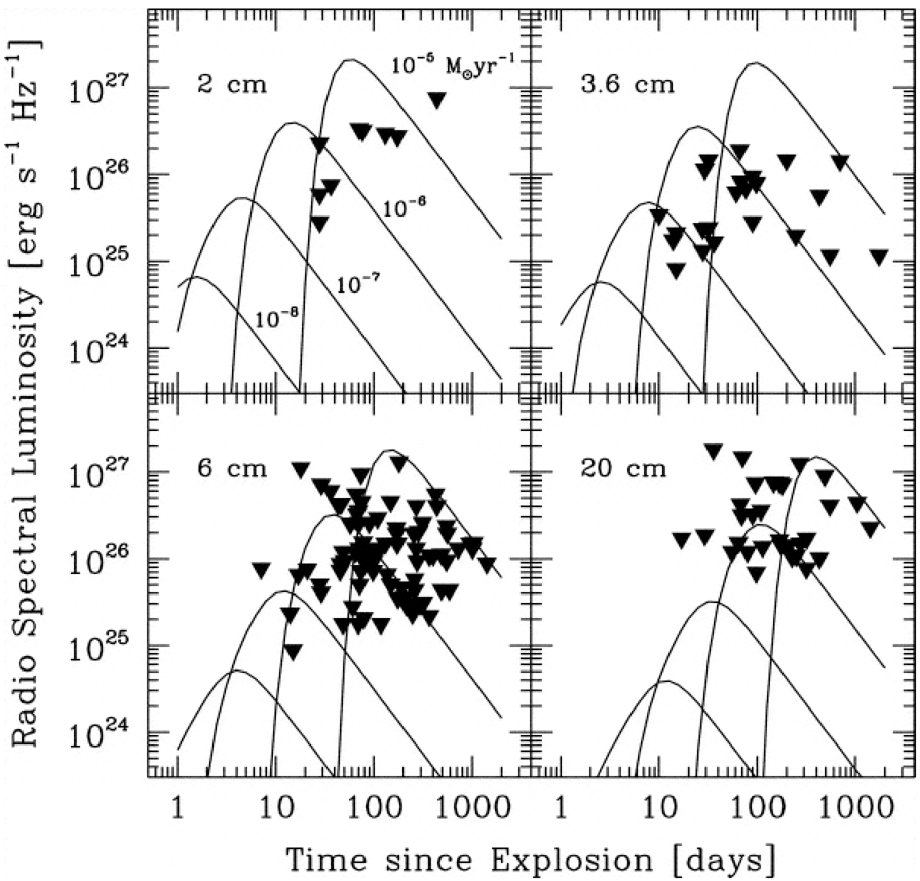

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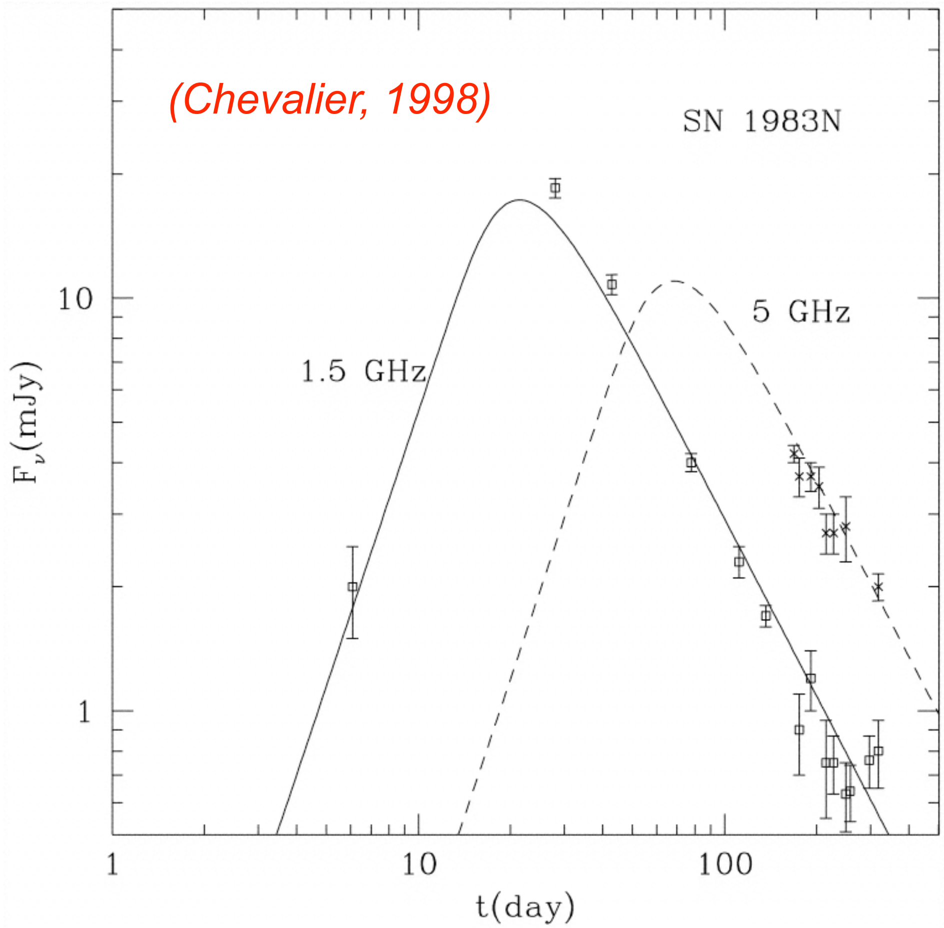

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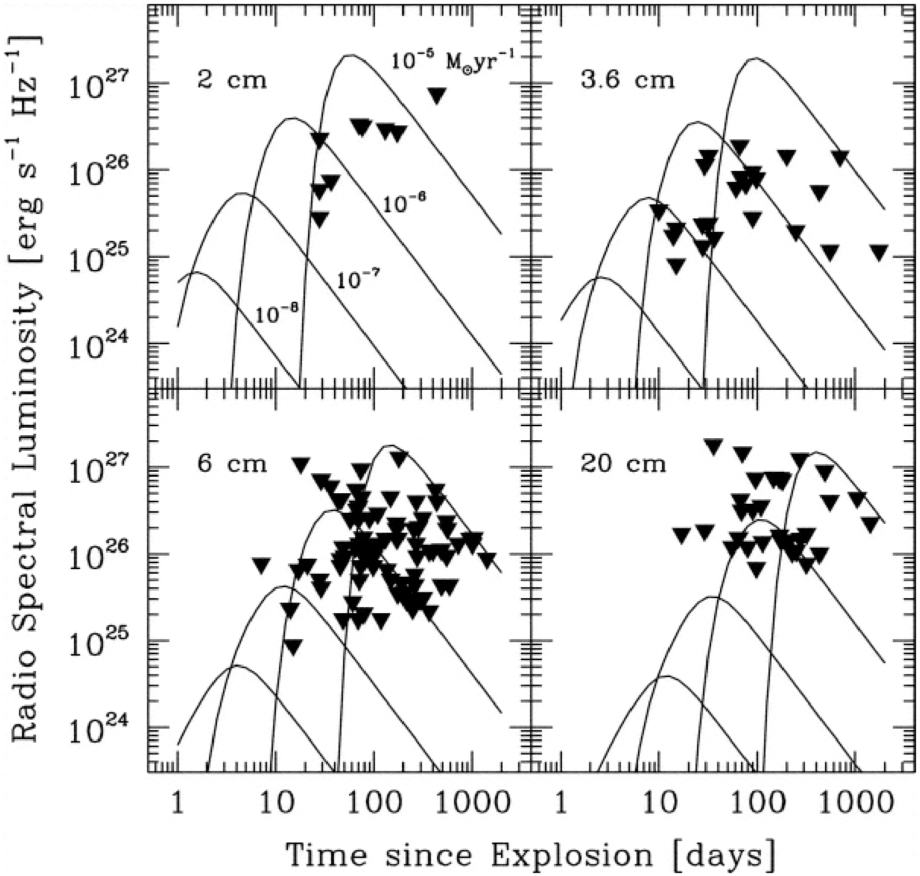

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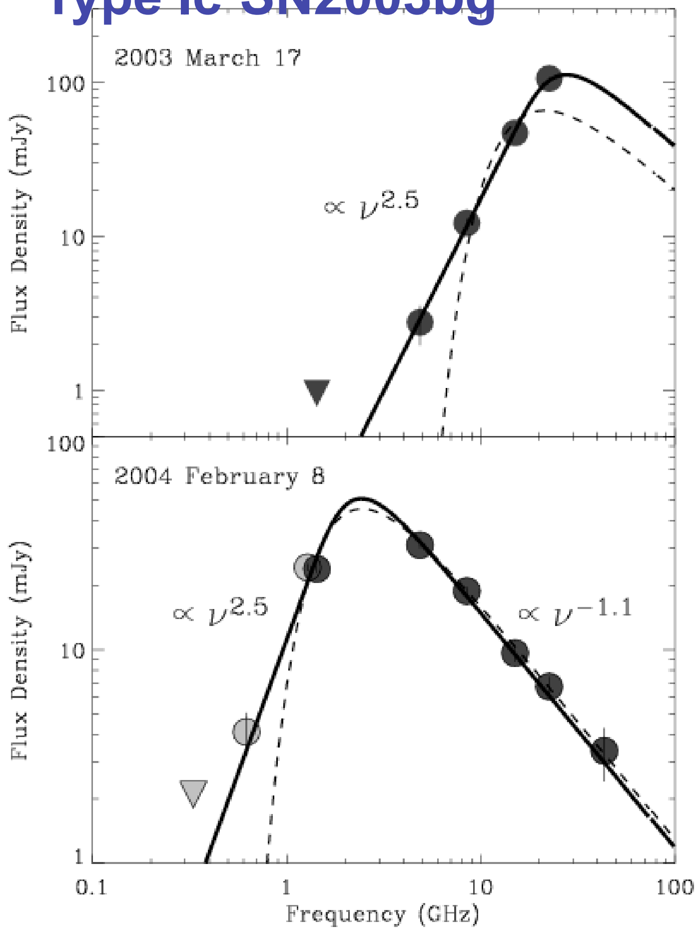
The correct method: assume SSA

Best example for SSA: Type Ic SN2003bg



(Soderberg et al, 2006, ApJ,)

Assume SNe Ia like SNe Ibc *(Chevalier)*

Stripped-envelope explosion in low density environment

SNe Ibc dominated by **SSA** *(Chevalier,98; Berger 2002; Soderberg 2005,2006)*

➔ Expect (and observe) $\nu^{2.5}$ spectrum (external FFA ➔ steeper spectrum)

➔ Assume **equipartition** of energy in electrons (ε_e) and magnetic fields (ε_B)

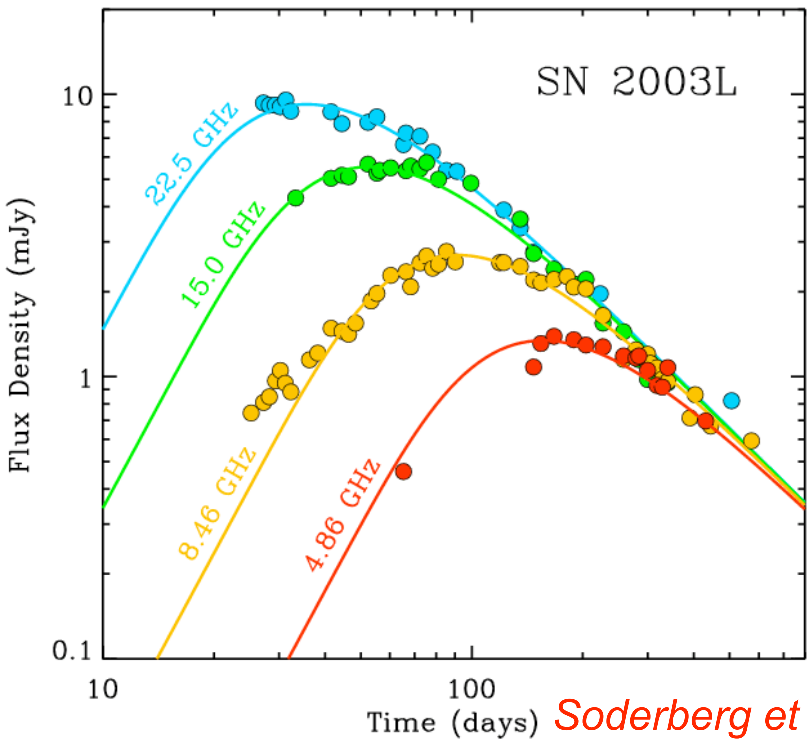
$$r \propto L_p^{8/17}\ \nu_p^{-33/34}$$

$$E_{tot} \propto L_p^{20/17}\ \nu_p^{-40/34}$$

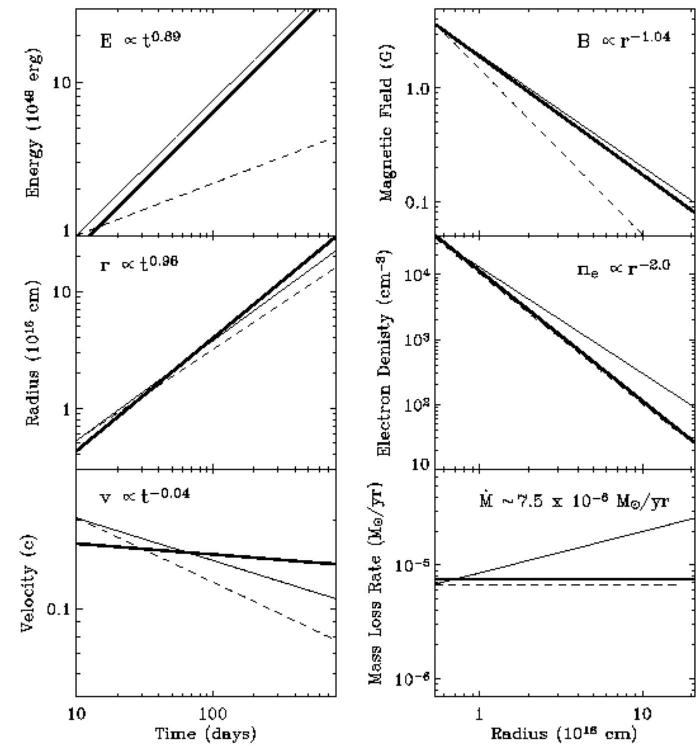
$$M_{dot}/v_w \propto L_p^{-4/17}\ \nu_p^{59/34}\ t_p^{2}\varepsilon_B^{-1}$$

Extracting Physical Parameters

*The temporal and spectral evolution of the radio light-curves enables us to trace the **post-shock energy density, radius, magnetic field, CSM density***



Soderberg et al, 2005



X-ray observations may additionally constrain **density** and $\varepsilon_e/\varepsilon_B$

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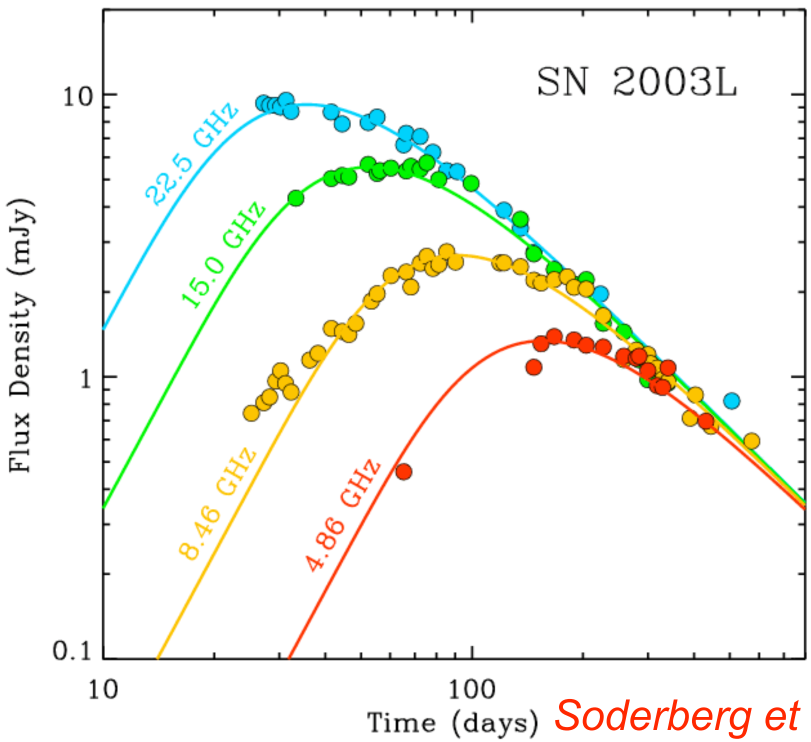

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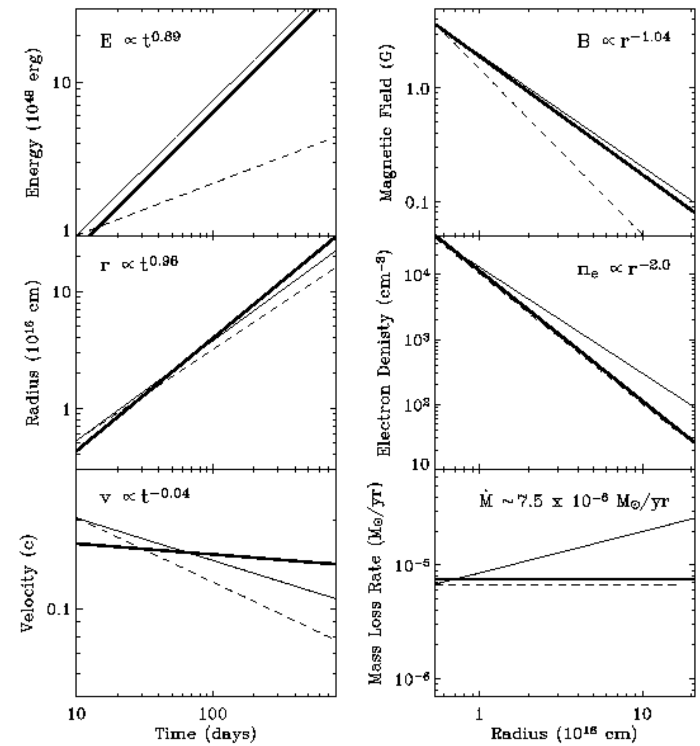
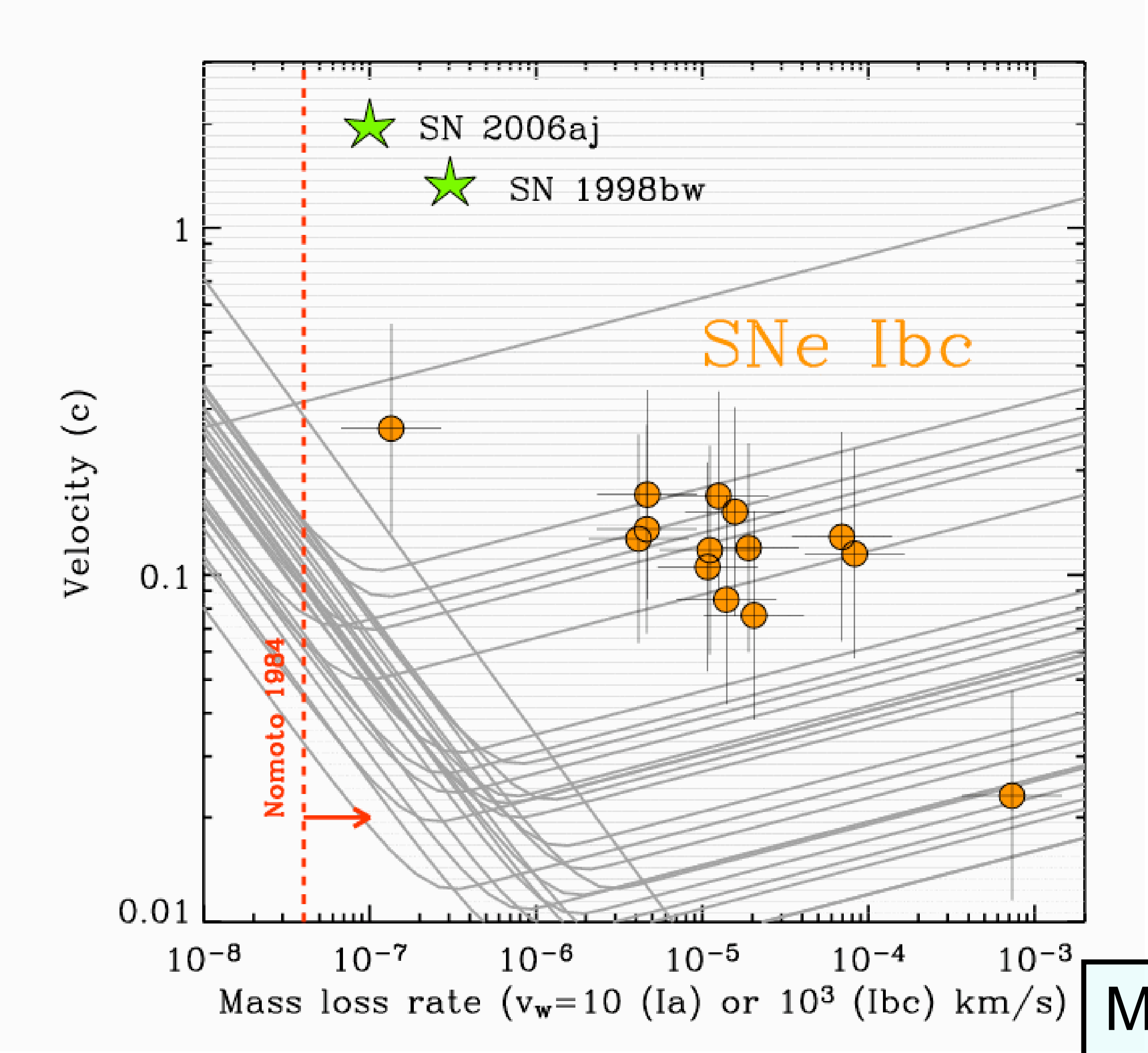


This analysis requires observations of radio peak!

The correct method: assume SSA



<u>I have assumed:</u>

- SN Ibc light-curve
- v_w = 10 km/s
- wind density profile
- equipartition ($\varepsilon_e = \varepsilon_B$)
- ε_B = 0.1
- v_s ~ 0.03-0.1c

M_{dot} < few x 10^{-8} $M_\odot$/yr

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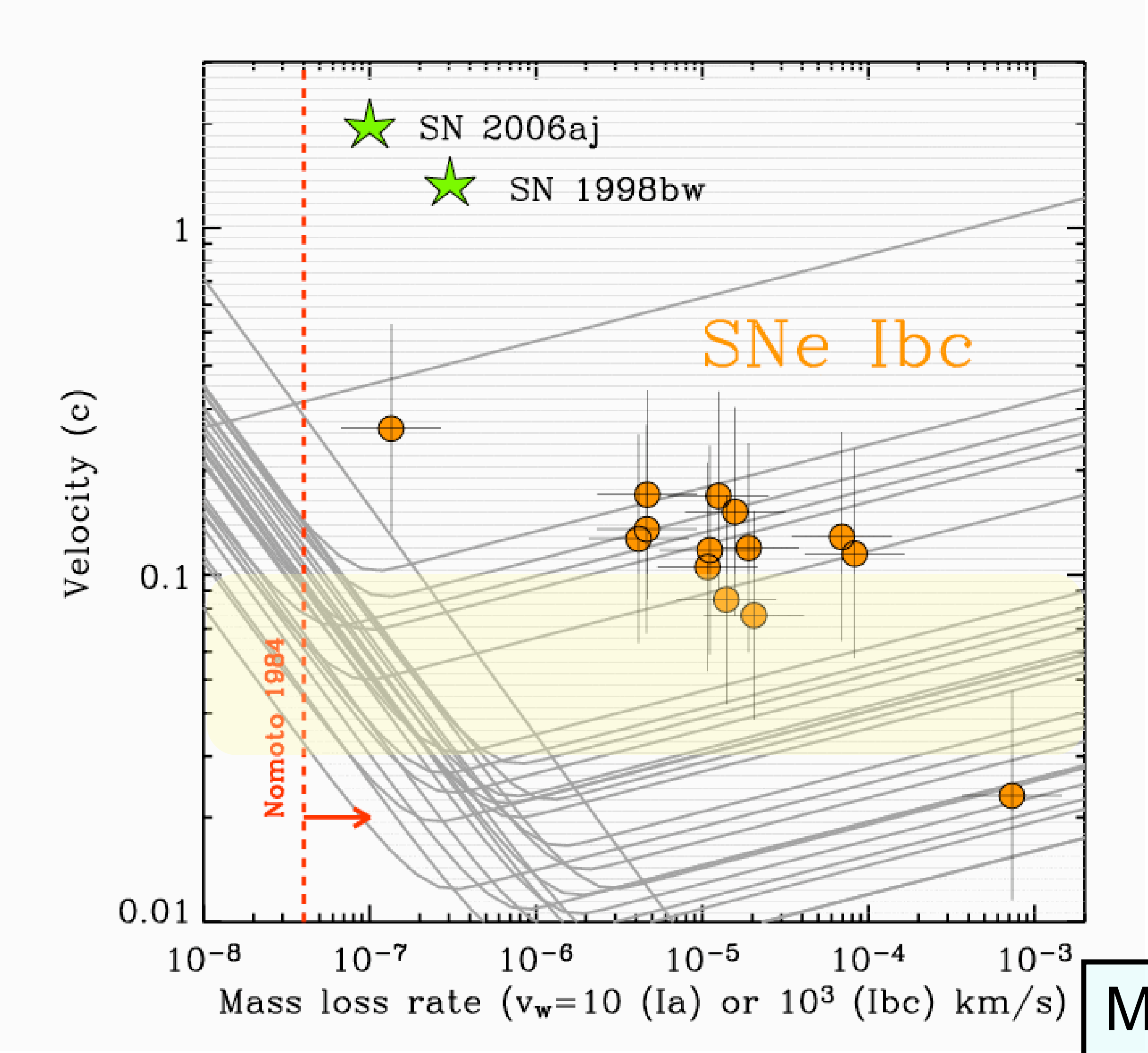

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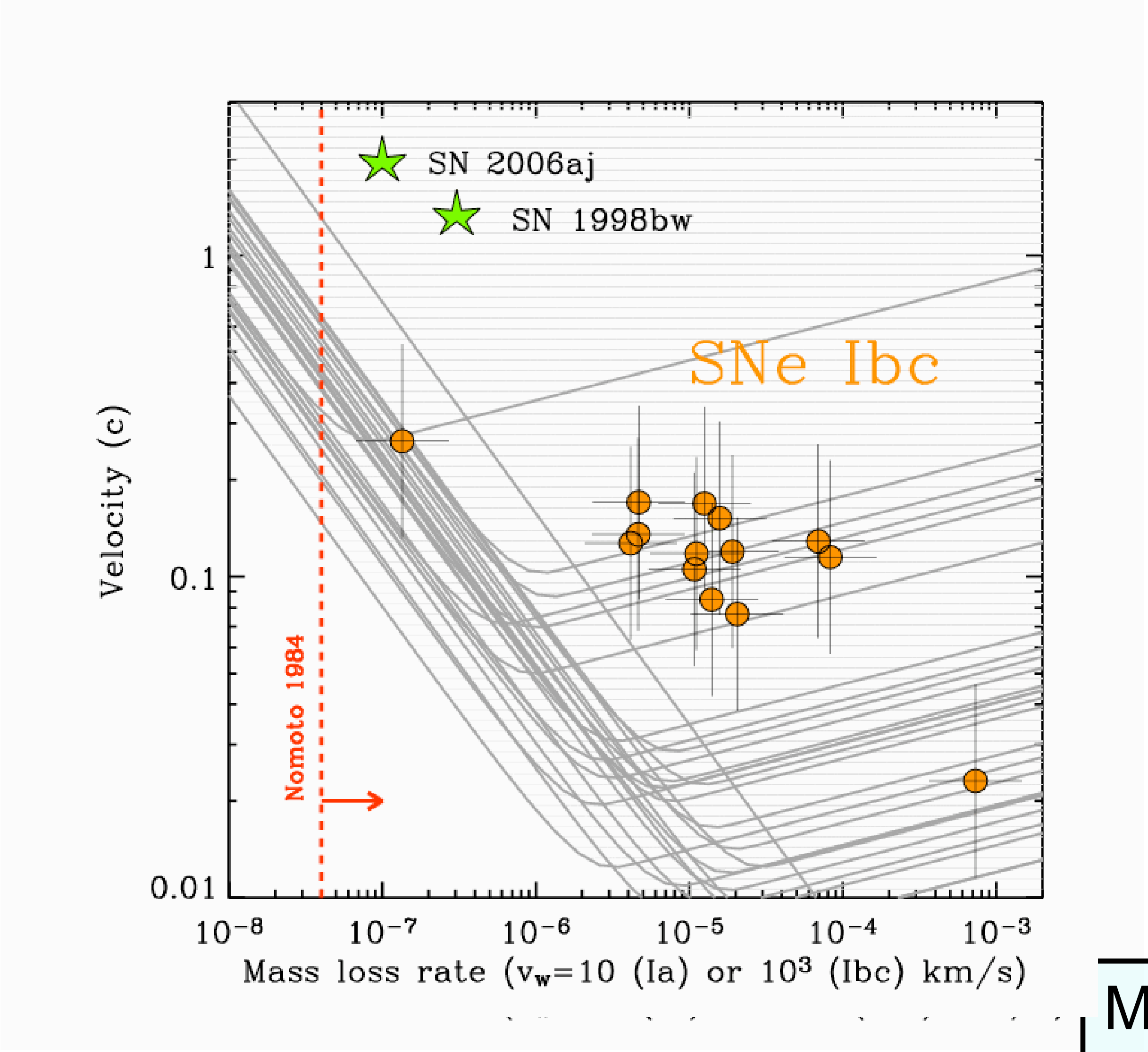

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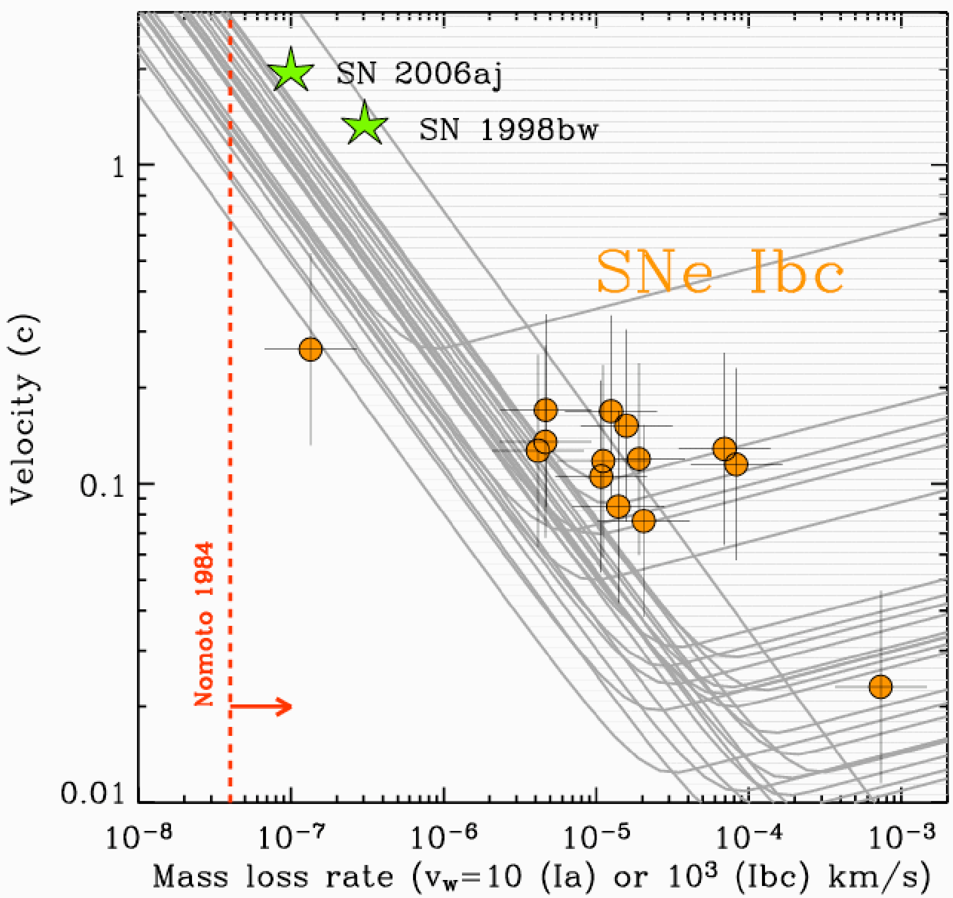
- SN Ibc light-curve
- v_w = 10 km/s
- wind density profile
- equipartition ($\varepsilon_e = \varepsilon_B$)
- ε_B = 0.1
- v_s ~ 0.03-0.1c

M_{dot} < few x 10^{-8} $M_{\odot}$/yr

The correct method: assume SSA



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The Future: 10x Sensitivity with EVLA (2008)

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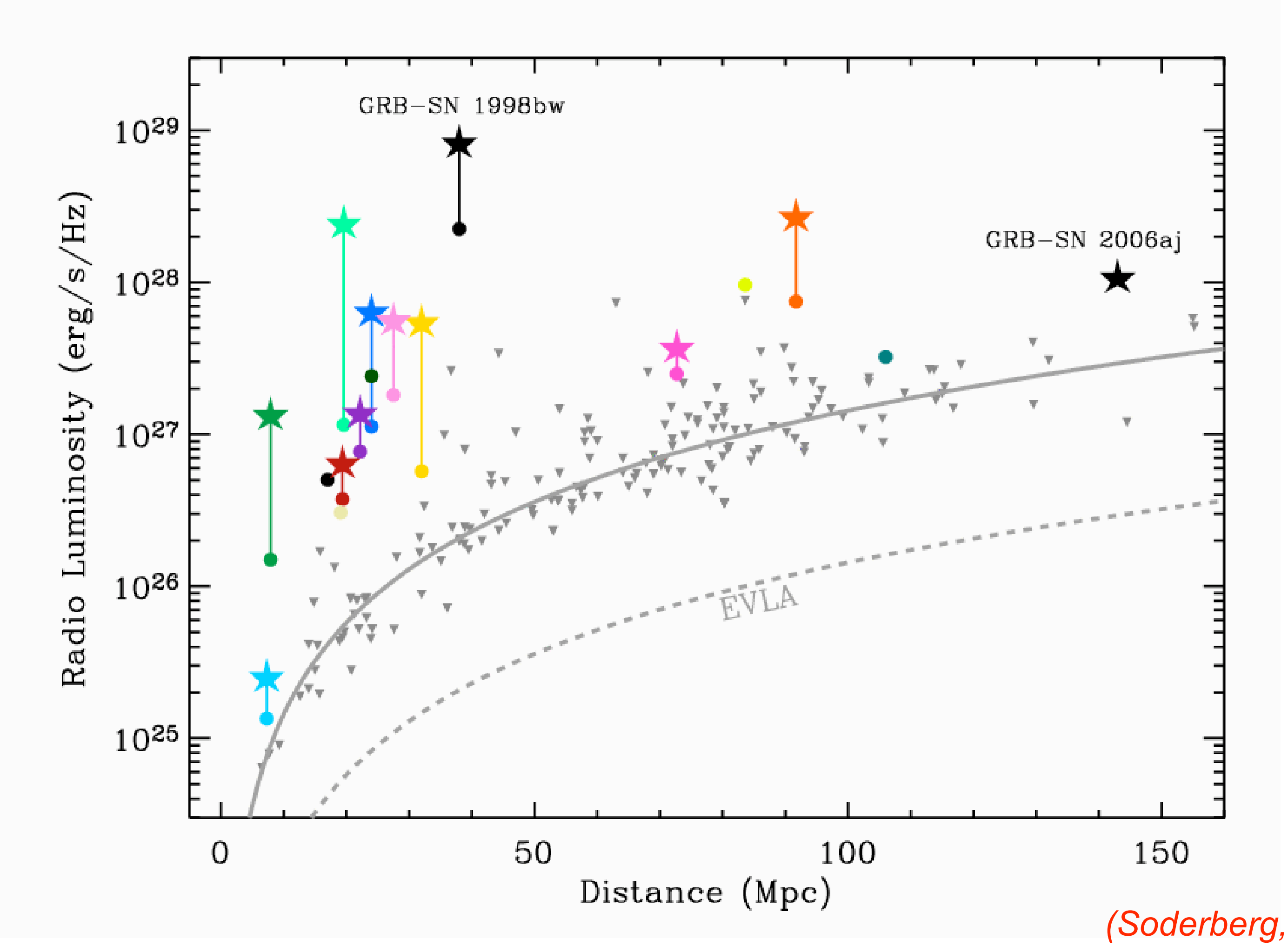

(Soderberg, PhD thesis)

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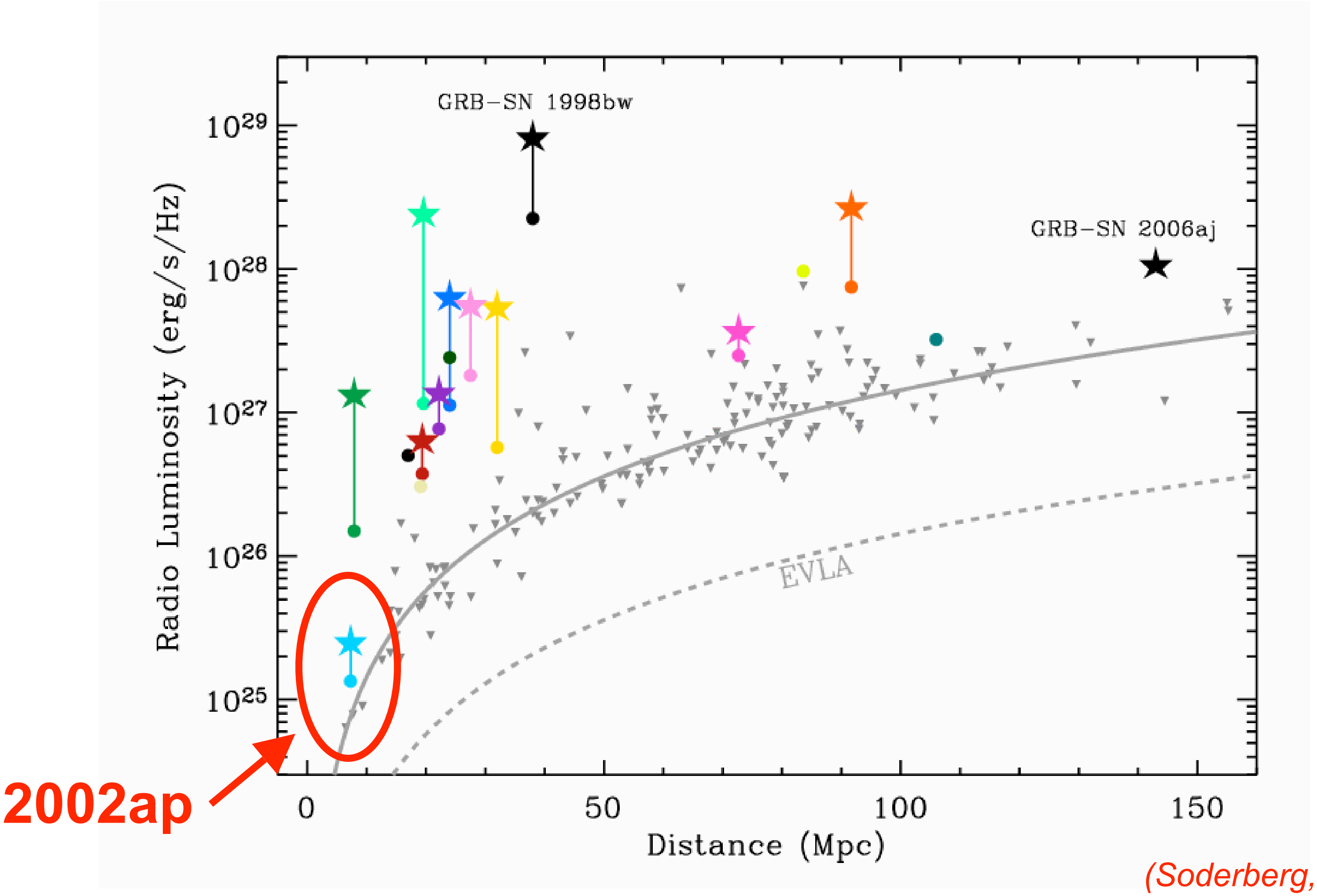

(Soderberg, PhD thesis)

Looking Forward, Making progress

- Hybrid SNe require **blind surveys** for their discovery (SDSS, PS1, LSST)
- Hybrid hosts **may be different** than the bulk population of SNe Ia hosts.
- Radio observations can probe any **engine-driven** material (VLA)
- X-ray and radio observations of normal SNe Ia are important programs to **search for CSI**
- BUT use **caution** when interpreting the data