SOFIA FIFI-LS [OI] and [OIII] Observations of the Supernova Remnant Cas A

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Collaborators

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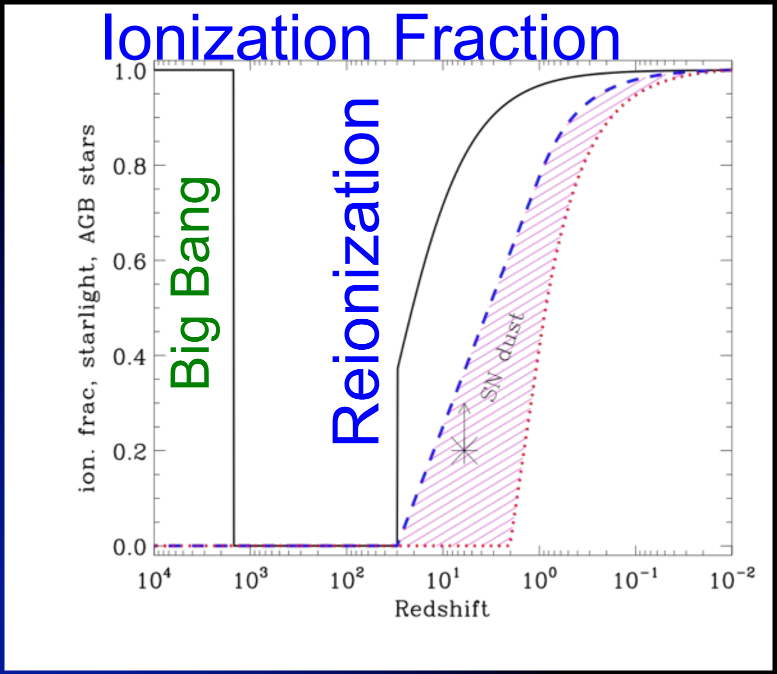
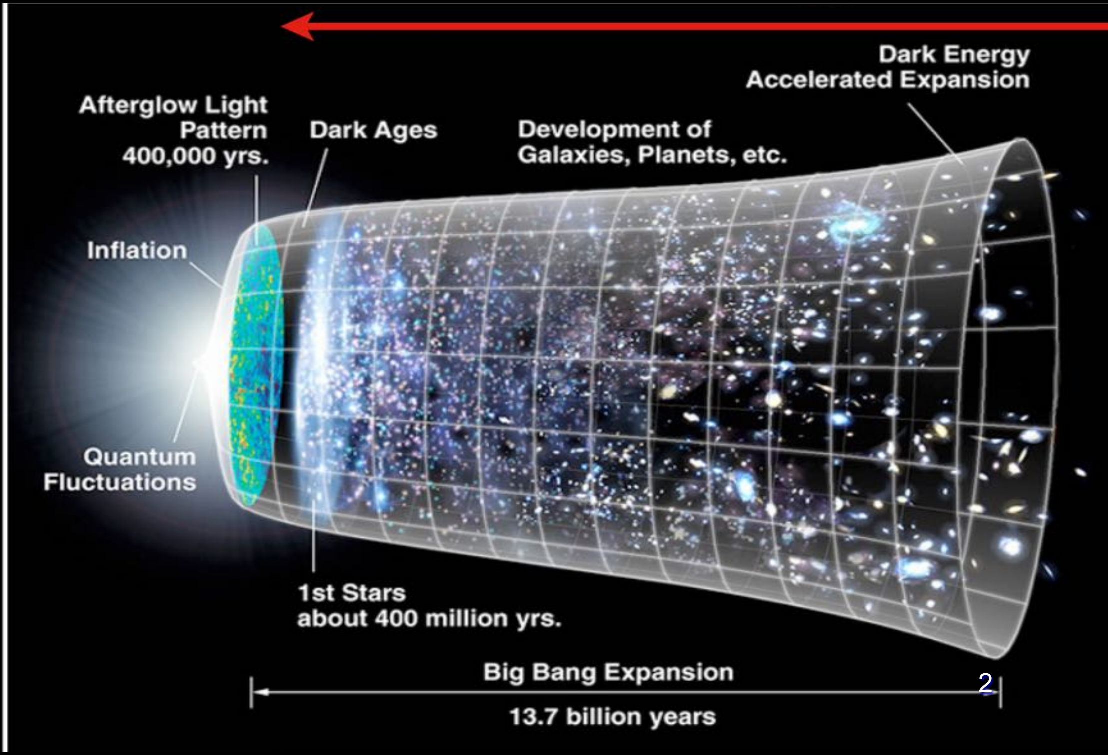
Introduction : Dust formation

- SN1987A shows dust formation in SN ejecta (Wooden et al. 1993)
- Huge quantity of dust is observed in high red-shift quasars or galaxies (Issak 2002; Bertoldi et al. 2003; Laporte et al. 2017 using ALMA) . Molecules of H_2 and CO are detected. Dust in the evolved stars requires too long time scale.
- Dust formation in SNe can explain dust in early Universe in theory (Todini 2001; Nozawa et al. 2003)
- YSNRs offer resolved structures

  of ejecta, CSM/ISM dust





Talk Outline

1) Dust formation in SN ejecta and mass observed in YSNRs:

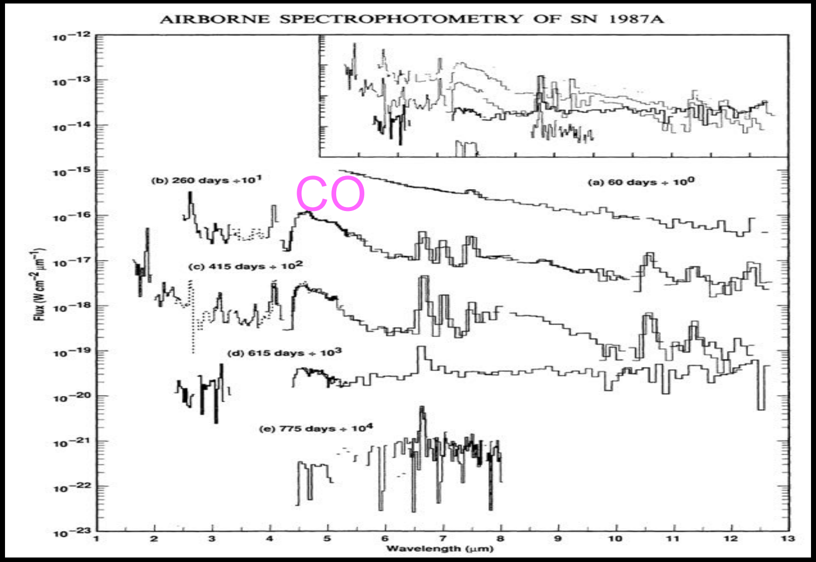
2) CO observations of ejecta-knots

3) Dust survival (dust destruction rate), and CO re-formation

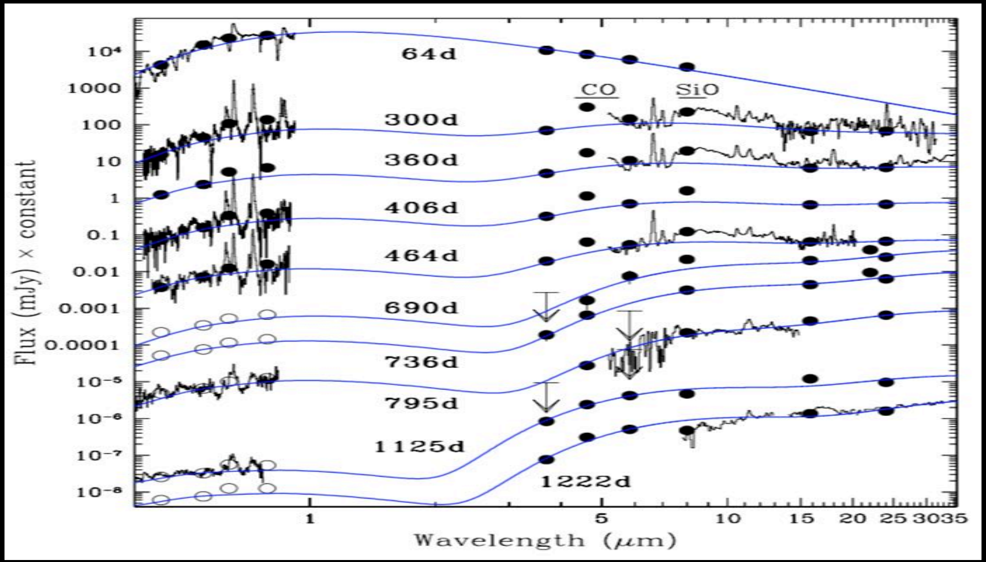
4) SOFIA [OI] and [OIII] observations of SN ejecta-CO knots

5) Properties of Ejecta/CO knots: lifetime of ejecta

First sign of dust formation in SN1987A and Dust mass from Recent SNe

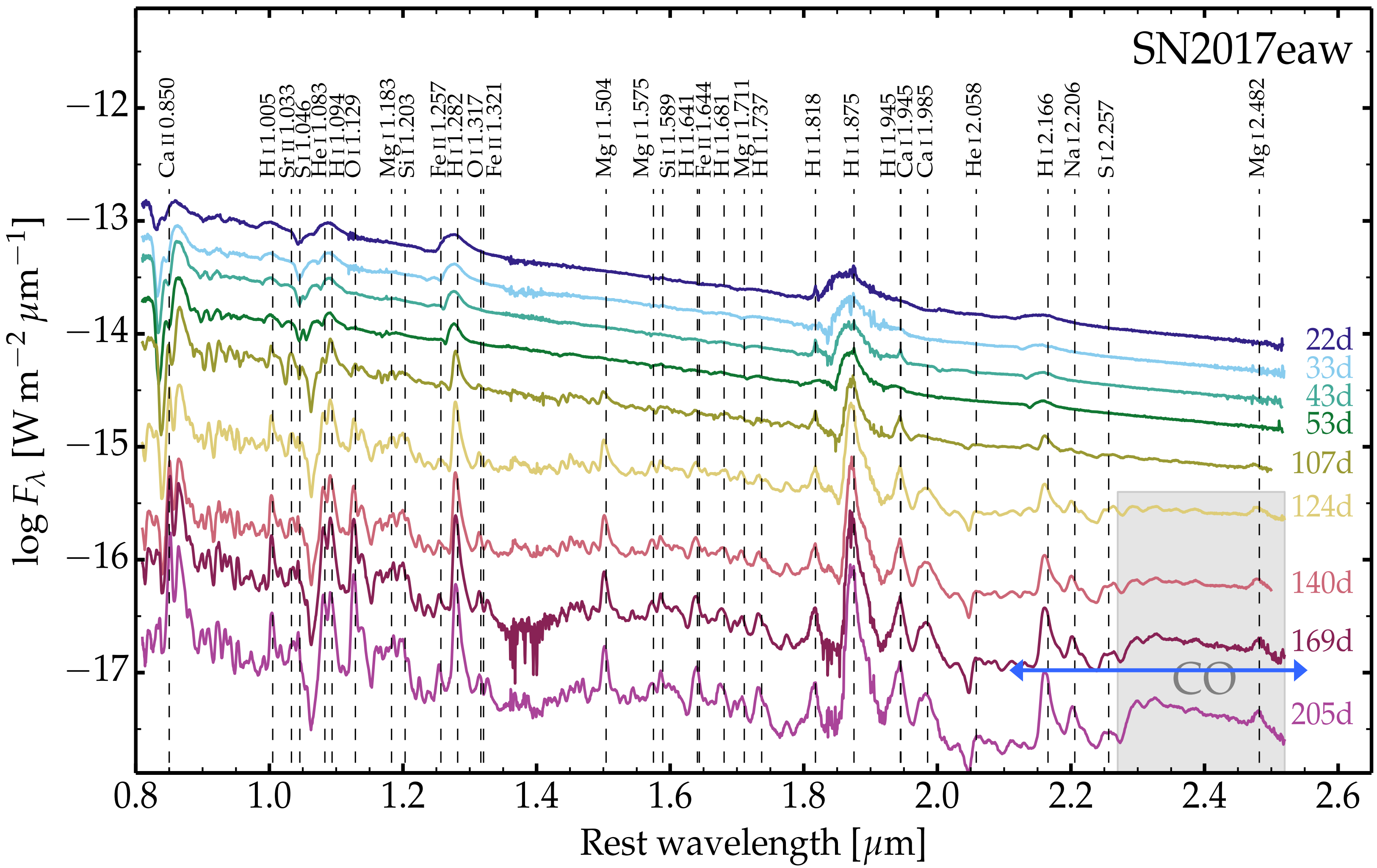


CO and dust (continuum change) detection in SN1987A (Wooden et al. 1999)



Dust increases with time but still ~ $10^{-3} M_\odot$ in SN2004et (Kotak et al. 2009)

- Typical values from recent SNe (within a few years after the explosion) only 10^{-4} - 10^{-3} (<<10^{-2}) $M_\odot$ (Kotak et al. 2009, Szalai et al. 2011; Rho et al. 2018; Tinyanont et al. 2019) →Opticall thick ejecta? (Dwek et al. 2018)
- Dust formation models predict ~1 $M_\odot$ dust per SN (Nozawa et al. 2003; Todina 2001; Sluder et al. 2018)



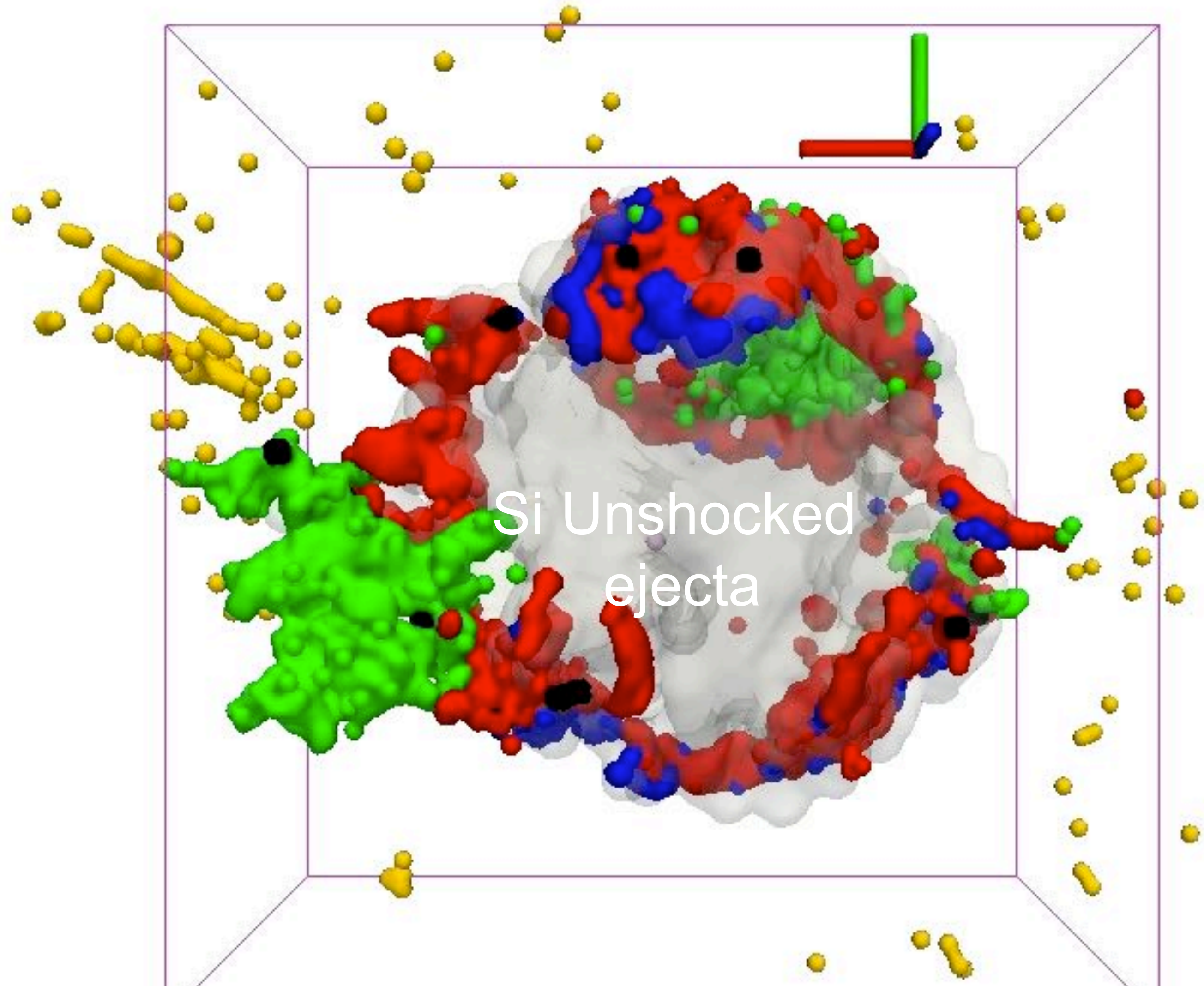
Nine Gemini GNIRS spectra of SN 2017eaw in 2017. (Rho et al. 2018): Dust starts to form soon after CO forms.

★ Continuum "flattens" from 2.1 μm , indicating emission from hot dust. Carbon: dust temperature of 1700 → 1400 K

★ More about dust of SN2017eaw: Tinyanont et al. 2019 (10^{-6} – 10^{-4} $M_\odot$)

Cas A SNR

- The youngest SNR: explosion in AD 1671 (347 yr old) and one of the best studied SNR in multi-wavelengths.
- Fast moving knots in optical as high as 11000 km/s
- Expansion velocity is 6000 km/s
- Progenitor is W-R star with 15-30 $M_{\odot}$
- Ejecta: strong Si, S and moderate Ar, Fe L and Fe K emission in X-rays. Highly clumpy ejecta of [SII] and [OIII] with 0.2-0.4”(0.003-0.007pc) in optical. Ejecta have highly enhanced abundances from nucleosynthetic yields.
- IR: ISO LWS observed a few spectra in IR.
- Synchrotron emission in radio, infrared and hard X-rays: Relativistic particle acceleration in the ejecta and in the forward shock material.

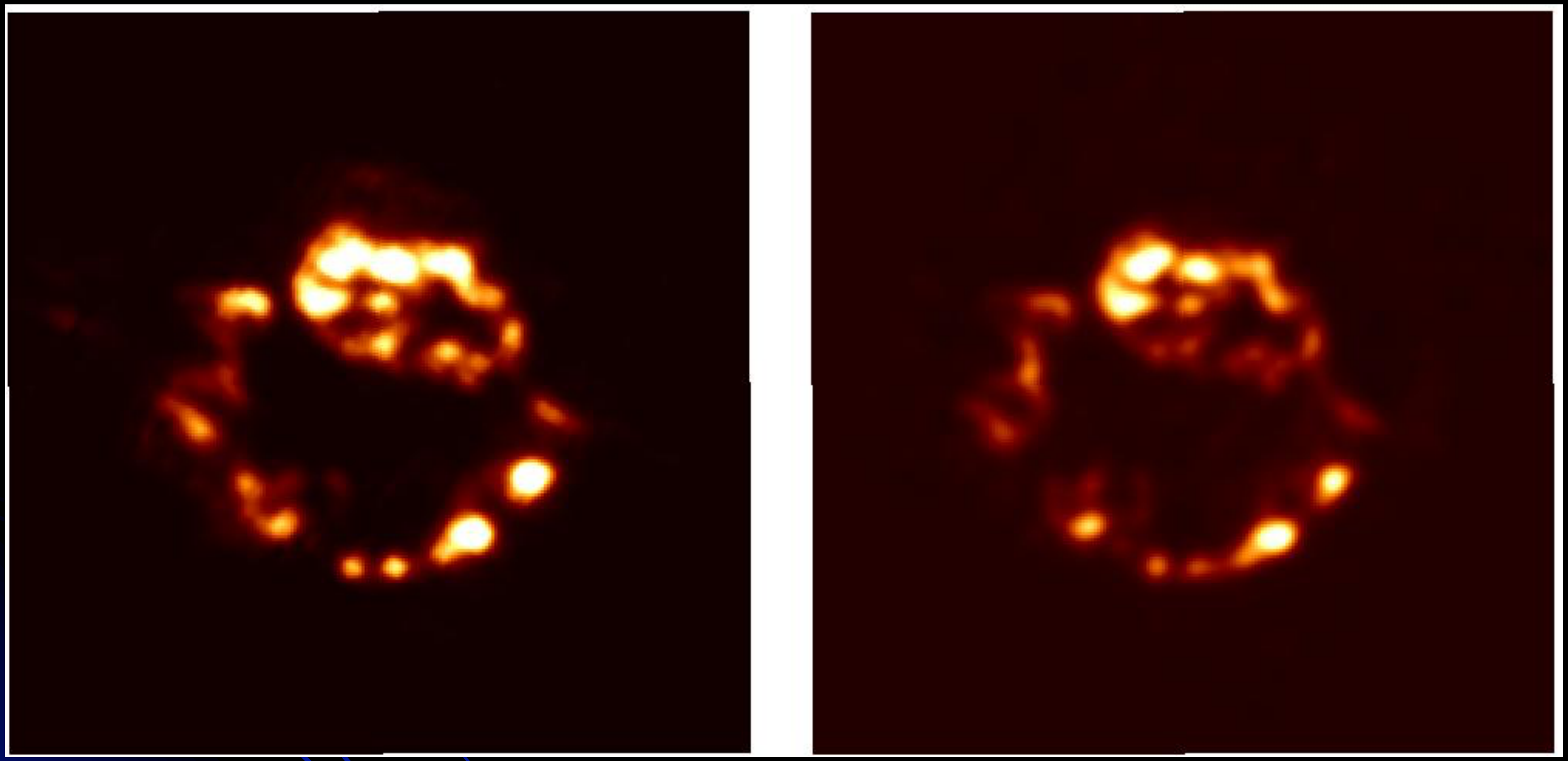


DeLaney et al. (2010) using Spitzer
Ar (IR)
SiII(IR)
g: Fe K (X-ray)
Si XIII (xray)
optical

Where is dust?

Cas A: Dust forms in Ejecta

Did dust grains form in the SN ejecta? SN-dust is confused with CSM/ISM and echo dust in SNe.



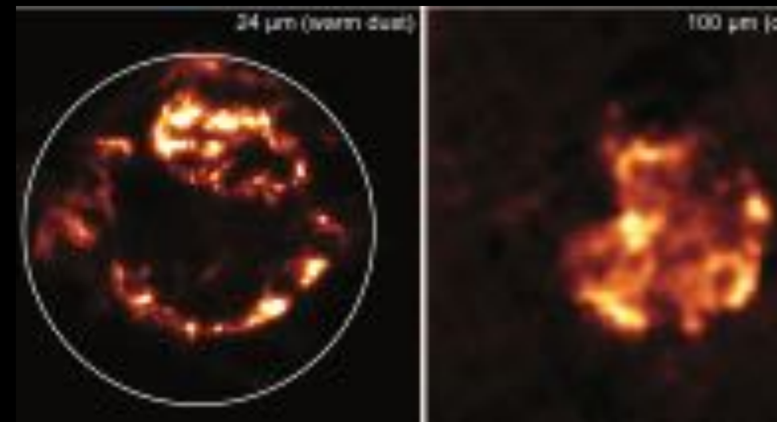
21μm dust map which is continuum map of 19-23μm subtracted by the baselines of neighboring wavelengths.

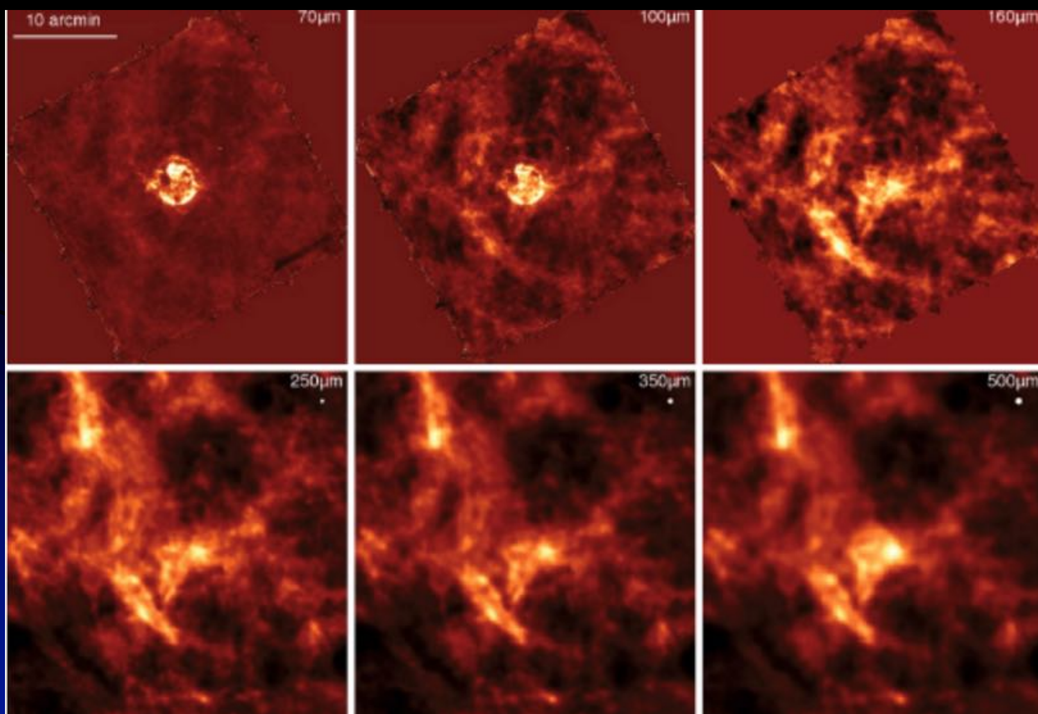
[Ar II] 7μm map (the resolution is convolved to match): remarkably similar to the dust map.

Cold Dust in CAS A

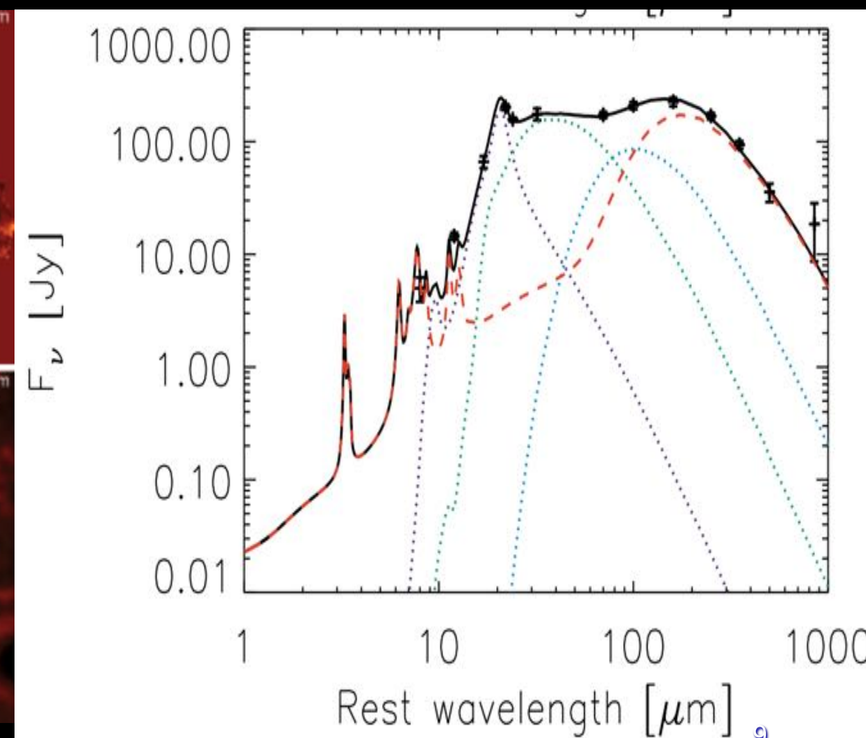
- Herschel PACS (70,100,160) + SPIRE (250,350,500) reveal 0.6 $\underline{M}_{\odot}$ of cold dust in inner region [Previously no cold dust was suggested (Krause et al. 2004).]

Warm dust vs Cold dust

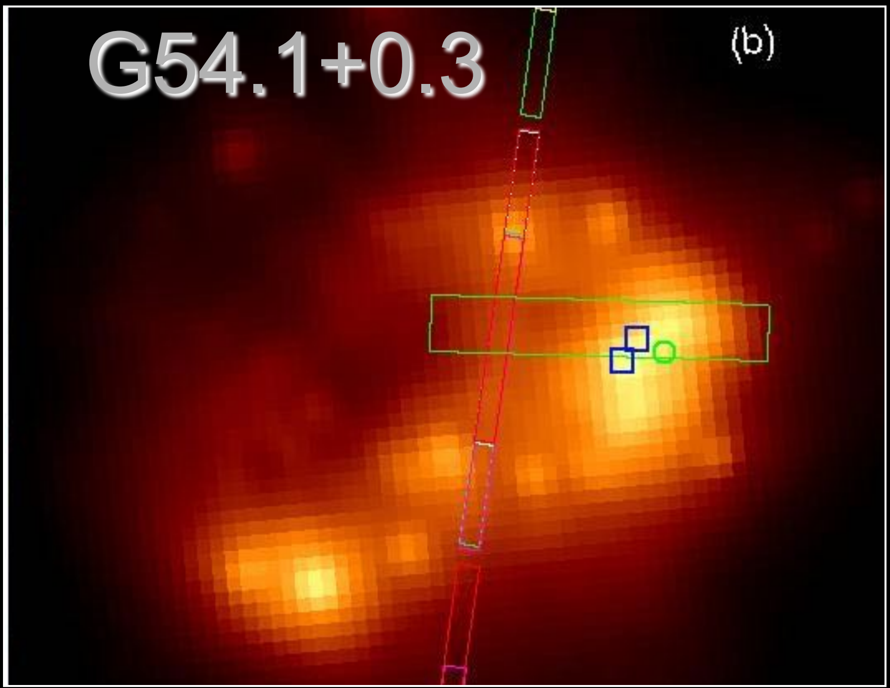


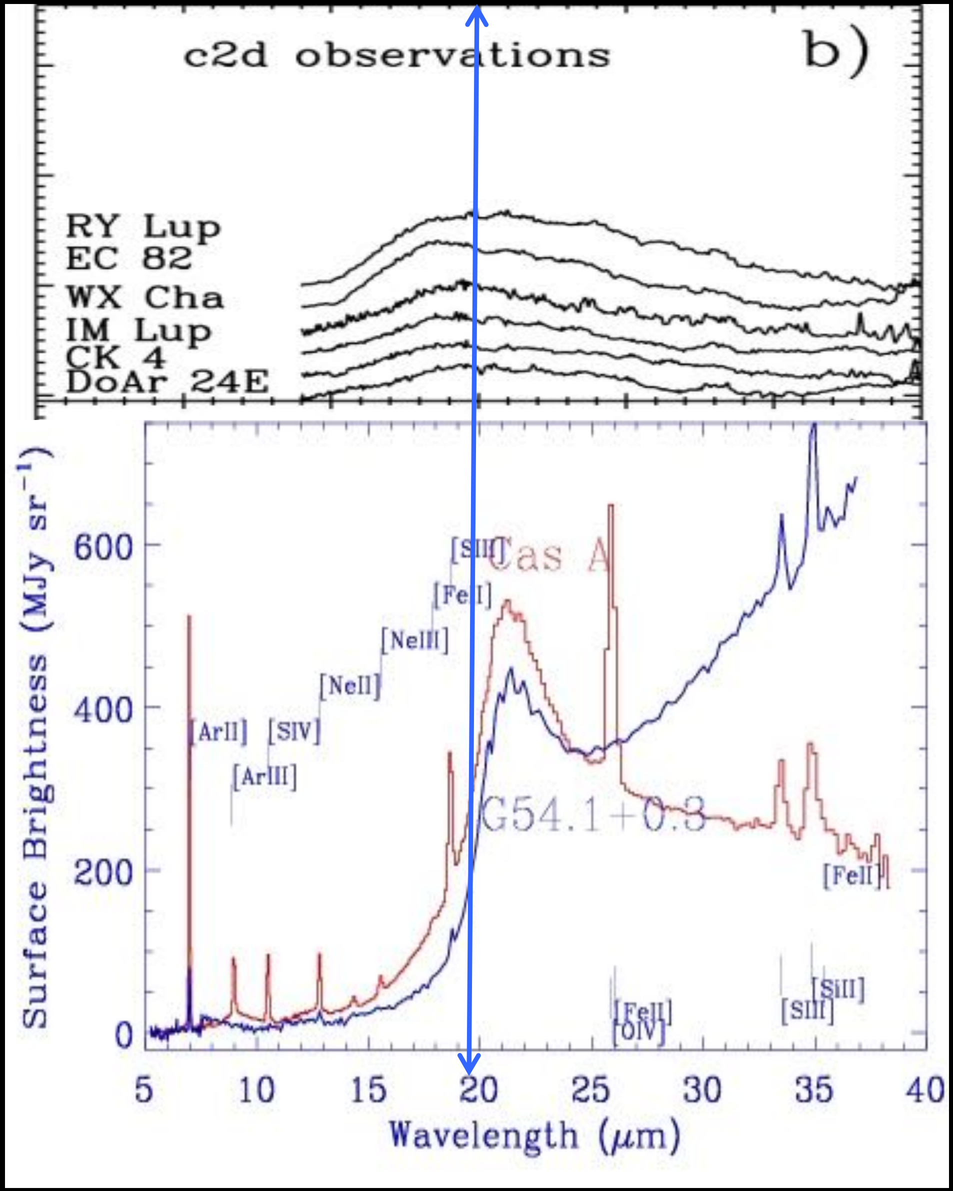


Barlow et al. (2010)



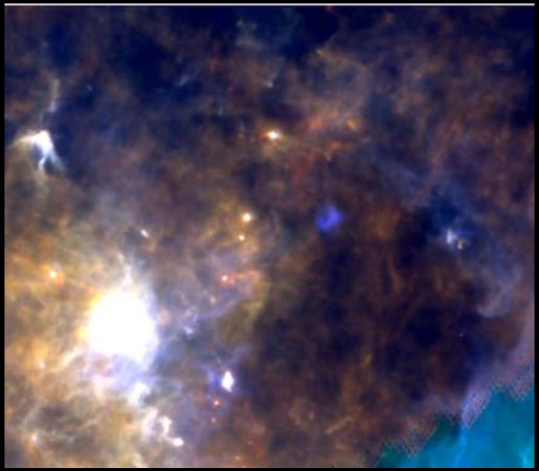
De Looze et al. (2017): dust mass of 0.6 $\underline{M}_{\odot}$

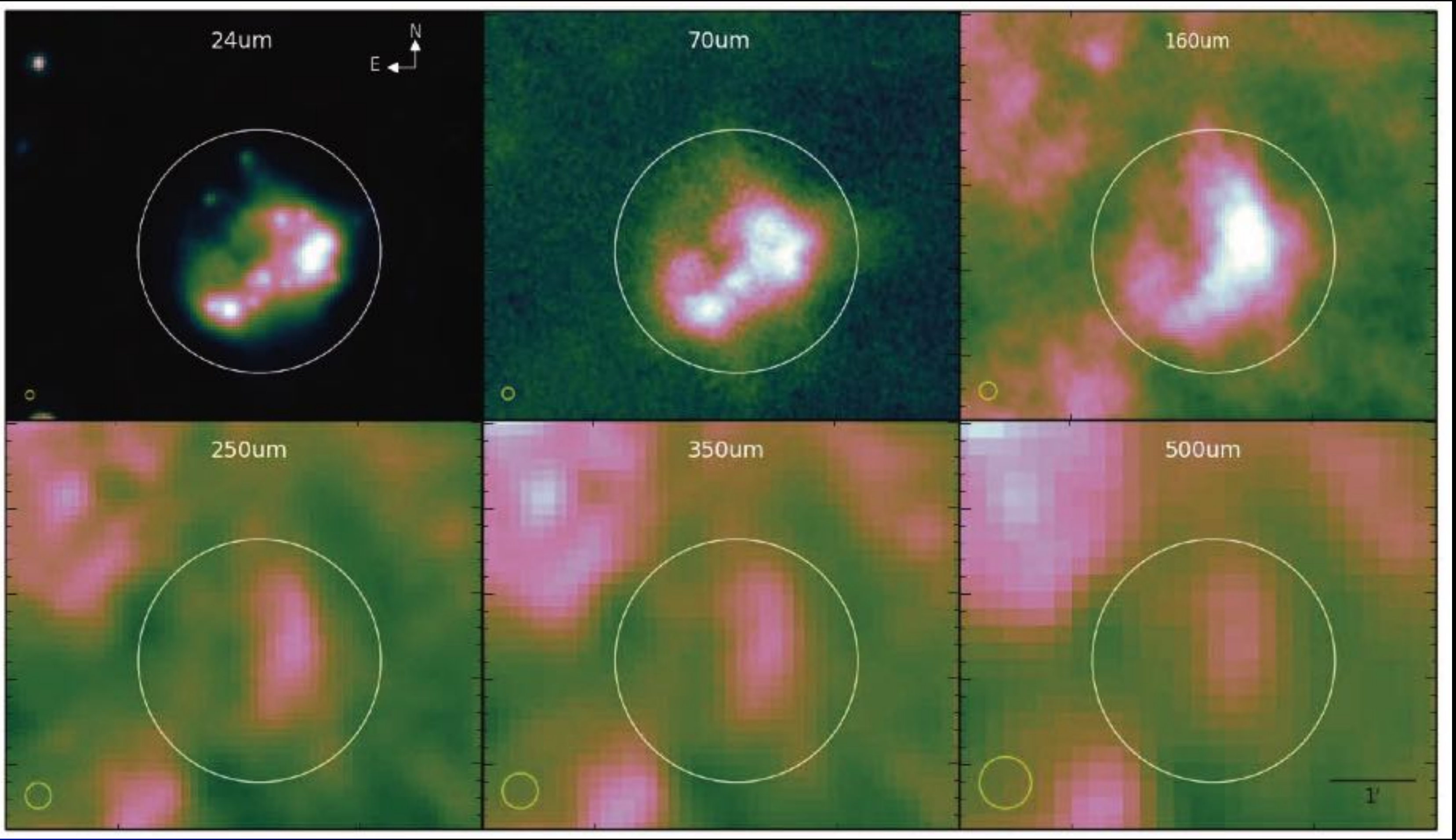




- We found IRAC and MIPS emission from the Crab-like SNR G54.1+0.3
- Dust Twin of Cas A; 21 μm dust
- Different dust feature from young stars or AGB (Carbon or FeO) stars

Dust in G54.1+0.3





Herschel Cold Dust

G54.1+0.3 (Crab-like SNR)

far-IR: green+blue
X-ray: yellow
radio:red

- Detection of Pre-solar grains of Silica (SiO_2):

Exploding Stars Make Key Ingredient in Sand, Glass

(JPL Press-release)

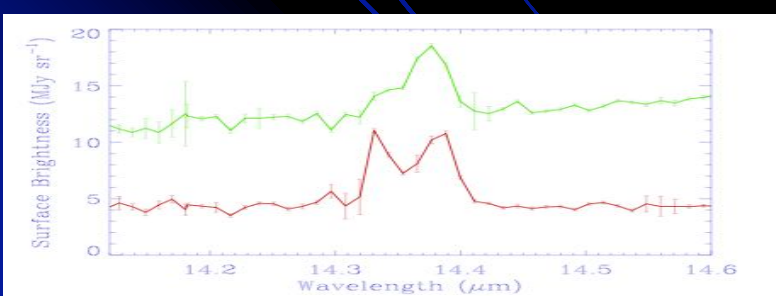
Dust mass ~0.1-0.9 $M_\odot$

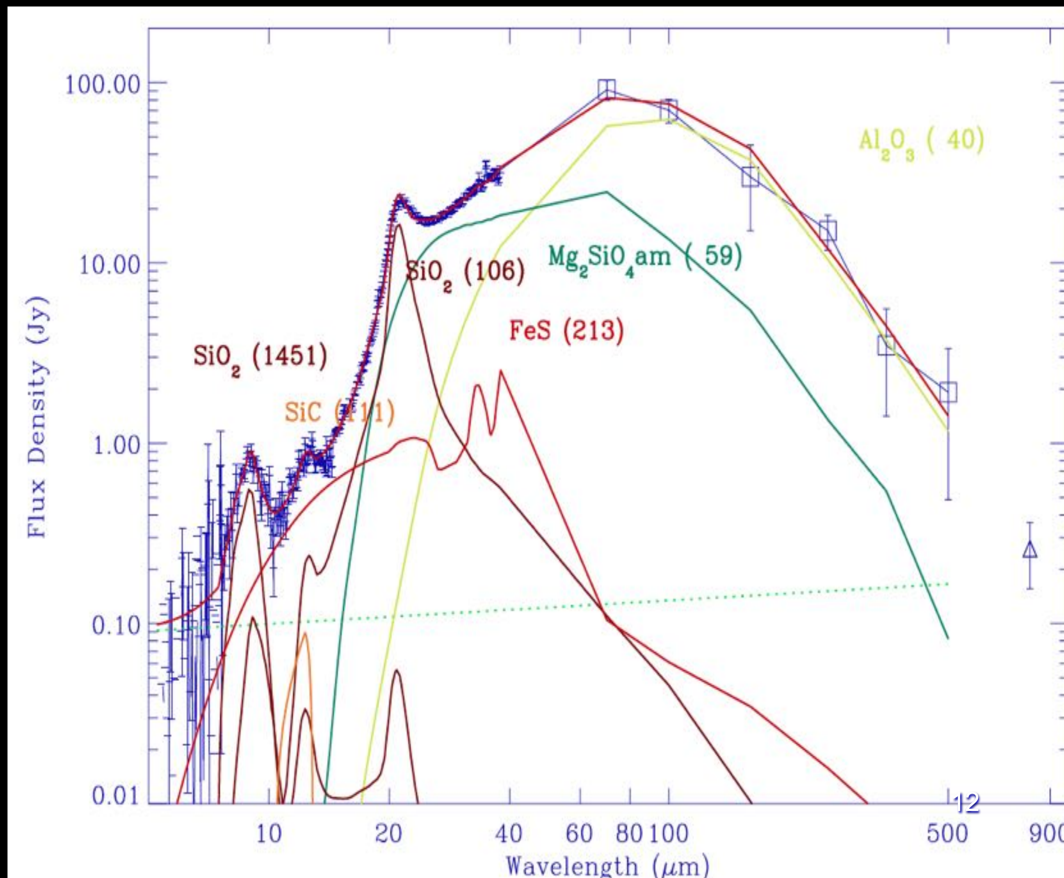
(Rho et al. 2018)

- G54.1+0.3 contains136 ms pulsar (in X-ray) and Pulsar wind Nebula (in radio) with ejecta shell (in far-IR)

- Ar ejecta (IRAC 8 micron map)

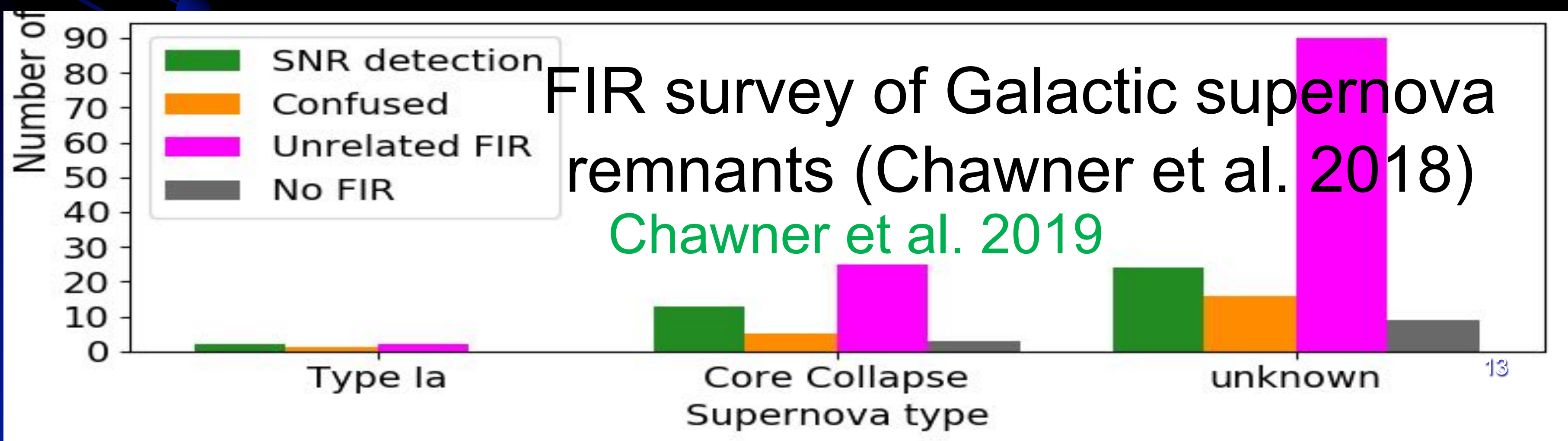
And [Ni I] at 14.8 μm: high velocity of 3600 km/s ➔Ejecta





Ejecta Dust in Pulsar Wind Nebulae

$M_d = 0.34 \pm 0.14\ M_\odot$ $M_d = 0.29 \pm 0.08\ M_\odot$ $M_d = 0.51 \pm 0.13\ M_\odot$



FIR survey of Galactic supernova remnants (Chawner et al. 2018)

Chawner et al. 2019

Dust mass in YSNRs:

YSNR(progenitor)	Mass ($M_{\odot}$) (Spitzer/**Herschel**)
Cas A (15-30 $M_{\odot}$)	0.02 – 0.054 $M_{\odot}$ (Rho et al. 2008): 0.04 $M_{\odot}$ (<0.1 $M_{\square}$; Arendt et al. 2014; 8-160um.) 0.075 $M_{\odot}$ (Barlow et al. 2010): **0.3-0.6 $M_{\odot}$** (De Looze et al. 2016):
E0102 (Type Ib)	**0.007-0.014** $M_{\odot}$ (Rho et al. 2009): 0.003 $M_{\odot}$ (Sandstrom et al. 2009)
G54.1+0.3 (15-35 $M_{\odot}$)	0.06 $M_{\odot}$ (Temim et al. 2010): **1.1$\pm$ 0.8 $M_{\odot}$ (Temin et al. 2017)** **0.1-0.9 $M_{\odot}$ (Rho et al. 2018)**
SN 1987A	**0.5-0.7 $M_{\odot}$** (Matsuura et al. 2011)
Crab Nebula (12 $M_{\odot}$)	**0.001-0.012** $M_{\odot}$ **(Temim et al. 2006, 2010)** **0.1** $M_{\odot}$ (Haley et al., 2012)

Photometry: G11.2-0.3: M_d= 0.34 ± 0.14 $M_{\odot}$, G21.5-0.9: M_d= 0.29 ± 0.08 $M_{\odot}$, Kes 75: M_d= 0.51 ± 0.13 $M_{\odot}$

How much SN-dust is destroyed by reverse shock?

- Do we understand dust evolution in galaxies?

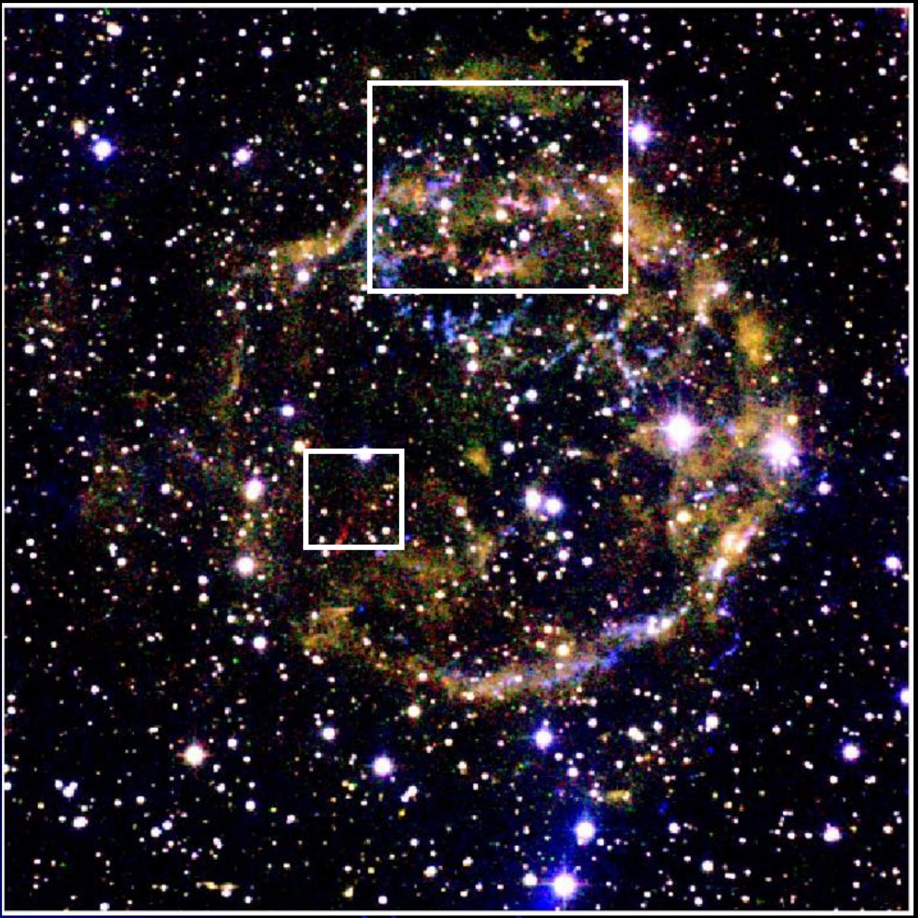
Dust destruction rate is higher than the total dust input from AGB and SNe.

- Dust Destruction rate from reverse shock: Dependence of grain species: 1-100%?

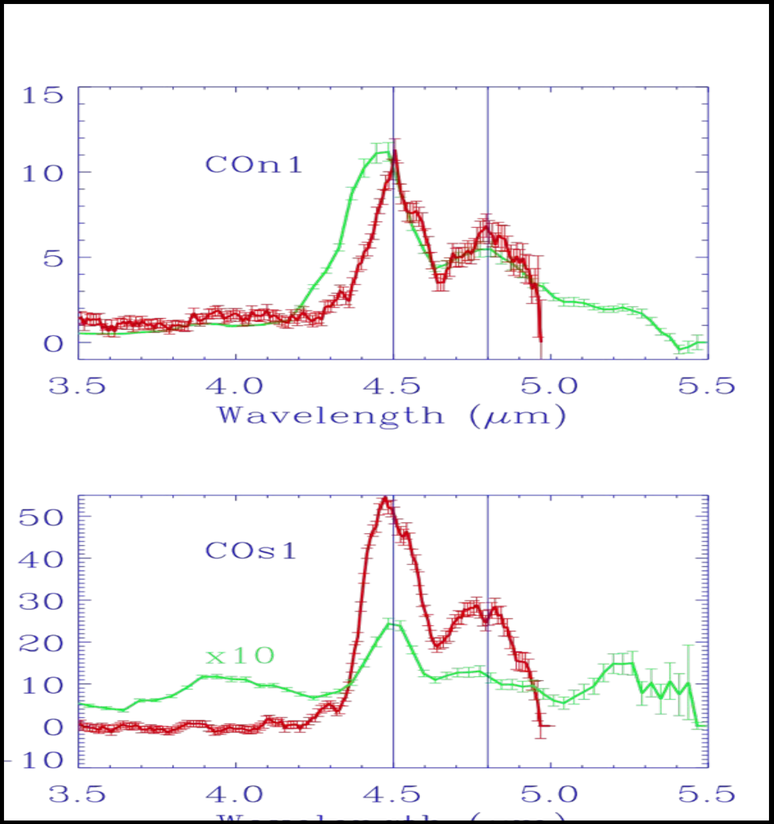
Ref	Dust destruction rate (%)	grains
Nozawa et al. (2007)	100	$MgSiO_3$
	45	Carbon
Bianchi & Schneider (2007)	97	
Nath et al. (2008)	1	
Silvia et al (2012)	4-56	C
	5-93	SiO_2

First Molecule Detection from SNR

Rho et al. (2009)

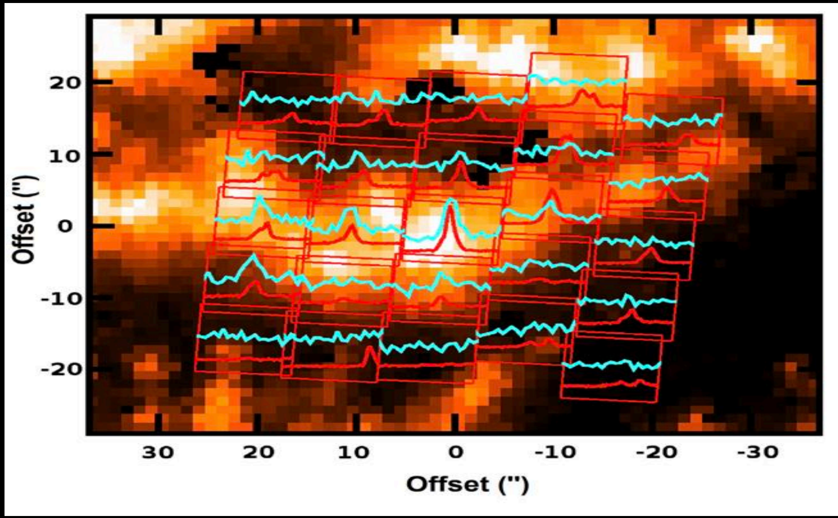


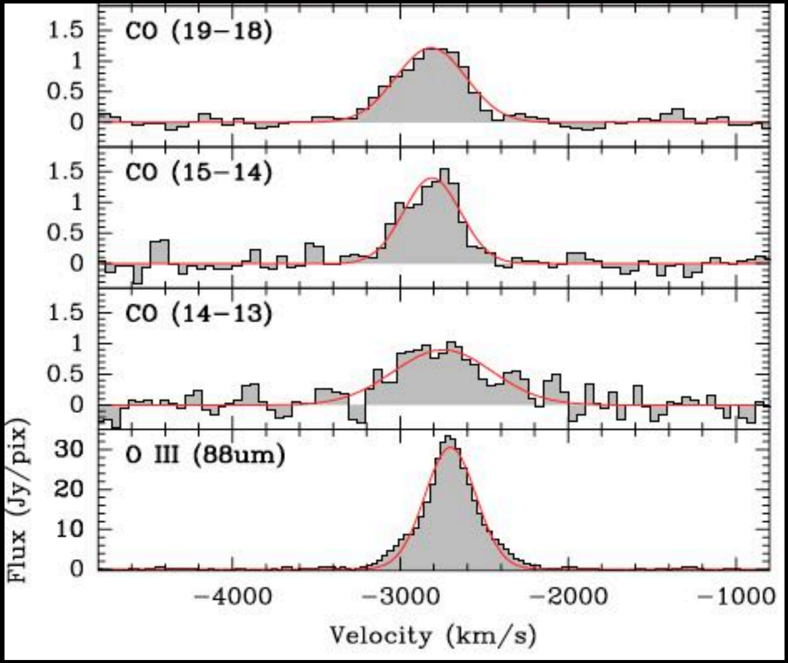
Near-IR imaging: CO filter (red): 2.294μm K-cont (green): 2.27μm
Pβ (blue):1.182μm;



CO Fundamental band using AKARI
N(CO)=4×10^{17} cm^{-2}
(n=10^{6} cm-3)
Rho et al. (2009)

CO detection with Palomar, AKARI and Herschel





Wallström et al. (2013)

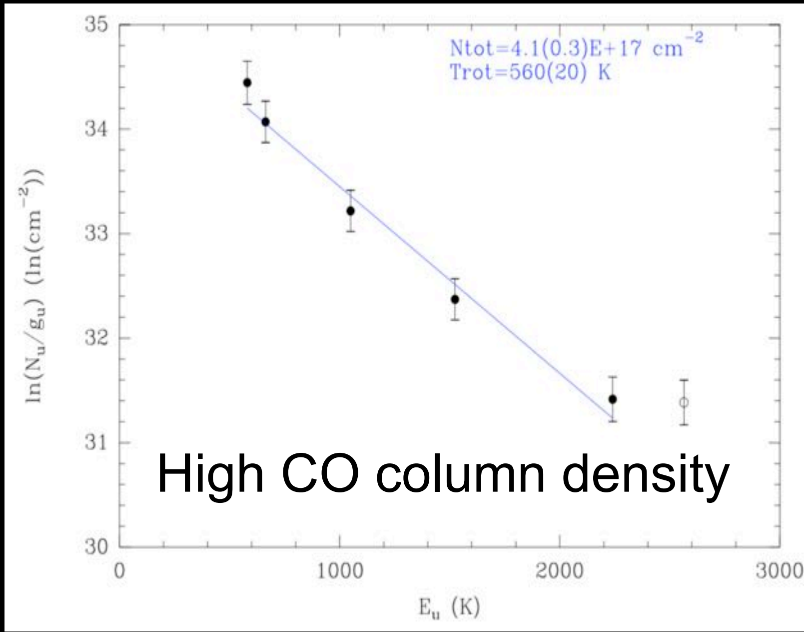
Herschel detected high-J CO with velocity width of 300 km/s, similar to that of [OIII] 88um

- $N_{CO}=4\times10^{17}cm^{-2}$, $n=10^{6}$ cm^{-3}
- 1T model : Trot=560 K

→CO reformation behind the shock

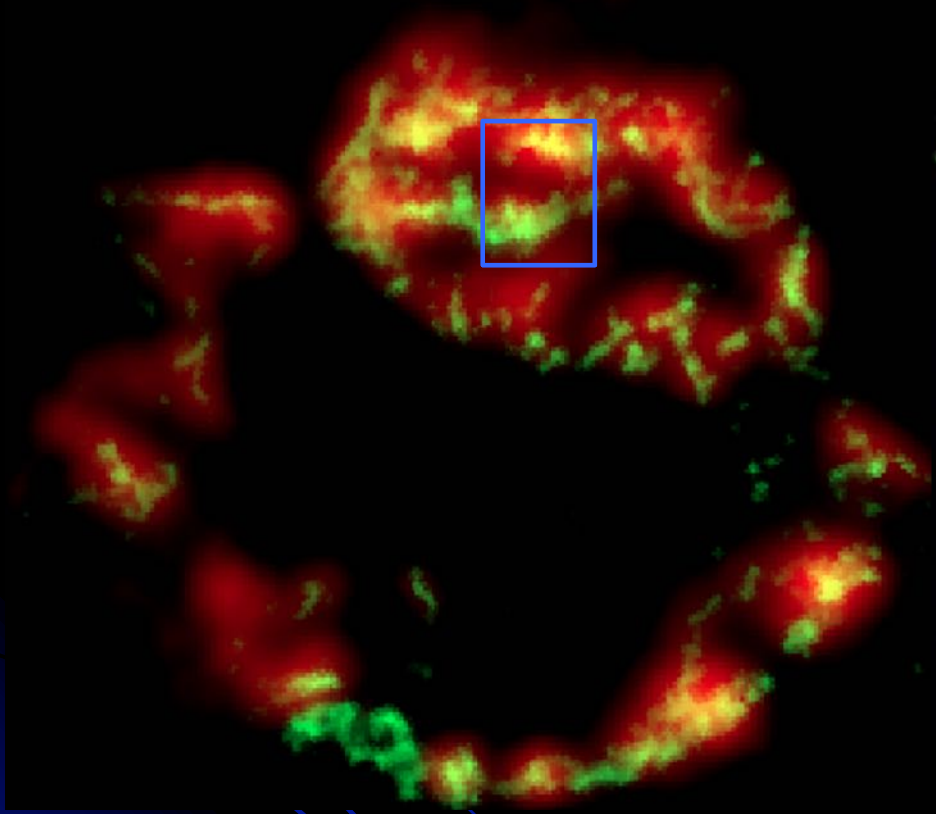
- Modeled by Chiara & Cherchneff (2014)

→ Dust may be protected by CO re-formation → lower dust destruction (CO shields the dust)

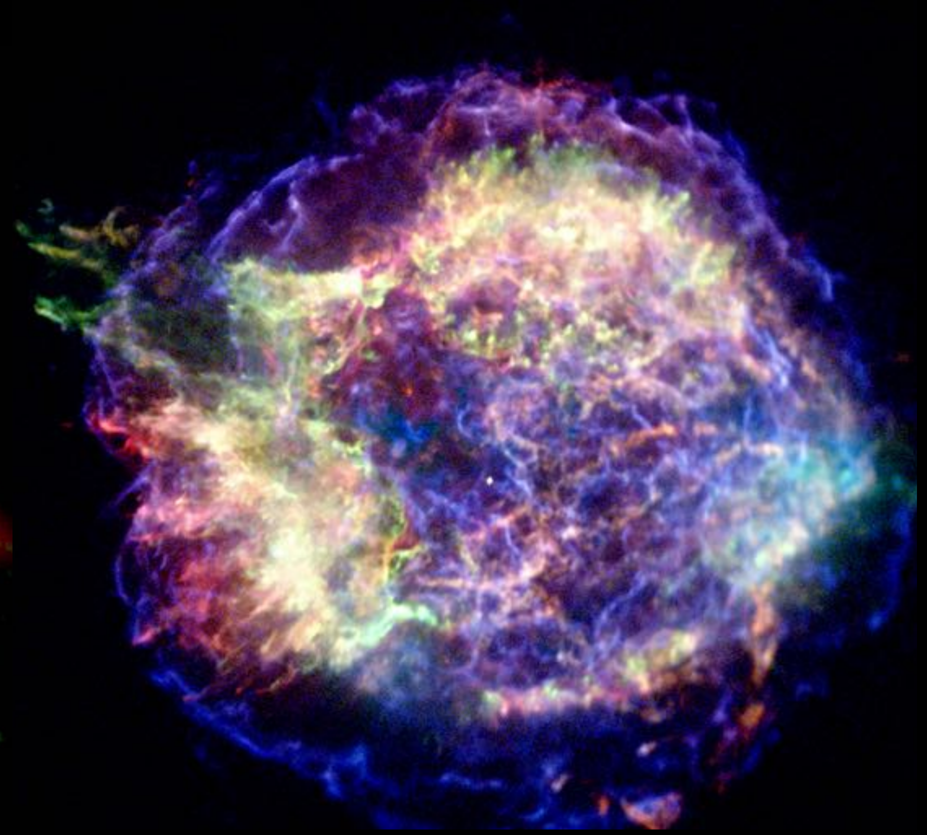


SiO_2 dust (red): using Spitzer IRS

CO (green): Spitzer Band2



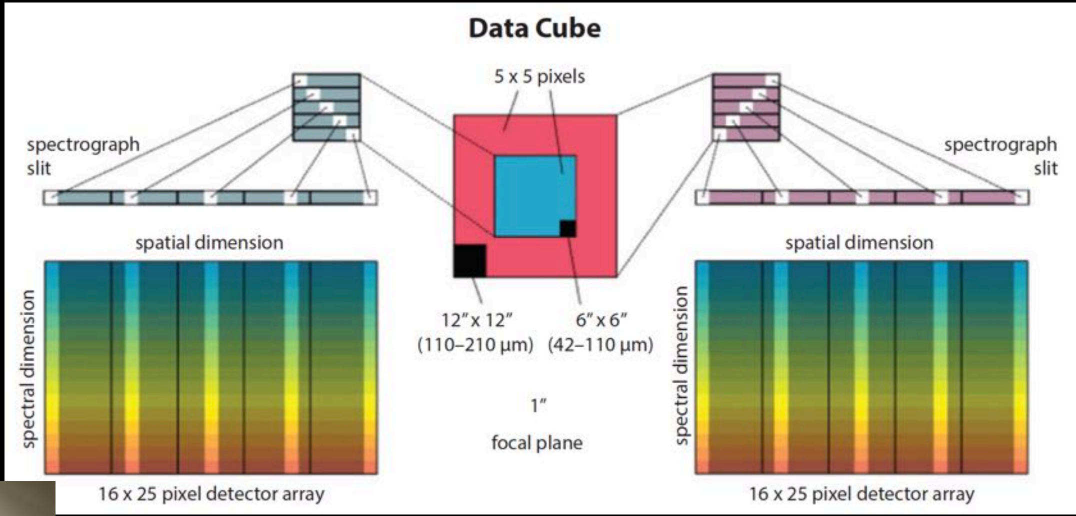
X-ray map Si, S, Fe

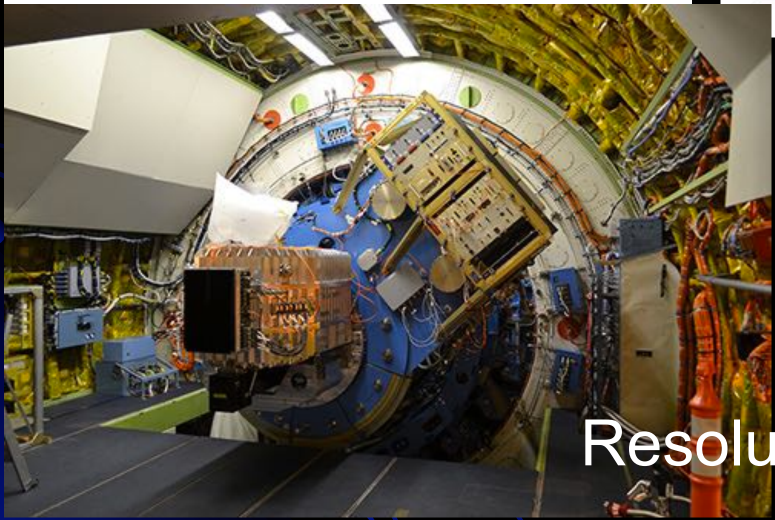


- Fundamental CO band detection (Rho et al. 2009, 2012)
- CO is within hot, X-ray plasma (10^7 K): one-to-one match
- Knots (0.2”-0.6” with HST: 6000-12000 AU)

SOFIA observation of Cas A with far-IR spectrometer (FIFI-LS)

- Integral-Field Far-IR Spectrometer
- 1st Gen Instrument
- PI A. Krabbe (Universität Stuttgart)



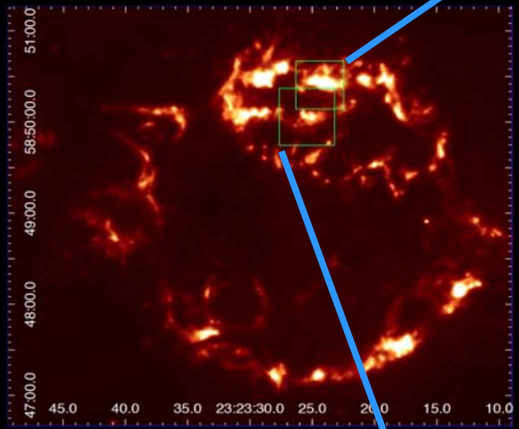


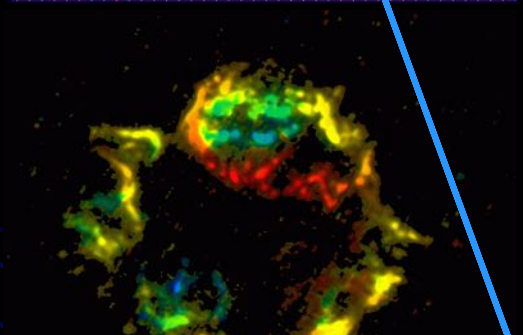
Channel Parameters

Channel	Field of View	Pixel Size	λ Range
Blue	30″x 30″	6″x 6″	51–120 μm
Red	1′x 1′	12″x 12″	115–203 μm

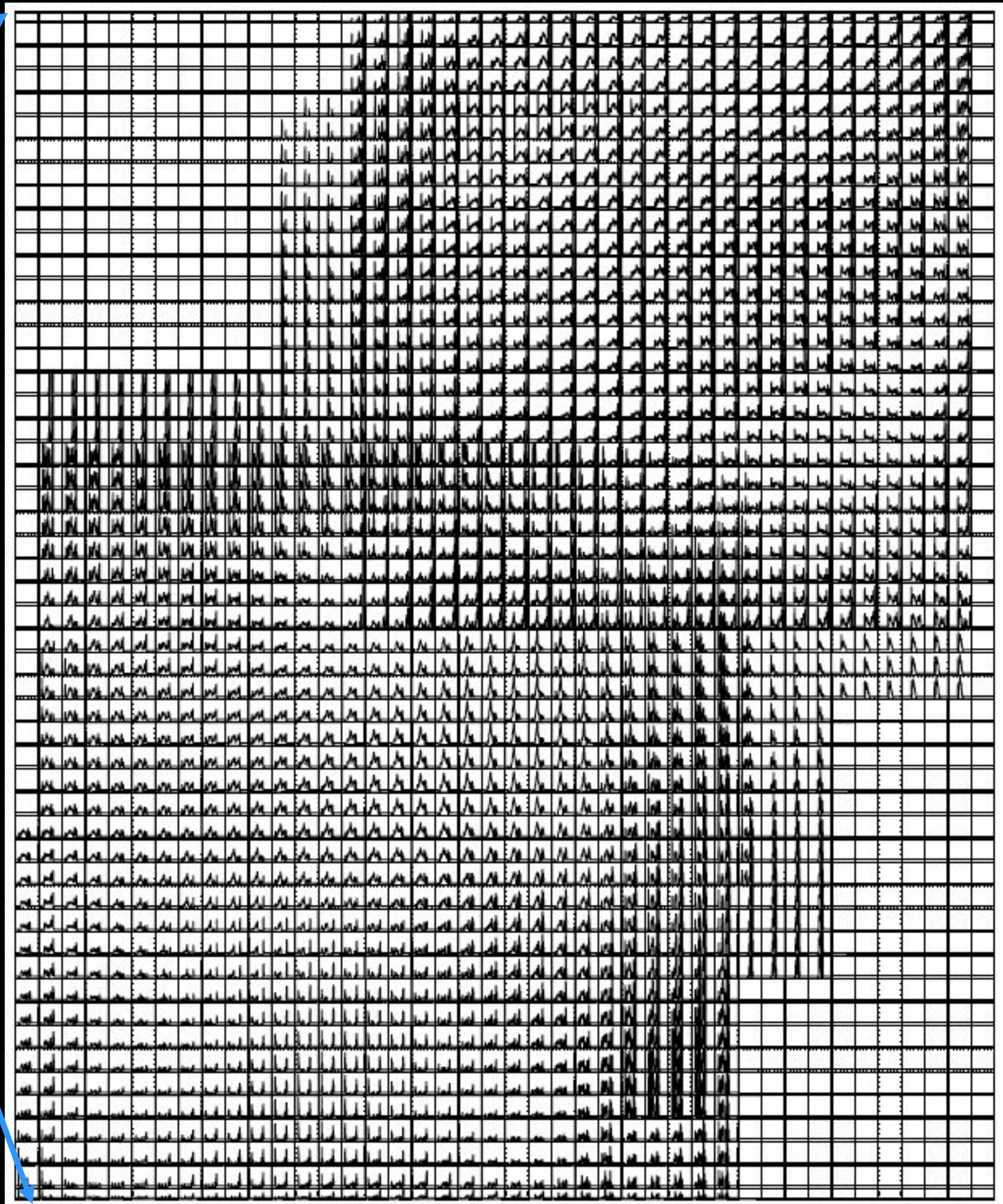
Resolution is comparable to Herschel PACS 6" at 63micron

Goal: Where are [OI] and [OIII] located relative to ejecta, CO and dust?

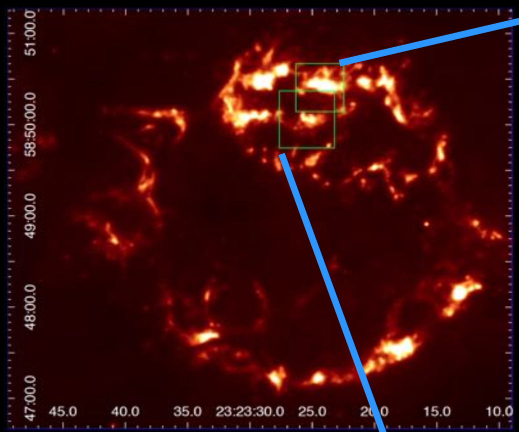


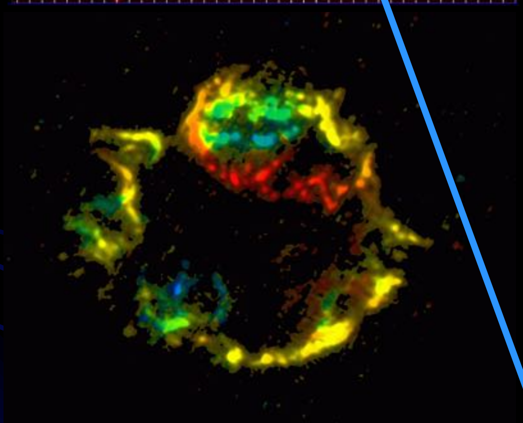


FIFI-LS observations
[OIII] 88 and 52um
[OI] 63um
42x56=2352 spectra
(1arcmin: 1" pixel size)

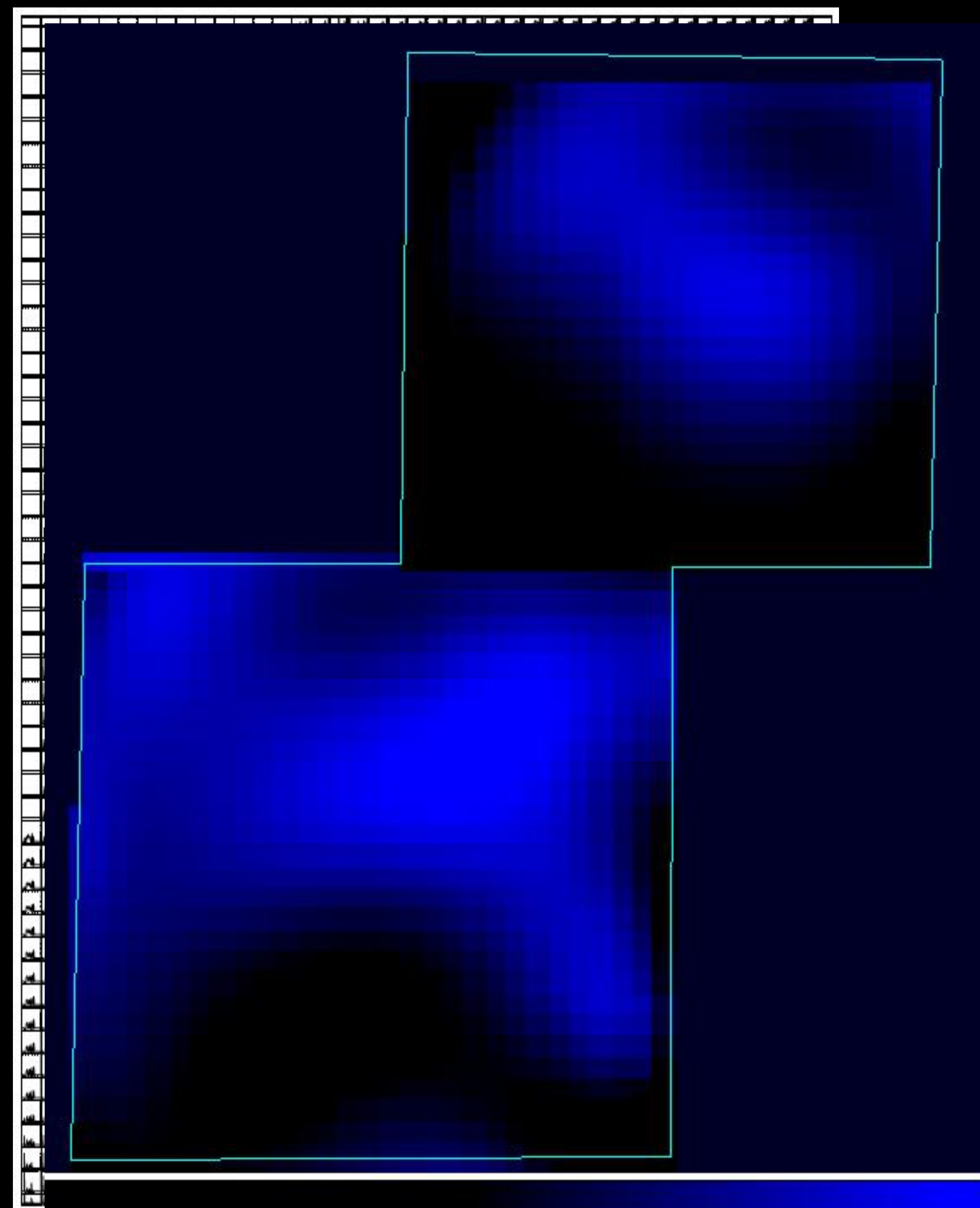


SOFIA [OI] and [OIII] Observations of Cas A





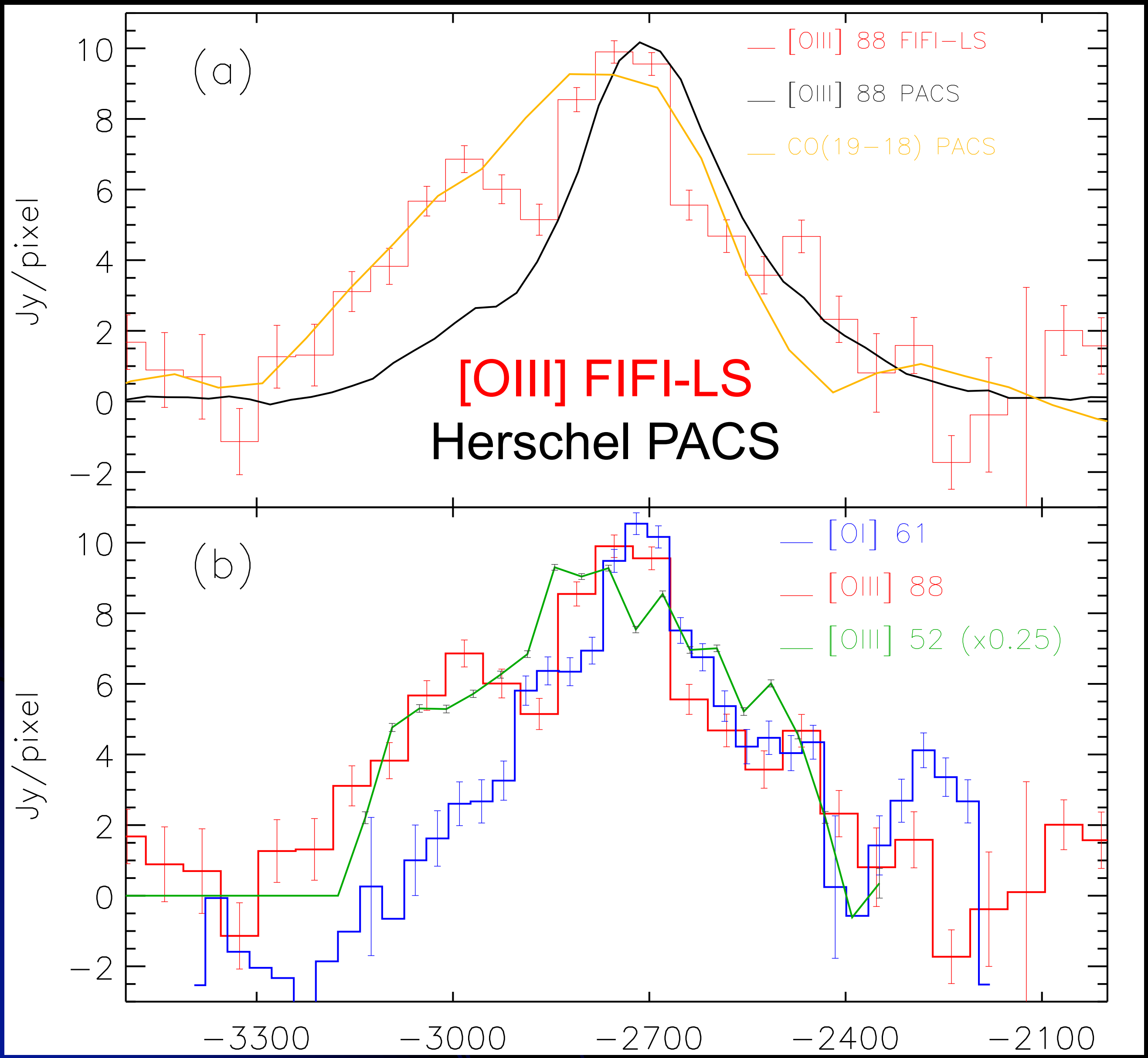
[OI]



Goal: Understand CO-dust-knot

FIFI-LS 42x56=2352 spectra (1')

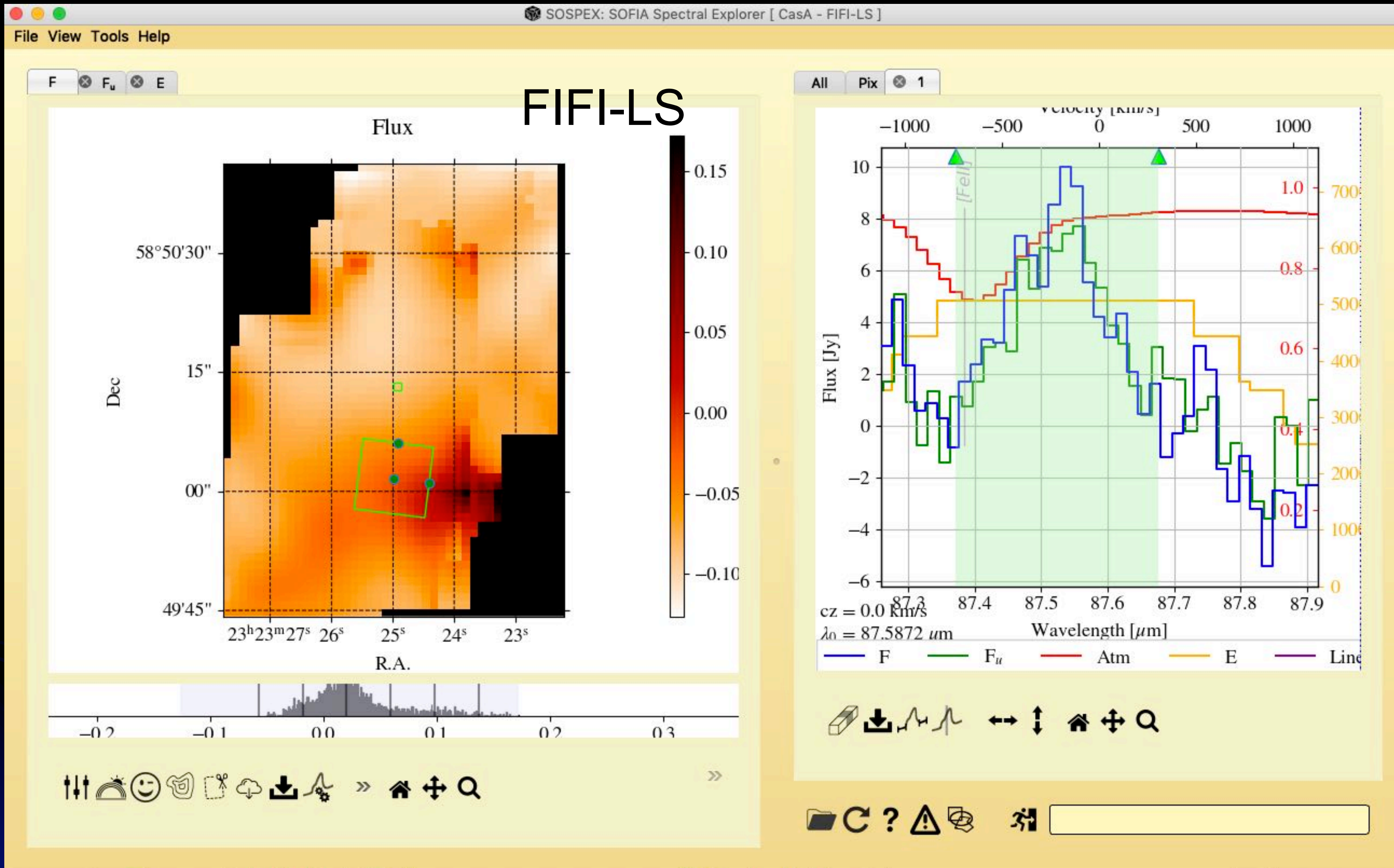
SOFIA FIFI-LS Spectra



FIFI-LS spectrum is comparable to PACS.
FIFI-LS has limited bandwidth

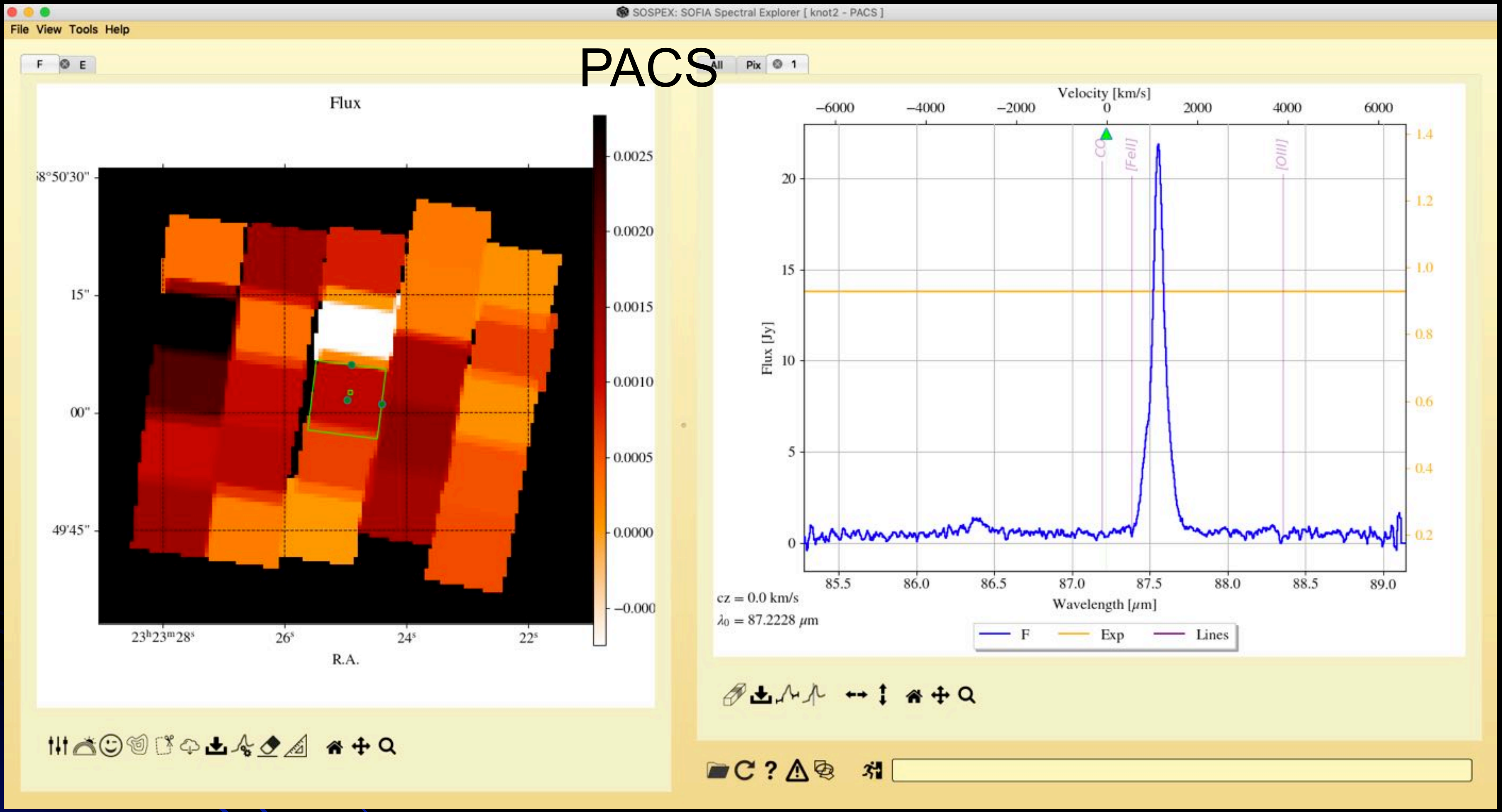
Shock models suggest [OIII] is pre-shocked gas and [OI] is post-shocked cooled gas (Borkowski 1990)

FIFI-LS



Data are reduced using SOSPEX tool (D. Fadda):

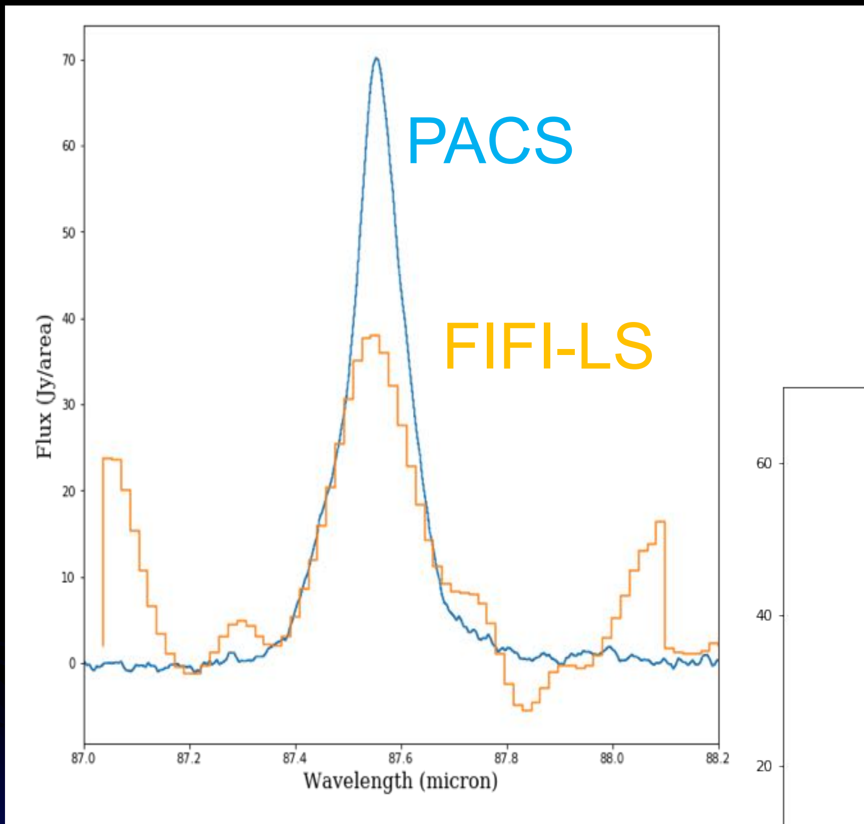
- Comparison between FIFI-LS and PACS data: FIFI-LS has dithers so better spatial information although the beam sizes are similar to each other.



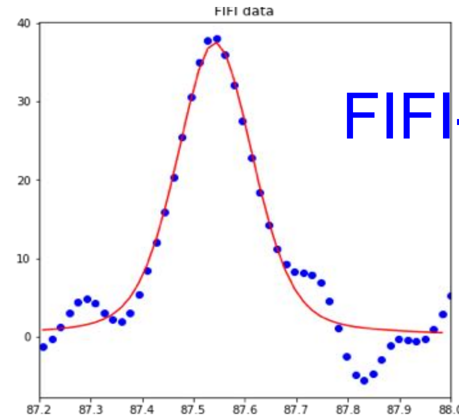
PACS:

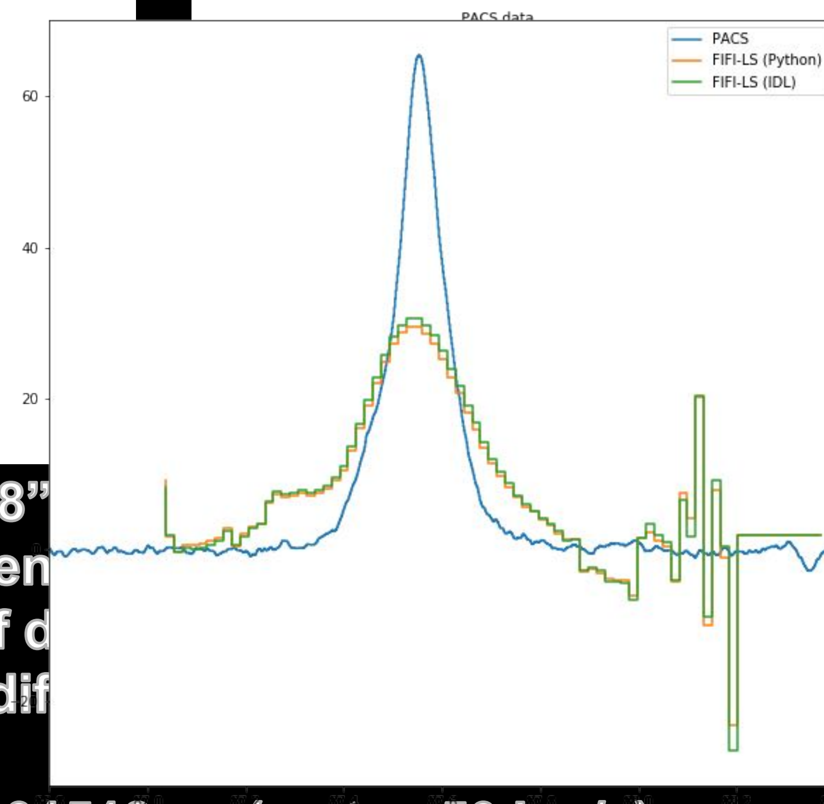
- Very little spatial information: 1 flux number per 9” pixel.
- A large variation of flux in pixel by pixel.
- A long wavelength coverage.

FIFI-LS vs PACS



New processing (off-line)





For a large aperture (9” vs 18”

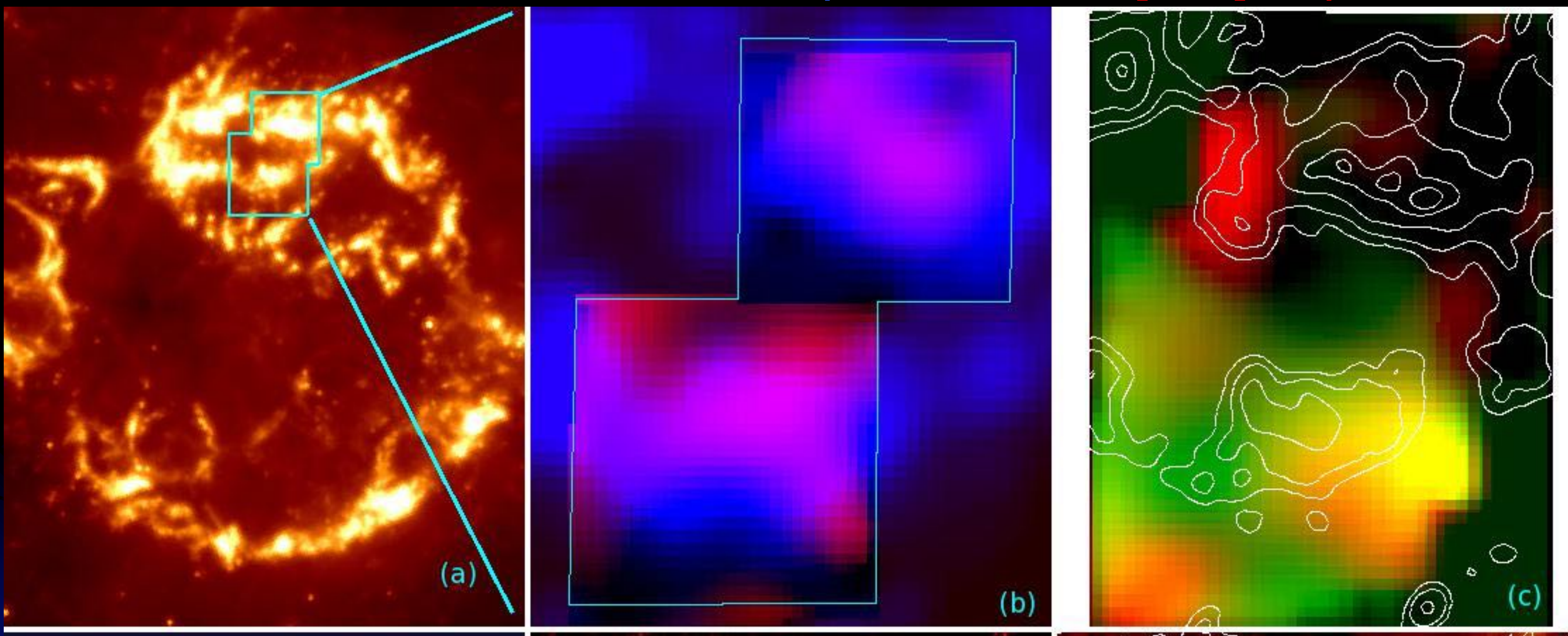
- Spectral resolution differen 24 km/s)
- FIFI-LS: large dithering of d pixel)
- Possibly only up to 15% dif w pipeline products)
- Wavelength difference: 0.01518µm (up to ~50 km/s).

Far-IR [OI] and [OIII] maps of Cas A

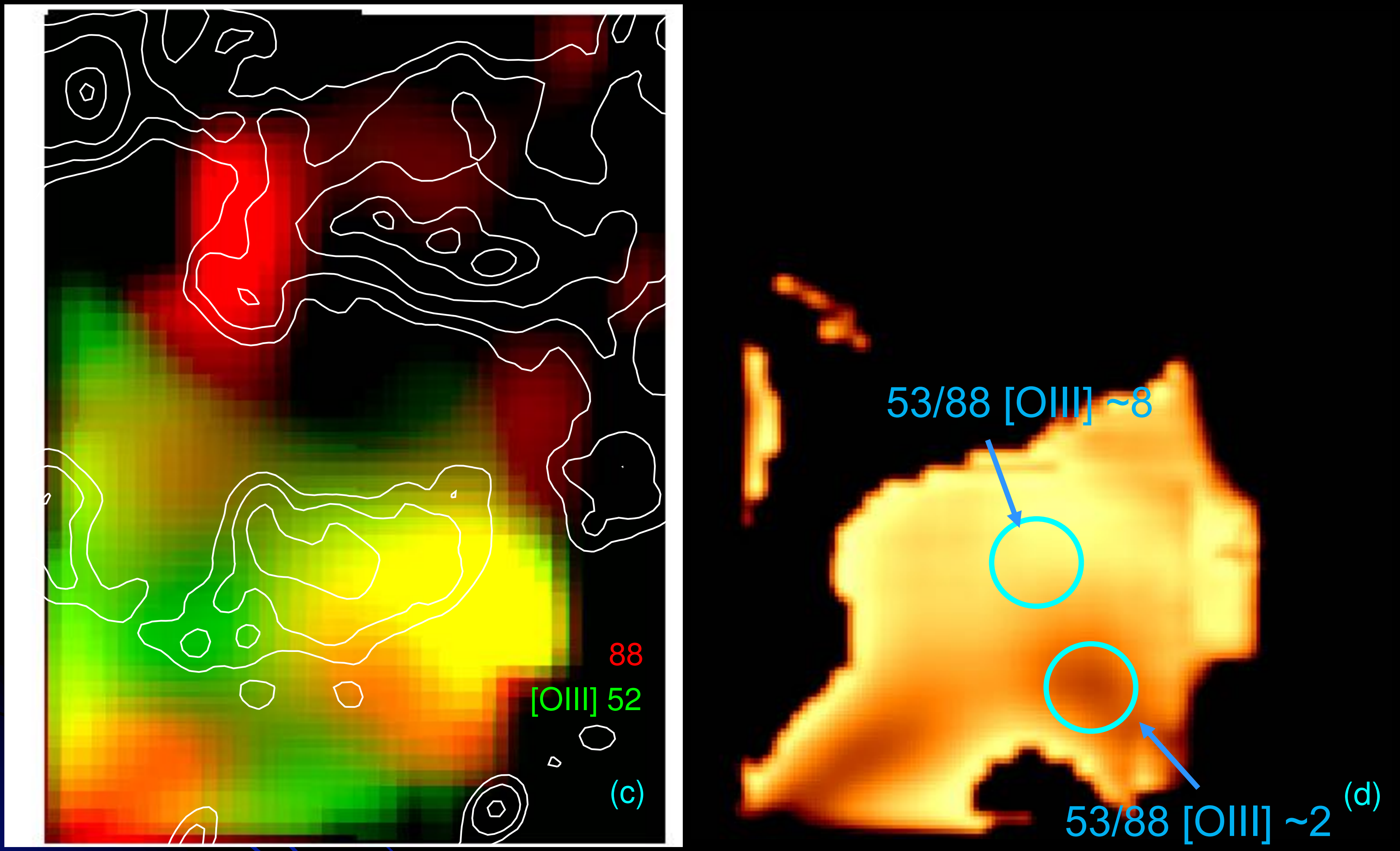
Spitzer 8μm Ar ejecta

[OI] 63μm red
CO 4-5μm blue

[OIII] 52μm green
[OIII] 88μm red



- [OI] 63μm emission is located to be close to CO/dust emission or dense ejecta, but slightly off to each other.
- [OIII] emission is diffuse, and the [OIII] peaks do not coincide with the ejecta knots; the ratio is a density indicator.

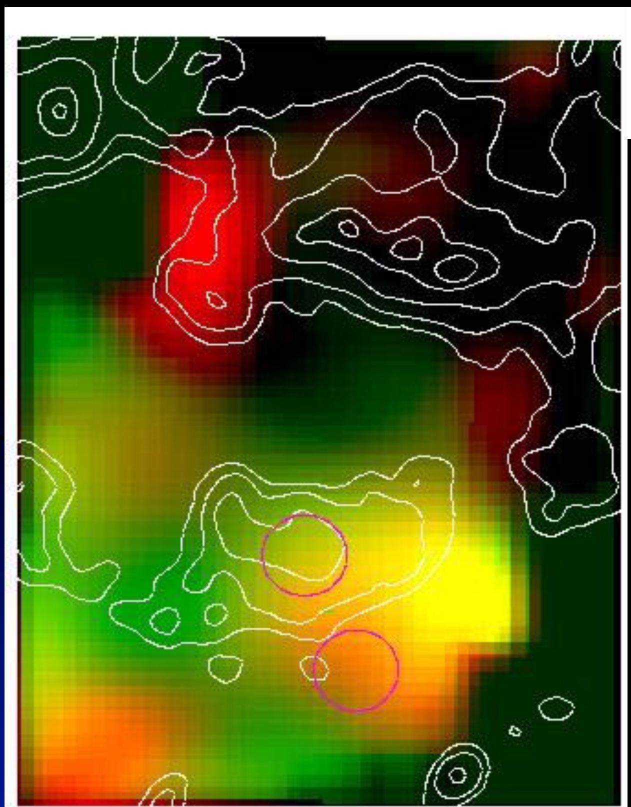


Comparison of [OIII], [OI], CO (Ar ejecta) and dust maps

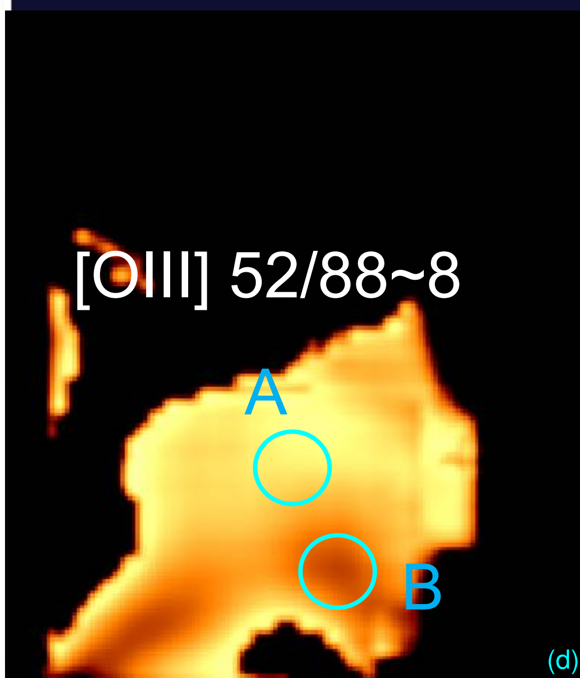
[OIII] 52/88 ratio map → density indicator

[OIII] 52μm green

[OIII] 88μm red

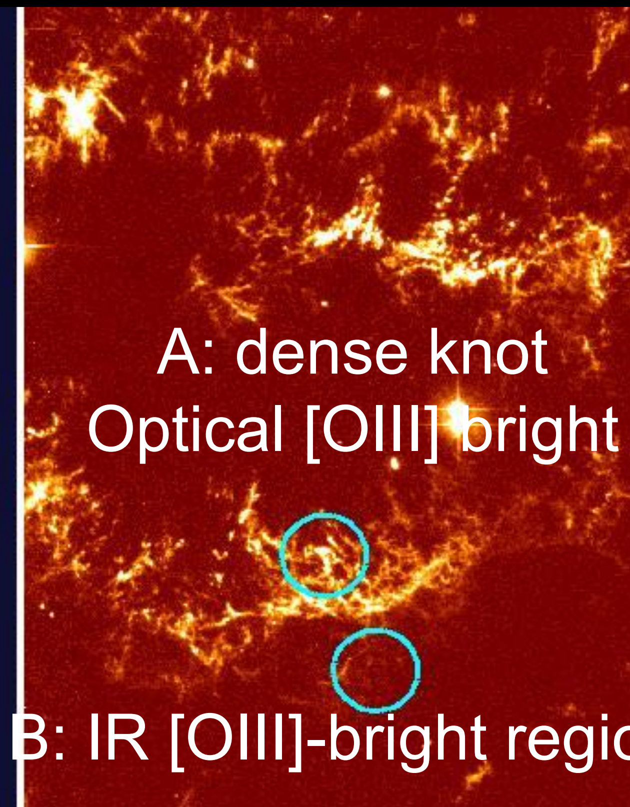


[OIII] 52/88 ratio

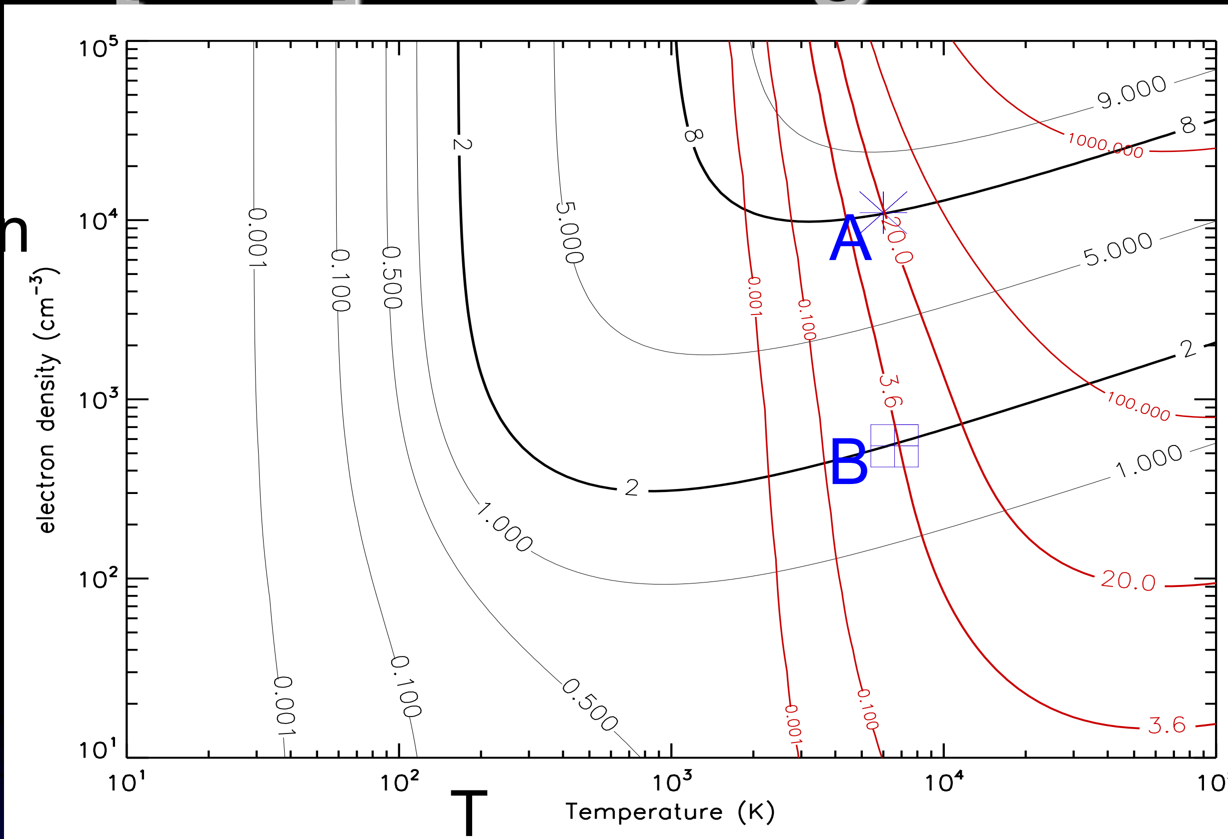


[OIII] 52/88~2

[OIII] optical 5007Å



[OIII] Line diagnostic analysis



52/88 ratio in black

5007/52 ratio in red

- The ratio of [OIII] 52/88 um (1-9) is a density indicator ranging 300-10^4 cm^{-3}

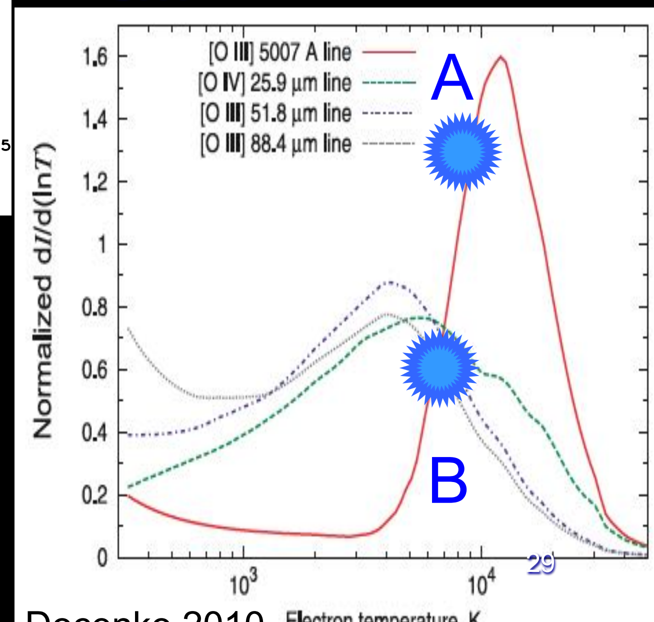
- Representative (n, T) are

A: Optical-bright [OIII], dense region:

10^4 cm^{-3}, ~6000K

B: IR-bright [OIII], diffuse region:

500 cm^{-3}, ~5500-6000K



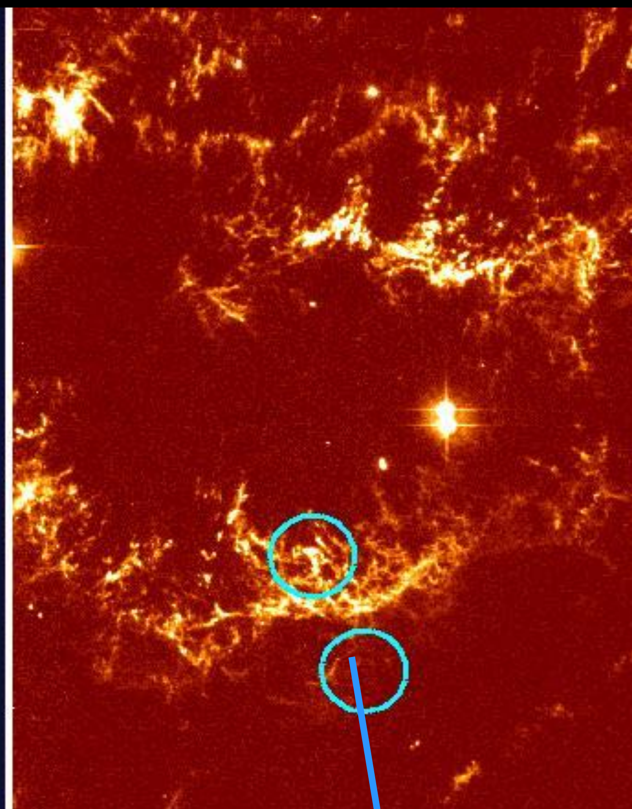
Docenko 2010

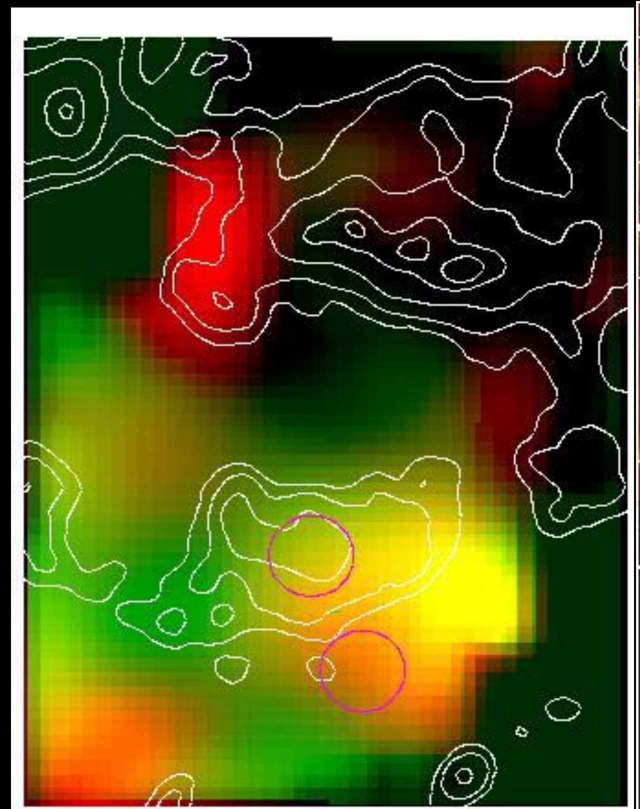
Evaporation continues in IR [OIII] to X-rays

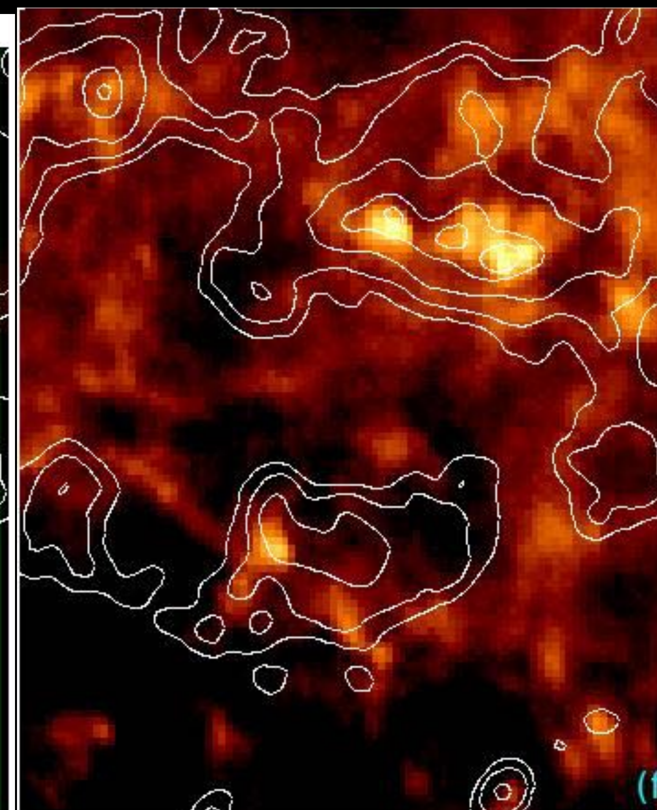
[OIII]5007

[OIII] 52µm green

Chandra X-ray

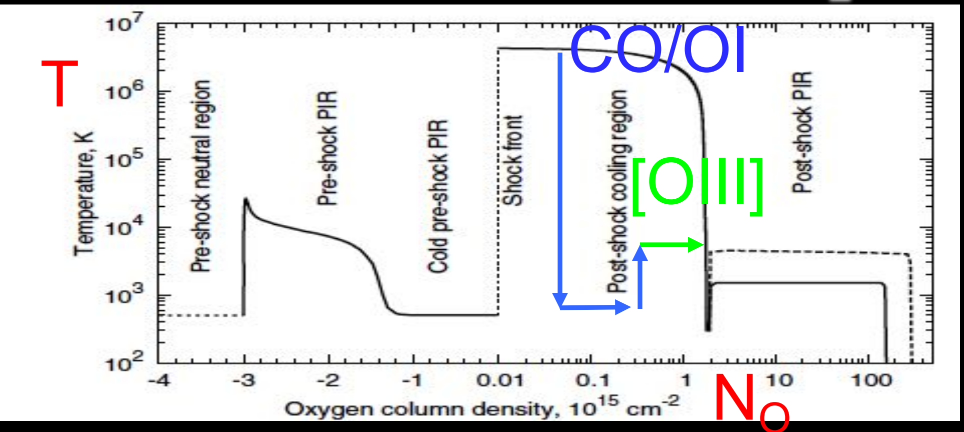


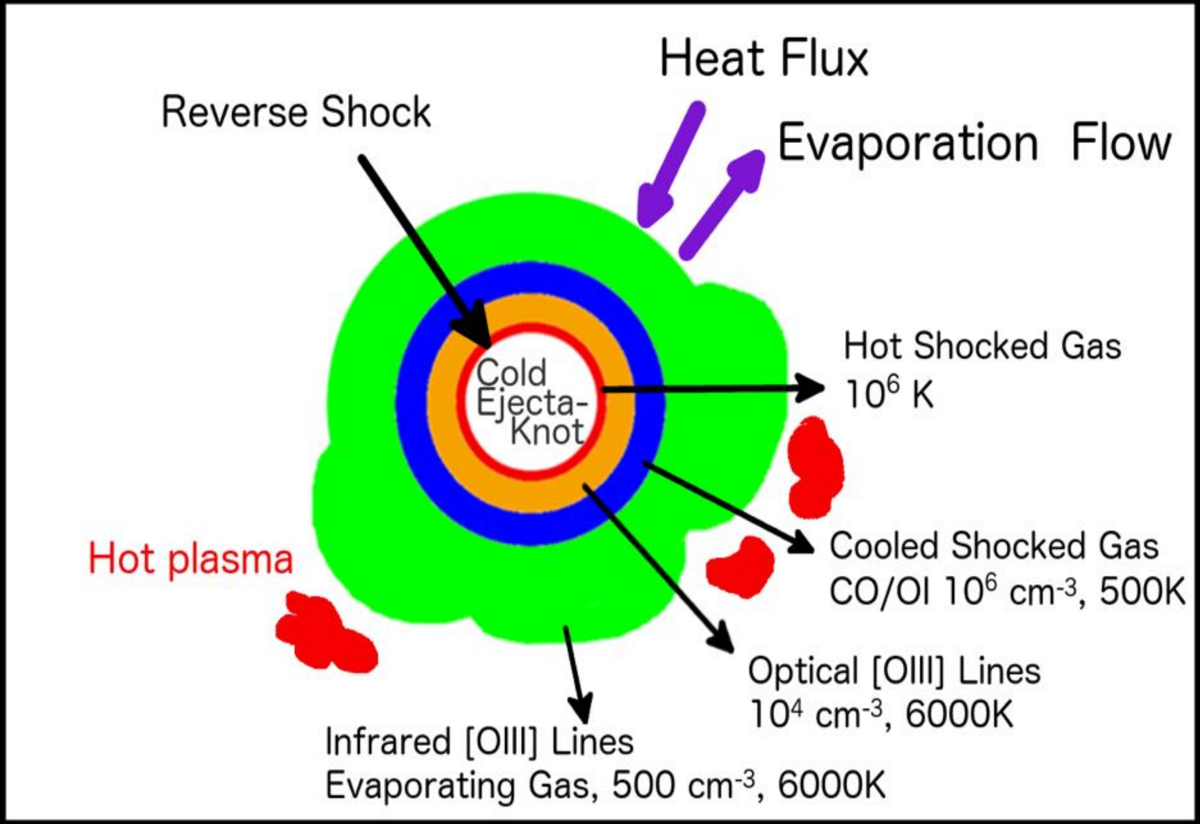




Evaporating gas→ IR Evaporating gas→ X-ray Evaporating gas → Hot plasma

Cartoon for [OIII], [OI], and CO





- [OIII] is from shocked gas by reverse shock with a range of density.
- [OI] layers imply a cooling zone behind the reverse shock.
- CO reformation behind the shock (Wallstrom et al. 2013; Biscaro & Cherchneff 2013) and the surrounding high density optical/IR regions reduces dust destruction rate.
- Energy balance between conduction and evaporating gas

Physical conditions of [OIII] emitting regions

emission	Density (cm^{-3})	Temperature (K)	Column density (cm^{-2})	ΔR (cm)	Pressure (cm^{-3} K)
IR [OIII]	$500\text{-}10^4$	6000-6500	10^{16}	$2x10^{13}/f$	$3x10^6 \text{--} 10^8$
optical [OIII]	10^4	6000	10^{15}	$10^{11}/f$	$1x10^8$
IR [OI]	$\sim10^6$	…	$2x10^{15}$	$2x10^9/f$	
CO	10^6	500, 2000	$5x10^{17}$	$5x10^{11}/f$	$(5\text{-}10)x10^8$
X-rays	3-3.5	$10^6\text{--}10^7$	..	..	$6x(10^6\text{--}10^{7})$

Mass loss and life time of clumps

- *Mass loss rate of the (o-rich) clumps*

  $\dot{M} = 4\,\pi R^2\, n\, M_o\, v \simeq 3 \times 10^{-5}\, M_\odot/yr$

- *The lifetime of the clumps*

$$\tau_C = \frac{4\pi R^2 N m_o}{4\pi R^2\, nv\, m_o} = \frac{N_{CO}}{X_{CO}\, nv} = \frac{300}{X_{CO}}\ yr$$

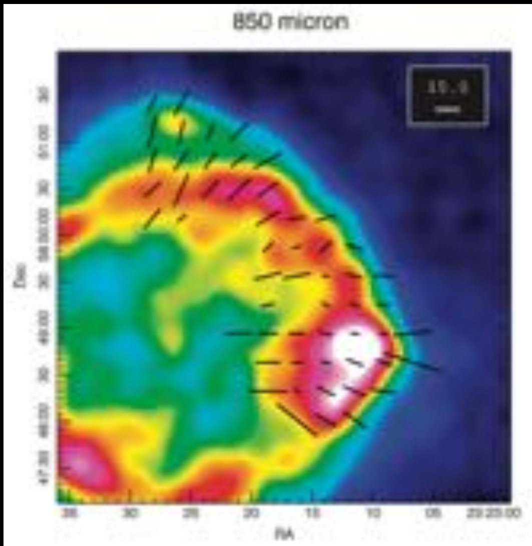
The lifetime of clumps (τ_C) is 10^4 yr with $X_{CO} = 0.01$

Dust in clumps can survive during YSNR stage.

Conclusion

- We present SOFIA [OI] and [OIII] observations of SN ejecta-CO knots in Cas A.
- The FIFI-LS spectra reveal that the line profiles of [O III] and [O I] are similar to those of the Herschel PACS [OIII] and CO lines (broad ejecta lines).
- We find that the [OIII] maps show very different morphology than the [OI] map. Both [OI] and [OIII] are shocked-gas.
- [OI] is post-shocked, dense, and cooled gas and correlated to CO gas.
- Infrared [OIII] is evaporating gas from the knot. The ratio of [OIII] 52/88 μm is a density indicator, and the density ranges 300-10^4 cm^{-3}.
- **Clump lifetime is longer than the age of YSNRs and CO-reformation and [OI] cooling significantly delay the dust destruction. → It explains why we observe a dust mass of the order of 1 $M_\odot$.**

Future



- Larger maps of [OIII] 52 and 88 μm to cover the entire Cas A (5'), e.g., unshocked ejecta at the center.
- Many fine-structure lines and continuum with JWST in connection to the O and dust maps: e.g., dust features from warm dust.
- Polarization map of Cas A (50% done in Cycle 7→ Cycle 8) →SN-dust separated from ISM-dust, dust composition and properties.

Thanks for SOFIA funding (e.g., Erick Young) to US-PI (Rho) for a foreign PI (Tielens) proposal and the grants of ADAP (NNX12AG97G) and of new ADAP in 2019.