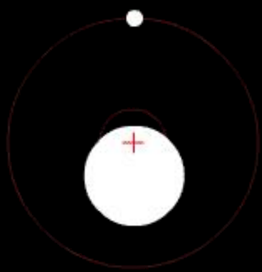
HIGH ENERGY EXOPLANET SCIENCE IN THE NEXT DECADE AND BEYOND

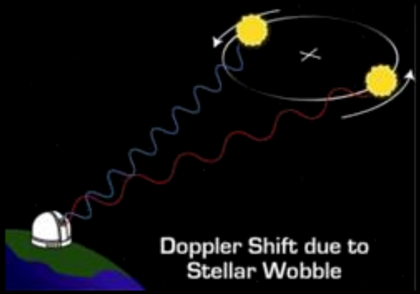
Scott Wolk (SAO/CfA)

What is Exoplanet Science?

Not just this

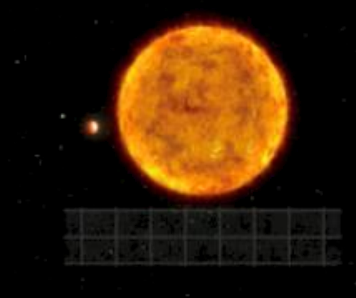


radial velocity — velocity shift of a star due to star+planet

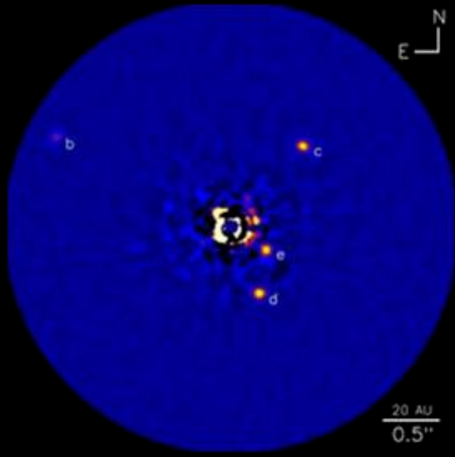


astrometry — seeing the reflex motion of the star due to star+planet system

transit — decrease in stellar light



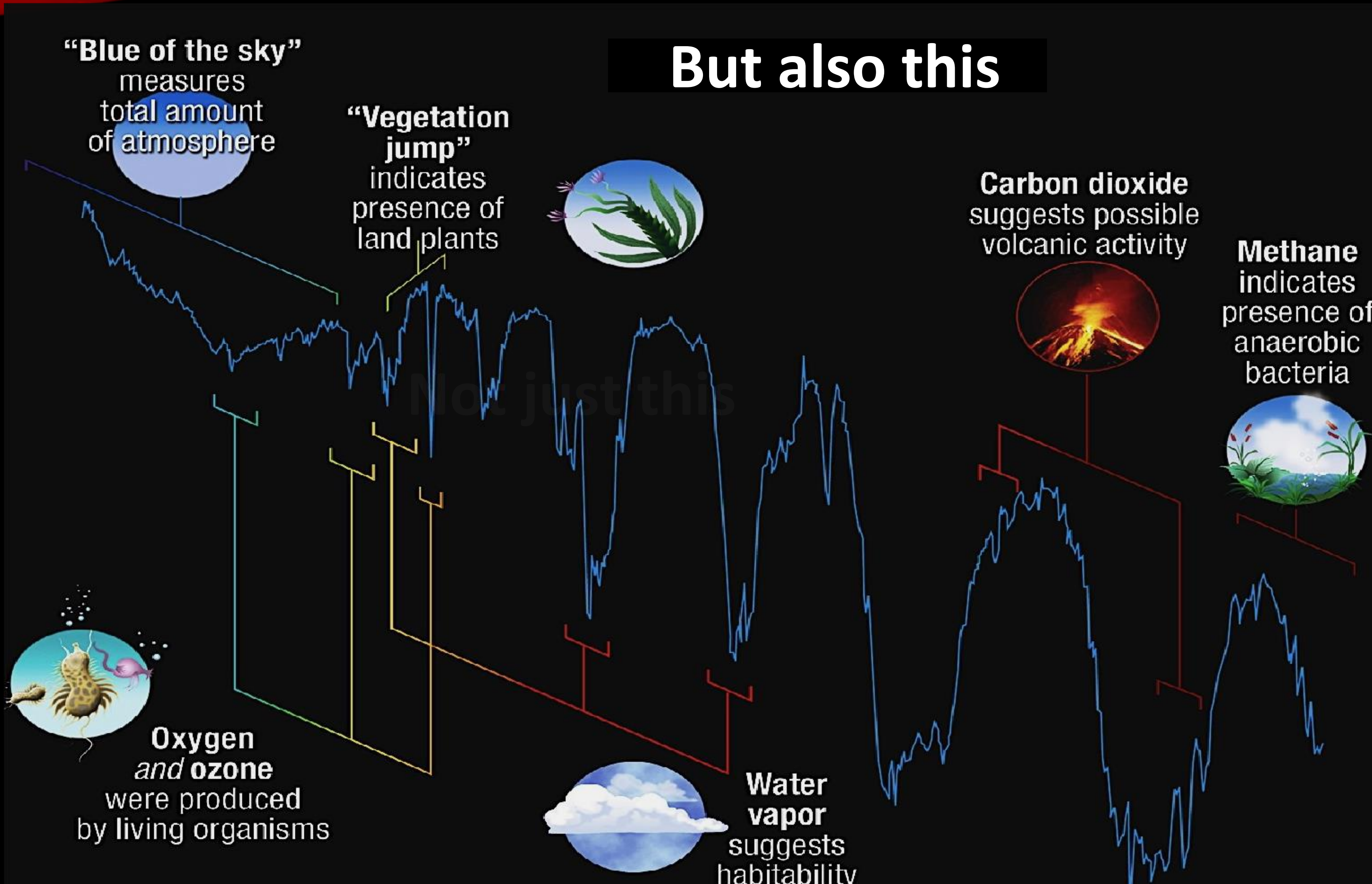
direct imaging — block out the light of the star to see the planet directly



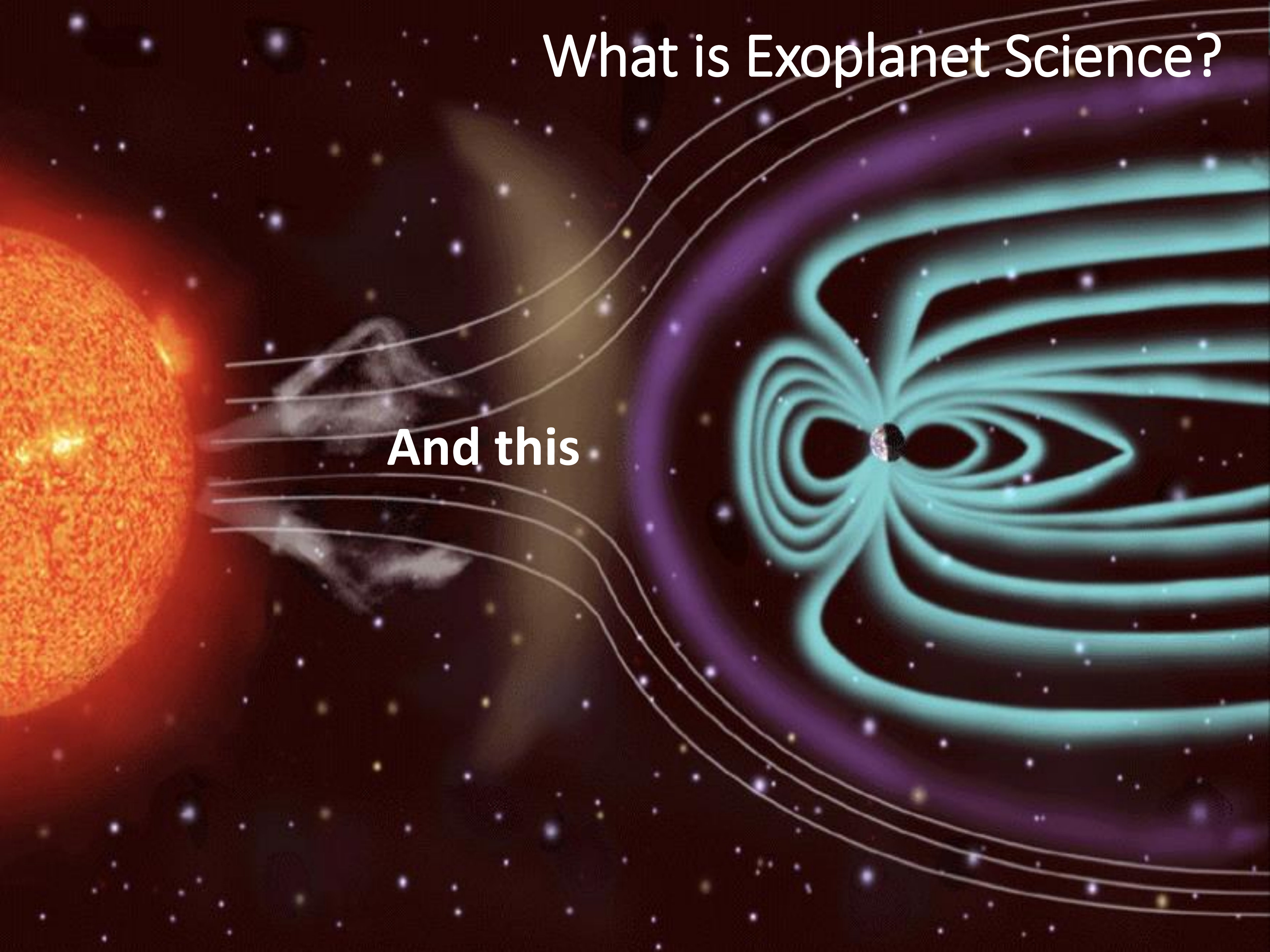
microlensing — gravitational lensing due to star+planet system passing in front of a background star

What is Exoplanet Science?

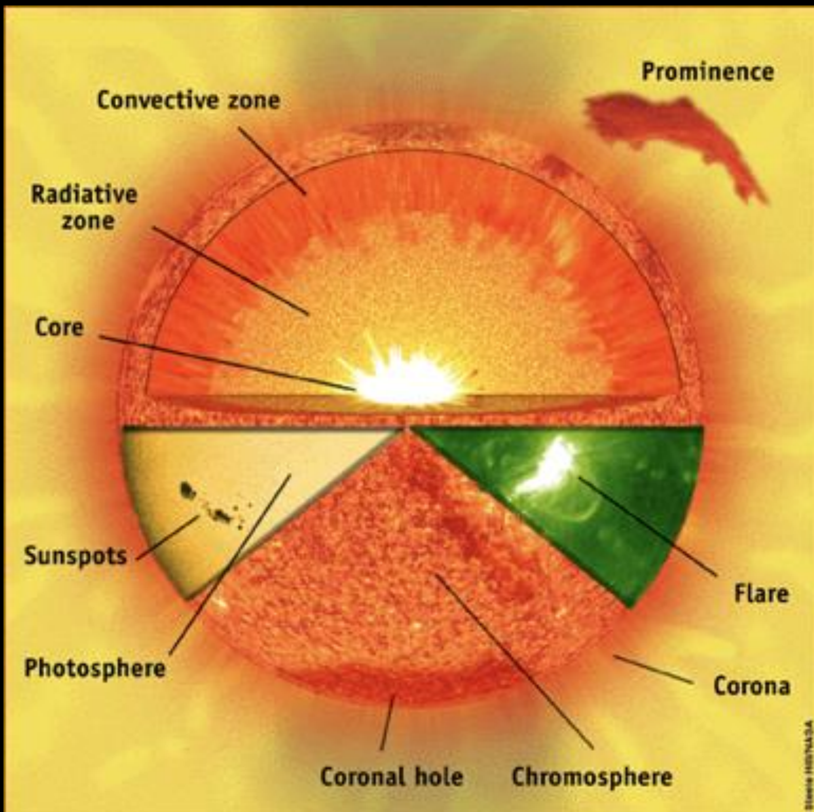
But also this

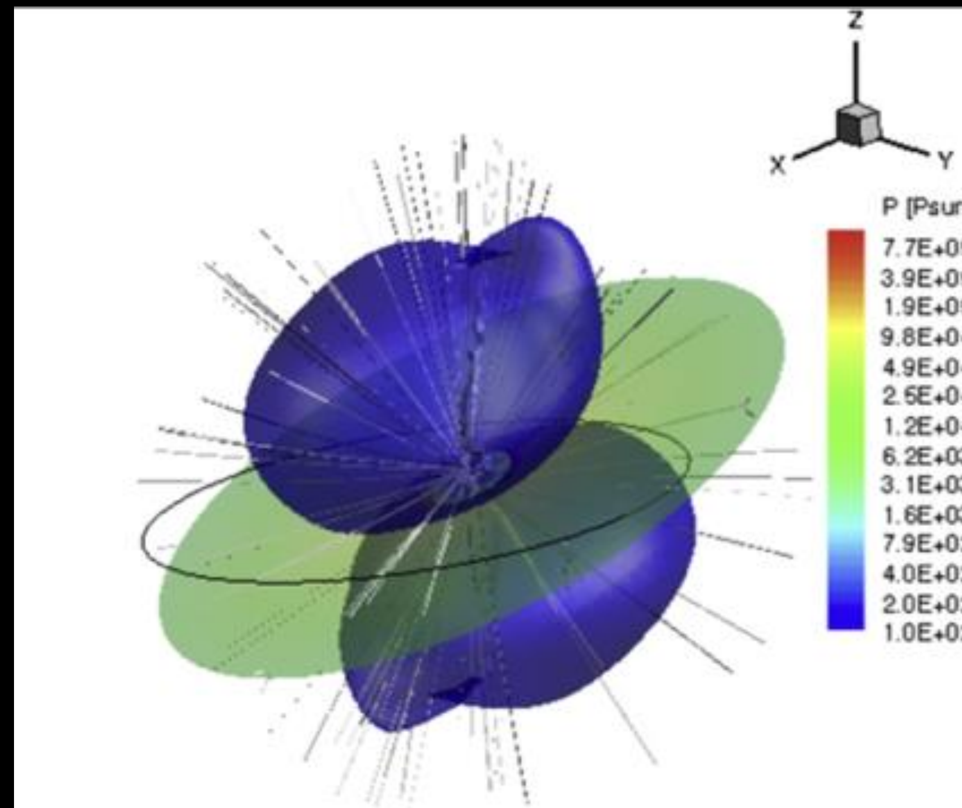


What is Exoplanet Science?



What is Exoplanet Science?





The star's magnetic field creates an ecosystem which helps to set the environment that planets (and life) experience (Lingam & Loeb 2018)
Stellar magnetospheres influence the inner edge of the traditional habitable zone (Garaffo et al. 2016, 2017).

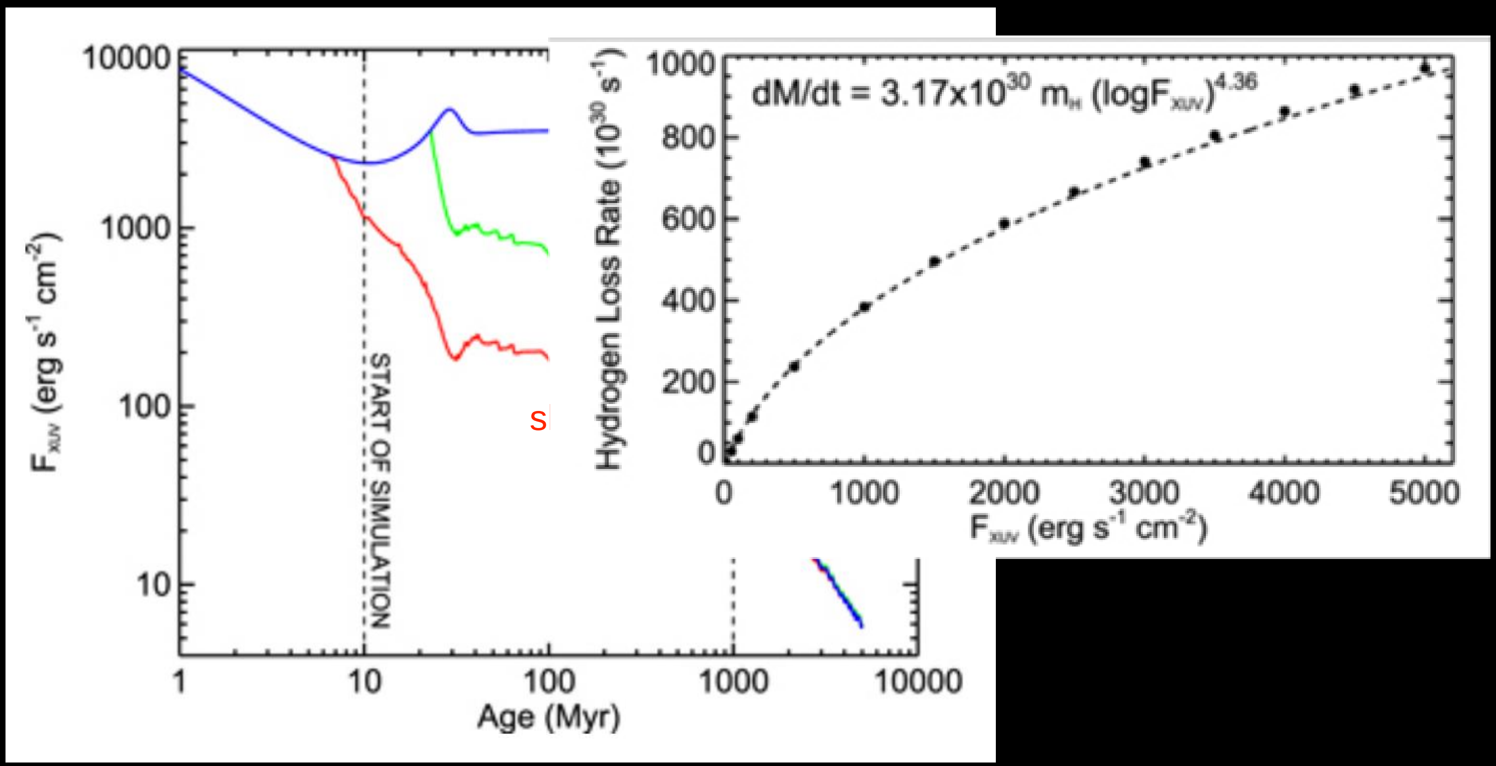
X-rays from stars affect exoplanets

- Some hot Jupiters appear inflated beyond what the bolometric luminosity would predict.
- X-Ray/EUV flux ➔ atmospheric expansion & escape (Lammier et al. 2003, Murray-Clay et al. 2009).
- X-Ray flux ➔ photochemistry changing the thermal budget (Laing et al. 2004; Burrows et al. 2008).
- Coronal radiation produces rapid photoevaporation of the atmospheres of planets close to young late-type stars (Sanz-Forcada et al. 2011, Kulow et al. 2014).

Potential Exoplanet Applications

How does the coronal emission of stars affect exoplanets?

- Stellar twins are not magnetic twins; star's X-ray emission at early ages is a much larger factor in planetary irradiation
- Planetary atmospheric evolution is fundamentally linked to XEUV emission
- X-rays trace magnetic structure directly



Johnstone et al. (2015)

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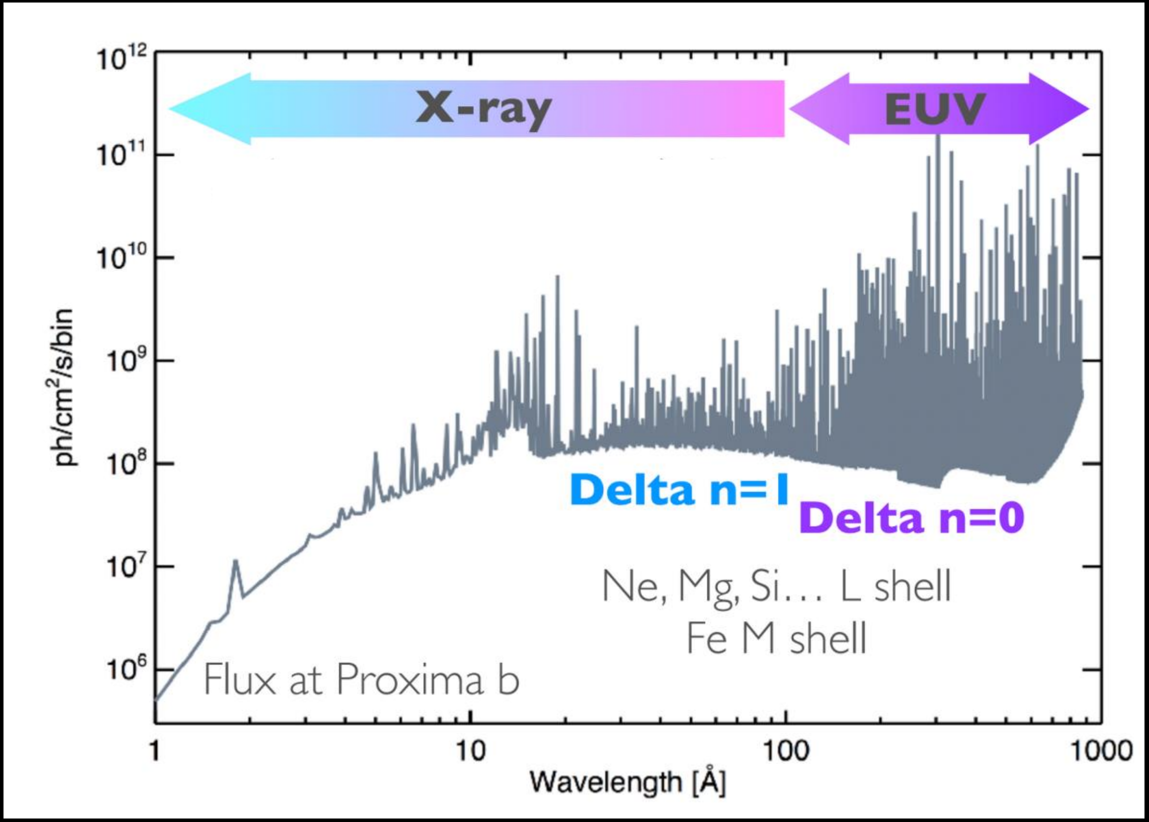

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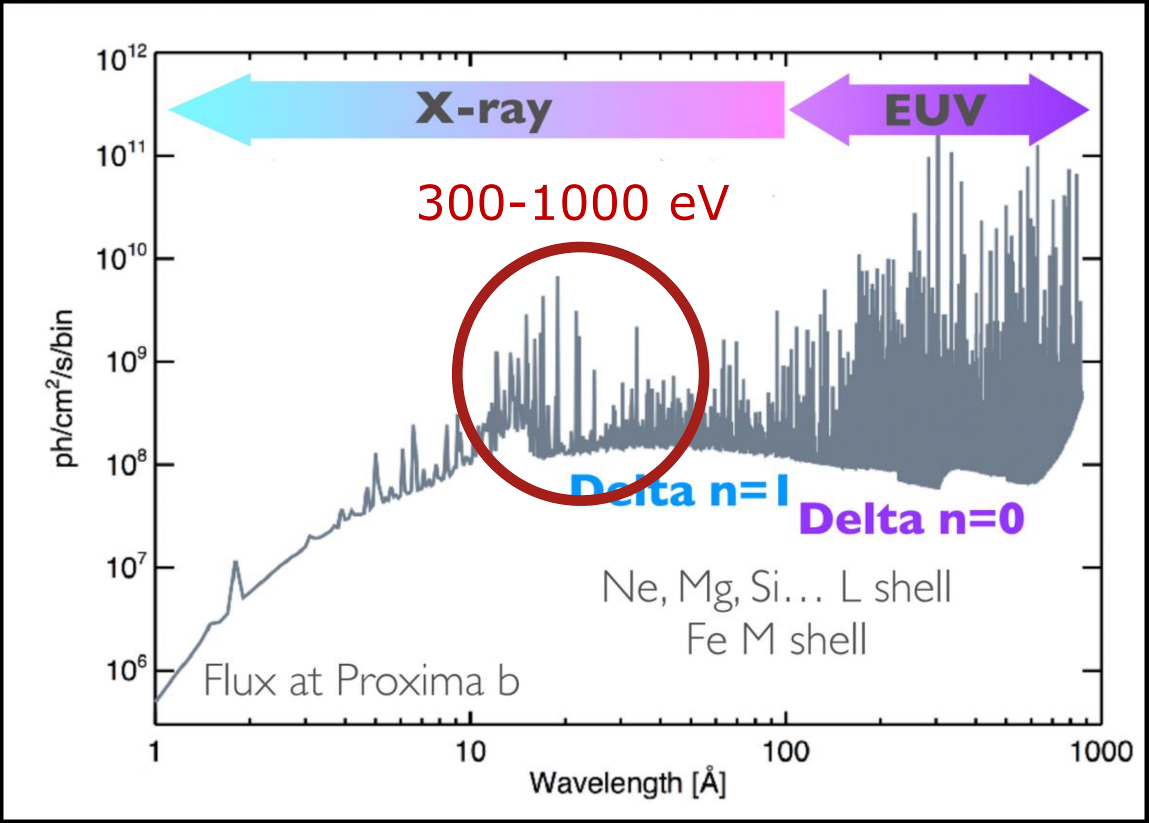

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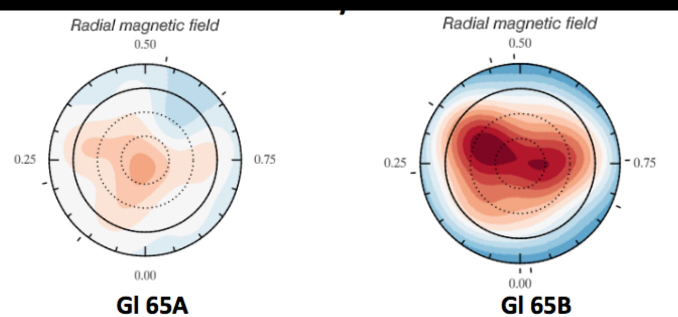
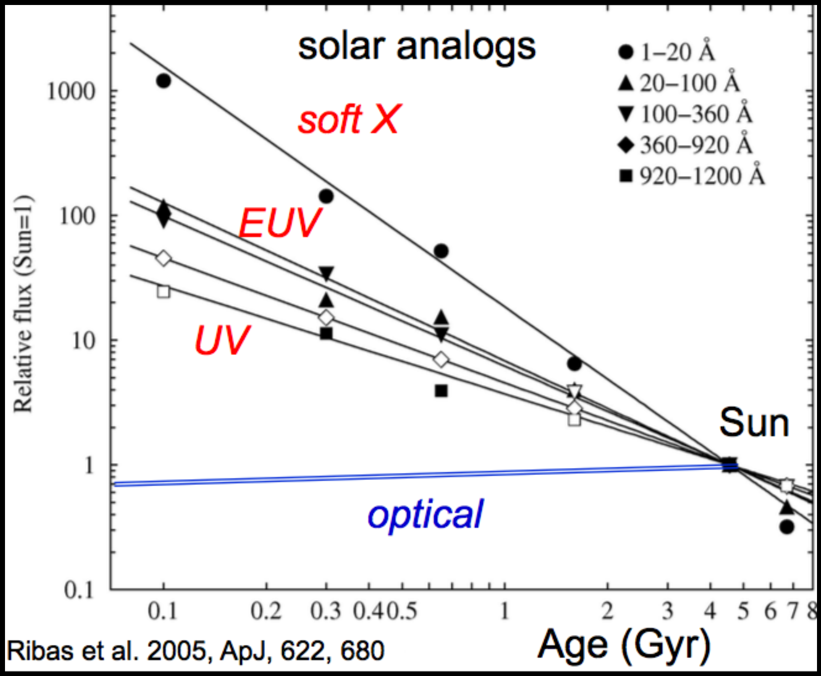


	Gl 65A	Gl 65B
Spectral class	M5.5Ve	M6Ve
Mass	0.1225 $M_\odot$	0.1195 $M_\odot$
Radius	0.165 $R_\odot$	0.159 $R_\odot$
Rot. vsini	28.5 km/s	30.6 km/s
Rot. period	5.86 hr	5.45 hr
Metall. [Fe/H]	-0.03	-0.12
<Bf> Stokes I	**5.2 kG**	**6.7 kG**
B_{dip} strength V	**0.3 kG**	**1.3 kG**
	complex, non-axisymmetric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

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



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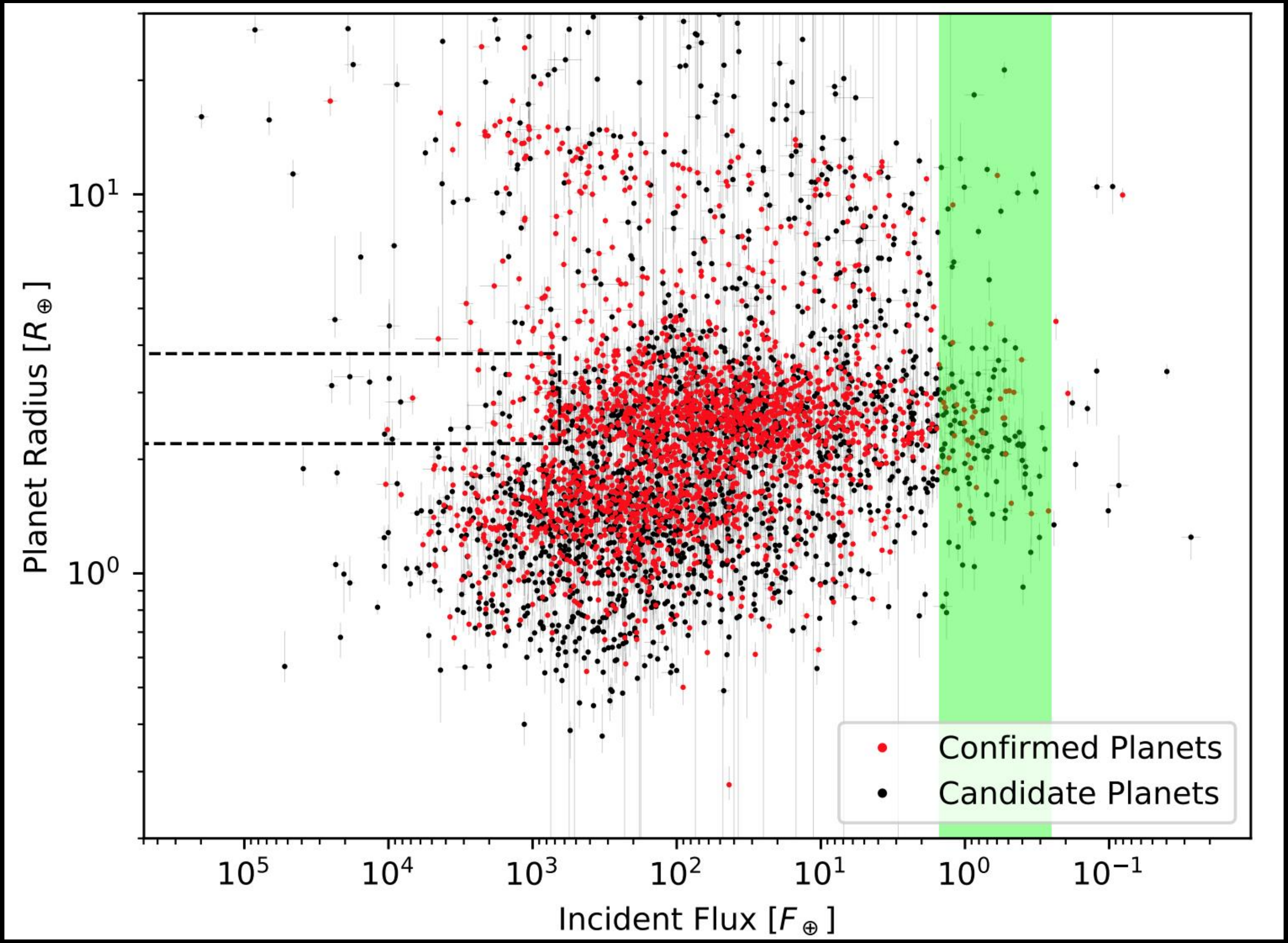
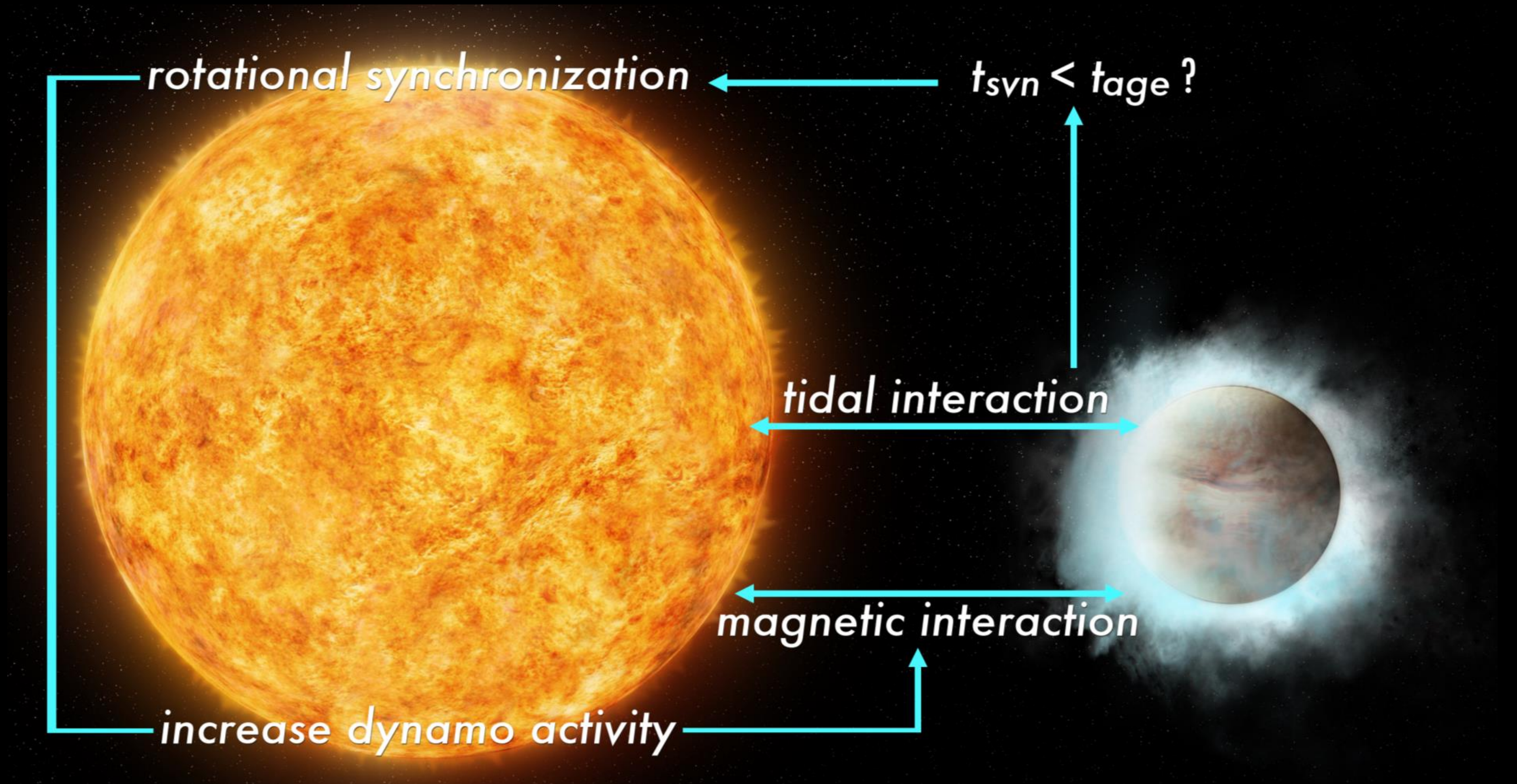


Berger et al. (2018)

…Exoplanets may affect their host stars X-ray flux

- Analytic studies show ➔ $F_{recon} \alpha a_p^{-3}$ (Saar et al. 2004)
- Tidal forces can work in two directions.
- Analytic models indicate field lines can connect the star to the planet, ruptures of the lines could give rise to flare-like activity (Lanza 2008).
- MHD simulations show strong feedback visible in X-rays (Cohen et al. 2011).

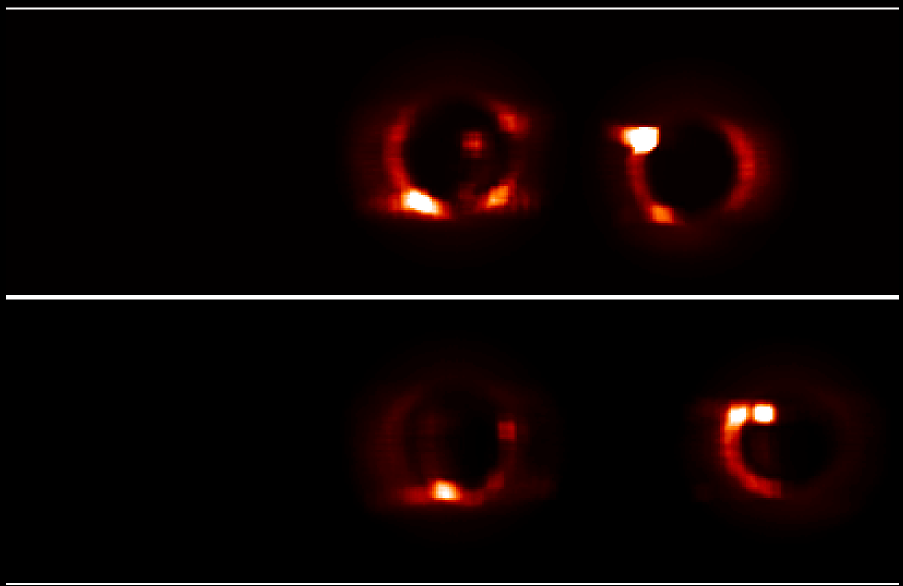
Star Planet Interaction



Scott J. Wolk

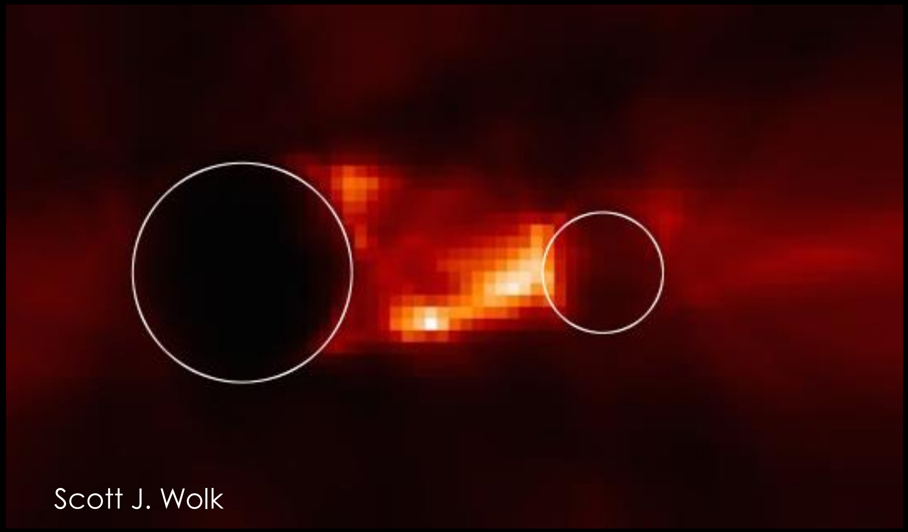
Cuntz et al. 2000

WE KNOW INTERACTIONS HAPPEN



binary star magnetic interaction

YY Gem (Güdel et al. 2001)

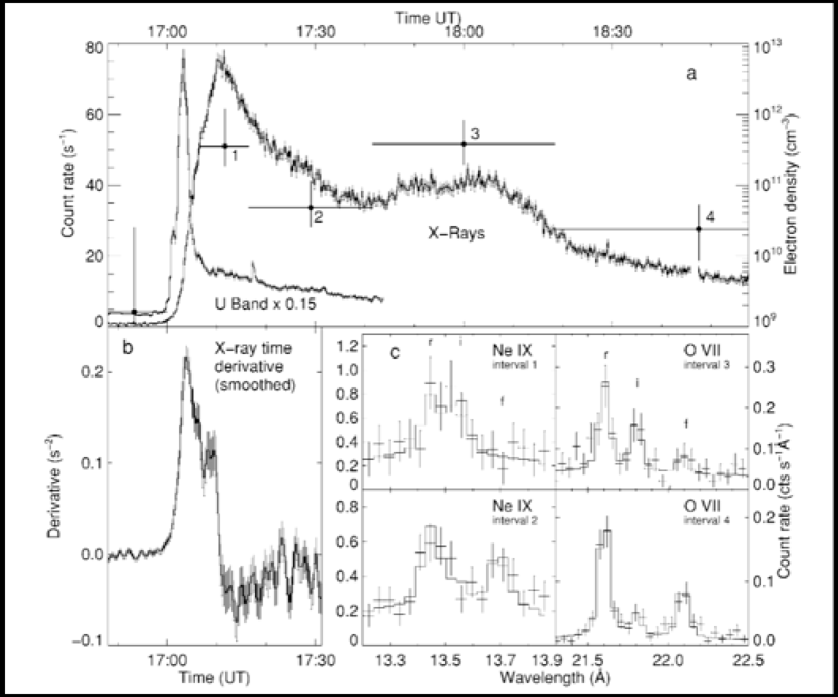


AR Lac (Siarkowski et al. 1996)

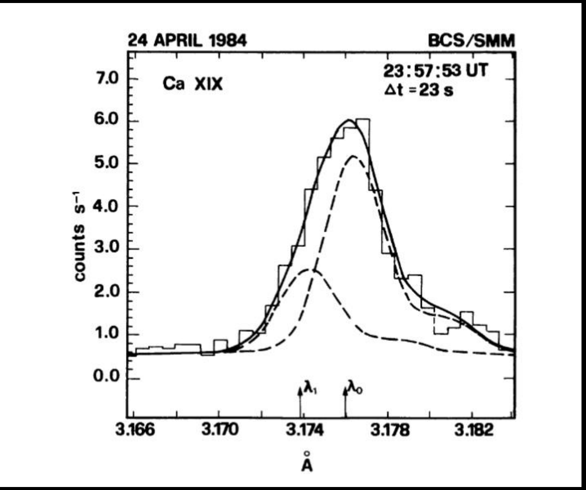
Potential Exoplanet Applications

How do the characteristics of flares change with time and what impact does this have on exoplanet conditions?

- Systematic change of T_{max}, E_{flare}, $L_{x,max}$ on flares of stars with varying mass, age, magnetic configuration as input to evolution of planetary irradiation
- Influence of energetic particles inferred from line profiles



Large flare on Proxima
Güdel et al. (2002)



- Blueshifts in solar flares up to several hundred km/s, coincide with start of nonthermal hard X-ray emission from accelerated particles (Antonucci et al. 1990)
- Peak in nonthermal line broadening occurs at same time as maximum amount of hard X-ray emission (Antonucci et al. 1982)

X-ray Flare of HD 189733

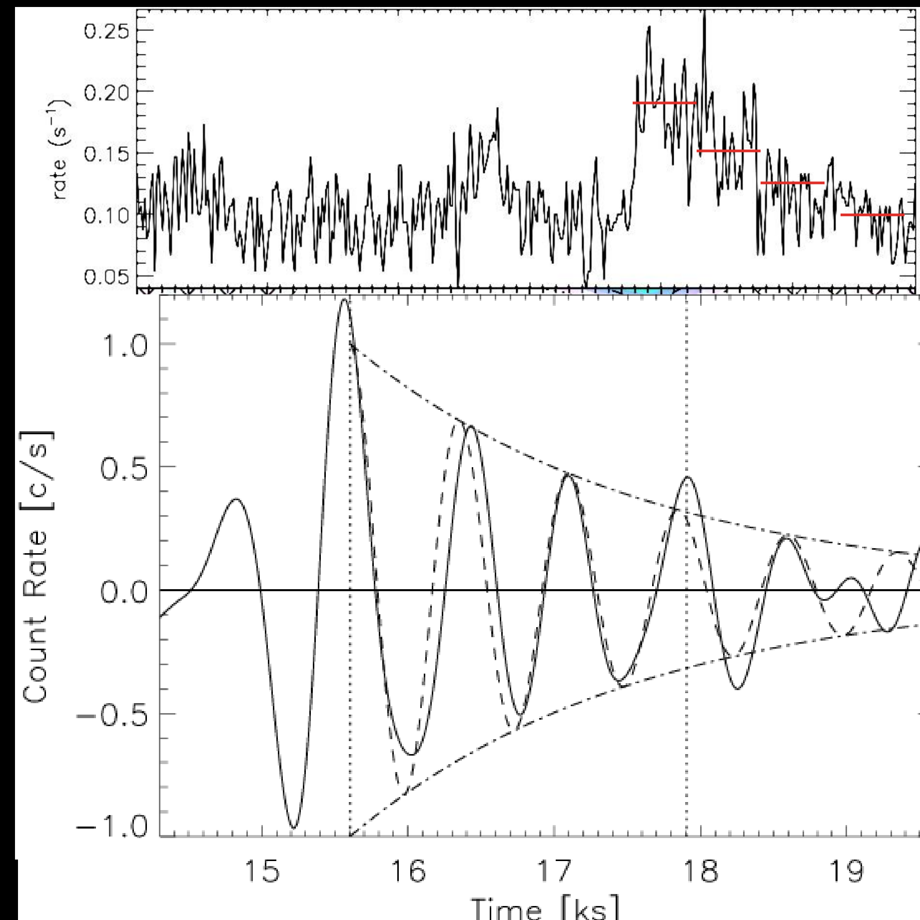
2D wavelet analysis of 2012 light curve
Description: A damped magneto acoustic oscillation in the flaring loop.

$\Delta I/I \sim 4$□$n k_B T/B^2$

$T \sim 12$ MK
n: density=5×10^{10} cm^{-3}
(from RGS data)

B ⟶ 40-100 G

$\tau \sim L/c_s$
$c_s = \sim T^{0.5}$
τ= oscillation period ~ 4 ks
$L = \text{Const. X } \tau_{osc} N T^{0.5}$
$L \sim 5 R_*$



Pillitteri et al. (2014)

Implication of the wavelet analysis

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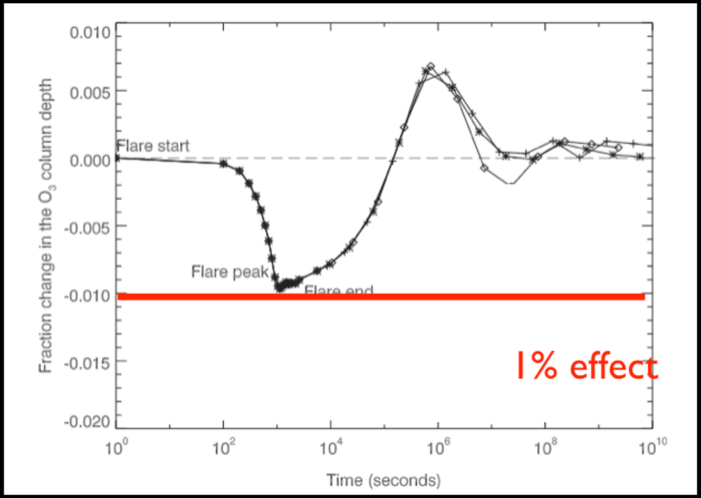
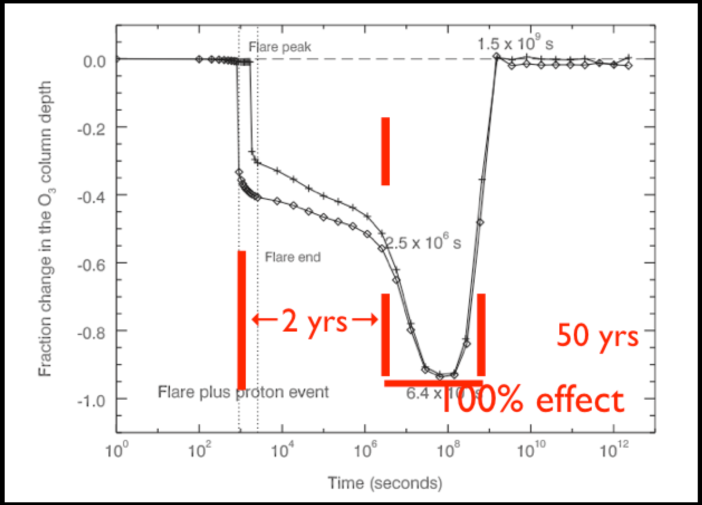


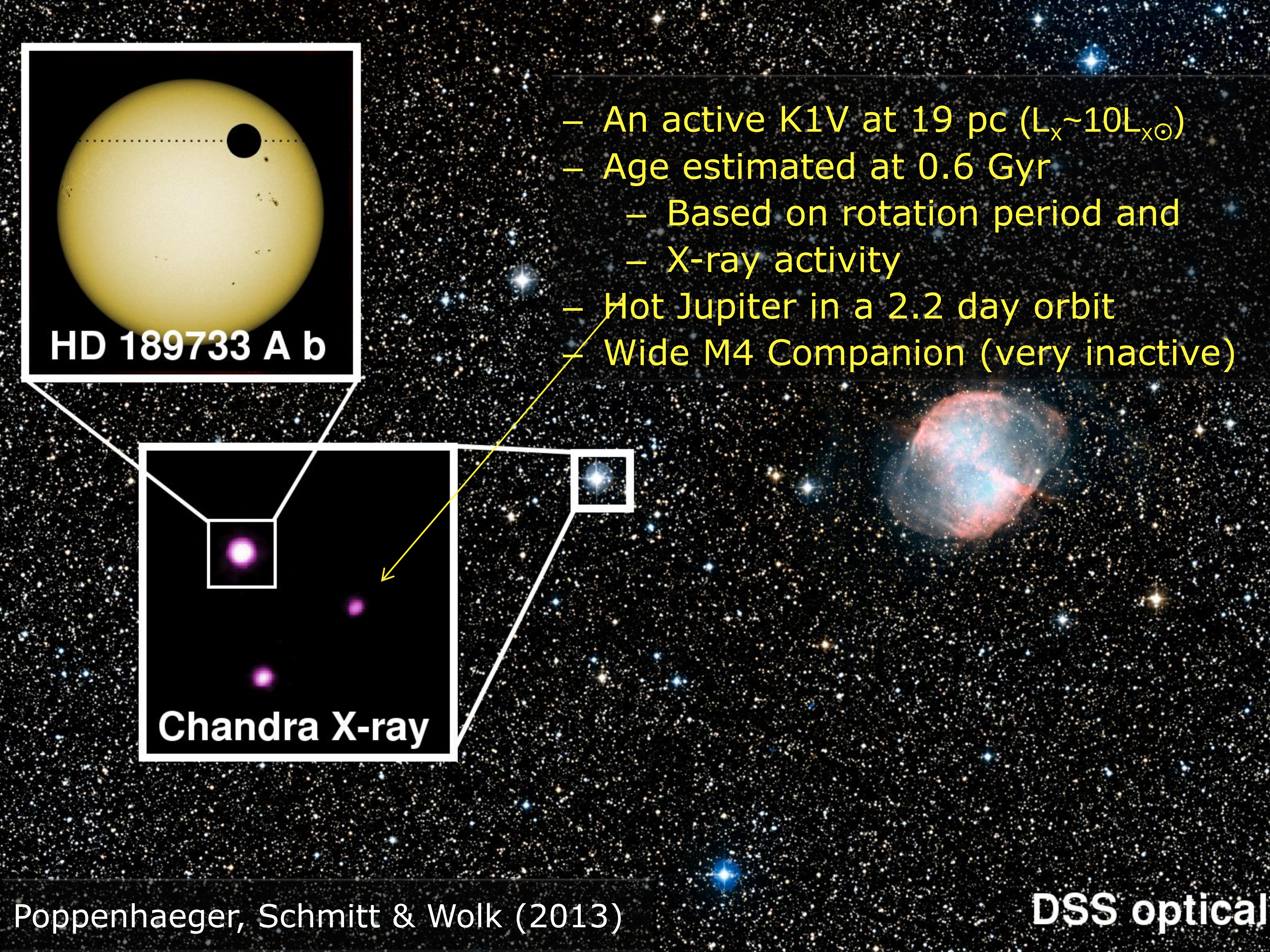
A UV flare only has a 1% effect on the depletion of the ozone layer of an Earth-like planet in the habitable zone of an M dwarf



A UV flare + proton event (>10 MeV) inferred from scaling from solar events, results in complete destruction of the ozone layer in the atmosphere of an Earth-like planet in the habitable zone of an M dwarf

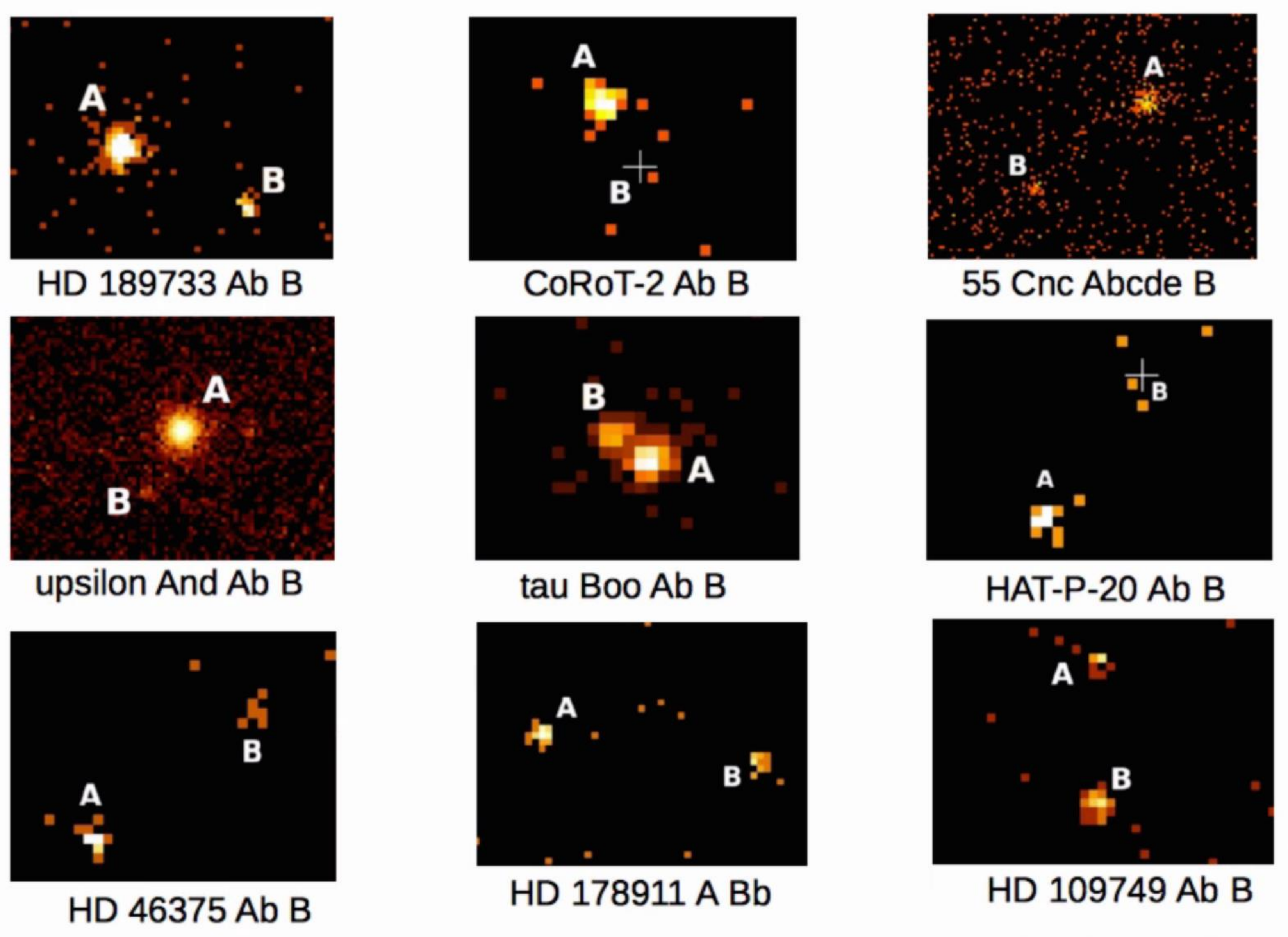
Segura et al. (2010)

- An active K1V at 19 pc (L_x~$10L_{x\odot}$)
- Age estimated at 0.6 Gyr
  - Based on rotation period and
  - X-ray activity
- Hot Jupiter in a 2.2 day orbit
- Wide M4 Companion (very inactive)

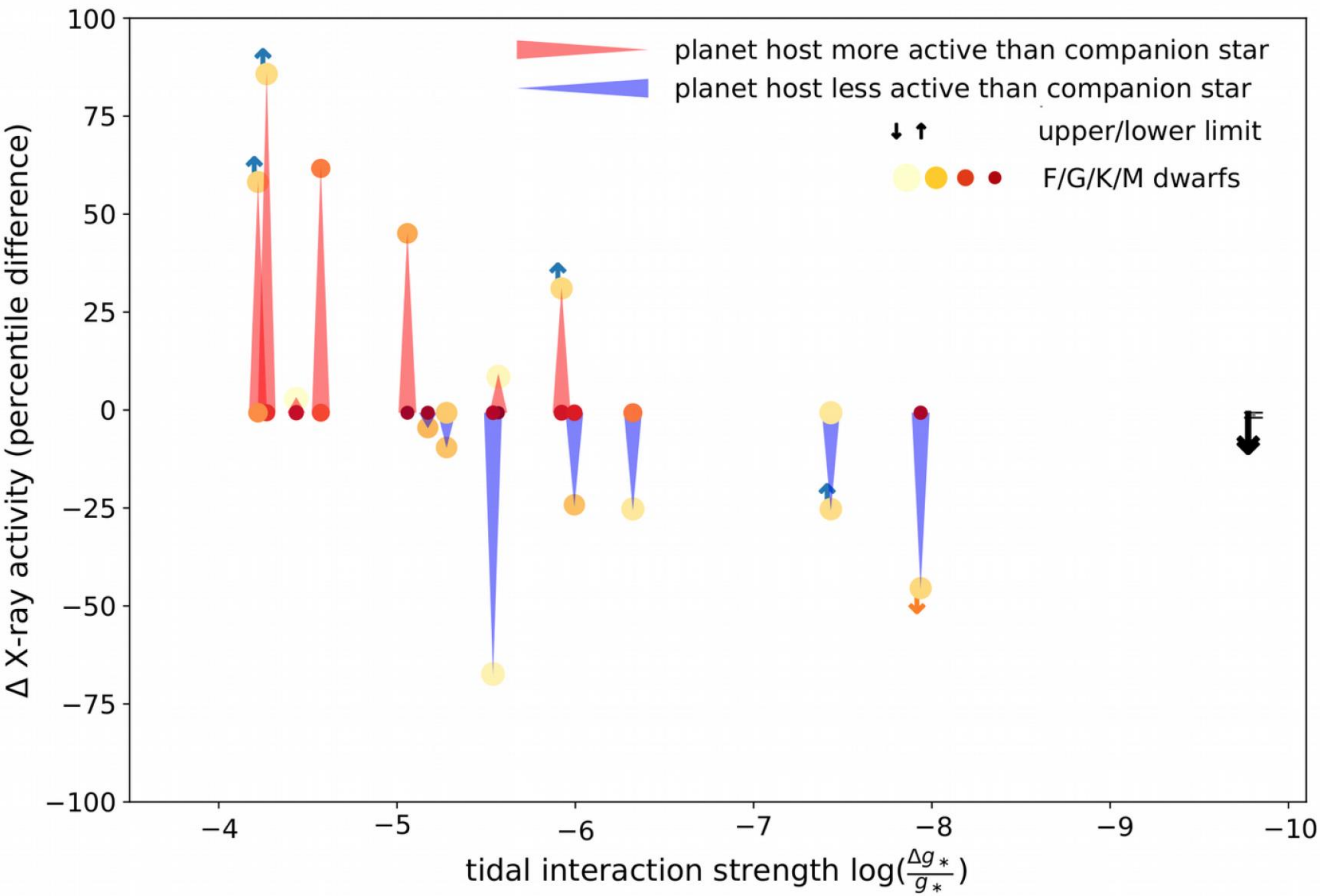


Poppenhaeger, Schmitt & Wolk (2013)

PLANET HOSTING WIDE BINARIES



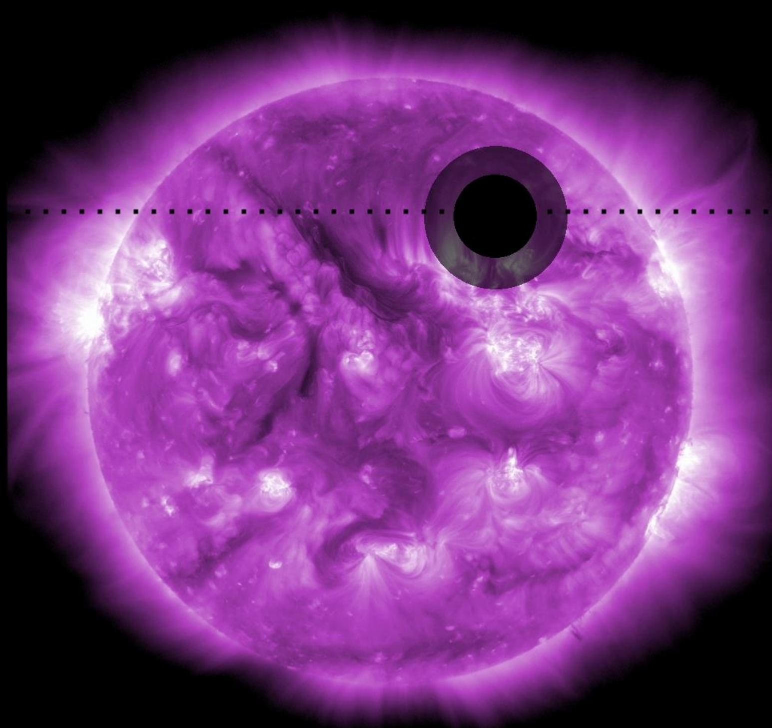
Several over-active systems

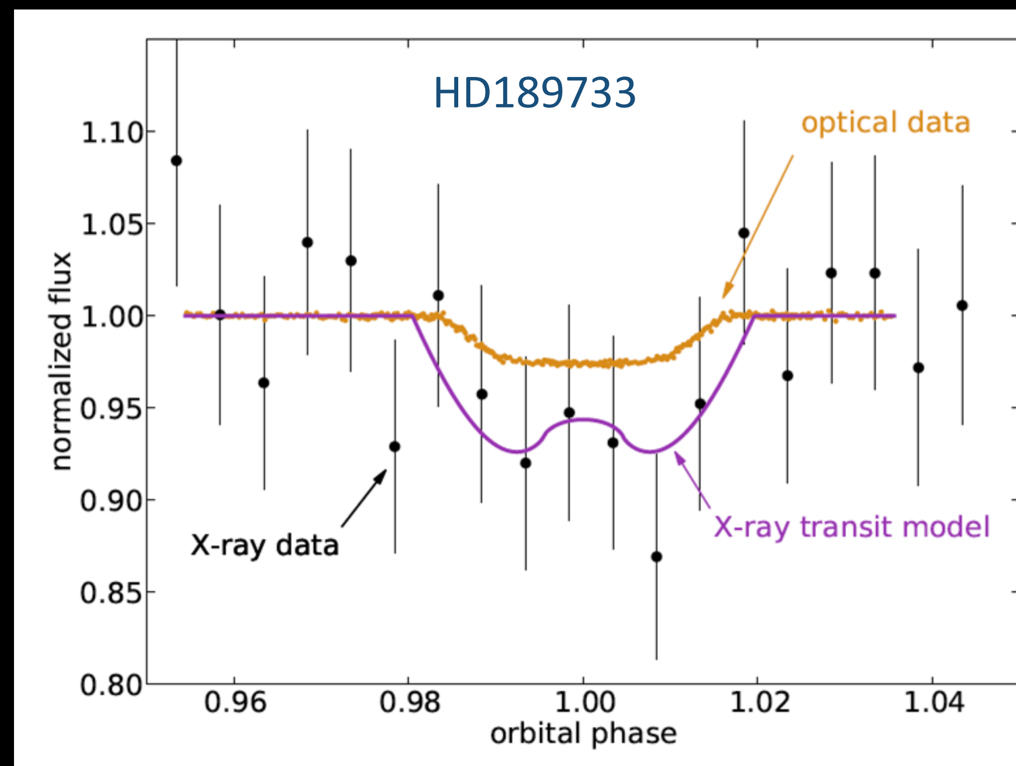


Measuring Exoplanet Atmospheres

How does the size of the exoplanet's atmosphere contribute to its mass loss?

- Planetary $\dot{M}$ depends on F_{XEUV}
- Larger estimated mass loss than if the planetary atmosphere is not extended
- Direct measures of atmospheric height





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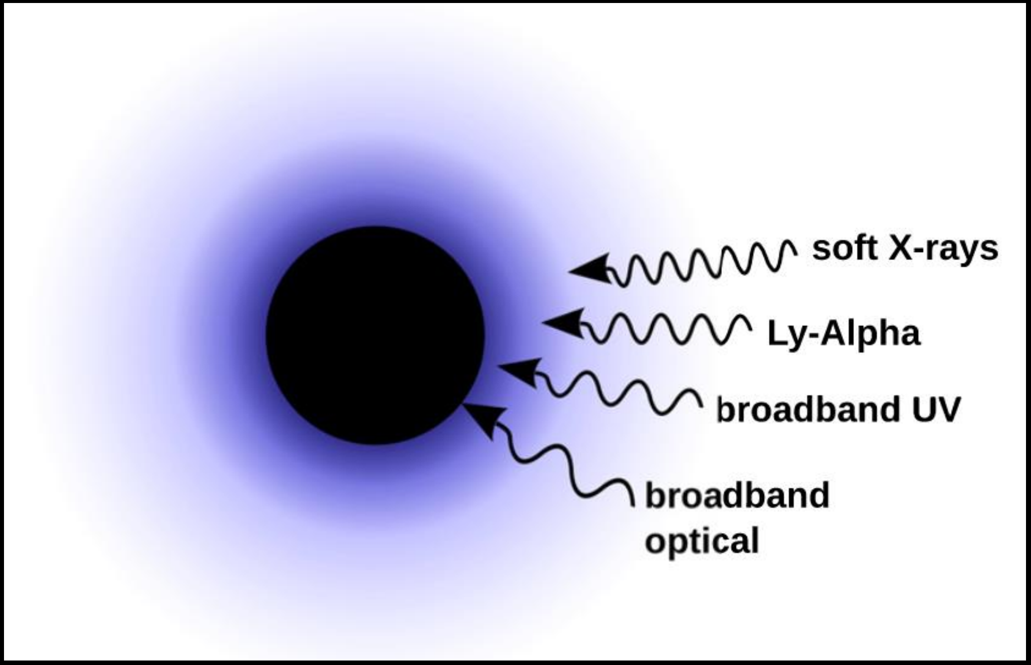
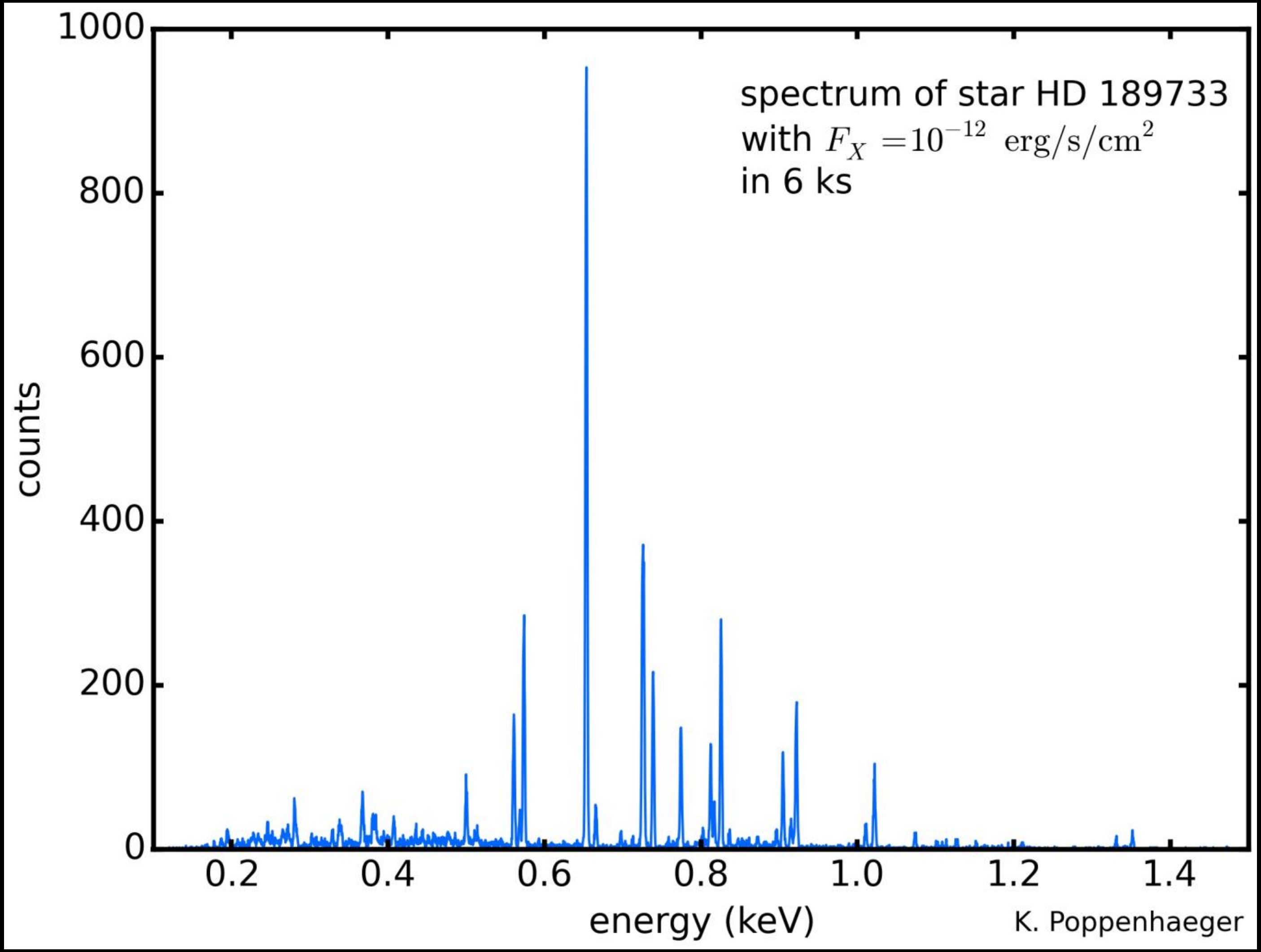
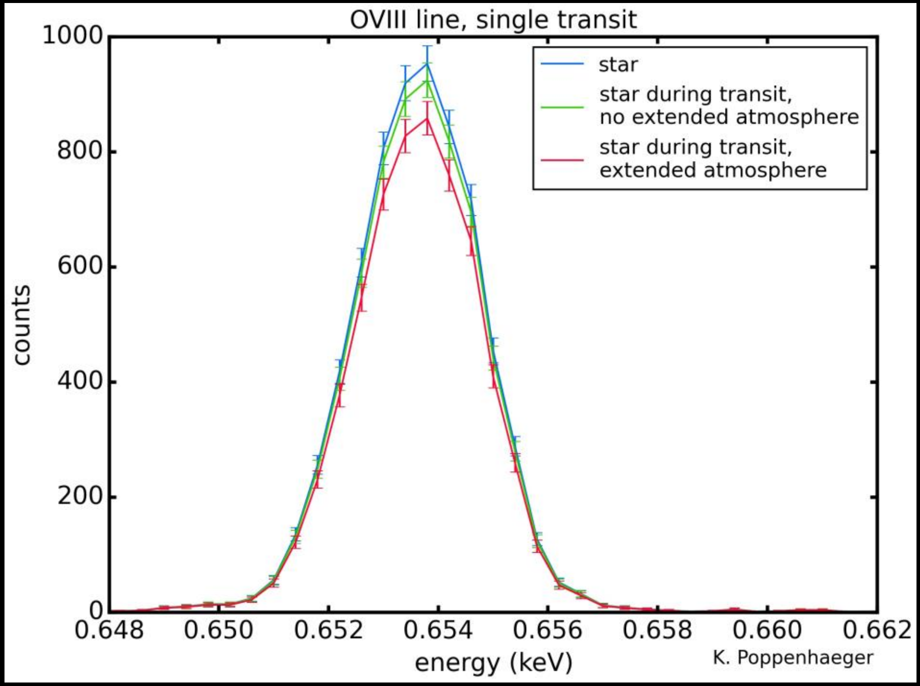


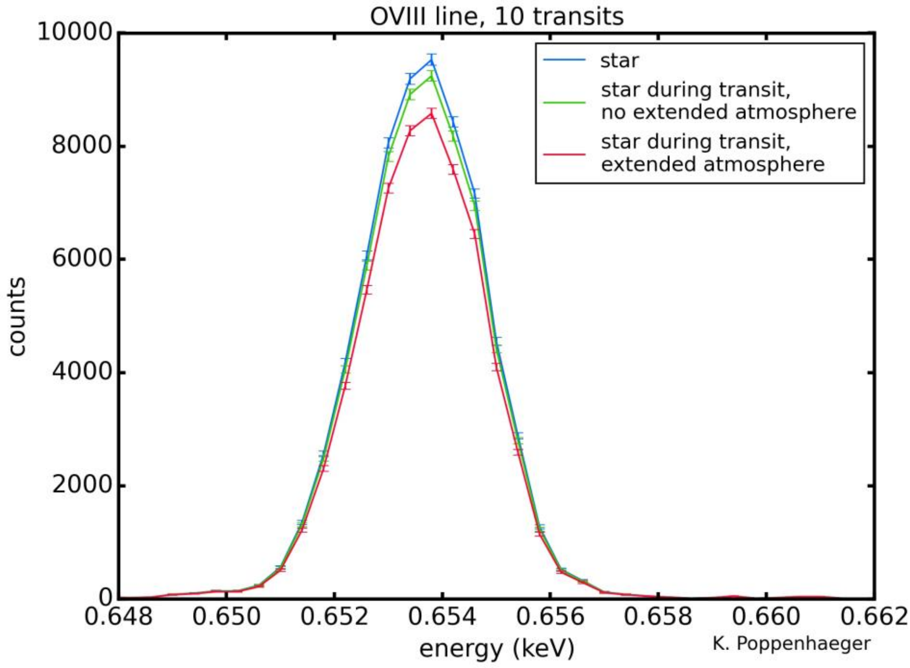
Poppenhaeger et al. (2013) for the hot Jupiter HD 189733b

Nominal Athena X-IFU Spectrum of HD 189733



Change of the OVIII line





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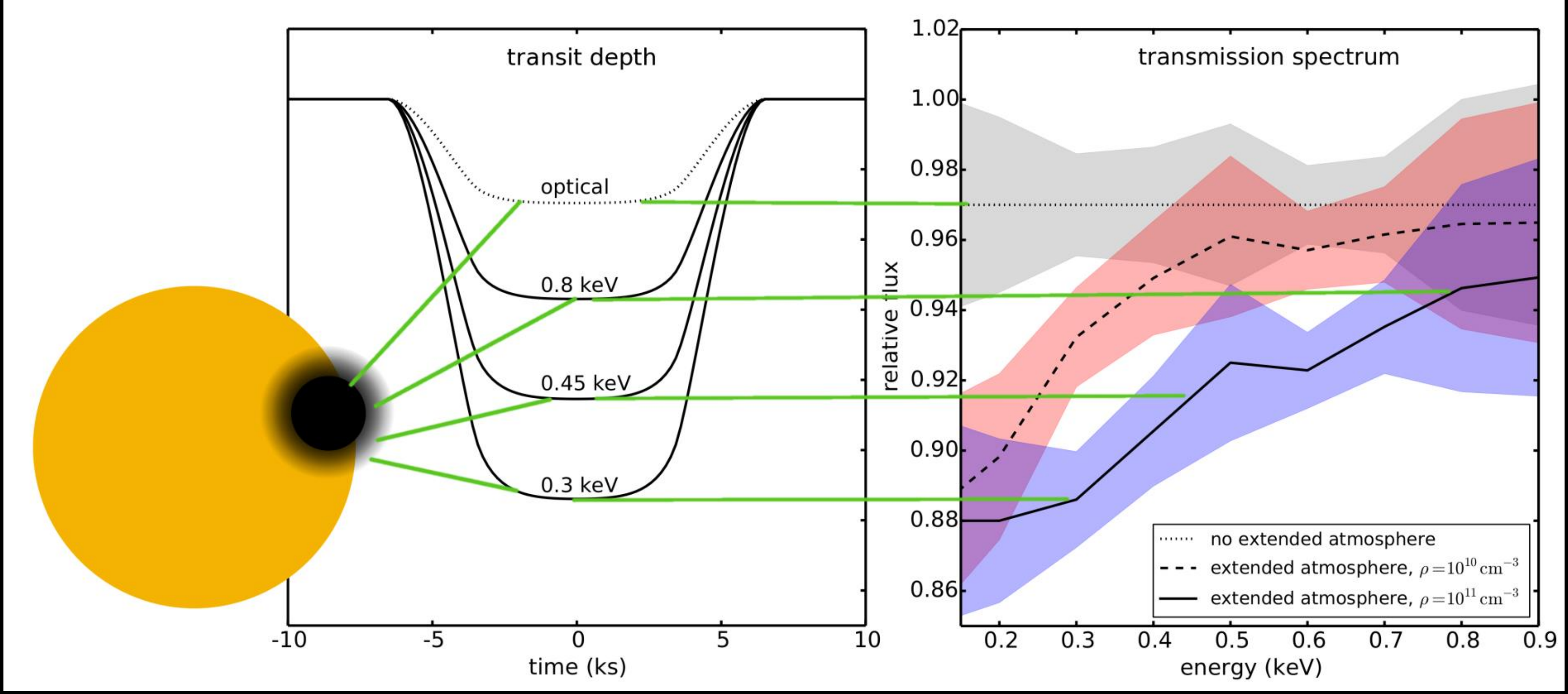


Future Exoplanet Stellar Studies

- Searching for habitability
- Focused on low mass M dwarfs
  - Habitable zones are closer to star
- Issues include destruction of atmosphere by:
  - Stellar flares and concurrent CME's
    - AD Leo can recover from massive flare/proton flux (Segura+ 2010)
  - Stellar UV to X-ray radiation
    - But UV is promising for catalyzing prebiotic chemistry (Ranjan & Sasselov 2016)
  - Stellar winds (Garaffo+ 2017; Wargelin & Drake 2002)
    - But planet's B field may channel particles only to polar regions (Driscoll+ 2013)

Potential Exoplanet Applications

The Athena will represent a major leap forward in X-ray capabilities

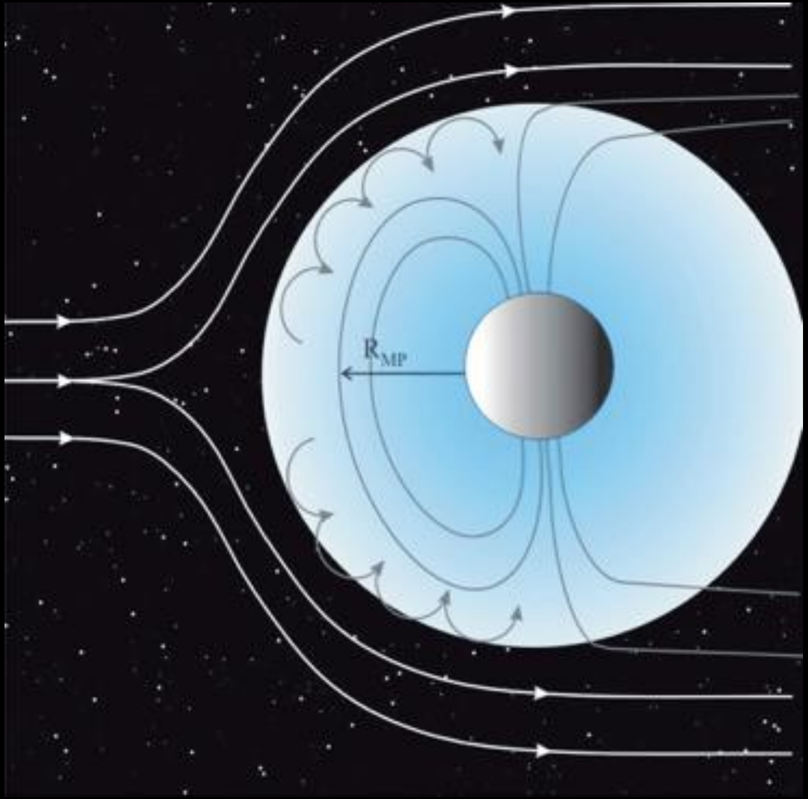
Athena will addresses questions relevant to furthering our understanding the energetic side of stellar ecosystems, constraining the impact of stellar activity on extrasolar planets and habitability:

- ✓ Where do planets form? How do they migrate?
- ✓ How does the coronal emission of stars affect exoplanets?
- ✓ How do Coronal Mass Ejections affect exoplaents
- ✓ How do the characteristics of flares change with time, and what impact does this have on exoplanet conditions?
- ✓ How do stellar winds change with time, and what impact does this have on exoplanet conditions?
- ✓ What kinds of systems show spin-up and create activity on their host stars.
- ✓ How does the size of the exoplanet's atmosphere contribute to its mass loss?

Measuring Exoplanet Environments

How do stellar winds change with time and what impact does this have on exoplanet conditions?

- Stellar wind mass loss critical to atmospheric escape process
- Detect charge exchange emission from nearest ~20 stars to constrain $\dot{M}$
- Coronal mass ejections play an important role in potential habitability; need a way to constrain them



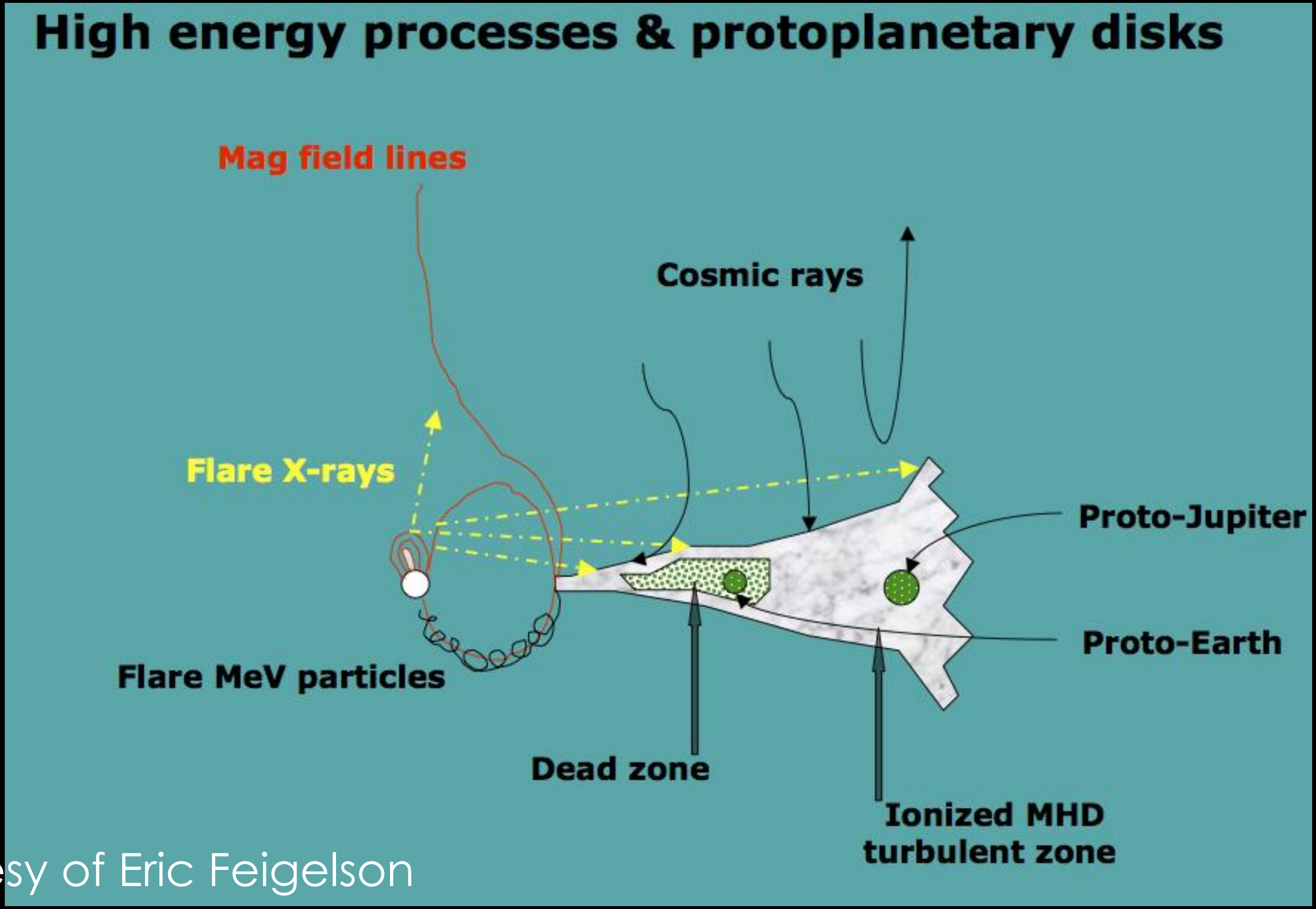
Future capabilities give several ways to detect CMEs:

1. Changes in column density during a flare
2. Detection of coronal dimming
3. Velocity signatures in the line profile

Potential Exoplanet Applications

Where do planets form? Where do they migrate?

- X-ray spectra of young stars show more than accretion plus magnetic activity
- X-rays implicated in rapid heating of protoplanetary disks
- After stars lose their disks X-ray surveys are the only way to find young stellar objects



Slide courtesy of Eric Feigelson

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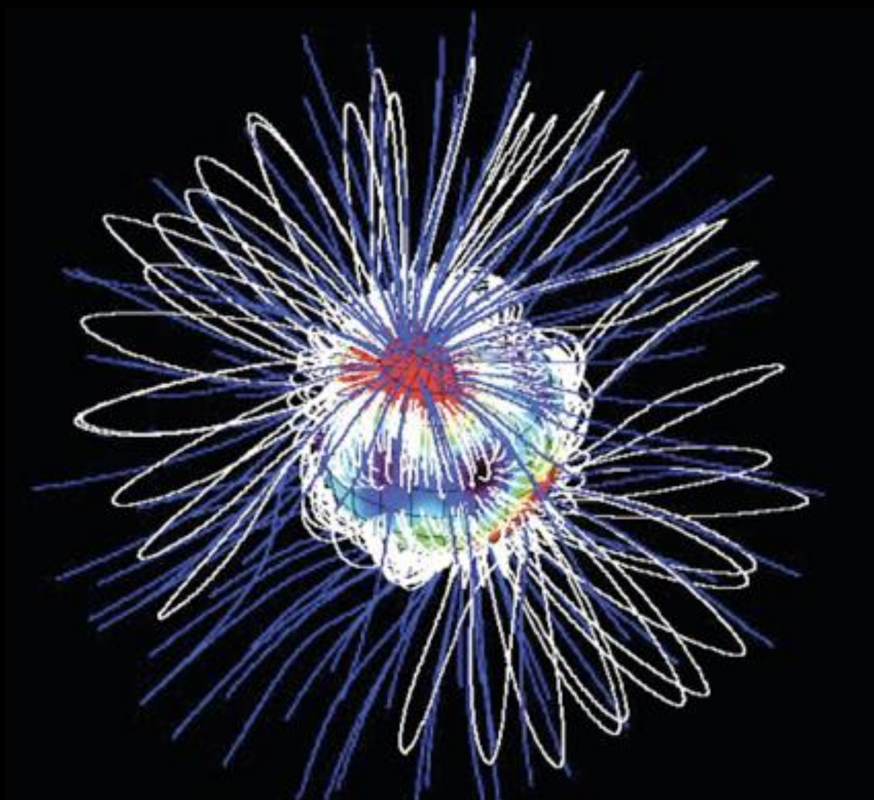
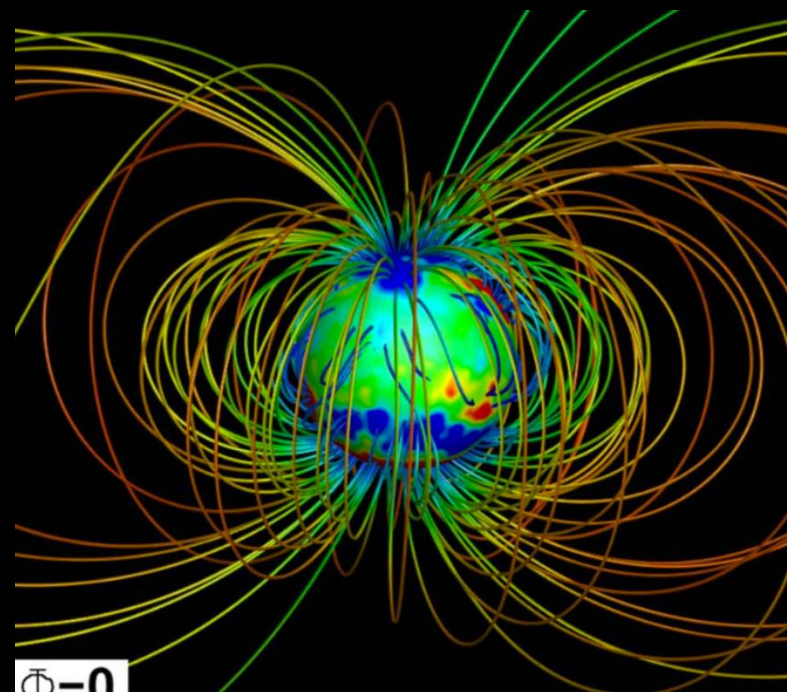


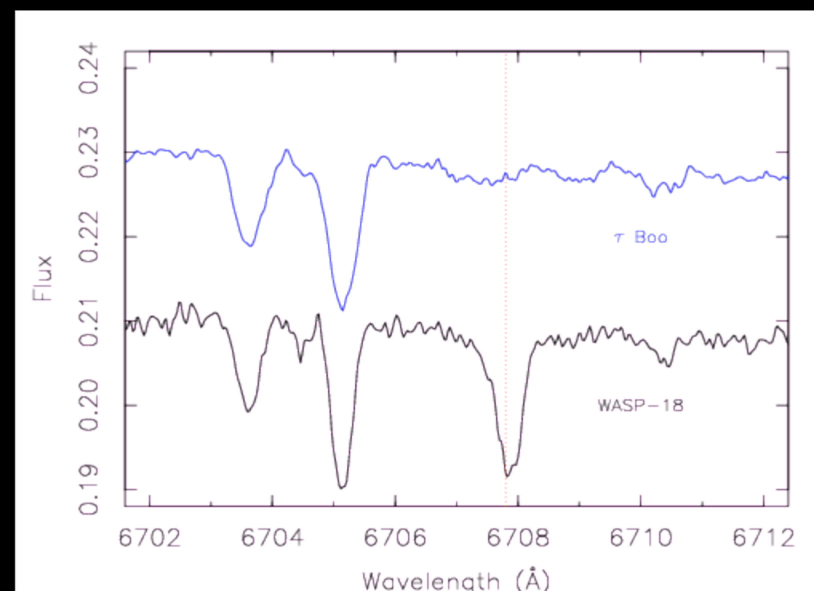
Donati & Landstreet (2009) extrapolation from photospheric magnetic field



Cohen et al. (2017) dynamo simulation

WASP-18 another kind of extreme

WASP 18 is YOUNG



Pillitteri et al. (2014)

Single star:
Young F6
WASP-18b 10.4 M_j, a~0.02 AU
P_{rot} =22.6h

L_x WASP-18 $< 10^{26.5}$ erg/s
L_x Tau Boo ~ 10^{28} erg/s
L_x Procyon ~ 10^{28} erg/s

WASP-18 another kind of extreme

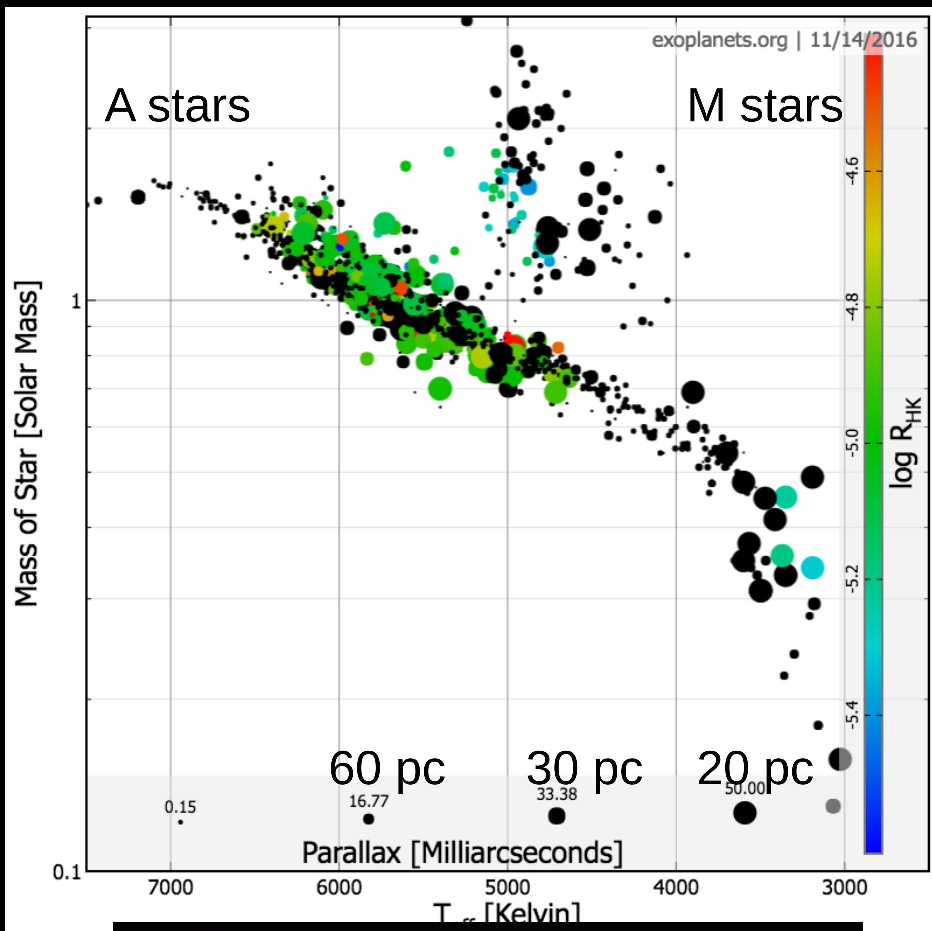
Star	T_{eff} K	R_{star} $R_{\odot}$	M_{star} $M_{\odot}$	M_{planet} M_{Jup}	Separation AU	$\log R'_{HK}$	H_P km	H_t km	H_t/H_P
WASP-18	6400	1.29	1.28	10.43	0.02047	-5.43	419	498.3	1.189
WASP-12	6300	1.599	1.35	1.404	0.02293	-5.5	600.1	122.3	0.204
WASP-14	6475	1.306	1.211	7.341	0.036	-4.923	458.7	44	0.096
XO-3	6429	1.377	1.213	11.79	0.0454	-4.595	505.5	39.4	0.078
HAT-P-7	6350	1.84	1.47	1.8	0.0379	-5.018	735.5	37.2	0.051
HAT-P-2	6290	1.64	1.36	8.74	0.0674	-4.78	625.6	14.6	0.023
Kepler-5	6297	1.793	1.374	2.114	0.05064	-5.037	740.9	14.1	0.019
HAT-P-14	6600	1.468	1.386	2.2	0.0594	-4.855	516	3.4	0.007
HAT-P-6	6570	1.46	1.29	1.057	0.05235	-4.799	545.9	2.6	0.005
Kepler-8	6213	1.486	1.213	0.603	0.0483	-5.05	568.8	2.3	0.004
WASP-17	6650	1.38	1.2	0.486	0.0515	-5.331	530.7	1.1	0.002
HAT-P-9	6350	1.32	1.28	0.67	0.053	-5.092	434.7	1	0.002
WASP-19	5500	1.004	0.904	1.114	0.01616	-4.66	308.5	55.2	0.179

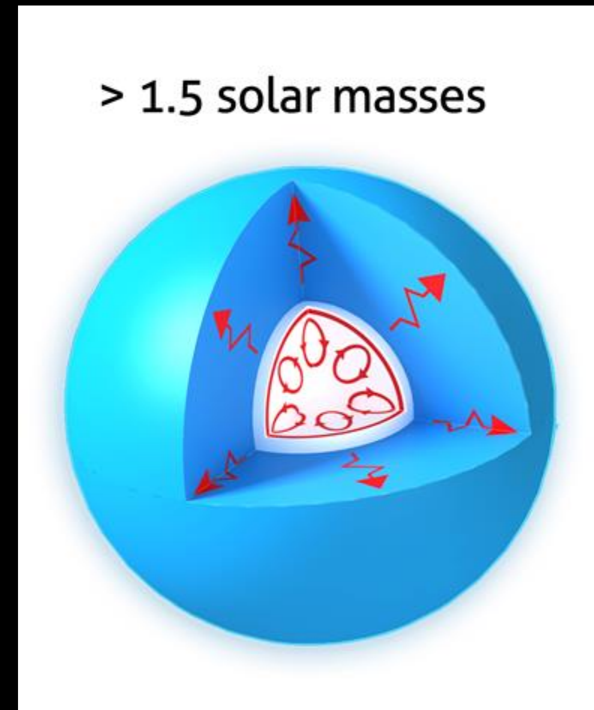
Pillitteri et al. (2014)

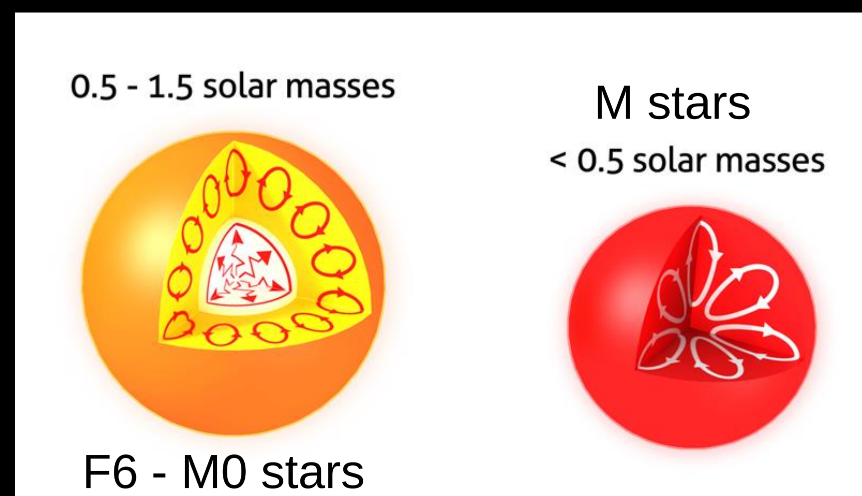
SOME EXOPLANET SYSTEMS

ESO

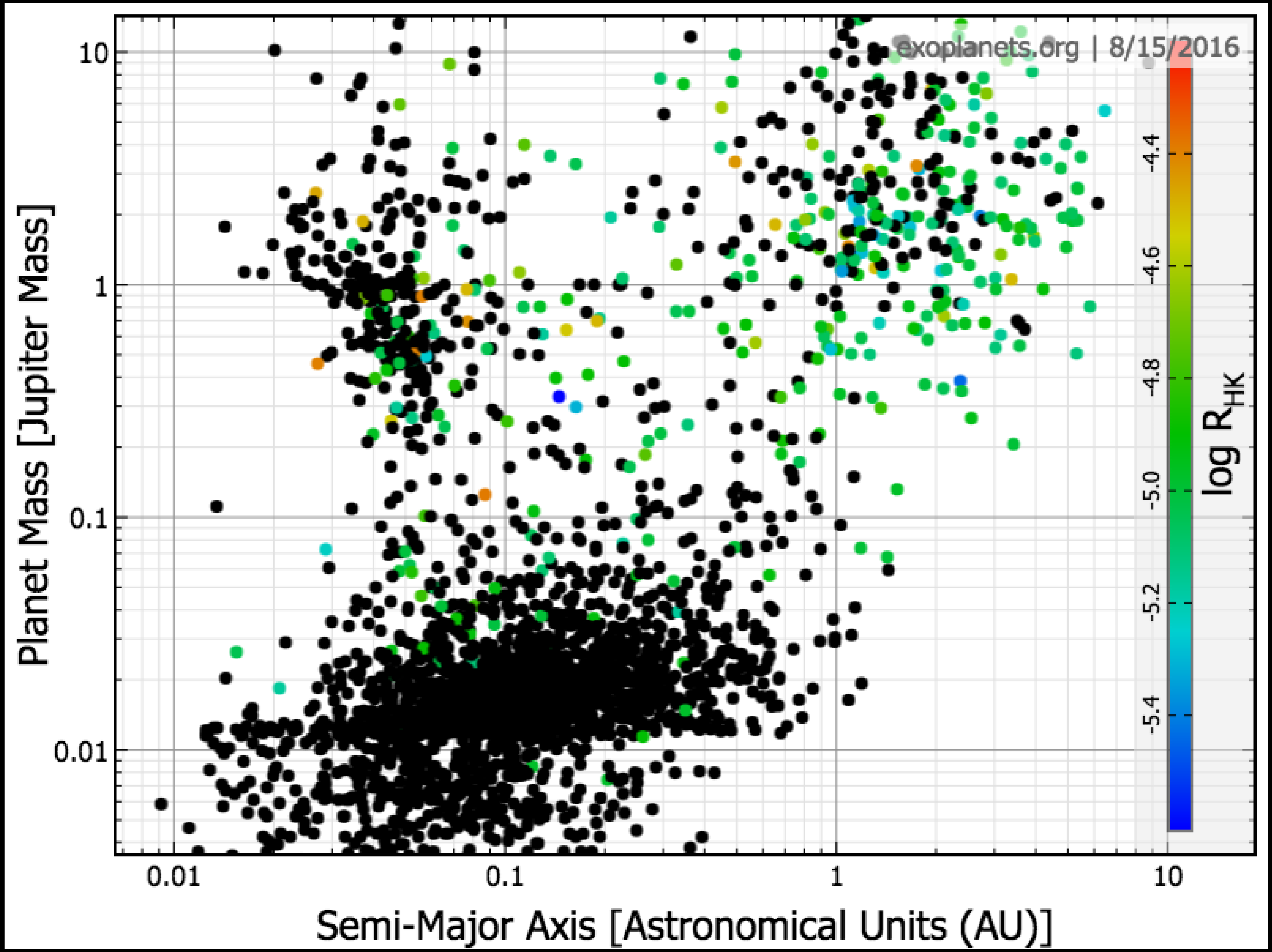
~2000 EXOPLANET HOSTS







THE EXOPLANET ZOO



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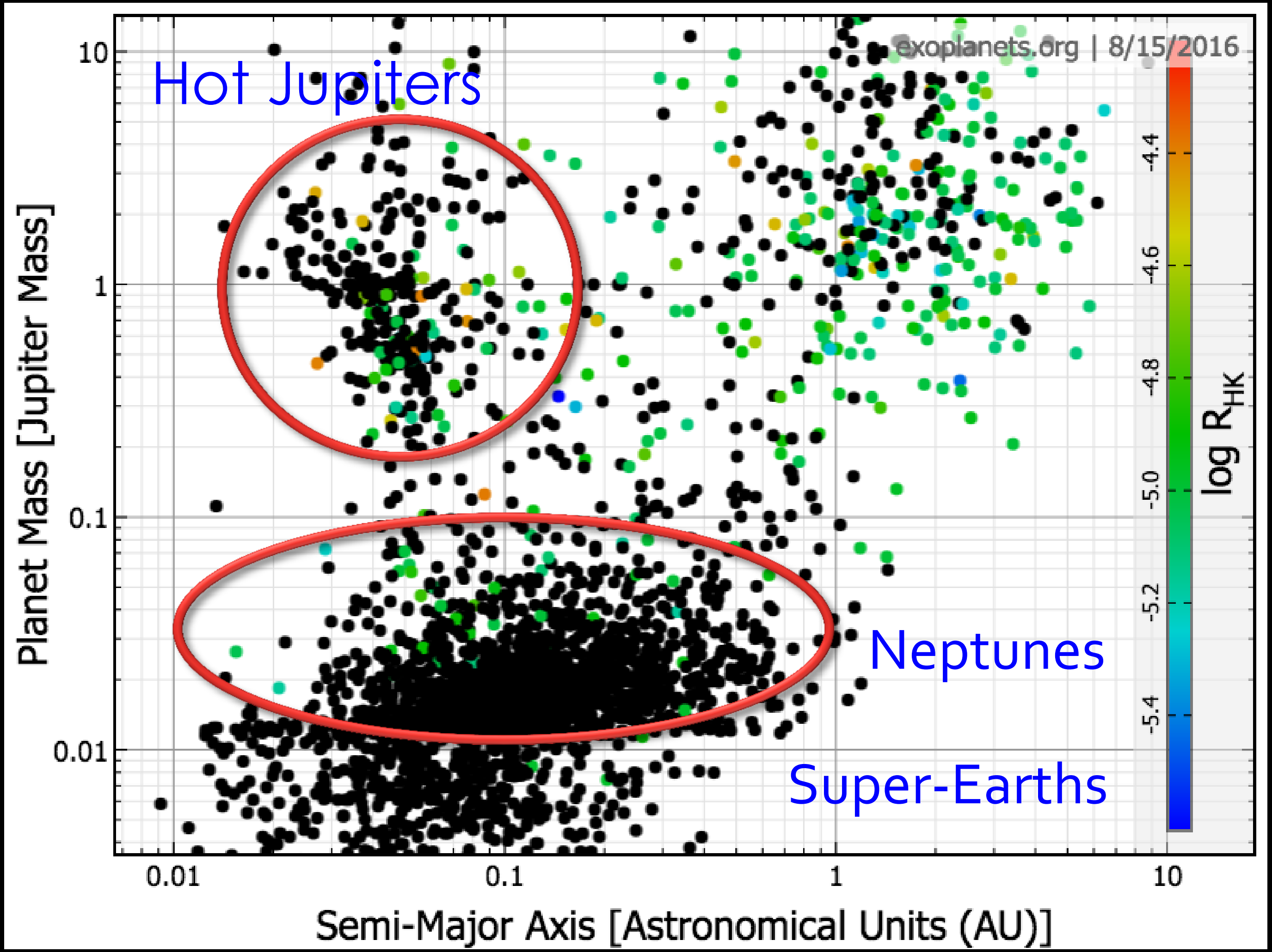

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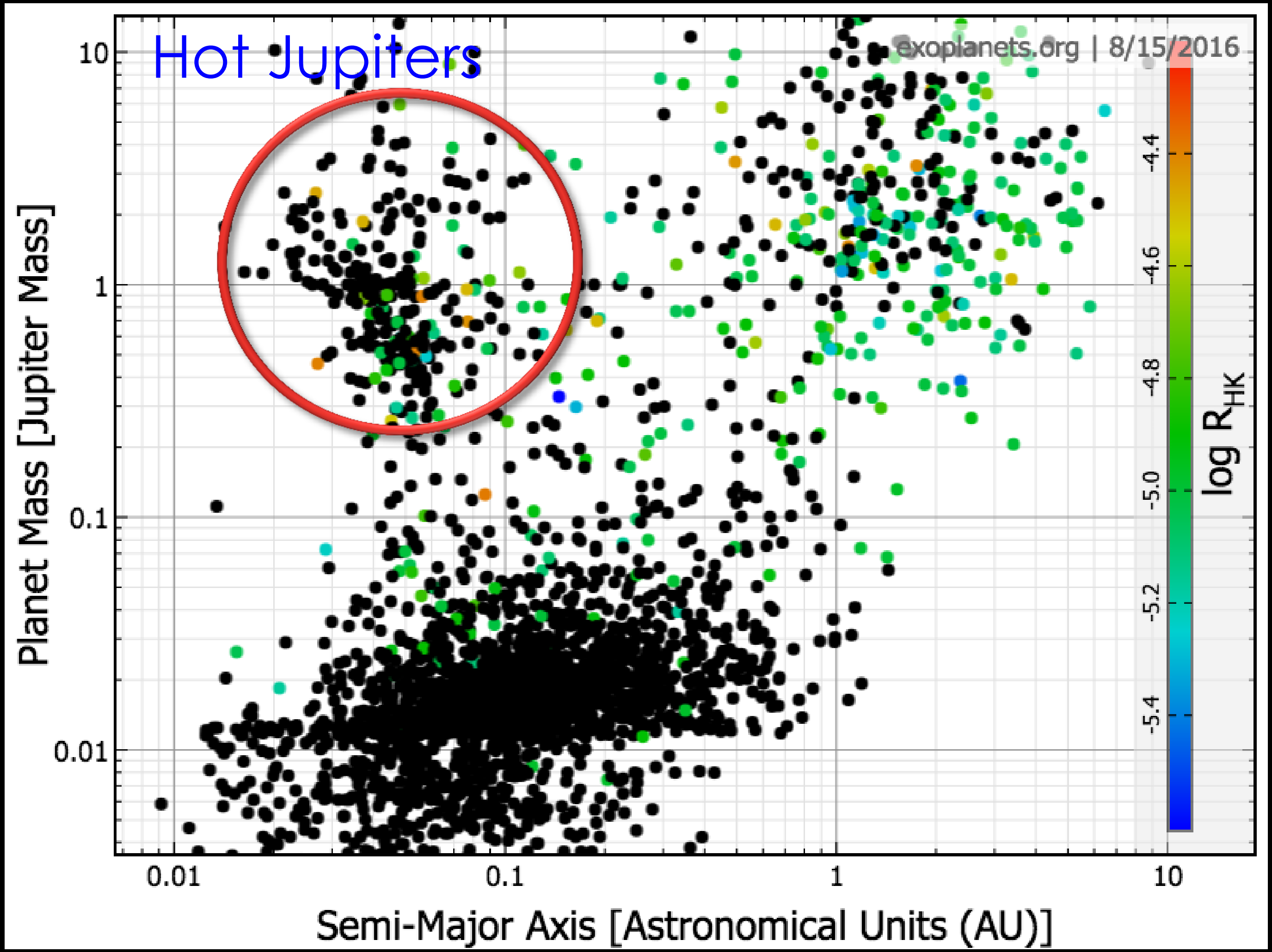

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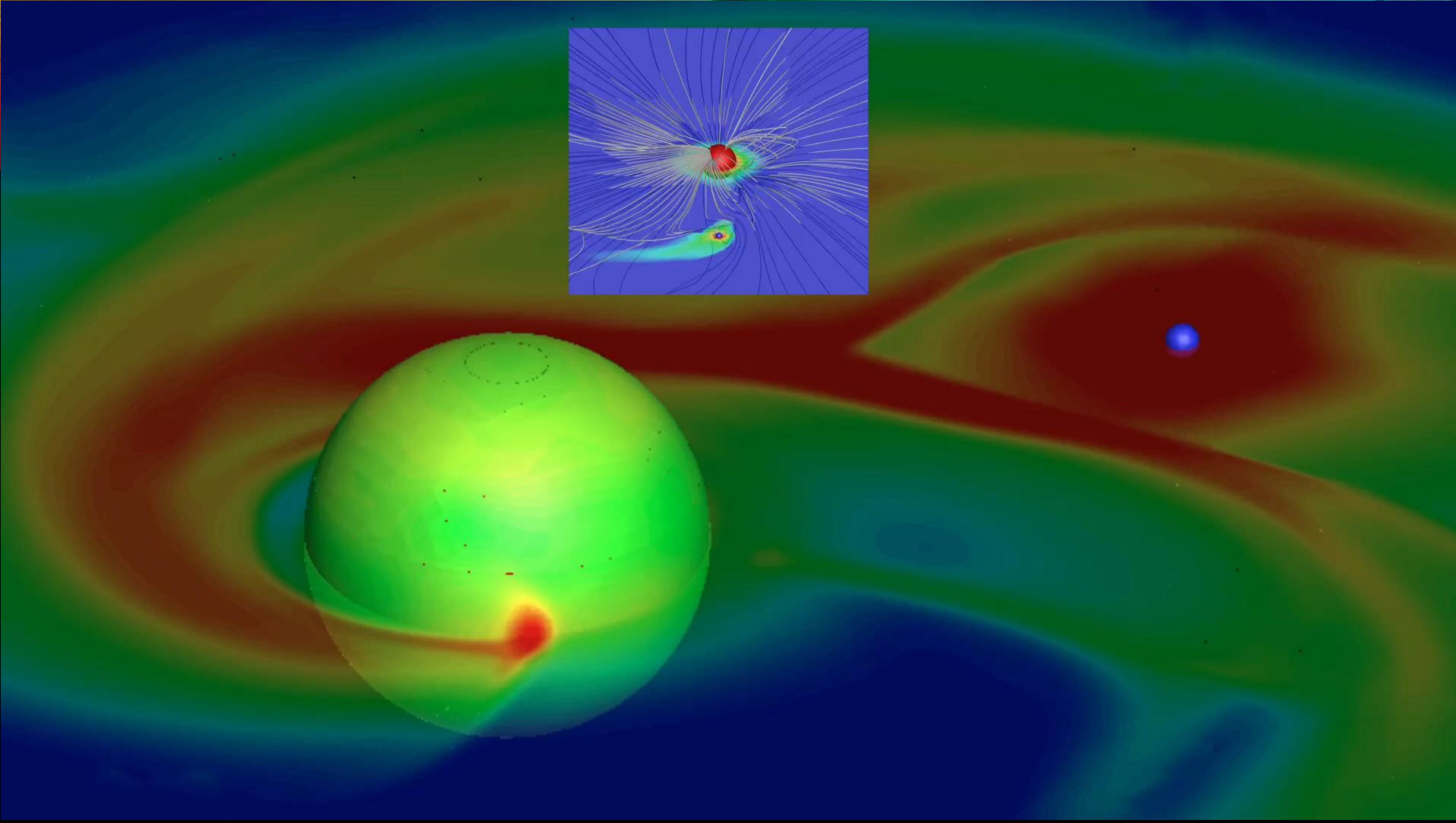
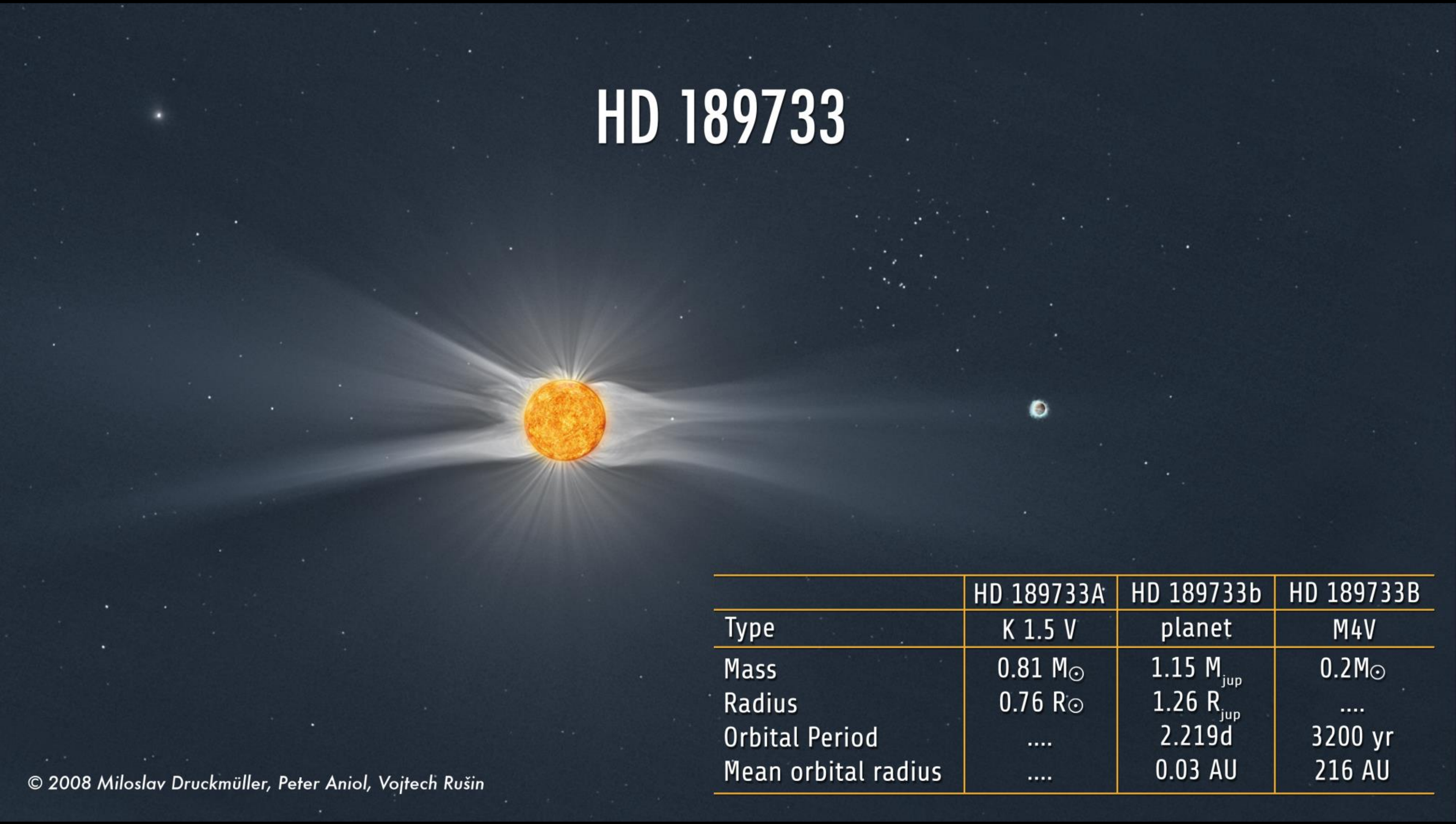


Cohen et al. (2011)

ONE EXTREME SYSTEM

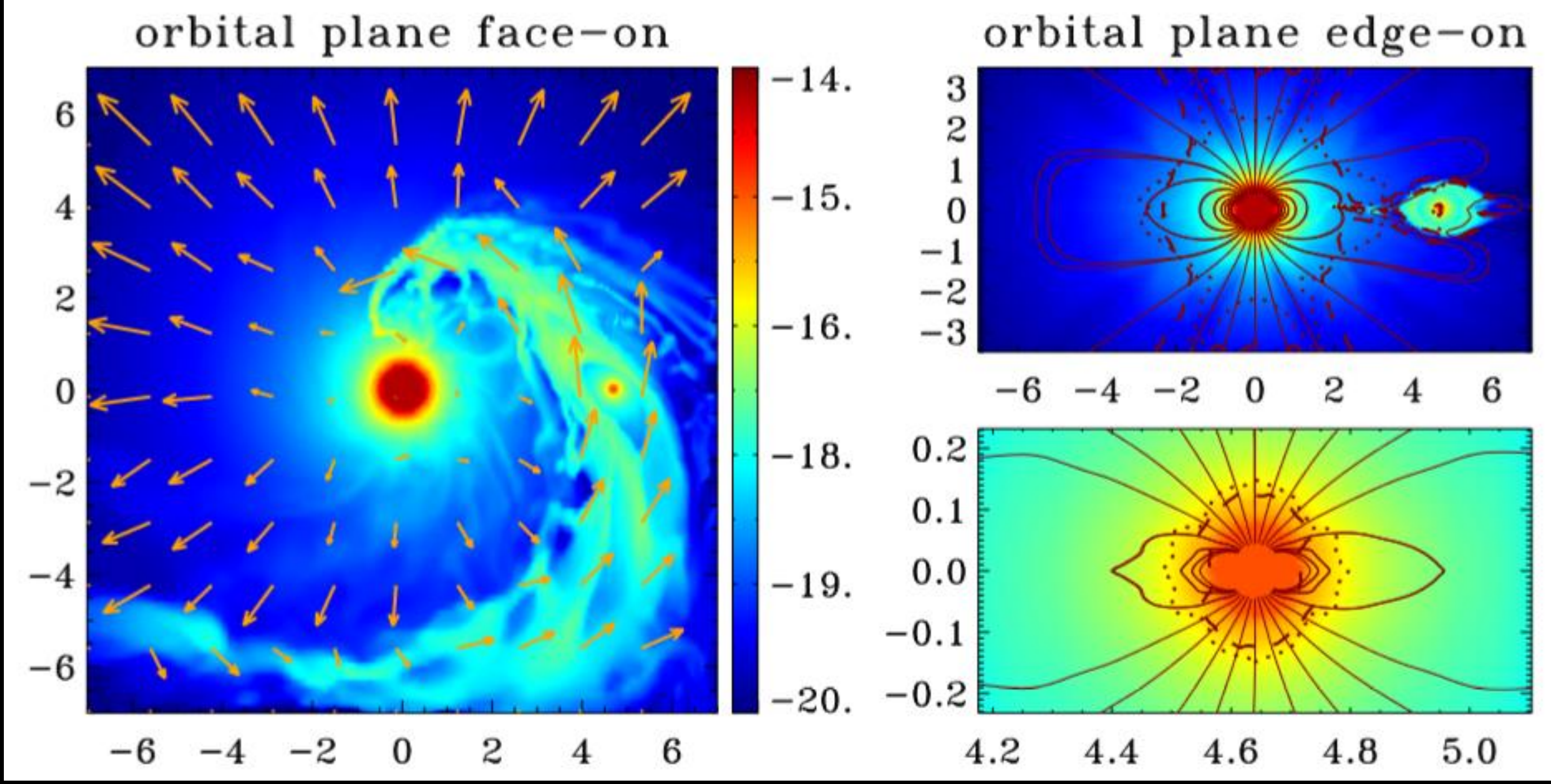


	HD 189733A	HD 189733b	HD 189733B
Type	K 1.5 V	planet	M4V
Mass	0.81 $M_\odot$	1.15 M_{jup}	0.2$M_\odot$
Radius	0.76 $R_\odot$	1.26 R_{jup}	....
Orbital Period	....	2.219d	3200 yr
Mean orbital radius	....	0.03 AU	216 AU

Plausibility Argument: Accreting Streams and Tails

⊕

High UV, ~ M_{jup}



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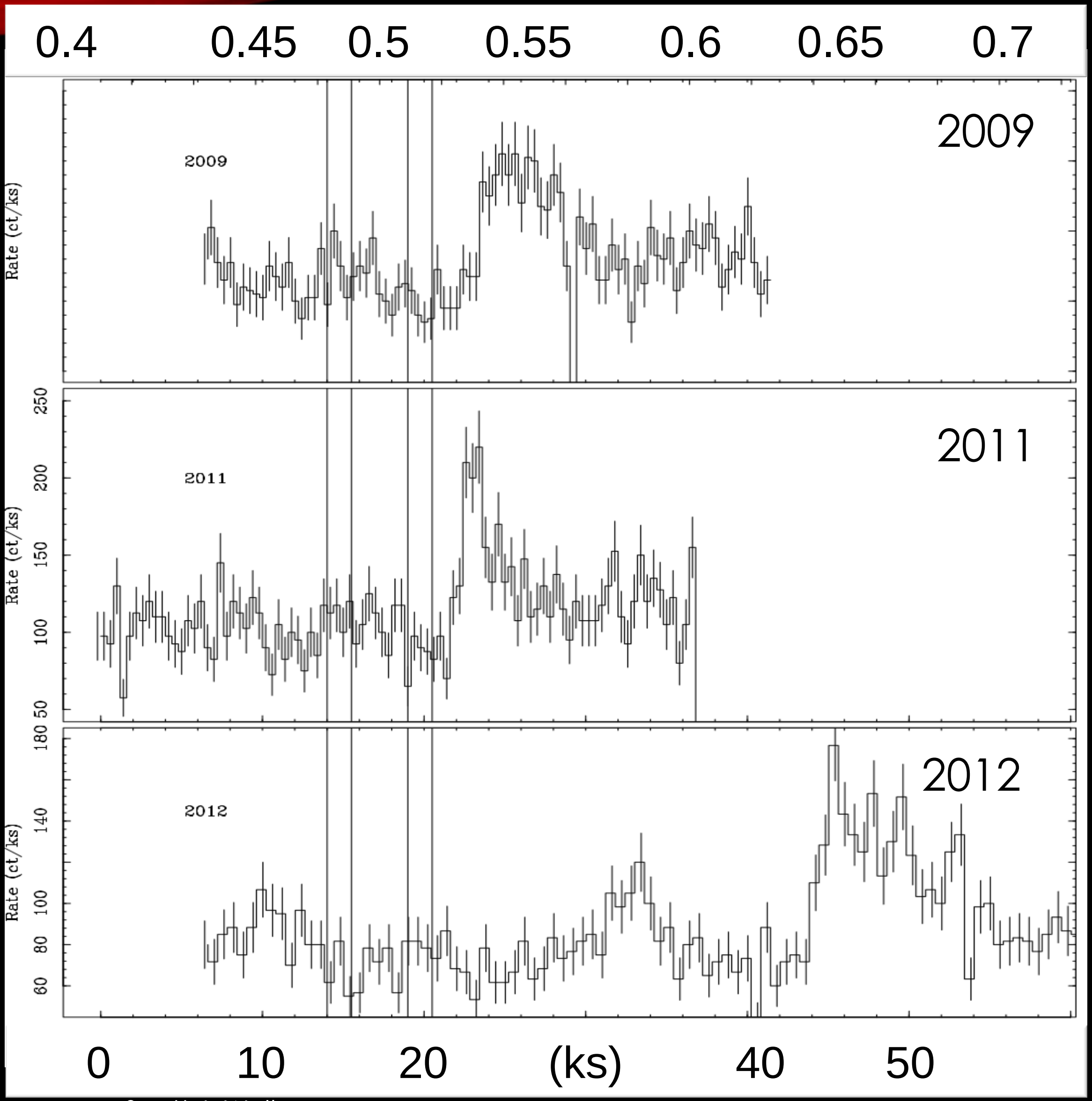
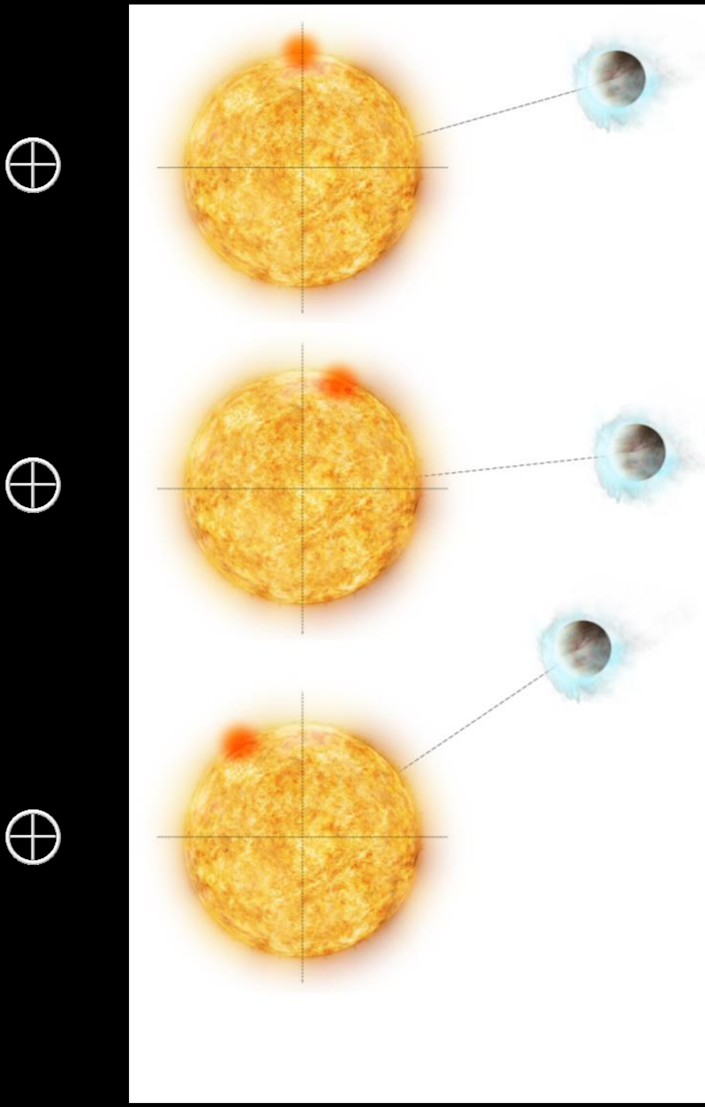
see Matsakos et al. (2015)

Phased Time Variability?

Pillitteri et al. (2014)





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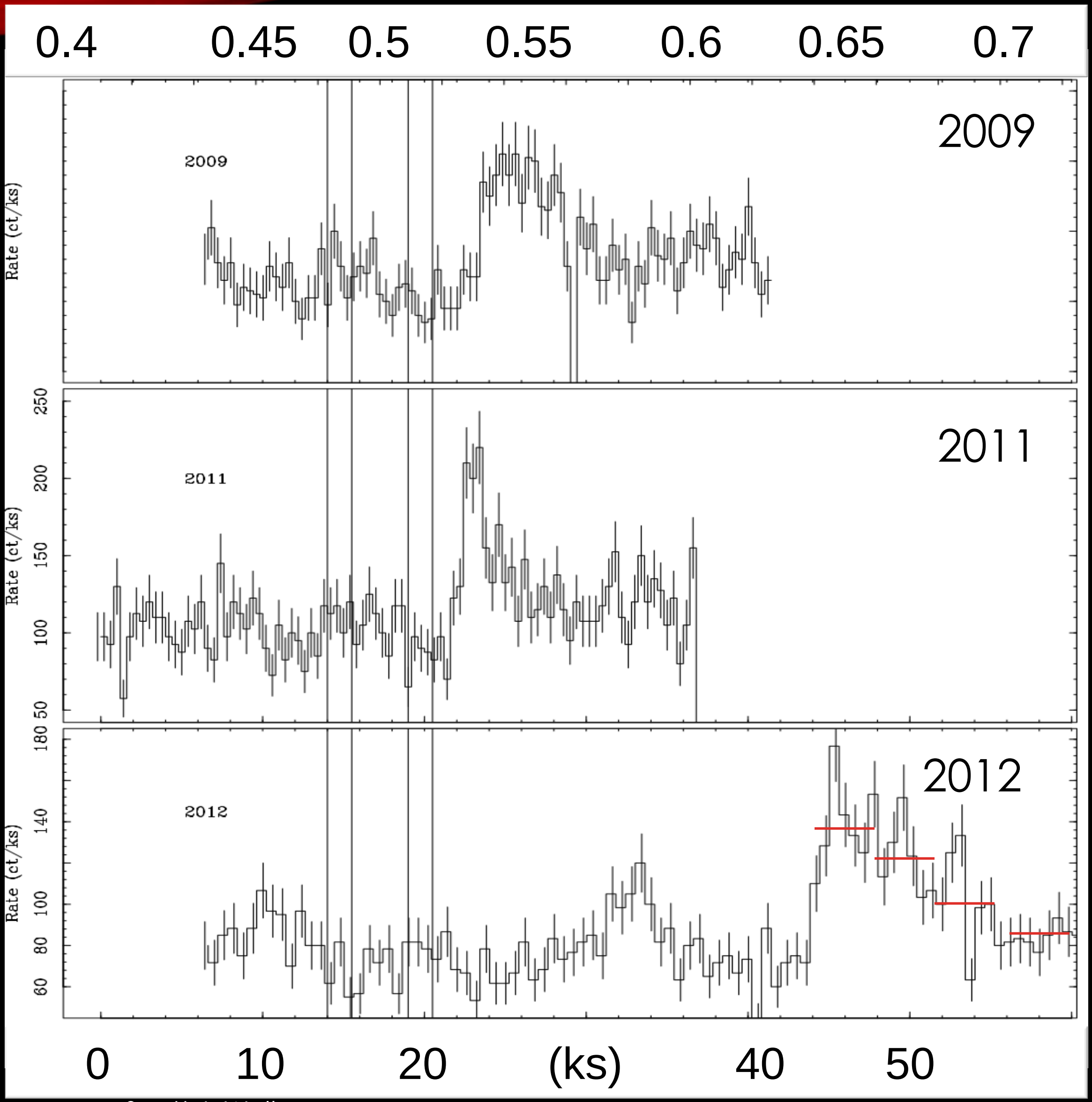
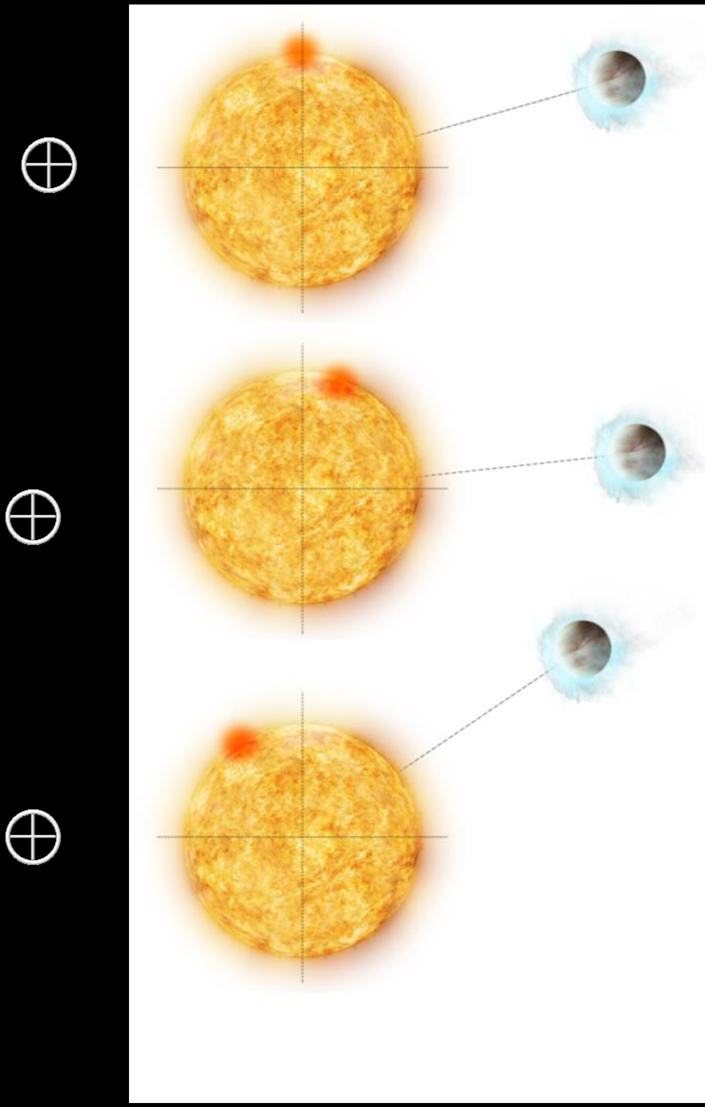
Long Lengthed Flare?

Pillitteri et al. (2014)





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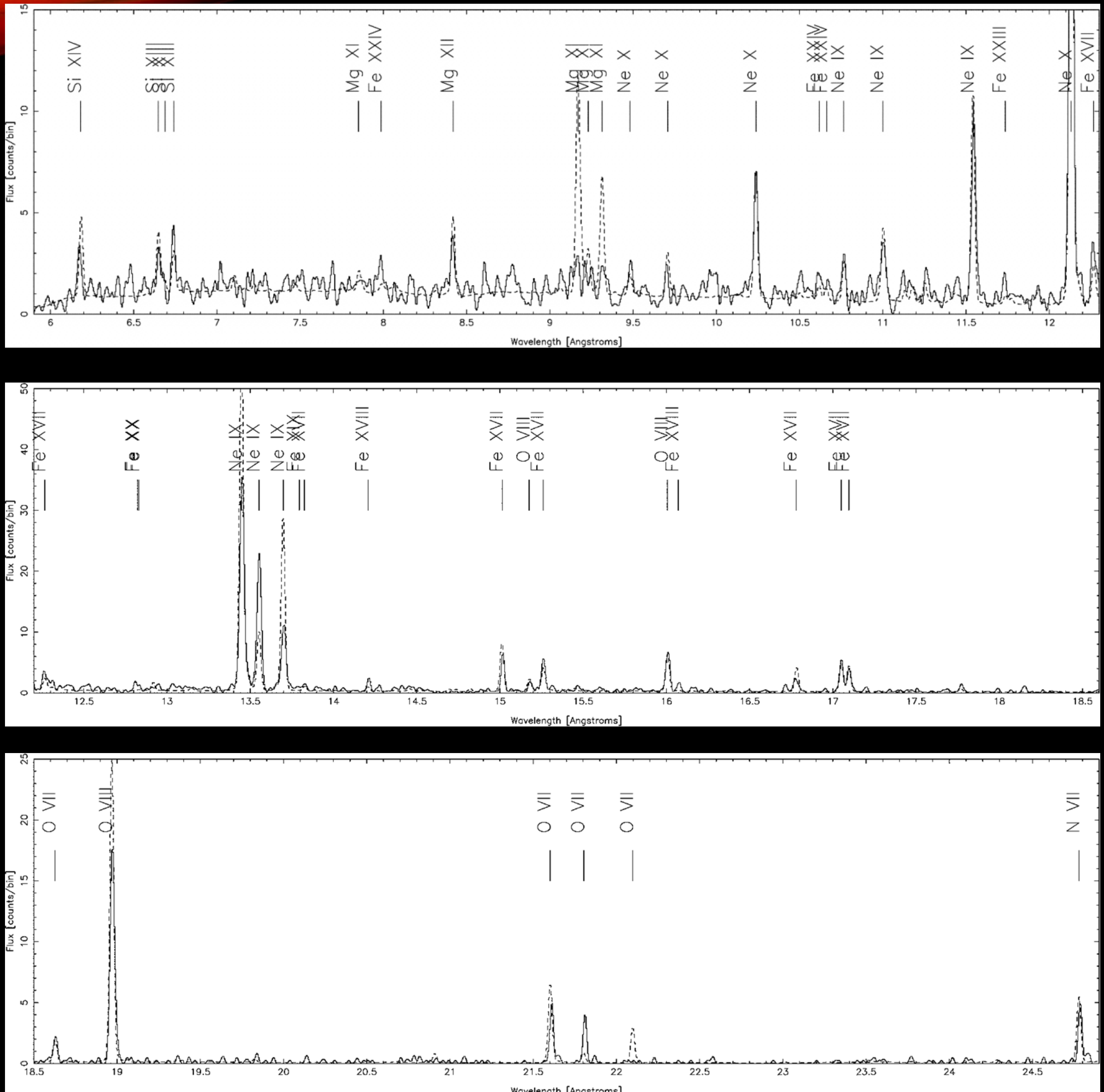
Conclusions

The Observatories of the next decade will represent a major leap forward in X-ray capabilities

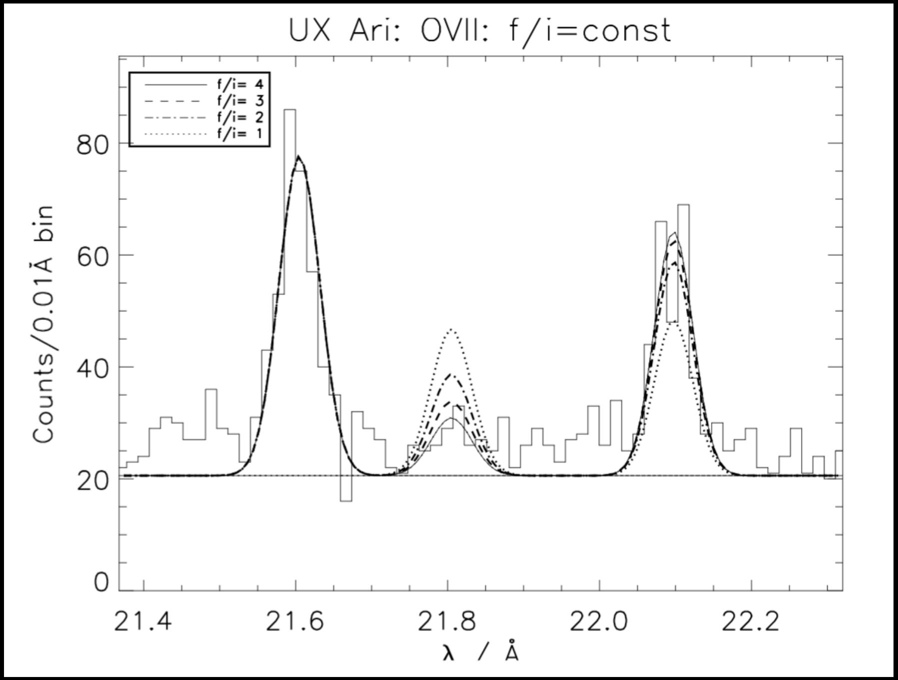
These missions will addresses questions relevant to furthering our understanding the energetic side of stellar ecosystems, constraining the impact of stellar activity on extrasolar planets and habitability:

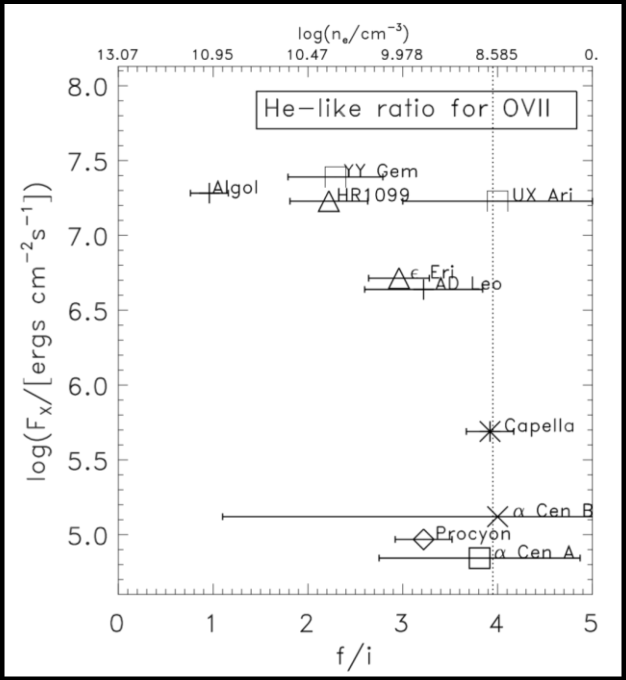
- ✓ Where do planets form? How do they migrate?
- ✓ How does the coronal emission of stars affect exoplanets?
- ✓ How do the characteristics of flares change with time, and what impact does this have on exoplanet conditions?
- ✓ How do stellar winds change with time, and what impact does this have on exoplanet conditions?
- ✓ How does the size of the exoplanet's atmosphere contribute to its mass loss?


Si XIV
Mg XI
Fe XXIV
Mg XII
Ne X
Ne IX
Fe XXIII
Fe XVII
Fe XX
Fe XVIII
O VIII
O VII
N VII
Flux [counts/bin]
Wavelength [Angstroms]

Densities

Need ability to resolve lines from nearby blends, underlying continuum
Densities enable constraints on length scales, dynamics

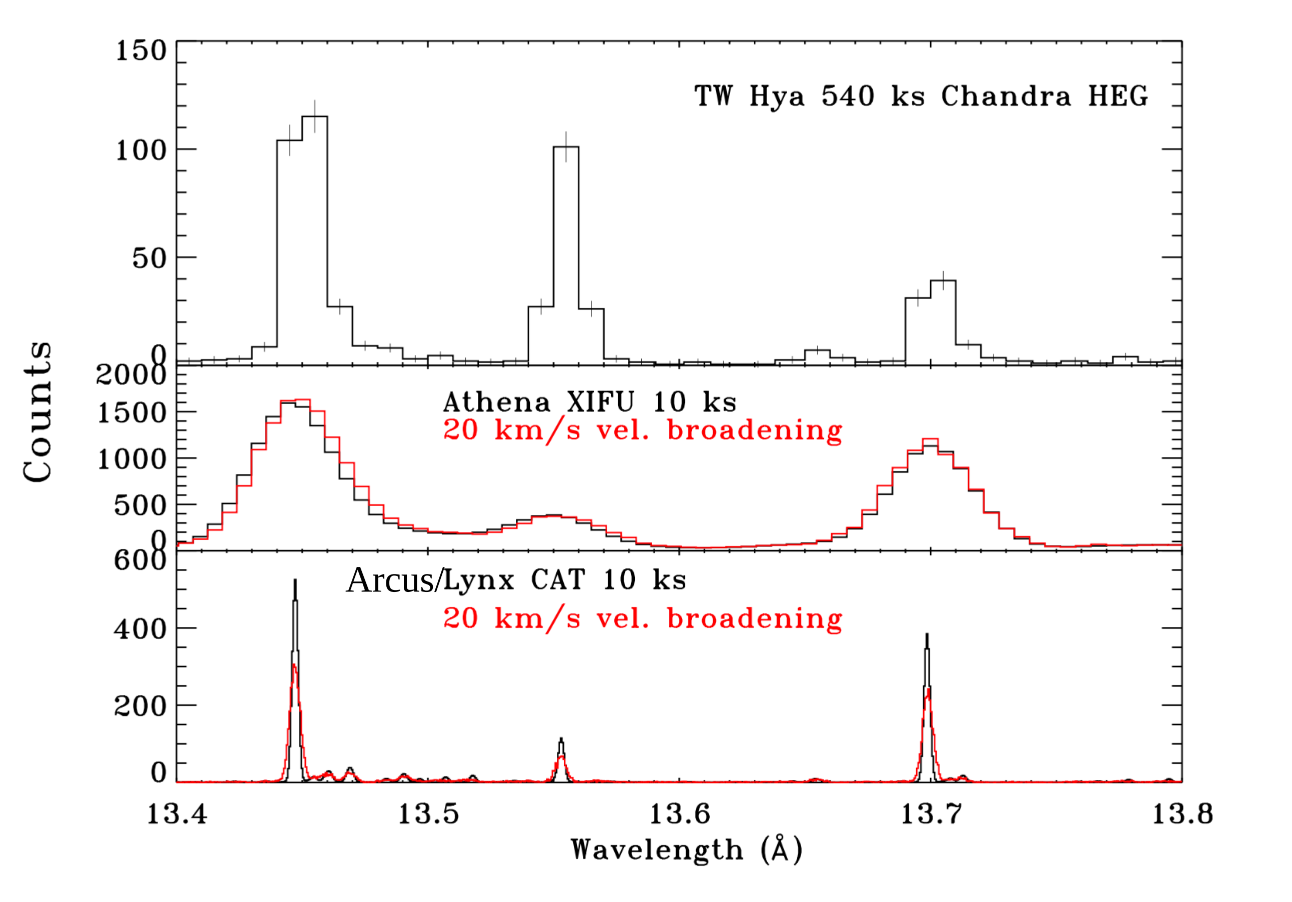




Ness

Accretion

- X-ray spectra of young stars show more than accretion plus magnetic activity
- X-rays implicated in rapid heating of protoplanetary disks
- After stars lose their disks X-ray surveys are the only way to find young stellar objects



One of the deepest, highest resolution X-ray spectra of a young star ever taken

Athena issues
-- continuum placement for measurement of triplet lines
--blending lines

Arcus/Lynx
--better quality than Chandra in 10/1 ks in Taurus-Auriga objects, 100/10 ks at Orion

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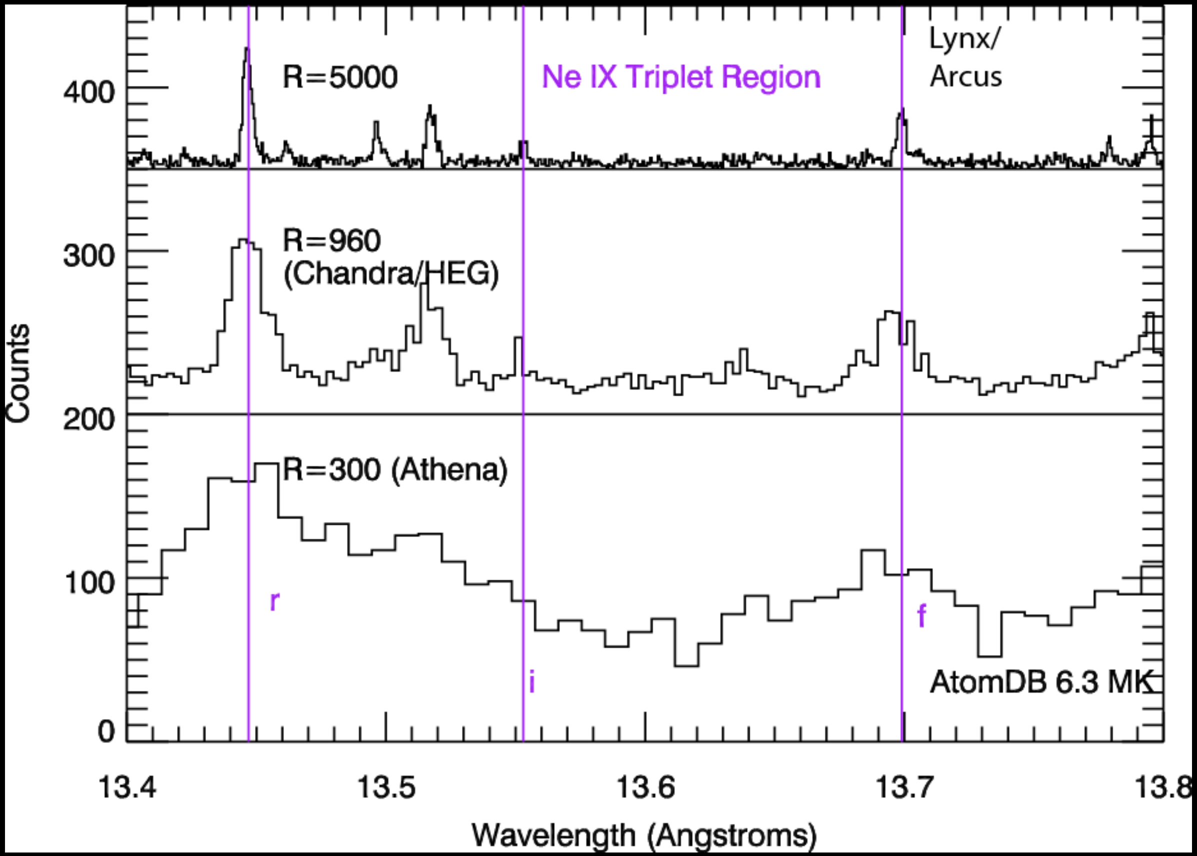

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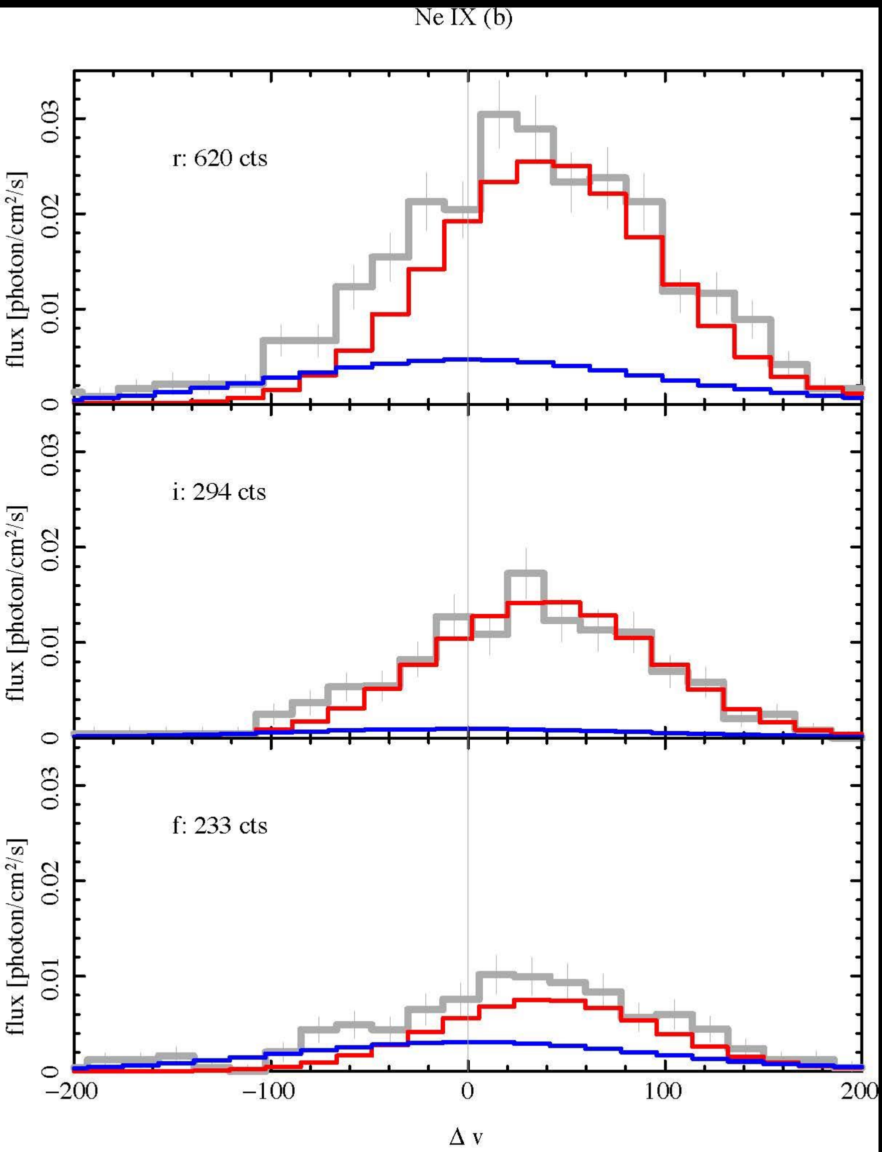
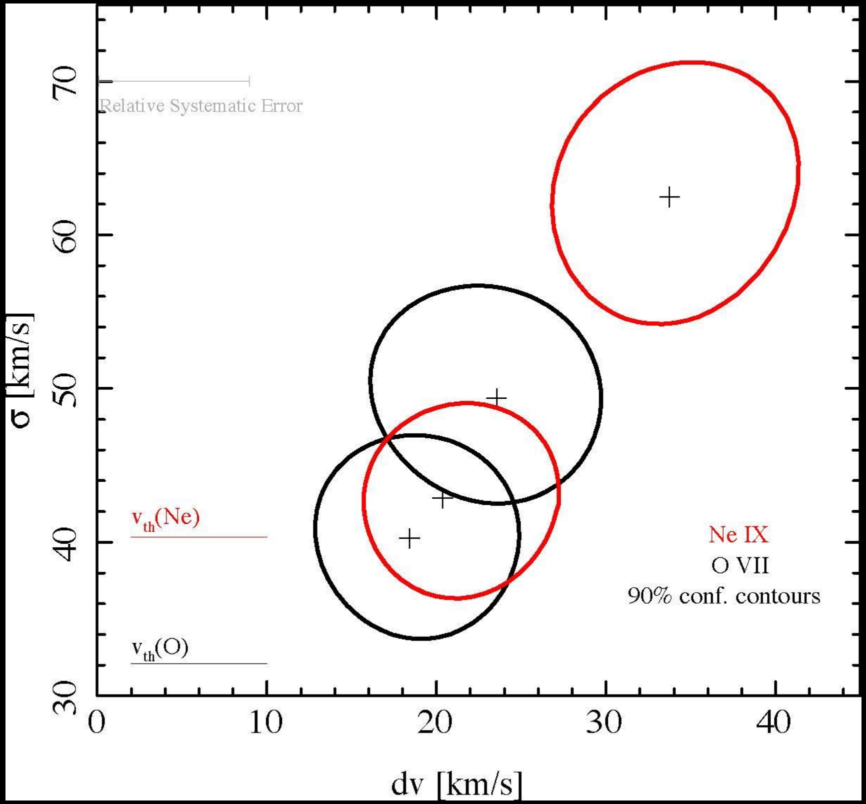
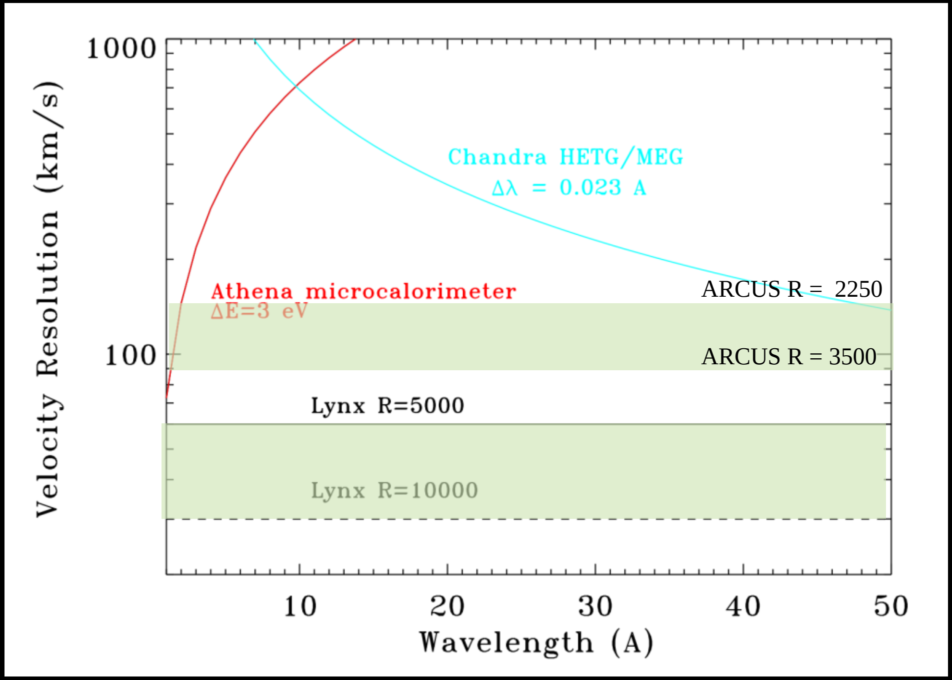
Accretion shocks

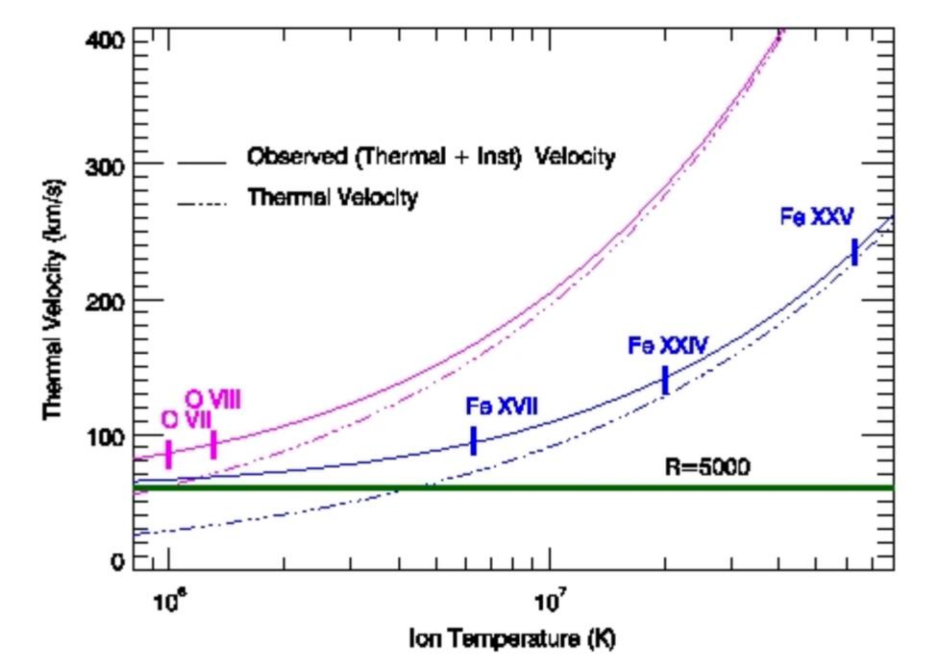




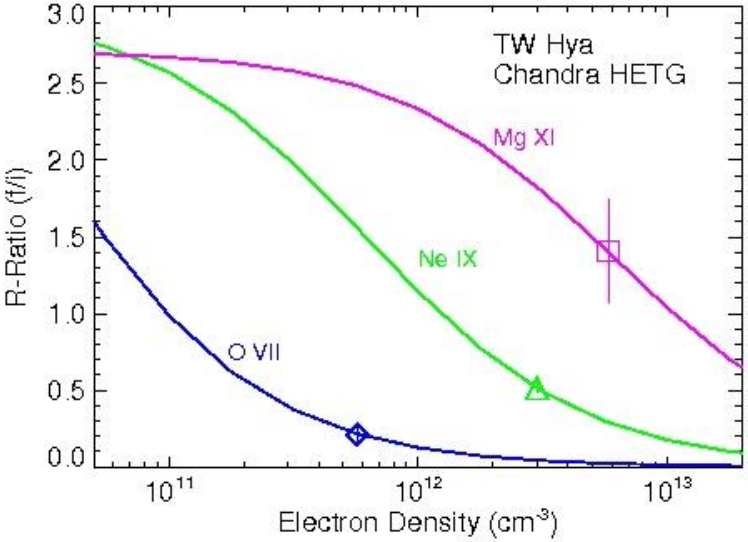
What will we be able to measure?

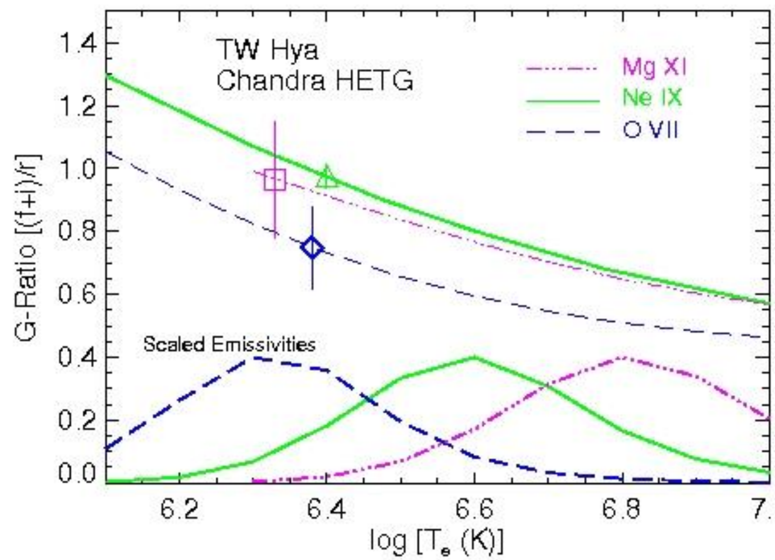
Resolving each line enables investigations of coronal dynamics, broadening mechanisms





X-RAY LINE RATIO DIAGNOSTICS FOR DENSITY AND TEMPERATURE





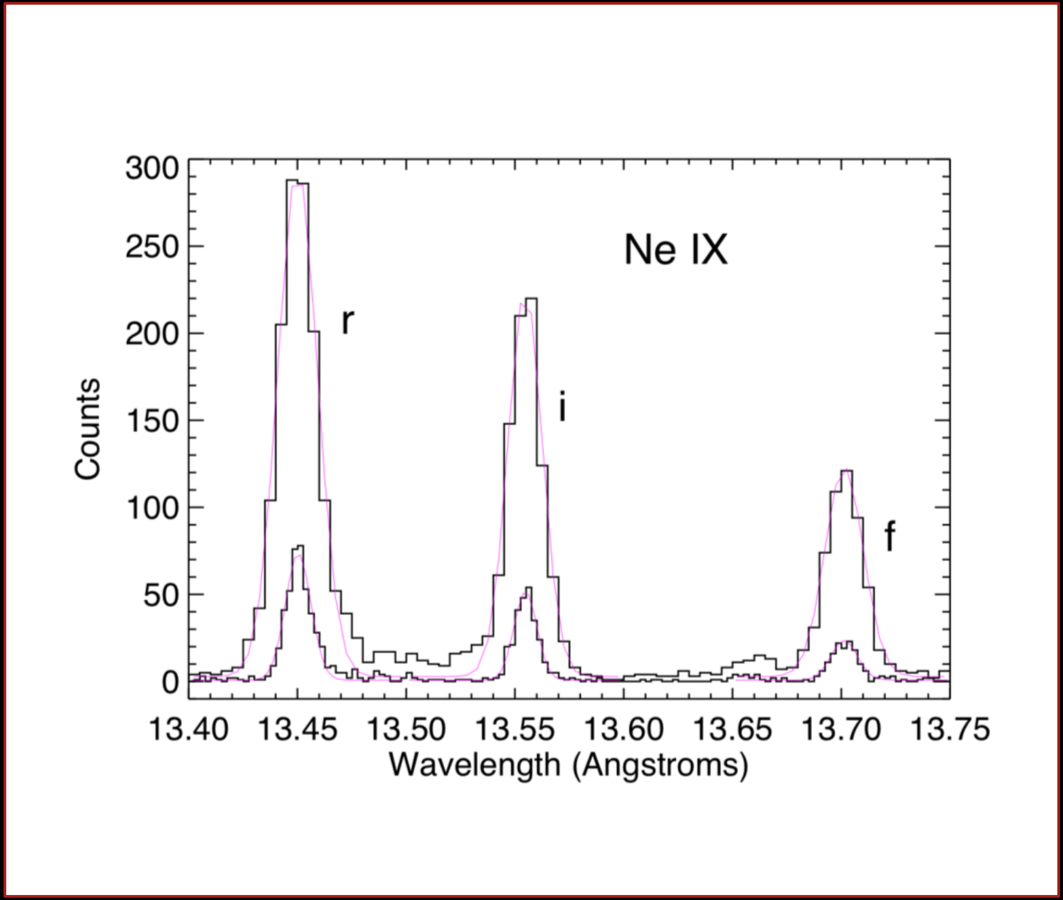
$N_e = 6 \times 10^{12}$ cm^{-3} Mg XI
3×10^{12} Ne IX
6×10^{11} O VII

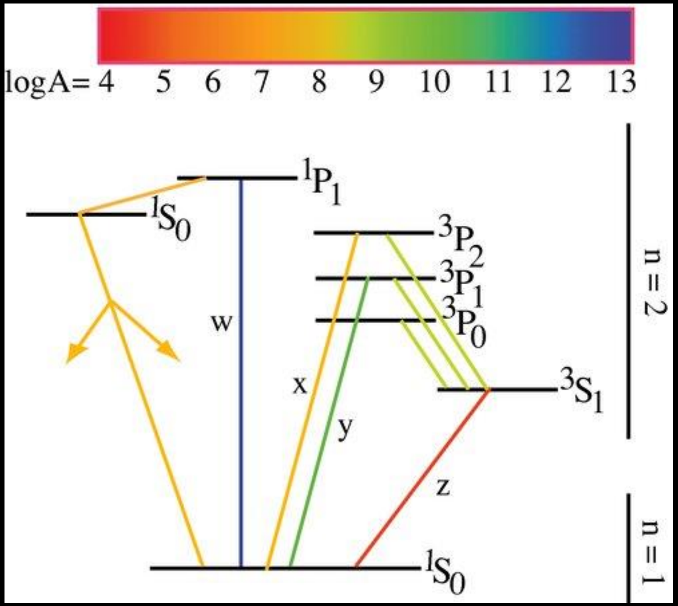
$T_e = 2.50 \pm 0.25$ MK

This looks like the accretion shock!

What will we be able to measure?

Resolving each line enables investigations of temperatures, densities coronal dynamics, broadening mechanisms

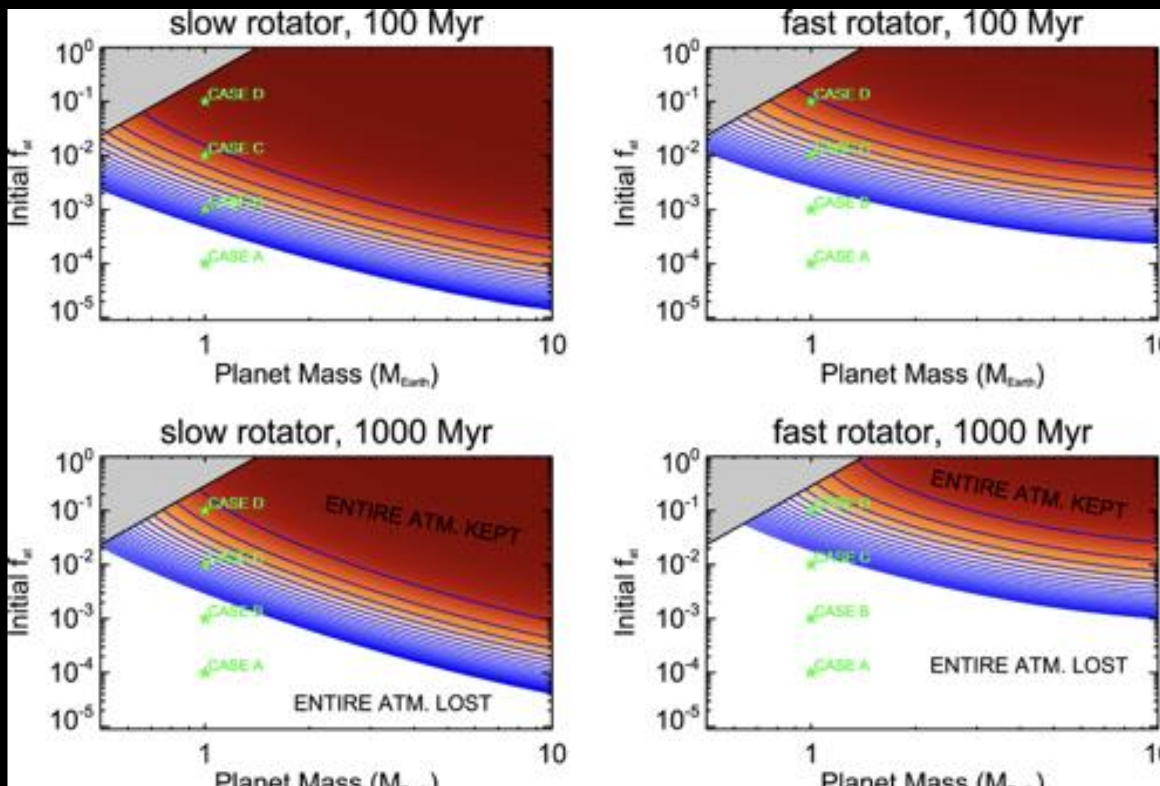




Potential Exoplanet Applications

How does the coronal emission of stars affect exoplanets?

- Stellar twins are not magnetic twins; star's X-ray emission at early ages is a much larger factor in planetary irradiation
- Planetary atmospheric evolution is fundamentally linked to XEUV emission
- X-rays trace magnetic structure directly

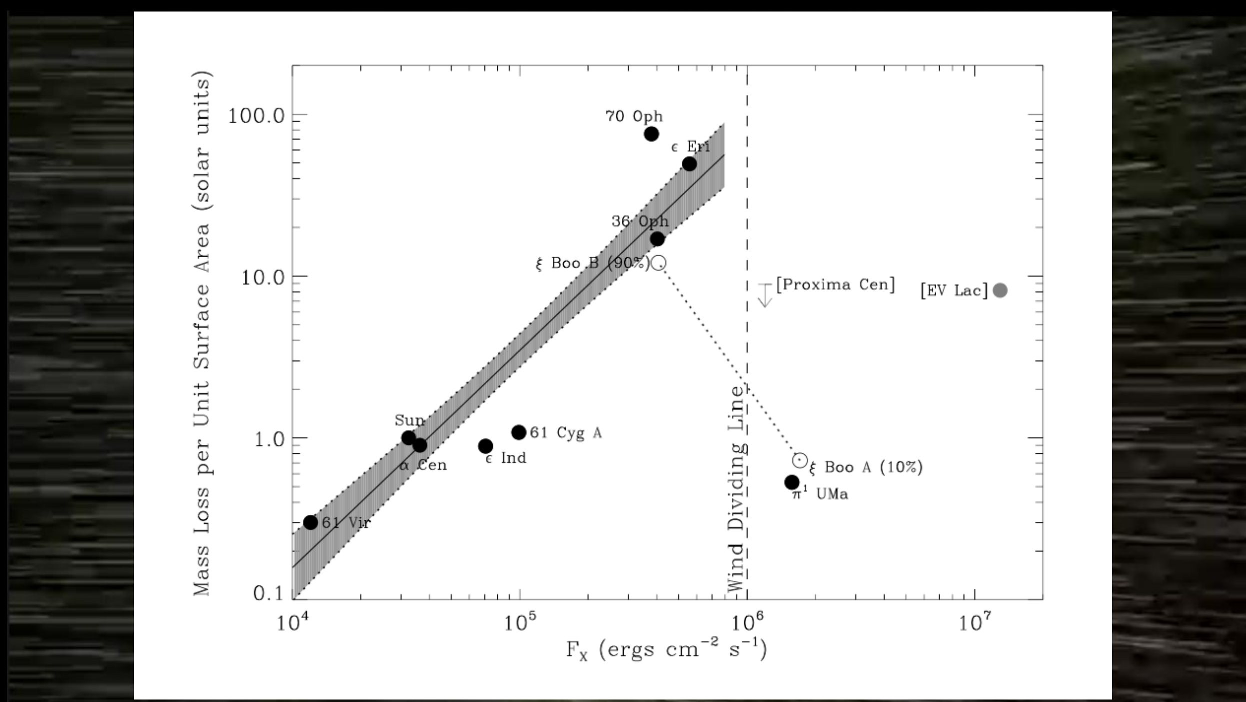


Johnstone et al. (2015)

Potential Exoplanet Applications

How do stellar winds change with time and what impact does this have on exoplanet conditions?

- Stellar wind mass loss critical to atmospheric escape process
- Detect charge exchange emission from nearest ~20 stars to constrain $\dot{M}$
- Coronal mass ejections play an important role in potential habitability; need a way to constrain them



Wood et al. (2004) indirect measures of stellar mass loss

Credit: NASA MAVEN mission

Potential Exoplanet Applications

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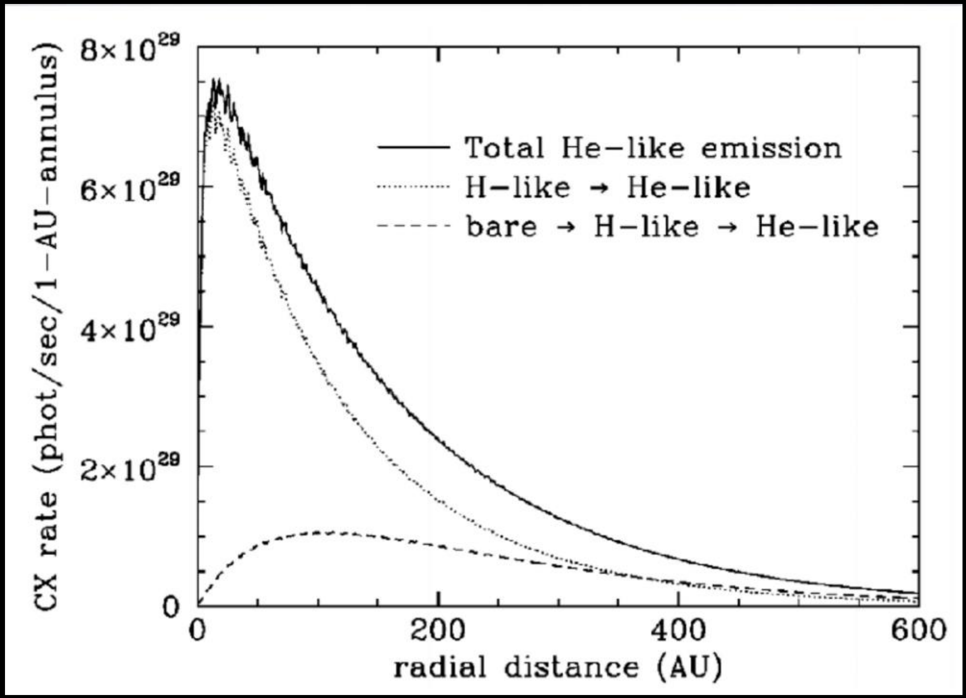
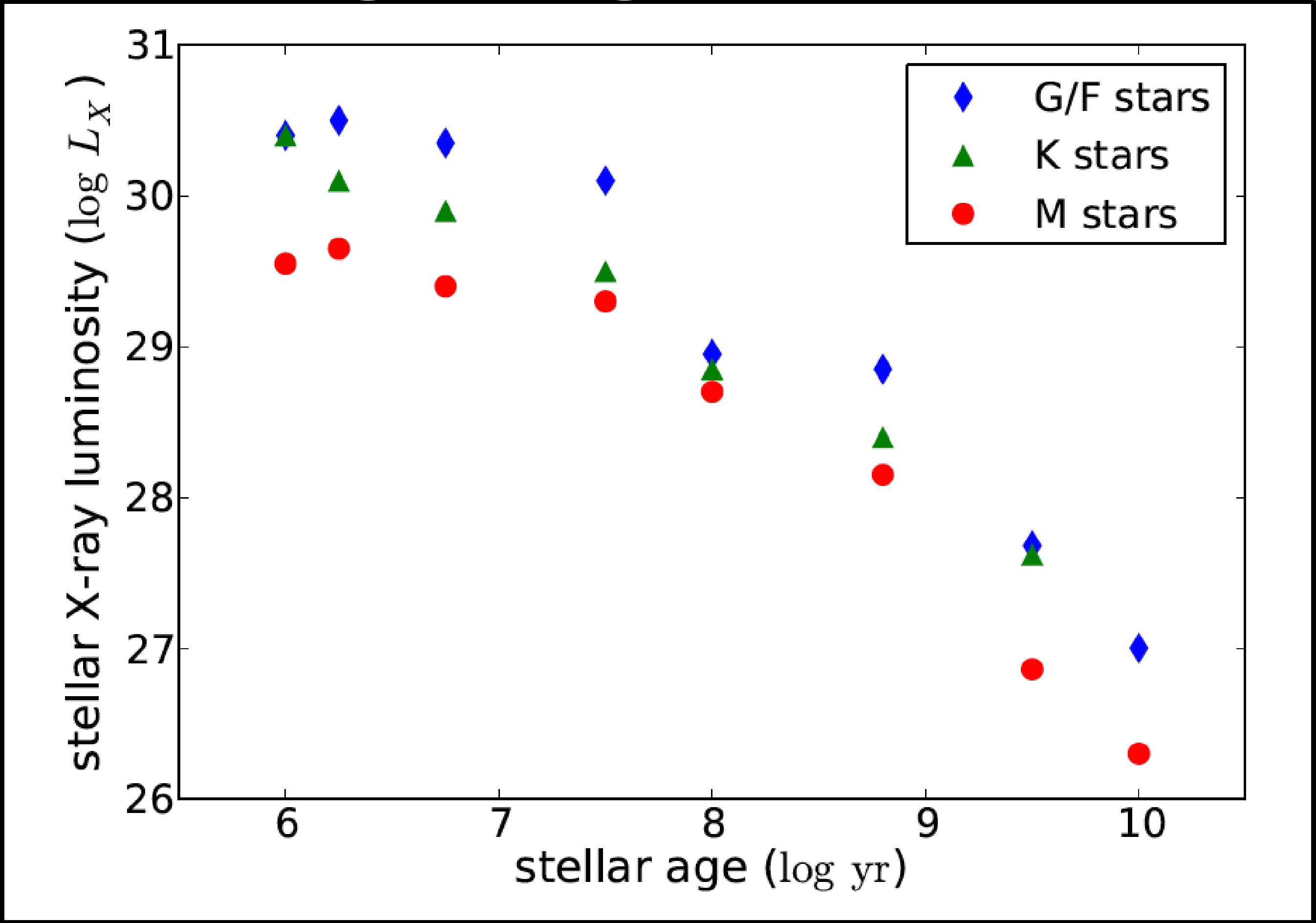


Wargelin & Drake (2001)
Upper limit on mass loss rate of Proxima from charge-exchange emission from interaction of stellar wind with ISM
Requires spatial resolution <0.5” to resolve CX from central point source
Applicable to ~20 nearby stars.

AGE-ACTIVITY RELATION



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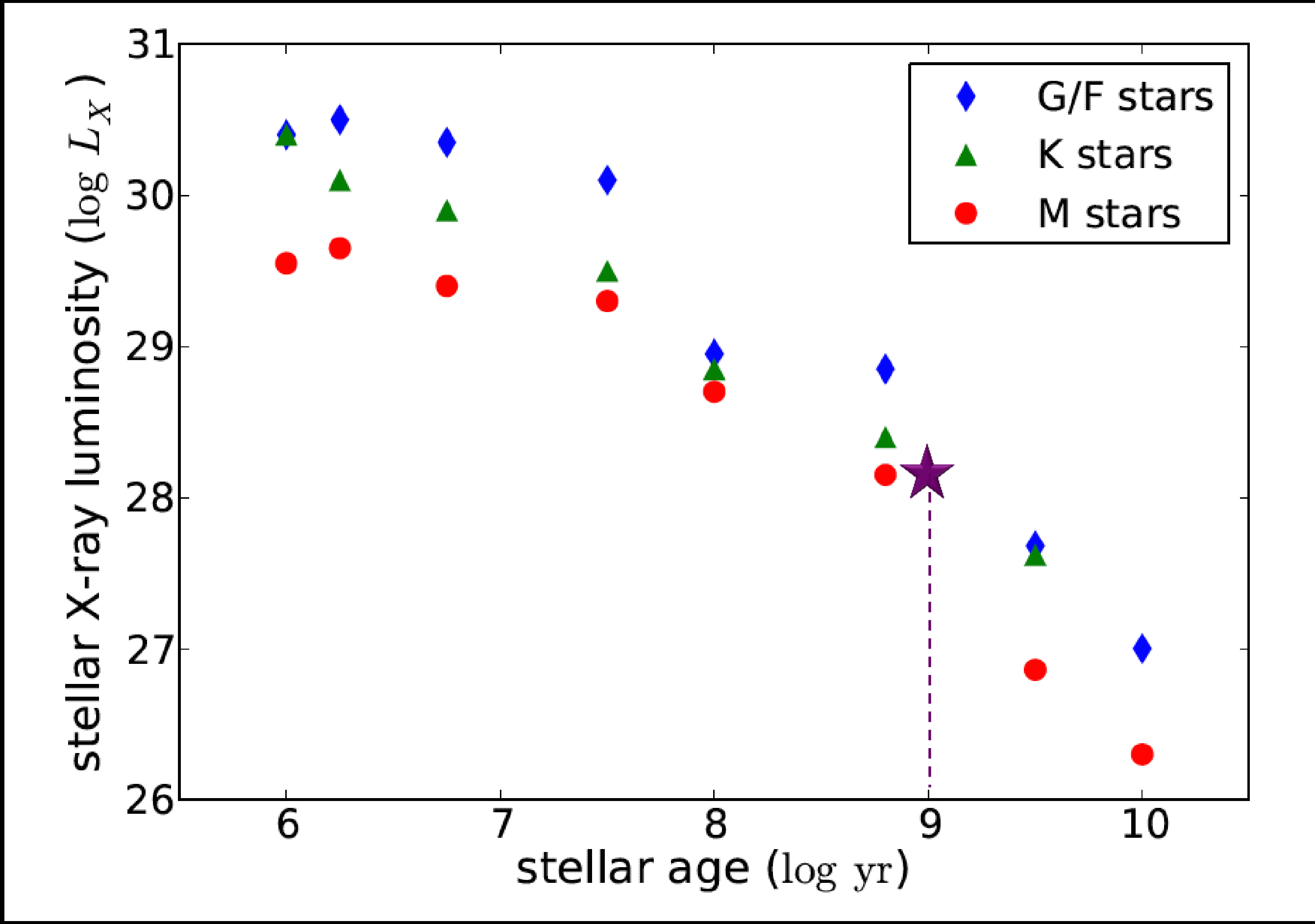
THE AGE OF HD 189733



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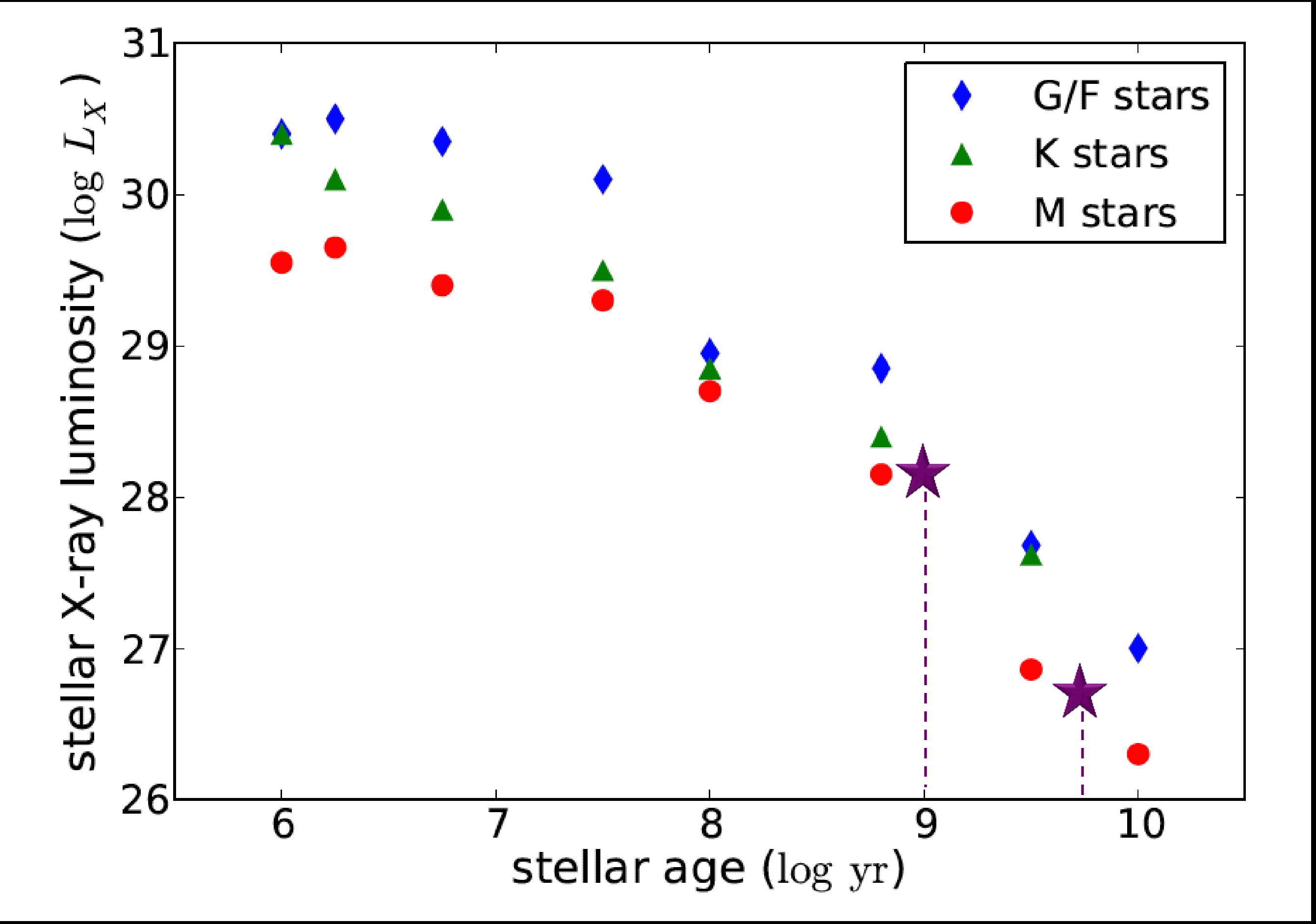
Poppenhaeger & Wolk (2014)

THE AGE OF HD 189733



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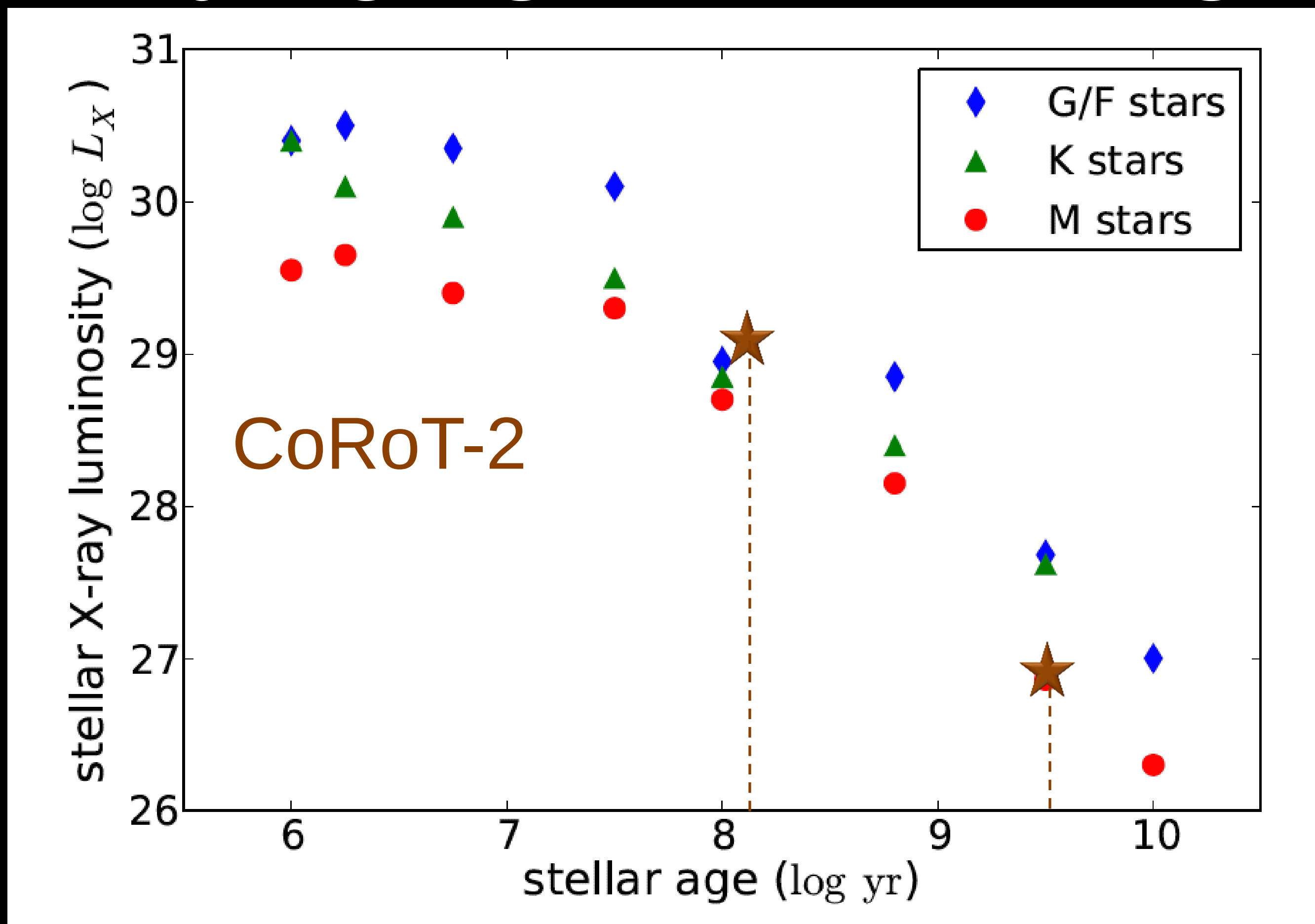
Poppenhaeger & Wolk (2014)

AGE/ACTIVITY IN THE STRONG TIDAL INTERACTION ASE



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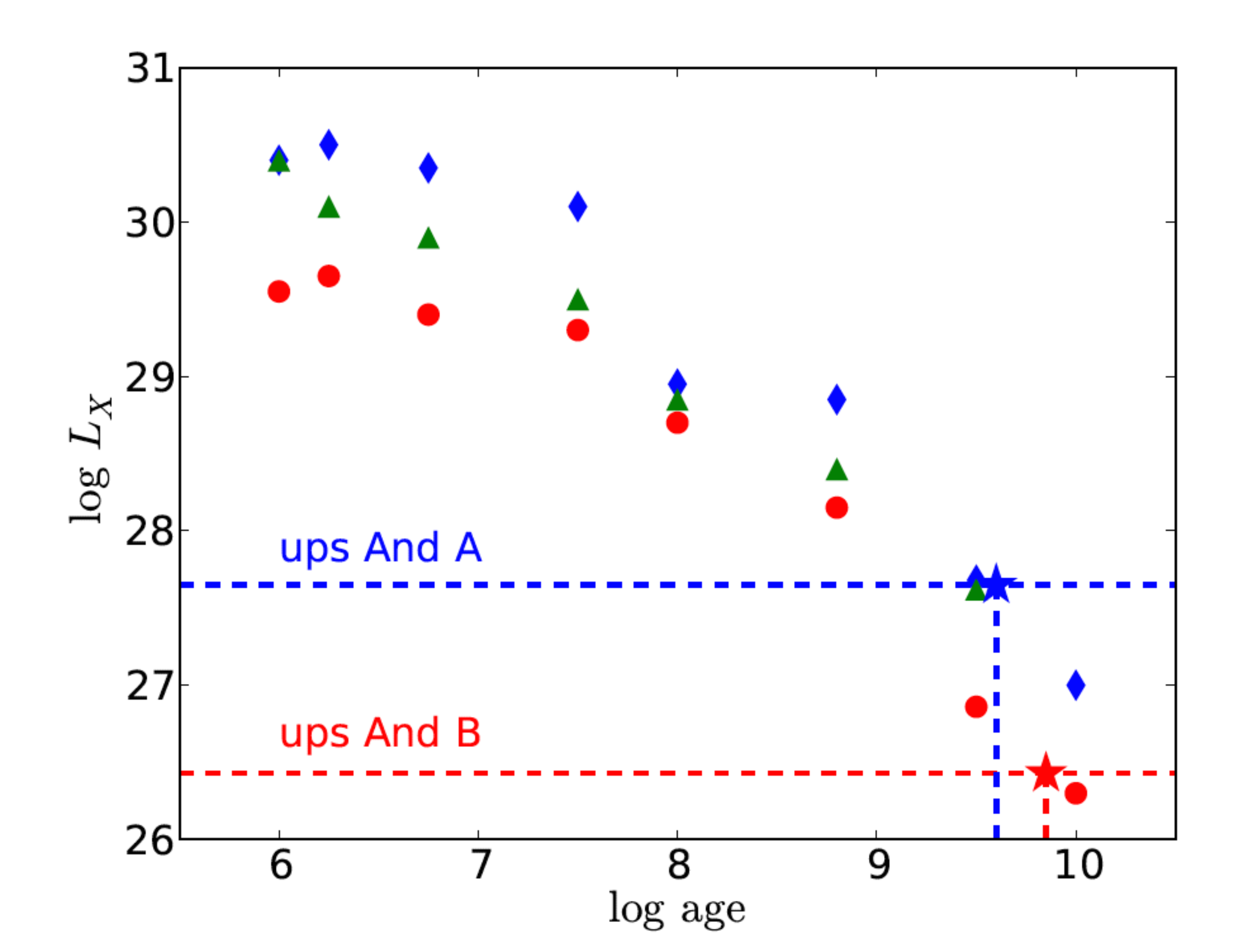
Poppenhaeger & Wolk (2014)

AGE/ACTIVITY IN THE WEAK TIDAL INTERACTION CASE



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Poppenhaeger & Wolk (2014)

INSTRUMENTATION IN THE NEXT DECADE AND BEYOND

- Xarm – µcal spectral resolution, poor angular resolution.
- Arcus – Dispersive grating resolution at low energies.
- AXIS – excellent angular resolution, large effective area, Si detectors
- Strobe – X/TAP – high count rate X-ray missions
- Athena – Better µcal spectral resolution, good angular resolution.
- Lynx – Even better µcal spectral resolution, better grating resolution and excellent angular resolution and area.

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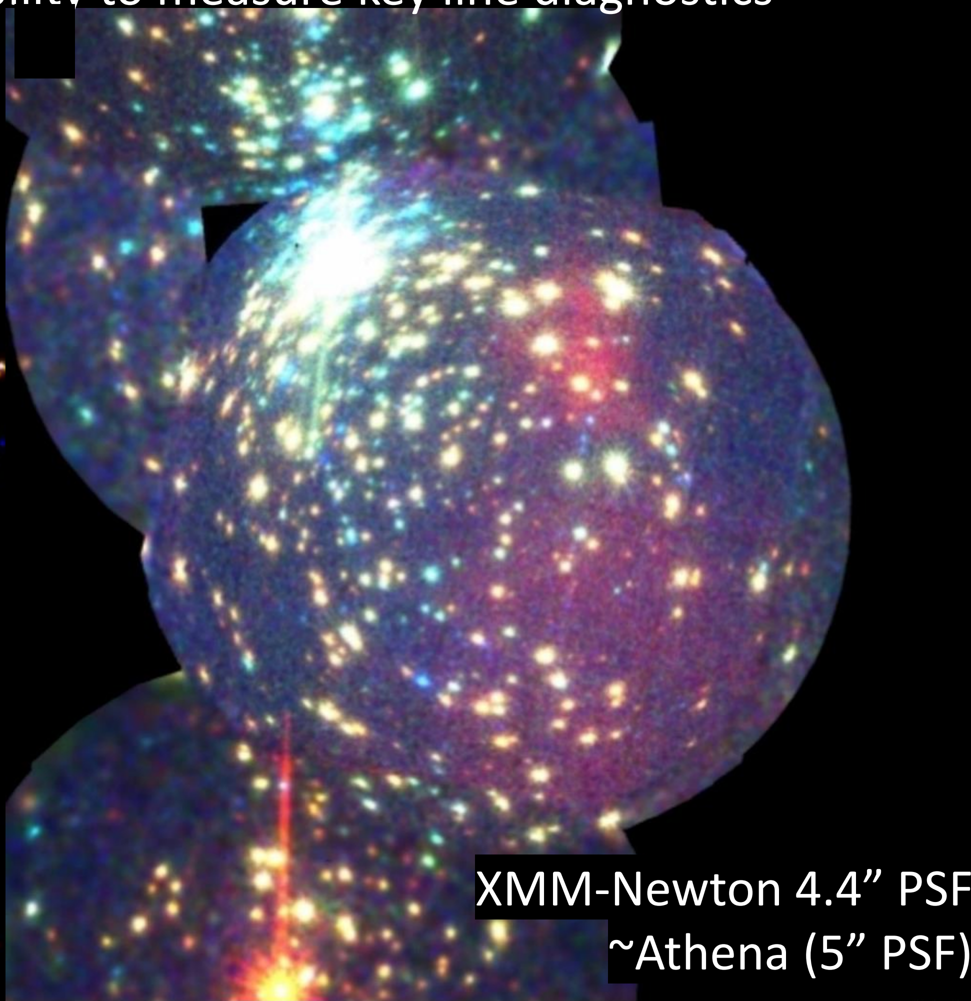
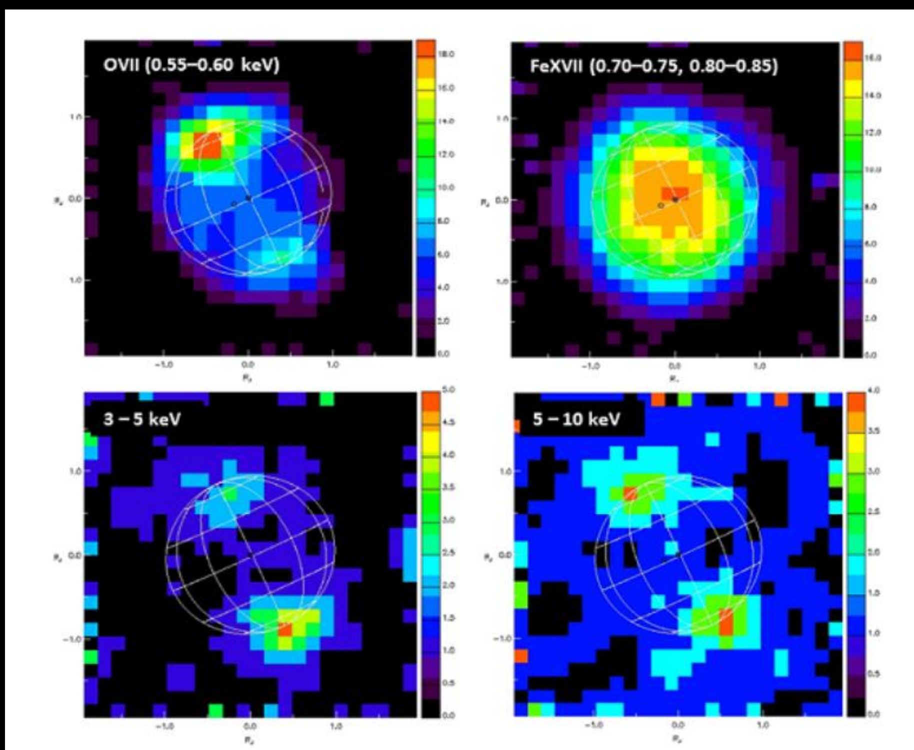
What will we be able to measure?

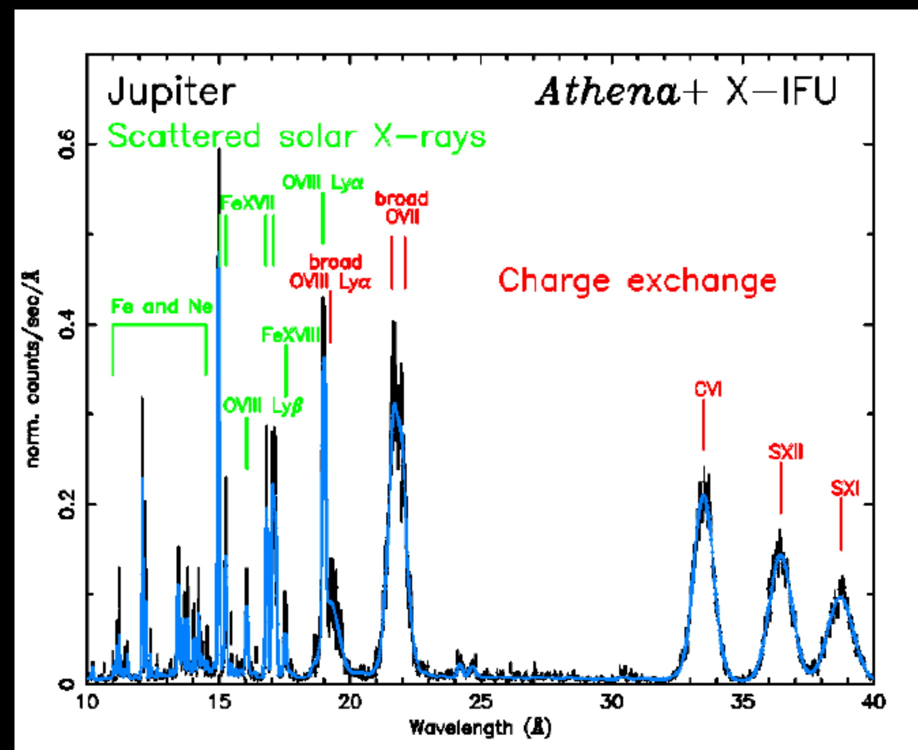
- Crisp X-ray images w/ability to separate sources and study diffuse emission
- Spatially resolved spectroscopy of point and diffuse emission
- Temporally resolve emission
- Good quality grating spectra with ability to measure key line diagnostics



Imaging Spectroscopy

μcalorimeters:
IFU spectra of extended objects such as PN, Comets, diffuse emission & planets





Branduardi-Raymont et al. (2007)

Imaging Spectroscopy

µcalorimeters:
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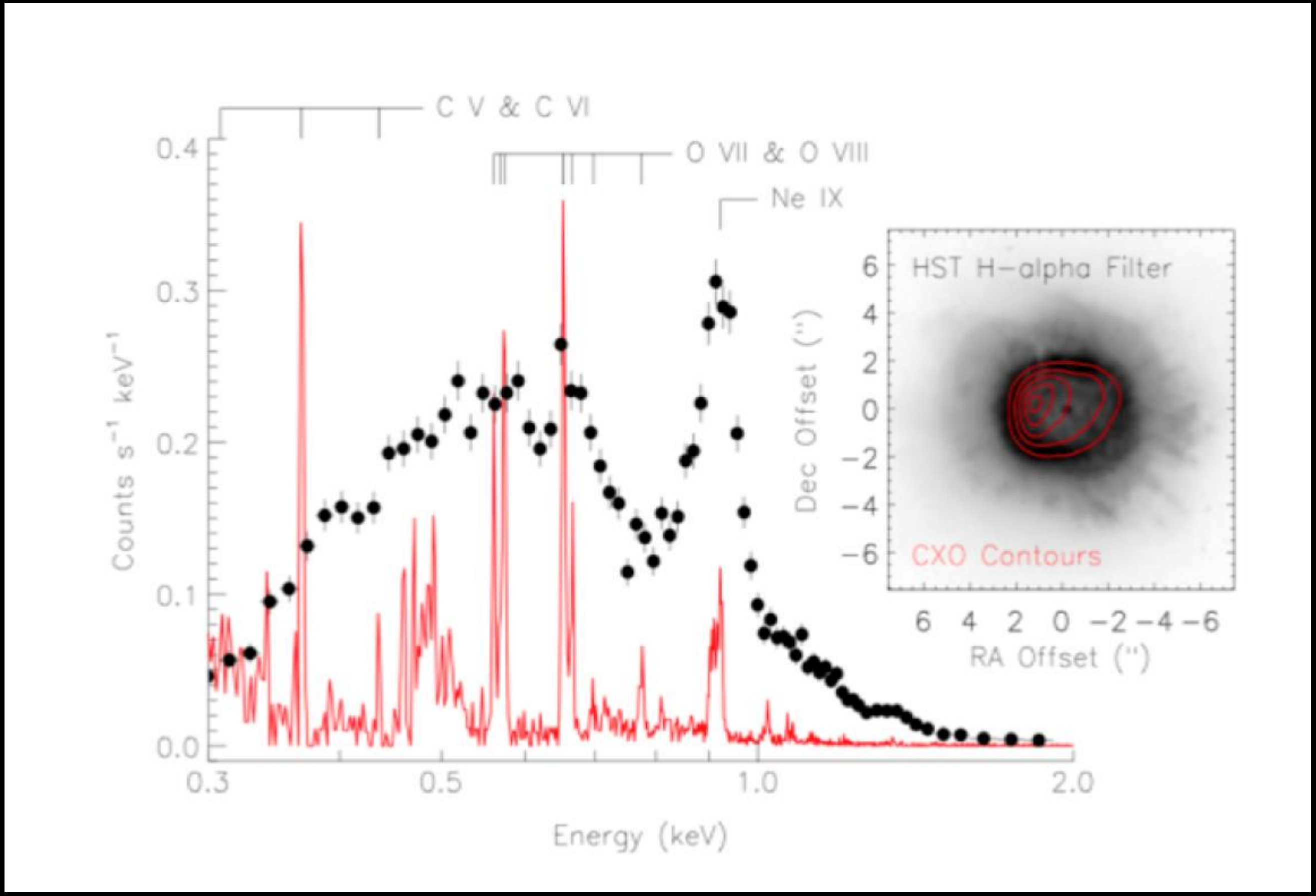
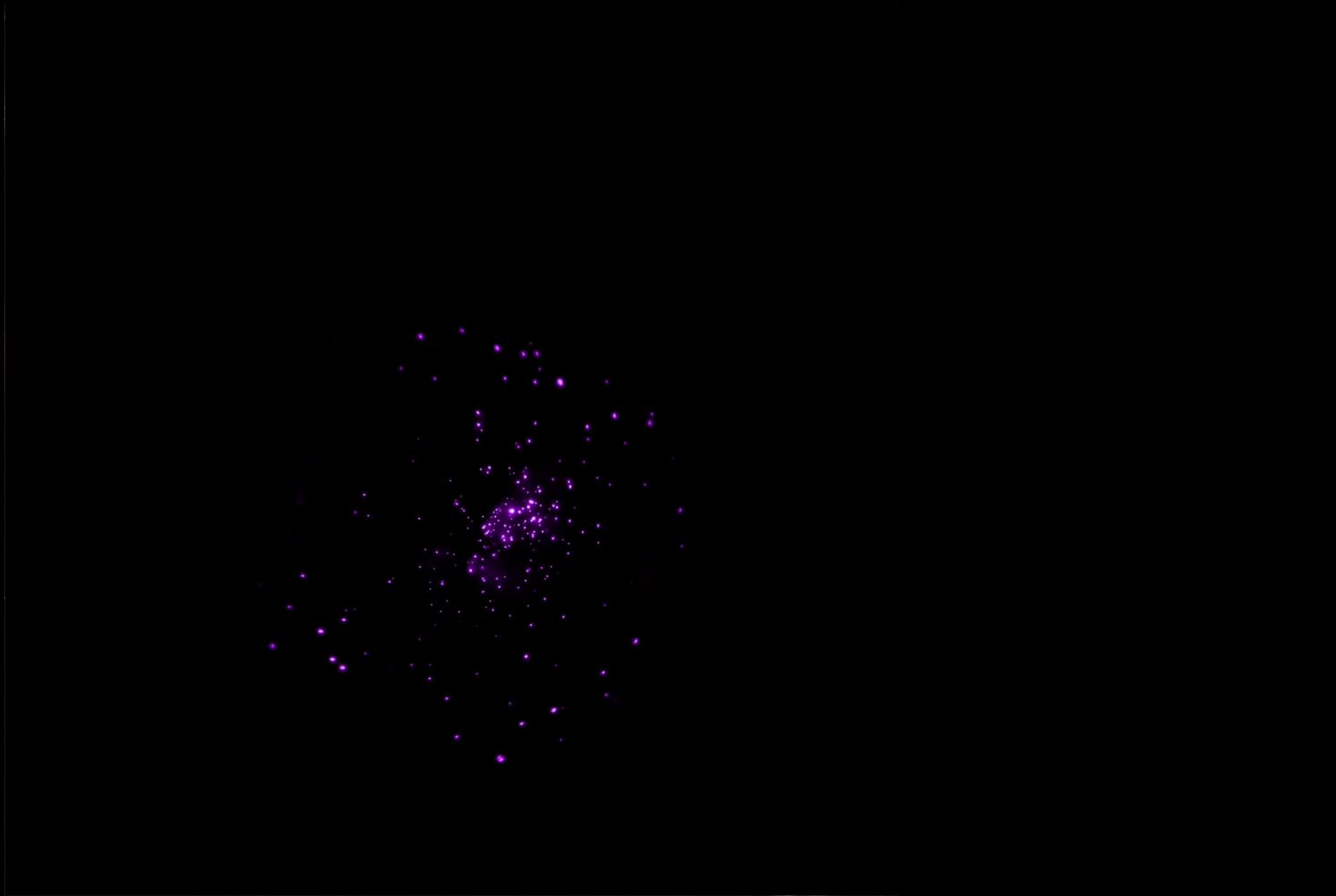


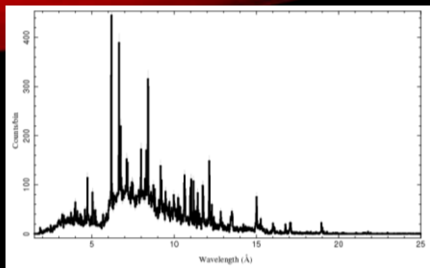
Studies of Nearby Star Formation Regions

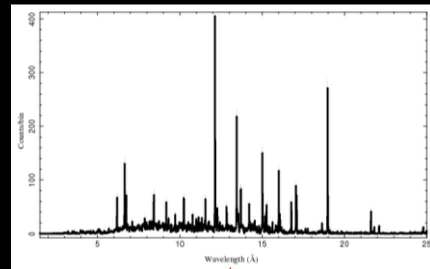
- Cluster Census
- Transition disk timescales
- X-ray effects on cluster morphology

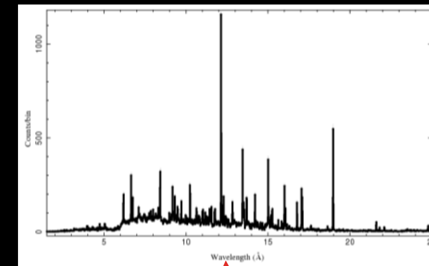
PSF is directly related to the reach of the telescope



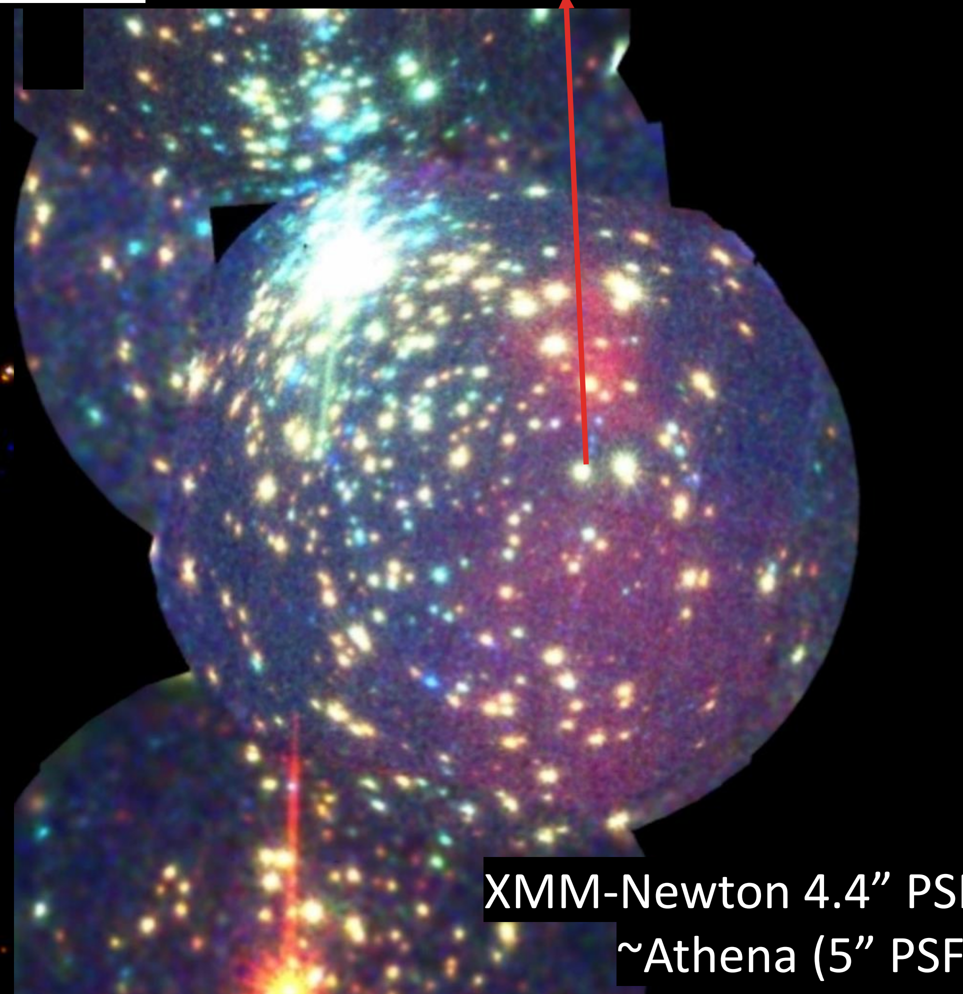
Studies of Nearby Star Formation Regions





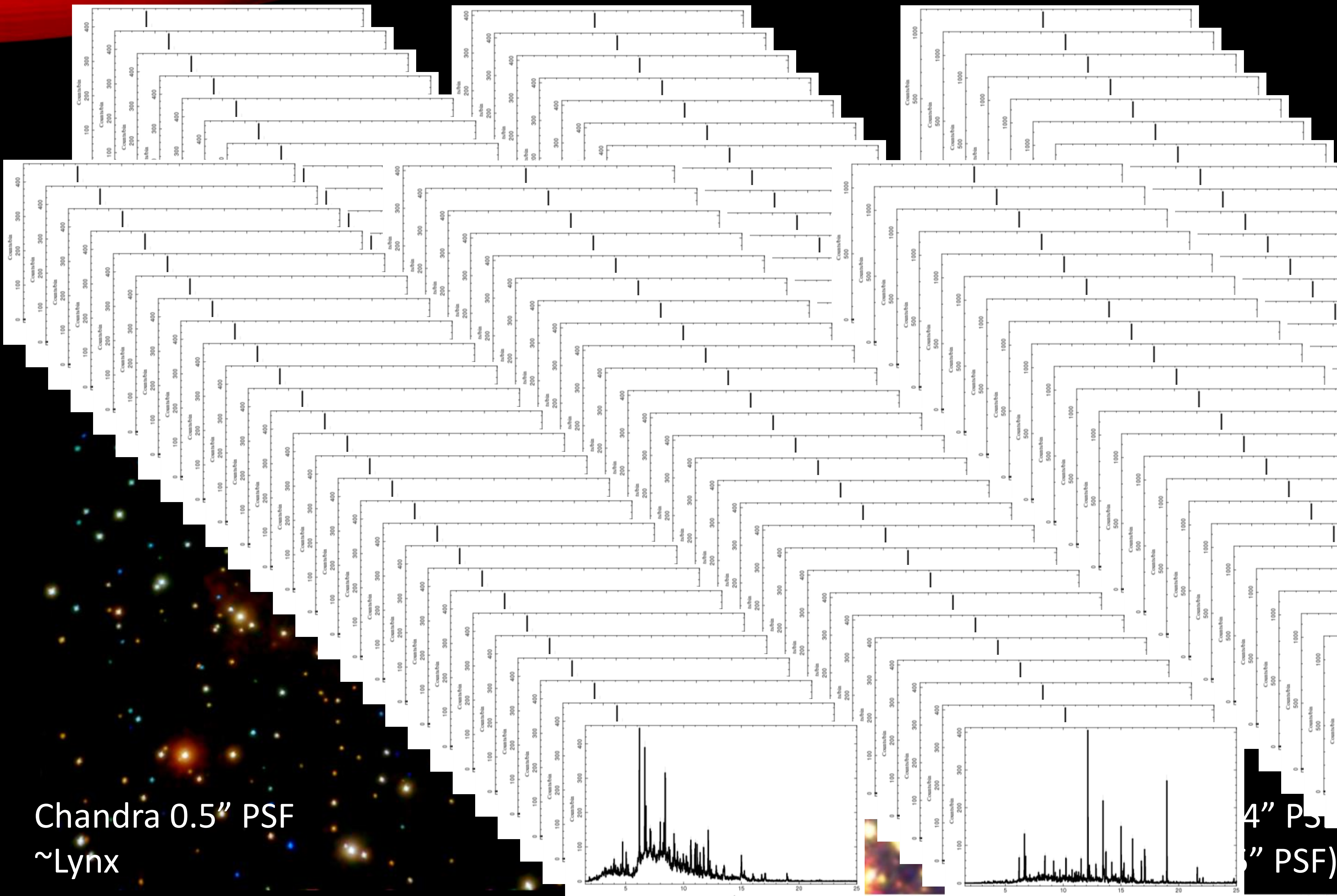


Chandra 0.5” PSF
~Lynx



XMM-Newton 4.4” PSF
~Athena (5” PSF)

Overwhelming datasets



Studies of Nearby Star Formation Regions

Well done with µcal imaging spectroscopy

- Cluster Census
- Transition disk timescales
- X-ray effects on cluster morphology
- Detecting grain evolution
- X-rays from protostars
- Effect of X-rays on forming planets disks
  - Especially flares.
- Understanding the magnetic fields.
- What are the statistics of radio flaring for young stellar objects?
- Are radio flares correlated with X-ray flares?
- Understanding diffuse emission and feedback.
- What is the relationship between X-rays and radio emission from YSOs?

Issues in Stellar Coronae

- Magnetic field generation via dynamo
  - Does the activity/rotation relation hold for low mass stars?
- ➢ Coronal heating and radiation
- ➢ Evolution of magnetic activity
  - Angular momentum loss in accreting stars
  - Accretion shocks
- Flares and coronal mass ejections (CMEs)
- Stellar wind drivers

This requires:
Dispersive Gratings

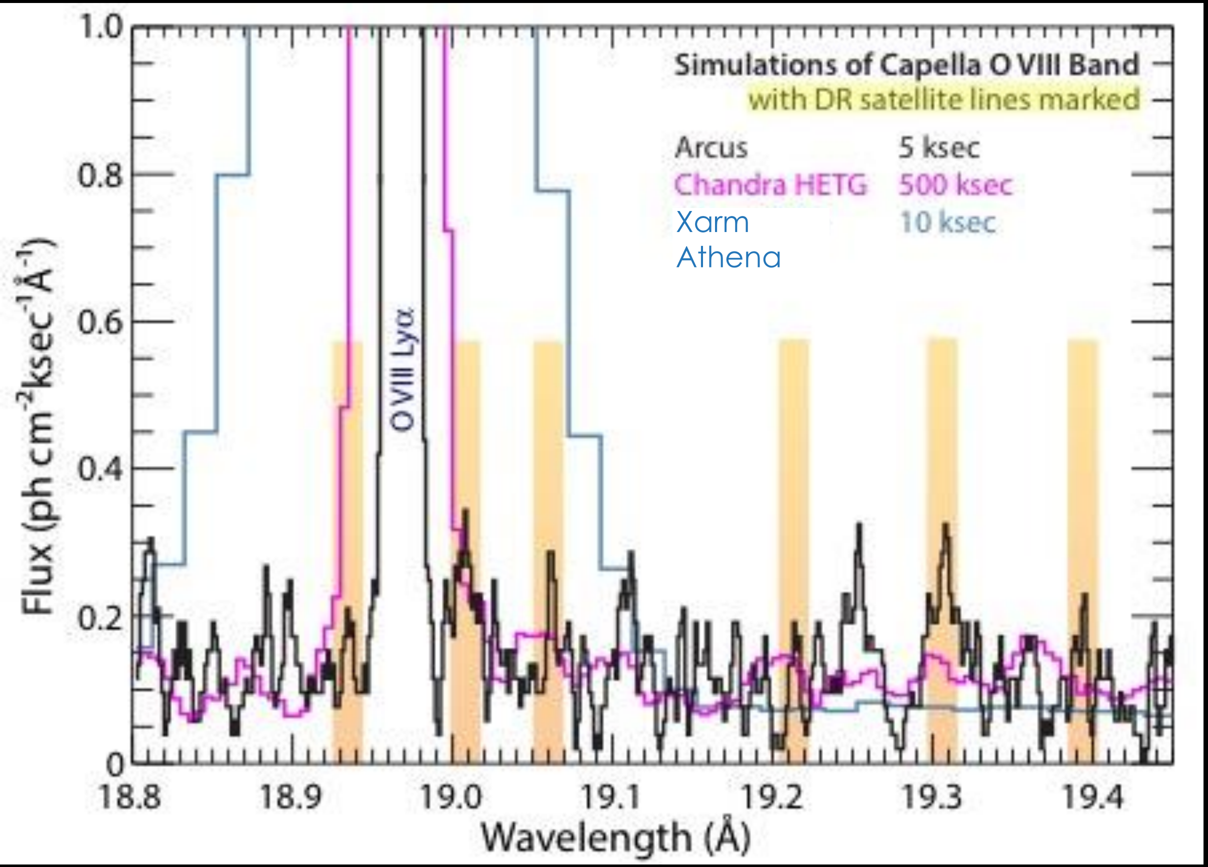
Chandra and XMM-Newton grating spectroscopy only available for a few dozen (active) stars.

Coronal Spectoscopy

Resolving each line enables investigations of coronal dynamics, broadening mechanisms

Testing coronal heating models using temperature-sensitive dielectronic recombination (DR) lines.

A 5ks *Arcus* observation will identify these lines; longer observations capture the changes in the dynamic coronal environment.



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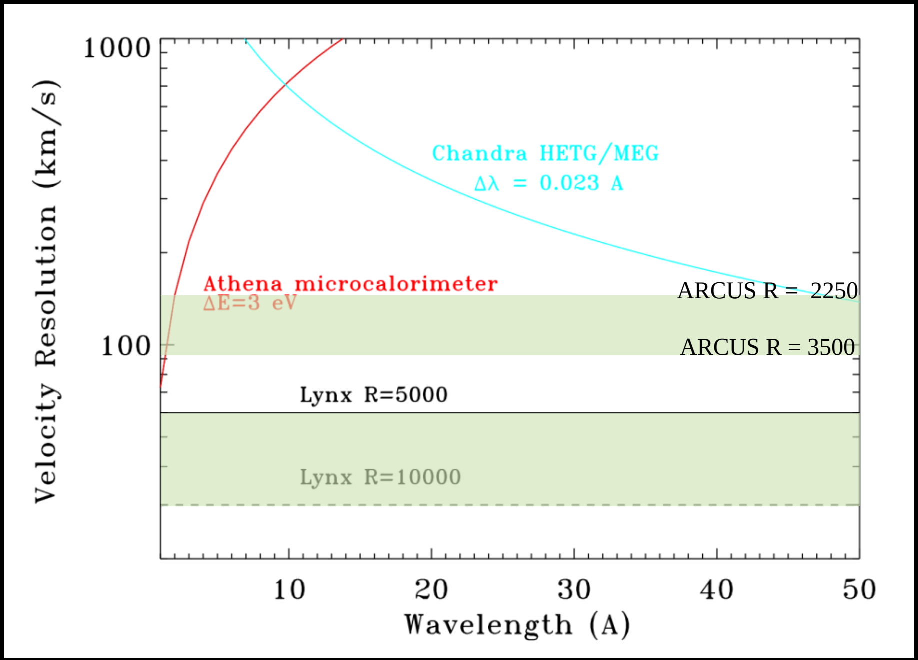
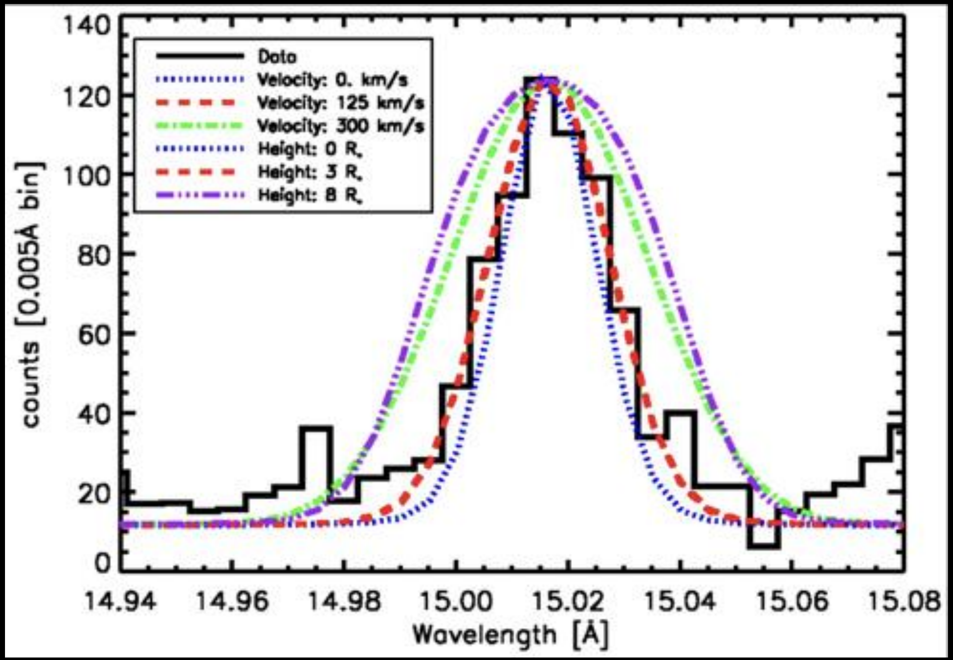
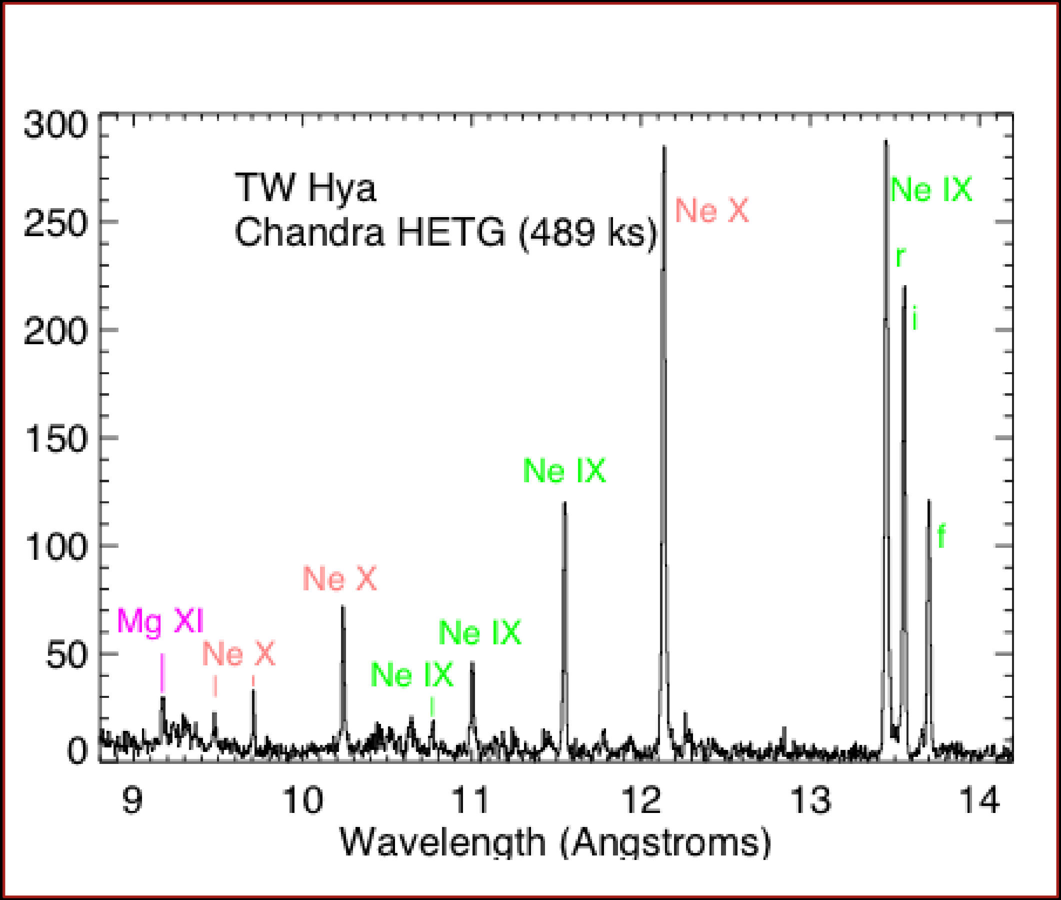




Chung et al. (2004) excess broadening of Algol interpreted as rotational broadening from a radially extended corona

Coronal and Accretion Dynamics

Resolving each line enables investigations of temperatures, densities coronal dynamics, broadening mechanisms



TW Hya is One of the deepest, highest resolution X-ray spectra of a young star ever taken

- X-ray spectra of young stars show more than accretion plus magnetic activity
- X-rays implicated in rapid heating of protoplanetary disks
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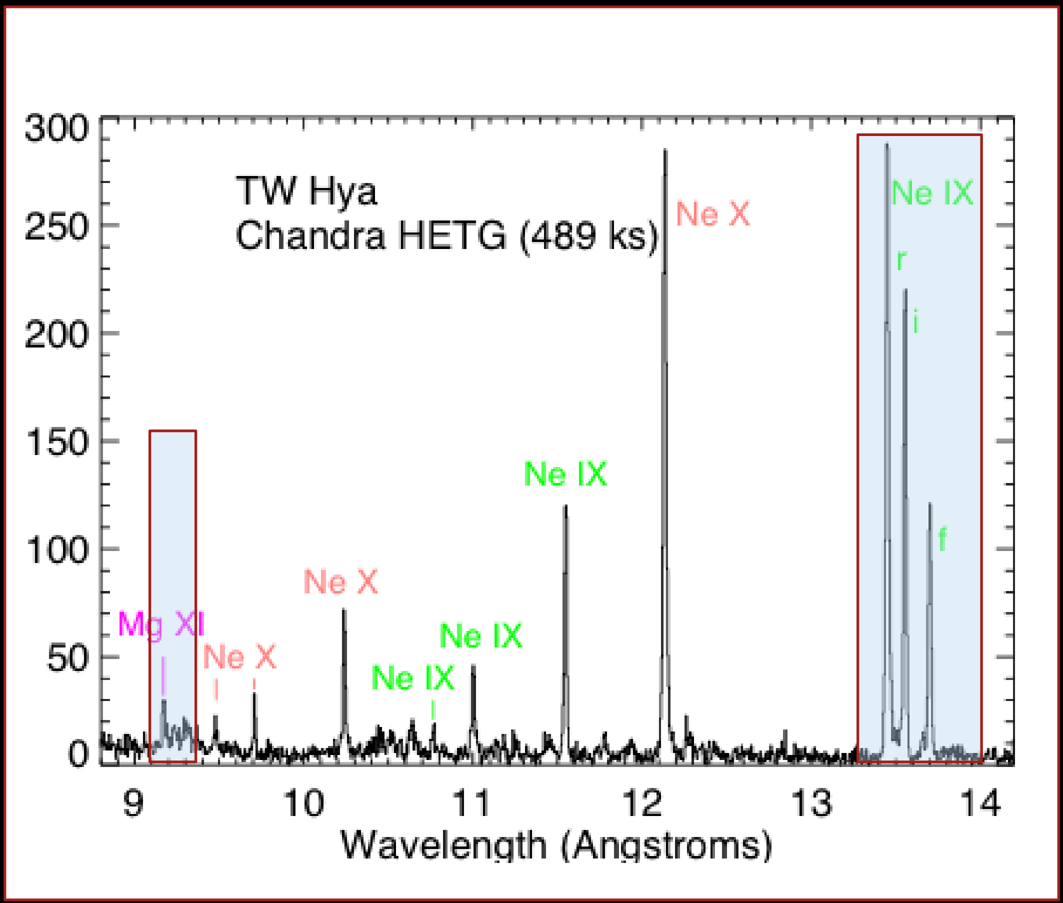

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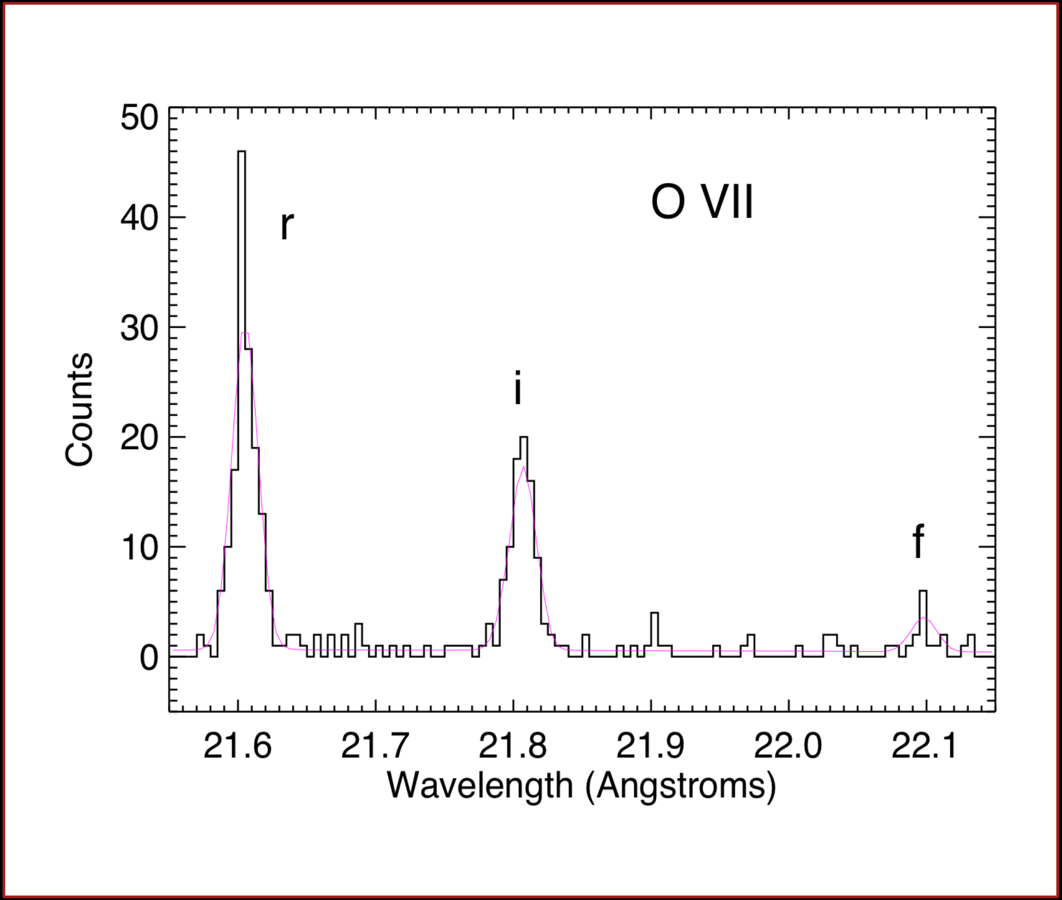

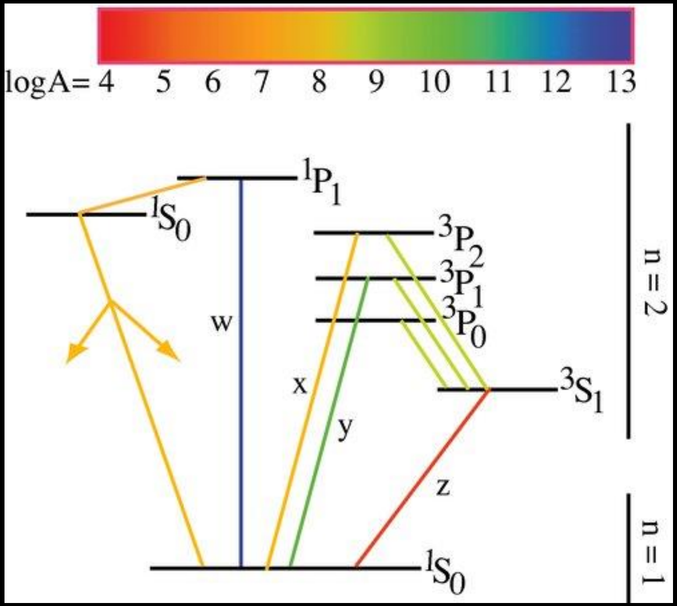

Smith et al. (2009)

Coronal and Accretion Dynamics

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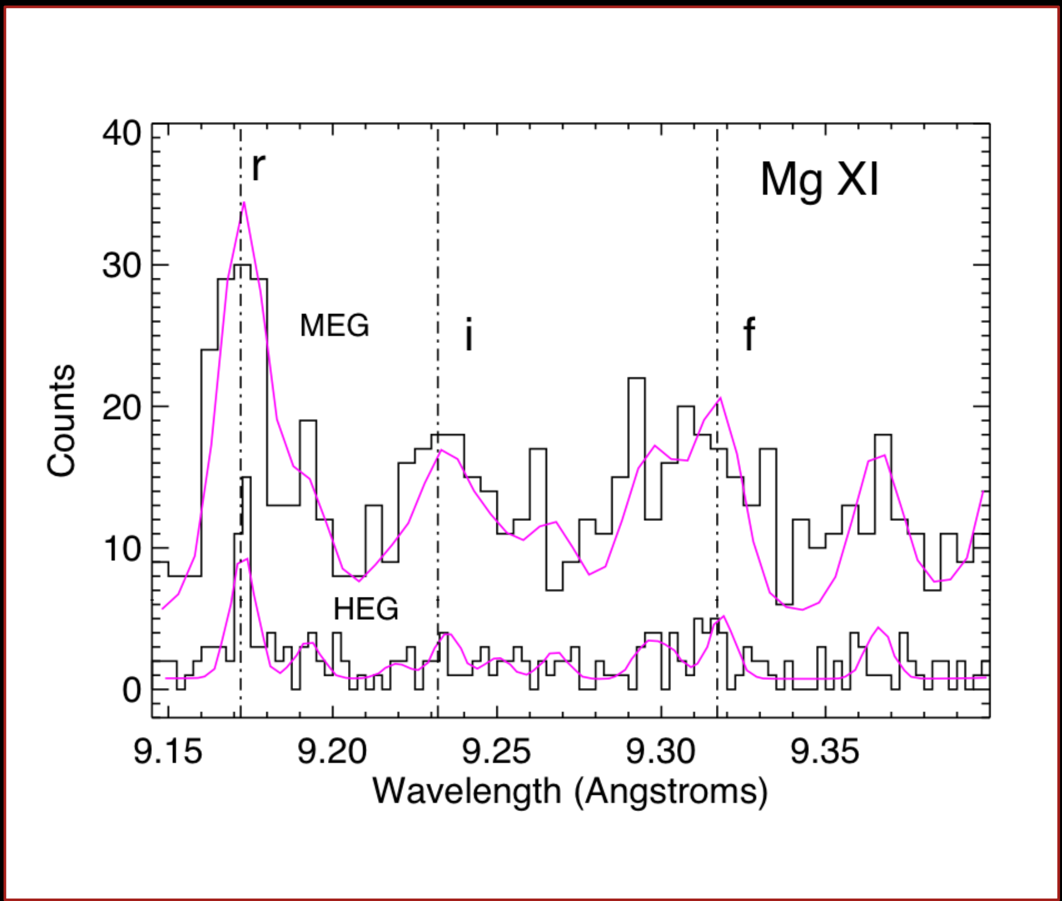

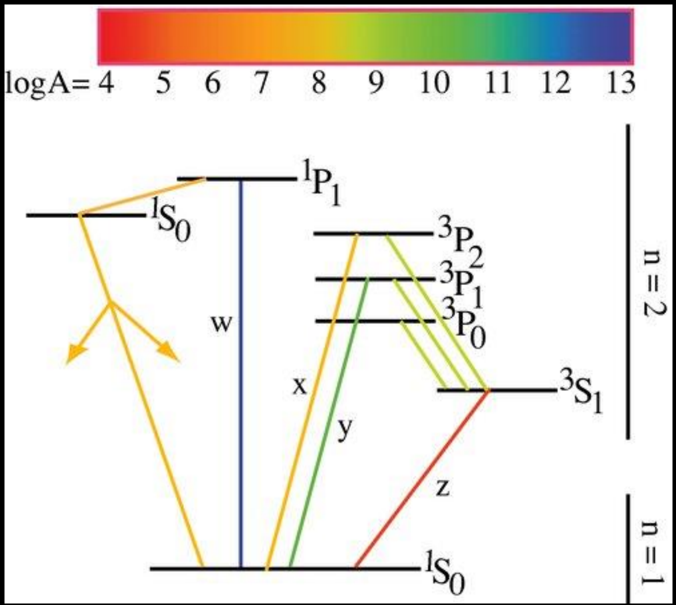

Potential Exoplanet Applications

Where do planets form? Where do they migrate?

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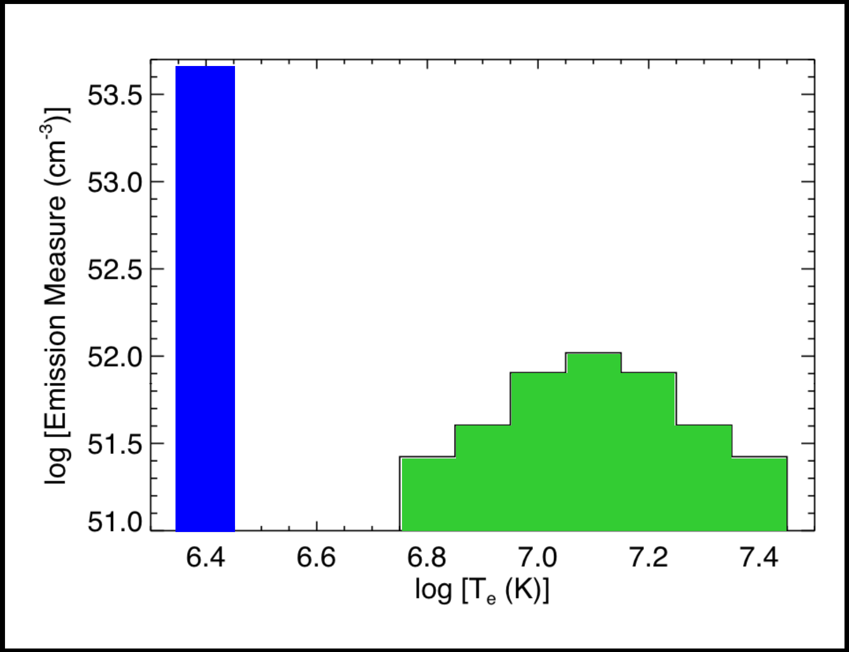
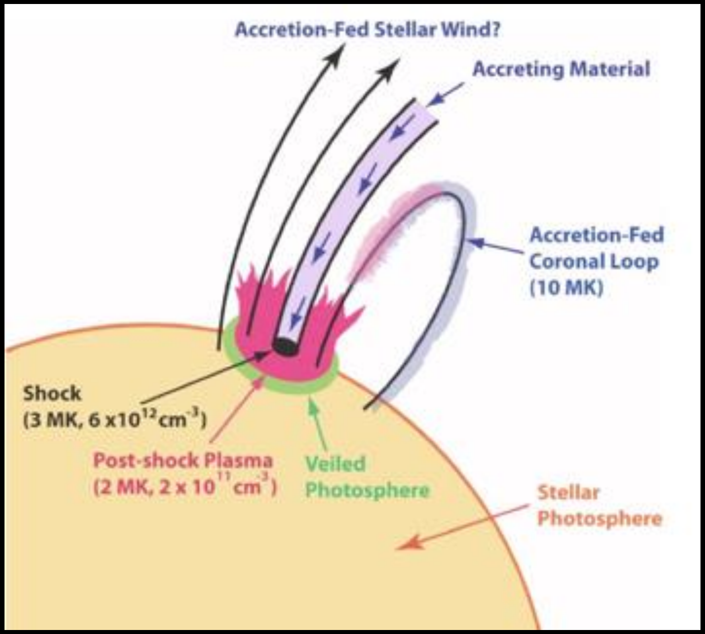
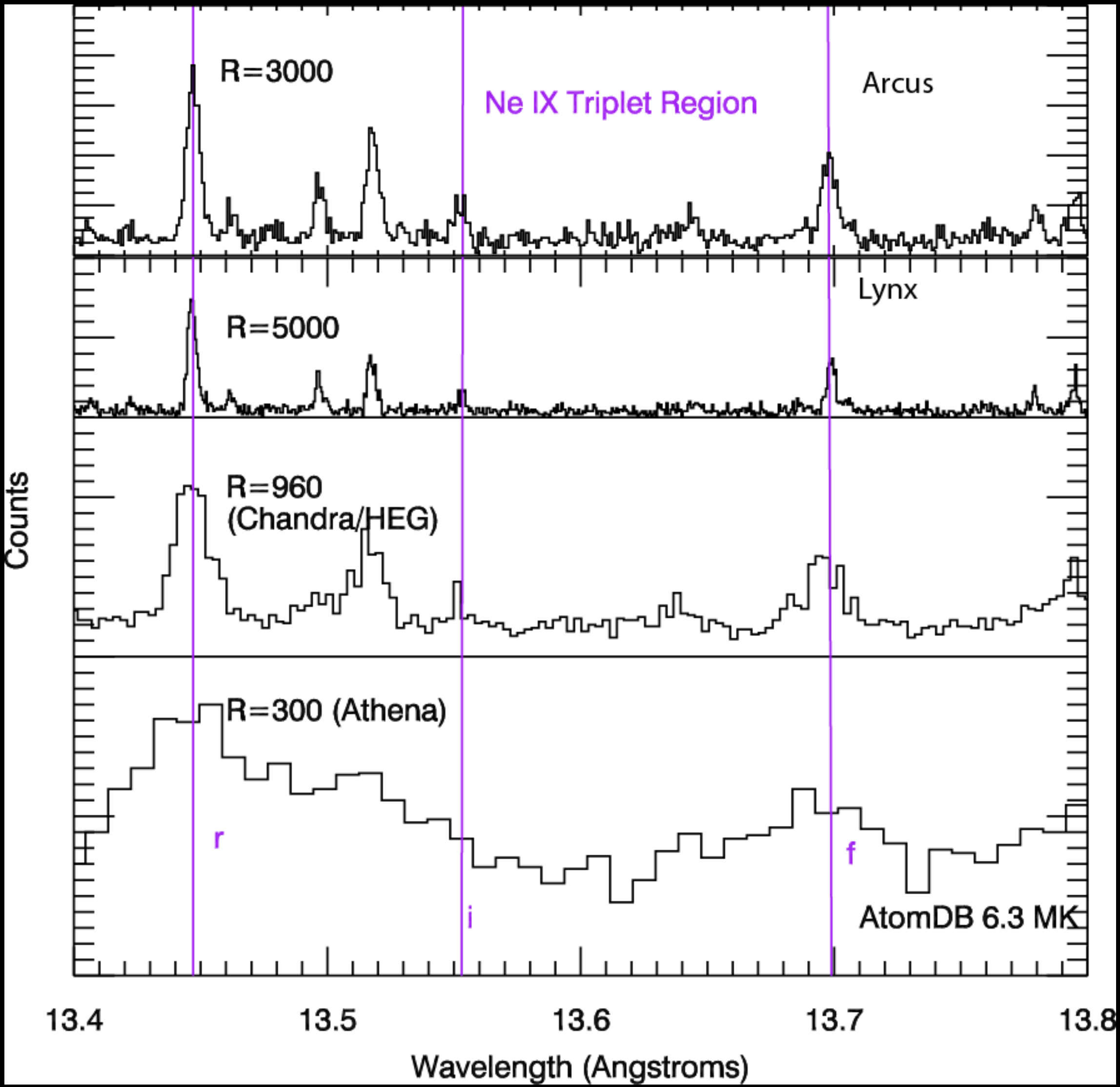




Brickhouse et al. (2010)

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

μcalorimeters ~~vs.~~ & Gratings



You need both

--Gratings don't image

μcal issues
-- continuum placement for measurement of triplet lines
--blending lines

Arcus/Lynx have dispersive gratings
--better quality than Chandra in ~10/1 ks in Taurus-Auriga objects, ~100/10 ks at Orion