Planetary Habitability around Active Stars

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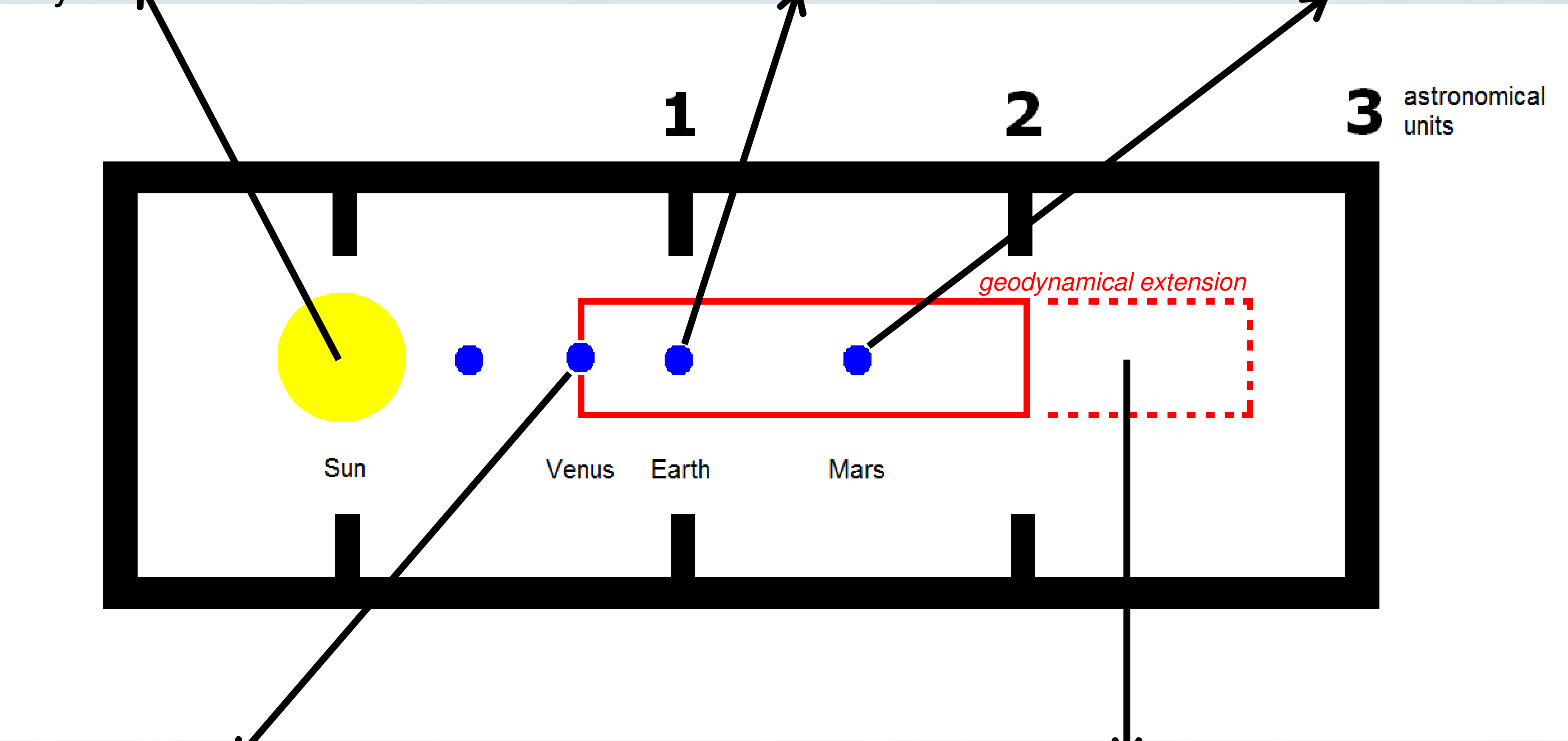
Observatório do Valongo

Habitable Zone as a Unifying Concept

How massive is your star?
How old is your star?
Where do you reside in the Galaxy?

How is your tectonics going for you?
Do you have enough radiogenic heating?
What is your Si/Fe ratio?
What is your crust/mantle/core ratio?
How good are you at surviving catastrophes?

How massive is your planet?
Can it hold its own?
Can you keep your magnetic field?



How close are you to the edge of the ZH?
How long do you have?
What is your water inventory?

Do you need geodynamics to stay habitable?
How long do you have?

Magnetic activity in low mass stars

differential rotation + convection + plasma = ***dynamo effect***

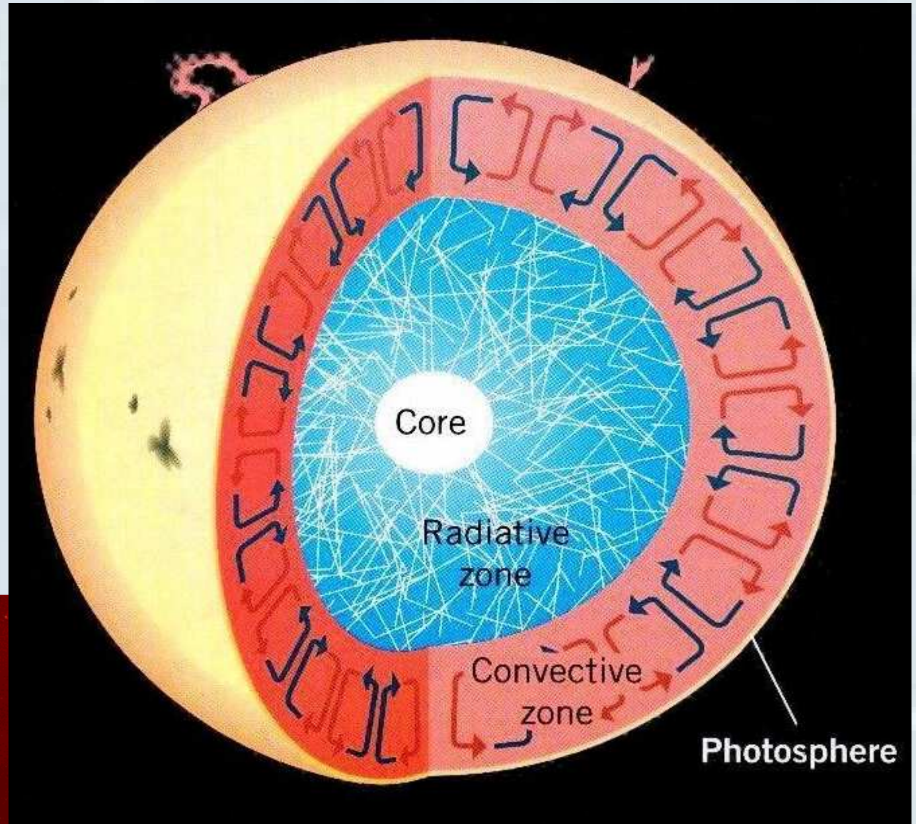
differential rotation: warps field lines

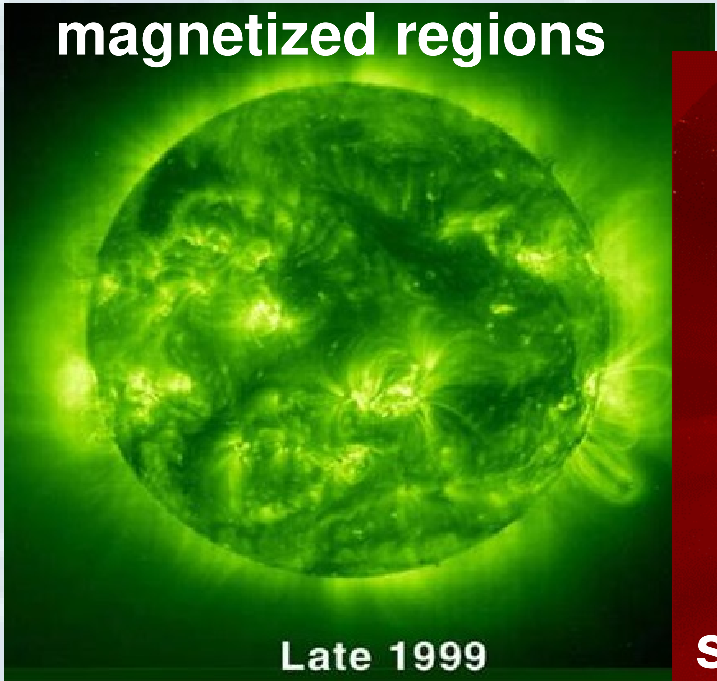
+

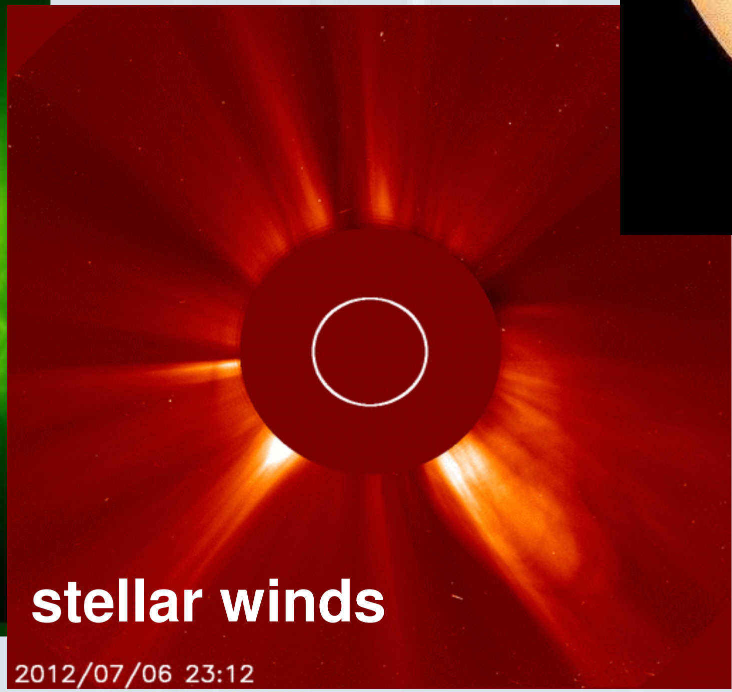
convective envelope: cyclonic turbulence

=

generation & amplification of magnetic fields







Energy is dissipated as:

Flares
Particle fluxes (WINDS)
Far ultraviolet photons
X-ray photons

Planetary evolution (even Earth's) driven by stellar emissions

Star as the overwhelmingly dominant **source of energy**

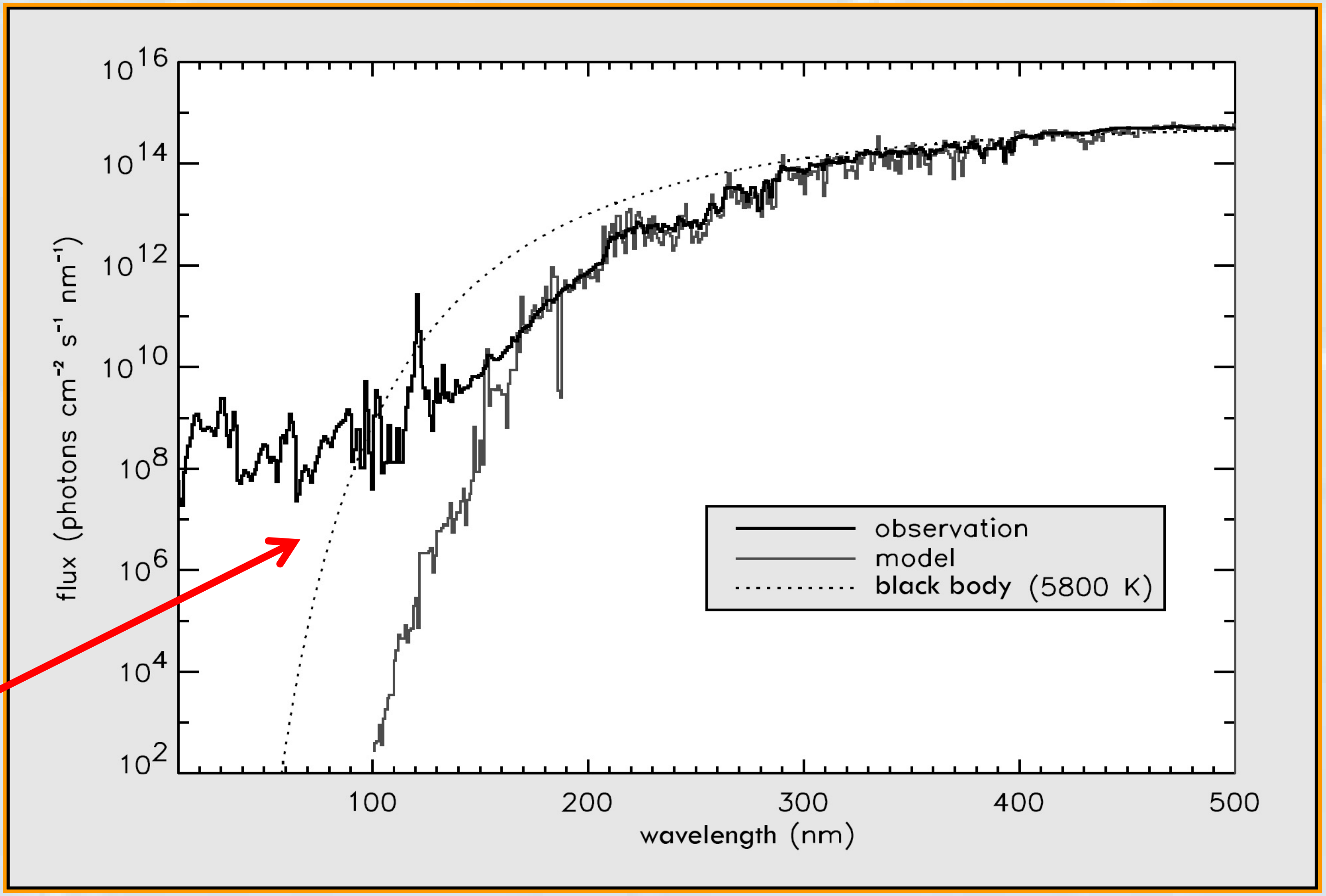
Days: rotational period & active regions
Hours: stellar flares & particle ejections
Years & hundreds of years: activity cycles (Sun's 11-yr)
Billions of years: rotational spin-down (nuclear timescales)

IMPORTANT MODULATIONS

Stellar radiation critically affects composition, thermal properties and **existence** of atmospheres

Models deviate from observations for

λ < 1700 Å : strongly non-thermal regime (magnetic)

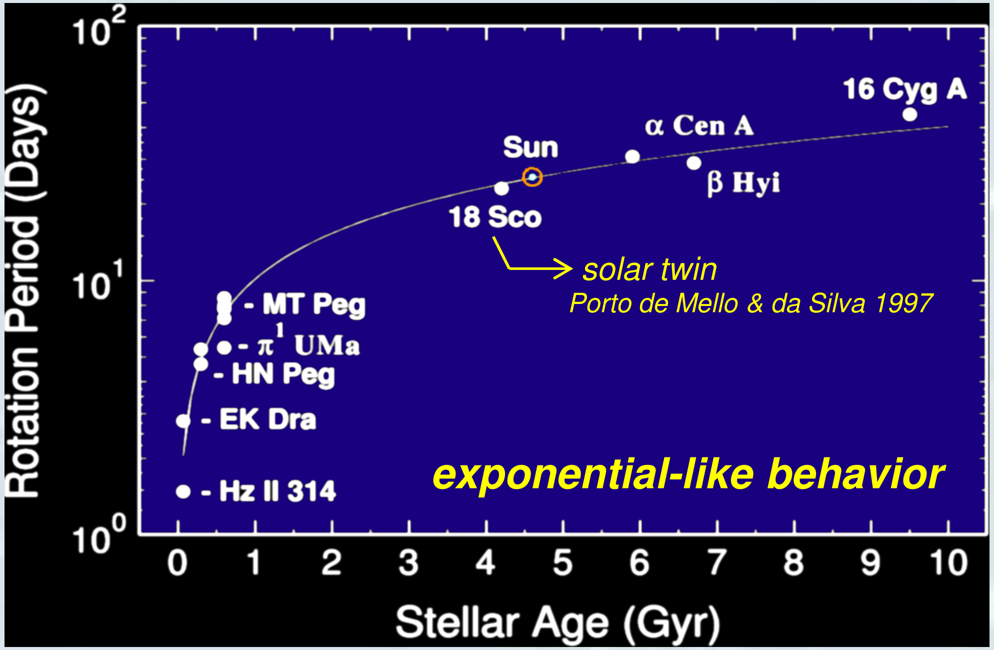


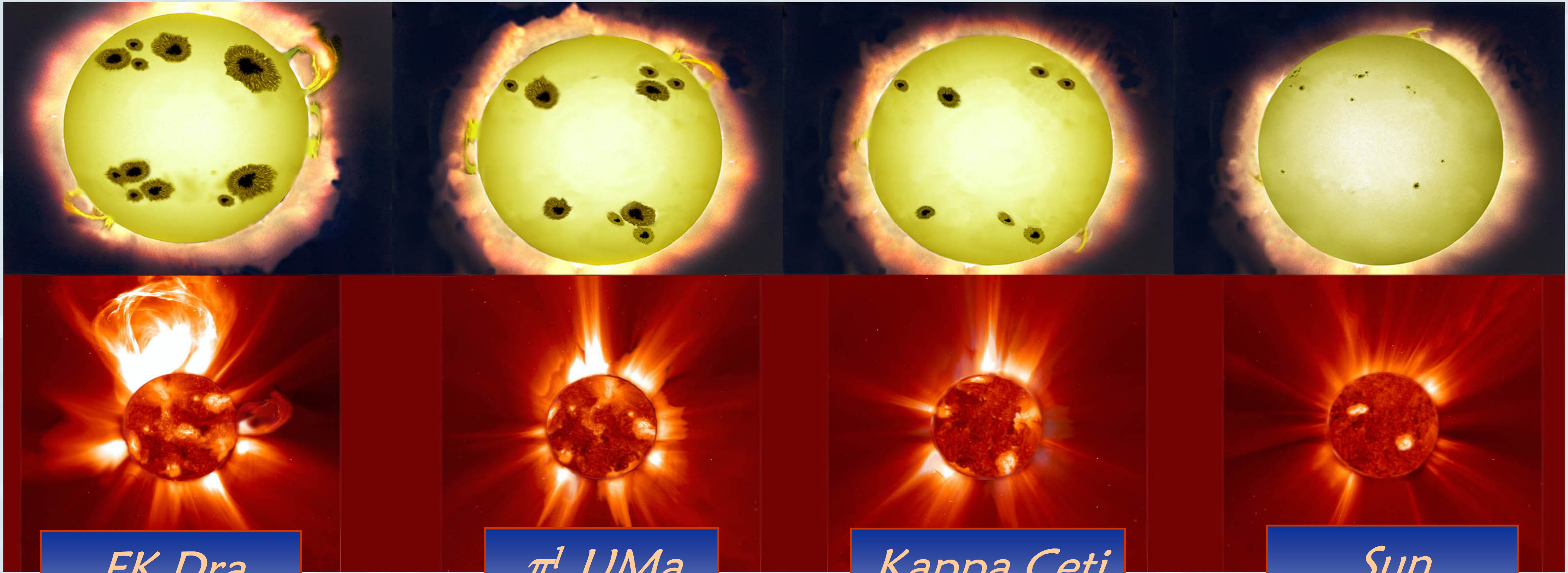
The Sun in Time

Sample of nearby stars (high fluxes) in narrow mass/composition range (same convective properties) PLUS good age estimates… not easy!

Güdel et al 1997

Young Sun: 10x faster rotation
MUCH enhanced magnetic activity





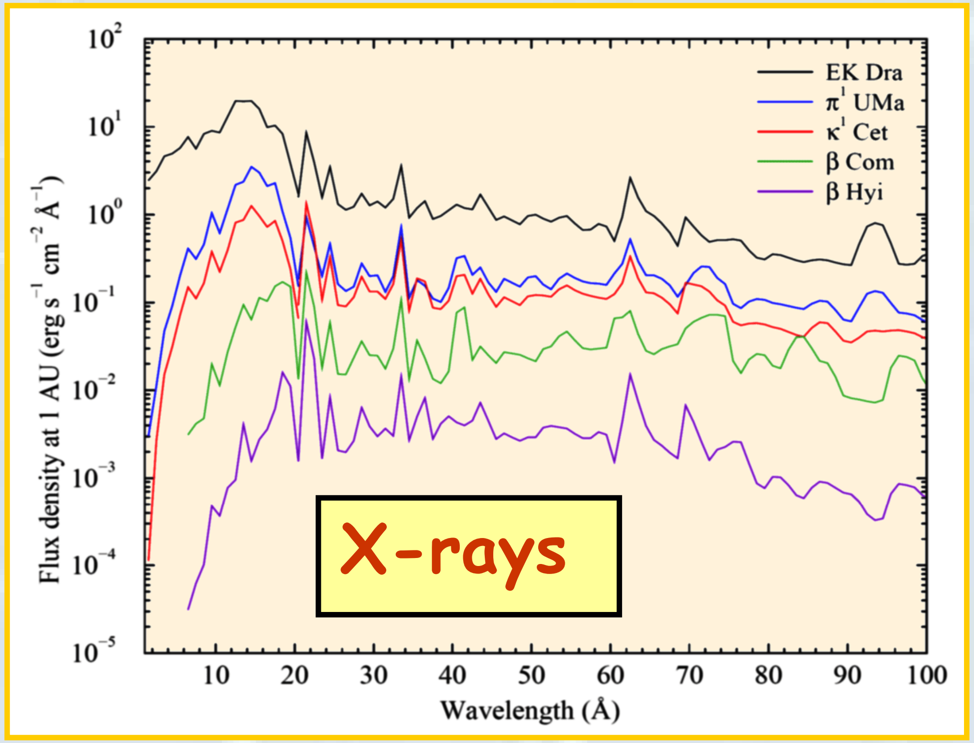
EK Dra 100 Myr

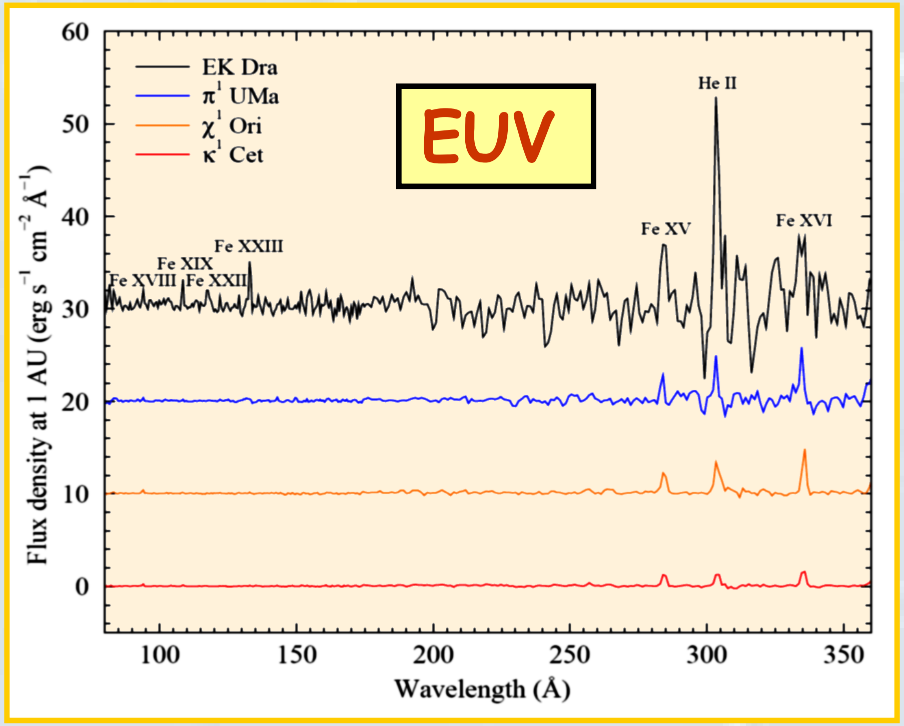
π1 UMa 300 Myr

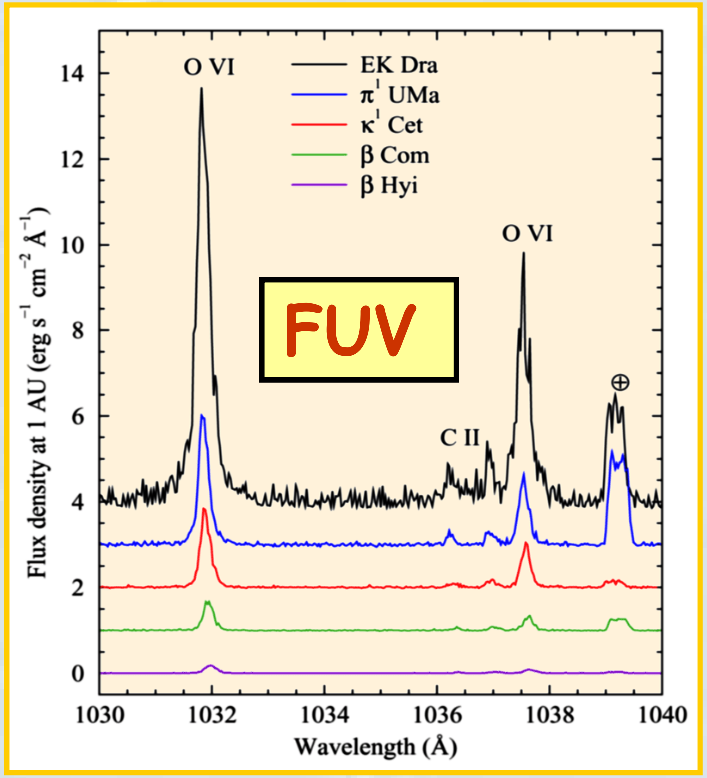
Kappa Ceti 700 Myr

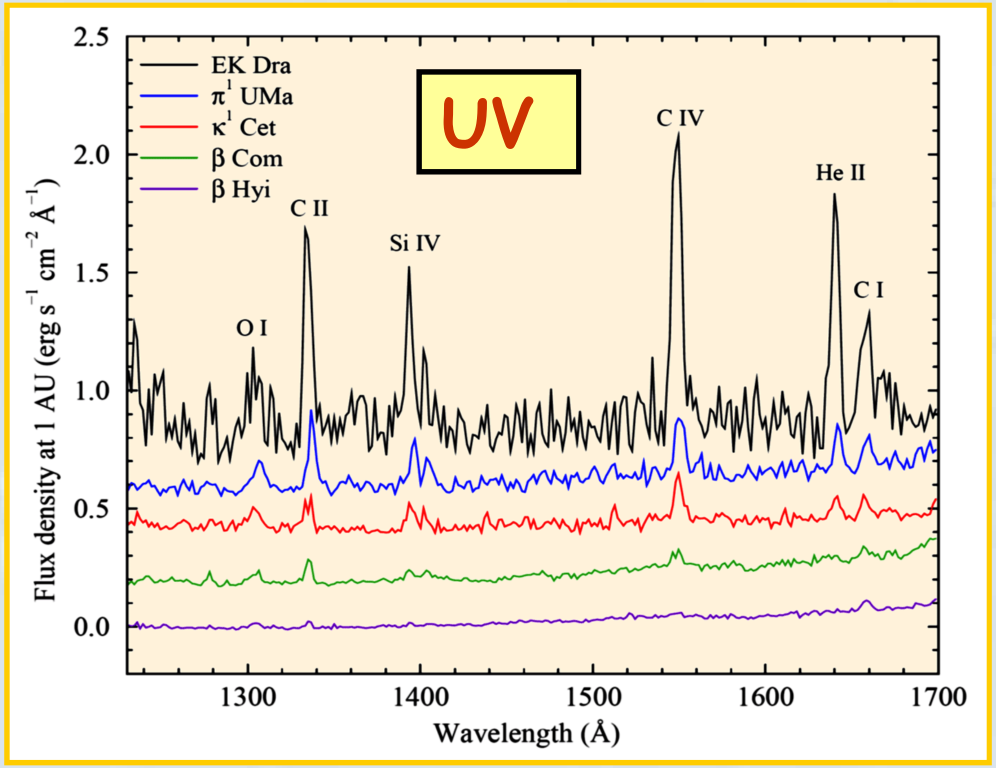
Sun 4.56 Gyr

Evolution in Time

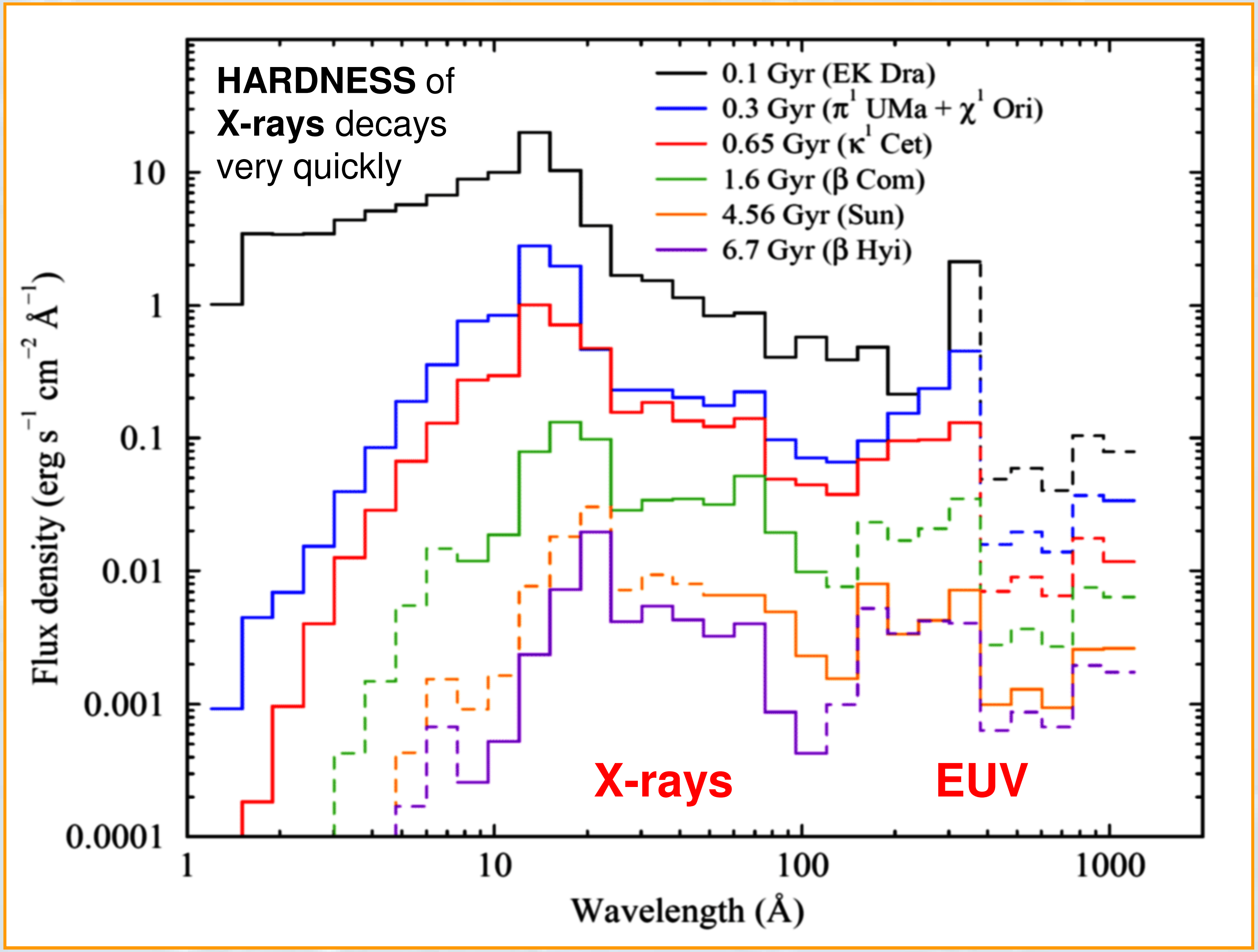








The Sun in Time



Güdel et al 1997
Ribas et al 2005
Ribas et al 2010

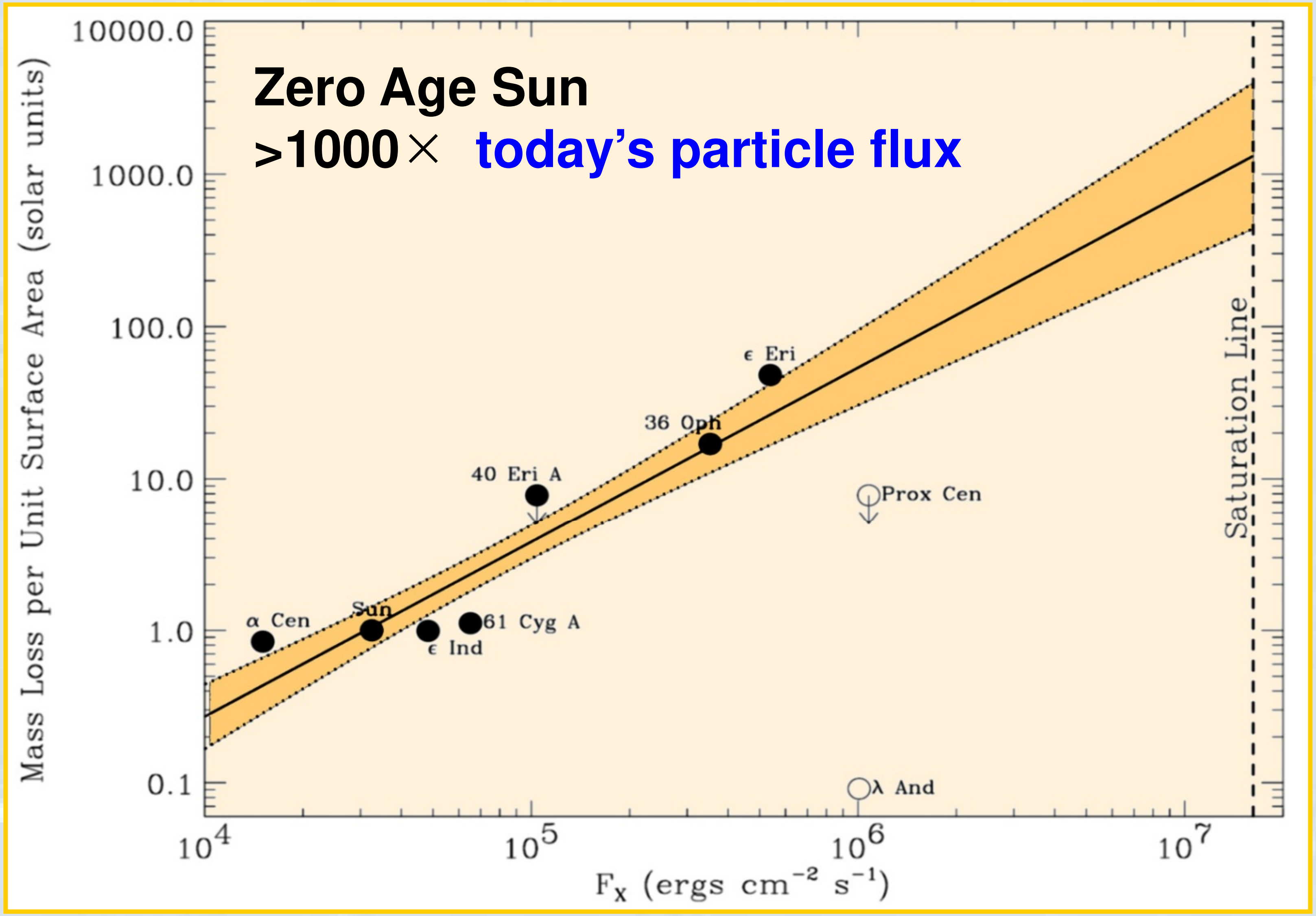
Very Young Sun had stronger emissions:

>1000× X-rays **10 to 100× Far/Extreme UV**

5 to 10× UV

Stellar Winds: Particle Fluxes

Low-mass stars have hot coronae: lose mass in open flux magnetic tubes
Mass-loss correlates well with X-ray luminosity

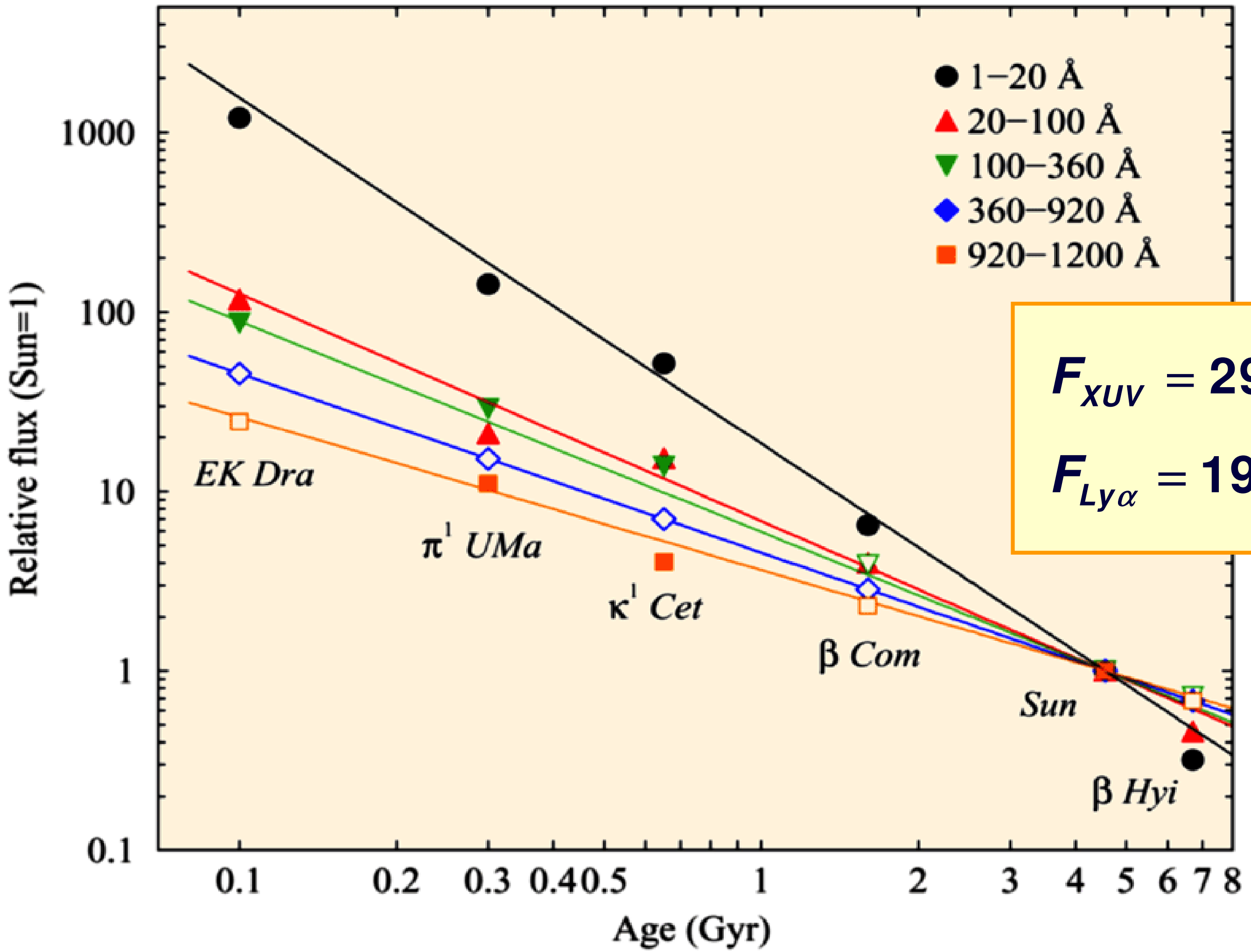


Possible solution to the *Faint Young Sun Paradox*?

Zero Age Sun slightly more massive?
More luminous!

Wood et al. 2002
do Nascimento Jr. et al. 2016

Evolution in Time



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

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

Ribas et al 2005

Similar results:

Zahnle & Walker 1982

Ayres 1997

- Flux density evolution scales well with **power-law relationships**
- 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 **Lyα line** (1215 Å) decreases with a slope of –0.72

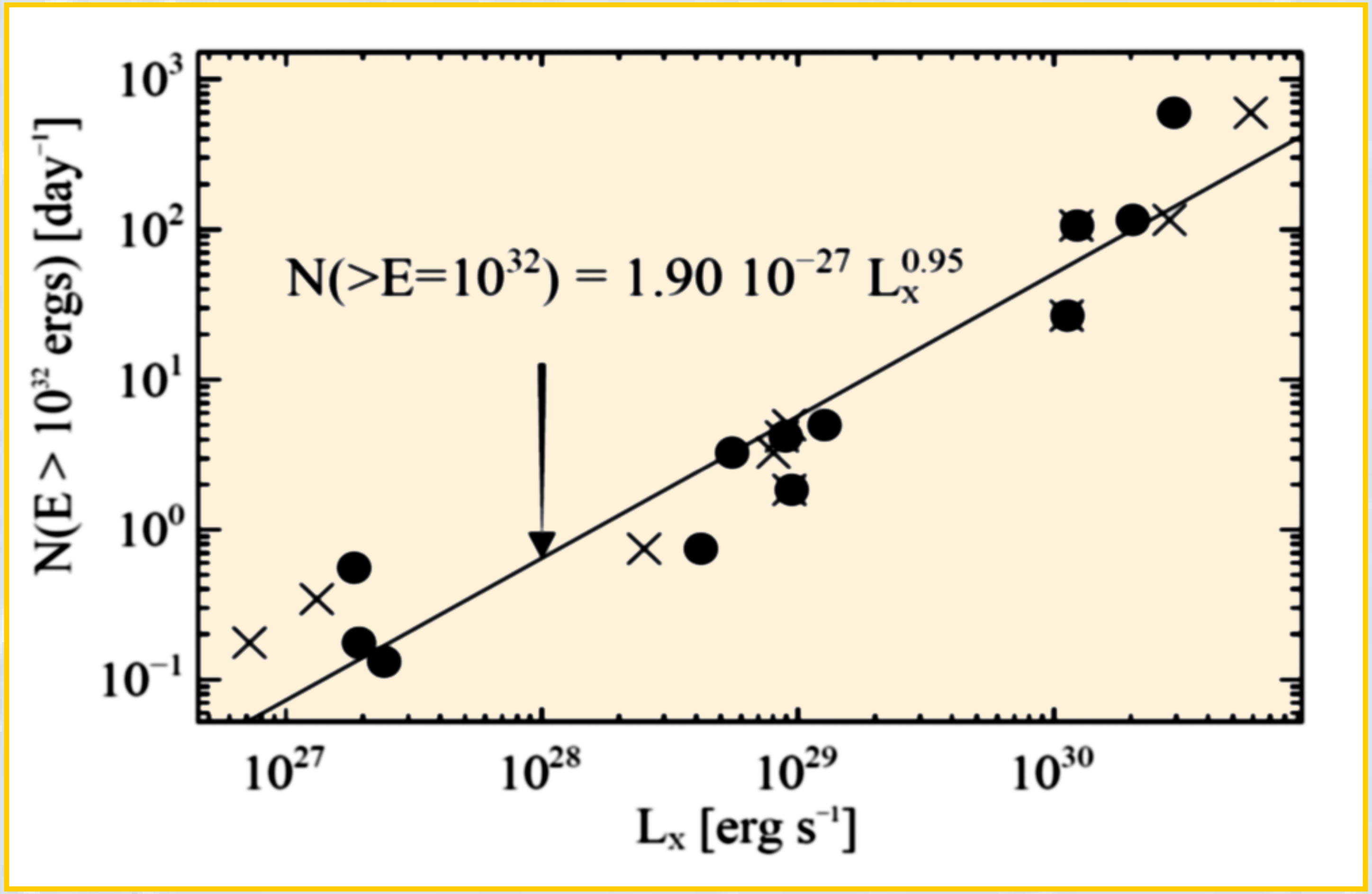
Short-term Variability (Flares)

- **Flares ⇨ Relative variations: 2-10x in X-rays to 1.2-1.5x in FUV-UV, but several times in particle flux**

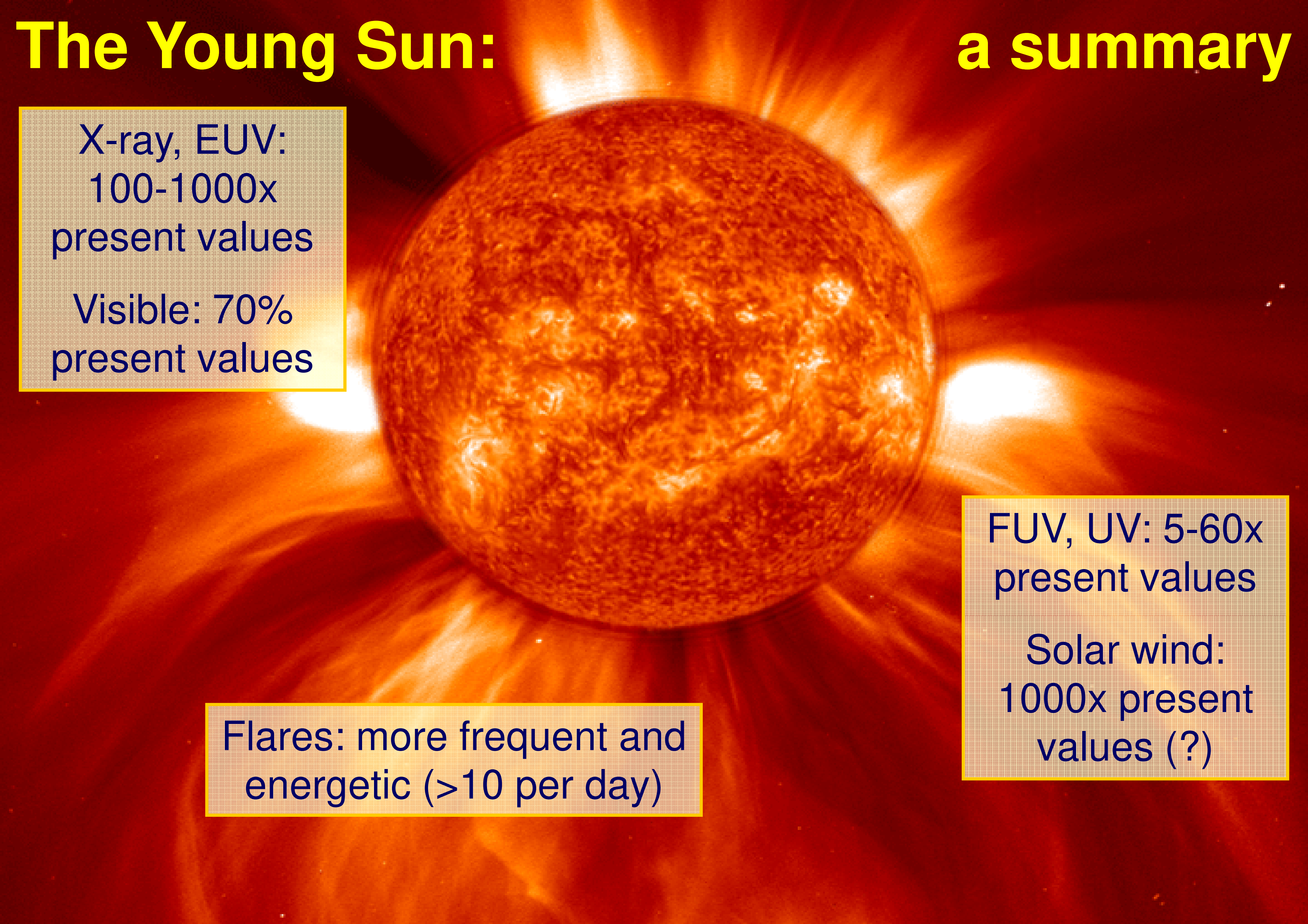
- **Large increase in high-energy flux over a few hours**

- **Low mass stars may have weakened winds as scaled with L_X** (mean wind dependent on open flux tubes)

- **Flare rates** also seem to scale with L_X (Audard et al 2000)



The Young Sun: a summary



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

Visible: 70% present values

FUV, UV: 5-60x present values

Solar wind: 1000x present values (?)

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

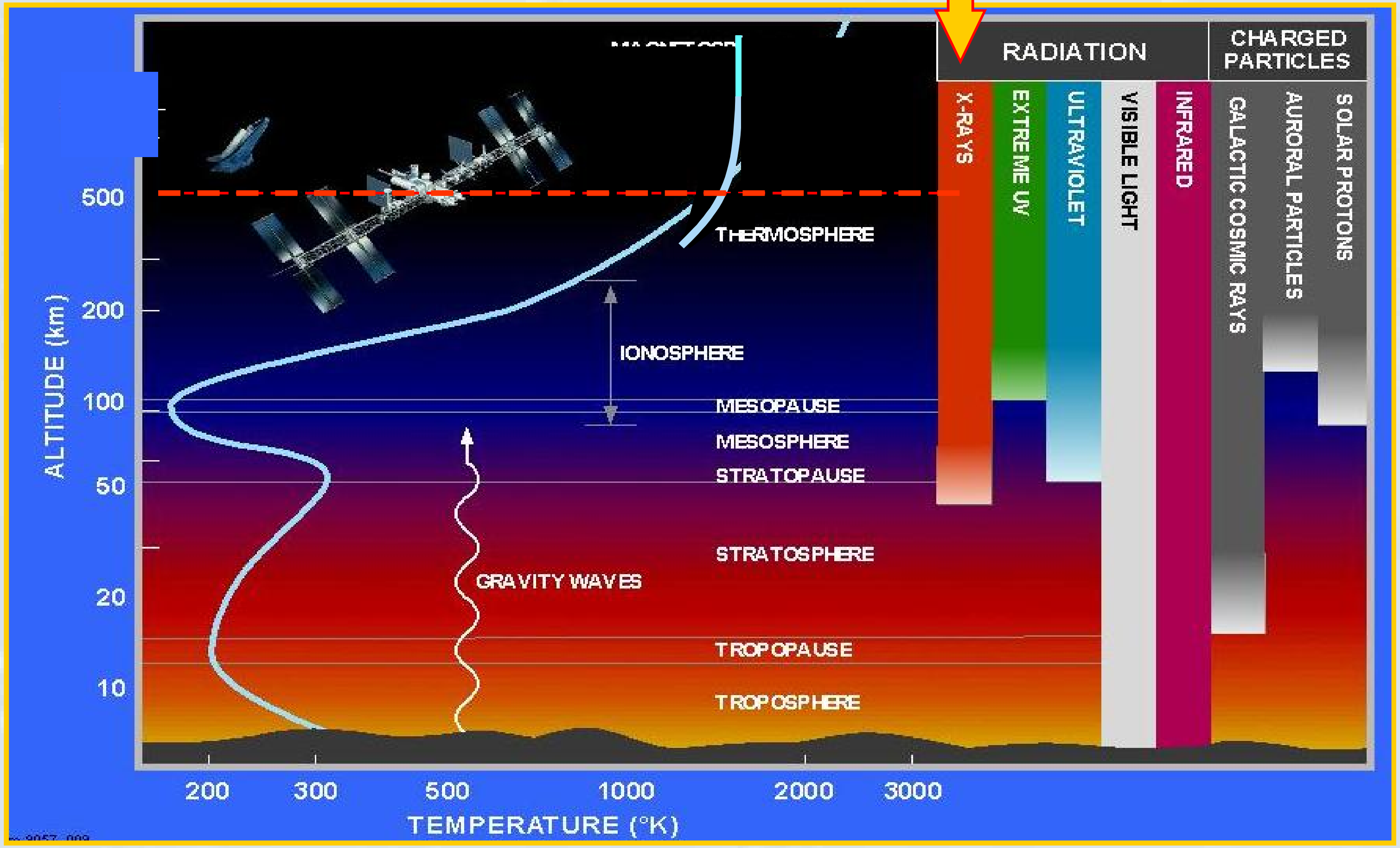
Radiative Effects on Planets

tiny fraction...
why bother?

Earth:

- Present $Flux_{XUV} = 3 \cdot 10^{-6}\ F_{total}$
- Young Sun $Flux_{XUV} = 5 \cdot 10^{-4}\ F_{total}$

High altitude thermalization



Energy deposited in **low density upper atmosphere**

Non-linear behavior: sheer power is not all there is – the process matters…

Particle winds: ionization, ion pick-up and sputtering

Planetary magnetic fields to the rescue

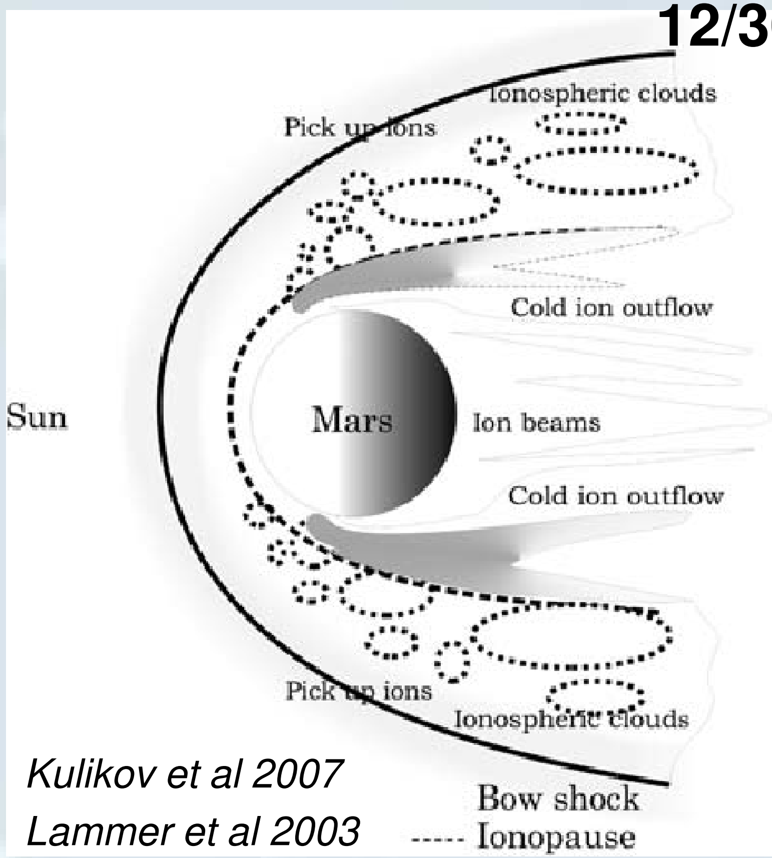
Water loss: Venus & Mars

Mars: **small** without (presently) **magnetic field**
Intense erosion of atmosphere

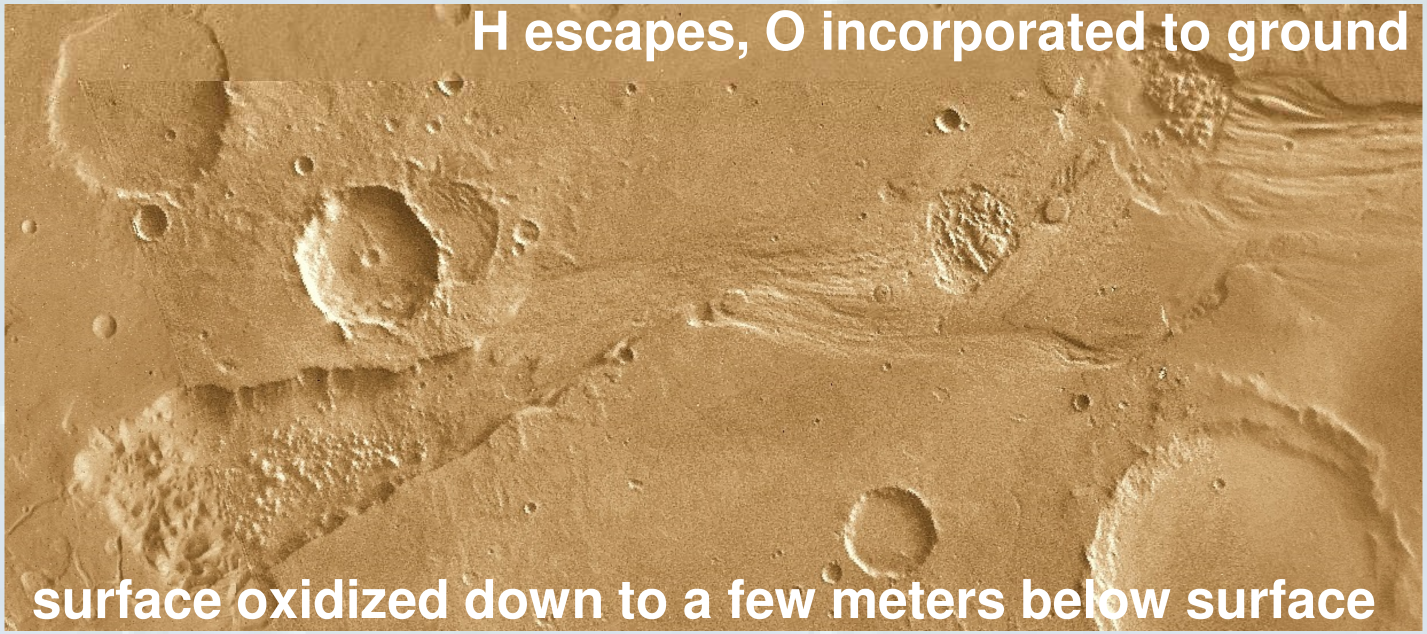
Surface water ~3.8 Gyr ago: greenhouse by CO_2 and CH_4 → $T_{surface} > 273$ K

Large impacts, core solidified, volcanoes stopped replenishing atmosphere → **erosion wins over**

Loss of **global Martian ocean ~10m deep** in 3.5 Gyr



Kulikov et al 2007
Lammer et al 2003



Venus: loss of 1% to 100% of a **full terrestrial ocean** in < 1 Gyr

Three habitable planets
in the Solar System
~4 Gyr ago?

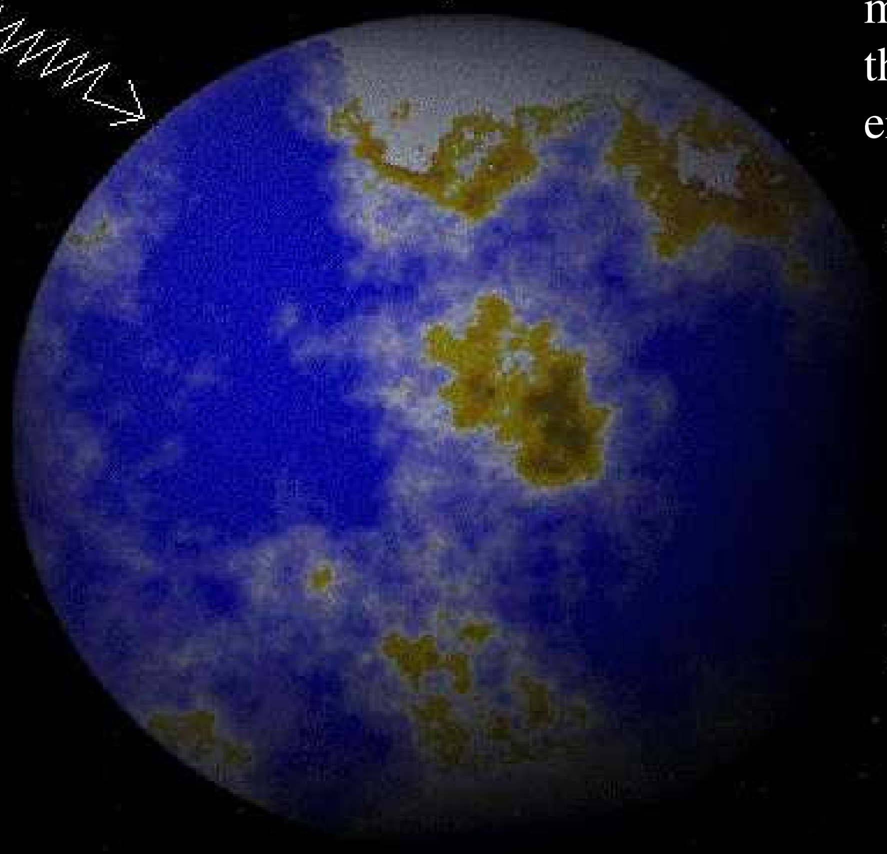
Effects of the Young Sun on the Young Earth

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…

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

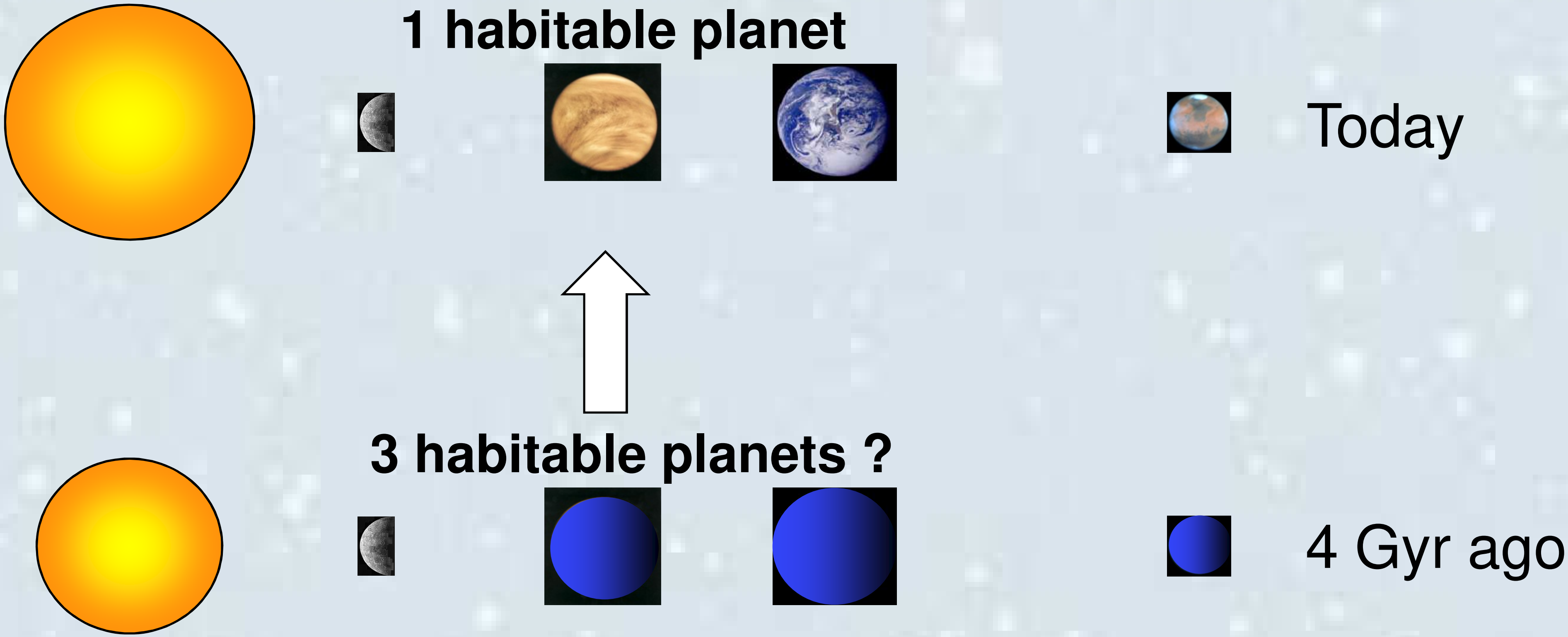
…allowing the enhanced Solar wind to carry away more atmospheric particles, thus causing atmospheric erosion



H+
β–
O++
N+

Enhanced Solar wind: 1,000 to 10,000 times present values

Many Faces of Habitability



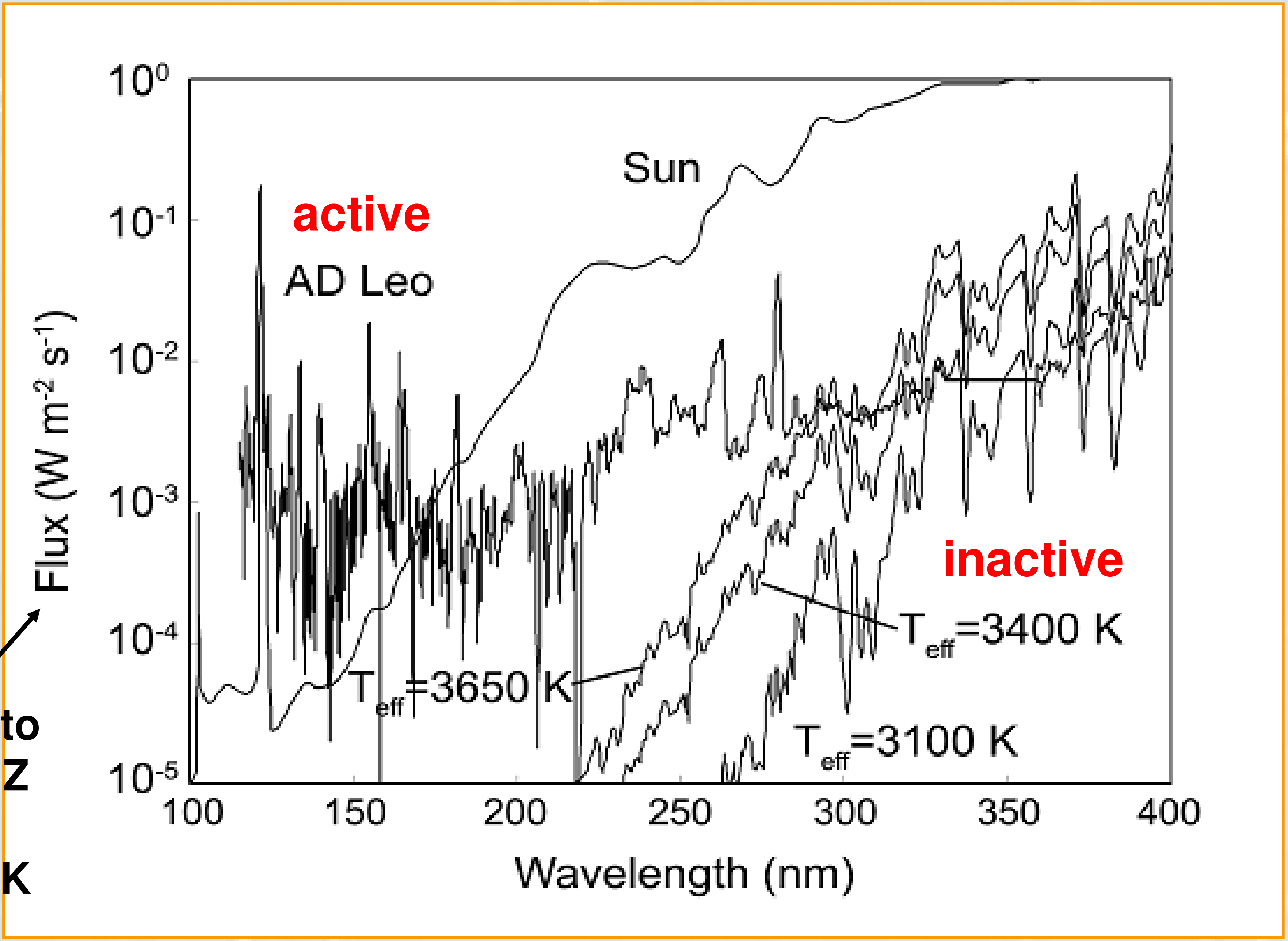
There is a lot more to the classical simplistic HZ picture
A planet inside the HZ may not be habitable!
A planet outside the habitable zone may be habitable!

Planet mass? Chemical composition (mantle/core/radiogenic heating)?
Atmosphere? Plate tectonics? Magnetic dipole? Parent star’s irradiance?

Lammer et al. 2009, Porto de Mello et al 2006

Segura et al. 2005

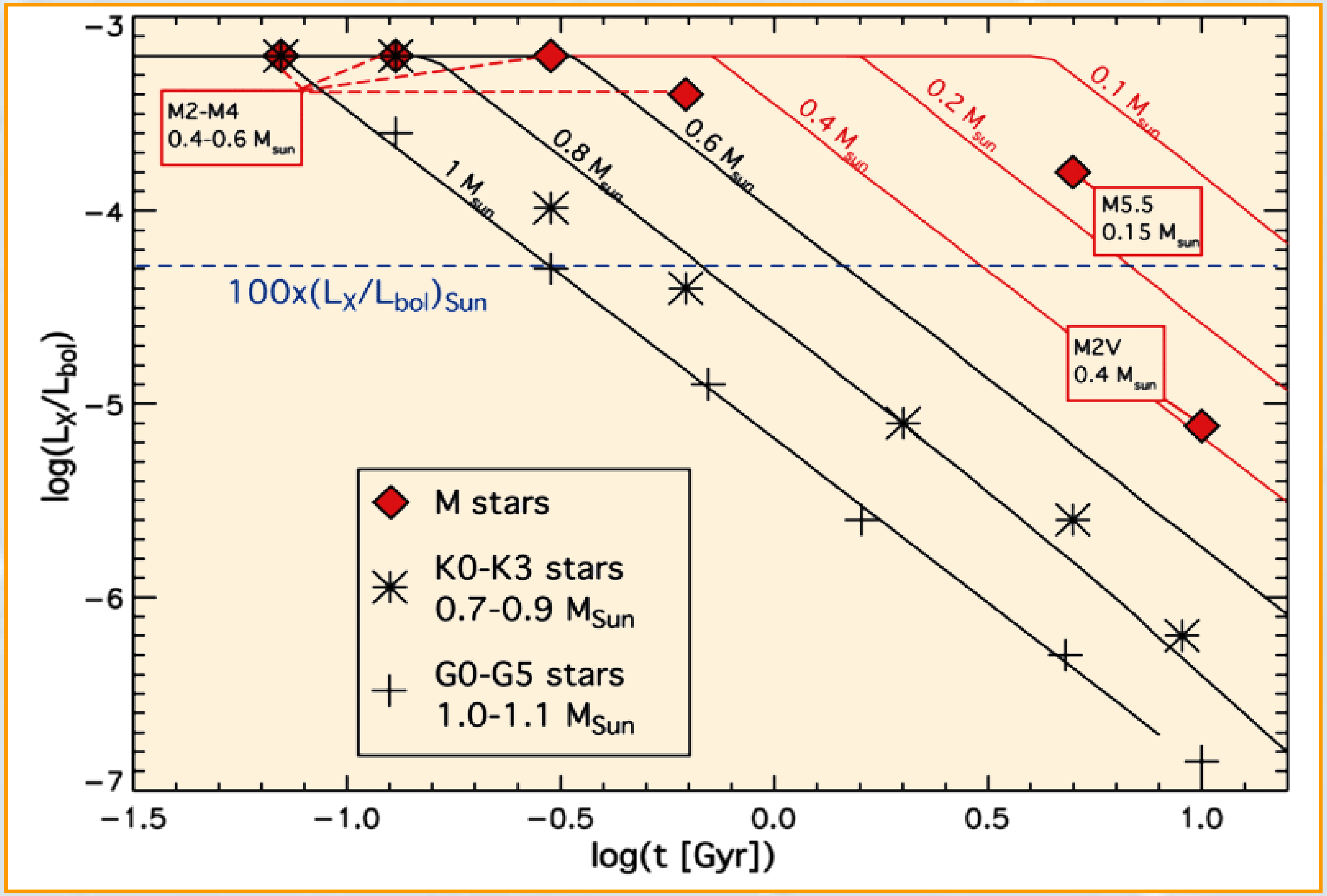
M dwarfs and their perils



Normalized to flux in the HZ

T_{planet} ~ 288 K

M dwarfs and their perils



Very low mass red dwarfs: keep **highly energetic emission phases** for up to

~7 Gyr

in contrast to solar-type stars

only **~100 Myr**

Very fast spin-down, but **VERY EFFICIENT dynamo**

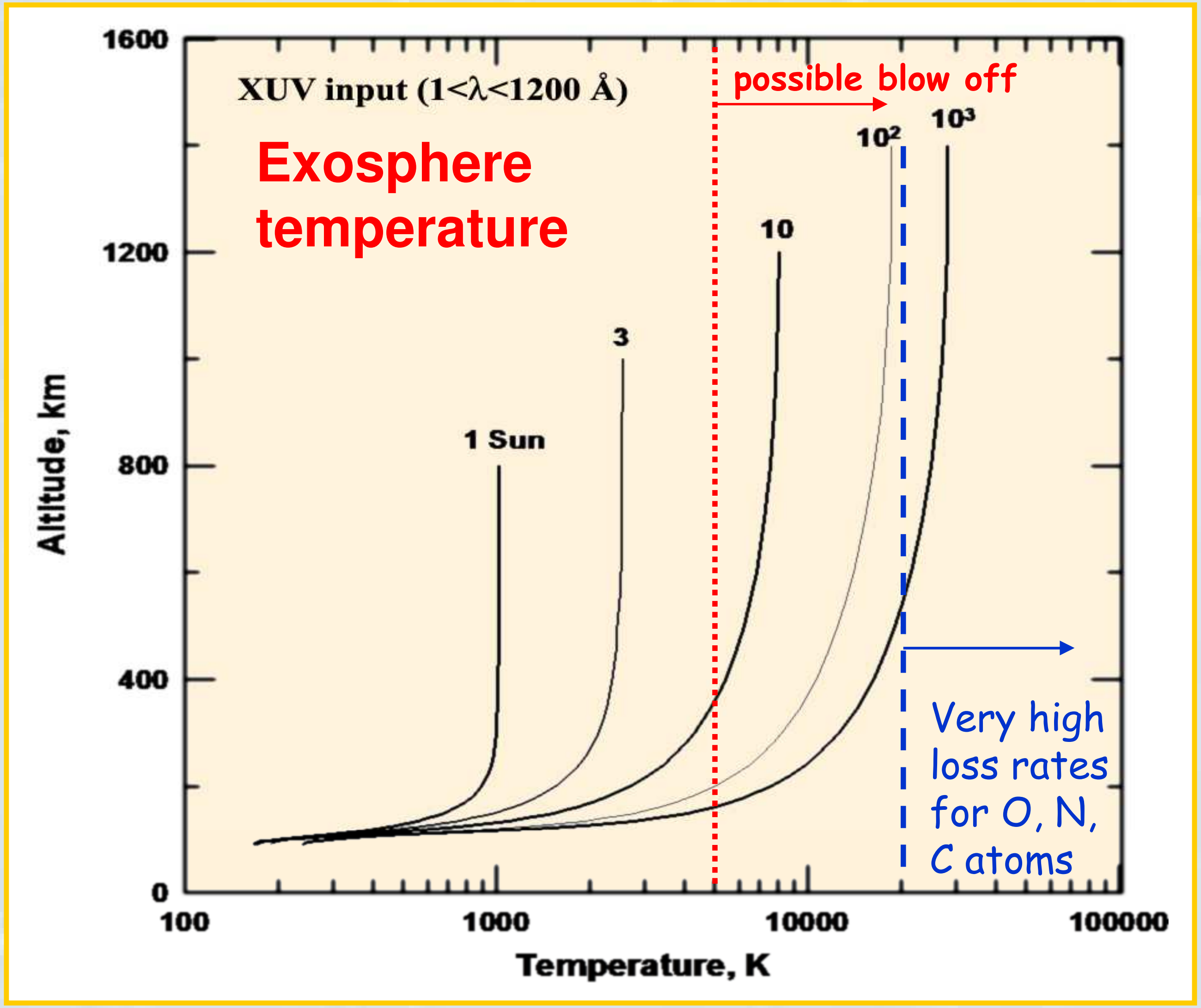
If emissions scale similarly to solar-mass G stars:

K stars ($0.7 < M < 0.9\ M_{sun}$): XUV 3-4× than G stars at same age

M stars ($< 0.6\ M_{sun}$): XUV 10-100× than G stars at same age

M- dwarfs and their perils

- For rocky planets in the habitable zone it remains to be seen if atmospheres are stable;
- **Especially relevant for M stars** (Scalo et al 2007);
- Calculations show that only CO_2-rich atmospheres (>1 bar) can survive and keep the water (IR cooling + avoid condensation on the dark side)



Kulikov et al. (2006, P&SS)

Rocky planets in M star HZs may not evolve into habitable worlds!

Far UV-UV: photochemical reactions:

$CO_2 \rightarrow CO + O$

$H_2O \rightarrow 2H + O$

$CH_4 \rightarrow C + 4H$

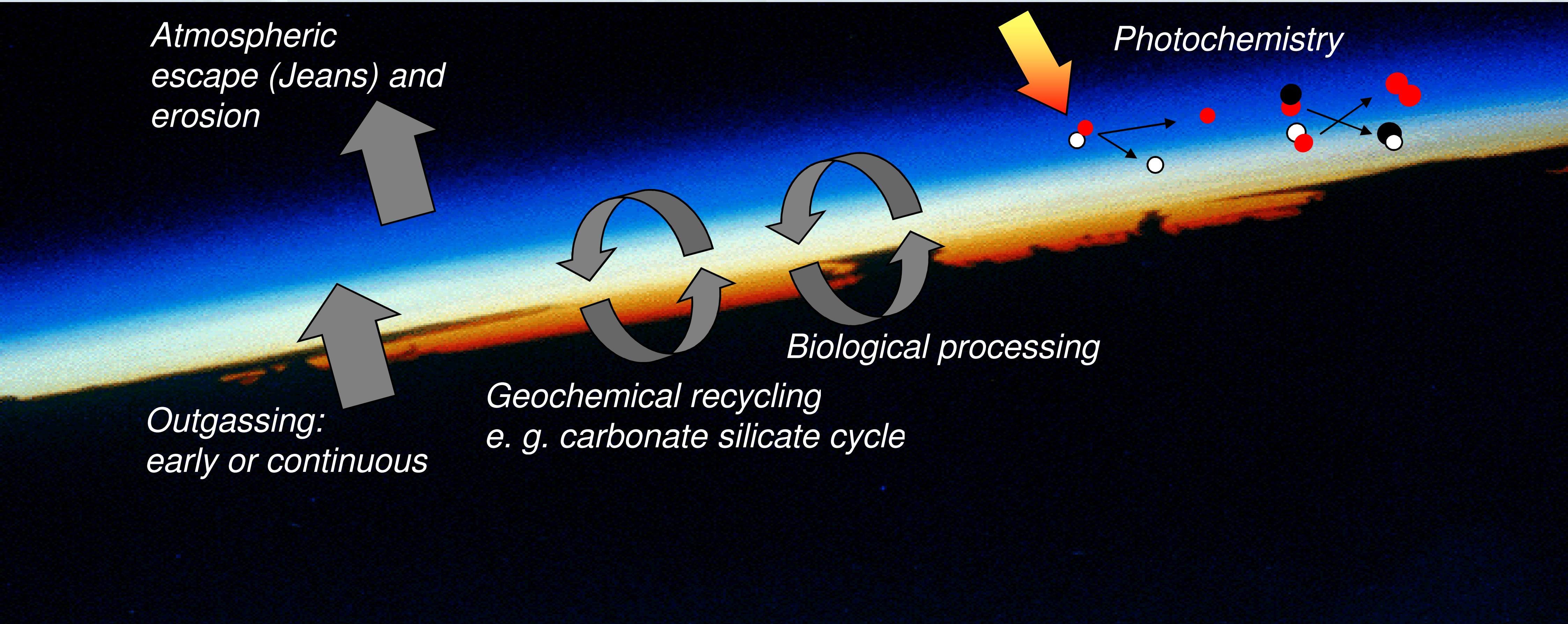
$NH_3 \rightarrow N + 3H$

$H_2O \rightarrow OH + O$

Photochemistry

XUV emissions heat, expand, and photoionize the exosphere

But also relevant to life: photochemistry $\rightarrow$ breakup of N_2, O_2, CH_4 & NH_3 and chemistry of NOx – **possible pre-organic chemistry**



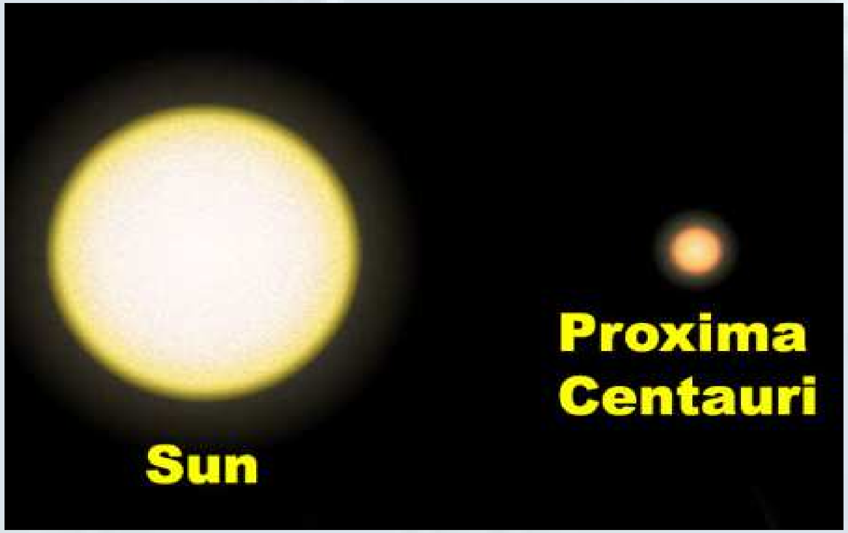
Case Study: Proxima Centauri_b

THE STAR:

MASS 0.12 solar
LUMINOSITY 1.6×10^{-3} solar
AGE ~4.8 Gyr

(Bazot et al 2016, Porto de Mello et al 2008)

Anglada-Escudé et al 2016



AN EARTHLIKE PLANET:

1.27 Earth mass
receives 65% of present Earth's flux

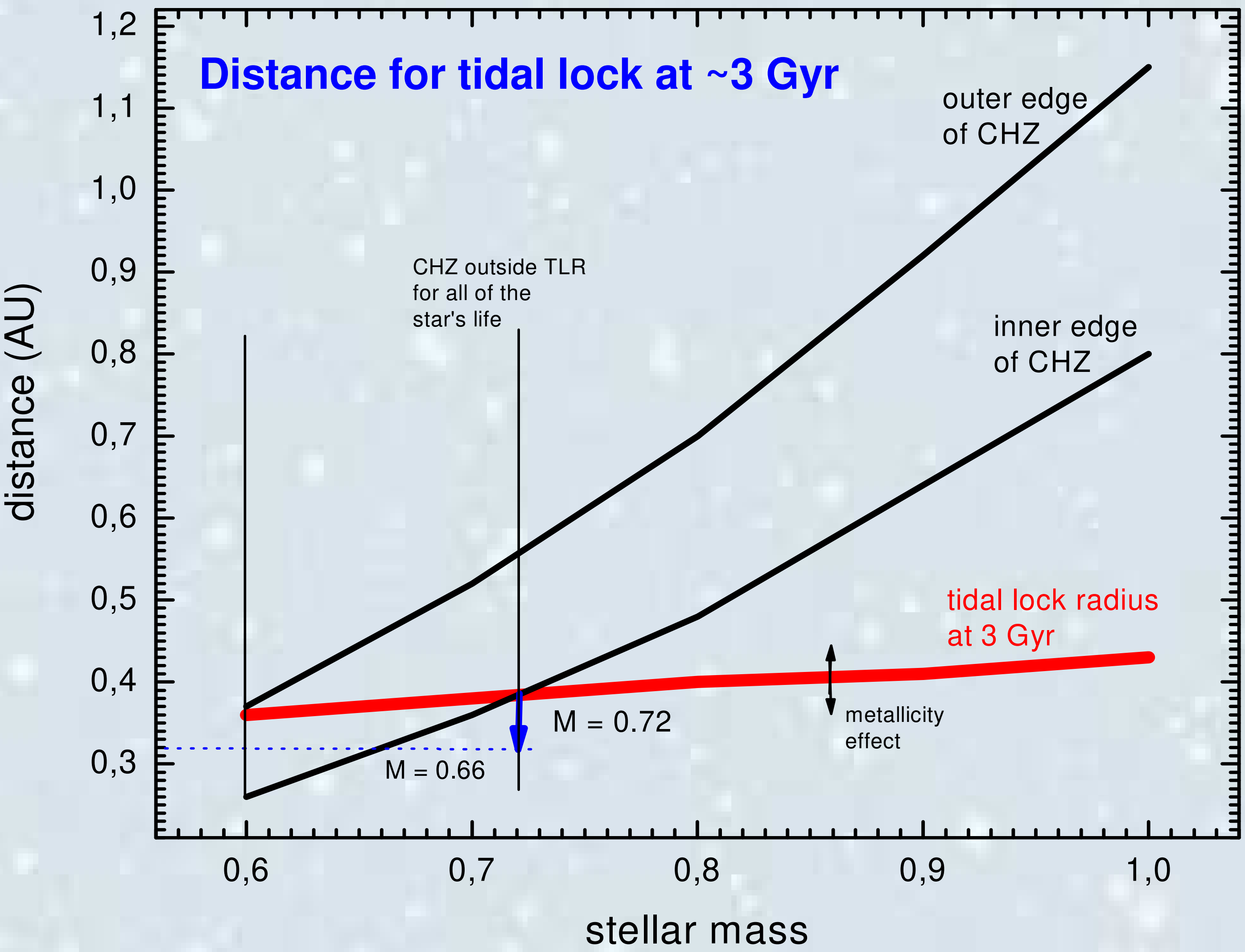
Much **closer HZ**

Much larger exposure to **XUV** + **winds**

Atmosphere expansion + magnestopheric compression = LOSSES

Much **extended phase** of **highly energetic magnetic activity**

Proxima Centauri b: Tidal Lock?



$$r_{tl} = 0.027\left(\frac{P_0\, t}{Q}\right)^{1/6} M^{1/3}$$

Kasting et al 1993

Runaway phase
Water loss

S_{eff} ~ 1.03 S_{Earth}
non-synchronous

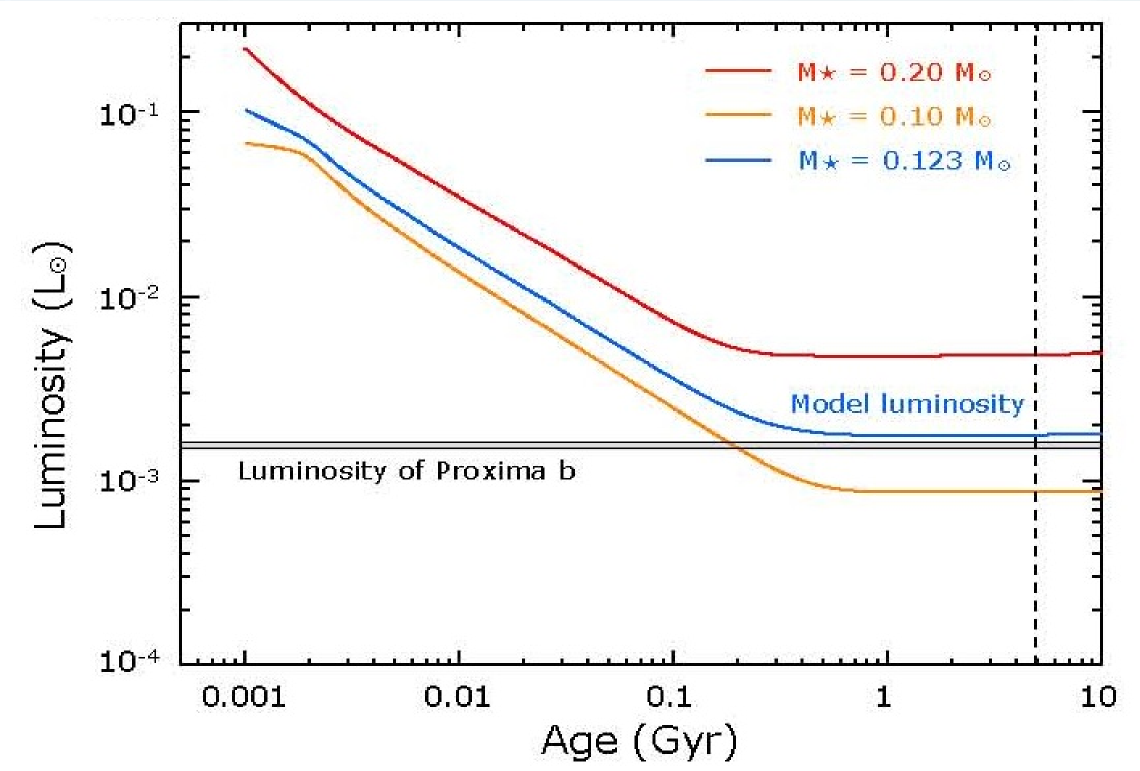
S_{eff} ~ 1.5 S_{Earth}
synchronous

Synchronous planets: **strong convective updraft** & perennial **cloud deck in the substellar point**, increasing albedo and hardening the atmosphere **against water loss** – even so, Proxima b may have spent **~200 Myr in runaway phase** (against Earth's few Myr)

Proxima Centauri_b: wind and XUV

Ribas et et al 2016

Extended phase of settling to stable H-burning



Proxima Centauri: **much higher luminosity** than present for ~1 Gyr: **Proxima_b was actually outside the HZ** – high rates of **volatile loss** are expected

Initial water inventory? Larger than Earth's? Volatile losses 1 to 20 EO_H

Up to 10× higher X-ray/EUV
Up to 100× higher particle flux

integrated over Proxima_b and Earth's lifetimes

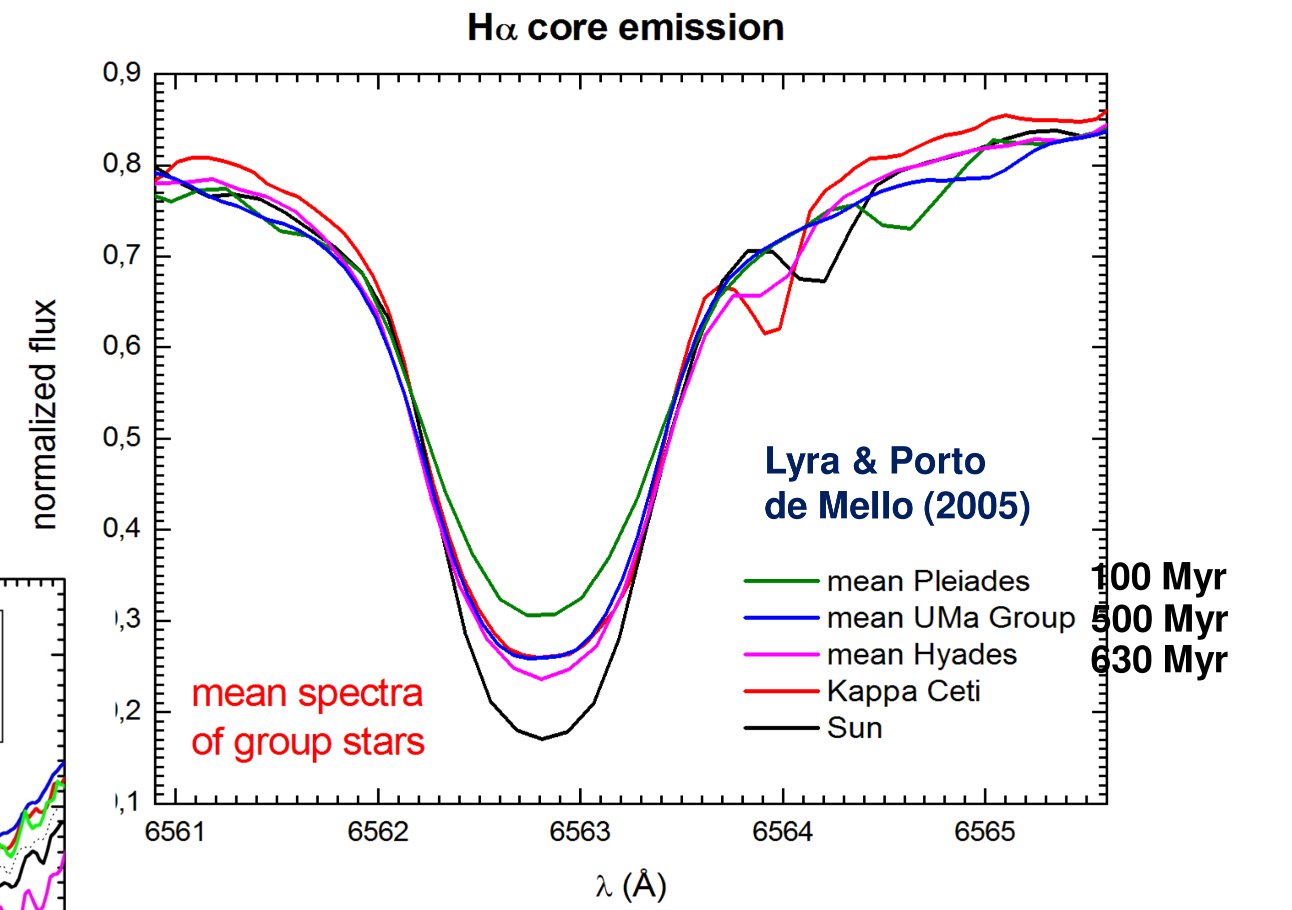
Also much harder X-ray spectrum

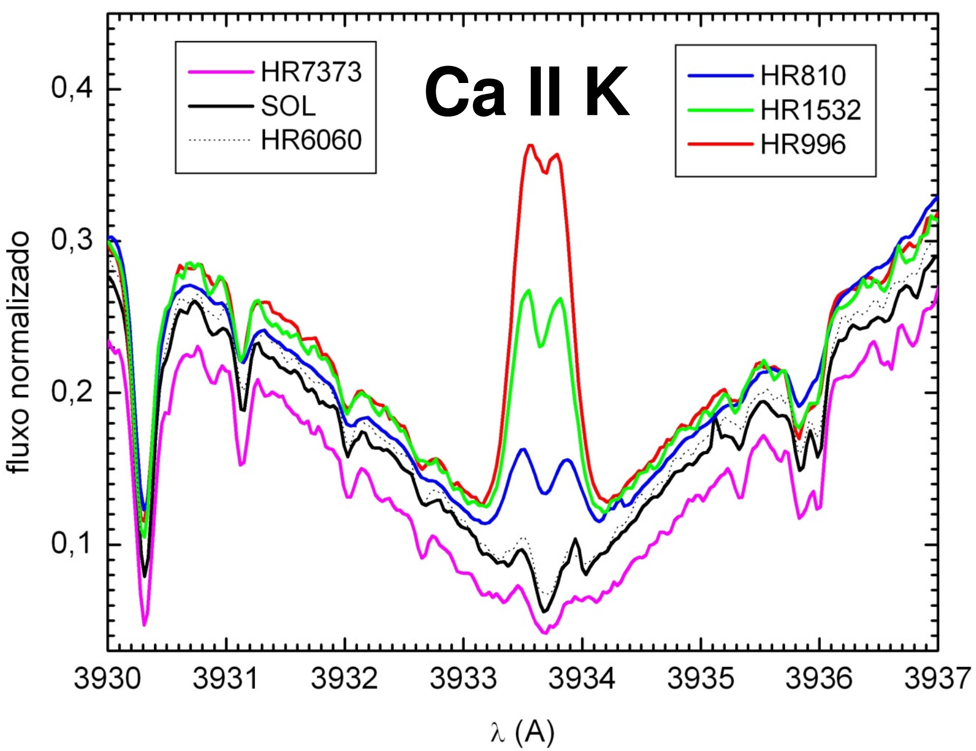
Total volatile loss depends **critically** on:
– **stellar wind evolution**
– **magnetic field of planet**

Case study: Kappa Ceti

HD 20630
V = 4.84
G3V- G5V type
P_{rot} = 9.2 days

distance = 9.2 pc



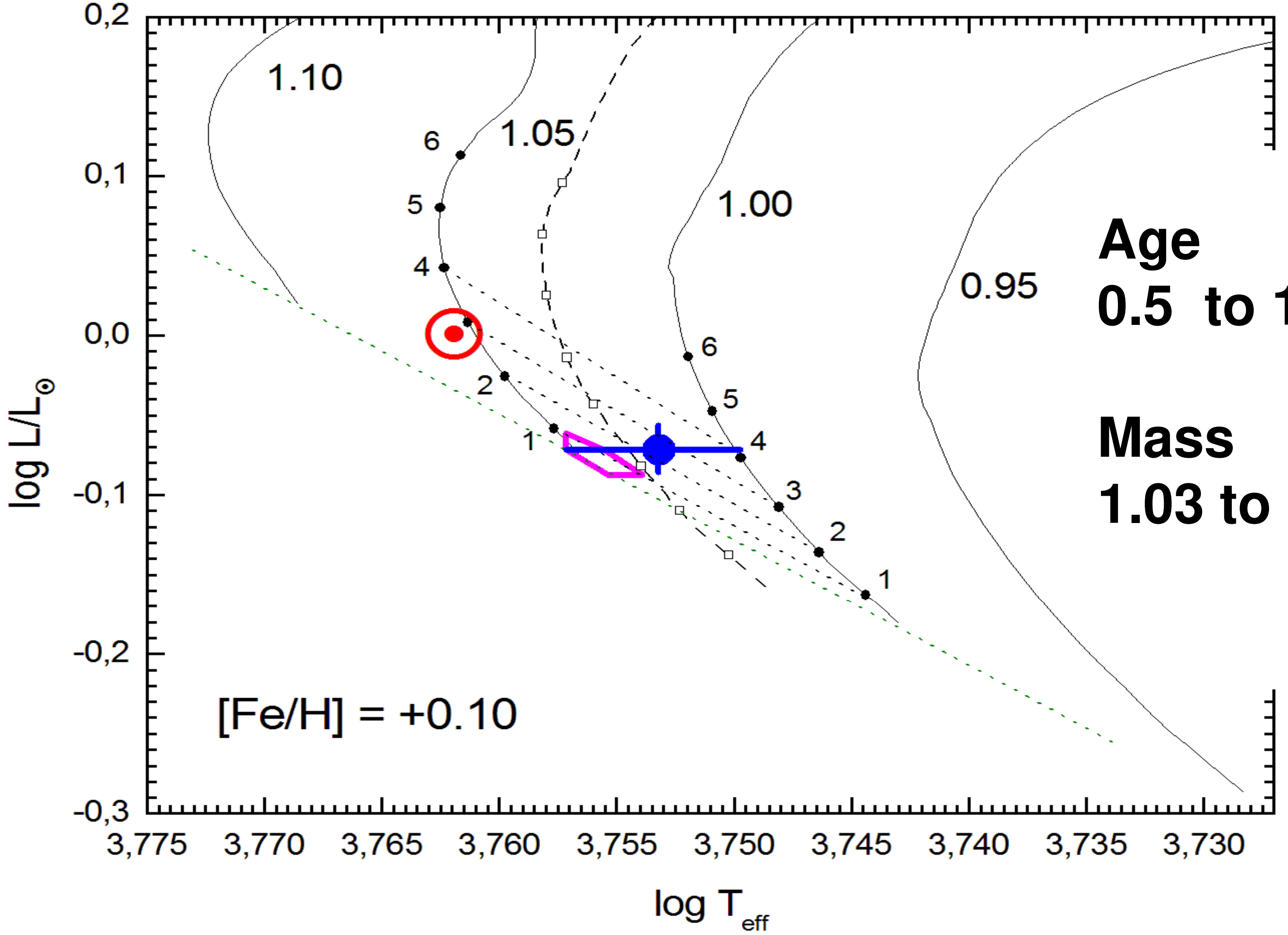


Nearby very solar-like star
Metallicity [Fe/H] ~ +0.10

Kappa Ceti

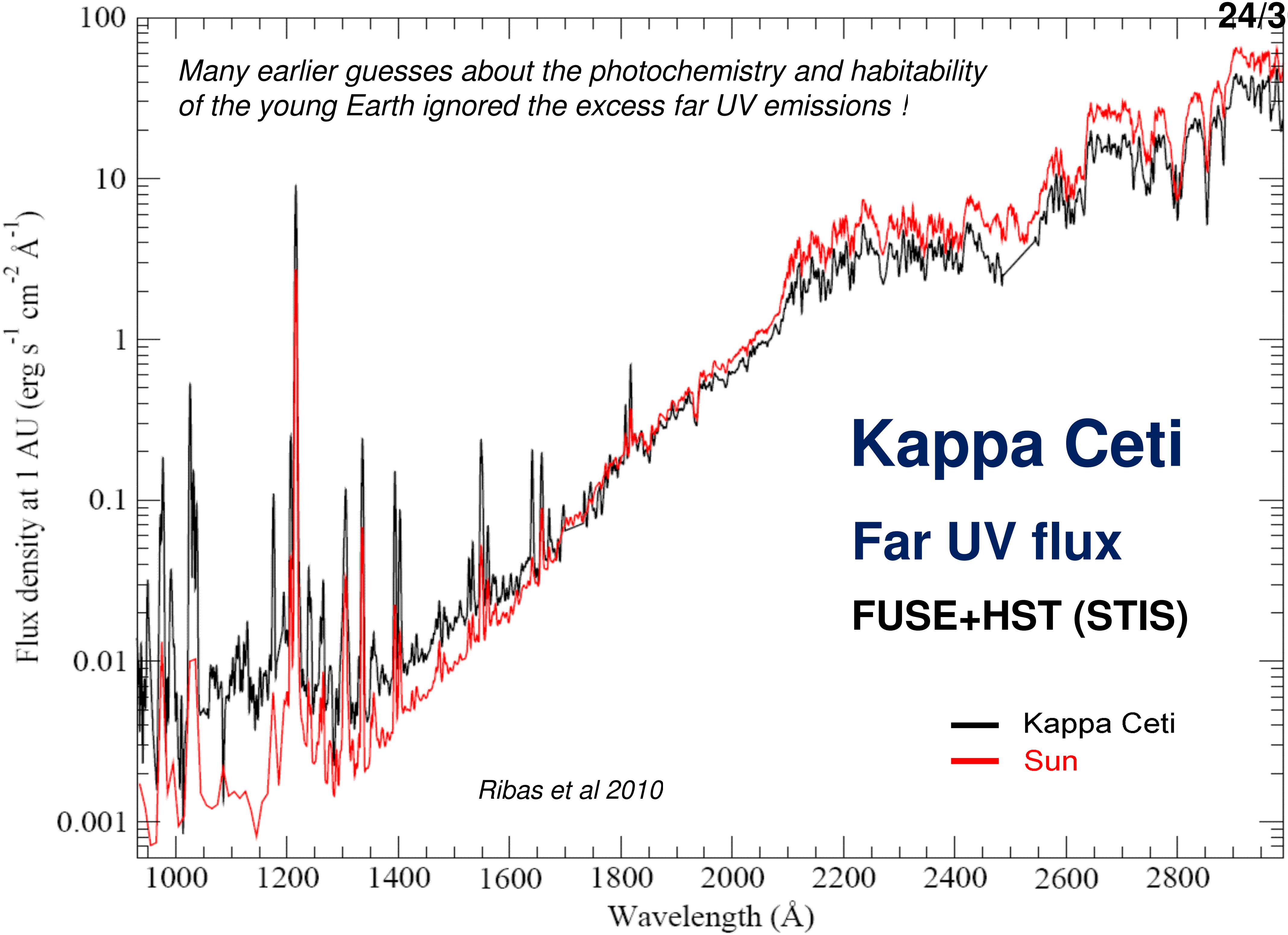
An analogue of the Sun when life arose on Earth

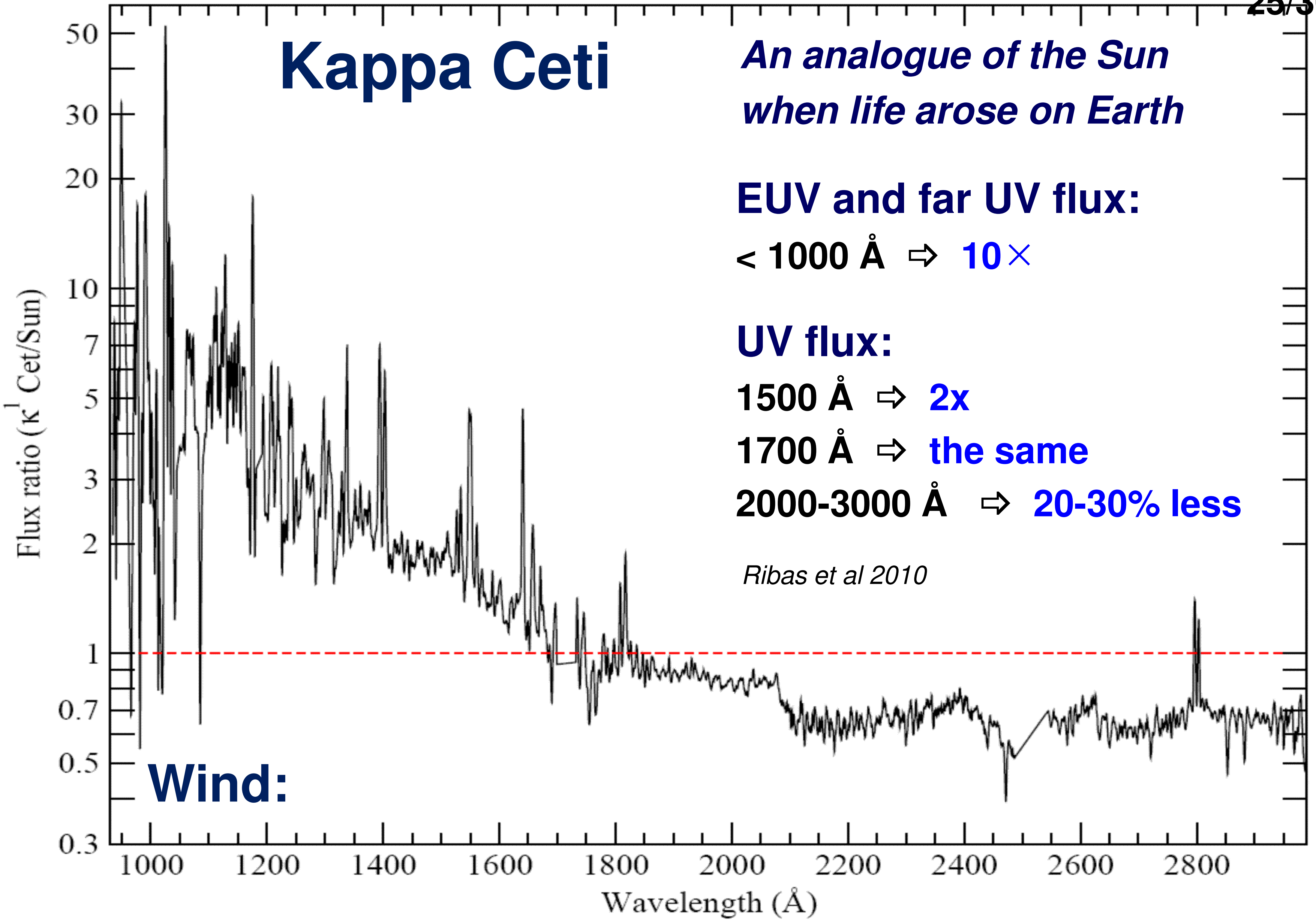
Ribas et al 2010
AJ, **714**, 384



Age
0.5 to 1.0 Gyr

Mass
1.03 to 1.05 $M_\odot$


Many earlier guesses about the photochemistry and habitability of the young Earth ignored the excess far UV emissions !
Kappa Ceti
Far UV flux
FUSE+HST (STIS)
Kappa Ceti
Sun
Ribas et al 2010
Flux density at 1 AU (erg s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
100
10
1
0.1
0.01
0.001
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800


Kappa Ceti
An analogue of the Sun
when life arose on Earth
EUV and far UV flux:
< 1000 Å ⇨ 10×
UV flux:
1500 Å ⇨ 2x
1700 Å ⇨ the same
2000-3000 Å ⇨ 20-30% less
Ribas et al 2010
Wind:
Flux ratio (κ¹ Cet/Sun)
Wavelength (Å)
0.3
0.5
0.7
1
2
3
5
7
10
20
30
50
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

Kappa Ceti

Prebiotic photochemistry in the far UV

Prebiotic and Archean Earth's atmosphere:
CO_2-rich and CH_4-rich (reducing)

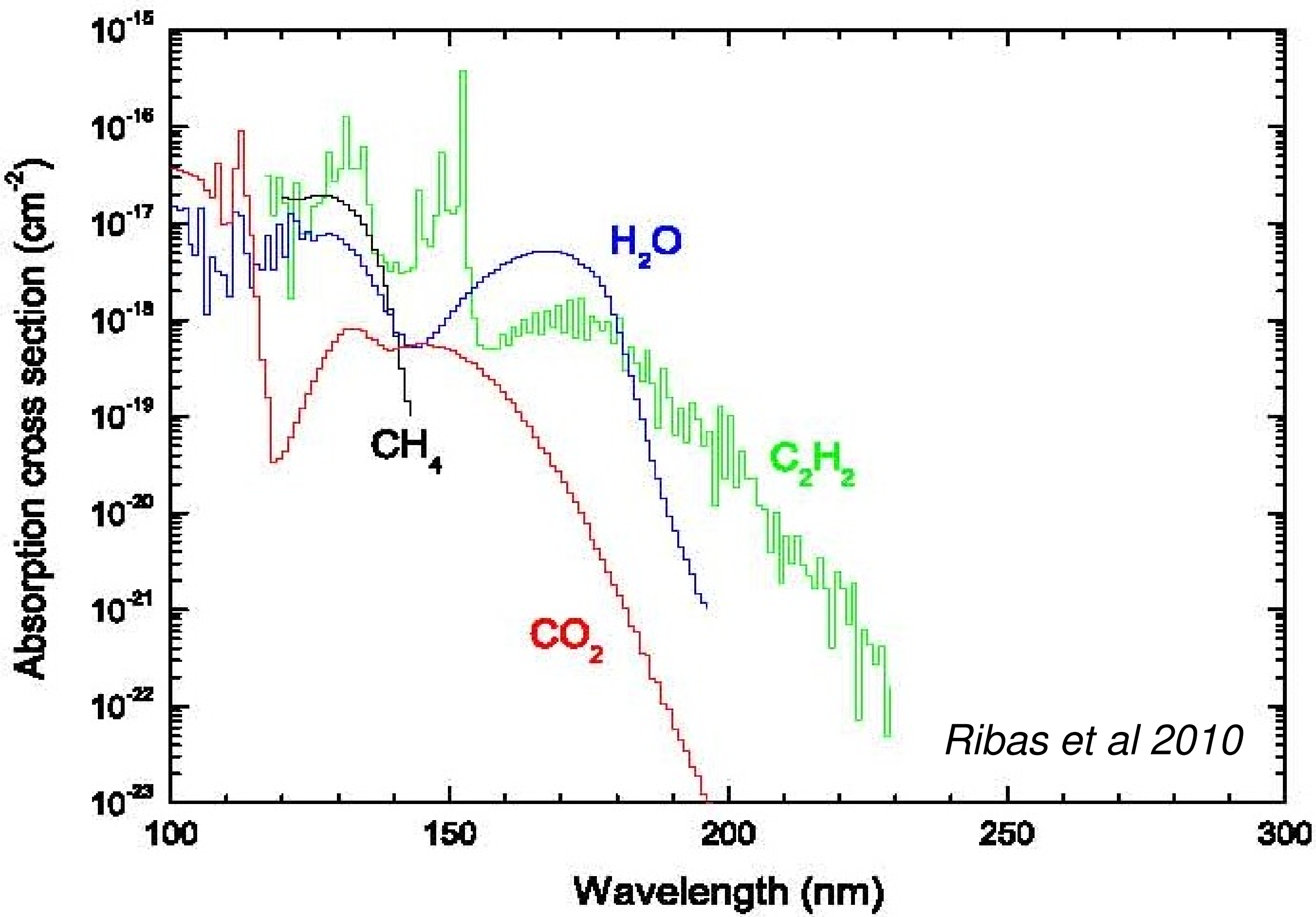


Figure 8. Photoabsorption cross sections of some molecules suspected to have been present in early Earth's atmosphere.

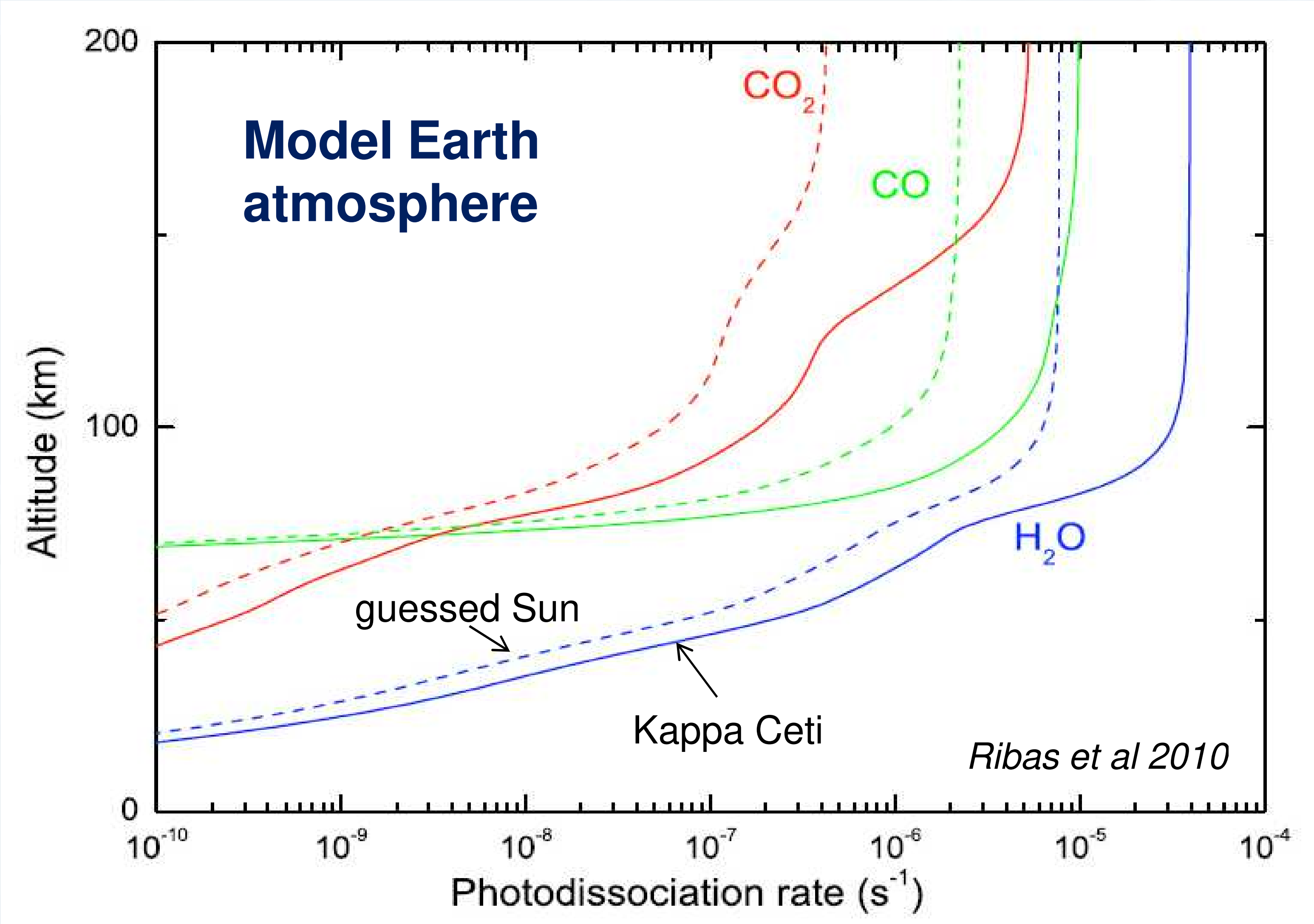
Model Earth atmospheres

Kasting et al 1993
mildly reducing

Pavlov et al 2001
very reducing

Efficient photodissociation rates mostly in the far UV

Kappa Ceti Prebiotic photochemistry in the far UV?



Prebiotic and Archean Earth's atmosphere:

CO_2-rich and CH_4-rich

mildly reducing early atmosphere

10× or more higher photodissociation rates at high altitude

Kappa Ceti

Prebiotic photochemistry in the far UV

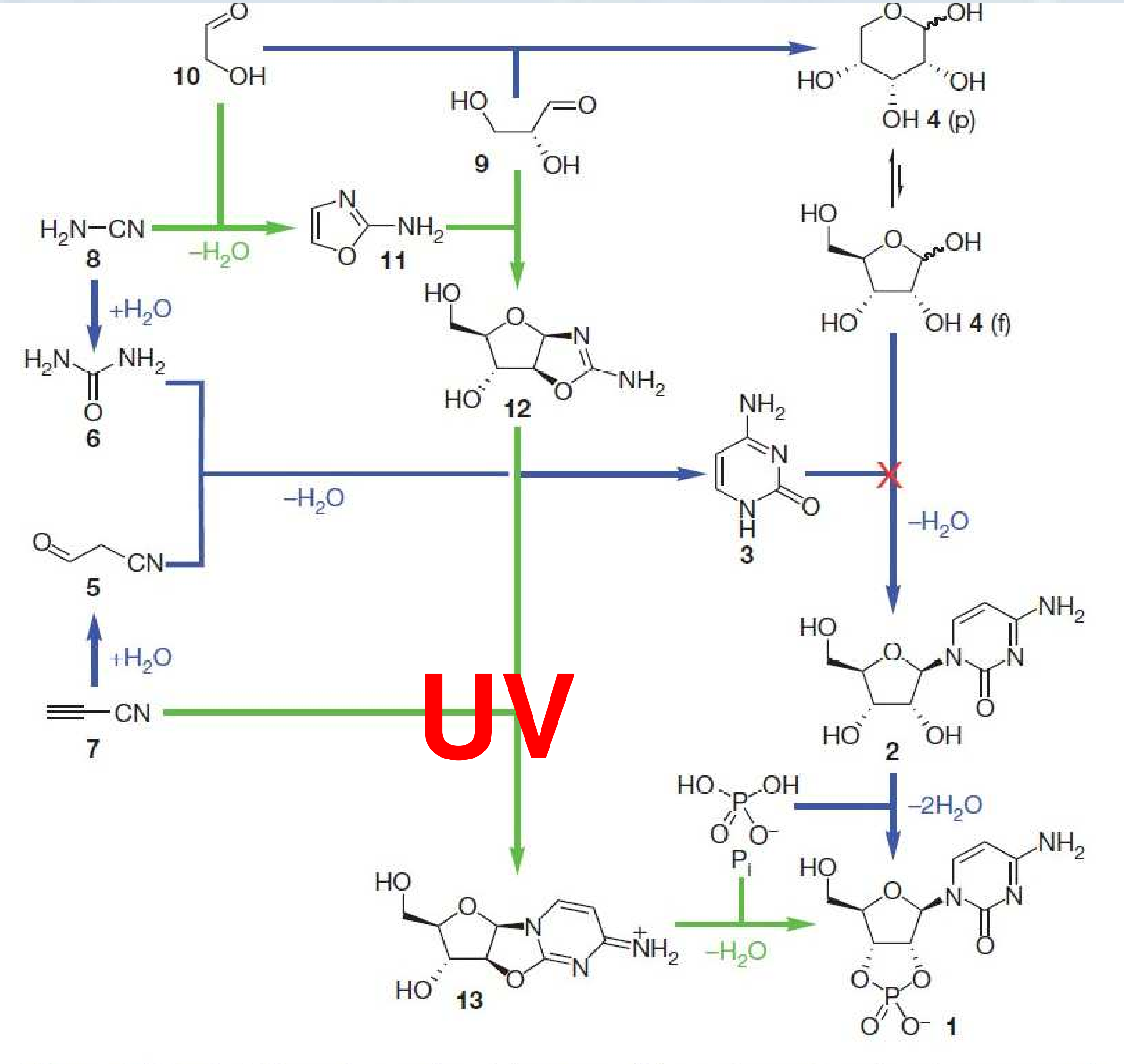


Figure 1 | Pyrimidine ribonucleotide assembly options. Previously assumed synthesis of β-ribocytidine-2′,3′-cyclic phosphate **1** (blue; note the failure of the step in which cytosine **3** and ribose **4** are proposed to condense together) and the successful new synthesis described here (green). p, pyranose; f, furanose.

RNA/DNA synthesis and the far UV

Powner et al 2009
Nature, vol.459, p.239

THE RIBOSE PROBLEM

Prebiotic nitrogenous base synthesis

Pyrimidine (thymine, citosine, uracil) ribonucleotide assembly **bypassing ribose** by means of UV flux

Kappa Ceti: particle flux

Spectropolarimetric NARVAL observations

Least Squares Deconvolution of the Stokes V parameters – Zeeman signature

Surface magnetic field reconstruction

Age
0.5 to 0.9 Gyr

Mass
1.00 to 1.04 $M_\odot$

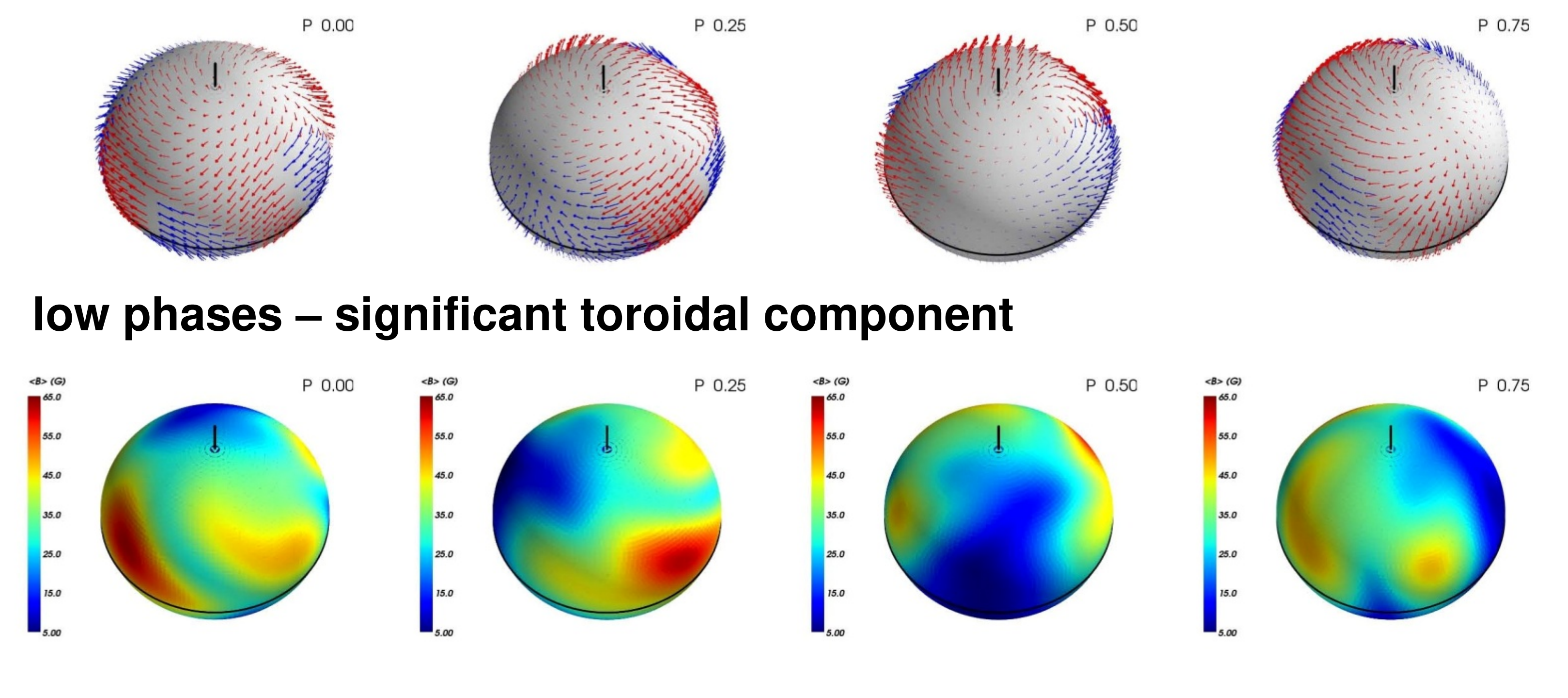


Figure 2. Large-scale magnetic topology of κ^1 Cet at different rotation phases indicated in the top right of each panel. The top row shows the inclination of field lines over stellar surface, with red and blue arrows depicting positive and negative field radial component values, respectively. The bottom row displays the field strength.

Surface-averaged field strength **24 G**

peak of 63 G

(Sun ~1 G)

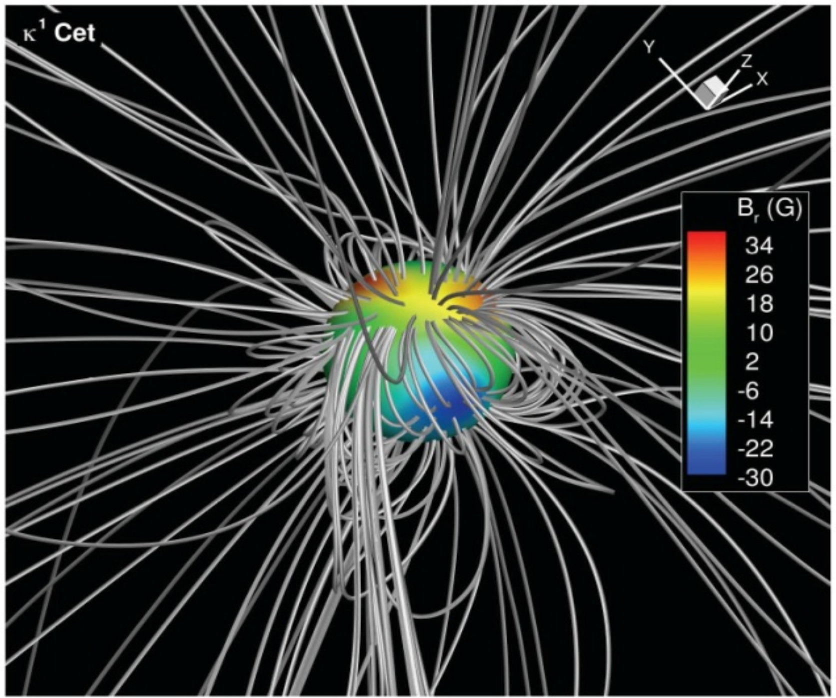
Nascimento et al 2016
ApJ Letters, **820**, L15x

Kappa Ceti: particle flux

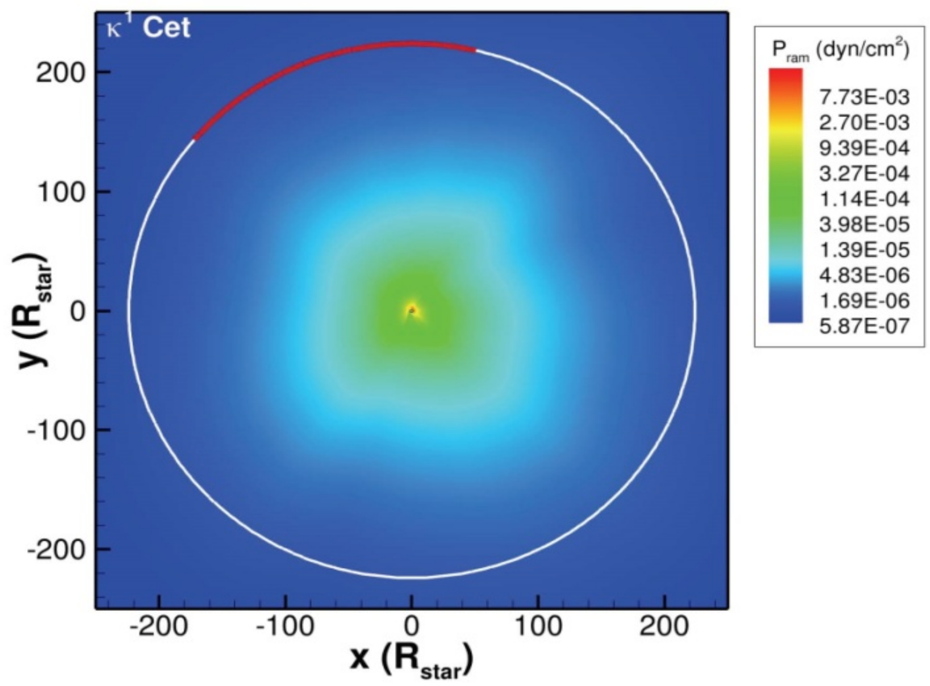
Kappa Ceti: **50x the present solar mass loss** – L_X-scaled values are 63-140x (*Wood et al 2014)*

Young Earth: **magnestopheric sizes 30%-50%** present sizes
Complex field topology – when polar cap develops, **enhanced particle loss in exosphere** – probably very relevant for the **evolution of Mars' volatile inventory**

Large scale field topology of Kappa Ceti



Wind ram pressure along orbit



Thanks!

Our Highlights

- **Stellar energetic emissions** of magnetic origin span a **wide range of behavior** in spectrum, total power and time scales across low mass stars
- Little known about the **magnetic evolution of the Sun** until recently
- **Sun much more active in the past:** much stronger high-energy emissions (up to **many orders of magnitude**) and particle winds
- **All low-mass stars** go through a similar high activity phase
- **Major loss effects** on atmospheres & volatile inventories of planets, but also including the drive of possible **biochemistry**
- **Severe threats to habitability** – complete loss of atmospheres and/or oceans, particularly for **red dwarfs**, which are **the most abundant hosts of Earthlike rocky planets**