Dust and Molecule Formation in Supernovae

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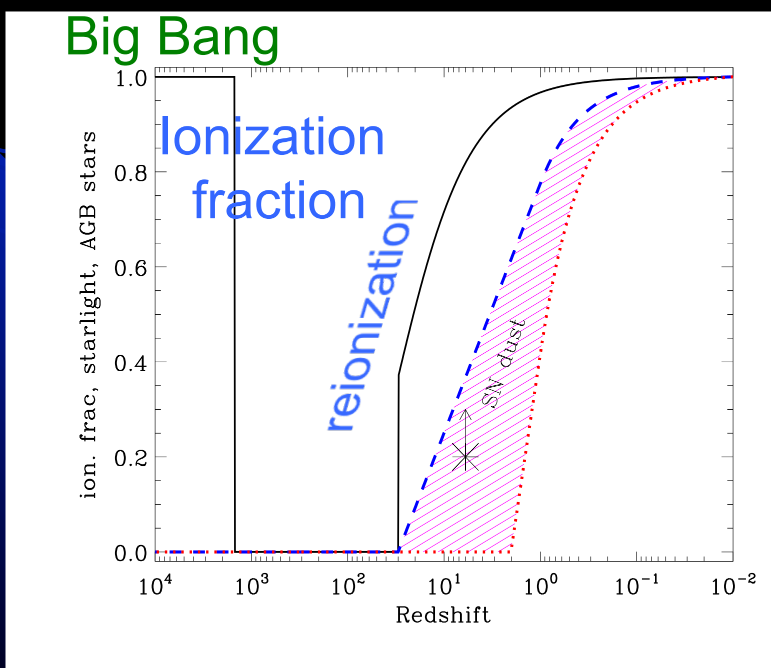
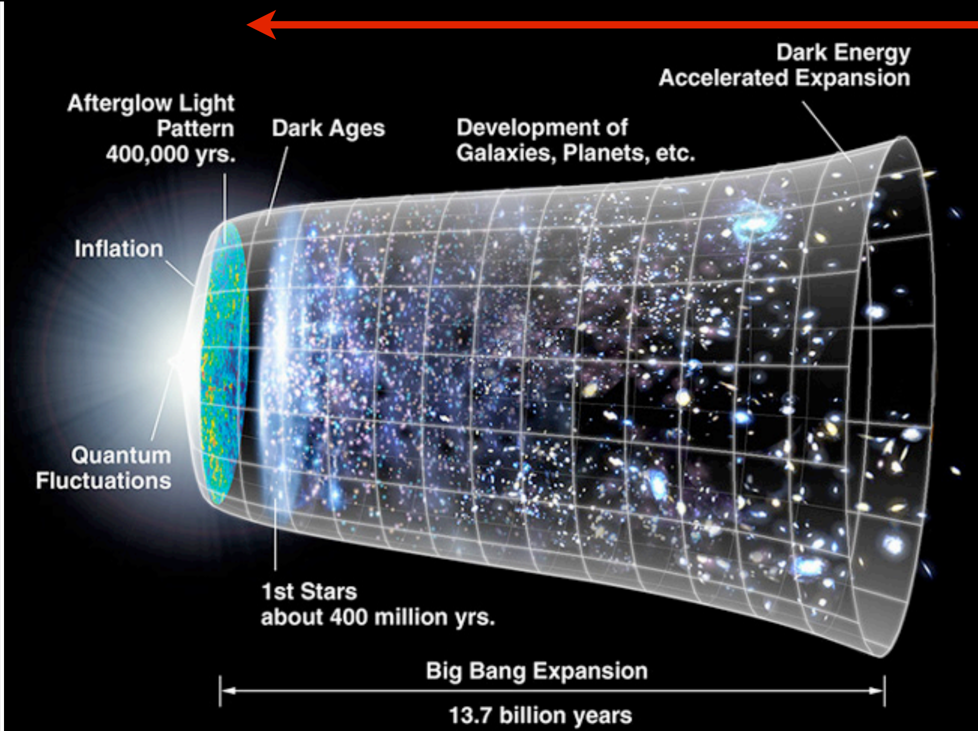
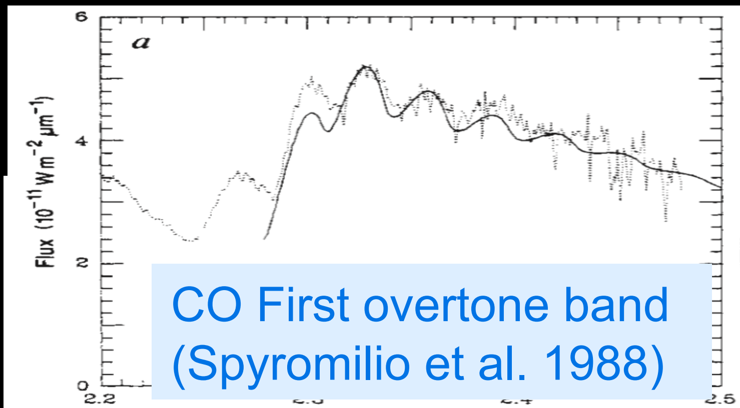
Introduction : Dust formation

- Huge quantity of dust is observed in high red-shift quasars or galaxies (Issak 2002) . 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)

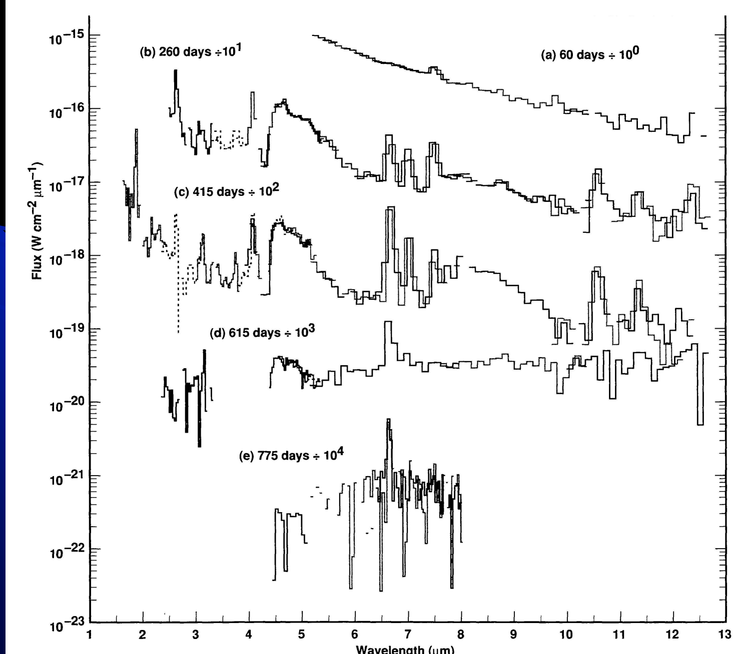




First sign of dust formation in SN1987A



CO First overtone band
(Spyromilio et al. 1988)



CO detection in SN1987A
(wooden et al. 199)

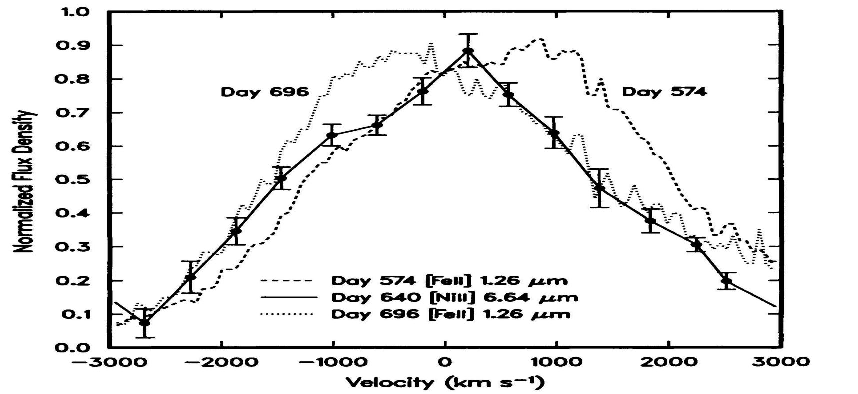
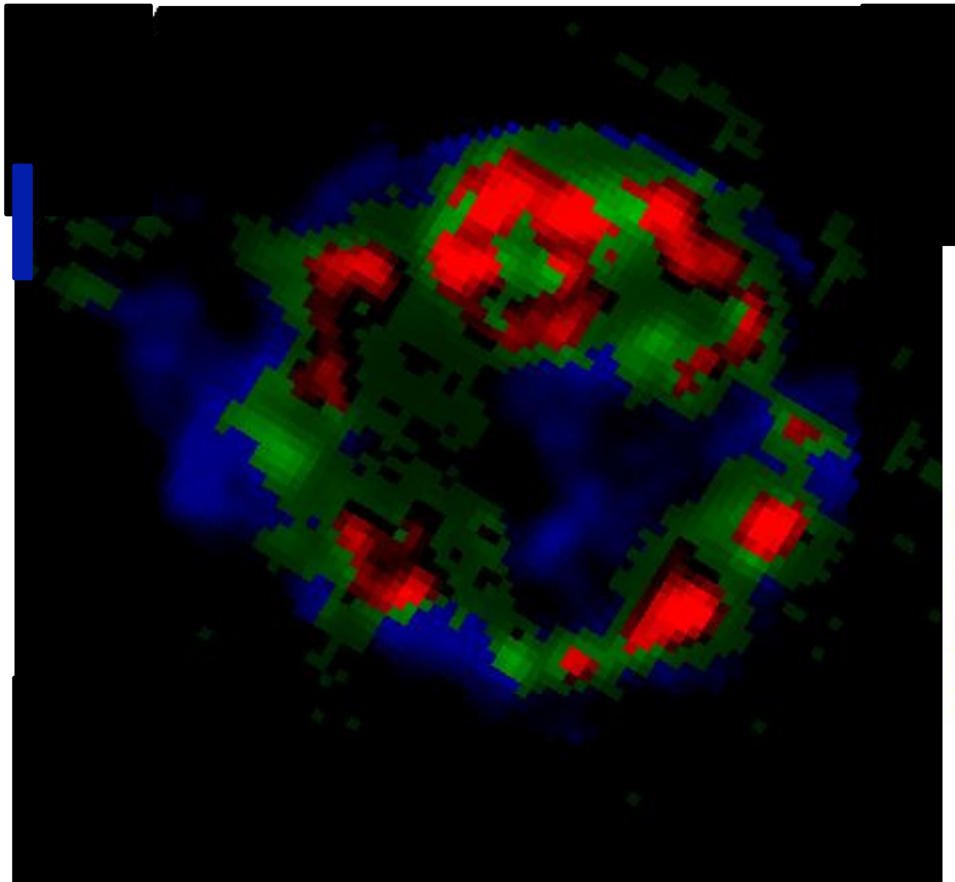


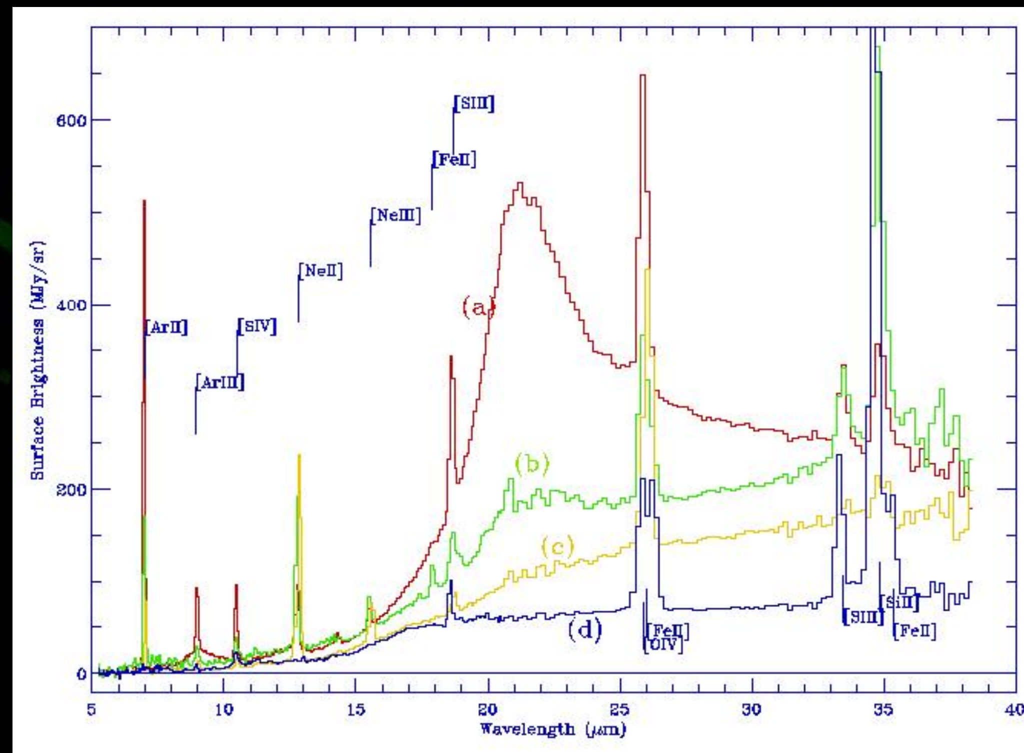
FIG. 3.—Comparison of the [Ni II] 6.6 μm profile at day 640 with the [Fe II] 1.26 μm profiles at day 574 (*dashed*) and day 696 (*dotted*) from Spyromilio et al. (1990).

Blue - and red-shifted lines (Colgan et al. 1988)

Observational evidence of dust formation comes from SN 1987A and Cas A. However, the observed mass is controversal; from $3x10^{-3}$~10^{-6} $M_\odot$ (Lagage 1996; Douvion et al. 2000, Arendt 1999) to a few tenth with SCUBA (Dunne et al. 2002); but the latter contains foreground clouds.

Distribution of Dust Composition in Cas A





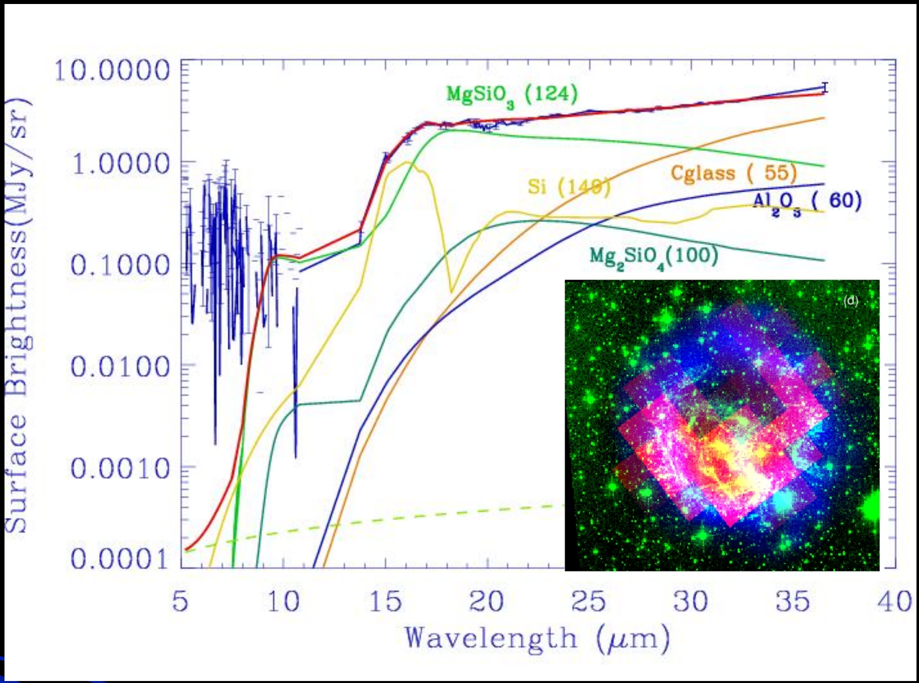
21μm-peak Dust:
SiO_2, Mg protosilicate +FeO

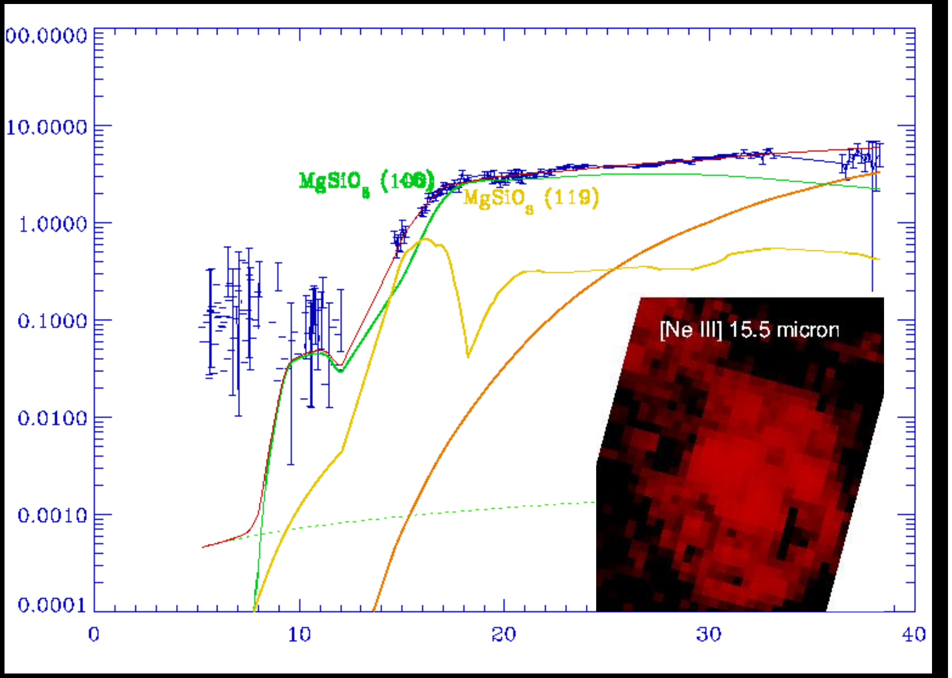
Weak 21μm dust: Carbon + FeO + Al_2O_3

Featureless Dust
Fe, C, Al_2O_3 (FeO)

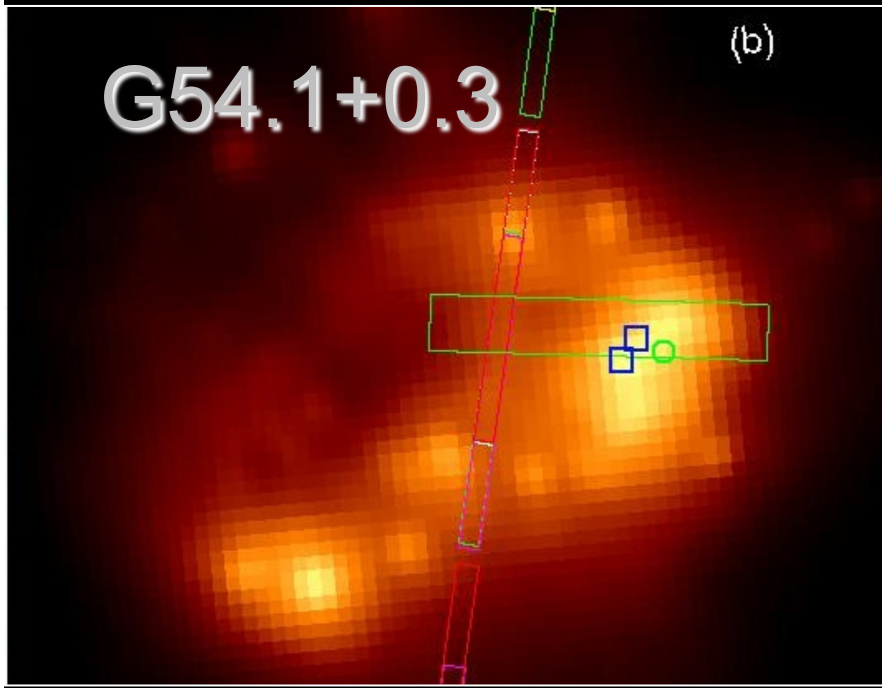
Total dust mass with Spitzer: 0.02-0.054 $M_{\odot}$ (Rho et al. 2008)
Dust mass with Herschel data: 0.075 $M_{\odot}$ (Barlow et al. 2010)

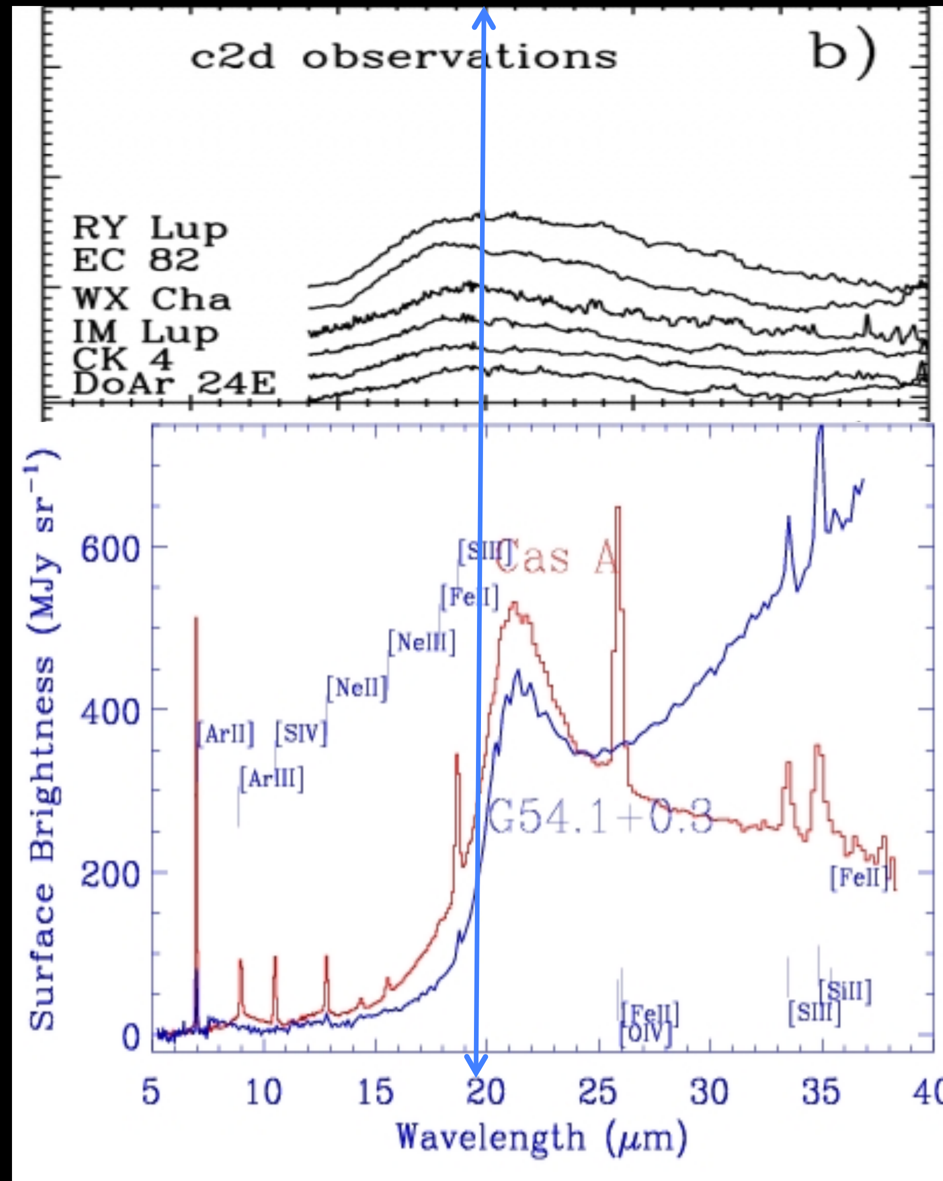
E0102 and N132D Ejecta





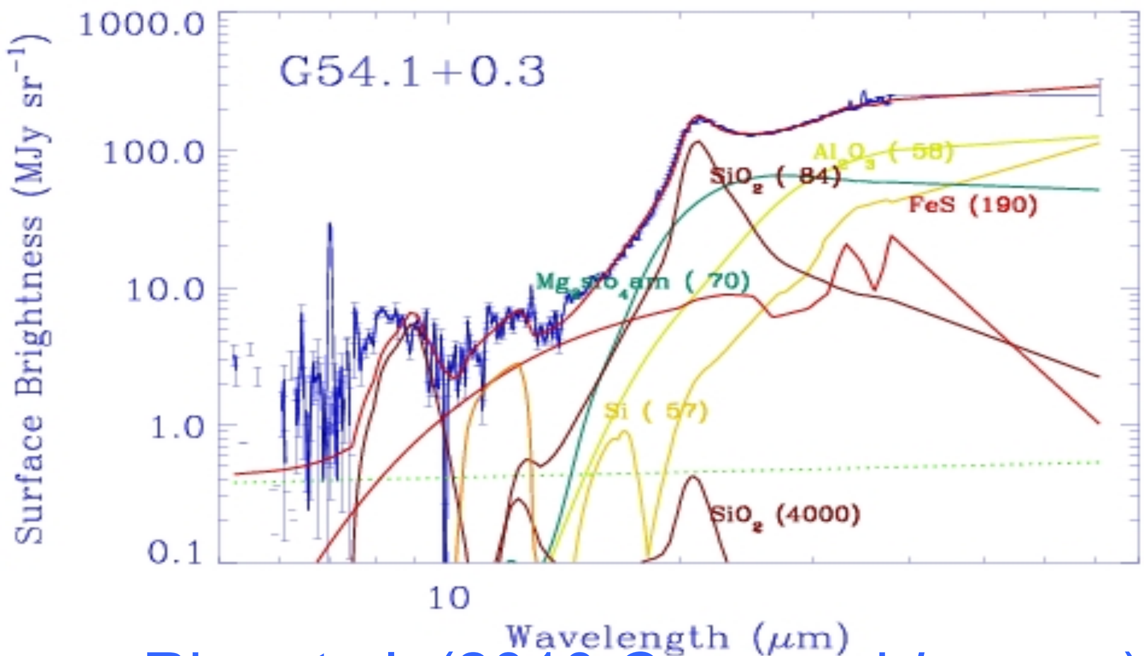
- Dust feature at 18 μm from both E0102 (in SMC) and N132D (in LMC) can be fit with $MgSiO_3$ and Si (C and Al_2O_3)
- E0102: total of dust mass of 0.007- 0.014 $M_\odot$ is formed in ejecta (Rho et al. 2009); 0.003 $M_\odot$ (Sandstrom et al. 2009)
- N132D: total dust mass associated with ejecta is > 8×10^{-3} $M_\odot$ and the rest are mixed with ISM (Rho, Tappe et al. in prep).



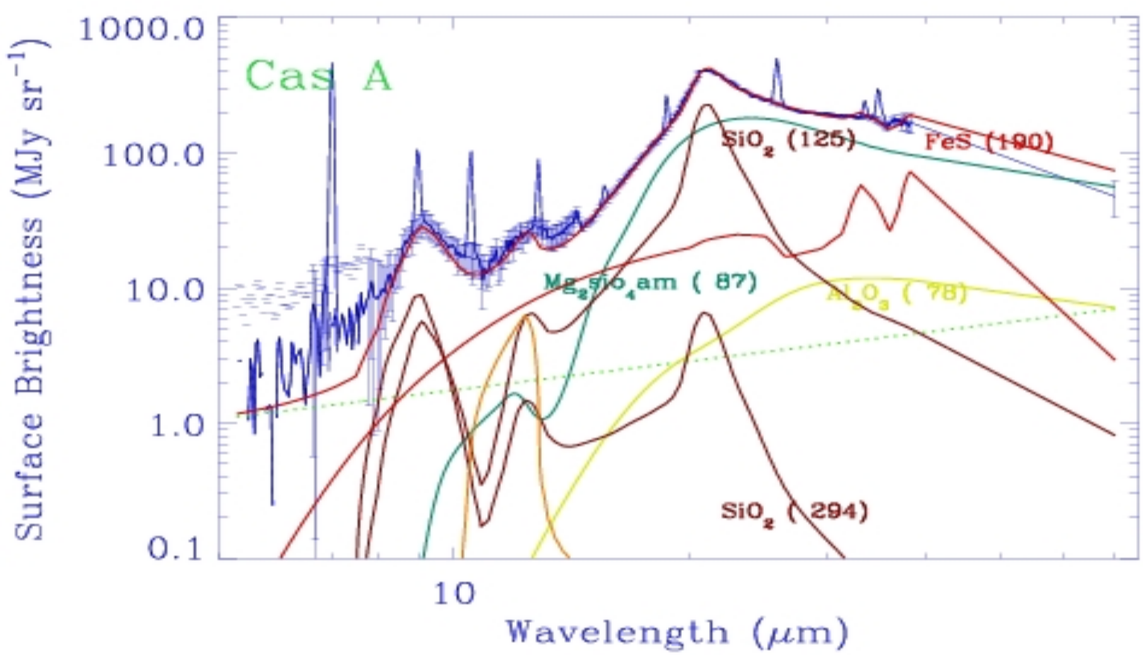


- We serendipitously found IRAC and MIPS emission from G54.1+0.3 and found dust feature similar to that of Cas A. We made follow-up submm observation using CSO SHARCII (350 μm) and LABOCA (870 μm)

Search for freshly formed dust using Spitzer archival data
Funded by Astrophysics Data Analysis Program (ADAP)



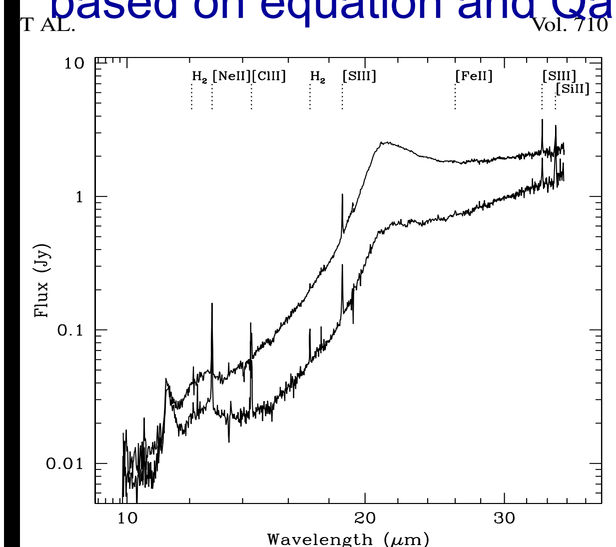
Rho et al. (2010 Cosp and *in prep.*)



G54.1+0.3

- 21-μm dust feature is remarkably similar dust to that of Cas A: Silica (SiO_2) is responsible for the 21 -μm dust and other composition includes **Mg_2SiO_4, Al_2O_3,** (FeS, SiC)

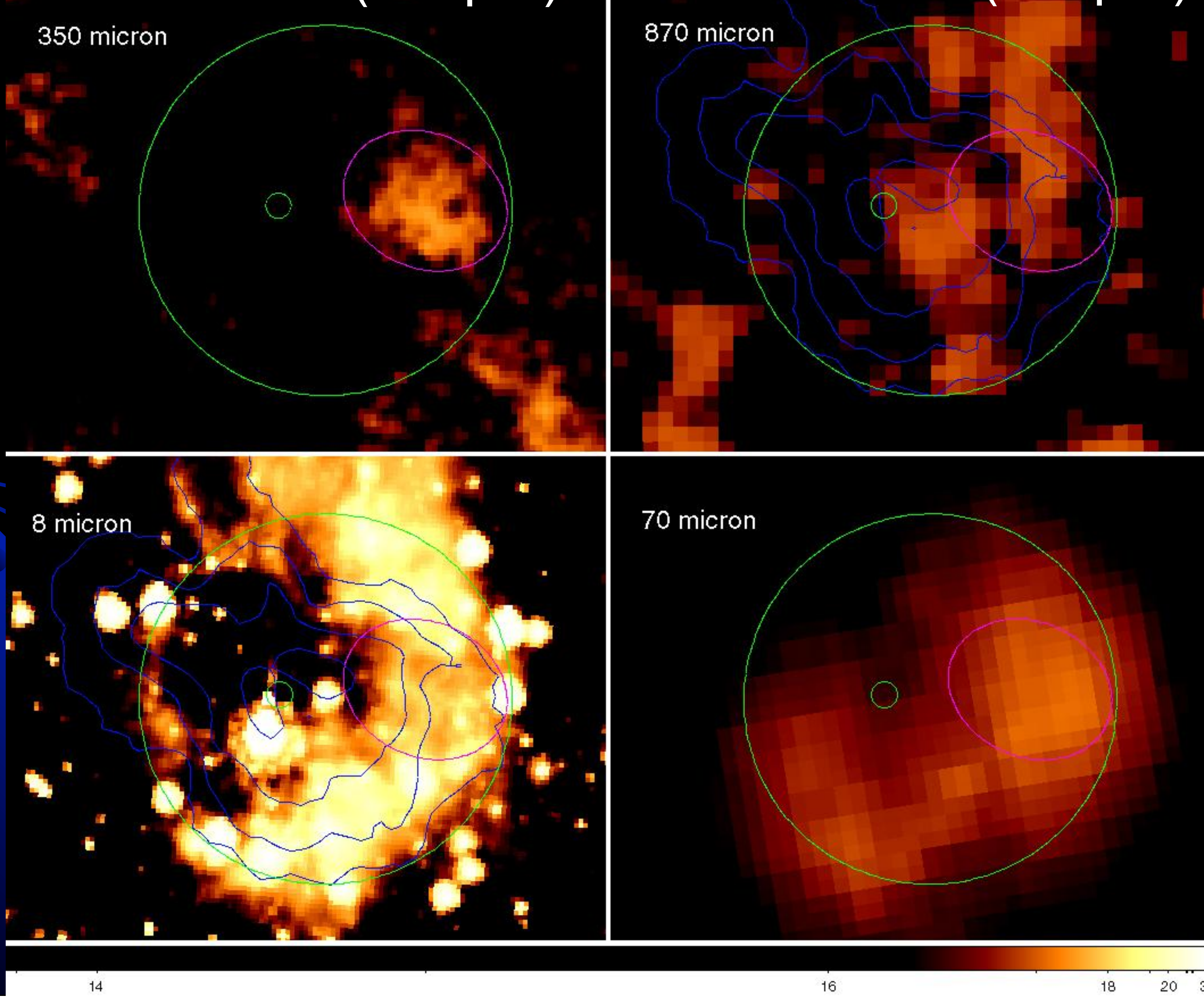
Temim et al. 2010: 0.06 $M_\odot$ based on equation and Qabs



SHARCII (350μm) of G54.1+0.3

Detection of submm emission (0.8 Jy at 350)

SHARCII (350μm) LABOCA (870μm)

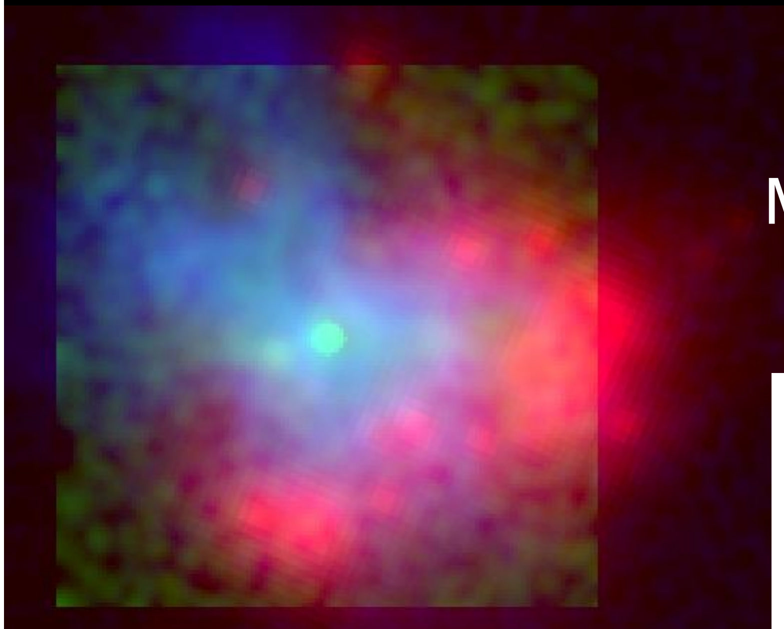


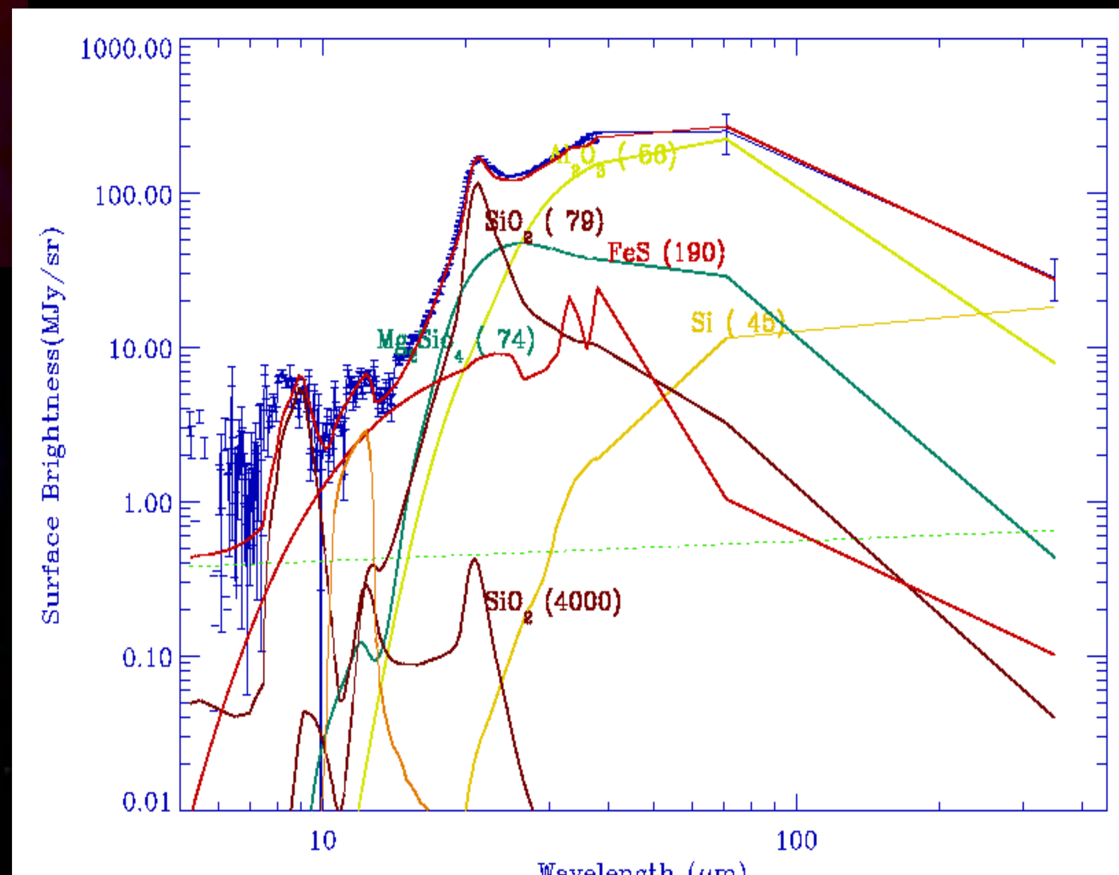
Dust Spectral fitting with submm

Dust mass ~0.1 $M_\odot$

Mass is sensitive to dust composition:

SiO_2, Mg_2SiO_4, Al_2O_3 (FeS and Si)





Dust mass in YSNRs

YSNR (progenitor)	Mass ($M_\odot$)
Cas A (15-30 $M_\odot$)	0.02 – 0.054 $M_\odot$ (Rho et al. 2008) **0.075 $M_\odot$** (Barlow et al. 2010)
E0102 (Type Ib, 32$M_\odot$)	**0.007-0.014** $M_\odot$ (Rho et al. 2009) 0.003 $M_\odot$ (Sandstrom et al. 2009)
N132D	> 8×10^{-3} $M_\odot$ (Tappe, Rho et al. in prep)
G54.1+0.3	**0.1** $M_\odot$ (Rho et al. 2010, 2011) 0.06 $M_\odot$ (Temim et al. 2010)

Why are the dust masses from YSNR larger than those of SNe?

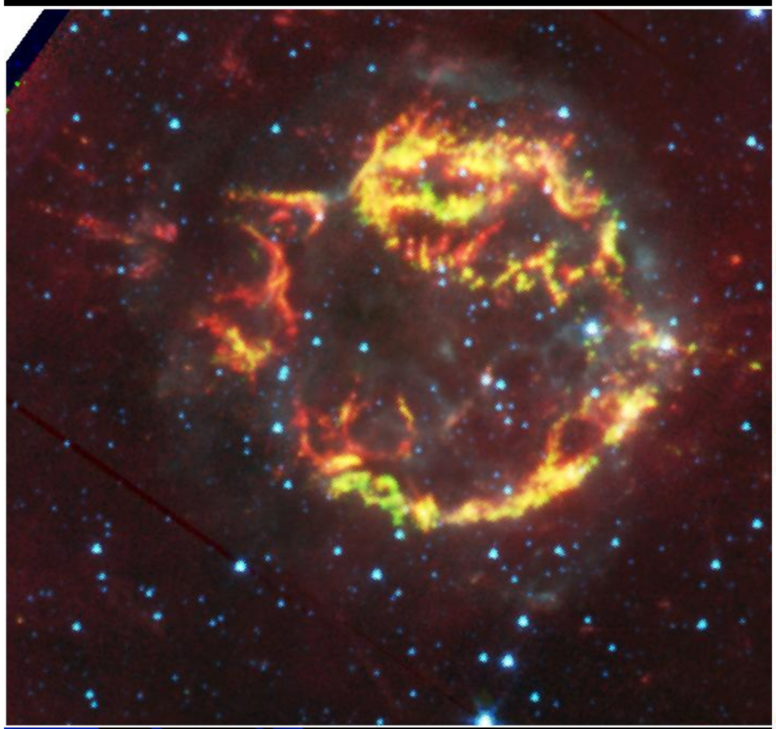
Lack of Carbon Dust

$C + O \rightarrow CO + h\nu$

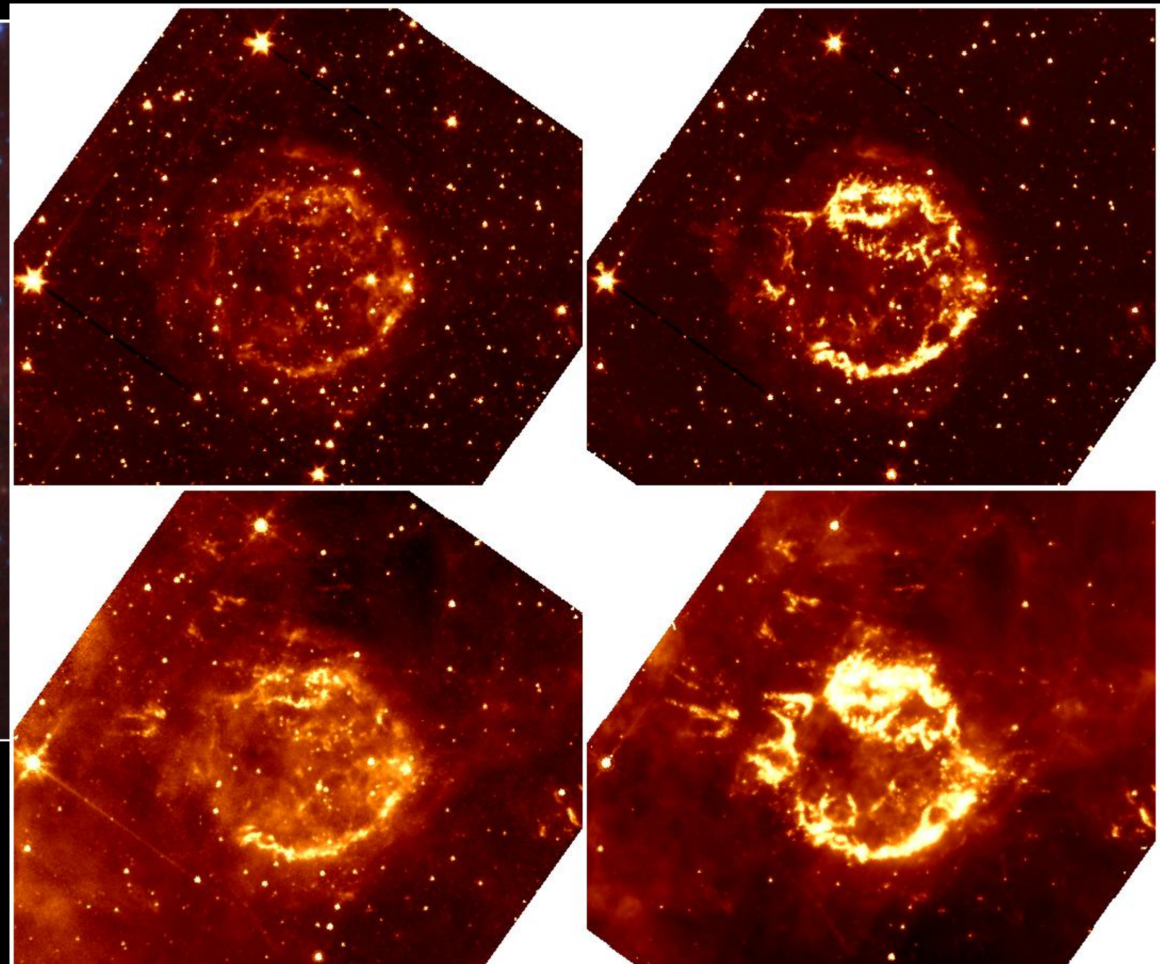
Estimating the mass of CO is important to probe dust formation chemistry.

Higher CO abundance → lower dust formation of carbon.

Spitzer IRAC images

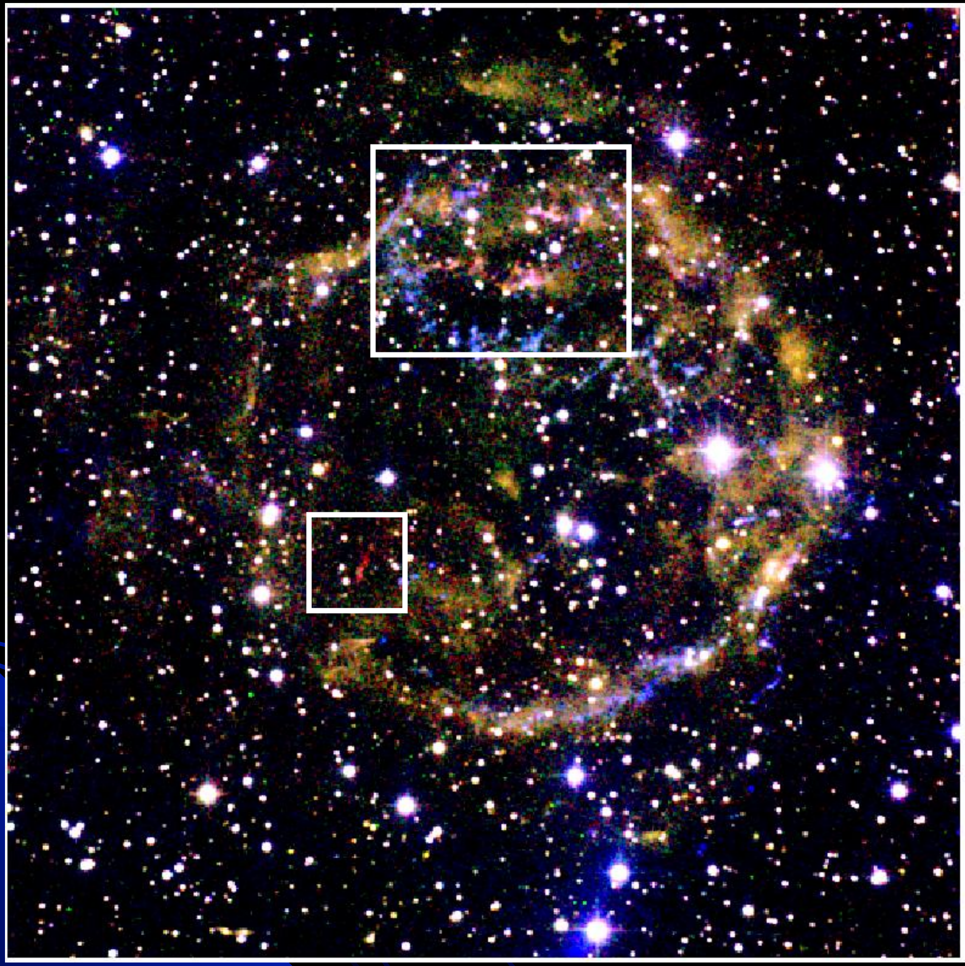


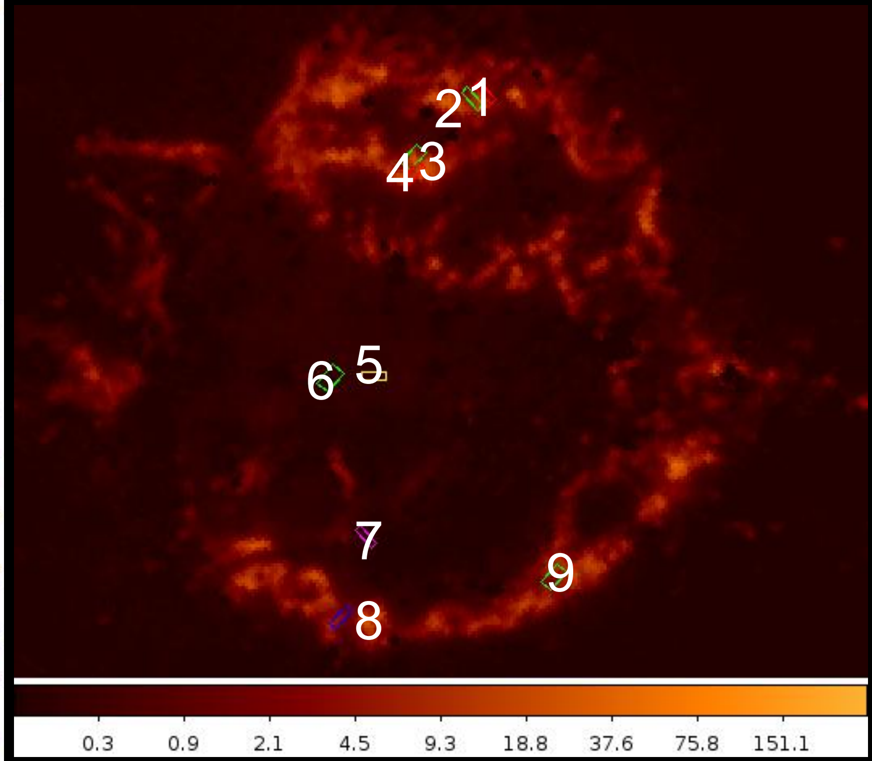
Three color IRAC image:
(Ennis et al., 2006, ApJ)
3.6 μm: blue, 4.5 μm: green, 8 μm: red



IRAC 3.6 μm: synchrotron
4.5 μm: Br α+ [Fe II]+ dust (maybe molecules??)
5.6 μm : FeII+dust, 8μm: Ar lines

CO detection in Imaging

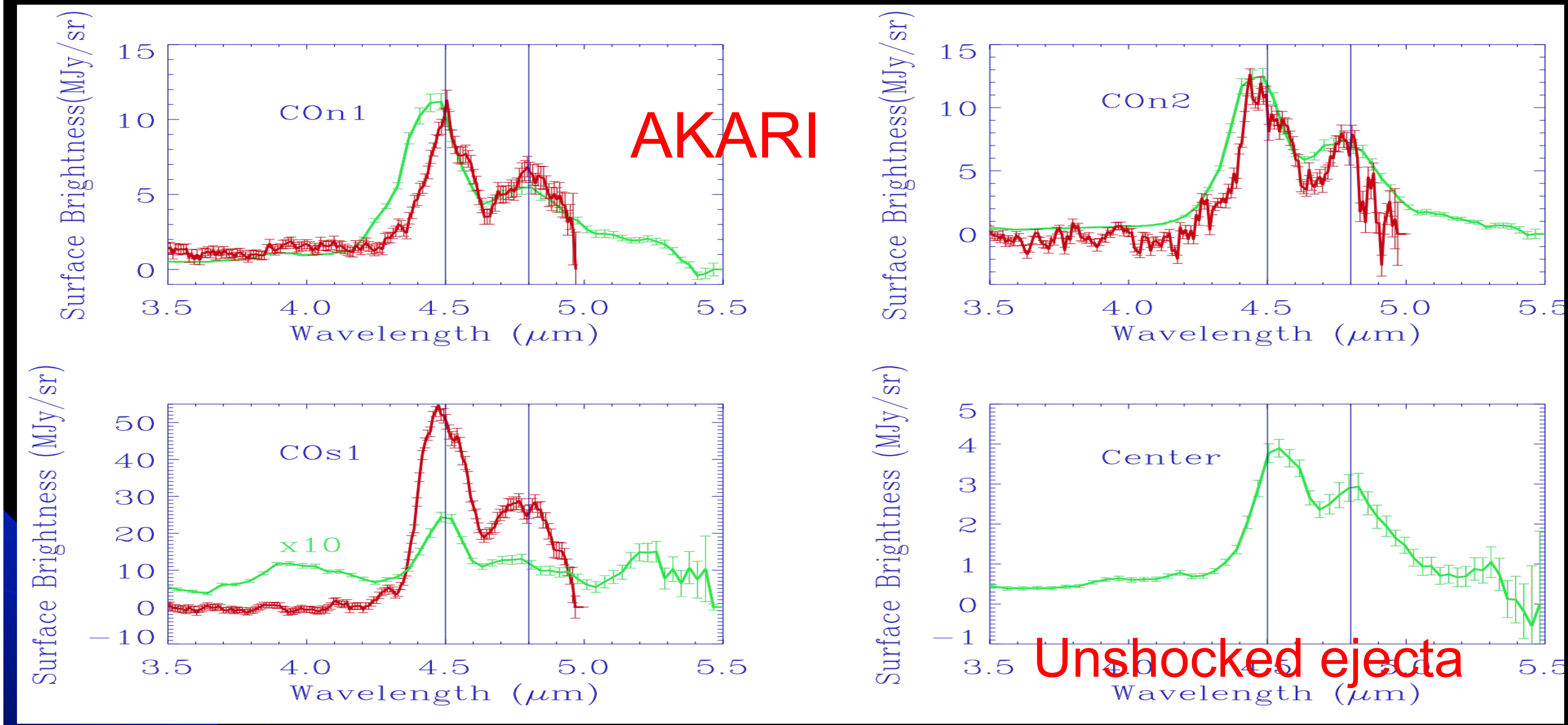




Positions of AKARI spectra

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

CO Fundamental Band Detection



-AKARI Japanese mission during warm phase with IRC

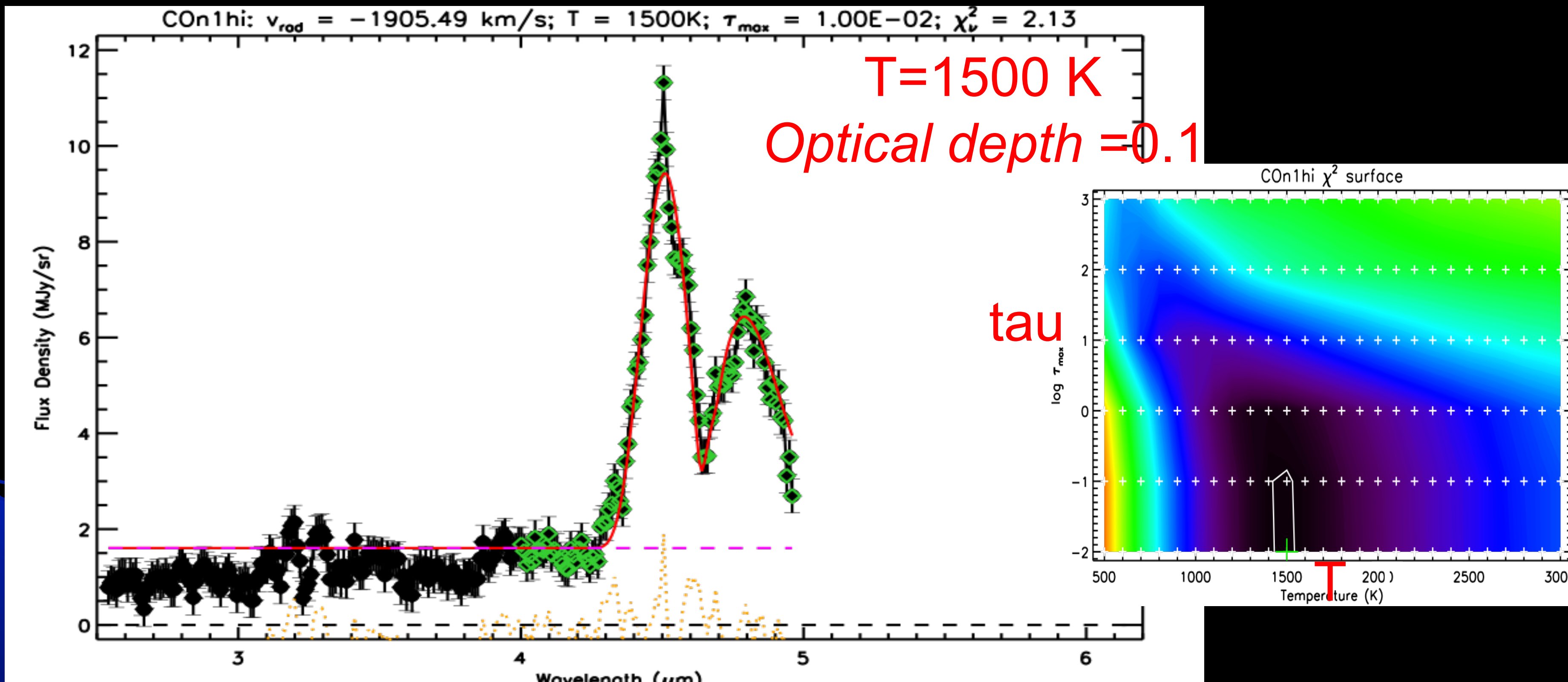
-Observations on Jan and Jul, 2009 towards 4 positions of Cas A

-Grism in red (prism in green) with an area of 3”x9” (5”x9”) and R=220 (150)

CO Fundamental Band dominant spectra: no other lines.

CO is observed in unshocked ejecta (CO formation in early SNe)

Spectral Model fitting:
Molecular Transition and Radiative Transfer

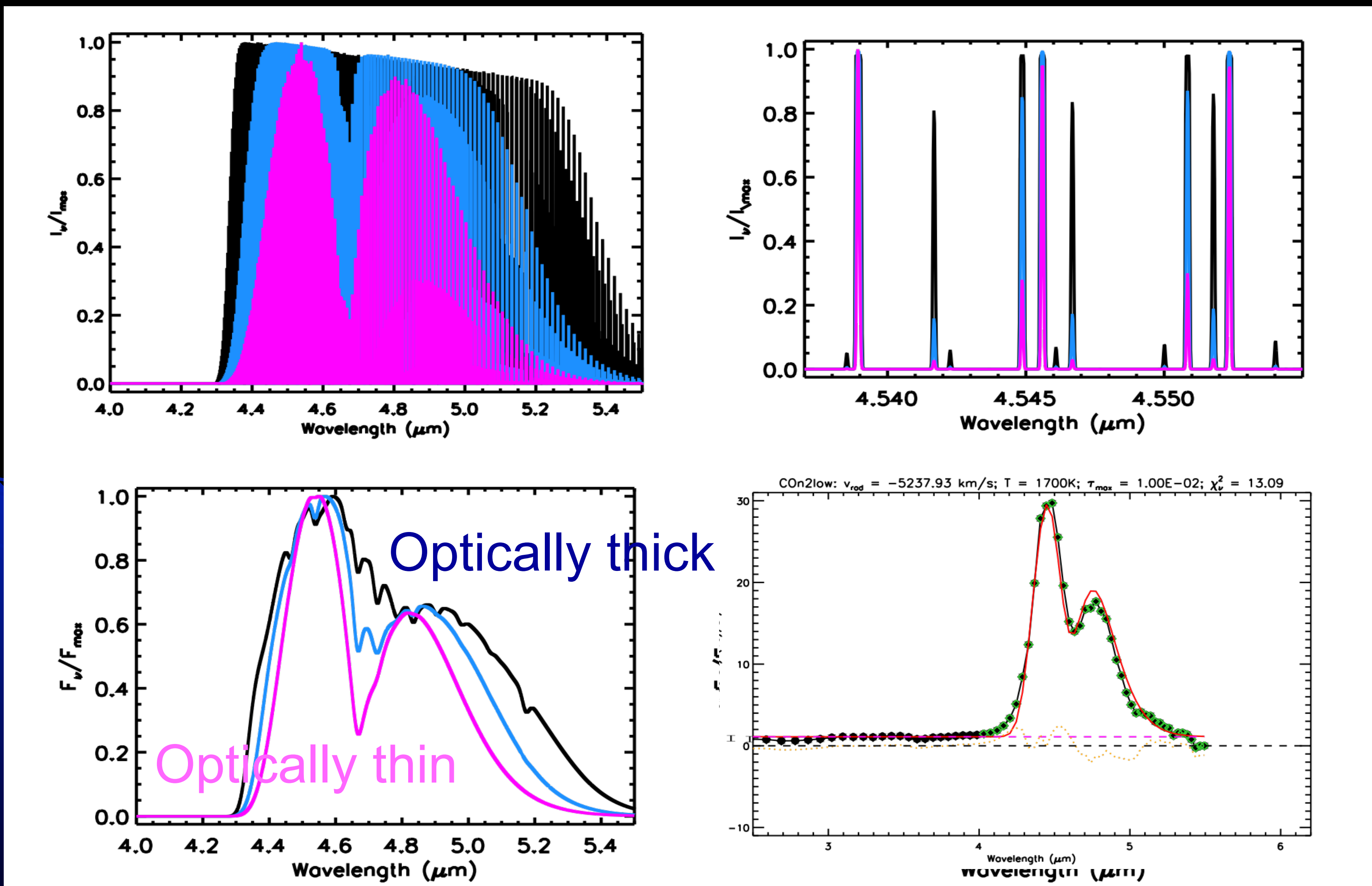


$I_v=n_2\,A_{21}\,hv_{21}\,\Phi\,/4\pi$ where Φ is the line profile

$I_v \sim B_v(T)\ \tau_v$ for $\tau_v << 1$

In LTE, temperature determines the fraction of total number of Molecules (N) in the excited state (Goorvitch 1994)

CO is optically thin

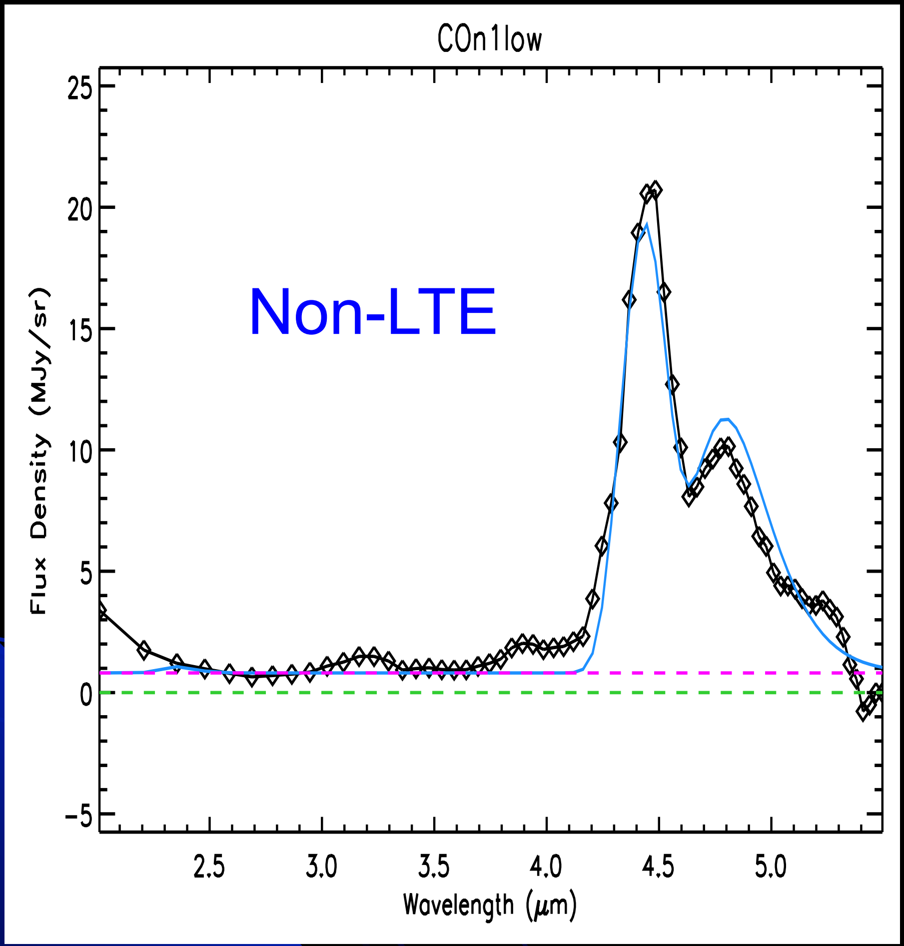


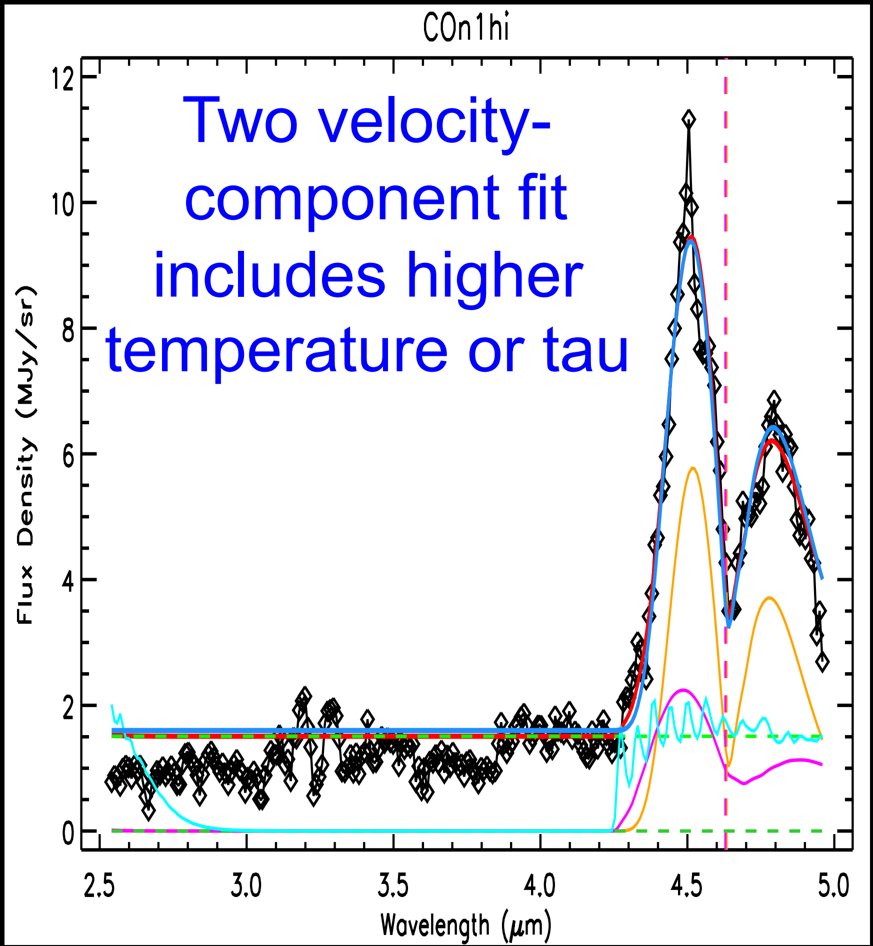
CO Spectral Fitting Results

- Temperature of CO is 900 – 2400 K
- Optically thin in Cas A

  (optically thick in SN1987A; Liu et al. 1992)
- Large doppler-shifted velocity is similar to that in ejecta (300 to -6000 km/s) but some shows different vel. from gas lines.
- CO mass within the single slit (3''x9'' or 5''x9''): $(0.12\text{-}1.6) \times 10^{-9}\ M_{\odot}$
- Presence of fundamental CO indicates a density $\sim 10^{6\text{-}9}\ \mathrm{cm}^{-3}$ (Gearhart, Wheeler & Swartz 1999)

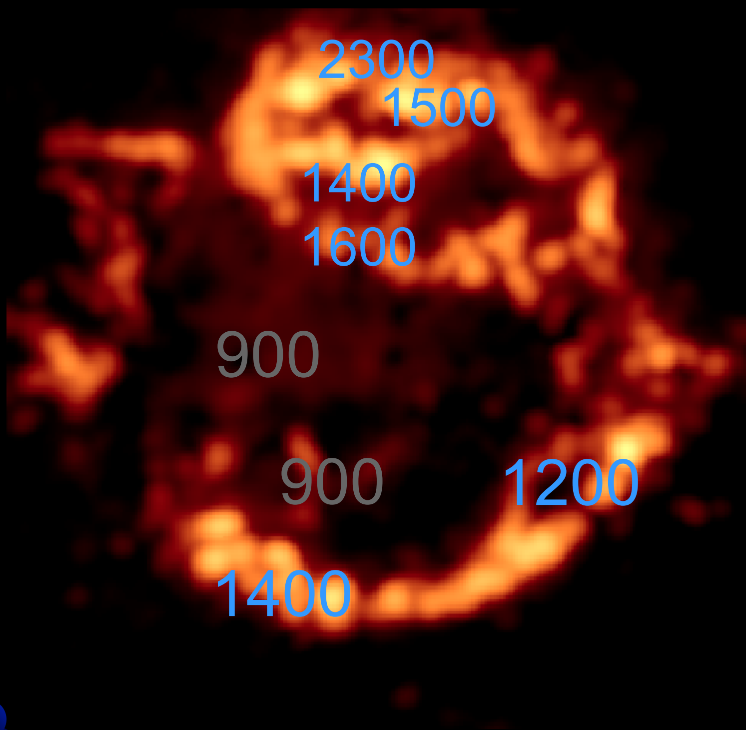
CO is in non-LTE





- ◆ Large residual in the fit indicates CO is in non-LTE
- ◆ Residual (band heads) of 2 velocity component fit shows higher T or tau

CO Fundamental Band Map:



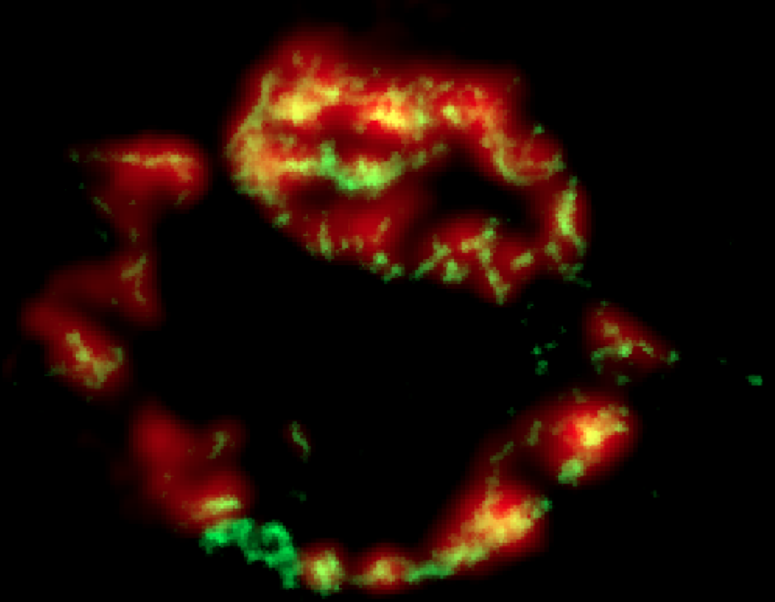
IRAC band 2 map is largely CO fundamental band: background and synchrotron radiation subtracted image

- ◆CO map is similar to ejecta or dust maps
- ◆Total CO mass : 6 x 10^{-7} $M_{\odot}$ (LTE) using scaling factor from the mass within the slit and CO fundamental map

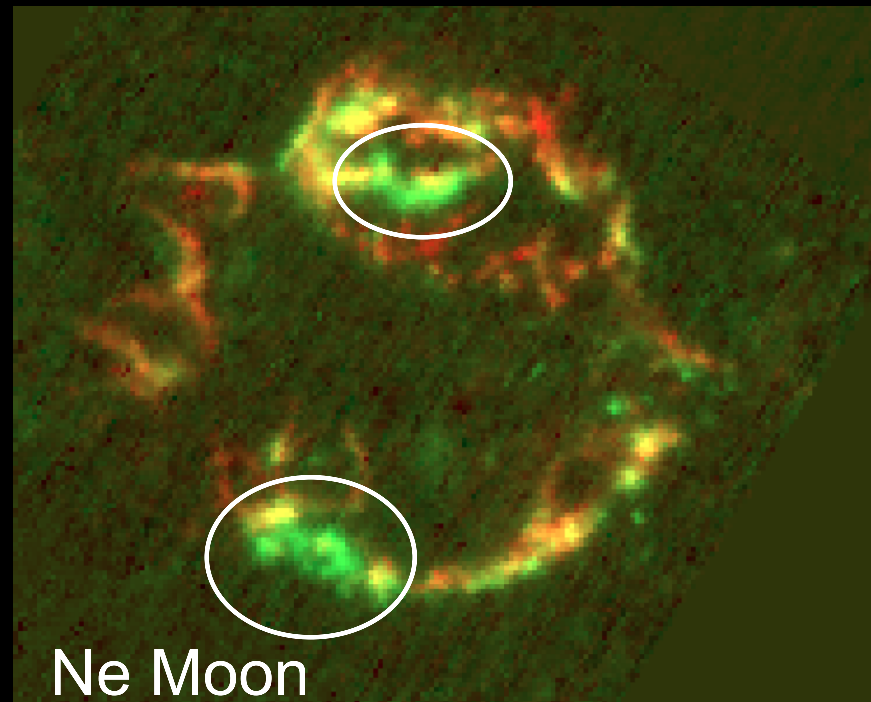
➔Lack of microscopic mixing in ejecta.

- ◆Lower temperature CO at unshocked ejecta.

SiO_2 dust (red) CO (green)



Ar (red) Ne (green)



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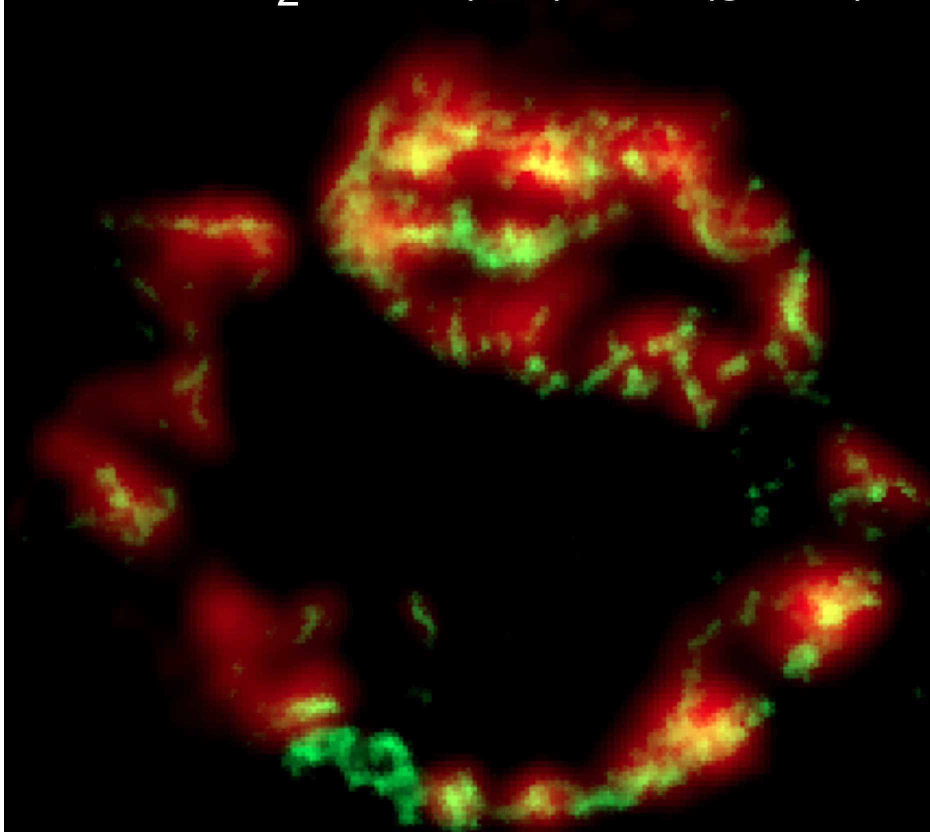
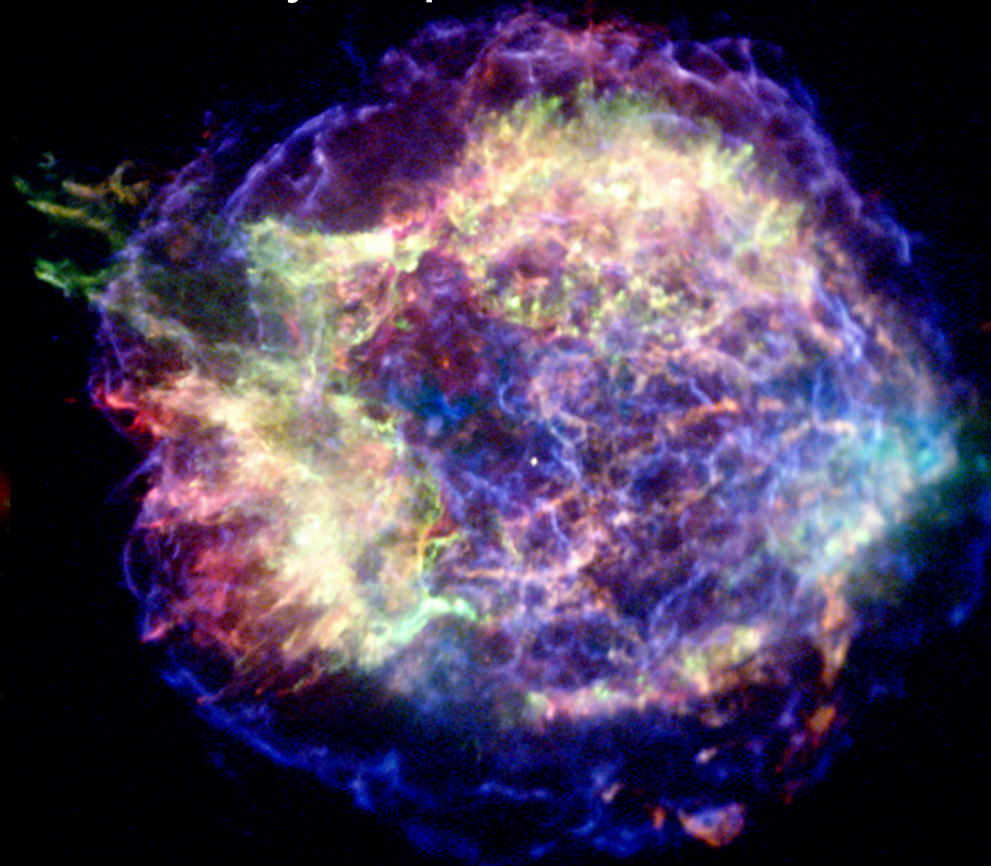
CO molecule has strong connection to Ne rich regions (green): outer layer of Ne, O, C, while SiO_2 is correlated to Ar or Si layers.

SiO_2 dust (red) CO (green)

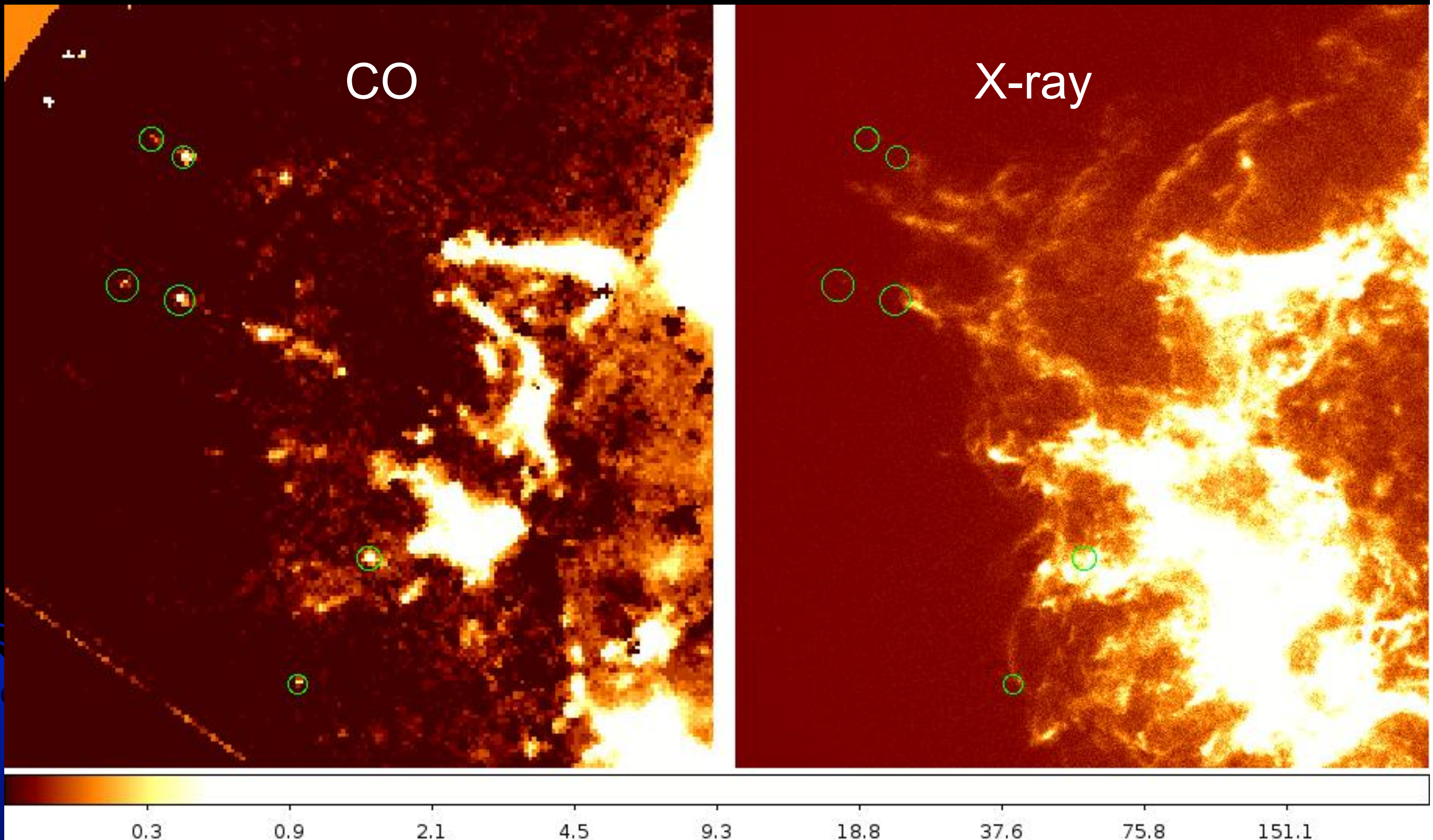


X-ray map Si, S, Fe

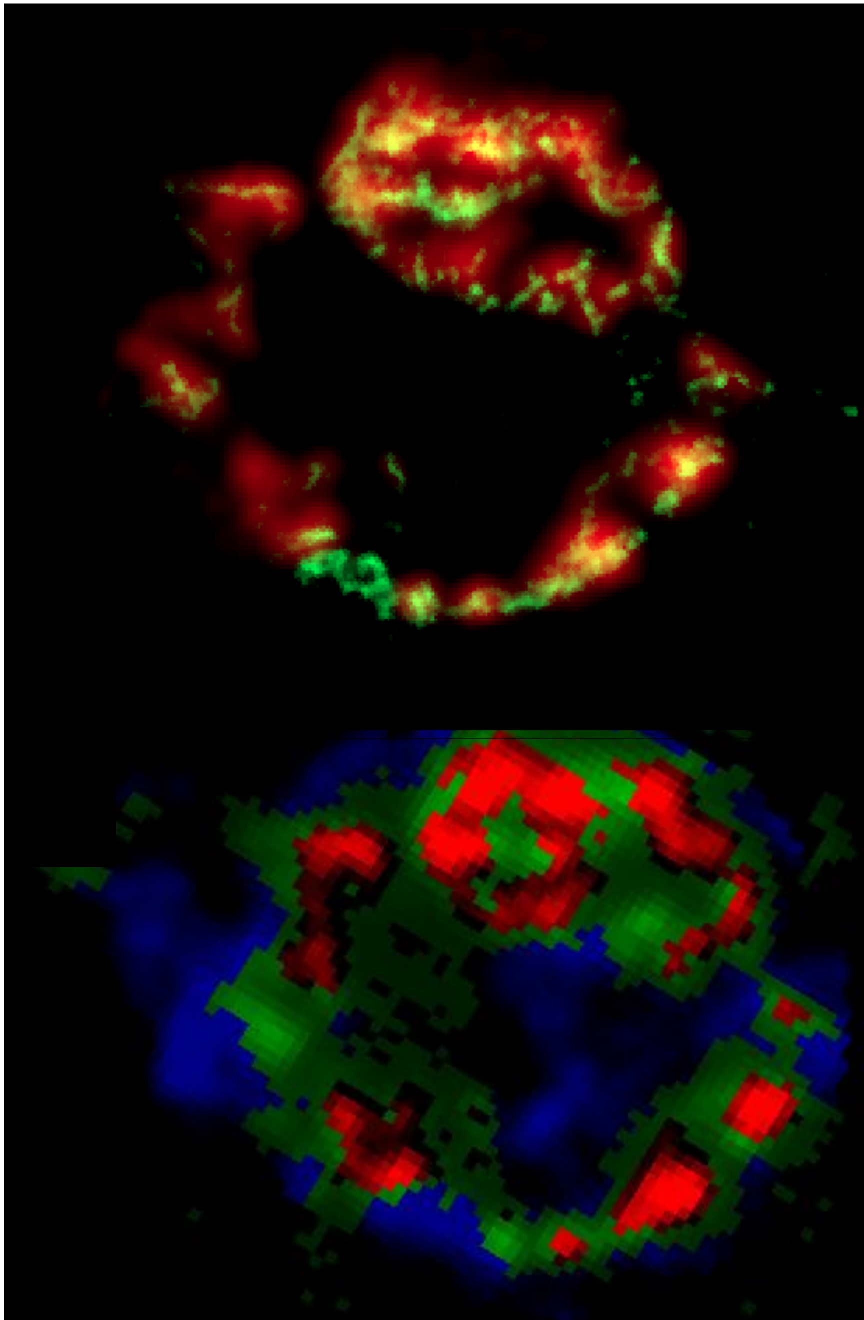


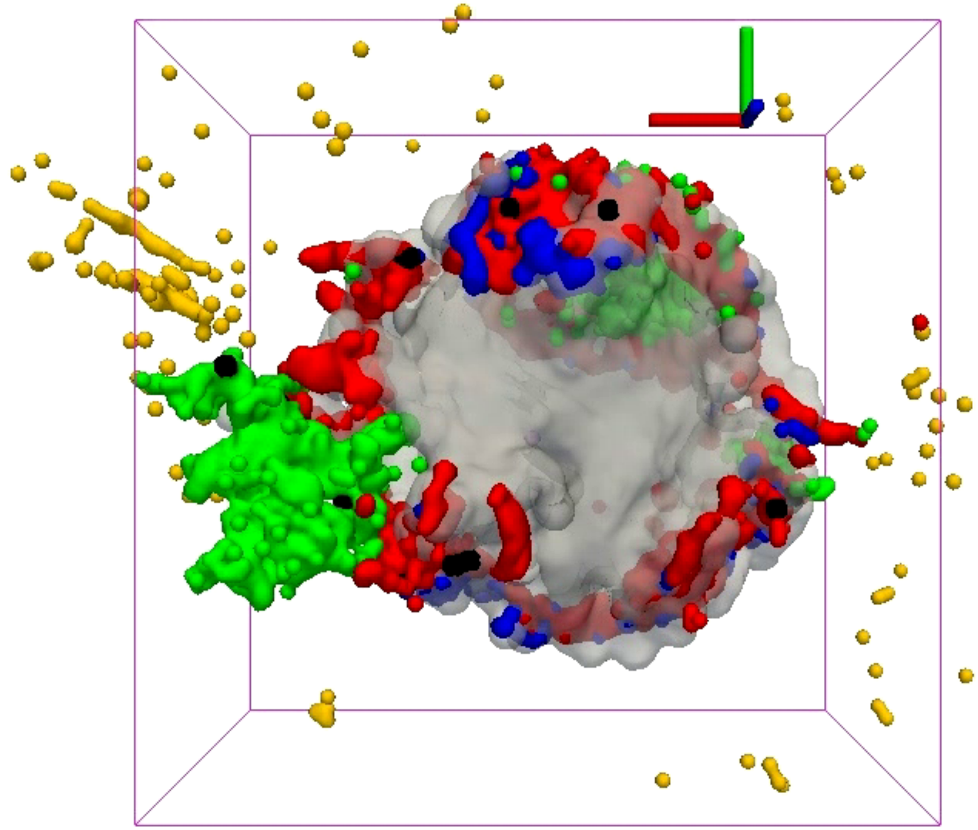
- CO is in hot, X-ray plasma (10^7 K): one-to-one match
- Knot (0.2”-0.6” with HST: 6000-12000 AU)

CO clumping and size: $\rho=10^6$ cm^{-3} and mass filling factor= $10^{-3}(10^{-6})$ ➔size D=600(60)AU



- CO knot was not dissociated by high E particle or He+ in ejecta.
- CO clumps propagation into ISM.
- CO knots from SNe can change ISM dust structures
  - ➔ clumping molecules in low density





DeLaney et al. (2010)

Ar (IR) SiII(IR) g: Fe K (X-ray) Si XIII (X-ray) optical

See http://chandra.harvard.edu/photo/2009/casa2/animations.html

Conclusion of CO detection in Cas A

- CO mass of Cas A could be an order of 10^{-4} -10^{-5} $M_\odot$($6x10^{-7}$ $M_\odot$) with non-LTE model, when analogy to SN1987A.
- It is surprising to see any amount of CO for a 300 yr-old SNR. Chemical processes continue for 300 yrs.
- CO is optically thin, and in non-LTE; T=900-2300 K, but some with higher temperature or optical depth.
- CO has not been destructed by high E particles or He+ for 300 years and signficant amount of C has been locked in CO.
- Microscopic Mixing is small in ejecta. Scale of knots which form dust and CO must be very small (self-shielding).
- Our observation supports that SNe could be important sites of molecule formation (10- 34% of the progenitor mass are molecules; Cherchneff & Lilly 2008).

Conclusion of Dust in SNe

- 21 μm dust feature is unique from SNe; G54.1+0.3, Cas A
- Dust masses from YSNRs are order of 0.05-0.1$M_\odot$
  This mass is much higher than those from SNe (<$10^{-4}M_\odot$), where the dust is too cold to be detected in infrared.
- Ejecta mass is 3.2$M_\odot$ in Cas A for 25 $M_\odot$ progenitor star (Hwang et al. 2010). ➔ Chieff et al. (2004) model predicts 22.3 $M_\odot$ ejecta. ➔The rest of ejecta mass could be a combination of dust and molecules.
- Accurate understanding of astrochemical processes from ejecta to molecules, molecules to dust is required to estimate fresh dust mass.
- We are just begun to understand dust formation in SNe and its importance in early Universe.
  Challenges will continue for a decade or more…