HIGH ENERGY STELLAR AND (EXO) PLANETARY SCIENCE IN THE NEXT DECADE AND BEYOND

Scott Wolk (SAO/CfA)

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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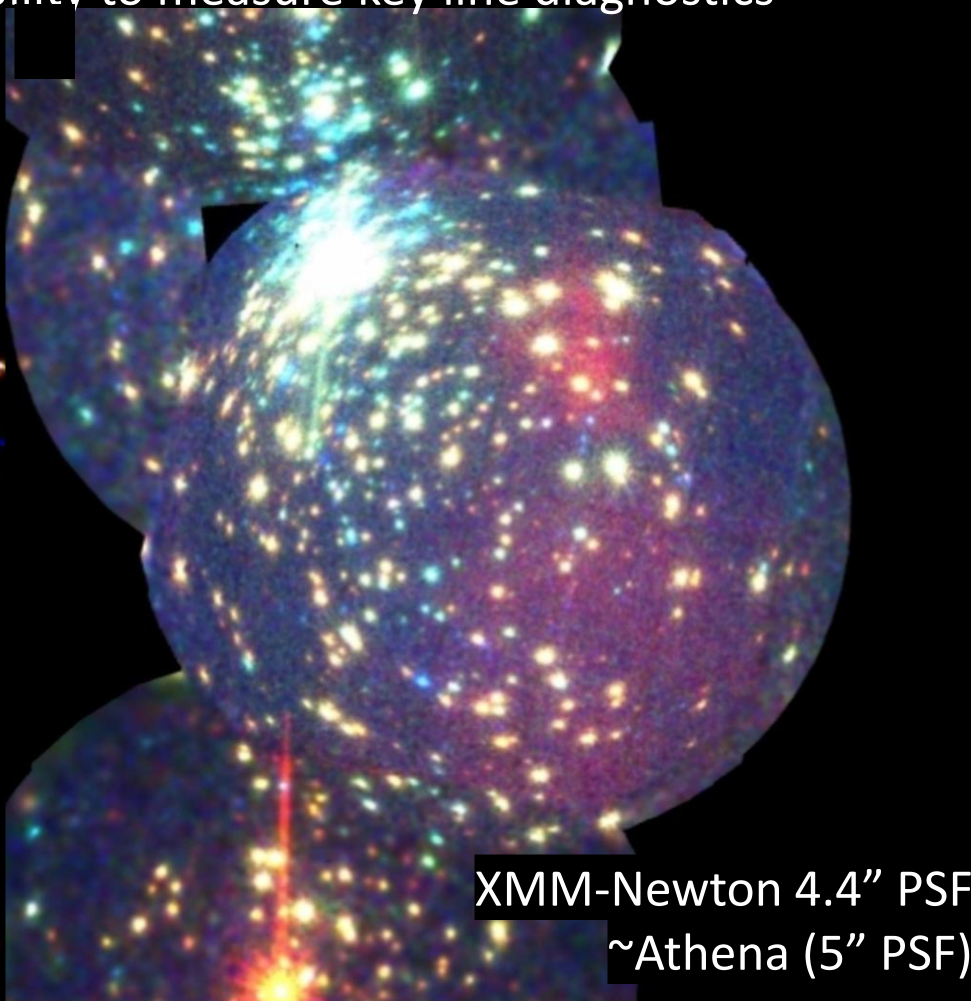
What will we be able to measure?

- 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

Chandra 0.5” PSF
~Lynx

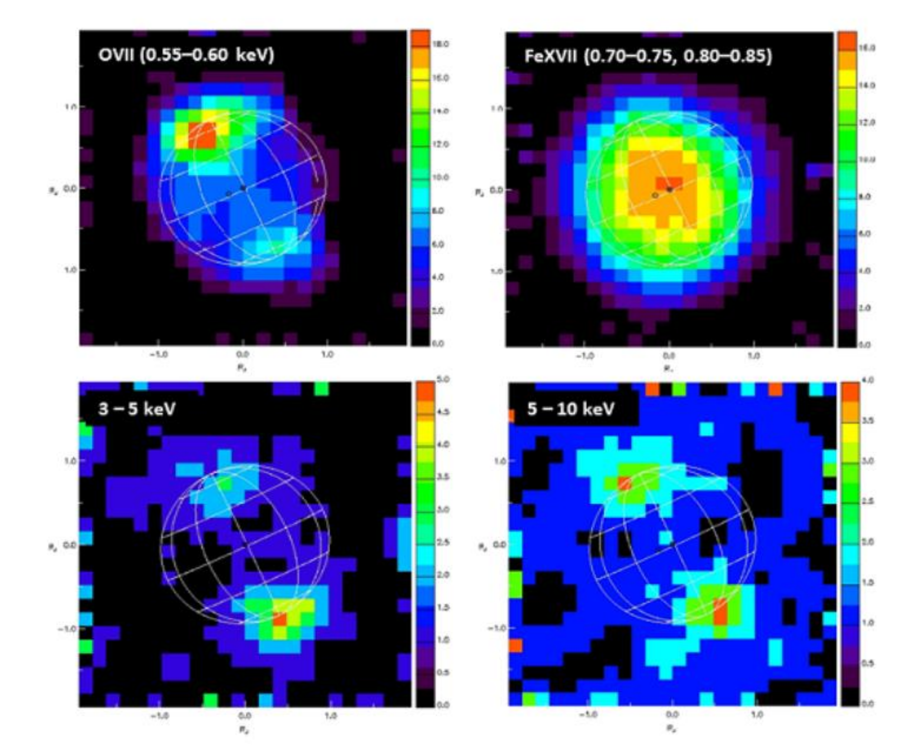


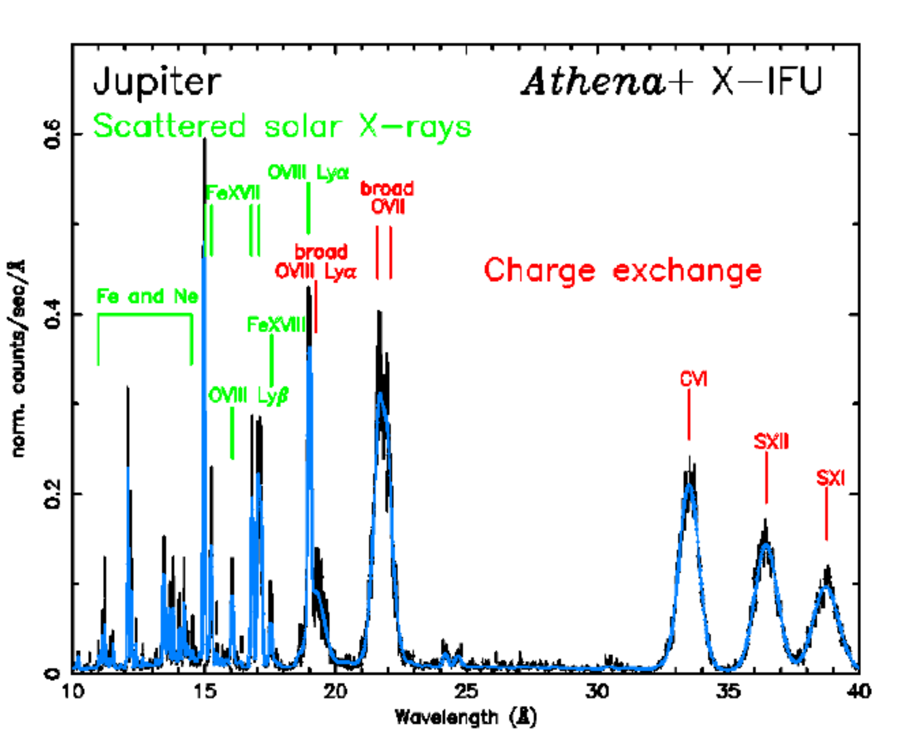
XMM-Newton 4.4” PSF
~Athena (5” PSF)

Imaging Spectroscopy

μcalorimeters:

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





Branduardi-Raymont et al. (2007)

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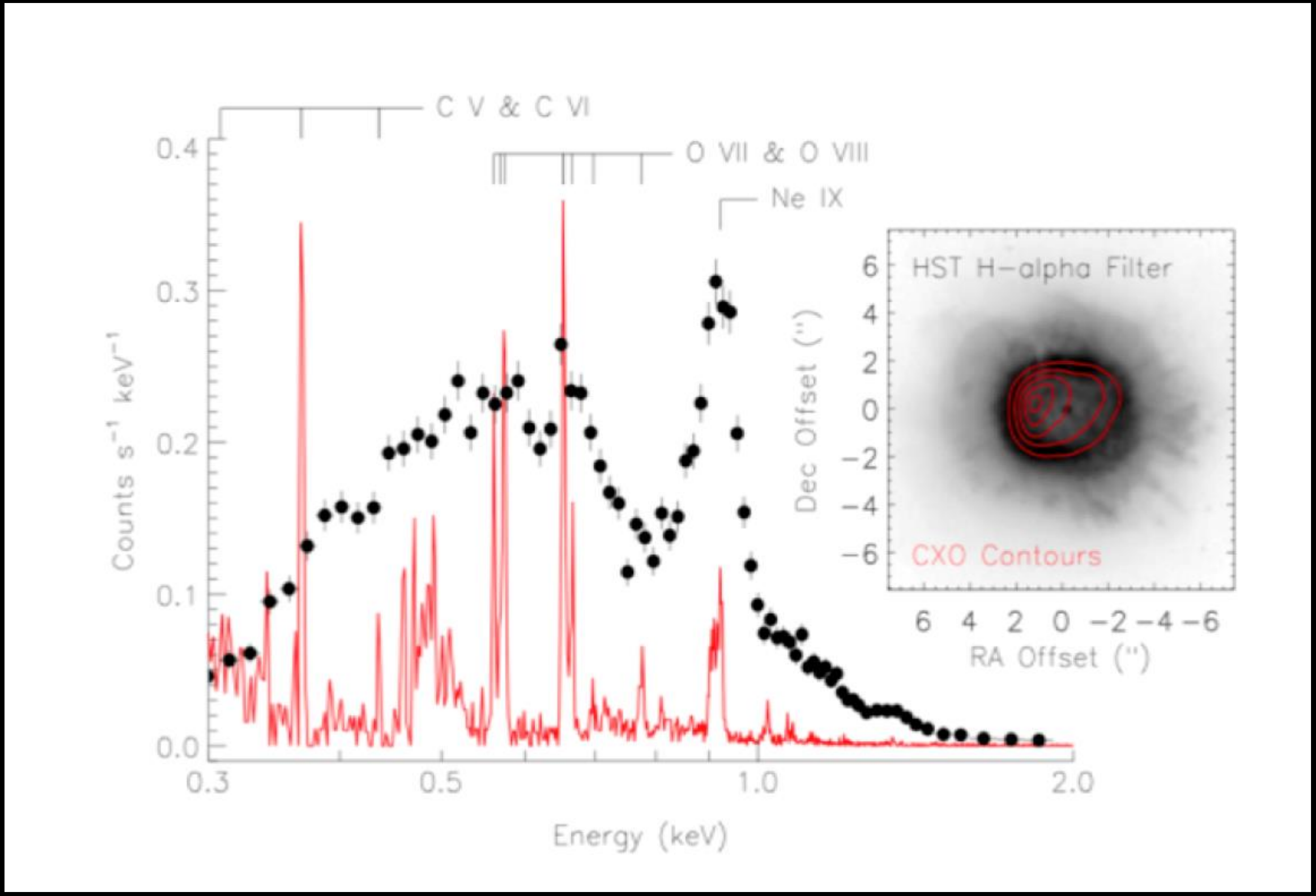
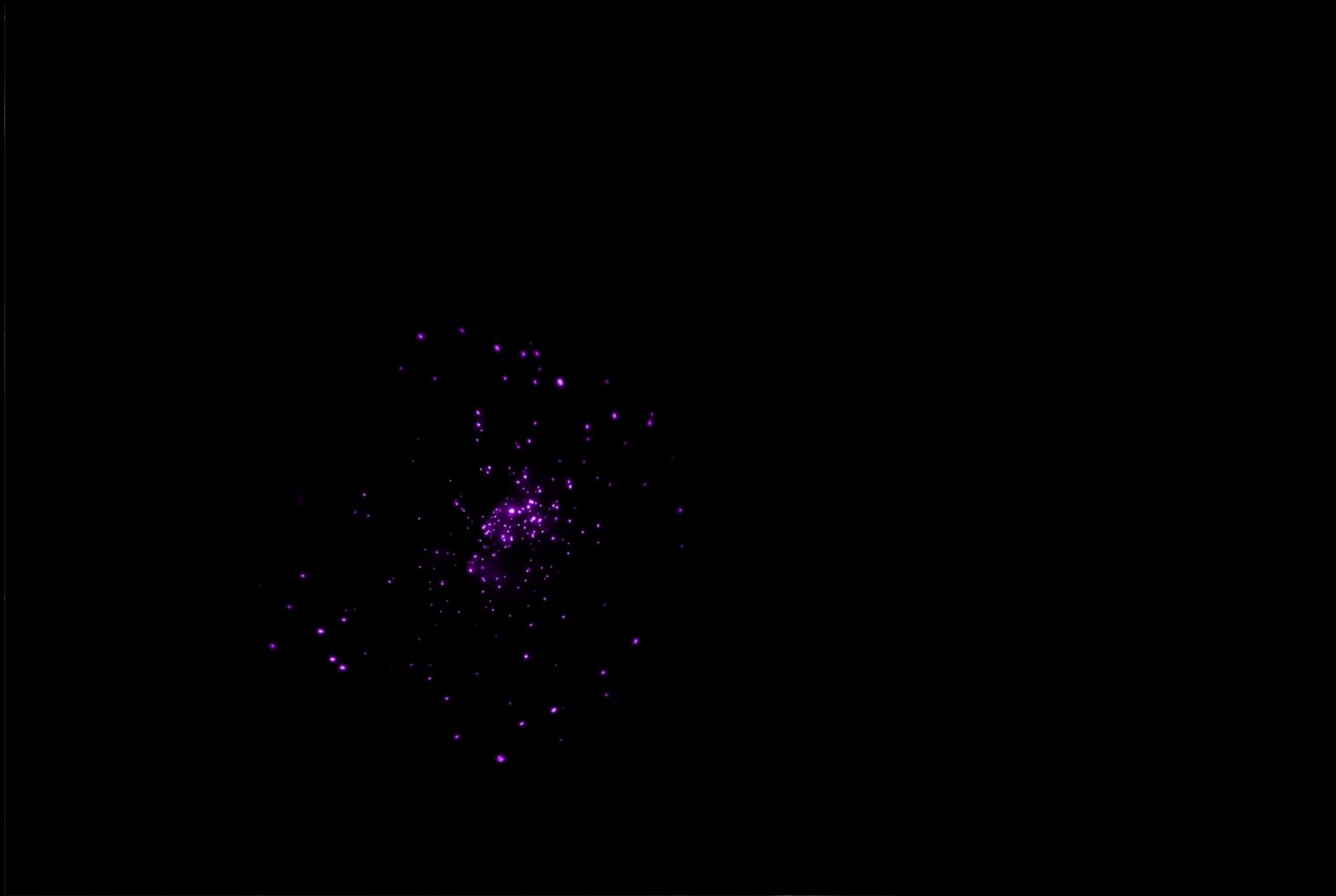


Studies of Nearby Star Formation Regions

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

PSF is directly related to the reach of the telescope



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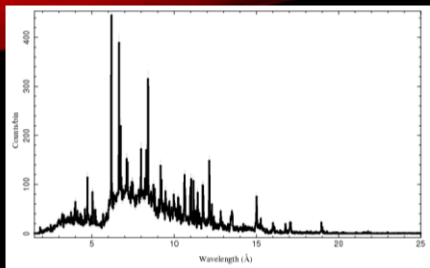
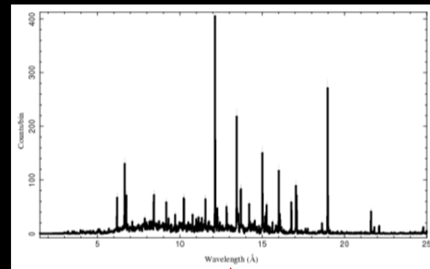
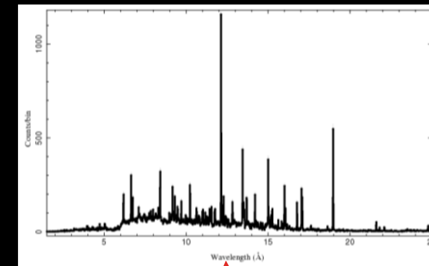
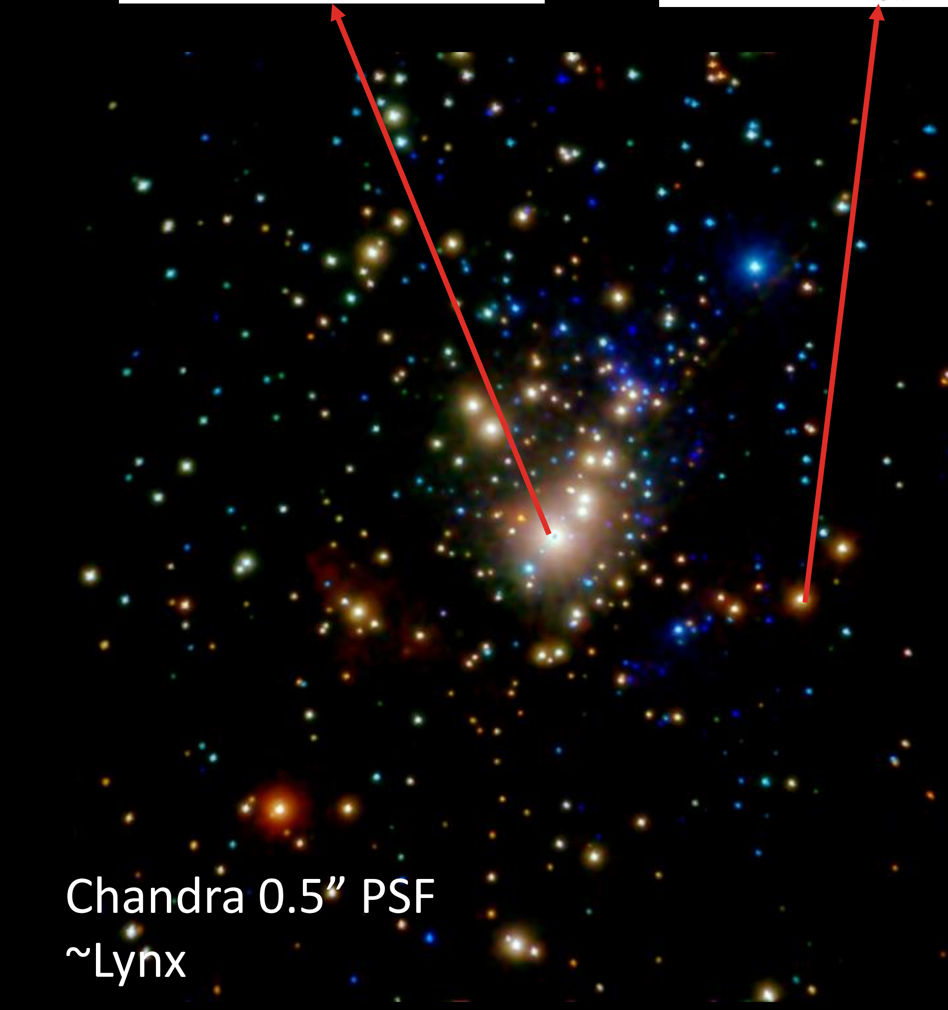
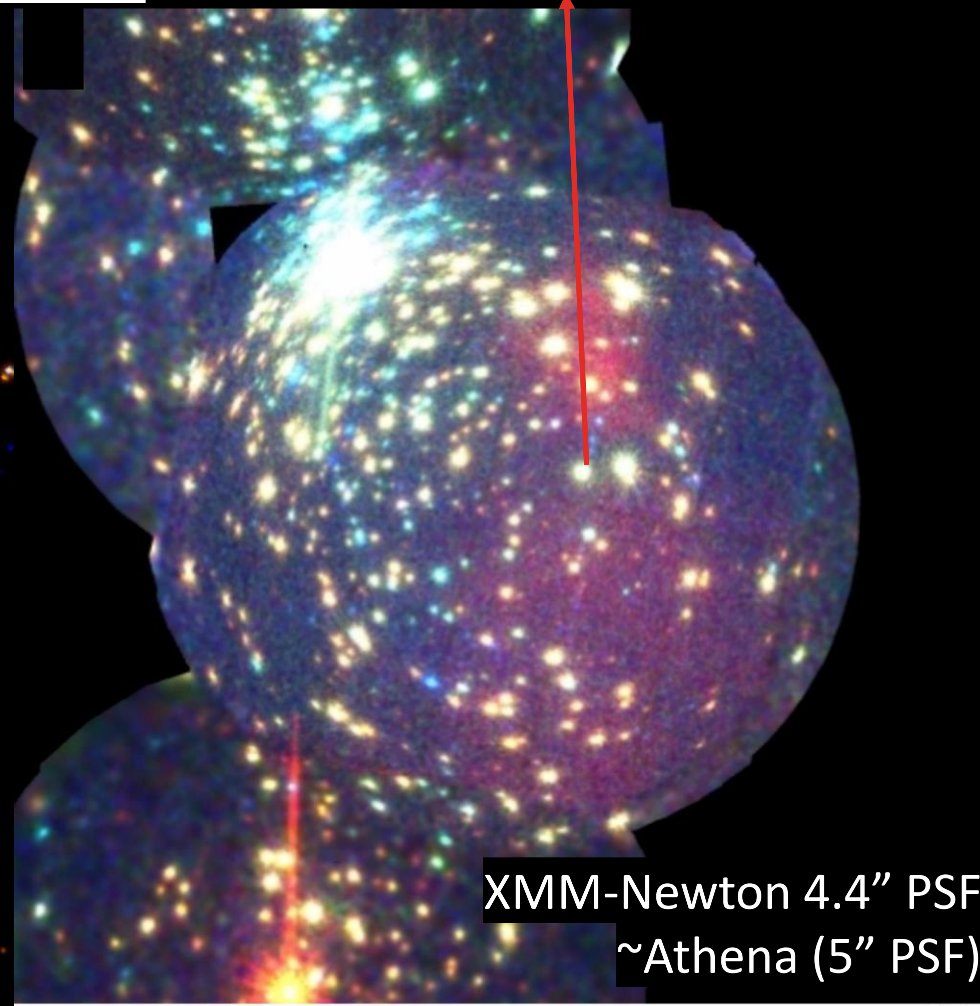


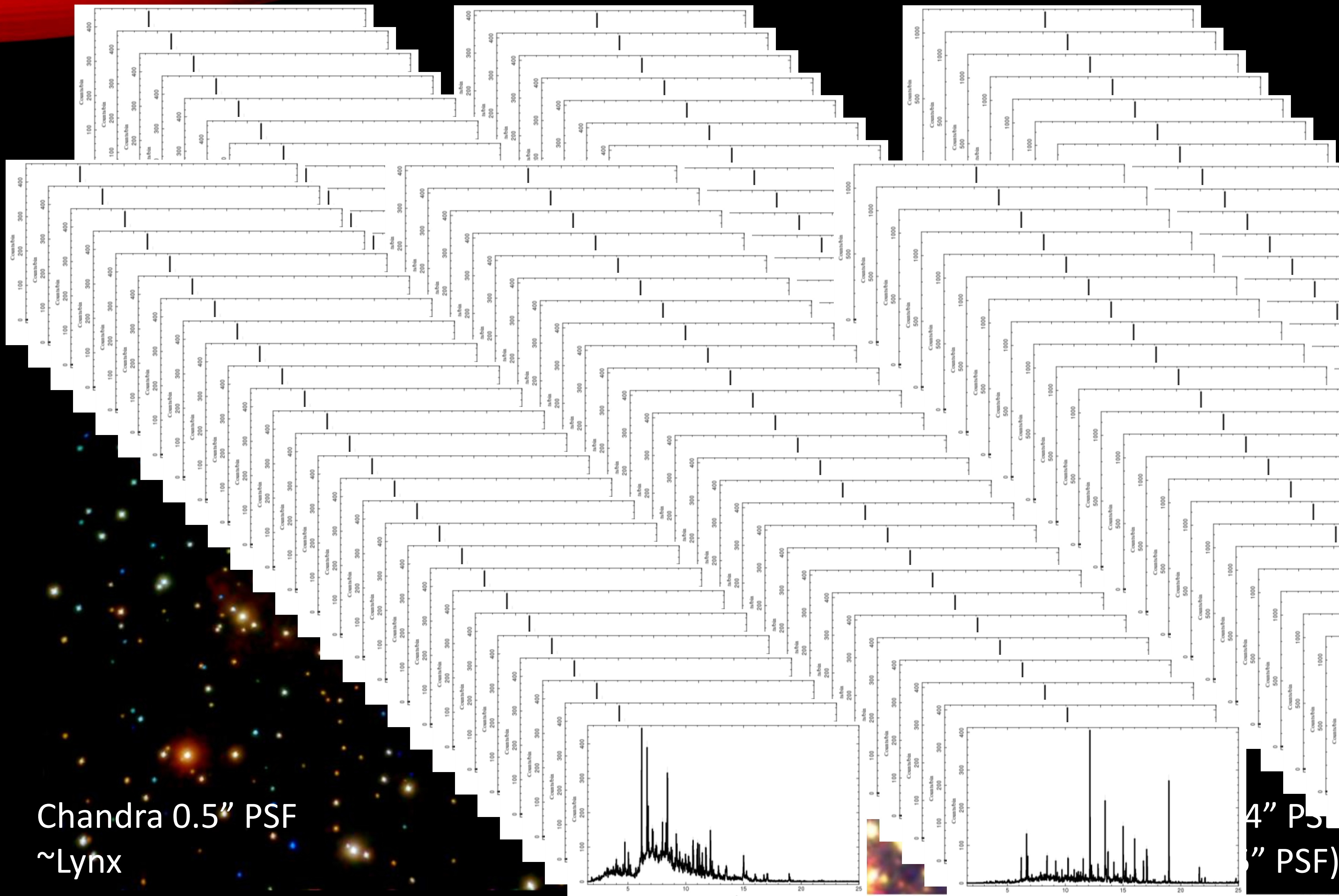








Overwhelming datasets



Studies of Nearby Star Formation Regions

Well done with μcal imaging spectroscopy

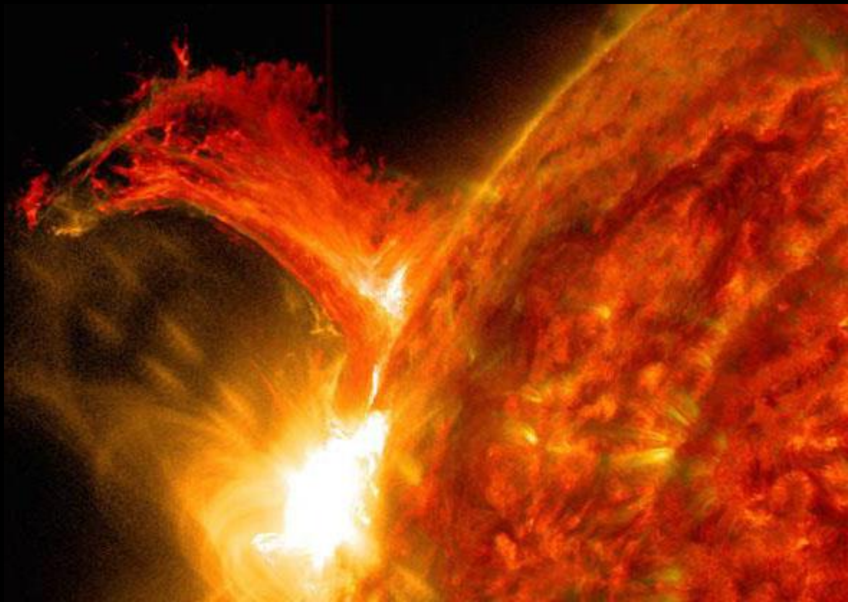
- Cluster Census
- Transition disk timescales
- X-ray effects on cluster morphology
- Detecting grain evolution
- X-rays from protostars
- Effect of X-rays on forming planets disks
    - Especially flares.
- Understanding the magnetic fields.
- What are the statistics of radio flaring for young stellar 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.

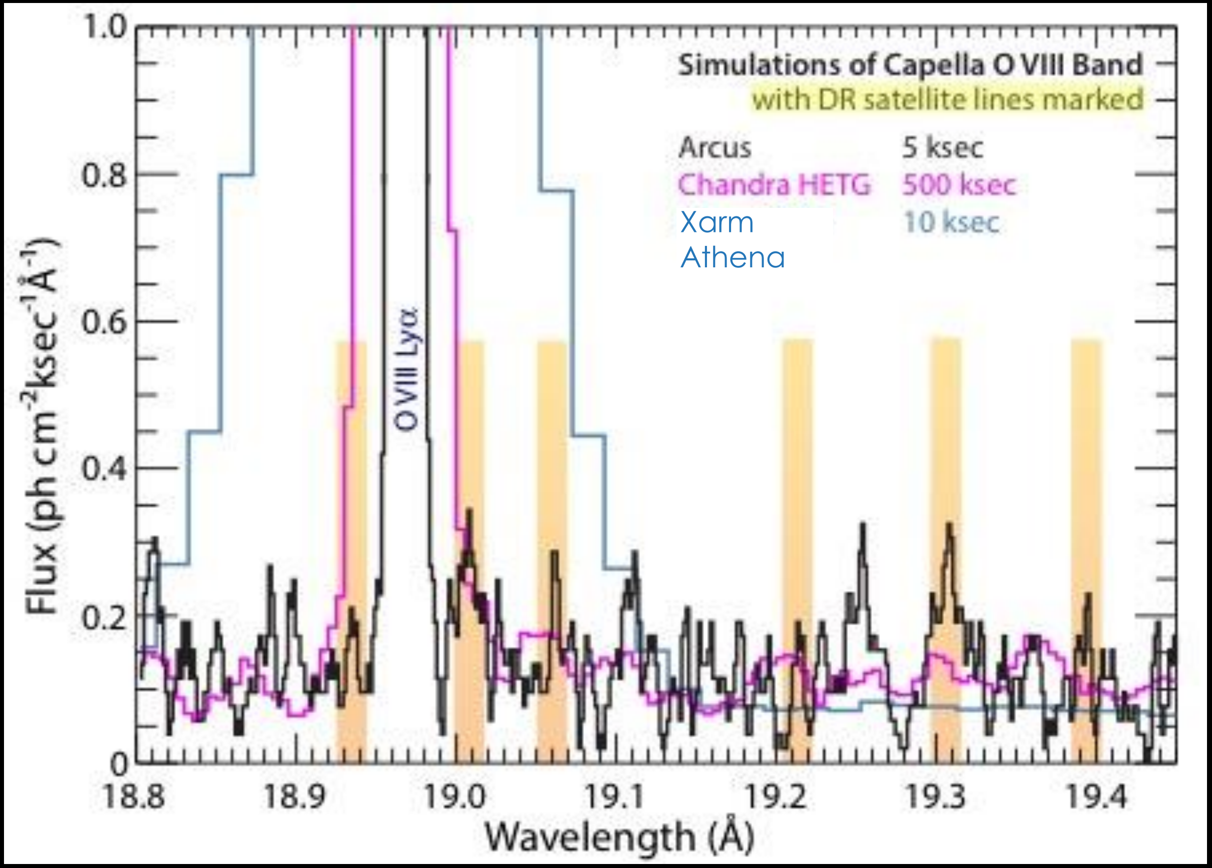


Coronal Spectoscopy

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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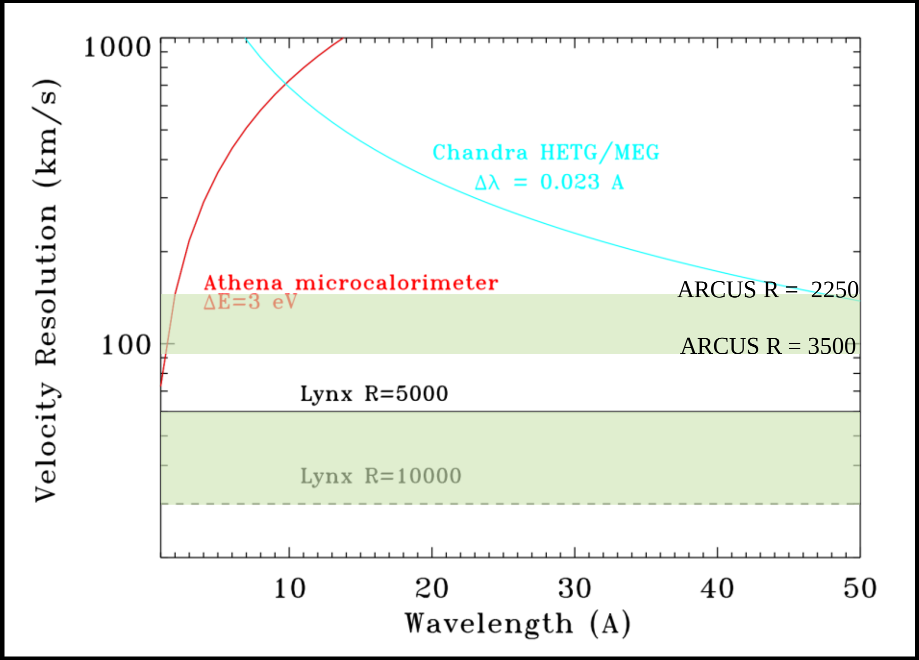
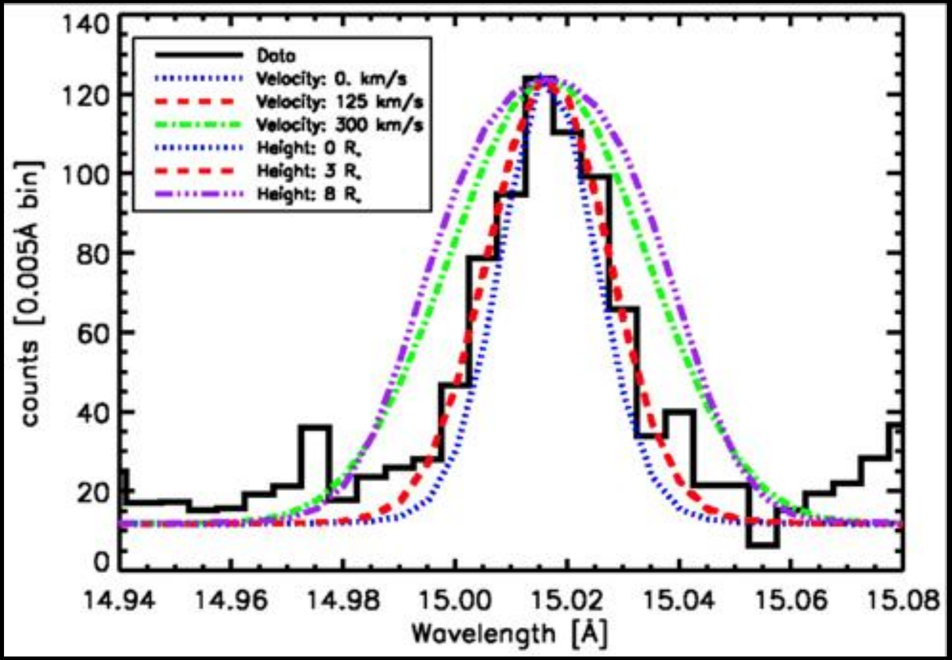
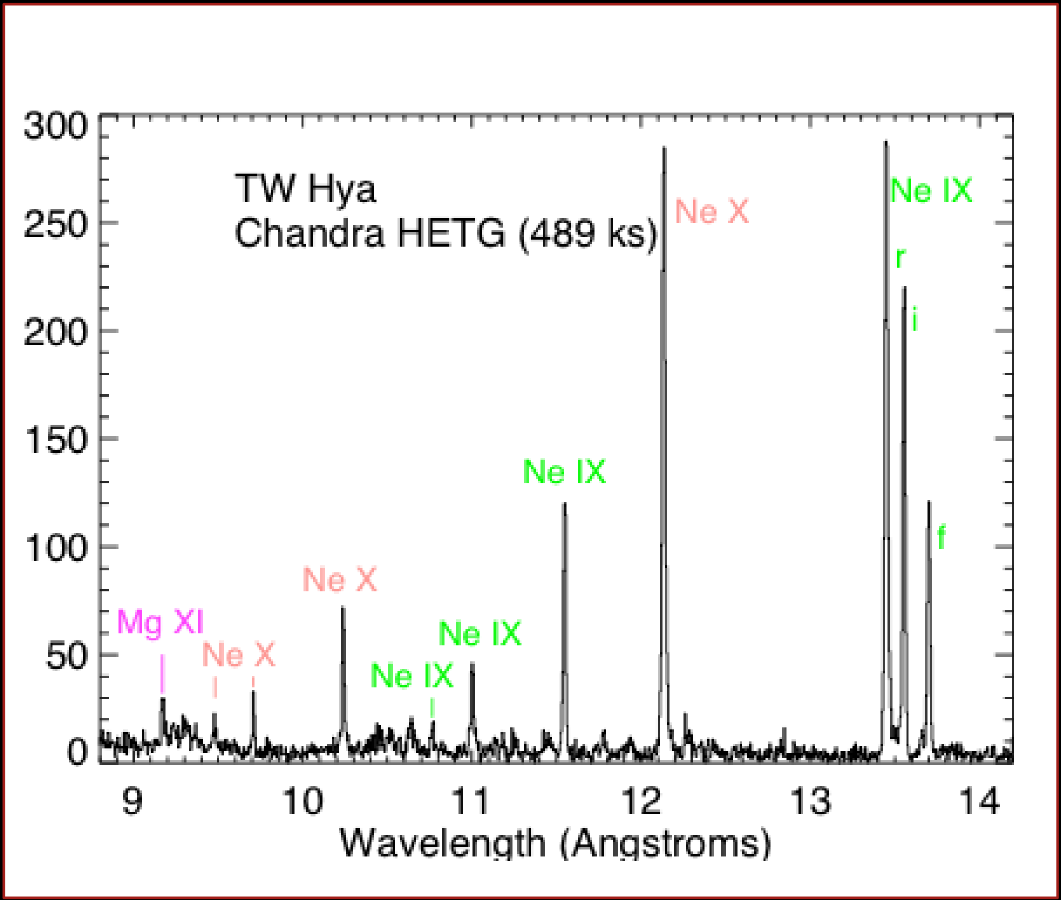




Chung et al. (2004) excess broadening of Algol interpreted as rotational broadening from a radially extended corona

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
- After stars lose their disks X-ray surveys are the only way to find young stellar objects

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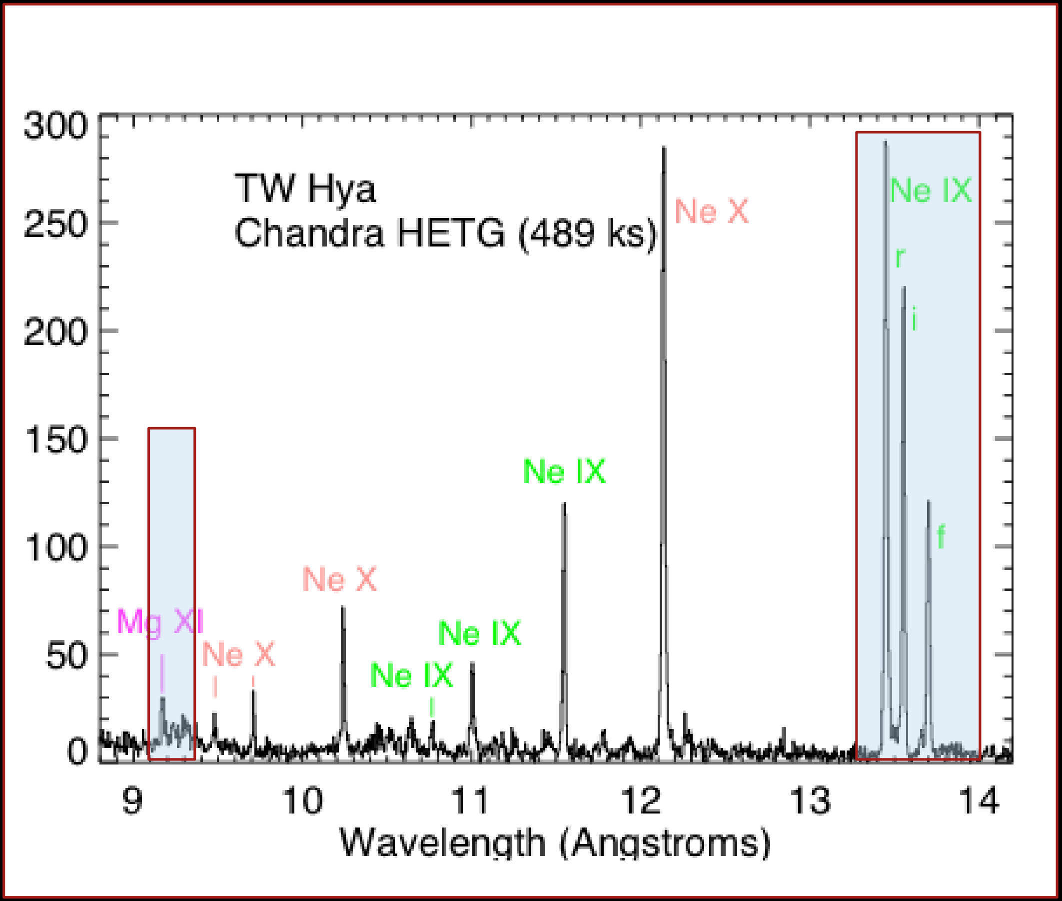

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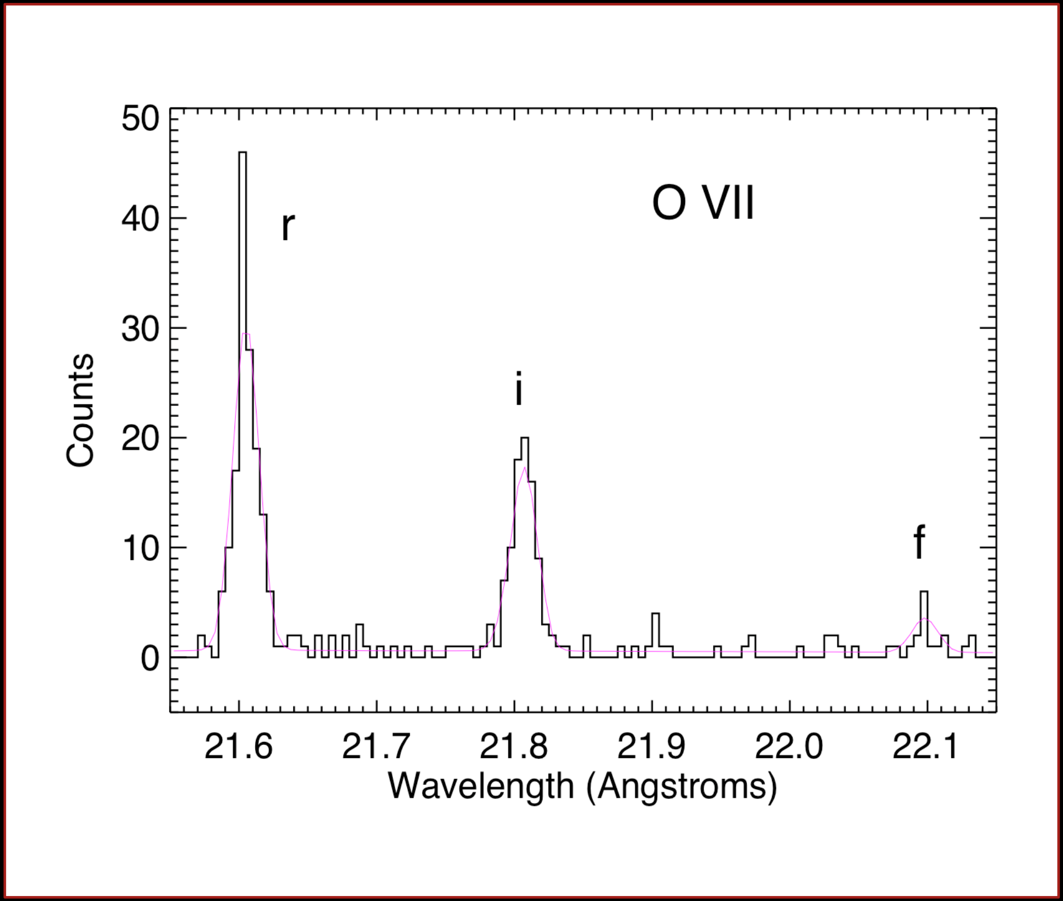

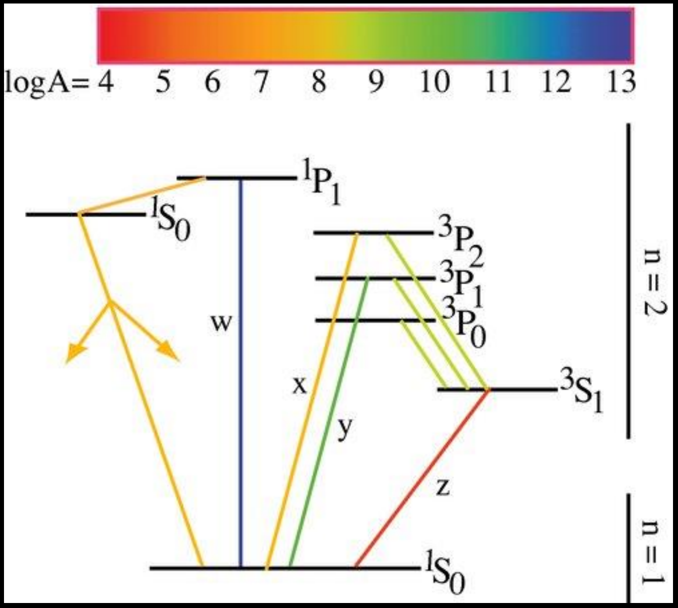

Smith et al. (2009)

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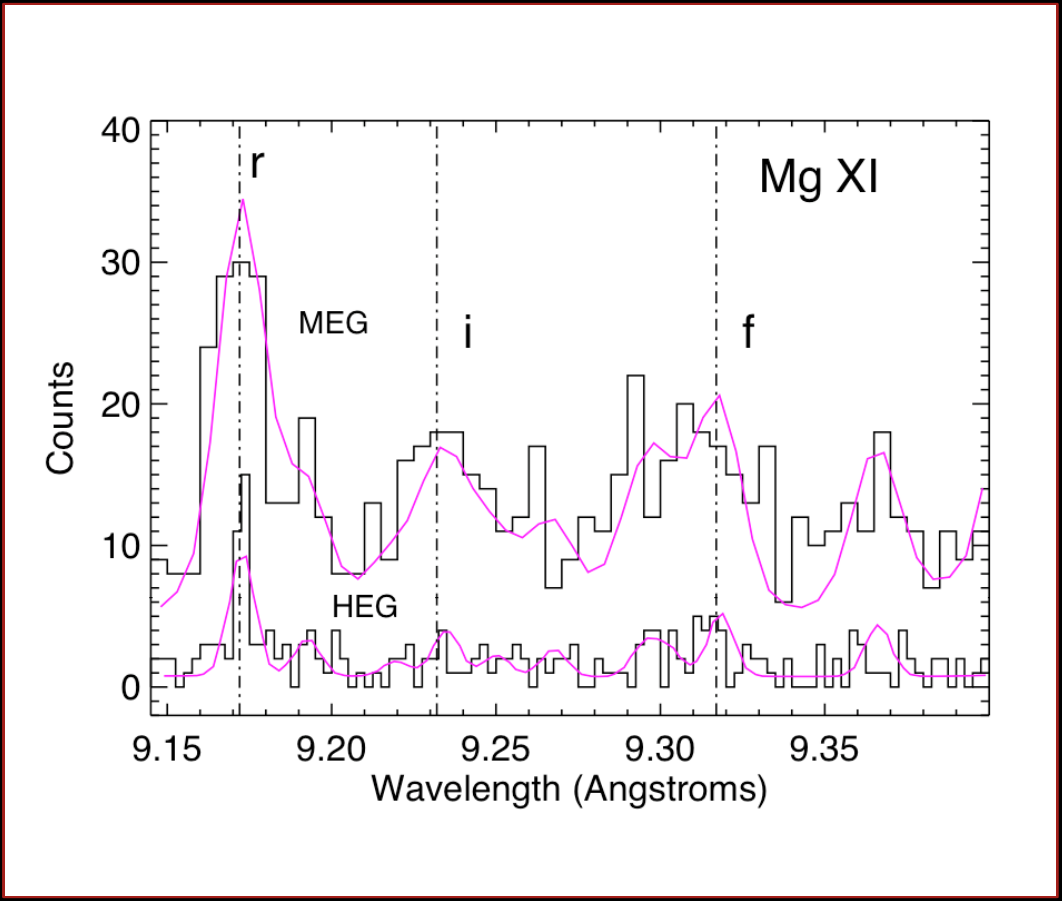

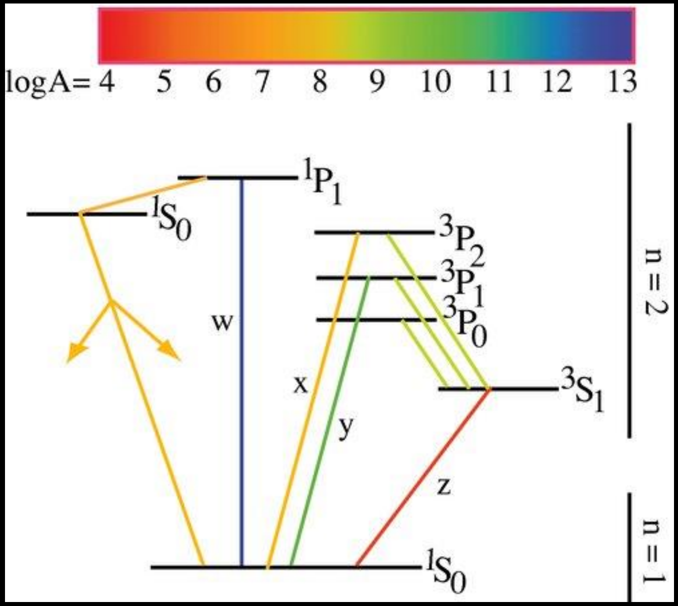

Potential Exoplanet Applications

Where do planets form? Where do they migrate?

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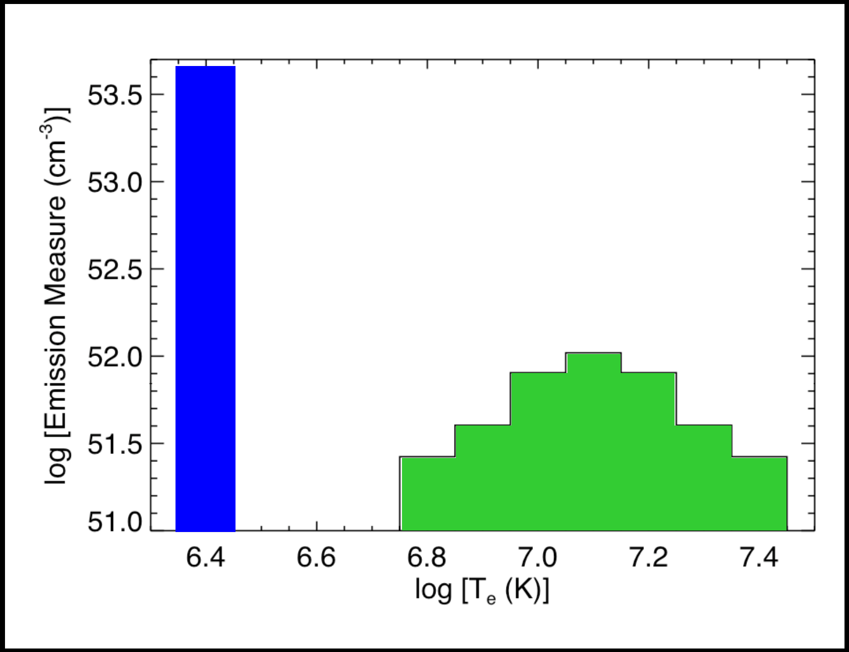
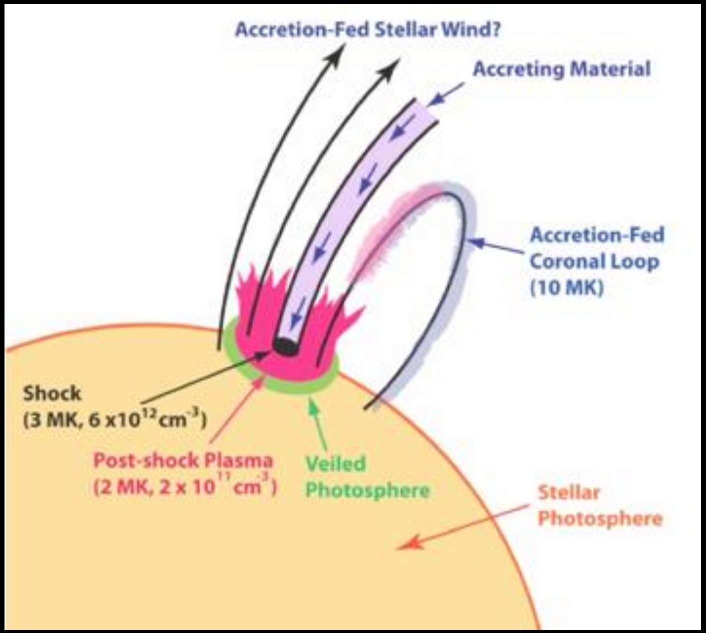
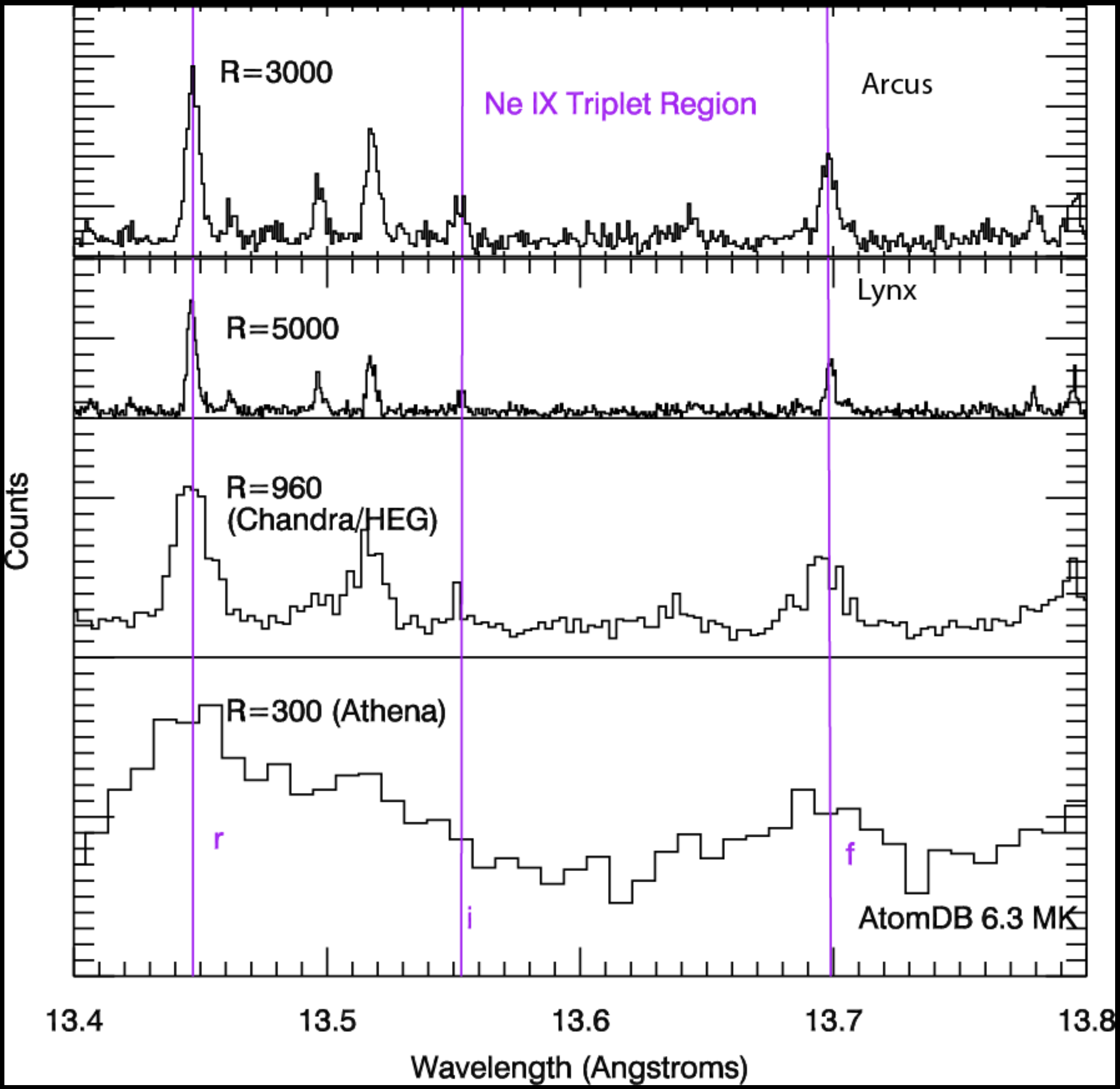




Brickhouse et al. (2010)

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

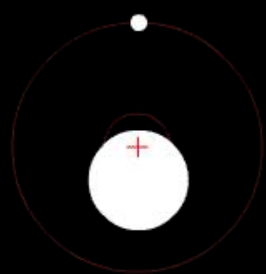
Arcus/Lynx have dispersive gratings
--better quality than Chandra in ~10/1 ks in Taurus-Auriga objects, ~100/10 ks at Orion

Future Stellar Studies

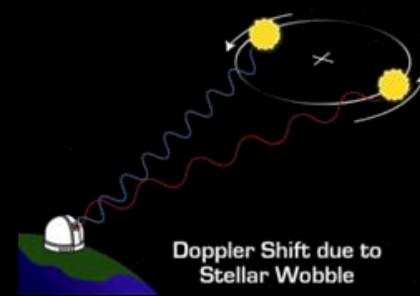
- Searching for habitability
- Focused on low mass M dwarfs
- Habitable zones are closer to star
- Issues include destruction of atmosphere by:
  - Stellar flares and concurrent CME's
    - AD Leo can recover from massive flare/proton flux (Segura+ 2010)
  - Stellar UV to X-ray radiation
    - But UV 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)

What is Exoplanet Science?

Not just this

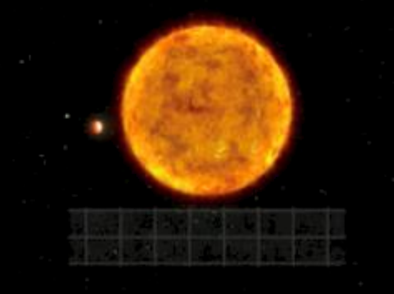


radial velocity — velocity shift of a star due to star+planet

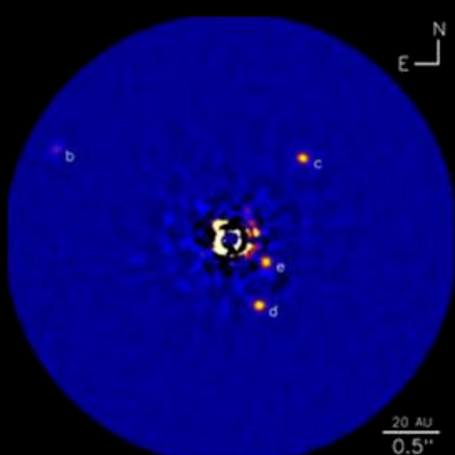


astrometry — seeing the reflex motion of the star due to star+planet system

transit — decrease in stellar light

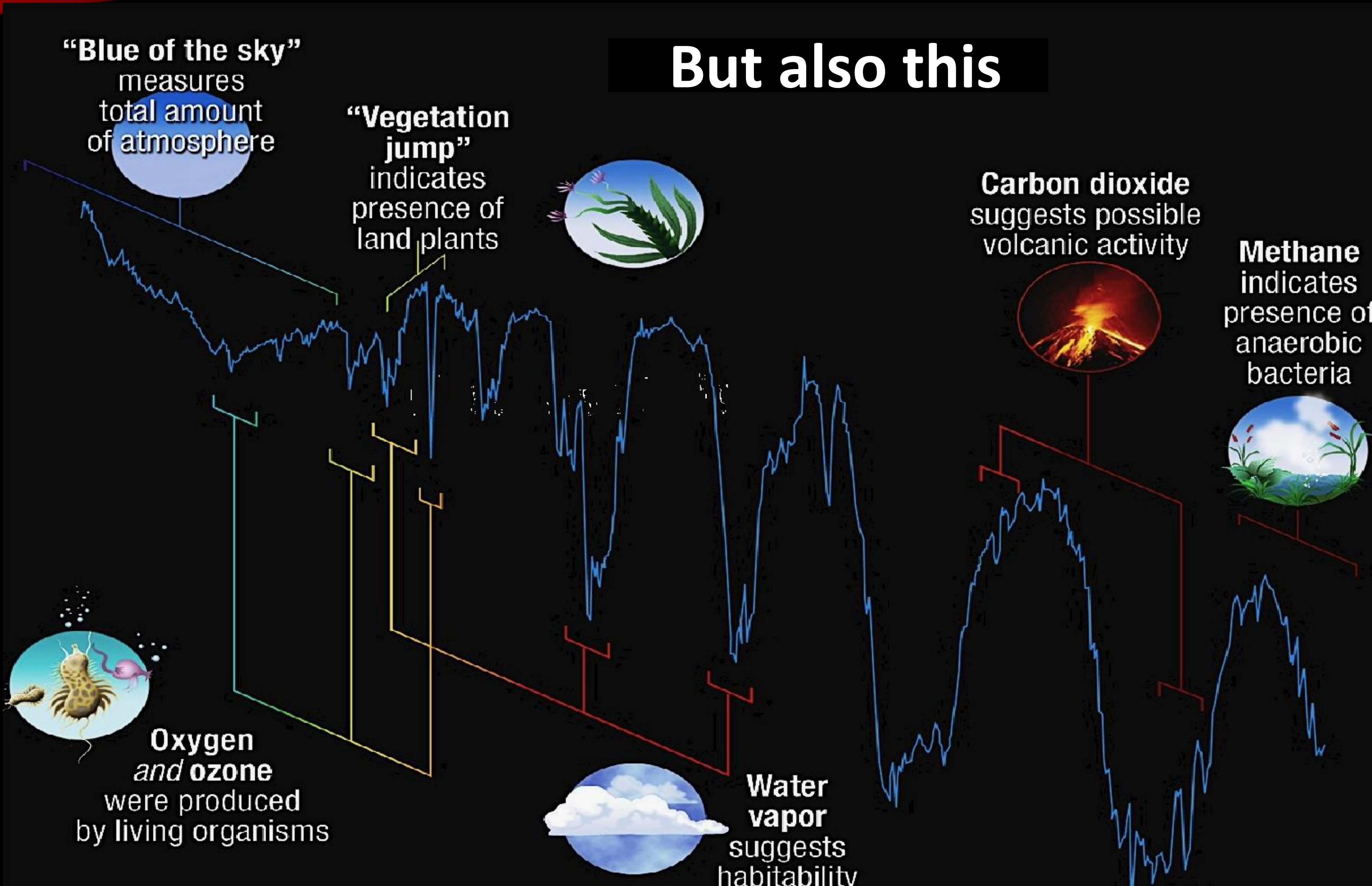


direct imaging — block out the light of the star to see the planet directly



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

What is Exoplanet Science?



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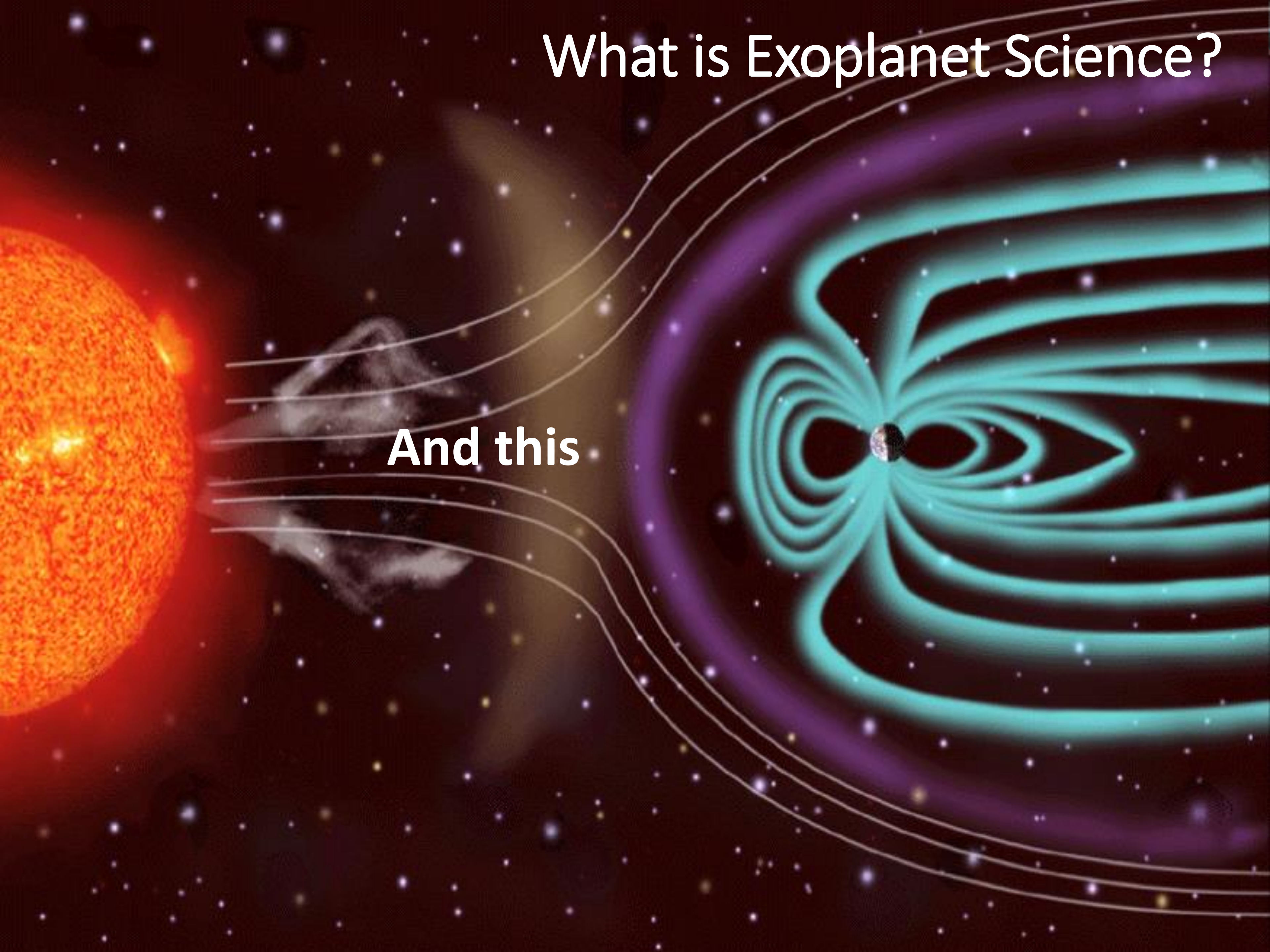

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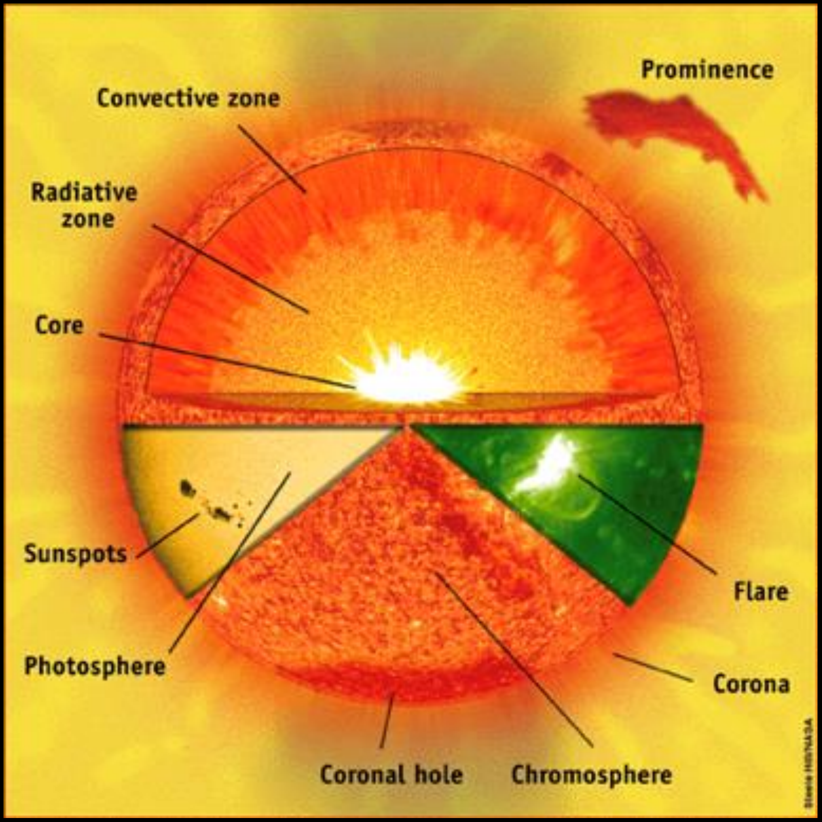

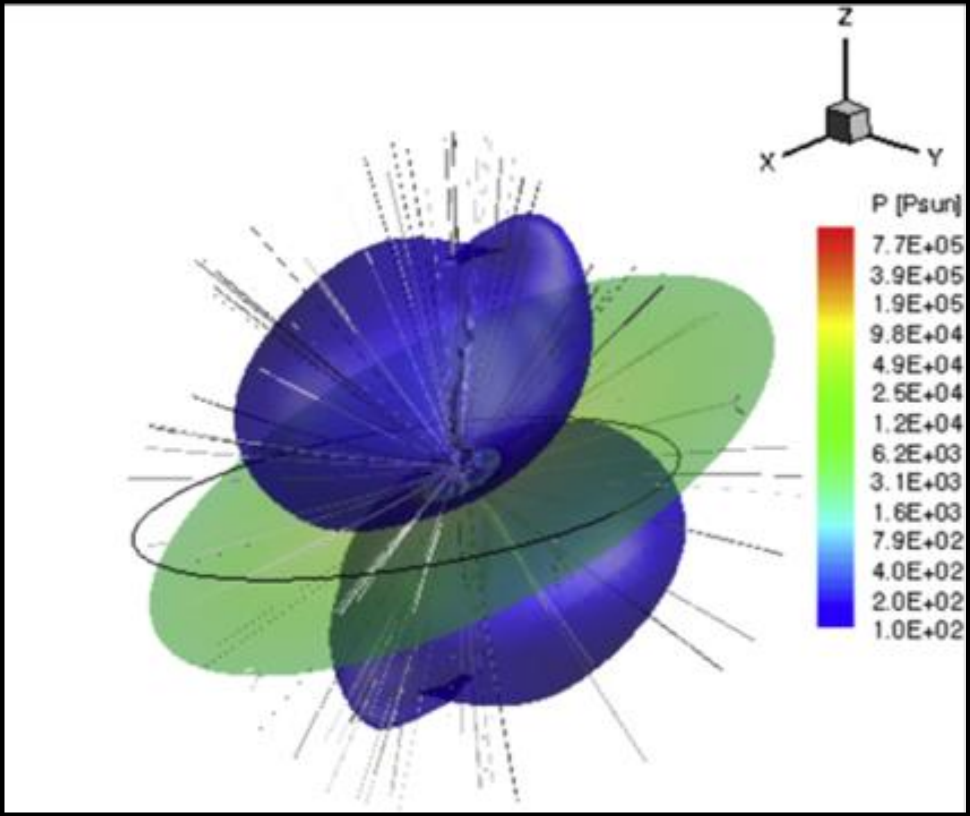

The star's magnetic field creates an ecosystem which helps to set the environment that planets (and life) experience (Lingam & Loeb 2018)
Stellar magnetospheres influence the inner edge of the traditional habitable zone (Garaffo et al. 2016, 2017).

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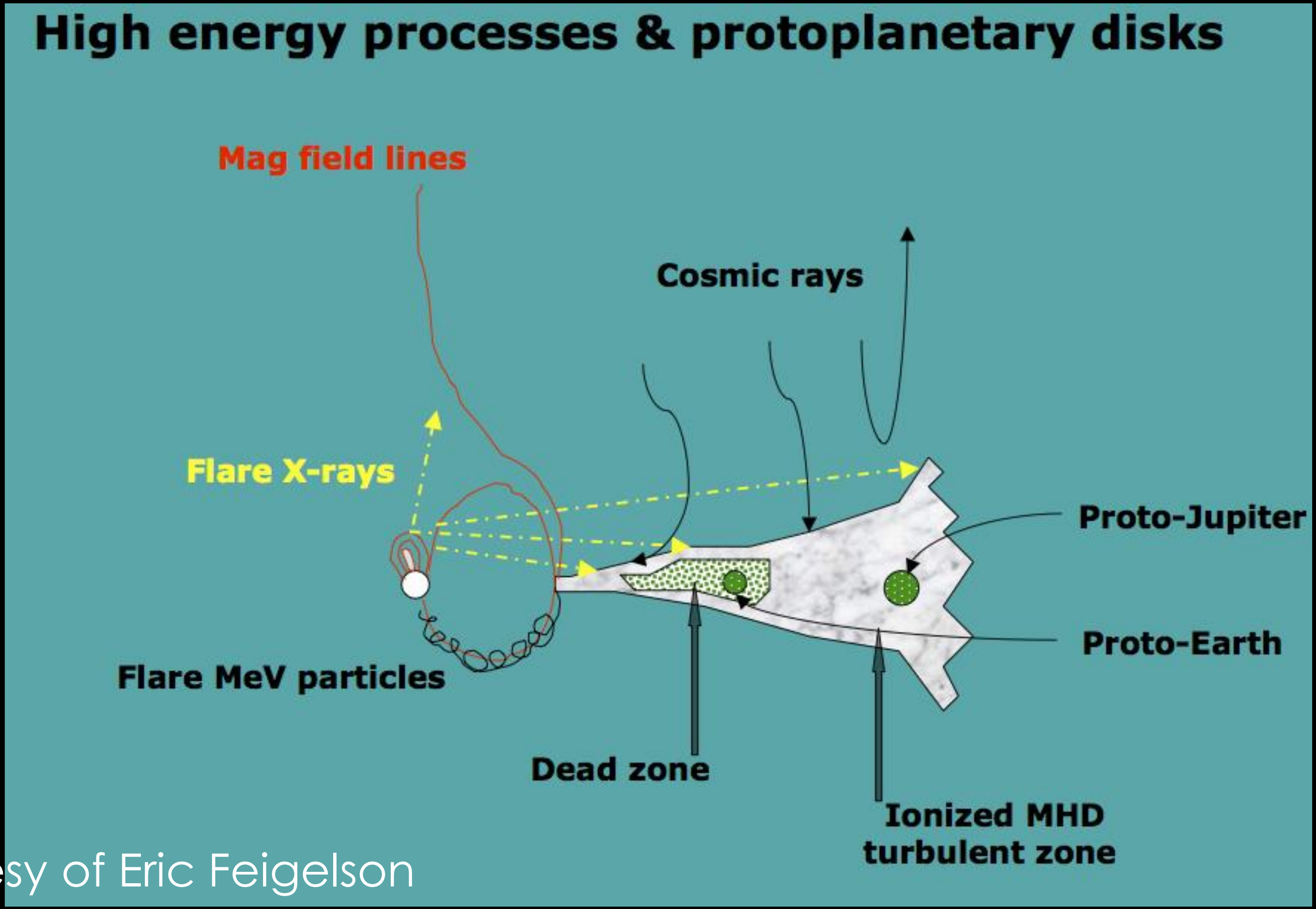
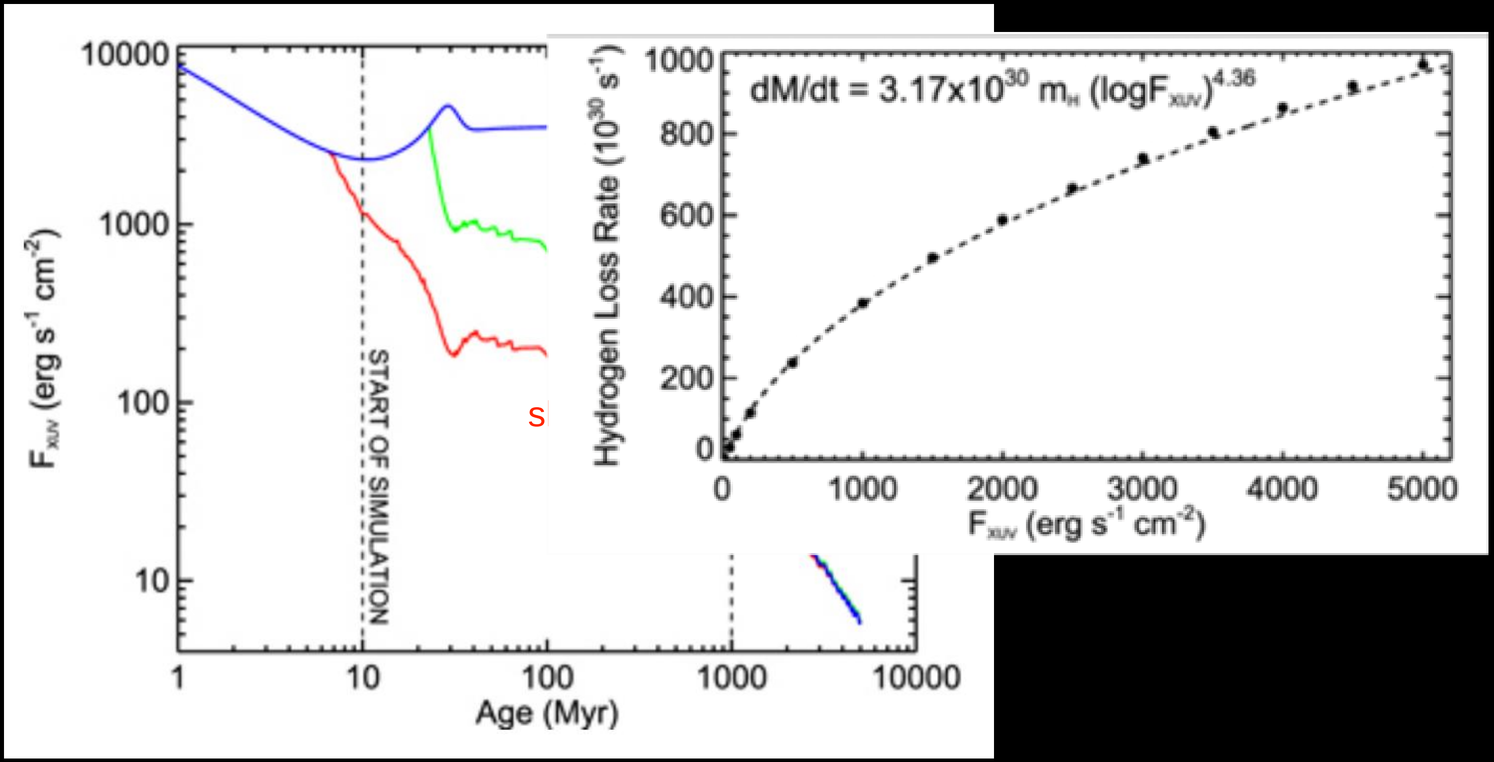


Slide courtesy of Eric Feigelson

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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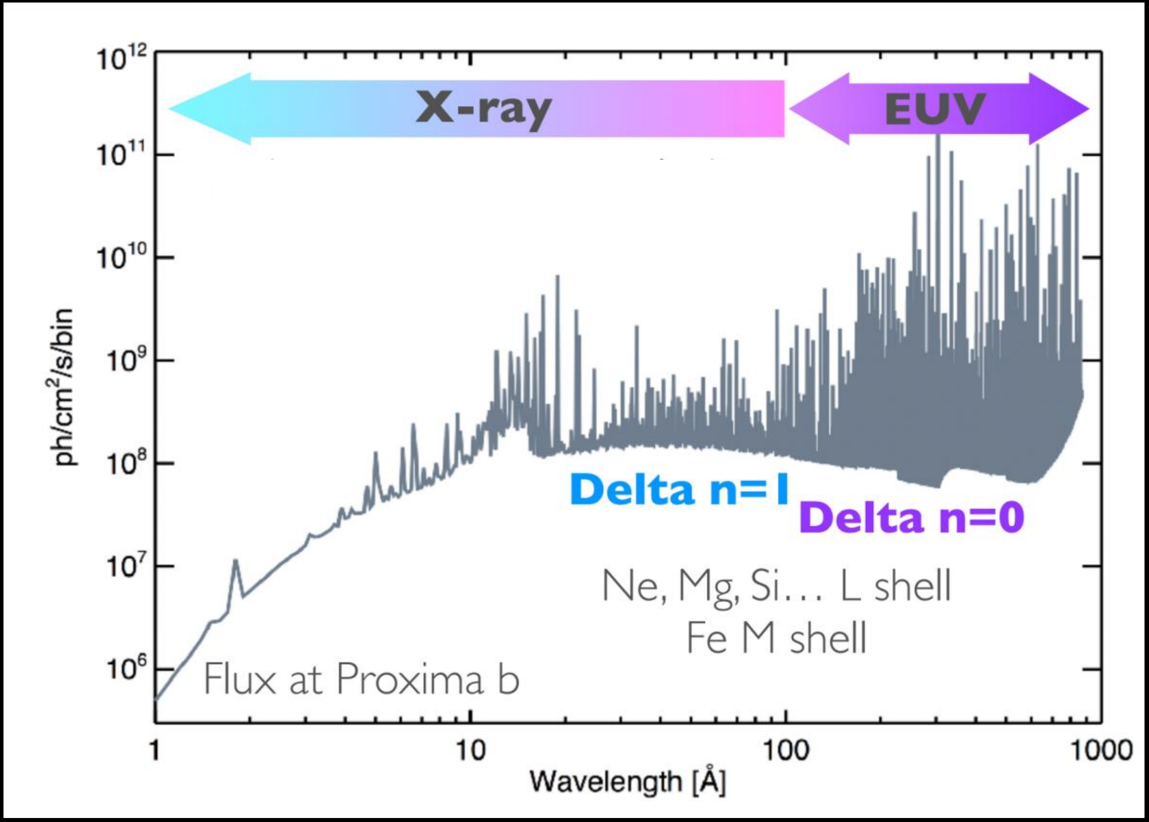

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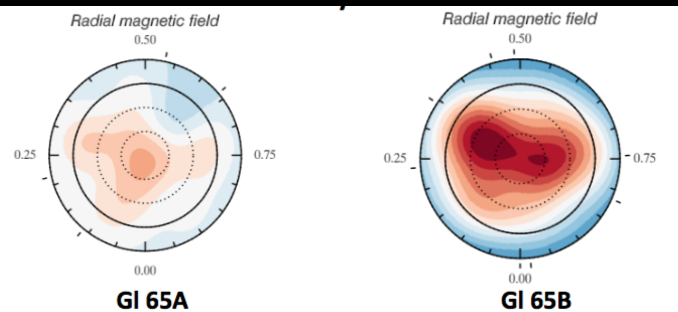
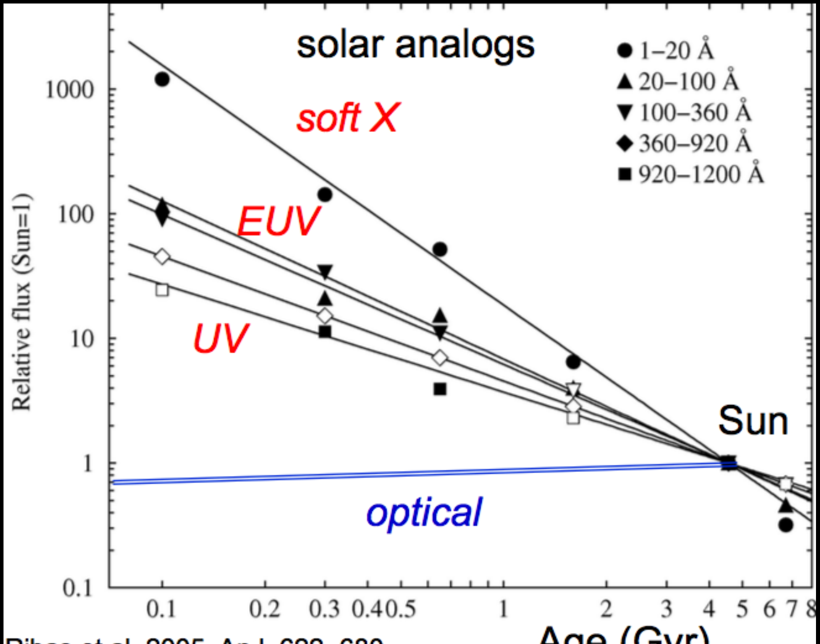


Spectral class	M5.5Ve	M6Ve
Mass	$0.1225\ M_\odot$	$0.1195\ M_\odot$
Radius	$0.165\ R_\odot$	$0.159\ R_\odot$
Rot. vsini	28.5 km/s	30.6 km/s
Rot. period	5.86 hr	5.45 hr
Metall. [Fe/H]	-0.03	-0.12
<Bf> Stokes I	**5.2 kG**	**6.7 kG**
B_{dip} strength V	**0.3 kG**	**1.3 kG**
	complex, non-axisymmetric	**axisymmetric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

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

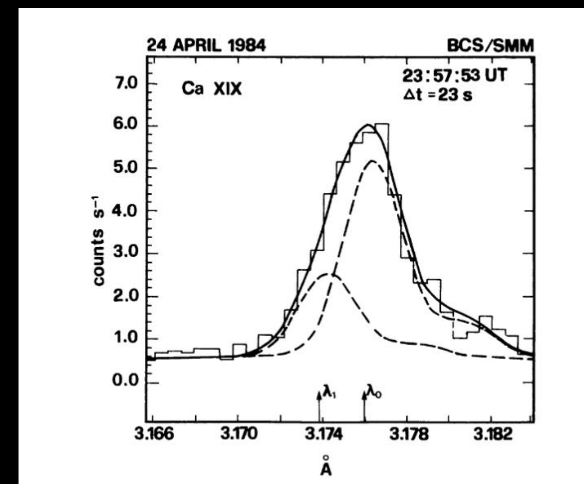


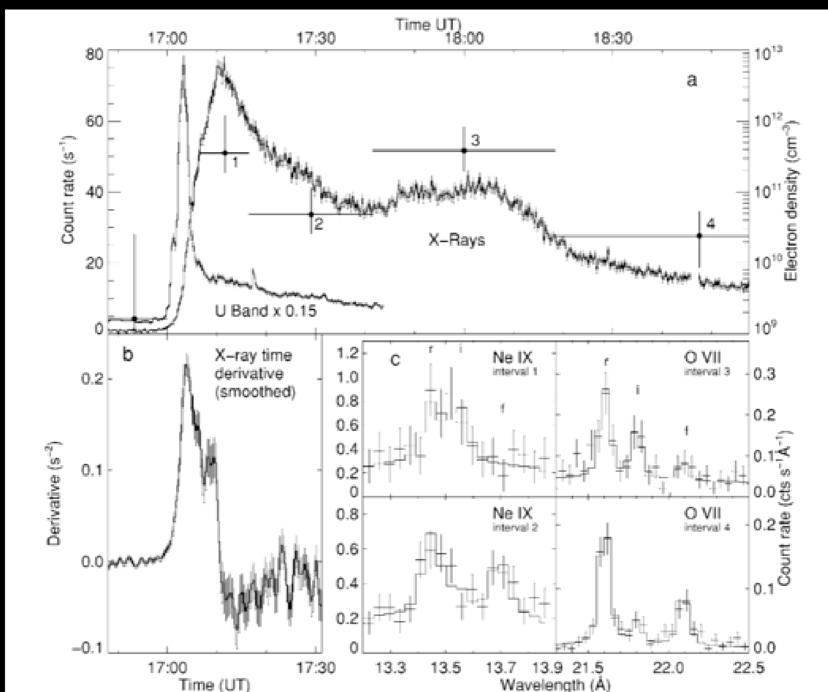
Ribas et al. 2005, ApJ, 622, 680

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

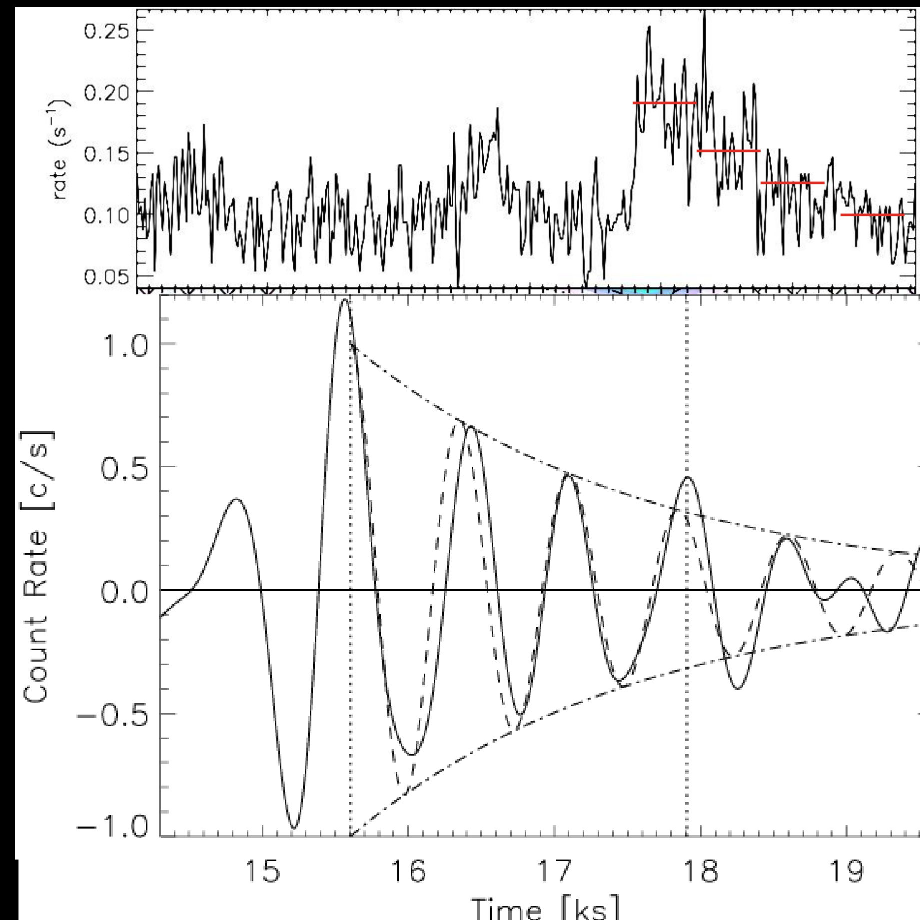
2D wavelet analysis of 2012 light curve
Description: A damped magneto acoustic oscillation in the flaring loop.

$\Delta I/I \sim 4\square n k_B T/B^2$

$T \sim 12$ 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=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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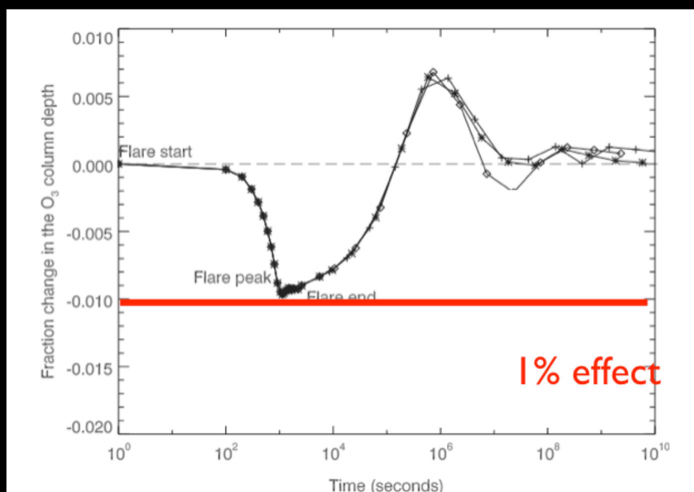
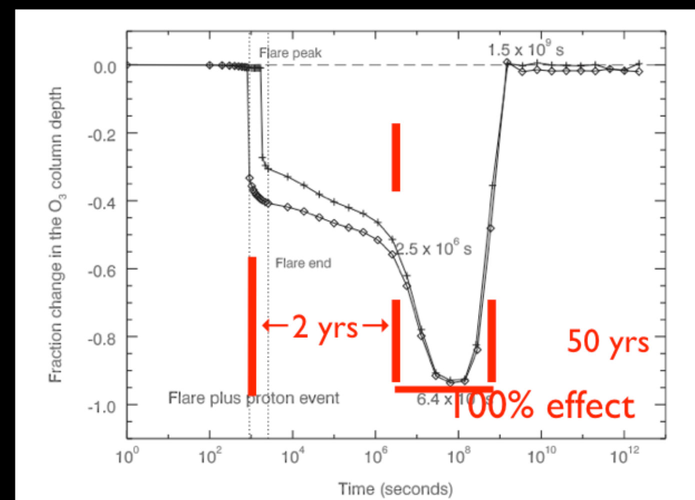


A UV flare only has a 1% effect on the depletion of the ozone layer of an Earth-like planet in the habitable zone of an M dwarf



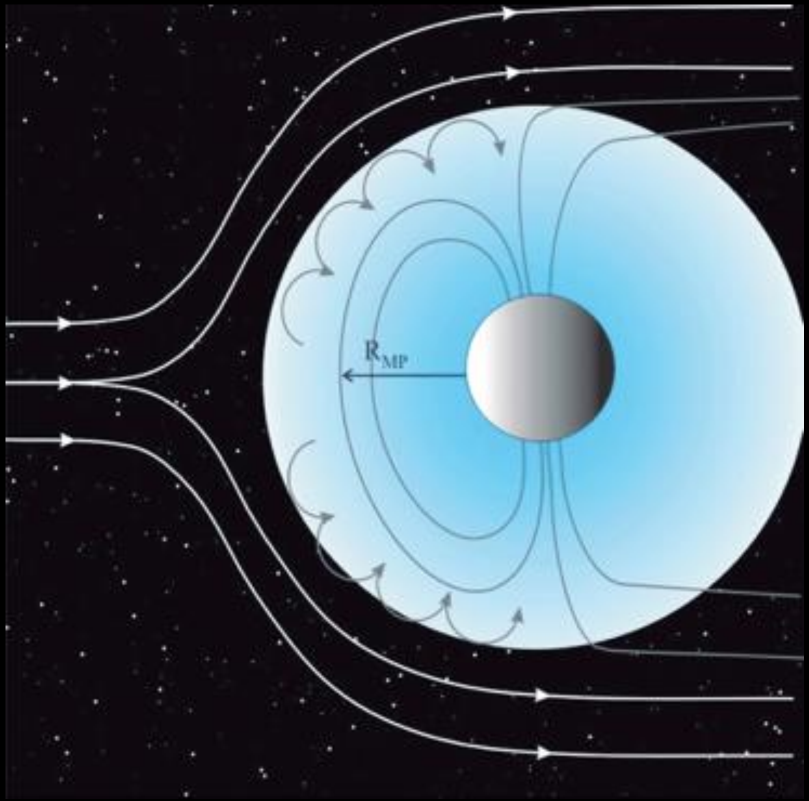
A UV flare + proton event (>10 MeV) inferred from scaling from solar events, results in complete destruction of the ozone layer in the atmosphere of an Earth-like planet in the habitable zone of an M dwarf

Segura et al. (2010)

Measuring ExoplanetEnvironments

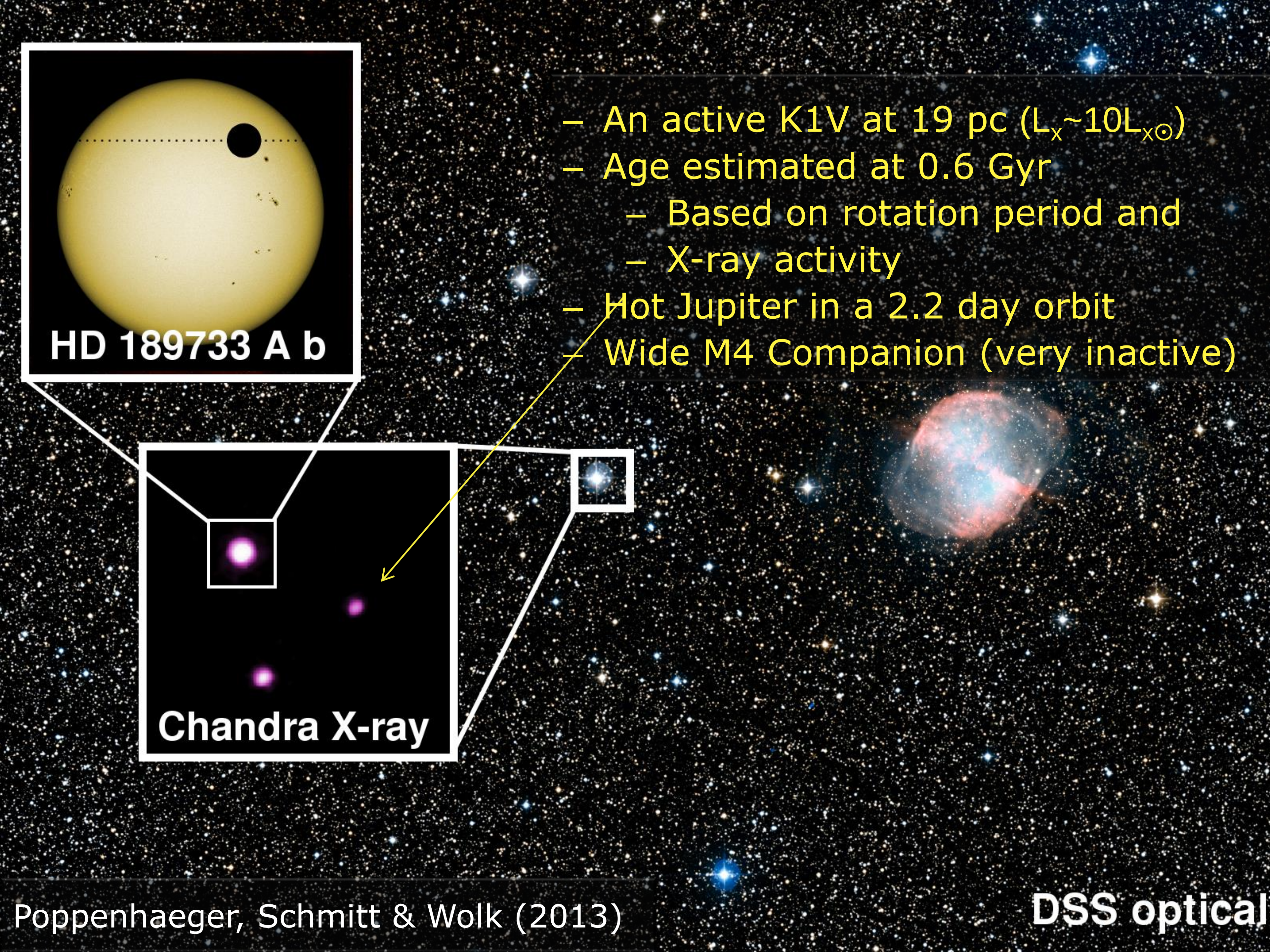
How do stellar winds change with time and what impact does this have on exoplanet conditions?

- 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



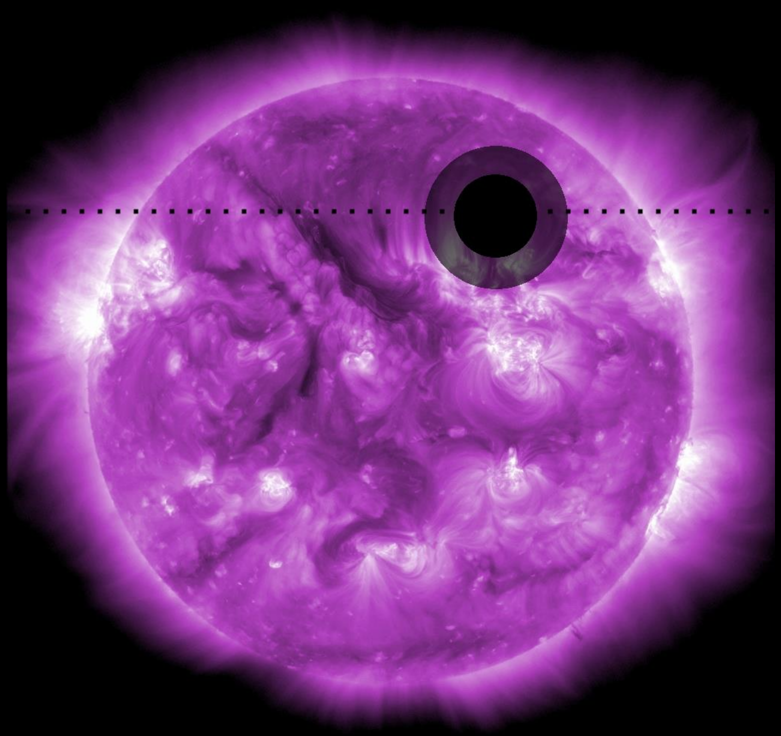
- An active K1V at 19 pc (L_X~$10L_{X\odot}$)
- Age estimated at 0.6 Gyr
  - Based on rotation period and
  - X-ray activity
- Hot Jupiter in a 2.2 day orbit
- Wide M4 Companion (very inactive)

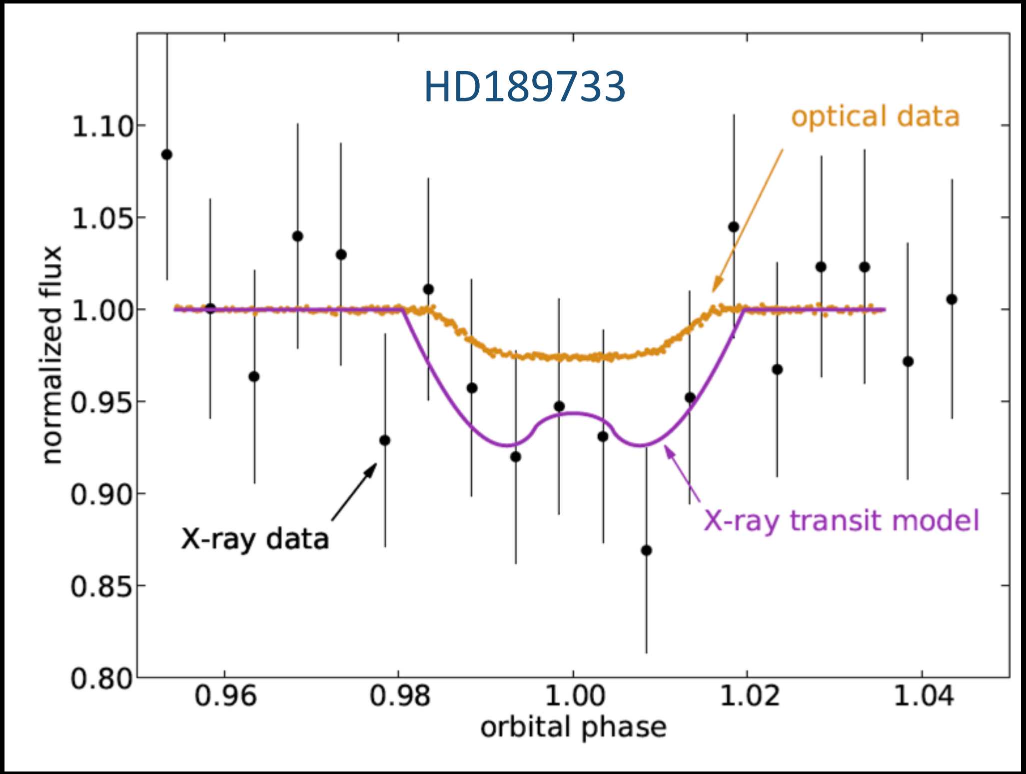
Poppenhaeger, Schmitt & Wolk (2013)

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





Poppenhaeger, Schmitt & Wolk (2013)

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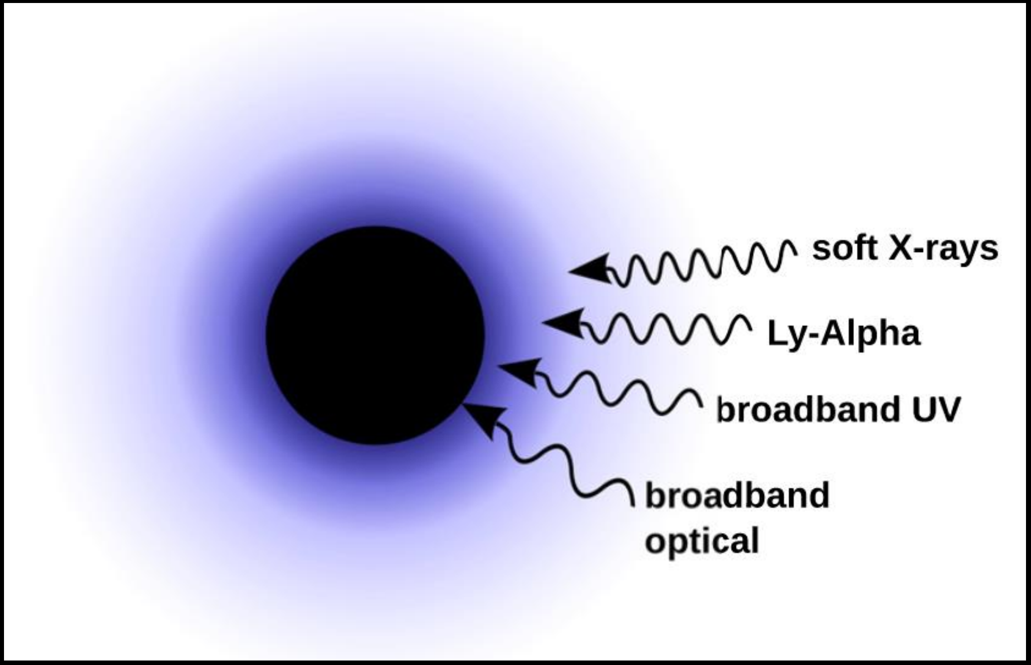

Poppenhaeger et al. (2013) for the hot Jupiter HD 189733b

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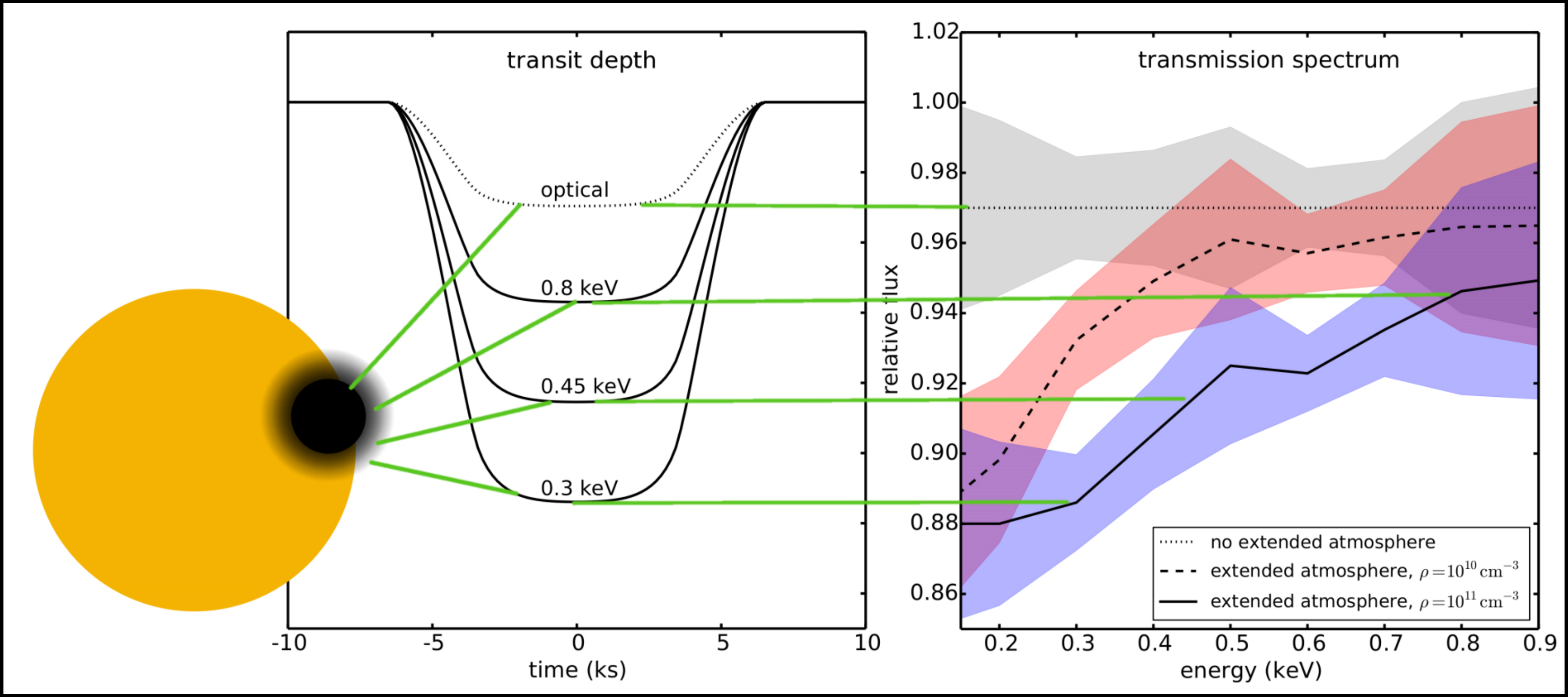
- Direct measures of atmospheric height



Potential Exoplanet Applications

The observatories of the next decade and a half 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?

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
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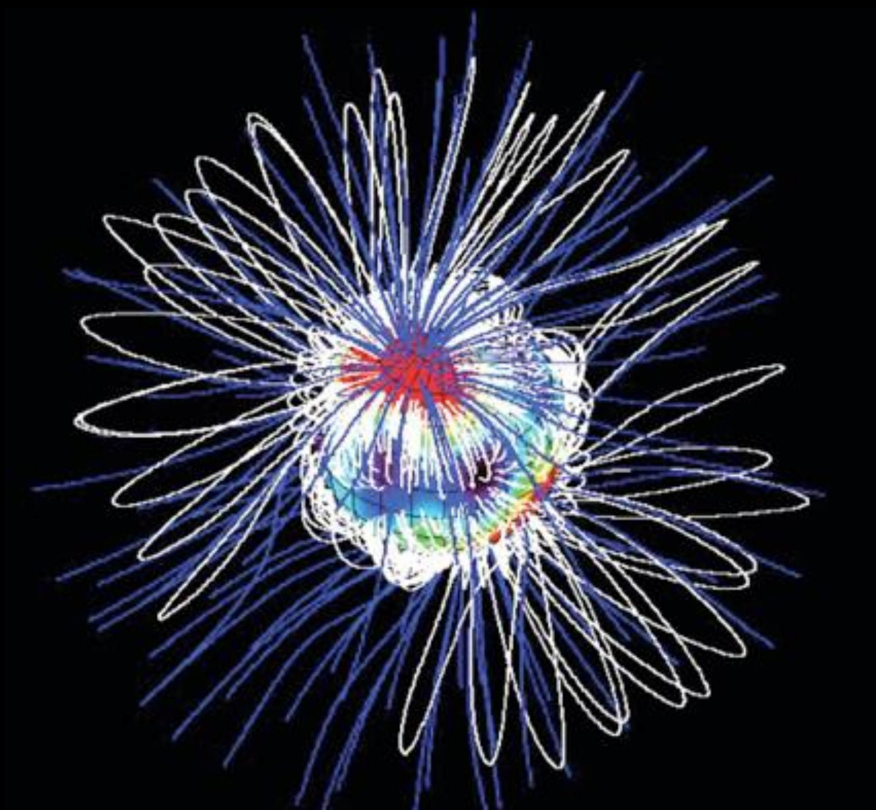
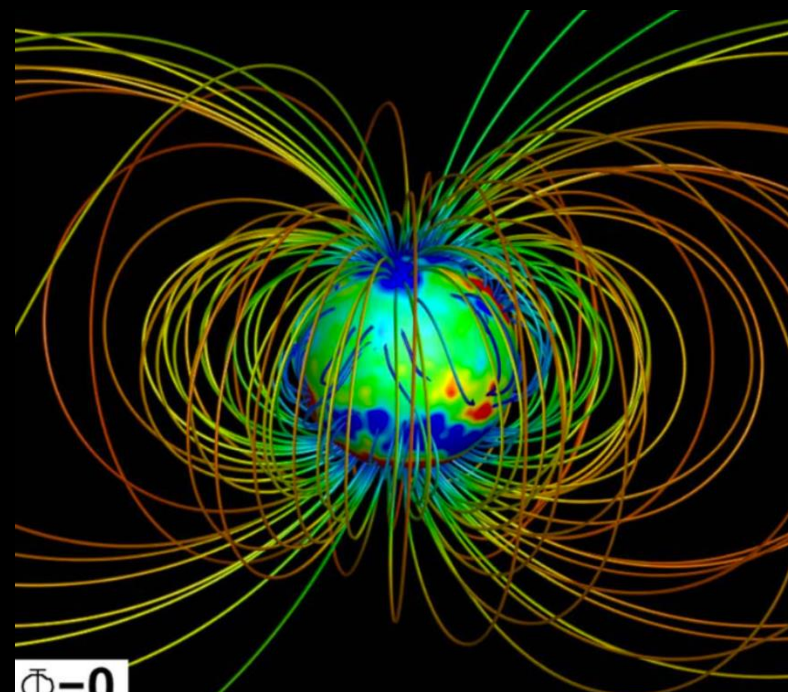


Donati & Landstreet (2009) extrapolation from photospheric magnetic field



Cohen et al. (2017) dynamo simulation

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:

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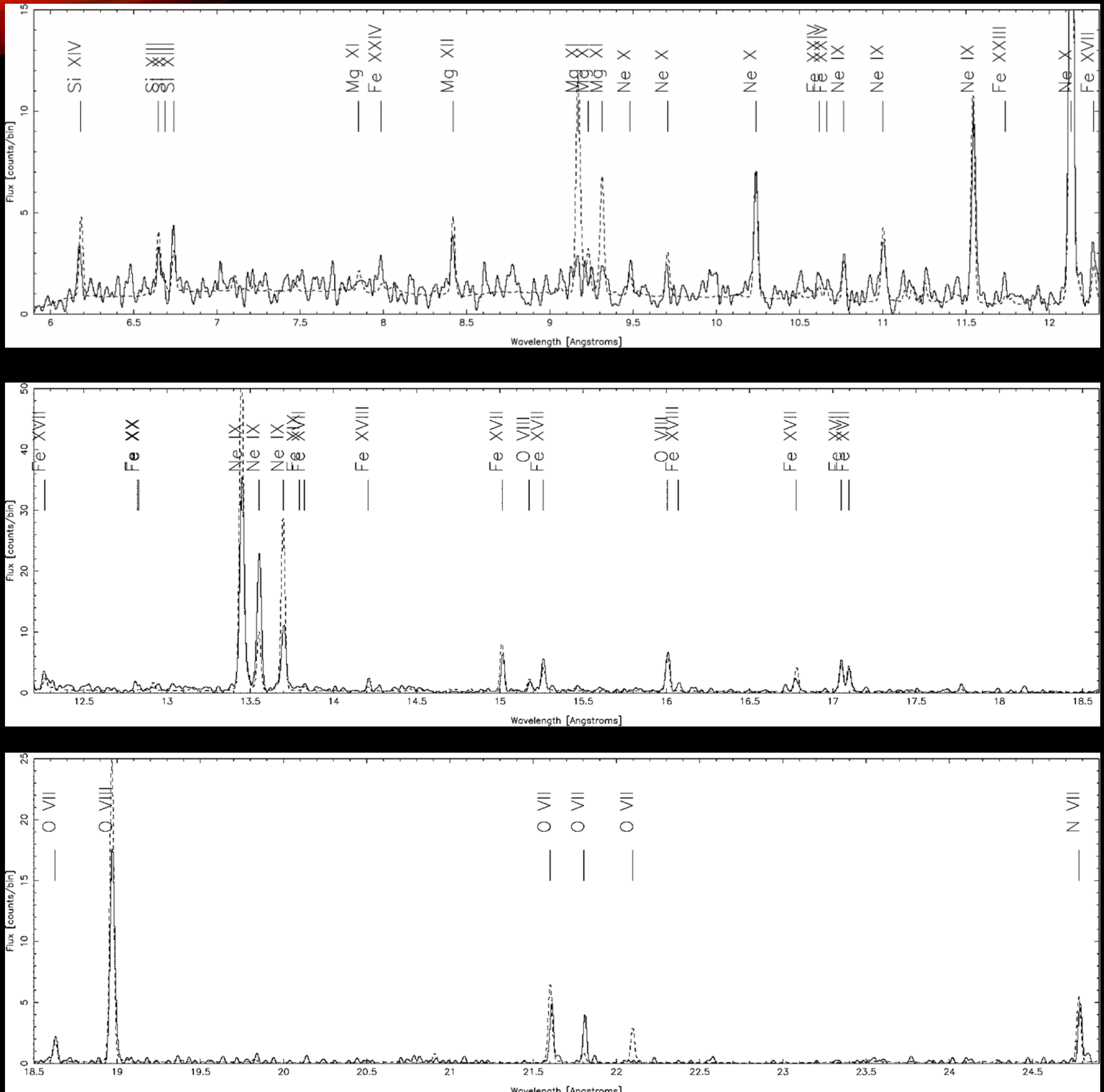
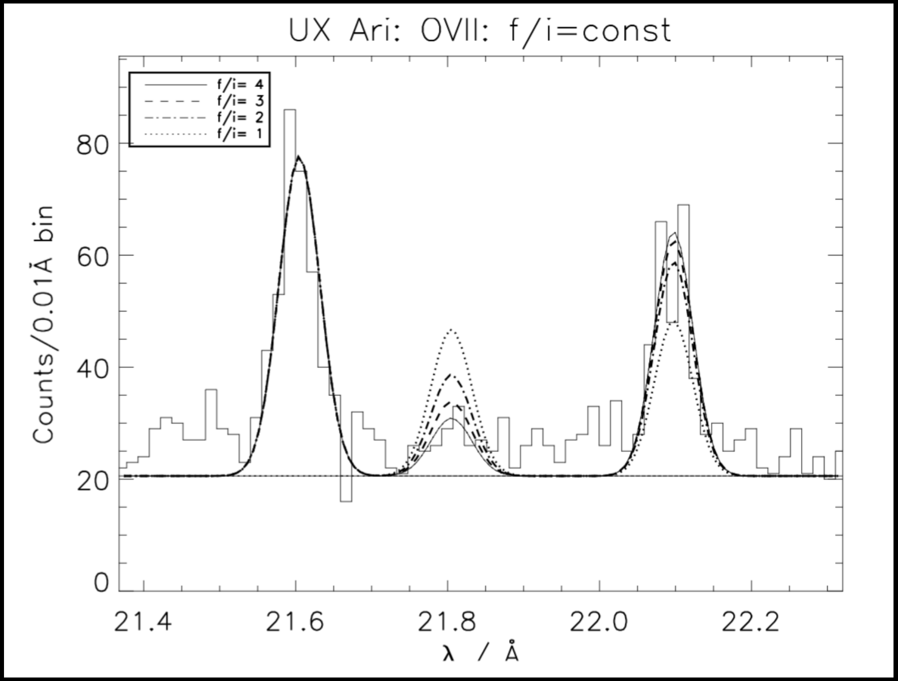
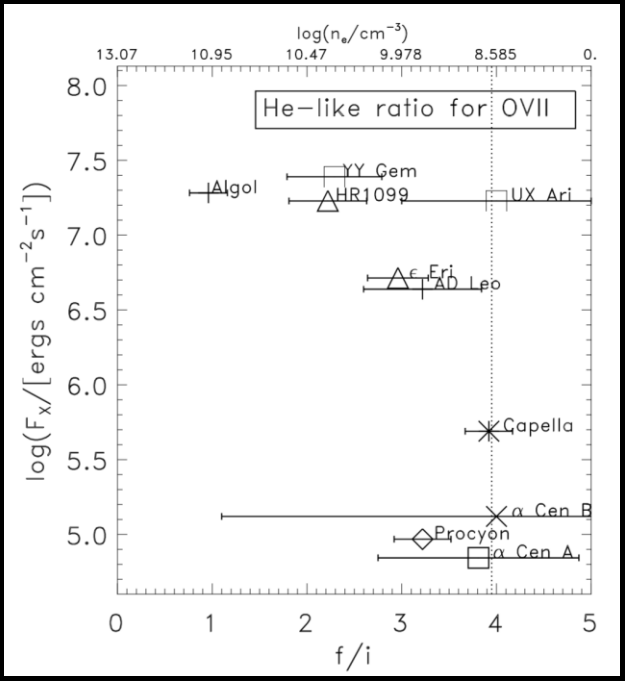

Flux [counts/bin]
Wavelength [Angstroms]

Densities

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

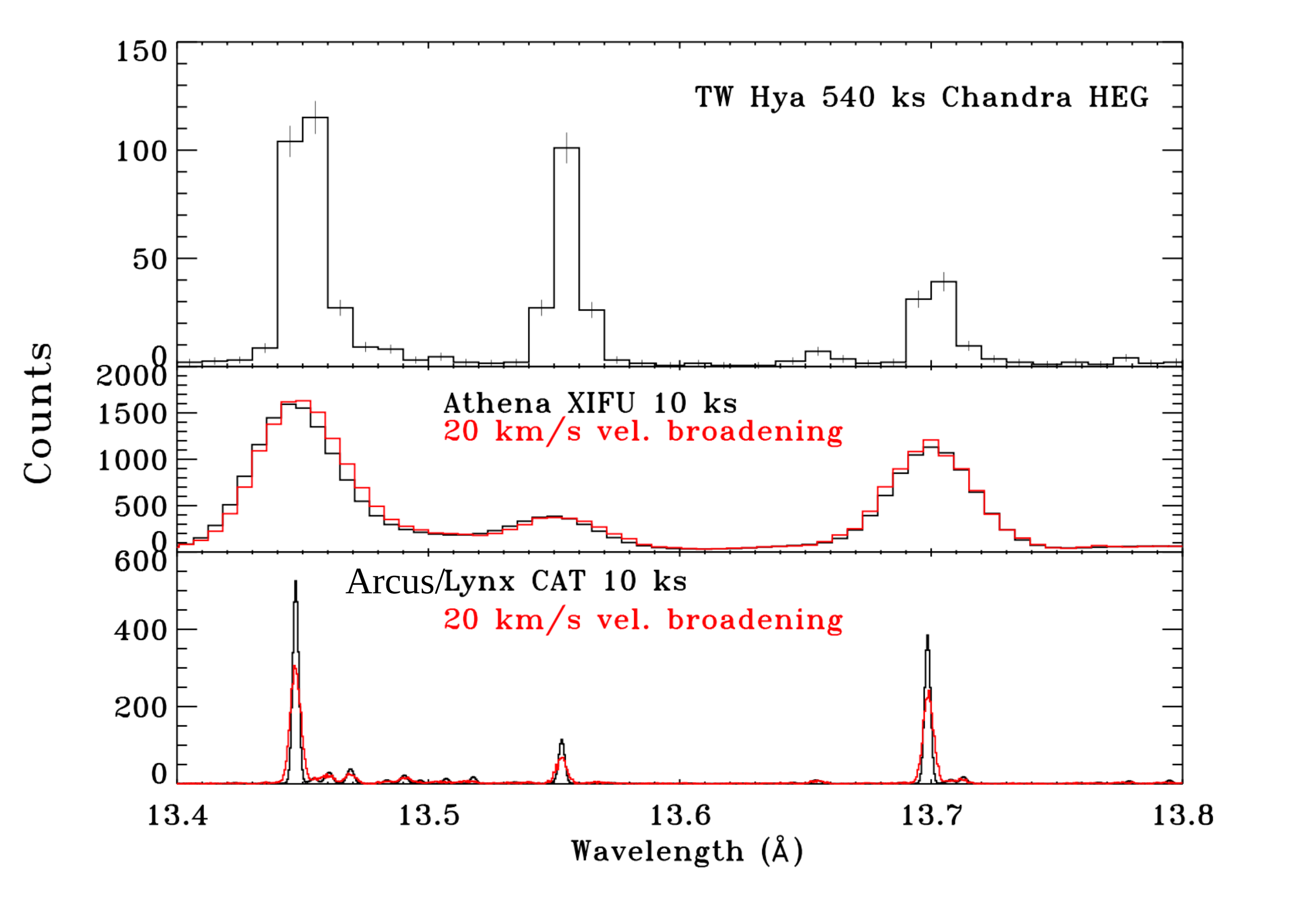




Ness

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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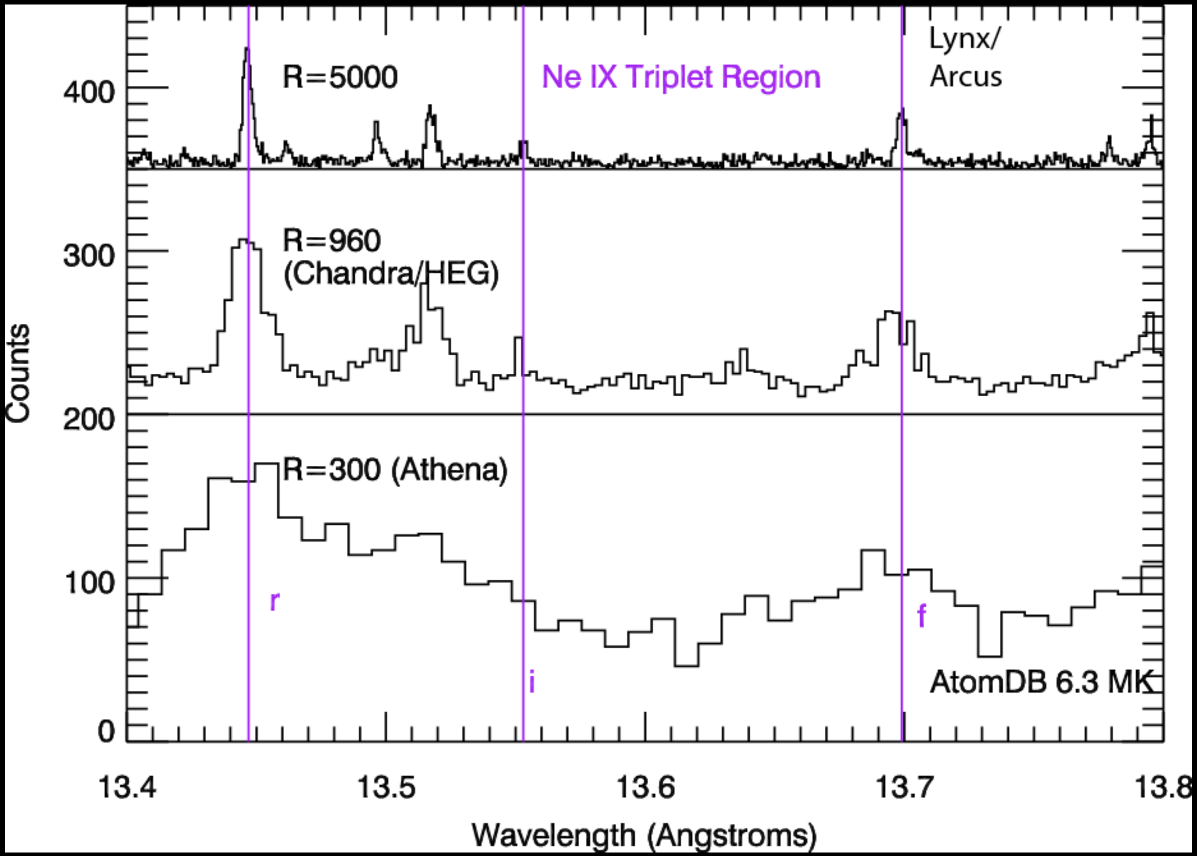

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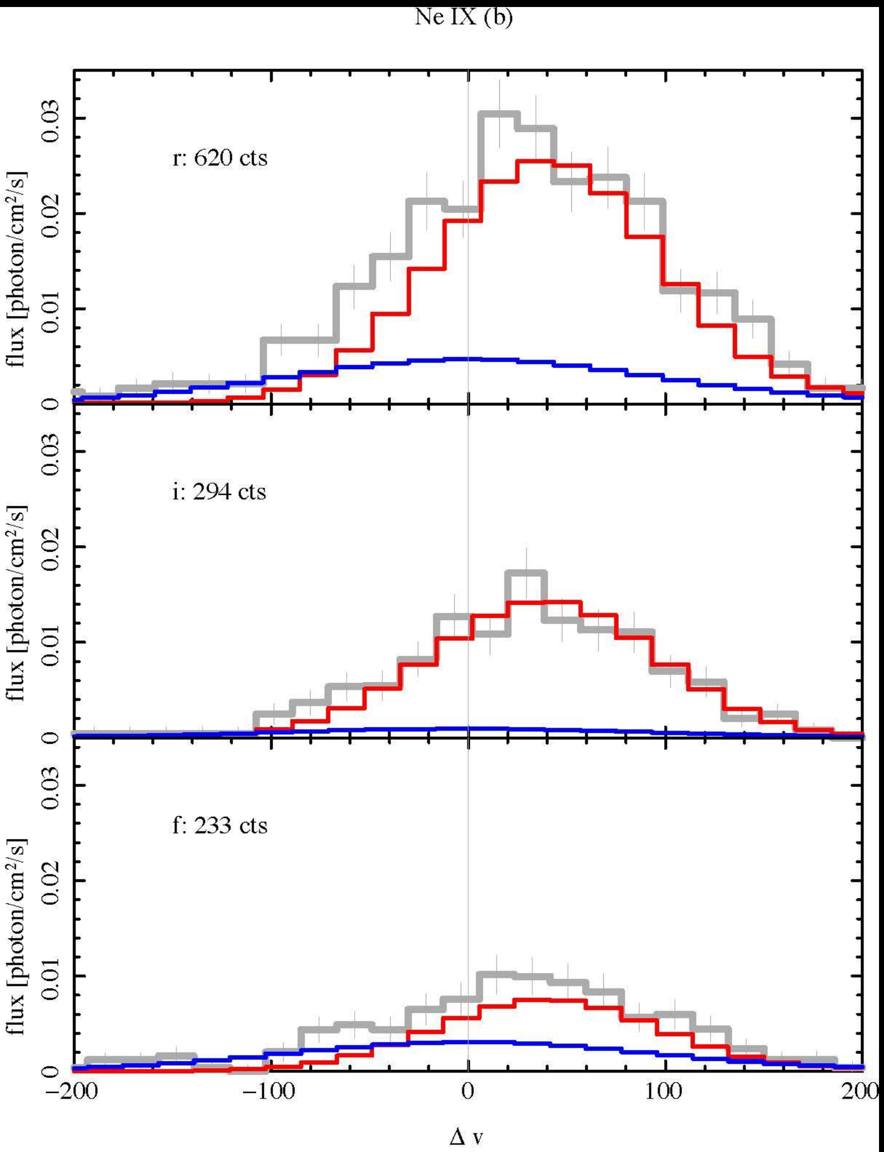
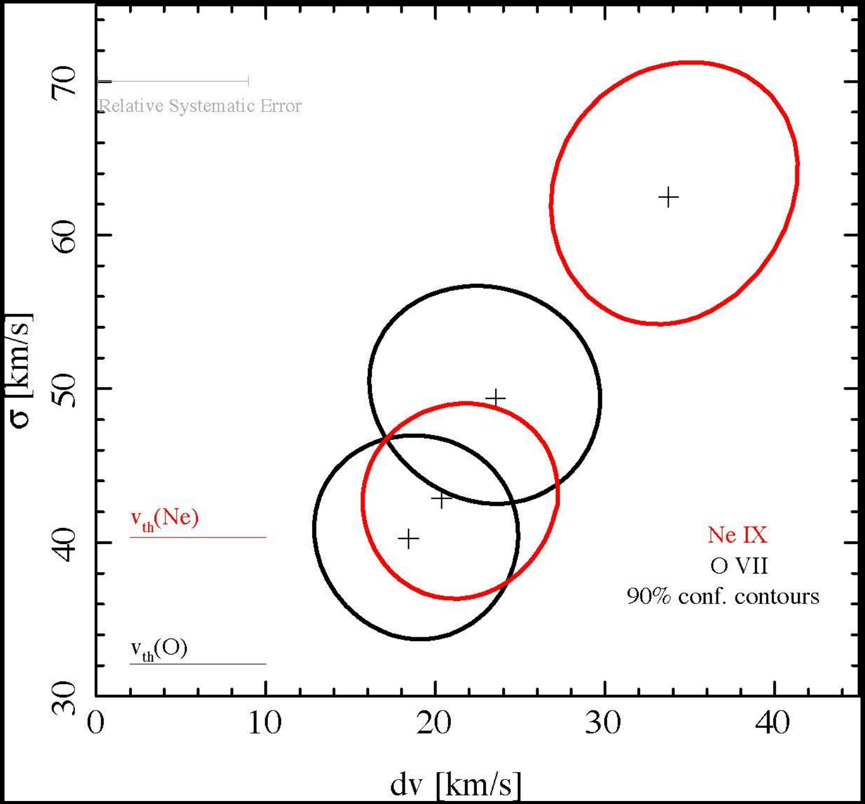
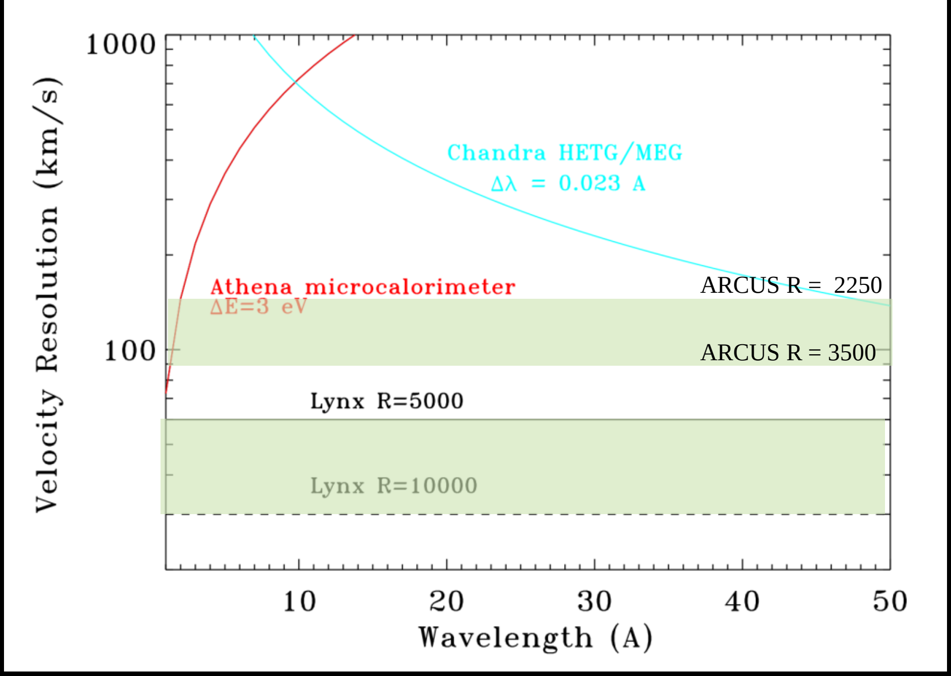
Accretion shocks

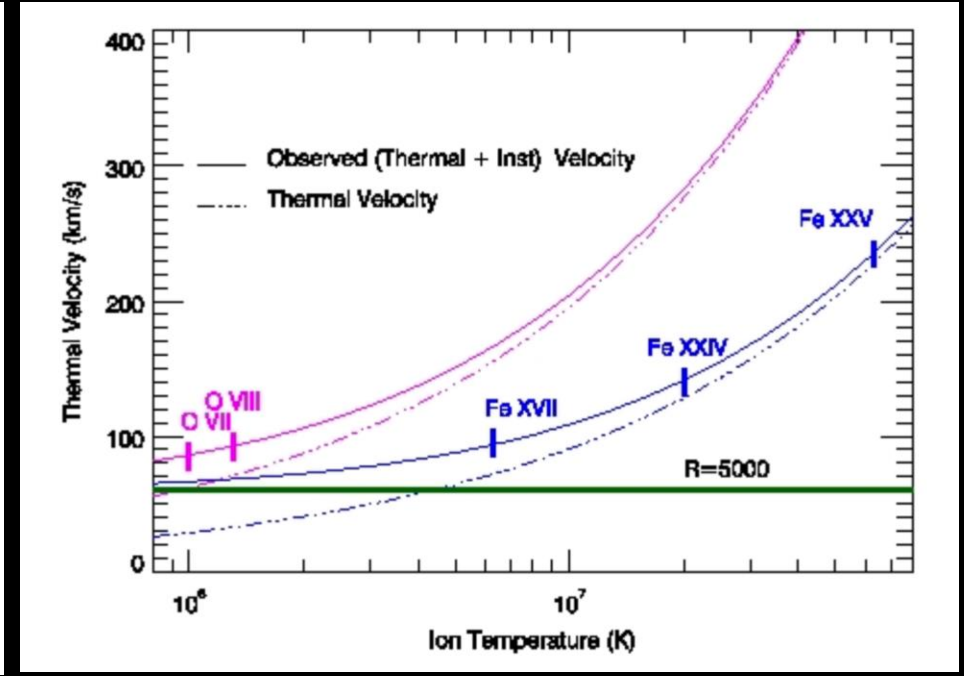




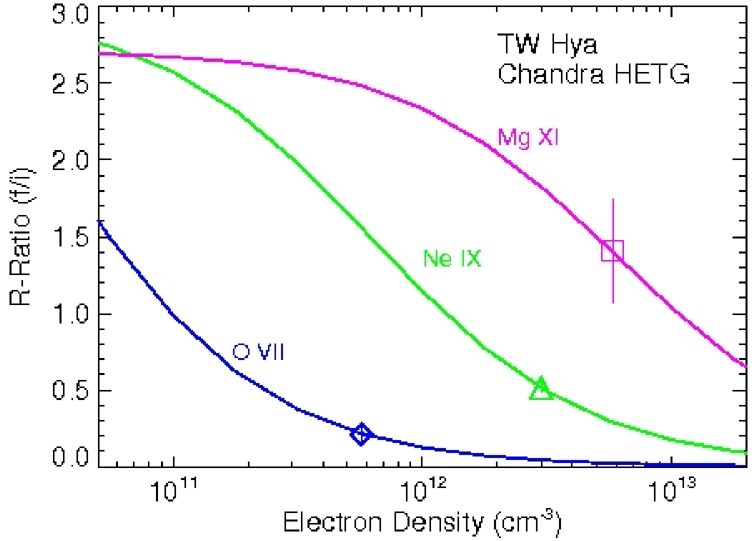
What will we be able to measure?

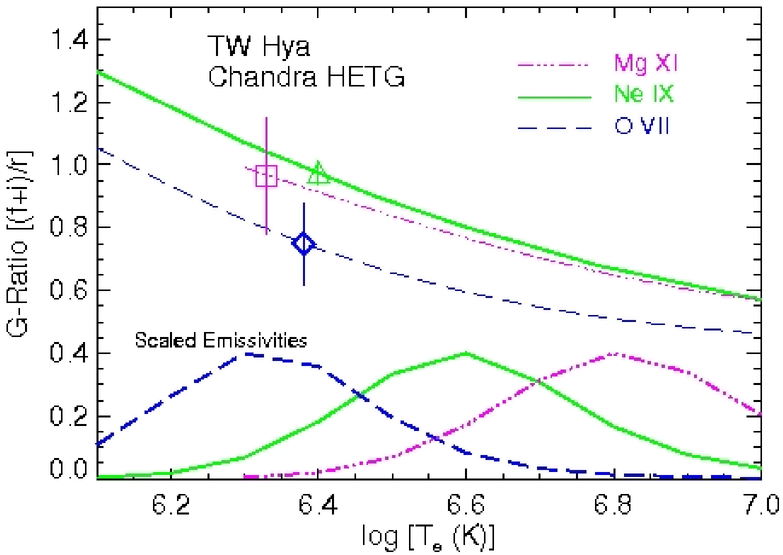
Resolving each line enables investigations of coronal dynamics, broadening mechanisms





X-RAY LINE RATIO DIAGNOSTICS FOR DENSITY AND TEMPERATURE





$N_e = 6 \times 10^{12}$ cm^{-3} Mg XI

3×10^{12} Ne IX

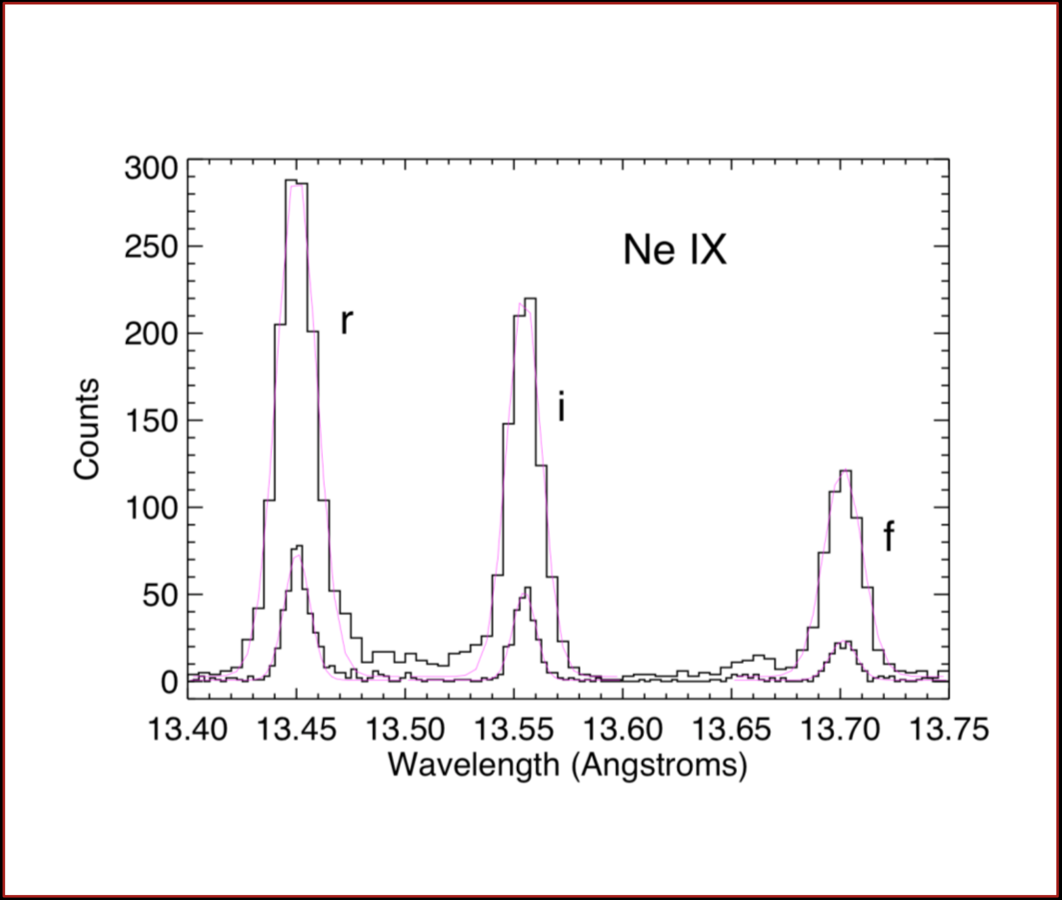
6×10^{11} O VII

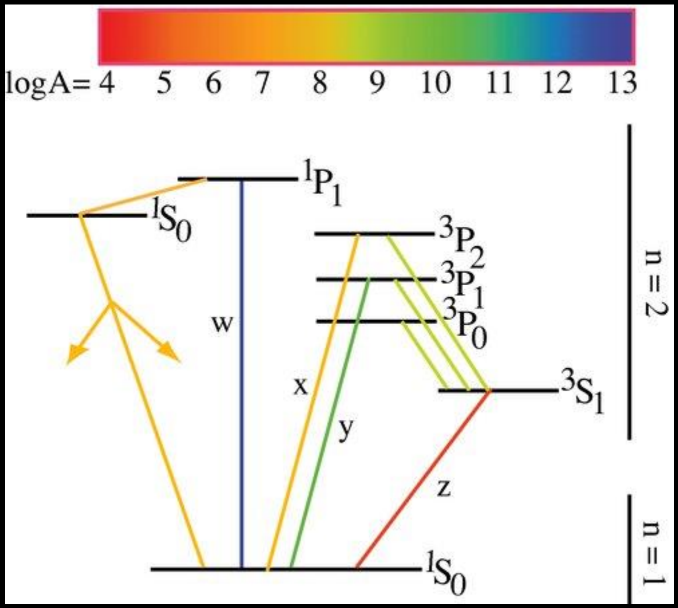
$T_e = 2.50 \pm 0.25$ MK

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

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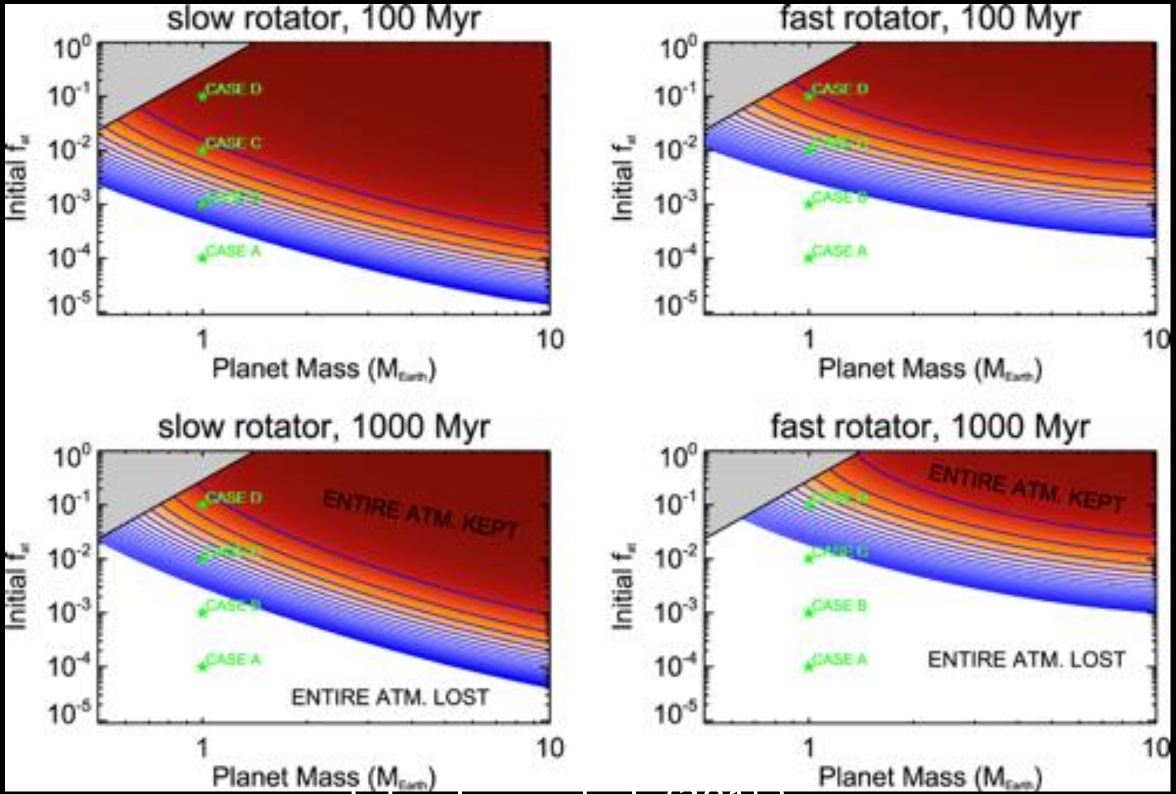
- Planetary atmospheric evolution is fundamentally linked to XEUV emission
- X-rays trace magnetic structure directly

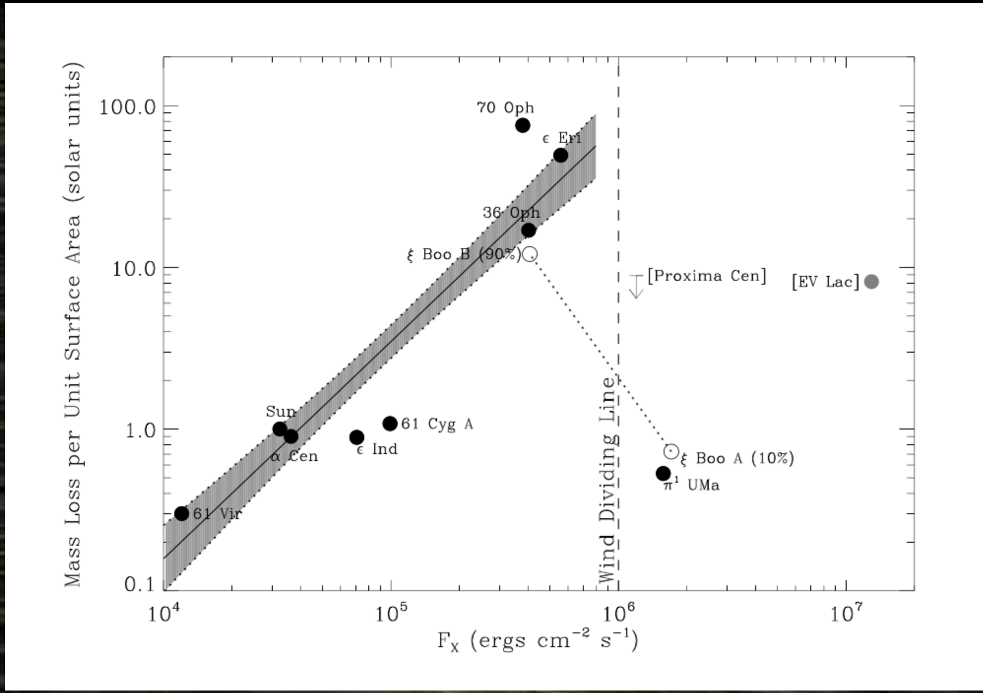


Johnstone et al. (2015)

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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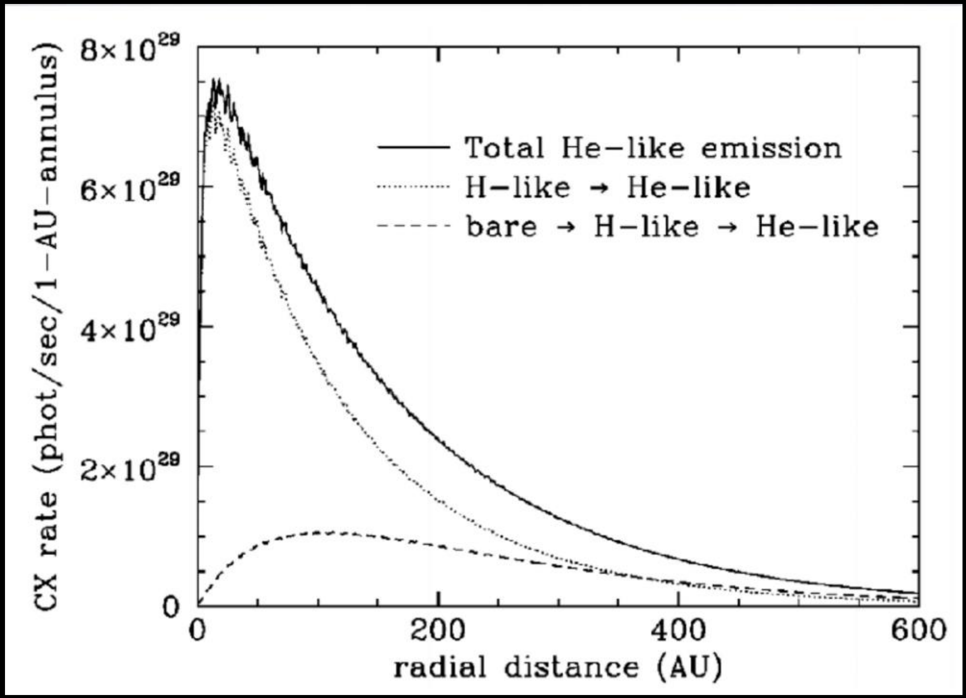

Wargelin & Drake (2001)
Upper limit on mass loss rate of Proxima from charge-exchange emission from interaction of stellar wind with ISM
Requires spatial resolution <0.5” to resolve CX from central point source
Applicable to ~20 nearby stars.