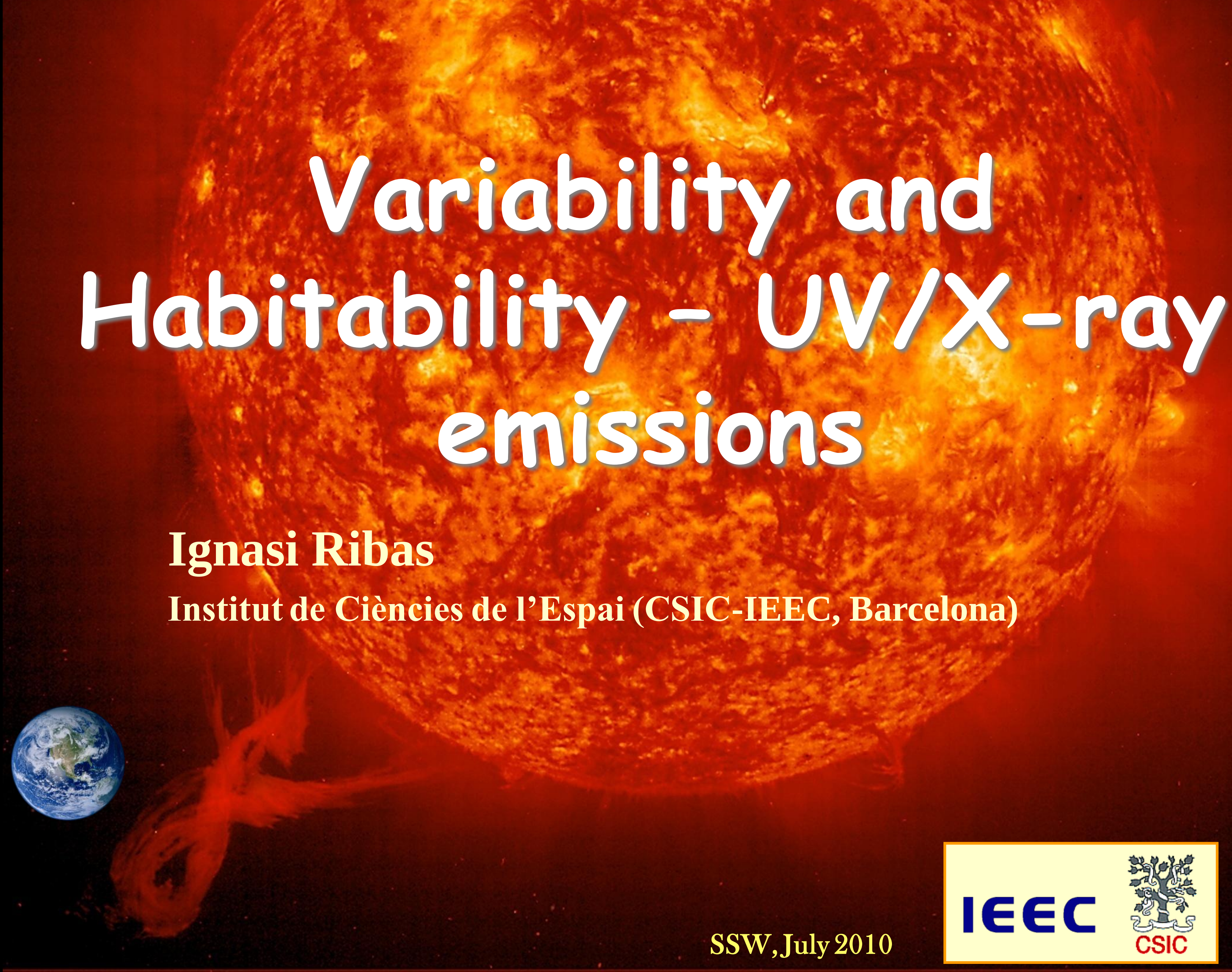


Variability and Habitability – UV/X-ray emissions

Ignasi Ribas

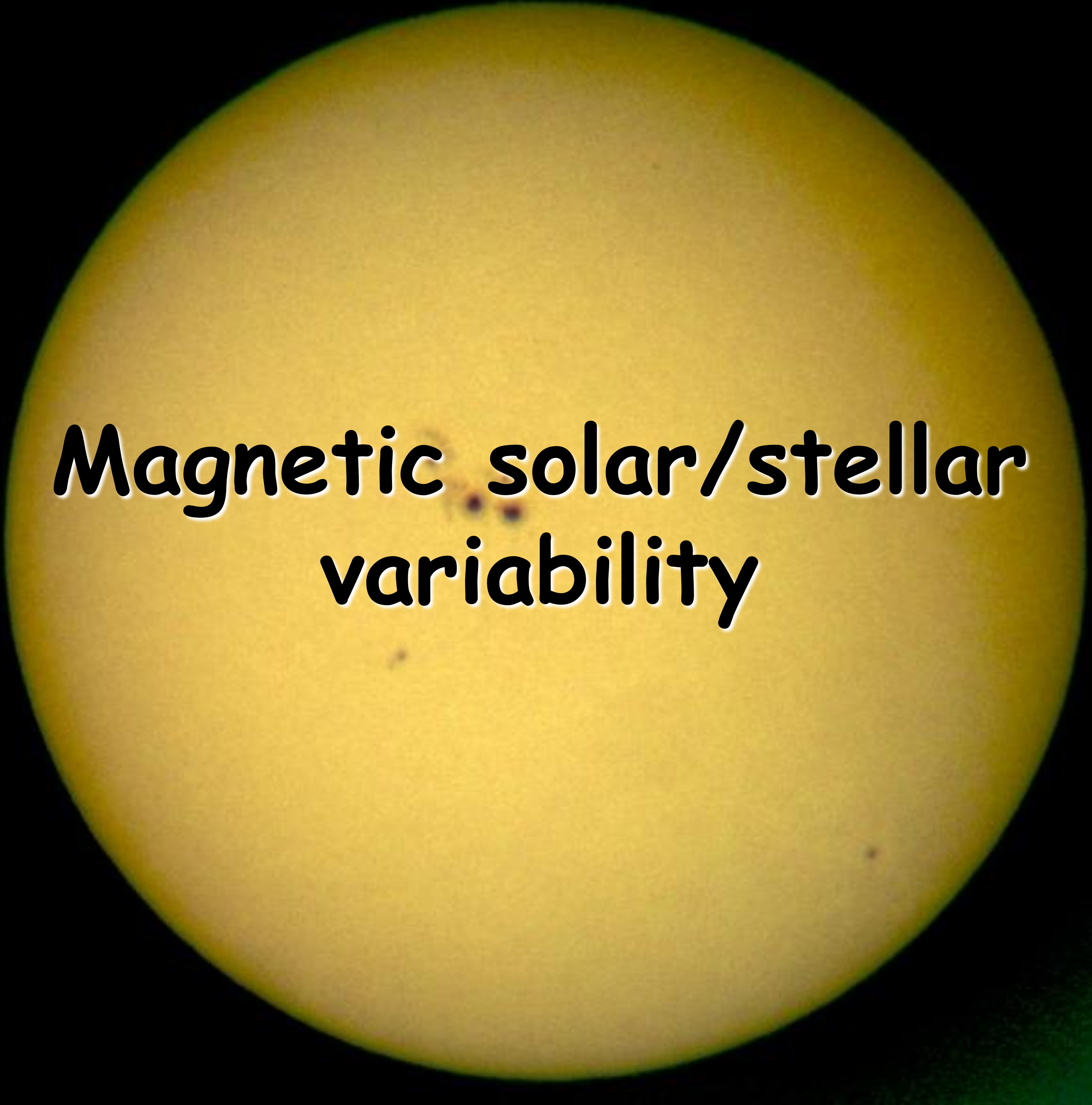
Institut de Ciències de l'Espai (CSIC-IEEC, Barcelona)

SSW, July 2010

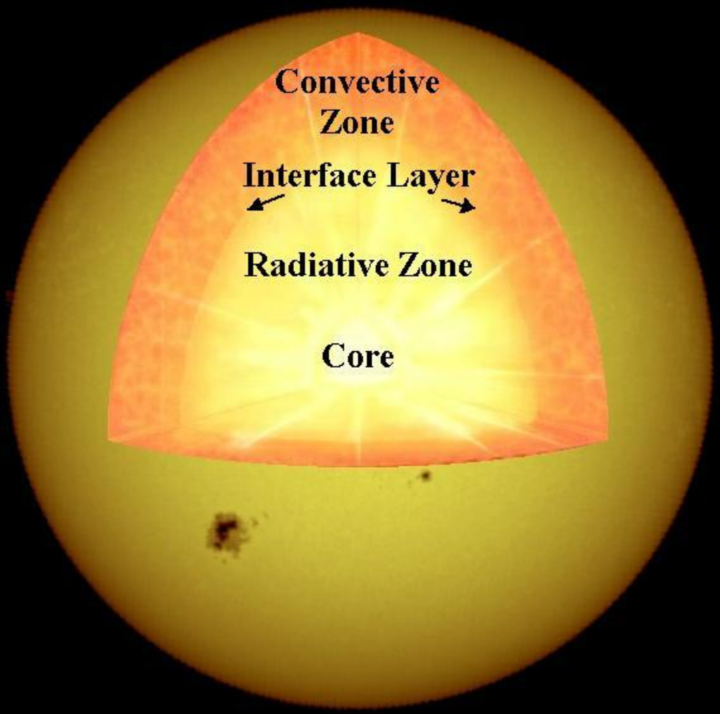
Our knowledge of planets is directly driven by our knowledge of the parent star…

- By ultimately determining the intrinsic properties of planets
  - The star is the overwhelmingly larger source of energy
  - The stellar radiations critically affect the composition, thermal properties and the mere existence of planetary atmospheres

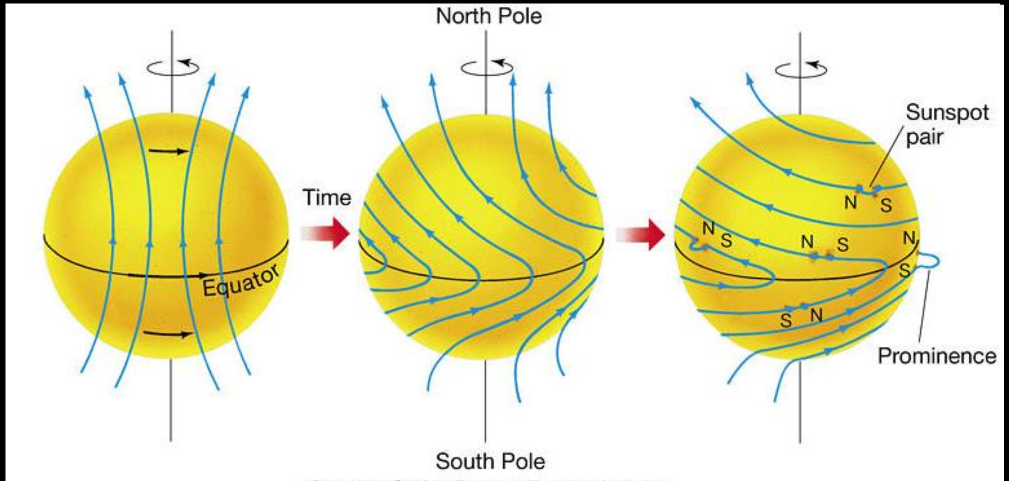
Magnetic solar/stellar variability



The Sun, and low-mass stars in general, are magnetically active



Magnetic *dynamo* theory
⇒ The rotation and the convective outer envelope interact to generate magnetic fields



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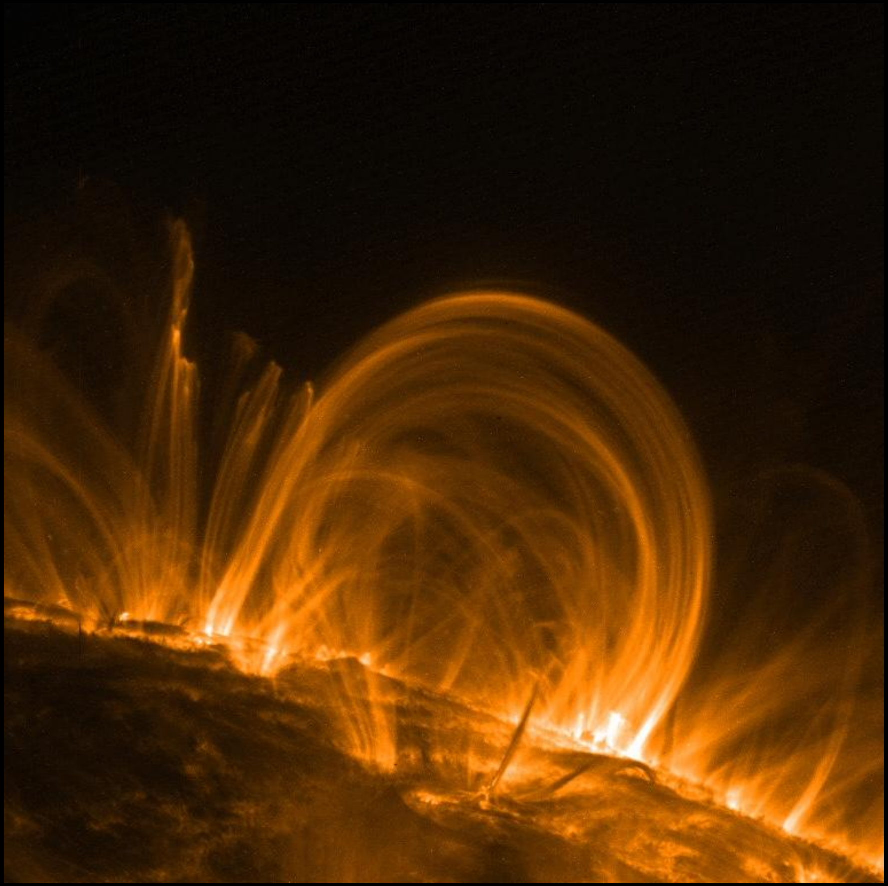
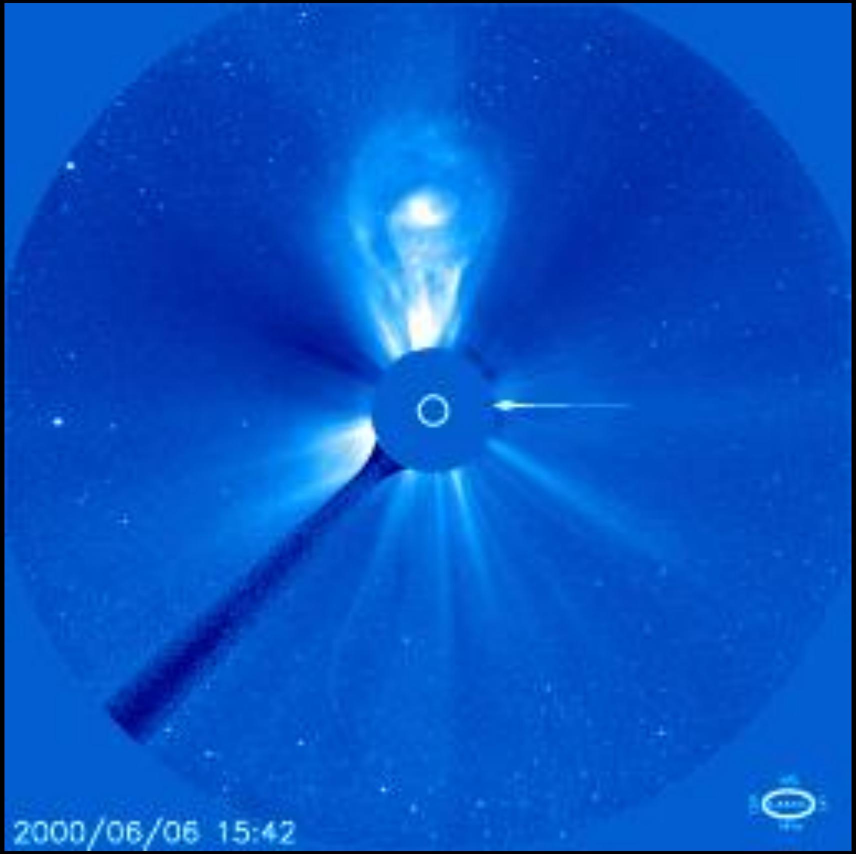
The magnetic activity is viewed as surface spots and the energy generated is released in the form of flares, high-energy radiation and mass ejection (solar wind)



Solar coronal loops observed by TRACE

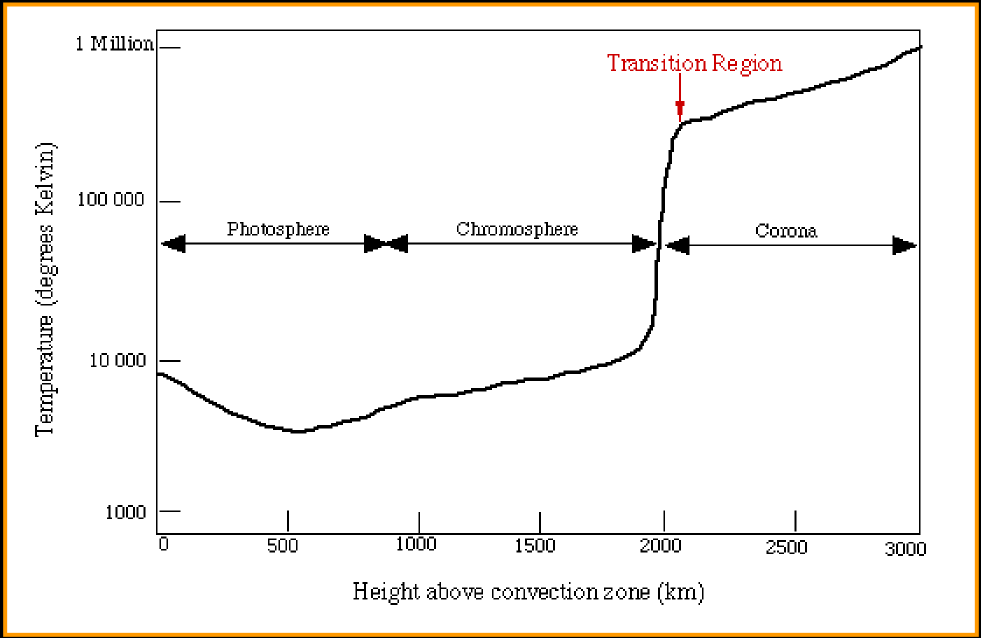


Solar CME observed by SOHO

The energy released contributes to heat the atmosphere of the Sun up to temperatures of a few million K

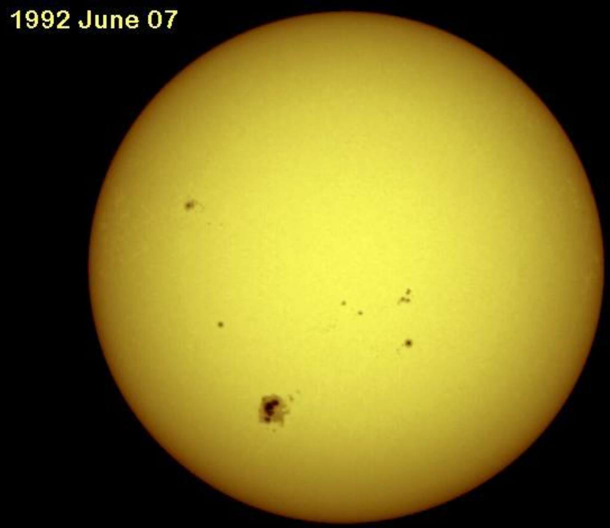
The vertical temperature profile indicates three regions above the solar photosphere:

- Chromosphere (~10 000 K)
- Transition region (~100 000 K)
- Corona (~1 000 000 K)

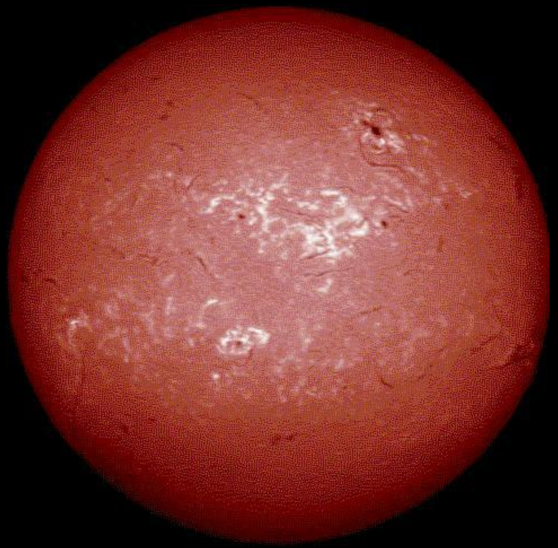


Each region has a distinct temperature and density and can be observed through different element species and wavelengths

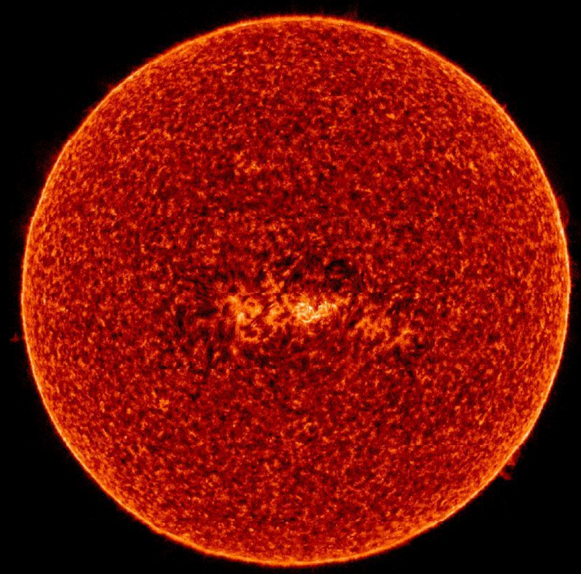
***Solar photosphere**: Optical continuum image*



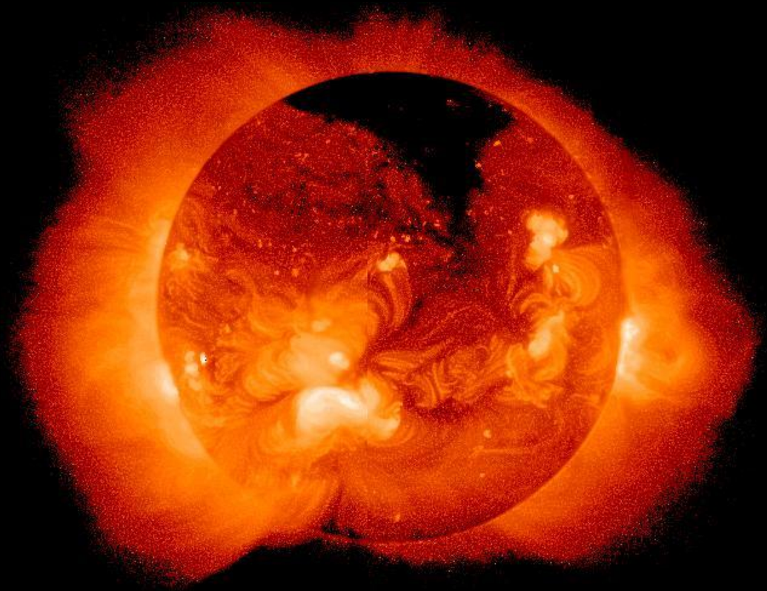
***Solar chromosphere**: Visible Hα image*



***Solar tr. region**: FUV SVI image*



***Solar corona**: X-ray image*



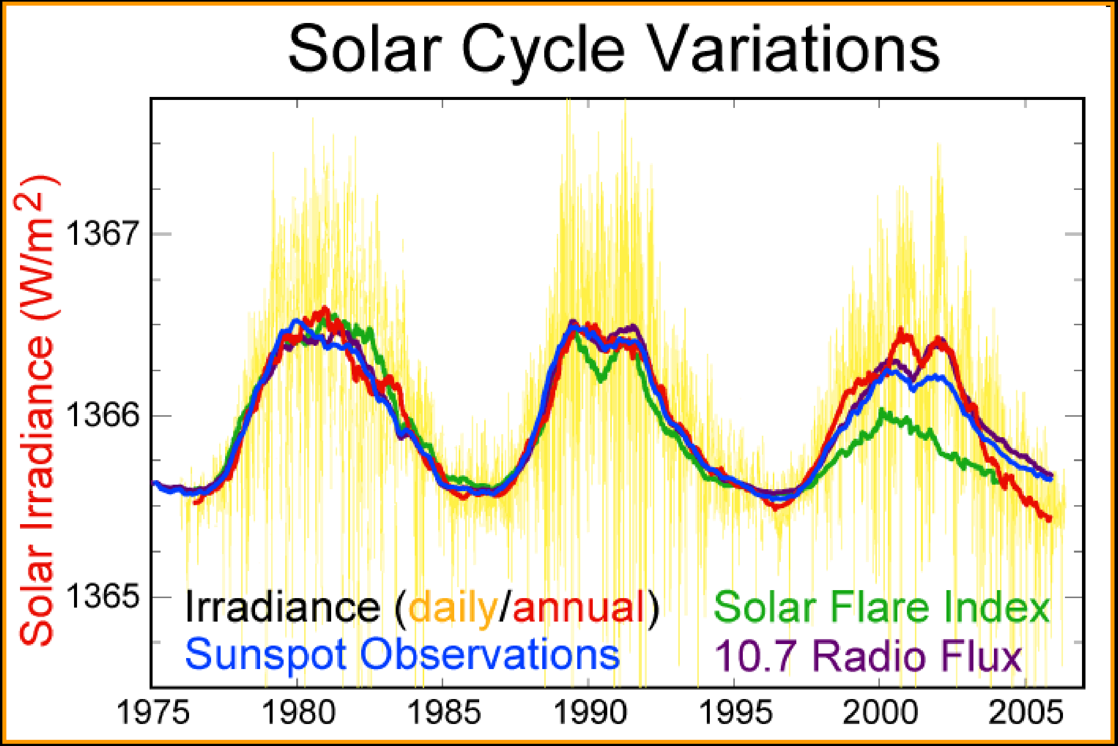
Another component of the active Sun is the solar wind: ions from the solar corona that are accelerated to speeds of about 400 km/s

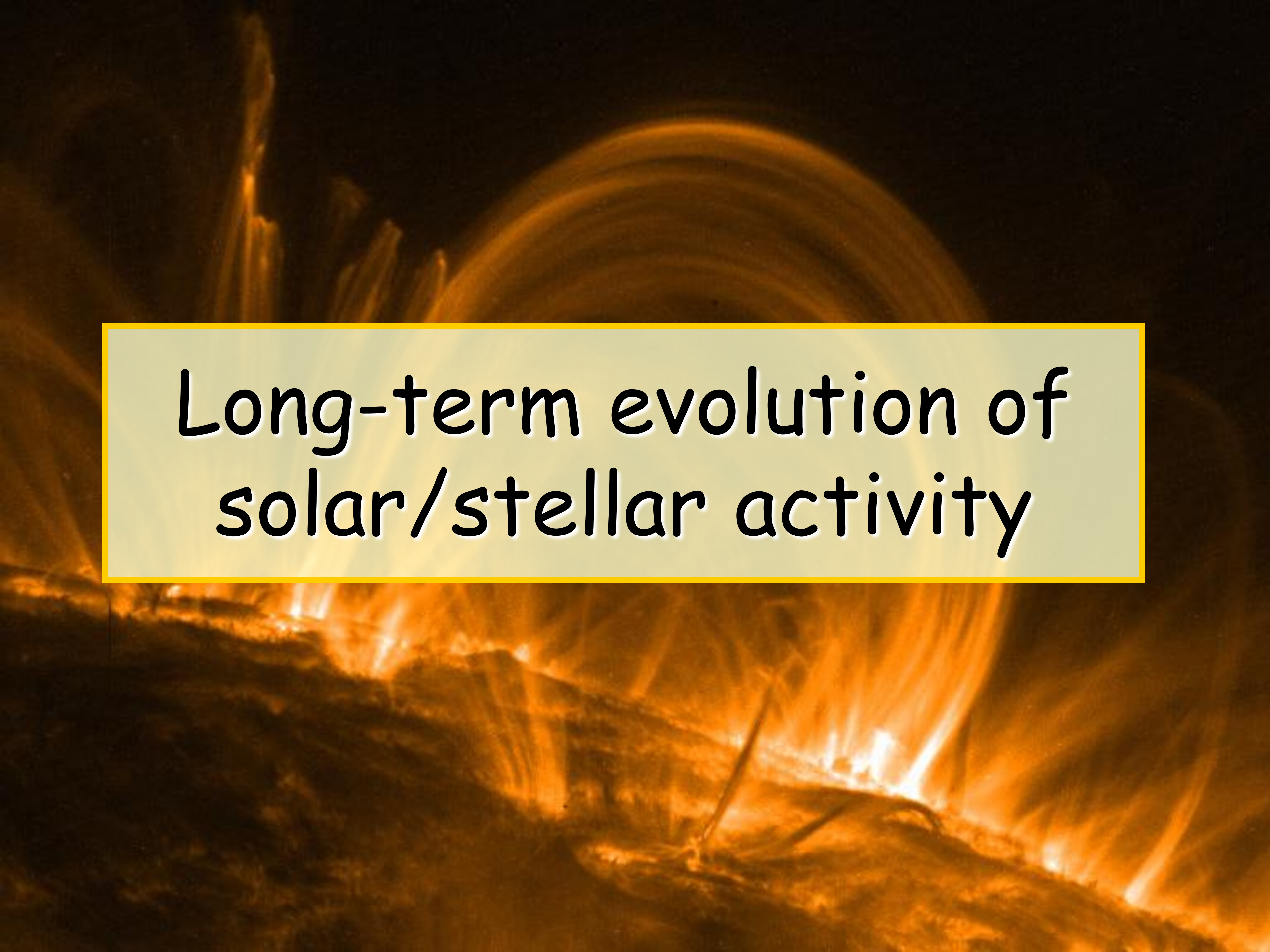
Direct evidence from the existence of the solar wind can be observed in the tails of comets

The ion and dust tails of comet Hale-Bopp

The accelerated ions strongly interact with Earth’s magnetosphere

- **The radiation and particle emissions are highly variable:**
  - **Hours: Stellar flares**
  - **Days: Rotational modulation (active regions coming on/off view)**
  - **Years: Activity cycle (Sun's 11 yr sunspot cycle)**
  - **Billions of years: Rotational spin-down (over evolutionary timescales)**

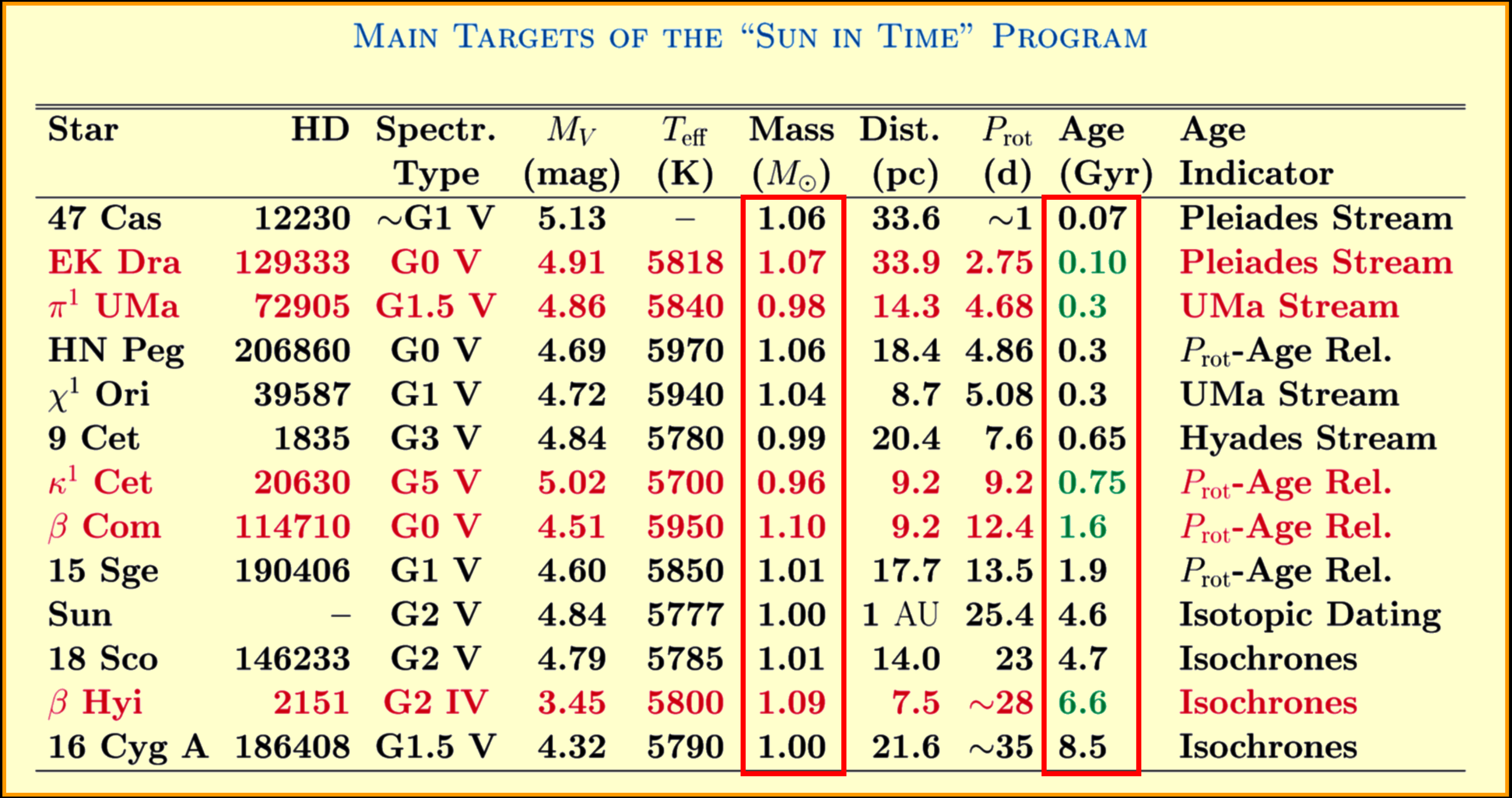




Long-term evolution of solar/stellar activity

Stellar proxies for the Sun

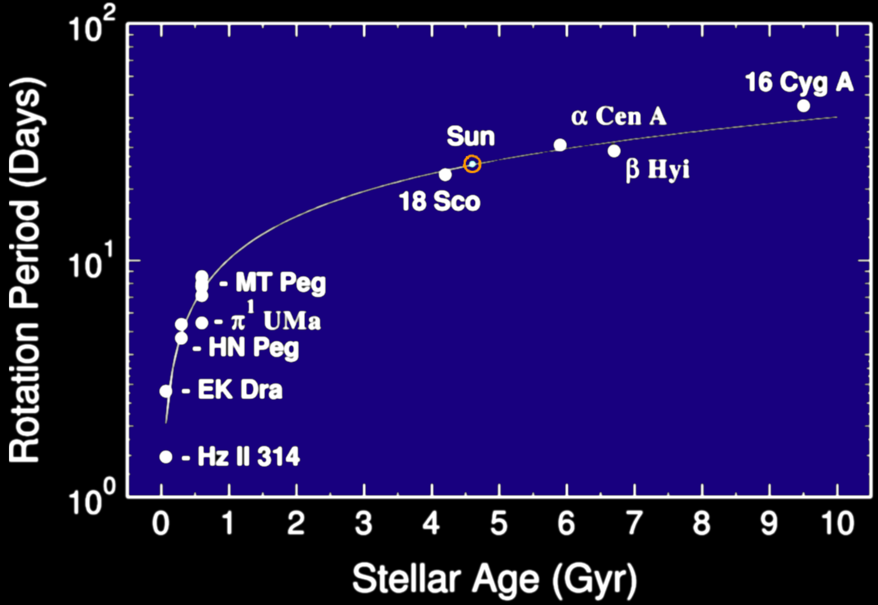
- It is difficult to compile a sample of nearby stars (so that they have high fluxes), within a narrow spectral interval (same convective zone depth) and with good age estimates
- Solar-type stars (G0-G5) – Güdel et al. (1997):

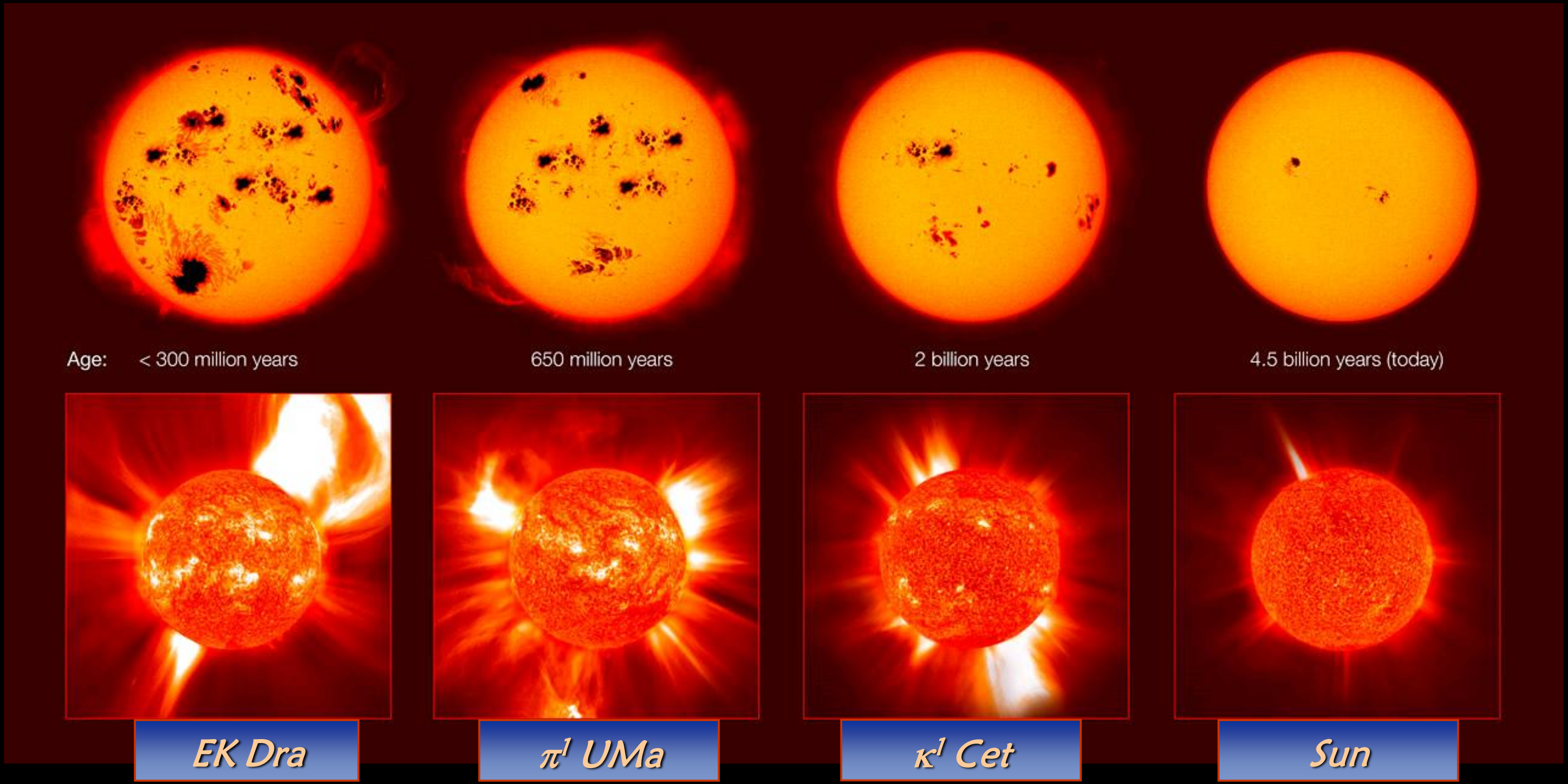


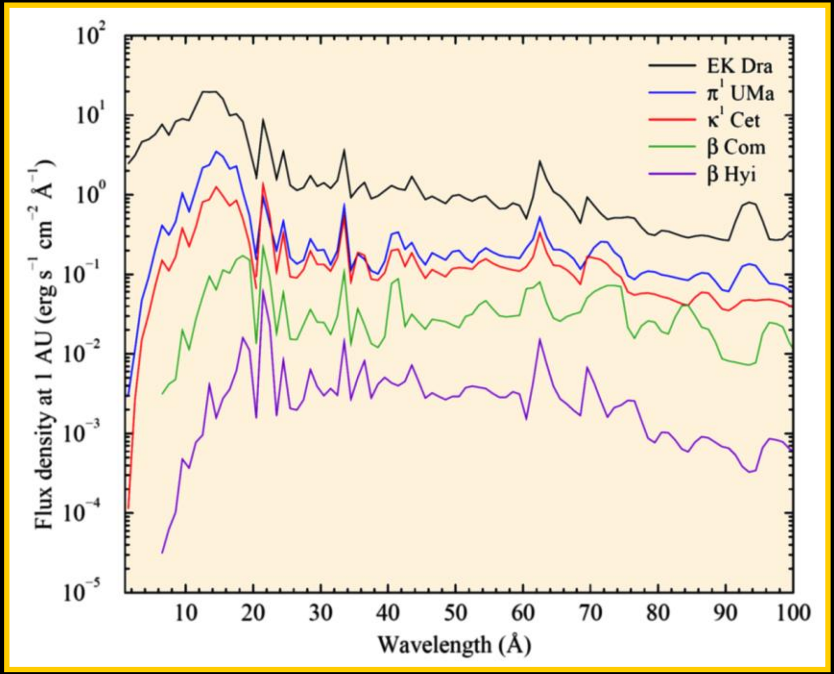
MAIN TARGETS OF THE “SUN IN TIME” PROGRAM

Star	HD	Spectr. Type	M_V (mag)	$T_{\rm eff}$ (K)	Mass ($M_\odot$)	Dist. (pc)	$P_{\rm rot}$ (d)	Age (Gyr)	Age Indicator
47 Cas	12230	~G1 V	5.13	–	1.06	33.6	~1	0.07	Pleiades Stream
EK Dra	129333	G0 V	4.91	5818	1.07	33.9	2.75	0.10	Pleiades Stream
π^1 UMa	72905	G1.5 V	4.86	5840	0.98	14.3	4.68	0.3	UMa Stream
HN Peg	206860	G0 V	4.69	5970	1.06	18.4	4.86	0.3	$P_{\rm rot}$-Age Rel.
χ^1 Ori	39587	G1 V	4.72	5940	1.04	8.7	5.08	0.3	UMa Stream
9 Cet	1835	G3 V	4.84	5780	0.99	20.4	7.6	0.65	Hyades Stream
κ^1 Cet	20630	G5 V	5.02	5700	0.96	9.2	9.2	0.75	$P_{\rm rot}$-Age Rel.
β Com	114710	G0 V	4.51	5950	1.10	9.2	12.4	1.6	$P_{\rm rot}$-Age Rel.
15 Sge	190406	G1 V	4.60	5850	1.01	17.7	13.5	1.9	$P_{\rm rot}$-Age Rel.
Sun	–	G2 V	4.84	5777	1.00	1 AU	25.4	4.6	Isotopic Dating
18 Sco	146233	G2 V	4.79	5785	1.01	14.0	23	4.7	Isochrones
β Hyi	2151	G2 IV	3.45	5800	1.09	7.5	~28	6.6	Isochrones
16 Cyg A	186408	G1.5 V	4.32	5790	1.00	21.6	~35	8.5	Isochrones

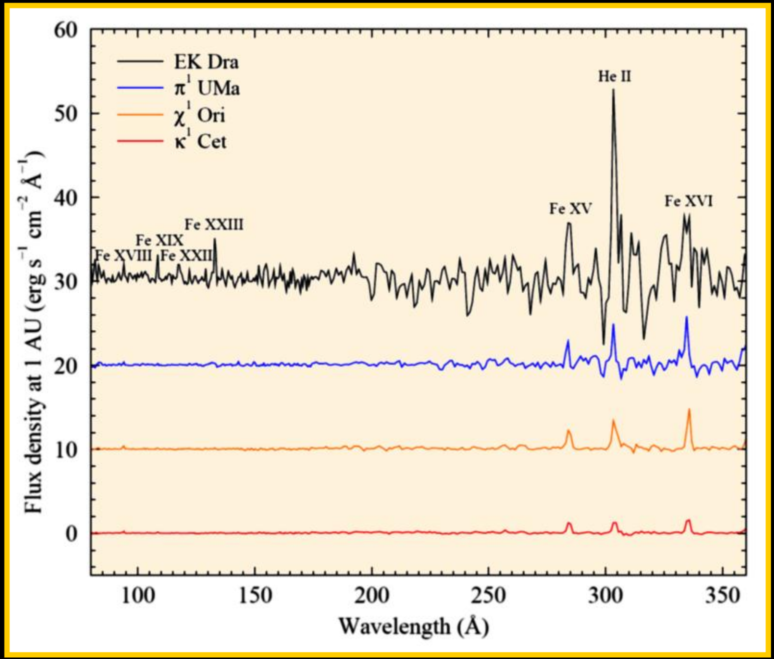
The young Sun rotated about 10 times faster than today and had enhanced magnetic activity





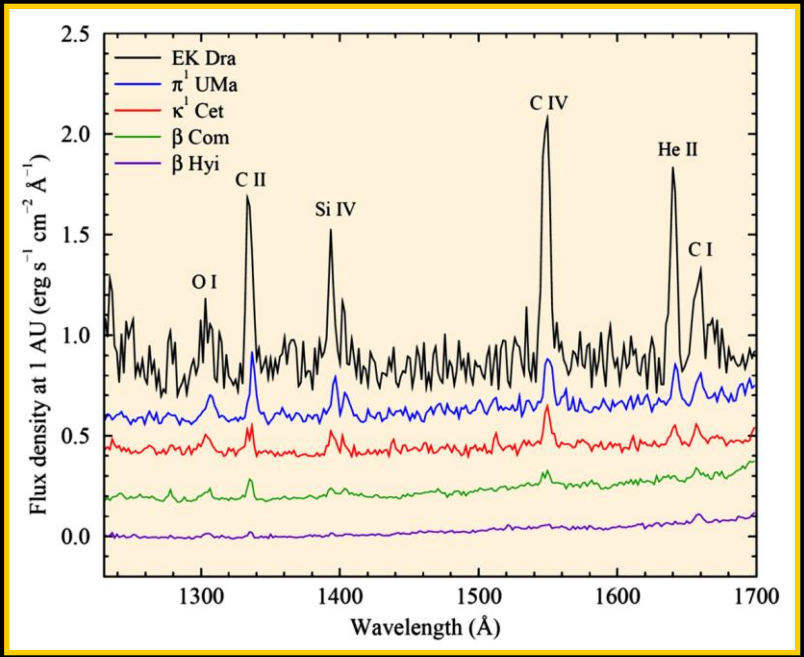


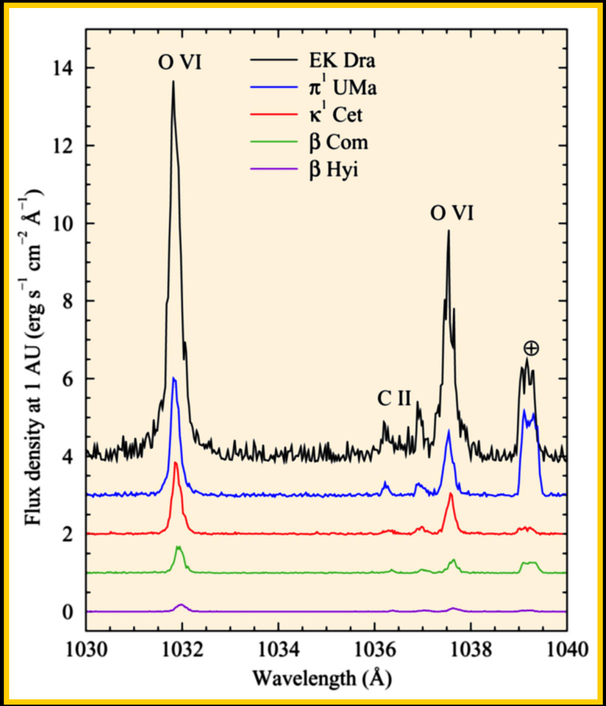
X-rays



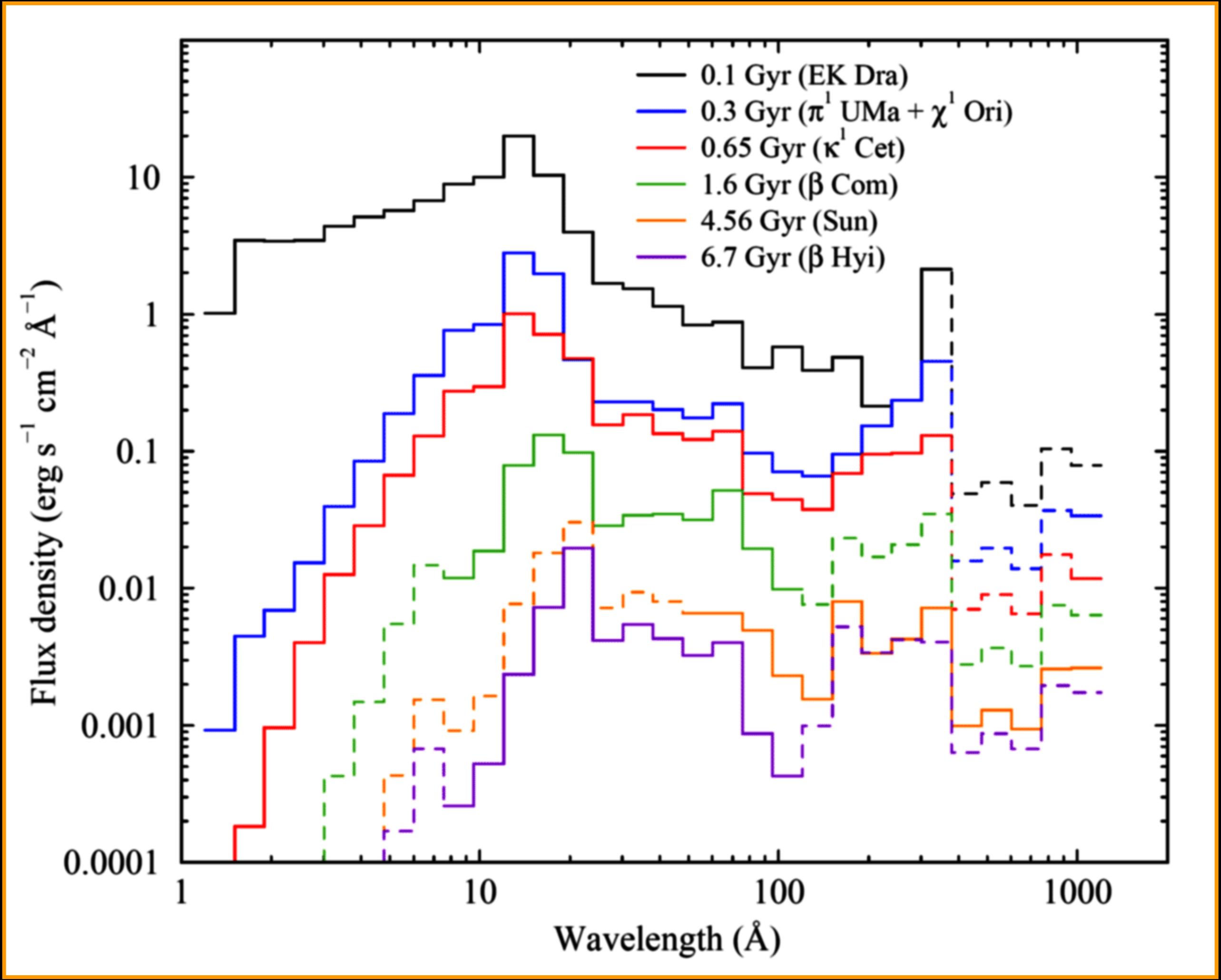
EUV

UV





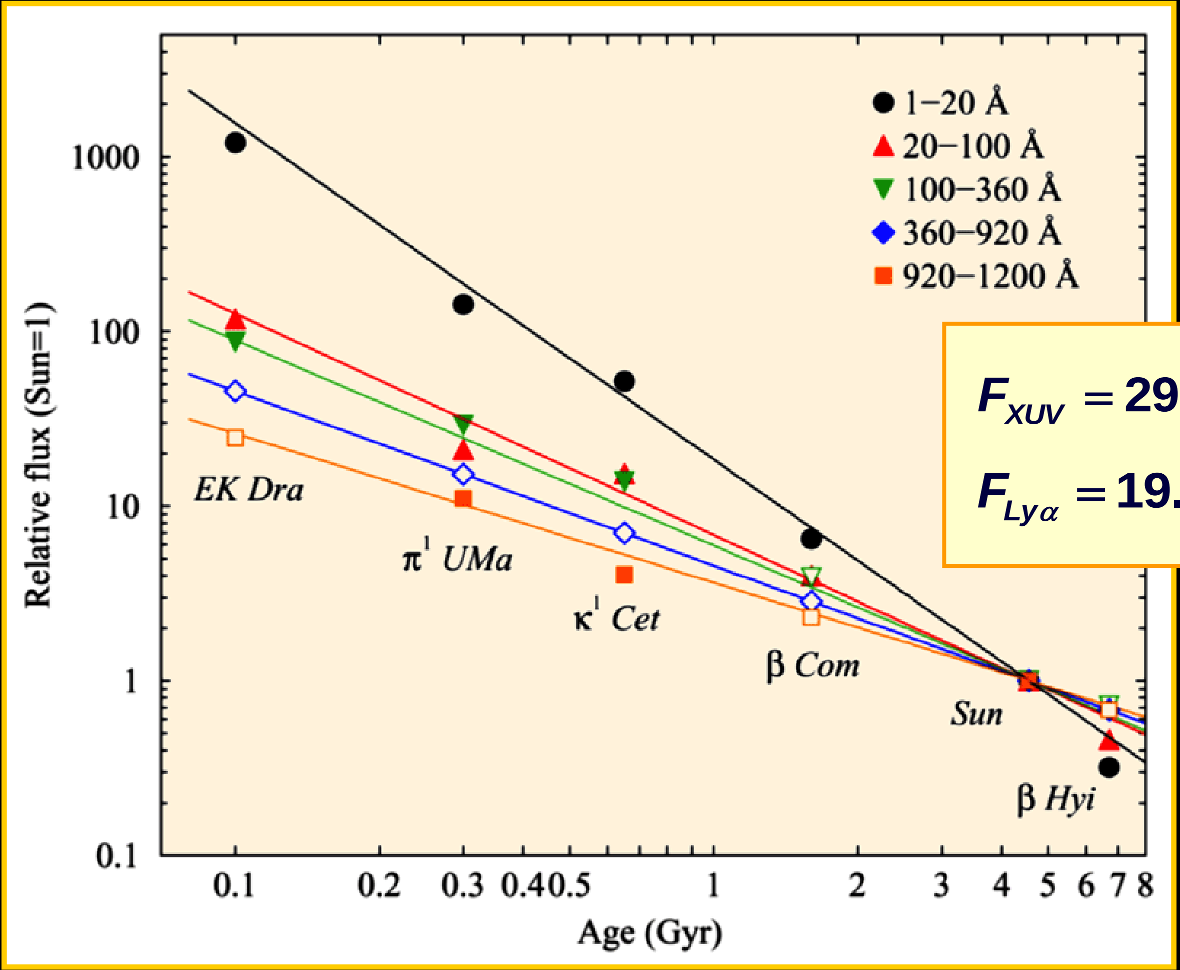
FUV



The young post-ZAMS Sun had stronger emissions:

- **100-1000x in X-rays**
- **10-100x in the EUV-FUV**
- **5-10x in the UV**

Ribas et al. (2005, ApJ)



$$F_{XUV} = 29.7\left[\tau(\mathrm{Gyr})\right]^{-1.23}\ \mathrm{erg\,s^{-1}\,cm^{-2}}$$

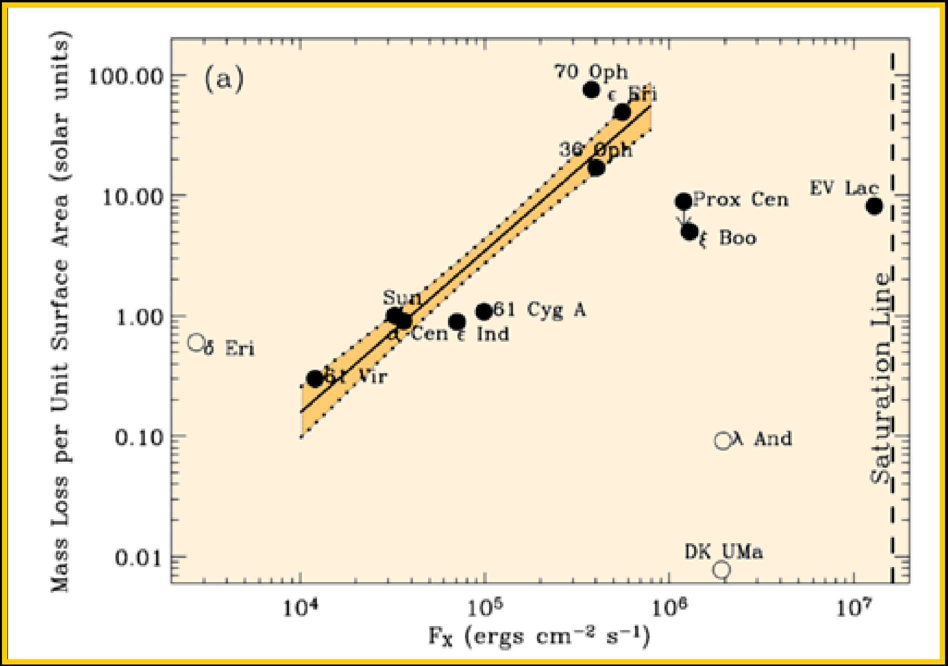
$$F_{Ly\alpha} = 19.2\left[\tau(\mathrm{Gyr})\right]^{-0.72}\ \mathrm{erg\,s^{-1}\,cm^{-2}}$$

Similar results:
Zahnle & Walker (1982)
Ayres (1997)

- **The flux density evolution scales well with power-law relationships**
- **The overall XUV flux (1-1200 Å) decreases with a slope of −1.2 ⇨ 3x higher than today 2.5 Gyr ago, 6x 3.5 Gyr ago, 100x ZAMS!**
- **The important Ly α line (1215 Å) decreases with a slope of −0.72**

Stellar winds (particle emissions)

- This is a further ingredient of stellar activity (stars have hot coronae and lose mass at a certain rate)
- This rate seems to correlate with Lx (Wood et al. 2002, 2005)!
- Mass loss scales with a power law of slope -2

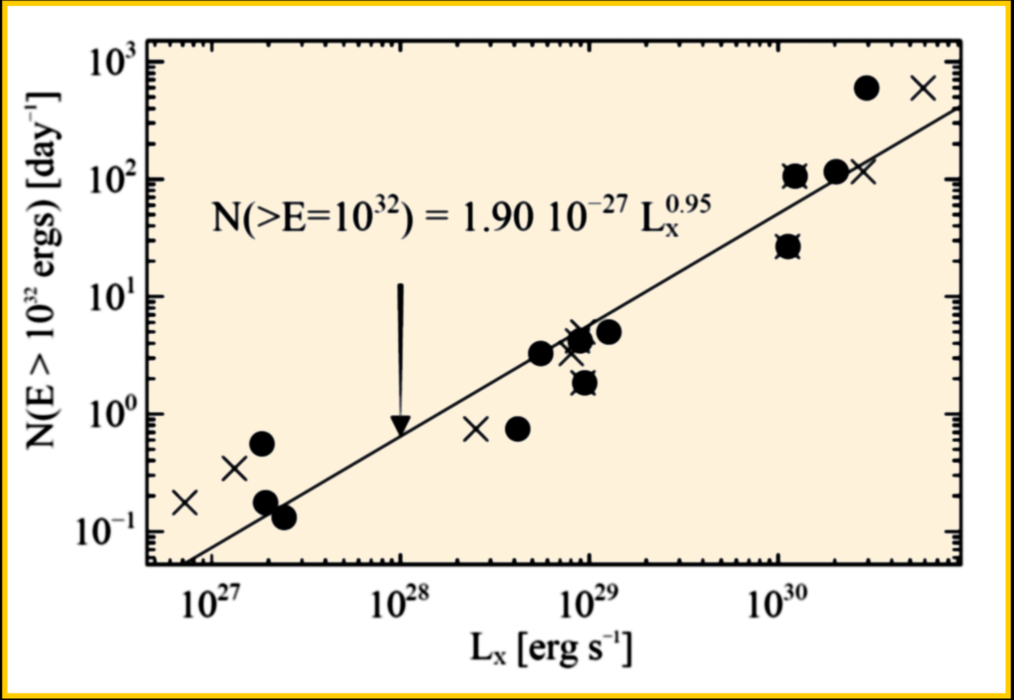


⇨ the wind of the young Sun could have been about 1000x stronger than today!

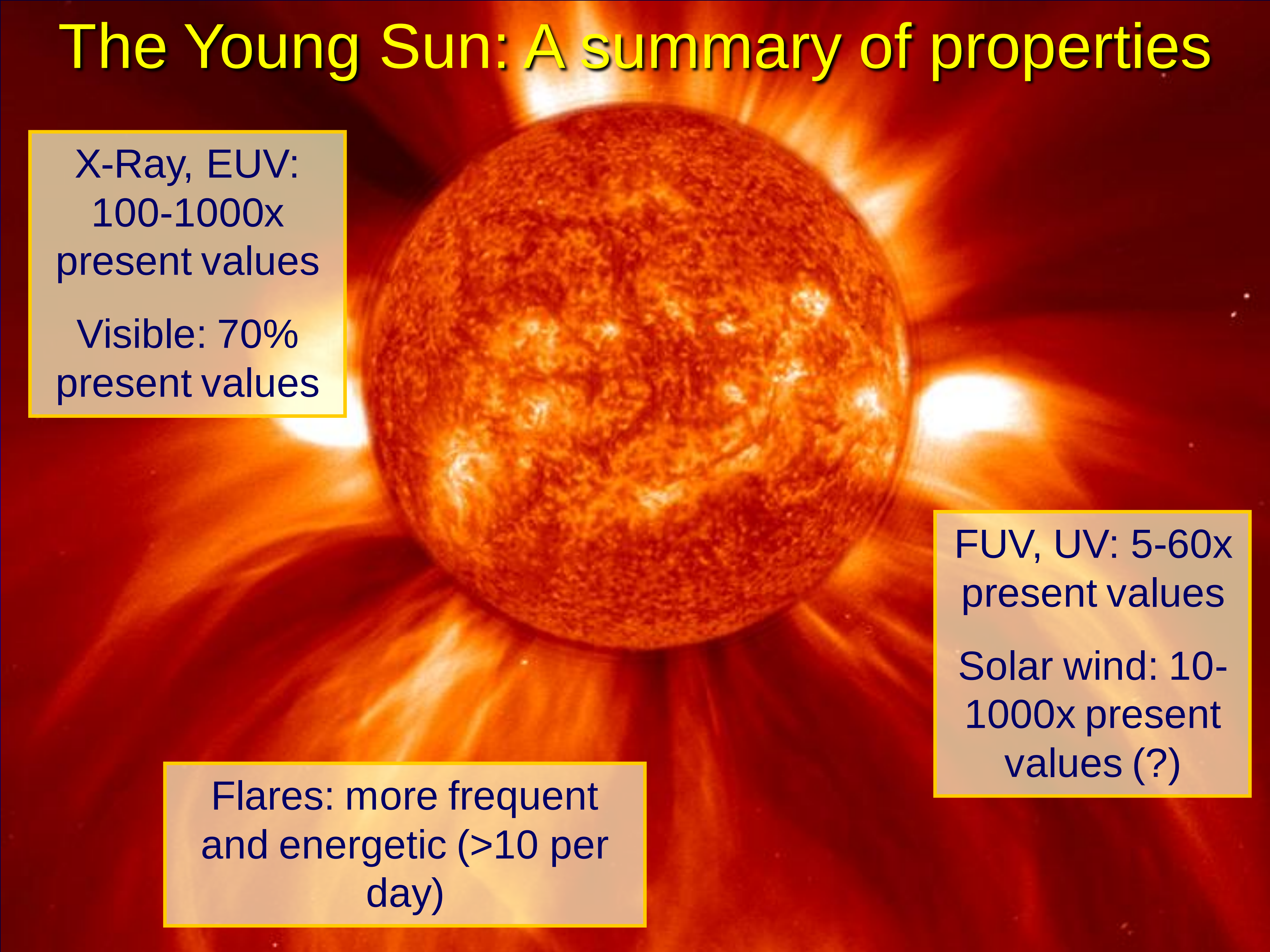
- Challenged by a theoretical study
- Holzwarth & Jardine (2006, A&A) ⇨ much weaker dependence with Lx
- Young Sun’s $\dot{M}$ = 10x today

Short-term variability (flares)

- Flares ➪ Relative variations: 2-10x in X-rays to 1.2-1.5x in FUV-UV, several times in particles
- These produce large increases in the high-energy flux over a few hours
- Flare rates also seem to scale with Lx (Audard et al. 2000)!



The Young Sun: A summary of properties



X-Ray, EUV: 100-1000x present values

Visible: 70% present values

FUV, UV: 5-60x present values

Solar wind: 10-1000x present values (?)

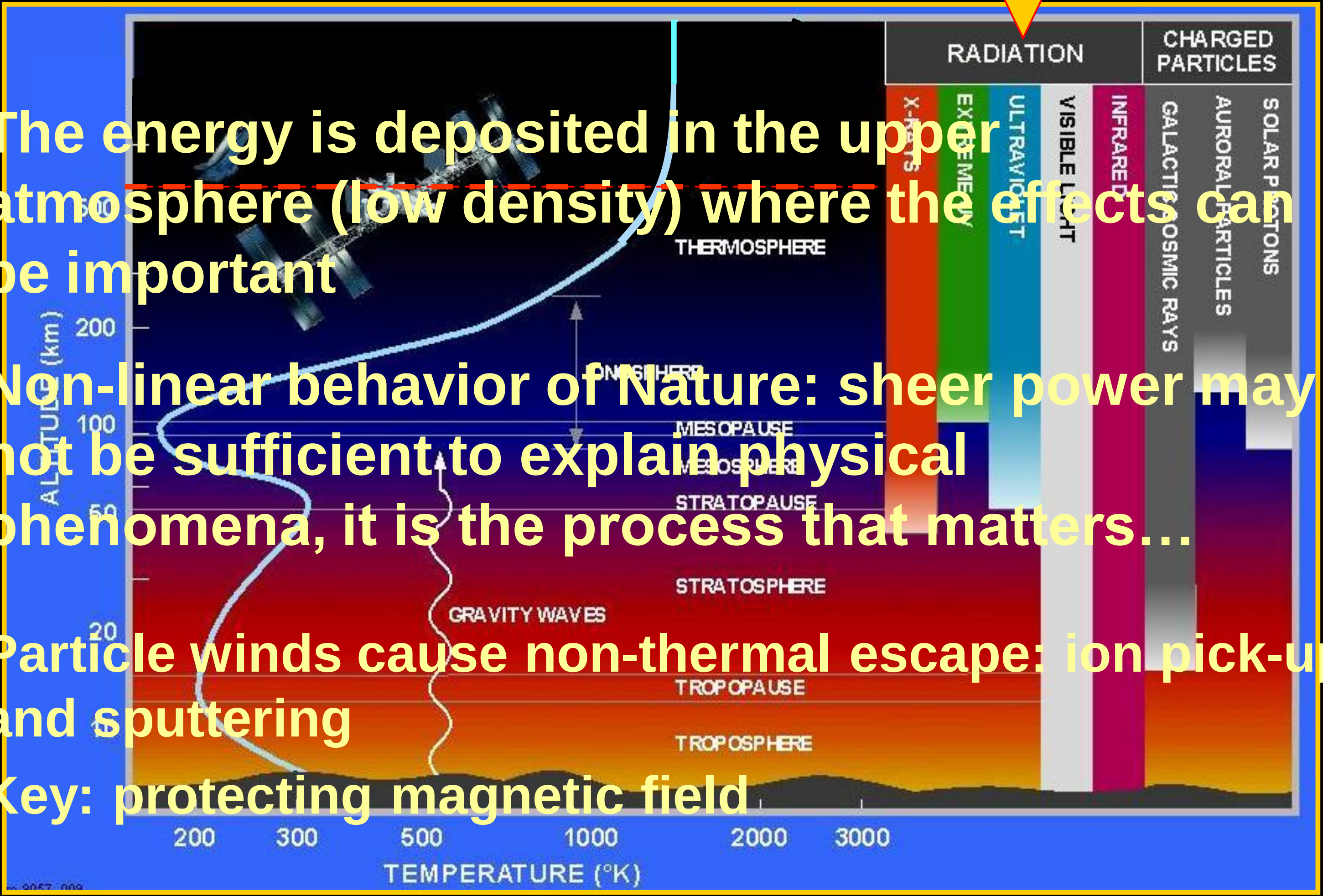
Flares: more frequent and energetic (>10 per day)

Effects on planets

Context:

Tiny fraction: why worry??

- Today $F_{XUV} = 3 \cdot 10^{-6}\ F_{bol}$
- Young $F_{XUV} = 5 \cdot 10^{-4}\ F_{bol}$



- The energy is deposited in the upper atmosphere (low density) where the effects can be important
- Non-linear behavior of Nature: sheer power may not be sufficient to explain physical phenomena, it is the process that matters…

- Particle winds cause non-thermal escape: ion pick-up and sputtering

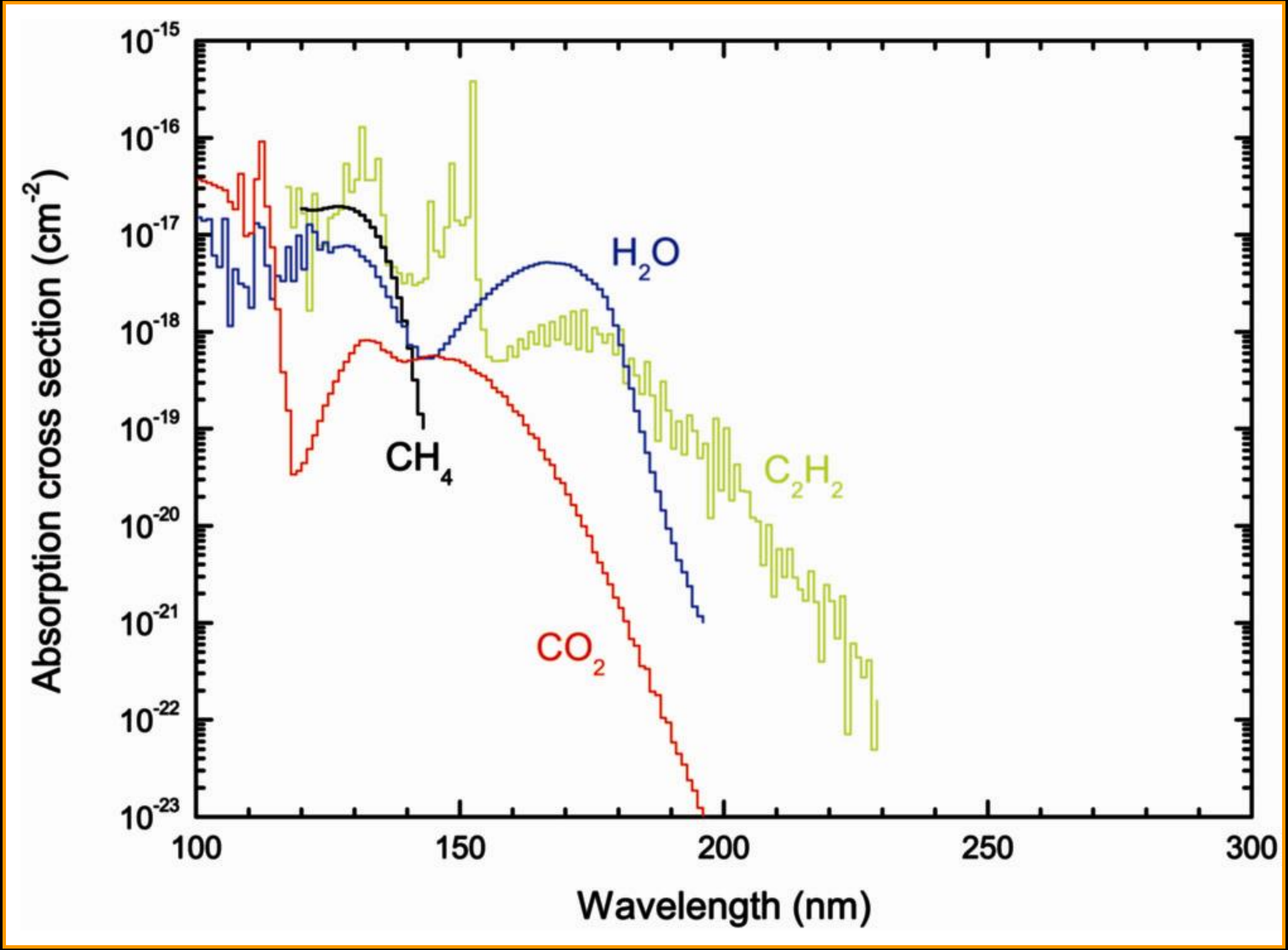
⇨ Key: protecting magnetic field

Water loss: Mars & Venus

- Mars is small and has no magnetic field ⇨ Intense erosion of atmosphere
- Had water in the past (-3.8 Gyr): greenhouse by CO_2 ⇨ $T_s > 273$ K
- Later, large impacts, core solidified and atmosphere was eroded away
- Evaporation can explain the loss of a global Martian ocean of 10 m in 3.5 Gyr
- H escapes and O is incorporated to ground ⇨ rusty surface (oxidized down to 2-5 m)
- A similar process could have occurred in Venus ⇨ Loss of 1-100% of a terrestrial ocean ($1.5 \cdot 10^{24}$ g) in less than a Gyr

Kulikov et al. (2006, 2007)

- **No impact on Earth…?**
- **Photochemical reactions also take place (at $\lambda < 200$ nm)…**

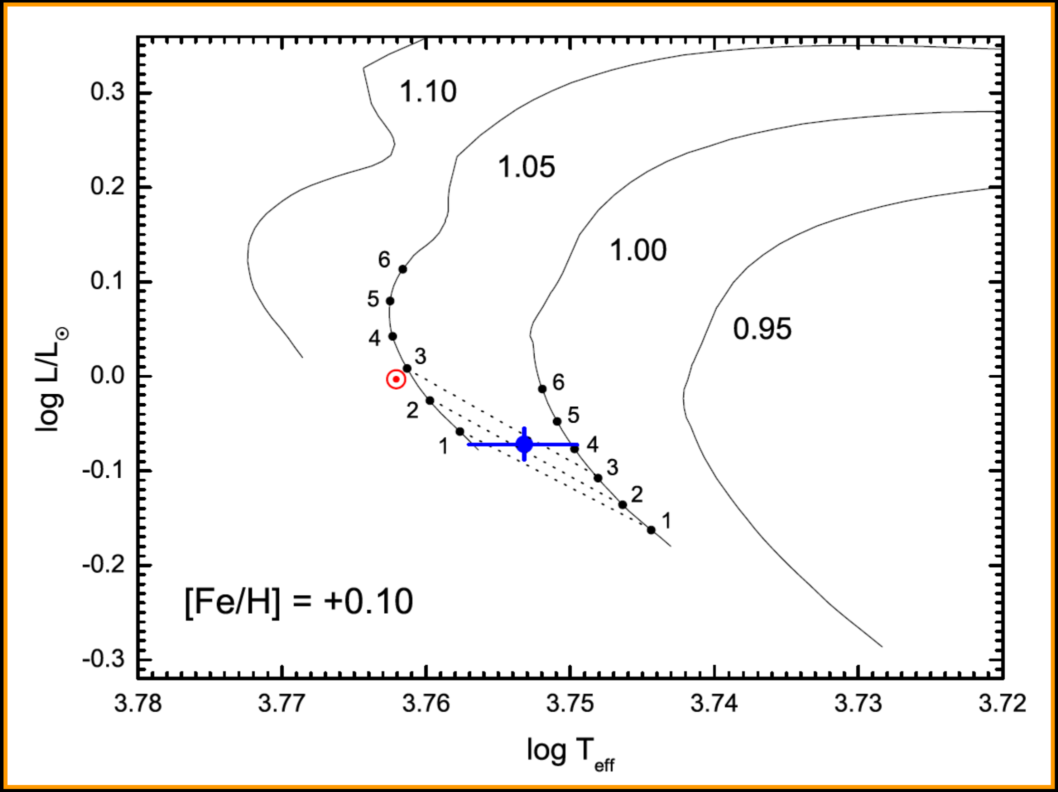


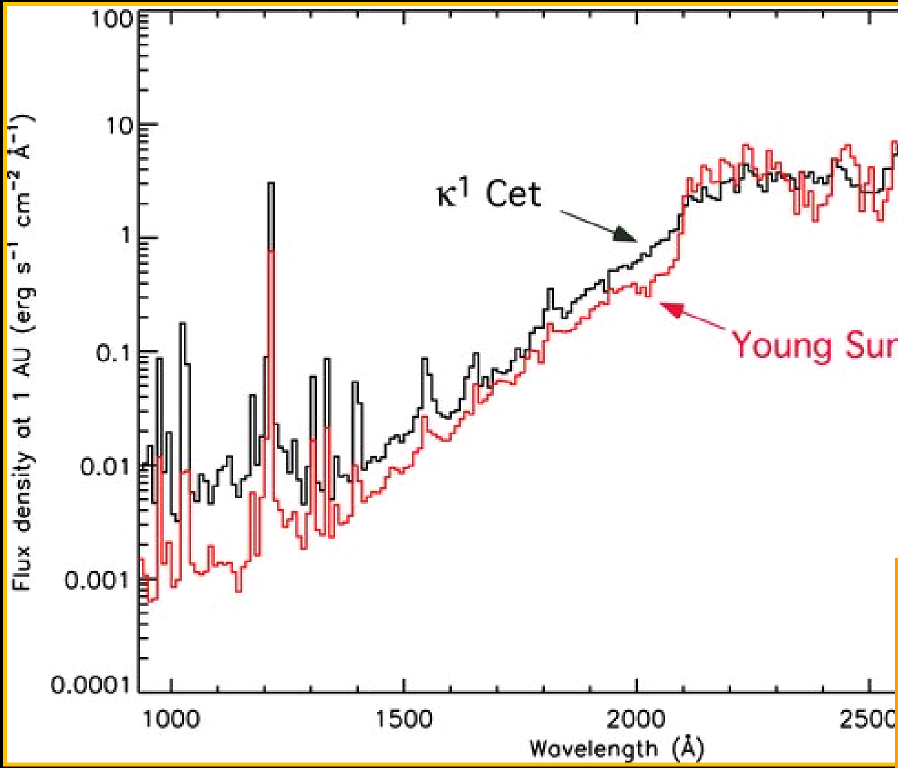
κ^1 Cet: The Sun when life appeared on Earth

- **Bright star**
- **Detailed analysis by Ribas et al. (2010, ApJ, 714, 384)**
- **Accurate temperature, luminosity, abundance and age…**

- **$T_{\mathrm{eff}} = 5665 \pm 30$ K**
- **$\log L/L_\odot = -0.070 \pm 0.016$**
- **$[\mathrm{Fe/H}] = +0.10 \pm 0.05$**
- **Age = 0.6 ± 0.2 Gyr**
- **$M = 1.045 \pm 0.011\ M_\odot$**

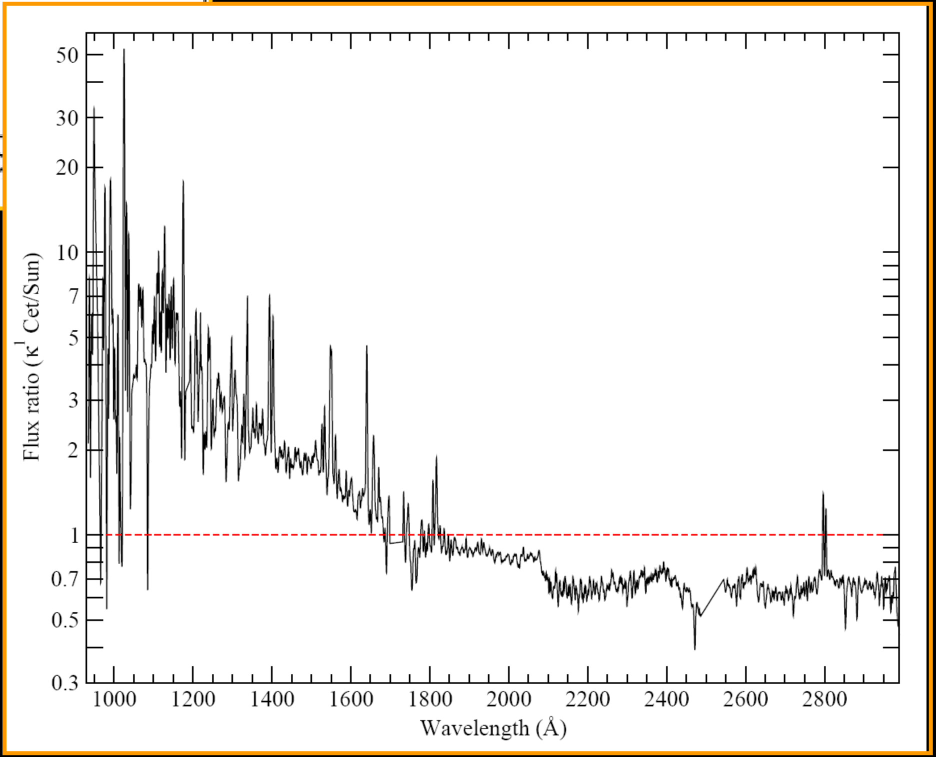
Solar analog at a crucial evolution stage!





High-energy emissions @ 3.9 Ga

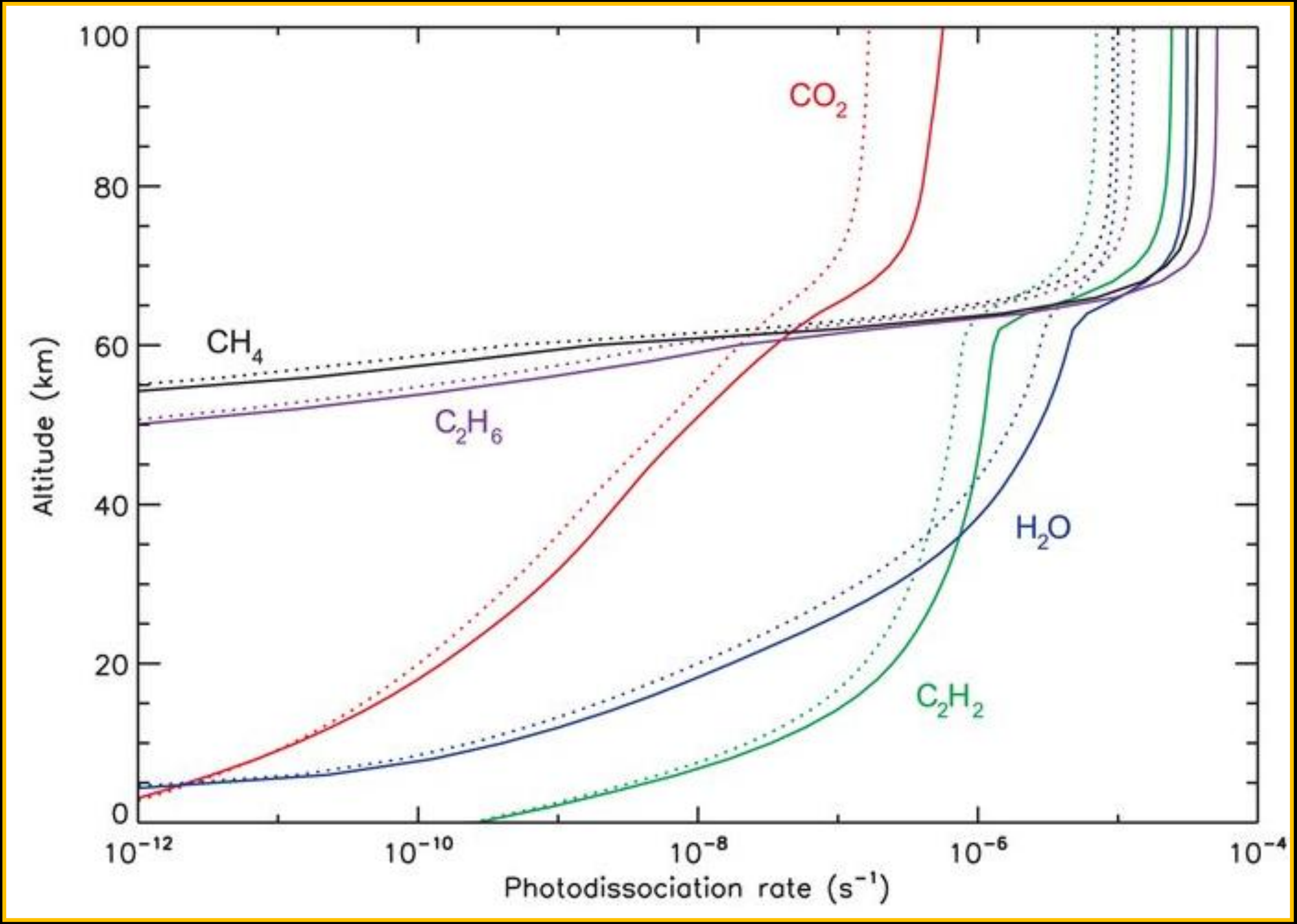
- 1-120 nm ⇨ 10x
- Lyα (122 nm) ⇨ 4x
- 150 nm ⇨ 2x
- 170 nm ⇨ same
- 200 nm ⇨ –20%
- 300 nm ⇨ –30%



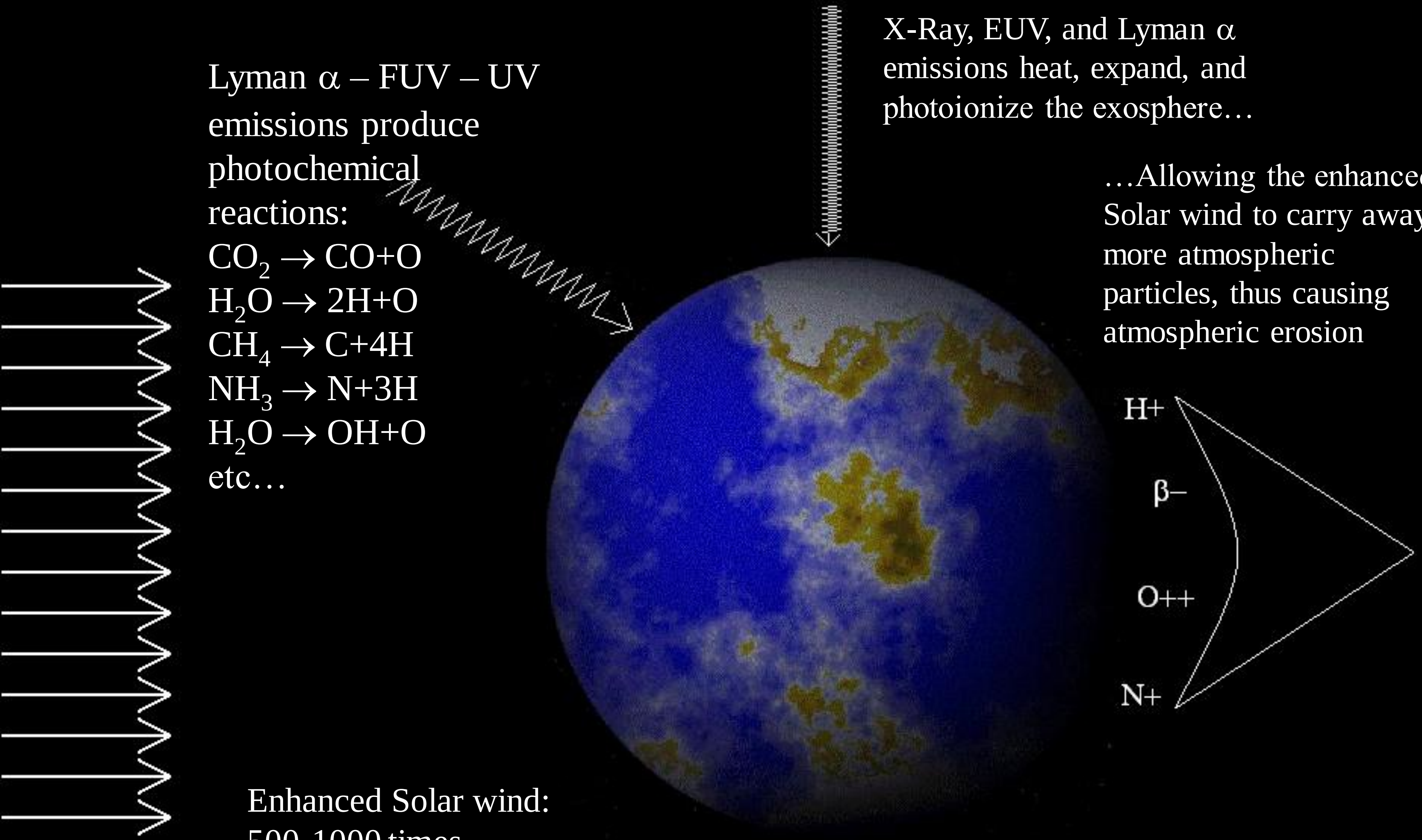
Significantly stronger emissions

Also in the critical UV region…

Earth @ 3.9 Ga



- **Pavlov et al. (2001) atmosphere**
- **3-4 x higher photodissociation rates**
- **Important impact on chemistry!**



X-Ray, EUV, and Lyman α emissions heat, expand, and photoionize the exosphere…

Lyman α – FUV – UV emissions produce photochemical reactions:
$CO_2 \rightarrow CO+O$
$H_2O \rightarrow 2H+O$
$CH_4 \rightarrow C+4H$
$NH_3 \rightarrow N+3H$
$H_2O \rightarrow OH+O$
etc…

…Allowing the enhanced Solar wind to carry away more atmospheric particles, thus causing atmospheric erosion

Enhanced Solar wind: 500-1000 times present values

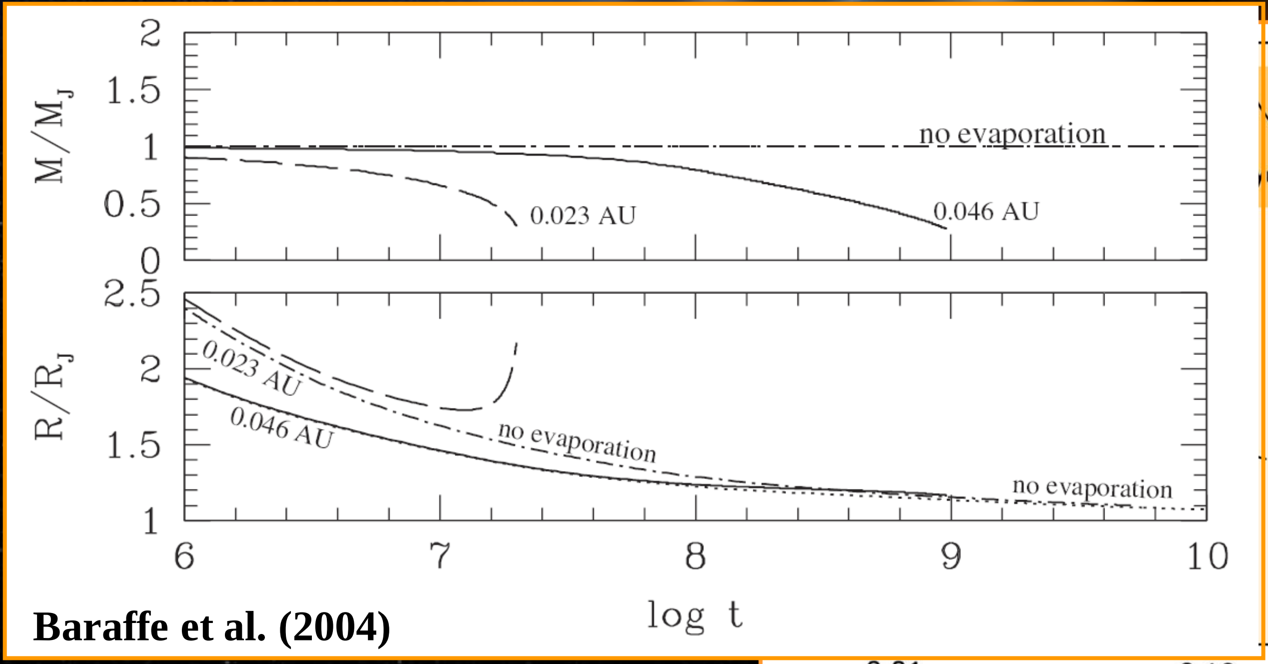
Effects of the young Sun on the Earth

Effects on exoplanets:

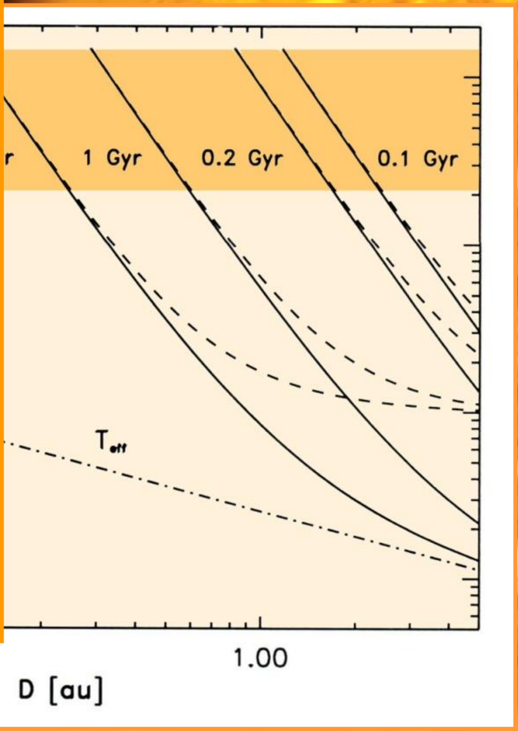
atmospheres and habitable zone

Hot Jupiter atmospheres

- Incoming XUV radiation ⇨ the exosphere can reach very high temperatures
- Loss of light particles (Jeans escape) or bulk expansion and mass loss (hydrodynamic escape)
- For hot Jupiters the mass loss can be large ($>10^{10}$ g s^{-1})

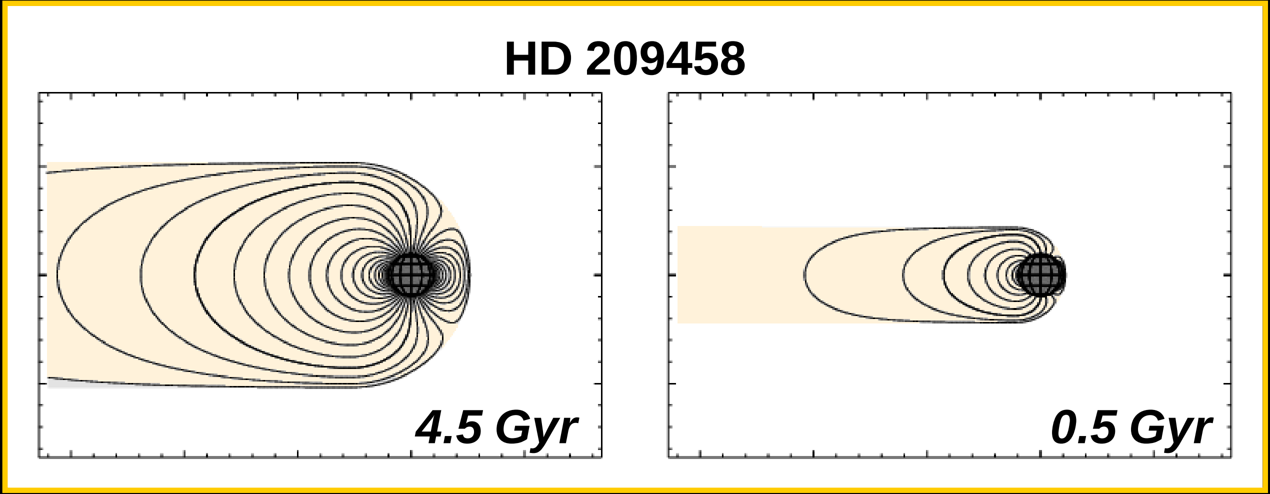


Baraffe et al. (2004)



Lammer et al. (2003)

- **Non-thermal loss processes also play a role**
- **Driven by the stellar particle flux (wind) ⇨ erosion by sputtering and ion pickup**
- **Planets have a protecting magnetic field but this can be weaker if synchronized**
- **Non-thermal losses can dominate (10x stronger)**
- **The particle flux was much higher in the past pushing the magnetopause below the exosphere radius**

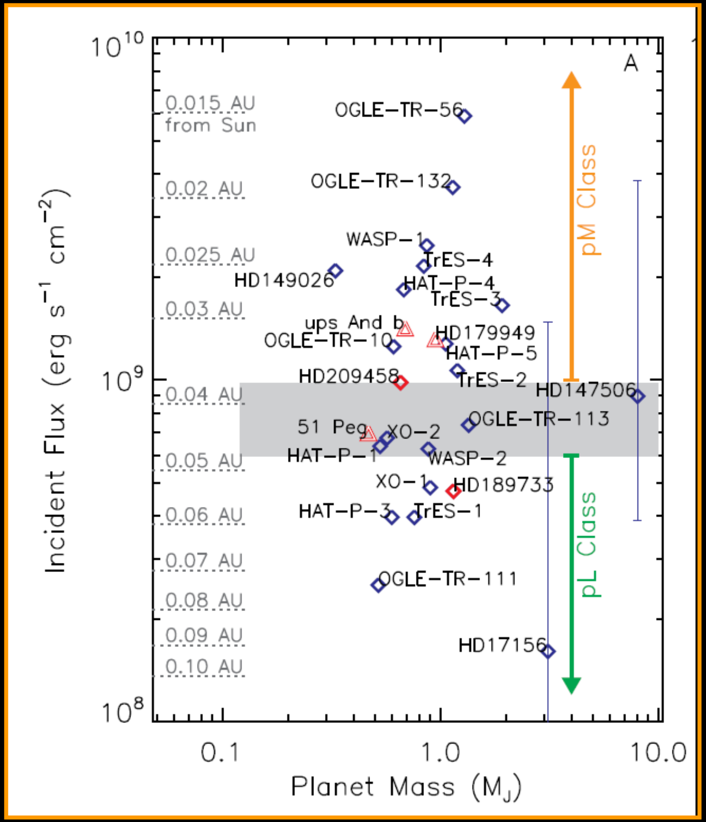


Grießmeier et al. (2004, 2008)

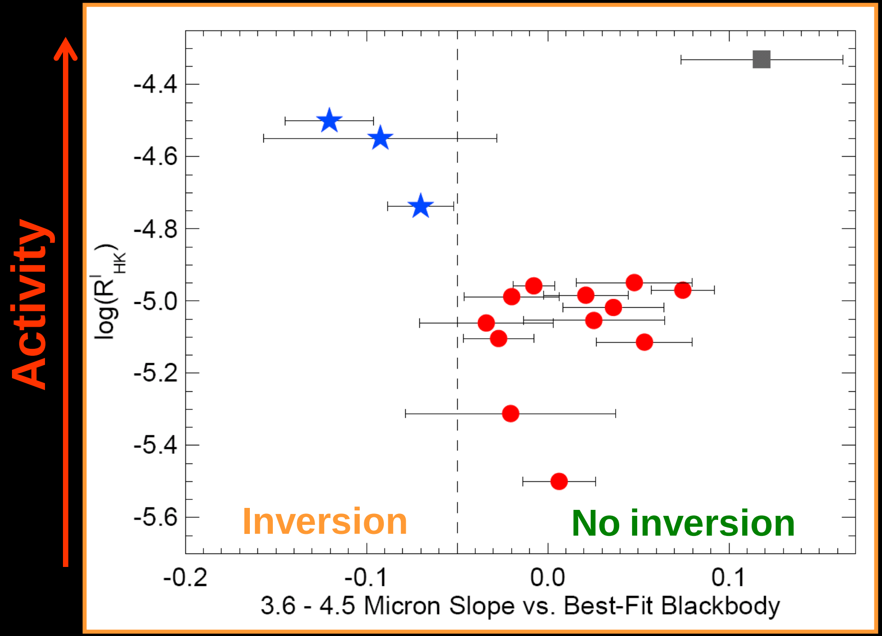
Atmospheric structure of hot Jupiters driven by stellar activity?

- Strong irradiation
- TiO & VO gas
- Day/night T contrast
- Inversion in T-P profile (hot stratosphere: 2000 K)

- Weaker irradiation
- TiO & VO condensates
- Homogeneous day/night T
- No inversion in T-P profile (cool stratosphere)



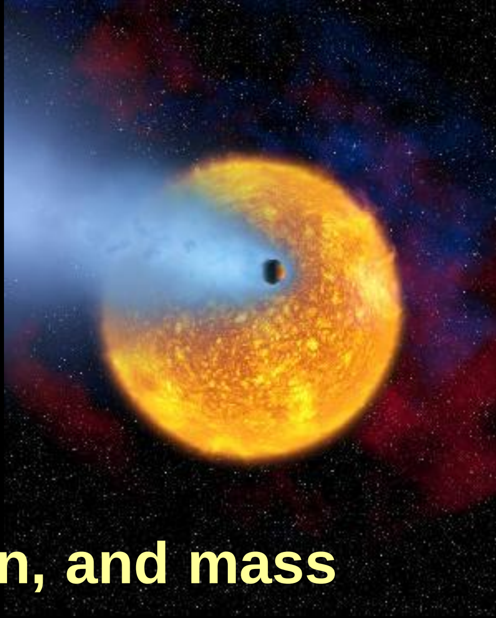
Fortney et al. (2007)



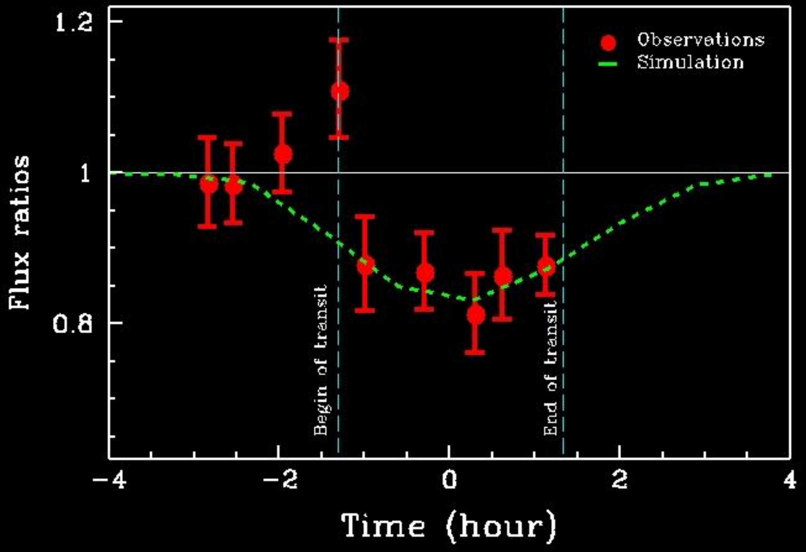
➢ **Link to VO/TiO chemistry not clear, other factors at play**

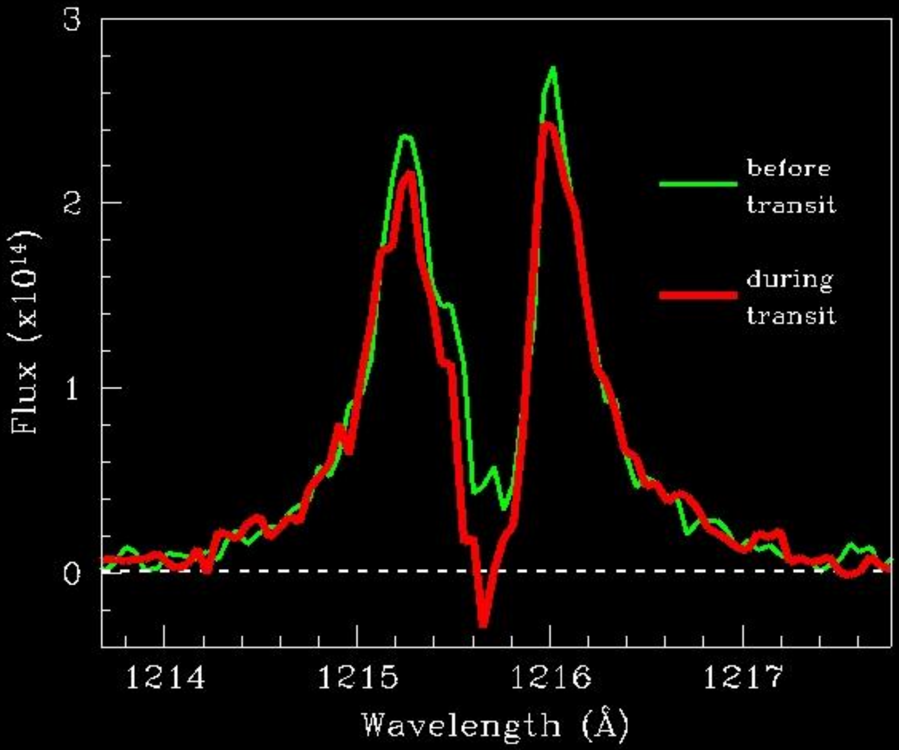
Knutson et al. (2010)

Evaporation caught in the act?

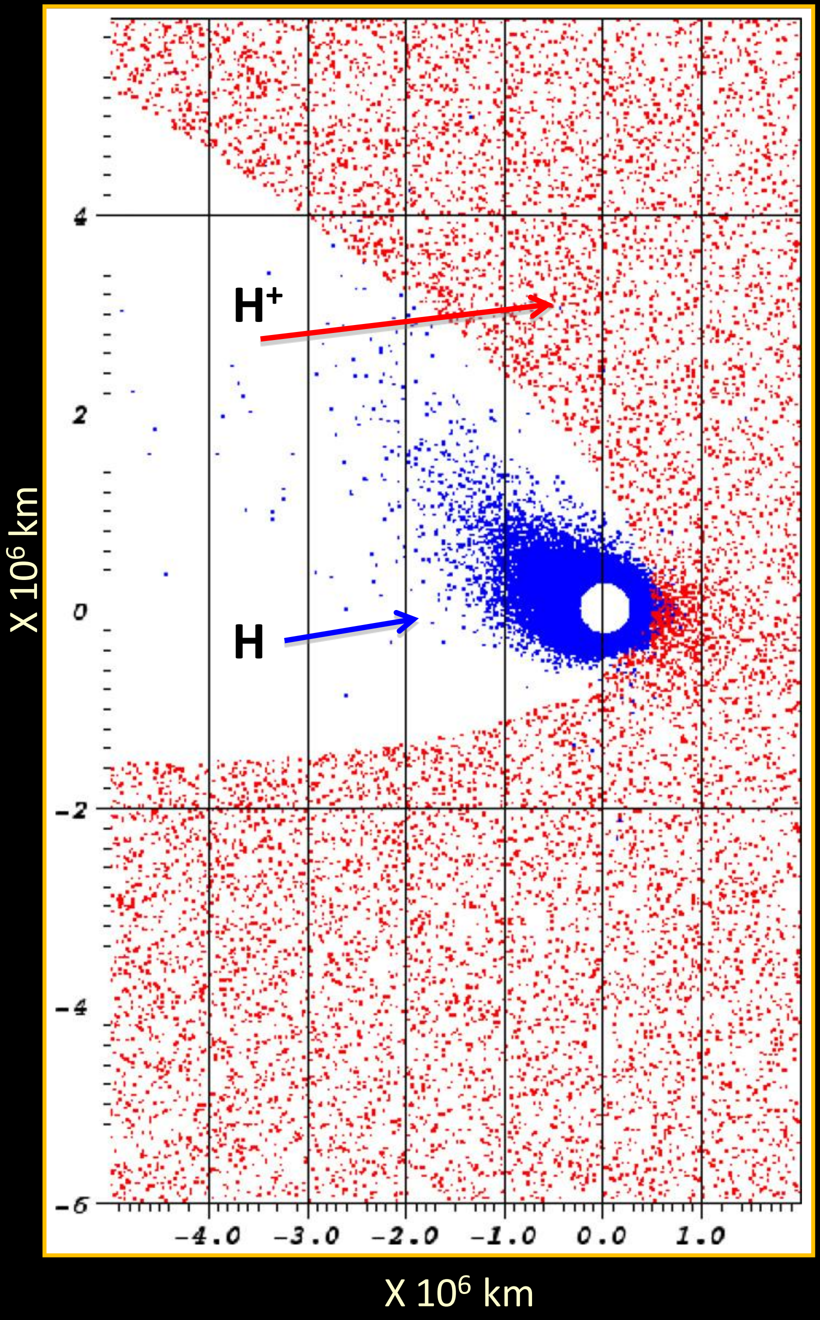


- Vidal-Madjar et al (2003) & recent papers
- 15% deep Lyman alpha transit 4.3 RJ
- Requires exospheric T ~ 10,000 K!
- Upper atmospheric T, atmospheric expansion, and mass loss are coupled
- Mass loss at 10^{10} g/s?



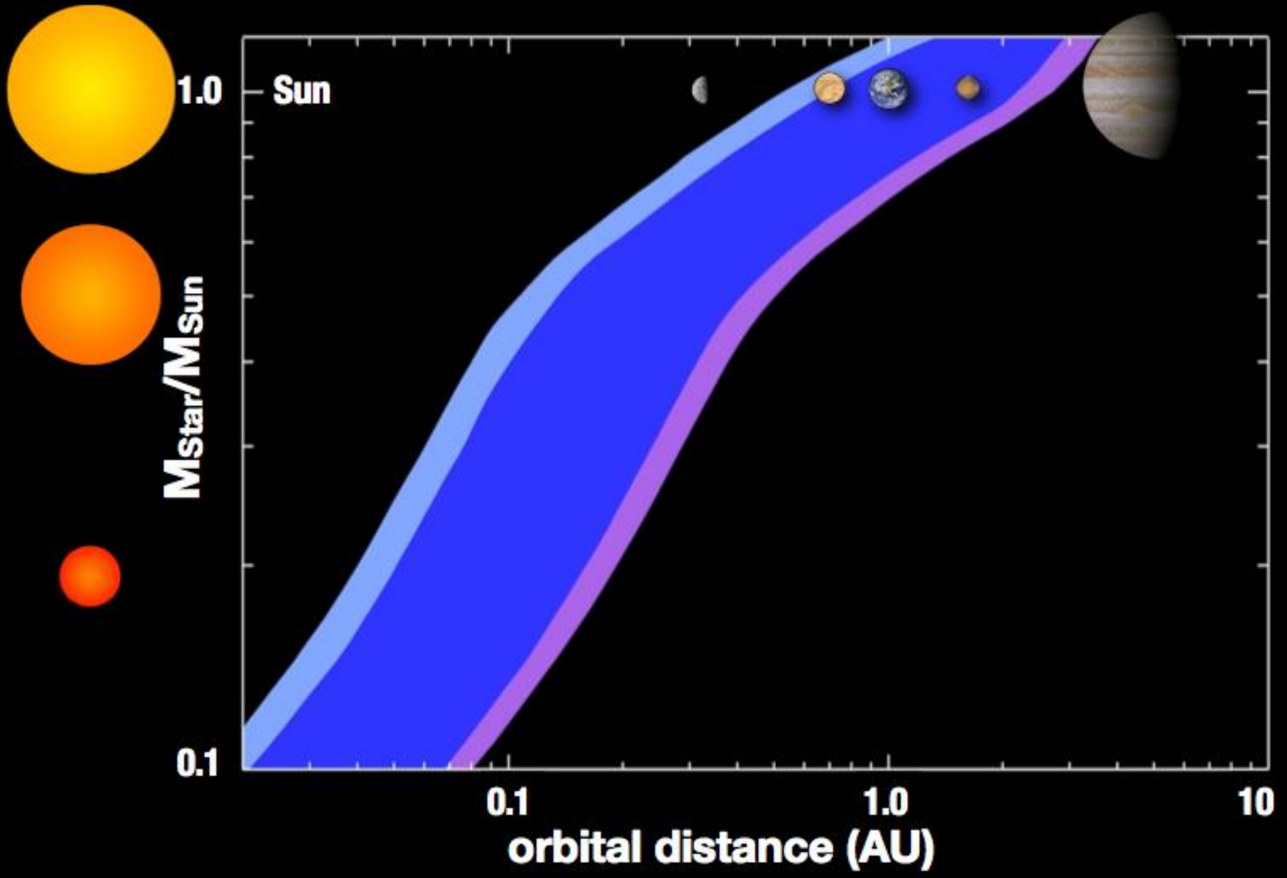


- **Other alternative explanations:**
  - **Ben-Jaffel (2008) & more**
    - **9% transit depth**
    - **No blueshift ⇨ Natural broadening in non-escaping atmosphere**
  - **Holmström et al. (2008) & more**
    - **Charge exchange between the neutral exosphere and the stellar wind protons produces a cloud of ENA (Energetic Neutral Atoms)**



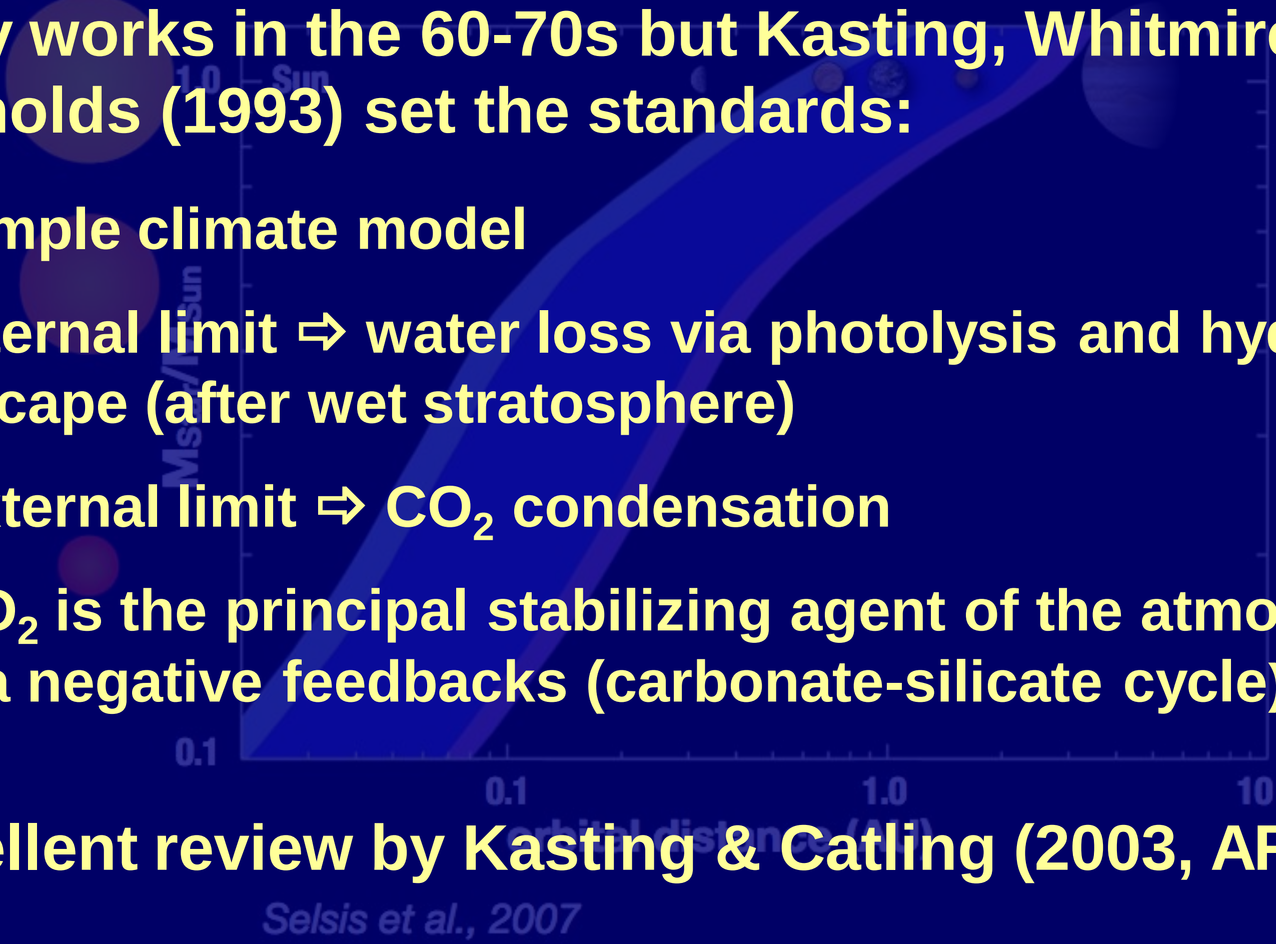
Planet habitability (habitable zone)

- **Requisite of liquid water on the planet's surface (stellar radiation)**



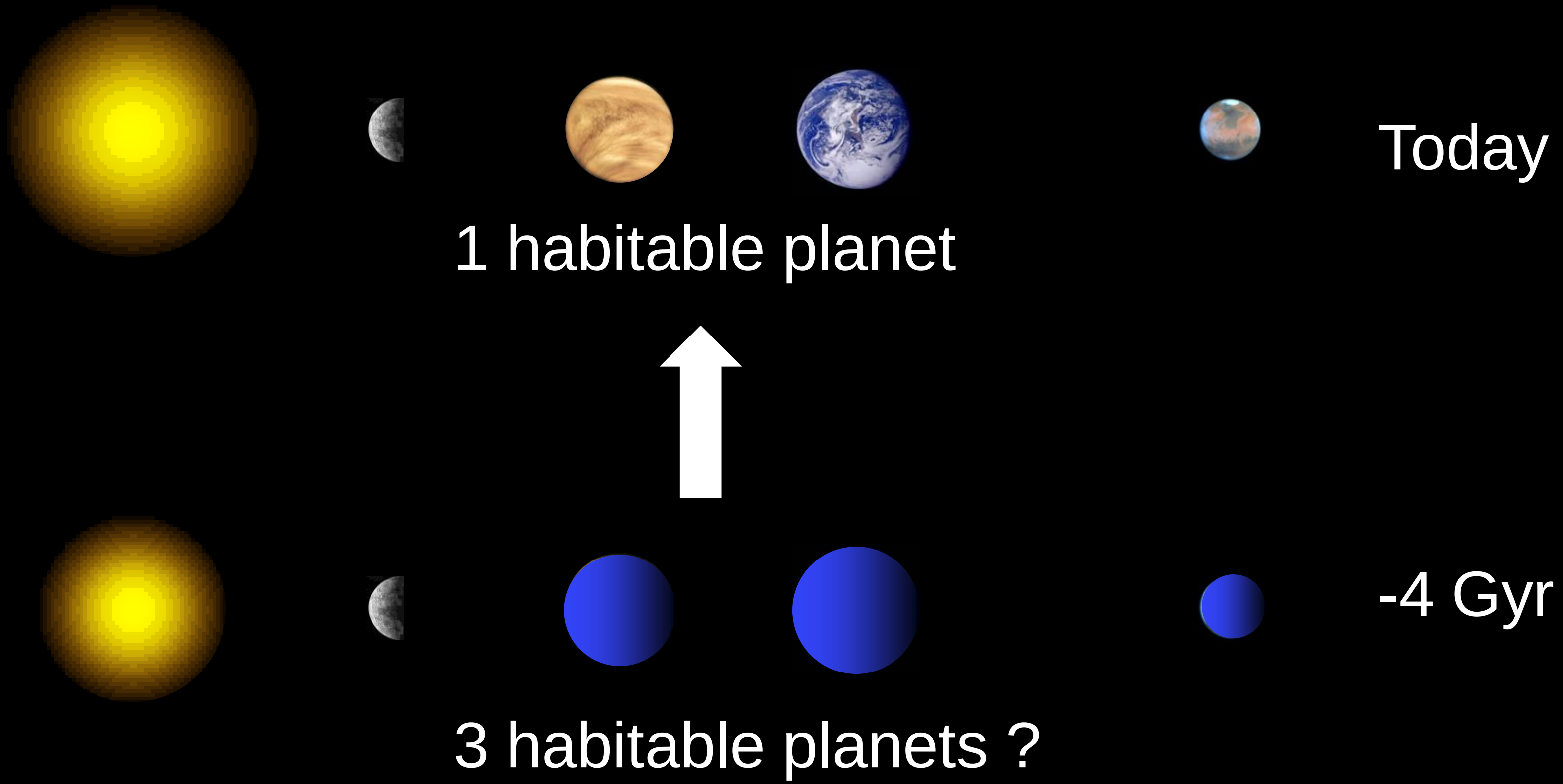
Selsis et al., 2007

Planet habitability (habitable zone)



Selsis et al., 2007

- Requisite of liquid water on the planet’s surface (stellar radiation)
- Early works in the 60-70s but Kasting, Whitmire & Reynolds (1993) set the standards:
  - –Simple climate model
  - –Internal limit ⇨ water loss via photolysis and hydrogen escape (after wet stratosphere)
  - –External limit ⇨ CO_2 condensation
  - –CO_2 is the principal stabilizing agent of the atmosphere via negative feedbacks (carbonate-silicate cycle)
- Excellent review by Kasting & Catling (2003, ARA&A)



Today

1 habitable planet

-4 Gyr

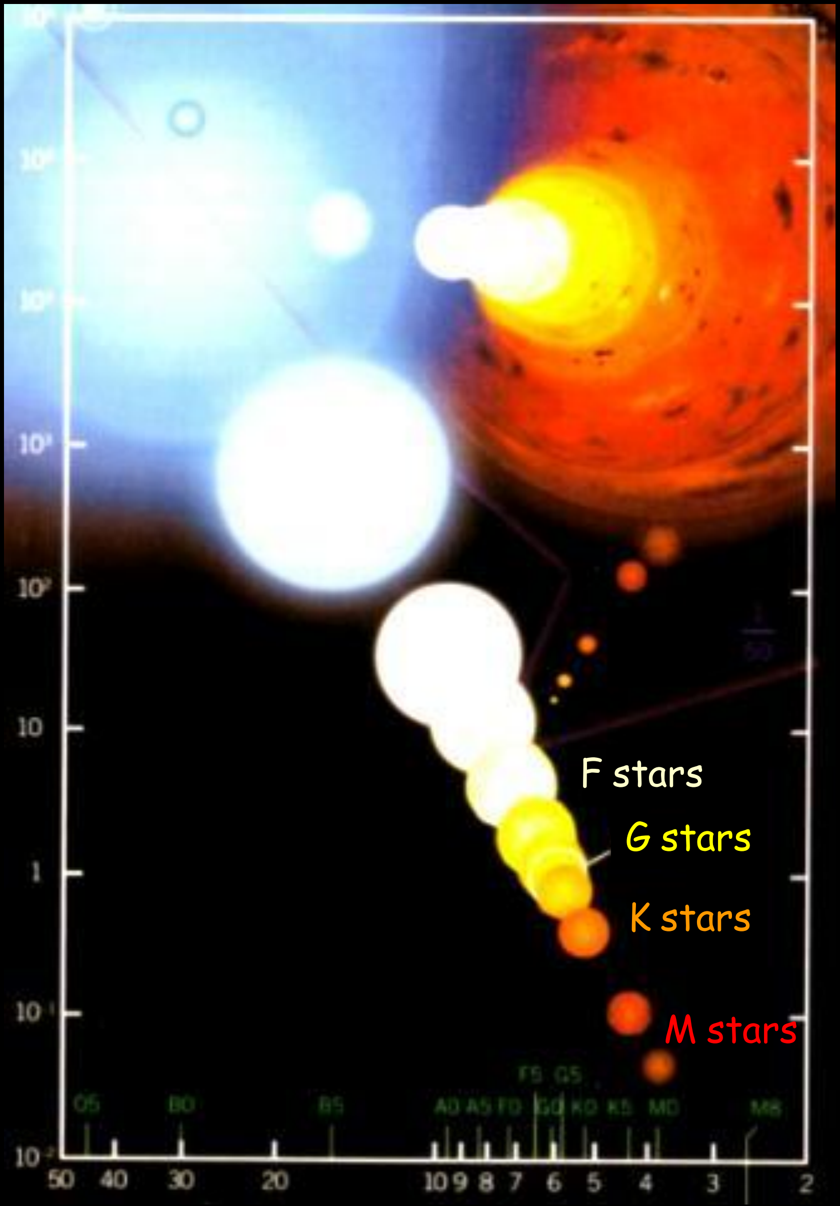
3 habitable planets ?

There is a lot more to this simplistic picture:

- A planet inside the HZ may not be habitable!
- A planet outside the habitable zone may be habitable!

Planet mass?, atmosphere?, plate tectonics?, magnetic dipole?, parent star's irradiance?
(see Lammer et al. 2009, A&ARv)

Other stellar types...

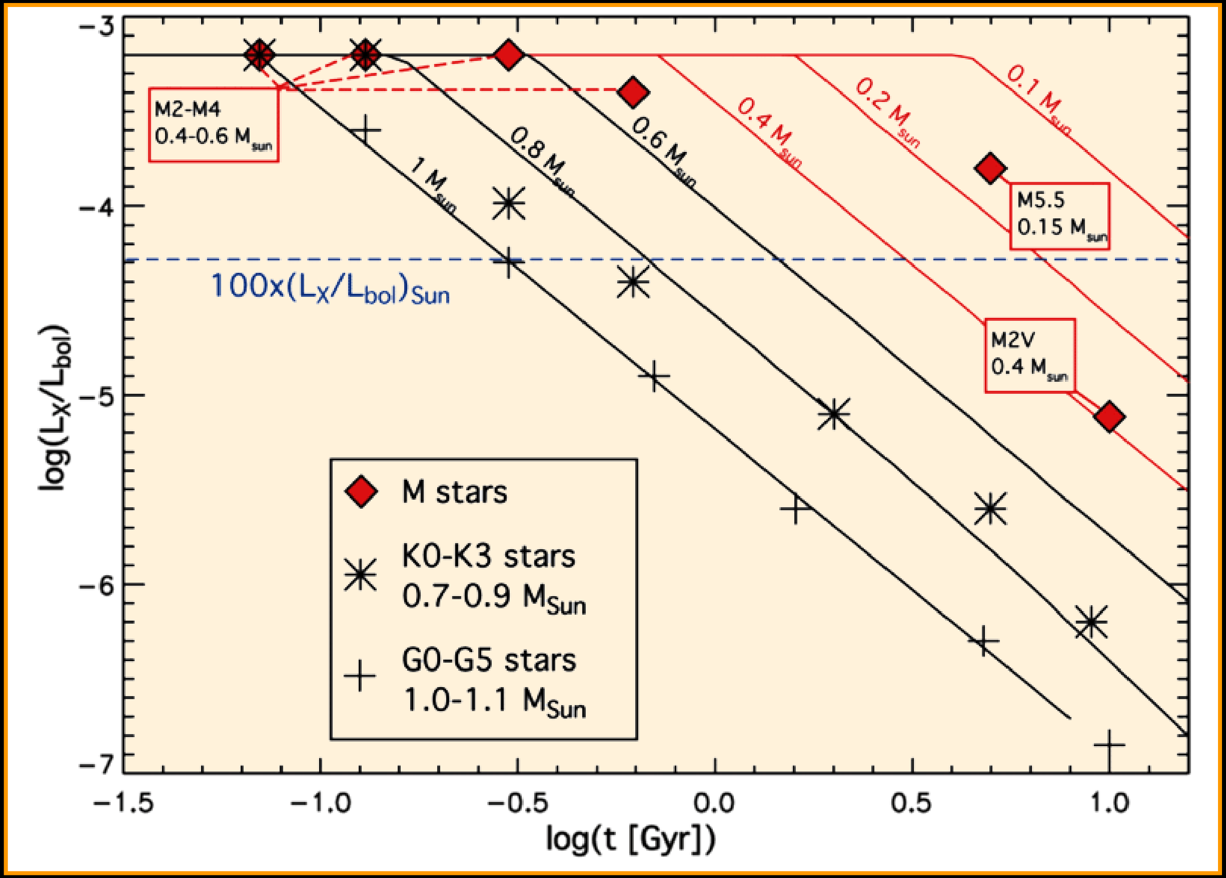


In principle low-mass stars are prime candidates for planet searches:

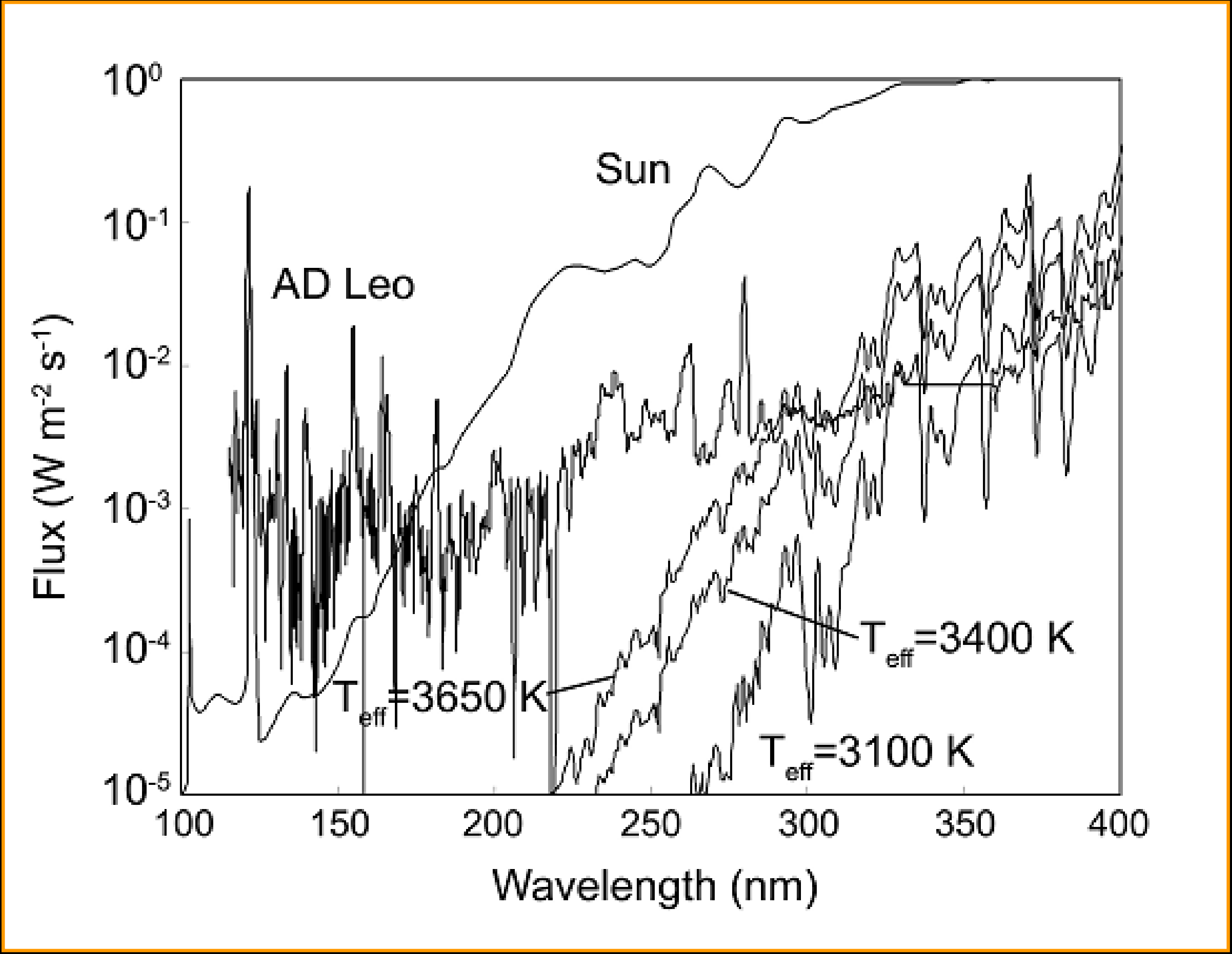
- ✓Very abundant in the solar neighborhood
- ✓Better contrast star/planet

Solar-type stars are active only when young…

but lower mass stars stay active for much longer!

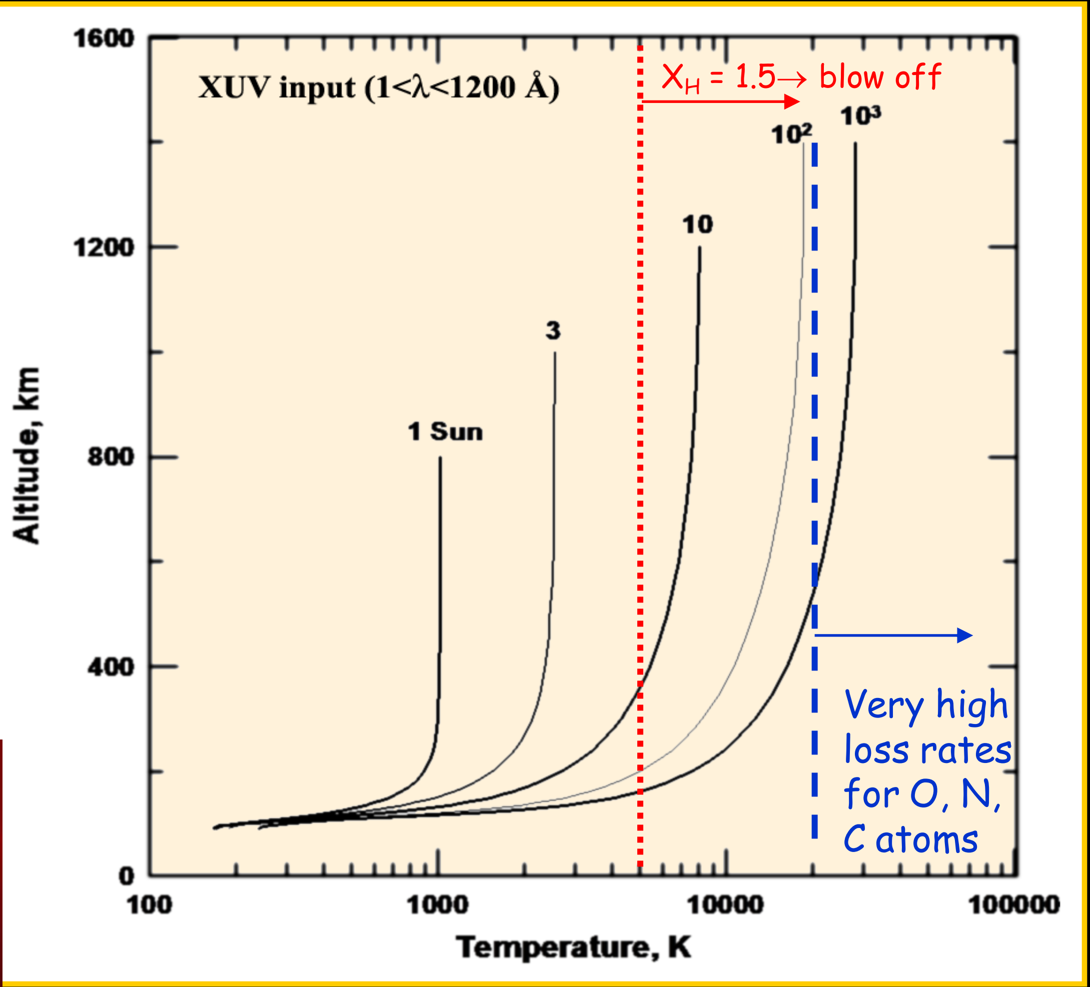


- ➢ The irradiances stay at saturated levels ($L_X/L_{bol}\approx10^{-3}$) for longer (up to 1 Gyr in the case of M stars!)
- ➢ If the emissions scale similarly to G stars:
  - K stars XUV ⇨ 3-4× XUV of G stars at same age
  - M stars XUV ⇨ 10-100× XUV of G stars at same age

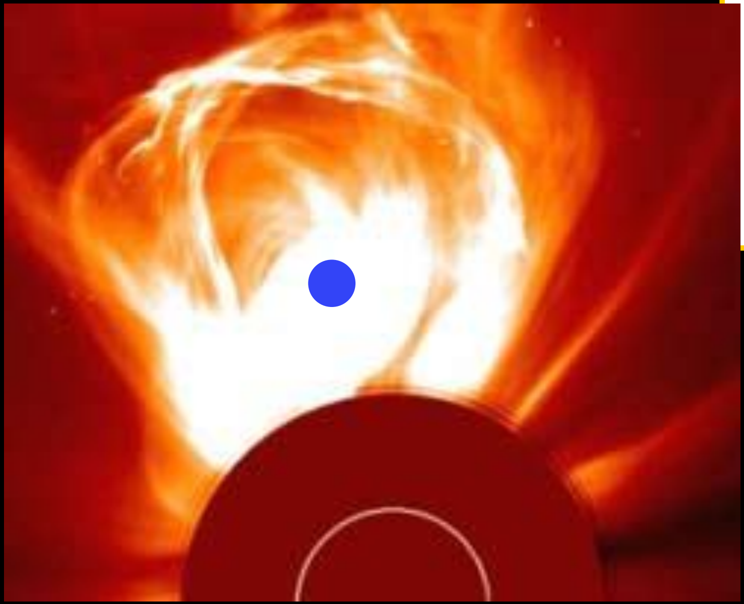


Segura et al. (2005, Astrobiology)

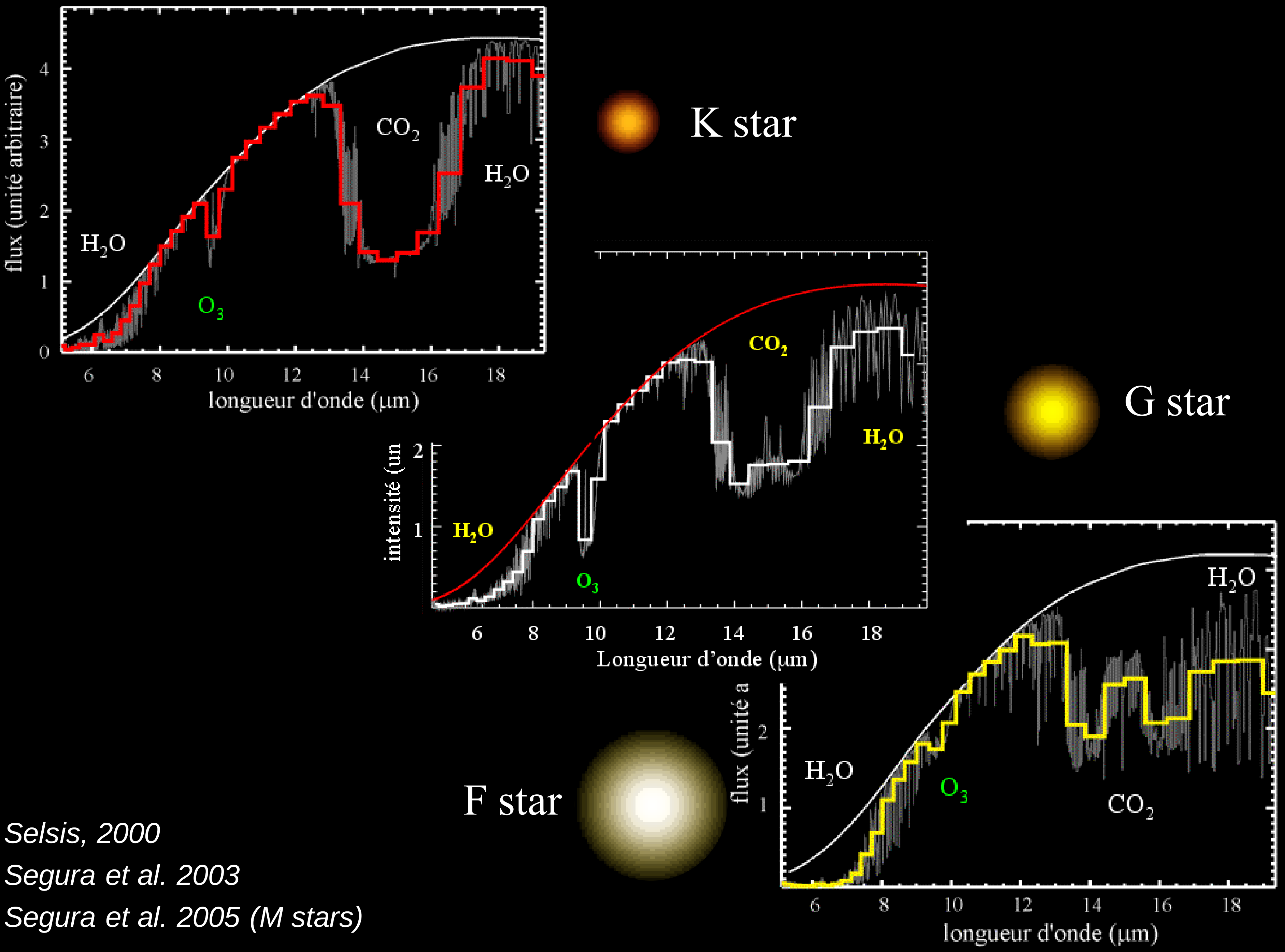
- **Are atmospheres of habitable planets around M-type stars stable? (Scalo et al. 2007)**
- **Only CO_2-rich atmospheres (>1-1.5 bar) can survive and keep the water**



Kulikov et al. (2006, P&SS)



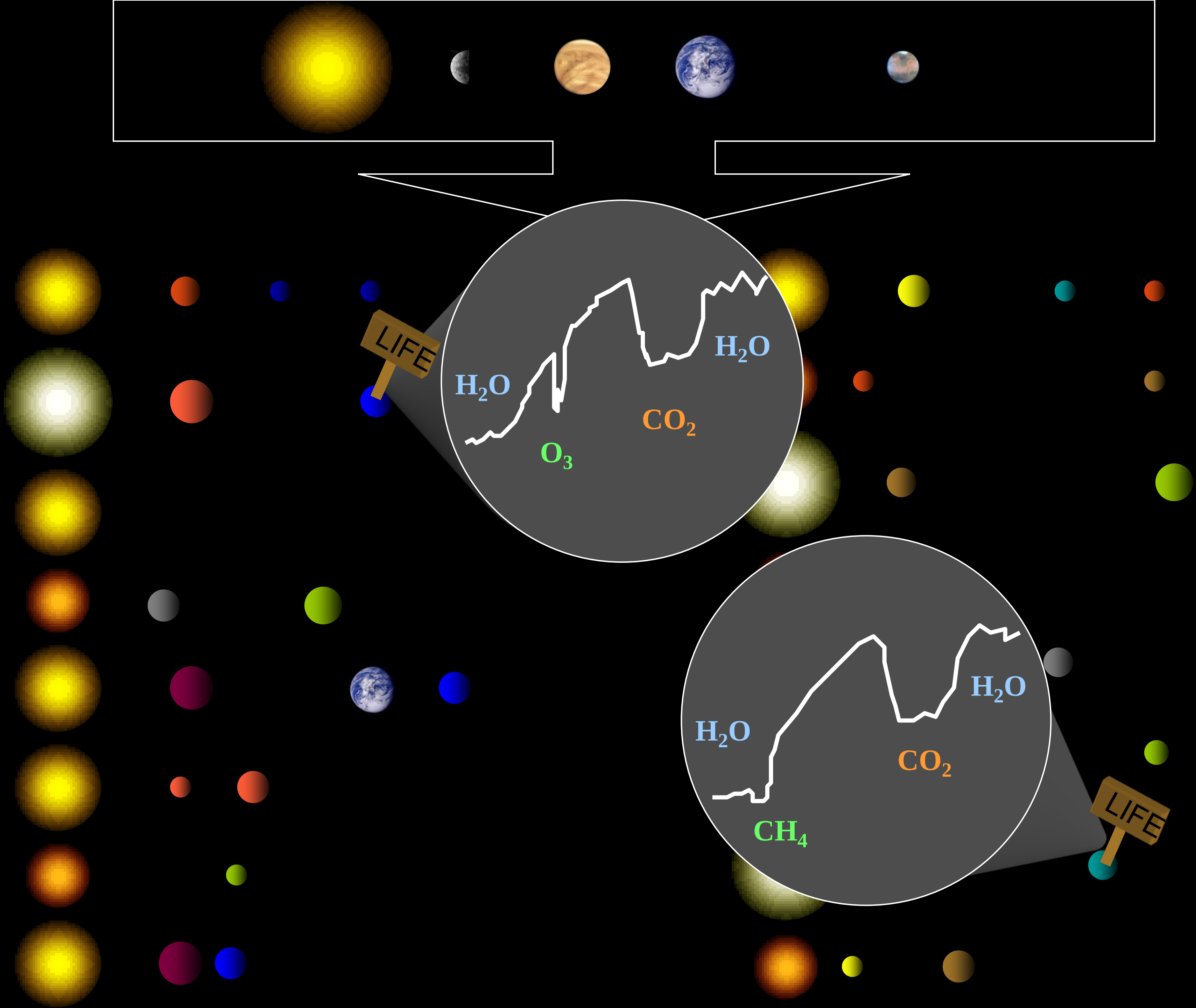
Rocky planets in M star HZs may never evolve into habitable worlds!



Selsis, 2000

Segura et al. 2003

Segura et al. 2005 (M stars)


LIFE
H_2O
O_3
CO_2
H_2O
H_2O
CH_4
CO_2
H_2O
LIFE