# High-Resolution X-Ray Spectroscopy of Southeastern Knots in Tycho’s SNR with XMM-Newton/RGS

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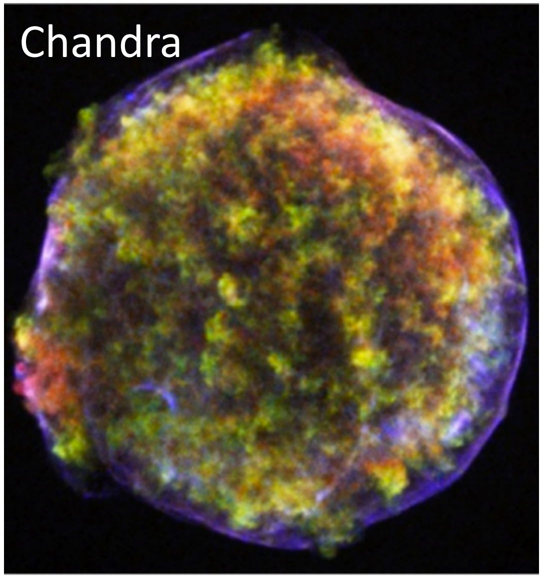
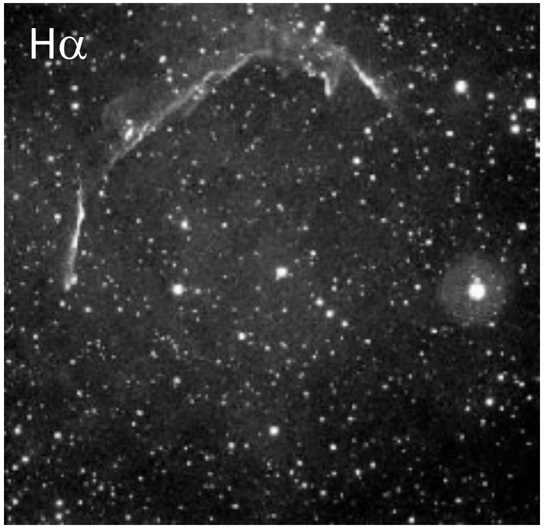
# Tycho's Supernova Remnant (SN 1572)

- A proto-typical Type Ia SN remnant (from a light-echo spectrum)
- Surviving companion not yet found.
  → SD vs. DD still unclear.
- Balmer-dominated shocks
- Cosmic-ray acceleration
- Clumpy SN ejecta
  Possibly due to initial clumpiness in the explosion (Williams+2017; Sato+2019)

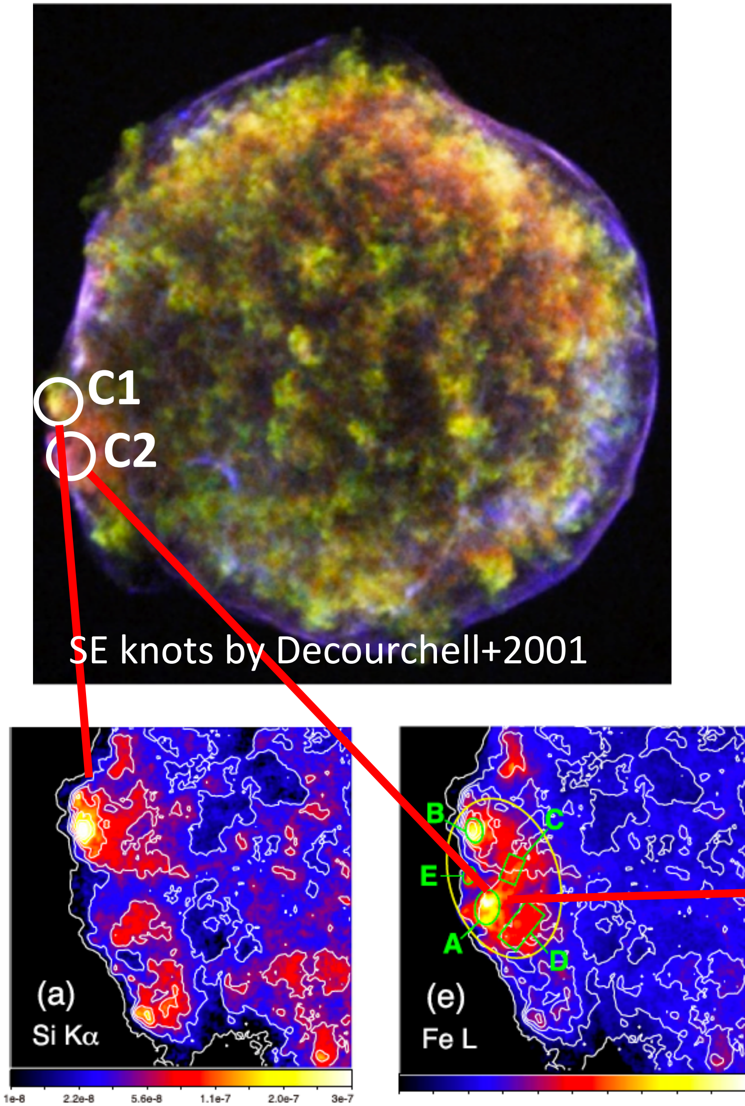


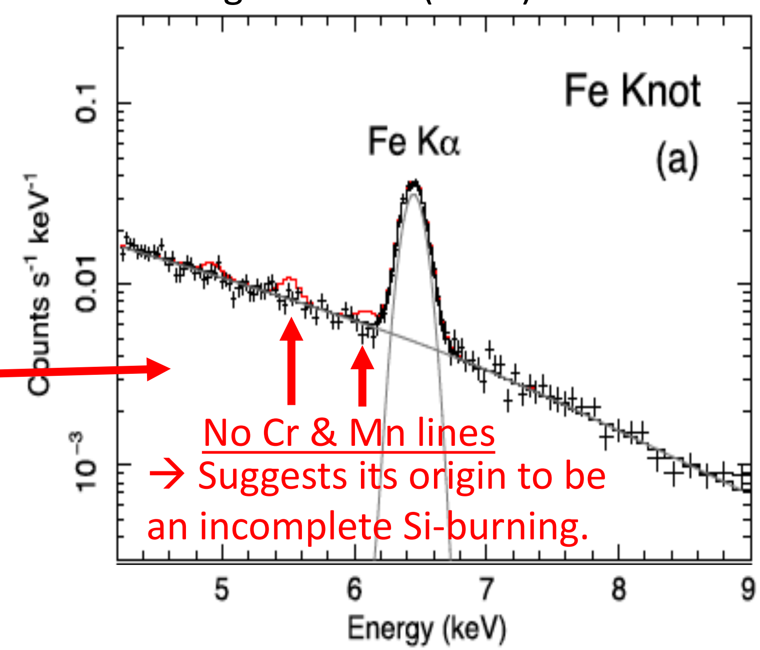
# Southeastern Protrusion

C1: Si-rich

C2: Fe-rich (+ ONeMg-rich by T. Sato)



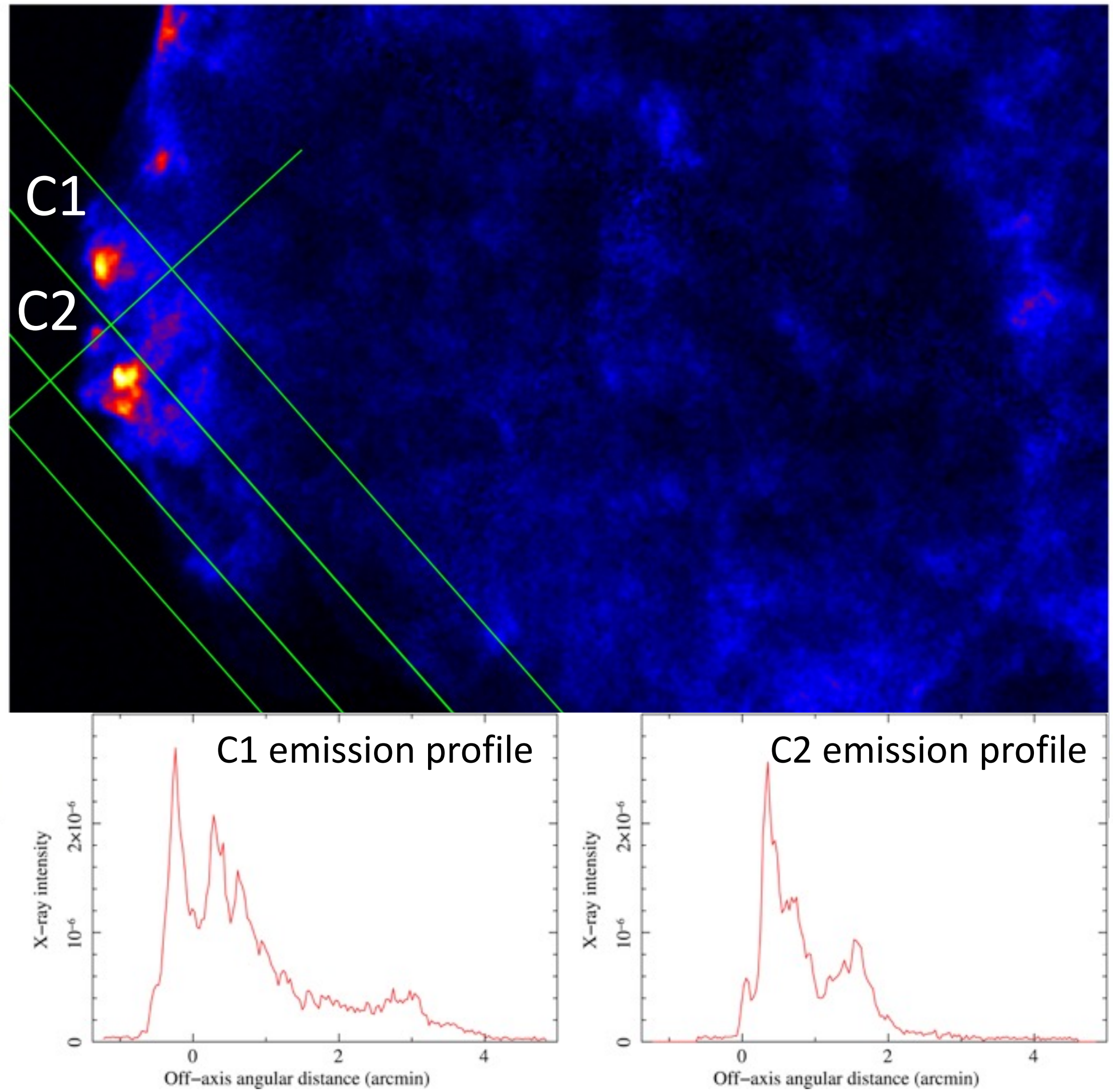

Yamaguchi et al. (2017)



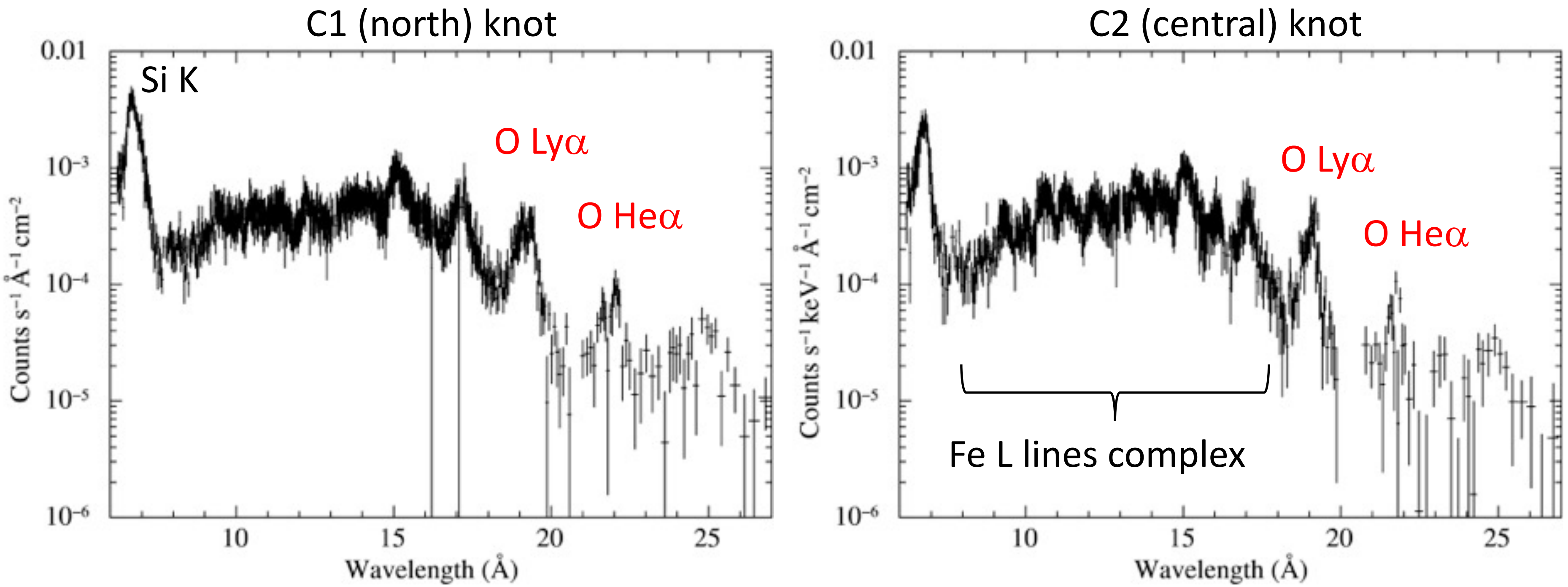
# XMM-Newton/RGS Observation

<u>XMM-Newton observation</u>
PI: B. J. Williams
Date: 2017-08-04
Exposure time: 150 ks

<u>Goals</u>
1) Measuring ion temperatures to see ion-$e^-$ T non-equilibration
2) Measuring O abundance to better understand SD vs. DD
3) Fe L diagnostics

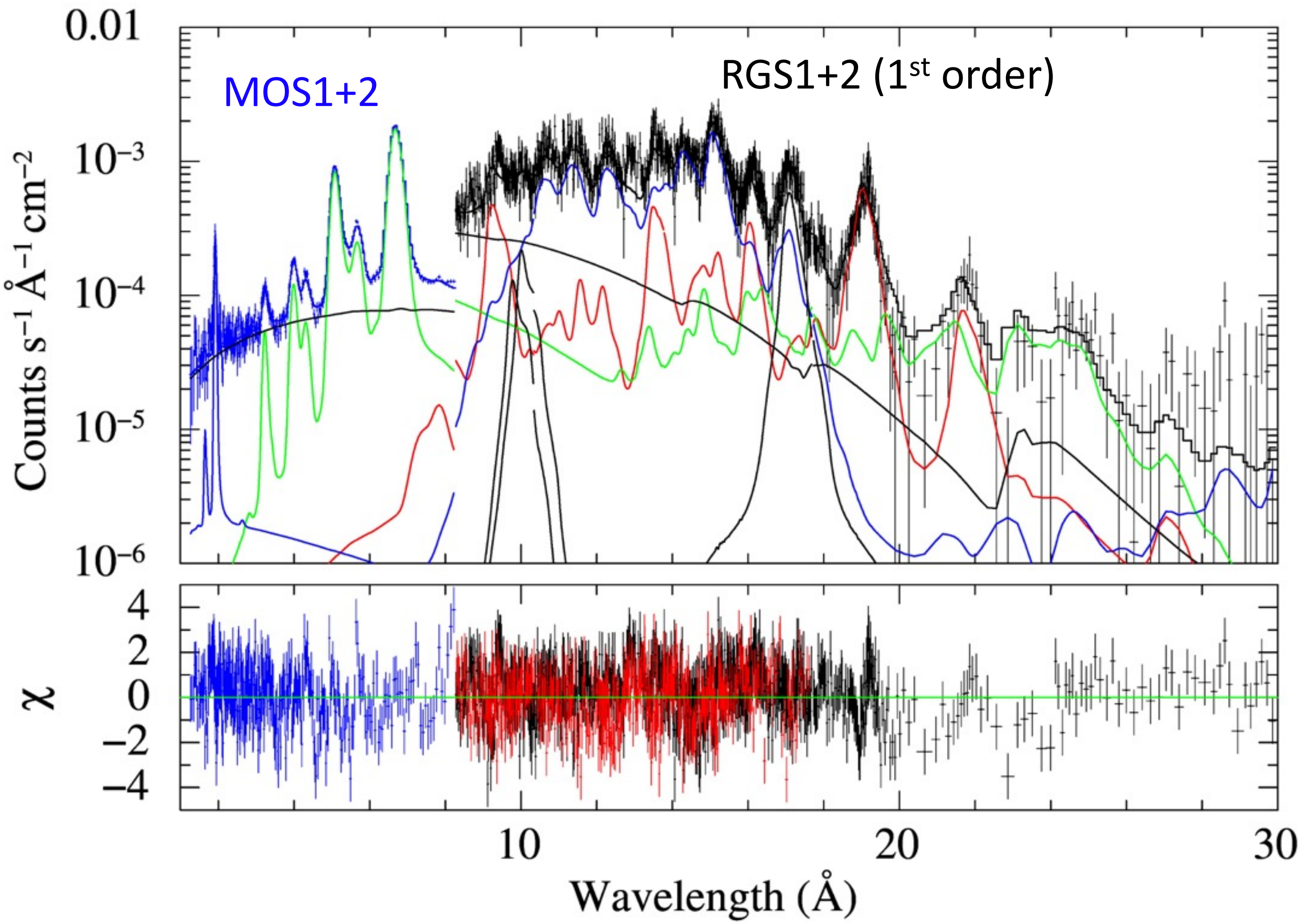


# RGS Spectra



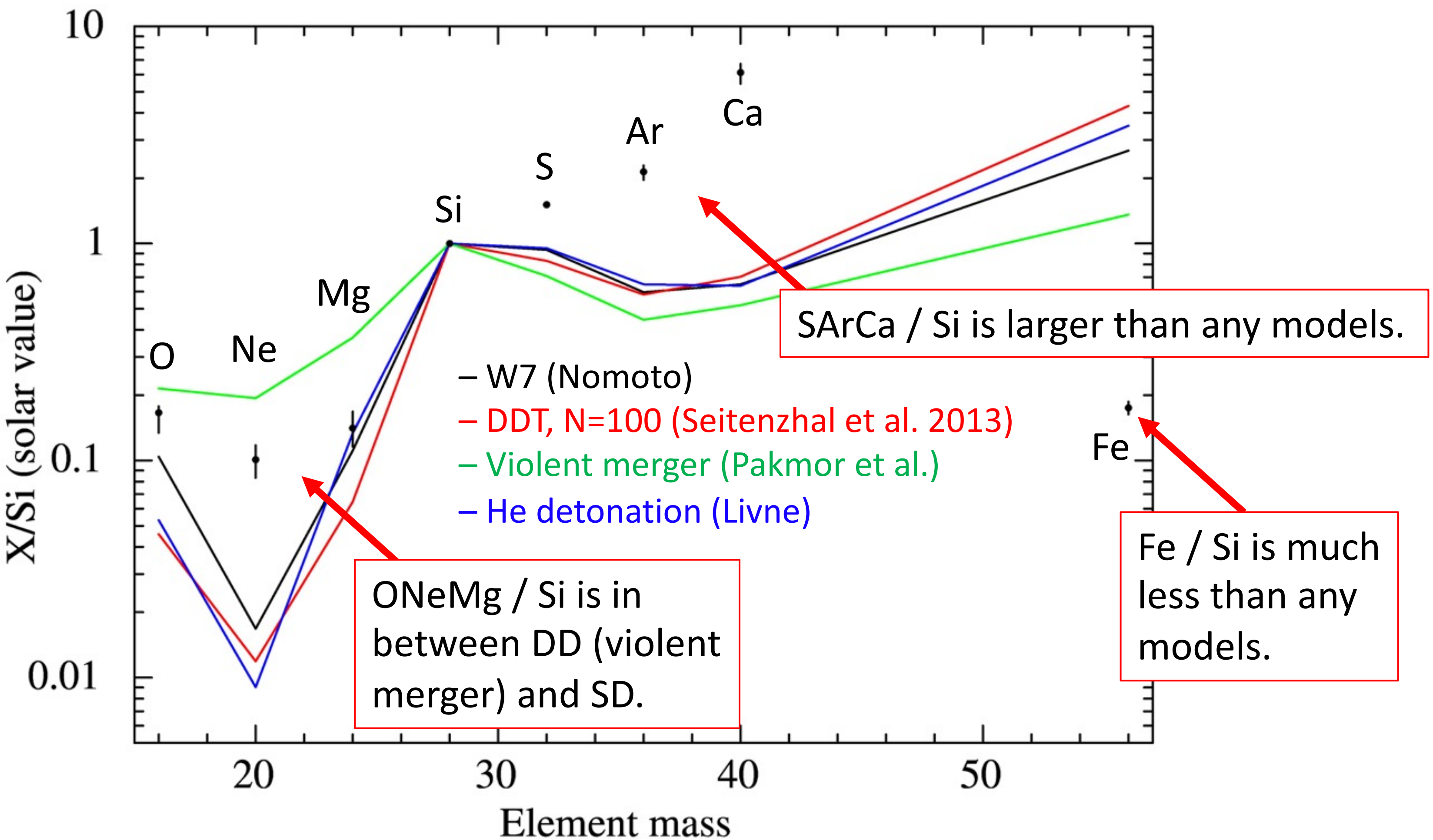

The first clear detection of O K lines from Tycho's SNR

# Spectral Fitting of the C2 Spectrum



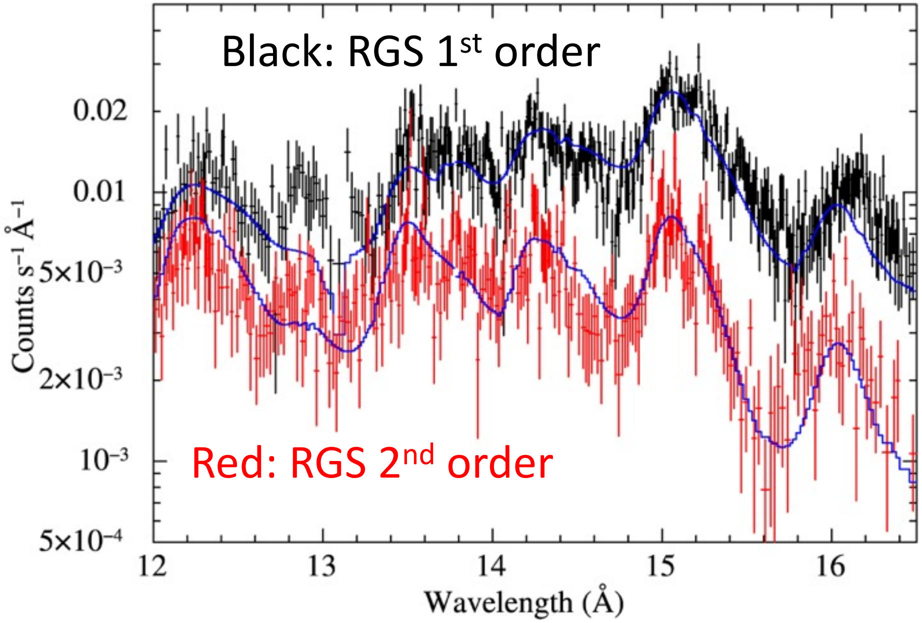

Model = (1) ONeMg + (2) IME + (3) Fe + (4) power-law

# Abundances




- The SD scenario is slightly better than DD.
  (considering possible ONeMg contamination from the swept-up ISM)
- Fe abundance is very low, suggesting its origin in the outer envelope.

# Line Broadening




Best-fit broadening (linearly scaled with energy):

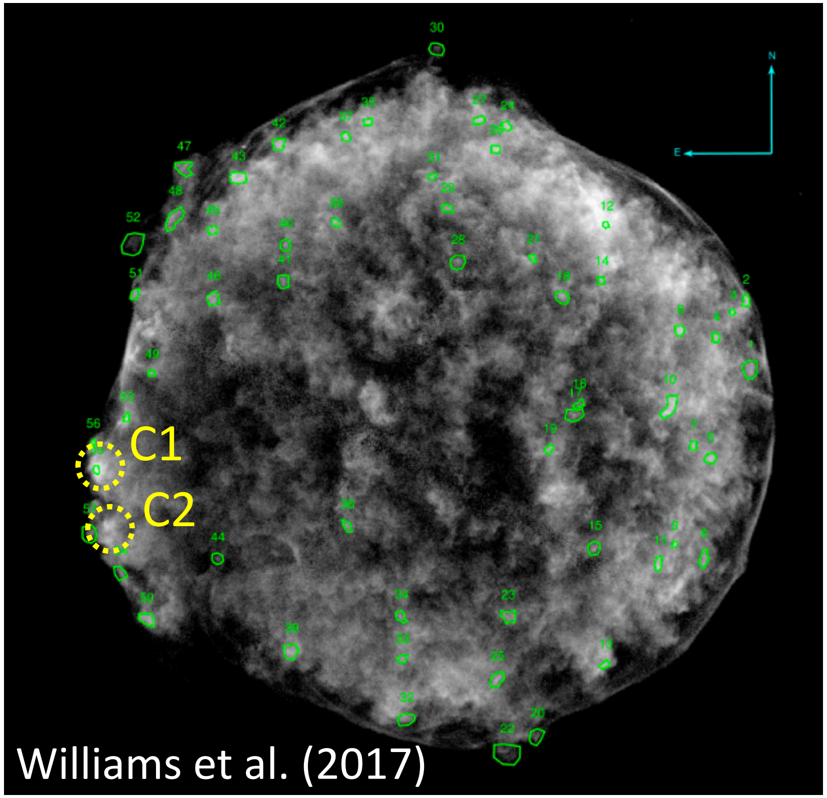
1 $\sigma$ = 30.1 $\pm$ 2.1 eV @ 6 keV, or 1 $\sigma$ = 5 eV @ 1 keV

$kT_a = (\sigma / E_0)^2 * m_a c^2 = (30\ \text{eV} / 6000\ \text{eV})^2 * M_a * 938000\ \text{keV}$

| $kT_O$ | $kT_{Ne}$ | $kT_{Mg}$ | $kT_{Si}$ | $kT_S$ | $kT_{Ar}$ | $kT_{Ca}$ | $kT_{Fe}$ |
|---|---|---|---|---|---|---|---|
| 0.4 $\pm$ 0.05 | 0.5 $\pm$ 0.07 | 0.6 $\pm$ 0.08 | 0.7 $\pm$ 0.10 | 0.8 $\pm$ 0.11 | 0.9 $\pm$ 0.12 | 1.0 $\pm$ 0.14 | 1.4 $\pm$ 0.19 |

in units of MeV

# Velocity of the SE Protrusion




| Region ID | $V_{total}$ (km/s) | |
|---|---|---|
| 55 | 6040 | C1 |
| 56 | 4990 | C1 |
| 57 | 6320 | C2 |
| 54 | 5970 | C2 |

$V_{shock} \sim 4/3 * V_{gas}$

$= 4/3 * 6150$ km/s $= 8200$ km/s for C2

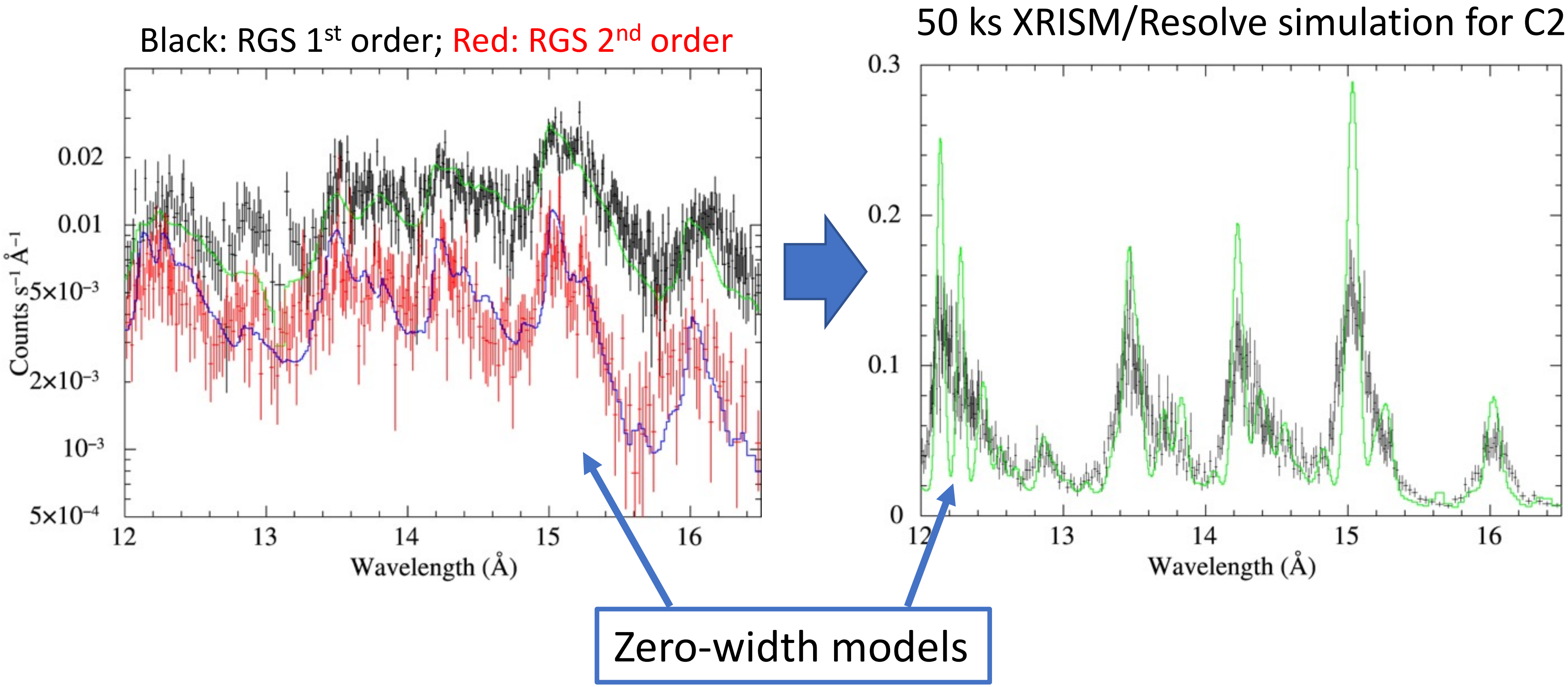
$kT_a = 3/16\ m_a\ V_{shock}^2$

| | $kT_O$ | $kT_{Ne}$ | $kT_{Mg}$ | $kT_{Si}$ | $kT_S$ | $kT_{Ar}$ | $kT_{Ca}$ | $kT_{Fe}$ |
|---|---|---|---|---|---|---|---|---|
| Observed | 0.4±0.05 | 0.5±0.07 | 0.6±0.08 | 0.7±0.10 | 0.8±0.11 | 0.9±0.12 | 1.0±0.14 | 1.4±0.19 |
| FS heating | 2.1 | 2.6 | 3.2 | 3.7 | 4.2 | 4.7 | 5.3 | 7.4 |

The observed temperatures (line widths) are much higher (narrower) than expected from the forward shock heating. → The knots were heated by a “slower” reverse shock.

Or, most of the shock energy goes into particle acceleration.

# Future Prospects for XRISM




The line width measurements with the RGS are not so solid, given the relatively large uncertainty on the RGS response function for diffuse sources.

XRISM/Resolve will determine the line widths accurately.

# Summary

- We observed the southeastern protrusion of Tycho's SNR with XMM-Newton.
- We analyzed RGS data, which successfully resolved a number of emission lines including O He$\alpha$, Ly$\alpha$, and Fe L complex, for the first time from this remnant.
- The relative abundances is more consistent with the SD model rather than the DD model.
- The line width was obtained to be 30 ($h\nu$ / 6 keV) eV. Since this is significantly larger than what is expected from the forward shock heating, the knot was likely heated by a slower reverse shock. There is a possibility that a substantial amount of shock energy goes into cosmic-ray acceleration (for either FS or RS heating).
- Future XRISM/Resolve observations will be helpful to determine the line widths (and abundances) more accurately.