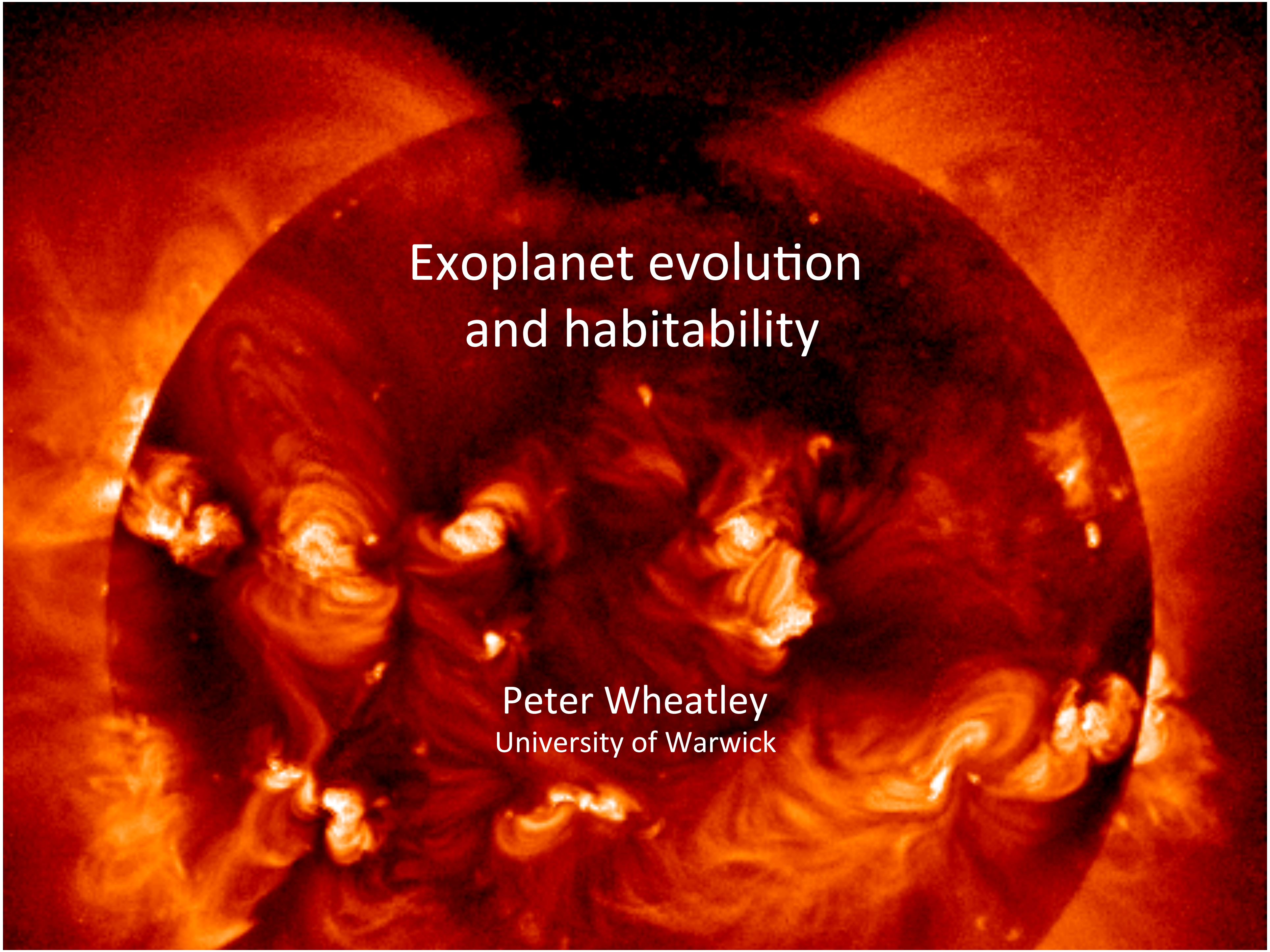


Exoplanet evolution and habitability

Peter Wheatley
University of Warwick

Radial velocity
discovery of 51 Peg b

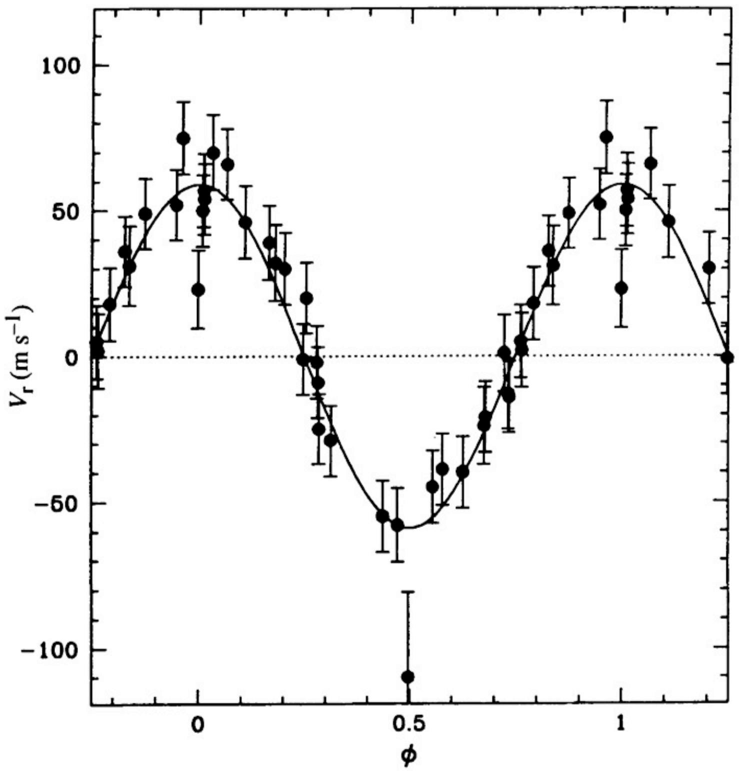
$M \sin i = 0.46\ M_J$
$a = 0.05$ au

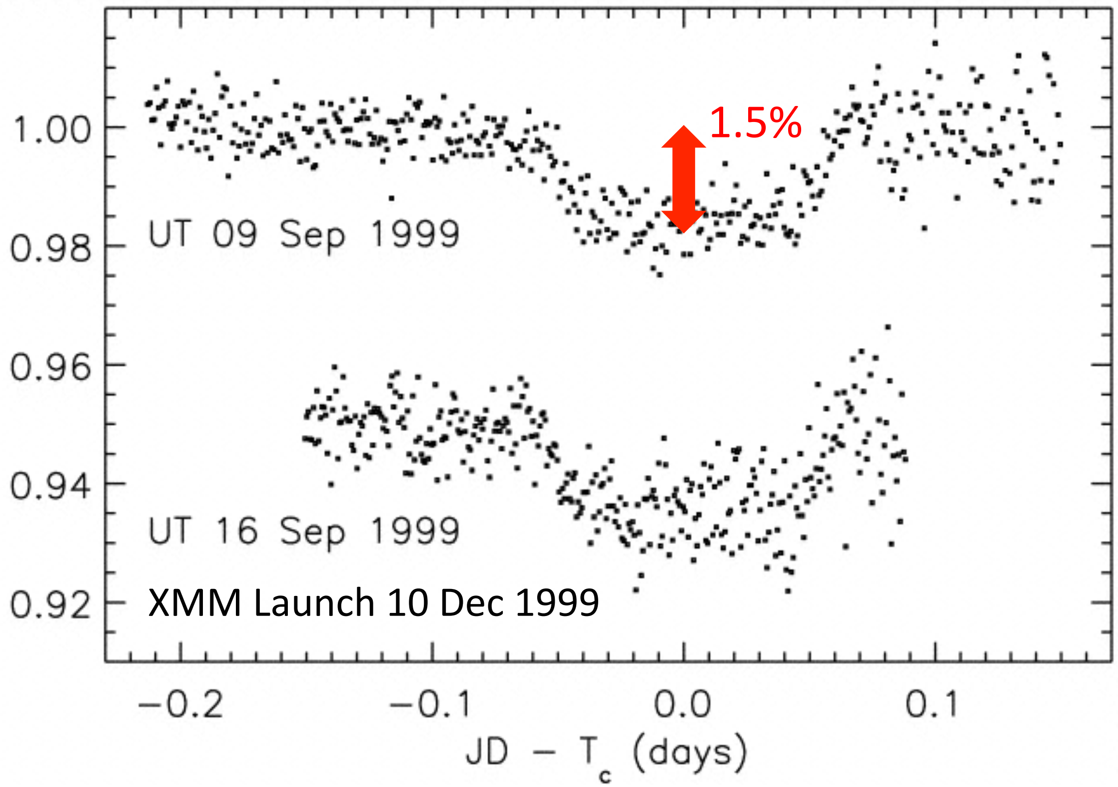
Mayor & Queloz 1995

Transits detected
for HD209458b

$M = 0.7\ M_J$
$a = 0.05$ au
$R = 1.4\ R_J$

Henry et al 2000
Charbonneau et al 2000





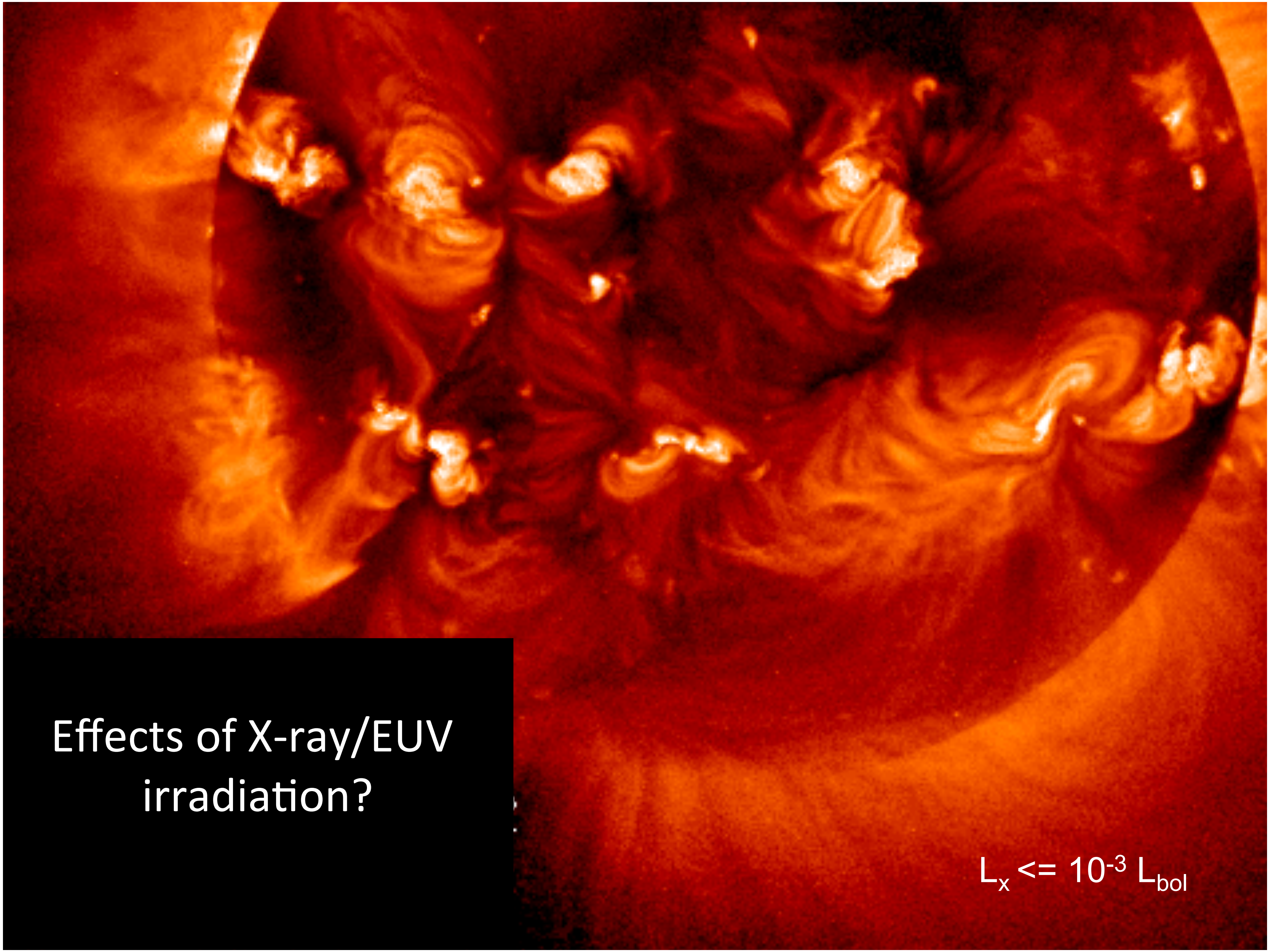
Star-Planet Interactions

- X-ray/EUV irradiation of planets
  - This talk

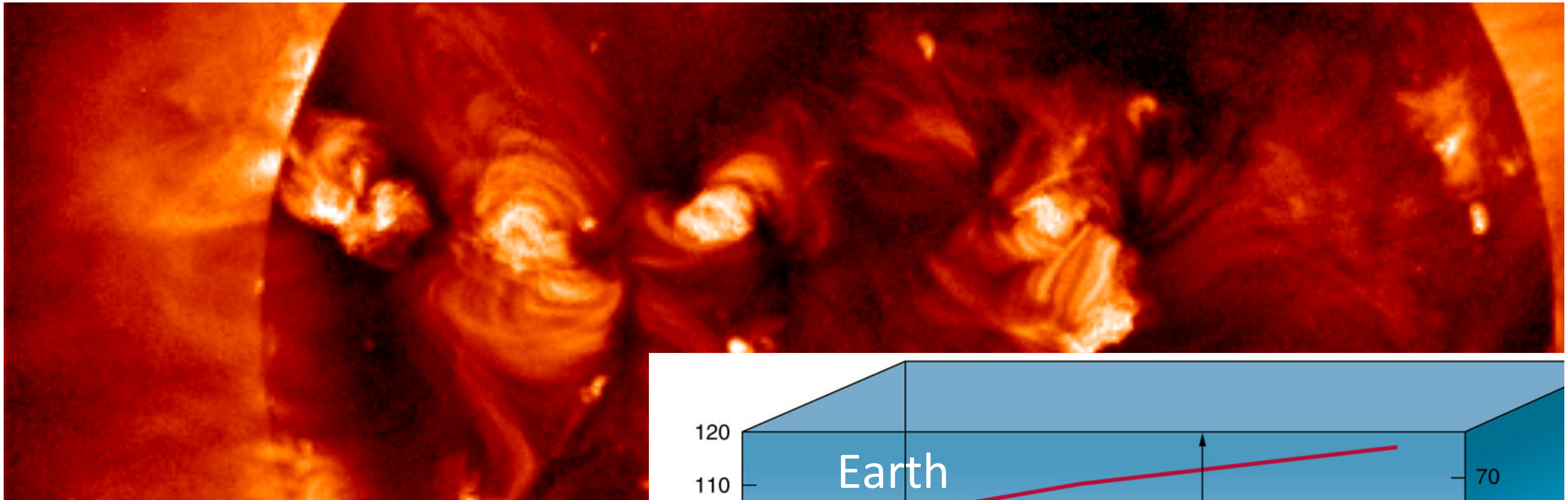
- Magnetic interactions, e.g.
  - Orbital modulation of activity indicators, Sholnik+03,05,08
  - Triggered flaring or accretion, Pillitteri+10,11, Maggio+15

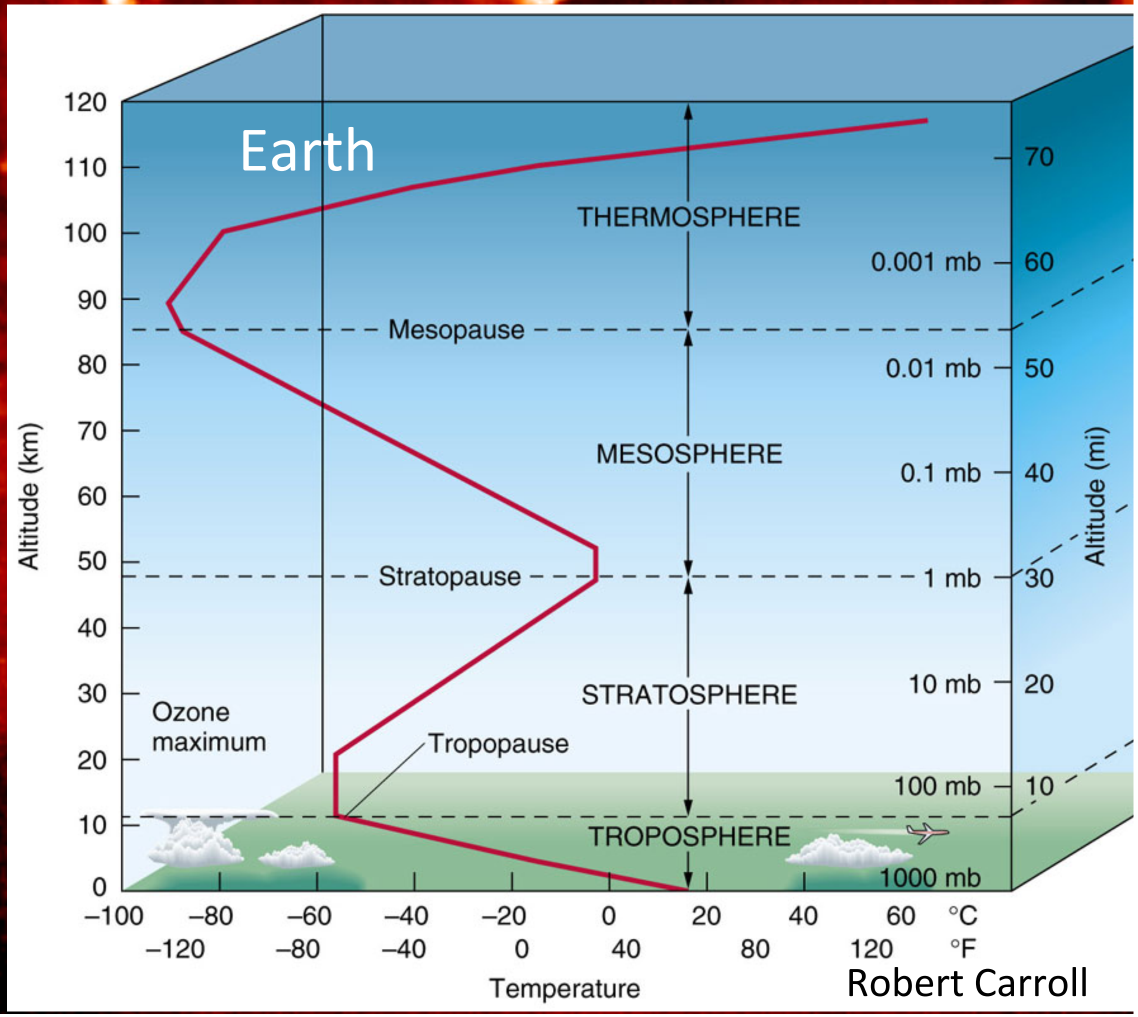
- Tidal interactions, e.g.
  - Enhancing X-ray emission, Poppenhaeger+14, Miller+15
  - Suppressing X-ray emission, Miller+12, Pillitteri+14

Talk by Antonio Maggio this afternoon…



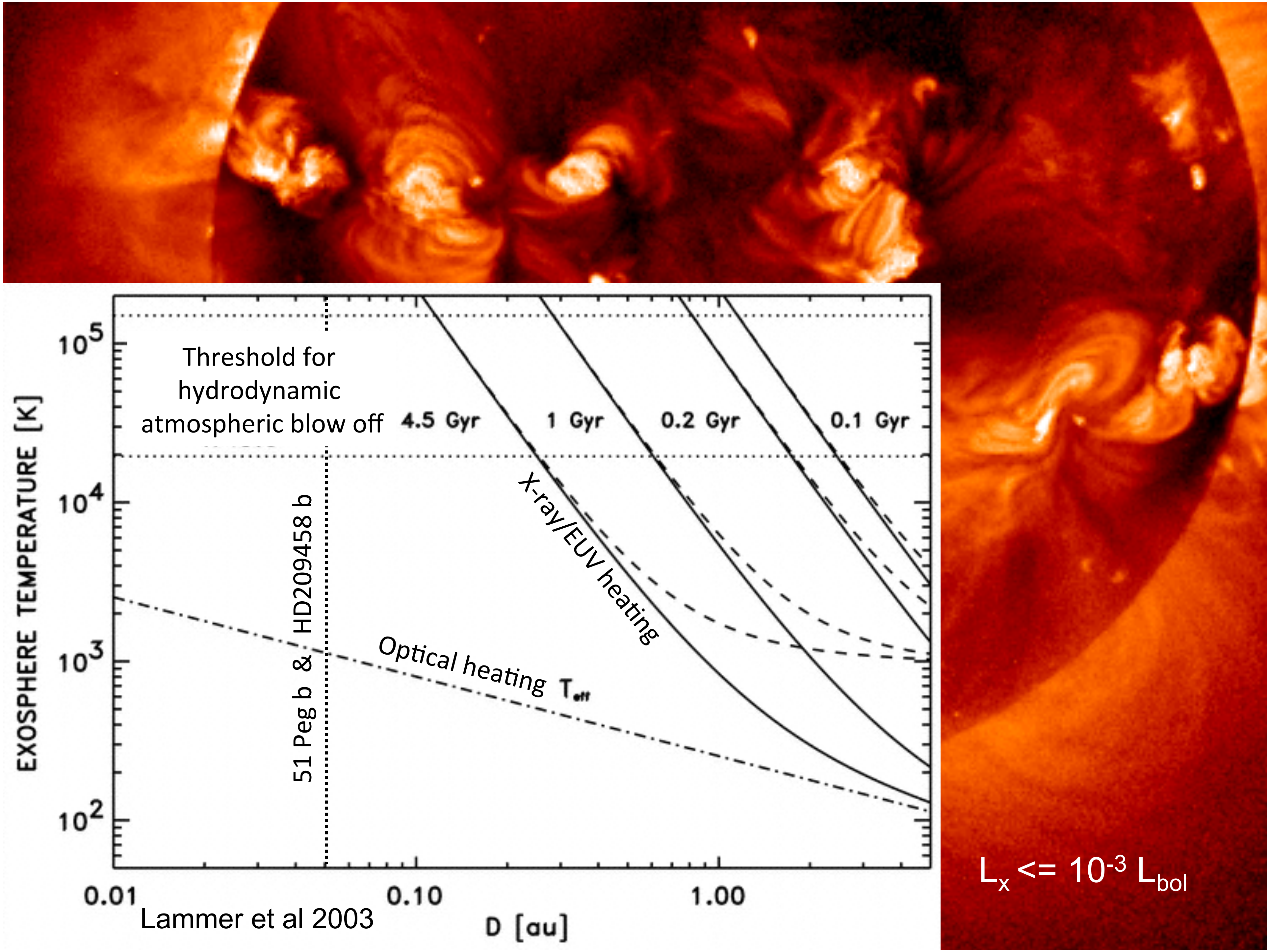
Effects of X-ray/EUV irradiation?





Robert Carroll

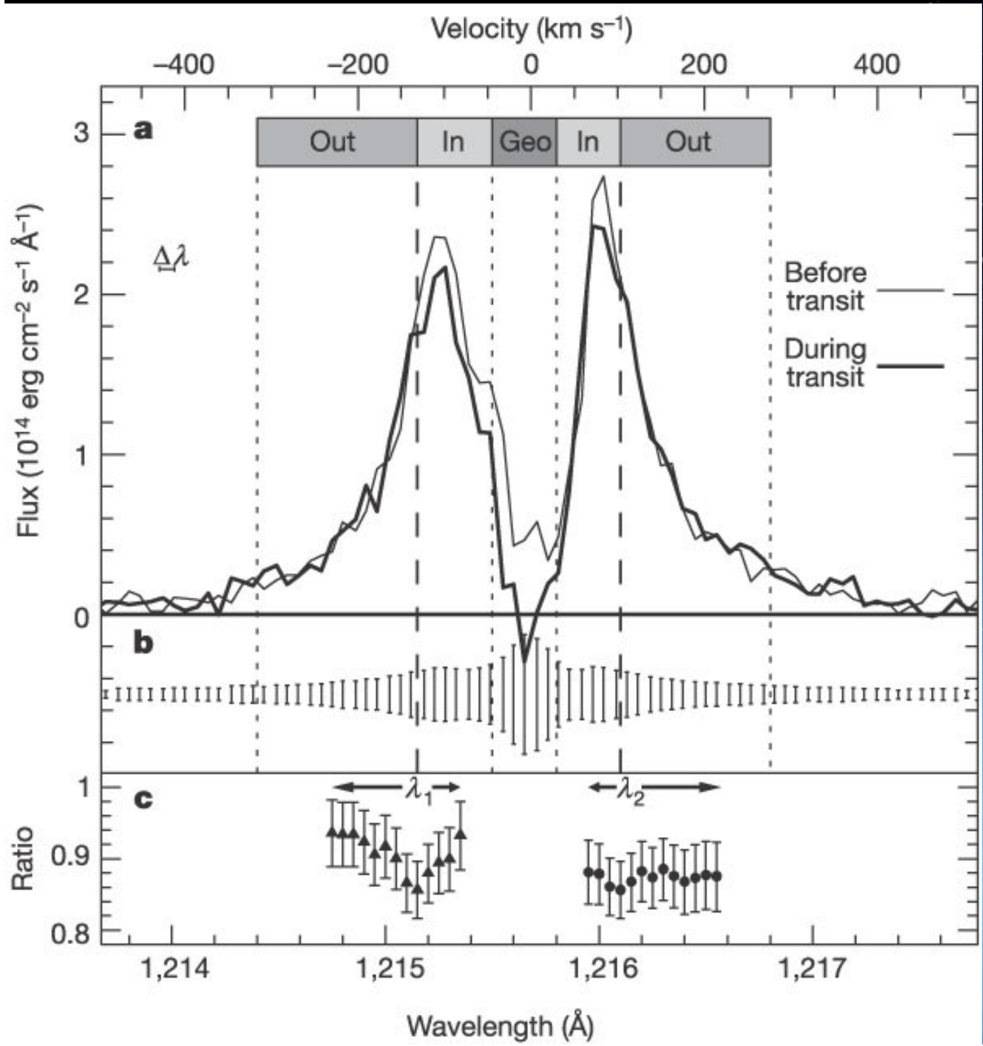
Effects of X-ray/EUV irradiation?

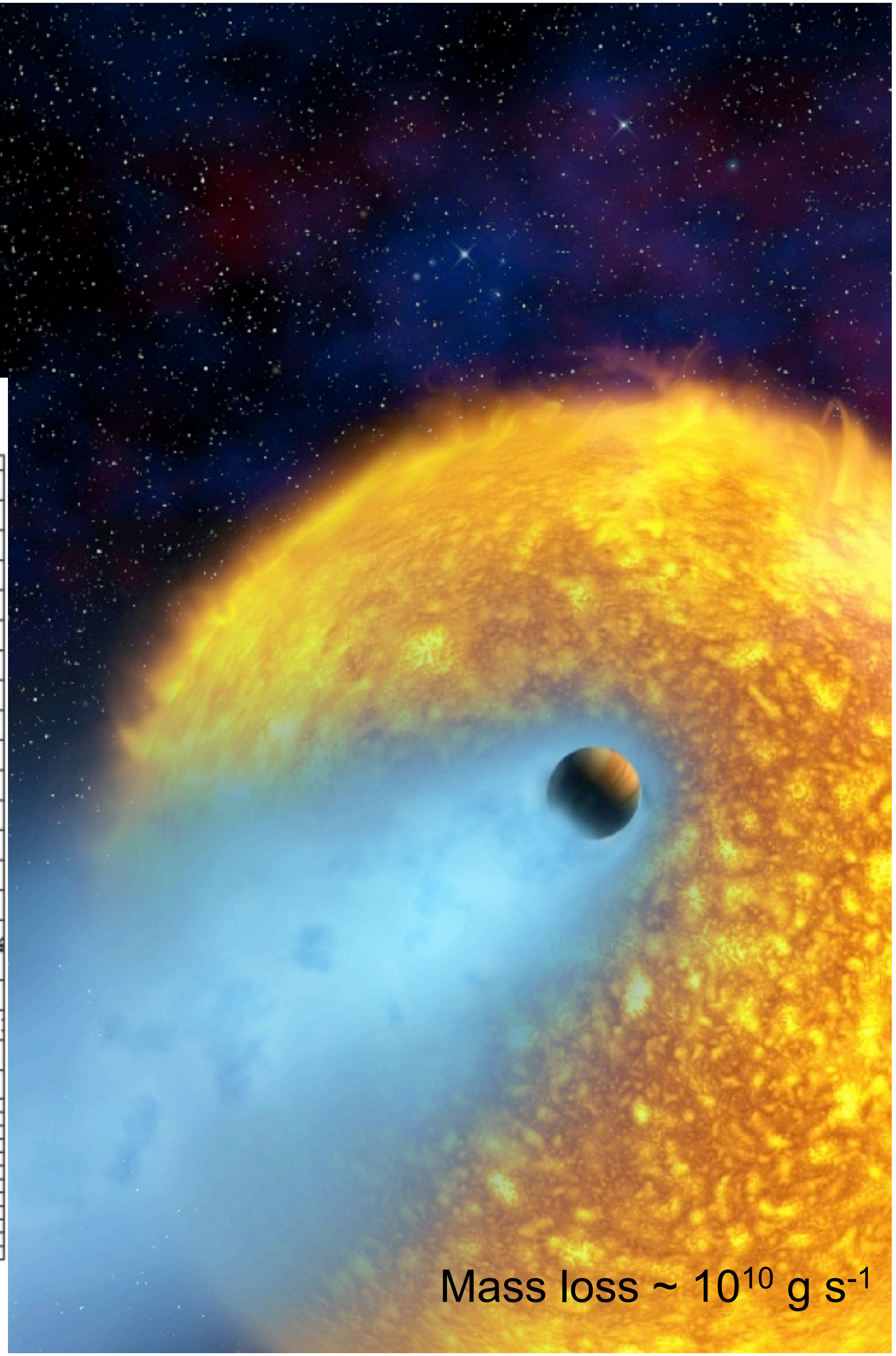


Threshold for hydrodynamic atmospheric blow off
4.5 Gyr
1 Gyr
0.2 Gyr
0.1 Gyr
X-ray/EUV heating
Optical heating T_{eff}
51 Peg b & HD209458 b
EXOSPHERE TEMPERATURE [K]
10^5
10^4
10^3
10^2
0.01
0.10
1.00
D [au]
Lammer et al 2003
$L_x <= 10^{-3} L_{bol}$

Exoplanet evaporation

Lyman-alpha transit of HD209458b
Vidal-Madjar et al 2003



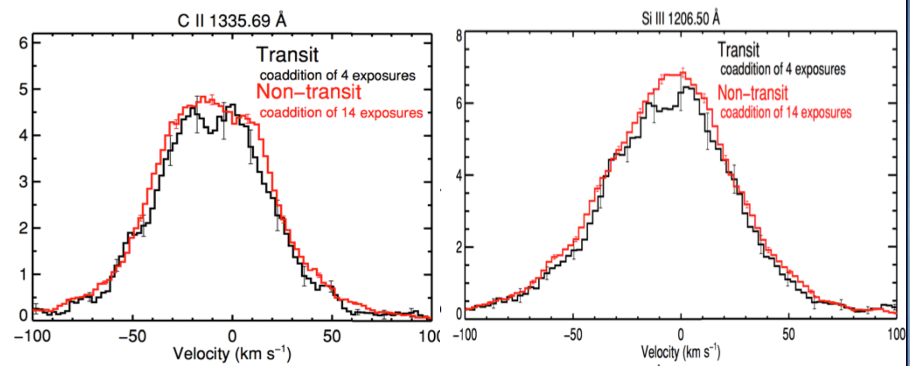


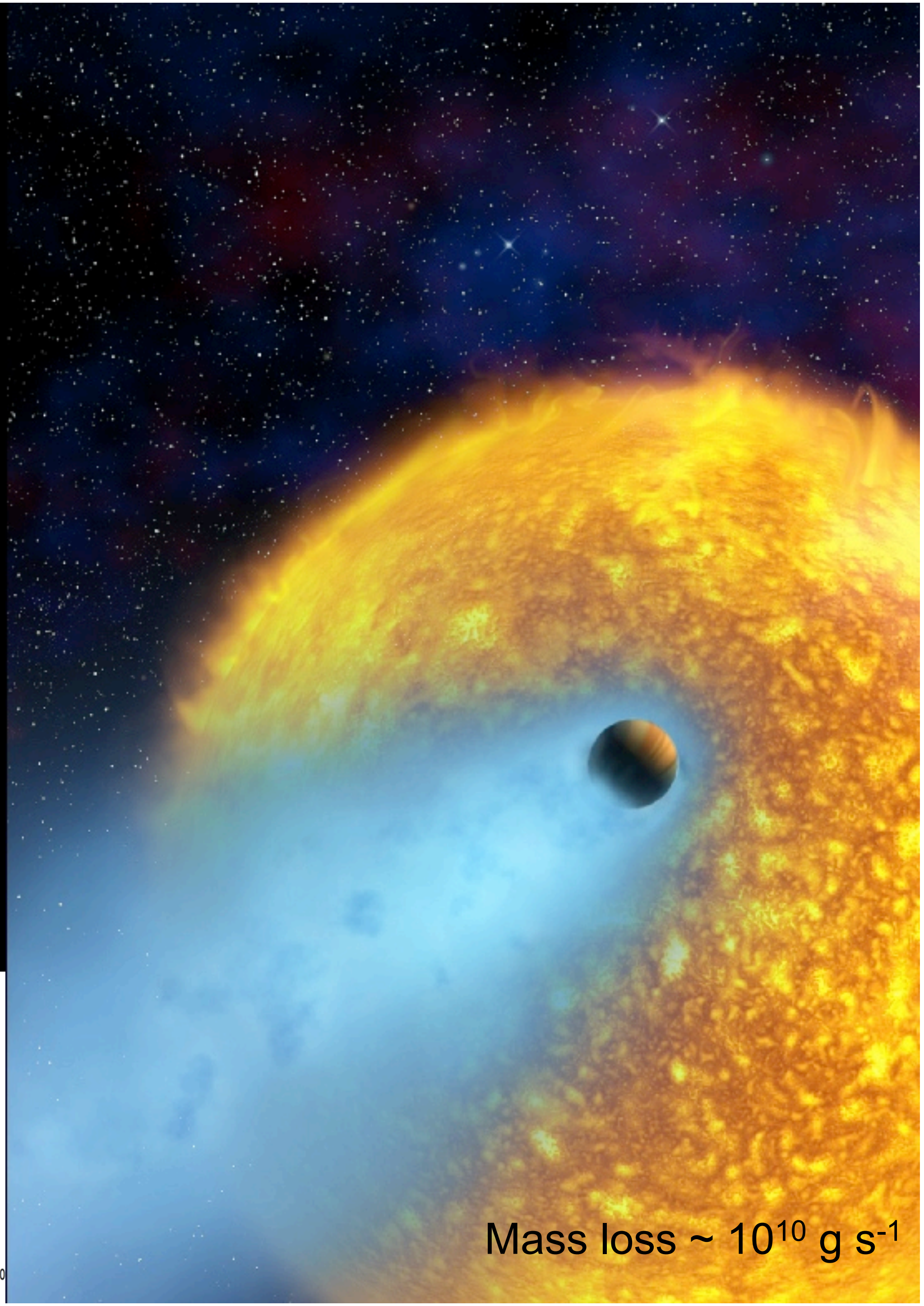
Exoplanet evaporation

Subsequent detection of heavy elements demonstrated hydrodynamical blow-off

HI	Vidal-Madjar et al 2003
OI, CII	Vidal-Madjar et al 2004
CII, SiIII	Linsky et al 2010
MgI	Vidal-Madjar et al 2013

Linksy et al 2010

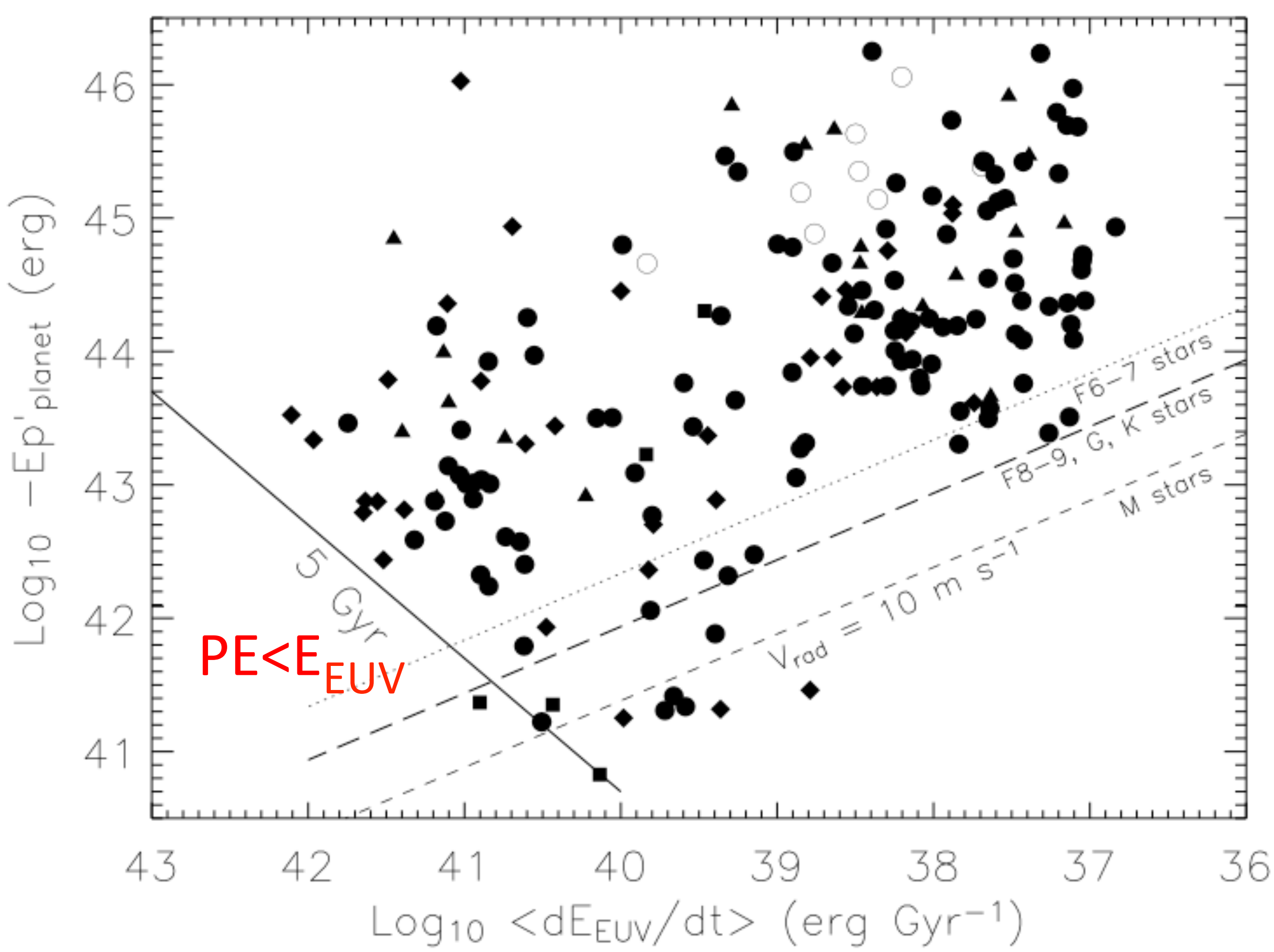




Is evaporation significant for exoplanet evolution?

Evaporation Energy diagram

Lecavalier des Etangs 2007

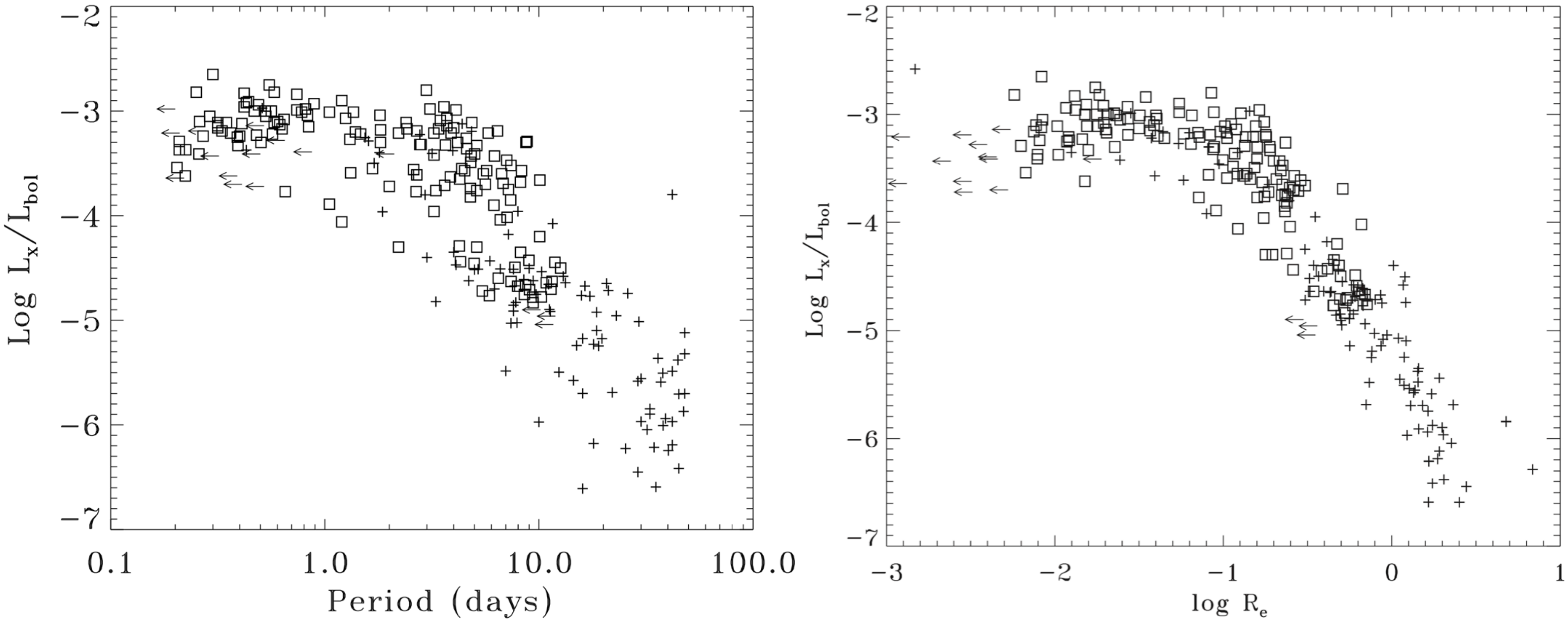


Planets with binding energies less than 5 Gyr of accumulated X-ray/EUV irradiation are missing.

Although these are mainly radial velocity planets with assumed constant X-ray/EUV flux

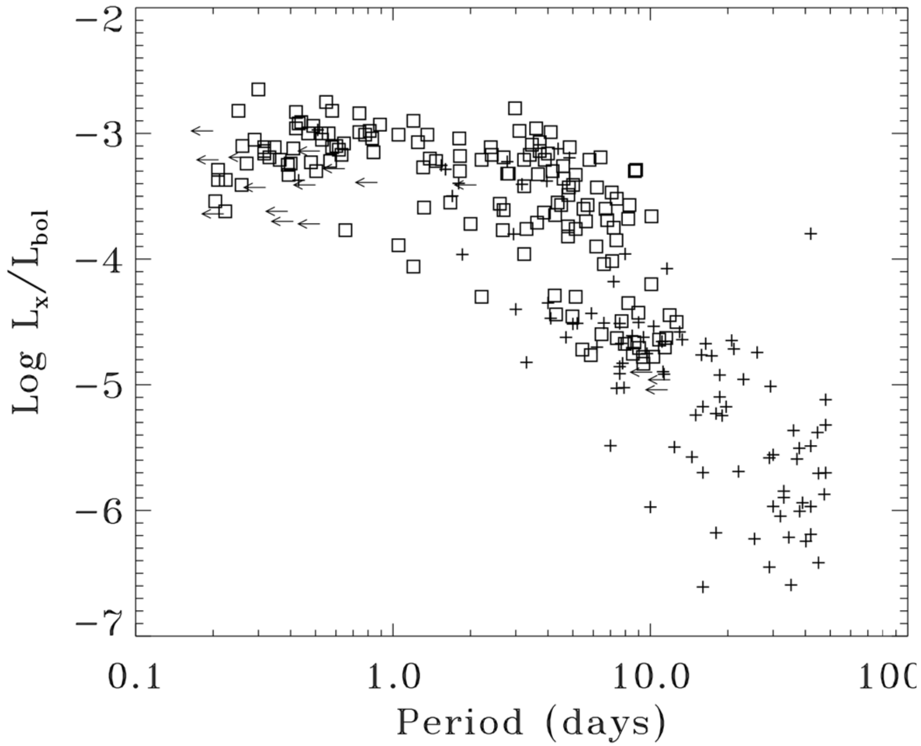
Late-type stellar X-ray emission

Pizzolato et al 2003

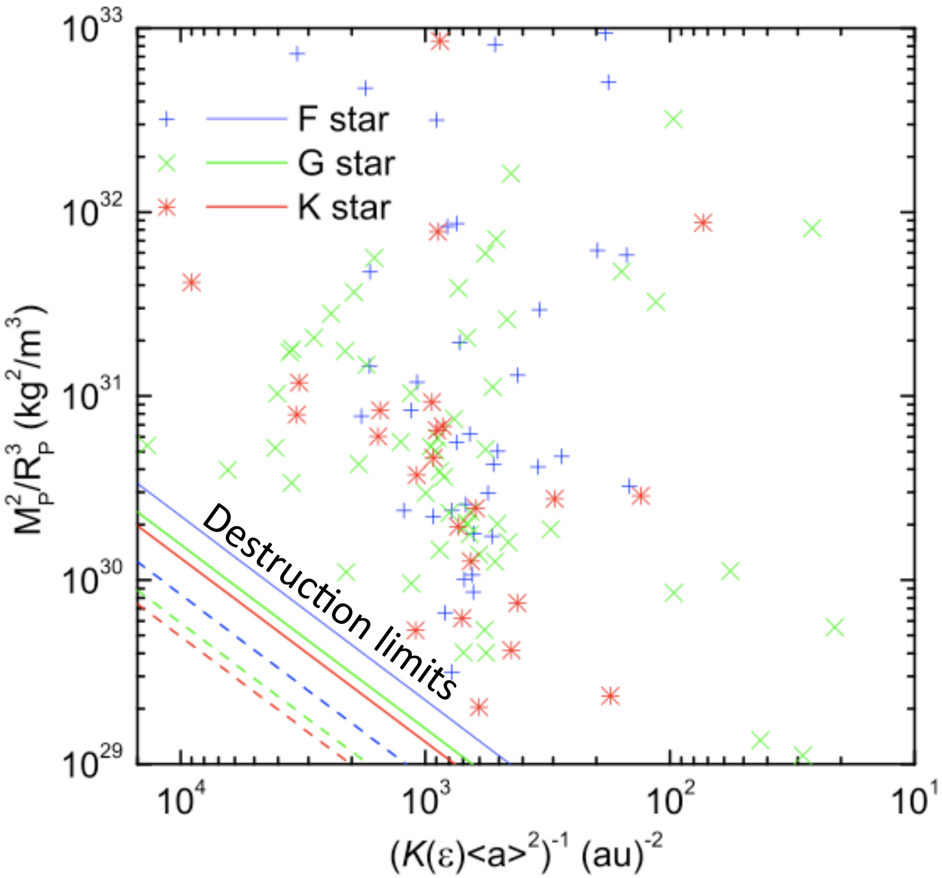


Late-type stellar X-ray emission

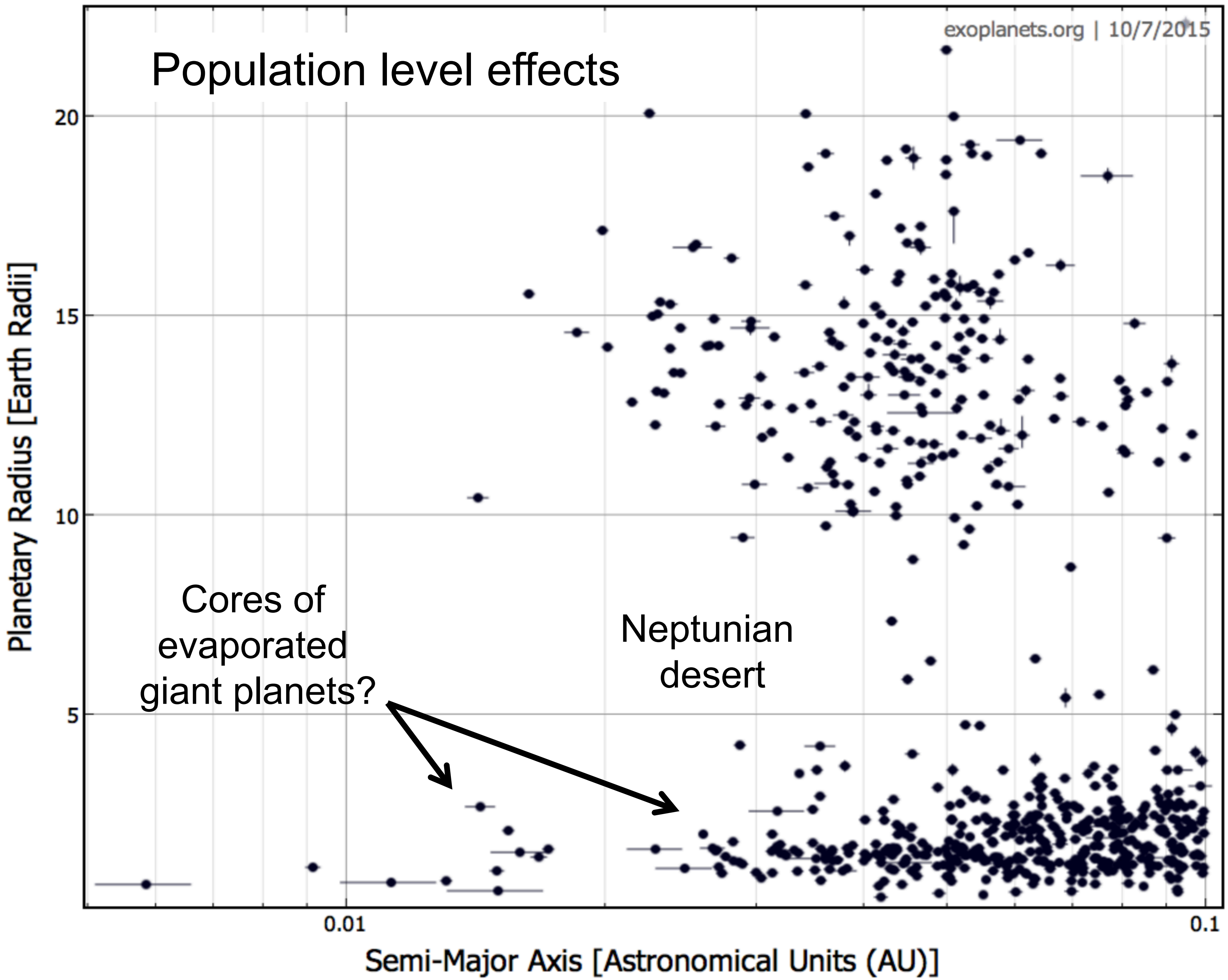
Pizzolato et al 2003



Jackson, Davis & Wheatley 2012



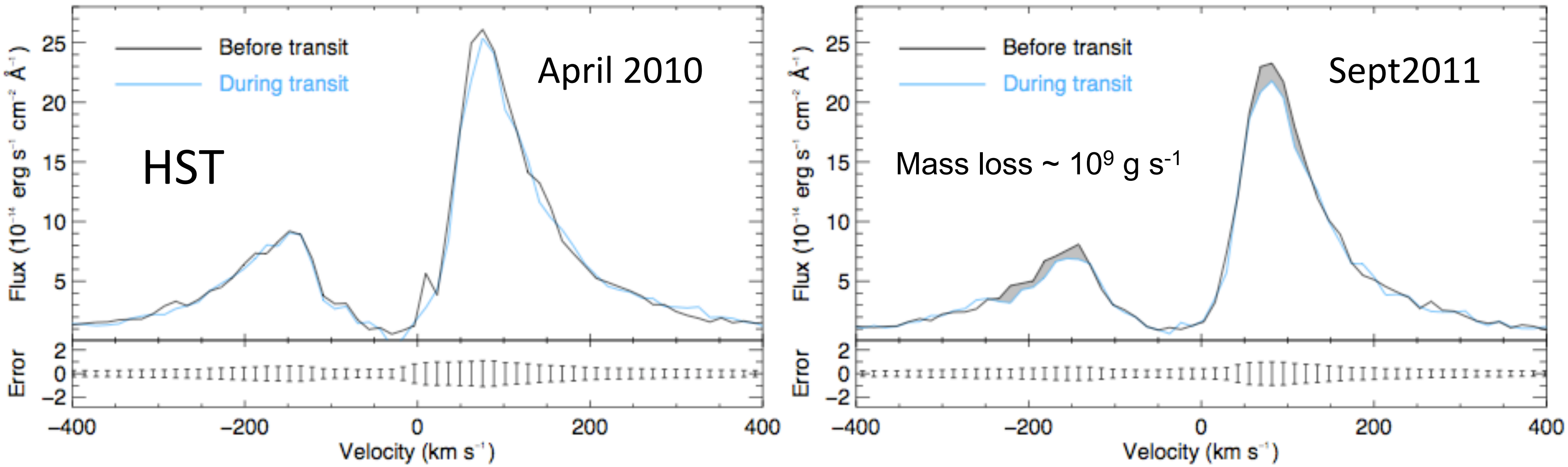
Only transiting exoplanets and accounting for history of X-ray/EUV emission

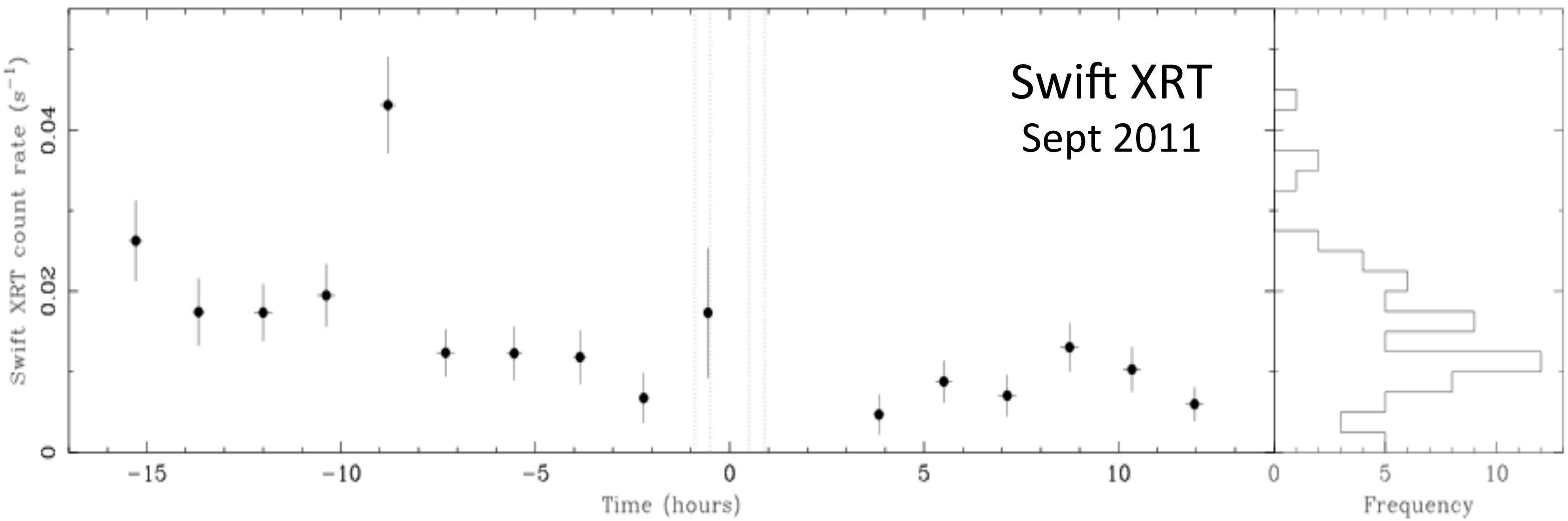


exoplanets.org | 10/7/2015
Population level effects
Cores of evaporated giant planets?
Neptunian desert
Planetary Radius [Earth Radii]
20
15
10
5
0.01
0.1
Semi-Major Axis [Astronomical Units (AU)]

Variable atmospheric escape from hot Jupiter HD189733b

Lecavelier des Etangs, Bourier, Wheatley et al, 2012



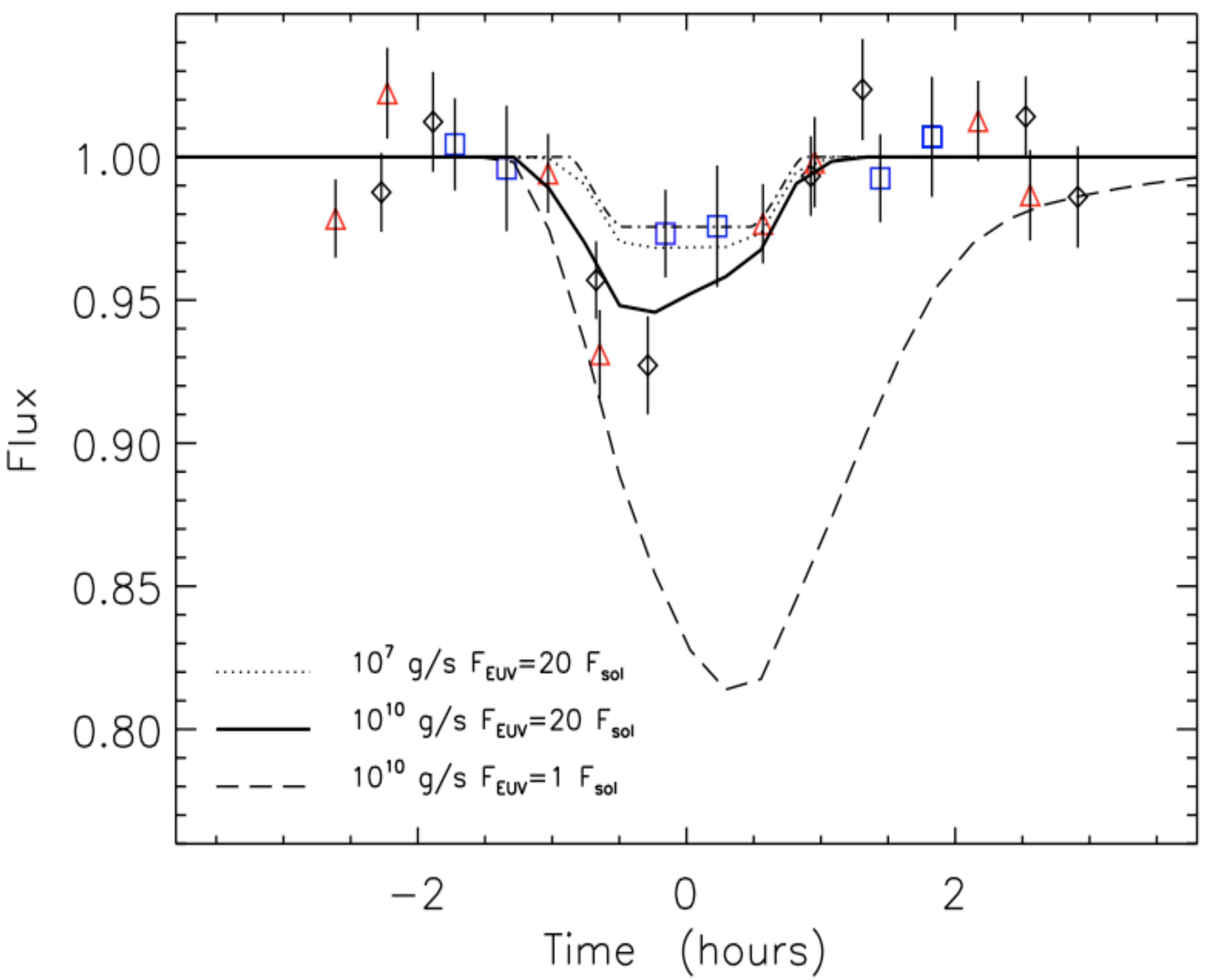


Simultaneous X-ray/UV observations needed for mass loss rate

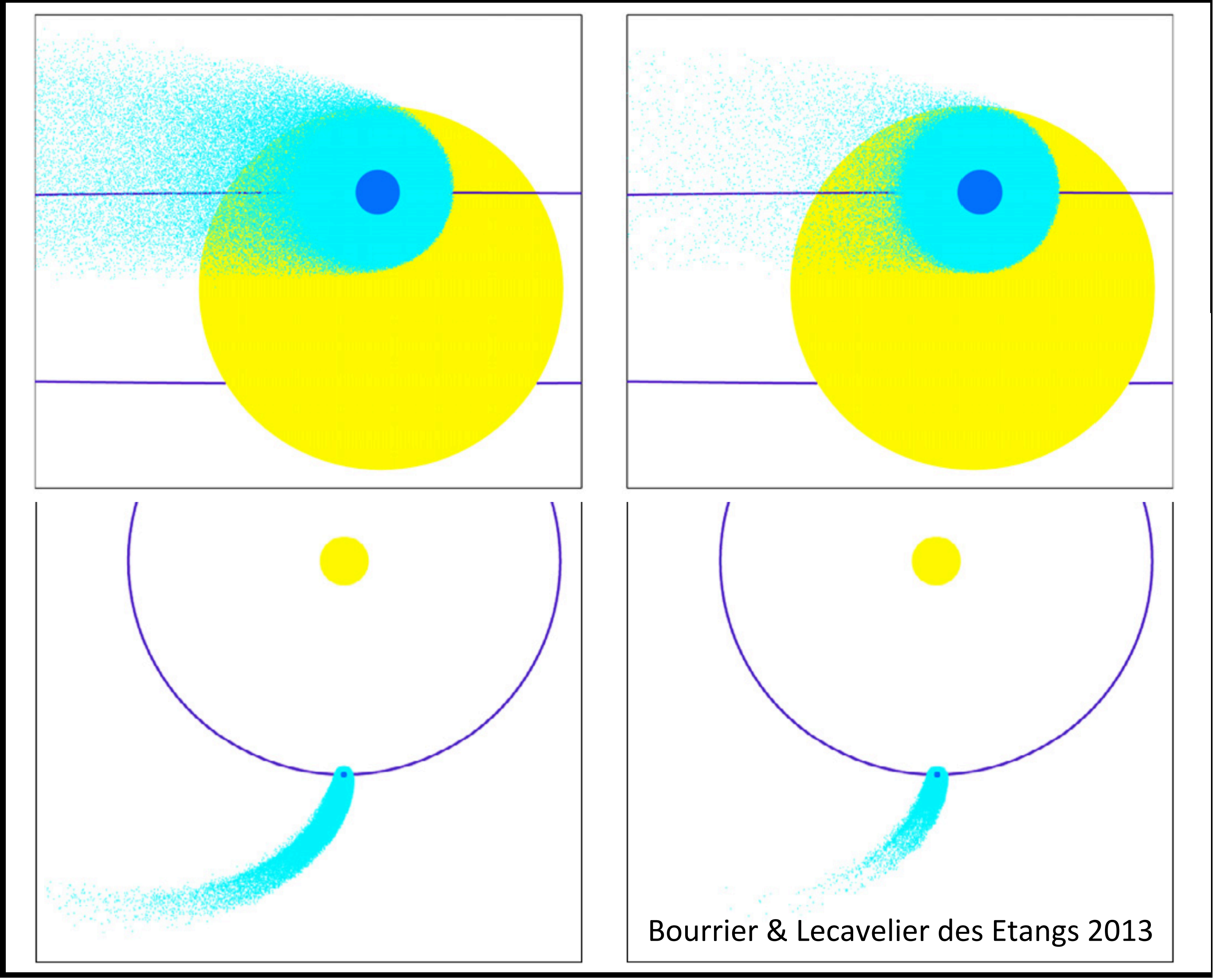
HD189733b

Lecavalier des Etangs et al 2010

X-ray/EUV flux provides energy driving mass loss, but also photoionises the escaping gas

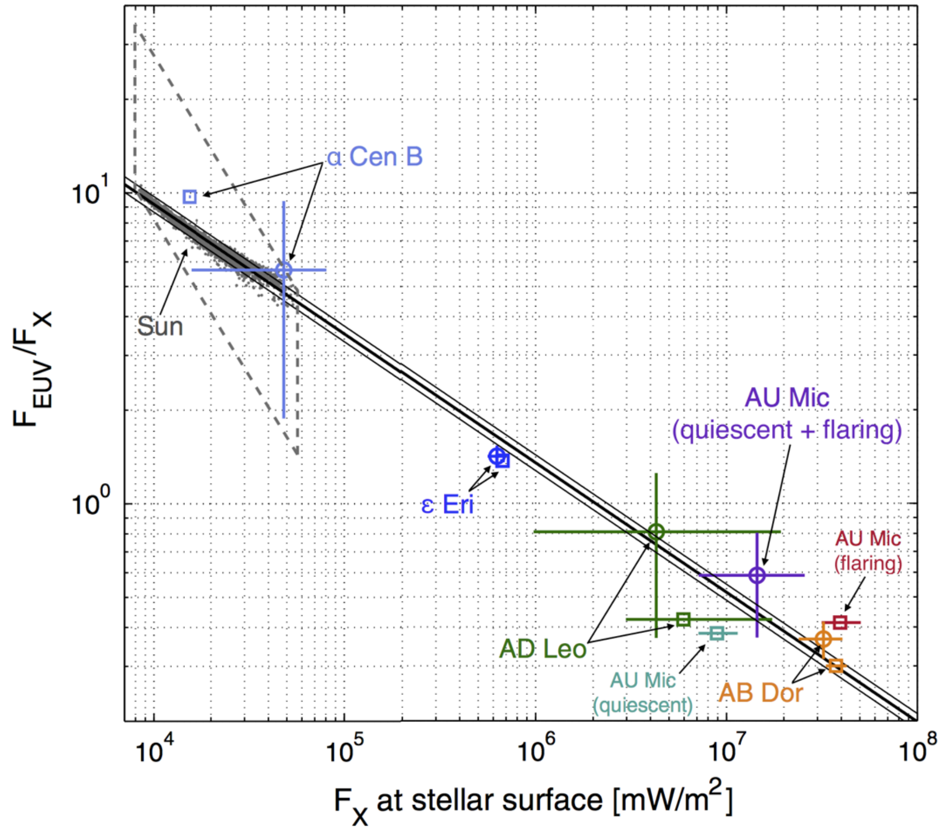


3d particle modeling of planetary wind

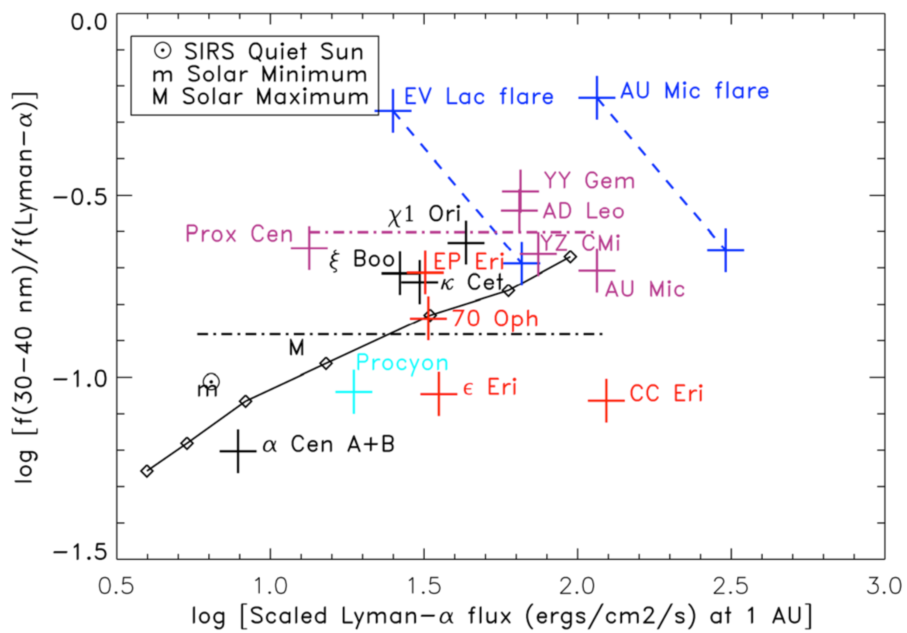


How to determine the EUV spectrum?

1) Extrapolate from X-rays using Solar spectrum
Chadney et al 2015, King et al (in prep)

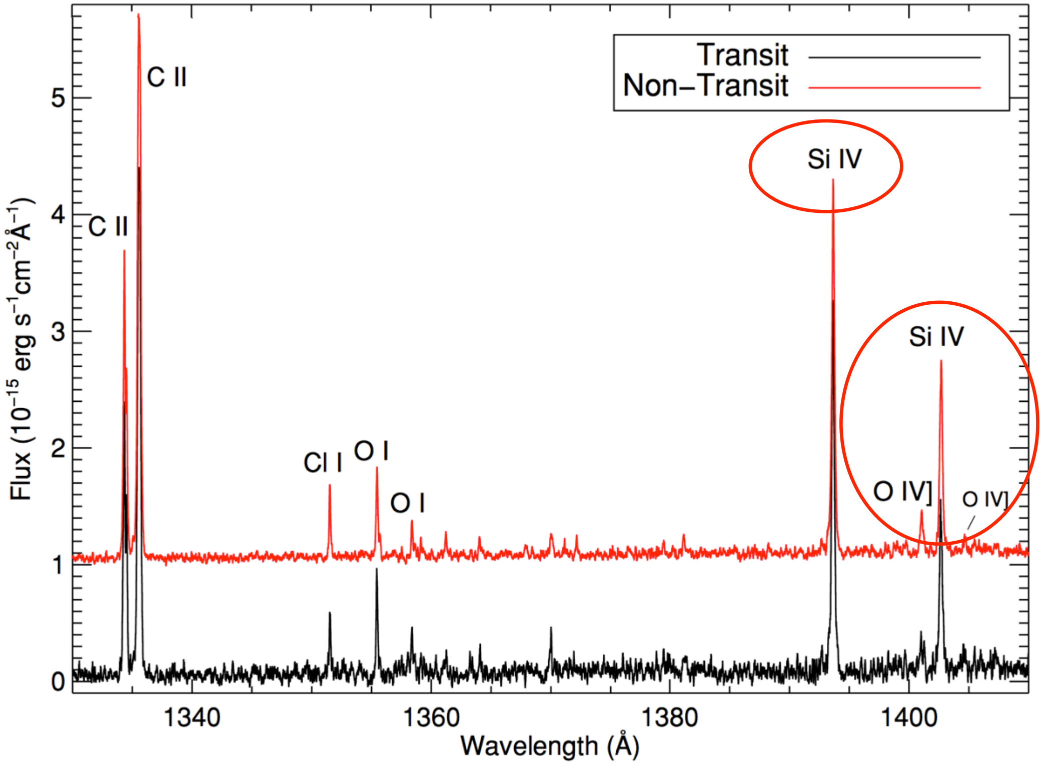


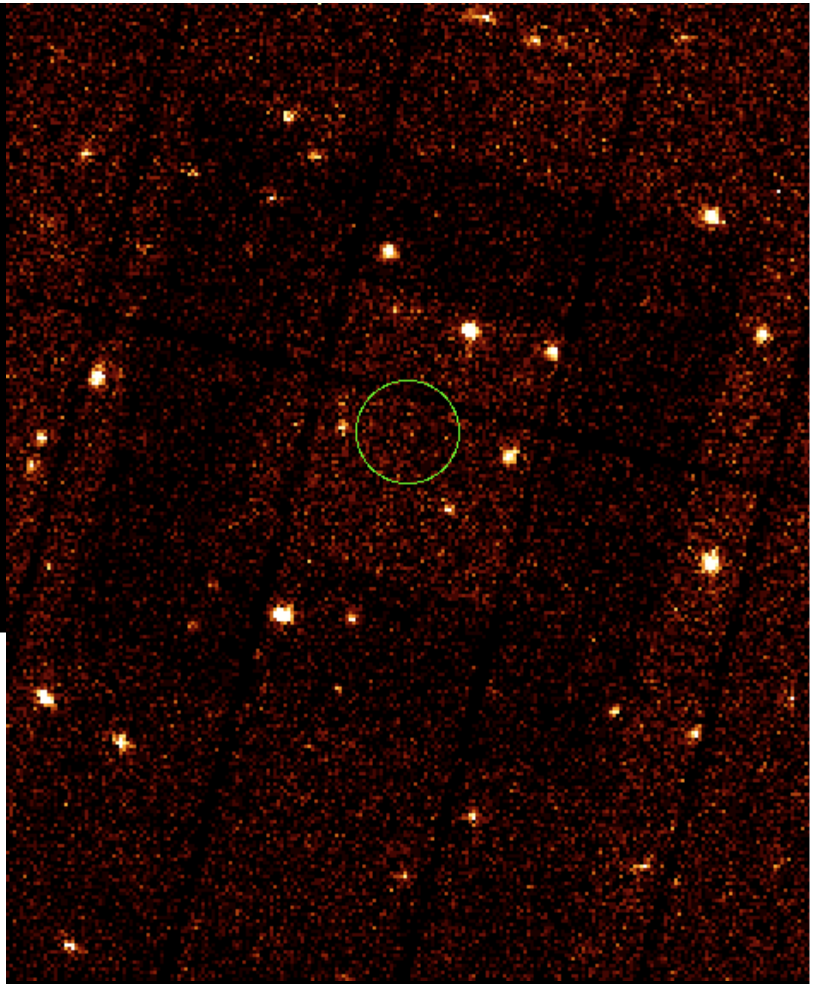
2) Extrapolate from Lyman-alpha using Solar spectrum and EUVE data
Linsky et al 2014, Youngblood et al 2016



3) EUV spectrum can be reconstructed from X-rays and high-excitation UV lines

HST COS spectrum of HD209458 Linsky et al 2010





HD209458 with XMM
Louden, Wheatley & Briggs 2016

Mass loss rate found to be 8-40 x 10^{10} g/s from CII lines assuming solar C abundance

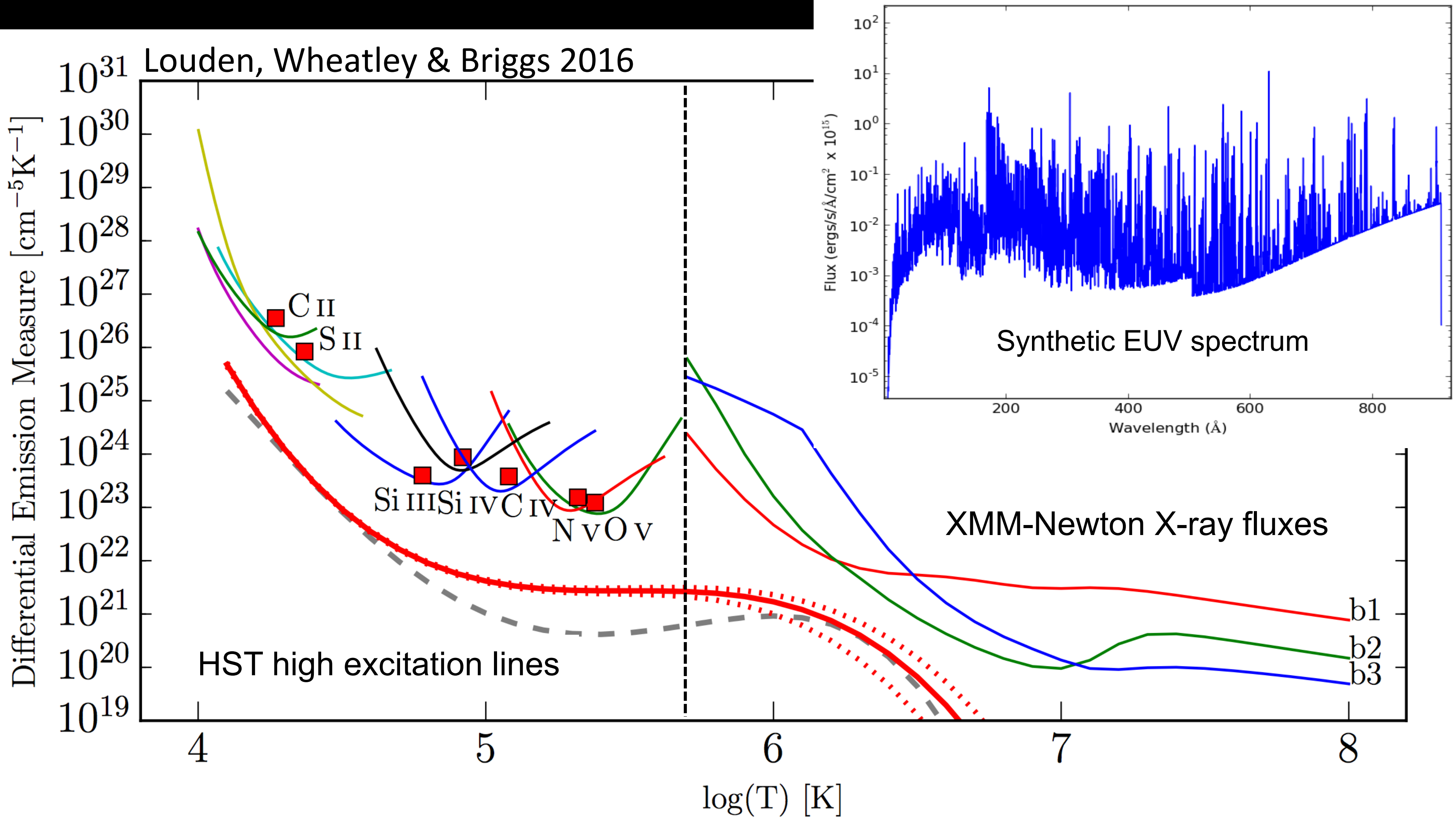
Reconstructing the EUV irradiation of HD209458b

EUV and X-ray emission similar to quiet Sun $L_{EUV} = 9 \times 10^{27}$ erg/s

Energy limited mass loss = 10×10^{10} g/s at 100% efficiency

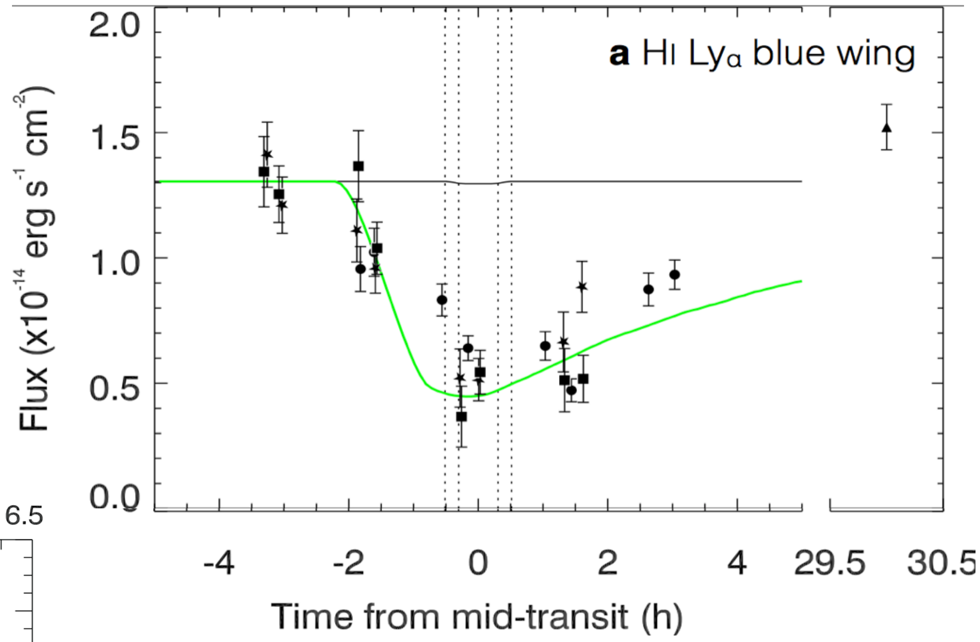
c.f. 8-40 x 10^{10} g/s estimate from the same COS data by Linsky+10

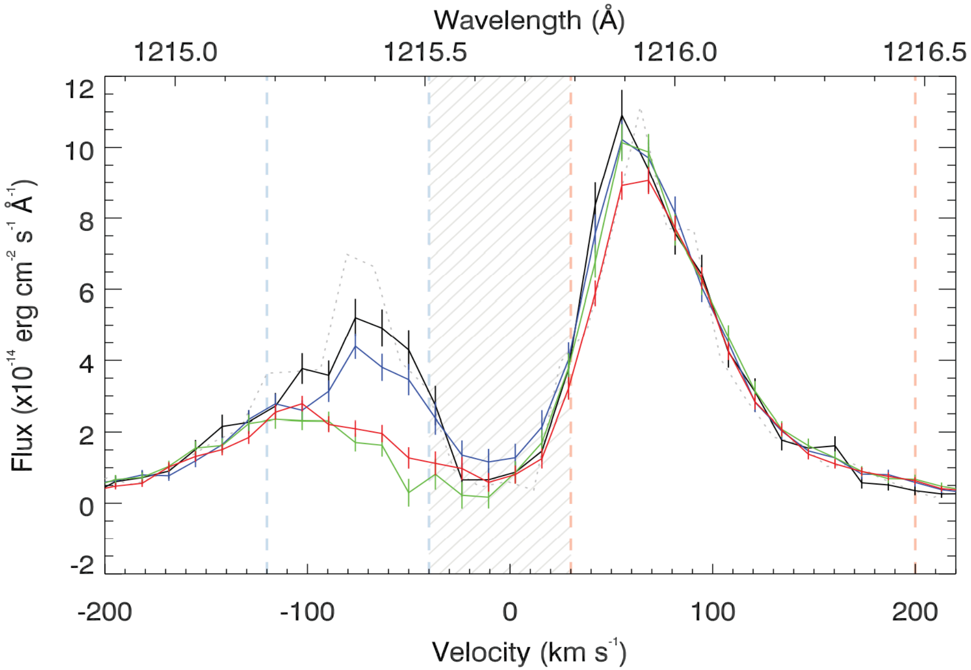
Louden, Wheatley & Briggs 2016

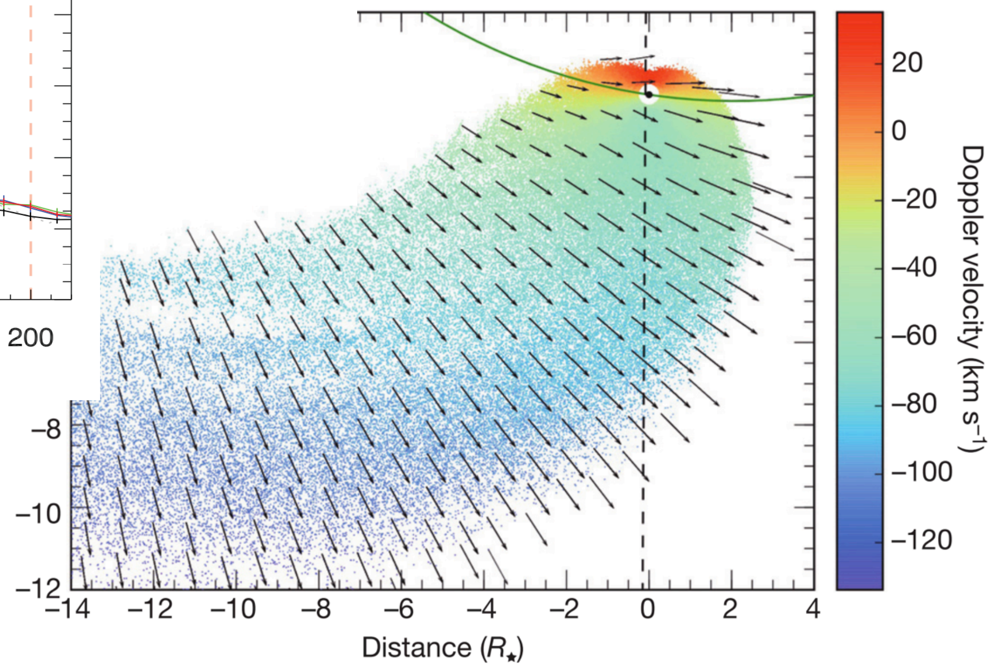


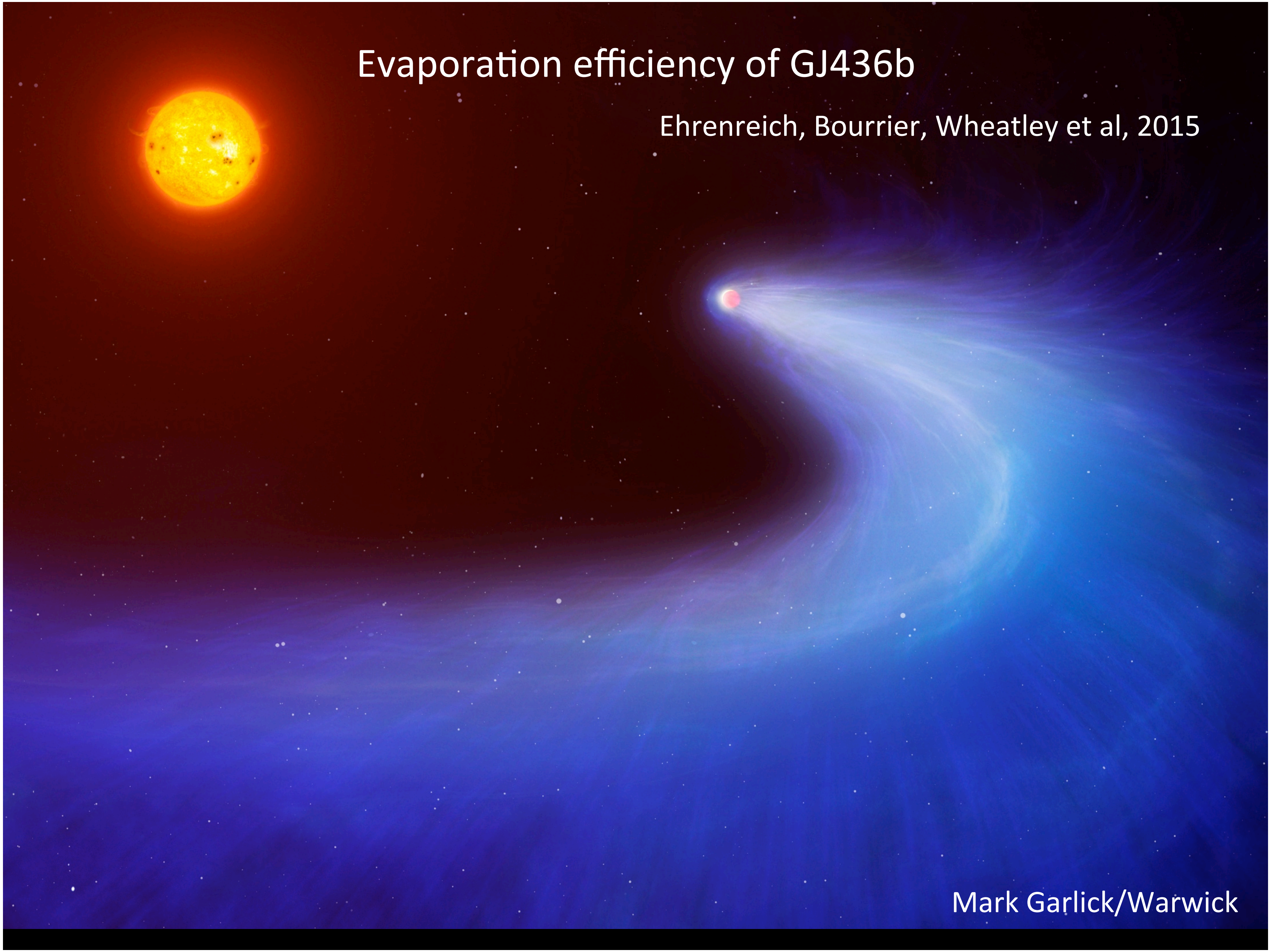
Evaporation of Neptune GJ 436b

Ehrenreich, Bourrier, Wheatley et al
2015 Nature



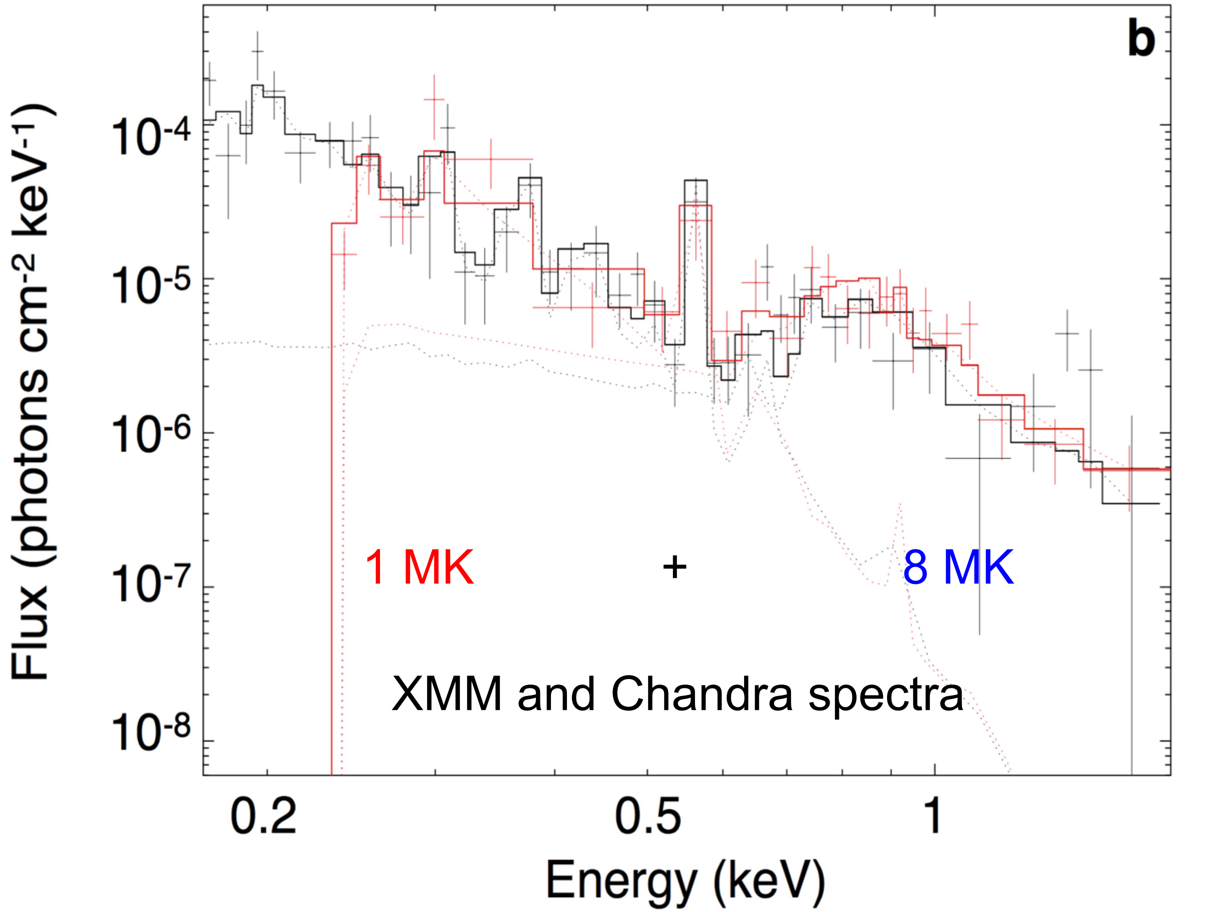





Evaporation efficiency of GJ436b
Ehrenreich, Bourrier, Wheatley et al, 2015
Mark Garlick/Warwick

Evaporation efficiency of GJ436b

Ehrenreich, Bourrier, Wheatley et al, 2015



Mass loss ~ 5 x 10^8 g/s

Requires only ~1% efficiency (assuming EUV scaling of Chadney+15)

During 1 Gyr of saturated X-ray emission may have lost 10% of initial mass

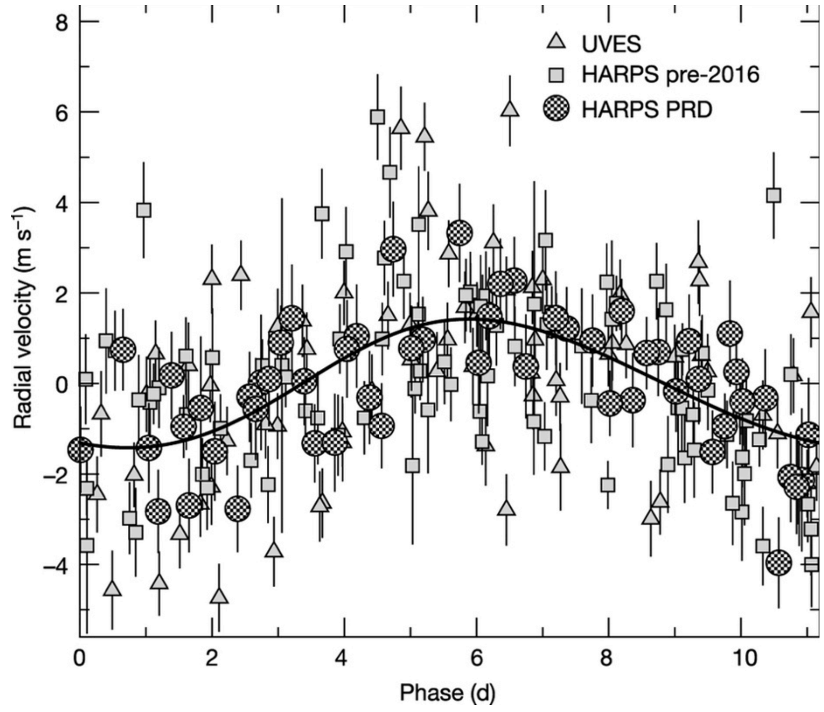
Mark Garlick/Warwick

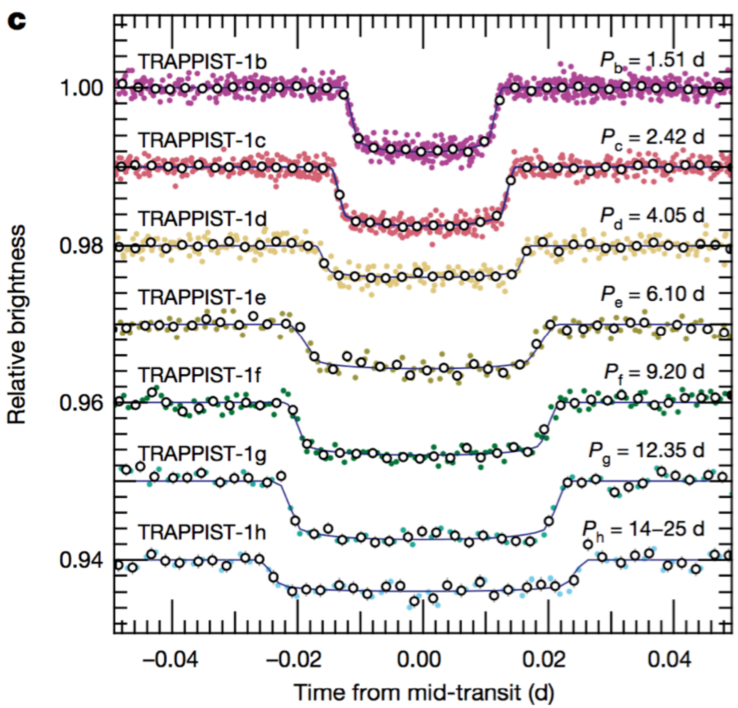
Earth-sized planets in the habitable zone

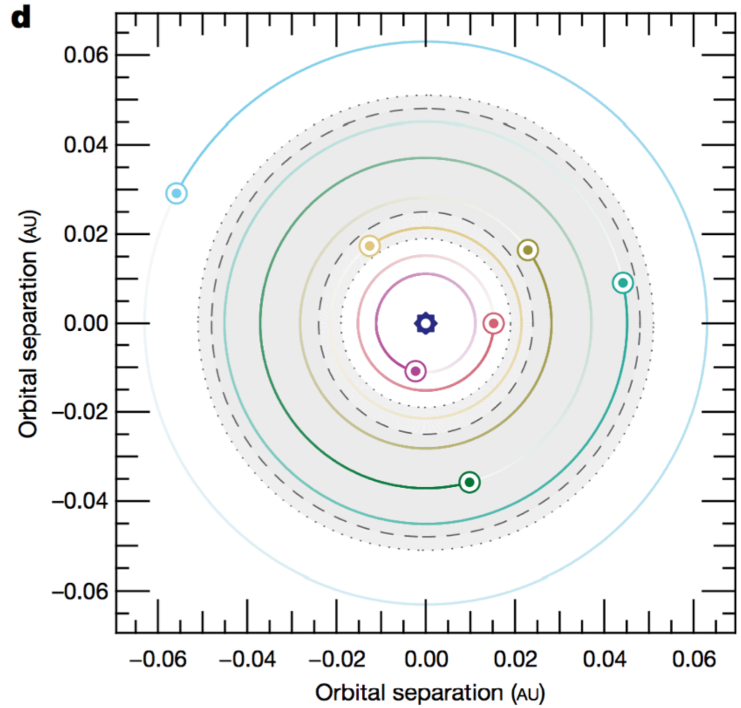
Proxima Cen b

Radial velocity detection of Earth-mass planet in habitable zone

Anglada-Escudé+16







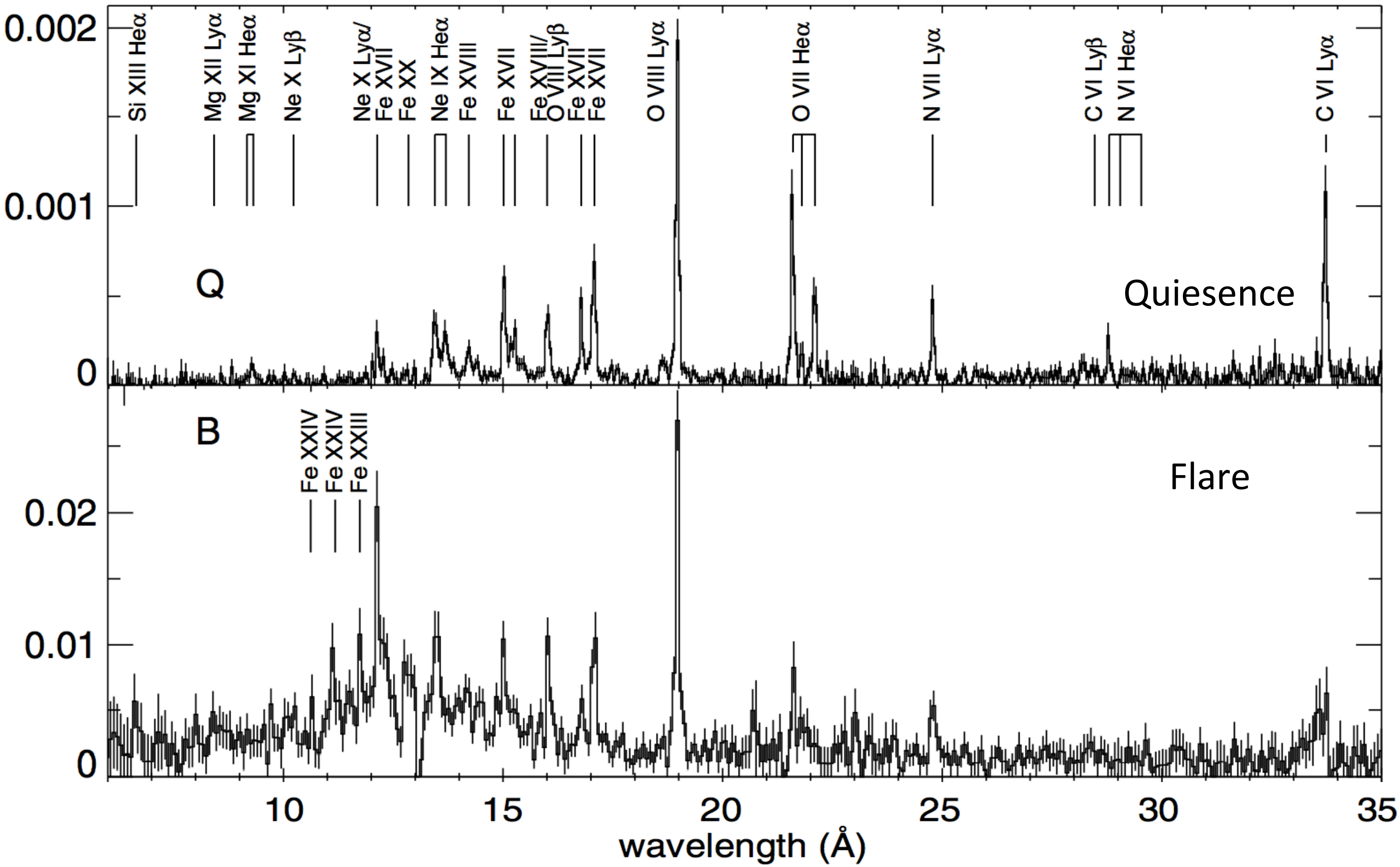
Trappist-1

7 Earths transiting an ultra-cool dwarf

Gillen+16,17

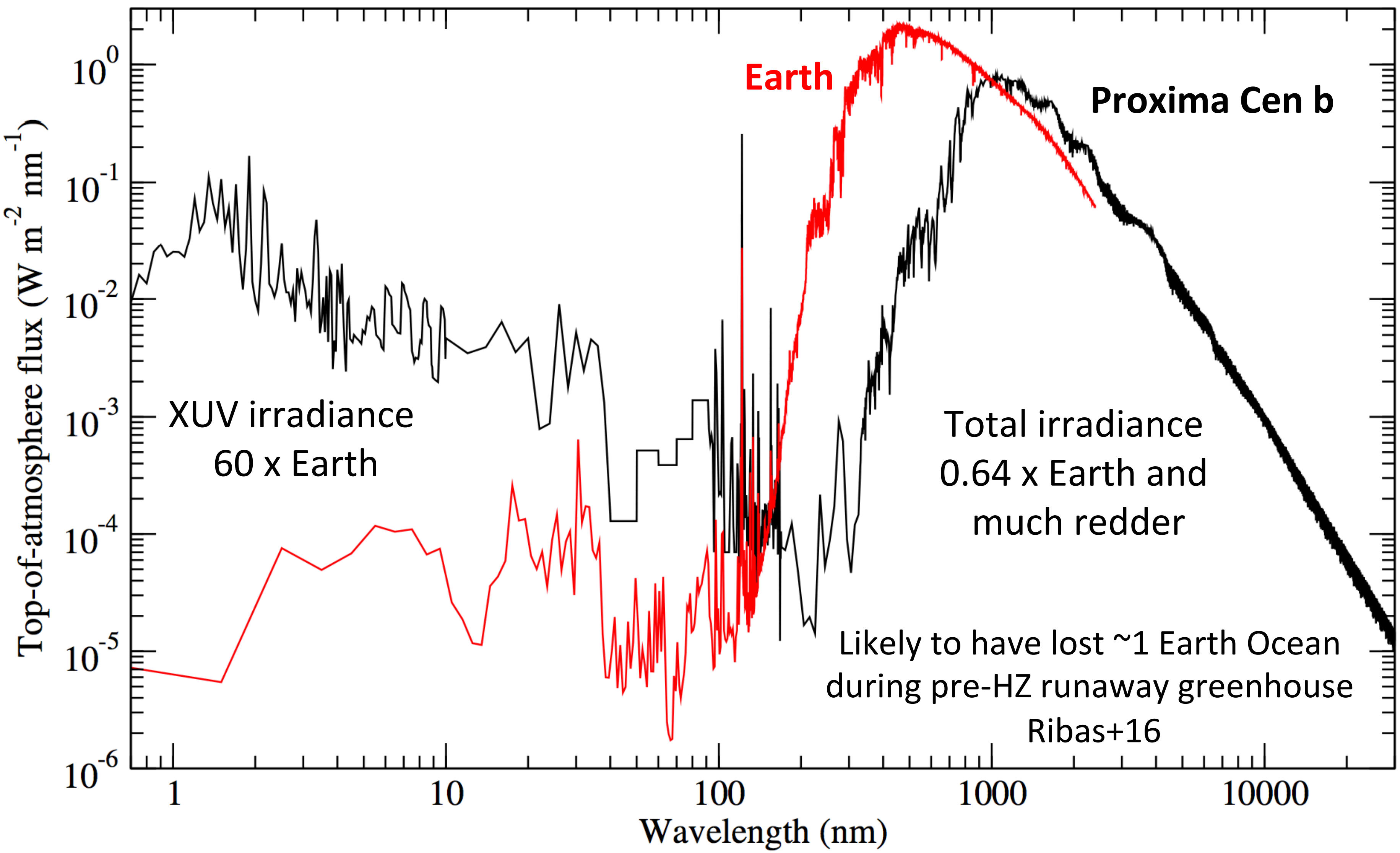
XMM-Newton RGS spectrum of Proxima Cen

Guedel et al 2004



Irradiance of Proxima Cen b compared with Earth

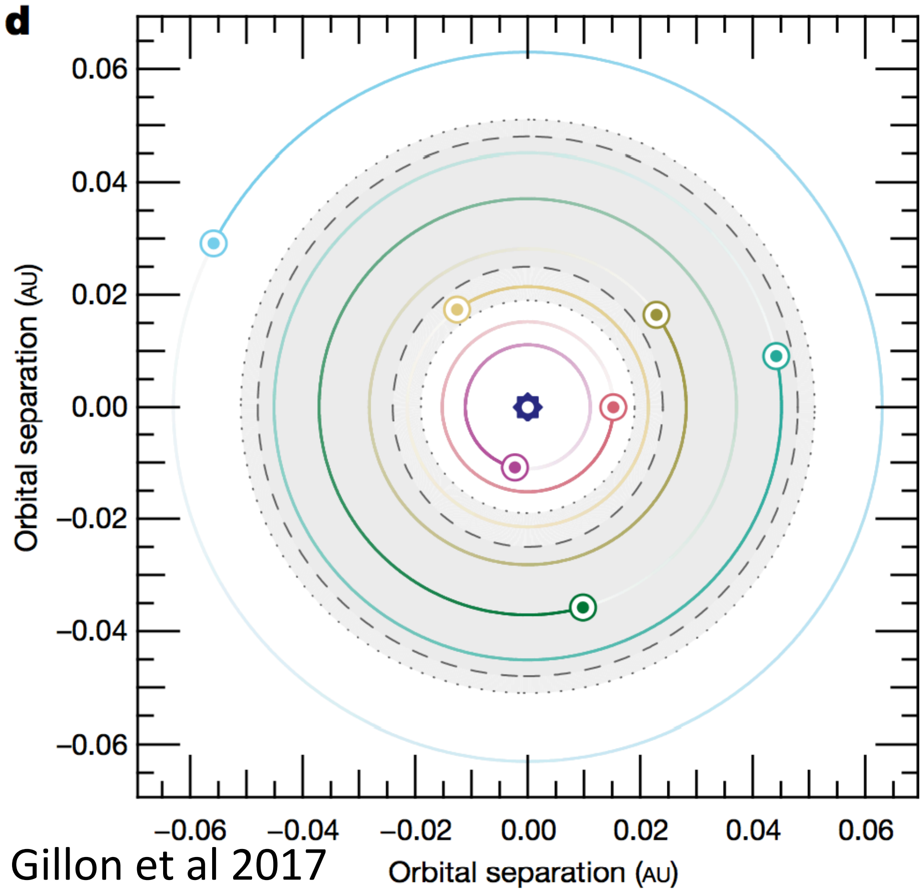
Ribas et al 2017

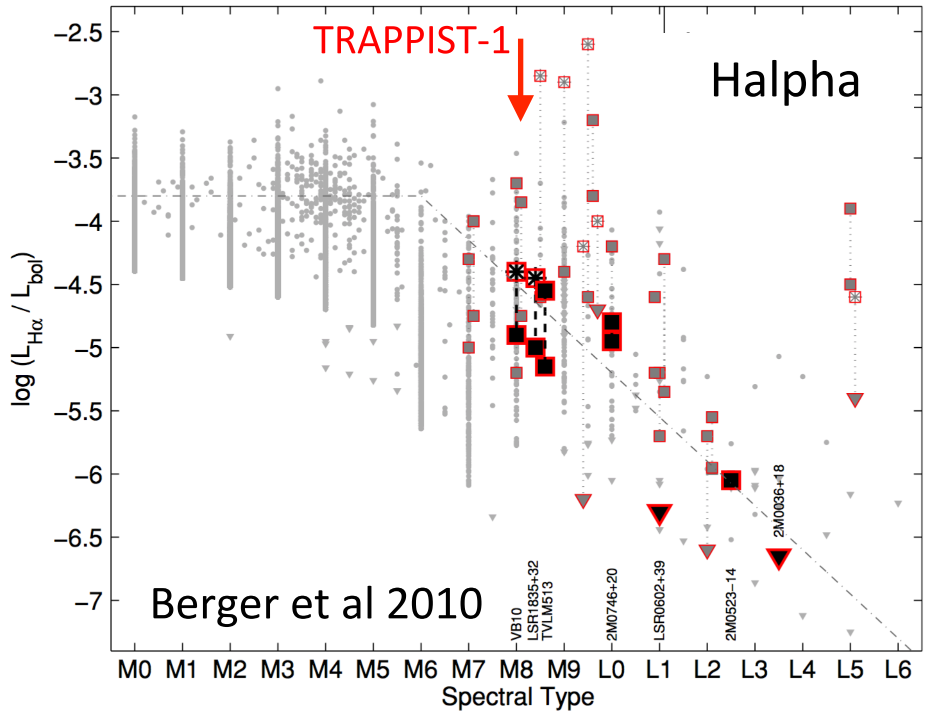


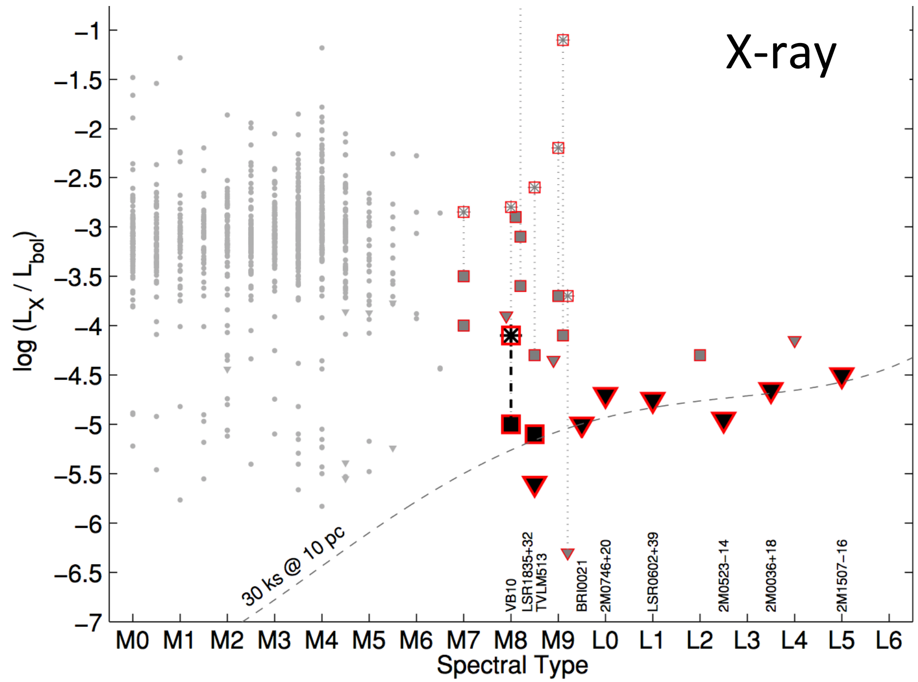
TRAPPIST-1

7 transiting Earths spanning HZ

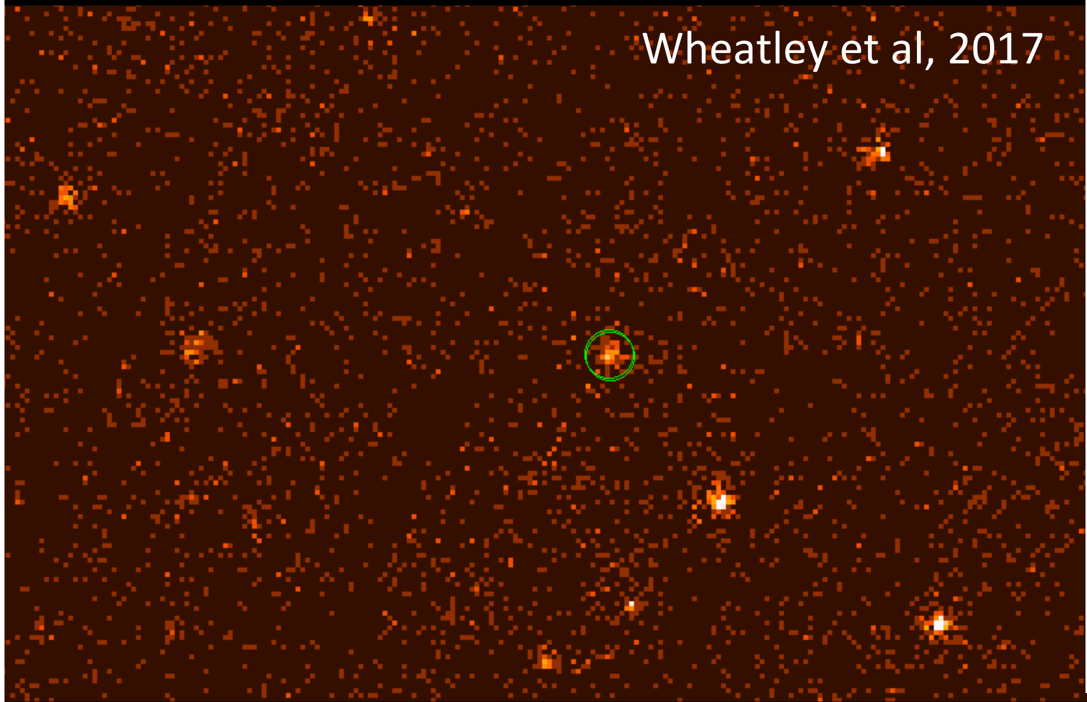
Extremely late-type M8 host star

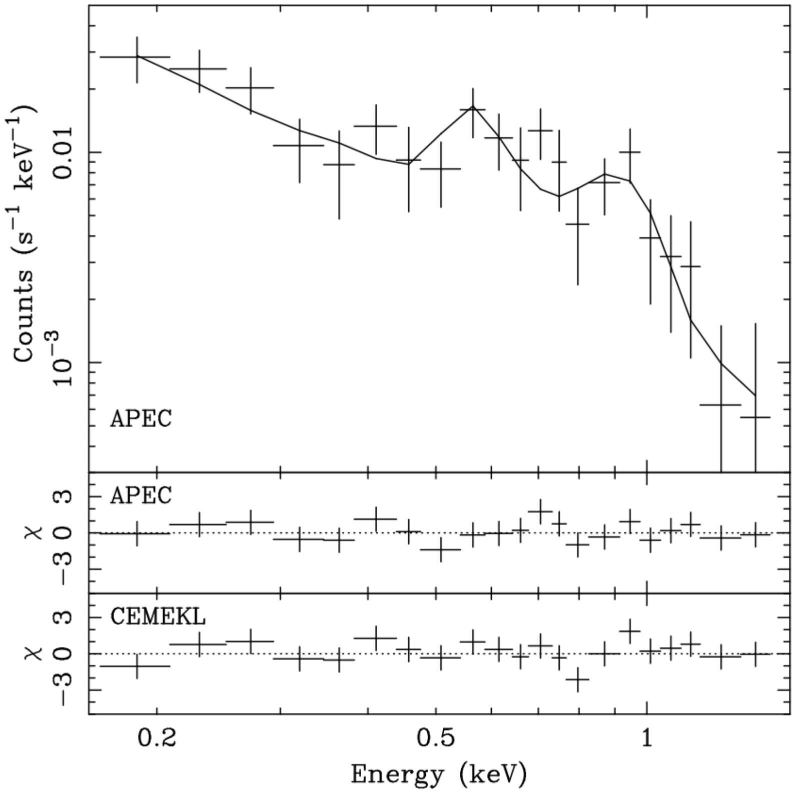






TRAPPIST-1 in X-rays





Strong XUV emission similar to quiet Sun despite L_{Bol} only 5×10^{-4} L_{sun}

$L_X/L_{Bol} \sim 3 \times 10^{-4}$
XUV irradiation is 50x stronger than assumed by Bolmont et al 2016

Models of water loss for this XUV flux show inner planets desiccated during initial runaway greenhouse, while HZ planets may have lost less than 1 Earth ocean - Bolmont et al 2017

Possible that M dwarf HZ planets with thick primordial H/He can be rendered habitable by XUV evaporation - Owen & Mohanty 2016

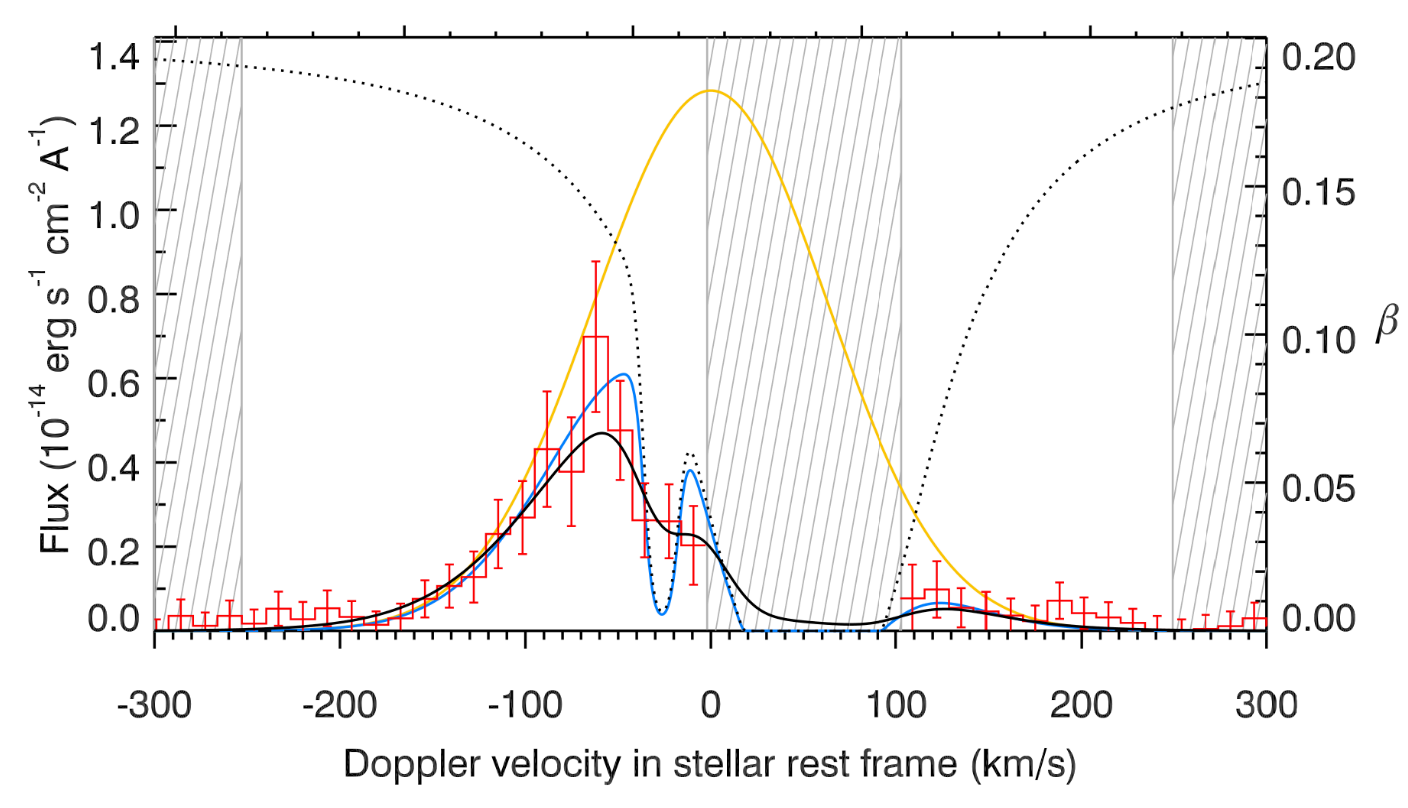
TRAPPIST-1 at Lyman-alpha

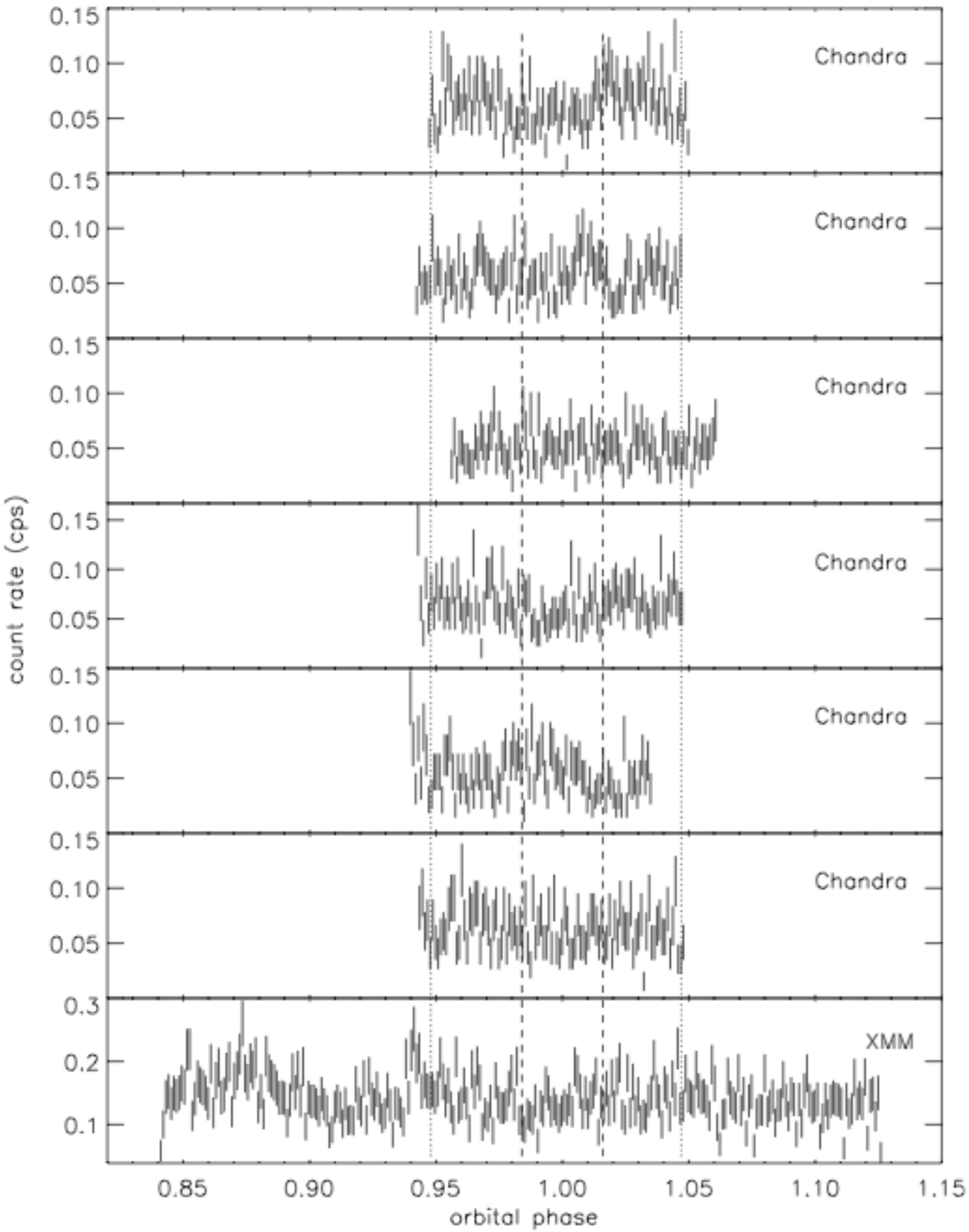
Lyman-alpha line detected with HST

Under luminous cf Proxima Cen despite similar X-ray luminosities, EUV uncertain

Water loss might be detectable in blue wing which is uncontaminated

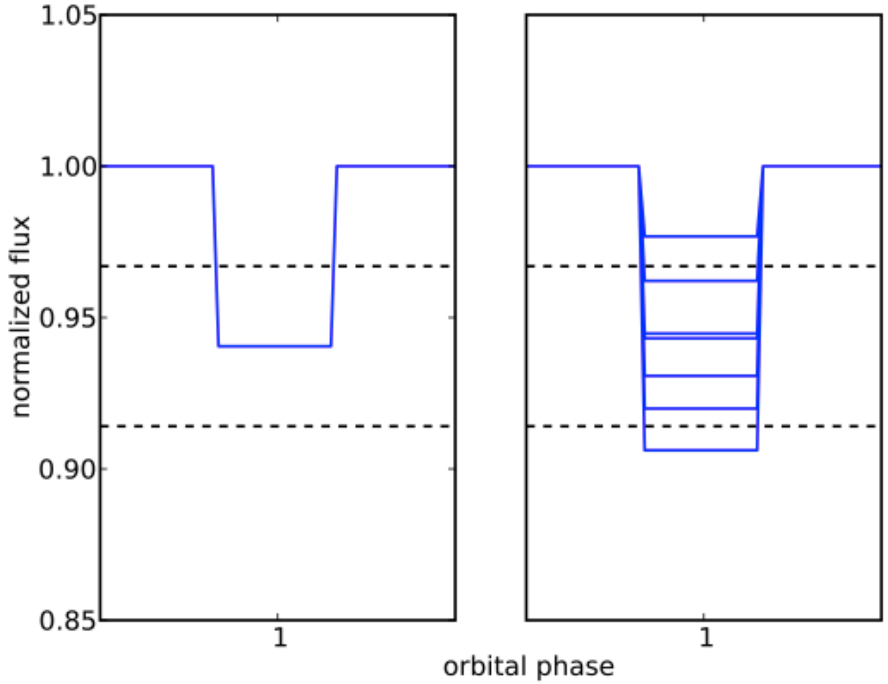
Bourrier, Ehrenreich, Wheatley et al 2017

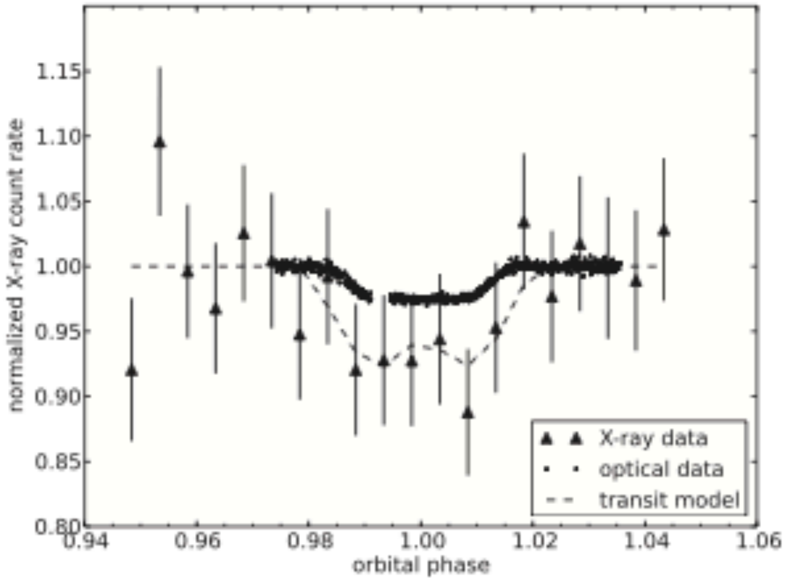




X-ray transit observations with Chandra & XMM

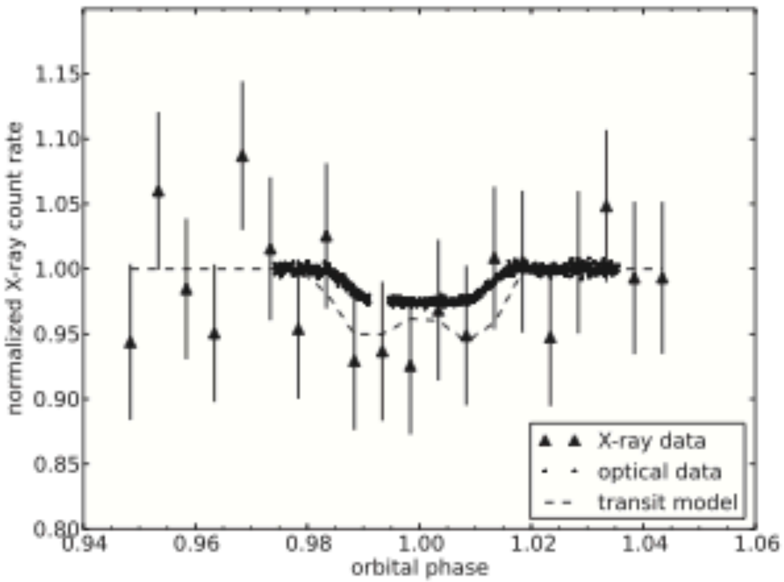
Poppenhaeger, Schmitt & Wolk 2013



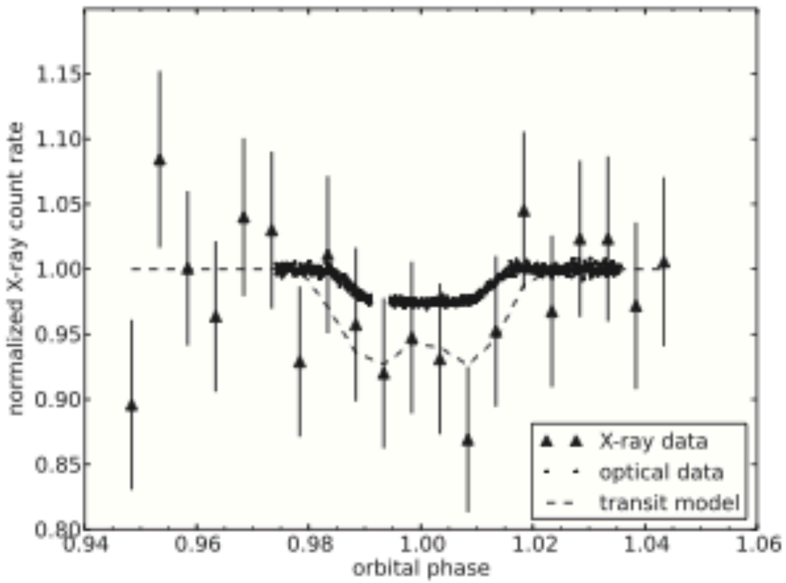


(b) Six data sets, excluding the potentially flaring *Chandra* observation

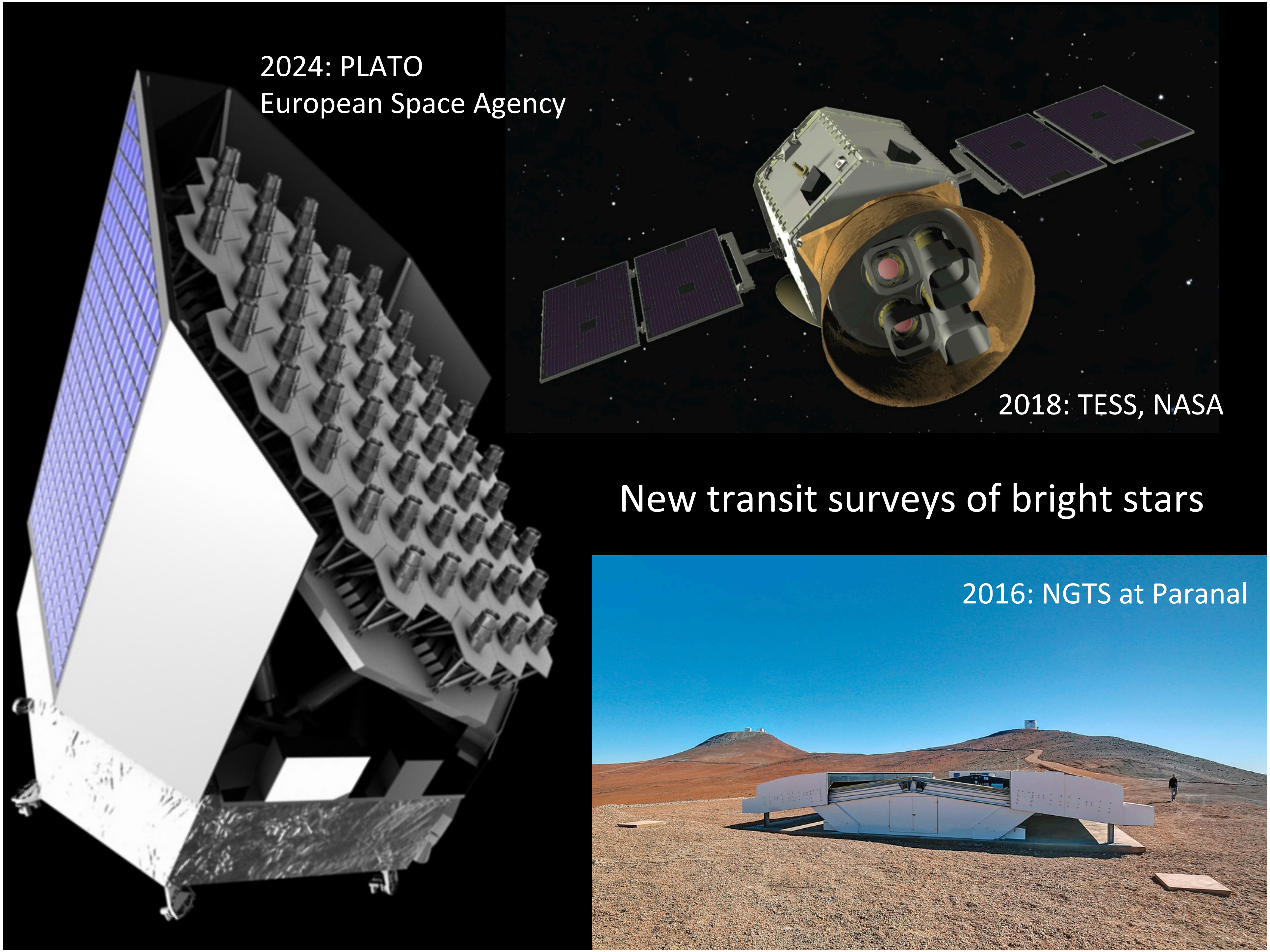
Poppenhaeger, Schmitt, & Wolk 2013



(c) Six data sets, excluding the potentially flaring *XMM-Newton* observation

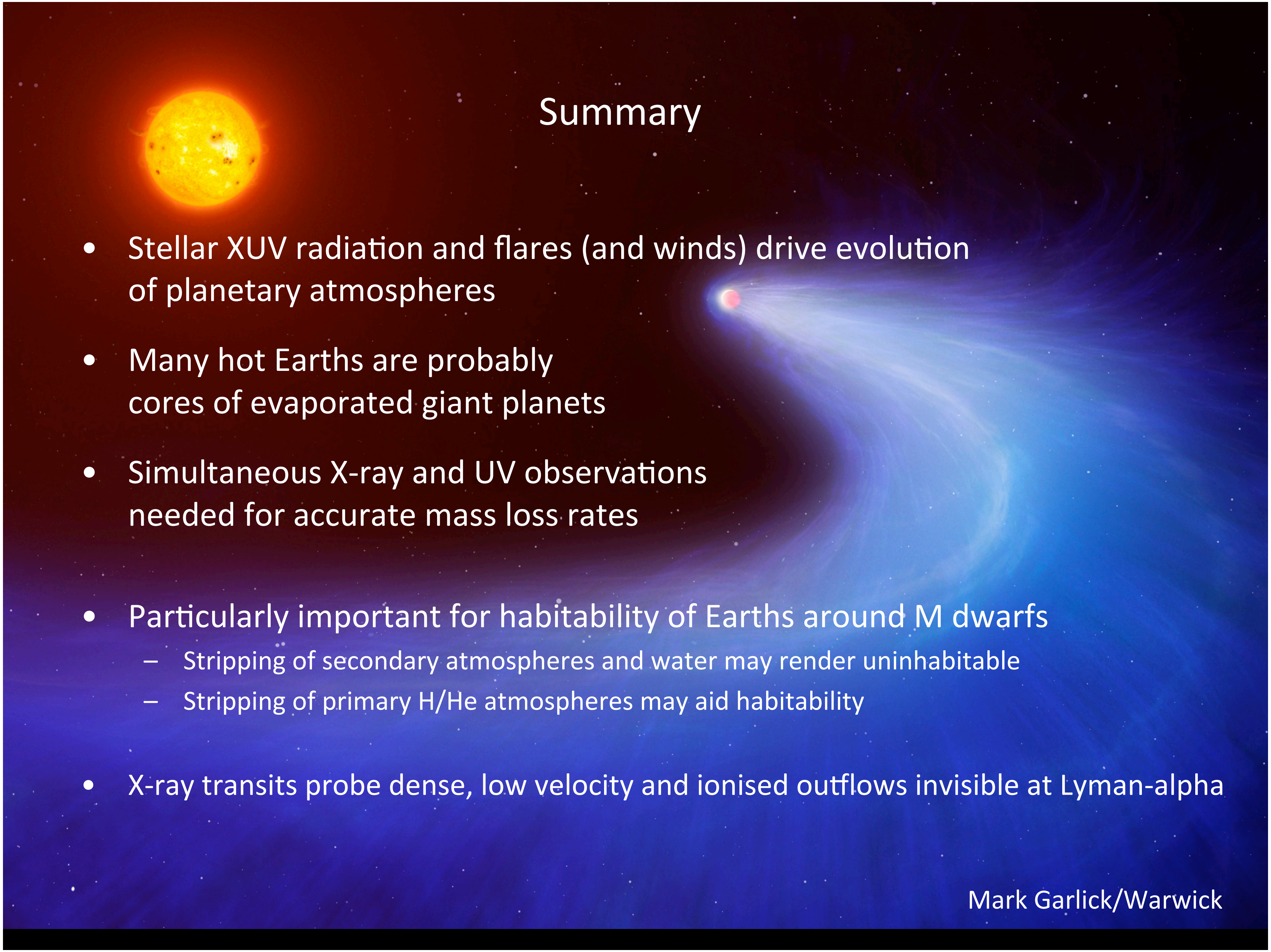


(d) Five quiescent data sets, excluding both potentially flaring observations


2024: PLATO
European Space Agency
2018: TESS, NASA
New transit surveys of bright stars
2016: NGTS at Paranal

Summary

- Stellar XUV radiation and flares (and winds) drive evolution of planetary atmospheres
- Many hot Earths are probably cores of evaporated giant planets
- Simultaneous X-ray and UV observations needed for accurate mass loss rates
- Particularly important for habitability of Earths around M dwarfs
  - Stripping of secondary atmospheres and water may render uninhabitable
  - Stripping of primary H/He atmospheres may aid habitability
- X-ray transits probe dense, low velocity and ionised outflows invisible at Lyman-alpha



Mark Garlick/Warwick