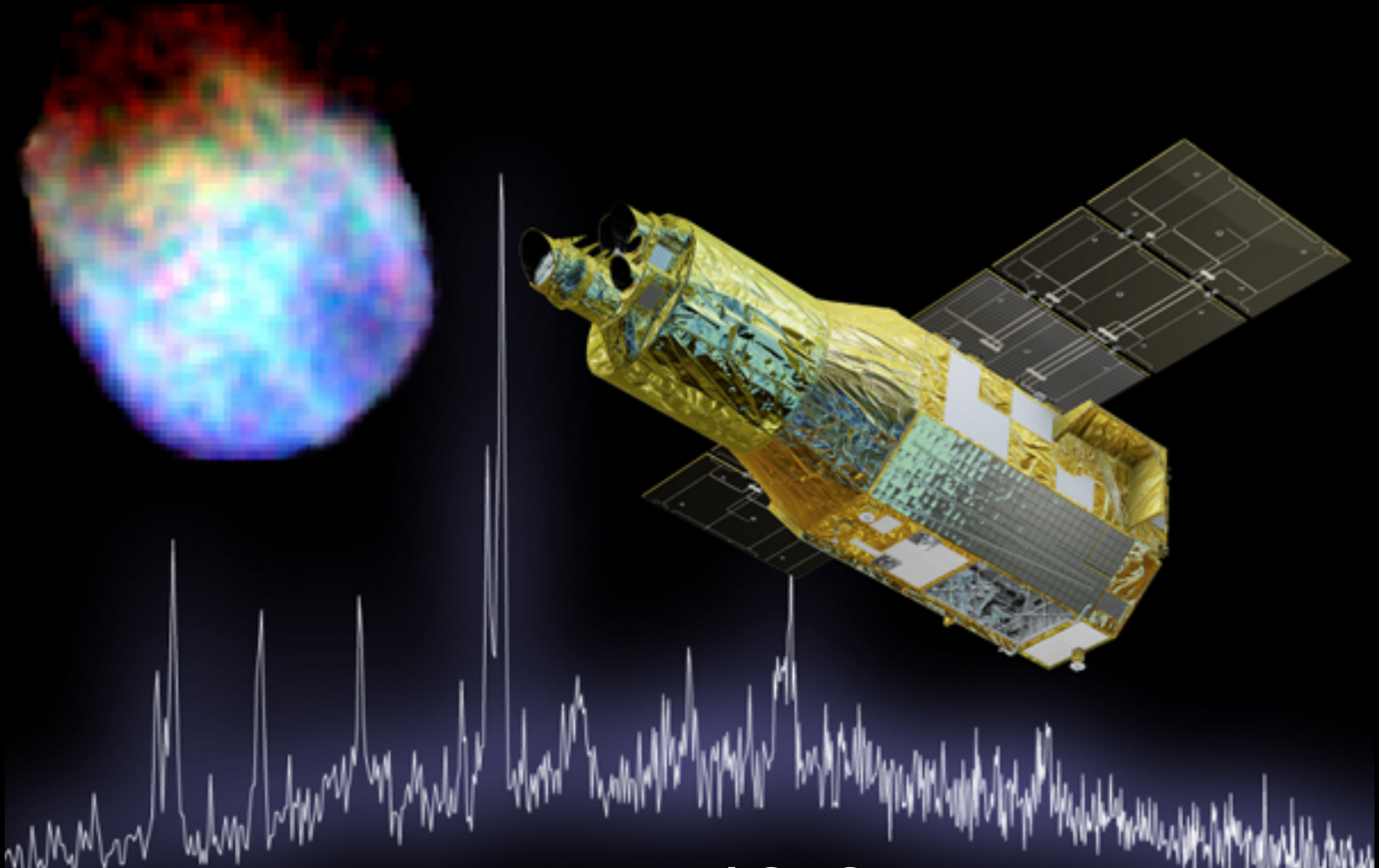
XRISM View of Supernova Remnants

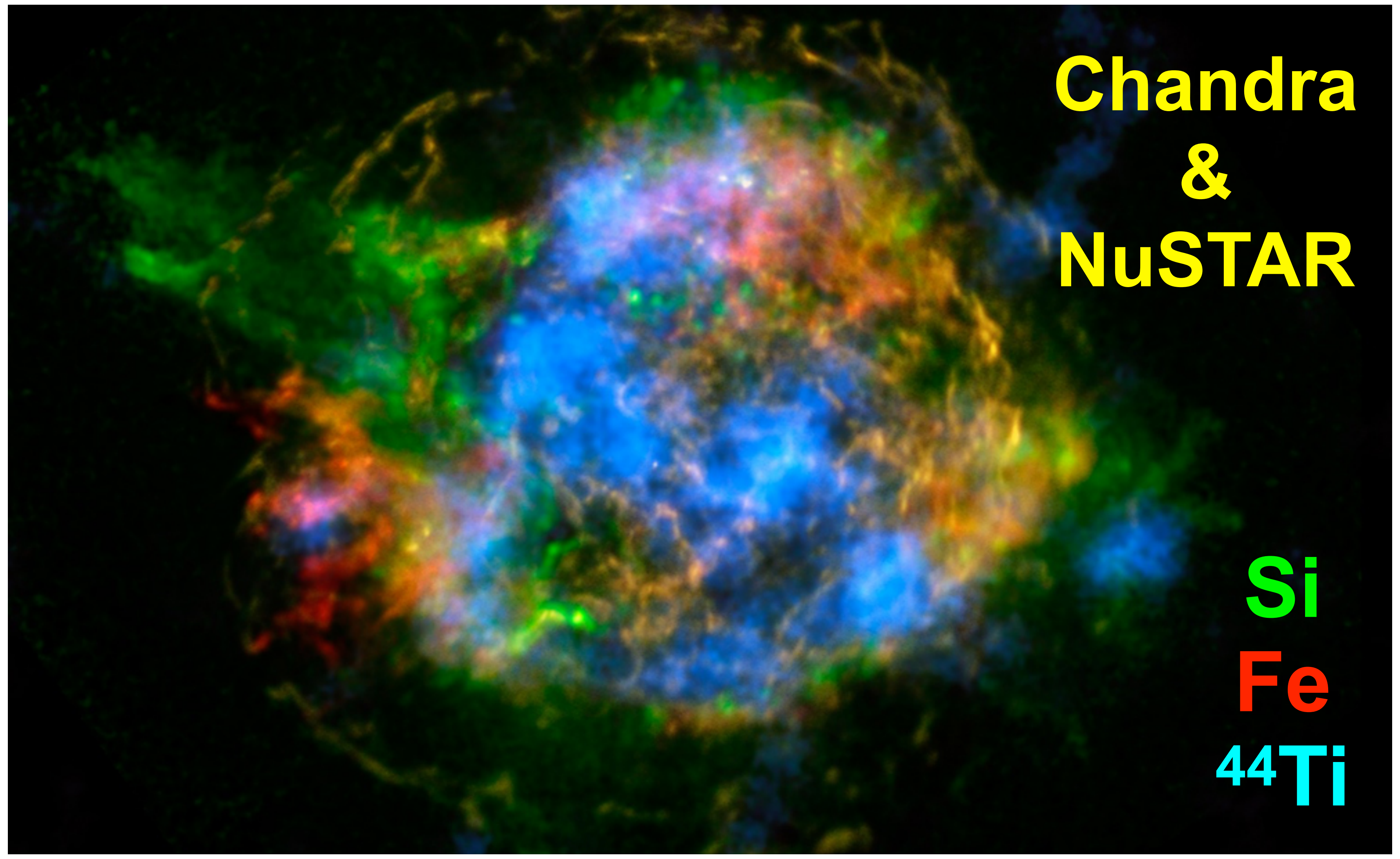


JAXA/ISAS

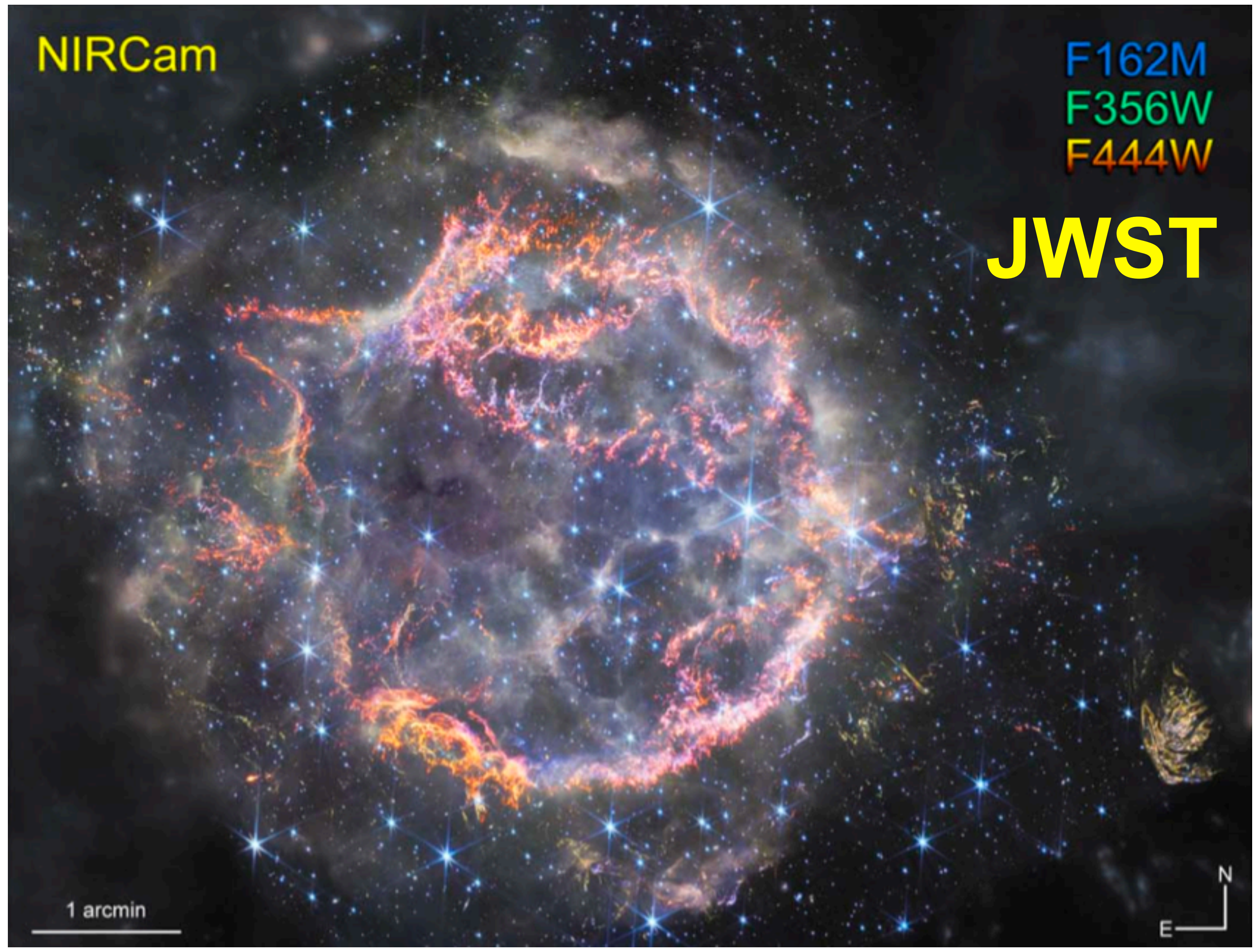
Hiroya Yamaguchi

Supernova remnants

- Shock heated gas and dust
- Interaction between freely-expanding SN ejecta and ISM forms shock waves
- Young SNRs provide us zoomed-in view of SN explosion



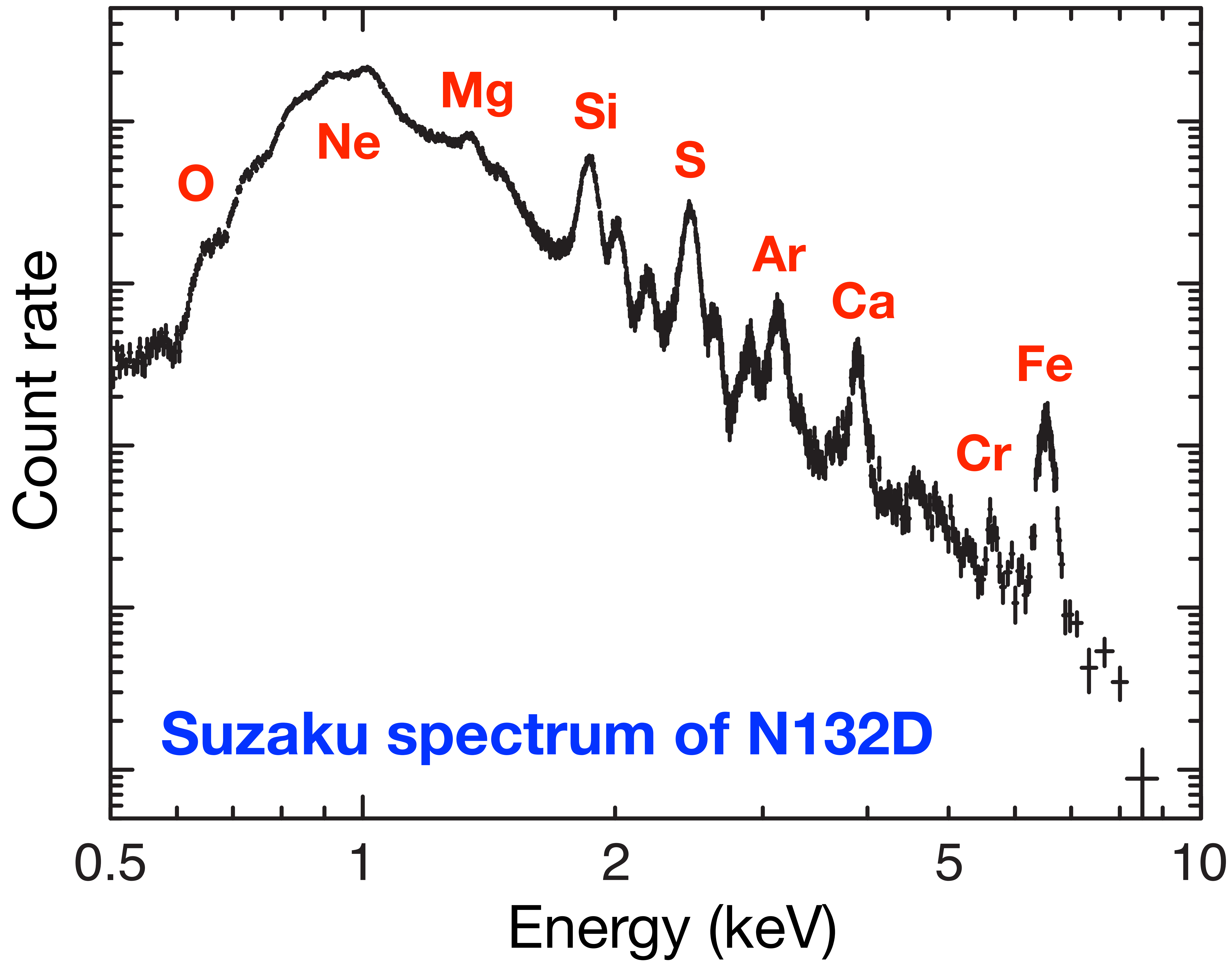
Pros
- Spatially resolved
- Optically thin (no need to solve RT)
- Long-lasting



Cons
- Statistics limited

Suitable for in-depth study of well-known objects

X-ray spectrum of SNRs



Simple!

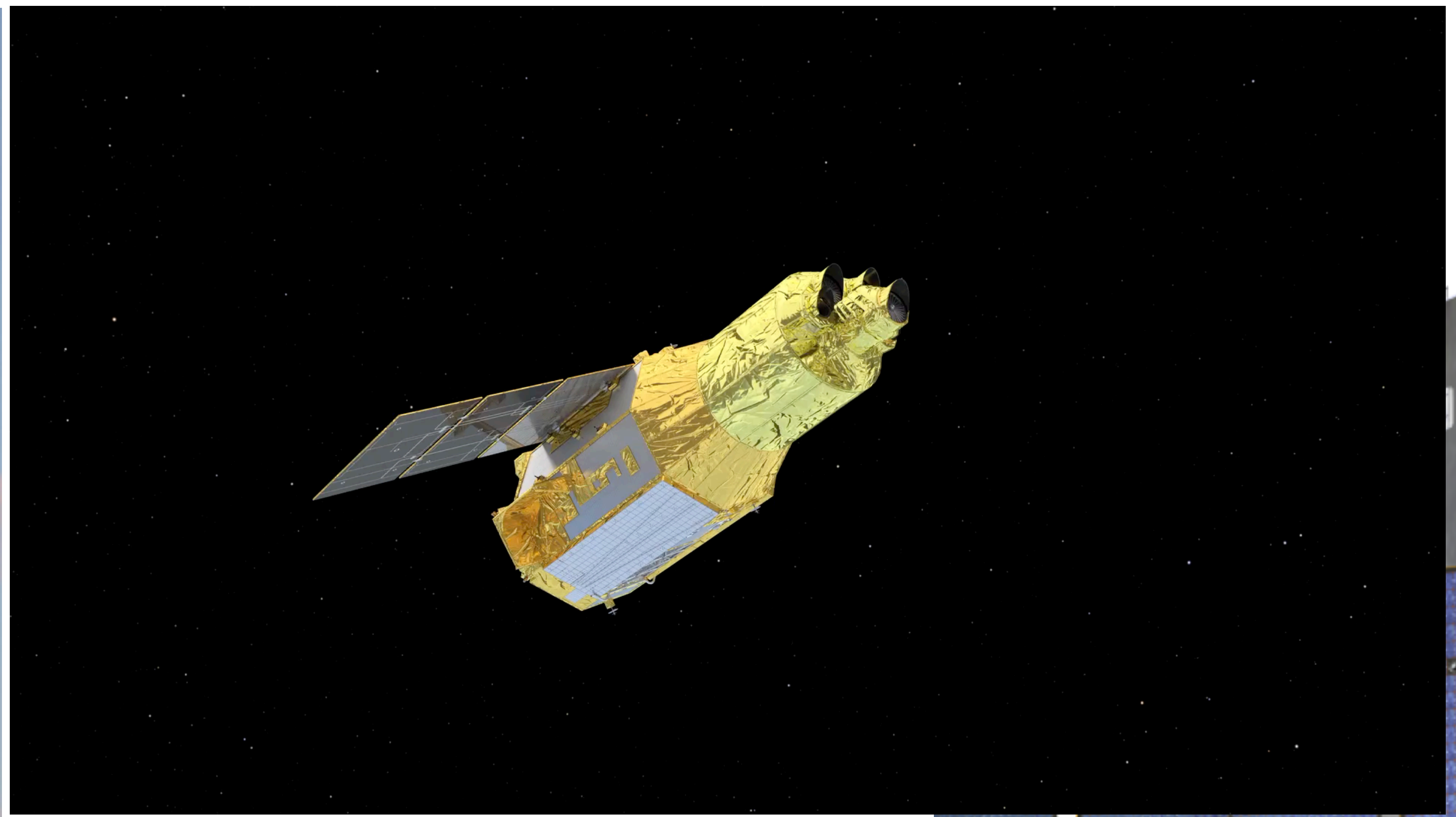
K-shell emission from (mostly) He-like and H-like ions, in order of atomic number

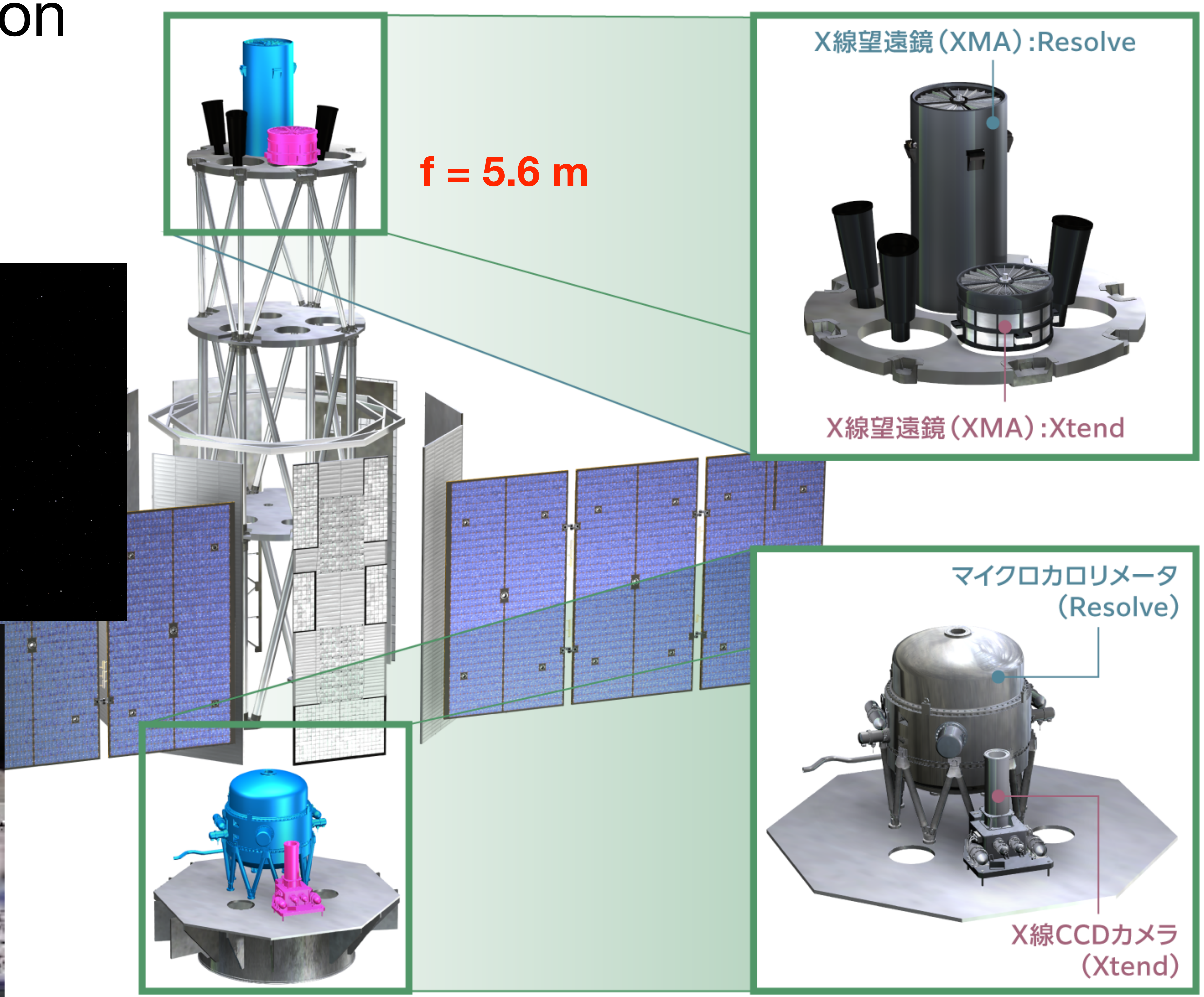
Abundance measurement relatively straightforward

Thermal properties (temperature, ionization degree) reflect SNR's dynamics

X-Ray Imaging and Spectroscopy Mission (XRISM)

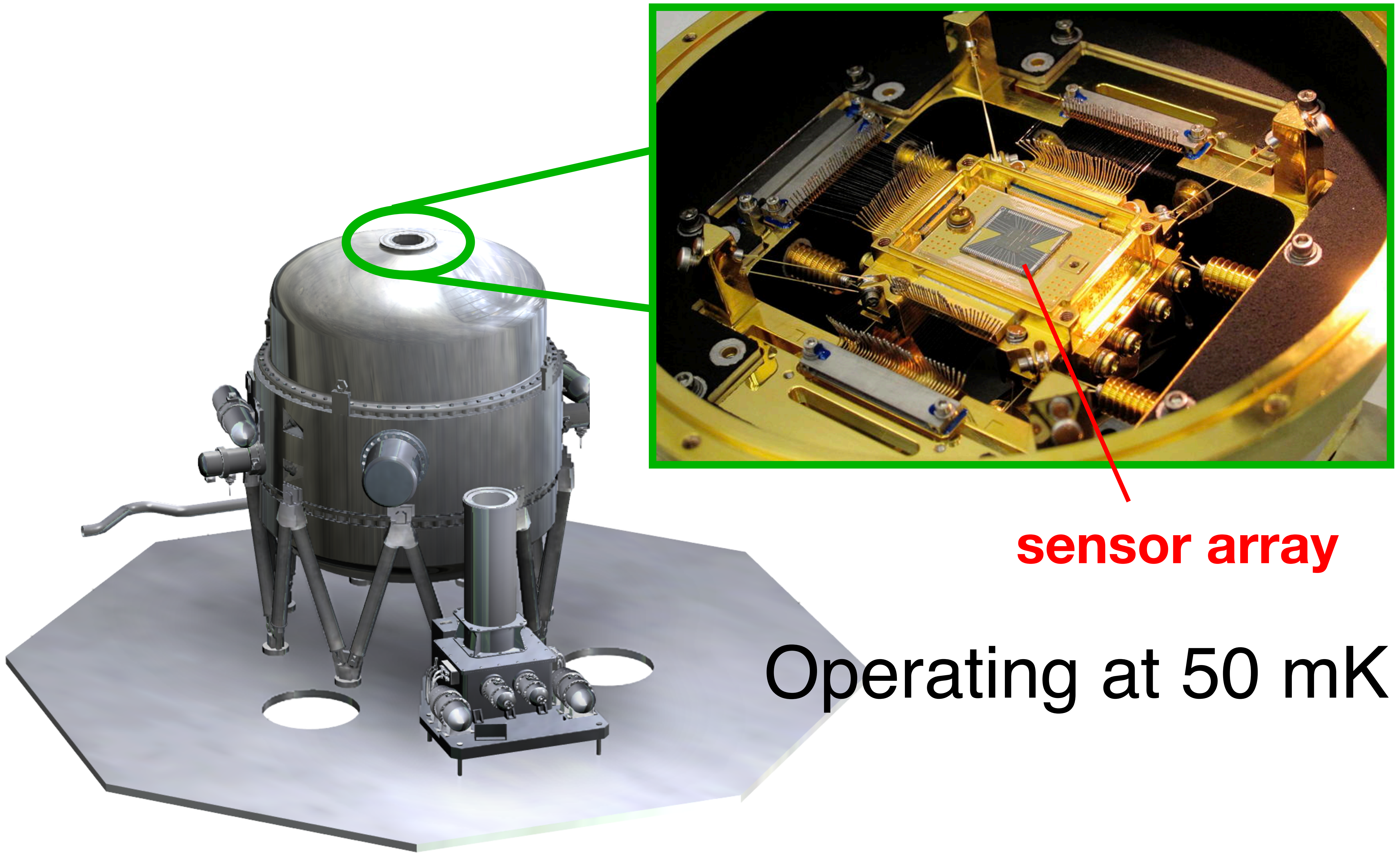
- International collaborative mission developed by JAXA and NASA
- Launched on Sep 7, 2023





Instruments on board XRISM

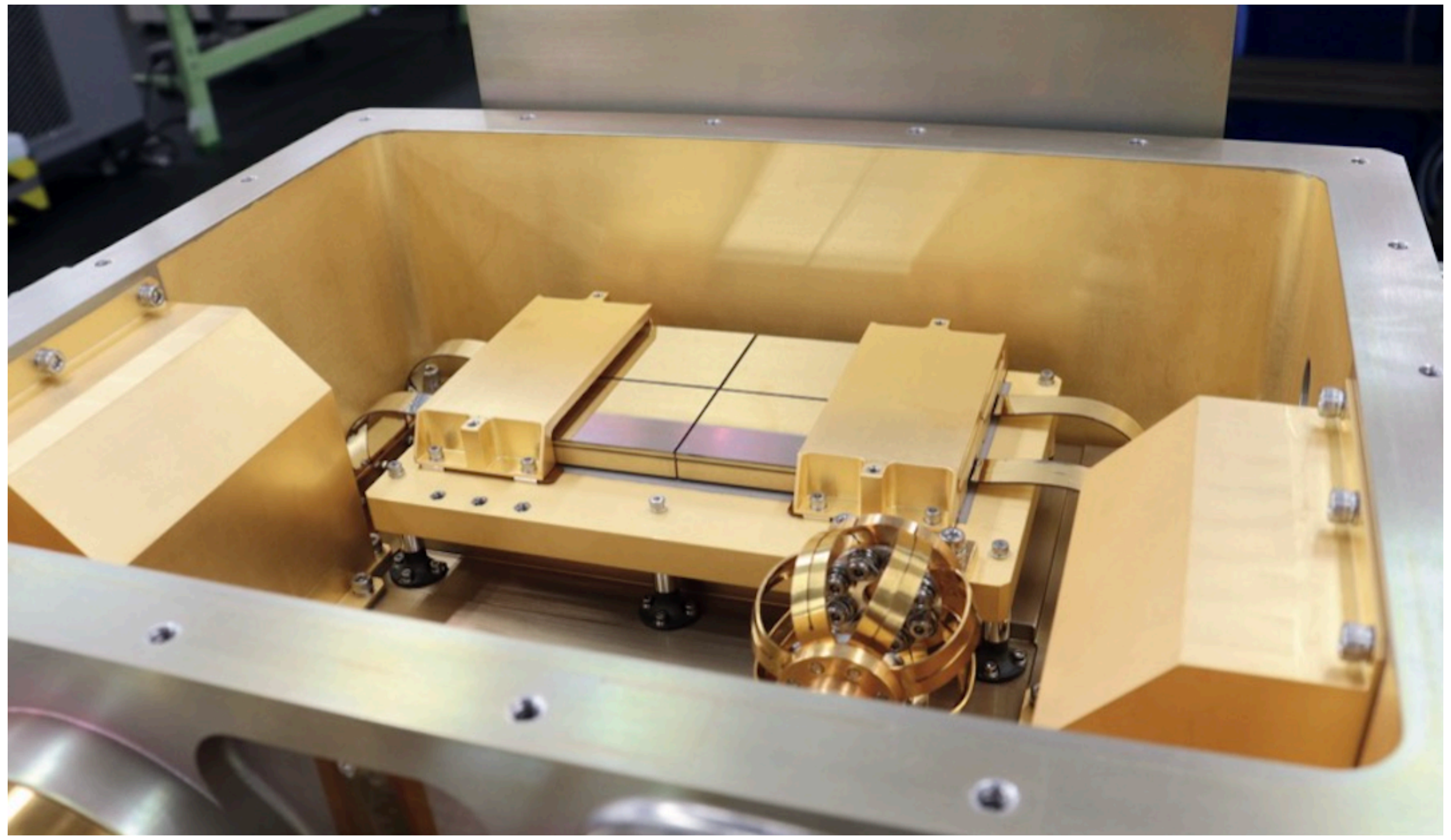
Resolve (X-ray microcalorimeter)



Operating at 50 mK

High spectral resolution
~5 eV @2-10 keV

Xtend (X-ray CCD)

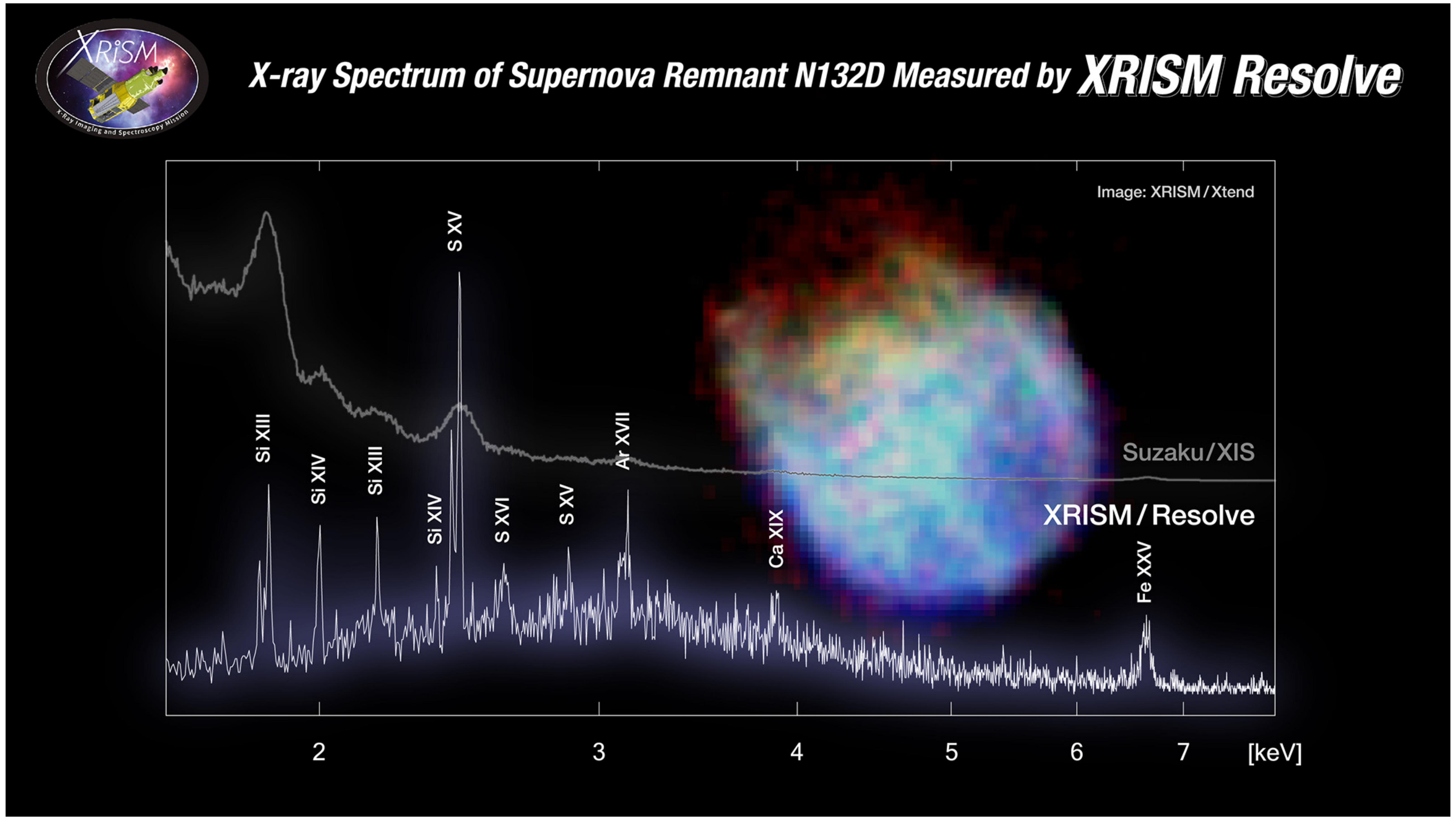


Wide field of view
38' x 38' (> full moon)

cf. Resolve's FoV: 3' x 3'

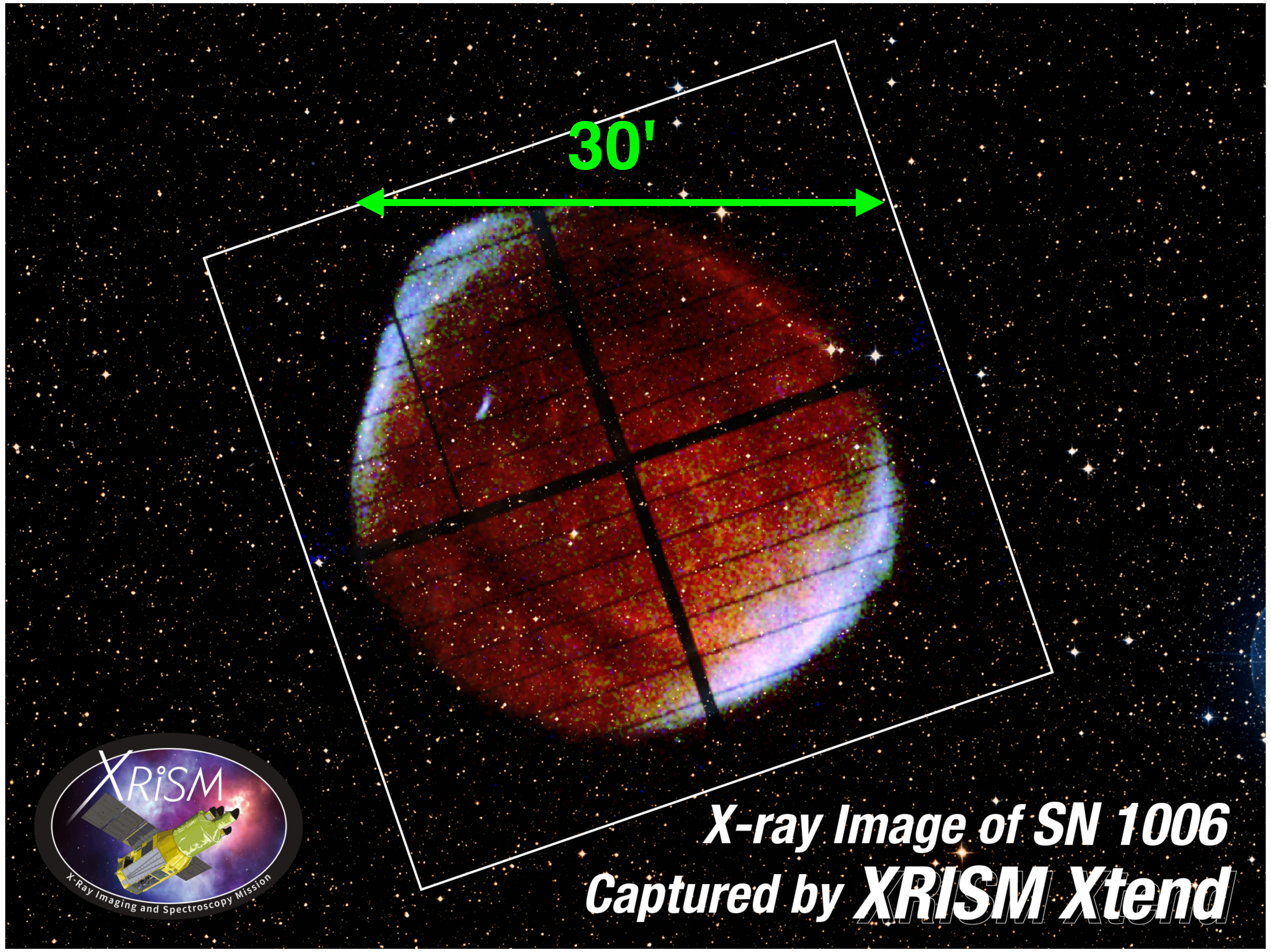
Performance demonstration

Resolve (X-ray microcalorimeter)



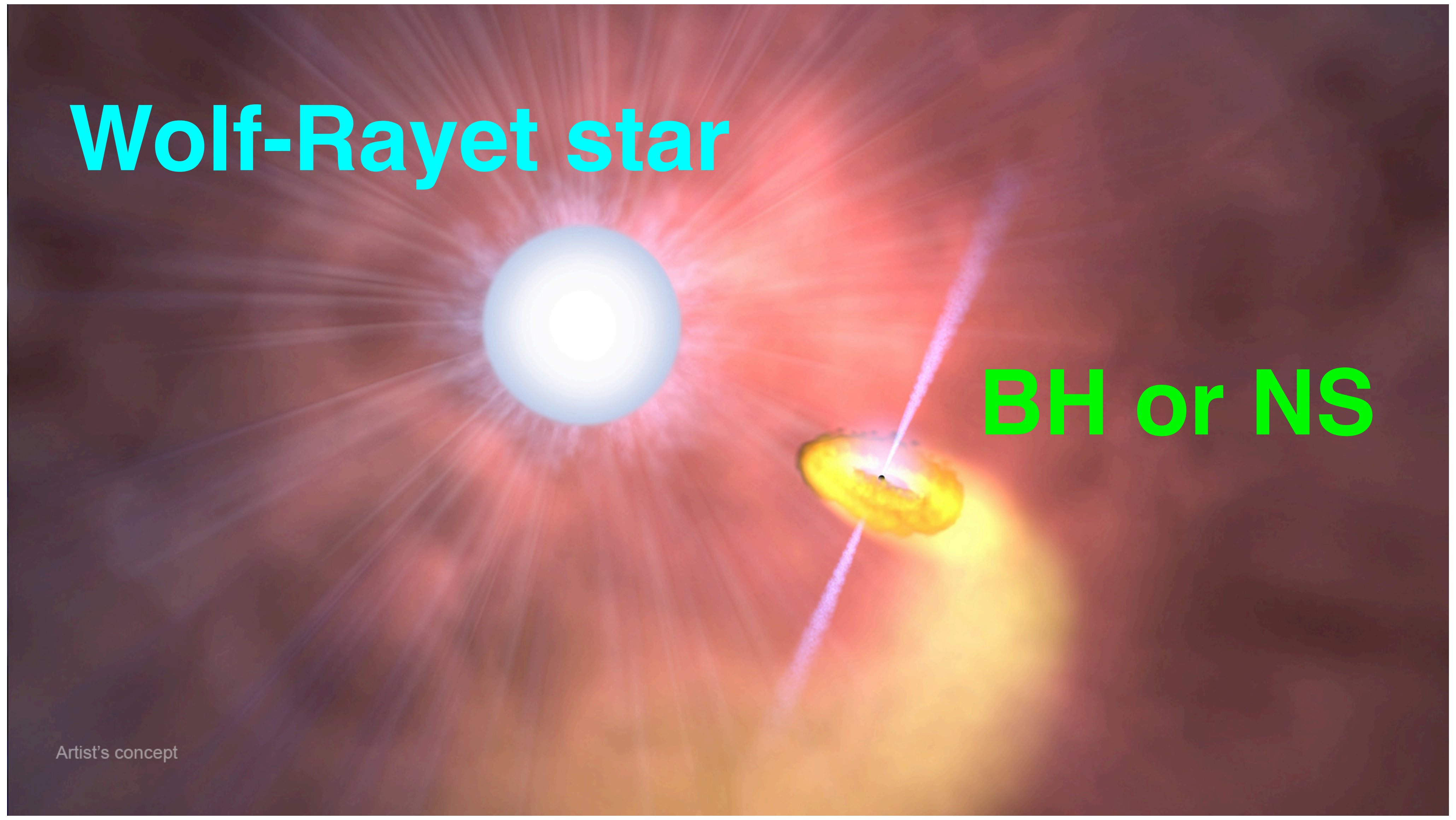
- Different quantum transitions resolved
- Good for measurements of abundances, velocity, and thermal properties of plasma

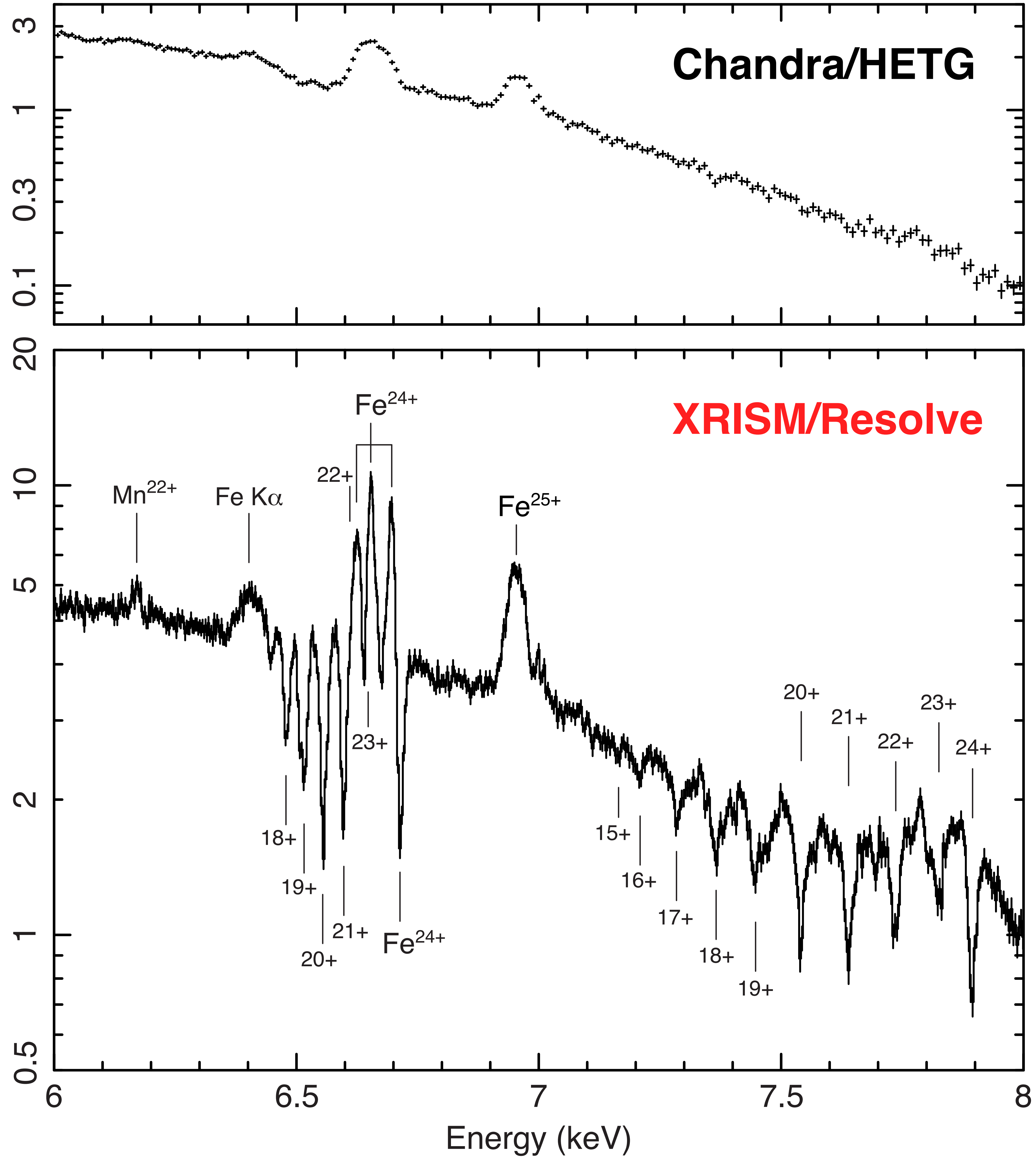
Xtend (X-ray CCD)



Performance demonstration

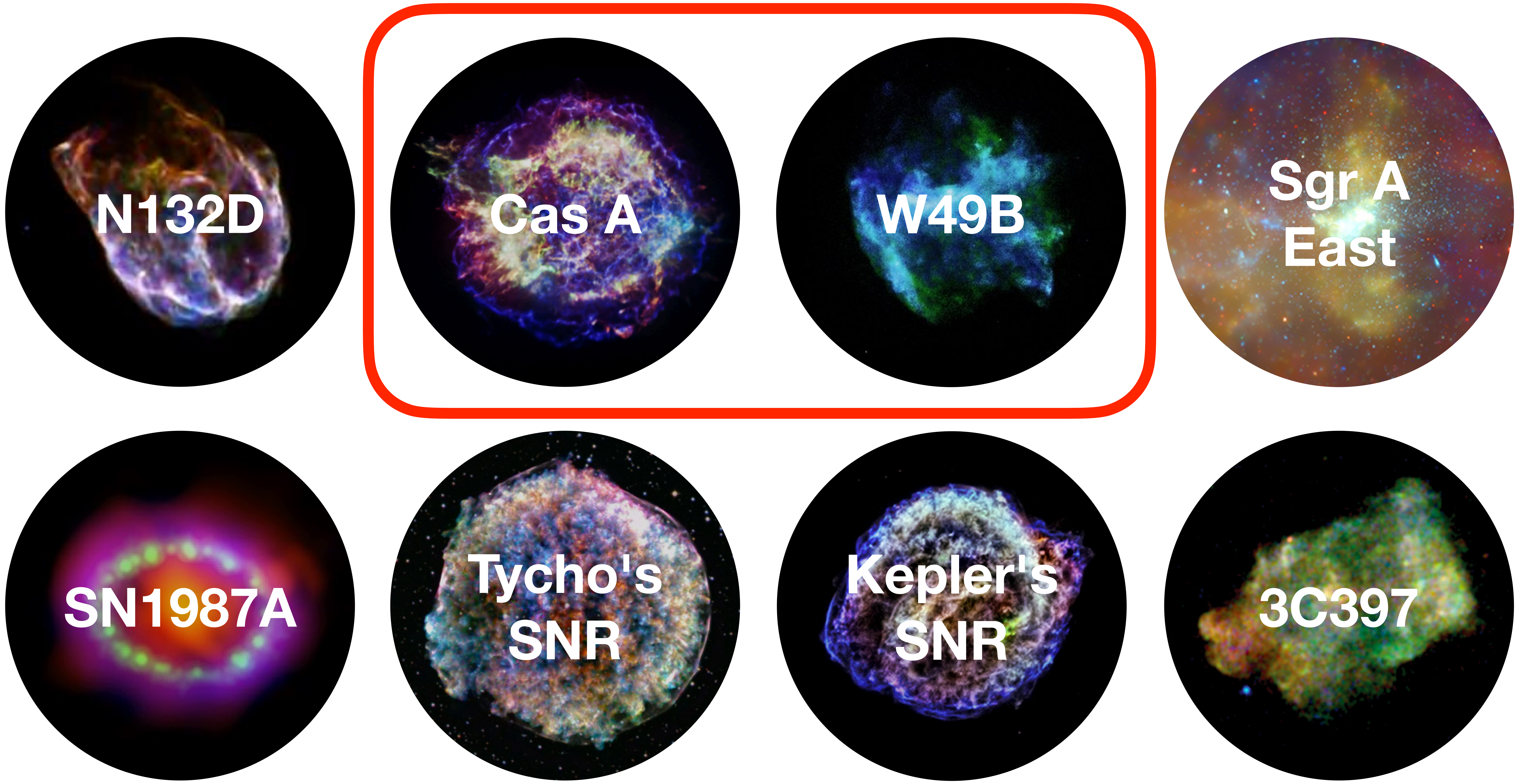
- Cygnus X-3, photon-ionized plasma surrounding an X-ray binary consisting of a WR star and compact object (BH or NS).
- Emission and absorption lines of Fe ions in various charge states resolved.



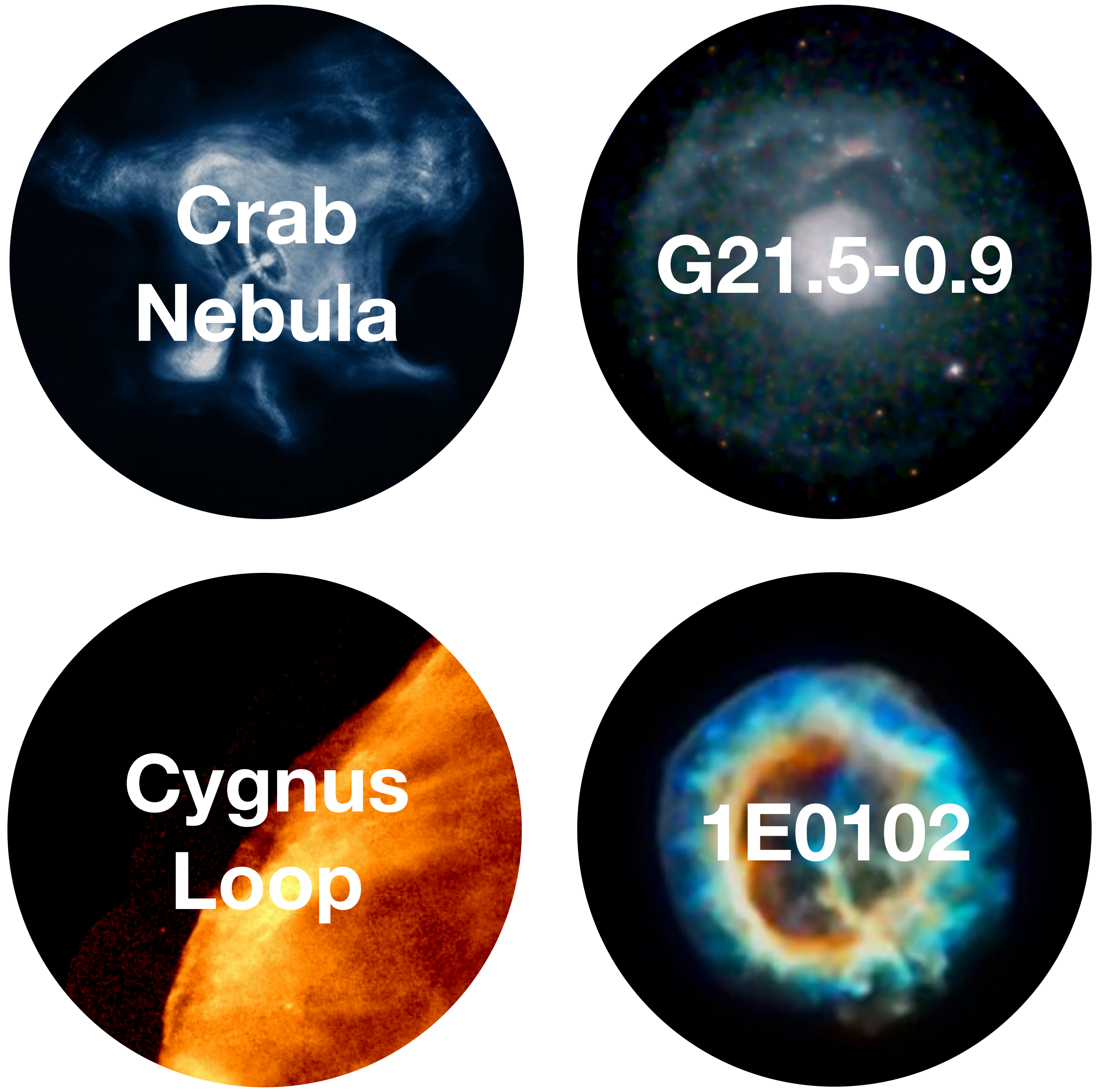


XRISM observations of SNRs

Observed for performance verification

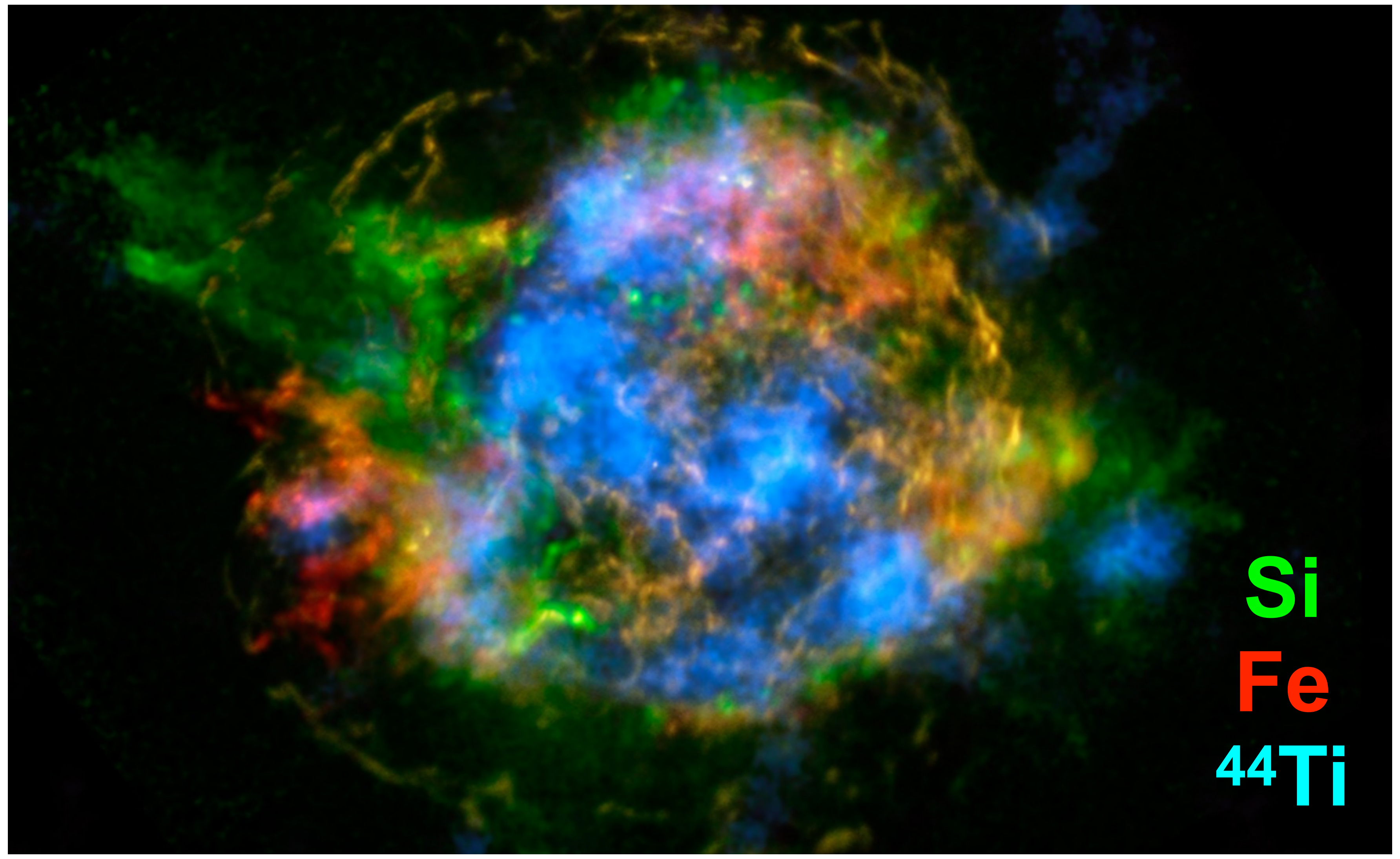


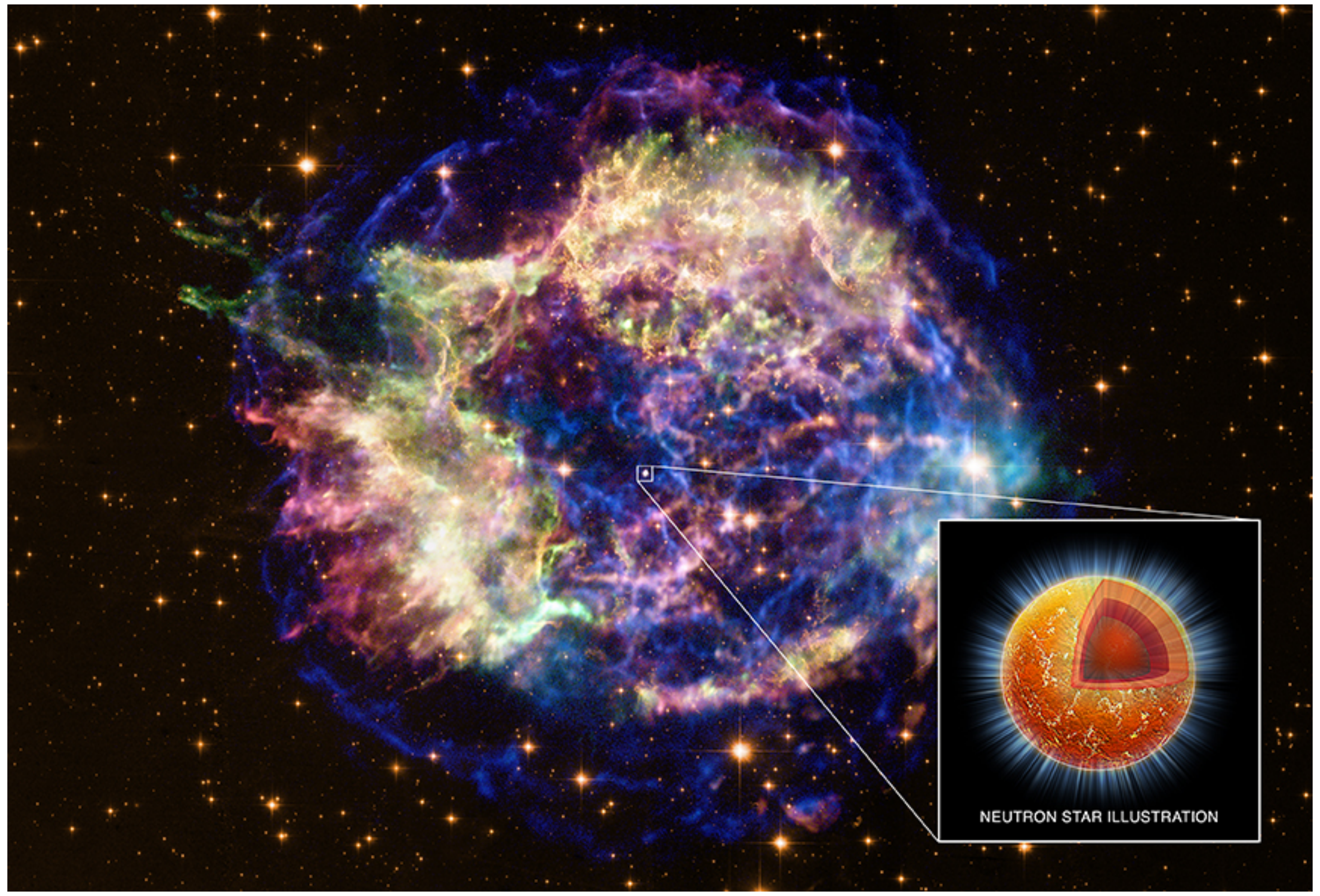
for calibration



Focusing on Cas A and W49B (two brightest SNRs) in this talk

Cas A



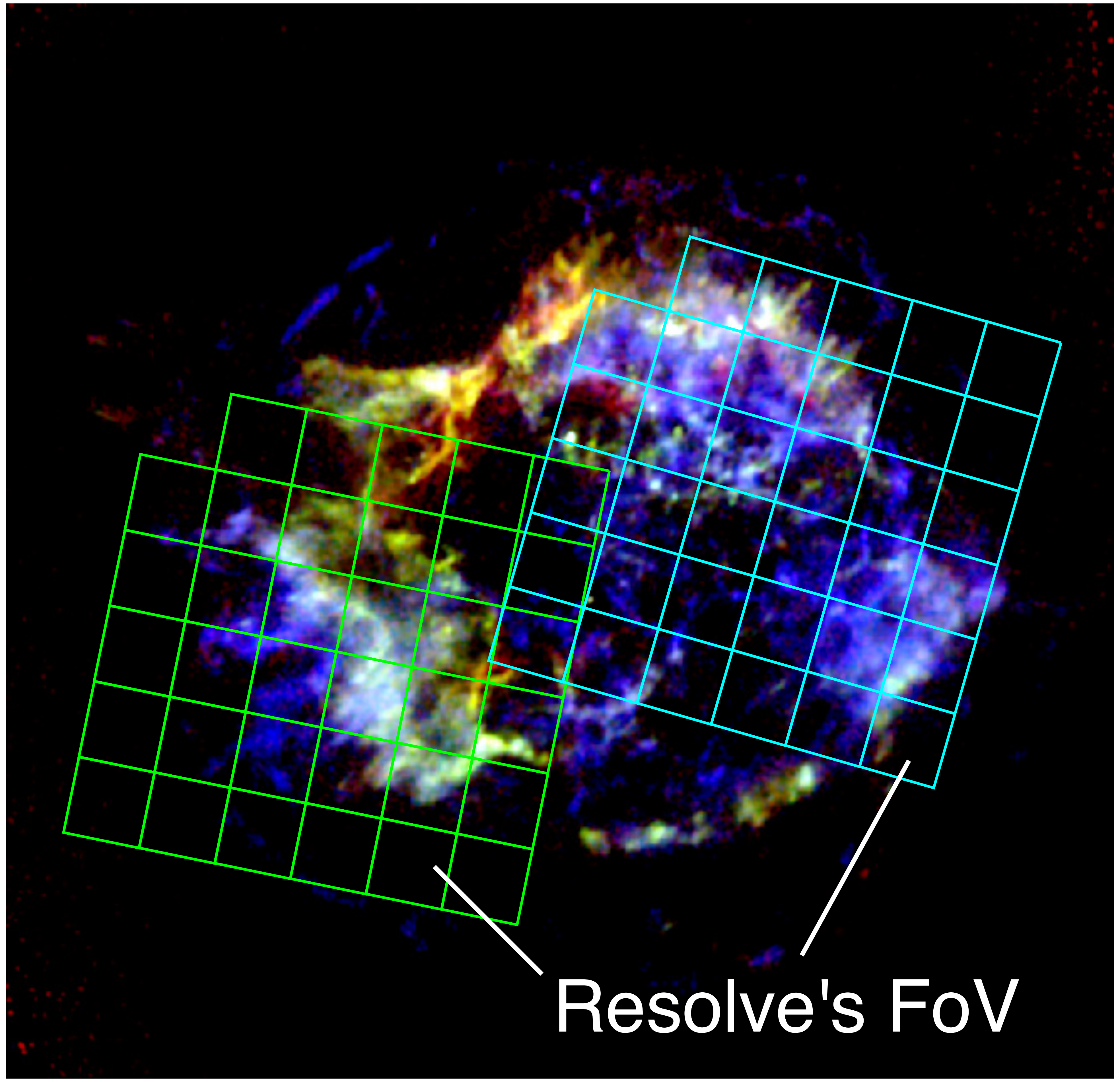


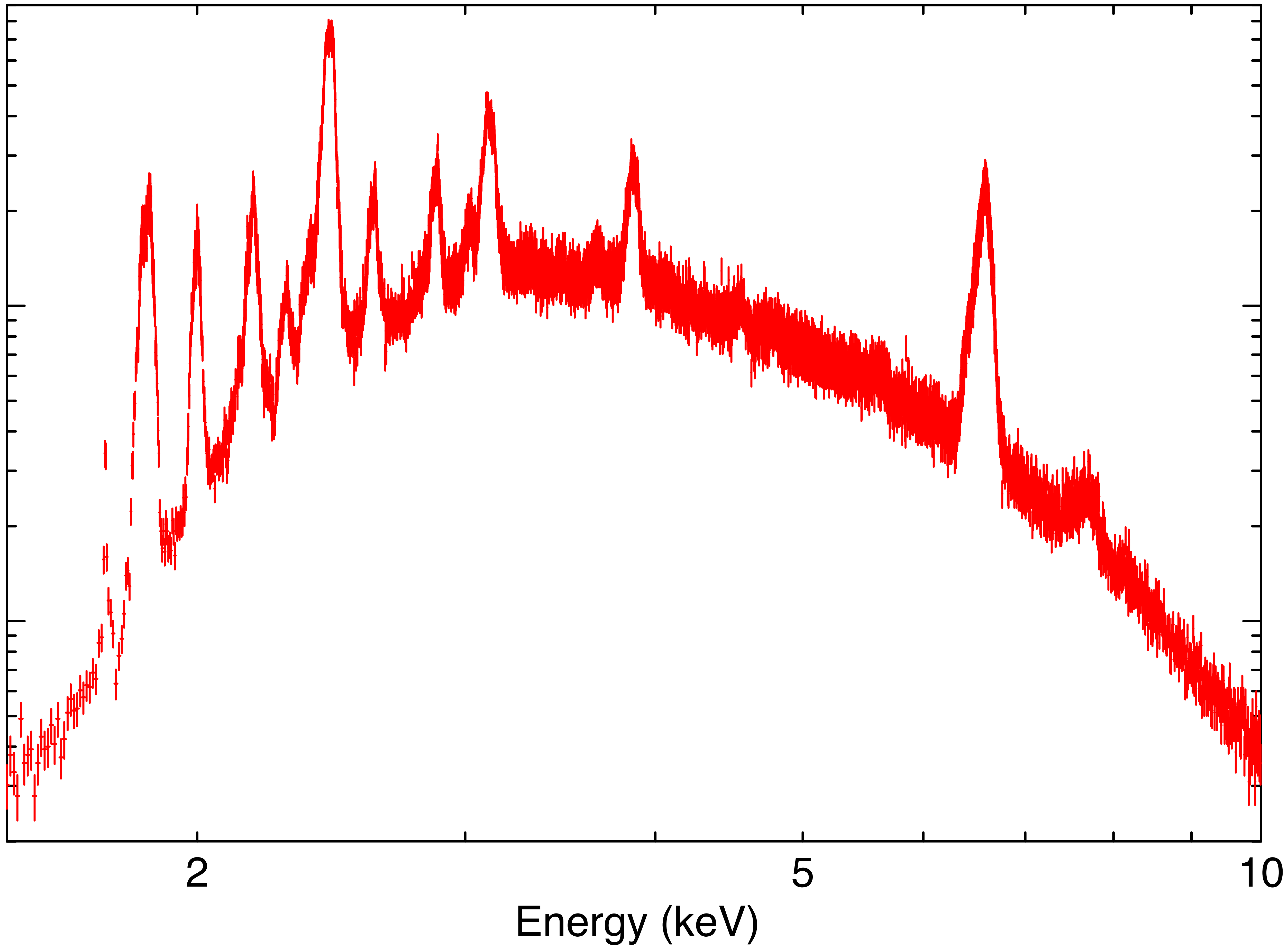
- Type IIb SN of ~350 yrs ago
  - Hydrogen envelope largely stripped
- $M_{ZAMS} \sim 15M_{\odot}$
  (Fesen+2006; Young+2006)
- Highly asymmetric ejecta distribution
  (e.g., Hwang+2004)
- ^{44}Ti yield of $1.3 \times 10^{-4} M_{\odot}$
  (e.g., Grefenstette+2014)
- NS moving toward south, opposite to the direction of the ^{44}Ti ejection
  (e.g., DeLaney+2013)

Ideal for studying SN CC mechanism

XRISM observations of Cas A

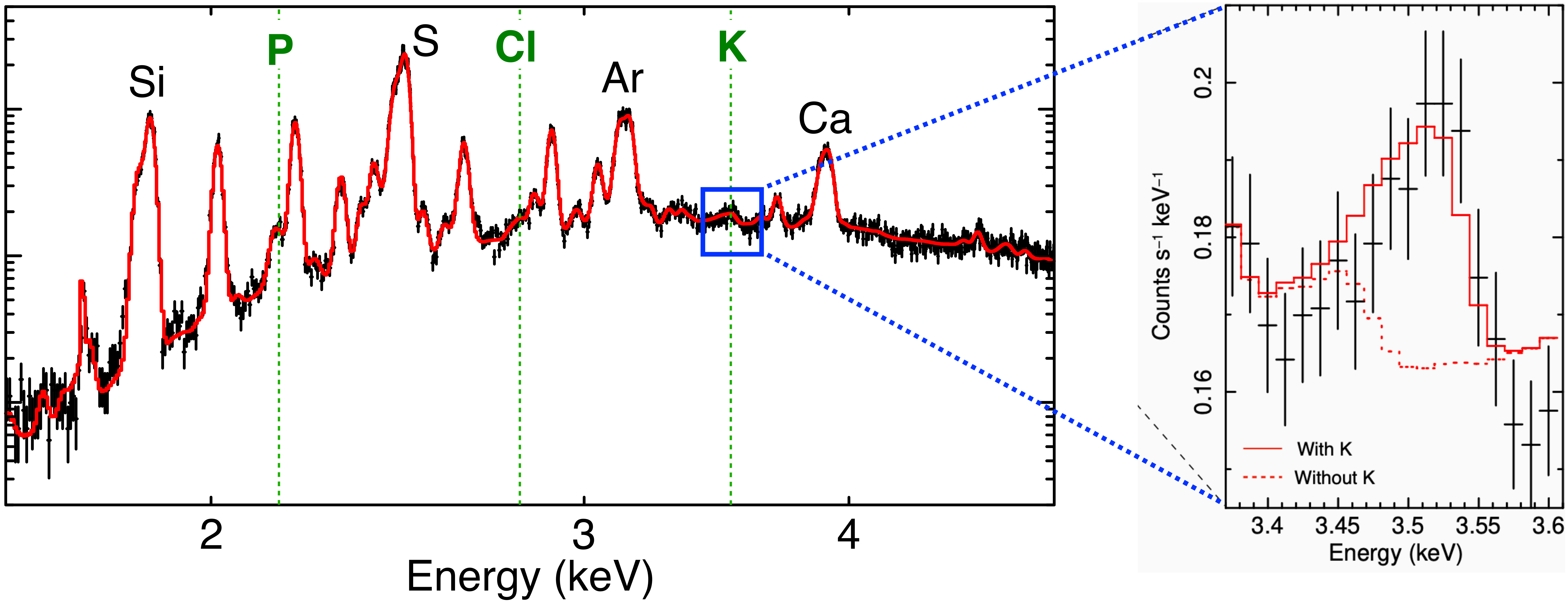
Two X-ray bright rims observed with deep exposure





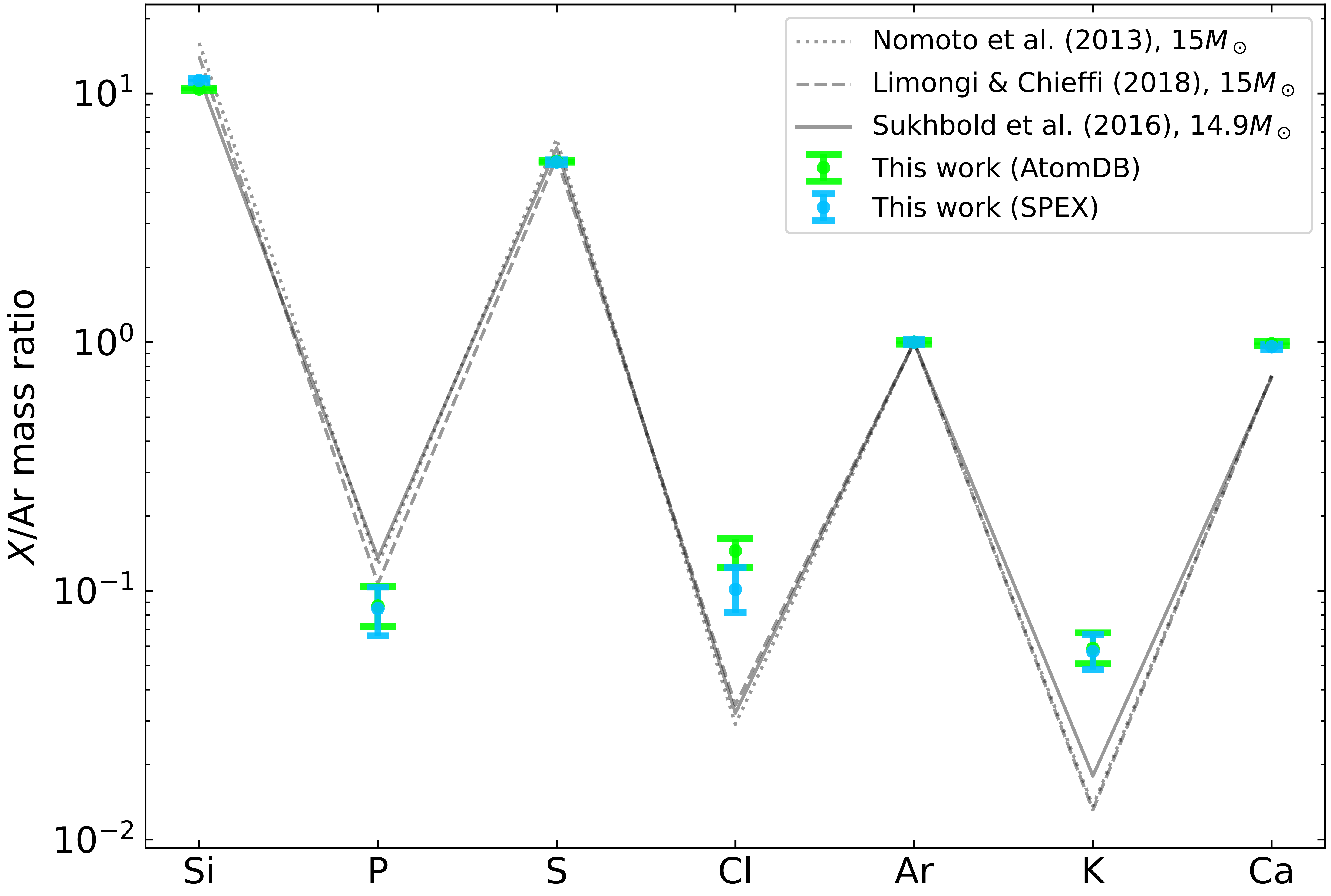
Detection of low-abundance elements

(This work is led by T. Sato, K. Matsunaga, and H. Uchida)



Emission lines of P, Cl, and K detected, enabling measurement of their abundances for the first time.

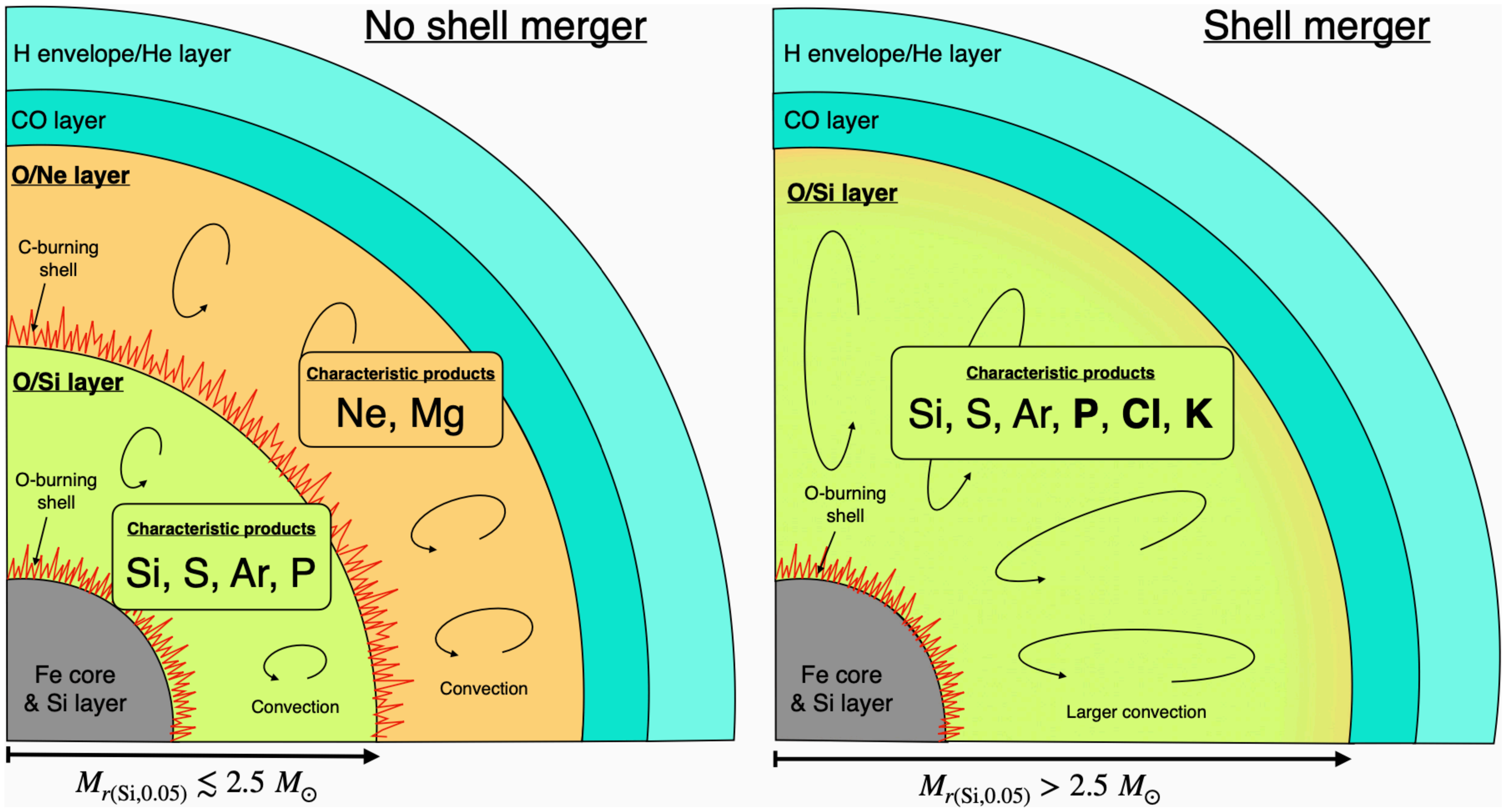
Measured mass ratio



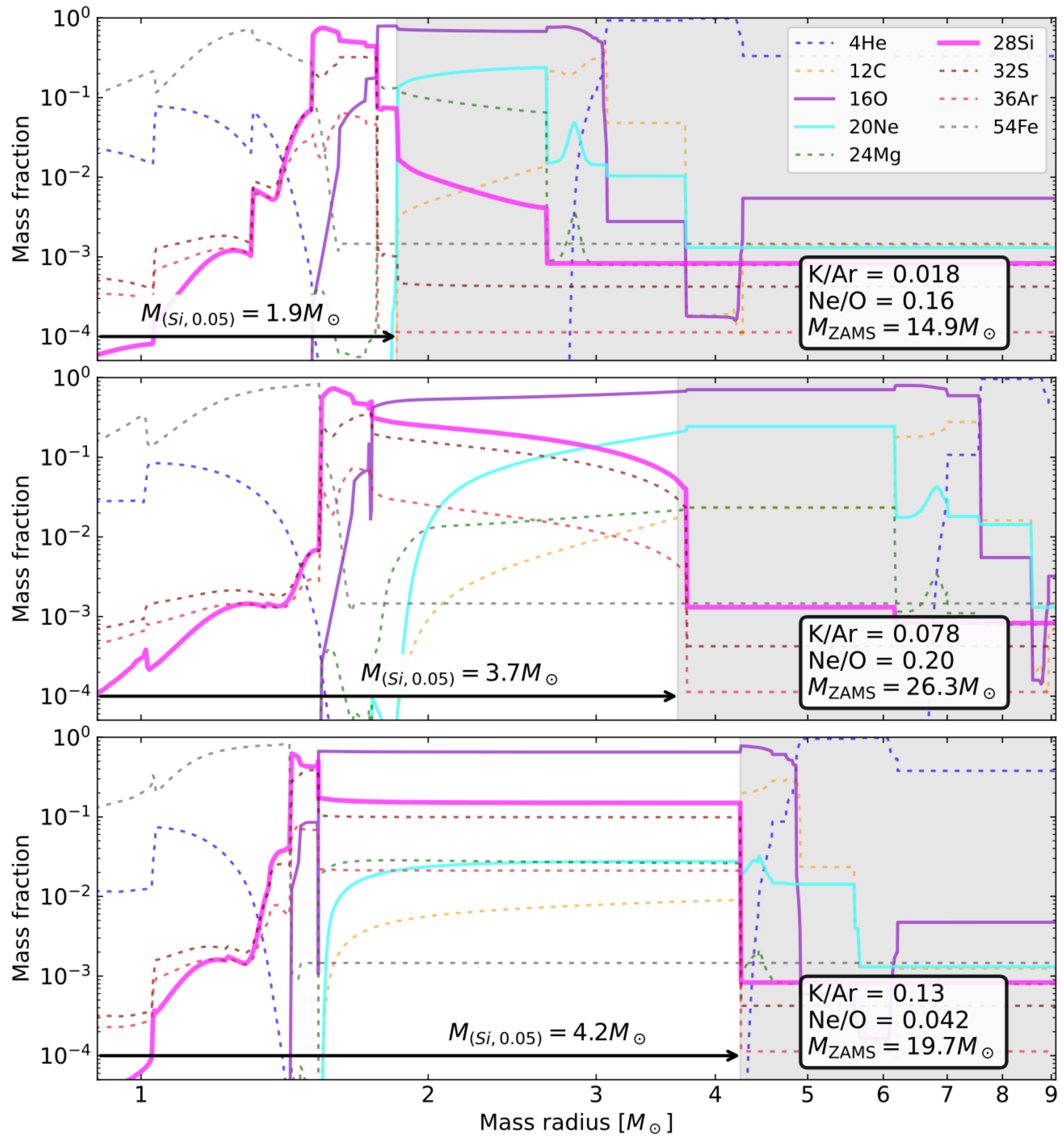
- K/Ar ~ 1 solar
- Higher than predictions of typical CC SN models

Possible interpretation

- Efficient production of P, Cl, and K took place due to merger of C-burning and O-burning shells before explosion
- Ne is burnt by this process. In fact, low Ne/O ratio observed in this SNR (Vink+1996)
- See Kai Matsunaga's poster for more details.



(Sukhbold+2016)



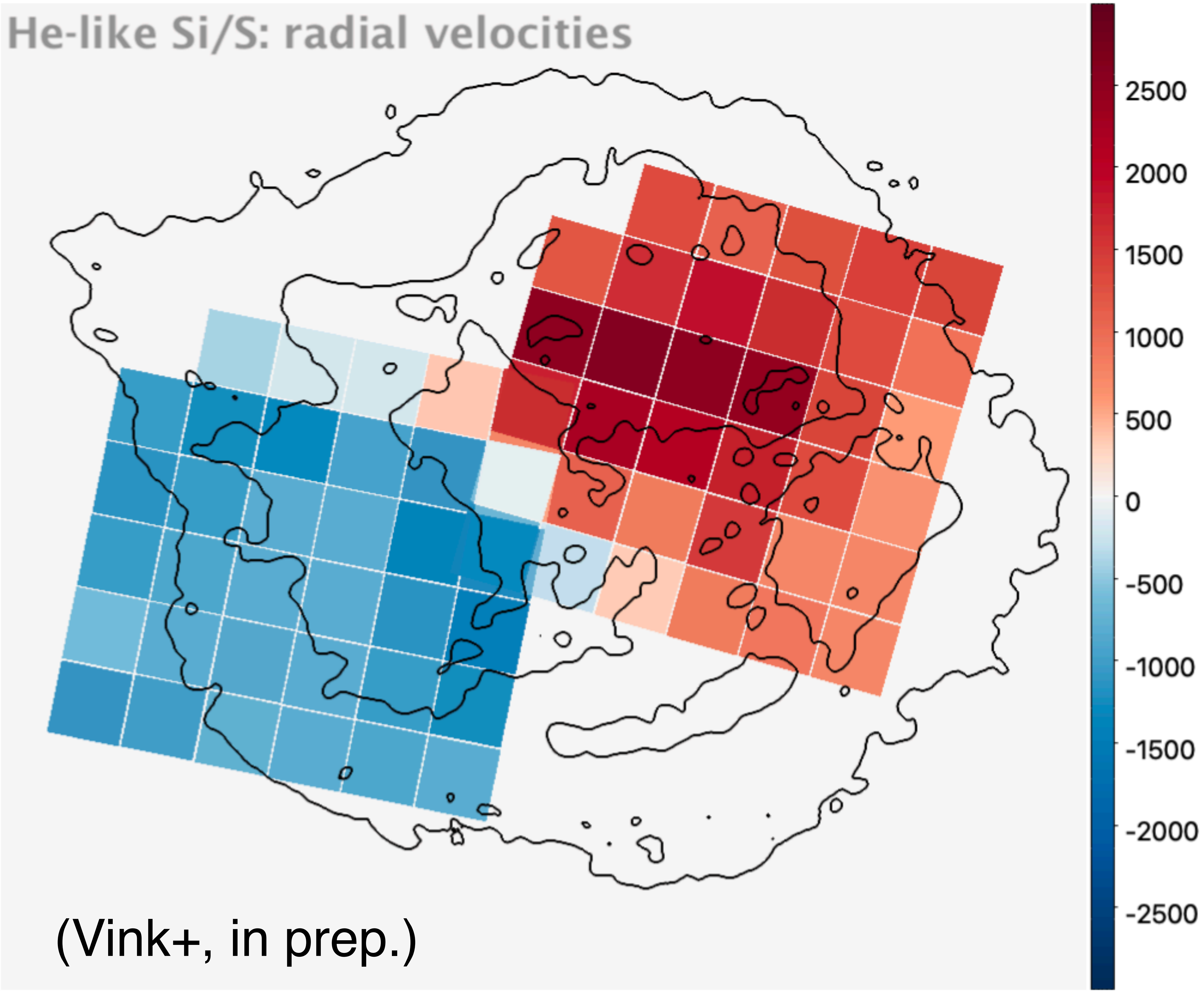
Velocity measurement

(This work is led by S. Suzuki)

- SW rim: blueshifted
- NW rim: redshifted

- Consistent with previous works

(e.g., Hwang+2001)

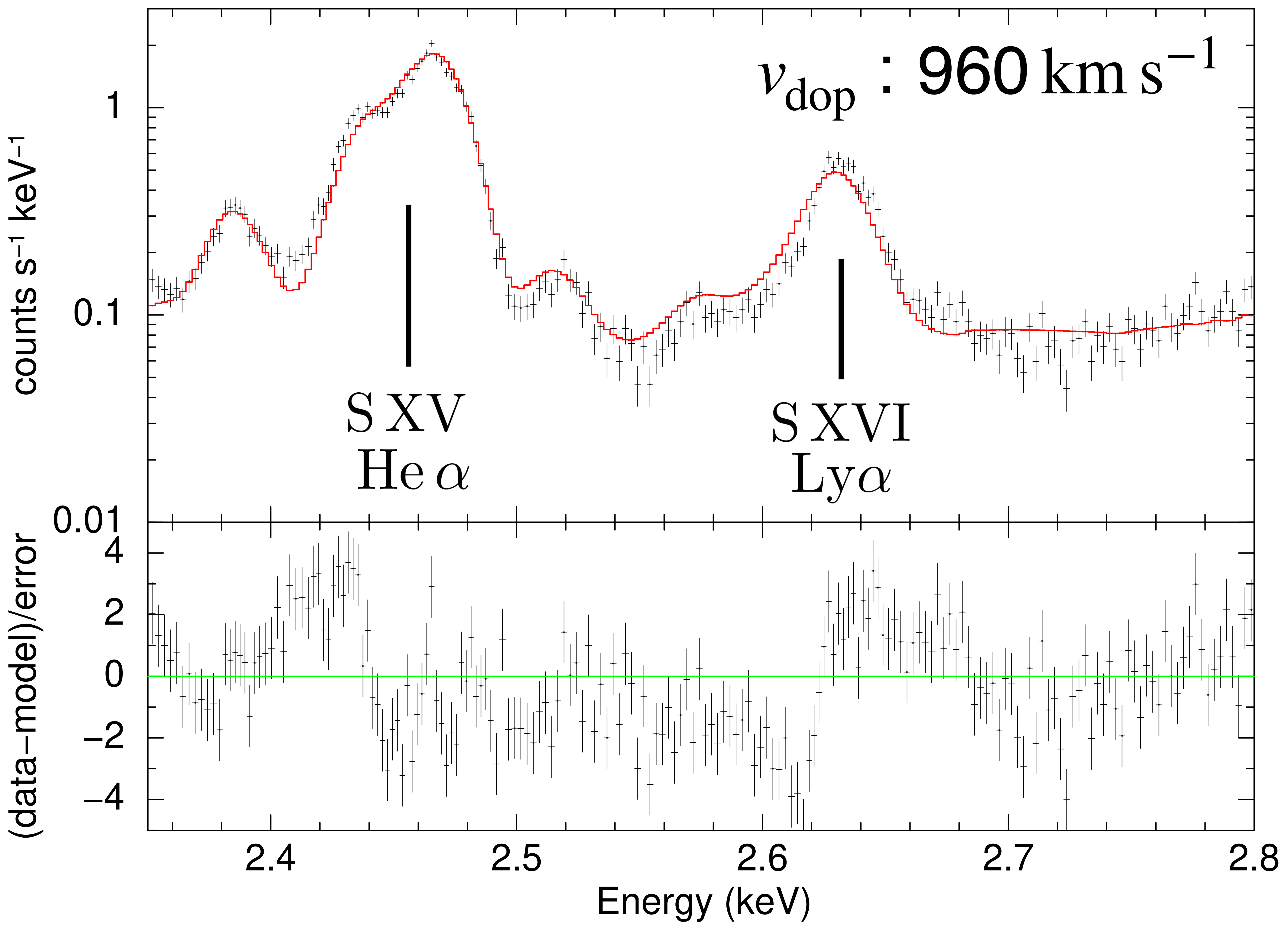


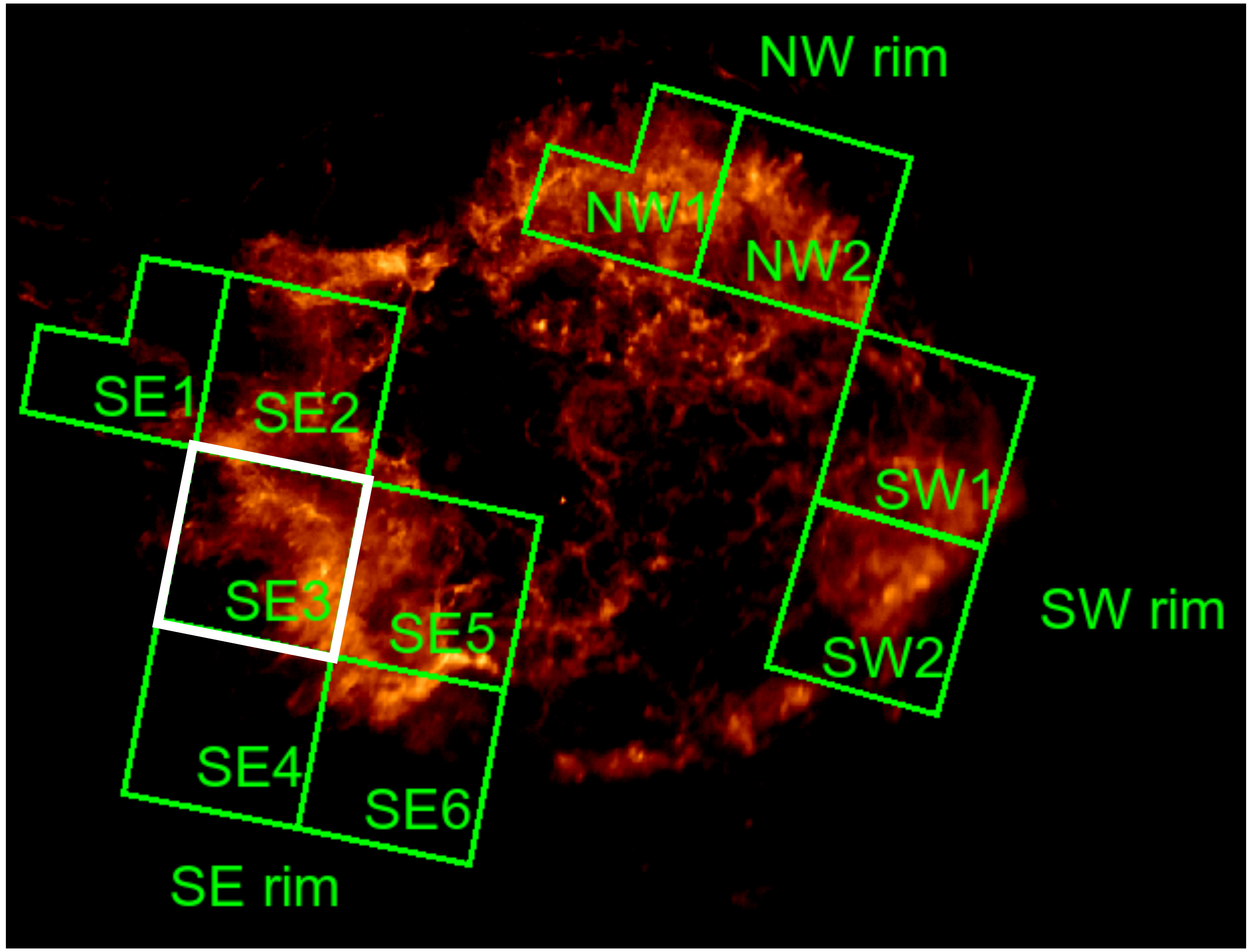
(Vink+, in prep.)

Velocity measurement

(This work is led by S. Suzuki)

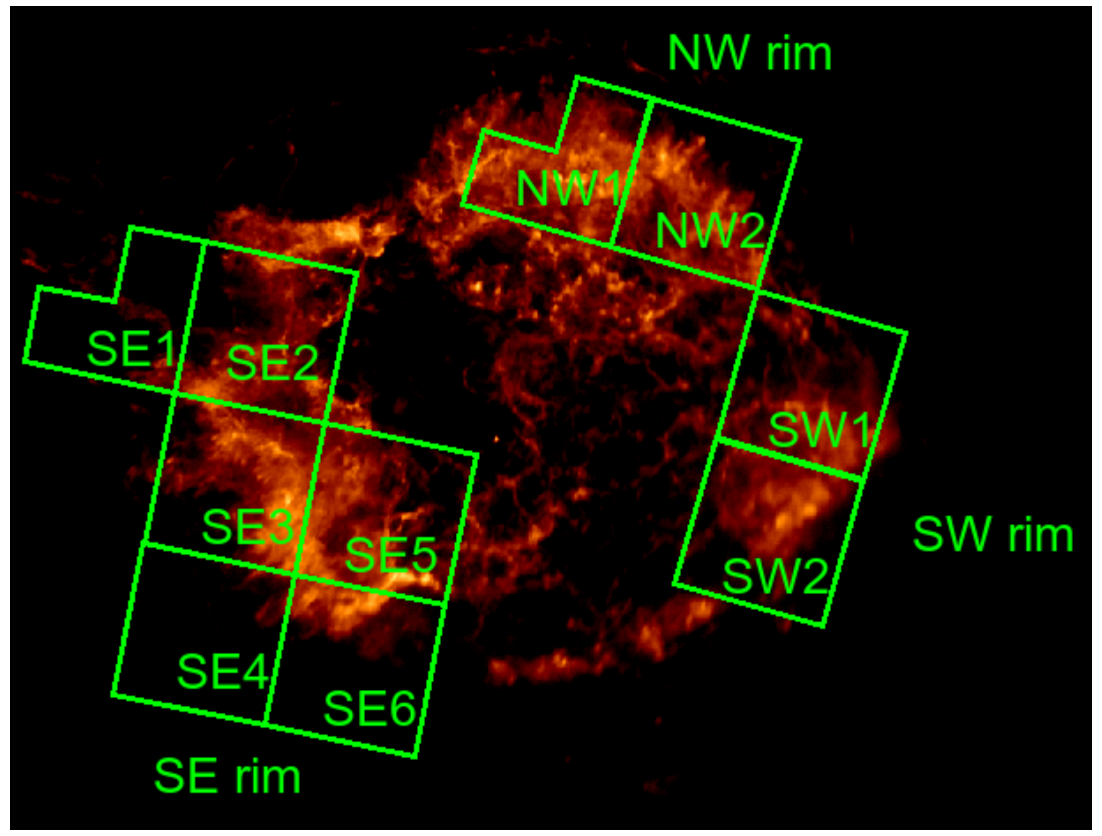
A single plasma model fails to fit the shifts observed in He-like and H-like emissions of identical elements



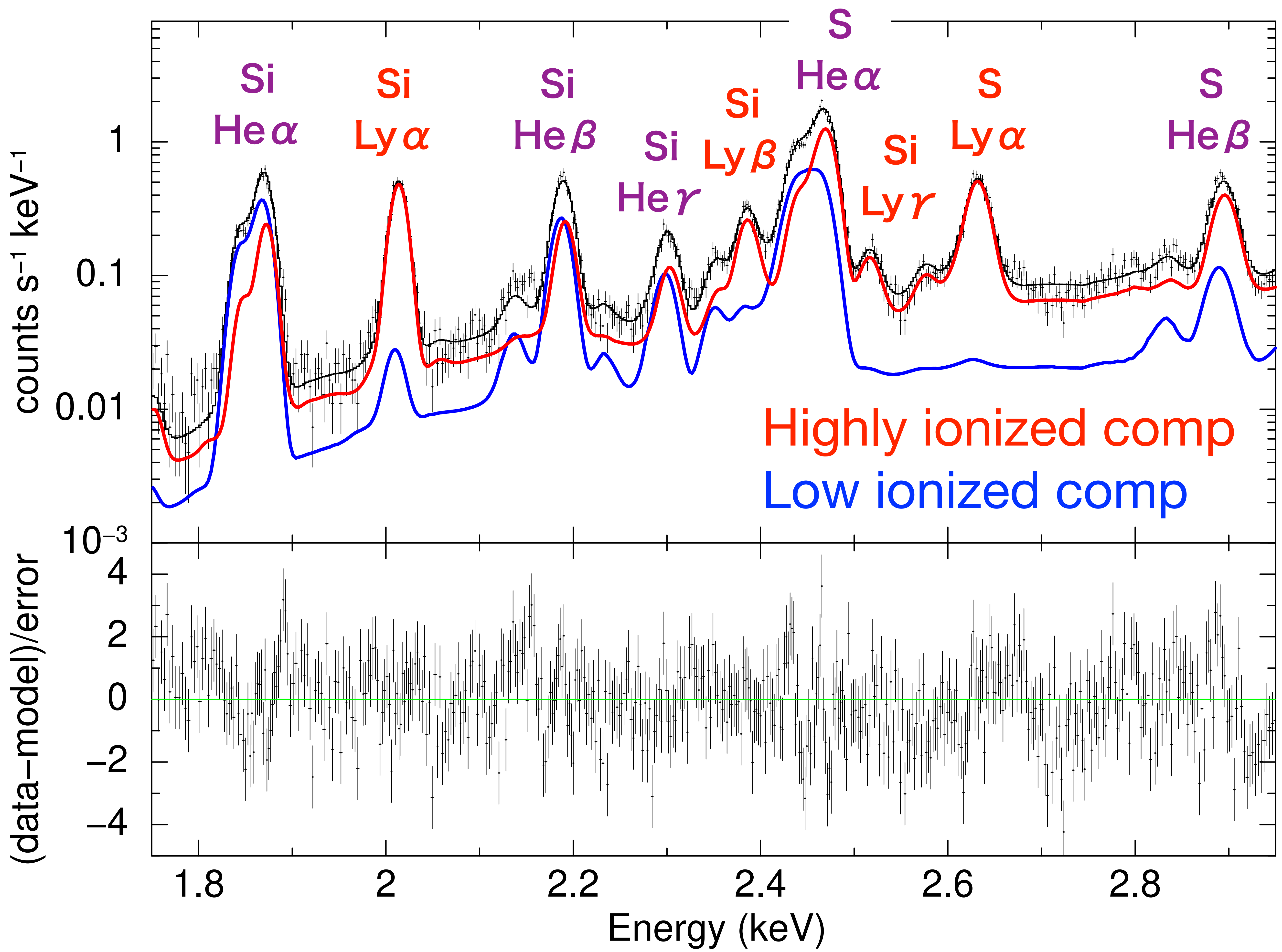


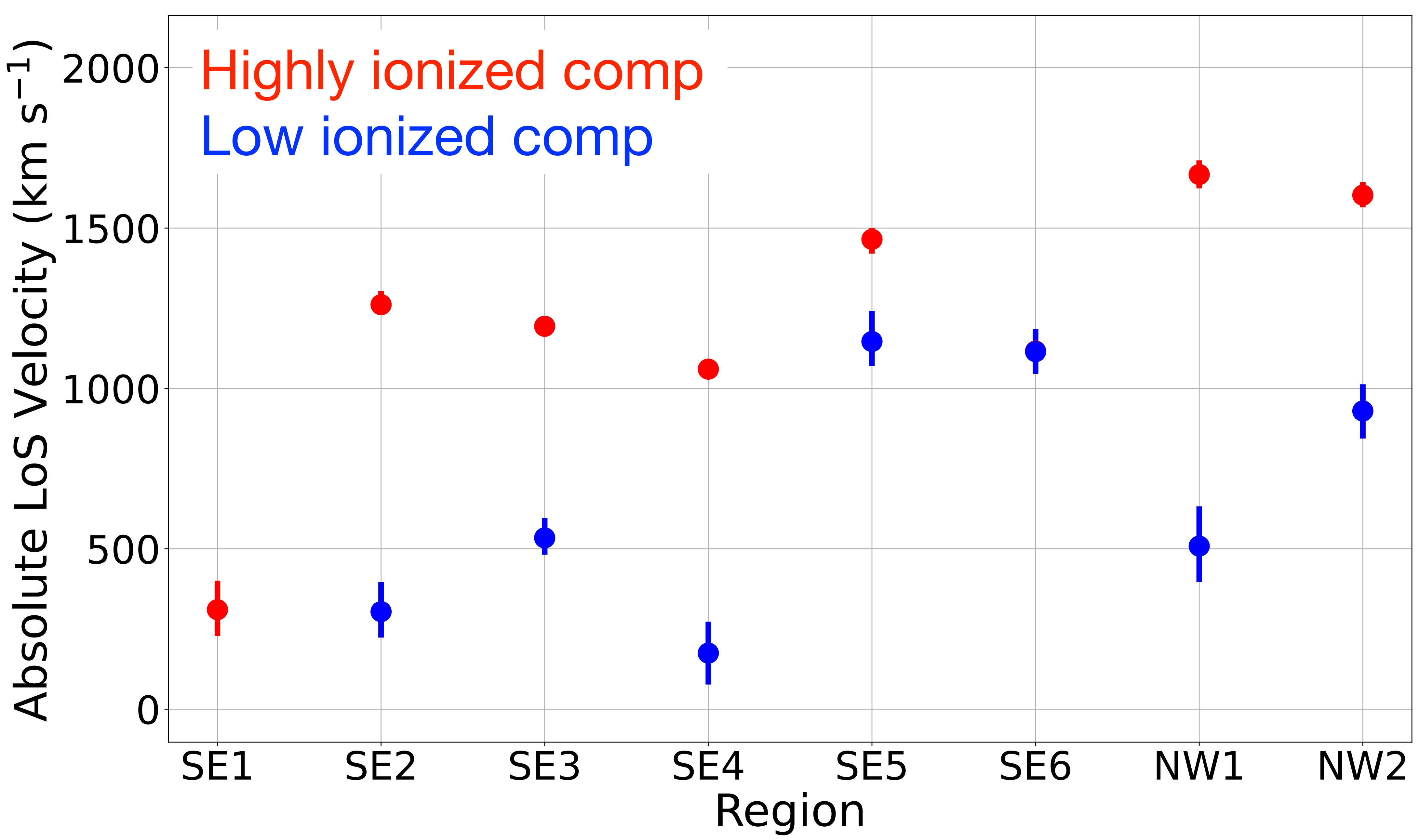
Presence of different plasma components with different radial velocities?

Two-component modeling



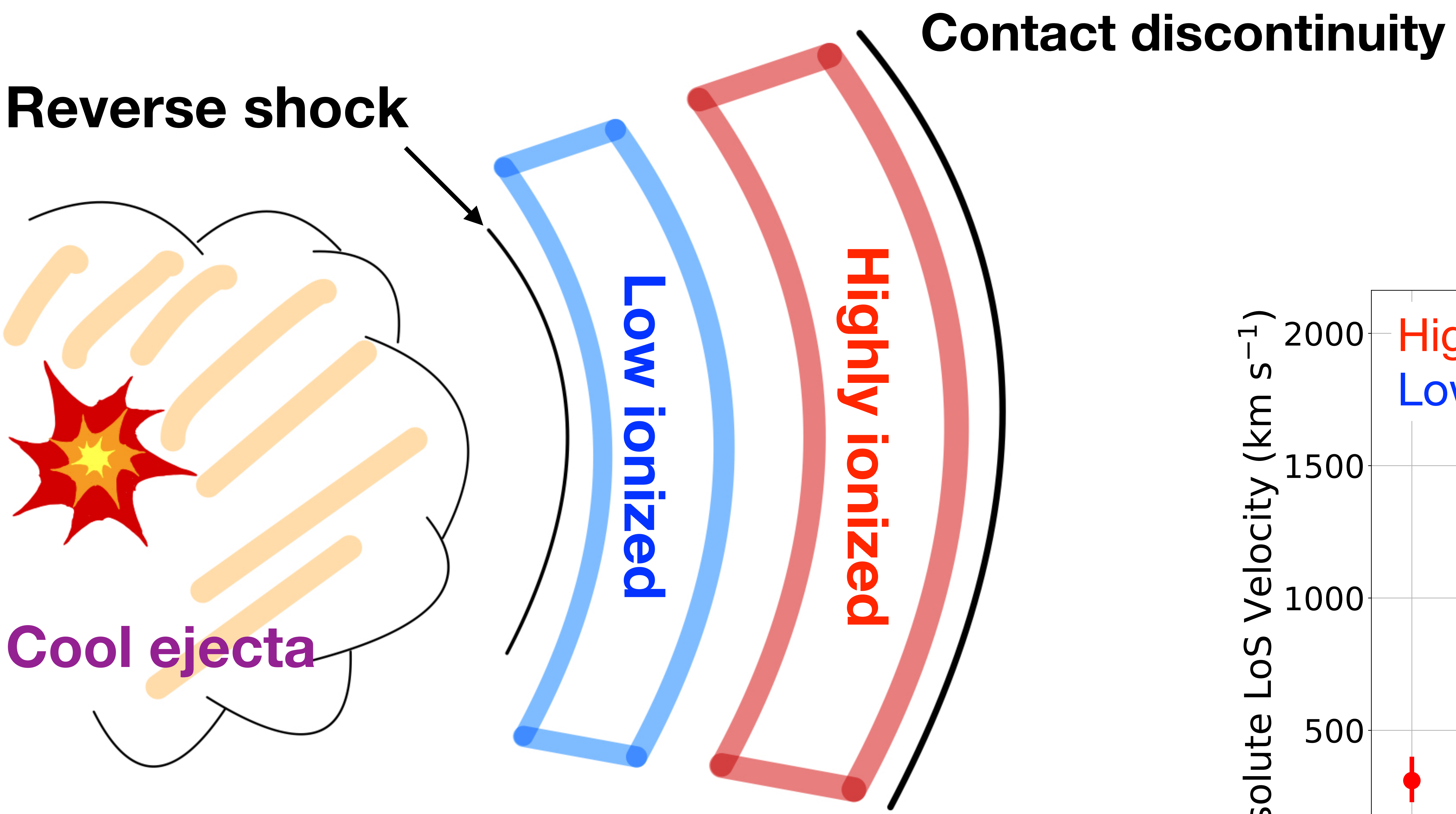
A two-component model successfully fits the spectrum in the Si/S K band.

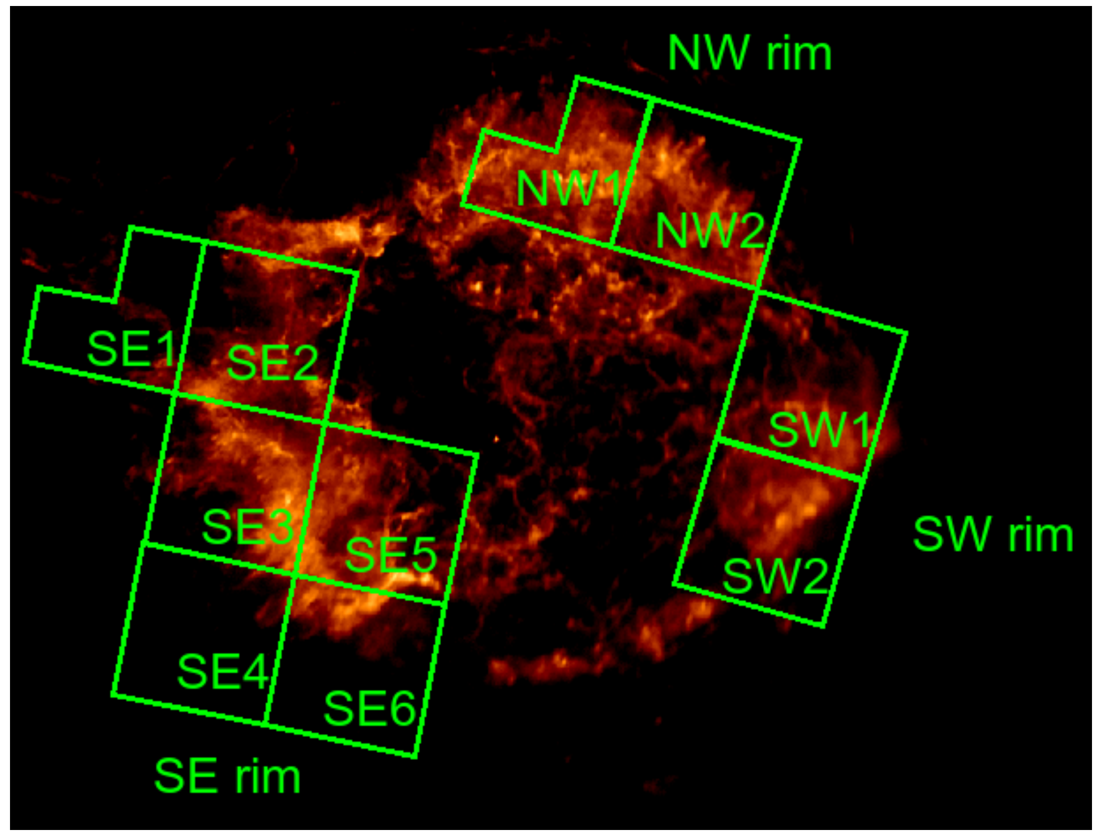


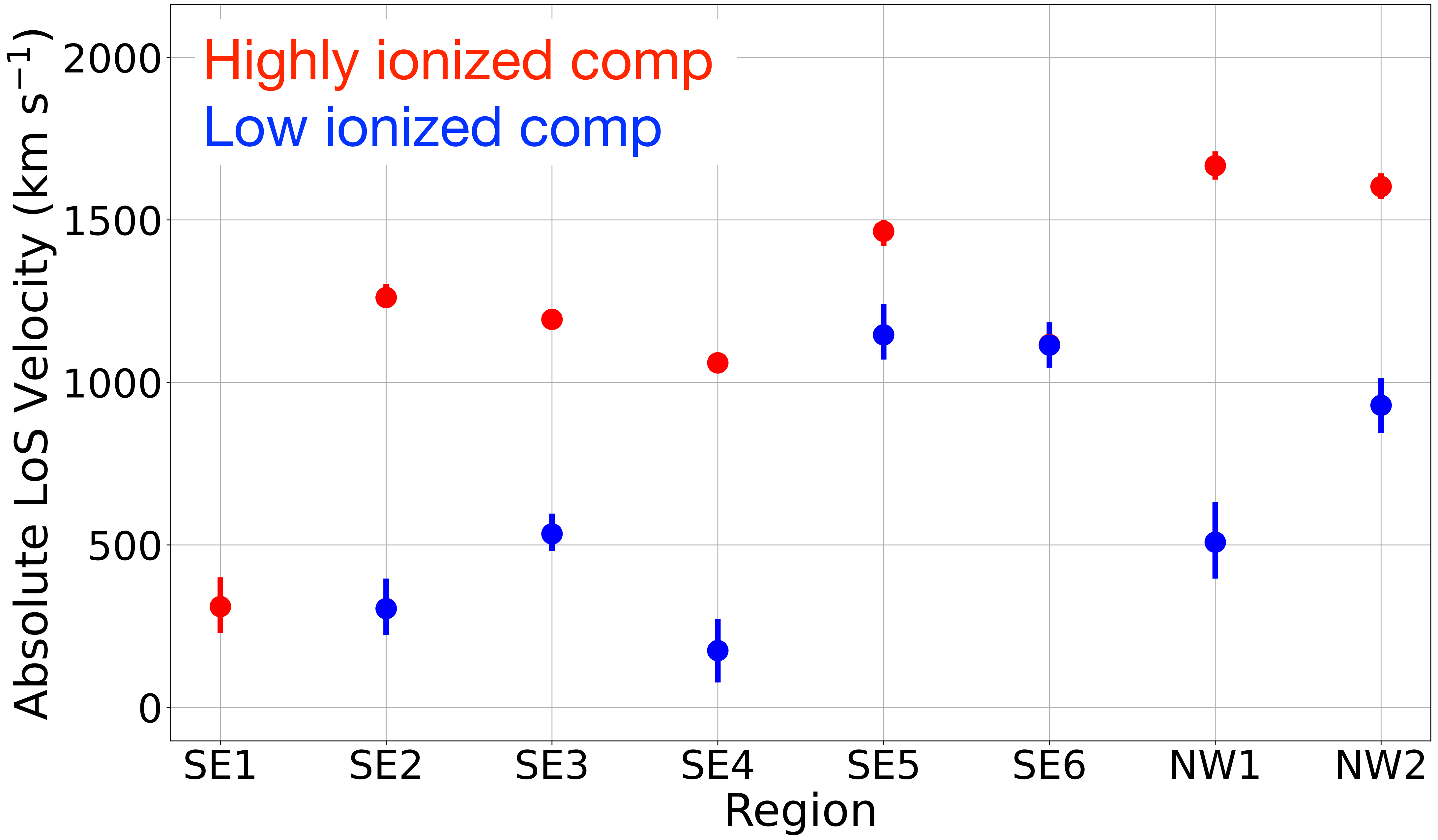


Higher velocity is confirmed in the highly ionized components

Two-component modeling







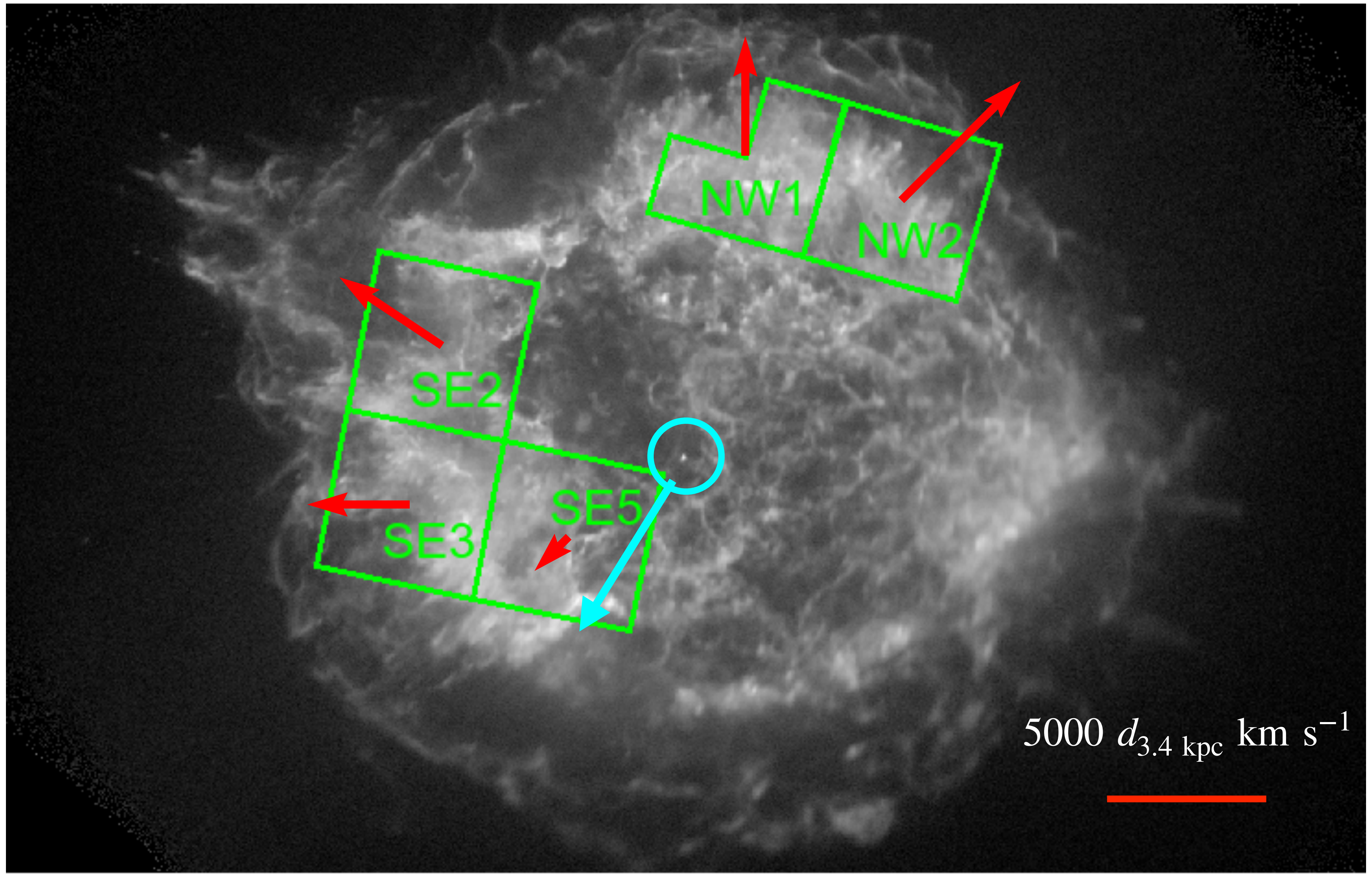
Outer ejecta was shock heated earlier
➔ Longer time for ionization

Lyα emission represents the outermost ejecta of the O-burning products

Higher velocity is confirmed in the highly ionized components

Three-dimensional velocity

Proper motion of Si Lyα emission is measured using Chandra data to reconstruct three-dimensional velocity of the shocked ejecta



NS is moving toward SE with v ~ 430 km/s
(Holland-Ashford+2024)

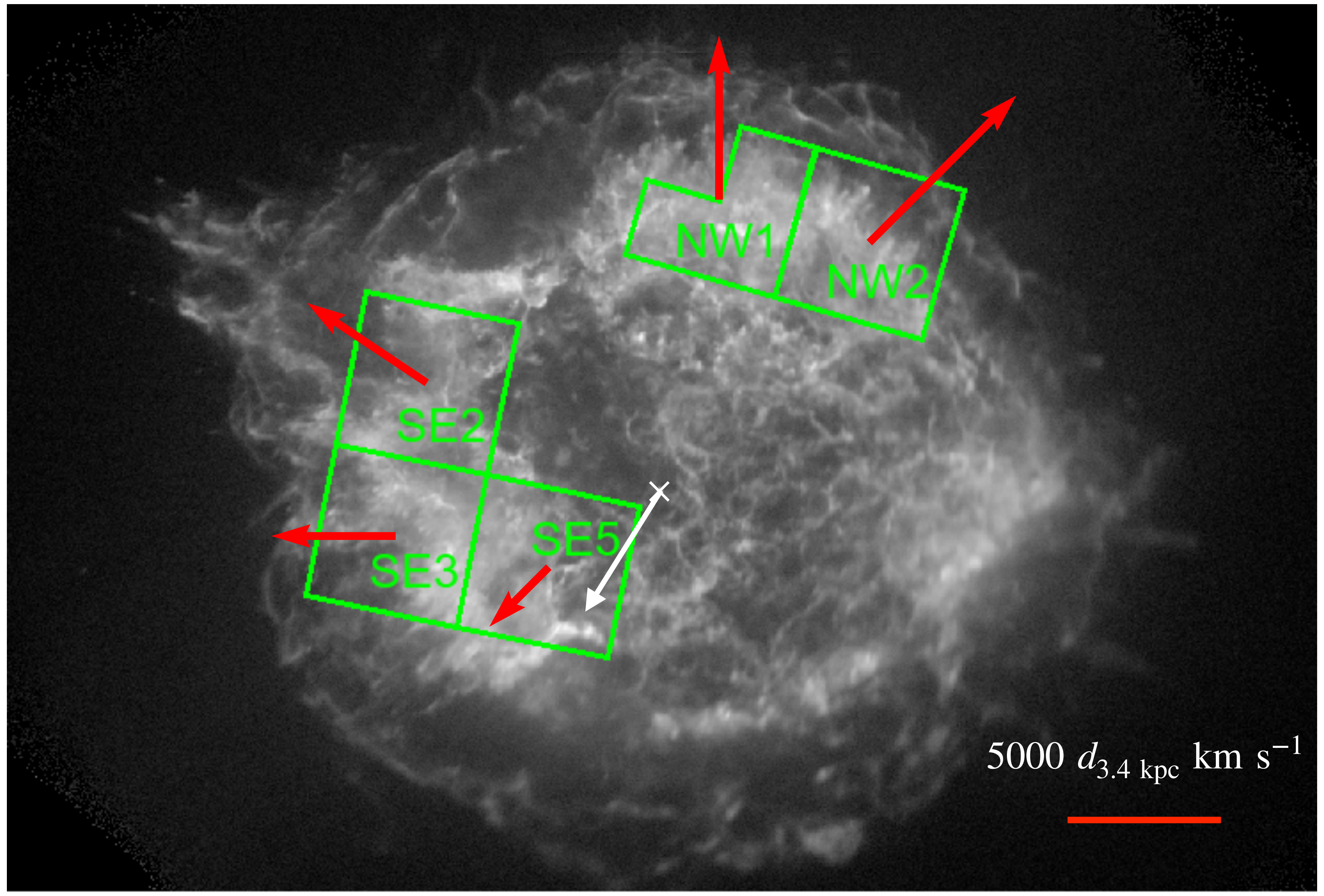
Region	$v_{\rm rad}$ (km s^{-1})	$v_{\rm prop}$ (km s^{-1})	$\theta(v_{\rm prop})$ (°)	$v_{\rm obs}$ (km s^{-1})
SE2	-1261^{+42}_{-26}	3799^{+372}_{-372}	56^{+5}_{-6}	4000^{+400}_{-400}
SE3	-1194^{+28}_{-32}	3161^{+372}_{-372}	90^{+4}_{-5}	3400^{+400}_{-400}
SE5	-1465^{+36}_{-44}	1490^{+372}_{-372}	135^{+14}_{-14}	2100^{+300}_{-300}
NW1	1667^{+44}_{-43}	3688^{+372}_{-372}	0^{+4}_{-4}	4000^{+400}_{-400}
NW2	1603^{+41}_{-38}	5216^{+372}_{-372}	315^{+4}_{-4}	5500^{+400}_{-400}

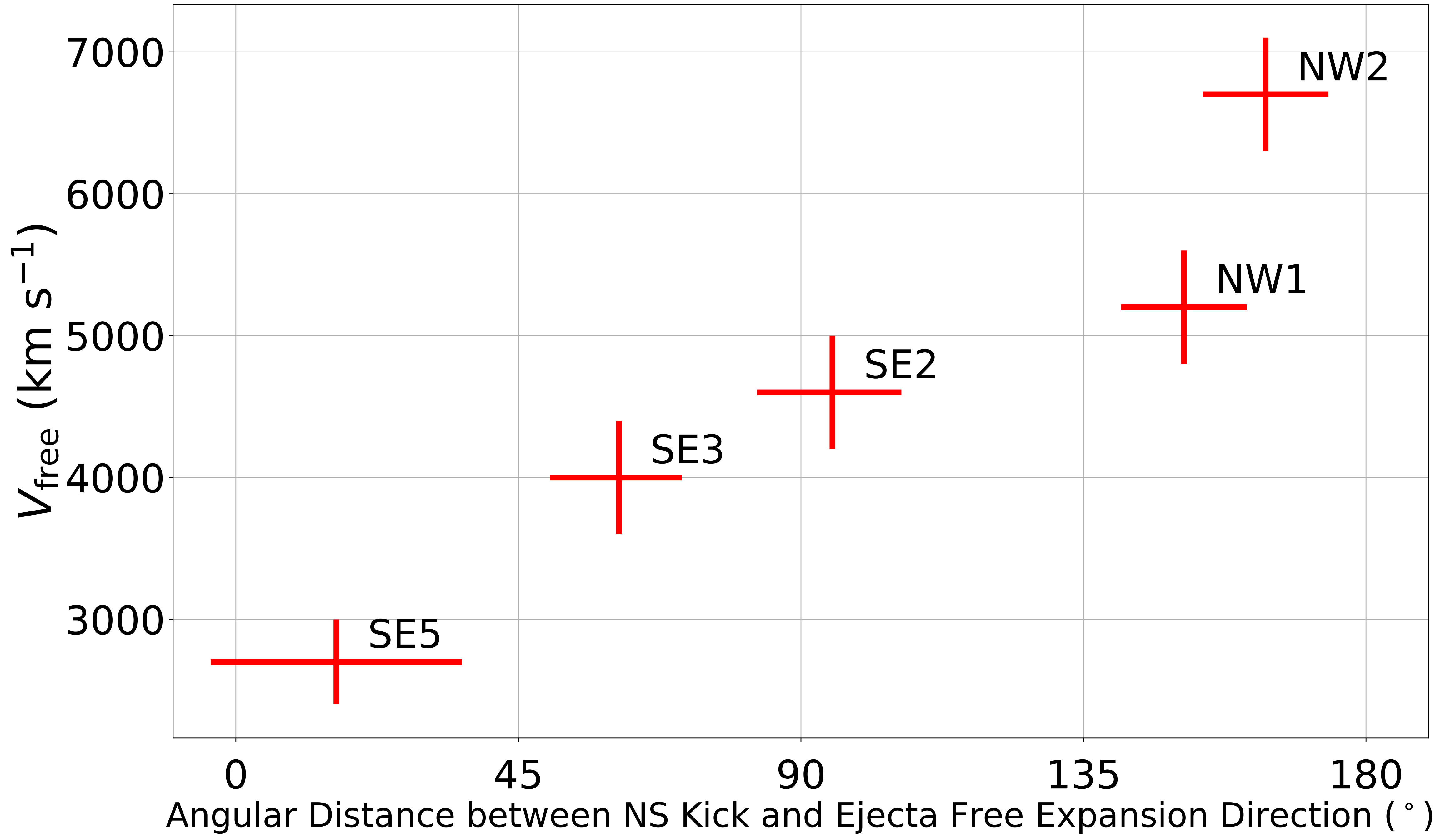
Lowest velocity found in SE5
➔ aligns with NS's proper motion

Highest velocity found in NW2
➔ opposite to NS's proper motion

Three-dimensional velocity

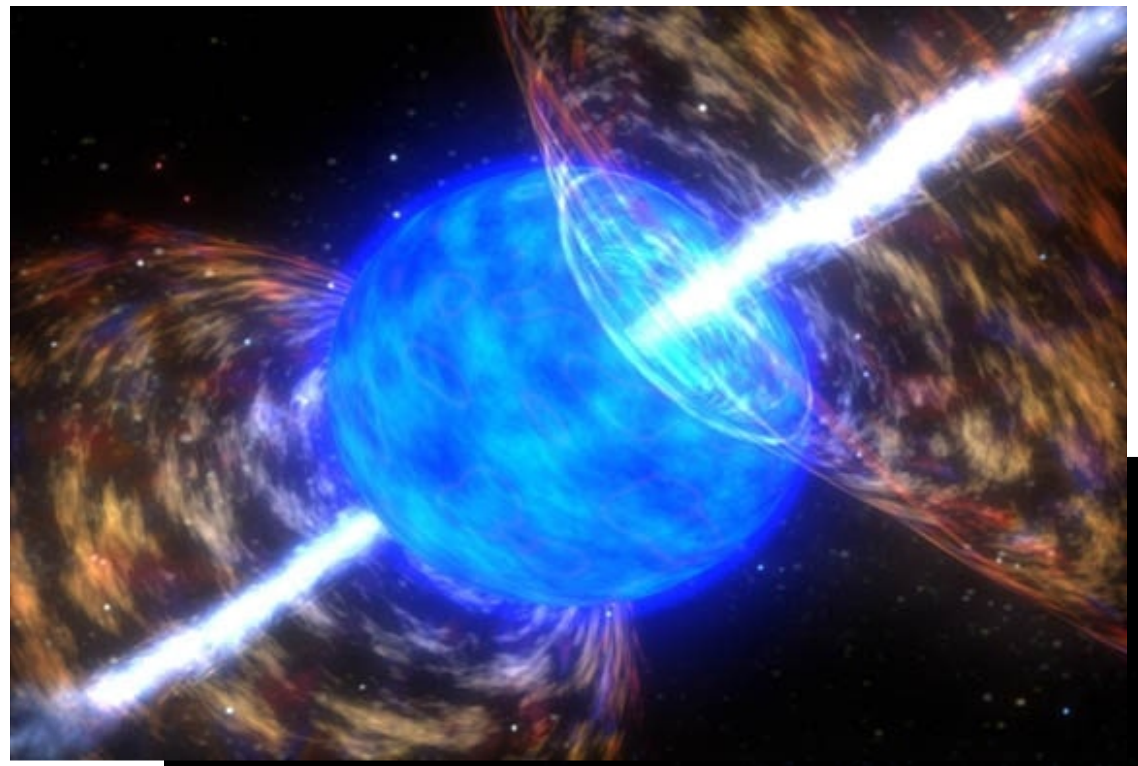
Pre-shock (free expansion) velocity estimated using the XRISM-measured thermal properties as well

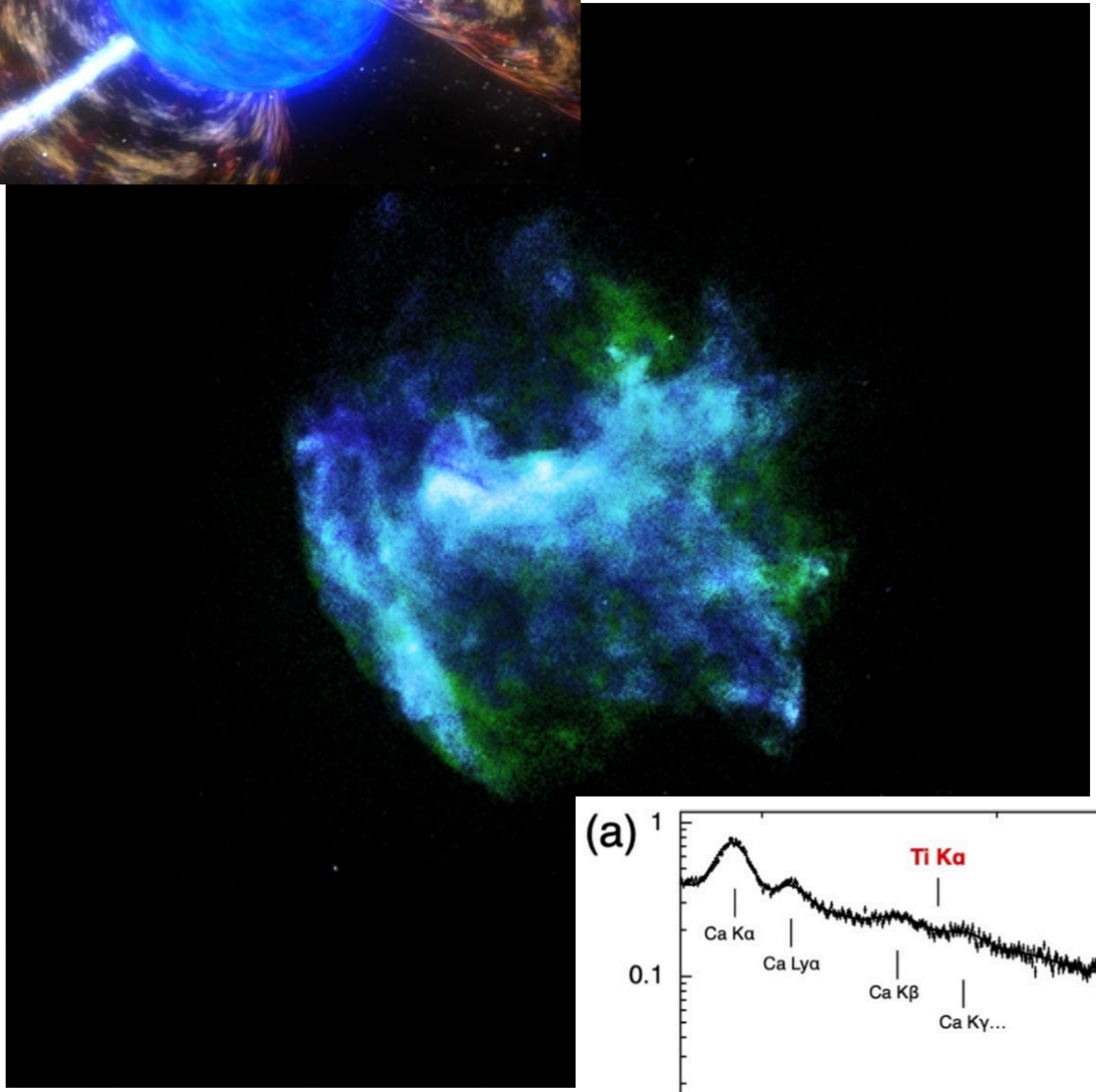




- High velocity, qualitatively consistent with Type IIb SN scenario.
- O-burning ejecta also likely associated with NS kick.
  Comparison with simulations encouraged.

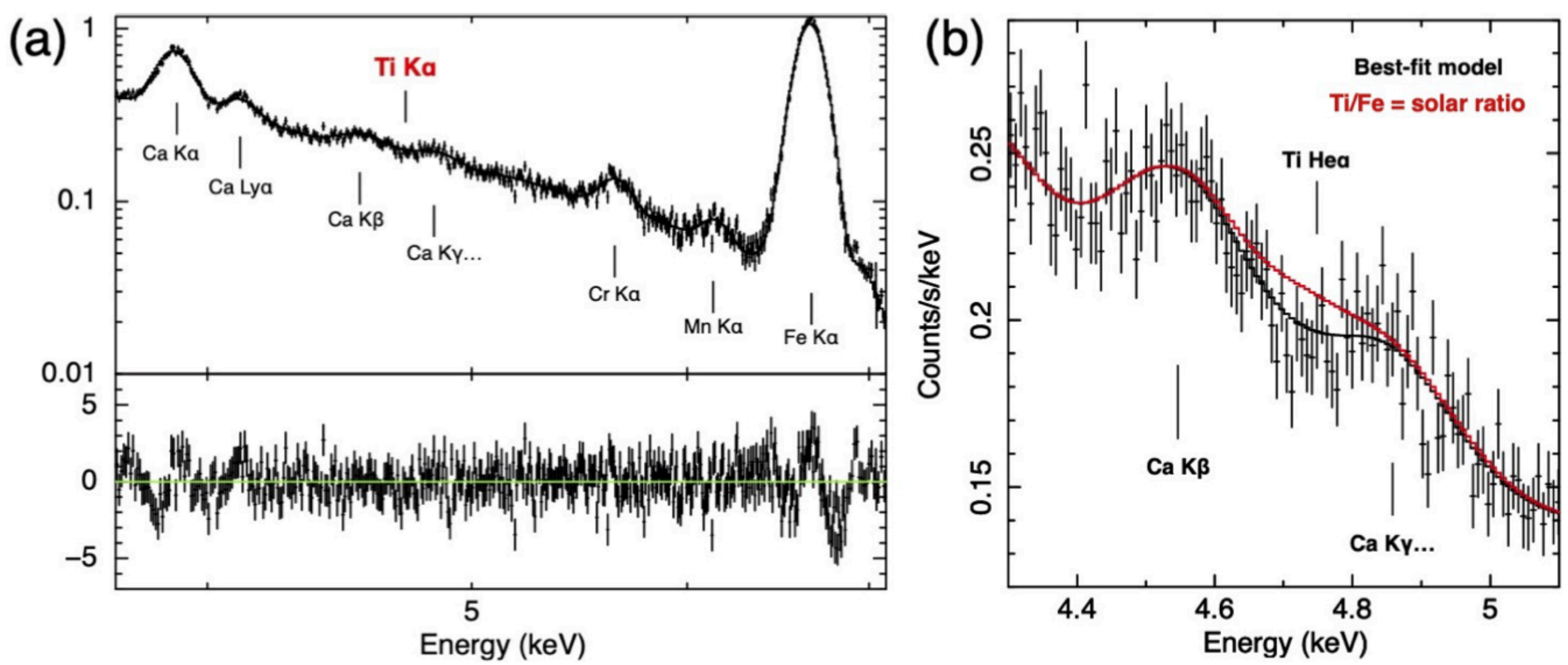
W49B

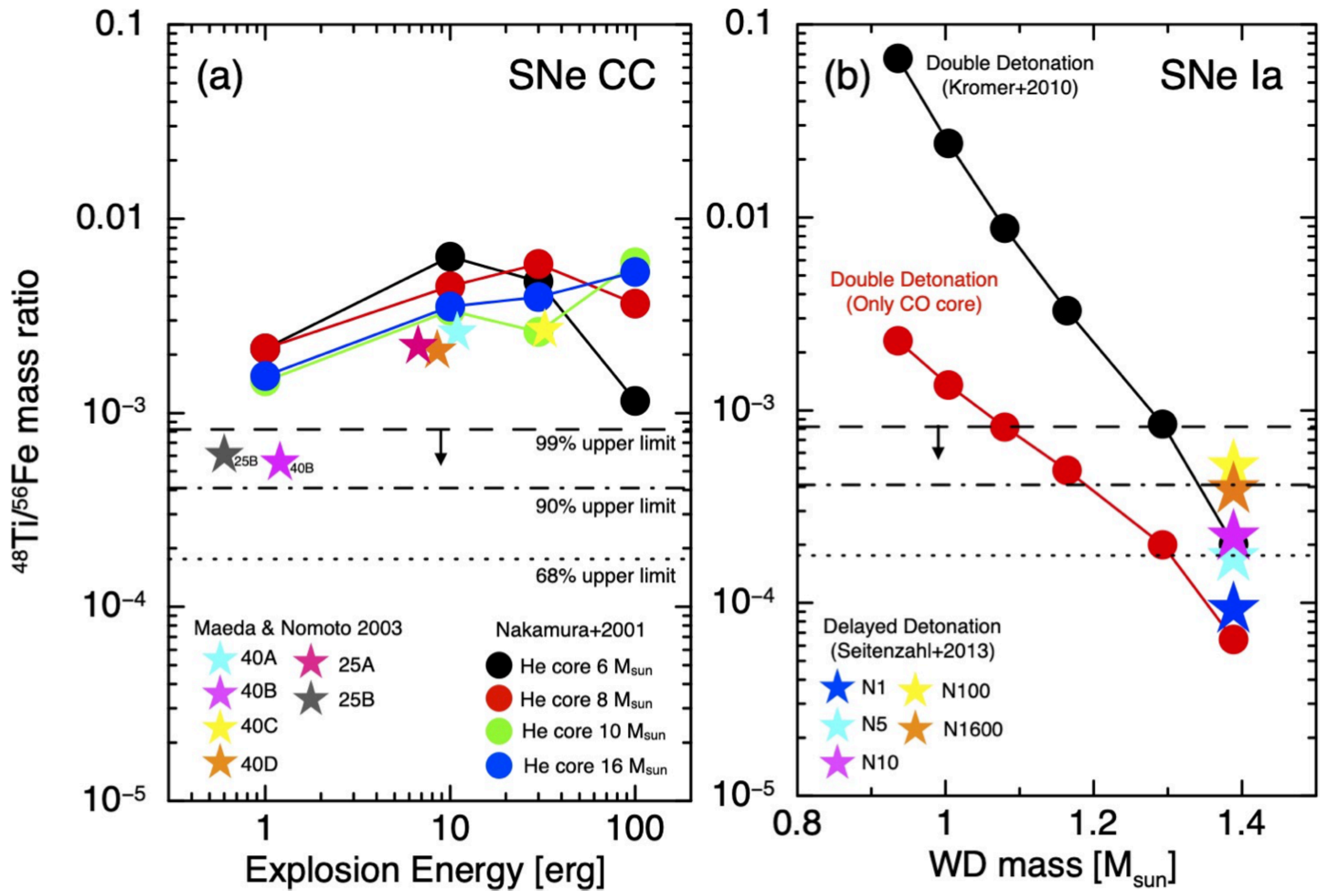




Peculiar SNR!

- In dense environment (n ~ 1000 cm^{-3})
- Bar-like morphology, reminiscent of jet ejection ➔ Type Ic origin? (Lopez+2013)
- Rich in Fe group elements, with lack of Ti ➔ Type Ia origin? (Sato+2024)





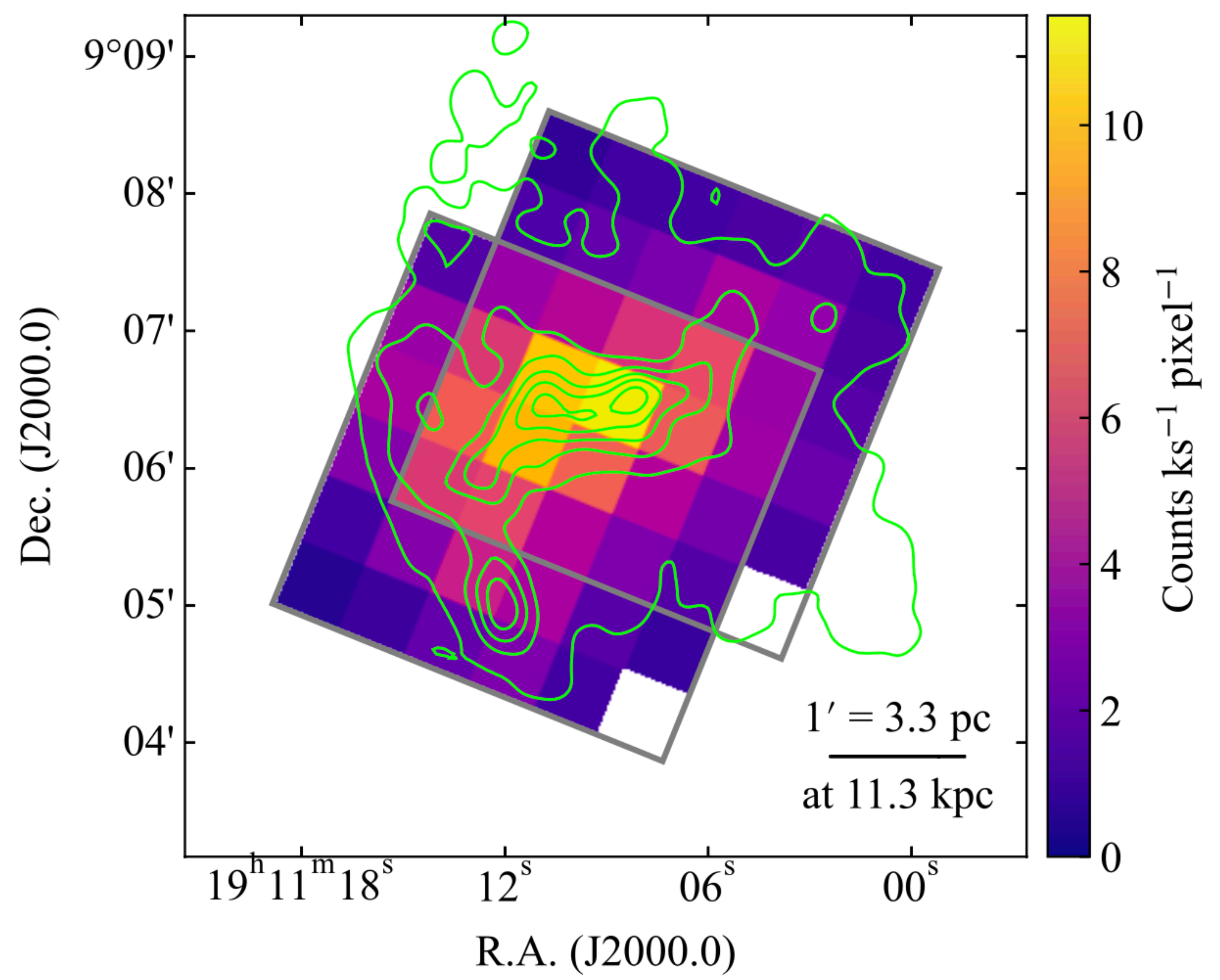
XRISM observations of W49B

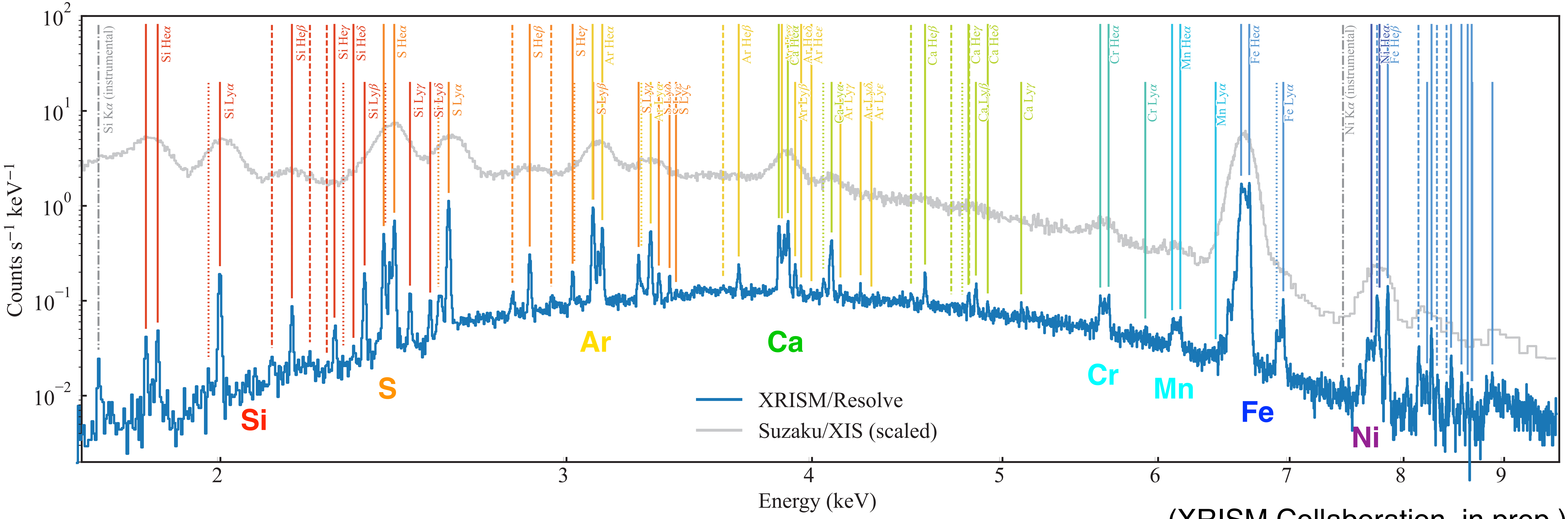
(This work is led by M. Sawada)

Whole SNR covered with two observations

Beautiful spectrum!

... Lack of Ti (and P, Cl, K) confirmed.

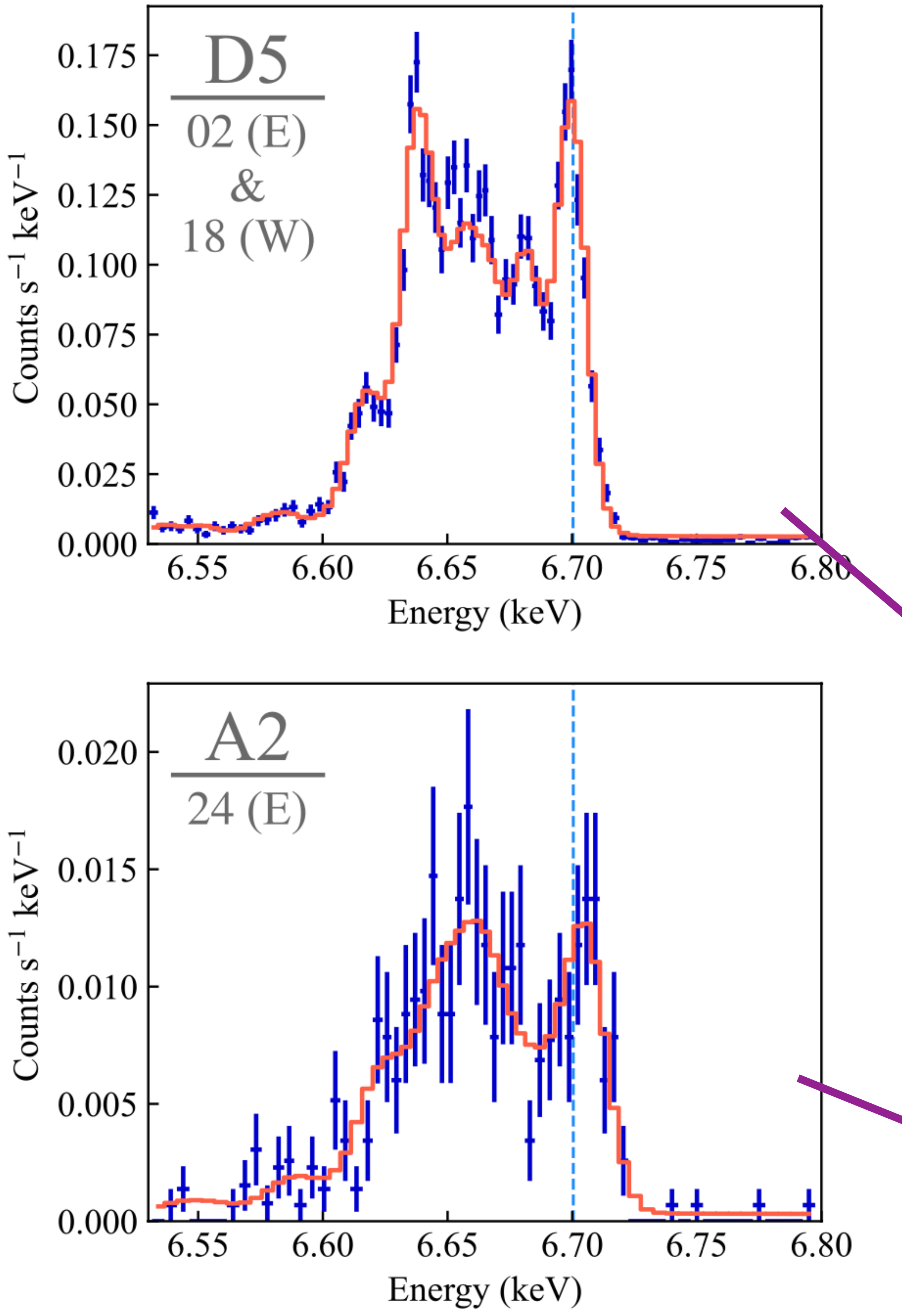


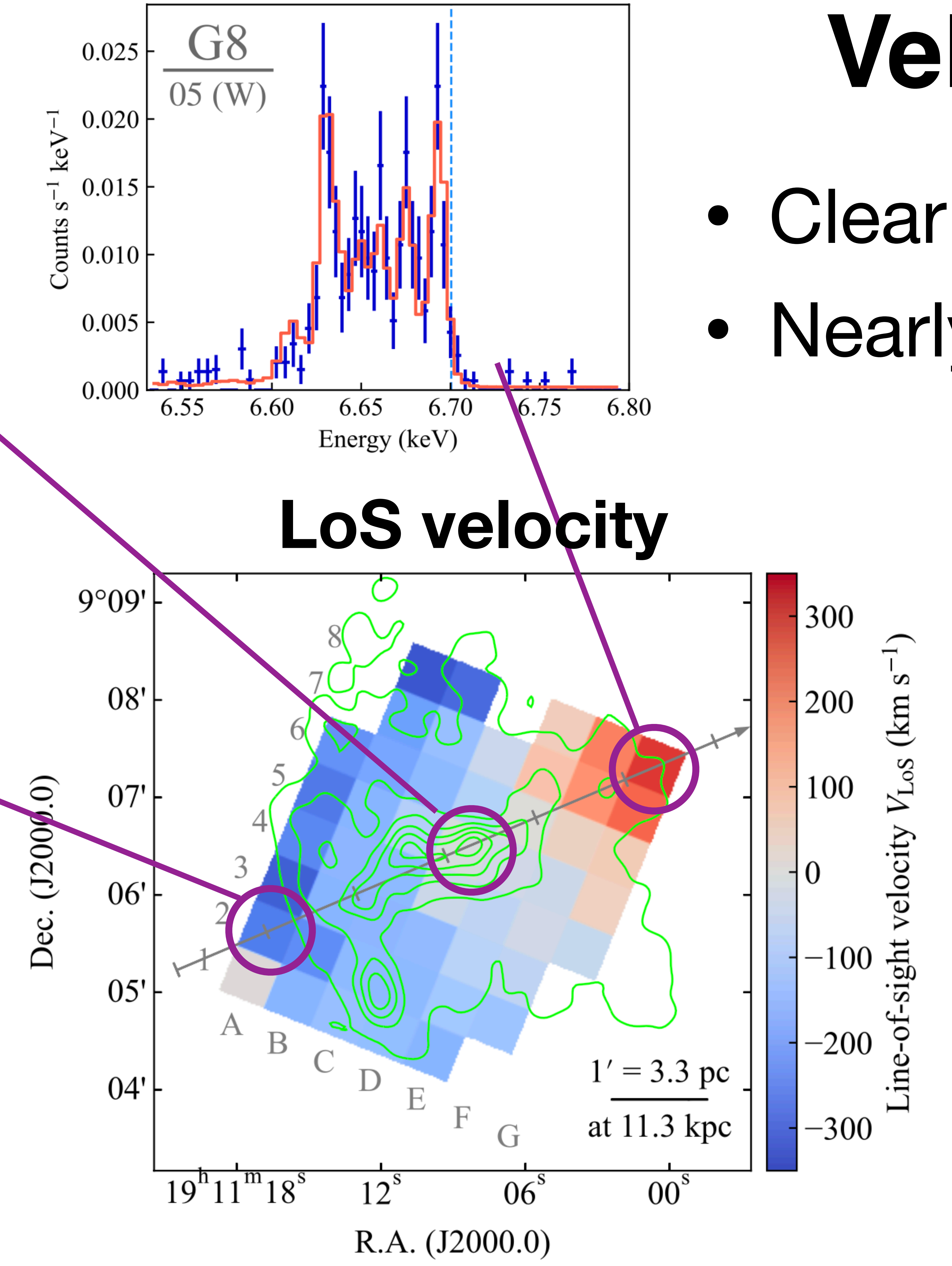


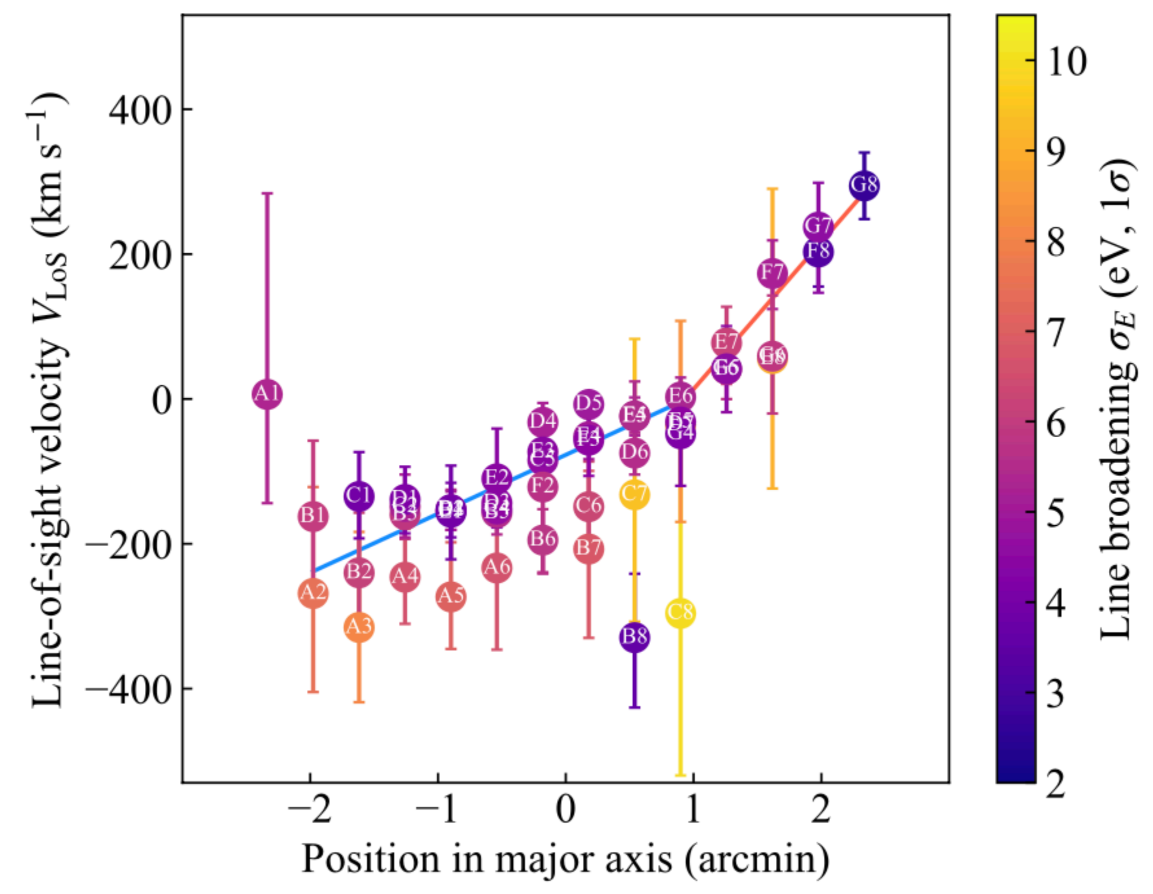
(XRISM Collaboration, in prep.)

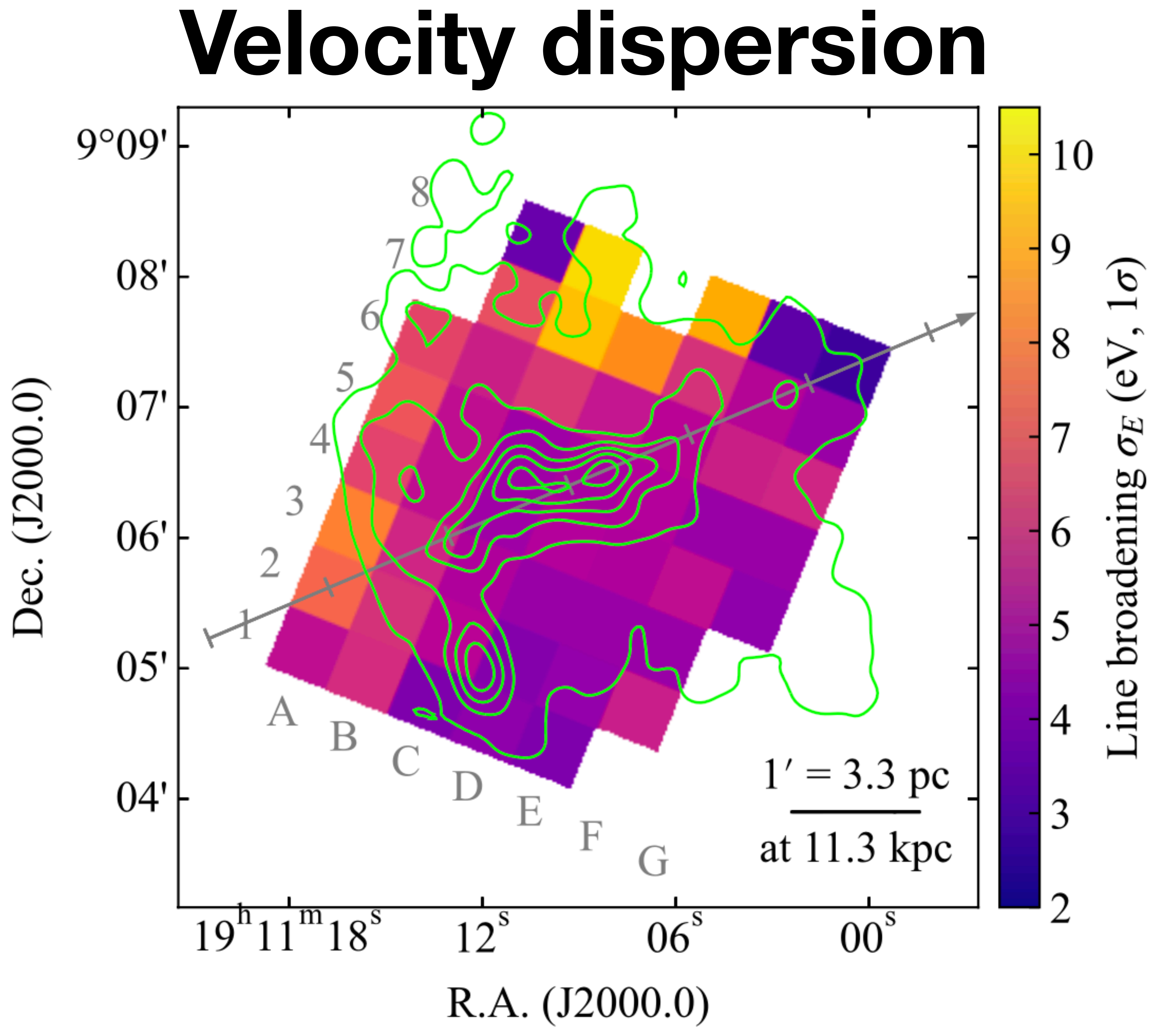
Velocity distribution

- Clear east-west velocity gradient
- Nearly uniform line width



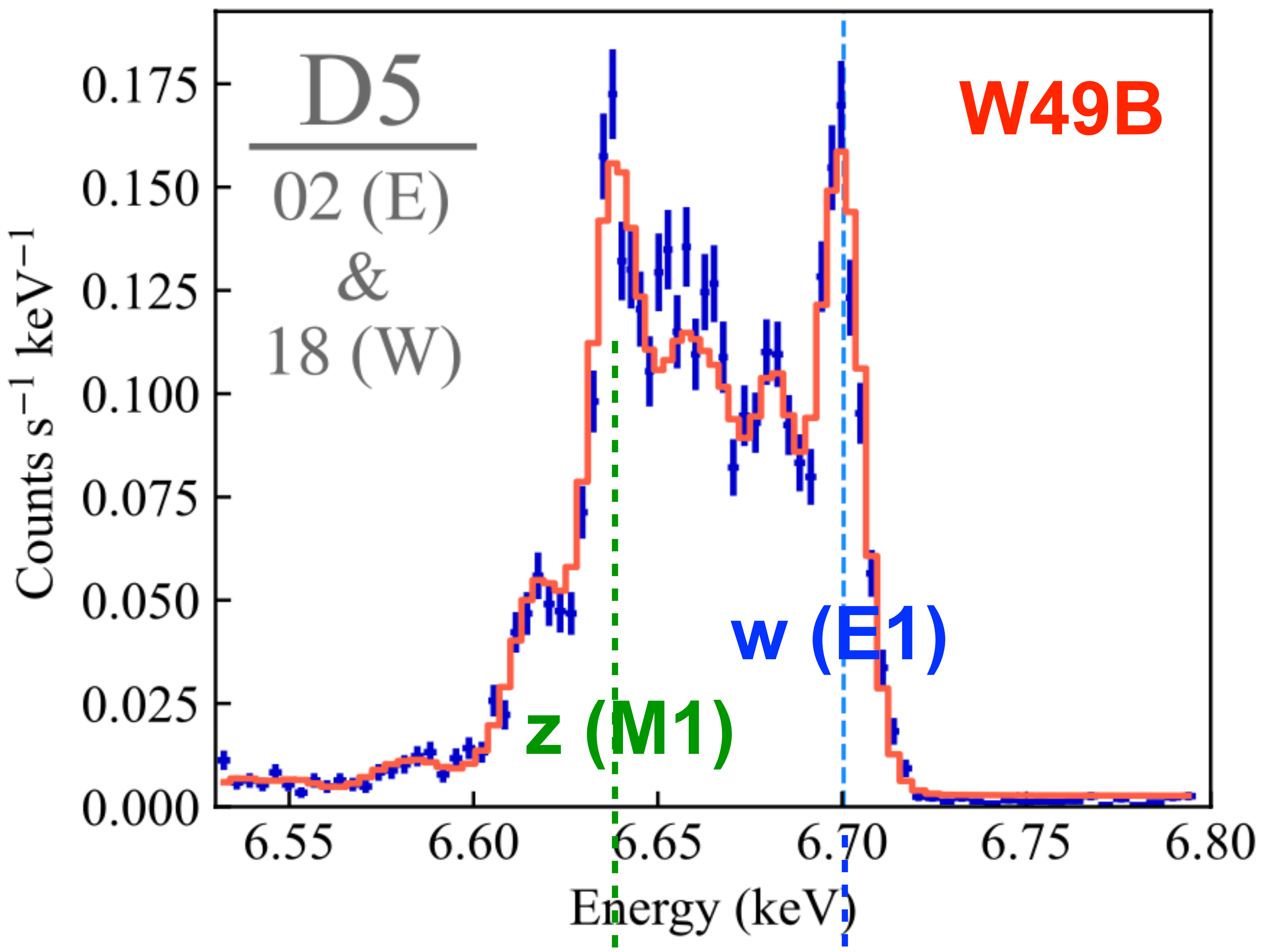




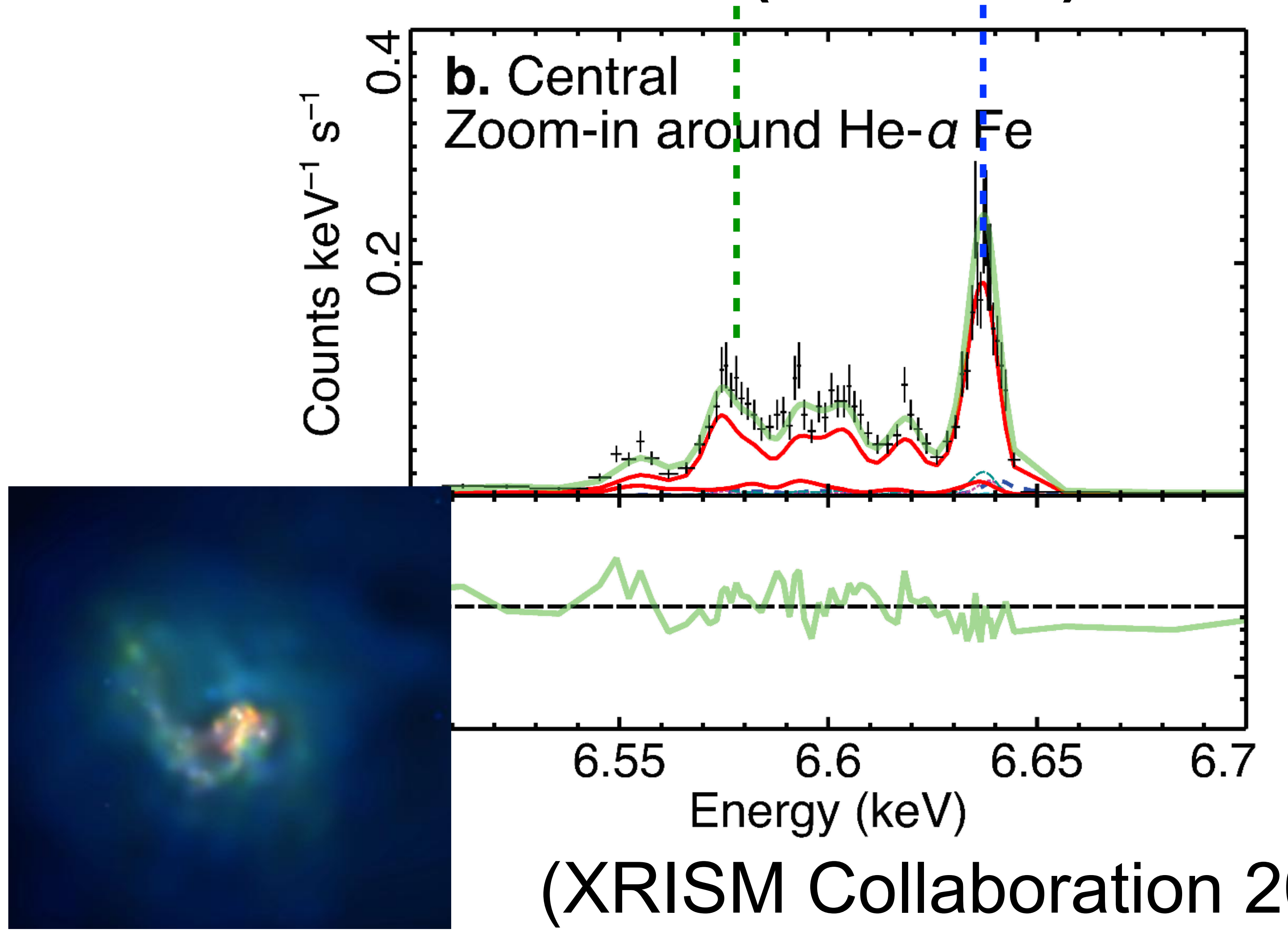


Consistent with bipolar flow scenario

Recombining plasma



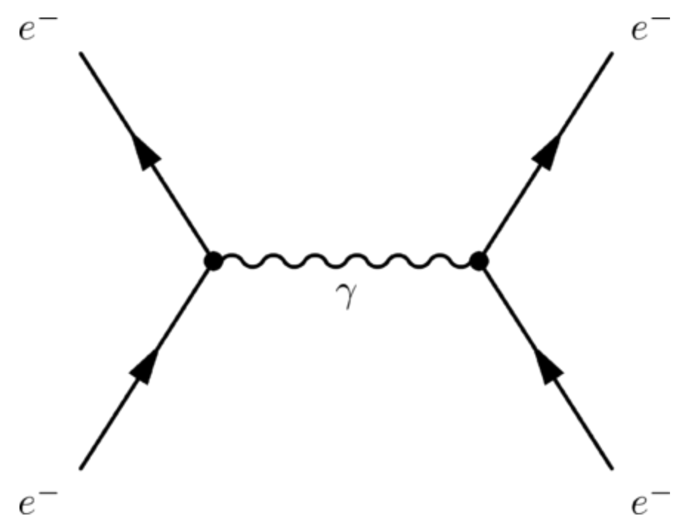
Centaurus Cluster (z = 0.011)



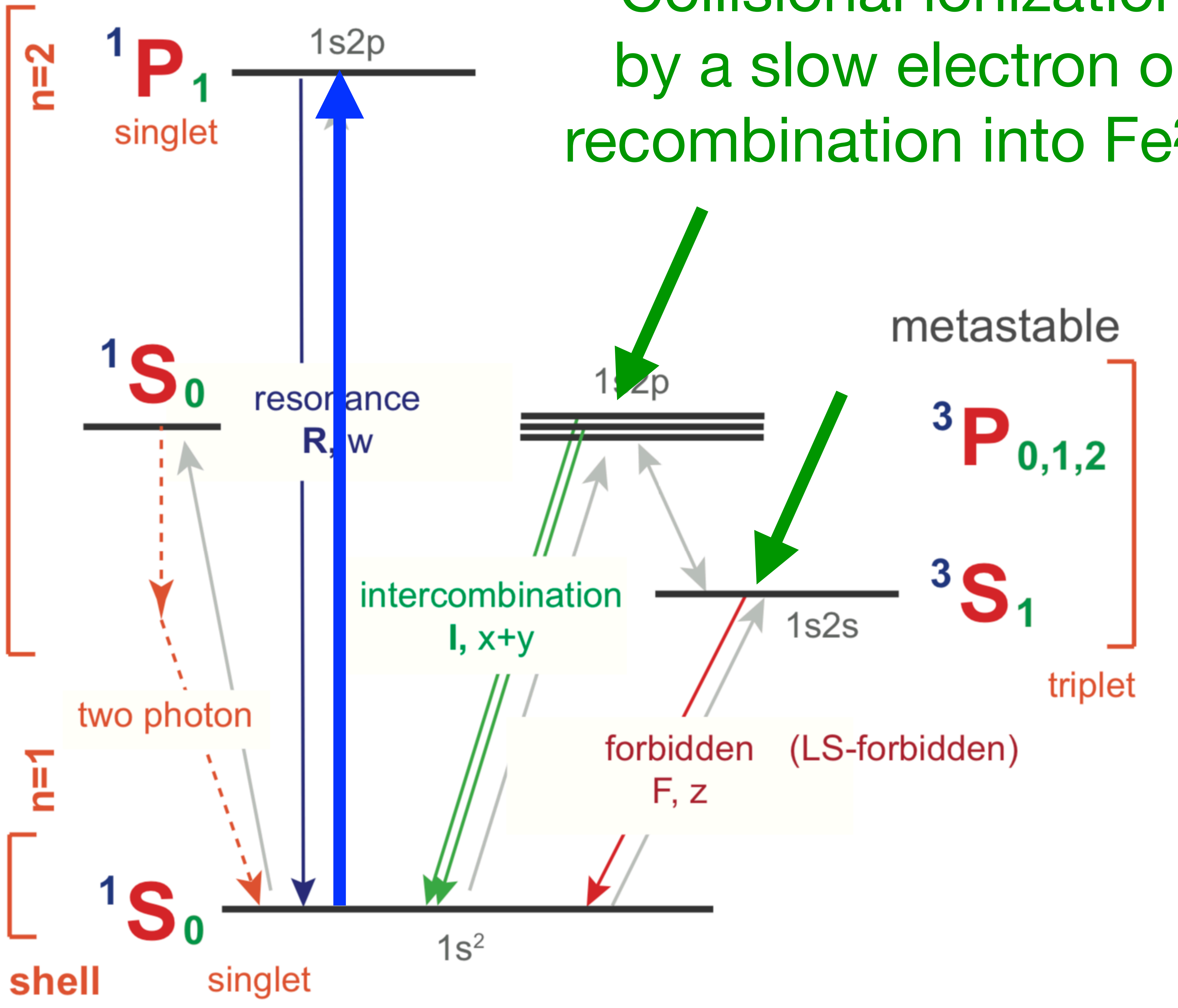
(XRISM Collaboration 2025)

Fe^{24+}

Collisional ionization by a fast electron



Collisional ionization by a slow electron or recombination into Fe^{25+}



Recombining plasma could be formed if explosion occurs in dense CSM (e.g., Moriya 2012)

Origin of W49B

?

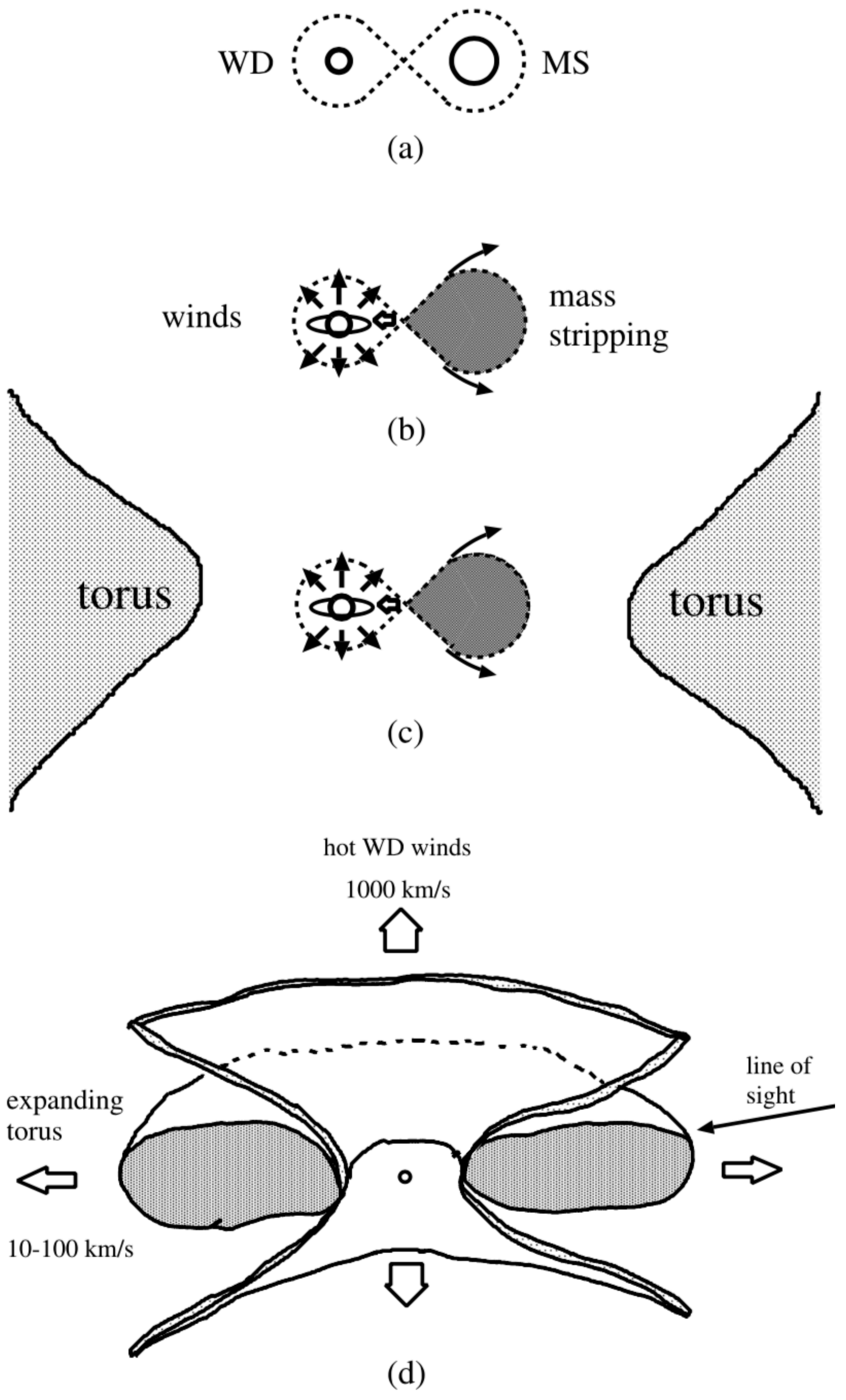
No single existing model explains the observed properties

Bipolar CC SN with low Ti yield?

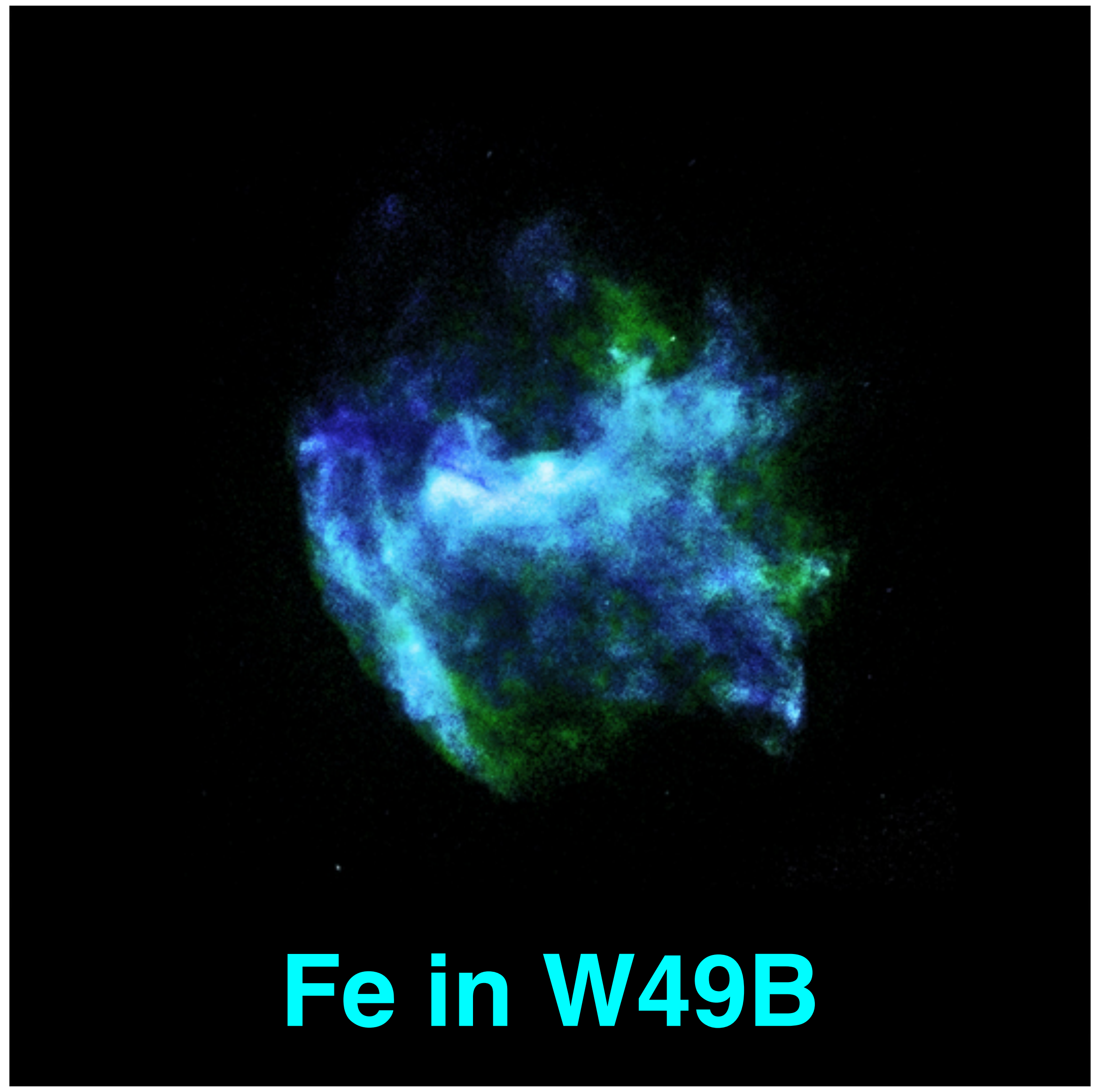
Highly asymmetric Type Ia(-ish) SN with dense CSM?

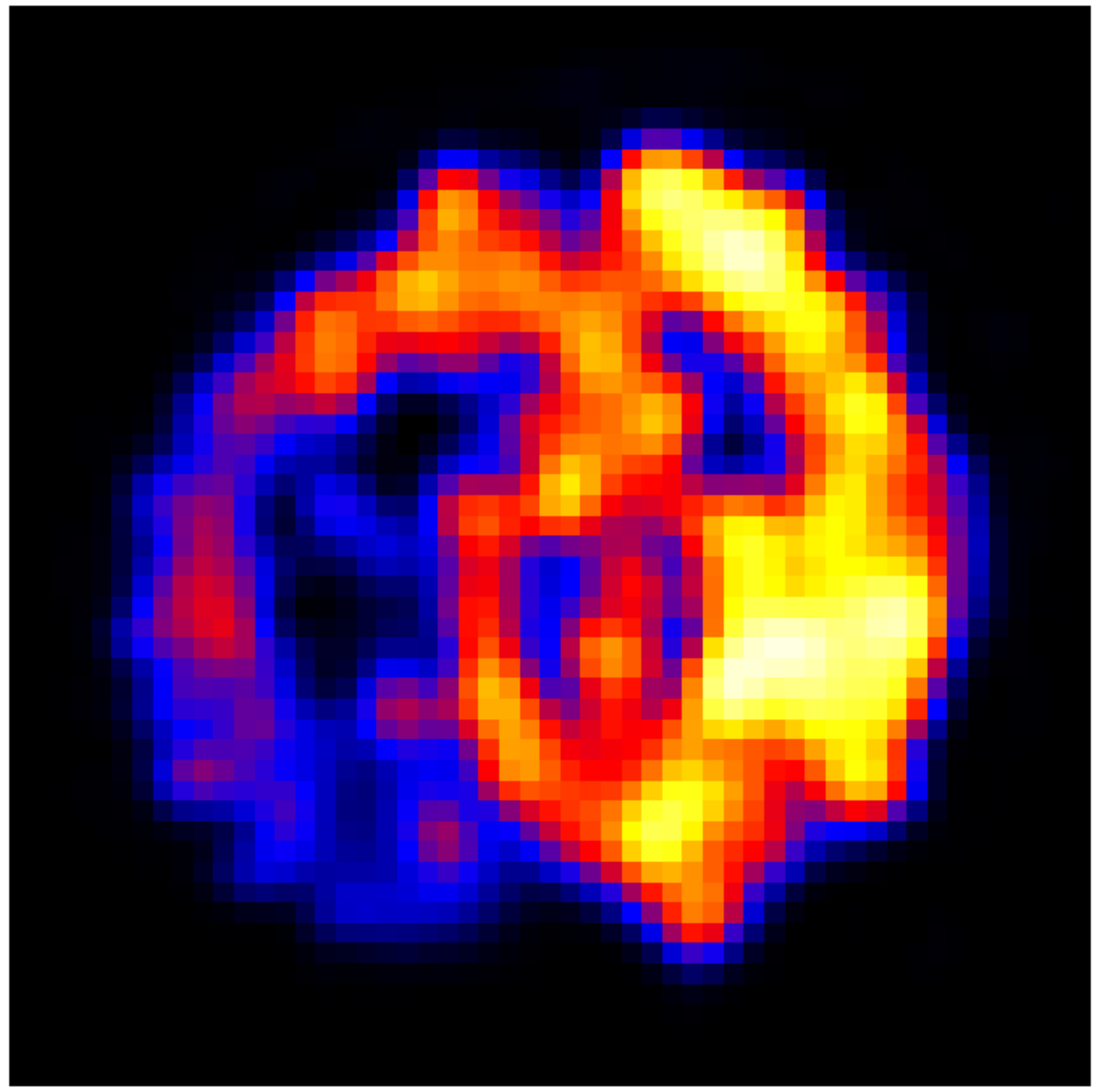
Origin of W49B

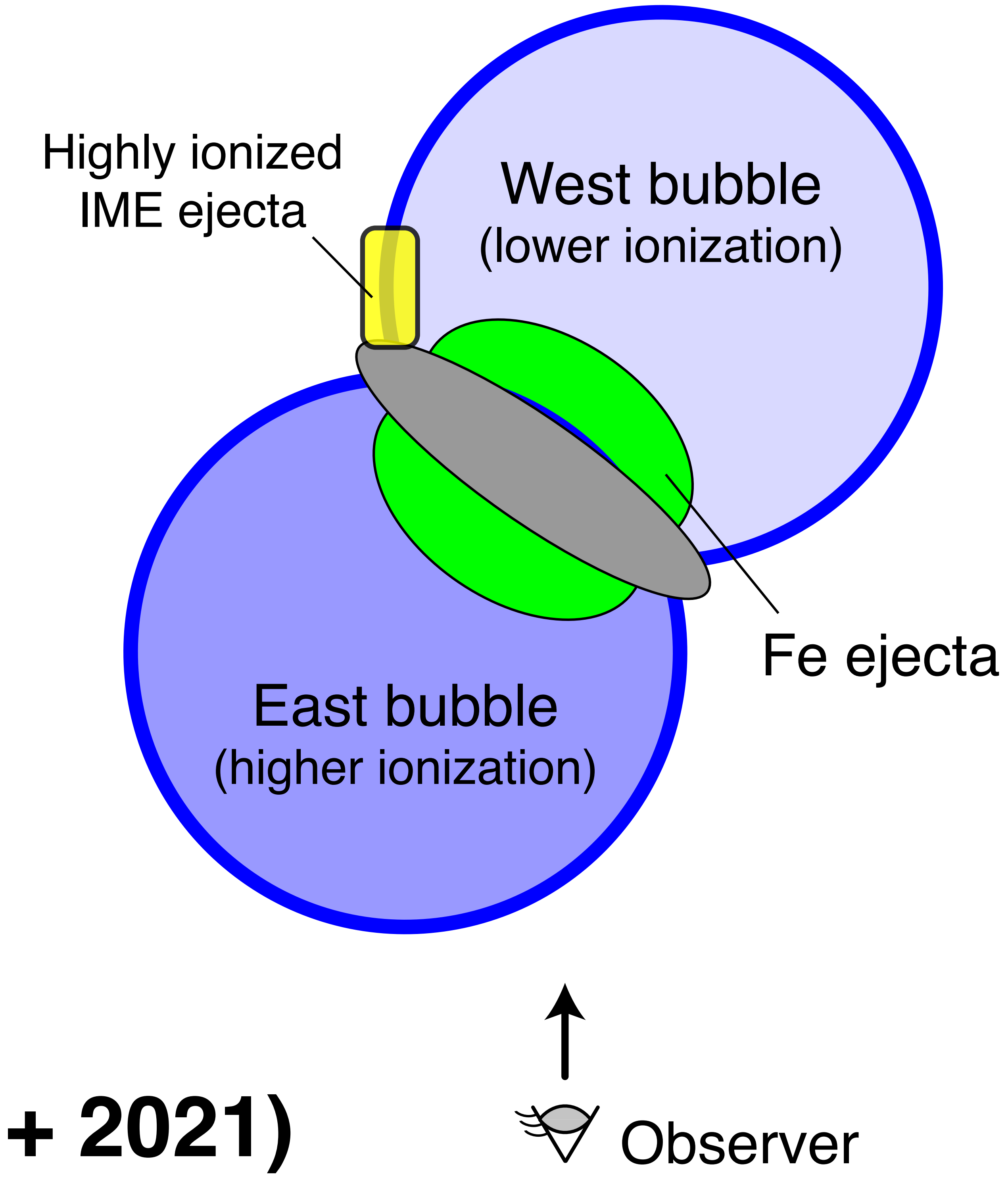
Bipolar structure could be formed in a Type Ia SNR if it exploded in torus-like CSM, but W49B is "too bipolar"!



(Hachisu+2008)



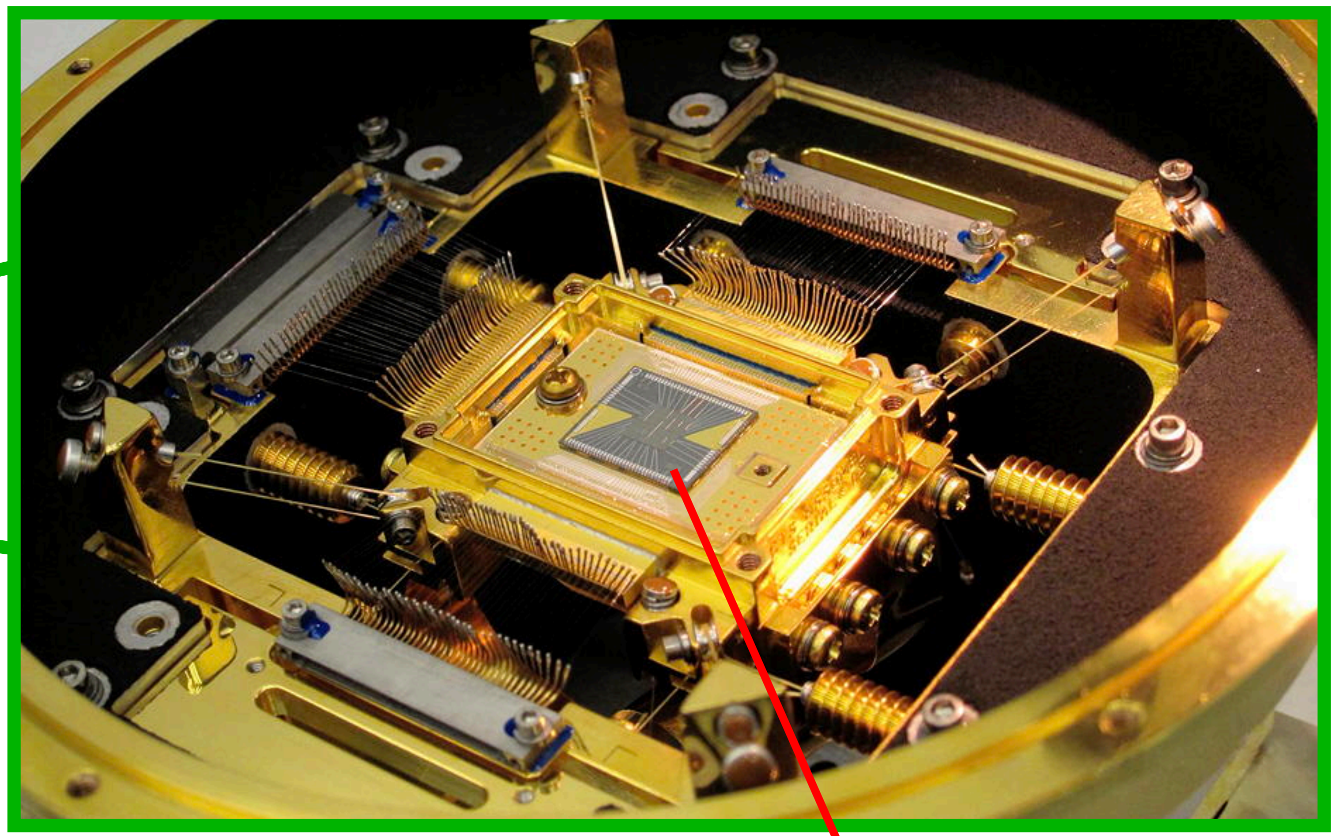




N103B (Yamaguchi+ 2021)

Instruments on board XRISM

Resolve (X-ray microcalorimeter)

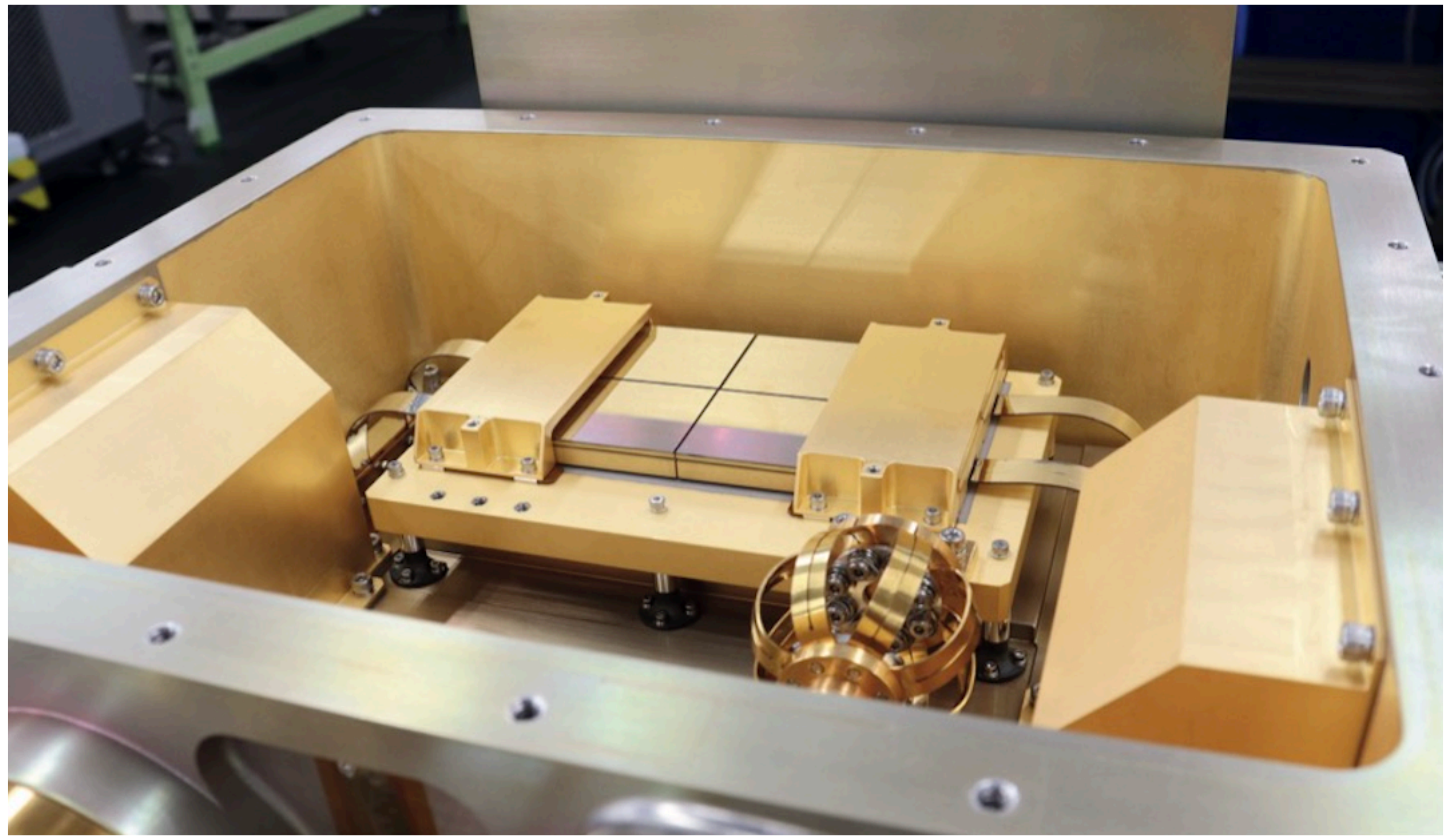


sensor array

Operating at 50 mK

High spectral resolution
~5 eV @2-10 keV

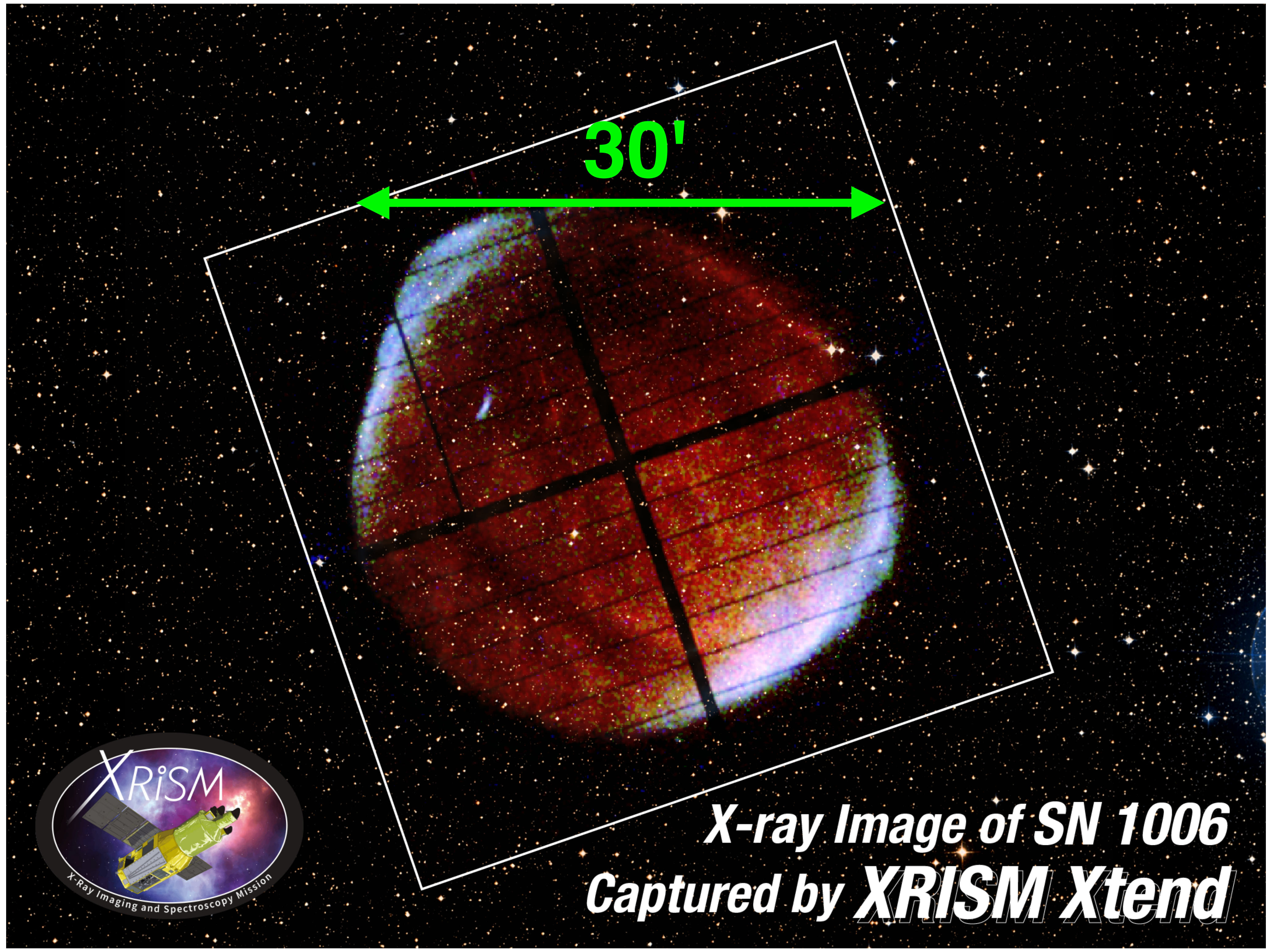
Xtend (X-ray CCD)

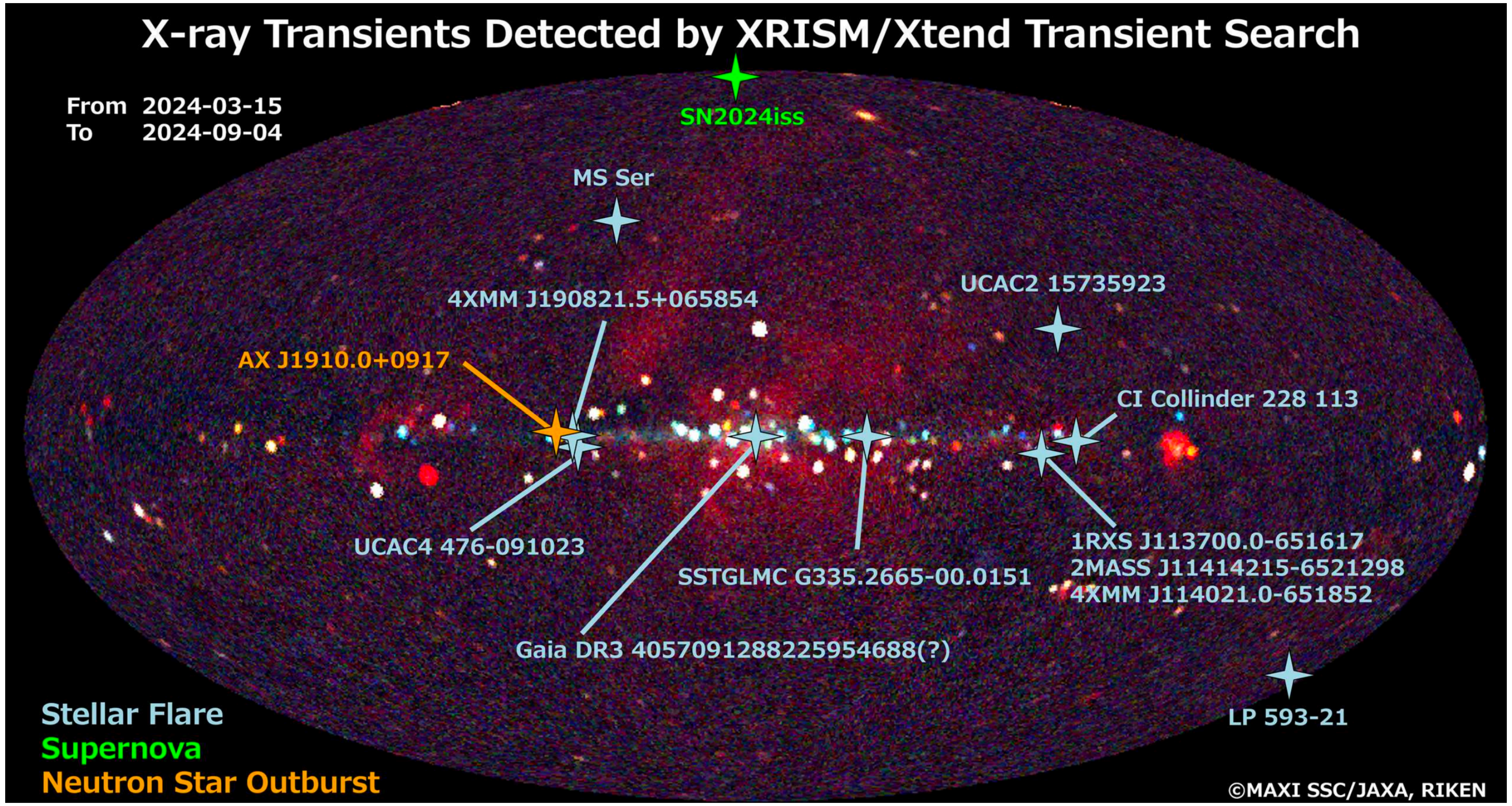


Wide field of view
38' x 38' (> full moon)

cf. Resolve's FoV: 3' x 3'

Many transients discovered



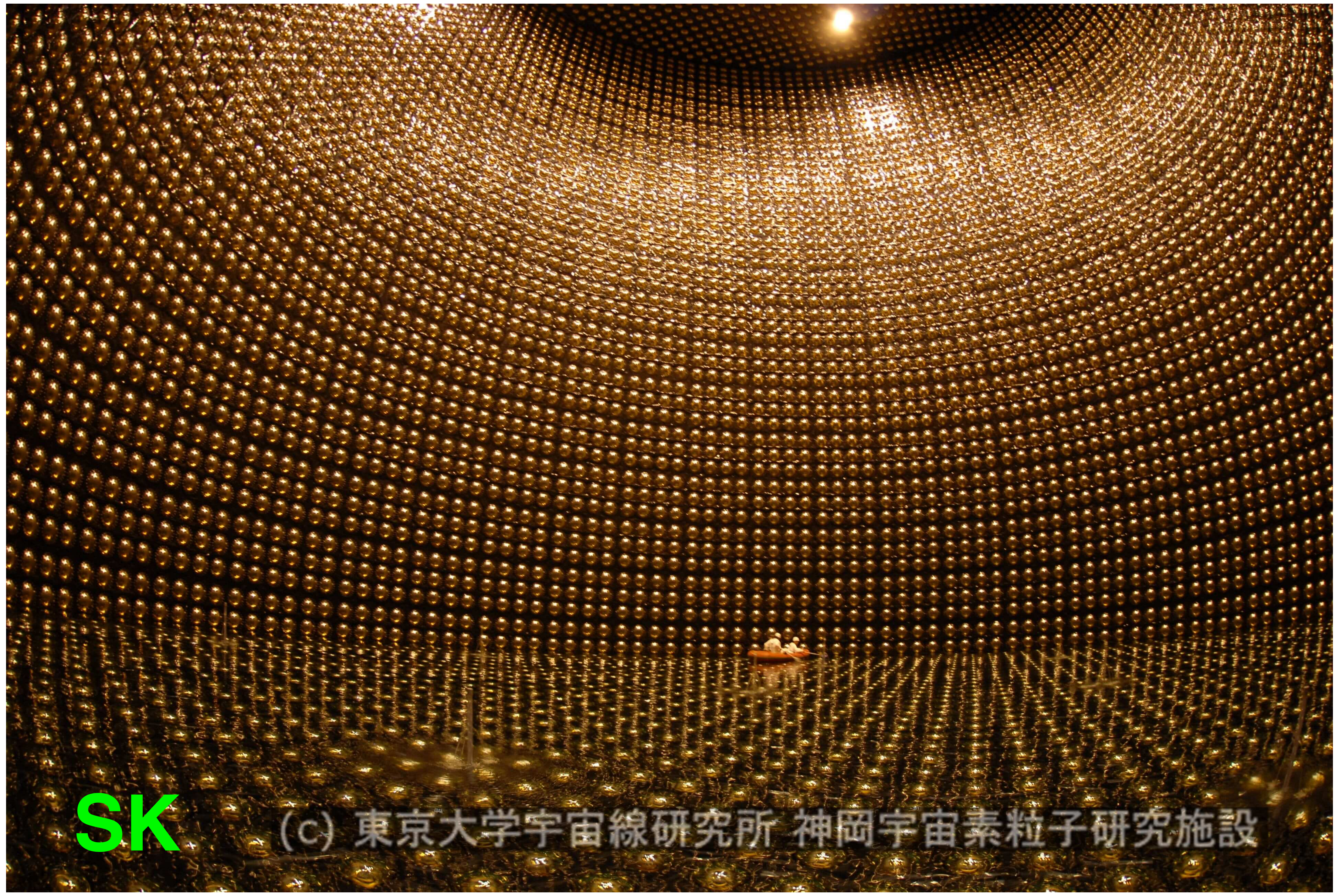


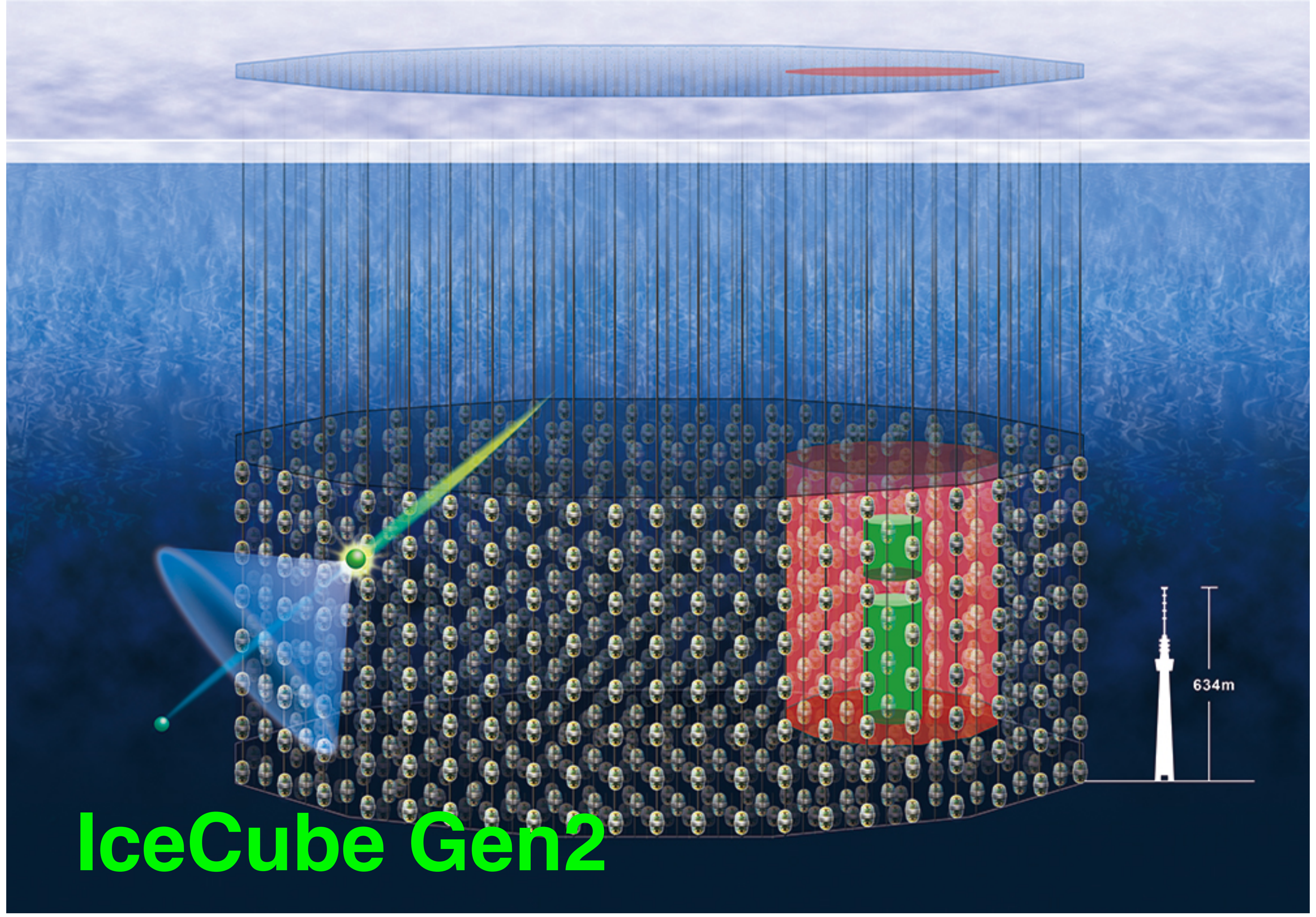
Mostly stellar flares so far

Good for SN/GRB observations as well

XRISM for MM astronomy

Started discussion for future collaborations with Super-Kamiokande and IceCube teams (Lead: H. Uchida)





Hoping to detect shock breakout / neutrino-source counterparts

Conclusions

- XRISM is providing us new insights into SNRs' progenitors and explosion mechanism.
- Cas A: High abundances of Cl and K (and perhaps high velocity of O-burning ejecta) indicate that "shell merger" took place before explosion.
- Cas A: Spherical asymmetricity in O-burning ejecta velocity and its relation with NS proper motion are confirmed.
- W49B: Peculiar SNR with bipolar flow of Fe ejecta and lack of Ti. No single model explains all the observational characteristics.
- XRISM makes theorists busy!

Announcements

General Observer program Cycle 2

Due: 4:30 p.m. JST May 15, 2025

First international conference

Oct 20-24, 2025, in Kyoto

Presentations on theoretical studies and MWL/MM observations are super welcome!

Save the date!