Seeing Stars in a New Light

What Have We Learned from 20 Years of Investigations with Chandra, and What Do We Still Need to Learn?

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Chandra 20th Anniversary Celebration Symposium
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On Past Futures and Future Futures

"We should always be aware that what now lies in the past once lay in the future" (historian Frederic William Maitland)

An AXAF By Any Other Name

– Hide authors and affiliations

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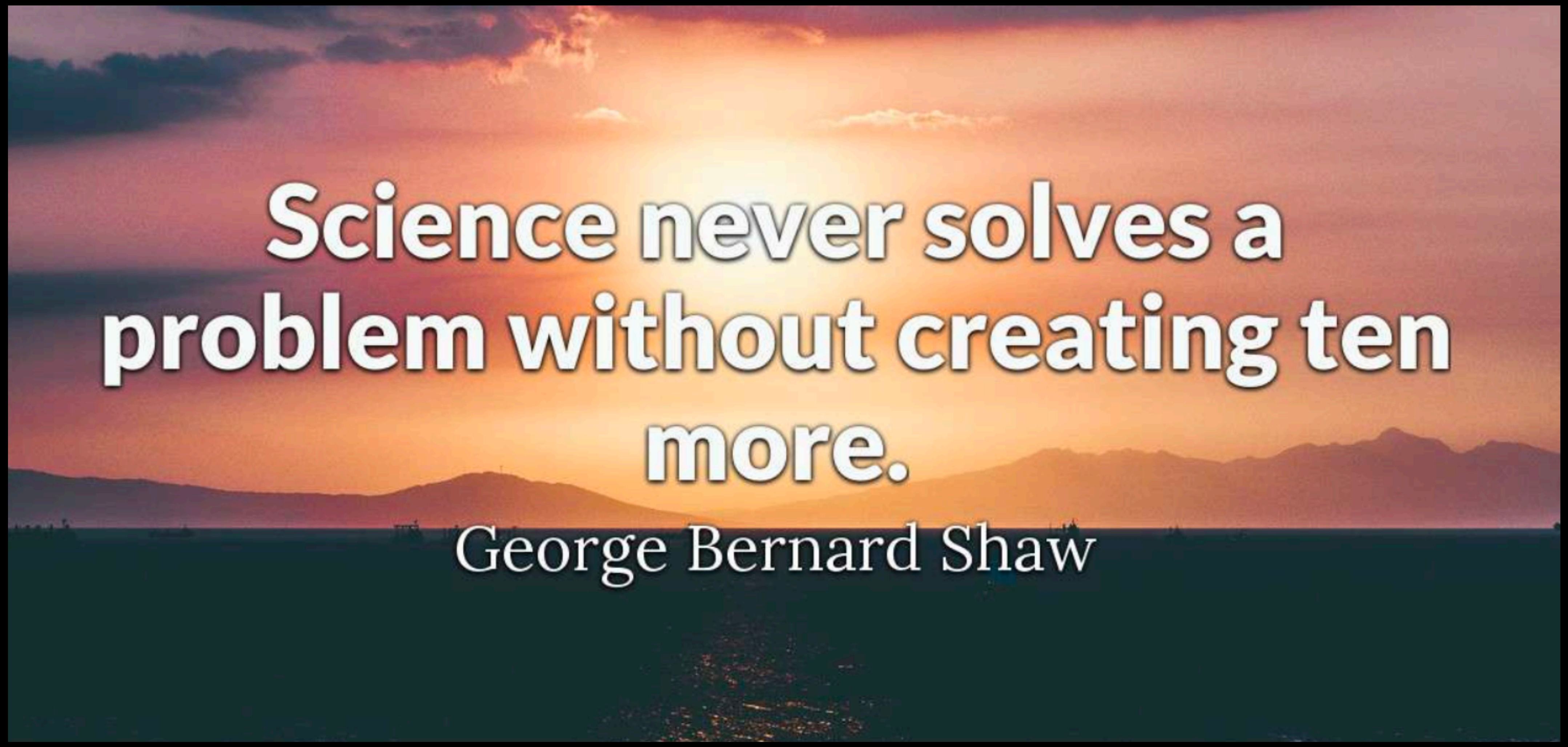
NASA has given its tongue-twisting Advanced X-ray Astrophysics Facility a more user-friendly name. The $2 billion space observatory, due to be launched this spring, has been christened the Chandra X-ray Observatory, after the late University of Chicago astrophysicist and Nobel laureate Subrahmanyan Chandrasekhar. An Idaho high school student and a California teacher independently suggested the name, which means "moon" or "luminous" in Sanskrit.

Chandra Has Been Expanding the Frontiers of our Ignorance

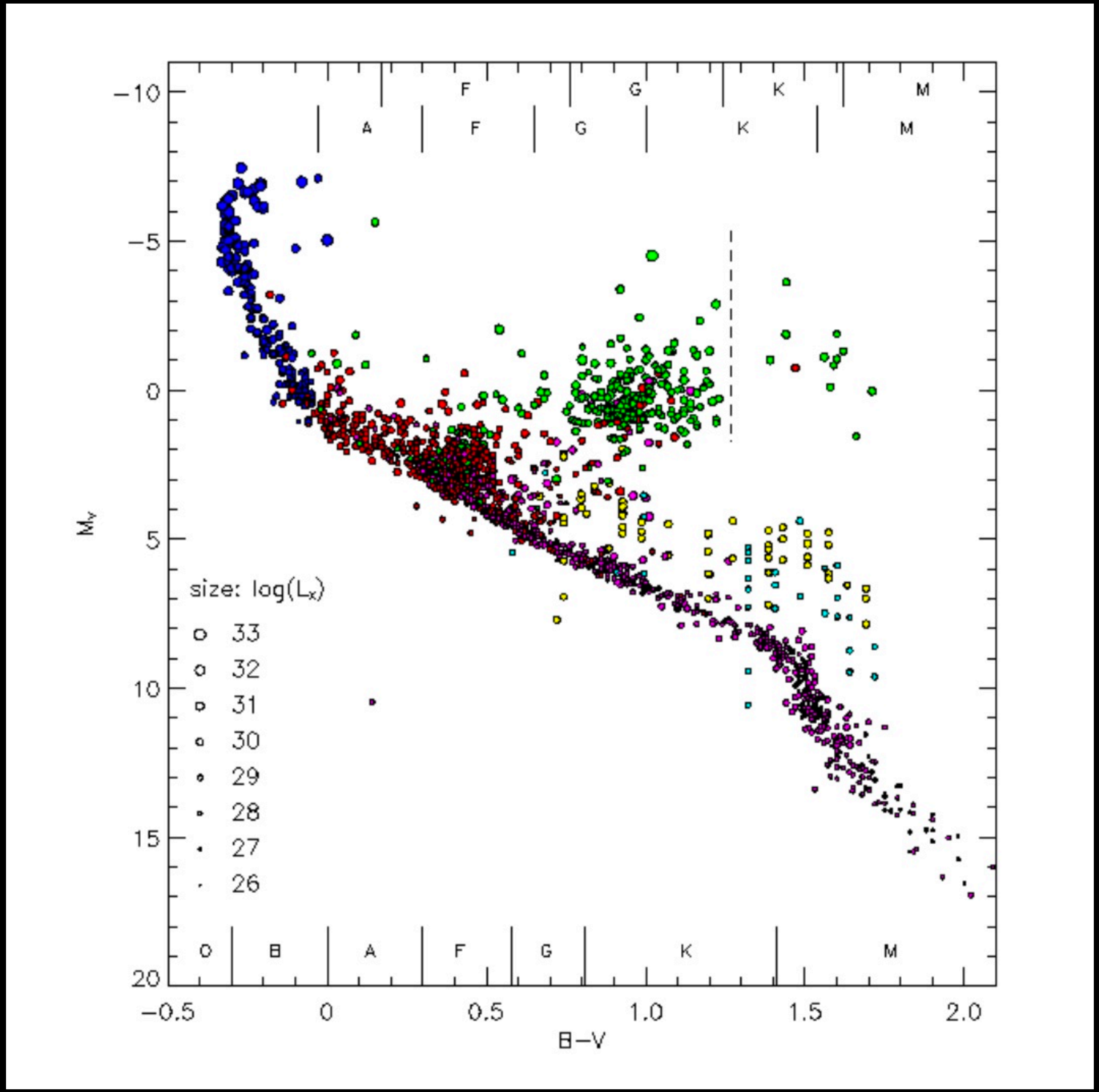


"Knowledge is a big subject. Ignorance is bigger. And it is more interesting."
— **Stuart Firestein, Ignorance: How It Drives Science**

X-ray HR diagram

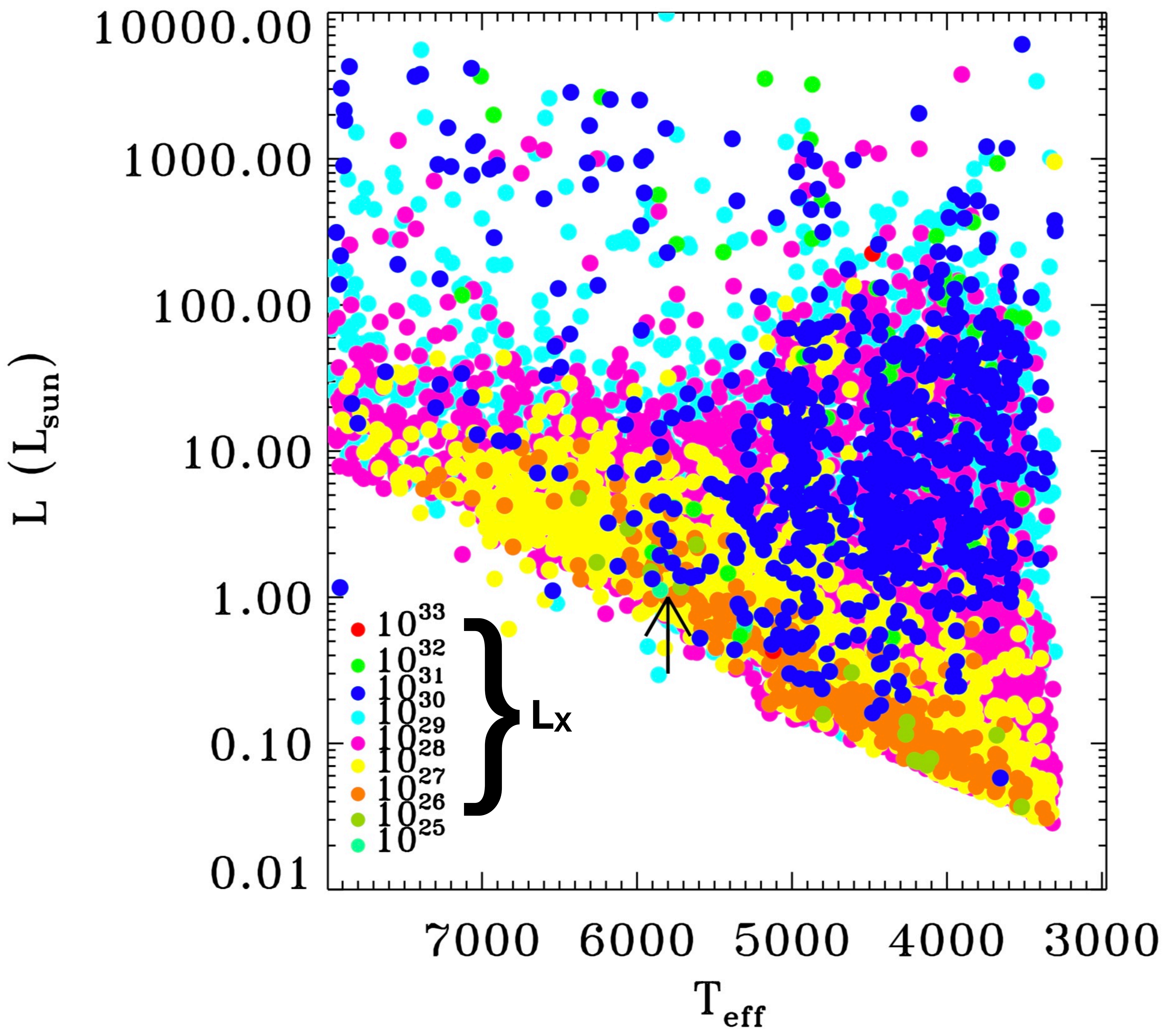
Uhuru	1970	339 sources	all sky
Einstein	1978	~10,000 sources	
ROSAT	1992	~135,000 sources	all-sky
Chandra	1999	317,167 (CSC2)	1.9% of sky

From Güdel (2004)
catalogs of ~2000 X-ray detected stars pre-Chandra



simple tale: X-rays are ubiquitous amongst many different types of normal stars

21st century X-ray HR diagram



Chandra Source Catalog (>300,000 sources) filtered for point sources, positive X-ray fluxes

cross-matched with Gaia DR2 (>10^9 sources) within 3 arcsec
G<17 for T_{eff}, L determination
parallax error <0.4 mas

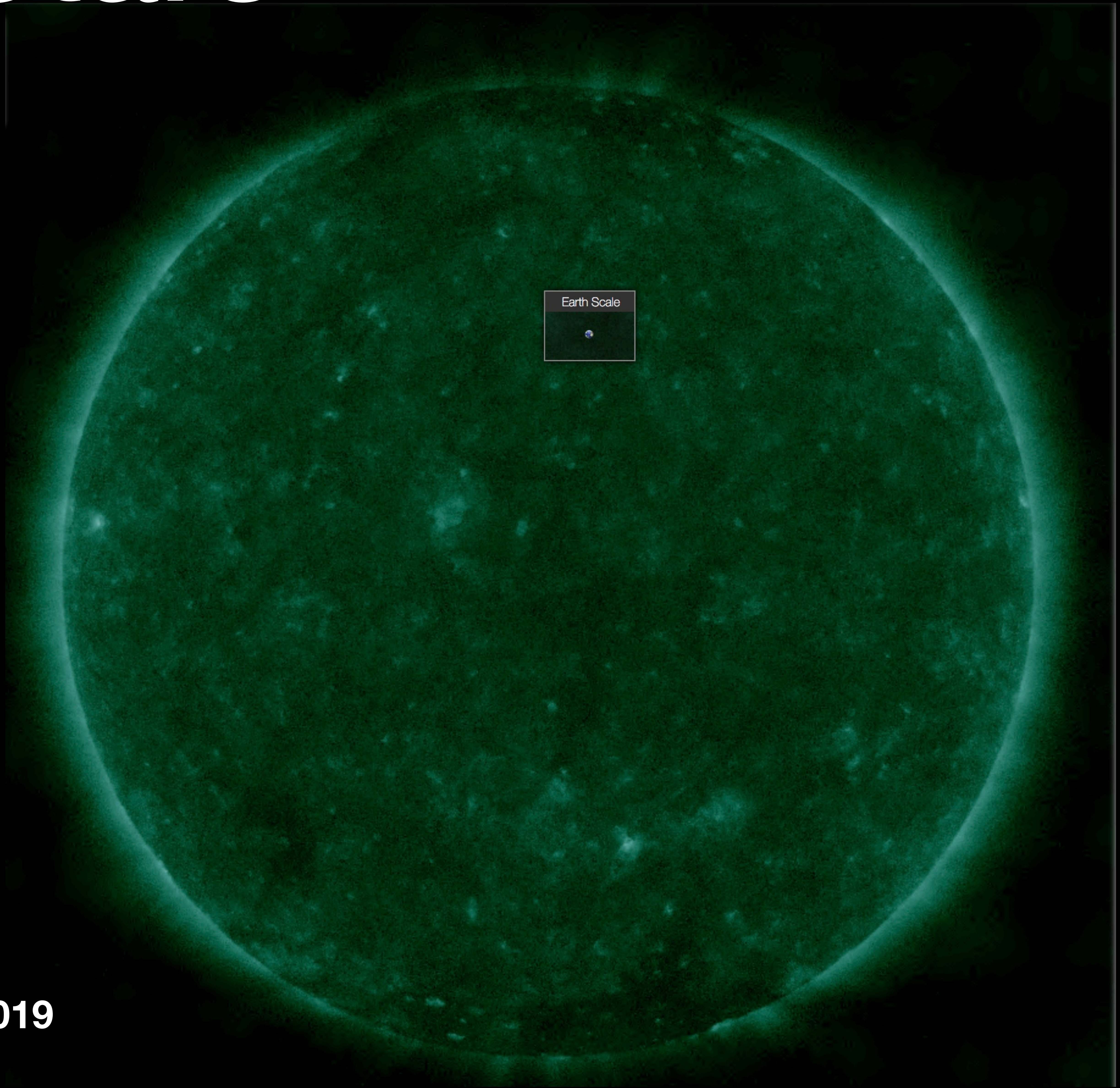
L, T_{eff}, parallax from Gaia
f_X from CSC2

thanks to Matt  **for assistance with this**

Cool Stars

Sun as the archetype, but is it the ultimate cool star?

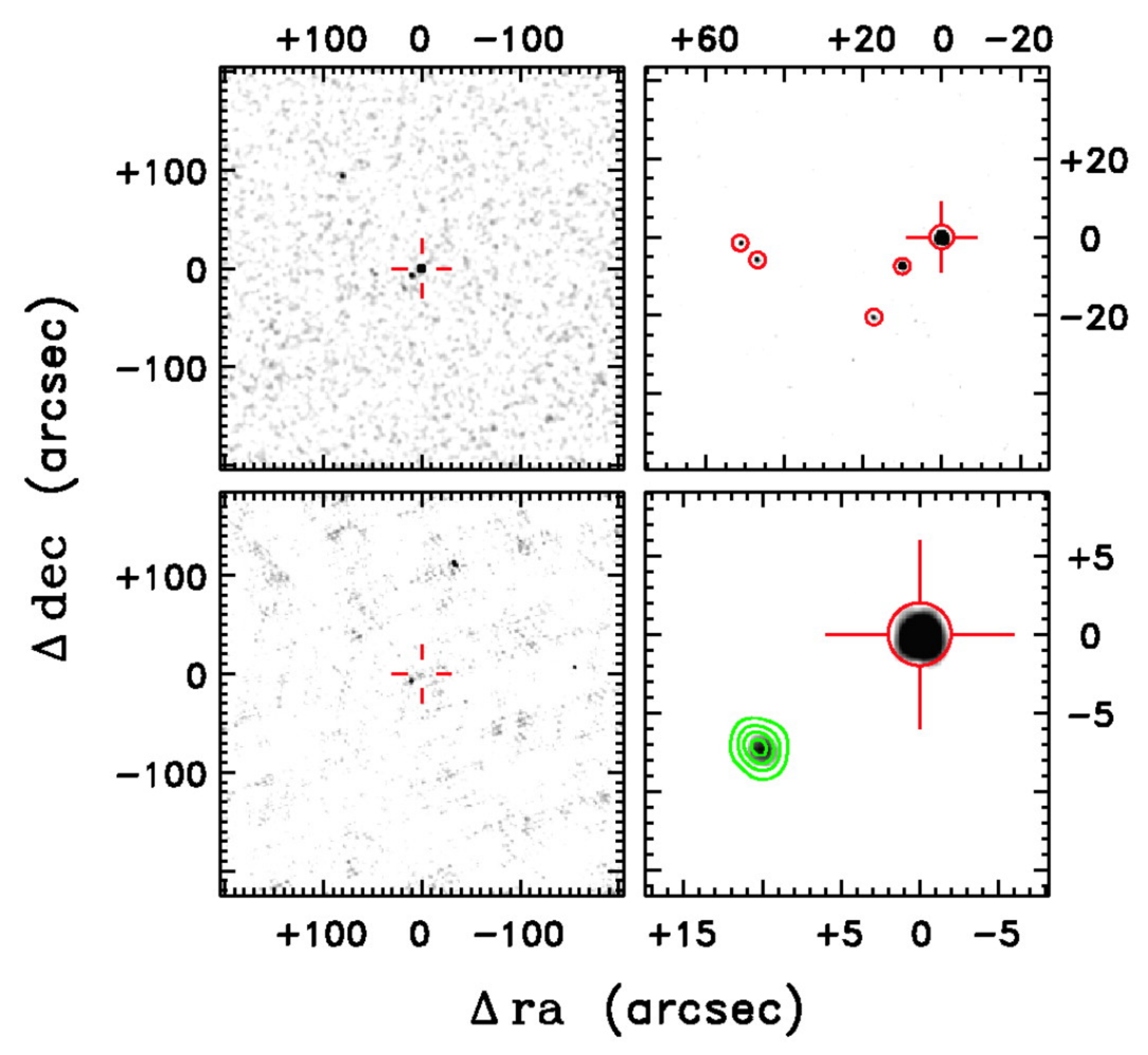
Physics of magnetic reconnection by exploring the much larger range of parameter space available (mass, radius, age, rotation, binary)



SDO/AIA 94 Å filter
Solar corona on Dec. 2, 2019

Cool Stars

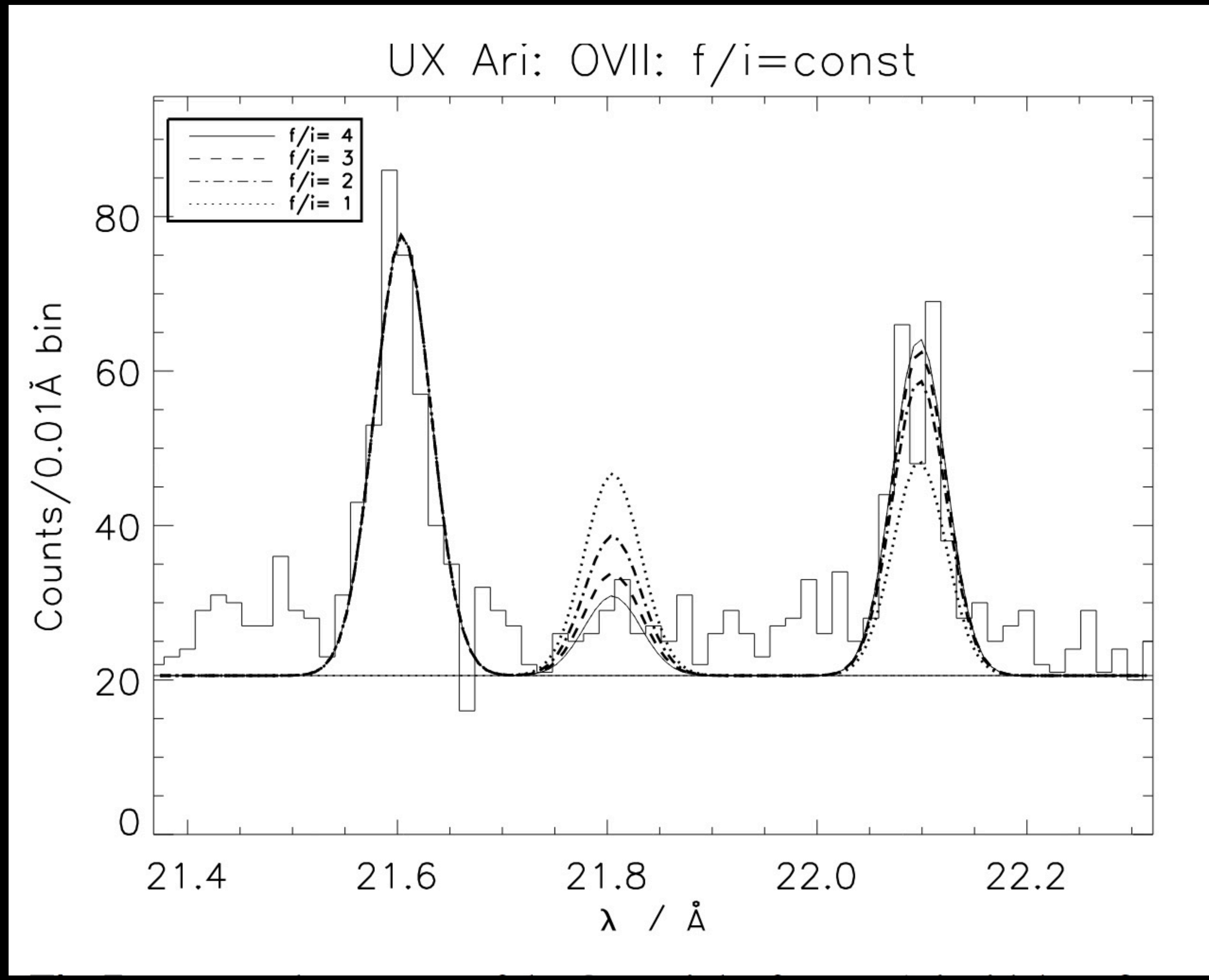
- Which stars produce X-ray emission? Simple answer: stars with an outer convection zone
- Co-existence of coronae and winds? role of unseen companions?
- Atypical joint properties of coronae plus chromospheric lines, plus positional offsets deduced from high spatial resolution HRC observations, point to contaminating cool stars



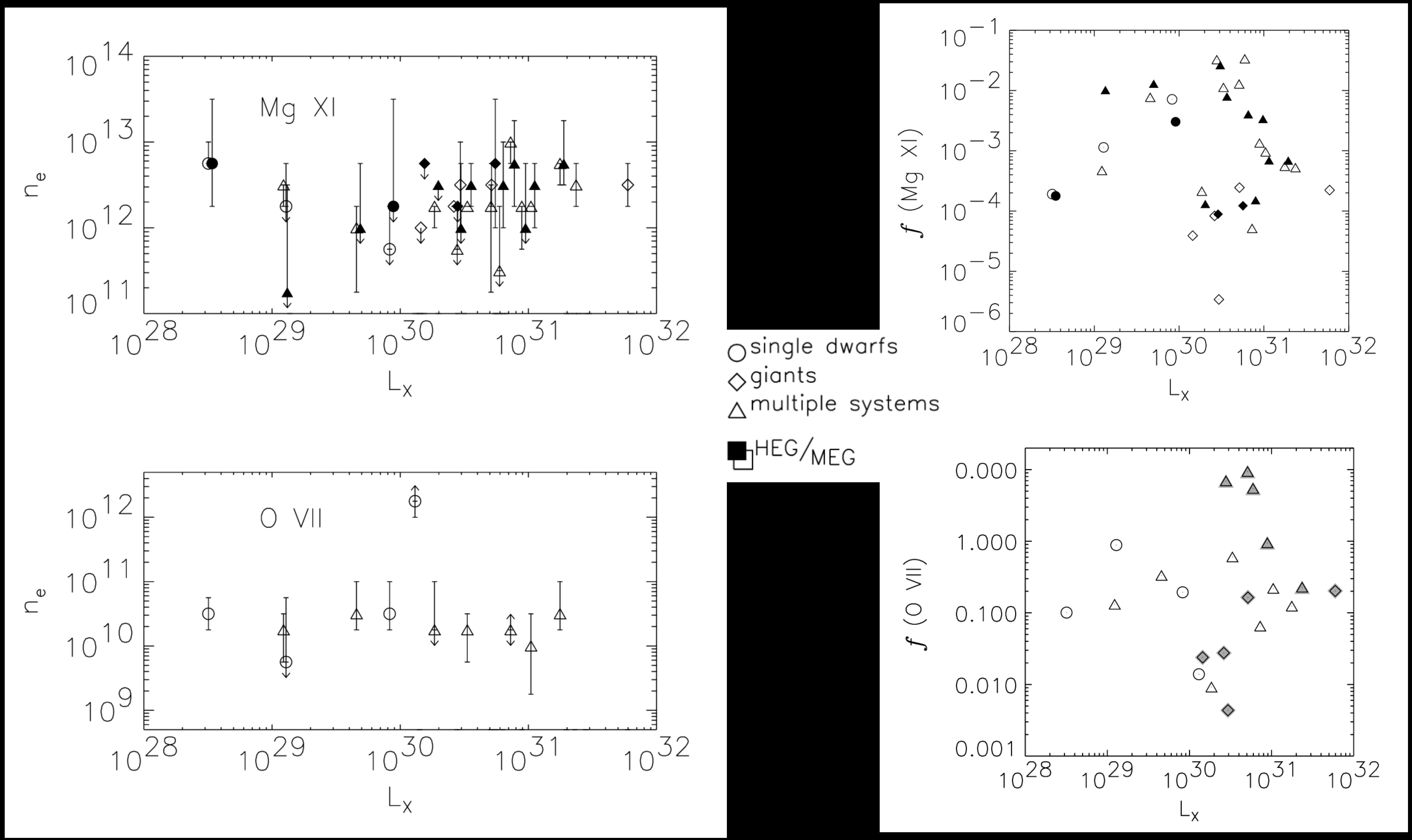
α TrA hybrid star **Ayres et al. (2007)**

Cool Stars

Density constraints enable coronal physics, filling factors



Ness et al. (2002)



Testa et al. (2004)

Cool Stars

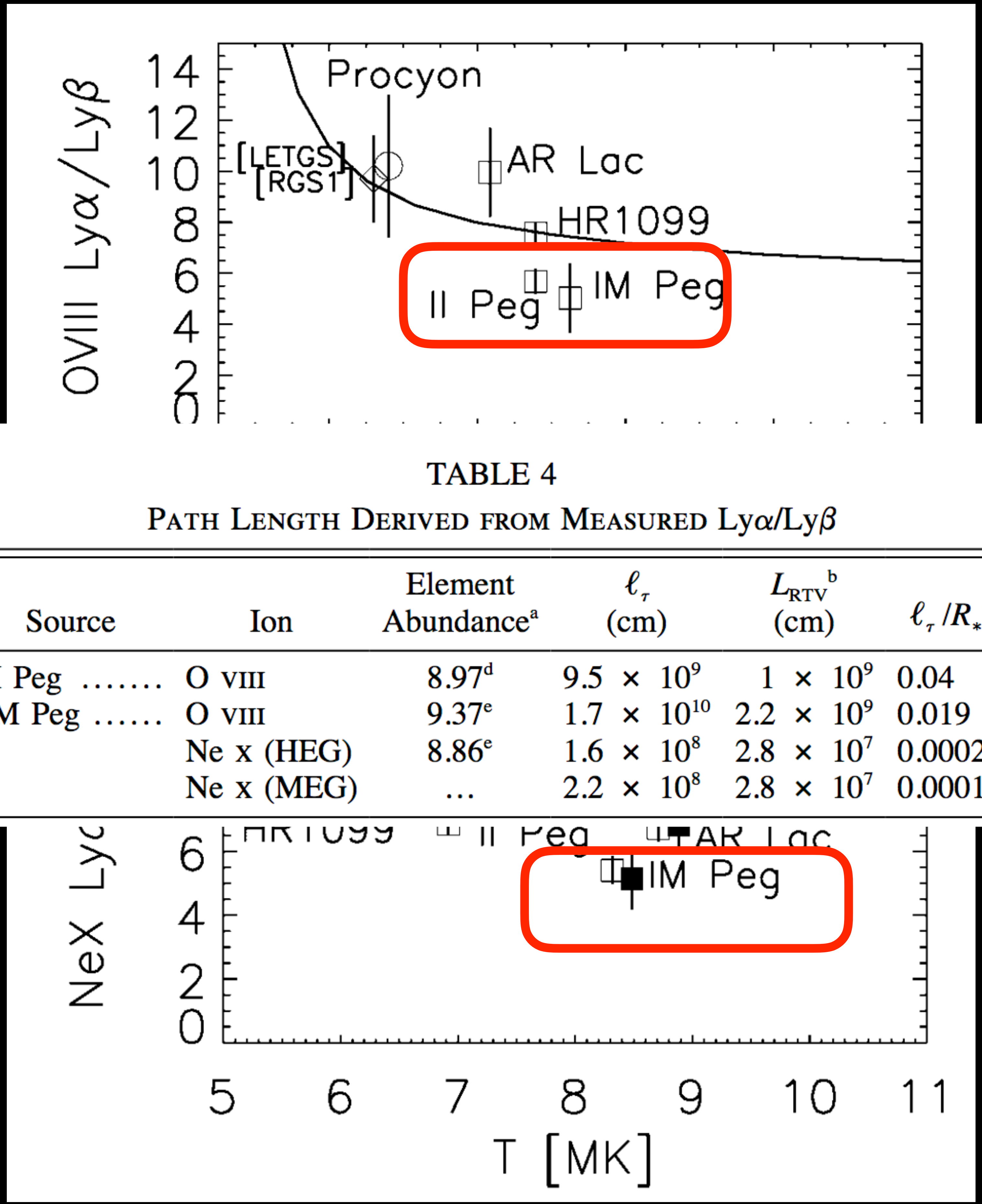


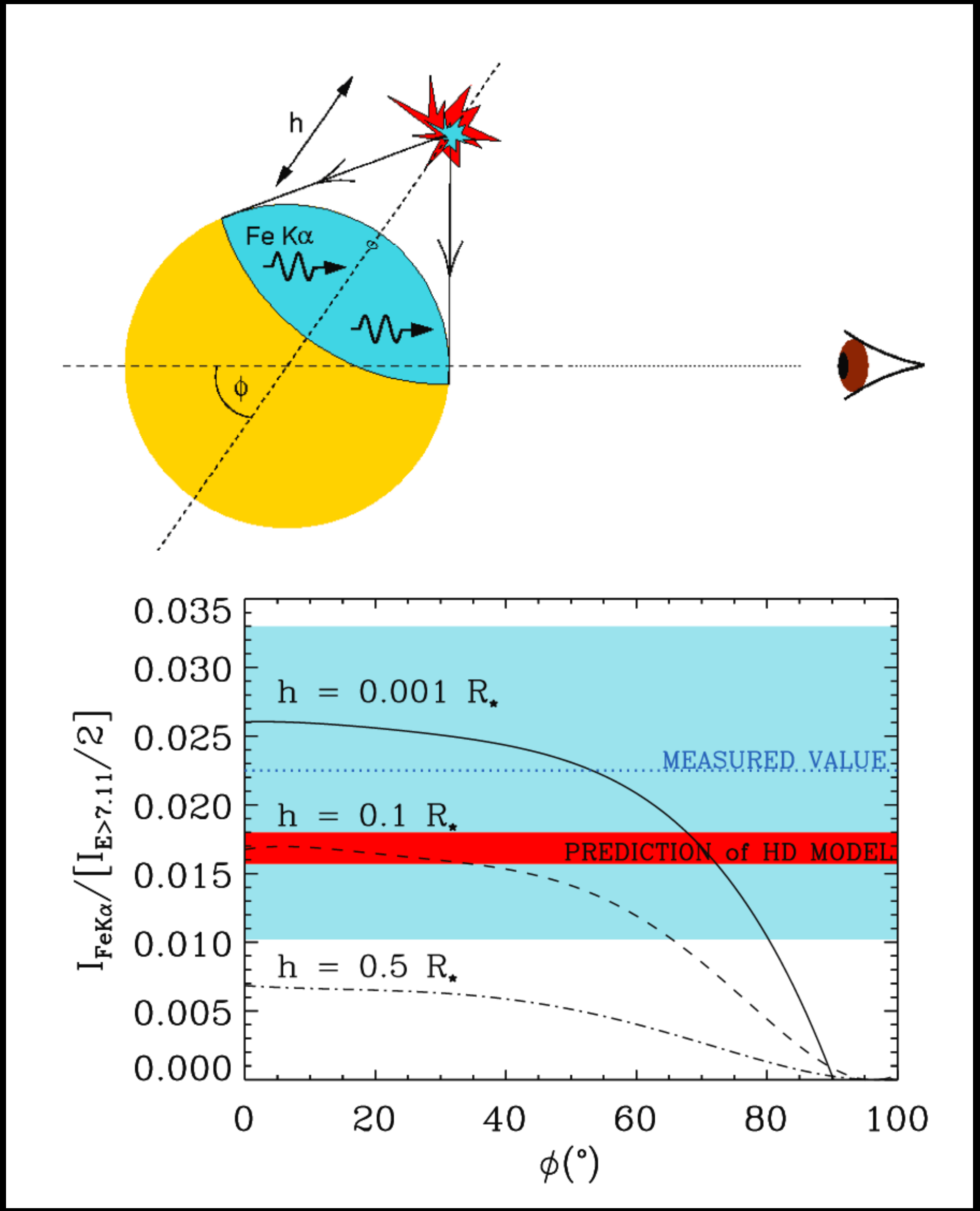
TABLE 4
PATH LENGTH DERIVED FROM MEASURED Lyα/Lyβ

Source	Ion	Element Abundance[a]	ℓ_τ (cm)	L_{RTV}[b] (cm)	ℓ_τ / R_*[c]
II Peg	O VIII	8.97[d]	9.5×10^9	1×10^9	0.04
IM Peg	O VIII	9.37[e]	1.7×10^{10}	2.2×10^9	0.019
	Ne X (HEG)	8.86[e]	1.6×10^8	2.8×10^7	0.0002
	Ne X (MEG)	...	2.2×10^8	2.8×10^7	0.00018

Testa et al. (2004) resonance scattering effects in active binary systems

Sizes of stellar coronae

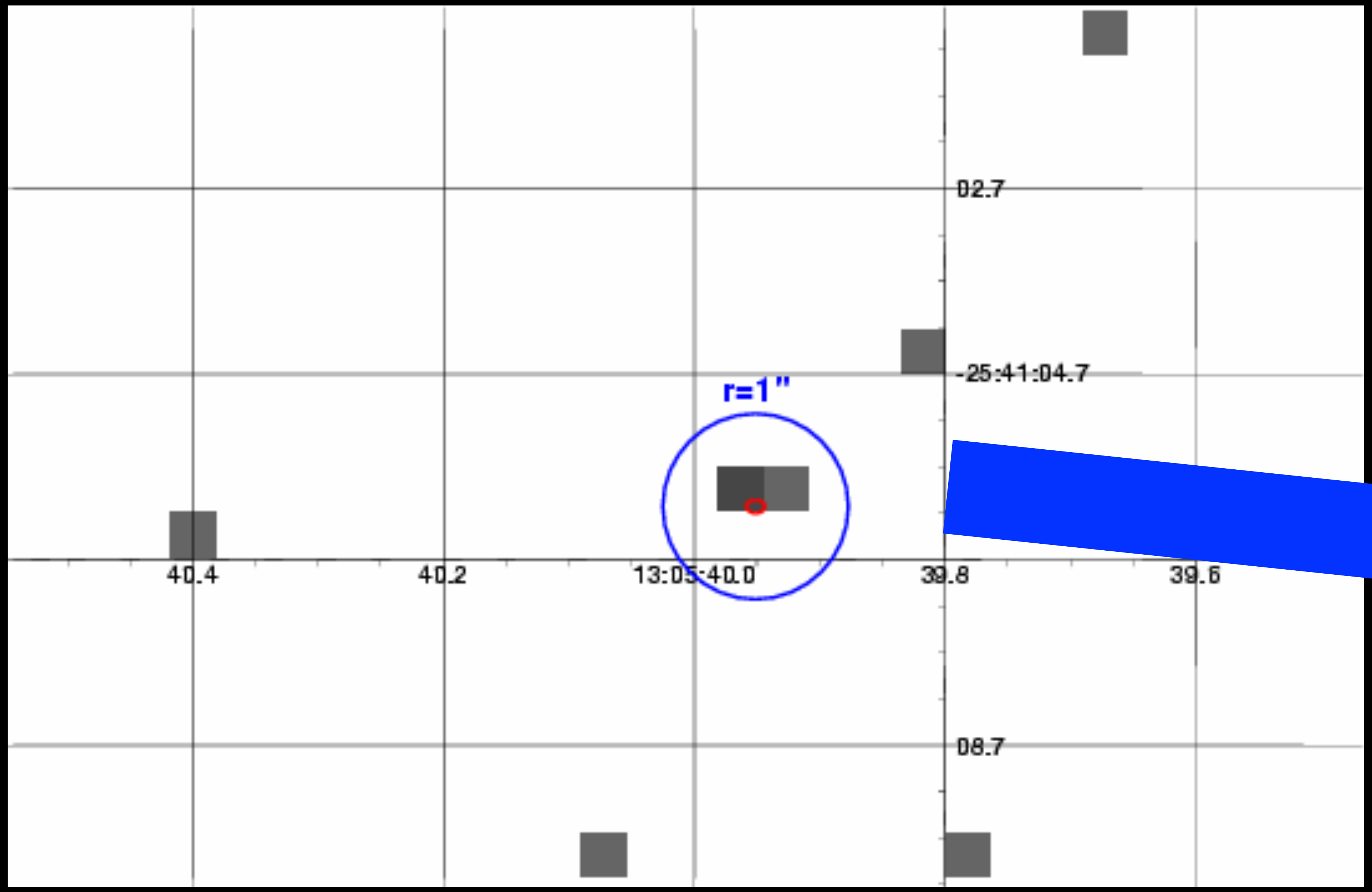
Compact coronae inferred from X-ray optical depths, Fe fluorescent emission & loop modeling of flares



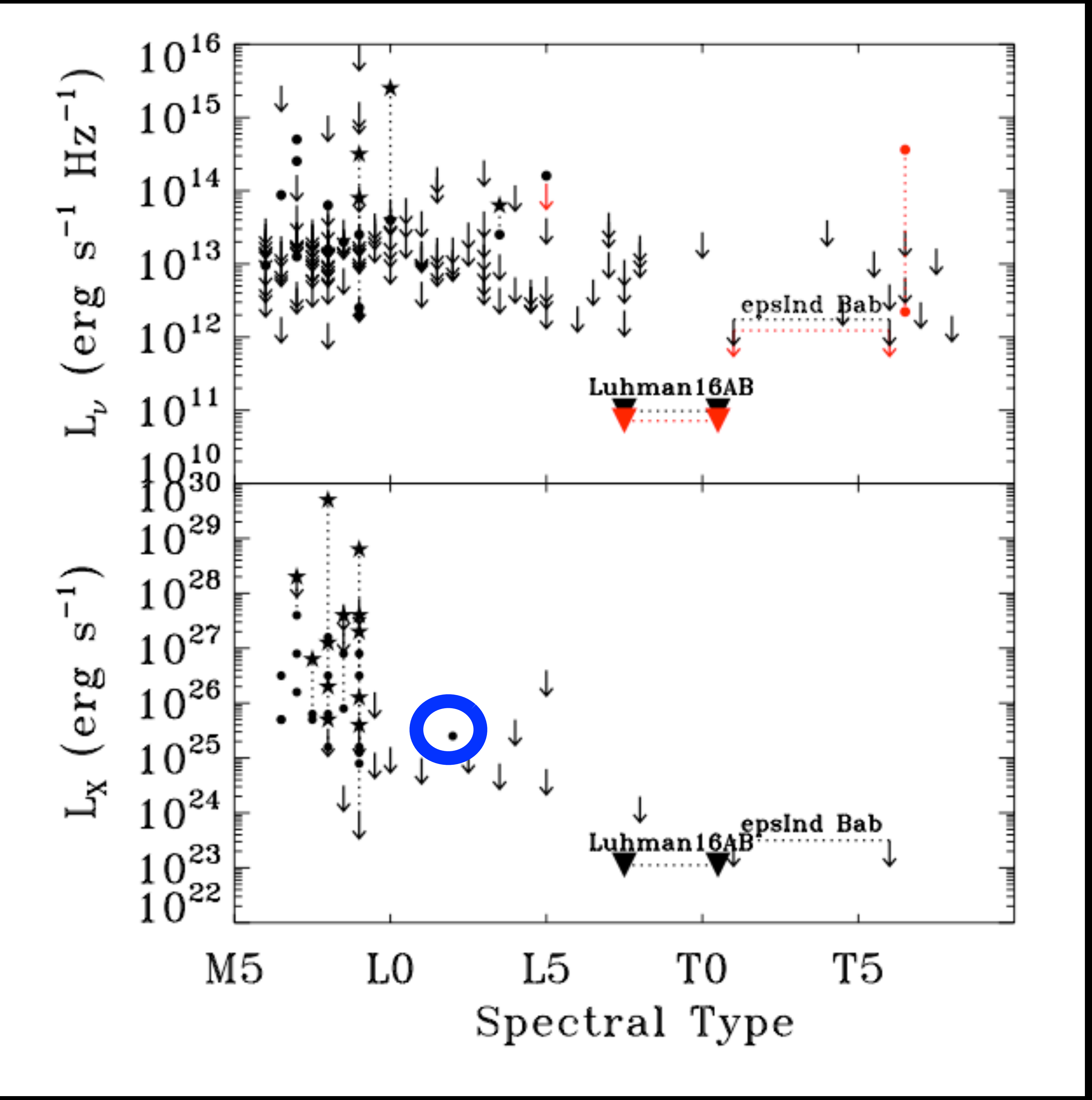
Testa et al. (2007) flare on an evolved star

Cool Stars

coolest stellar types emitting X-rays (Audard et al. 2005)



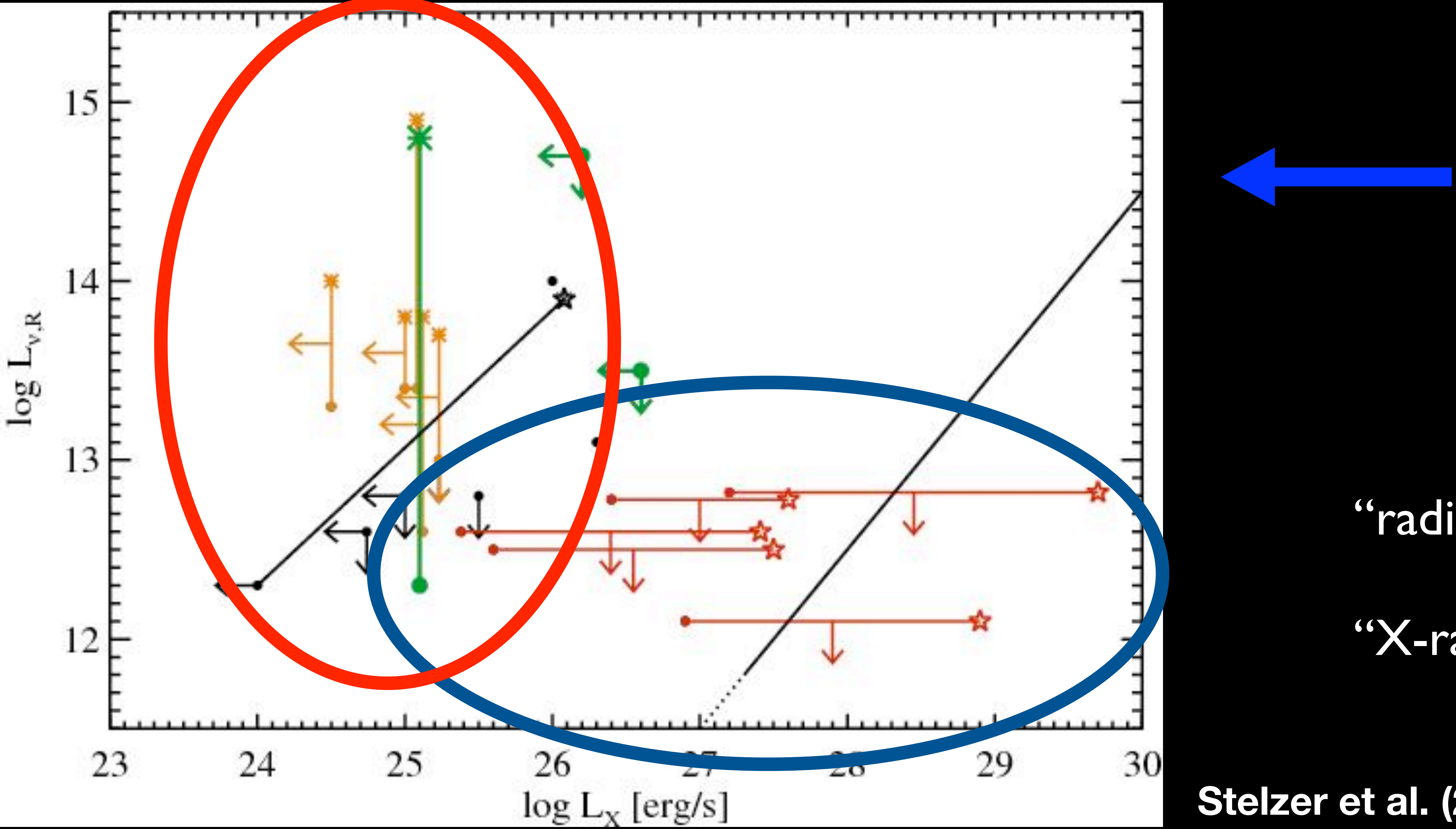
L2+L3 dwarf binary detected
with 4 photons!
Audard et al. (2007)



Osten et al. (2015)

Cool Stars

coolest stellar types emitting X-rays & nature of the dynamo



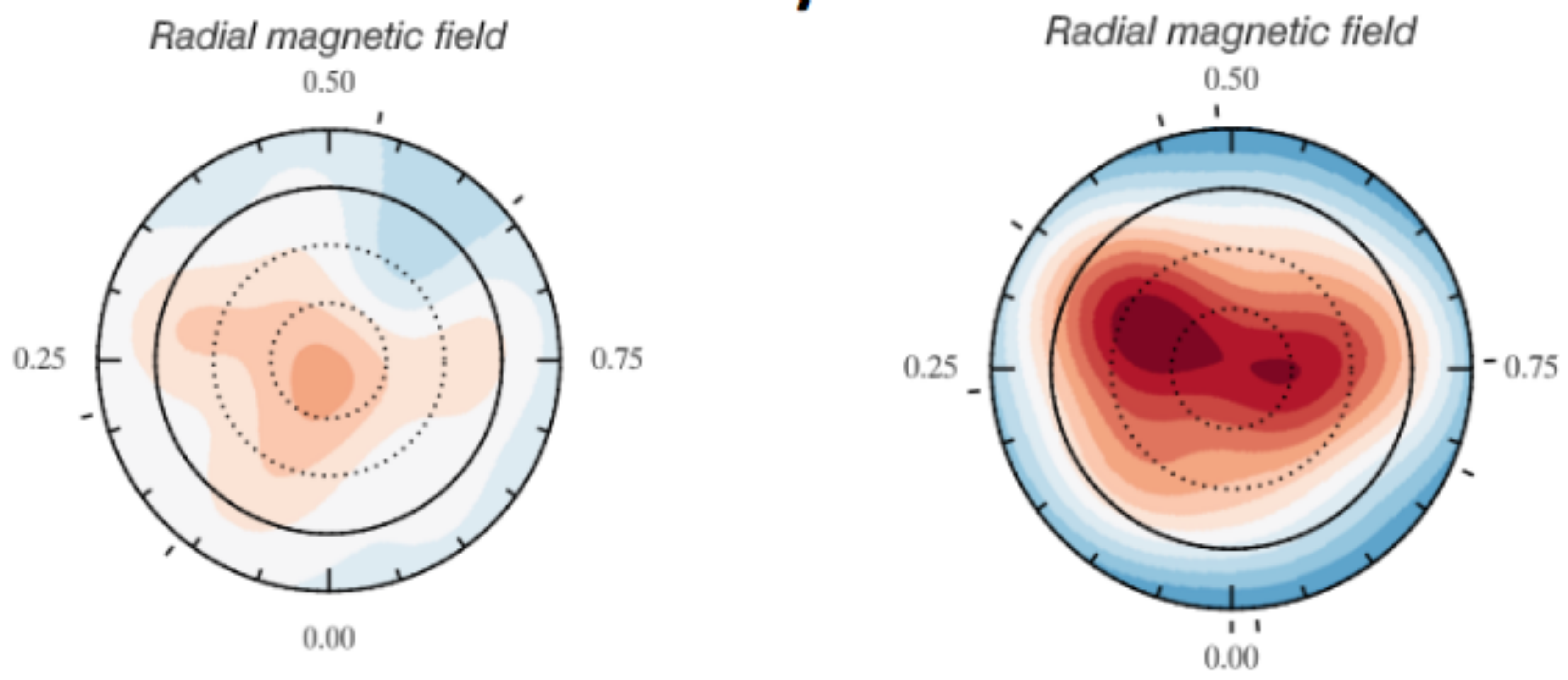
Güdel-Benz relation for solar flares, active stars

"radio-loud/X-ray quiet"
and
"X-ray-loud/radio quiet"

Stelzer et al. (2012)

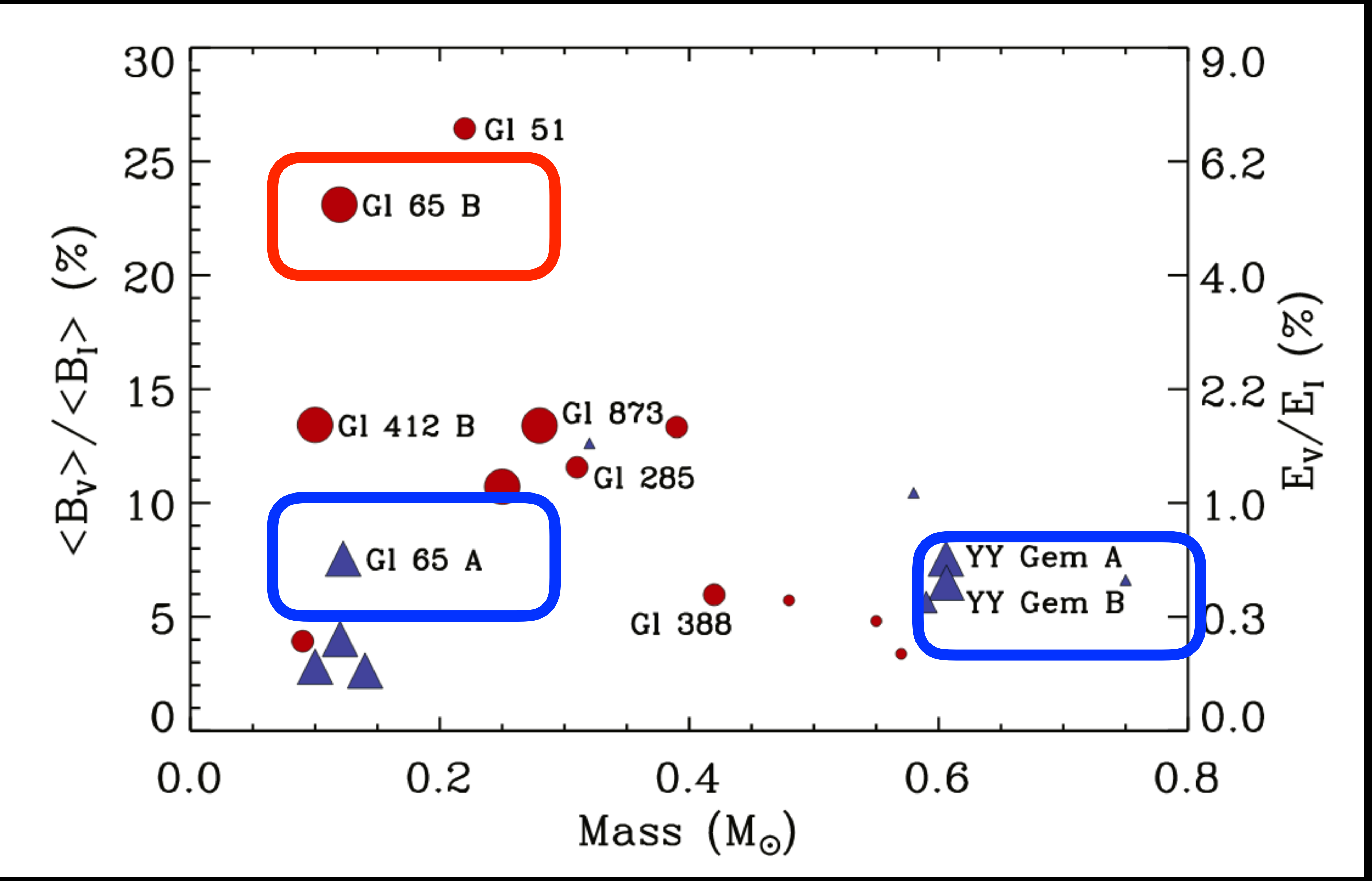
Cool Stars

Stellar twins are not magnetic twins, and this affects X-ray emission



	Gl 65A	Gl 65B
Spectral class	M5.5Ve	M6Ve
Mass	0.1225 $M_\odot$	0.1195 $M_\odot$
Radius	0.165 $R_\odot$	0.159 $R_\odot$
Rot. vsini	28.5 km/s	30.6 km/s
Rot. period	5.86 hr	5.45 hr
Metall. [Fe/H]	-0.03	-0.12
<Bf> Stokes I	**5.2 kG**	**6.7 kG**
B_{dip} strength V	**0.3 kG**	**1.3 kG**
	complex, non-axisymmetric	**axisymmetric dipole**

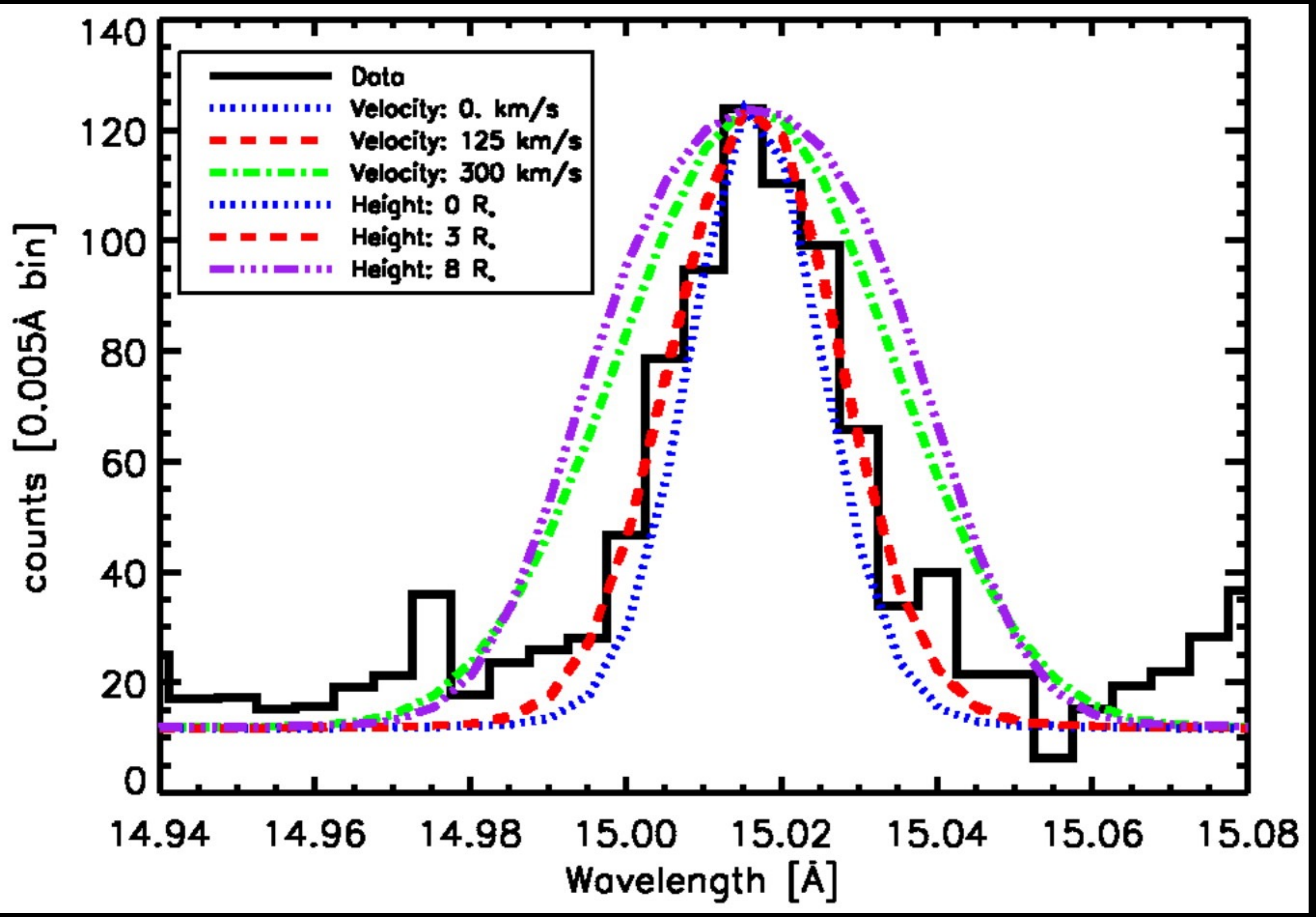
Kervella et al. 2016, Barnes et al. 2016, Kochukhov et al. 2017, Lynch et al. 2017



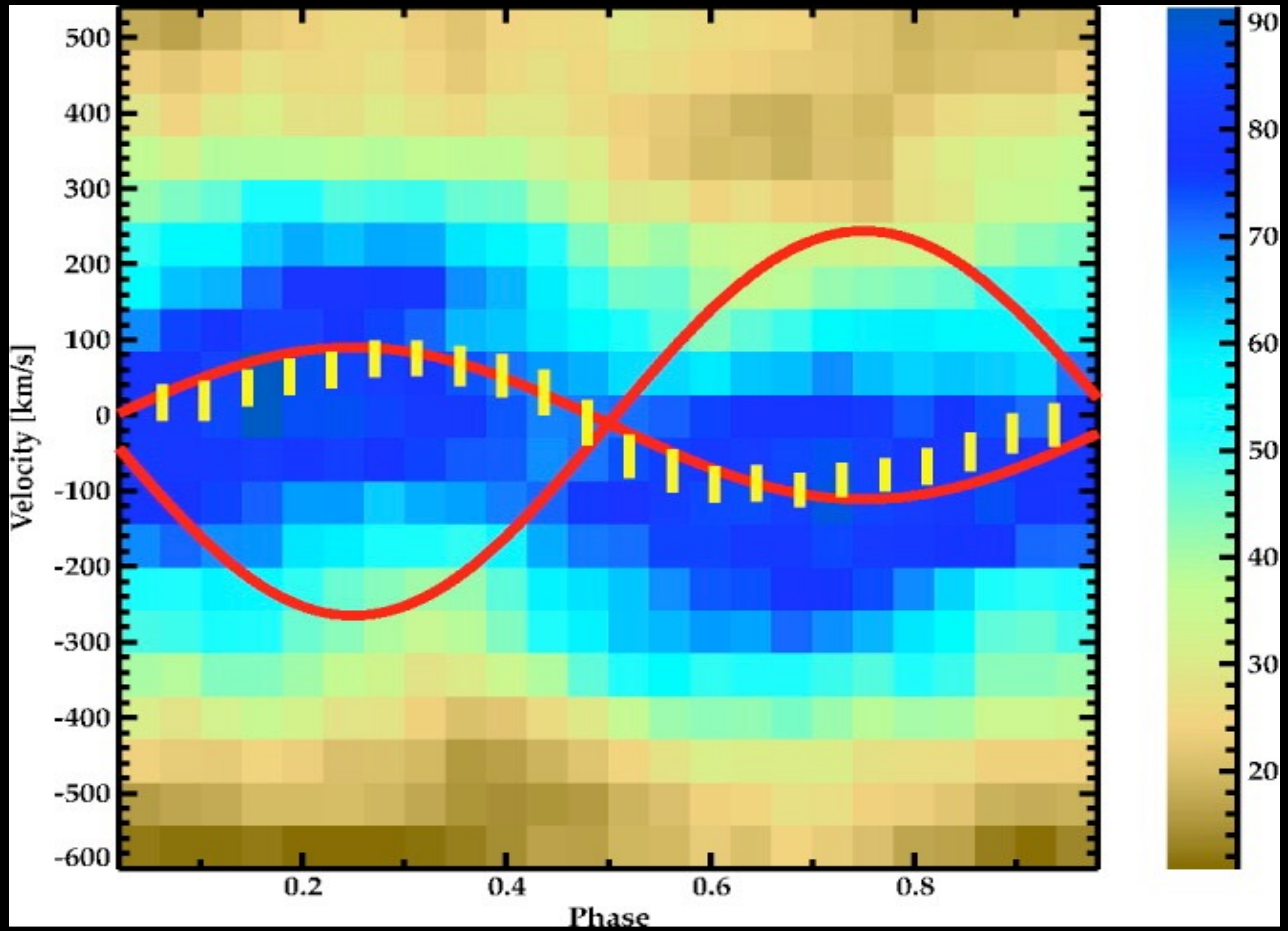
Kochukov & Shulyak (2019)
-nearly identical stars of the YY Gem binary do have similar magnetic topologies, along with Lx
-while the two components of Gl 65 do not

Cool Stars

spatial structuring of stellar coronae



Chung et al. (2004)
excess broadening of Algol interpreted as rotational broadening from a radially extended corona



VW Cep; Huenemoerder et al. 2006

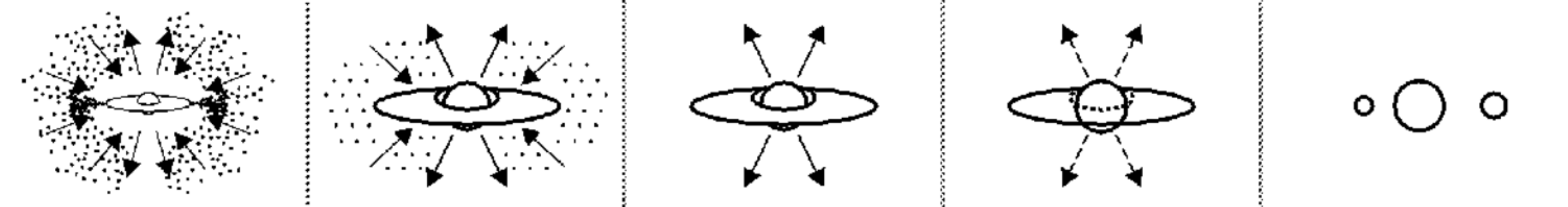
X-ray emission follows the more massive star in the contact binary

compact corona occurs at the pole of the primary

Young Stars/Protostars

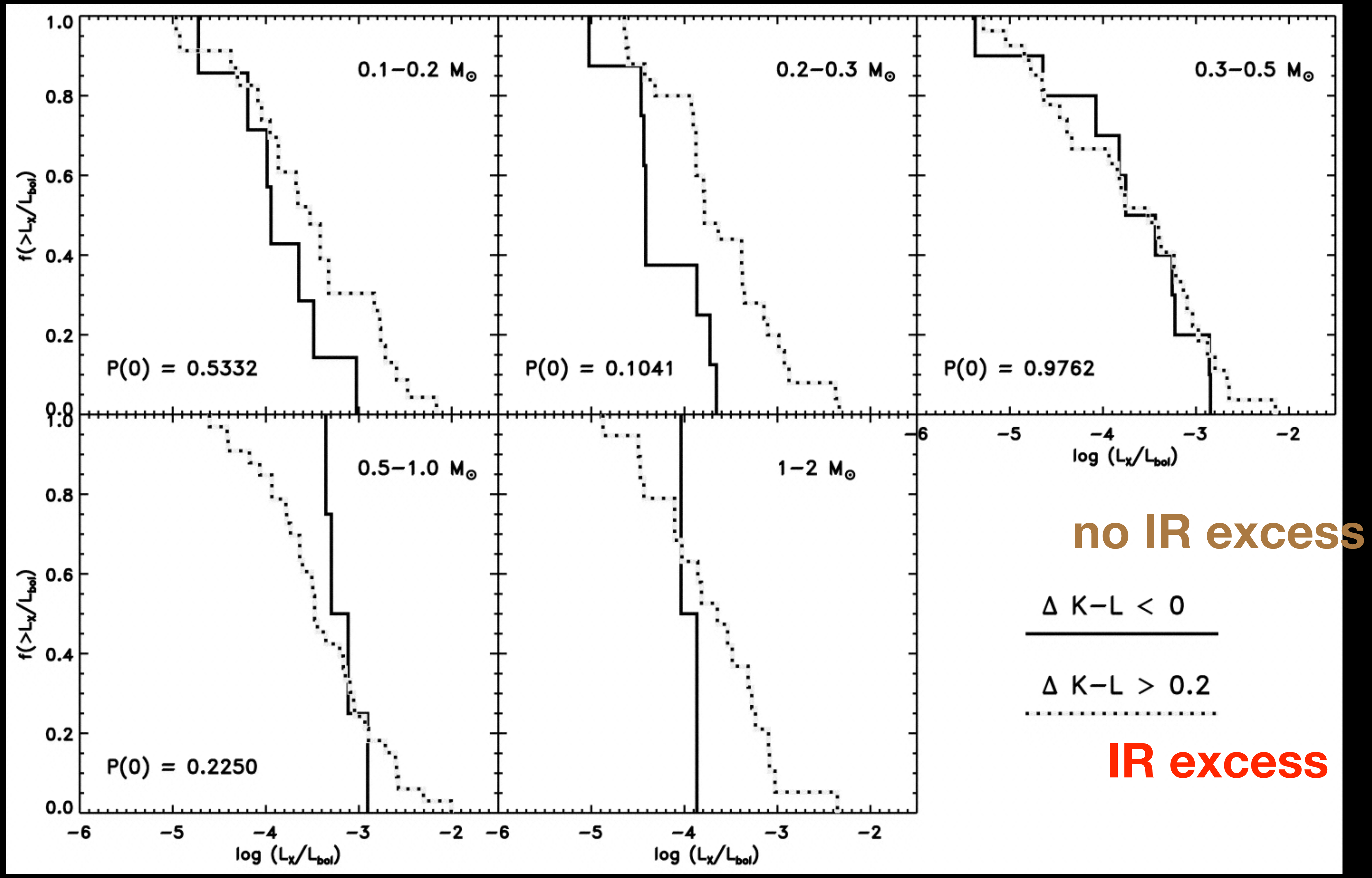
star formation as one of the outstanding problems in astrophysics. . . planet formation a (related) close second

Young Stars/Protostars

Properties	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
Sketch					
Age (years)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/Infrared Class	Class 0	Class I	Class II	Class III	(Class III)
Disk	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-ray	?	Yes	Strong	Strong	Weak
Thermal Radio	Yes	Yes	Yes	No	No
Non-Thermal Radio	No	Yes	No ?	Yes	Yes

canonical figure from Feigelson & Montmerle (1999)

Young Stars/Protostars



Preibisch et al. (2005)

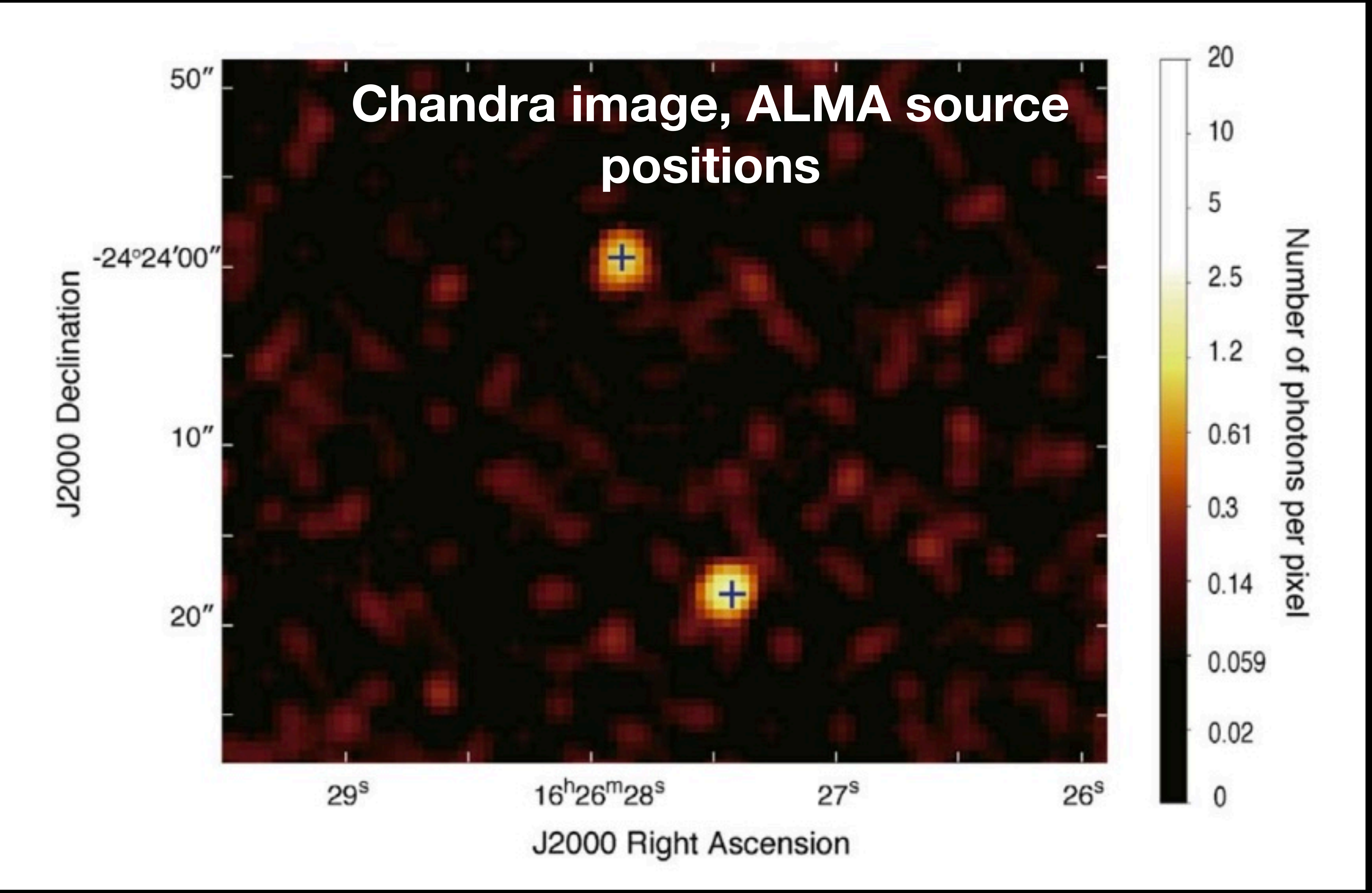
- IR excess criteria for selecting pre-main sequence stars misses those without disks.
- There is no X-ray quiet population of pre-main sequence stars; Chandra observations of the Orion Nebula Cluster detected 98.5% of the PMS stars known from optical and IR studies (Preibisch & Feigelson2005).

Young Stars/Protostars

class 0 sources of X-rays?

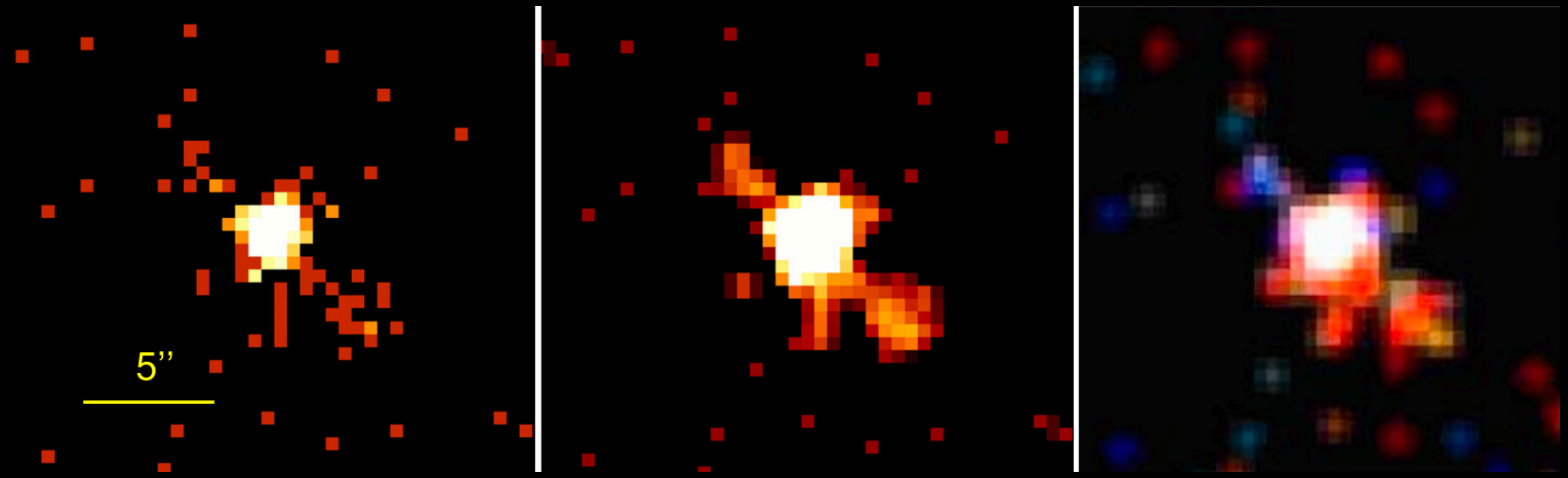
- Romine et al. (2016) 1109 candidate protostars in 14 star forming regions, using conservative selection criteria: IR excess emission, median X-ray energy >4.5 keV

- Kawabe et al. (2018) presents evidence for bona fide protostars or proton-brown dwarfs in extremely early evolutionary stages, based on (i) faint X-ray source, (ii) CO outflows, (iii) mass 0.01-0.3 M_{sun}, SEDs like those of first hydrostatic cores



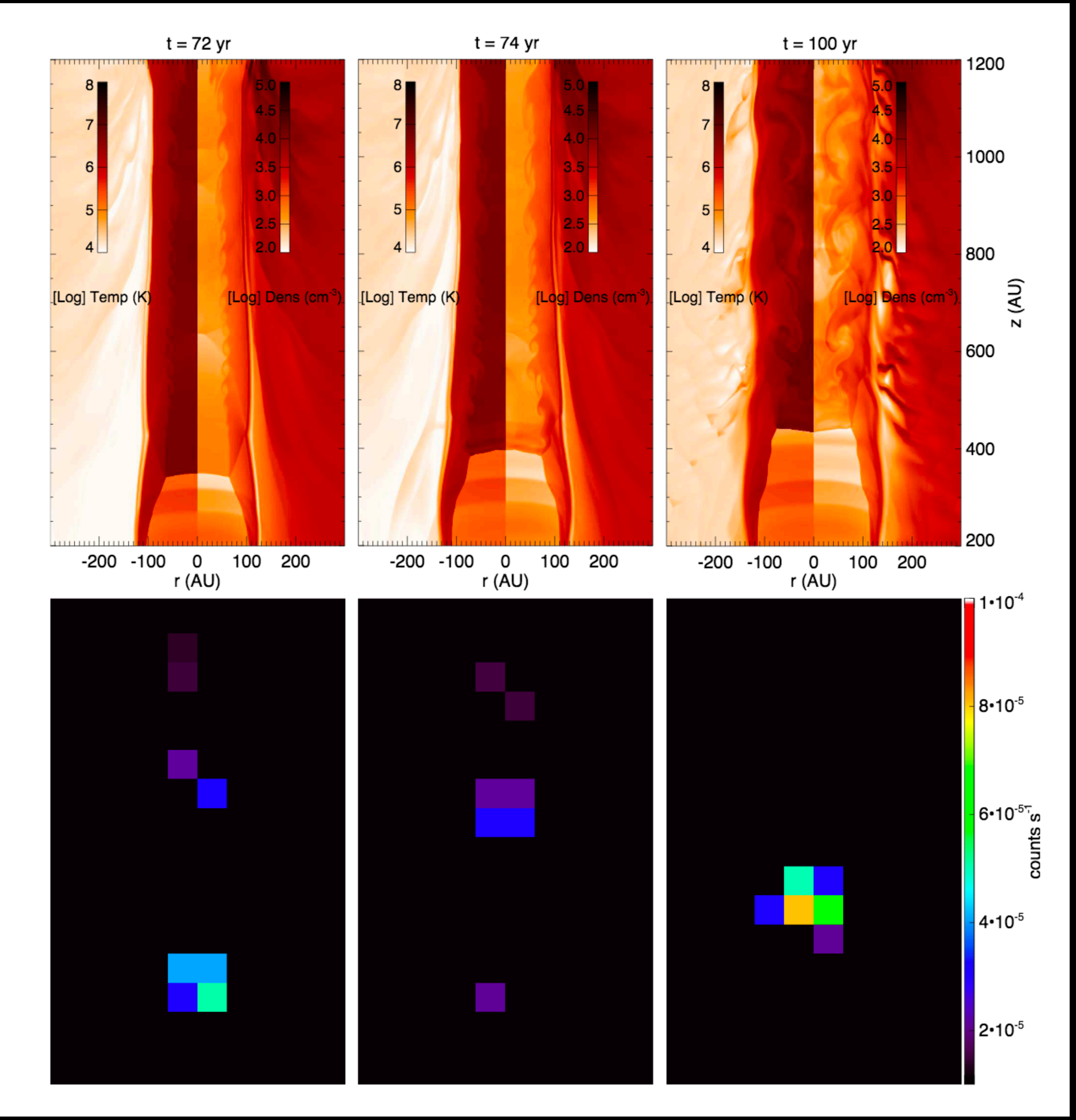
Kawabe et al. (2018)

Young Stars/Protostars



Gudel et al. (2008)

- X-rays from DG Tau jet detected out to 5” from the star
- Pressure in the hot gas contributes to expansion, magnetic field collimates jet

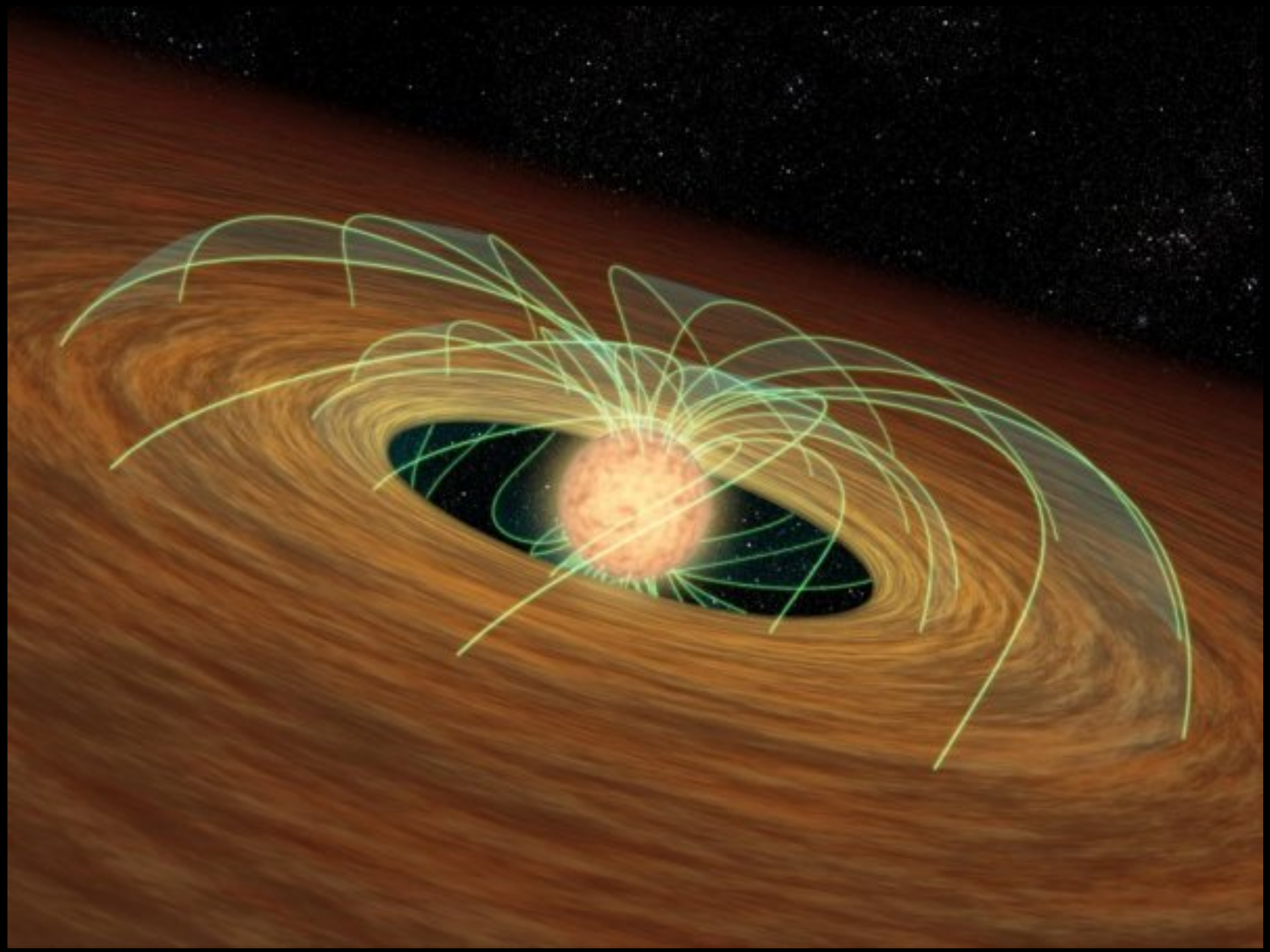


Ustamujic et al. (2018) quasi-stationary shock at jet base plus perturbations

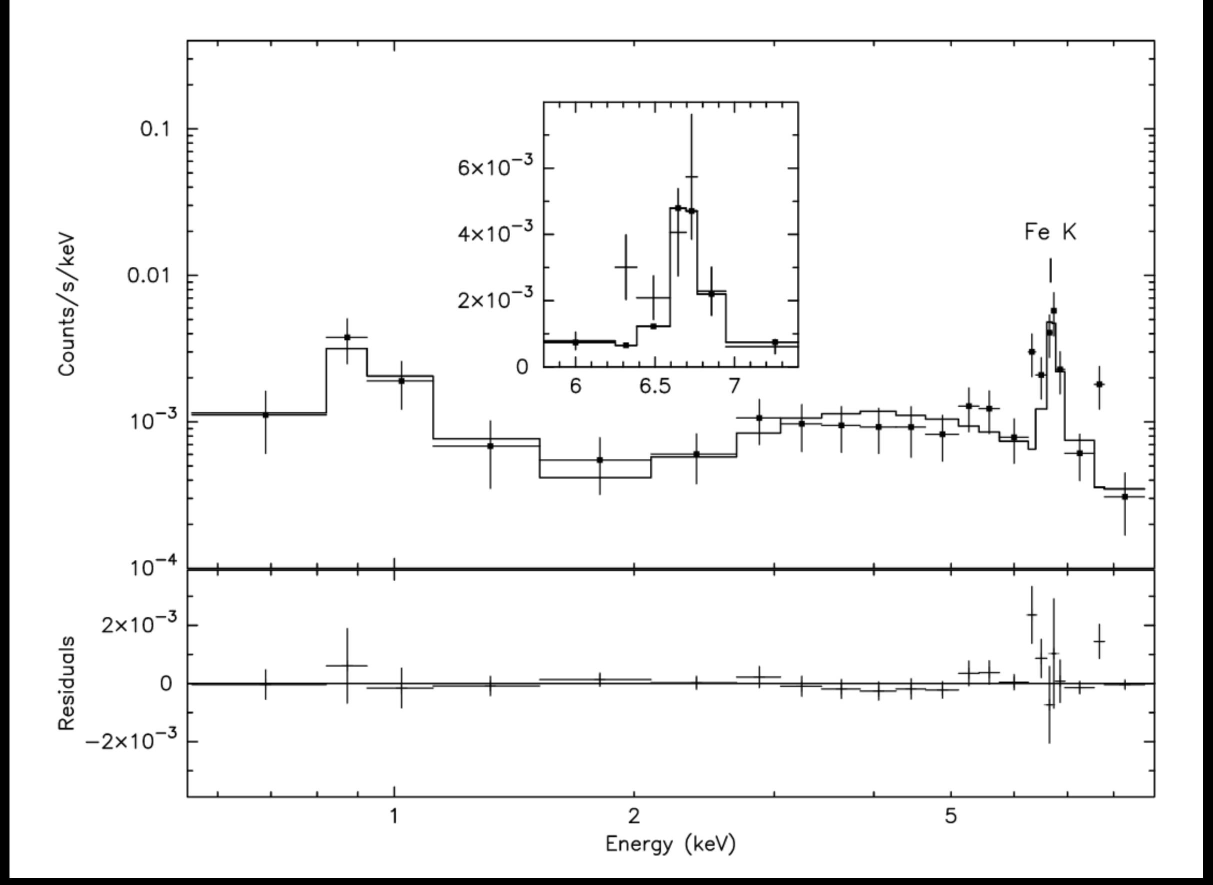
note timescale — topic for Chandra’s 30th fête?

Young Stars/Protostars

- range of accretion events from pre-main sequence stars: periodic, sporadic or bursty
- FU Or outbursts $\dot{M}_{acc}$ up to 10^{-4} M_{sun}/yr lasting decades, 5-6 magnitude brightness increase
- EX Or outbursts are shorter, repetitive, with lower peak $\dot{M}_{acc}$



Young Stars/Protostars

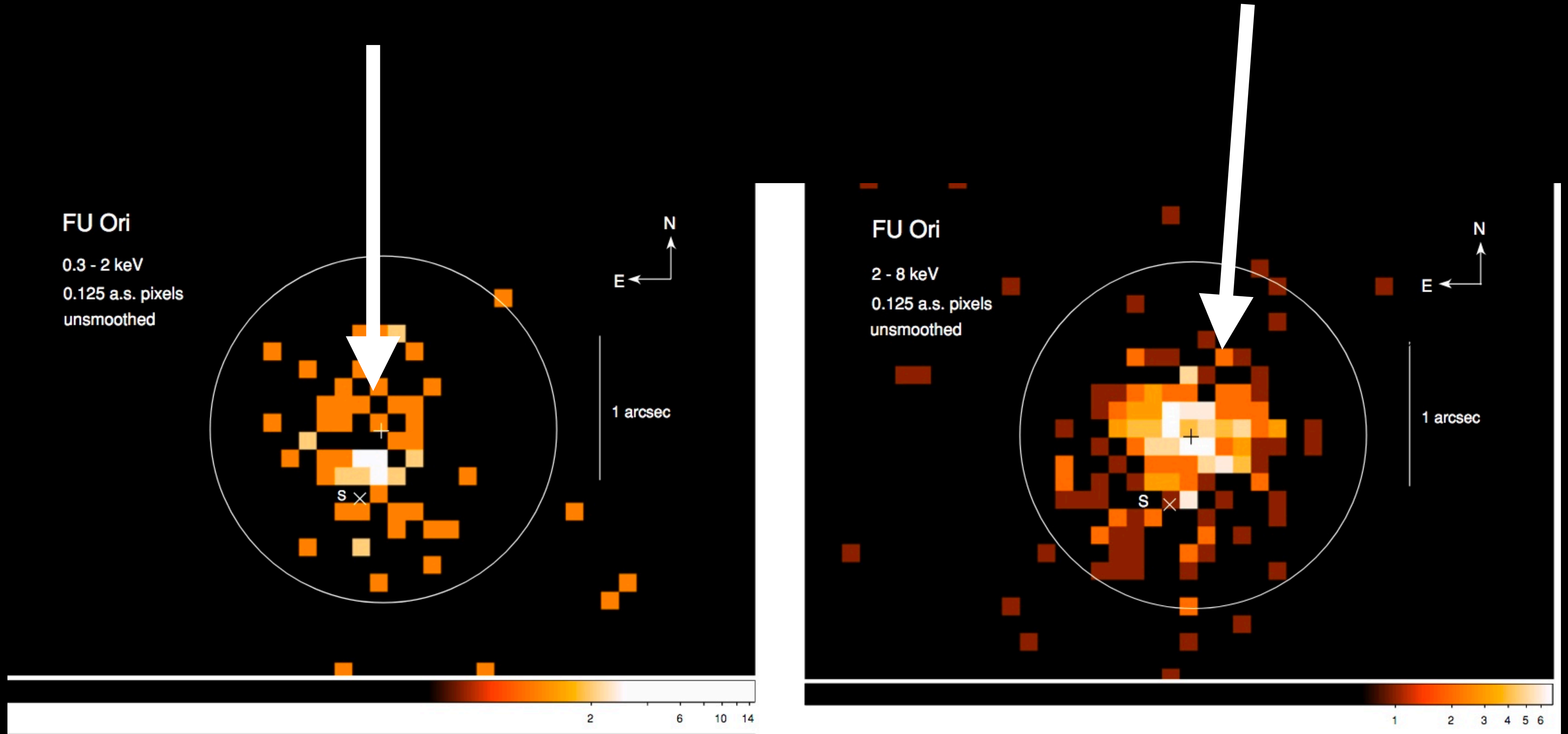


Skinner et al. (2006) XMM-Newton spectrum of FU Or showing double absorption components

excess absorption from accreting gas, powerful wind, or both?

cooler gas is offset

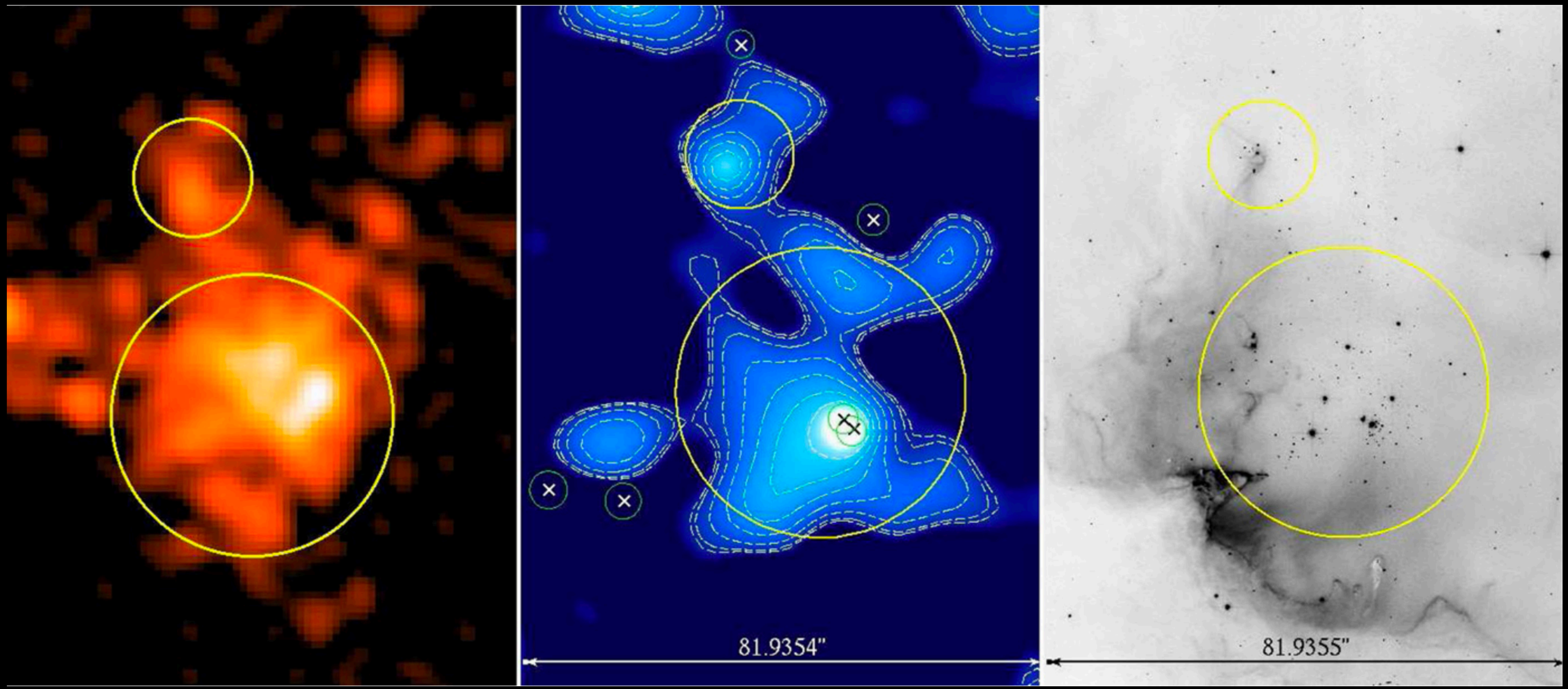
high T gas coincident with FU Or



Skinner et al. 2010 high resolution image explains multi-component spectrum of FU Or

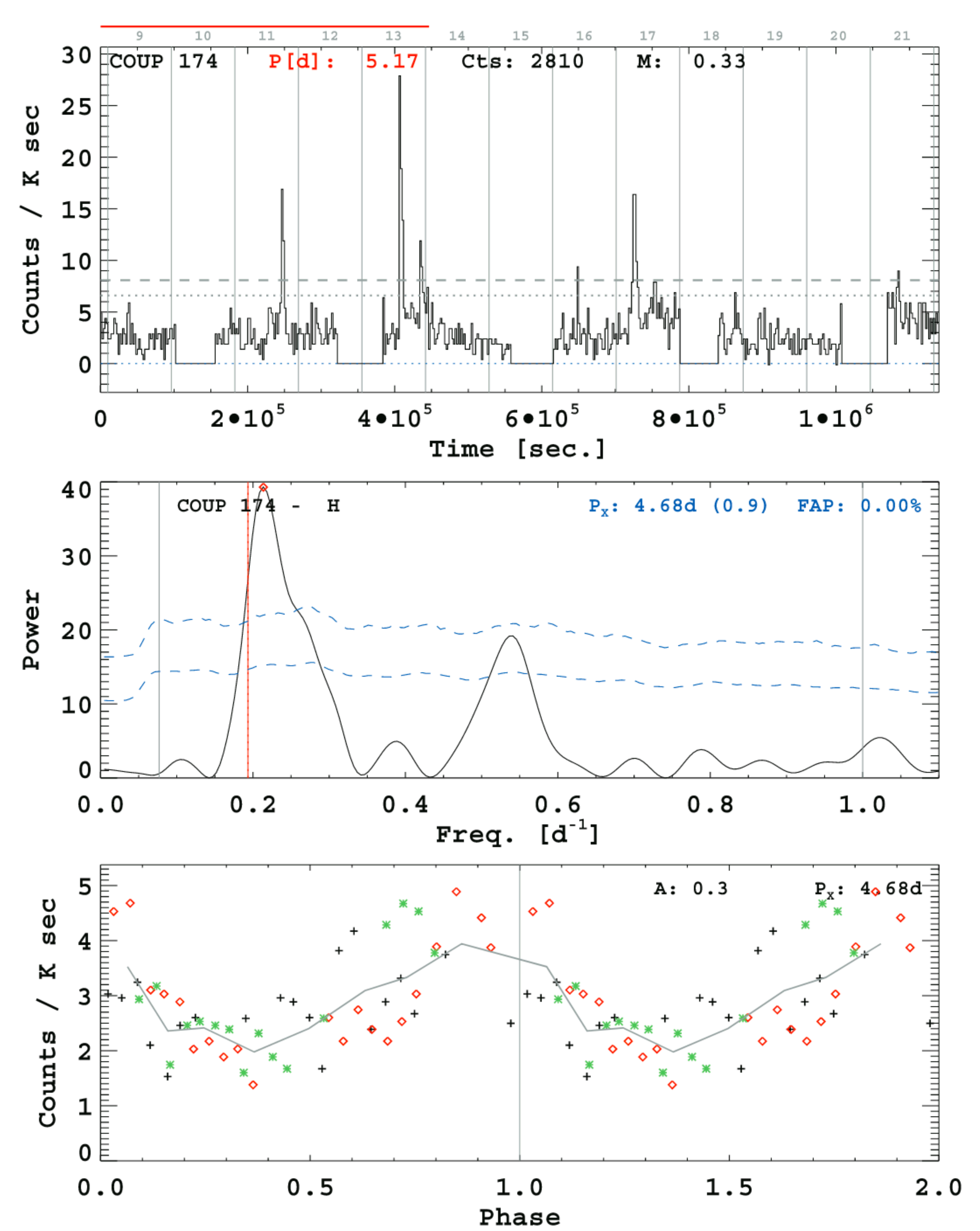
Young Stars/Protostars

Oskinova et al. (2013)
(left) stellar density map of low-mass PMS stars
(middle) Smoothed Chandra image, with two point sources
(right) HST/ACS F658N comparison



- Discovery of X-ray emission from PMS stars and YSOs outside the Milky Way
- Spectral shape of the extended X-ray emission from the sub-clusters agrees well with global X-ray properties of low-mass population of Orion Nebula Cluster
- Inference that accretion and dynamo processes in low-mass stars of the SMC are similar to those in the Galaxy

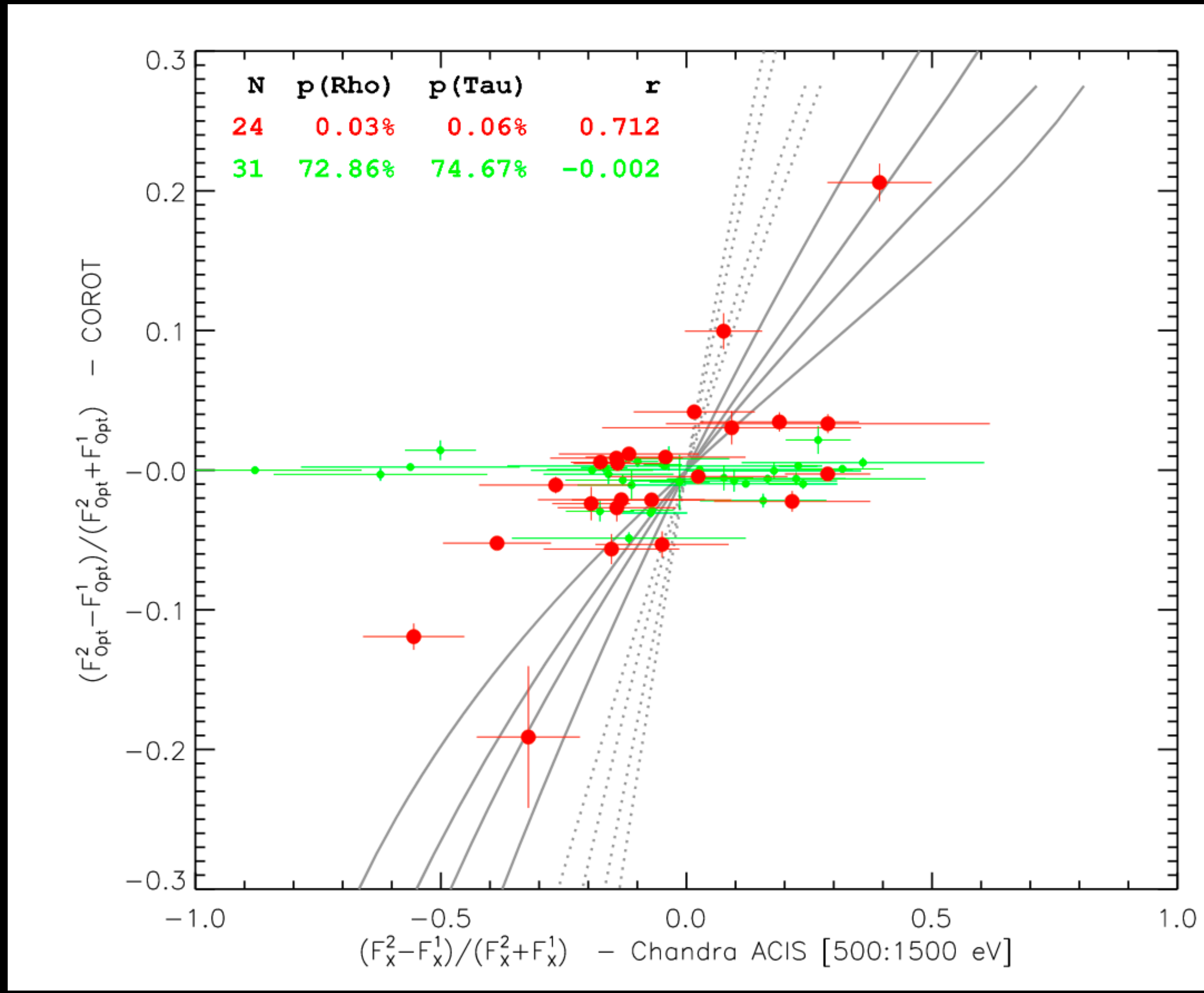
Young Stars/Protostars



Flaccomio et al. (2005) X-ray periods at level of, or half the optical period

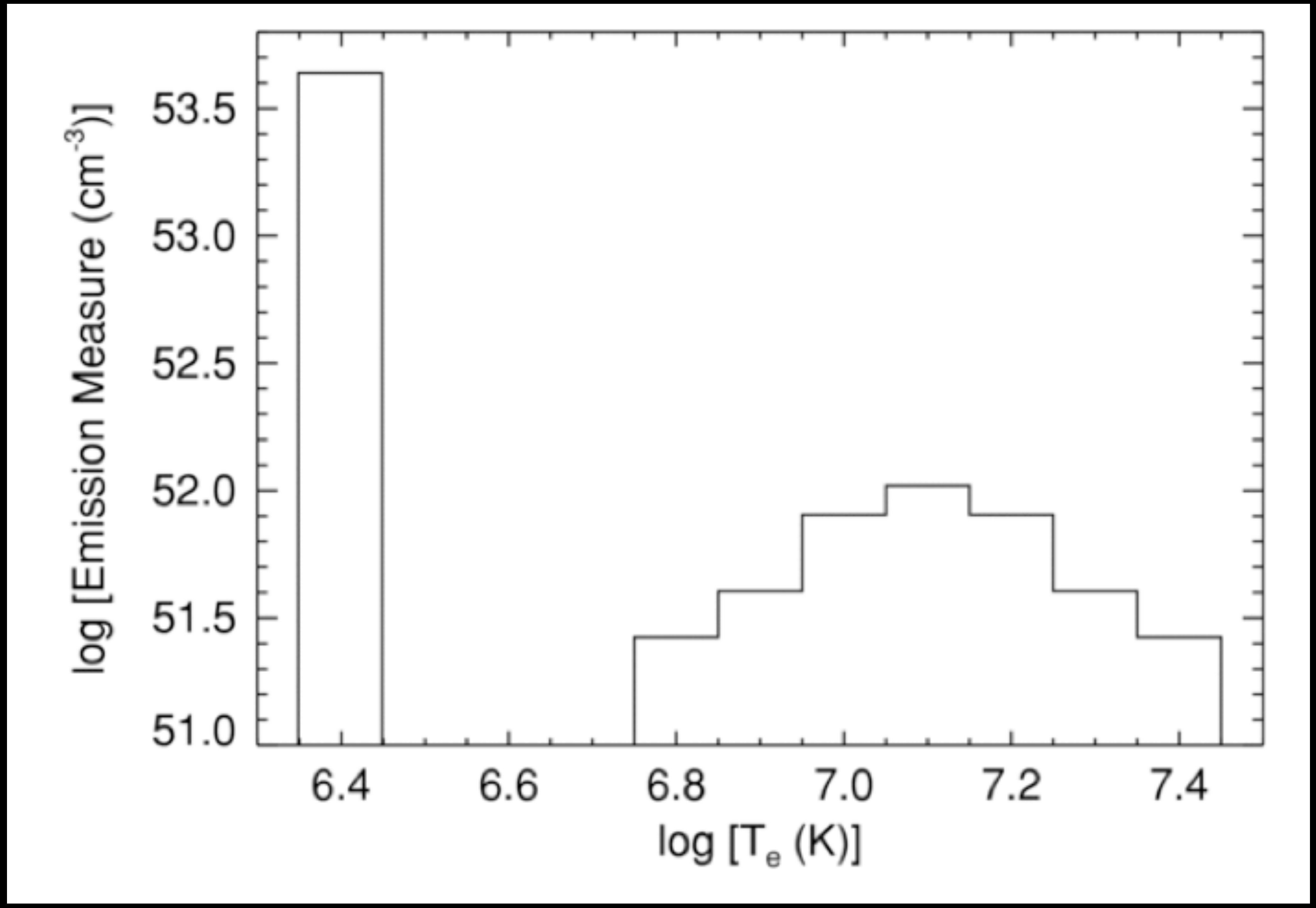
Rotational modulation of X-ray emission

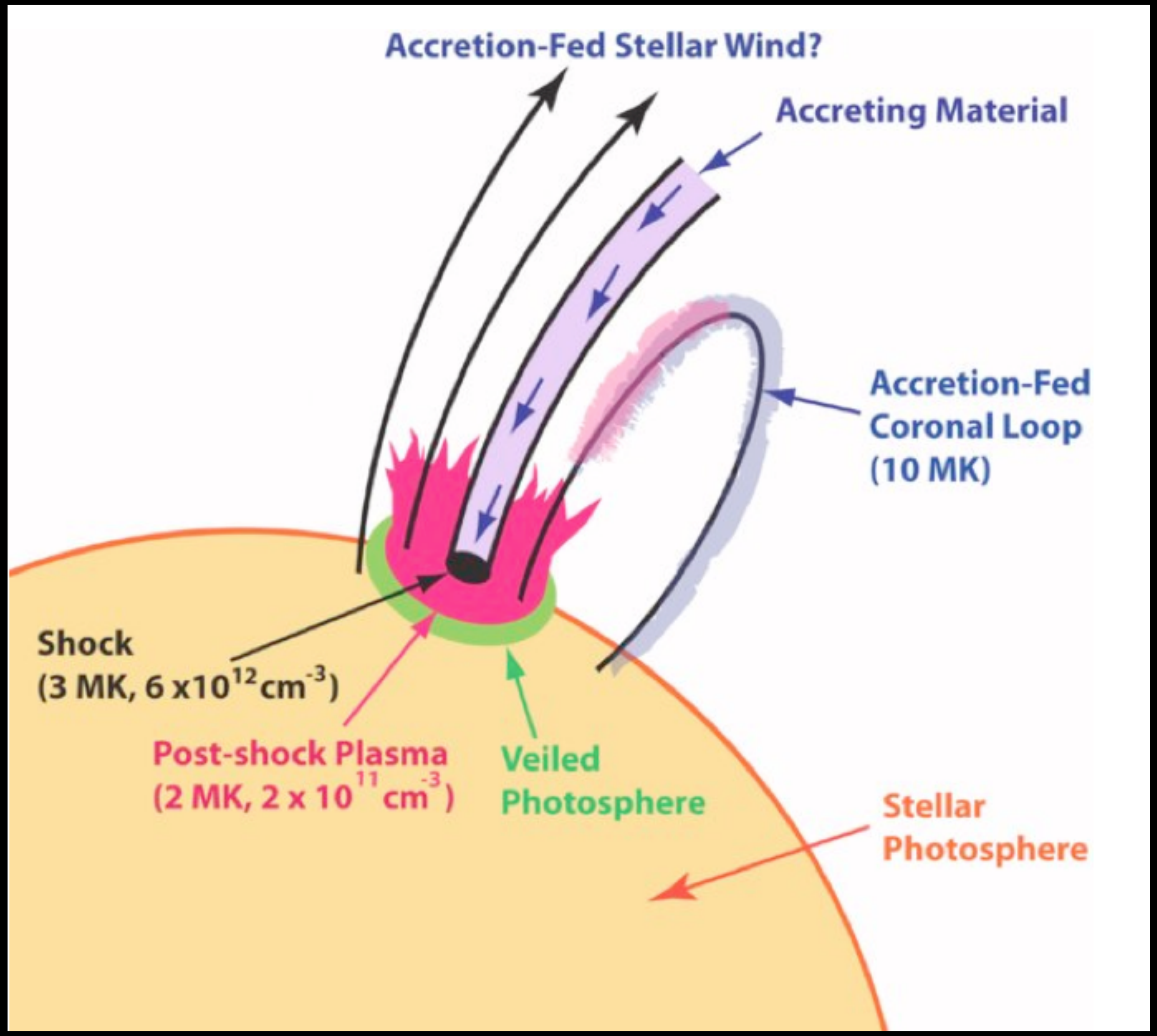
- Accretion impact on coronal plasmas?
- Flaring loops that connect star to the disk



Flaccomio et al. (2010) correlated optical-soft X-ray variability seen only for classical T Tauri stars

Young Stars/Protostars





Brickhouse et al. (2010)

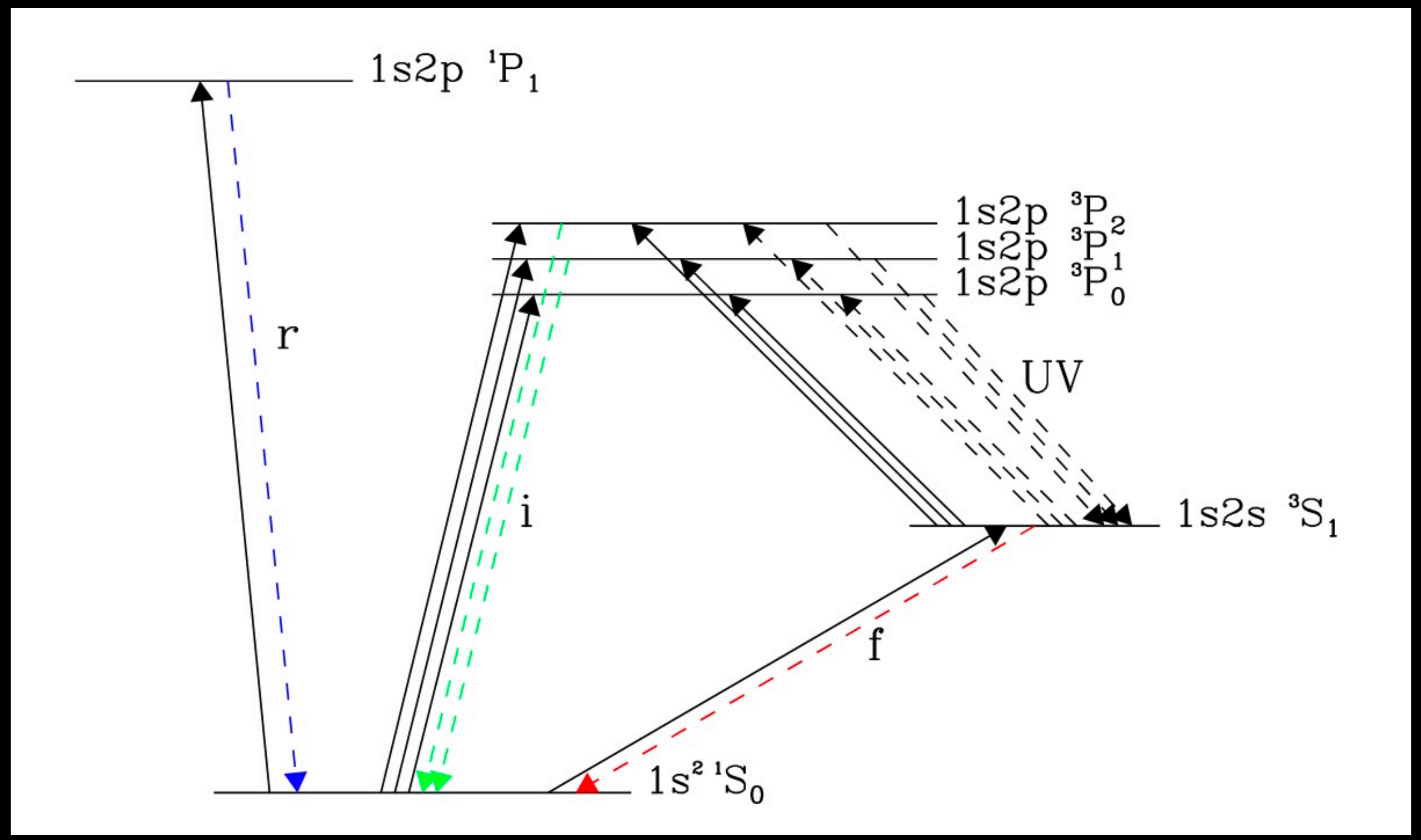
The impact of a high quality X-ray spectrum: need more than accretion source + coronal source to explain all the miriad diagnostics (electron density, electron temperature, absorbing column)

Hot Stars

- Critical agents in galactic evolution
  - Radiative input into surrounding star forming region
  - Kinetic energy input in form of massive winds
  - Supernovae explosions
- Pre-Chandra: knew that most O and B stars were X-ray sources, $L_x \sim 10^{-7} L_{bol}$; several models for X-ray emission, including shock models and coronae
  - "a widely held belief at the end of the 1990s. . .that theory and observations largely agree and that only a few items remain to be clarified before hot star winds can be regarded as 'understood'" (review by Puls, Vink & Najarro 2008)
- Spectral resolution enables study of line profiles, crucial for detailed understanding of X-ray emission mechanism, wind properties, abundances
  - Different classes of X-ray emission: shocks embedded in the stellar wind, magnetically channeled wind shocks, colliding winds

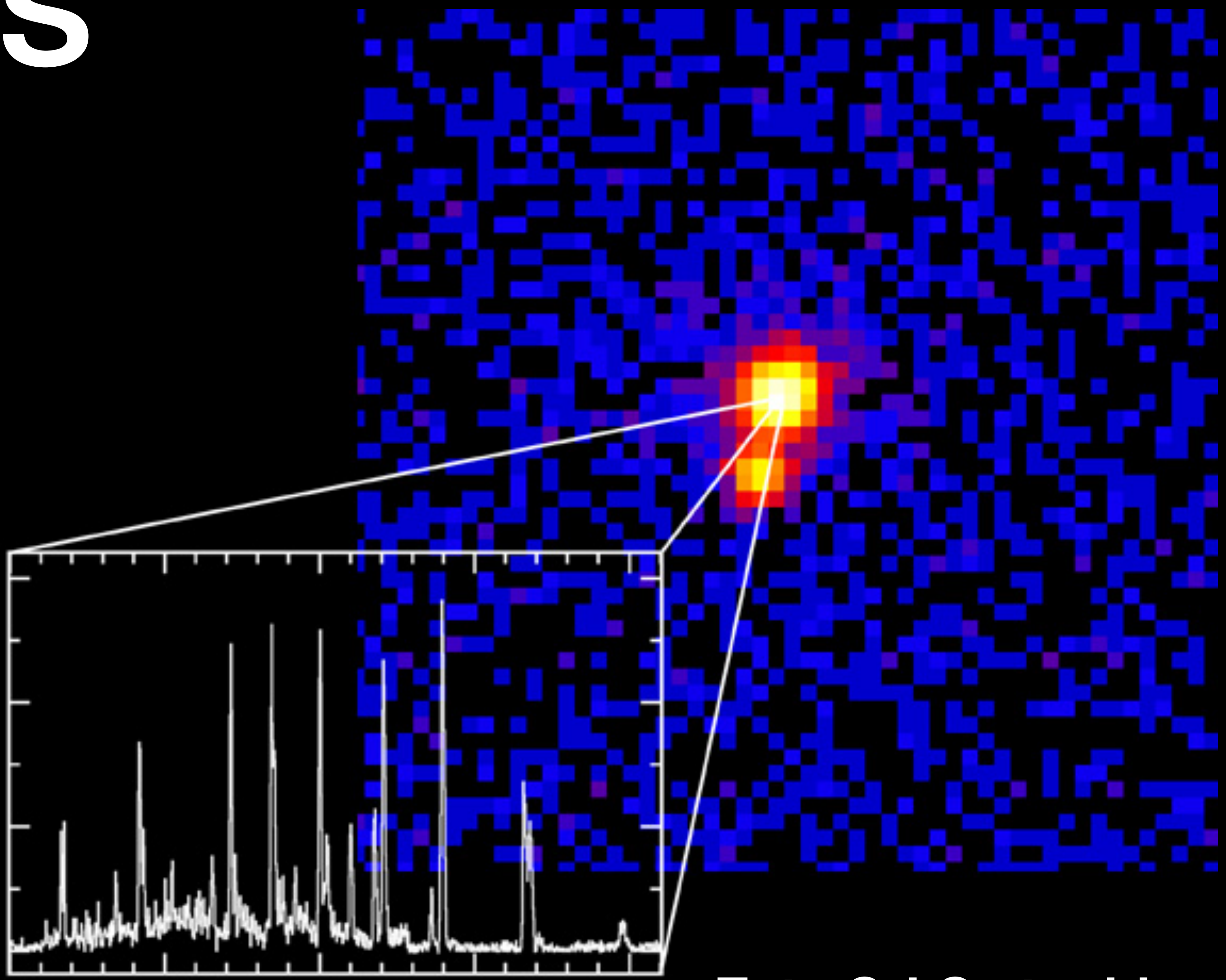
30 Dor

Hot Stars



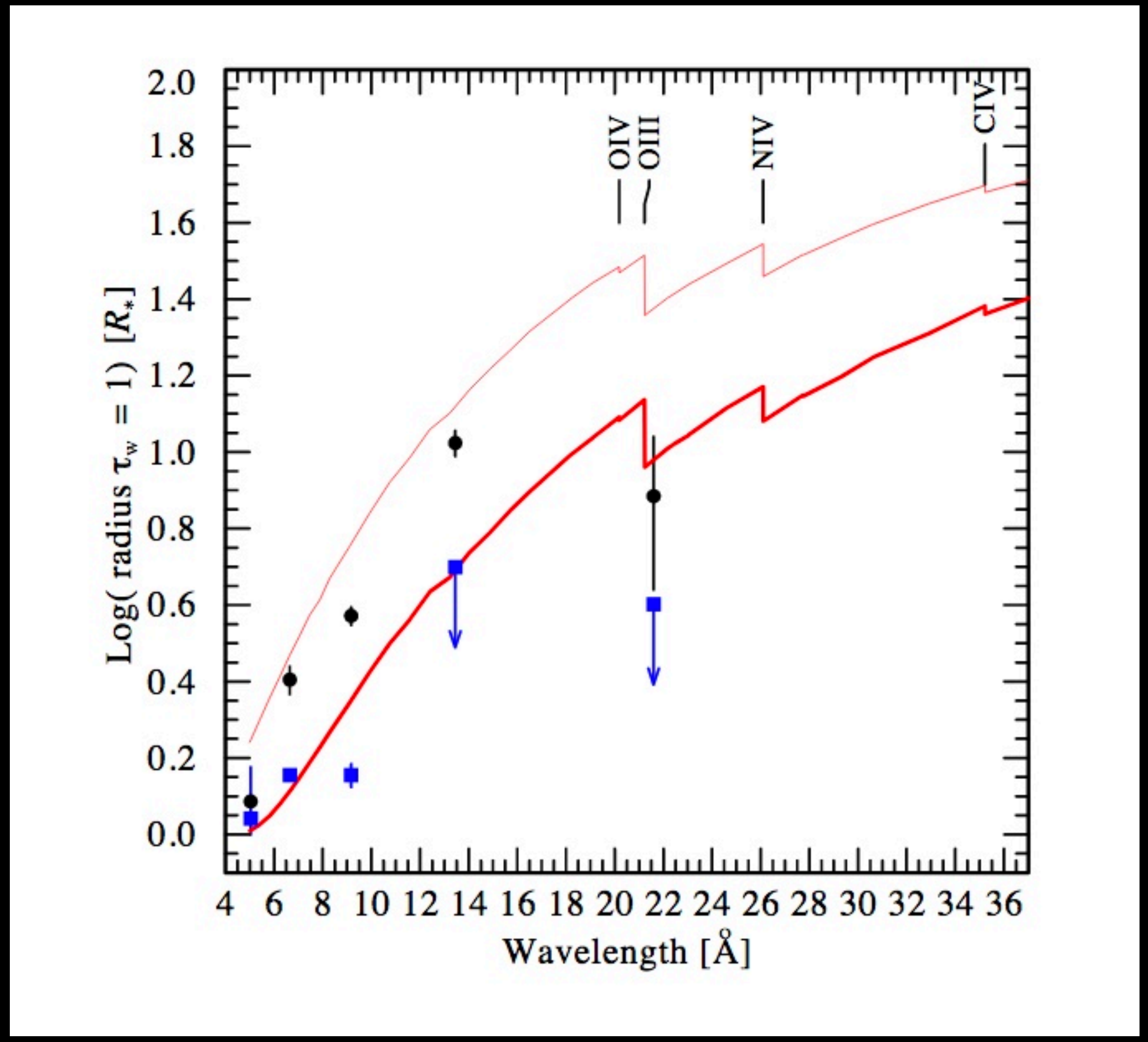
“normal” O & B stars

- Line-driven instability explains gross properties of high resolution spectra from normal O stars (spectral softness, large line widths from high velocity of shock-heated wind)
  - Expected asymmetric, skewed line shapes
- X-ray emission line strengths & shapes are key diagnostics of wind structure



Zeta Ori O star binary

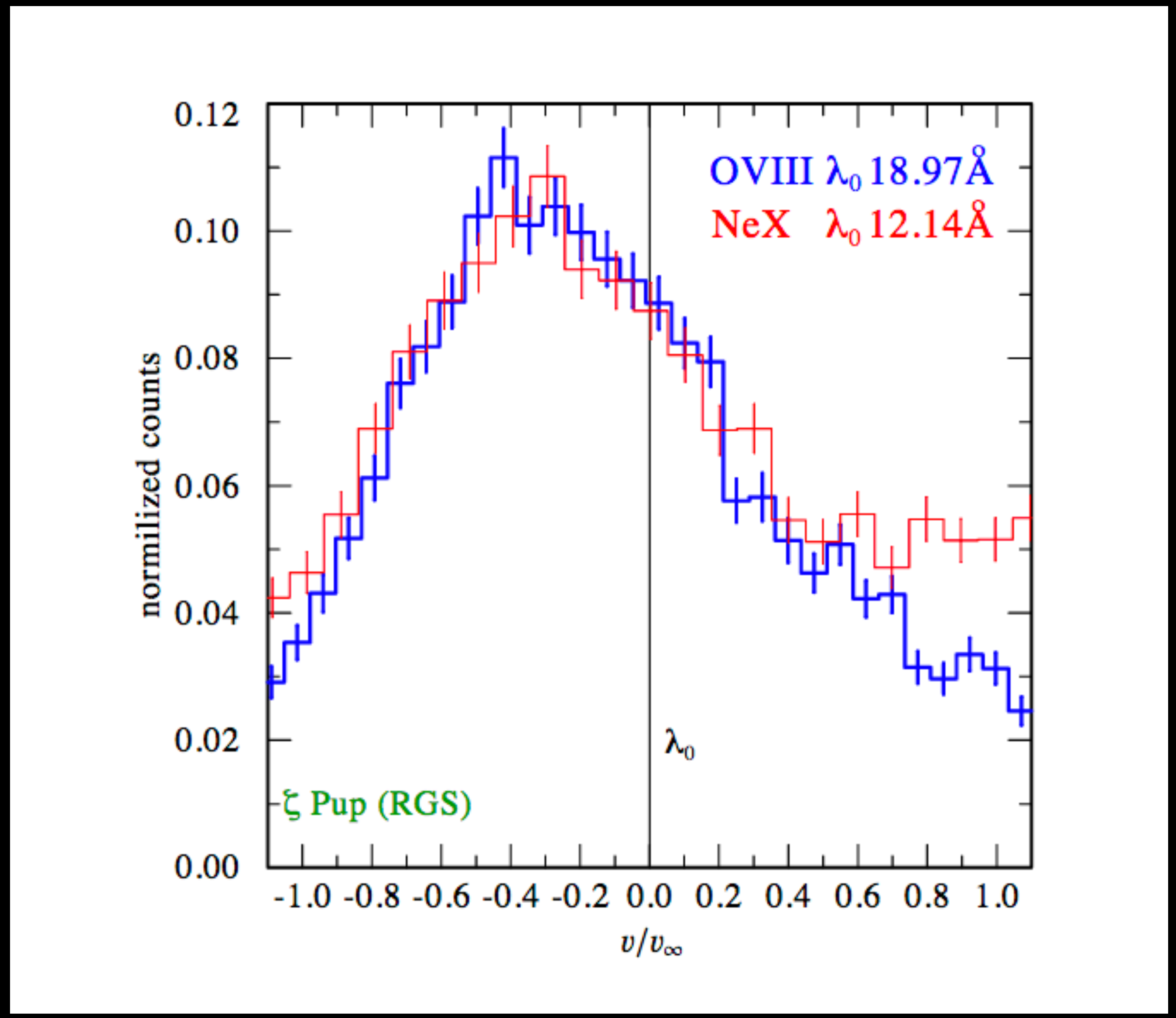
Hot Stars



8.7x10^{-6} Mdot/yr

2.5x10^{-6} Mdot/yr

radii inferred from fir analyses
radii inferred from wind opacities for an unclumped wind



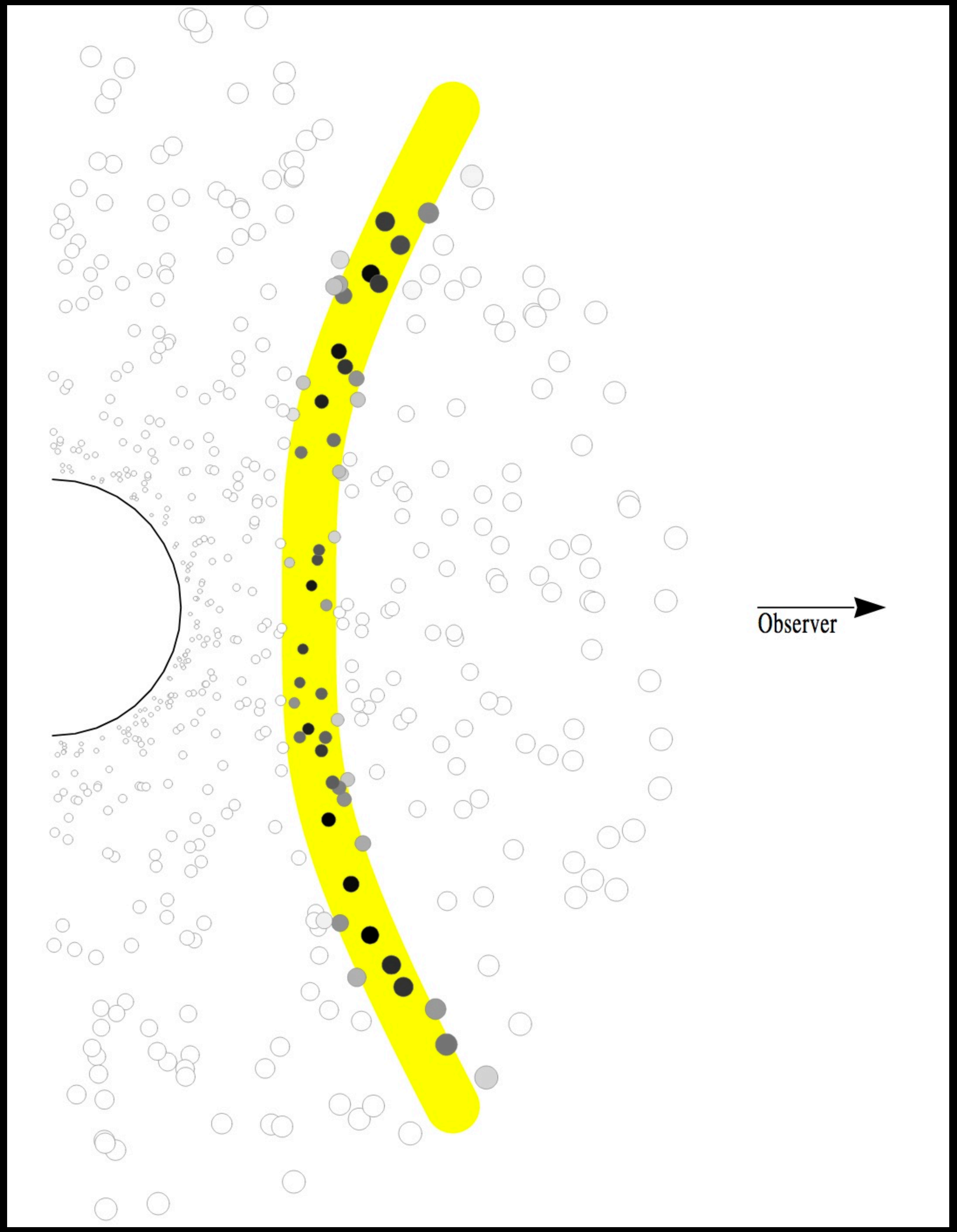
Oskinova et al. (2008)

line widths at different wavelengths are similar

- X-ray emission line strengths & shapes are key diagnostics of wind structure; quantitative analysis of lines shows disagreement with standard model
  - Red parts of profile less attenuated than expected based on wind optical depths (Owocki & Cohen 2001)
  - Continuum opacity increases with wavelength, but no impact on line widths of different Z ions has been noted (Waldron & Cassinelli 2007)
  - Discrepancy between location of emission region inferred from fir analyses and from fitting line profiles

Hot Stars

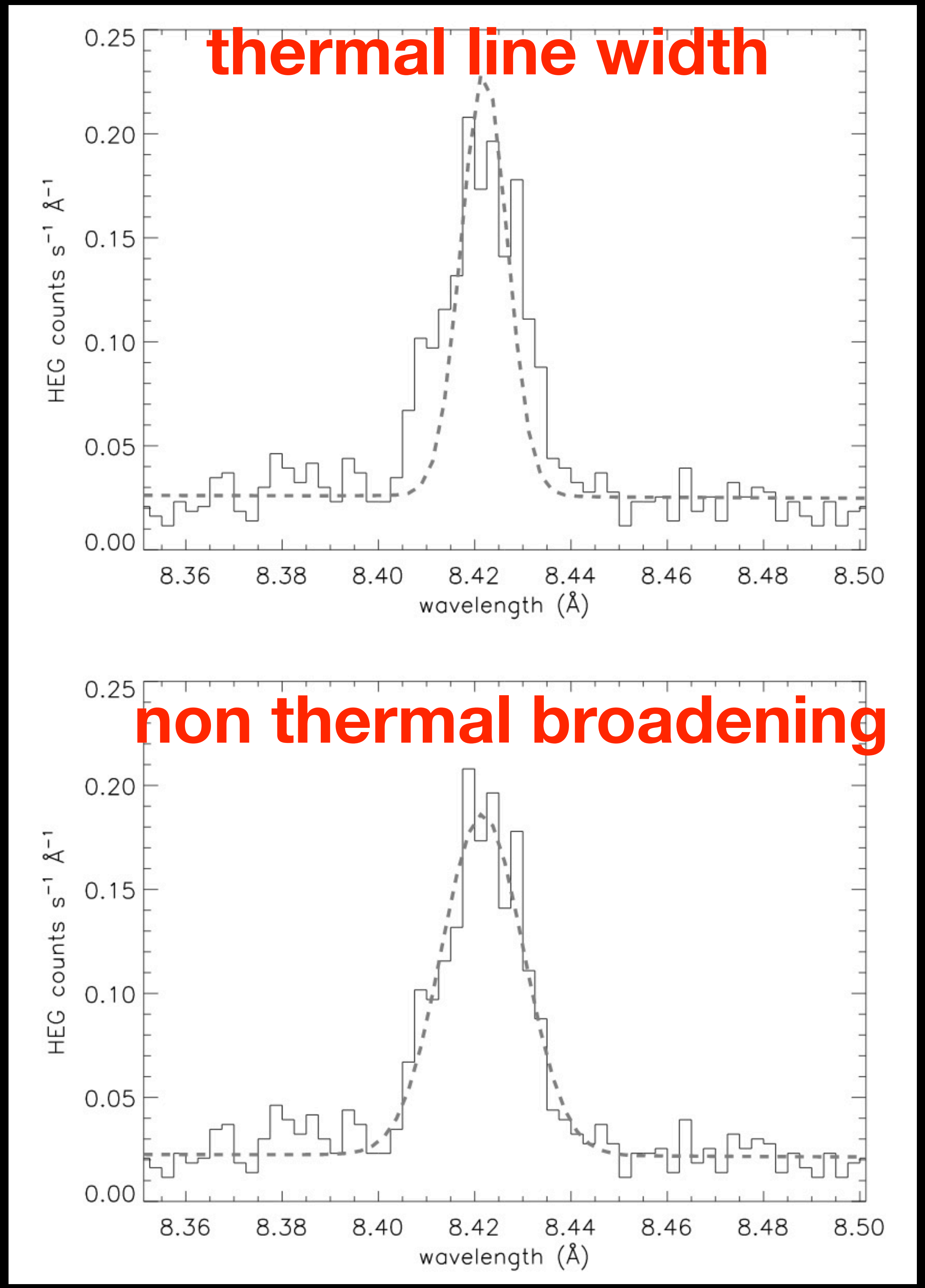
- Implies non-homogeneous stellar wind models:
  - Clumping affects wind optical depth, line profile shape — pancakes have nearly symmetric emission line profiles (e.g. Oskinova et al. 2006)
  - Porous nature of spatially structured stellar winds can reduce bound-free absorption of X-rays emitted by wind shocks (Owocki & Cohen 2006)

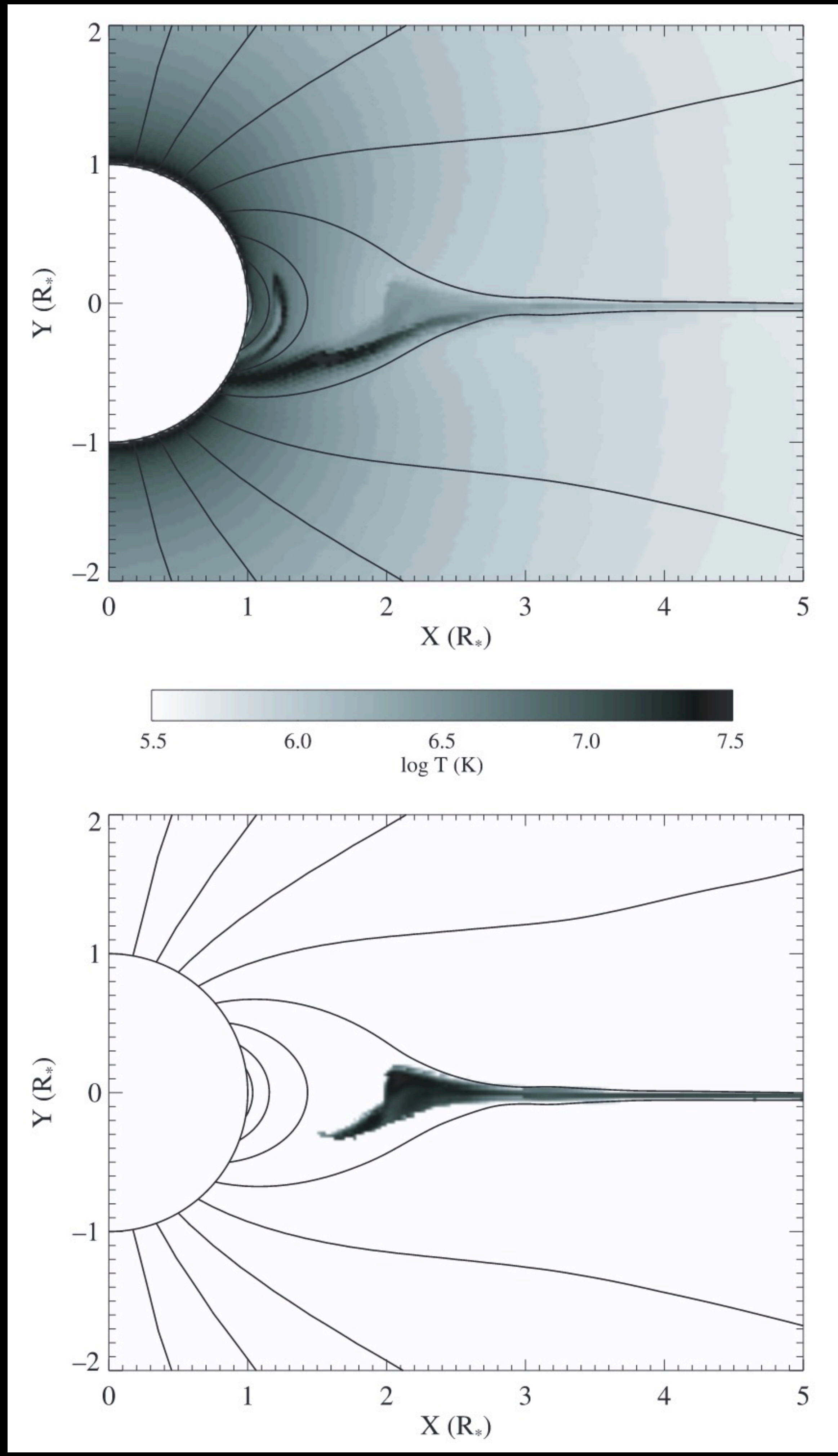


Oskinova et al. (2007)
clumping in a stellar wind

Hot Stars

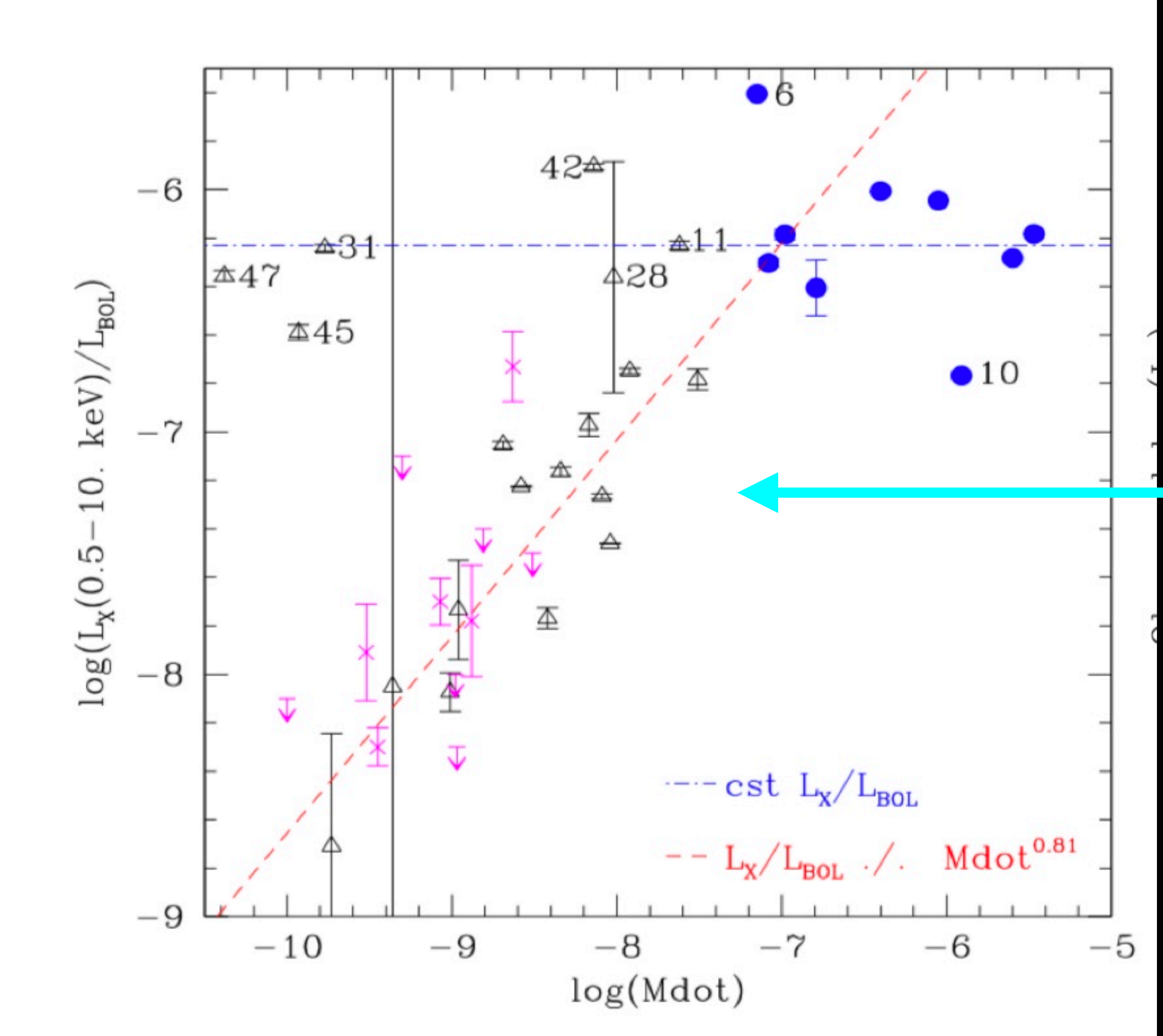
- θ^1 Ori C was the only "normal" hot star known at the time to possess a global magnetic field (now we know that 10% of massive stars exhibit strong, globally ordered magnetic fields)
  - X-ray spectra revealed moderately hard X-ray emission
  - Line profiles nothing like what is expected for line-driven winds
- Stellar winds trapped & channeled in closed magnetic loops, leading to magnetically confined wind shocks





Gagné et al. 2005

Hot Stars



O stars

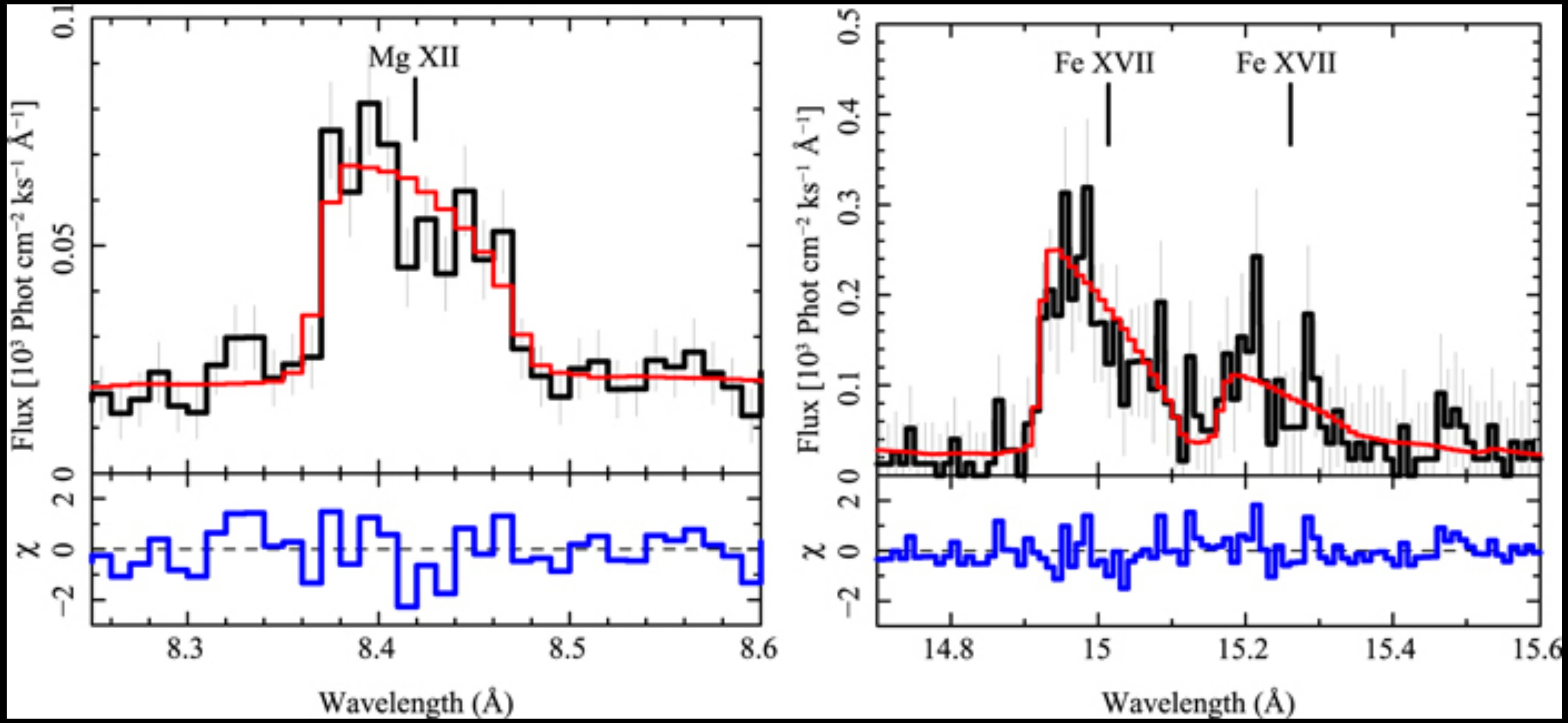
B stars

Properties of magnetic massive stars show different proportionality between X-ray emission and mass-loss rate

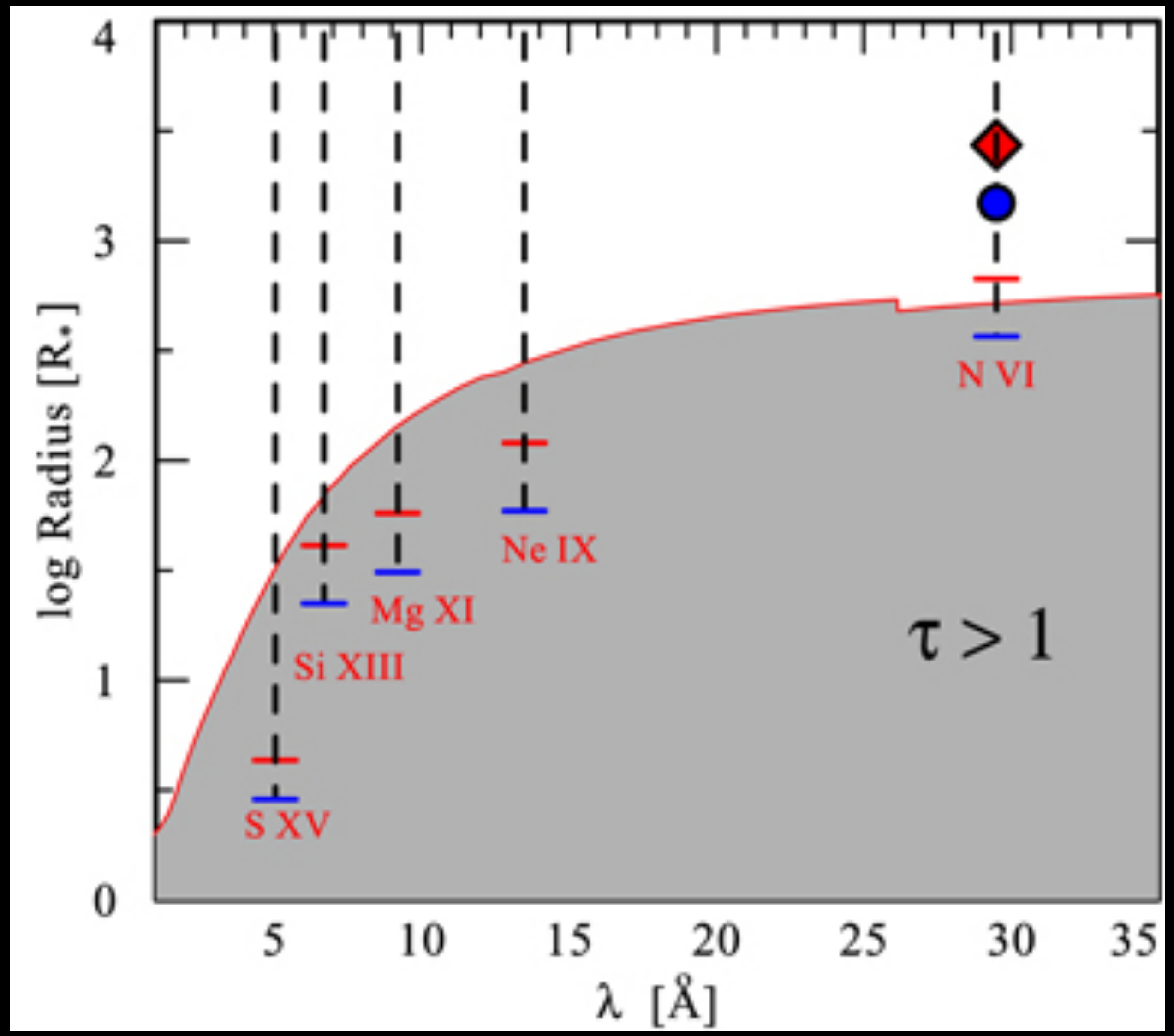
At odds with canonical $L_x/L_{bol} \sim 10^{-7}$ expected for normal OB stars

ud-Doula et al. (2014)

Hot Stars



Wolf-Rayet stars



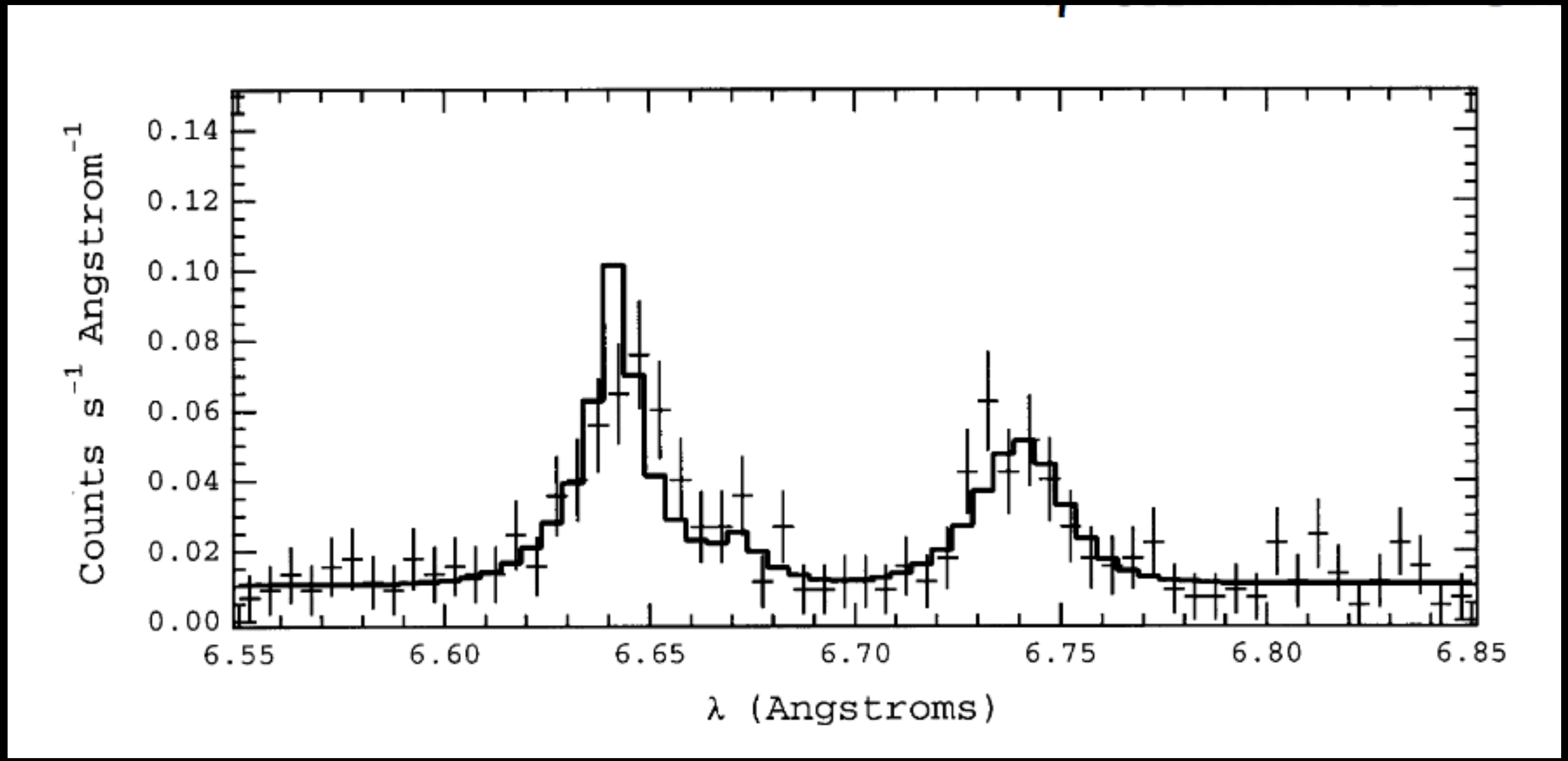
Huenemoerder et al. (2015) X-ray line profiles of WR6
asymmetric line profiles,
optical depth unity in photoabsorption of X-ray emission is expected to be at relatively large radii.

Oskinova et al. (2012) outside wind acceleration zone where line-driving instability could create shocks
X-ray temp up to 50 MK within unchecked stellar wind
iron line @6.4 keV: 2 components, cool wind permeated with hot X-ray emitting plasma
wind must be porous to allow X-rays to escape
X-rays formed when fast wind rams into slow “sticky” clumps?

Hot Stars

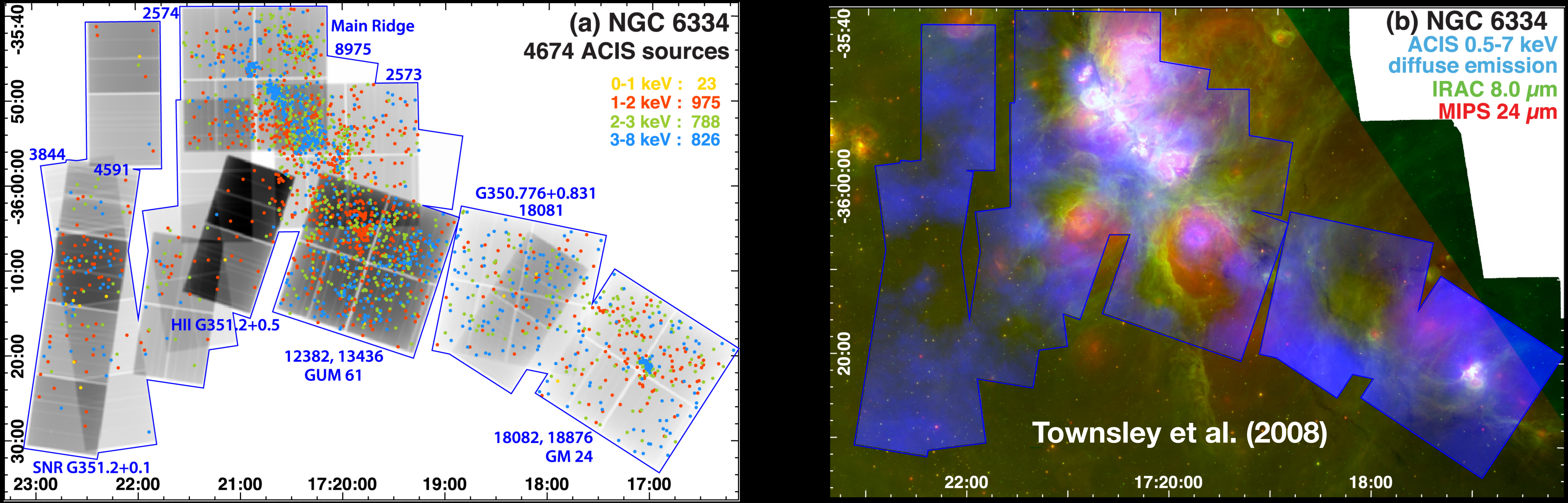
Eta Carina

- Massive luminous blue variable, strong historic eruptions
- Binary hypothesis suggested pre-Chandra
- Grating observations reveal that X-ray emission originates from the shocked wind of the companion (primary wind has low velocity), constrain mass-loss rate and terminal wind velocity of secondary, use to infer stellar properties



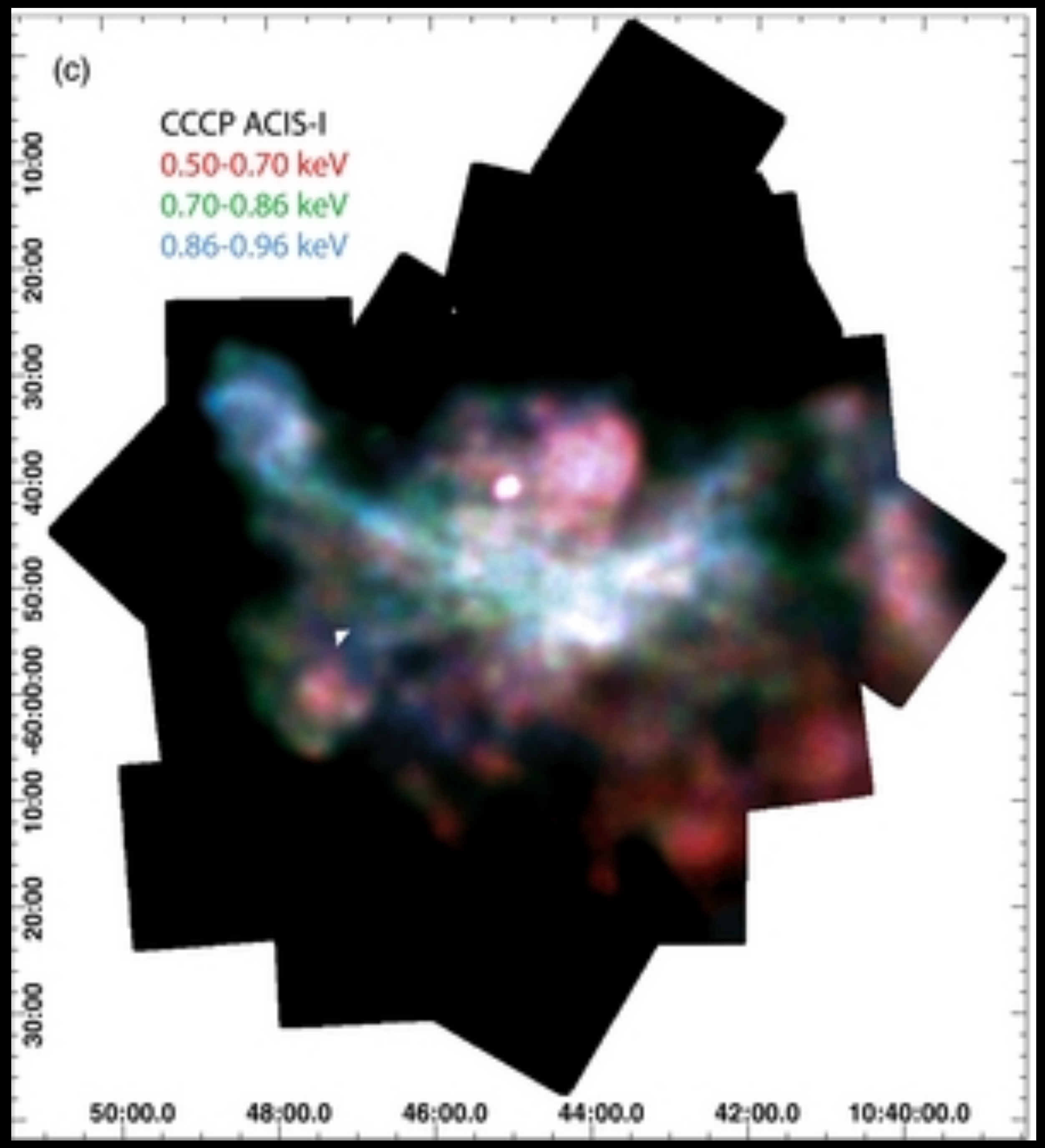
Corcoran et al. (2001) helium-like triplets of Eta Car
strong forbidden line emission shows X-rays produced far from stellar photosphere
high densities support wind wind collision model

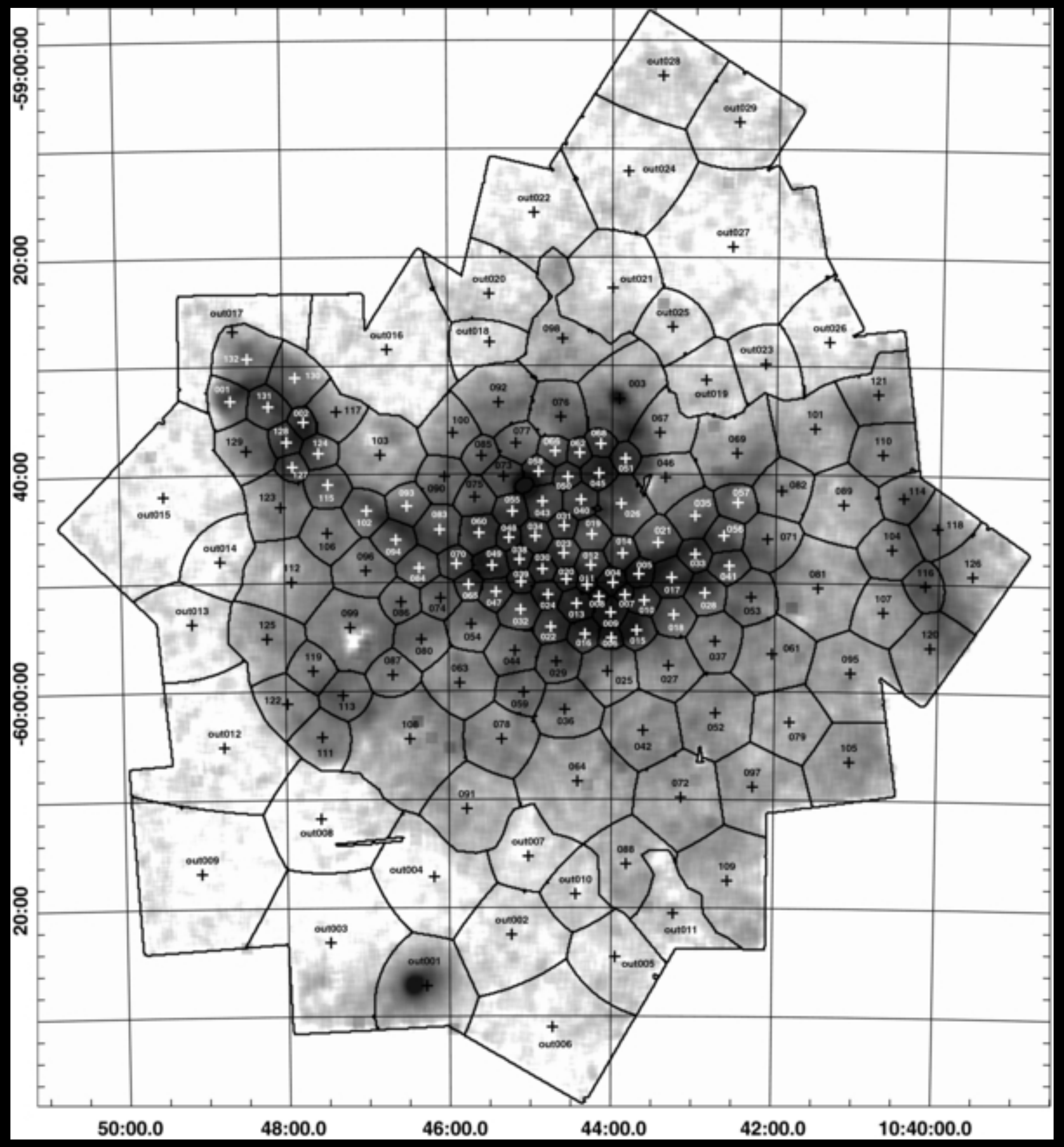
Diffuse Gas in Star-Forming Regions

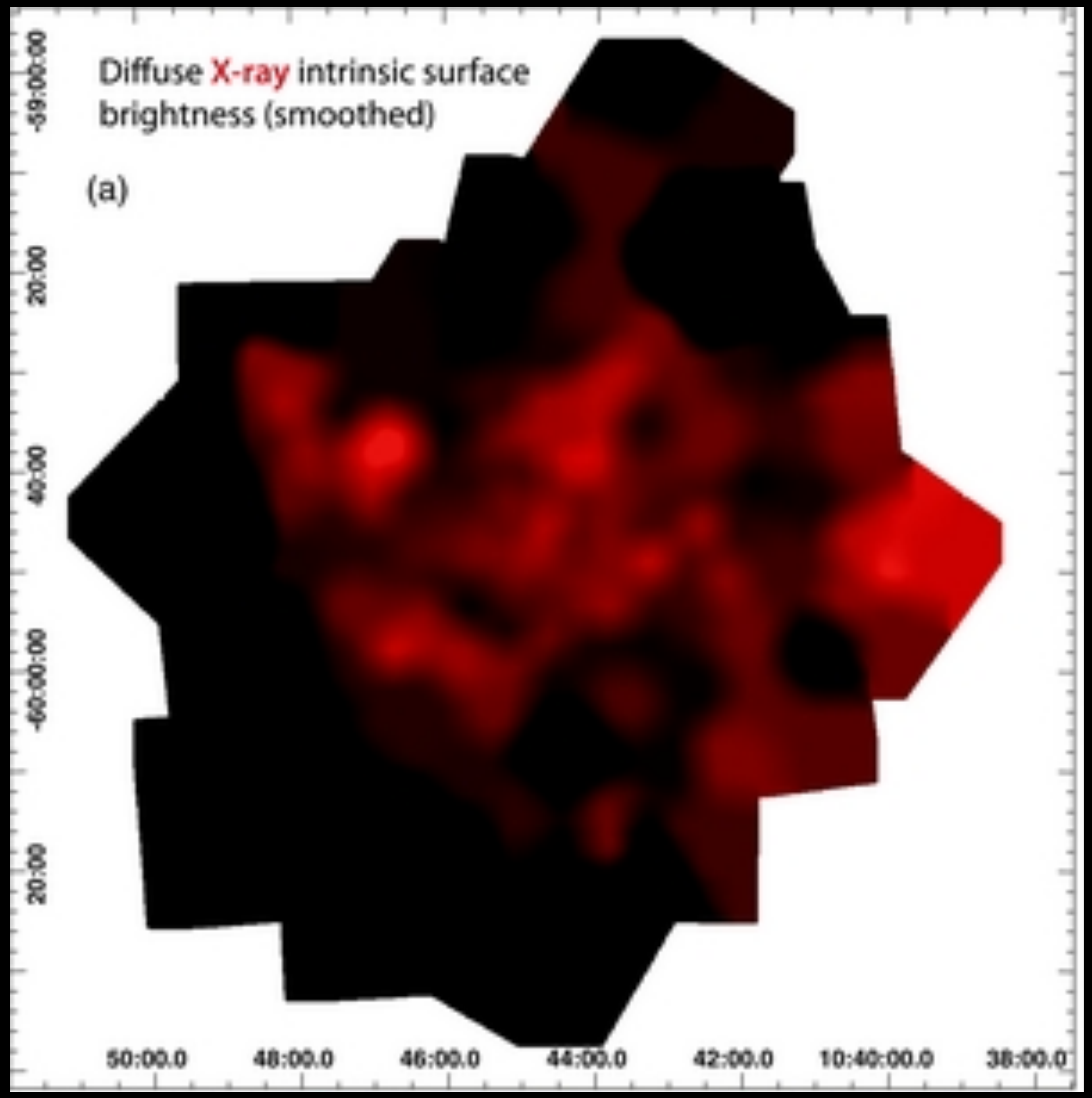


- Unresolved X-ray emission due to hot plasma threading massive star-forming regions, result of feedback from the winds and supernovae of massive stars
- Star formation occurs in the presence of 1-10 MK plasma
- Need high spatial resolution X-rays to separate point sources from underlying diffuse emission

Diffuse Gas in Star-Forming Regions







- Diffuse X-ray emission in the Carina nebula, remains quite clumpy even after accounting for absorption impacts apparent surface brightness

- Anti-correlation between X-ray emission and dense ionized gas

Townsley et al. (2011)

- Line-like correlated residuals in X-ray spectral fits suggest charge exchange at interfaces of hot plasma and cold neutral pillars, ridges, clumps

Common Themes for High-Energy Stellar Astrophysics

Spatial Resolution

diffuse emission

pt. source separation

line broadening

binary motion

Spectral Resolution

abundances

wind diagnostics

emission line diagnostics of T, n_e

flaring variability

Temporal Variability

modulation on rotational or orbital timescale

Towards Future Futures

- Chandra X-ray Observatory health is good, should continue for many more years
- Exploit synergies with other facilities, either through joint programs, or making use of new discoveries (e.g. rotation periods from Kepler/K2/TESS, wealth of stellar data from Gaia)
- Advocate for future missions to extend Chandra’s legacy