Mysteries of exoplanets and low-mass stars and how to shed new X-ray light on them

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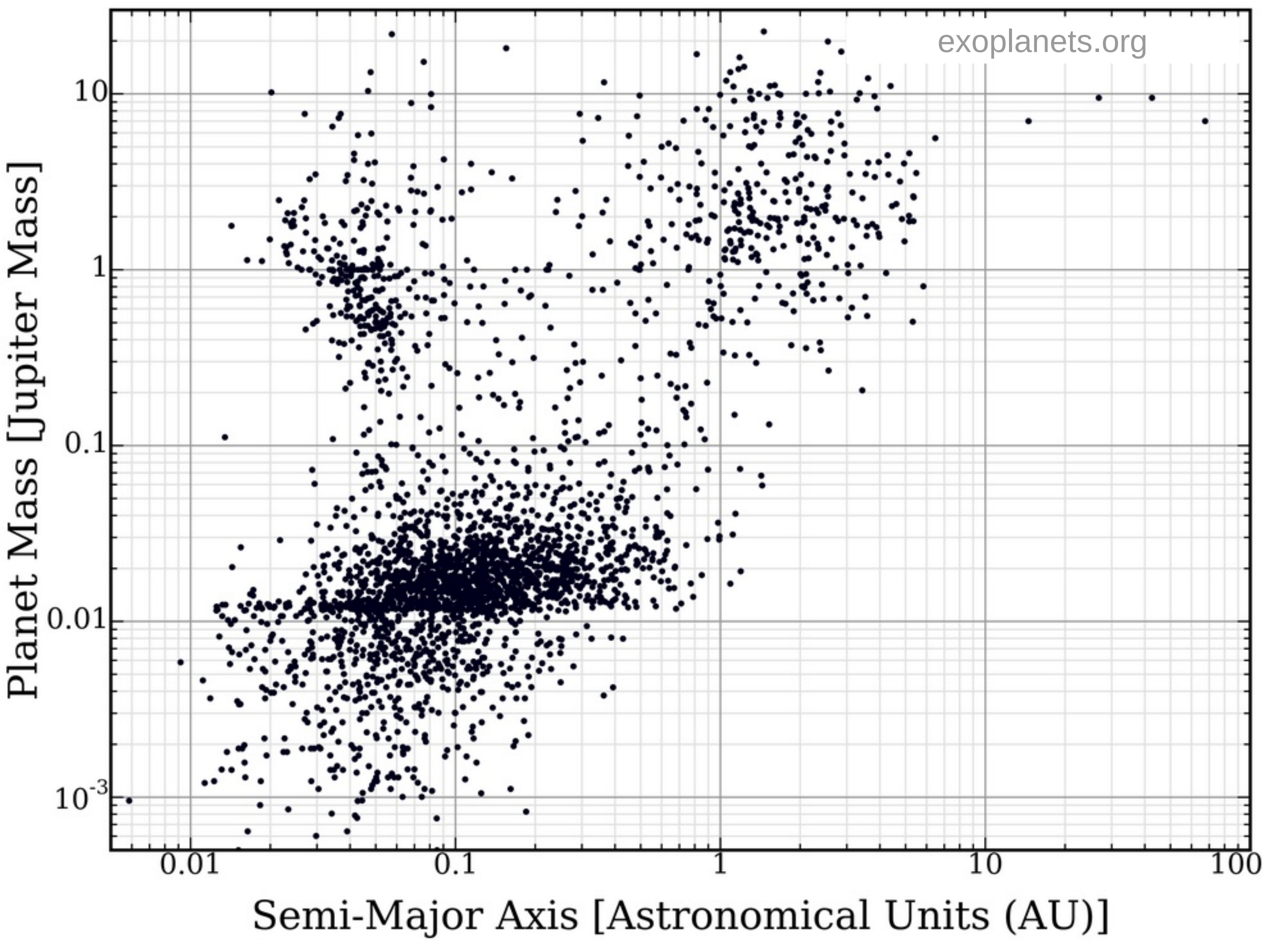
The exoplanet zoo



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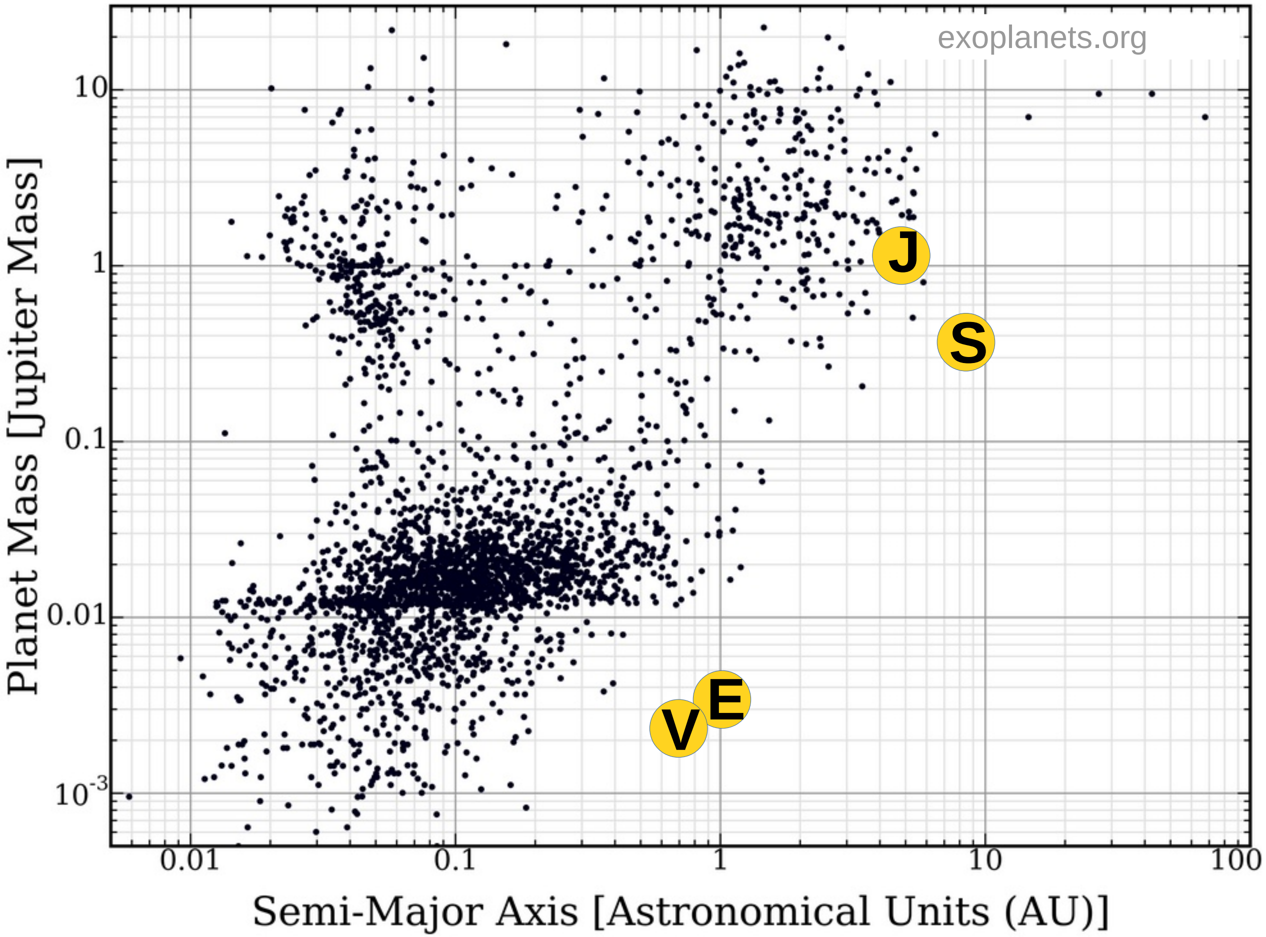

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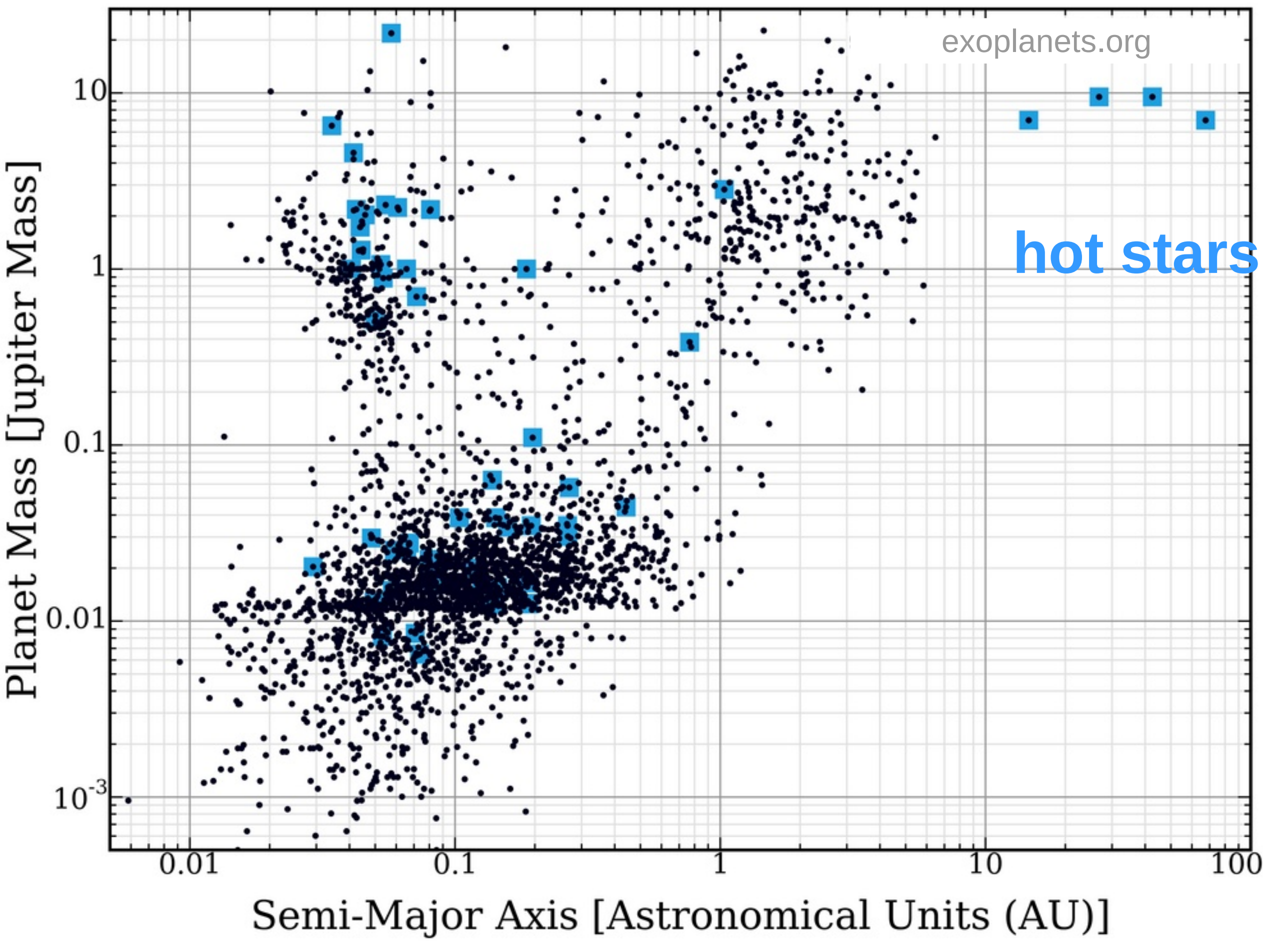

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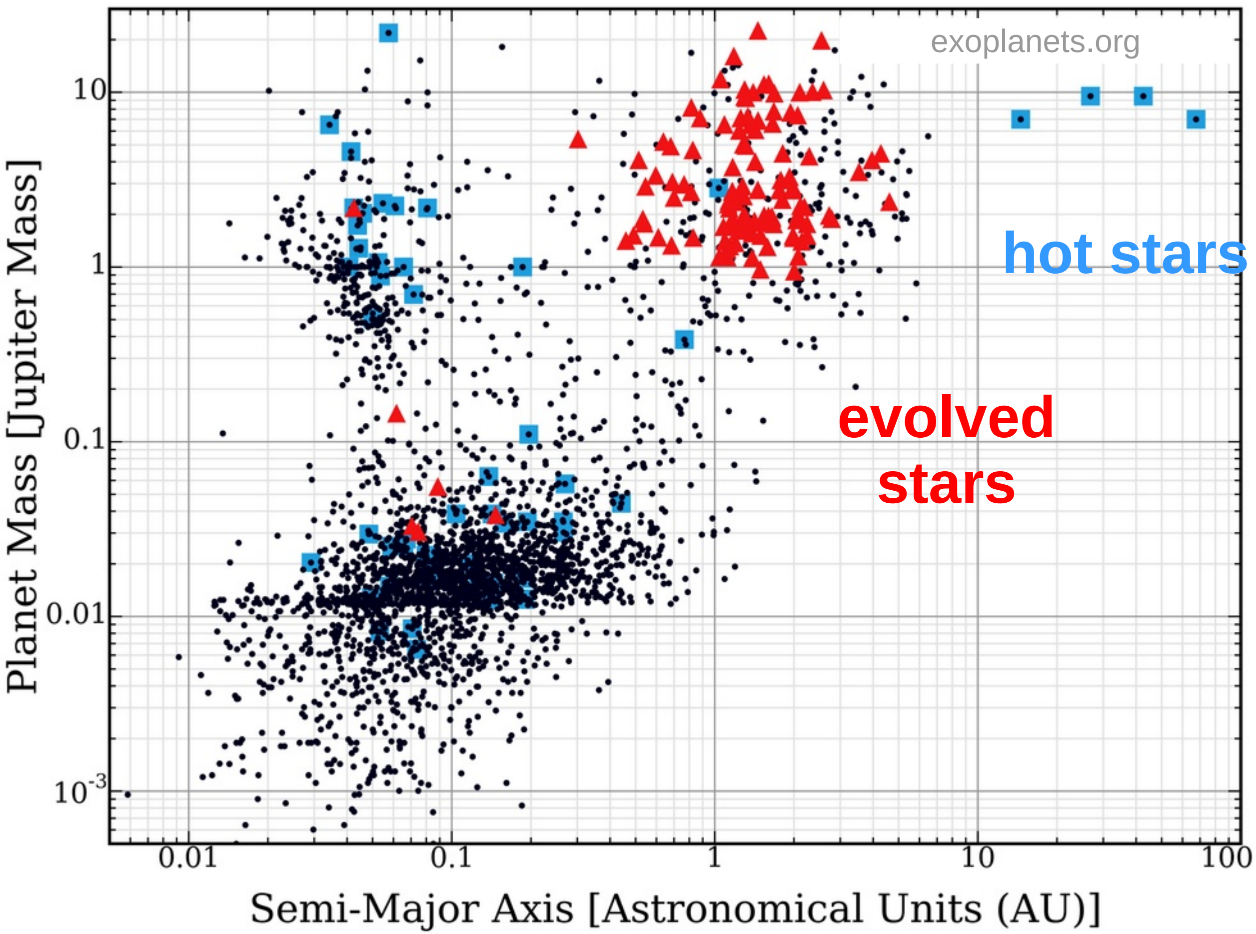
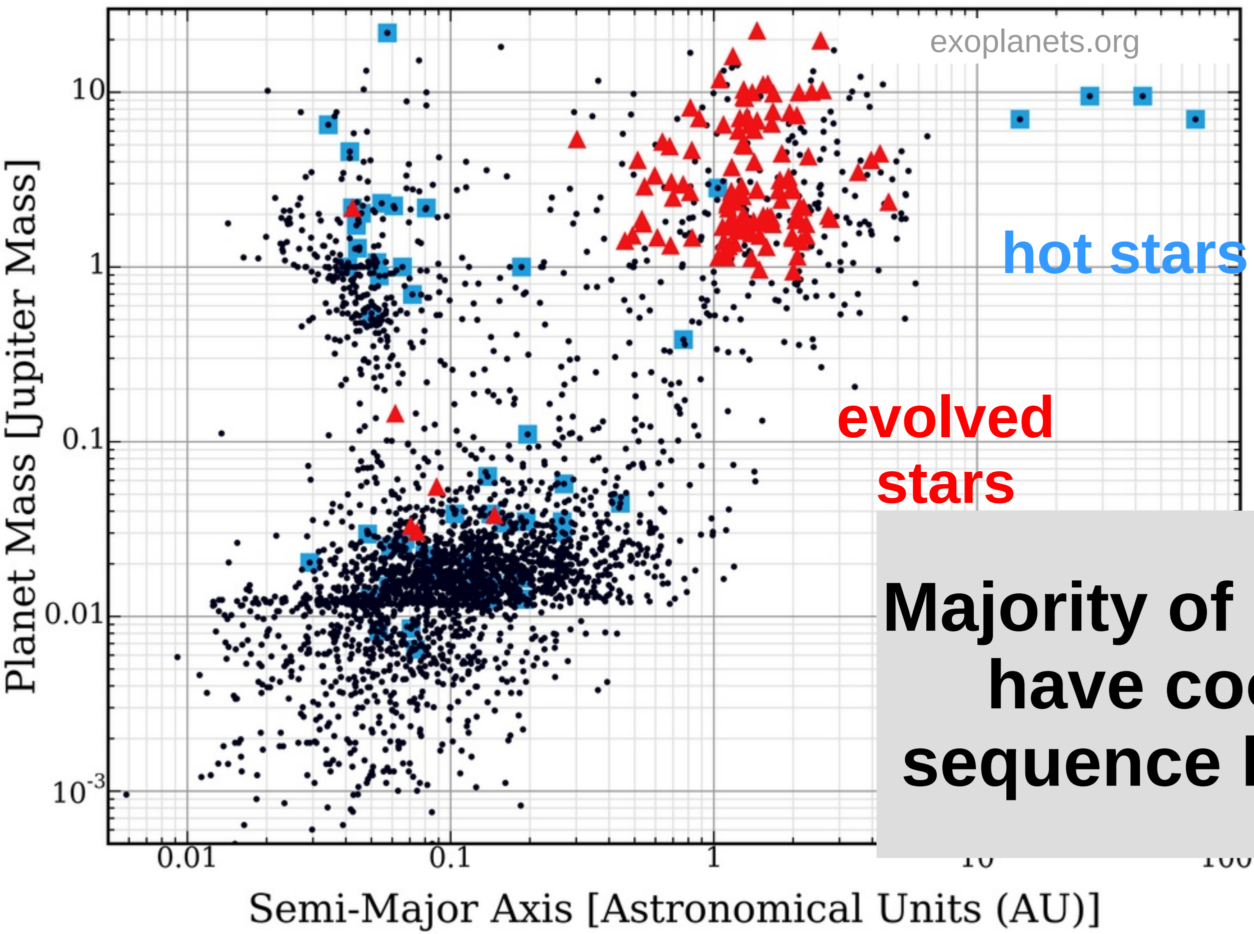


hot stars

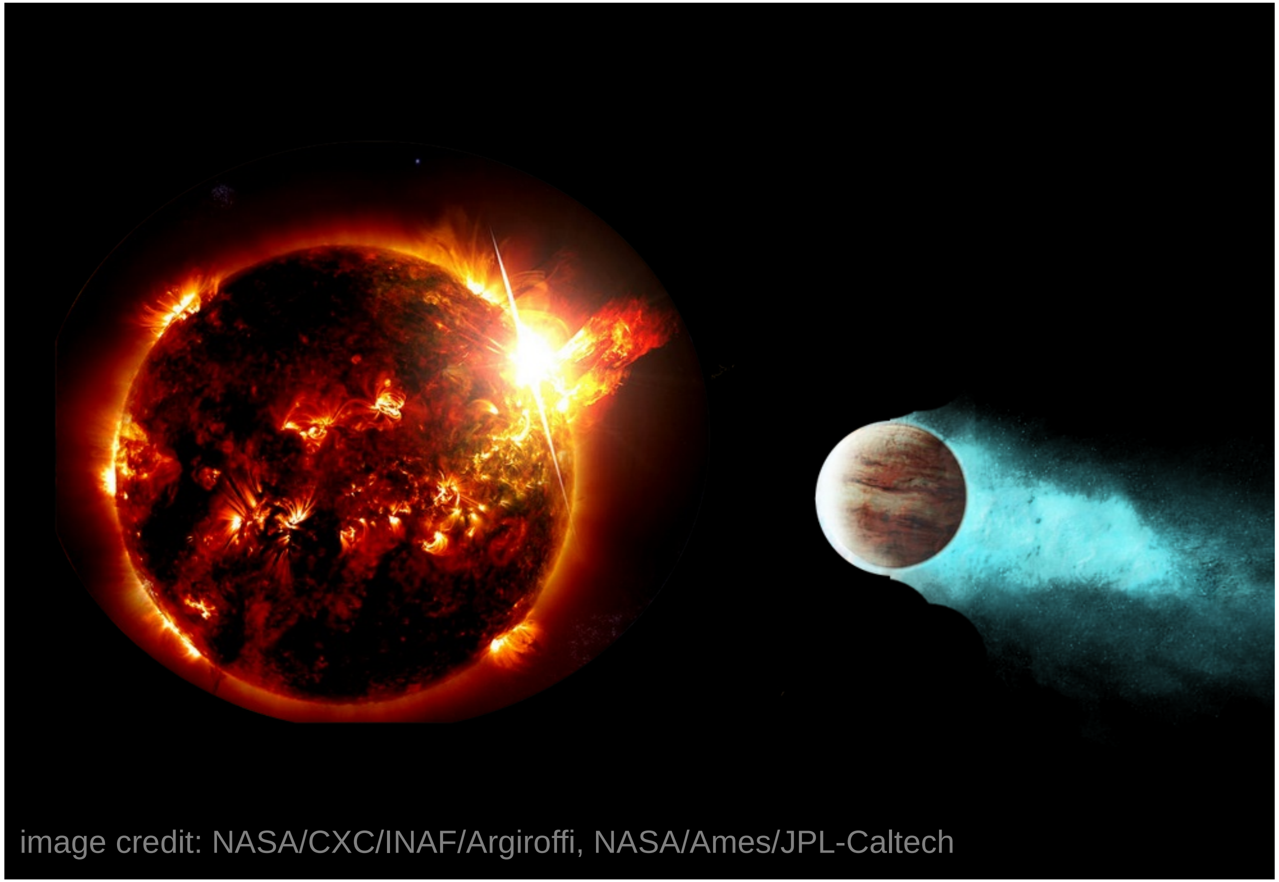
evolved stars

The exoplanet zoo



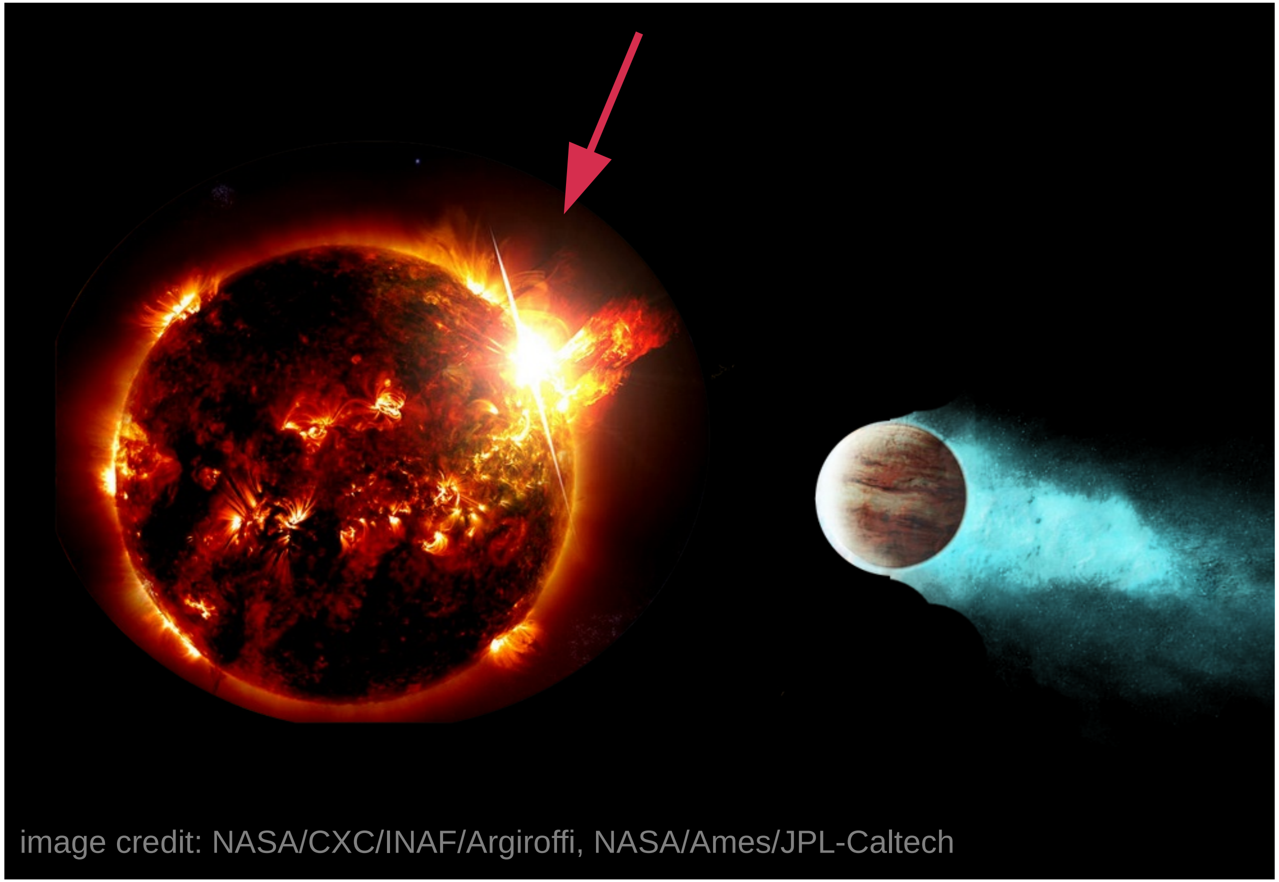
Majority of exoplanets have cool main-sequence host stars!

Stars & exoplanets & high-energy phenomena



- stellar corona, flares, mass ejections
- exoplanetary evaporation, atmosphere chemistry/physics
- star-planet interactions (planet influencing star)

Stars & exoplanets & high-energy phenomena



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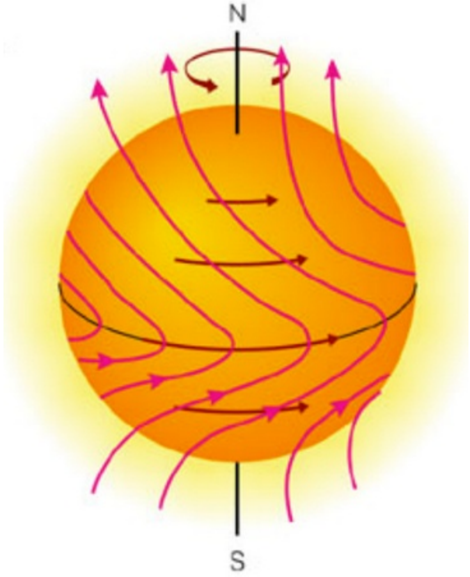
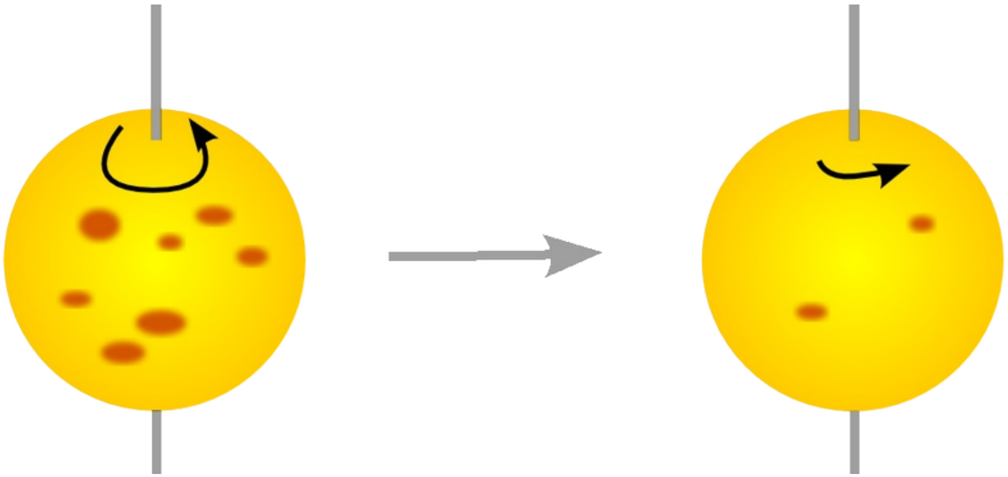
Stellar rotation and magnetism



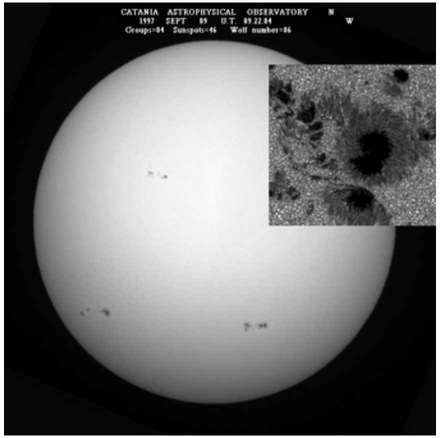
differential rotation causes time-variable magnetic field via dynamo processes

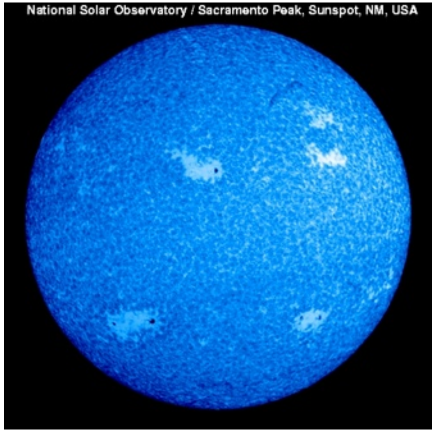


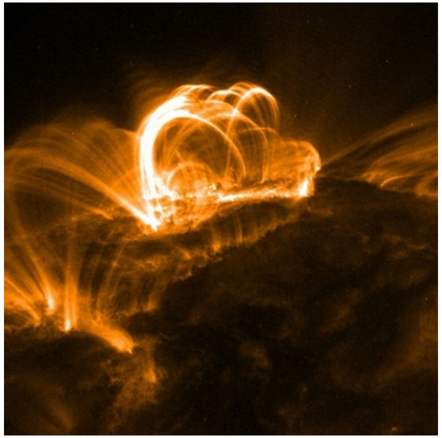
magnetic activity causes ionized wind which carries away angular momentum

cool stars spin down over time and their magnetic activity ceases

X-rays from cool stars







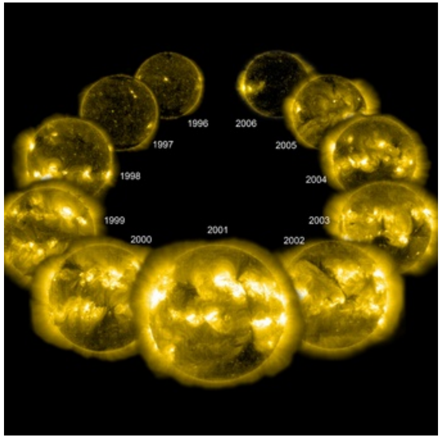
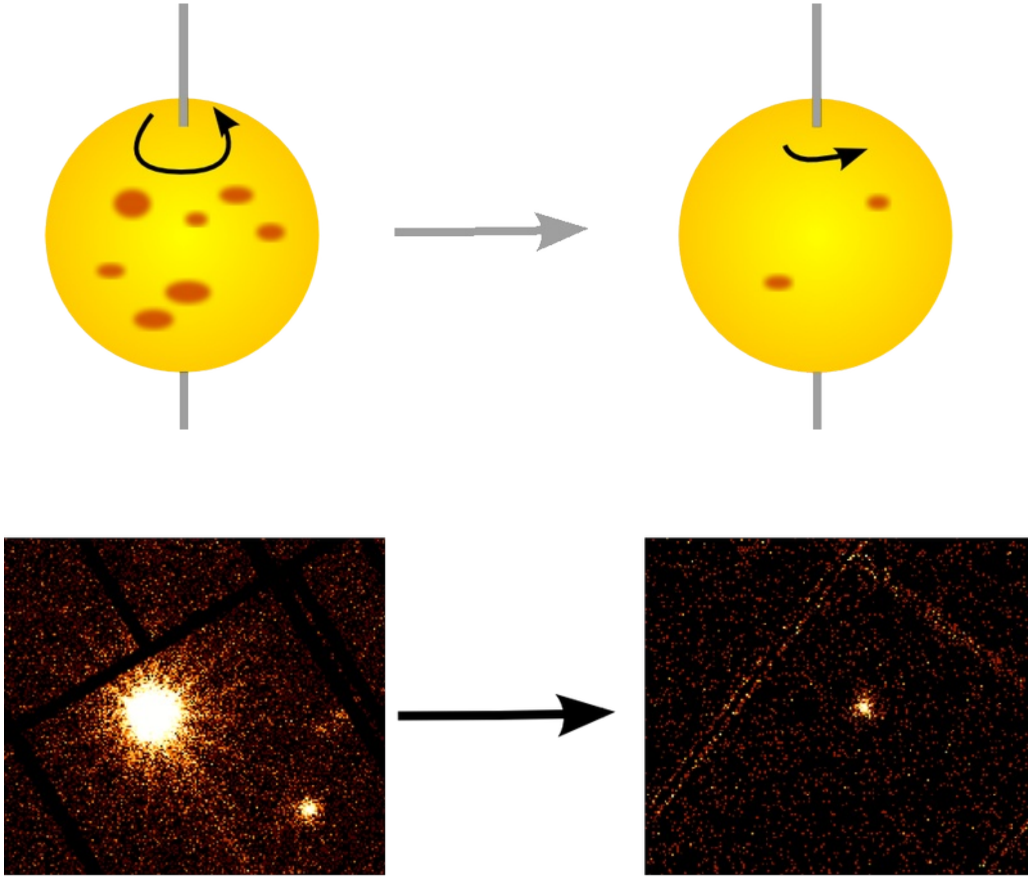


image credit: NSO/NASA/CAO

Stars create X-rays as thermal emission from their coronae

Coronae exist because of the stellar magnetic dynamo

X-rays from cool stars



magnetic braking:

angular momentum loss of star through shedding of magnetized wind

causes decrease in all magnetic phenomena

Evaporation of planetary atmospheres

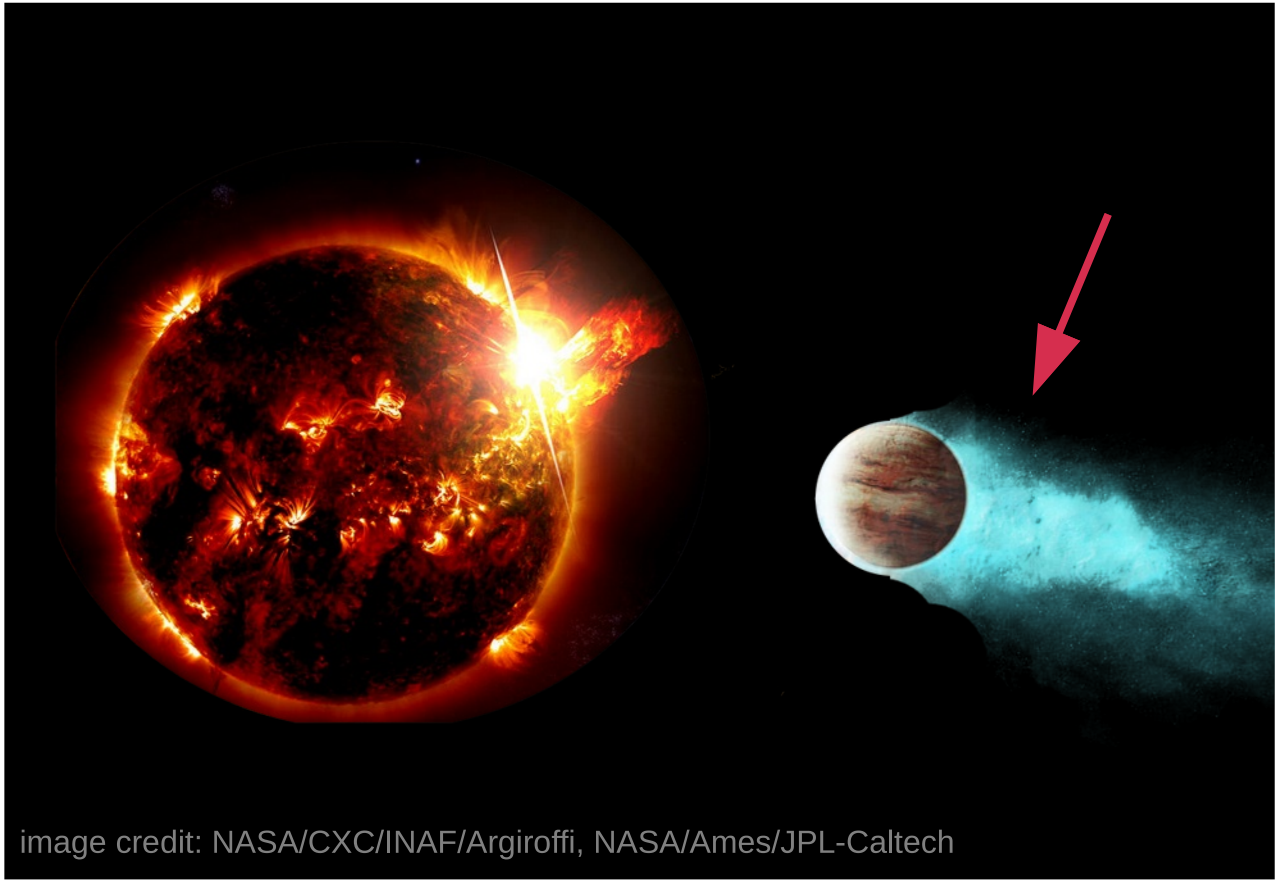
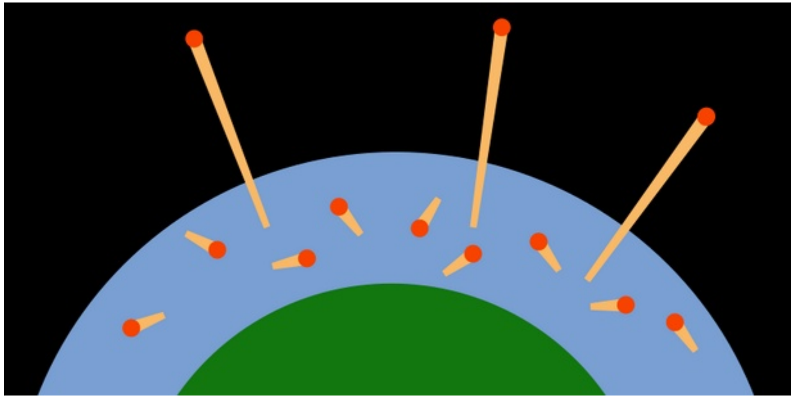


image credit: NASA/CXC/INAF/Argiroffi, NASA/Ames/JPL-Caltech

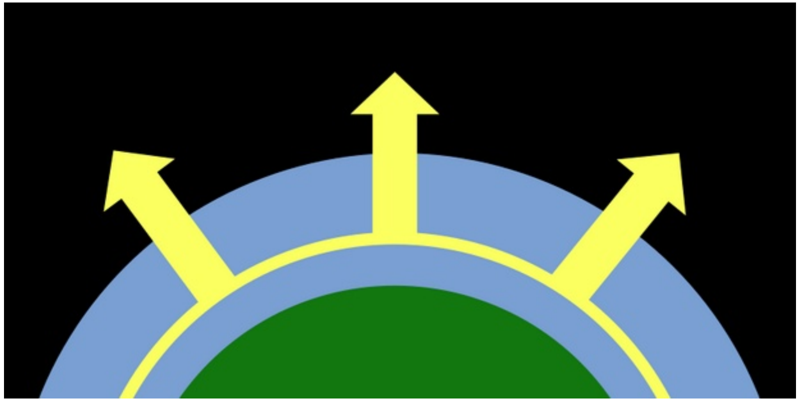
Survival of exoplanet atmospheres

Jeans escape:



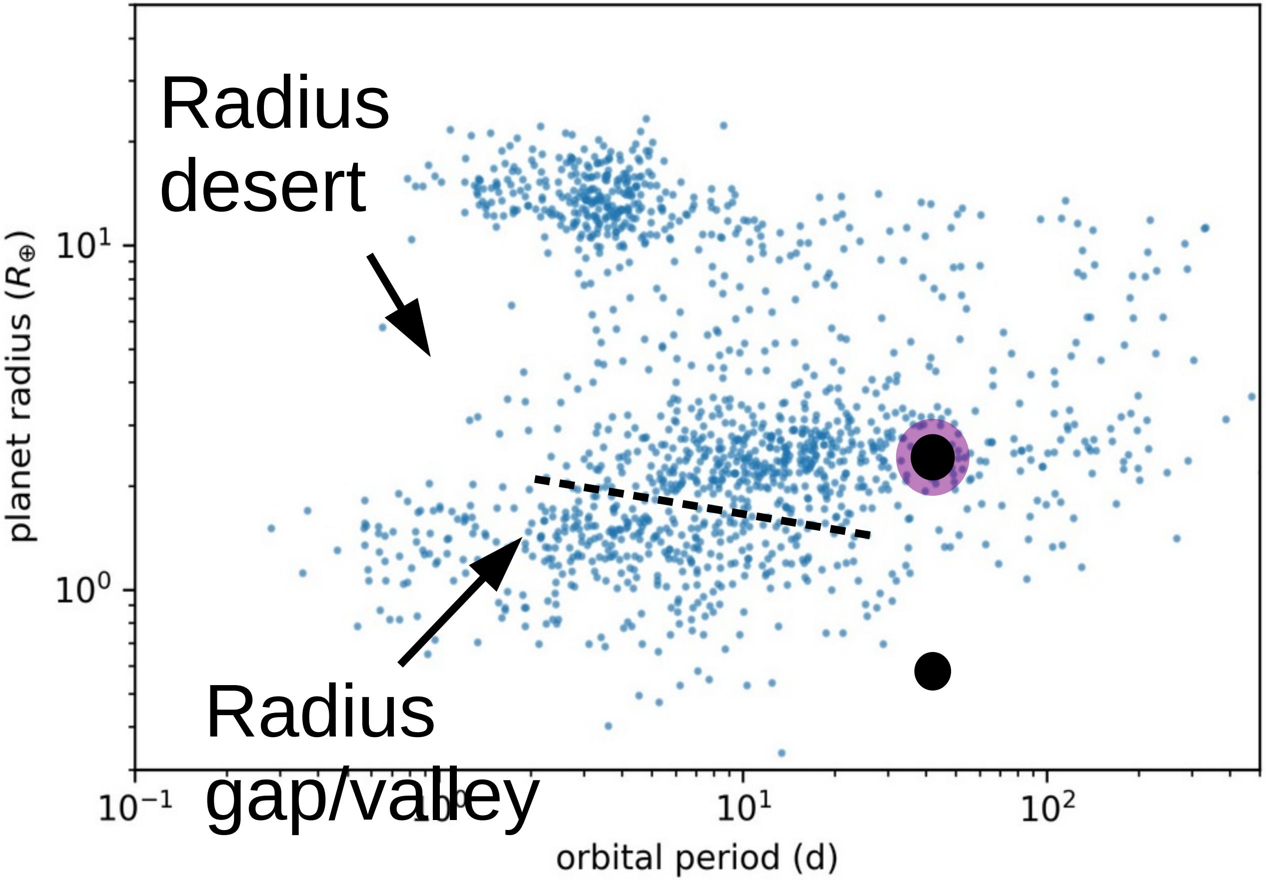
Escape from high-velocity tail of Maxwell-Boltzmann distribution

Hydrodynamic escape:



Heating of atmospheric layer by X-ray and extreme-UV photons, wind-like escape

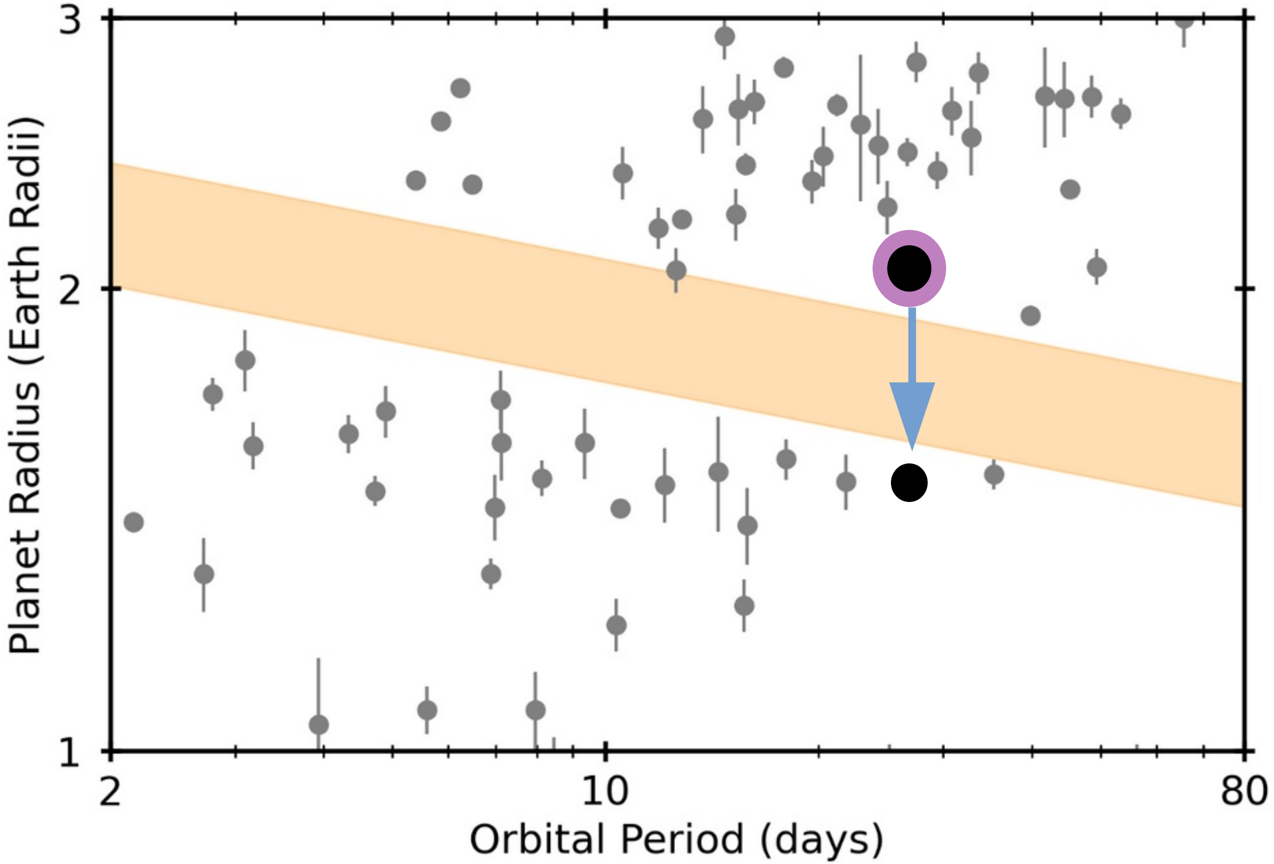
From H/He envelopes to rocky planets



See Fulton et al. (2017), van Eylen et al. (2018);

see also Kubyshkina et al. (2018), Berger et al. (2020), Gupta & Schlichting (2020), Loyd et al. (2020)

From H/He to rocky planets: evaporation



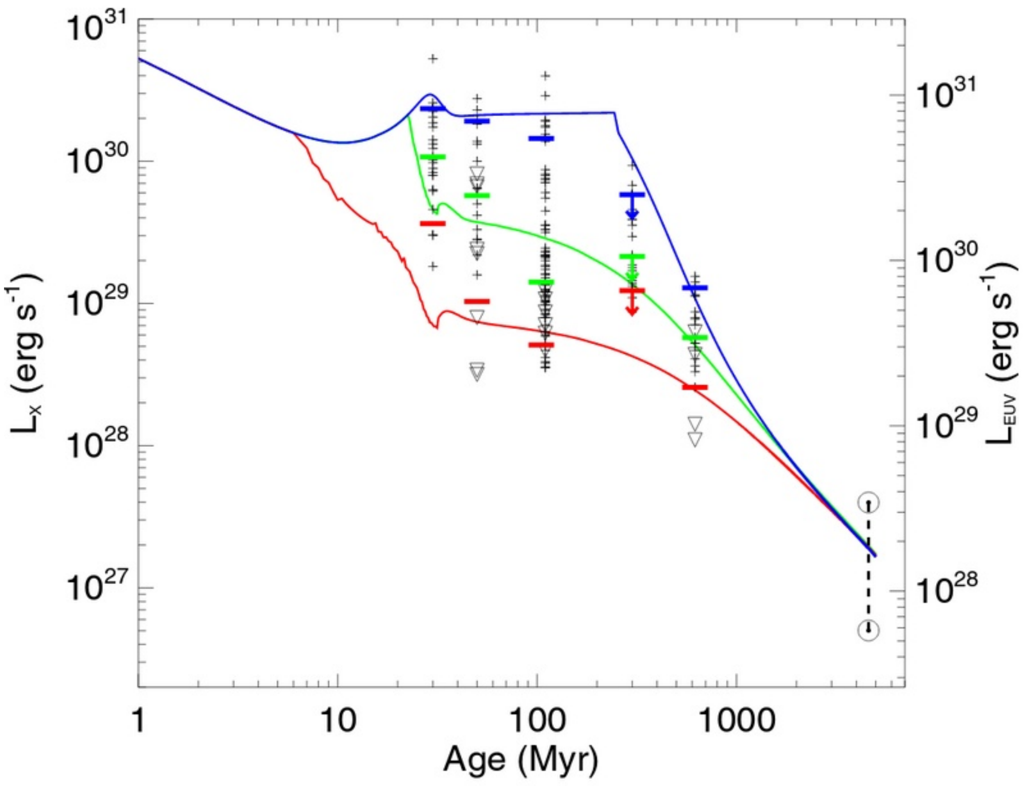
„Fulton gap“; plot adapted from Huber et al. (2022)

Stellar X-ray evolution over time

X-rays from stars drive atmospheric escape

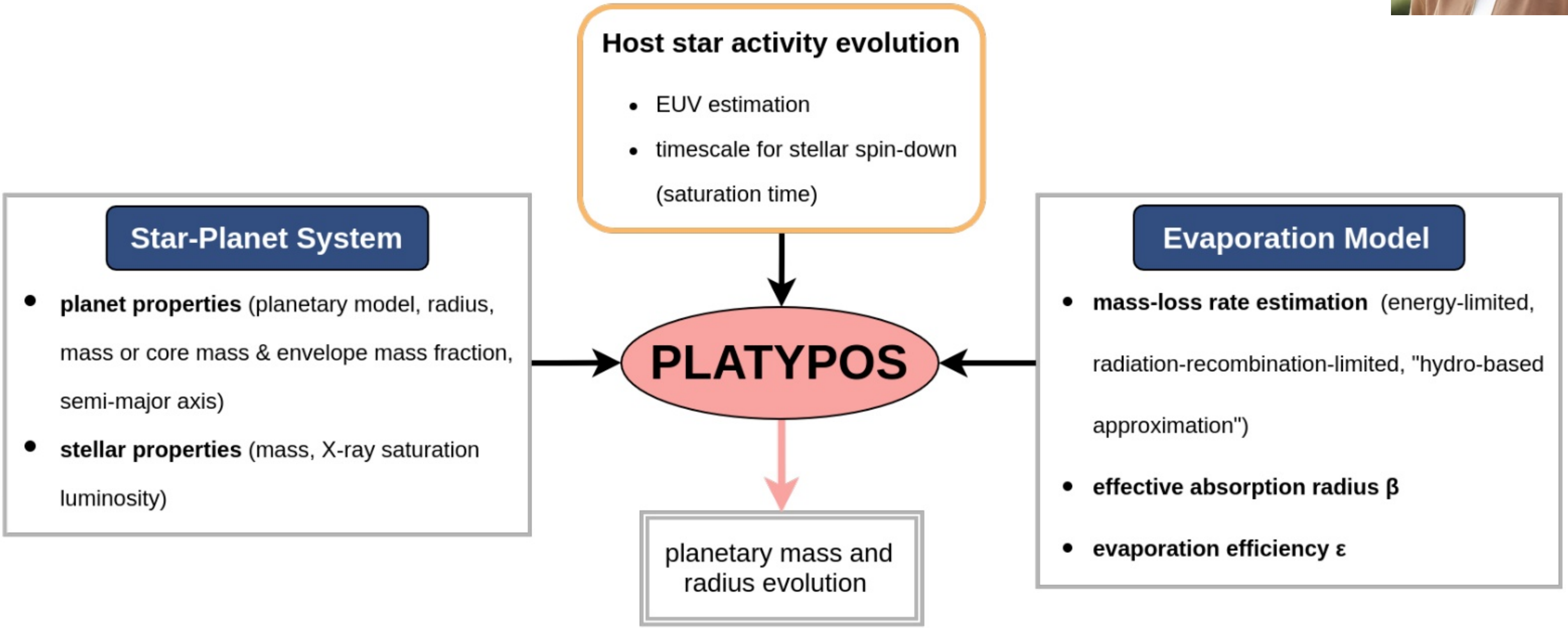
However, stars can follow different X-ray luminosity tracks over time!

→ needs to be modelled statistically.



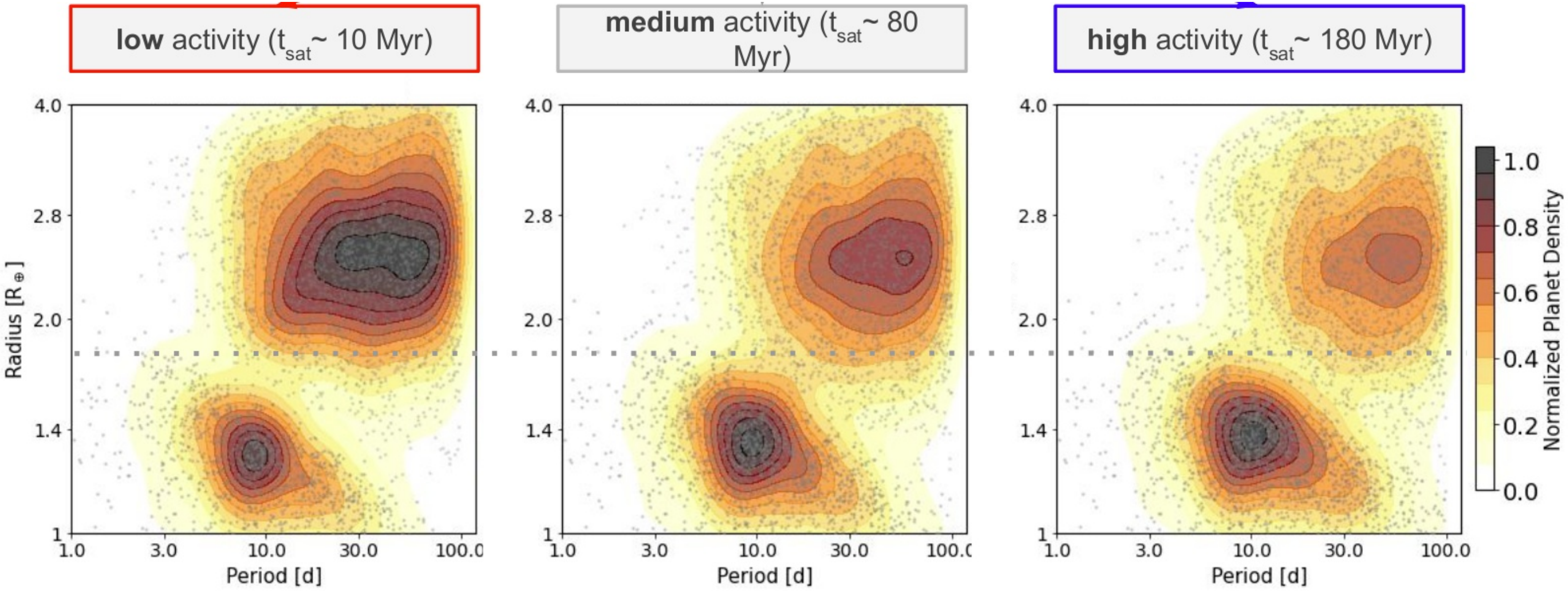
stellar data from Tu, Güdel et al. 2015

PLATYPOS - PLAneTarY PhOtoevaporation Simulator



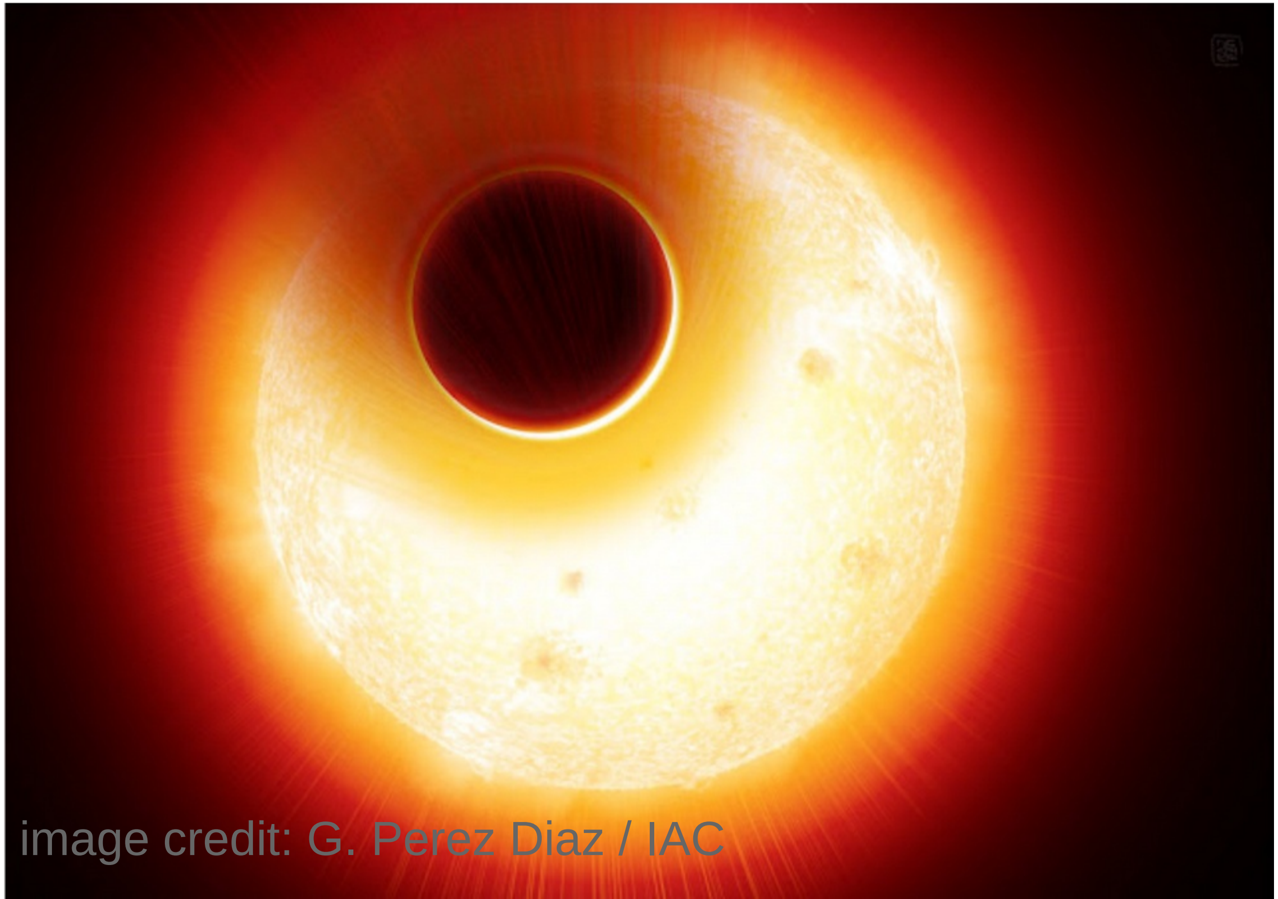
Ketzer & Poppenhaeger 2022

Populations react to stellar activity tracks



Ketzer & Poppenhaeger 2023

Observable signatures of currently on-going exoplanet evaporation



Exoplanet atmospheres: transits & eclipses

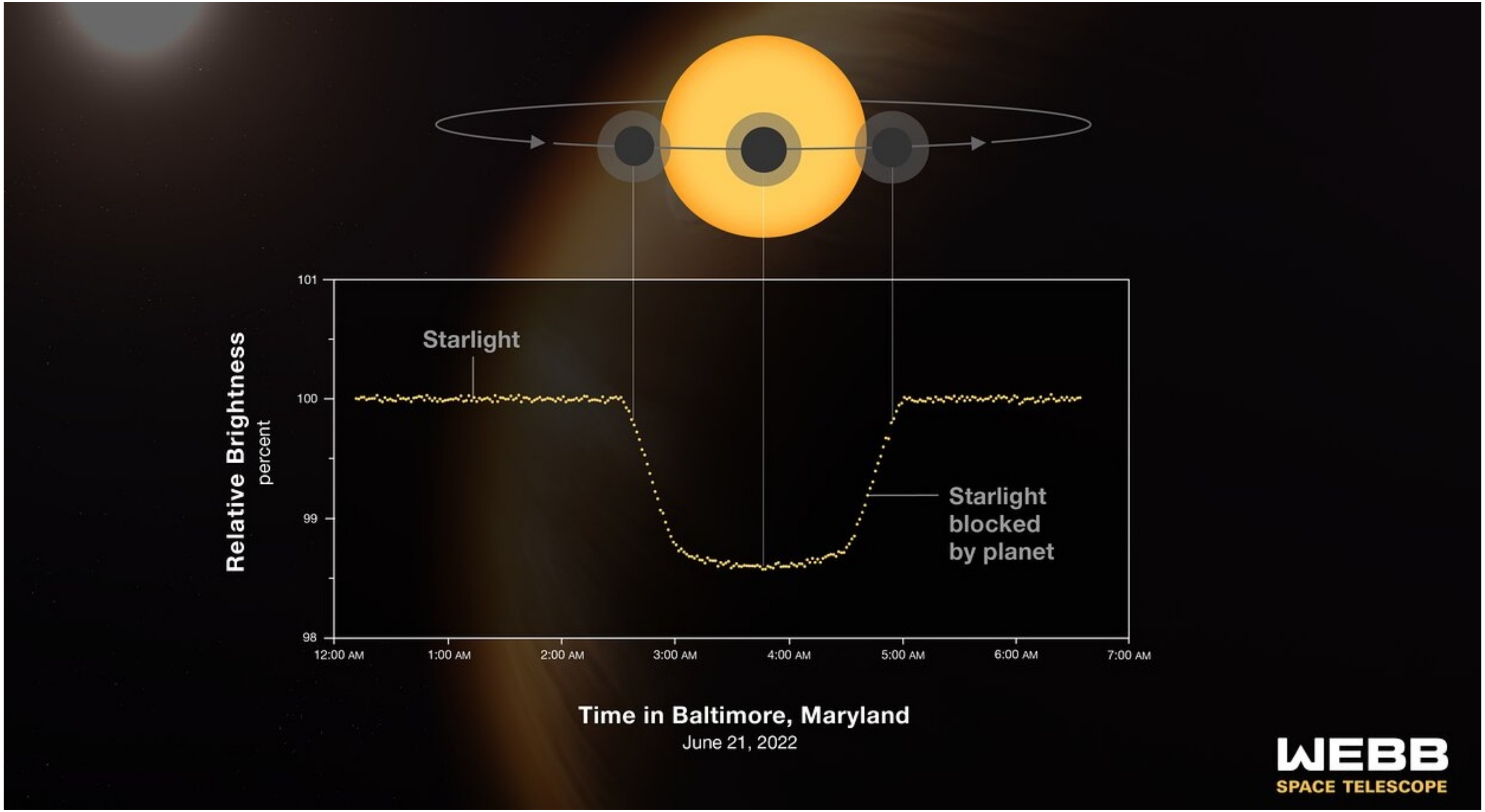


image credit: NASA, ESA, CSA, STScI, and the Webb ERO Production Team

Atmospheres and high-energy photons

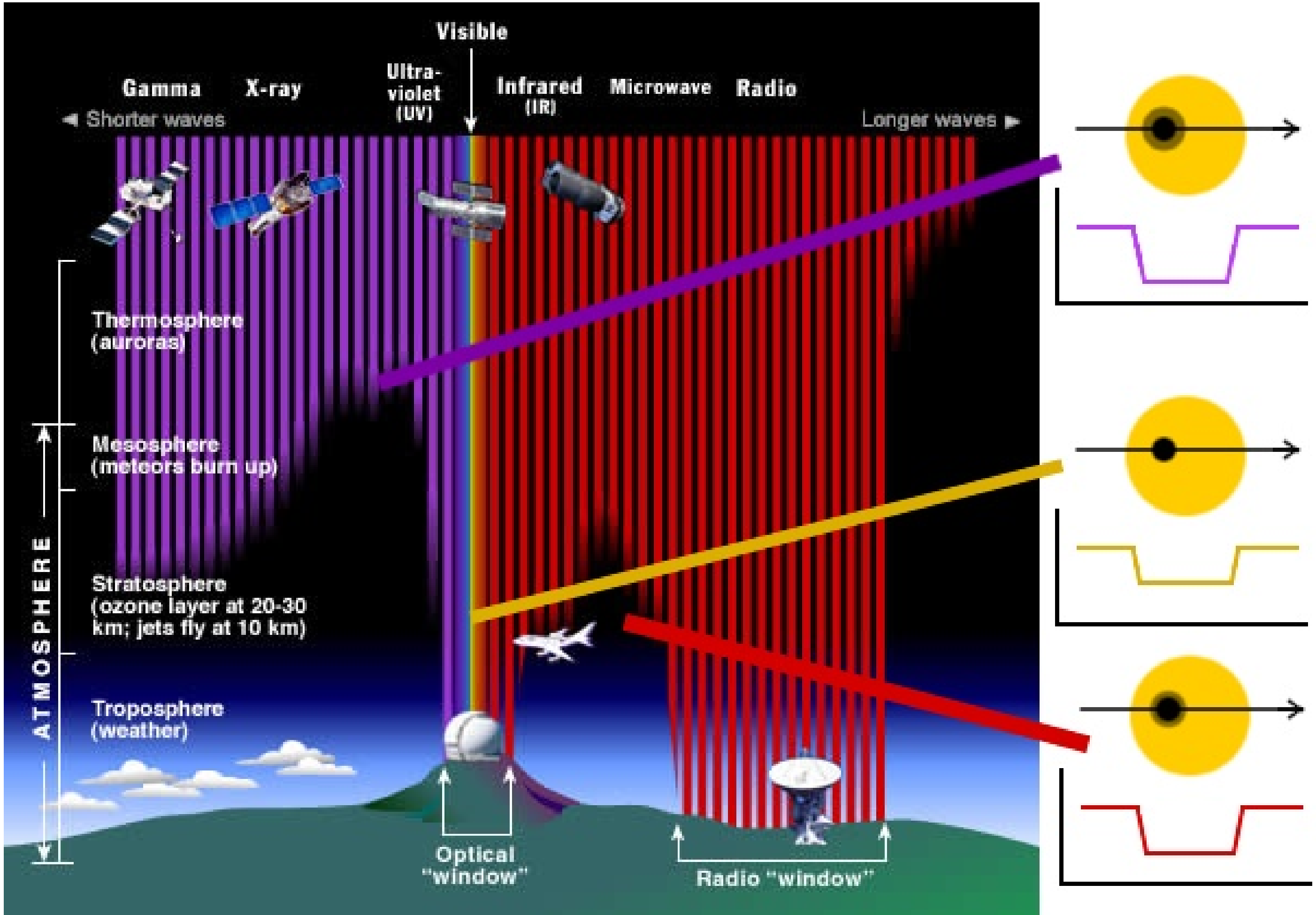
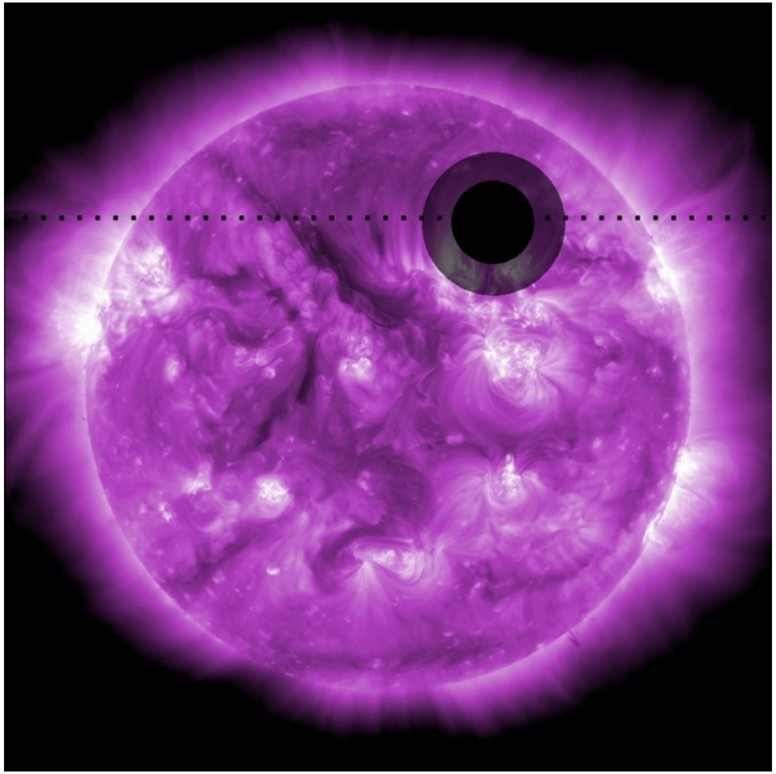
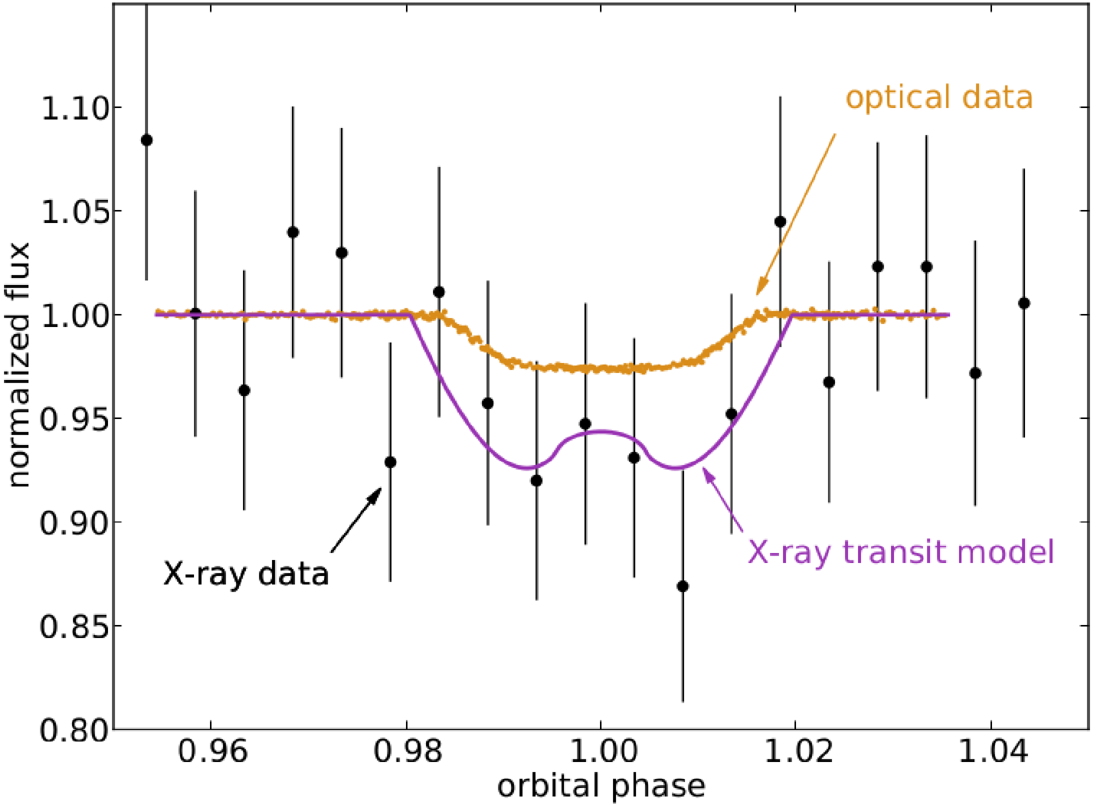


image credit: NASA

Extended atmospheres in X-rays

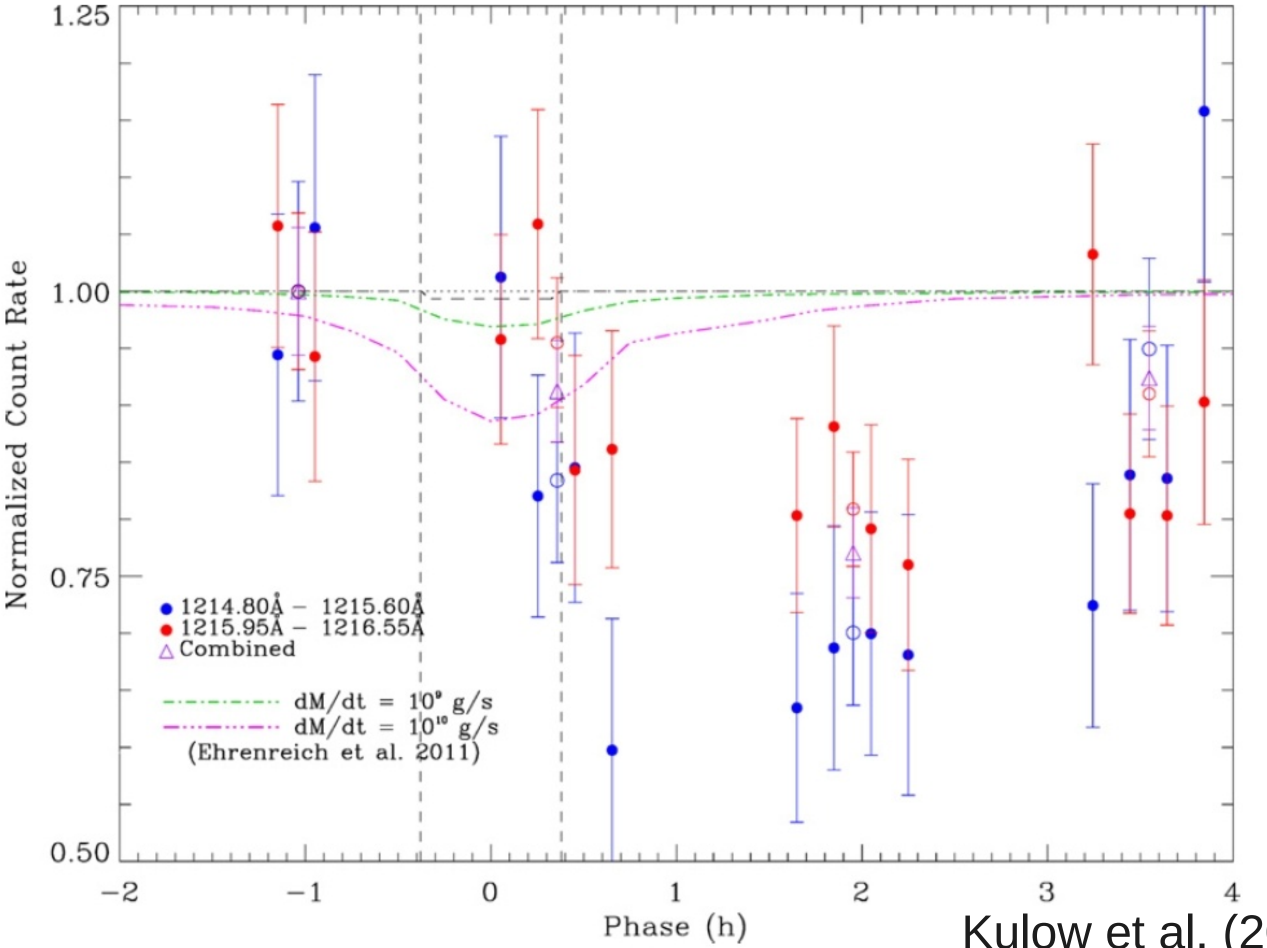


Hot Jupiter HD 189733 b



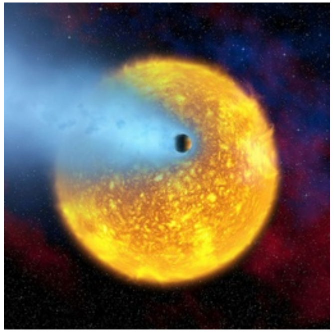
Poppenhaeger et al. (2013)

Extended atmospheres in UV



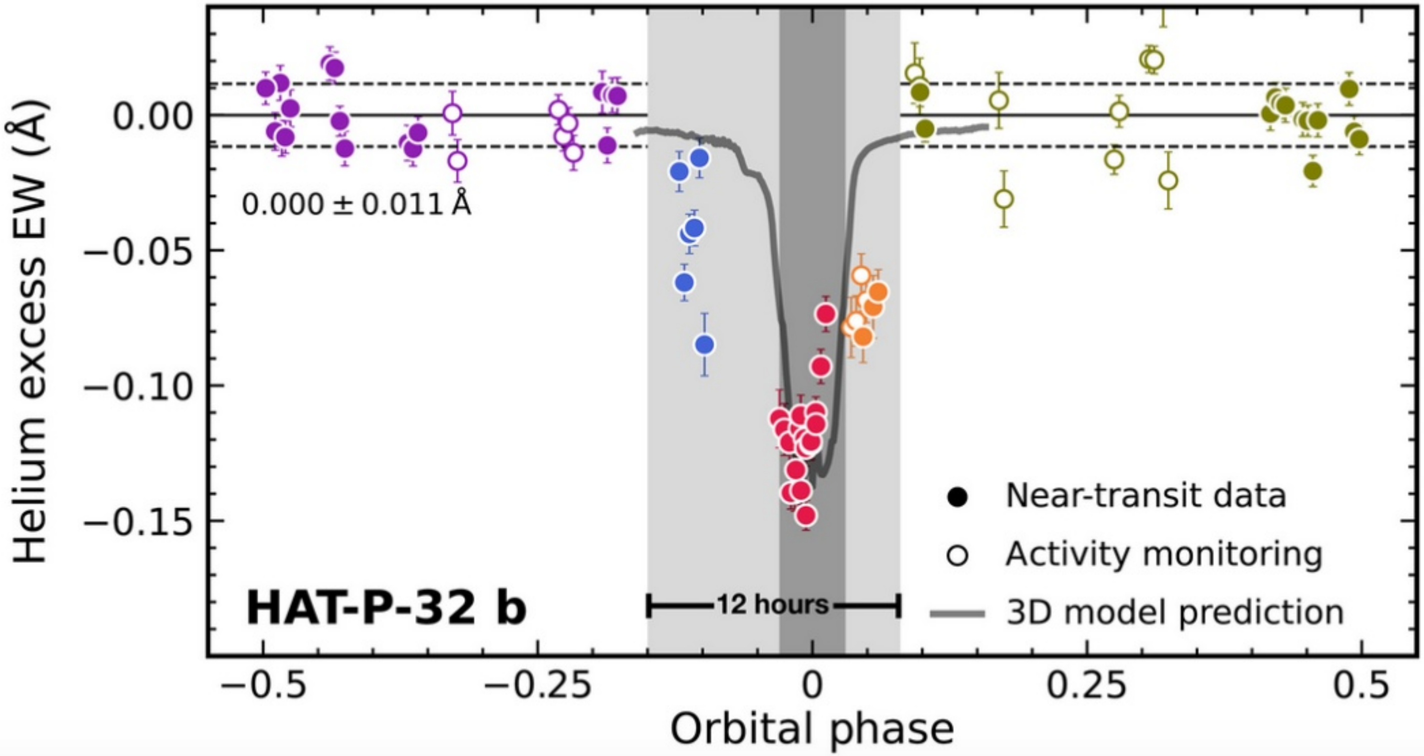
Hot Neptune GJ 436 b:

comet-like tail



Kulow et al. (2014), Ehrenreich et al. (2015)

Extended atmospheres in He 10380 (IR)



Hot Jupiter HAT-P-32 b: big tidal tails

Zhang, Morley et al. (2023)

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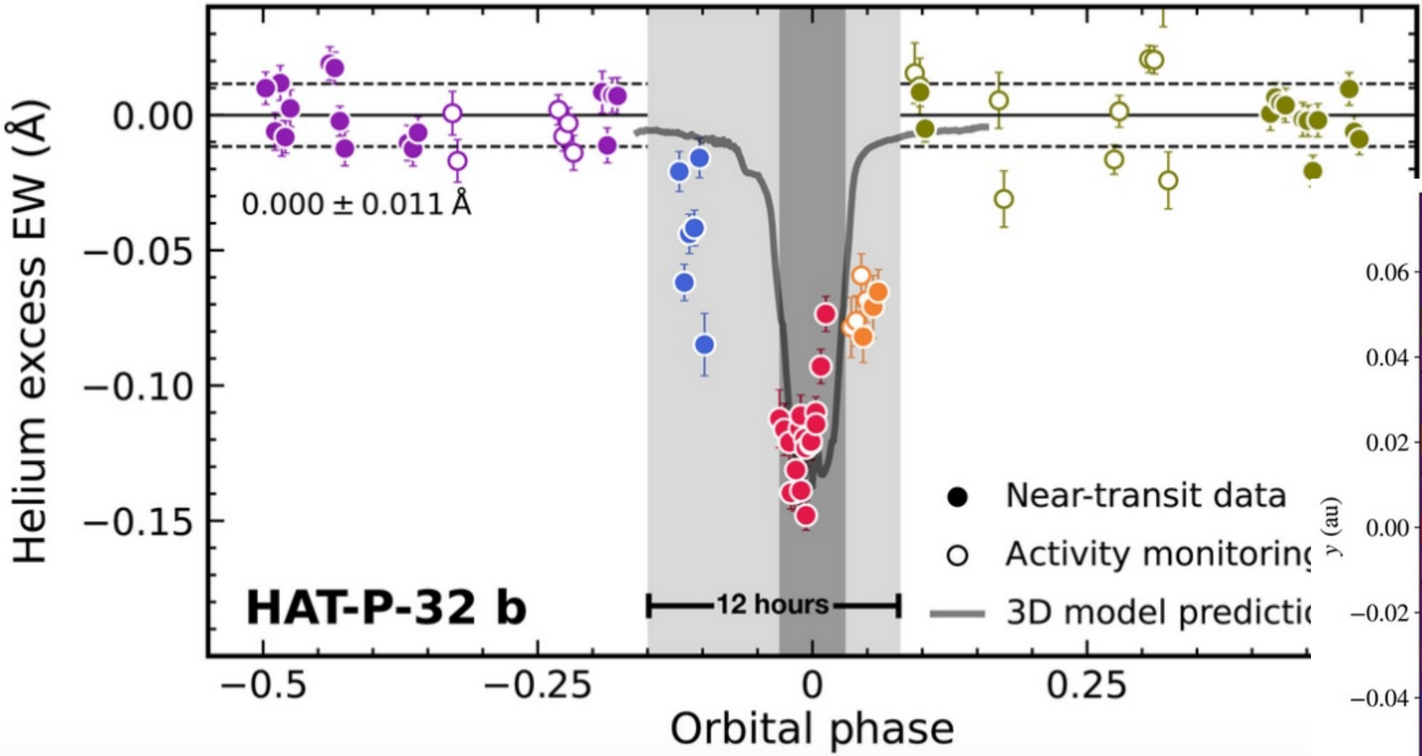

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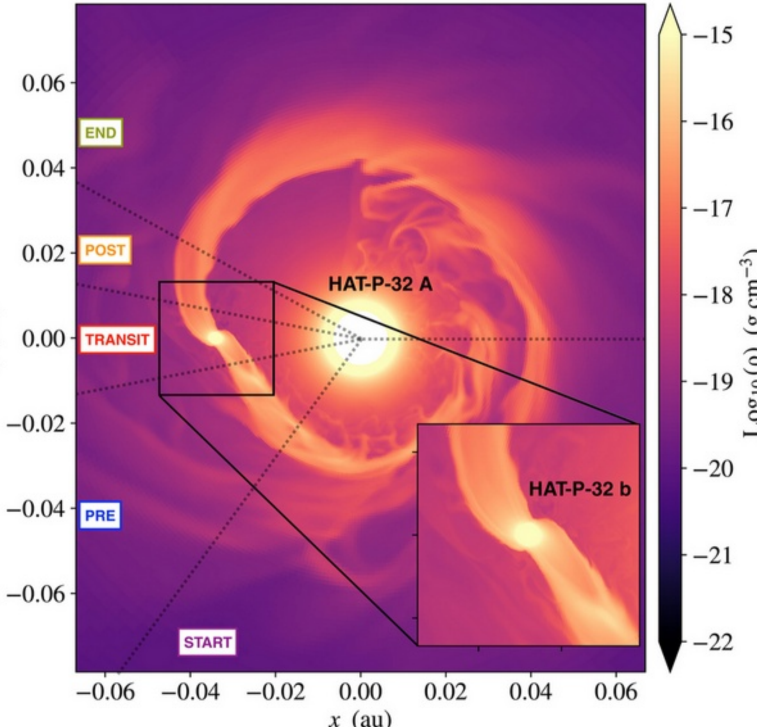
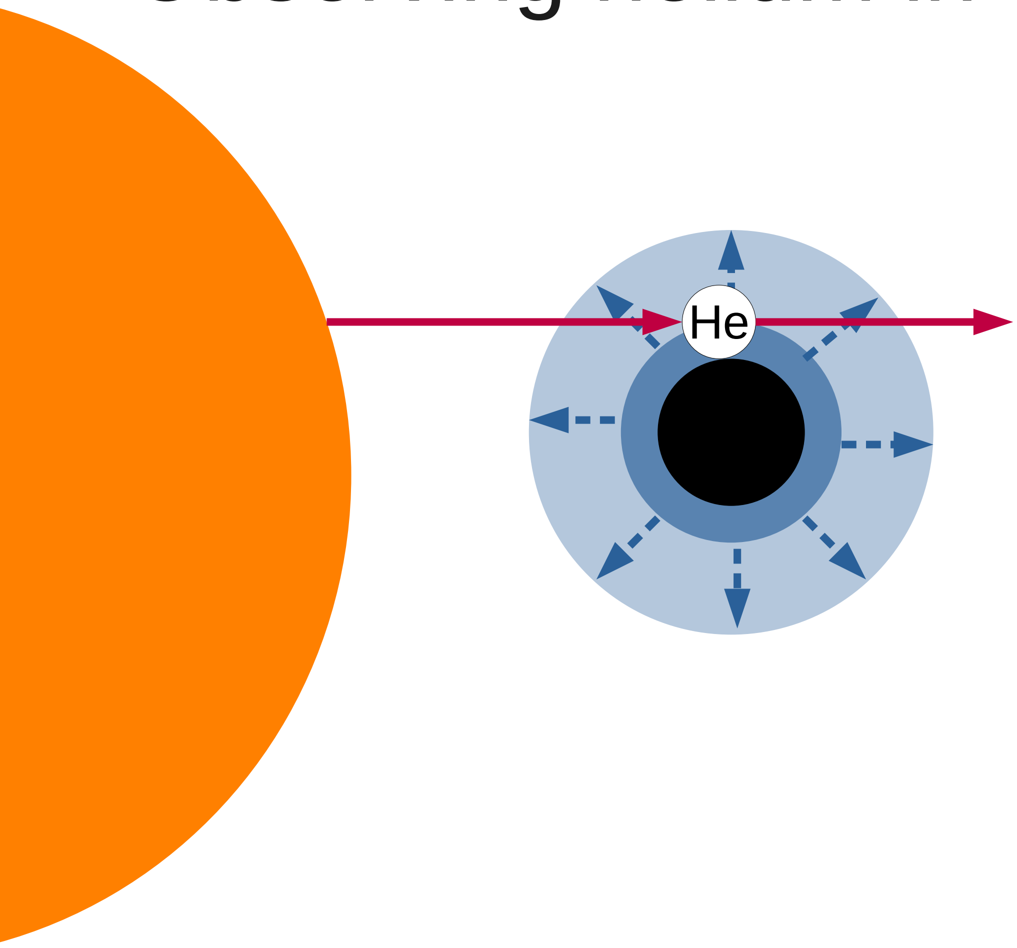


Zhang, Morley et al. (2023)

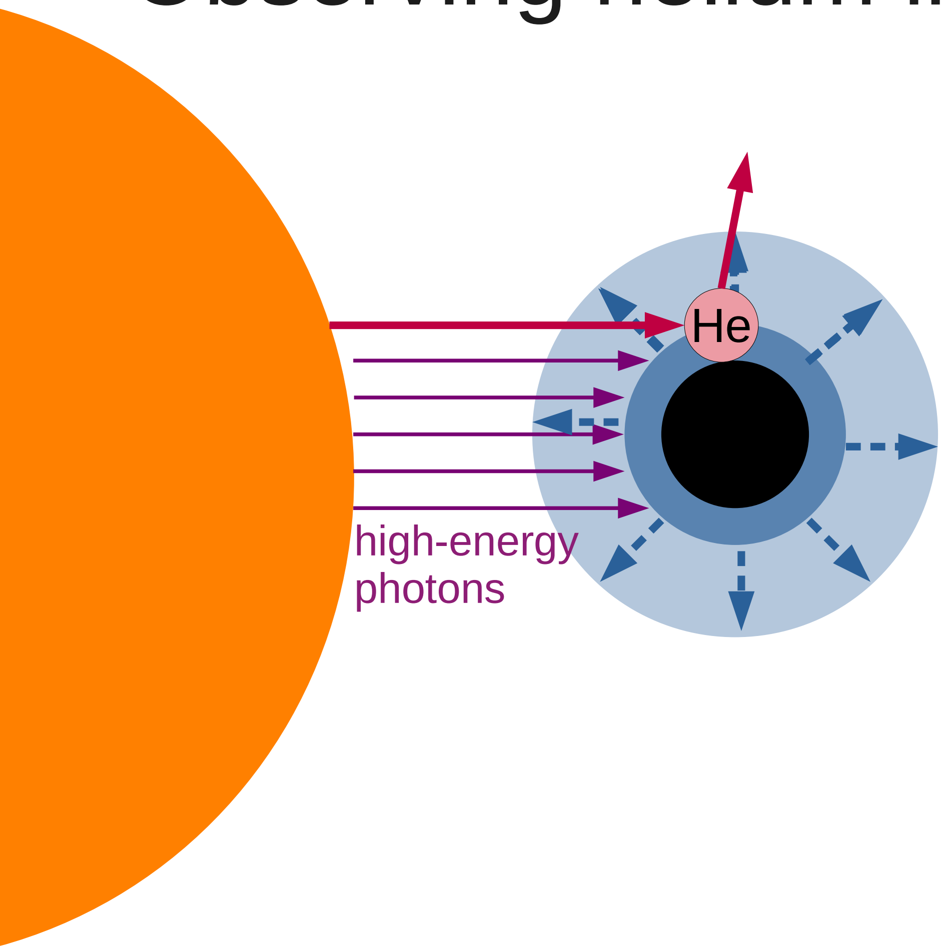
Observing helium in exoplanet atmospheres



Need to excite helium in exoplanet atmosphere first to make it absorb in infrared He lines (stellar high-energy photons make that happen!)

see Oklopcic & Hirata (2018)

Observing helium in exoplanet atmospheres



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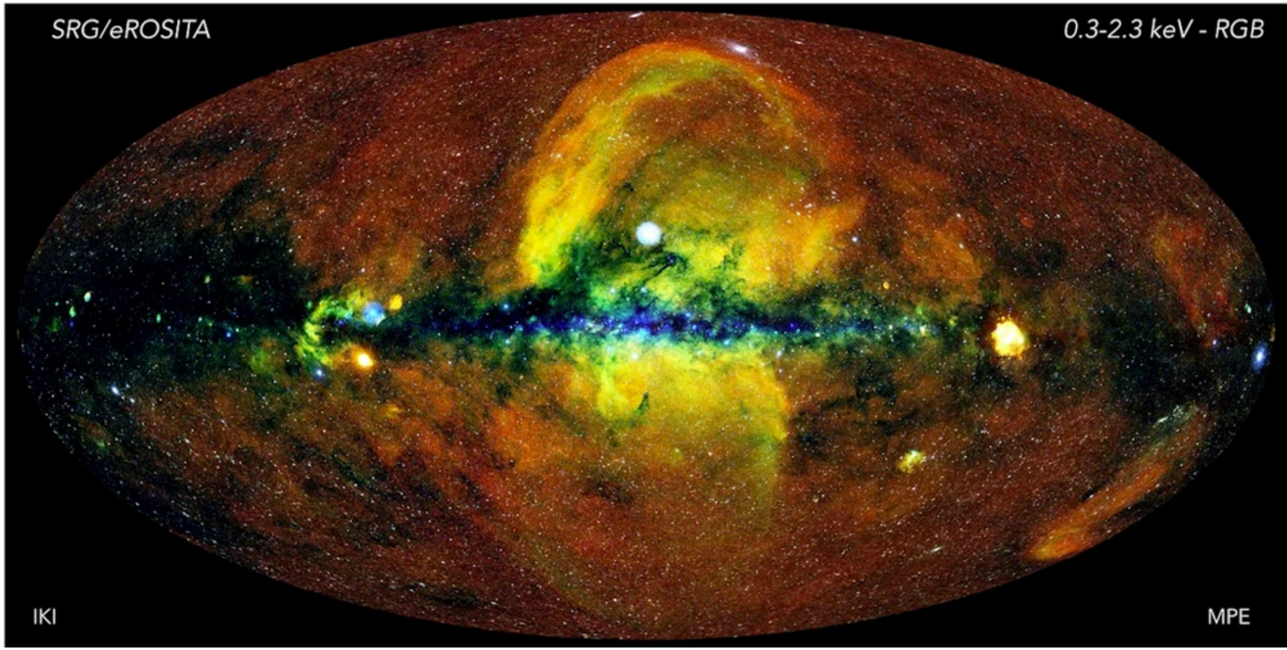
Estimating present-day X-ray irradiation of planets

eROSITA X-ray survey: many new X-ray detections of exoplanet host stars

→ allows mass-loss estimates for planets

→ identify best candidates to study ongoing evaporation



see Foster, Poppenhaeger et al. (2022)

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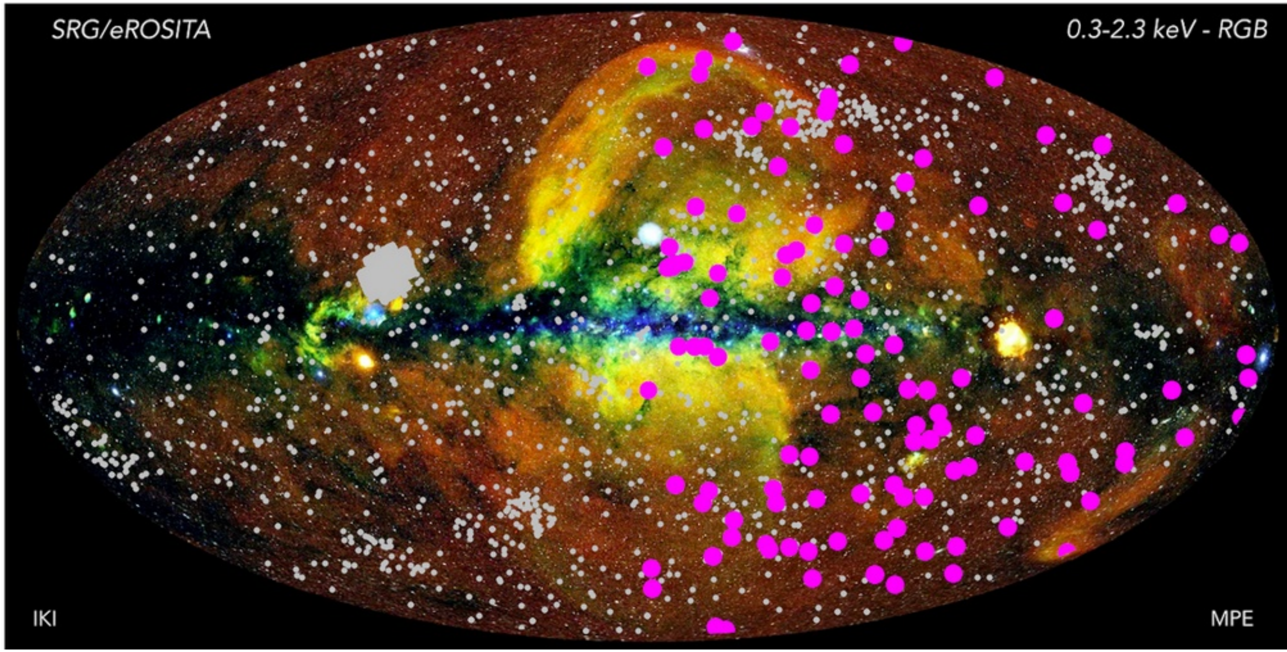
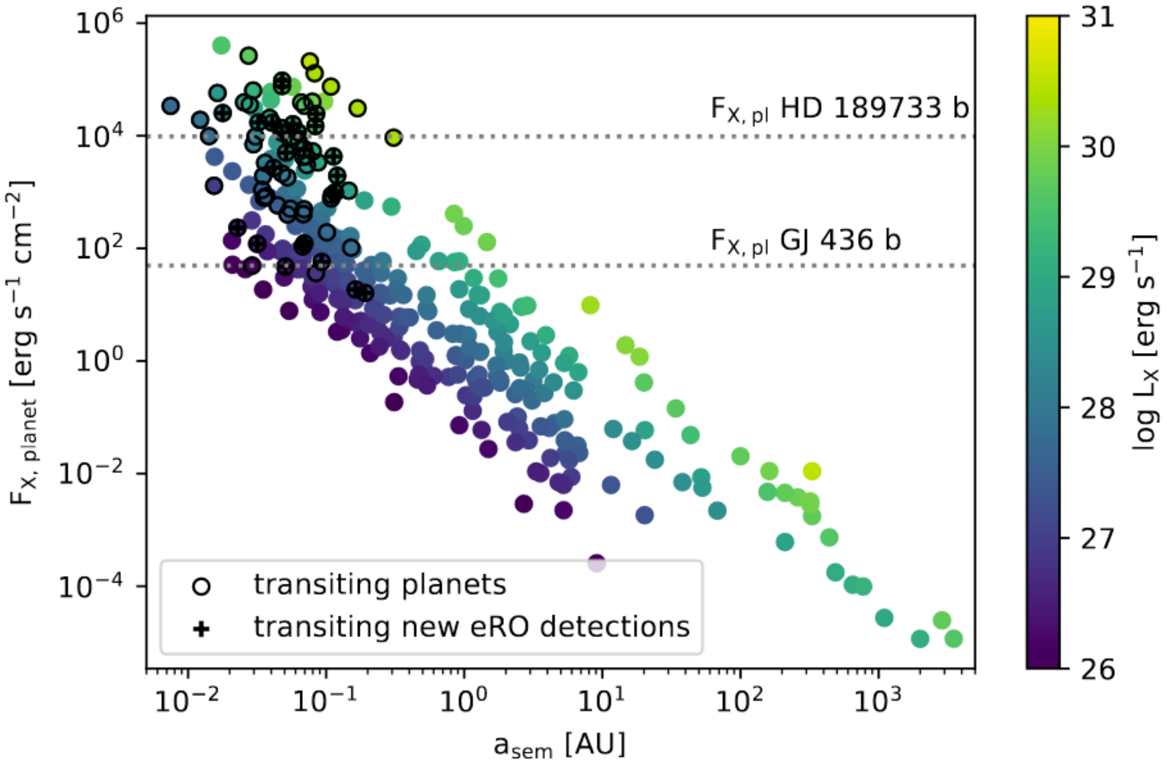


see Foster, Poppenhaeger et al. (2022)

Estimating present-day X-ray irradiation of planets

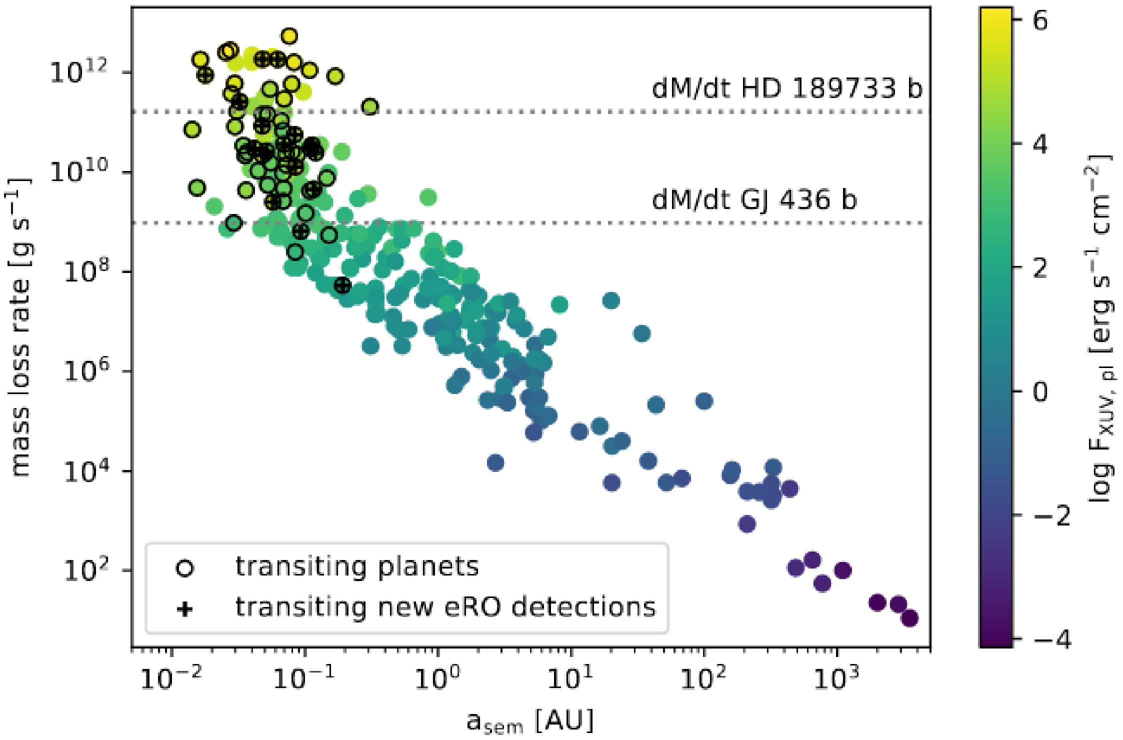
Many new exoplanets with high X-ray irradiation levels, suitable for follow-up observations of atmospheres at other wavelengths.



Foster, Poppenhaeger et al. (A&A 2022)

Estimating present-day X-ray irradiation of planets

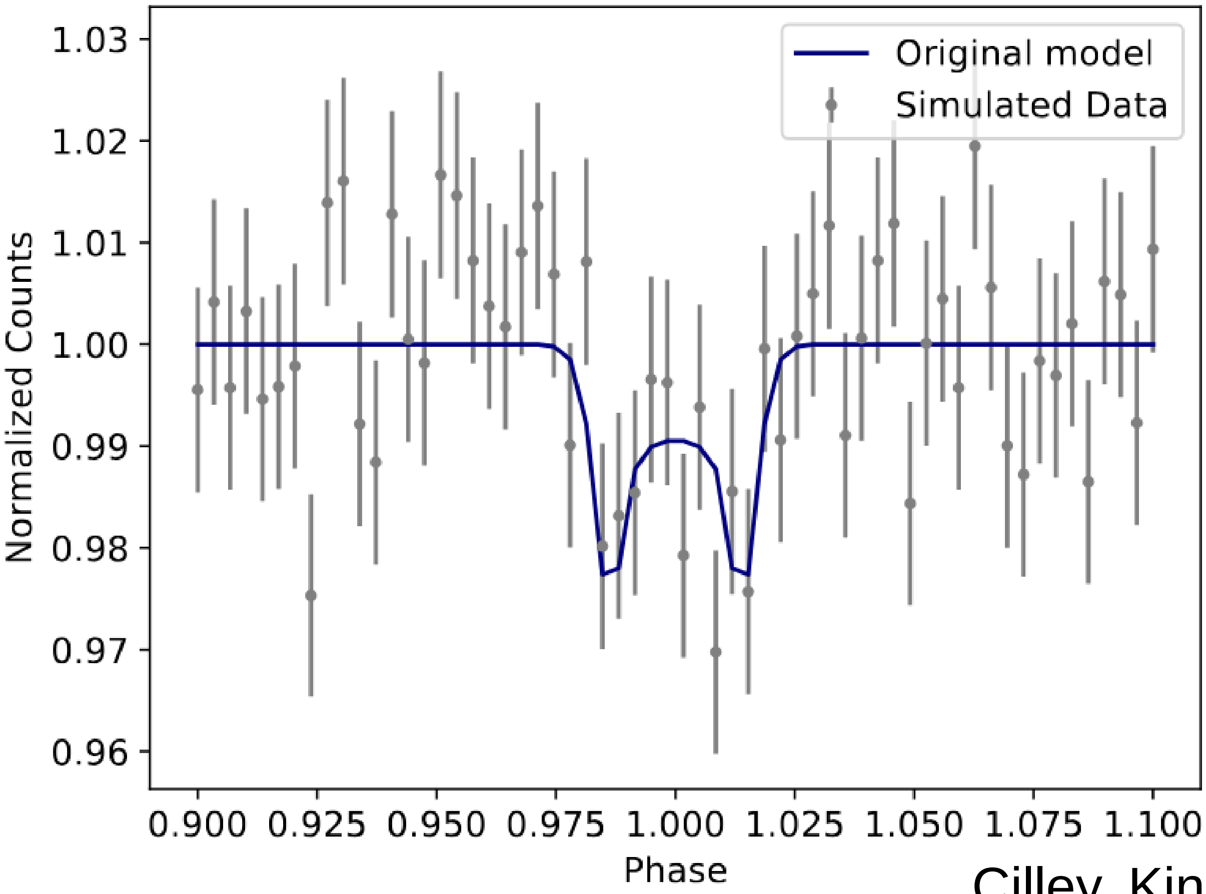
High mass loss rates expected from irradiation levels!



Foster, Poppenhaeger et al. (A&A 2022)

Exoplanet X-ray transits with NewAthena

transit depth 2.5%



Cilley, King & Corrales (2024)

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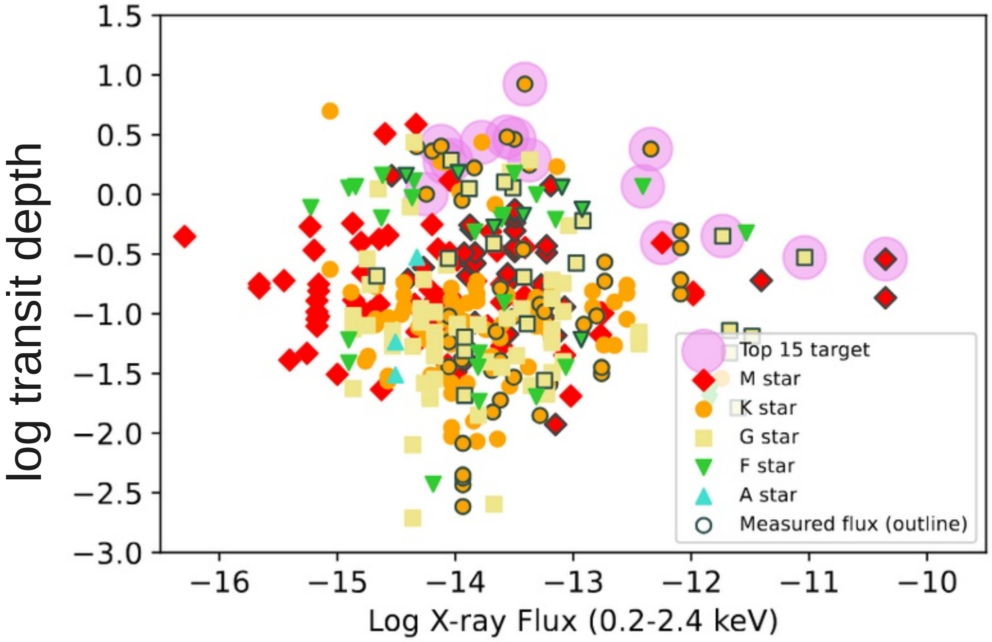
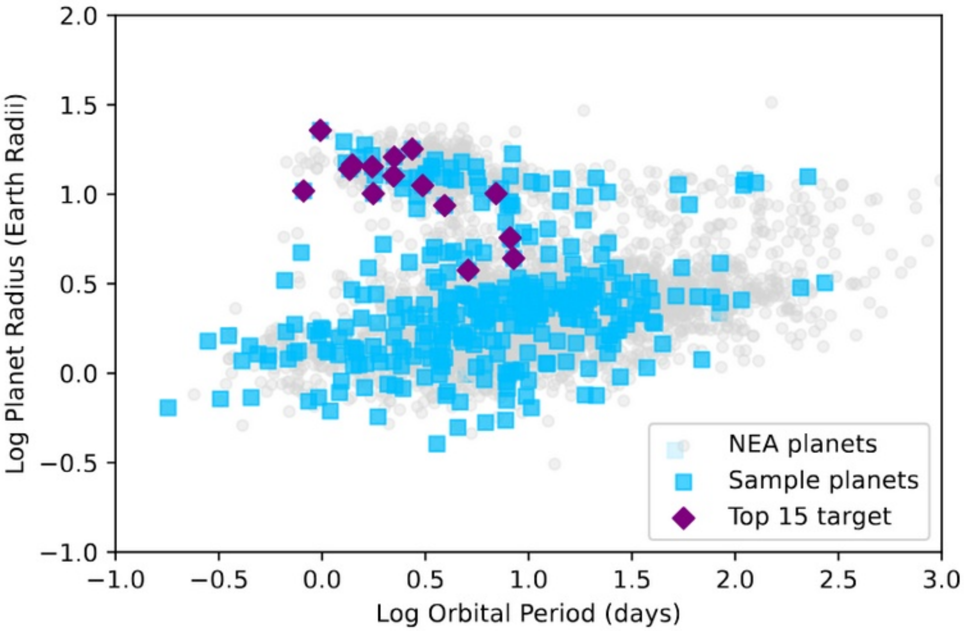
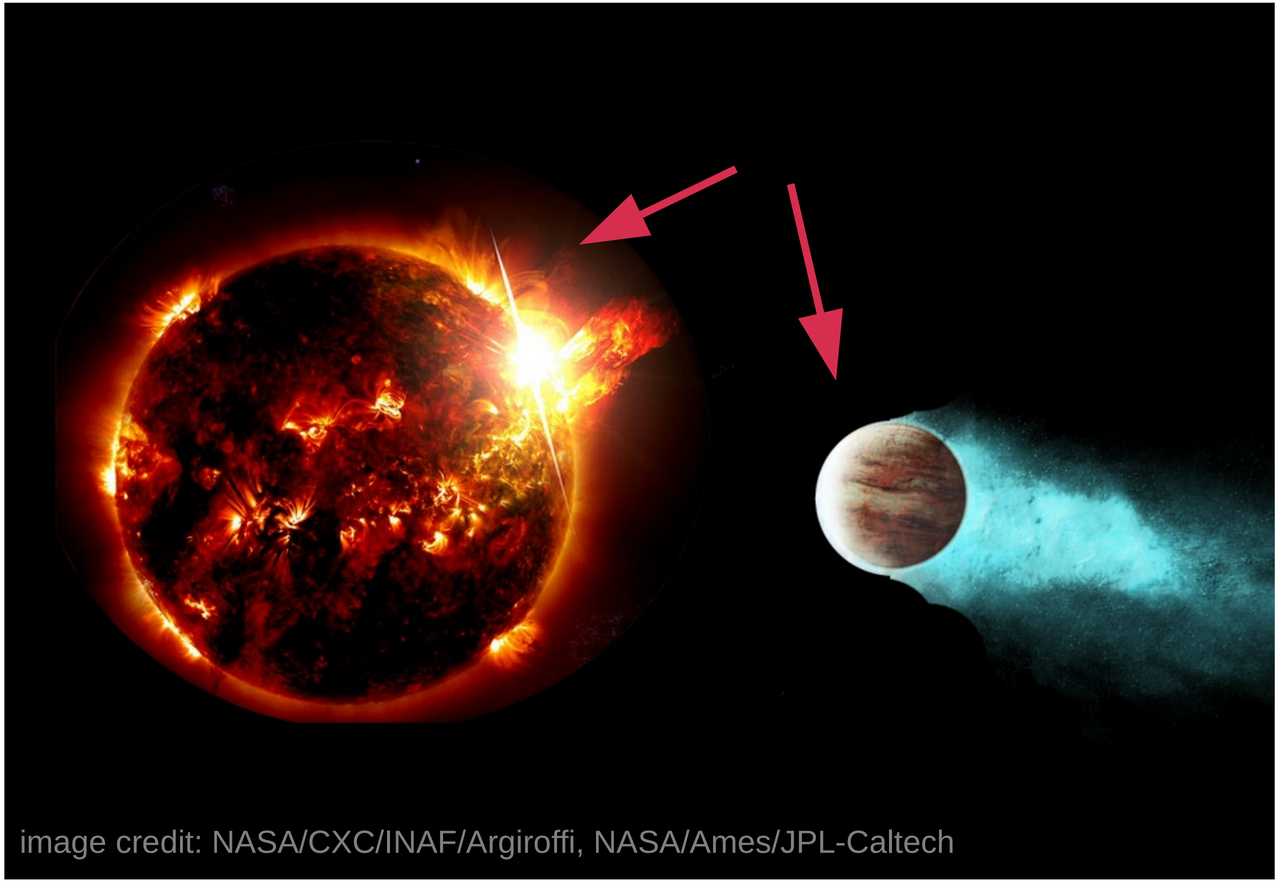


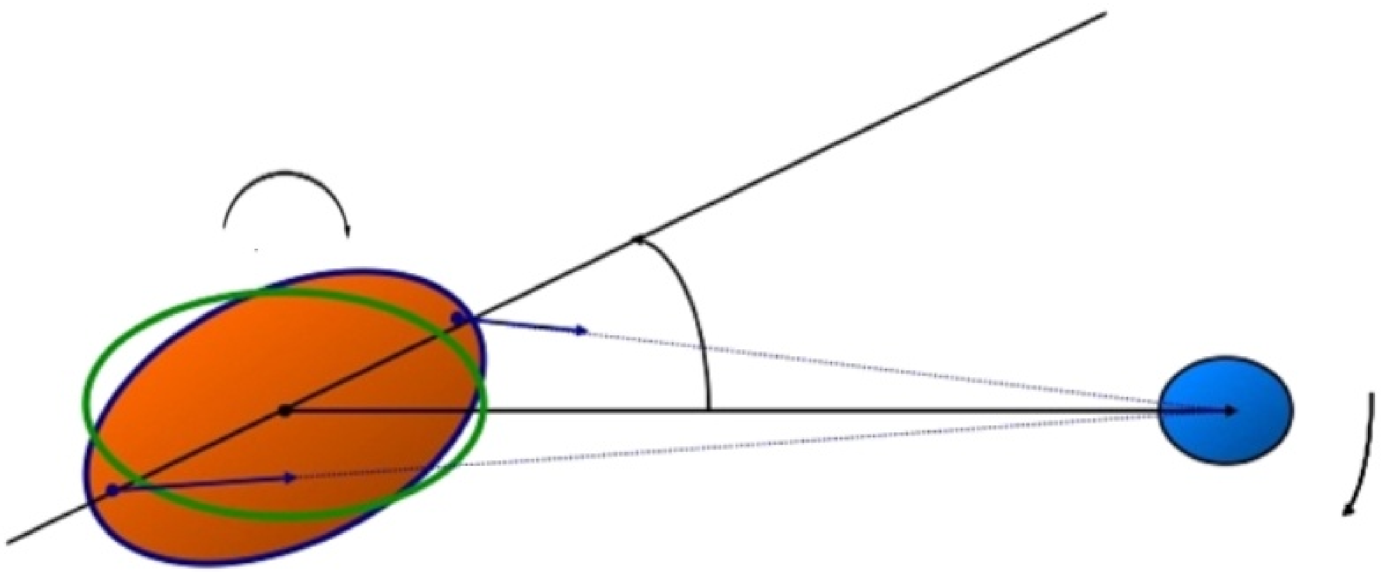


Cilley, King & Corrales (2024)

Star-planet interactions
changing stellar X-ray properties

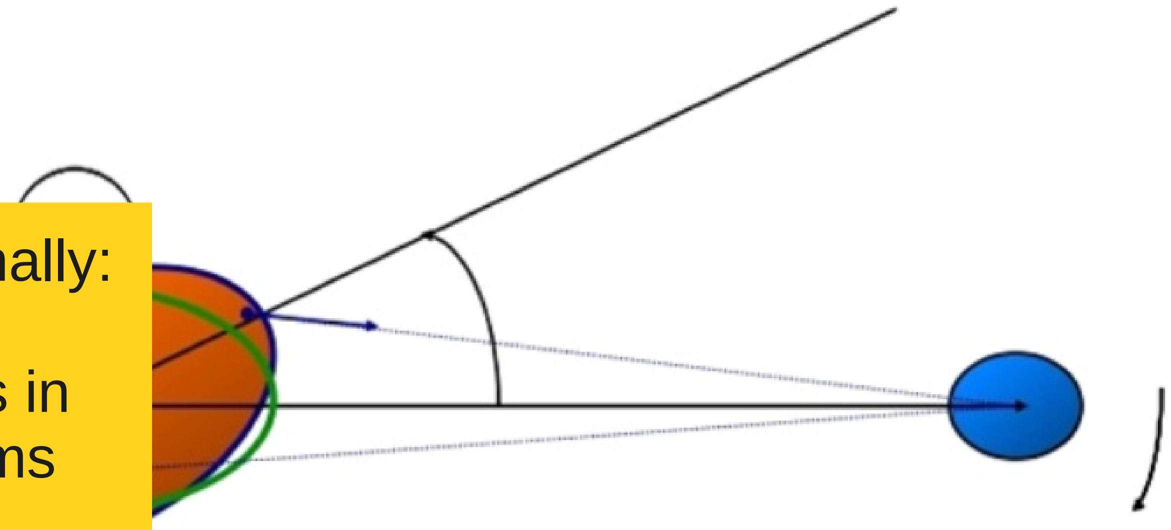


Tidal star-planet interaction



Mathias & Remus (2013), see also
Lanza & Mathis (2016)

Tidal star-planet interaction



Testable observationally:

planet-hosting stars in wide binary systems

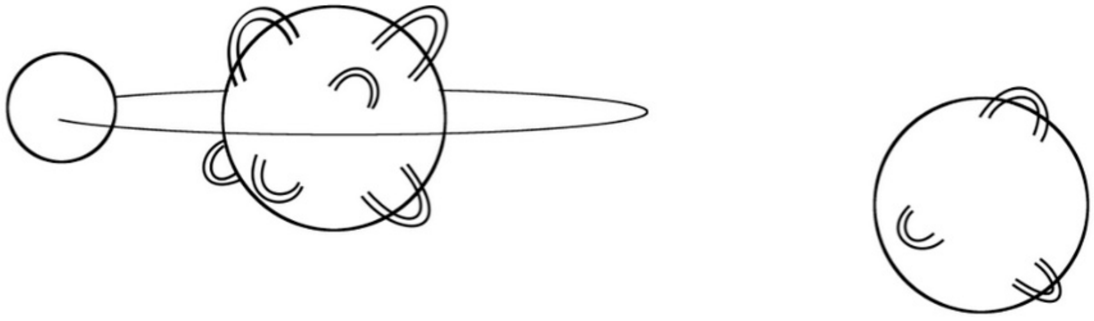
discrepancies in rotation & activity evolution

Poppenhaeger & Wolk (2014)

Wide binaries with exoplanets

Do stars with Hot Jupiters have higher activity than their co-eval stellar companions?

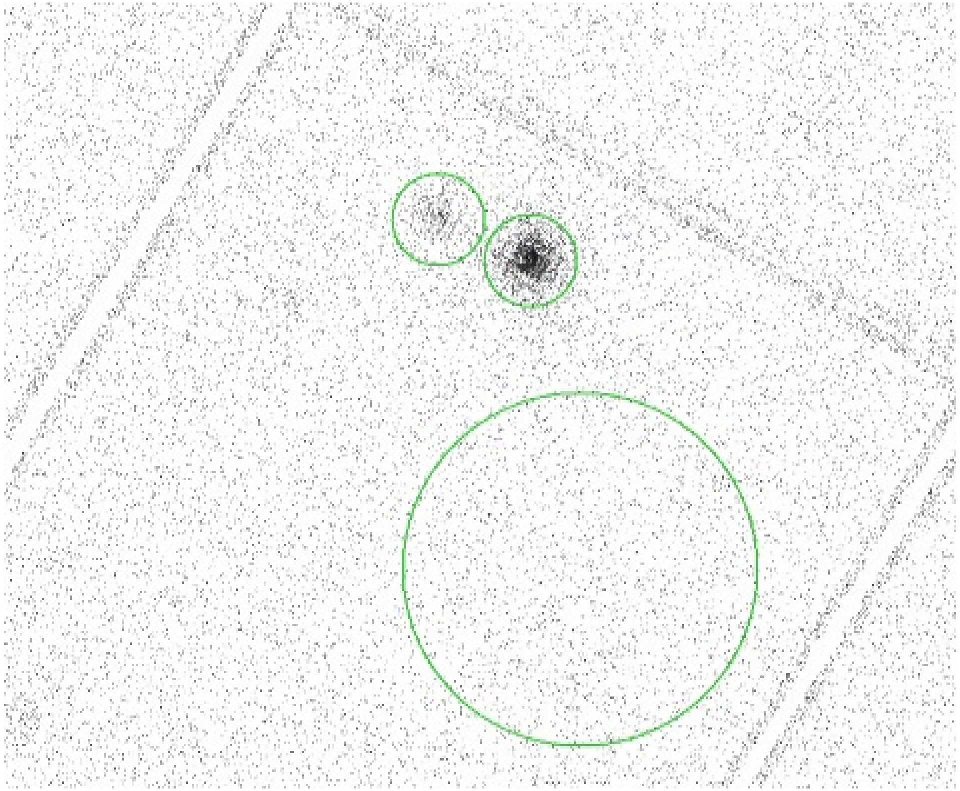
Tidal interaction -> spin up of host star?



Wide binaries with exoplanets

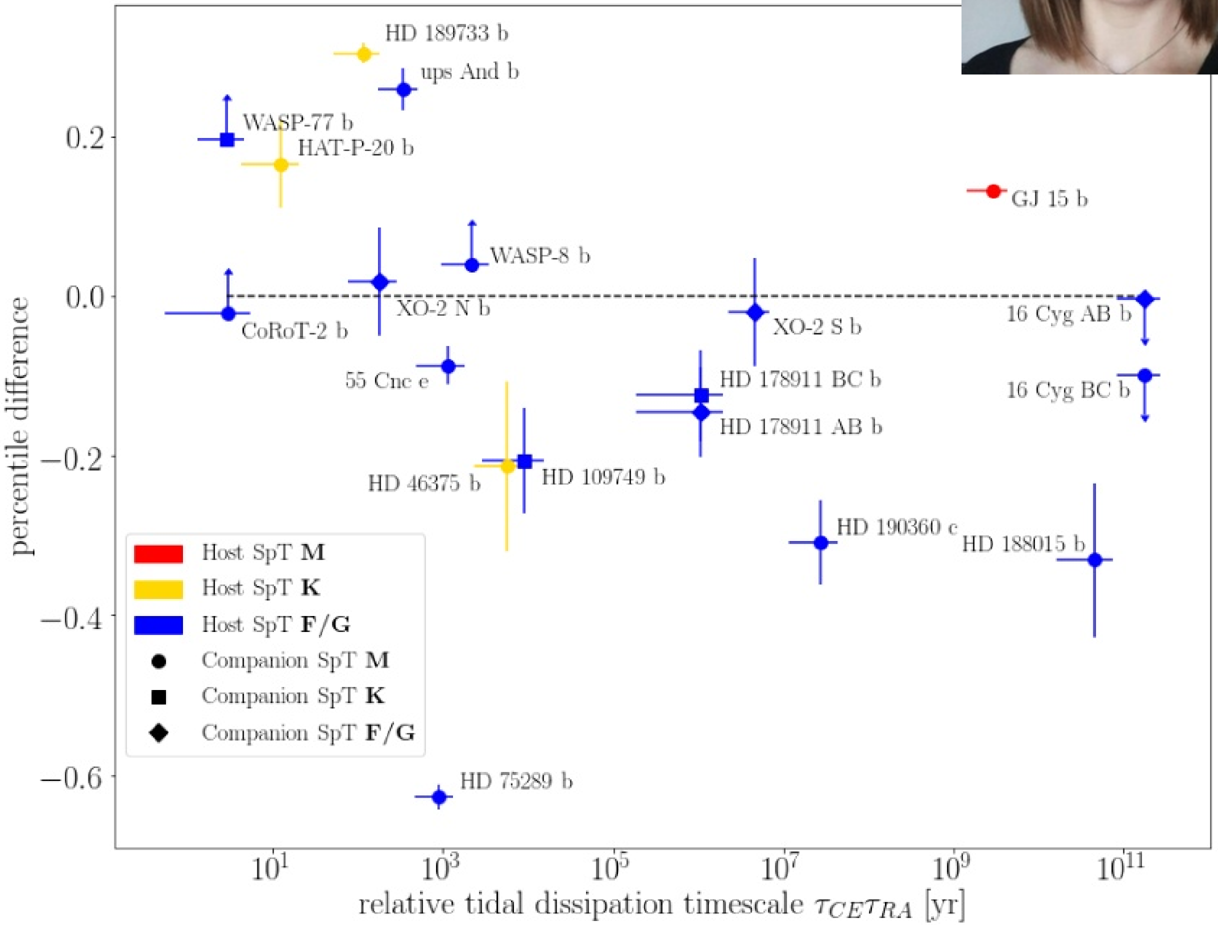
Test with X-ray observations of wide stellar binaries.

-> 20 suitable systems observed with XMM and Chandra.



Wide binaries with exoplanets

Stars with Hot Jupiters have higher X-ray activity than their same-age stellar companions at wide distances



Ilic, Poppenhaeger & Hosseini (2022)

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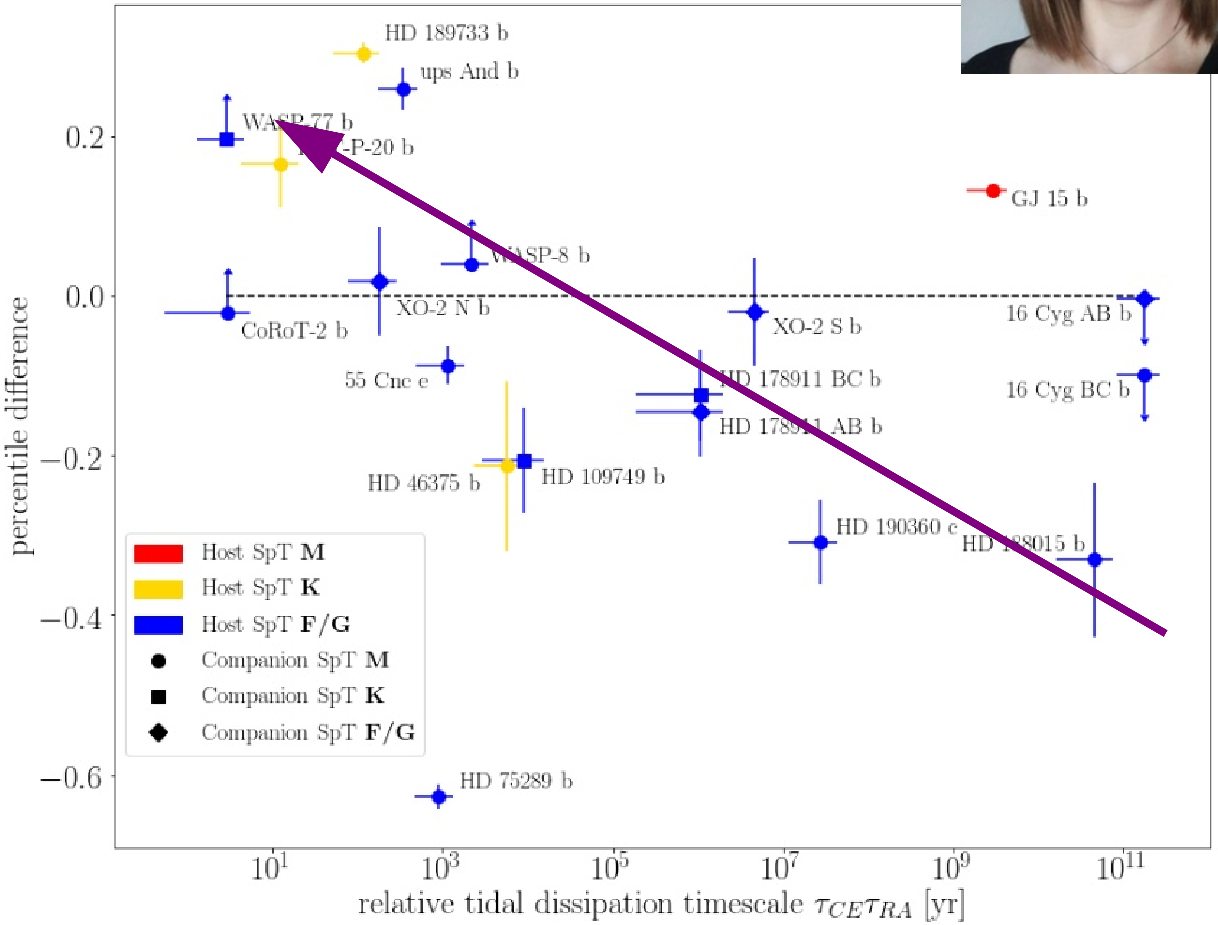
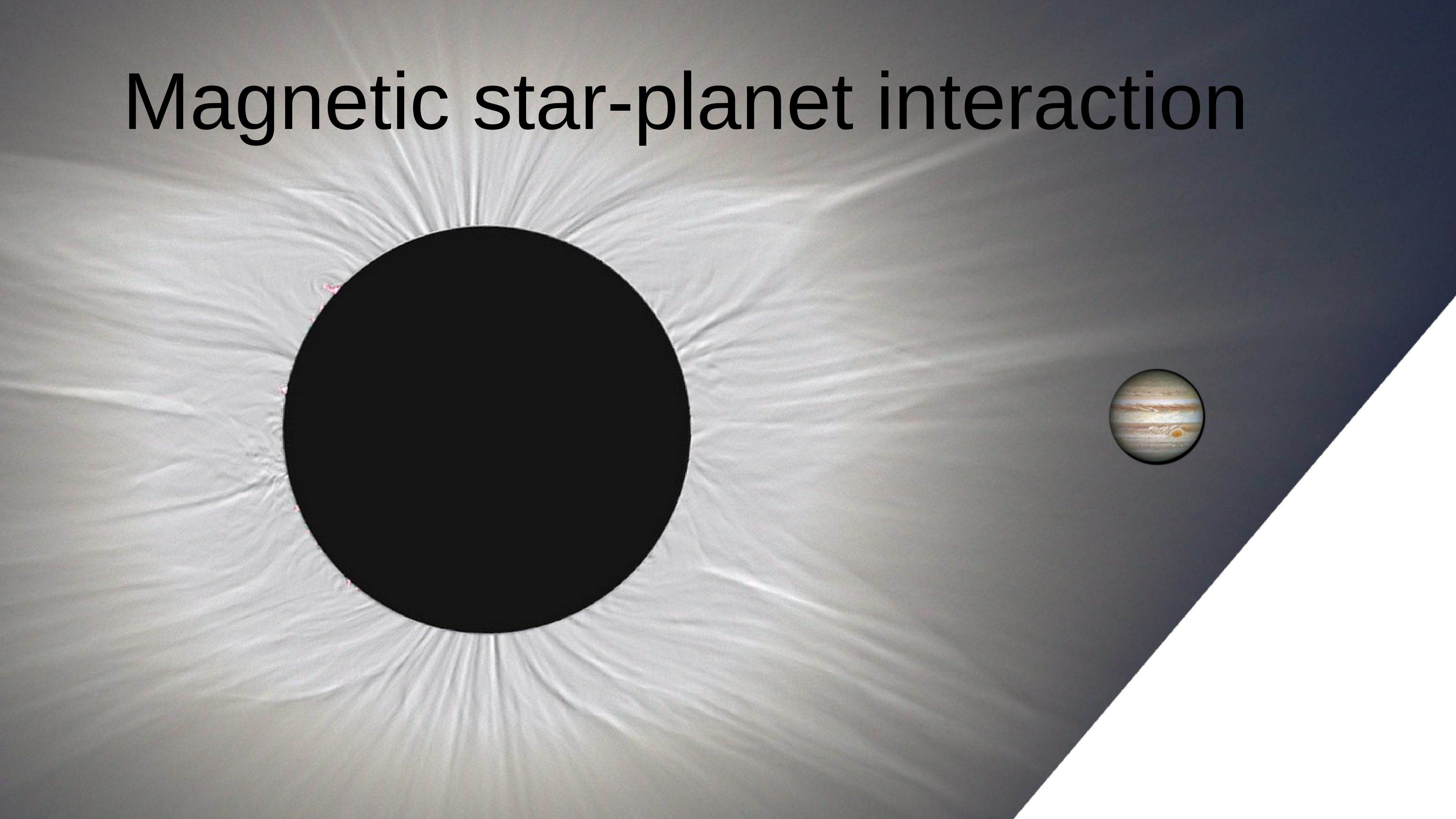


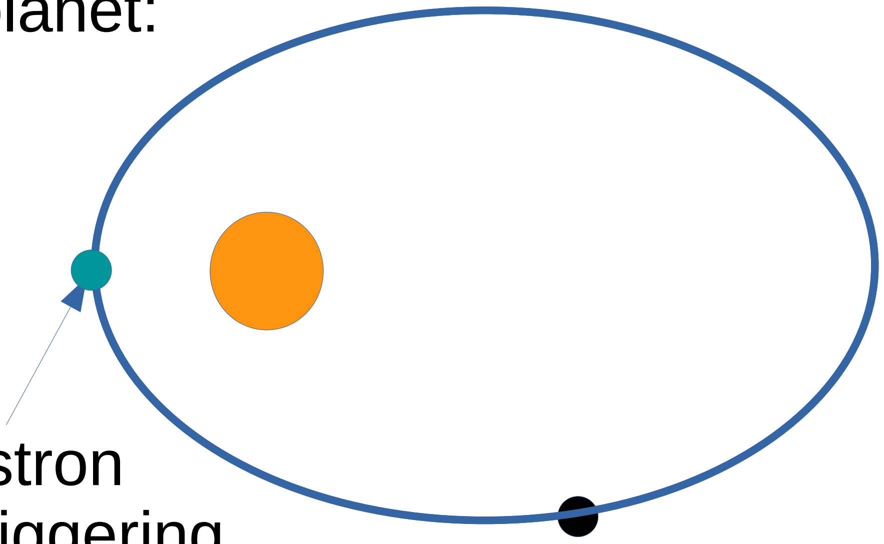
Ilic, Poppenhaeger & Hosseini (2022)

Magnetic star-planet interaction



Planets in eccentric orbits

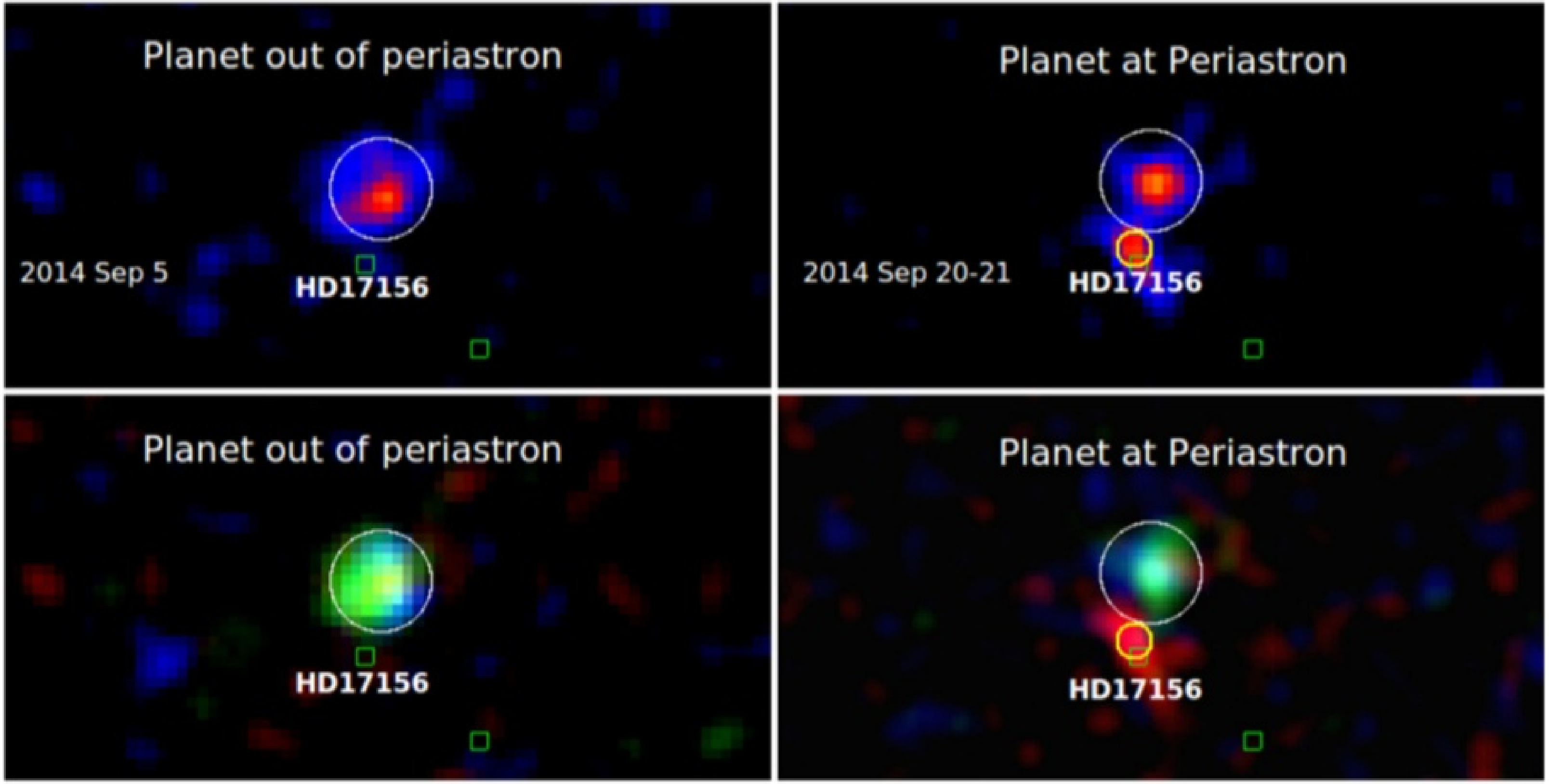
star + planet:



periastron
-> flare triggering

This should depend on
the planet's magnetosphere!

Planets in eccentric orbits

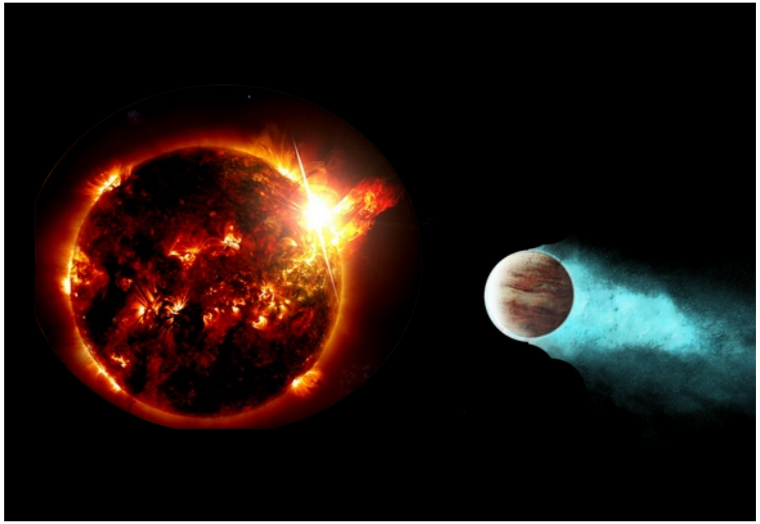


eccentric Jupiter HD 17156

Maggio et al. (2015)

X-ray prospects for star-planet systems in the NewAthena era

- Host stars:
  - characterize stellar X-ray spectra also for old, very low-mass M dwarfs
  - improve age-activity relationship where possible



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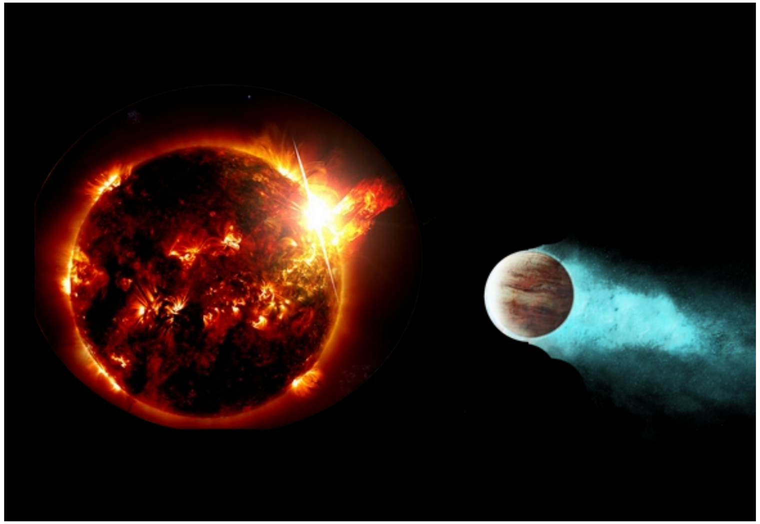

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- Exoplanets: measure transit depths in X-rays for representative sample of exoplanets, connect to evaporation processes
- Star-Planet Interactions (SPI):
  - quantify tidal SPI for different stellar masses and interior structures
  - identify whether SPI flare triggering is a ubiquitous phenomenon