Seeing Between the Lines: Insights into Supernova Remnants with High-Resolution X-ray Spectroscopy

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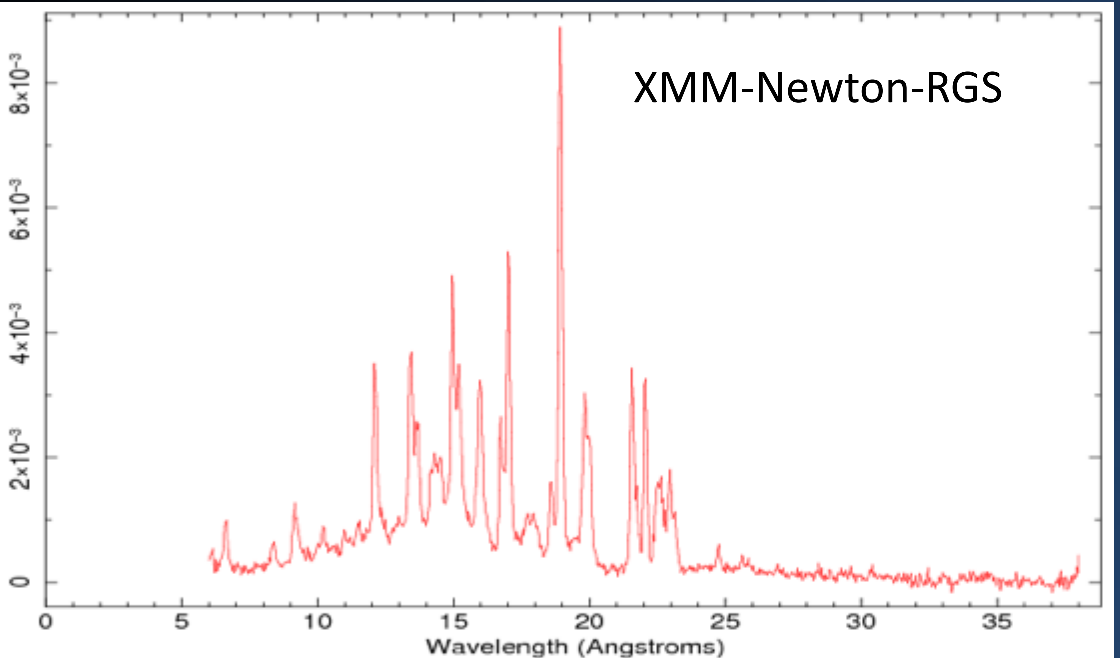
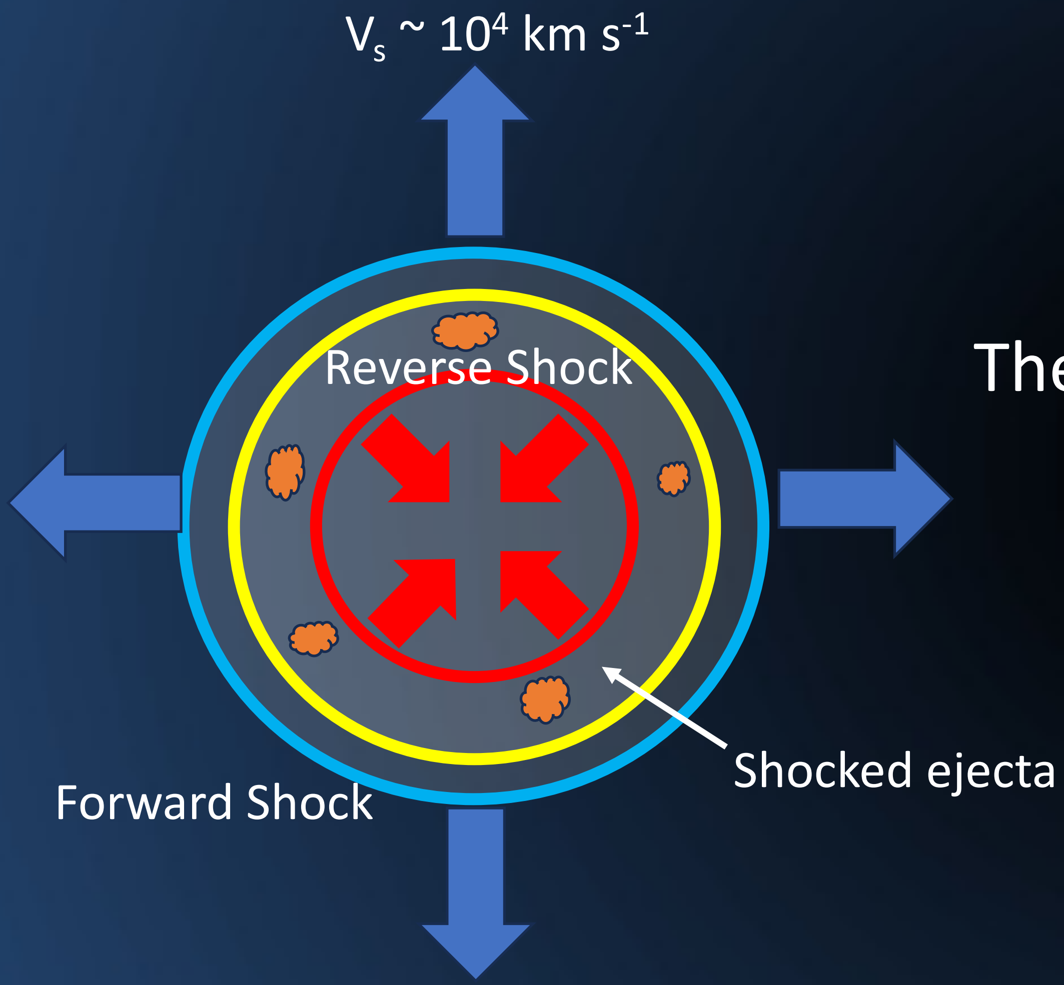
Chandra High-Resolution X-ray Spectroscopy Workshop

August 1st, 2023

Credit: X-ray: (NASA/CXC/Penn State/S.Park et al.); Optical: NASA/STScI/UIUC/Y.H.Chu & R.Williams et al

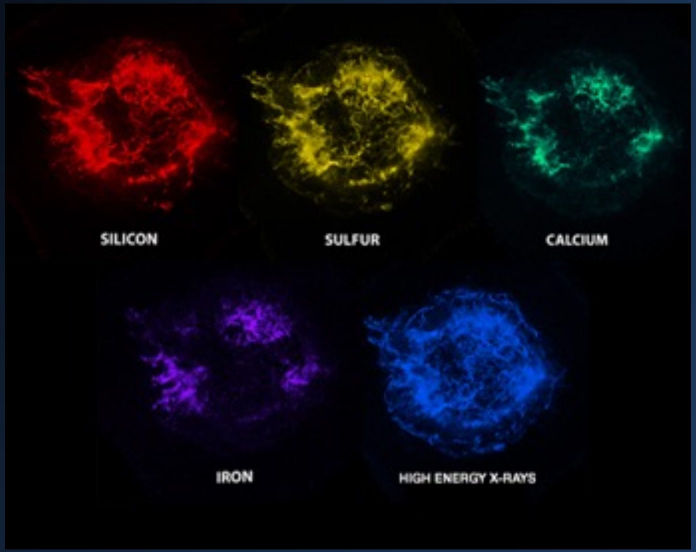


Supernova Remnant Emission



Thermal line emission

Cassiopeia A

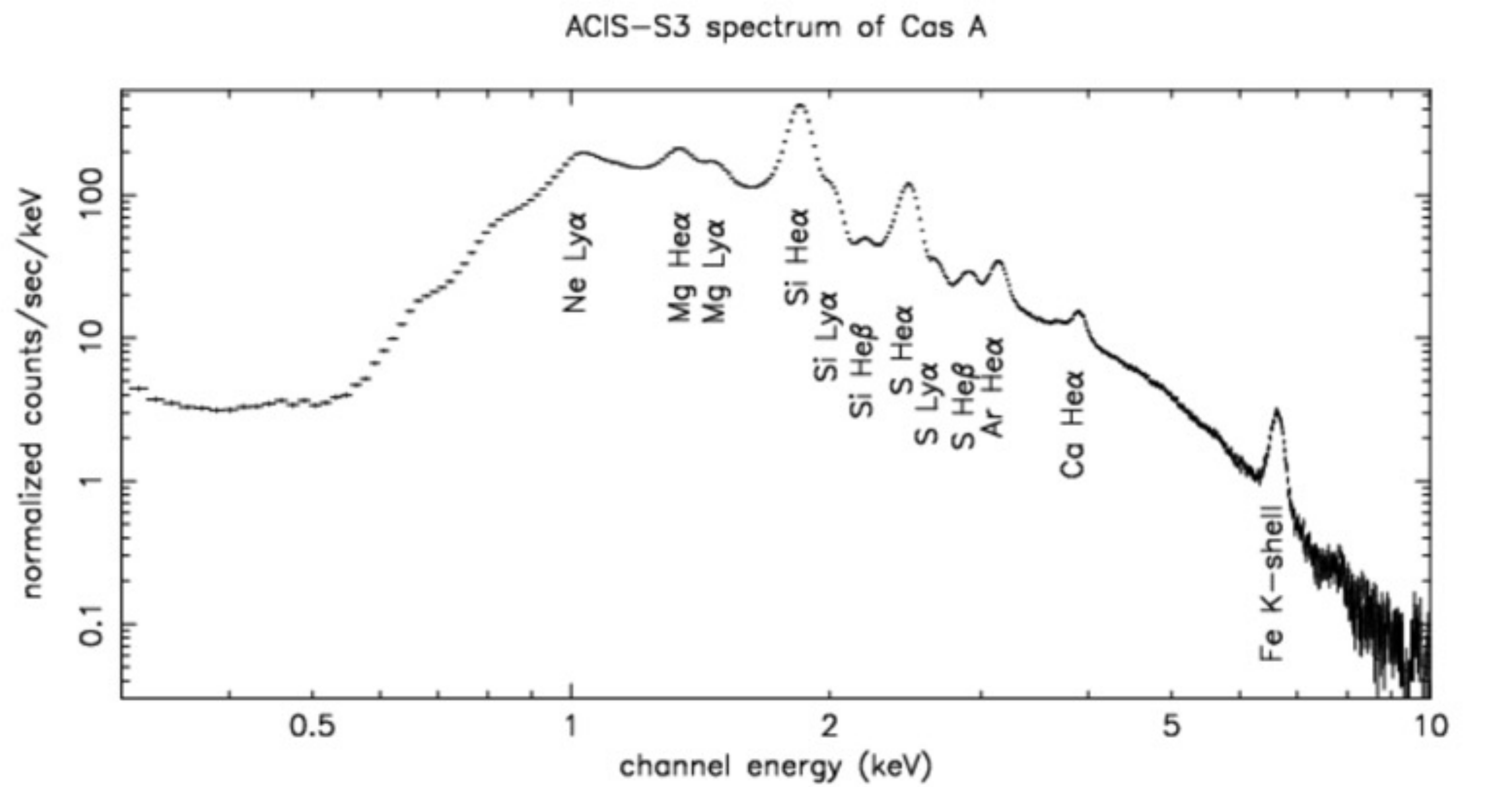


Credit: NASA/CXC/SAO

X-ray Spectra of Supernova Remnants

- Nucleosynthesis products of supernovae have prominent emission lines in the 0.5 - 10 keV band
  - Intermediate-mass elements (O, Ne, Mg, Si, S, Ar, Ca)
  - Iron-group elements (Fe, Ni, and trace elements).
- Plasmas have typical electron temperatures from 0.2 - 5 keV

"Medium Resolution"



https://hea-www.cfa.harvard.edu/ChandraSNR/sample_spectrum.html

Medium vs High-Resolution X-ray Spectroscopy

1E0102.2-7219

Credit: (NASA/CXC/MIT/D.Dewey et al. & NASA/CXC/SAO/J.DePasquale);

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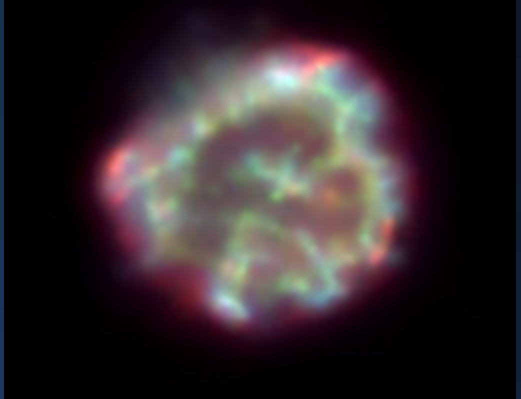
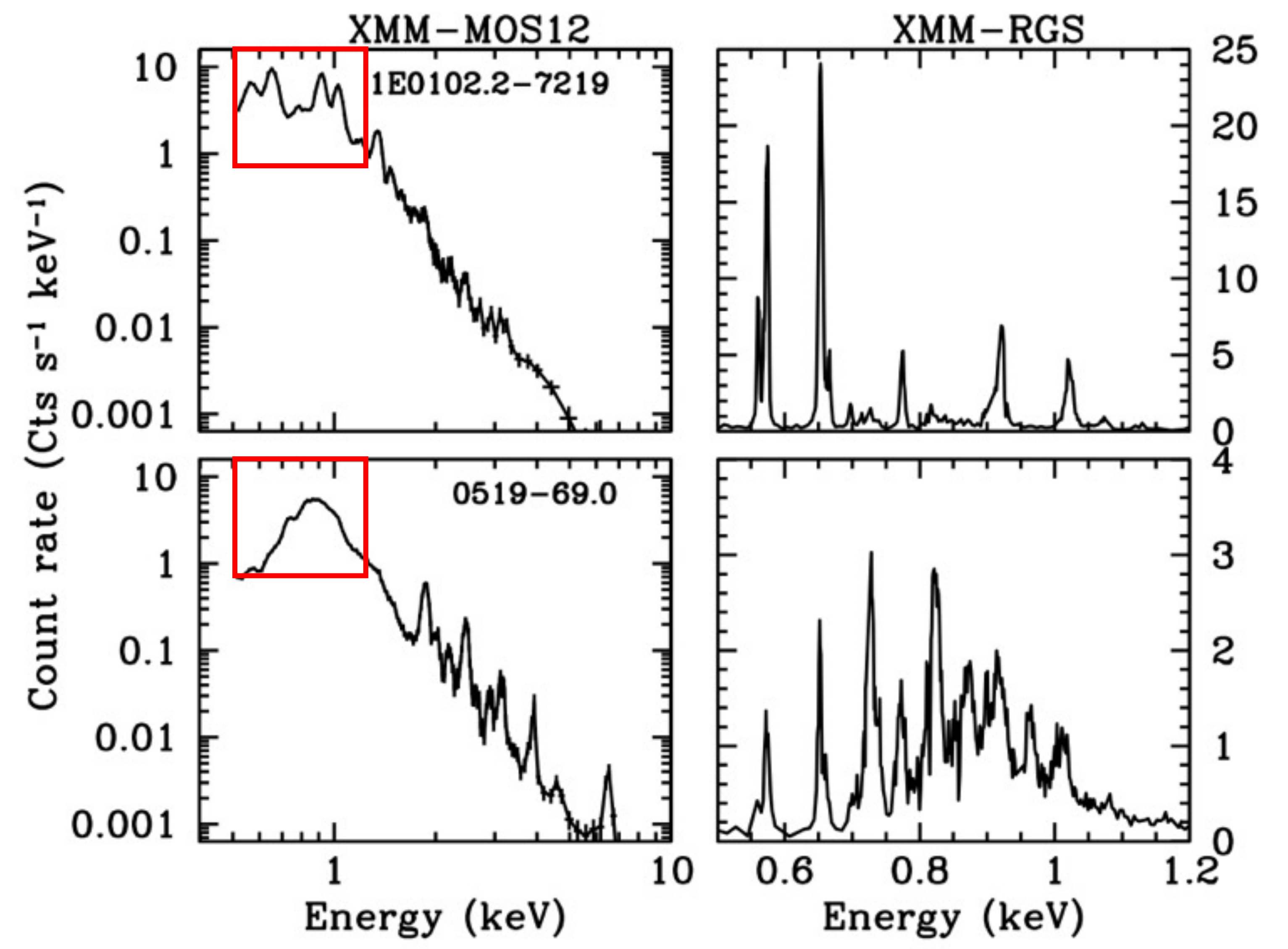


Credit: NASA/CXC/SAO

Medium Resolution High Resolution

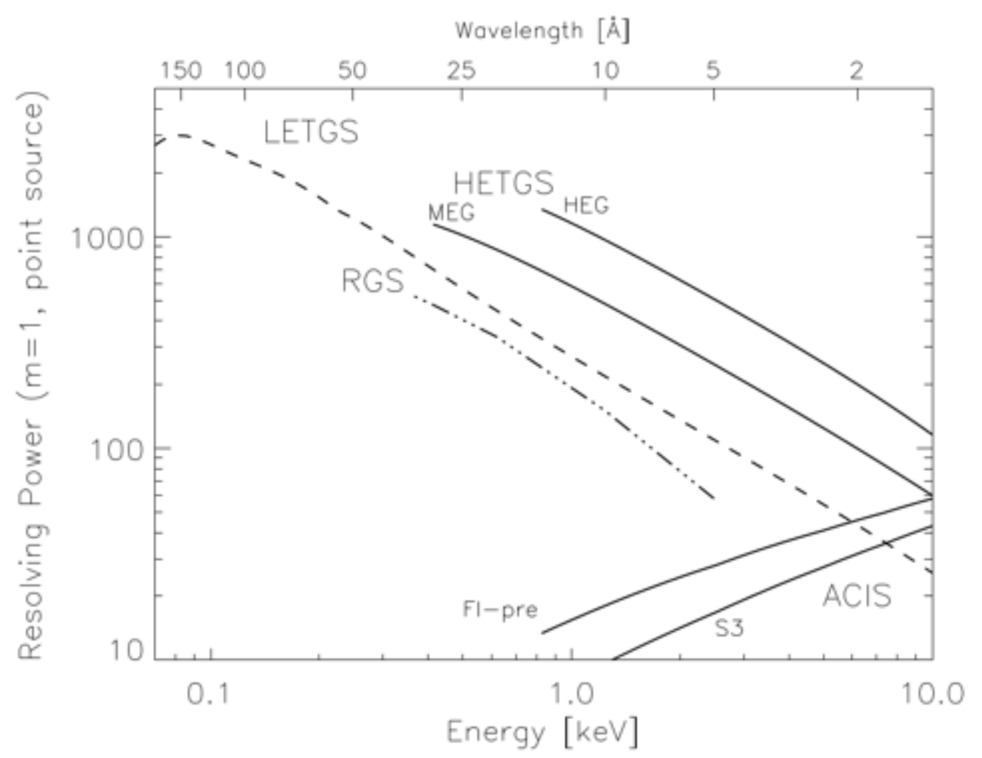


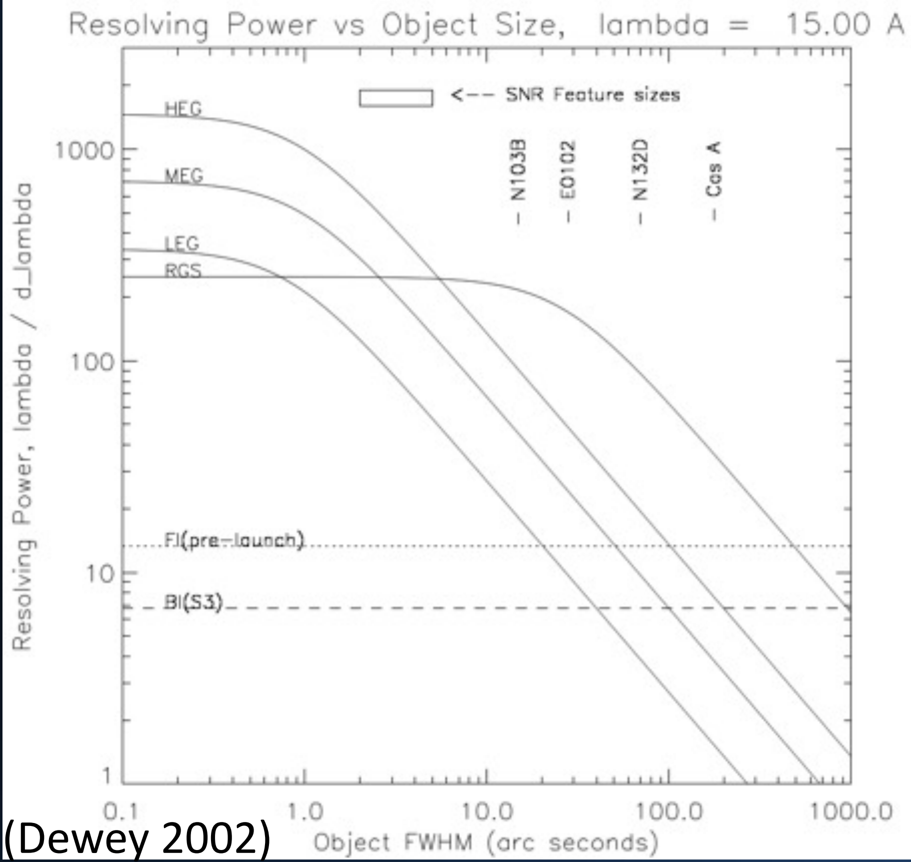
(Vink 2012)

Modern High-Resolution X-ray Spectrometers

Dispersive (Gratings)

- Chandra
  - LETG
  - HETG
- XMM-Newton
  - RGS





(Dewey 2002)

Non-Dispersive(Microcalorimeter)

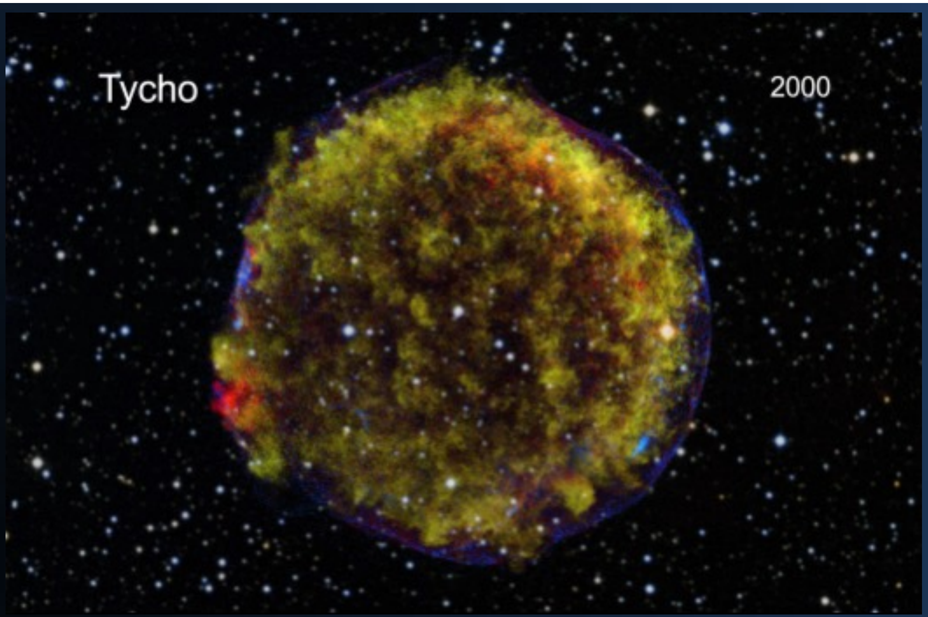
- Hitomi
  - SXS
  - ~ 5 eV FWHM in 0.3 – 12 keV band

Studying SNRs with High-Resolution X-ray Spectroscopy

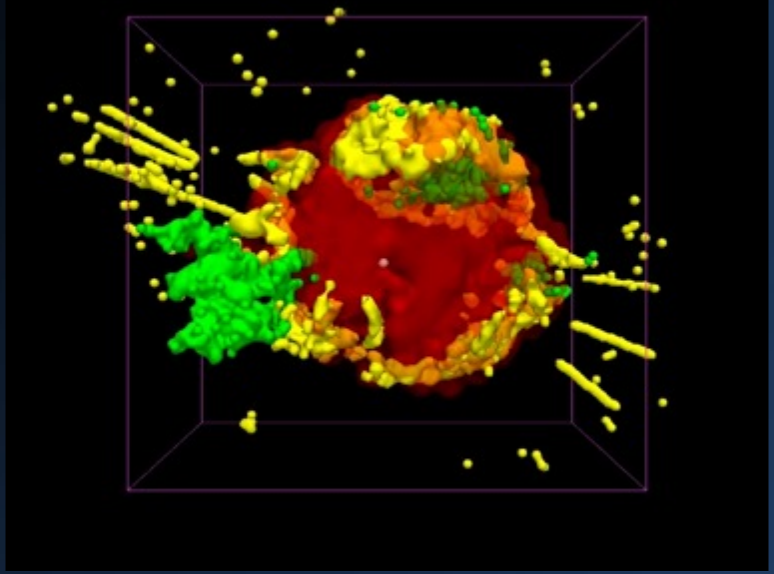
- High-resolution X-ray spectroscopy (HRXS) grants the ability to distinguish closely-spaced emission lines in an X-ray spectrum
- What insights into supernova remnants can be gained with HRXS?

Insights into Supernova Remnants with HRXS

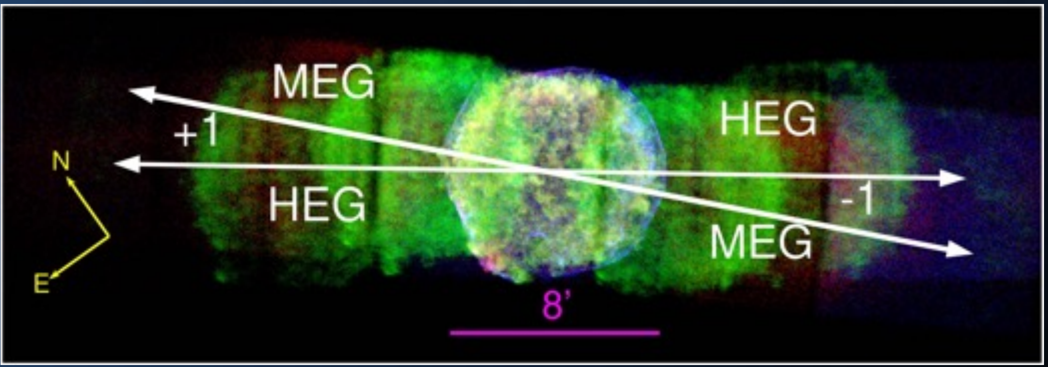
- **Kinematics**
  - **Precision Doppler shift measurements ---> Reveals detailed 3D Structure**
    - **Error down to 100's of km s^{-1}**
  - **Subtle asymmetries in ejecta distribution constrain explosion mechanisms**
  - **Investigate the properties of the surrounding medium**

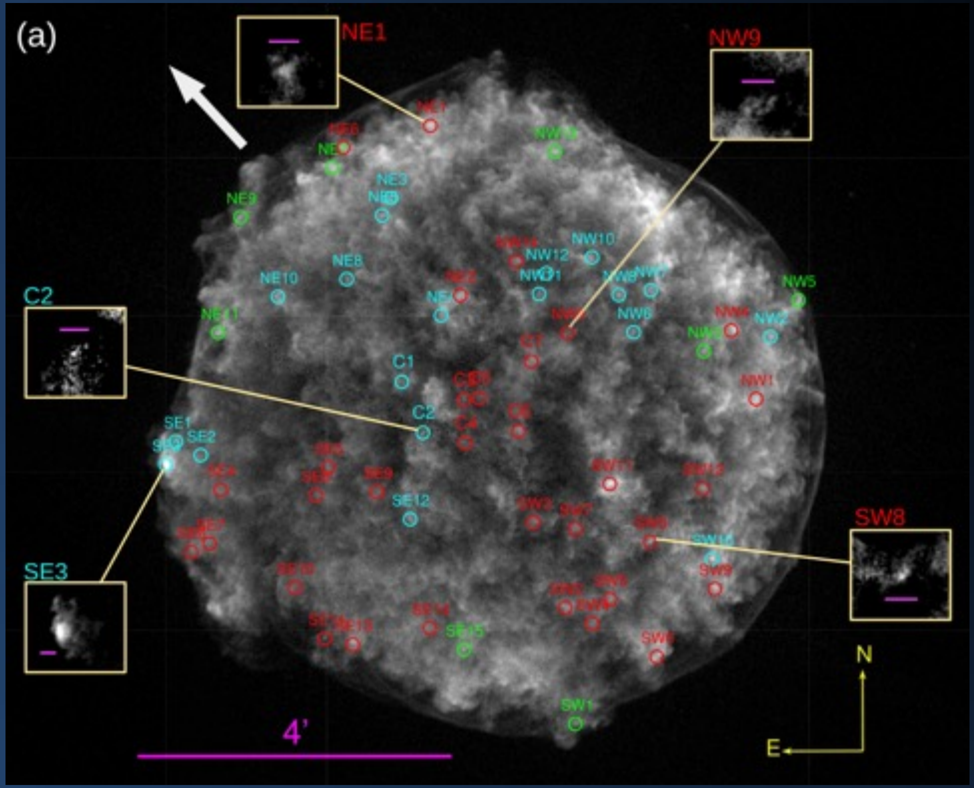


Cas A

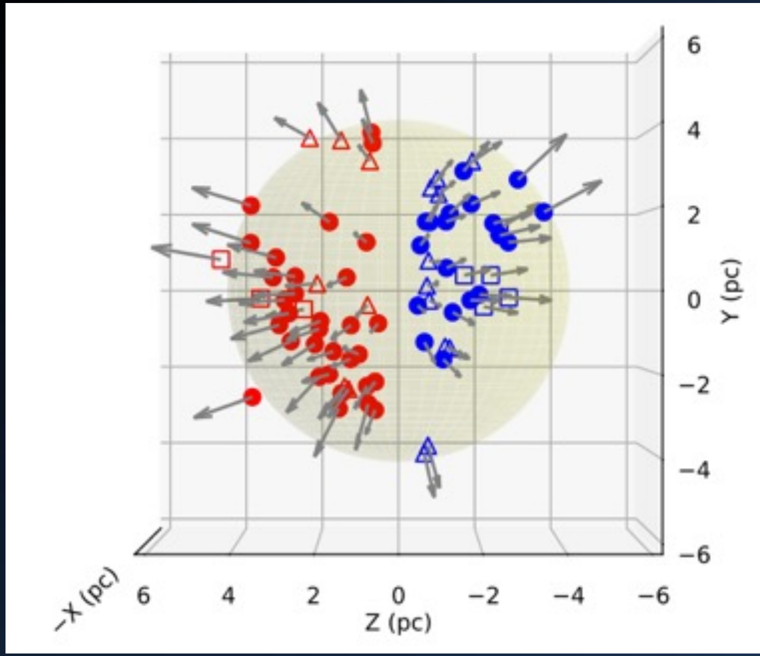


3D Velocity Distribution in Tycho (Millard et al. 2022)

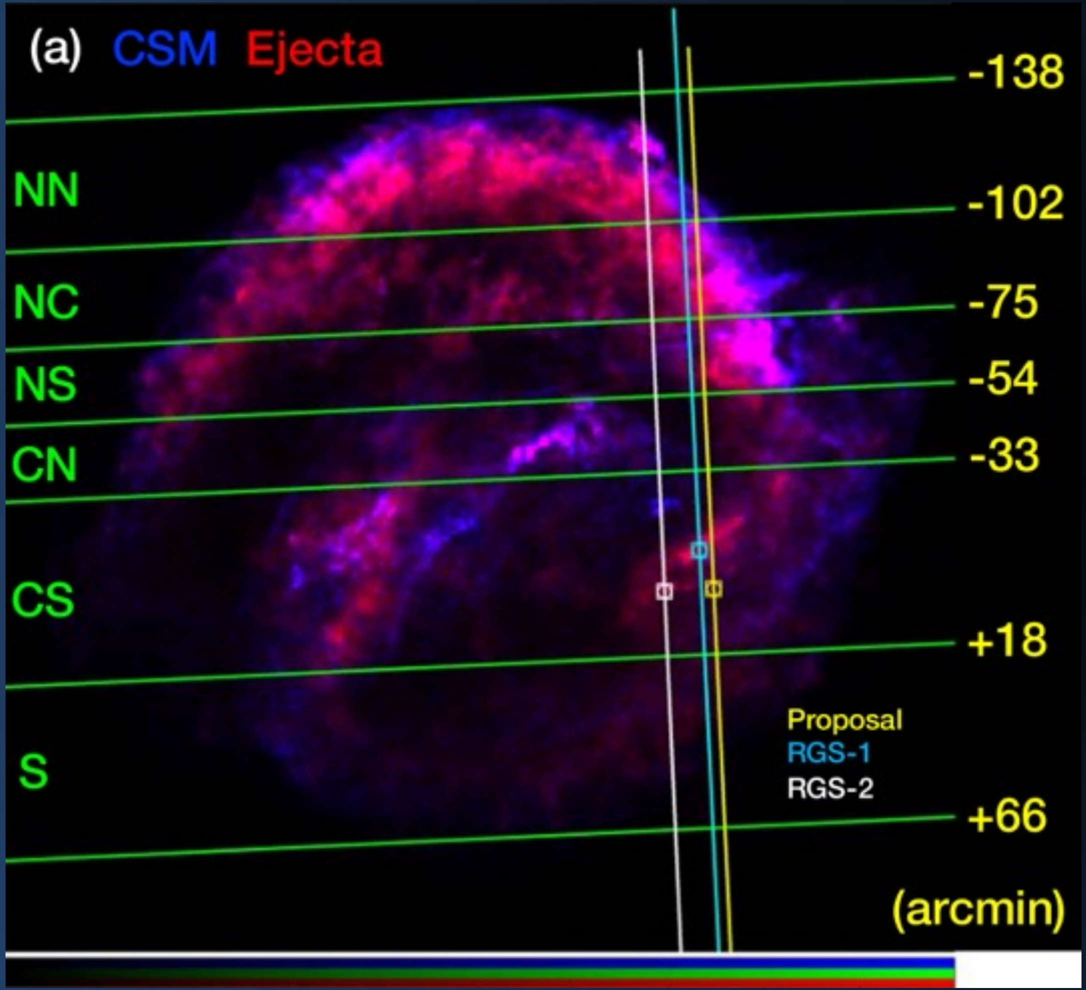




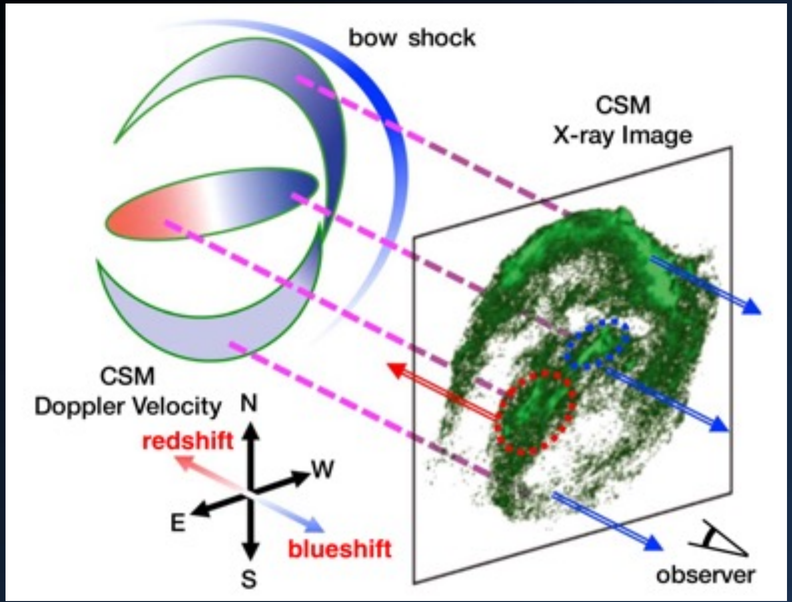
- Chandra HETG observation of Tycho (59 regions)
- Ejecta v_r up to ~5500 km s^{-1}
  - Velocity error ~ 500 km s^{-1}
- Generally higher ejecta speeds toward the SE
- Apparent large-scale asymmetry
  - Northern half mostly blueshifted
  - Southern half mostly redshifted



CSM Kinematics in Kepler (Kasuga et al. 2021)

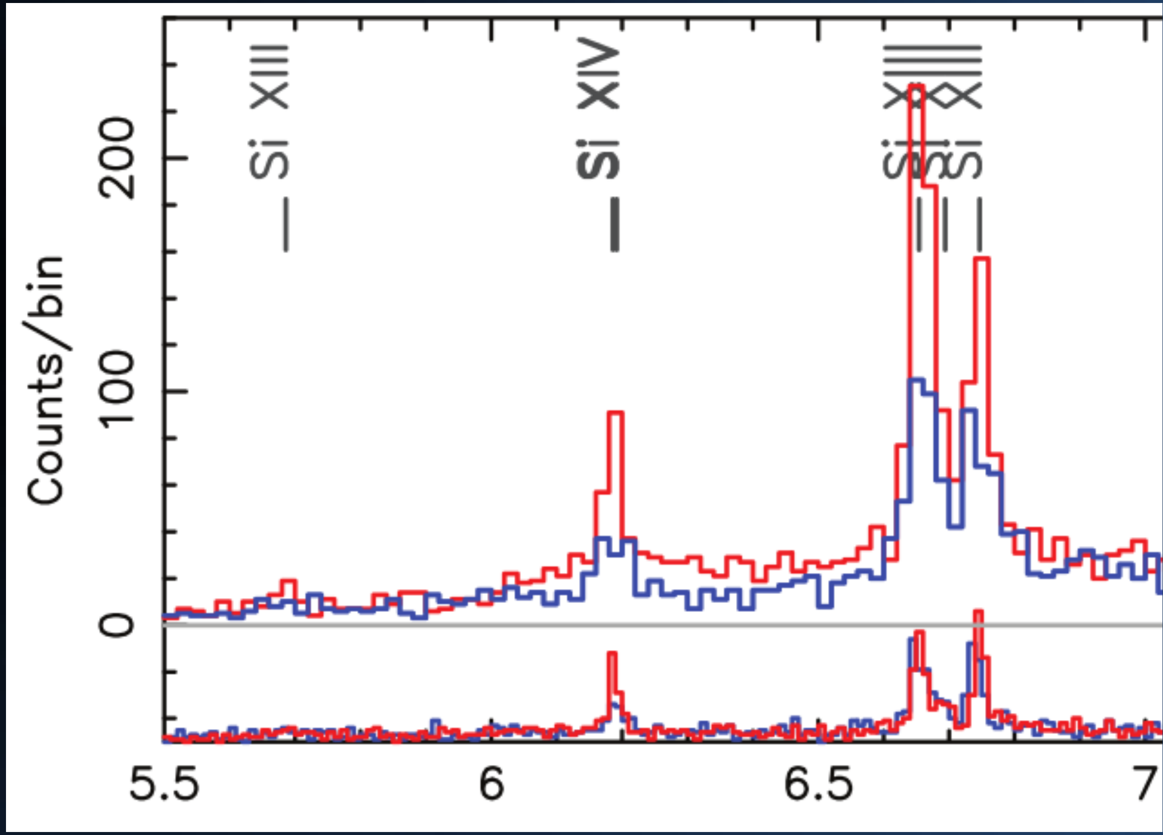


- XMM-RGS observation of Kepler
- Studying dense, asymmetric circumstellar medium (CSM
- CSM is blueshifted with a velocity of up to 500 km s^{-1} at edge
  - Consistent with runaway AGB star as progenitor
- Central bar structure, indicative of torus
  - Northwest half is blueshifted
  - Southeast half is redshifted



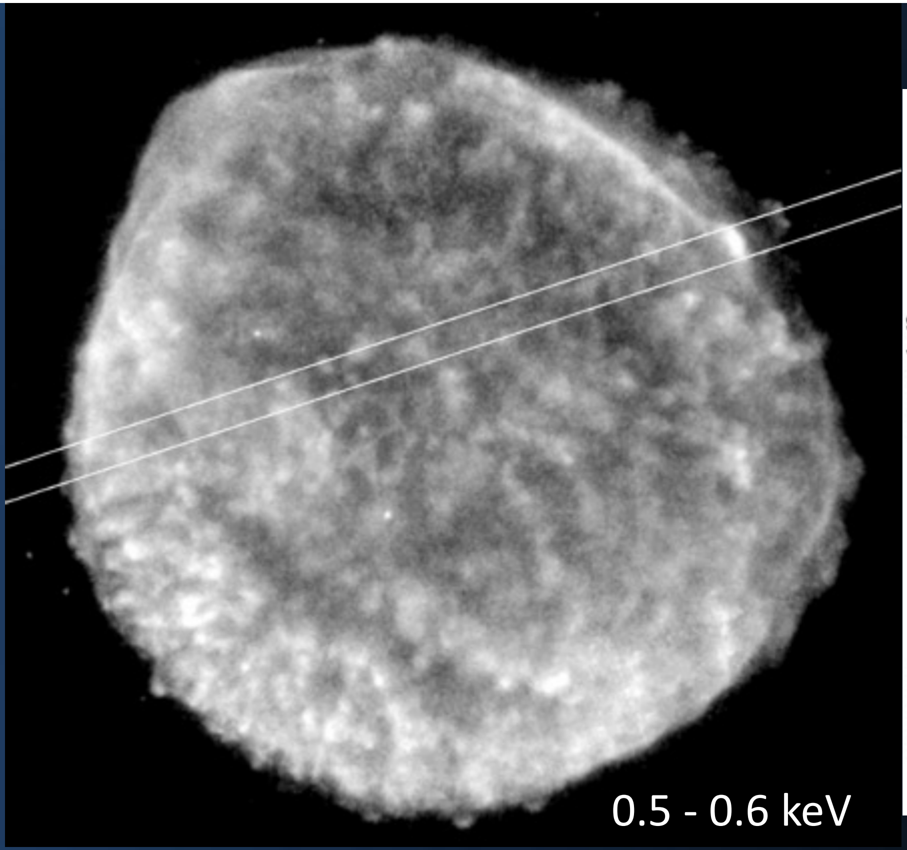
Insights into Supernova Remnants with HRXS

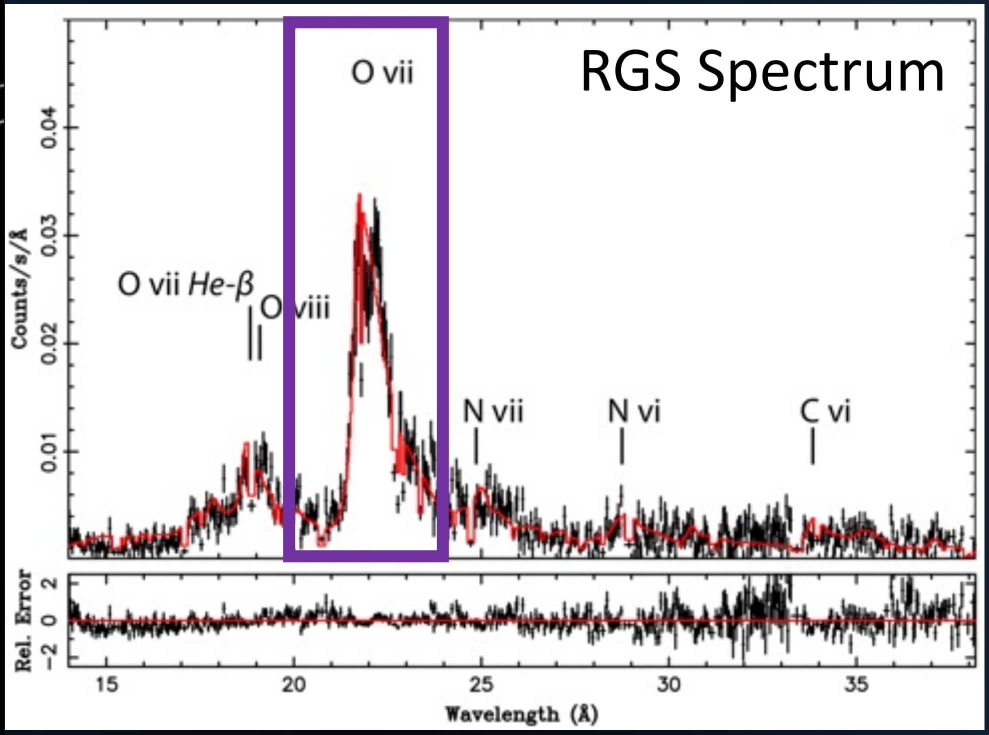
- **Plasma diagnostics**
  - **Electron temperatures**
    - **He-like K α / He-like K β ratio**
    - **He-α / Ly-α ratio**
    - **G-ratio (*f* + *i*)/*r* in He-like ions**
  - **Ion temperatures**
    - **Line broadening (~ 1 eV)**
    - **Detection requires E / Δ E > 100**

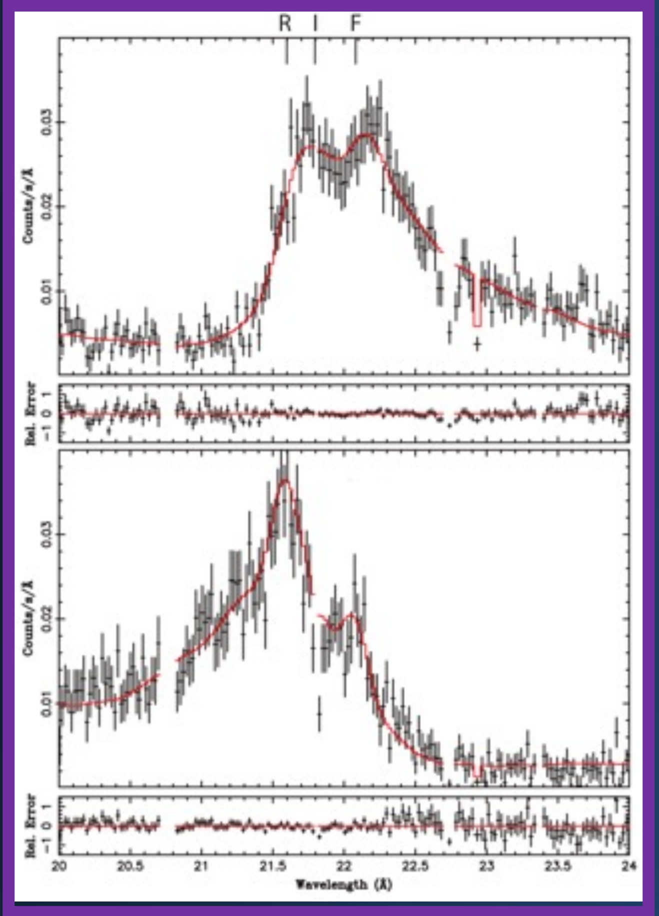


(Dewey 2008)

Ion Temperature in SN 1006 (Broersen et al. 2013)



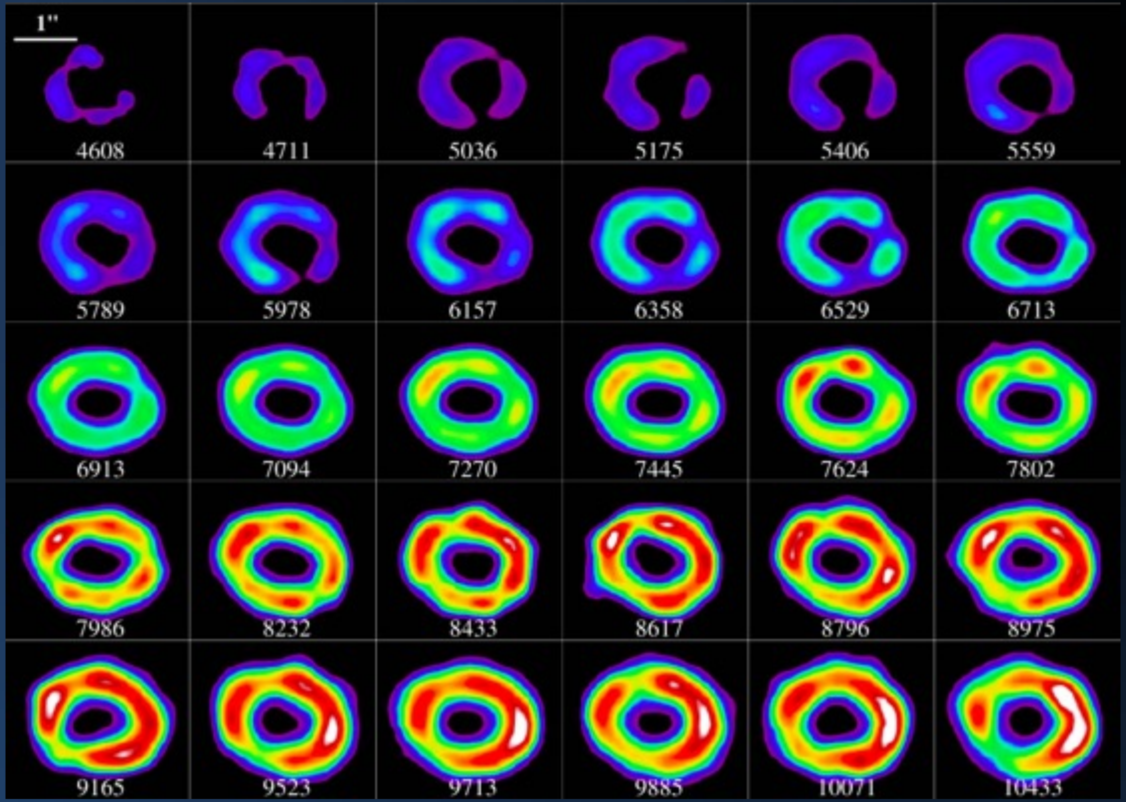




- XMM-Newton-RGS observation of SN 1006
  - Bright ejecta knot in northwestern region
- Measured Doppler broadening of the O VII line
  - σ = 2.46 ± 0.3 eV, corresponds to $kT_{O\ VII} = 275^{+72}_{-63}$ keV
  - Electron temperature was measured at 1.35 ± 0.10 keV with CCD spectroscopy
  - Temperatures between species are not in equilibrium

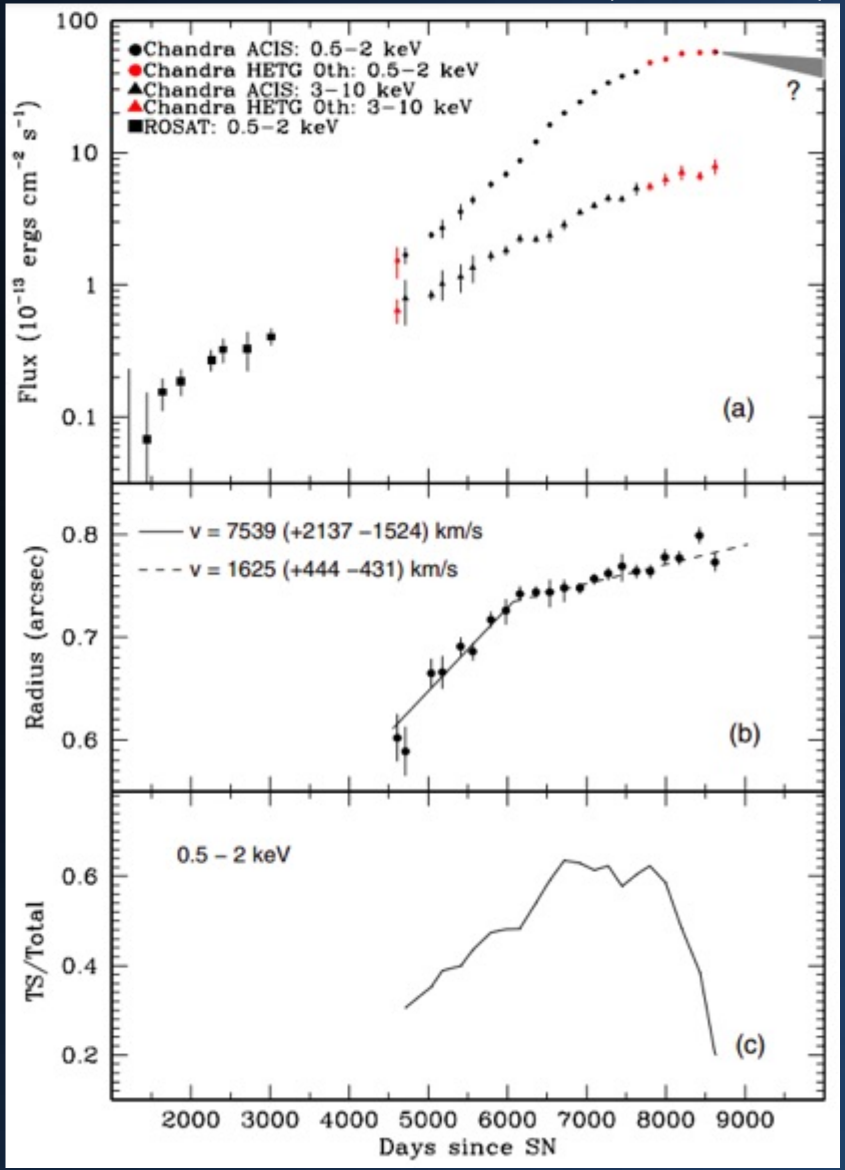
Evolution of SN 1987A

- SN 1987A has been regularly monitored with Chandra since its launch in 1999
- Revealed blastwave impact with equatorial ring (ER)
  - Sudden decrease in the blast wave velocity
  - Dramatic increase in the soft X-ray flux
- Light curve begins to flatten at ~ 7000 days



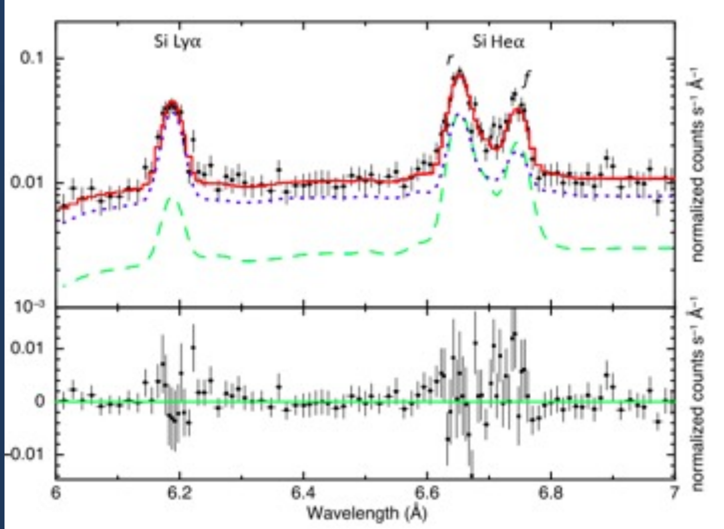
(Frank et al. 2016)

(Park et al. 2011)

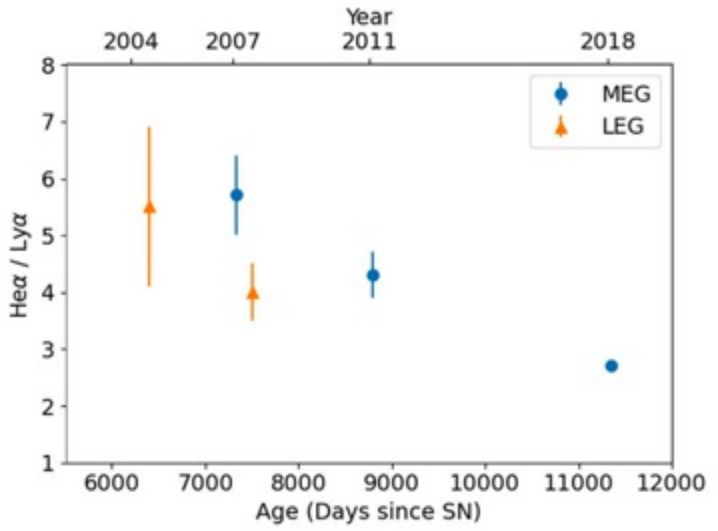


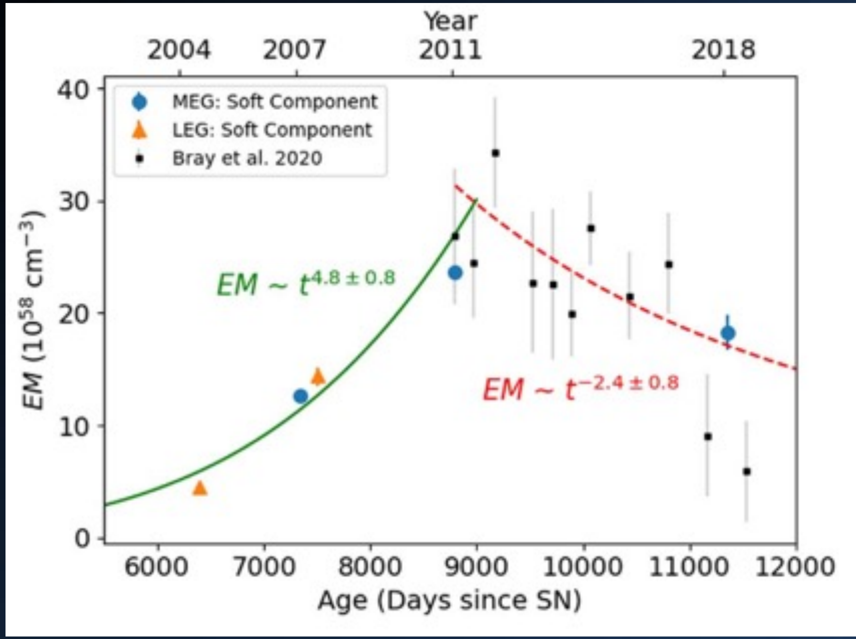
Evolution of SN 1987A (Ravi et al. 2021)

Chandra HETG



- Significant changes in the X-ray line-flux ratios (among H- and He-like Si and Mg ions) in 2018
- Coincide with recent changes in electron temperatures and volume-emission measures
- Transitionary phase - the shock leaves the ER and propagates into a red supergiant wind
- No significant elemental abundance evolution as of 2018

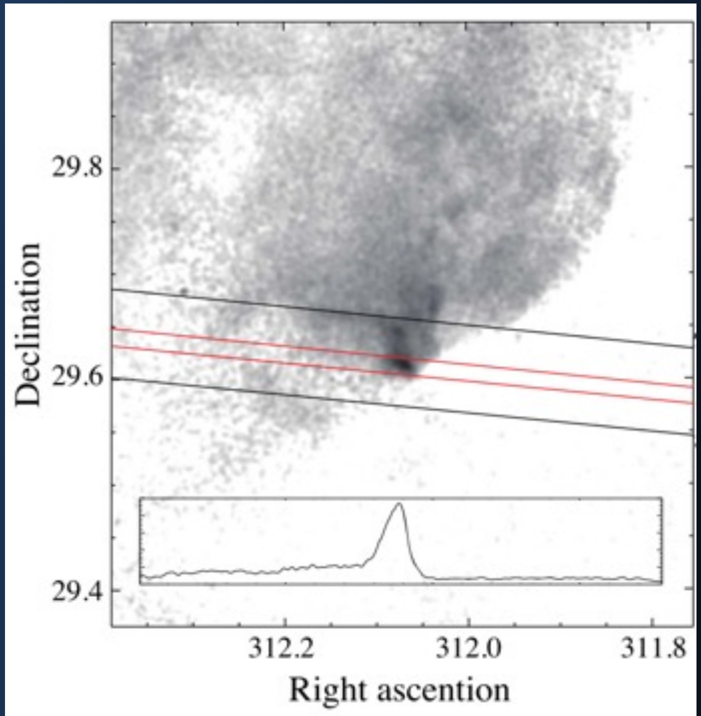


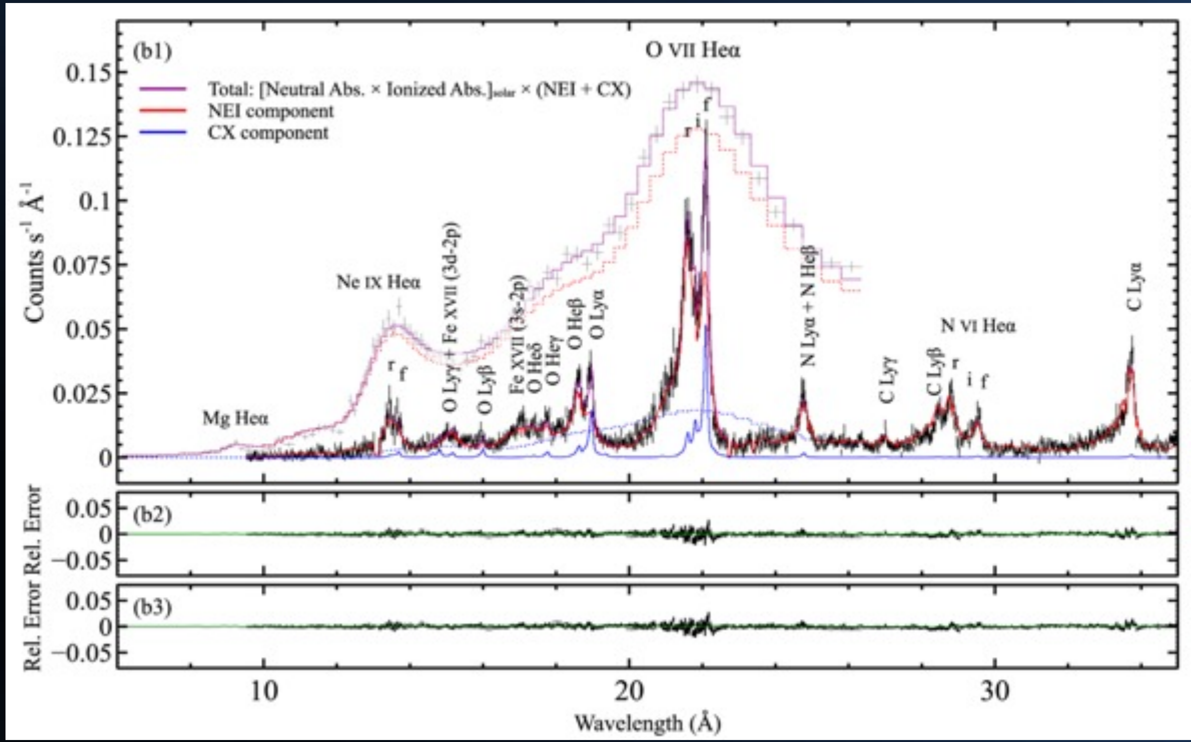


Insights into Supernova Remnants with HRXS

- Charge exchange and resonance scattering predicted in SNRs; evidence remains elusive
- Charge exchange (CX)
  - One or more electrons are transferred from one atom to another
  - The receiving ion may be left in an excited state after the exchange
  - May deexcite by releasing an X-ray
- Resonance scattering (RS)
  - High column density of ions along the line of sight may scatter resonance line photons
- Elemental Abundances

CX in the Cygnus Loop (Uchida et al. 2019)

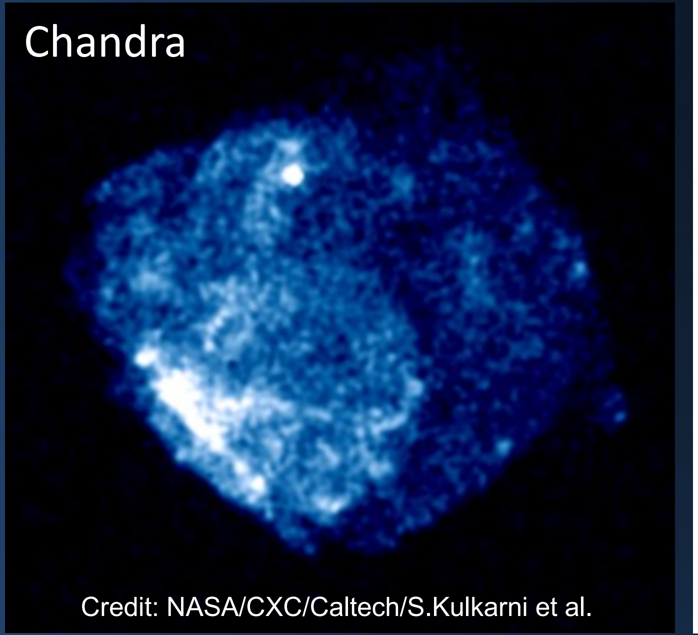


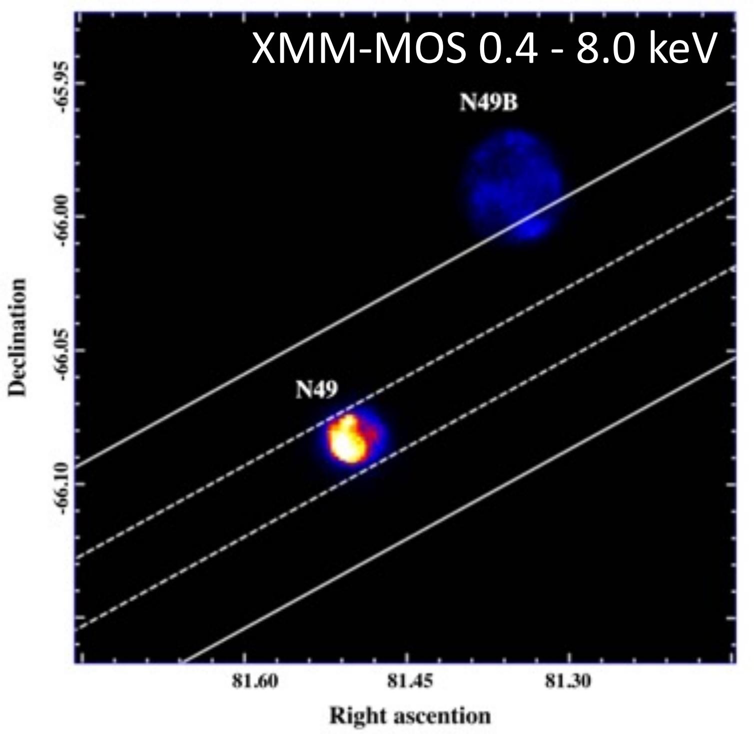


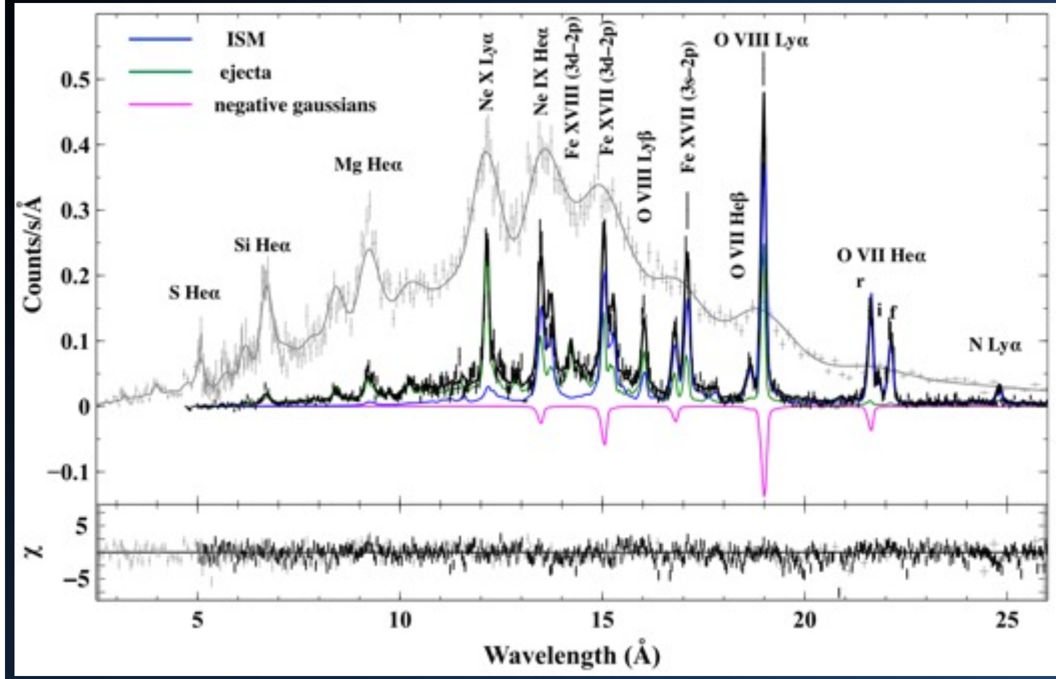
- Southwestern knot (SW-K) region studied with XMM-Newton-RGS
- High forbidden-to-resonance line ratio of O VII Heα
- Soft-band (10–35 Å) spectrum is well explained by a thermal component with charge exchange X-ray emission.
- Measured low elemental abundance of the SW-K confirms "low-abundance problem" in evolved SNRs

Resonance Scattering in N49 (Amano et al. 2020)

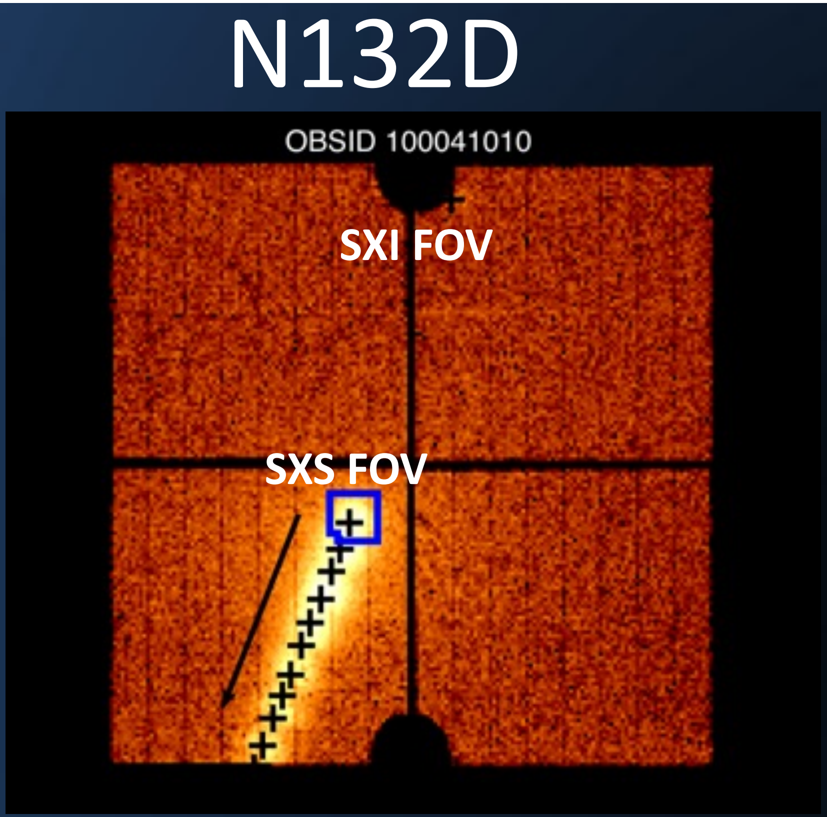
- XMM-Newton-RGS spectrum of N49 shows a high G-ratio of O VII Heα lines as well as O VIII Lyβ/α and Fe XVII (3s–2p)/(3d–2p) ratios
  - Can be explained by resonance scattering
- Resonance scattering has a large impact on measurements of the oxygen abundance.

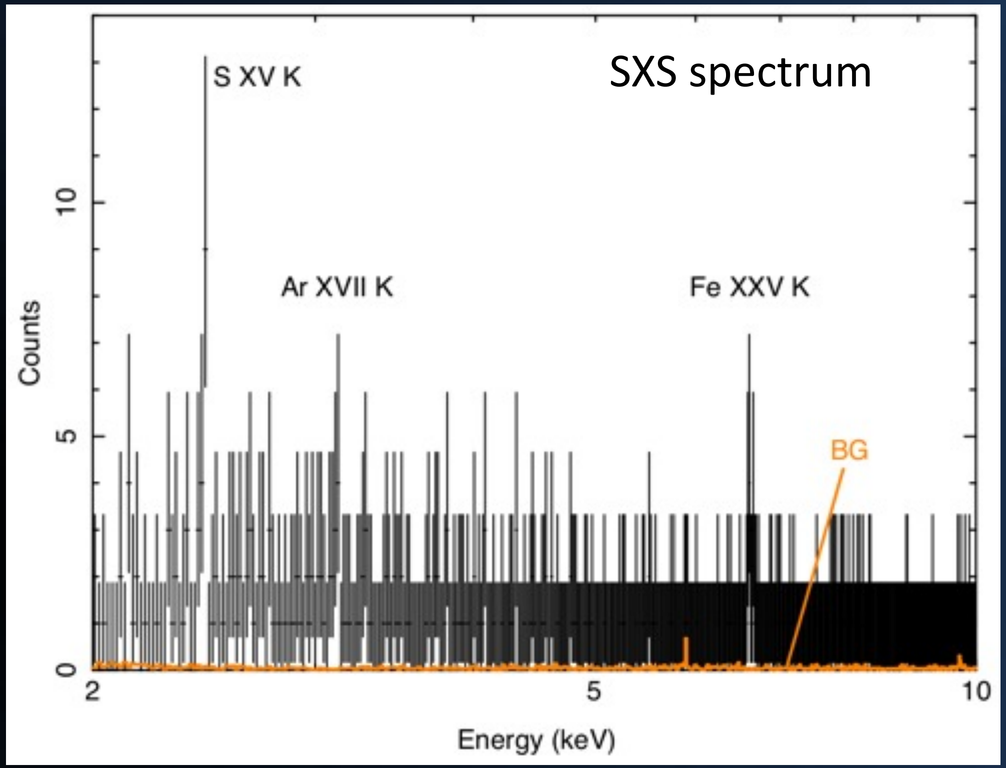






Hitomi Observation of N132D (Hitomi Collab. 2018)





- Very short observation of only 3.7 ks due to loss of attitude
- Fe emission is highly redshifted at ~ 800 km s^{-1} compared to the local ISM in the LMC
- Fe ejecta may be highly asymmetric, since no blueshifted component is found

Future HRXS Detectors

- XRISM (X-Ray Imaging and Spectroscopy Mission)
  - Resolve

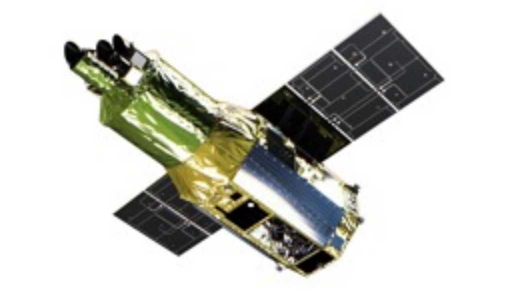
Suzaku XRS --> Hitomi SXS --> XRISM Resolve

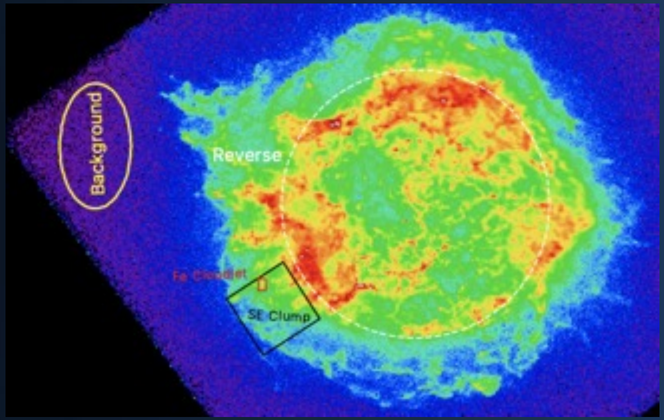
  - Launch planned for August 26, 2023

		XRISM Resolve	LEM
Energy band, keV		0.4–12	0.2–2
Effective area, cm^2	0.5 keV 6 keV	50 300	1600 0
Field of view		3′	30′
Grasp, 10^4 cm^2 $arcmin^2$	0.5 keV	0.05	140
Angular resolution		75″	15″
Spectral resolution		7 eV	1 eV (central 7′), 2 eV (rest of FOV)
Detector size, pixels (equiv. square)		6×6	118×118

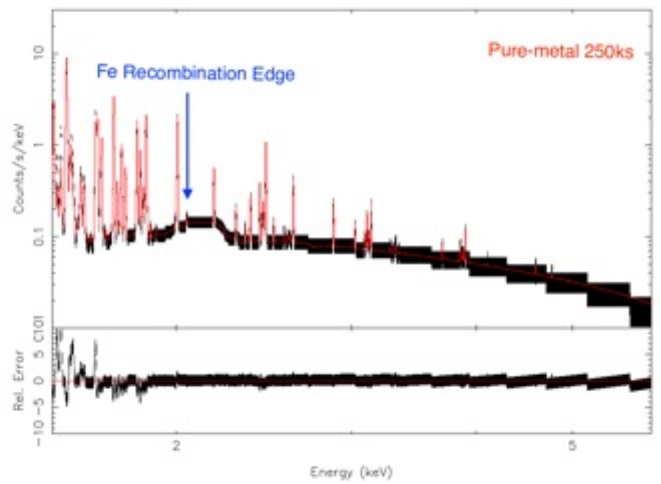
(Kraft et al. 2022)

- LEM (Line Emission Mapper)
  - X-ray Probe for the 2030s





Simulated Cas A XRISM spectrum



(Greco et al. 2020)

Acknowledgements

- Thank you to ….
  - The workshop Science/Local Organizing Committees
  - The CXC team
- For a detailed review, please see
  - Katsuda, S., “High-Resolution X-Ray Spectroscopy of Supernova Remnants”, arXiv e-prints, 2023. doi:10.48550/arXiv.2302.13775