The role of X-rays in exoplanet evolution and habitability

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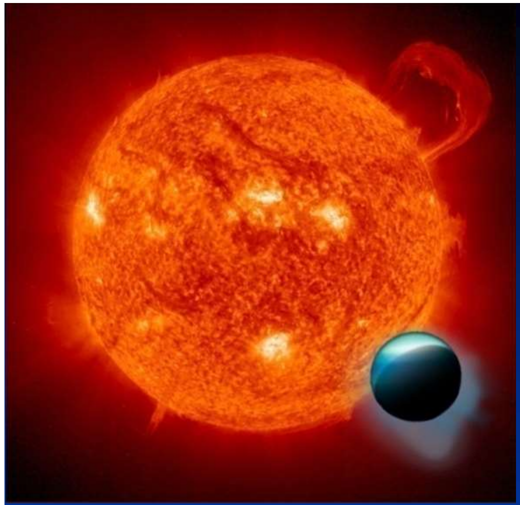
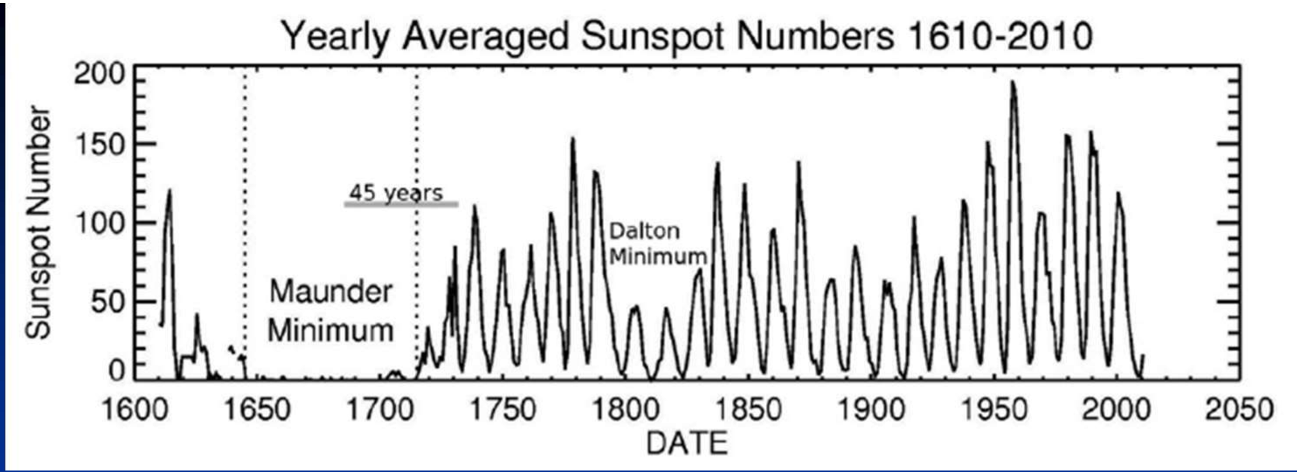
XUV ionizing radiation

Photons with λ < 912 Å ionizes H atoms, and may generate secondary UV photons. Strong effects on planets:

1. Earlier dissipation of protoplanetary disk (<10 Myr) → Settles initial planet mass
2. Atmospheric evaporation
3. Photochemistry changes. Life evolution (XUV friend or foe?)





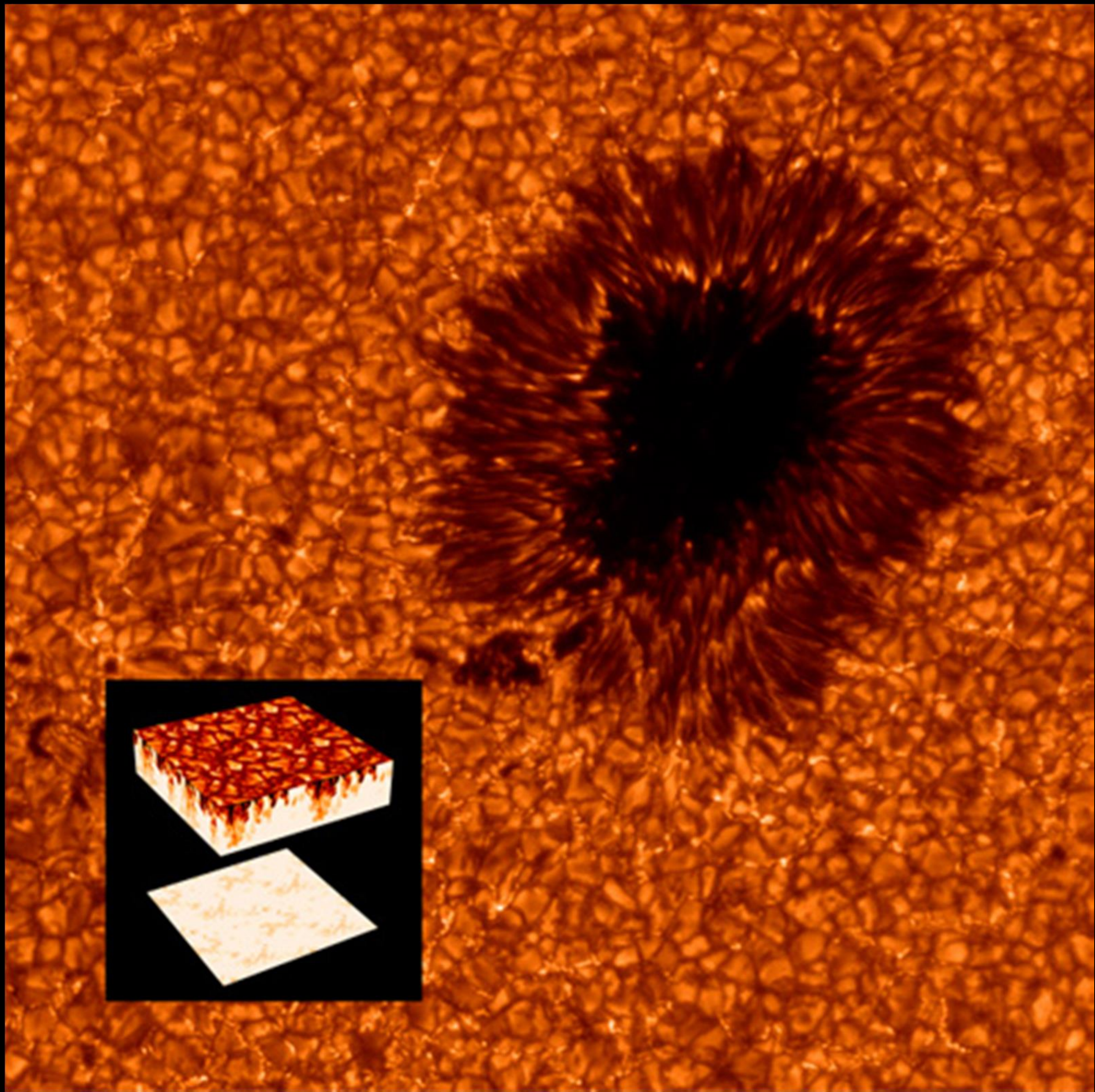
Planetary climate

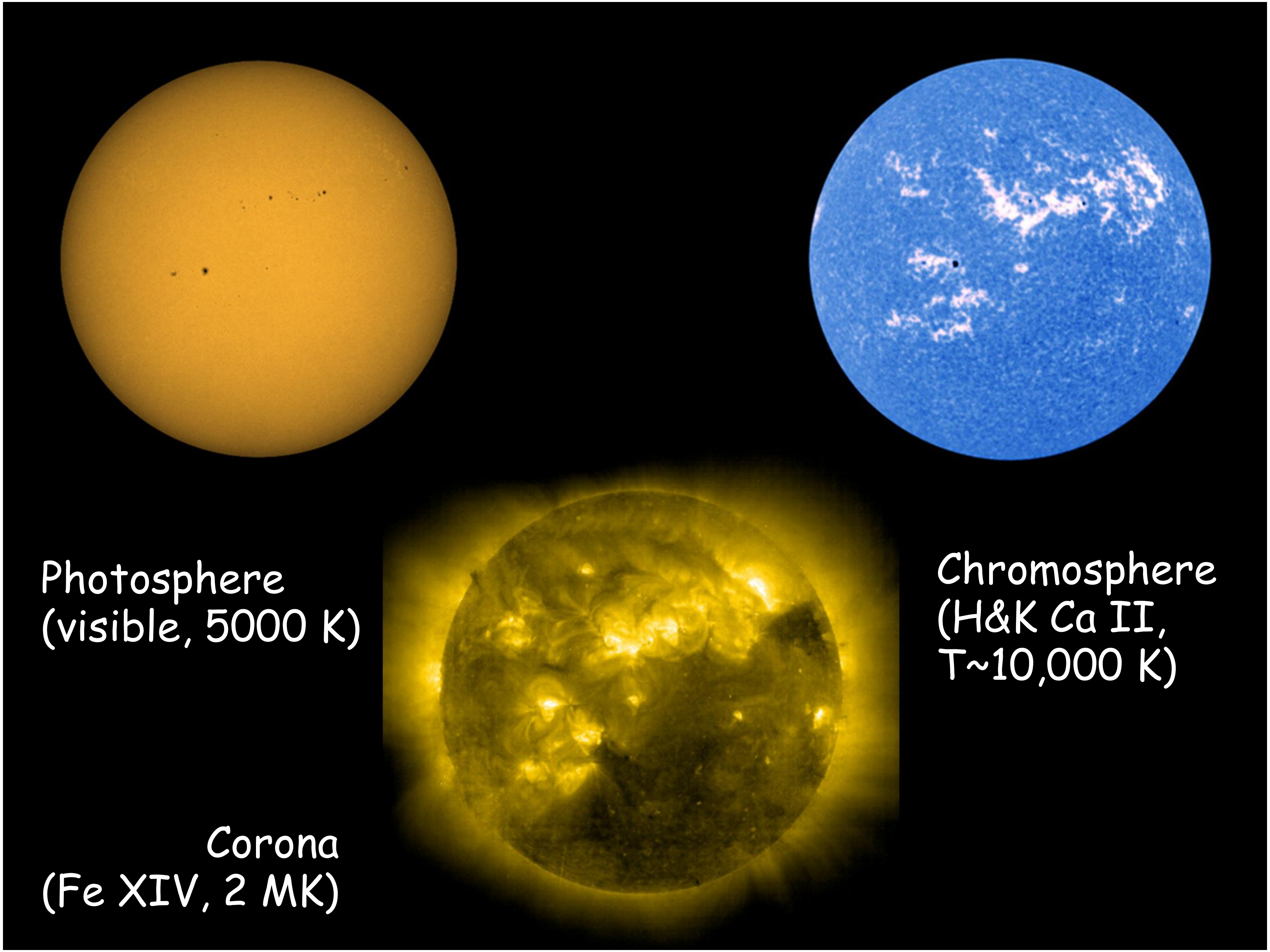
Atmospheric heating and evaporation

Atmospheric chemistry

Life evolution

Aurorae

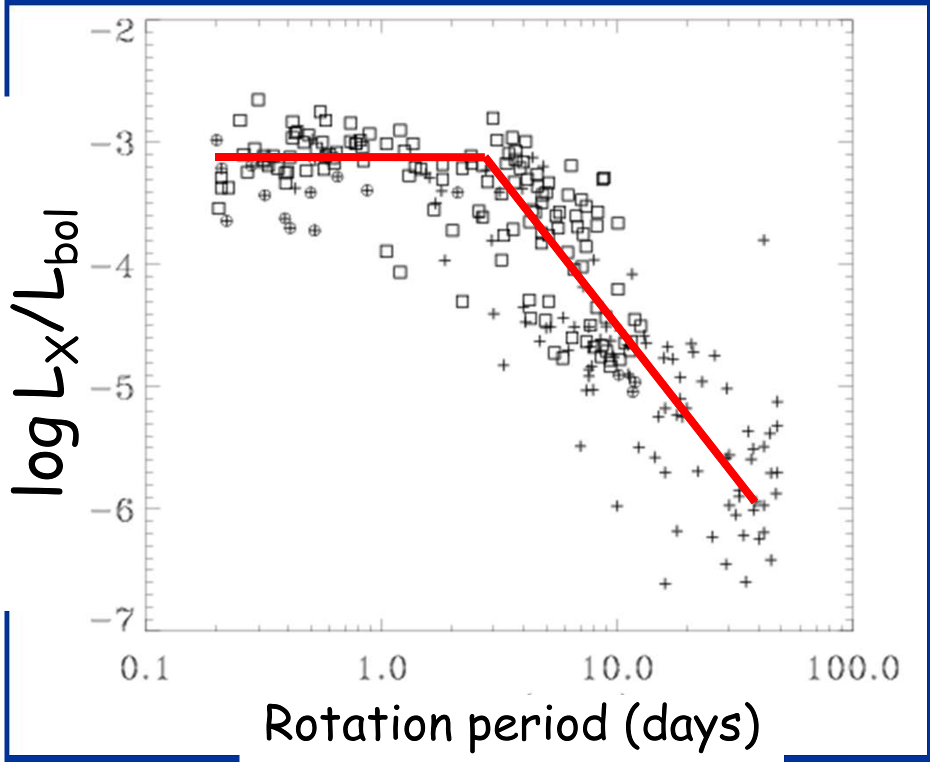


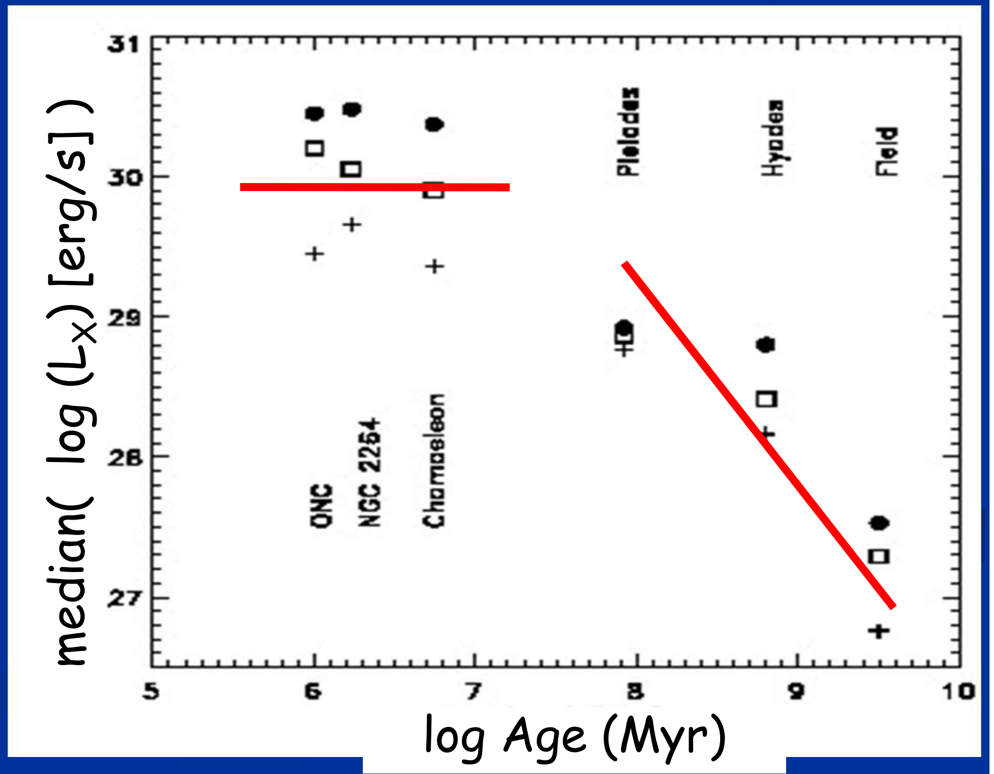

Photosphere
(visible, 5000 K)
Chromosphere
(H&K Ca II,
T~10,000 K)
Corona
(Fe XIV, 2 MK)

All flux in X-rays, EUV and FUV (≈1-1300 Å) is originated in the corona, transition region and upper chromosphere.

X-rays evolution with time

- Late type stars (F, G, K, M) have a corona.
- Activity depends on rotation. Rotation depends on age
- X-rays will decrease as star gets older (slower rotator)



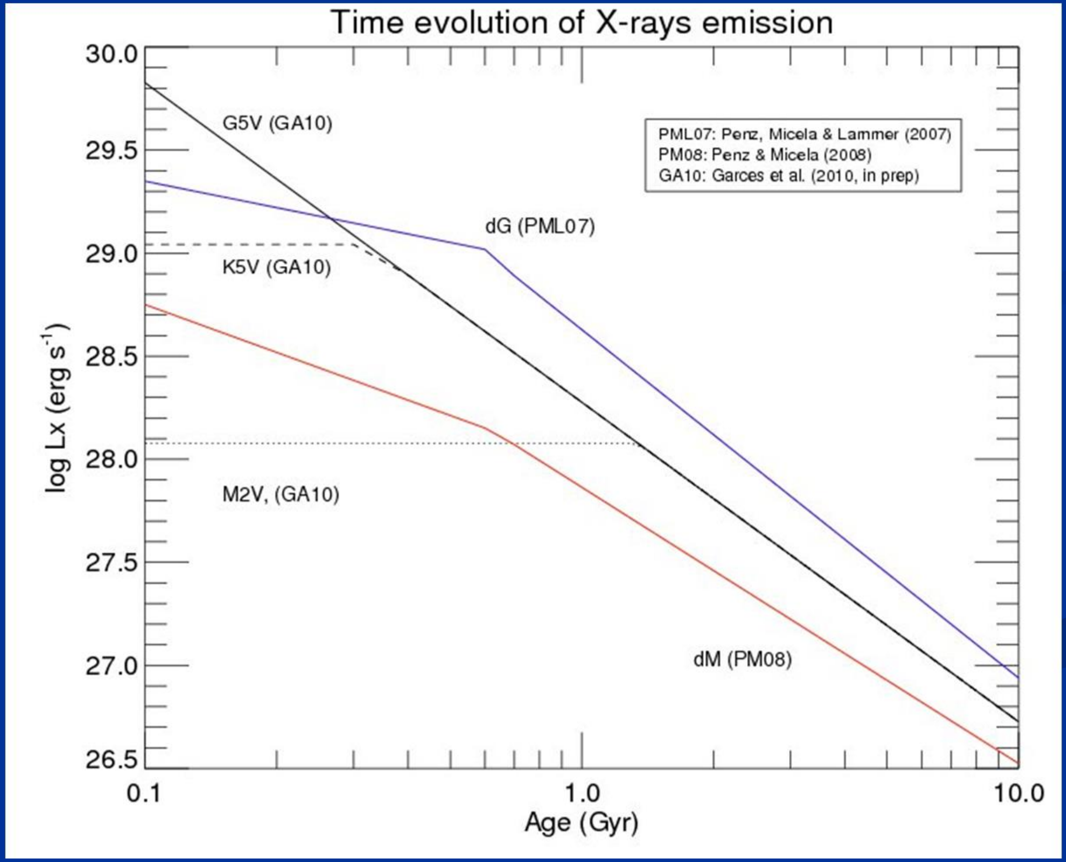


Time evolution of XUV

We should care about rotational age, rather than real age

Dependency log Lx vs log T:

- Maggio (1987): -1.5 (G)
- Ayres (1997): -1.74 (G2V)
- Ribas et al. (2005): -1.92 (1-20 Å), -1.27 (20-100 Å) (G2V)
- Penz et al. (2007): -1.69 (G)
- Penz & Micela (2008): -1.34 (M)
- Garcés et al. (2011): -1.55 (G-M)

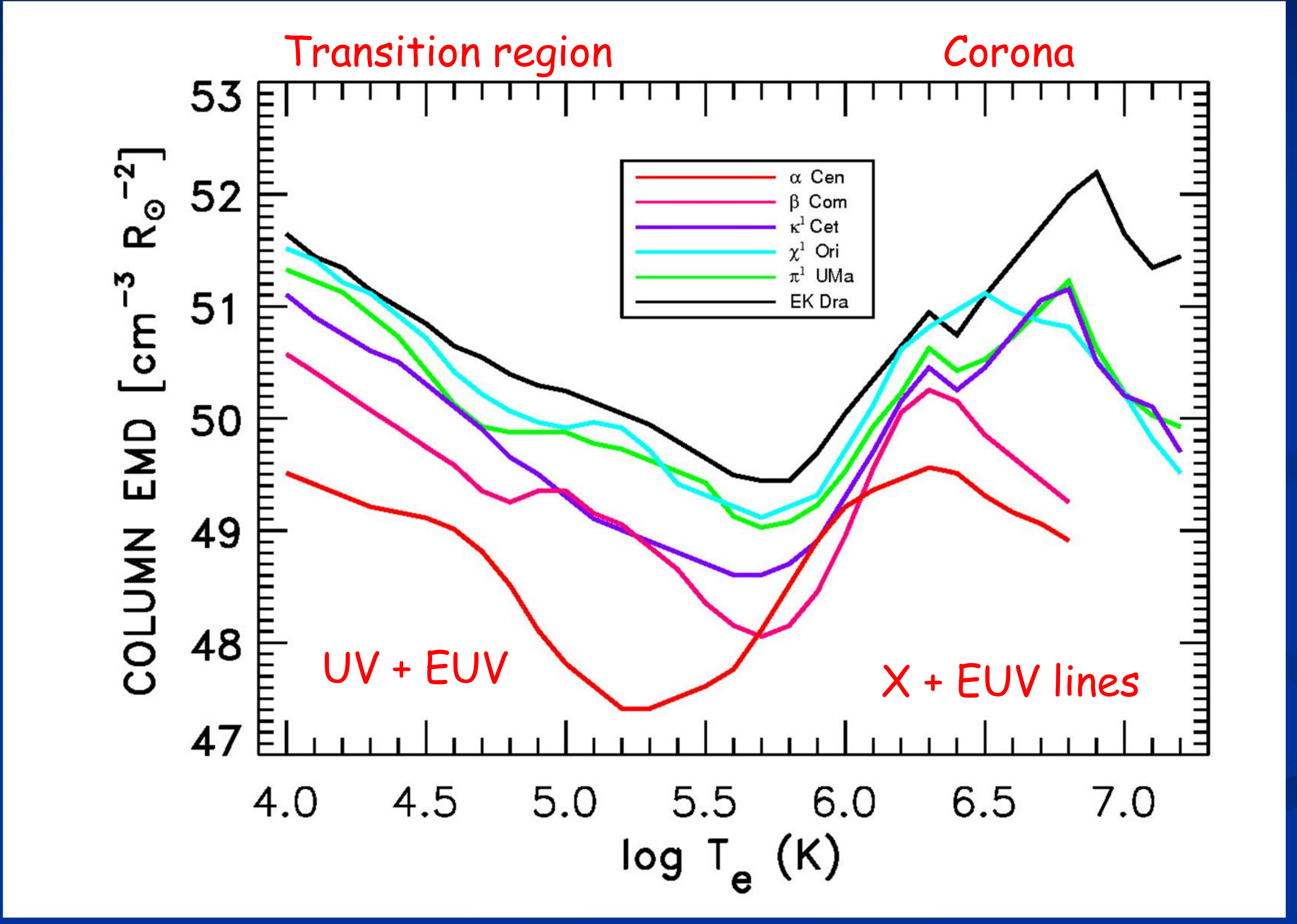


How to know XUV radiation

X-rays (1-100 Å) o.k. EUV (100-920 Å) absorbed by interstellar medium

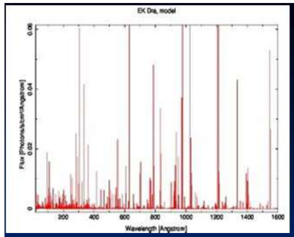
- Use solar spectrum to scale it by stellar size: only as first approximation
- Use coronal model to create a SED (Cnossen+ 2007, Sanz-Forcada+ 2011 – X-exoplanets): High spectral resolution SED. Best possible.

A coronal model requires information on both transition region and corona

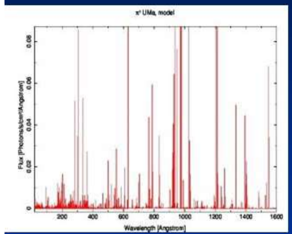


Sanz-Forcada & Ribas (2015, in prep.)

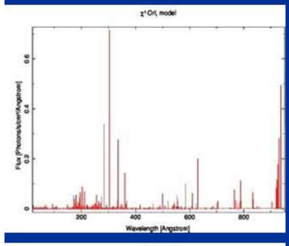
Solar evolution



EK Dra

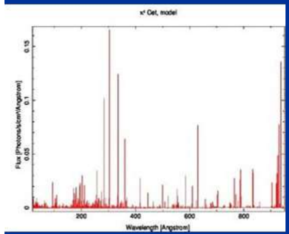


π^1 UMa

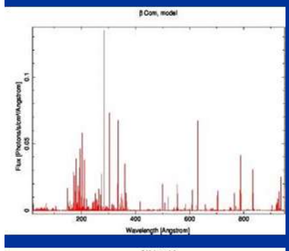


χ^1 Ori

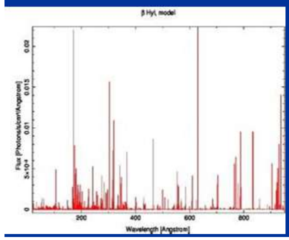
t



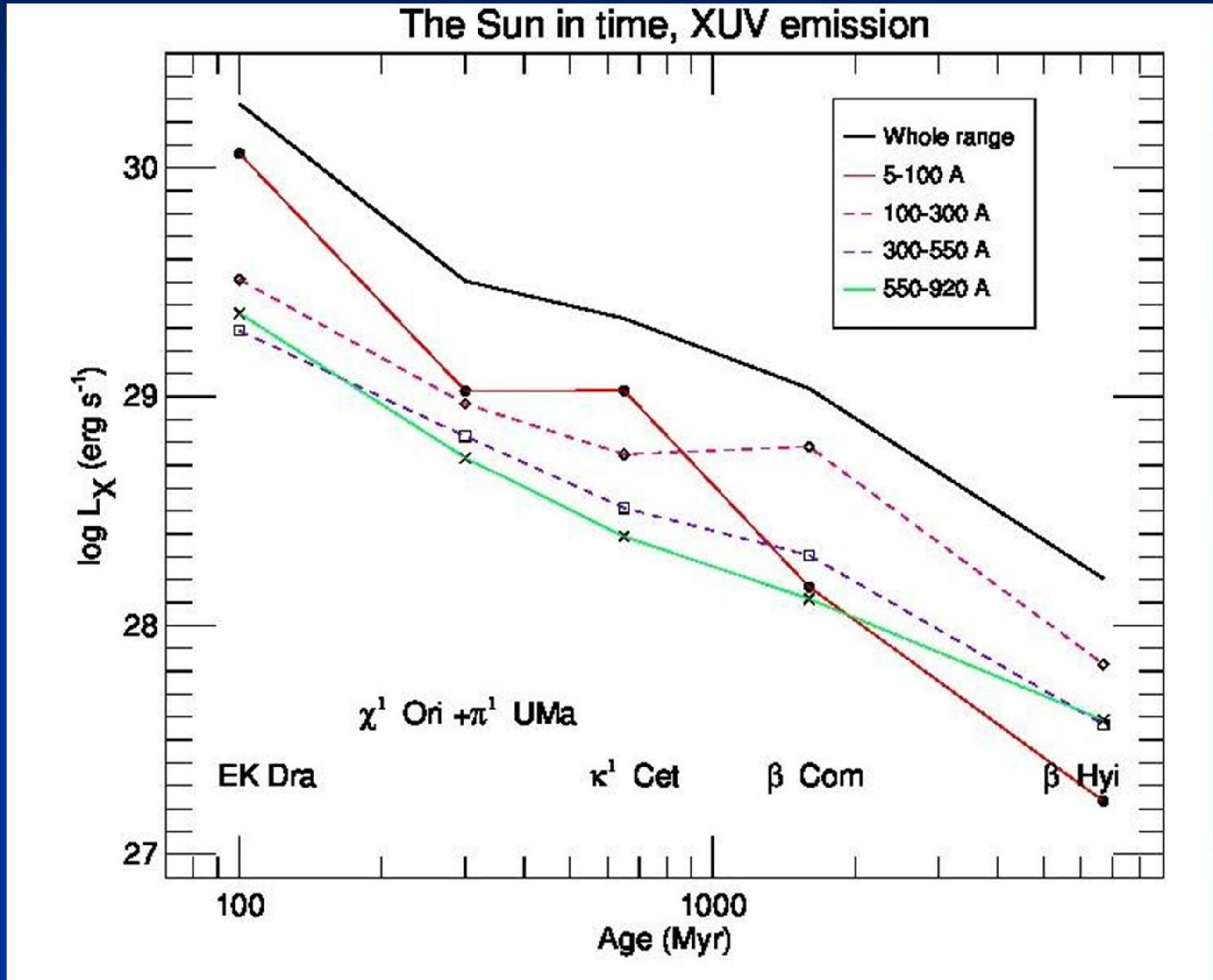
κ^1 Cet



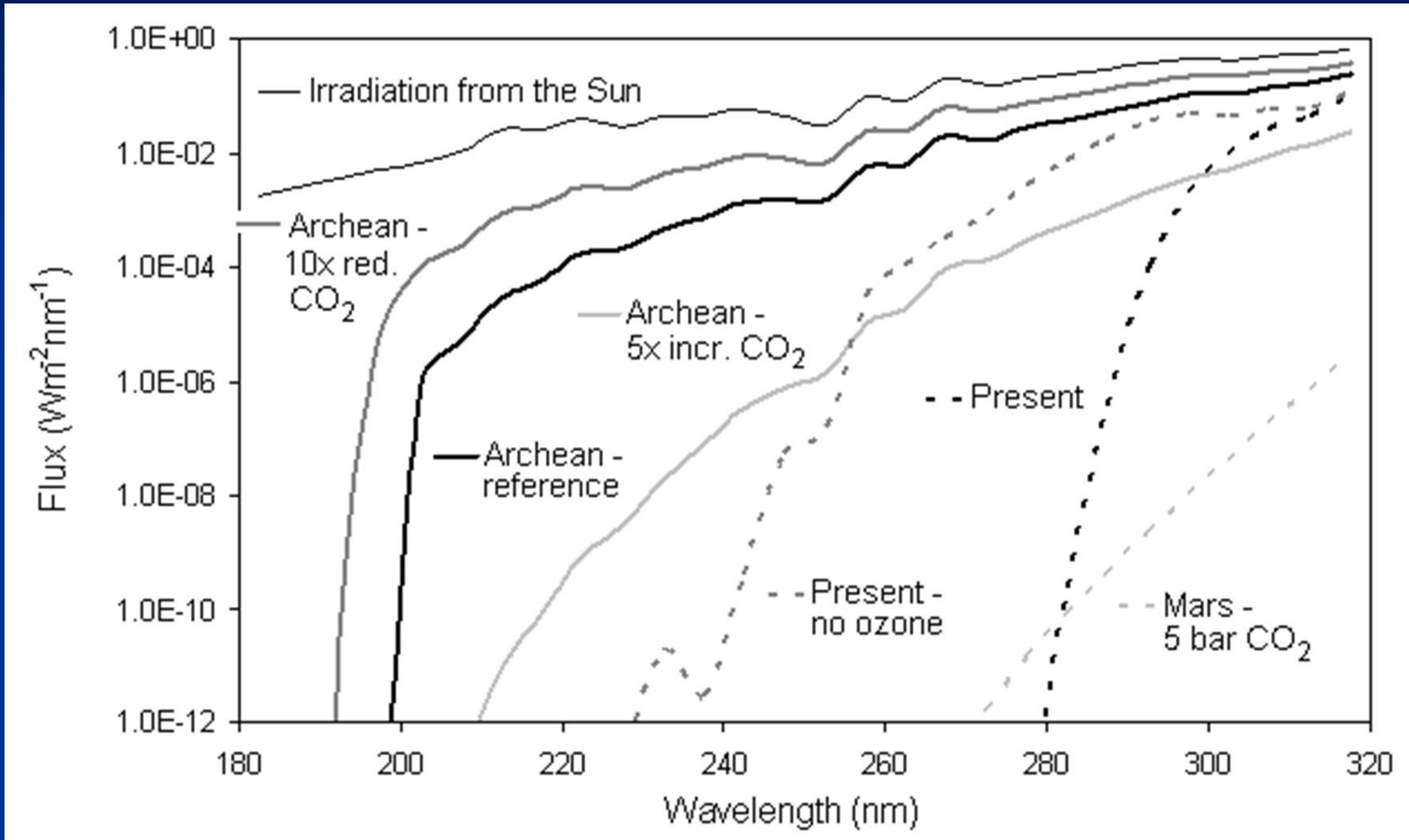
β Com



β Hyi



Habitat of early life: Solar X-ray and UV radiation at Earth's surface 4-3.5 Gya

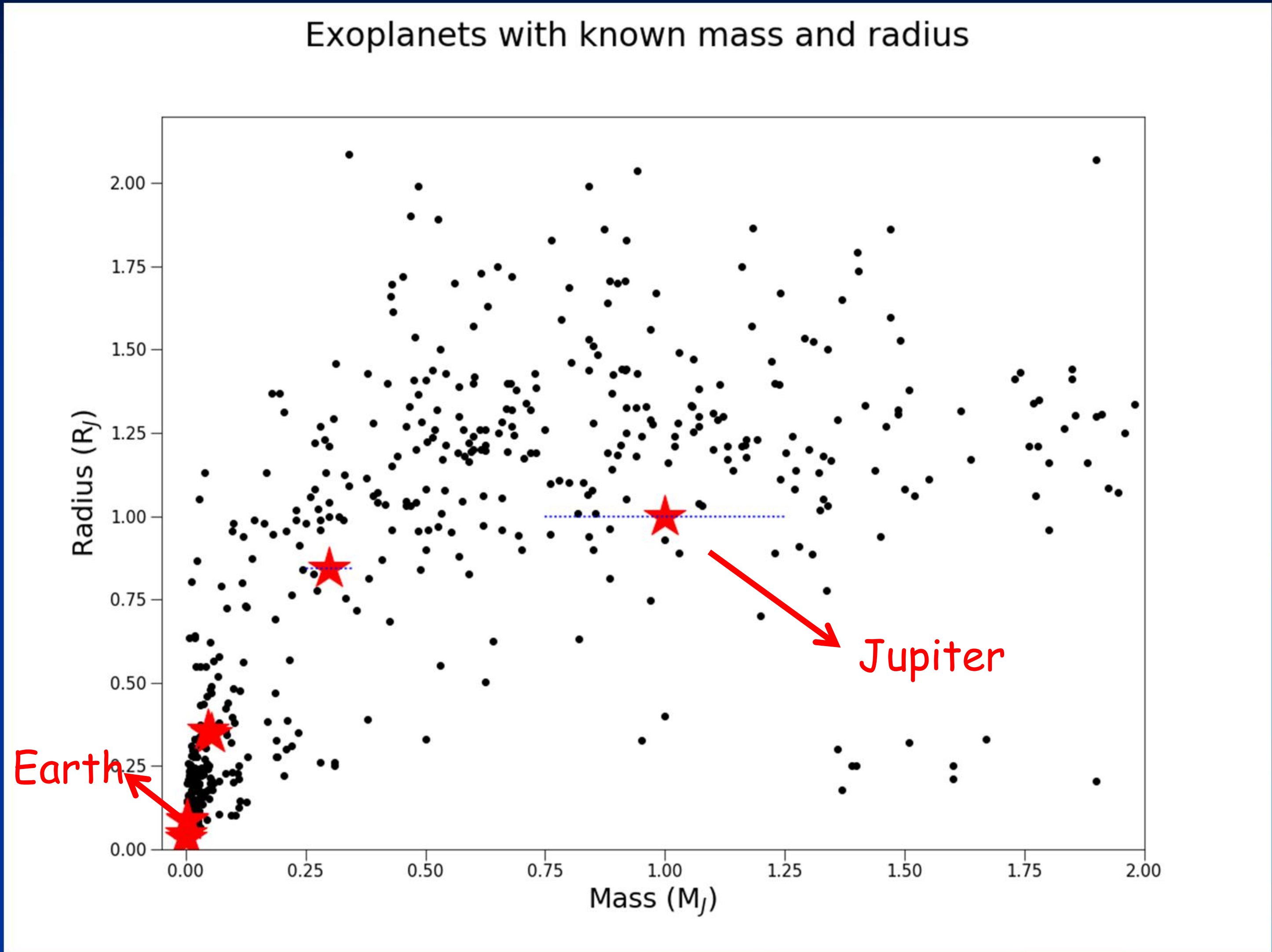


Cnossen, Sanz-Forcada, et al. (2007), JGRE 112, 2008

Early Sun had ~100 times more Lx than present Sun

Secondary photons might bring even higher UV flux

Transiting planets have short period orbits, thus they are very close to the star (bias)…



… they receive much XUV radiation, they are inflated

Mass loss

- Coronal radiation (X-rays, EUV) heats the planet atmosphere, yielding evaporation.
- Planet gravity tries to keep the atmosphere.

Expansion radius (β≥1)

Coronal flux (EUV+X)

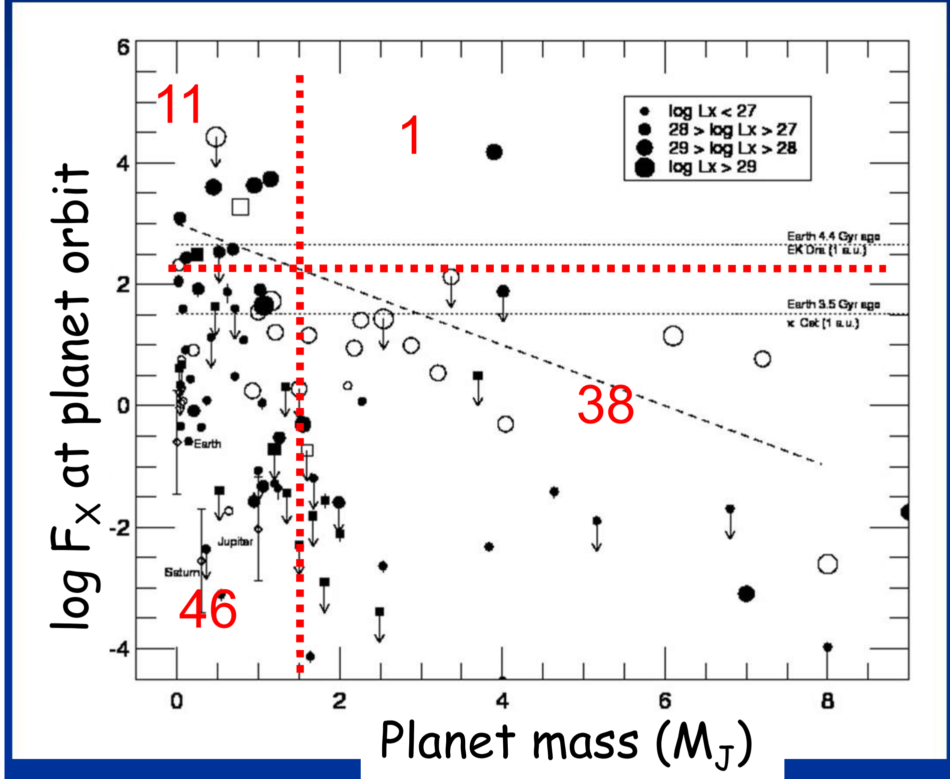
$$\dot{M} = \frac{\pi \beta^3 R_p^3 F_{XUV}}{GKM_p} \Rightarrow \dot{M} = \frac{3\beta^3 F_{XUV}}{4GK\rho} \Rightarrow \dot{M} \geq \frac{3F_{XUV}}{4G\rho}$$

Roche lobe fill-in (K≤1)

Planet density

Watson et al. (1981), Lammer et al. (2003), Baraffe et al. (2004), Erkaev et al. (2007)

X-ray flux vs planet mass



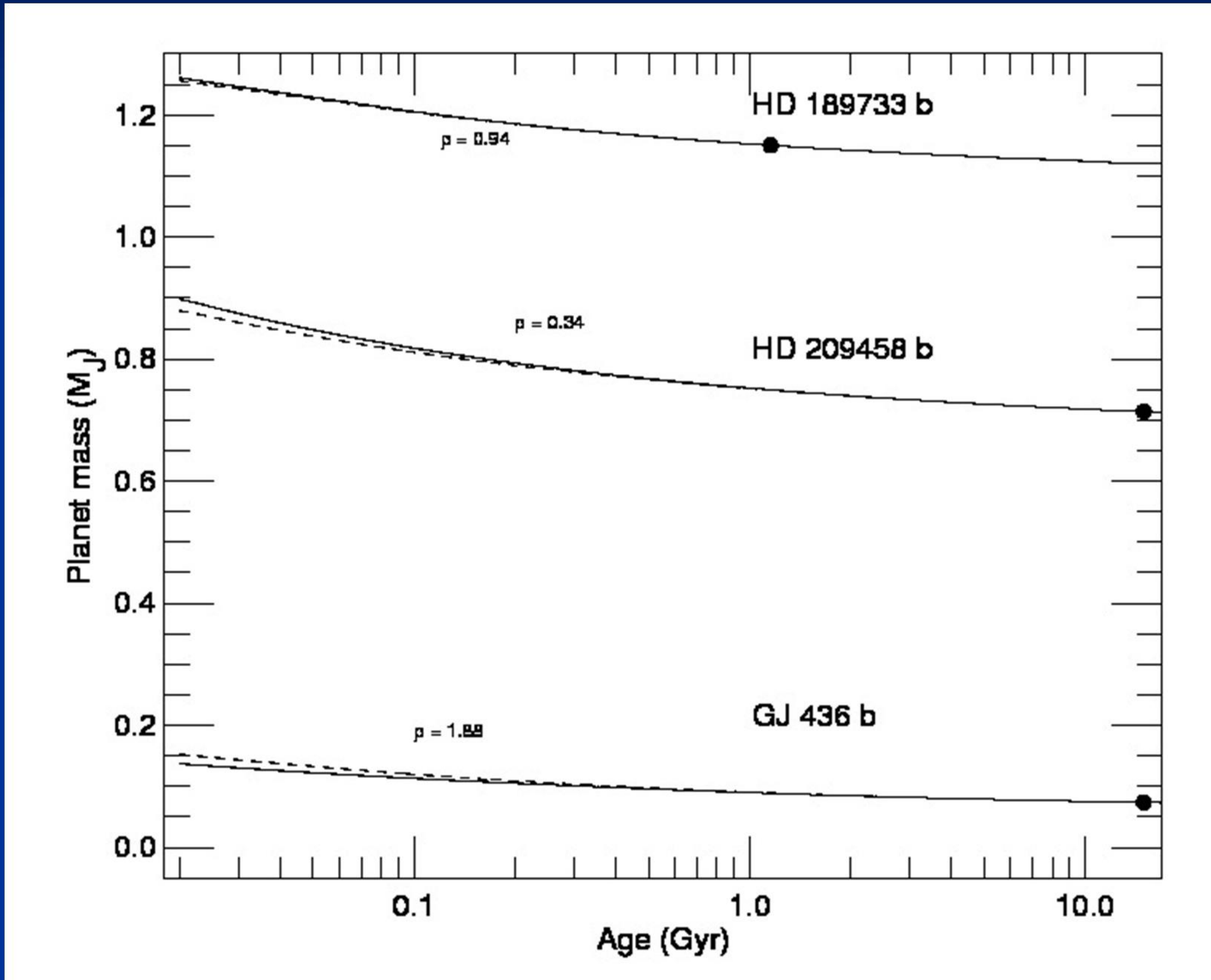
Sanz-Forcada et al. (2010, 2011)

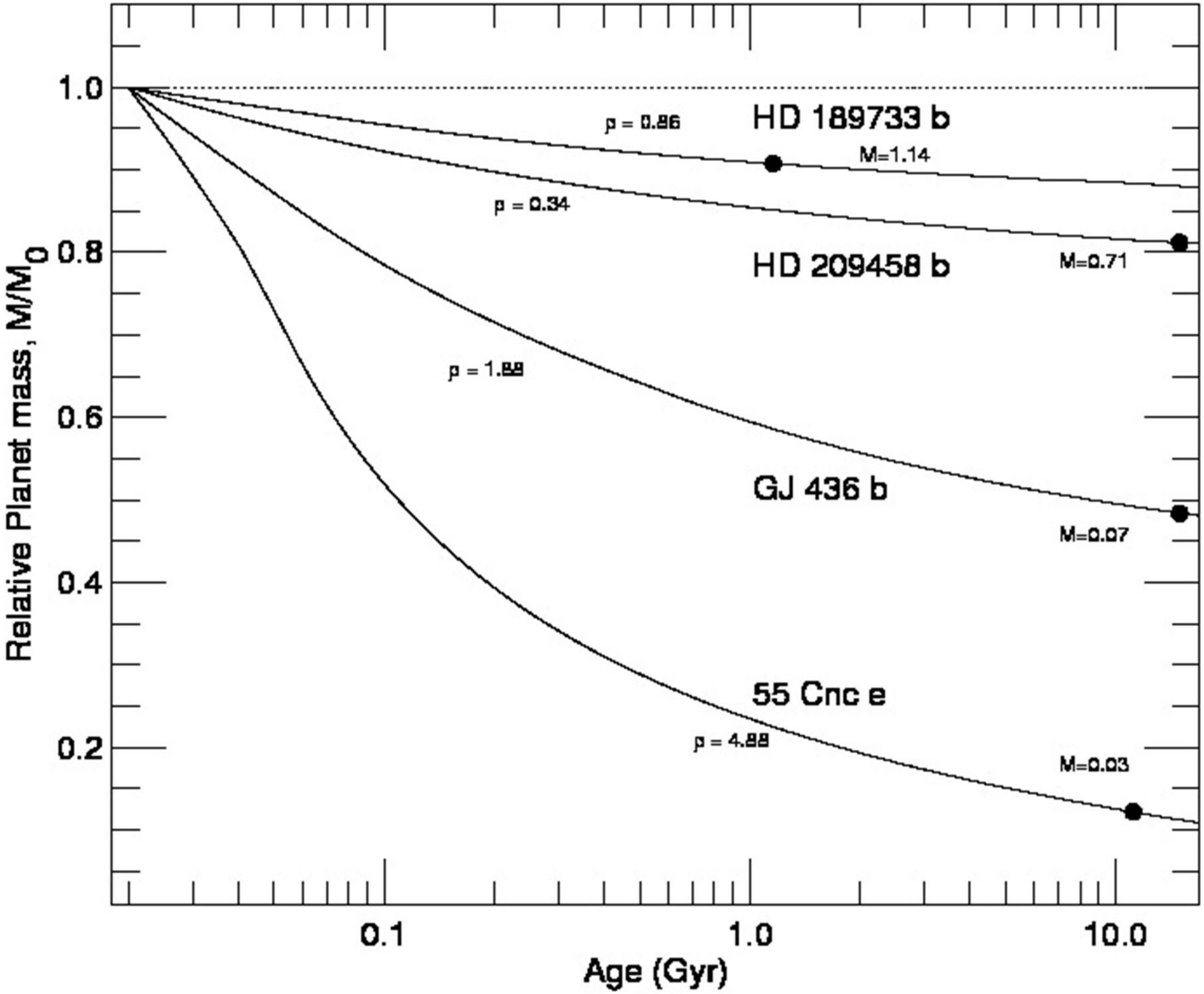
● Dwarfs ○ ROSAT ◊ Solar System
■ Subgiants ● XMM/Chandra

Lack of massive planets being irradiated.
Possible explanations:

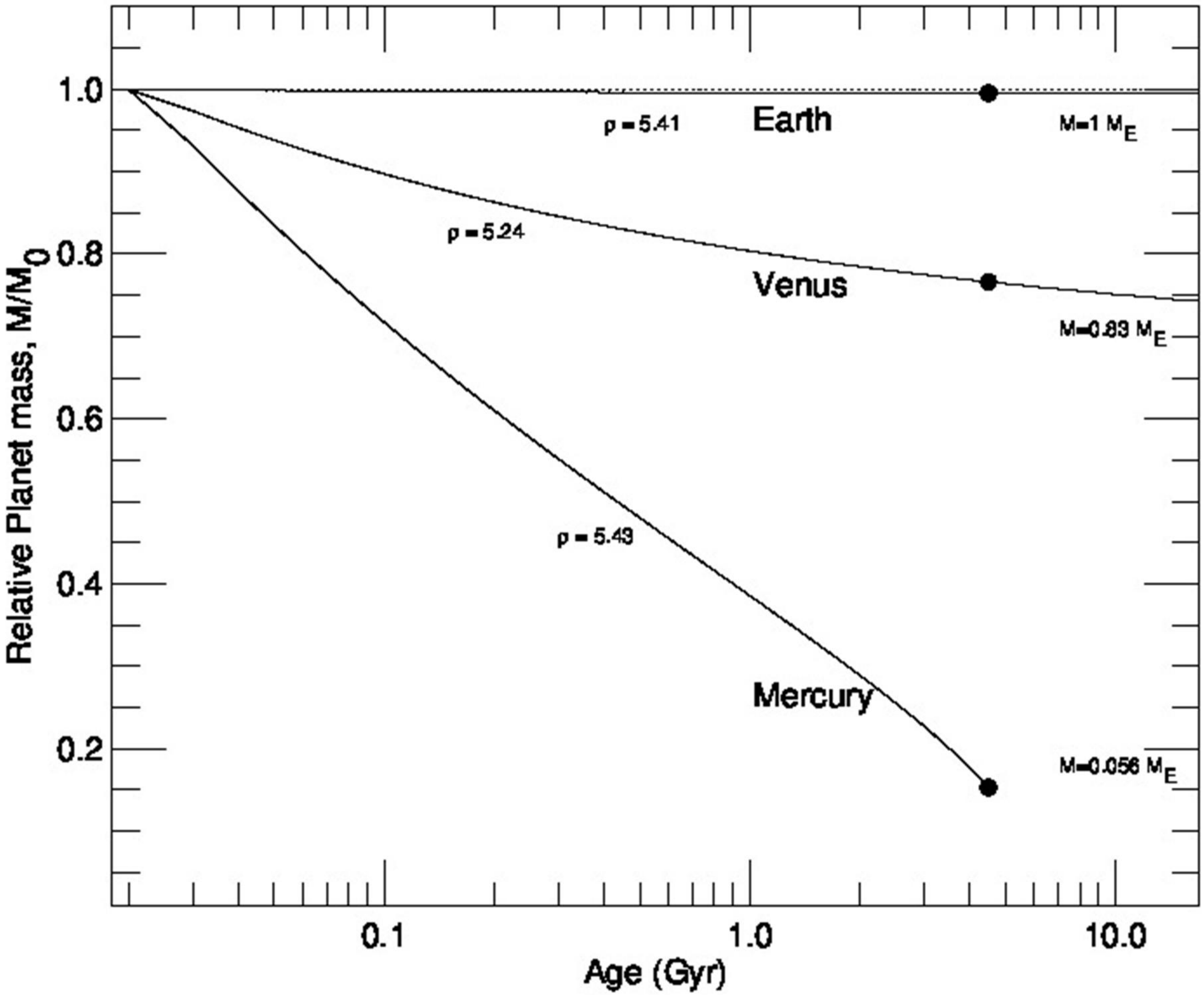
- Rapid mass loss during first Gyr
- Effects of planet formation
- A combination of both

Planet mass evolution





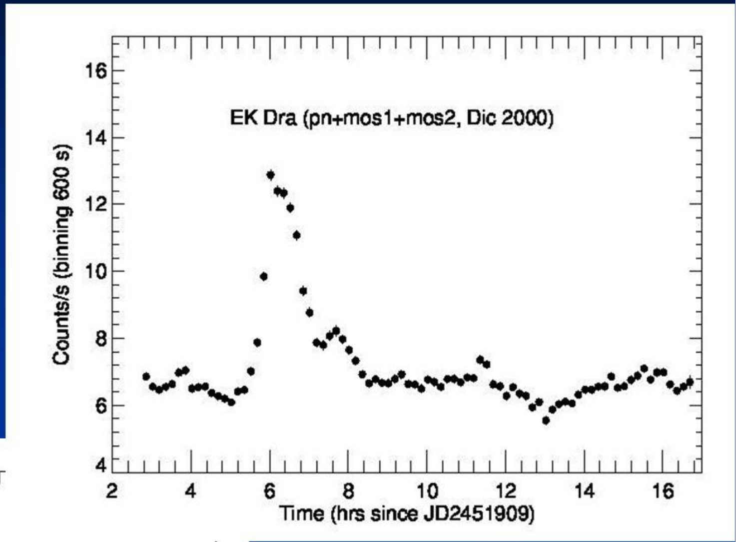
Relative Planet mass, M/M_0
Age (Gyr)
1.0
0.8
0.6
0.4
0.2
0.1
1.0
10.0
HD 189733 b
p = 0.86
M=1.14
p = 0.34
HD 209458 b
M=0.71
p = 1.88
GJ 436 b
M=0.07
55 Cnc e
p = 4.88
M=0.03

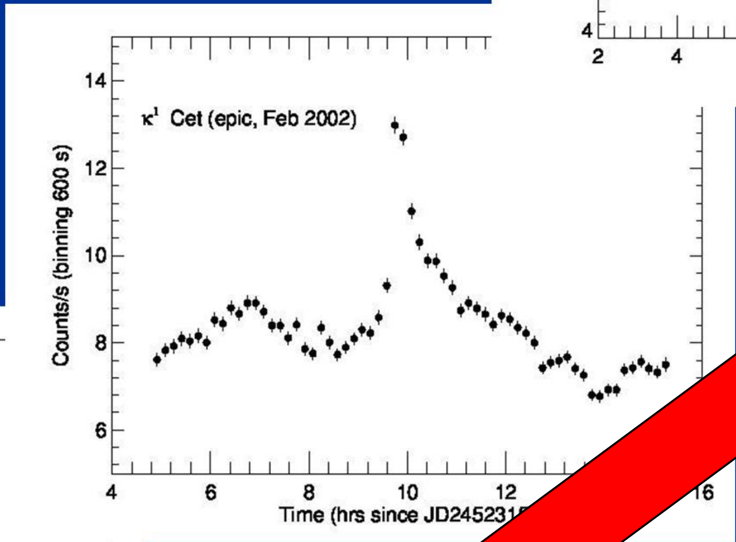


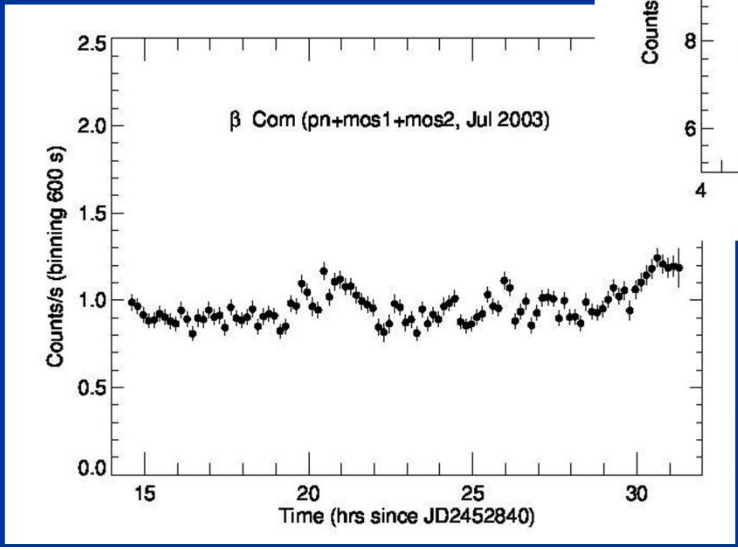
1.0
0.8
0.6
0.4
0.2
Relative Planet mass, M/M0
ρ = 5.41
Earth
M=1 ME
ρ = 5.24
Venus
M=0.83 ME
ρ = 5.43
Mercury
M=0.056 ME
0.1
1.0
10.0
Age (Gyr)

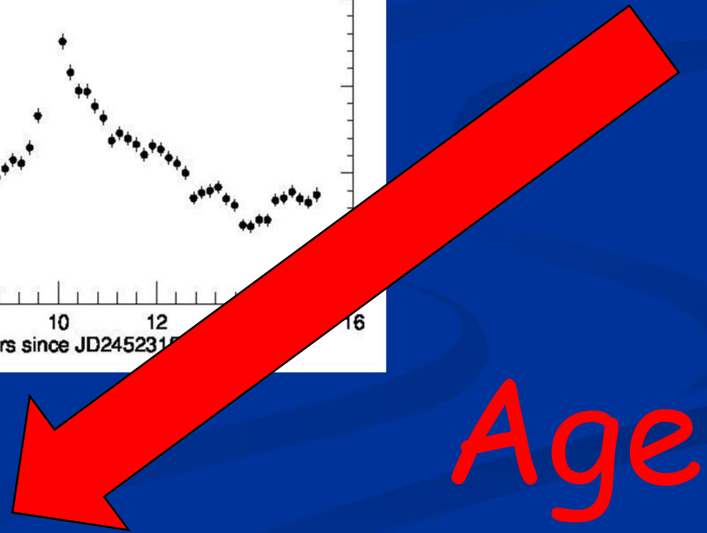
Variability (flares, cycles, CMEs)

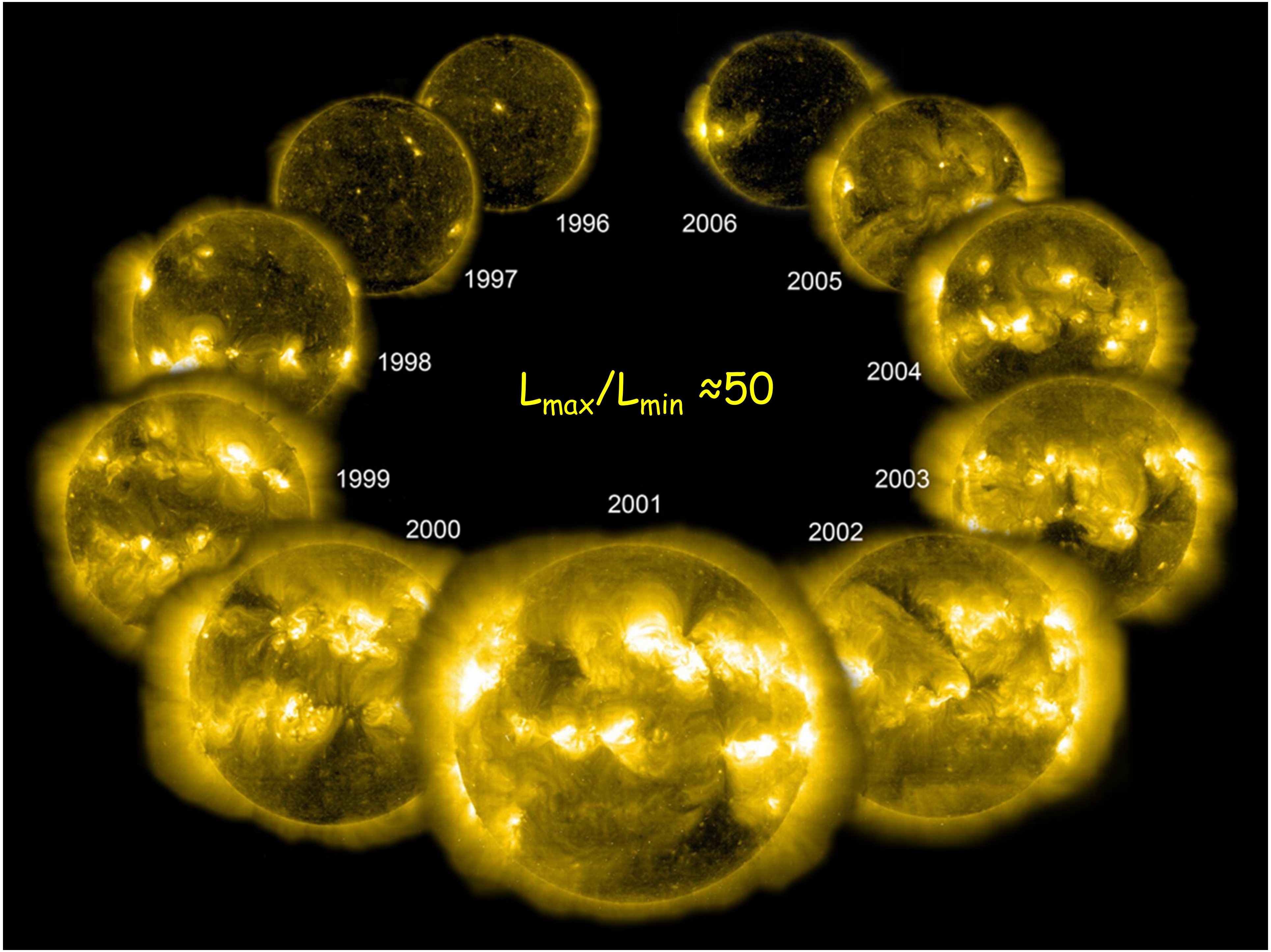
- Flares are episodic
- More frequent in young stars
- Increase atmosphere electron density (Chadney+ 2017)

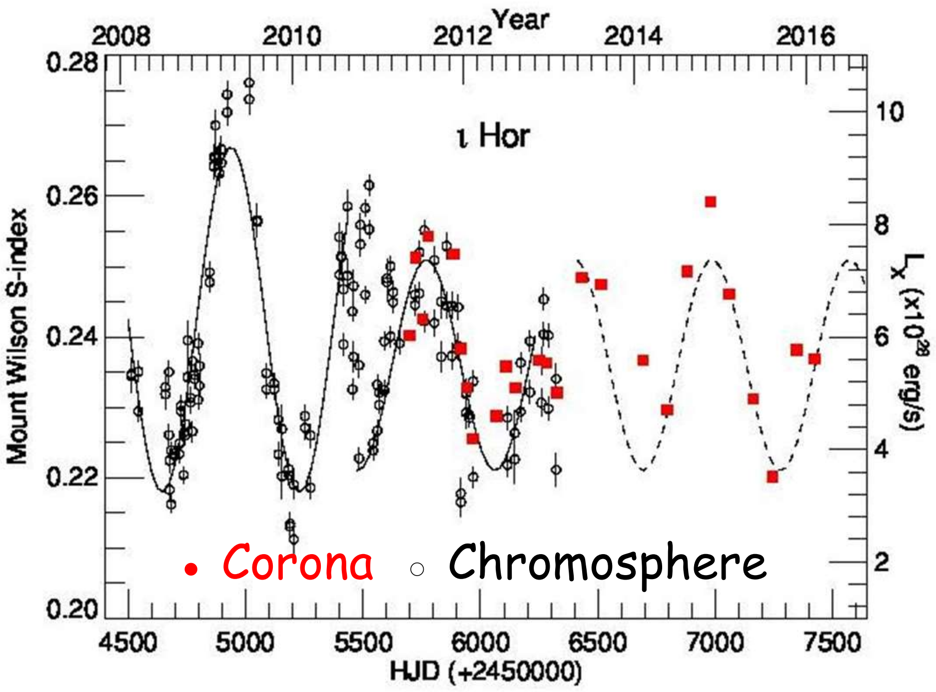









1996
2006
1997
2005
1998
2004
$L_{max}/L_{min} \approx 50$
1999
2003
2001
2000
2002



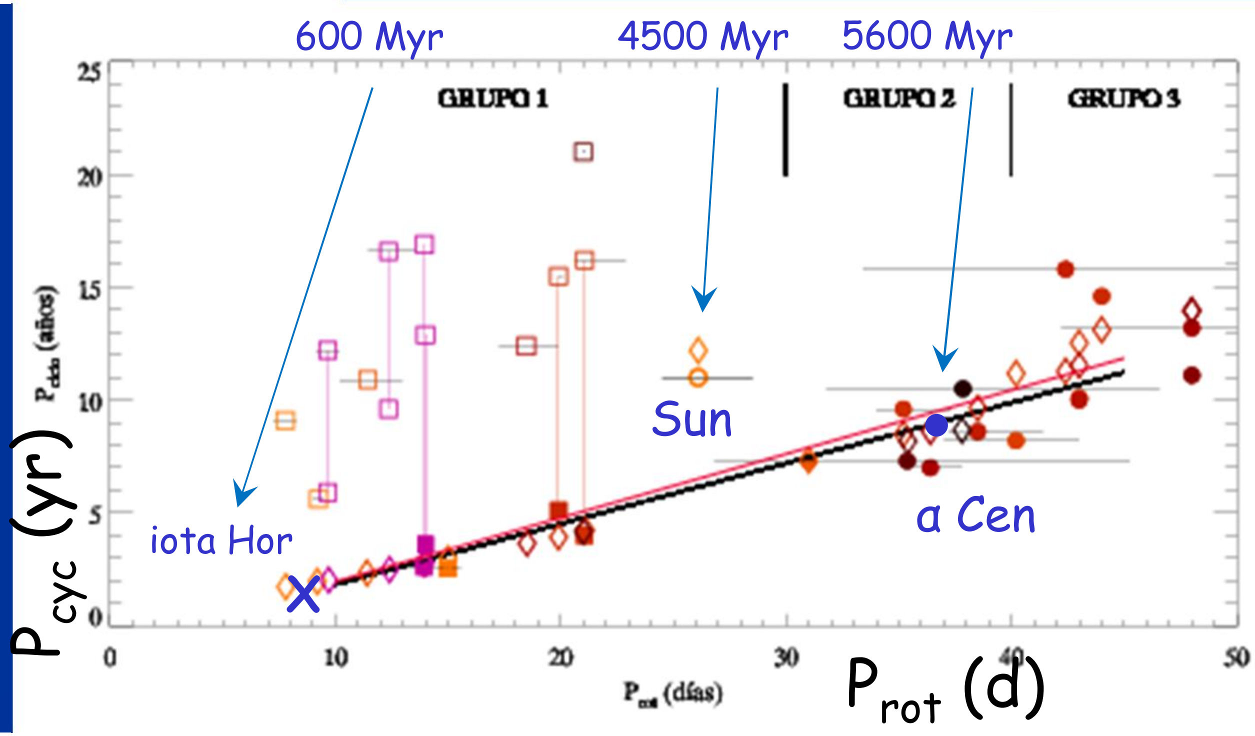
Sanz-Forcada, Stelzer & Metcalfe (2013, 2016)

iota Hor (age similar to κ Cet): earliest coronal cycles observed, amplitude factor ~2

Amplitude increases with age

- G0V, age 600 Myr
- Cycle of 1.6 yr
- ι Hor b: 1.9 M_J / 0.9 a.u.
- L_{max}/L_{min} ≈2 (<< 50)

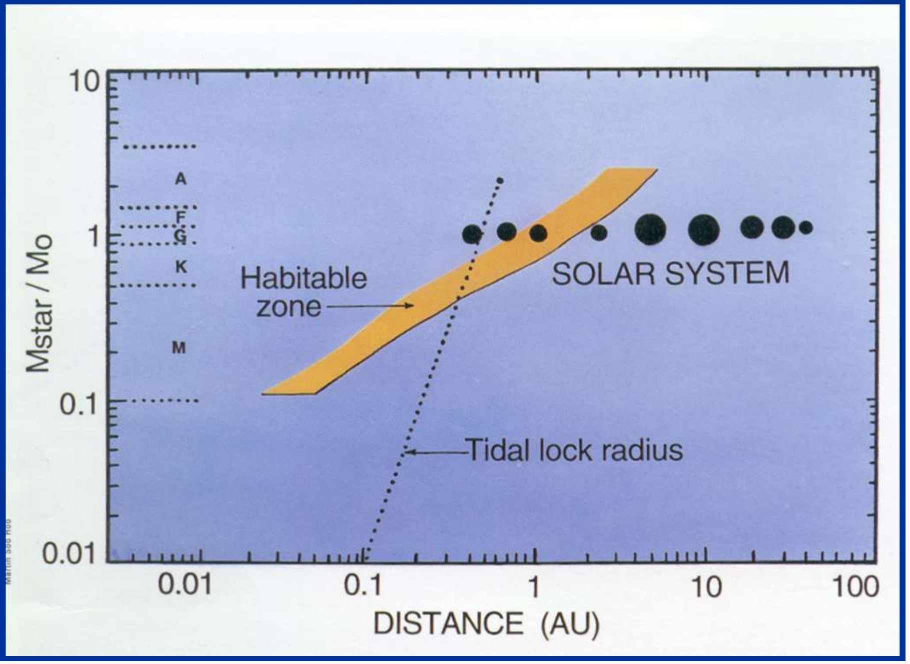
Lorente & Montesinos (2005)



Coronal Mass Ejections

- CMEs are made of charged particles
- If they reach the planet they may erode substantially the atmosphere (take away charged particles - "ion picking")
- Probability (~ d^2) to reach the HZ is 25 times larger (M0), or up to 200 times larger (M5), than in a G2

See also Chadney et al. (2015, 2017) for effects of radiation in atmospheres of planets around M active stars



Open questions

- Is the higher XUV radiation of the early Sun the answer to the Young Sun Paradox?
- Are solar cycles inducing a modulation in the planet atmosphere? What is the effect on the planet? (earliest solar cycles started ~3.9 Ga)

Conclusions

- Stellar high energy radiation has strong influence in planet atmosphere
- XUV radiation decreases with age. Still high at 500-1000 Myr (life emerged on Earth)
- Short term variability frequent at young ages
- Watch out for long term variability (at least factor ~2)
- M stars have a probability of a CME impact on HZ planet increased by a factor of 200 (M5V vs G2V)