# THE DUST MASS IN CAS A FROM SPATIALLY RESOLVED HERSCHEL PHOTOMETRY

Ilse De Looze[1], Mike Barlow[1], Jeonghee Rho[2], Mikako Matsuura[3], et al.

[1]University College London
[2]SETI Institute, CA
[3]Cardiff University

Supernova remnants, Chania, Crete, June 10th 2016

# ORIGIN OF DUST

- Historically, steady mass loss from **evolved AGB stars**

  = primary source for ISM dust

**<u>Problem:</u>** Detection of large quantities of **dust in high-z galaxies**

- **<u>Supernovae (SN)</u>** (Type II) proposed as dust sources. →

- <u>Alternative explanation:</u> "grain regrowth" in the ISM

SN need to produce **0.1-1 $M_\odot$** of dust to account for dust mass @ high redshift

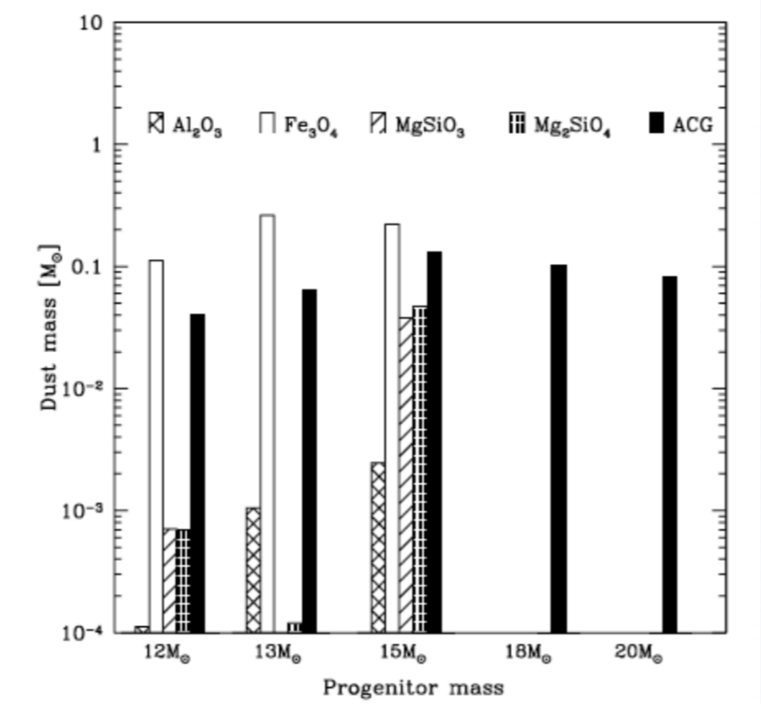
# ORIGIN OF DUST

- <u>Dust production rate of SN = very uncertain</u>

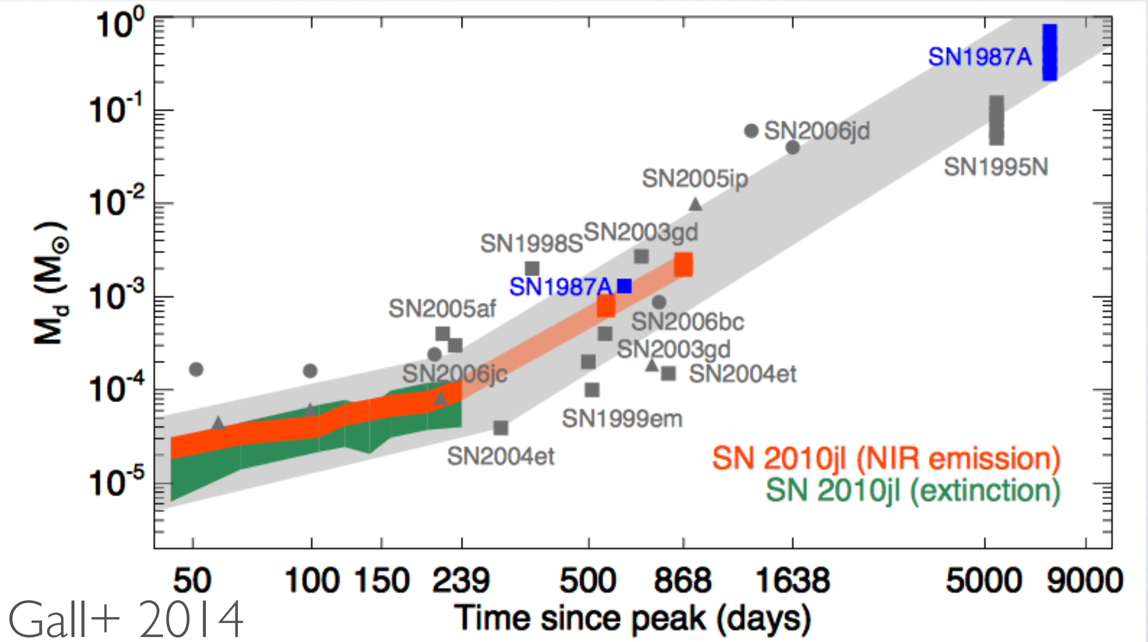
Models ⟷ observations

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)

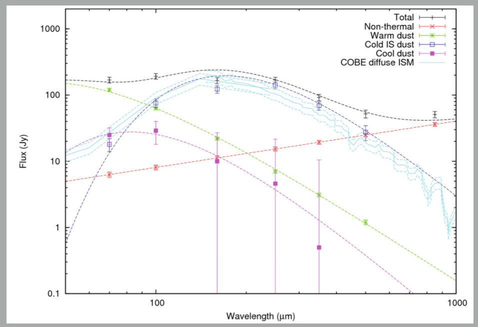



Gall+ 2014

# ORIGIN OF DUST

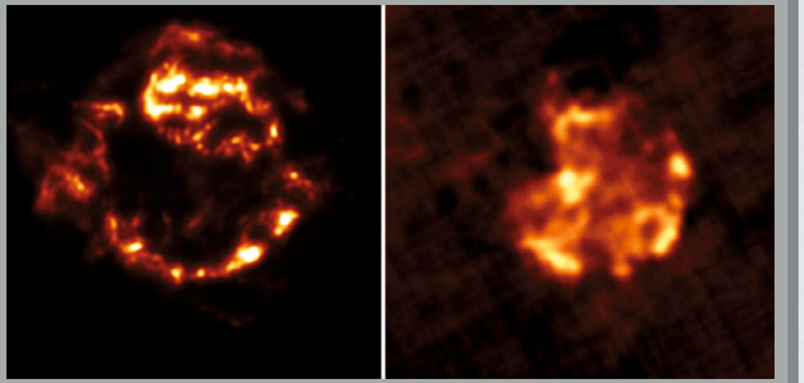
- Herschel + ALMA observations

## Cas A

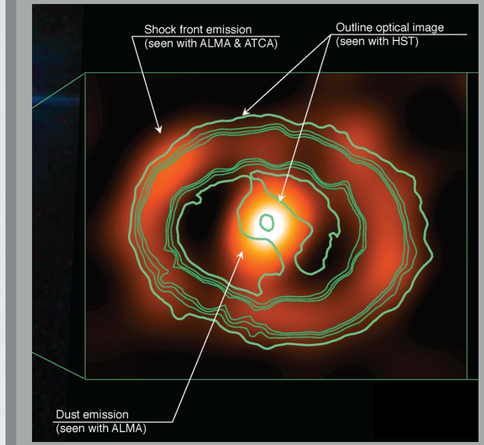



Rho+ 2008, Barlow+ 2010, Arendt+ 2014

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

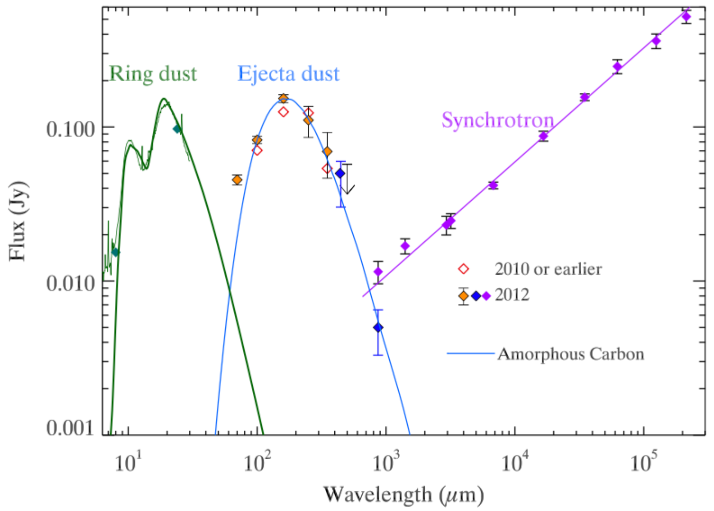


## SN 1987A

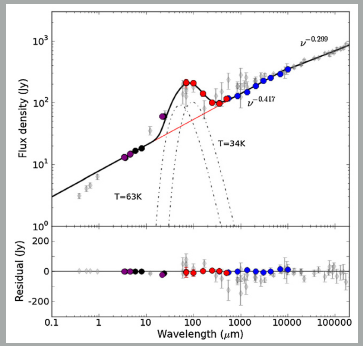



Matsuura+ 2011, Indebetouw+ 2014, Matsuura+ 2015

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

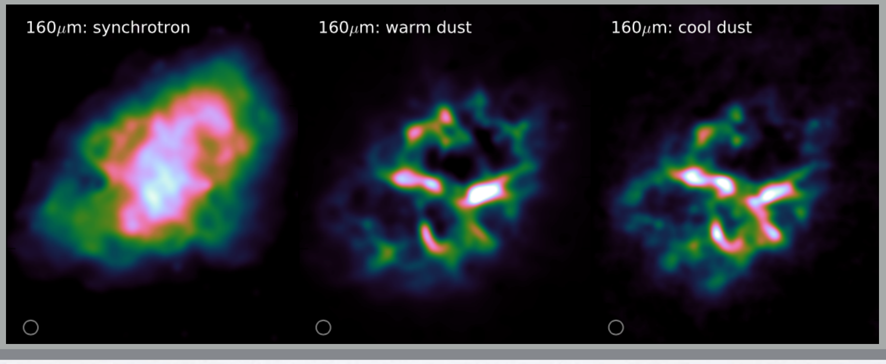



## Crab Nebula



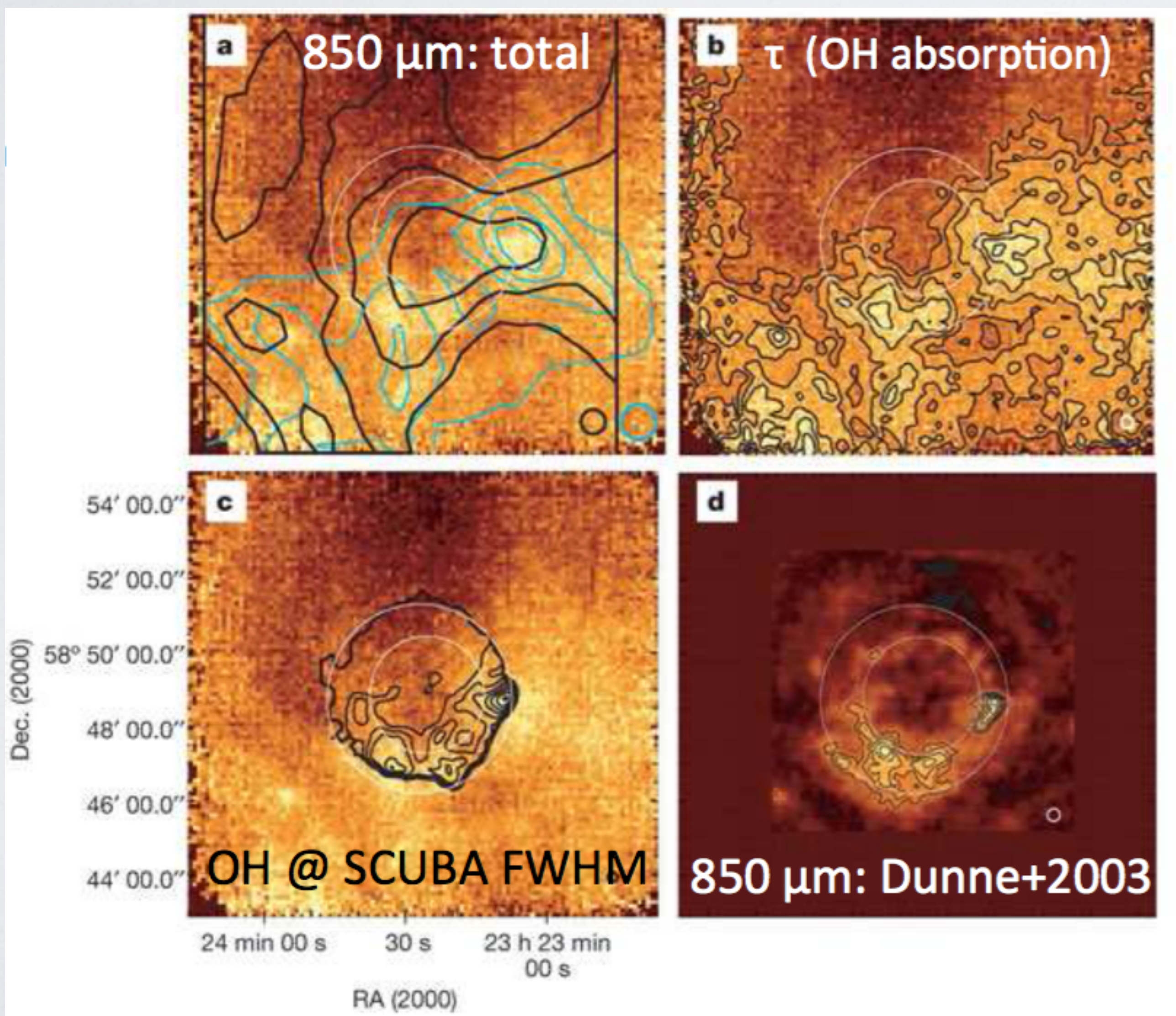

**0.24M$_\odot$ of 28K dust**

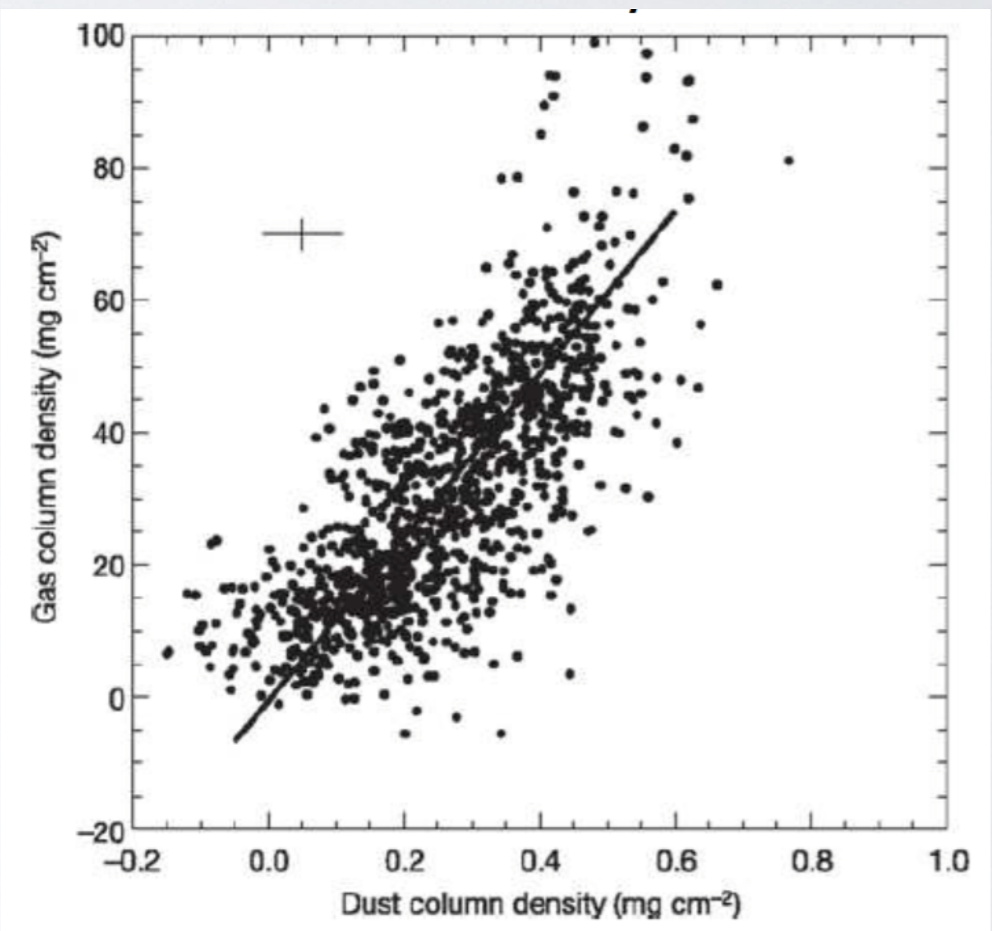
Gomez+ 2012, Owen & Barlow 2015



# CAS A IN THE LITERATURE

- SCUBA 850 µm: **2-4 $M_\odot$** of dust @ 18 K !!! (Dunne et al. 2003)



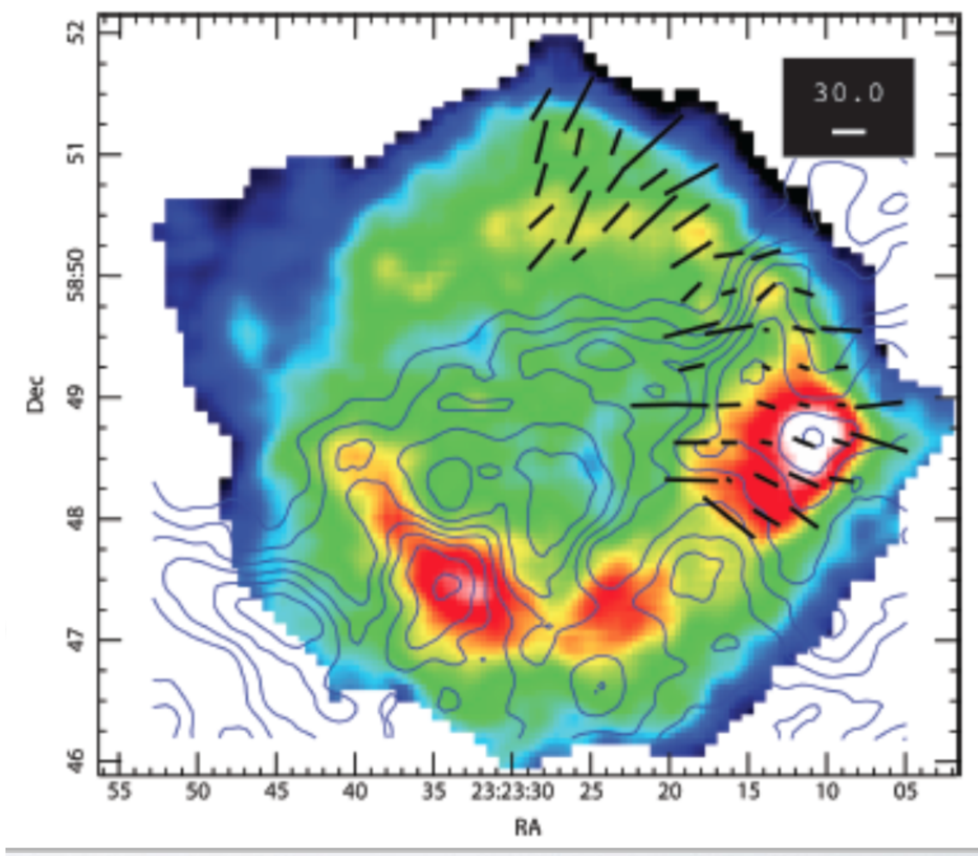




- 850 µm emission due to foreground dust (Krause+2004)

# CAS A IN THE LITERATURE

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

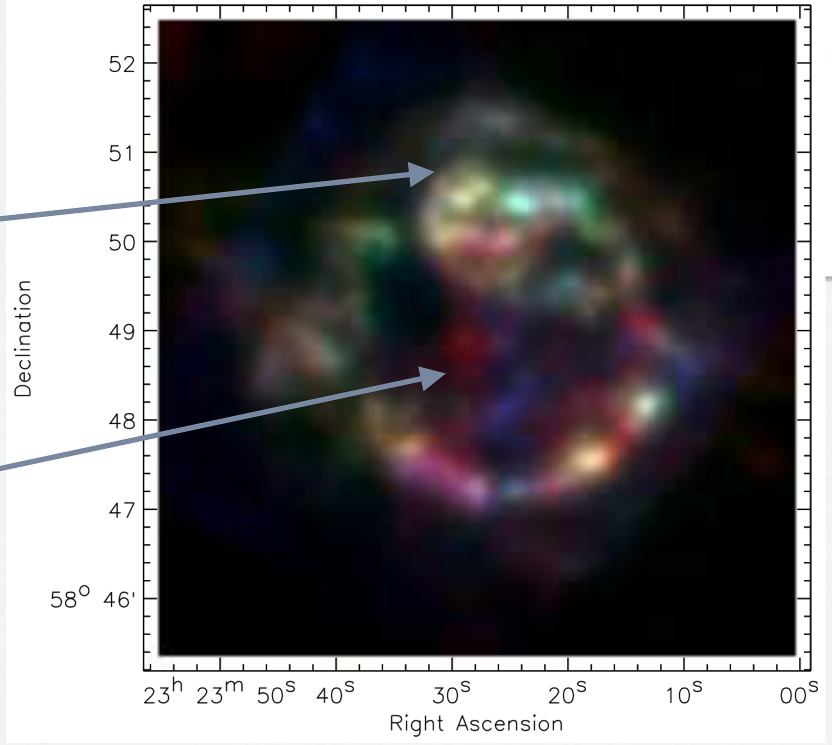
- Spitzer 24/70/160 **μ**m photometry+
  IRS spectra (Rho+ 2008, Arendt+ 2014)




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

**<0.1 M$_\odot$** of dust

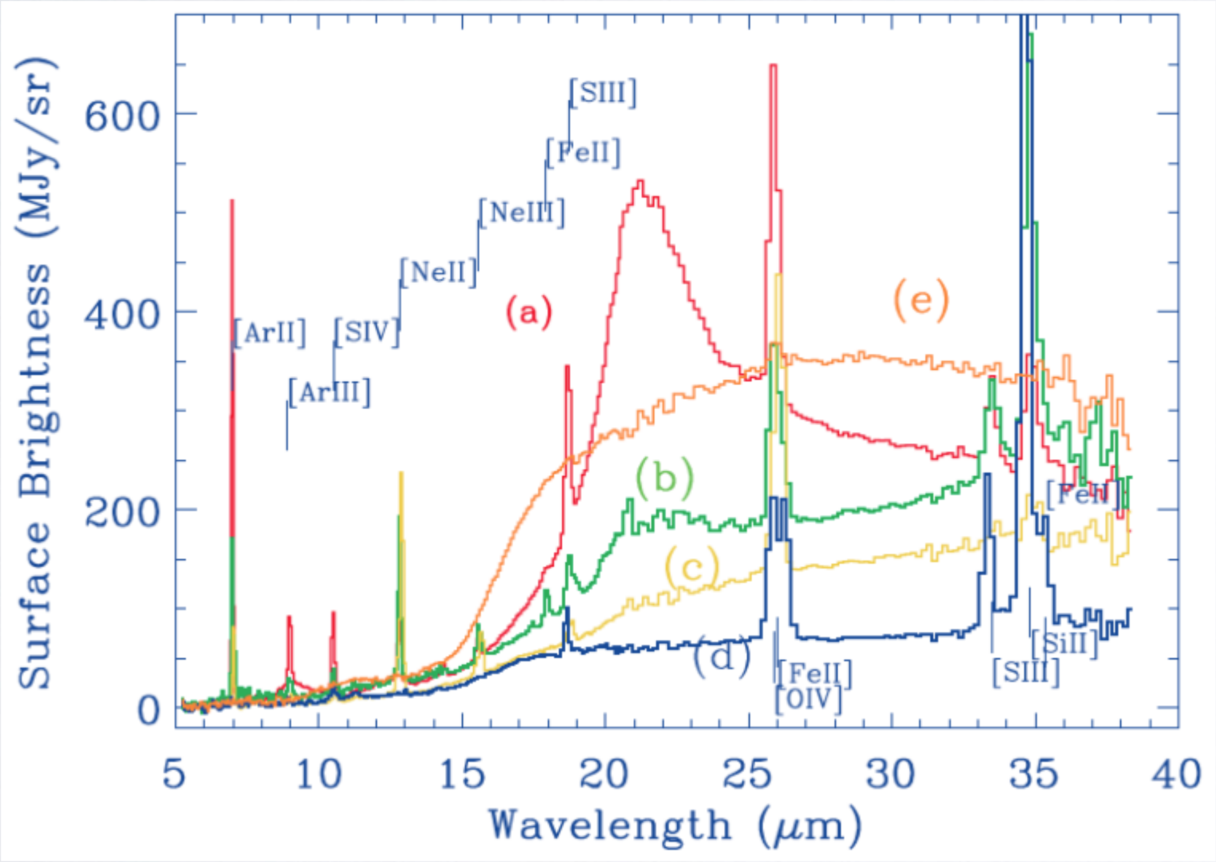
(Sibthorpe+ 2010, Barlow+ 2010, Arendt+ 2014 )

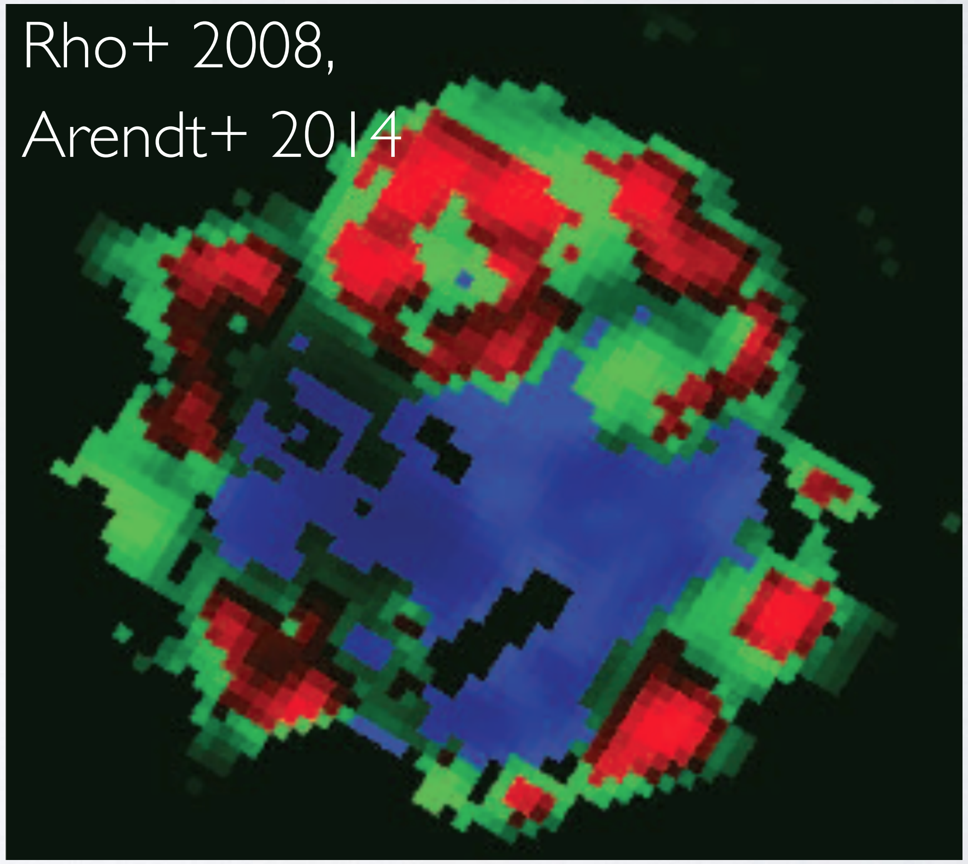


# CAS A IN THE LITERATURE

- Spitzer IRS spectra

→ show huge variety in grain composition

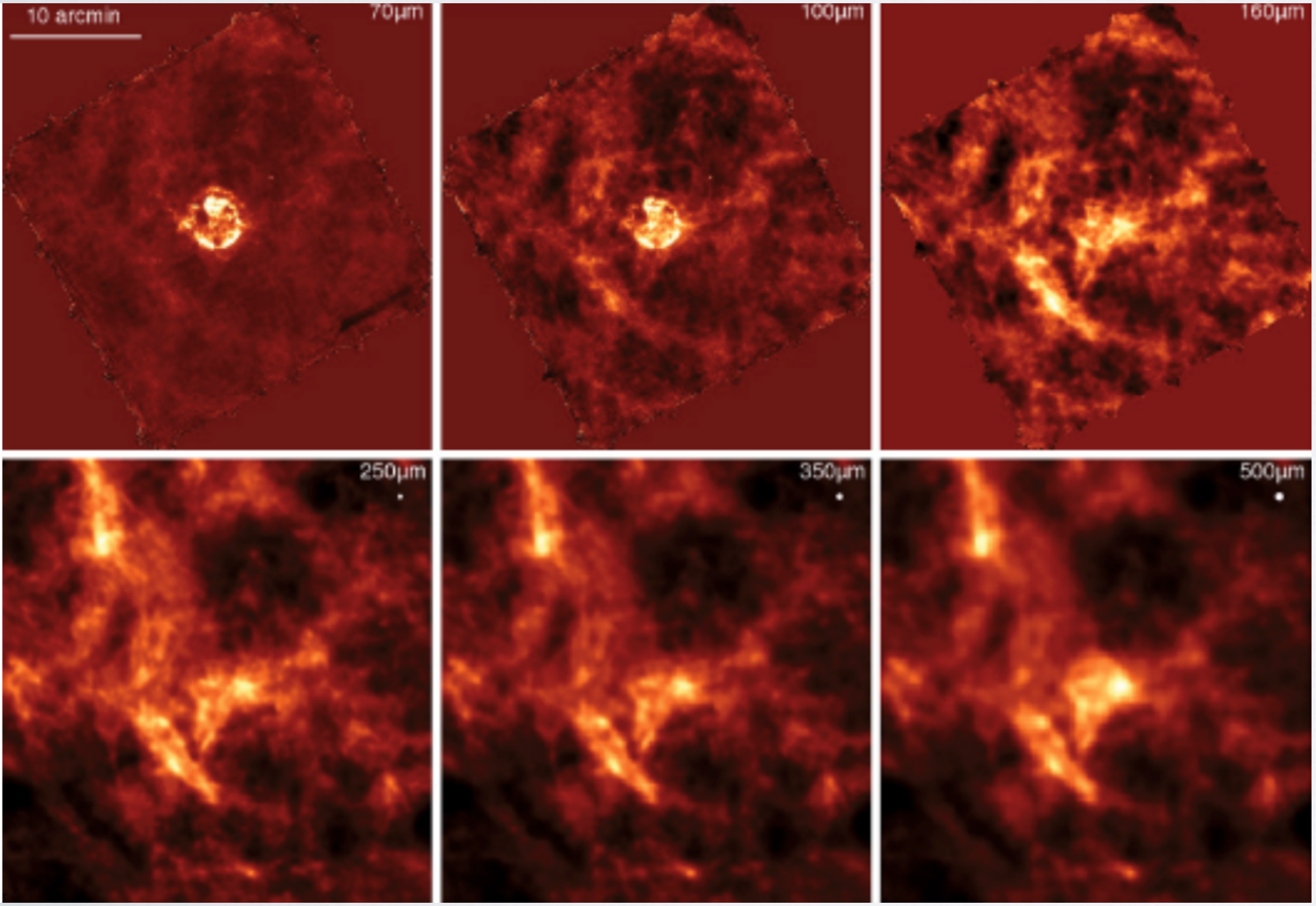


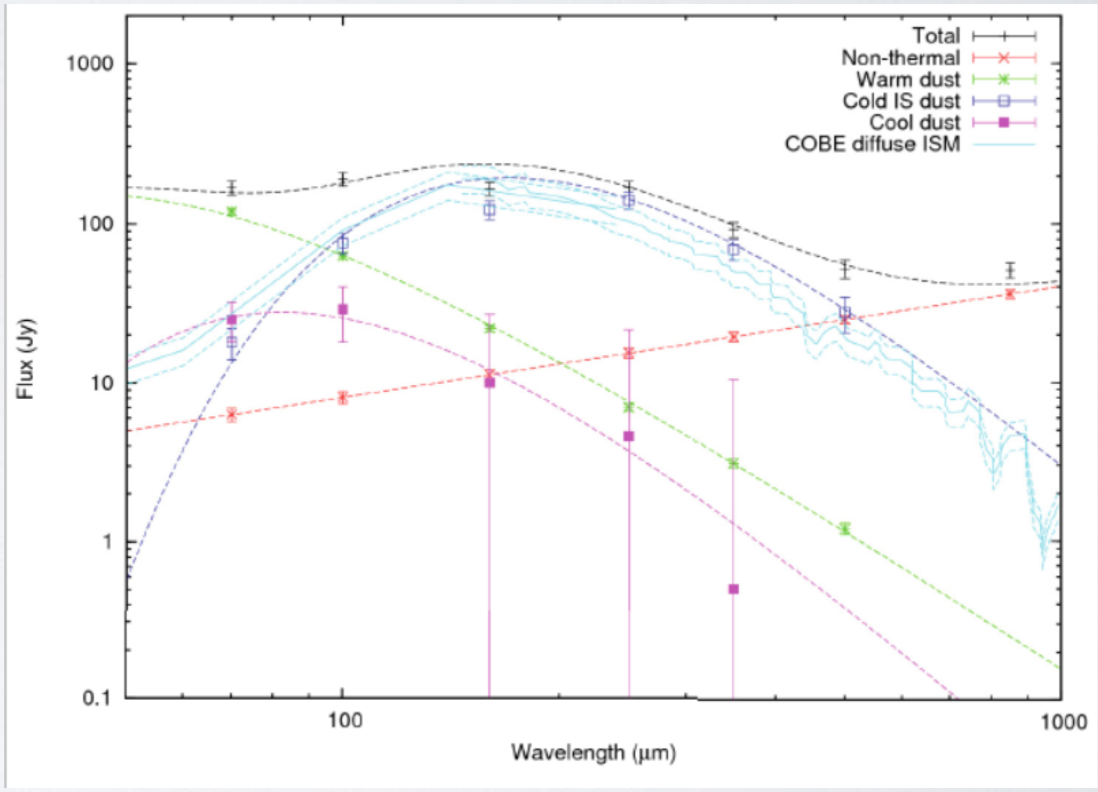

- Mostly silicate-type grains ($MgSiO_3$, $Mg_{2.4}SiO_{4.4}$), but also $Al_2O_3$, amorphous carbon, $CaAl_{12}O_{19}$

# 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)

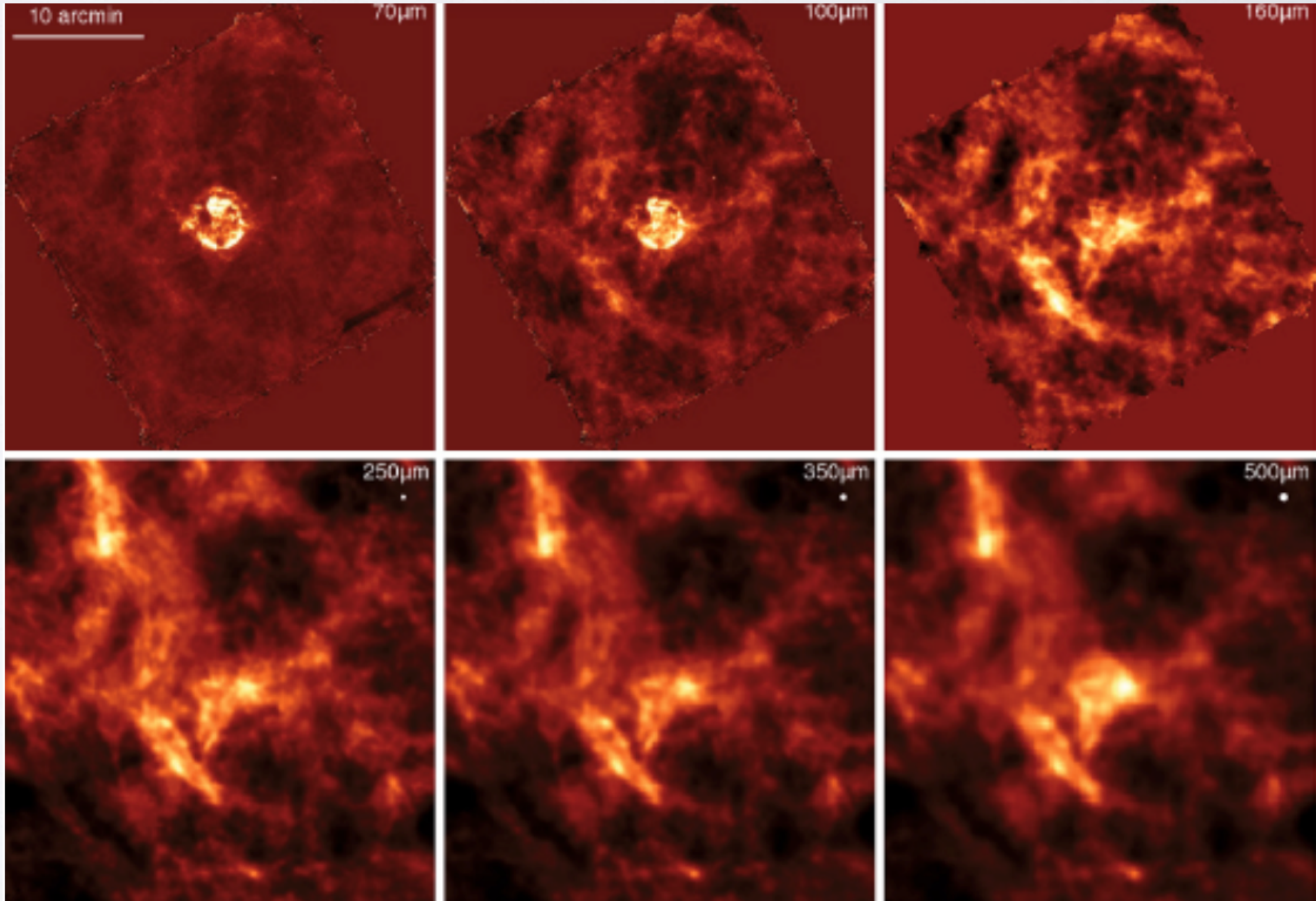


# CAS A IN THE LITERATURE

**Large disagreements** about dust mass formed in Cas A!

**Why?**

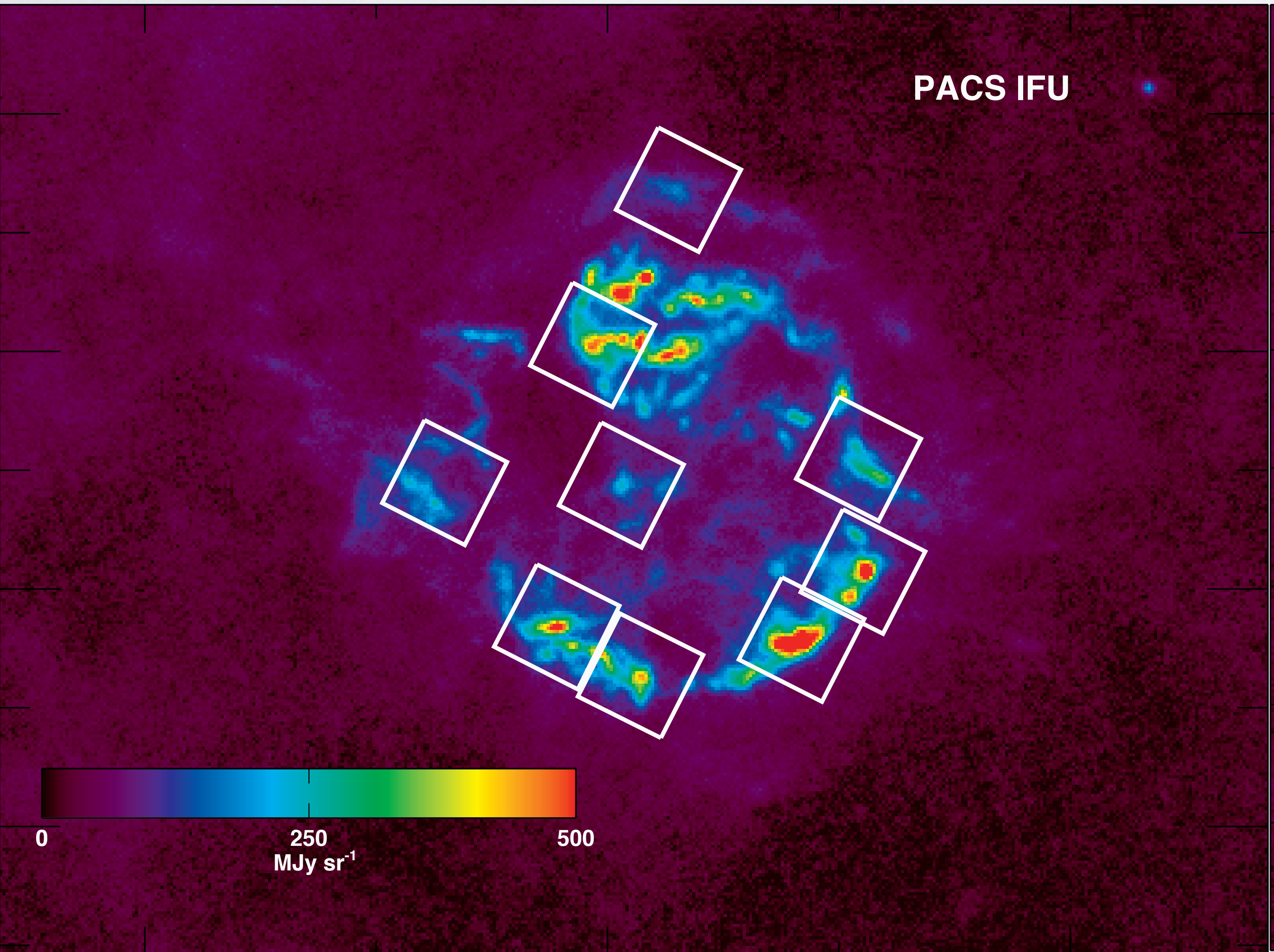
+ Colder dust emits at longer wavelengths: *the colder the dust, the greater the required dust mass*

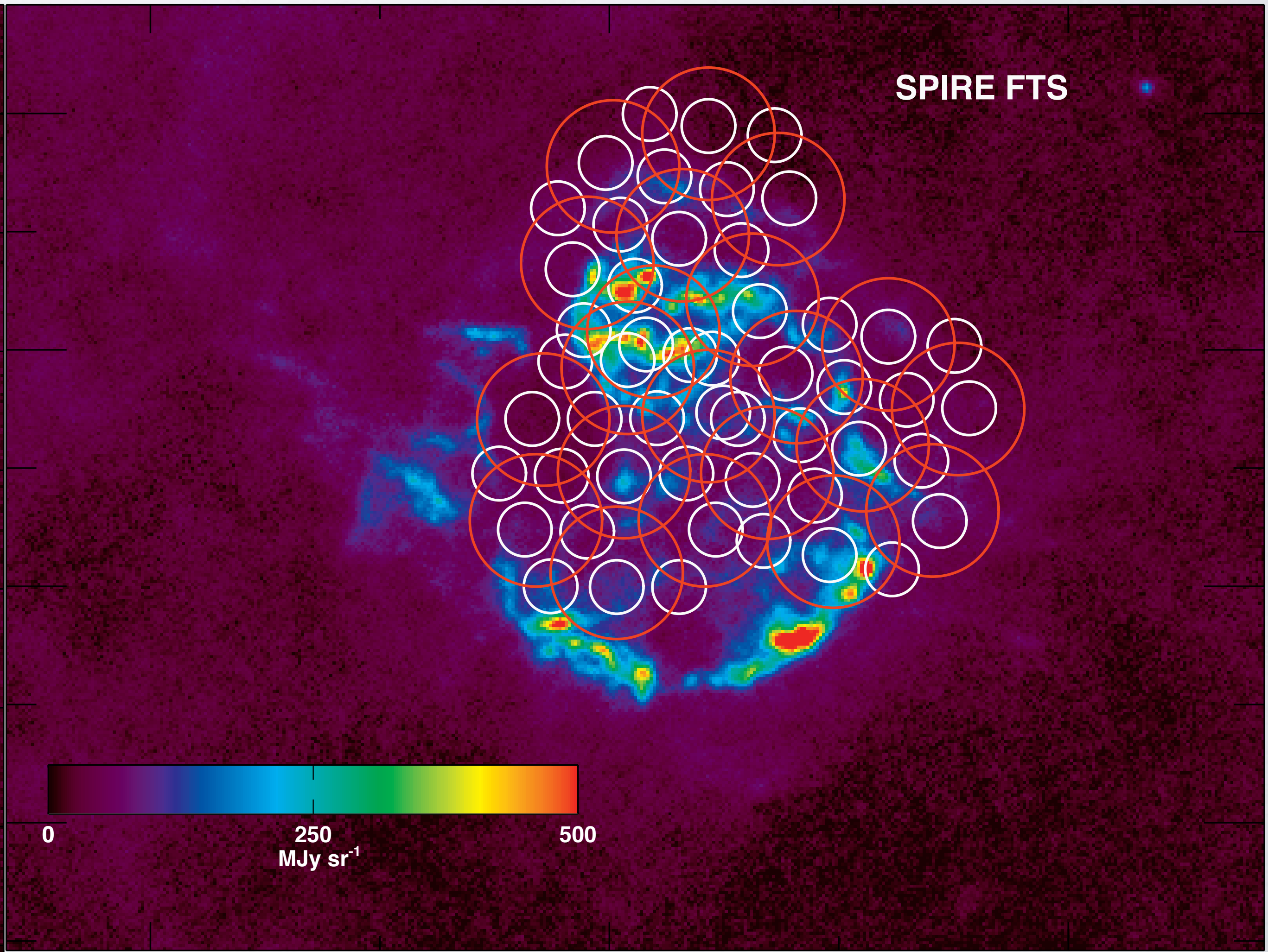



+ Difficult to separate:
  - SN dust
  - synchrotron radiation
  - ISM dust
  - line emission

# OUR NEW APPROACH

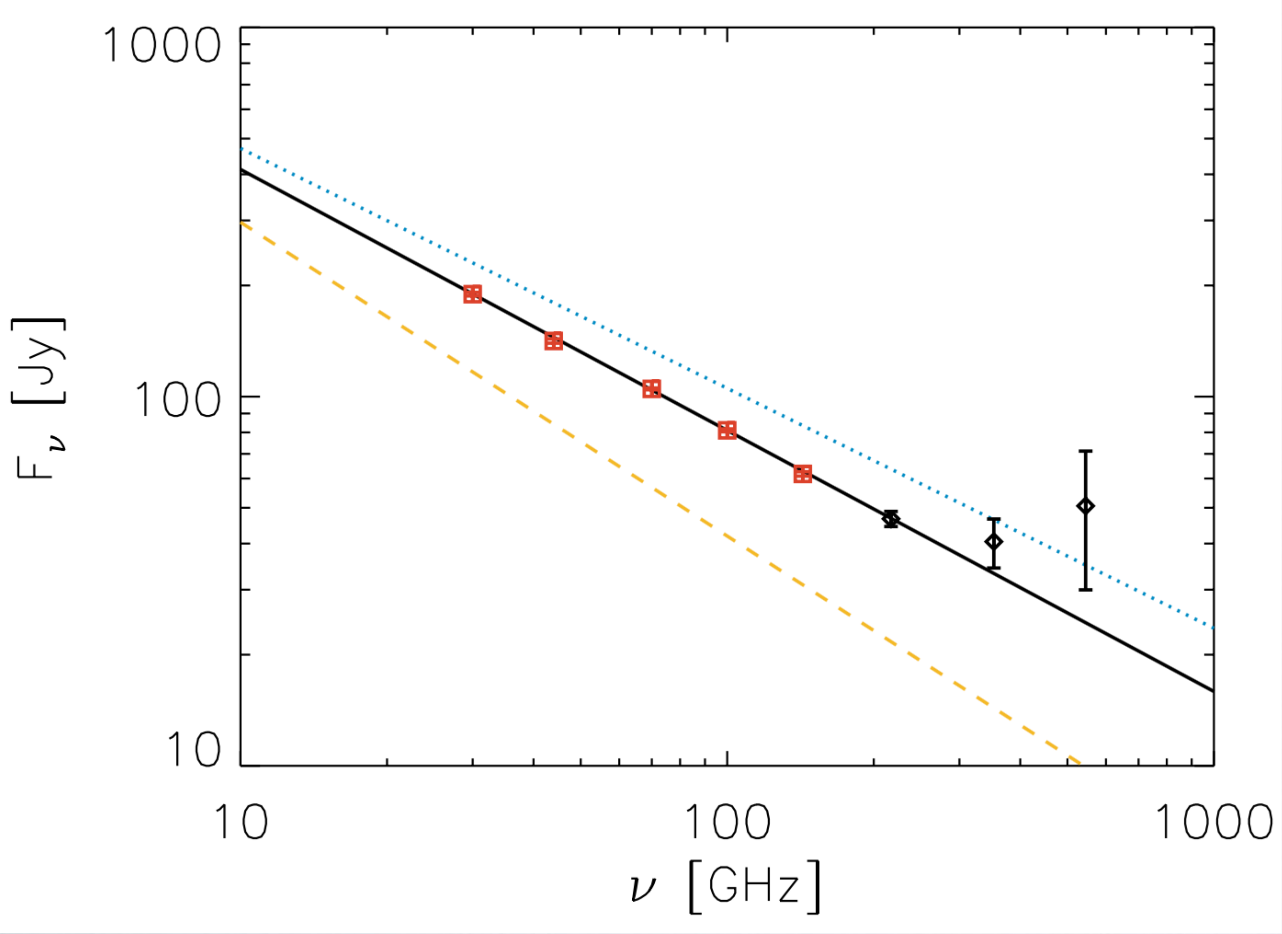
- Spatially resolved component separation using:
  - IRAC 8 μm + WISE 12 μm + MIPS 24 μm
  - Herschel PACS 70/100/160 μm+SPIRE 250/350/500 μm images
  - PACS IFU spectra + SPIRE FTS spectra + Planck photometry

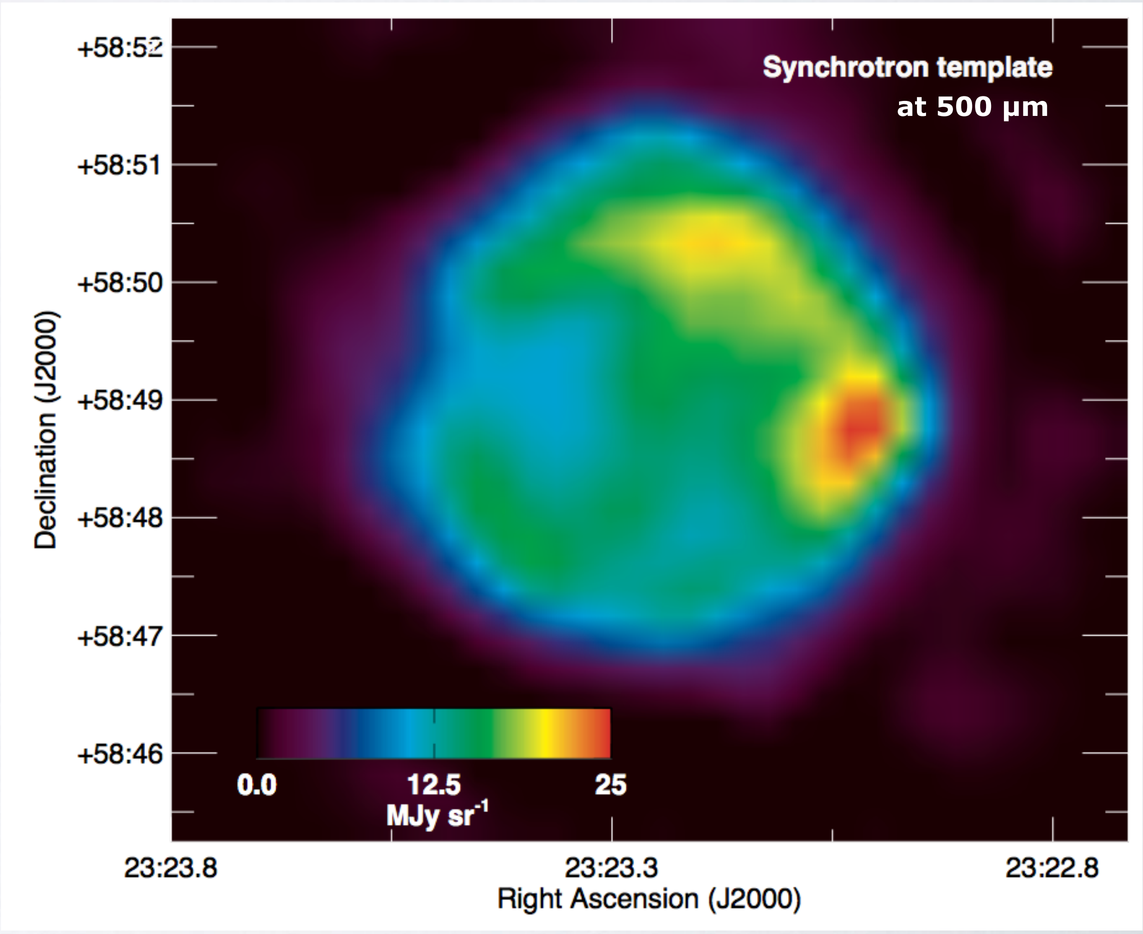


# CAS A: SYNCHROTRON RADIATION

- Spectral index (α=-0.707) + normalisation factor determined from recent Planck data
- Extrapolation of 3.7 mm emission to IR/submm



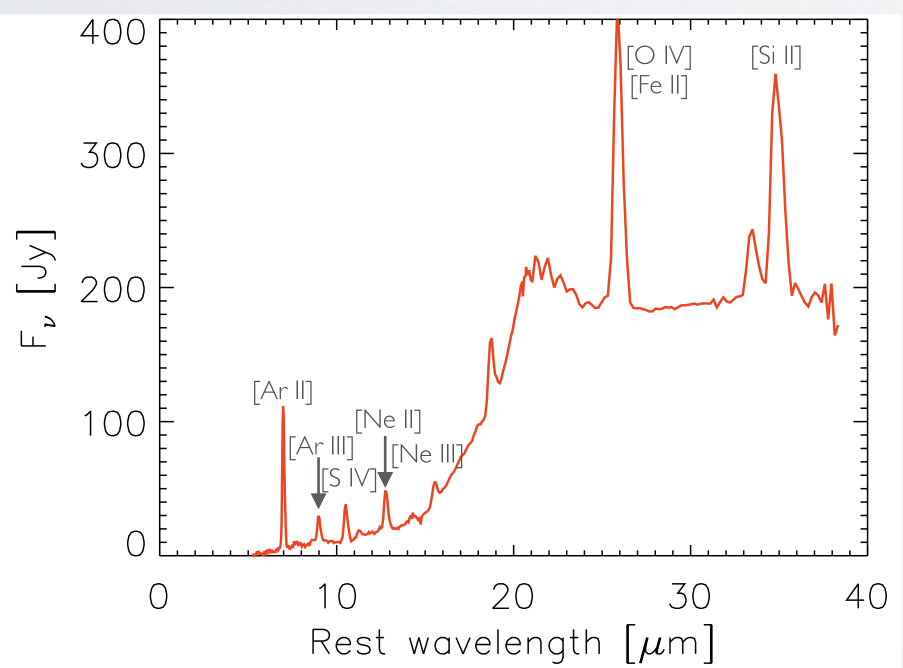
# CAS A: LINE EMISSION

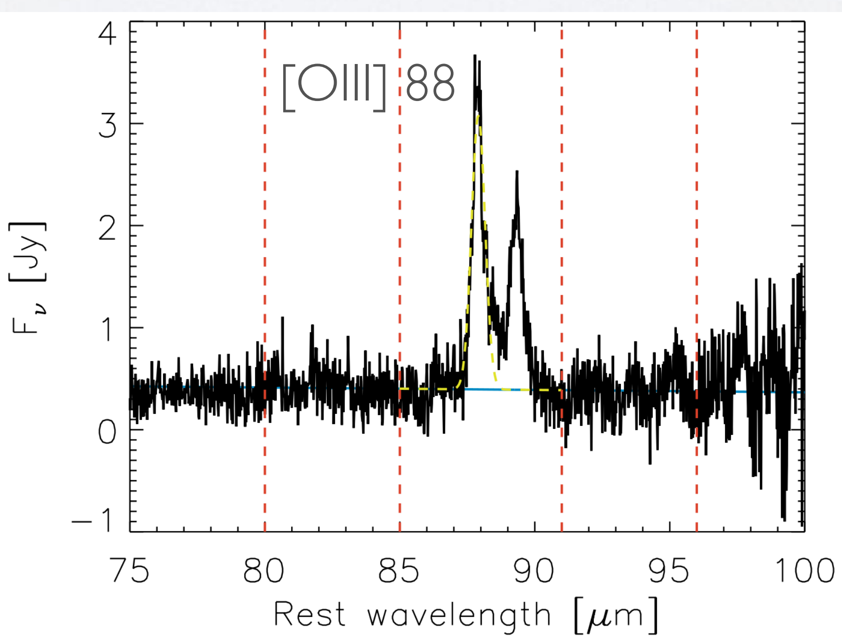
Determine line contribution from:

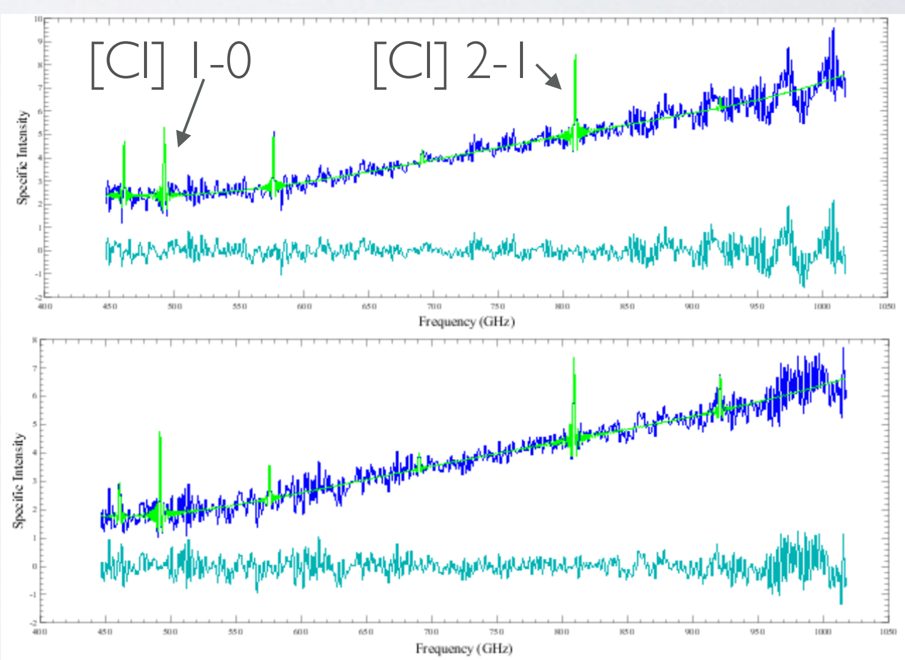
- Spitzer IRS spectra ([Ar III], [Ar II], [S IV], [Ne II], [NeIII])

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

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



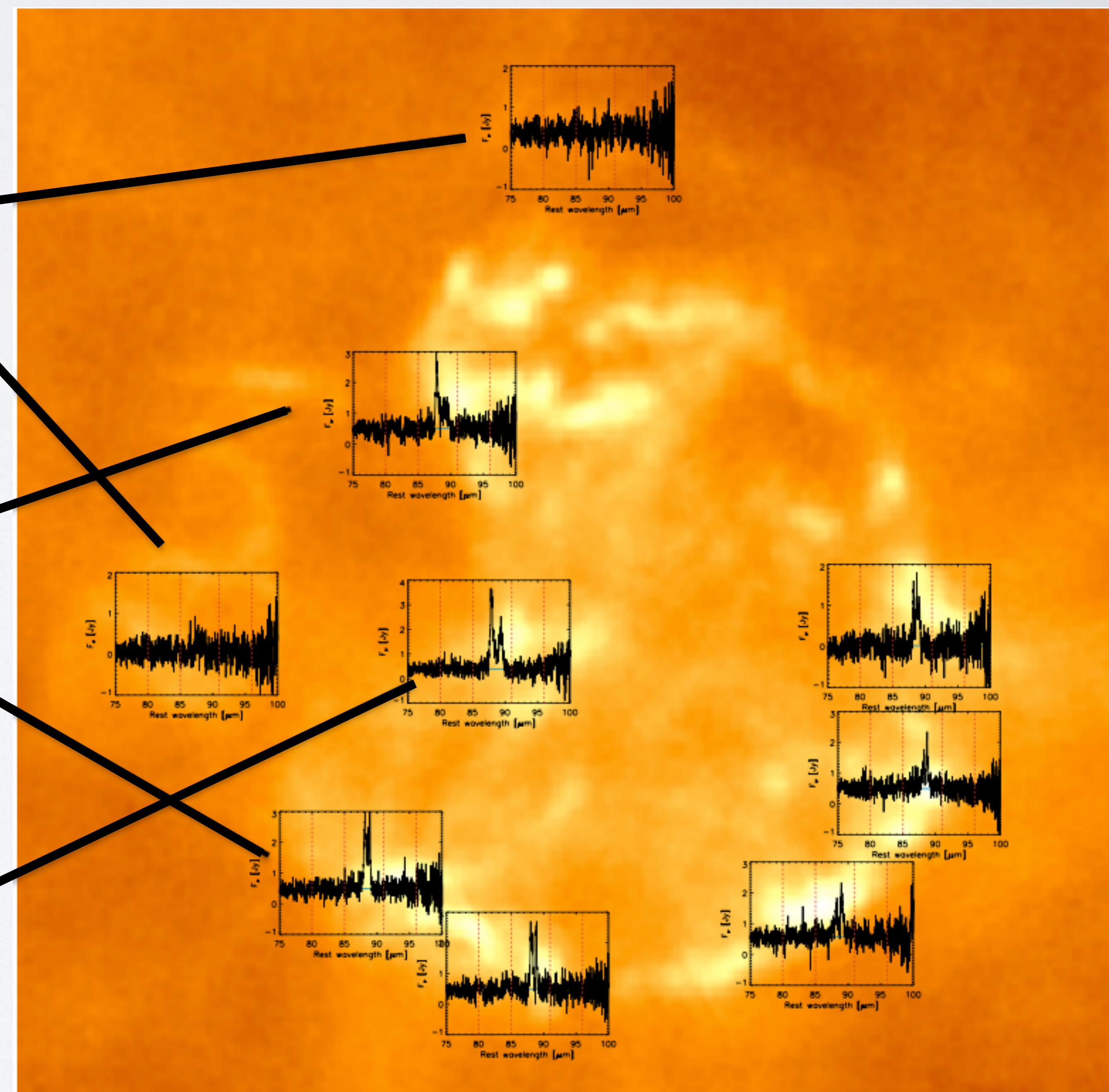
# CAS A: LINE EMISSION

[OIII]88 line contributes significantly to PACS 100 **μ**m band

No line contamination in outer regions

2-3% line contamination in reverse shock regions

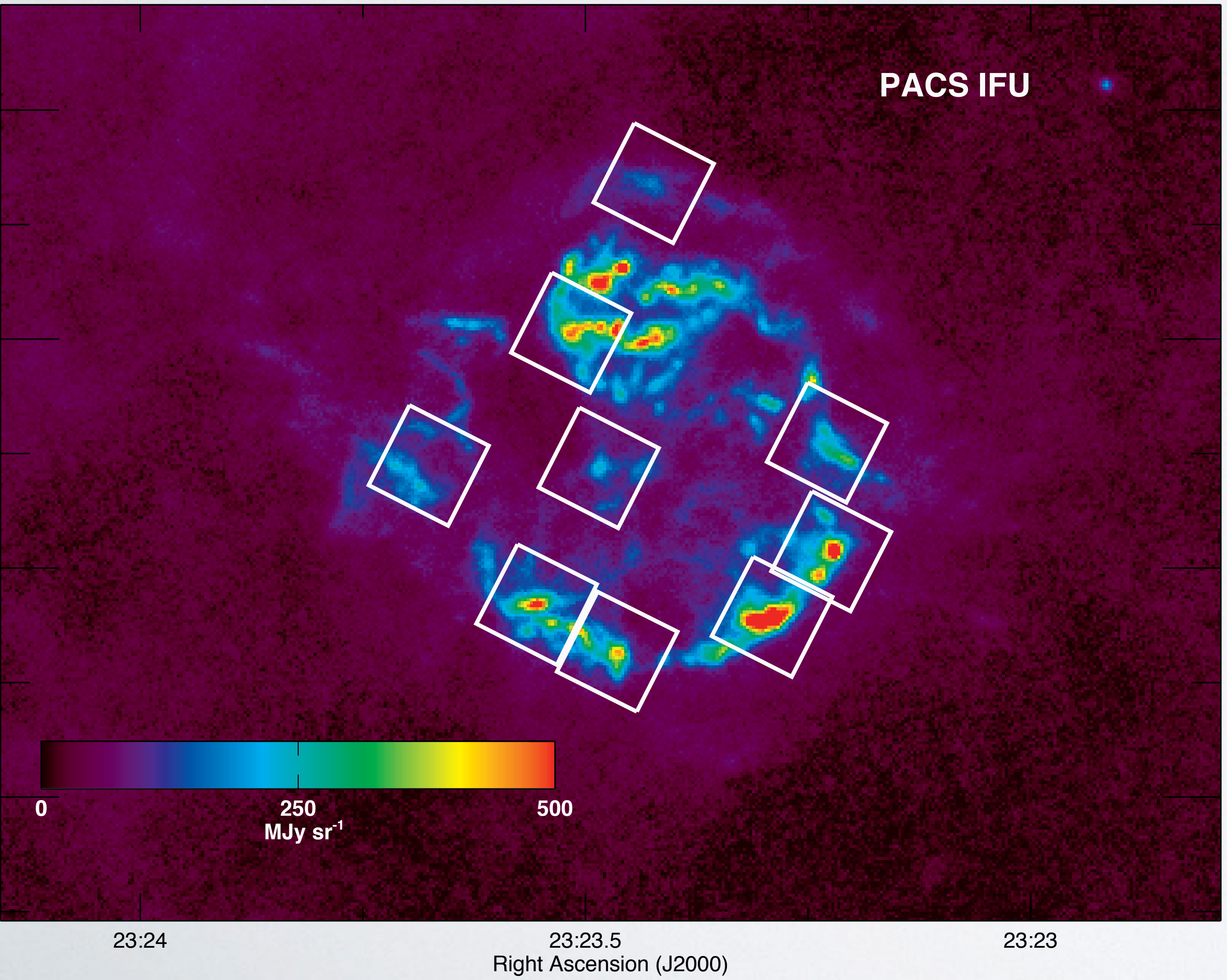
4-5% [OIII]88 line contribution in inner regions

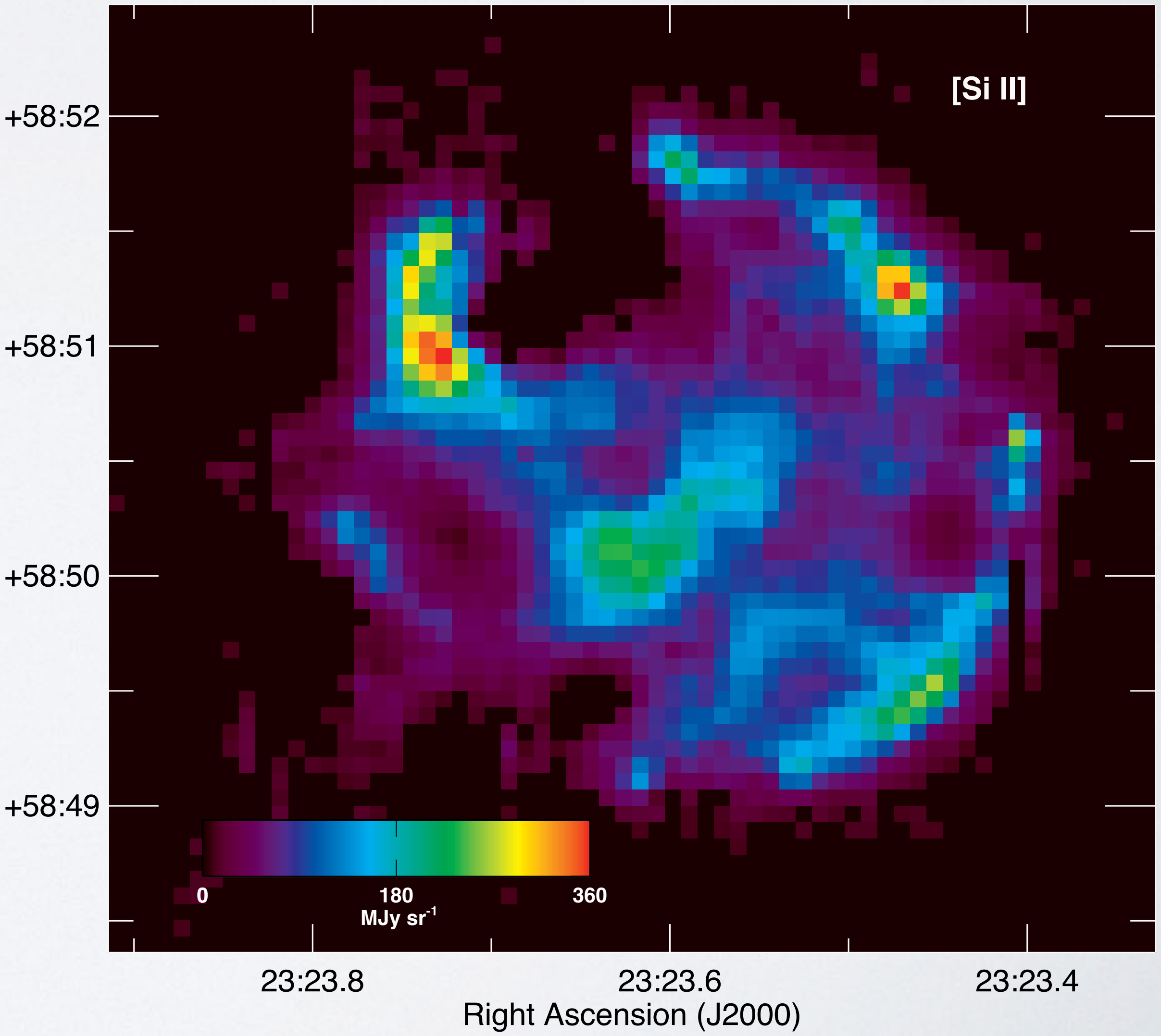


# CAS A: LINE EMISSION

PACS IFU does not cover entire remnant,

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

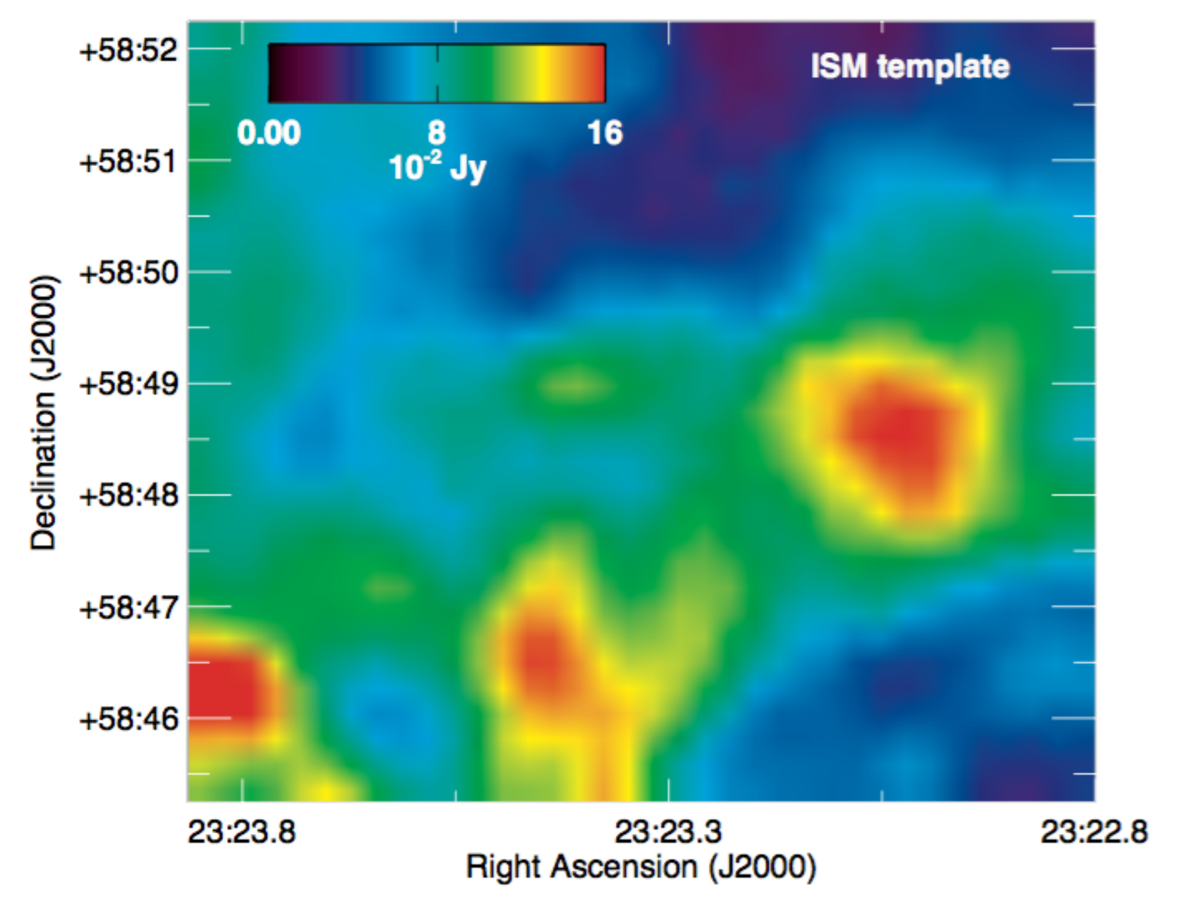


# CAS A: ISM CONFUSION

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

(assuming that SN dust contributes marginally @ 500 µm)



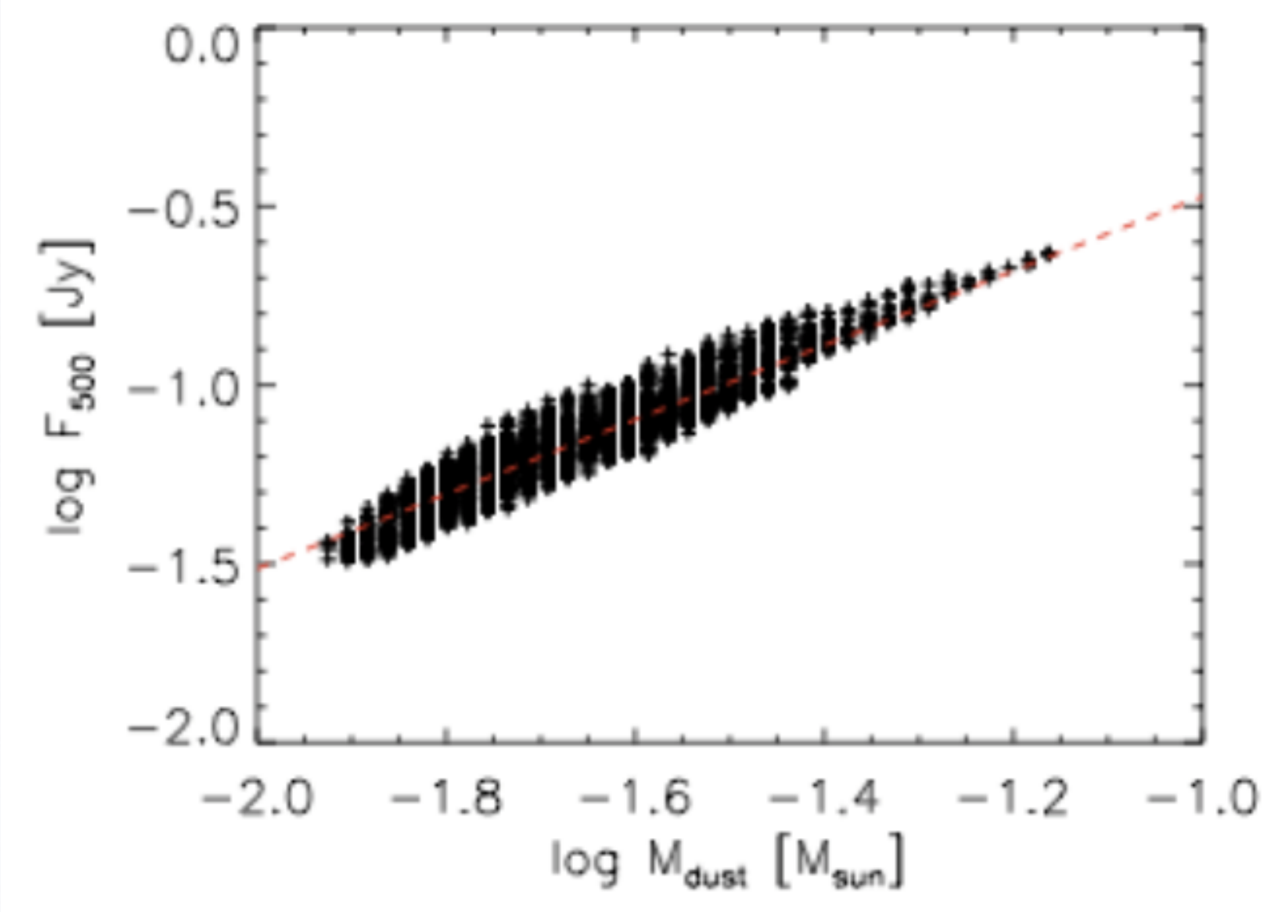
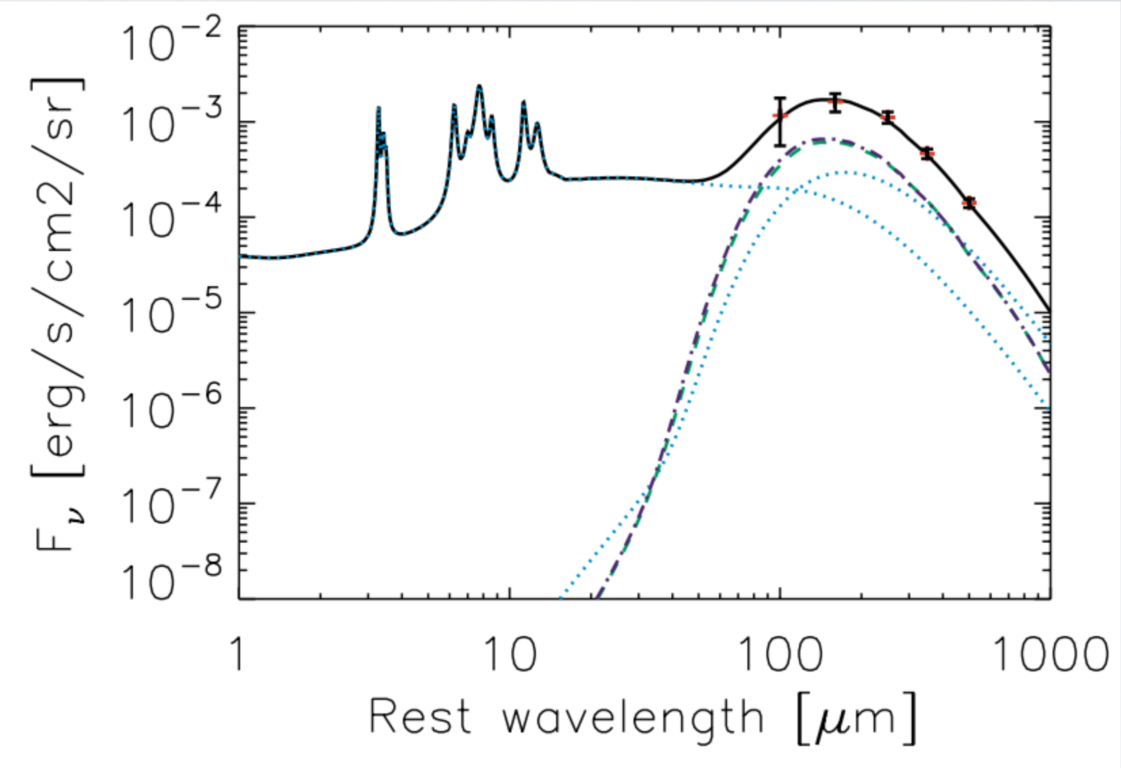



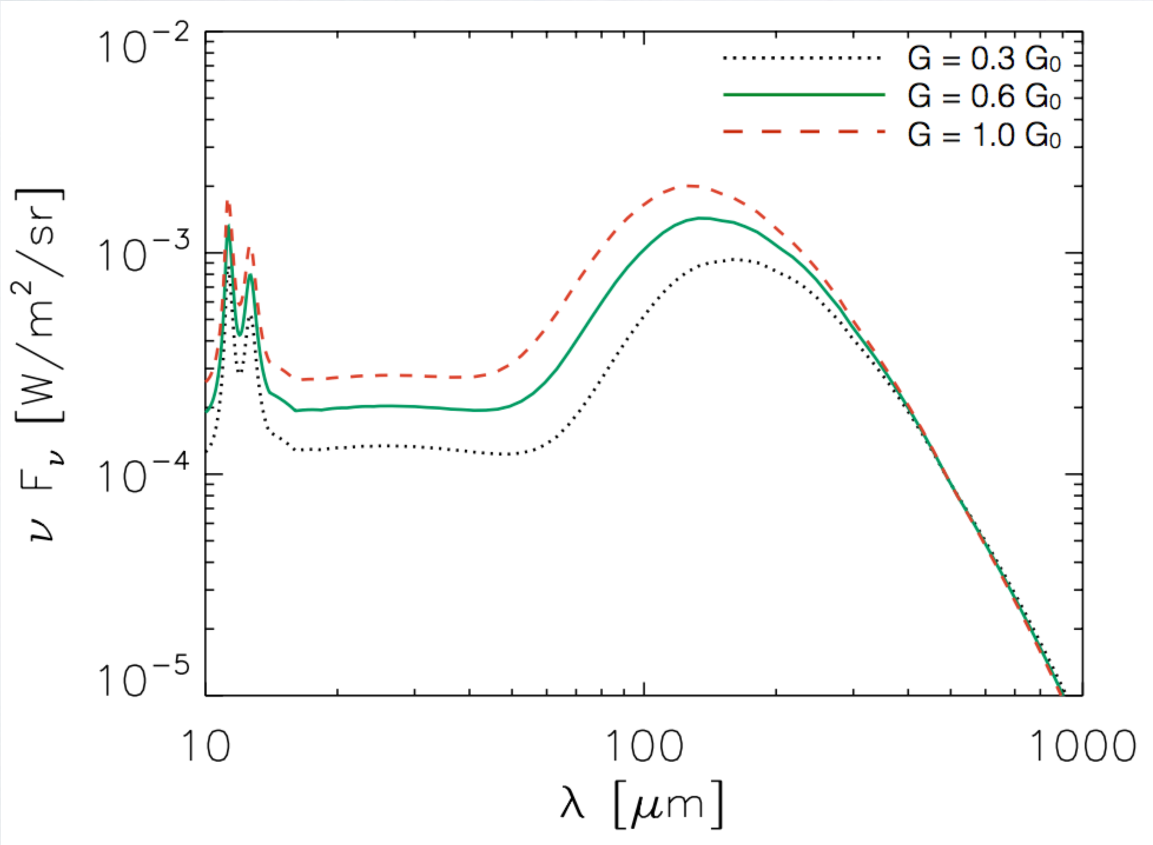

Fig: **Left**: SPIRE 500 µm map (with synchrotron emission subtracted)
**Right**: Correlation between $F_{500}$ and $M_d$ (ISM) for SED models with fixed $G=0.6G_0$.

# 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

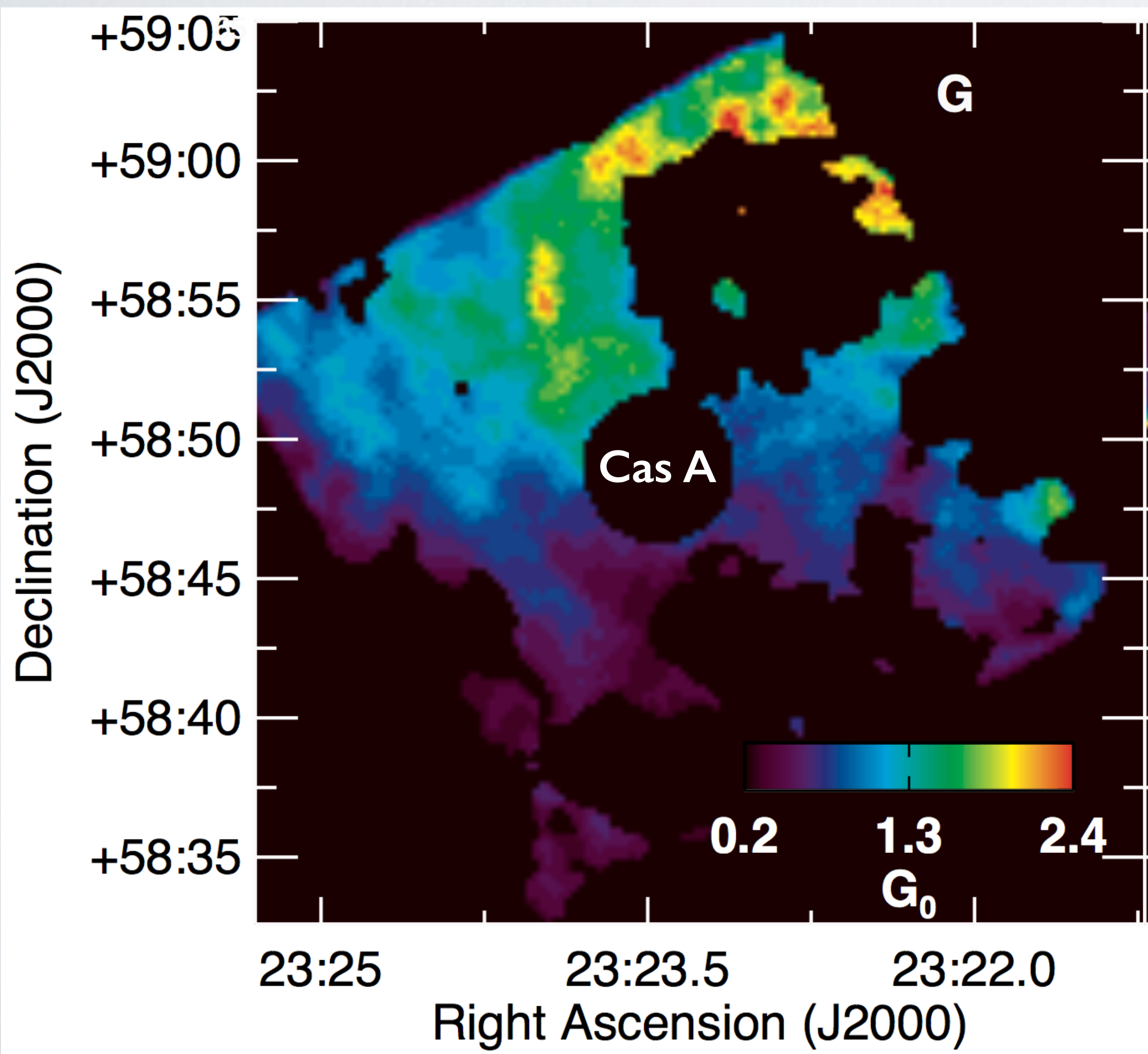
$G = 0.6G_0 \longrightarrow T_d = 16.4$ K

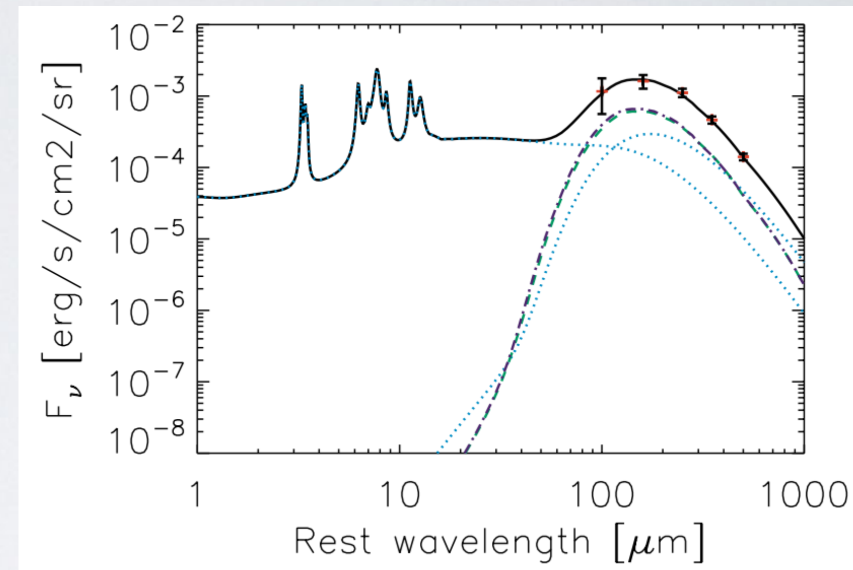
$G = 1.0G_0 \longrightarrow T_d = 17.9$ K

****Habing field G*** = FUV radiation field (6-13.6eV), normalised to $G_0$ = 1.6x10-3 erg/s/cm$^2$

# CAS A: ISM CONFUSION

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



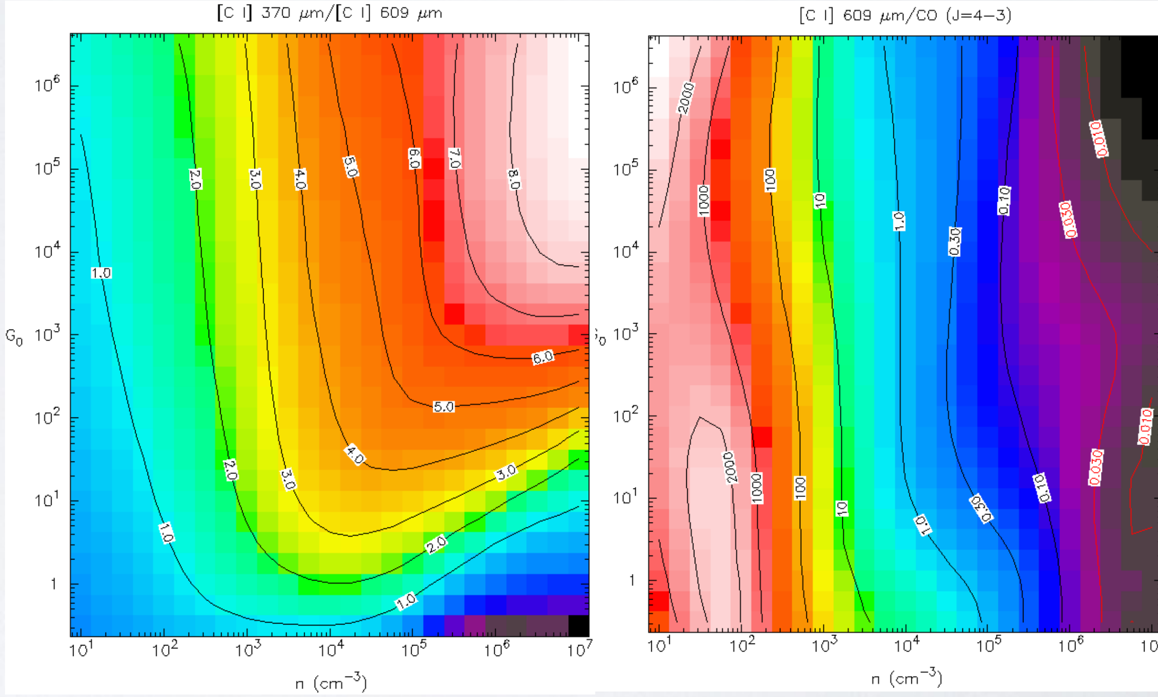

**Radiation field?**

- G varies from 0.2 $G_0$ to 2.4 $G_0$ in the observed field around Cas A

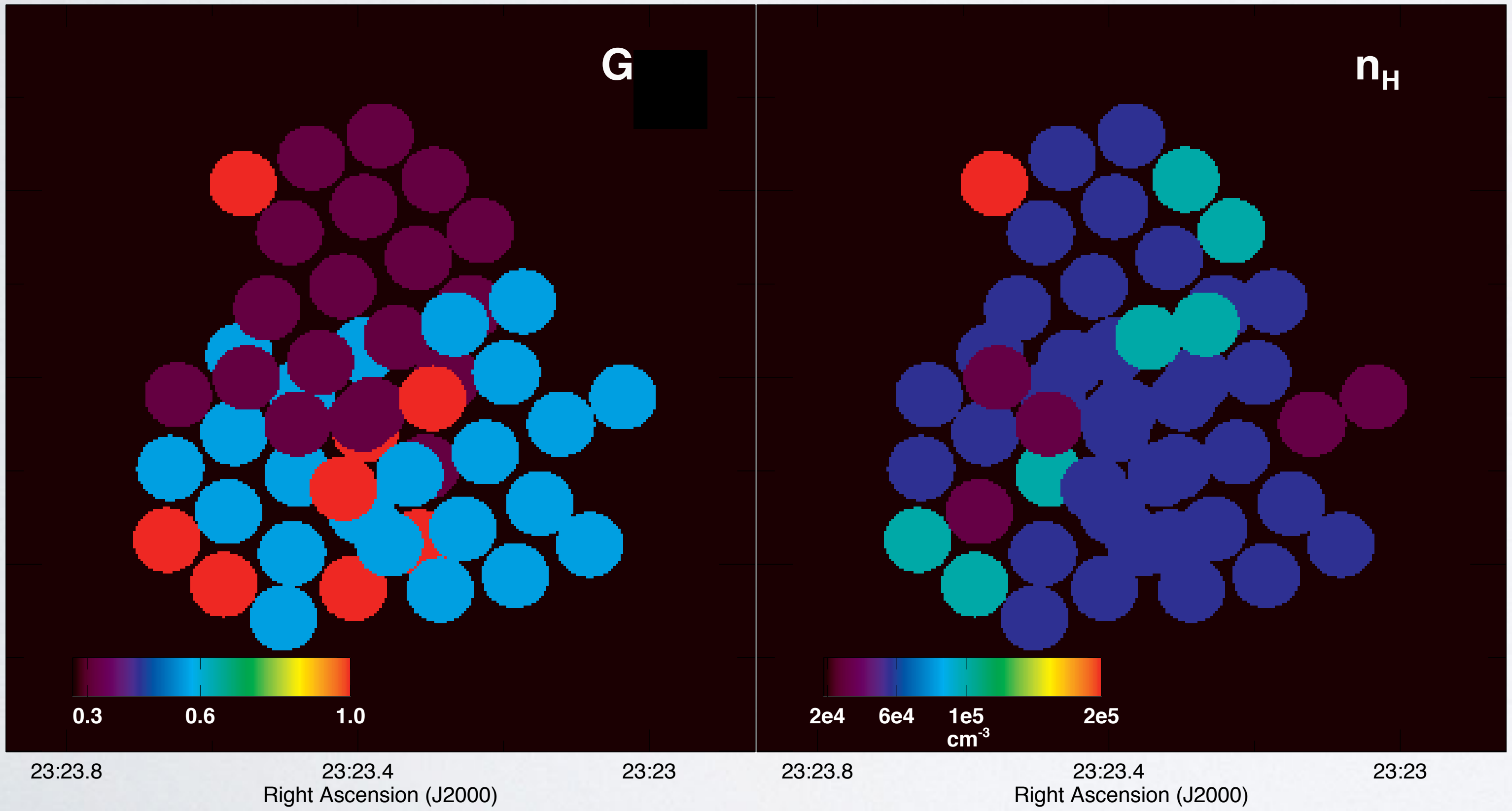
- in immediate vicinity of Cas A, G varies from 0.3 $G_0$ to 1.0 $G_0$

# 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



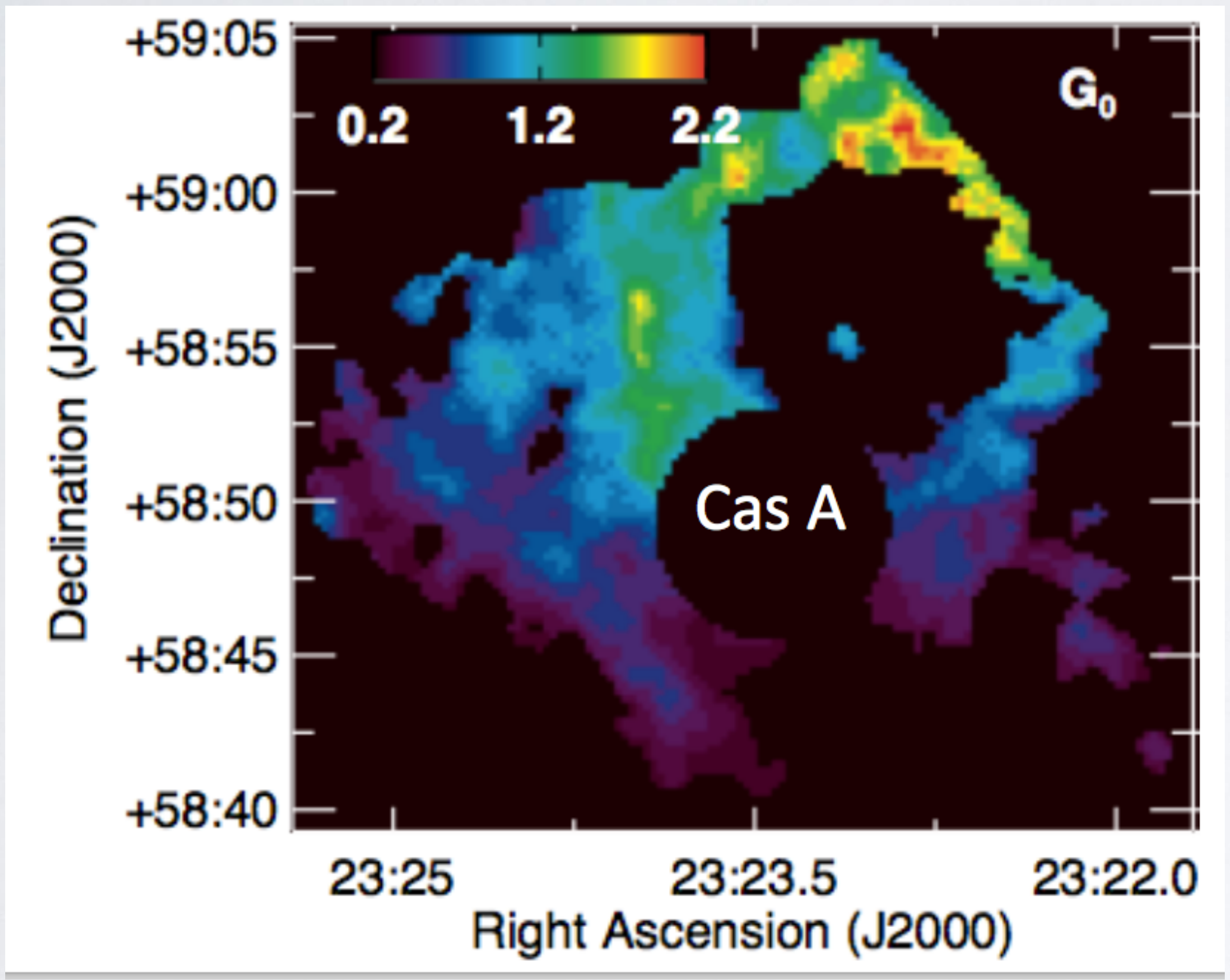

PDR toolbox
Pound & Wolfire (2008)

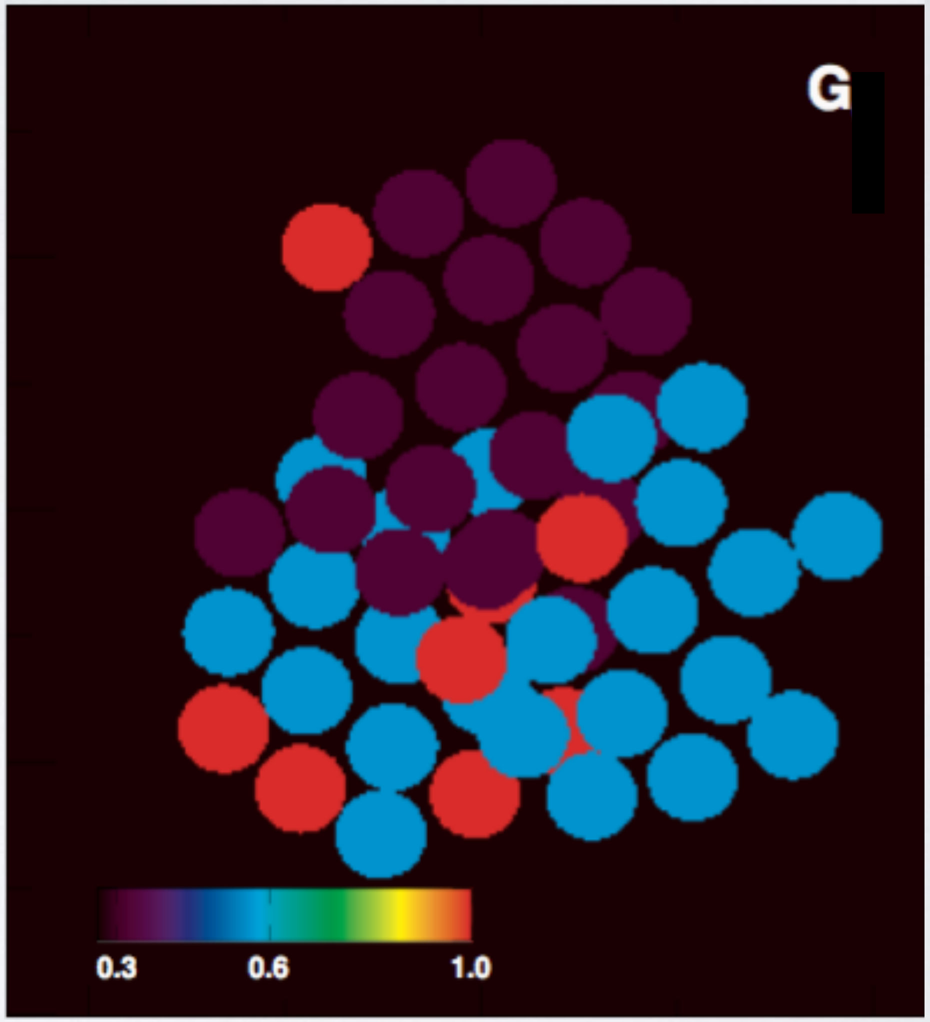



→ G varies from 0.3 $G_0$ to 1.0 $G_0$, with **median of G = 0.6 $G_0$**

# CAS A: COMPONENTS

Based on the two independent approaches: G=0.6 $G_0$ is best model



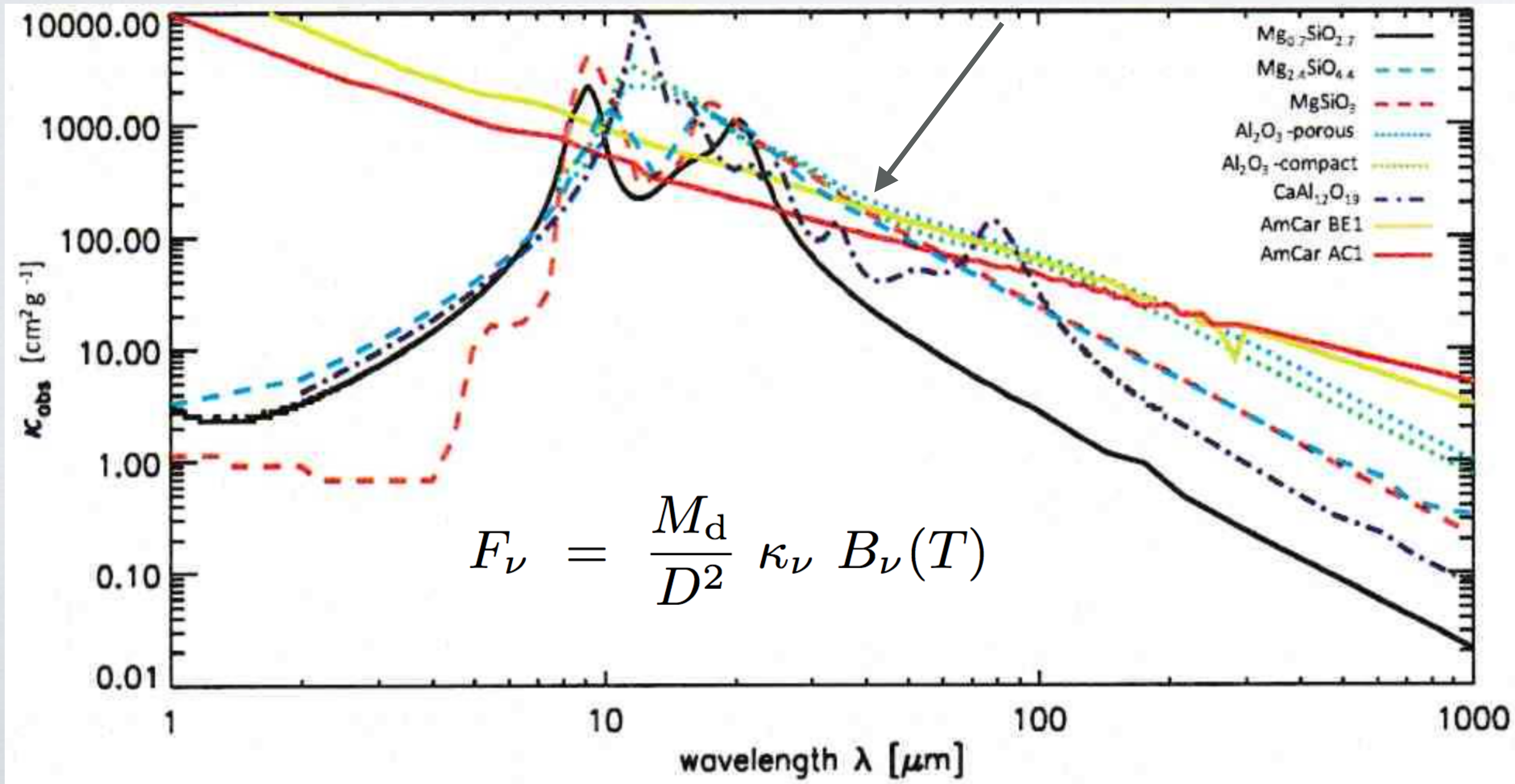

SED fitting and PDR models and residual maps all conclude:
G = 0.6 $G_0$ provides the best fit along the Cas A sightline

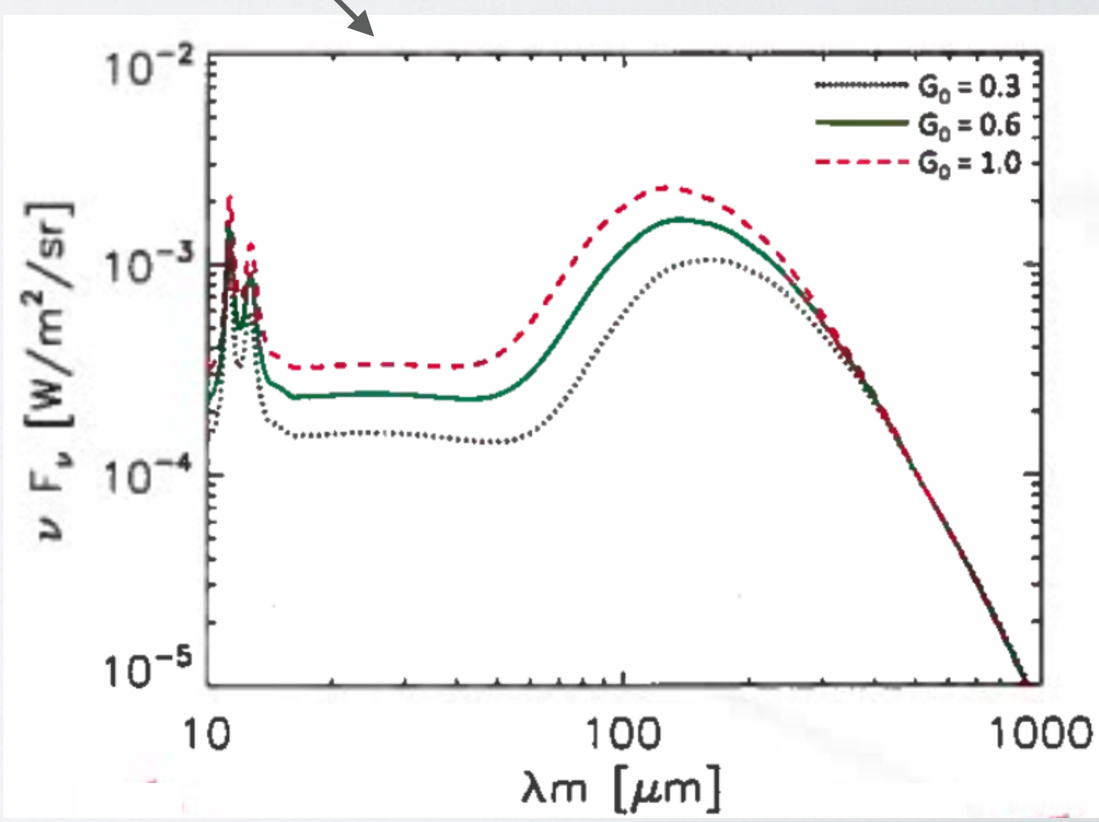
# CAS A: SED FITTING

**<u>Step 1</u>**: subtraction of line+synchrotron emission

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

**<u>Step 3</u>**: repeat modelling for ISM with $G_0$ = 0.3, 0.6, 1.0
and various dust species



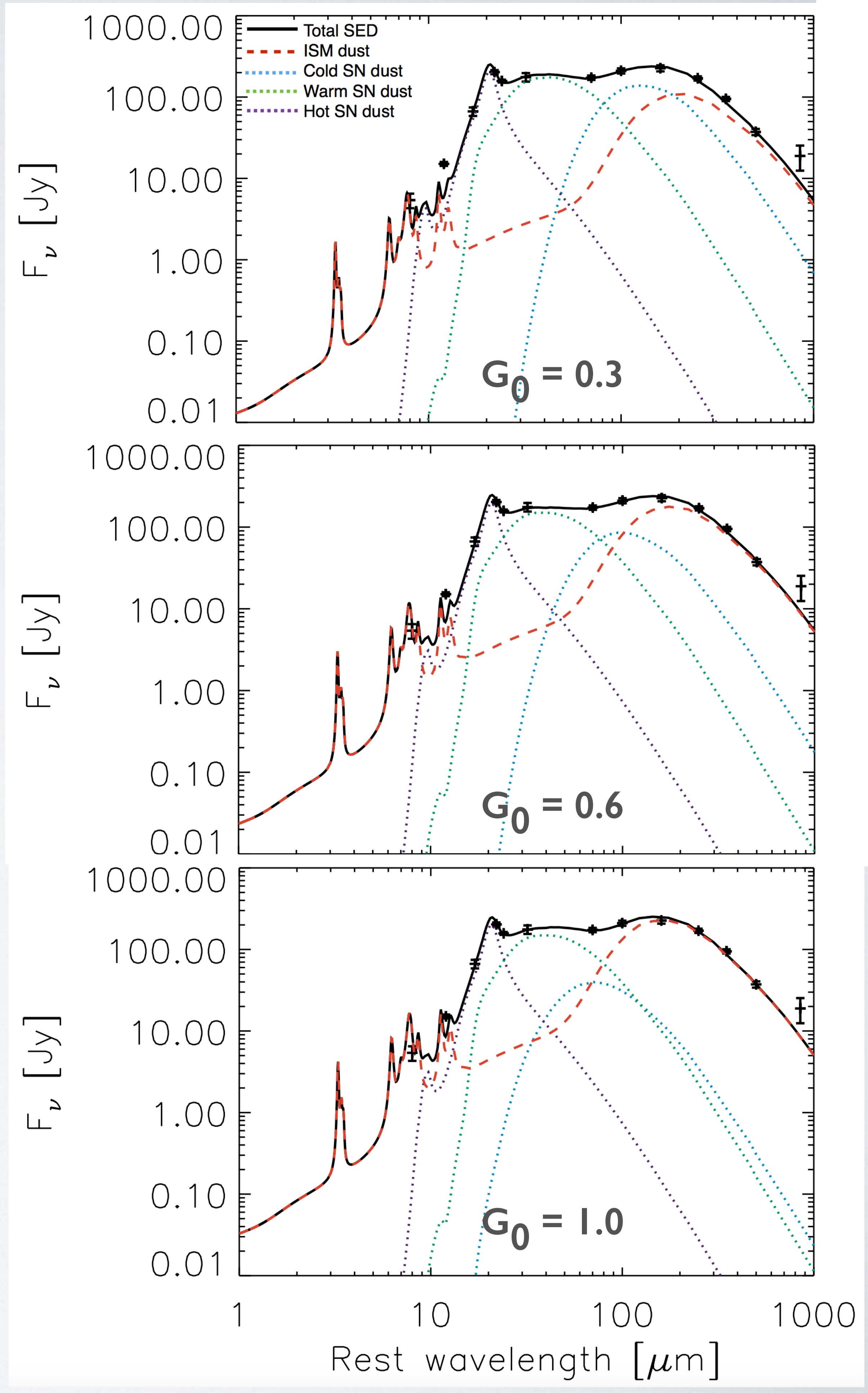
# CAS A: GLOBAL FITS

- For G = 1.0 $G_0$: max ISM contribution, little SN dust emission left
- SN dust mass depends on dust composition
- we rule out $Mg_{0.7}SiO_{2.7}$, $Al_2O_3$, $CaAl_{12}O_{19}$ based on nucleosynthesis model predicted heavy element availability (Woosley & Weaver 1995)

**Results for ISM model with G=0.6$G_0$:**

| Dust species | $M_d$ [$M_\odot$] | $T_d$ [K] | Lower $M_d$* | Max $M_d$** |
|---|---|---|---|---|
| $Mg_{0.7}SiO_{2.7}$ | 50.3 | 26 | 11 | 1.21 |
| $MgSiO_3$ | **2.9** | **29** | **1.0** | 1.37 |
| $Mg_{2.4}SiO_{4.4}$ | **2.6** | **29** | **0.8** | 0.93 |
| Amorphous carbon | 0.7 | 30 | 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

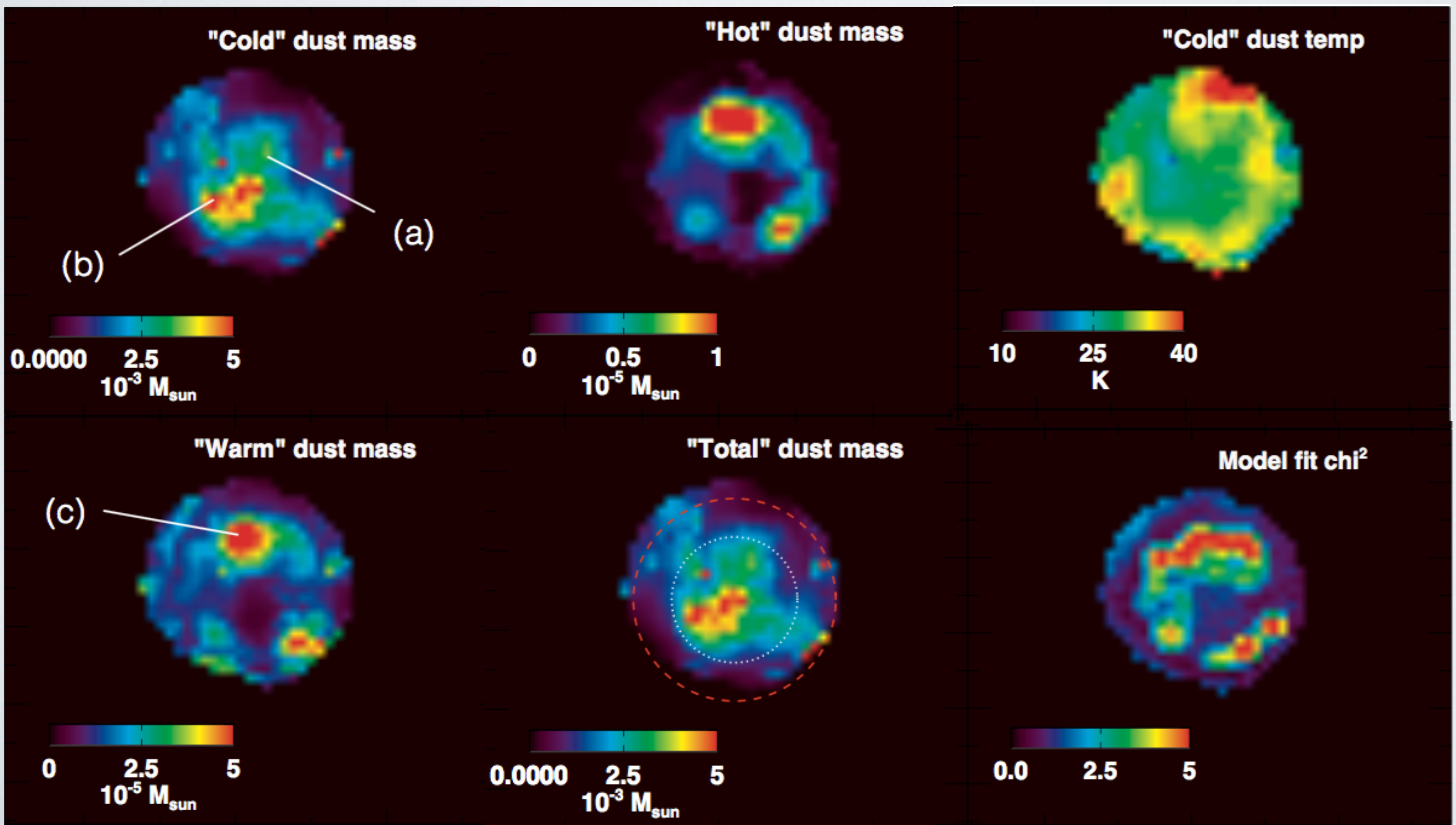


# CAS A: RESOLVED FITS

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

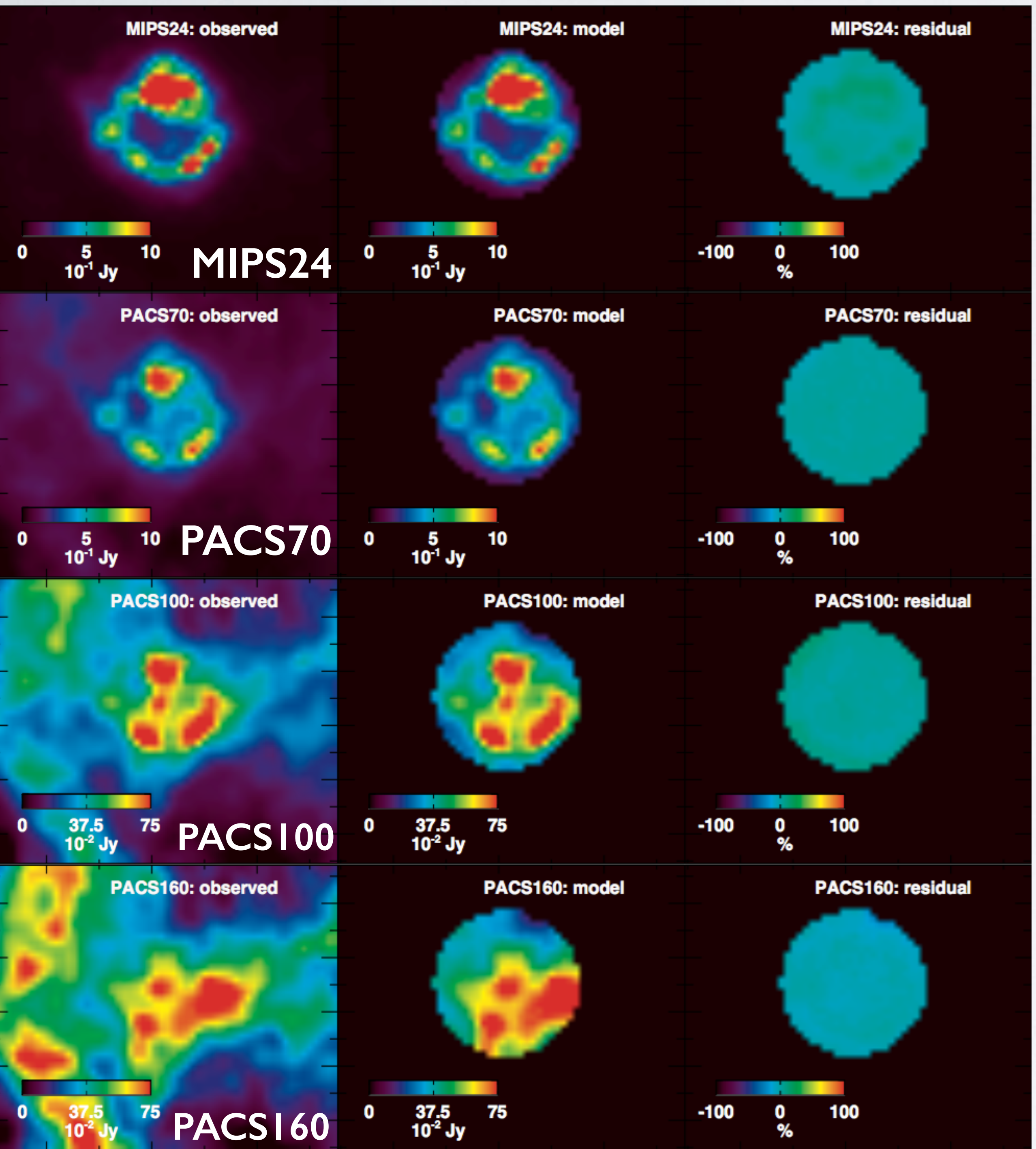
⟶ 79 (36'' pixels) and 438 (14'' pixels) resolution elements

**<u>SN components at different temperatures:</u>**

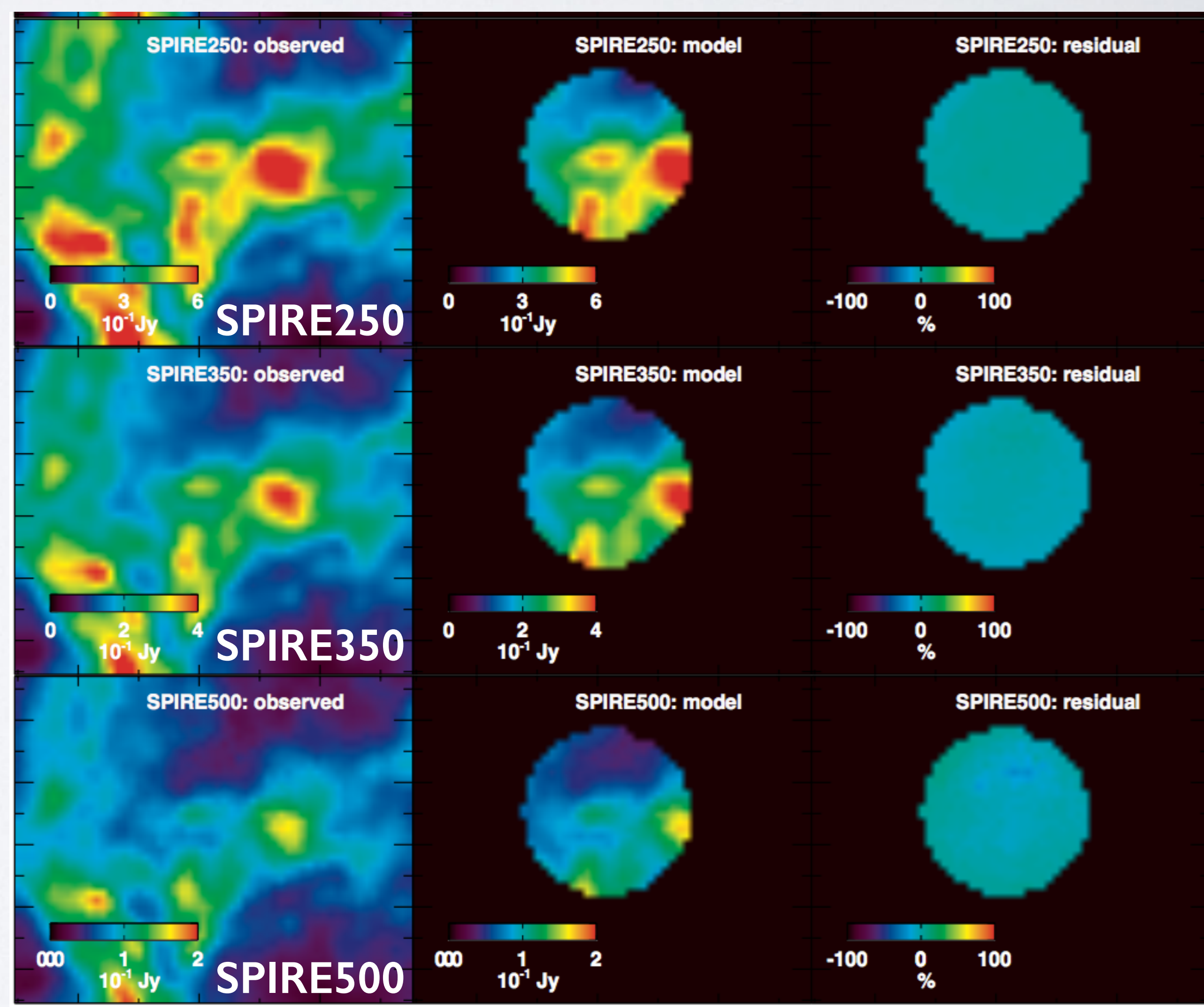


# CAS A: RESOLVED FITS

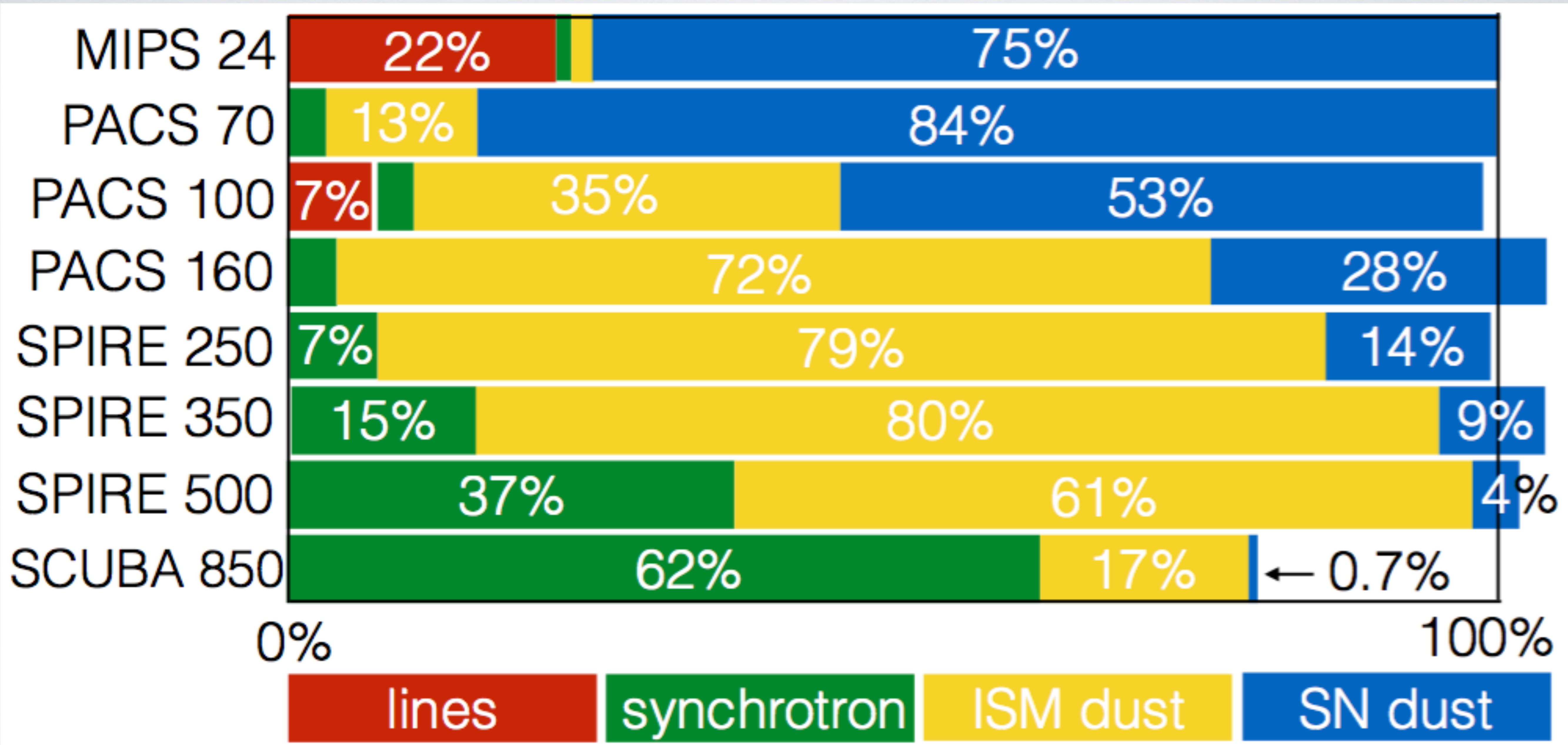
**Model safety check:** how does model compare to data?




Observations Model Residual



# CAS A: COMPONENTS



# CAS A: MAIN RESULTS

1. Best SED fits using **silicate-type grains** ($MgSiO_3$, $Mg_{2.4}SiO_{4.4}$)
   → ruling out $CaAl_{12}O_{19}$, $Al_2O_3$, $Mg_{0.7}SiO_{2.7}$ as dominant dust species

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

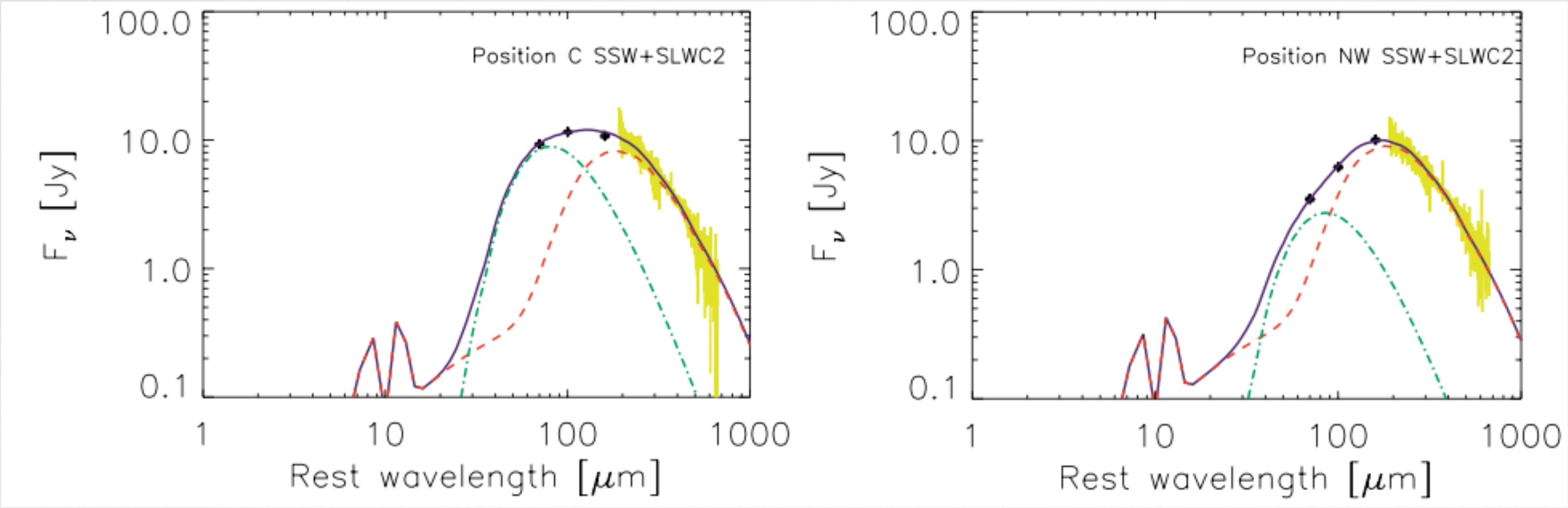
3. Best-fit model predicts **0.5-0.7 $M_\odot$ of (~30 K) silicate dust**
   → sufficient to explain dust in early Universe*

| | **Global SED fits** | | **Spatially resolved fits** | | |
|---|---|---|---|---|---|
| Dust species | $M_d$ [$M_\odot$] | Lower $M_d$ | $M_d$ [$M_\odot$] | Lower $M_d$ | Max $M_d$ |
| $MgSiO_3$ | 2.9 [29K] | 1.0 | **0.7 [30K]** | 0.3 | 1.37 |
| $Mg_{2.4}SiO_{4.4}$ | 2.6 [29K] | 0.8 | **0.5 [32K]** | 0.2 | 0.93 |
| Am. carbon | 0.7 [30K] | 0.04 | 0.4 [29K] | 0.04 | 0.29 |

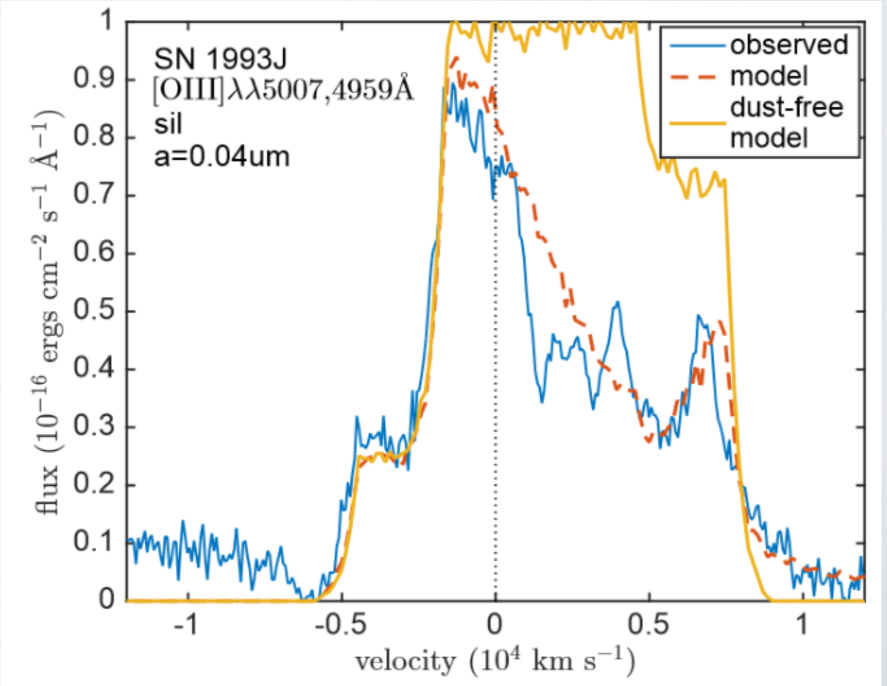
*if produced by other SNR + not destroyed by reverse shock

# FUTURE OUTLOOK

**1.** Analyse SPIRE FTS spectra (190-650 μm) of Cas A to get better constraint on dust emissivity




**2.** Infrared analyses = limited by resolution ⟶ determine SN dust mass based on Hα, [OIII] line asymmetries*

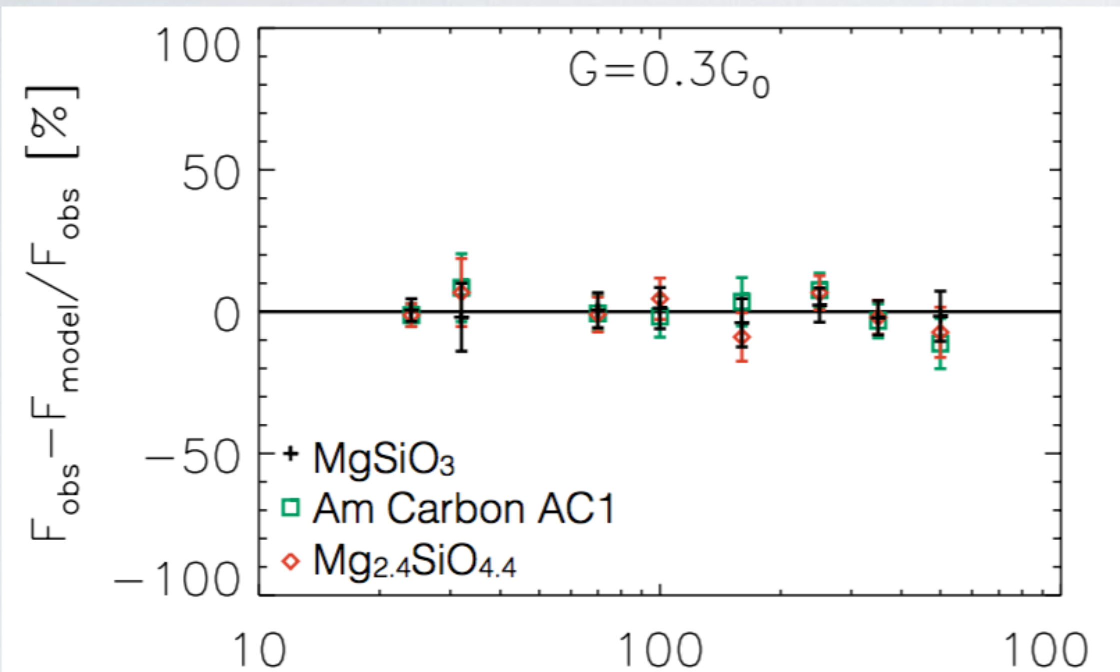


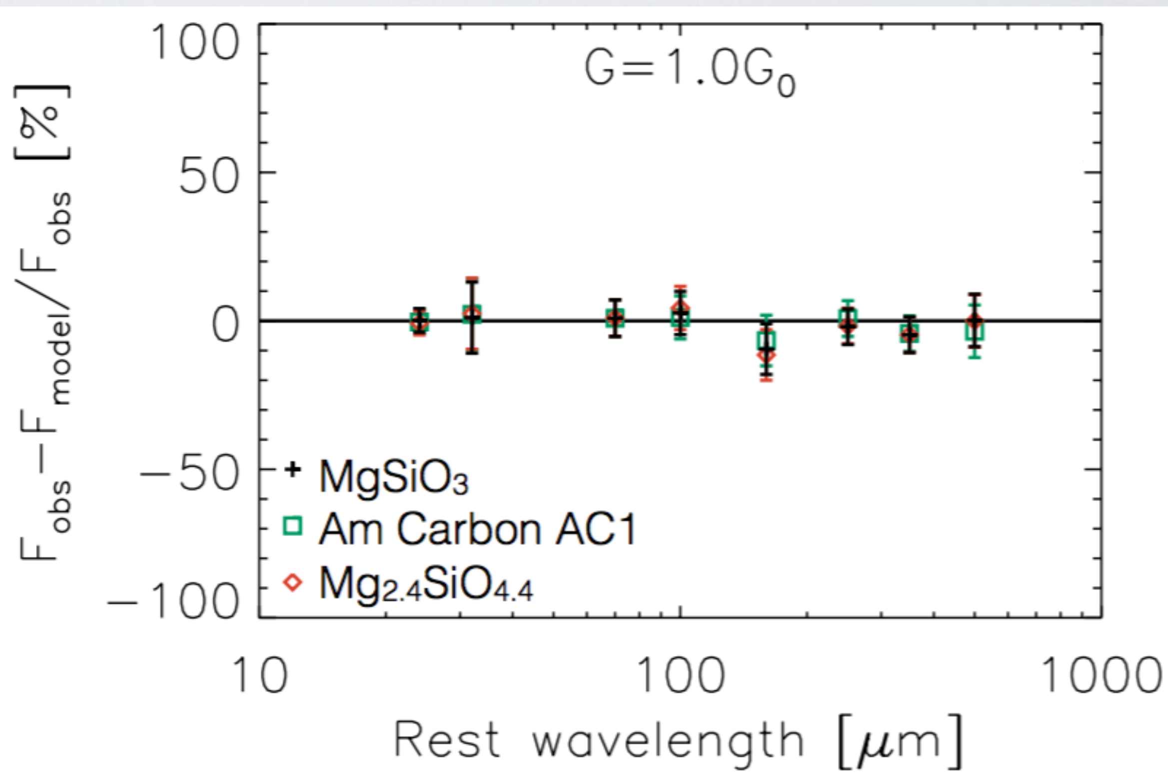

Bevan & Barlow 2016

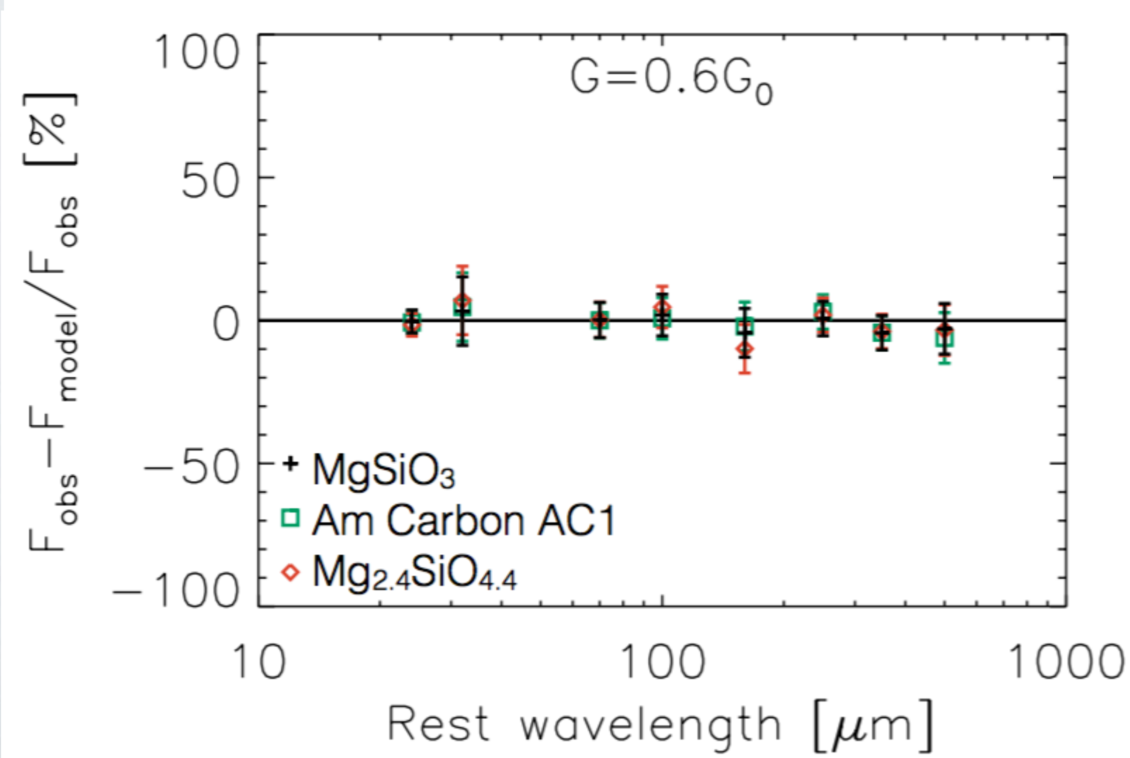
*We have an accepted ESO program to obtain X-SHOOTER spectra for 25 SNR

# CAS A: GLOBAL FITS

**<u>Model safety check:</u>** how does model compare to data?

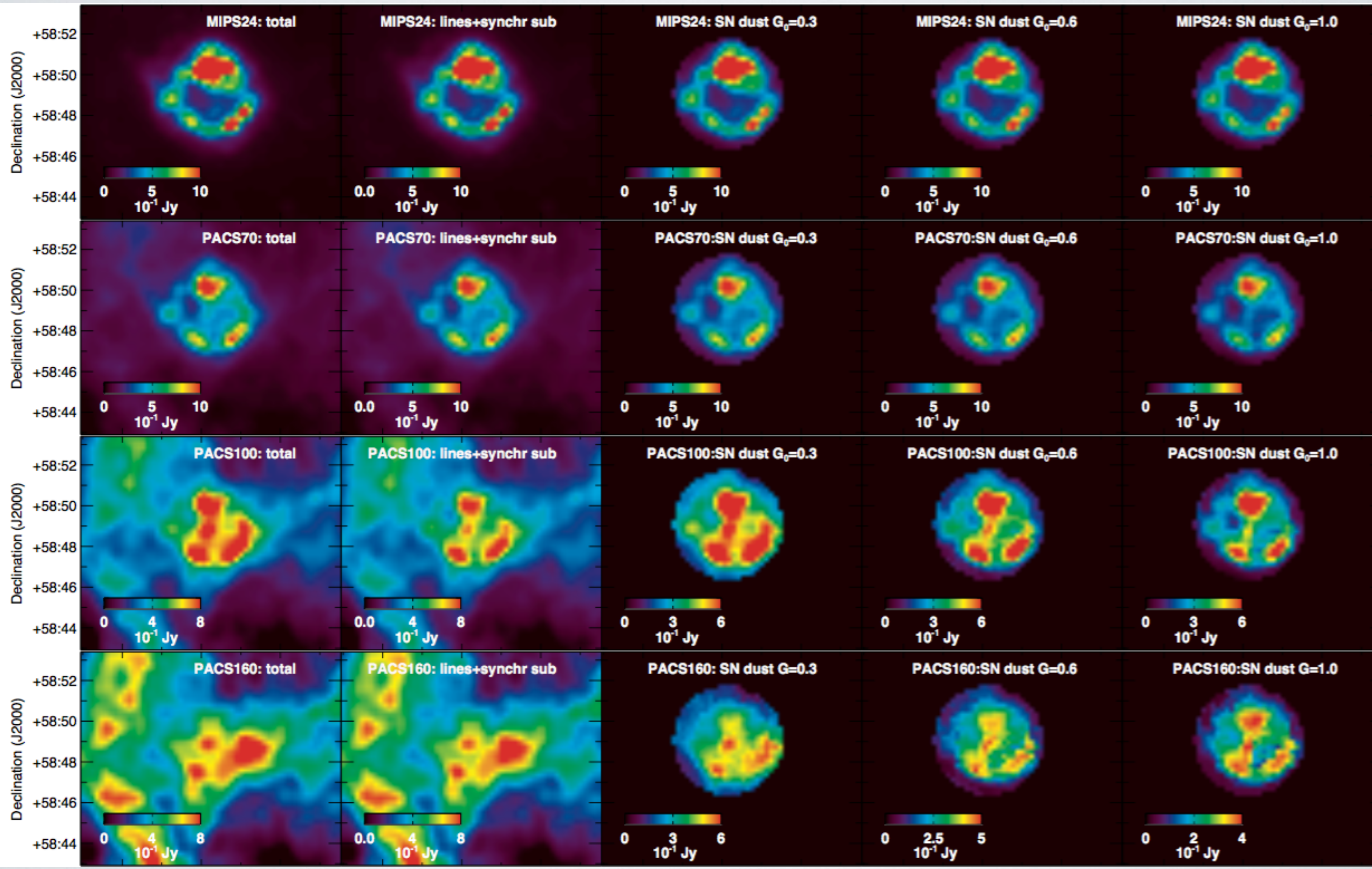


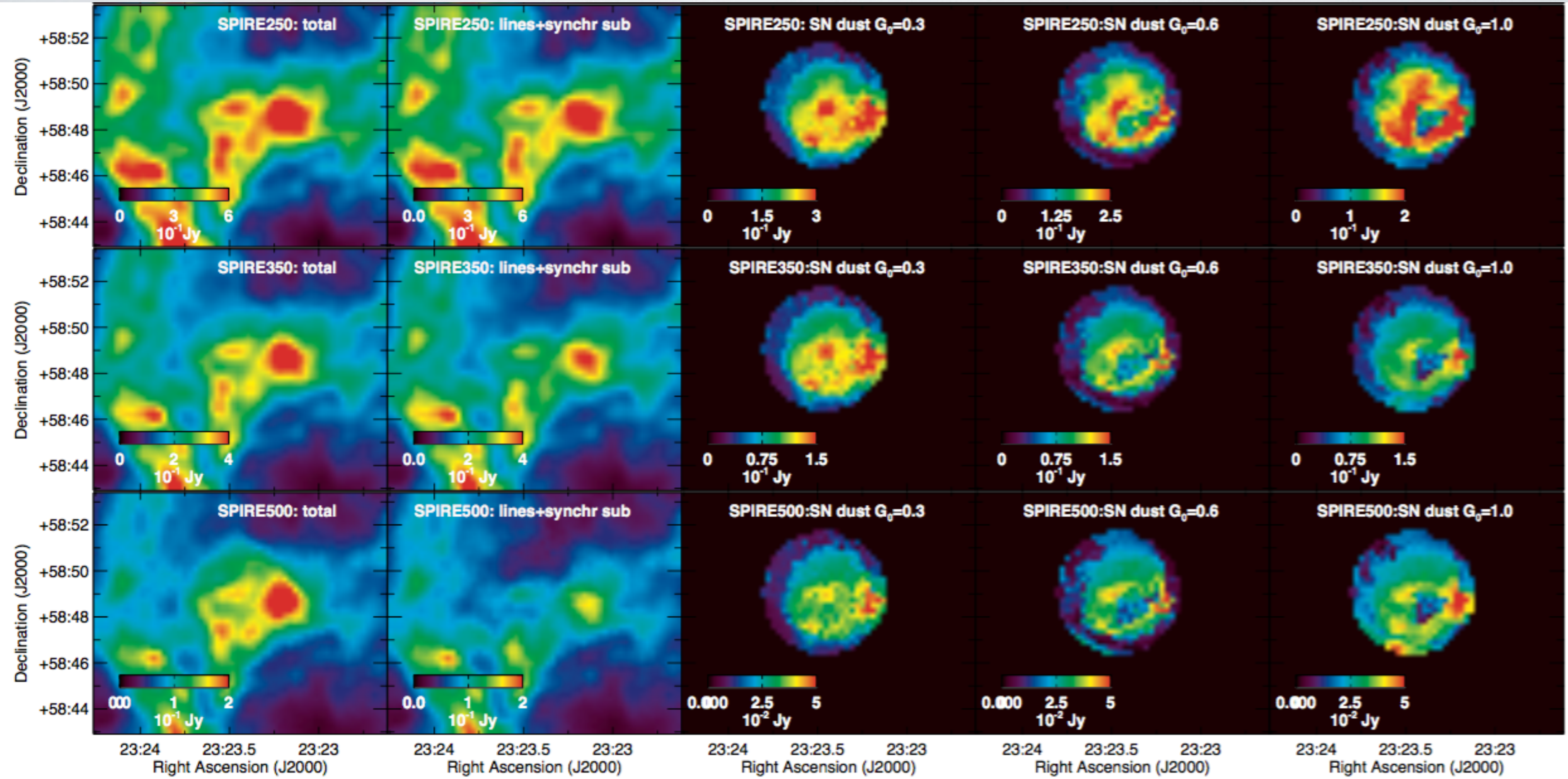




- Good agreement between model & observations !

# CAS A: COMPONENTS



# CAS A: COMPONENTS



# CAS A: SCUBA850

SCUBA850: Model versus observations