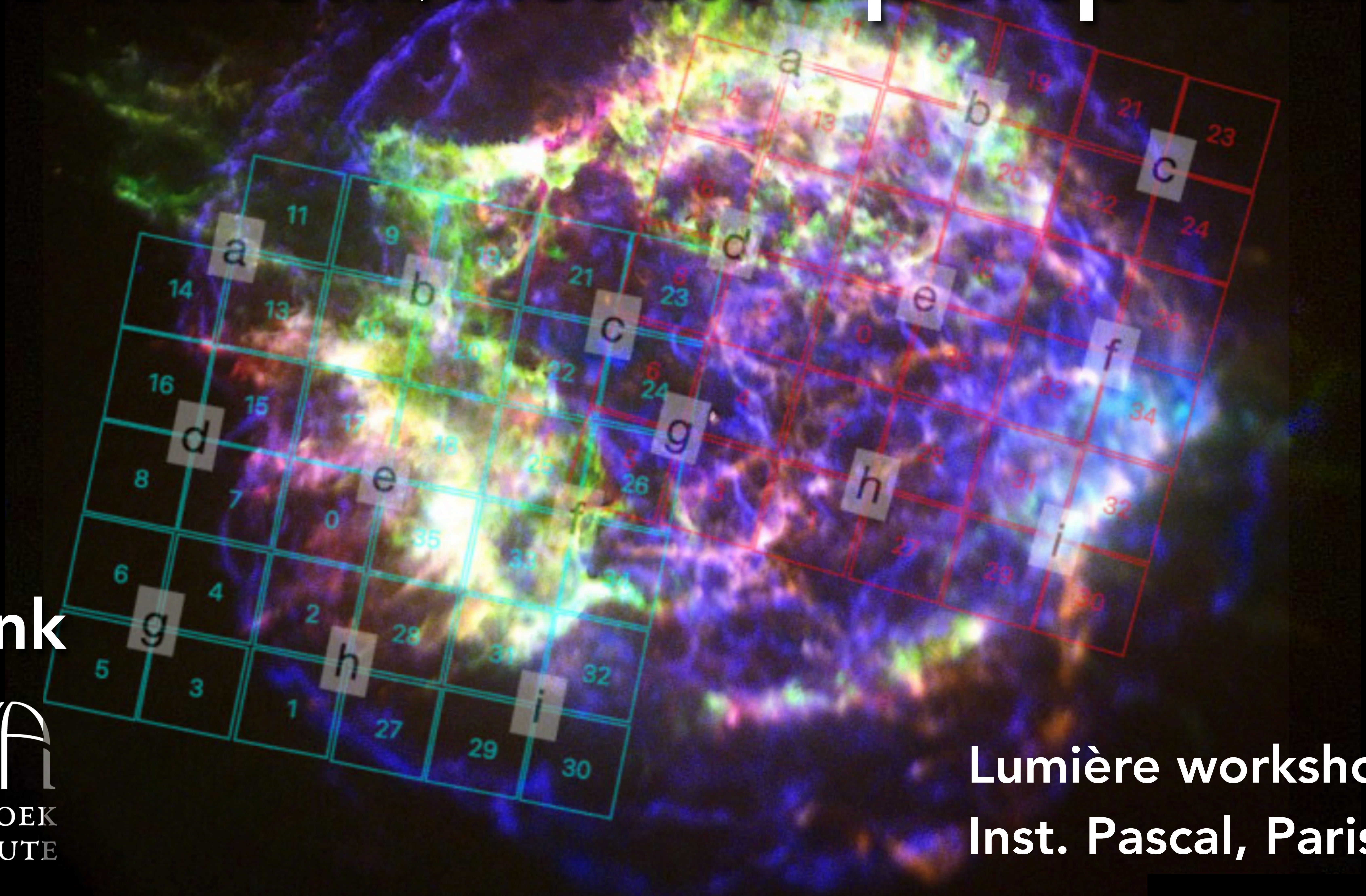
X-ray emission from supernova remants the XRISM/Resolve perspective



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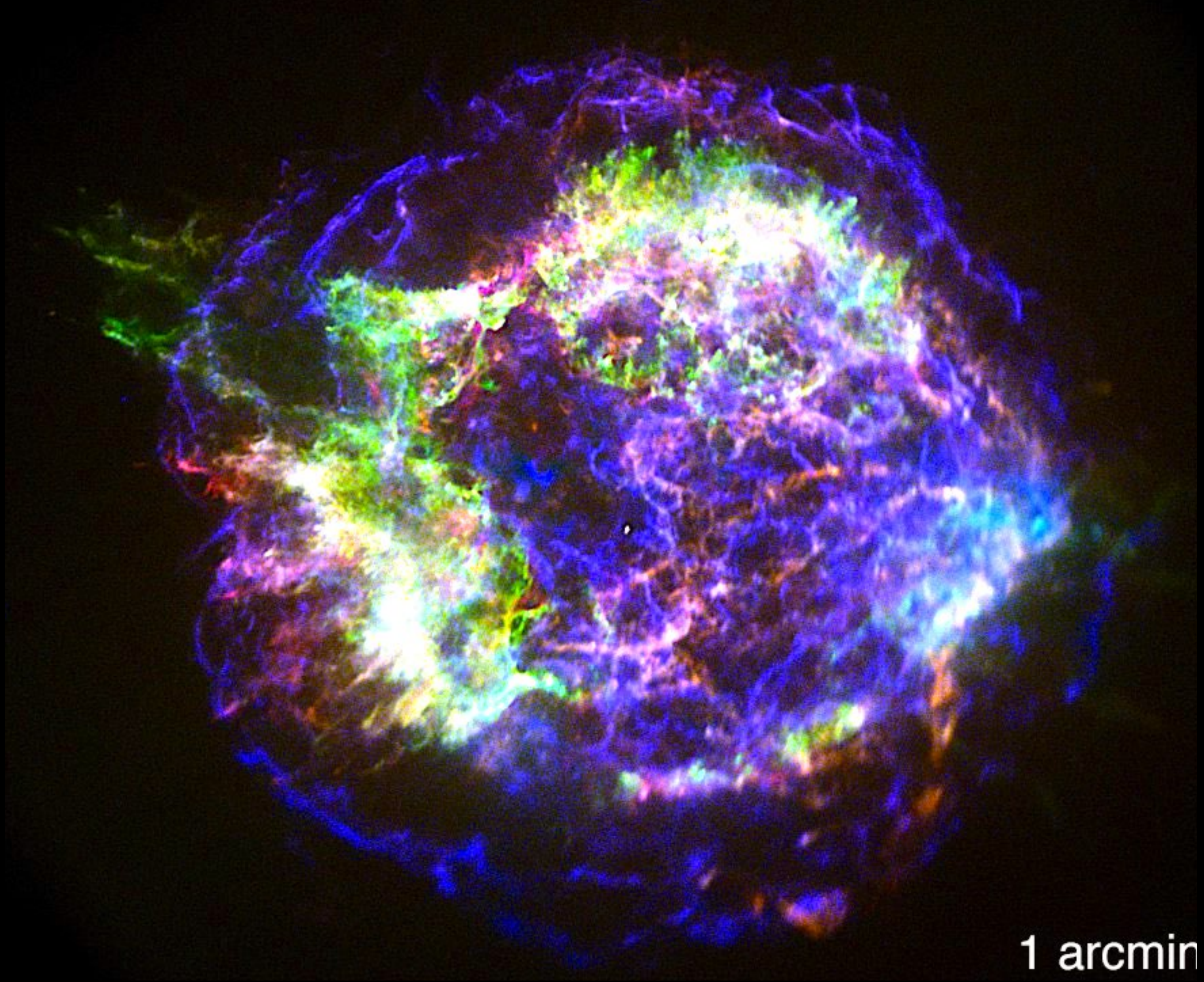
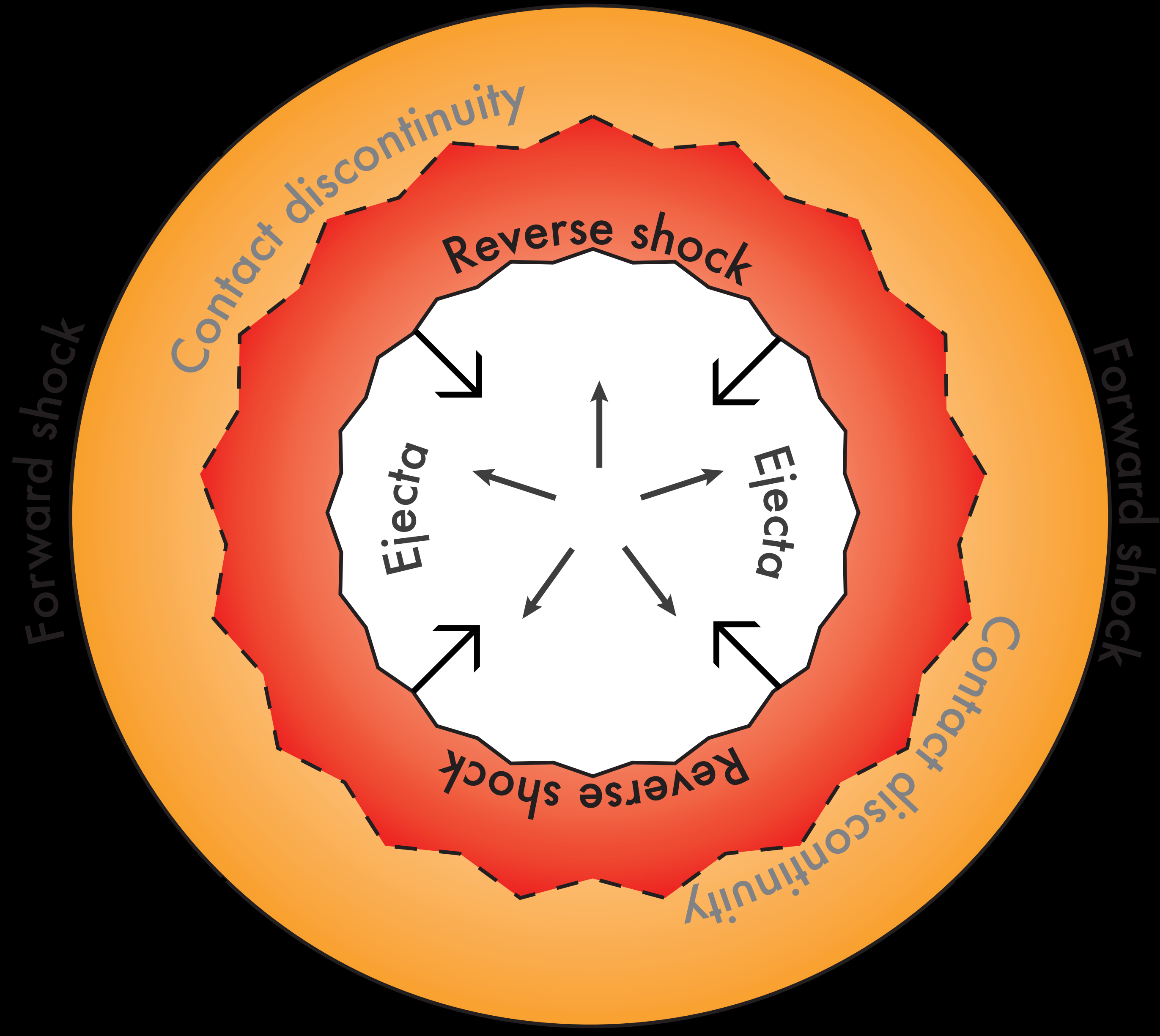
ANTON PANNEKOEK INSTITUTE

Lumière workshop 12-1-2026
Inst. Pascal, Paris/Saclay

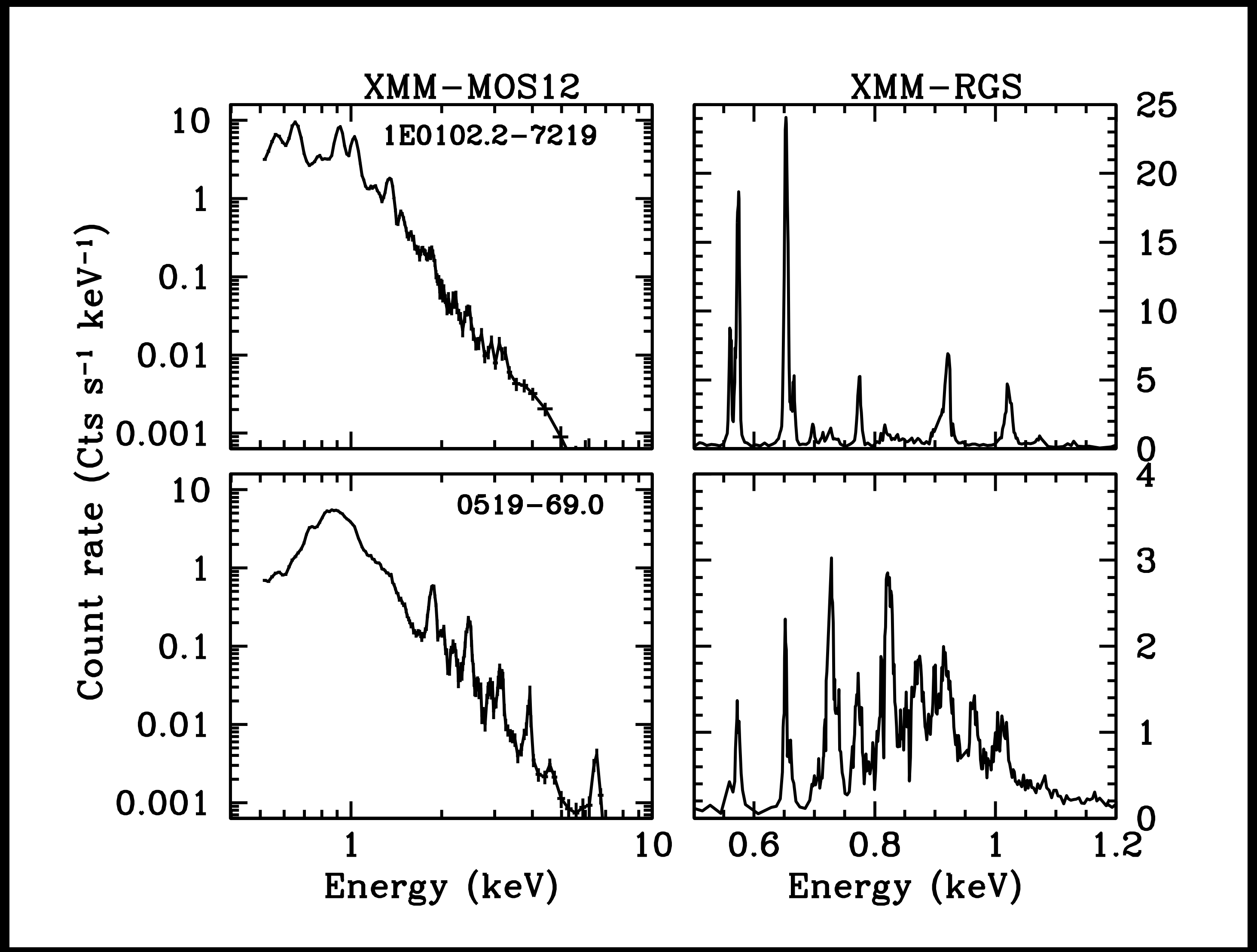
Supernova remnant science

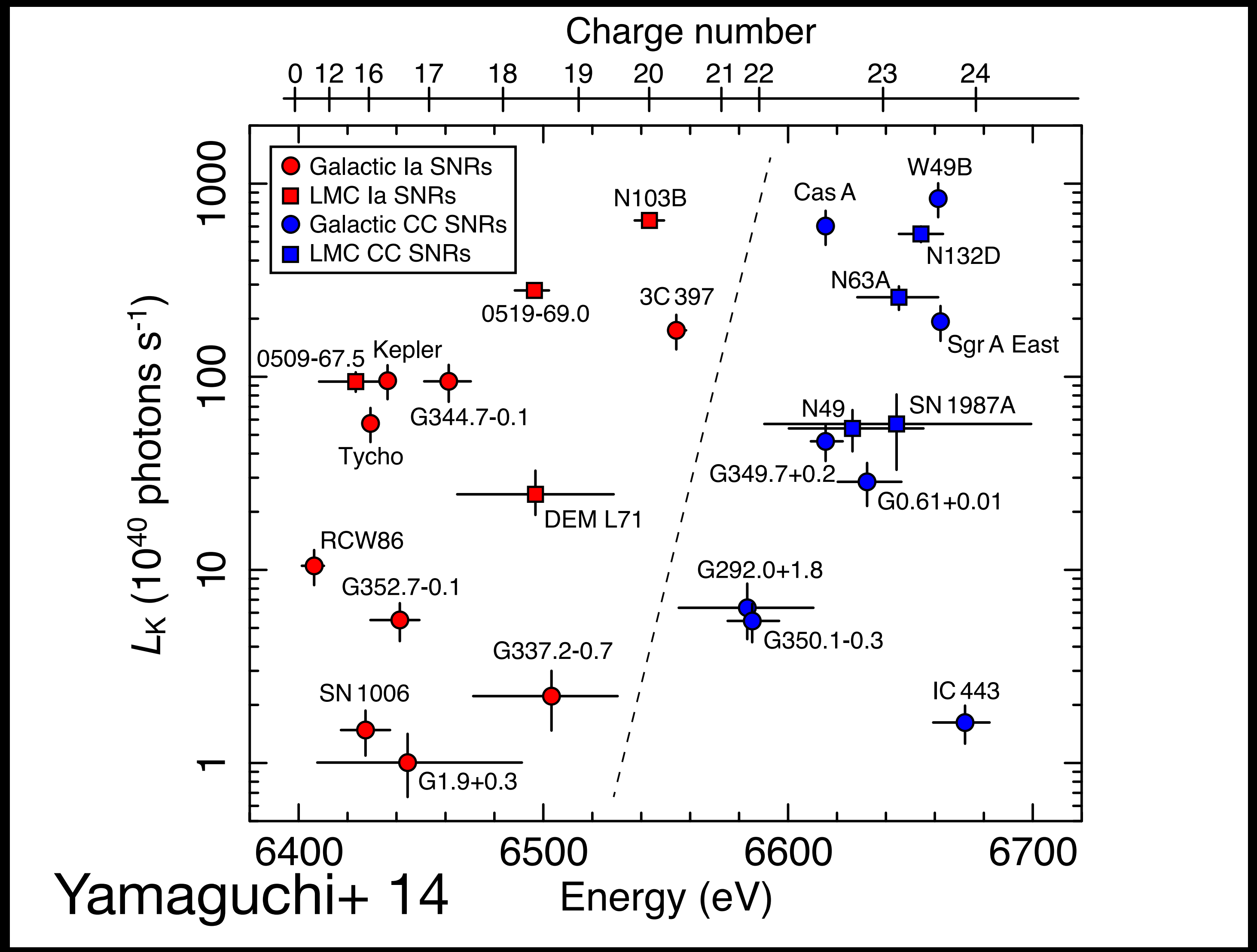
- Study explosions & nucleosythesis products”
  - X-rays: all elements Z~8 - 28
  - Type Ia vs core-collapse explosions?
  - Explosion (a)symmetries (3D)
  - Connection with neutron stars/pulsars
- Study last stellar phases CCSNe: CSM interactions
- Collissionless shock physics:
  - cosmic-ray acceleration & magnetic fields
    (X-rays: synchrotron radiation)
  - non-equilibration electrons/ions
- Non-equilibrium ionization





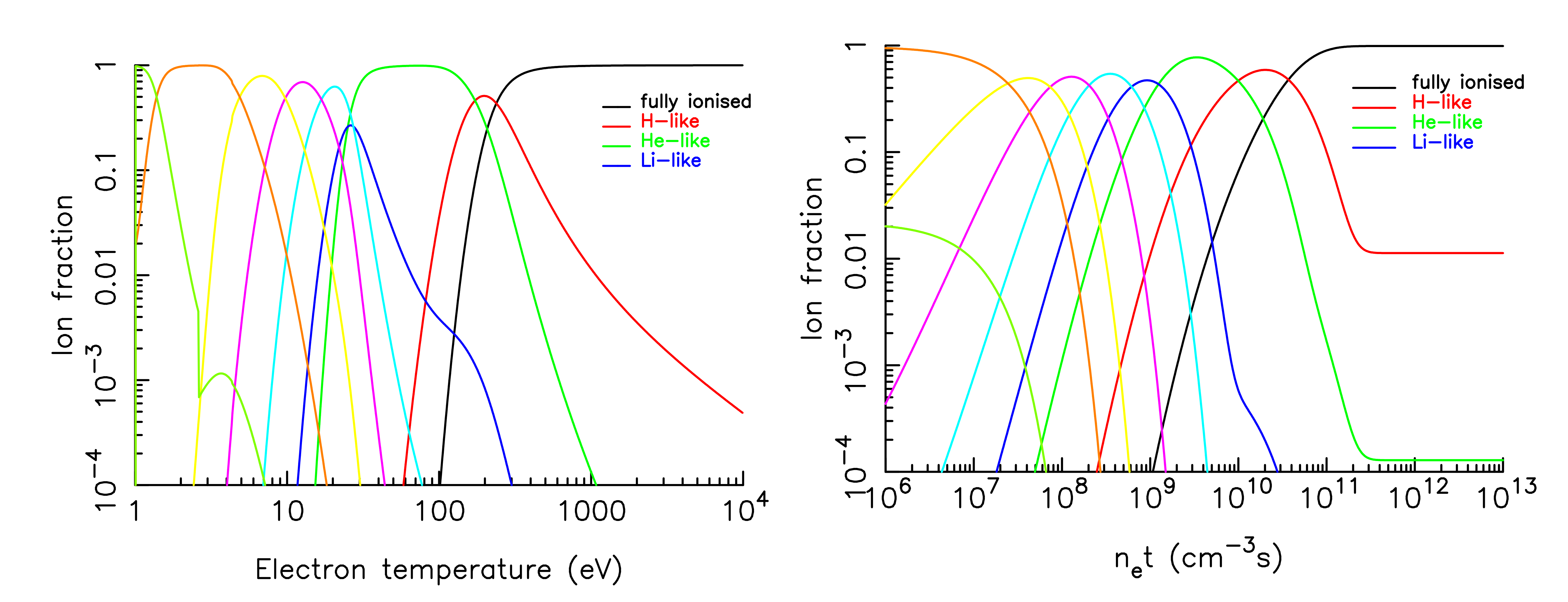
X-ray nucleosynthesis studies





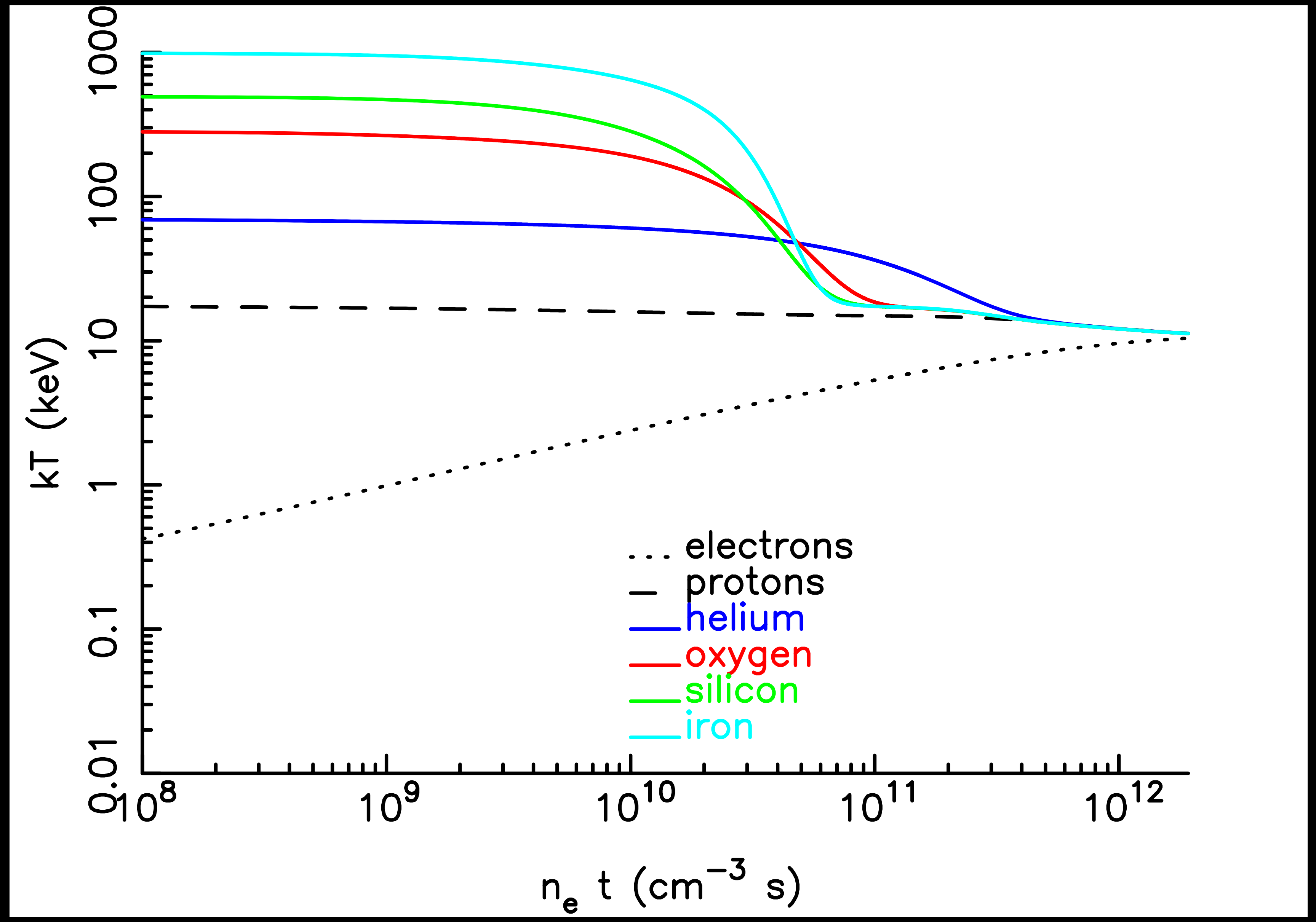
- Young *core-collapse* SNRs: **prominent O, Ne, Mg**
  - beware: ~0.1M_{sun} of may provide strong Fe-K features
  - alpha-rich freeze out products
  - large diversity
- Young *Type Ia* SNRs: **prominent Fe**/Ni, strong Fe-L complex, also IME
  - expect high Mn/Cr ratio for Chandrasekhar explosions
- Additional diversity: how much did reverse shock move into ejecta?

Non-equilibrium ionization



- Not(?)-encountered in other optically thin hot plasmas:
  - Ionization state determined by kT_e & $n_e t$ (time and electron density)
- Most SNRs: plasma is underionized (hotter than indicated by ionization)
  - not enough time to reach equilibrium
- Some mature SNRs: underionized
  - Electrons must have cooled, ionization lagged behind
  - Unclear what caused cooling: adiabatic expansion, heat condution?

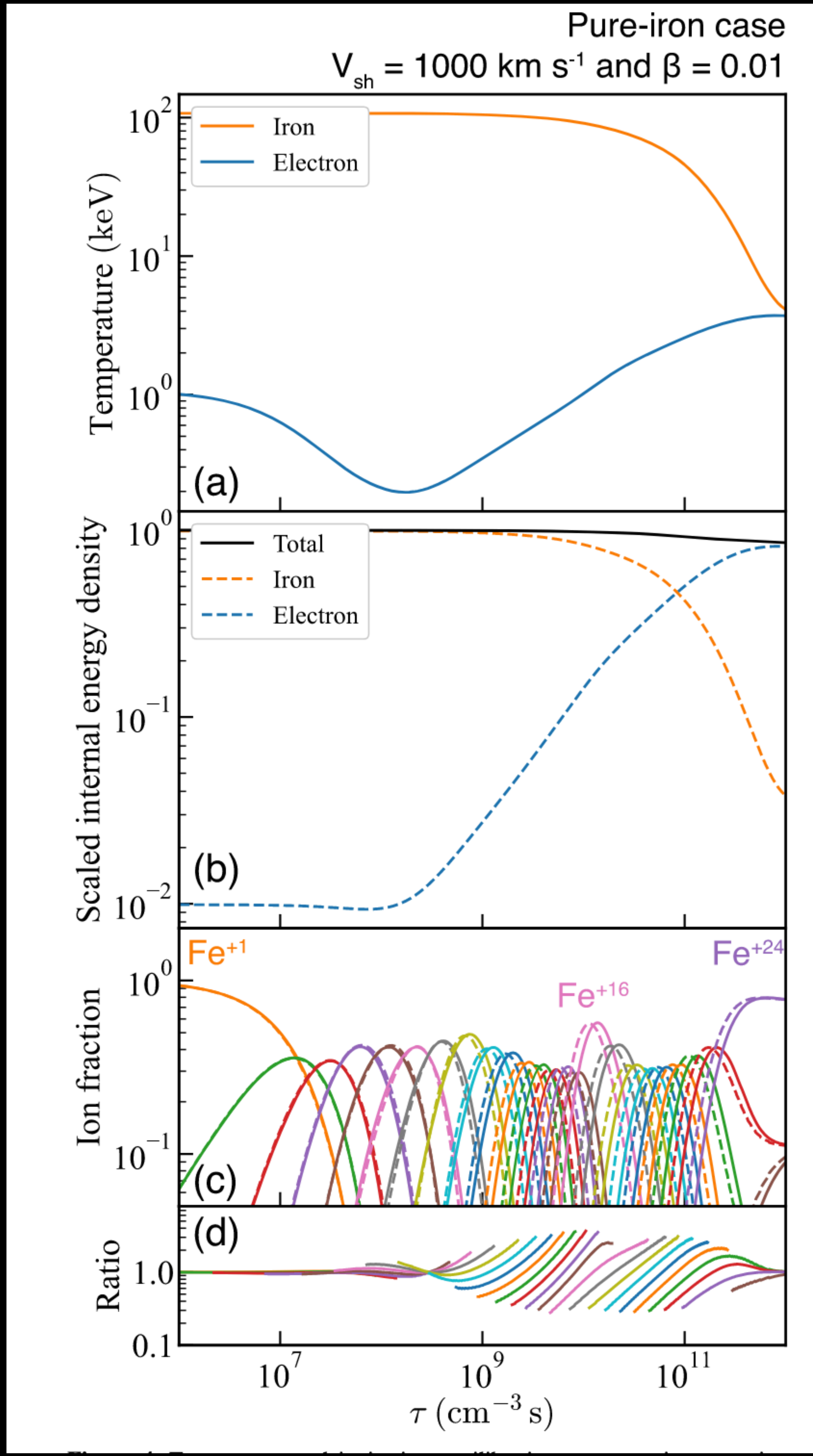
Collisionless shocks & electron/ion non-equilibrium



- Shock heating: preserving mass/momentum/energy flux accross shock
  - Strong shock: $\rho_2 = 4\rho_1,\ kT = \frac{3}{16}\mu m_p V_s^2 \approx 30\ \left(\frac{V_s}{5000\ \mathrm{km/s}}\right)^2 \mathrm{keV}$
- Collisionless heating: not by particle-particle collisions, but *collective* effects
- Fast collisionless shocks: $kT_e = \beta kT_{ion},\ \ \beta < 1$ (typically $\beta \lesssim 10\,\%$)
- Subsequently slow Coulomb equilibration kT_e & kT_{ion}
- Cosmic-ray acceleration may drain more energy: $kT_{ion} = (1 - w_{cr})\frac{3}{16}m_{ion}V_s^2$

Further complications: pure metal plasmas

Oshiro+ 24

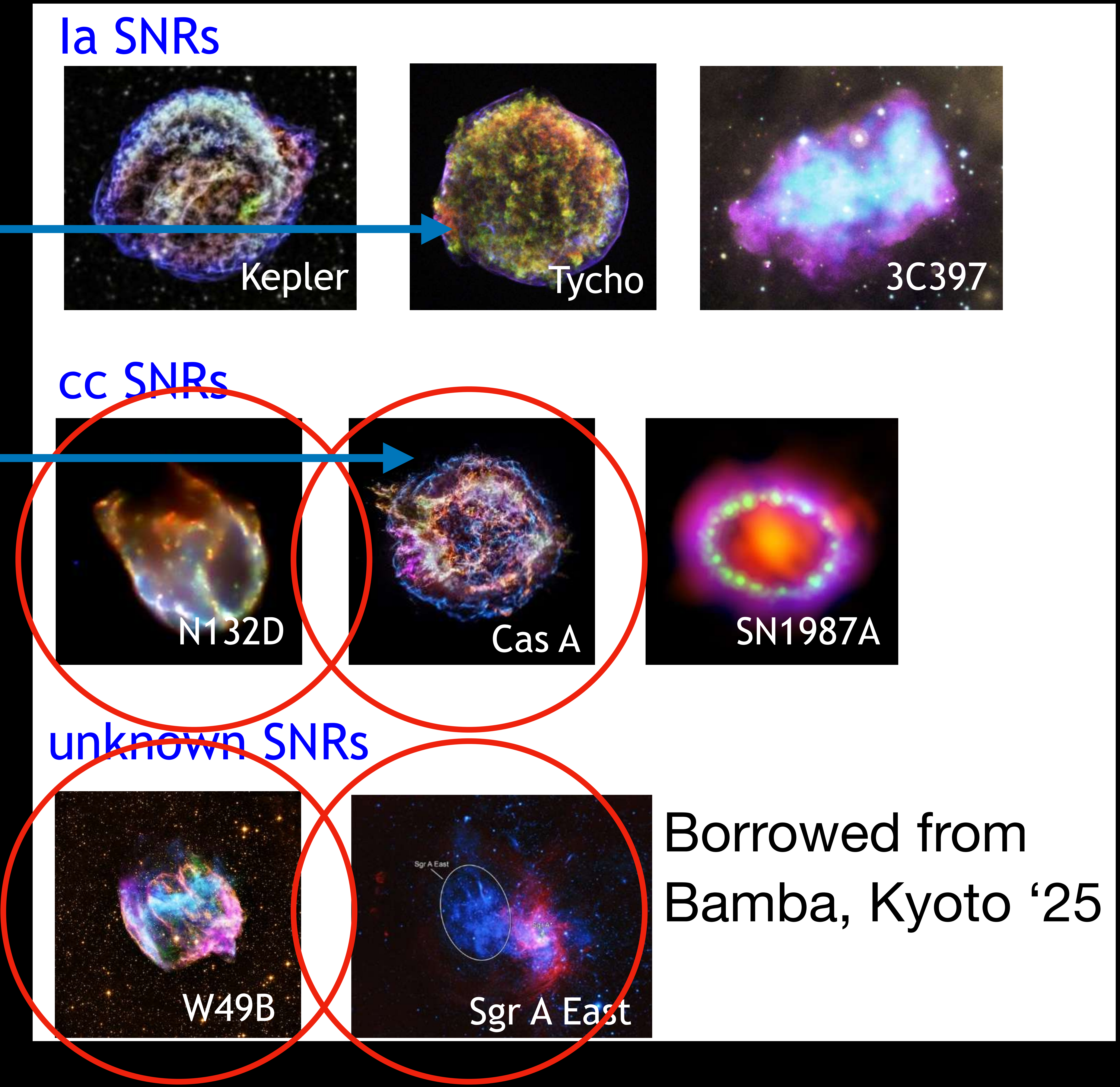


- Young massive core collapse/Type Ia: no hydrogen in plasma
- Reverse shock velocity poorly known
  - $V_{rs} = \left| \frac{R_{\rm rs}}{t} - \frac{dR_{\rm rs}}{dt} \right|$
- As ionization progresses:
  - more electrons -> divide same energy over more particles + ionization losses
  - Coulomb exchanges enhance due to Z^2 dependence
  - need to keep track of ionizations

XRISM observations of SNRs and what we learned

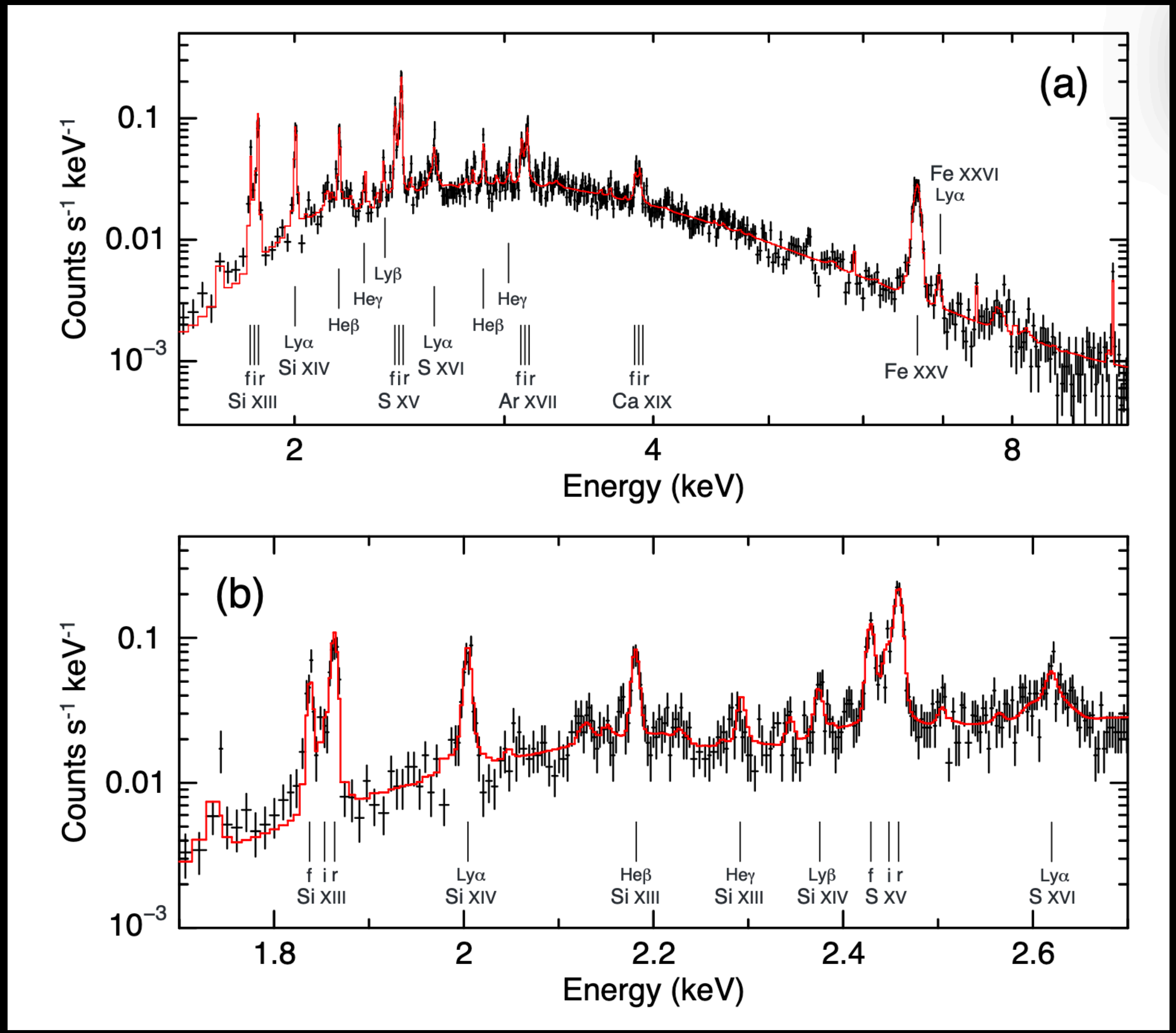
Giuffrida

Agarwal

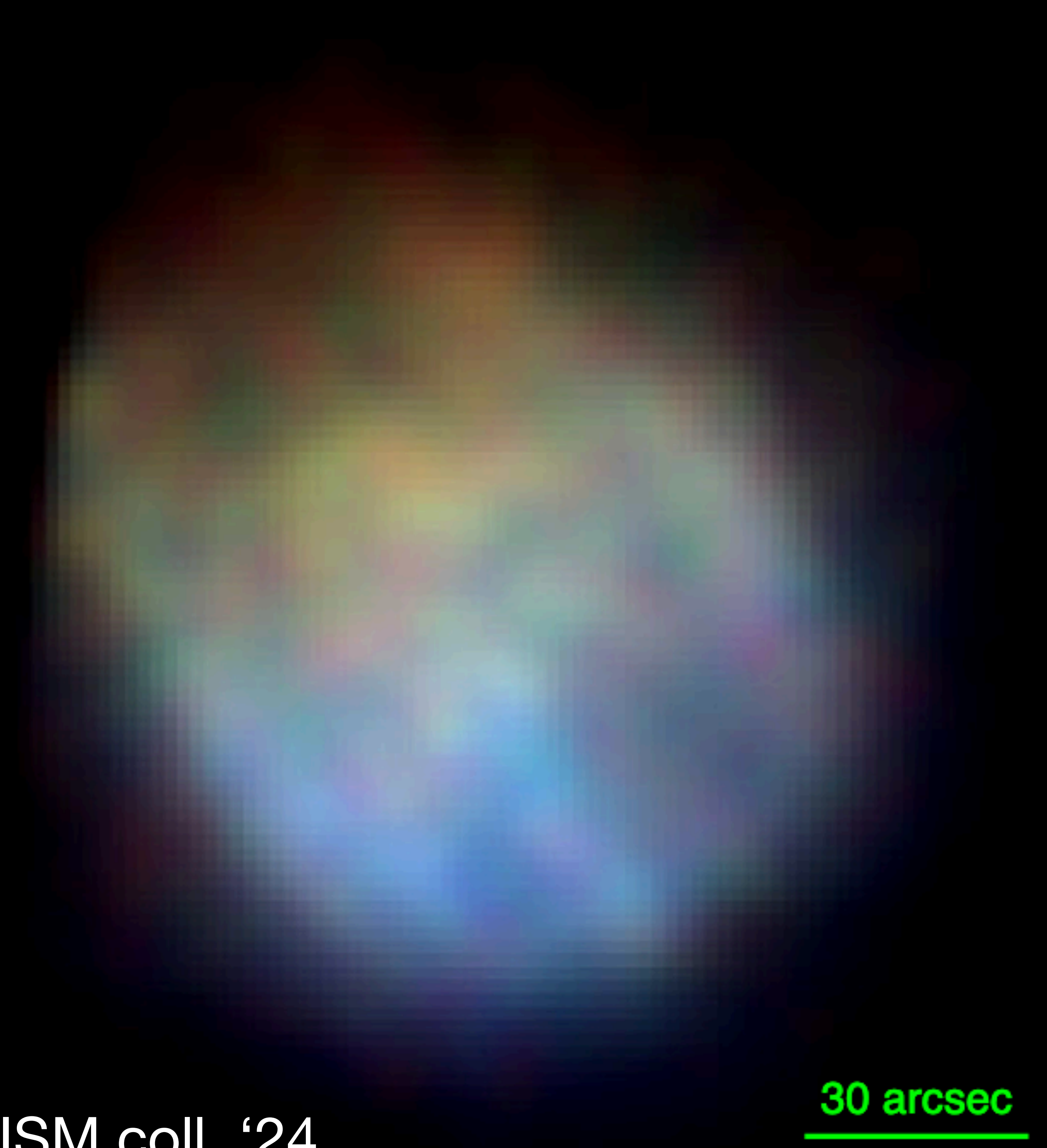


- Launch: Sept 7, 2023
- Concentrate on Resolve:
  - $\Delta E \approx 4.5 eV$
- Bummer! Gate-valve closed:
  - No X-rays below 2 keV
  - PV phase changed: hard spectra

XRISM First light: LMC N132D



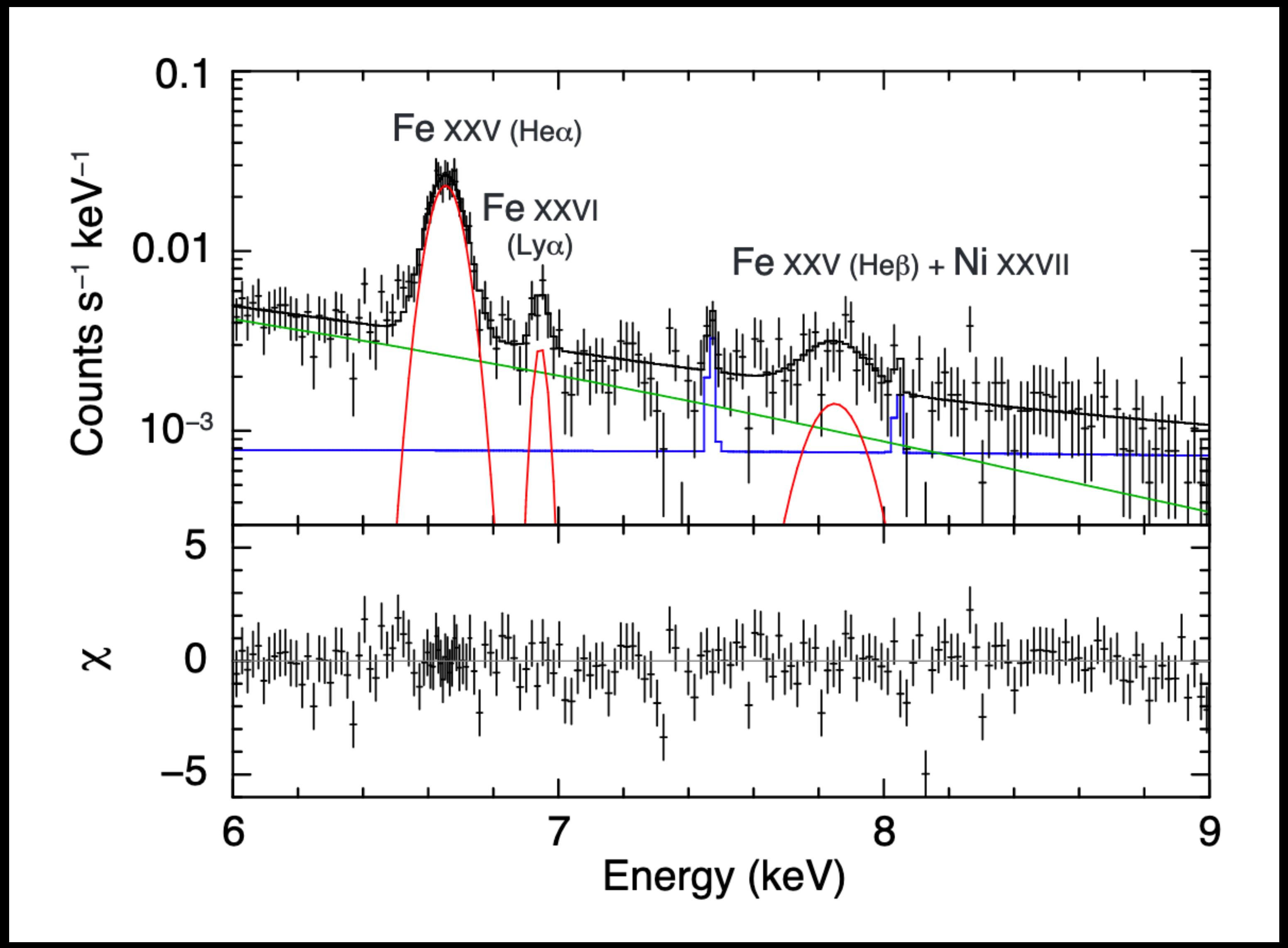
XRISM coll. '24

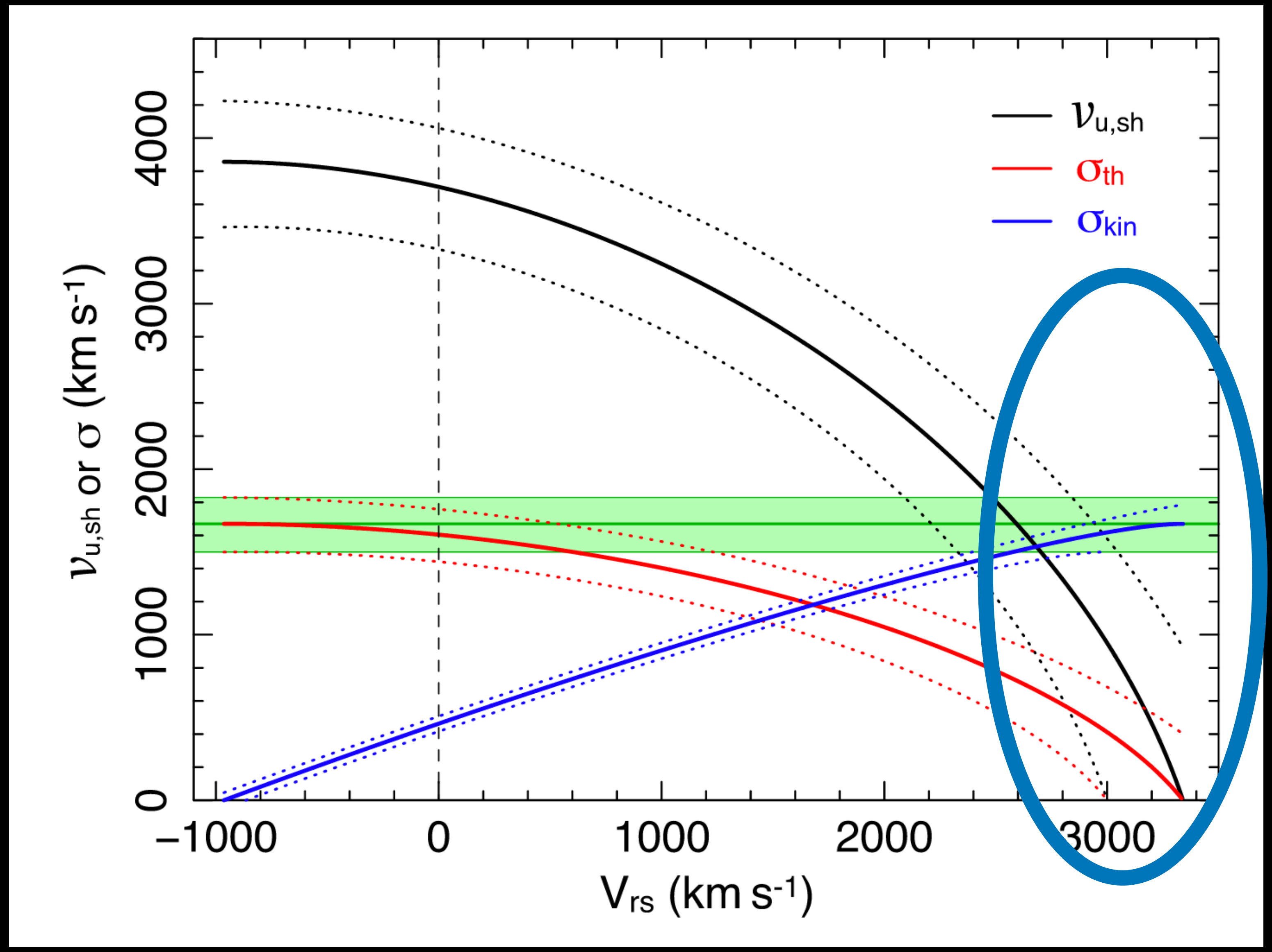


- ~2500 oxygen-rich core collapse SNR
  - "Older cousin Cas A"
  - very energetic ~5x10^{51} erg (bright gamma-ray source)
  - Optical ejecta
  - X-ray appears CSM rather than ejecta dominated, except Fe-K

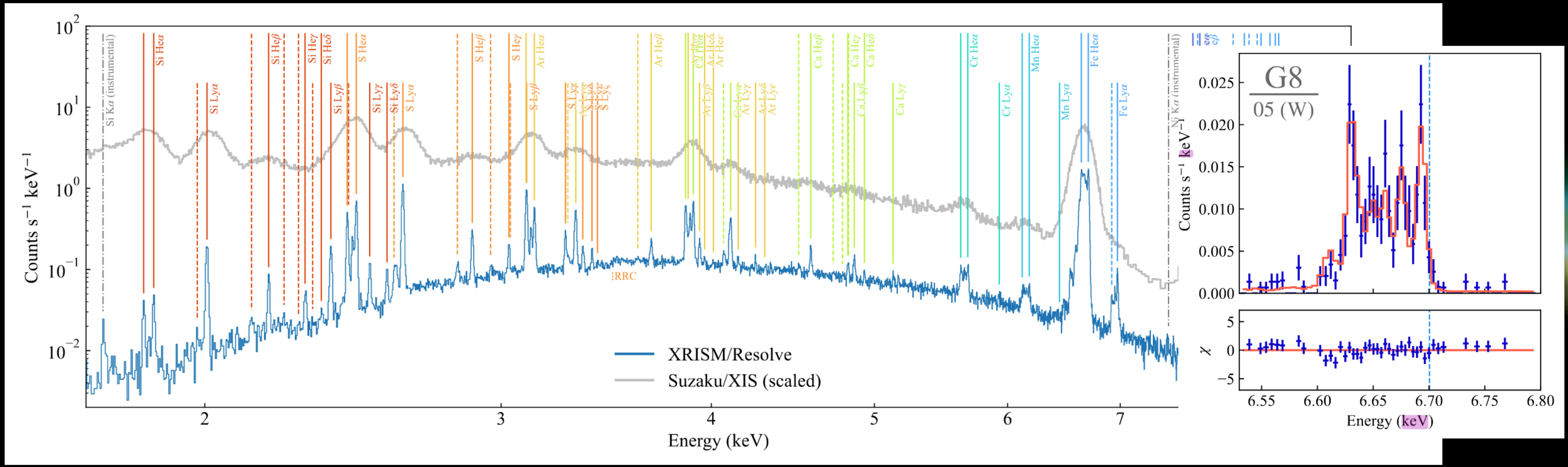
N132D: Evidence for thermal ion broadening

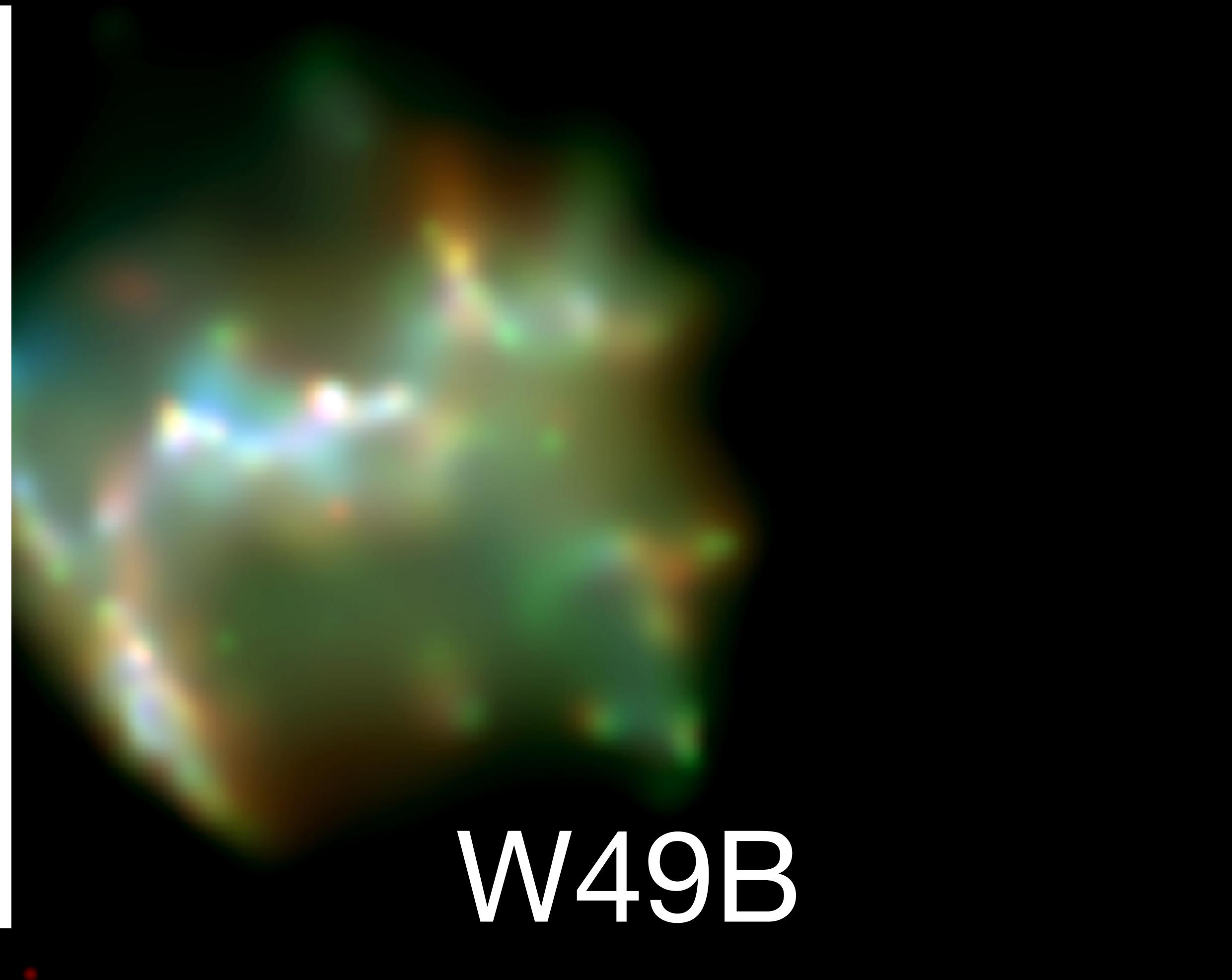
- Rich Fe-K physics:
  - H-like Doppler shift 900 km/s different from He-like
  - Fe-K Heα broadened, $\sigma_v = 1670 \pm 170$ km/s
- Most likely explanation:
  - Strong reverse shock
  - Likely dominated by thermal ion broadening
  - Only possible for pure metal plasma
  - Requires $V_{rs(ejecta\ frame)}$~3700 km/s



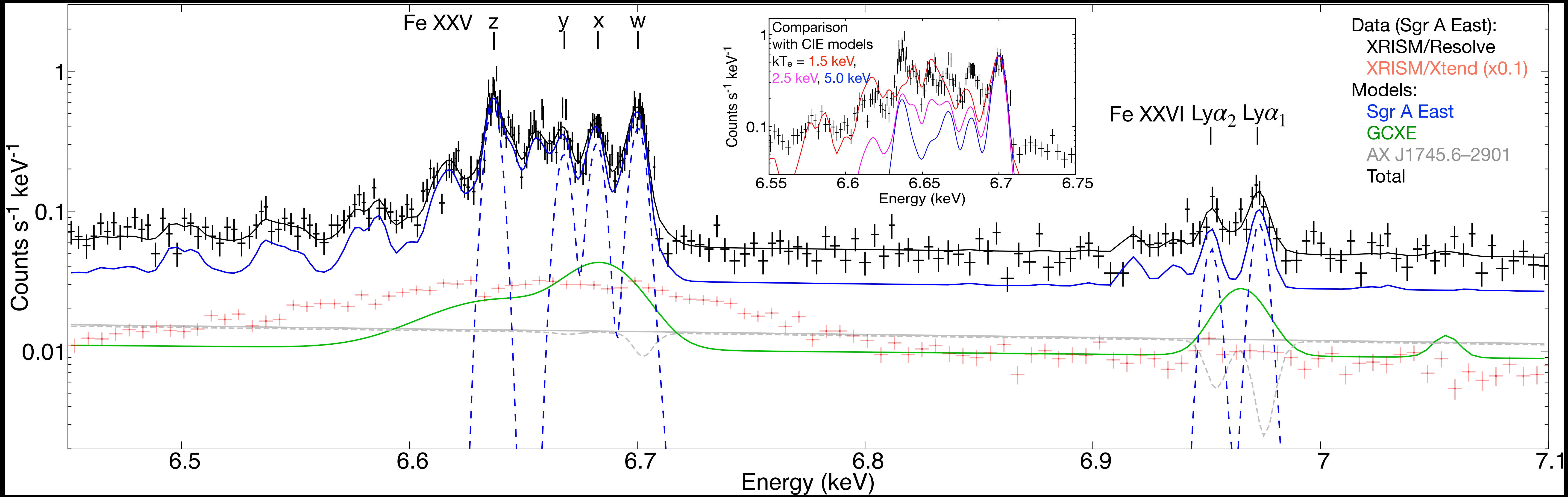


Two beautiful spectra of puzzling SNRs: W49B & SGR Aeast





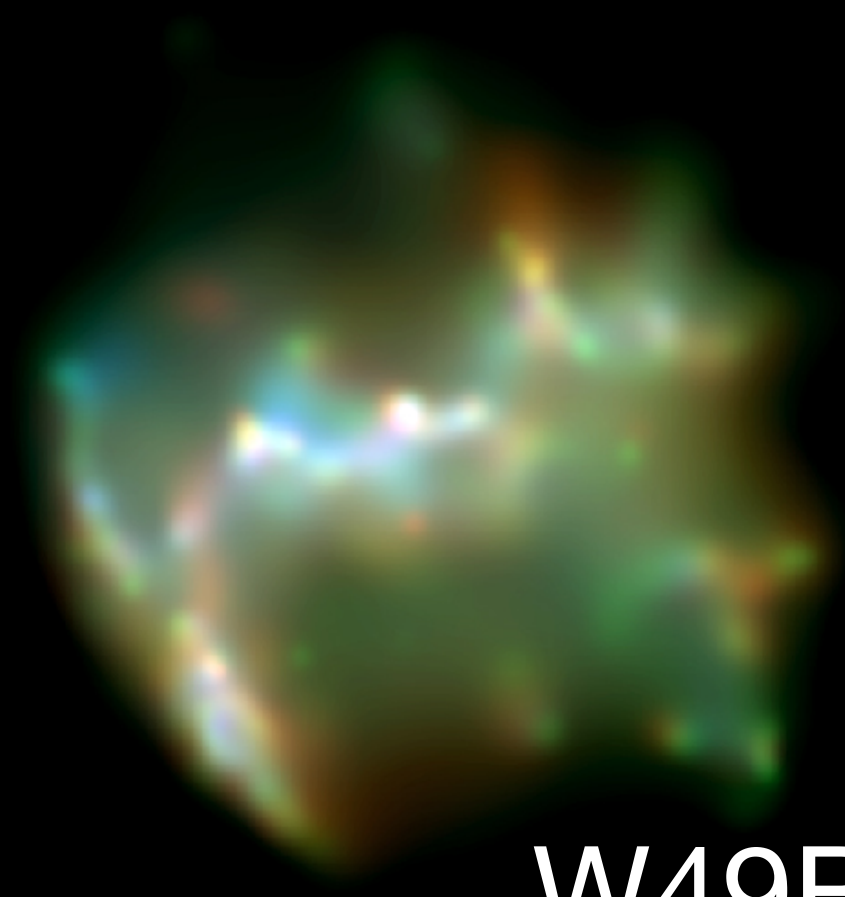
XRISM coll. '25



XRISM coll. '25

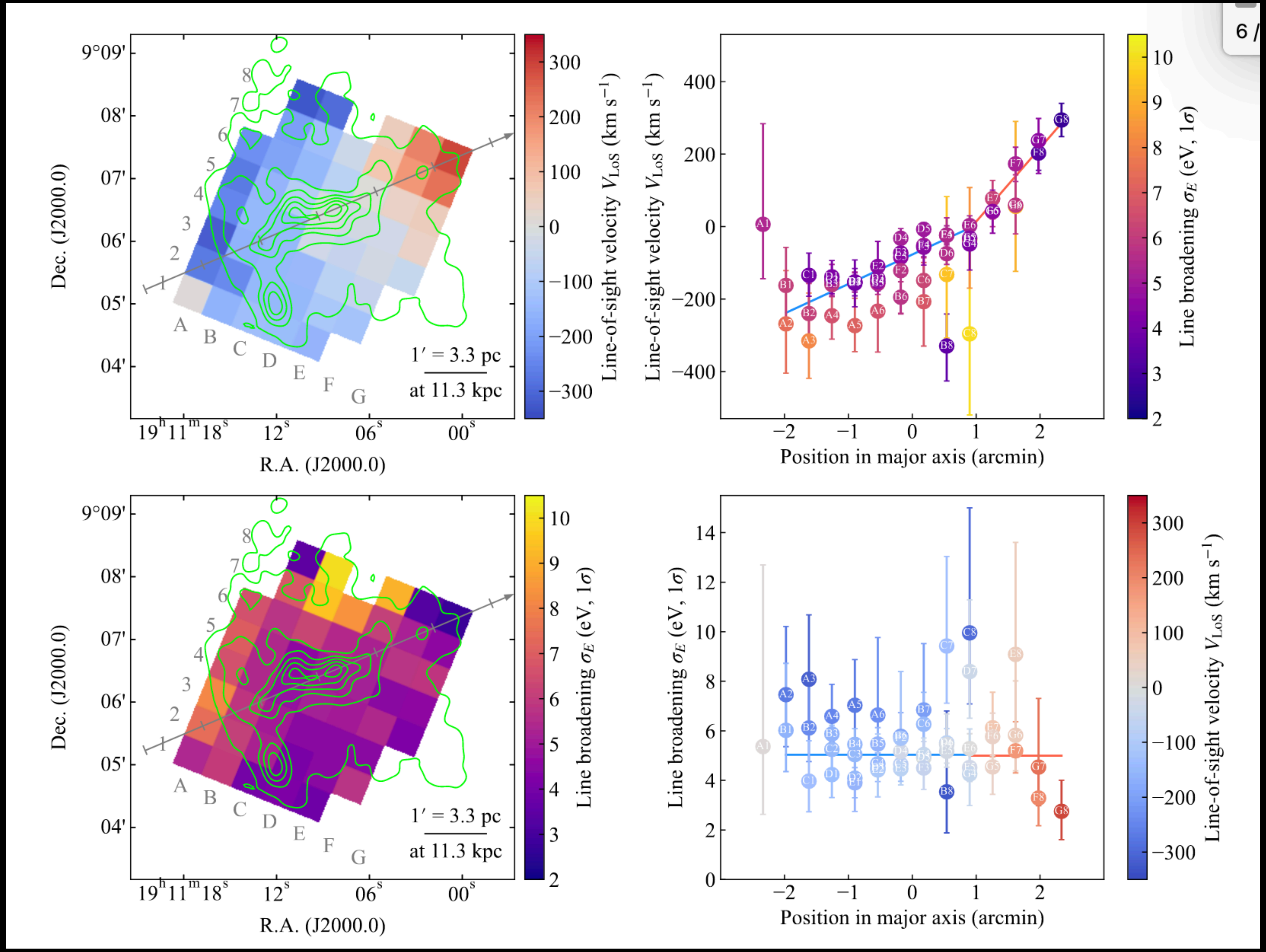
Two beautiful spectra of puzzling SNRs: W49B & SGR Aeast

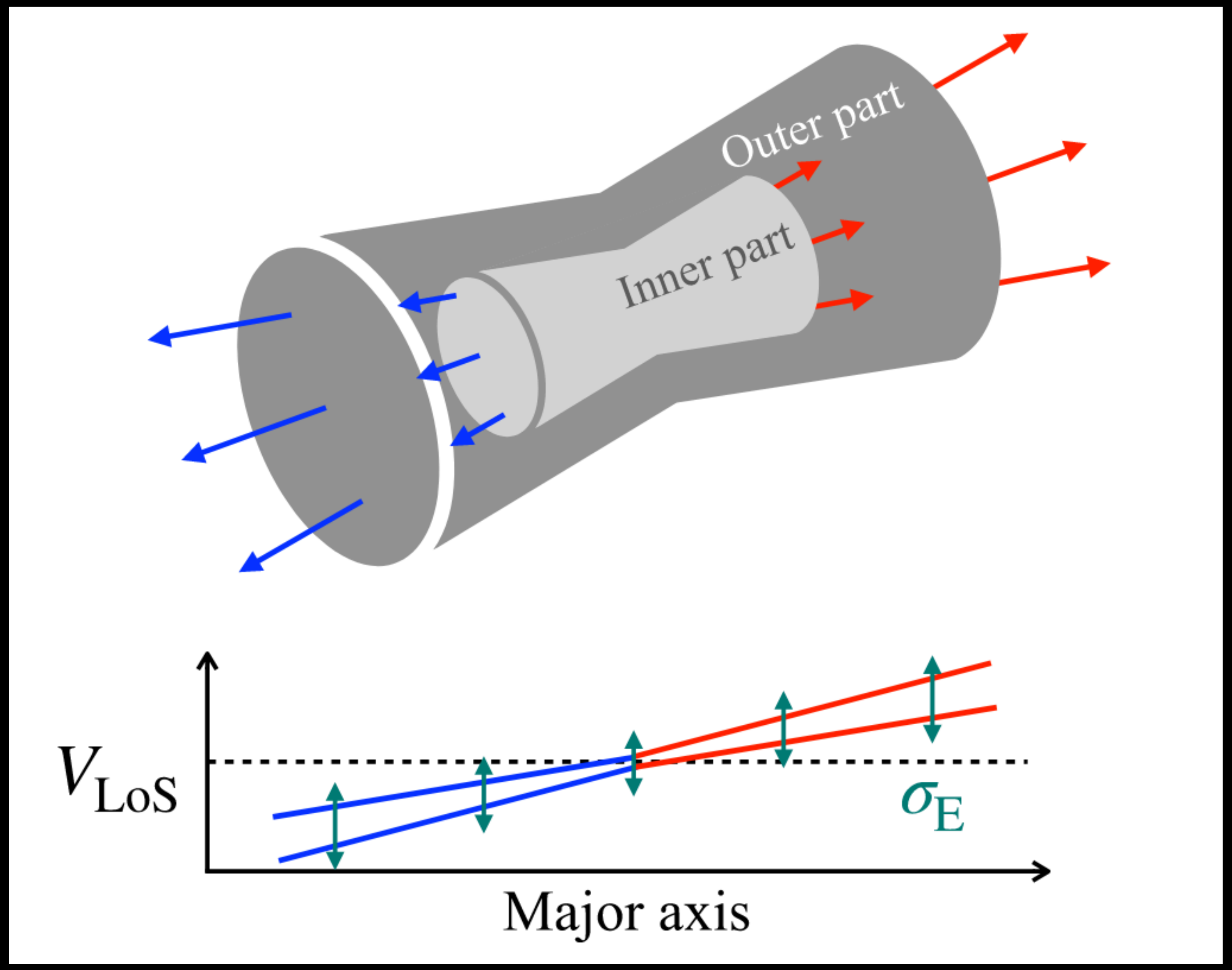
- Both are mixed-morphology SNRs
  - not much line broadening
- They have *over*-ionized plasmas
  - W49B: $n_{e}t = (1-6)10^{11}\ \mathrm{cm^{-3}s},\ kT_{e} \approx 4 \rightarrow 1.5\ \mathrm{keV}$
  - SGR Ae: $n_{e}t = 7.7 \times 10^{11}\ \mathrm{cm^{-3}s},\ kT_{e} \approx 10(\mathrm{fixed}) \rightarrow 1.7\ \mathrm{keV}$
  - Origin of over-ionization not known
- Explosion origin uncertain:
  - W49B: core collapse, GRB explosion, or Type Ia? (abundances favor Type Ia)
  - SGR A-east: Type IaX SNR? (Zhou+ 21)



W49B

Bipolarity in W49B

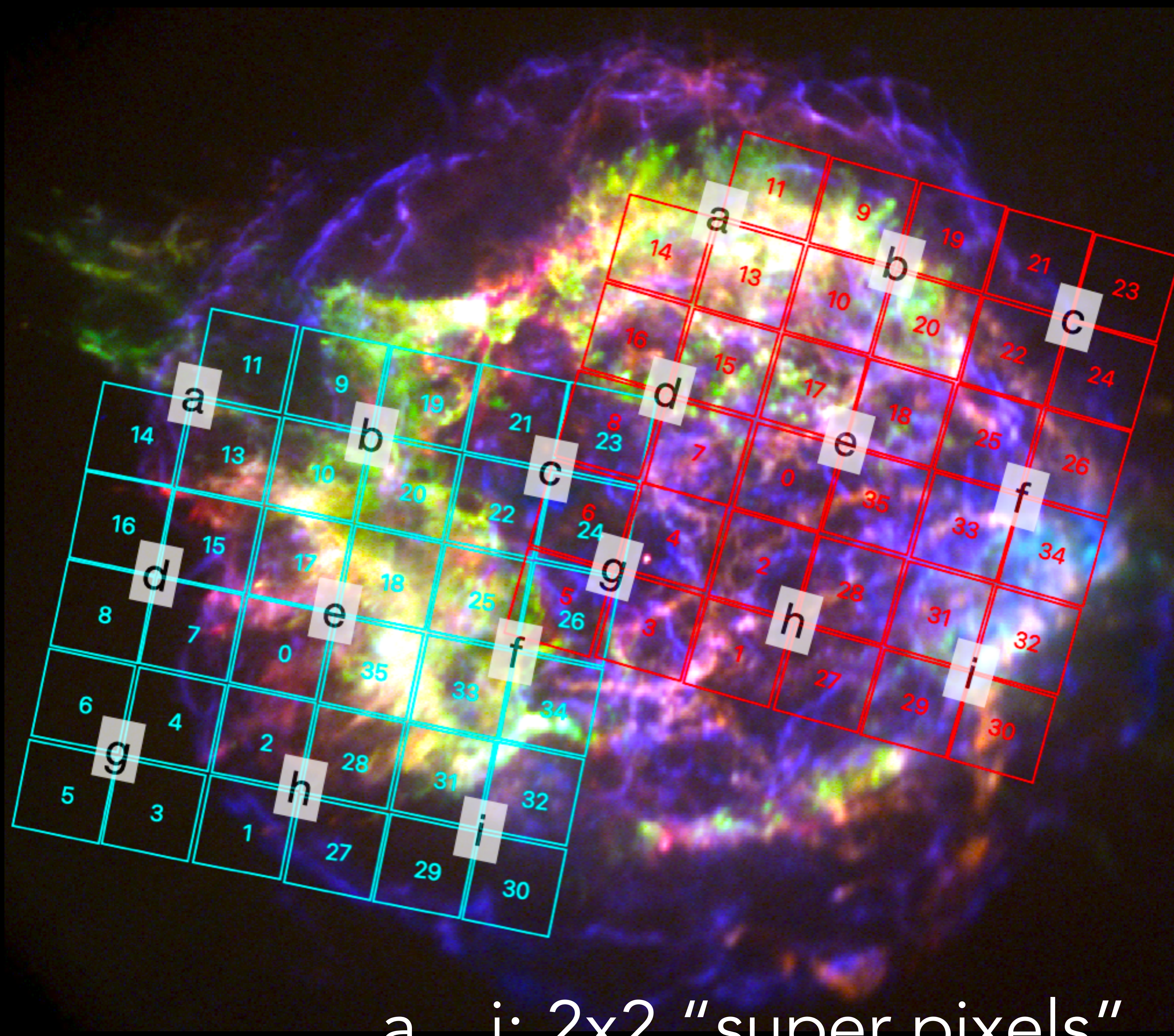




- W49B has a bar along which velocities change
- Suggests bipolar outflow
  - A jet? -> but if explosion created jet it, shouldn’t still be center?
  - Funnel created by reverse shock interaction?

XRISM/Resolve observations Cassiopeia A

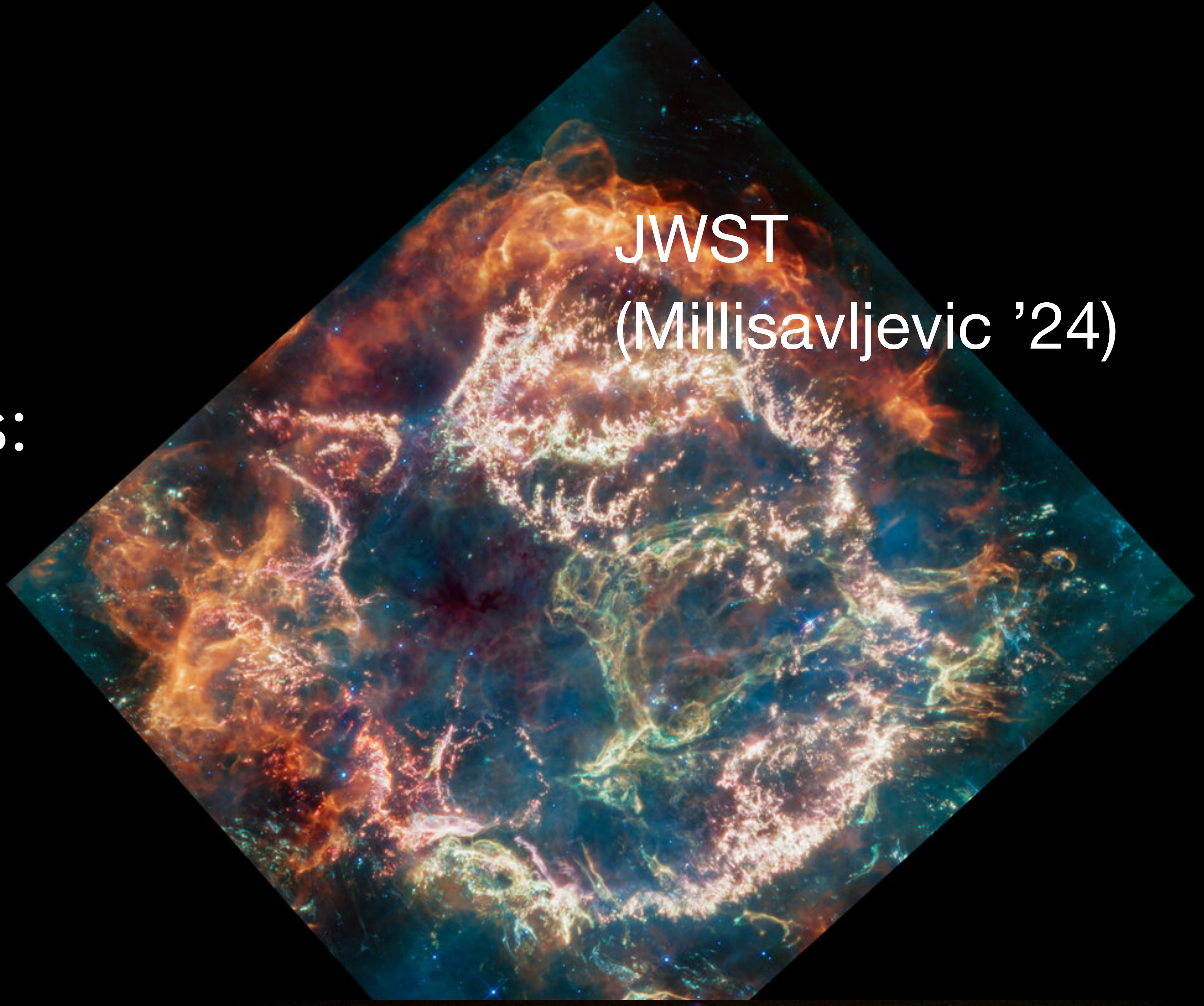
- Youngest known Galactic core-collapse SNR
  - ~350 yr old, d=3.4 kpc, D=5.5 pc
  - stripped SN (~2-4 M_{sun} of ejecta)
  - evolves in dense wind
  - oxygen-rich -> pure metal plasmas
  - X-ray synchrotron emission forward & rev. shock
- XRISM observations:
  - 182 ks (SE) + 167 ks (NW)
- Papers: Plucinsky+ '25, Sato+ '25, Vink+ '25, Bamba+ '25

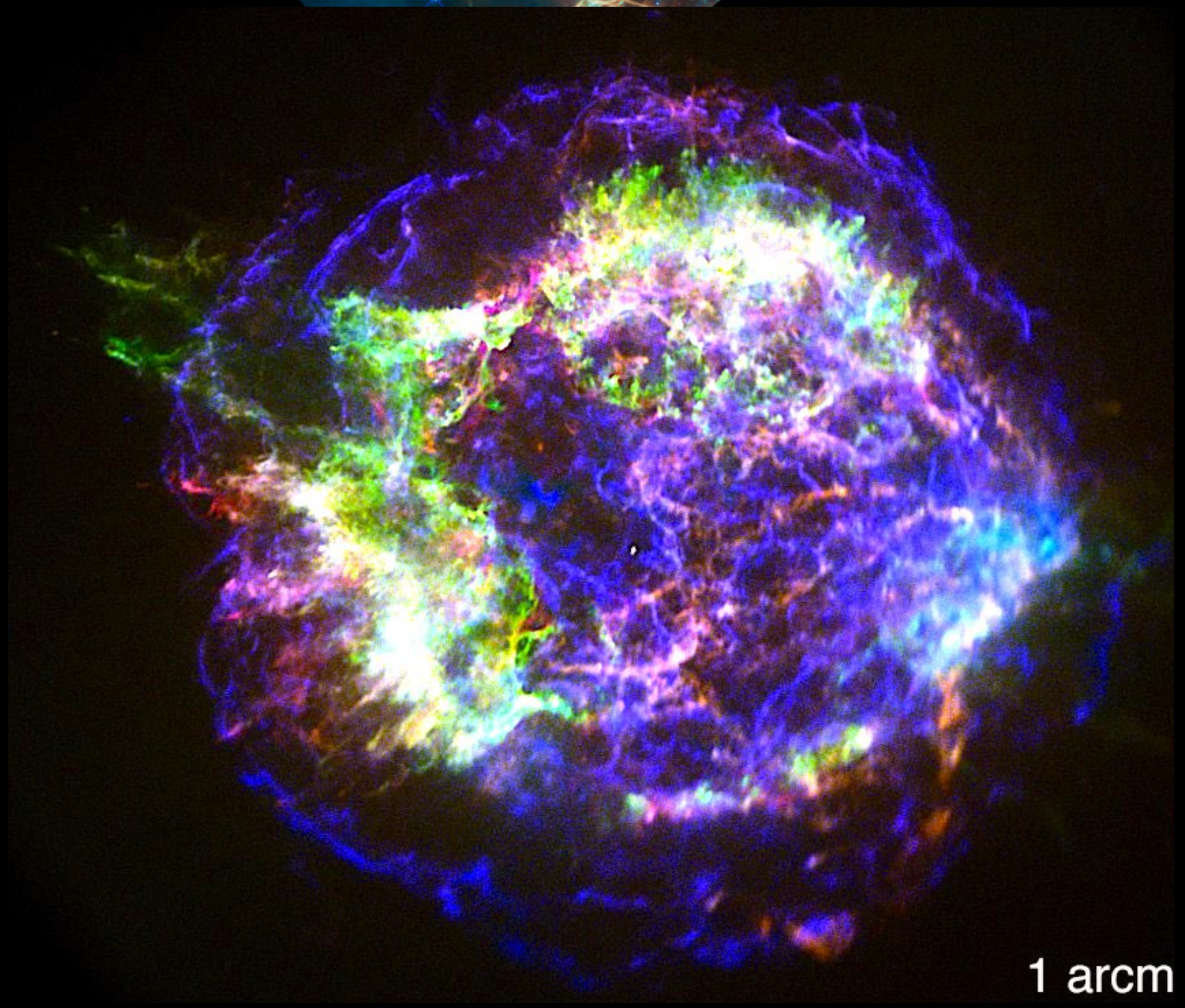


a…i: 2x2 “super pixels”

Challenge 1: intrinsic complexity

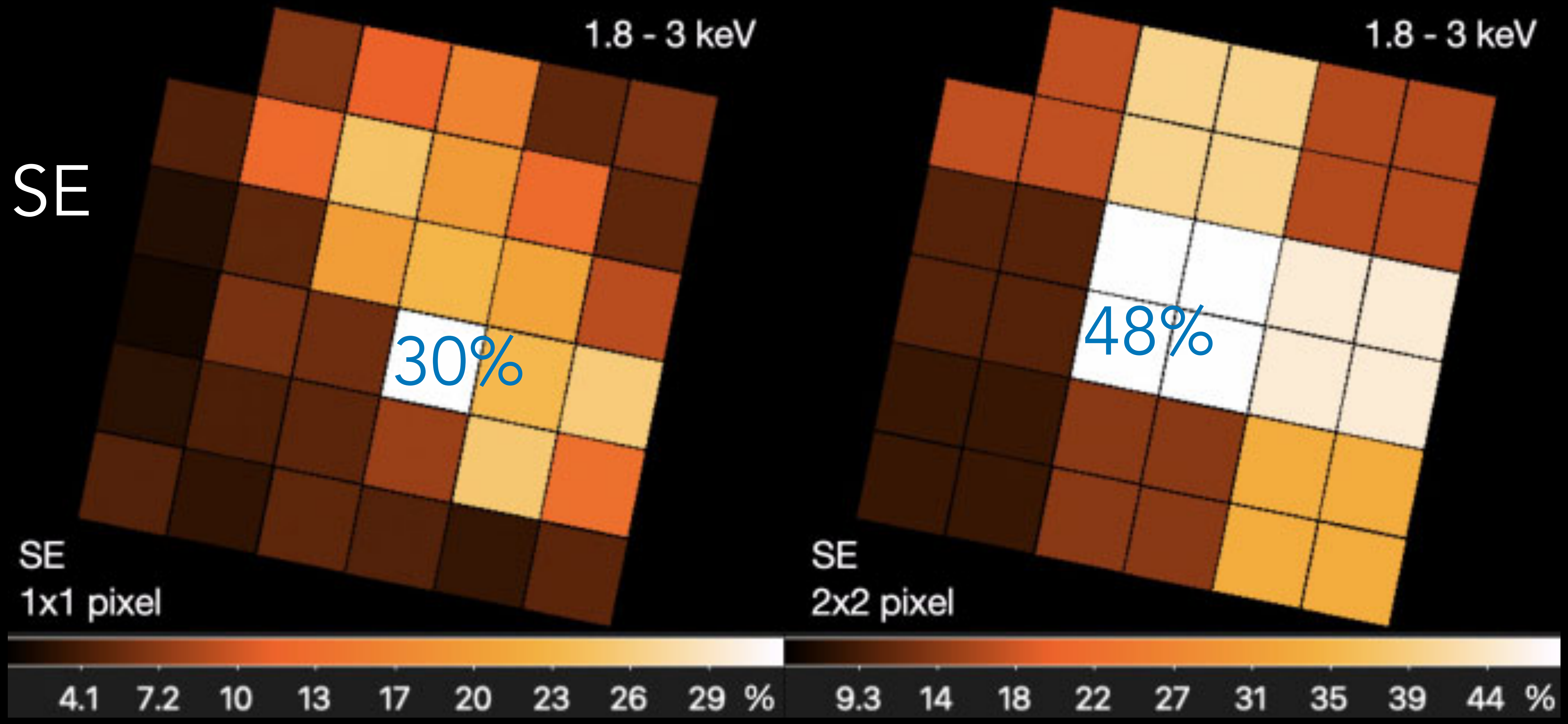
- Cas A's X-ray spectrum has many different components:
  - pure metal plasma: Si-rich and Fe-rich knots
    - Fe overtaken Si-rich maretial
  - strong synchroton continuum
  - thermal emission from shocked CSM
    - is there, but difficult to disentangle
    - dense CSM: "green monster"
- Many lines, and lines intrinsically broadened:
  - overlapping lines (e.g. satellite lines)
  - superposition of ionization stages
  - high-resolution is only of partial use
  - (but lineshapes are interesting as well!)

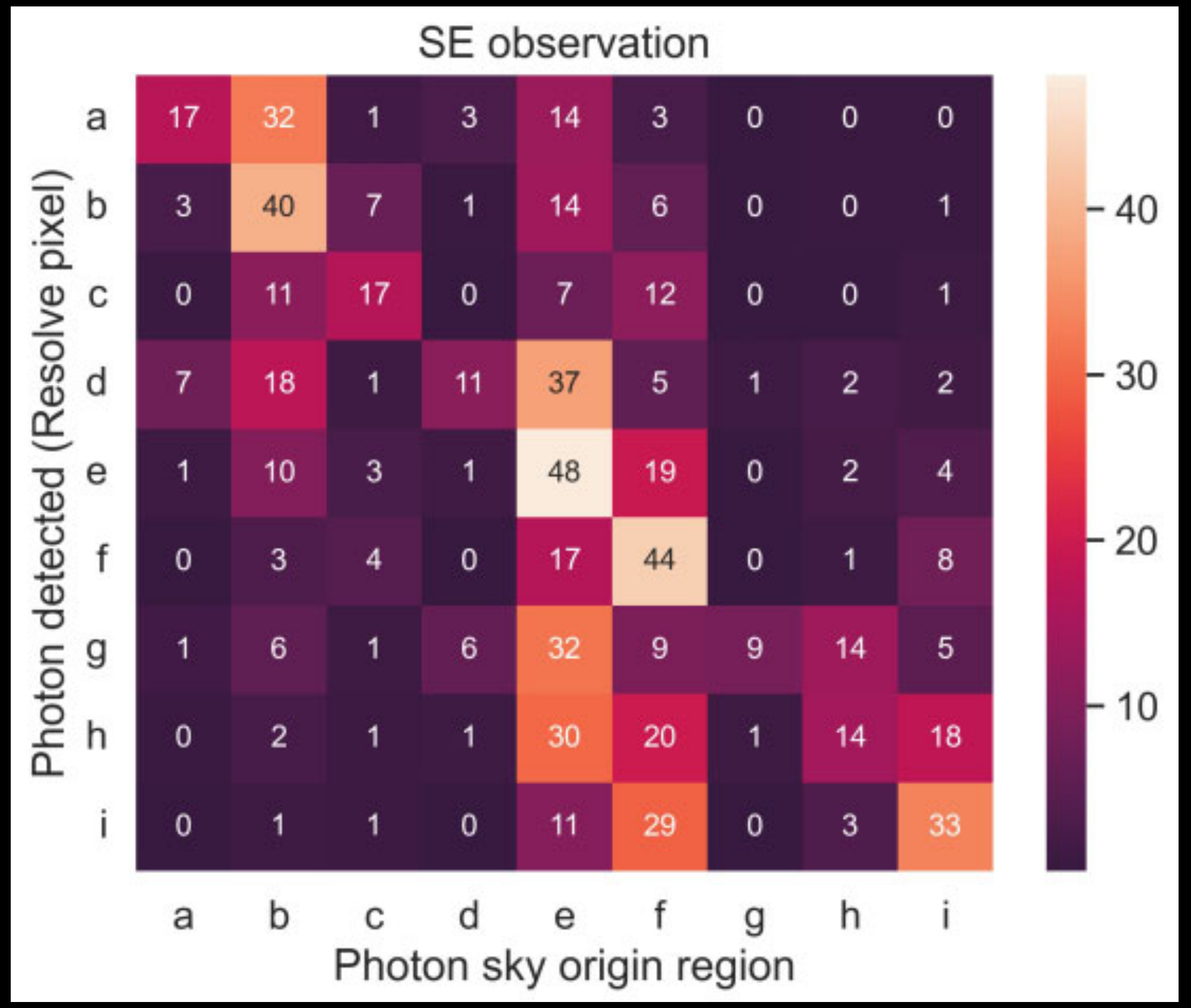




Challenge 2: Spectral-spatial mixing

Plucinsky, Agarwal, et al. 2025





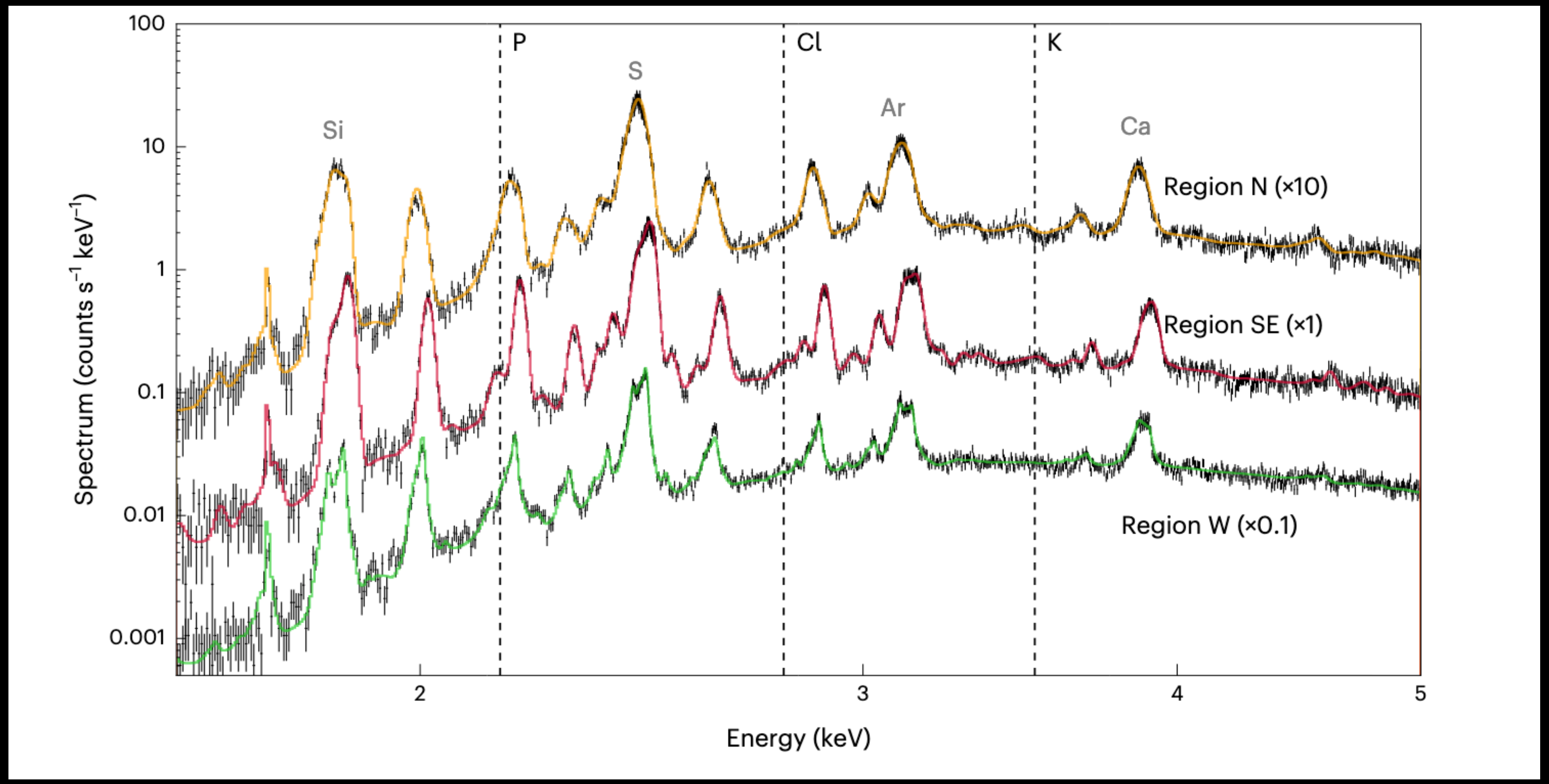
“Spatial response matrix”

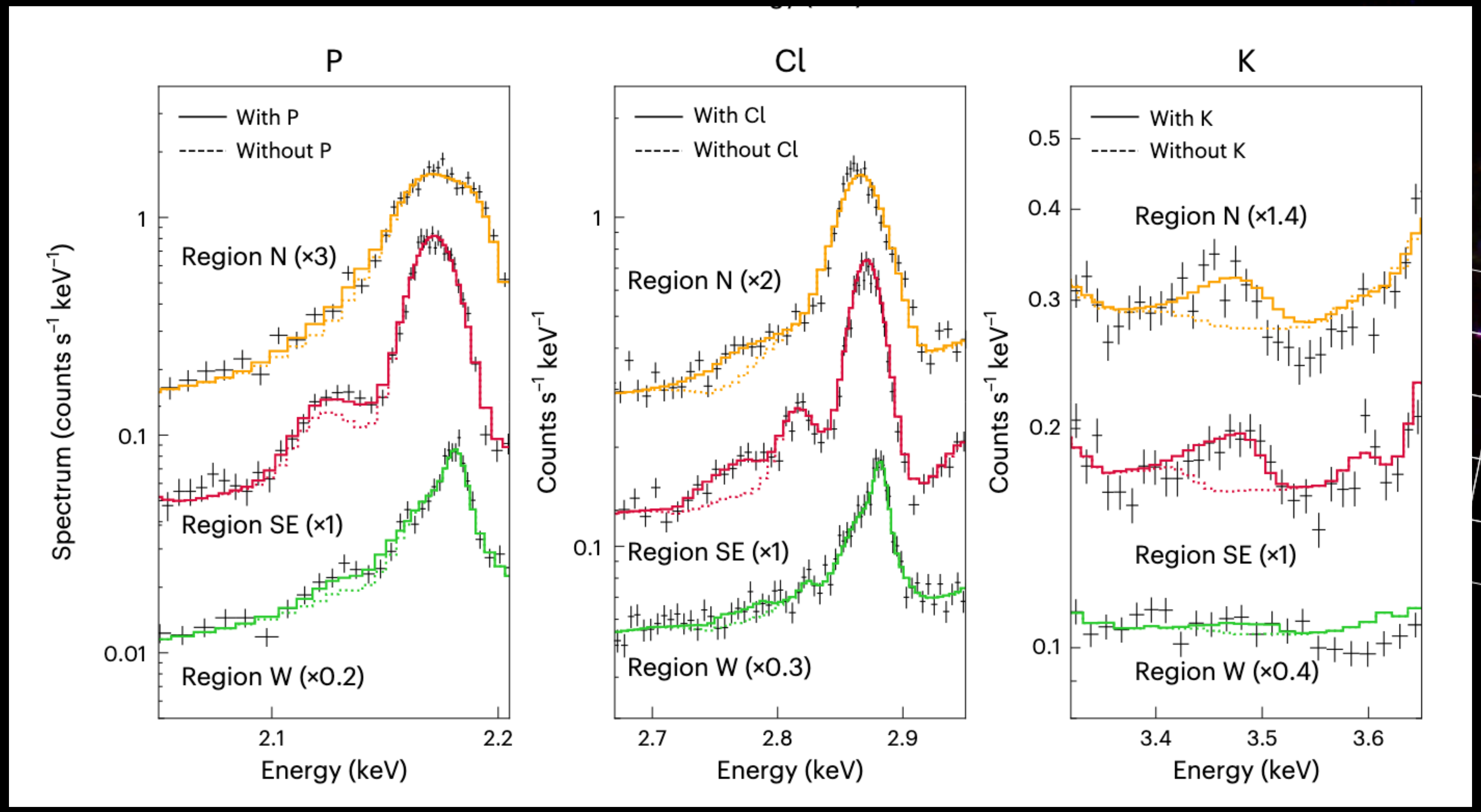
- Spectral-spatial mixing a large concern
- Model: montecarlo Chandra events with Resolve PSF
- In Cas A regions with very specific compositions: SSM energy dependent
  - Super-pixel fraction from sky-region <50%! (<30% for physical pixels)

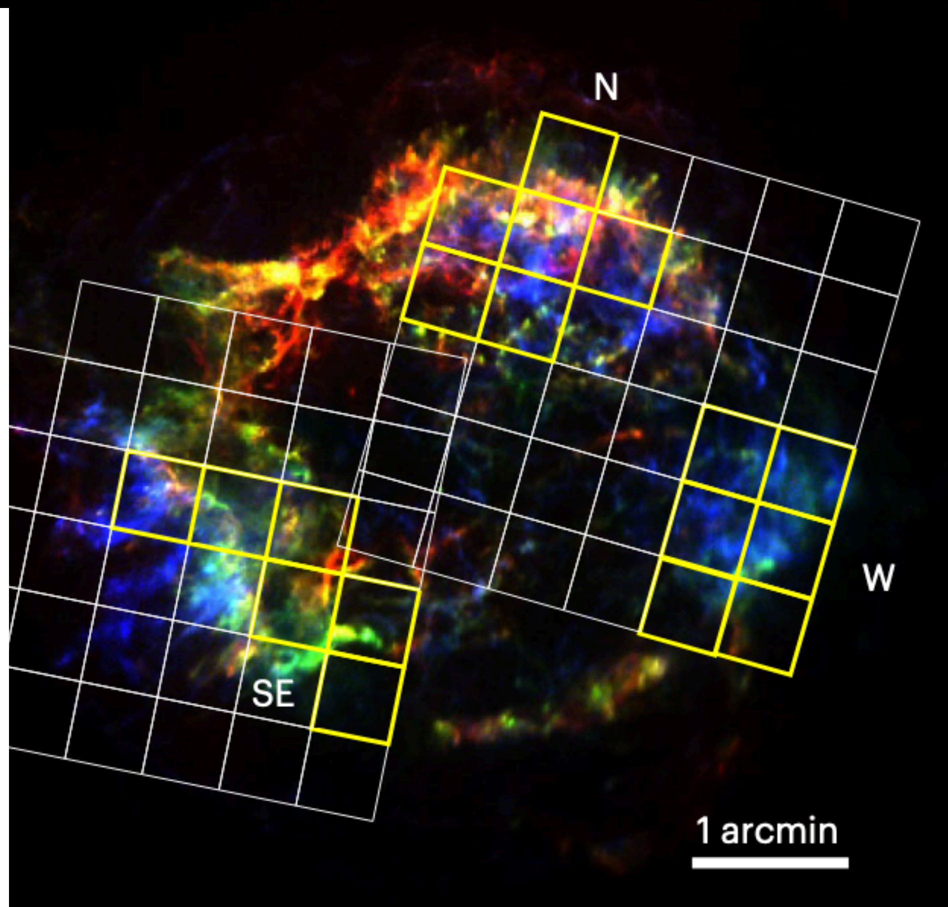
Challenge 3: spectral analysis: what model(s) to use?

- Multiple NEI to cover temperature range?
  - vpshock model: intrinsic $n_e t$ gradients, but is it the correct one?
- What to do with multiple ejecta components? full metal plasma or not?
- What are the effects of clumping?
- Full mapping:
  - What to do with spectral/spatial mixing?
    - for now larger "super" pixels
    - future: combine with Chandra?
  - Response matrices are very large: calculations are slow!
  - Adding complexity = adding degeneracies + adding CPU time
  - Uncertainties about ARFs to use
- Approach by Agarwal+ '25:
  - Using Bayesian approach with SPEX
  - Two full metal plasmas (vpshock: intermediate mass elements + Fe/Ni)+ X-ray synchrotron
    - Assume O,Ne,Mg part of IME group -> but O dominates thermal continuum
    - ignore for now thermal CSM plasma

Chlorine & Potassium in Cas A



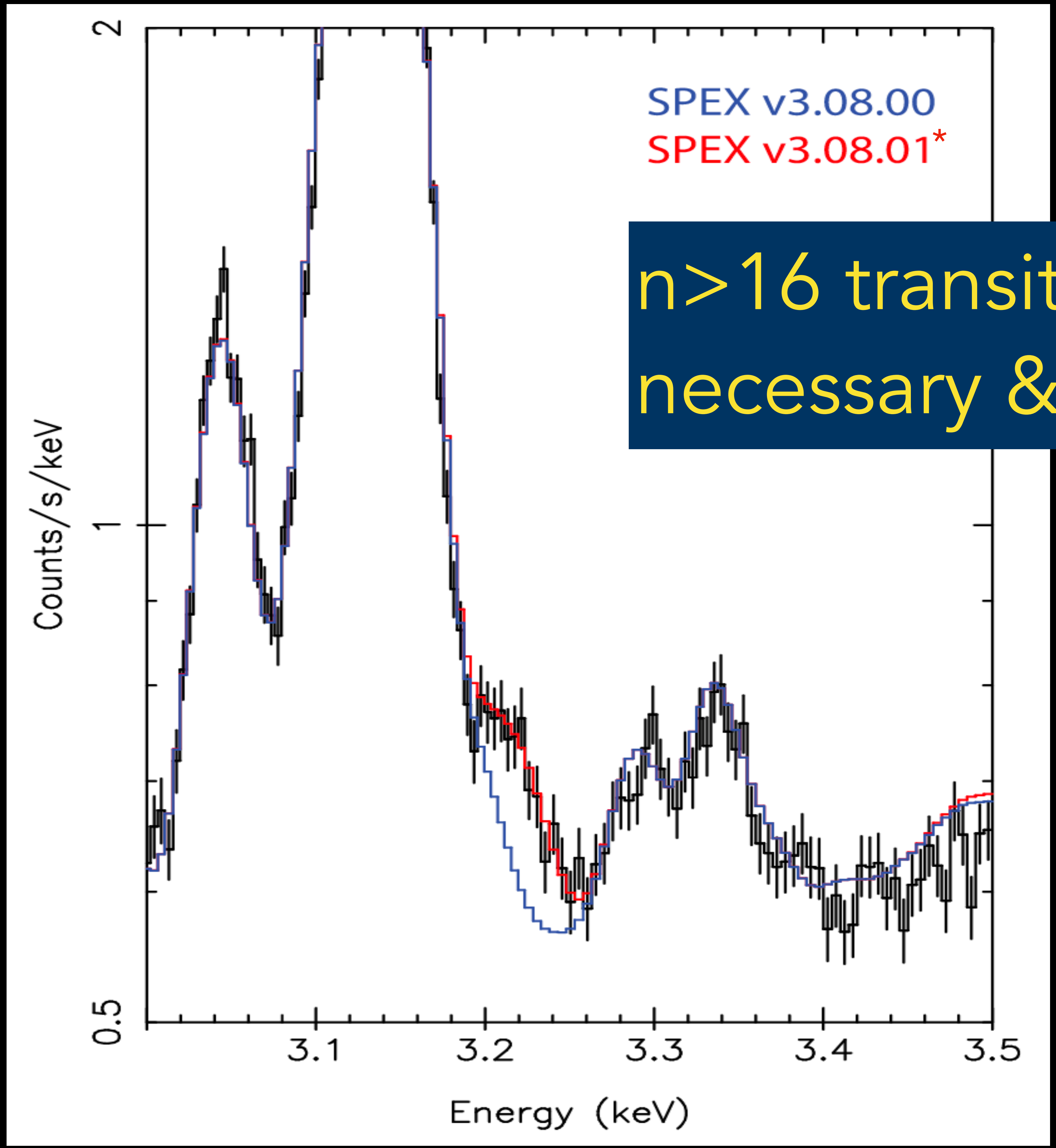




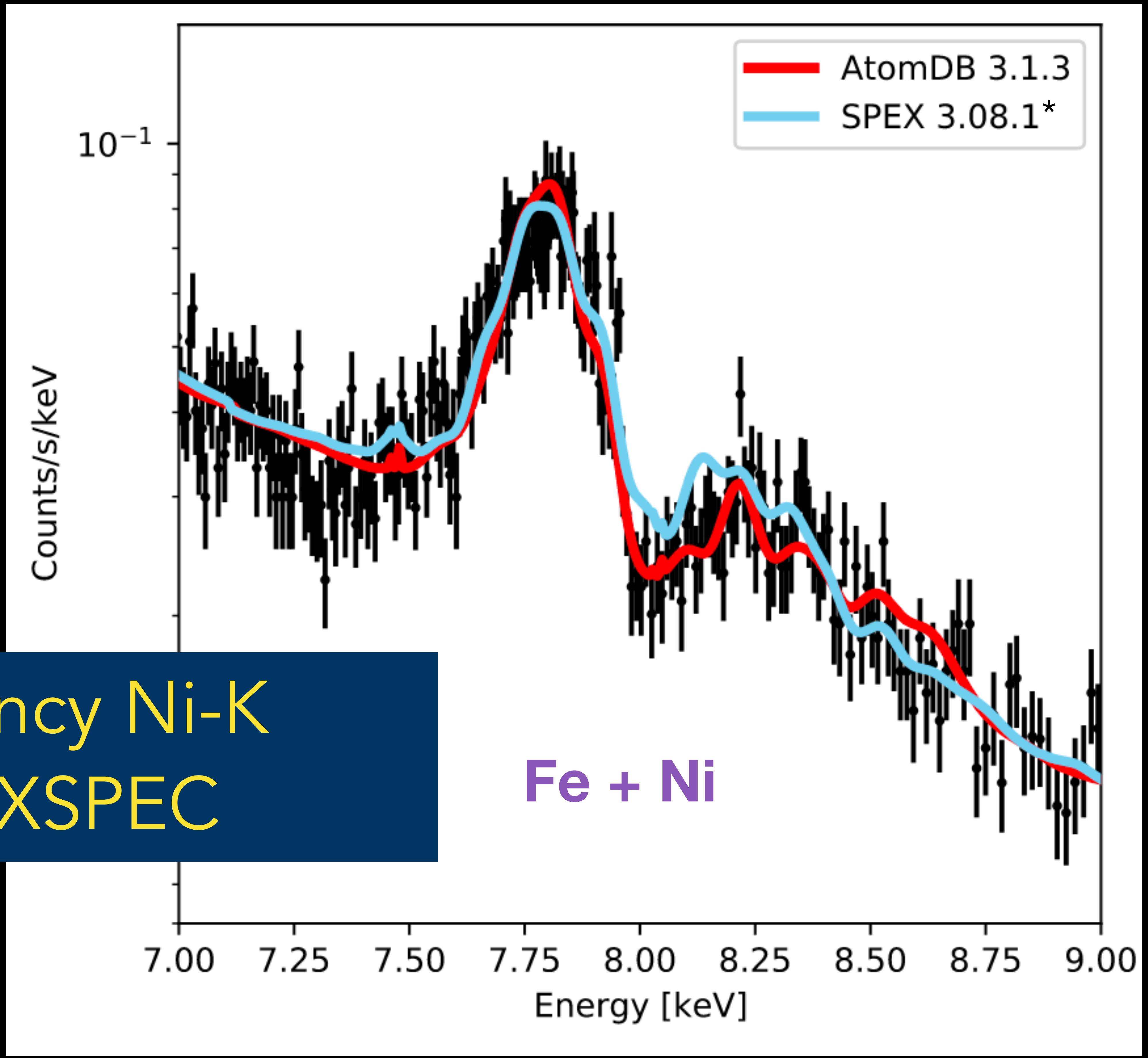
Sato+ '25

- Odd-Z element nucleosynthesis poorly understood (underpredicted)
- Study of P, Cl, K in Cas A:
  - P: not significantly detected
  - Cl, K: detected > 5 sigma
  - Variation accross the SNR
  - Abundances higher than models

Cas A drives updates to XSPEC & SPEX



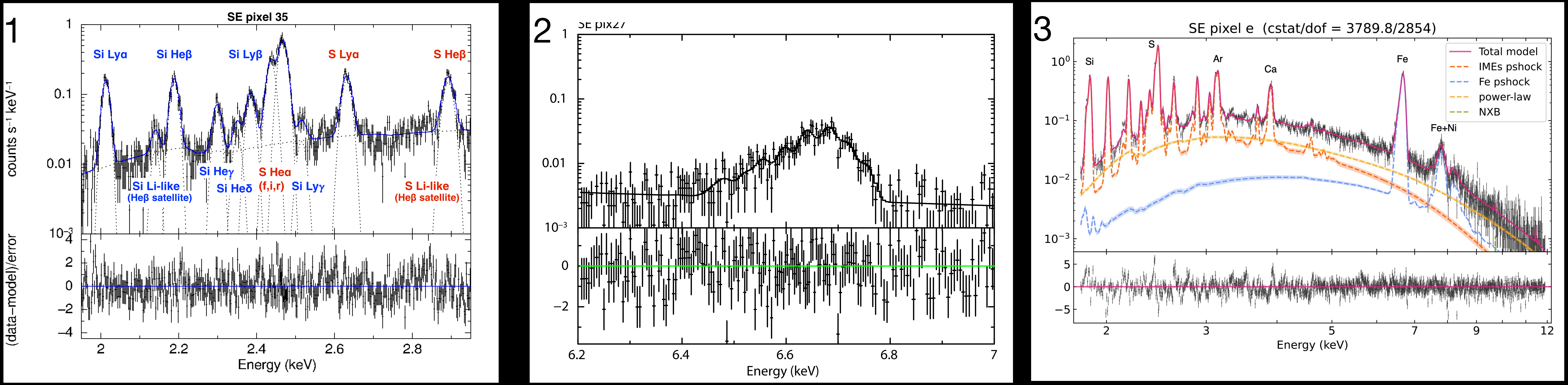
n>16 transitions S XV:
necessary & updated



discrepancy Ni-K
SPEX vs XSPEC

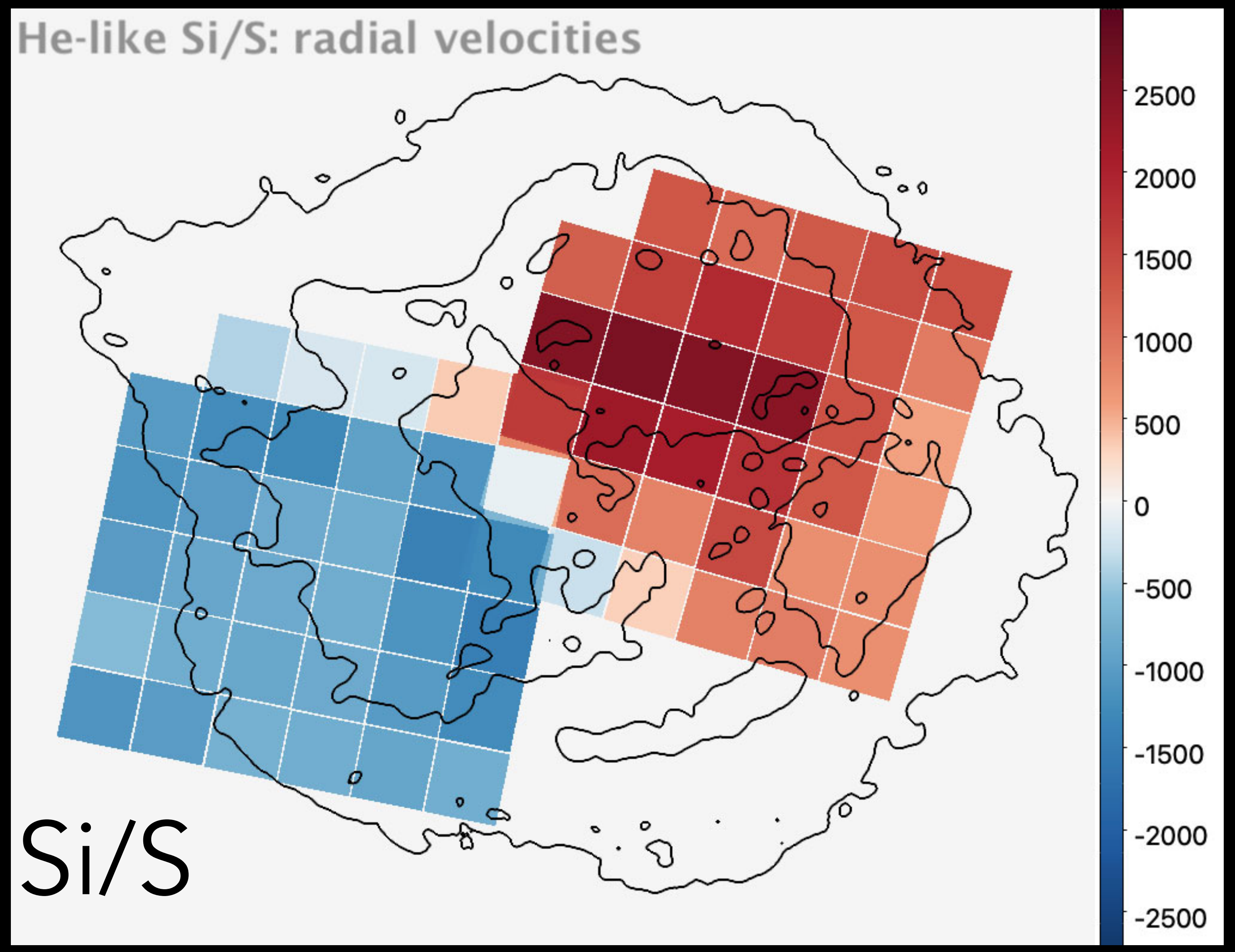
- Thanks to team members and spectroscopy wizzards Adam Foster & Liyi Gu!

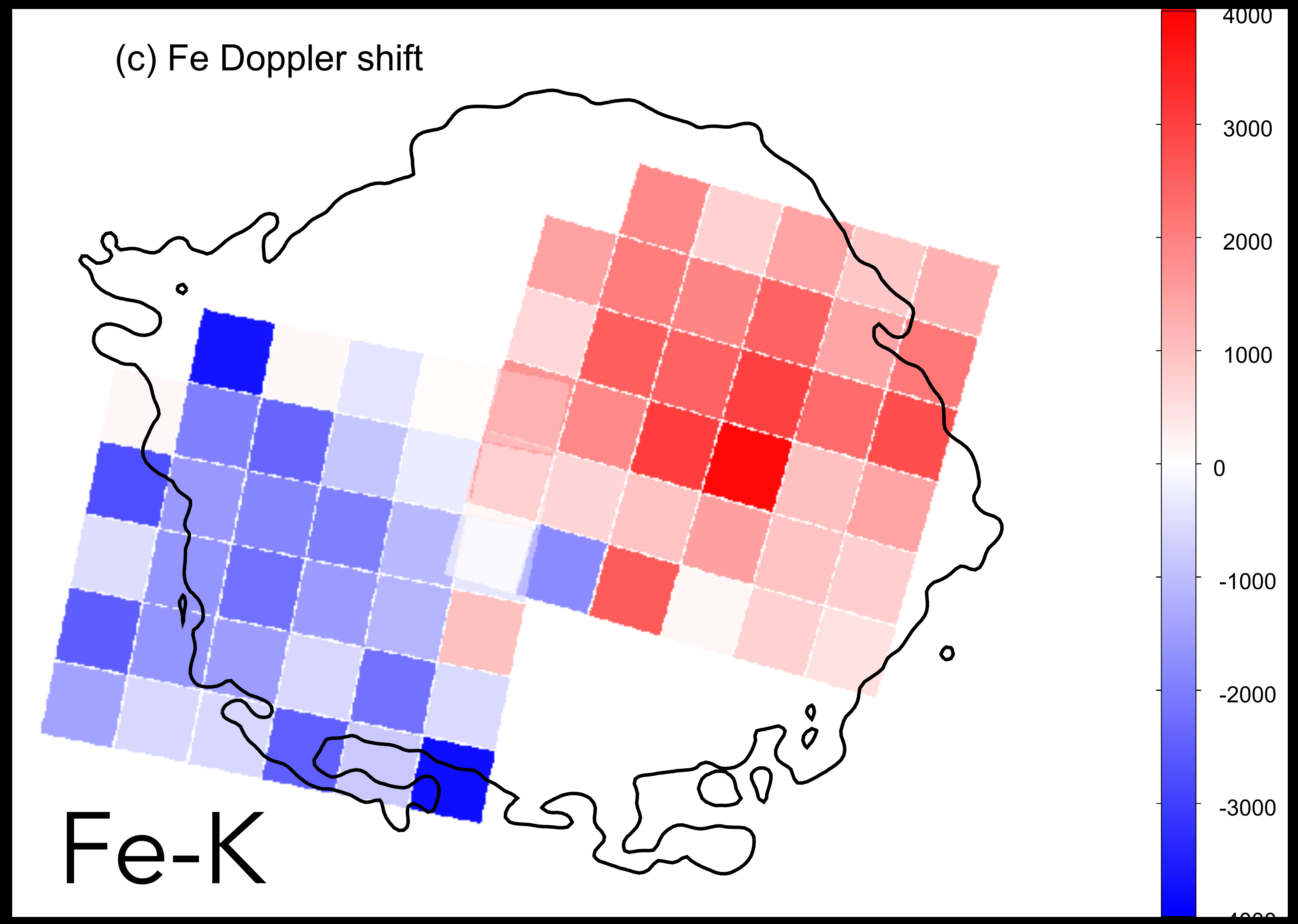
Methods for mapping radial velocities and line shapes

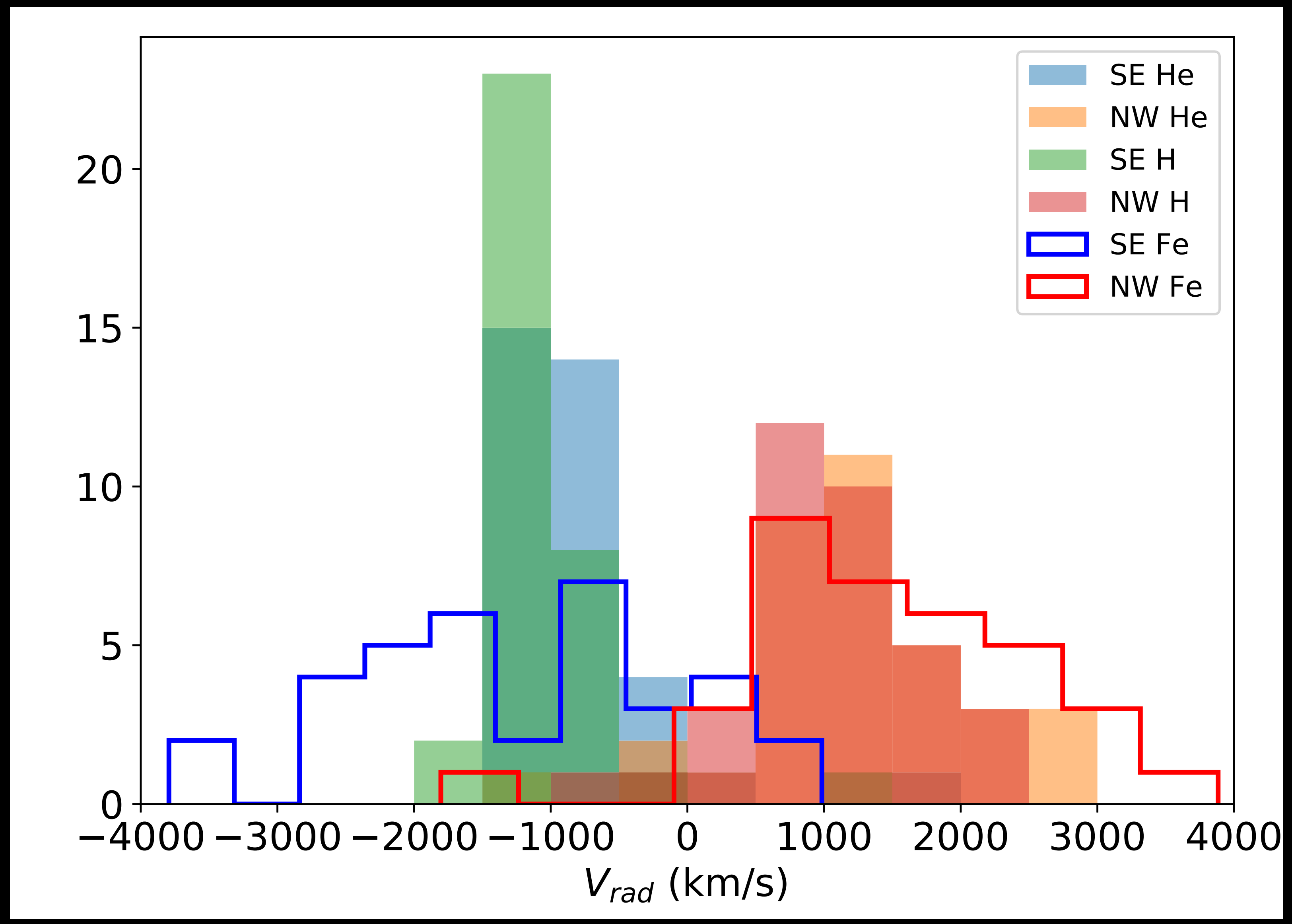


1. Fit with gaussians, requires well defined lines: Si & S K lines 1.9-2.9 keV (Vink+ ’25)
    - Fast, less sensitive to atomic code omissions
    - Coupled subselections: He- vs H-like lines
2. Use full spectral non-equilibrium ionization code on partial spectrum (Bamba+ ’25)
    - Slow, potential degeneracies in kT_e/n_et, but necessary for many lines Fe-K complex
3. Fit total spectrum with multicomponent non-equilibrium ionization code (Agarwal+ ’26)
    - CPU intensive, requires modeling choices

Radial velocities

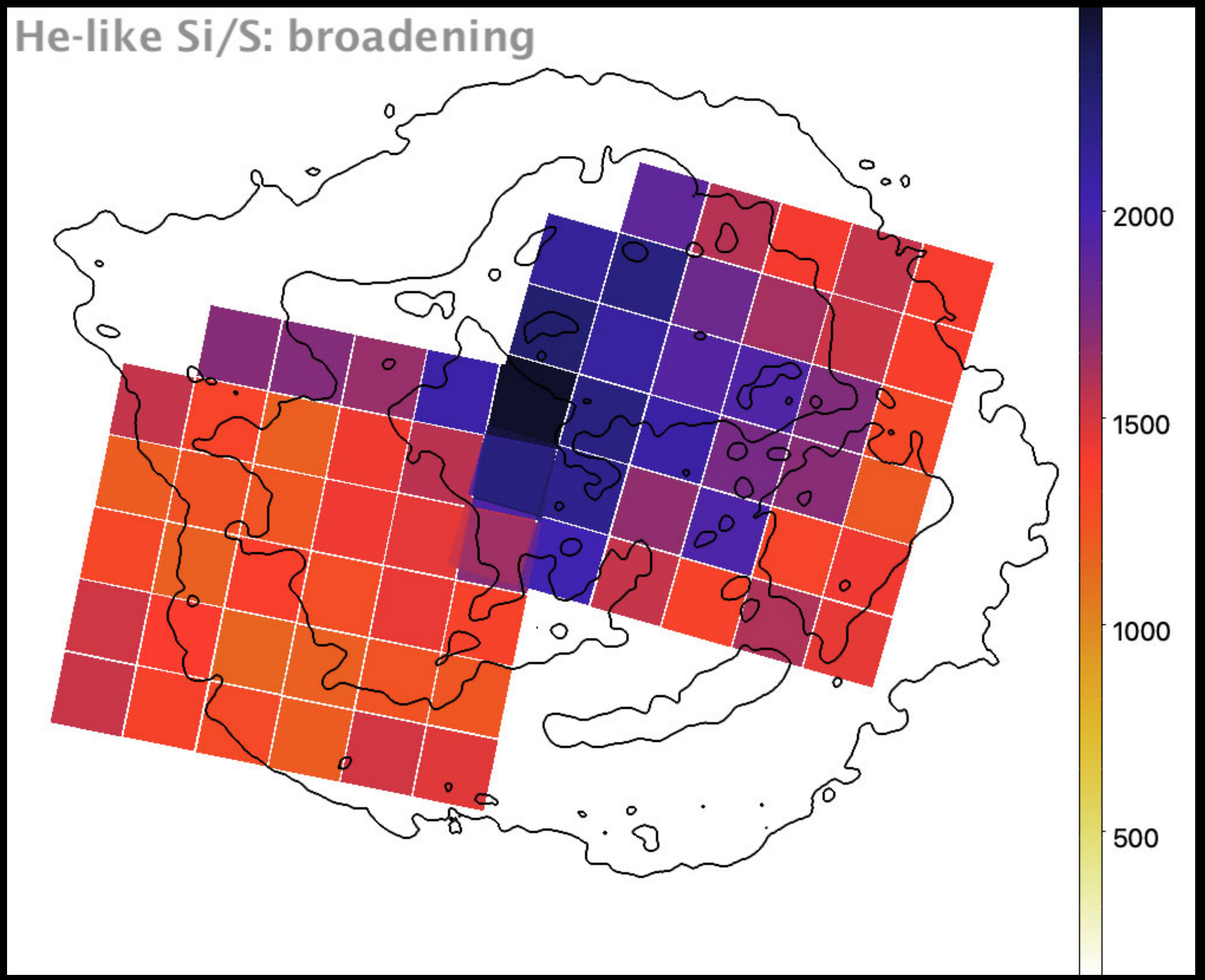


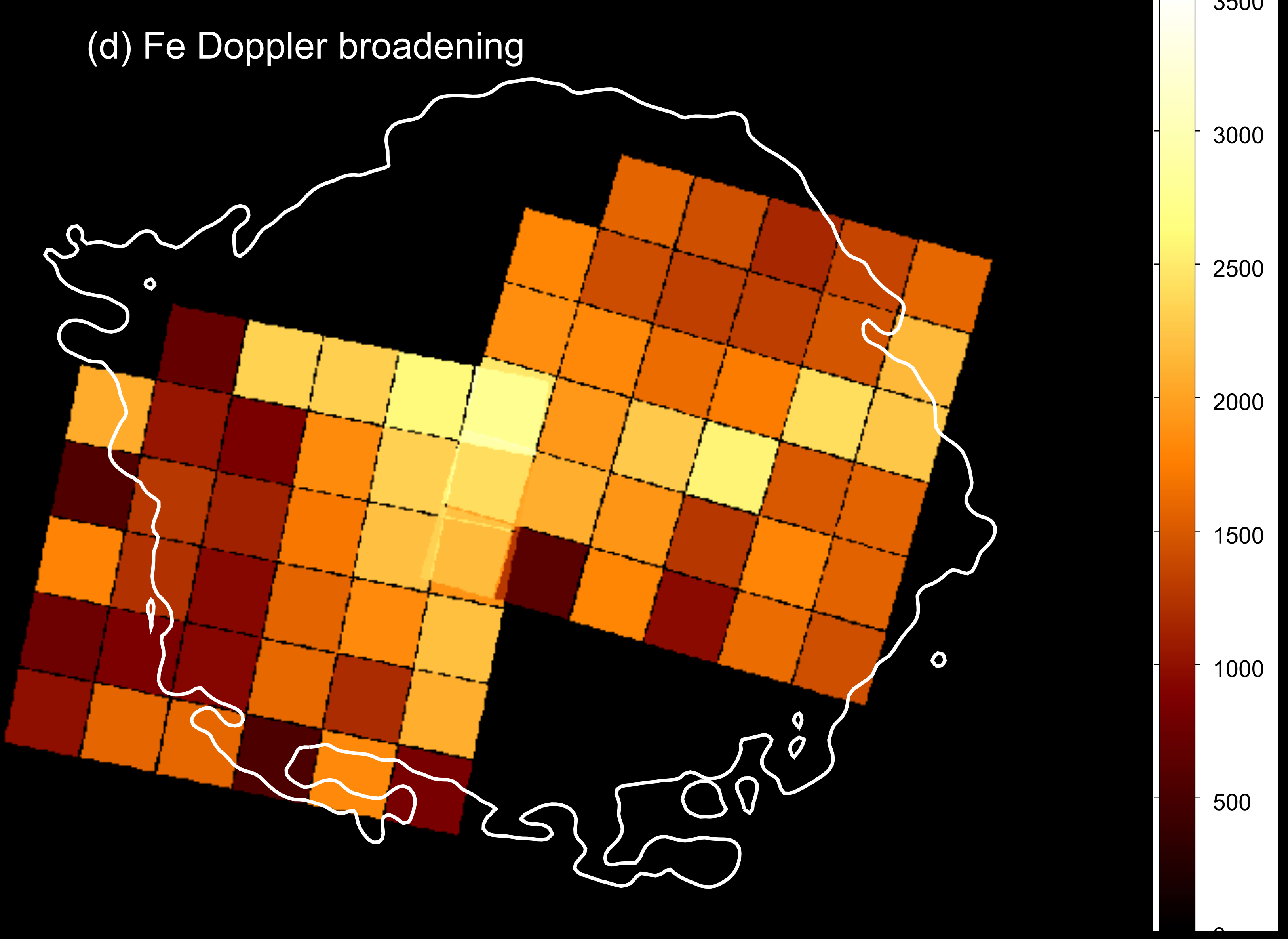


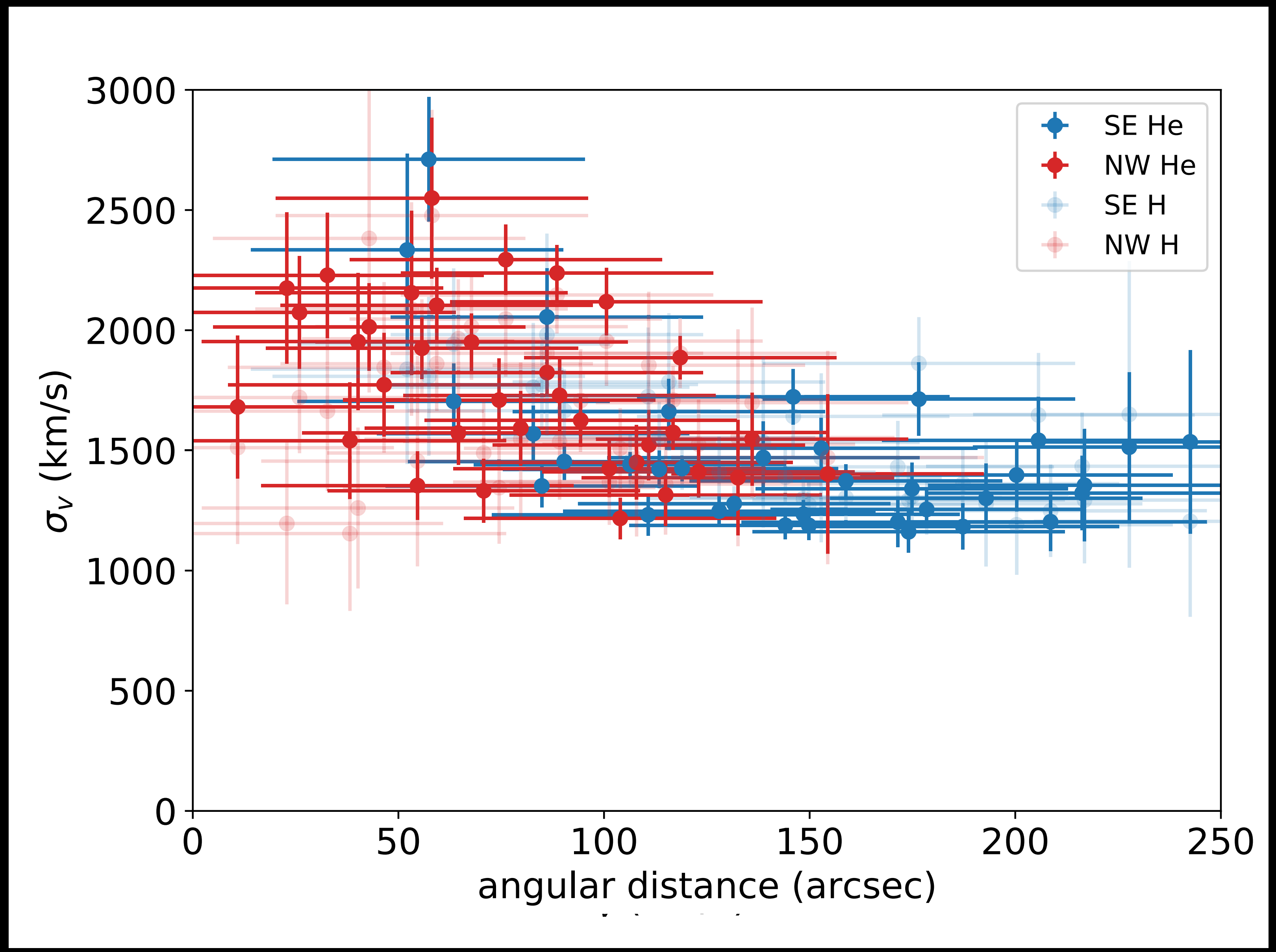


- Two-sided: SE blueshifted (frontside) and NW redshifted (backside)
  - Known since 1980s, but mostly from line centroids
- Fe has broader distribution (faster) than Si/S: overtaken Si/S in three dimensions!
  - Fe: $|V_{\rm rad}| \lesssim 4000$ km/s : Si/S: $|V_{\rm rad}| \lesssim 2600$ km/s

Line broadening



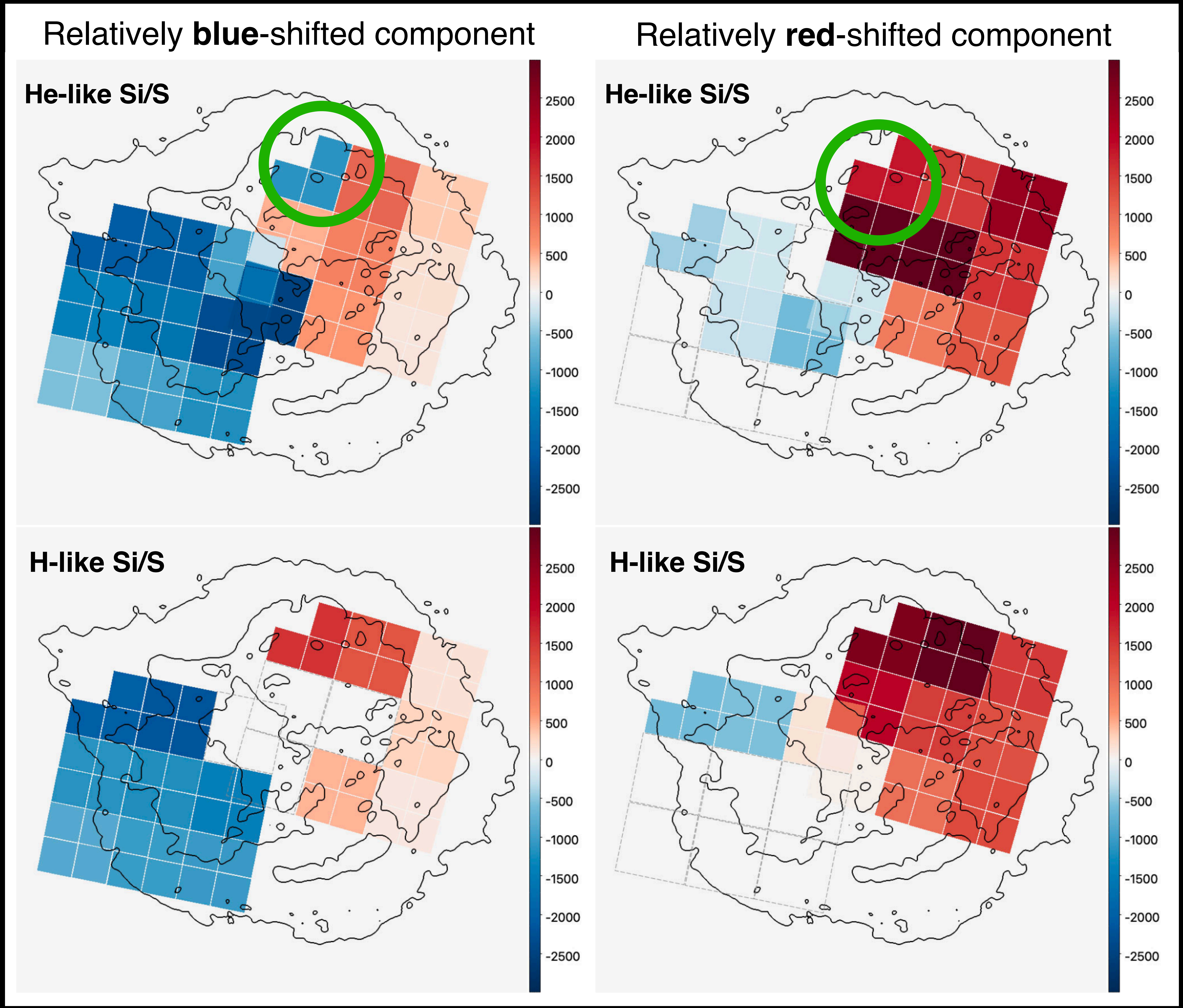




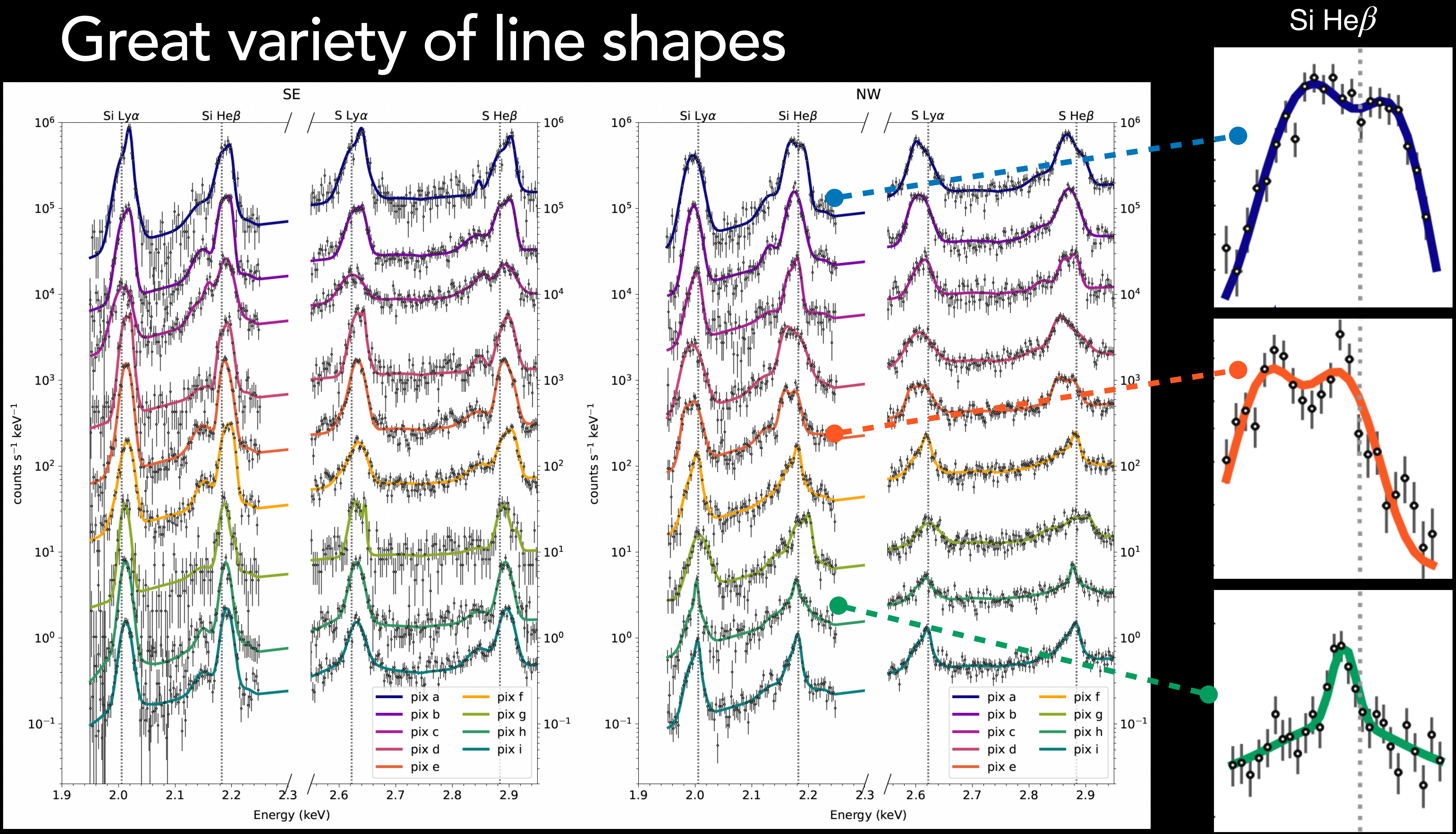
- Unique to XRISM Resolve
- Causes: 1. variations in bulk motions along LoS; 2. ion thermal broadening
- General: $\sigma_v \approx 1000 - 2500$ km/s, but some narrow Fe-K lines in some pixels
- For Si/S: thermal broadening $\sigma_v \lesssim 1000$ km/s
  - Reverse shock: $V_{\rm rs} = \frac{4}{\sqrt{3}} \sigma_{v,th} \lesssim 2300$ km/s

SE/NW dichotomy due to uneven mix frontside backside?

- Fit 2 gaussians:
  - Only for "clean" lines (H-like, Heβ)
  - Full sampling, Bayesian approach
    → *UltraSPEX*
  - 2 gaussians only if it improves the fit
- Surprise:
  - Both components on same side!
  - Exception: pixel *a* NW (He)

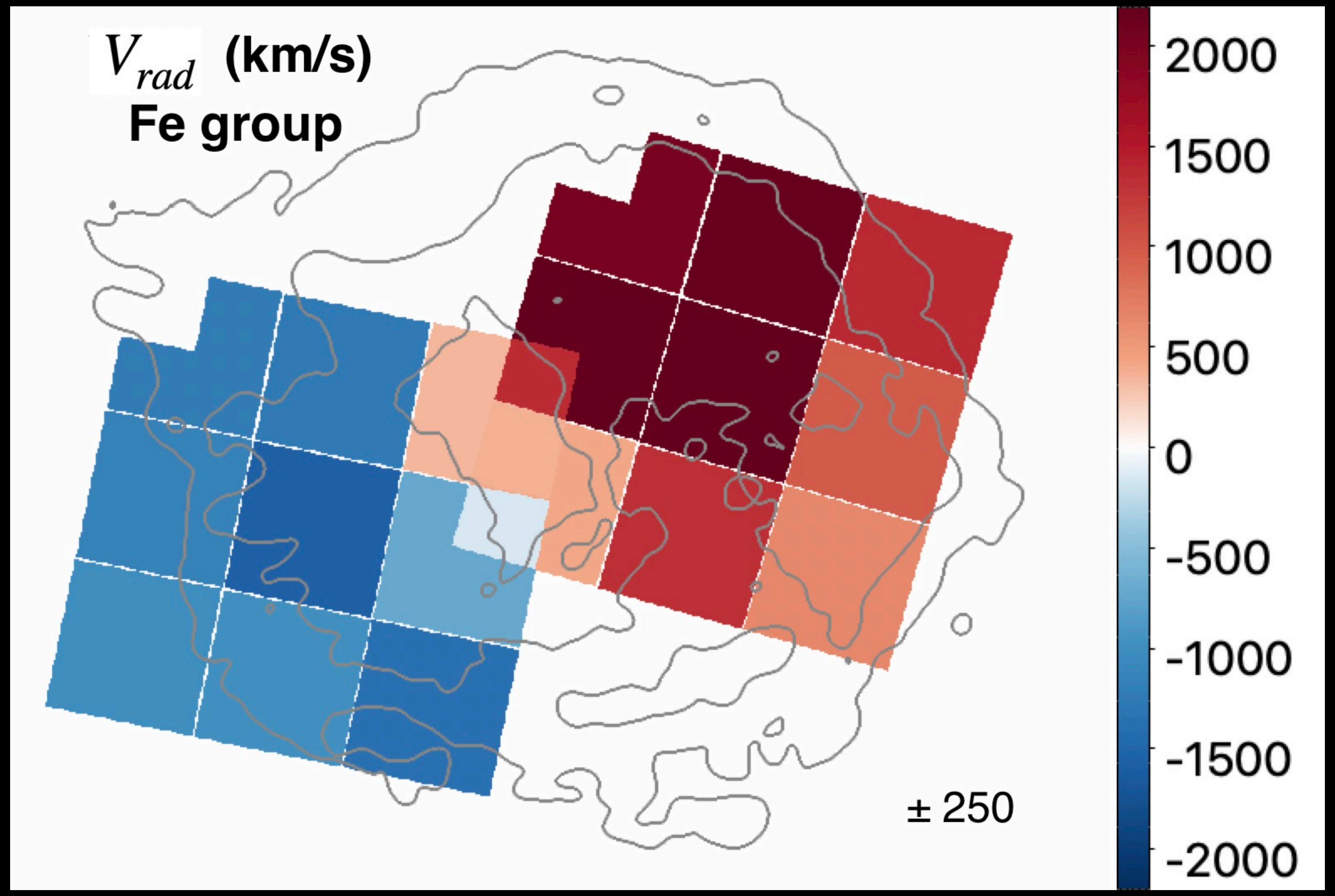


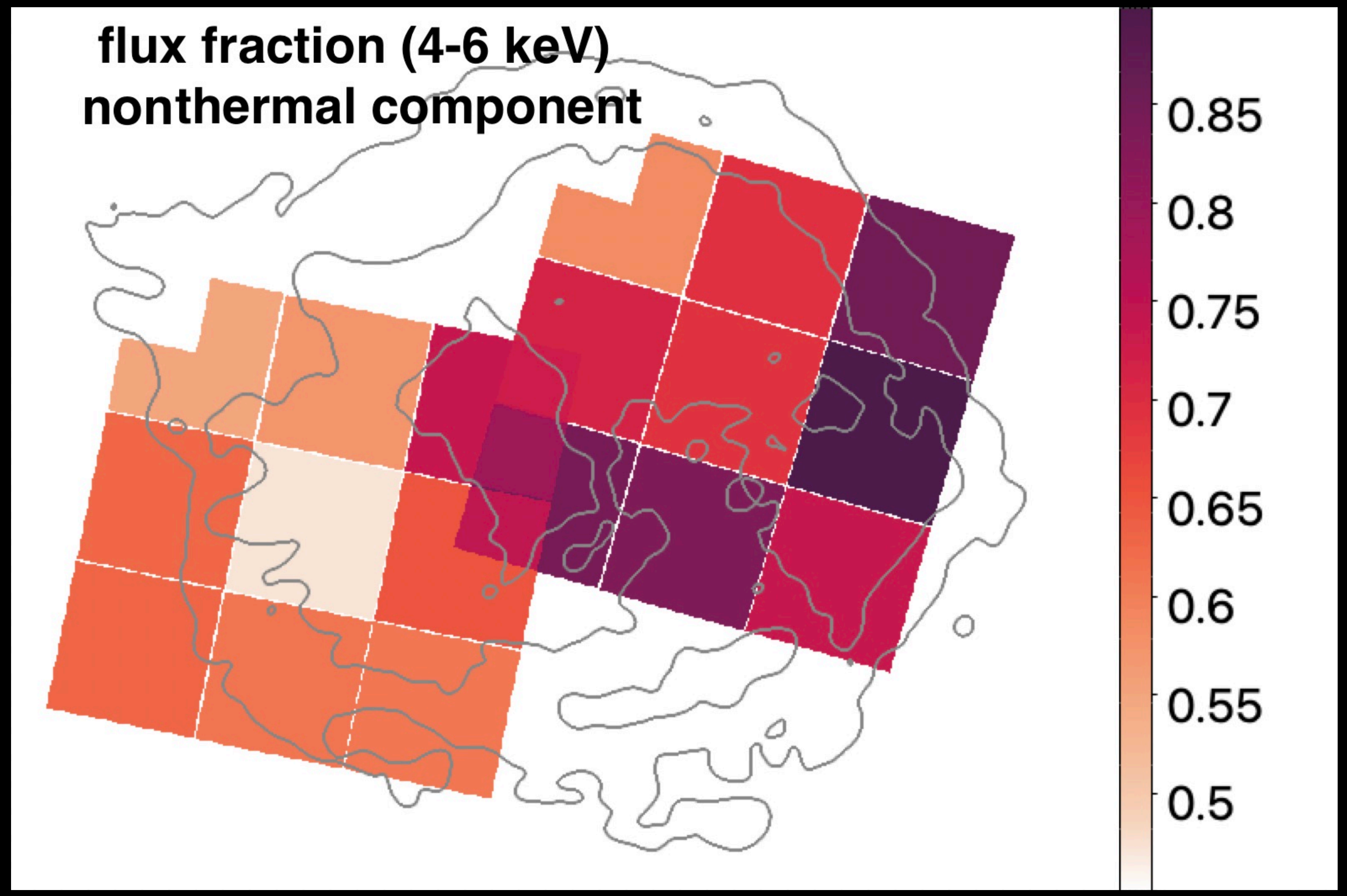
Great variety of line shapes

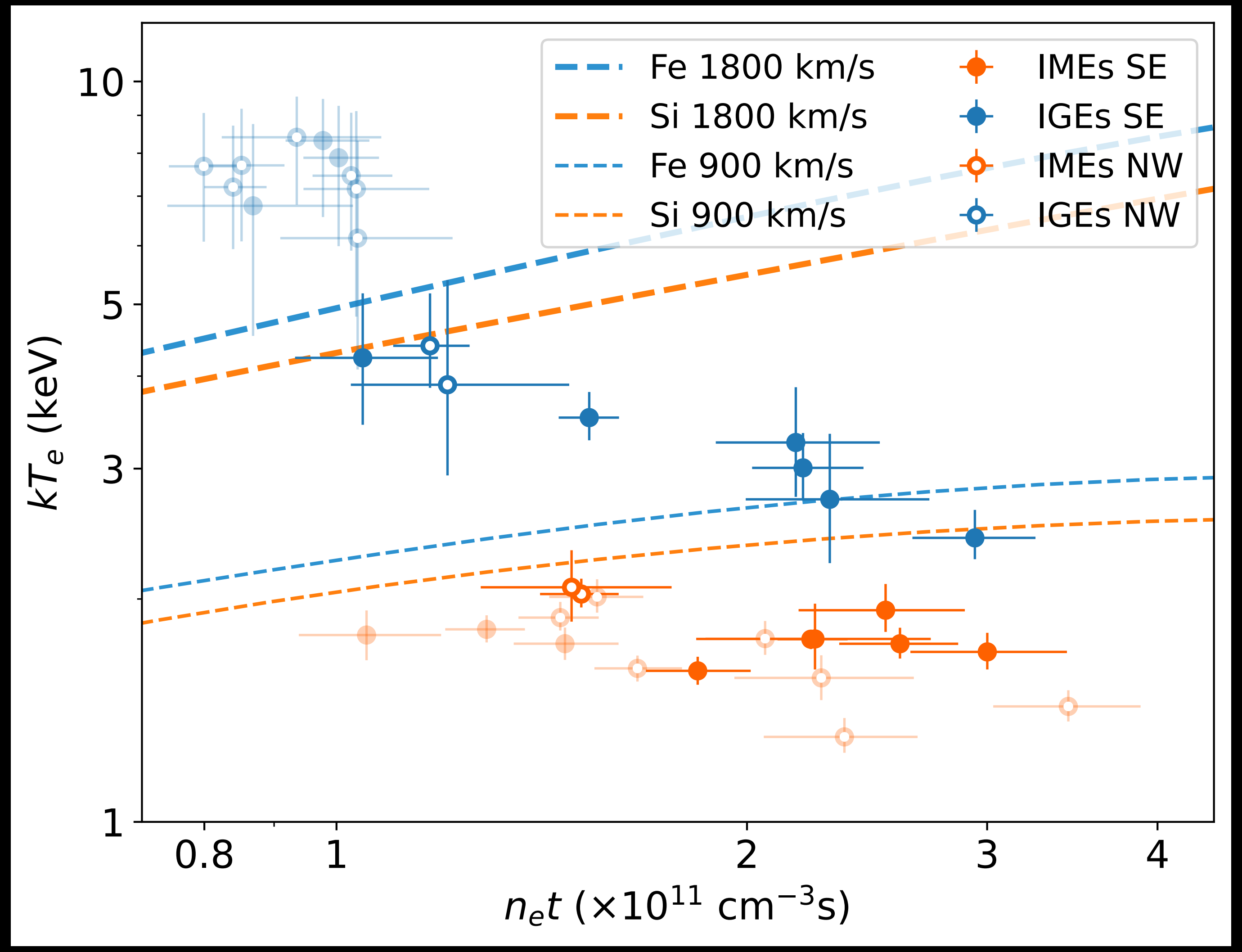


Results of full modeling with *UltraSPEX*

Agarwal+ '26: see talk!







- Confirmation of velocity/broadening structures
- Nonthermal component: **>50% of continuum is synchrotron!**
- Anti-correlation of kT_e vs $n_e t$:
  - disagrees with kT equilibration process (electrons heat as function of $n_e t$)!
  - kT_e to low for reverse shock velocity
  - best explanation: emission dominated by clumps-→ boost $n_e t$, lowers $V_s \propto \sqrt{\rho}$

Conclusions

- Supernova remnants provide rich, interesting but complex astrophysics
  - nucleosynthesis
  - dynamics
  - non-equilibrium physics
- XRISM provides the first hints at what can be achieved with hi-res X-ray spectroscopy
  - new elements, rich velocity structures, thermal line broadening
- XRISM also shows the challenges
  - intrinsic complexity associated with variety of radiation components
  - problems of spectral-spatial mixing
  - large matrices, long computation times