Supernovae with SKA

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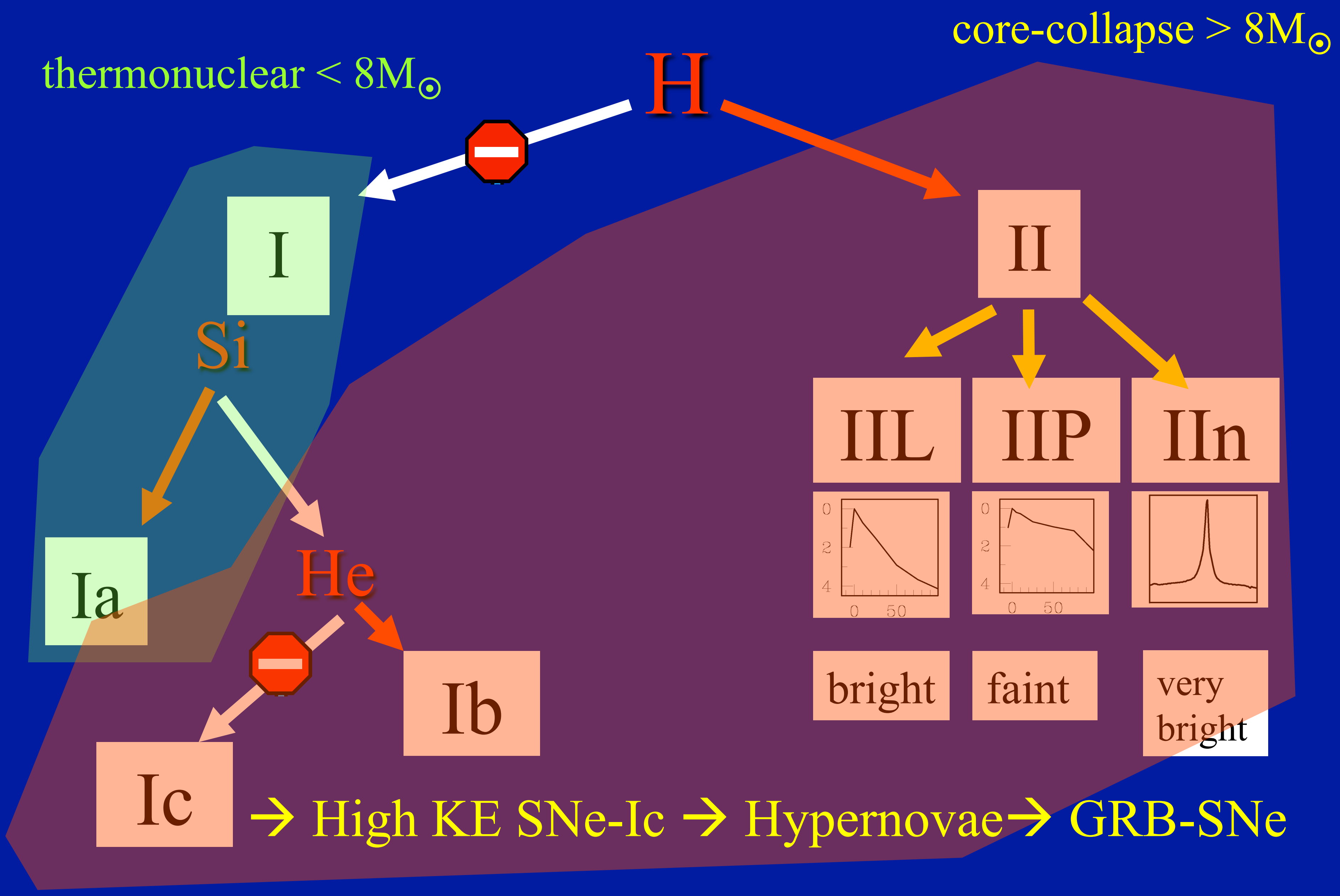
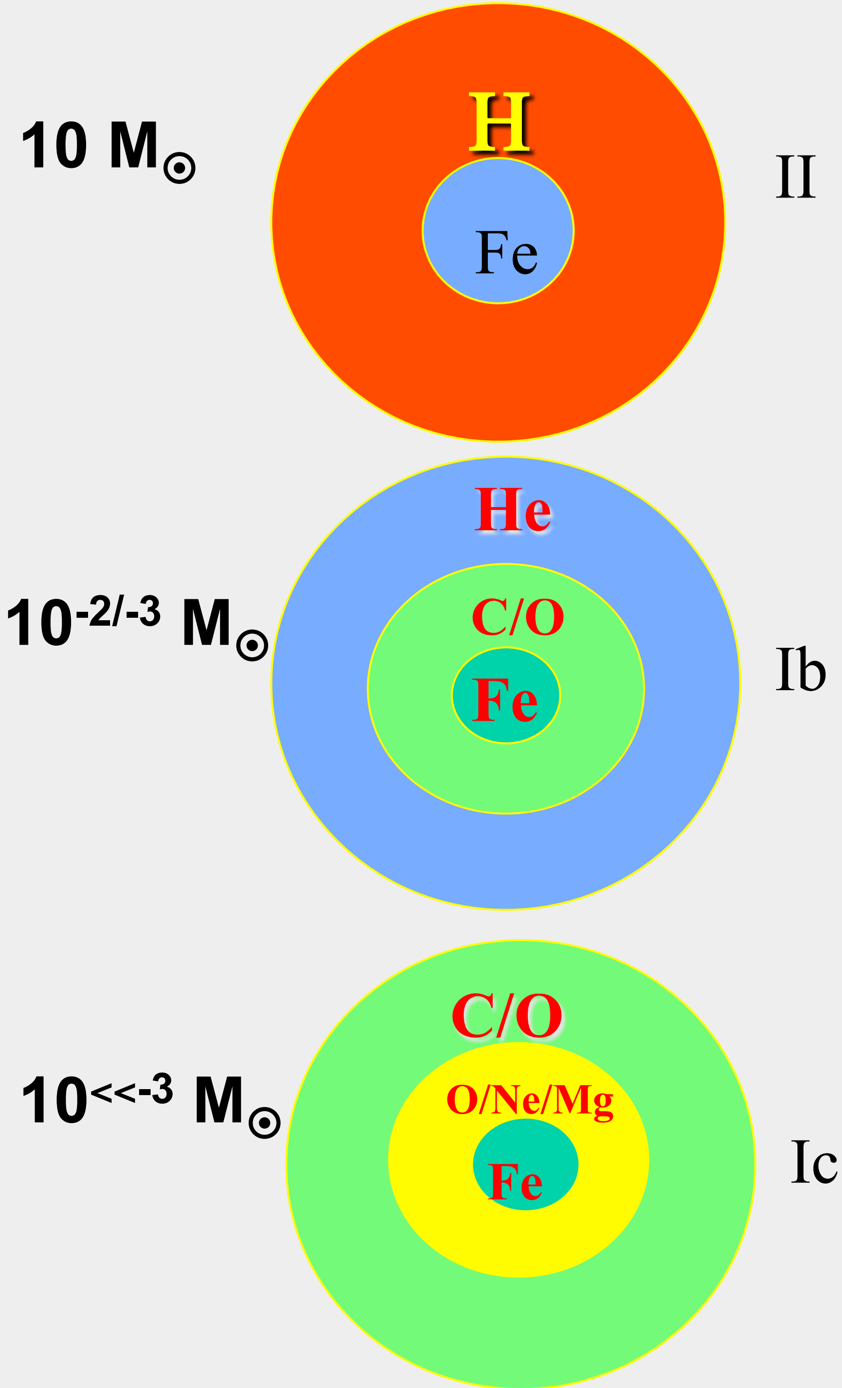
Summary

- Supernova Taxonomy
- Radio-SN Observations (SKA will do it better)
- The impact of SKA on SN studies
  (CC-SNe; SNe-Ia; GRB-SNe, GRBs)
- Conclusions

Supernova taxonomy



Core-Collapse



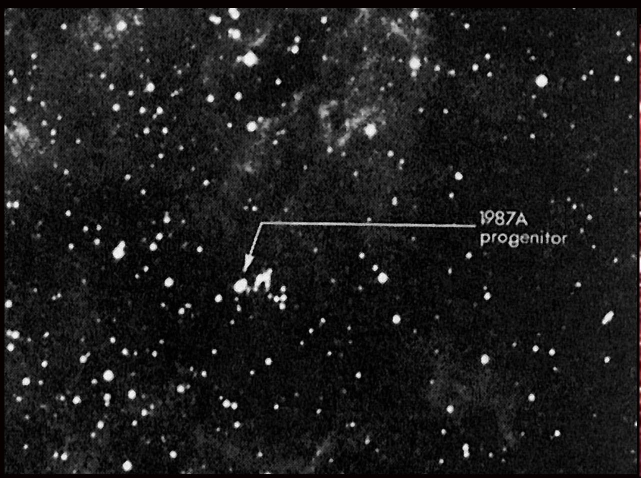
These spectral differences are theoretically explained by differences in progenitors, particularly they derive from the status of the H envelope when the collapse of the core occurs.

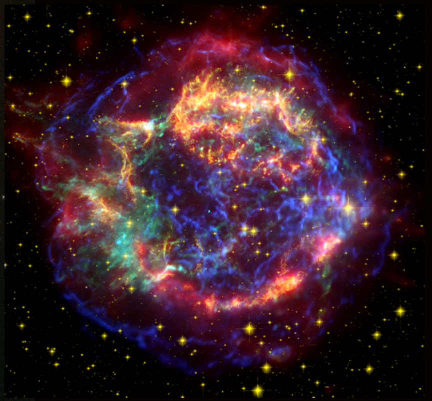
Why Radio-SNe?

The study of radio emission provides valuable insight into SN shock/CSM interaction:

- History of pre-SN evolution
- Mass-loss rate and its evolution with time → Mass of the progenitors on the MS
- Nature of the progenitor (RSG? BSG? W-R? Binary?)
- Future evolution to SNR

Why radio SNe? (a short SN Story….)





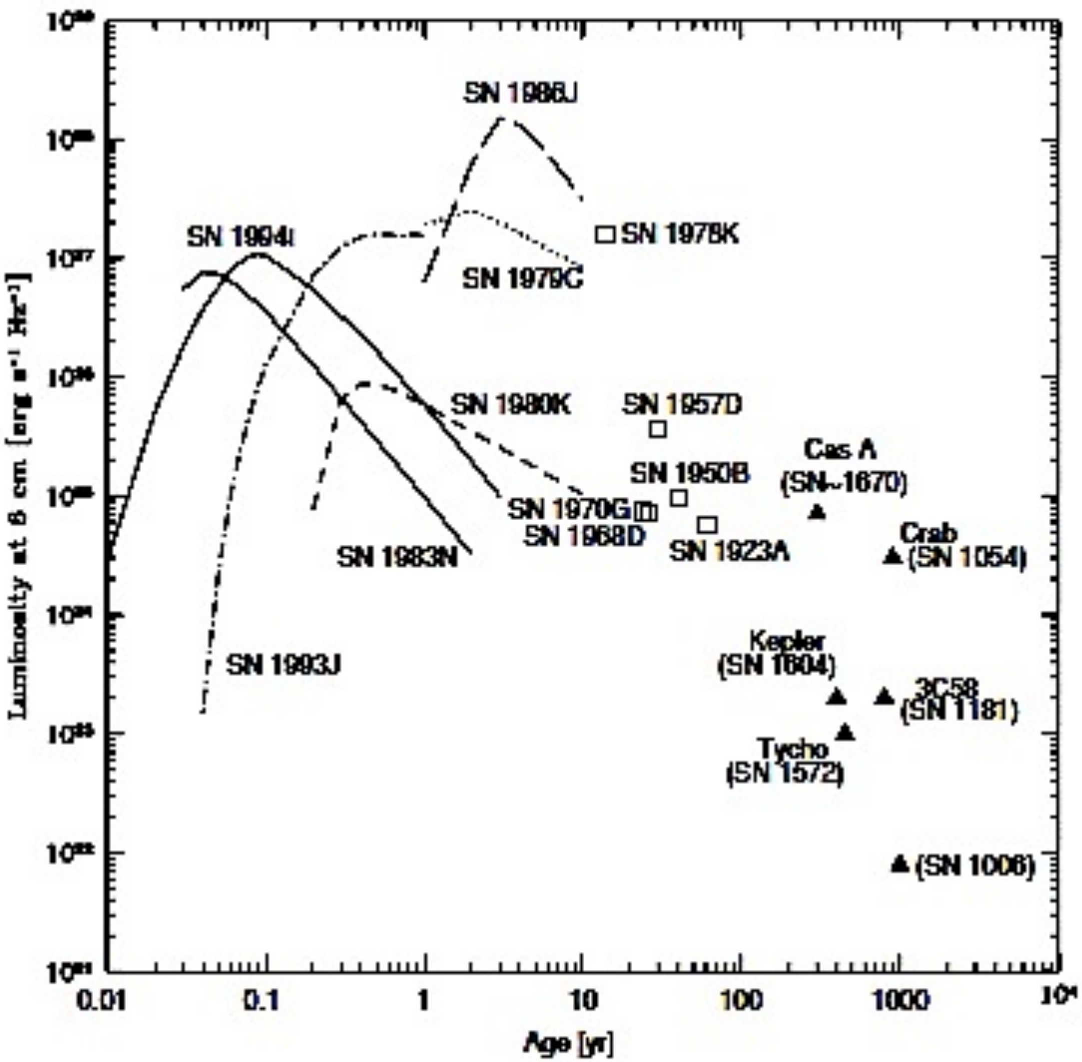
~10^7 years ago

23 Feb 1987

~ 2003

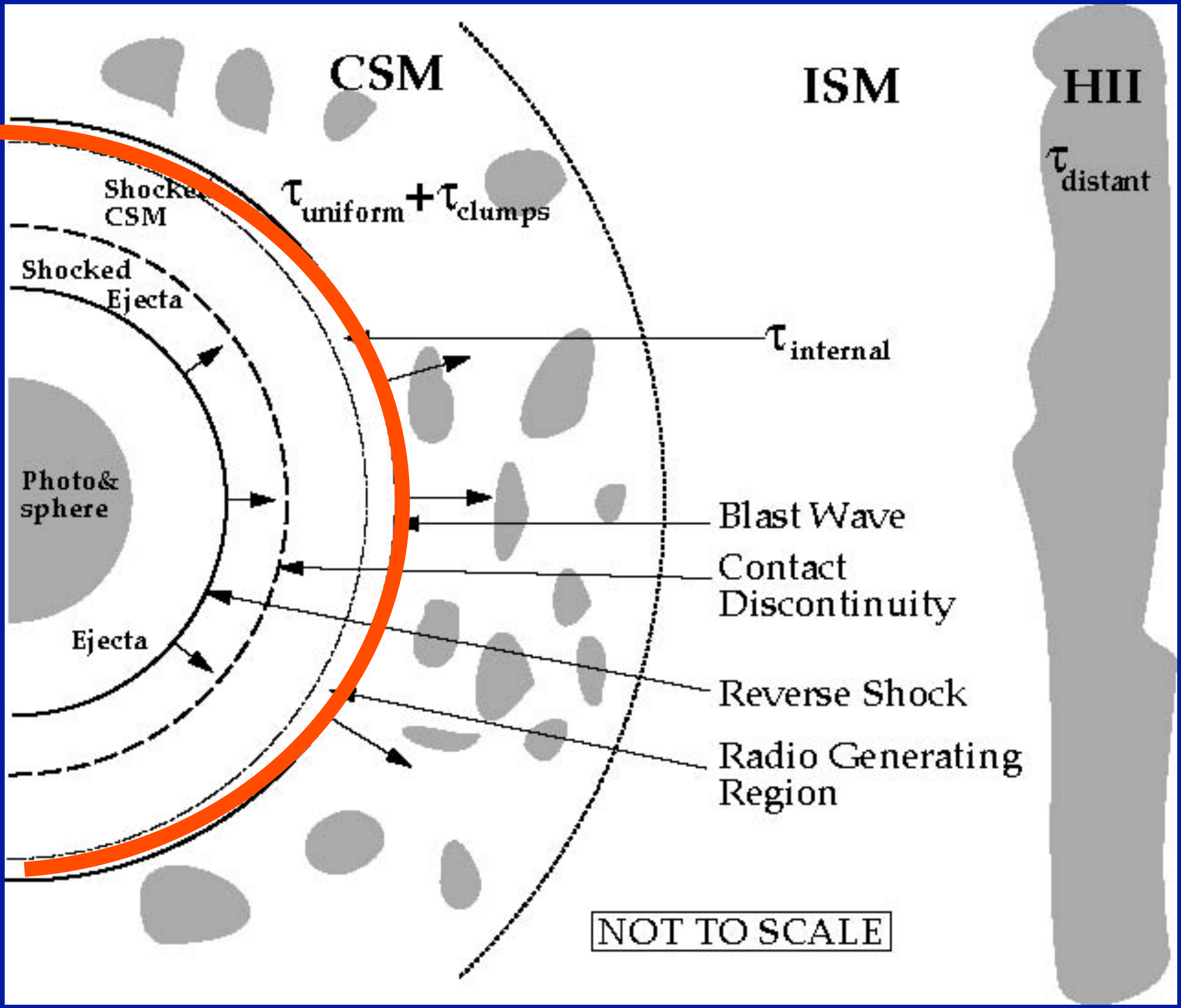
~ 2500

Why Radio-SNe?



There exists a large gap in time between the oldest SNe observed in the last decades and the youngest SNRs such as Cas A (~ 1680) . Bridging this gap, will allow to understand the progenitor and SNR evolution, the interaction with the CSM, to asses their energy and chemical input into the ISM. The SKA would allow detection of dozens of old SNe (i.e. very young SN remnants) which may still be radio emitters, but are below the current sensitivity limit.

SN-CSM Interaction



The relativistic e- and the magnetic field necessary for synchrotron emission arise from the SN blastwave interacting with a high density CSM which has been ionized and heated by the initial X/UV flash. The CSM density decreases as an inverse power of the radius : $\rho_{CSM} \sim$ M_dot / v(wind) x r^{-s} For a constant mass loss rate and constant wind, s=2

Chevalier 1982, 84 Chevalier & Fransson 1994

Modeling Equations (1)

Weiler et al. 1986, 2002; Montes et al. 1997

$$S(\mathrm{mJy}) = K_1 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha} \left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\beta} e^{-\tau_{\mathrm{external}}} \left(\frac{1 - e^{-\tau_{\mathrm{CSM_{clumps}}}}}{\tau_{\mathrm{CSM_{clumps}}}}\right) \left(\frac{1 - e^{-\tau_{\mathrm{internal}}}}{\tau_{\mathrm{internal}}}\right)$$

External Absorption: Uniform & Distant

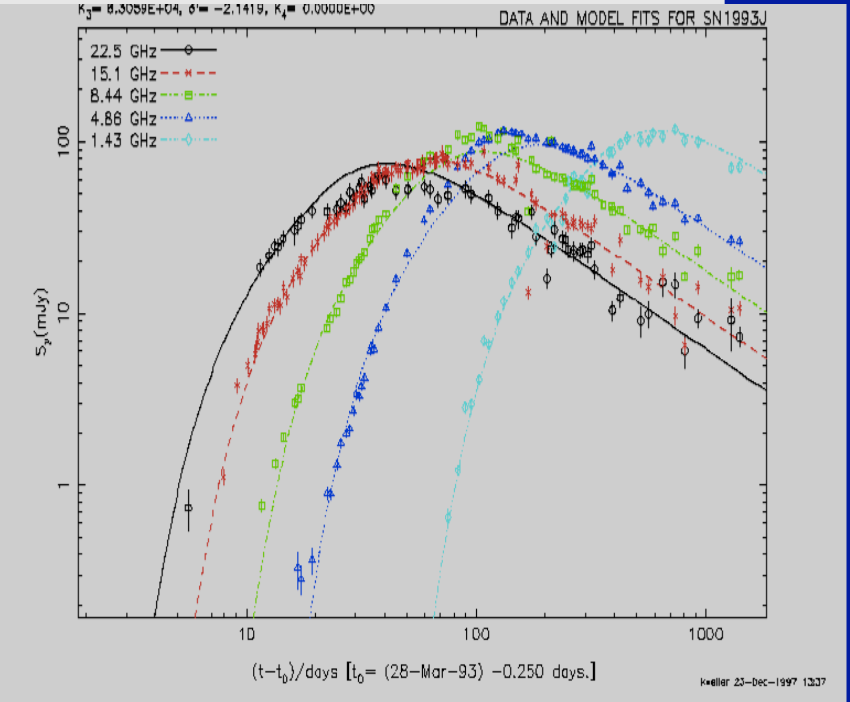
$$\tau_{\mathrm{external}} = \tau_{\mathrm{CSM_{uniform}}} + \tau_{\mathrm{distant}}$$

$$\tau_{\mathrm{CSM_{uniform}}} = \tau = K_2 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1} \left(\frac{t -}{1\ \mathrm{d}}\right.$$

$$\tau_{\mathrm{distant}} = \tau'' = K_4 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}$$

External Absorption: Clumpy or Filamentar

$$\tau_{\mathrm{CSM_{clumps}}} = K_3 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1} \left(\frac{t - t_0}{1\ \mathrm{day}}\right.$$



Modeling Equations (2)

Internal Absorption: SSA & Mixed f-f Absorption/Nonthermal Emission

$$\tau_{\text{internal}} = \tau_{\text{internal}_{\text{SSA}}} + \tau_{\text{internal}_{\text{ff}}}$$

$$\tau_{\text{internal}_{\text{SSA}}} = K_5 \left(\frac{\nu}{5\ \text{GHz}}\right)^{\alpha-2.5} \left(\frac{t-t_0}{1\ \text{day}}\right)^{\delta''}$$

$$\tau_{\text{internal}_{\text{ff}}} = K_6 \left(\frac{\nu}{5\ \text{GHz}}\right)^{-2.1} \left(\frac{t-t_0}{1\ \text{day}}\right)^{\delta'''}$$

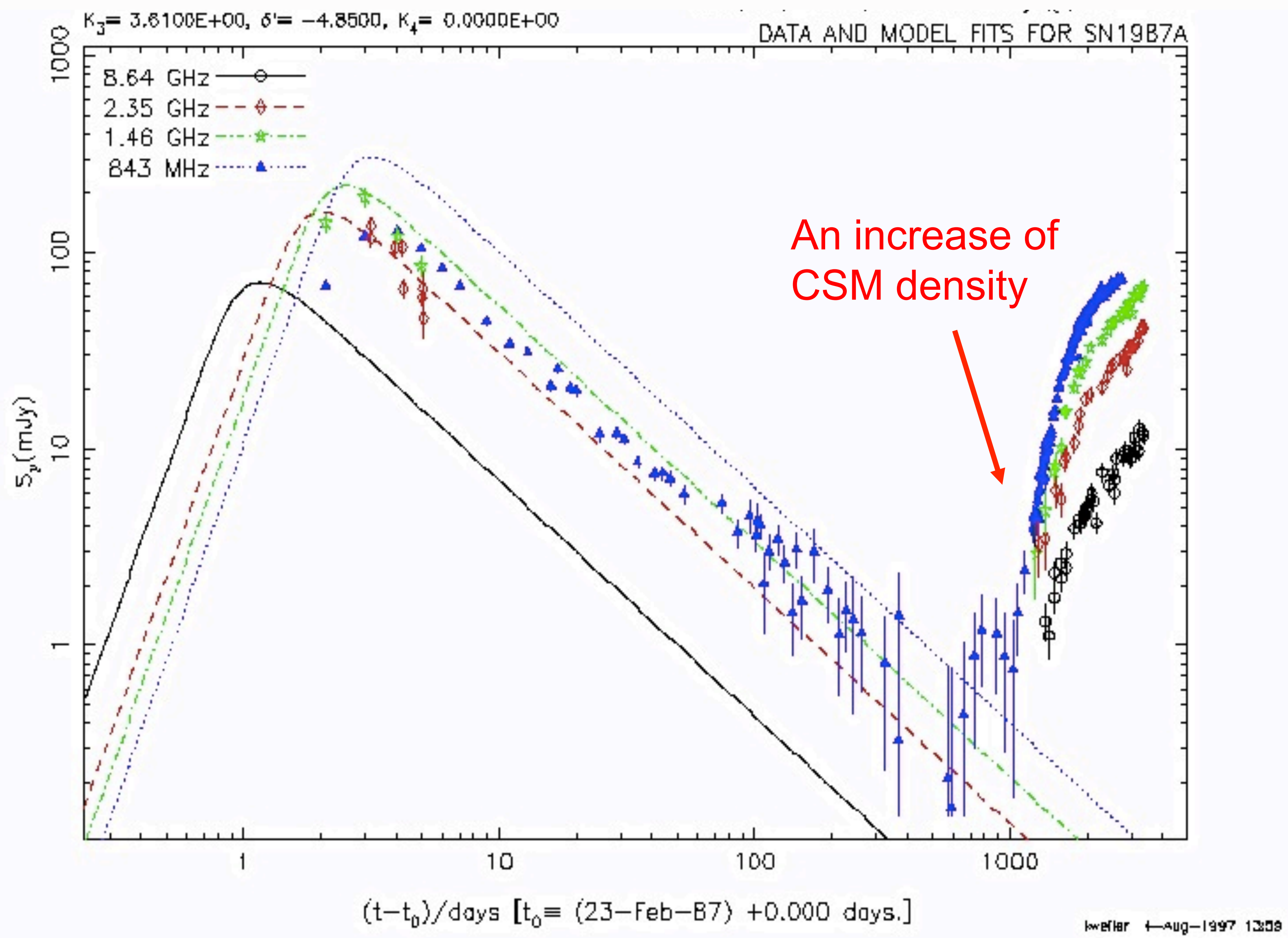
Circumstellar Interaction: Estimation of progenitor’s mass-loss rate

$$\frac{\dot{M}\,(M_\odot\,\mathrm{yr}^{-1})}{(w_\mathrm{wind}/10\ \mathrm{km\ s}^{-1})} = 3.0\times10^{-6} < \tau_\mathrm{eff}^{0.5} > m^{-1.5}\left(\frac{v_\mathrm{i}}{10^4\ \mathrm{km\ s}^{-1}}\right)^{1.5}\times \left(\frac{t_\mathrm{i}}{45\ \mathrm{days}}\right)^{1.5}\left(\frac{t}{t_\mathrm{i}}\right)^{1.5m}\left(\frac{T}{10^4\ \mathrm{K}}\right)^{0.68}\ \phi$$

(Weiler et al. 1986, 1990, 2002, 2007)

$r \sim t^m \quad m<1$

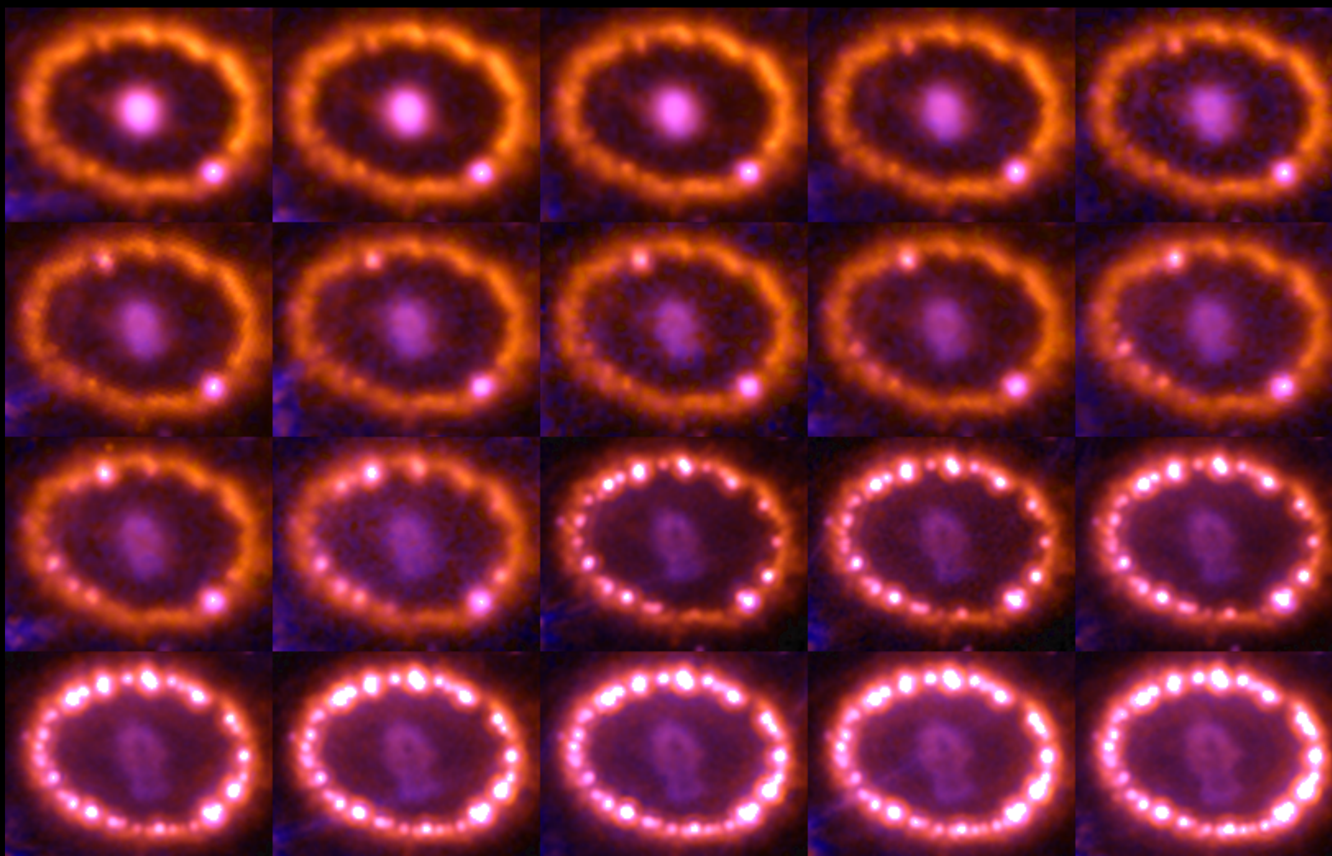
SN1987A


K3= 3.6100E+00, δ'= −4.8500, K4= 0.0000E+00
DATA AND MODEL FITS FOR SN1987A
8.64 GHz
2.35 GHz
1.46 GHz
843 MHz
An increase of
CSM density
Sν(mJy)
1000
100
10
1
1
10
100
1000
(t−t0)/days [t0≡ (23−Feb−87) +0.000 days.]

10 years later the ring started lighting up…

An earlier ejection about 20,000 years before explosion

1996



2006

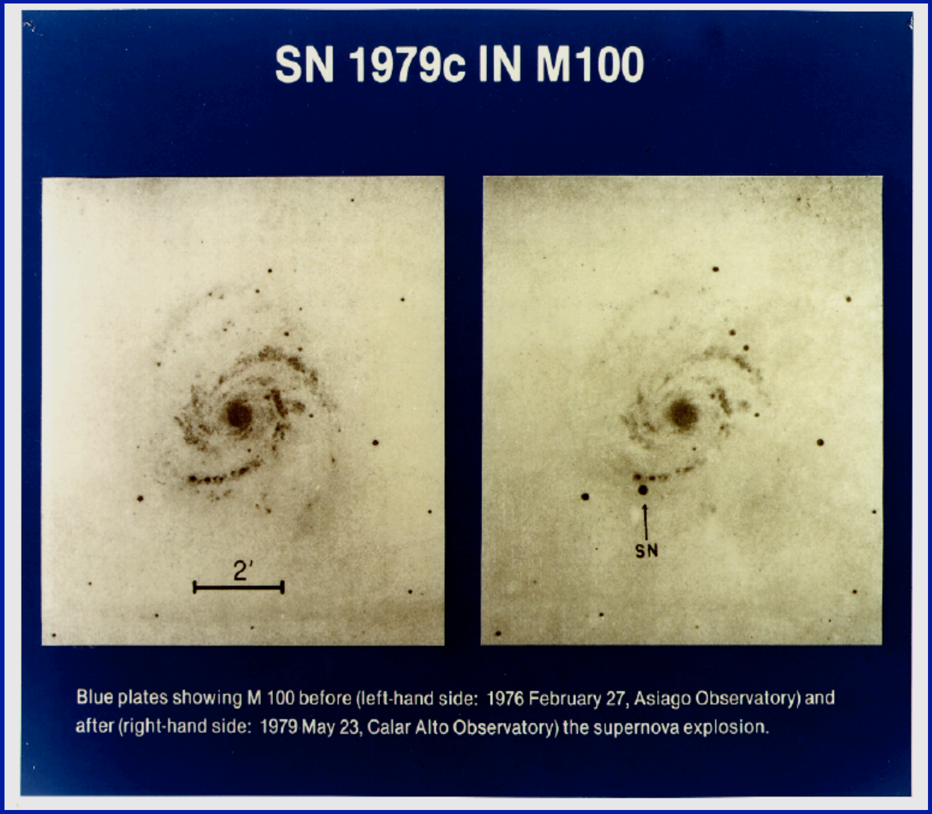
More than 20 spots now seen to brighten, due to the collision of the ejecta with the central ring.

Over the next decades, as the entire ring will light up, the Evolutionary history of the star's mass loss will be revealed

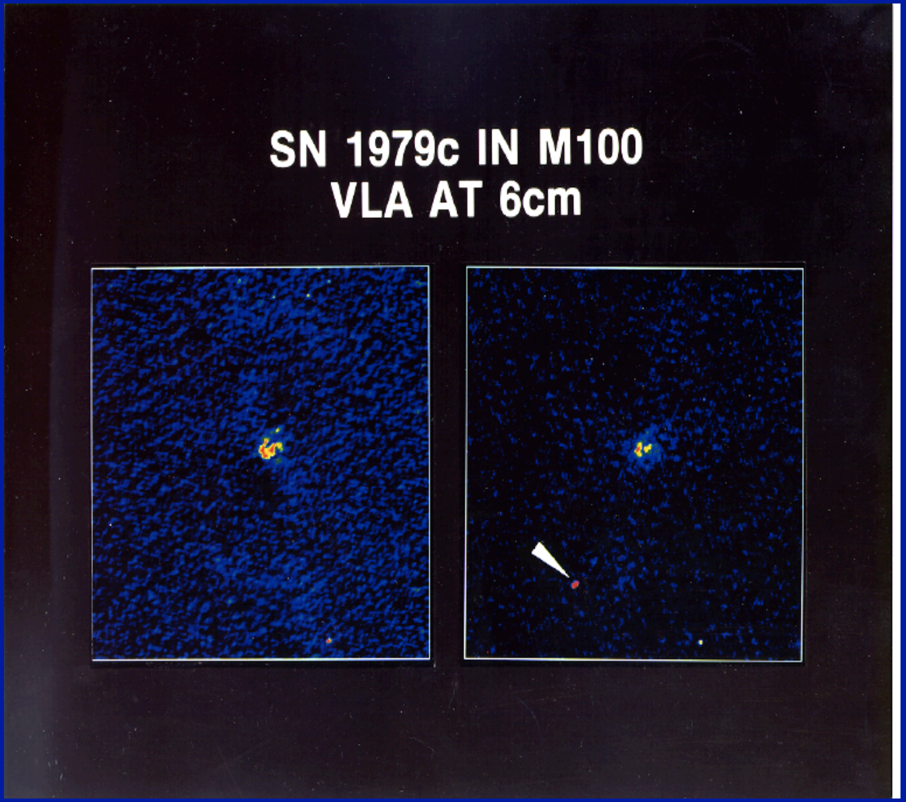
Type IIL

Optical/Radio SN1979C

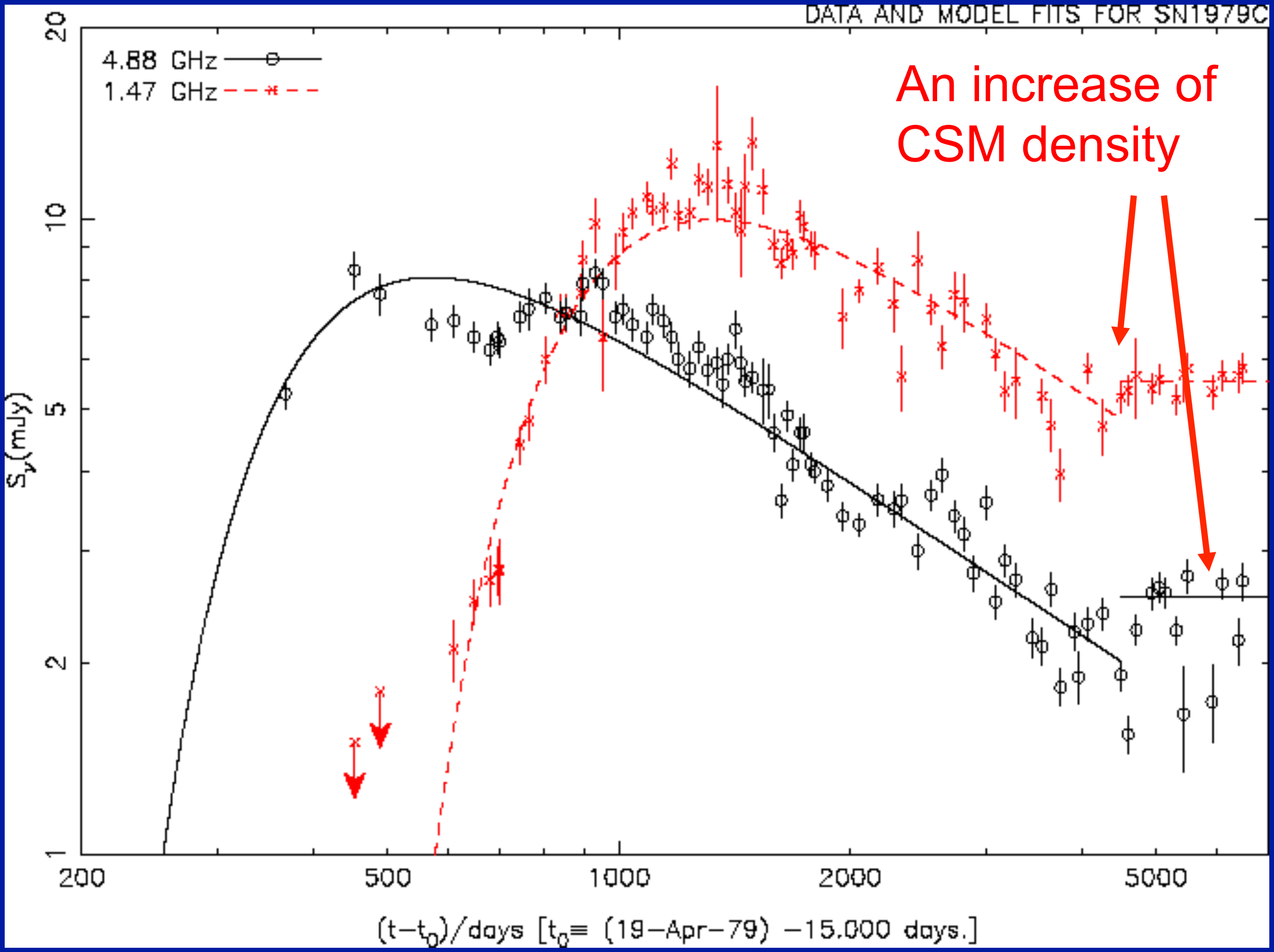
- Optical



- Radio



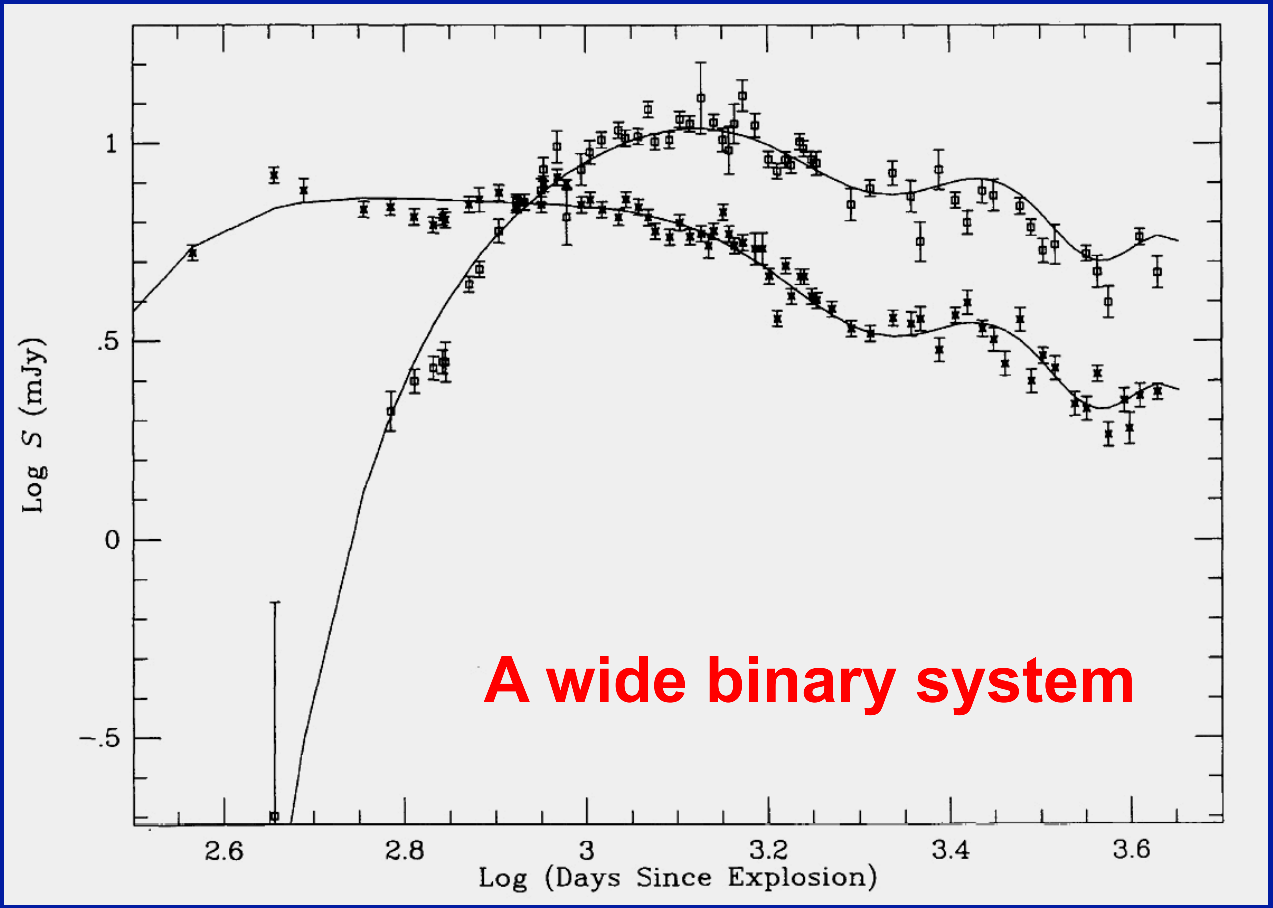
SN1979C: Twenty Years of Observations

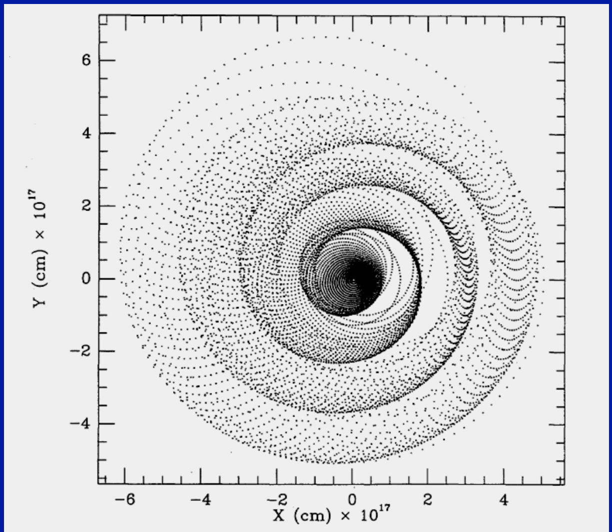


About 20,000 years before exploding the progenitor ejected a discrete shell?

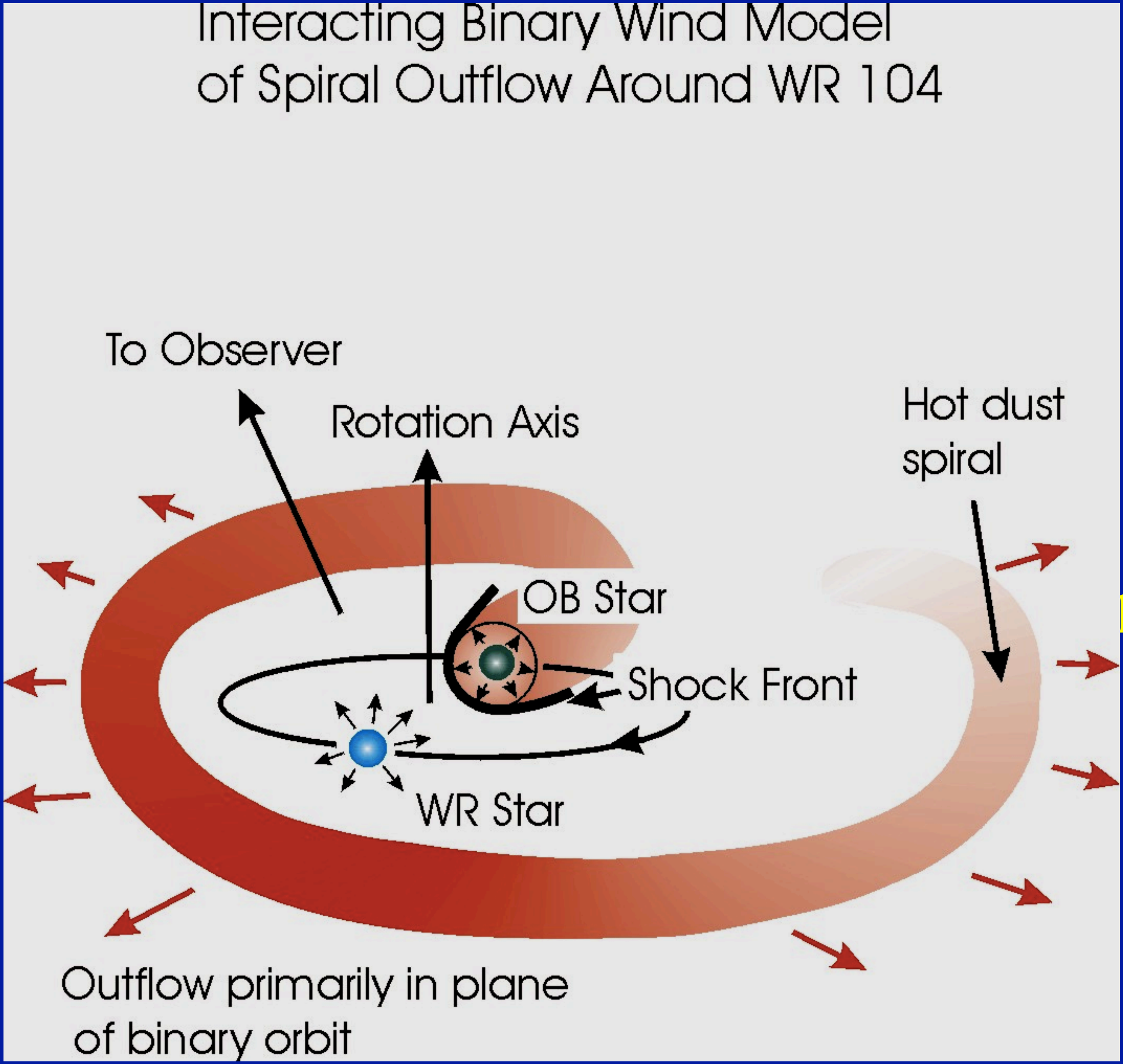
Pulsational instability?

SN 1979C: A Sinusoidal Fit





Spiral pattern expected for a binary system including 15 and 10 $M_\odot$ stars that are orbting around each other with a period of ~5000 days


Interacting Binary Wind Model
of Spiral Outflow Around WR 104
To Observer
Rotation Axis
Hot dust
spiral
OB Star
Shock Front
WR Star
Outflow primarily in plane
of binary orbit

1.

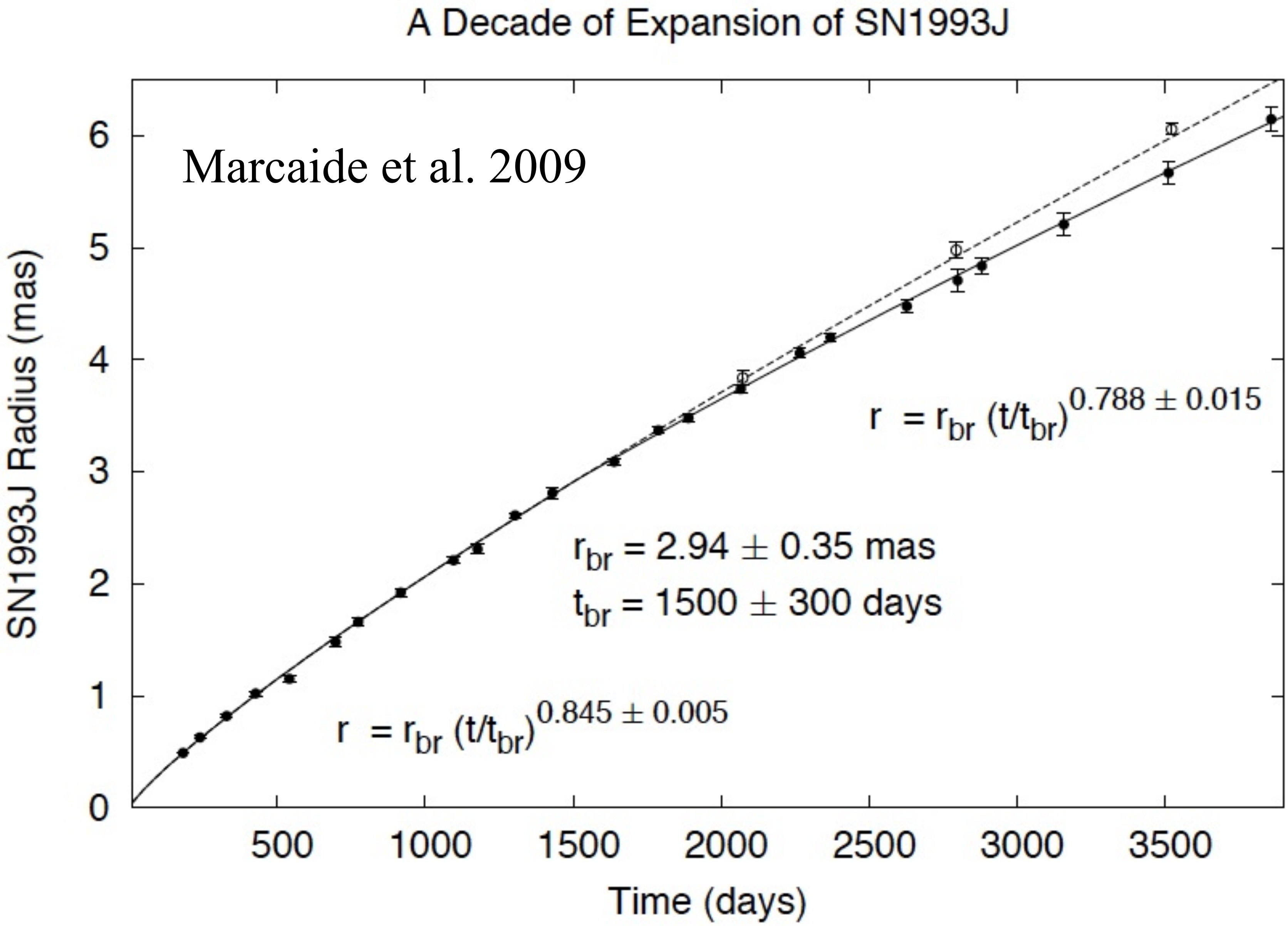
Why Radio-SNe? cont'd

Distances:

- Radio observations of the blastwave + optical spectroscopic observations → indipendent distance measurements

A Decade of Expansion of SN1993J

J.M. Marcaide, A. Alberdi,
I. Martí-Vidal, E. Ros, et al.



+ assumptions of symmetry and optical/radio line velocities allows independent distance estimates to be made (e.g. Bartel et al. 1985)

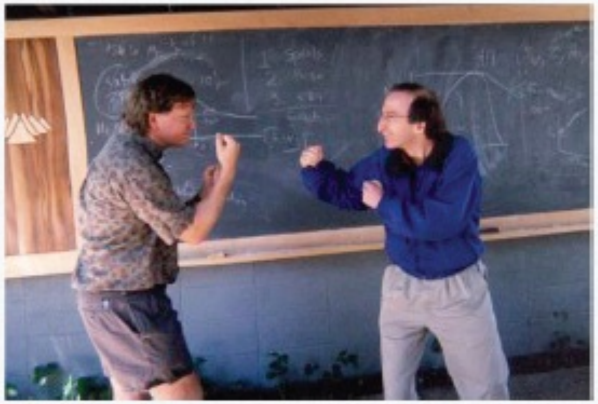
The need for the SKA

Type Ia Supernovae

"The fact that we do not know yet what are the progenitor systems of some of the most dramatic explosions in the universe has become a major embarrassment and one of the key unresolved problems in stellar evolution".

M. Livio (2000)

40 years and counting



- Despite SNe Ia are used for "precision cosmology"*, the nature of the progenitor system[s] is still unknown.

most papers on Ia progenitors start with a similar sentence

*"precision ignorance" (Lazio's talk)

VLA Observations of SNIa

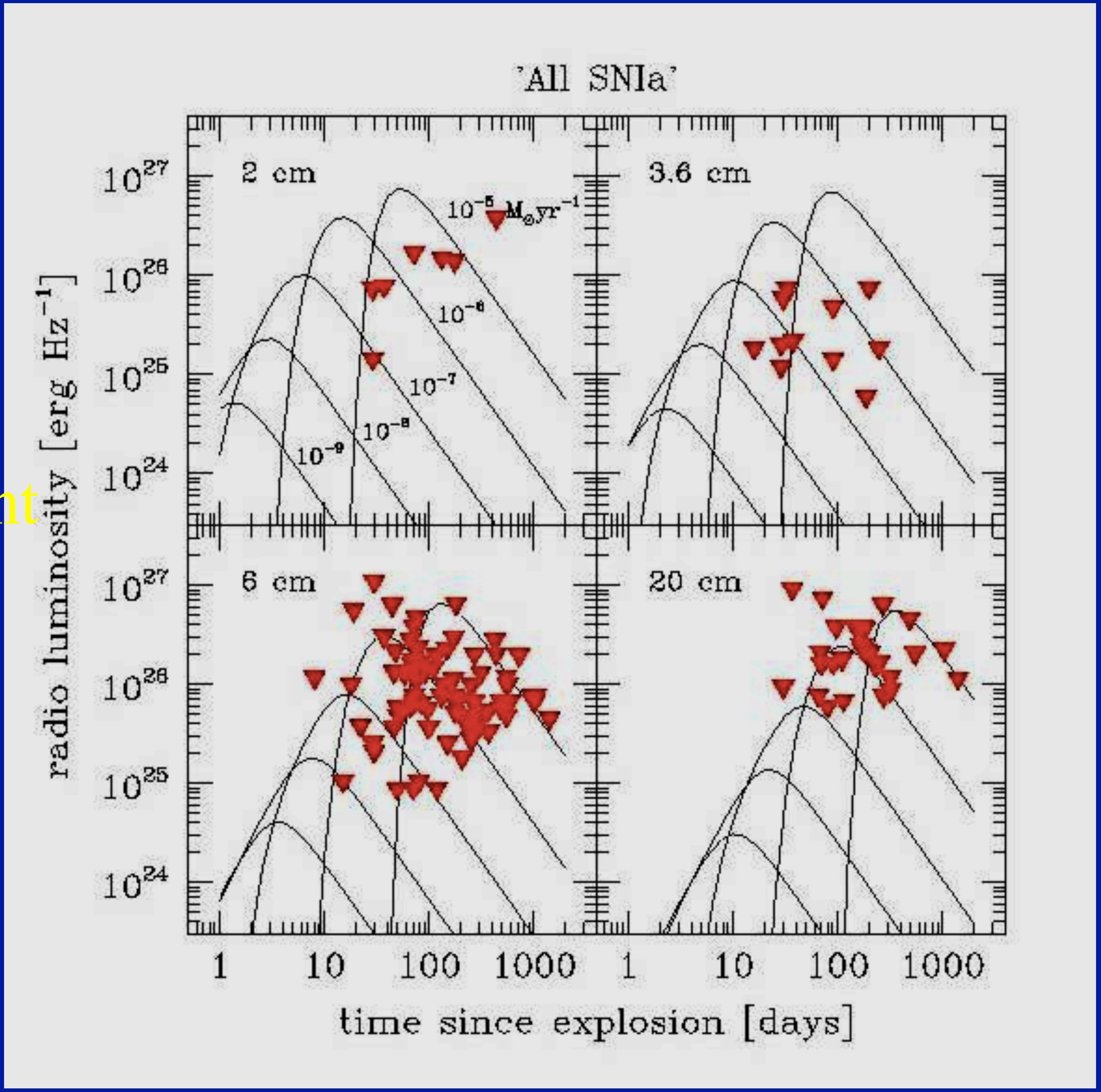
Panagia et al 2006

- Observed **27 SNIa** over 24 years of monitoring

- **NO** detection

All SNIa at once

The most stringent
upper limit
is about
3×10^{-8} $M_\odot$ yr^{-1}

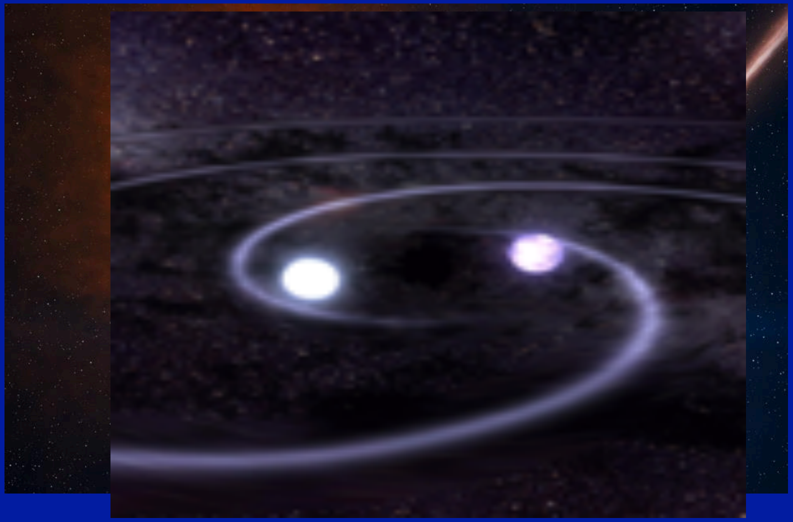


Supernovae Ia

- No SN Ia has been detected so far in the radio, implying a very low density for any possible circumstellar material established by the progenitor system, before explosion. Current upper limits to a steady mass-loss rate for individual SN systems as low ~ $3\times10^{-8}\ M_{\odot}\ yr^{-1}$.
  → no symbiotics

- ~ $10^{-9}\ M_{\odot}\ yr^{-1}$ → CVs

- < $10^{-10}\ M_{\odot}\ yr^{-1}$ → DD

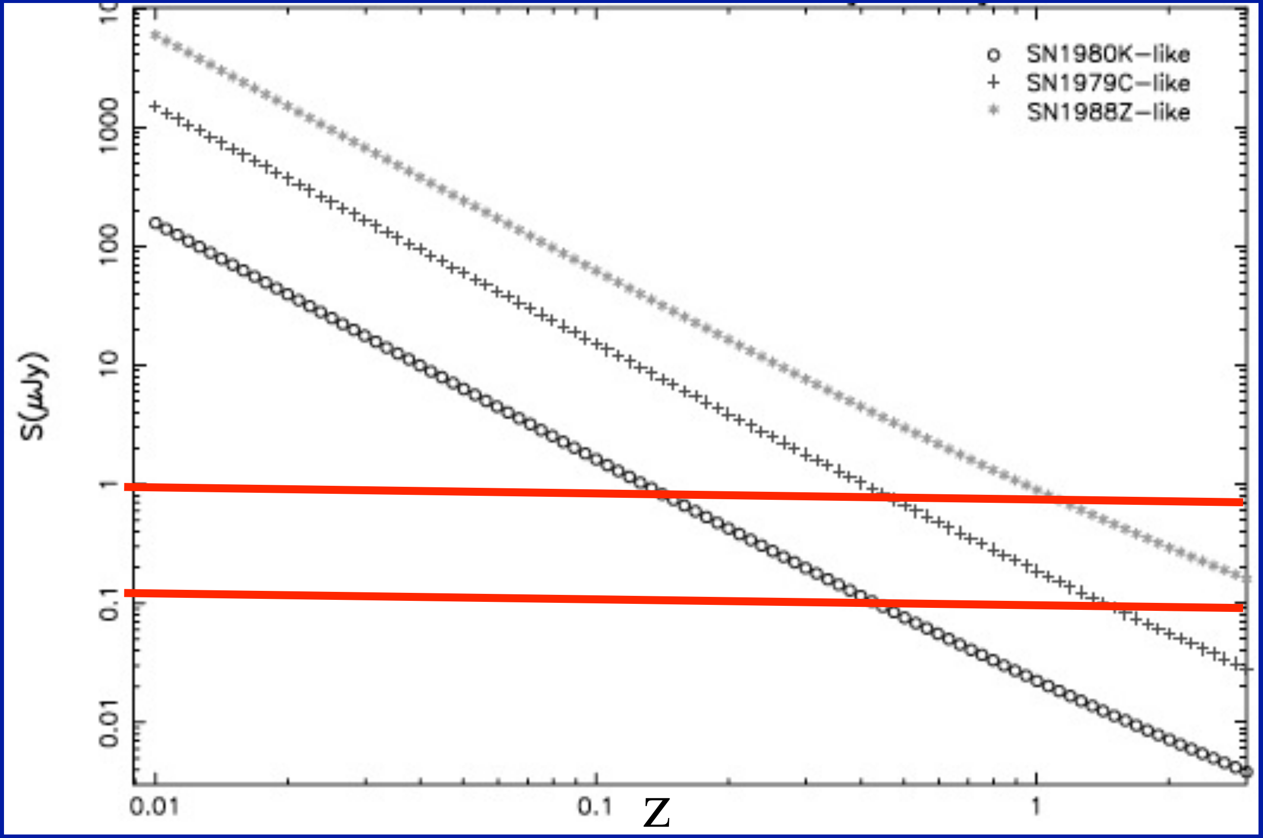


Supernovae II

Supernovae II

Radio observations of SNe-II are strongly biased due to large differences in the radio lumninosity of CC- SNe. SN 1987A and SN 1993J could be detected in radio because they were nearby. “Standard” events, like SN 1980K (10^{26} erg s^{-1} Hz^{-1} at 6 cm), can be observed to Virgo distance. The ultra luminous 1988Z-like (~10^{28} erg s^{-1} Hz^{-1} at 6 cm) objects up to 100 Mpc.

Supernovae II



With an improved sensitivity level of 1μJy, one can detect the brightest of RSNe, such as the Type IIn SN 1988Z at the cosmologically interesting distance of z = 1 and at a sensitivity level of 0.1 μJy one can even study more normal Type II RSNe, such as SNe 1979C and 1980K, at such cosmologically interesting distances.

Z

Supernovae Ib/c

GRB-SN census (z < 0.3)

GRB	SN	z	Ref.
GRB 980425	SN 1998bw	0.0085	Galama et al. 1998
GRB 030323	SN 2003dh	0.16	Hjorth et al. 2003 Stanek et al. 2003
GRB 031203	SN 2003lw	0.11	Malesani et al. 2004
GRB 060218	SN 2006aj	0.033	Campana et al. 2006 Pian et al. 2006
GRB 080109	SN 2008D	0.007	Soderberg et al. 2008 Mazzali et al. 2008
GRB 100316D	SN 2010bh	0.06	Chornoch et al., Bufano et al., Starling et al. 2011
GRB 120422A	SN 2012bz	0.28	Melandri et al. 2012

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GRB 120422A	**SN 2012bz**	**0.28**	**Melandri et al. 2012**

GRB-SN census (z > 0.3)

GRB	SN	z	Ref.
GRB 021202	SN 2002lt	1.002	Della Valle et al. 2003
GRB 050525A	SN 2005nc	0.606	Della Valle et al. 2006
GRB 081007	SN 2008hw	0.53	Della Valle et al. 2008
GRB 091127	SN 2009nz	0.49	Cobb et al. 2010 Berger et al. 2011
GRB 101219B	SN 2010ma	0.55	Sparre et al. 2011
GRB 060729	SN ?	0.54	Cano et al. 2011
GRB 090618	SN ?	0.54	Cano et al. 2011

A relativi ... ted

γ−ray bur

A. M. ... ata[3],

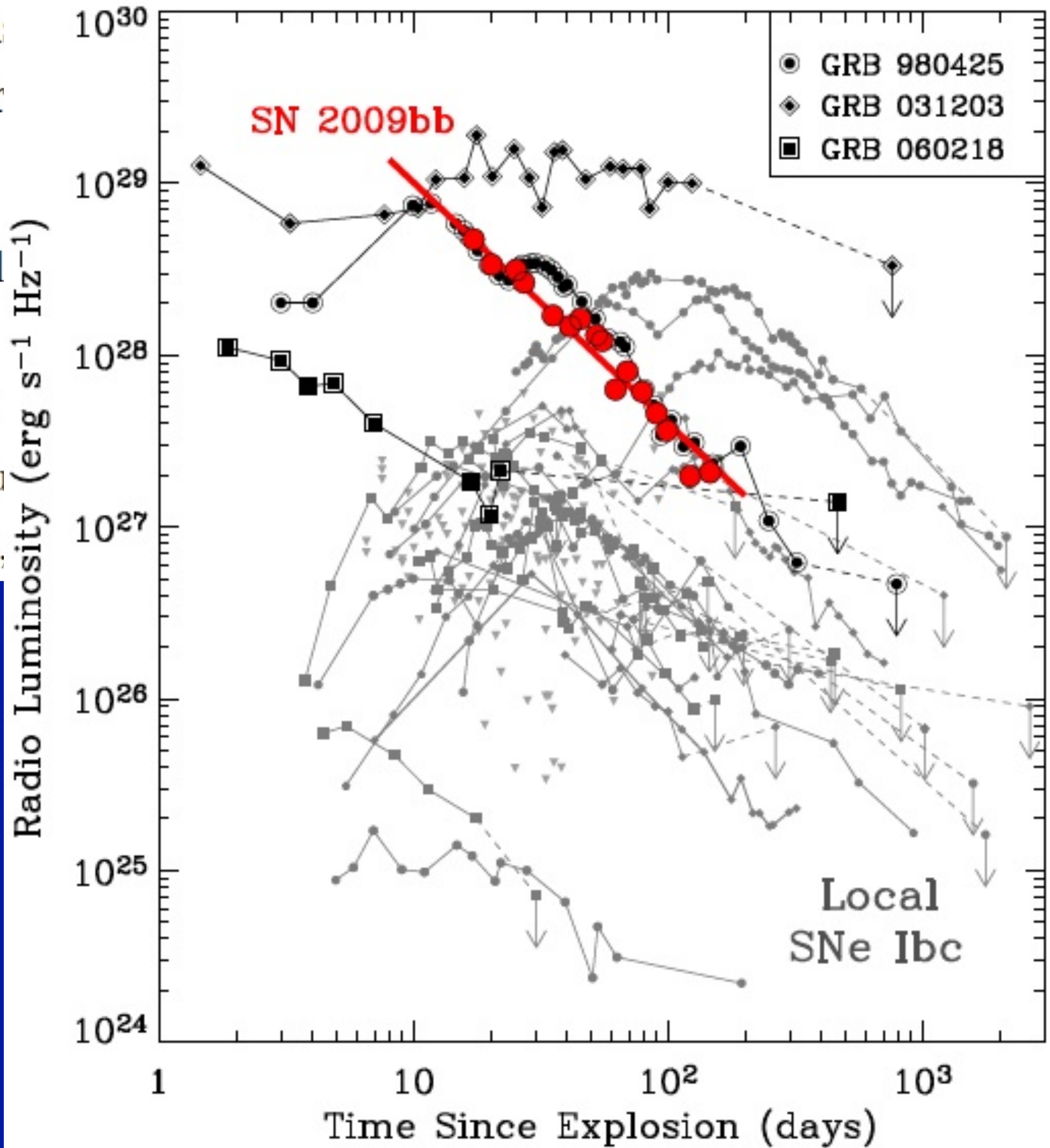
R. A. Cheval ... ete[1],

V. Chaplin[7], ... [9,10],

N. Chugai[11], ... ox[4],

E. M. Levesqu ... ner[1],

P. A. Milne[16],



Improving Supernovae II and Ibc rates

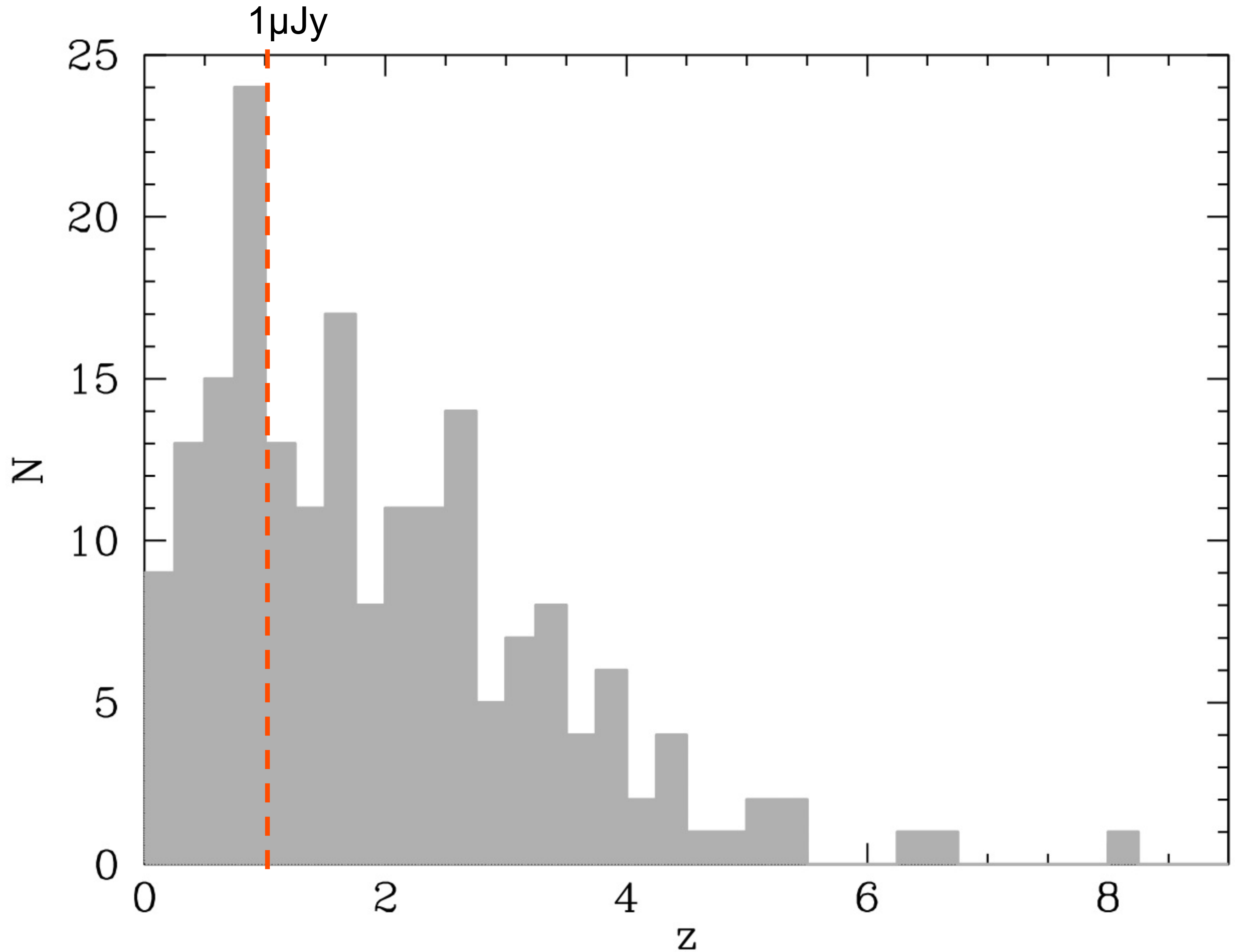
Radio observations of SNe –II and -Ibc suffer of similar bias. Most SNe are discovered during optical surveys. However extinction and proximity to the nuclei of the galaxies can led to “hidden” SNe which are missed by present surveys (it might be >70% ; Maiolino et al. 2002 Mannucci et al., 2003; Mattila et al., 2004; Cresci et al., 2007)

Following the long term radio evolution after peak flux density allows to describe the structure of the CSM and to detect (and classify) the SN type.

Gamma-Ray Bursts

Gamma-Ray Bursts

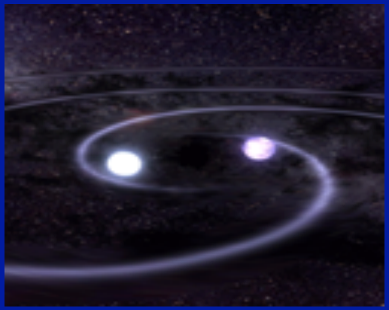
For GRBs, the narrowness of the relativistic jets ($4\text{-}5^{o}$ up to $\sim 20^{o}$), which give rise to γ-ray and X-ray bursts, implies that most outbursts are missed. The more isotropic radio emission coupled with the SKA sensitivity will increase dramatically the number of direct detections of GRBs, then yielding an independent measurement of the frequency of occurrence of GRBs.



10^{-4} < GRB/SNe-Ibc < 3×10^{-2} Guetta & DV 2007

Synergy with LIGO-VIRGO

Binary systems have provided indirect detection of gravitational waves



SKA could find an array of binary systems that could be used to search for gravitational waves in synergy with LIGO-VIRGO GWs detectors

Bower, G.C., et al., 2007, ApJ, 666, 346
Nakar, E., & Piran, T., 2011, Nature, 82, 478

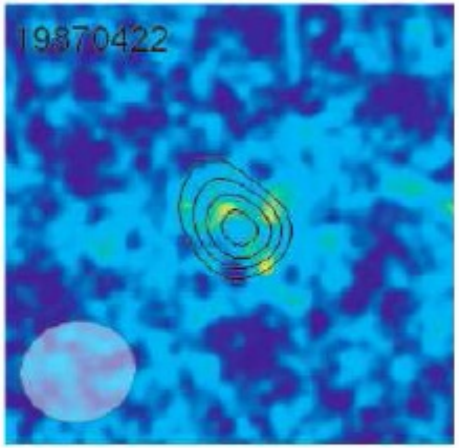
RT 19870422

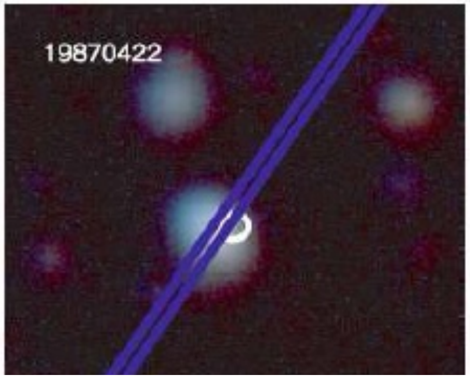
RT 19870422 at 5 GHz, 1 Gpc

2 month long-duration extragalactic event

low-density host environment inferred from optically thin synchrotron emission (> 1 GHz)

Candidate source: Radio-afterglow to a merger-induced GRB event (NS/NS or NS/BH coalescence)





NS-NS mergers can launch subrelativistic outflows. The interaction with CSM produce radio-flares with peak emission at 1.4GHz that persists at μJy level for days/weeks at $z < 1$ (see Nakar & Piran 2011)

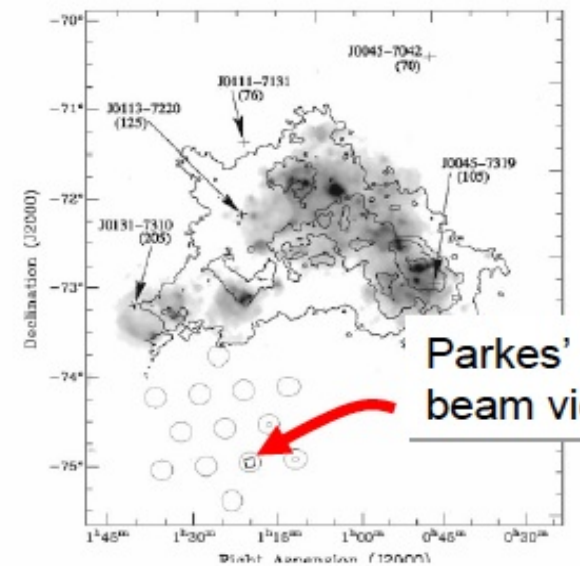
Lorimer, D., et al., 2007, Science, 318, 777
Van Putten, M.H.P.M., 2001, Phys. Rev. Lett., 2001, 87, 091101

PARKES' 2007 short radio burst

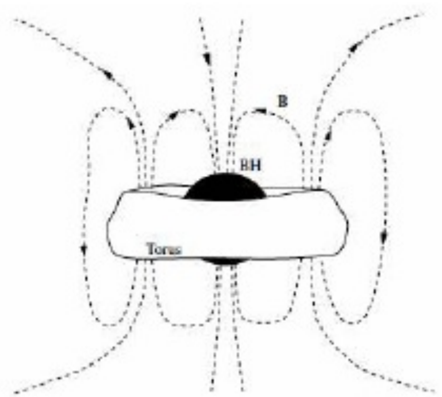
RT of 5 ms at 1.4 GHz, z~0.1

short-duration extragalactic event

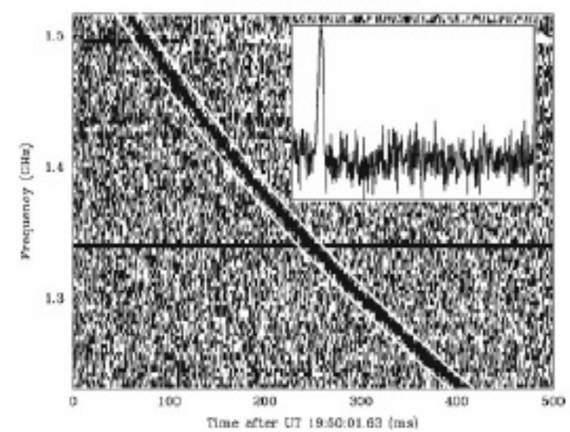
Candidate source: hyper-accreting magnetized high-density disk or torus around a slowly rotating BH: the "naked" inner engine of a short GRB following coalescence of a NS with a slowly rotating Kerr BH



Parkes' 13 beam view



van Putten & Della Valle



Conclusions

- **Transition RSNe to SNRs:** Little is left of the progenitor star after the explosion. Without direct information (e.g. 1987A) about the progenitors, examination of the SN environment is the only way to constrain –on empirical grounds-- ages and masses of the progenitors. From (current) 2 radio detections/yr → ~ 50 detections/year (with SKA).

- **SNIa:** SKA has the potential to explore the M_dot values for a sample of ~ 10^3 SNe-Ia. M_dot measurements close to ~ 10^{-7} $M_{\odot}$ yr^{-1} would point toward SD progenitors. Low values of M_dot, close to 10^{-11} $M_{\odot}$ yr^{-1} or smaller would prove that SNe-Ia are produced in the detonation/deflagration of DD systems.

Conclusions cont'd

- **CC-SNII**: Because v_{wind} ~ 10 km/s and v_{shock} ~ 10^4 km/s, SKA will be a "time machine, which will allow to piece together the mass loss evolution of the SN progenitors (e.g. 1987A).
  - Clumpy CSM vs. uniform CSM
  - Evidence for pre-SN binary system wind collisions
  - Better SN rates, not limited by absorption or dust → better galaxy chemical evolution modeling.
  - Observations of CC-SNe up to z < 1:
    - i. direct probe of SF outside the Local Universe
    - ii. Radio distance measurements in the LU will allow H_o measurements independent of optical SN surveys. Measurements of the cosmological parameters, q_o or Ω may be possible.

Conclusions cont'd

- **GRB-SNe**:
  -- direct detections of GRB events without gamma trigger, via detection of the associated relativistic SN.
  -- direct measurement of the branching ratio GRB/Ibc, since the bias due to the beaming is alleviated at radio λ (current uncertainties about 3 orders of magnitudes → beaming)

- **Synergy with GWs detectors:** Mergers between NS + NS or BH + NS are strong sources of gravitational waves that emit also at radio wavelengths for days/weeks within the capability of **SKA** up to z <1. An electromagnetic signature that persisted for weeks after the GW event would strengthen any future claim of a detection of gravitational waves.