Spitzer and Herschel Studies of Dust formation by Supernovae

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on behalf of

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Background

- The heavy element and dust enrichment of galaxies is believed to be the result of mass loss during the final stages of stellar evolution.

- Low and intermediate mass AGB stars are observed to form dust in their outflows, sometimes at high rates (e.g. O-rich and C-rich Mira variables)

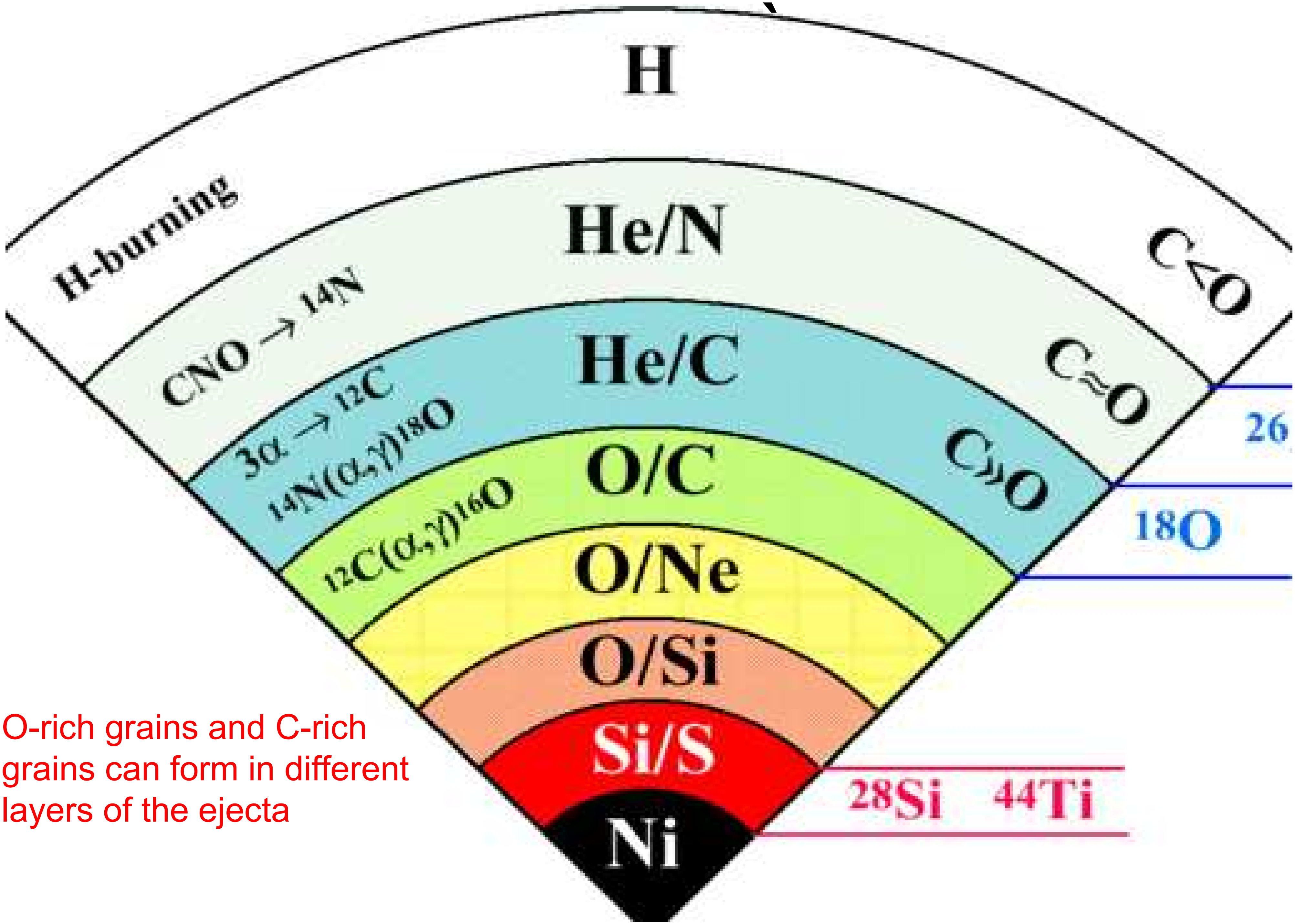
- Since low and intermediate mass stars have relatively long main sequence lifetimes, until a decade or so ago the standard picture was that large galaxies such as the Milky Way steadily increased their dust content and dust-to-gas ratios with time.

- This picture has undergone review following the discovery at submillimeter wavelengths (starting with SCUBA) of high-z massive star-forming galaxies that were deduced to have very large emitting dust masses.

- Given the youth of these galaxies, massive stars and their core-collapse SNe have been proposed to be the source of the dust found within them.

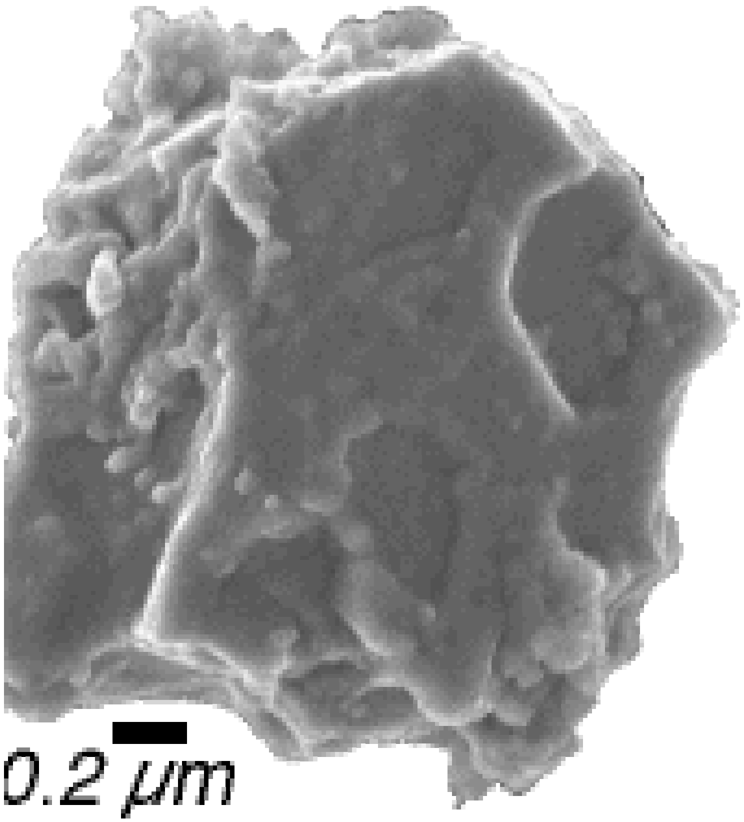
From dust nucleation modelling, Kozasa et al. (1991), Todini & Ferrara (2001) and subsequent authors have predicted that 0.1 - 1.0 solar masses of dust should condense in the ejecta of of a typical high-redshift core collapse supernovae within a few years of outburst, corresponding to a condensation efficiency for the available refractory elements of > 0.2. Similarly high condensation efficiencies appear to be required (Morgan & Edmunds 2004) to explain the ~10^8 solar masses of dust deduced to exist in some high redshift QSOs.

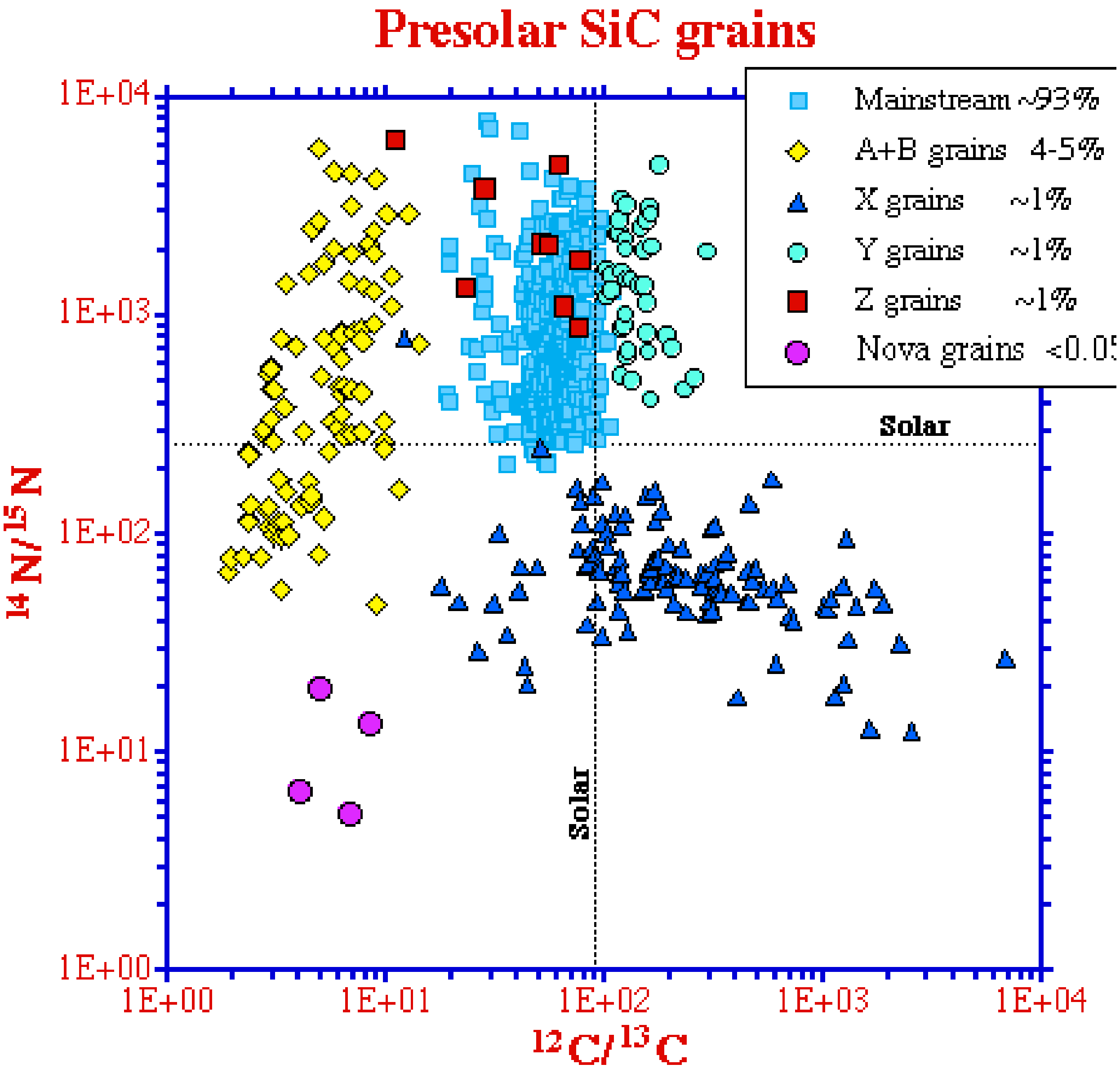
Onion-skin structure of a pre-supernova massive star



O-rich grains and C-rich grains can form in different layers of the ejecta

Pre-solar meteoritic grain inclusions include examples that are dominated by r-process isotopes, indicating a supernova origin





from http://presolar.wustl.edu/work/grains.html#SurfaceProperties

For the formation and survival of dust, a number of physical processes can be important:

(I) dust production by the progenitor before the SN event, producing a circumstellar (CS) shell, e.g. LBVs such as eta Carina.

(II) dust condensation in the SN ejecta

(III) destruction of ejecta dust by forward and reverse shocks in the SNR and destruction of CS dust by the UV/optical flash from the SN

(IV) dust condensation in a cool dense shock where the ejecta encounters a CS shell

(V) Destruction of interstellar dust by SN ejecta shockwaves

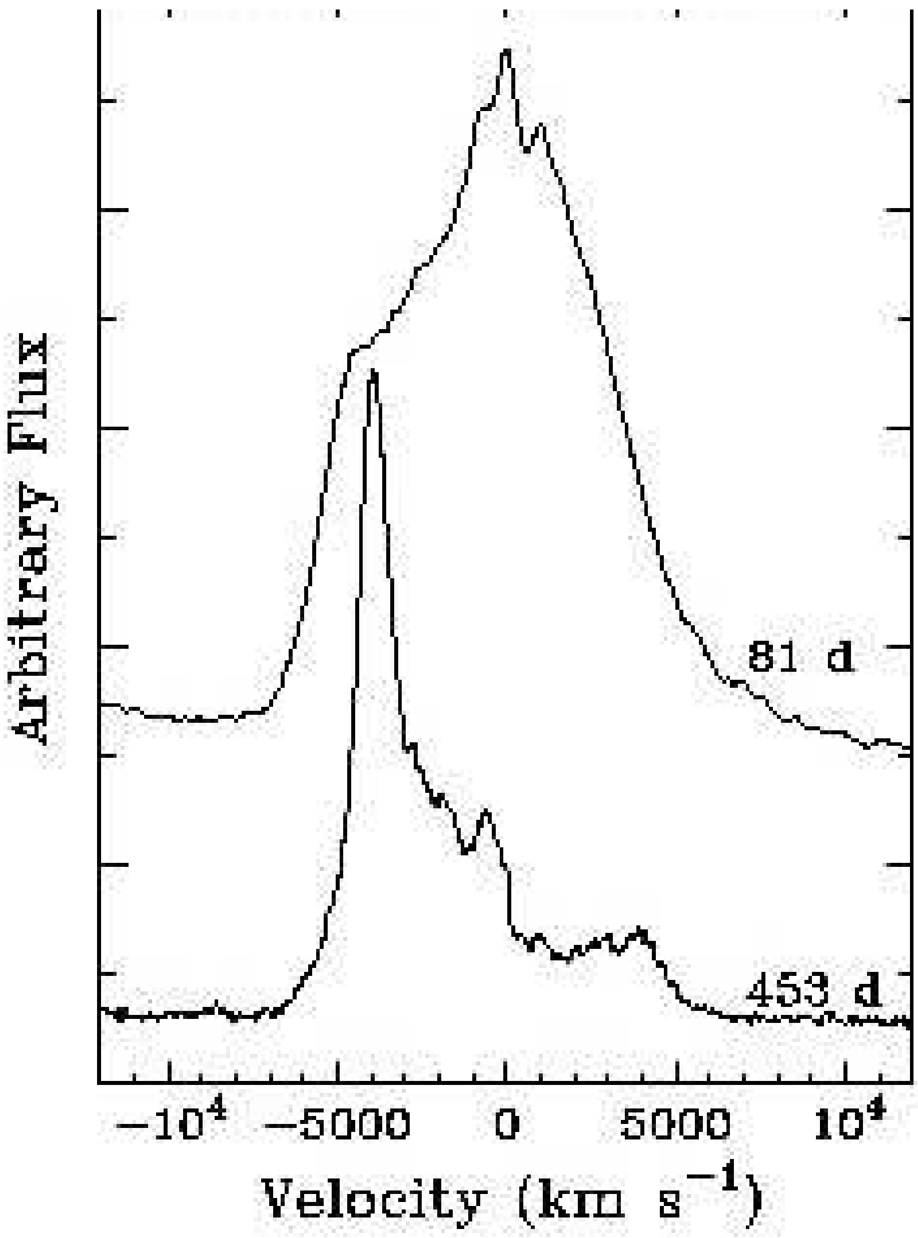
Three methods for detecting the formation of dust in young (<1000 days) supernovae ejecta:

(1) detection of thermal IR emission from the newly formed dust. However, the use of this method alone can be compromised by pre-existing nearby dust (e.g. circumstellar dust), which can be heated by the supernova light flash.

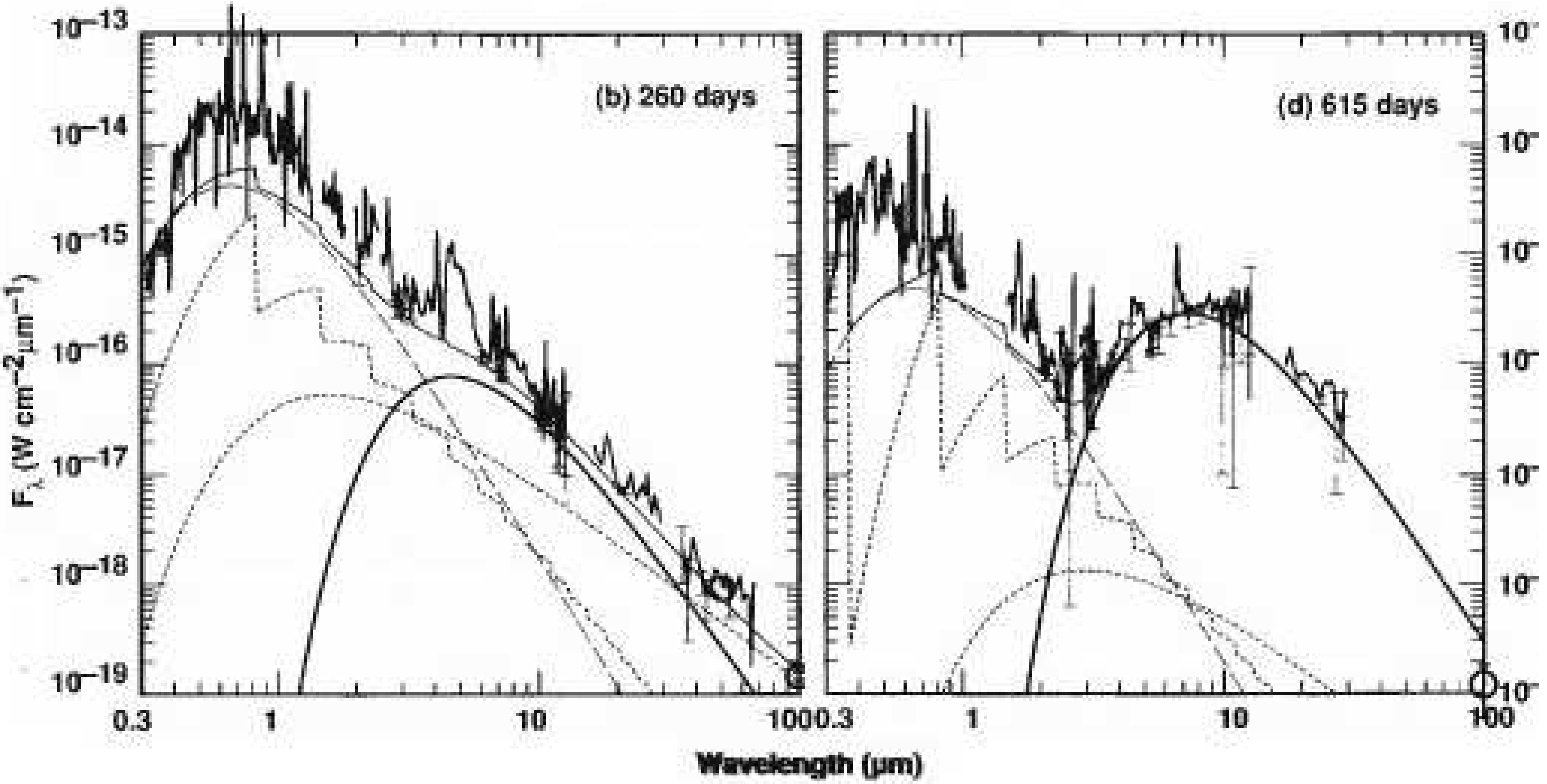
(2) detection of a dip in the SN light curve that can be attributed to extinction by newly formed dust. Pre-existing dust cannot produce such a dip.

(3) detection of the development of a red-blue asymmetry in the SN emission line profiles, attributable to the removal by newly formed dust of some of the redshifted emission from the far side of the SN ejecta (Lucy et al. 1989).

Method (1) is normally required if dust masses are to be derived, but it ought to be supported by one or both of (2) and (3).



Hα profile evolution for SN 1998S (from Leonard et al. 2000; see also Pozzo et al. 2004, who estimated that 10^{-3} M_{Sun} of dust had formed)



Optical and KAO IR spectrophotometry of SN 1987A, illustrating the onset of thermal dust emission by day 615. From Wooden et al. (1993).

Prior to the launch of the Spitzer Space Telescope, only a handful of SNe had been observed to form dust, with the prime example being SN 1987A. From ground-based and KAO optical to mid-IR observations, the derived mass of newly formed dust in SN 1987A up to day 1000 was estimated to be no more than ~10^{-3} solar masses (c.f. Wooden et al. 1993).

The SEEDS collaboration was formed to carry out sensitive mid-IR `Surveys for the Evolution of Emission from Dust in Supernovae’. Using primarily the Spitzer Space Telescope (SST) and the Gemini N and S telescopes, recent, nearby SNe were observed, to determine the extent to which massive star SNe and their progenitors produce dust, with the aim of quantifying their contribution to the dust budgets of galaxies.

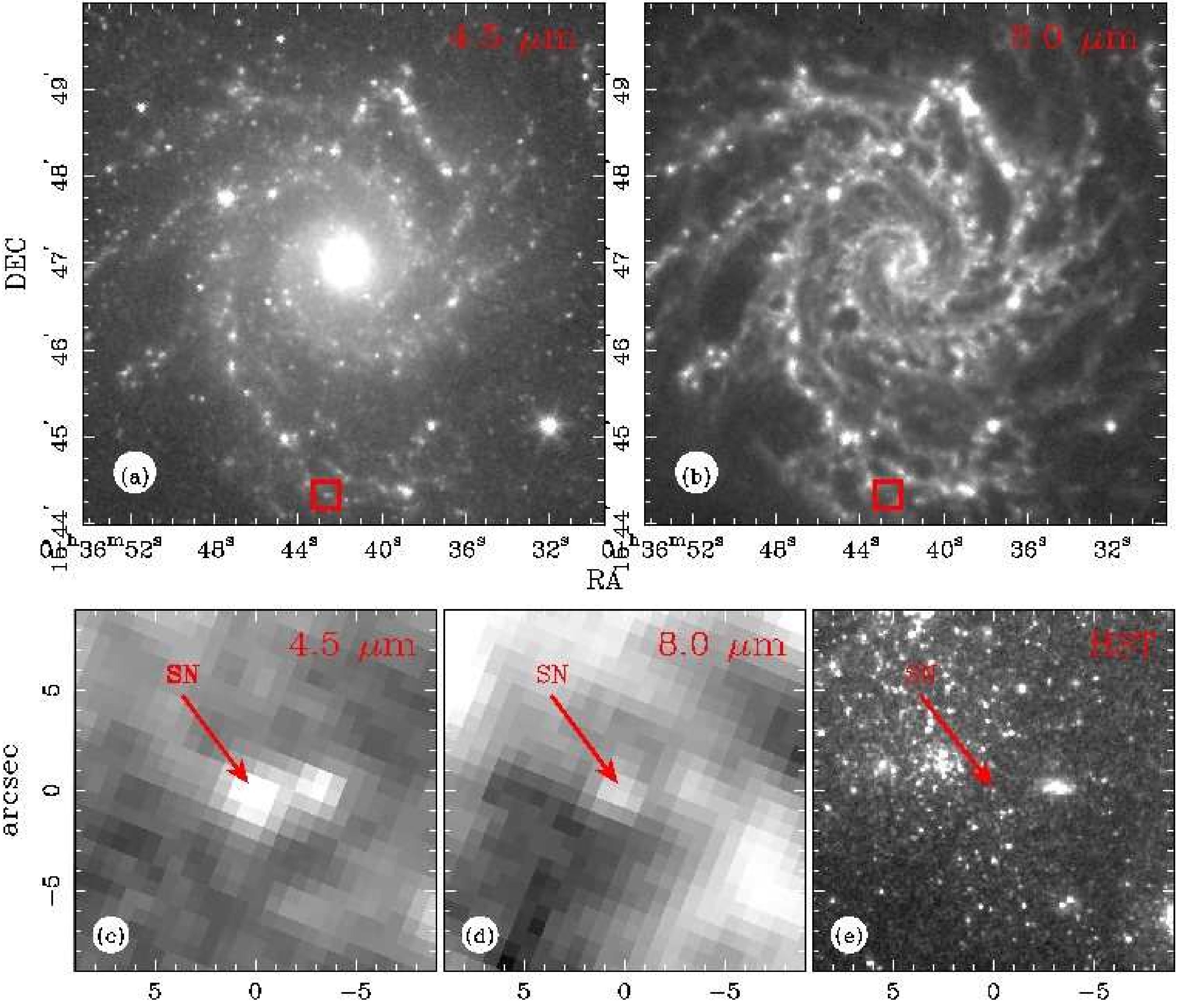
Used Gemini-N Michelle and Gemini-S TReCS from 2001, plus Spitzer Space Telescope IRAC 3.6-8.0μm, IRS 16um and MIPS 24μm photometric imaging observations from 2004, of massive-star supernovae that had occurred in relatively nearby galaxies (<15 Mpc) over the previous 1-4 years. Aim: to search for signatures of newly formed dust in the SN ejecta.

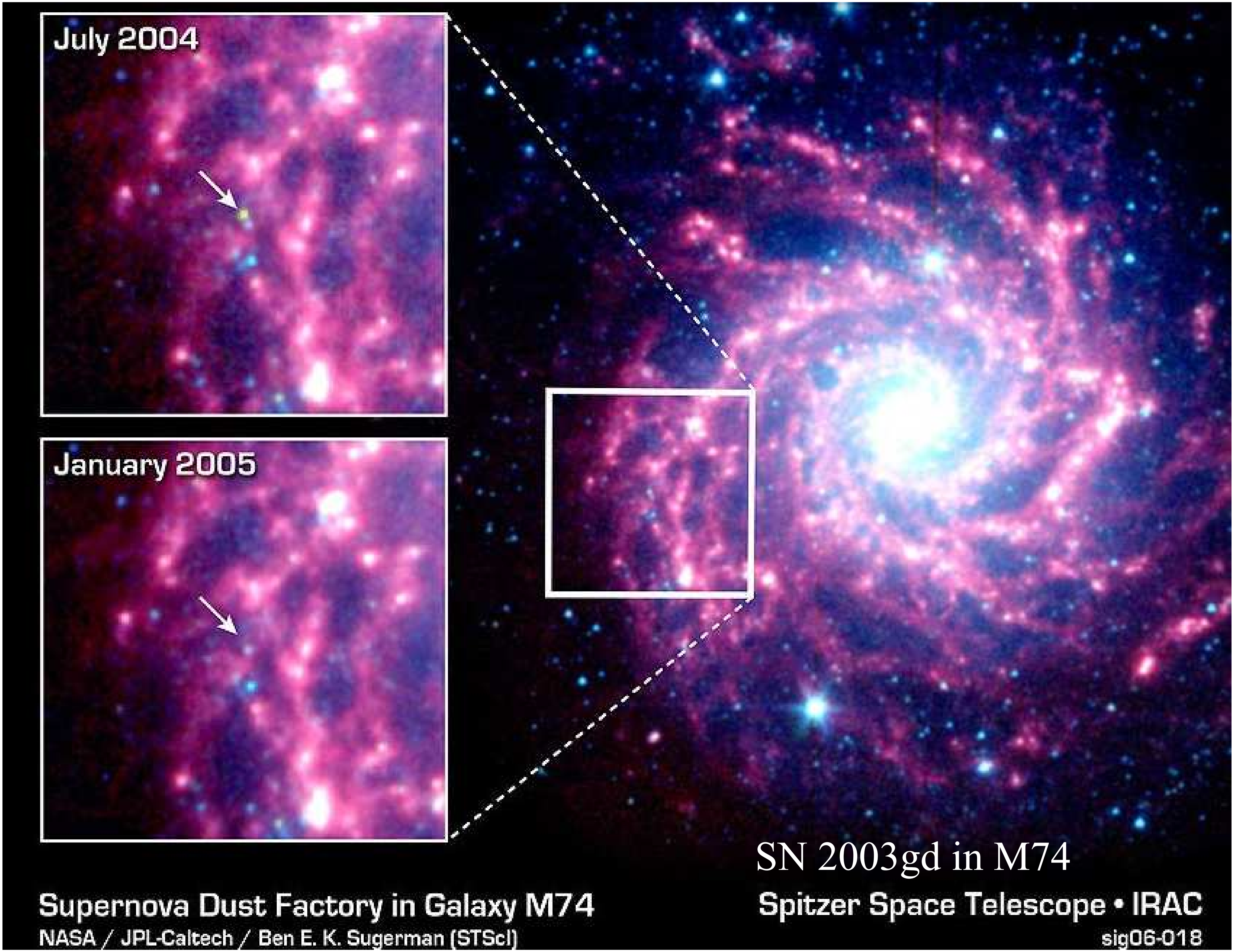
The emission from newly formed SN dust is expected to peak at mid-IR wavelengths, appearing after about 400 days (SN 1987A did this and current SN dust formation models predict it).

Also used SINGS Legacy Programme IRAC and MIPS imaging data for nearby galaxies that contained recent core collapse SNe.

An example: supernova SN 2003gd in NGC 628 (Messier 74)

Day
499





SN 2003gd in M74

Supernova Dust Factory in Galaxy M74

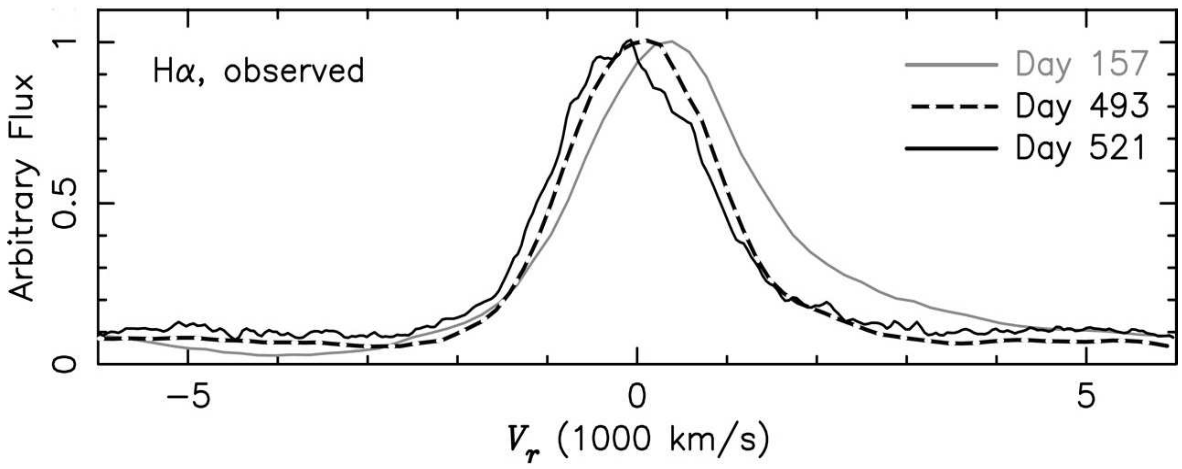
NASA / JPL-Caltech / Ben E. K. Sugerman (STScI)

Spitzer Space Telescope • IRAC

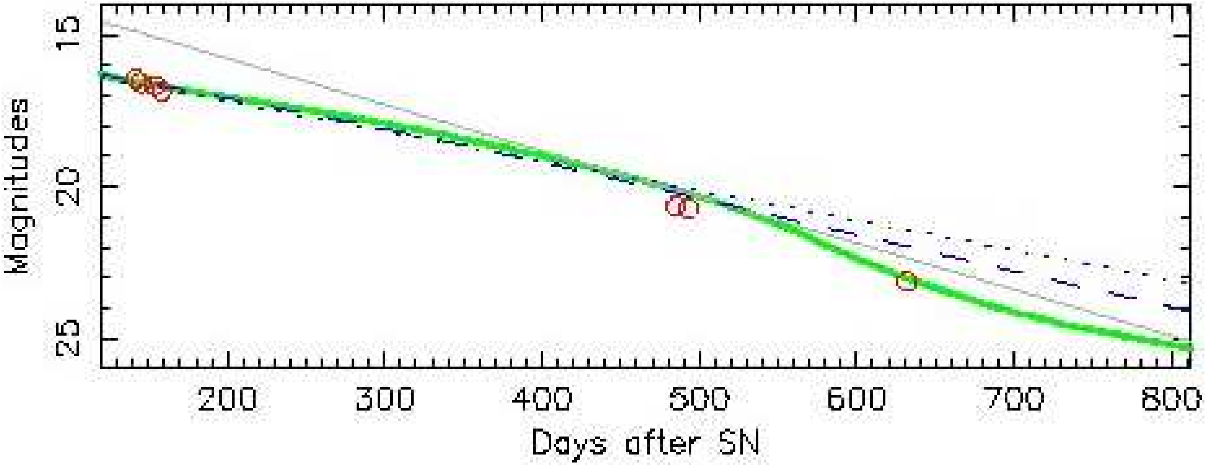
sig06-018

SN 2003gd, Type IIP, D = 9.3 Mpc

Further evidence for dust condensation in the SN ejecta:

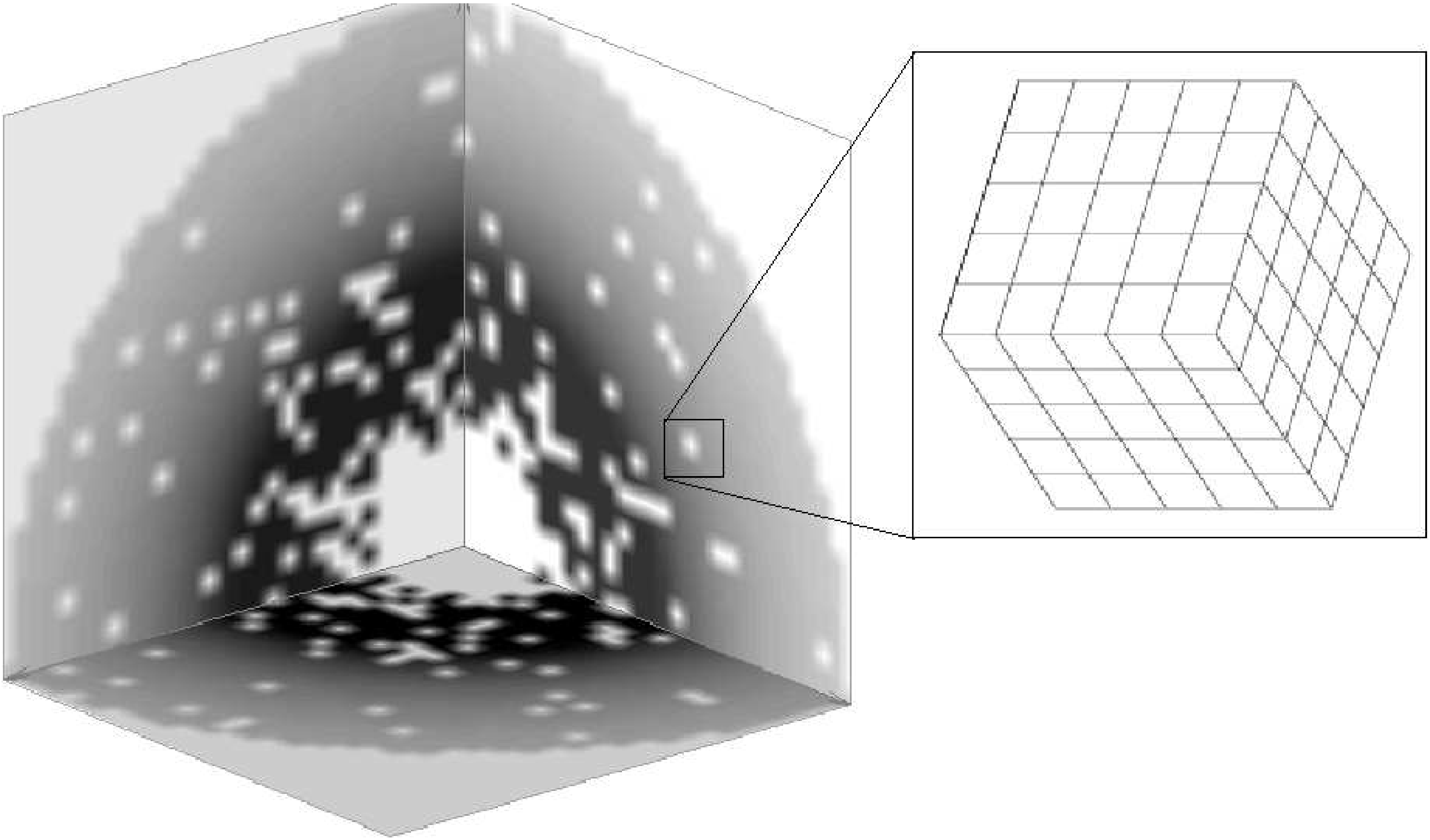


Asymmetric blue-shifted emission lines - dust forming in the ejecta preferentially extinguishes emission from receding (i.e. red-shifted) gas.



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 R on day 499 for 2003gd and 0.8 -1.9 mags on day 678.



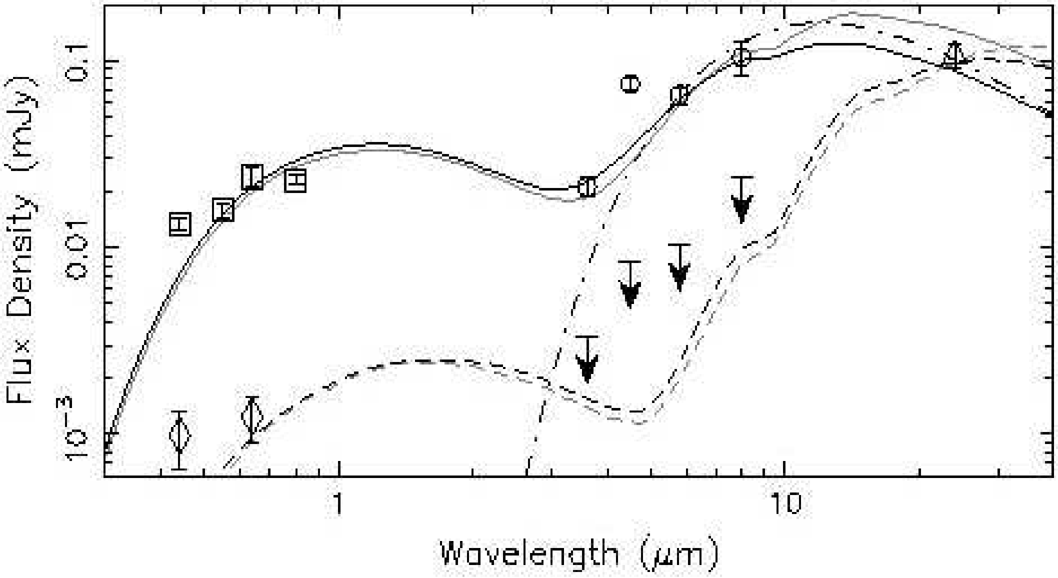
Clumpy SN ejecta models calculated with dusty-MOCCASIN using a mother-grid of 61^3 cells; mother cells that contain clumps are resolved by a subgrid of 5^3 cells. (from Ercolano et al. 2007)

SN 2003gd, Type IIP, D = 9.3 Mpc

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

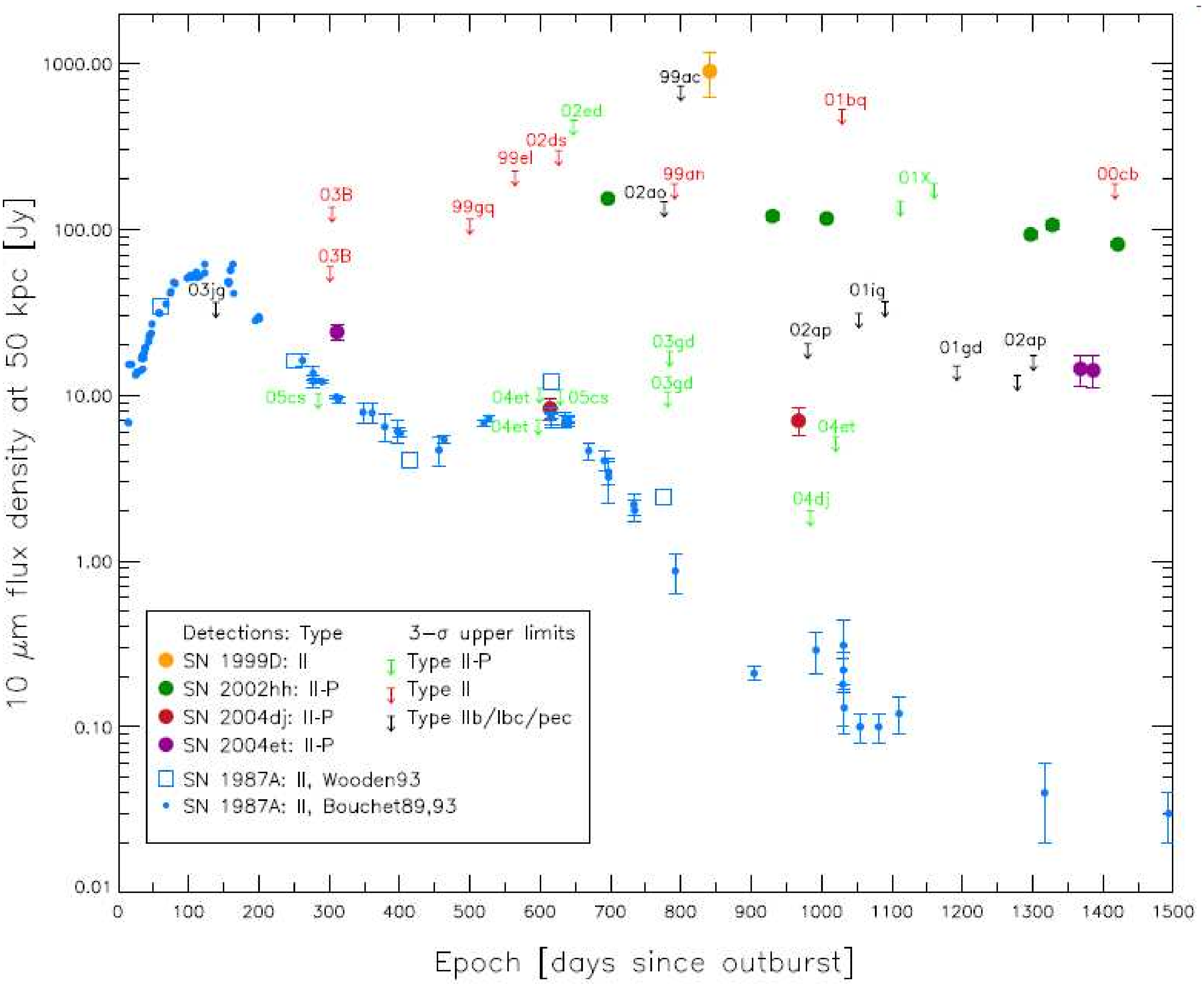
- Estimating the dust mass: 3-D Monte-Carlo RT code MOCASSIN (Ercolano et al. 2005) - Smooth and clumpy dust distributions modelled.
- Summary of the lower (smooth) and upper limits (clumpy) to the dust mass estimates shown in the table below.

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

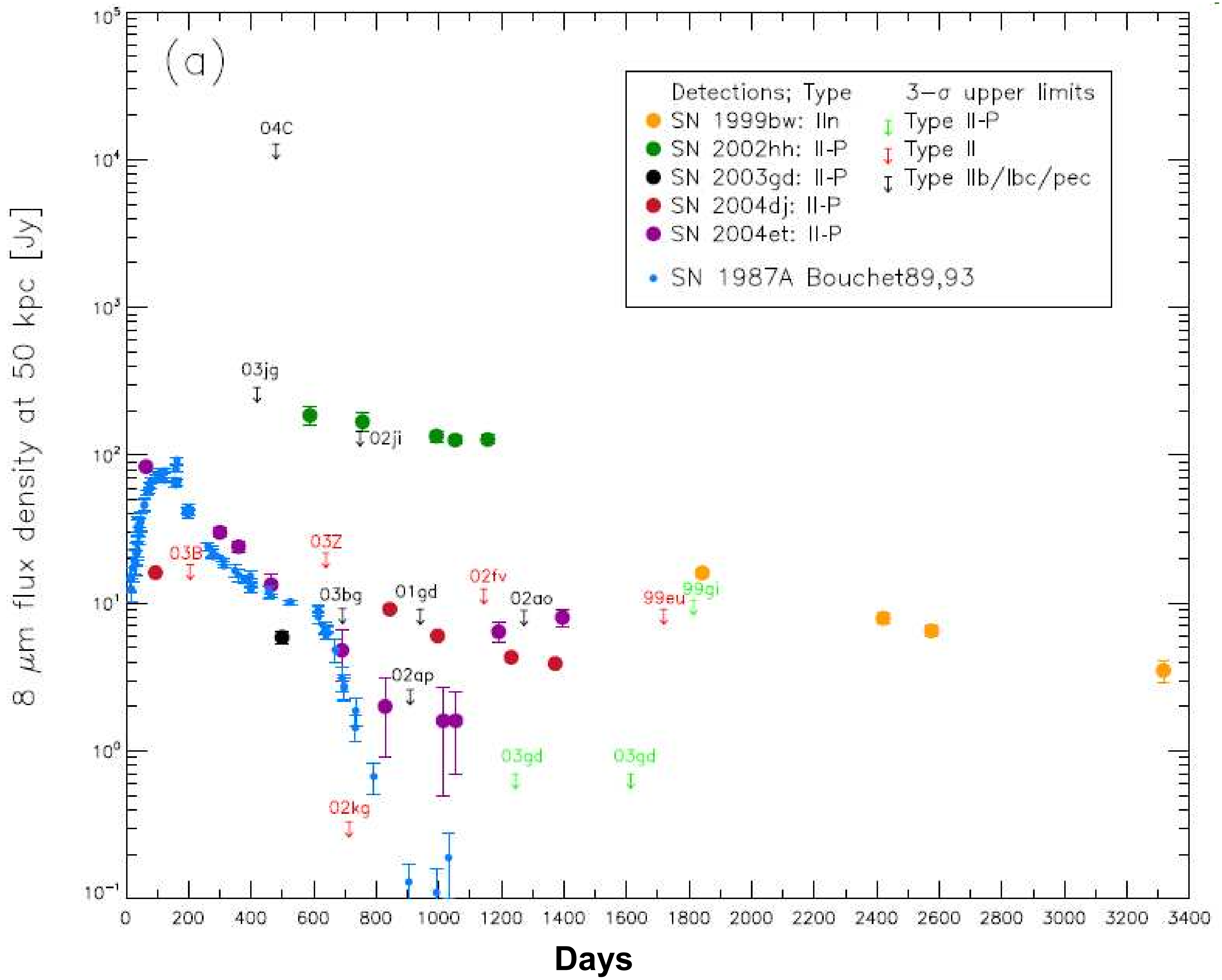


(from Sugerman et al. 2006)

Gemini 11um SN upper limits, scaled to SN1987A distance (50 kpc)



Spitzer 8um SN upper limits, scaled to SN1987A distance (50 kpc)



J. Fabbri (2011, PhD thesis); SEEDS collaboration: SN dust masses from mid-IR data

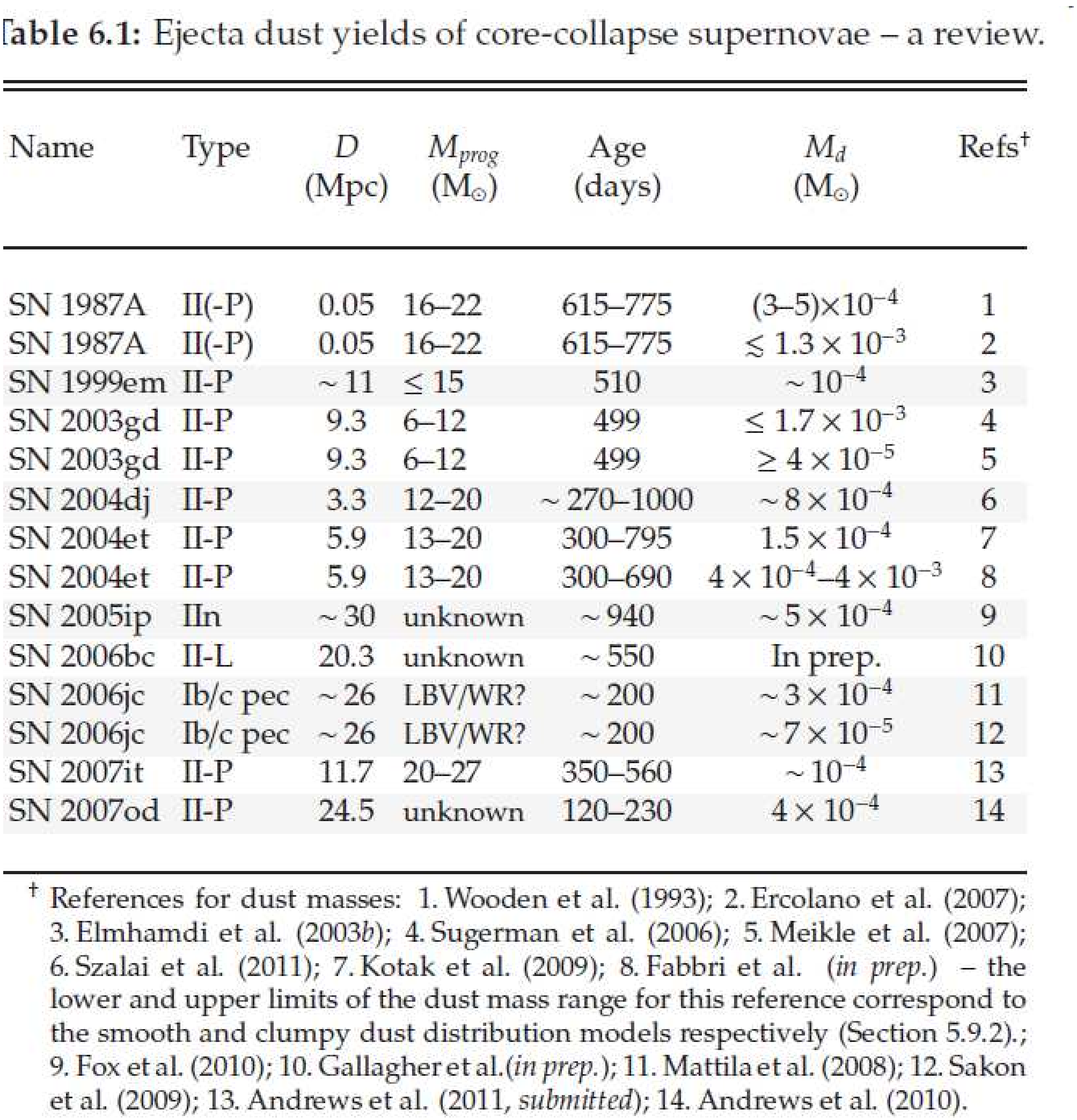


Table 6.1: Ejecta dust yields of core-collapse supernovae – a review.

Name	Type	D (Mpc)	M_{prog} ($M_\odot$)	Age (days)	M_d ($M_\odot$)	Refs[†]
SN 1987A	II(-P)	0.05	16–22	615–775	$(3–5)\times10^{-4}$	1
SN 1987A	II(-P)	0.05	16–22	615–775	$\lesssim 1.3\times10^{-3}$	2
SN 1999em	II-P	~ 11	≤ 15	510	$\sim 10^{-4}$	3
SN 2003gd	II-P	9.3	6–12	499	$\lesssim 1.7\times10^{-3}$	4
SN 2003gd	II-P	9.3	6–12	499	$\gtrsim 4\times10^{-5}$	5
SN 2004dj	II-P	3.3	12–20	$\sim$ 270–1000	$\sim 8\times10^{-4}$	6
SN 2004et	II-P	5.9	13–20	300–795	1.5×10^{-4}	7
SN 2004et	II-P	5.9	13–20	300–690	$4\times10^{-4}–4\times10^{-3}$	8
SN 2005ip	IIn	~ 30	unknown	~ 940	$\sim 5\times10^{-4}$	9
SN 2006bc	II-L	20.3	unknown	~ 550	In prep.	10
SN 2006jc	Ib/c pec	~ 26	LBV/WR?	~ 200	$\sim 3\times10^{-4}$	11
SN 2006jc	Ib/c pec	~ 26	LBV/WR?	~ 200	$\sim 7\times10^{-5}$	12
SN 2007it	II-P	11.7	20–27	350–560	$\sim 10^{-4}$	13
SN 2007od	II-P	24.5	unknown	120–230	4×10^{-4}	14

[†] References for dust masses: 1. Wooden et al. (1993); 2. Ercolano et al. (2007); 3. Elmhamdi et al. (2003*b*); 4. Sugerman et al. (2006); 5. Meikle et al. (2007); 6. Szalai et al. (2011); 7. Kotak et al. (2009); 8. Fabbri et al. (*in prep.*) – the lower and upper limits of the dust mass range for this reference correspond to the smooth and clumpy dust distribution models respectively (Section 5.9.2).; 9. Fox et al. (2010); 10. Gallagher et al. (*in prep.*); 11. Mattila et al. (2008); 12. Sakon et al. (2009); 13. Andrews et al. (2011, *submitted*); 14. Andrews et al. (2010).

SN1987A: 1-2x10^{-3} Msun of dust after 2 years.

J. Fabbri (2011, PhD thesis); SEEDS collaboration

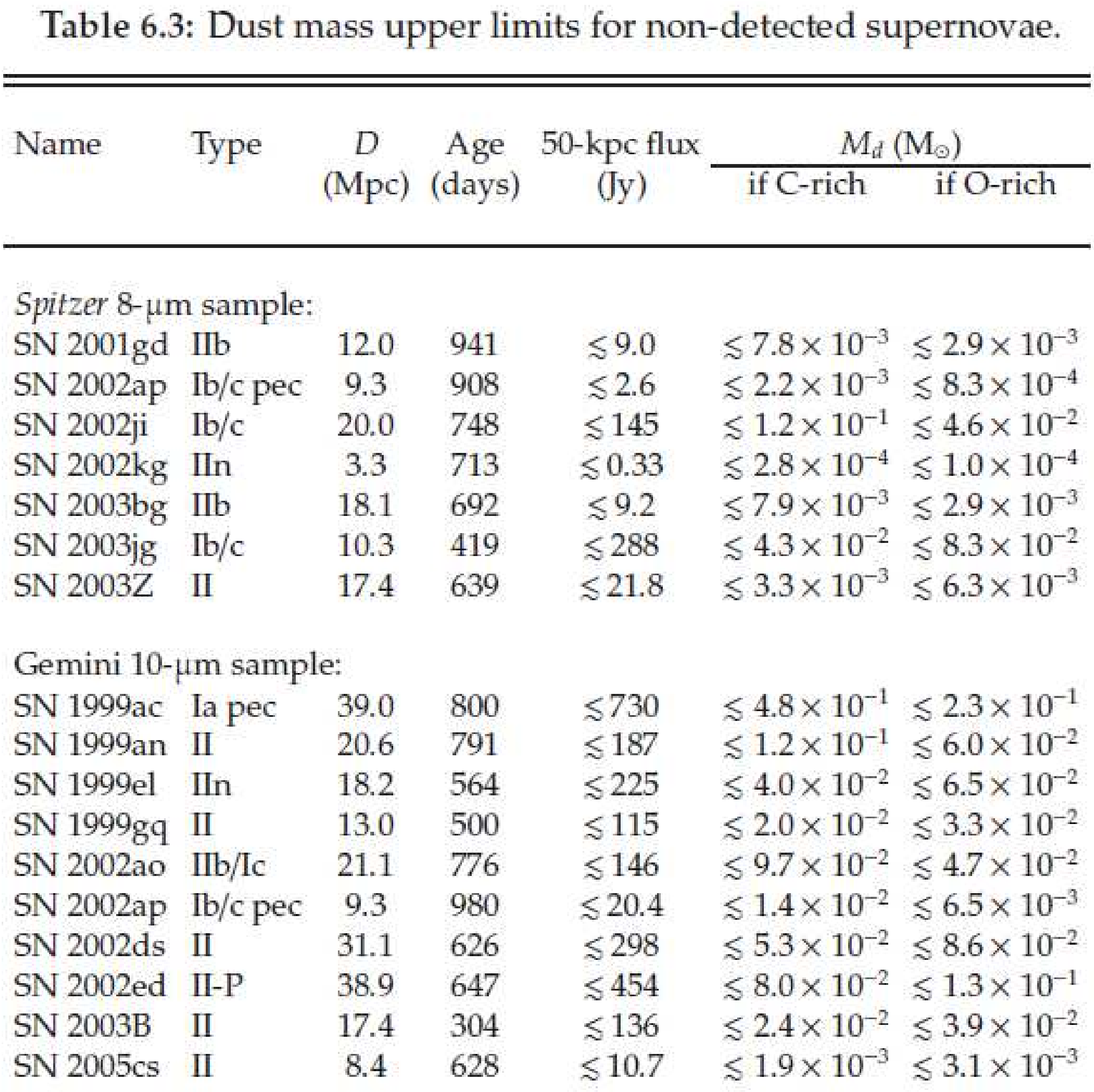


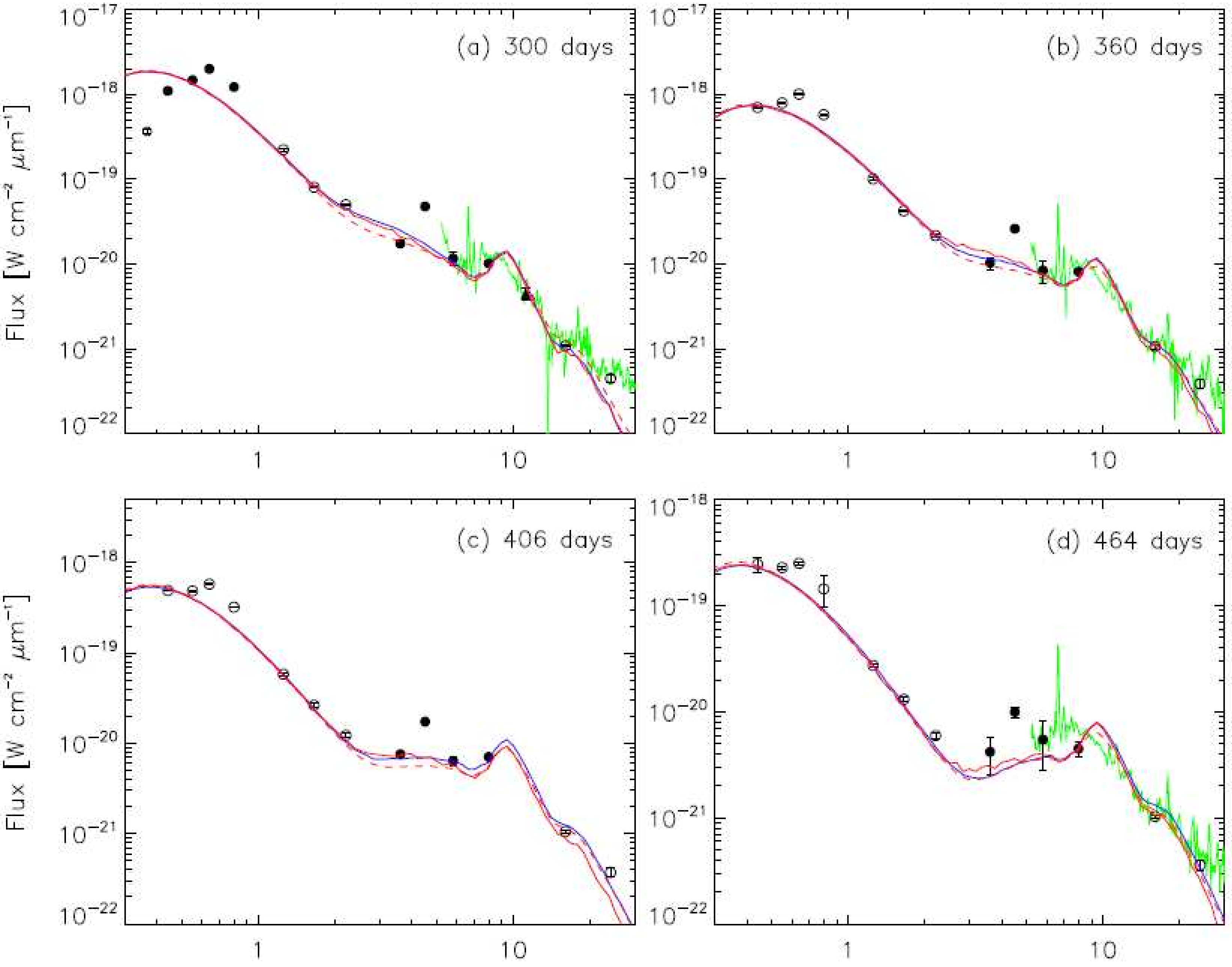
Table 6.3: Dust mass upper limits for non-detected supernovae.

Name	Type	D (Mpc)	Age (days)	50-kpc flux (Jy)	M_d (M$_\odot$) if C-rich	M_d (M$_\odot$) if O-rich
Spitzer 8-μm sample:						
SN 2001gd	IIb	12.0	941	$\lesssim 9.0$	$\lesssim 7.8\times10^{-3}$	$\lesssim 2.9\times10^{-3}$
SN 2002ap	Ib/c pec	9.3	908	$\lesssim 2.6$	$\lesssim 2.2\times10^{-3}$	$\lesssim 8.3\times10^{-4}$
SN 2002ji	Ib/c	20.0	748	$\lesssim 145$	$\lesssim 1.2\times10^{-1}$	$\lesssim 4.6\times10^{-2}$
SN 2002kg	IIn	3.3	713	$\lesssim 0.33$	$\lesssim 2.8\times10^{-4}$	$\lesssim 1.0\times10^{-4}$
SN 2003bg	IIb	18.1	692	$\lesssim 9.2$	$\lesssim 7.9\times10^{-3}$	$\lesssim 2.9\times10^{-3}$
SN 2003jg	Ib/c	10.3	419	$\lesssim 288$	$\lesssim 4.3\times10^{-2}$	$\lesssim 8.3\times10^{-2}$
SN 2003Z	II	17.4	639	$\lesssim 21.8$	$\lesssim 3.3\times10^{-3}$	$\lesssim 6.3\times10^{-3}$
Gemini 10-μm sample:						
SN 1999ac	Ia pec	39.0	800	$\lesssim 730$	$\lesssim 4.8\times10^{-1}$	$\lesssim 2.3\times10^{-1}$
SN 1999an	II	20.6	791	$\lesssim 187$	$\lesssim 1.2\times10^{-1}$	$\lesssim 6.0\times10^{-2}$
SN 1999el	IIn	18.2	564	$\lesssim 225$	$\lesssim 4.0\times10^{-2}$	$\lesssim 6.5\times10^{-2}$
SN 1999gq	II	13.0	500	$\lesssim 115$	$\lesssim 2.0\times10^{-2}$	$\lesssim 3.3\times10^{-2}$
SN 2002ao	IIb/Ic	21.1	776	$\lesssim 146$	$\lesssim 9.7\times10^{-2}$	$\lesssim 4.7\times10^{-2}$
SN 2002ap	Ib/c pec	9.3	980	$\lesssim 20.4$	$\lesssim 1.4\times10^{-2}$	$\lesssim 6.5\times10^{-3}$
SN 2002ds	II	31.1	626	$\lesssim 298$	$\lesssim 5.3\times10^{-2}$	$\lesssim 8.6\times10^{-2}$
SN 2002ed	II-P	38.9	647	$\lesssim 454$	$\lesssim 8.0\times10^{-2}$	$\lesssim 1.3\times10^{-1}$
SN 2003B	II	17.4	304	$\lesssim 136$	$\lesssim 2.4\times10^{-2}$	$\lesssim 3.9\times10^{-2}$
SN 2005cs	II	8.4	628	$\lesssim 10.7$	$\lesssim 1.9\times10^{-3}$	$\lesssim 3.1\times10^{-3}$

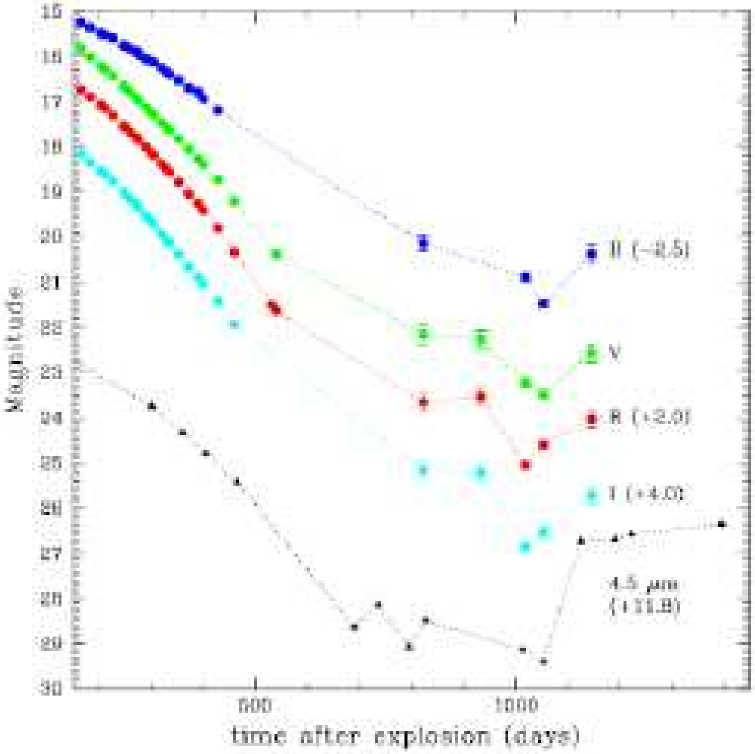
- Recent work on two supernovae, SN 2004et and SN 2008S
- Both erupted in NGC 6946 (a supernova factory; 9 since 1917)

SN 2004et (Fabbri et al. MNRAS, in press)

3×10^{-3} Msun of dust formed by day 690

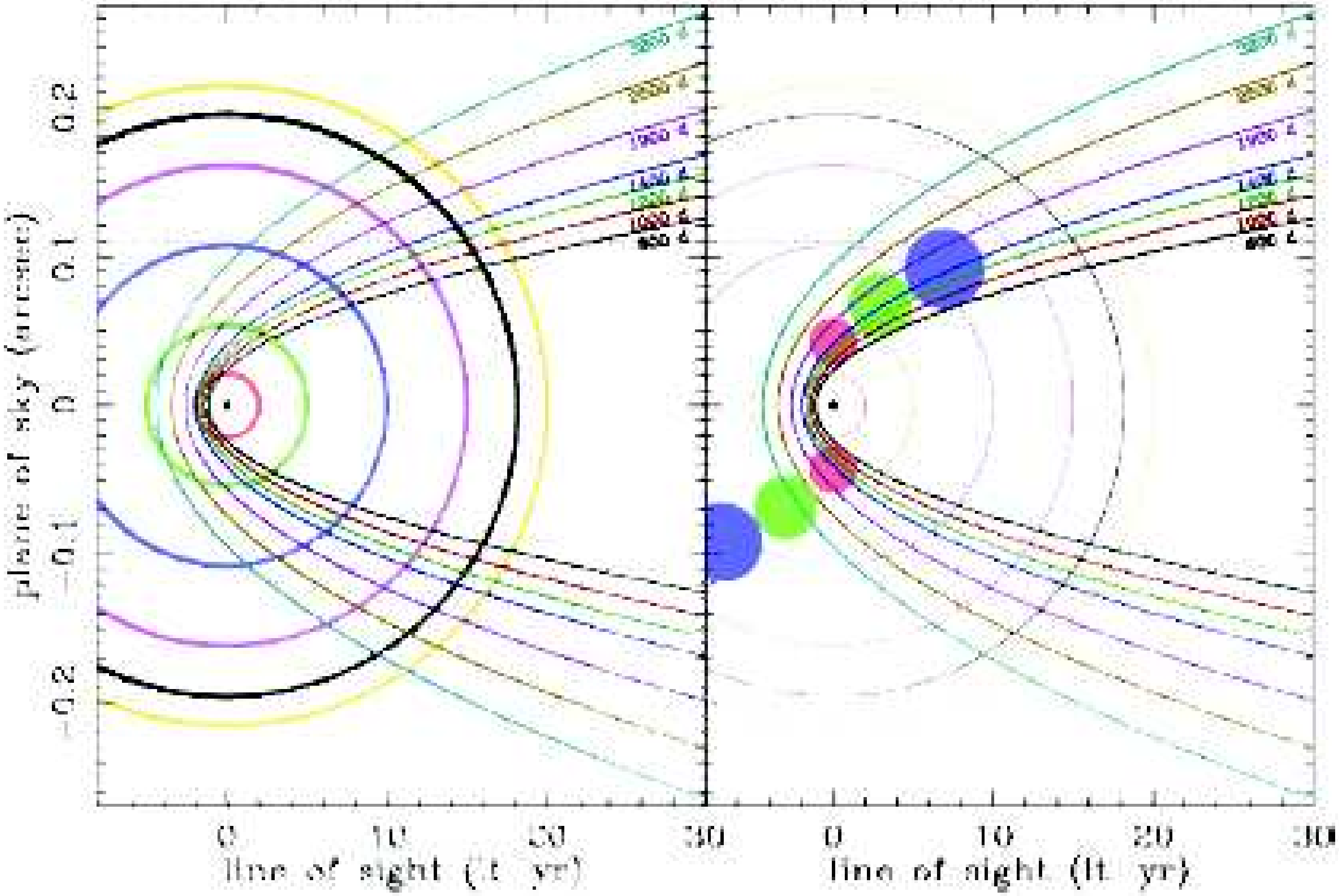


- Then, at around day 1000, it re-brightened at all wavelengths, but remained unresolved with HST on day 1216



- Appears to be a light echo from pre-existing circumstellar dust
- Sugerman, Wesson et al (in prep.)

- Timing of echo and HST observations place strong constraints on location of echoing material

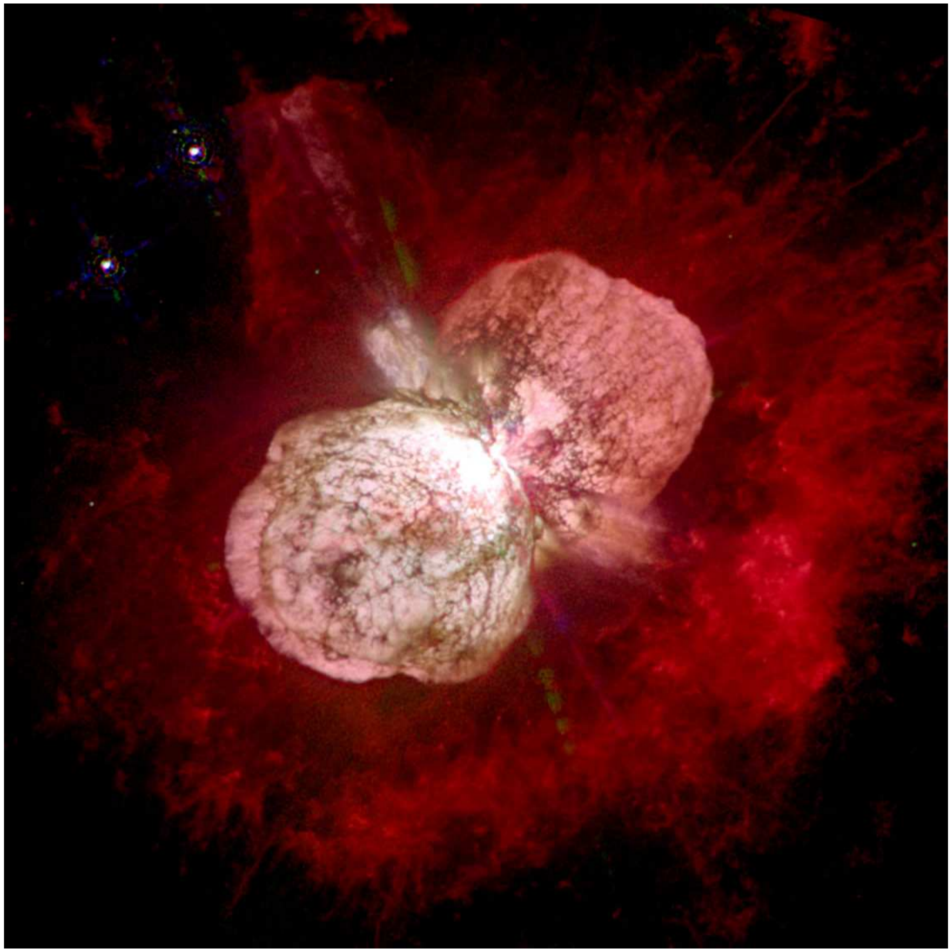


SN 2004et

- RT modelling of echo shows that a toroidal ring of dust can account for observed IR SED evolution
- Mass of dust in toroid is $\sim 0.025 M_{\odot}$
- Models of the IR emission during first 1000 days show formation of $3 \times 10^{-3} M_{\odot}$
- So total mass is $\sim 0.03 M_{\odot}$ - getting closer to the quantities required to explain high-z dust

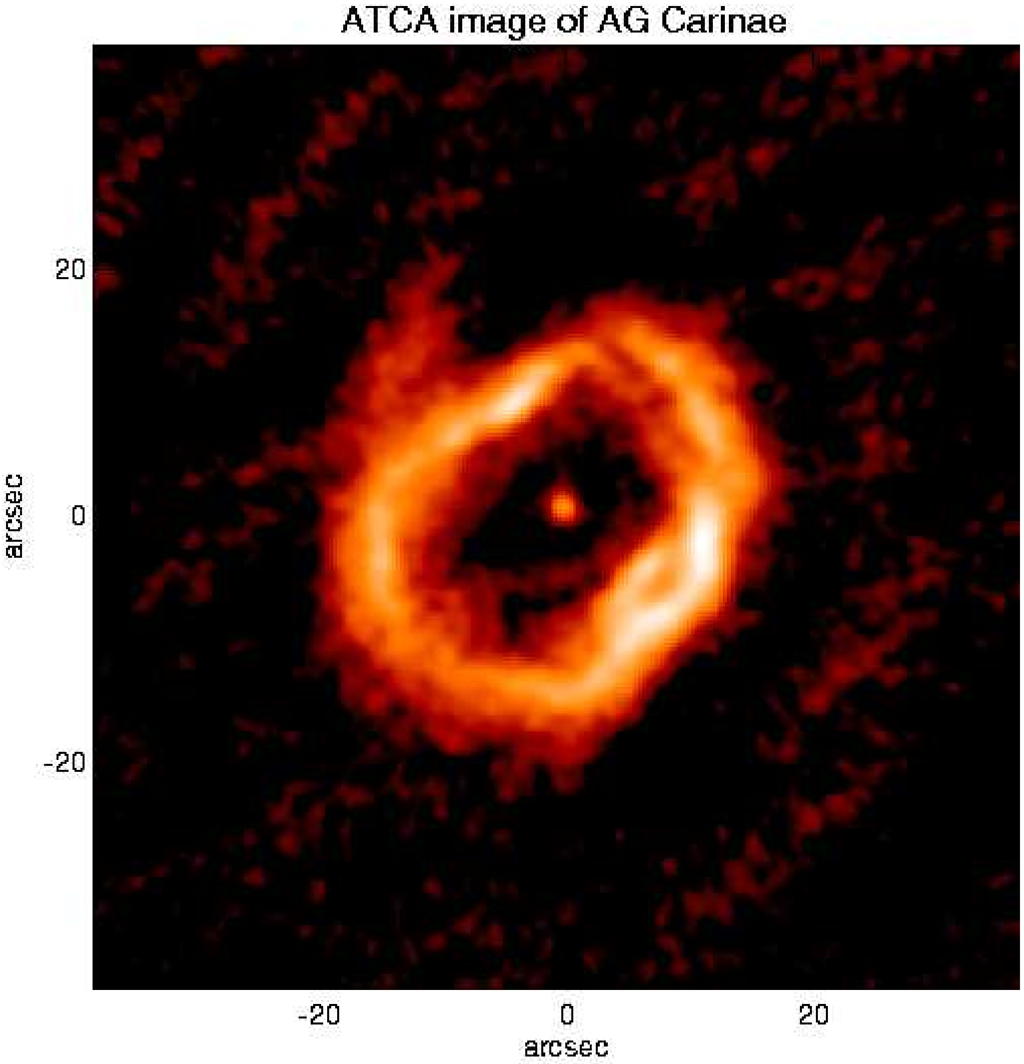
Dust creation by Luminous Blue Variable (LBV) events

Eta Carinae



Gomez et al. (2009): LABOCA -> 0.4 Msun of 82K dust; created in 1848 outburst

AG Carinae



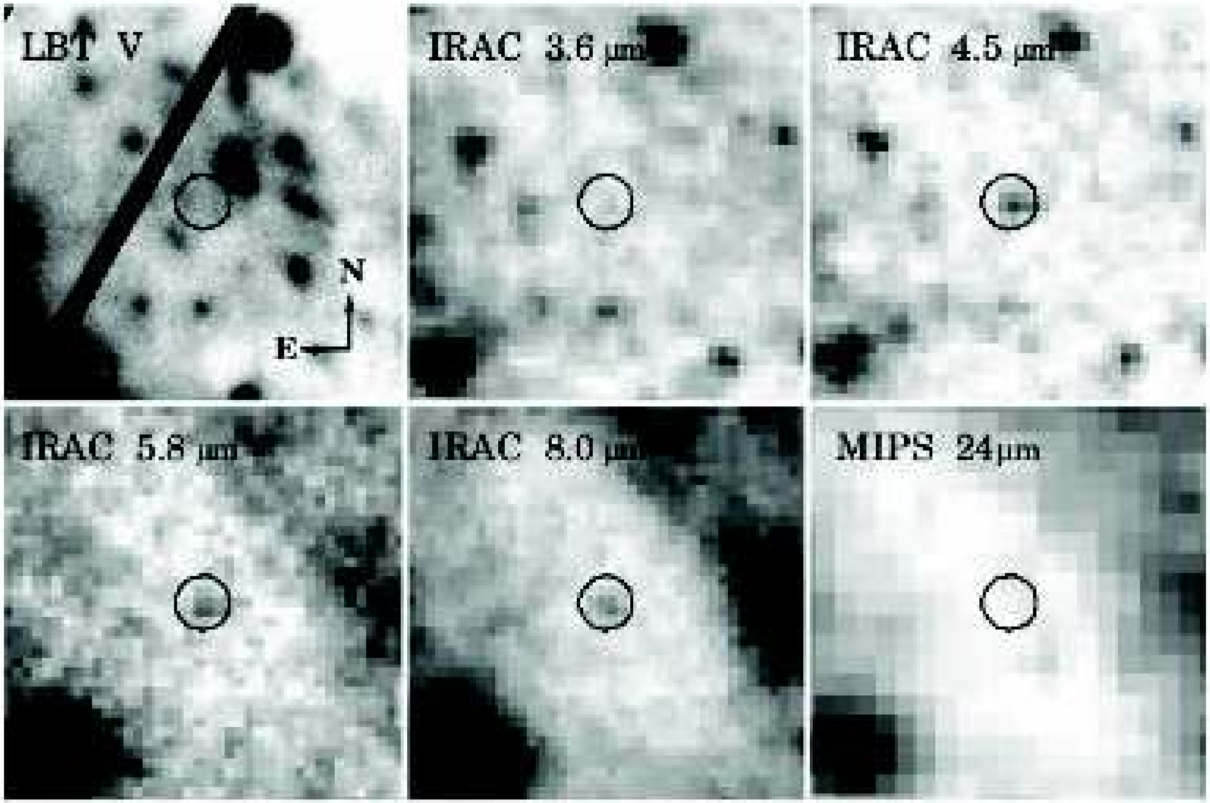
Voors et al. (2009): ISO -> 0.25 Msun of dust

Super-AGB Stars? SN 2008S in NGC 6946

3^{rd} SN in last decade in NGC 6946 (9^{th} since 1917)

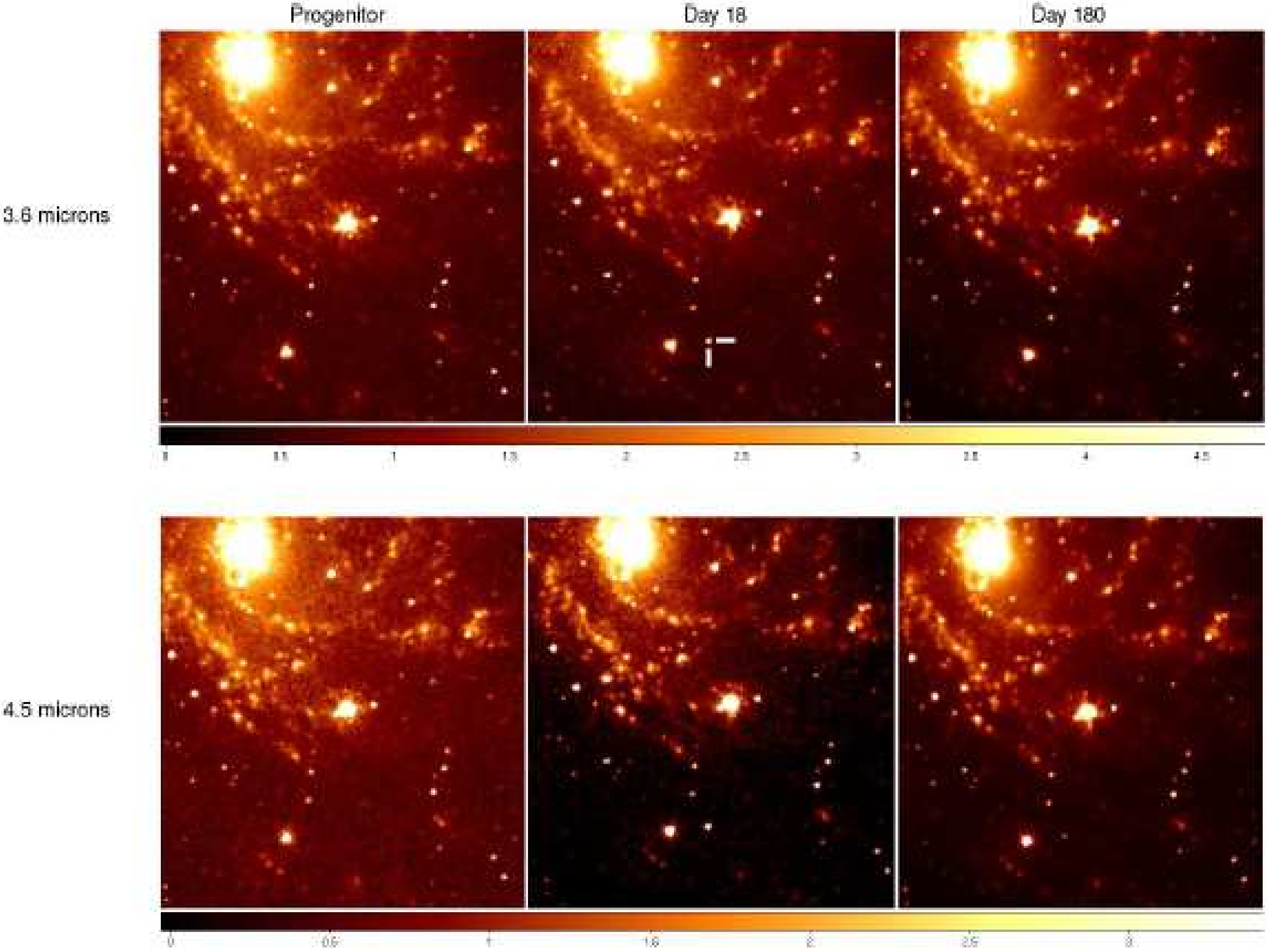
- Discovered in Feb 2008.
- Serendipitous pre-explosion optical images revealed no progenitor
- But a mid-IR source was observed in *Spitzer* images

Prieto et al. 2008

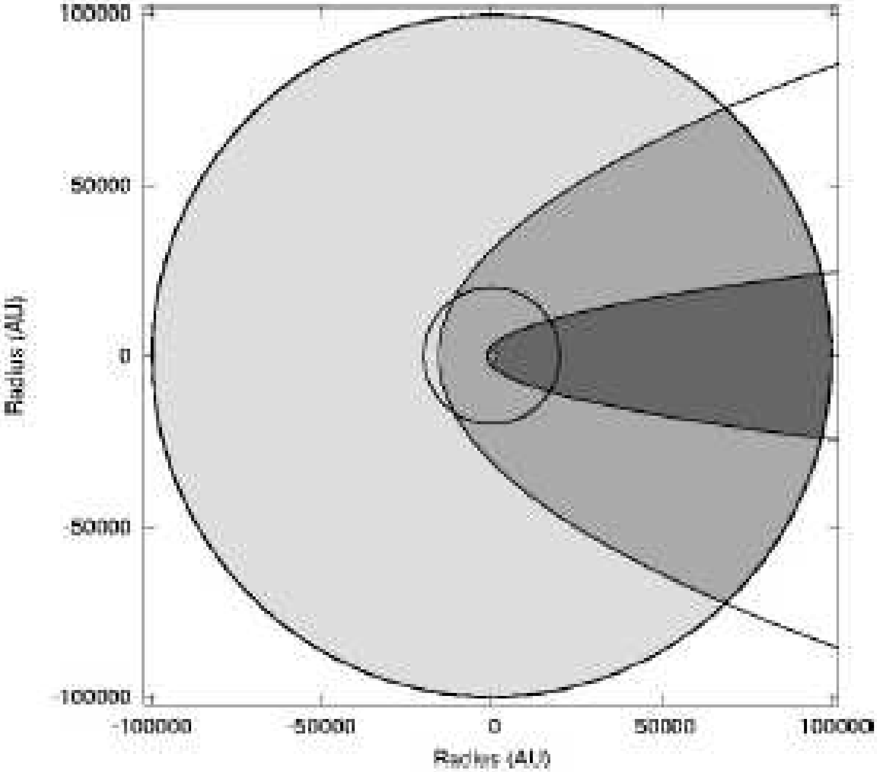


- Spitzer observations of SN 2002hh in Feb and July 2008 detected the new object in the mid-IR

  (Wesson et al. 2010, MNRAS)



- Constructed models using MOCASSIN. Carbon shell with $\rho \propto r^{-2}$ used for all epochs
- Light travel time has to be accounted for - easy with a 3D code

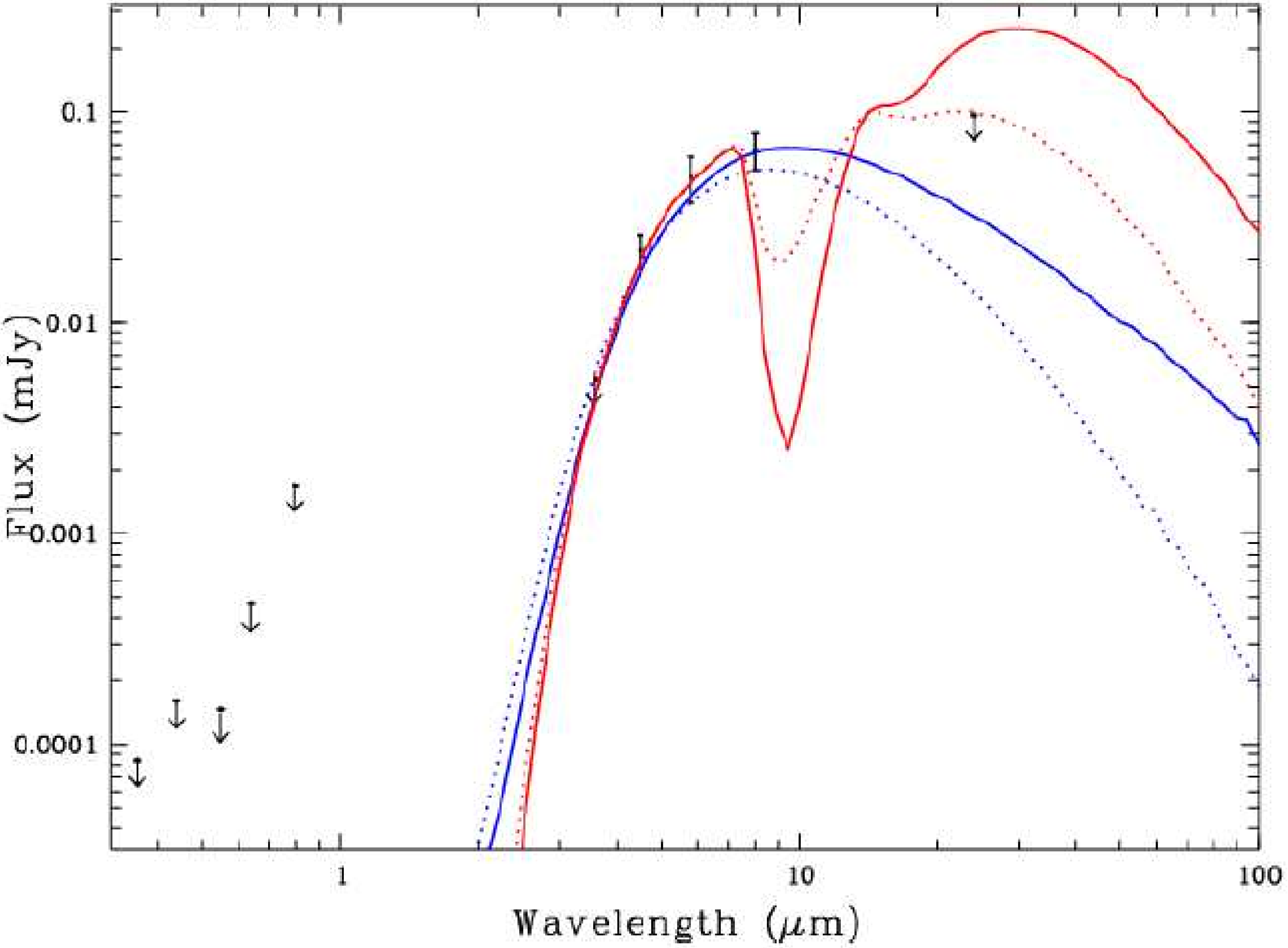


- Observations give strong constraints on inner radius and dust composition
- Little constraint on outer radius and therefore total mass

SN 2008S in NGC 6946
Pre-outburst SED

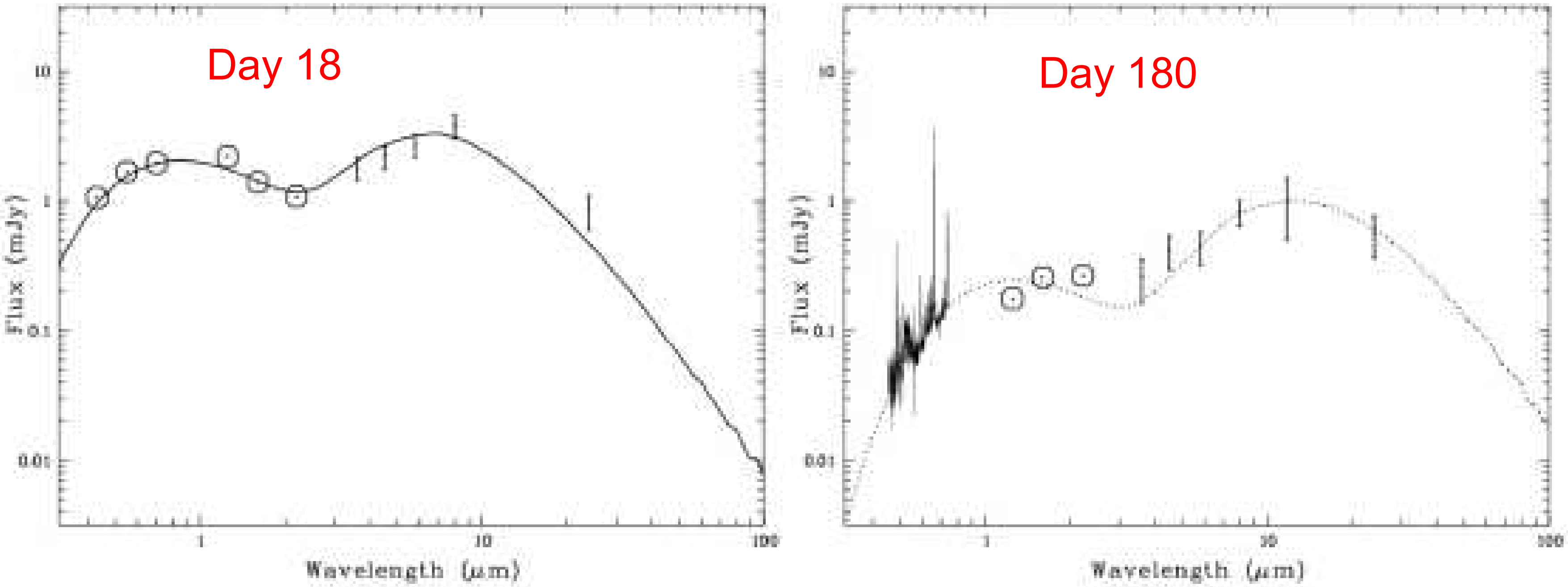
blue: carbon dust

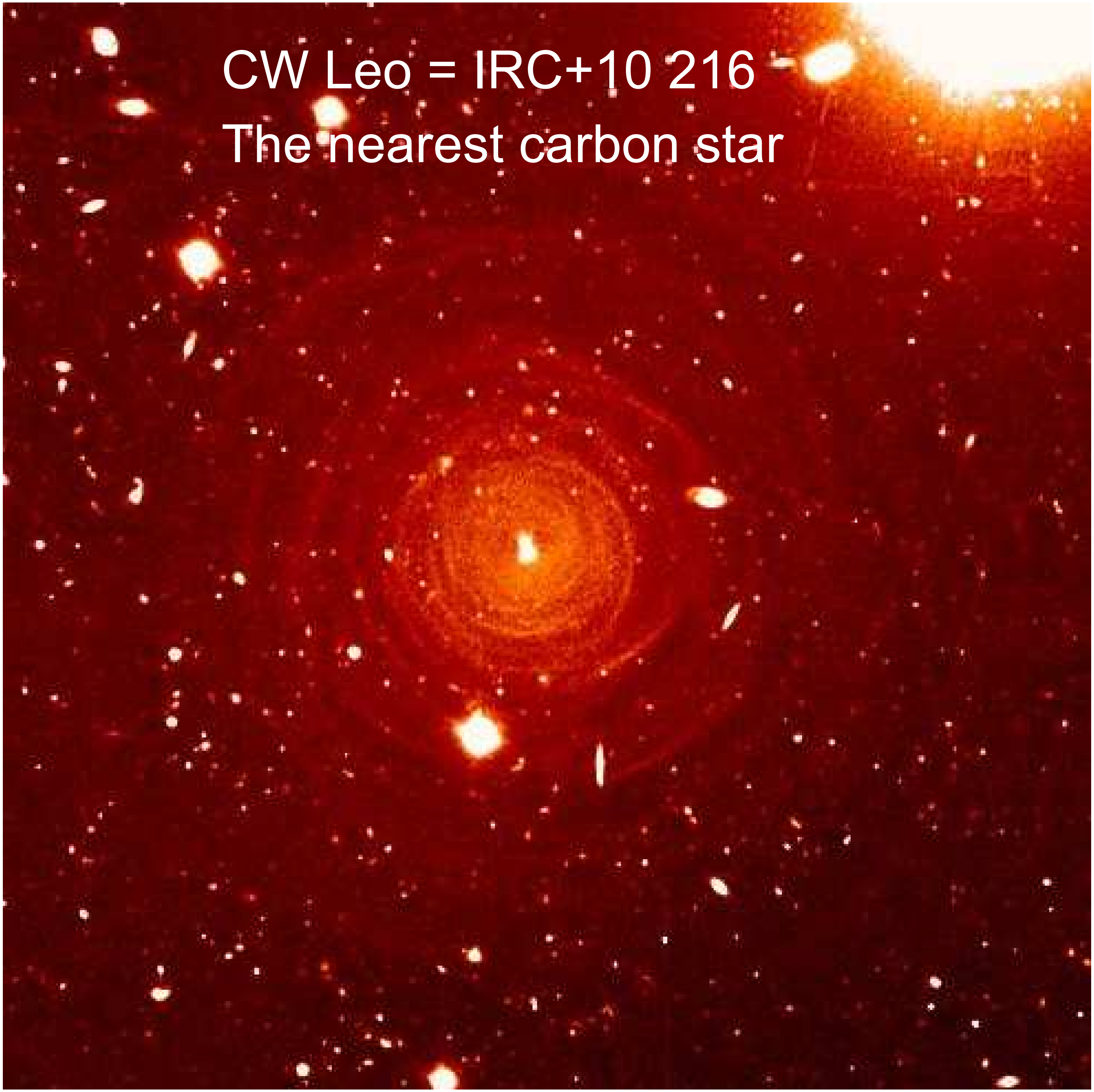
red: silicate dust



- Outburst removed all dust within 1250AU
- Increasing inner radius makes huge difference to optical depth, but small difference to total mass
- τ_V reduced from 13.4 to 0.76; M_{dust} reduced by only 2%
- Surviving dust mass up to 0.01 $M_\odot$

SN 2008S





CW Leo = IRC+10 216
The nearest carbon star

Analogous to the progenitor of SN 2008S?

Image by Leao et al. (2006)

Visual band; ESO 8m VLT

200”x200” FoV

Distance ~135 pc

Av ~ 20 mags

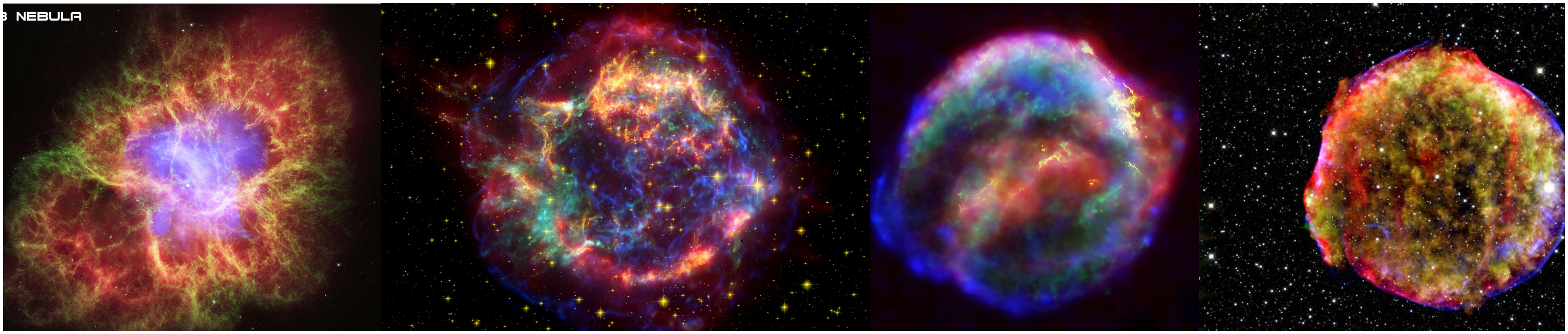
- Was SN 2008S actually a supernova? Jury is still out
- Thompson et al. (2009) posit existence of new class of transient - SN 2008S, NGC300-OT and M85-OT are examples
- Progenitor mass estimated to be 6-10$M_\odot$
- If all stars in this mass range produce 0.01$M_\odot$ of dust, their input into young galaxies is comparable to the input by t<1000d supernovae

Herschel MESS SNR Observing Programme

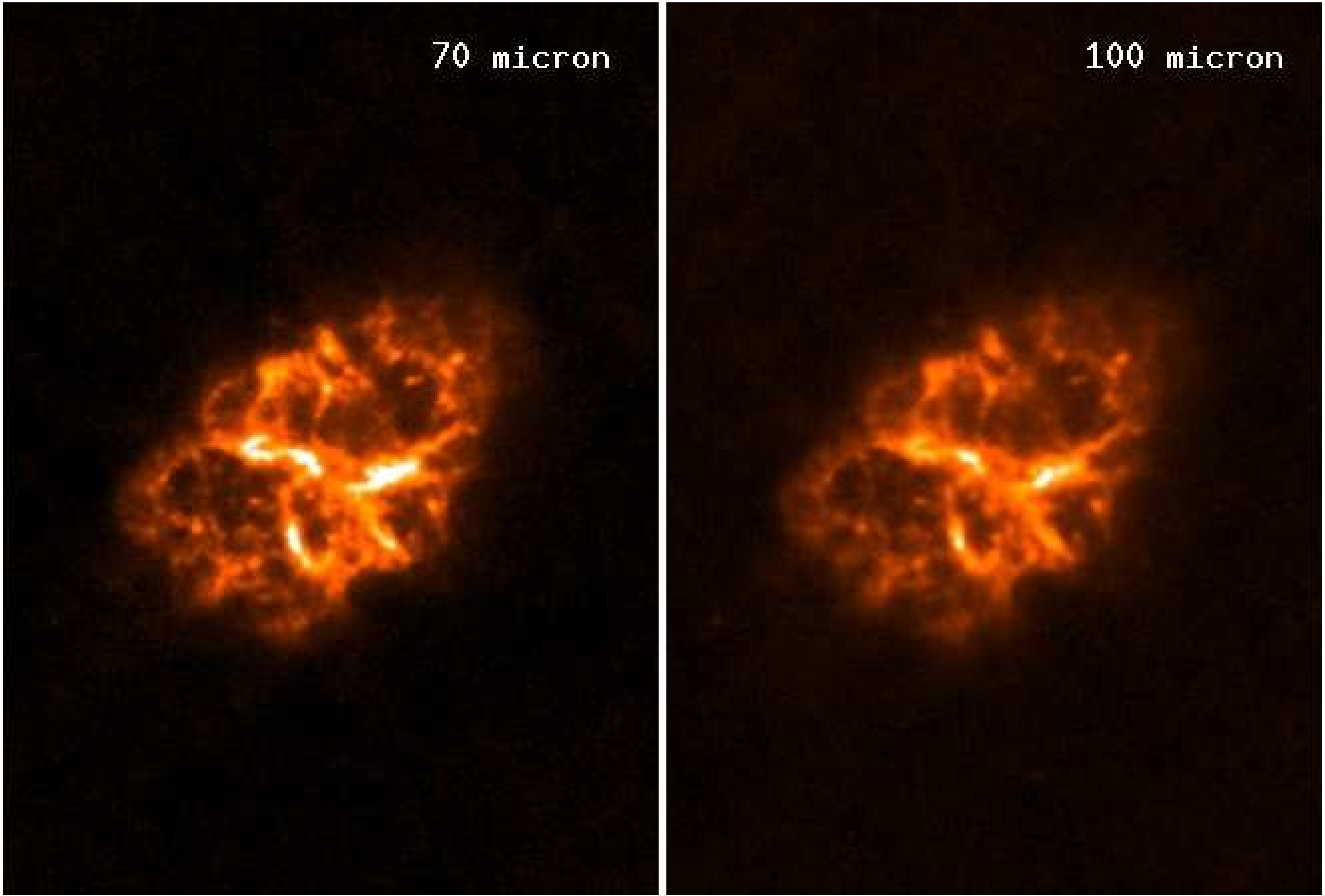
Targets: 5 young Galactic supernova remnants

1680	IIb	(Cas A)
1604	Ia (?)	(Kepler)
1572	Ia	(Tycho)
1181 (?)	II (pulsar)	(3C58)
1054	II (pulsar)	(Crab)

Nearby; swept-up ISM mass still low
Best objects to study dust content of young SNRs

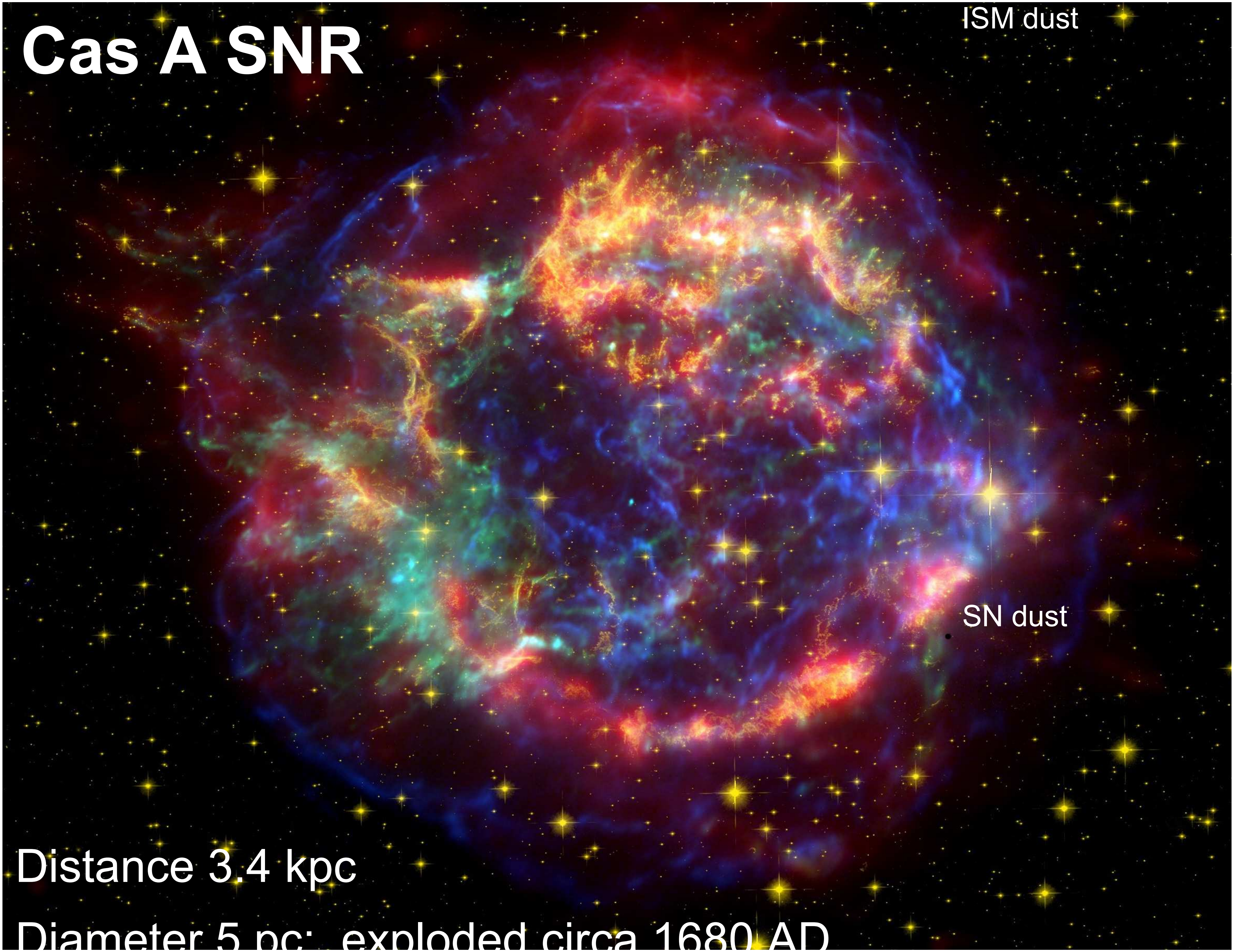


The Crab Nebula with PACS



Krause et al. (in preparation)

Cas A SNR



- Distance 3.4 kpc
- Diameter 5 pc; exploded circa 1680 AD

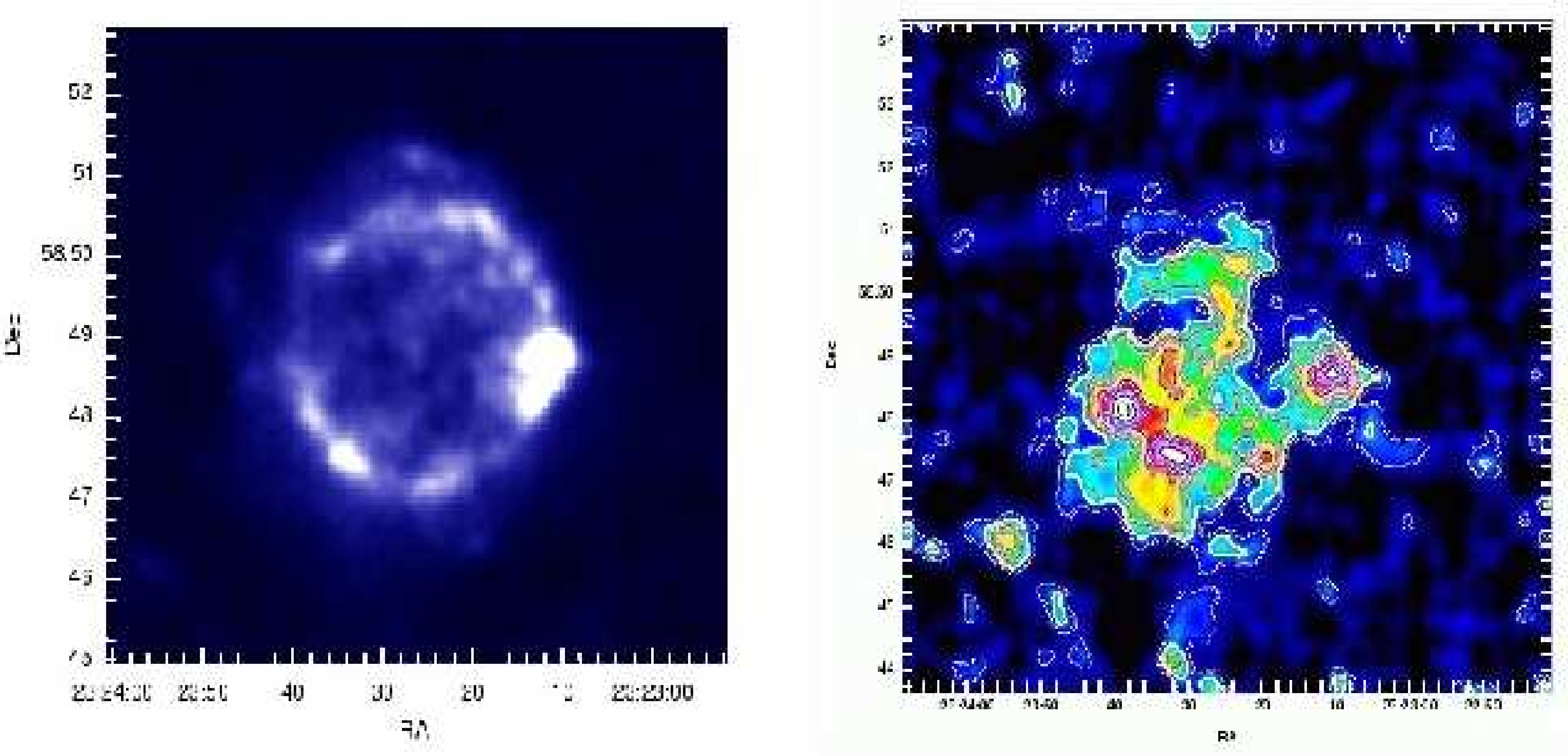
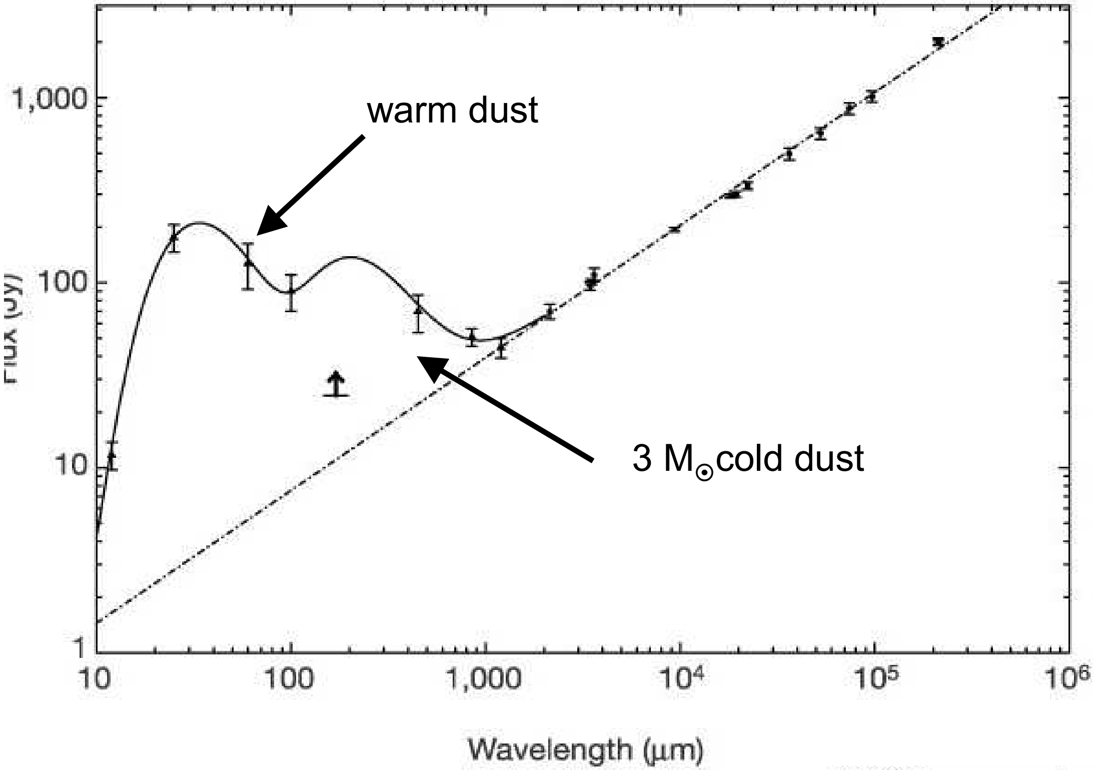


Figure 4: SCUBA images of Cas A, from Dunne et al. (2003). Left: 850-μm image; right: 450-μm image. The morphological difference between the two images was attributed to cold (18 K) dust emission dominating at 450 μm, while two-thirds of the emission at 850 μm is due to synchrotron radiation.

From SCUBA submm maps, Dunne et al. (2003) and Morgan et al. (2003) reported that several solar masses of new, cold (T = 18 K) dust were present in the young Cas A and Kepler SNRs.

Dust in Cas A



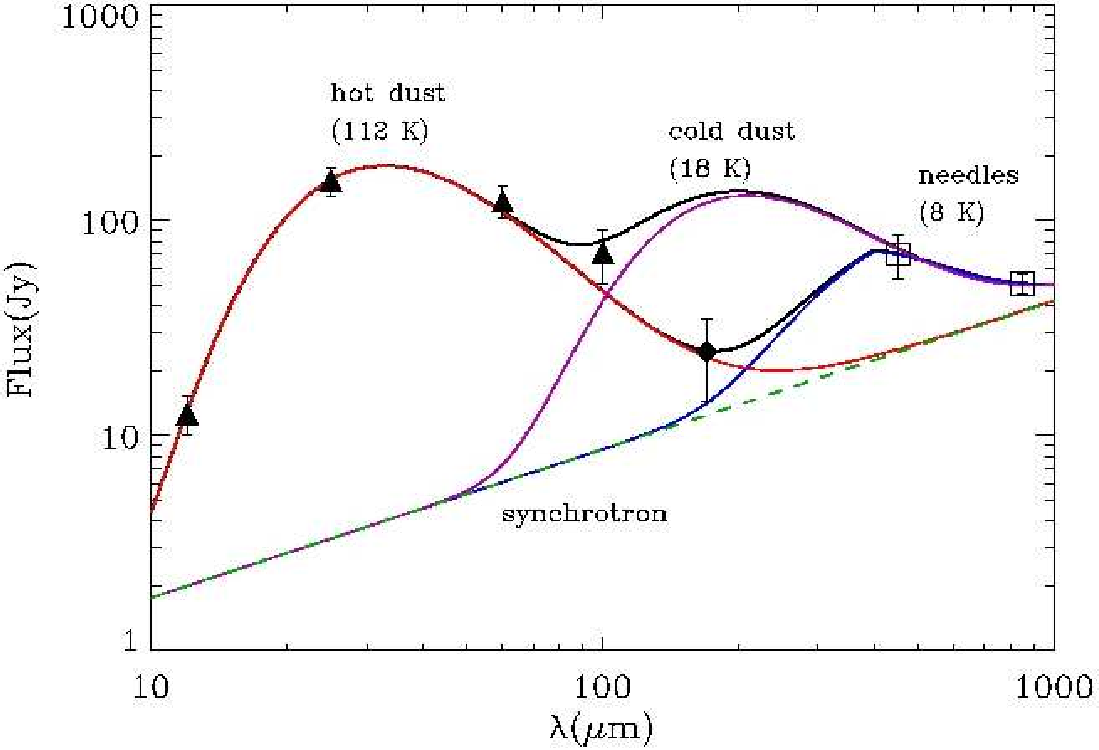
warm dust

3 $M_\odot$ cold dust

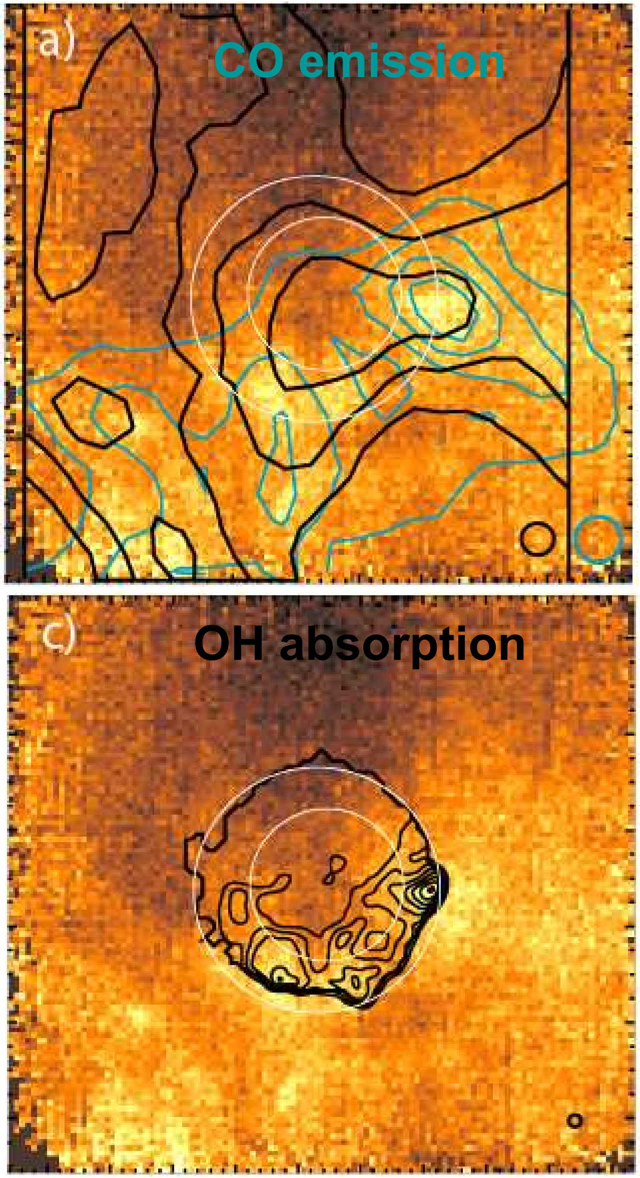
Dunne et al. 2003

Dwek 2004:

<10^{-3} Msun if iron needles

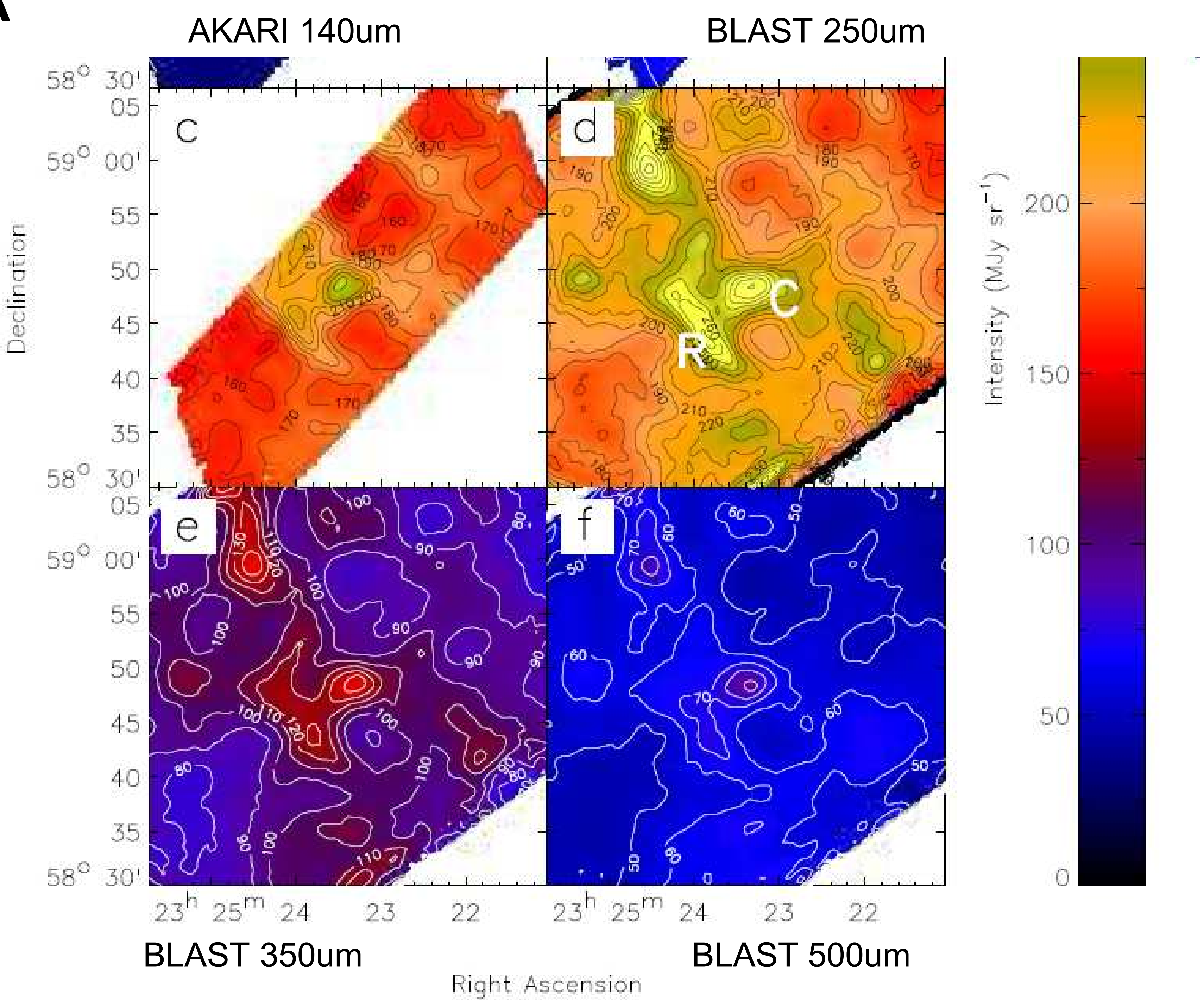


Krause et al. (2004) argued that most of the submm emission observed from Cas A originated from a foreground molecular cloud that could be seen in CO.



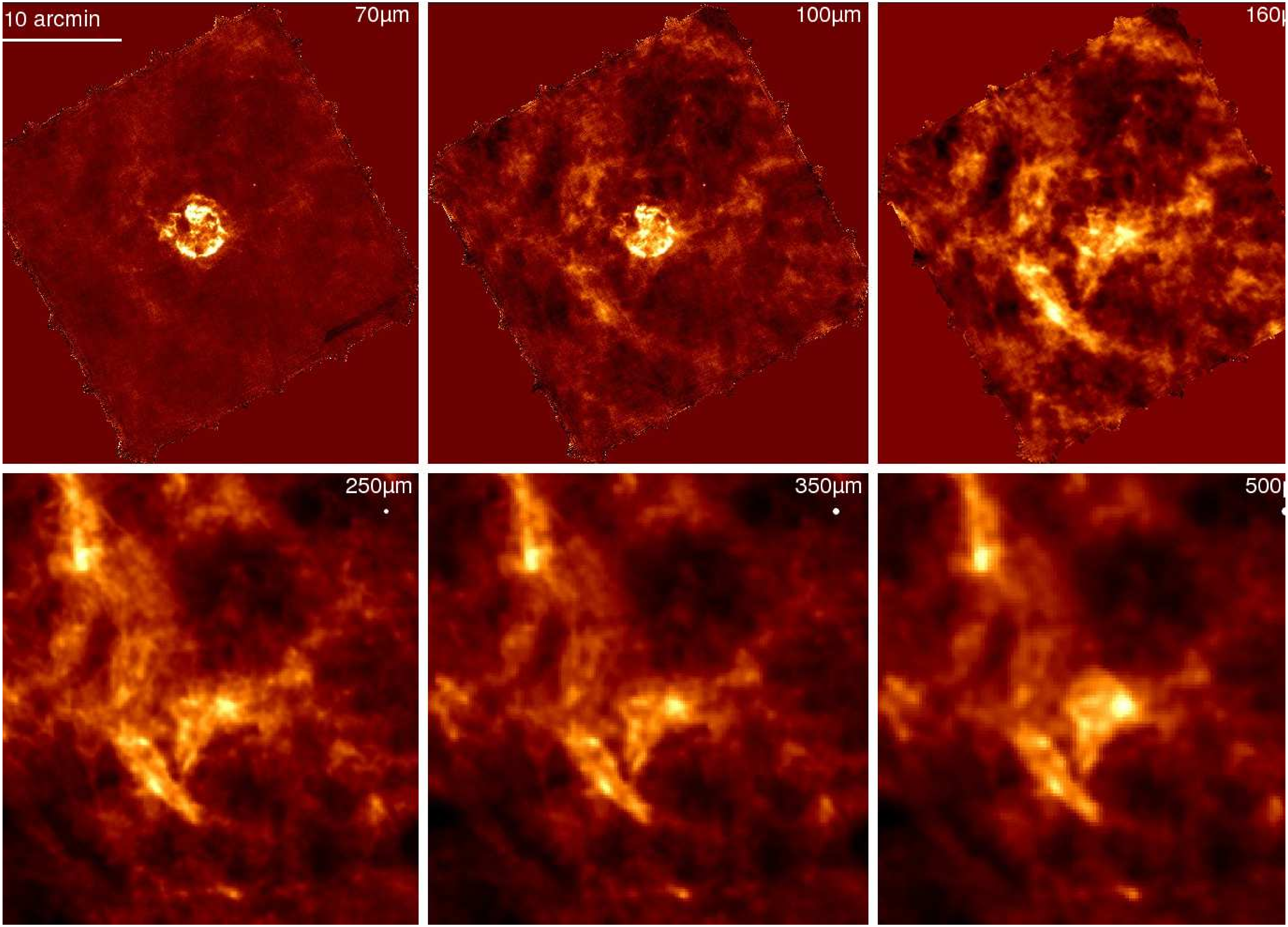
First radio detection of a molecule in space was of OH in absorption towards Cas A (Weinreb et al. 1963)

Cas A

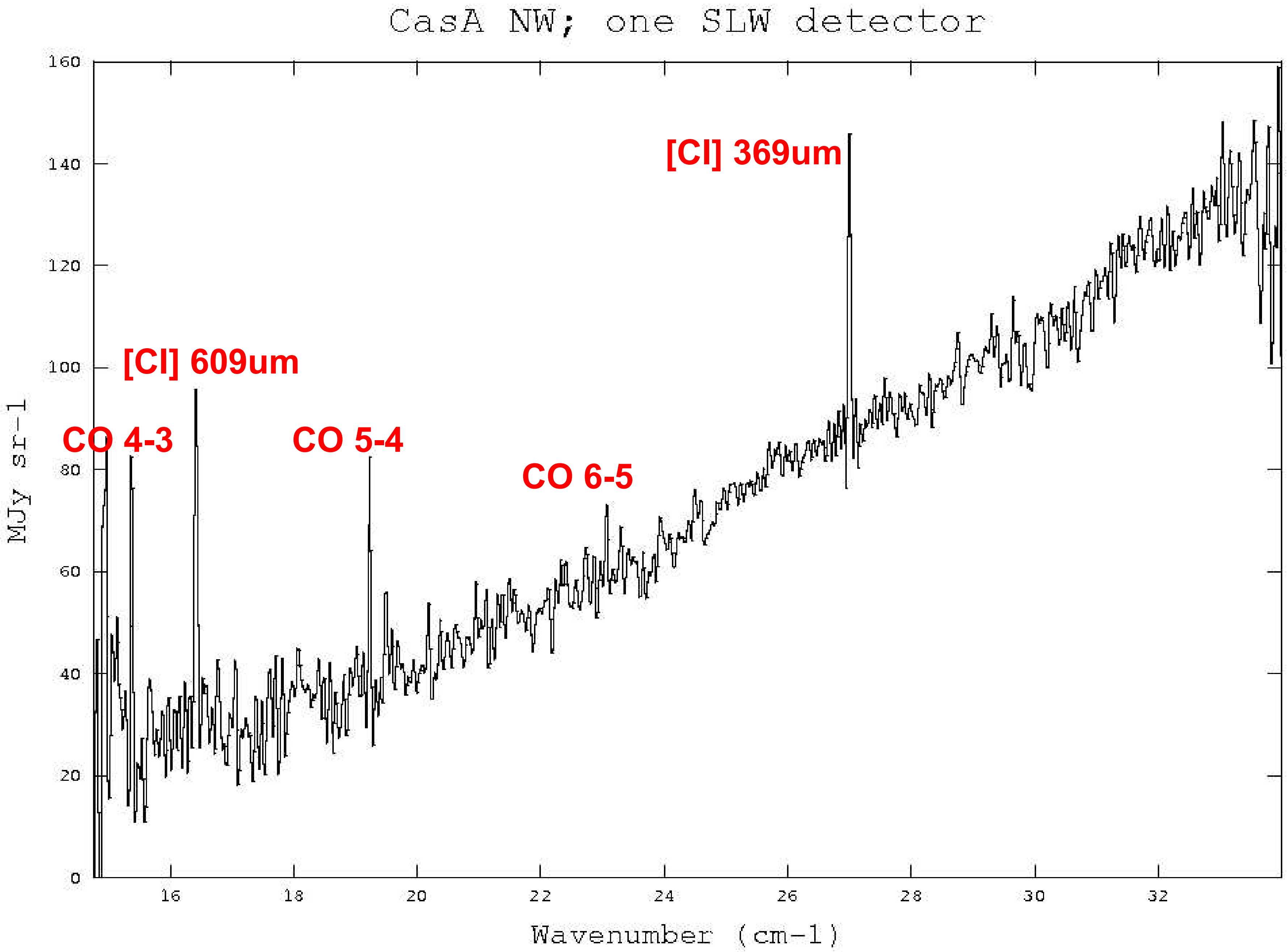


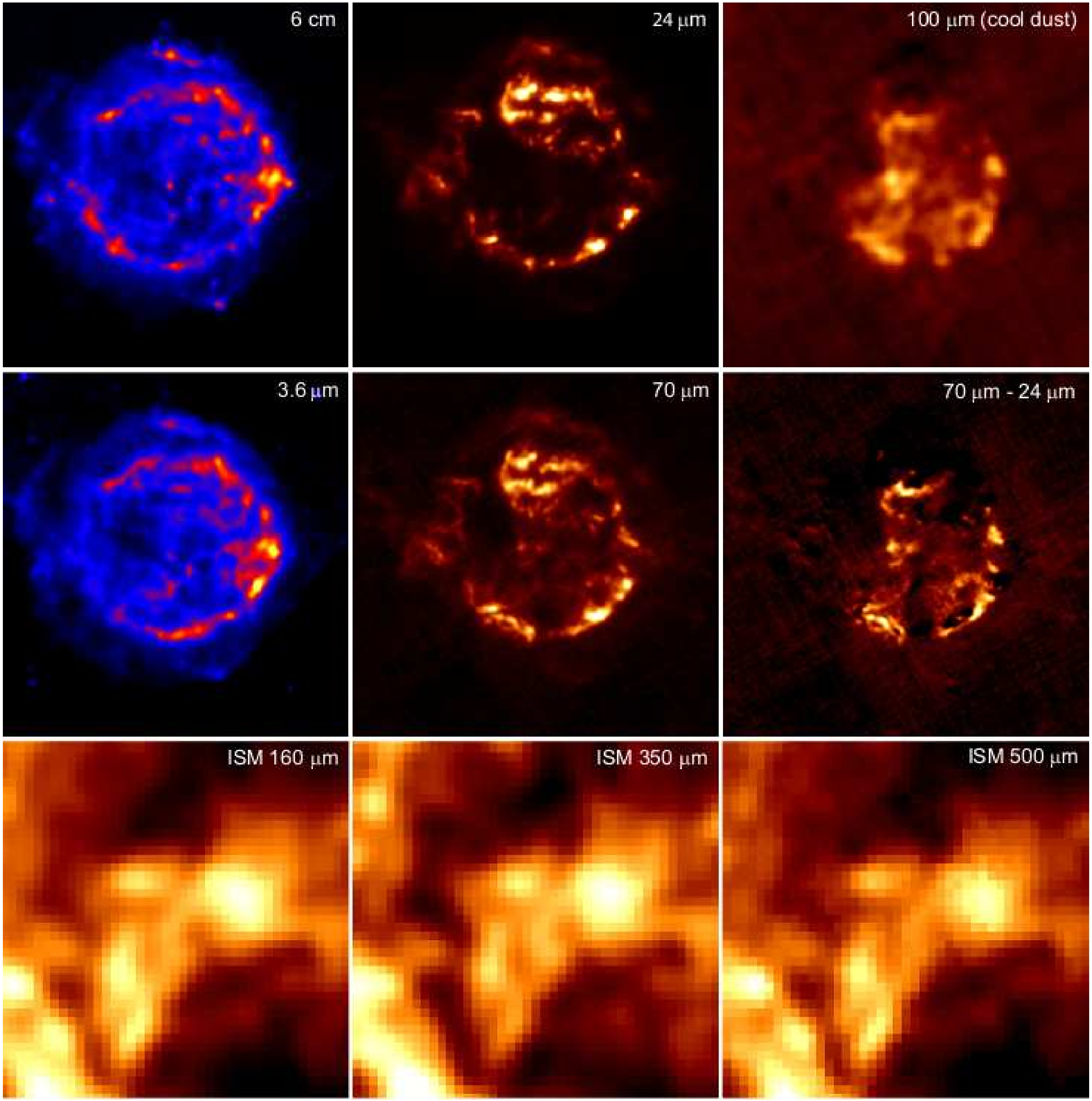
Sibthorpe et al. 2011; M(dust) = 0.06 Msun

Cas A 70-500um



SPIRE FTS spectrum (single pixel)

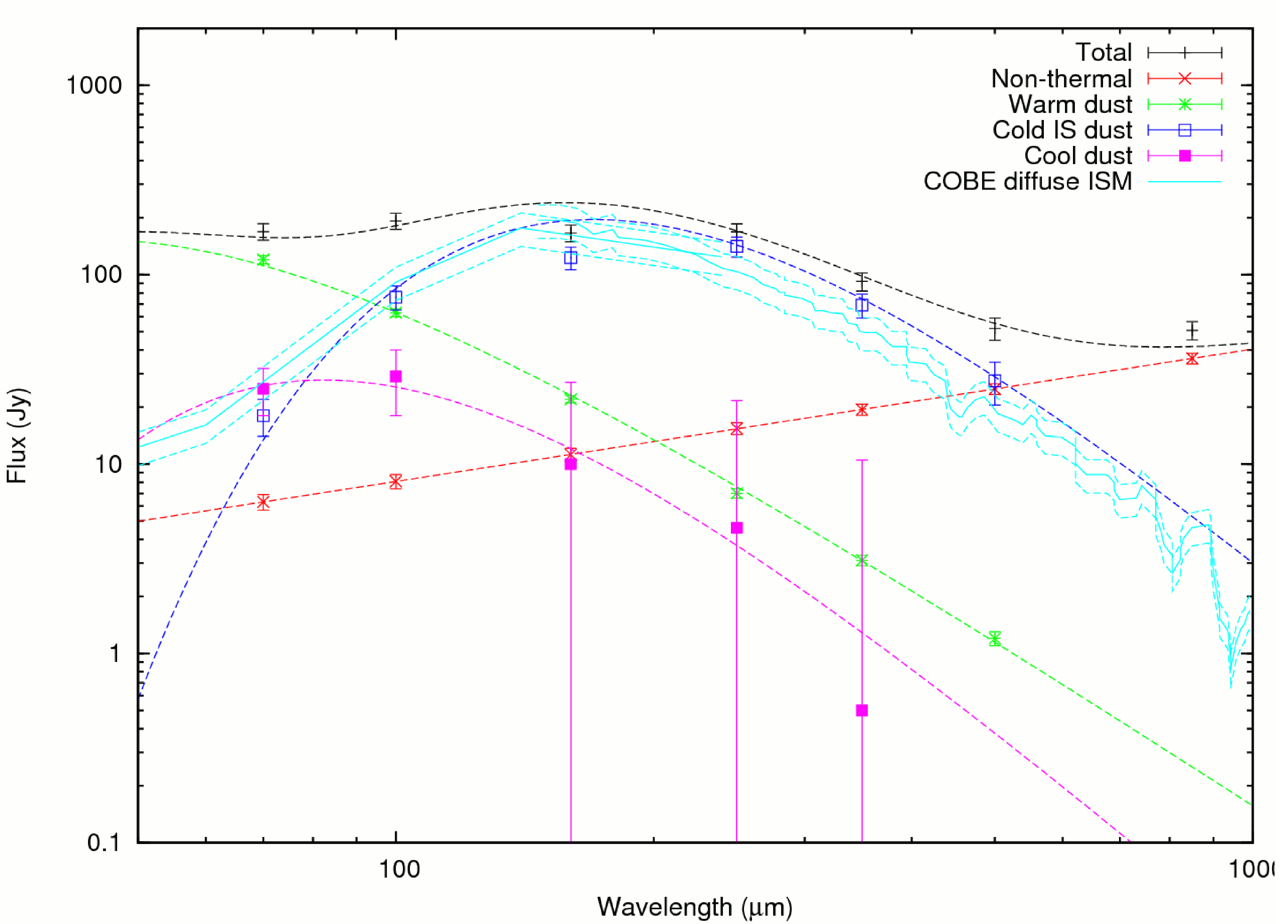


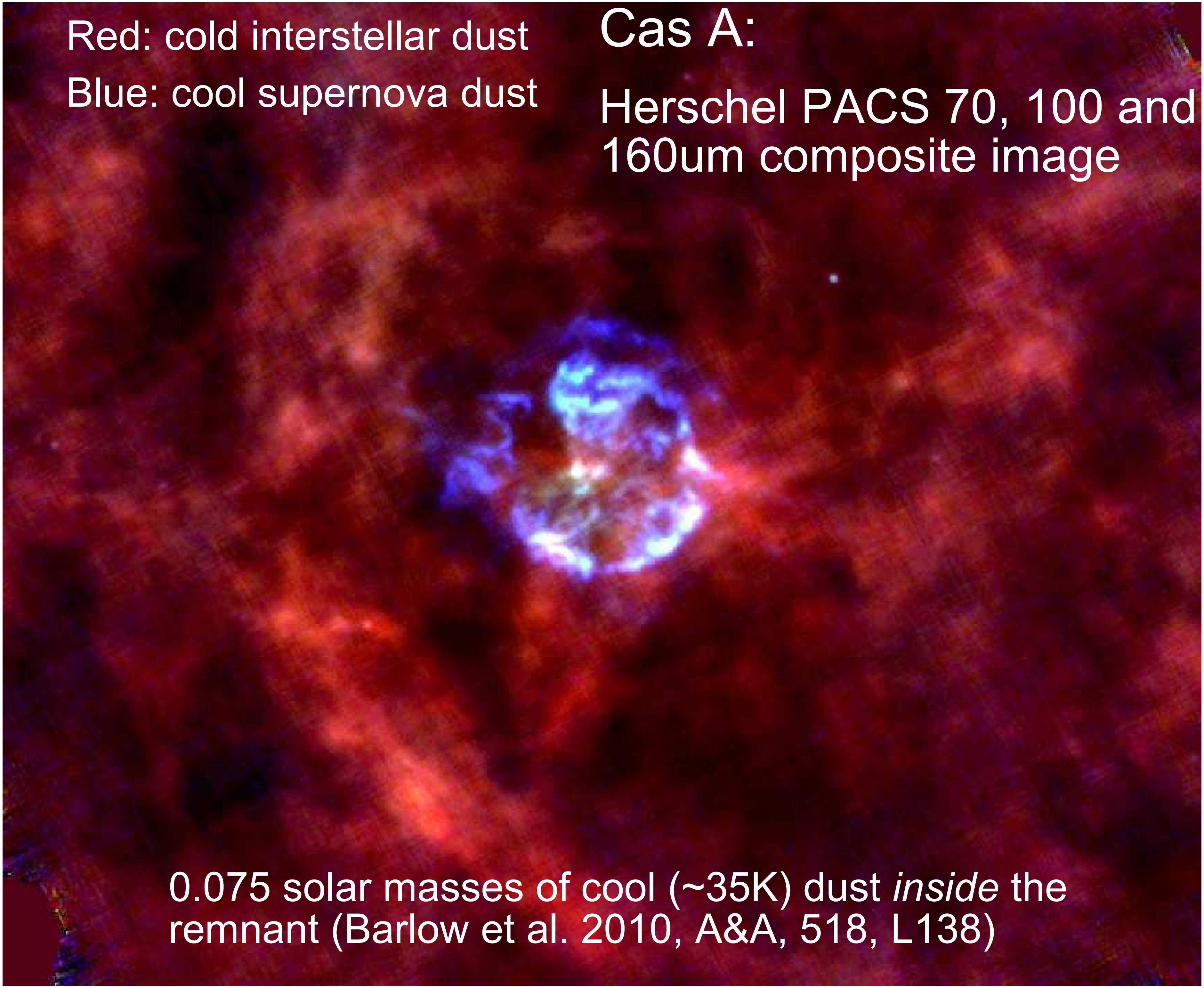


Cas A

near-IR - radio

Cas A 50-1000um SED (Barlow et al. 2010)





Cas A:

Herschel PACS 70, 100 and 160um composite image

Red: cold interstellar dust

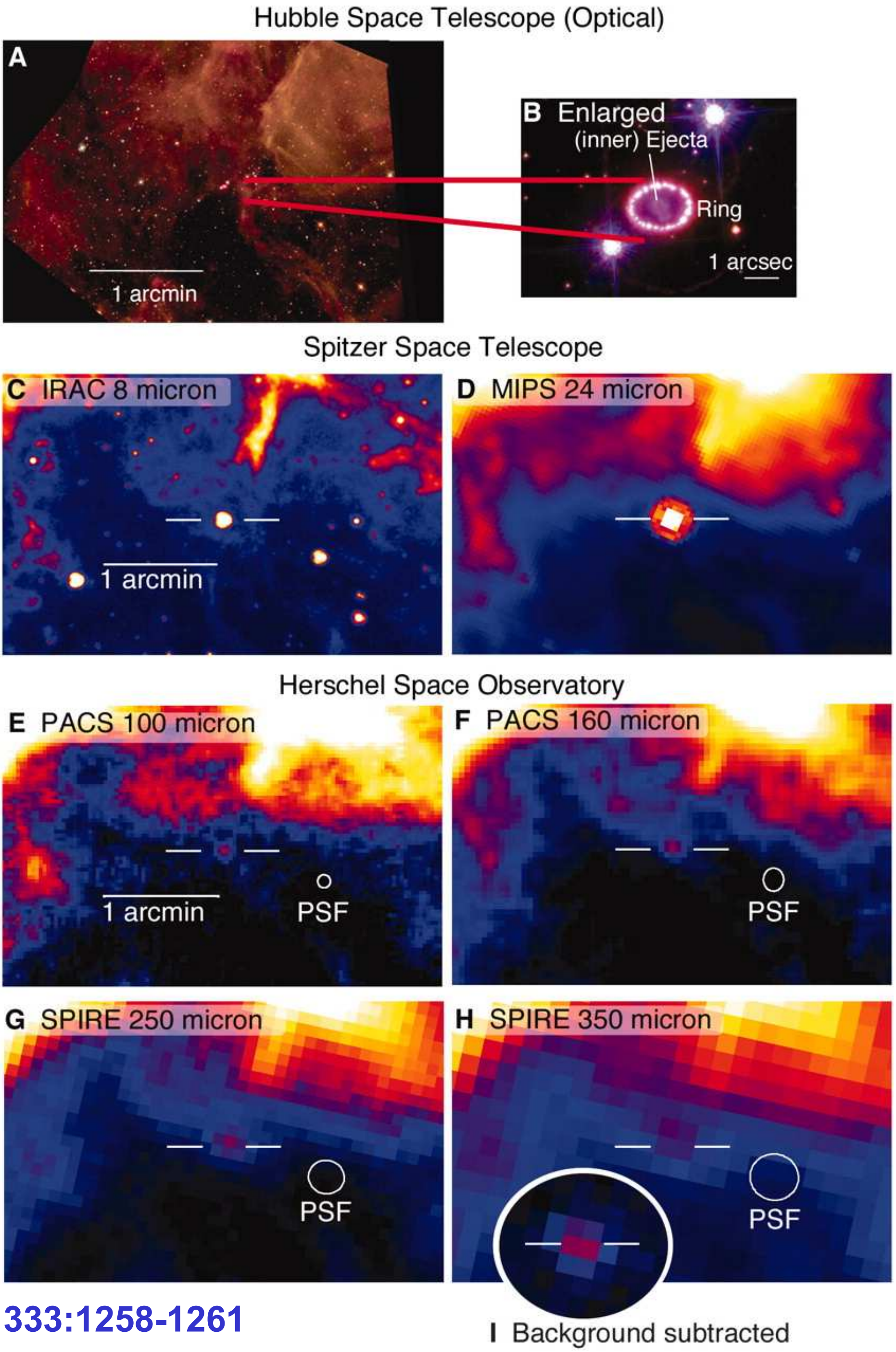
Blue: cool supernova dust

0.075 solar masses of cool (~35K) dust *inside* the remnant (Barlow et al. 2010, A&A, 518, L138)

The far-IR emission from many Galactic SNRs suffers significant confusion from foreground/background emission by cold interstellar dust.

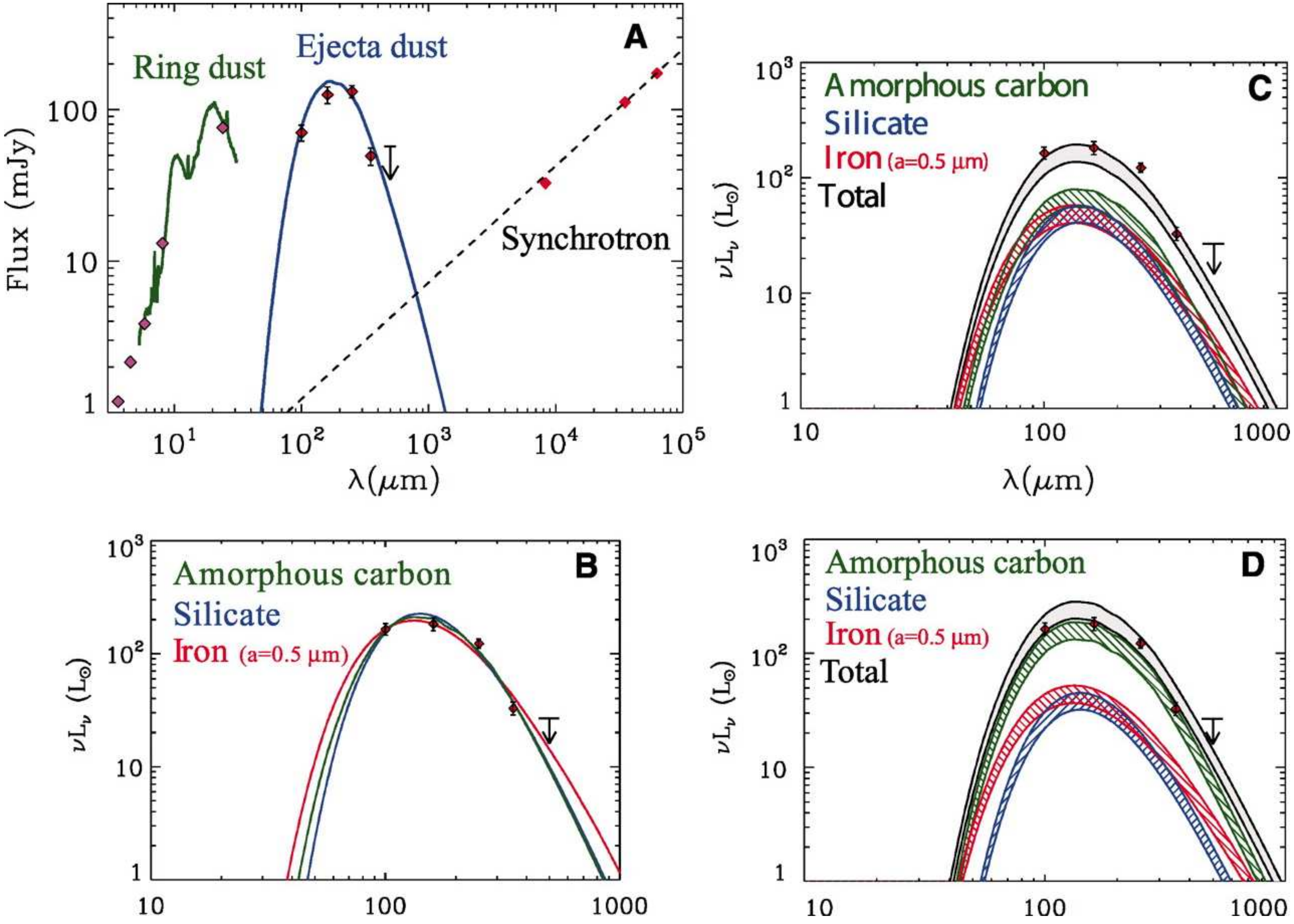
This is less of a problem for the LMC and SMC. The Herschel Heritage Key Project (PI: M. Meixner) has mapped both galaxies, including SN 1987A.

Herschel images of SN 1987A region, together with Spitzer mid-IR and Hubble optical images



M Matsuura et al. Science 2011;333:1258-1261

The infrared spectral energy distribution of SN 1987A



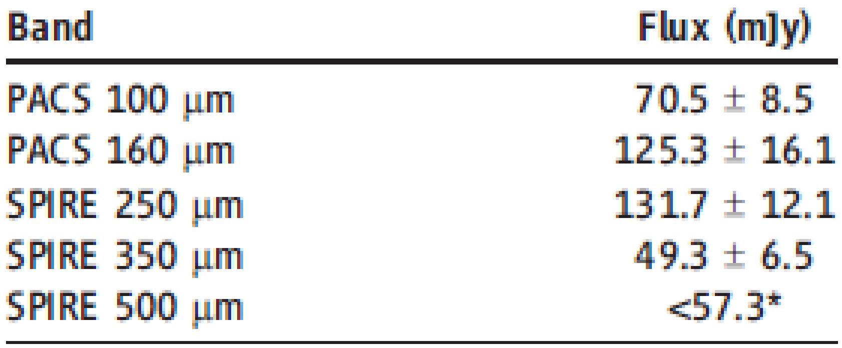
M Matsuura et al. Science 2011;333:1258-1261

Science

AAAS

A massive dust reservoir in SN 1987A

(M Matsuura et al. Science 2011;333:1258-1261)



Band	Flux (mJy)
PACS 100 μm	70.5 ± 8.5
PACS 160 μm	125.3 ± 16.1
SPIRE 250 μm	131.7 ± 12.1
SPIRE 350 μm	49.3 ± 6.5
SPIRE 500 μm	<57.3*

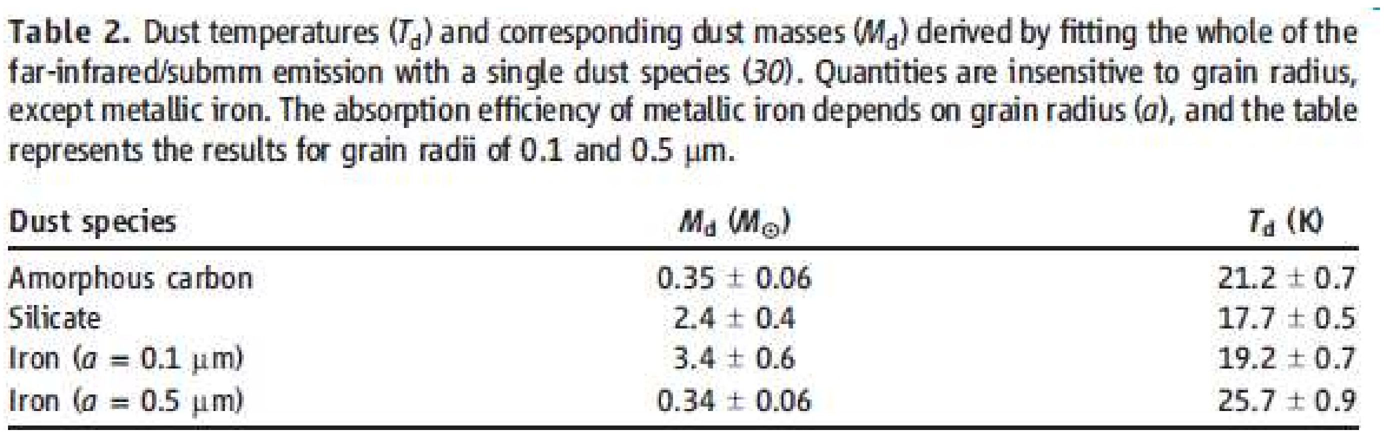


Table 2. Dust temperatures (T_d) and corresponding dust masses (M_d) derived by fitting the whole of the far-infrared/submm emission with a single dust species (*30*). Quantities are insensitive to grain radius, except metallic iron. The absorption efficiency of metallic iron depends on grain radius (*a*), and the table represents the results for grain radii of 0.1 and 0.5 μm.

Dust species	M_d ($M_\odot$)	T_d (K)
Amorphous carbon	0.35 ± 0.06	21.2 ± 0.7
Silicate	2.4 ± 0.4	17.7 ± 0.5
Iron (a = 0.1 μm)	3.4 ± 0.6	19.2 ± 0.7
Iron (a = 0.5 μm)	0.34 ± 0.06	25.7 ± 0.9

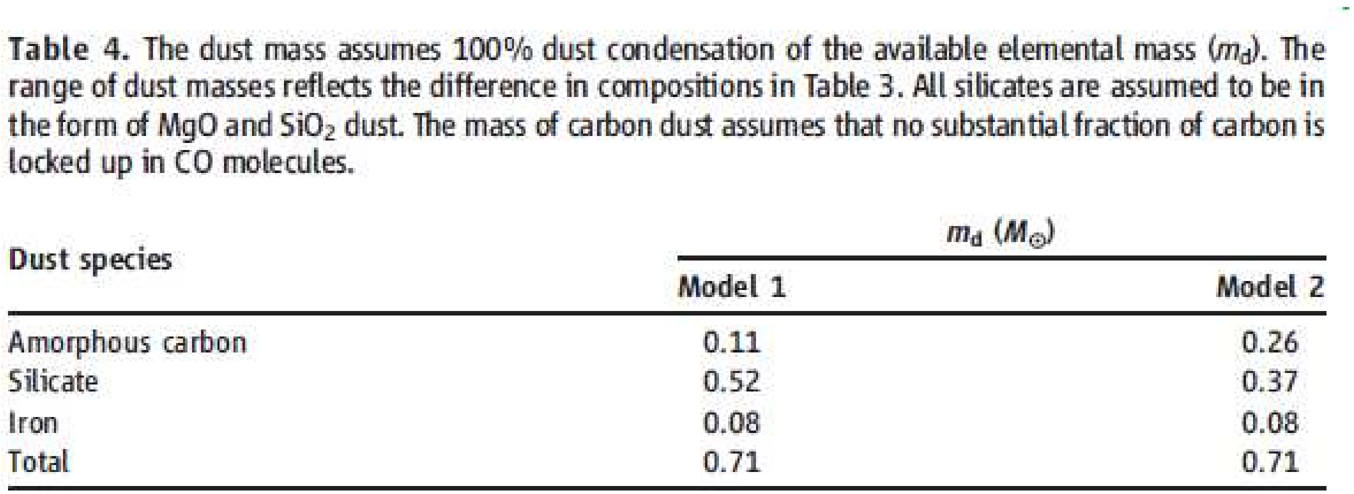


Table 4. The dust mass assumes 100% dust condensation of the available elemental mass (m_d). The range of dust masses reflects the difference in compositions in Table 3. All silicates are assumed to be in the form of MgO and SiO_2 dust. The mass of carbon dust assumes that no substantial fraction of carbon is locked up in CO molecules.

Dust species	m_d ($M_\odot$)	
	Model 1	Model 2
Amorphous carbon	0.11	0.26
Silicate	0.52	0.37
Iron	0.08	0.08
Total	0.71	0.71

The mass of cold dust in SN1987A's ejecta found by Herschel 23 years after outburst is nearly 1000 times larger than the mass of warm dust measured at mid-IR wavelengths in the first 3 years after outburst.

Could this mass of cold dust have existed during the first few years?

During the first few years after outburst, models predict that the heating rate from ^{56}Co decay γ-rays should keep the gas at ~5000 K and any dust at a few hundred K. From a variety of evidence, SNe ejecta are known to be clumpy. Clumpy models can accommodate more dust than smooth models but 3D modelling indicates that it would be very difficult to hide nearly a solar mass of cold dust during the first few years without producing very large internal extinctions in the ejecta (a dust black-out).

Another possibility is that dust has continued to nucleate and grow during the intervening 20 years since the early-phase mid-IR observations took place.

Future Prospects:

A combination of mid-IR and far-IR observations will be needed to properly characterize the dust SED evolution of future core collapse SNe, in order to derive reliable masses for warm and cold dust components.

A 23-year old supernova similar to SN1987A would produce a 350um flux of only 0.015 mJy at 3 Mpc, difficult even for ALMA. However, ALMA could detect several-hundred year old SNRs similar to Cas A out to significantly larger distances.

JWST's MIRI 5-30um instrument would be 50x more sensitive than Spitzer's IRAC and MIPS. But even if not cancelled, now unlikely to fly before 2018.

Once Herschel's helium runs out (by late-2012/early-2013), SOFIA will be the only game in town for obtaining coverage of the 20-300um region. Extended coverage of the time evolution of SN1987A with FORCAST and HAWC will be easy. Coverage of any new Local Group SN should also be feasible; but more difficult for more distant objects.

Summary: Massive stars and their core collapse supernovae are still viable candidates to account for the large masses of dust found in high-z massive galaxies

Do total dust masses in large galaxies peak very early and then decrease with time?