Physical conditions in dense molecular knots in the supernova remnant Cassiopeia A

Sofia Wallström
Onsala Space Observatory

In collaboration with C. Biscaro, O. Berné, J. Black, I. Cherchneff, S. Muller, J. Rho, F. Salgado, A. Tielens

Dust in the universe

- Large dust masses seen in galaxies at $z > 6$
  - $M > 10^8\ M_\odot$[1] formed in < 1 billion years
- Competing theories:
  - Supernovae[2]
    - Short timescales, plenty of refractory elements
  - AGB stars[3]
    - Main dust producers in our galaxy, largest stars may have short enough timescales
  - ISM growth[4]
    - Supernovae/AGB dust production insufficient so dust is grown mainly in the ISM, seeded by supernovae/AGB

[1]e.g. Bertoldi et al. 2003
[2]e.g. Gall et al. 2011
[3]e.g. Valiante et al. 2009
[4]e.g. Michalowski et al. 2010

Dust in supernovae

- Theoretically, supernovae produce enough dust to explain high-z observations
  - 0.1 to 1 $M_{\odot}$ per SN[(1)]
- But only small amounts of dust seen a few years post-SN
  - 10^{-5} to 10^{-2} $M_{\odot}$ from IR observations[(2)]
    - Note this is warm dust

[(1)]e.g. Todini & Ferrara 2001, Cherchneff & Dwek 2010
[(2)]e.g. Lucy et al. 1989, Sugerman et al. 2006

Dust in supernova remnants (1)

- Larger cold dust masses seen in SNRs
  - About 0.1 $M_\odot$ in Cas A[(1)]
  - 0.4 to 0.7 $M_\odot$ in SN 1987A[(2)]
  - Modeling shows dust growth continues ~5 years after SN explosion[(3)]
- But few young SNRs to study SN dust yields
  - Have to be nearby and young enough to distinguish SN dust from pre-existing ISM dust

[(1)] Rho et al. 2008, Barlow et al. 2010
[(2)] Matsuura et al. 2011
[(3)] Sarangi & Cherchneff 2015

Dust in supernova remnants (2)

- Also, observed SNR dust not yet reprocessed by the reverse shock
  - When SN shockwave sweeps up enough circumstellar/ISM material, it forms a reverse shock
  - Shock velocity ~1000 km/s

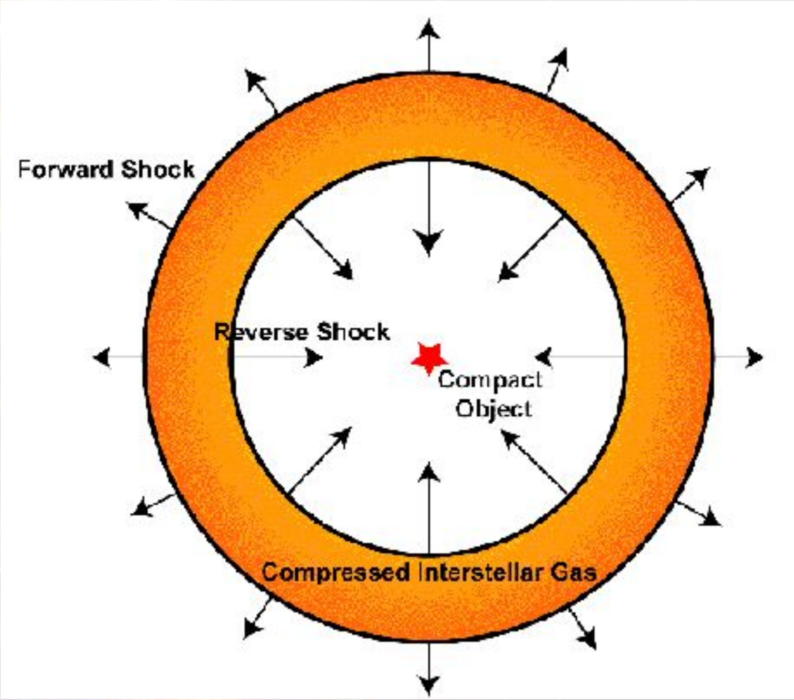


Image credit: NASA's HEASARC

- Models estimating dust destruction vary widely depending on e.g. grain composition/size and ejecta composition, destroying ~10-100% of SN dust[1]

[1] e.g. Nozawa et al. 2007, Silvia et al. 2012

Dust survival: ejecta composition

- Dense SN ejecta knots likely to be very important for dust survival
  - Rayleigh-Taylor instabilities following SN explosion
    - Highly inhomogeneous ejecta: dense knots
  - Dense knots promote formation of molecules and dust growth
    - High density also slows reverse shock
    - ~200 km/s shock does limited damage to dust[1]
- In general, need more observational data to constrain dust destruction models

[1]Jones et al. 1994, 1996

Cassiopeia A

- One of the rare SNRs we can observe ejecta
  - ~330 years old and 3.4 kpc away
- Large dust masses
  - 0.025 $M_{\odot}$ warm dust[1] associated with reverse shock
  - 0.075 $M_{\odot}$ unshocked cold dust[2]

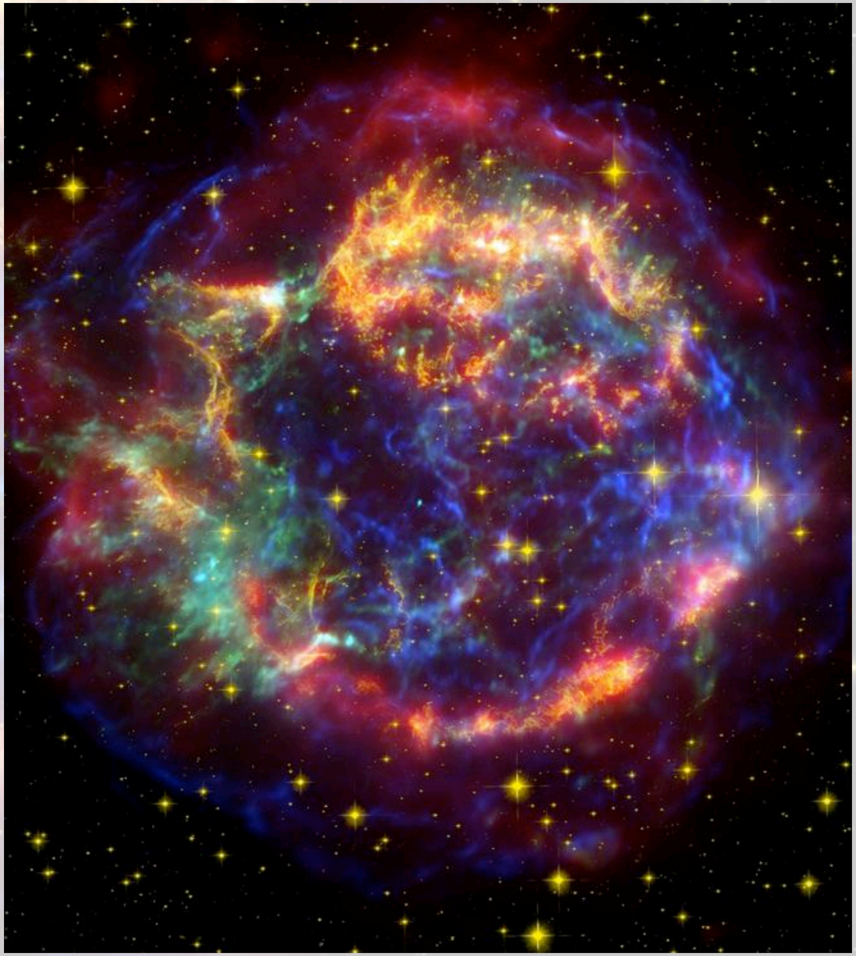


Image Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

[1]Rho et al. 2008
[2]Barlow et al. 2010

Cassiopeia A

- Ro-vibrational CO detected[(1)]
  - In many small (<0.8”) knots
  - Coincident with reverse shock
- Difficult to derive physical conditions

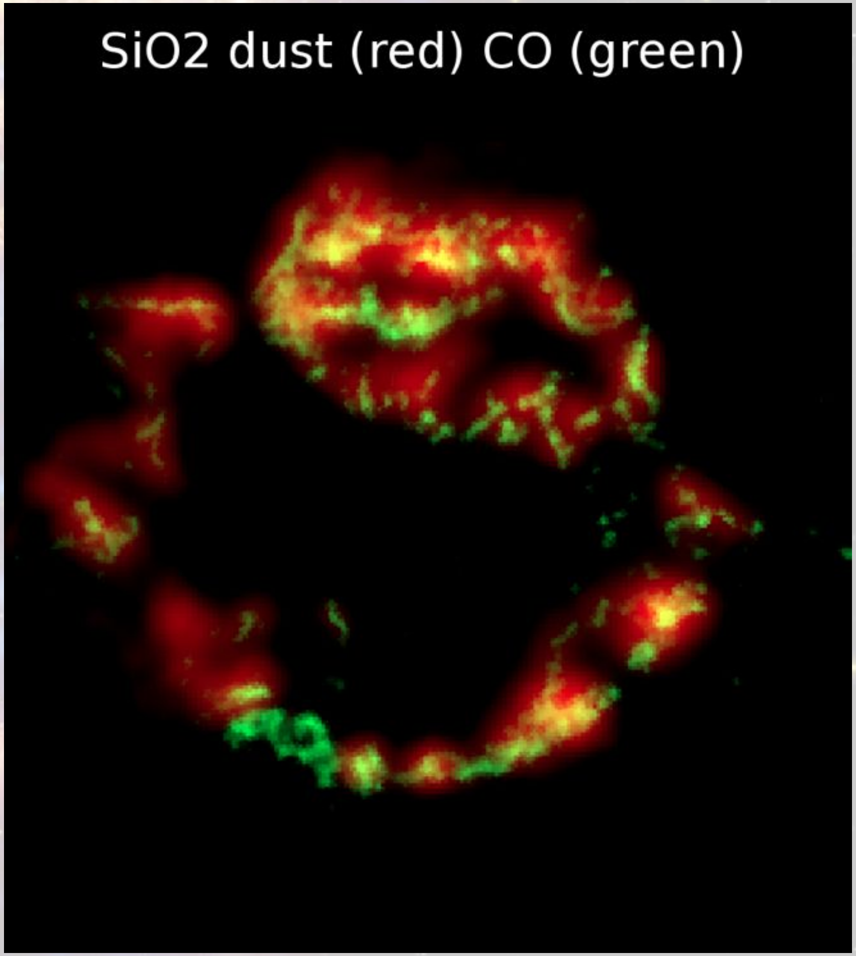
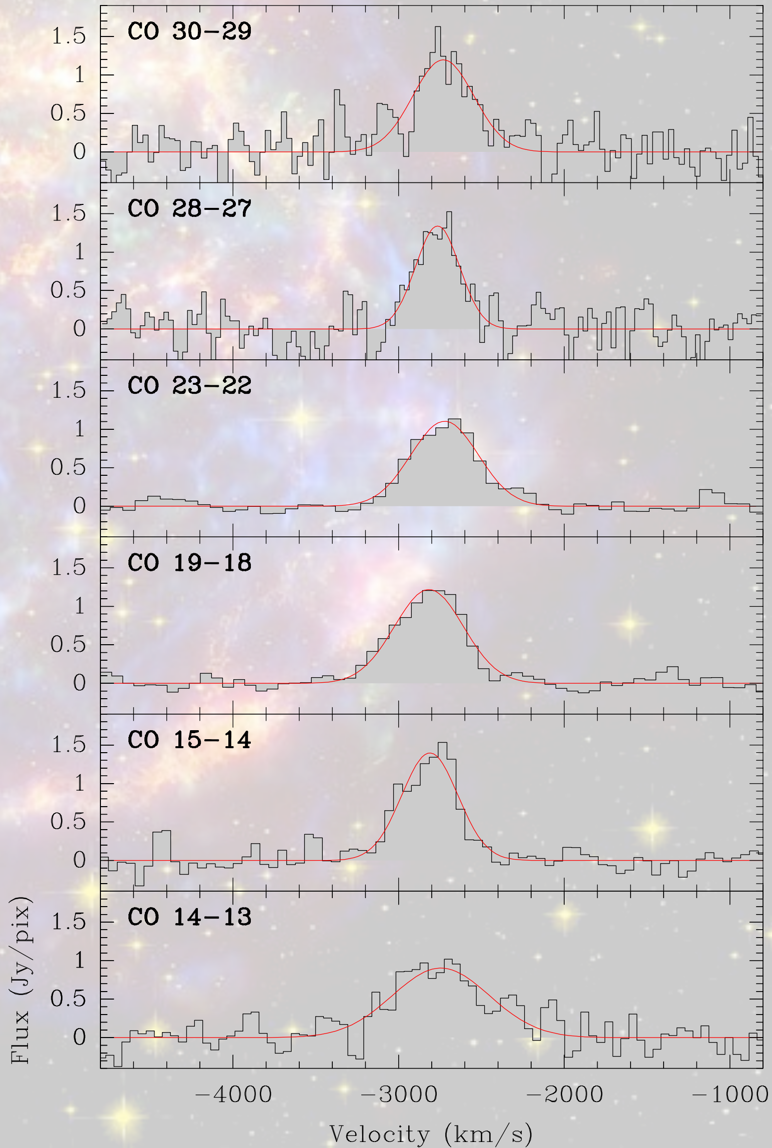


Image credit: J. Rho

[(1)]Rho et al. 2009, 2012

Herschel PACS observations (1)

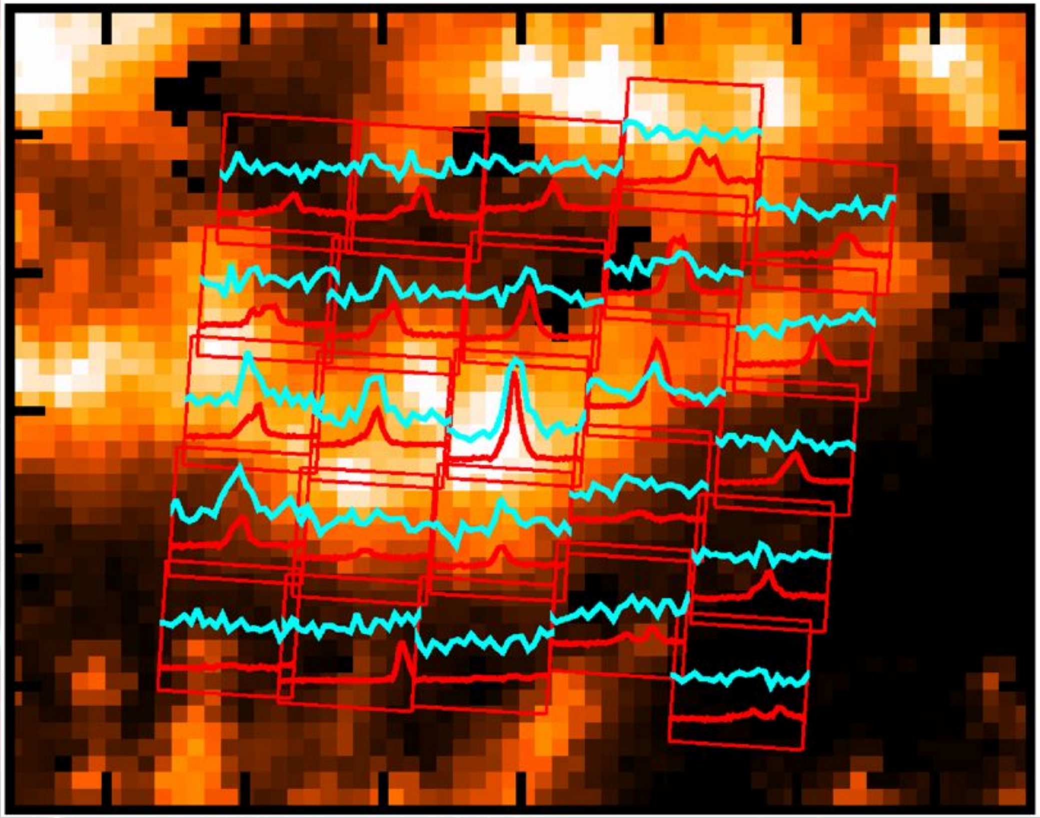
- Brightest CO knot targeted in several rotational CO lines[(1)]
- Blueshift of -2800 km/s
- Broad lines ~400 km/s
- Physical conditions:
  - Large column density (10^{19} cm^{-2})
  - Dense (10^5 to 10^6 cm^{-3})
  - Warm (500-1000 K)



[(1)]Wallström et al. 2013

Herschel PACS observations (2)

- Variation across the PACS footprint, both in CO (blue) and [OIII] 88 μm (red)
  - More variation in [OIII] as it traces pre-shock gas
  - CO emission to the west (left) may imply additional knot(s)



Spectra overlaid on a Spitzer/IRAC image of the CO vibrational emission

Reverse shock region

- At the shock front: increase in density and temperature
- Photons from shock front cause pre-shock PIR and post-shock PIR
  - Similar in temperature, but very different densities

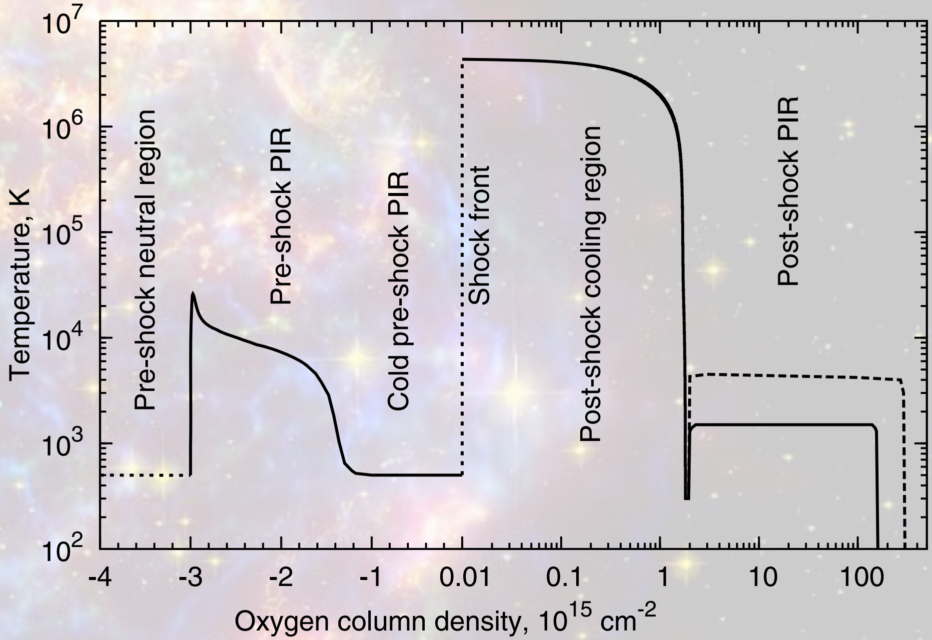


Image from Docenko & Sunyaev 2010

PIR = photoionized region

CO knots in Cas A

- CO most likely in post-reverse-shock region, given the density, temperature, and broad lines
- Large column density of warm gas indicates an additional heating source
  - CO cooling time ~100 days
  - UV photons from the shock front and diffuse X-ray flux both insufficient
  - Most likely electron conduction from the surrounding plasma

Thermal conduction by electrons

- Thermal conduction into a dense ejecta knot balanced by evaporation flow from knot surface
  - Evaporation from knots into the hot gas determines the temperature and structure of SNRs[(1)]
    - Thought to control the evolution of SNRs and their role in the large scale structure of the ISM[(1)]
    - Thermal conduction is thought to be responsible for so-called mixed- morphology SNRs[(2)]
  - There is little direct evidence for the importance of thermal conduction in the survival of knots in SNRs

[(1)] McKee & Ostriker 1977
[(2)] Rho & Petry 1998

Follow-up

- No more Herschel, but still want to study
  - Characteristics of pre- and post-shock gas
  - Interrelationship of molecular and neutral/ionic atomic gas
  - The role of heat condution by electrons
  - The possible role of molecular knots in protecting SN dust

SOFIA Cycle 2 with FIFI-LS

- Cycle 2 SOFIA observations with FIFI-LS
  - Similar to Herschel PACS, for combination with previous data
  - Perfect for our broad lines (~400 km/s) and spatial variation
- I got to fly with SOFIA in April 2014!

The FIFI-LS proposal (1)

- Short project (<1h) to detect fine-structure lines of [OIII] 88 and 52 μm, and [OI] 63 μm
  - [OIII] 88 μm also observed with Herschel
    - Direct comparison with CO observations
  - Determine the characteristics and interrelationship of the molecular and neutral/ionic atomic gas

The FIFI-LS proposal (2)

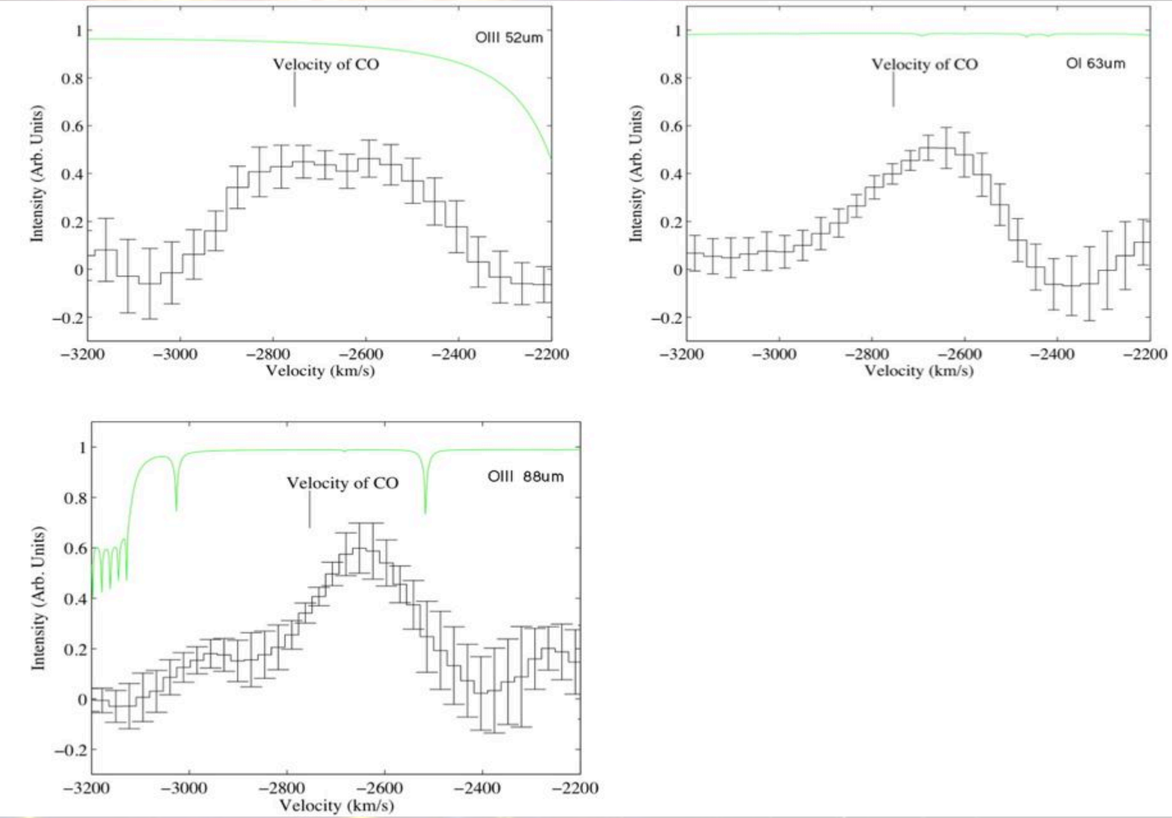
- Lines with various critical densities to disentangle contributions from
  - lower density pre-shock photoionized zone
  - higher density post-shock photoionized zone
    - E.g. [OI] 63 μm has critical density of 10^5 cm^{-3}, tracing the dense post-shock gas and may be a main coolant of this gas
- Velocity-resolved line profiles of the knot in different tracers
  - Velocity shifts and difference in line-width associated with pre- and post-shock gas

The FIFI-LS proposal (3)

- Address the following questions
  - What are the pre-shock and post-shock conditions in dense ejecta knots?
  - Are the observed variations in the mid-IR CO emission related to variations in the pre-shock density, column density or the presence of additional heating sources for the gas?
  - What is the importance of electron energy conduction for the heating of the gas?
  - How are dense knots in supernova ejecta processed by the reverse shock, and how well can they protect dust?

SOFIA cycle 2 observations

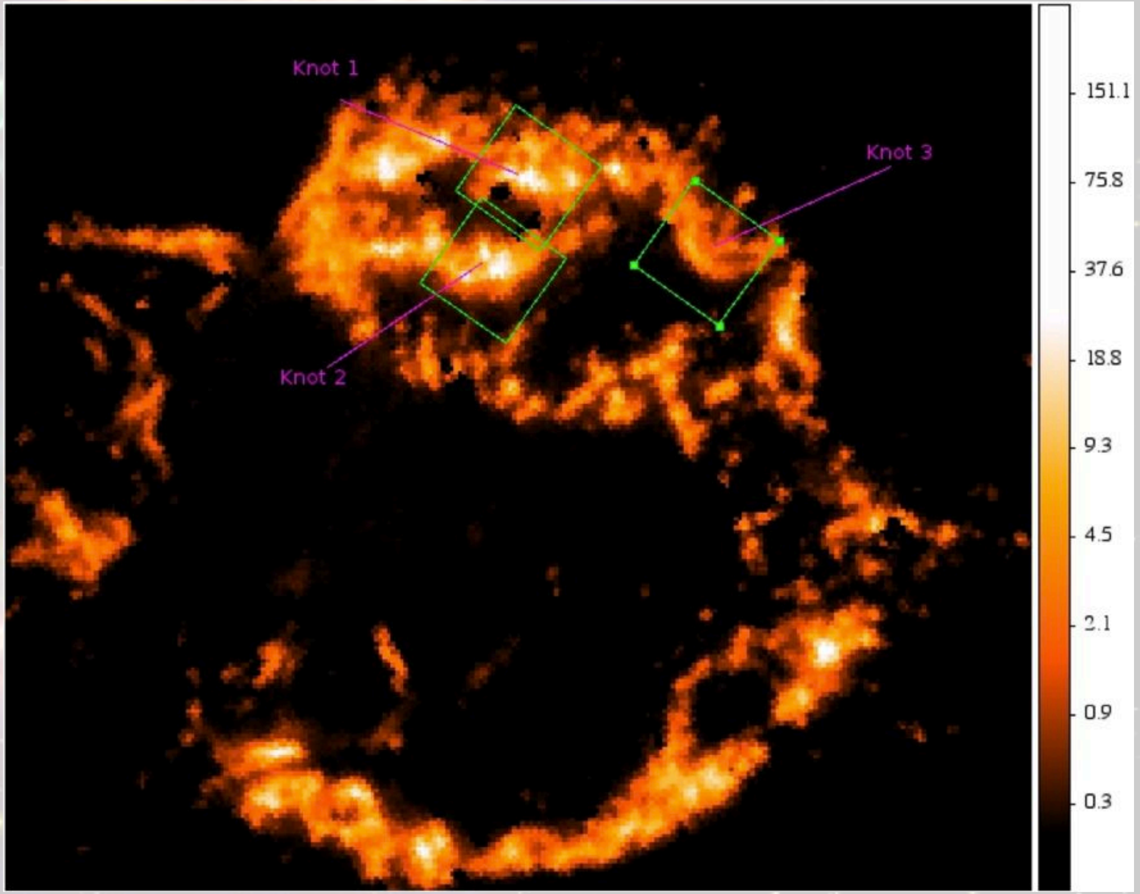
- Lines detected with short integration times
- Shown here are quick-look reduction results
  - Sufficient for Cycle 3 followup proposal



Telluric absorption calculated by RATRAN shown in green

SOFIA Cycle 3 with FIFI-LS

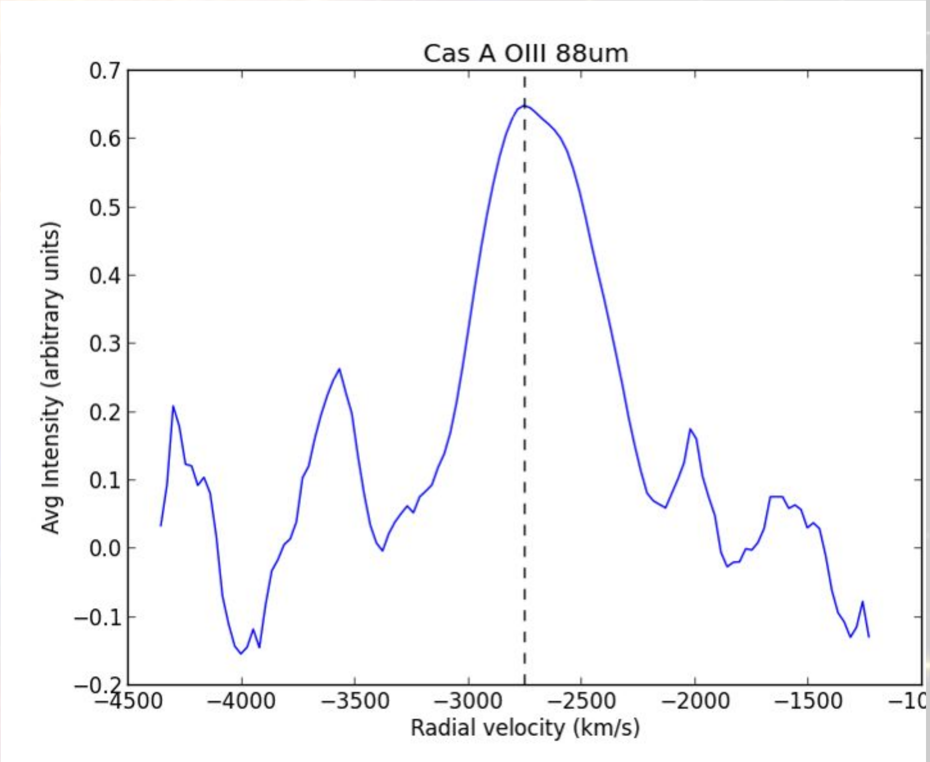
- Follow-up observations in Cycle 3
- Targeting the same lines at 3 bright CO positions in Cas A
- Total observing time ~15 hours



4.5 µm Spitzer map of ro-vibrational CO emission in Cas A (Rho et al. 2009)

Preliminary Cycle 3 result

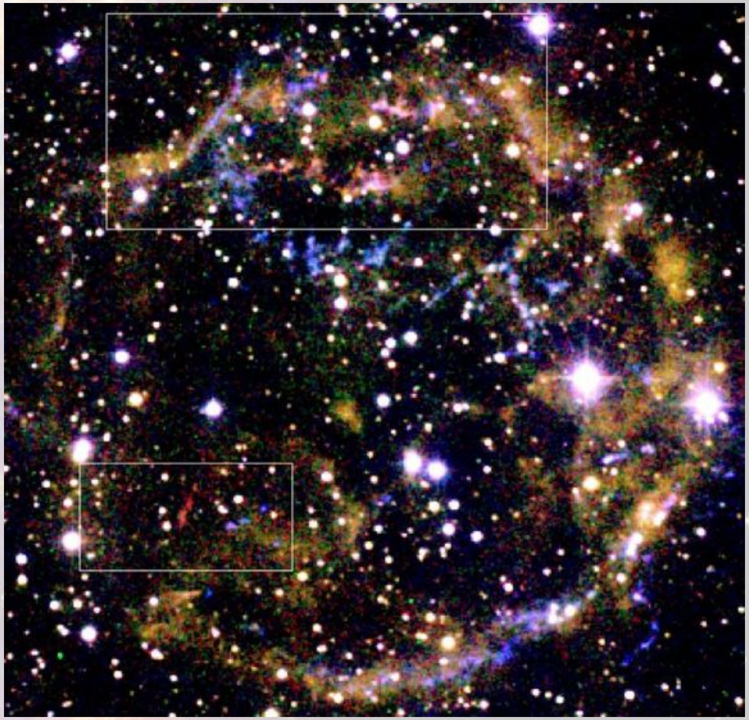
- A few observing flights completed
  - More flight time scheduled in autumn
- As yet only quick-look reduction results
  - Chop/nod subtracted and reduced using spatial and spectral flat fields
  - Wavelength calibrated but not telluric corrected or flux calibrated



Dashed line marks the CO velocity

Summary

- Dense molecular knots in Cas A important for SNR impact and evolution
  - Study interplay with neutral/ ionic gas
- Waiting for complete, reduced Cycle 3 FIFI-LS data
  - Derive column densities, temperatures; look at spatial variation; disentangle pre- and post-shock contributions…



Color image of Cas A, with CO 2-0 overtone emission at 2.3 µm in red, K-continuum in green and Pβ in blue (Rho et al. 2009)