Dust Production by Supernovae and Massive Stars

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What is the origin of the interstellar dust in galaxies?

Up until the late-1990's the standard picture was that steady mass loss from cool evolved stars was the primary source for the refractory (=high melting point) dust grains found in the interstellar media (ISM) of our own and other galaxies, e.g. silicates and amorphous carbon dust. Since asymptotic giant branch (AGB) mass-losing stars have only low and intermediate mass progenitors, the assumption was that the dust content of galaxies built up slowly, as these lower mass stars evolved off the main sequence over time.

From 1998 onwards, submillimetre detections, with SCUBA and later instruments, of large quantities of dust in high redshift galaxies forced more consideration to be given to core-collapse supernovae (CCSNe) from massive stars as potential major sources of dust.

Core Collapse Supernovae as dust sources:

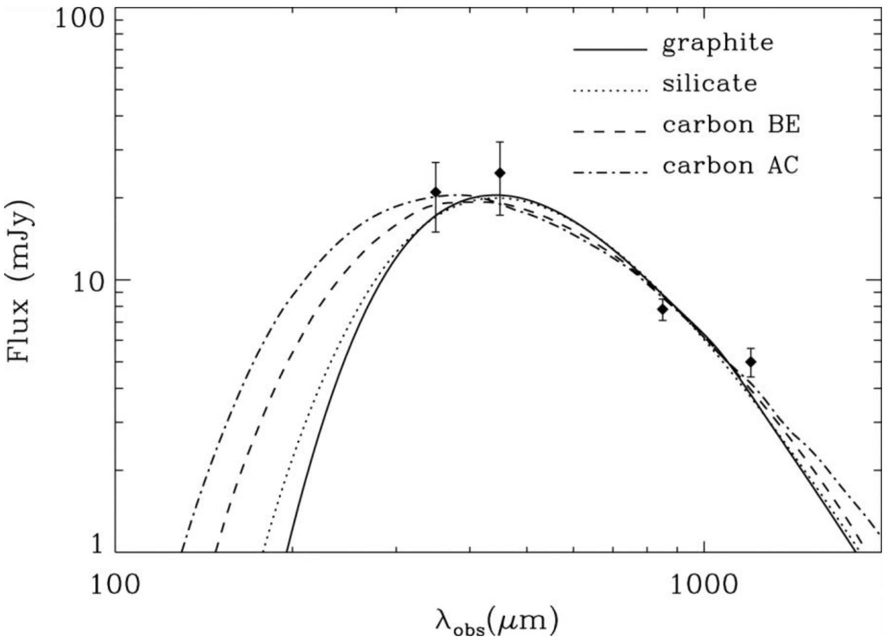
Hoyle & Wickramasinghe (1970) proposed that the high heavy element abundances in supernova ejecta would lead to efficient dust formation.

CCSN dust nucleation modelling has been carried out by e.g.

Kozasa+1989,1991; Todini & Ferrara 2001; Clayton+2001; Nozawa+2003, 2006; Schneider+2004; Deneault+2006,2009,2017; Bianchi & Schneider 2007; Cherchneff & Dwek 2010; Sarangi & Cherchneff 2013, 2015; Biscaro & Cherchneff 2014; Mauney & Lazzati 2018

These have predicted that up to 0.1 - 1.0 Msun of dust will begin to condense within a few hundred days in the ejecta of typical high-z CCSNe, corresponding to a condensation efficiency for the available refractory elements of >20%. The models predict that dust formation should be complete *within just a few years of outburst*.

Dust destruction by CCSN reverse shocks has been treated by several of the above papers, and by Nozawa+2007,2010; Silvia+2010,2012; Bocchio+2016; Biscaro & Cherchneff 2016; Micelotta+2016. Large grains survive longer because the sputtering erosion rate da/dt is independent of grain radius a.



SDSS J1148+5251, a QSO at z=6.4, emitting 500 Myr after the Big Bang

Dust Mass ~ $2x10^8$ Msun
Stellar Mass ~ $3x10^{10}$ Msun

Dwek, Galliano & Jones 2007

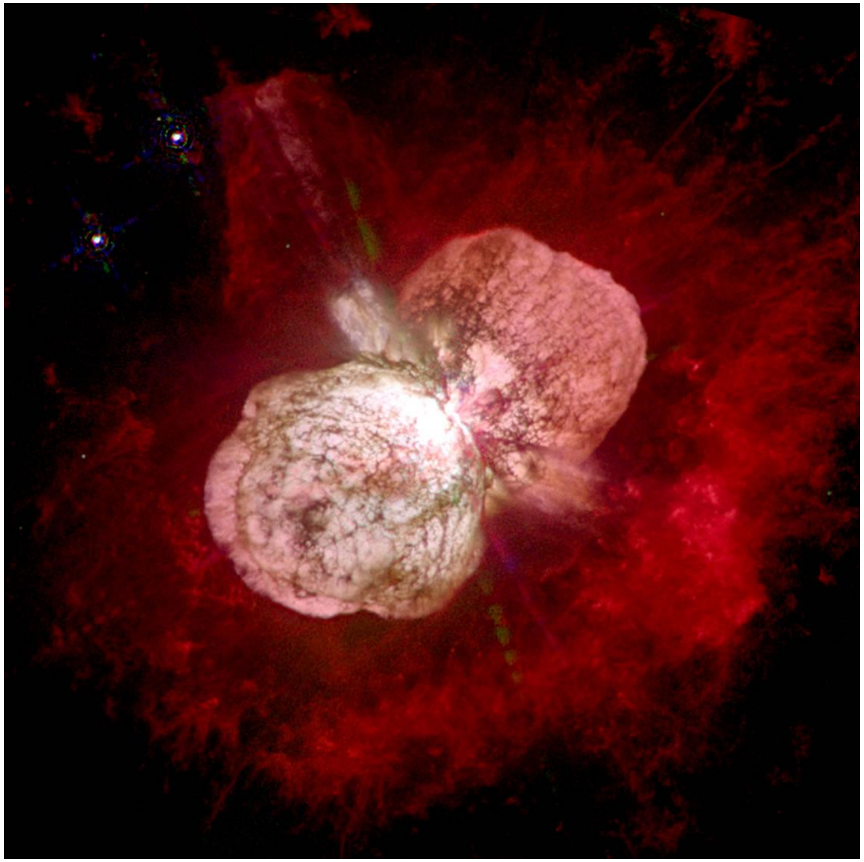
A1689-zD1 at z~7.5. Emitting 380 Myr after Big Bang
Dust Mass ~ $4x10^7$ Msun
Watson et al. 2015
Stellar Mass ~ $1.9x10^9$ Msun

A2744_YD4 at z=8.38. Emitting 315 Myr after Big Bang
Dust Mass ~ $6x10^6$ Msun
Laporte et al. 2017
Stellar Mass ~ $2x10^9$ Msun

If all stars with M > 8 Msun (0.2% of total) produce a CCSN, then 0.5-1.0 Msun of dust per CCSN is needed to provide the observed dust masses.

Dust creation by Luminous Blue Variable (LBV) events

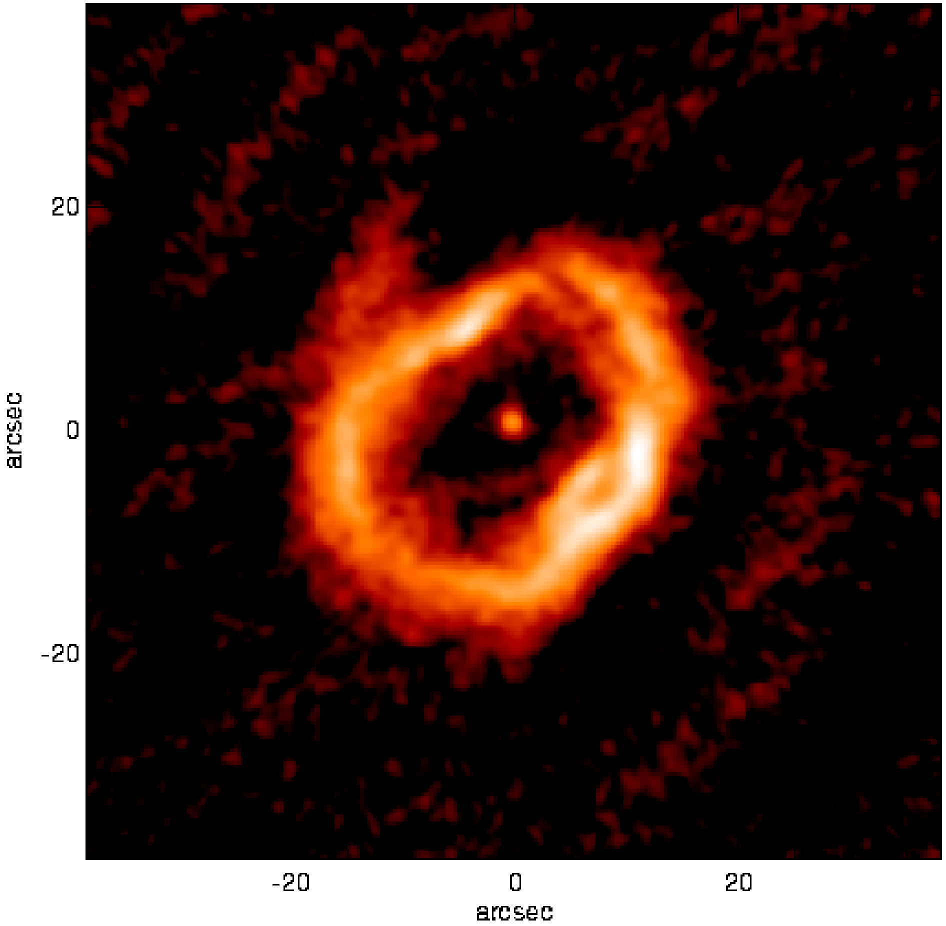
Eta Car



Morris et al. (2017): ***Herschel*****: 0.4 Msun of dust (formed in 19th century great outburst)**

AG Car

ATCA image of AG Carinae



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

Stars >25 Msun have been suggested to collapse to black holes, with no SN event. If so, the dust produced by their prior LBV events might be their main dust contributions.

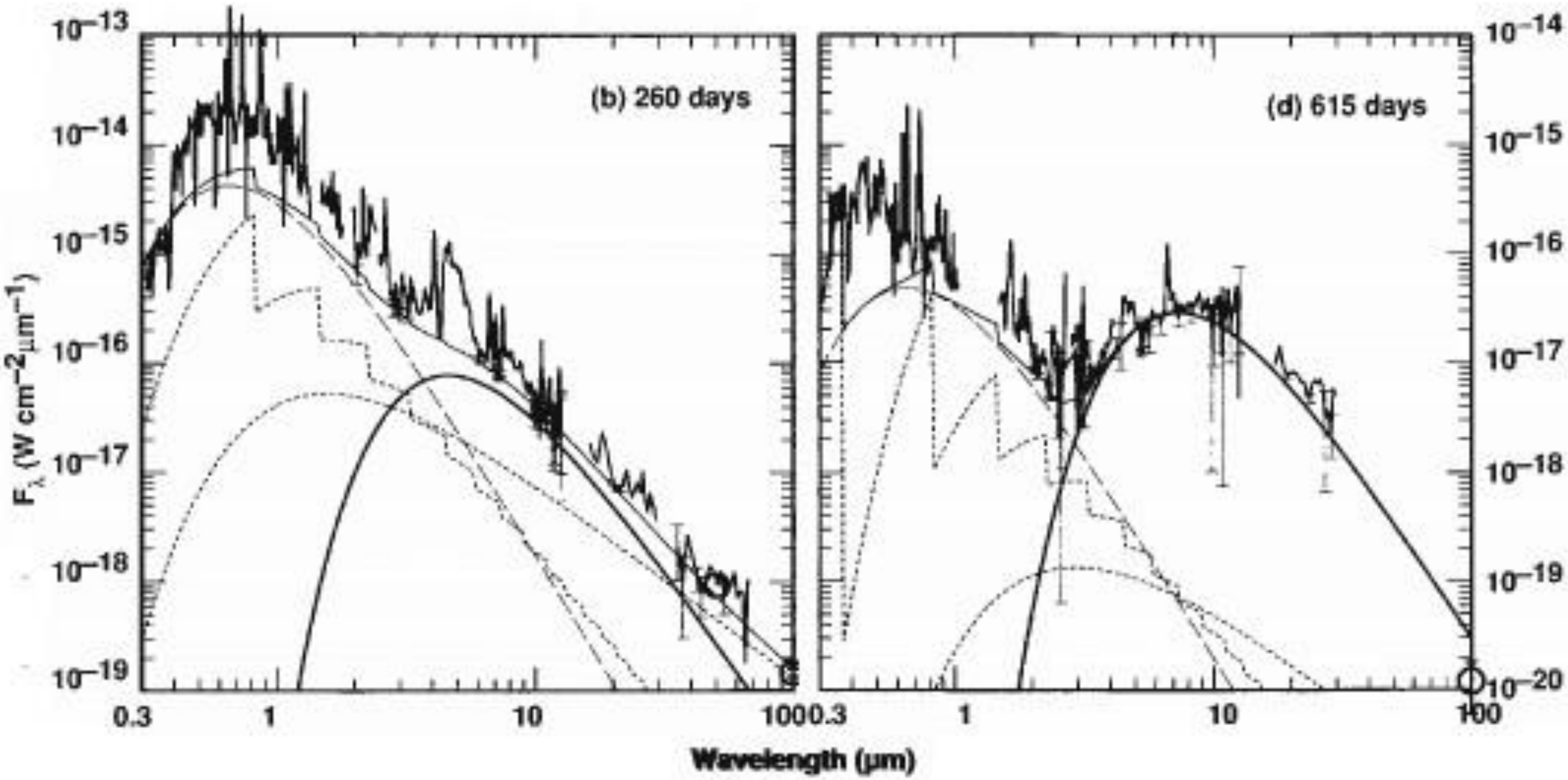
Methods for detecting the formation of dust in supernova ejecta:

(1) 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.

(2) detection of thermal IR-mm emission from the newly formed dust. Its time evolution can be distinguished from that of pre-existing dust.

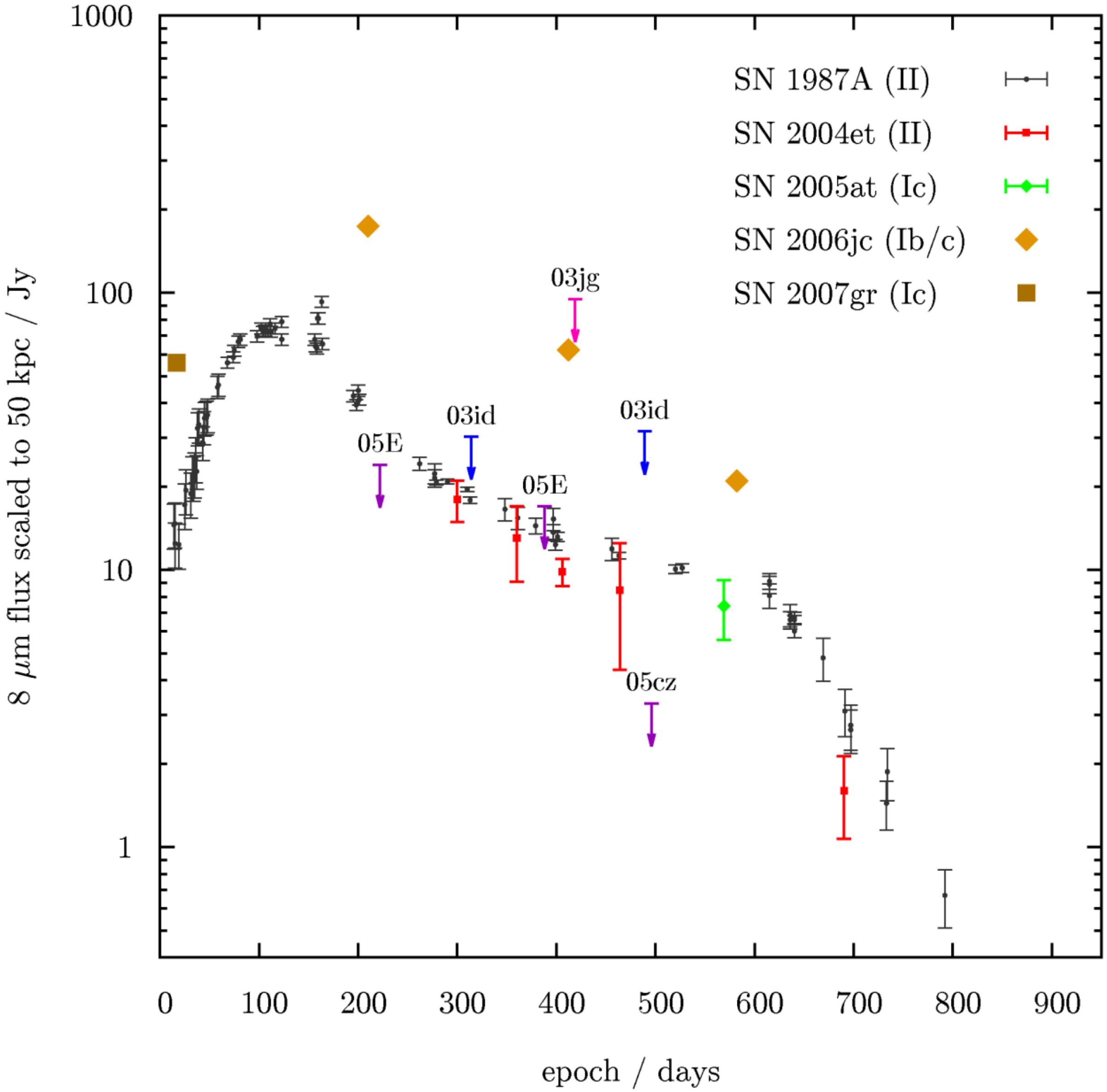
(3) detection of the development of a red-blue asymmetry in the SN emission line profiles, attributable to the preferential removal by newly formed dust of redshifted emission from the far side of the SN ejecta (Lucy et al. 1989).

Thermal Dust Emission from Supernova 1987A



Ground-based and *KAO* airborne infrared observations from 1987-1988 of Supernova 1987A, in the LMC showed the onset of infrared dust emission during the second year. Dust mass by day 775 estimated to be >10^{-4} Msun. (Bouchet et al. 1991; Wooden et al. 1993)

The advent of the *Spitzer Space Telescope* in 2003 enabled core collapse supernovae in more distant galaxies to be studied at mid-IR wavelengths



Spitzer CCSN 8um detections and upper limits, scaled to 50 kpc.

Two Type II CCSNe (1987A and 2004et) vs. three Type Ib/c CCSNe.

Conclusion: SN1987A was a typical CCSN in the mid-IR

Typically no more than (1-2)x10^{-3} $M_{\odot}$ of warm dust formed and emitting in the mid-IR (5-30um) within first 2 - 3 yrs.

O. Karczewski (2013, PhD thesis)

More than 200 supernovae have been followed by *Spitzer* since its launch in 2003, including cold *Spitzer*, warm *Spitzer* since then.

Tinyanont+ 2016 used warm *Spitzer* to survey, at 3.6 and 4.5um, 190 galaxies within 20 Mpc that had hosted 141 SNe since 1901.
44 SNe were detected (8 Type Ia's and 36 CCSNe).

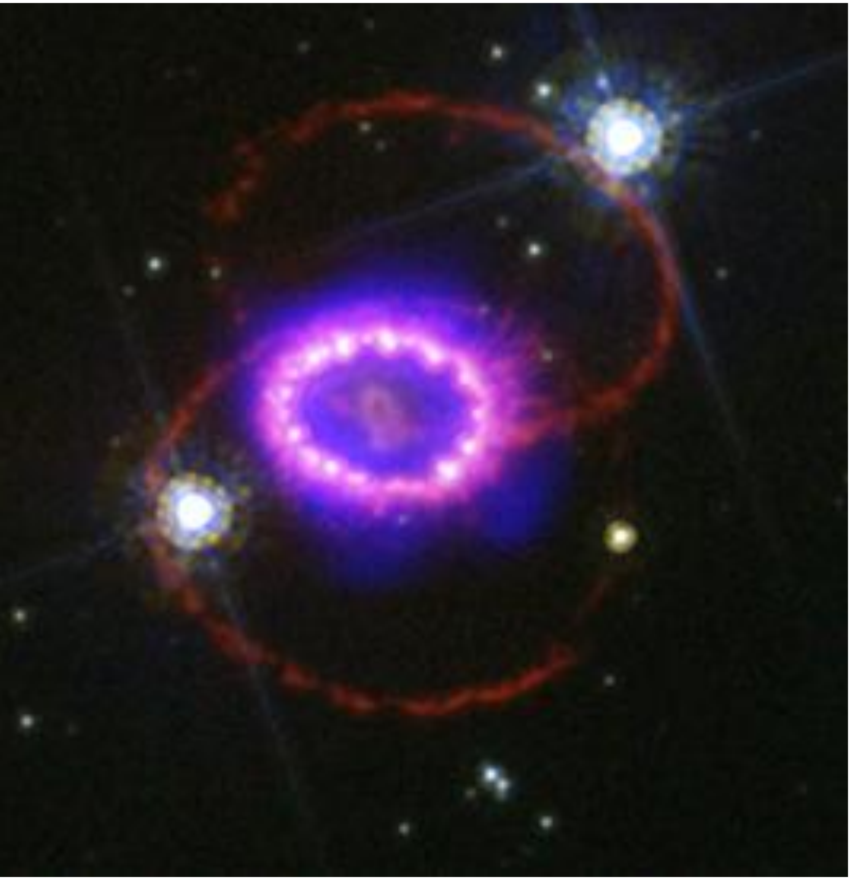
Szalai+ 2018 used *Spitzer* IRAC archival data to study the sites of 1100 supernovae, detecting 121 of them, including 48 new detections.

Spitzer has not detected thermal dust emission from any Type Ia SNe but has detected warm dust emission from many CCSNe, with deduced warm dust masses ranging from 10^{-6} to 10^{-2} Msun: a very efficient machine for detecting the onset and early development of T>150K dust emission.

Cooler dust emits less efficiently than warm dust, so requires larger dust masses to match a flux at a given wavelength.

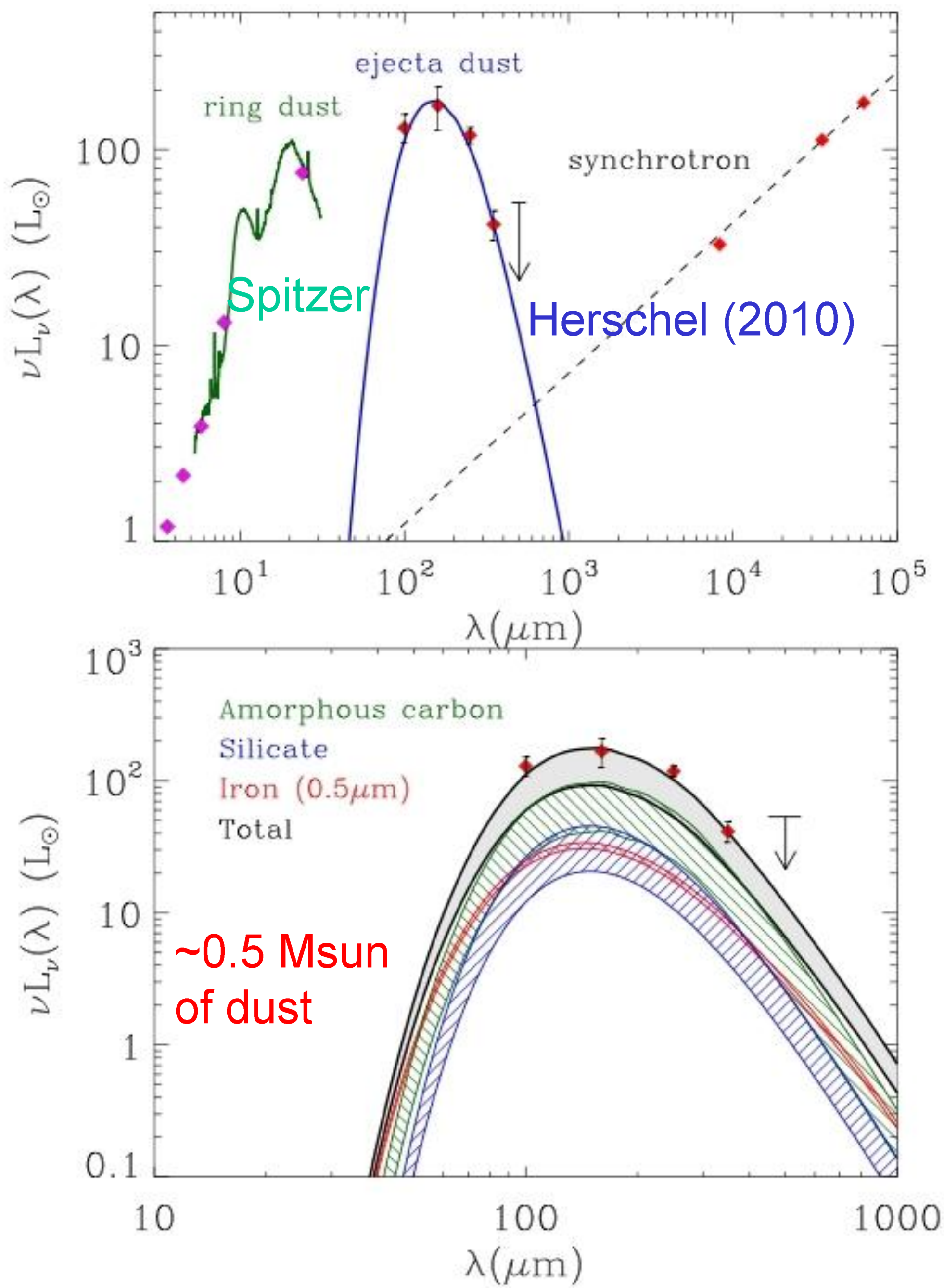
So what about at longer IR wavelengths? (> 40um)

In 2010 the *Herschel* Heritage survey of the LMC detected SN 1987A at far-IR wavelengths (100um and longwards)



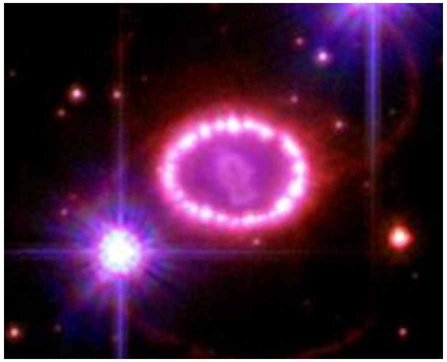
Supernova 1987A: *HST* image showing the rings and the faint inner ejecta.

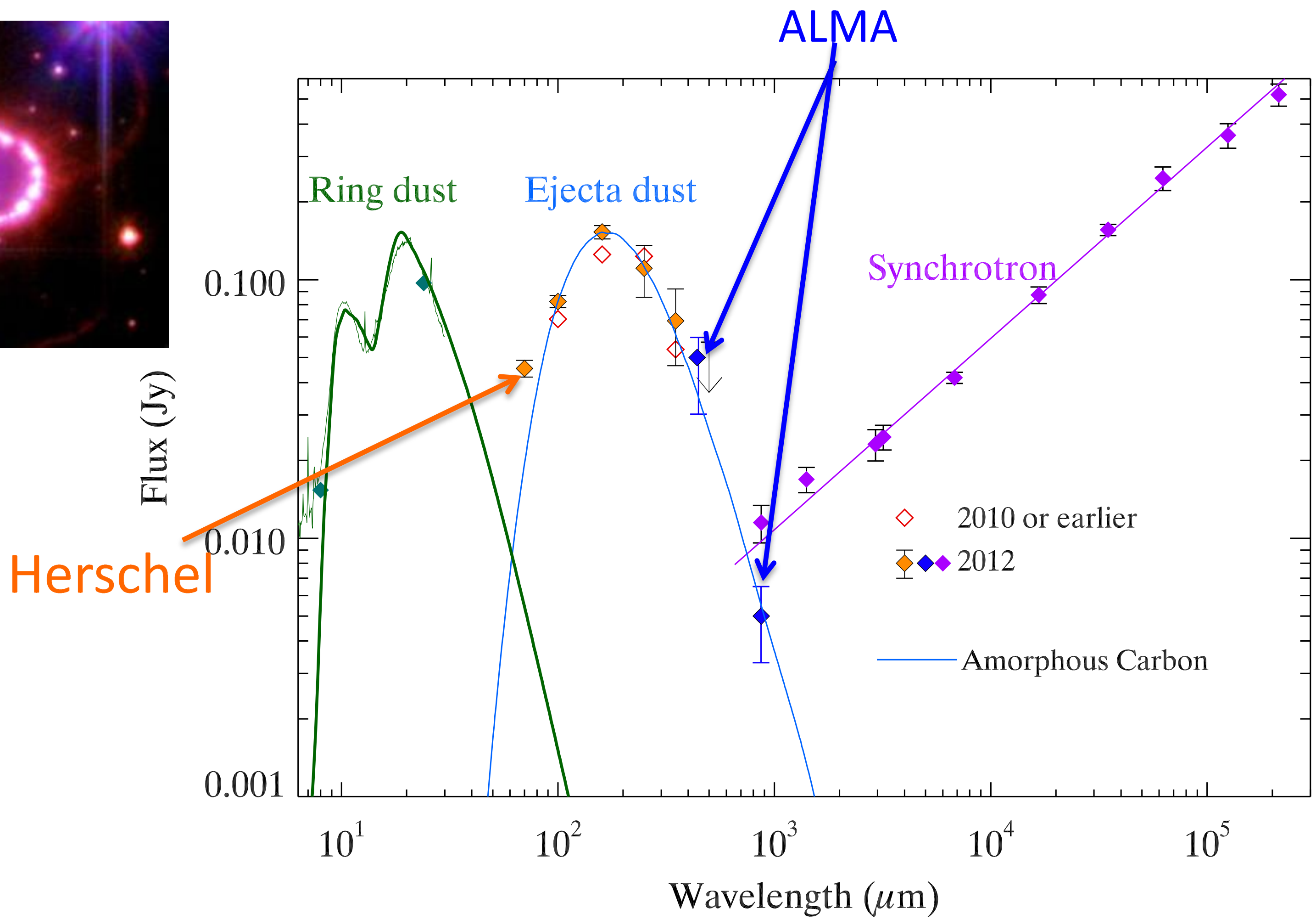
Matsuura et al. (2011) SED of SN 1987A



SN 1987A at Year 23-25

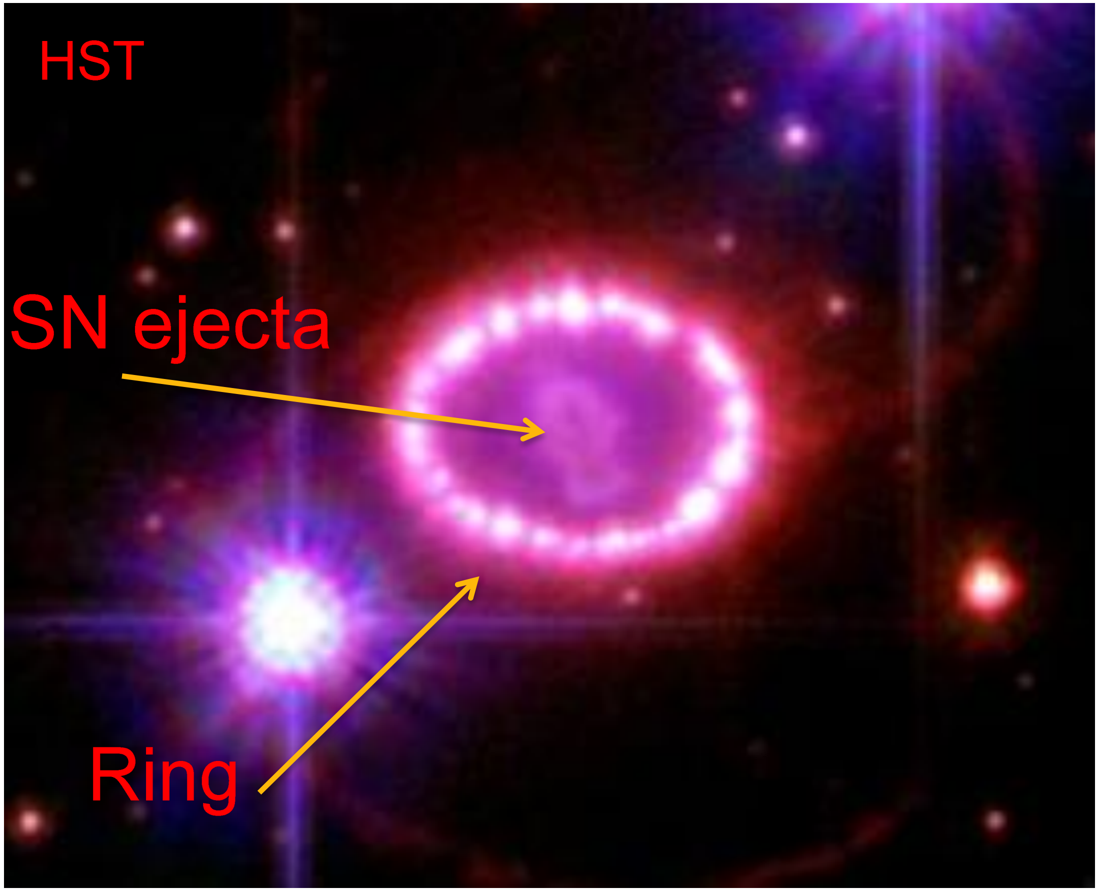
Further pointed observations in 2012 by *Herschel* and by ALMA traced the cold dust (0.4-0.7 Msun of dust at T~23K, ~200,000 earth masses)



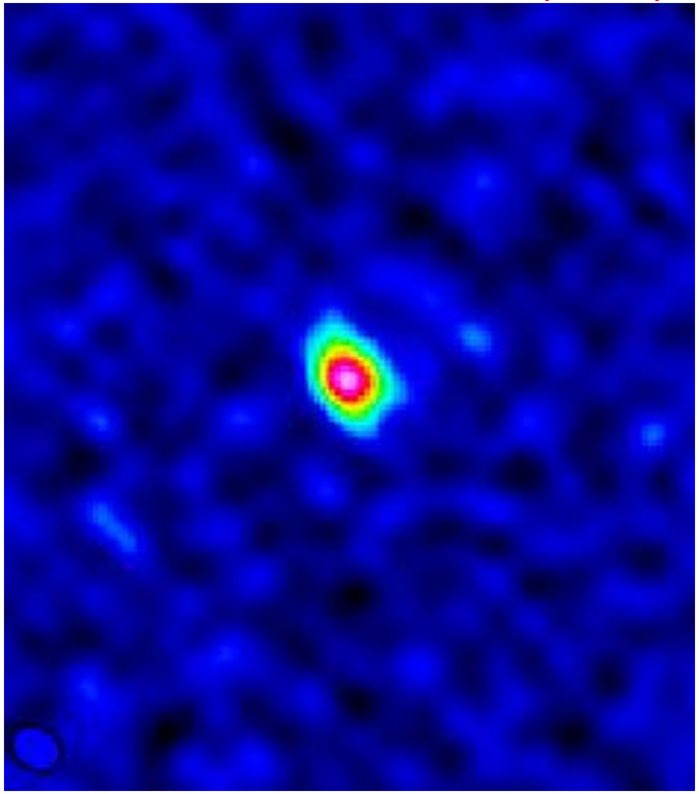


Matsuura et al. 2011, 2015; Indebetouw et al. 2014

ALMA resolved the cold dust, located in the inner ejecta

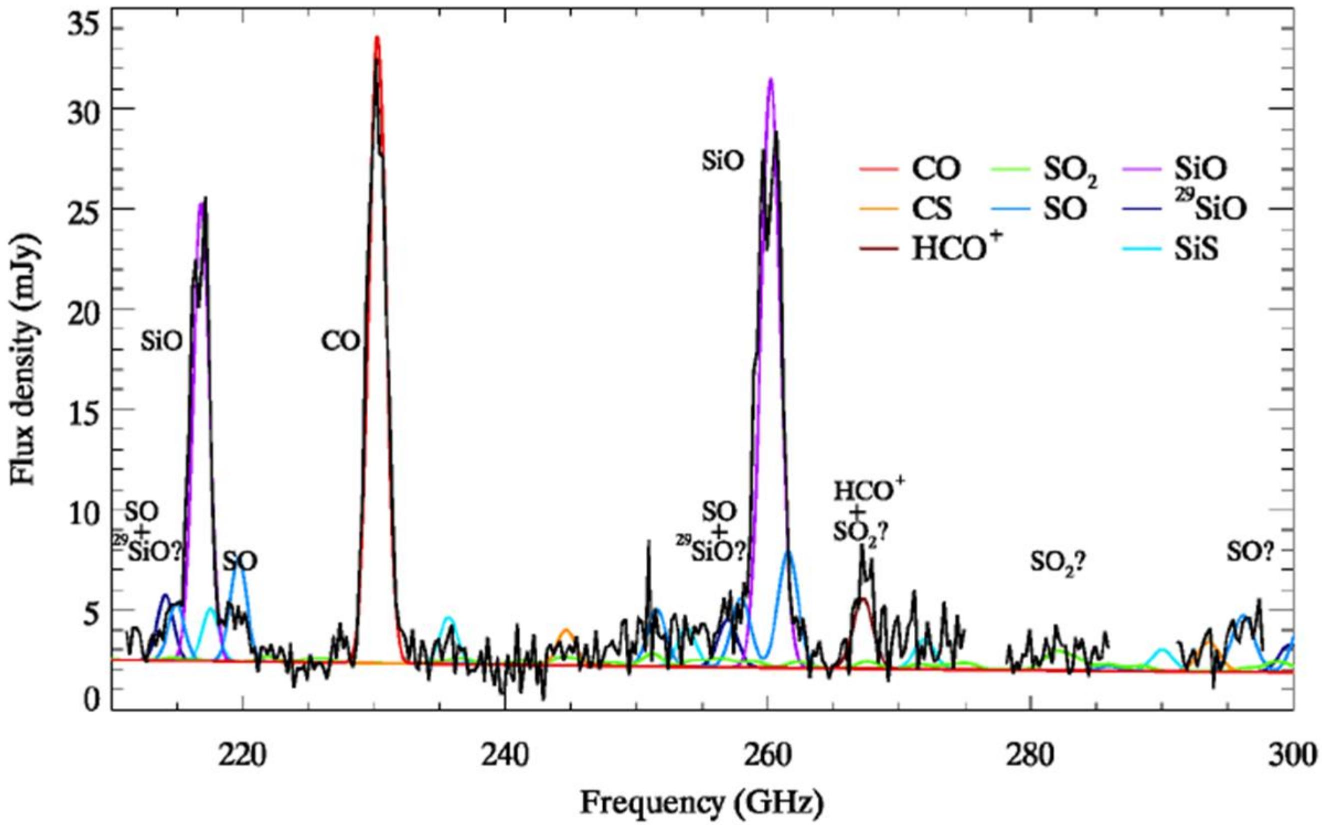


ALMA 450 microns (dust)

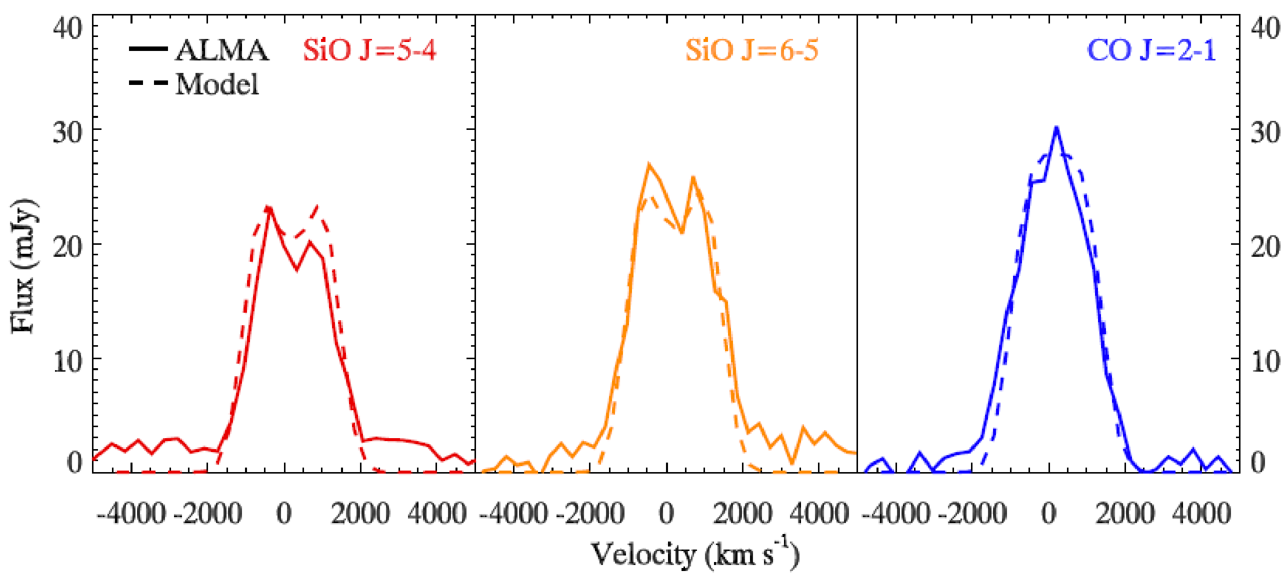


See also Poster 145 by Cigan et al.

(Indebetouw et al. 2014)



ALMA Cycles 2 & 3
Bands 6 & 7
(Matsuura et al. 2017; see her talk in next Session)



double-peaked profile: SiO distribution must be asymmetric

ALMA Band 6 observations of SN 1987A in Cycles 2 and 3, CO 2-1 and SiO 5-4

Combined angular resolution = 50 mas (Abellan et al. 2017)

Outer angular diameter of molecular line emission = 280 mas.

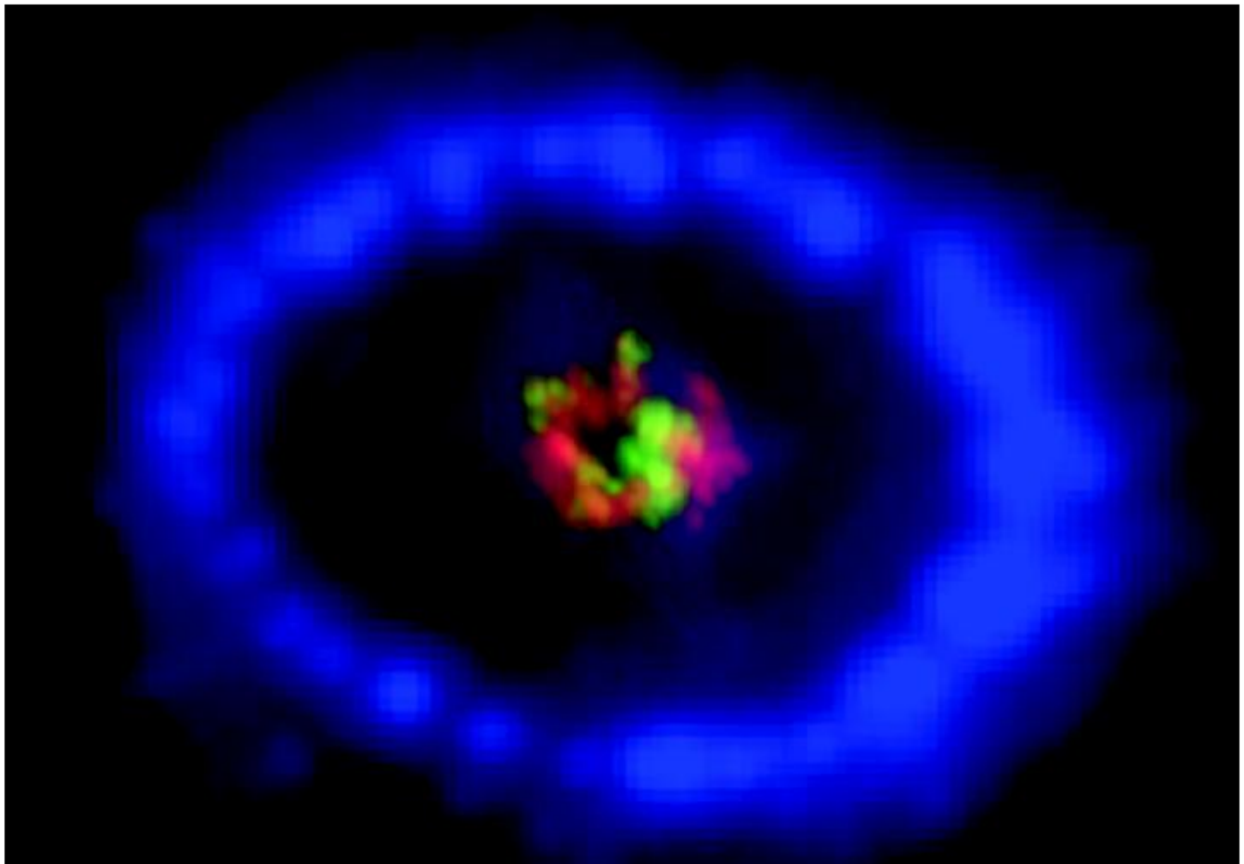
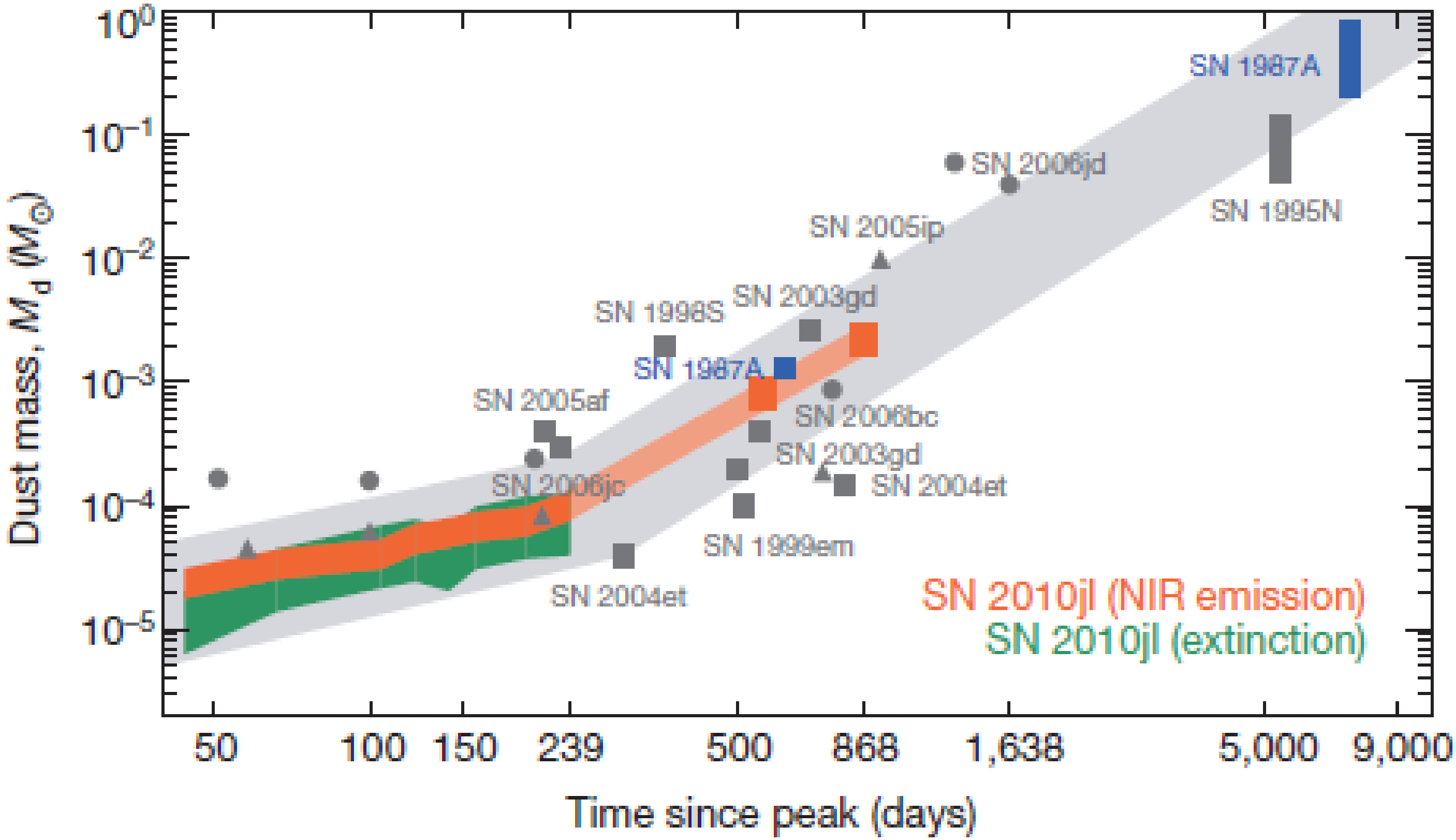
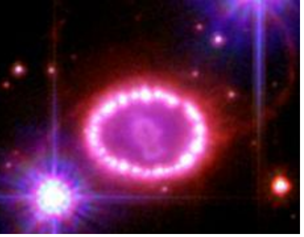


Figure 1: Molecular emission from SN 1987A. The large blue ring delineates Hα emission from the circumstellar ring (
ALMA observations velocity-integrated CO 2-1 (red) and SiO 5-4 (green) are the more compact emission in the center

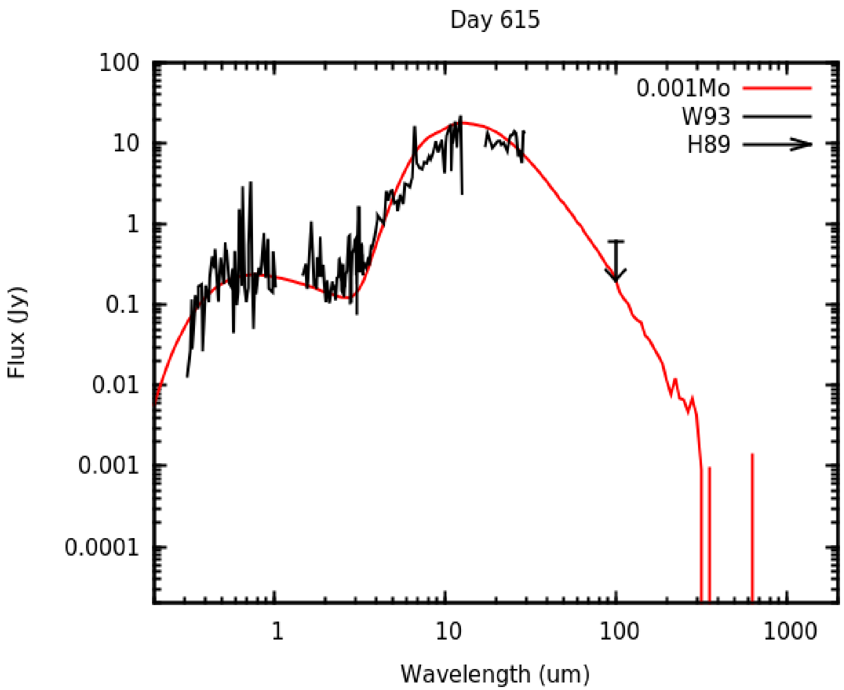
Gall et al. (2014): CCSN dust masses versus epoch



Gall et al. (2014) also analysed the HI emission line decrement of the Type IIn SN 2010jl at multiple epochs, finding evidence for grey CS dust extinction, implying the formation of large dust grains.



Modelling the time evolution of SN 1987A's optical and infrared SED



Wesson et al. 2015

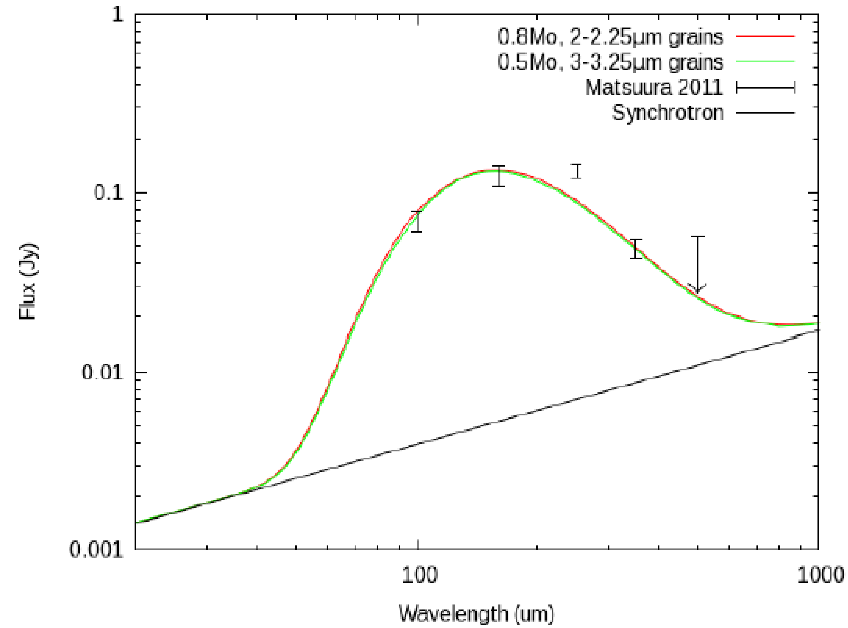


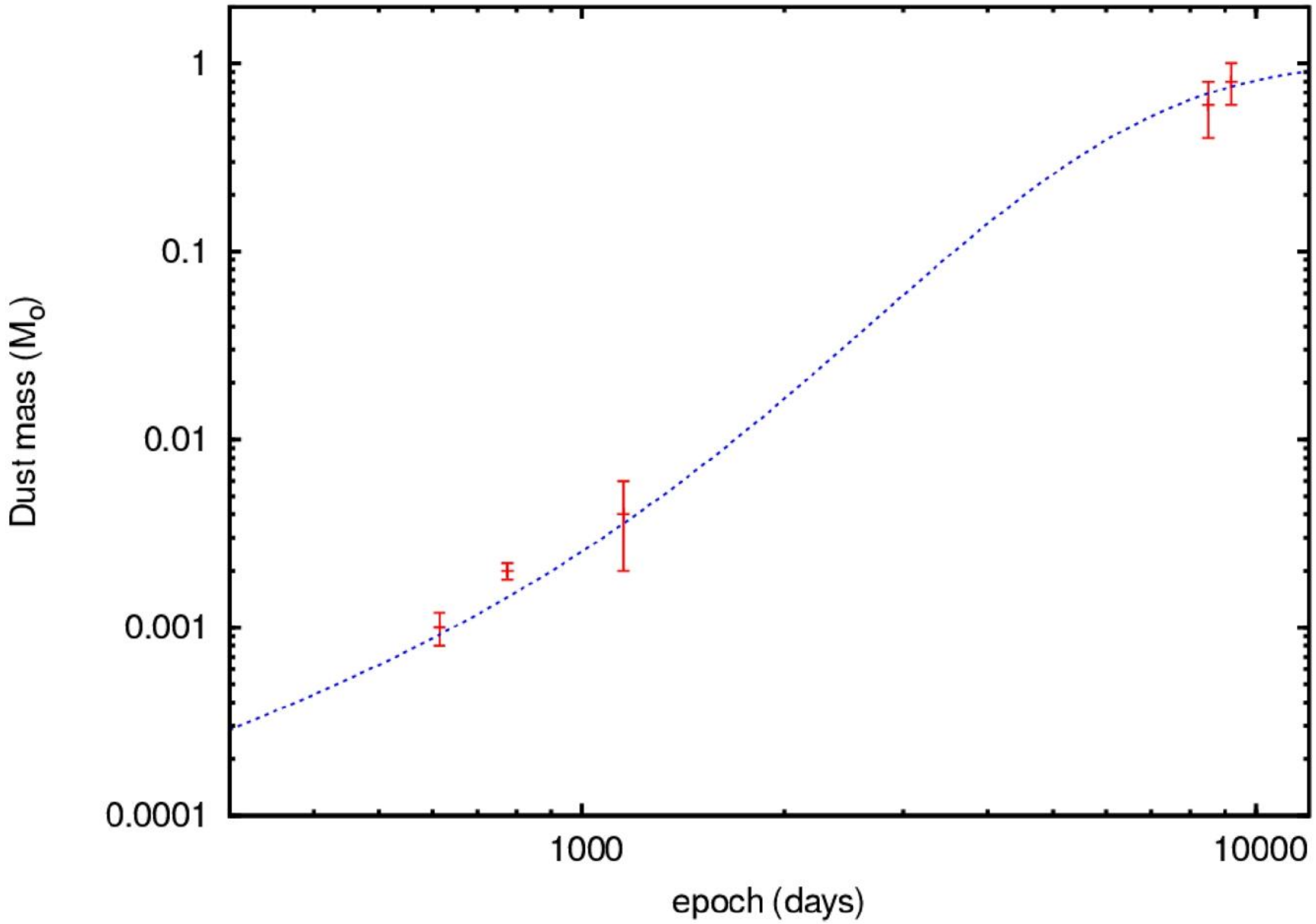
Figure 11. Best fitting models for day 8515: M=0.7 $M_\odot$, f=0.1, 85% carbon, 15% silicates, 2.005μm< a <2.25μm, and M=0.5 $M_\odot$, f=0.1, 85% carbon, 3.005μm< a <3.25μm.

Day 615: 5×10^{-4} Msun of clumped amorphous carbon dust

Day 8515: 0.6 Msun of clumped *large* carbon dust grains

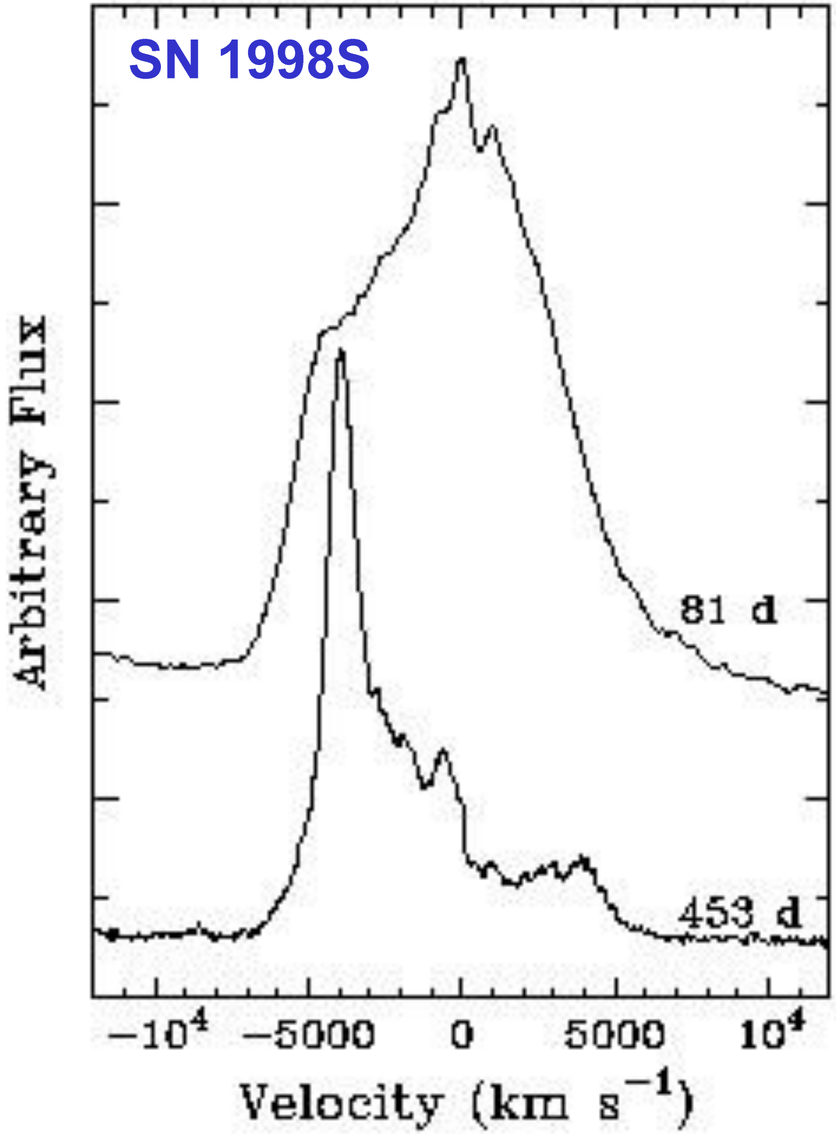
Wesson et al. 2015

SN 1987A's dust mass appears to have grown from ~0.002 $M_\odot$ at Year 3 to ~0.6 $M_\odot$ by Year 25, by which epoch large carbon grains (a ~ 2um) were needed to fit the SED.



Wesson et al. 2015

Alternative method for estimating dust masses in CCSN ejecta: use the optical red-blue line profile asymmetries caused by internal dust



SN 1988S Hα profile evolution, from Leonard et al. (2000)

Removal of red wing of line profile (receding, far-side) by internal dust that formed between day 81 and day 453

Lucy et al. (1989) modelled SN 1987A's late-time asymmetric [O I] 6300, 6363A line profile to estimate a newly formed dust mass of up to 3×10^{-4} $M_\odot$ by day 775, in agreement with the value from mid-IR SED analyses.

SN 1987A: DAMOCLES model fits to Hα & [O I] 6300,6363A profiles (Bevan & Barlow 2016)

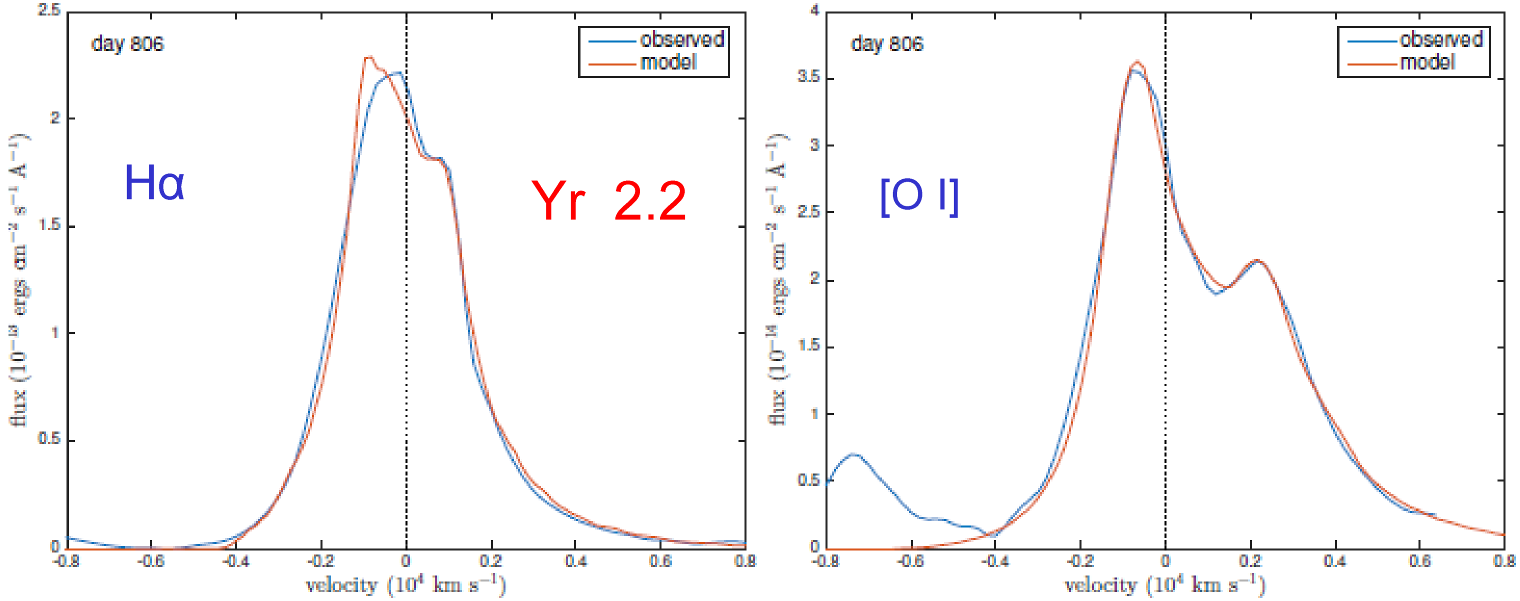


Figure 15. Best clumped fit to the day 806 Hα line and [O I] λ6300,6363 Å doublet as per parameters detailed in Table 3.

After 11 yrs, the Hα profile was distorted by reverse shock driven by ring interaction

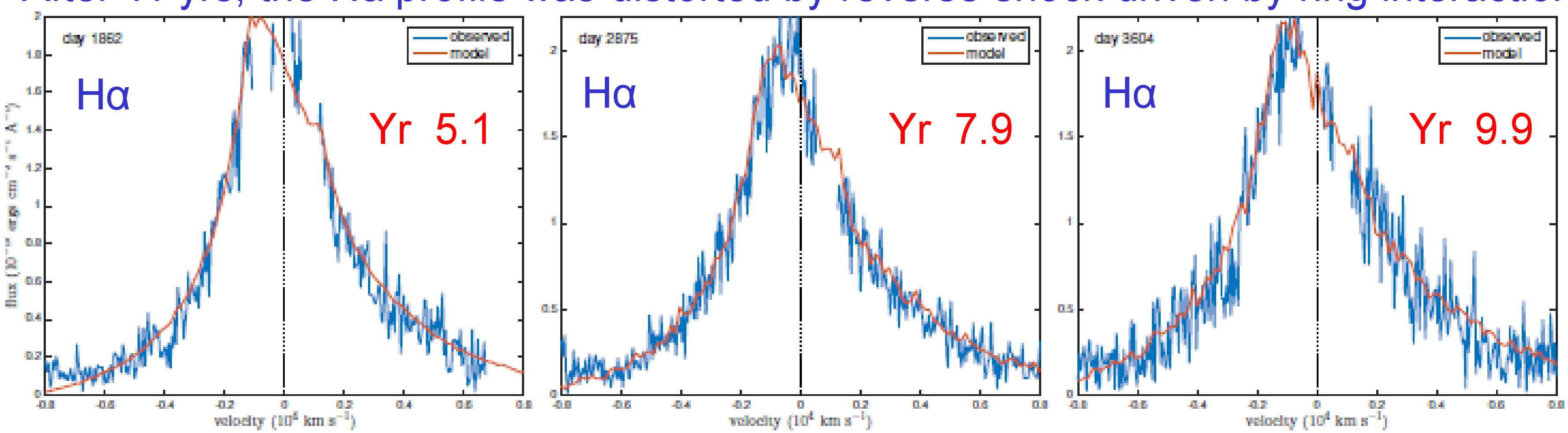
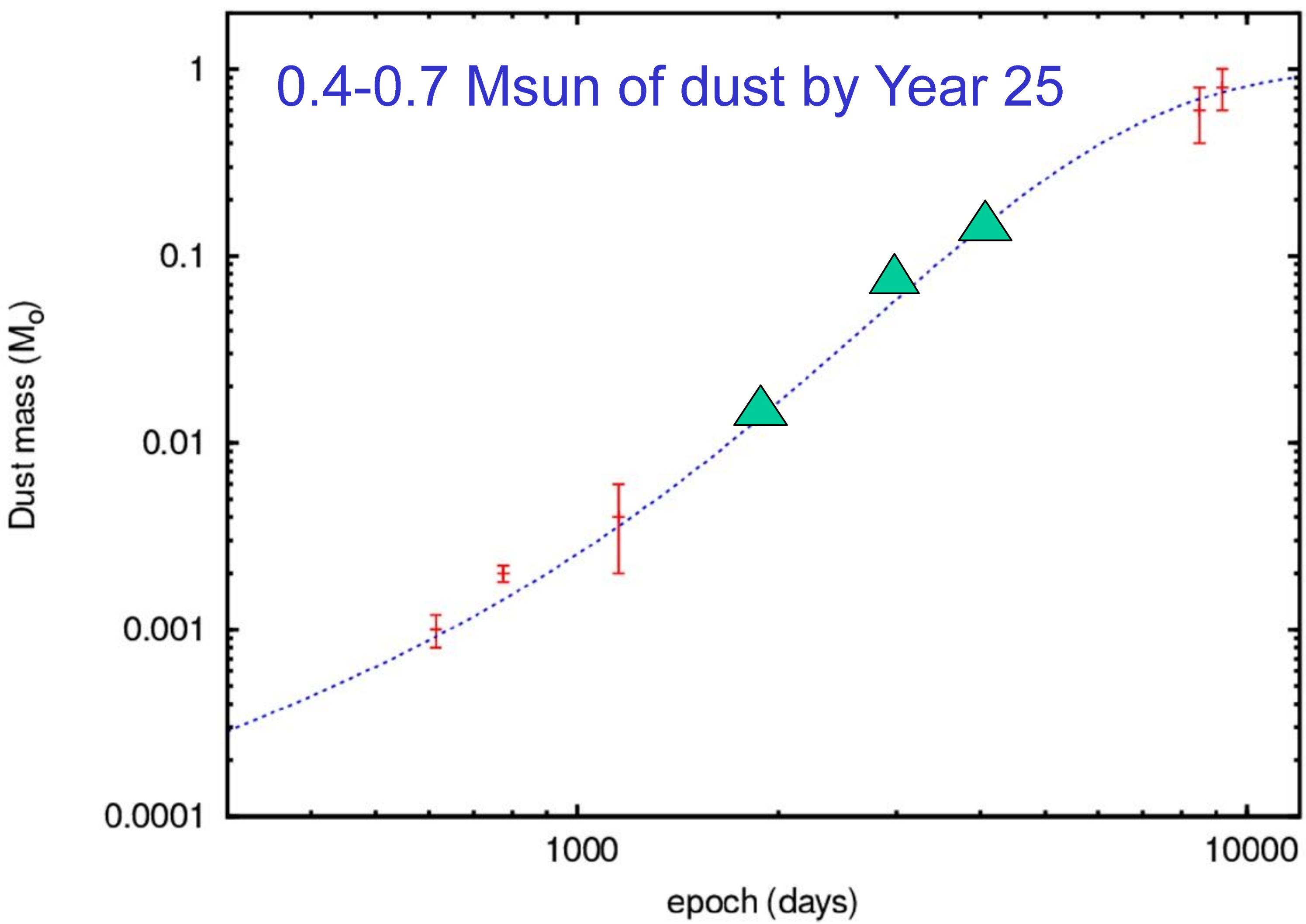
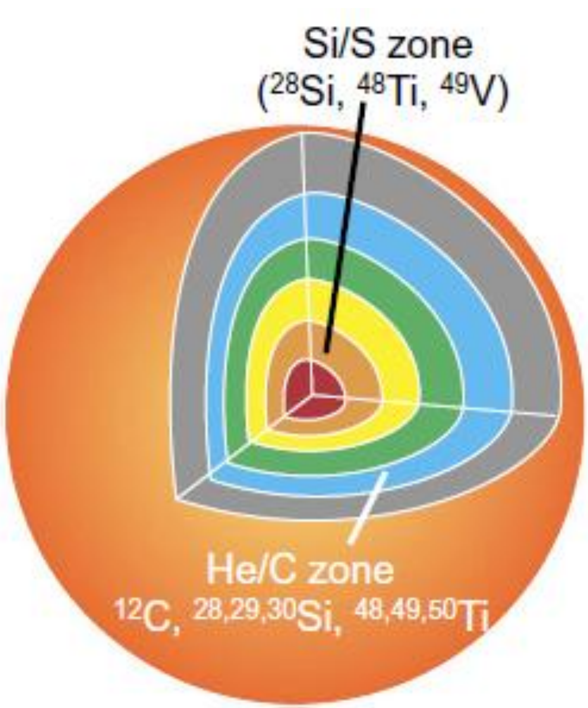


Figure 17. Best clumped fit to the Hα line at days 1862, 2875 and 3604 as per parameters detailed in Table 4 with $a = 3.5\mu m$.

SN 1987A's dust mass growth: the first 25 years

Red: Mid-IR or Far-IR SED-fit dust masses, in Msun (Wesson et al. 2015)
Green: Halpha red-blue line-asymmetry dust masses (Bevan & Barlow 2016)





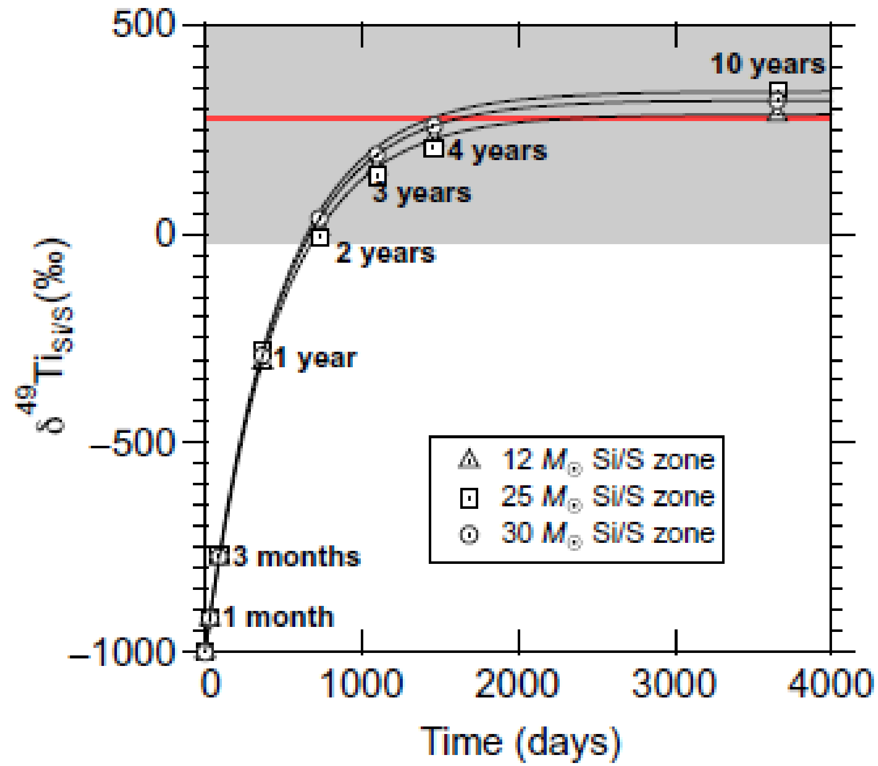


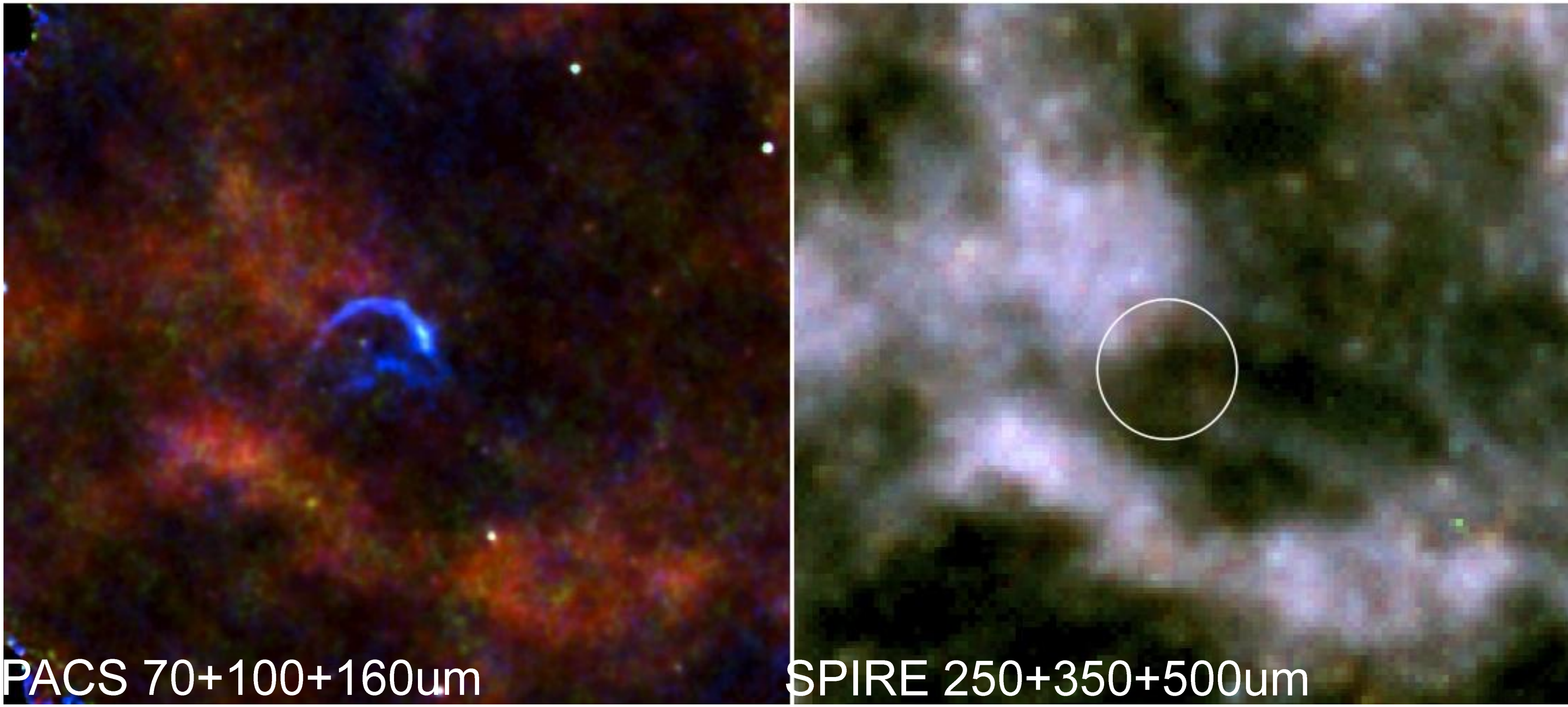
Fig. 4. Growth curves of δ^{49}Ti in the Si/S zone resulting from ^{49}V decay after the SN explosions (black lines with symbols) predicted by models for solar metallicity

Pre-solar SiC grains from CCSNe: the ^{49}V/^{49}Ti chronometer shows that the SiC grains formed at least 2 years, and up to 10 years or more, after the supernova explosion.

(Liu, Nittler, Alexander & Wang, 2018, Sci. Adv. 4)

What about Type Ia supernovae?

Kepler's supernova of 1604 (Gomez et al. 2012a)



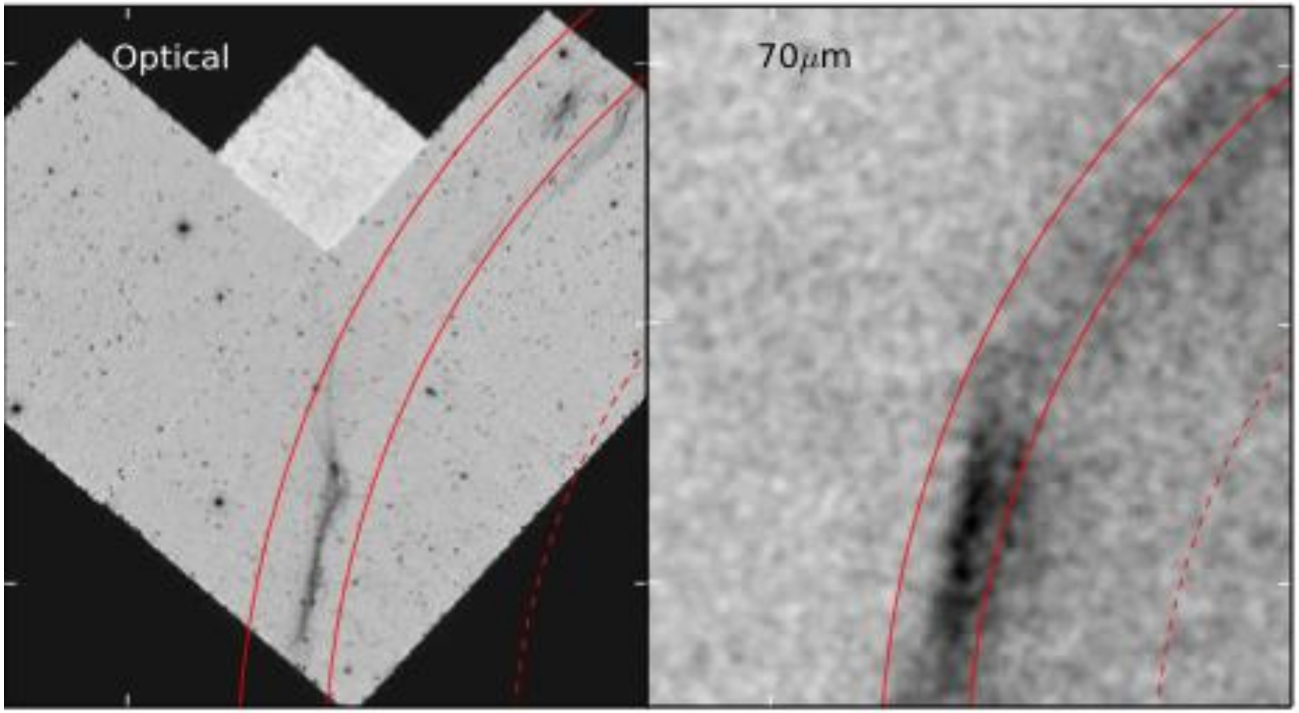
T=82+-5 K
Md ~ $3x10^{-3}$ Msun CSM dust
at edge, for D = 4.0 kpc

T=20K
Md = 2.1 Msun (but interstellar dust)

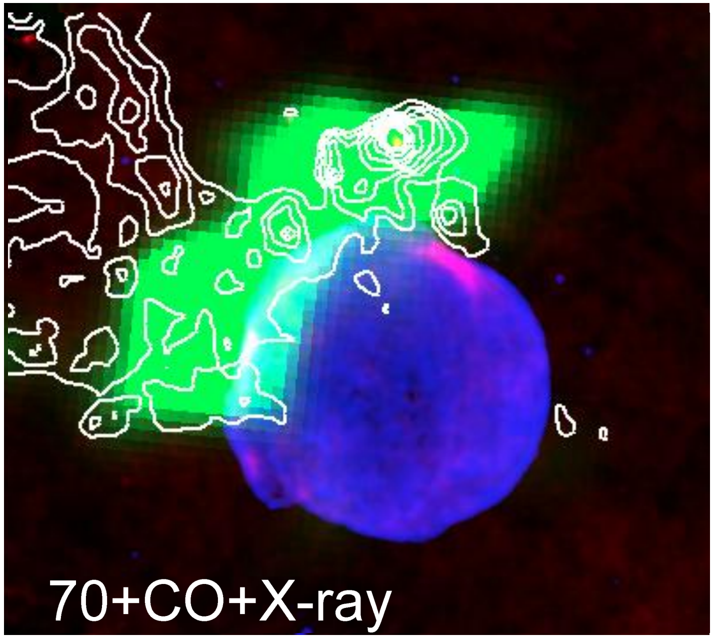
No cold dust inside the remnant

Tycho's SN of 1572

We see hot dust where the blast wave meets surrounding IS gas



No cold dust inside the remnant



Gomez et al. 2012a

Spitzer mid-IR observations of multiple Type Ia SNe failed to detect any warm dust emission from newly formed grains within the first 3 years, while *Herschel* failed to detect any cool dust emission from inside the 400-yr old Tycho and Kepler Type Ia SNRs.

Type Ia supernovae are believed to provide most of the iron found in galaxies such as the Milky Way; up to 0.5 Msun of Fe per Type Ia.

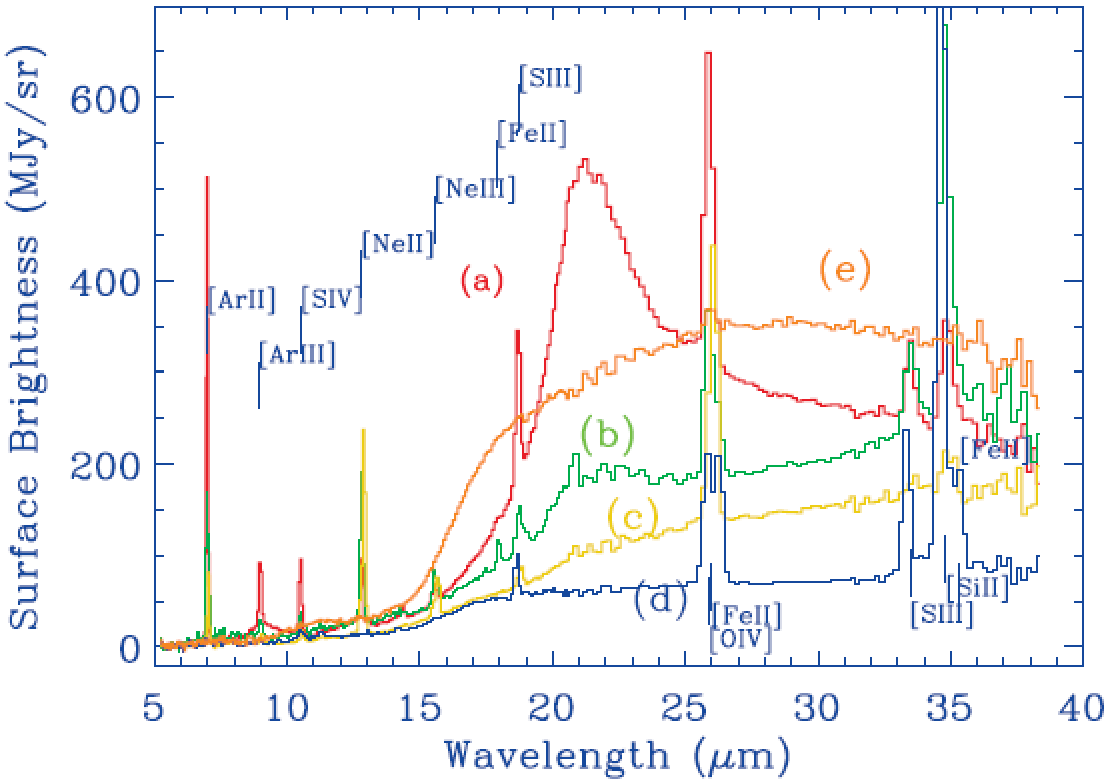
The absence of dust particles inside Tycho and Kepler implies that their iron atoms must be in the gas-phase. The higher expansion velocities of Type Ia's, together with higher charged particle and photon densities, may be responsible (see e.g. Nozawa et al. 2011).

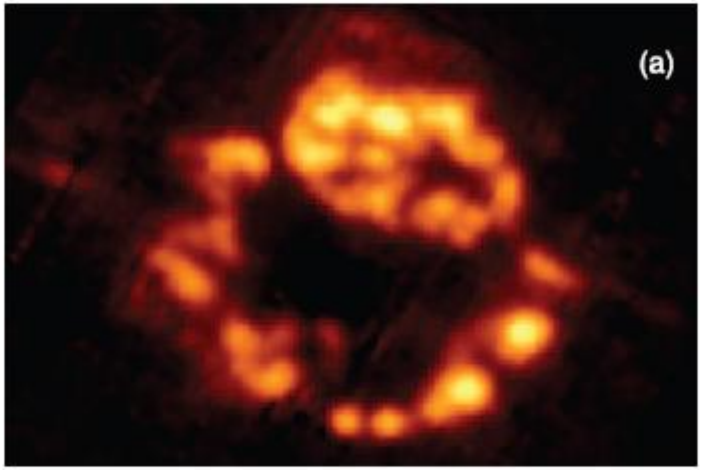
Yet in the diffuse ISM, gas-phase Fe has depletion factors of 10-100, with the missing atoms presumed to be locked up in dust grains.

What is the origin of the Fe-bearing ISM dust?

Cassiopeia A: a highly O-rich core-collapse supernova remnant
Age ~ 340 yrs

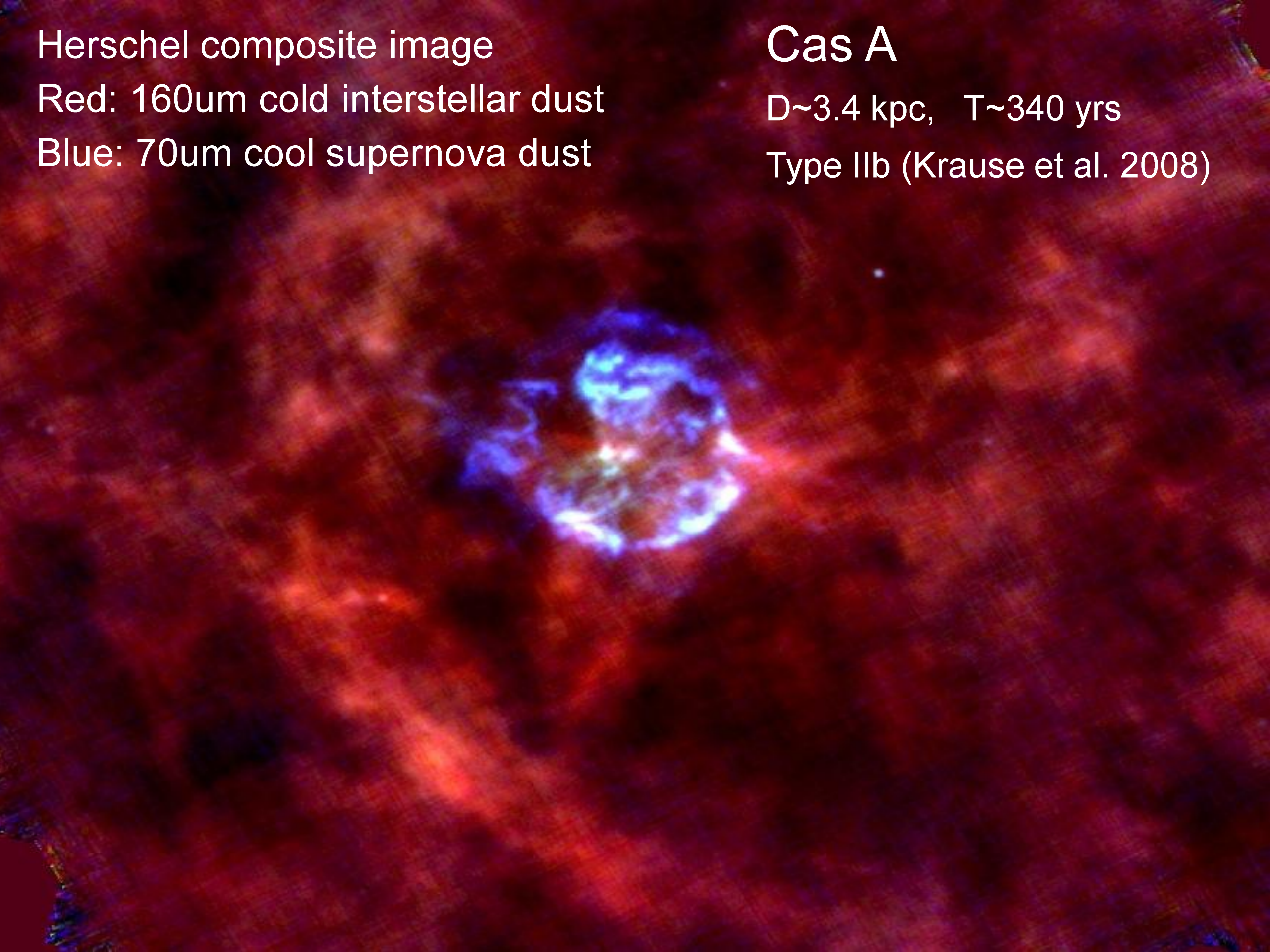
Rho et al. (2008) carried out *Spitzer* spectral imaging

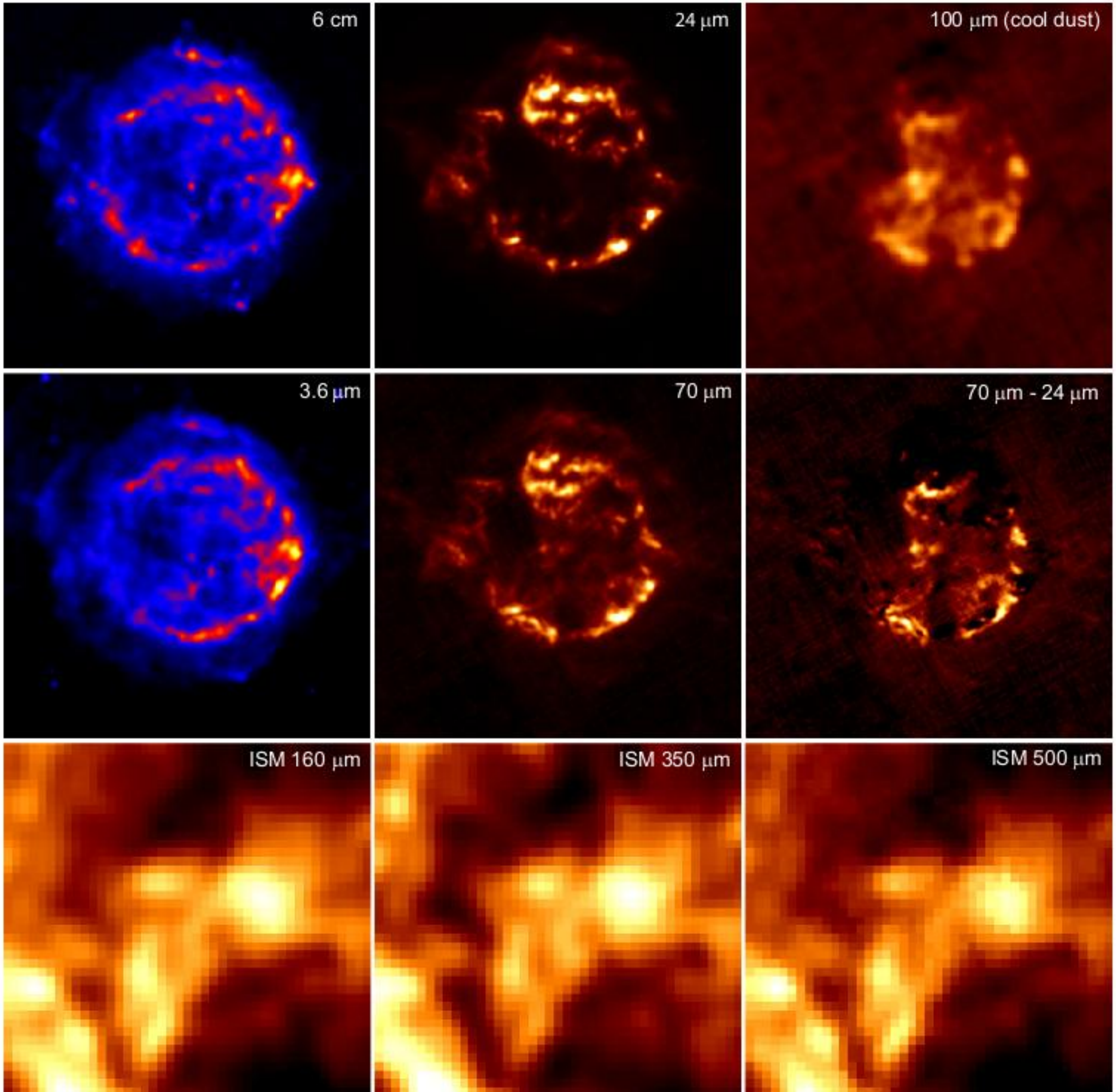




The 21um dust emission is coincident with the reverse shock

Strong 21um emission feature seen in many places; can be fitted by various silicate components


Herschel composite image
Red: 160um cold interstellar dust
Blue: 70um cool supernova dust
Cas A
D~3.4 kpc,   T~340 yrs
Type IIb (Krause et al. 2008)

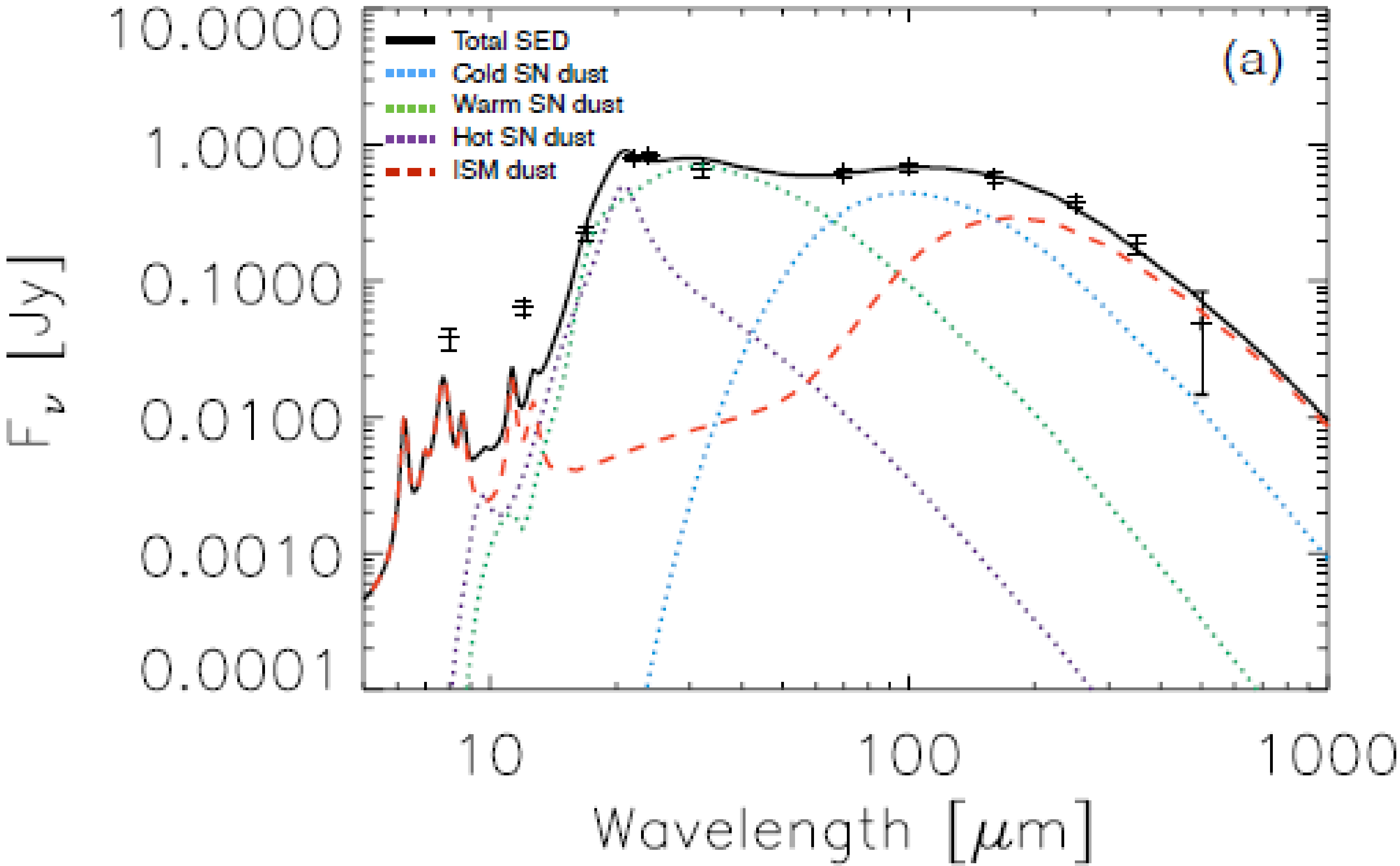


Cas A

near-IR/far-IR/ radio

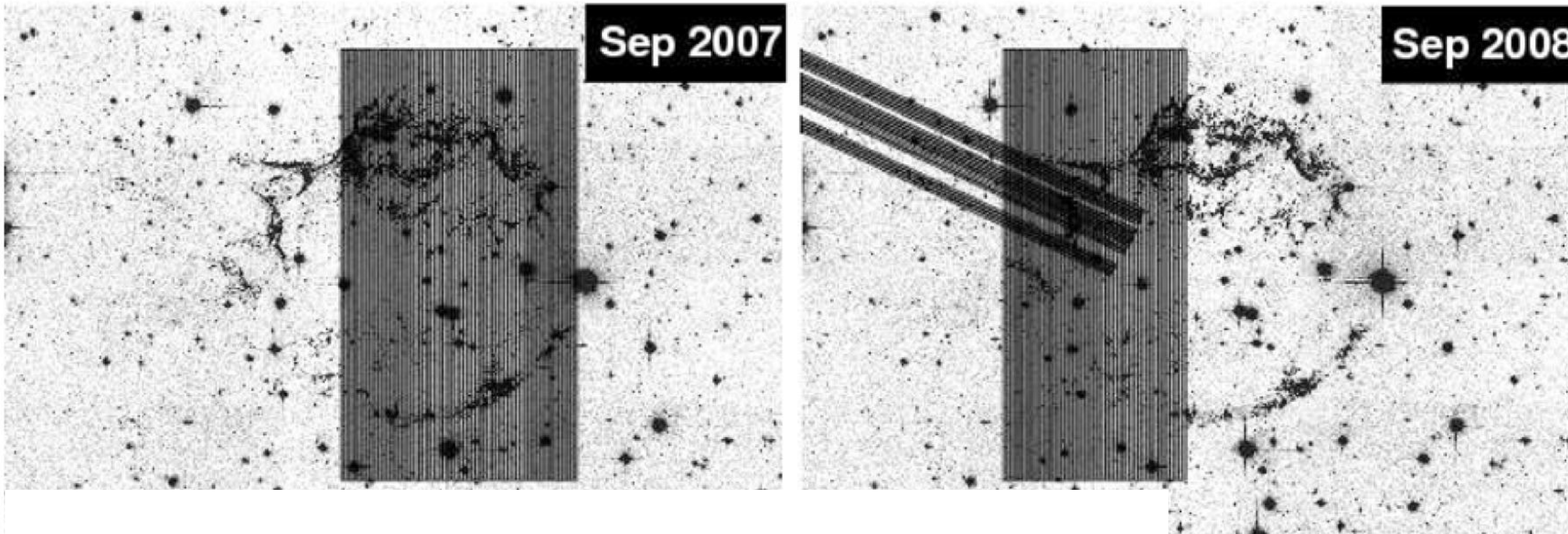
Barlow et al. (2010)

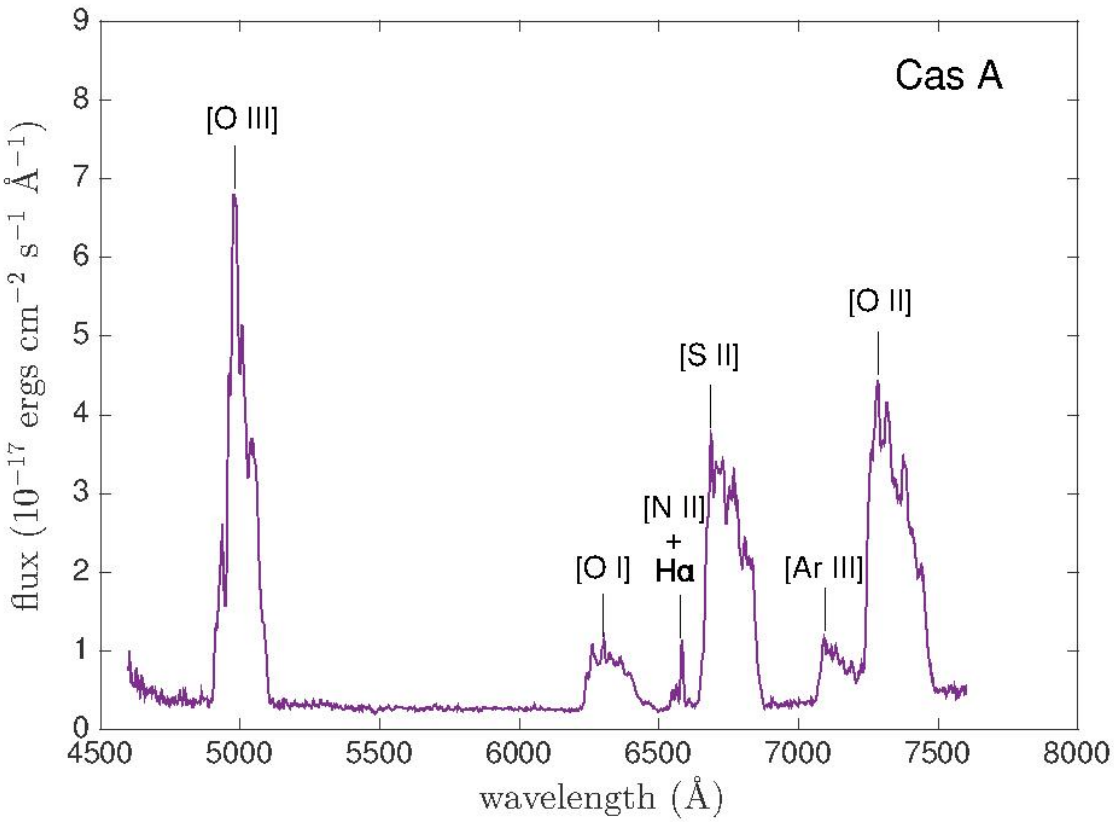
For this O-rich SNR, silicates (Rho et al. 2008) were used to fit the global dust SED, giving ~ 0.1 Msun of dust



Spatially resolved *Herschel* PACS and SPIRE and *Spitzer* images were convolved to SPIRE 500um resolution; synchrotron component subtracted; and multiple SN + ISM dust components fitted. Plot shows SED fit for just a single spaxel.

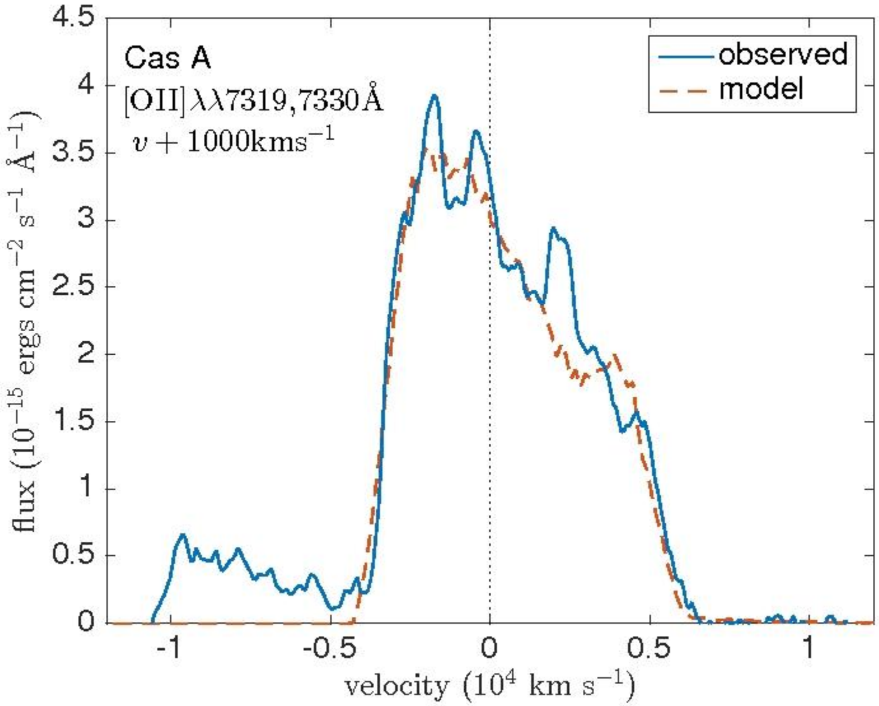
(De Looze et al. 2017; see next talk for further details)

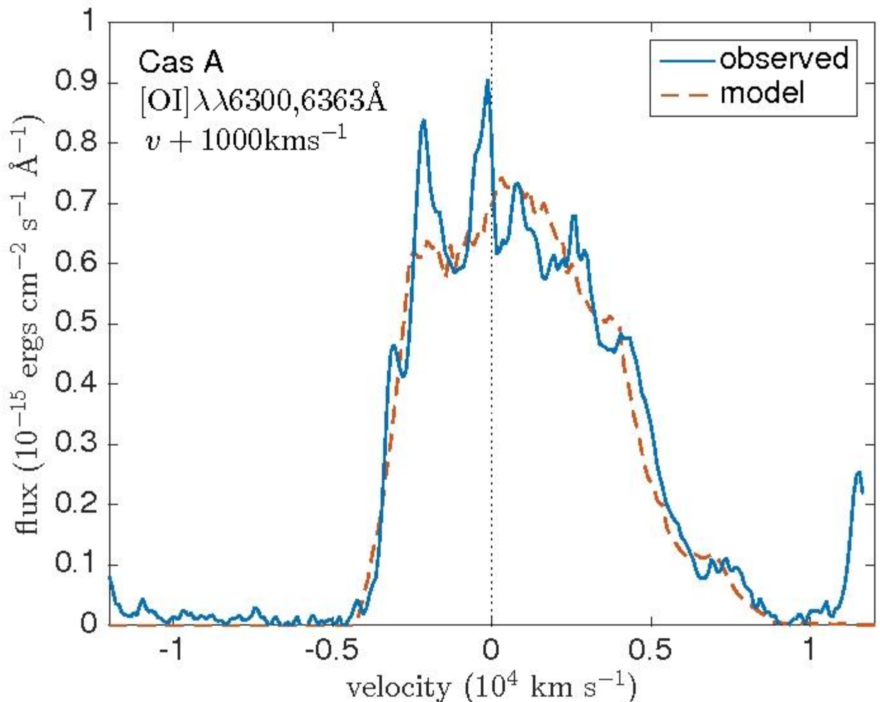




If Cas A (5 arcmin at 3.4 kpc) was at 1Mpc it would have an angular diameter of 1 arcsec

Integrated optical spectrum of the complete nebula (Milisavljevic et al 2012)



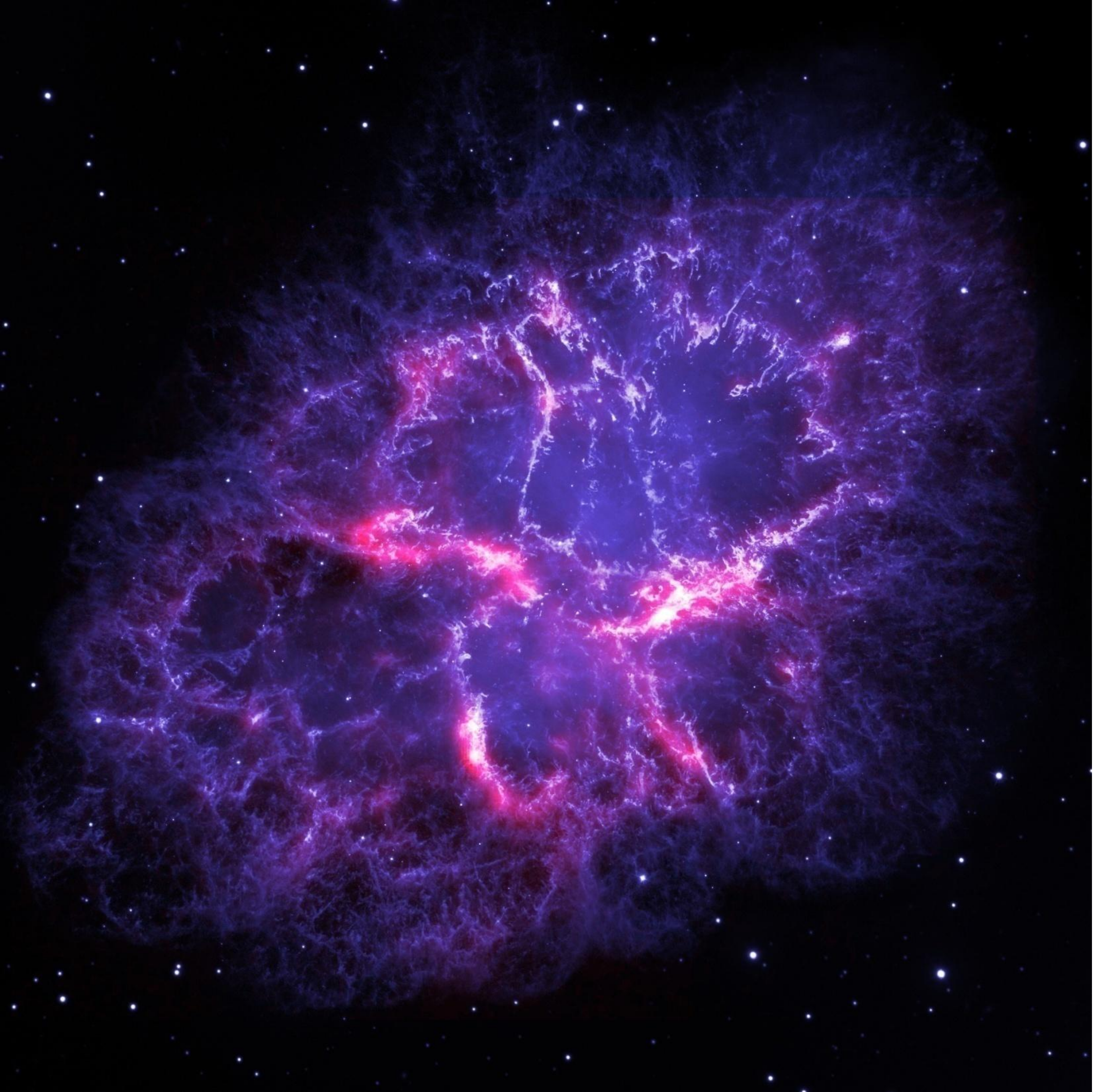


CC-SNR Cas A (t ~330 yrs)

Smooth dust model
Vmax=5000 km/s
Vmin=3250 km/s;

Dust mass = 1.1 $M_\odot$
(50% sil, 50% amC)

Bevan et al. 2017



Crab Nebula: a 960-yr old carbon-rich CC-SNR, containing a pulsar wind nebula

Blue-white: HST optical emission line imagery

Red: Herschel PACS 70um

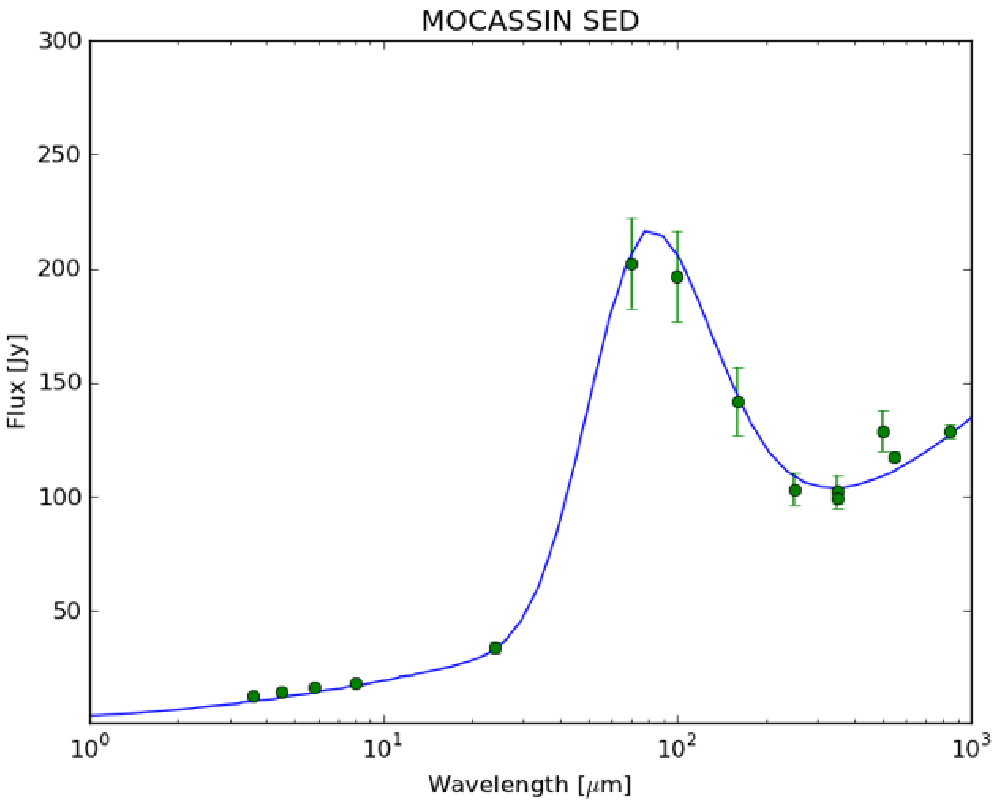
Owen & Barlow 2015

Gomez et al. (2012b): empirical analysis of Herschel observations of the Crab Nebula: 0.1-0.2 Msun of dust

Owen & Barlow (2015): Moccasin gas+dust photo-ionization model (ionized by Pulsar Wind Nebula radiation)

Nebular C/O = 1.35 by number

Gas-to-dust mass ratio ~ 30

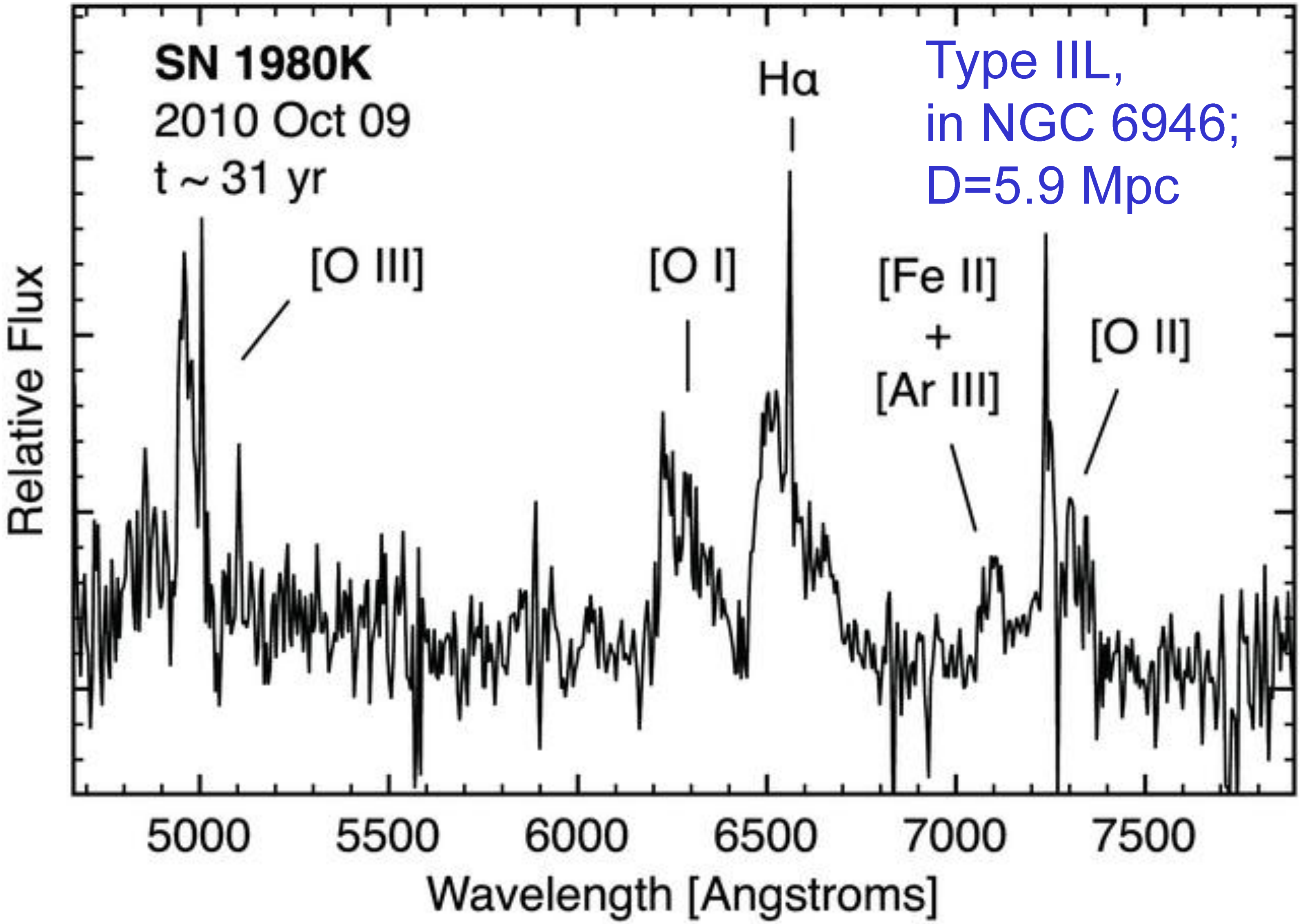


Smooth dust models:

~ 0.25 Mo of amorphous carbon dust

Large (>1um) grains needed

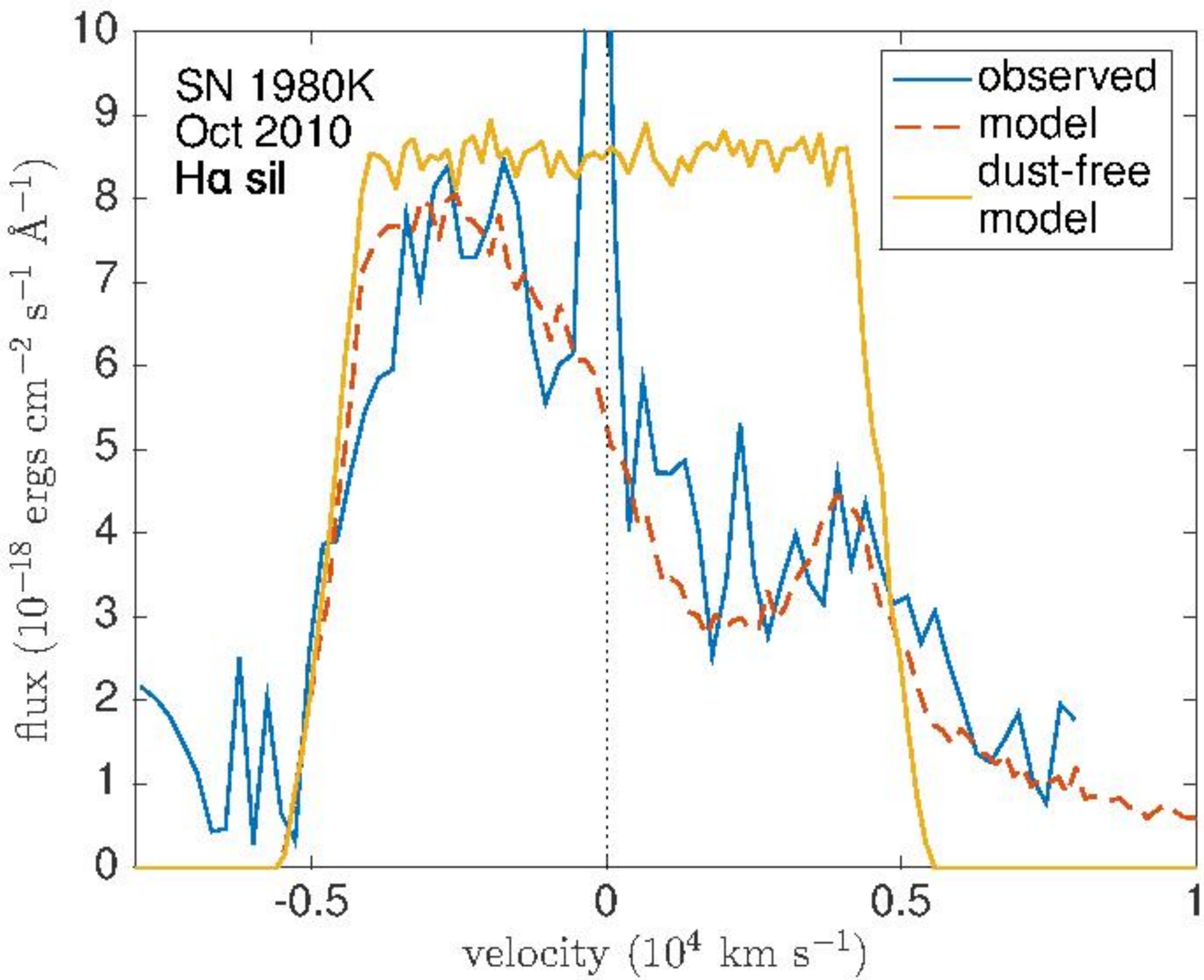
For a spatially resolved dust mass analysis, see next talk.



Spectrum from Milisavljevic et al. (2012): Spectra of a number of old CCSNe are available for modeling line profile asymmetries to derive dust masses.

Bevan et al. 2017

SN 1980K in NGC 6946; t = 31 Yr (D=5.9 Mpc)



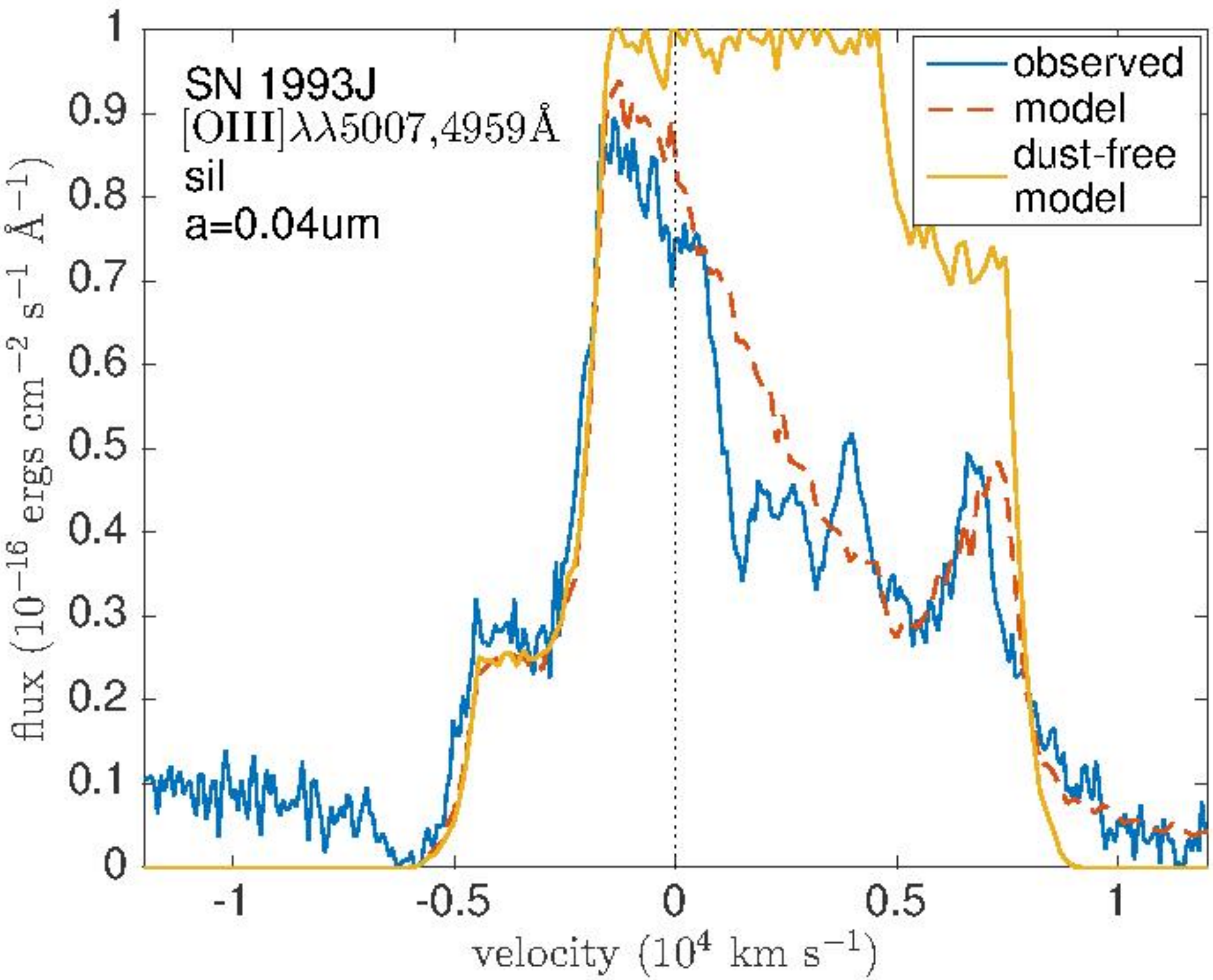
a=0.1um silicate grains provide best match.

Halpha's red scattering wing requires a dust albedo of ~0.8 -> can be fit by sufficiently large silicate particles.

0.12-0.30 $M_\odot$ of clumped dust

Bevan et al. (2017)

SN 1993J in M81; t = 16 yr (D=3.7 Mpc)



Vmax=6000 km/s
Vmin=4500 km/s

Clumped dust models:

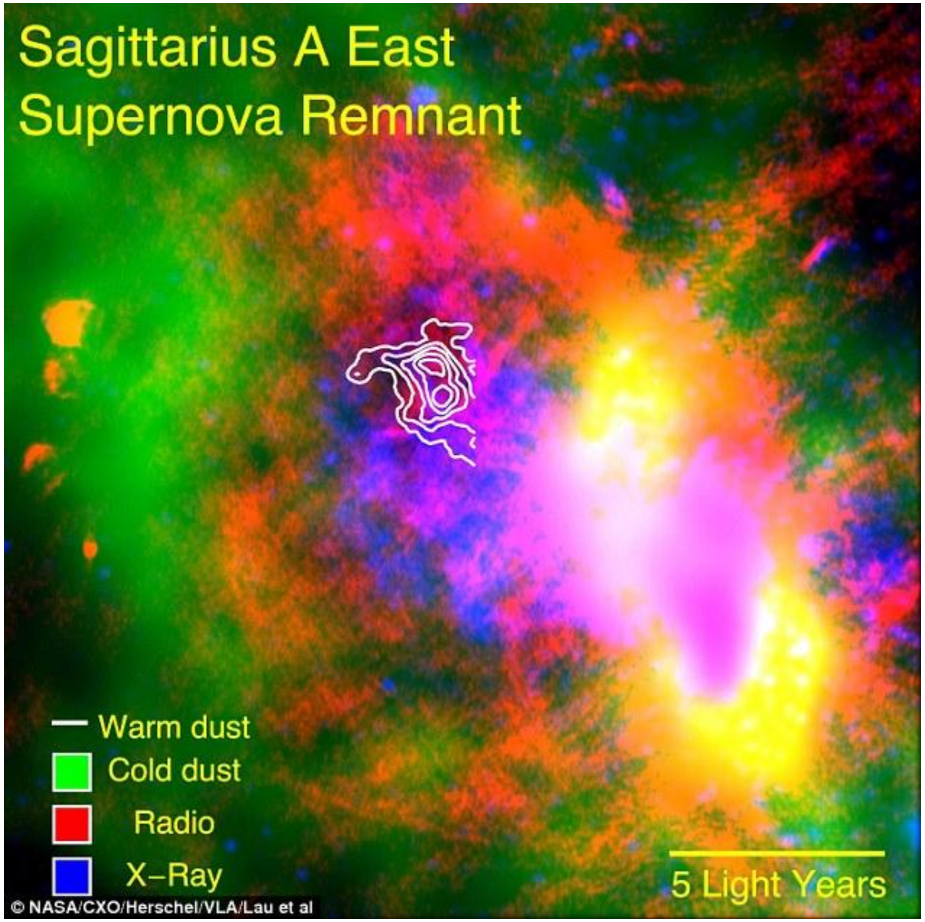
Silicate: 0.08-0.15 $M_\odot$

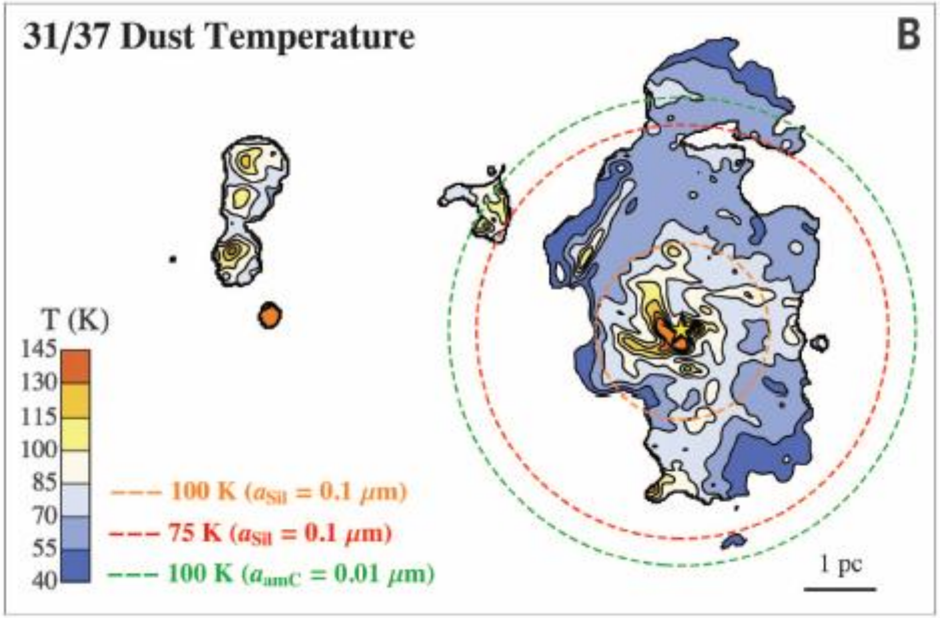
amC: up to 0.18 $M_\odot$

Bevan et al. (2017)

Lau et al. Science 2015: *Spitzer, SOFIA and Herschel* observations of the 10,000-yr old Sgr A East SNR, at the Galactic Centre.

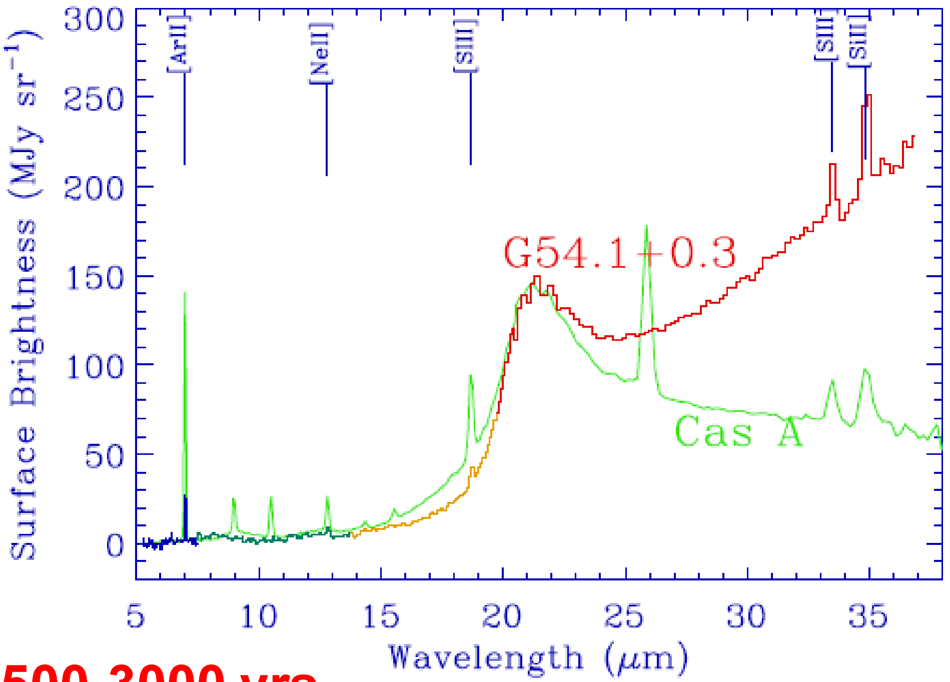
T ~ 100K warm dust, with a dust mass of ~0.02 Msun. Any cold dust emission present would likely have been drowned out by cold ISM dust emission.





G54.1+0.3: Another pulsar wind SNR

Herschel+*Spitzer* data has been analysed by Temim+2017 and Rho+2018

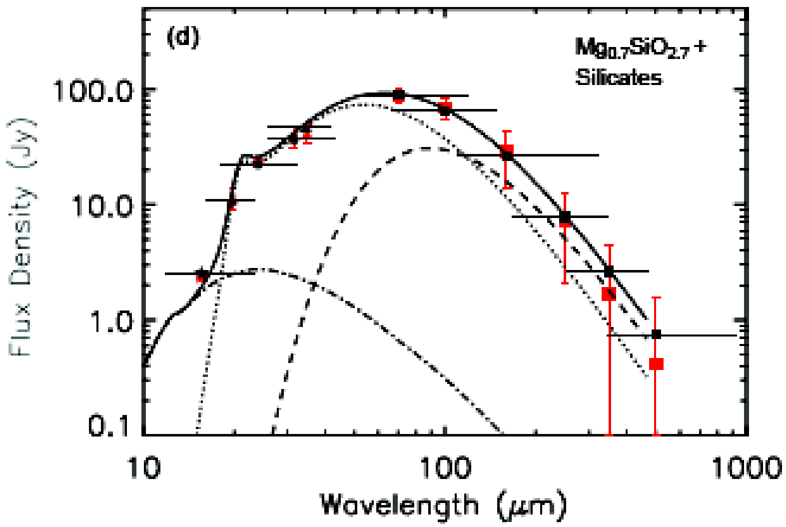


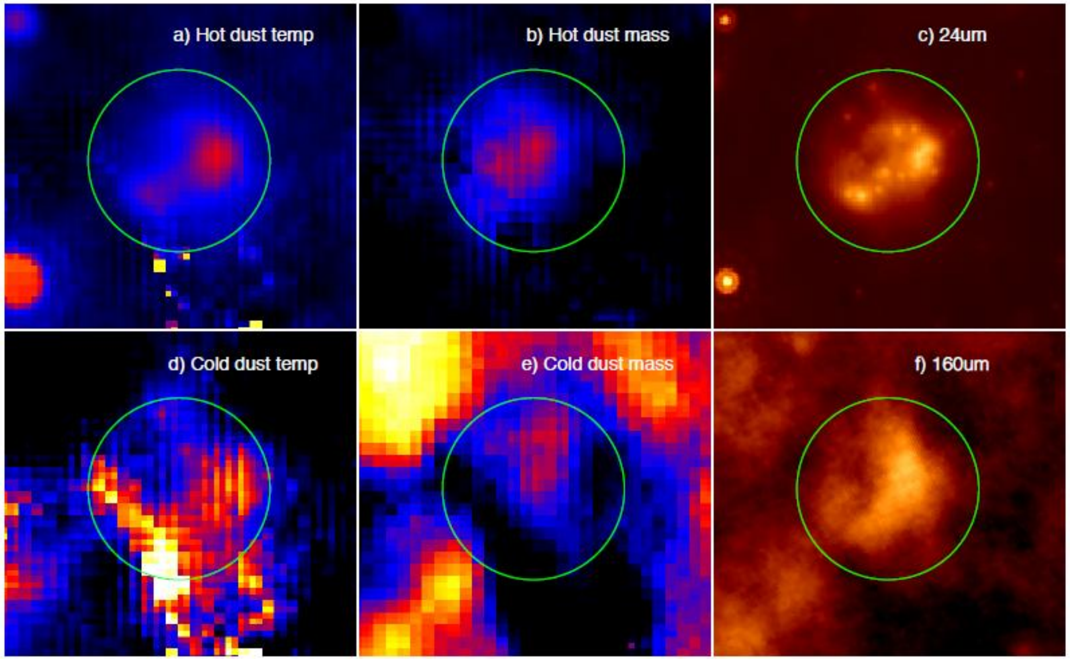
Total dust mass:

1.1 - 1.5 $M_\odot$ Temim+2017

0.2 - 0.9 $M_\odot$ Rho+2018

Age: 1500-3000 yrs





CCSN(R) dust masses from *Herschel* observations:

SN 1987A Year 25: 0.4-0.7 $M_\odot$ of T~23K AmC+silicates
(Matsuura et al. 2011, 2015; Indebetouw et al. 2014)

Cas A Year 340: 0.3-0.6 $M_\odot$ of T~30K silicates
(De Looze et al. 2017)

Crab Year 960: 0.1 - 0.25 $M_\odot$ of T~34K carbon dust (but see next talk)
(Gomez et al. 2012; Owen & Barlow 2015)

G54.1+0.3 Year 1500-3000 0.9 – 1.5 $M_\odot$
(Temim et al. 2017; Rho et al. 2017)

CCSN dust masses from red-blue line asymmetries:

SN 1987A, Type IIP, Year 10: 0.17 $M_\odot$ (Bevan & Barlow 2016)

SN 1993J, Type IIb, Year 16: 0.08 - 0.18 $M_\odot$ (Bevan et al. 2017)

SN 1980K, Type IIL, Year 31: 0.12 - 0.30 $M_\odot$ “

Cas A, Type IIb, Year ~340: 1.1 $M_\odot$ “

H. Chawner et al. (2018) have used *Herschel* HiGAL data to search for cool dust emission from Galactic SNRs in the range -60 < l < +60 (see her talk in next session).

Red-blue emission line asymmetry modelling has been used to determine late-epoch ejecta dust masses for SN 1995N (R. Wesson; see talk in next session) and for SN 2005ip (A. Bevan; Poster 124).

Summary

(a) CCSN dust masses appear to grow for up to 20 years.

(b) Large (~1um) grain sizes are frequently needed to fit late-epoch far-IR/submm SEDs and red-blue emission-line asymmetries.

(c) CCSN/CCSNR dust mass results obtained to date are consistent with the 0.1 – 1.0 $M_\odot$ per event deduced to be required in order to explain the very large dust masses found in some high redshift galaxies at $z > 6$.