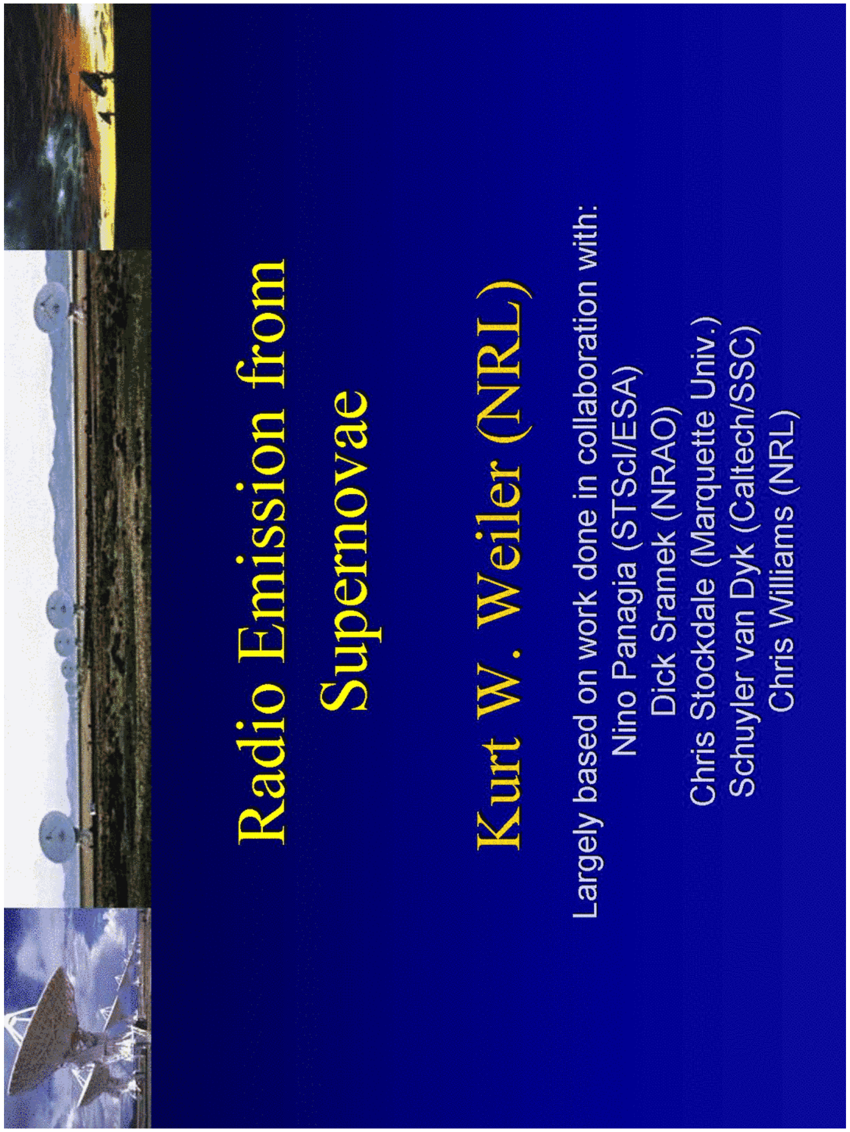
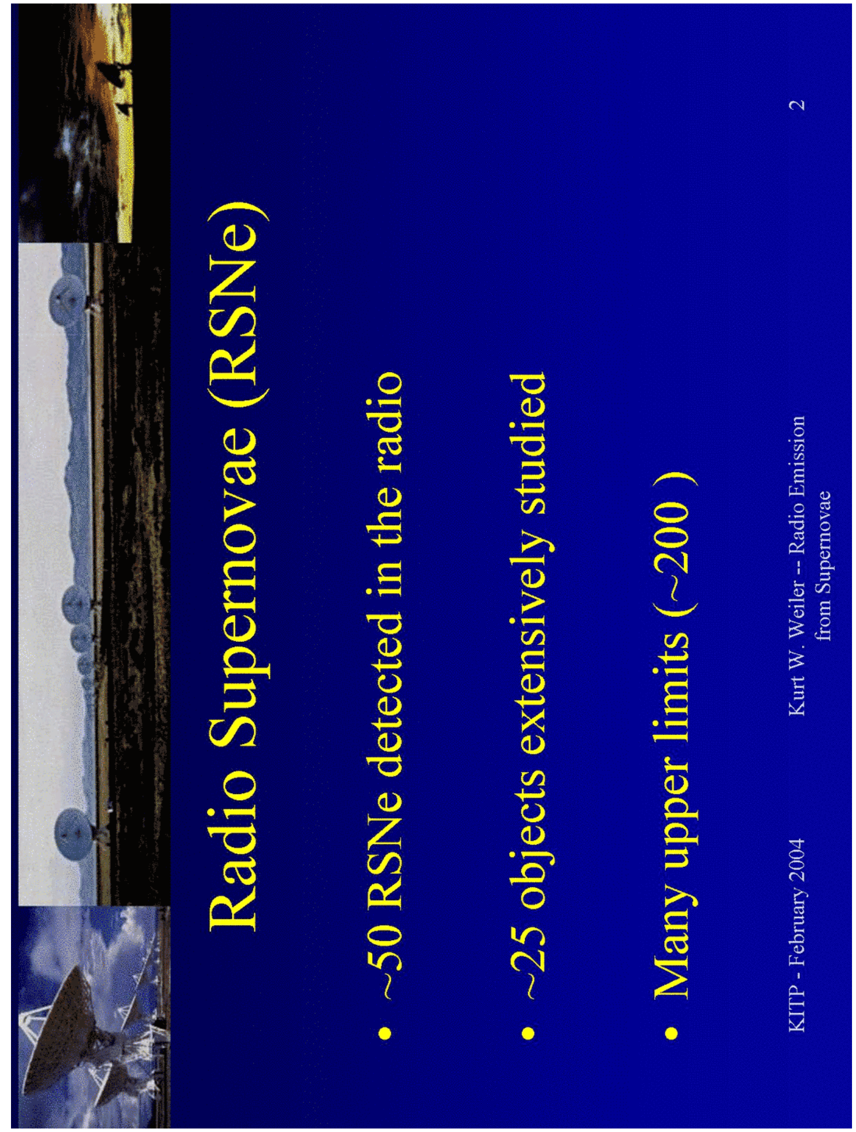

Radio Emission from
Supernovae
Kurt W. Weiler (NRL)
Largely based on work done in collaboration with:
Nino Panagia (STScI/ESA)
Dick Sramek (NRAO)
Chris Stockdale (Marquette Univ.)
Schuyler van Dyk (Caltech/SSC)
Chris Williams (NRL)


Radio Supernovae (RSNe)
• ~50 RSNe detected in the radio
• ~25 objects extensively studied
• Many upper limits (~200)
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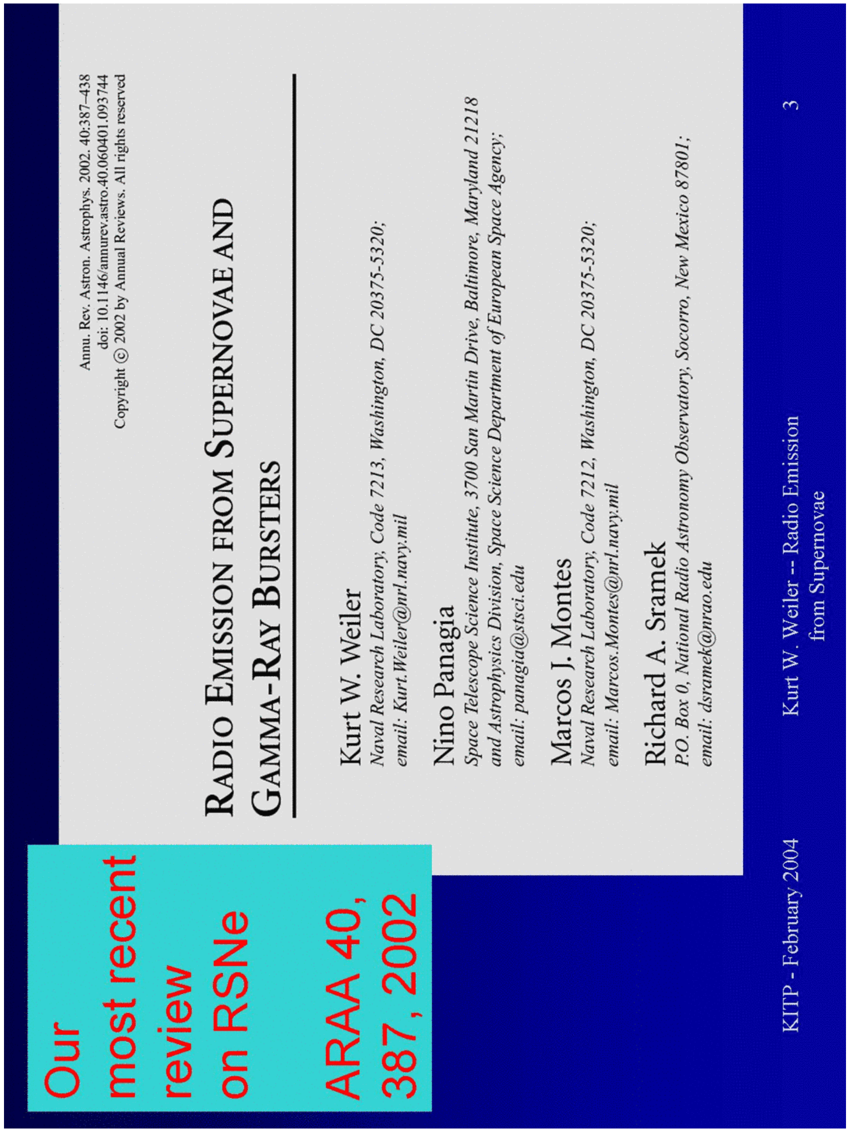
Annu. Rev. Astron. Astrophys. 2002. 40:387–438
doi: 10.1146/annurev.astro.40.060401.093744
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RADIO EMISSION FROM SUPERNOVAE AND GAMMA-RAY BURSTERS
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Richard A. Sramek
P.O. Box 0, National Radio Astronomy Observatory, Socorro, New Mexico 87801; email: dsramek@nrao.edu
Our most recent review on RSNe
ARAA 40, 387, 2002
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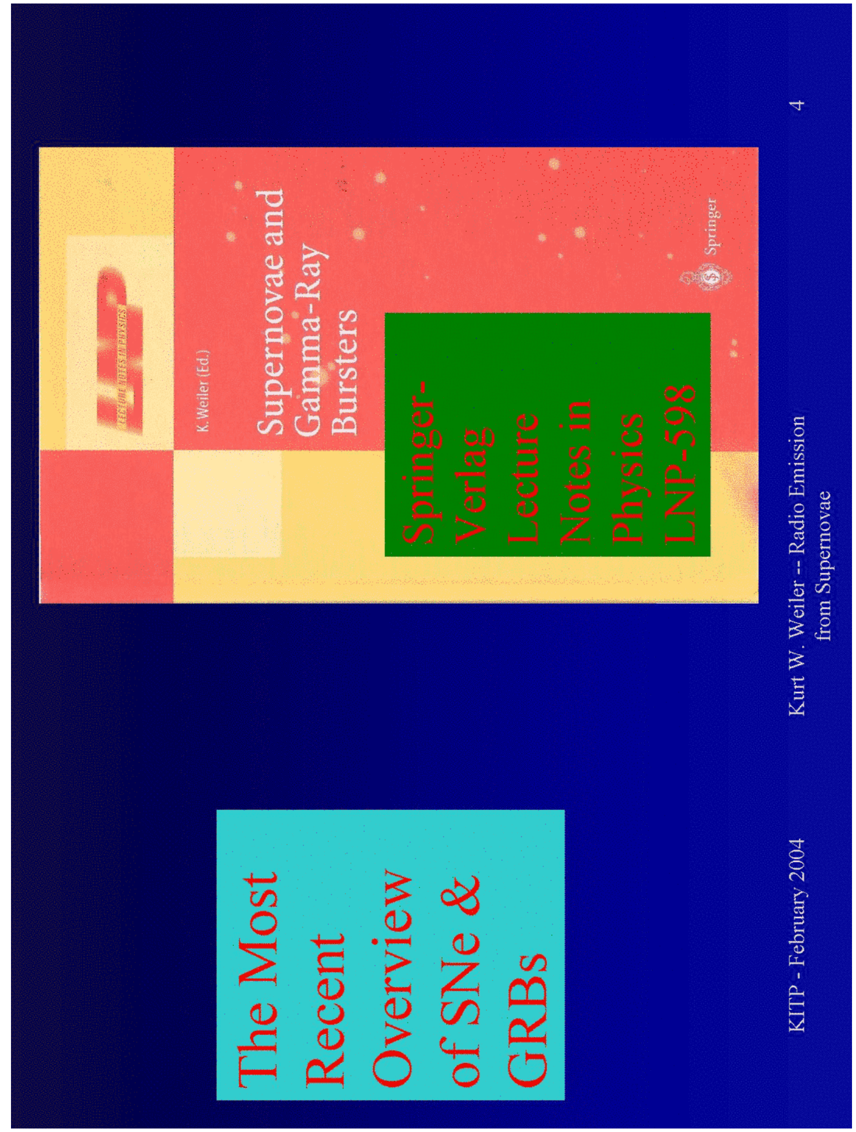
K. Weiler (Ed.)
Supernovae and Gamma-Ray Bursters
Springer
Springer-Verlag Lecture Notes in Physics LNP-598
The Most Recent Overview of SNe & GRBs
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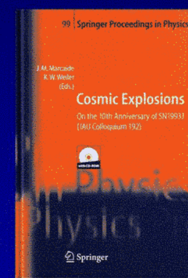
Two Recent Proceedings now Available

- Proceedings of the April 2003 meeting held in Valencia, Spain -- Cosmic Explosions: On the 10th Anniversary of SN 1993J
- Proceedings of the June 2004 meeting held in Padua, Italy – 1604 - 2004: Supernovae as Cosmological Lighthouses



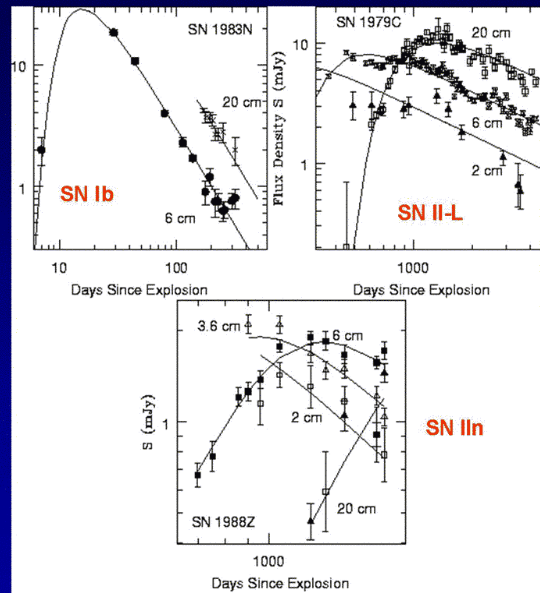
Why Study RSNe?

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

- Structure of the circumstellar medium
- Pre-explosion mass-loss rate and changes therein
- History of pre-SN evolution
- Nature of the progenitor

Radio Supernovae

- "Turn on", first at high ν, progressing to lower ν (decreasing absorption)
- Power-law decline after maximum at each ν
- Transition from "optically thick" spectral index α (where $S_\nu \sim \nu^{+\alpha}$) to an "optically thin" asymptotic value
- Nonthermal emission with very high T_B



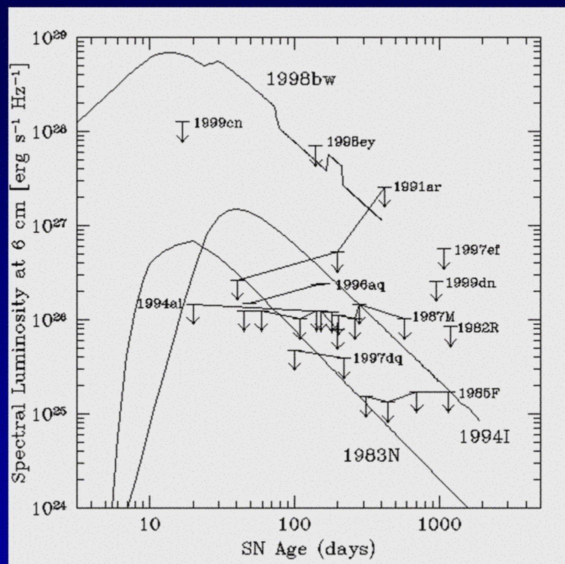
Comparison of RSNe & rGRBs

- Differences with "standard" RSNe
  - Interstellar scintillation (ISS)
  - Cosmological (z ~ 1)
  - Relativistic effects
- Higher mass-loss rates than normal Type Ib/c (but affected by assumptions)
- Much more radio luminous than normal Type Ib/c (but not if boosted by Γ ~ 10)
- Rare
- Type Ia and "Fast-Hard" GRBs still undetected

Type Ib/c Supernovae

GRB association is rare!

RADIO



<3% (Berger, etal. ApJ 599, 408 (2003))

[Van Dyk et al., 2006, in prep.]

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Standard Model Physical Parameters

[Chevalier ApJ, 259, 302, 1982]

- Red Supergiant (RSG) progenitor
- Slow (10 km s^{-1}), dense (10^{-6} - 10^{-4} $M_{\odot}$ yr^{-1}) wind
- $\rho \propto r^{-2}$ [$\rho \propto M_{dot}/(w_{wind}\ r^2)$] density profile
- Circumstellar Medium (CSM) ionized by SN UV/X-ray flash
- Relativistic electrons & enhanced magnetic field arise from shock/CSM interaction
- Ionized CSM provides free-free absorption *(f-f, FFA)*
- Synchrotron Self-Absorption (SSA) may play a role in some objects at early times

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Circumstellar Interaction

parameterized radio light curves

[Weiler et al. ARAA 40, 387, 2002]

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

$$\tau_{\mathrm{external}} = \tau_{\mathrm{CSMuniform}} + \tau_{\mathrm{distant}}$$

$$\tau_{\mathrm{CSM_{uniform}}} = \tau = K_2 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1} \left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\delta}$$

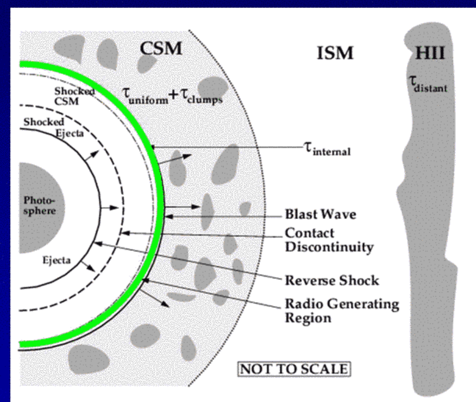
$$\tau_{\mathrm{distant}} = \tau'' = K_4 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}$$

$$\tau_{\mathrm{CSM_{clumps}}} = \tau' = K_3 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1} \left(\frac{t - t_0}{1\ \mathrm{day}}\right)^{\delta'}$$

$$\tau_{\mathrm{internal}} = \tau_{\mathrm{internalSSA}} + \tau_{\mathrm{internalFFA}}$$

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

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



K_2, K_3 = external, homogeneous and clumpy optical depth on day 1;

K_4 = external, distant optical depth;

K_5, K_6 = internal SSA and FFA optical depth on day 1

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Circumstellar Interaction

estimation of progenitor's mass-loss rate

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

Case 1: Absorption by a homogeneous external medium
Case 2: Absorption by a statistically large number of clumps or filaments
Case 3: Absorption by a statistically small number of clumps or filaments
(see Weiler et al. ARAA 40, 387, 2002)

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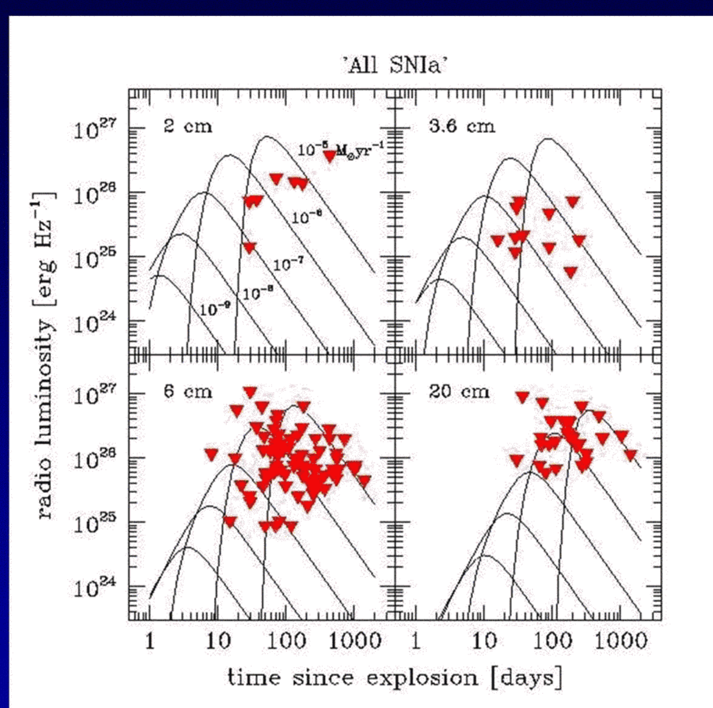
Derived Properties of RSNe

- Type Ia SNe never detected: very low pre-SN mass loss rates (<3 x 10^{-8} $M_{\odot}$ yr^{-1})
- Type II SNe -- slowly evolving radio emitters, with:
  - Flatter spectrum: α = > -1.0 (generally)
  - Slow decay: β = -0.7 -- -1.4
  - Mass loss rates 10^{-6} -- 10^{-4} $M_{\odot}$ yr^{-1}
  - Most how late time deviation from a smooth radio light curve
- Type Ib/c -- rapidly evolving radio emitters, with:
  - Steep spectrum: α = < -1.0 (generally)
  - Fast decay: β = -1.2 -- -1.6
  - Mass loss rates 10^{-7} -- 10^{-6} $M_{\odot}$ yr^{-1}
  - Associated (rarely) with GRBs
- Deviations from this "standard" picture are, of course, the most interesting

All SNIa at once

The lowest
2σ upper limit
is about
3×10^{-8} $M_{\odot}$ yr^{-1}



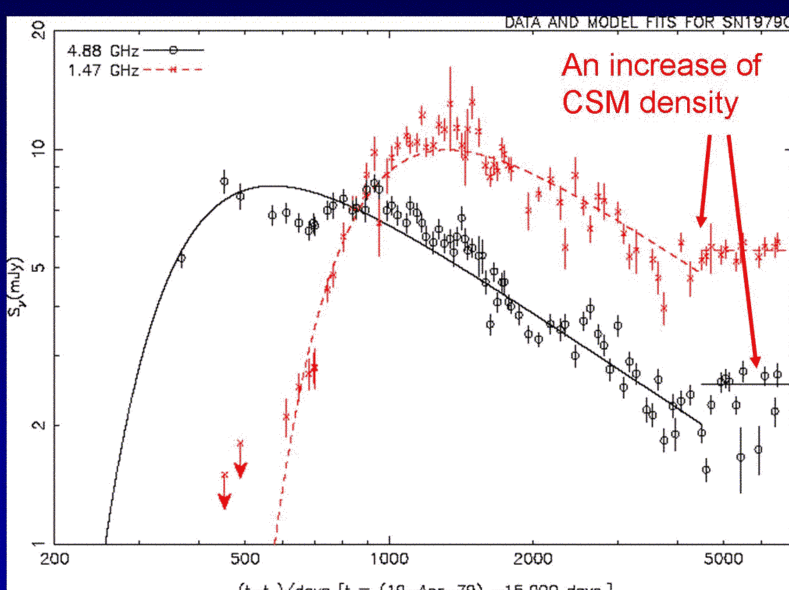
Constraints on SNIa Progenitors

The requirement that accretion rates higher than $10^{-7}\ M_{\odot}\ yr^{-1}$ are needed to make a WD mass exceed the Chandrasekhar mass and an upper limit to the mass loss rates $< 3 \times 10^{-8}\ M_{\odot}\ yr^{-1}$ implies:

- Single Degenerate Scenarios:
  - Rule out WD accretion via stellar wind from a massive binary companion in a symbiotic system
  - WD accretion from a relatively low mass companion via Roche lobe overflow is possible, but requires relatively high efficiency (>60 – 80%)
- Double Degenerate Scenario:
  - Not ruled out by the available upper limits

(Panagia et al., submitted)

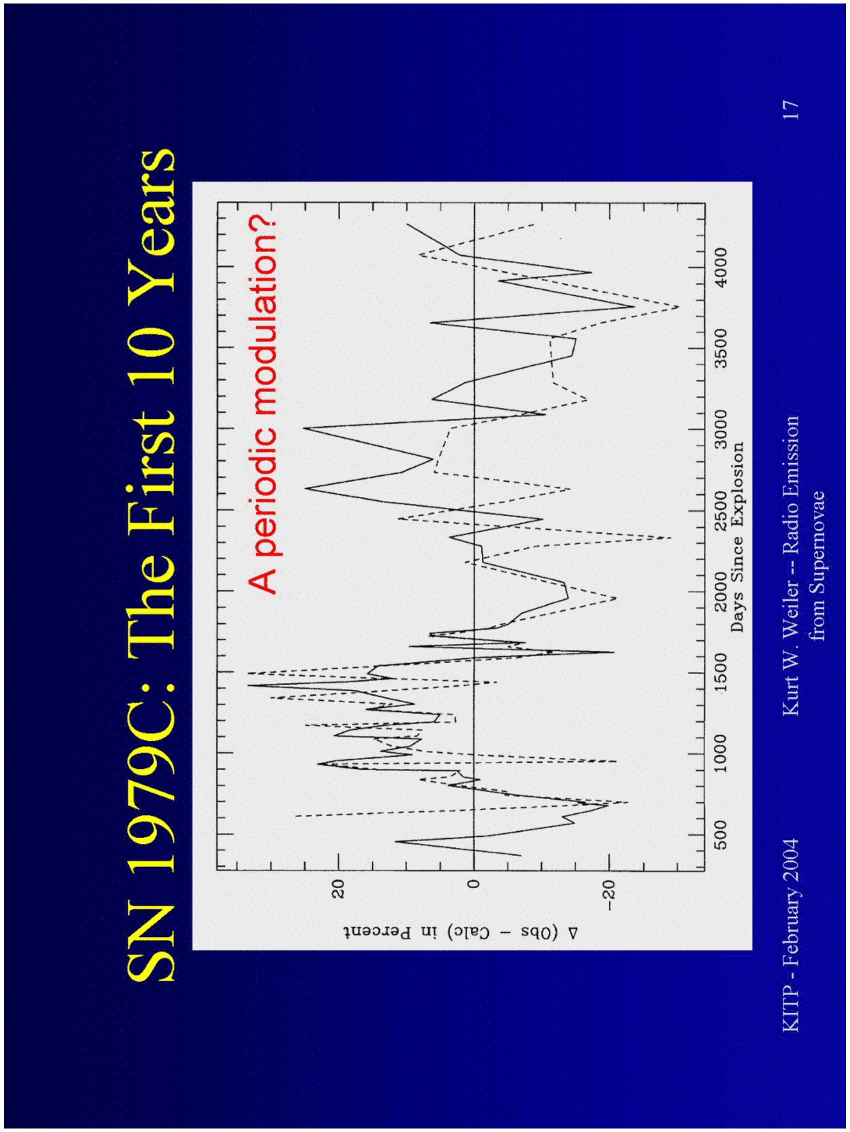
SN1979C: Twenty Years of Observations



About 10,000 years before exploding the progenitor ejected a discrete shell?

Pulsational instability?

Consistent with Immler etal. (ApJ 632, 283, 2005) constant X-ray emission since day ~5800.


SN 1979C: The First 10 Years
A periodic modulation?
Δ (Obs − Calc) in Percent
Days Since Explosion
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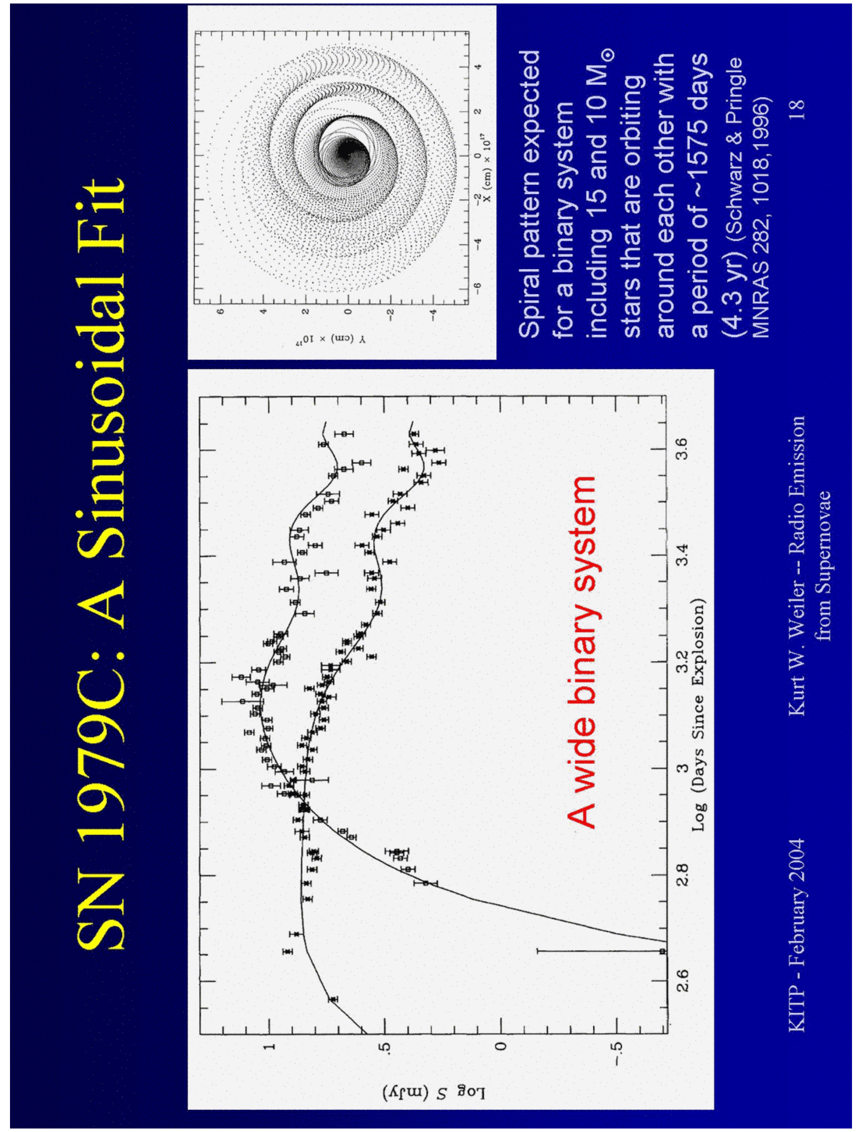
SN 1979C: A Sinusoidal Fit
A wide binary system
Log S (mJy)
Log (Days Since Explosion)
Spiral pattern expected for a binary system including 15 and 10 M⊙ stars that are orbiting around each other with a period of ~1575 days (4.3 yr) (Schwarz & Pringle MNRAS 282, 1018,1996)
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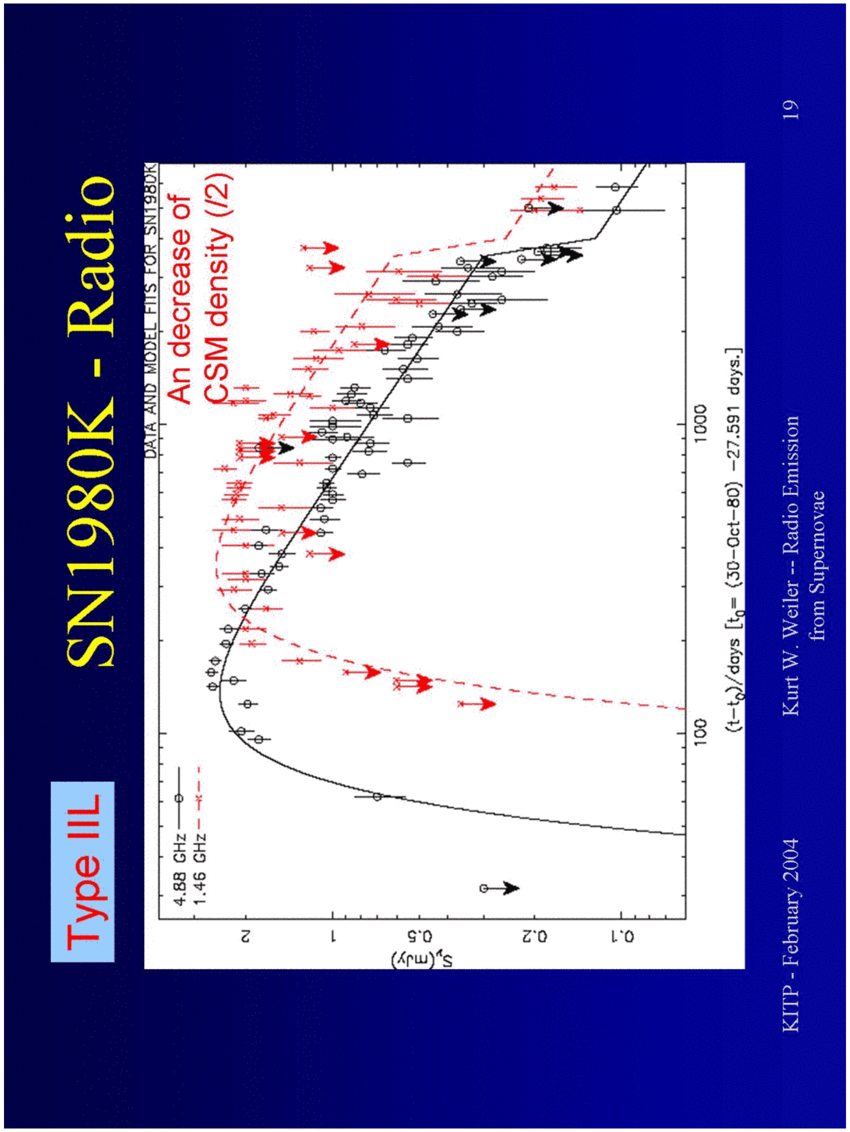
SN1980K - Radio
Type IIL
DATA AND MODEL FITS FOR SN1980K
An decrease of CSM density (/2)
4.88 GHz
1.46 GHz
Sν(mJy)
(t−t0)/days [t0= (30−Oct−80) −27.591 days.]
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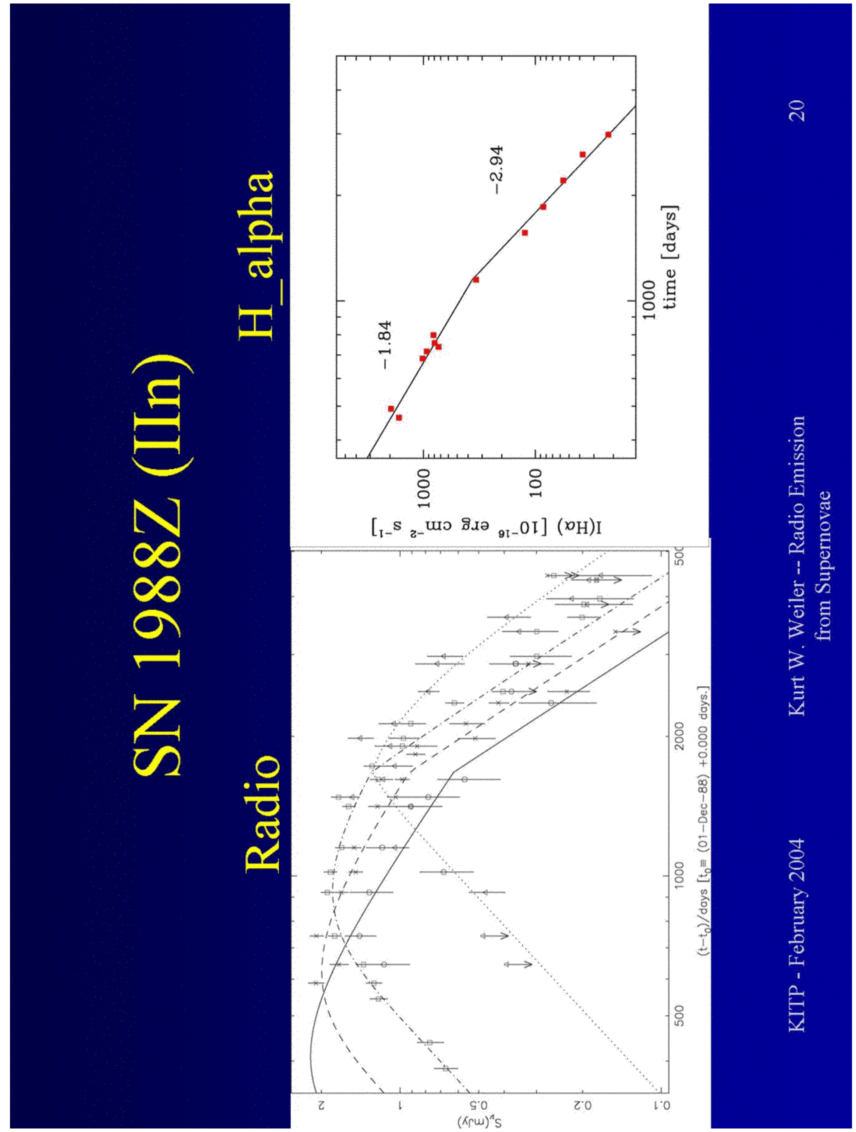
SN 1988Z (IIn)
Radio
H_alpha
−1.84
−2.94
time [days]
I(Hα) [10^-16 erg cm^-2 s^-1]
Sν(mJy)
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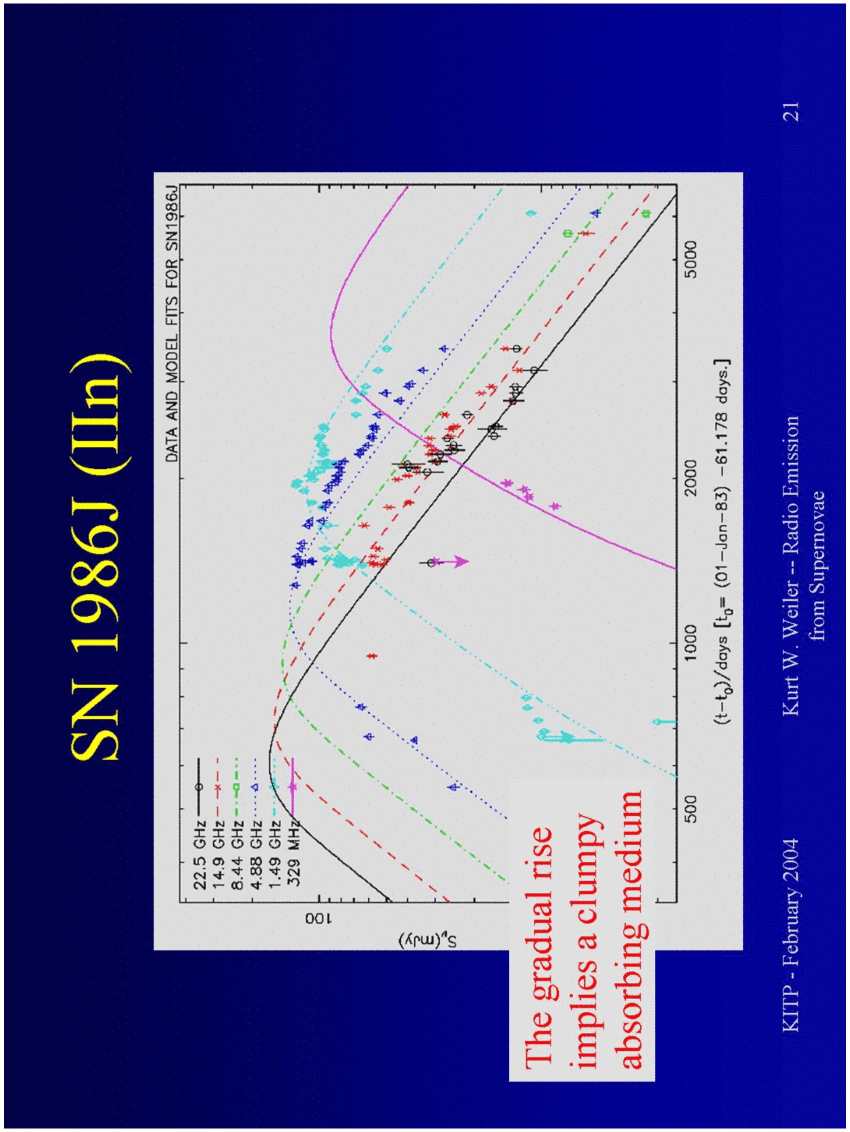
SN 1986J (IIn)
DATA AND MODEL FITS FOR SN1986J
22.5 GHz
14.9 GHz
8.44 GHz
4.88 GHz
1.49 GHz
329 MHz
S_ν(mJy)
100
500
1000
2000
5000
$(t-t_0)$/days [t_0= (01-Jan-83) −61.178 days.]
The gradual rise implies a clumpy absorbing medium
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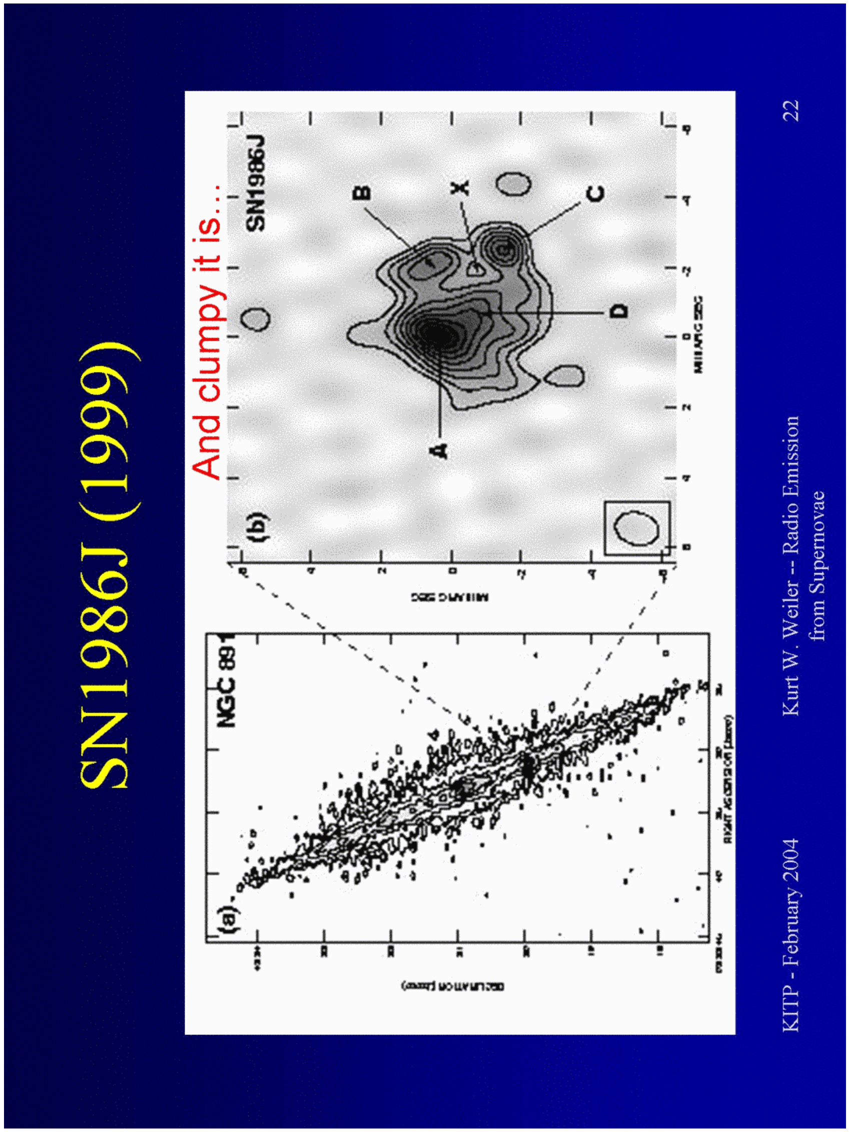
SN1986J (1999)
And clumpy it is…
(a)
NGC 891
(b)
SN1986J
A
B
C
D
X
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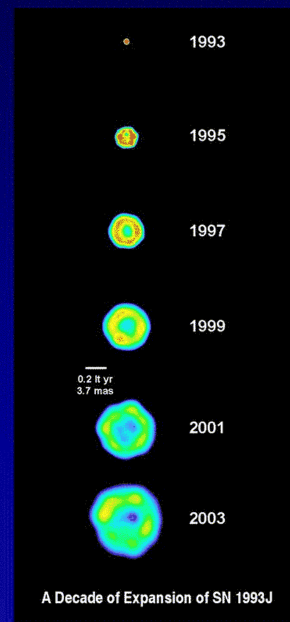
SN1993J: VLBI Observations

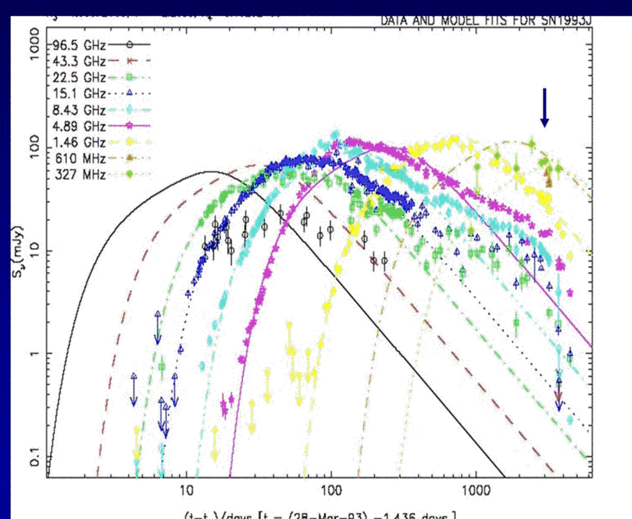
Expansion of SN 1993J
– first 10 years

[Marcaide et al. 2004]



SN 1993J – Light Curves

- Possible spectral index change (Chandra etal, ApJ 612, 974.\, 2004)
- Possible Synch aging (Chandra etal, ApJL 604, L97, 2004)



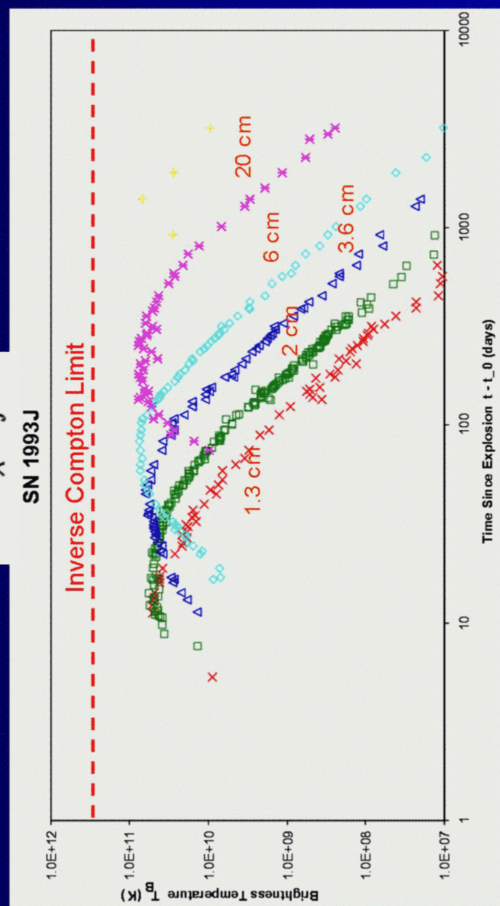
Supernova 1993J in M81

Brightness Temperature

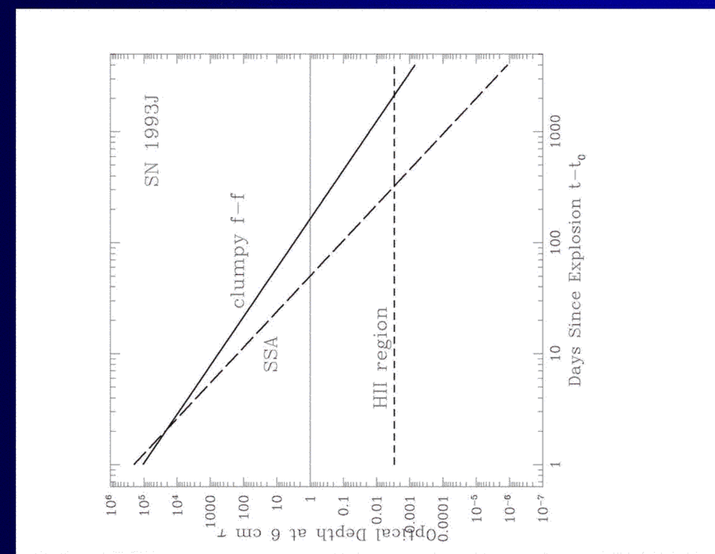
[assuming v_{exp}=10000 km s^{-1}]

Van Dyk et al 1994, 2006 in n preparation

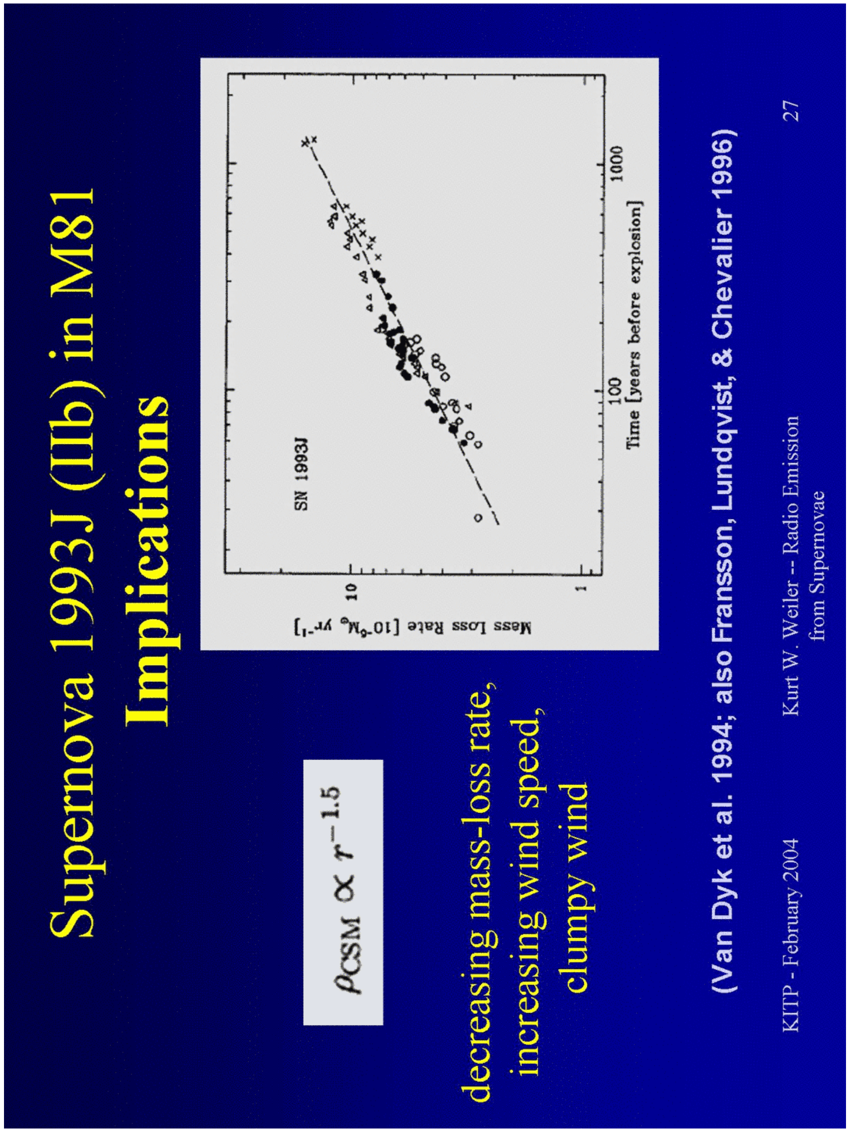
$$S \propto \frac{2kT_B}{\lambda^2}\int d\Omega$$



Van Dyk et al 2006, in n preparation



As you might expect, SSA is not significant in the radio evolution


Supernova 1993J (IIb) in M81
Implications
$\rho_{CSM} \propto r^{-1.5}$
SN 1993J
Mass Loss Rate [$10^{-6} M_\odot$ yr^{-1}]
Time [years before explosion]
1
10
100
1000
decreasing mass-loss rate,
increasing wind speed,
clumpy wind
(Van Dyk et al. 1994; also Fransson, Lundqvist, & Chevalier 1996)
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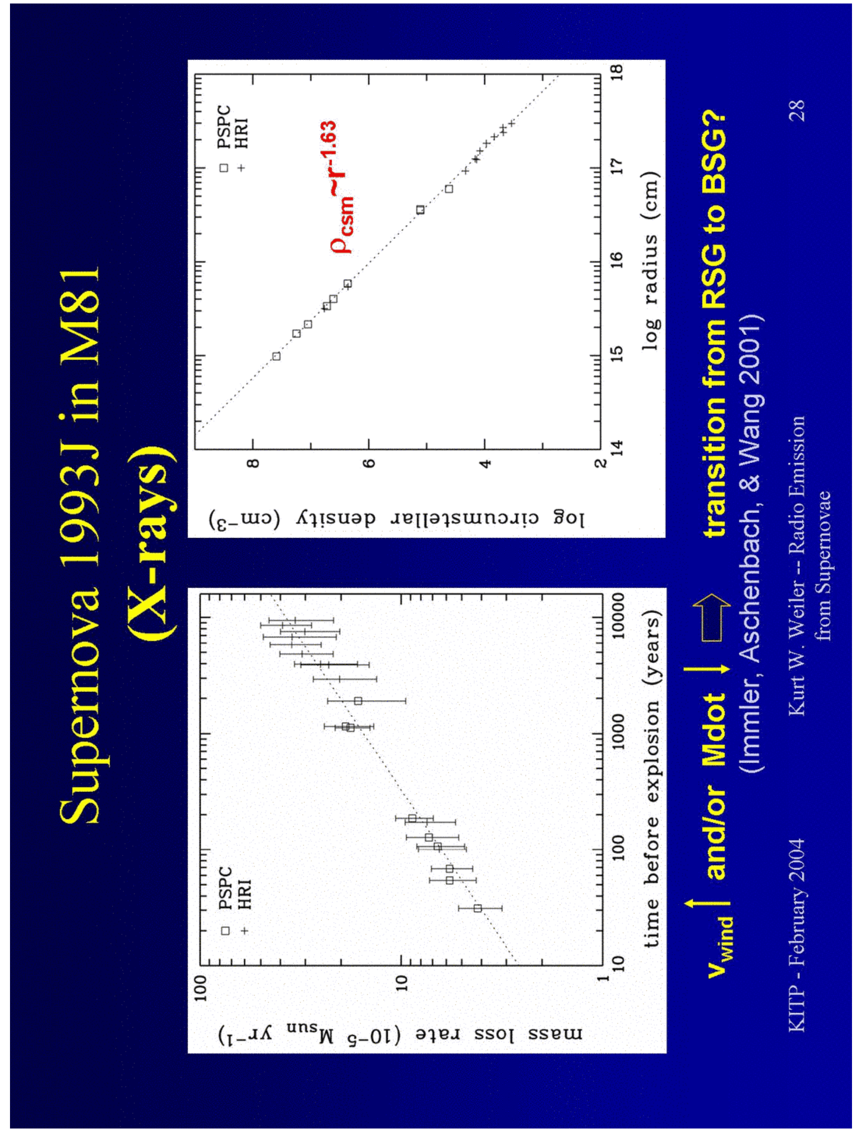
Supernova 1993J in M81
(X-rays)
mass loss rate (10^{-5} M_{sun} yr^{-1})
time before explosion (years)
PSPC
HRI
1
10
100
1000
10000
log circumstellar density (cm^{-3})
log radius (cm)
ρ_{csm}~$r^{-1.63}$
2
4
6
8
14
15
16
17
18
v_{wind} ↑ and/or Mdot ↓ ⇧ transition from RSG to BSG?
(Immler, Aschenbach, & Wang 2001)
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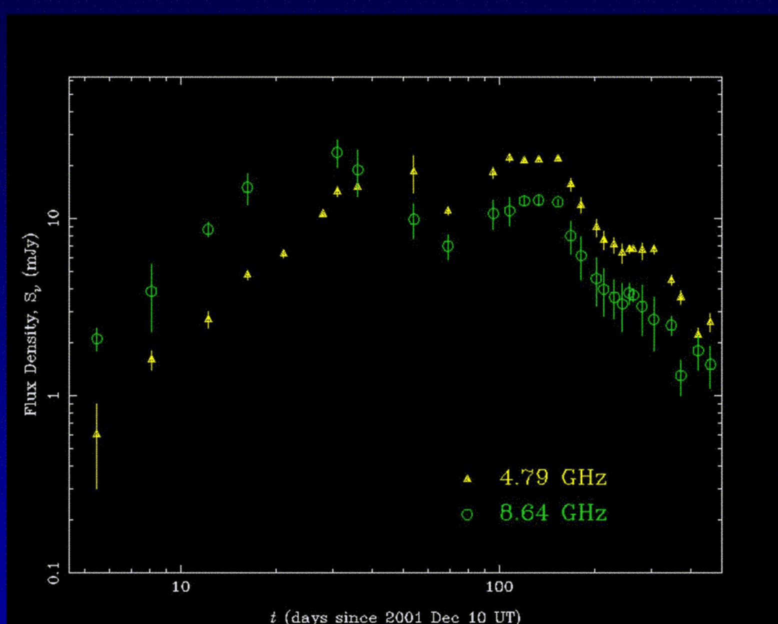
SN 2001ig (IIb) - A Chronology

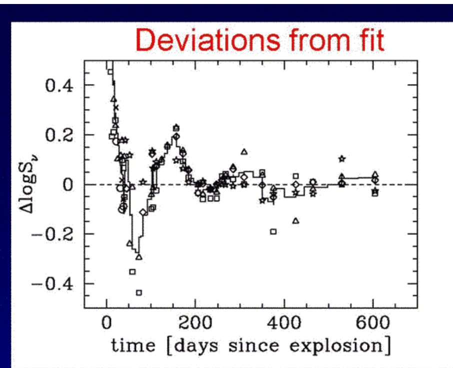
[Ryder et al. MNRAS 2004]

- Dec 10.43 2001 UT: discovery by R. Evans in NGC 7424 (SAB(rs)cd, D=11.5 Mpc, $\delta = -41°$).
- Early spectroscopy (LCO 6.5m, ESO NTT) suggested similarities with SN 1993J (Type IIb).
- Dec 15 UT: Detected with ATCA at 8.6 GHz.
- May 2002: Detected with ACIS-S/*Chandra* – L(0.2–10 keV) ~ 10^{38} erg s^{-1}.
- Oct 2002: Transition to Type Ib/c complete.

Radio "light curve"

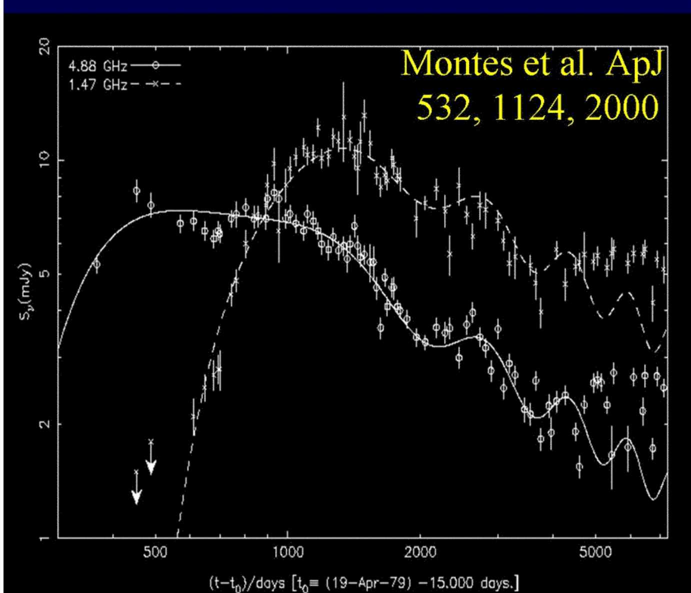


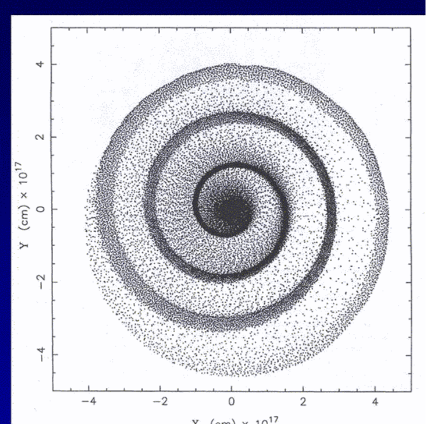
Episodic mass-loss?



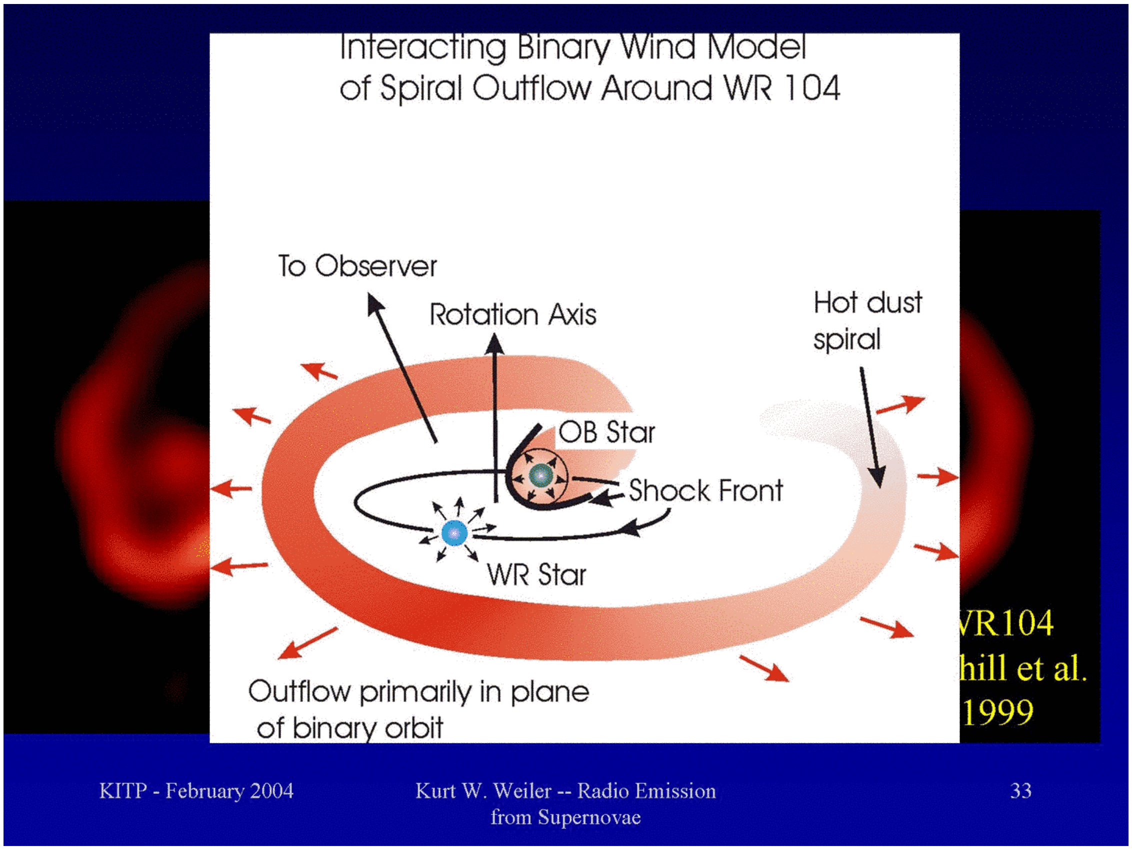
- Bumps and dips with $P \sim 150$ days.
- $v_{exp} \sim 15{,}000$ km s^{-1} $\Rightarrow R = 0.006$ pc.
- $w = 10$ km s^{-1} $\Rightarrow t \sim 600$ yr.
- $t >>$ stellar pulsation timescales, but perhaps consistent with thermal pulse (C/He flashes) periods in 5–10 $M_\odot$ AGB stars.

Analogy with SN 1979C





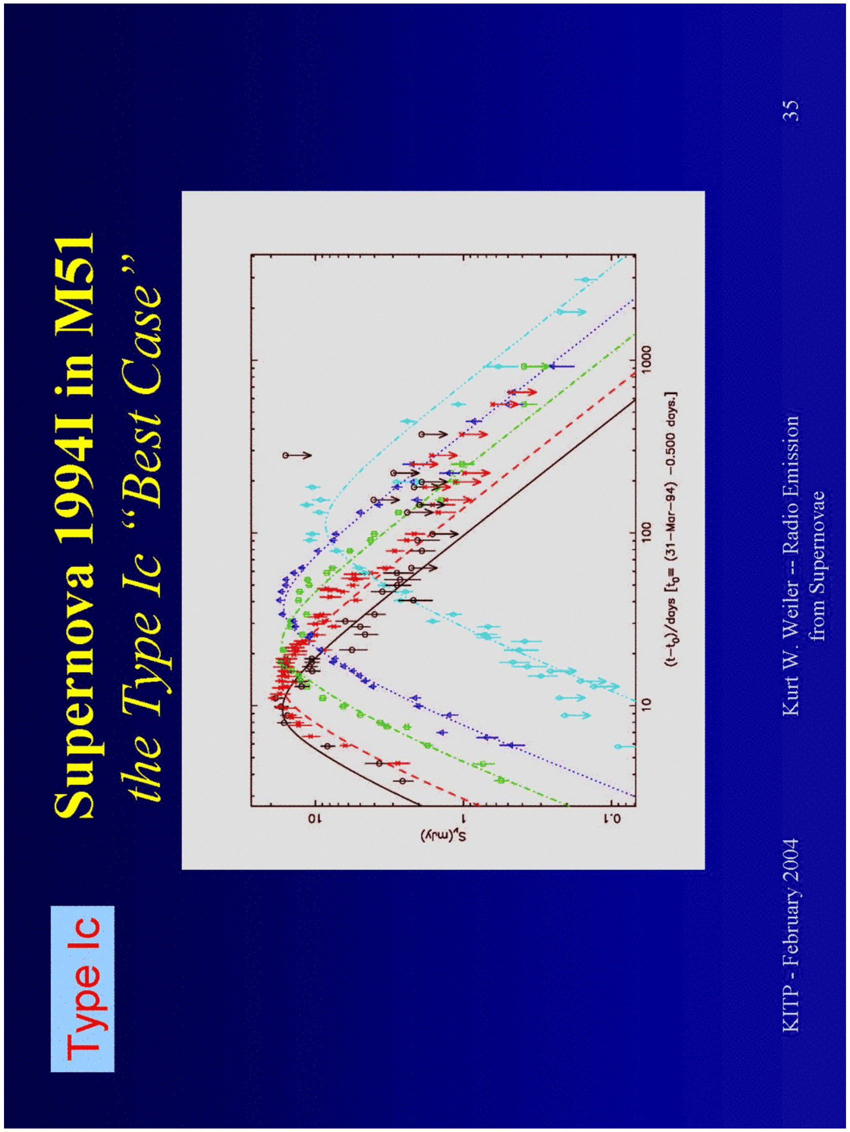
Schwarz & Pringle MNRAS 282, 1018, 1996



SN 2001ig summary

(See astro-ph 0401135)

- SN 2001ig is a Type IIb comparable with SN 1993J, but late-time radio light-curve akin to SN 1979C.
- Spectral index evolution ⇒ changes in CSM density, rather than optical depth.
- Mass-loss variability (~600 yr) consistent with:
  - WR progenitor wind modulated by eccentric orbital motion about massive binary companion?


Type Ic
Supernova 1994I in M51
the Type Ic "Best Case"
S_ν(mJy)
(t−t_0)/days [t_0= (31−Mar−94) −0.500 days.]
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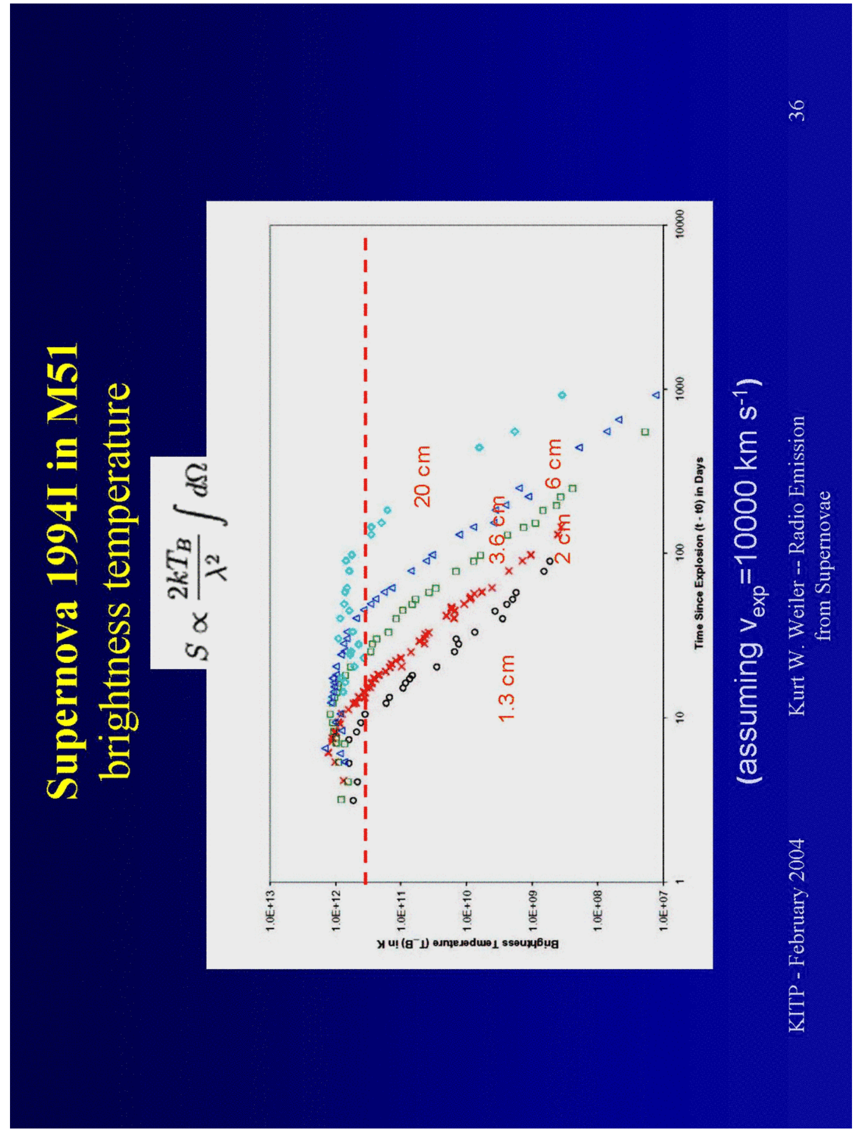
Supernova 1994I in M51
brightness temperature
$S \propto \frac{2kT_B}{\lambda^2} \int d\Omega$
Brightness Temperature (T_B) in K
Time Since Explosion (t - t0) in Days
20 cm
6 cm
3.6 cm
2 cm
1.3 cm
(assuming v_{exp}=10000 km s^{-1})
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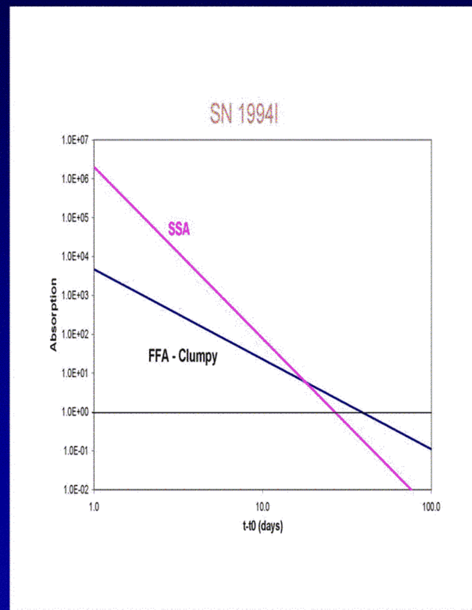
Supernova 1994I in M51 Absorption

For SN1994I SSA is clearly significant in the early radio evolution



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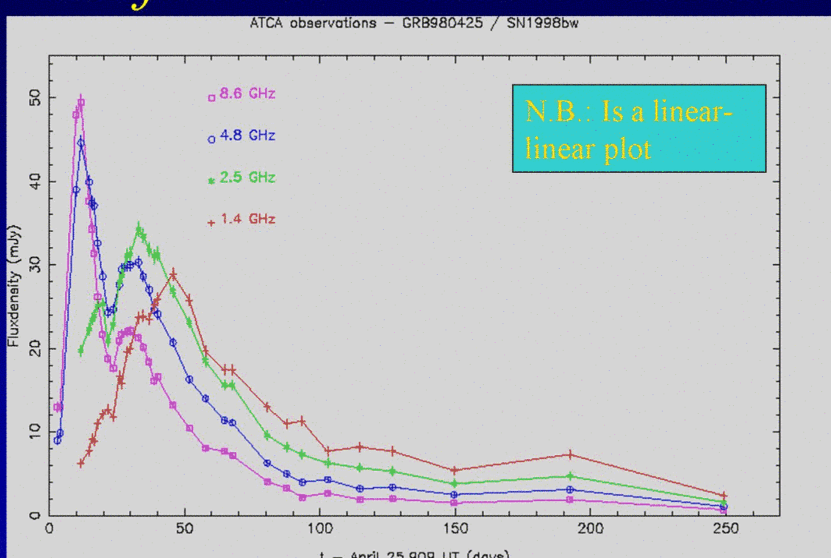
http://www.narrabri.atnf.csiro.au/\~mwiering/grb/grb980425/

ATCA Observations of SN 1998bw the *first* SN-GRB Evidence



N.B.: Is a linear-linear plot

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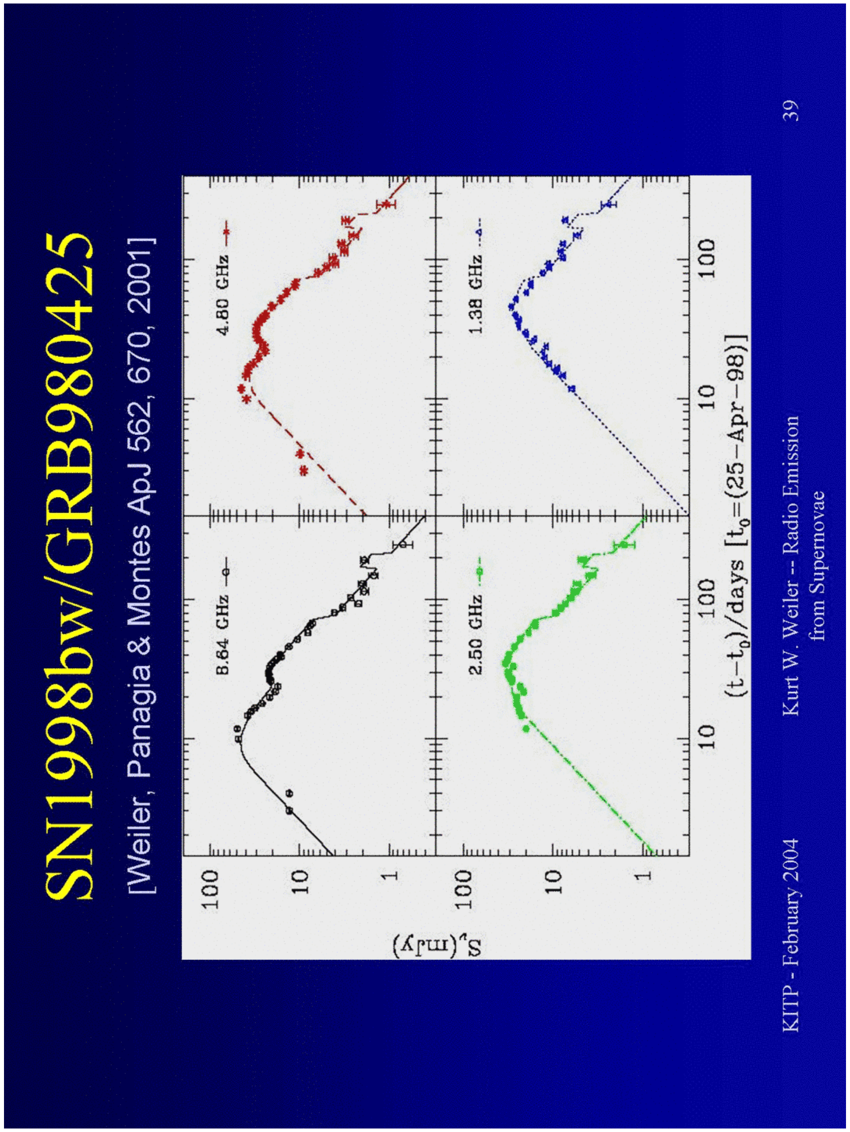
SN1998bw/GRB980425
[Weiler, Panagia & Montes ApJ 562, 670, 2001]
8.64 GHz
4.80 GHz
2.50 GHz
1.38 GHz
S_ν(mJy)
(t−t_0)/days [t_0=(25−Apr−98)]
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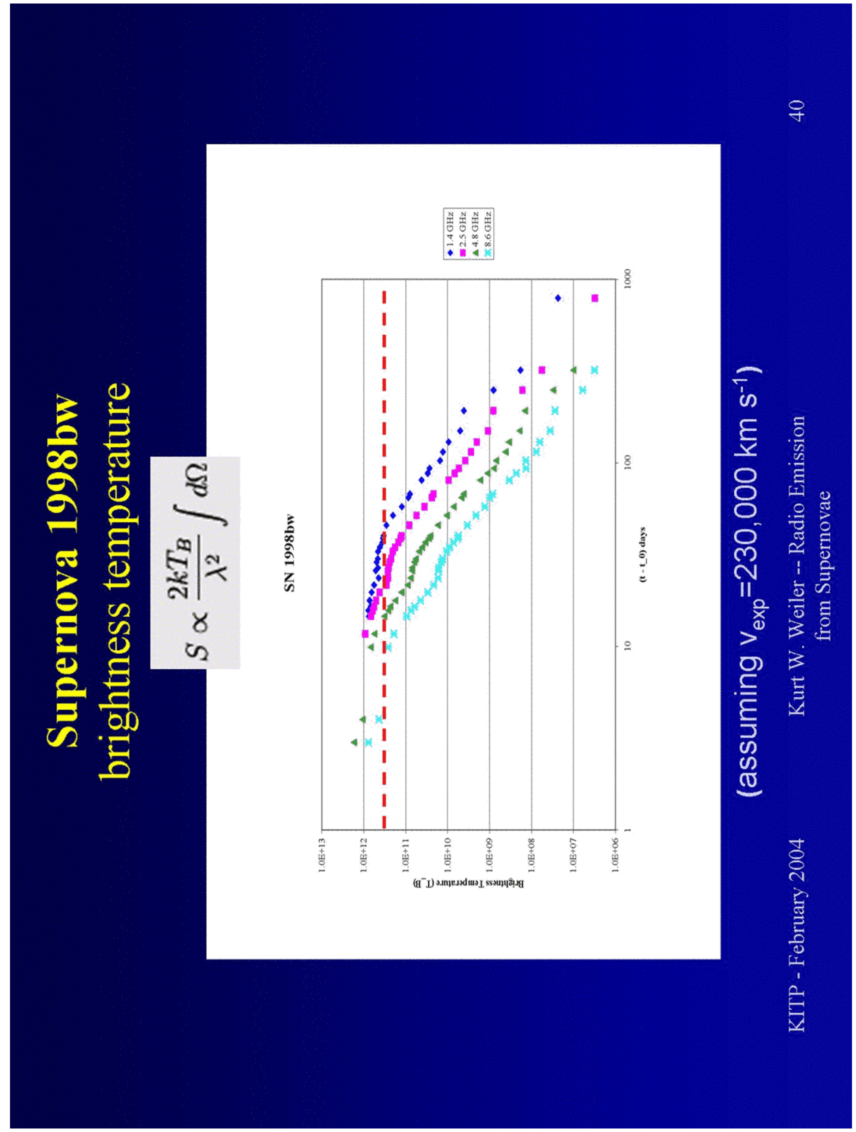
Supernova 1998bw
brightness temperature
$S \propto \frac{2kT_B}{\lambda^2} \int d\Omega$
SN 1998bw
(assuming v_{exp}=230,000 km s^{-1})
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Kurt W. Weiler -- Radio Emission from Supernovae
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SN1998bw/GRB980425

- Shock speed = 230,000 km s^{-1} ($\Gamma = 1.6$)
- 60% increase in emission near Day 25, returns to normal near Day75
- Same increase between Day 149 & Day 249 seen at Day 192
- Implied 30% density enhancement at intervals of ~9,000 yr (Comparable to 1979C & 1980K)
- Highly clumped medium ($K_2 = 0$); filling factor ~ 10%
- $M_{dot} \sim 3.5 \times 10^{-5}\ M_{\odot}\ yr^{-1}$

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SUMMARY - I

- *SNe classes are distinct in radio emission properties (thus distinct in CSM environments):*
  - *SNe Ia are undetectable at VLA's limiting sensitivity (so far)*
  - *SNe Ib/c turn on and off quickly*
  - *SNe II evolve more slowly*
- *RSNe are sensitive to M_{dot}/w_{wind} (~ pre-SN mass loss rate)*
- *RSNe sample the CSM ⇒ properties of the pre-SN wind density & structure -- unique stellar evolution probe*
- *Because $v_{wind} \sim 10$ km/s and $v_{shock} \sim 10^4$ km/s, radio observations are a "time machine"*

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SUMMARY - II

- SNIa: Very small (<3 x 10^{-8} M_{sun} yr^{-1}) matter outflow from pre-SNIa systems
- SNII:
  - Red Supergiant Winds (but SN 1987A)
  - Essentially all change their evolution on a timescale of ~ x 10^4 yrs
  - Clumpy CSM and/or cylindrically symmetric density distributions
  - Variable mass loss rates over 10^4 years time scales
  - Evidence for pre-SN binary system wind collisions
- SNIb/c:
  - More tenuous CSM than SNII
  - Much higher shock speeds
  - Evolve much faster

FINISH