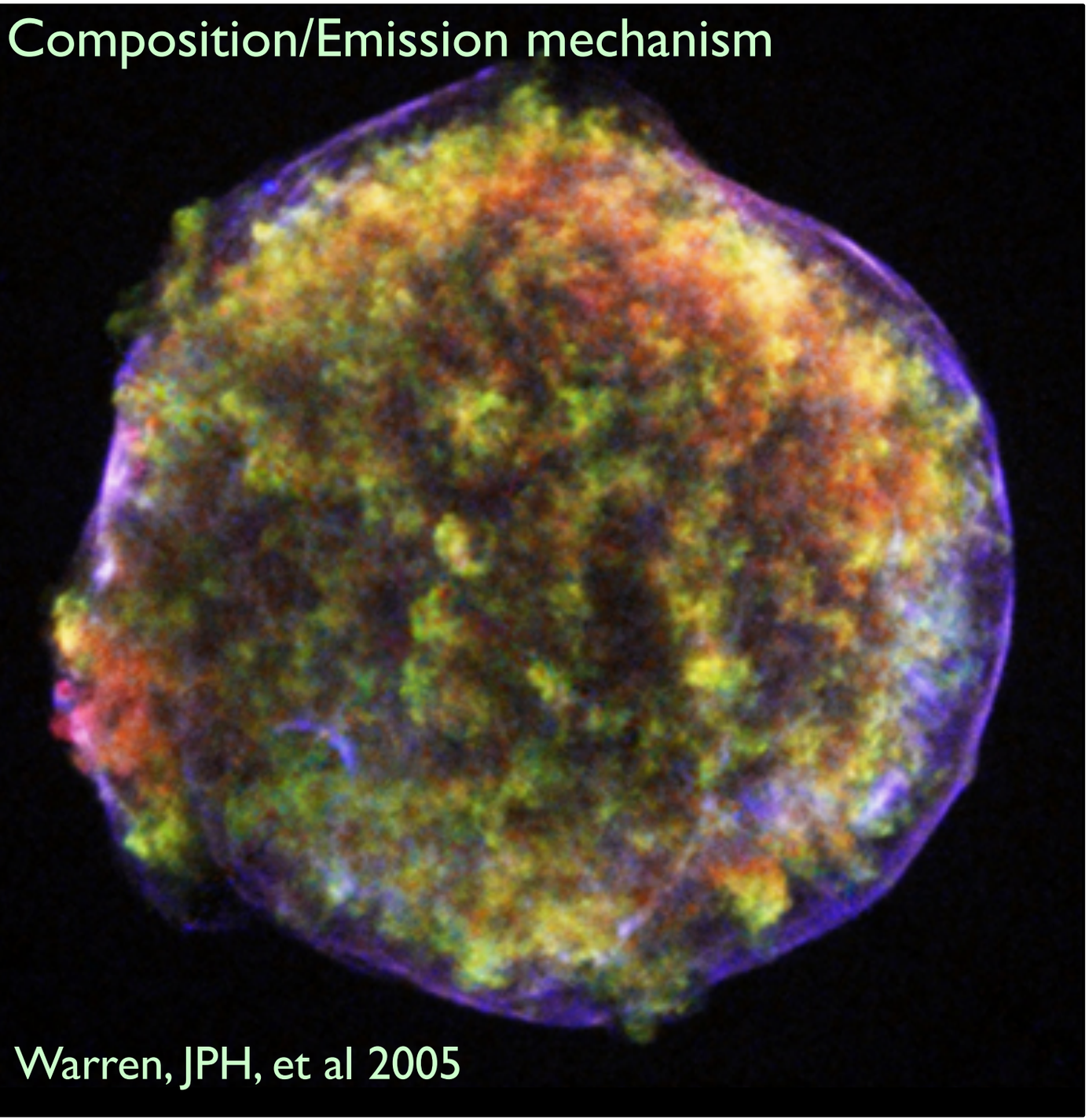
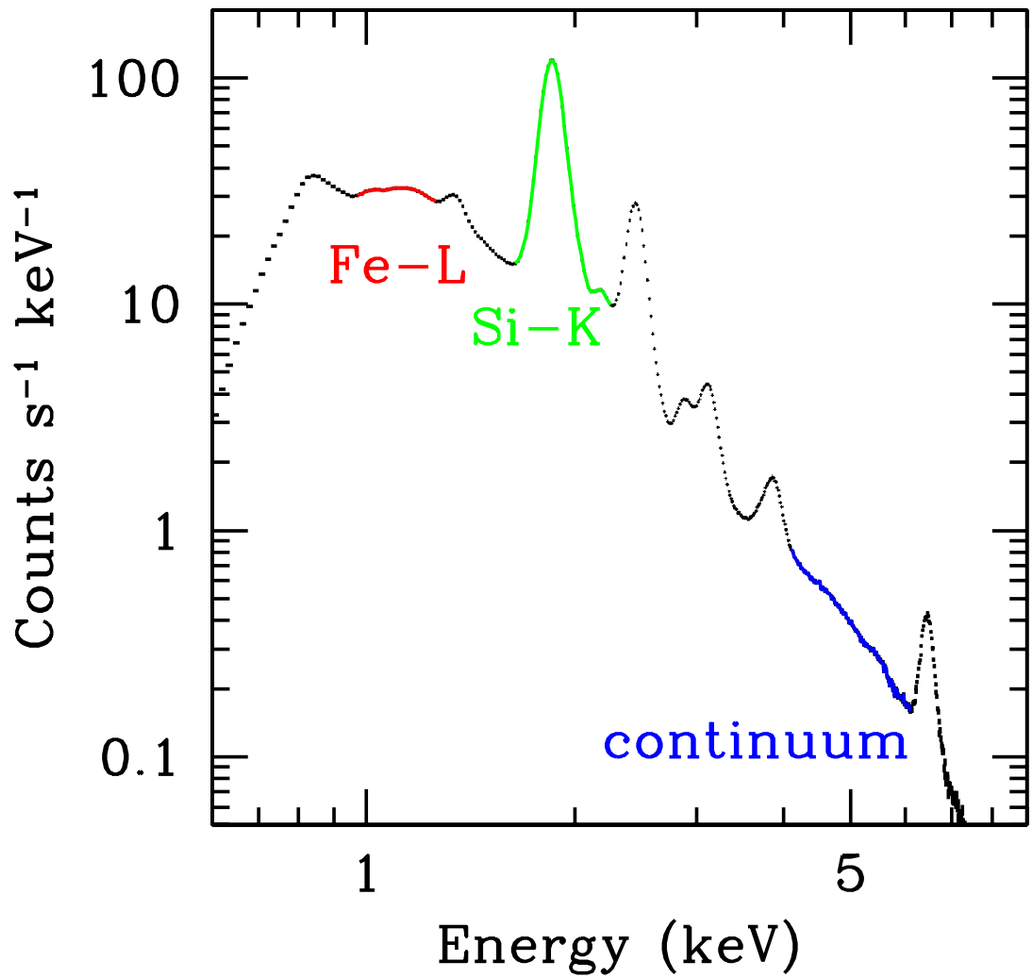
A Kinematic Study of Tycho's SNR

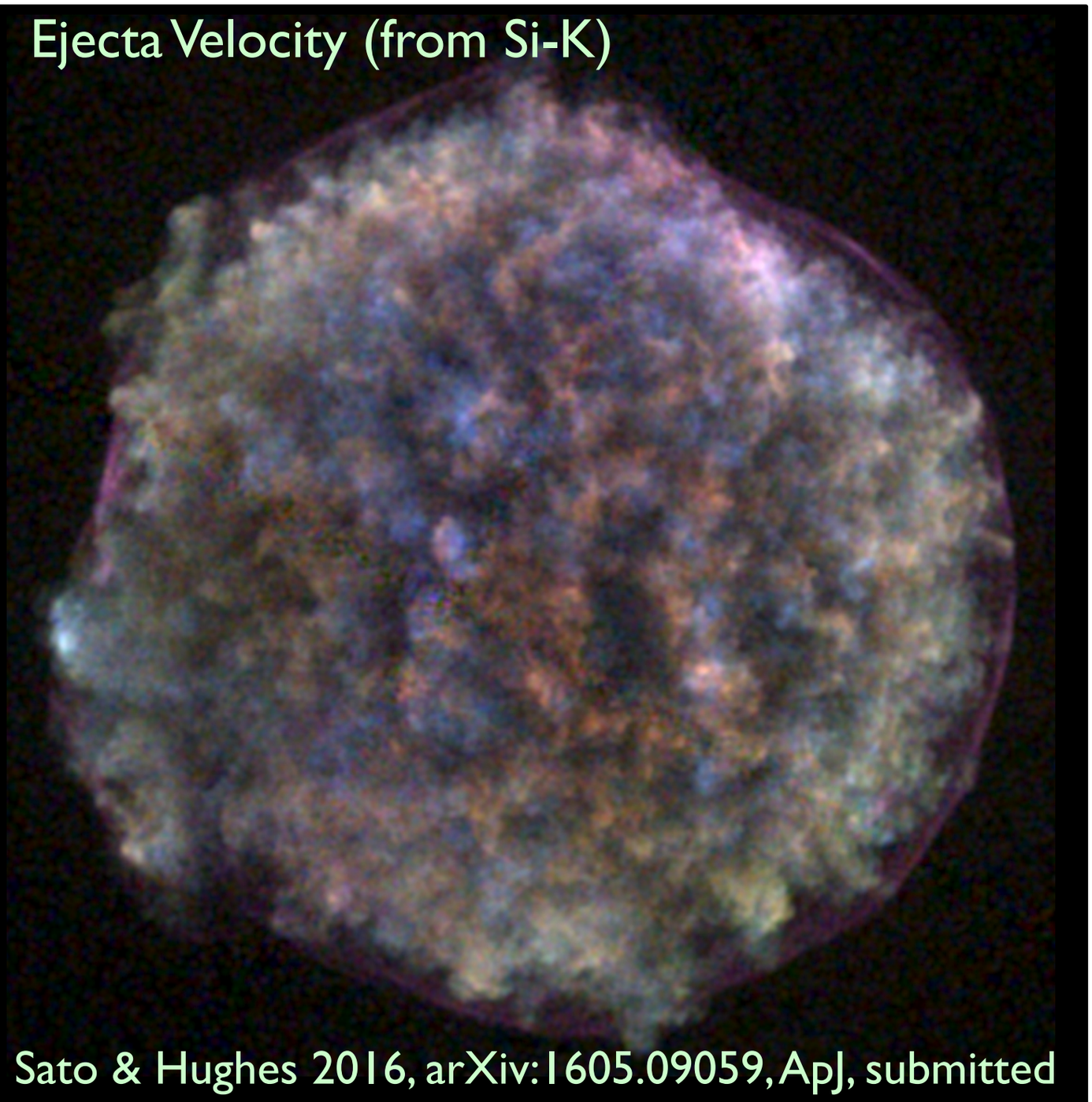
Jack Hughes (Rutgers University) and
Toshiki Sato (Tokyo Metropolitan University)

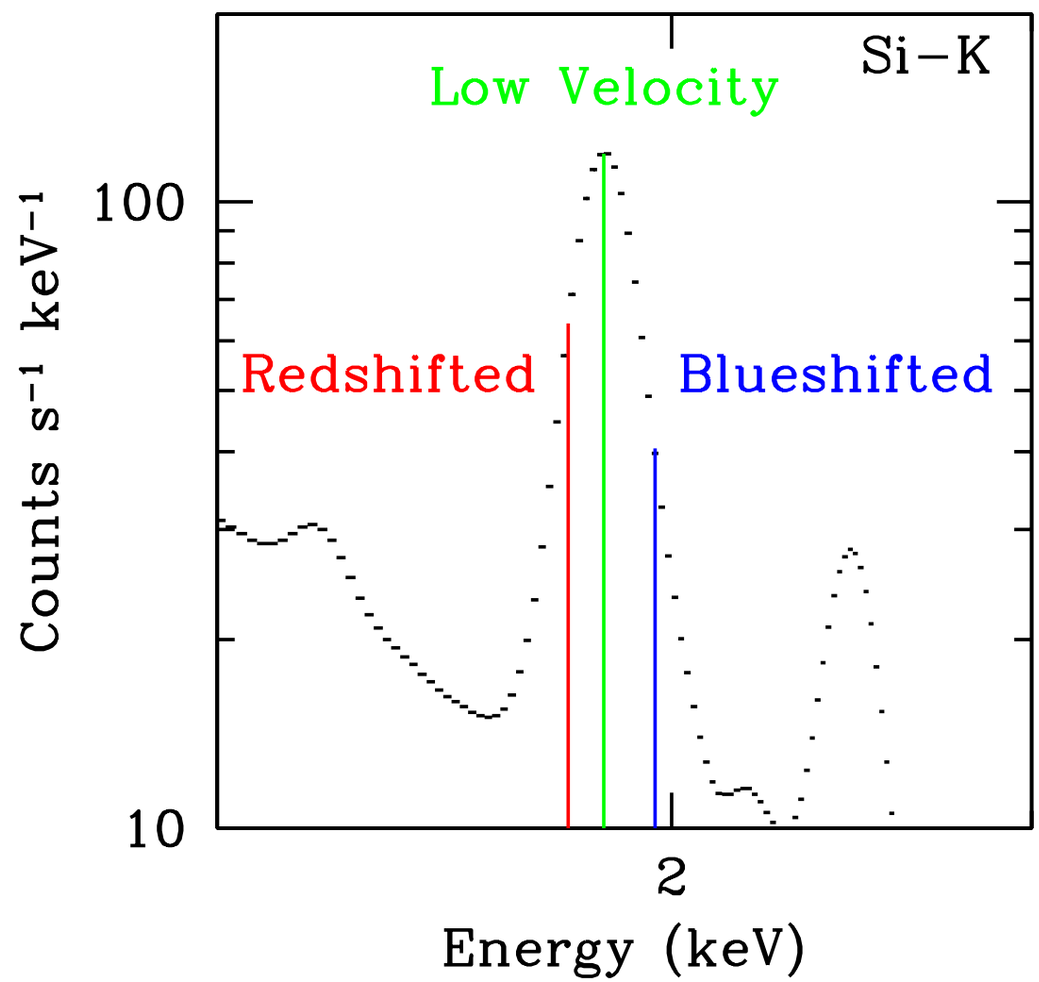




A Kinematic Study of Tycho's SNR

Jack Hughes (Rutgers University) and
Toshiki Sato (Tokyo Metropolitan University)





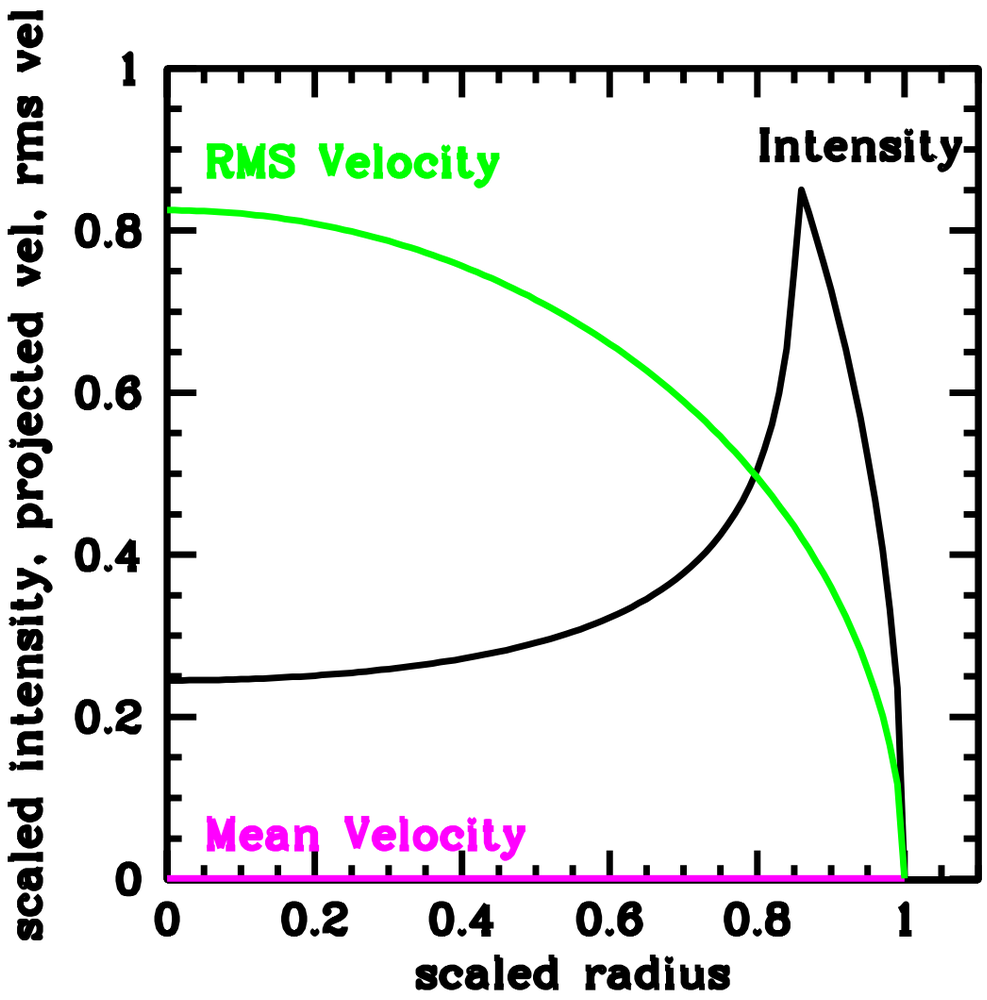
Using deep *Chandra* LP from 2009

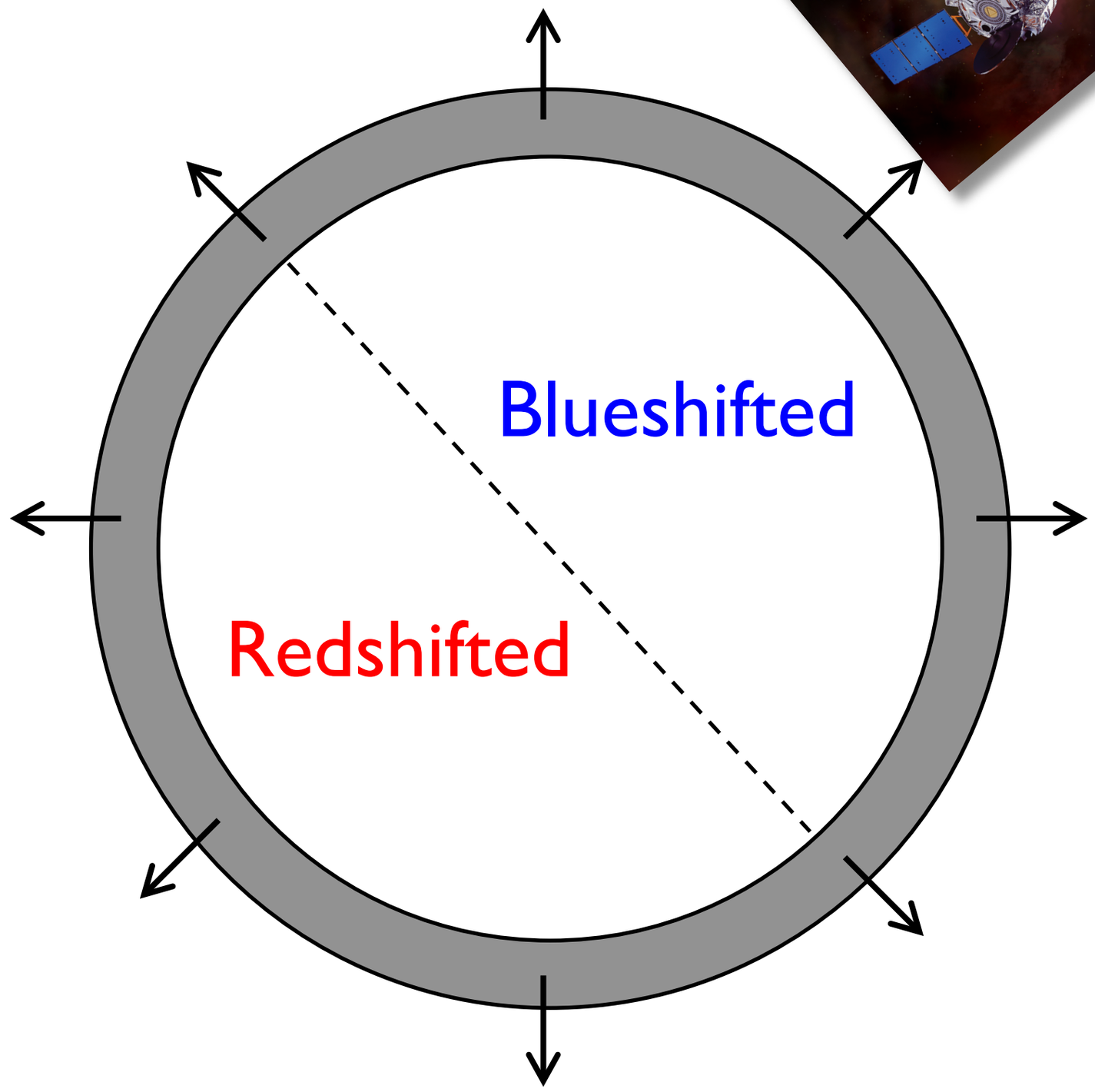
Talk Plan

- Radial profiles
- Double Gaussian fit
- Mean photon energy map
- Spectral analysis of individual blobs
- Large scale distribution of apparent velocities
- Southeastern knots
- Ion temperatures

Radial Profile Expectations

Optically thin, see both front and back halves; Spherical symmetry

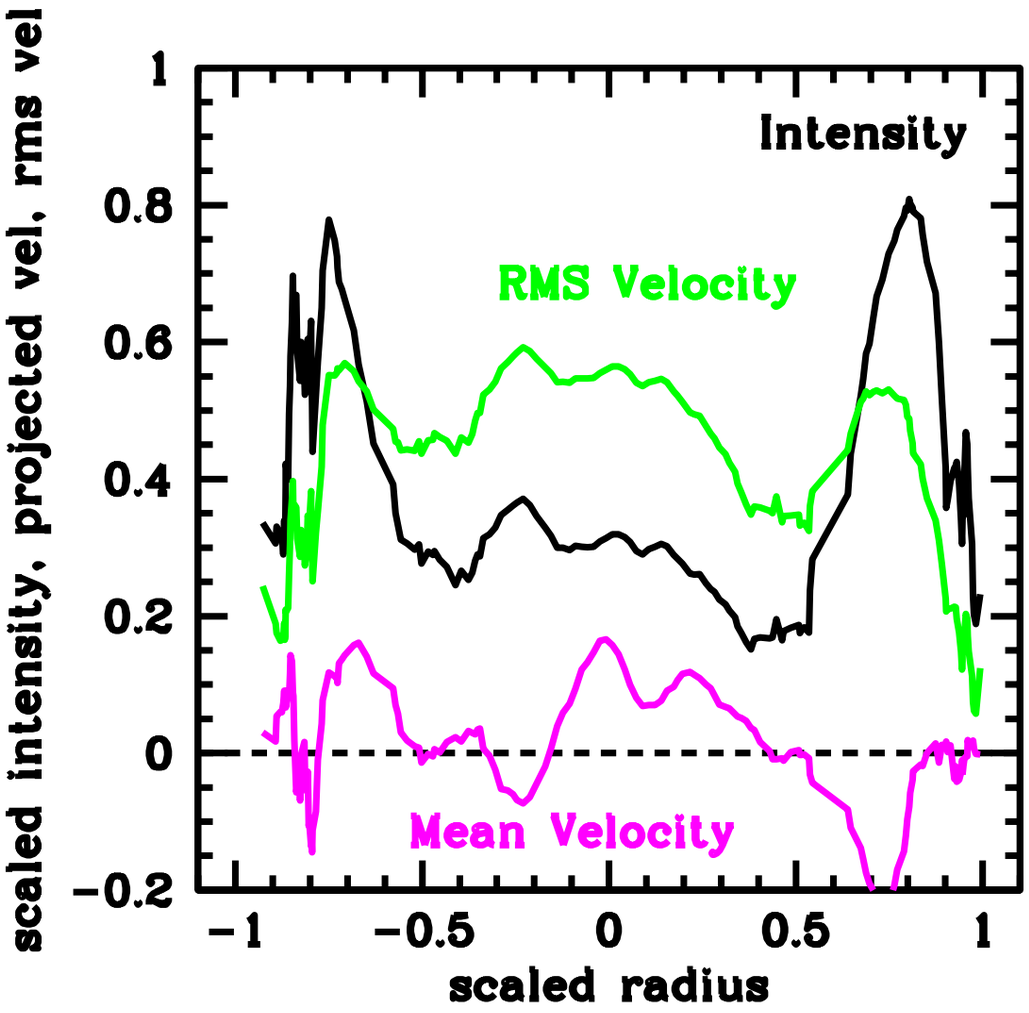


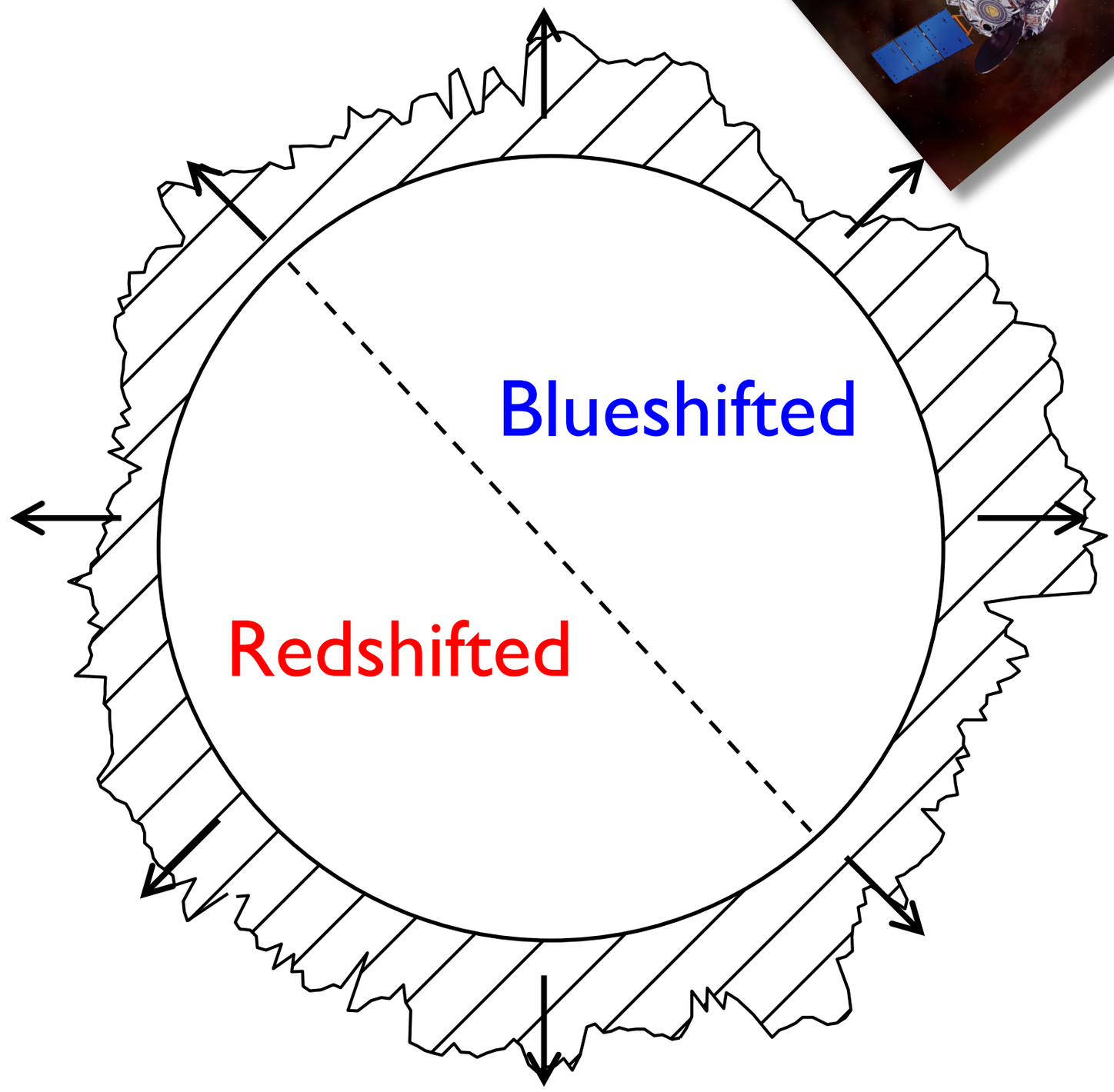


Red- & blueshifted hemispheres perfectly balanced

Radial Profile Expectations

Optically thin, see both front and back halves, Projected CD location

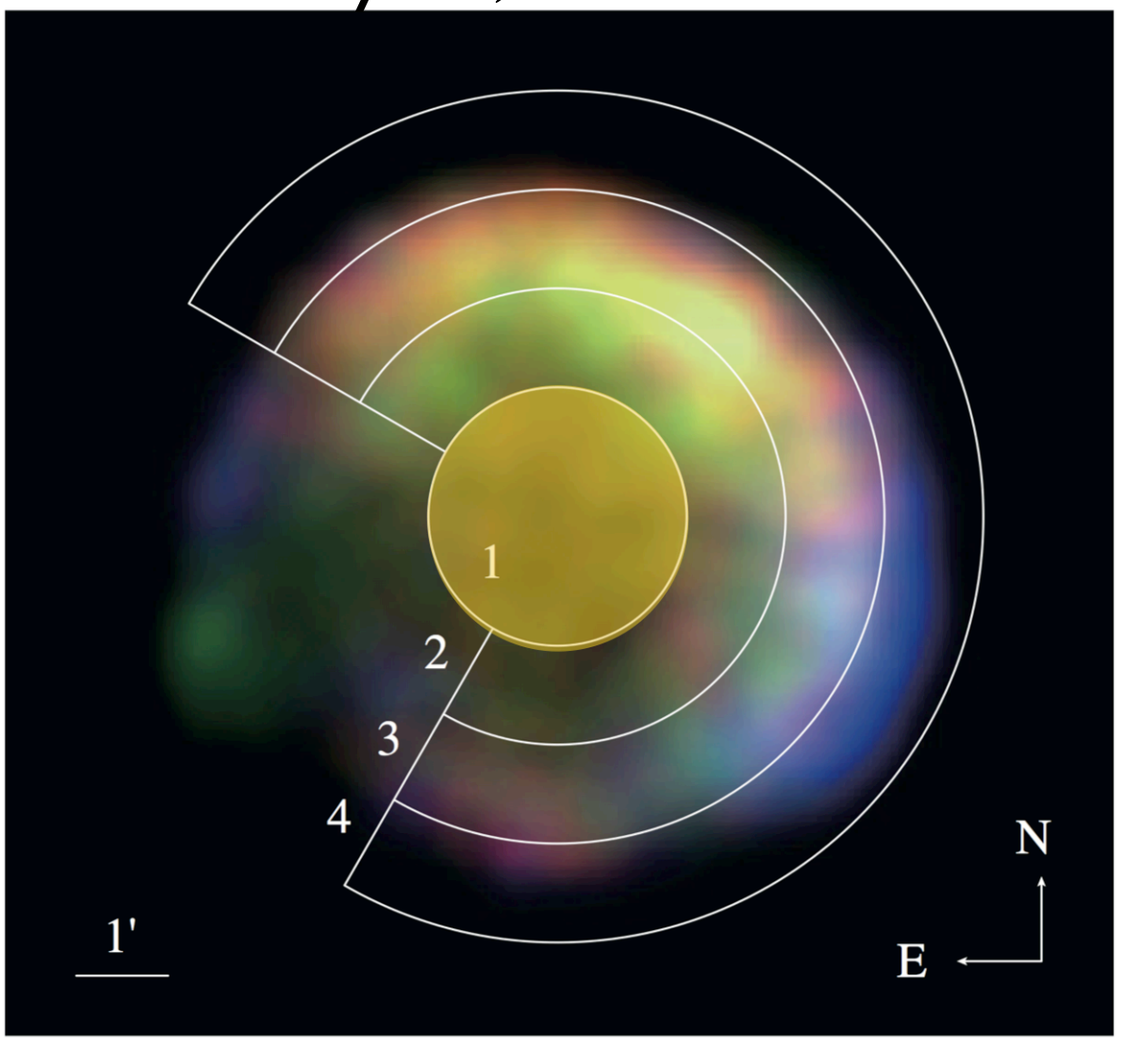




Red- & blueshifted hemispheres do not balance

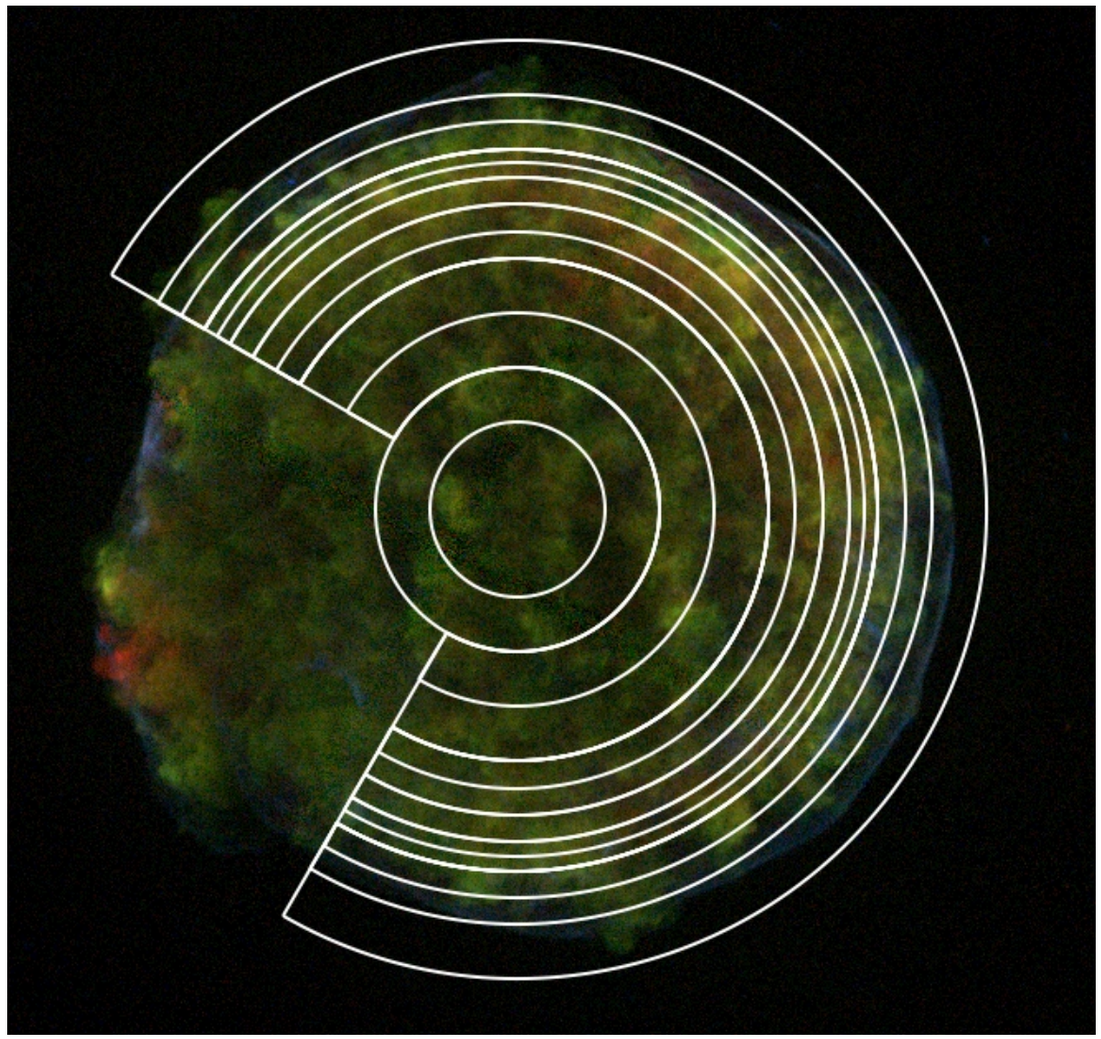
Radial Profiles

Suzaku: Hayato, et al 2010



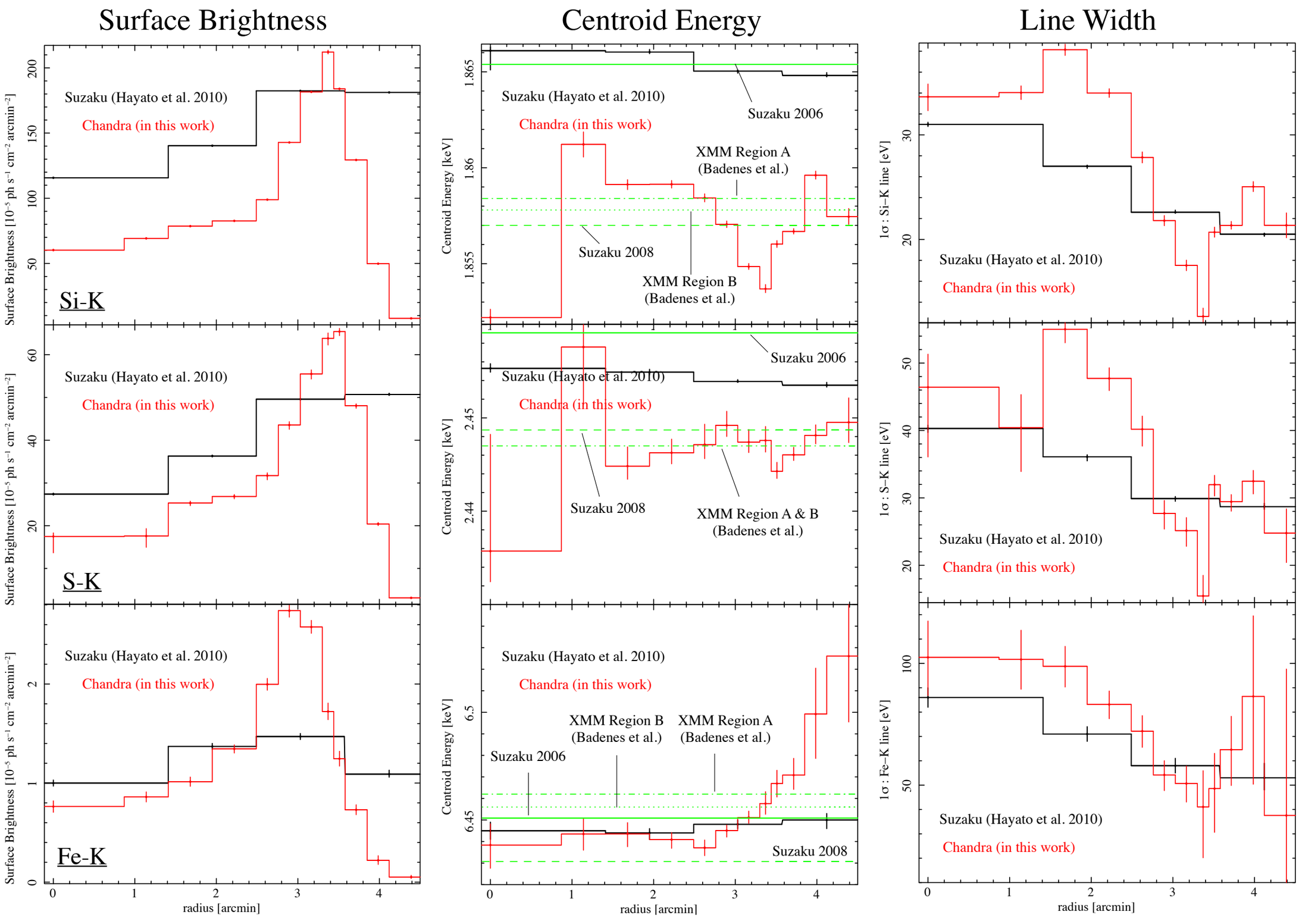
Si-K,Fe-K, 7-13 keV cont.
4 annuli

Chandra: this work



Fe-L,Si-K, 4-6 keV cont.
12 annuli
Deep LP from 2009

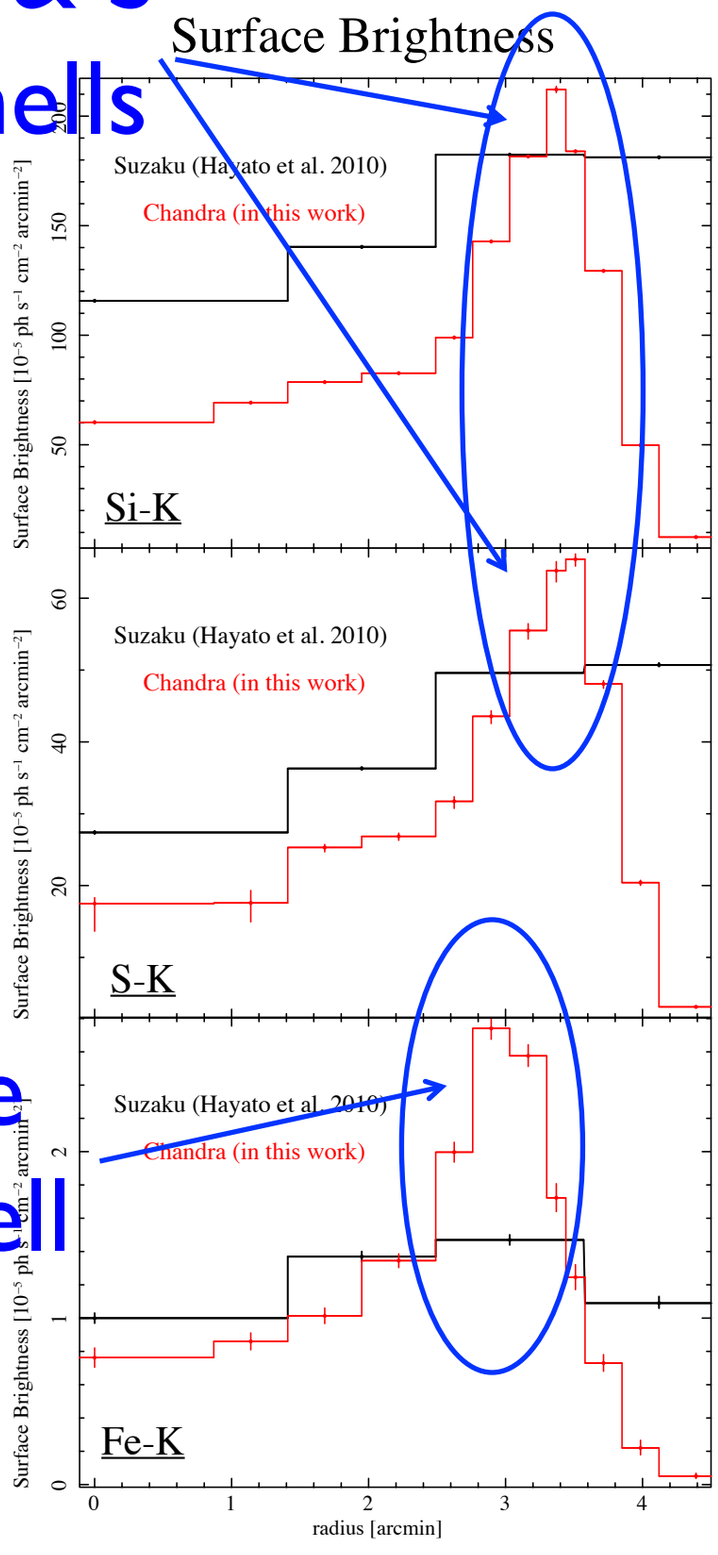
Radial Profiles

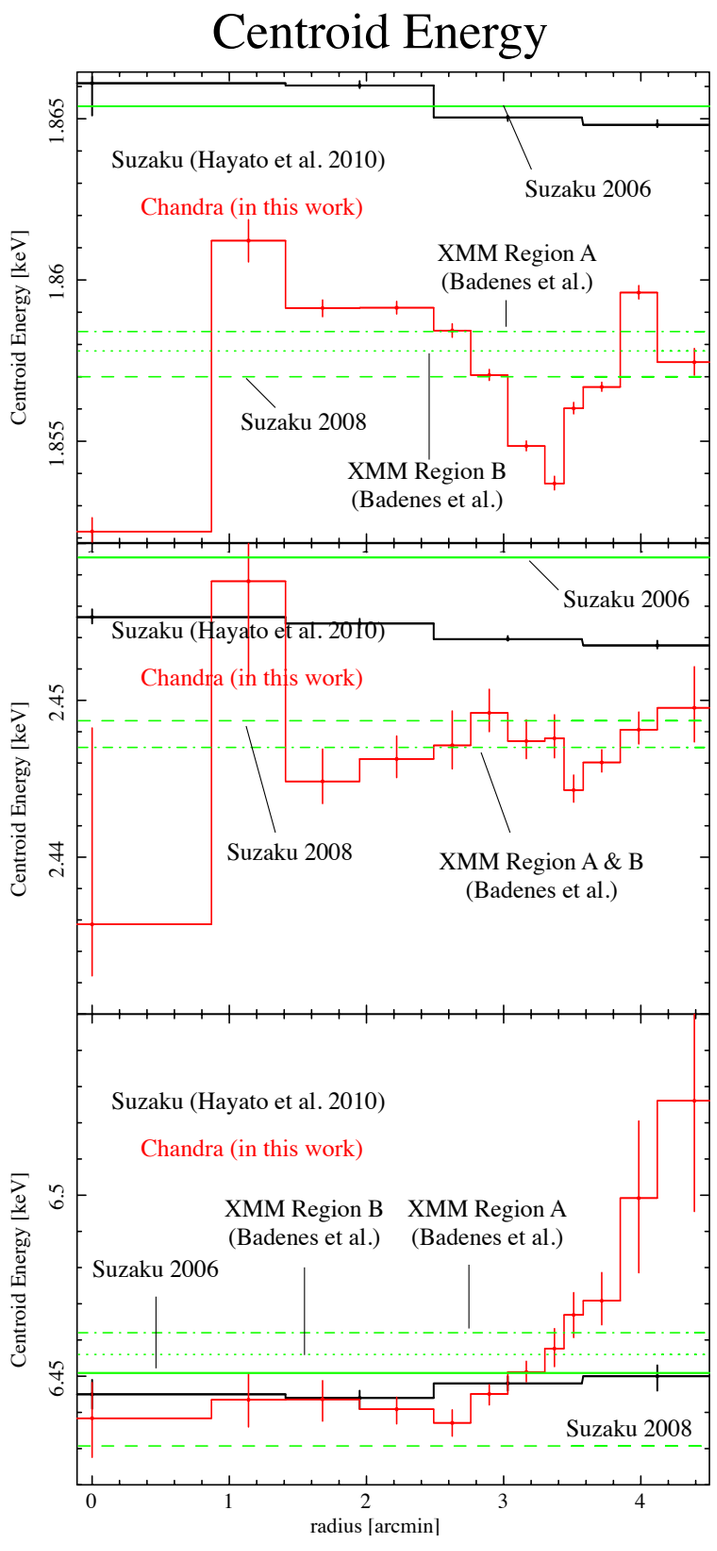


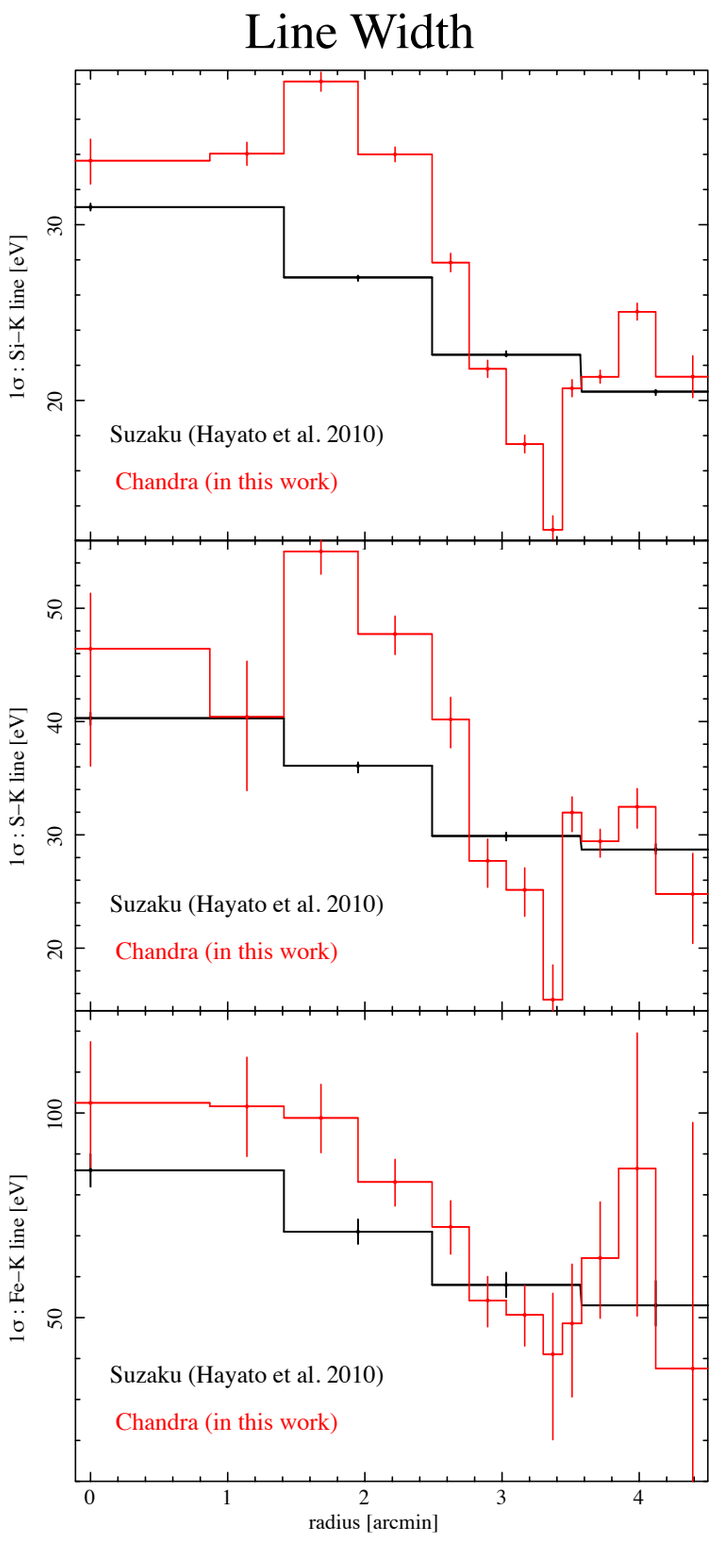
Radial Profiles

Si & S shells

Fe shell





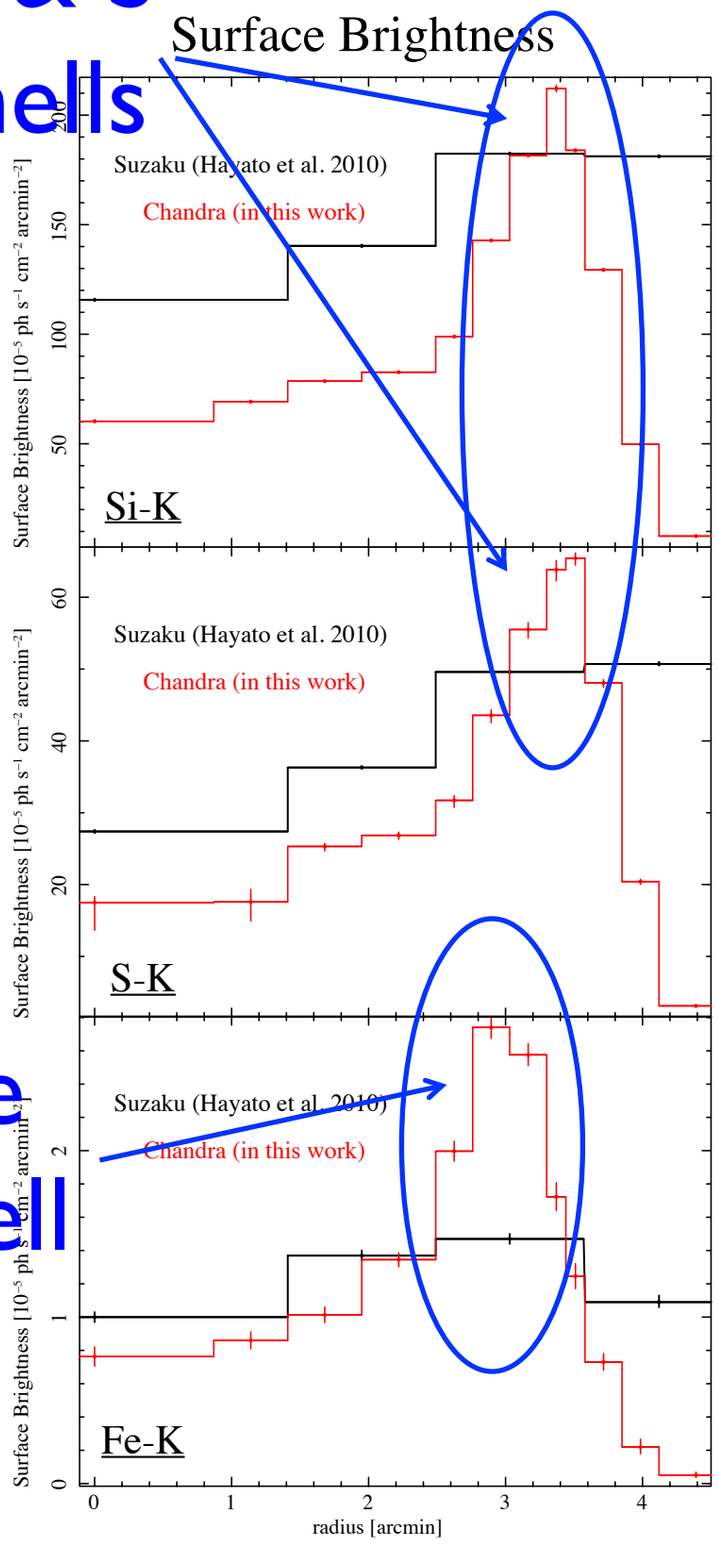


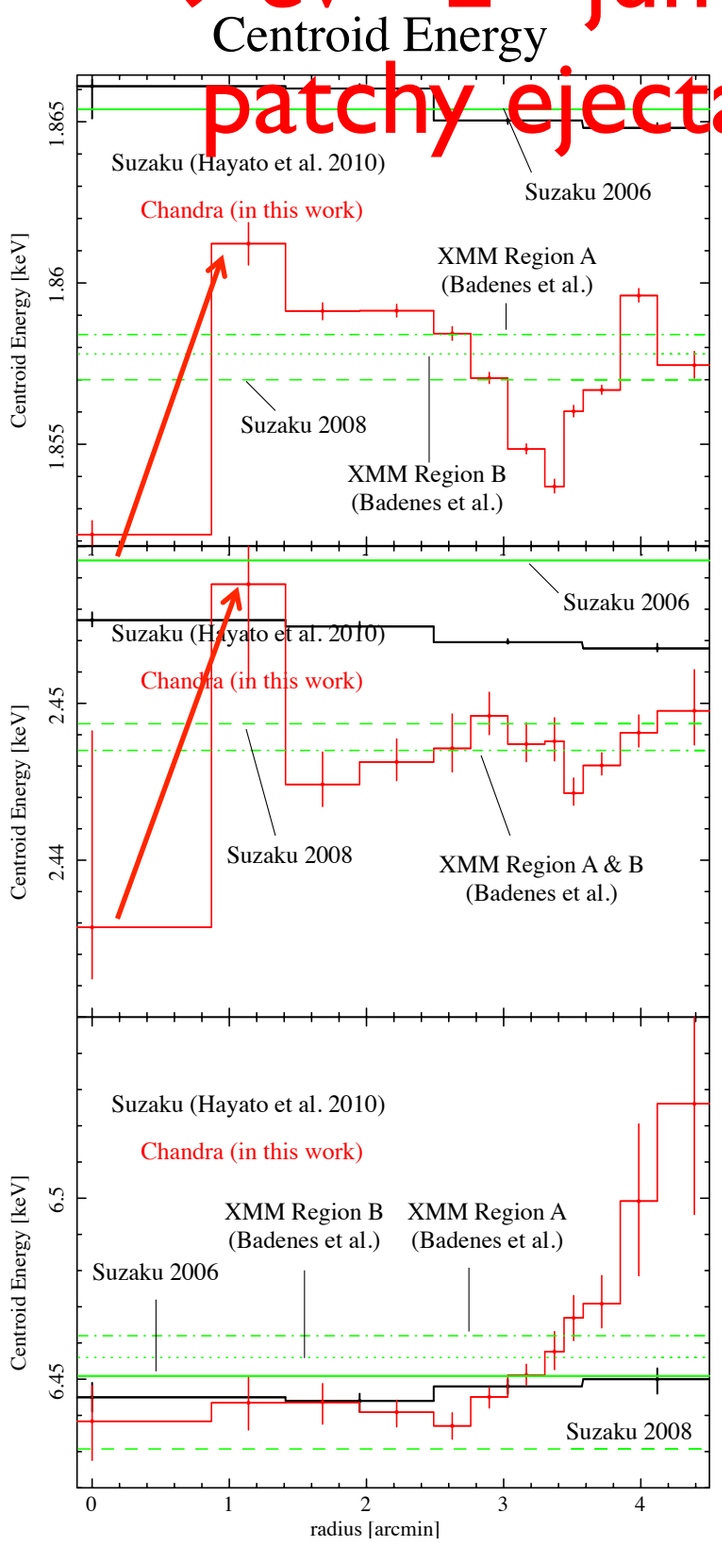
Radial Profiles

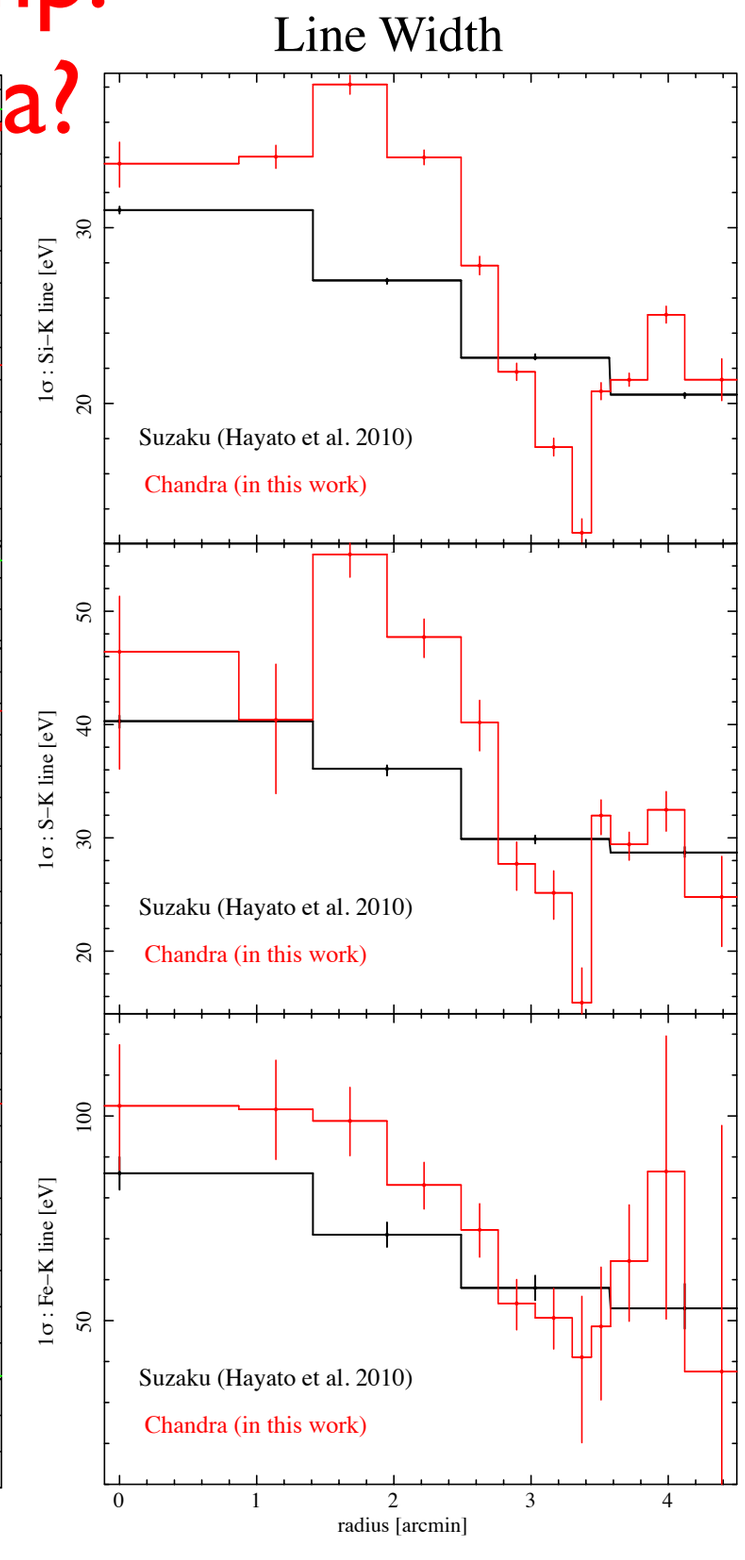
Si & S shells

9 ev <E> jump: patchy ejecta?

Fe shell







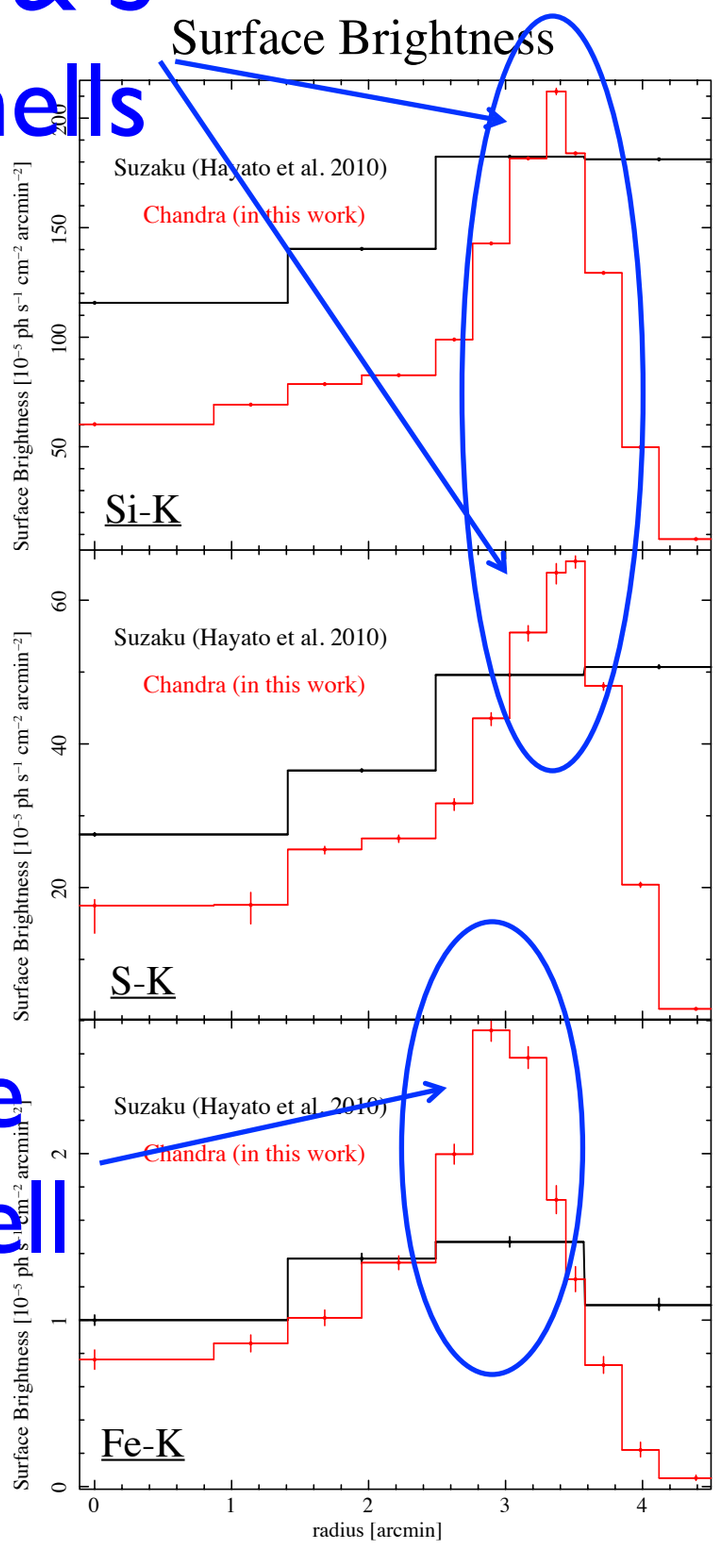
Radial Profiles

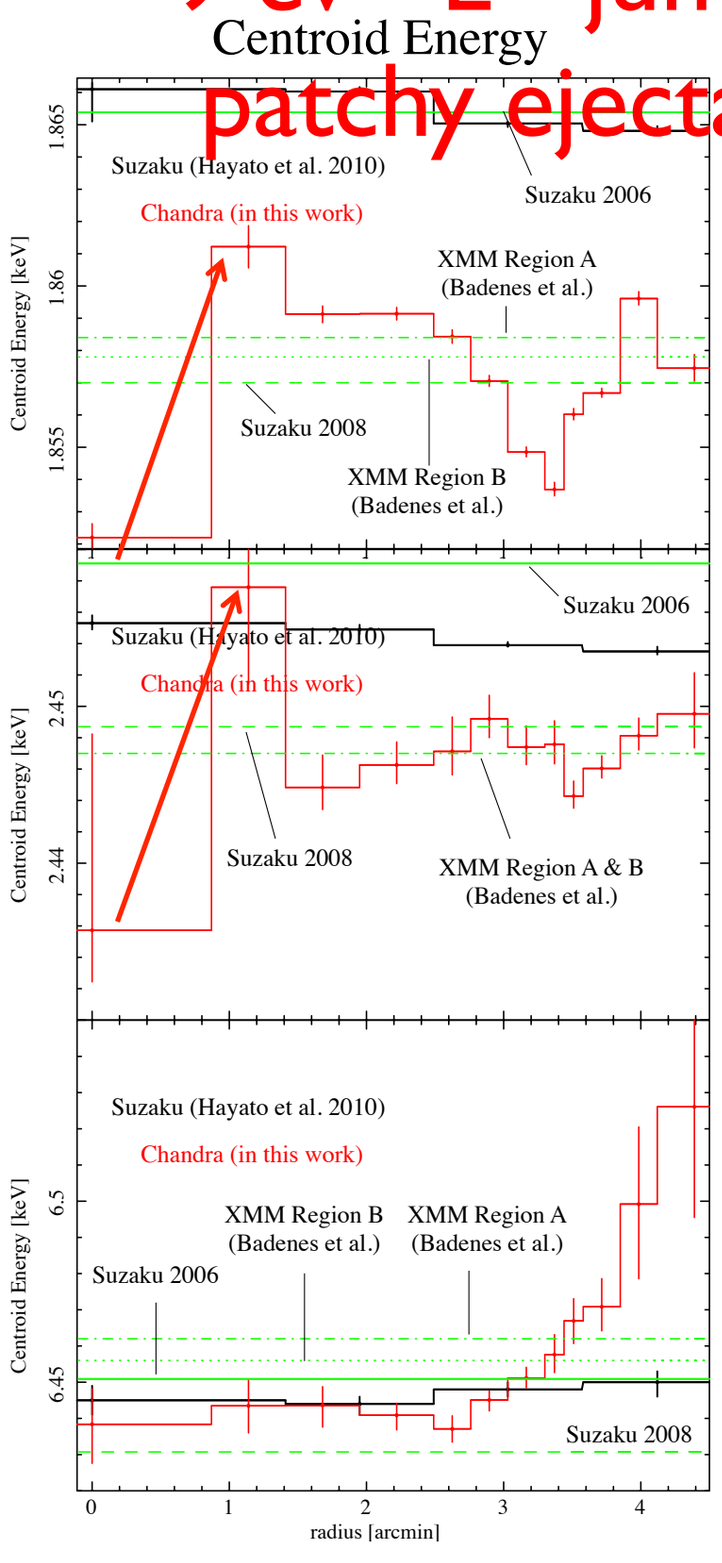
Si & S shells

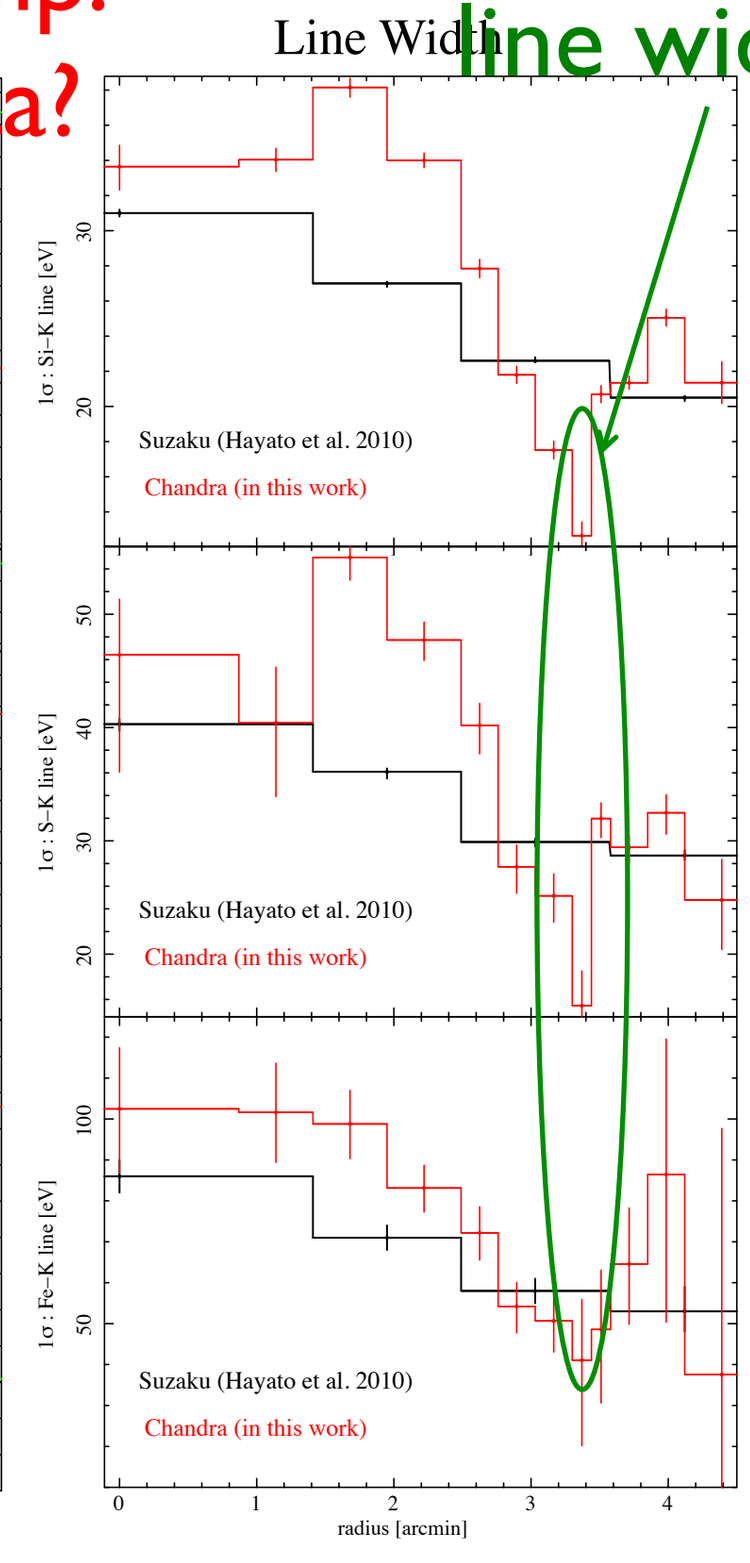
9 ev <E> jump: patchy ejecta?

Deep min in line width

Fe shell





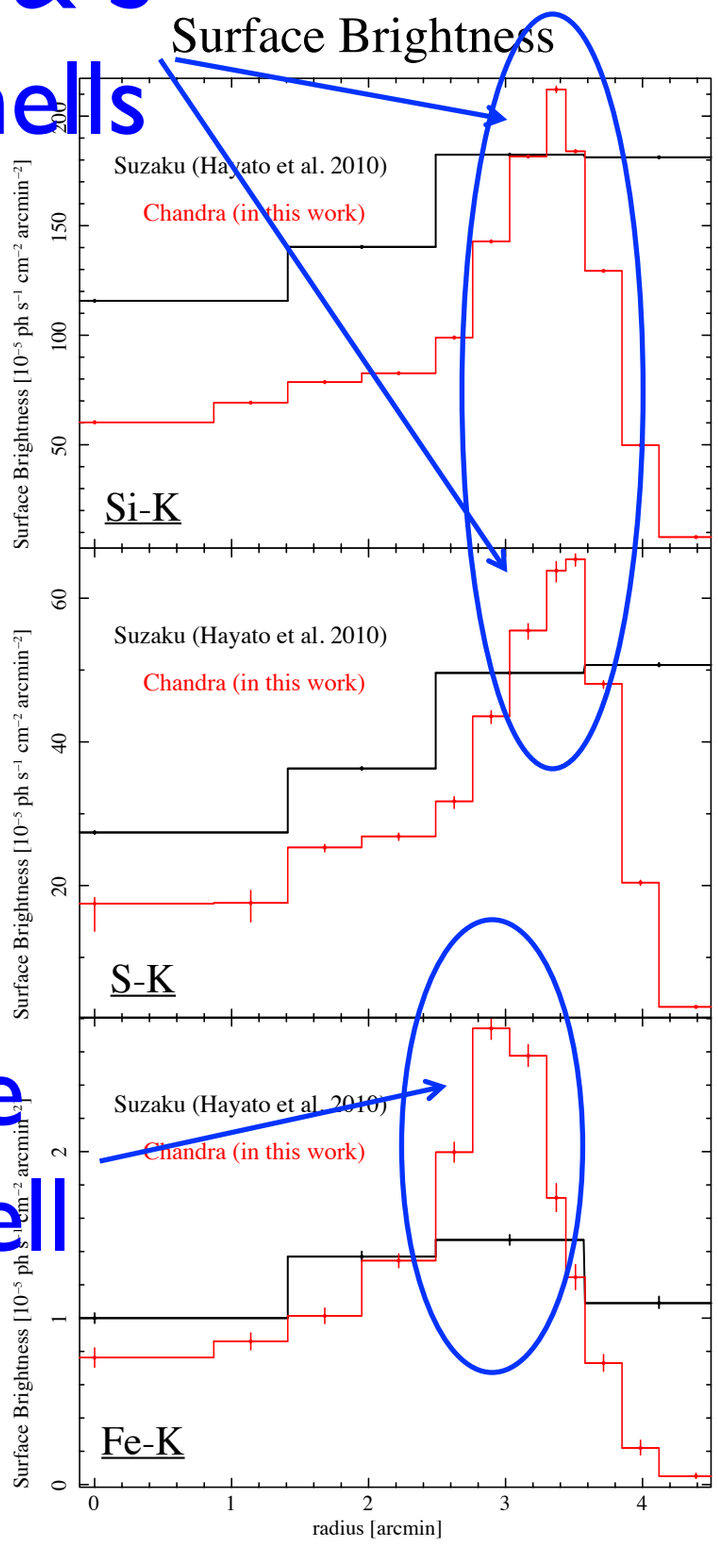


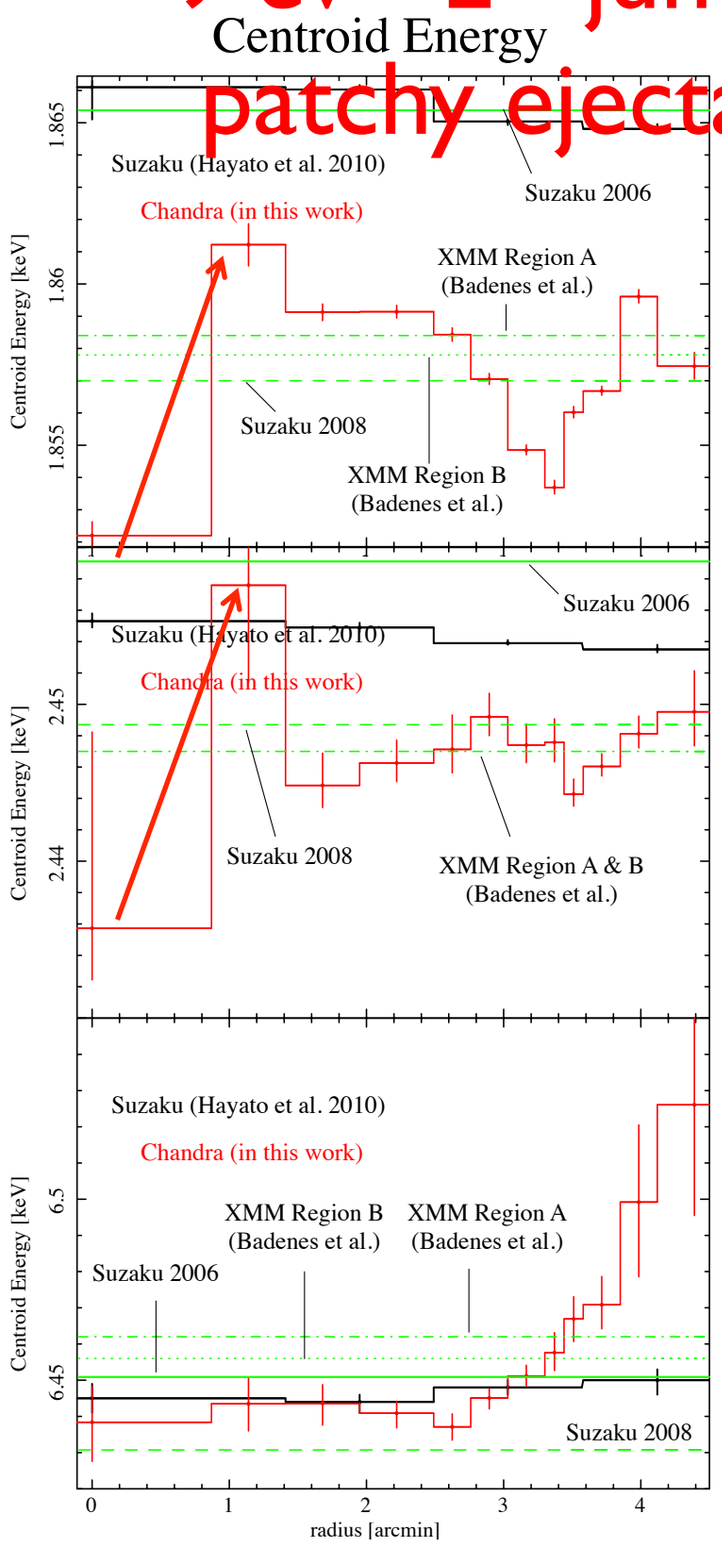
Radial Profiles

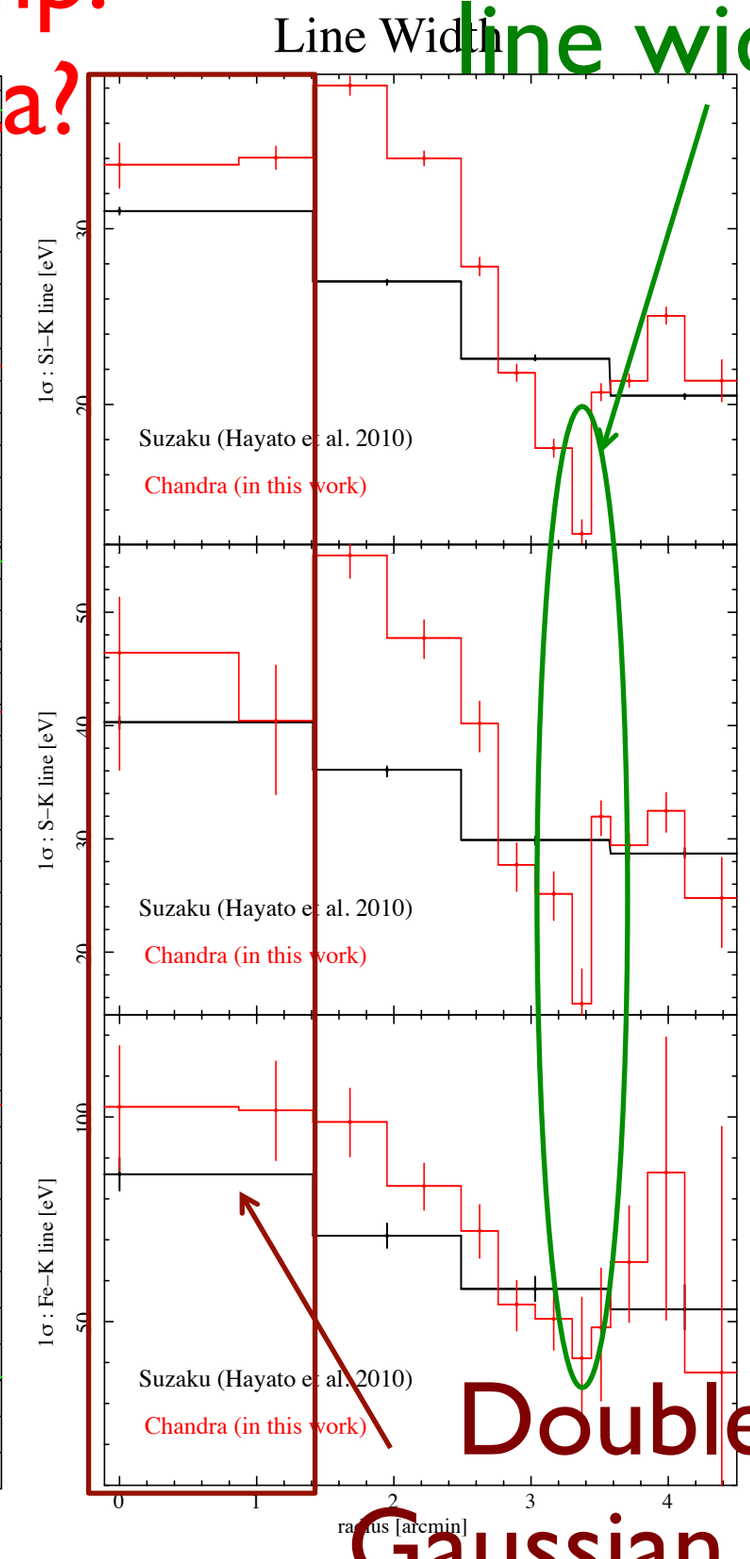
Si & S shells

9 ev <E> jump: patchy ejecta?

Deep min in line width





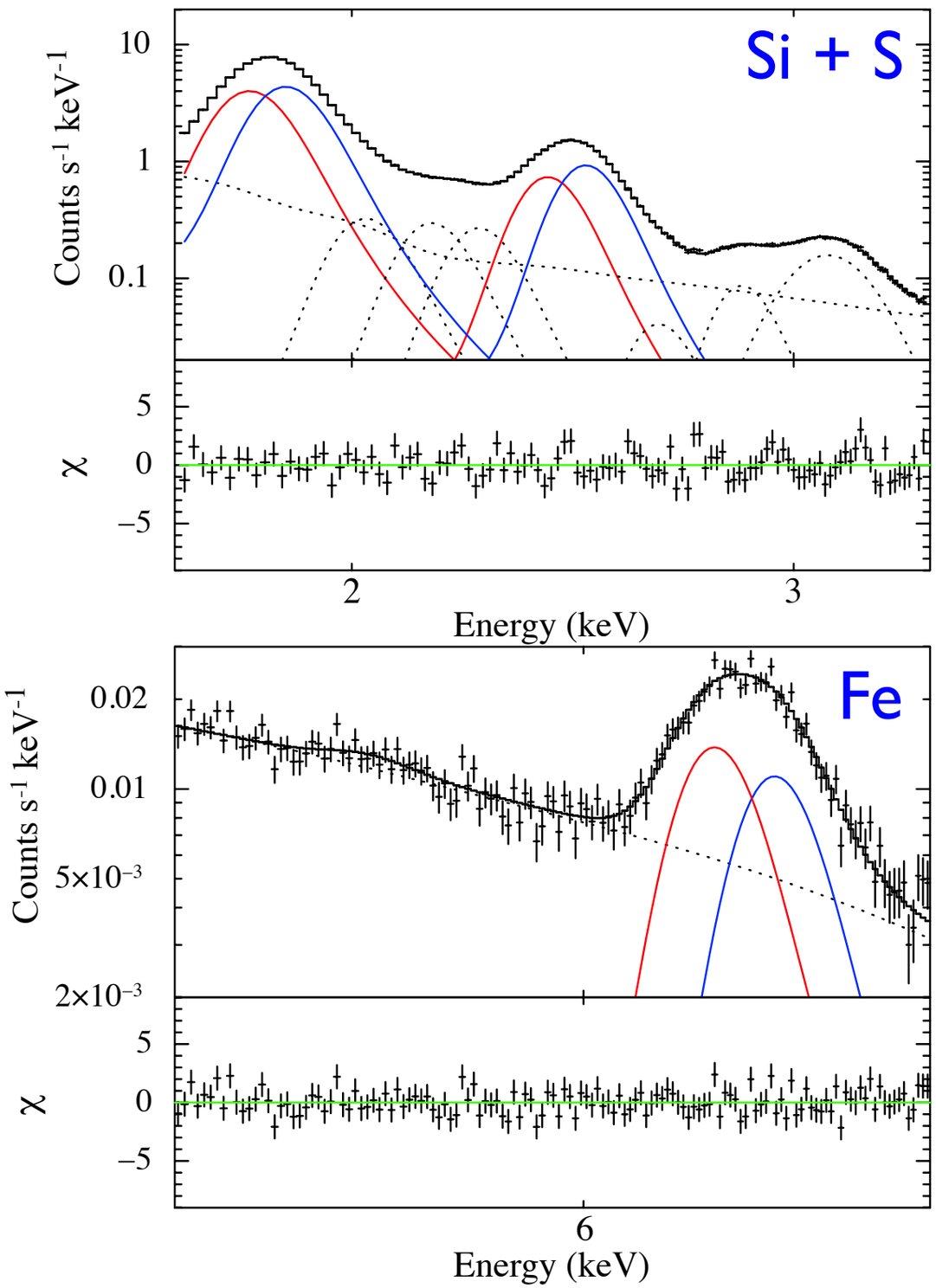


Fe shell

Double Gaussian fits

Double Gaussian Fits

Chandra ACIS-I



Fits agree with Hayato+2010

Lines	$v_{\rm exp}$ (km s^{-1}) (this work)	$v_{\rm exp}$ (km s^{-1}) (Hayato et al. 2010)
Si-Kα	4840 ± 340	4730^{+30}_{-20}
S-Kα	5480^{+450}_{-700}	4660 ± 50
Fe-Kα	4200 ± 800	4000 ± 300

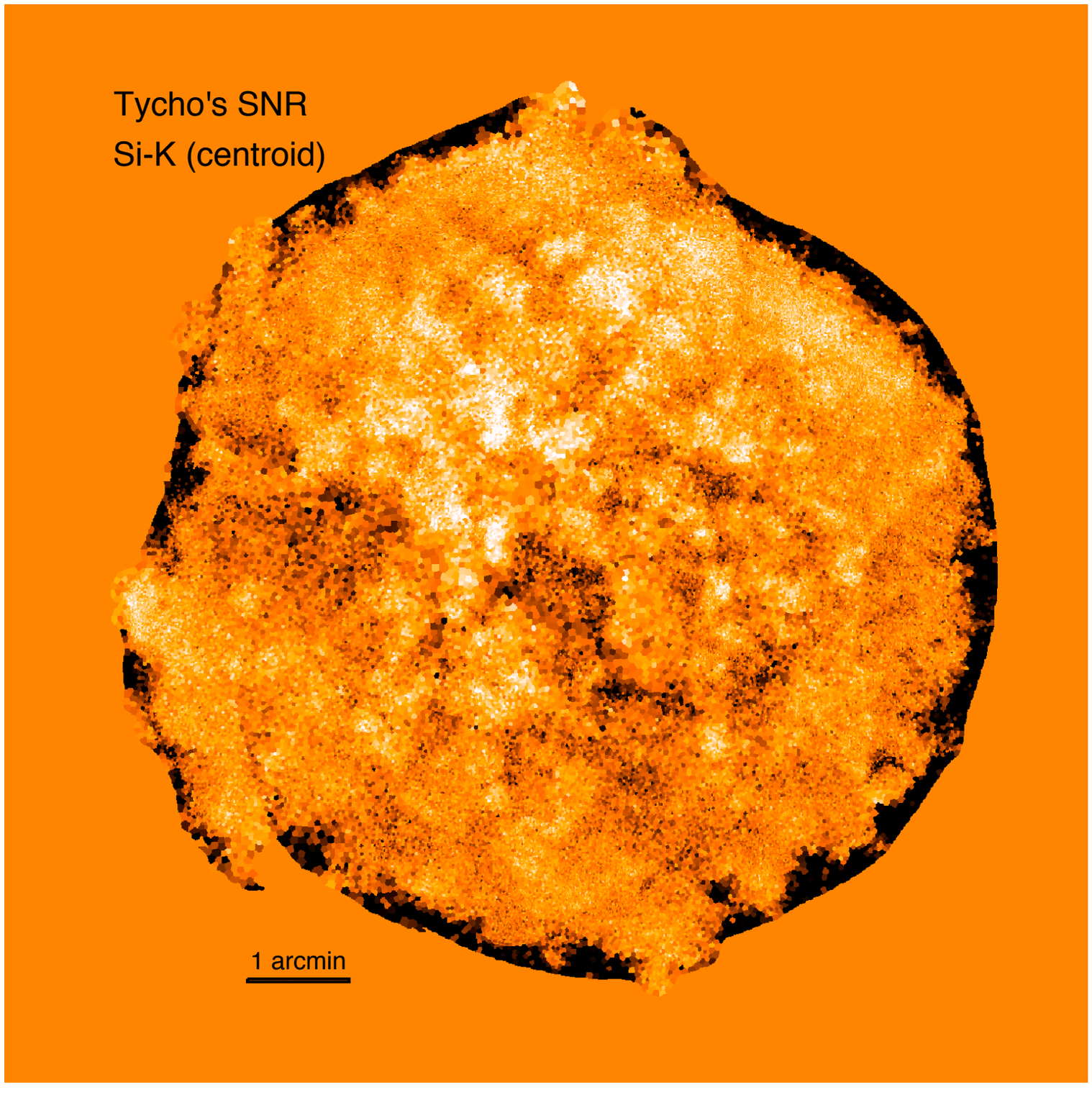
Compare Si v_{exp} with ejecta proper motion (Katsuda+2010)

$$\mu = (0.267 \pm 0.056)'' \, \mathrm{yr}^{-1}$$

to yield distance

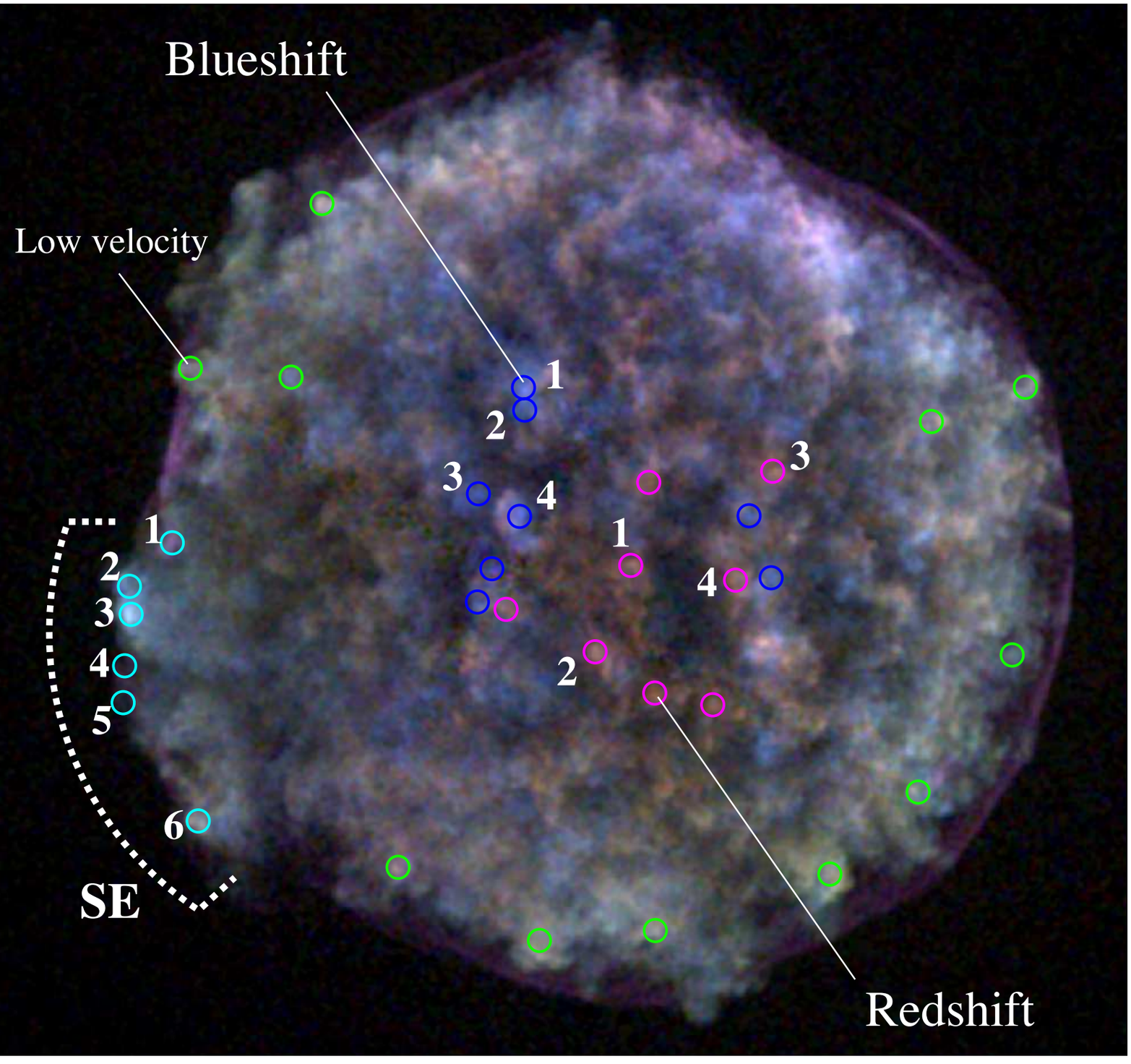
$$D = 3.8 \pm 0.3 \, ^{+1.0}_{-0.7} \, \mathrm{kpc}$$

Mean Si-K Line Centroid



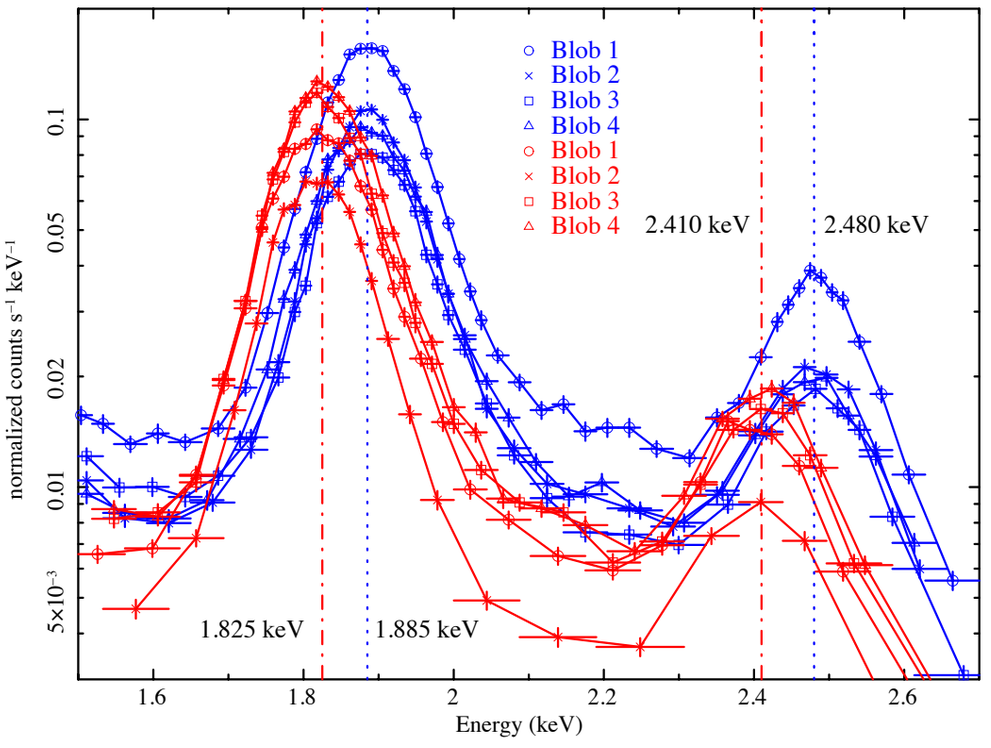
- 1.6-2.1 keV band
- Binned spatially: Voroni Tessellation with S/N=20
- Values vary from 1.816 keV (dark) to 1.879 keV (light)
- Full range is ~9700 km/s
- Dark outer rim – nonthermal emission
- Dominated by patchy features, some also in intensity

Spectral Analysis of Individual Blobs

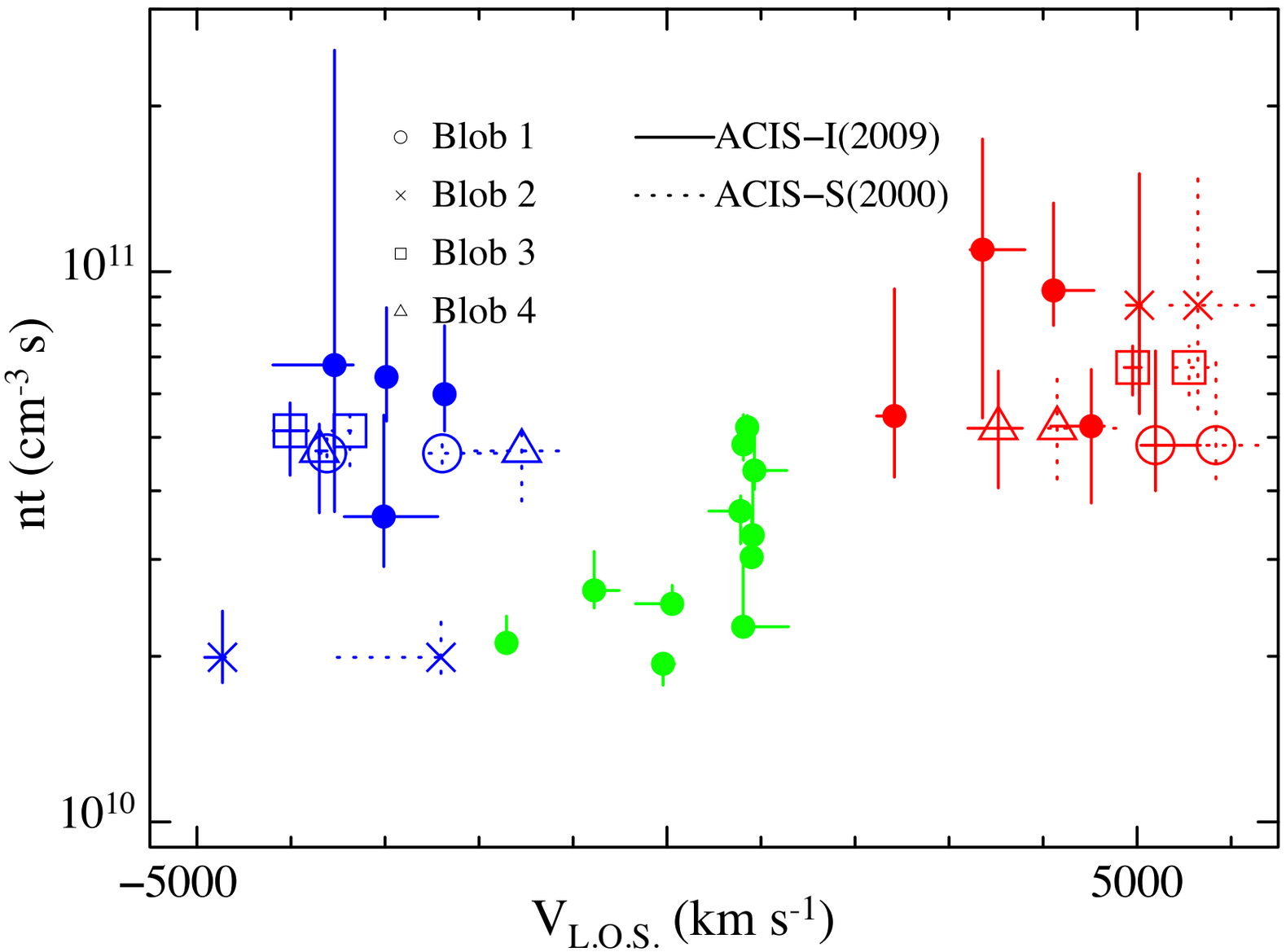


(R=1.77 keV, G=1.84 keV, B=1.96 keV)

- Slice Si-K line (RGB)
- Select 33 knots: 8 red, 8 blue, 11 low v, 6 SE knots for NEI model fits
- 4 red + 4 blue knots joint fits with ACIS-S



Spectral Analysis of Individual Blobs



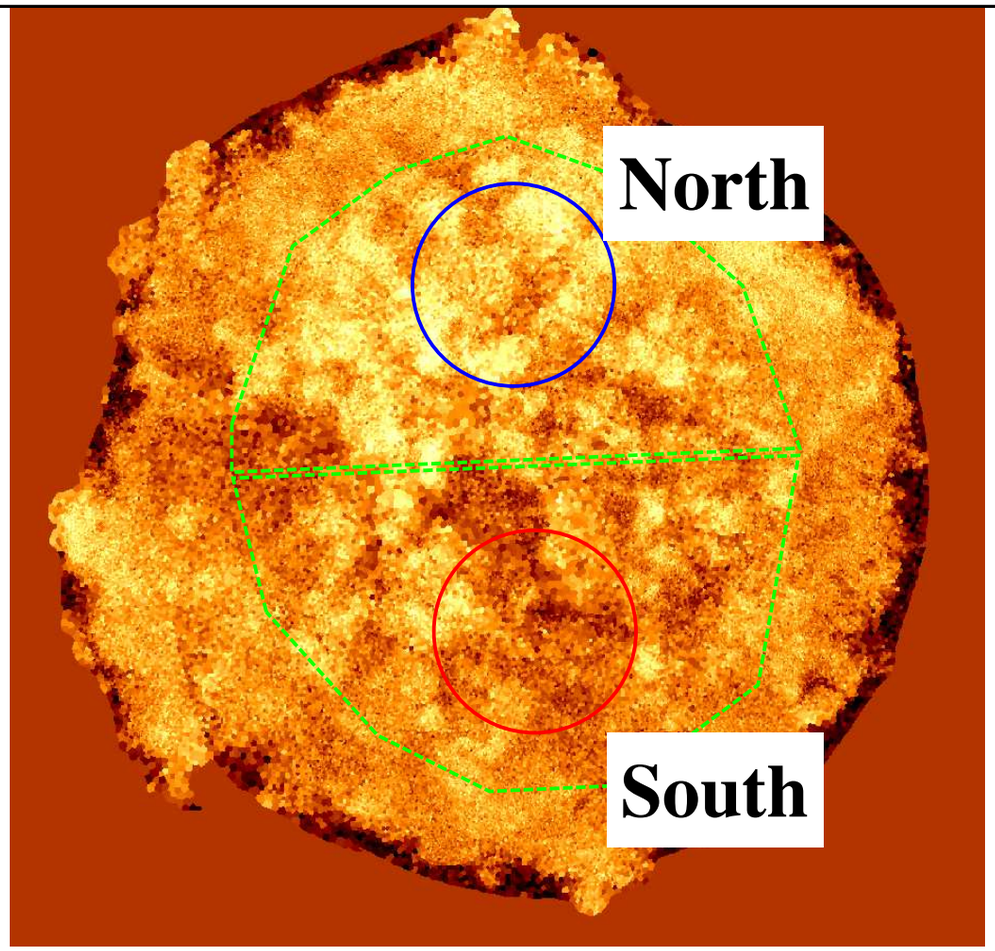
- Radial velocity robust with respect to ionization age
- Systematic v-error: ~500-2,000 km/s
- Local background vs. sky background: increases |v| by ~1,000-2,000 km/s

Conservative allowed range of radial vels: −7,800 to 5,000 km/s

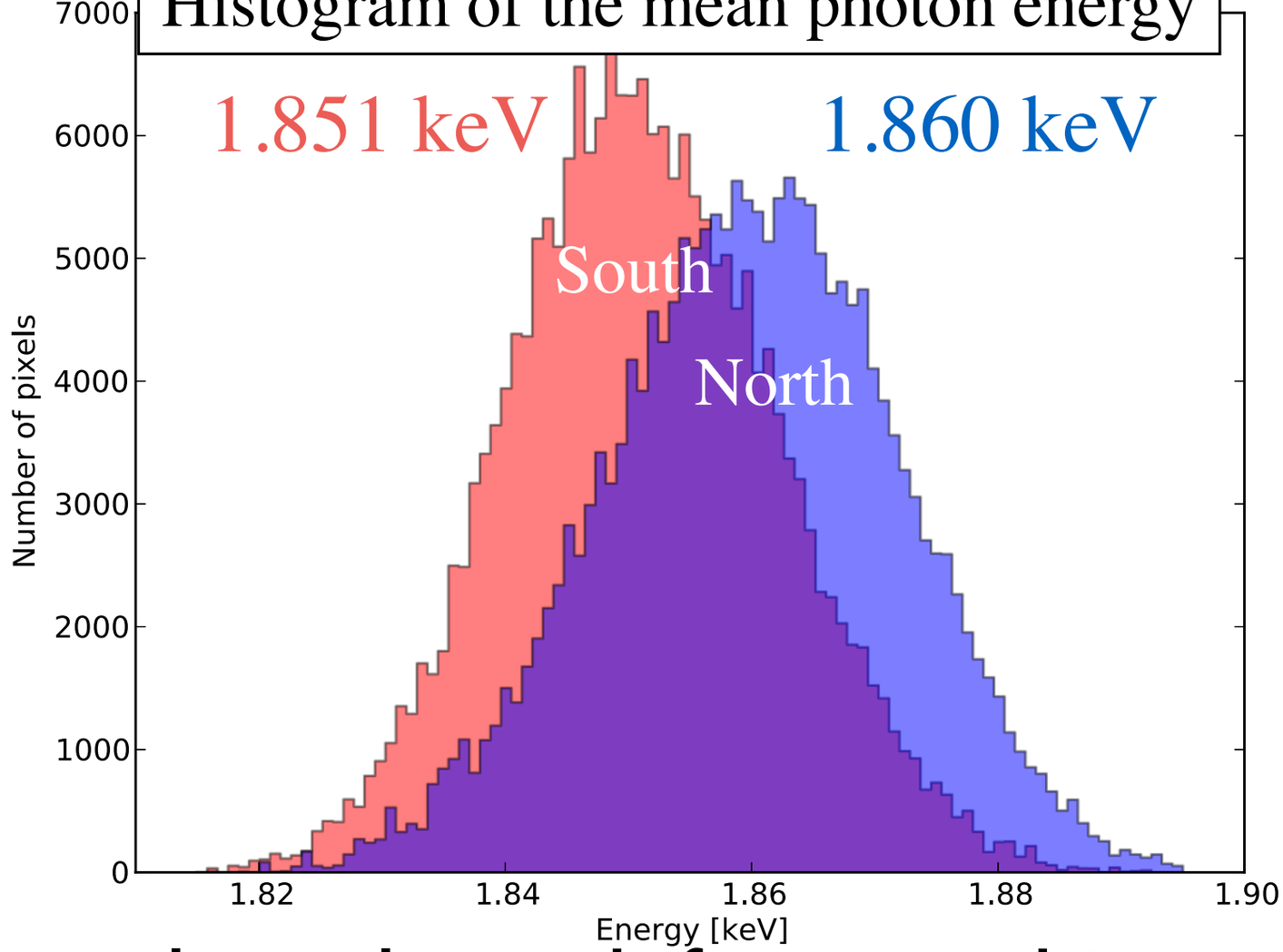
Large scale distribution of apparent velocities

Northern half is more blueshifted than southern half, by about 2000 km/s.

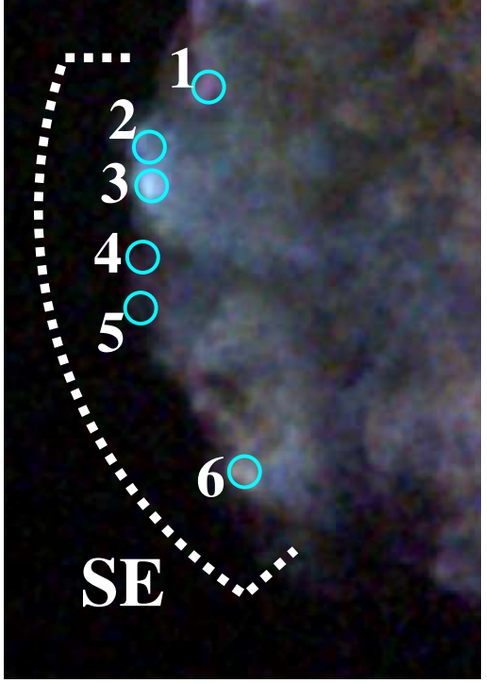
Mean photon energy map of Si-K



Histogram of the mean photon energy



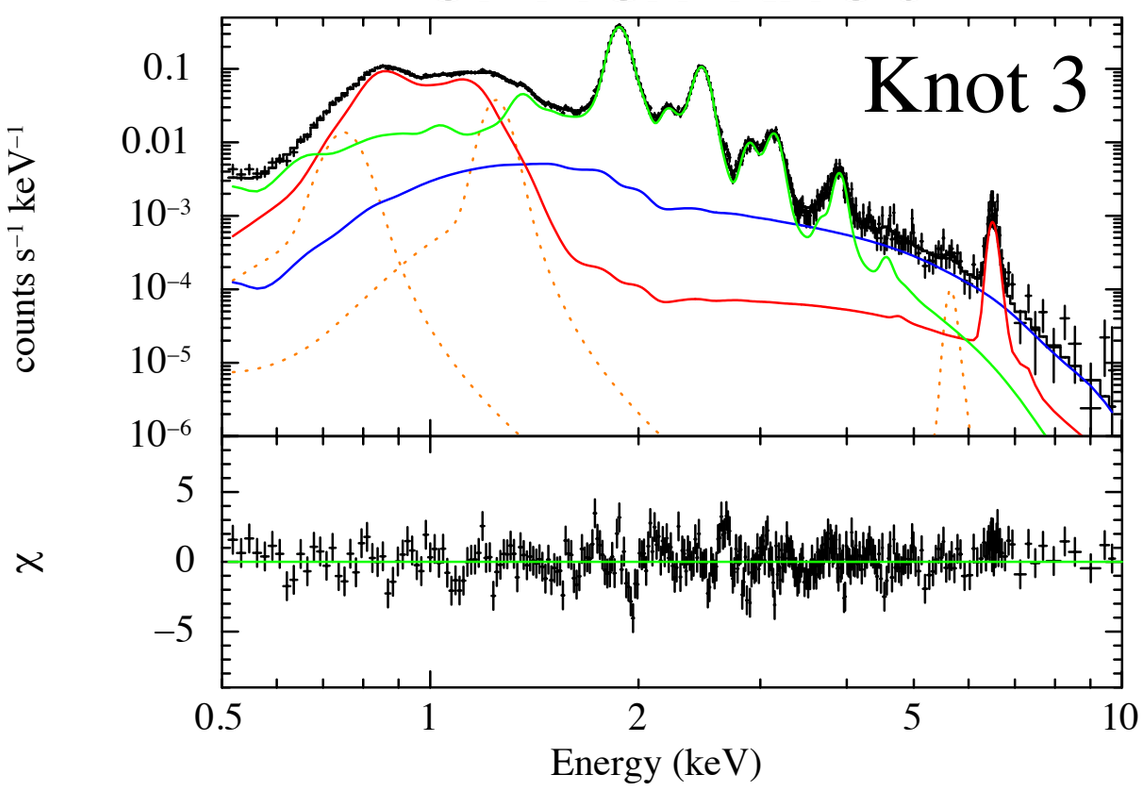
Ejecta density variations: result replicated if approaching northern quadrant has ~2x higher ejecta density



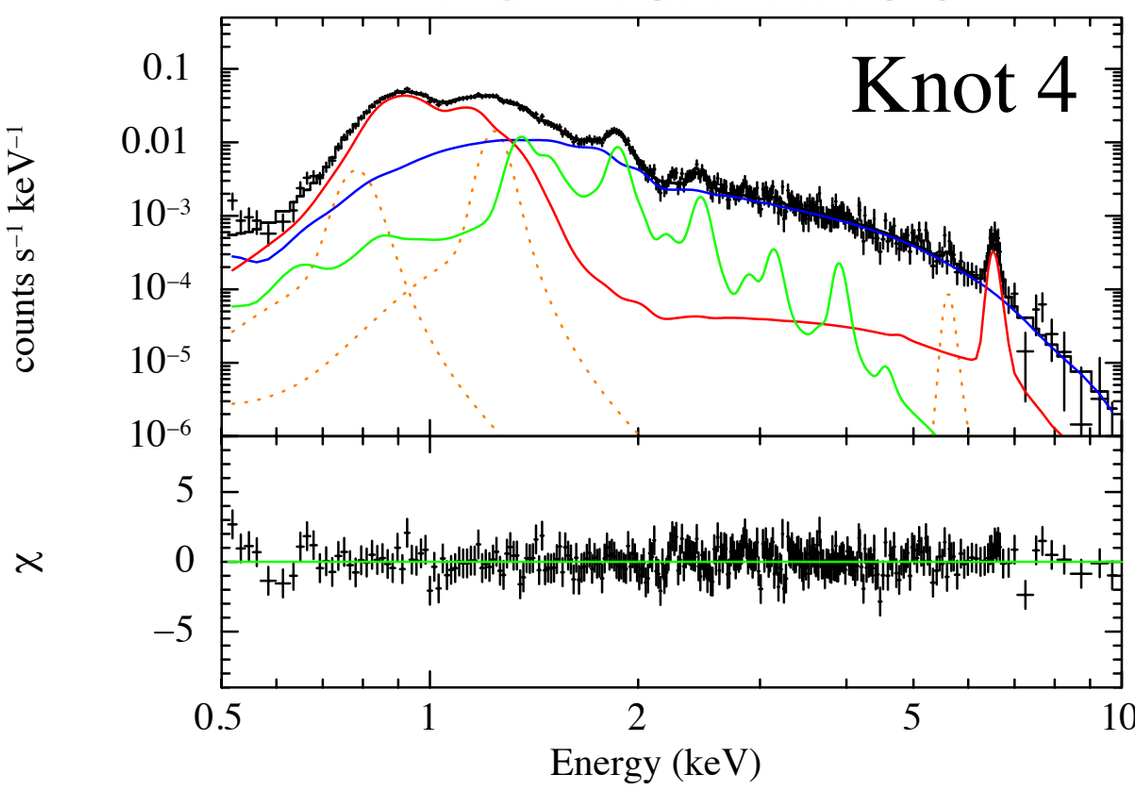
Southeastern knots

radial velocities (km/s)					
Knot1	Knot2	Knot3	Knot4	Knot5	Knot6
−2300	−2400	−2400	−1900	−1000	+900

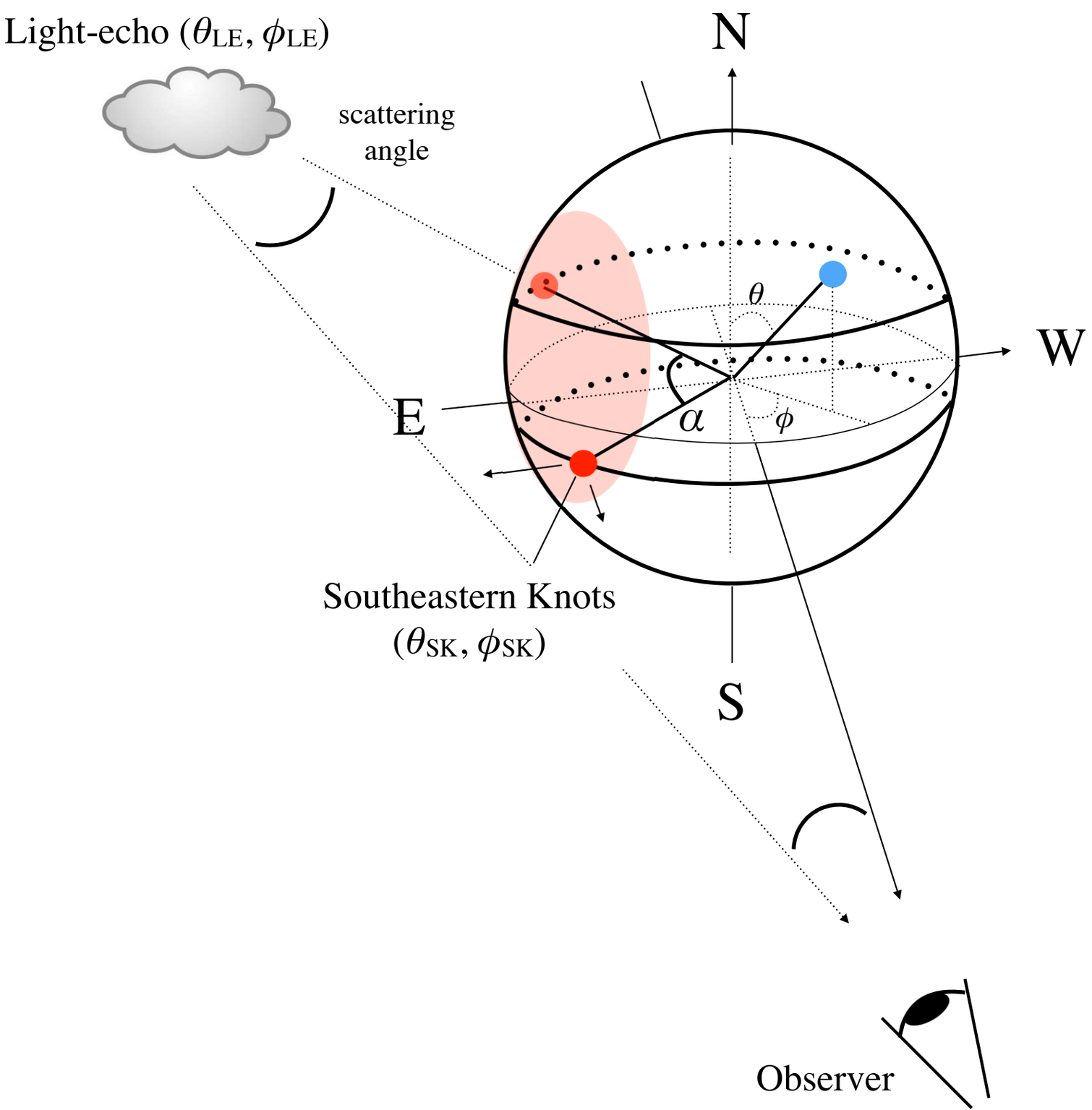
Si-rich knot



Fe-rich knot



SE knots and Tycho Light Echo



- Light echo is 3° away at P.A. 62°
- Mean of SE knots is at P.A. 102°
- Combine proper motion and radial vel to find SE knots moving at angle 24° out of sky plane
- Direction to light echo is ~58° away from SE knots

SE knots and Tycho Light Echo

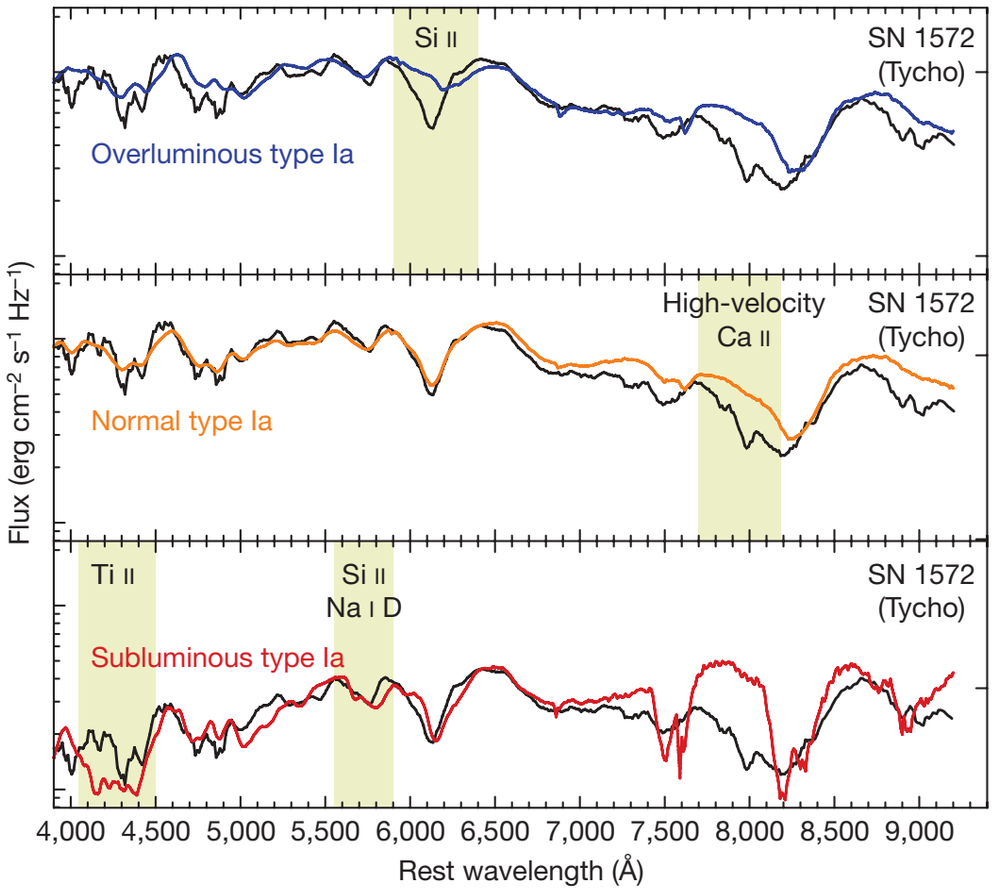
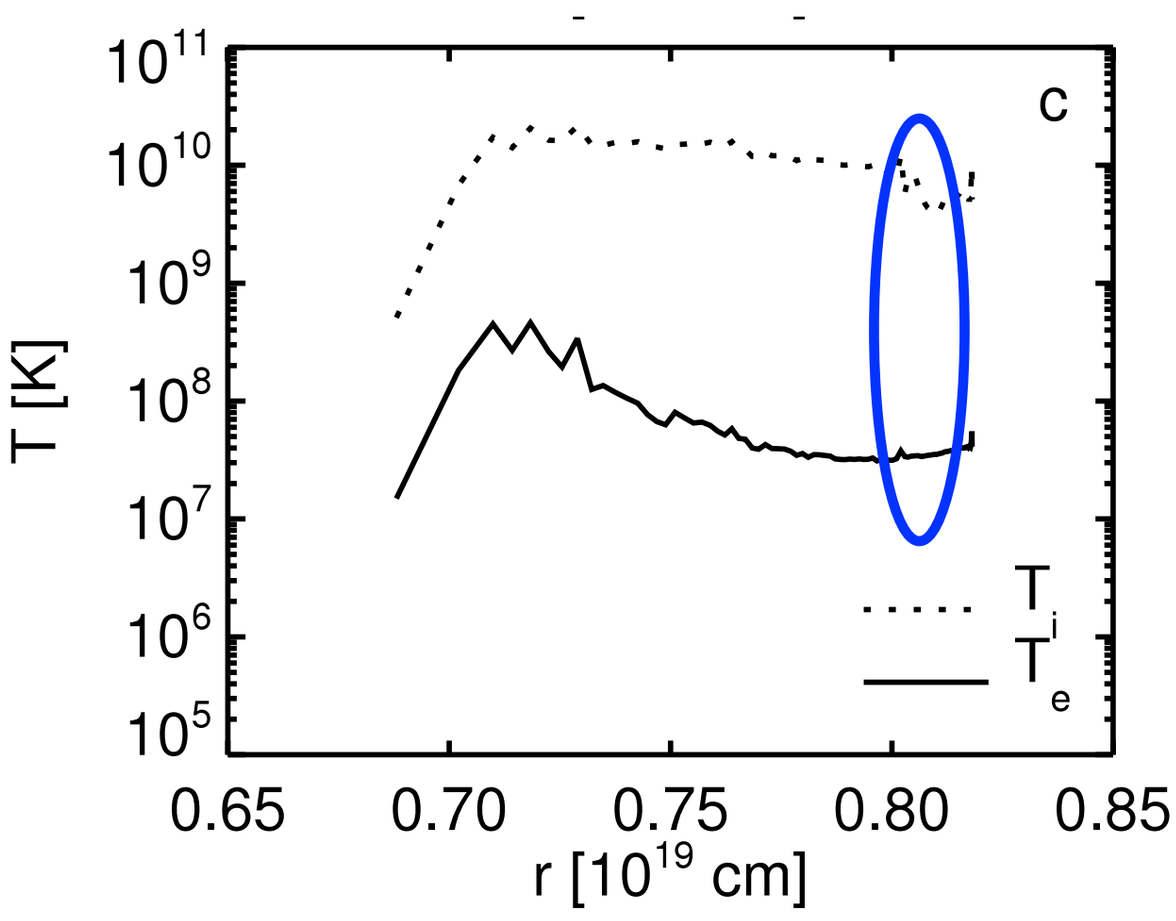


Figure 3 | Comparison of SN 1572 with type Ia supernovae of different luminosities. Spectral templates of subluminous, normal and overluminous type Ia supernovae are shown in comparison with the spectrum of SN 1572. The spectrum of SN 1572 has been corrected for a scattering angle of $\theta = 84^\circ$ and a foreground extinction of $A_V = 4.2$ mag as described for Fig. 2. The comparison spectra have been derived as the time averages of spectral series[19] over days 0–90 after explosion and scaled to the spectrum of SN 1572. Specific features typical of the three subtypes are indicated. For the comparison with the intrinsically redder subluminous template, the spectrum of SN 1572 was de-reddened for a foreground extinction of $A_V = 3.9$ mag.

- Light echo spectrum shows high velocity Ca II absorption (fairly common in SN Ia and signaling some asymmetry)
- SE knots are likely too far away to be responsible for the high velocity feature
- Are other, more typical knots the possible source?

Ion Temperatures

Parameter	Si	S	Fe
Min. width (eV)	12.6	15	41
T (MeV)	1.20±0.15	1.1±0.5	0.5 ~ 3



Badenes+2006

- Convert to temperature (ignoring turbulence)

$$\sigma_{\rm th} = \frac{E_a}{c}\sqrt{\frac{kT_a}{m_a}}$$

- Measured at the outer edge of the ejecta – far downstream of the reverse shock – has experienced strong post-shock evolution
- 1D hydro model at CD:

T_{ion} ~ 0.9 MeV, Te ~3.4 keV

- Observed:

T_{ion} ~ 1.2 MeV, Te ~1.3 keV

Summary

- Radial profiles of intensity, line centroid, and line width of Si, S, and Fe with *Chandra*
  - generally consistent with previous work
  - deep minimum in line width profile at ~3.4'
  - expansion velocity of shell 4840±340 km/s; D=3.8±0.3 $^{+1}_{-0.7}$ kpc
- Si-K line center map shows large centroid shifts (~60 eV) with largest range near center and variation on scales of arcseconds to arcminutes
- Spectral analysis with NEI models shows radial velocity measurement is robust to other spectral parameters (e.g., ionization age) that can influence line centroids
  - velocity range: −7,800 to 5,000 km/s
- Observed ion temperatures of T_{ion} ~ 1.2 MeV consistent with 1D models
- SE knots likely unrelated to high velocity feature in light echo

Outlook

This project was initiated in anticipation of *Hitomi* SXS observations of Tycho's SNR.

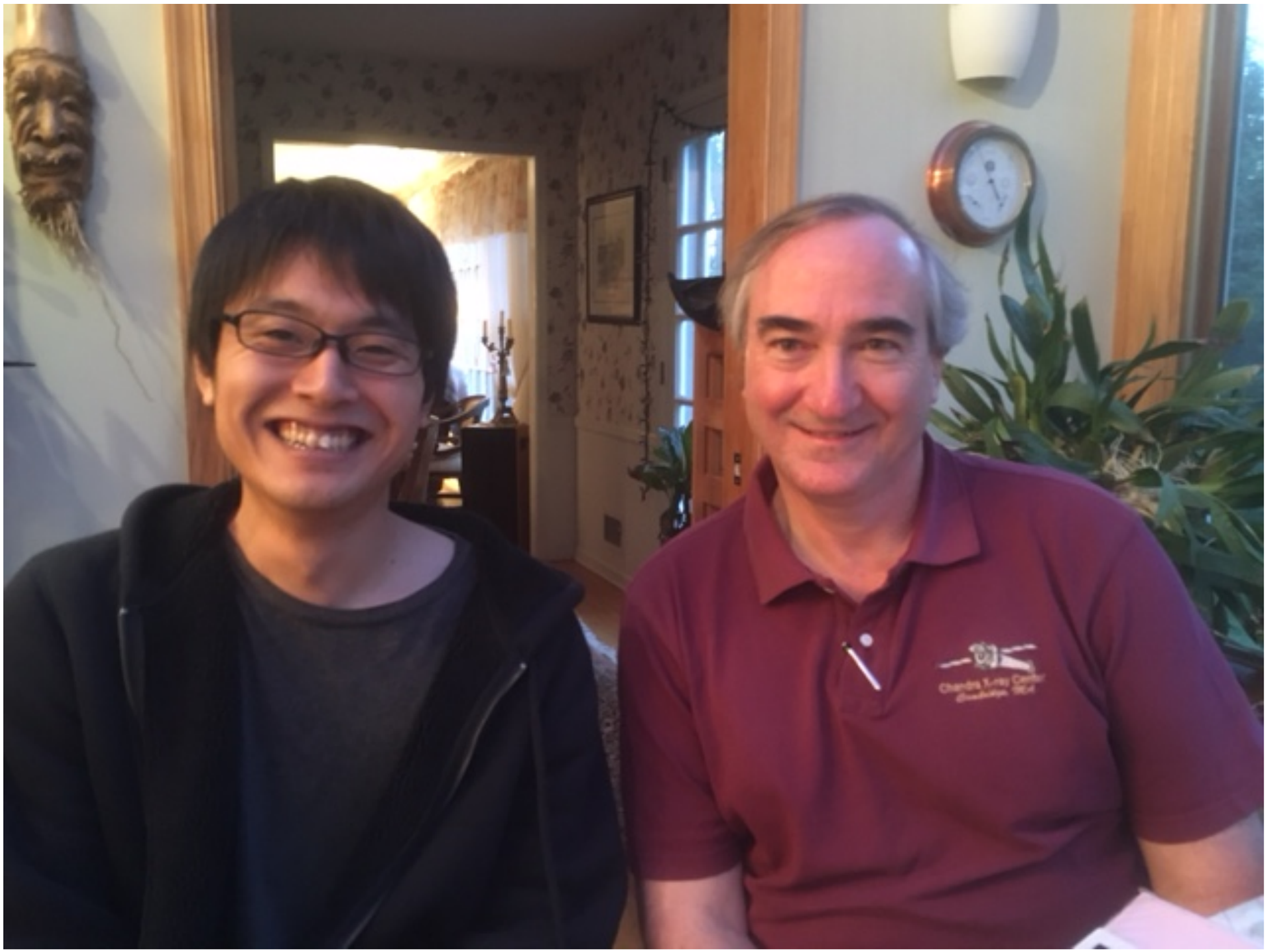
Hitomi was sadly lost in March 2016

Our *Chandra* study shows the richness of the science that can be extracted from the kinematics of SNRs and *Chandra* can still do more (before *Athena* or a *Hitomi*-like recovery mission)

Chandra HETG has observed Cas A (Lazendic+2006) and G292.0+1.8 (Bhalerao+2015) and Kepler is awaiting observation this cycle (PI: S. Park).

Hopefully more SNRs will be observed with *Chandra* HETG.

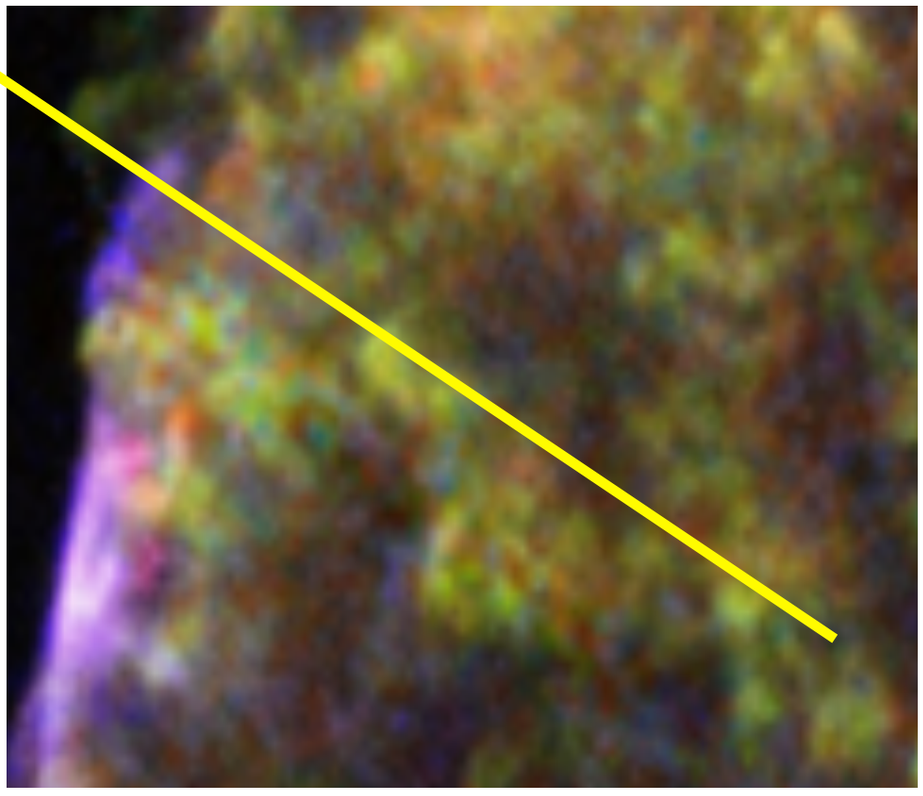
The End



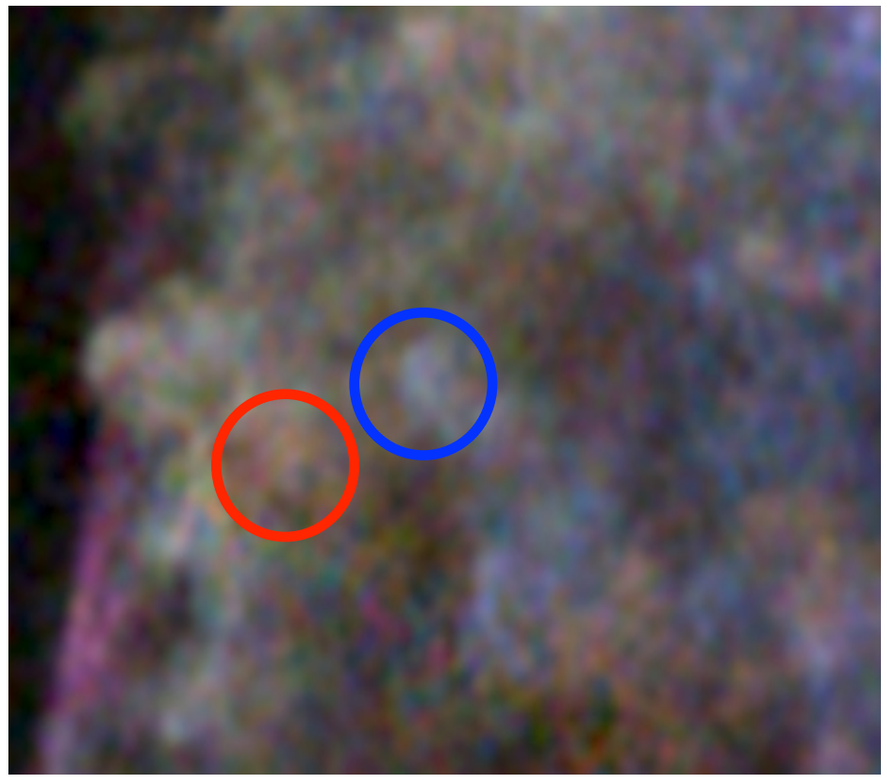
The View to the Light Echo

To light echo

FeL/SiK/Cont



Velocity



Compact Si-rich knots, with well defined radial velocities, exist along the line of sight to the light echo.
No peculiar abundance knots (like those in the SE) along this l.o.s.