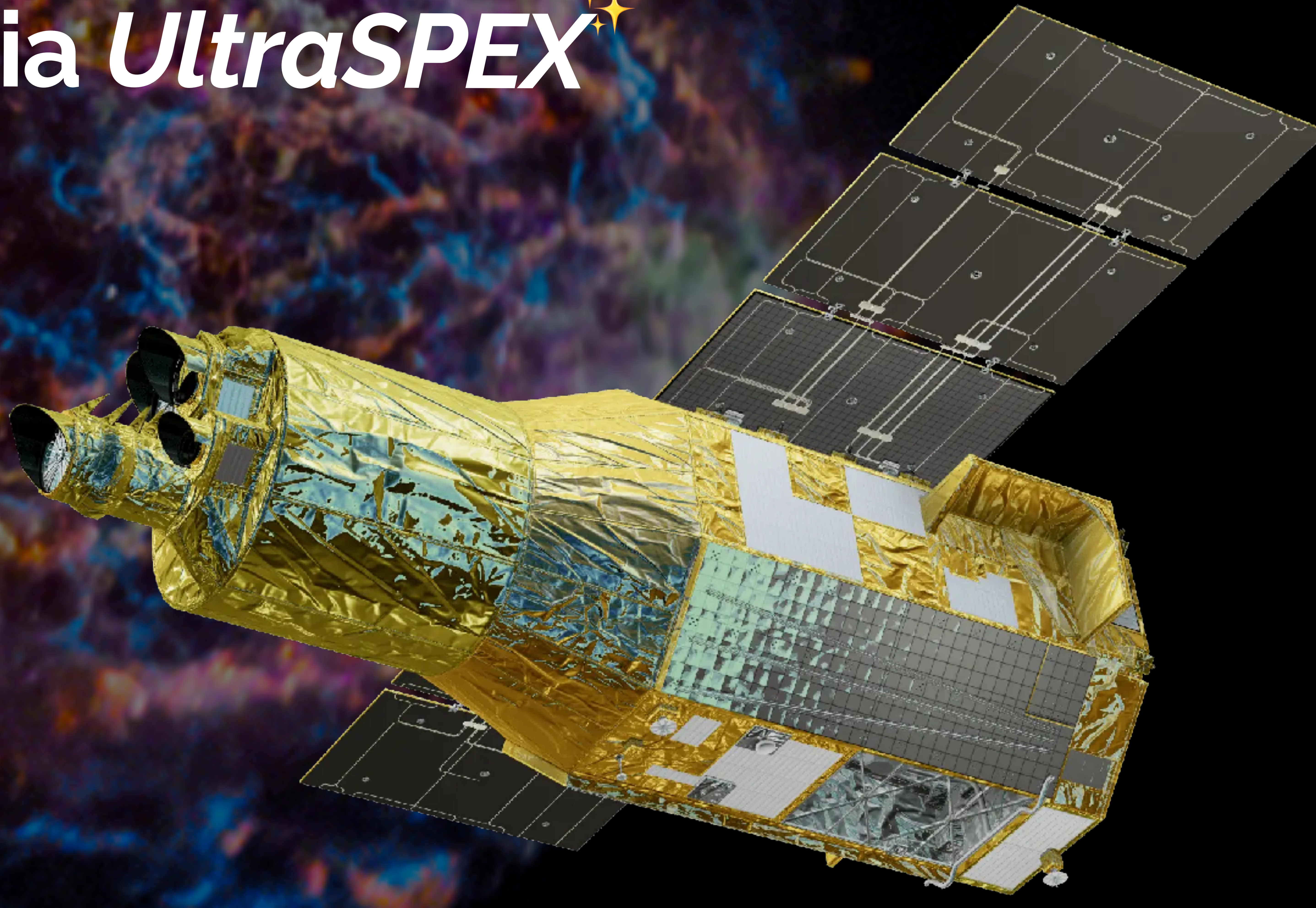
ANTON PANNEKOEK
INSTITUTE

XRISM analysis of SNR Cassiopeia A: a Bayesian study via *UltraSPEX*✨



Manan Agarwal
m.agarwal@uva.nl

Lumière | 12 January 2026 | Paris, France

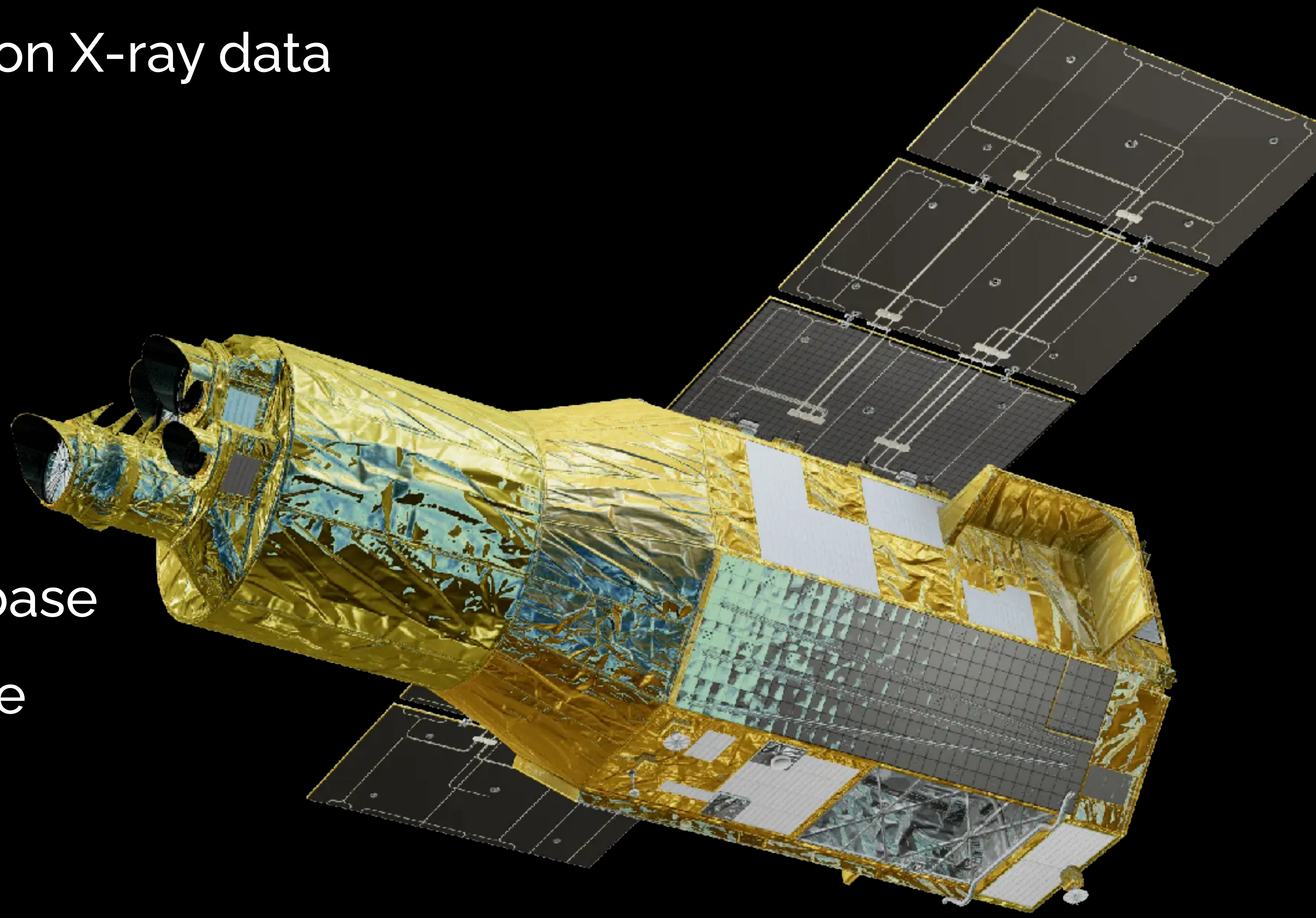
XRISM

X-Ray Imaging and Spectroscopy Mission

Unprecedented high spectral resolution X-ray data

But for analysis...

- Very large response matrices
  XRISM XL RMF ~1 GB
- More than 10,000 bins
- Needs comprehensive atomic database
- Requires extensive exploration of the parameter space



UltraSPEX✨

Agarwal, M.,+ (submitted)

Python tool — integrates UltraNest with SPEX

Why use *UltraSPEX*?

UltraNest
(Bayesian framework with Nested Sampling)

- Extensively explore parameter space
- Supports high-dimensional, multimodal distribution
- Robust to parameter degeneracies
- Bayesian evidence
- Parallelizable

+

SPEX

- Optimally bin the response file (XRISM XL RMF 800 MB -> 20 MB)
- Comprehensive atomic database
- Higher customizability of models
- Tunable optimisations for quick calc (e.g., ignore ions, ignore broadening)

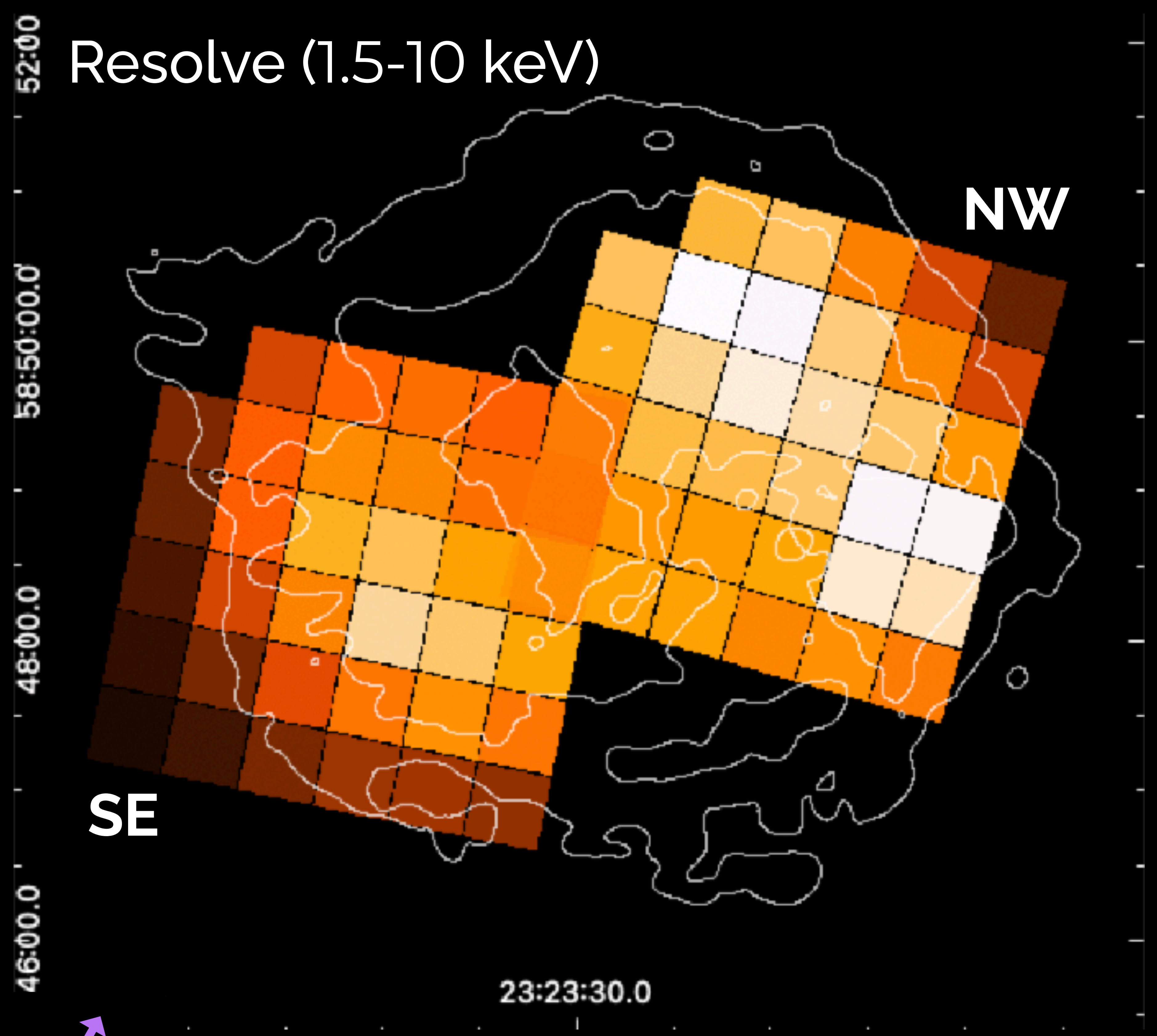
Cassiopeia A

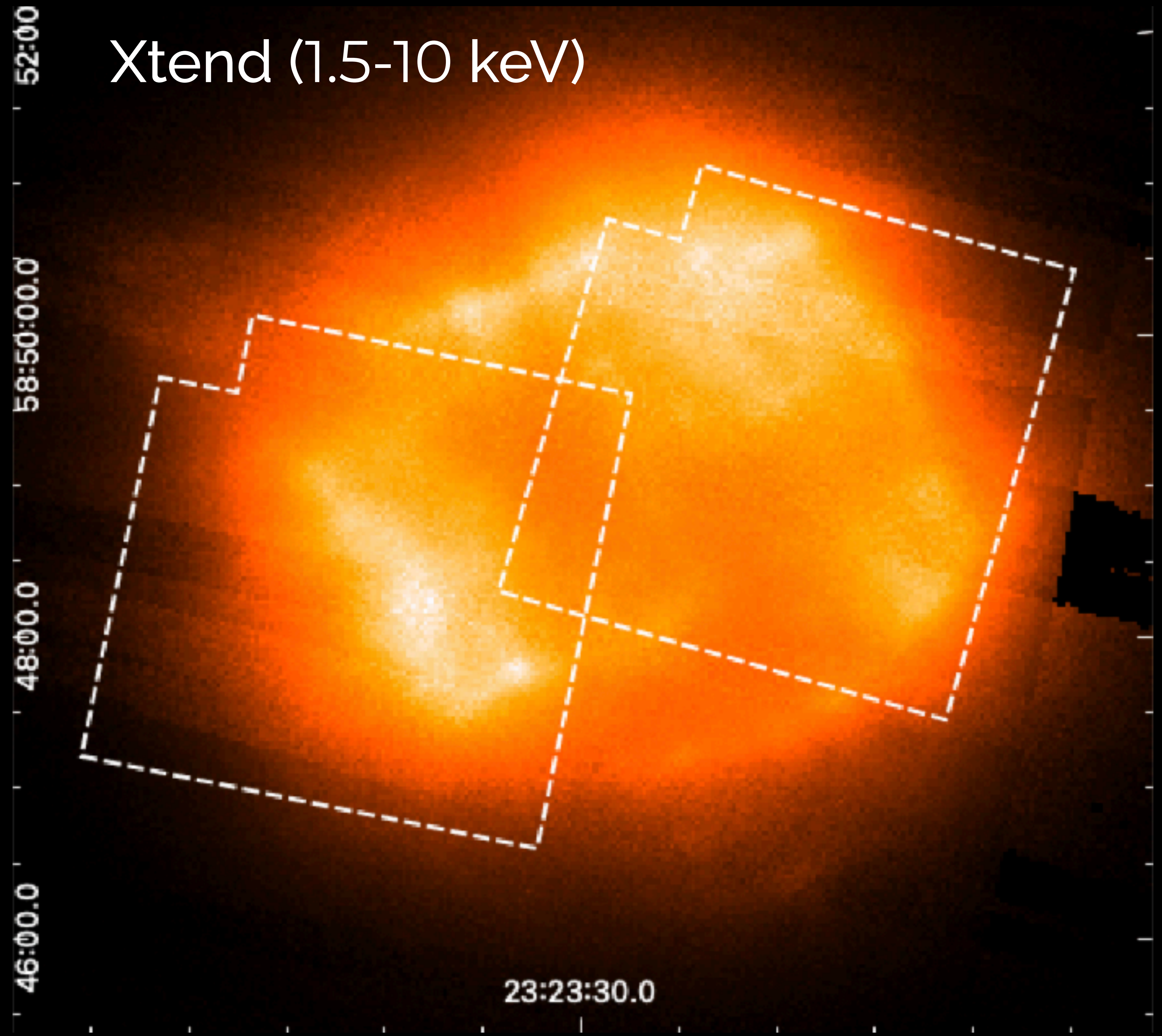
dead-star of the show

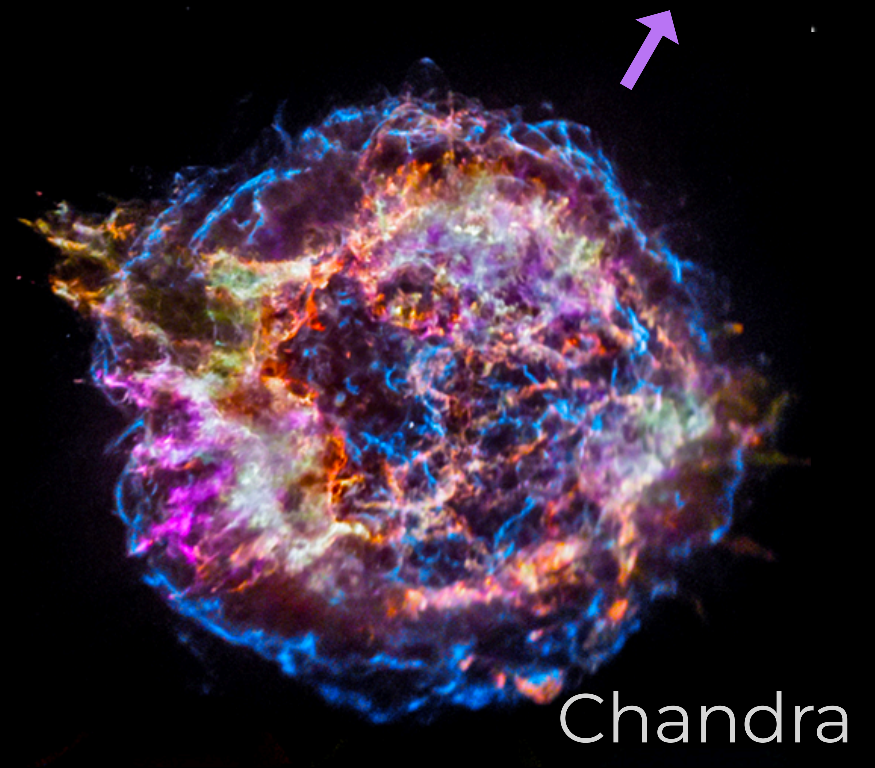
- **Youngest galactic core-collapse supernova** (~350 years)
- Nearby (~3.4 kpc or ~11,000 light-years)
- Light Echoes (Rest et al. 2008, Krause et al. 2008)
  - Secure spectroscopic classification (**Type IIb**) i.e. stripped envelope explosion of a red supergiant (15-25 $M_\odot$)
  - Light echoes from different vantage points show asymmetric explosion
- Neutron star
- Benchmark system to study the formation and destruction of dust
- Brightest object in radio, and very bright in X-ray thus very well-studied across all wavelengths

XRISM Observations of Cas A

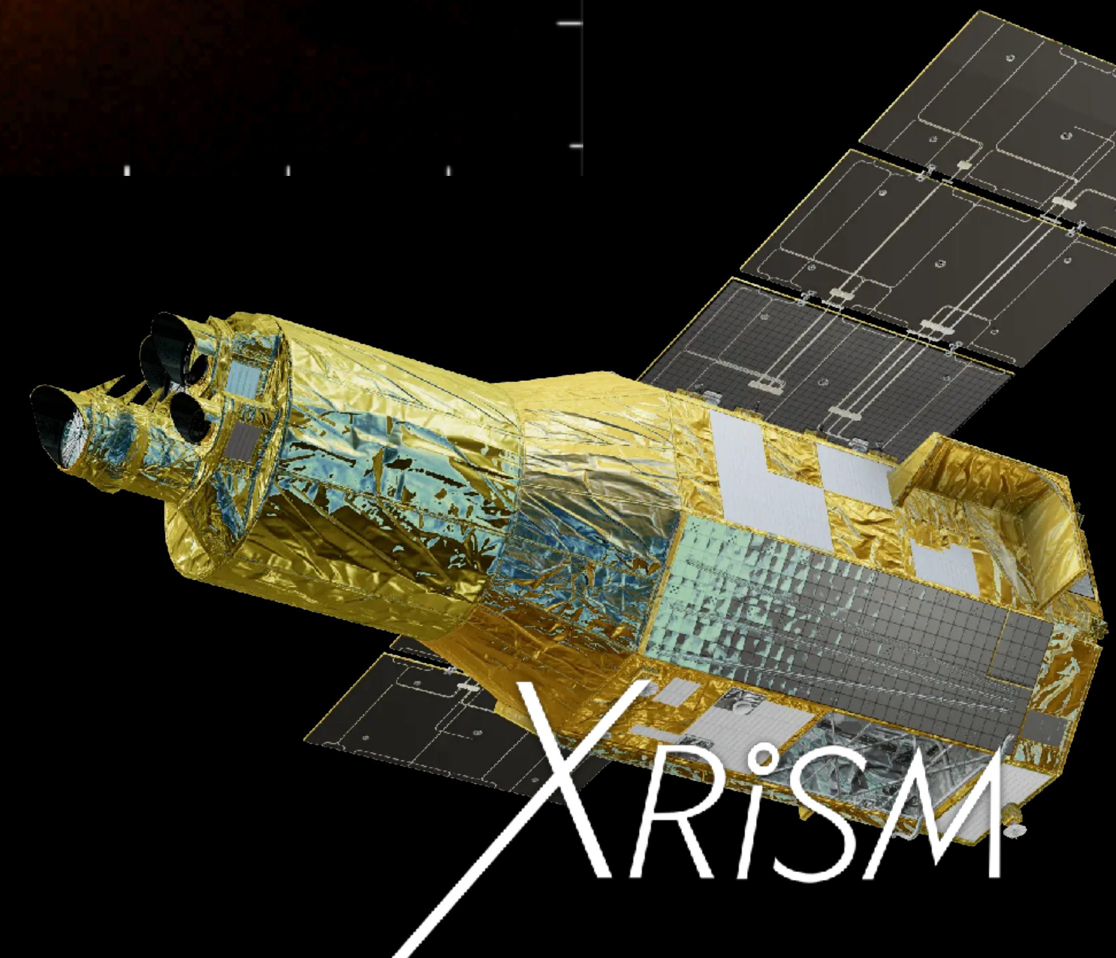
PI: Paul Plucinsky



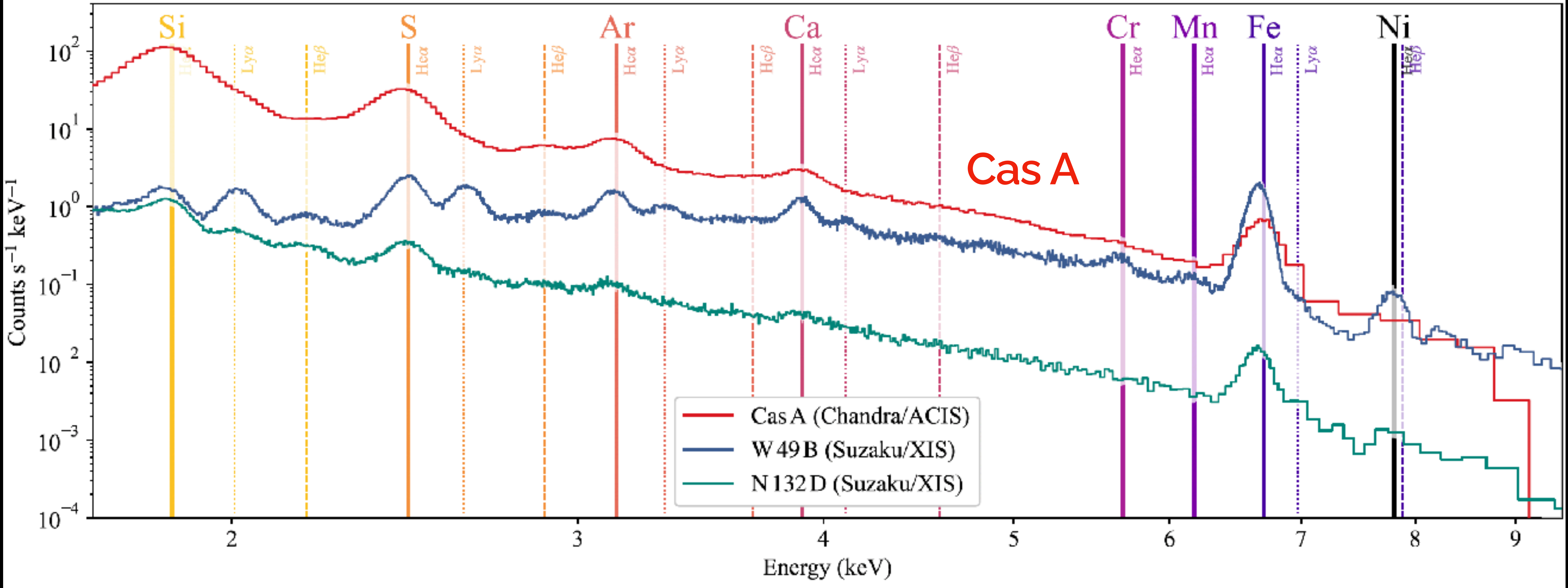




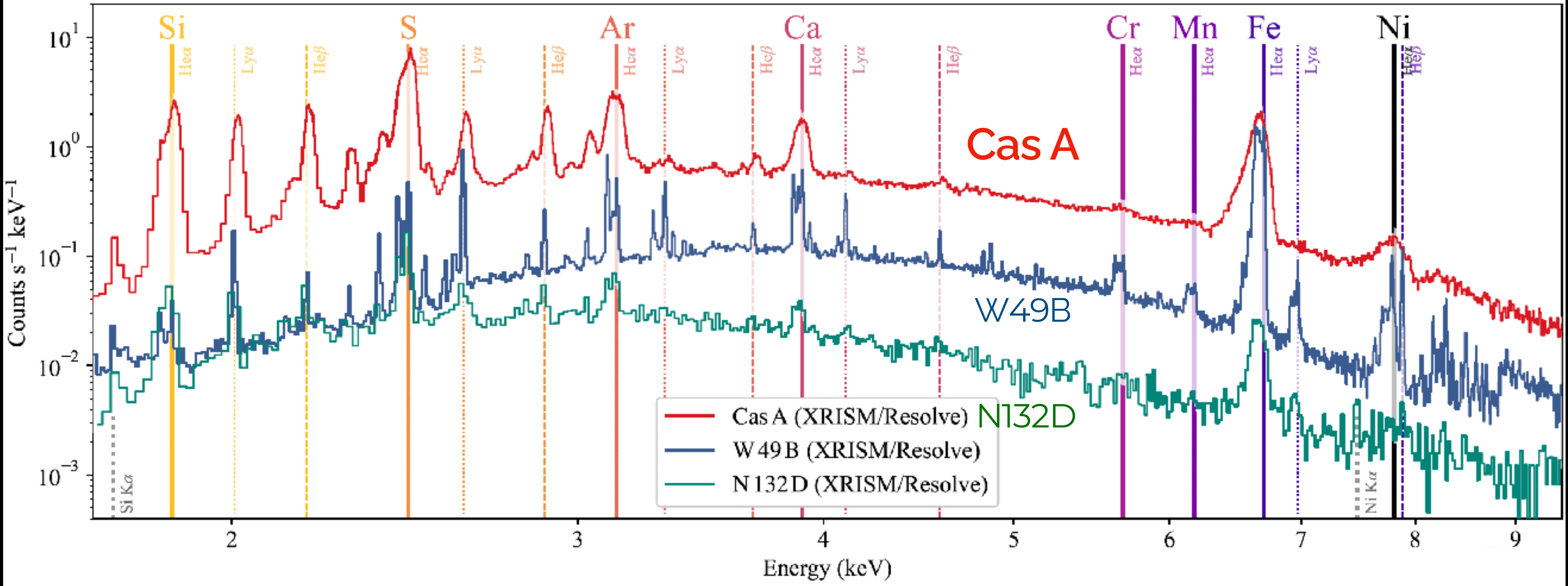
ObsID	Exposure (ks)	%Hp events
00129000 (SE)	182	96.6
00130000 (NW)	167	96.2



Chandra / Suzaku
X-ray CCDs



XRISM (Resolve)
Microcalorimeter



Credits: M. Sawada; XRISM

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XRISM Cassiopeia A

- **Overview paper**
  Plucinsky P., Agarwal M.,+ 2025 *(PASJ XRISM special issue)*
- **Mapping Dynamics of Si/S ejecta**
  Vink J., Agarwal M.,+ 2025 *(PASJ XRISM special issue)*
  Suzuki+ 2025 *(PASJ XRISM special issue)*
- **Mapping Dynamics of Fe ejecta**
  Bamba A., Agarwal M.,+ 2025 *(PASJ XRISM special issue)*
- **Detection of P, Cl, and K**
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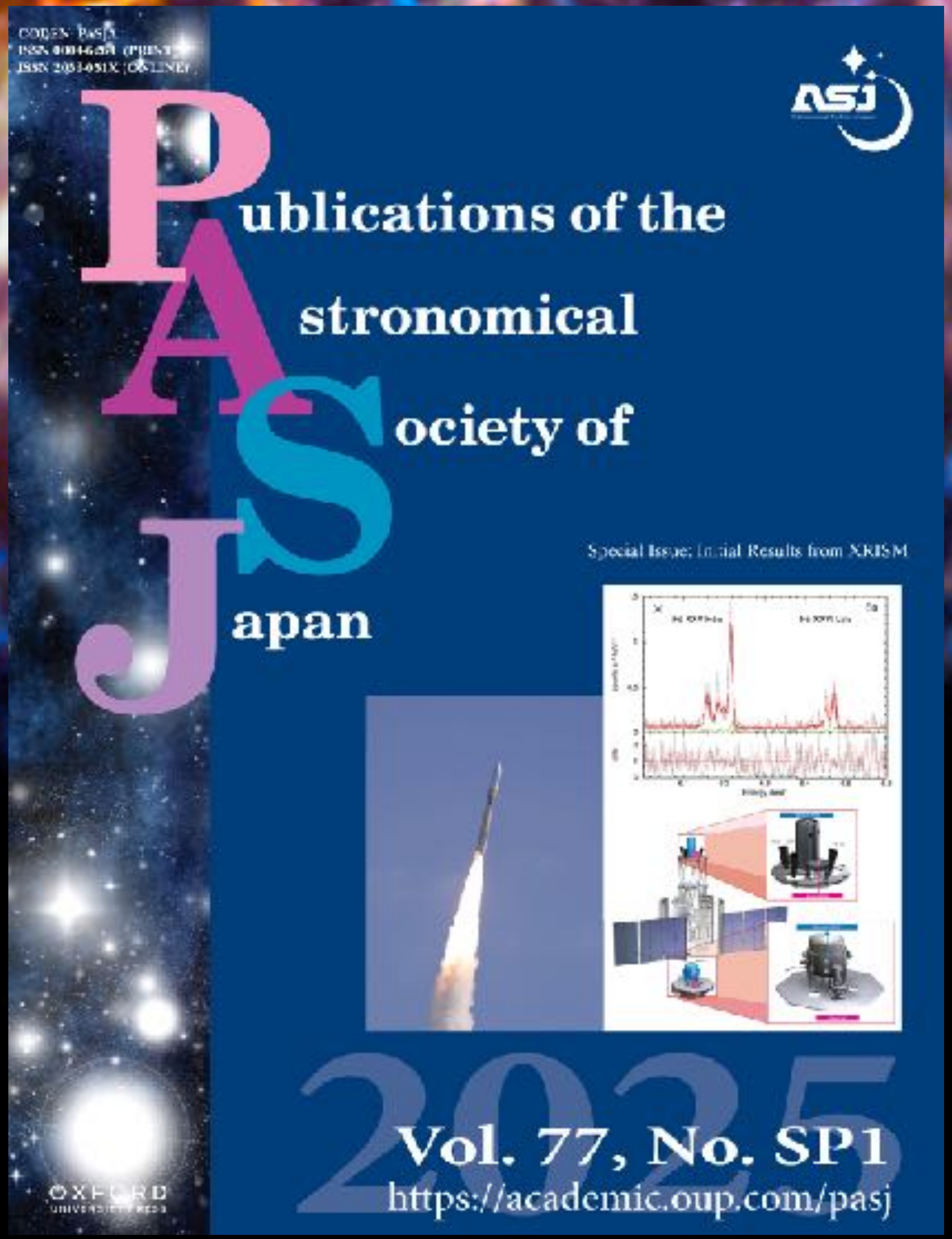
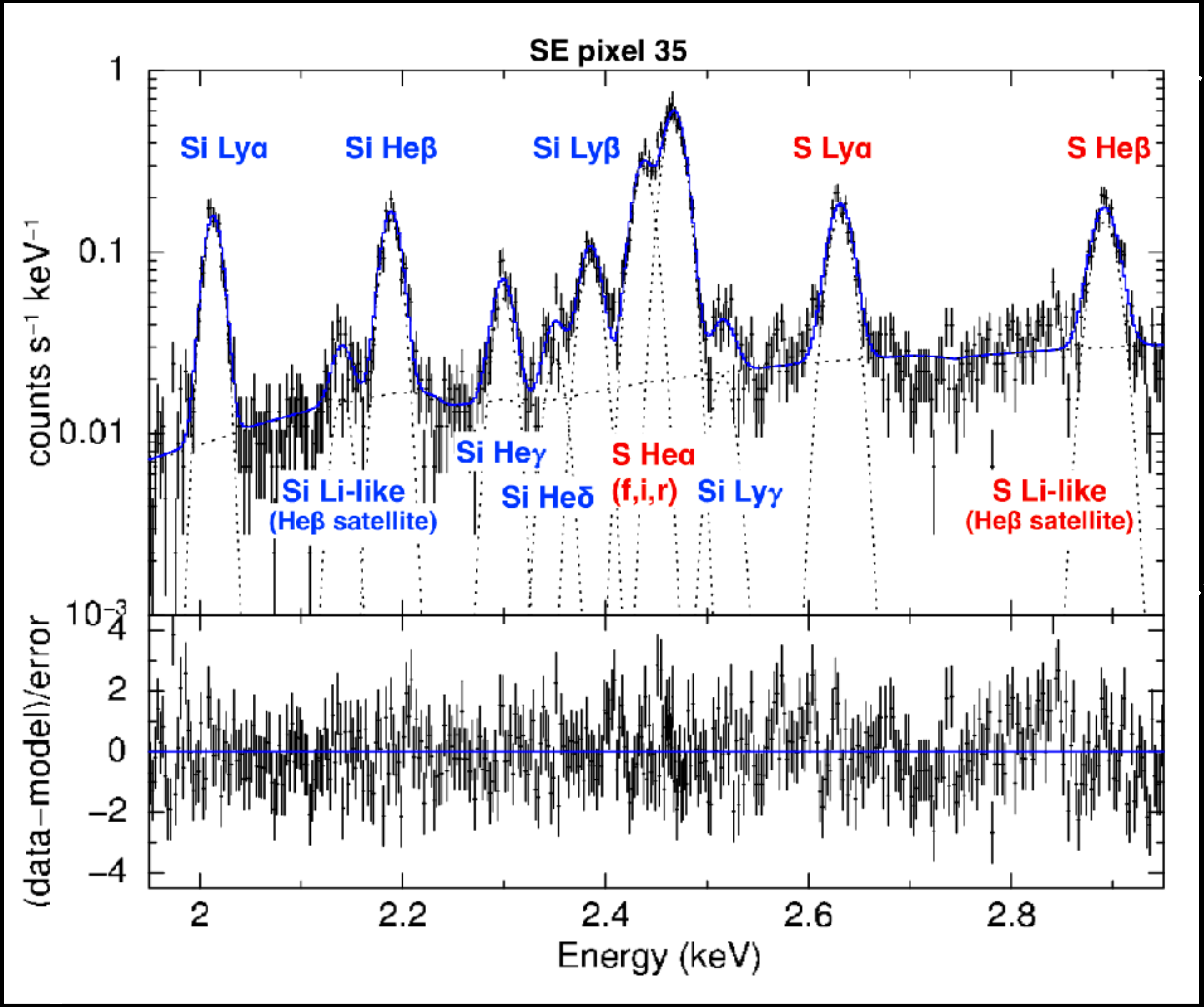
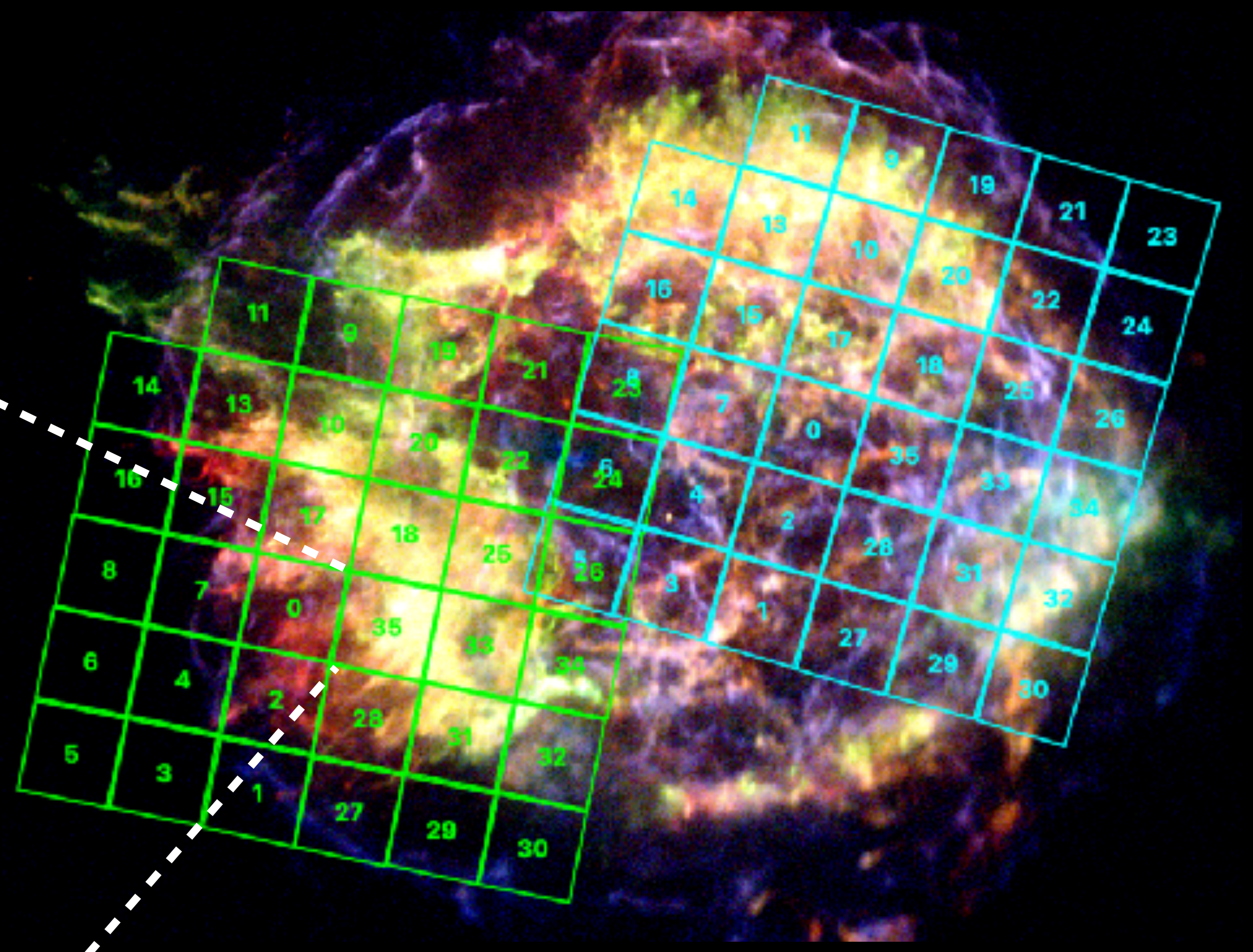
- **Mapping Plasma properties - Physical model - UltraSPEX**
  Agarwal M.,+ *(submitted to ApJ)*



Mapping dynamics of Si/S ejecta - Gaussian analysis

Vink J., Agarwal M.,+ 25 (PASJ special issue)





Goal: understand asymmetries

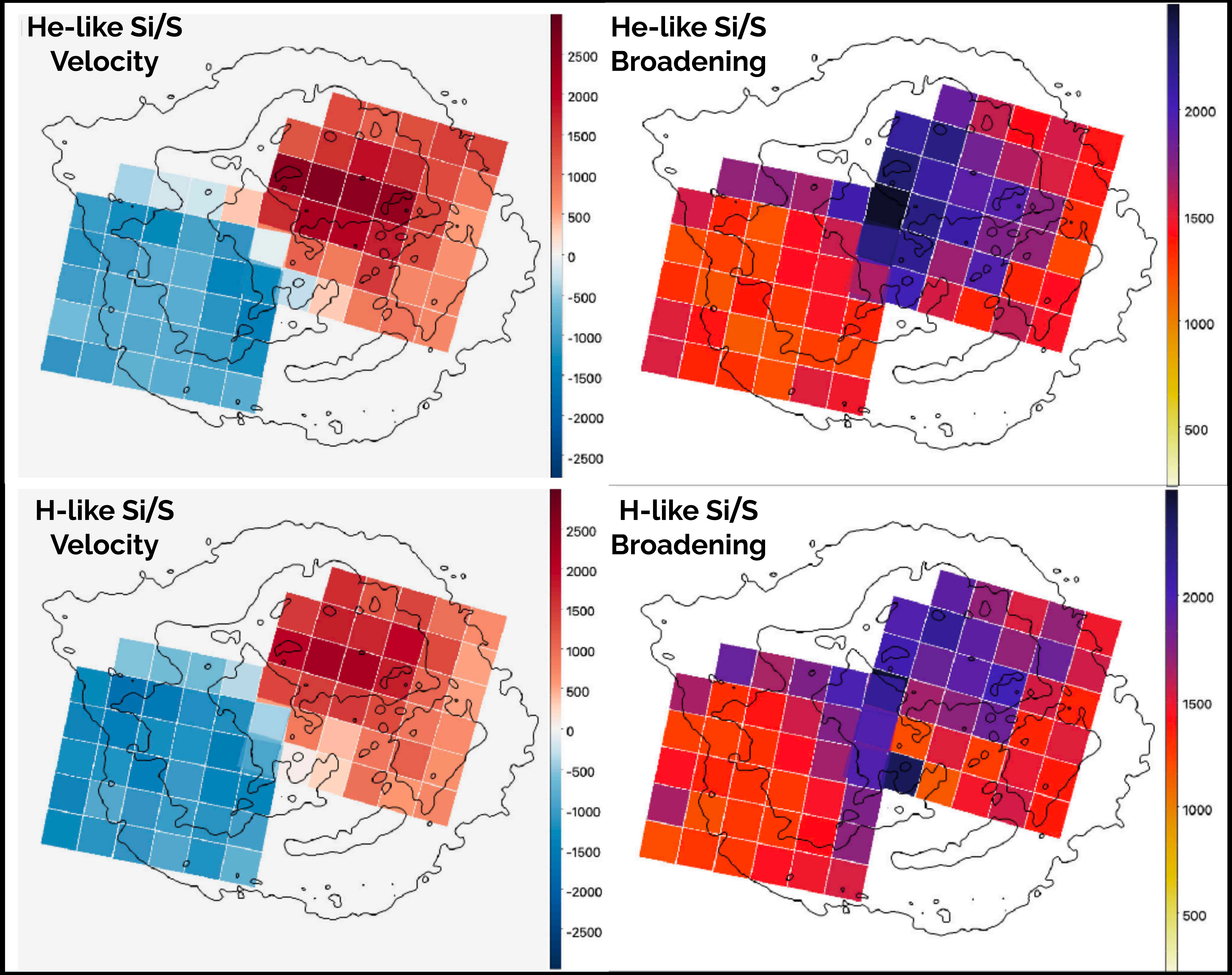
1.95 - 2.95 keV

Resolved individual lines of Si XIII, Si XIV, S XV, and S XVI

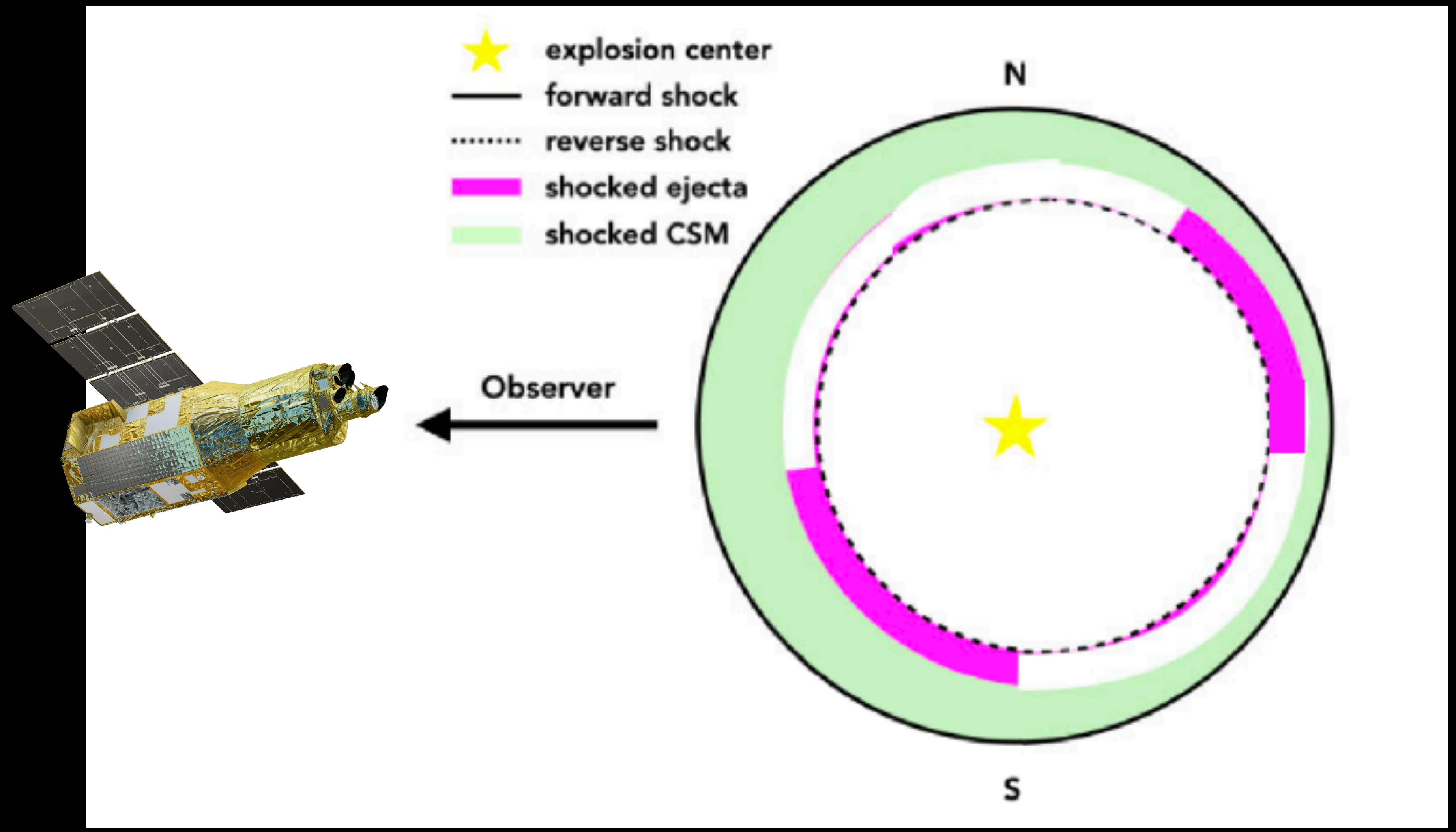
H-like and He-like lines have systematically different Doppler shifts across the remnant

H-like lines faster than He-like

Vink J., Agarwal M.,+ 25 (PASJ special issue)

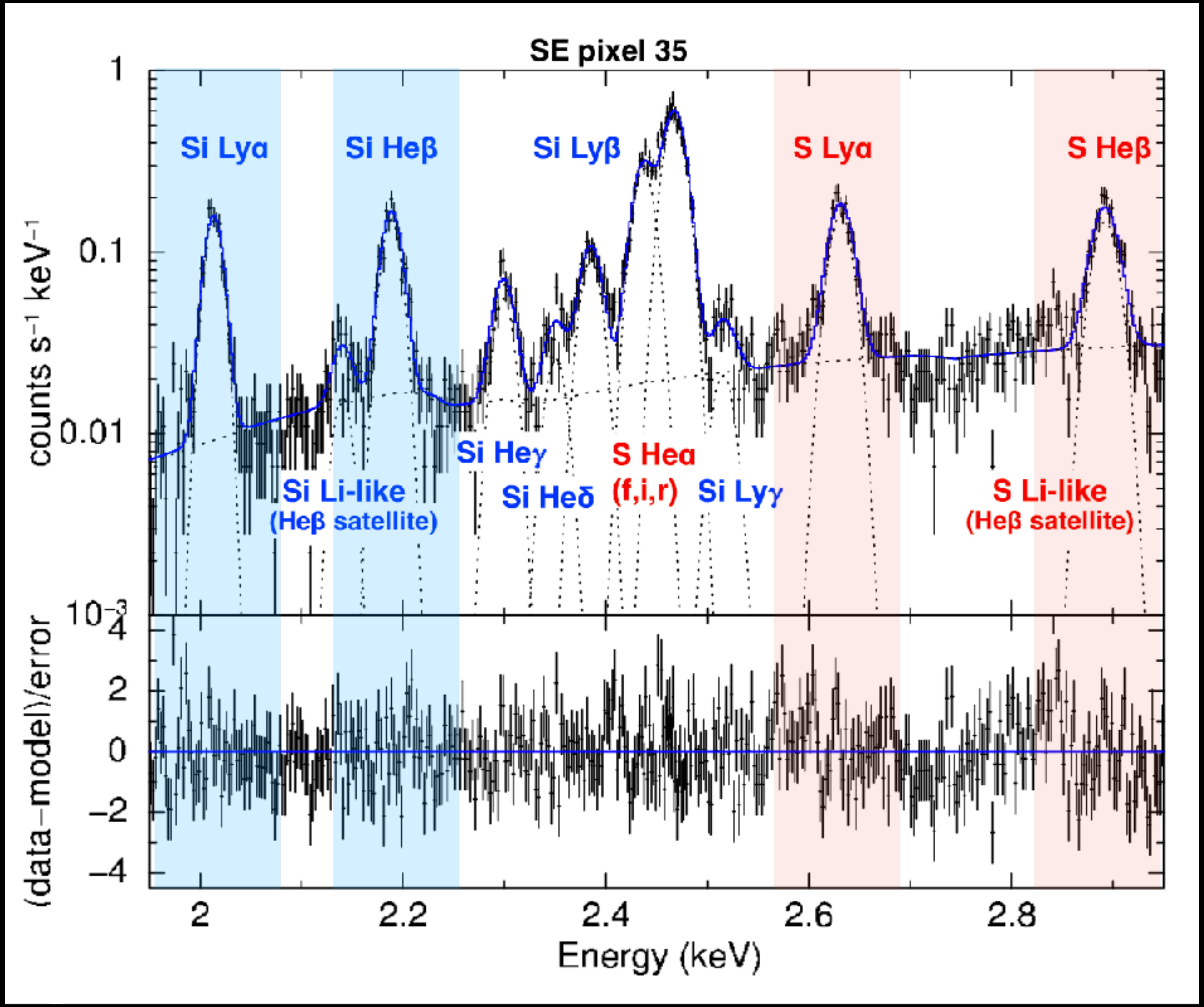


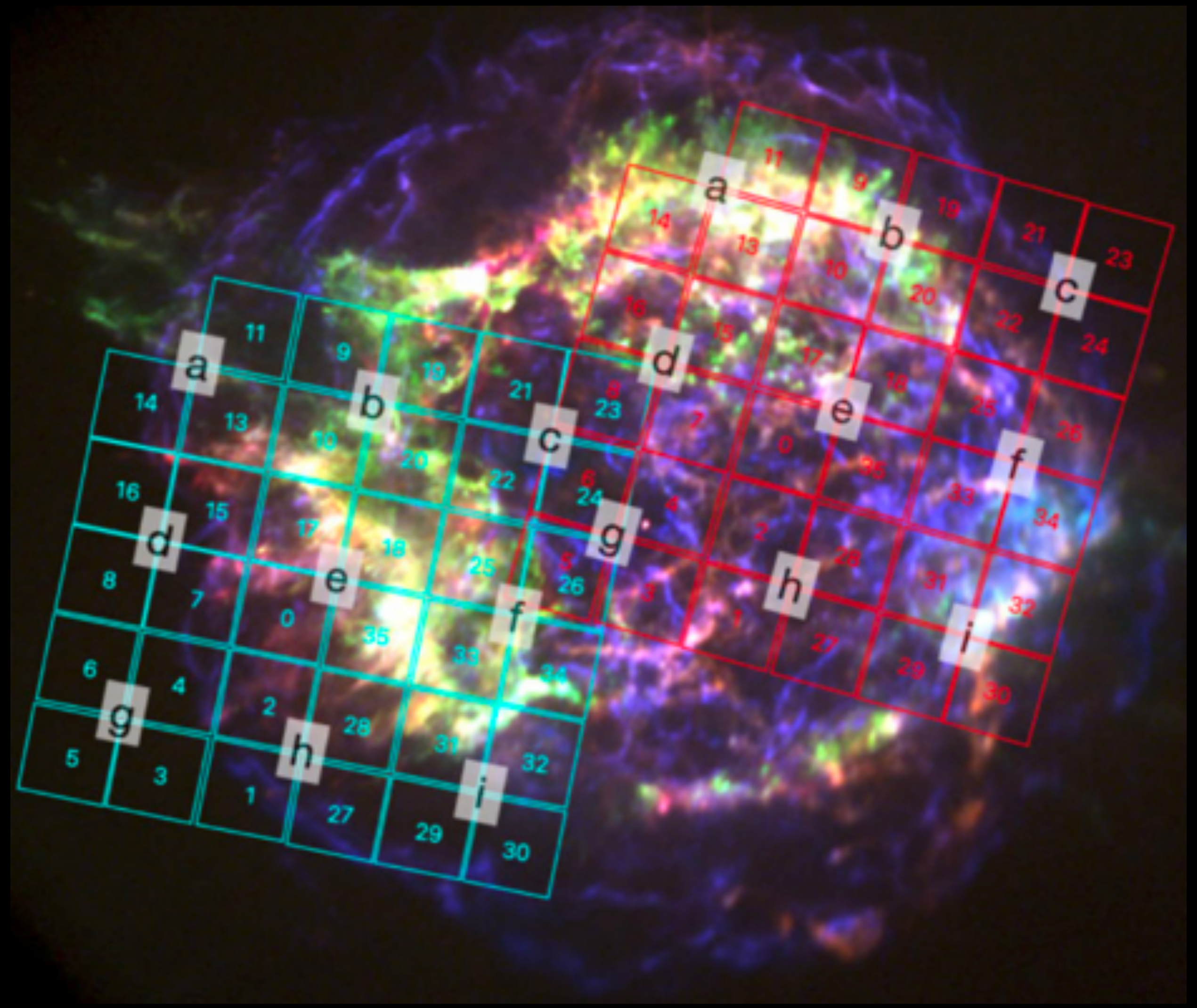
- Generally, the **H-like lines have a higher absolute velocity** compared to He-like lines
- Suzuki+ 25, we explain this with a two-component NEI model - the **ejecta with a higher velocity** are shock heated earlier, and thus a **higher ionization** is achieved
- Caveat: In some regions in NW we find He-like lines to be faster



Dynamics of Si and S ejecta - Double Gaussian analysis

Vink J., Agarwal M.,+ 25 (PASJ special issue)

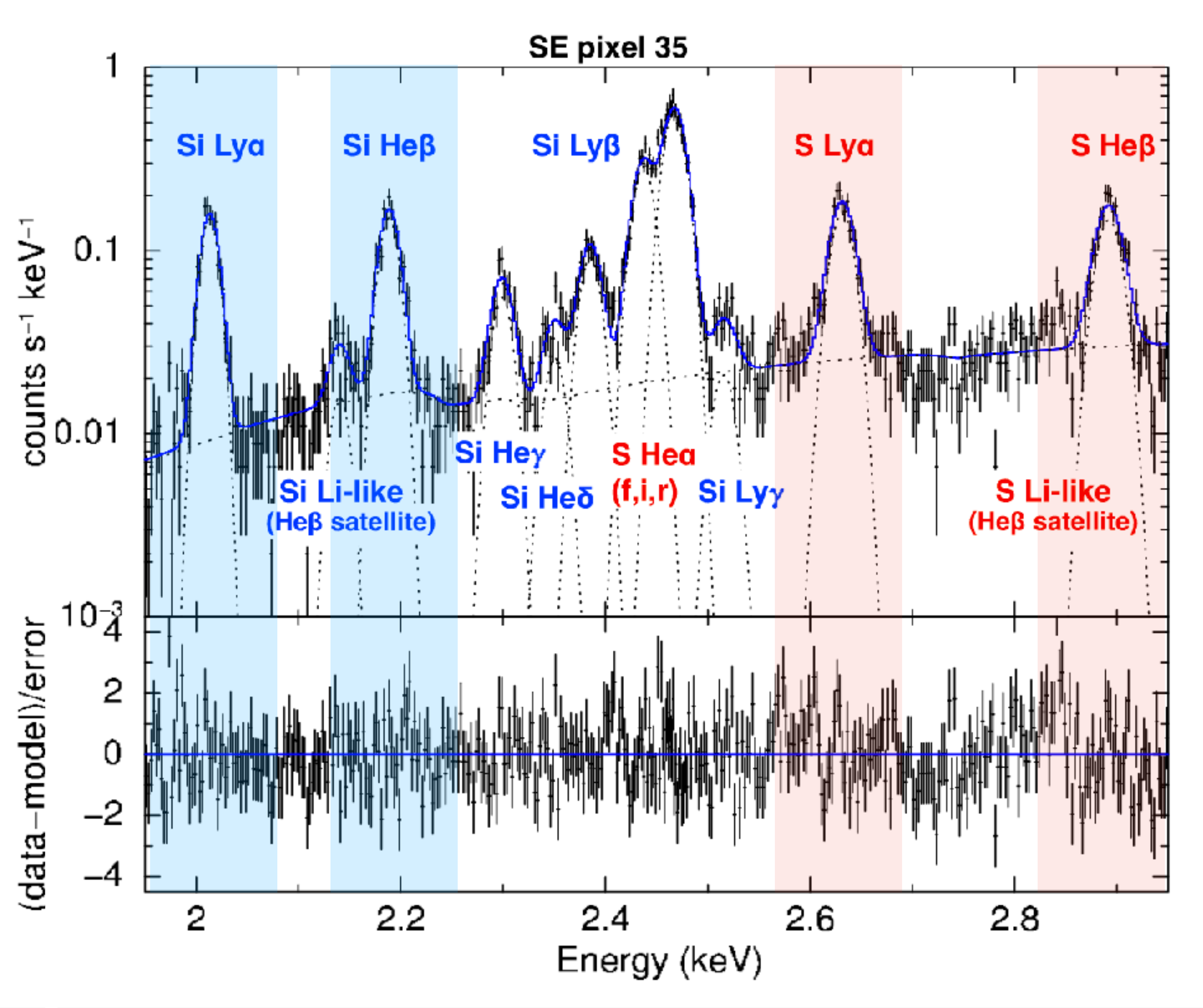


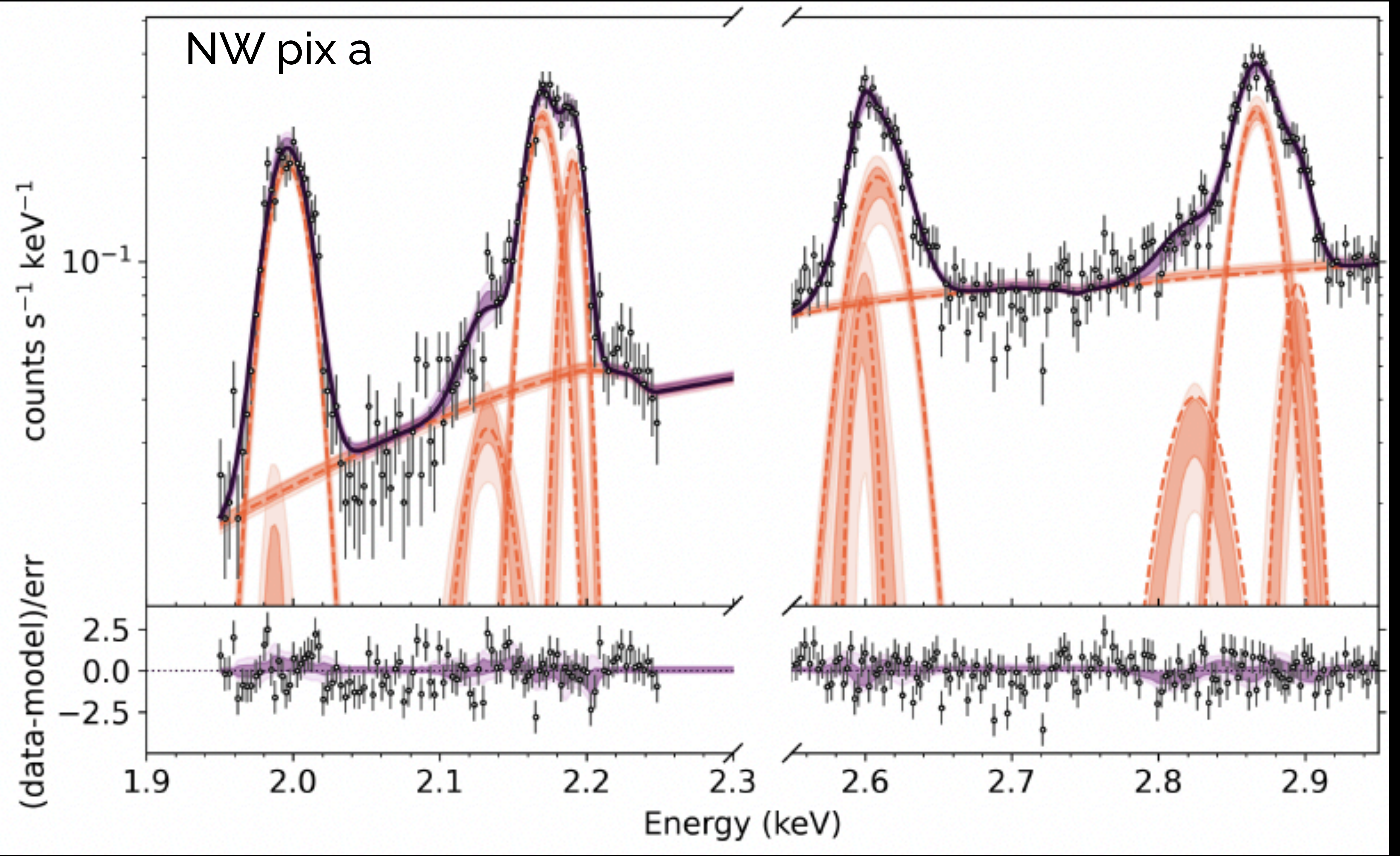


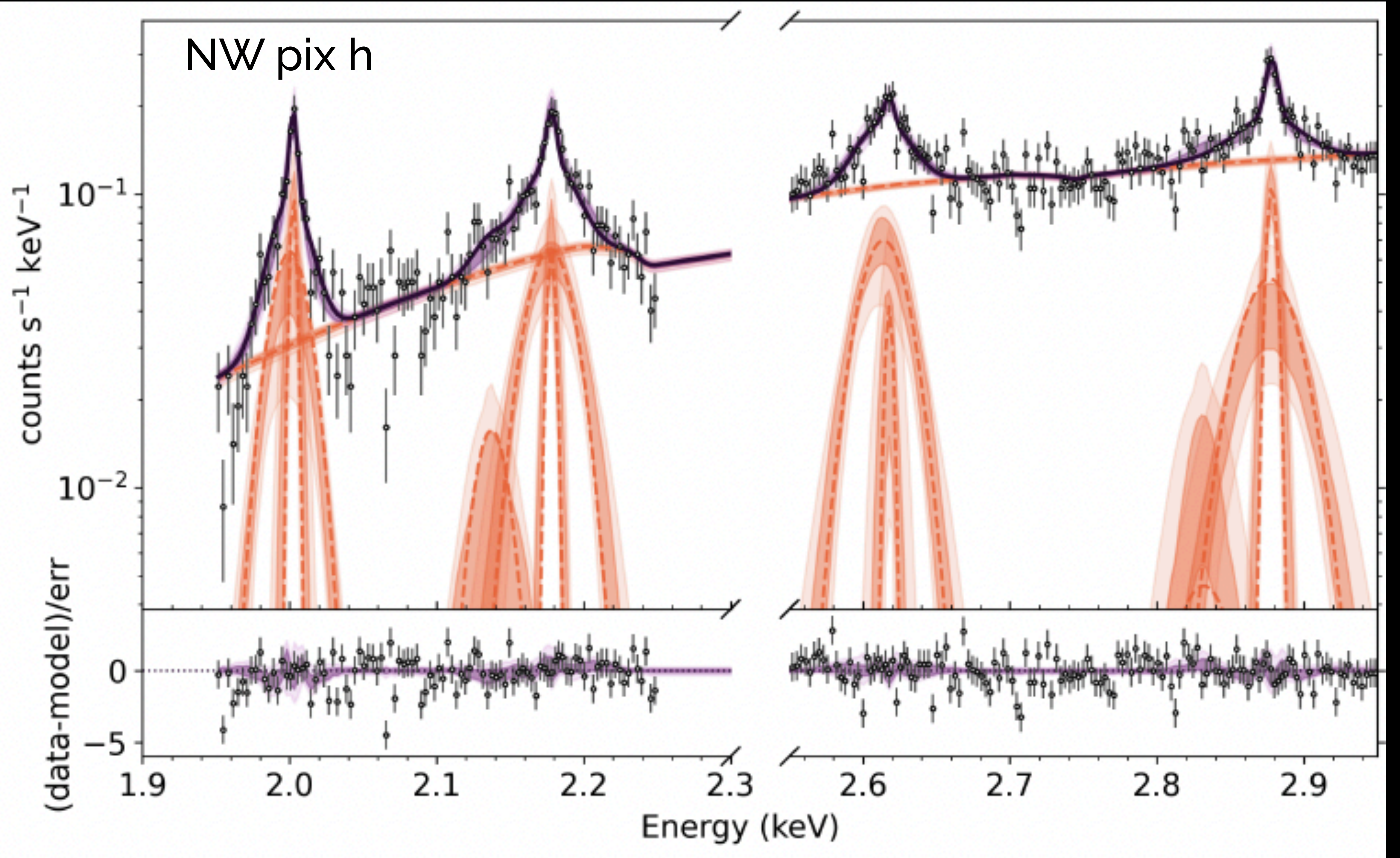
- **Si Lyα, Si Heβ, S Lyα, S Heβ**
  Individual and isolated lines at XRISM resolution
- 2 x 2 XRISM/Resolve pixel regions i.e. 1’ x 1’
- Double gaussians
  - Relatively blueshifted and relatively redshifted component
  - Doppler shift and broadening are coupled between H-like and He-like lines

UltraSPEX fits

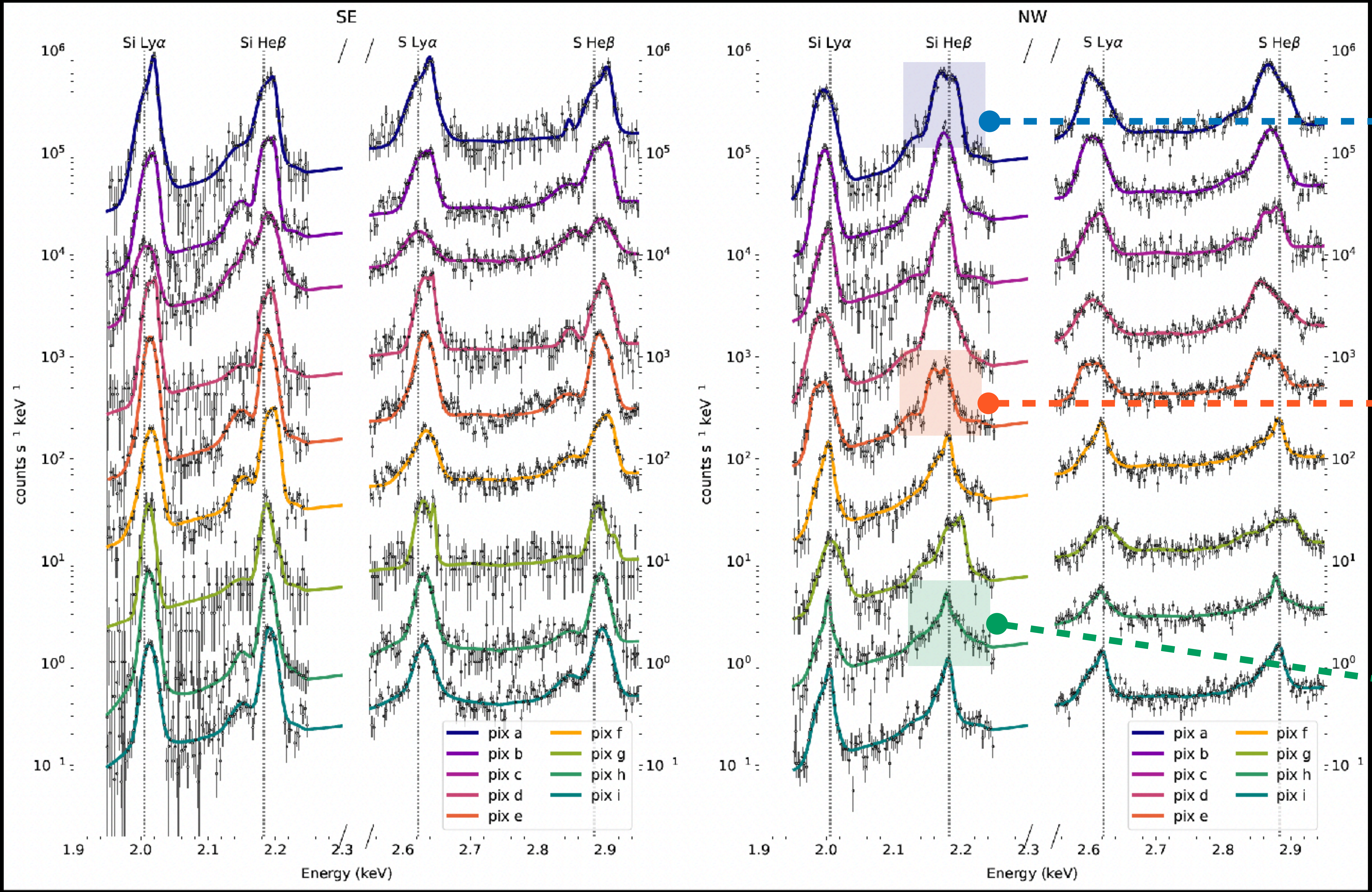
Vink J., Agarwal M.,+ 25 (PASJ special issue)

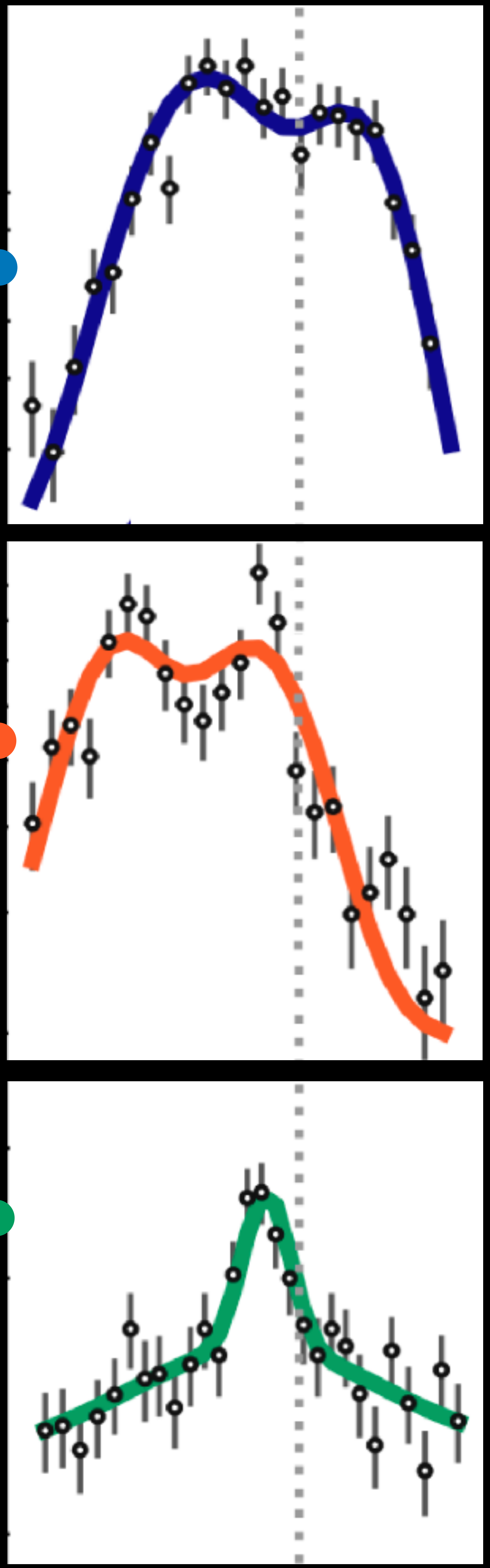






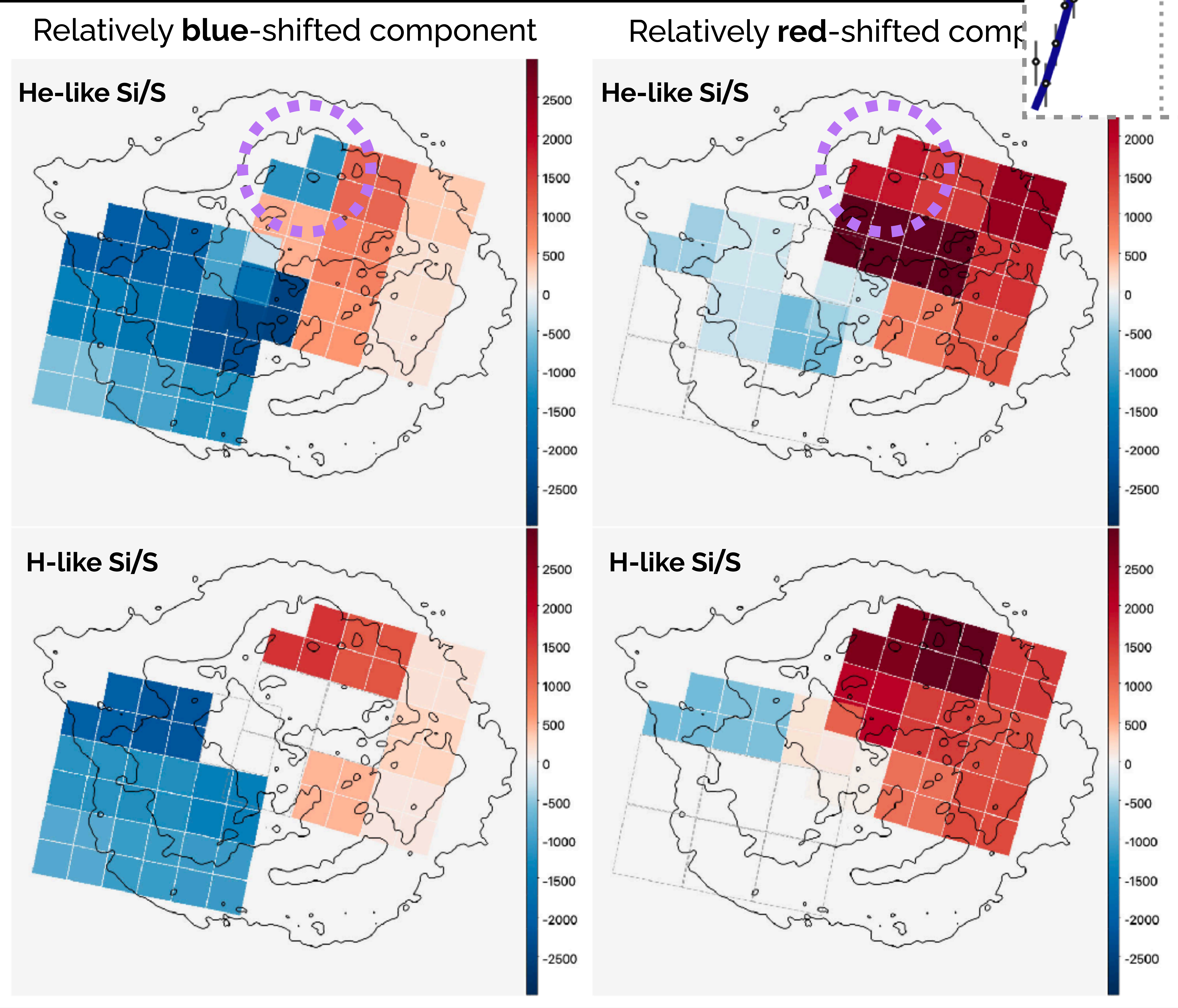
Double Gaussian fitting - line profiles (Vink J., Agarwal M.,+ 25)

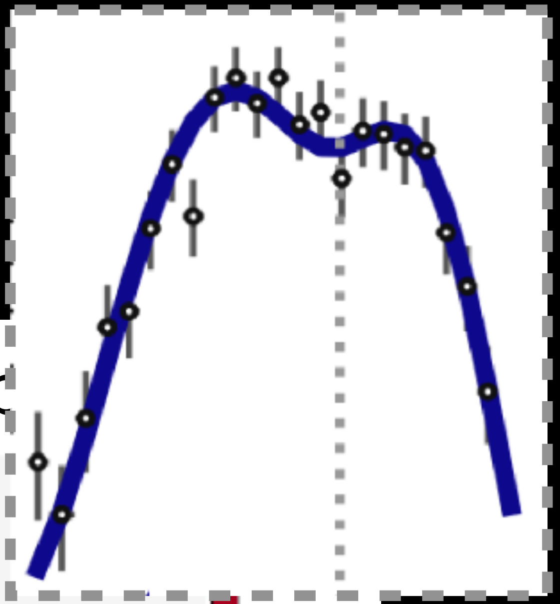




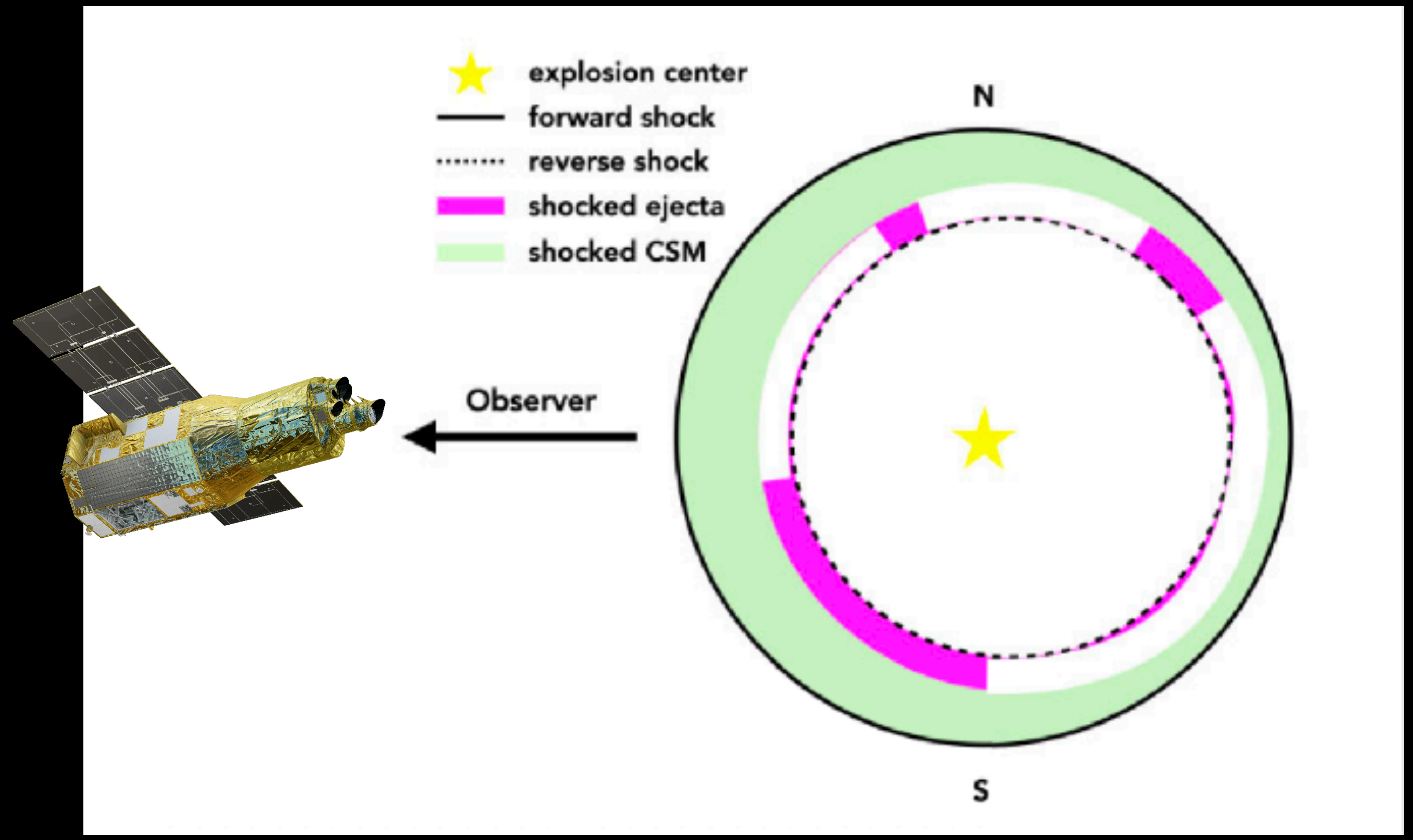
Redshift of Si and S ejecta

Vink J., Agarwal M.,+ 25



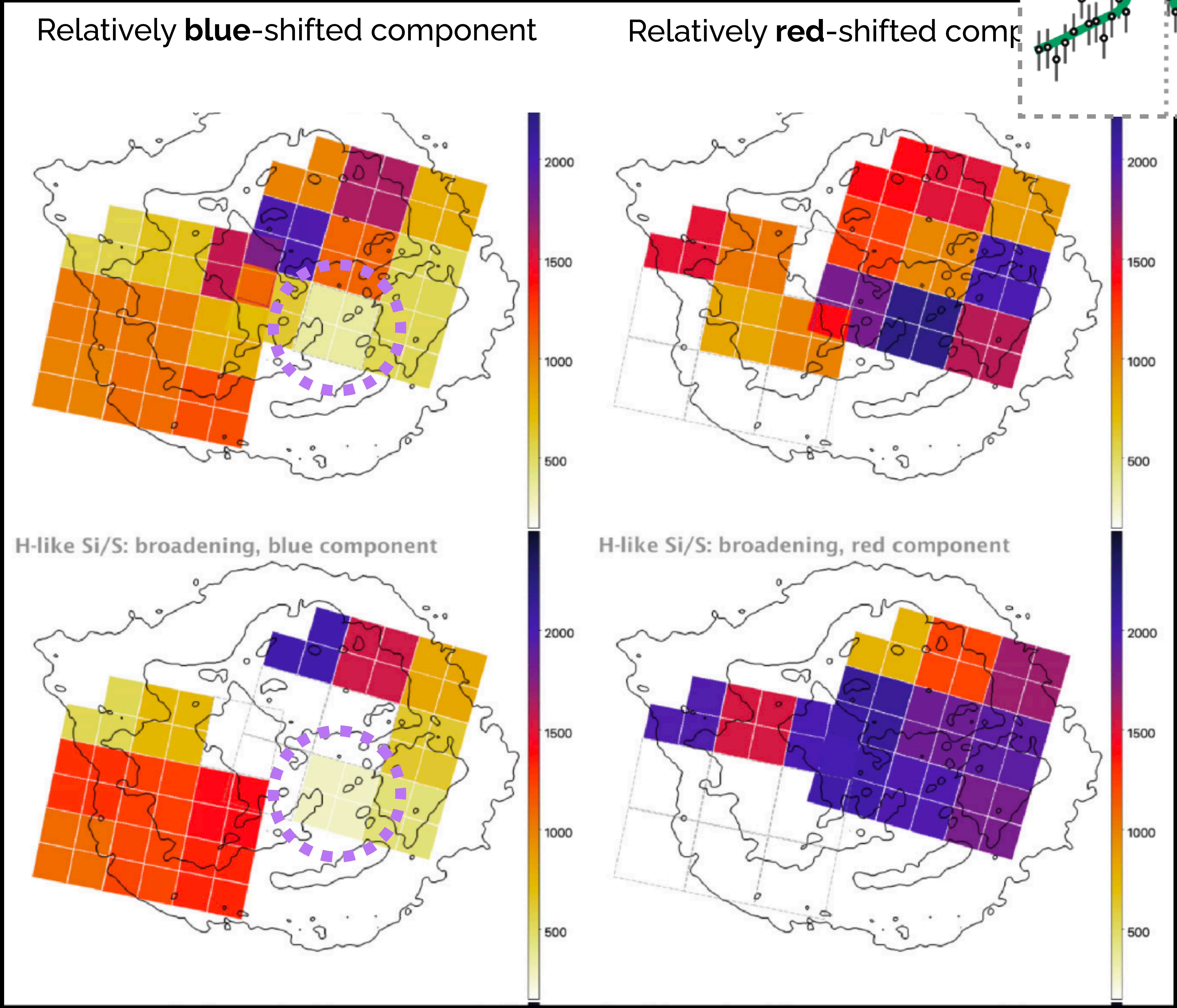


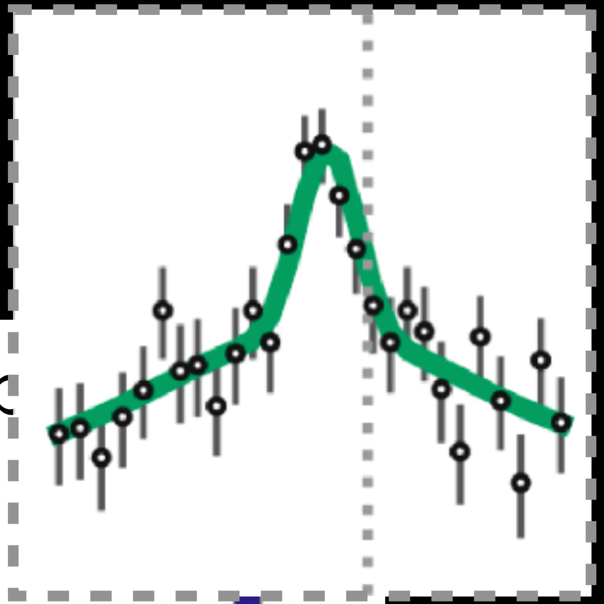
- Both components are either red-shifted (NW) or blue-shifted (SE)
- Except north, distinct red-shifted (1850 km/s) and blue-shifted (-1150 km/s) components
- Narrow, low-velocity components near the center likely originate from shocked CSM, but their exact origin remains ambiguous



Broadening of Si and S ejecta

Vink J., Agarwal M.,+ 25





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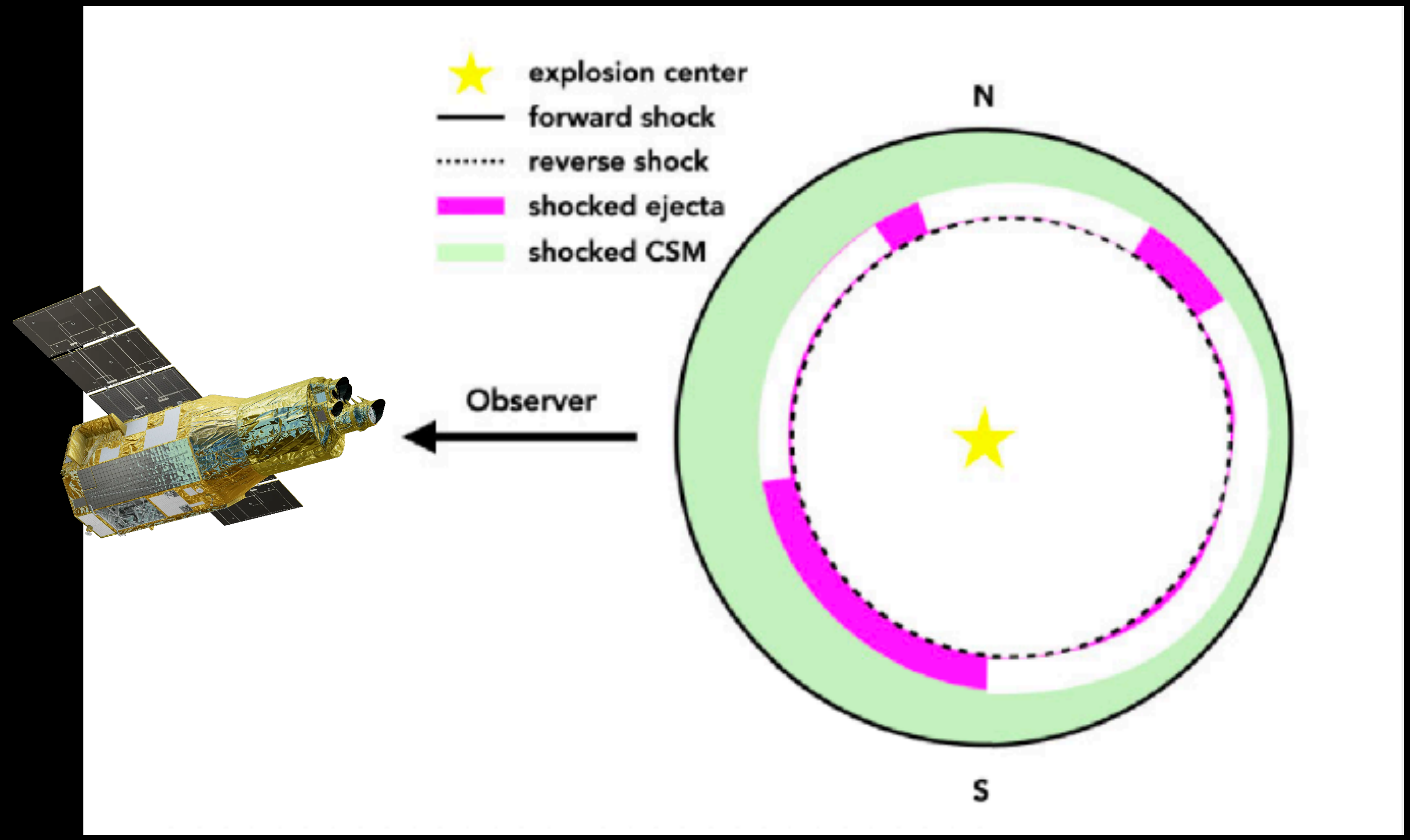

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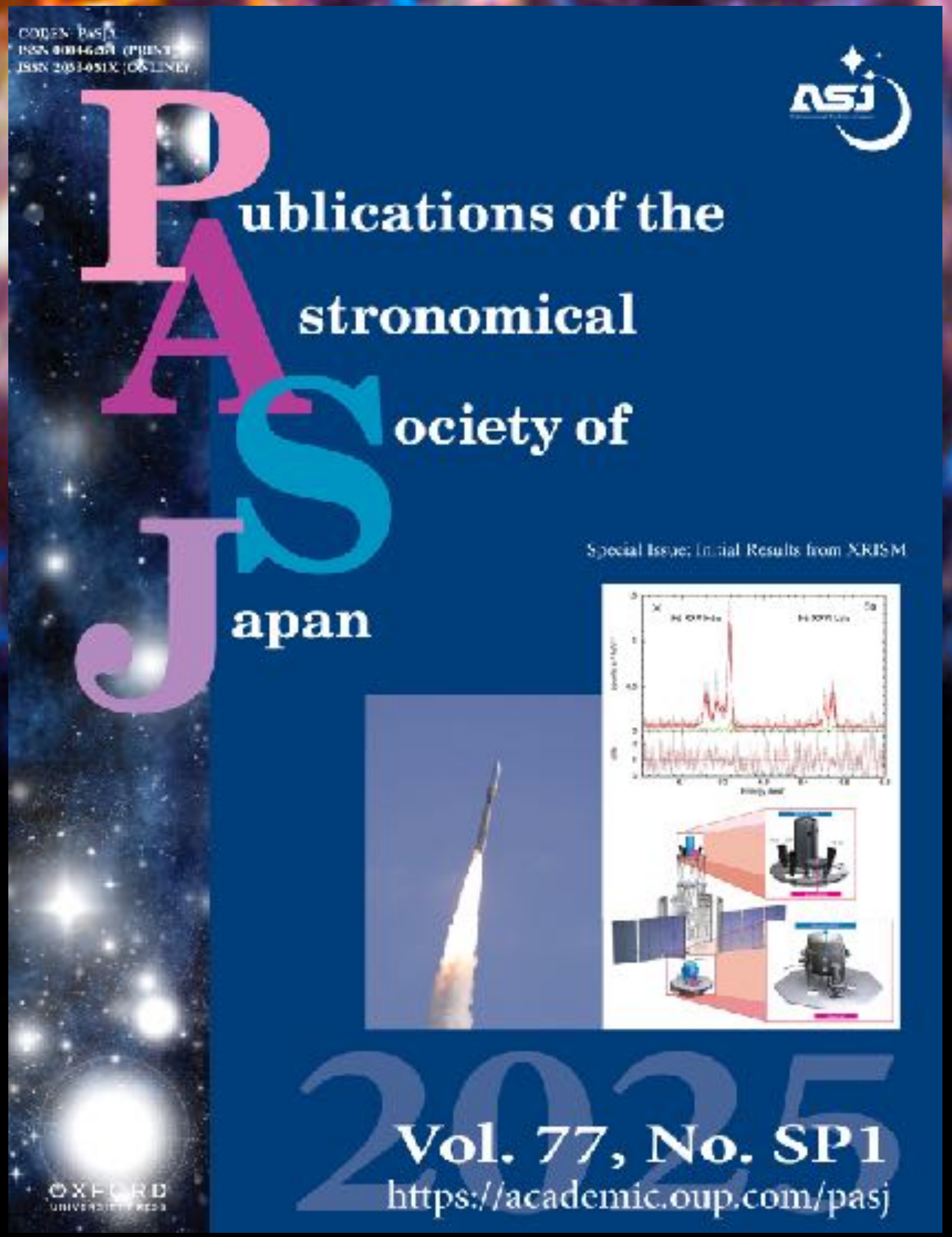
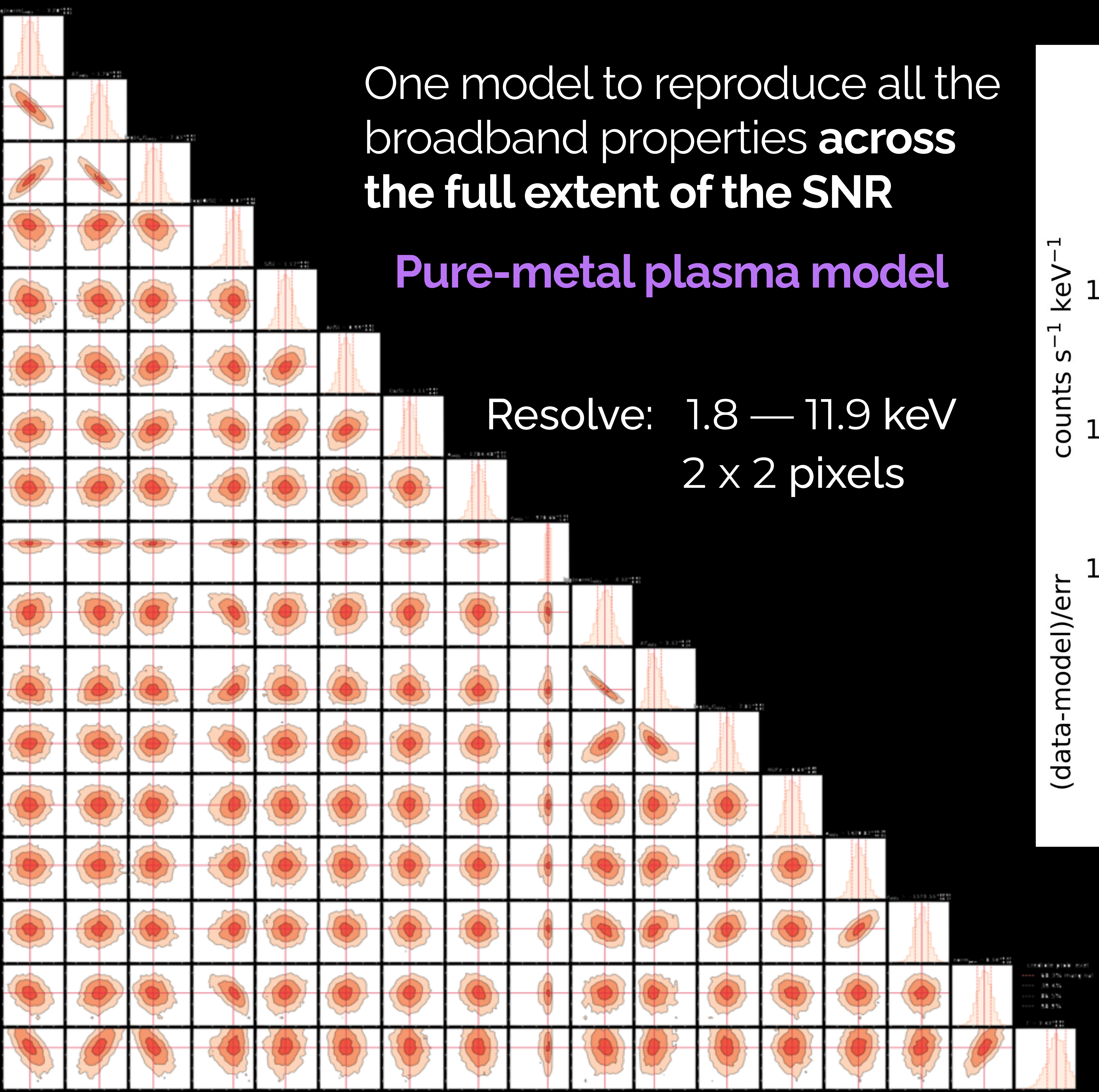


Mapping plasma parameters - *UltraSPEX*

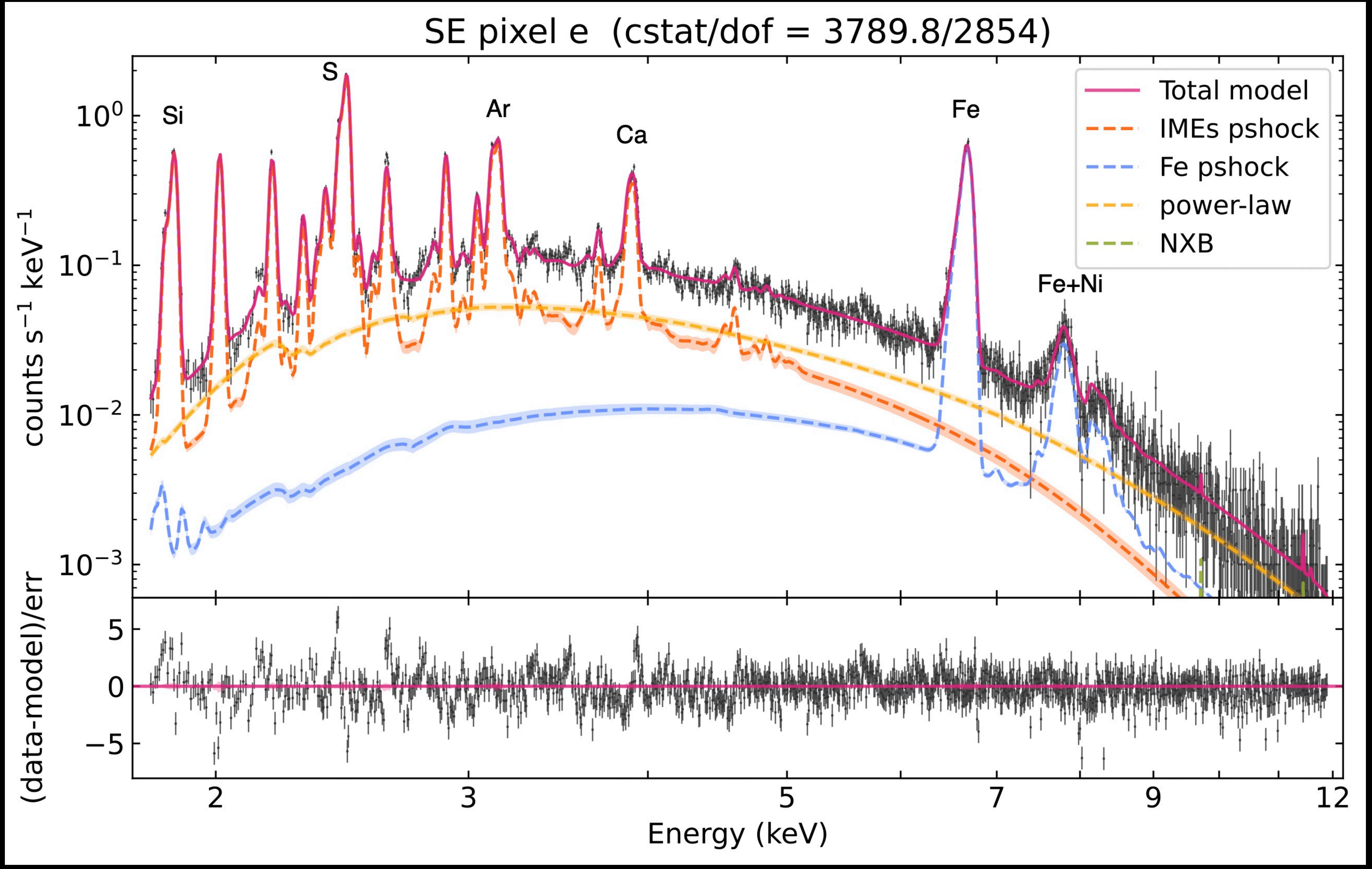
Agarwal, M.,+ (submitted)



One model to reproduce all the broadband properties **across the full extent of the SNR**

Pure-metal plasma model

Resolve: 1.8 — 11.9 keV
2 x 2 pixels



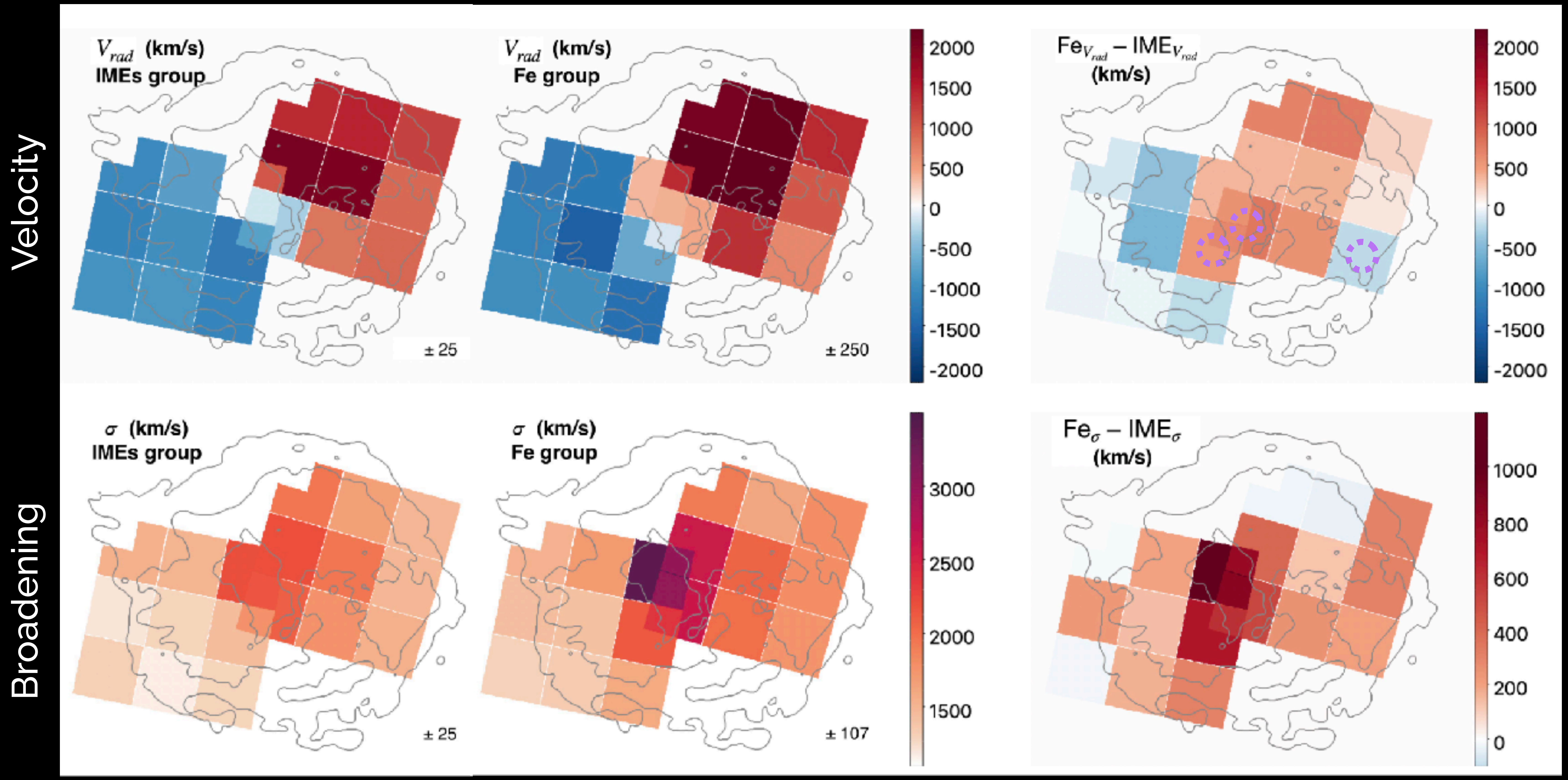
Model:
tbabs (pshock_IMEs + pshock_FeNi + powerlaw) + NXB

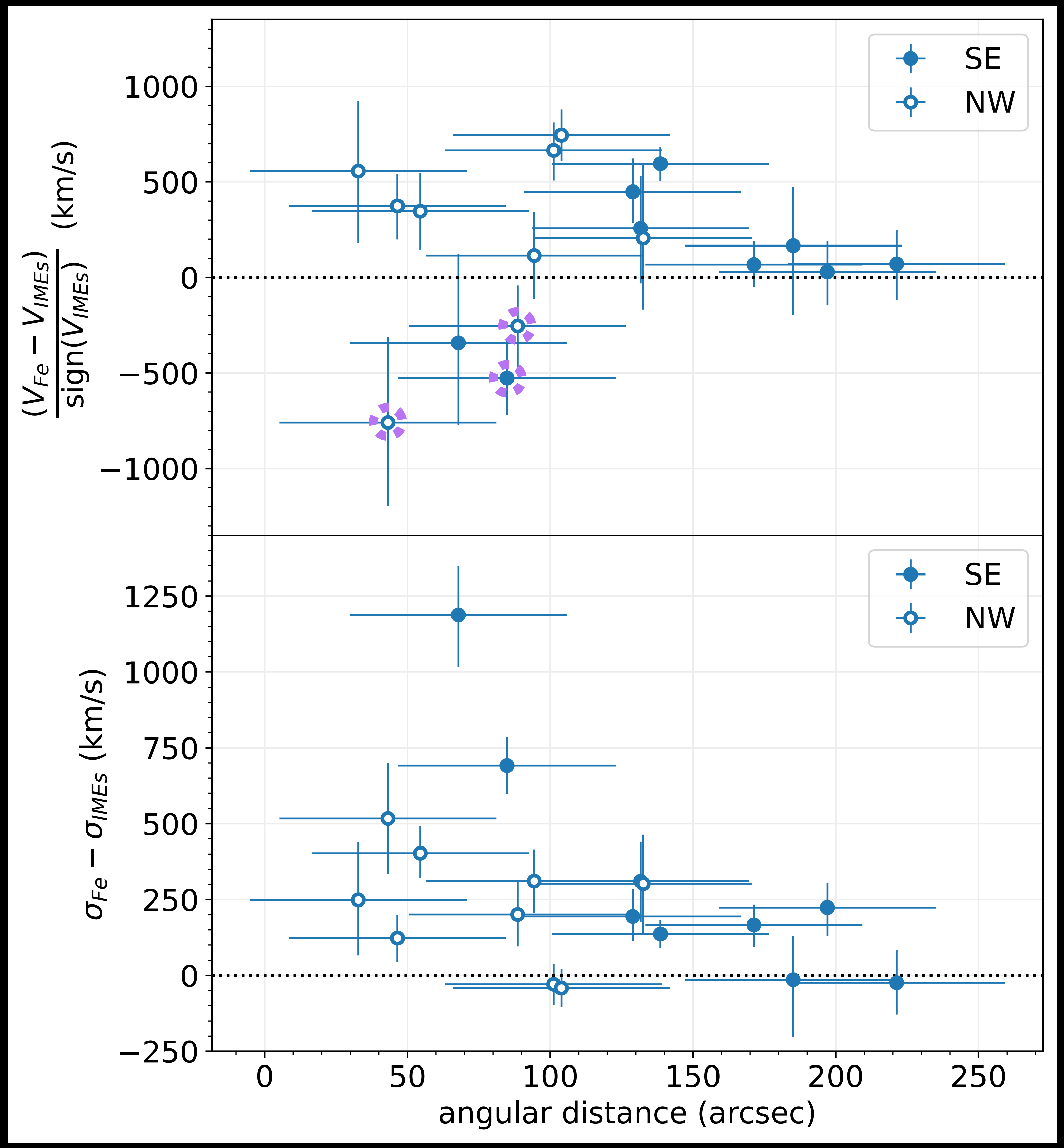
Plasma dynamics

Asymmetric uncertainties and multimodal posteriors for redshift

Plasma dynamics

- Fe-group has both higher Doppler velocity and Doppler broadening than the IMEs in most regions
- The Doppler kinematic differences between IMEs and IGEs are highest near the center and decrease radially outwards.

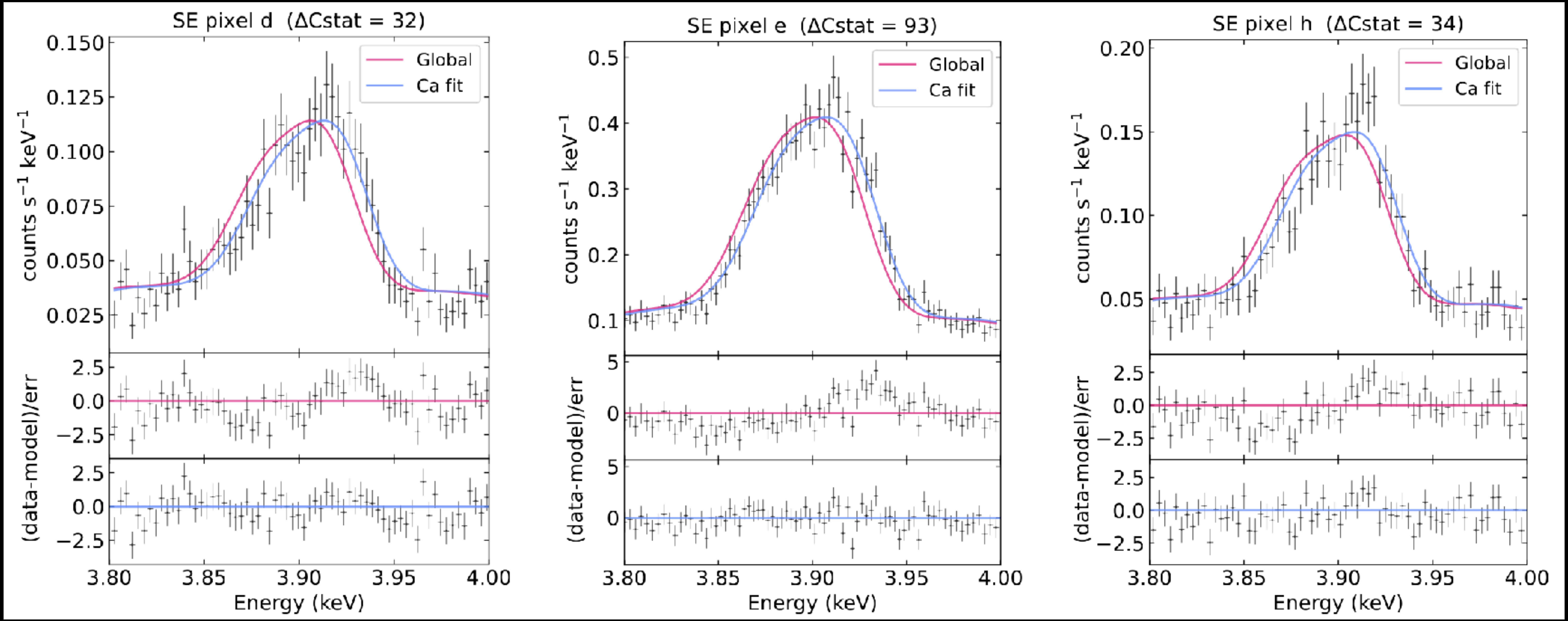




Plasma dynamics

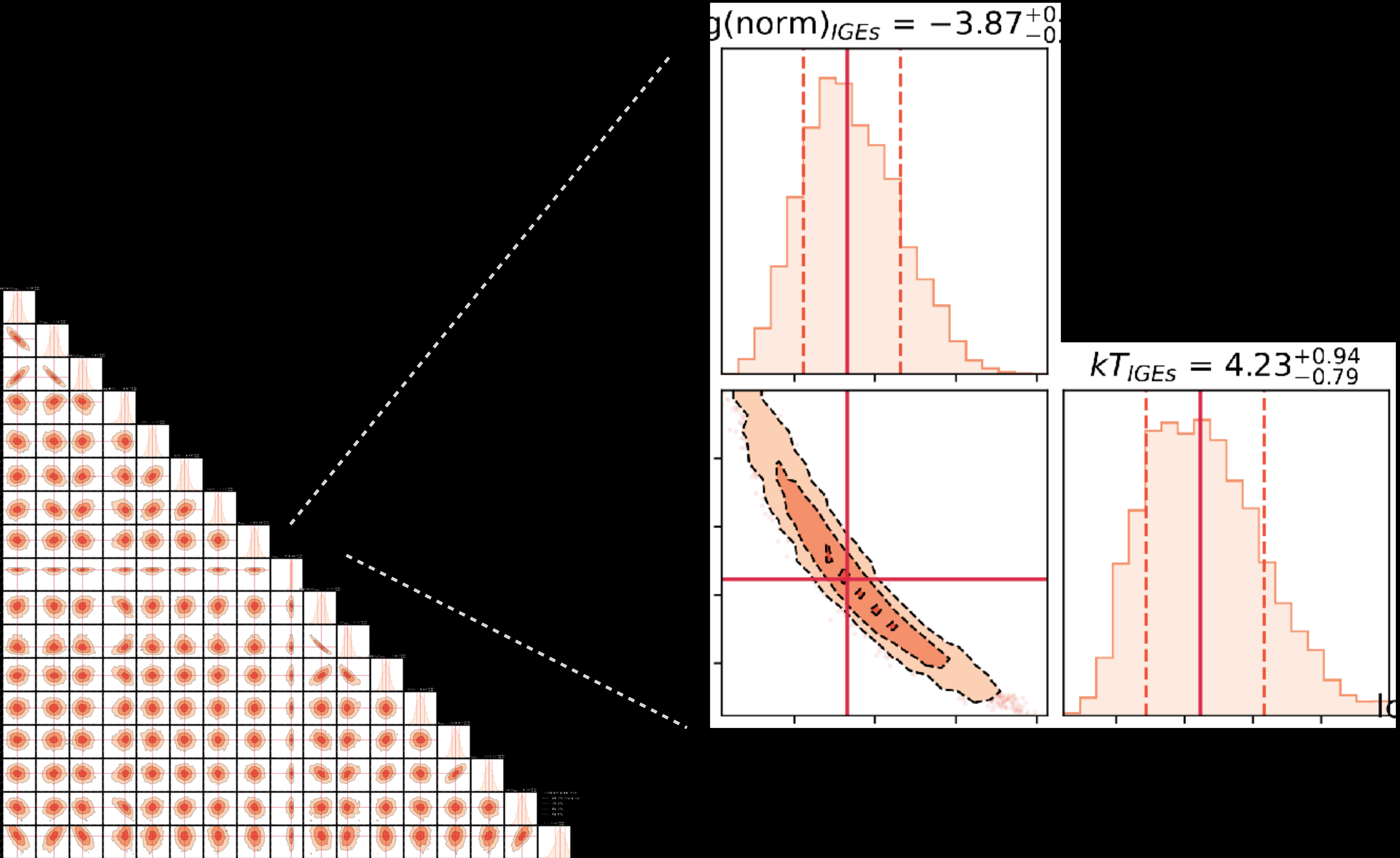
Ca has higher Doppler velocities than the IMEs, and even Fe, in some SE regions

Ca ~ -1500 km/s, i.e., more than 500^{+100}_{-100} km/s faster than IMEs



Electron temperature

Several local minima

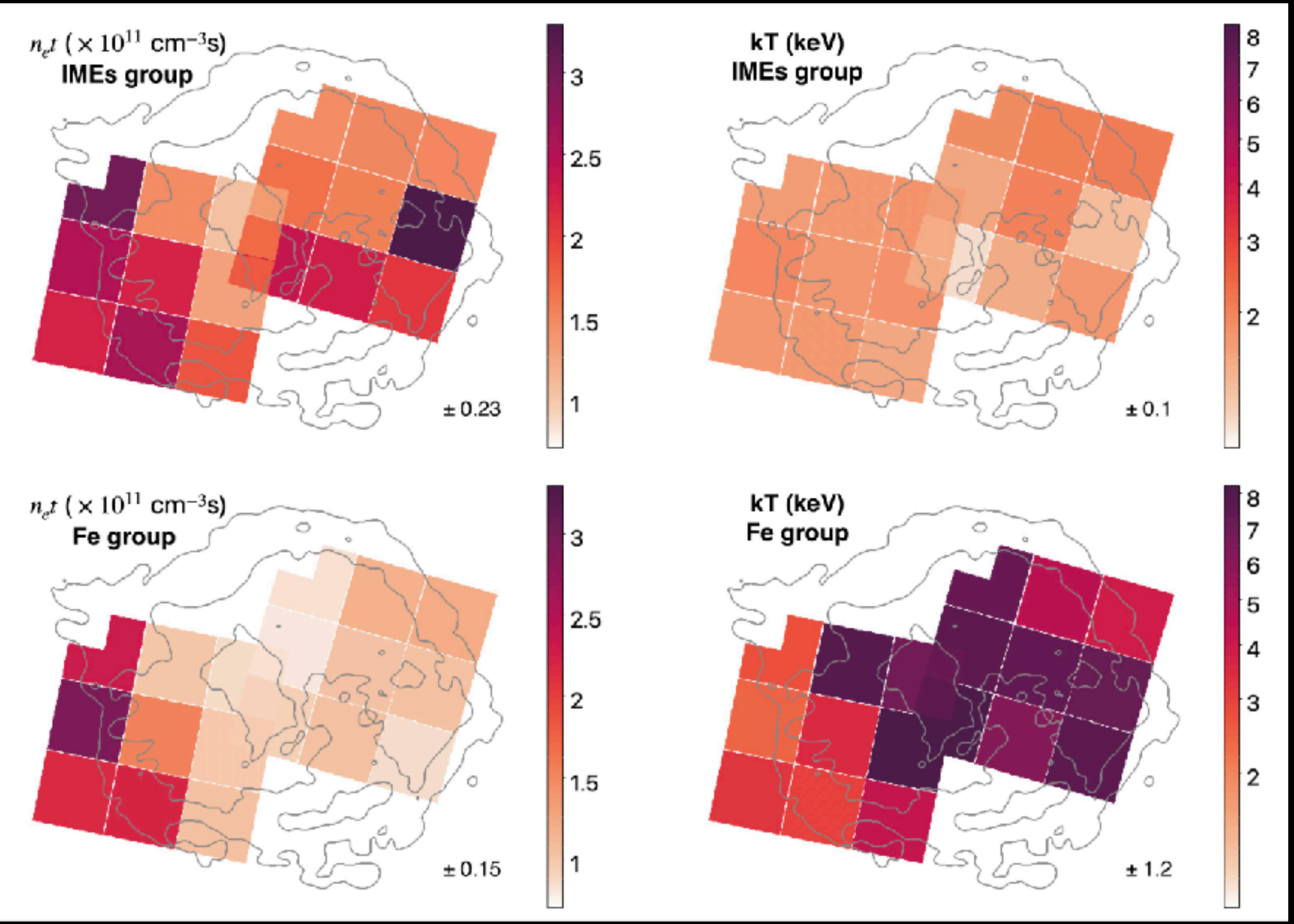


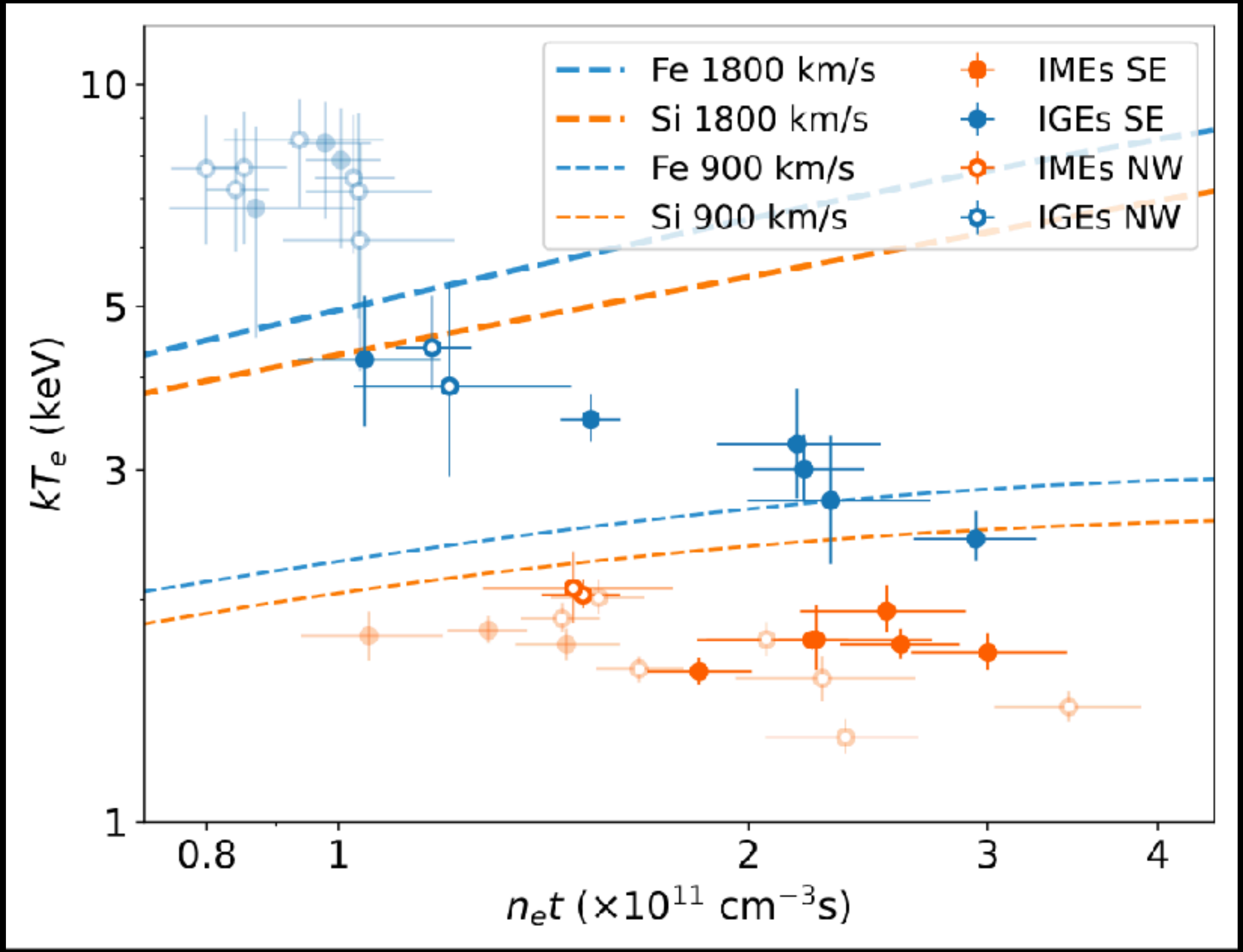
Ionisation age and electron temperature

- Characterise the thermal and ionization states of the plasma

- We find generally lower values for electron temperature than expected.
- An intriguing anti-correlation between ionisation age and electron temperature

The ejecta was shocked at a lower velocity than expected, and the n_e was higher than expected, likely due to clumping

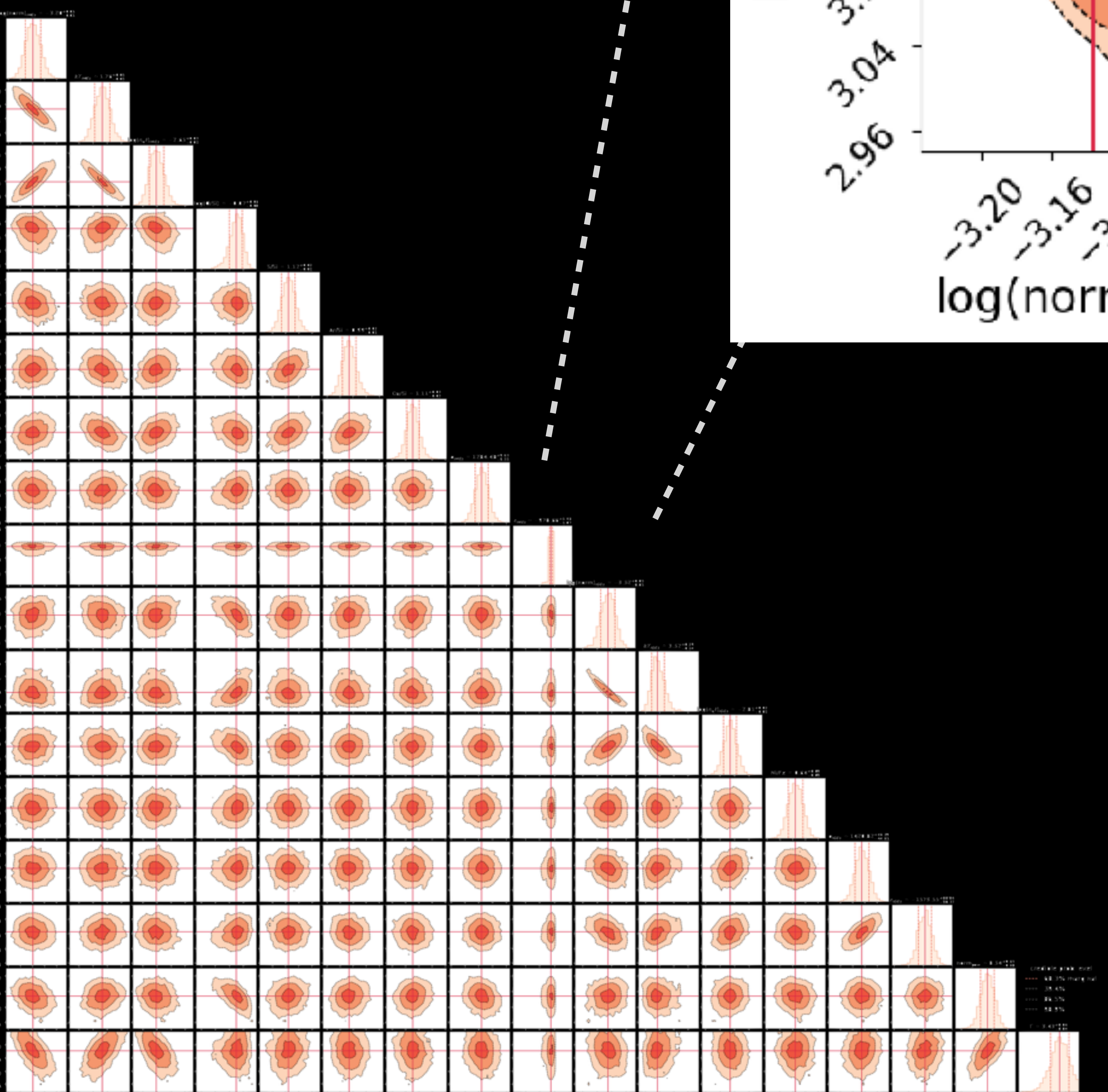


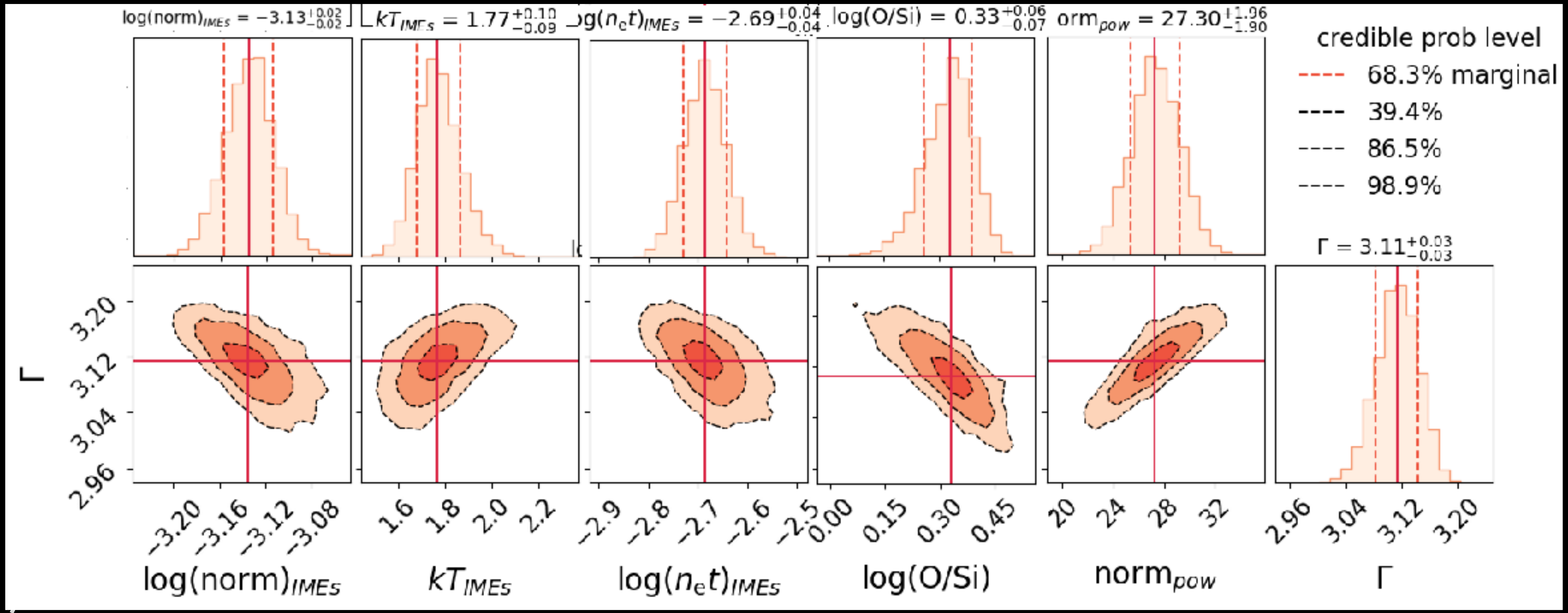


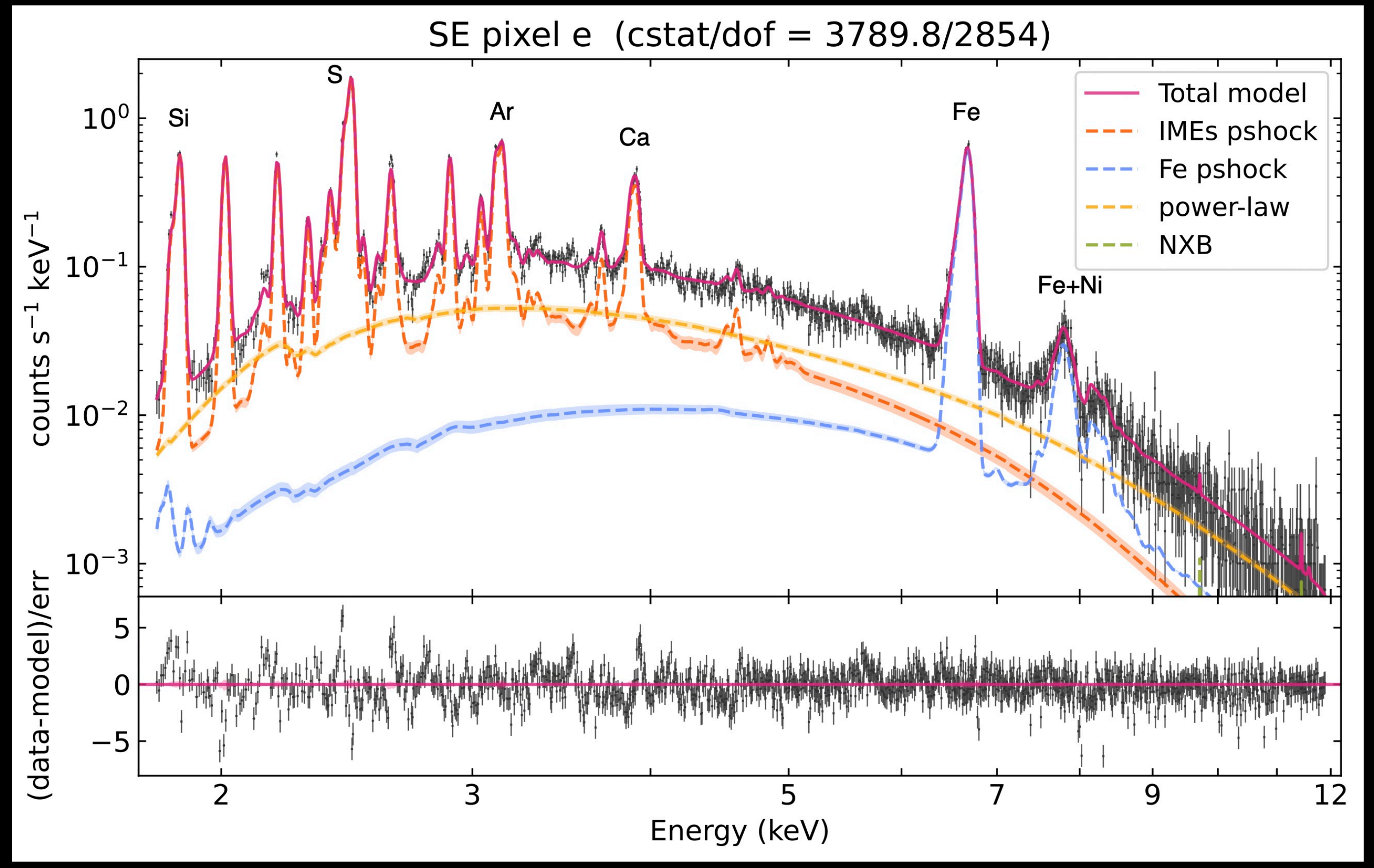
curves from Ohshiro+24

Nonthermal emission

Several parameter degeneracies



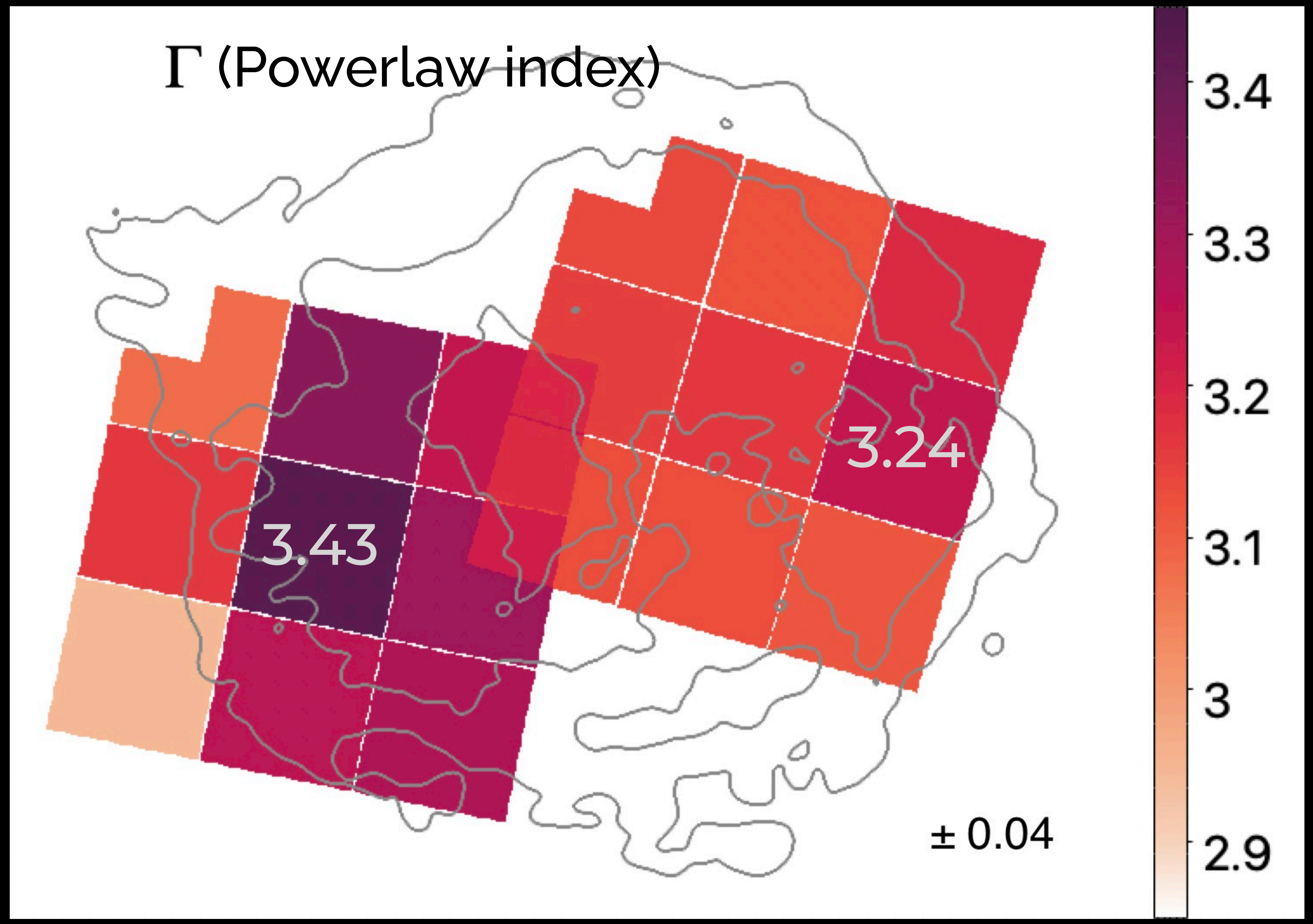


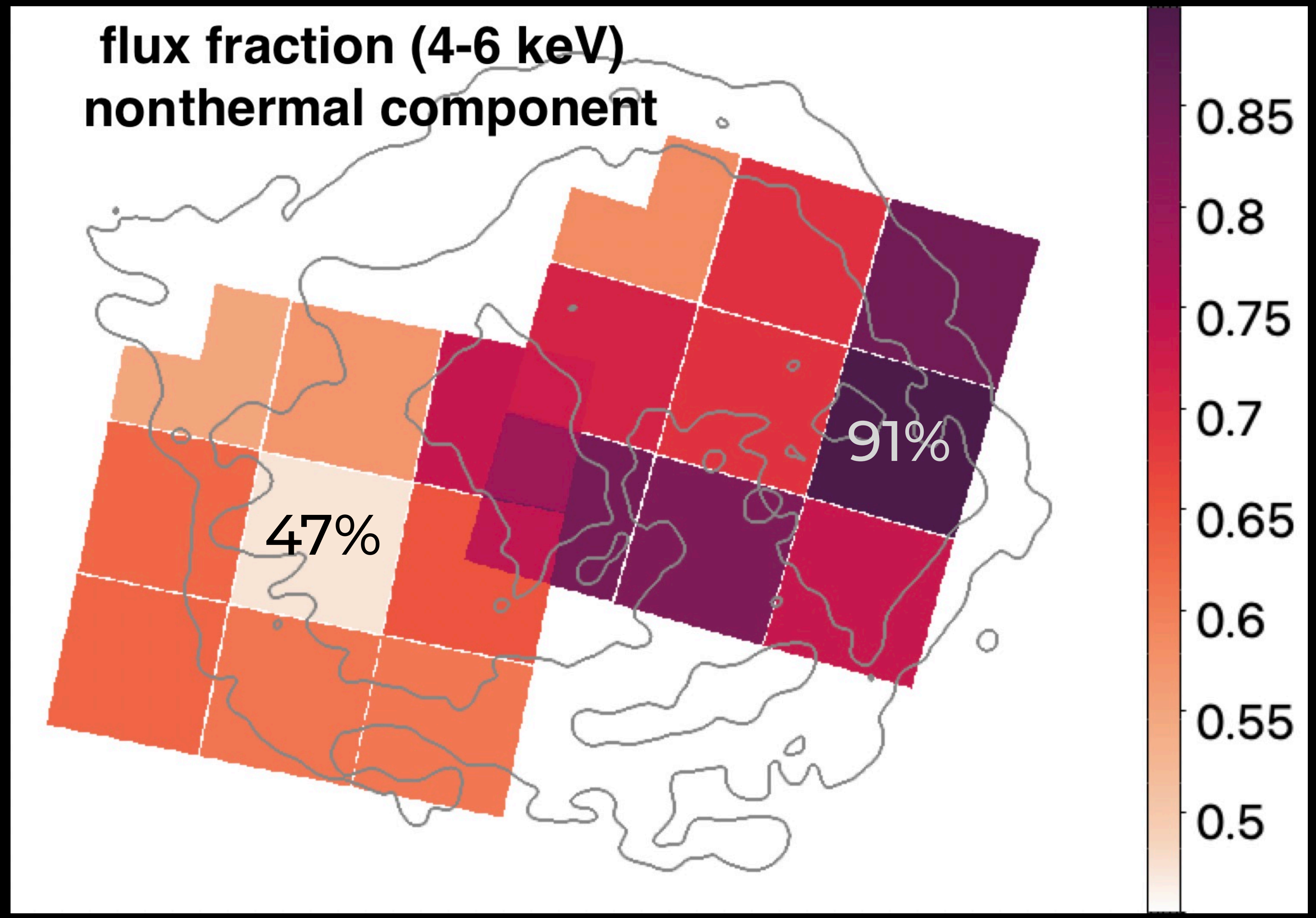


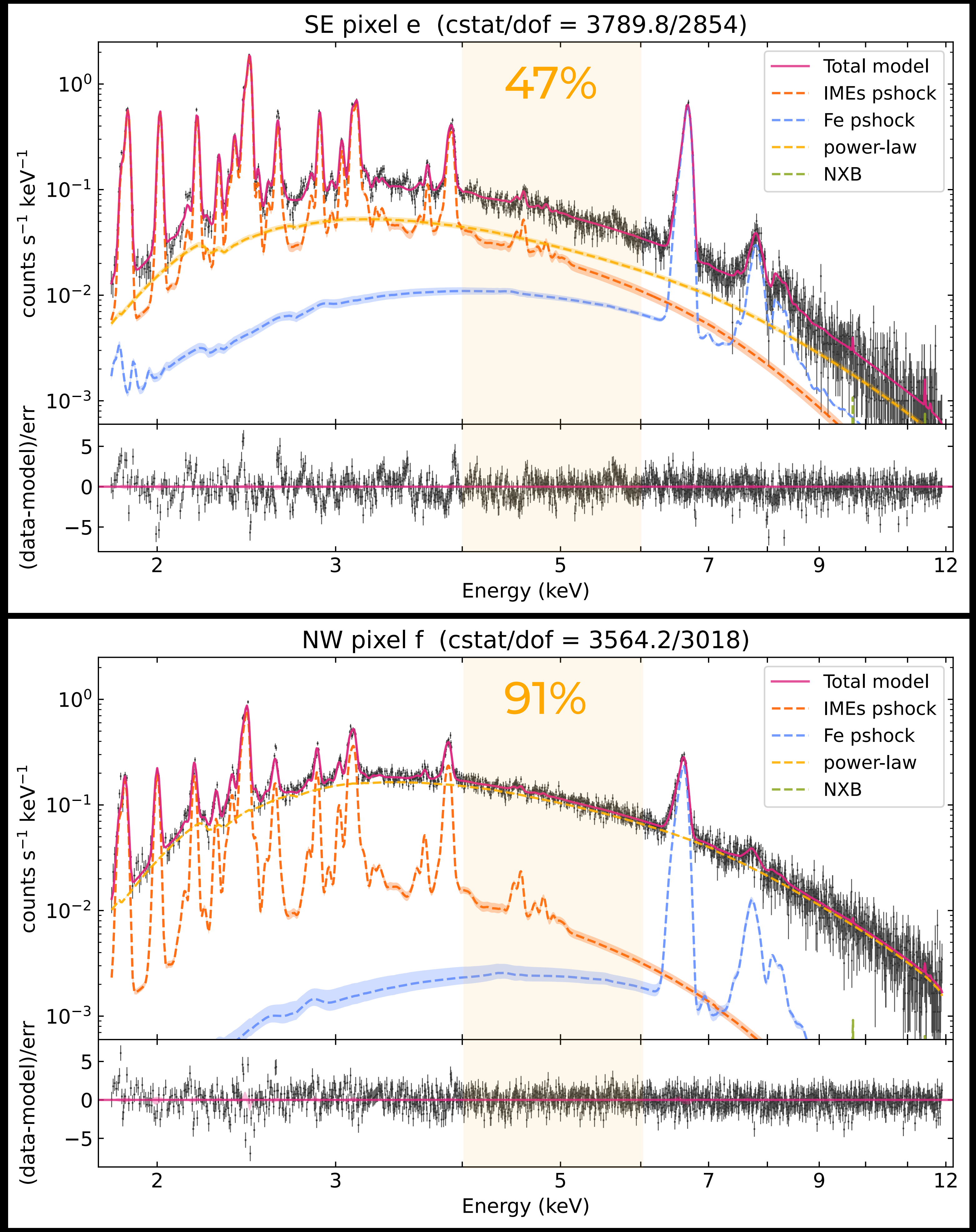
Nonthermal emission

Western regions show enhanced nonthermal emission and a harder spectrum

We find a high (**>50%**) contribution of nonthermal emission to the 4–6 keV continuum flux across the remnant







UltraSPEX

new Python tool to do Bayesian model fitting with SPEX

maximize the scientific return of your high-resolution data

- Si/S ejecta dynamics — **incomplete shell structure** - Vink J., Agarwal M.,+25
  - Most regions, either redshifted (NW) or blueshifted (SE) — match the patchy, knotty shell structure seen in optical data
  - Except in the **north,** where **both sides of the shocked ejecta shell are visible**
  - **Narrow lines (<500 km/s) in the center**, potentially shocked CSM
- Mapping plasma properties — physical modeling with UltraSPEX - Agarwal+26 (submitted)
  - **High abundance ratios** of Ar/Si, Ca/Si and Ni/Fe at the **base of the jets**
  - Fe-group faster and broader than IMEs in most regions (interesting exception with Ca)
  - Evidence for **lower-than-expected shock velocities** in the past and **highly clumpy ejecta**
  - **High (>50%) nonthermal contribution** throughout the remnant

m.agarwal@uva.nl

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