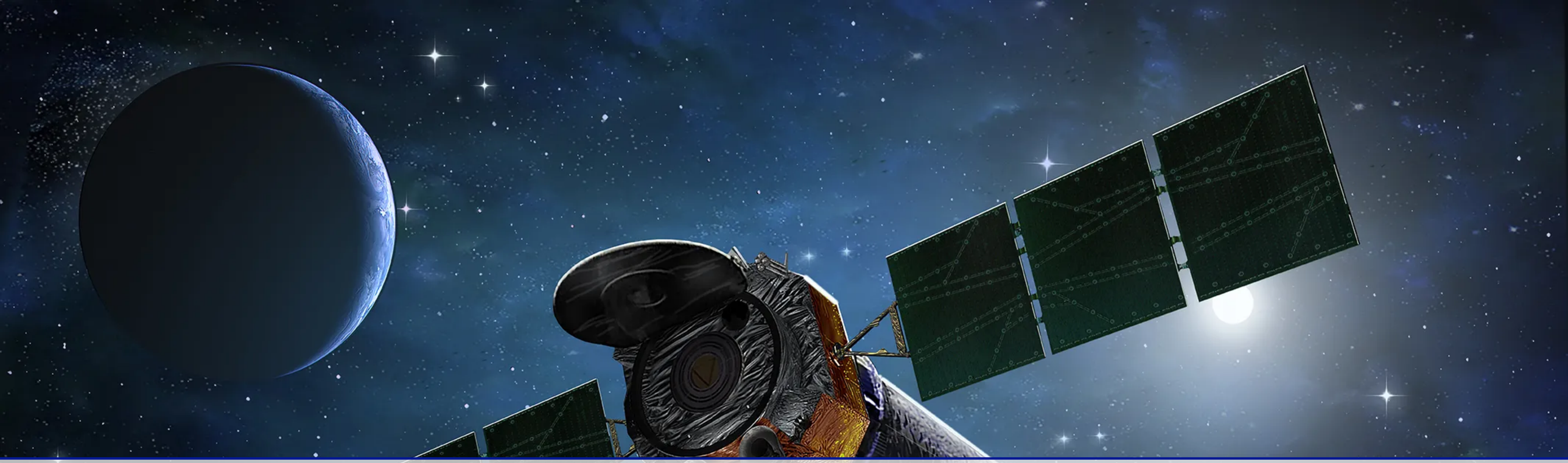
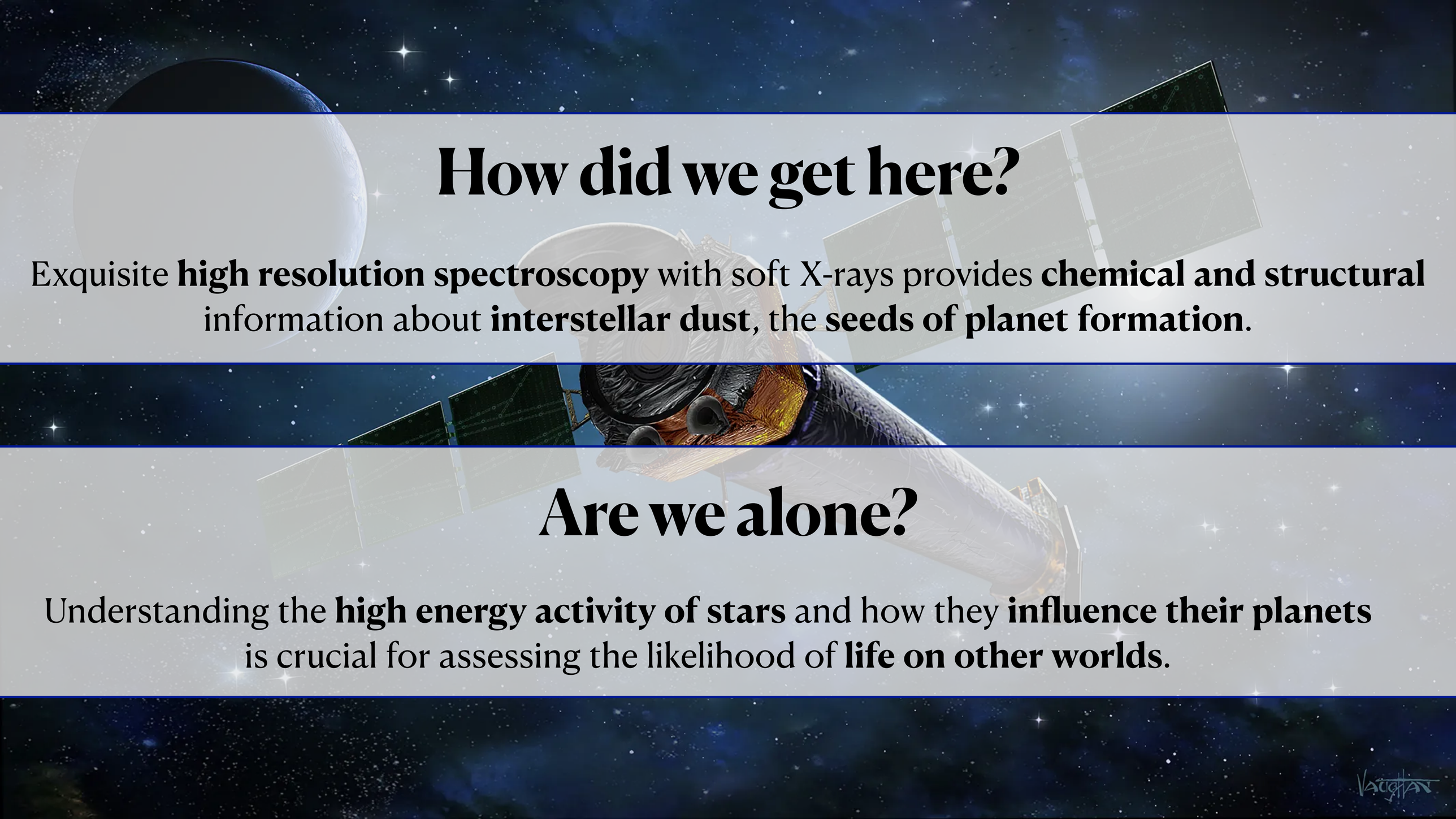


From Cosmic Dust to Habitable Worlds: 25 years of insights from *Chandra*

L. Corrales, University of Michigan

in collaboration with I. Psaradaki, D. Savin, E. Gotthelf, N. Schulz, J. Yang, C. Canizares, E. Costantini, S. Zeegers, F. Paerels, R. Smith, S. Heinz, G. W. King, R. Cilley, P. Wheatley, K. Stassun, M. Kounkel, H. M. Gunther, D. Principe, and many more

VAUGHAN



How did we get here?

Exquisite **high resolution spectroscopy** with soft X-rays provides **chemical and structural** information about **interstellar dust**, the **seeds of planet formation**.

Are we alone?

Understanding the **high energy activity of stars** and how they **influence their planets** is crucial for assessing the likelihood of **life on other worlds**.

Astromineralogy

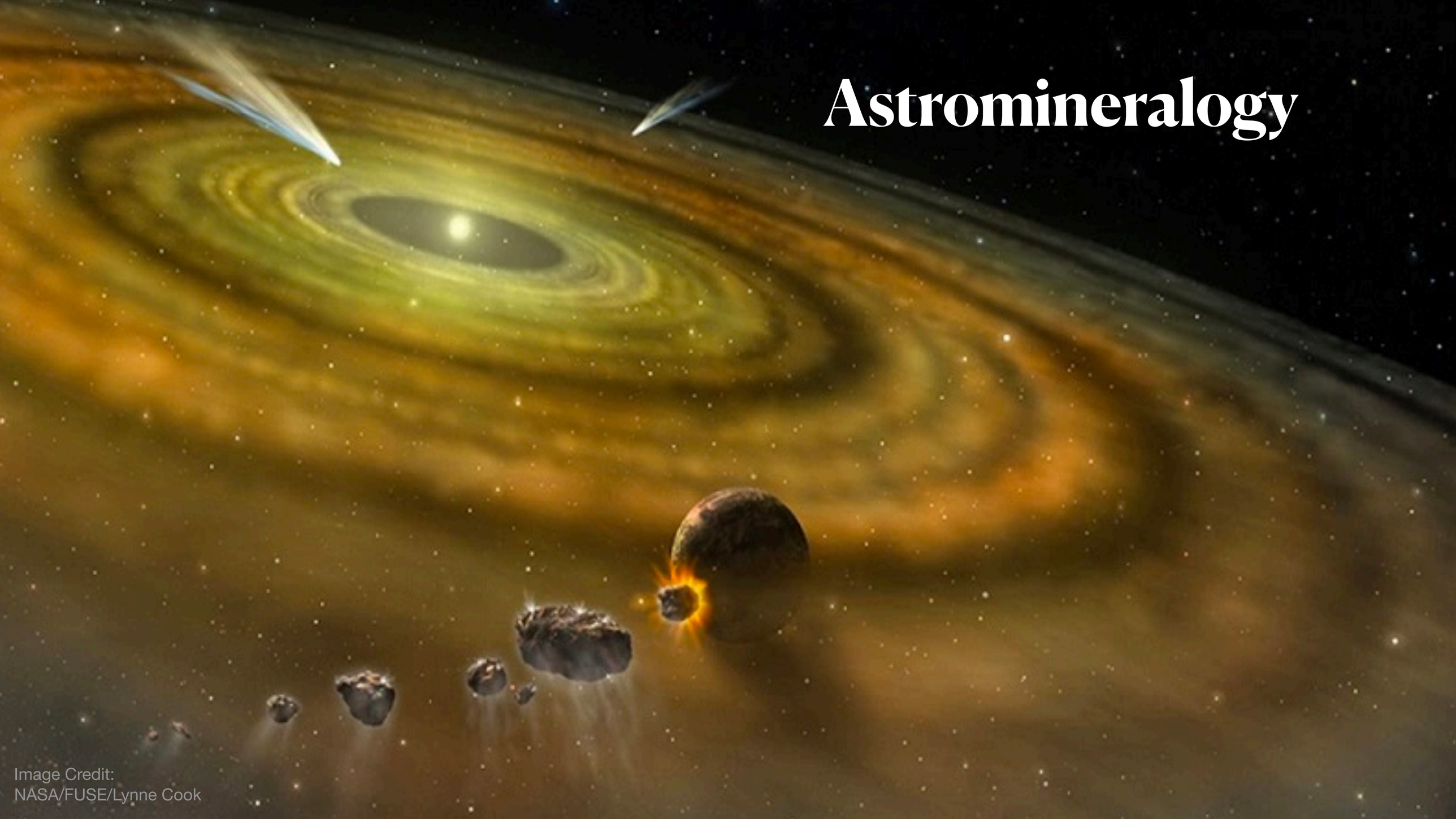
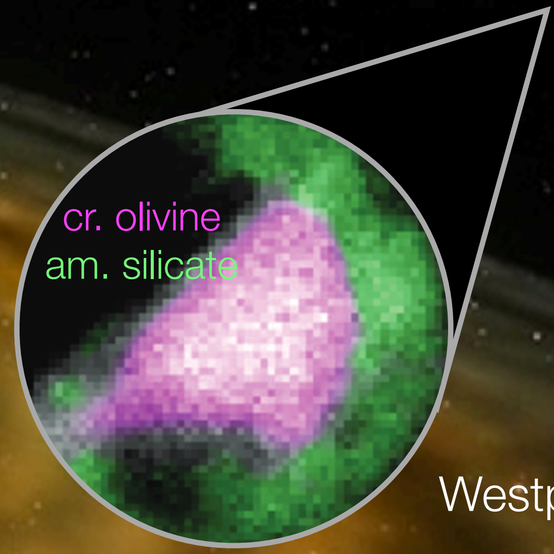


Image Credit:
NASA/FUSE/Lynne Cook

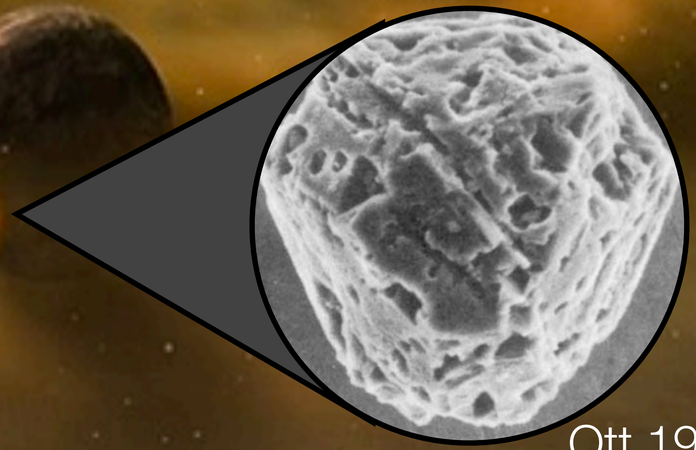
How does interstellar dust contribute to planet formation?

Bradley+ 2022



Westphal+ 2014

SiC



Ott 1993

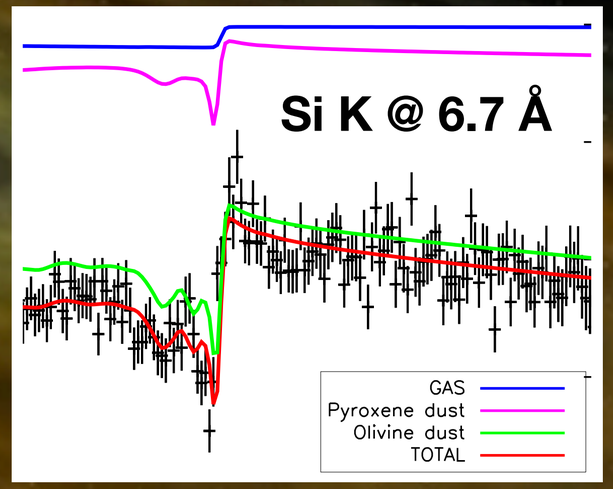
Image Credit:
NASA/FUSE/Lynne Cook

The true formation and processing sites are an open area of research.

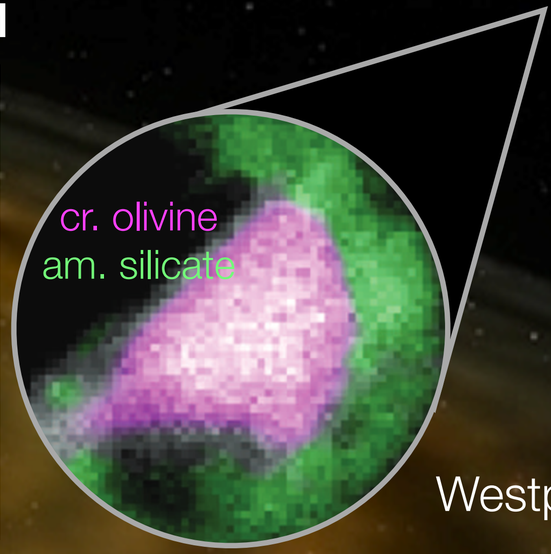
The spectra of distant X-ray binaries probe interstellar dust in extinction

Bradley+ 2022

X-ray absorption spectrum of GX 5-1

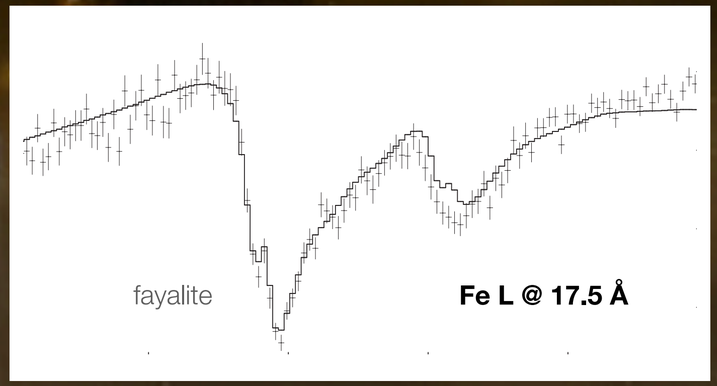


Zeegers+ 2017



Westphal+ 2014

X-ray absorption spectrum of Cyg X-2

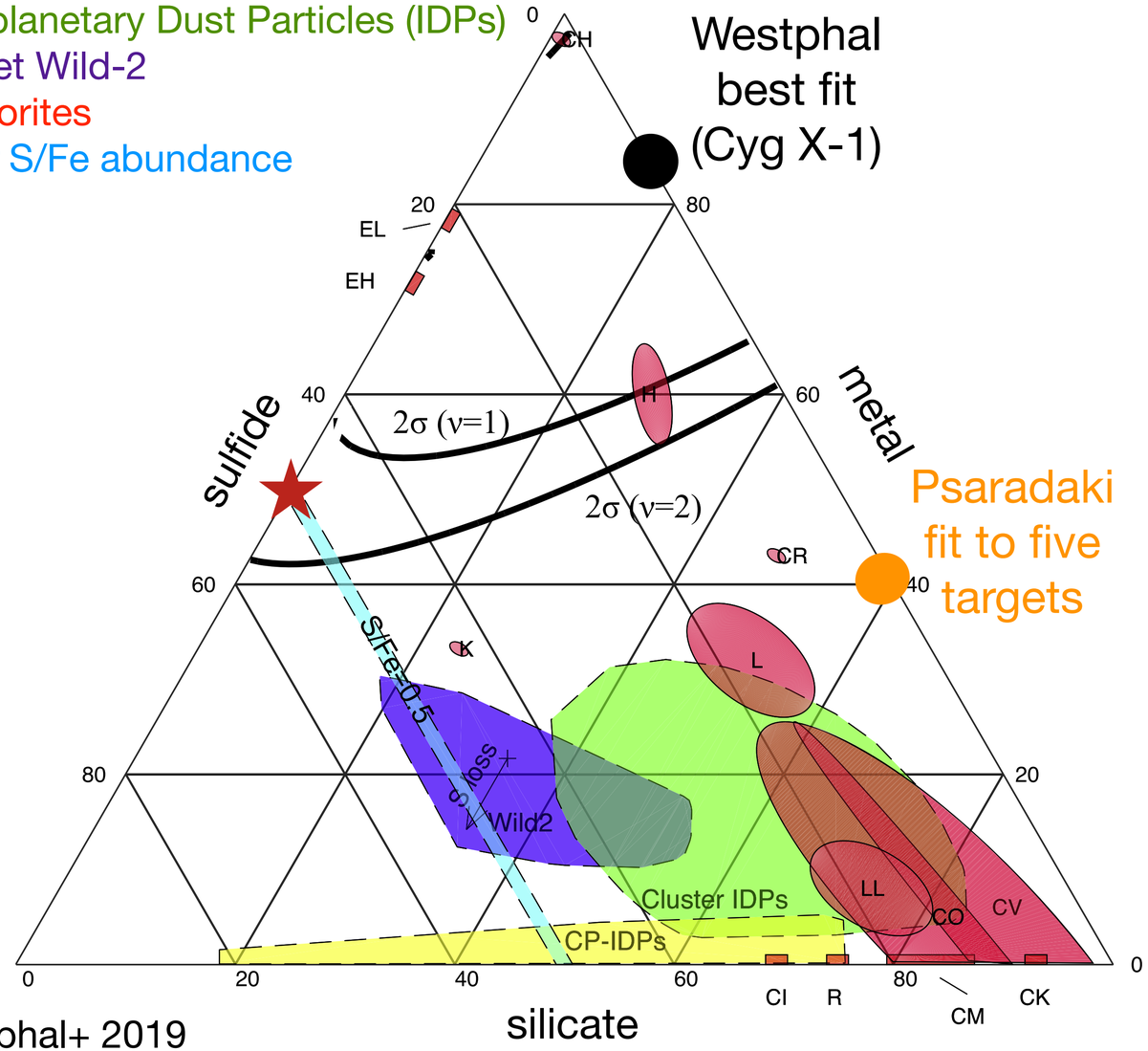


Corrales+ 2024 (see also Psaradaki+ 2023, Westphal+ 2019)

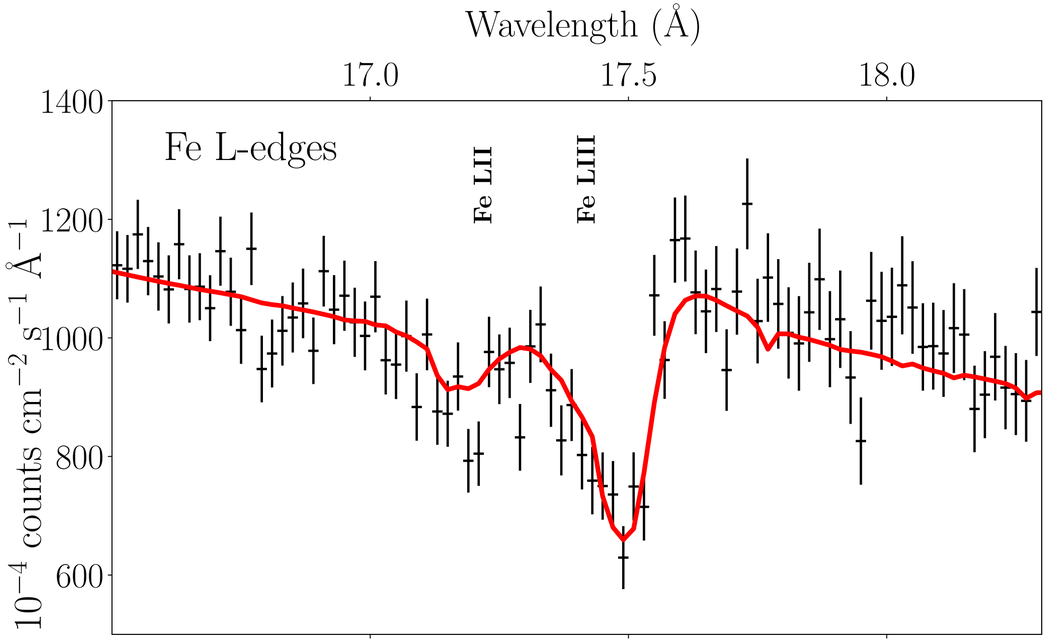
Image Credit:
NASA/FUSE/Lynne Cook

Case Study: Iron

Interplanetary Dust Particles (IDPs)
Comet Wild-2
Meteorites
Solar S/Fe abundance



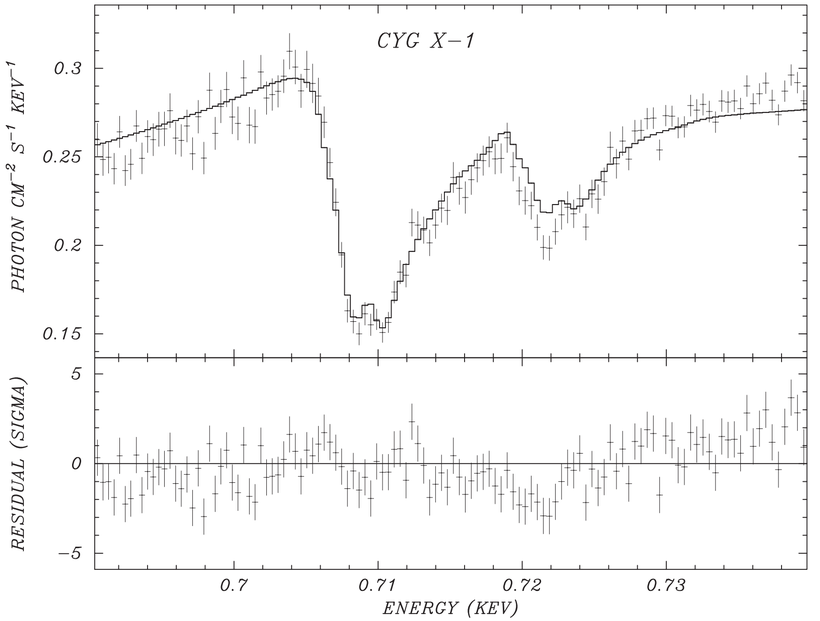
Westphal+ 2019



Psaradaki+ 2023

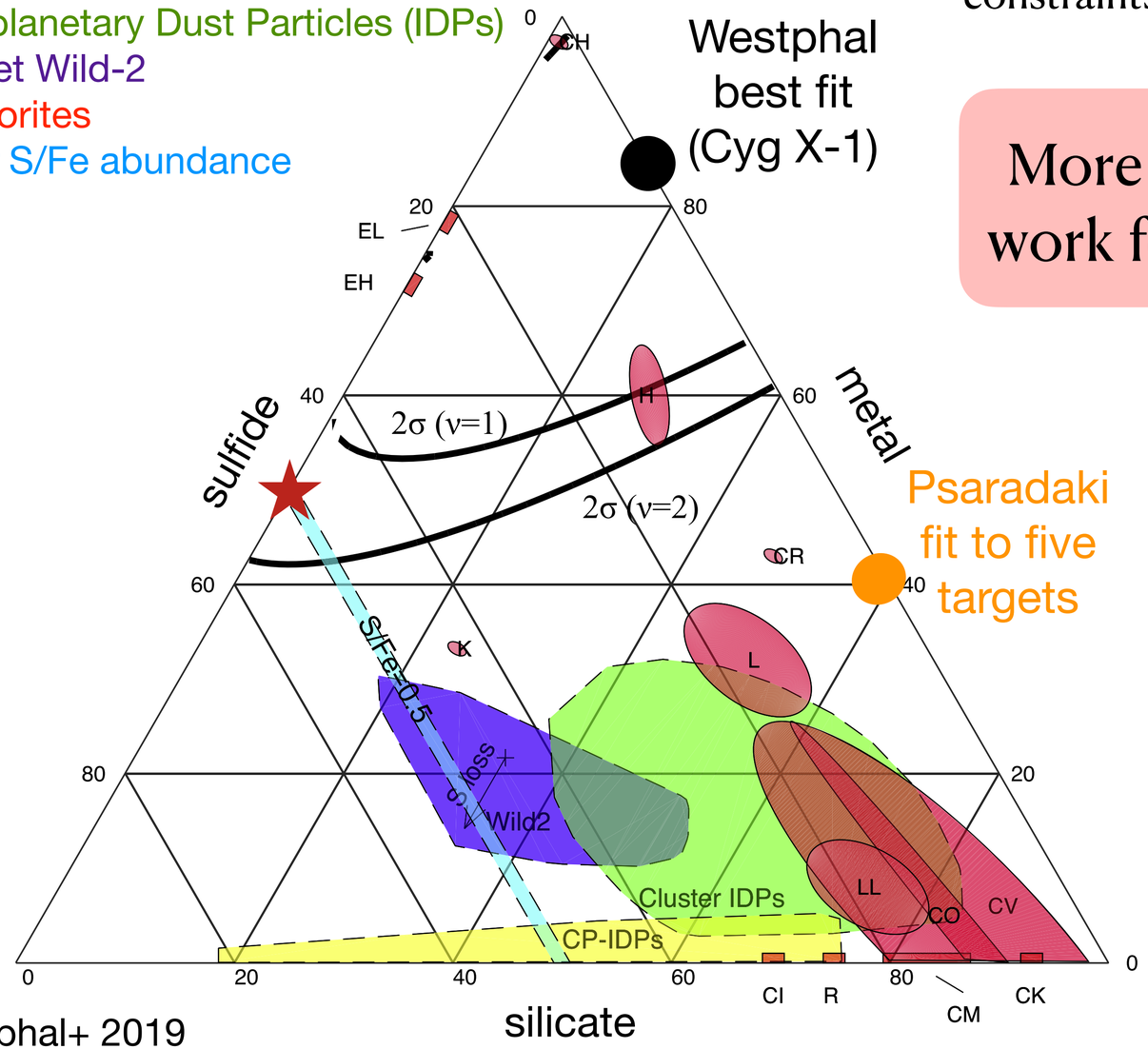
Case Study: Iron

Comprehensive review of Lee+2009 cross-sections: **Fe-oxides** are the preferred fit based on abundance constraints (**Corrales+ 2024**)

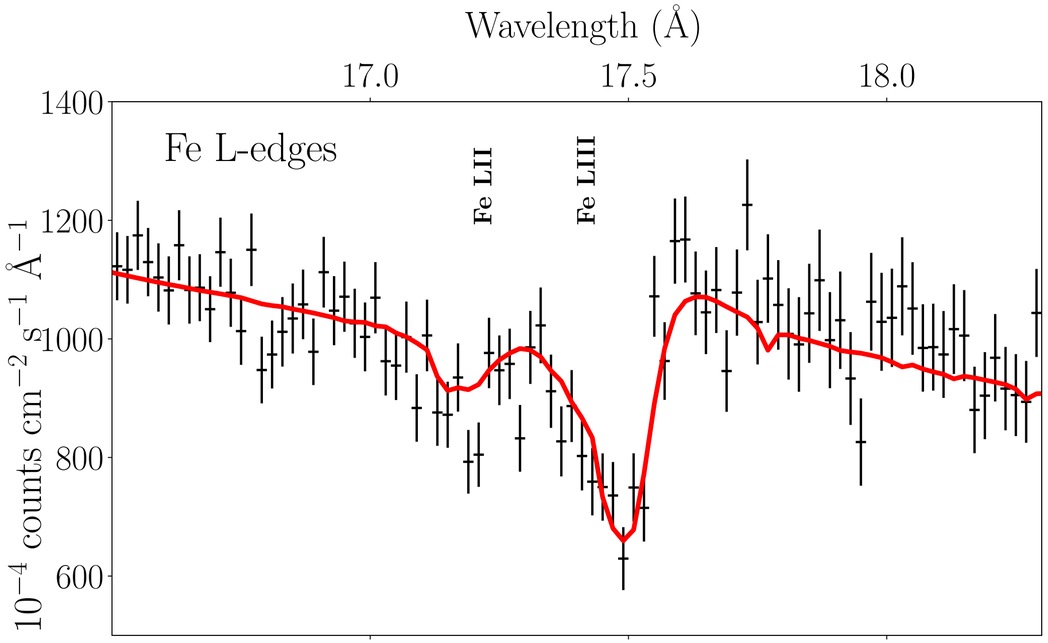


More laboratory work forthcoming

Interplanetary Dust Particles (IDPs)
Comet Wild-2
Meteorites
Solar S/Fe abundance

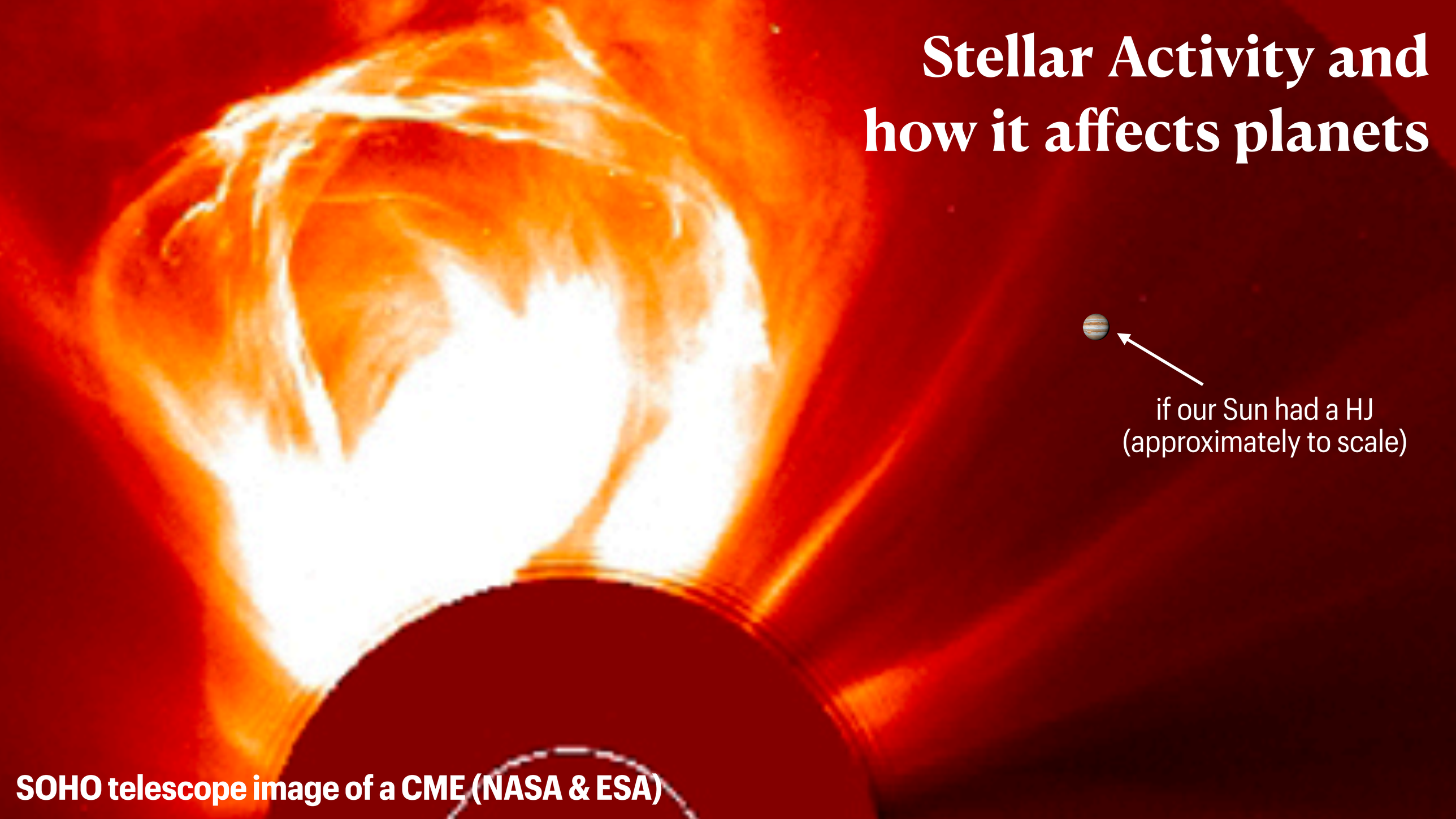


Westphal+ 2019



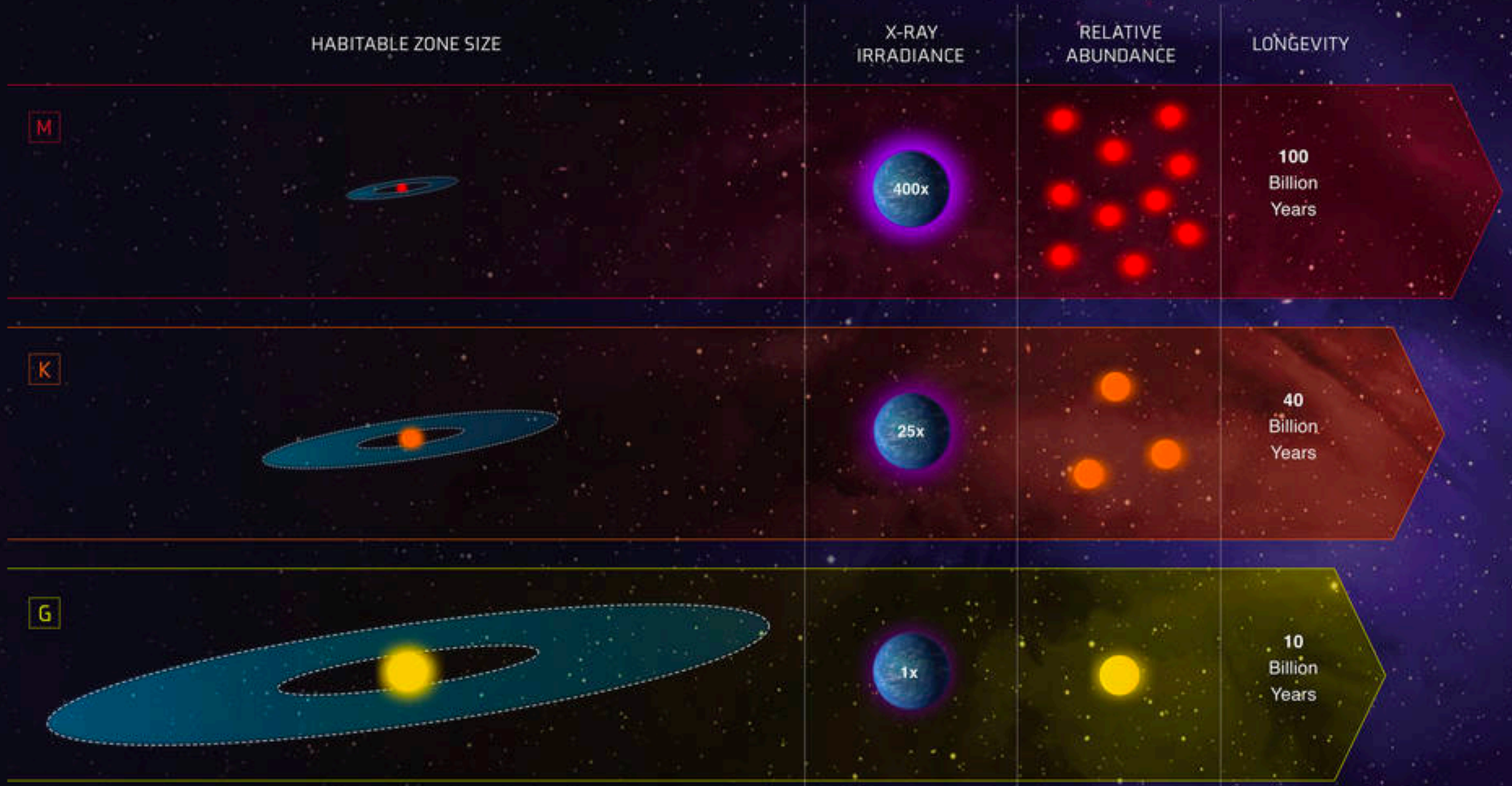
Psaradaki+ 2023

Stellar Activity and how it affects planets



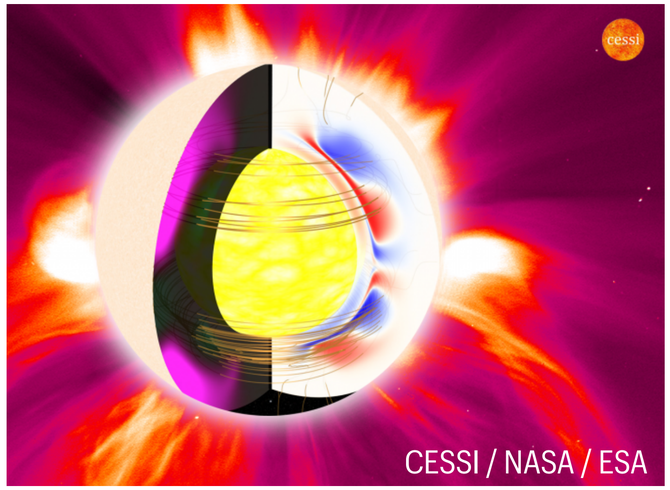
if our Sun had a HJ
(approximately to scale)

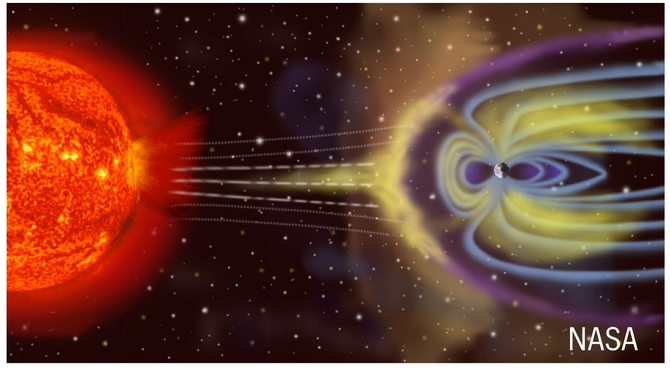
SOHO telescope image of a CME (NASA & ESA)

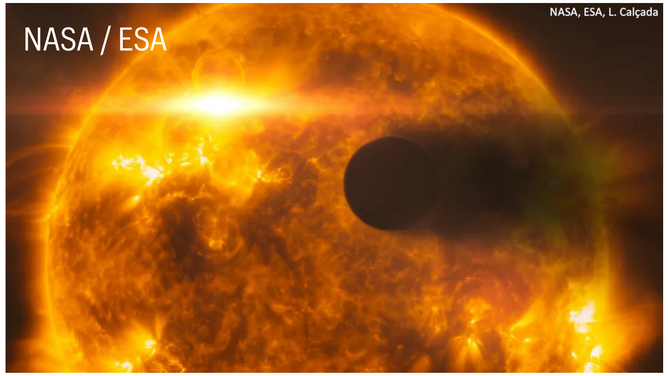


Majority of habitable worlds are subject to more high energy irradiation and stellar activity

Factors Affecting Exoplanet Habitability - Meadows & Barnes (2018)







Stellar Effects

Metallicity
Composition & Structure
Isotopic Abundance
Cosmic Rays
Stellar Interactions
Galactic Location
Orbit
Orbital Evolution
Birth Environment
Rotation
Age
Wind
Magnetic Field
Companions
Radius
Mass
Luminosity
Activity
Spectral Energy Distribution
Spectrum
Luminosity Evolution

Planetary Systems

Minor Planets
Exomoons
Dust
Impact Flux
Eccentricity
Orbital Evolution
Tides
Volatile Delivery
Masses
Sibling Planets
Orbits

Planetary Properties

Interior
Outgassing
Thermal Evolution
Structure
Magnetic Field
Volcanism
Density
Tectonics

Orbital Dynamics
Semi-major Axis
Oblateness
Eccentricity
Obliquity
Rotation Rate

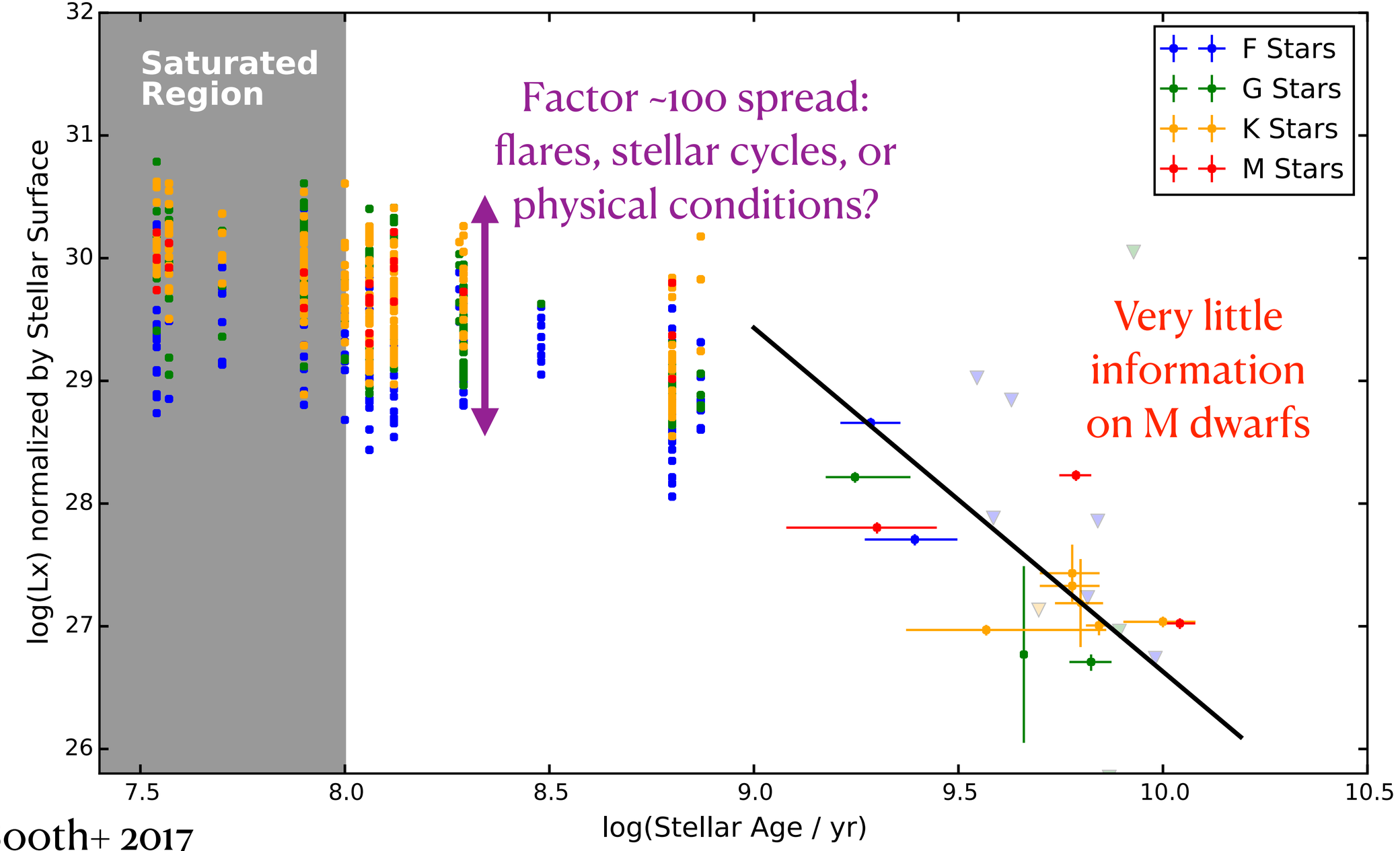
Biology

Atmosphere
Escape
Composition
Clouds & Hazes
Evolution
Structure
Dynamics
Isotopic Ratios
Surface Pressure
UV Shielding
Climate

Albedo
Mass
Radius

Surface
Inhomogeneities
Technology
Temperature
Ocean
Composition
Weathering

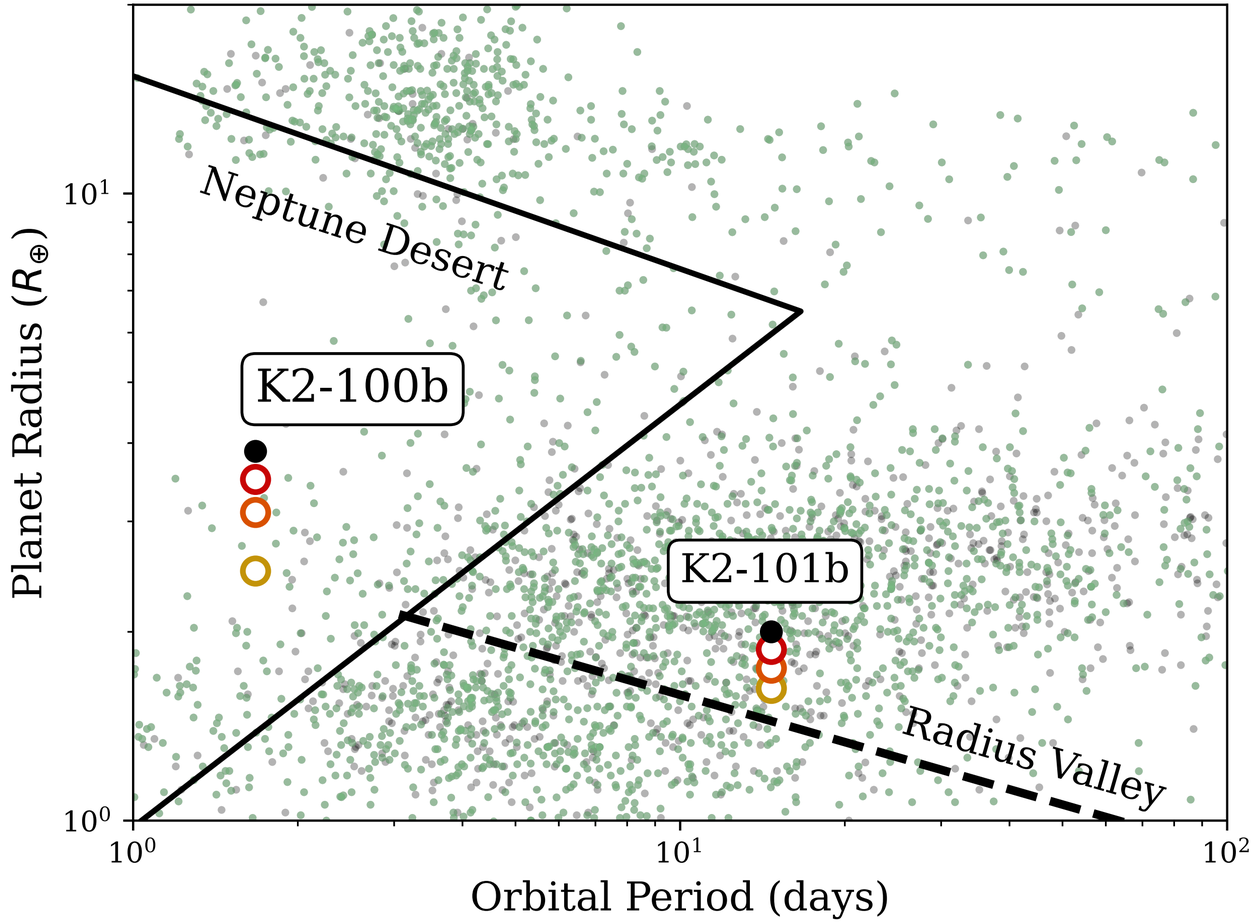
How does stellar activity fade with time?

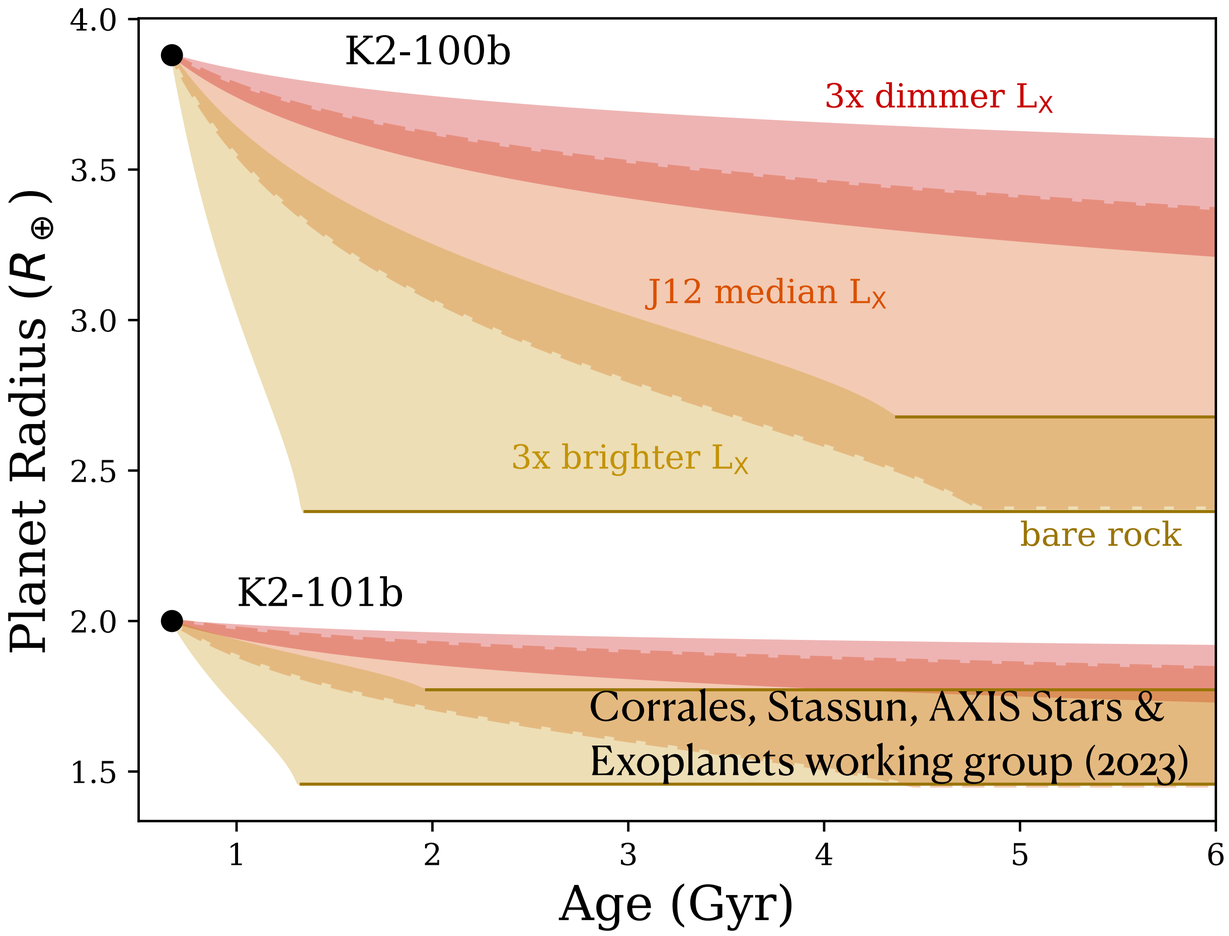


Booth+ 2017

XUV driven atmospheric escape can remove a planet's gas envelope

What are the progenitors of super-Earths of sub-Neptunes? How quickly do they evolve?





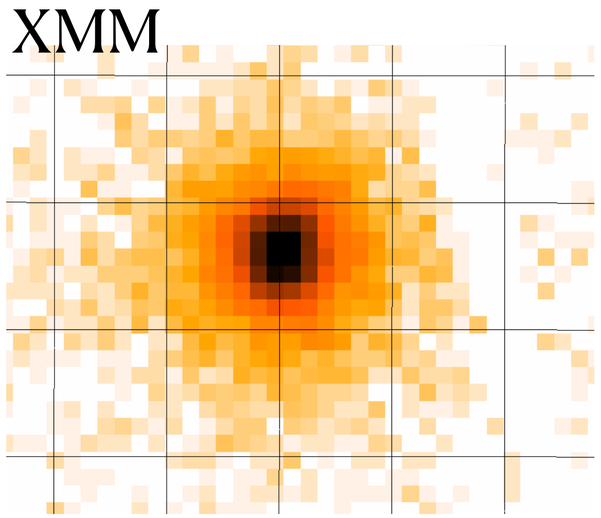
Uncertainty in activity-age relations leads to different outcomes for individual systems.

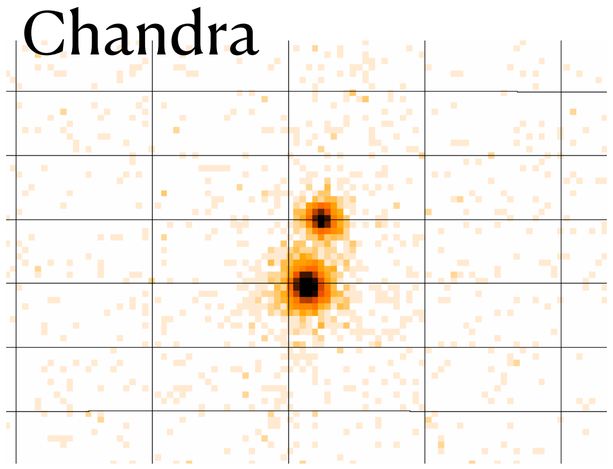
Predicting the future of planetary systems

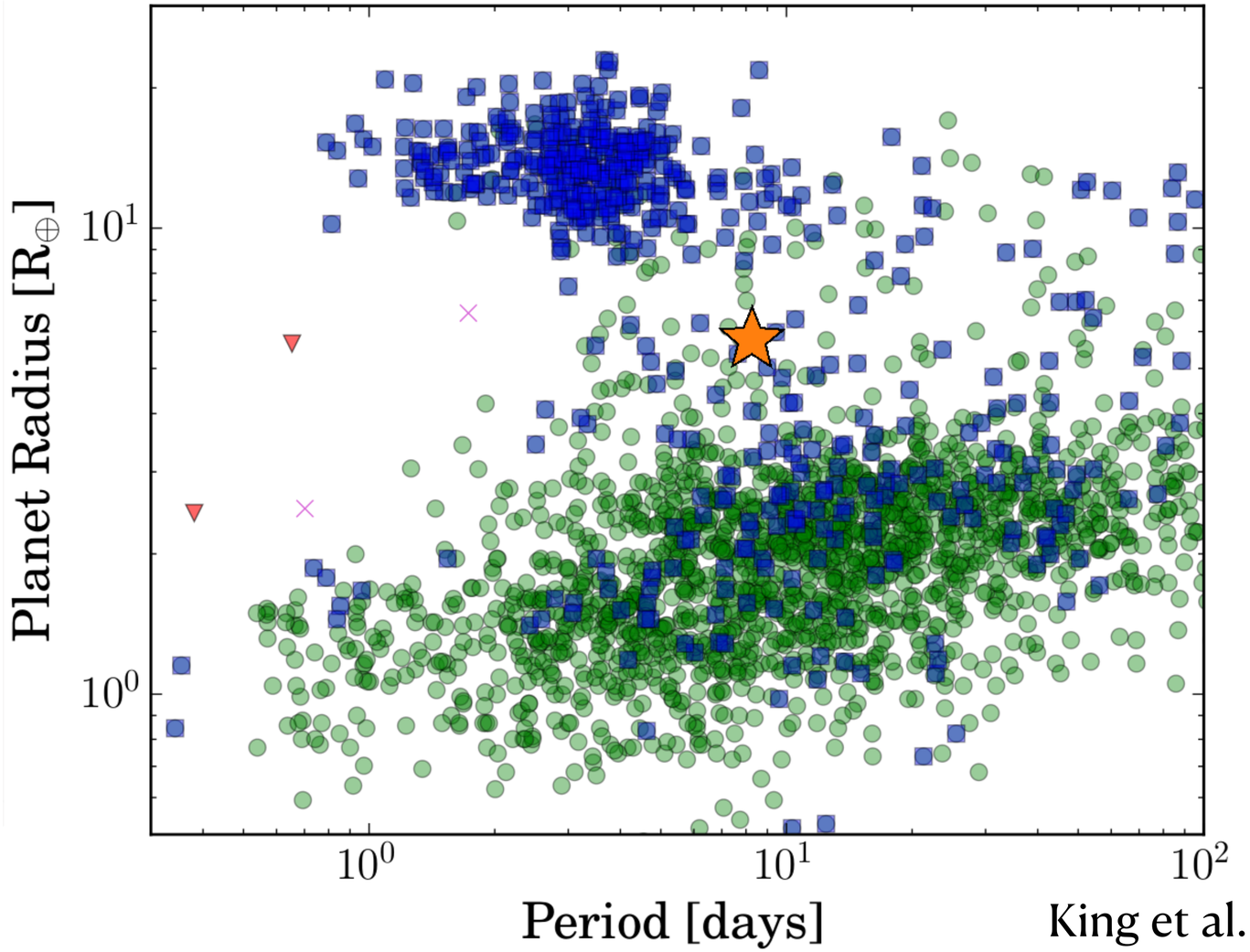
George W. King

DS Tuc A b — a young gaseous planet orbiting a sun-like star

45 Myr old, in a binary star-system, size between Neptune and Saturn



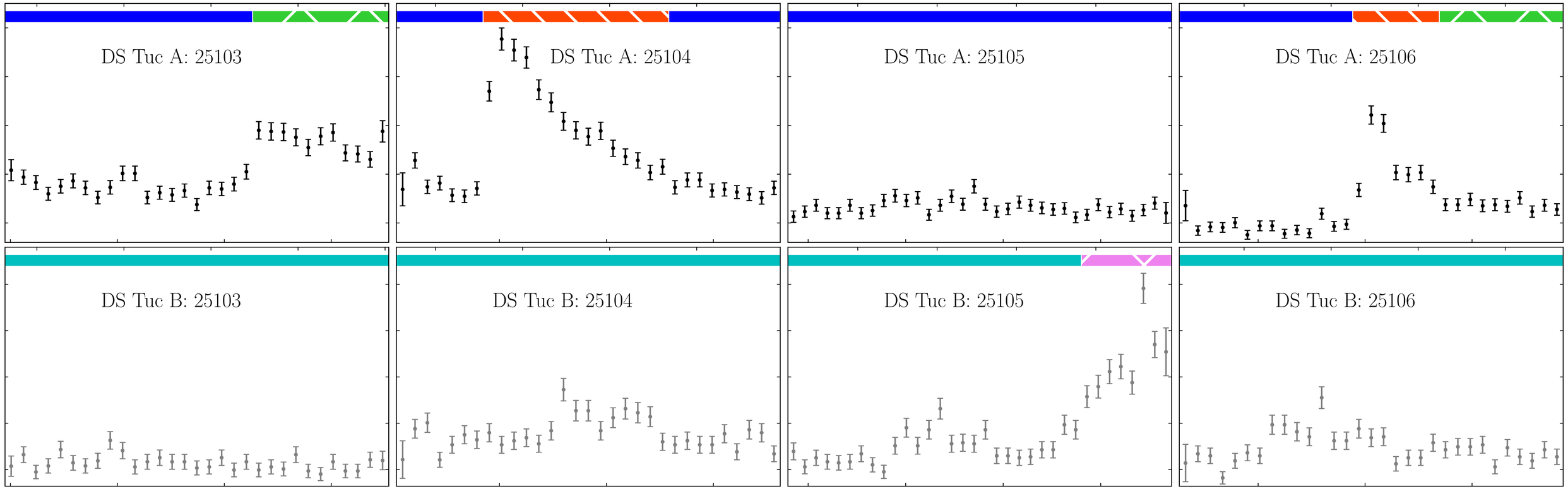




King et al. (in review)

DS Tuc A b — a young gaseous planet orbiting a sun-like star

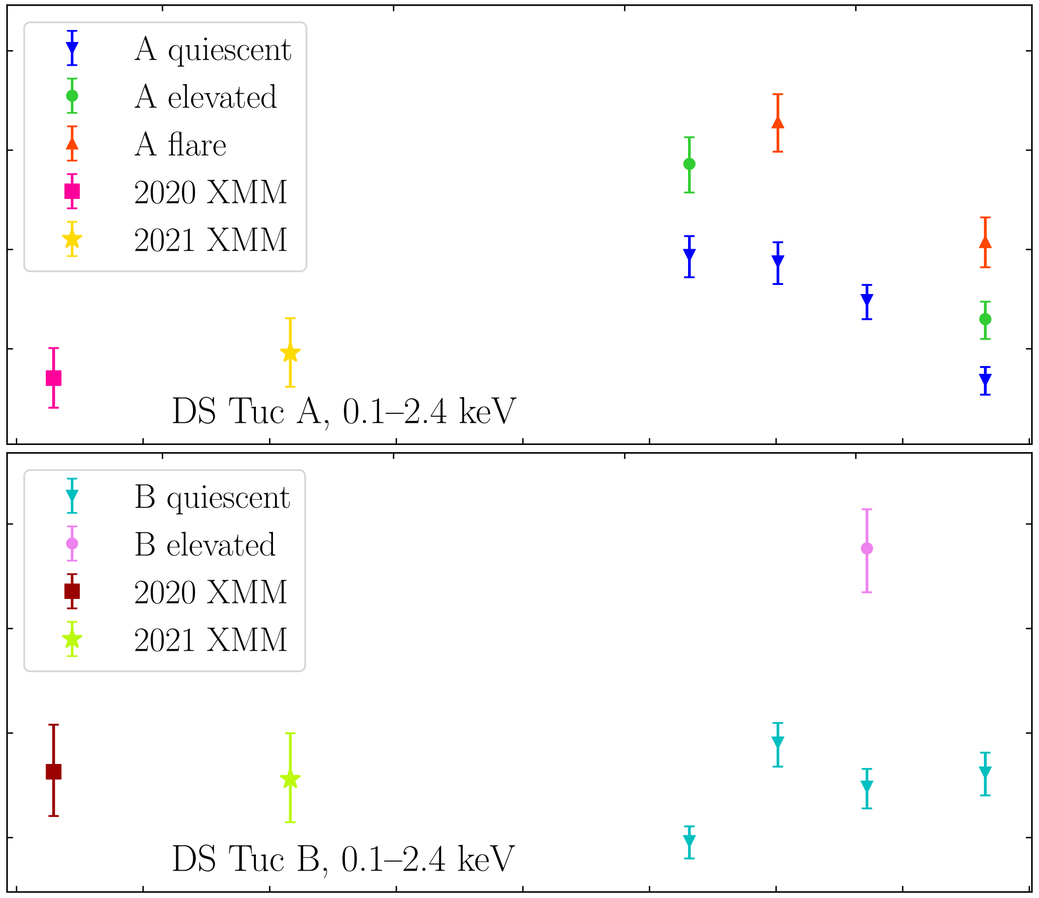
A year-long Cycle 22 campaign captured flares and periods of elevated X-ray brightness

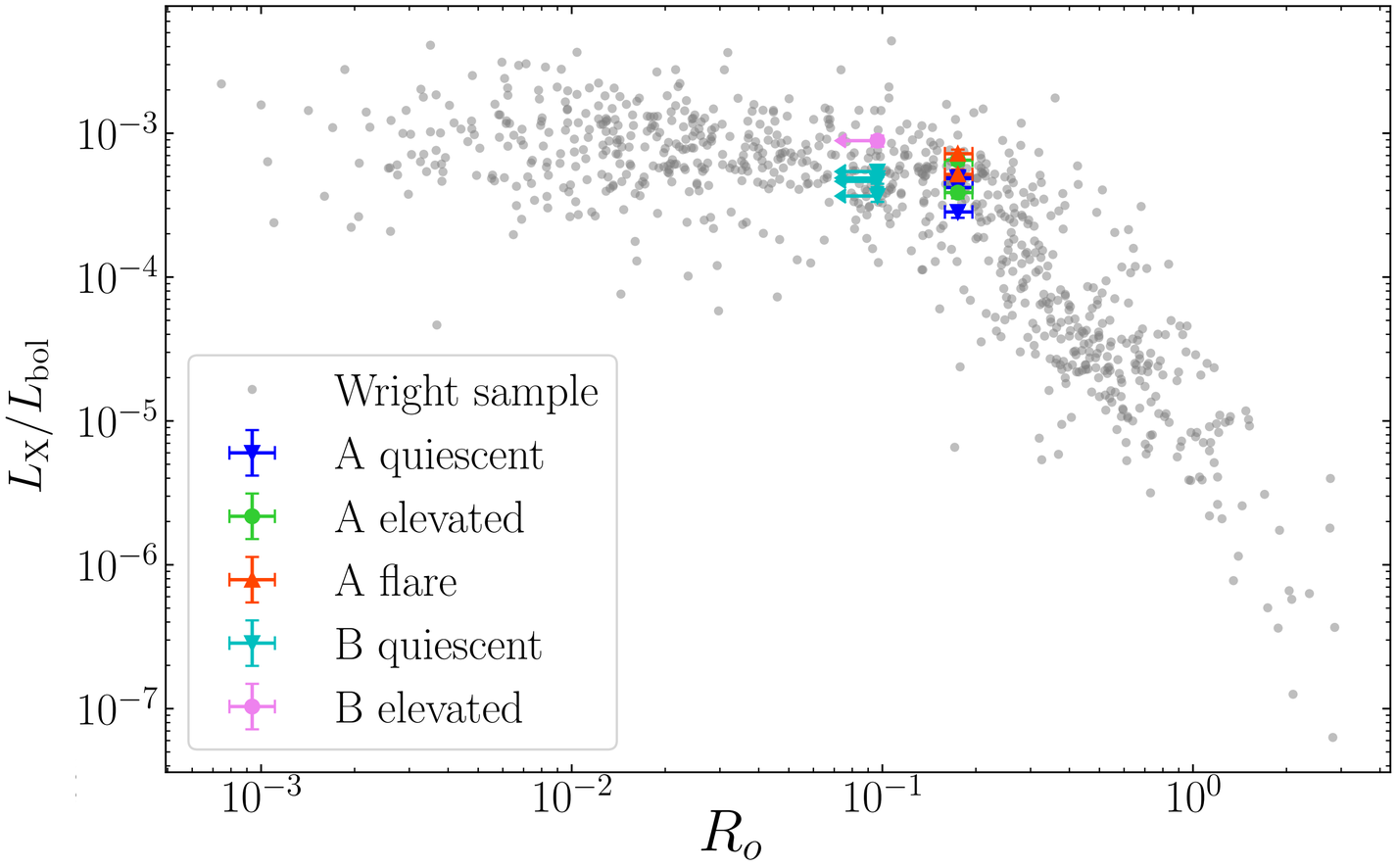


King et al. (in review)

DS Tuc A b — a young gaseous planet orbiting a sun-like star

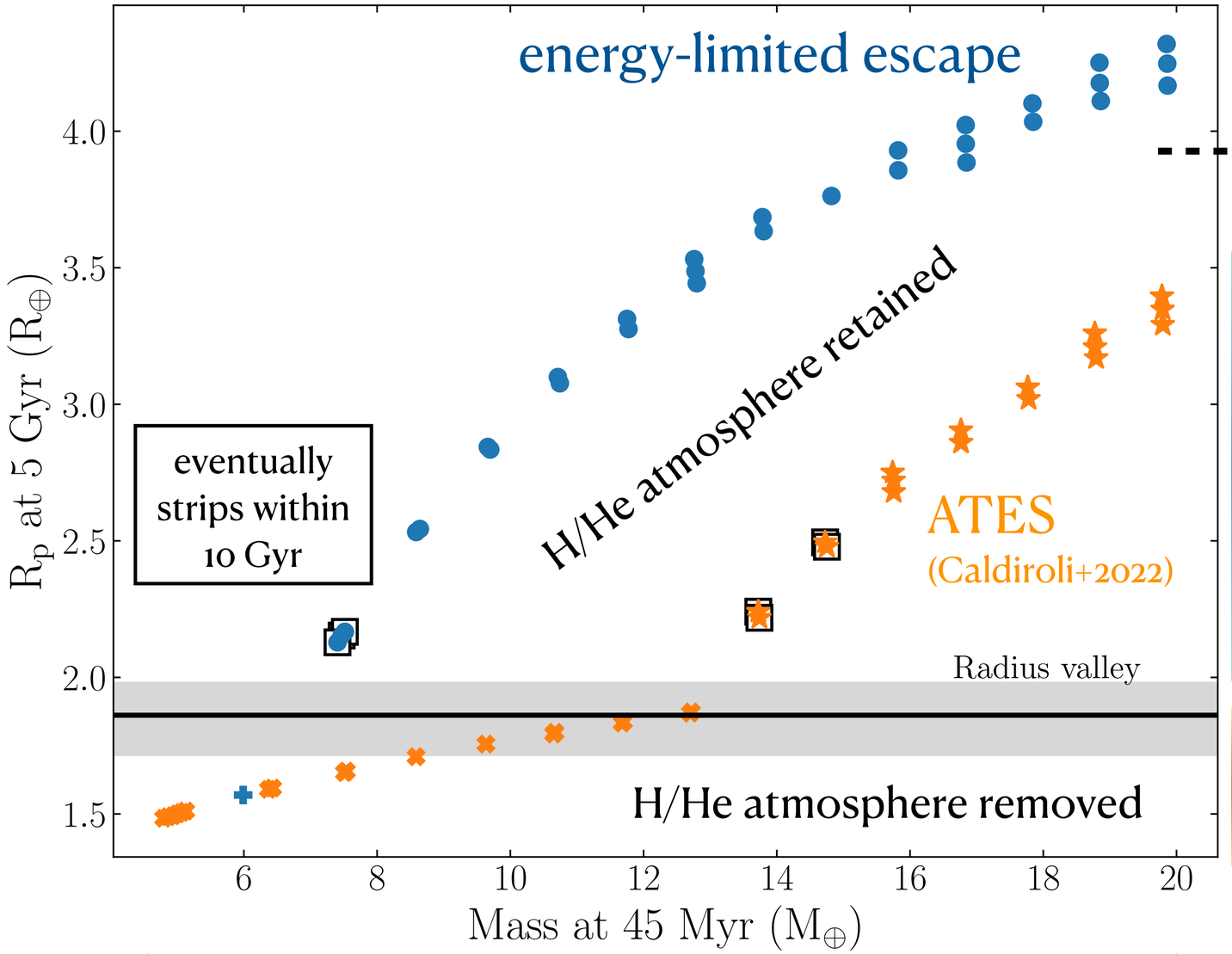
Potential hints at a stellar cycle — in context with age-activity relations





King et al. (in review)

DS Tuc A b — a young gaseous planet orbiting a sun-like star



What kind of planet will it be in 5 Gyr?

Neptune

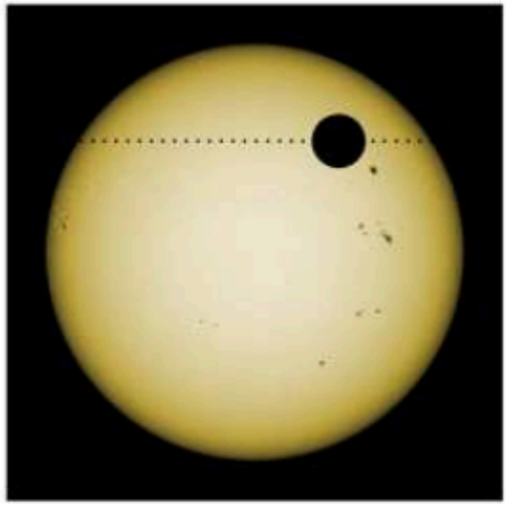
sub-Neptune

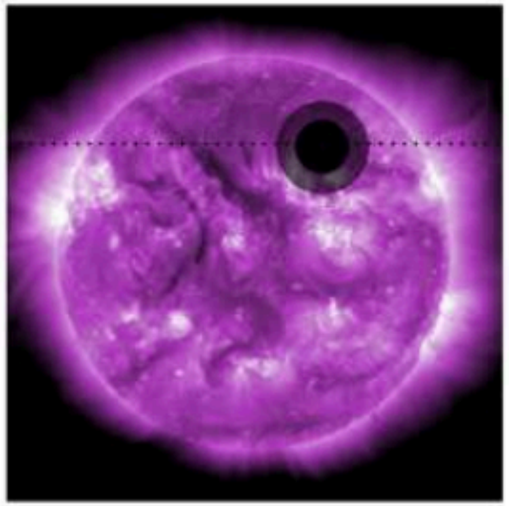
super-Earth

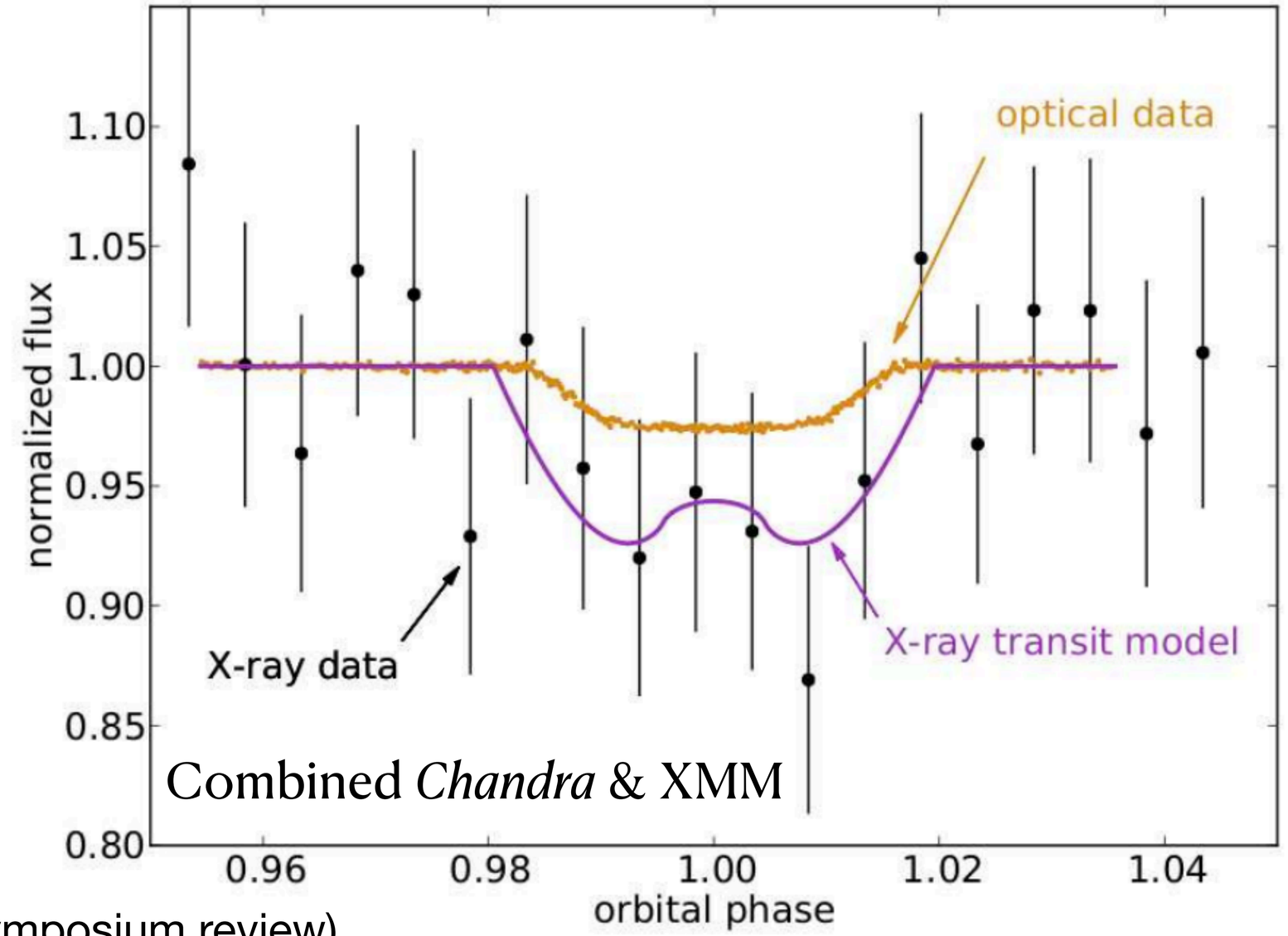
mass uncertainty

King et al. (in review)

Are X-ray transits a feasible method for studying atmospheric escape?

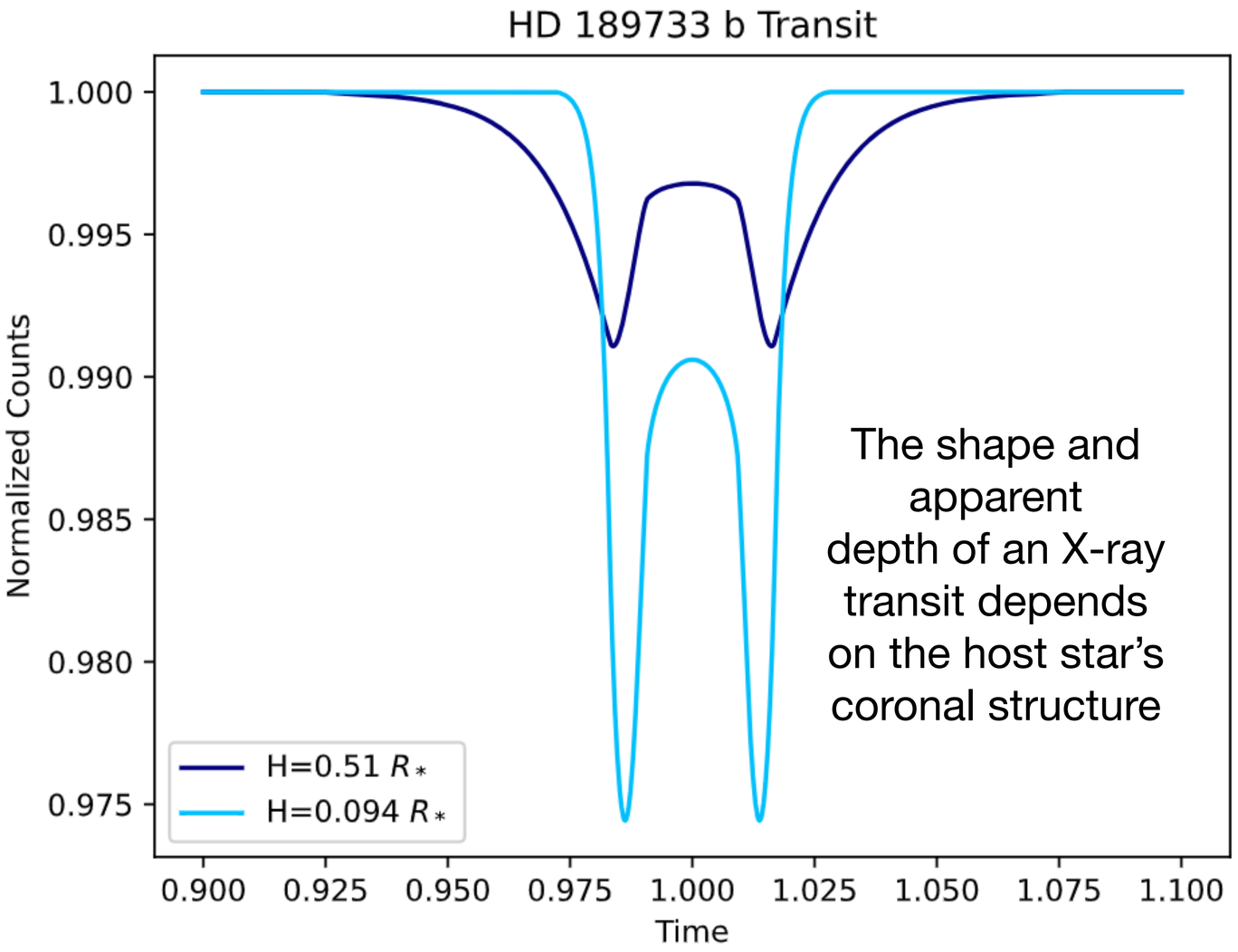






Poppenhaeger 2014 (CoRoT symposium review)

Are X-ray transits a feasible method for studying atmospheric escape?



Simulated *NewAthena* observing campaign

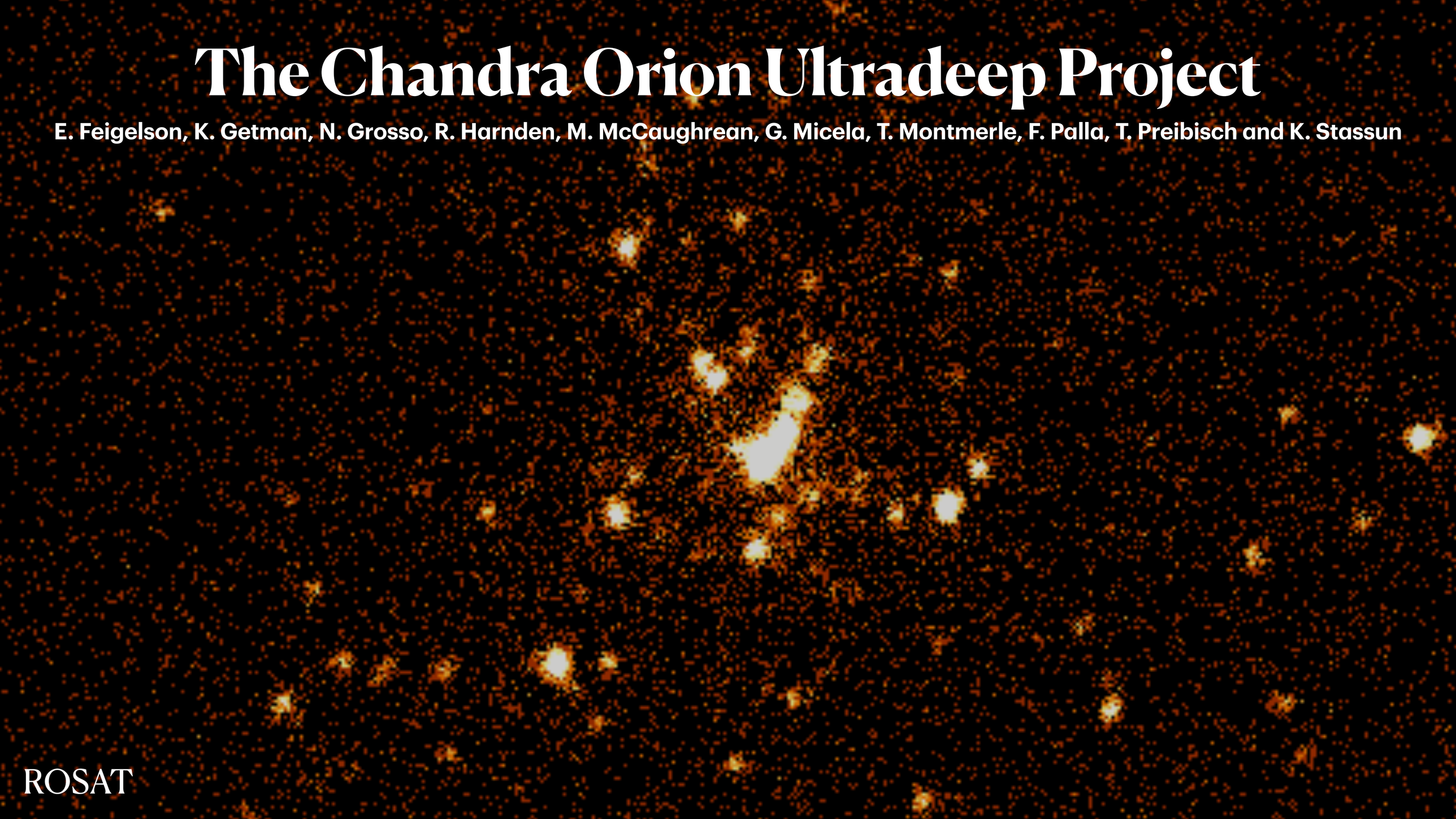
Planet	$1.5 \times R_p$	Sig (σ)	$2 \times R_p$	Sig (σ)
HD 189733 b	$< 10^{-5}$	$\geq$4.4	$< 10^{-5}$	$\geq$4.4
HIP 65 A b	$< 10^{-5}$	$\geq$4.4	$< 10^{-5}$	$\geq$4.4
WASP-93 b^{r}	$< 10^{-5}$	$\geq$4.4	$< 10^{-5}$	$\geq$4.4
AU Mic b	$< 10^{-5}$	$\geq$4.4	$< 10^{-5}$	$\geq$4.4
WASP-140 b	6.3×10^{-4}	3.4	$< 10^{-5}$	$\geq$4.4
WASP-135 b^{a}	2.7×10^{-3}	3.0	$< 10^{-5}$	$\geq$4.4
TOI-620 b^{r}	0.03	2.1	1.6×10^{-4}	3.8
HIP 67522 b	1.9×10^{-3}	3.1	$< 10^{-5}$	$\geq$4.4
WASP-80 b	0.01	2.5	2.7×10^{-5}	4.2
DS Tuc A b	0.02	2.3	1.2×10^{-4}	3.9
WASP-180 A b	0.02	2.4	8.7×10^{-5}	3.9
WASP-77 A b	0.07	1.8	0.02	2.2
WASP-43 b	0.08	1.8	2.8×10^{-3}	3.0
WASP-52 b^{a}	0.04	2.0	4.5×10^{-5}	4.1
WASP-145 A b^{a}	0.23	< 1.5	0.04	2.0

Cilley*, King & Corrales (2024); King et al. (2024)

*Current UMich junior!

The Chandra Orion Ultradeep Project

E. Feigelson, K. Getman, N. Grosso, R. Harnden, M. McCaughrean, G. Micela, T. Montmerle, F. Palla, T. Preibisch and K. Stassun



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Chandra

The Chandra Orion Ultradeep Project

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Chandra's incredible imaging resolution remains unsurpassed, enabling study of young stars in crowded systems

Chandra

The Chandra Orion Ultradeep Project

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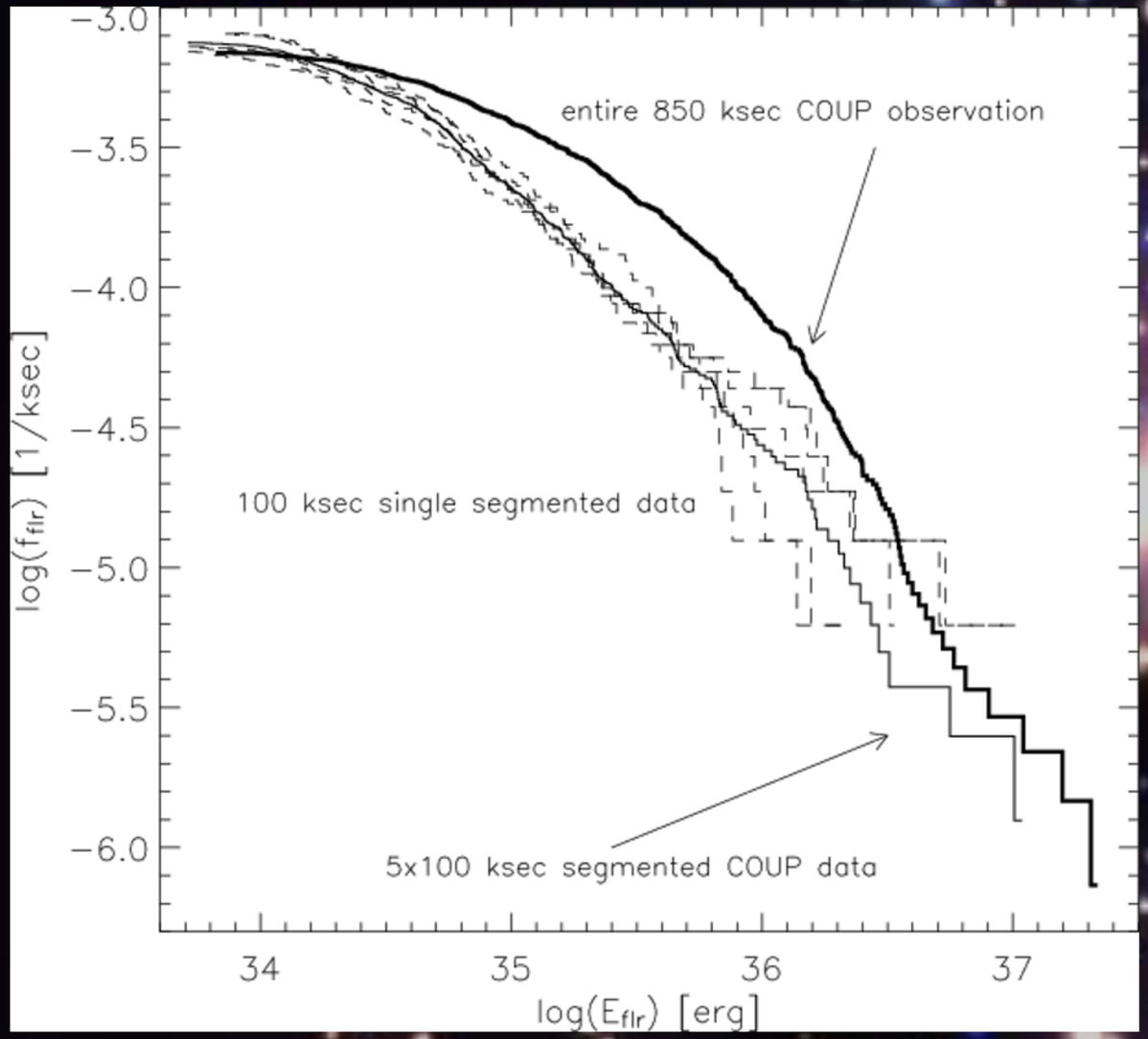
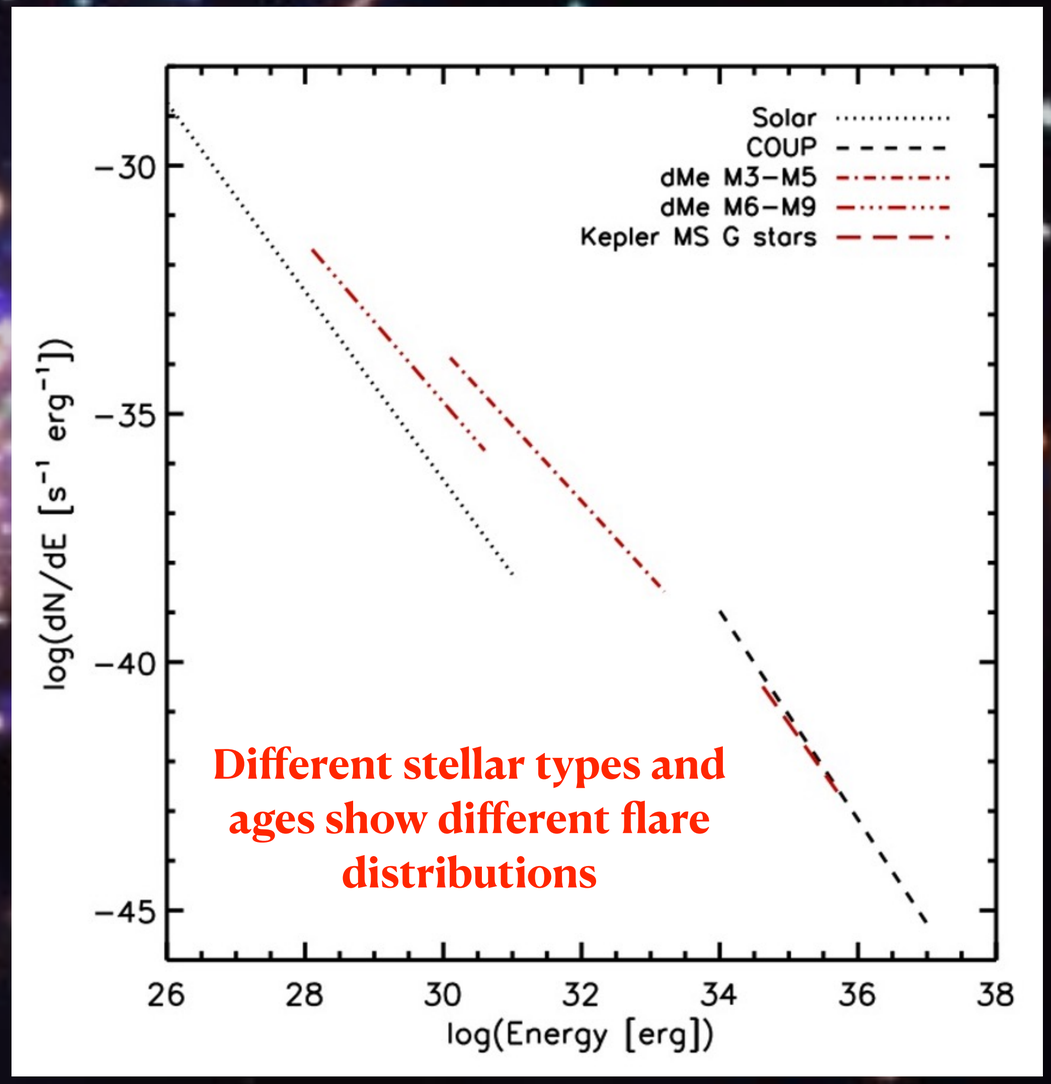


Colombo+2007, see also Caramazza+2007

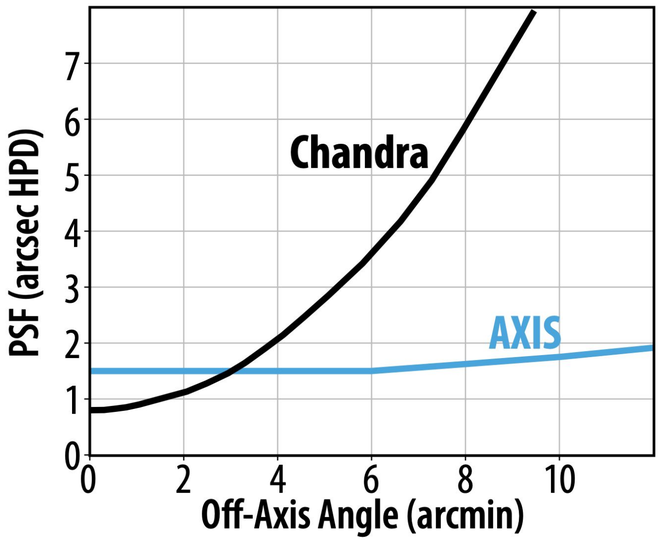


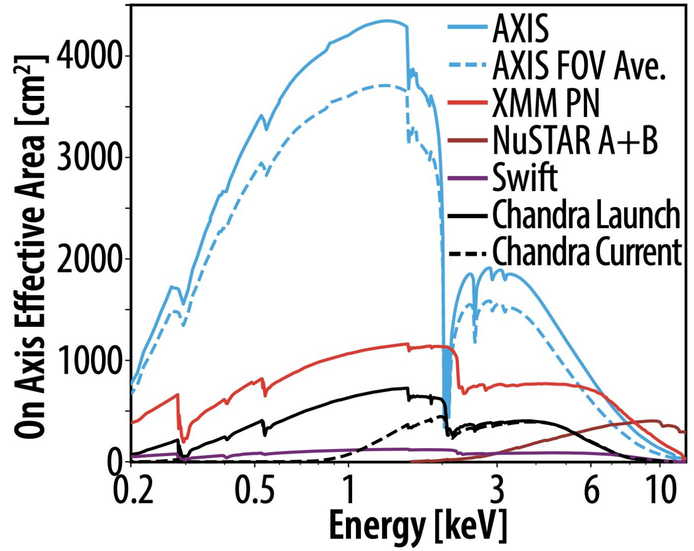
Aarnio+2012, K. Stassun

Chandra's pioneering work provides new windows on stellar activity

Parameter	Baseline Value
PSF	1.50" on-axis, 1.75" FoV-ave (HPD)
Effective Area (incl. detector)	4200 cm^2 at 1 keV; 830 cm^2 at 6 keV
FoV	24 arcmin diameter
Bandpass	0.3-10 keV
Readout rate	>5 fps
Slew rate	120 deg. / 9.5 min.
Orbit	Low-inclination (5 deg) LEO

New working group members welcome for Phase A study





Conclusions

- *Chandra*'s HETG and LETG instruments enable detailed studies of interstellar dust composition and structure, which we can compare to suspected interstellar grains in our solar system to illuminate planetary growth processes
- The laboratory data and models are still catching up — *Chandra*'s data and archives will continue to deliver for decades

- *Chandra*'s unsurpassed resolution enables detailed studies of stellar activity across ages (COUP survey, Wright et al., etc)
- The ability to resolve stellar binary systems like DS Tuc allows us to study the role of atmospheric evaporation in planetary evolution
- *Chandra*'s contributions to the discovery of an X-ray transit opens a world of possibility
- Future missions are built upon *Chandra*'s legacy of scientific breakthroughs