The dust masses in SN 1980K, SN 1993J and Cas A from red-blue line profile asymmetries

Antonia Bevan, Mike Barlow
(UCL)

Dan Milisavljevic
(CfA)

Motivation: the origin of the dust in galaxies

Up until the late-1990’s the standard picture was that steady mass loss from evolved AGB stars was the primary source for the refractory dust grains found in the ISMs of our own and other galaxies (e.g. silicate and amorphous carbon dust).

From 1998 onwards, submillimetre detections of large quantities of dust in high-z galaxies, beginning with SCUBA, forced a change to this picture, in favour of considering core-collapse supernovae as potential dust sources. Recent analyses of dust mass loss rates from Local Group AGB populations have found that they fall short of explaining the current interstellar dust masses of their galaxies (e.g. Matsuura et al. 2009, 2015).

Core Collapse Supernovae as dust sources:

From dust nucleation modelling, Kozasa et al. (1991), Todini & Ferrara (2001) and subsequent authors have predicted that 0.1--1.0 Msun of dust should condense in the ejecta of of a typical high-z core-collapse supernovae (CCSNe) within a few years of outburst, corresponding to a condensation efficiency for the available refractory elements of > 20%.

Similarly high condensation efficiencies are required (Morgan & Edmunds 2004; Dwek, Galliano & Jones 2007) to explain the ~10^8 solar masses of dust observed in a number of QSOs and SMGs at z>6, emitting at less than 1 Gyr after the Big Bang. Only relatively high mass stars can have evolved quickly enough in this time (i.e. AGB stars with initial masses of 5-8 $M_\odot$ and >8 $M_\odot$ stars producing CCSNe).

However, observations at mid-IR wavelengths (SN 1987A with the KAO and multiple CCSNe with Spitzer) typically detected emission from less than 10^{-3} $M_\odot$ of newly formed warm dust (Td > 150K) at <1000 days.

The advent of Herschel in 2009 enabled much colder dust, with emission peaking longwards of 70um, to be detected from young CCSN remnants. The colder dust gets, the greater the mass of dust that is needed in order to produce a given flux at a specific far-IR wavelength.

Dust Masses from Herschel for CC-SNRs with ages <1000 yrs:

Cas A (330 yrs): at least 0.10 $M_\odot$ of T~35K silicates

(Barlow et al. 2010, Rho et al. 2008)

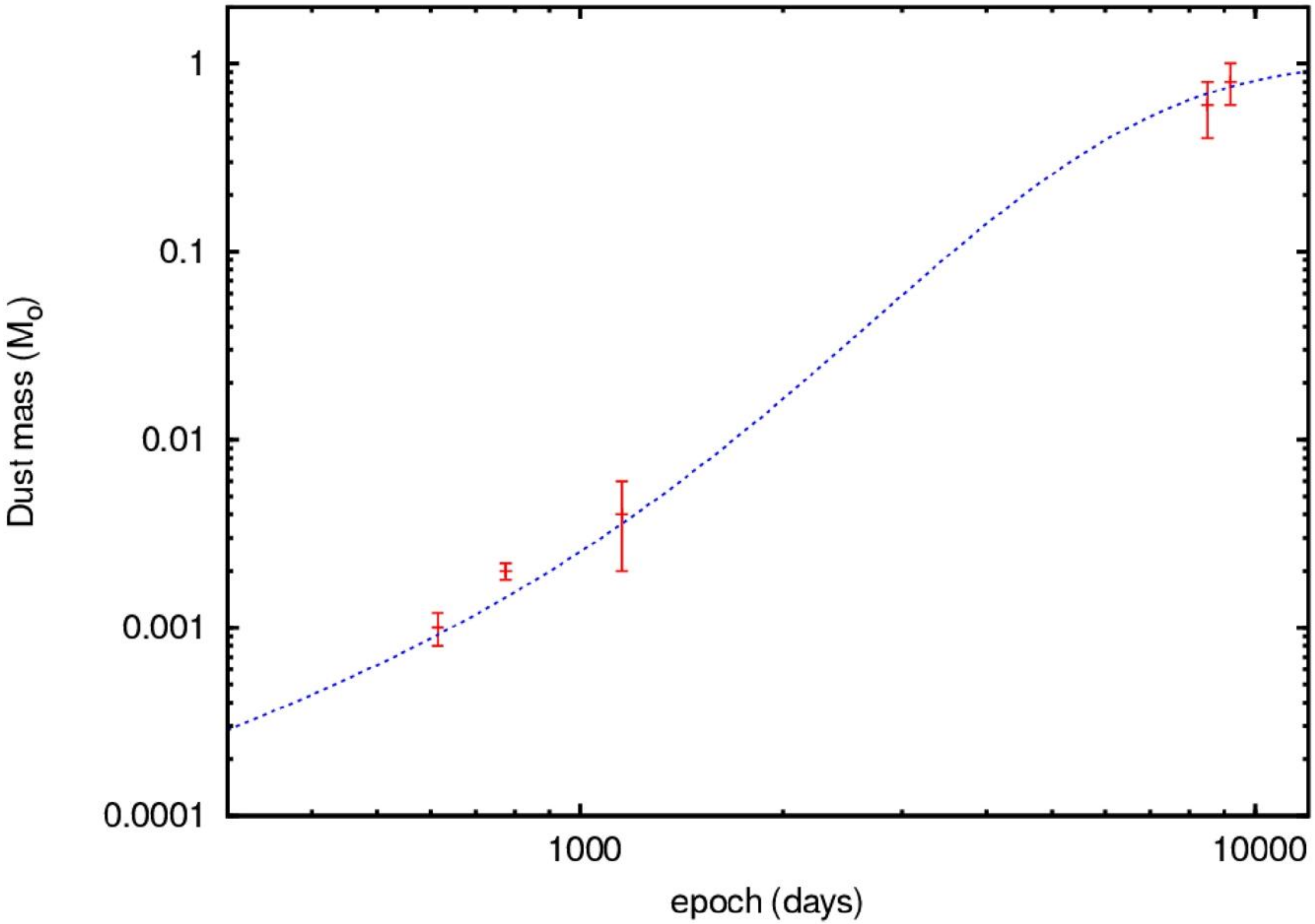
Crab (960 yrs): 0.25 - 0.32 $M_\odot$ of T~34K AC carbon dust

(Gomez et al. 2012; Owen & Barlow 2015)

SN 1987A (25 yrs): 0.6 $M_\odot$ of T~23K AC+silicate dust

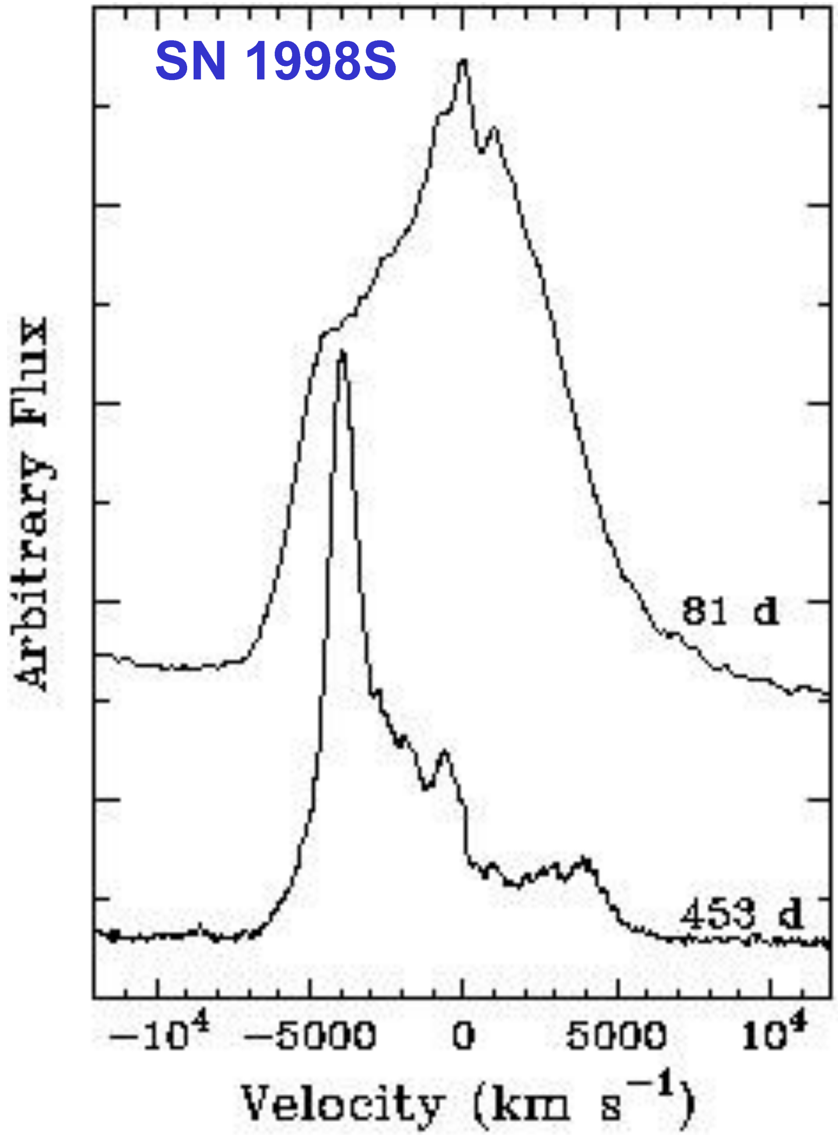
(Matsuura et al. 2011; Indebetouw et al. 2014, Matsuura et al. 2015)

SN 1987A’s dust mass has grown from ~0.002 $M_\odot$ at Year 3 to ~0.6 $M_\odot$ at Year 25.



Wesson et al. (MNRAS, 2015)

We need another method for estimating dust masses in CCSN ejecta: red-blue line profile asymmetries due to internal dust



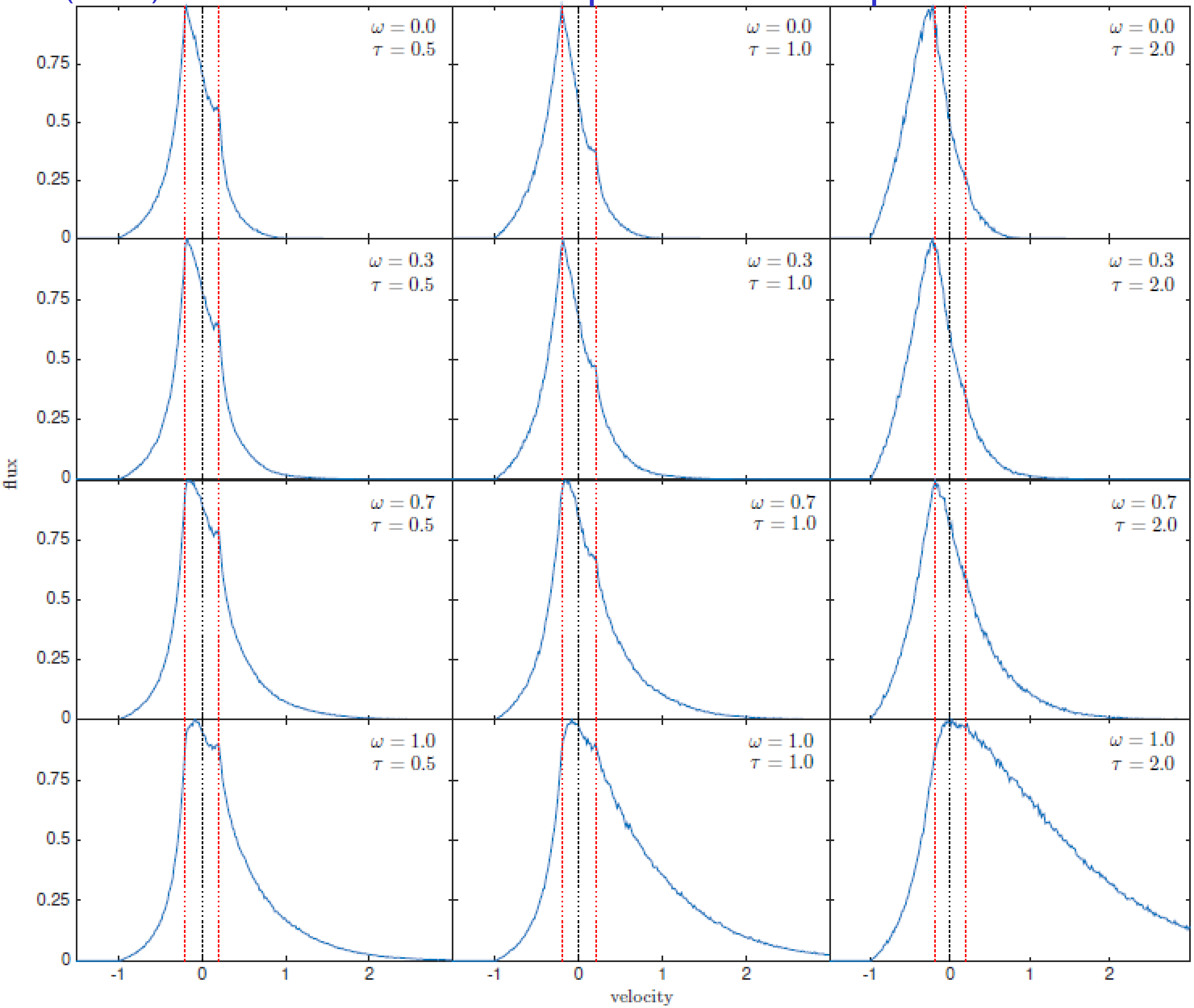
SN 1988S Hα profile evolution from Leonard et al. (2000)

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 $3x10^{-4}$ $M_{\odot}$ by day 775.

(2016)

Effects of internal dust albedo and optical depth on SN line profiles



SN 1987A Halpha & [OI] 6300,6363A profiles

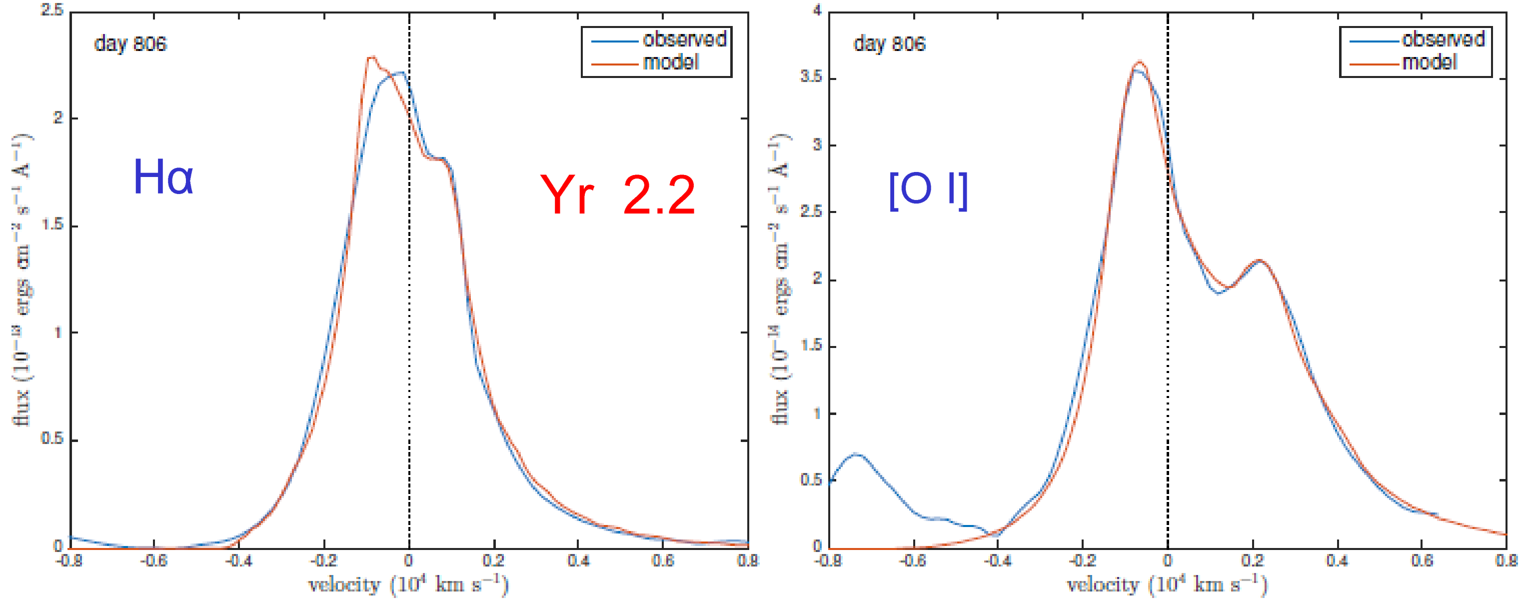


Figure 15. Best clumped fit to the day 806 Hα line and [O I] λ6300,6363 Å doublet as per parameters detailed in Table 3.

After 1999, the Hα profile is distorted by reverse shock driven by ring interaction

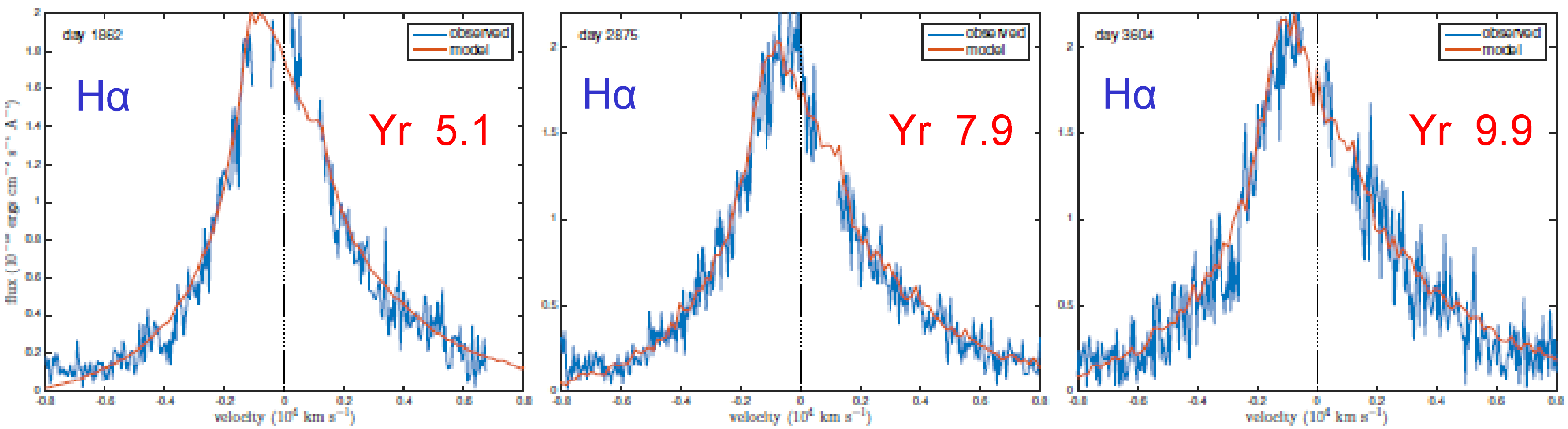


Figure 17. Best clumped fit to the Hα line at days 1862, 2875 and 3604 as per parameters detailed in Table 4 with $a = 3.5\mu$m.

Bevan & Barlow (2015): 87A dust masses from Ha profile models

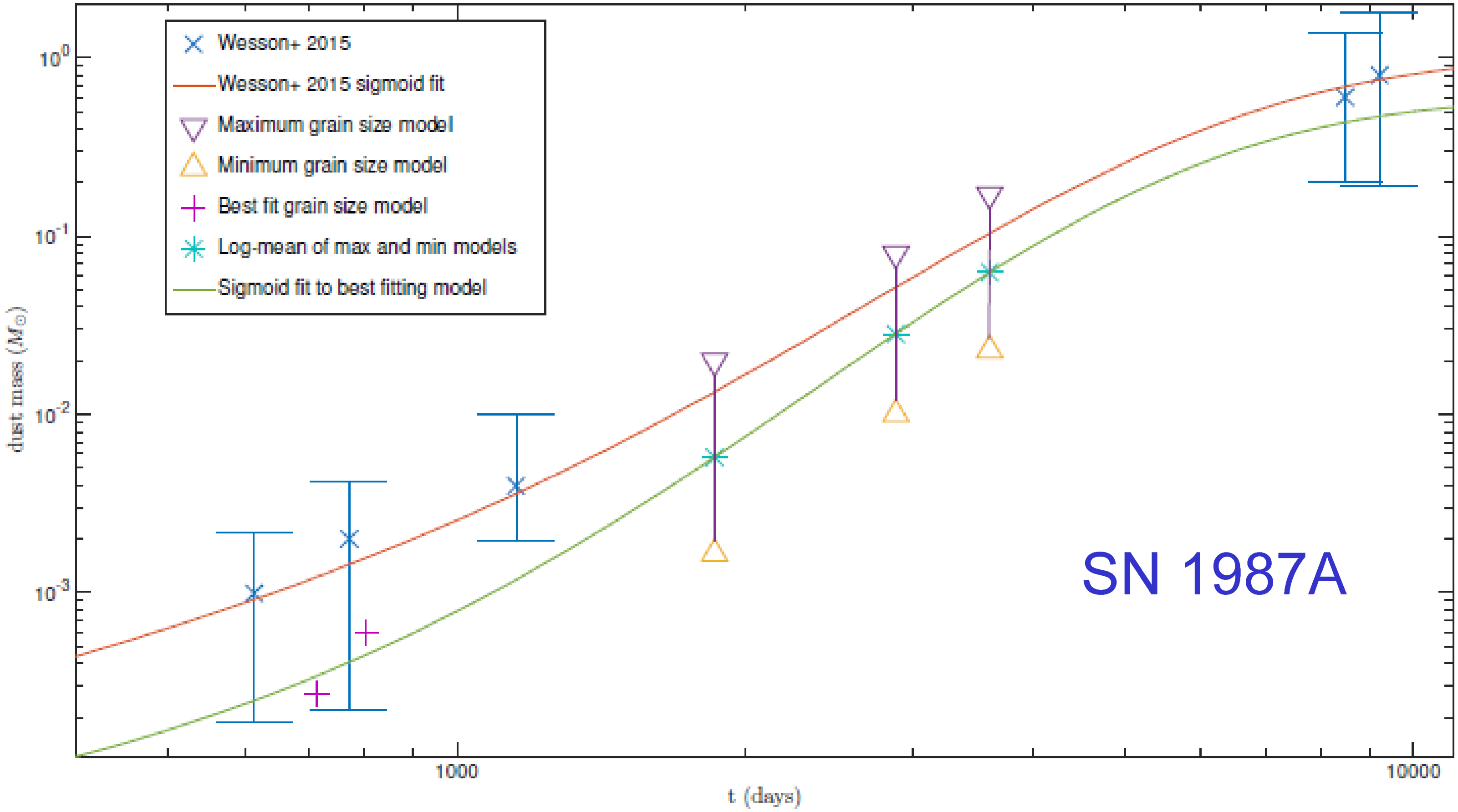
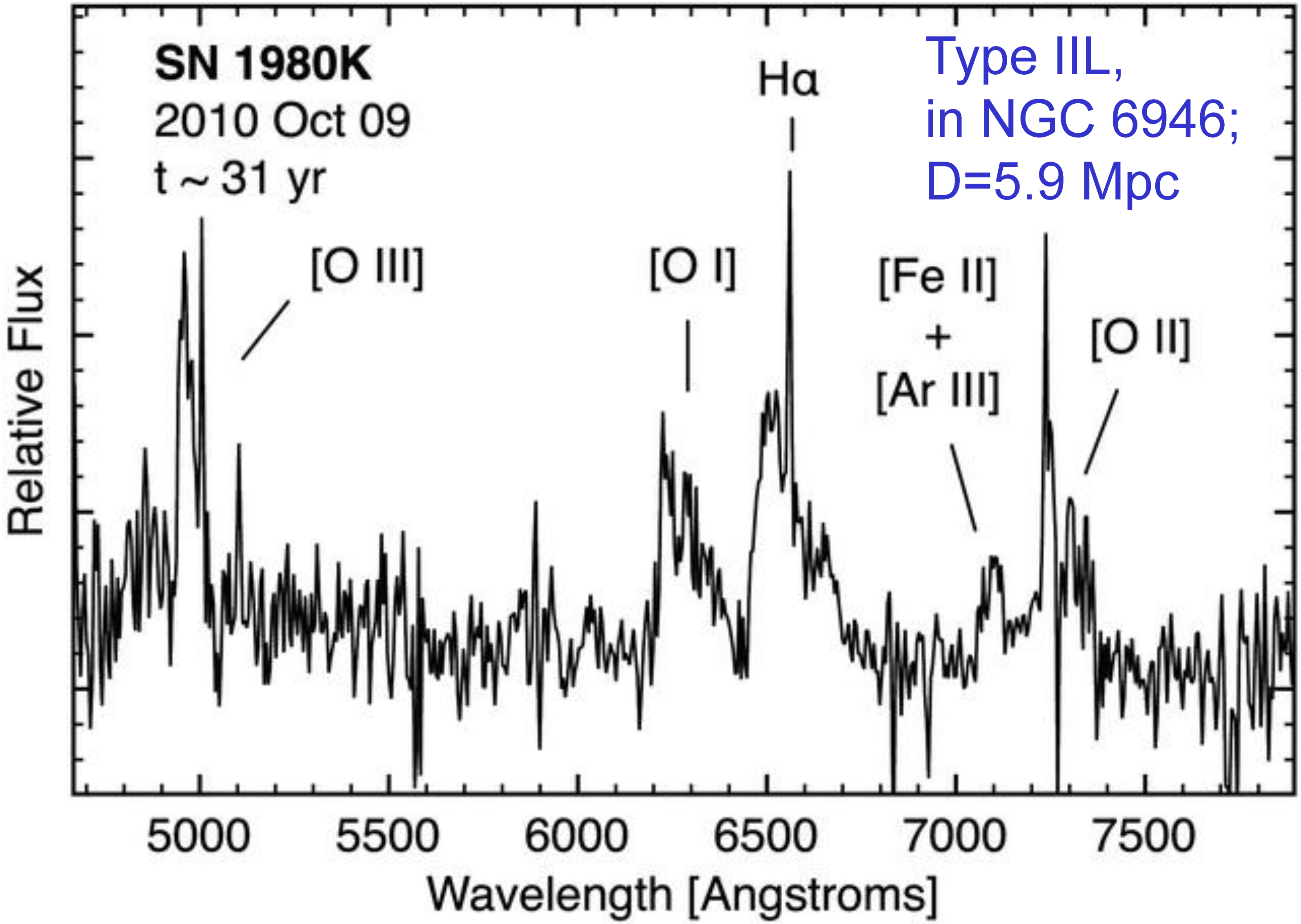
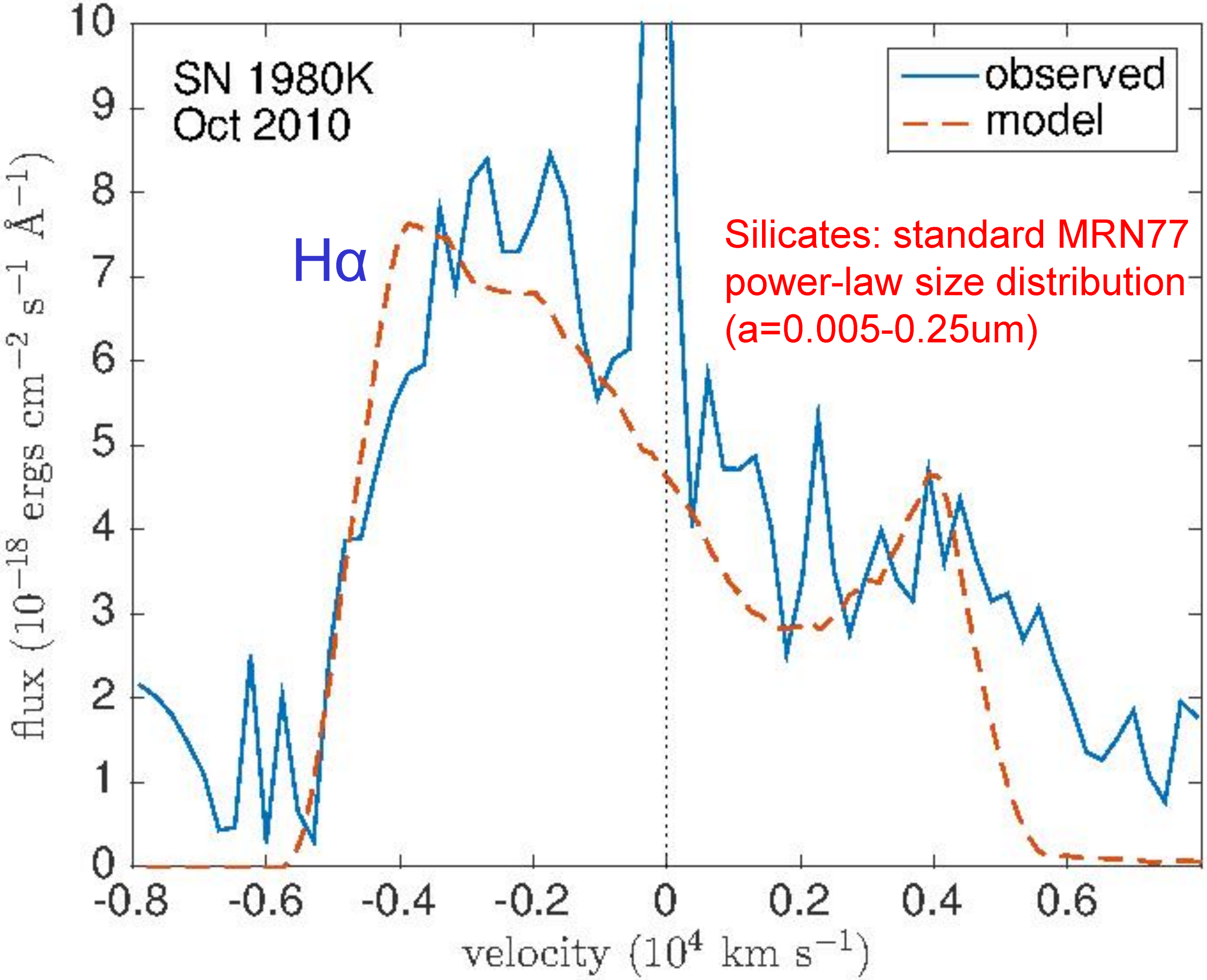


Table 4. Details of the parameters used for the best fitting clumped models with $a = 3.5\mu$m.

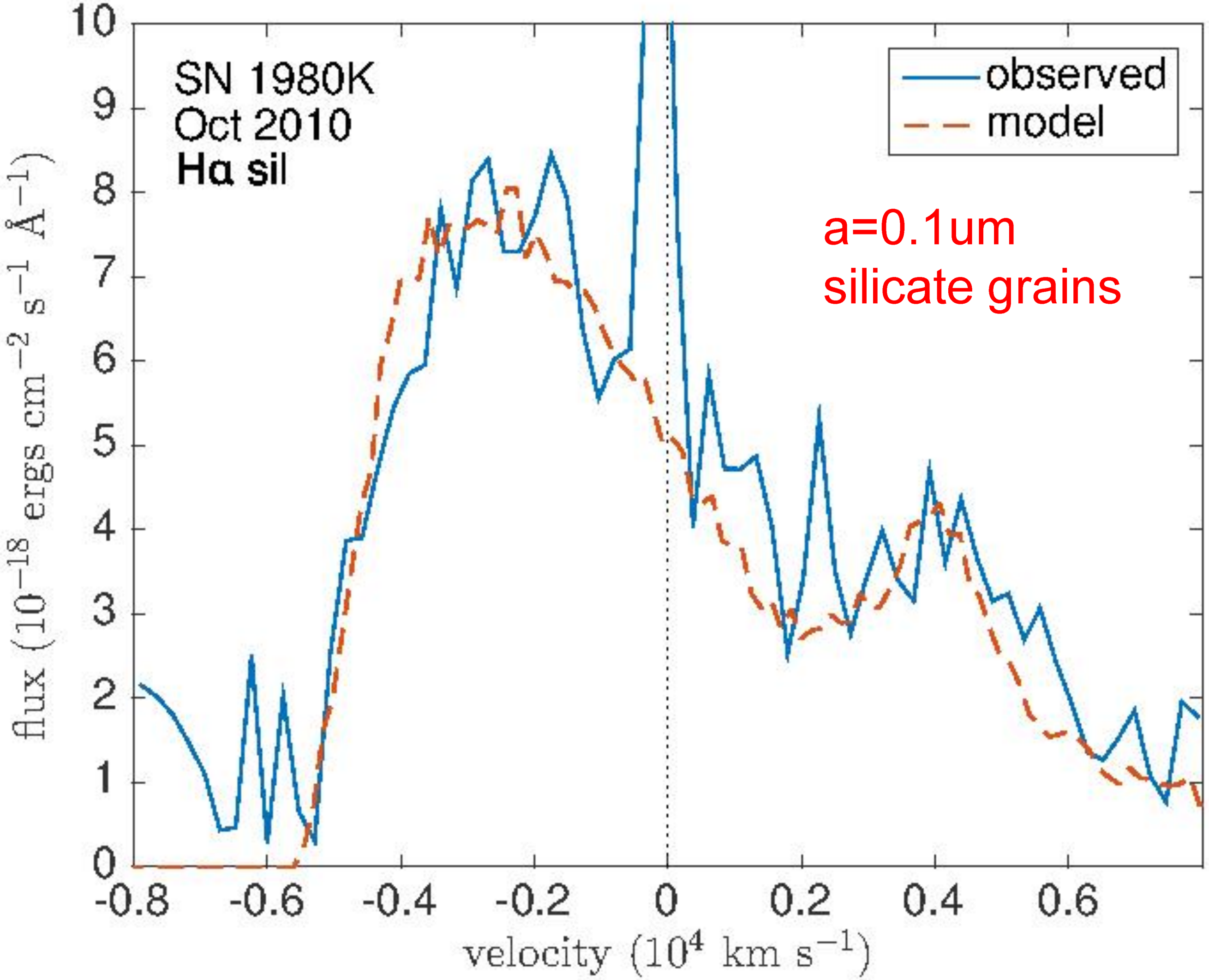
day	V_{max} (km s^{-1})	R_{in}/R_{out}	β	M_{dust} ($M_{\odot}$)	a (μm)	R_{out} (cm)	R_{in} (cm)	$\tau_{H\alpha}$	τ_V	Figure No.
1862	8500	0.14	1.9	2.00E-02	3.50	1.37E+17	1.91E+16	0.85	1.70	17
2875	9500	0.12	2	8.00E-02	3.50	2.36E+17	2.83E+16	1.15	2.30	17
3604	10250	0.12	2	1.70E-01	3.50	3.19E+17	3.83E+16	1.33	2.67	17



Spectrum from Milisavljevic et al. (2012): A number of old CCSNe are available for modeling line profile asymmetries to derive dust masses. Their late-time nebular line emission might be produced by reverse shocks, by external OB stars, or by PWNs



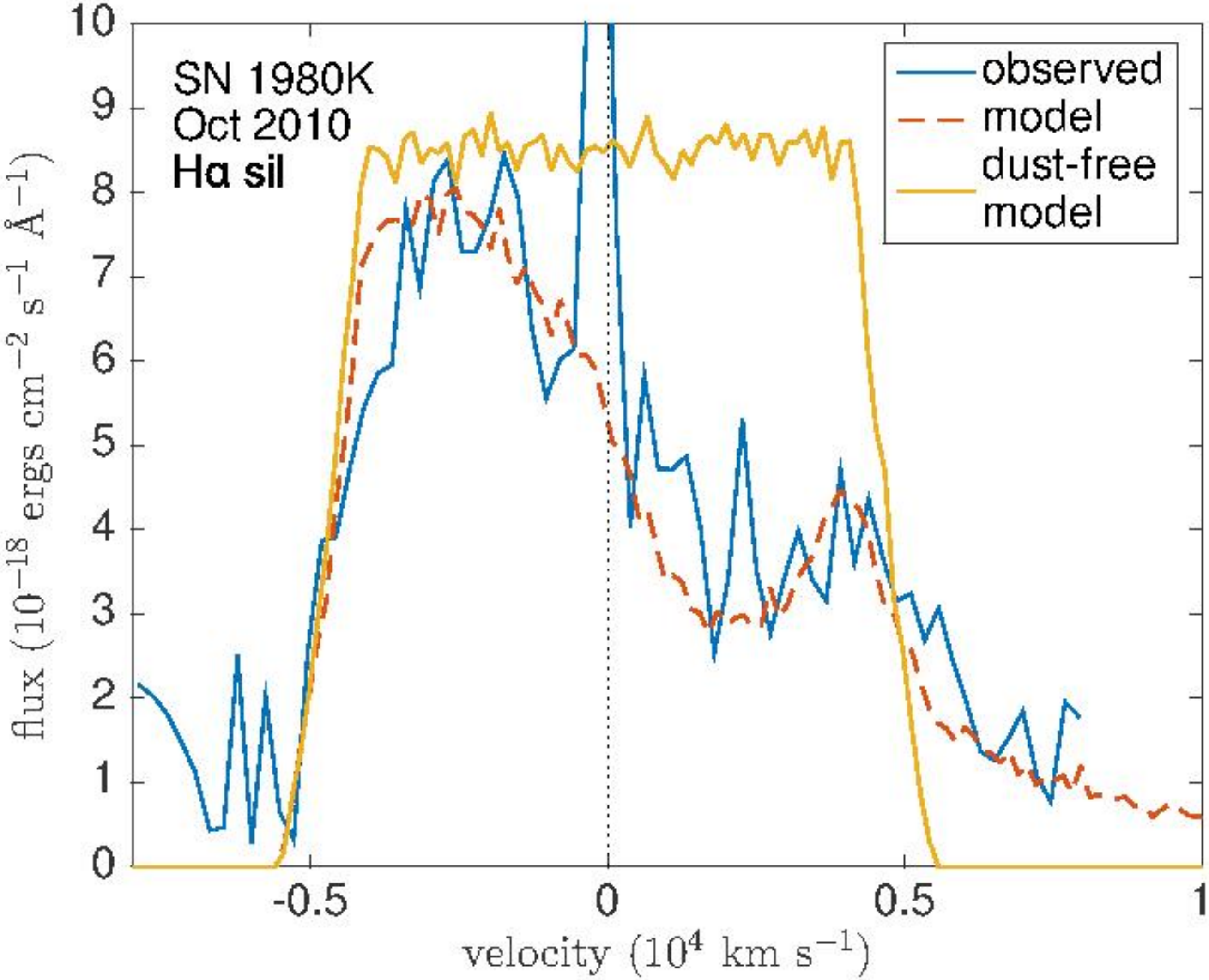
MRN77 silicate dust can't fit the observed red scattering wing



Smooth gas emission
Vmax=5500 km/s
Vmin=4125 km/s

Red scattering wing requires a dust albedo of ~0.8 -> can be fit by sufficiently large silicates.

Amorphous carbon grains (lower albedo) produce a worse fit to the red scattering wing

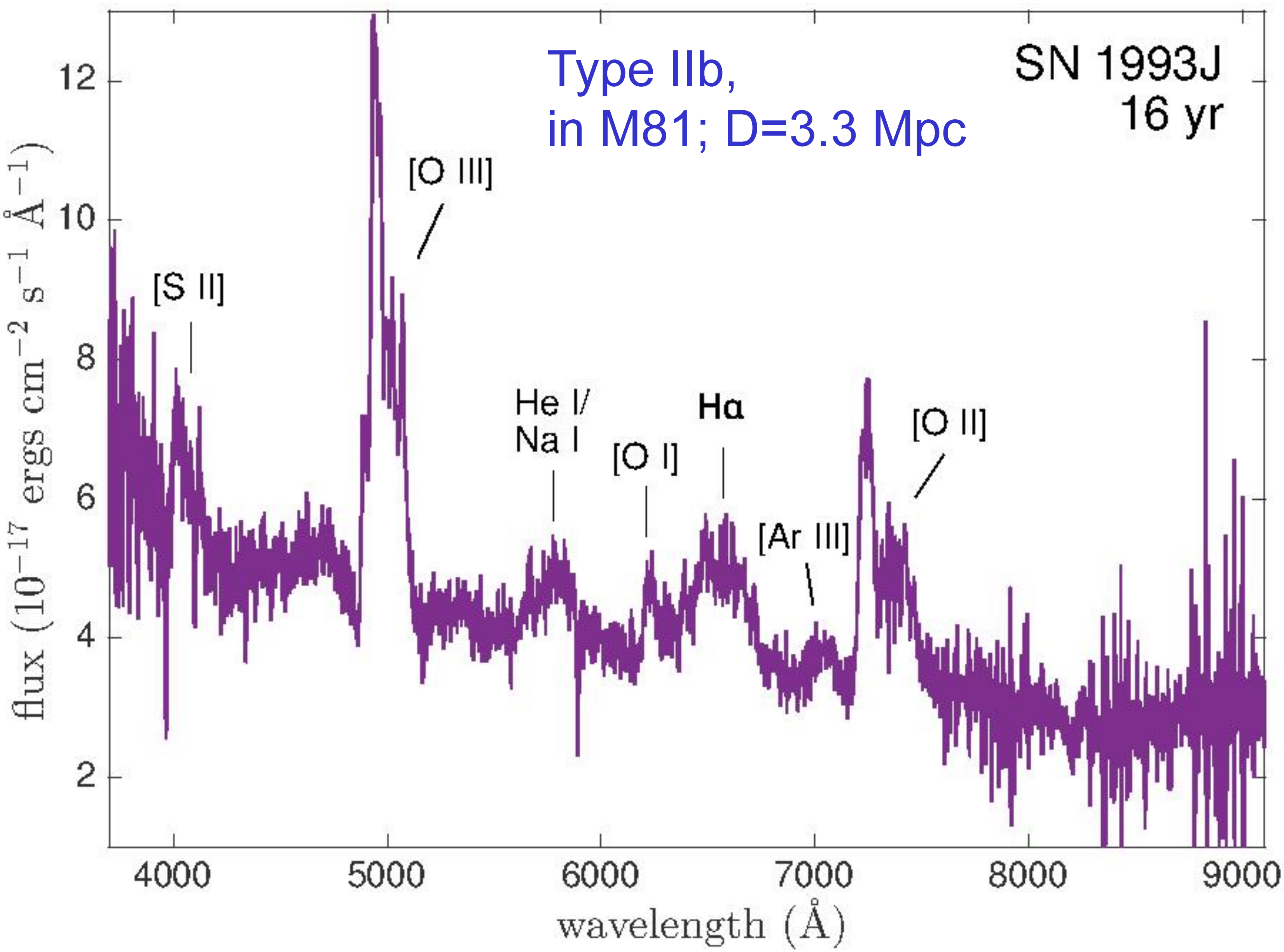


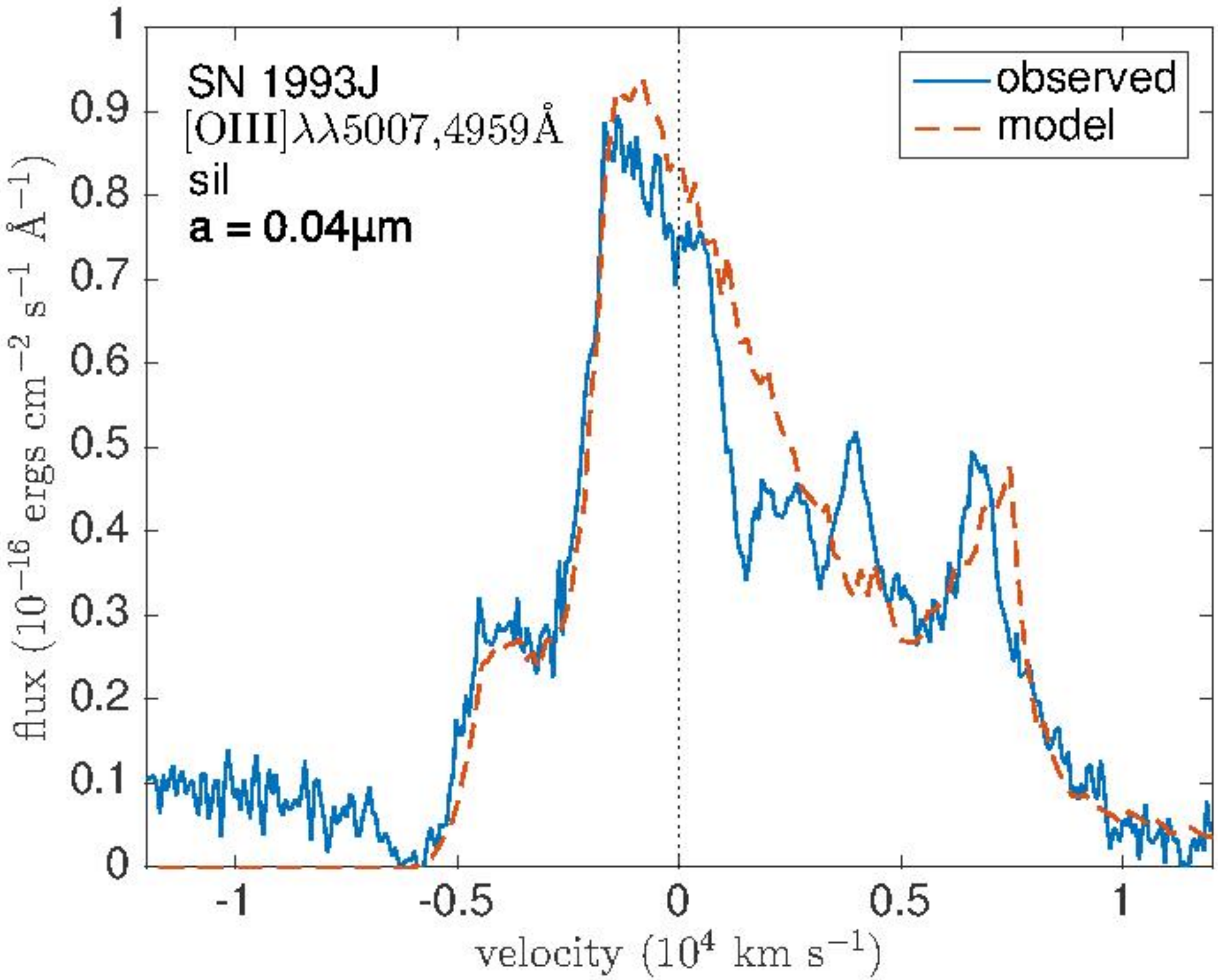
a=0.1um silicate grains provide best match.

0.10-0.20 $M_\odot$ (smoothly distributed dust)

0.12-0.30 $M_\odot$ (clumped dust, f=0.1, $R_{cl} = R_{out}/25$)

Milisavljevic et al. (2012)

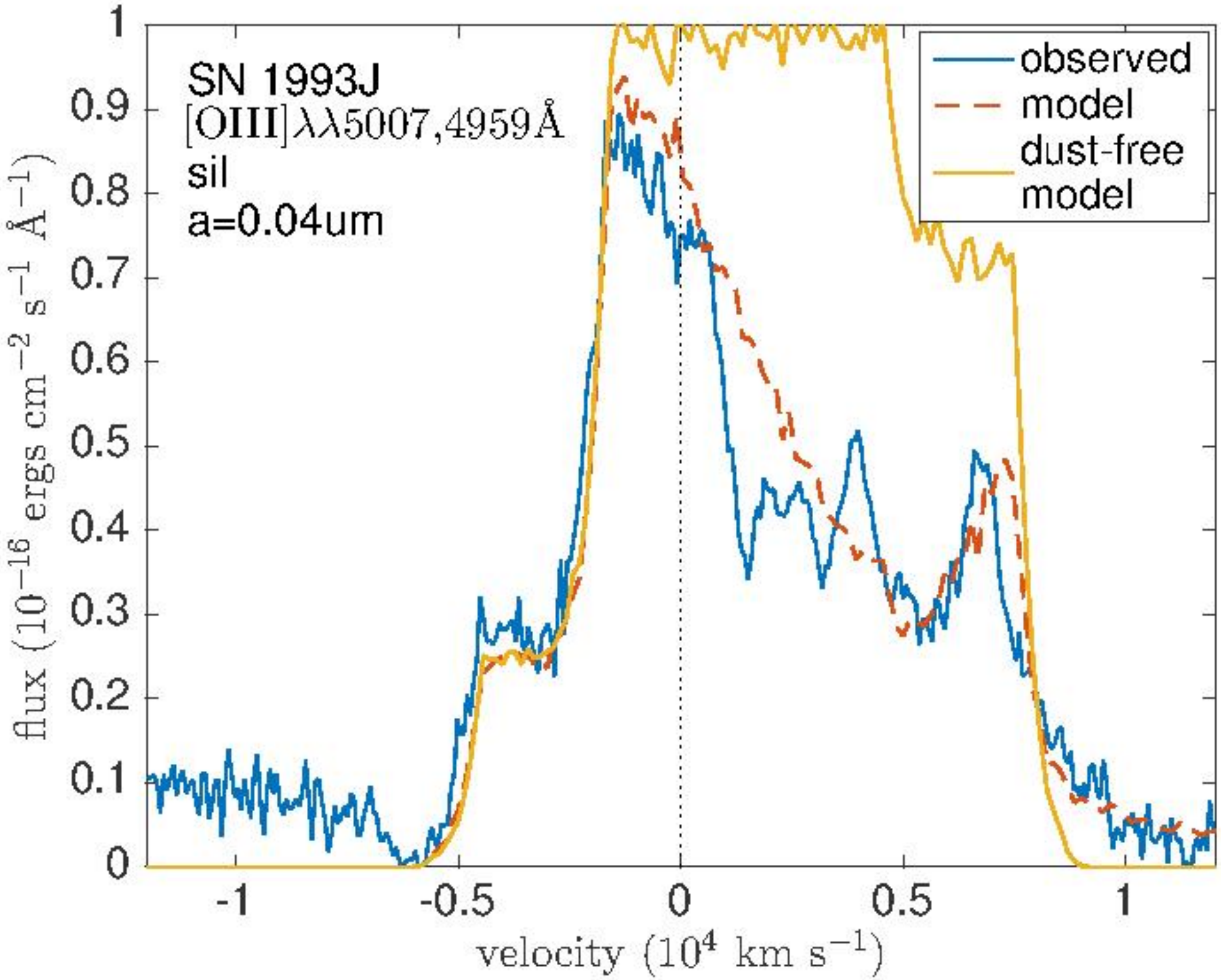




Model assumes smooth gas emission – but it's clearly clumped.

Extended red scattering wings are again present but weaker.

Can be fitted with either silicate or amC grains



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

Smooth dust models:

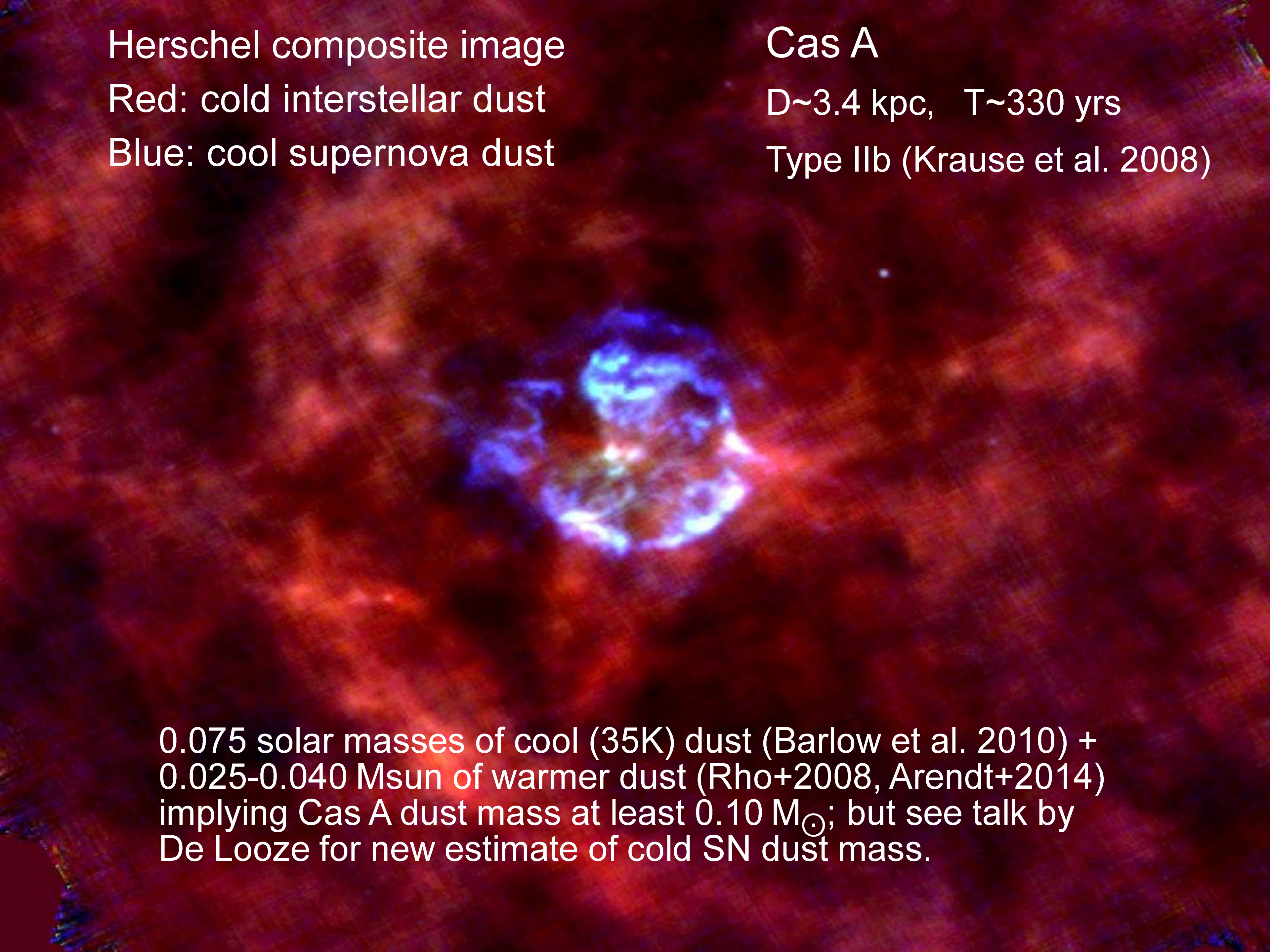
Silicate: 0.05-0.10 $M_\odot$

amC: up to 0.12 $M_\odot$

Clumped dust models:

Silicate: 0.08-0.15 $M_\odot$

amC: up to 0.18 $M_\odot$



Herschel composite image

Red: cold interstellar dust

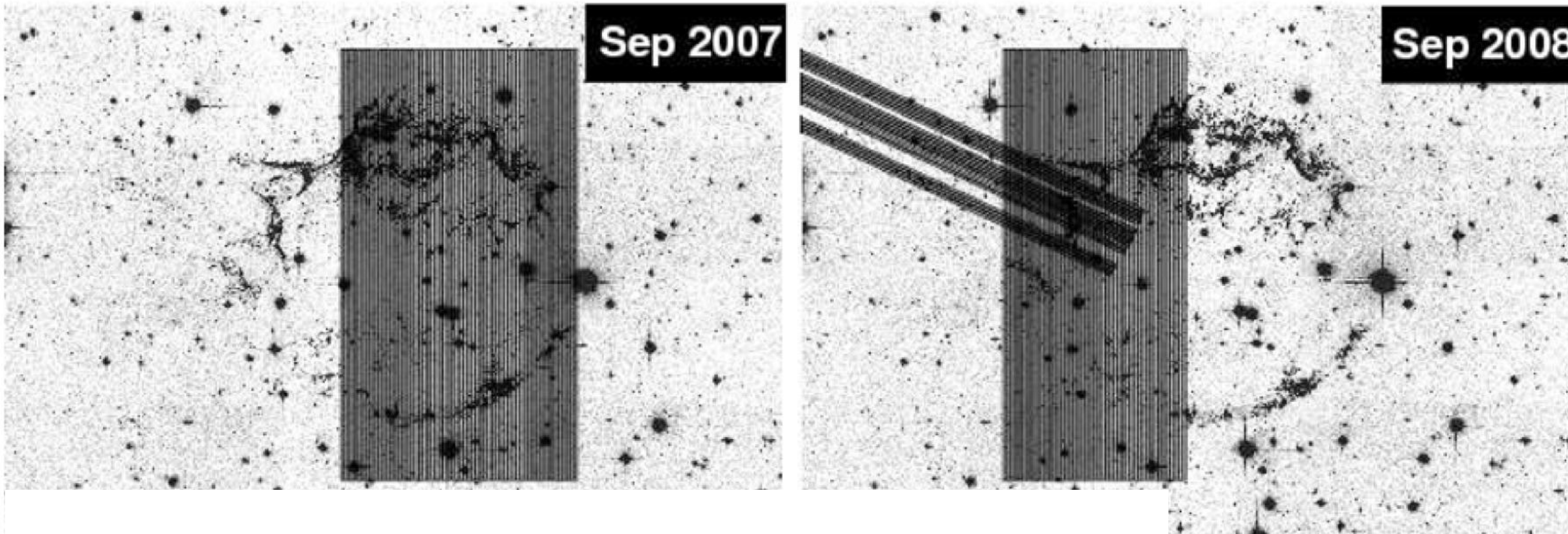
Blue: cool supernova dust

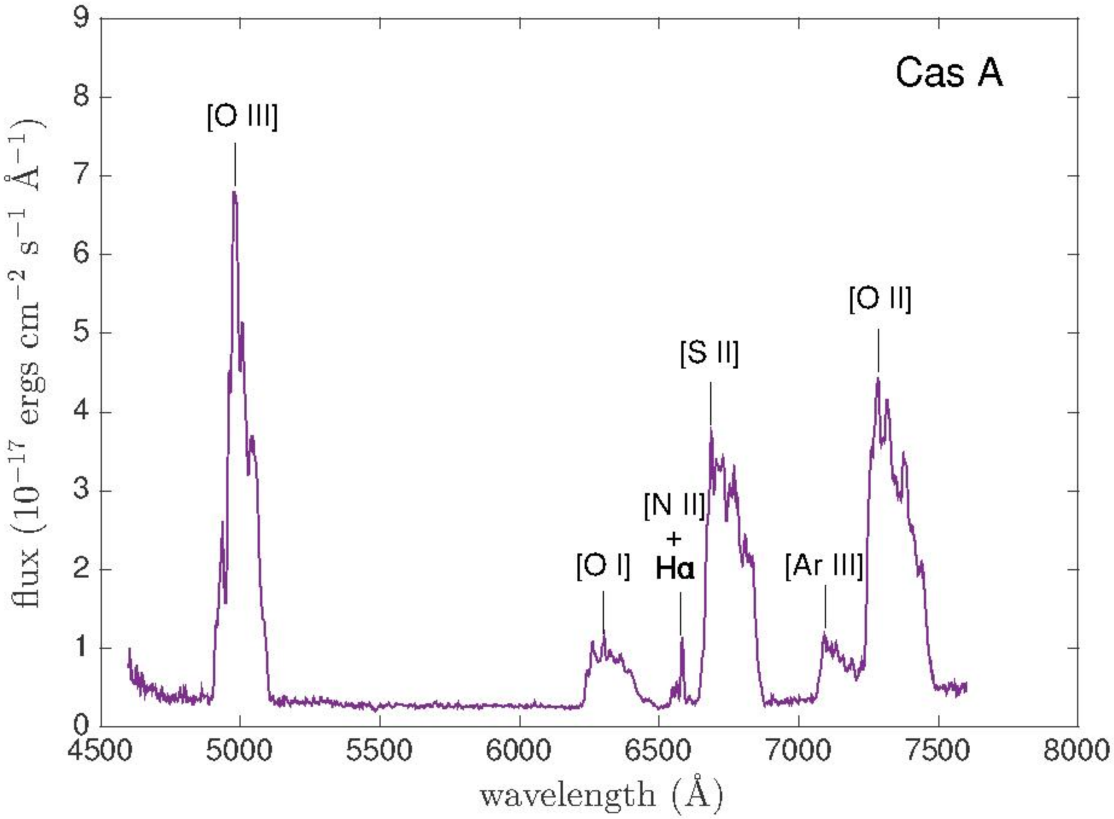
Cas A

D~3.4 kpc, T~330 yrs

Type IIb (Krause et al. 2008)

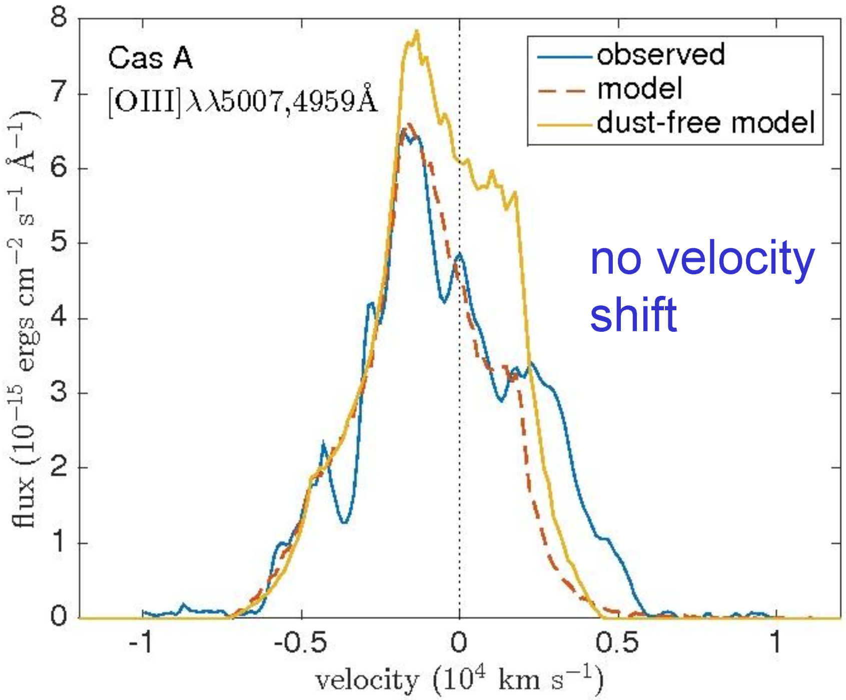
0.075 solar masses of cool (35K) dust (Barlow et al. 2010) +
0.025-0.040 Msun of warmer dust (Rho+2008, Arendt+2014)
implying Cas A dust mass at least 0.10 $M_{\odot}$; but see talk by
De Looze for new estimate of cold SN dust mass.





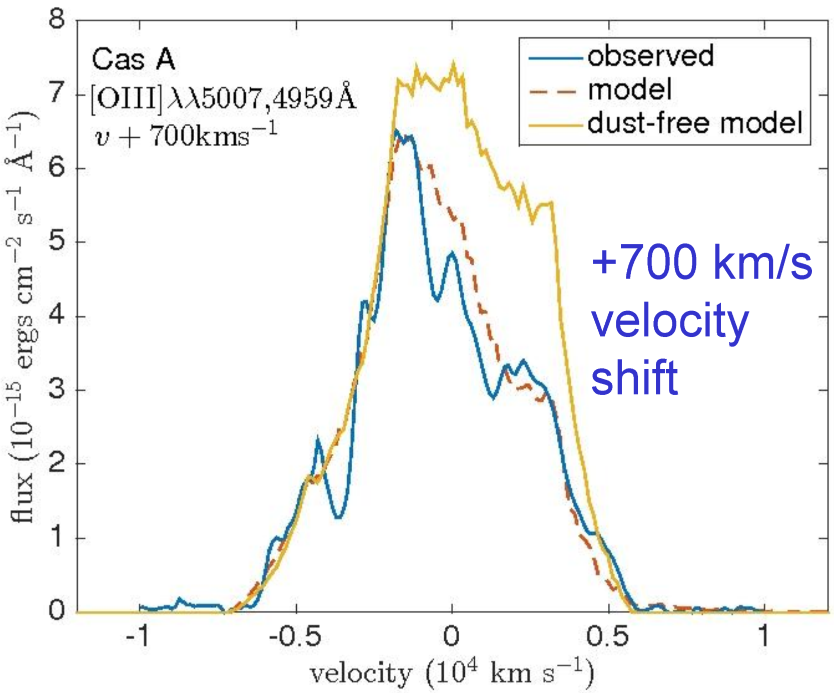
What would the spectrum of Cas A look like if it was at 1 Mpc and unresolved?

Integrated optical spectrum from the complete nebula
(Milisavljevic et al 2012; Milisavljevic & Fesen 2013)



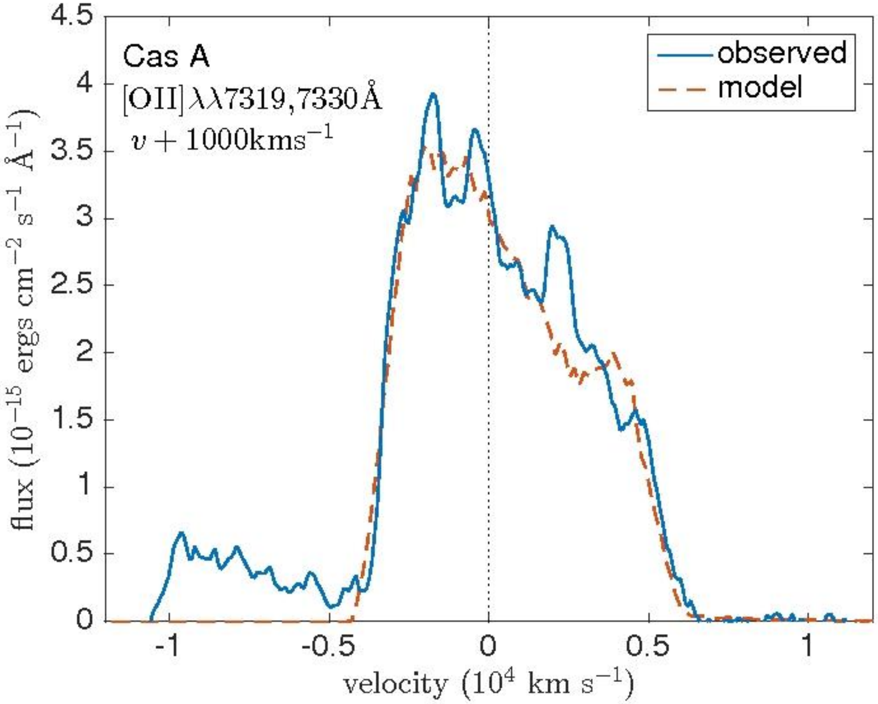
Smooth dust model
Vmax=4500 km/s
Vmin=1800 km/s

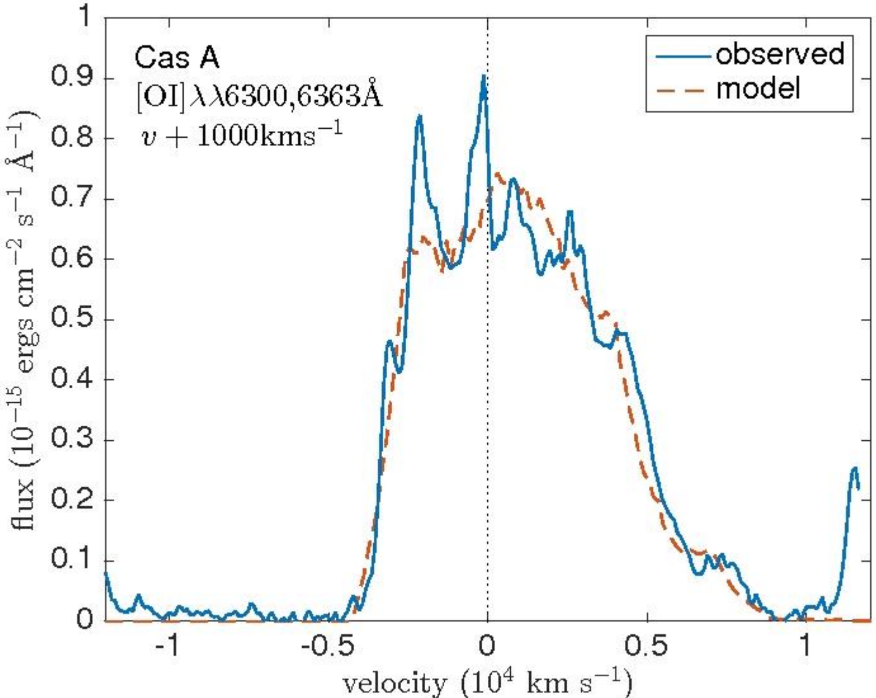
Dust mass = 0.9 $M_\odot$
(50% sil, 50% amC)



Smooth dust model
Vmax=5000 km/s
Vmin=2500 km/s;
with velocity shift of +700 km/s

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





Smooth dust model
Vmax=5000 km/s
Vmin=3250 km/s;
and velocity shift of +1000 km/s

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

Delaney et al. (2010) measured line radial velocities between -4000 and +6000 km/s for Cas A and derived a mean velocity offset of +859 km/s.

i.e. midway between 700 km/s offset found here for [OIII] lines and 1000 km/s offset found for [OI] and [OII] lines.

SUMMARY

SNR Dust Masses from red-blue line asymmetries:

SN 1987A, Type IIP, Year 10: 0.17 $M_\odot$

SN 1993J, Type IIb, Year 16: 0.08-0.18 $M_\odot$

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

Cas A, Type IIb, Year ~330: 1.1 $M_\odot$

Next: 50hrs of VLT time have been assigned in the current semester to obtain X-shooter optical and NIR spectra of 25 SNe with ages between 4 and 60 years since outburst.