Mid-IR Spitzer and Gemini studies of dust production in core-collapse supernovae

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and the SEEDS collaboration

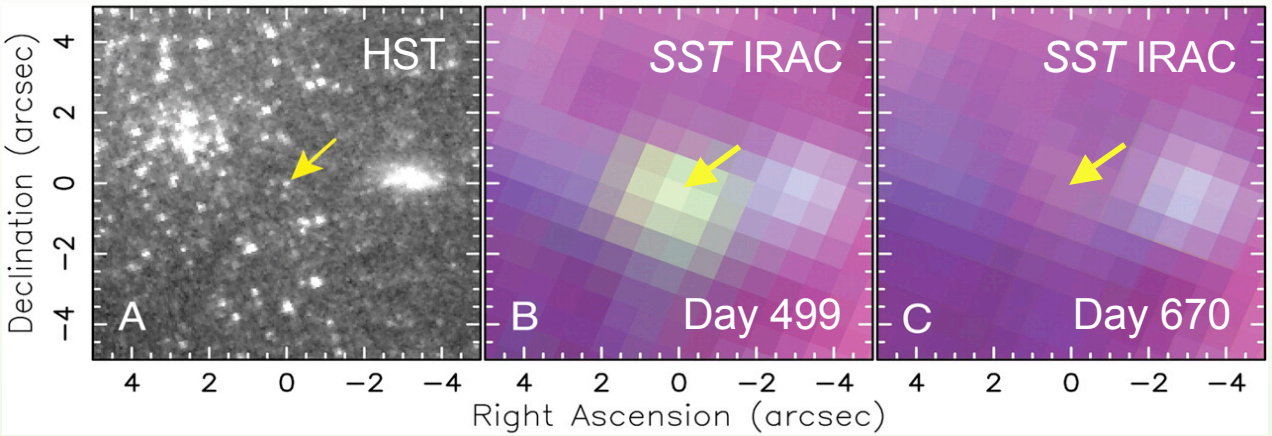
NAM 2007 - Parallel session 33: The Origins of Dust in the Universe

- **SEEDS** - an international collaboration formed in 2004
- Sensitive mid-IR `**S**urvey for the **E**volution of **E**mission from **D**ust in **S**upernovae'
- Strategy: Using primarily the *Spitzer Space Telescope* and Gemini telescopes we are observing recent, nearby SNe
- Aims: To determine the extent to which massive star SNe and their progenitors produce dust, and quantify their contribution to the dust budgets of galaxies

- Emission from newly formed SN dust is expected to peak at mid-IR wavelengths (~5 to [25-40] μm), appearing after about 400 days (SN 1987A did this and current SN dust formation models predict it, e.g. Todini and Ferrara, 2001).
- Awarded *Spitzer* time over several cycles, for IRAC and MIPS imaging of massive-star SNe that have occurred in relatively nearby (< 15 Mpc) galaxies over the previous 1-4 years.
- Also used SINGS Legacy Programme IRAC and MIPS data of nearby galaxies (Kennicutt et al. 2003).
- Awarded Gemini time over several semesters, for Michelle (11.2 and 18.1 μm) imaging and GMOS spectroscopy.

SN 2003gd in NGC 628

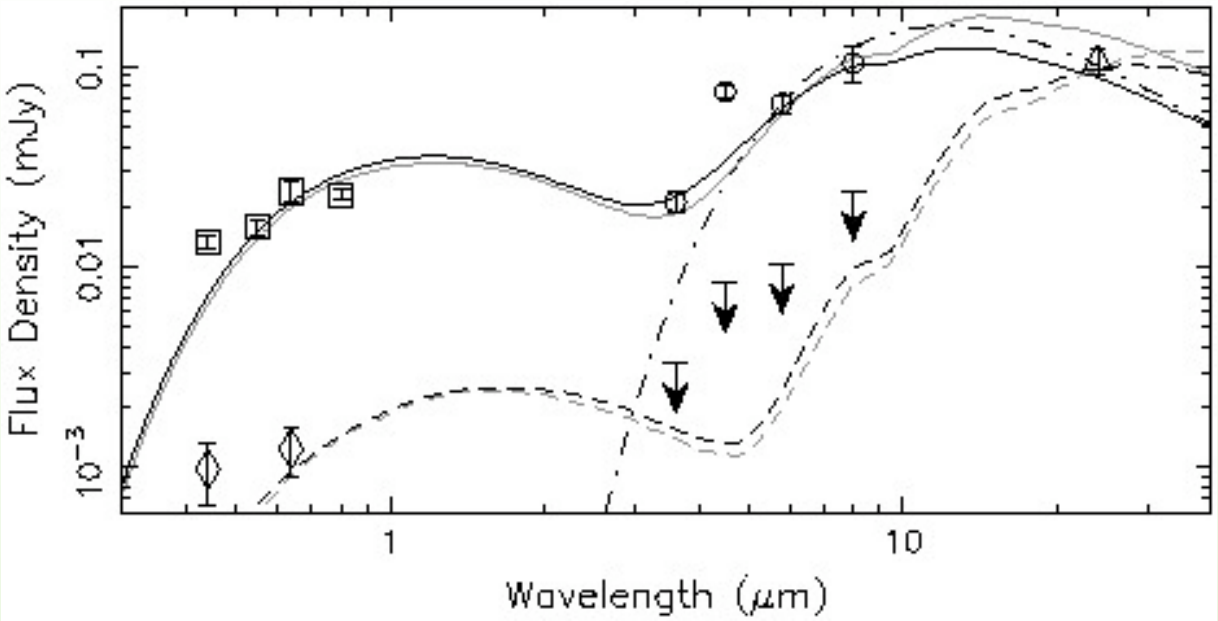
Explosion date: March 18, 2003 - Type IIP, D = 9.3 Mpc



A. *HST* WFPC2 F606W image of SN progenitor (Van Dyk et al. 2003, Smartt et al. 2004).
B. & C. - False-colour *SST*-IRAC images of the SN taken on (B) July 28, 2004 (SINGS data) and (C) Jan 15, 2005 (GO-3248, PI: Meikle) - 3.6 μm, 4.5 μm, 8 μm.

- *Spitzer* archival data - spatially enhanced to 0″.75/pixel.
- Inc. SINGS MIPS data of NGC 628 at 24 μm obtained on Jan 23, 2005 (day 678).
- HST image identifies progenitor star.

Optical and infrared SED of SN 2003gd

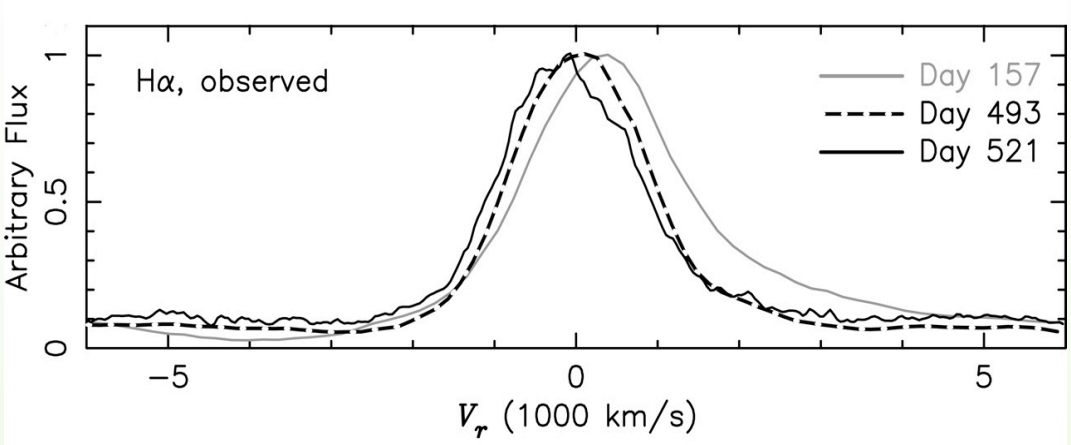


Day 499 (upper) and day 678 (lower fits).

Squares	-	Optical photometry on day 493 (Hendry et al. 2005).
Diamonds	-	Optical photometry extrapolated from day 632 to day 678 based on the evolution of SN 1987A.
Circles	-	IRAC data from day 499.
Arrows	-	Upper limits to IRAC data from day 670.
Triangle	-	MIPS datum from day 678.

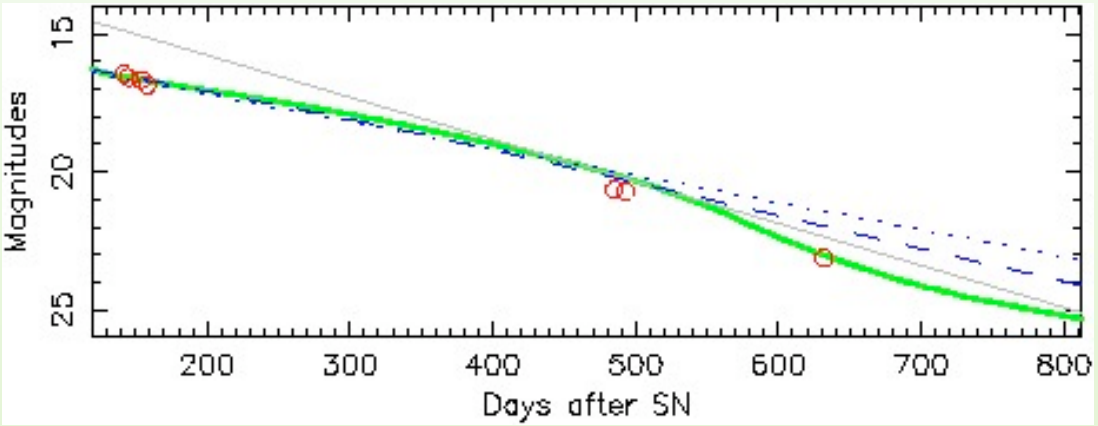
- Dot-dash curve is a 480 K blackbody with $L = 4.6 \times 10^5\ L_{Sun}$ and radius 7×10^{15} cm.
- The other curves are MOCASSIN RT models for day 499 (solid lines) and day 678 (dashed lines), for either uniform (black) or clumped dust (grey).
- Size, temp. and variability of SEDs are consistent with dust cooling within the SN ejecta.

Further evidence for dust condensation in the SN ejecta…



Asymmetric blue-shifted emission lines - dust forming in the ejecta preferentially extinguishes emission from receding (i.e. red-shifted) gas.

Increase in optical extinction - as evidenced by the dip in the light curve of SN 1987A scaled to the fluxes of SN 2003gd (red circles).



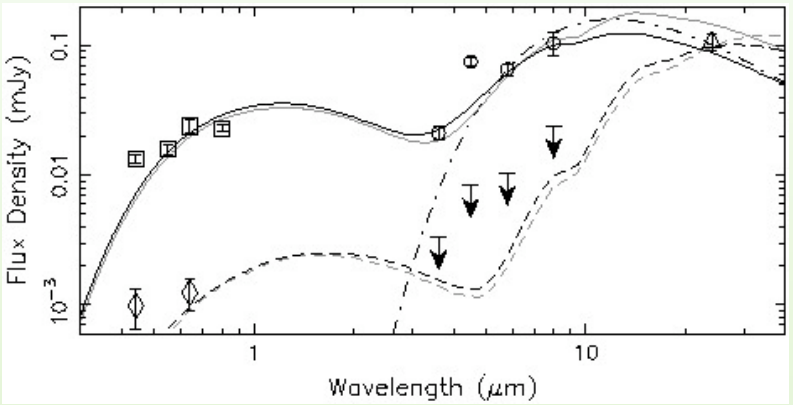
Additional extinction by dust is inferred to have occurred after day 500 for both SNe, corresponding to 0.25-0.5 mags at day 499 for 2003gd and 0.8-1.9 mags at day 678.

SN 2003gd, Type IIP, D = 9.3 Mpc

❖ Observations point overwhelmingly to dust forming within the ejecta of SN 2003gd, beginning 250-493 days after outburst.

- Estimating the dust mass: 3-D Monte-Carlo RT code MOCASSIN (Ercolano et al. 2005) - Smooth and clumpy dust distributions modelled.
- Summary of the lower (smooth) and upper limits (clumpy) to the dust mass estimates for the 2 epochs are shown in the table below.

Day	Model	A_R	$M_{dust}(M_{Sun})$
499	Smooth	0.40	2.0×10^{-4}
499	Clumpy	0.65	1.7×10^{-3}
678	Smooth	1.48	2.7×10^{-3}
678	Clumpy	1.22	2.0×10^{-2}

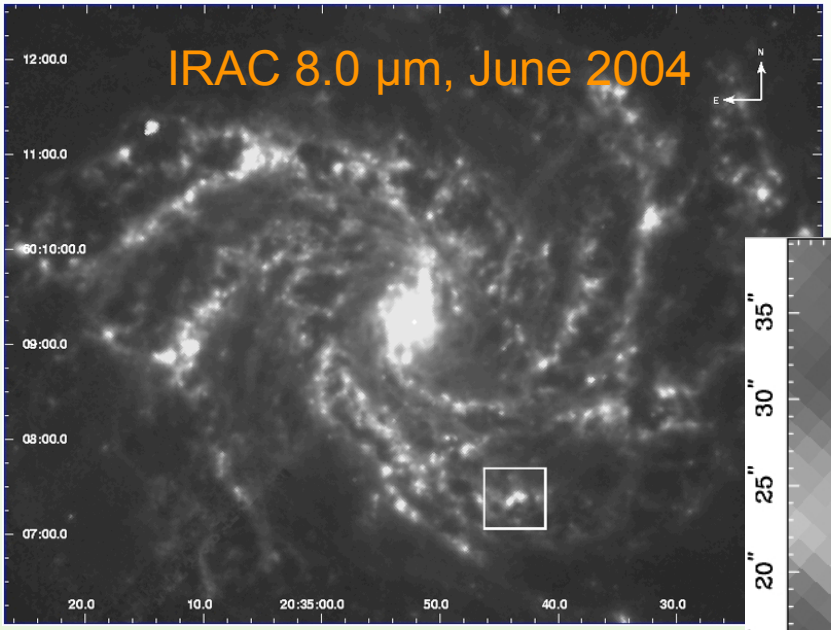


- Clumpy modelling at day 678 indicates condensation efficiency of ≤0.12 close to the 0.2 needed to account for the dust content of high-z galaxies.

-- Sugerman et al. 2006 --

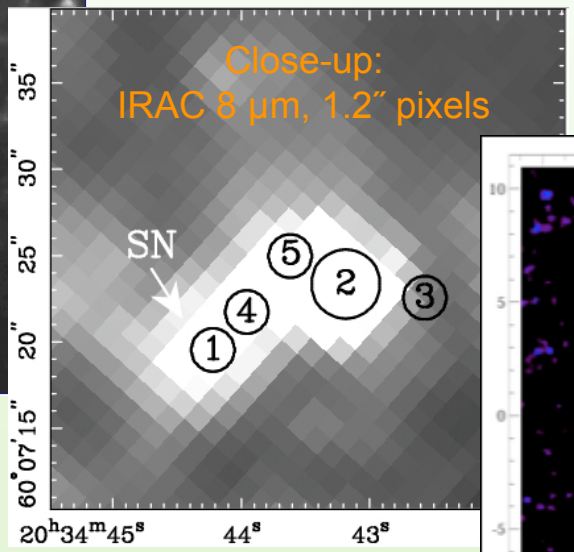
SN 2002hh in NGC 6946

Discovered Oct 27, 2002 - Type IIP, D = 5.9 Mpc

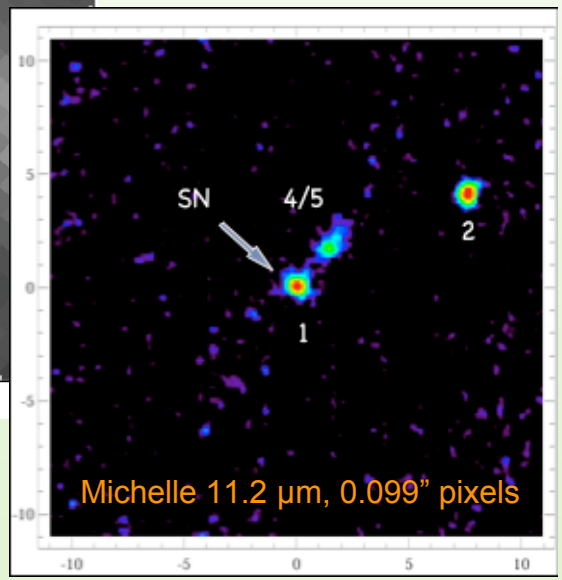


SINGS Legacy data

Crowded field

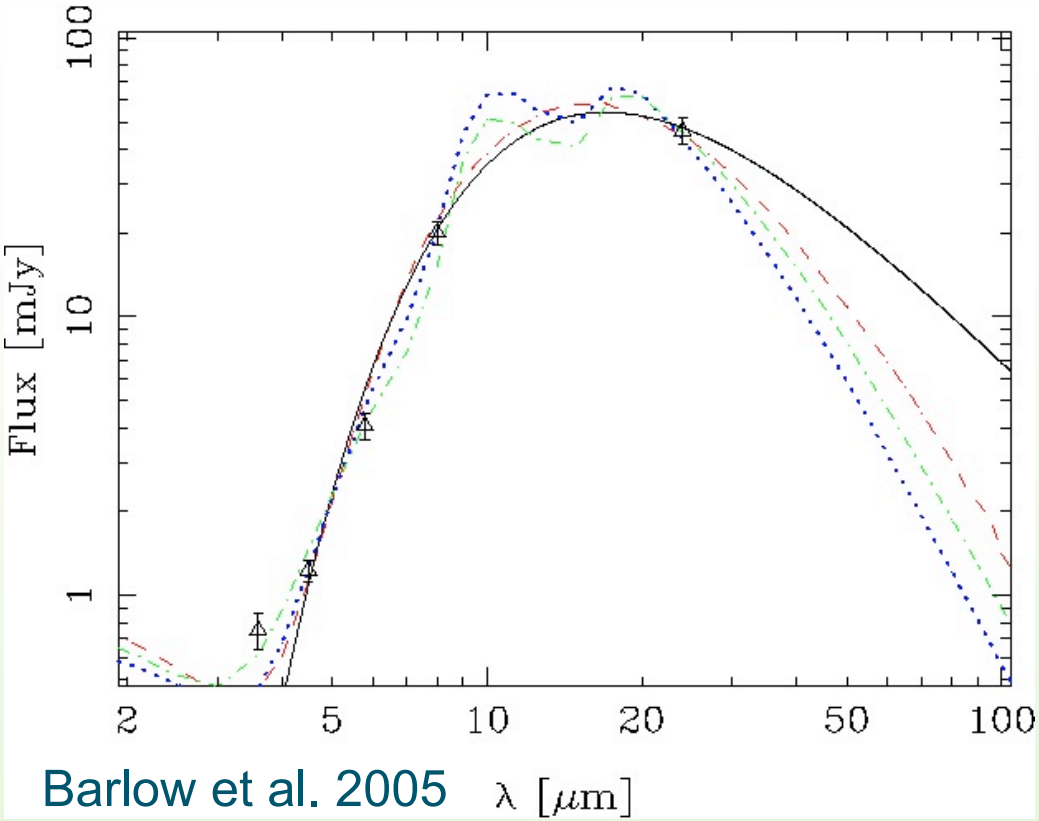


Sep 2004,
Gemini-N
DDT



Mid-IR discovery Barlow et al. 2004

SN 2002hh, Type IIP, D = 5.9 Mpc



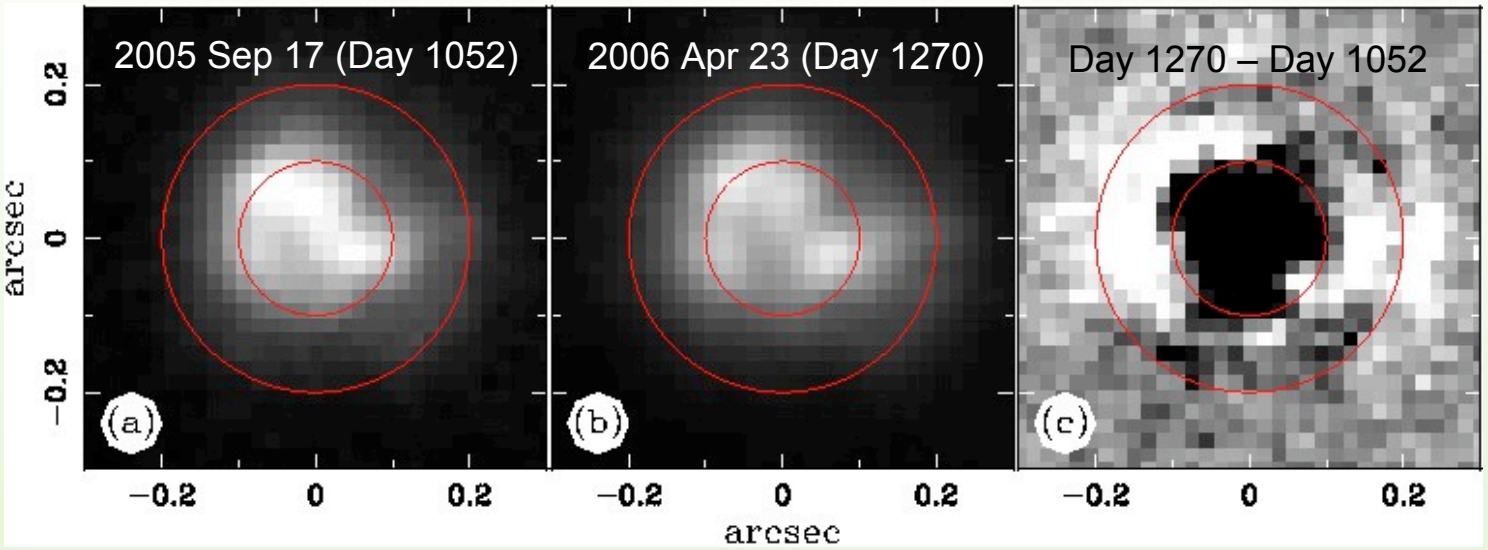
Barlow et al. 2005

- The SED is reasonably well fit by a 300 K BB, which indicates a minimum emitting radius, R ≈ 10^{17} cm and L = 1.6 x 10^{7} L_{Sun}.
- For the IR, a more realistic λ^{-1} emissivity gives R = 5 x 10^{17} cm.
- R is far too large for emitting dust to be formed in ejecta (would take > 10 yrs for material to reach this radius).

- Infer dust already there from a previous phase of mass loss.
- Dust modelling estimates total dust masses in the range 0.10 – 0.15 M_{Sun}.

Optical images of SN 2002hh taken with the *HST* ACS/HRC F606W filter (PI: Sugerman)

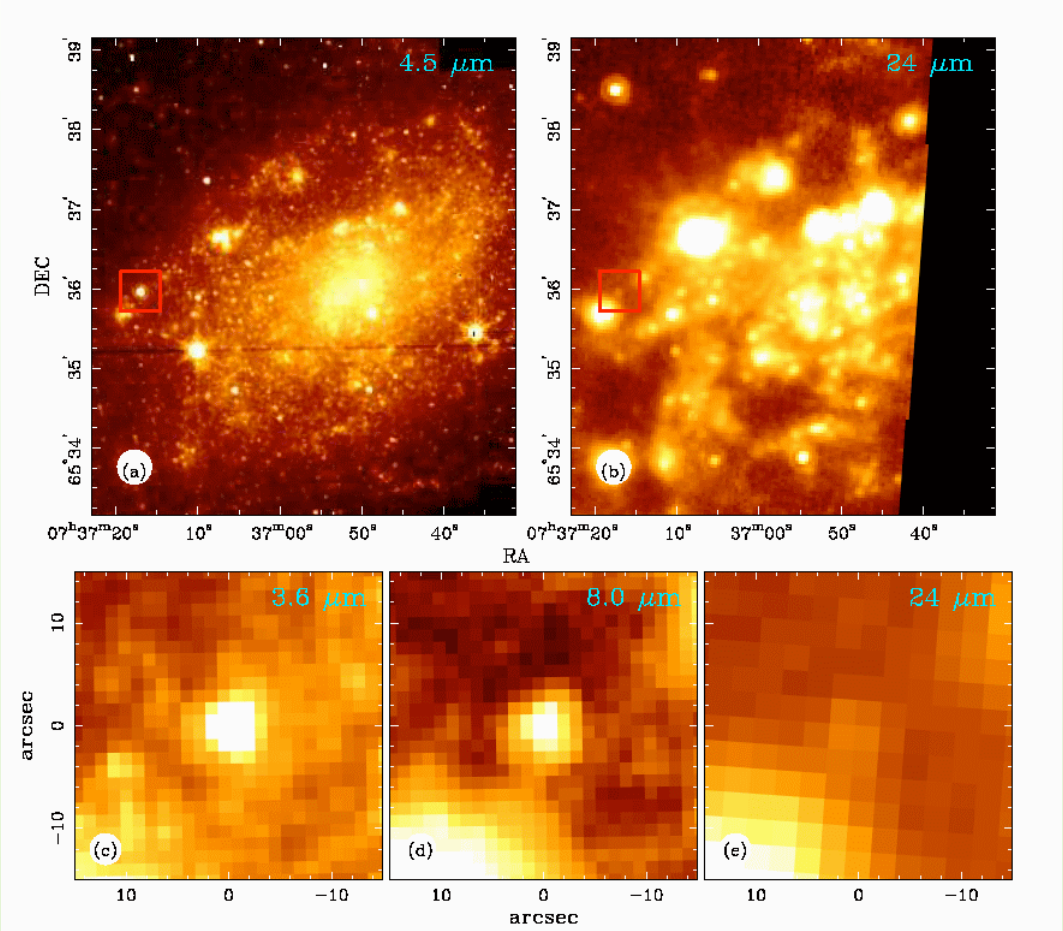
The difference image of the 2 epochs highlights the apparent expansion of the optical light echo.



- Preliminary analysis indicates the echo has occurred from a thick dust distribution that is located about 2-8 lightyears, or (2-8) x 10^{18} cm, in front of the SN.
- Given that SN 2002hh is a Type IIP (plateau) supernova, it appears that its extended light curve may be explicable in terms of the just-resolved light echo revealed by these images.

SN 2004dj in NGC 2403

Discovered July 31, 2004 - Type IIP, D = 3.3 Mpc

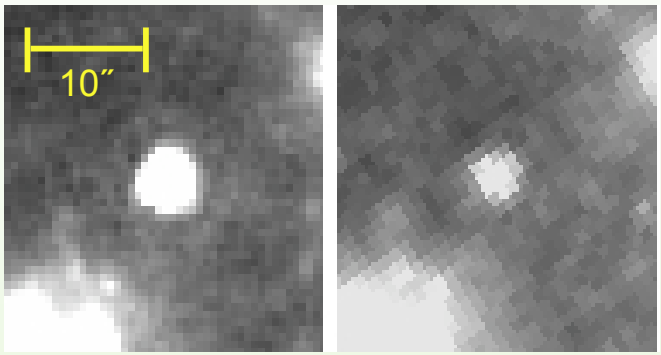


- SINGS Legacy data observed in October 2004 with IRAC + MIPS.
- We reported its mid-IR discovery in Sugerman 2005.

SN 2004dj, Type IIP, D = 3.3 Mpc

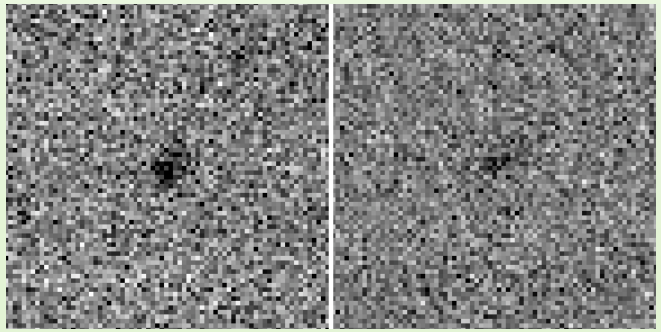
- Observed with *Spitzer* over a number of epochs from day 90 to day 996 (PI's: Van Dyk, Meikle, and Sugerman), and with Gemini Michelle in the N' filter at days 614 and 967 (PI: Barlow).

Day 92 Day 996

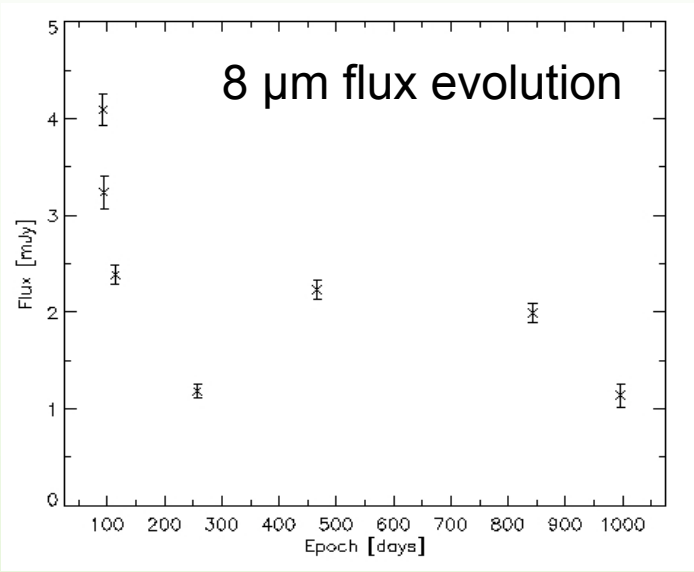


SST IRAC 5.8 μm

Day 614 Day 967



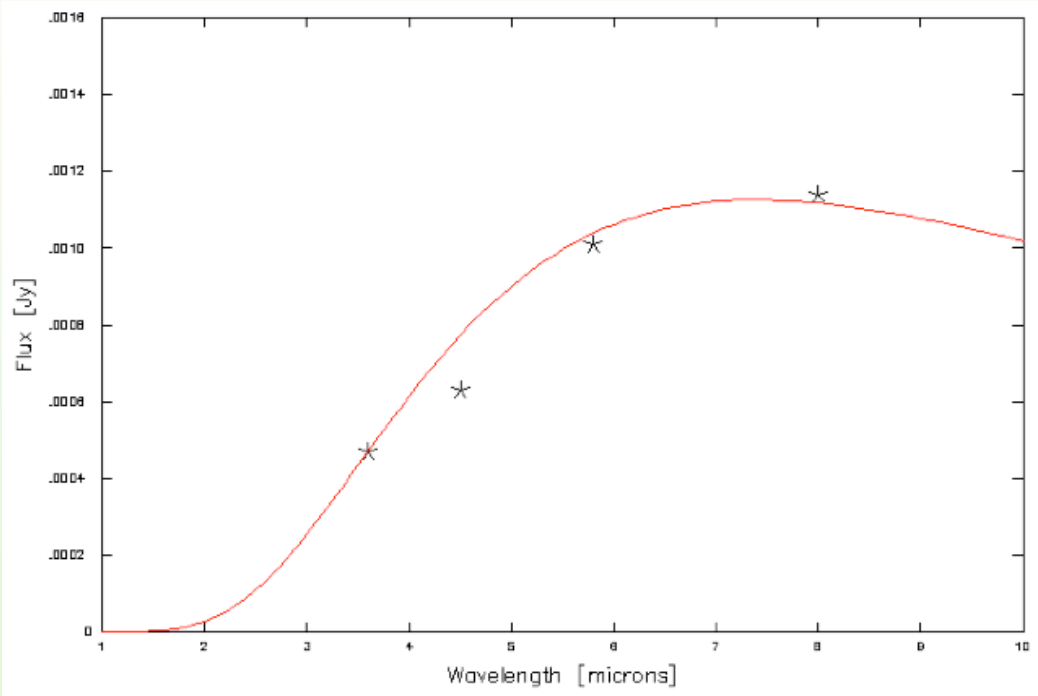
Gemini Michelle N' (11.2 μm)



- Fading evident in the mid-IR

SN 2004dj, Type IIP, D = 3.3 Mpc

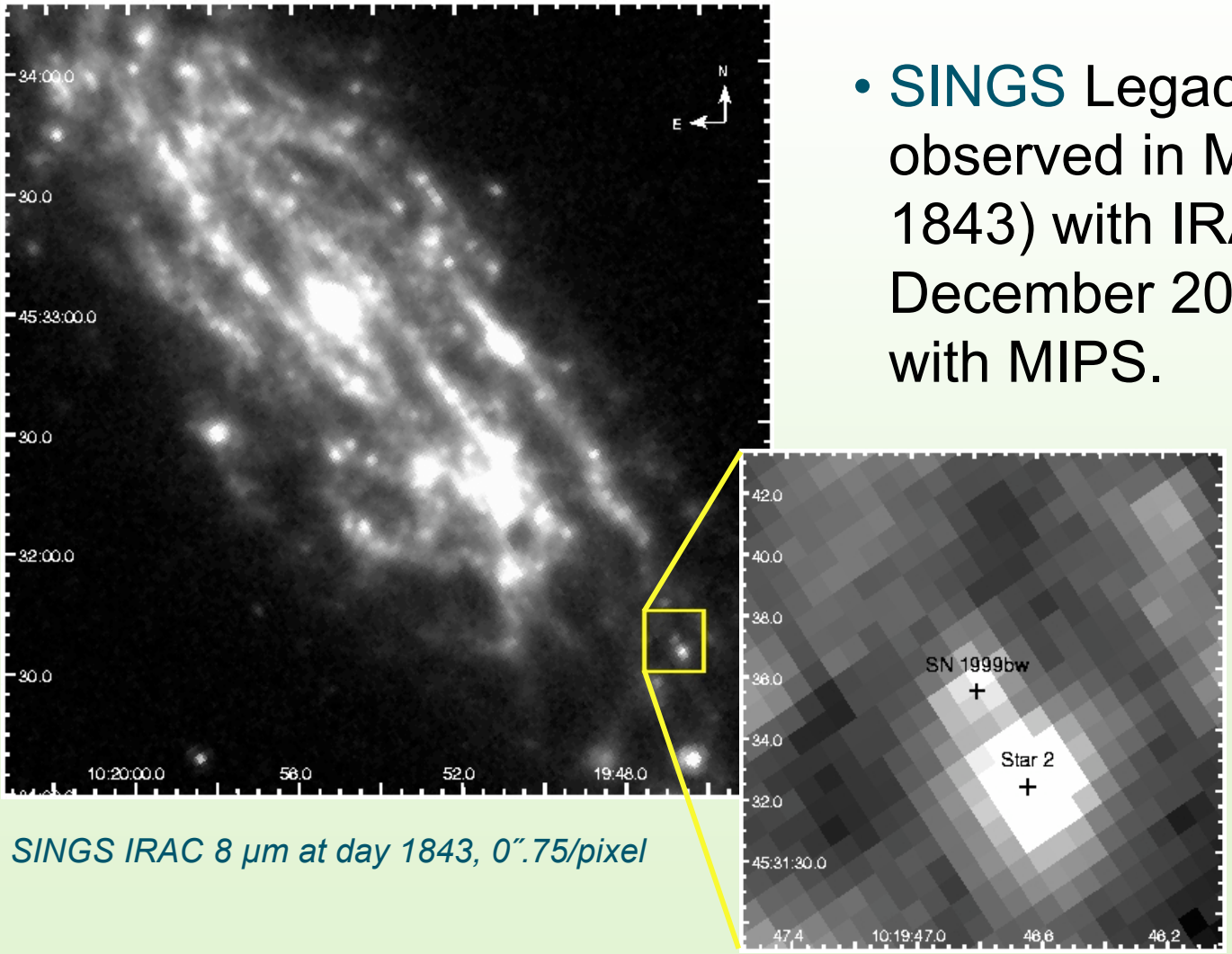
- 690 K BB fit to day 996 IRAC data => an emitting radius of ~0.8 x 10^{17}cm for a distance of 3.3 Mpc, and L = 26 x 10^{7} L_{Sun}, which indicates min. ejecta speeds of c. 9000 km/s.



- This is just plausible, but is it more likely we are seeing an IR echo from a CS shell?
- Continuing to monitor this SN…

SN 1999bw in NGC 3198

Discovered April 15, 1999 - Type IIn, D = 14.5 Mpc



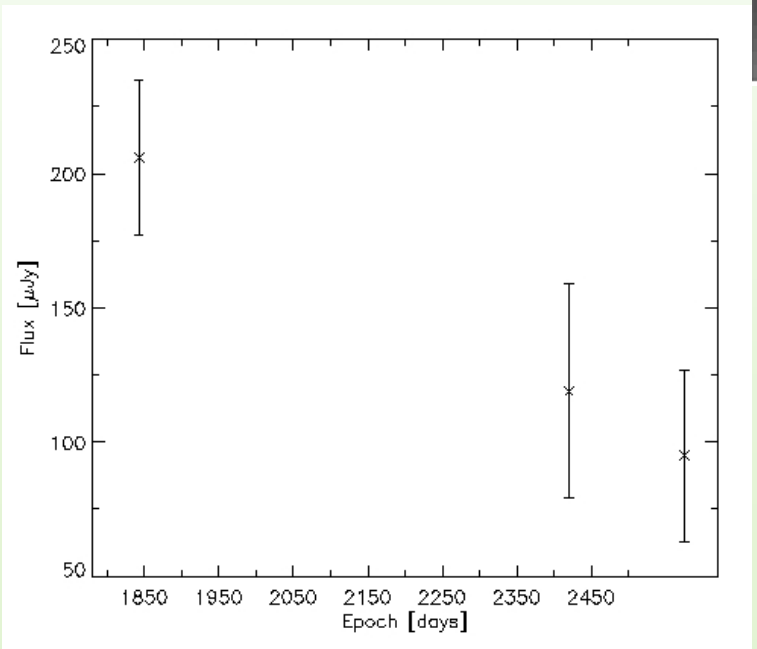
SINGS IRAC 8 μm at day 1843, 0″.75/pixel

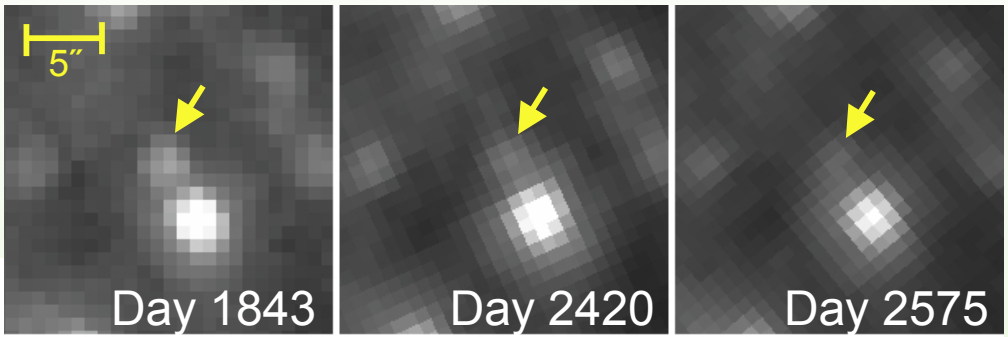
- SINGS Legacy data observed in May 2004 (day 1843) with IRAC + in December 2004 (day 2063) with MIPS.
- We reported its mid-IR discovery in Sugerman et al. 2004.

SN 1999bw, Type IIn, D = 14.5 Mpc

- 2nd and 3rd epoch IRAC and MIPS data with GO project 20320 (PI: Sugerman) in Nov/Dec 2005 and May 2006.

8 μm flux evolution





Decline of the 8 μm flux - fades by factor of ~2 over c.700 days
5.8 μm flux fades by factor of ~3 over same period.

SN 1999bw, Type IIn, D = 14.5 Mpc

- Whilst the decline of the mid-IR emission and best-fitting BB temperatures are consistent with fading and cooling dust, it is very unusual that this is occurring so long after outburst. SN 1987A had faded completely in the mid-IR by day 1000.

- Cannot rule out possibility of a light echo, but see no evidence for the distinctive scattering and dispersion of the light (as seen for SN 2002hh) from Cycle 14 (day 2748) *HST* ACS/HRC optical imaging.

- Analysis ongoing + continued monitoring with *HST* and *Spitzer*…

SN 2005cs in M51

Discovered June 27, 2005 - Type IIP, D = 8.4 Mpc

- Observed with Gemini-Michelle on April 7, 2006 (day 284) and March 17, 2007 (day 628) in the semi-broad N' filter at 11.2 μm but not detected.
- 3-σ upper limit of 0.38 mJy at day 678 is at the level SN 1987A would have had at that distance at that epoch.
- Initial *Spitzer* IRAC data obtained in Cycle 3 (day ~550) do not reveal a detection.
- Indicates that this SN did not produce any dust?
- We continue to monitor this SN with Gemini, *Spitzer* and *HST*.

Preliminary Conclusions

SN	D [Mpc]	Progenitor mass (M_{Sun})	Dust formation?
2003gd	9.3	6-12	yes
2002hh	5.9	unknown	maybe; pre-existing dust - yes
2004dj	3.3	12-15	maybe; but CS dust more likely
1999bw	14.5	unknown	yes; late onset
2005cs	8.0	7-12	unlikely

- Awarded combined *HST* Cycle 16 and *SST* Cycle 4 time to continue monitoring all of the above SNe including several others.
- Continued monitoring of SNe with Gemini-Michelle and GMOS spectroscopy and lots of data requiring further analysis!