XRS Stellar Life Cycles WG

Stellar Life Cycles covers a wide range of science, including all stages of stellar evolution, ISM, planets and the solar system, and relationship to Galactic structure.

1. **Stellar Birth and the ISM (Chair: Lopez; 15 members)**
2. **Stellar Life (Chair: Osten; 19 members)**
3. **Stellar Death (Chair: Pooley; 12 members)**
4. **Supernova Remnants (Chair: Lopez; 17 members)**
5. **X-ray Binary Populations (Chair: Ptak; 19 members)**
6. **Solar System and Exoplanets (Chair: Wolk; 8 members)**

Big Questions / Topics

1. Star formation
2. Magnetic fields and atmospheric structuring
3. Mass loss
4. Exoplanet atmospheres
5. Supernova explosion mechanisms
6. Census of compact objects in other galaxies

Stellar Birth & ISM

Compelling science question: how do massive stars form?

- Role of XRS: resolve & detect faint/distant star clusters
  - Larger exploring volume relative to Chandra
  - Go down to lower masses; get X-ray luminosity function
  - Enables comparison of star clusters; easier to survey large areas
  - Bonus science: stellar winds/mass loss, diffuse emission

Specifications: spatial resolution crucial; effective area important to get down to lower masses, probe higher column regions

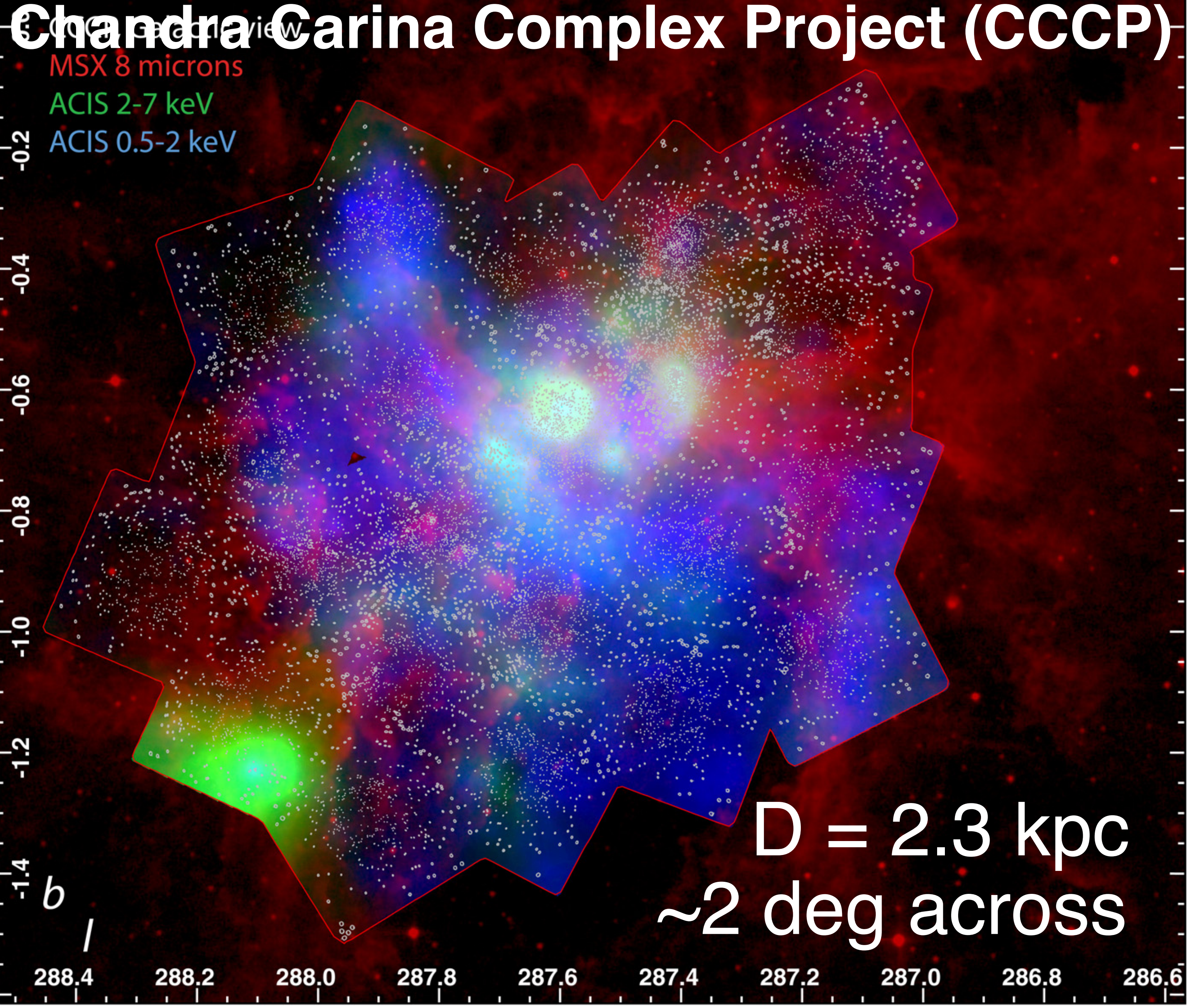
Other compelling science:

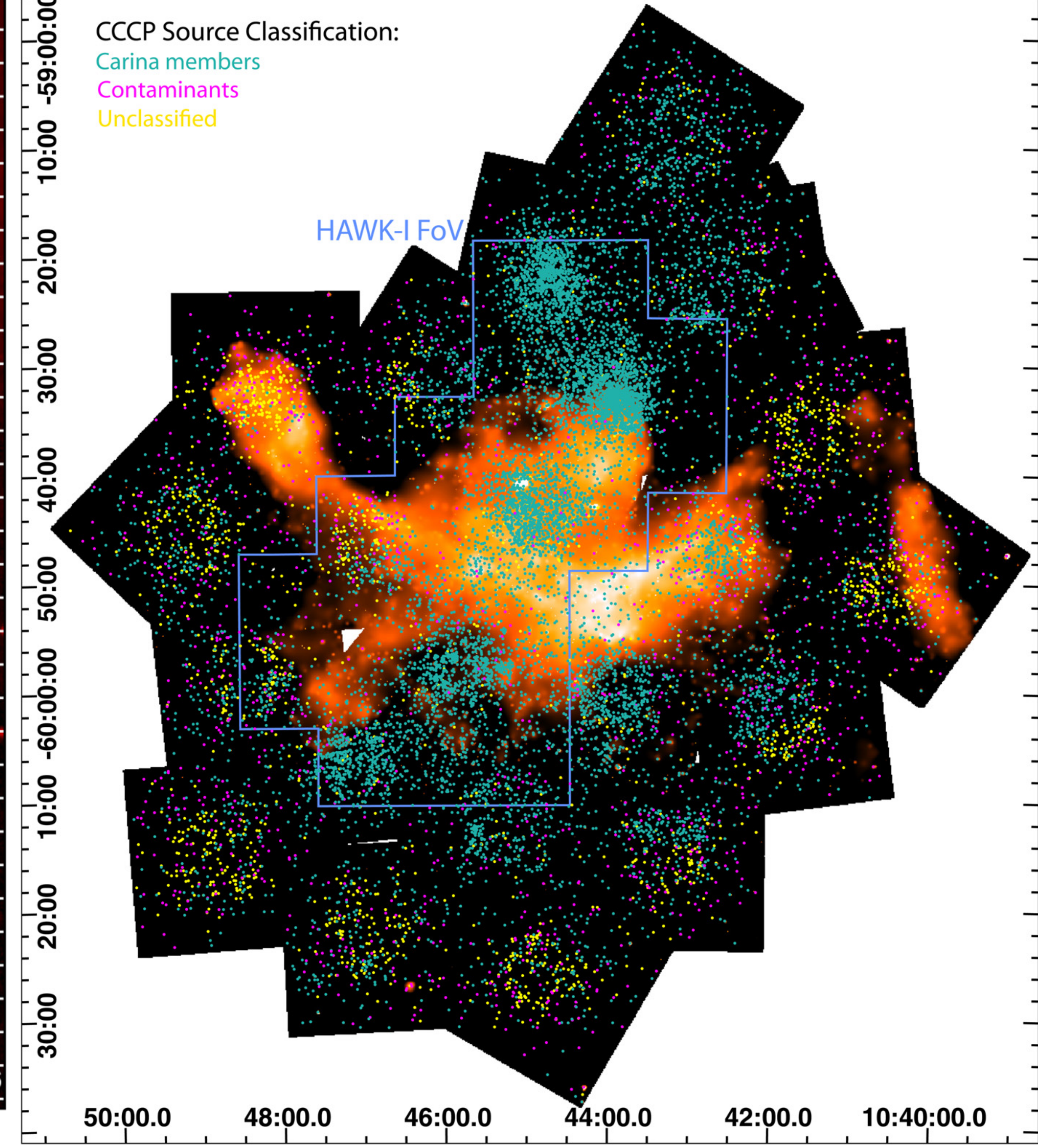
Accretion in early systems (high throughput <1 keV, gratings)

Dust-grain composition from X-ray absorption (<1 keV, gratings)

Metal abundances of ISM (need down to 0.3 keV to get C, gratings)

Chandra Carina Complex Project (CCCP)





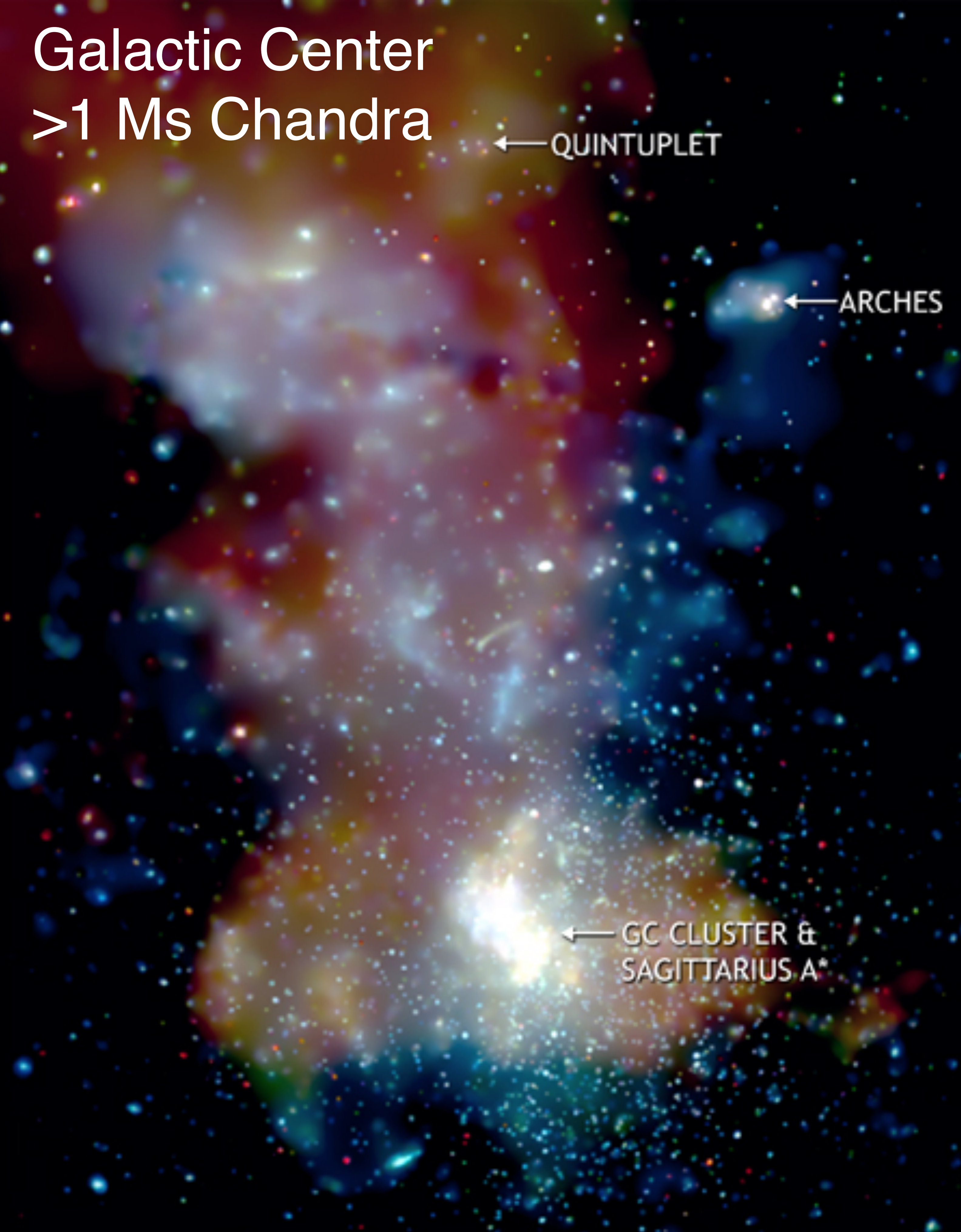
22 ACIS-I pointings x 60 ks each = 1.2 Ms total

Townsley et al. 2011

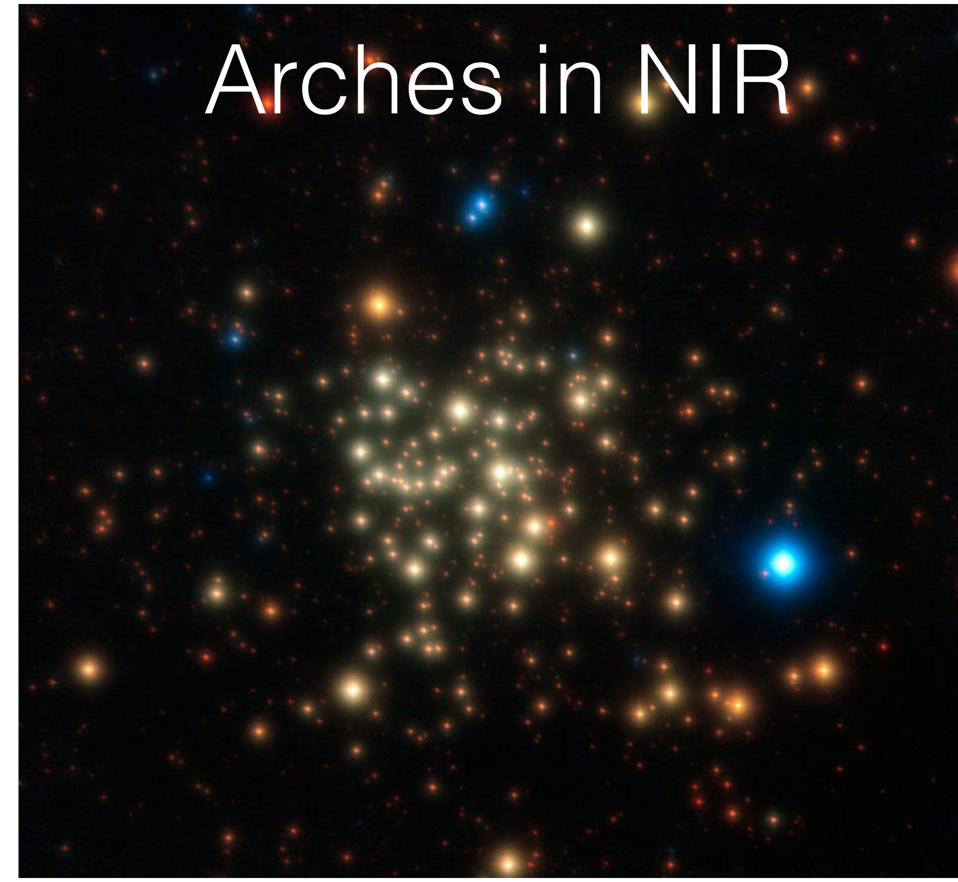
Detected ~400 YSOs, >14,000 total sources

~3% point sources >100 net counts; ~60% >10 net counts

Spatial resolution crucial; increased effective area gets equivalent mapping for more distant clusters, highly absorbed point sources, and sensitivity to lower mass stars; sensitivity/resolution off-axis important



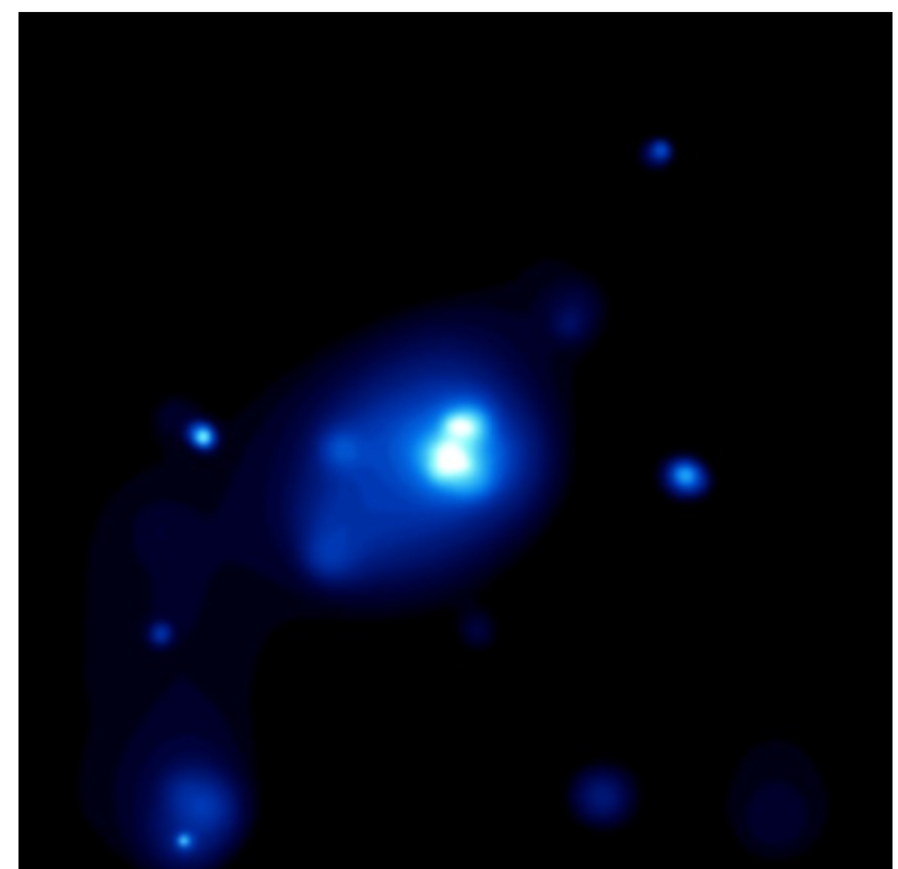
Wang 2006



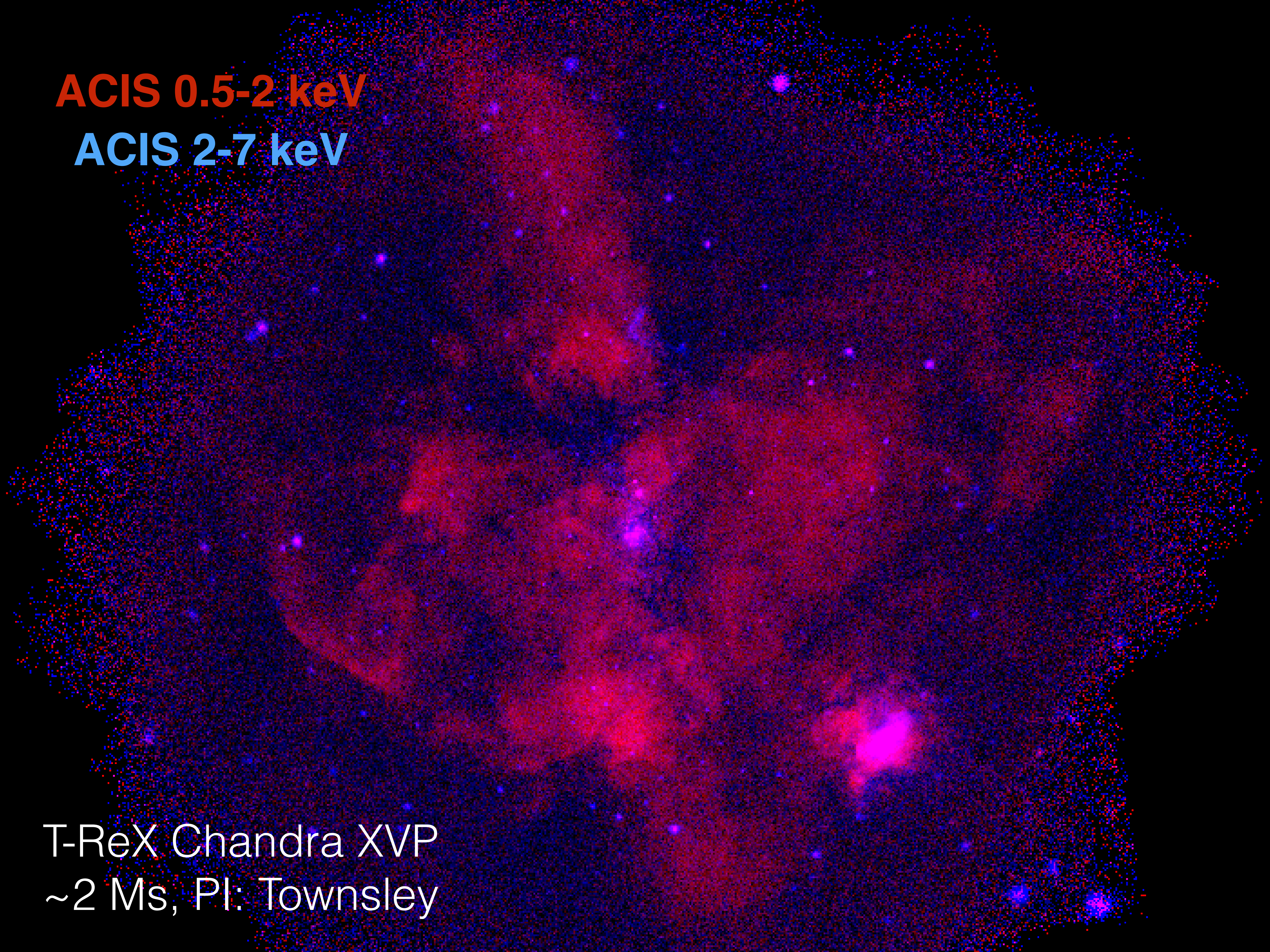
ESO/Espinoza

~15" across

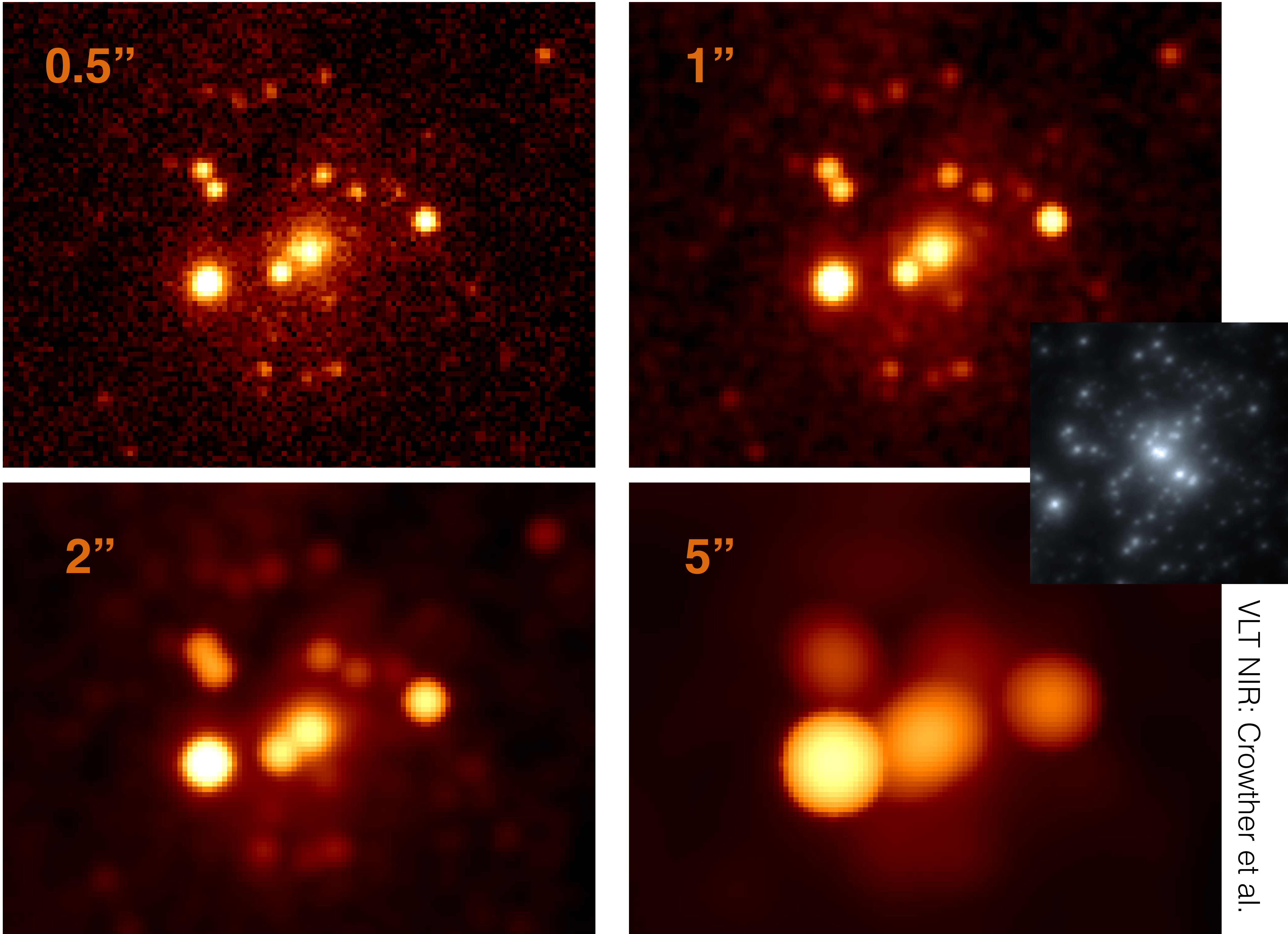
$N_H \sim 10^{23}$ cm^{-2}



Yusef-Zadeh et al. 2002


ACIS 0.5-2 keV
ACIS 2-7 keV
T-ReX Chandra XVP
~2 Ms, PI: Townsley

R136 Star Cluster, 1’ box



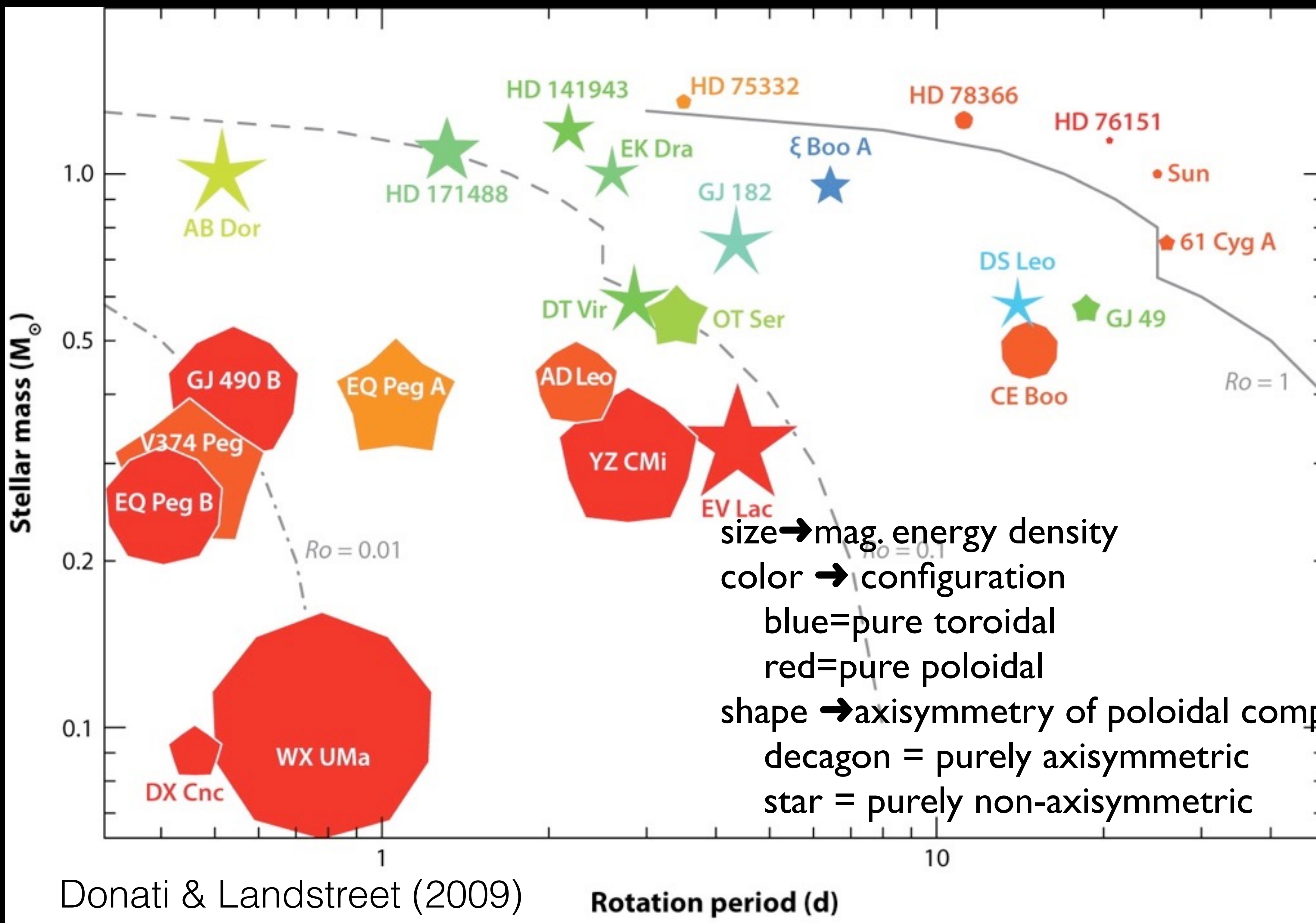
VLT NIR: Crowther et al.


Stellar Life Questions

Stellar Life Questions

- ***How does the dynamo generation of magnetic fields control structuring and dynamics of stellar outer atmospheres?***
  - Stars with outer convection zone: young stars, solar-like stars, M dwarfs but also evolved cool stars
  - Current results based on high resolution spectroscopy have been biased towards the X-ray brightest objects due to the current sensitivity limits.
  - Increase in spectral resolution expands plasma diagnostics: flows, turbulence, length scales through opacity effects.
  - Important for understanding not just the star, but impact on environment (disks, planets)
  - Key Constraints: A_{eff} at low E (<2 keV), spectral resolution at low E, low E cutoff (<0.4 keV), spatial resolution to separate binary members & resolve neighbors in nearby star forming regions
- ***How do stars lose mass and how does mass-loss impact the life cycle of stars in the past, present, and future, & as a function of metallicity??***
  - Key Constraints: A_{eff} at low E (<2 keV), spectral resolution at low E, low E cutoff, spatial resolution to separate binary members & resolve neighbors

Complexity in Surface Magnetic Field Structures Almost Certainly Leads to Differences in Coronal Characteristics



size➜mag. energy density

color ➜ configuration

blue=pure toroidal

red=pure poloidal

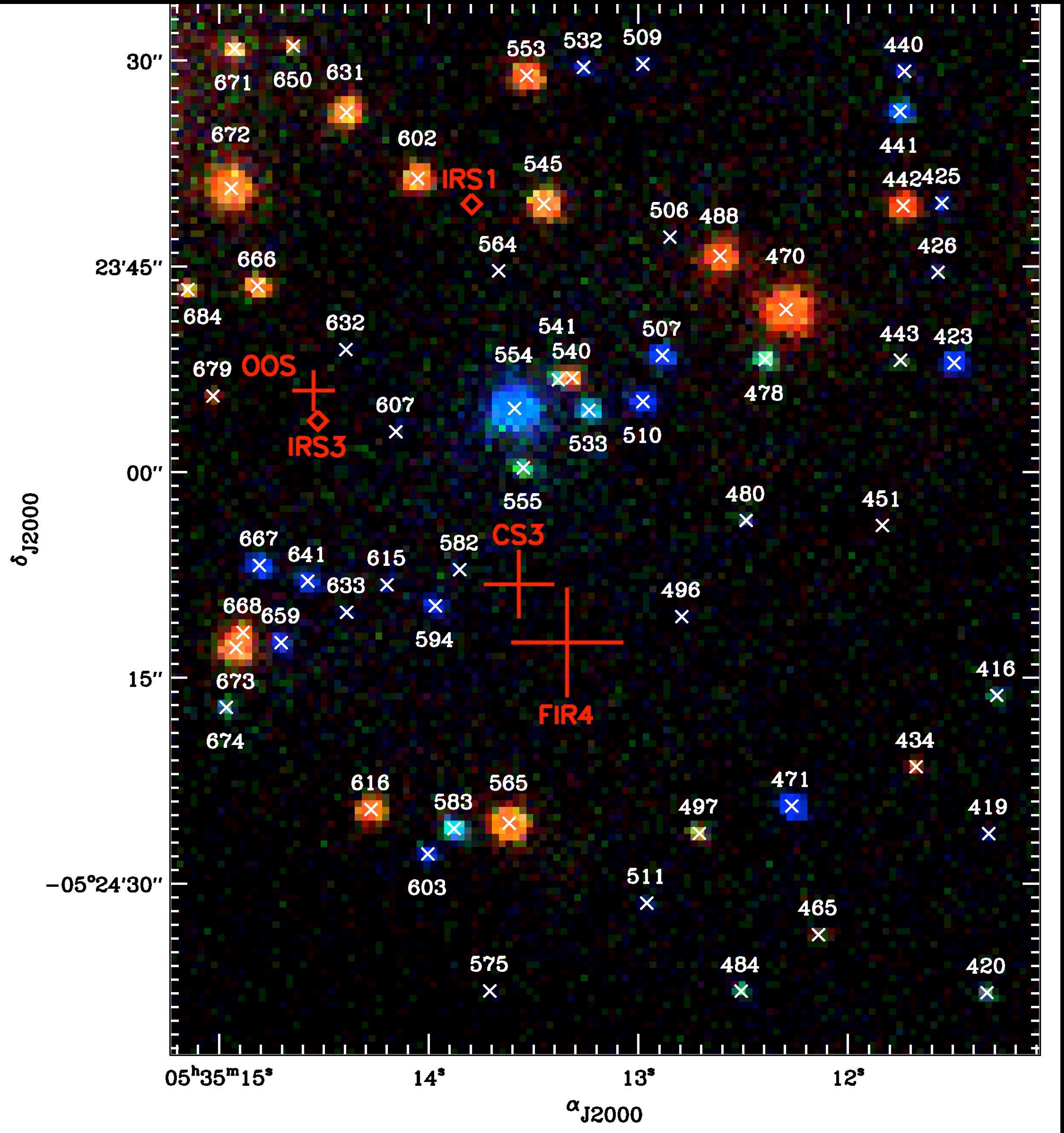
shape ➜axisymmetry of poloidal comp

decagon = purely axisymmetric

star = purely non-axisymmetric

Donati & Landstreet (2009)

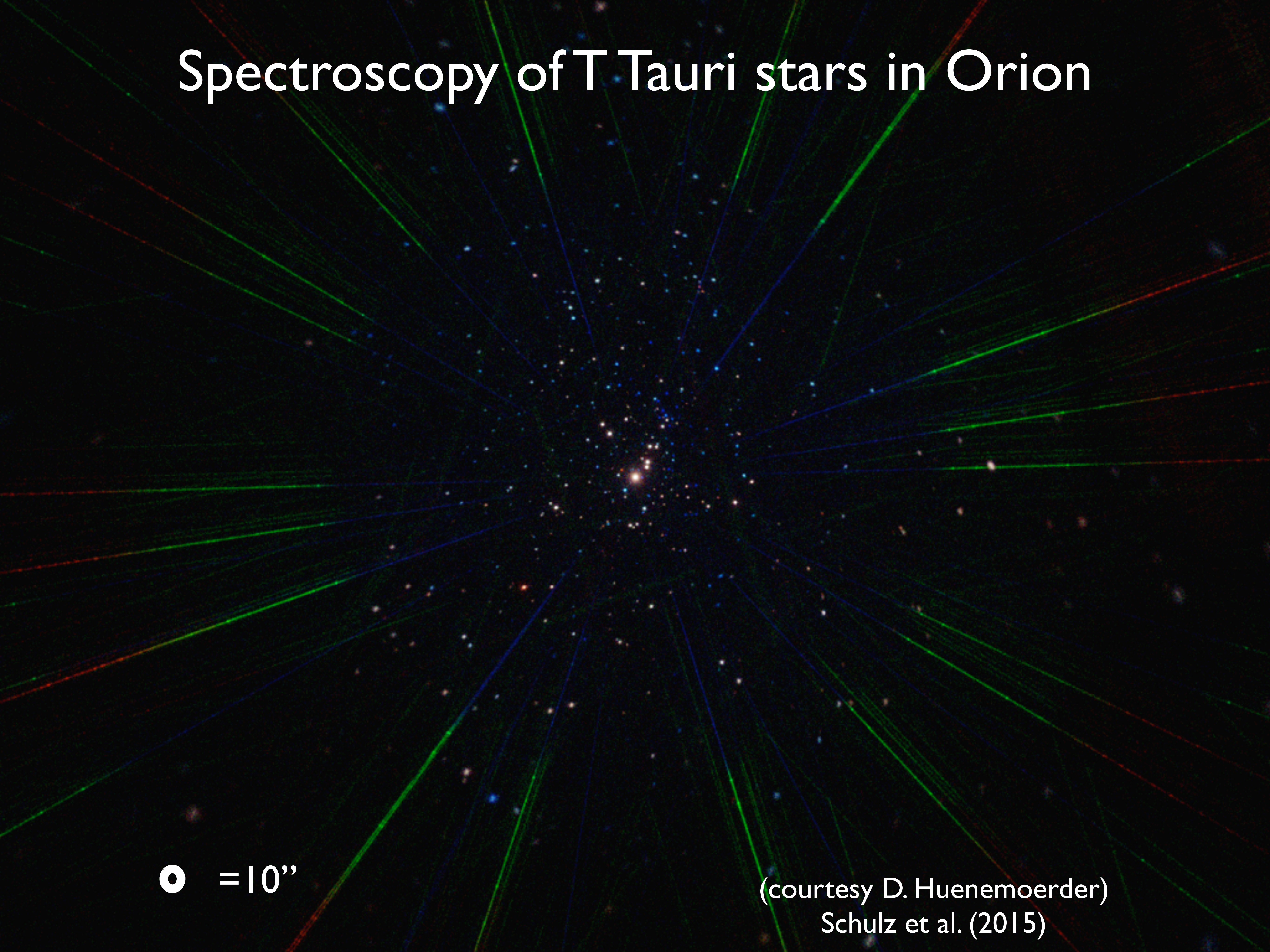
X-rays & star, planet formation: finding the young stars



COUP; Feigelson et al. 2005

McCaughrean 2005

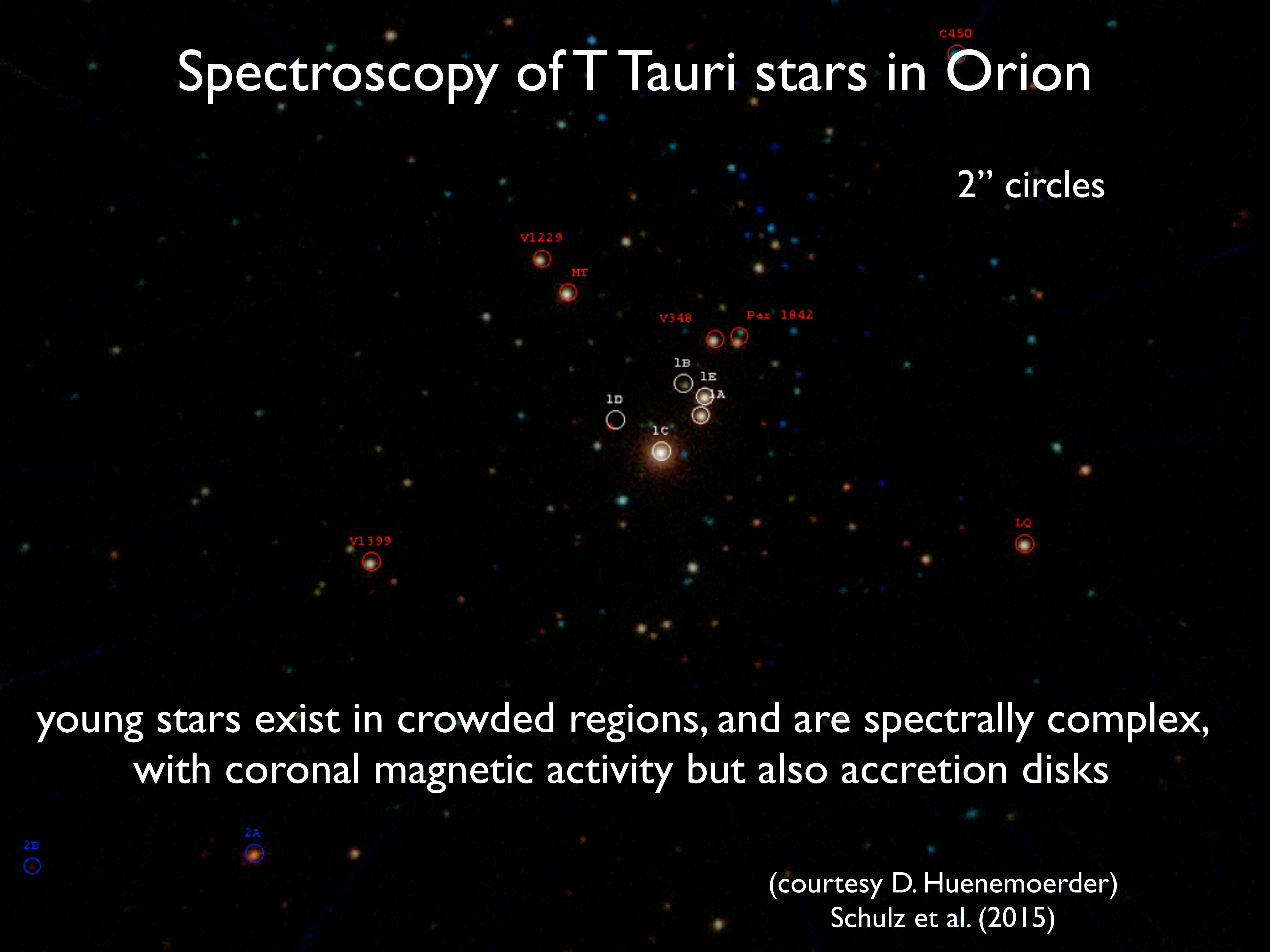
Spectroscopy of T Tauri stars in Orion



(courtesy D. Huenemoerder)
Schulz et al. (2015)

Spectroscopy of T Tauri stars in Orion

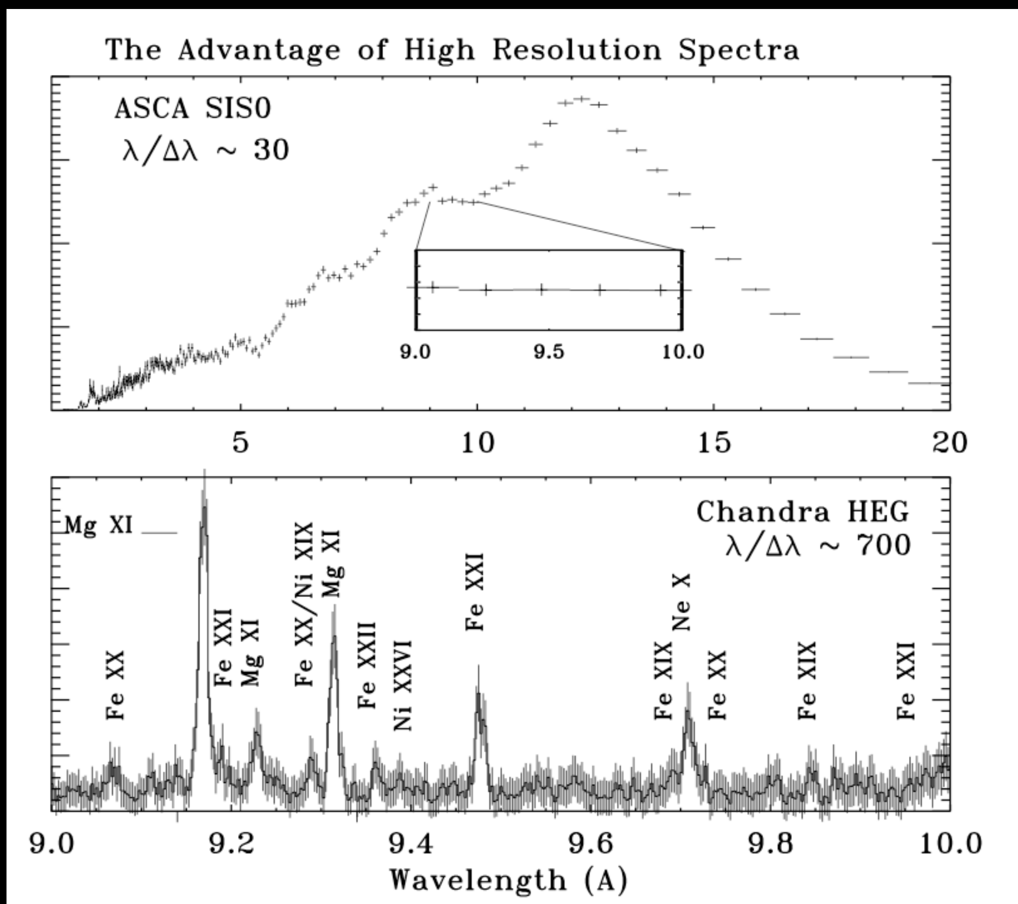
2” circles



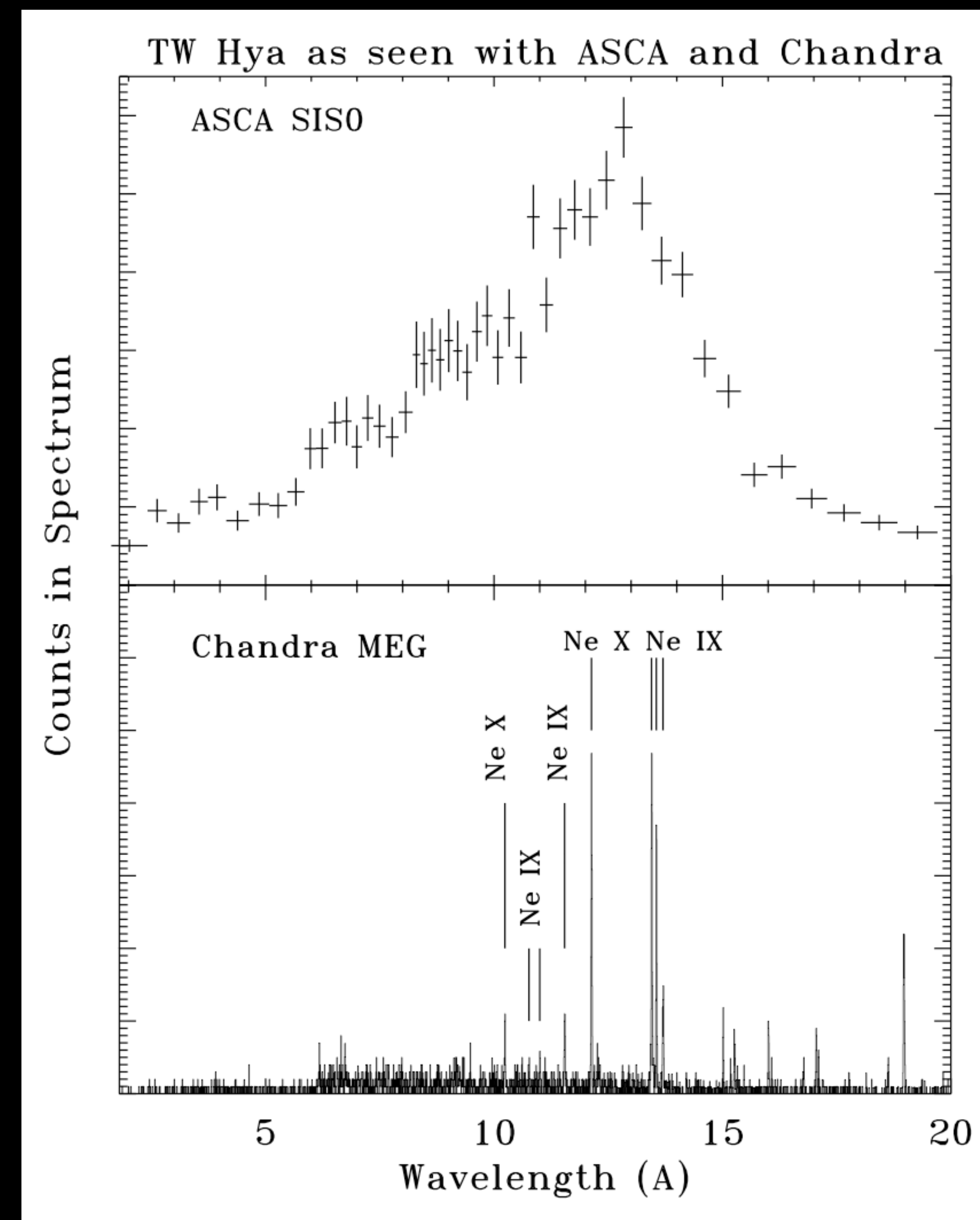
young stars exist in crowded regions, and are spectrally complex, with coronal magnetic activity but also accretion disks

(courtesy D. Huenemoerder)
Schulz et al. (2015)

From Simplicity to Complexity: The Advantage of High Spectral Resolution



coronally active star (Osten et al. 2002) vs. corona +accretion shock + warm post-shock plasma (Brickhouse et al. 2010) revealed through high resolution spectroscopy

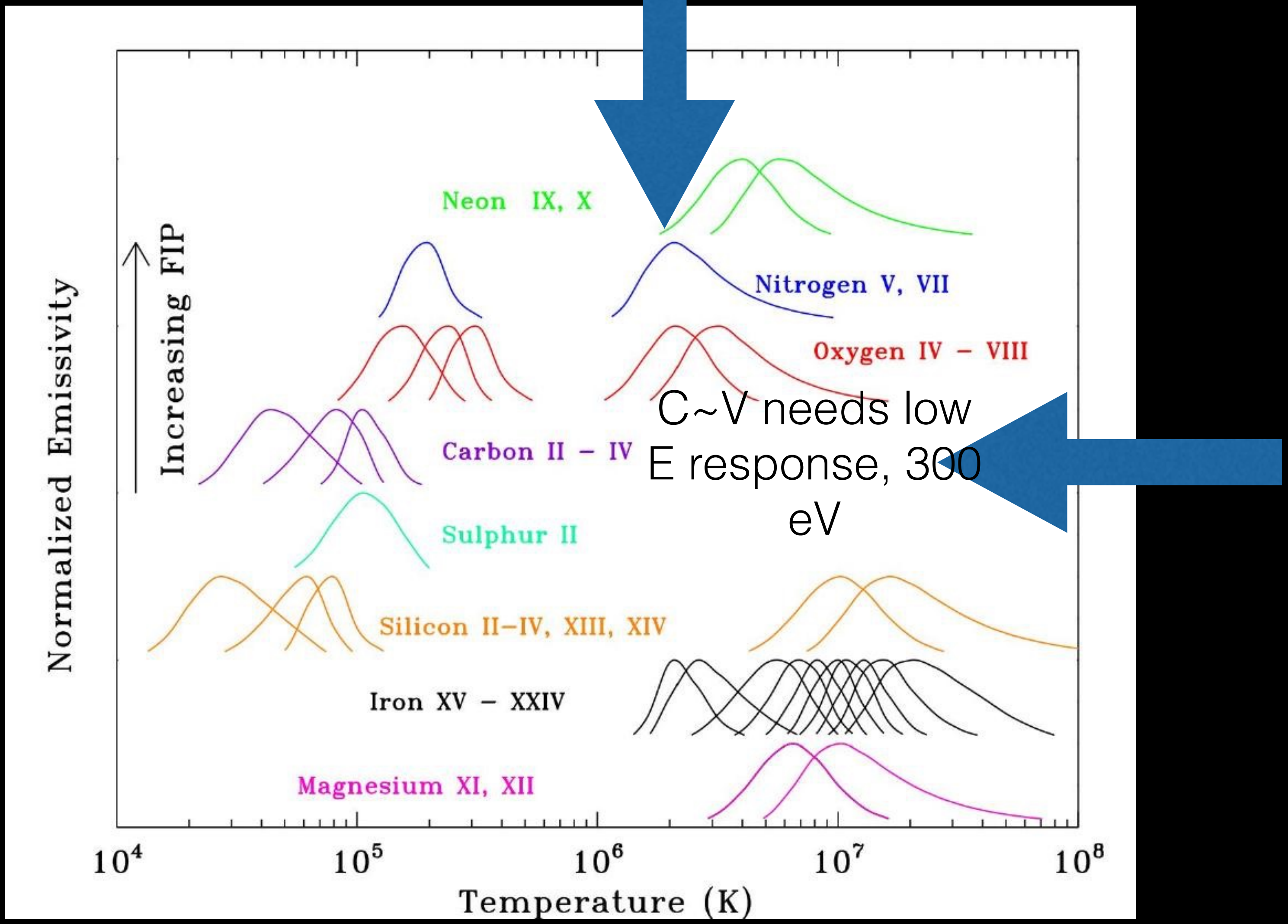


Need spectral resolution at low E

Spectroscopy of Cool Stellar Atmospheres:

- **multi-temperature**
- multi-density
- multi-abundance
- spatially structured
  line velocity widths give
  constraints on spatial structuring
- turbulent
- dynamic
  red/blue shifts reveal dynamics,
  wave processes
- variable

N~VII need low E response



Osten et al. (2003)

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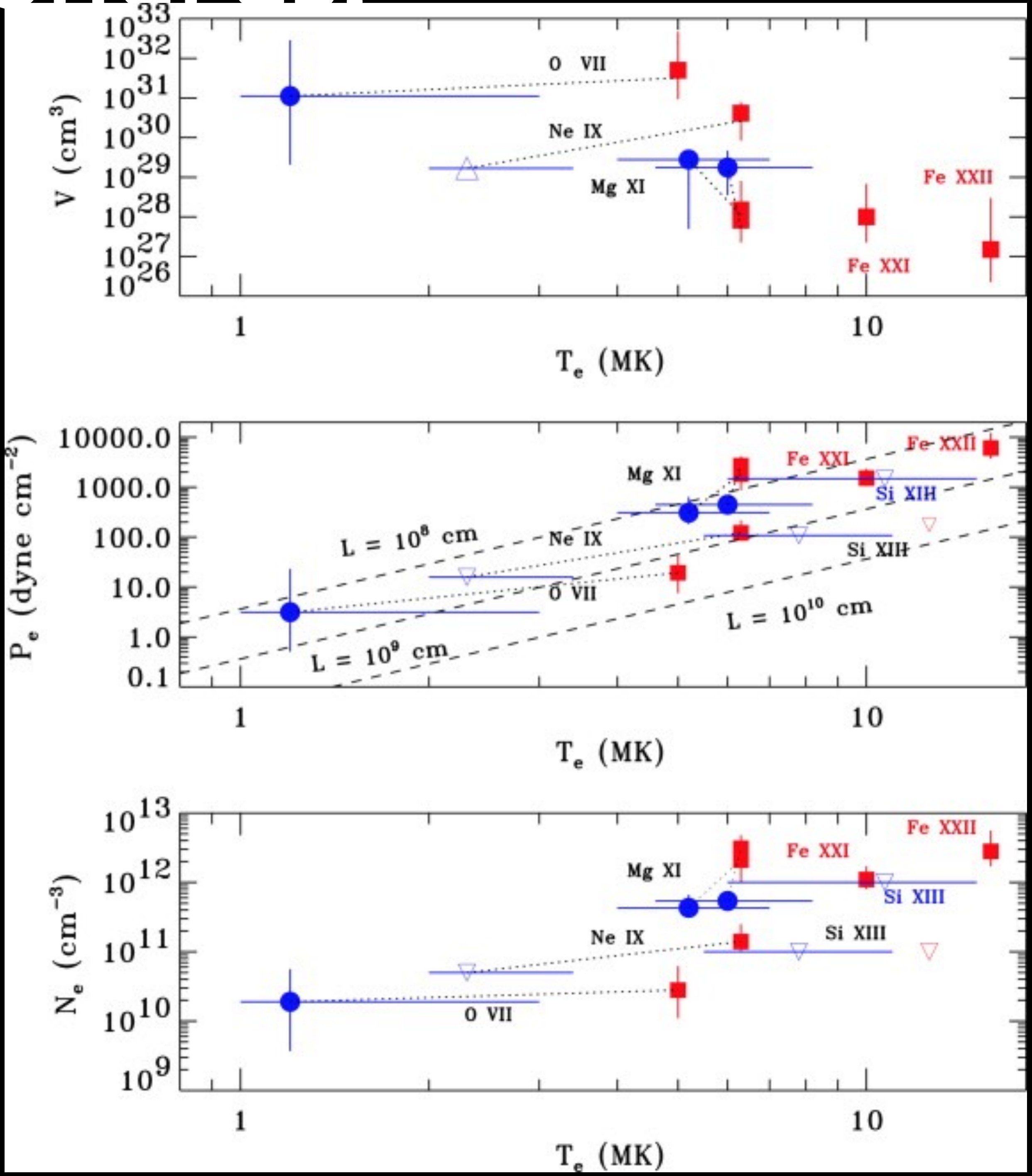

Osten et al. (2003)

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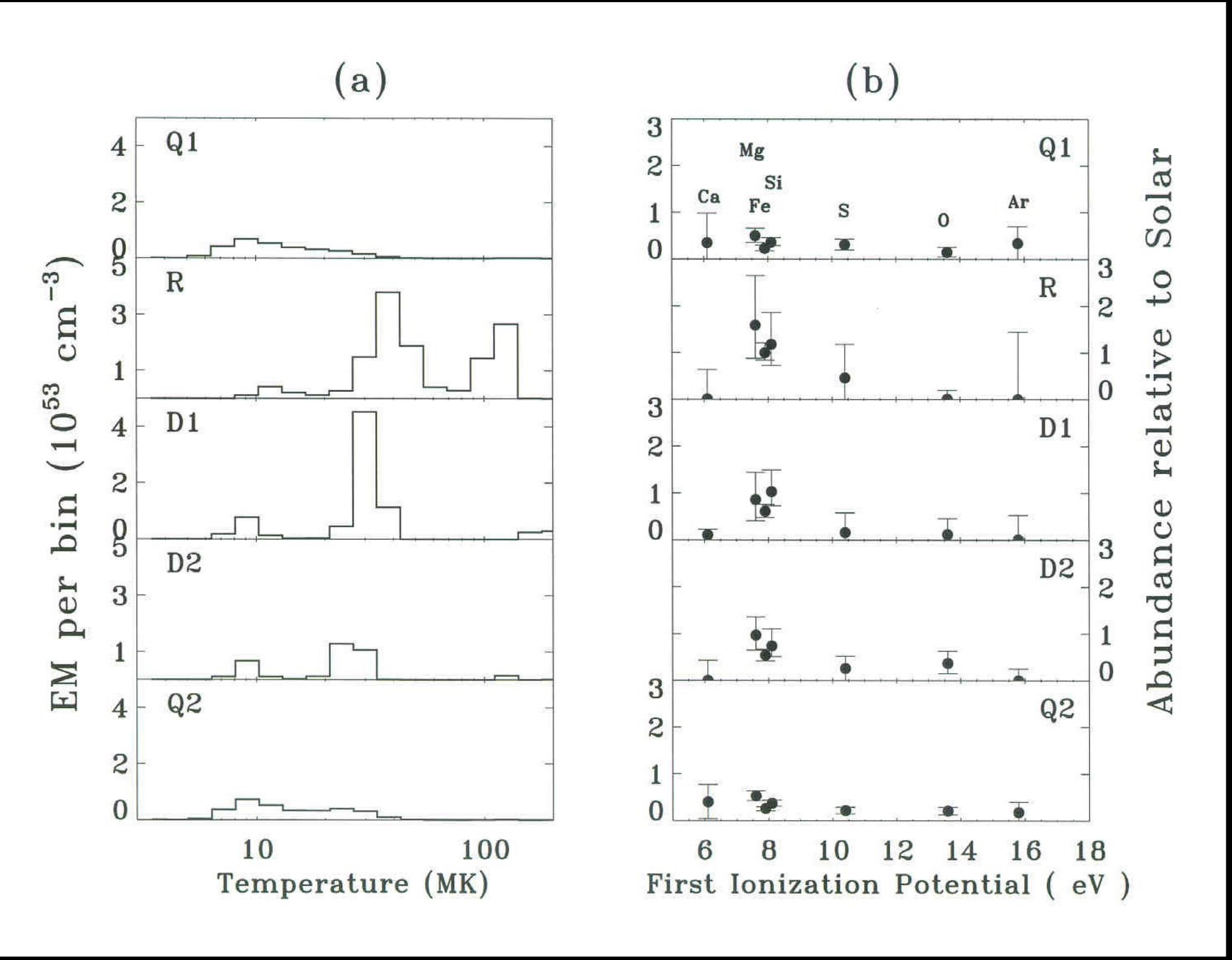

Osten et al. (2000)

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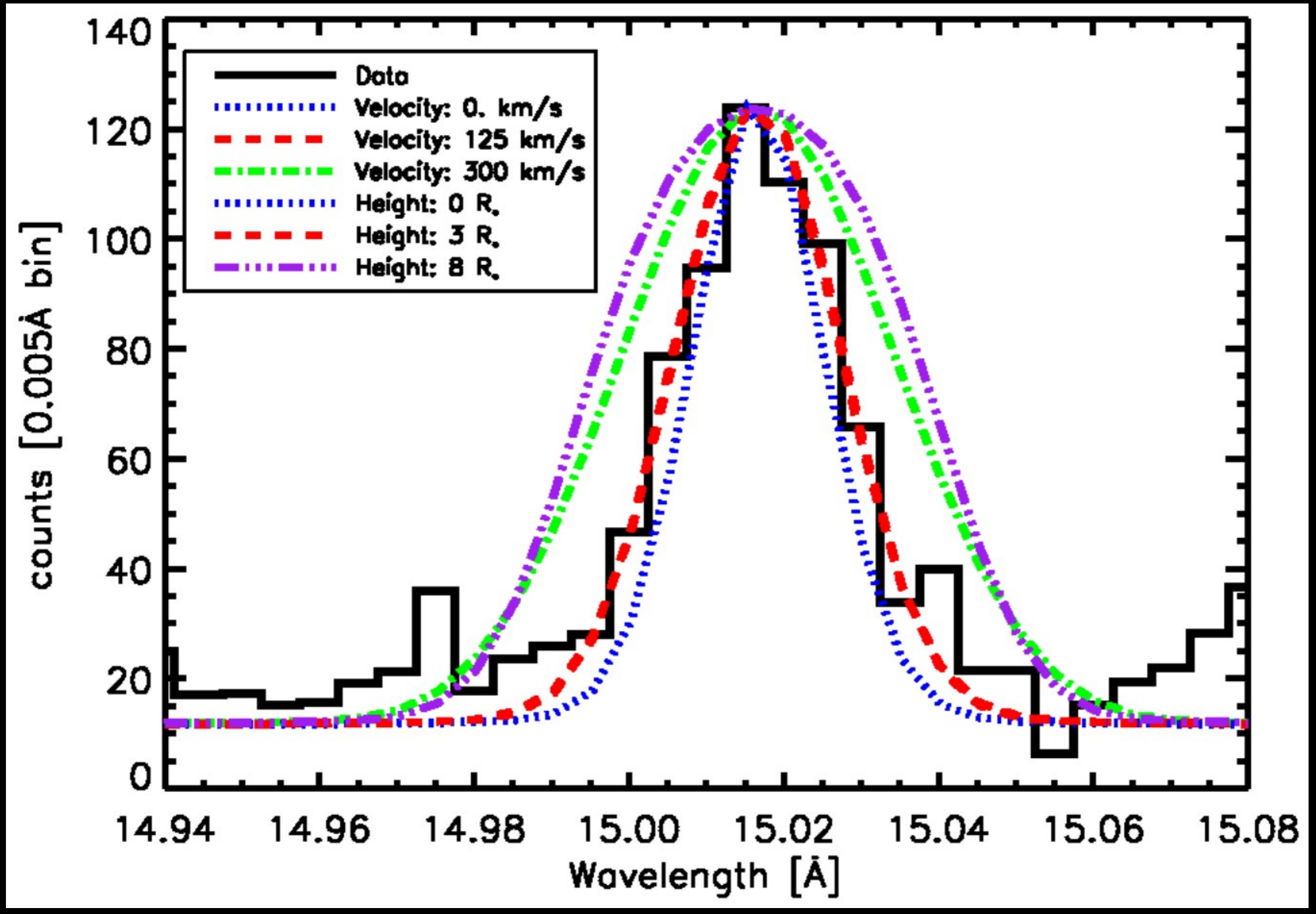

Chung et al. (2004)

excess broadening of Algol interpreted as rotational broadening from a radially extended corona

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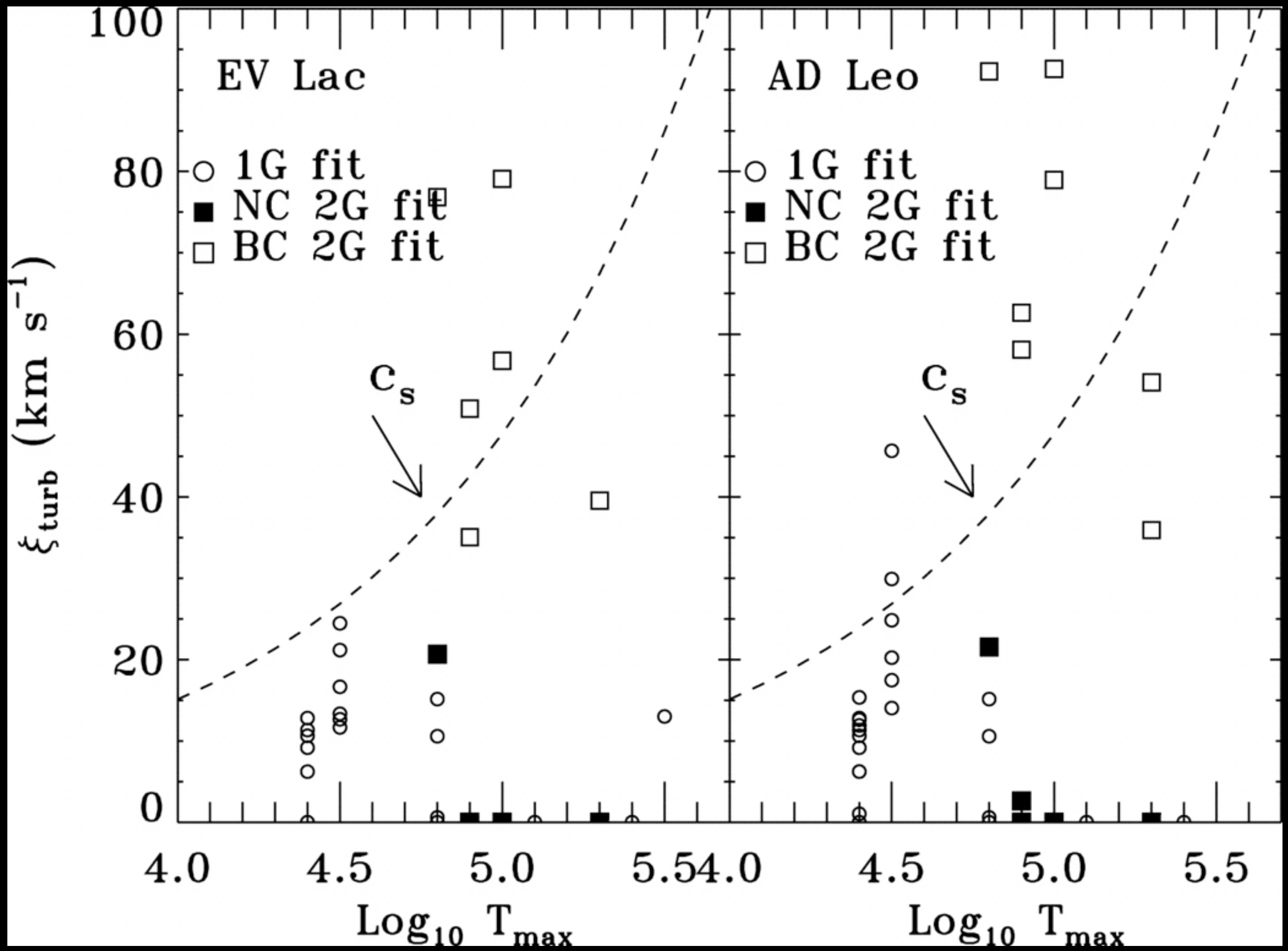

Osten et al. (2006)
excess line widths in UV transition region emission lines

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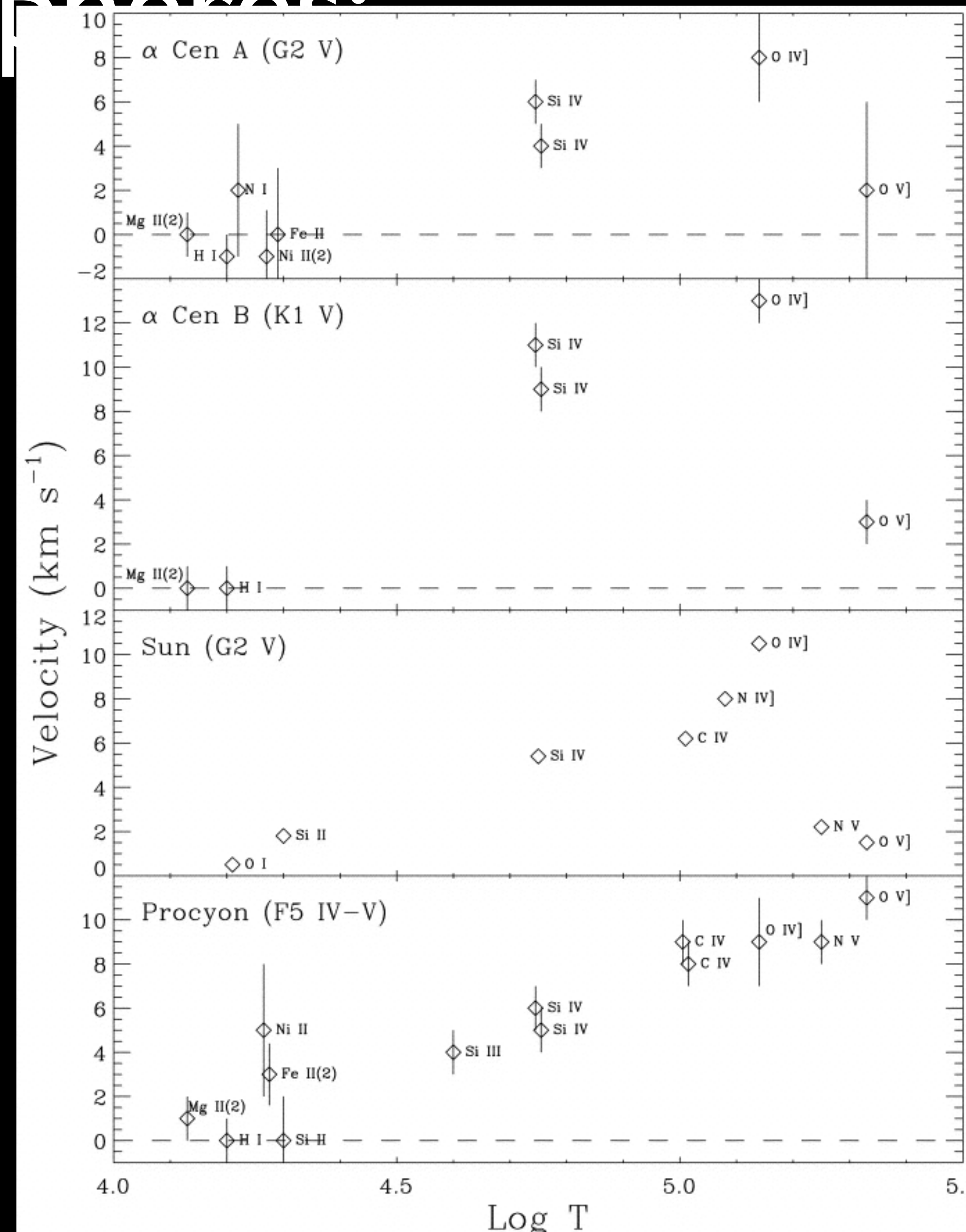

Wood et al. (1997)

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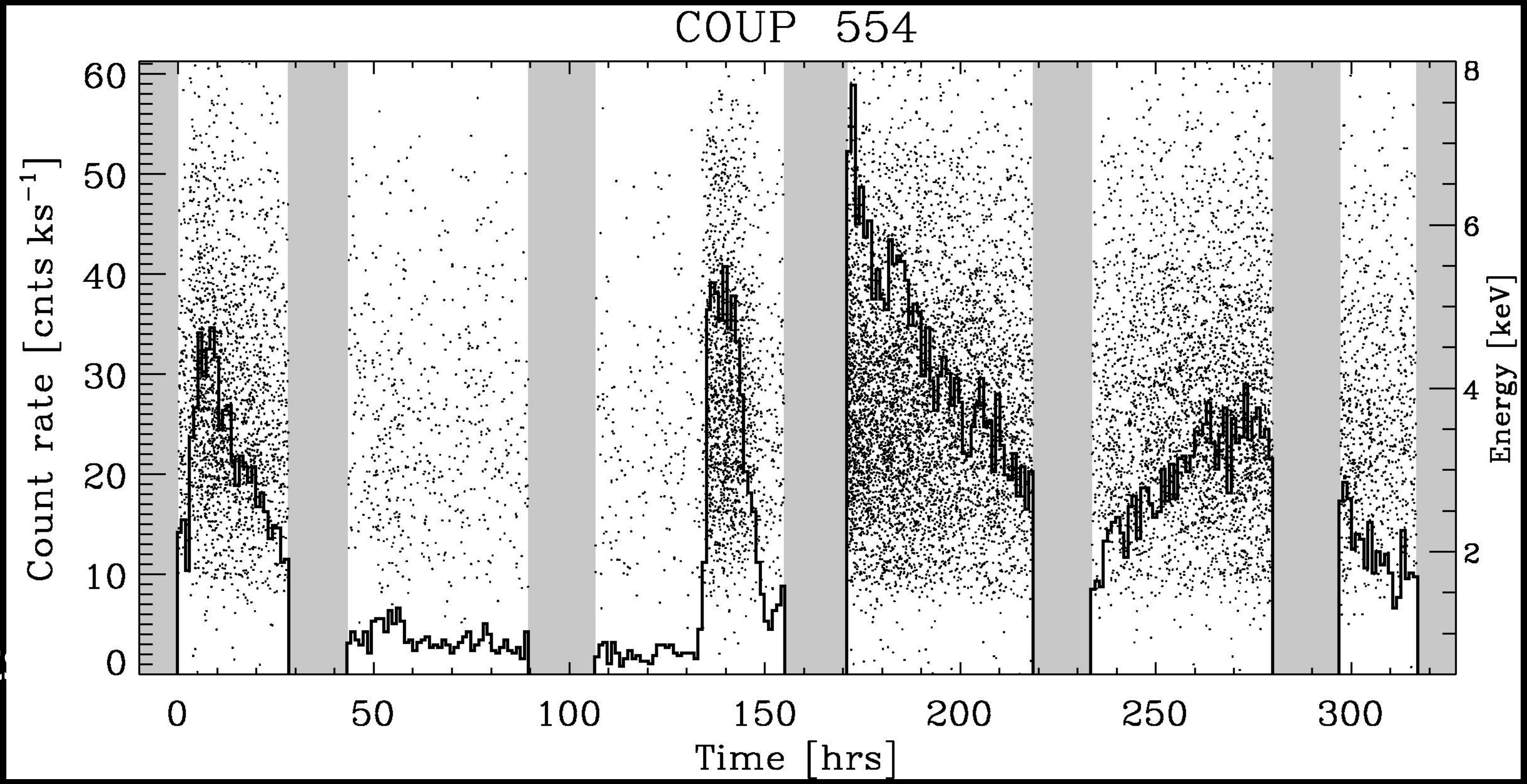

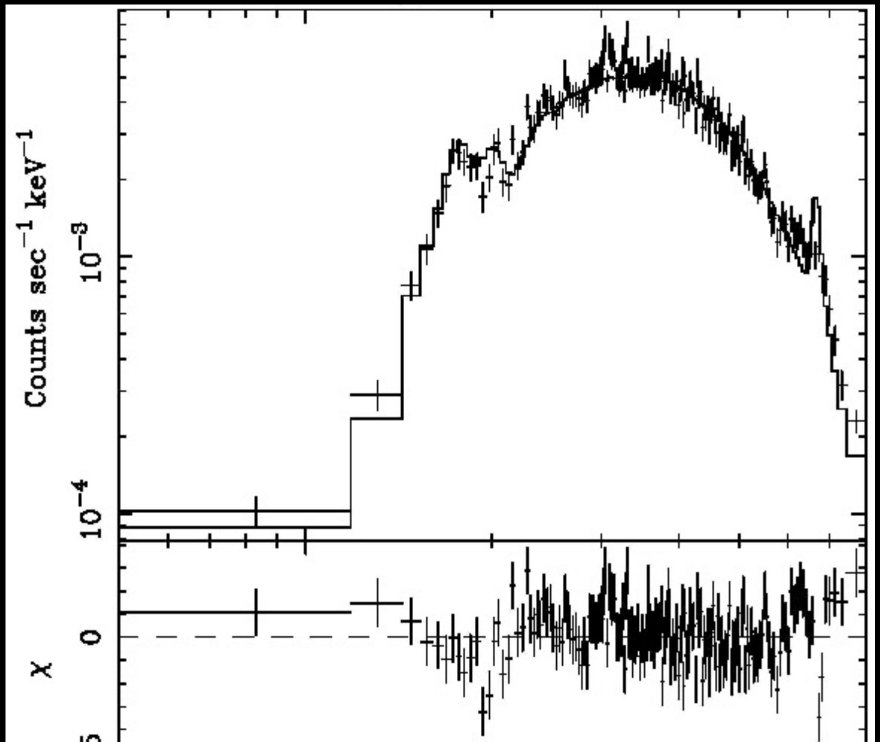

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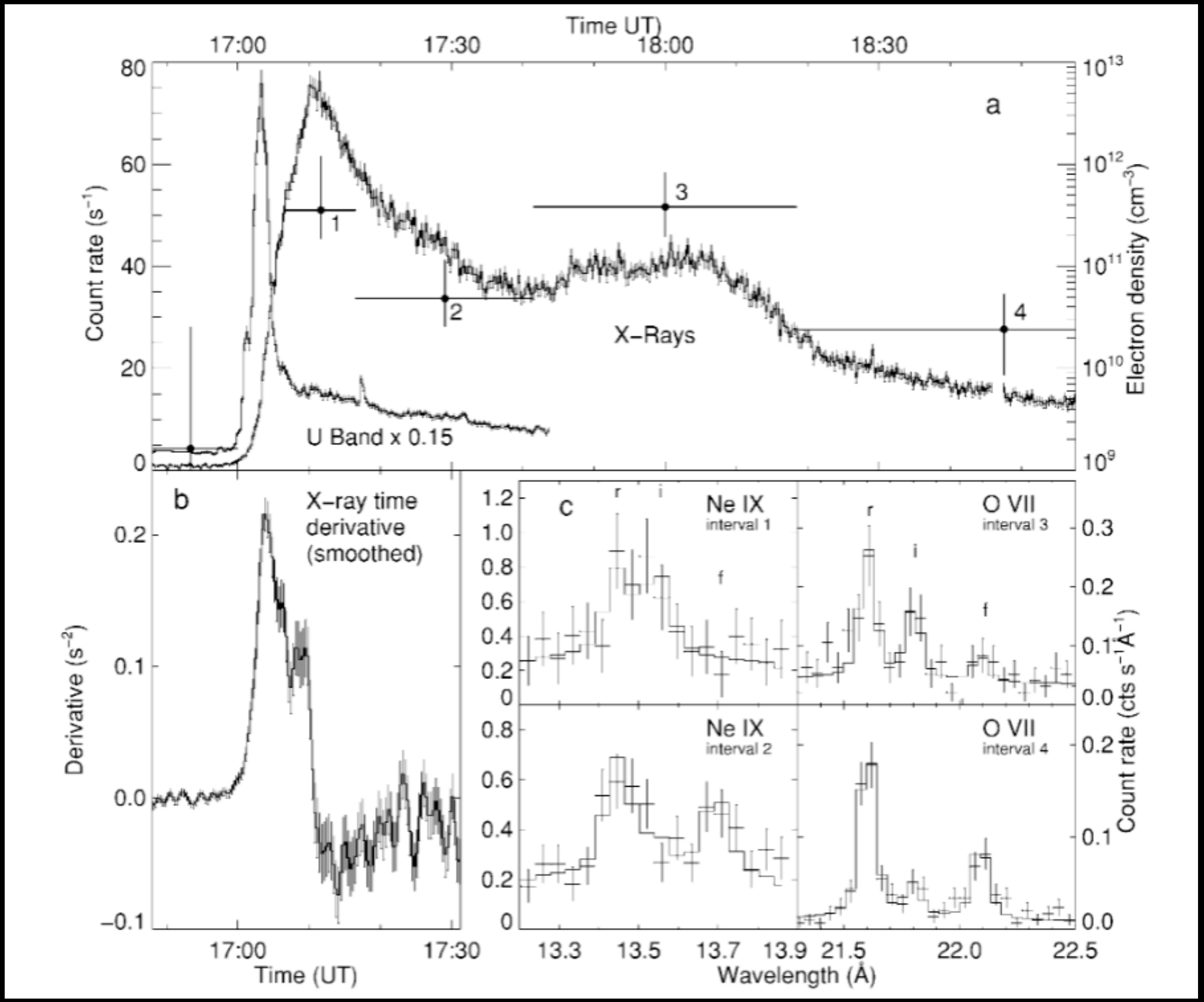
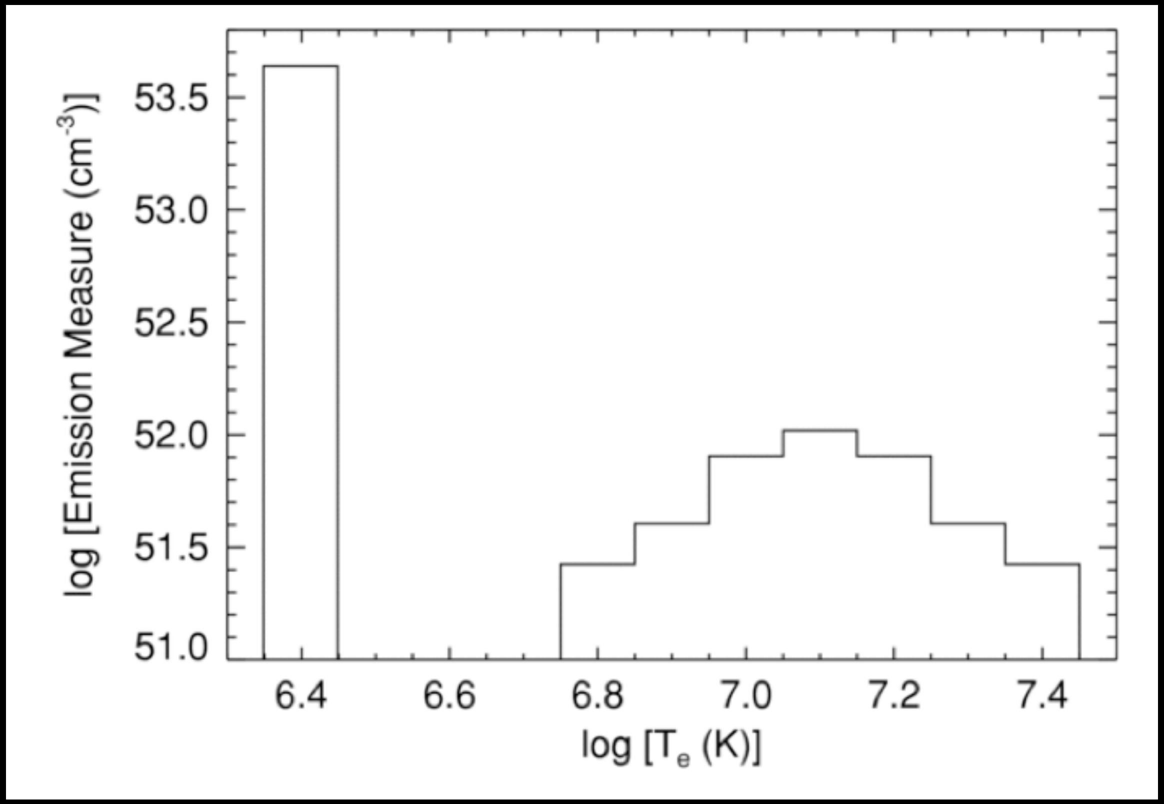
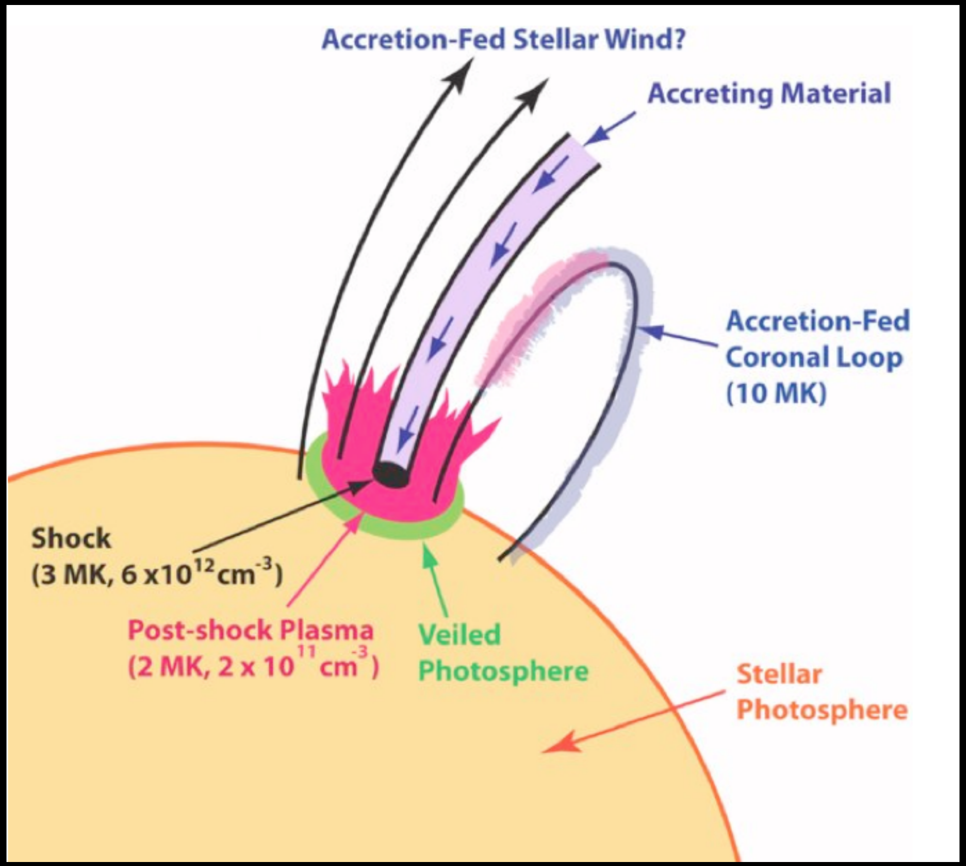


Güdel et al. (2002)

Young stellar objects additionally have accretion spectral diagnostics





Brickhouse et al. (2010)

The impact of a high quality X-ray spectrum: need more than accretion source + coronal source to explain all the miriad diagnostics (electron density, electron temperature, absorbing column)

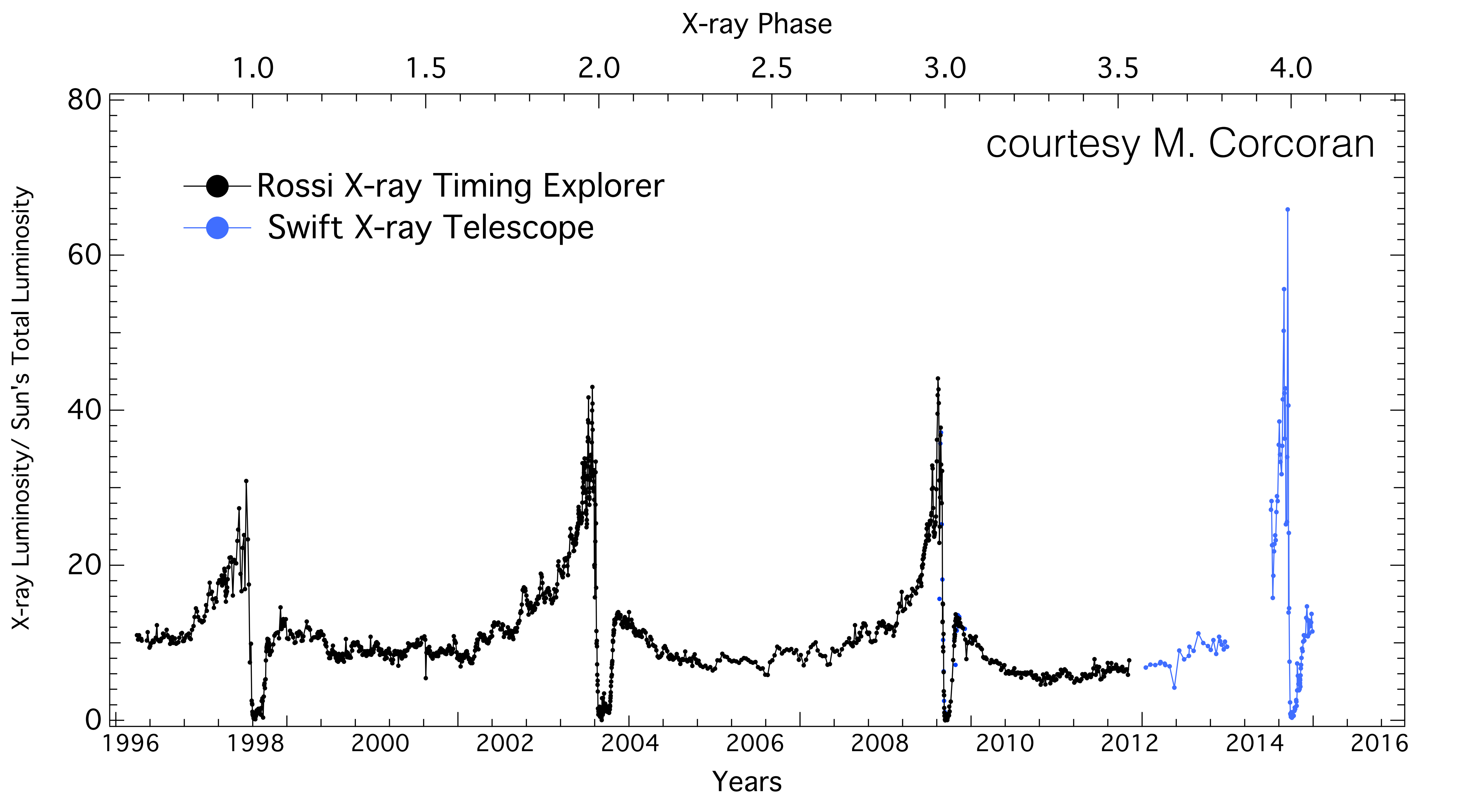
photon-starved science: of ~120 nondegenerate targets of grating observations in Chandra archive, only ~10 have been T Tauri stars

Very Massive Stars: Nature's Time Bombs

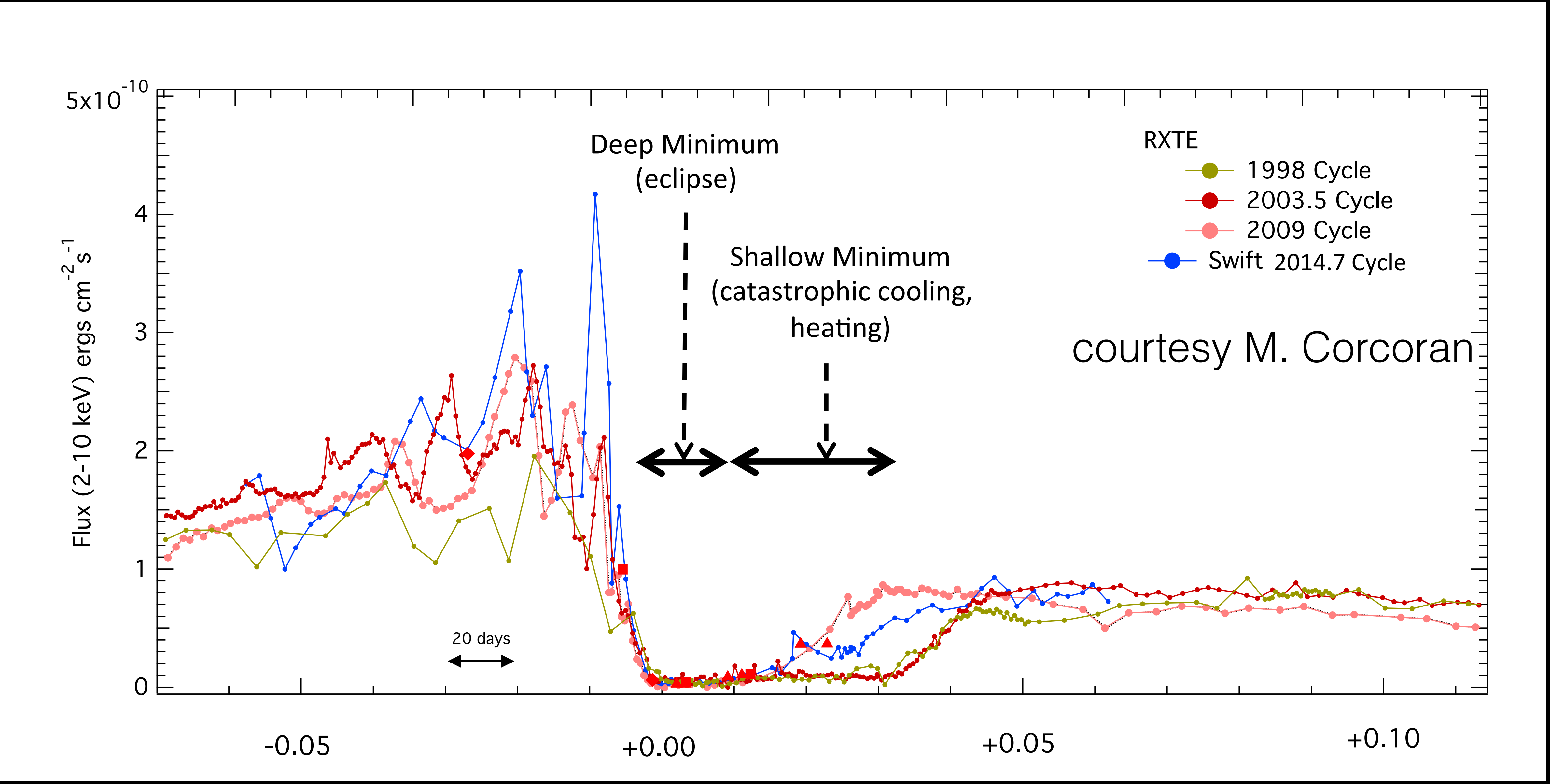
- More than 20 times as massive as the Sun
- Extremely bright & hot (surface temperatures 20,000-50,000 C)
- Extremely powerful stellar winds
- X-ray emission from gas at millions of degrees (the "corona") within the stellar wind
- Live fast, die young; explode as supernovae
- Produce relativistic neutron stars, black holes
- Produce heavy elements needed for life

courtesy M. Corcoran

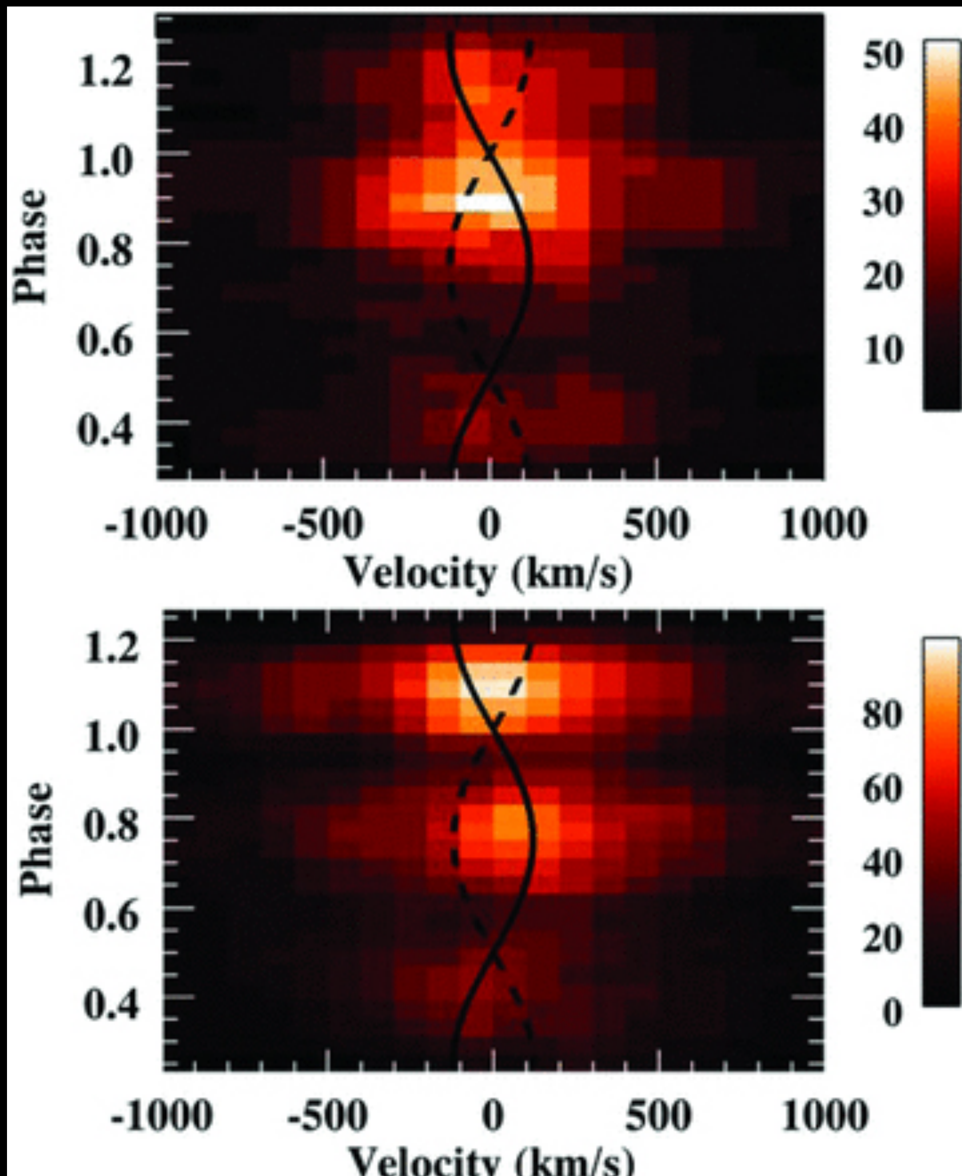
Colliding Wind X-ray Variability, 1996-2014



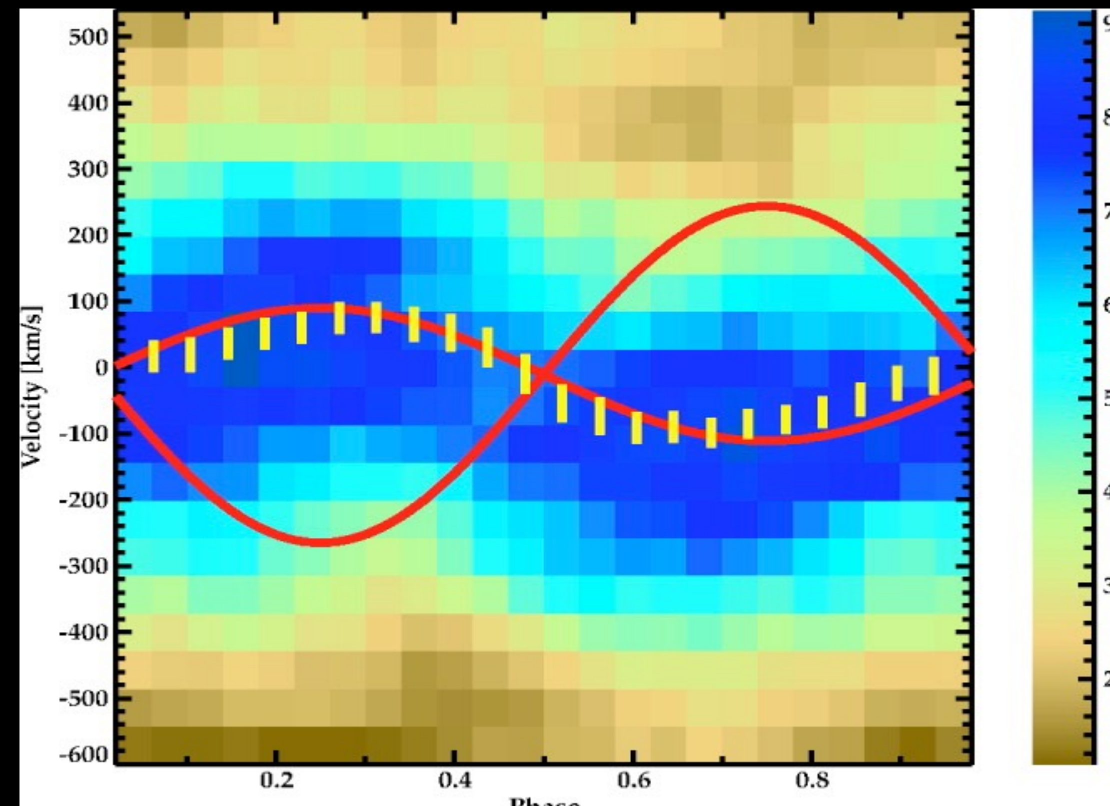
Changes Around Periastron Passage in the Wind-Wind Collision



X-rays Trace Magnetic Structures in Cool Stars



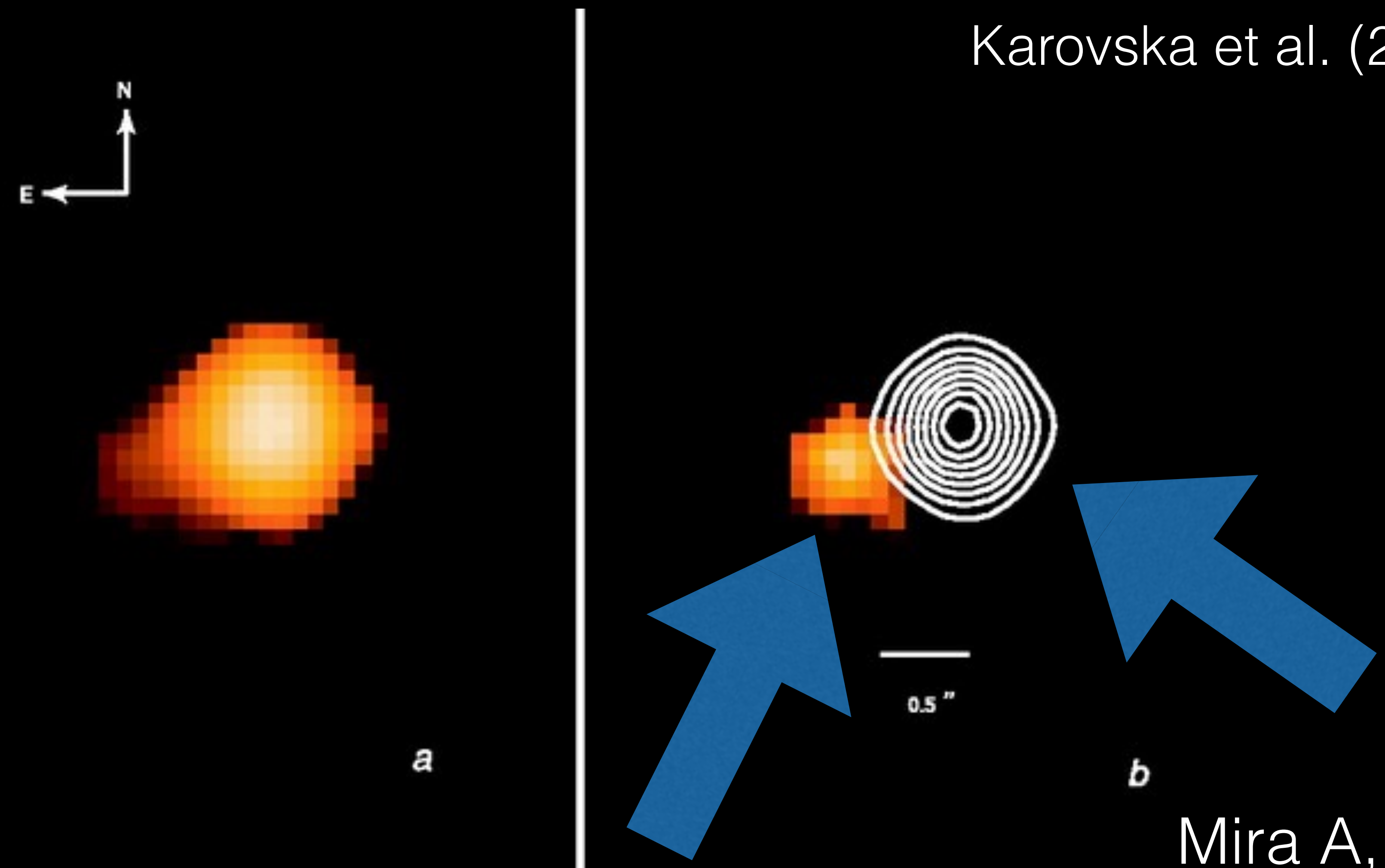
Hussain et al. (2012) looked at phase-folded Chanda/HETG spectra of the nearby eclipsing M dwarf binary YY Gem to investigate magnetic structure on cool stars



VW Cep; Huenemoerder et al. 2003

X-ray emission follows the more massive star in the binary

X-rays Trace Magnetic Structures in Cool Stars



Karovska et al. (2005)

Mira A, red giant

Mira B, white dwarf

Mira A X-ray source: unexpected X-ray emission from a red giant star. Points to localized magnetic field (non-dynamo) generation?

Hussain et al. (2012)

simulation

FWHM=200 km/s,
300 cnts peak

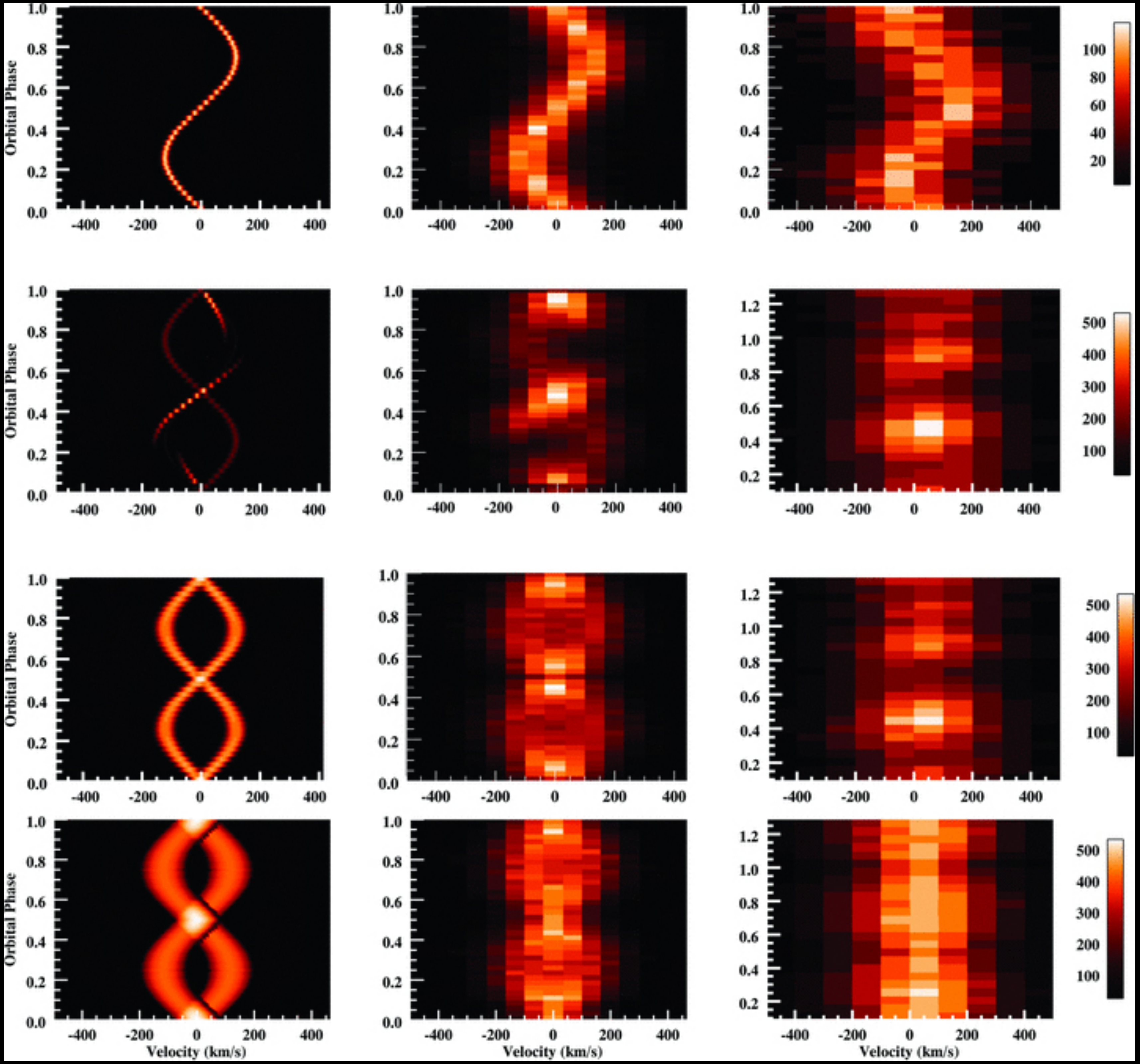
FWHM=400 km/s,
500 cnts peak

compact region
on primary

primary: 2 ARs,
secondary 1 AR

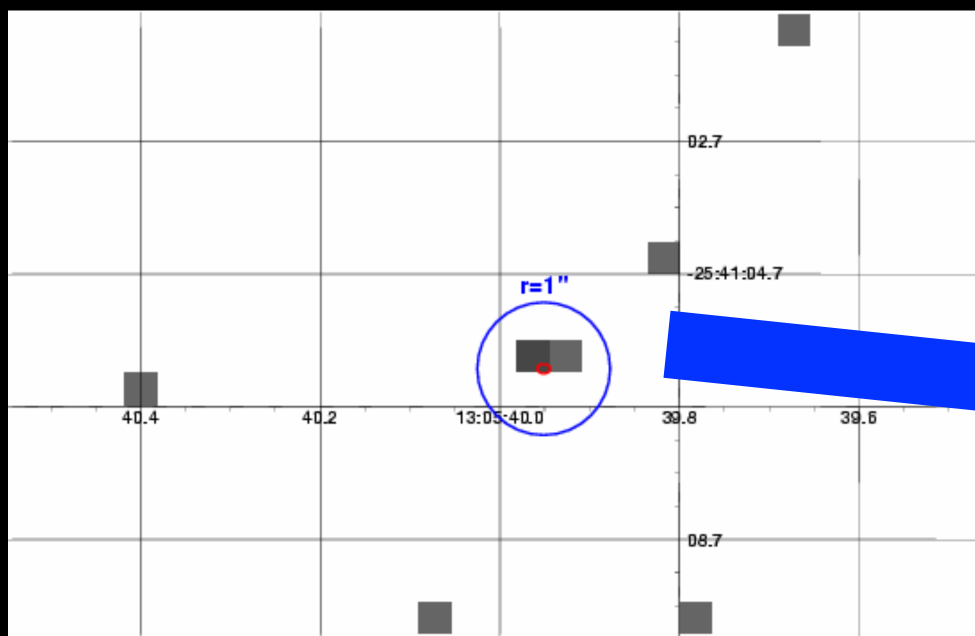
evenly
distributed
compact coronae
($<0.05R_{star}$)

evenly distributed
coronae ($>R_{star}$)

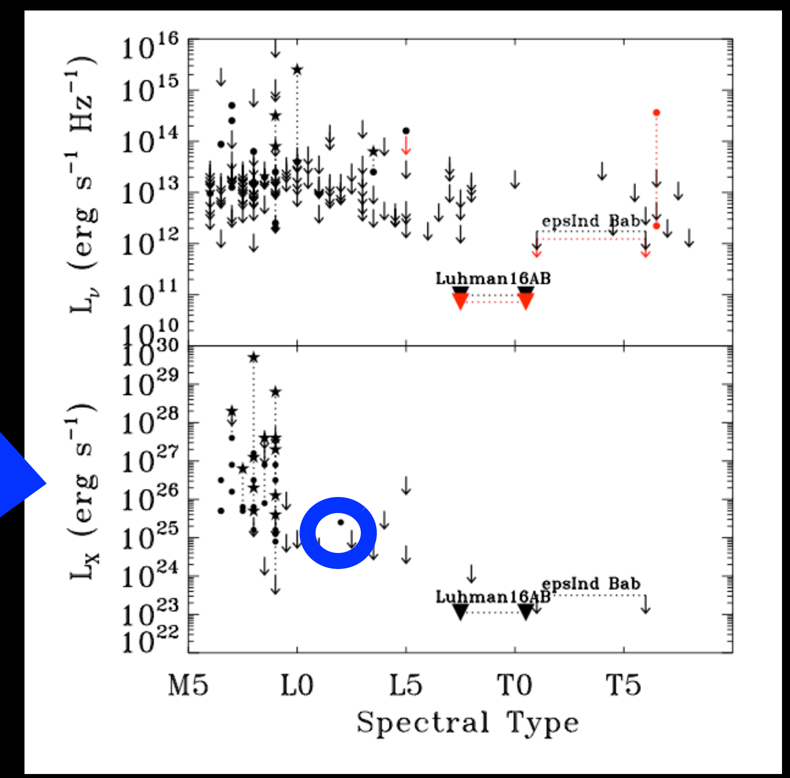


Dynamos at the End of the Main Sequence

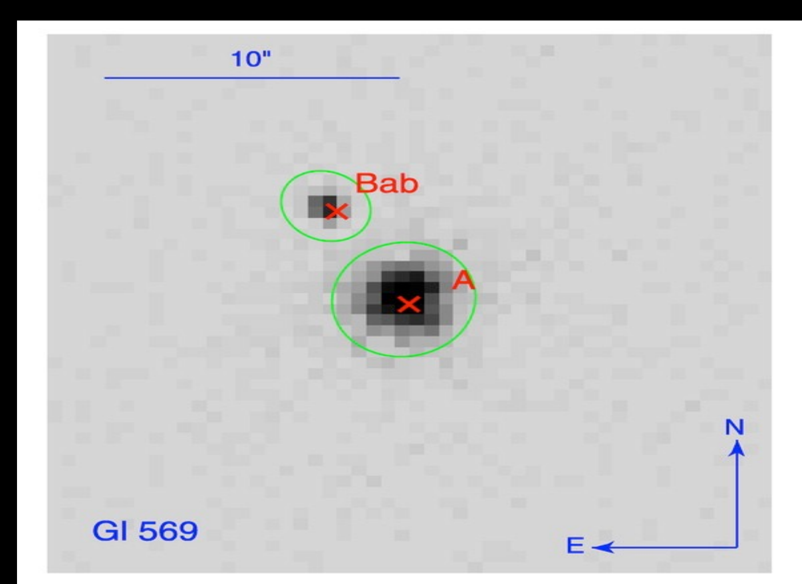
need sensitivity and spatial resolution



4 photons= detection!
Audard et al. (2007)

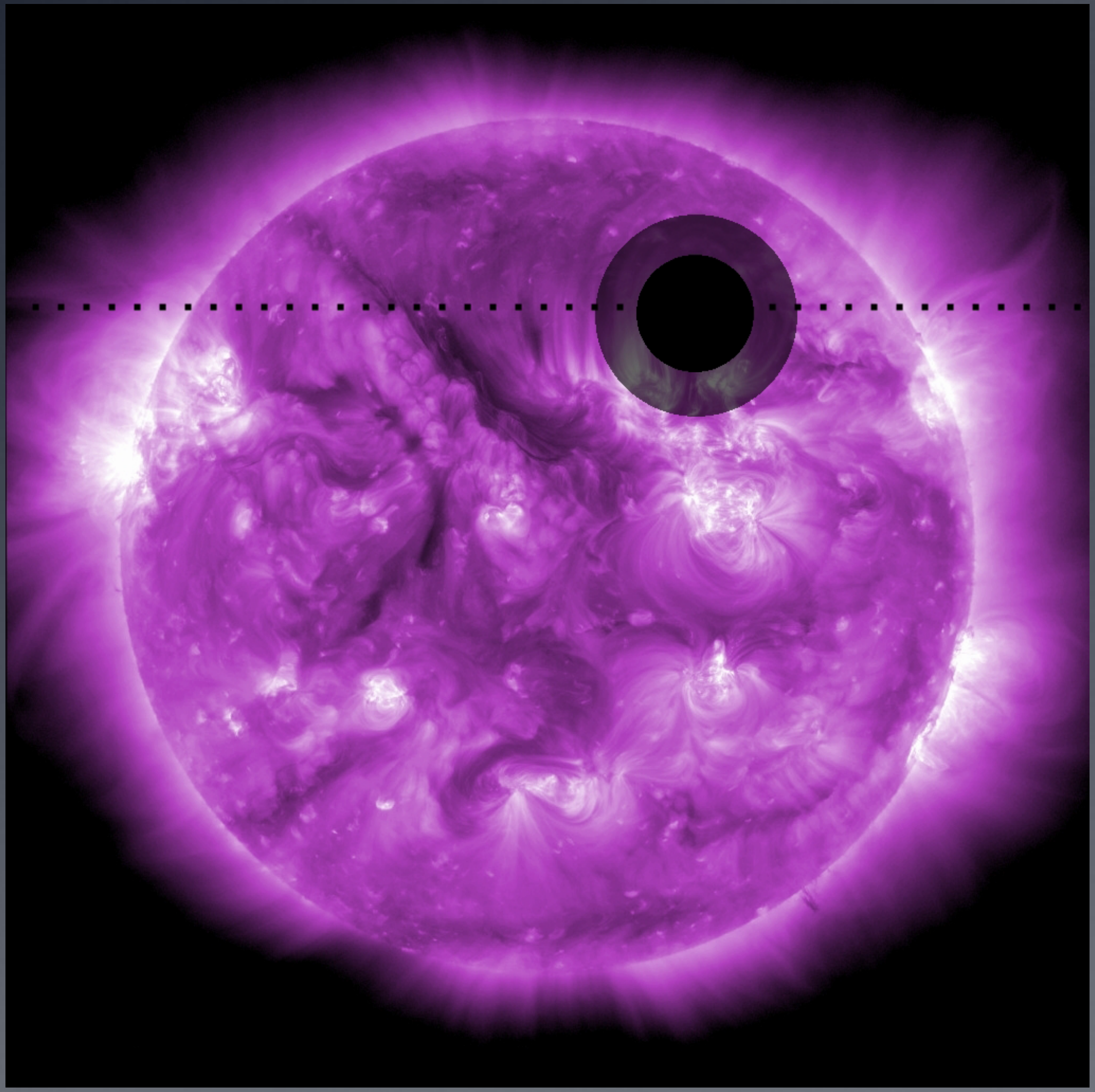


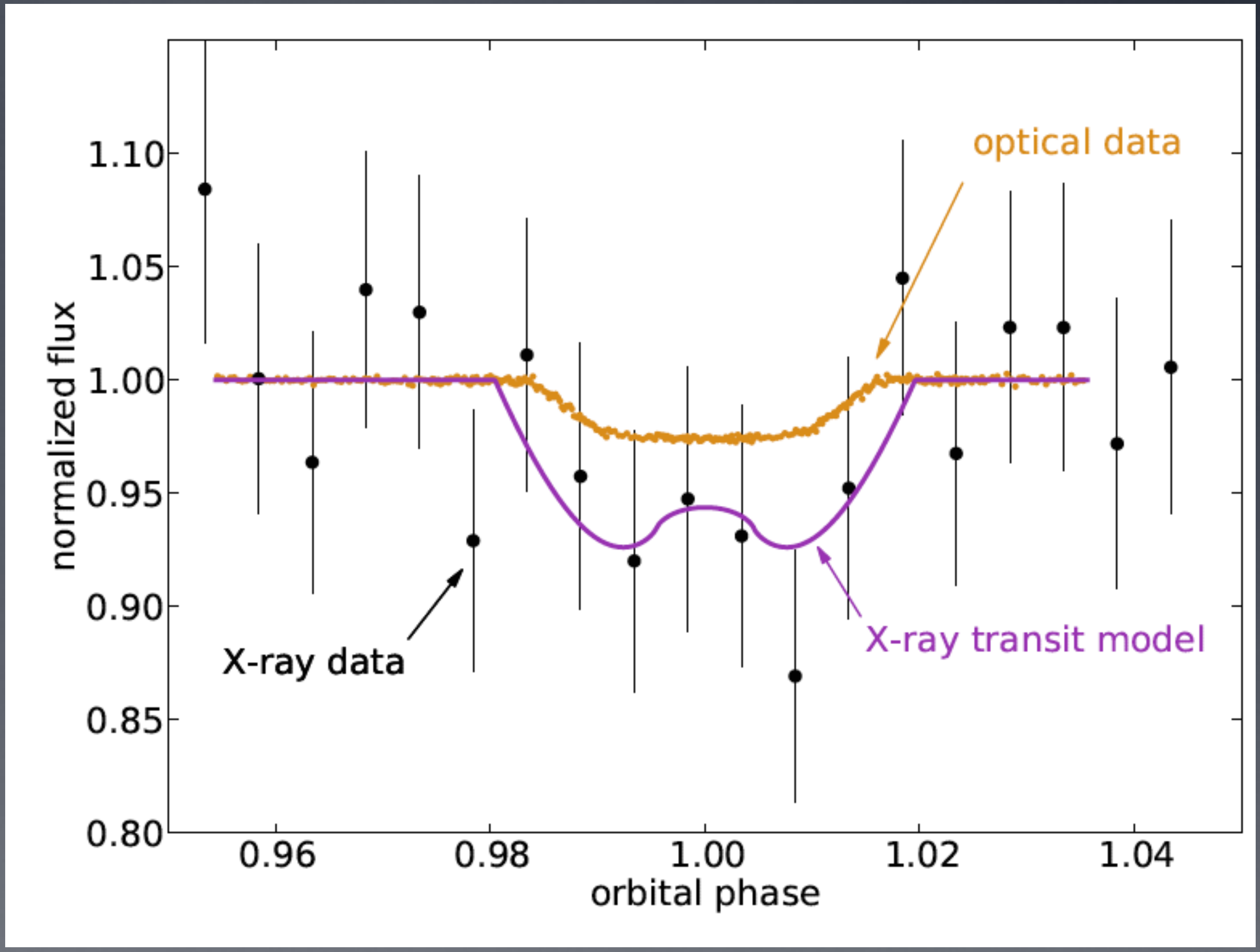
Osten et al. (2015)



Stelzer et al. (2005)

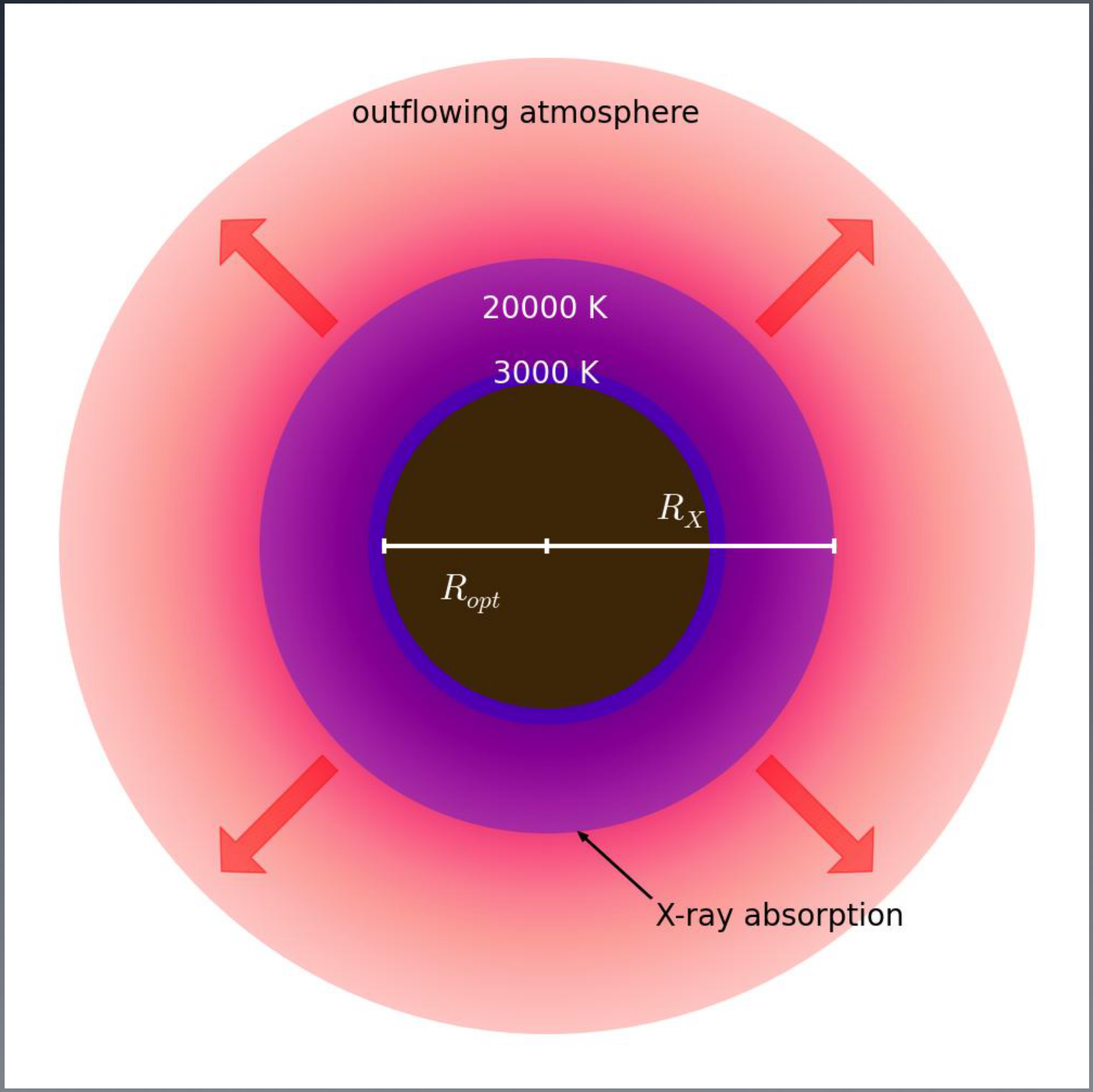
Transit of HD 189733 – 7 CXO observations co-added





Poppenhaeger, Schmidt & Wolk (2013)

Planetary Atmosphere: Toy Model



$H = kT/\mu_m g$

$\Delta D \sim HR_{Pl}/R_*$

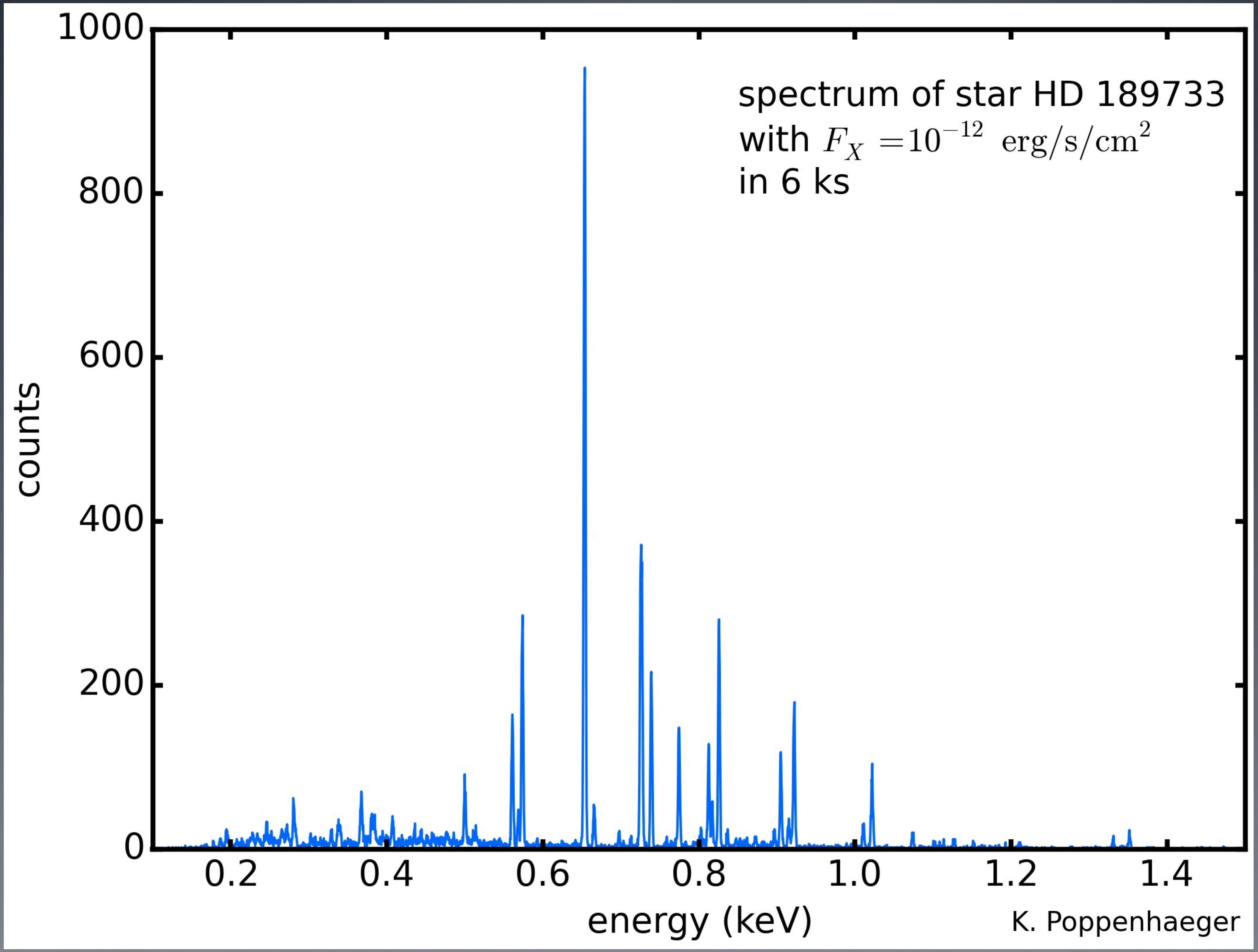
Miller-Ricci & Fortney (2010)

To be X-ray opaque
density at $1.75R_{Pl}$: 10^{11} cm^{-3}

high-altitude temperature:
~ 20,000K

Poppenhaeger, Schmitt & Wolk (2013)

Nominal Lynx X-ray Spectrum of HD 189733



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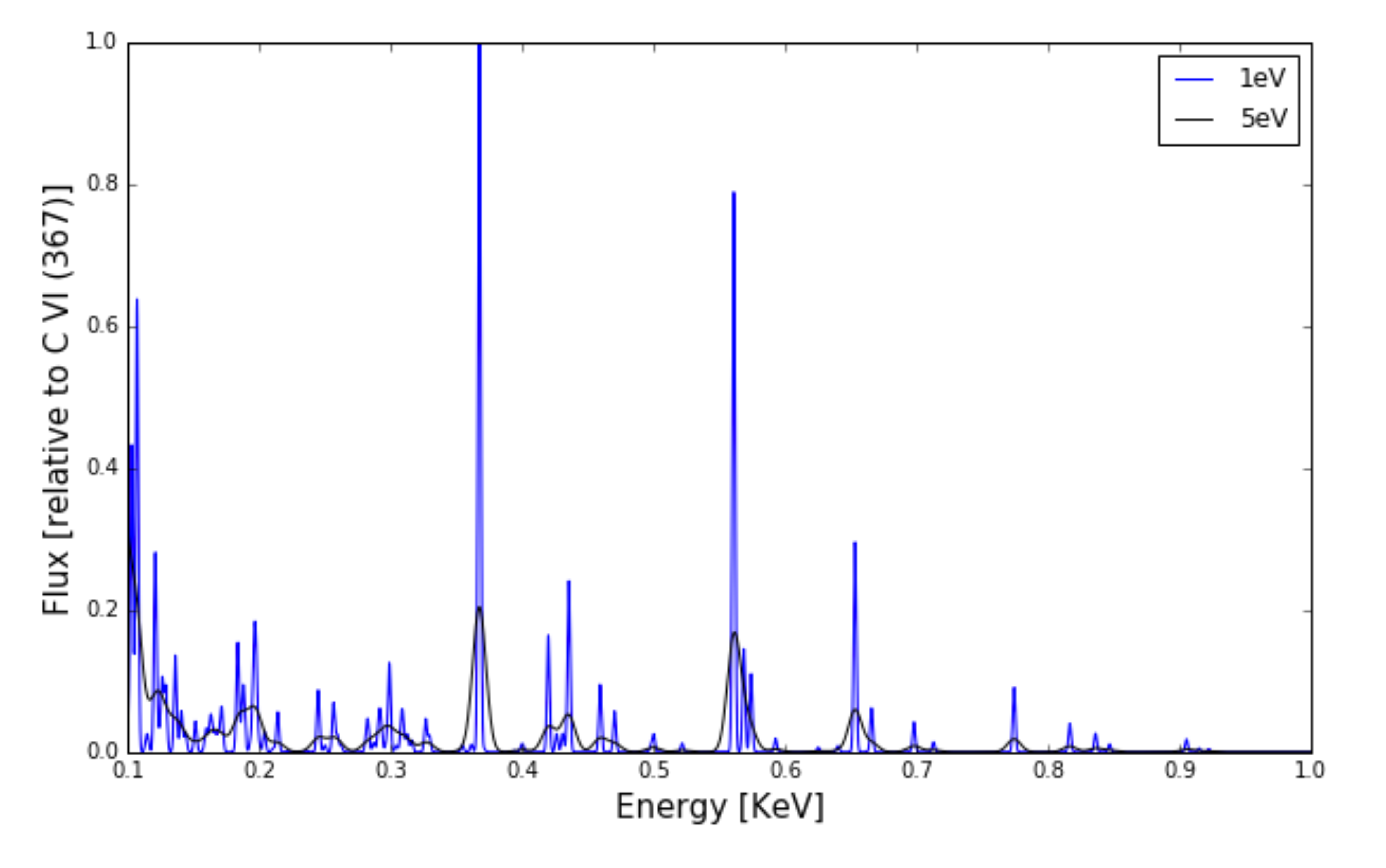
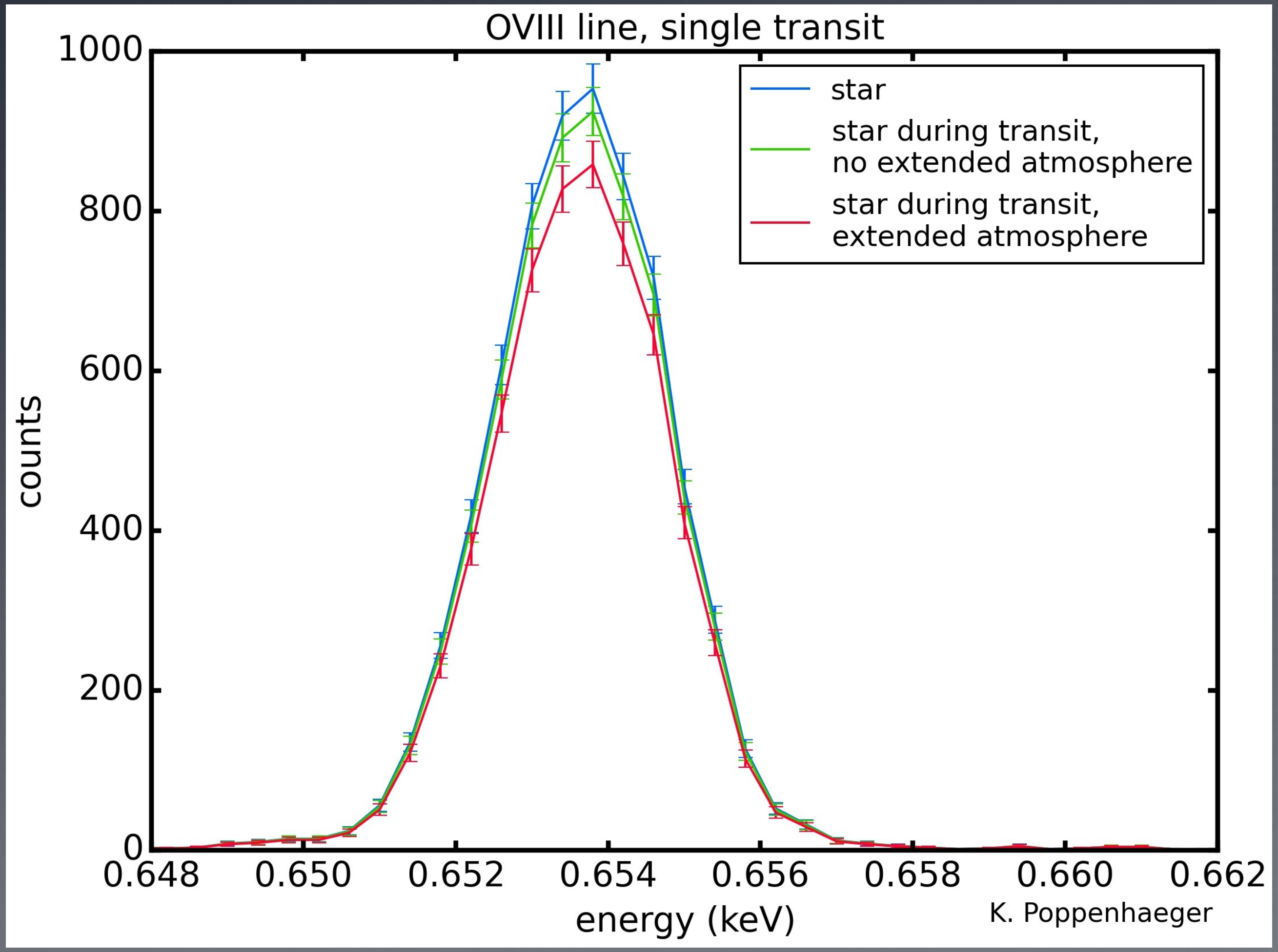
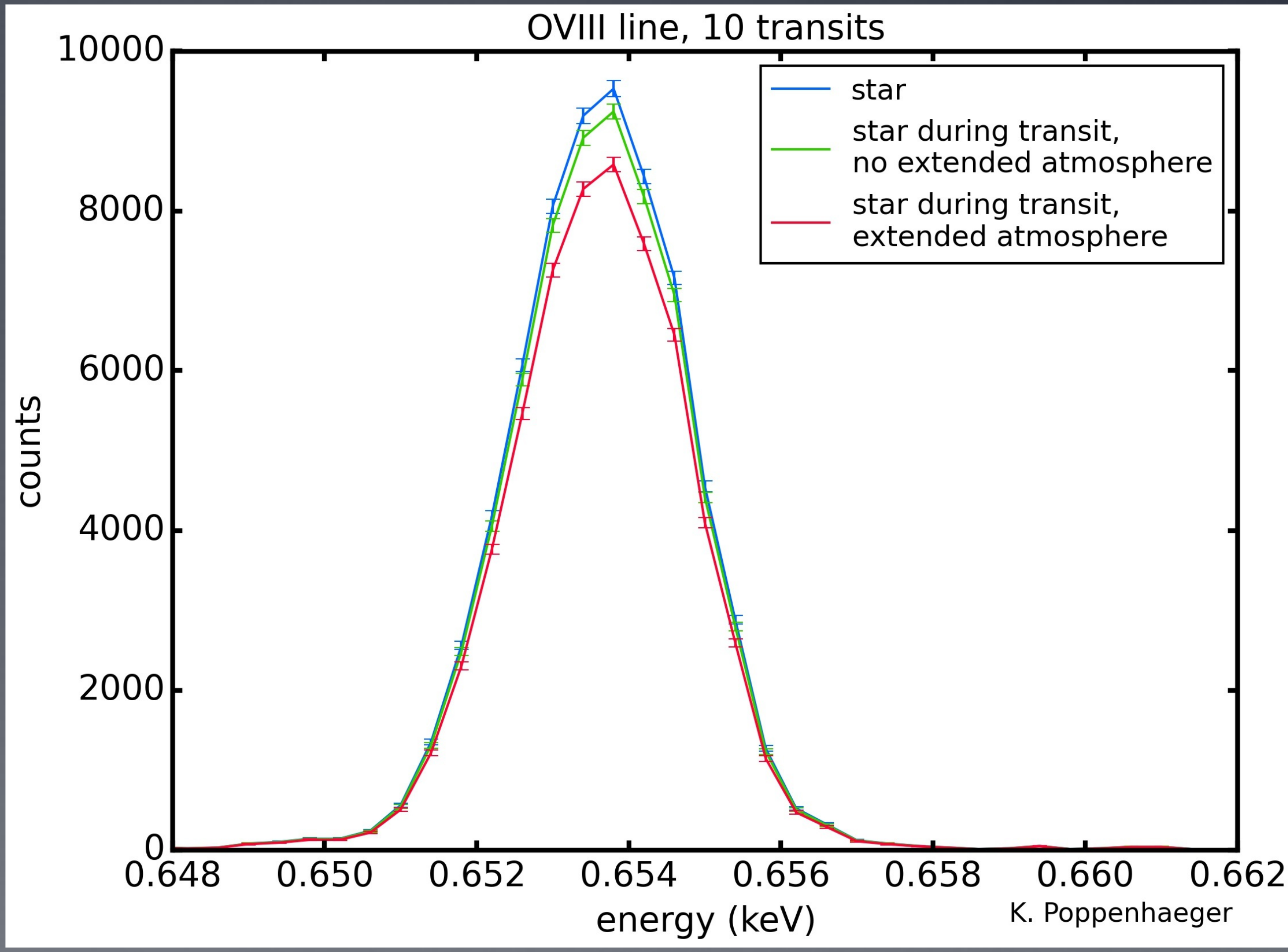
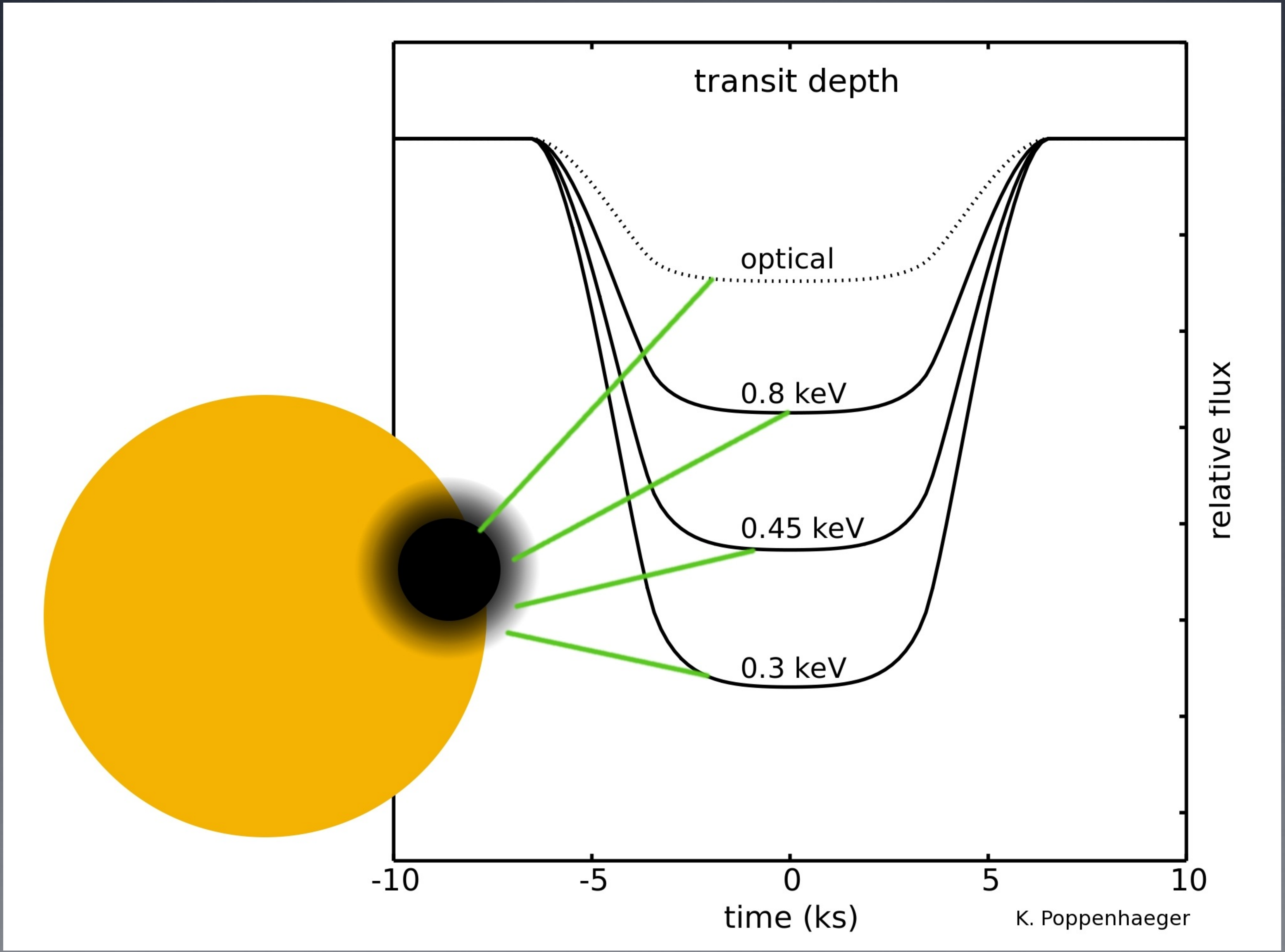


Change of the OVIII line



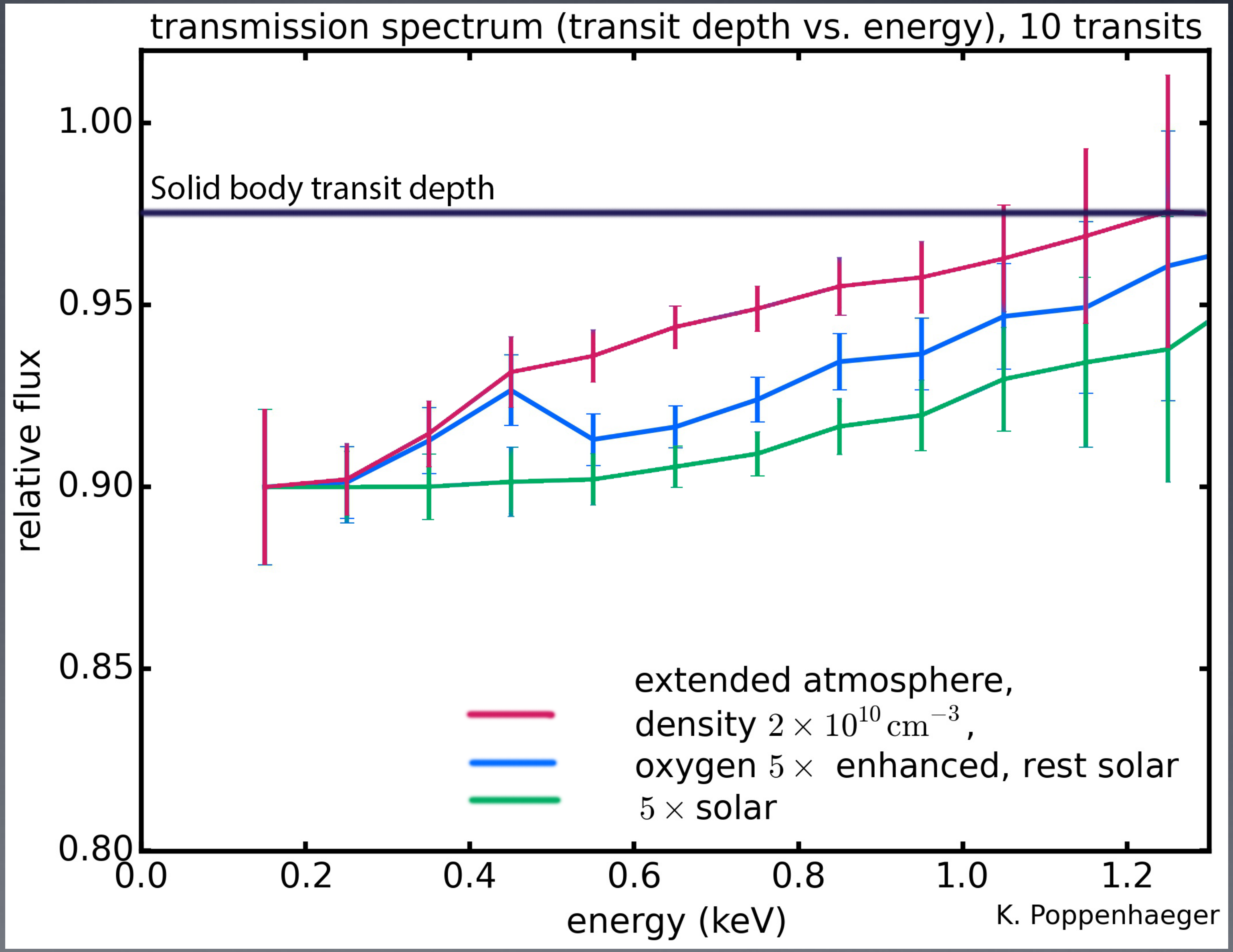


Optical depth versus energy



We will be able to compare exoplanet atmospheres

- The flux reduction during the transit of a Hot Jupiter in different energy bands, assuming an unocculted stellar X-ray flux of 10^{-12} erg s^{-1} cm^{-2}, an optical exoplanetary transit depth of 3% and a maximum extent of the outer atmosphere of twice the optical radius and different reasonable assumptions about the upper planetary atmosphere.
- 200 ks total observing time.



Future Synergy

- There are about 50,000 stars in the RASS.
  - These have Lynx count rates > 1cps.
- About 14,000 RASS sources at in the Tycho catalog with V> 11.5 – within the TESS survey.
- Somewhere between 0.3 and 1.3 percent of all stars host a hot Jupiter (cf. Wright 2012).
  - 150-650 RASS sources are Hot Jupiter hosts.
    - Assume 250 (0.5%)
  - Probability of a transit of a hot system is ~ 15%
  - More than 35 X-ray bright transiting sources.

Stellar Death

supernovae, gamma-ray bursts, planetary nebulae

- Compelling science question: *how can we figure out / constrain the SN explosion mechanism?*

- Compelling science answers:
  - Study a (much) larger sample of SNRs to understand morphology, eject distributions, and central compact objects
  - Study the evolution of a SN→SNR (1987A)

- It will be tough to show a unique advantage over Athena for GRBs and nearby, young SNe.

- We haven't thought much about PNe.

There are predictions for what 1987A will look like in 2027.

Studying its morphology will require sub-arcsec resolution.

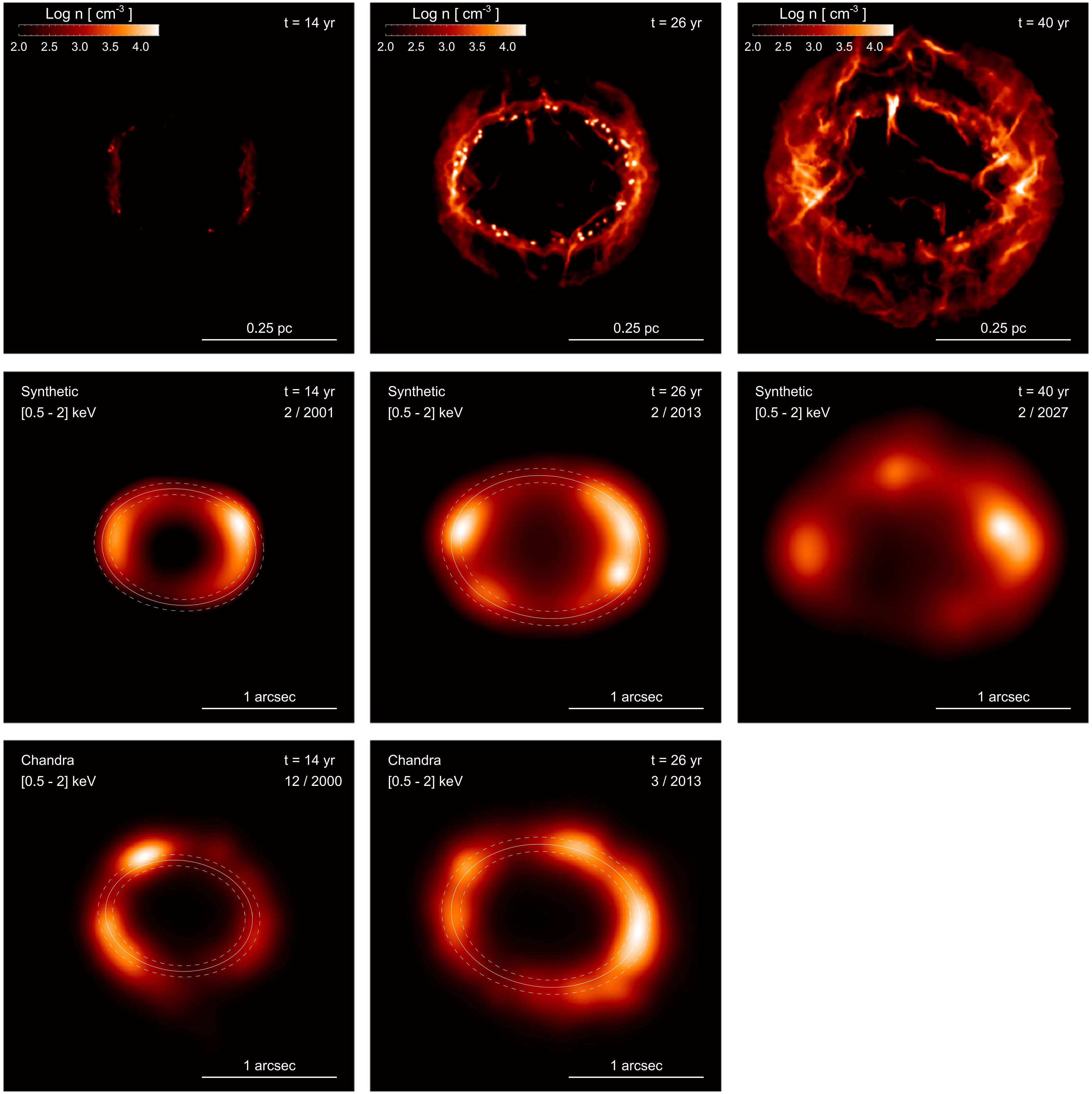


Figure 4. Interaction of the blast wave with the nebula. (Top) Three-dimensional volume rendering of the particle density of the shocked plasma at the labeled times. (Middle) Corresponding synthetic maps of X-ray emission in the [0.5, 2] keV band integrated along the line of sight. Each image has been normalized to its maximum for visibility and convolved with a Gaussian of size 0.15 arcsec to approximate the spatial resolution of *Chandra* observations (Helder et al. 2013). (Bottom) Maps of X-ray emission of SN 1987A collected with *Chandra* at the labeled times, and normalized to their maximum for visibility (see Appendix B). The overplotted ellipsoids represent the projection of circles lying in the equatorial plane of SN 1987A and fitting the position of the maximum X-ray emission in each observation. The dashed lines show an uncertainty of 10%.

(An animation of this figure is available.)

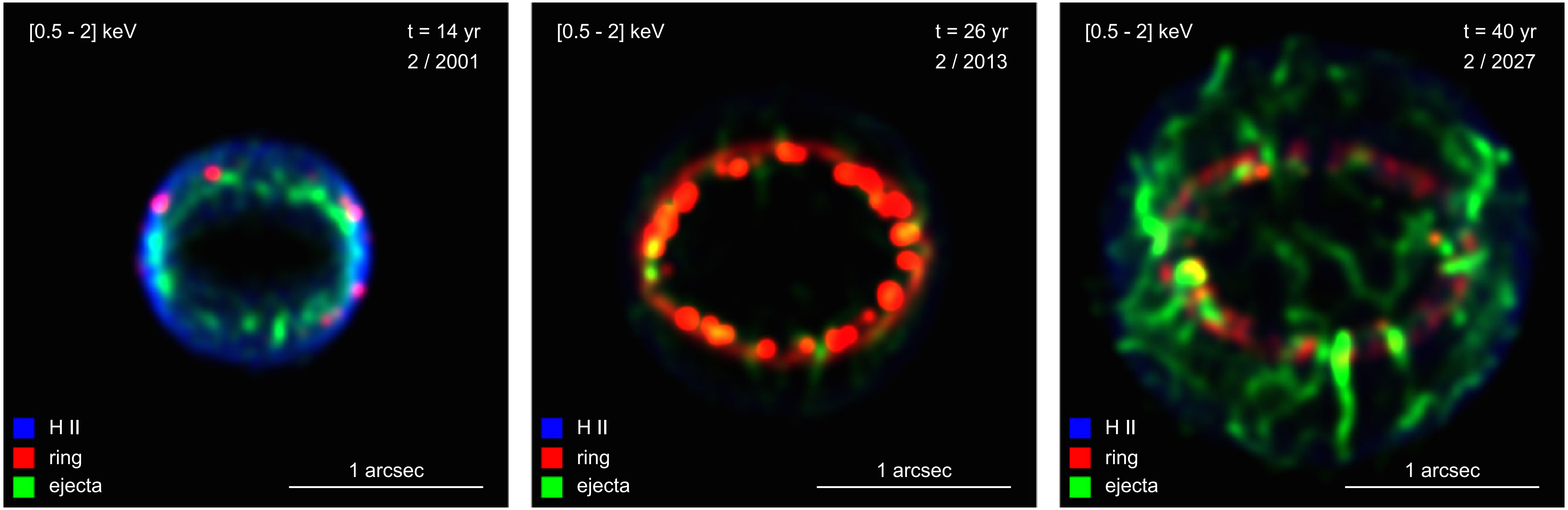


Figure 8. Three-color composite images of the X-ray emission in the [0.5, 2] keV band integrated along the line of sight at the labeled times. Each image has been normalized to its maximum for visibility and smoothed with a Gaussian of size 0.025 arcsec. The colors in the composite show the contribution to emission from the different shocked plasma components, namely the ejecta (green), the ring (red), and the H II region (blue).

Its spectrum has also been simulated (for Athena), and we are trying to do the same for XRS/Lynx.

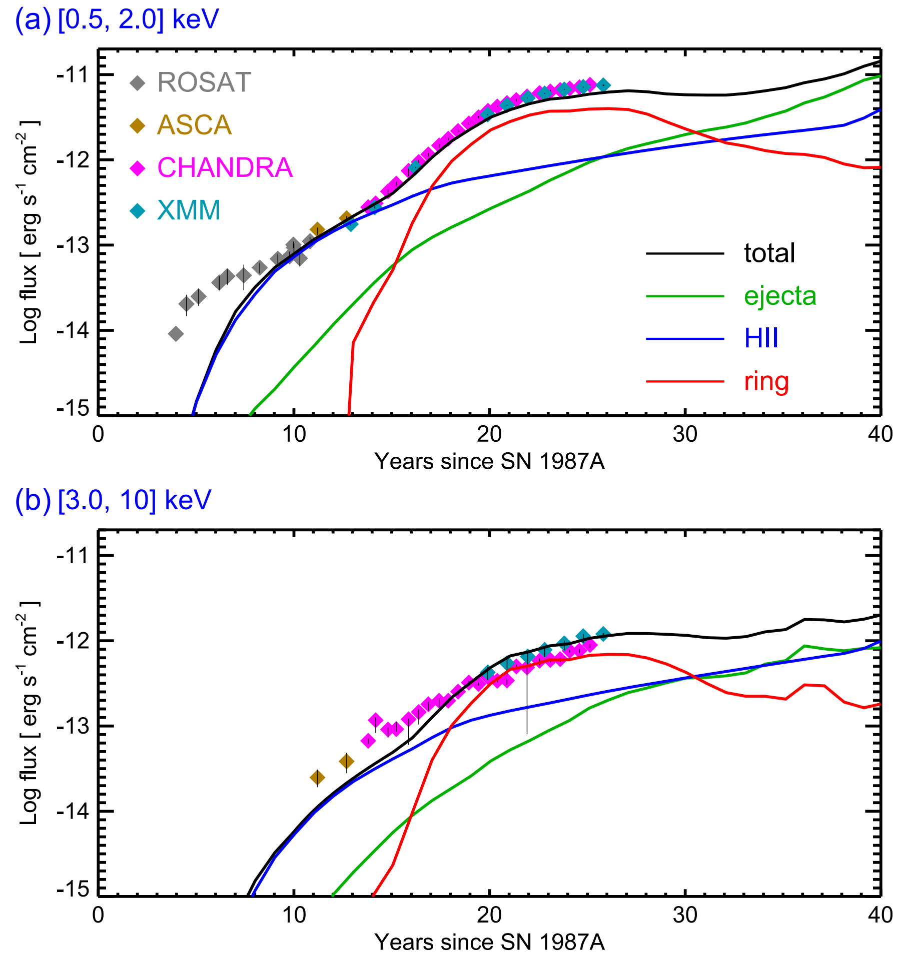


Figure 9. As in Figures 5(b) and (c) for a model with envelope mass $M_{\rm env} = 17$ $M_\odot$, ejecta energy $E_{\rm SN} = 1.2 \times 10^{51}$ erg, and with the density profile of ejecta in the high-velocity shell approximated by a power law with index $\alpha = -9$ (run SN-M17-E1.2-N9 in Table 3). The parameters of the CSM of this model are reported in Table 4.

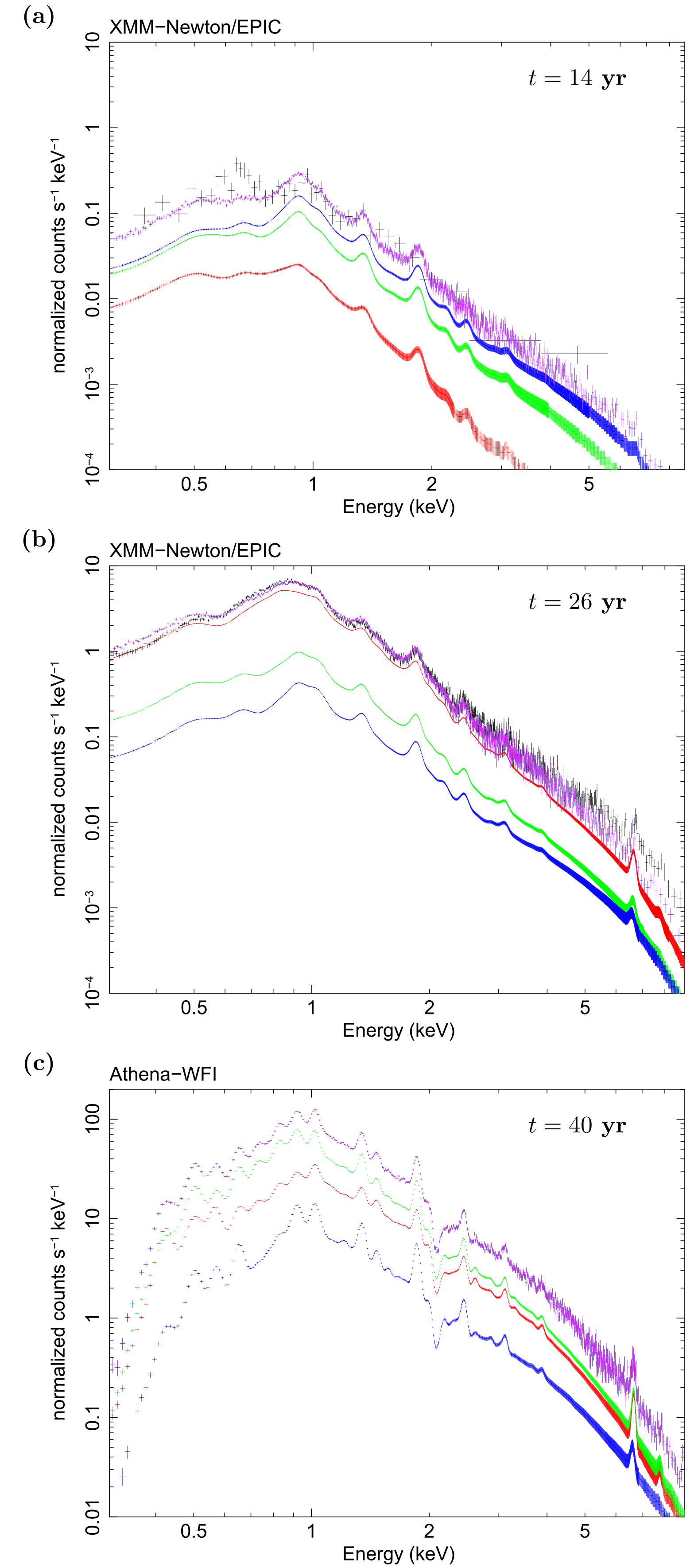
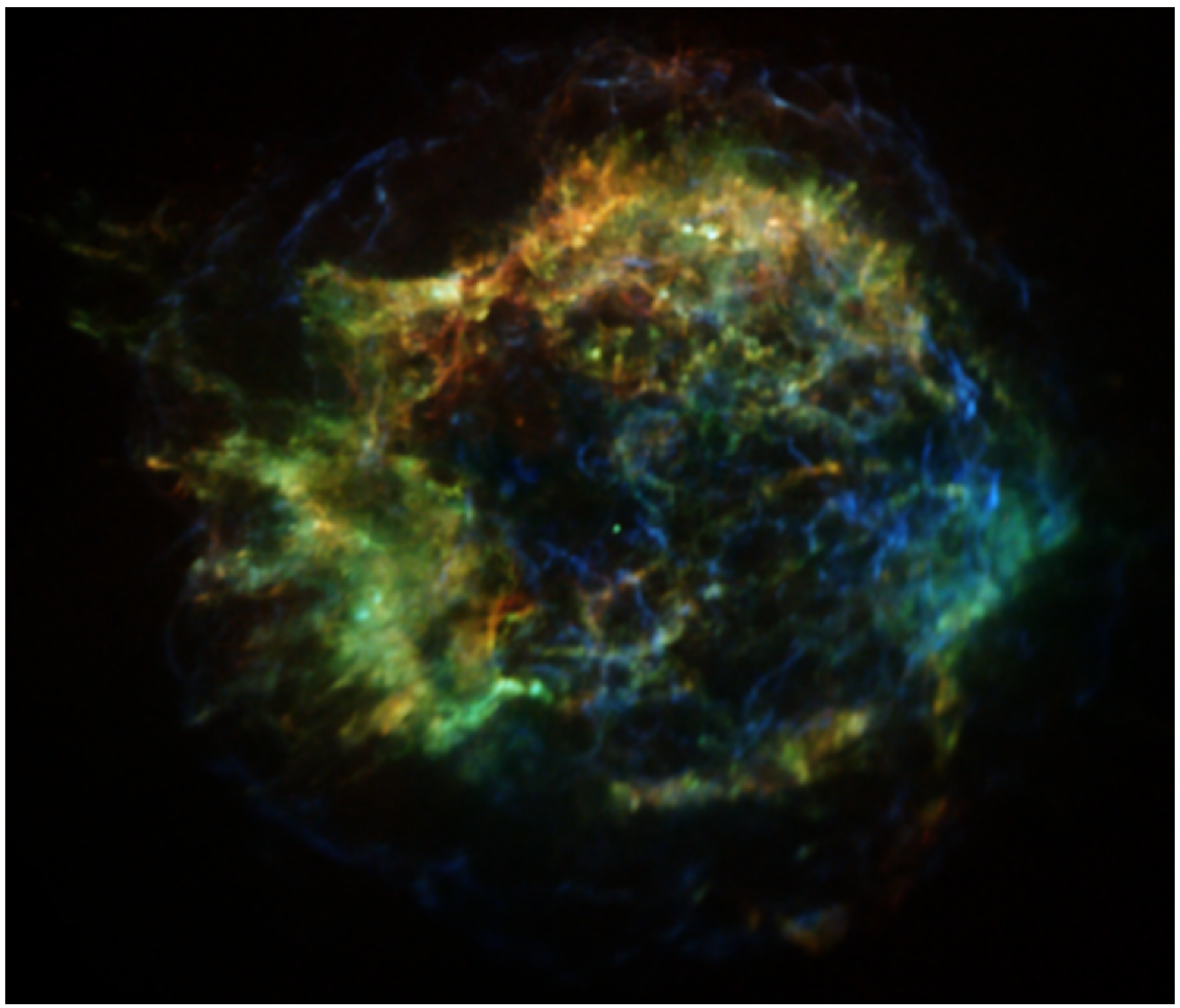


Figure 6. Synthetic and observed X-ray spectra of SN 1987A. (a) *XMM-Newton*/EPIC-pn spectra at $t = 14$ years. The true spectrum is marked in black (see Appendix B); the synthetic spectrum from the whole shocked plasma is marked in magenta; the contributions to emission from the different shocked plasma components are marked in green (ejecta), red (ring), and blue (H II region). (b) As in Figure 6(a), for $t = 26$ years. (c) As in Figure 6(a), for $t = 40$ years and for spectra as they would be collected with *Athena*/WFI.

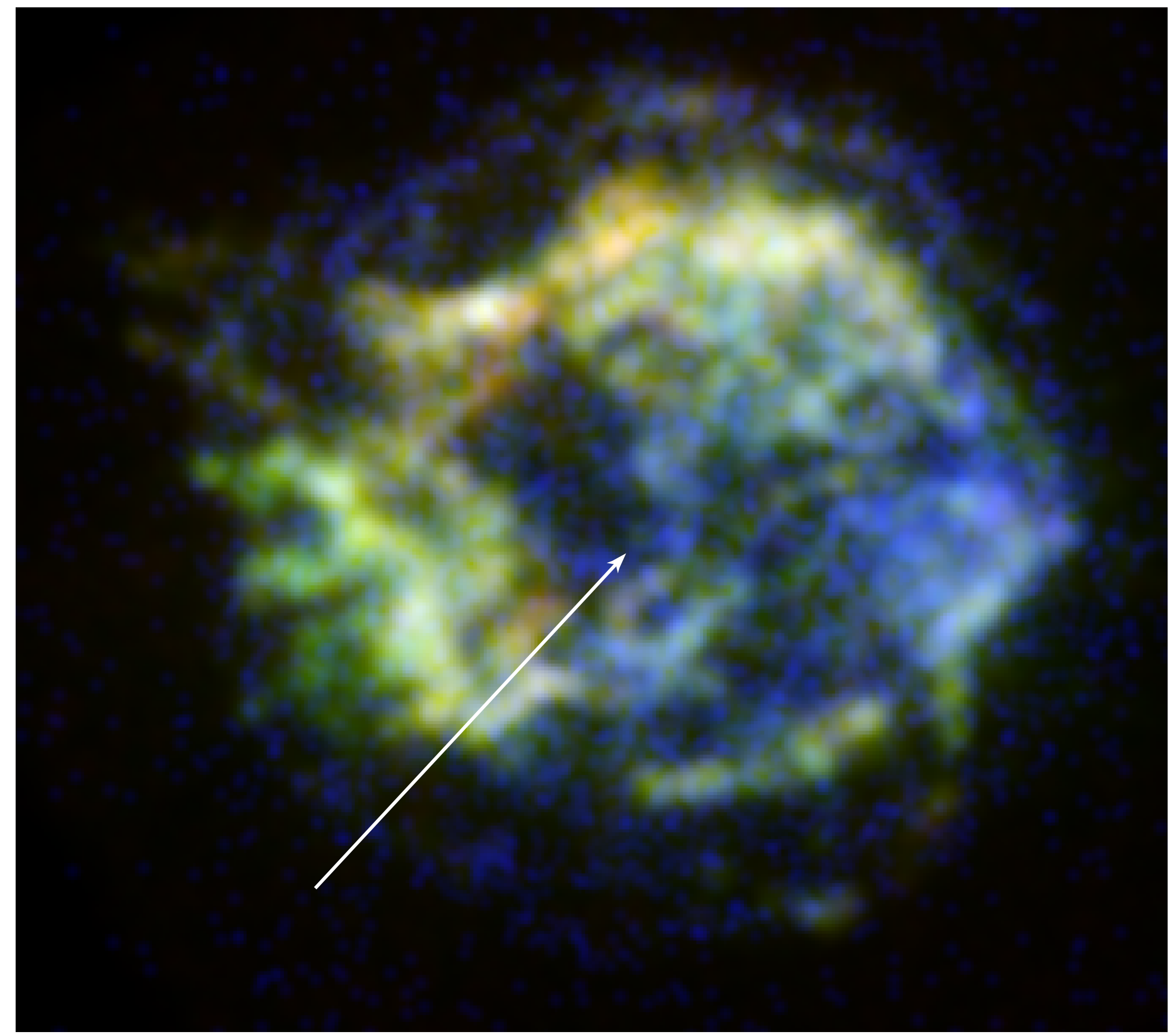
We have explored the possibility of studying large numbers of SNRs in the LMC in modest (~50 ks) exposures by putting Cas A in the LMC.

Cas A in MW

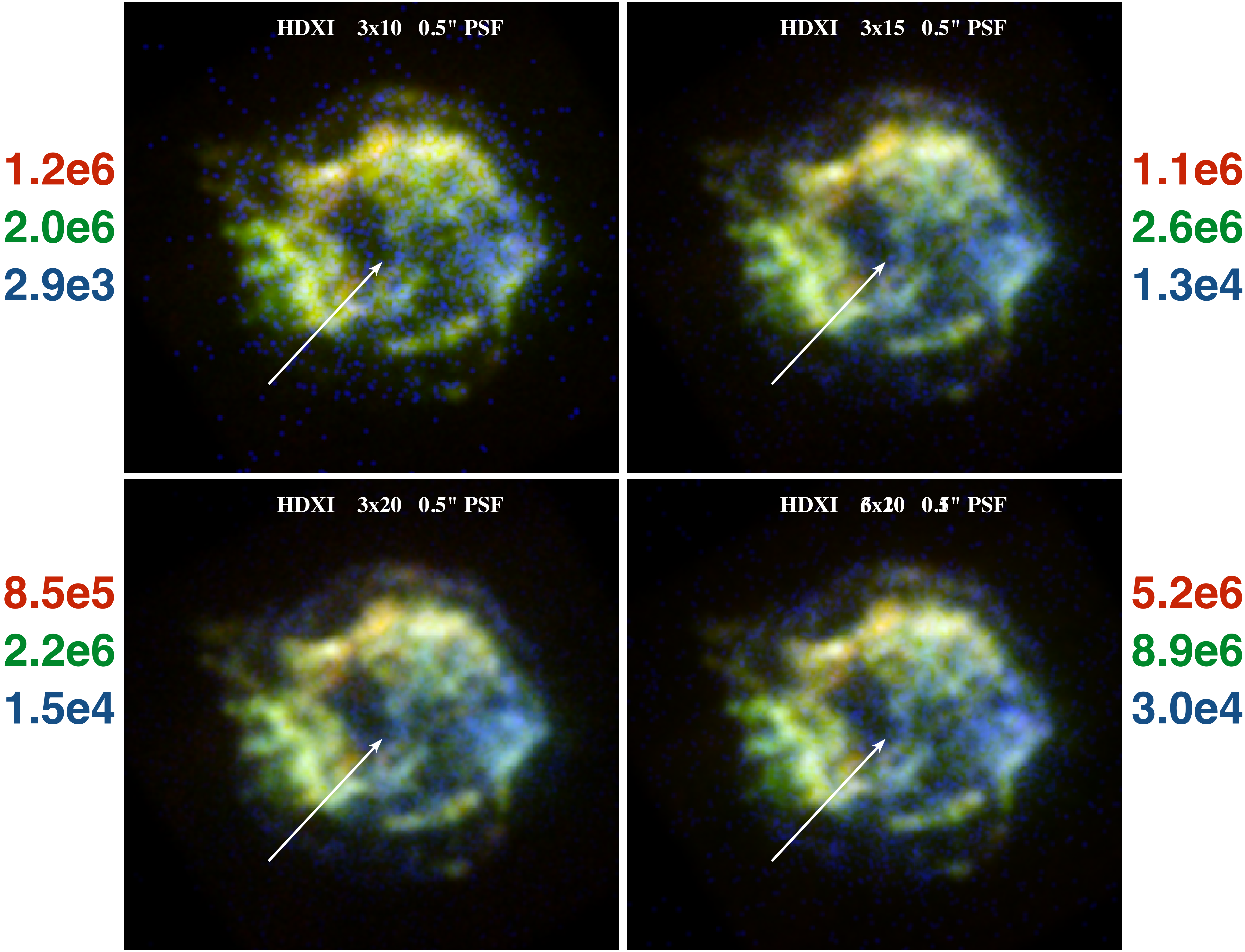


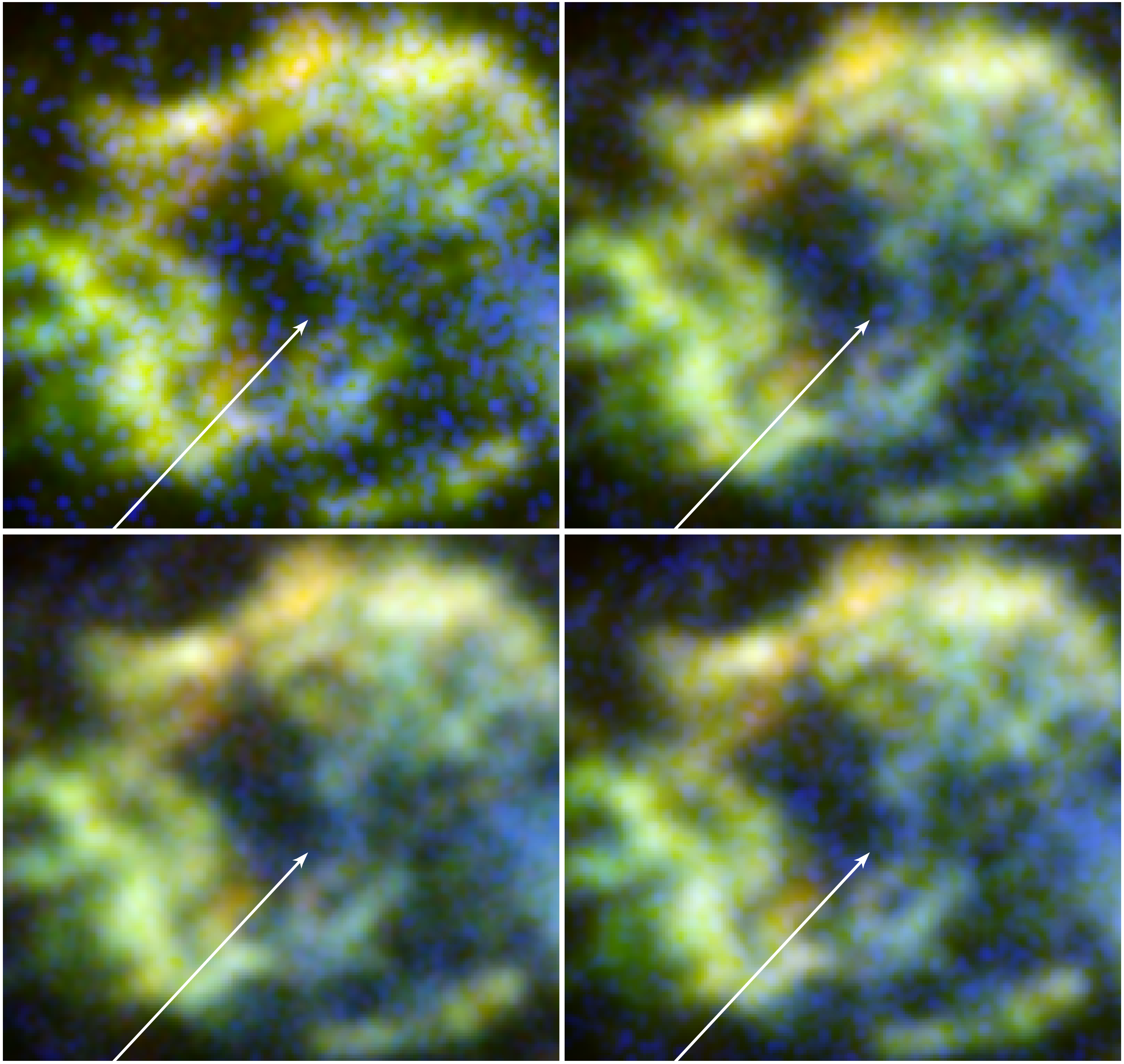
Chandra 150 ks

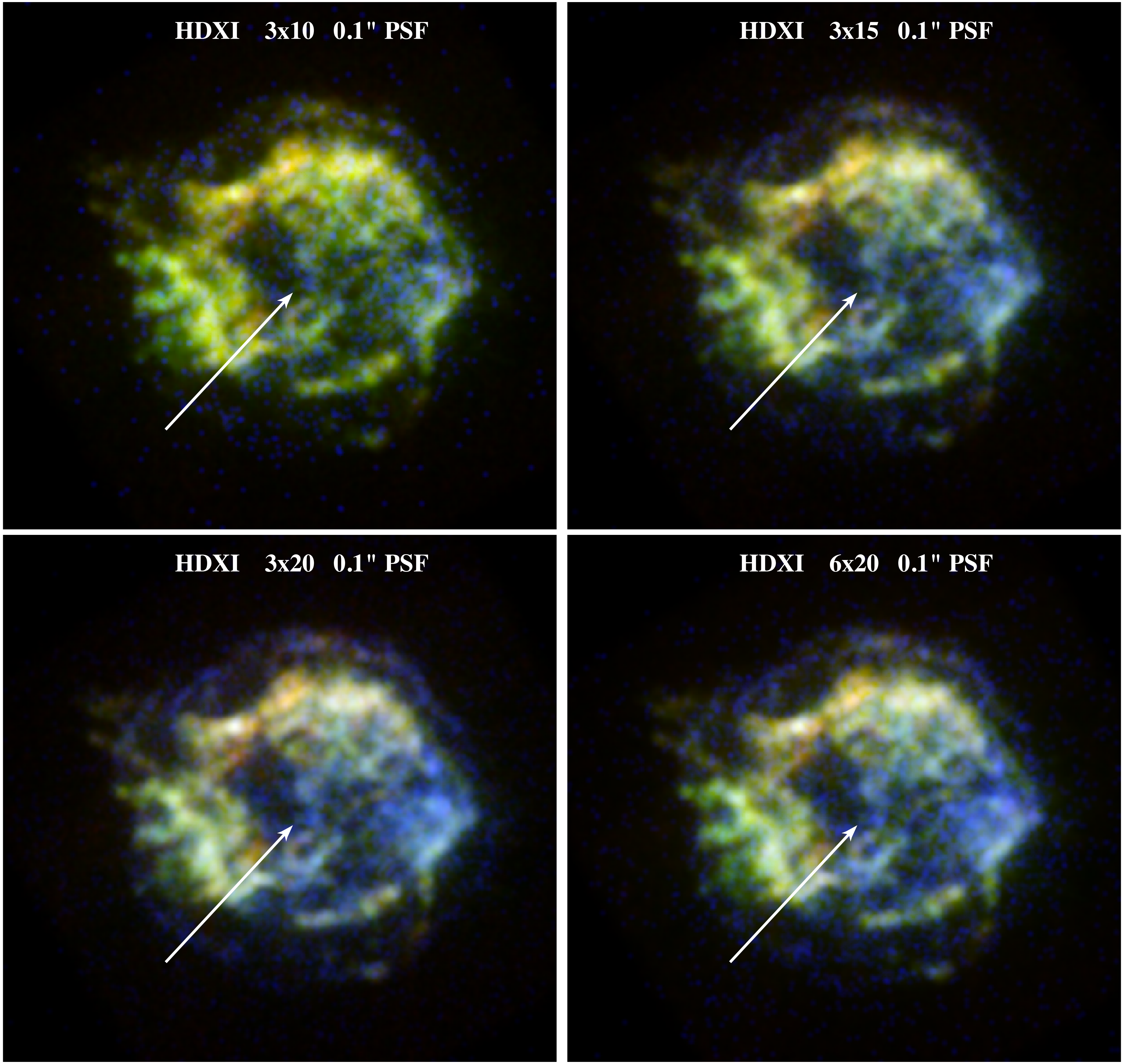
Cas A in LMC

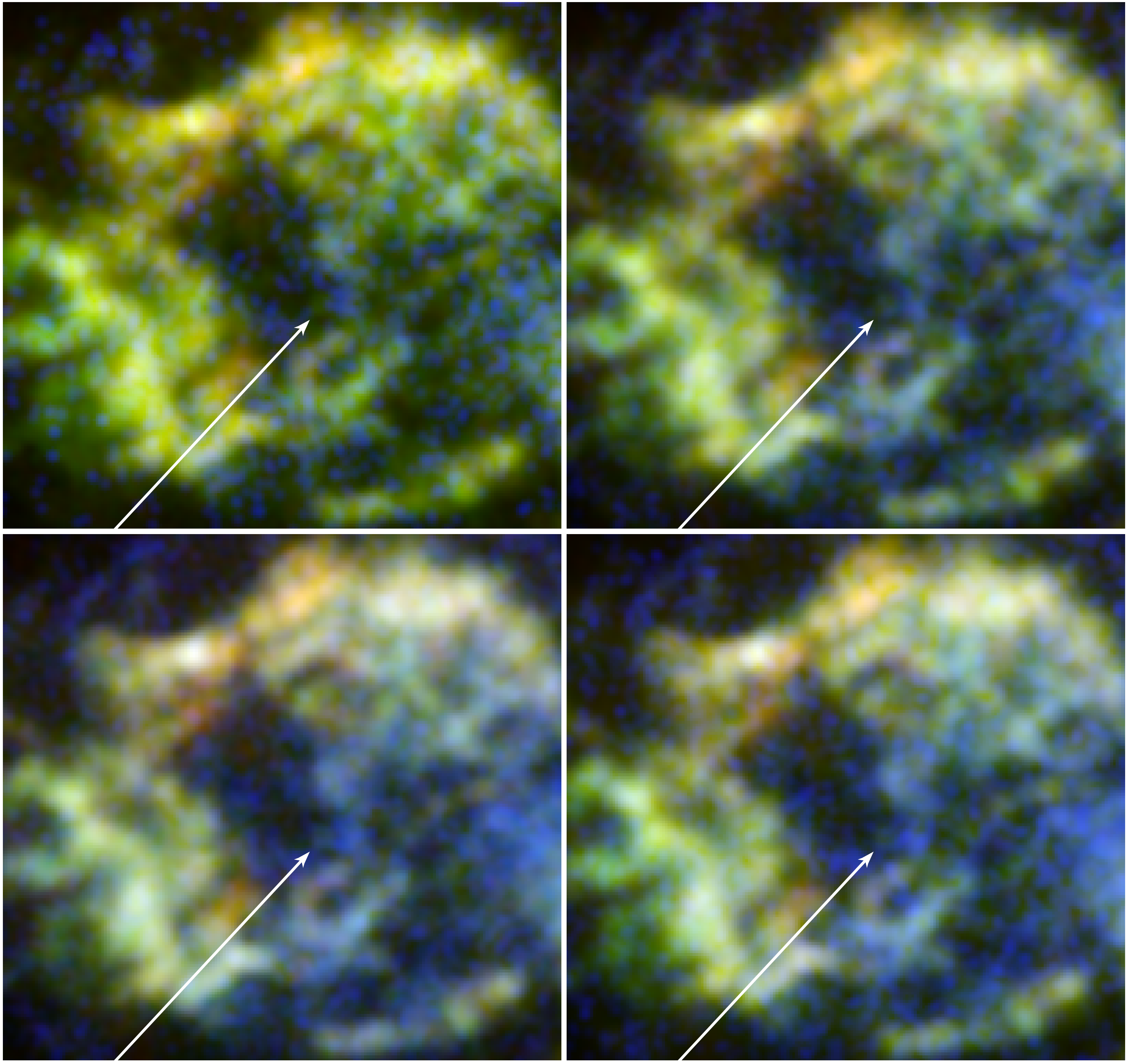


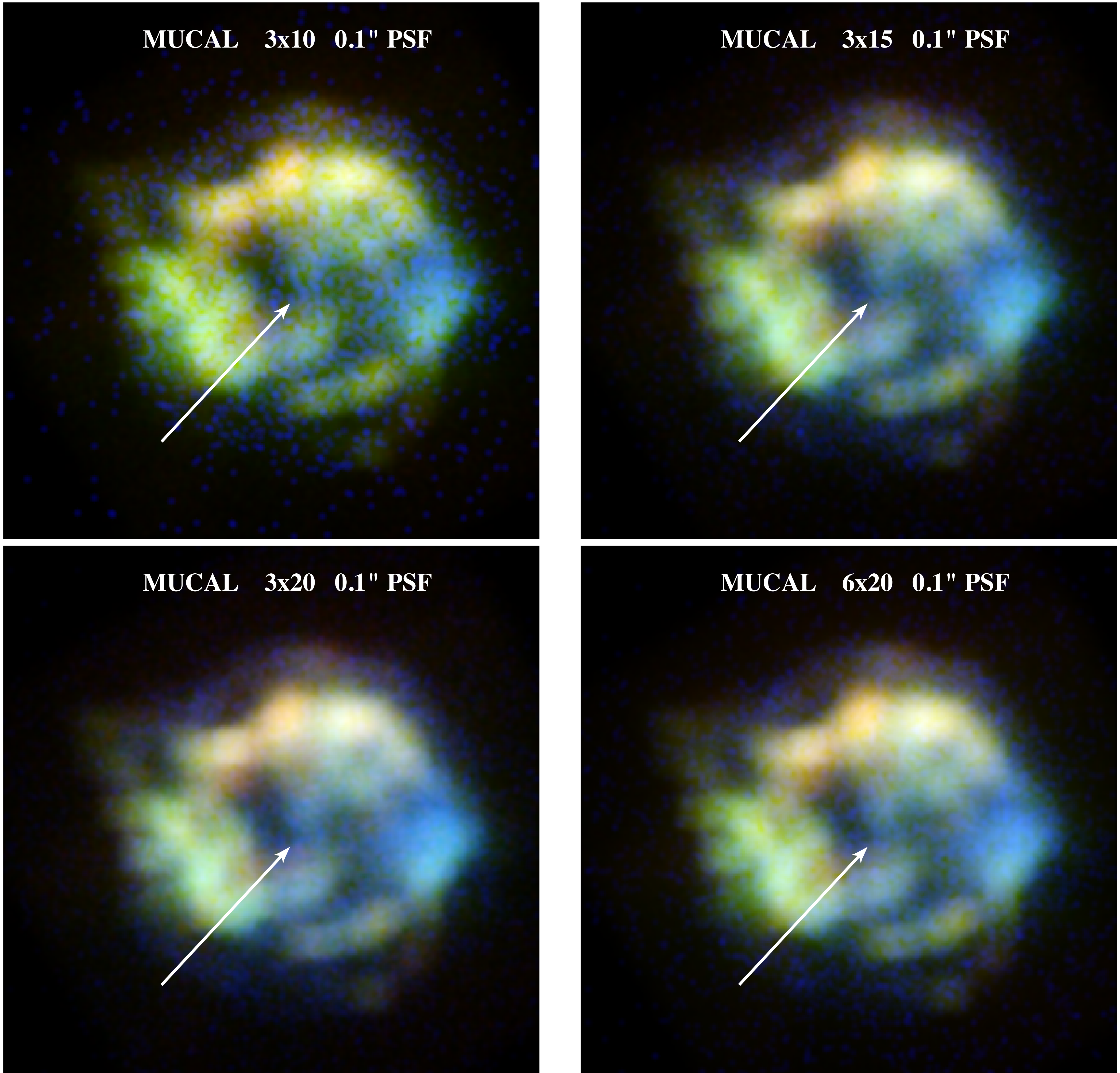
XRS/Lynx 50 ks
0.1” PSF
6x20 configuration


HDXI 3x10 0.5" PSF
HDXI 3x15 0.5" PSF
HDXI 3x20 0.5" PSF
HDXI
PSF
1.2e6
2.0e6
2.9e3
1.1e6
2.6e6
1.3e4
8.5e5
2.2e6
1.5e4
5.2e6
8.9e6
3.0e4




HDXI 3x10 0.1" PSF
HDXI 3x15 0.1" PSF
HDXI 3x20 0.1" PSF
HDXI 6x20 0.1" PSF




MUCAL 3x10 0.1" PSF
MUCAL 3x15 0.1" PSF
MUCAL 3x20 0.1" PSF
MUCAL 6x20 0.1" PSF

Supernova Remnants

Compelling science questions: how do supernovae explode?

- Role of XRS: study large sample of SNRs, especially in nearby galaxies
    - Ejecta composition, velocity structure
    - Morphologies, small-scale mixing
    - Neutron star kicks
    - Shock-heated CSM, interaction with molecular clouds

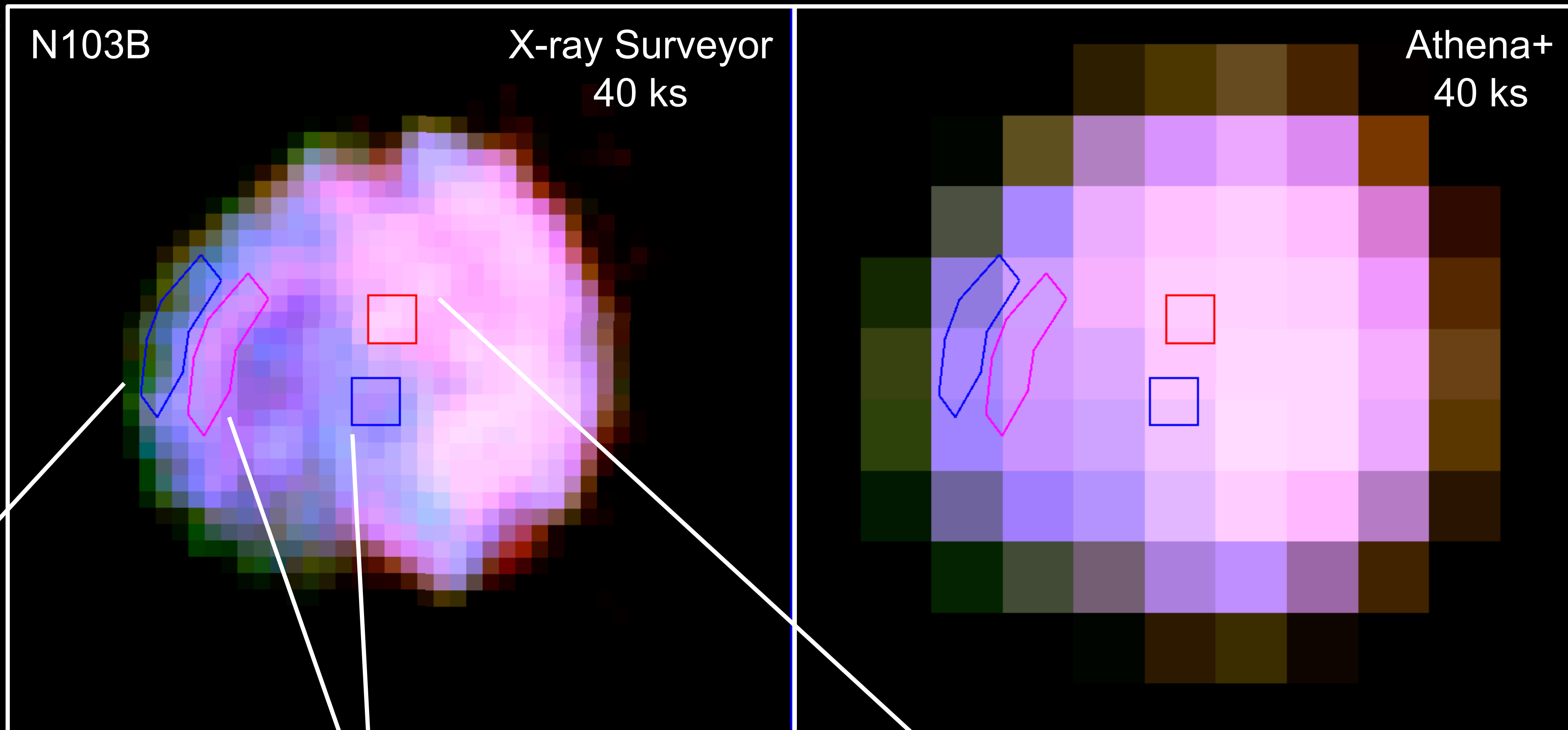
Specifications: Microcalorimeter, spatial resolution, up to >10 keV

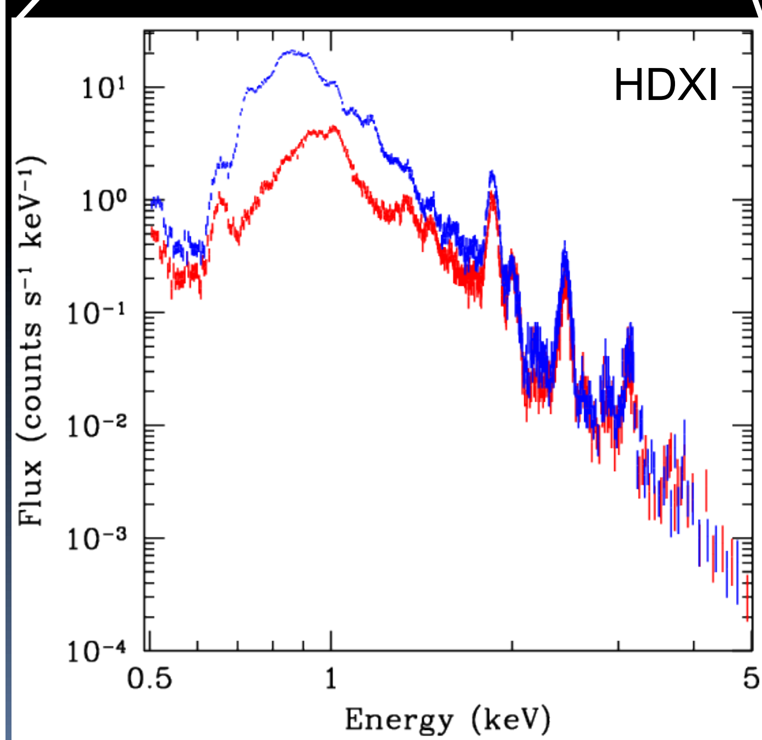
Other compelling science:

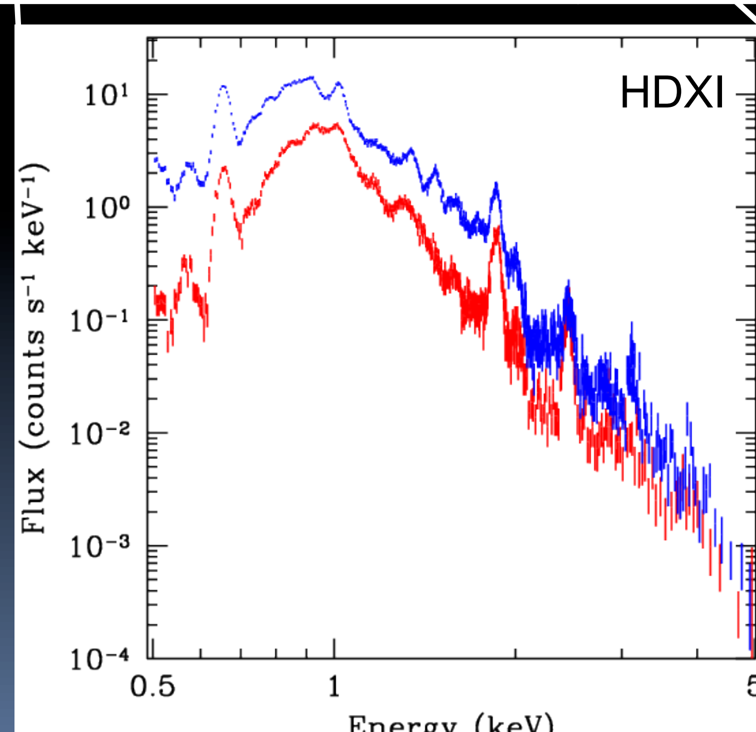
Shock heating: ionization state of plasmas (microcalorimeter)
Particle acceleration in shocks (spatial resolution, effective area, 10 keV)
Pulsar wind nebulae (spatial resolution, effective area, 10-15 keV)

Magellanic Cloud SNRs

B. Williams (GSFC)

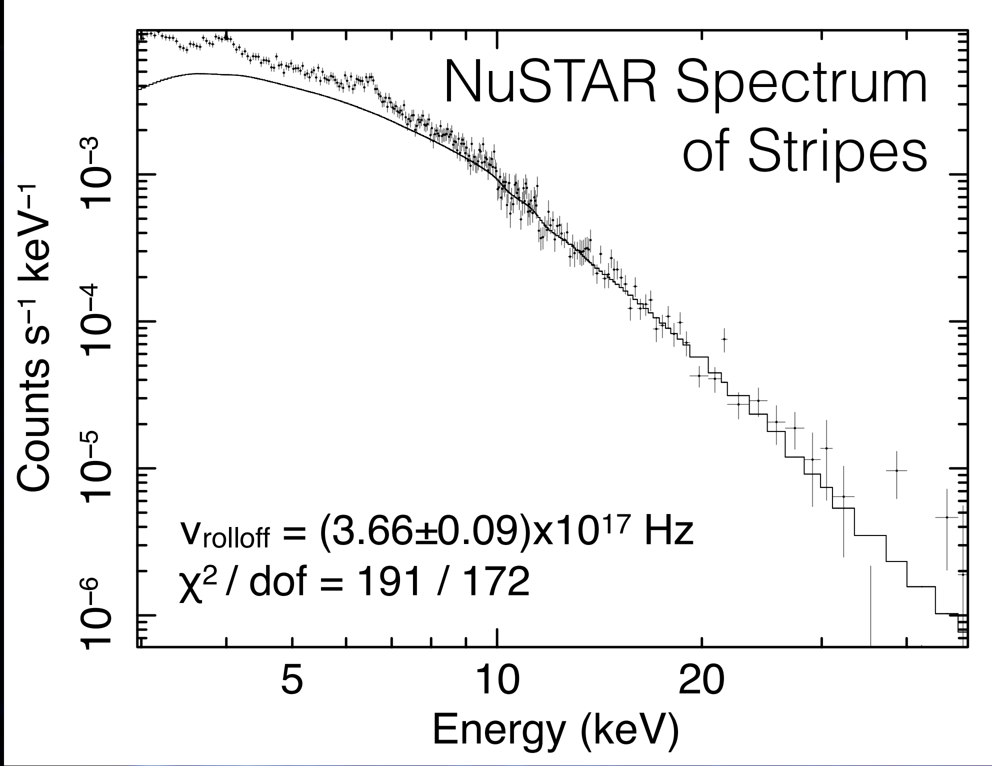




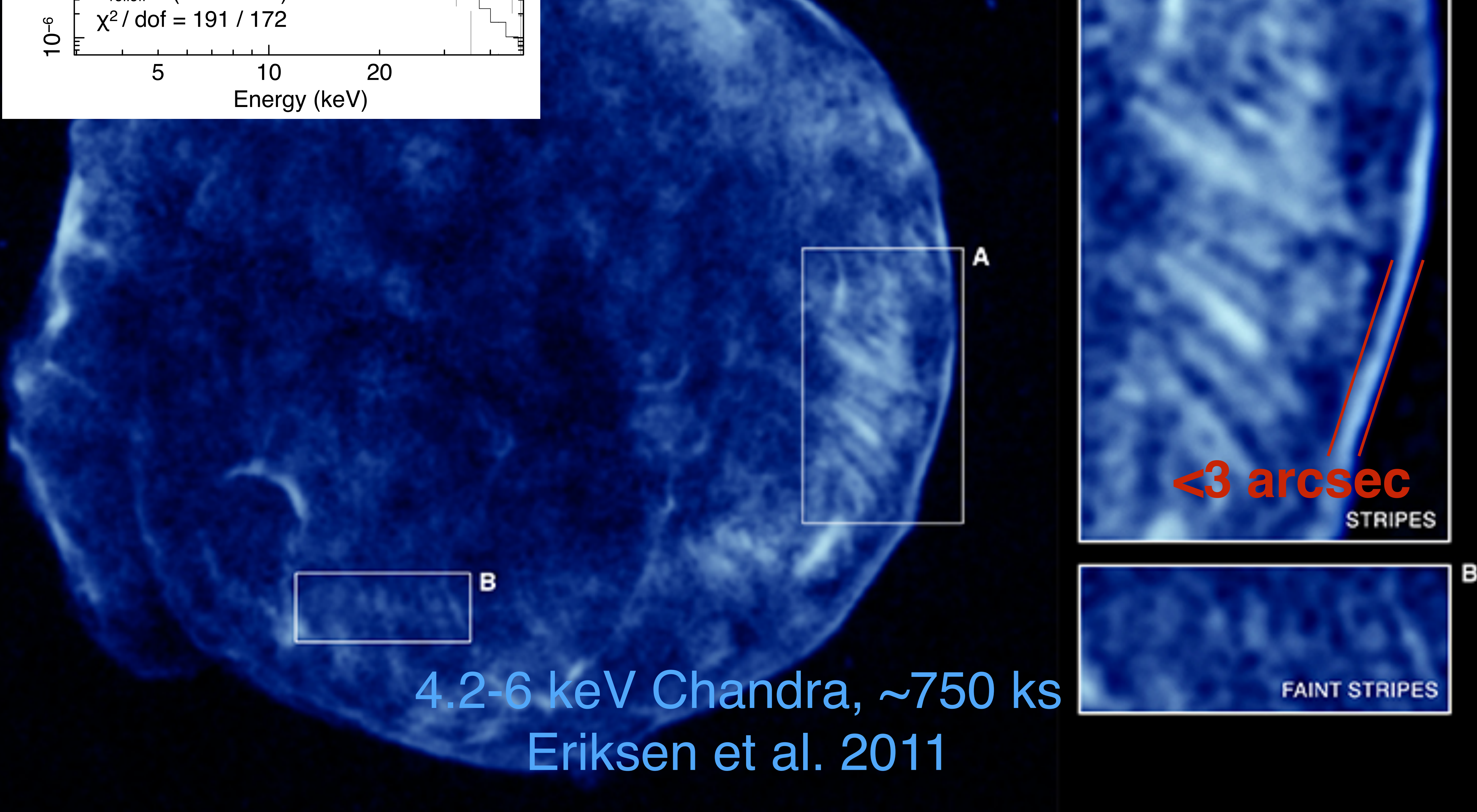


Example: N103B in LMC

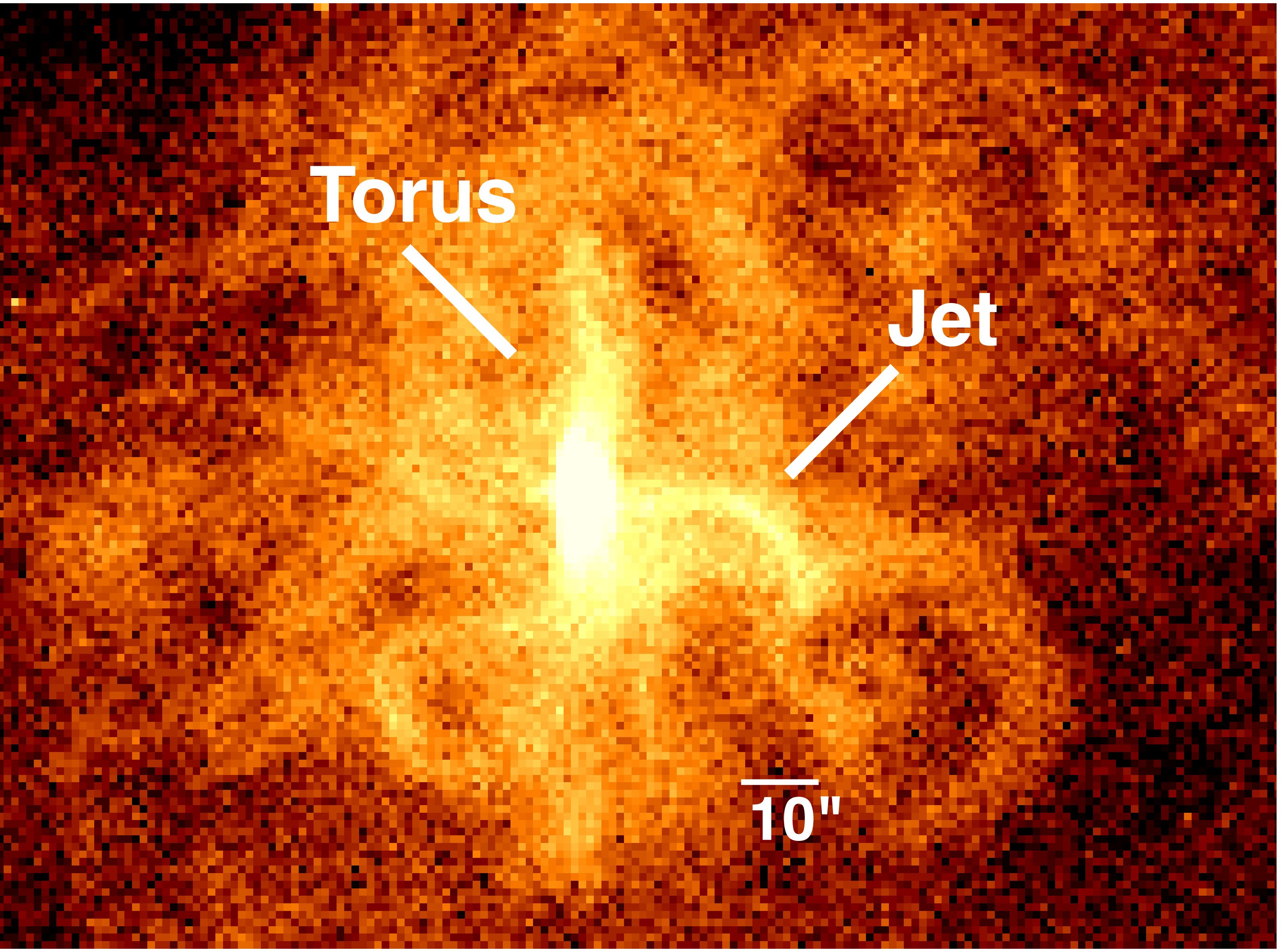
- Type Ia SNR similar to Kepler
  - strong evidence for CSM interaction
- Chandra studies show evidence for spectral variations on multiple scales
- Arcsecond resolution required to probe spectrum on physically important scales.



Lopez et al. 2015



Pulsar Wind Nebulae



0.5-7 keV Chandra
392 ks, PI: Slane

Role of XRS:

Resolve faint PWN features and host SNRs

Identify PWN in external galaxies

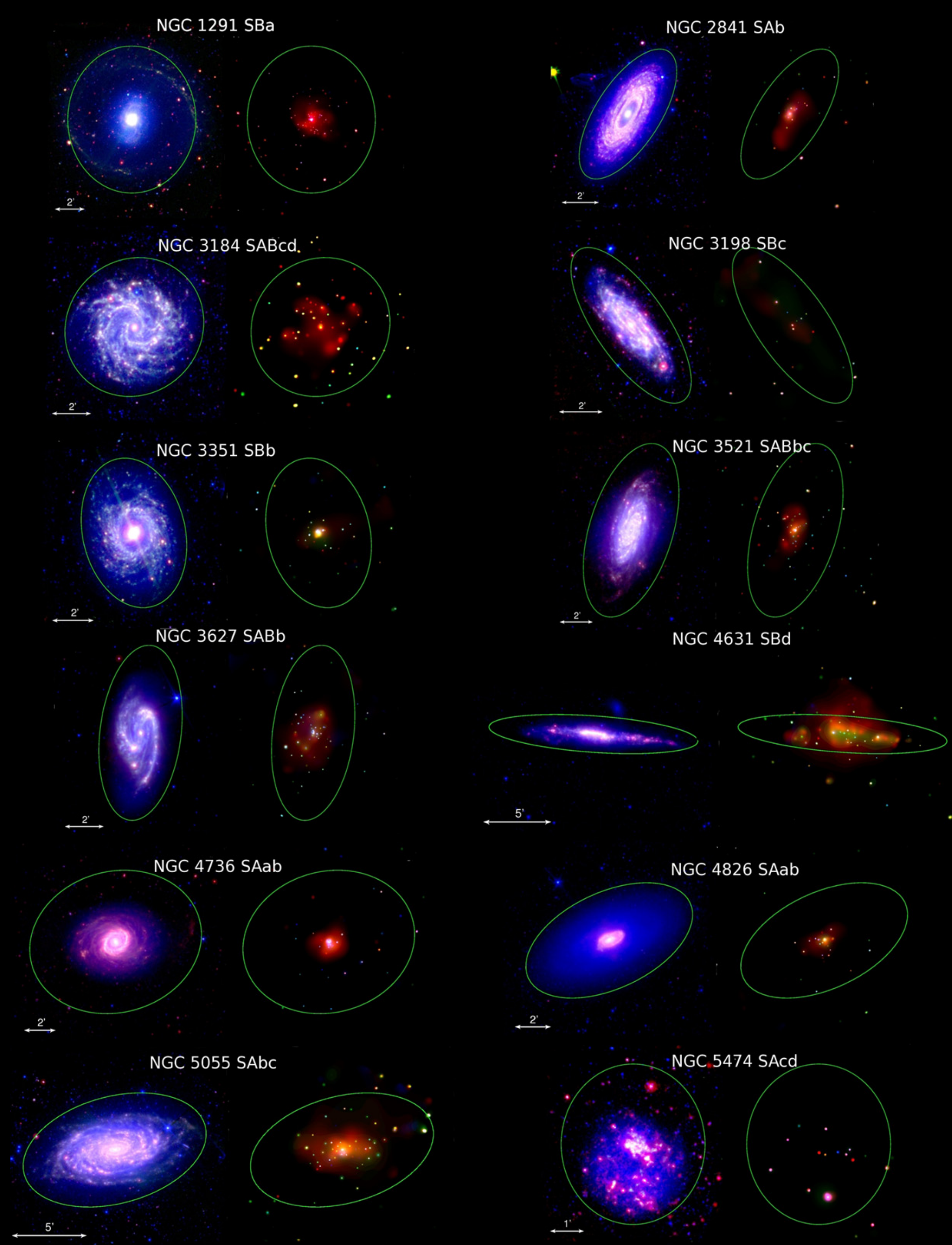
Monitor longterm variability easily

Image resolution critical to separate thermal + non-thermal SNR emission, pulsed radiation from pulsar, synchrotron from PWN

X-ray Binary Populations Science that would be enabled by X-ray Surveyor

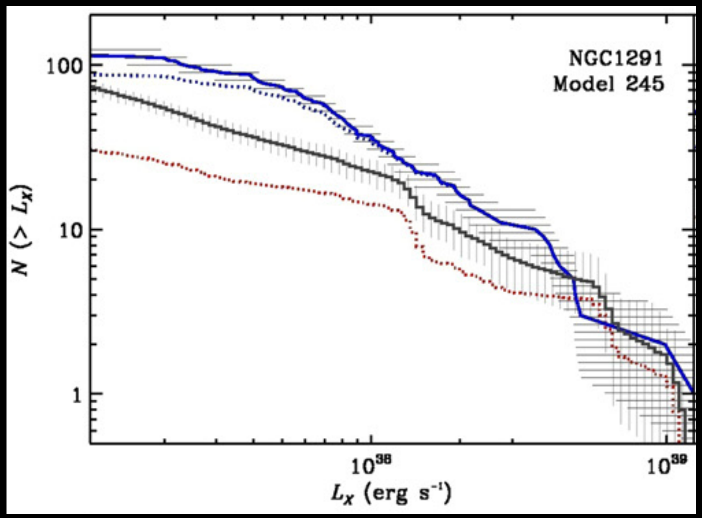
- Census of all compact matter binaries (white dwarf, neutron stars, black holes) down to lower luminosities and in galaxies at larger distances: drives higher effective area, smaller PSF
    - Distribution of WD, NS, BH systems as a fn. of star formation rate, star-formation history, mass, metalicity, etc.
        - would help constrain stellar evolution and X-ray binary evolution models, LIGO GW rate estimates / interpretation
        - Determination of accretion states would also need to be determined to constrain models of XRB evolution and to properly distinguish BH and NS systems
            - monitoring of large regions in the MW, Local Group and/or nearby galaxies would enable the duty cycle of accretion states to be determined
    - Mass function of NS and BHs: requires high spatial resolution to uniquely identify stellar counterparts
- *Incomplete List of Other topics*
    - Isolated neutron stars
    - Extragalactic pulsars, in “normal” XRBs and ULXs at higher distances
    - Direct evidence of feedback/outflows from X-ray binaries via X-ray lines, resolved ionization regions

Normal/Star-forming Galaxies

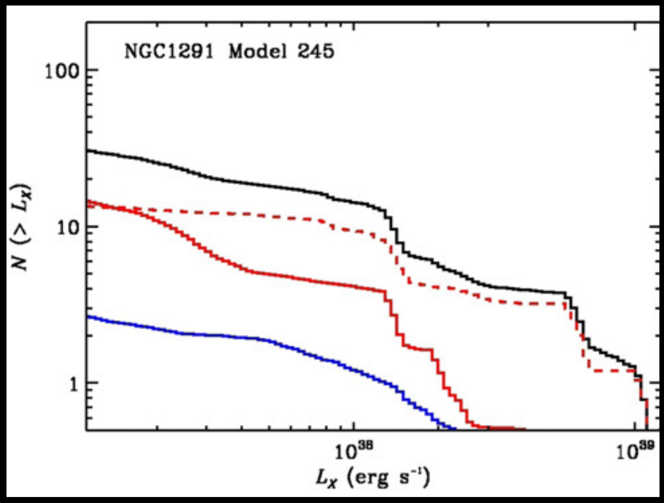


Chandra survey of SINGS galaxies at D ~ 10 Mpc (Tzanavaris et al. 2013)

- Comparison of observed XLFs to theoretical XLF models based on SFH, metalicity, SFR, etc. can be extended to lower luminosities and/or larger distances with PSF size <~ 1" and effective area at least 10X Chandra

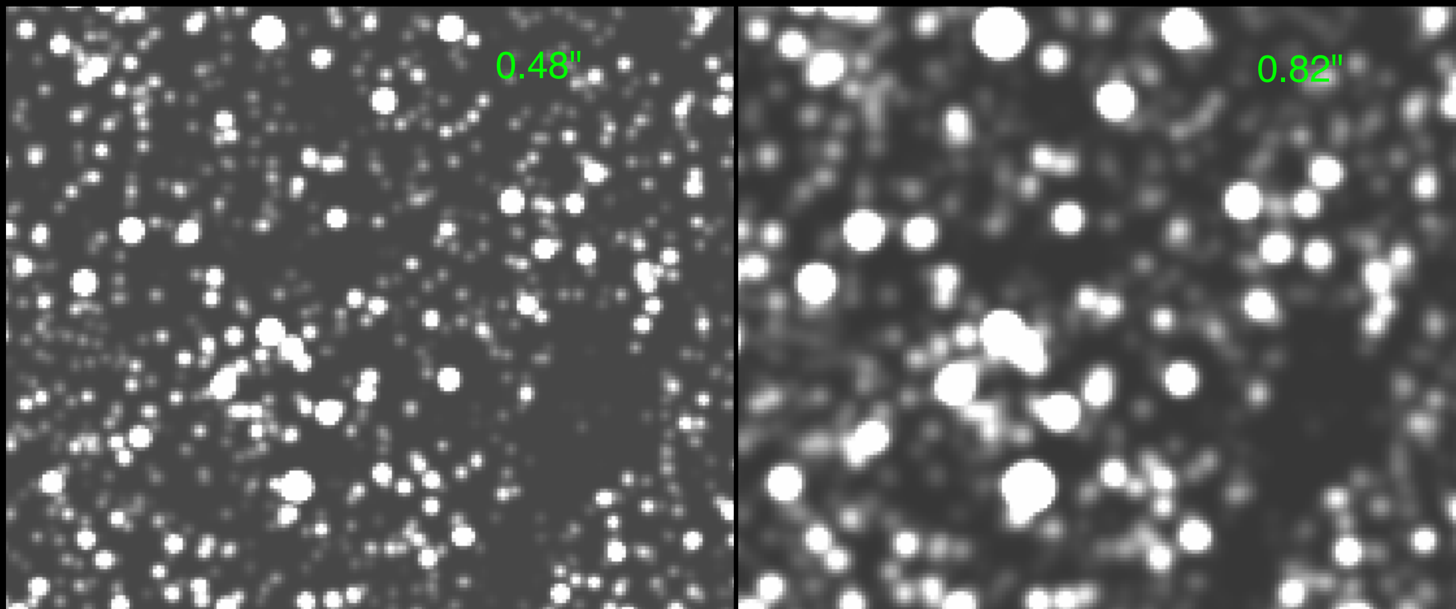


Best-fitting theoretical model



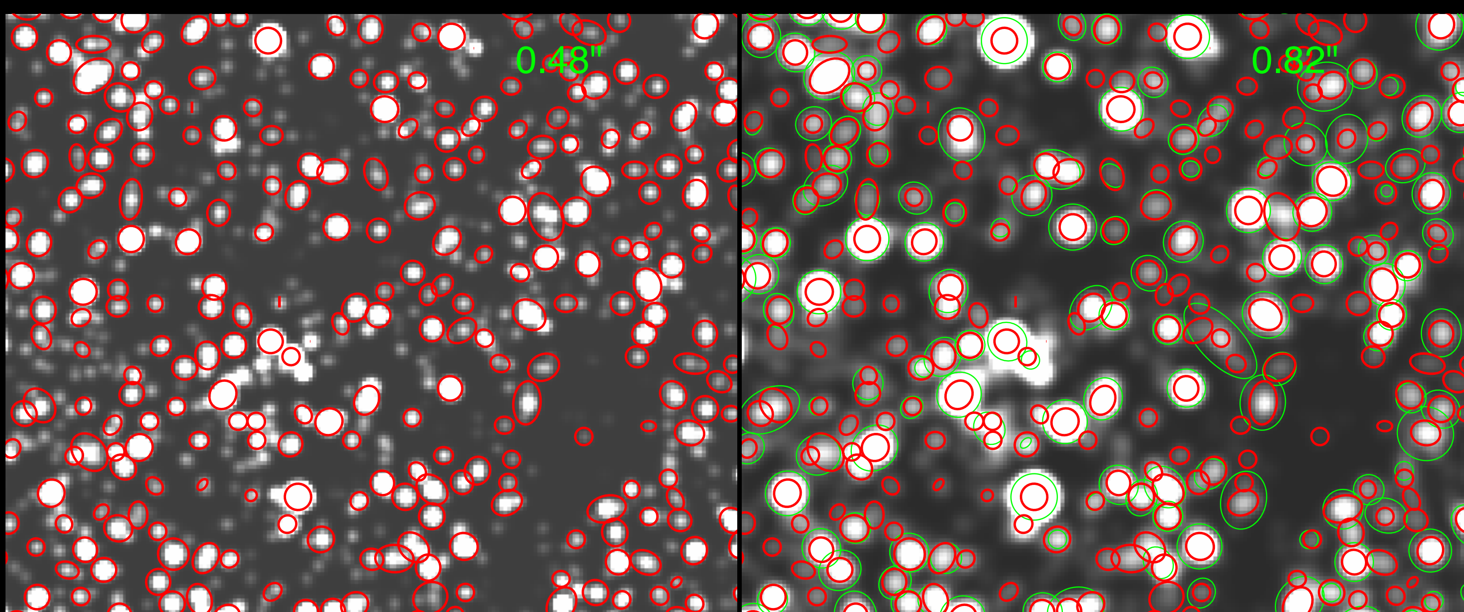
Low-mass and high-mass XRB populations inferred from model

Normal/Star-forming Galaxies



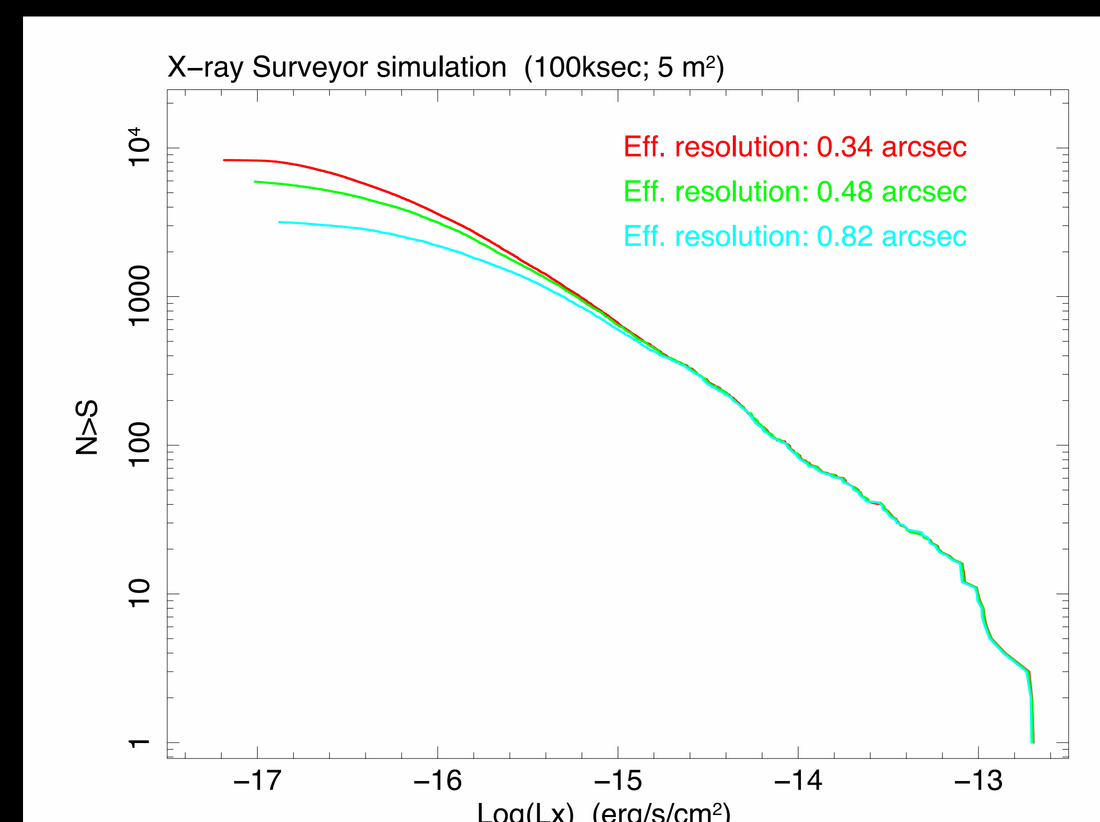
XRS simulation of M81 including HMXBs, LMXBs, background AGN

Source positions based on HST data



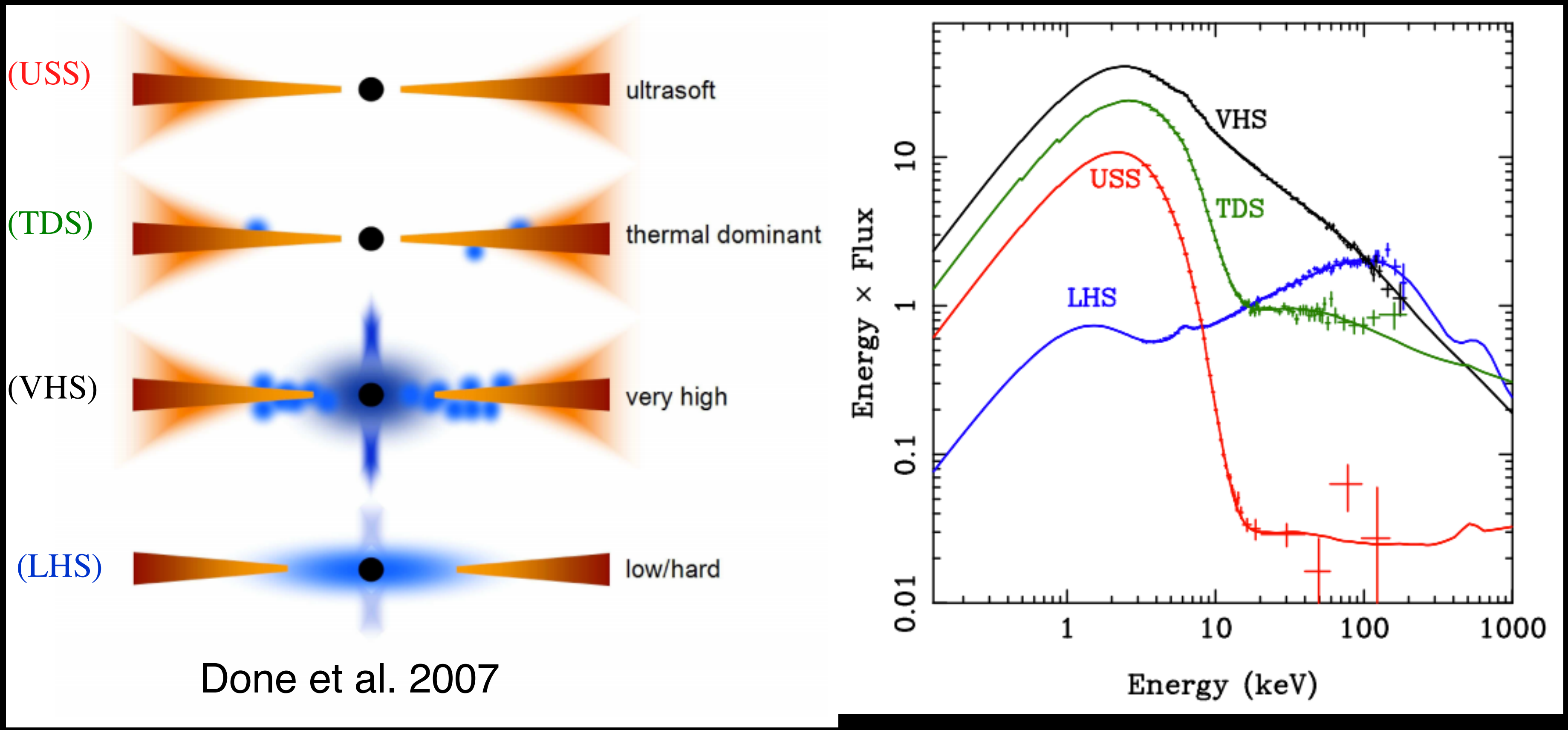
Sources detected in 0.48” and 0.82” images

LogN-LogS based on different simulated images



Accretion States

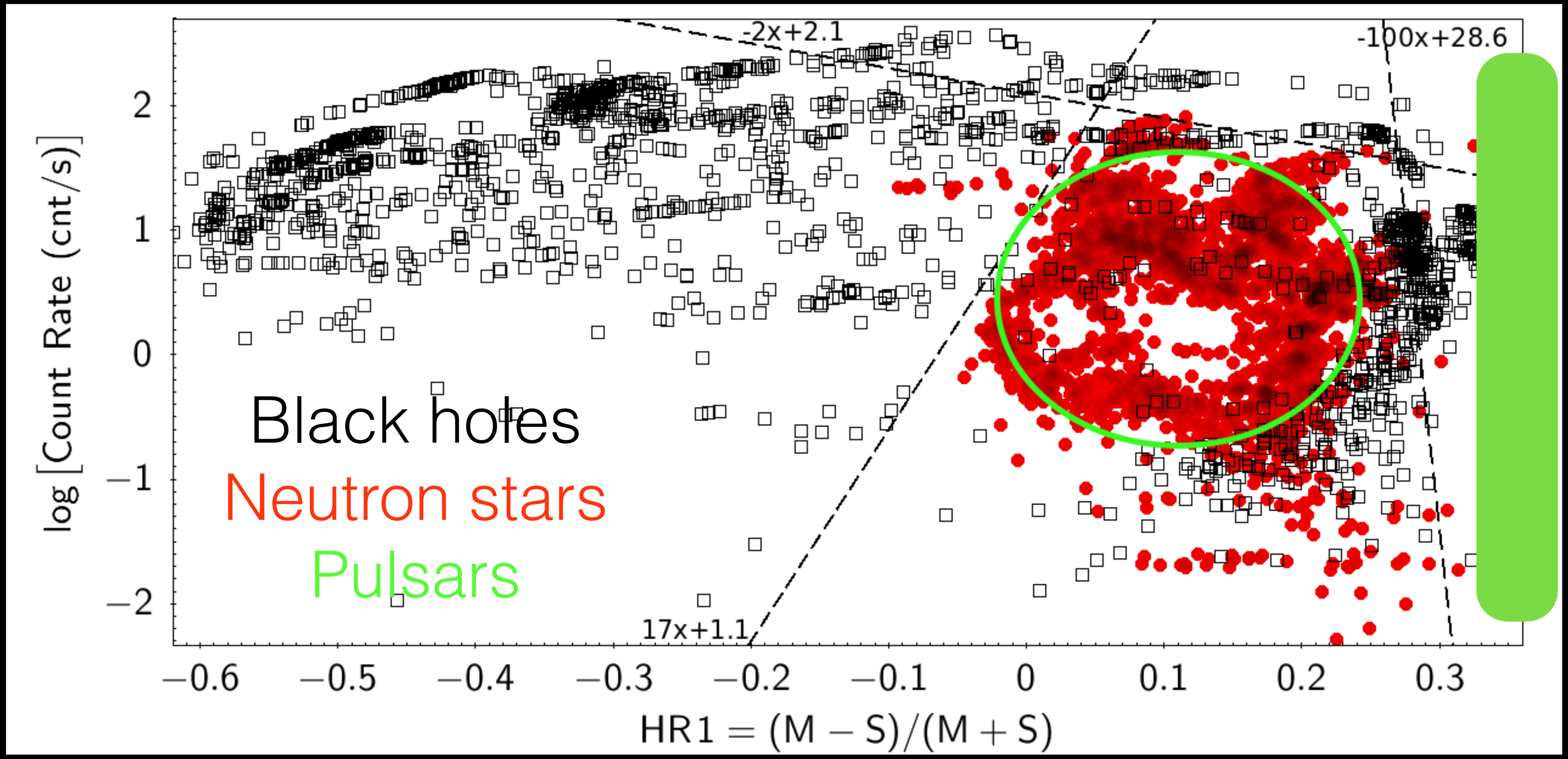
- XRS would have the potential to study the accretion states of large numbers of XRBs in the LG and nearby galaxies, including monitoring of accretion state duty cycles (drives effective area and FoV)
- Due to degeneracy of the spectra below 10 keV having effective area > 10 keV (rest-frame) would be very beneficial… coverage to ~ 15 keV would be sufficient especially for z>0 galaxies.



Done et al. 2007

Compact Object Classification

- XRS could also characterize the compact object populations by spectrally separating pulsars, from black-holes, and low magnetic field neutron stars (drives effective area and FoV)
- Due to degeneracy of the spectra below 10 keV having effective area > 10 keV (rest-frame) would be very beneficial… coverage to ~ 15 keV would be sufficient especially for z>0 galaxies.



S=4 - 6 keV
M=6-12keV

Next Steps

- Simulations of galaxies at various distances (LG, 10 Mpc, 25 Mpc, 100 Mpc, etc.) to assess what fraction of the XRB population can be resolved in reasonable (~ 100 ks?) exposures assuming "official" effective areas and 0.1", 0.5", 1" resolution
  - For nearby galaxies, start with observed Chandra XLF and extrapolate to lower luminosities using theoretical models
  - For distance galaxies, simulate XRB populations assuming theoretical models and observed or model SFH
  - Evaluate ability to measure XLFs, determine source population types and accretion state duty cycles, and impact of these to constrain XRB evolution models
- Test impact of E>10 keV effective area