THE DUST PRODUCED IN SNR: THE CASE OF CAS A

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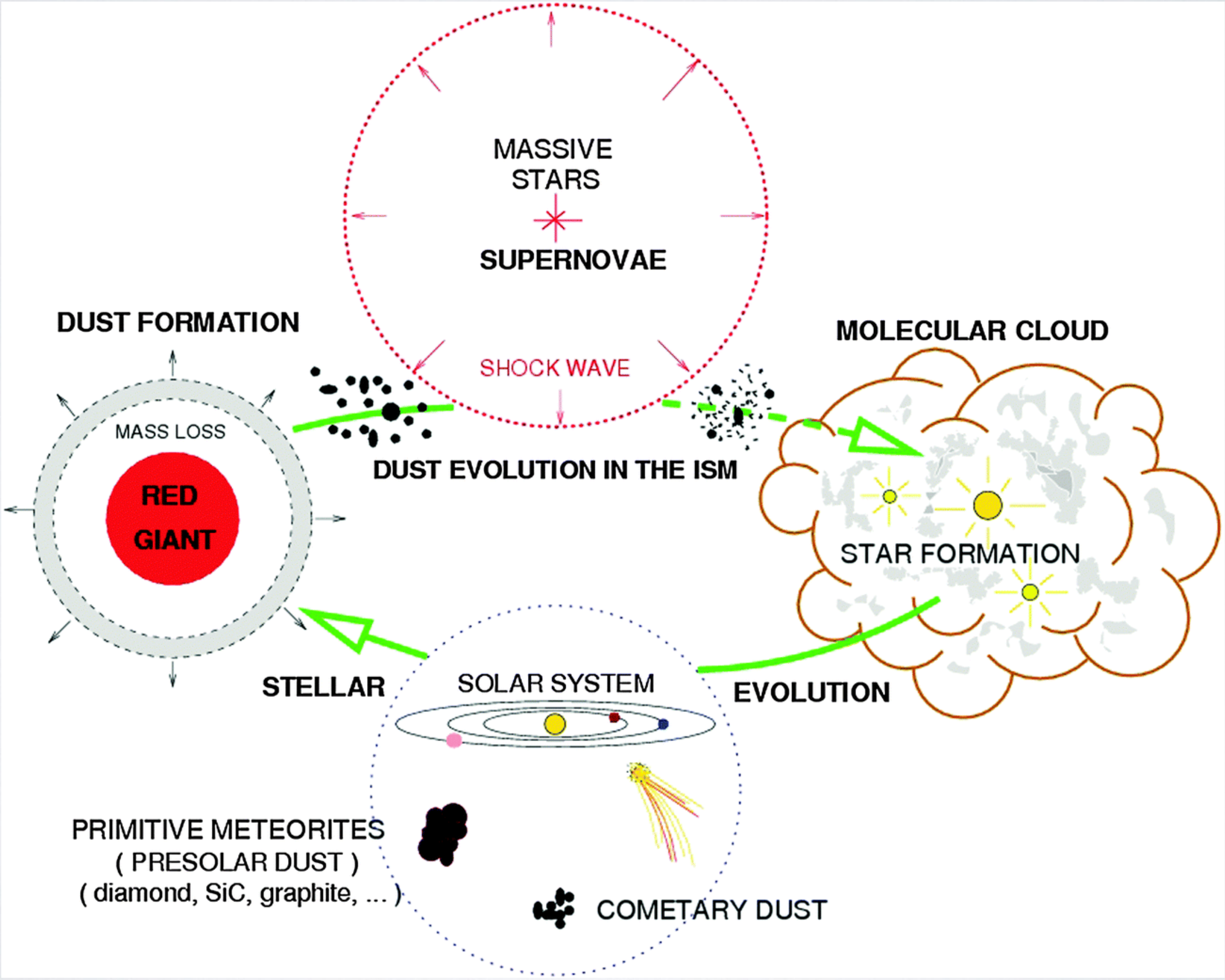
OUTLINE

- Origin of dust in galaxies
- Dust in SNR: Cassiopeia A
- Increasing the sample of SNR:
  RT modelling of optical line profiles
- Future work

ORIGIN OF DUST



ORIGIN OF DUST

- Historically, steady mass loss from evolved AGB stars = primary source for ISM dust

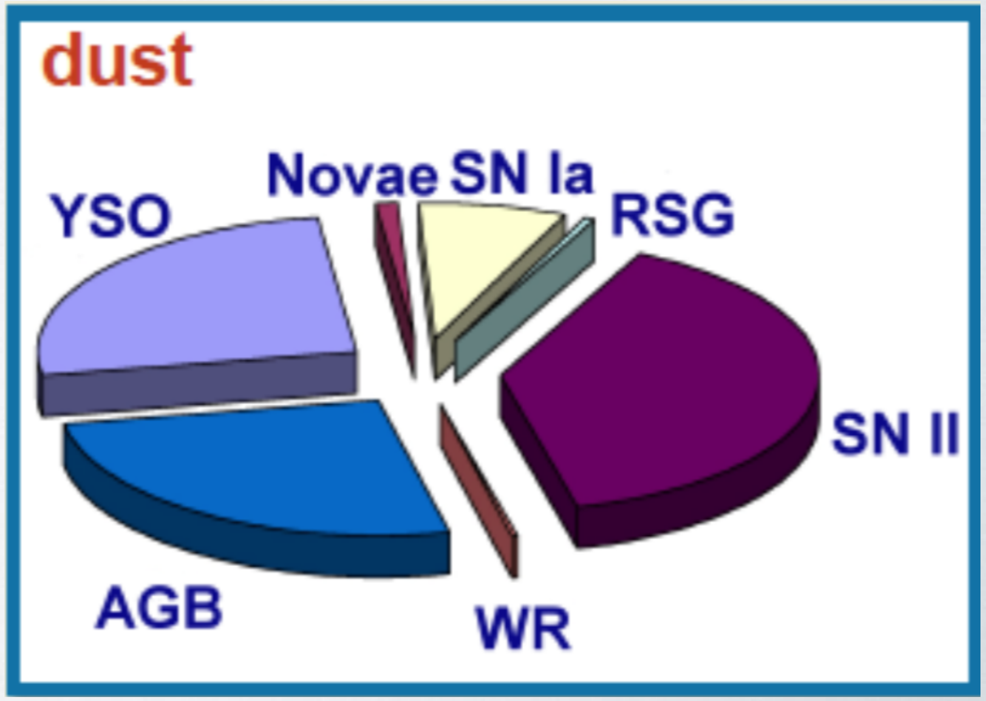
Problem:

- Detection of large quantities of dust in high-z galaxies

→ no generation of evolved stars is yet present

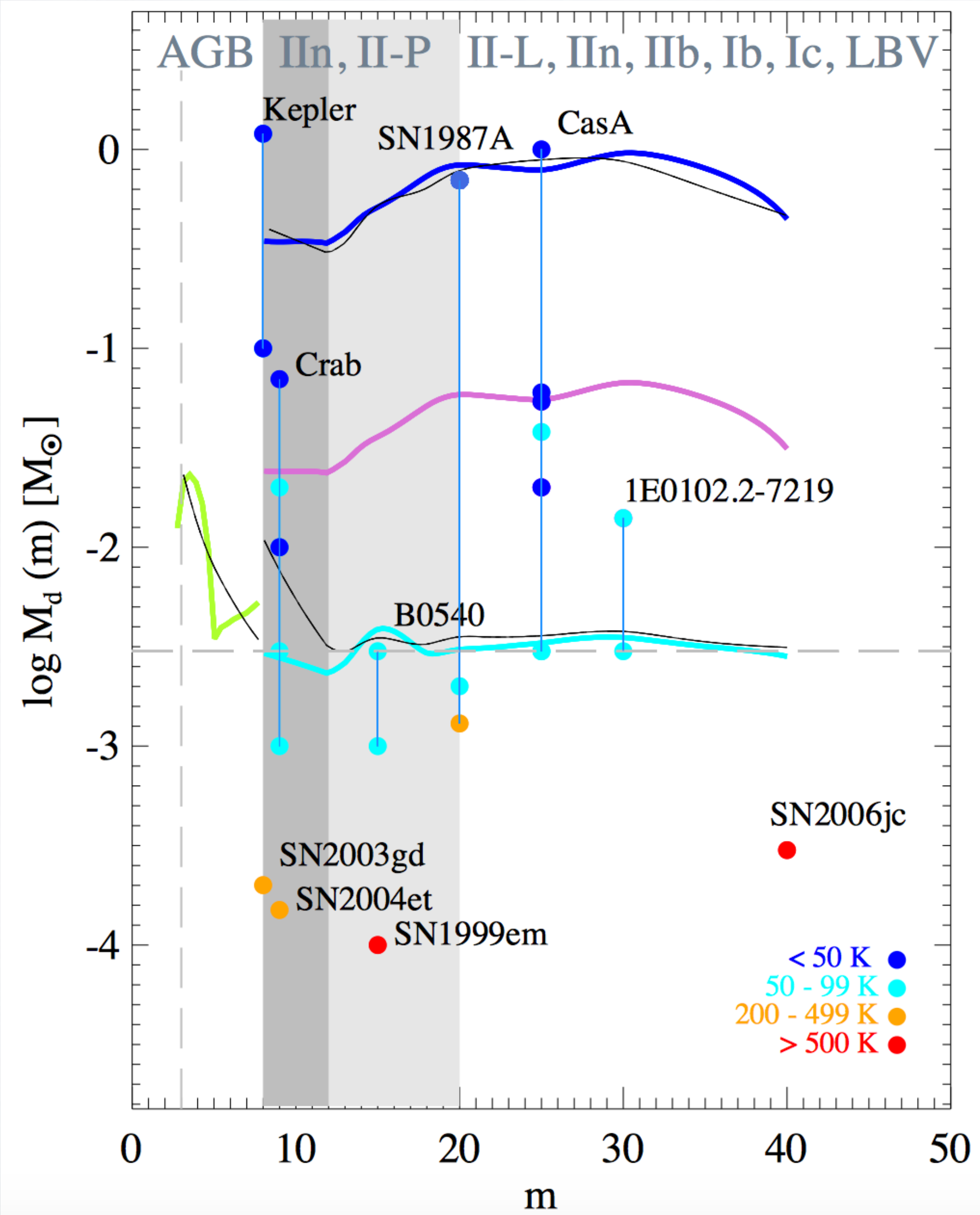
- Supernovae (SN) (type II) proposed as dust resources.

- Alternative explanation: "grain regrowth" in the ISM (???)



ORIGIN OF DUST

- Dust production rate of SN = very uncertain



- SN need to produce **0.1-1 M⊙** of dust to account for dust mass @ high redshift

Gall+ 2011

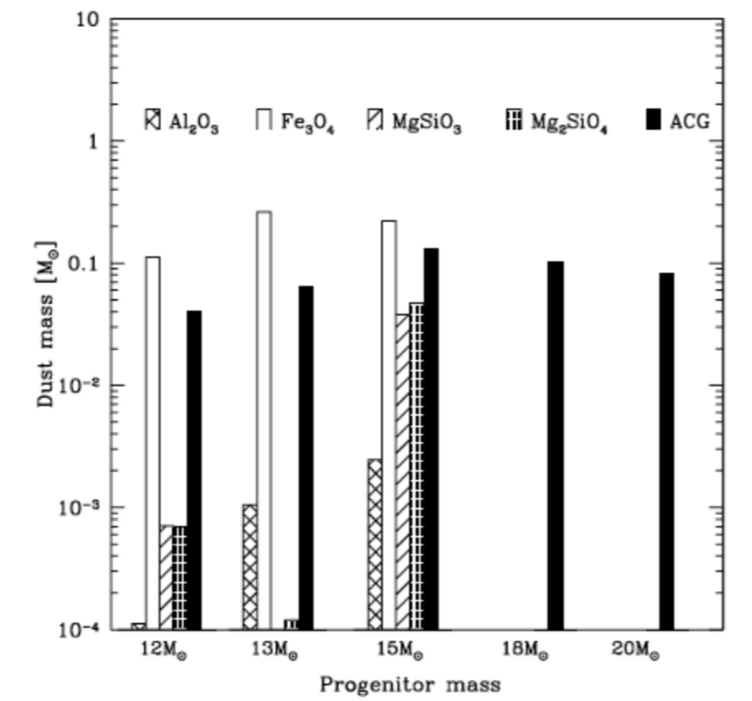
ORIGIN OF DUST

- Dust production rate of SN = very uncertain

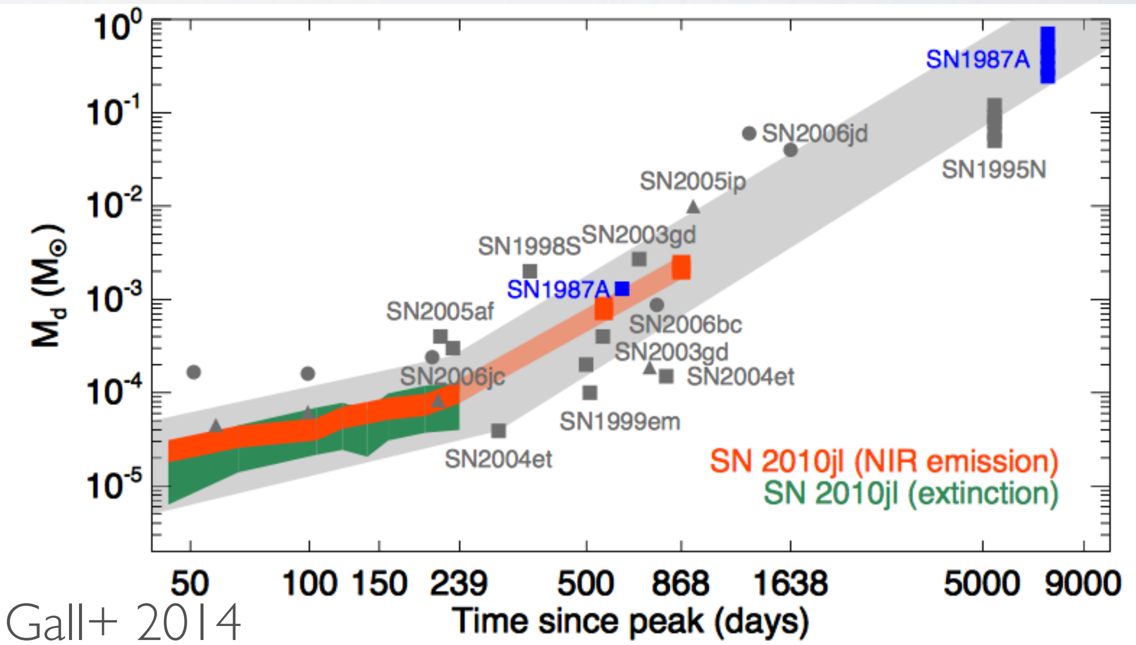
Models ⟷ observations

Dust nucleation modelling predict that 0.1-1 M☉ of dust should condense in SN (type II).

Before launch of Herschel, evidence for formation of not more than **10^{-3}-10^{-2} M☉** of new dust in SN type II



Todini & Ferrara (2001)

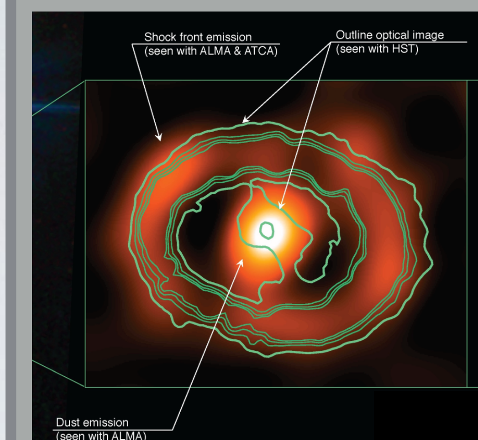


Gall+ 2014

ORIGIN OF DUST

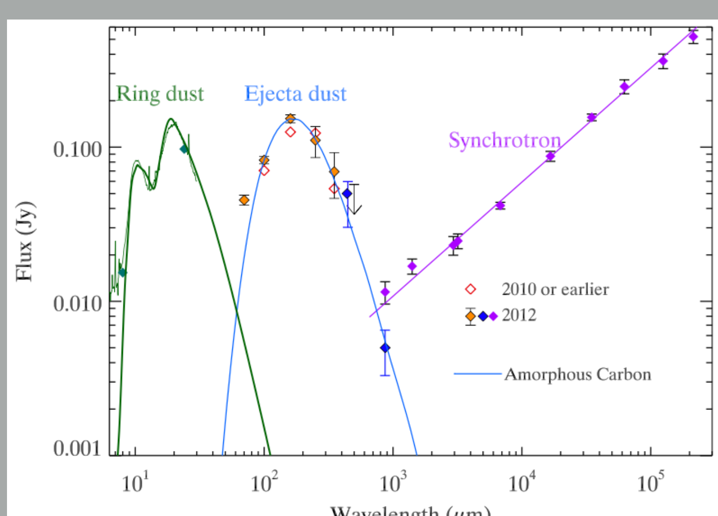
- Herschel + ALMA observations

SN 1987A

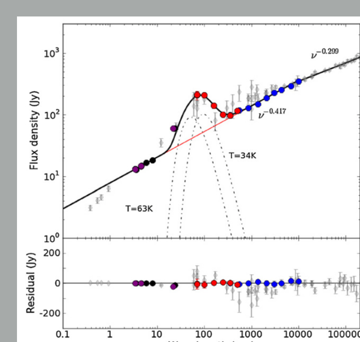


Matsuura+ 2011,
Indebetouw+ 2014,
Matsuura+ 2015

0.3M$_\odot$ carbon dust+
0.5M$_\odot$ silicate dust

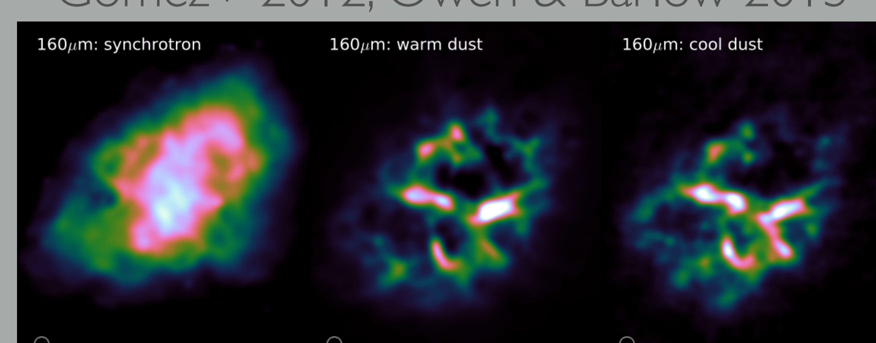


Crab Nebula

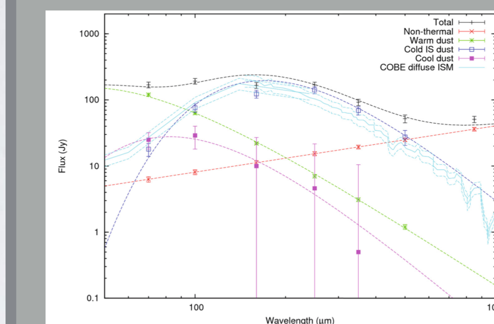


0.24M$_\odot$ of
28K dust

Gomez+ 2012, Owen & Barlow 2015

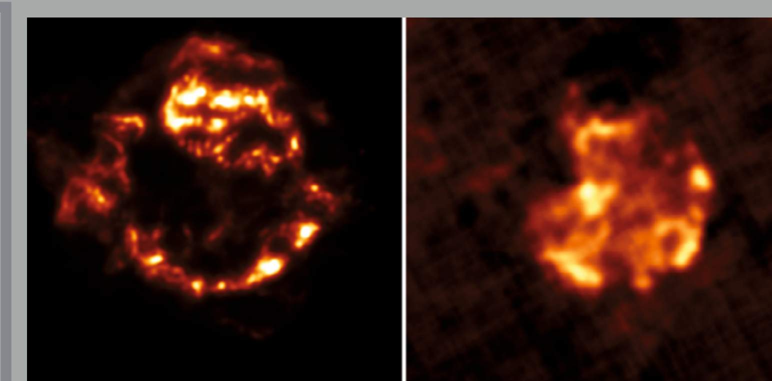


Cas A



Rho+ 2008,
Barlow+ 2010,
Arendt+ 2014

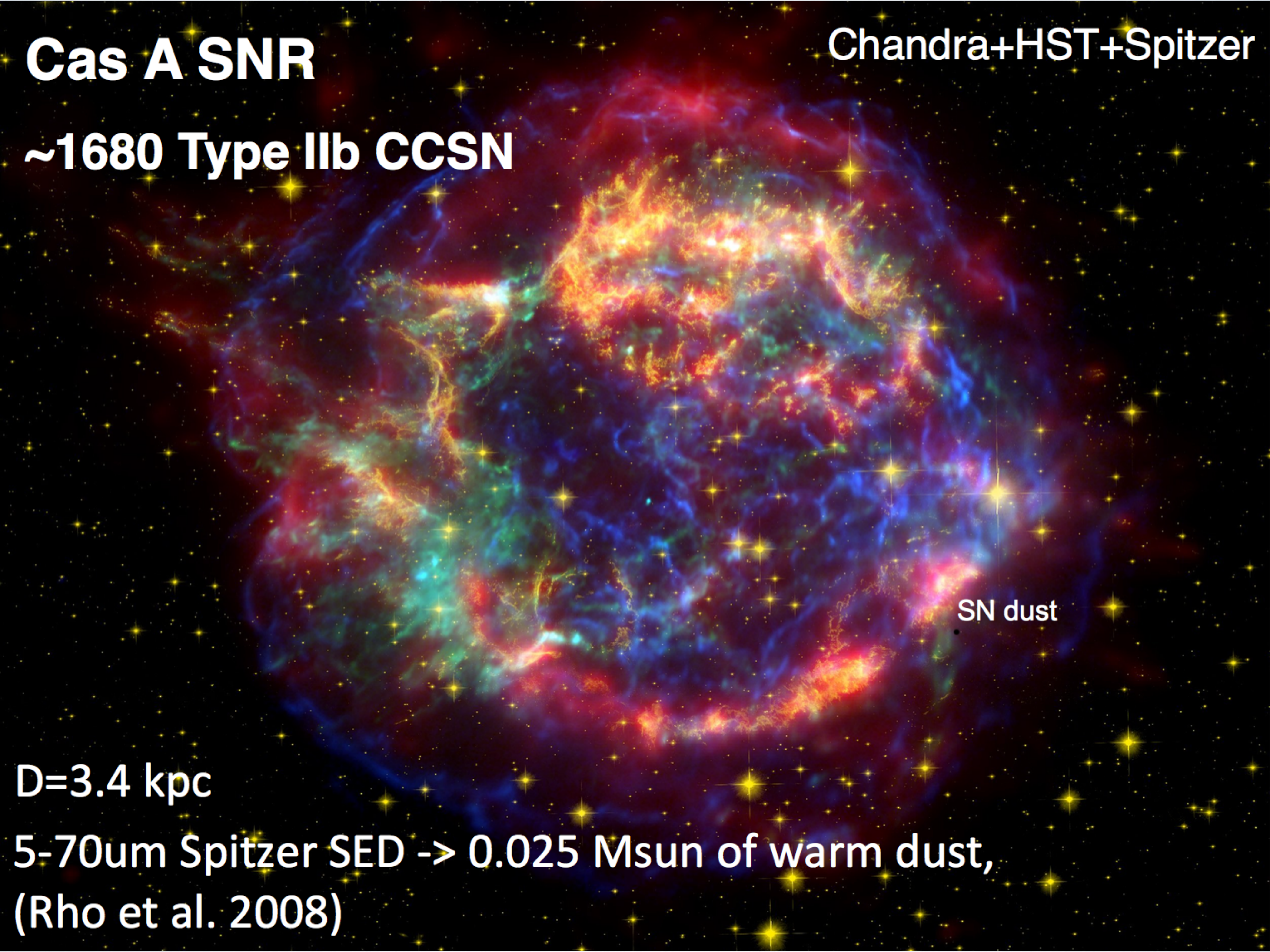
0.025-0.040 M$_\odot$ of 80K dust
+ 0.075 M$_\odot$ of 35K dust



Cas A SNR

Chandra+HST+Spitzer

~1680 Type IIb CCSN

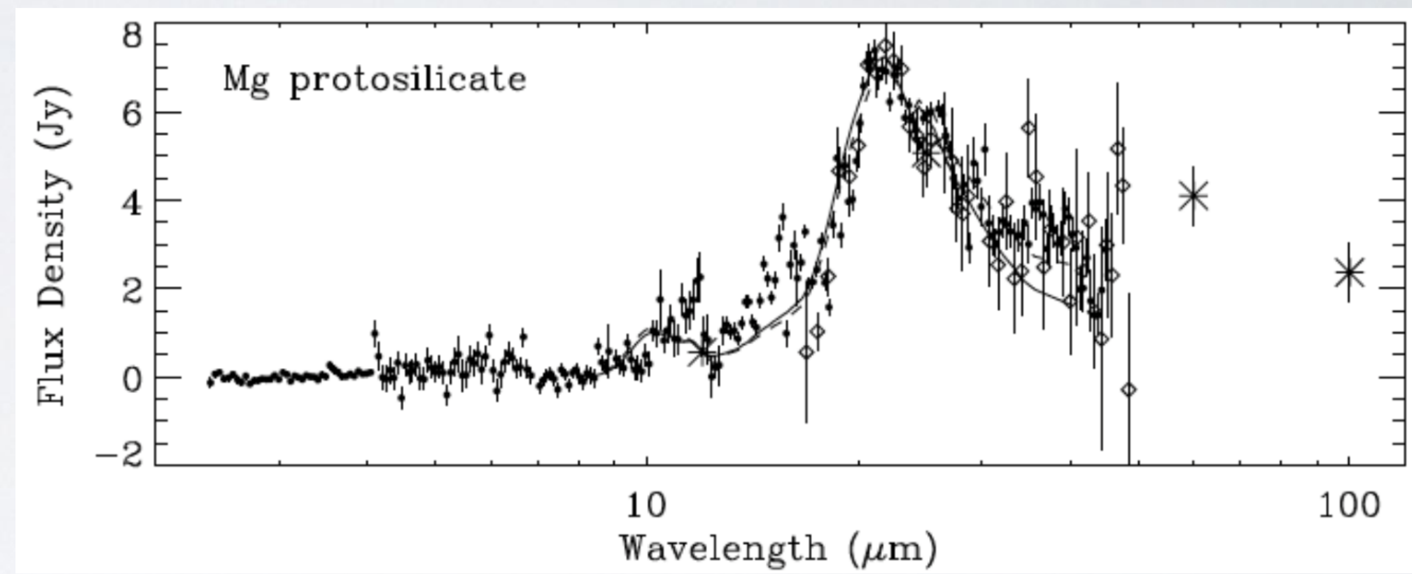


D=3.4 kpc

5-70um Spitzer SED -> 0.025 Msun of warm dust, (Rho et al. 2008)

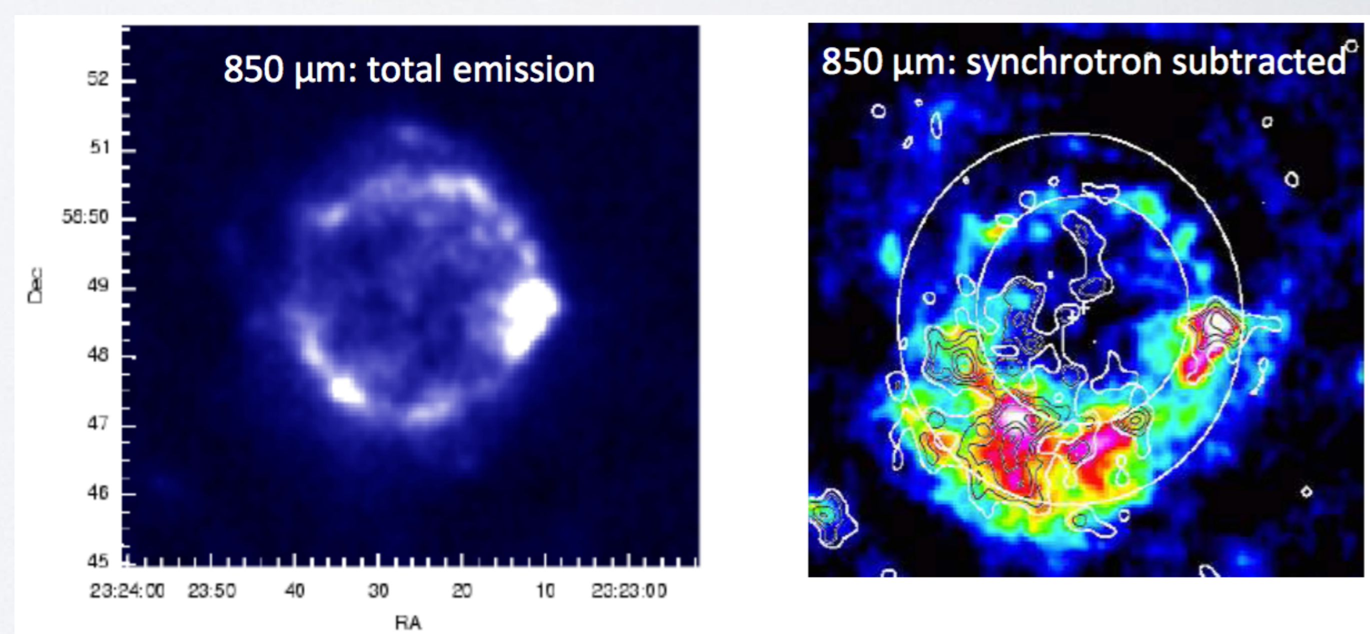
CAS A IN THE LITERATURE

Cas A was extensively observed by IRAS, ISO, Spitzer, SCUBA, AKARI, BLAST, Herschel, …



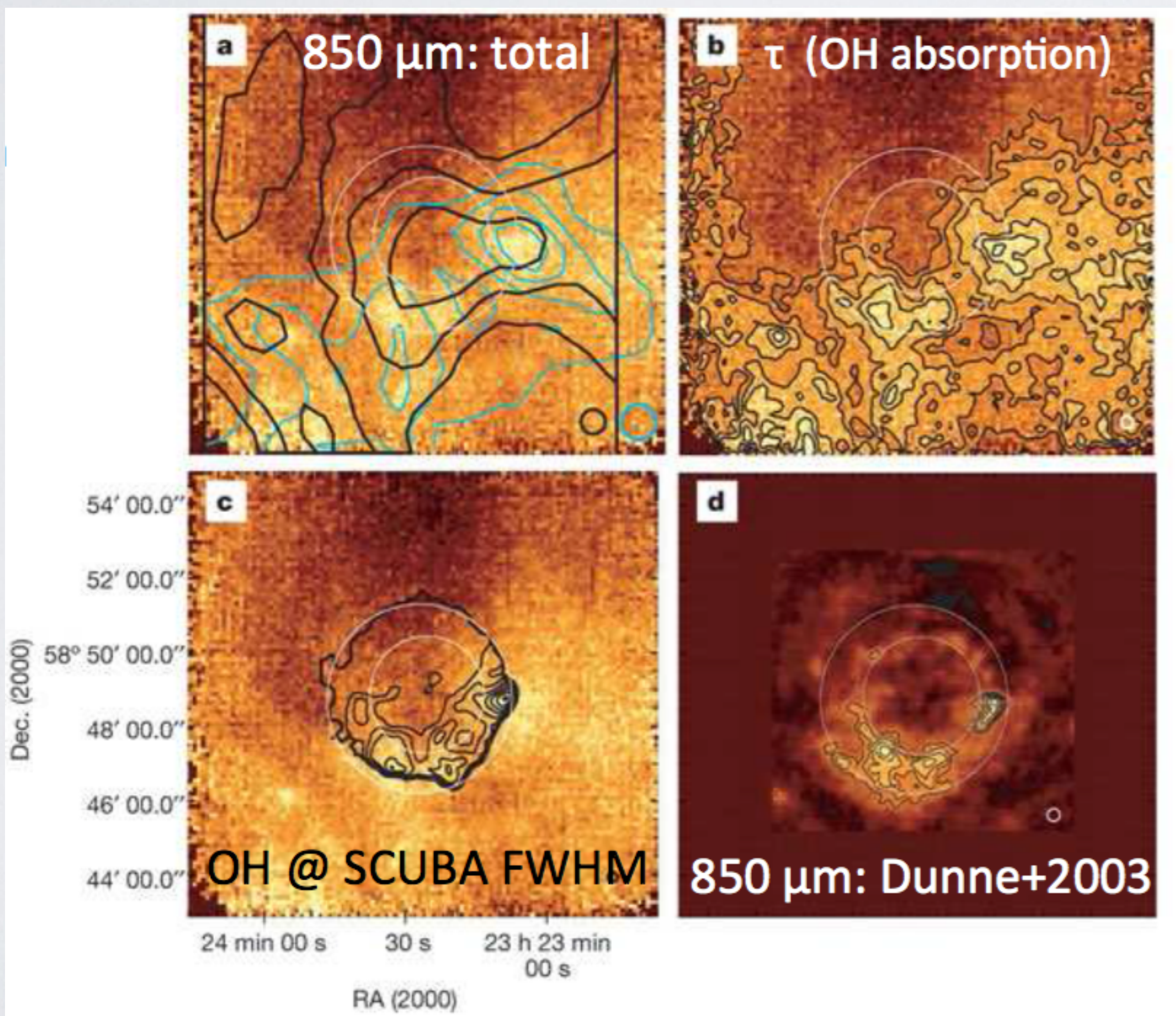
- *ISO/IRAS* (Arendt+1999):
  0.04 M$_\odot$ of dust @ 52 K

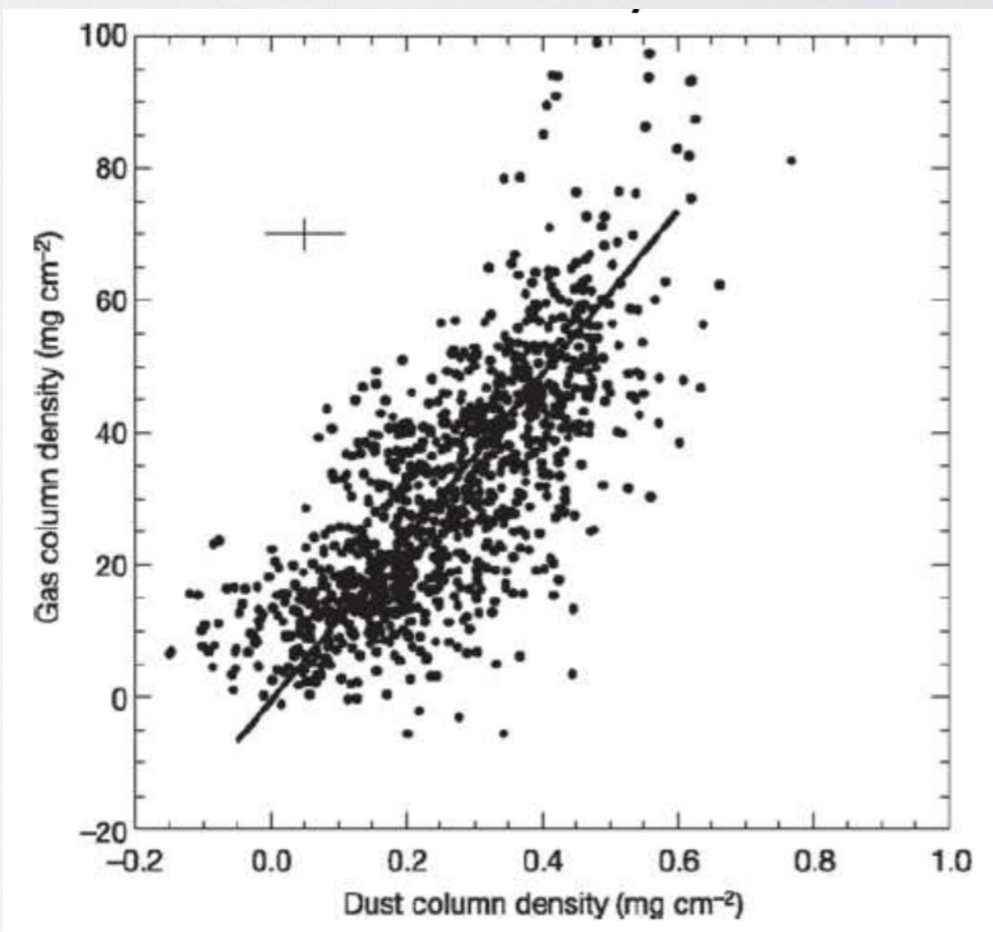
- SCUBA 850 **μ**m (Dunne et al. 2003)
  2-4 M$_\odot$ of dust @ 18 K !!!



CAS A IN THE LITERATURE

- SCUBA 850 μm: **<u>2-4 M$_\odot$</u>** of dust @ 18 K !!! (Dunne et al. 2003)



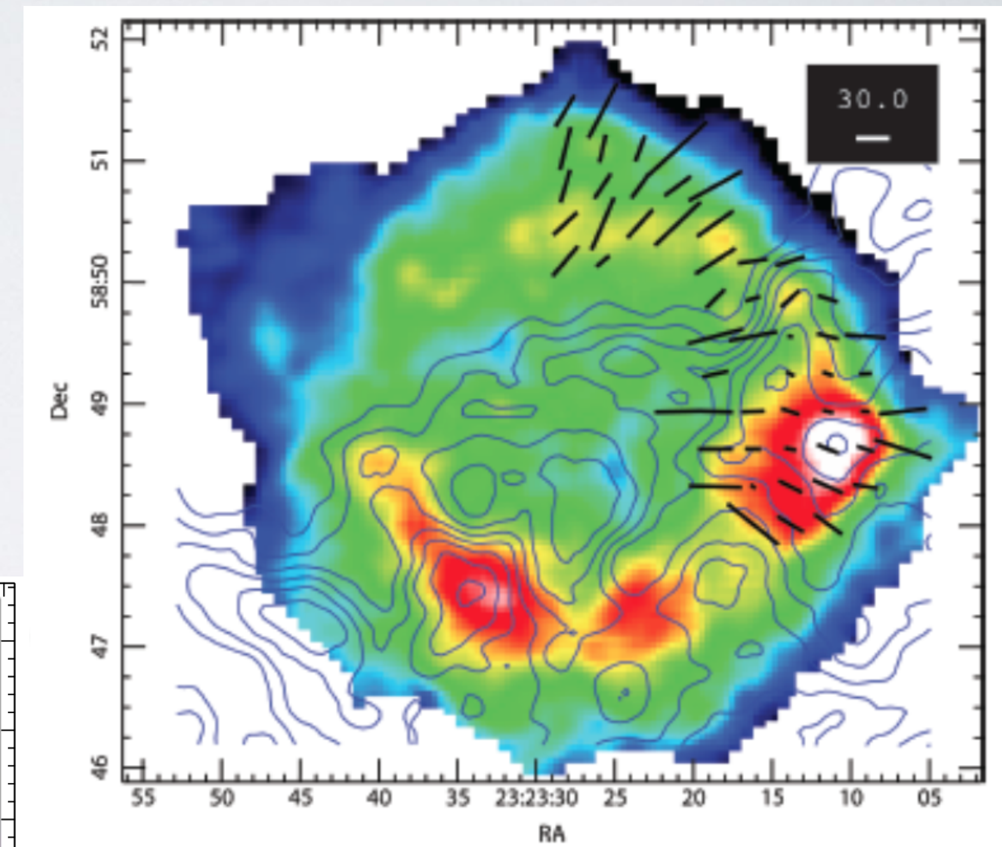


- 850 μm emission due to foreground dust (Krause+2004)

CAS A IN THE LITERATURE

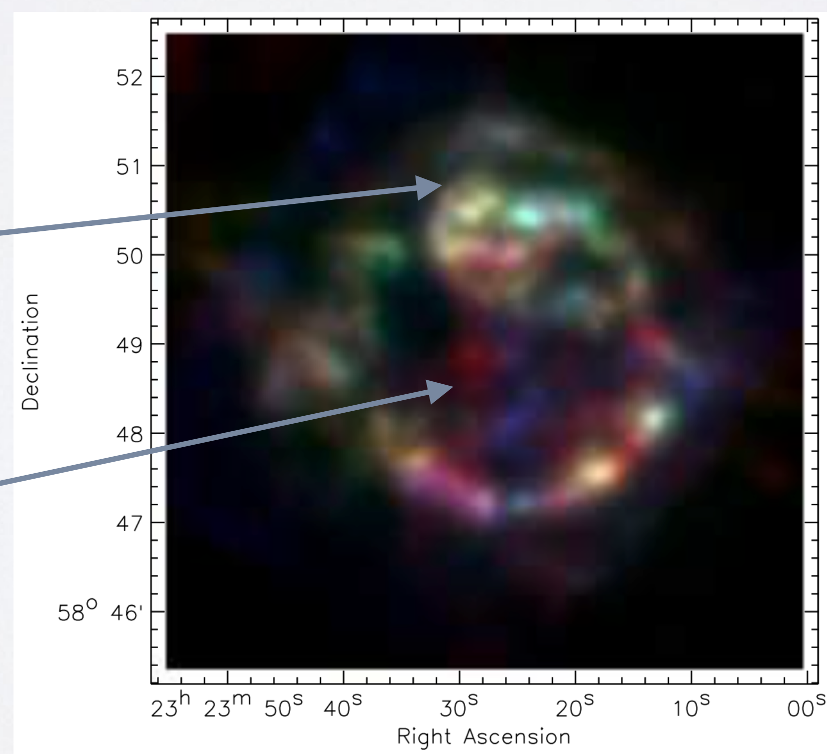
- *JCMT 850* **μ**m polarisation data (Dunne+ 2009):
  Polarisation attributed to **1 M$_\odot$** of dust

- Spitzer 24/70/160 **μ**m photometry+
  IRS spectra (Rho+ 2008, Arendt+ 2014)



0.04 M$_\odot$ of warm
silicate dust in
shocked regions (Arendt+ 2014)

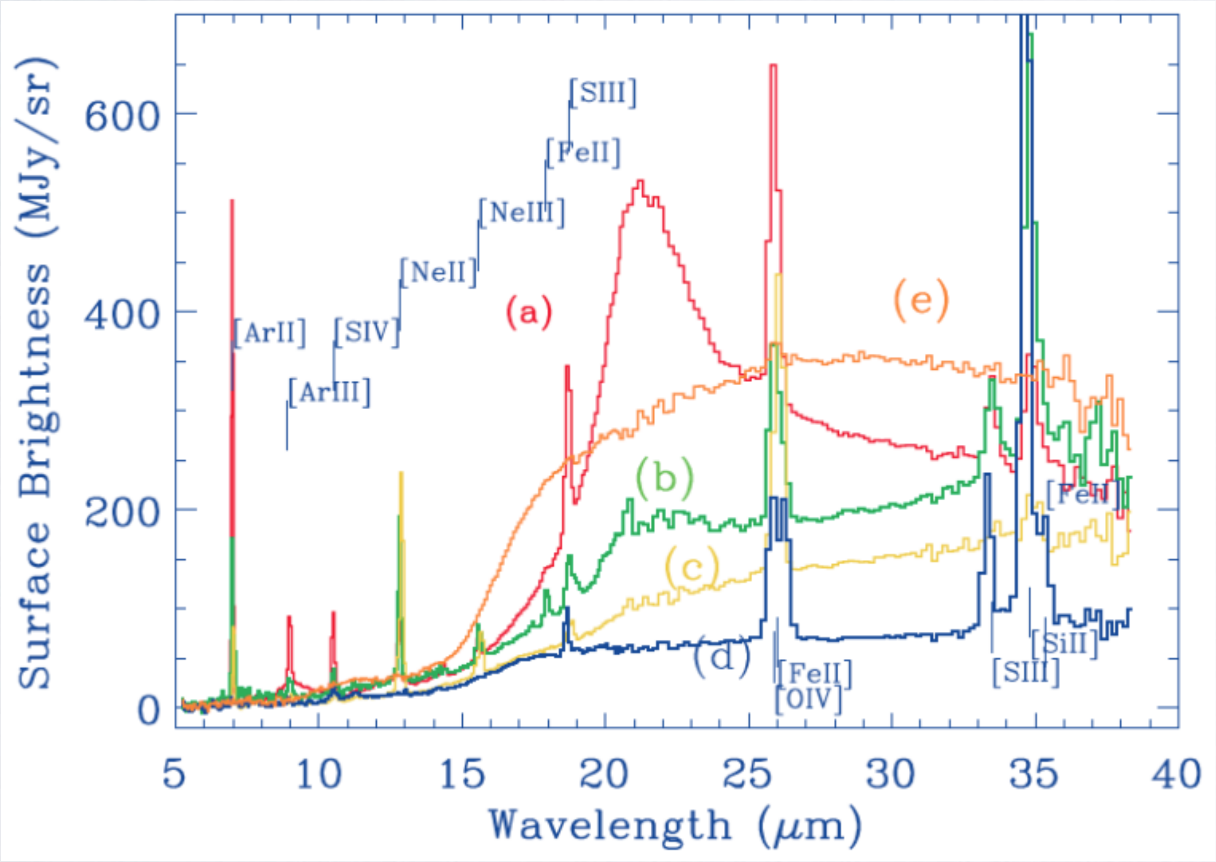
<0.1 M$_\odot$ of dust
(Sibthorpe+ 2010, Barlow+ 2010,
Arendt+ 2014)

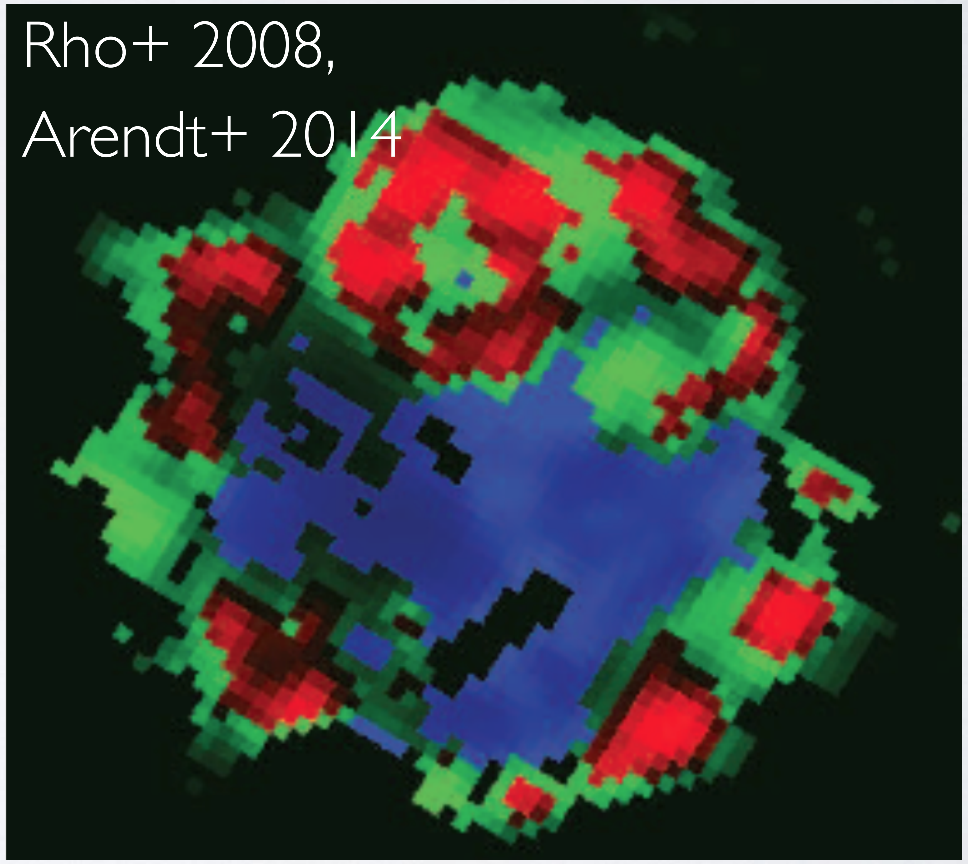


CAS A IN THE LITERATURE

- Spitzer IRS spectra

→ show huge variety in grain composition

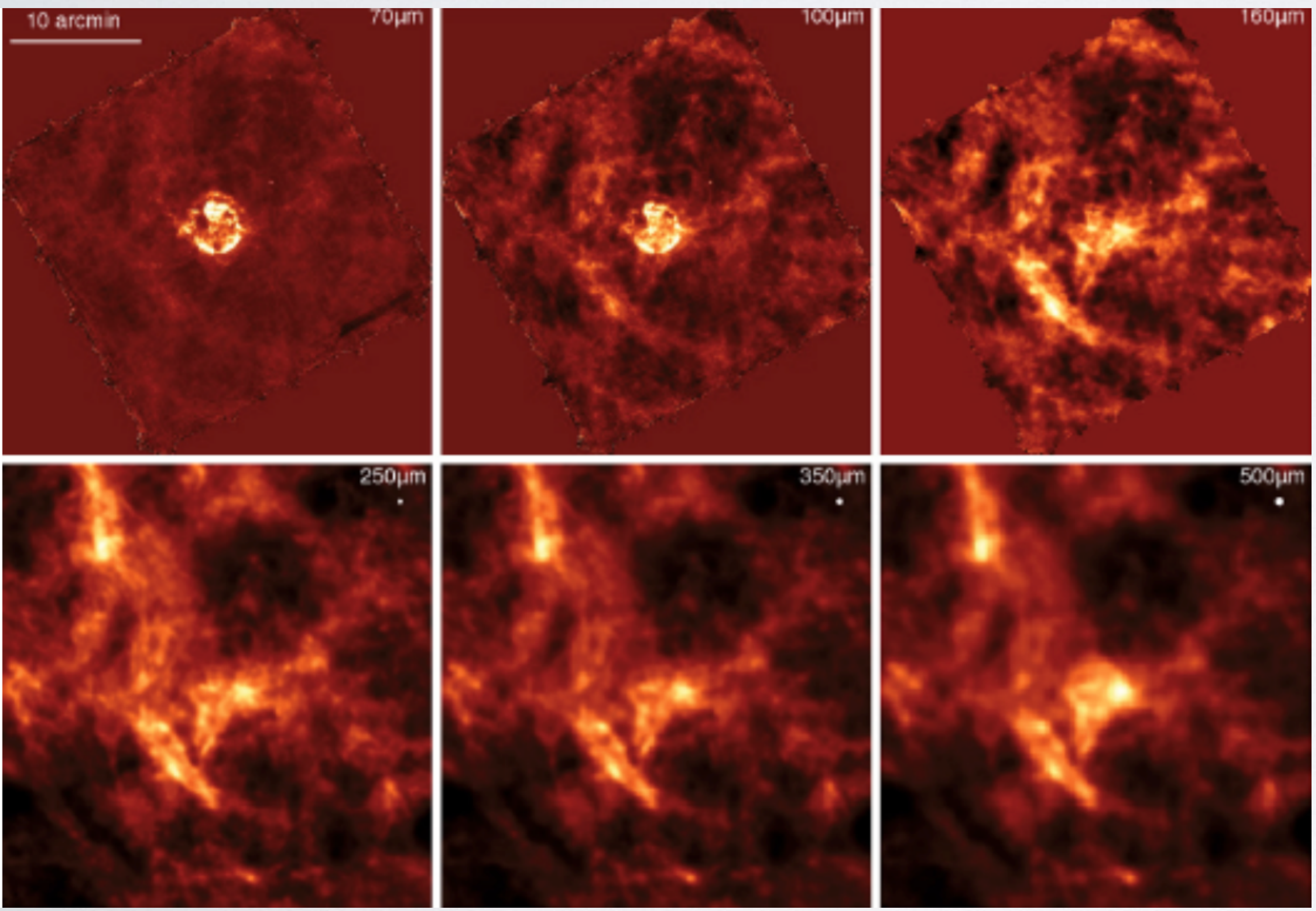




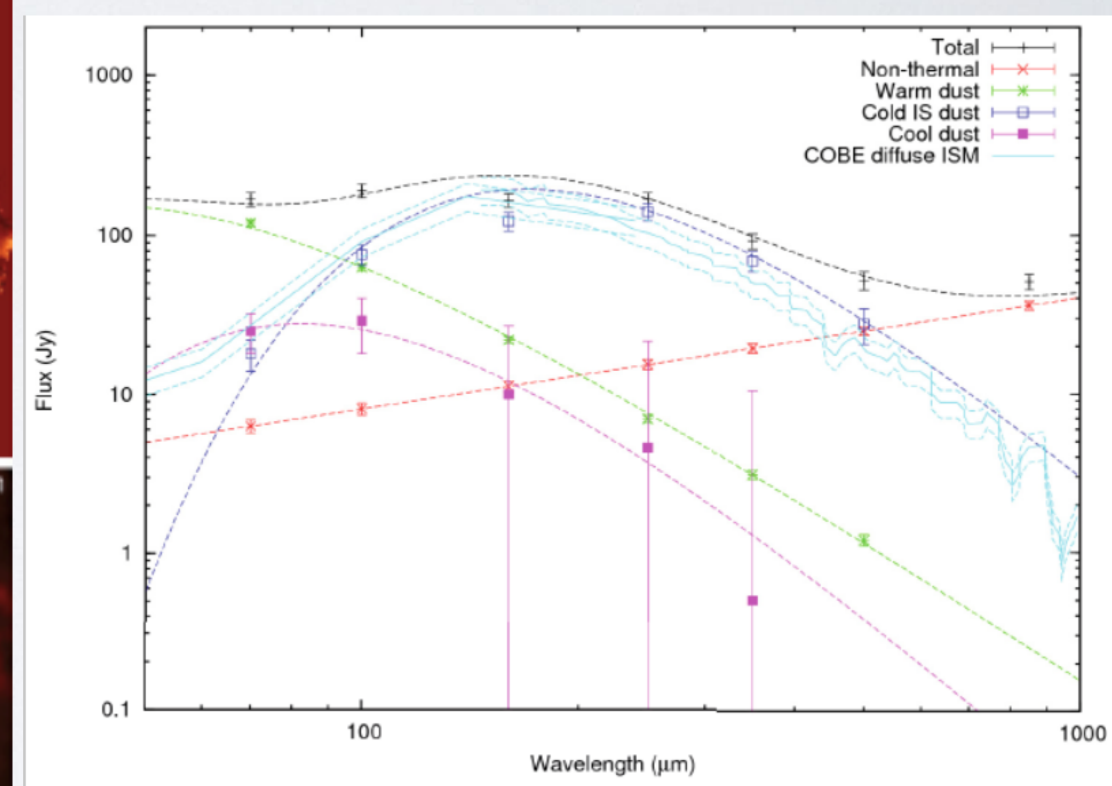
- Mostly silicate-type grains ($MgSiO_3$, $Mg_{2.4}SiO_{4.4}$), but also Al_2O_3, amorphous carbon, $CaAl_{12}O_{19}$

CAS A IN THE LITERATURE

- Herschel PACS (70,100,160) + SPIRE (250,350,500)
  0.075 $M_\odot$ of dust @ 35 K in inner region



Barlow et al. (2010)



CAS A IN THE LITERATURE

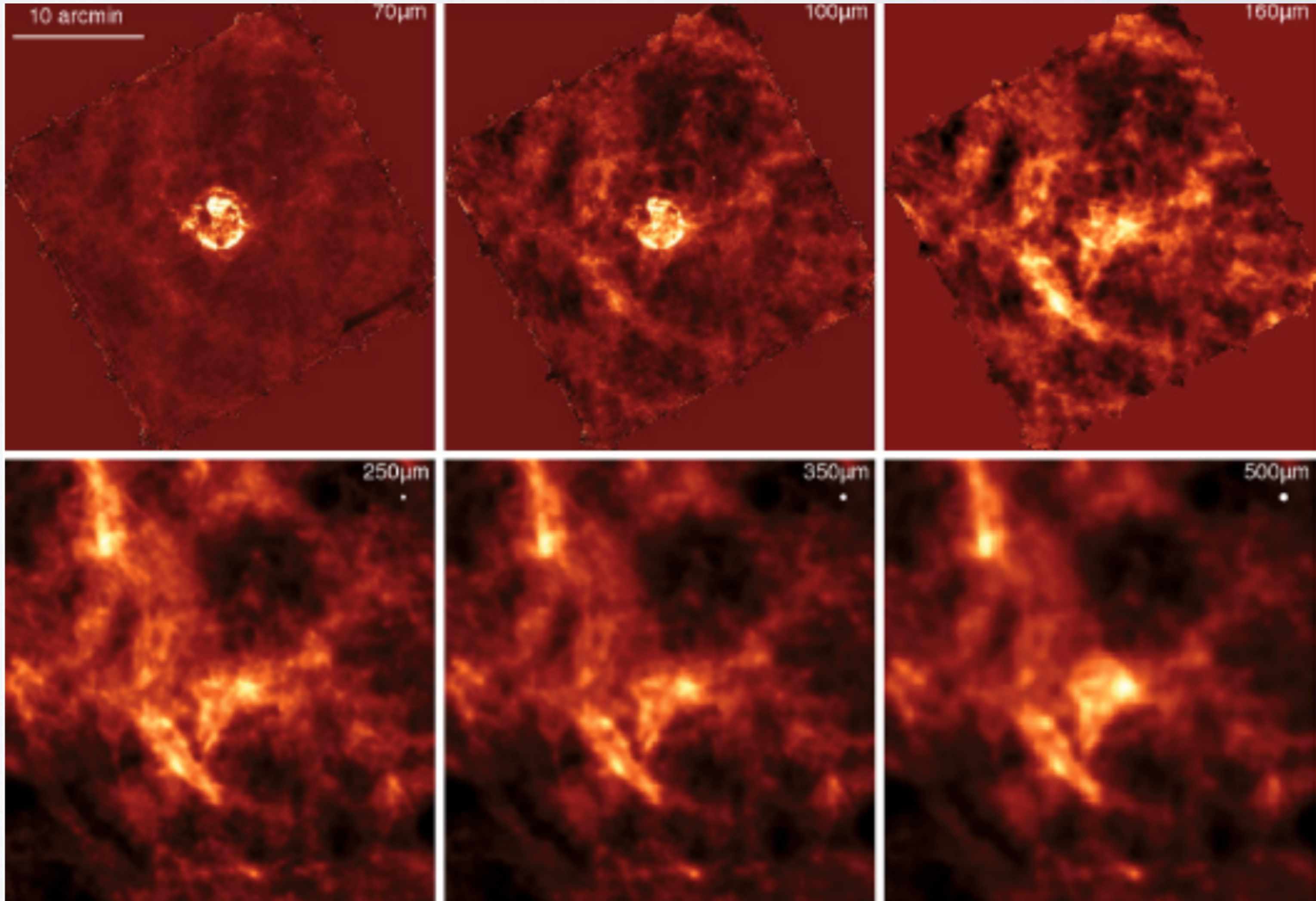
<u>Large disagreements</u> about dust mass formed in Cas A!

<u>Why?</u>

+ <u>Colder dust emits at longer wavelengths</u>: *the colder the dust, the greater the required dust mass*

+ <u>Difficult to separate</u>:

- SN dust
- synchrotron radiation
- ISM dust
- line emission



CAS A IN THE LITERATURE

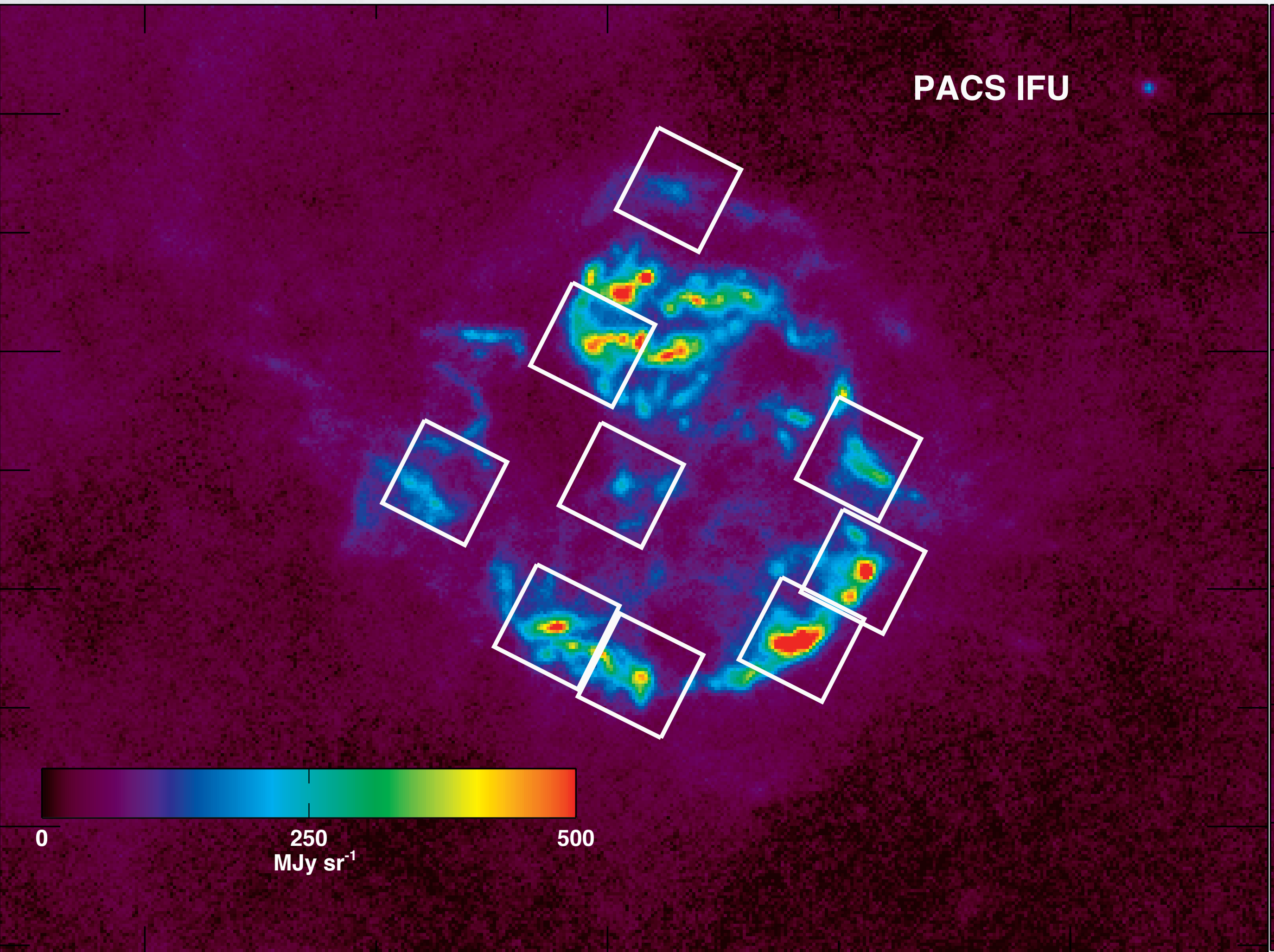
<u>General consensus:</u>

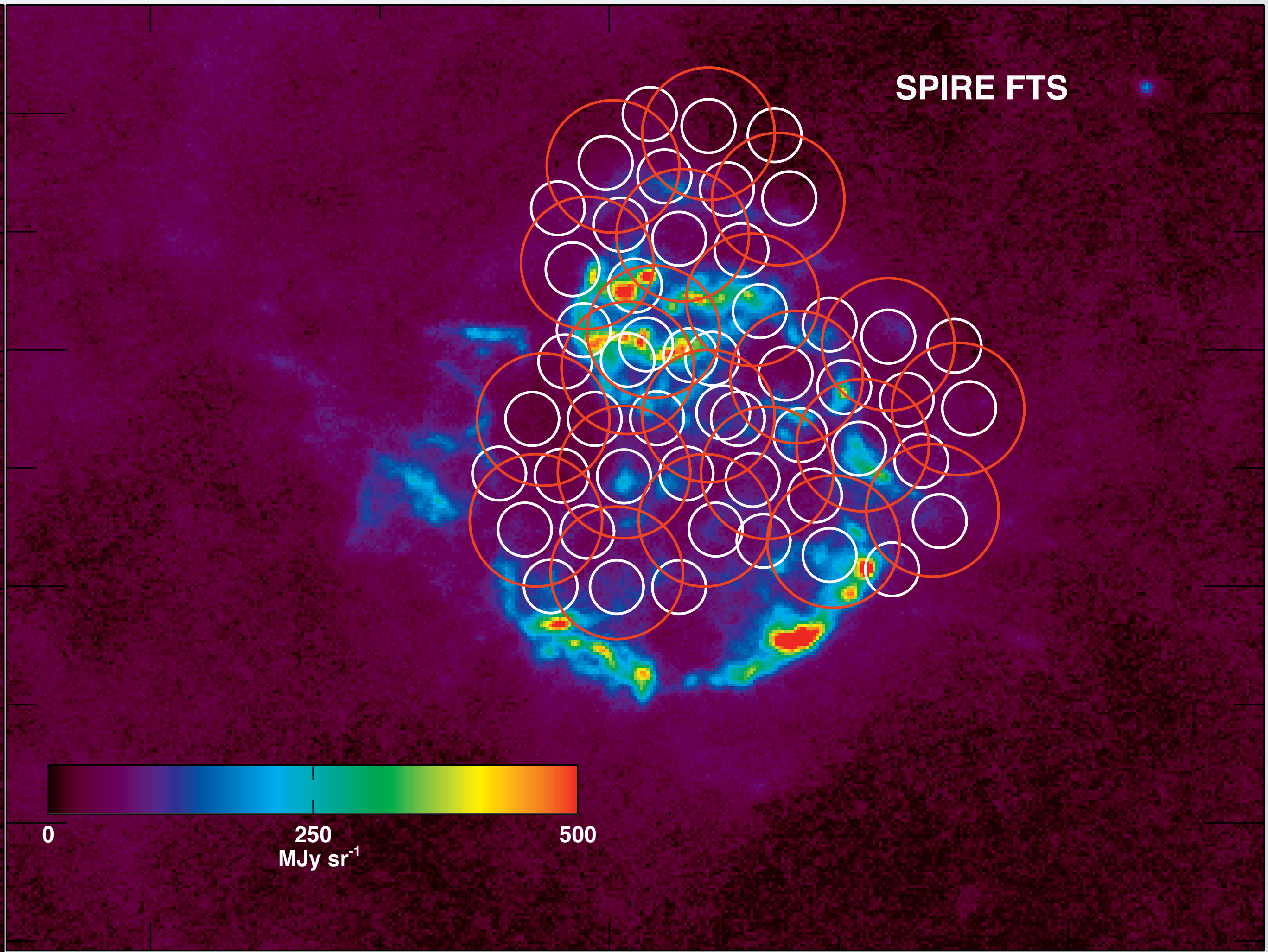
- Warm dust (75-100 K) in shocked ejecta
- Colder dust (<0.1 $M_\odot$) is found in unshocked regions interior to reverse shock! Composition = uncertain
- Excess emission at 850 micron: cold SN dust, ISM, dust polarisation?

→ ***Need for spatially resolved analysis of various components (synchrotron, ISM, SN dust emission, line emission)***

OUR NEW APPROACH

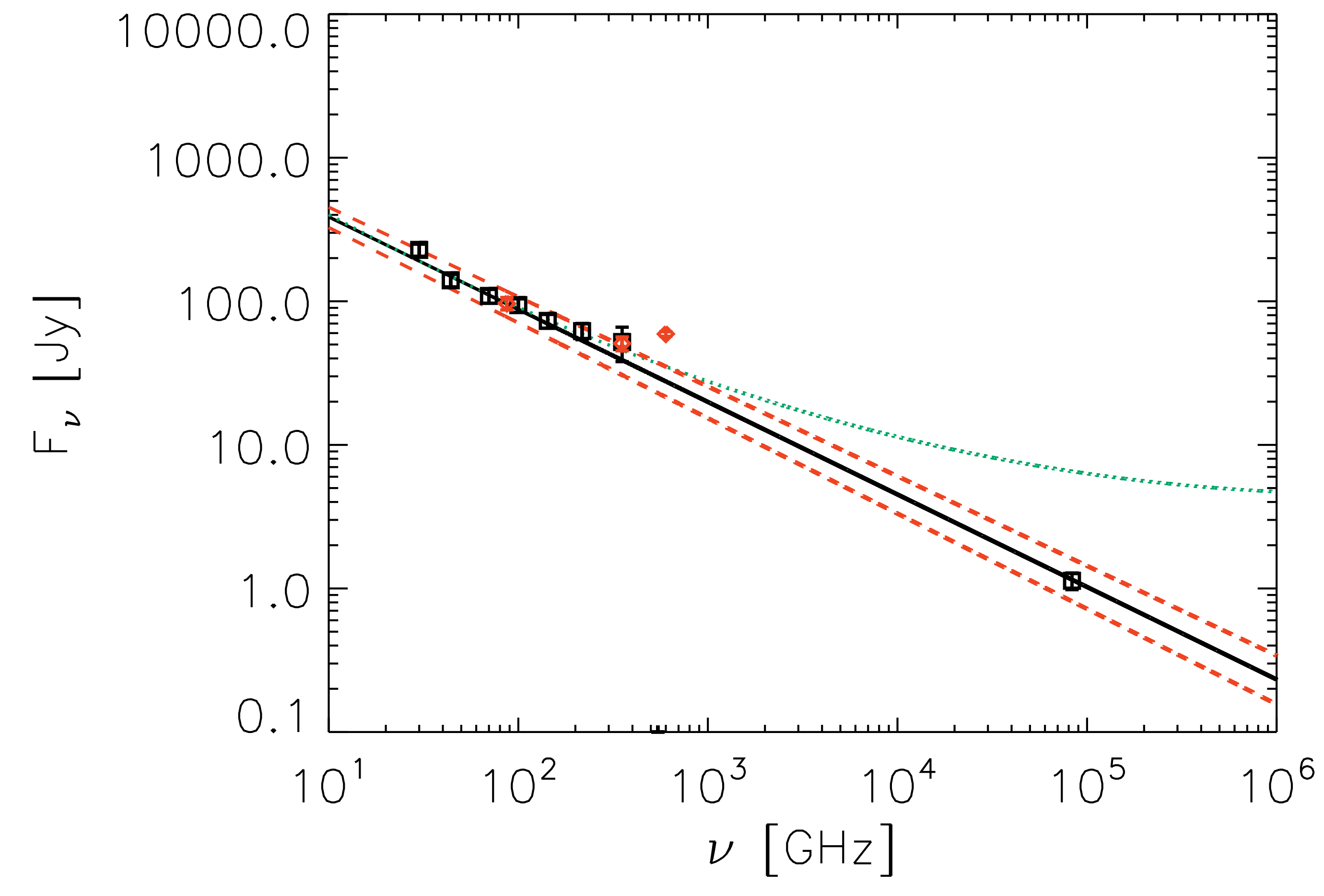
- Spatially resolved component separation using:
- IRAC 3.6 + 8 μm + WISE 12 + 22 μm + MIPS 24 μm
- Herschel PACS 70/100/160 μm+SPIRE 250/350/500 μm images
- PACS IFU spectra + SPIRE FTS spectra + Planck photometry

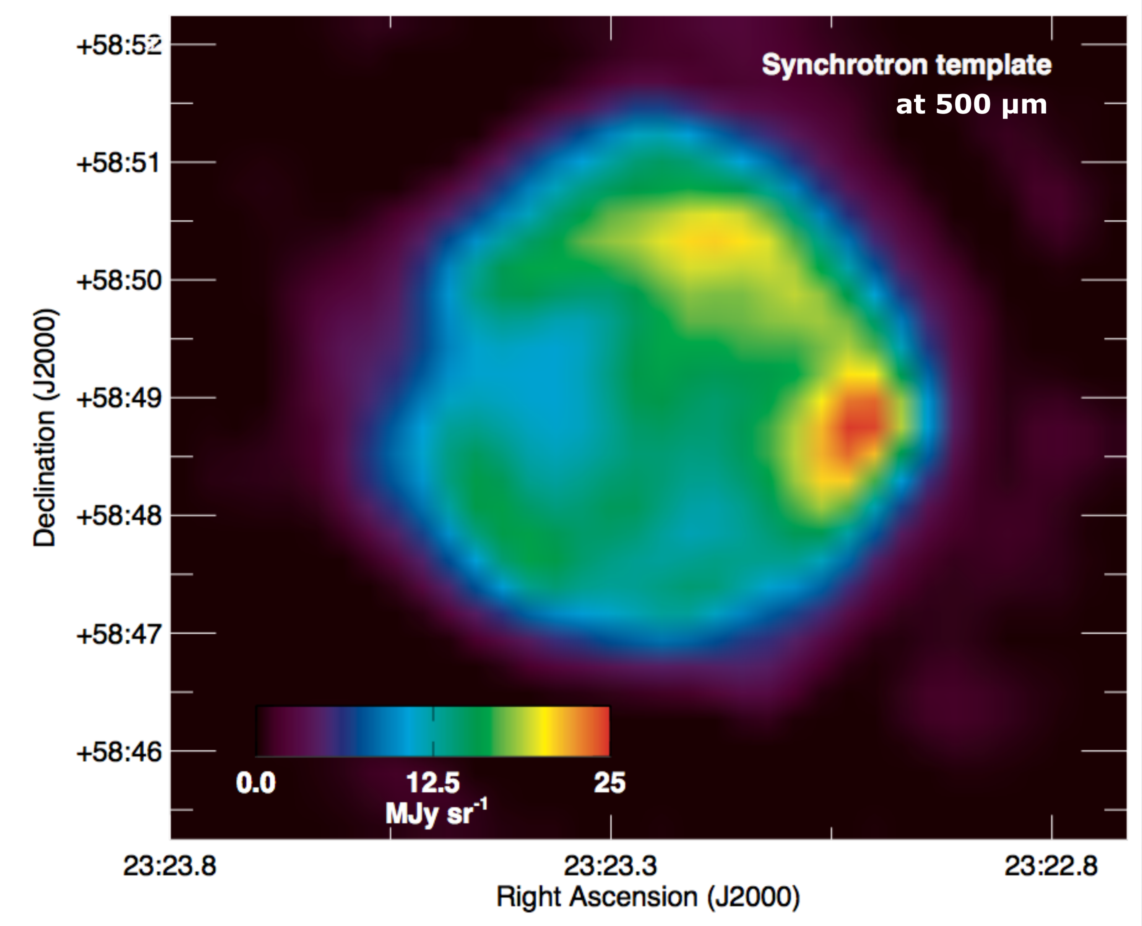




CAS A: SYNCHROTRON RADIATION

- Spectral index (α=-0.644) + normalisation factor determined from recent Planck data + IRAC 3.6 micron emission
- Extrapolation of 3.7 mm emission to IR/submm





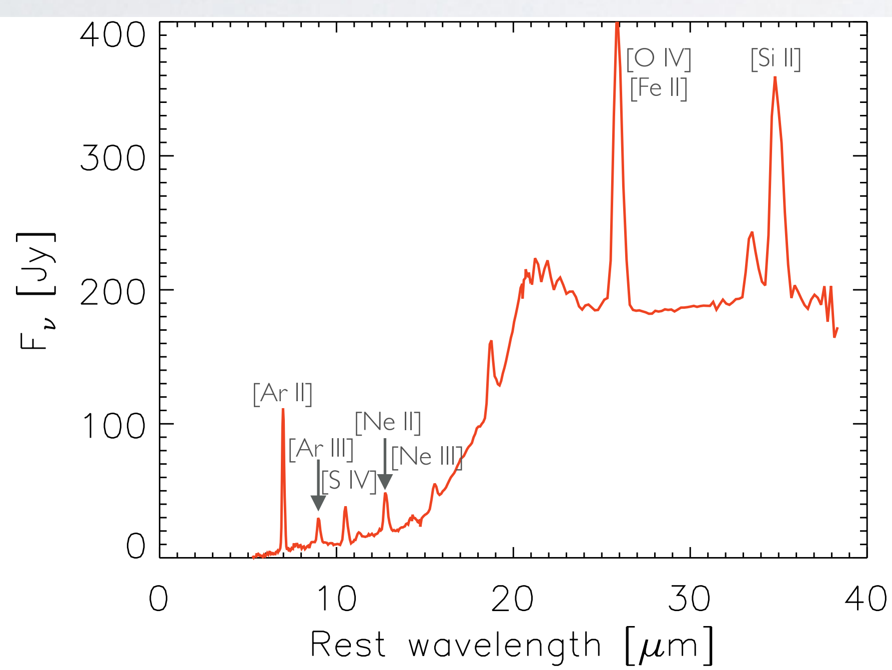
CAS A: LINE EMISSION

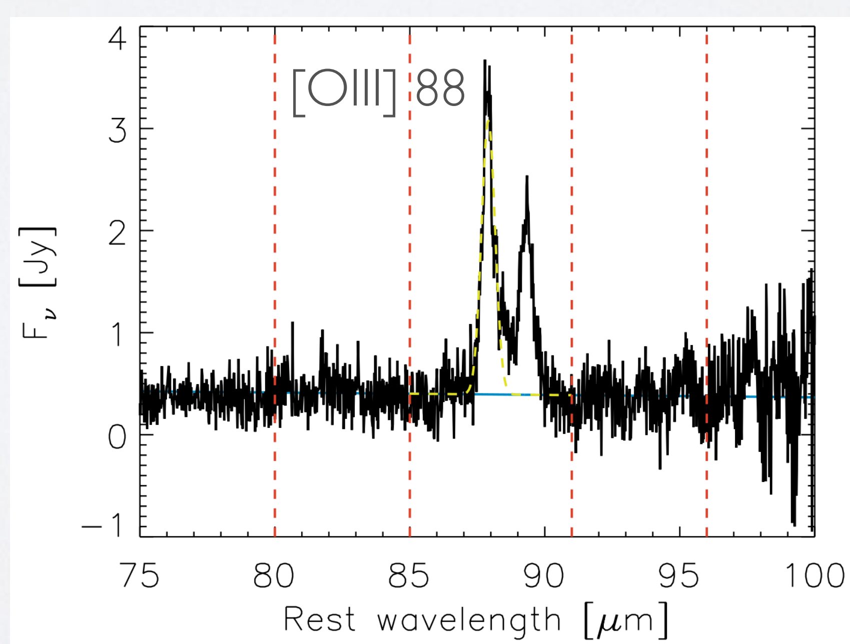
Determine line contribution from:

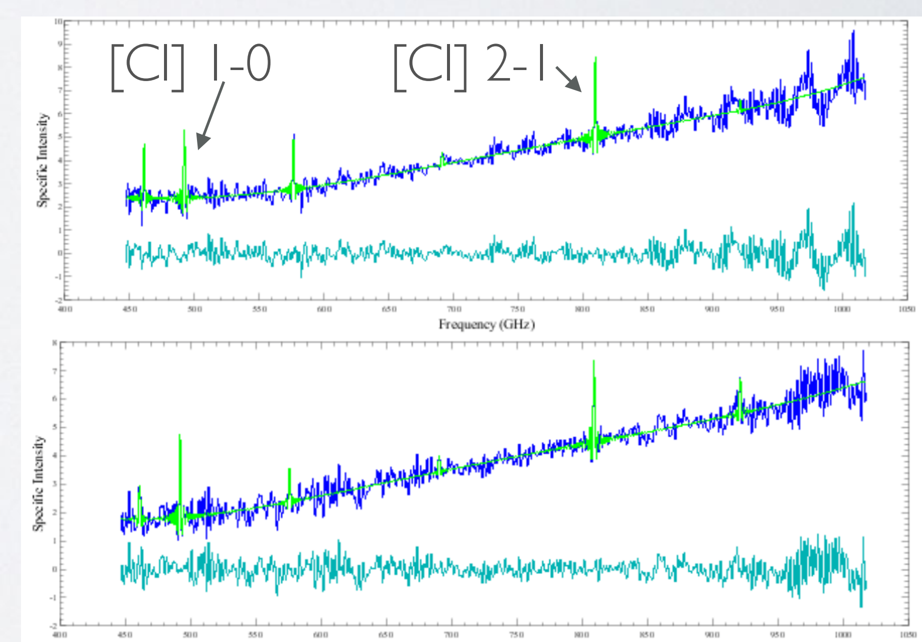
- Spitzer IRS spectra ([Ar III], [Ar II], [S IV], [Ne II], [NeIII])

- PACS IFU ([OI] 63µm, [OIII] 88µm, [OI] 145µm, [CII] 158µm)

- SPIRE FTS (CO rotational lines + [CI] lines)







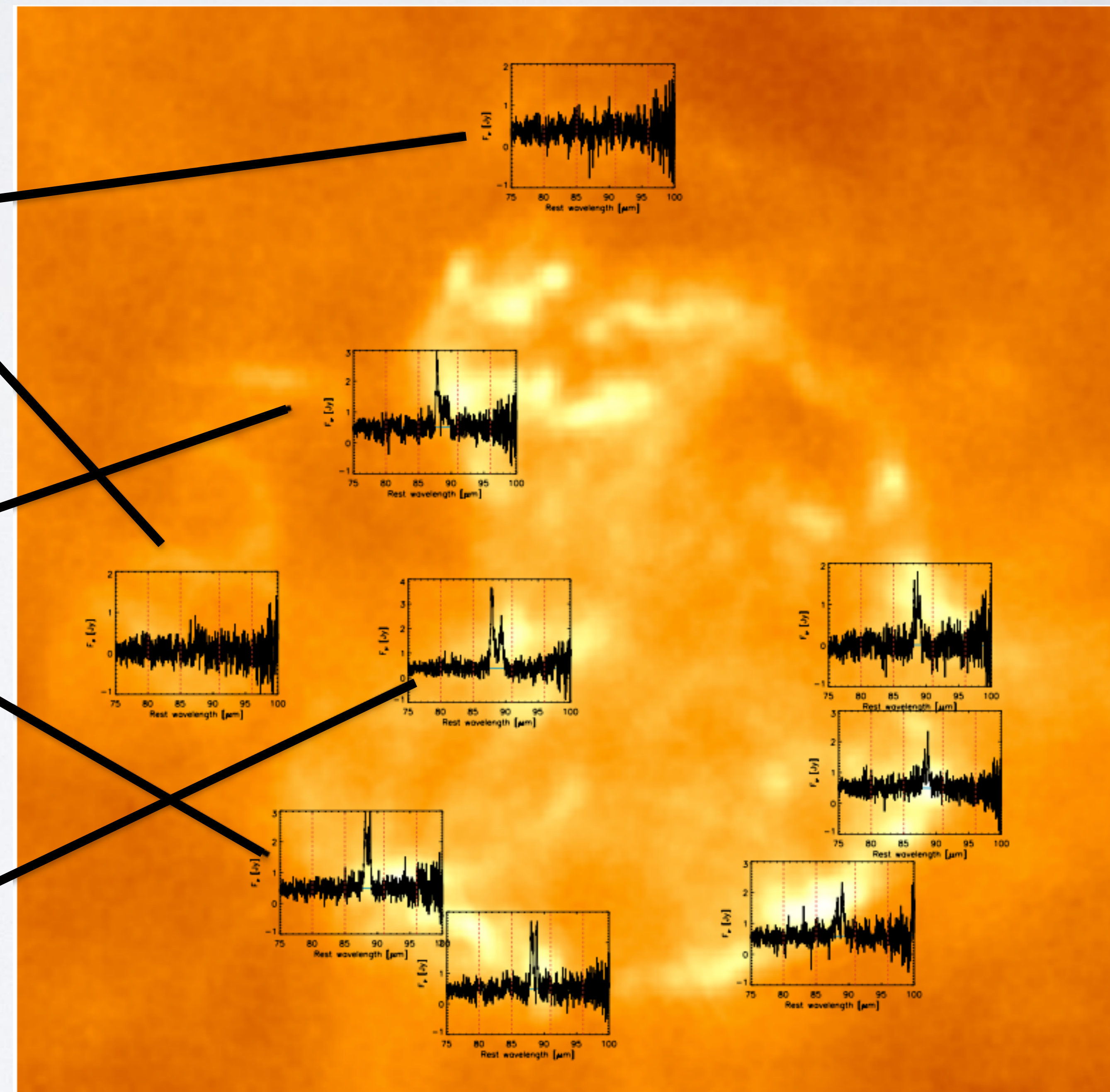
CAS A: LINE EMISSION

[OIII]$_{88}$ line contributes significantly to PACS 100 μm band

No line contamination in outer regions

2-3% line contamination in reverse shock regions

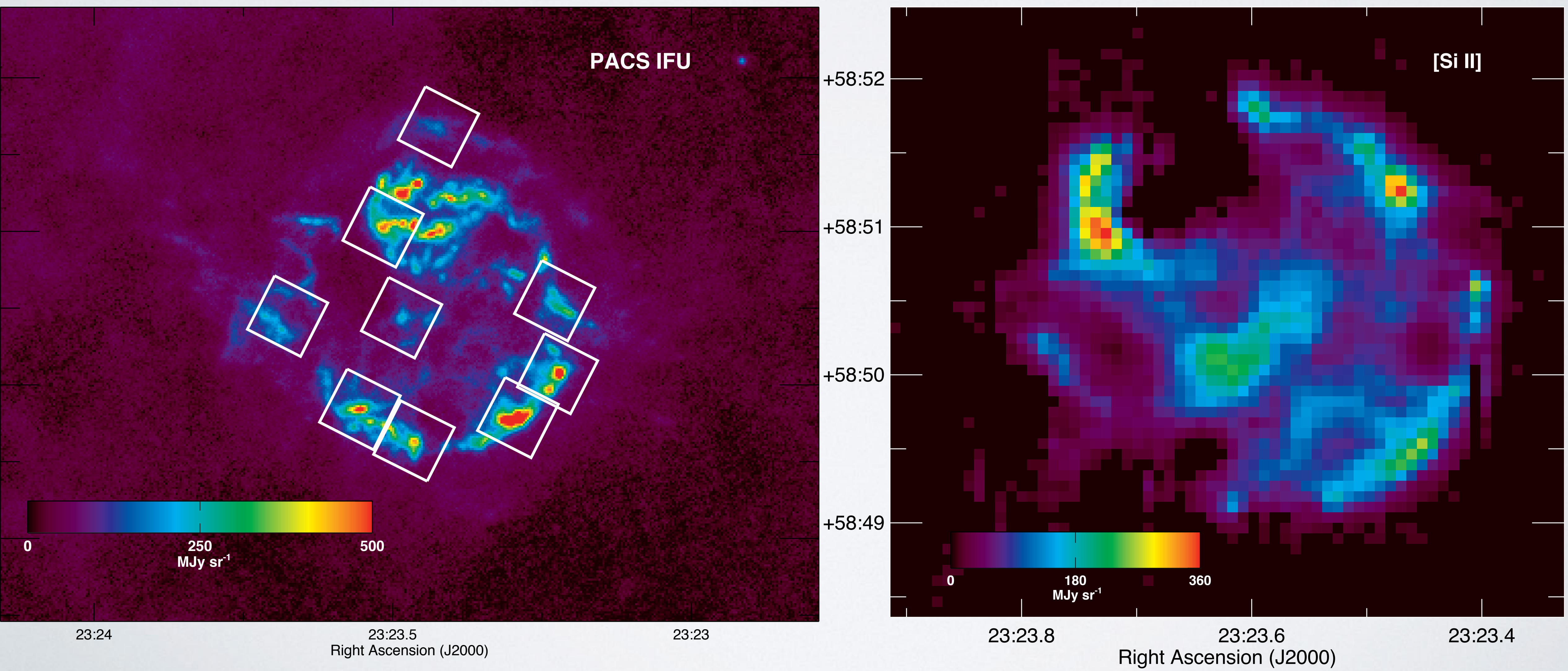
4-5% [OIII]$_{88}$ line contribution in inner regions



CAS A: LINE EMISSION

PACS IFU does not cover entire remnant,

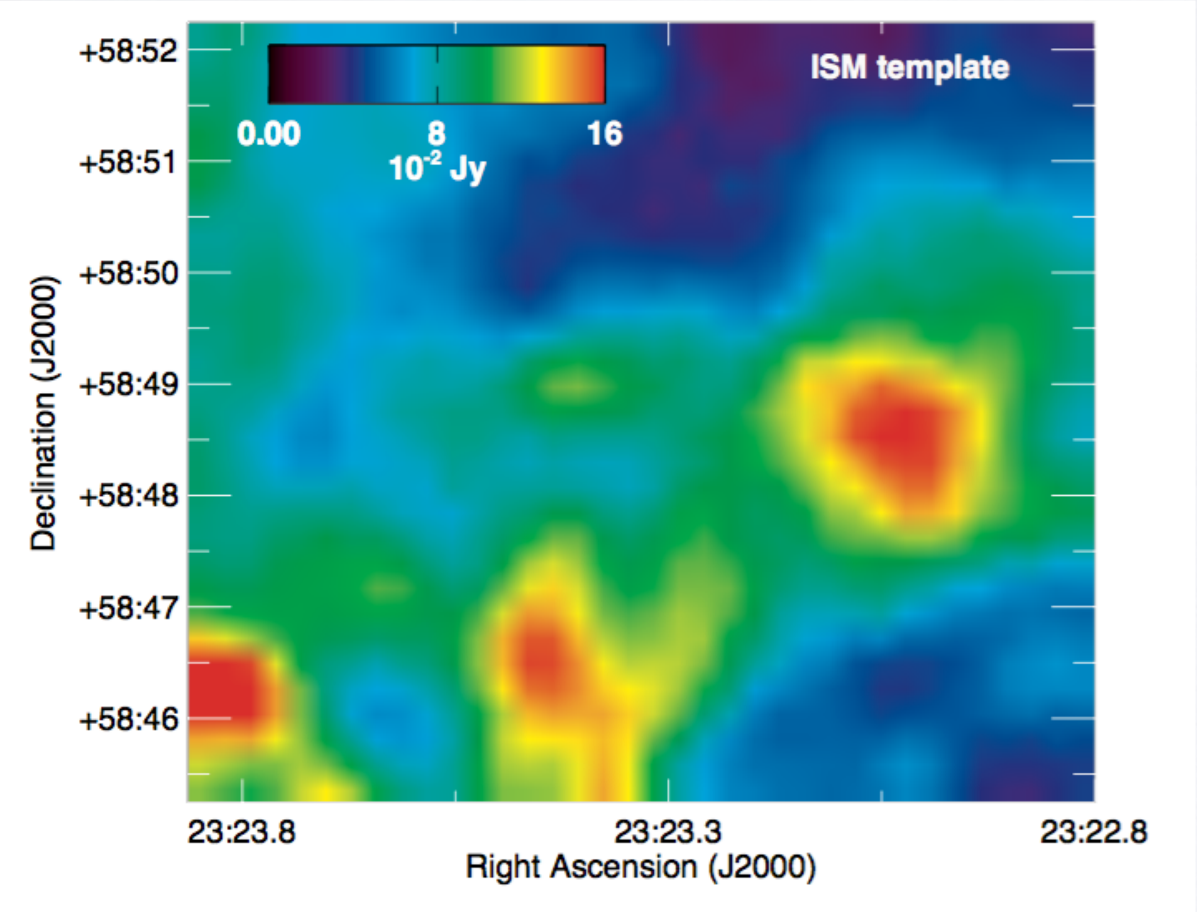
→ we use [Si II]$_{35}$ line to trace [OIII]$_{88}$ line contribution



CAS A: ISM CONFUSION

Use **SPIRE 500 μm** image as **ISM dust density tracer**!

(assuming that SN dust contributes marginally @ 500 μm)



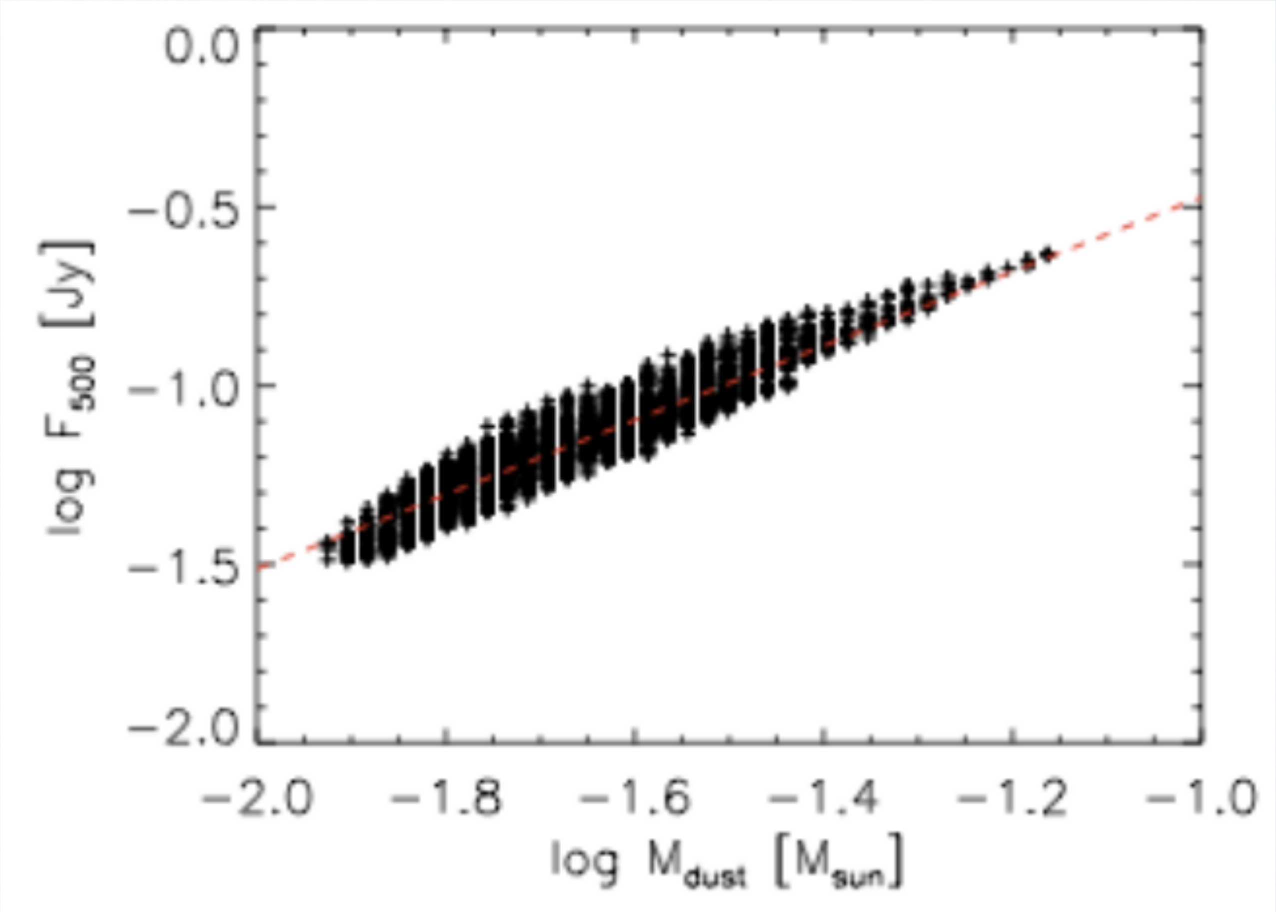
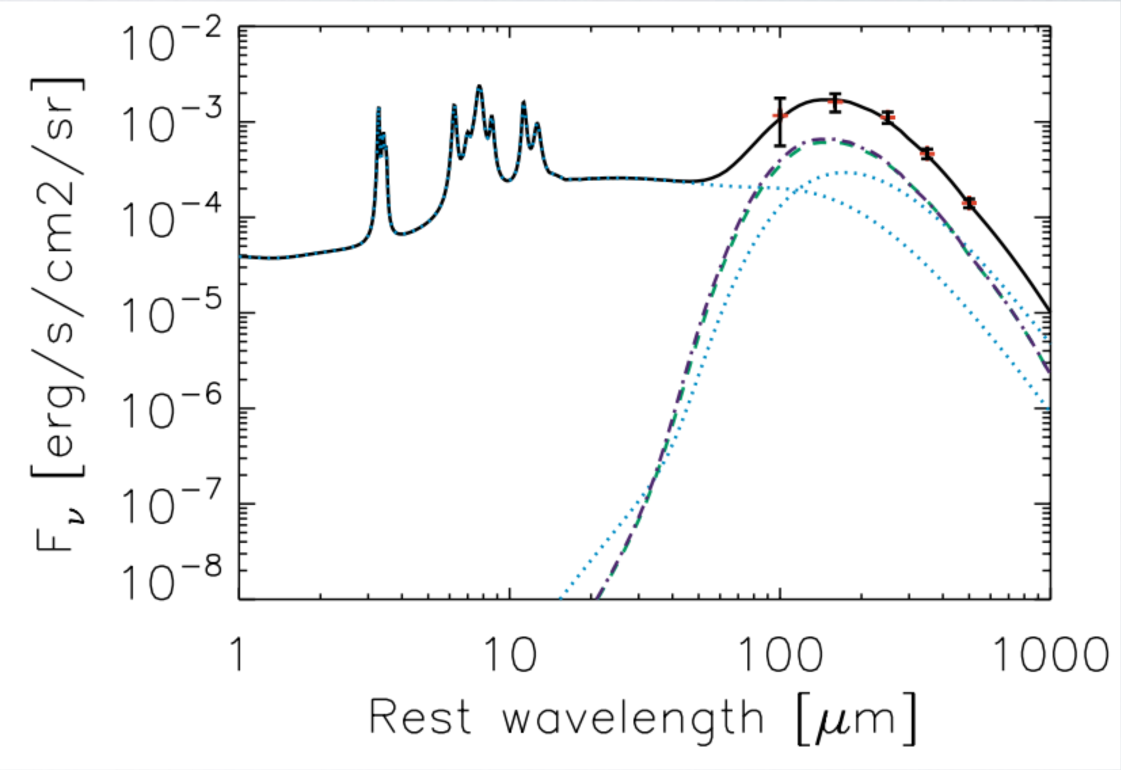


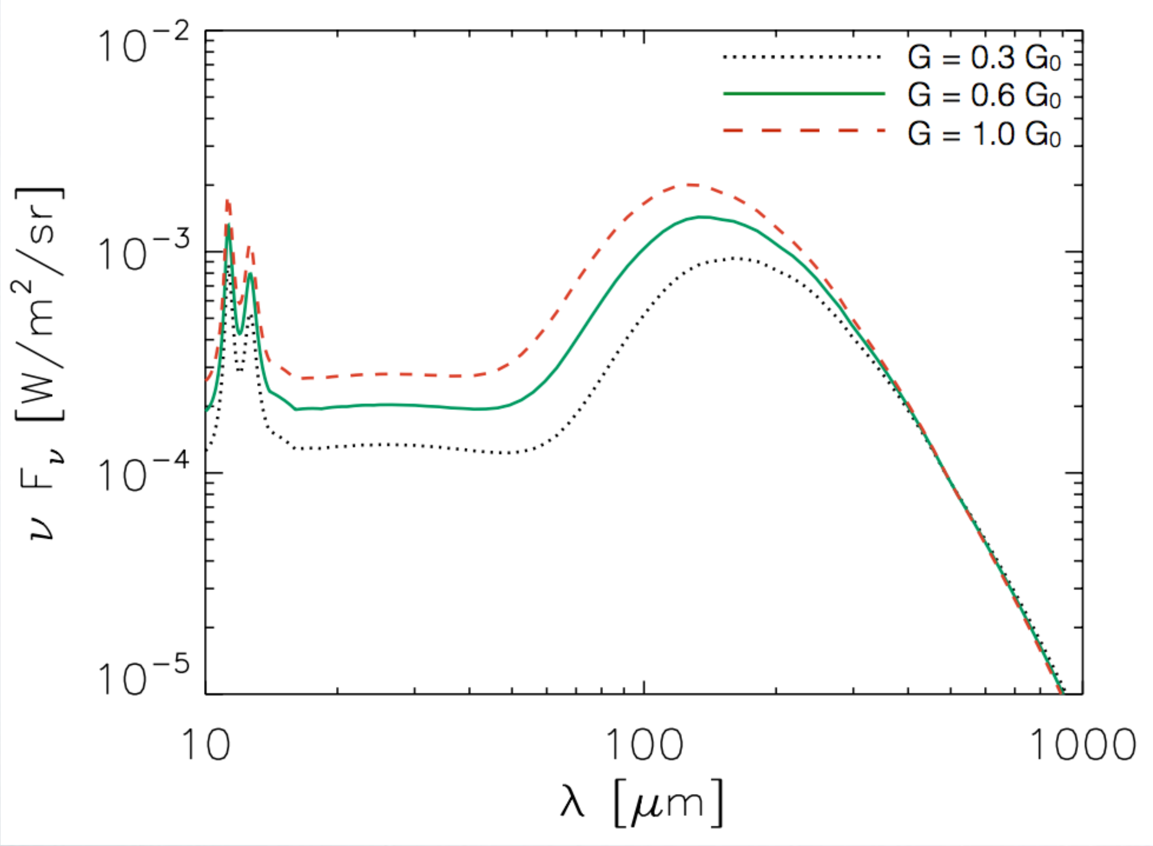
Fig: **Left**: SPIRE 500 μm map (with synchrotron emission subtracted)
Right: Correlation between F_{500} and M_d (ISM) for SED models with fixed $G=0.6G_0$.

CAS A: ISM CONFUSION

SED template?

Jones et al. 2013 dust model,
(hydrocarbons + amorphous silicates)
calibrated on Milky Way data





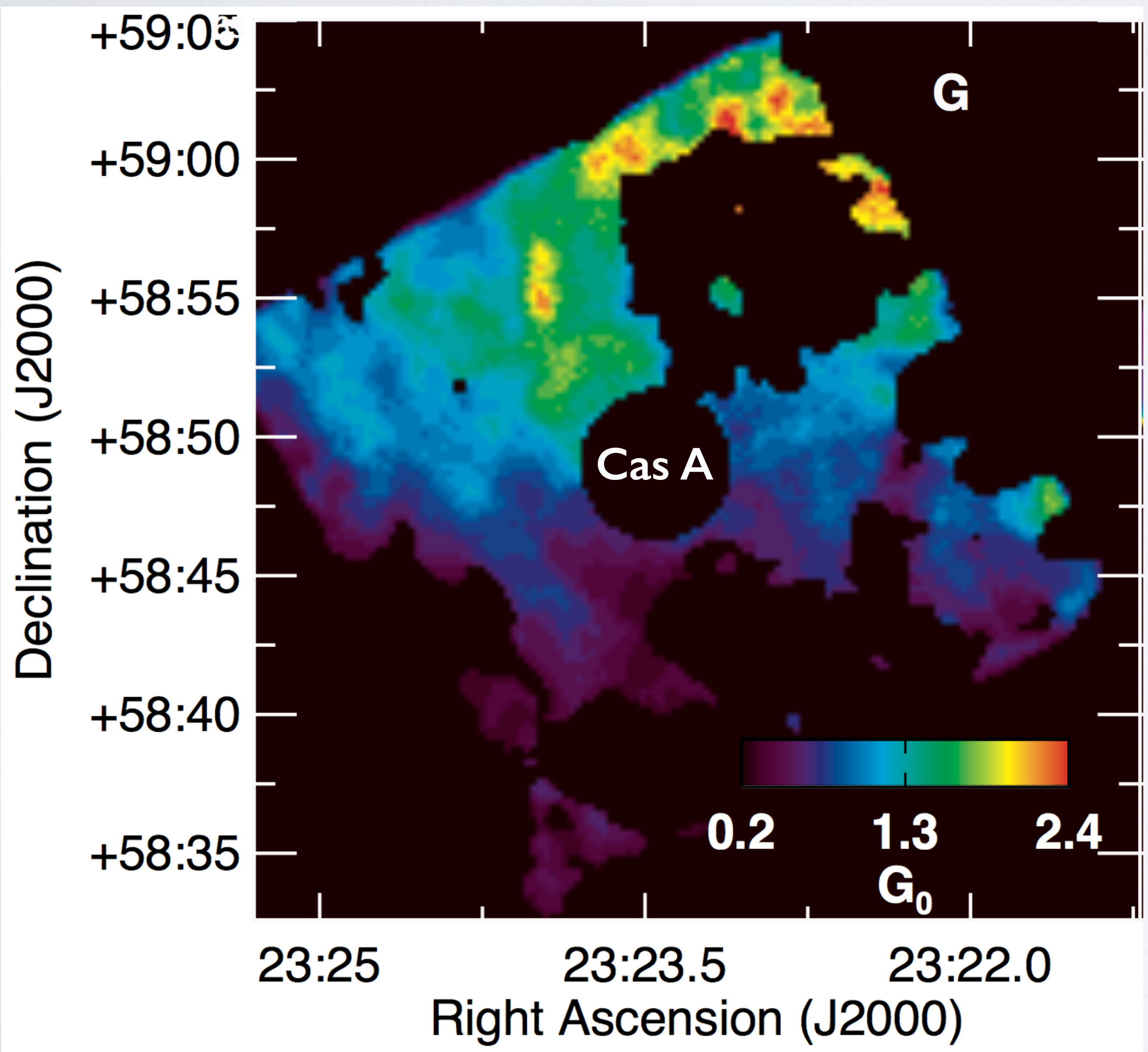
IS dust emission depends on radiation field **G***
heating the dust:

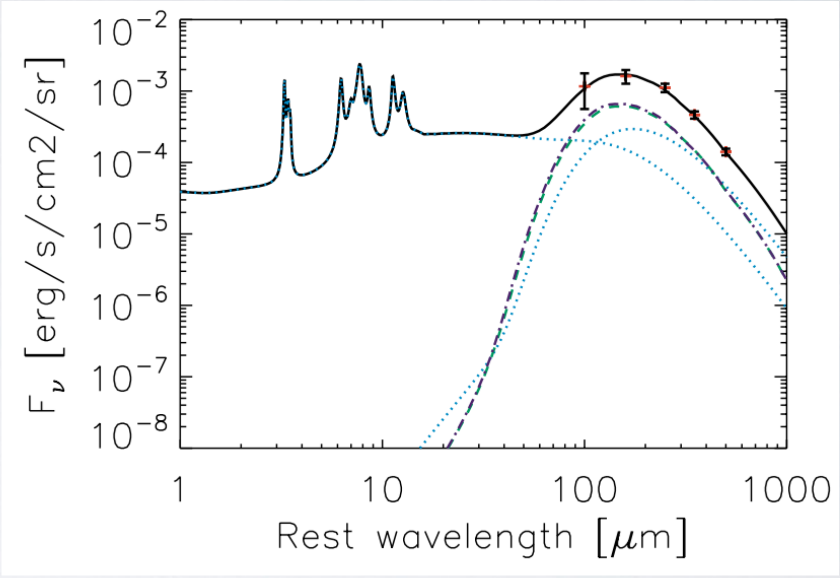
$G = 0.3G_0 \longrightarrow T_d = 14.6$ K
$G = 0.6G_0 \longrightarrow T_d = 16.4$ K
$G = 1.0G_0 \longrightarrow T_d = 17.9$ K

****Habing field G*** = FUV radiation field (6-13.6eV), normalised to G_0 = 1.6x10-3 erg/s/cm²

CAS A: ISM CONFUSION

Method: Determine radiation field based on SED models of the ISM regions around Cas A.



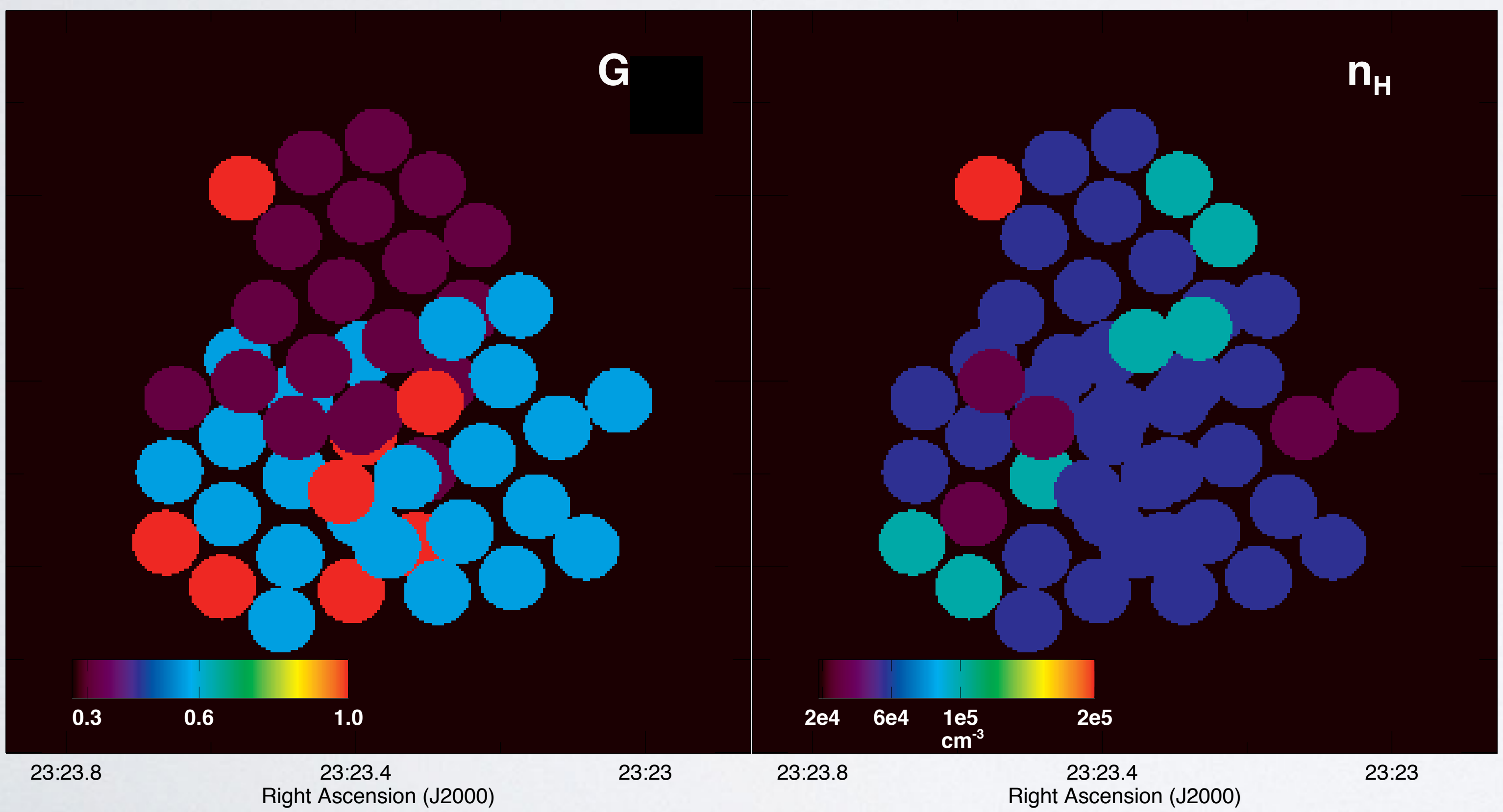


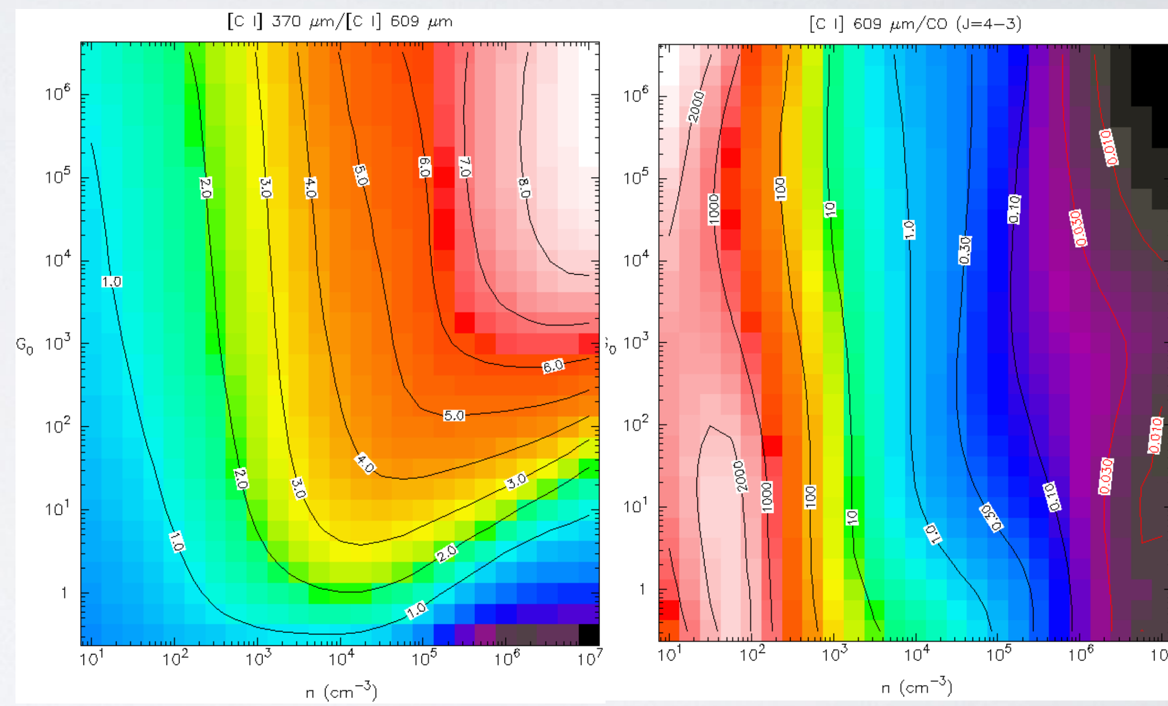
Radiation field?

- G varies from 0.2 G_0 to 2.4 G_0 in the observed field around Cas A
- in immediate vicinity of Cas A, G varies from 0.3 G_0 to 1.0 G_0

CAS A: ISM CONFUSION

Alternative method: PDR modelling based on fitting relative intensities of [CI] 1-0, 2-1, CO(4-3) lines detected in the ISM near to Cas A with Herschel SPIRE FTS





PDR toolbox
Pound & Wolfire (2008)

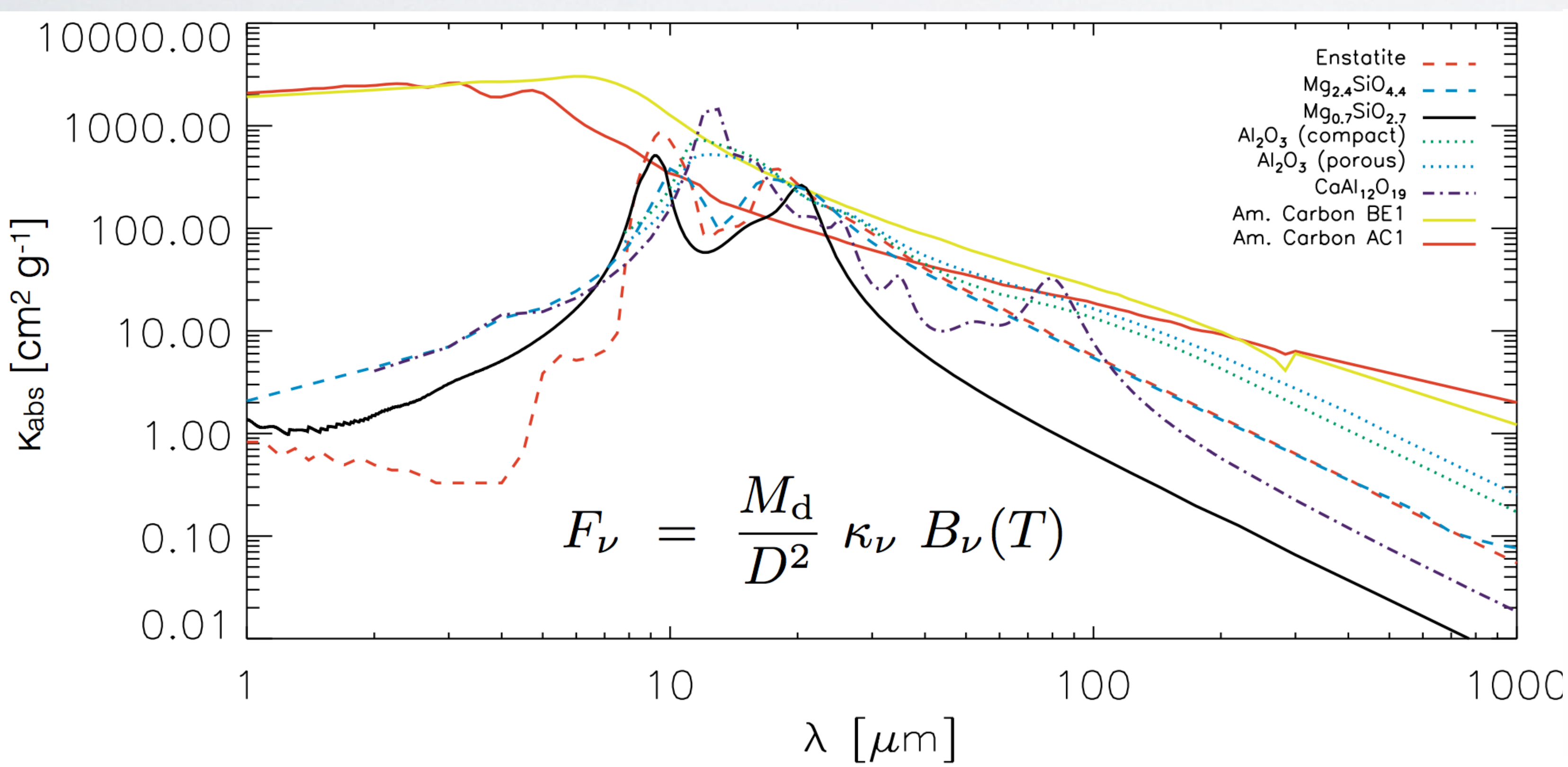
→ G varies from 0.3 G_0 to 1.0 G_0, with **median of G = 0.6 G_0**

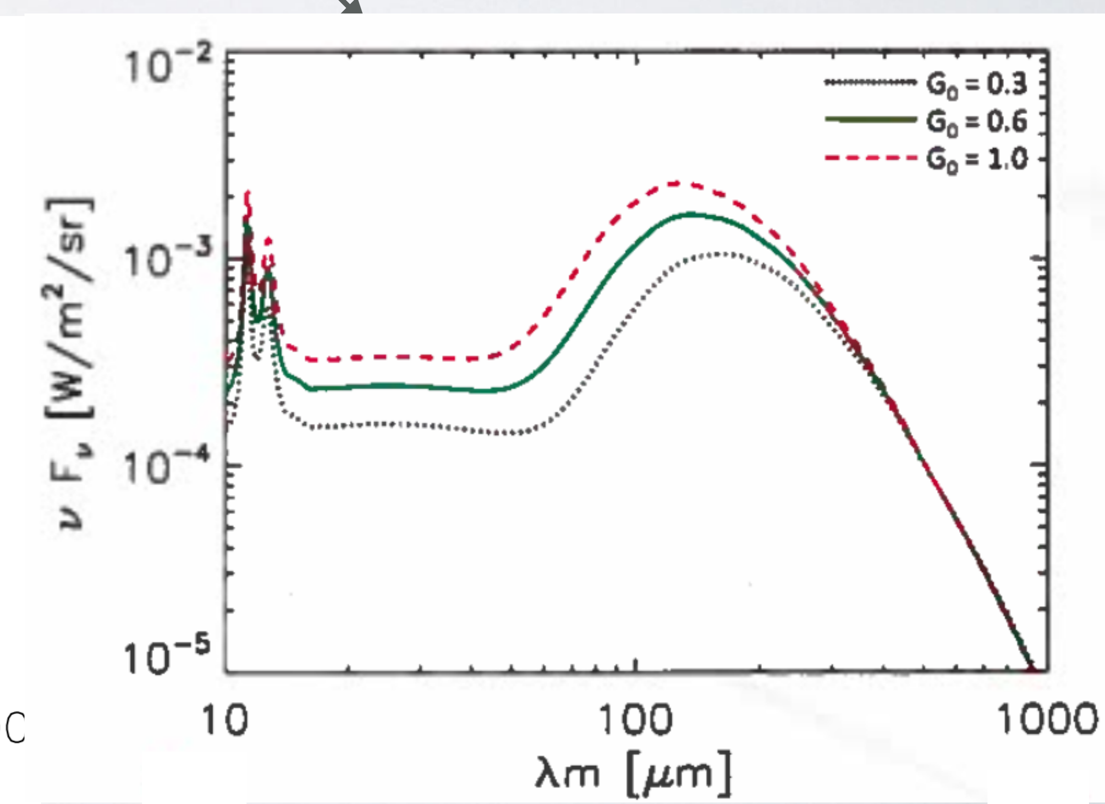
CAS A: SED FITTING

Step 1: subtraction of line+synchrotron emission

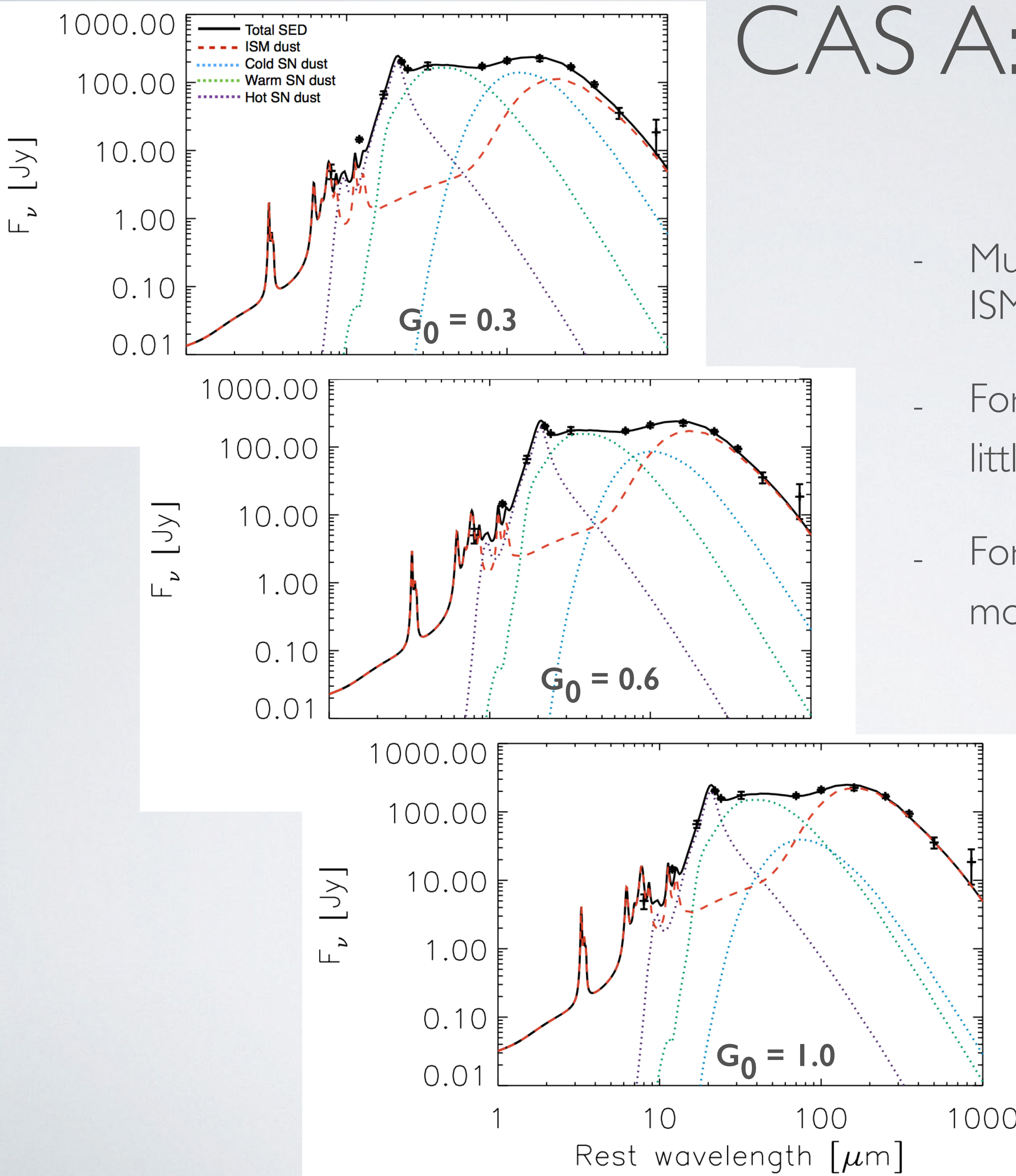
Step 2: fit 17-500 μm SED with multi-component ISM+SN (hot, warm, cold) model

Step 3: repeat modelling for ISM with G = 0.3, 0.6, 1.0 G_0 and various dust species





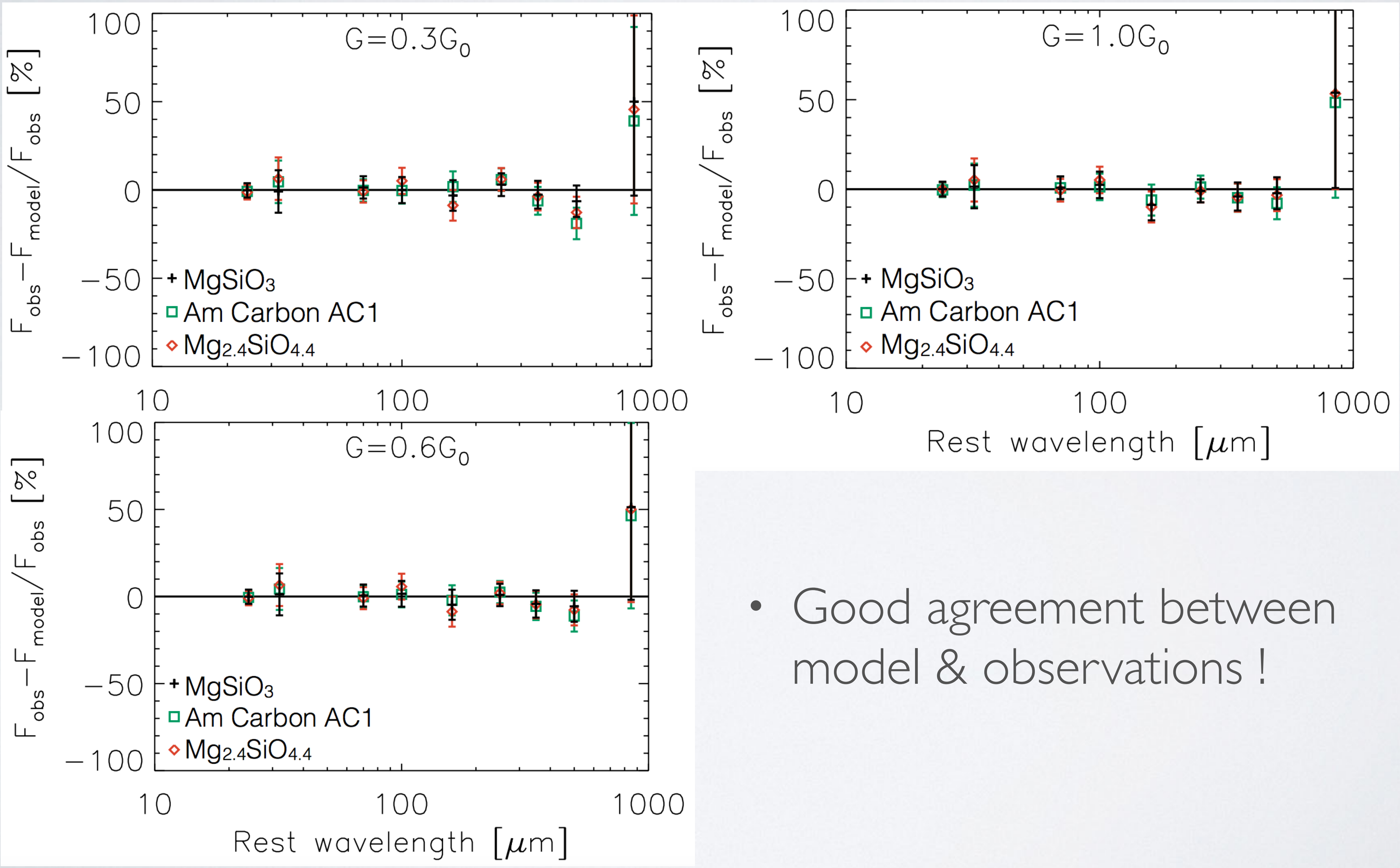
CAS A: GLOBAL FITS



- Multi-component SED:
  ISM + 3 SN components at different T_d
- For G = 1.0 G_0: max ISM contribution, little SN dust emission left
- For G = 0.3 G_0: min ISM contribution, more room for SN dust emission

CAS A: GLOBAL FITS

Model safety check: how does model compare to data?



- Good agreement between model & observations !

CAS A: GLOBAL FITS

SN dust mass depends on

1.) ISM model ($G=0.3, 0.6, 1.0G_0$)

2.) dust composition

SED fitting results for ISM models with

Dust species	**$G=0.3G_0$:**			**$G=0.6G_0$:**			**$G=1.0G_0$:**		
	M_d(SN) [$M_\odot$]	T_d(SN) [K]	M_d(min)* [$M_\odot$]	M_d(SN) [$M_\odot$]	T_d(SN) [K]	M_d(min)* [$M_\odot$]	M_d(SN) [$M_\odot$]	T_d(SN) [K]	M_d(min)* [$M_\odot$]
$Mg_{0.7}SiO_{2.7}$	222±36	21	43±4	13.5±1.9	33	5.7±0.8	4.4±1.0	38	3.4±1.0
$MgSiO_3$	12.4±1.5	24	3.5±0.3	**3.5±0.6**	**28**	**0.7±0.1**	0.4±0.1	38	0.1±0.0
$Mg_{2.4}SiO_{4.4}$	6.9±0.9	26	2.7±0.3	**2.2±0.5**	**29**	**0.6±0.1**	0.1±0.1	62	0.1±0.1
Amorphous carbon	1.8±0.1	27	0.2±0.0	0.8±0.3	29	0.04±0	1.1±2.1	23	0.03±0

*M_d (min): SED models without SN contribution at 500 μm

CAS A: GLOBAL FITS

- We calculate the maximum M_d for a given species based on available metals
- We rule out $Mg_{0.7}SiO_{2.7}$ and $CaAl_{12}O_{19}$ based on nucleosynthesis model predicted heavy element availability (Woosley & Weaver 1995)

—> best SED fits with silicate-type grains ($MgSiO_3$, $Mg_{2.4}SiO_{4.4}$)

SED fitting results for ISM models with $G=0.6G_0$:

Dust species	M_d [$M_\odot$]	T_d [K]	Lower M_d*	Max M_d**
$Mg_{0.7}SiO_{2.7}$	13.5	33	5.7	1.21
$MgSiO_3$	**3.5**	**28**	**0.7**	1.37
$Mg_{2.4}SiO_{4.4}$	**2.2**	**29**	**0.6**	0.93
Amorphous carbon	0.8	29	0.04	0.29

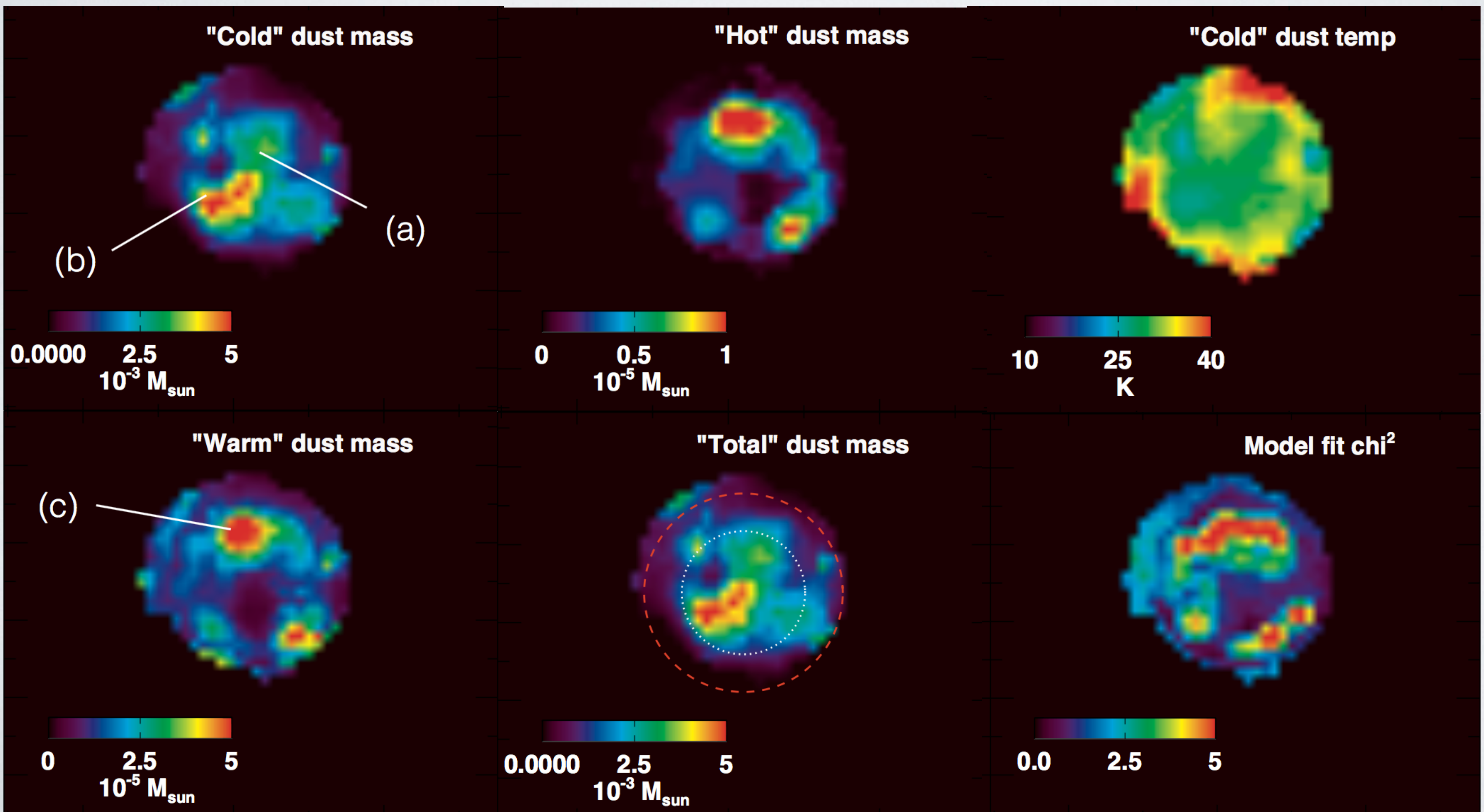
*Lower M_d : SED models without SN contribution at 500 μm
**Max M_d : based on available material from nucleosynthesis models

CAS A: RESOLVED FITS

All maps convolved to SPIRE 500 μm resolution (FWHM =36.3"=0.6pc)

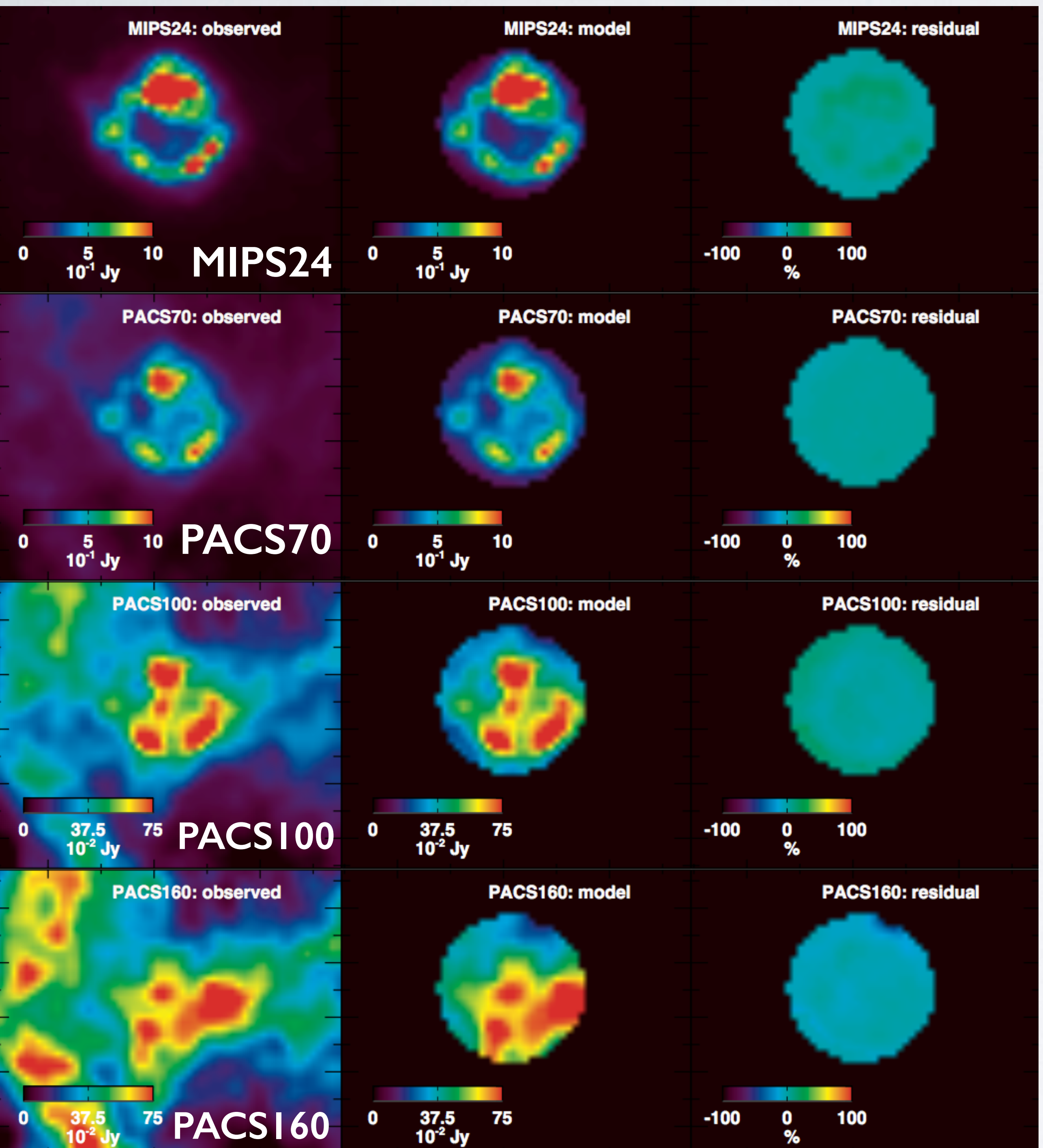
→ 79 (36" pixels) and 438 (14" pixels) resolution elements

SN components at different temperatures:

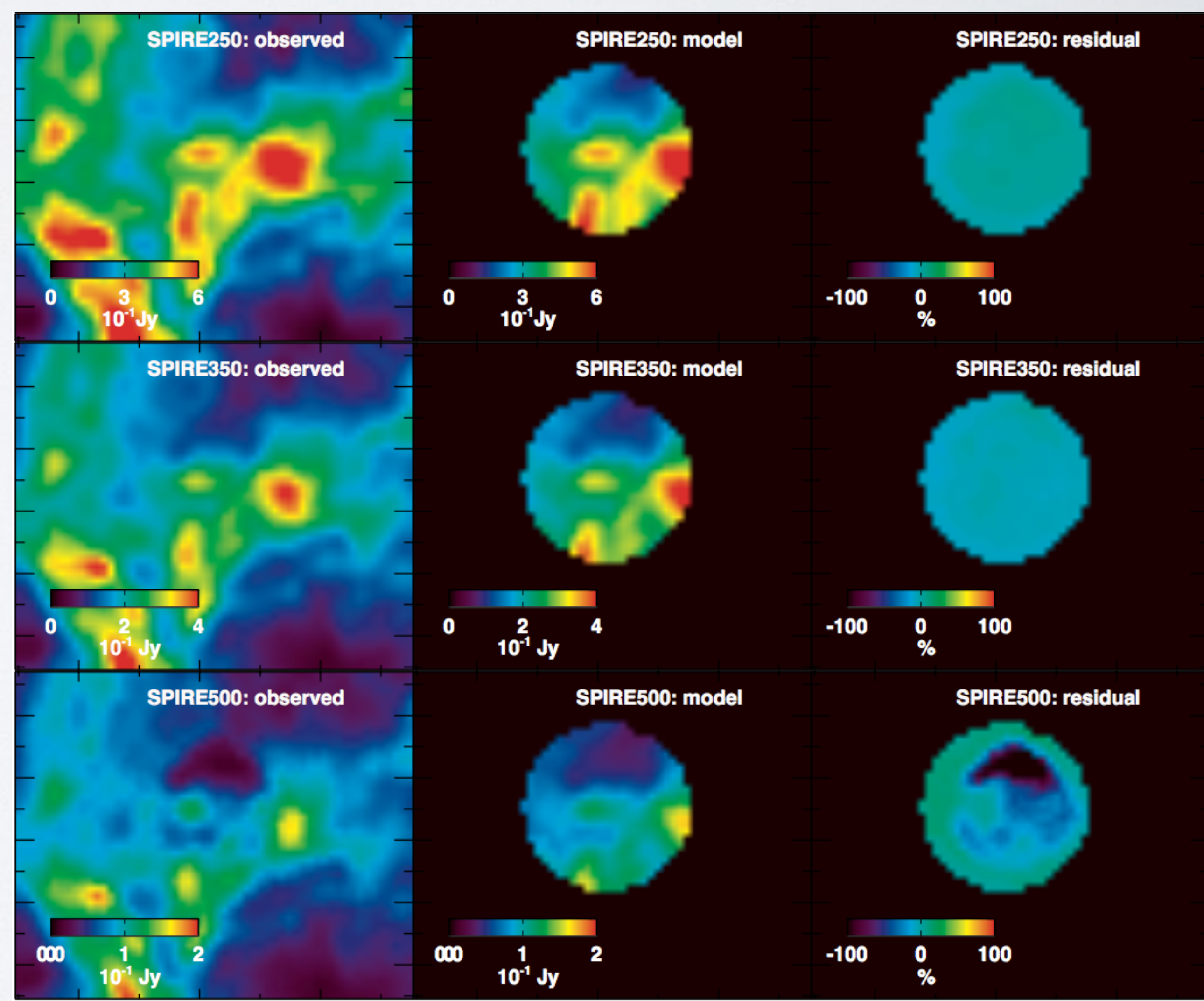


CAS A: RESOLVED FITS

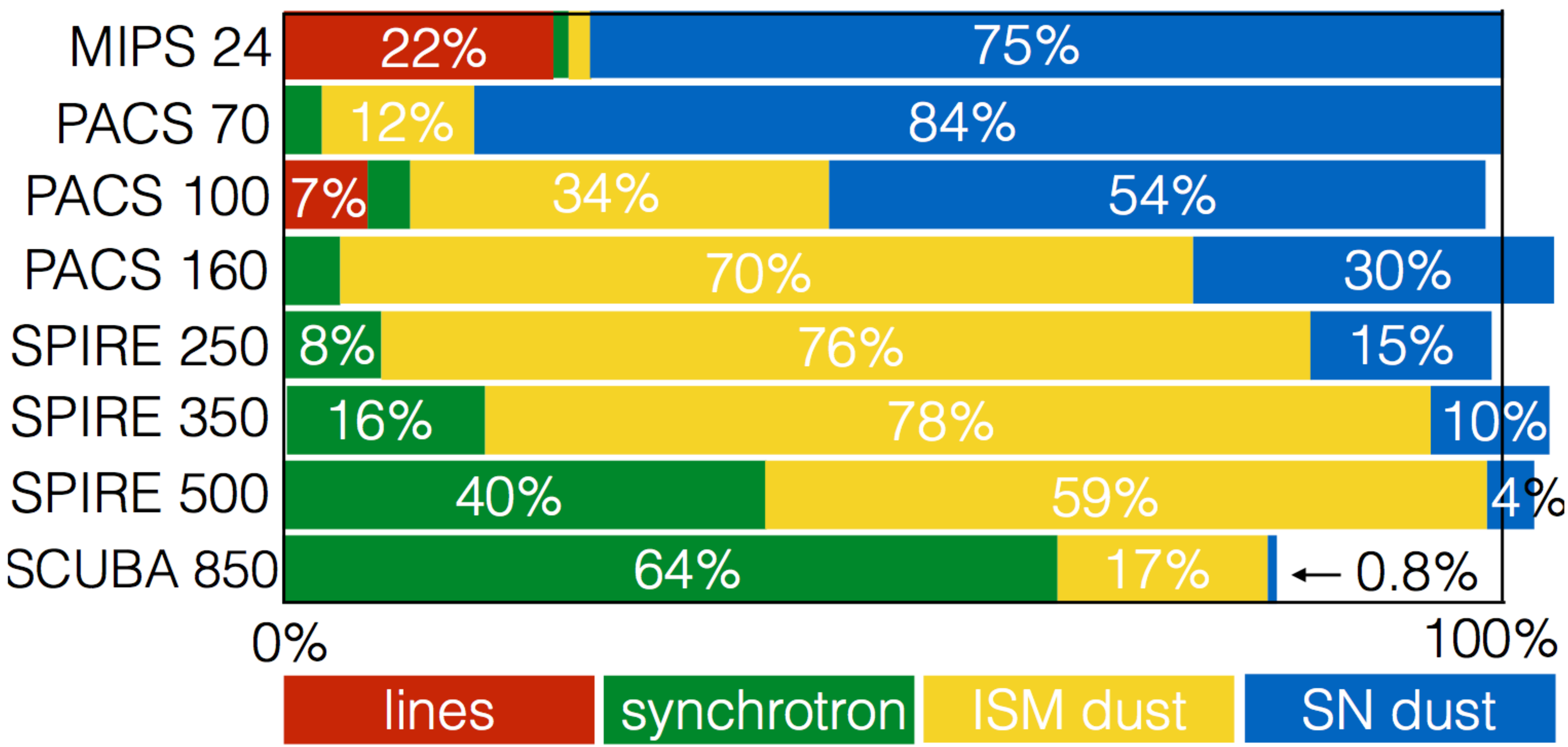
Model safety check: how does model compare to data?



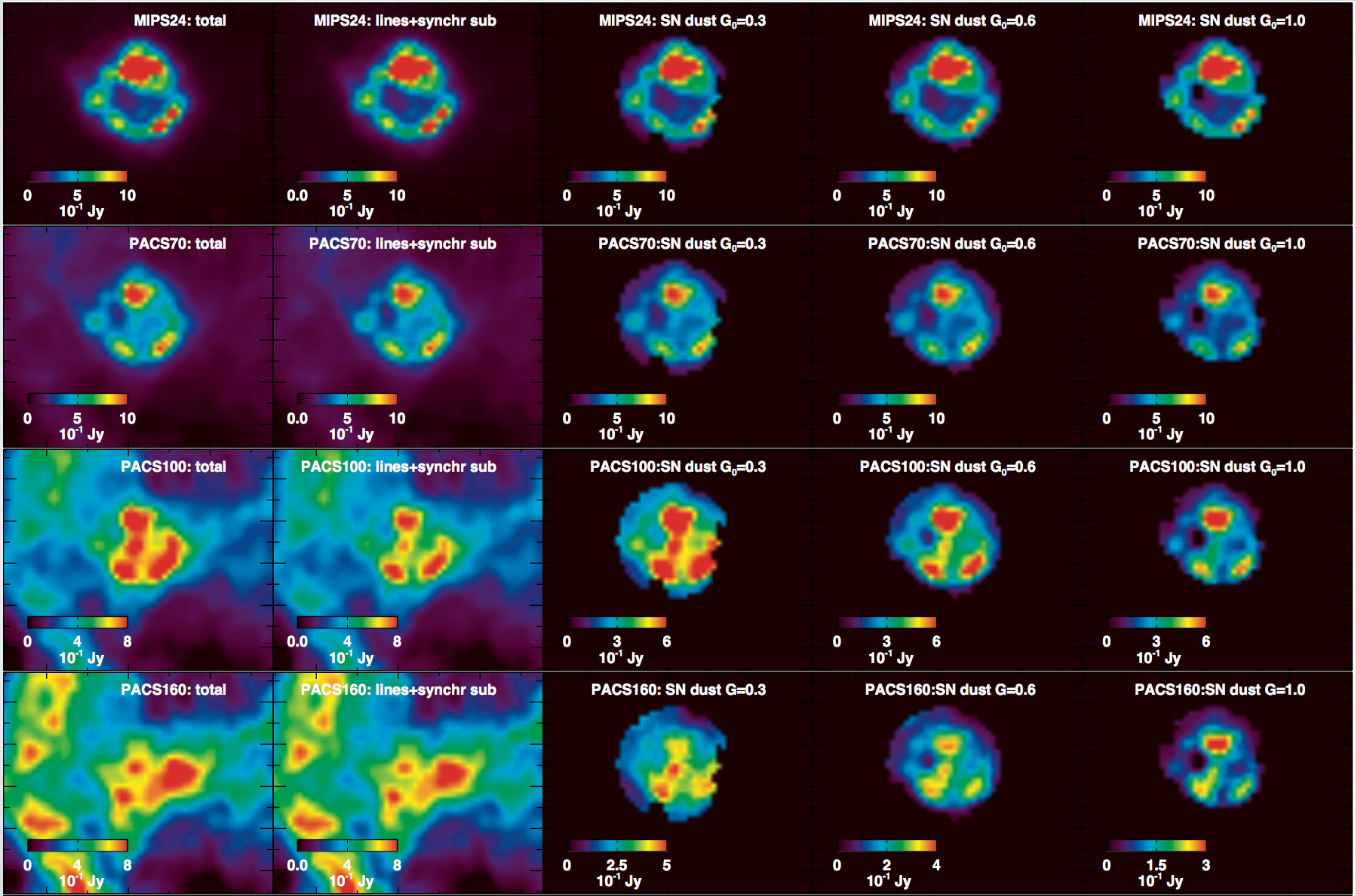
Observations Model Residual



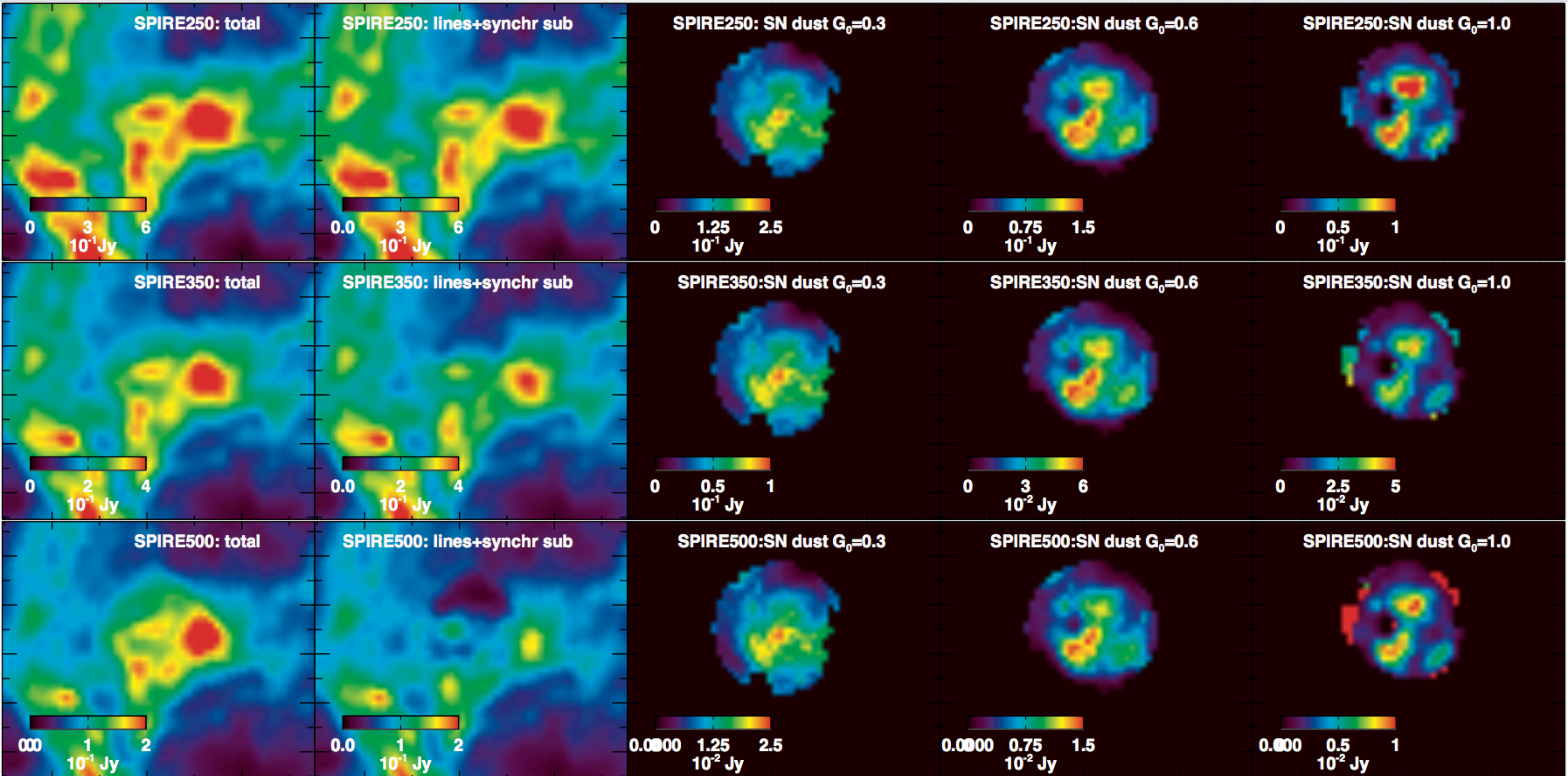
CAS A: COMPONENTS



CAS A: COMPONENTS

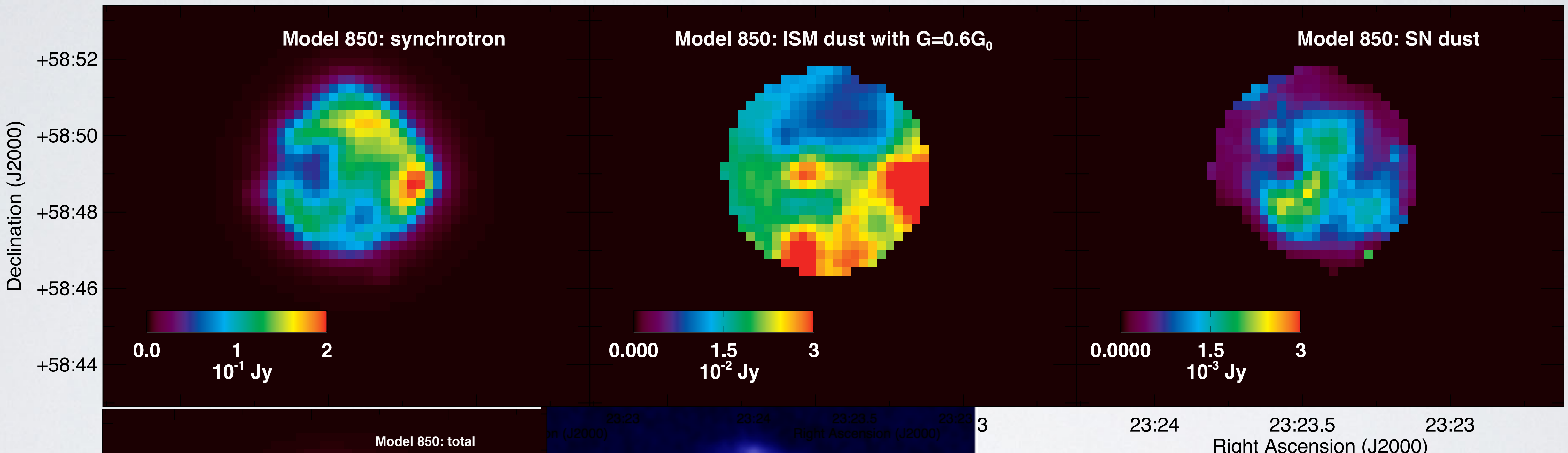


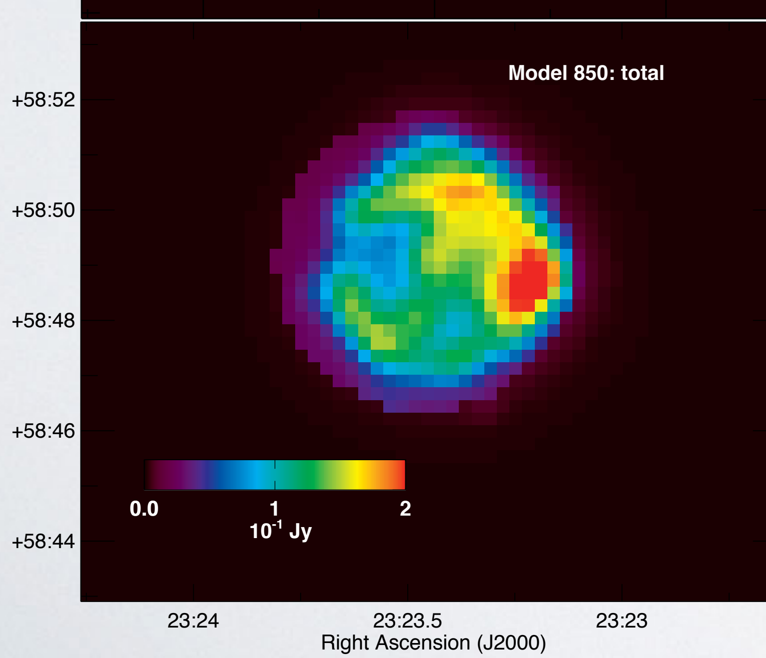
CAS A: COMPONENTS



CAS A: SCUBA850

SCUBA850: Model versus observations





CAS A: RESOLVED FITS

SN dust mass depends on

1.) ISM model ($G=0.3, 0.6, 1.0G_0$)

2.) dust composition

SED fitting results for ISM models with

	$G=0.3G_0$:		$G=0.6G_0$:		$G=1.0G_0$:		
Dust species	M_d(SN) [M⊙]	T_d(SN) [K]	M_d(SN) [M⊙]	T_d(SN) [K]	M_d(SN) [M⊙]	T_d(SN) [K]	Max M_d**
$Mg_{0.7}SiO_{2.7}$	64.7	20	29.3	21	10.7	14	1.21
$MgSiO_3$	1.9	27	**0.7**	**30**	0.3	34	1.37
$Mg_{2.4}SiO_{4.4}$	0.1	35	**0.4**	**32**	0.1	36	0.93
Amorphous carbon	0.7	28	0.5	28	0.7	30	0.29

**Max M_d : based on available material from nucleosynthesis models

CAS A: RESOLVED FITS

- Lower SN dust mass from resolved SED fitting (compared to global fit)
- We rely on resolved SED fitting results because the resolved fitting better captures the variation in spectrum from one location to another

Global SED fitting results:

Dust species	M_d [$M_\odot$]	T_d [K]	Max M_d**
$Mg_{0.7}SiO_{2.7}$	13.5	33	1.21
$MgSiO_3$	**3.5**	**28**	1.37
$Mg_{2.4}SiO_{4.4}$	**2.2**	**29**	0.93
Amorphous carbon	0.8	29	0.29

Spatially resolved SED fitting results:

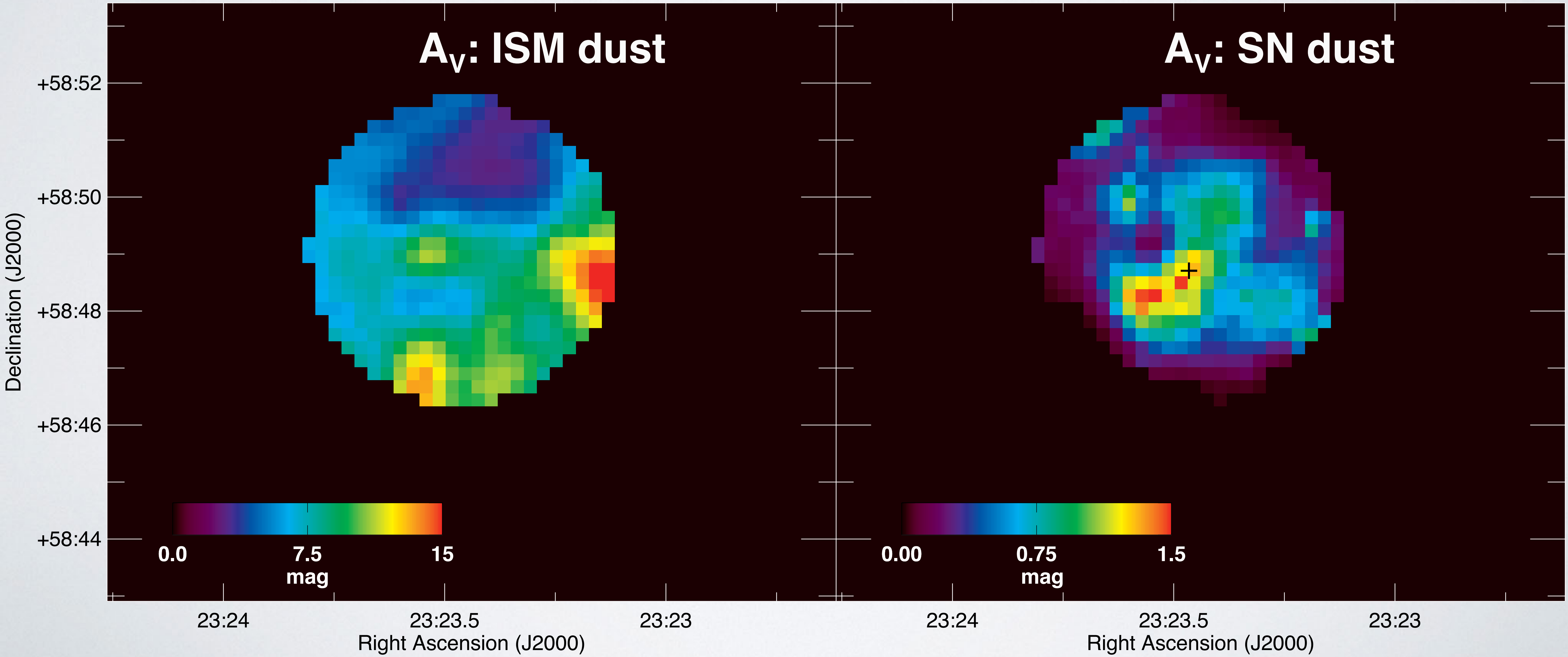
Dust species	M_d [$M_\odot$]	T_d [K]	Max M_d**
$Mg_{0.7}SiO_{2.7}$	29.3	21	1.21
$MgSiO_3$	**0.7**	**30**	1.37
$Mg_{2.4}SiO_{4.4}$	**0.4**	**32**	0.93
Amorphous carbon	0.5	28	0.29

*M_d (min): SED models without SN contribution at 500 μm

INTERSTELLAR EXTINCTION MAP

Based on SED dust mass + assuming a foreground screen geometry, we can derive the visual extinction A_V from ISM and SN dust.

High A_V values towards the centre prevent us from observing a possible binary companion.



CAS A: MAIN RESULTS

1. Best SED fits using **silicate-type grains** ($MgSiO_3$, $Mg_{2.4}SiO_{4.4}$)
   → ruling out $CaAl_{12}O_{19}$ and $Mg_{0.7}SiO_{2.7}$ as dominant dust species

2. Cold SN dust is distributed ~smoothly within reverse shock region
   → **dust destruction by reverse shock**
   → dust ejection along jets (?)

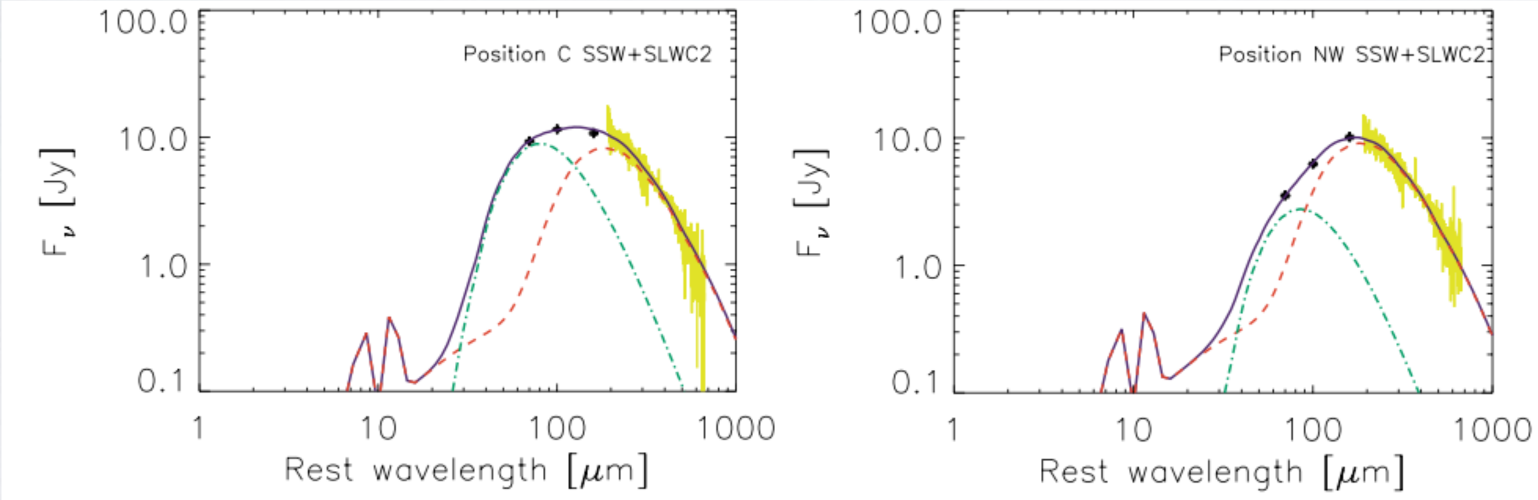
3. Best-fit model predicts **0.4-0.7 $M_\odot$ of (~30 K) silicate dust**
   → sufficient to explain dust in early Universe*

Dust species	M_d [$M_\odot$]	T_d [K]	Max M_d**
$MgSiO_3$	**0.7**	**30**	1.37
$Mg_{2.4}SiO_{4.4}$	**0.4**	**32**	0.93
Amorphous carbon	0.5	28	0.29

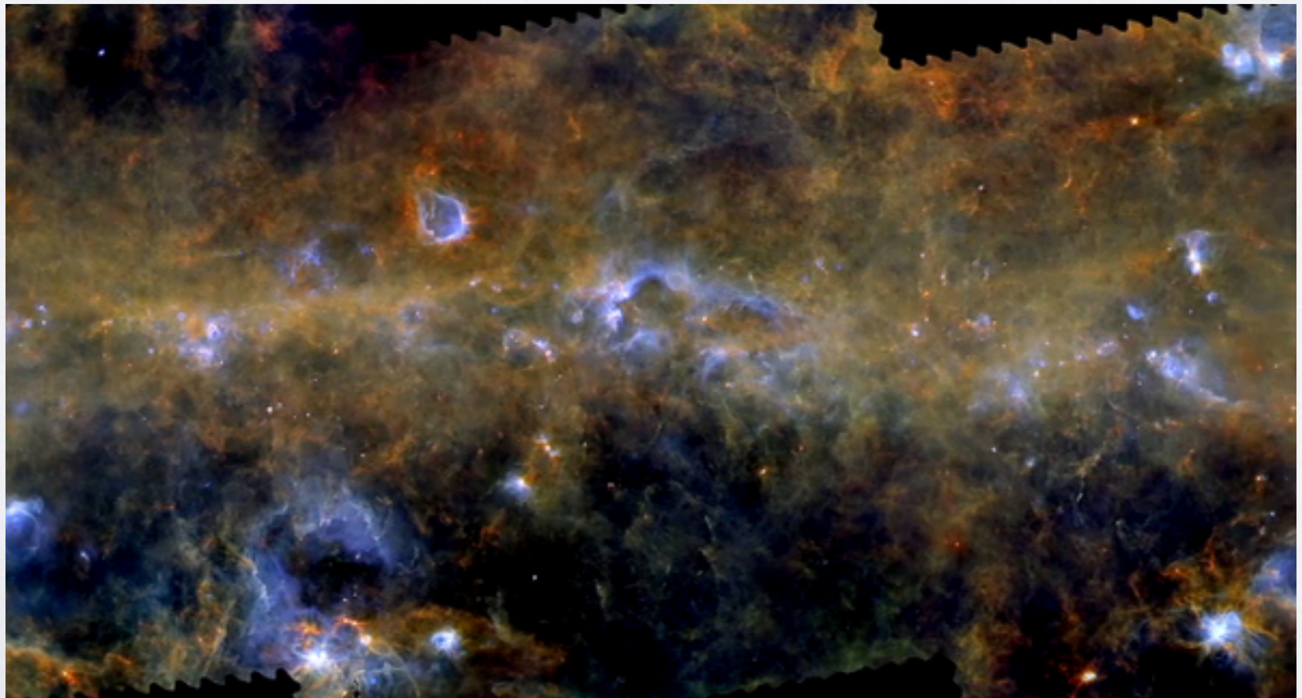
*if produced by other SNR + not destroyed by reverse shock

FUTURE OUTLOOK

1. Analyse SPIRE FTS spectra (330-650 μm) of Cas A to get better constraint on dust emissivity



2. Similar study of other Galactic SNR based on HiGal data



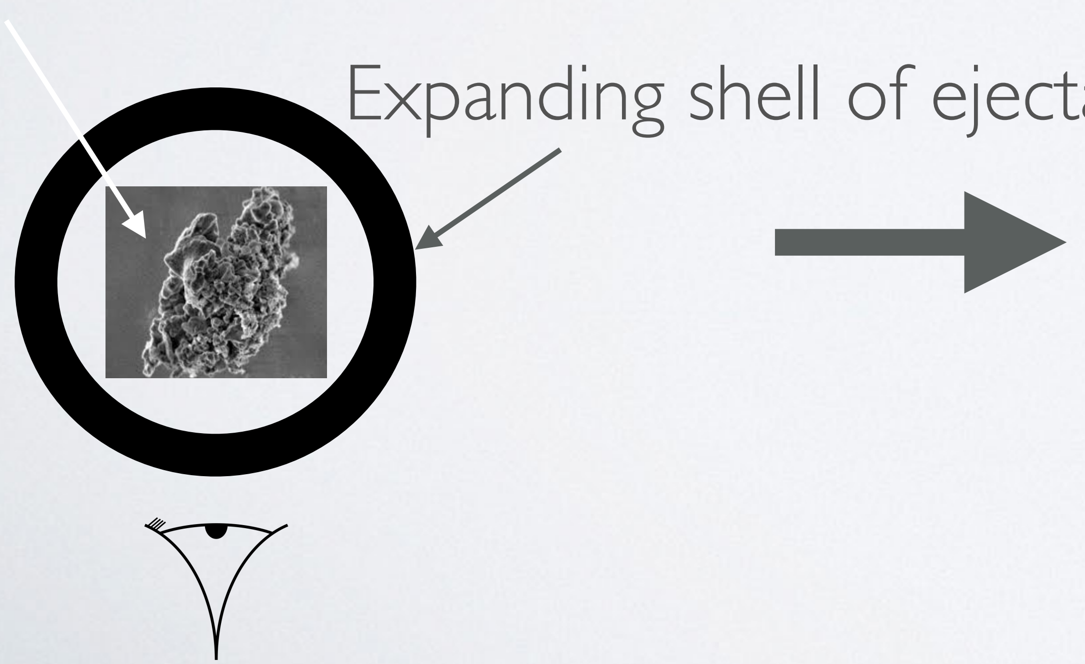
Molinari+ 2016

INCREASING THE SAMPLE SIZE

Infrared wavelength domain = poor resolution
ALMA not sensitive beyond SN1987A
—> how do we determine SN dust mass beyond the Local Group?

Alternative way of deriving the SN dust mass:
—> look at effect of dust on optical line profiles!
—> determine SN dust mass based on Hα, [OIII] line asymmetries

Dust formation in the unshocked ejecta



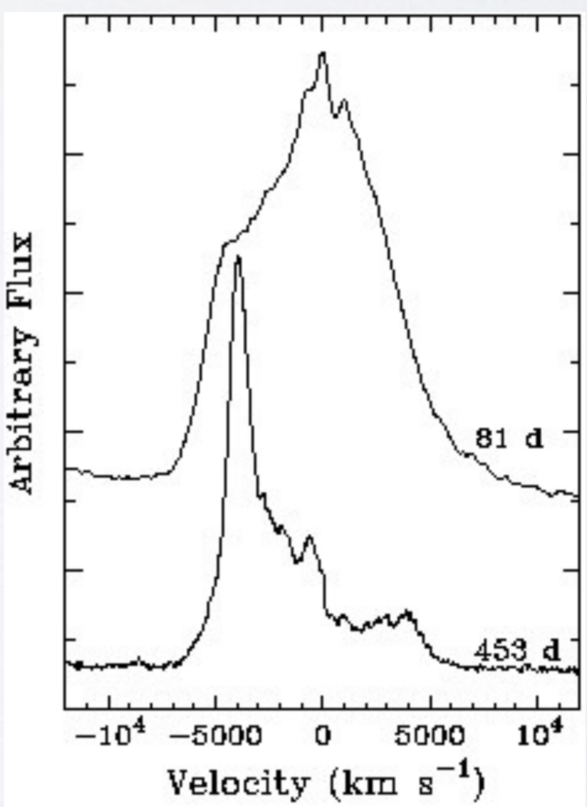


Fig. SN 1988S Hα profile evolution from Leonard et al. (2000)

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

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

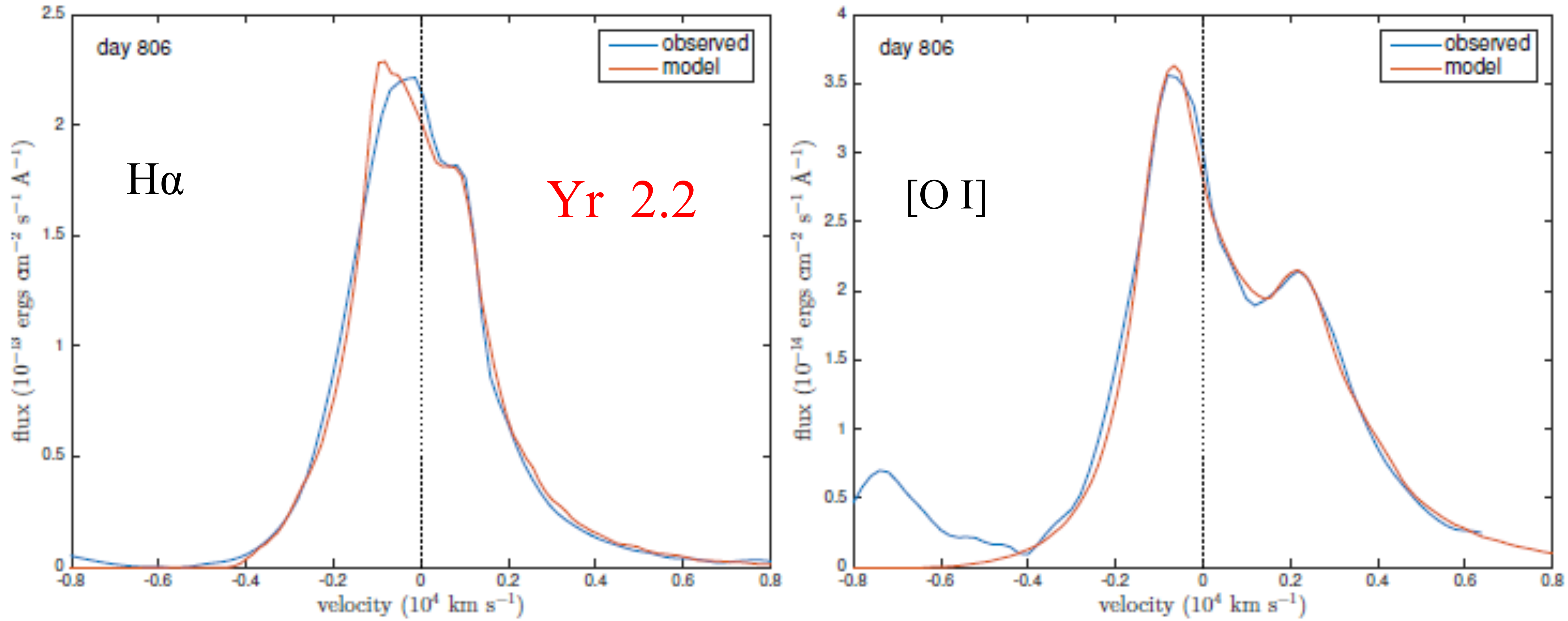


Figure 15. Best clumped fit to the day 806 Hα line and [O I] λ6300,6363 Å doublet as per parameters detailed in Table 3.

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

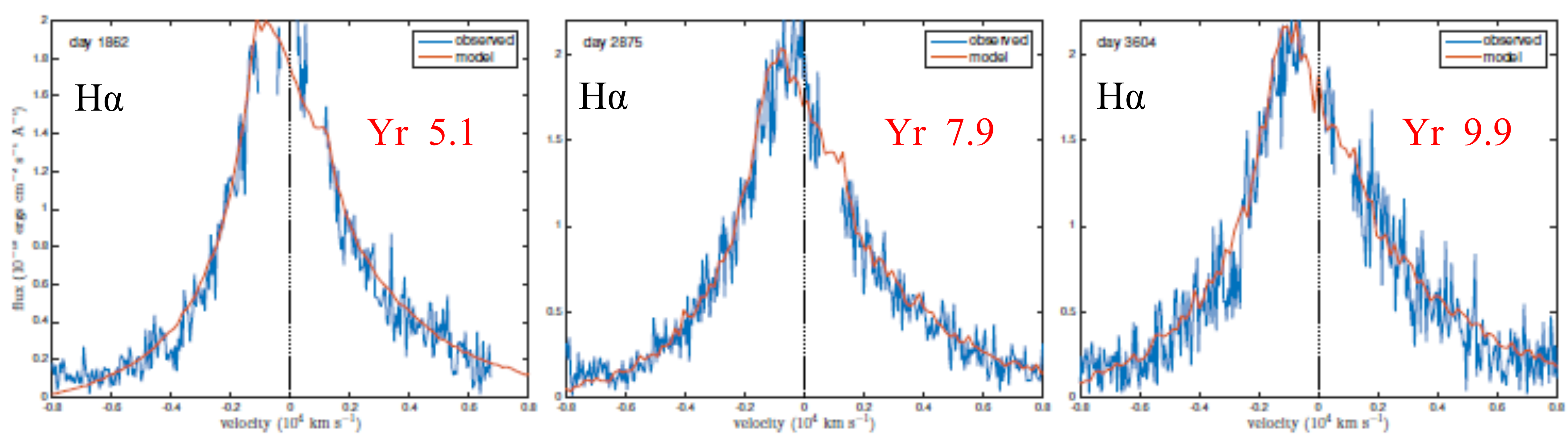


Figure 17. Best clumped fit to the Hα line at days 1862, 2875 and 3604 as per parameters detailed in Table 4 with $a = 3.5\mu$m.

Bevan & Barlow 2016

Bevan & Barlow (2016): 87A dust masses from Ha profile models

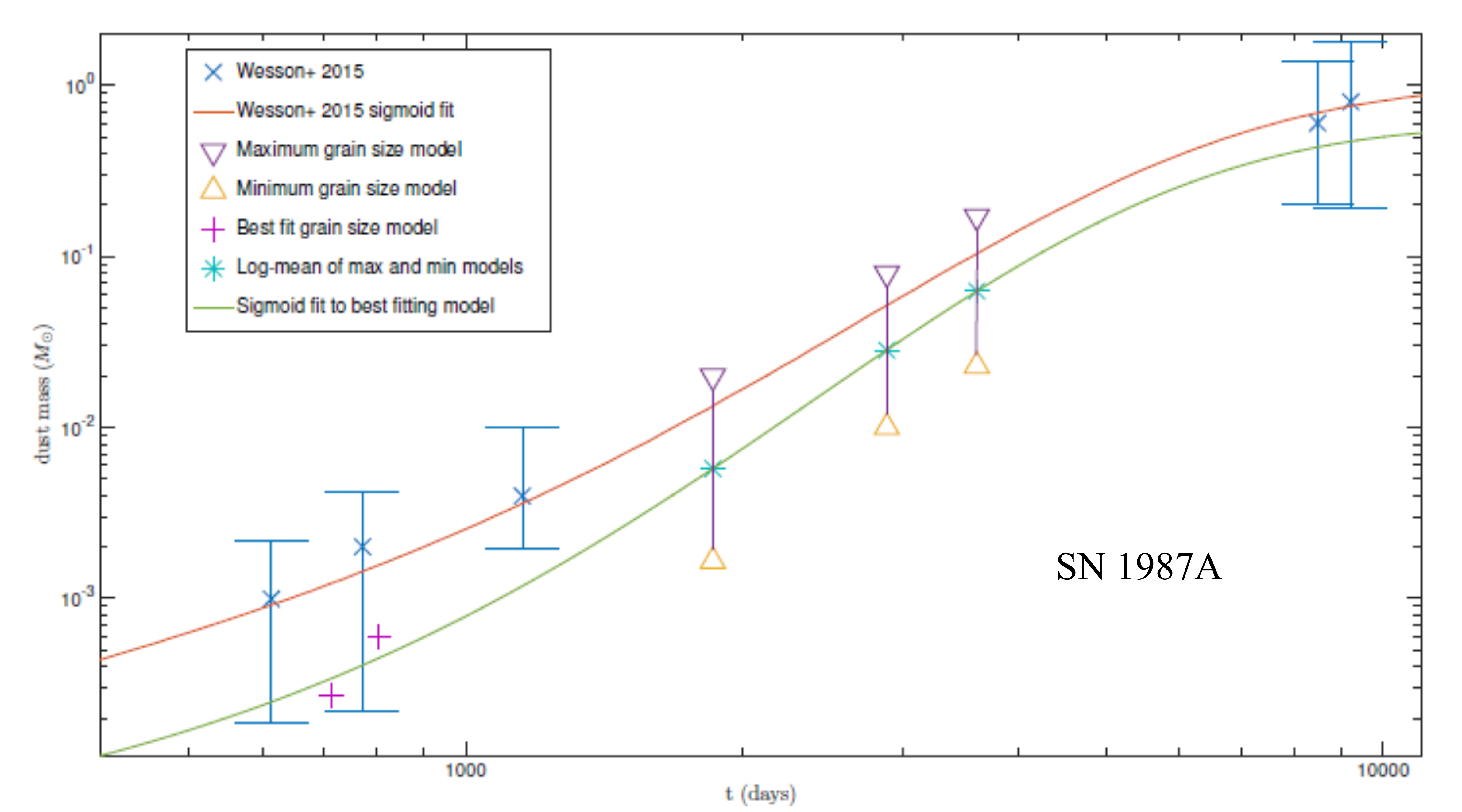
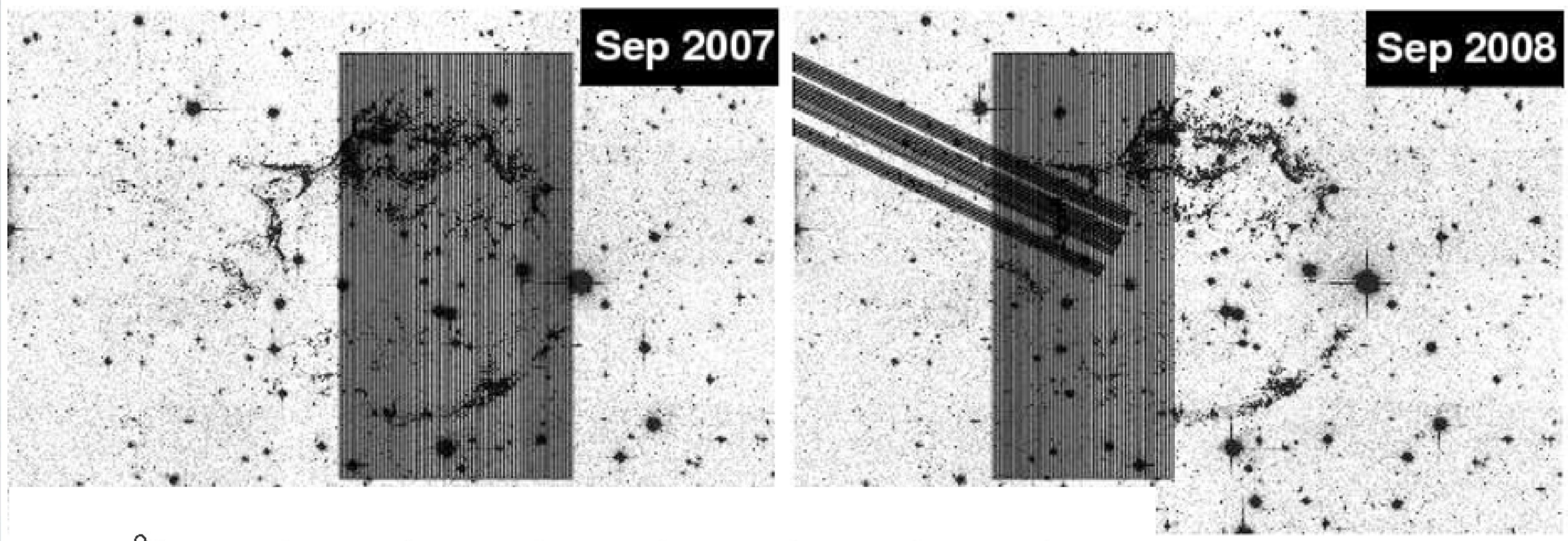
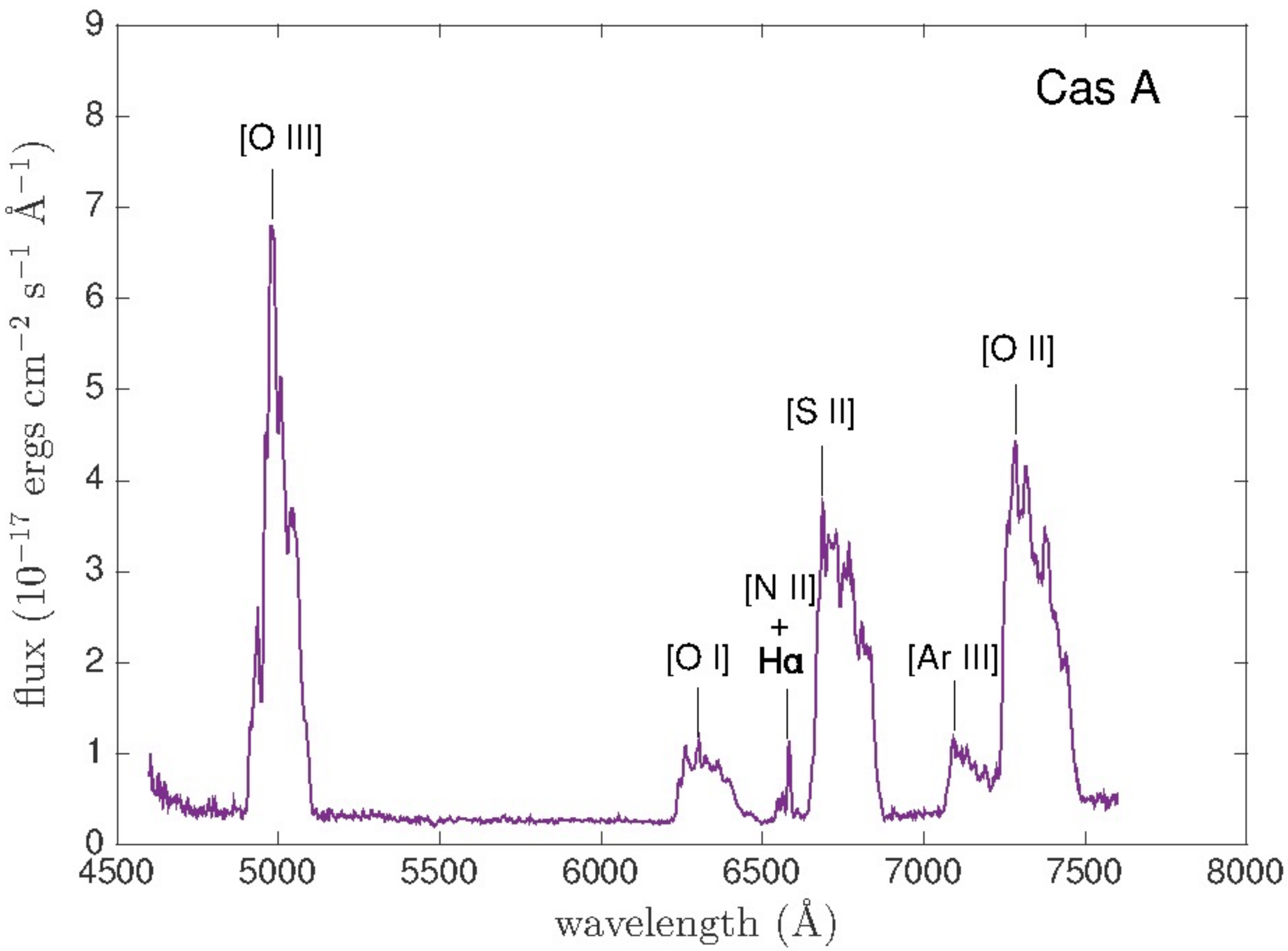


Table 4. Details of the parameters used for the best fitting clumped models with $a = 3.5\mu$m.

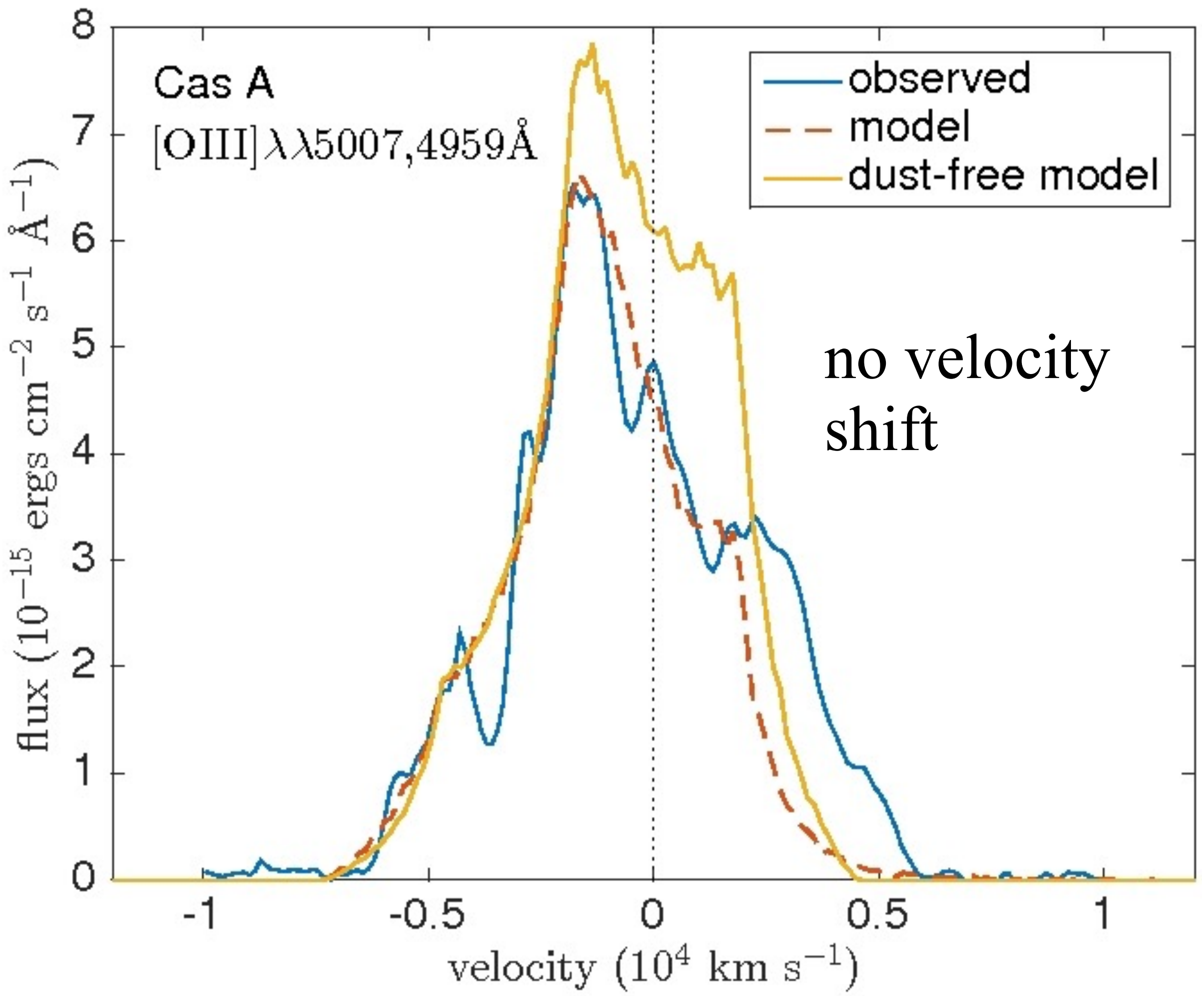
day	V_{max} (km s^{-1})	R_{in}/R_{out}	β	M_{dust} ($M_\odot$)	a (μm)	R_{out} (cm)	R_{in} (cm)	$\tau_{H\alpha}$	τ_V	Figure No.
1862	8500	0.14	1.9	2.00E-02	3.50	1.37E+17	1.91E+16	0.85	1.70	17
2875	9500	0.12	2	8.00E-02	3.50	2.36E+17	2.83E+16	1.15	2.30	17
3604	10250	0.12	2	1.70E-01	3.50	3.19E+17	3.83E+16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





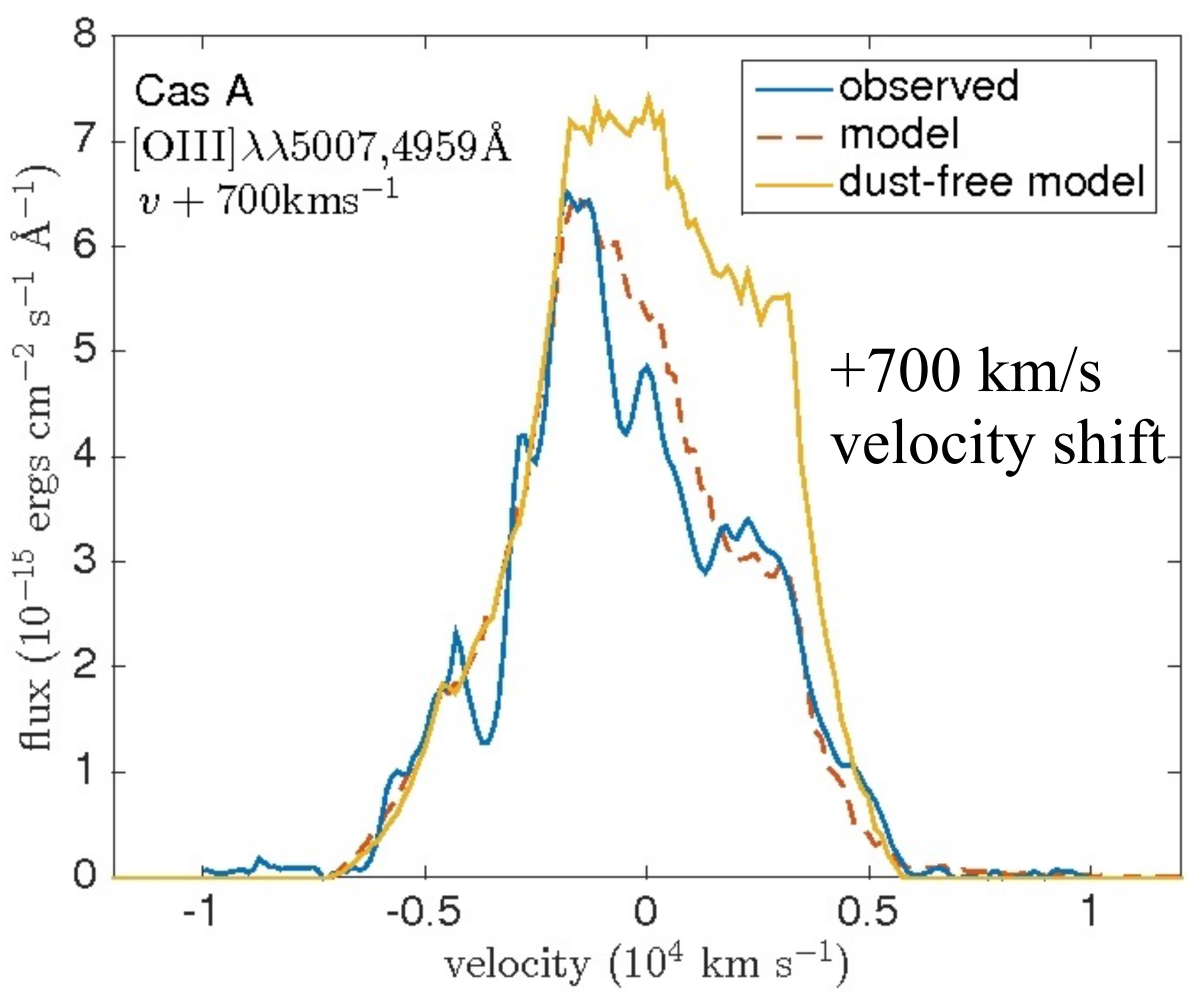
What would the spectrum of Cas A look like if it was at 1 Mpc and unresolved?

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



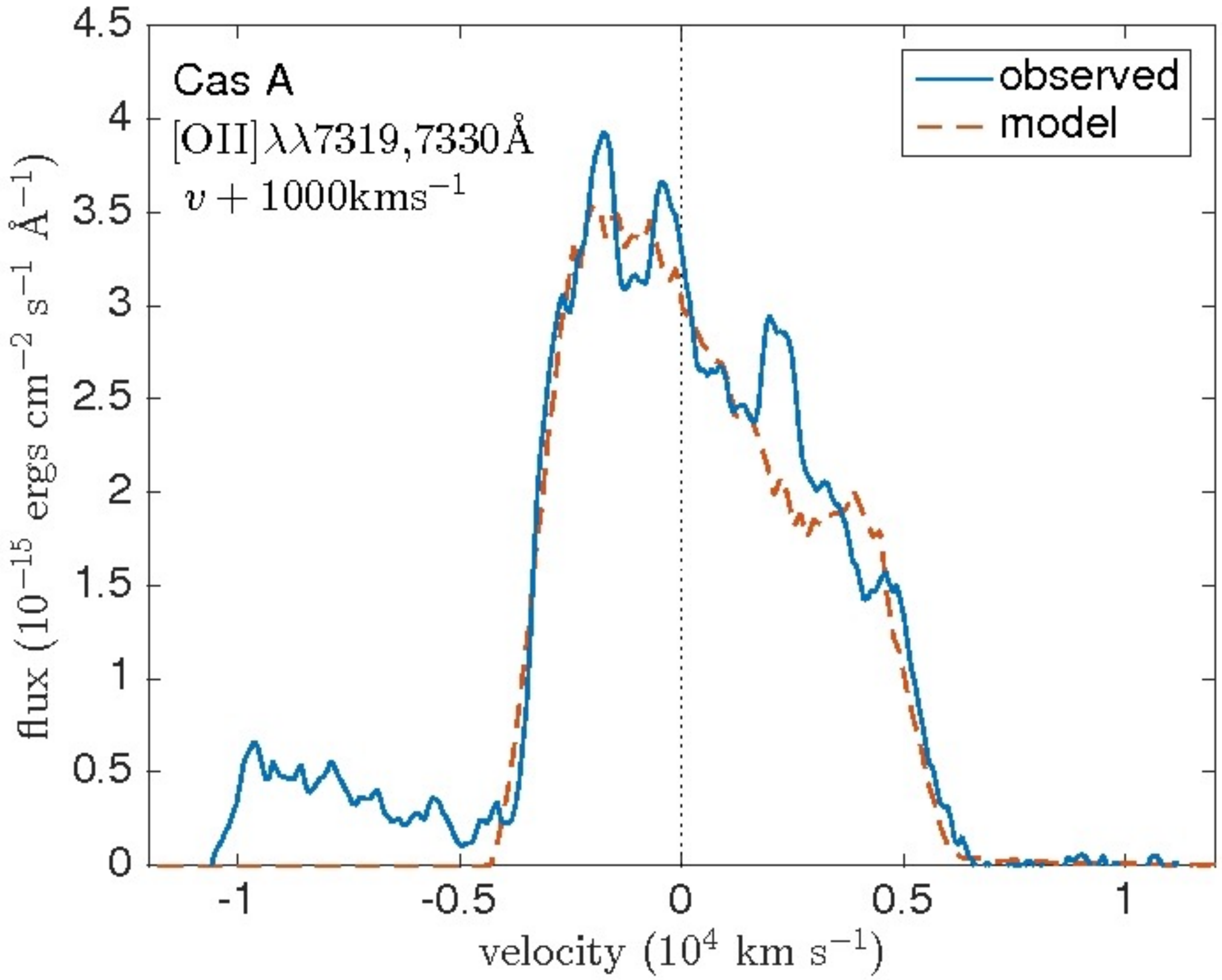
Smooth dust model
V_{max}=4500 km/s
V_{min}=1800 km/s

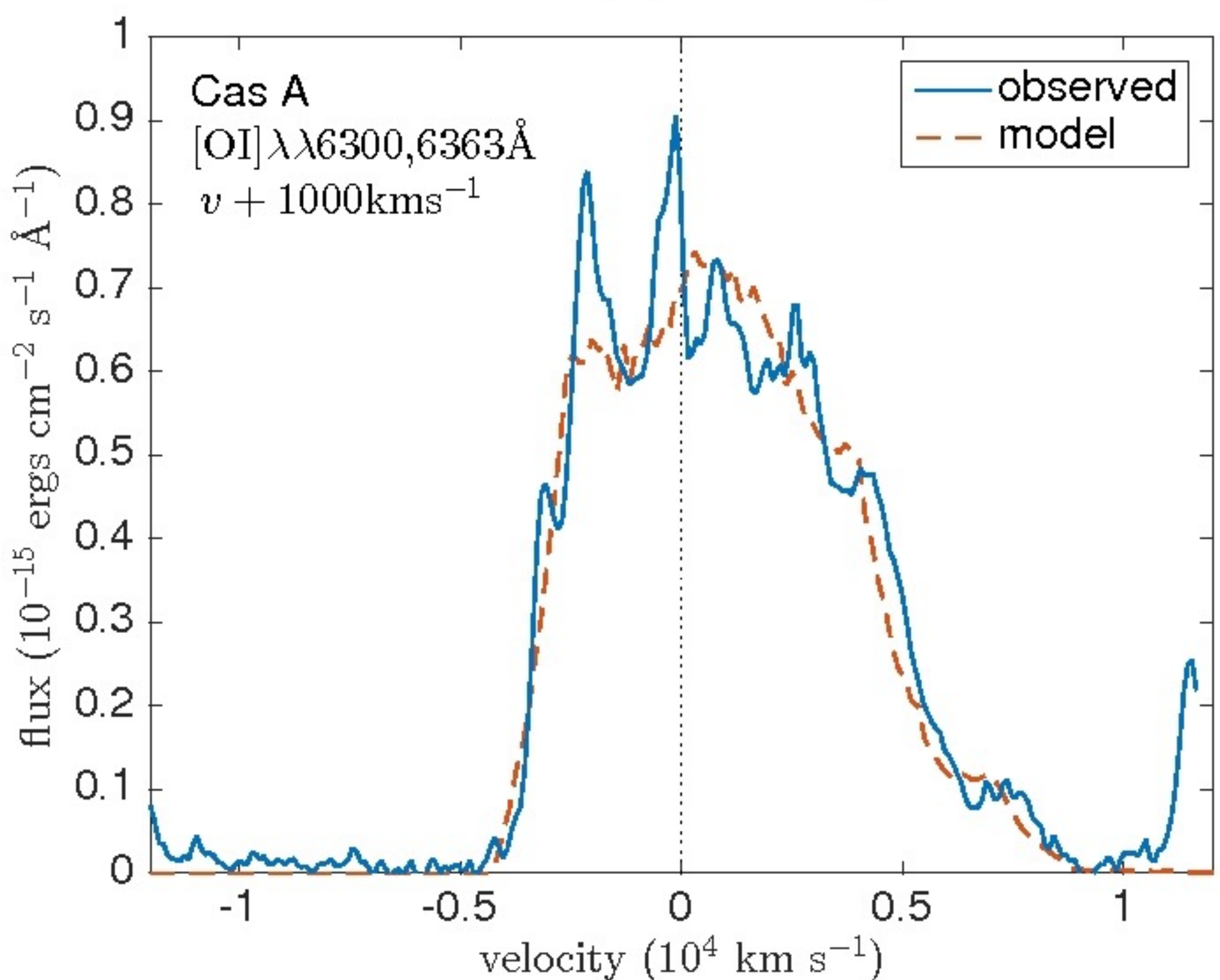
Dust mass = 0.9 $M_{\odot}$
(50% sil, 50% amC)



Smooth dust model
V_{max}=5000 km/s
V_{min}=2500 km/s;
with velocity shift of +700 km/s

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





Smooth dust model
V_{max}=5000 km/s
V_{min}=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.

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.

→ Stay tuned for first results!

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

8 *Antonia Bevan and M. J. Barlow*
(2016)