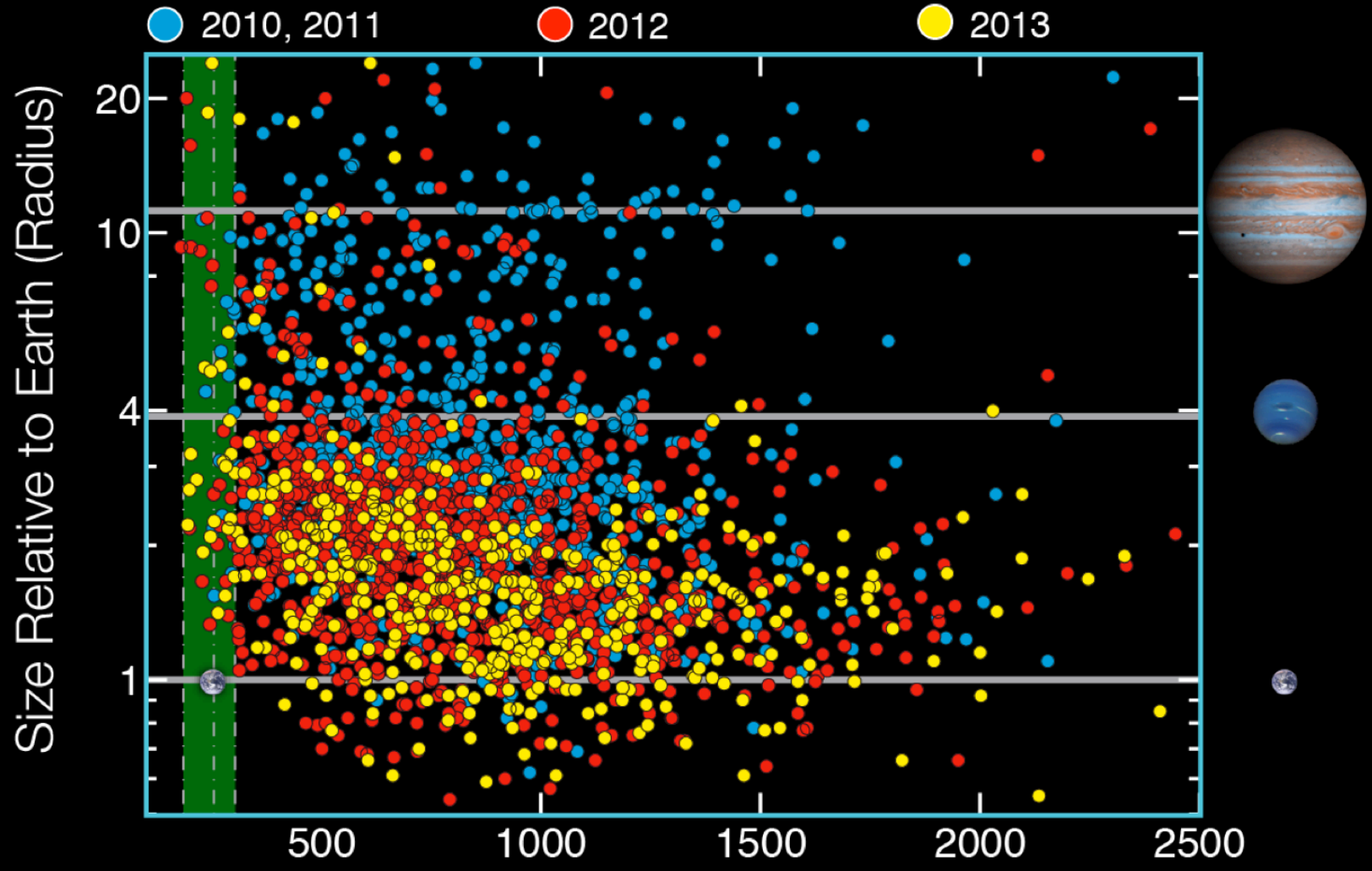
Astrophysical Conditions for Planetary Habitability

M. Güdel, R. Dvorak, N. Erkaev, J. Kasting,
M. Khodachenko, H. Lammer, E. Pilat-Lohinger, H. Rauer,
I. Ribas, B. Wood

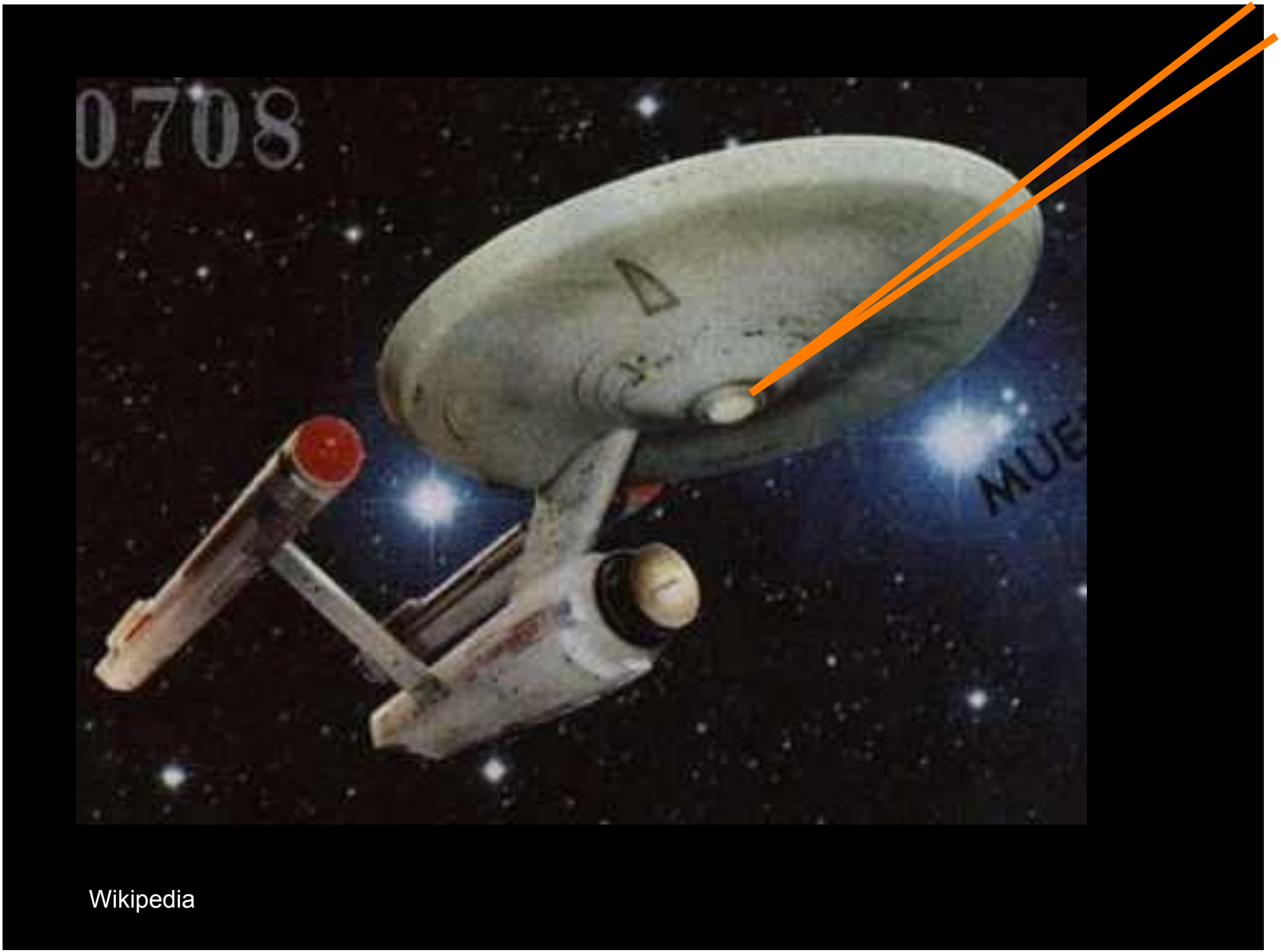
Candidates in the Habitable Zone

As of January 7, 2013



Chapter D. Fischer

Source: Christopher Burke, AAS presentation, Long Beach, CA, Jan. 7, 2013



Wikipedia

First Requirement for Life (as we know it): A Liquid or Solid Surface

- It is difficult, or impossible, to imagine how life could get started on a gas giant planet
- Need a liquid or solid surface to provide a stable P/T environment
- This requirement is arguably universal

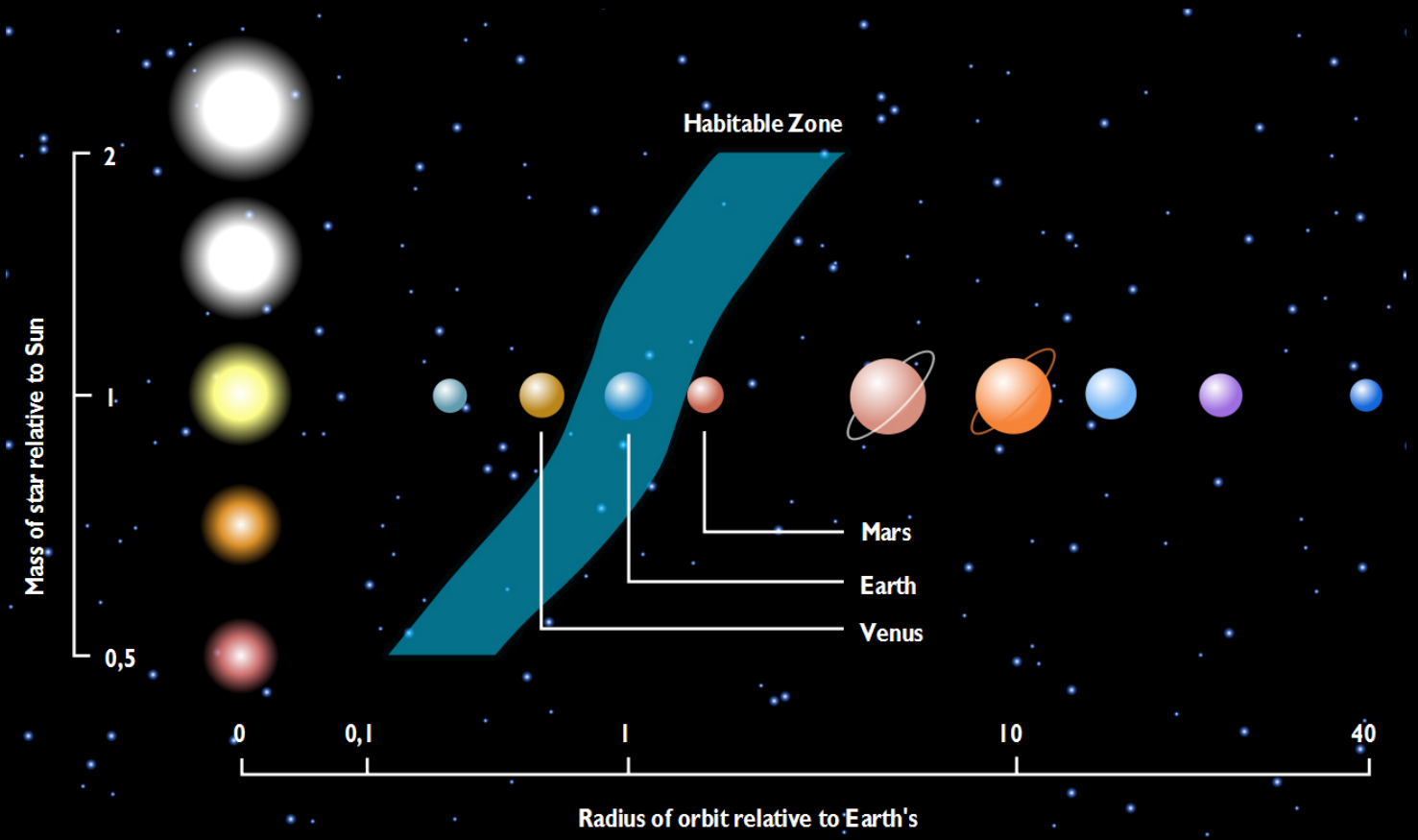
NASA

Second Requirement for Life (as we know it): Liquid Water

- Life on Earth is carbon-based (DNA, RNA, and proteins) and requires liquid water
- So, our first choice is to look for other planets like Earth

NASA

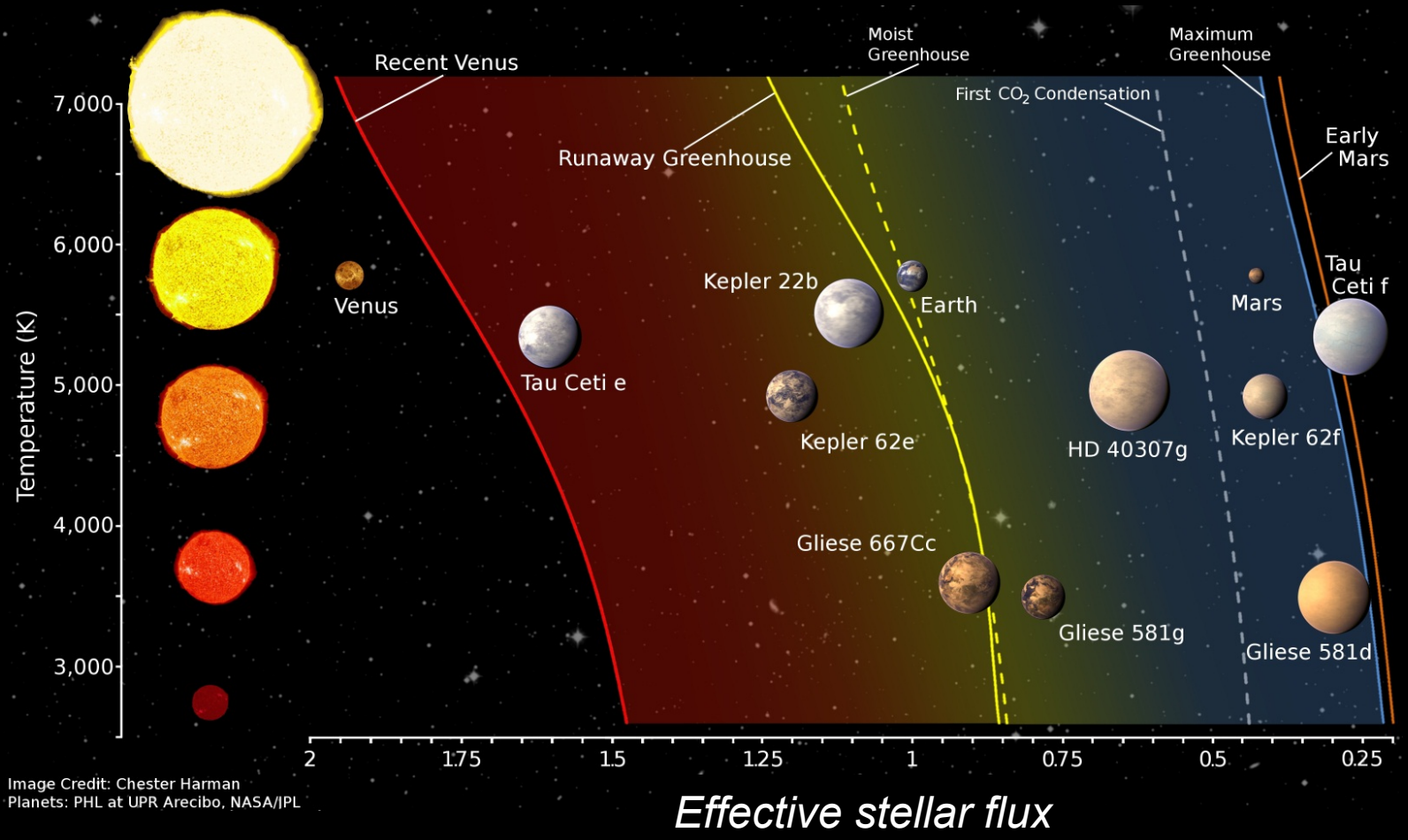
The ZAMS Habitable Zone



The ZAMS liquid water habitable zone, as defined by Kasting et al. (1993). Based on water evaporation/loss, maximum greenhouse, Mars and Venus

http://www.dlr.de/en/desktopdefault.aspx/tabid-5170/8702_read-15322/8702_page-2/

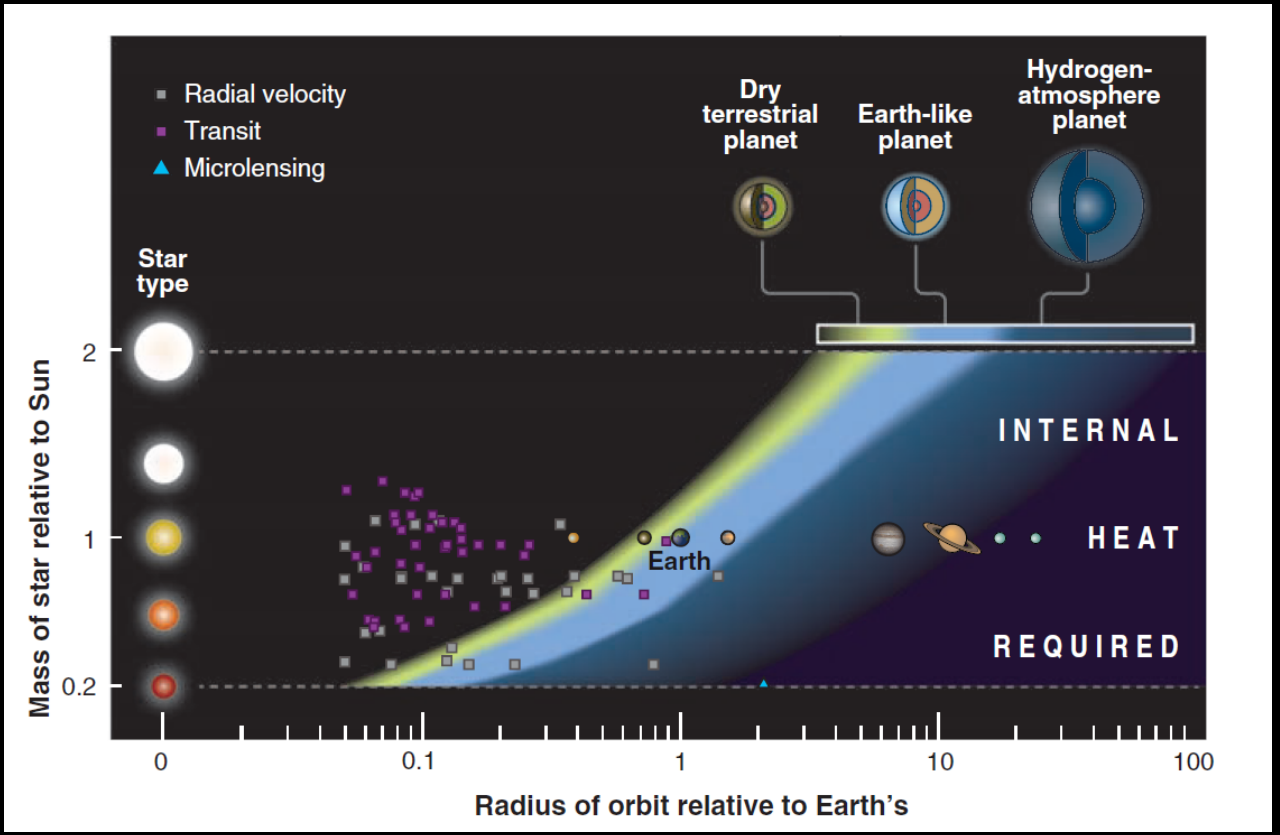
Revised Conventional HZ Limits



- Revised greenhouse limits on the inner edge of the HZ → closer to 1 AU
- But, fully saturated atmospheress assumed and cloud feedback neglected.
- Inner edge could be anywhere within red zone. Requires 3-D climate models.

Kasting et al. (2013), redrawn from Kopparapu et al. 2013, ApJ, 765, 131

Molecular H_2 has been shown to be a surprisingly good greenhouse gas, especially in a dense N_2 atmosphere (Wordsworth & Pierrehumbert 2013)



S. Seager, Science, April, 2013

- HZ outer edge as far out as 10 AU?
- E.g. 3-M_E super-Earth with captured 40-bar H_2 atmosphere @ 1 AU

  (Pierrehumbert and Gaidos, 2011)

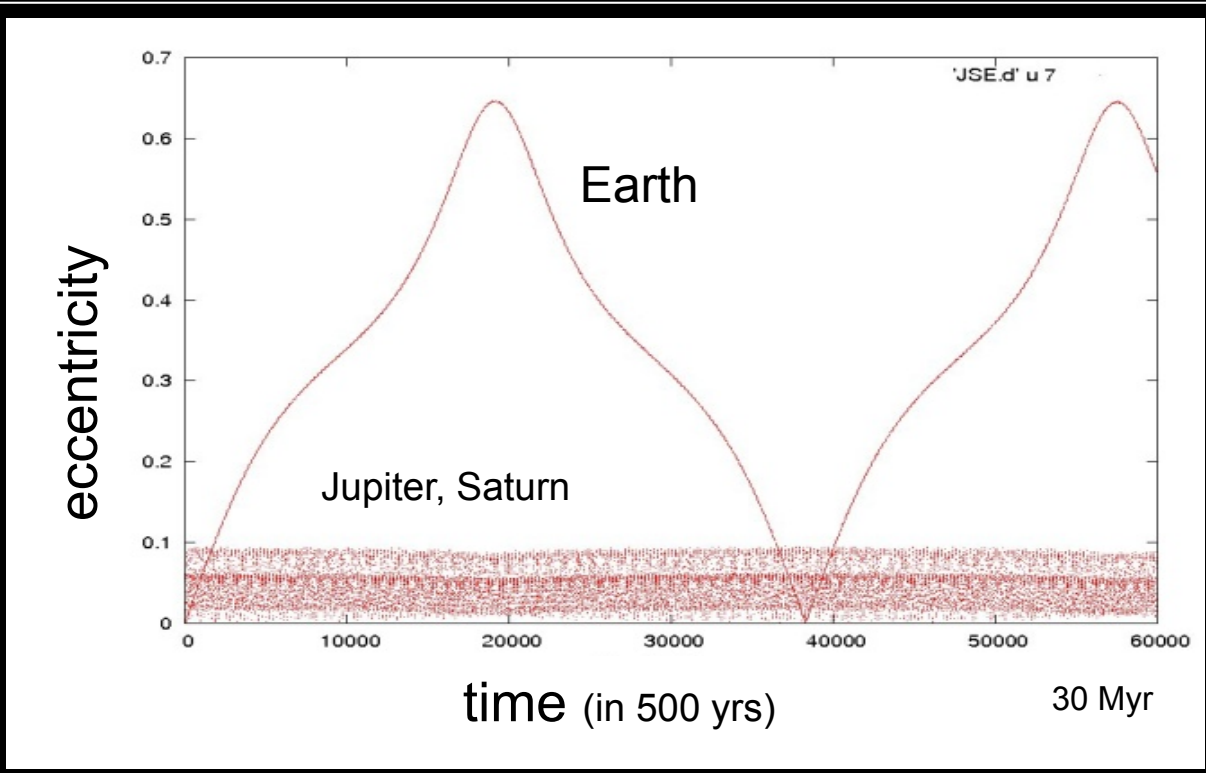
Giants Matter: Dynamical Stability

Dynamically important:

- Interaction between giant planets during migration (Nice Model, Grand Tack)
- Final position of giants after migration

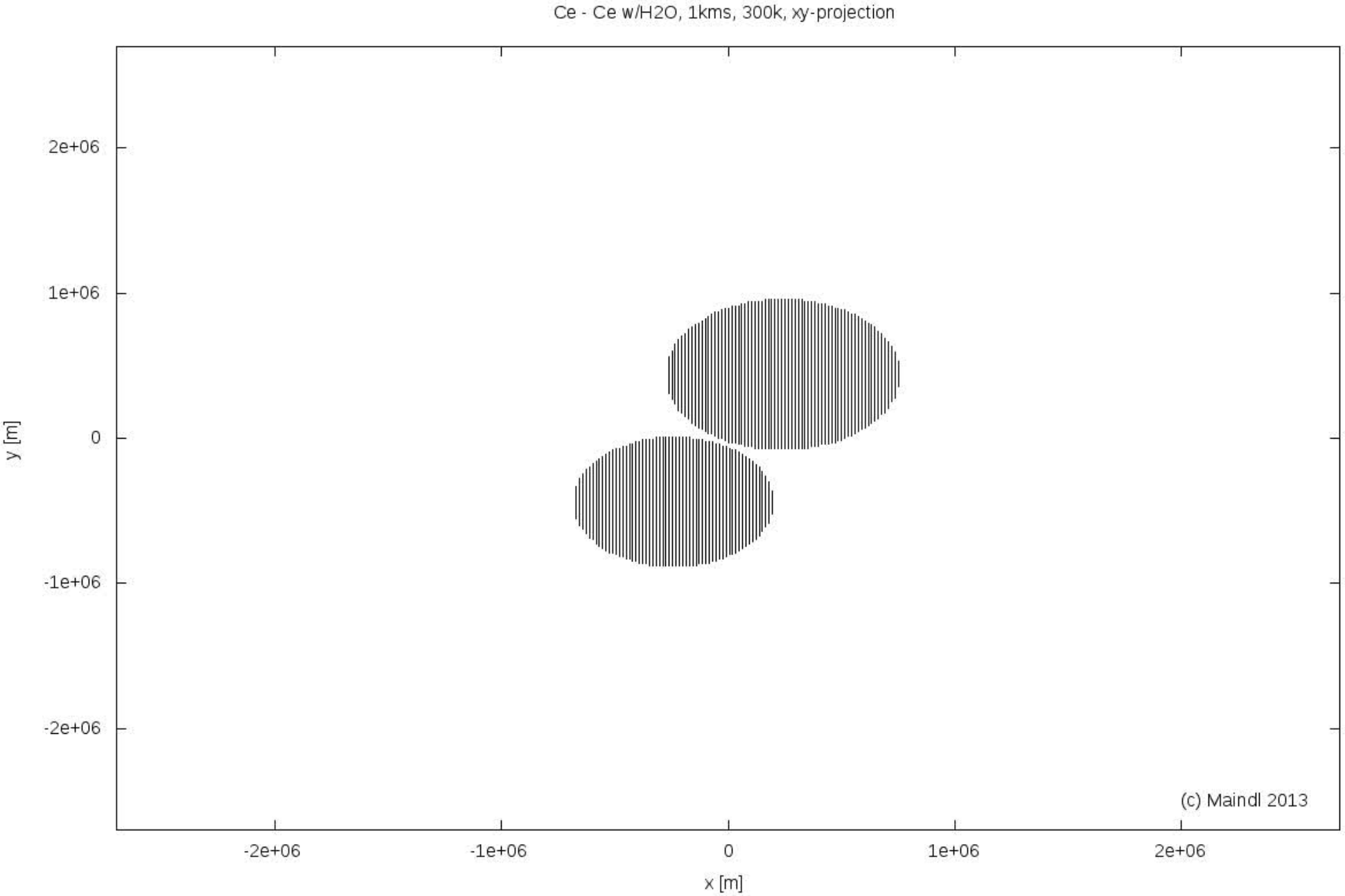
Chapter C. Baruteau
Chapter M. Davies
Chapter S. Raymond

Pilat-Lohinger 2013, Int. J. Astrobiology, subm.



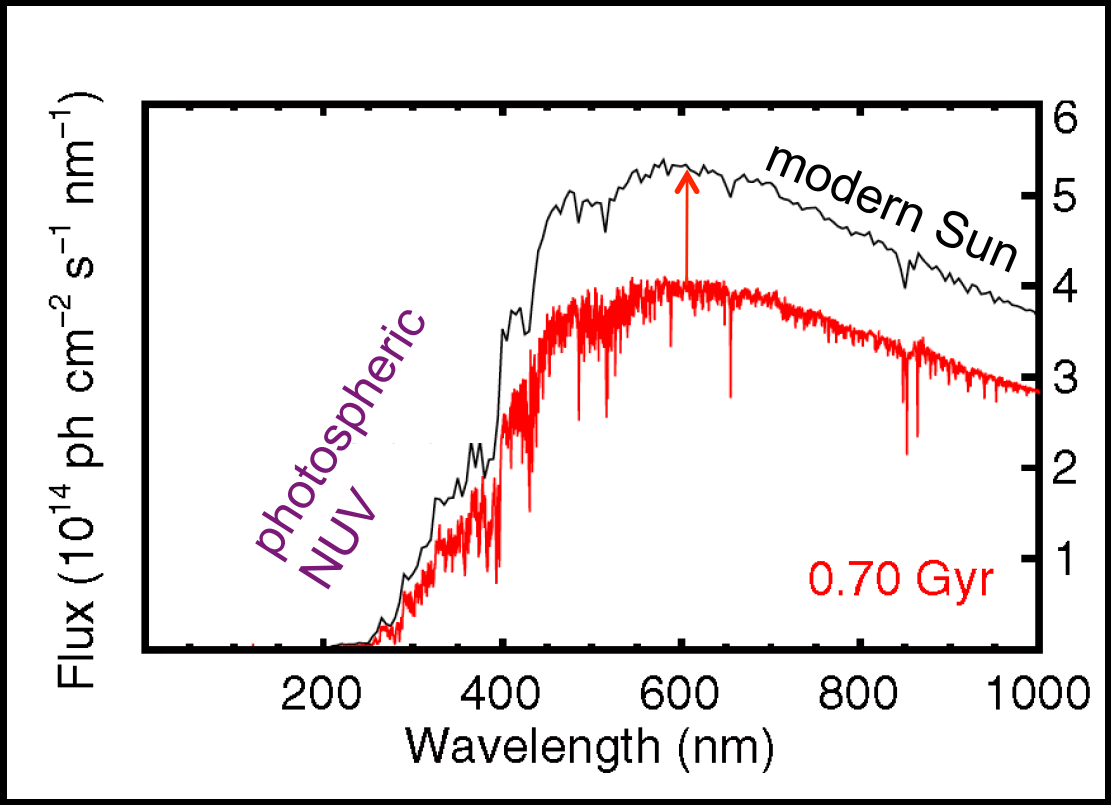
Pilat-Lohinger+ 2008, ApJ, 658, 1639

Saturn at 8.7 AU instead of 9.5 AU: massive secular perturbation (perihelion motion) by *Jupiter* on eccentricity of Earth orbit!



2 Ceres-like bodies (9.9×10^{20} g), 1 km/s = 10x v_{esc}, 70% basalt, 30% water
3D “solid-state” SPH simulation, 300,000 SPH particles (Th. Maindl, in progress)

Stellar Radiation Matters: The Sun got Brighter



Claire et al. 2012, ApJ, 757, 95

Internal evolution:
Sun's L_{bo} and T_{ef} increase on main-sequence.

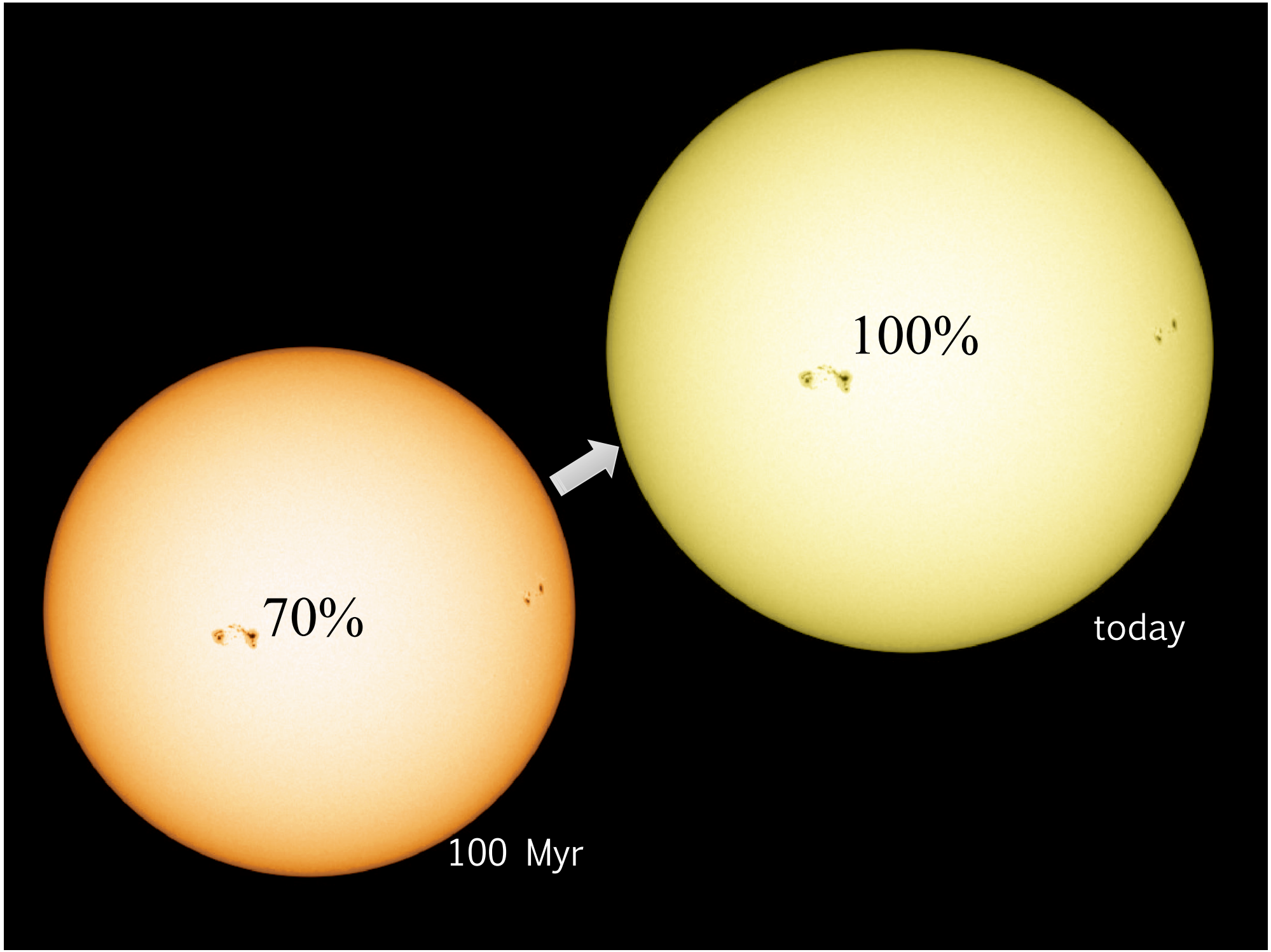
ZAMS to present:

L_{bol} 70% → 100%

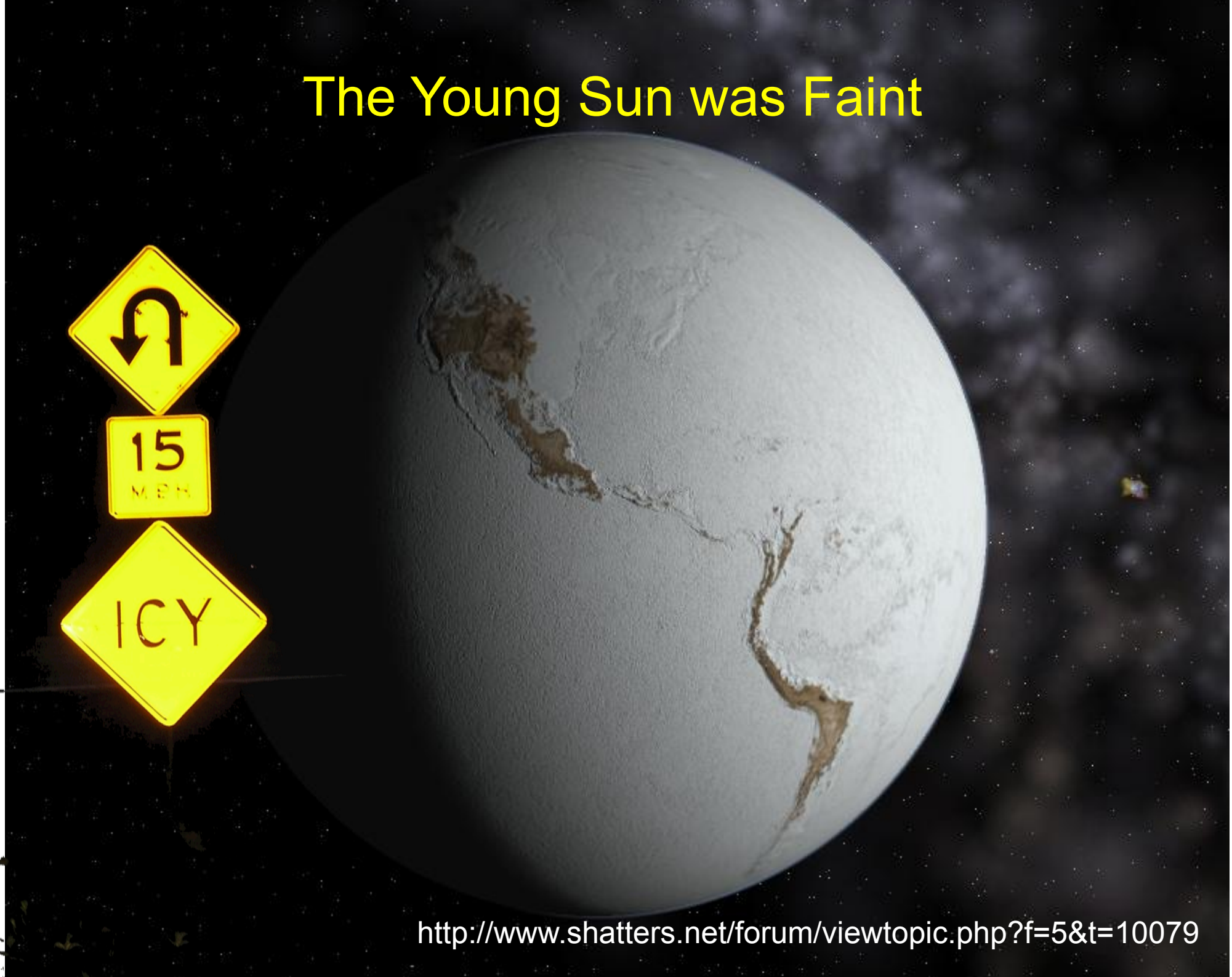
T_{eff} 5656 K → 5780 K

(e.g., Sackmann & Boothroyd 2003)

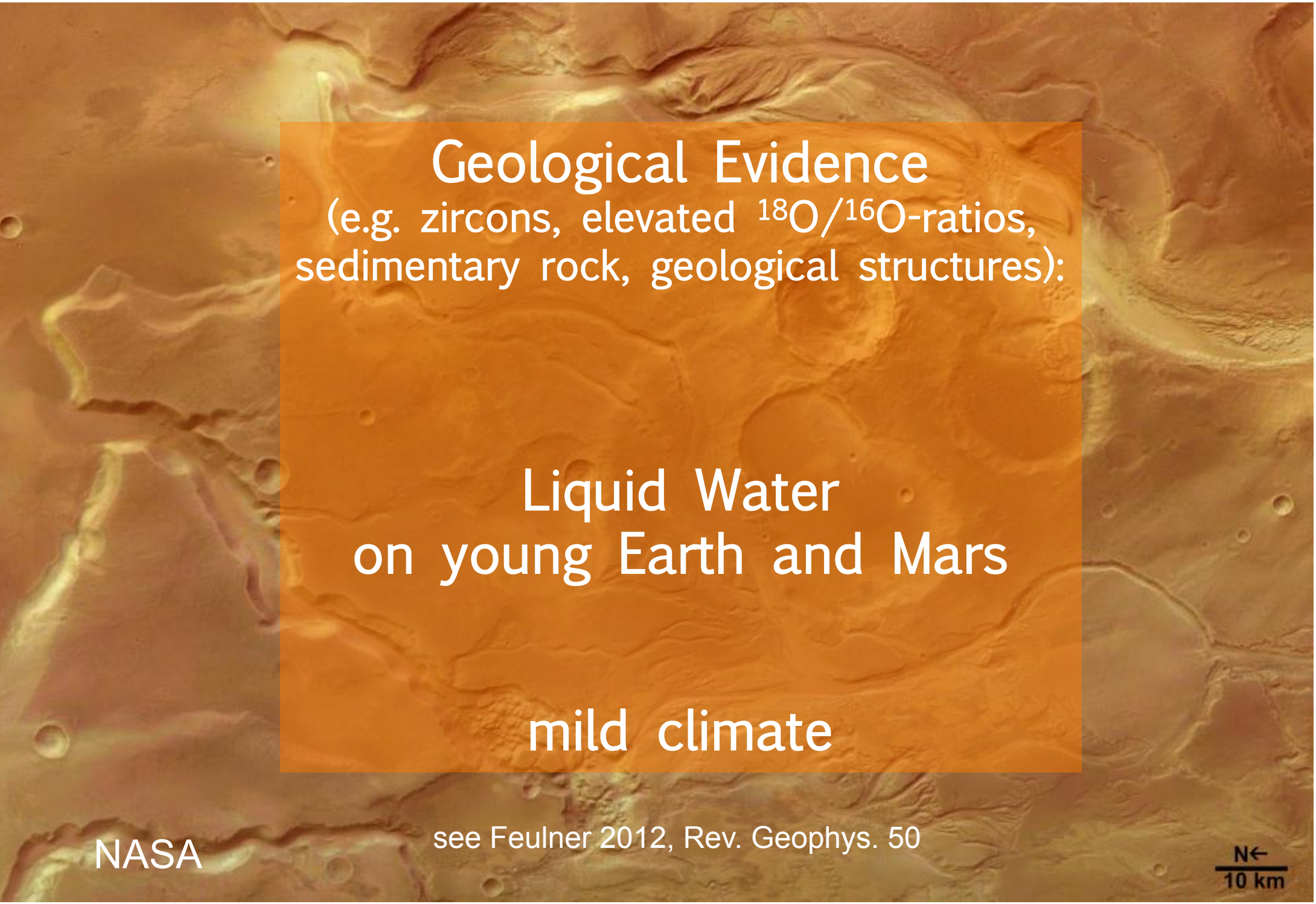
Important for near-UV flux!


100%
70%
today
100 Myr

The Young Sun was Faint



http://www.shatters.net/forum/viewtopic.php?f=5&t=10079


Geological Evidence
(e.g. zircons, elevated $^{18}O/^{16}O$-ratios,
sedimentary rock, geological structures):
Liquid Water
on young Earth and Mars
mild climate
NASA
see Feulner 2012, Rev. Geophys. 50
N←
10 km

Ways out:

Additional greenhouse gases

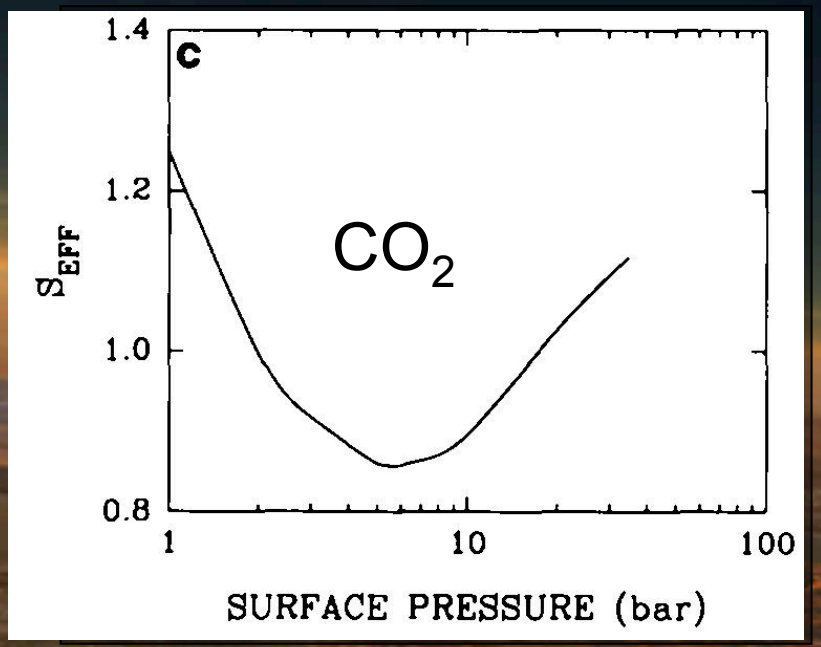
CH_4 or NH_3 (but form hazes)

C_2H_6, OCS, N_2O, SO_2, CO_2+N_2,...

(Kuhn & Atreya 1979, Haqq-Misra+ 2008, Ueno+ 2009, Grenfell+ 2011...)

problem for Mars: any CO_2 pressure insufficient for liquid water on Mars. Would need higher solar luminosity.

Or additional H_2 (Ramirez+, submitted)

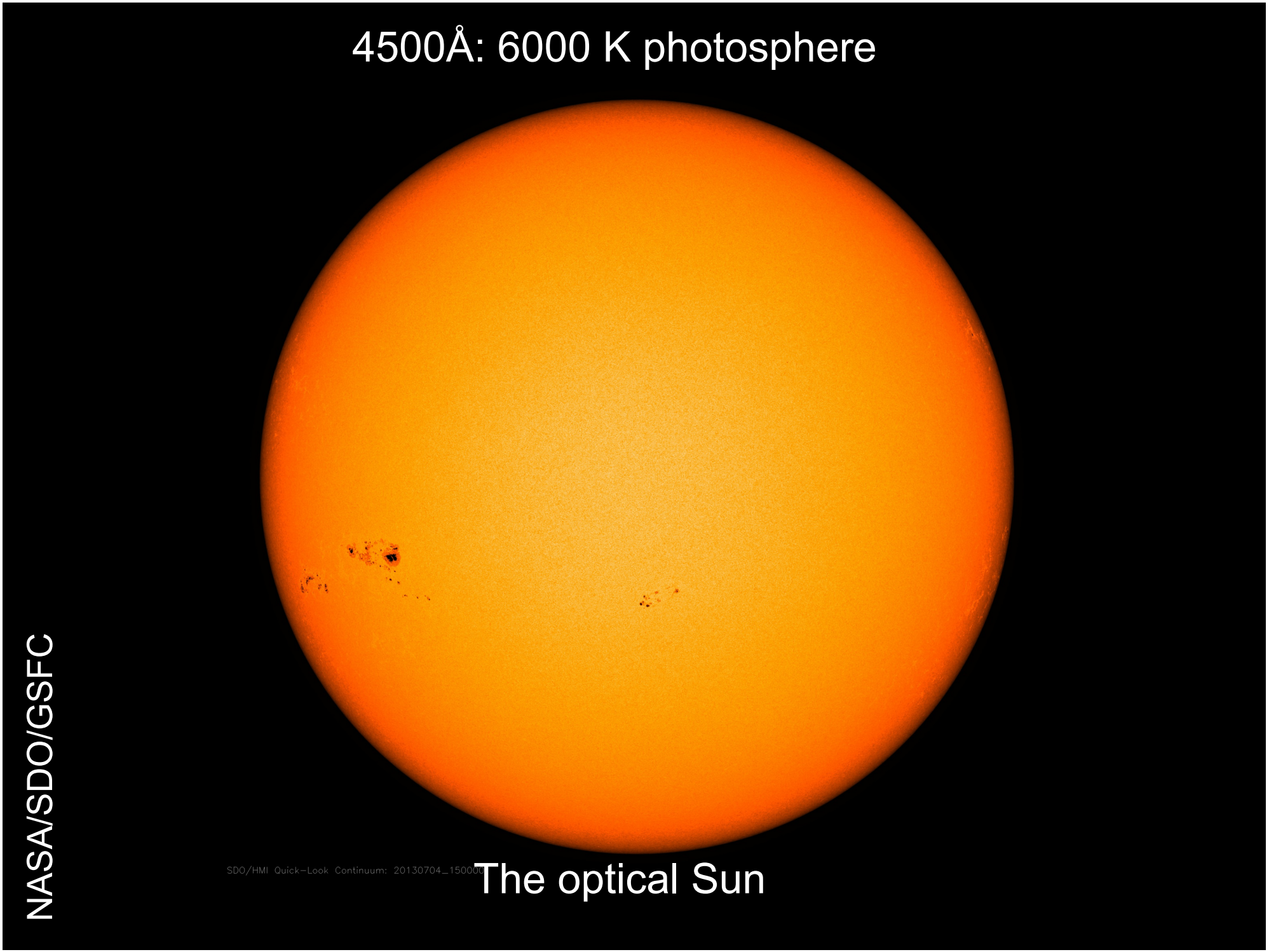


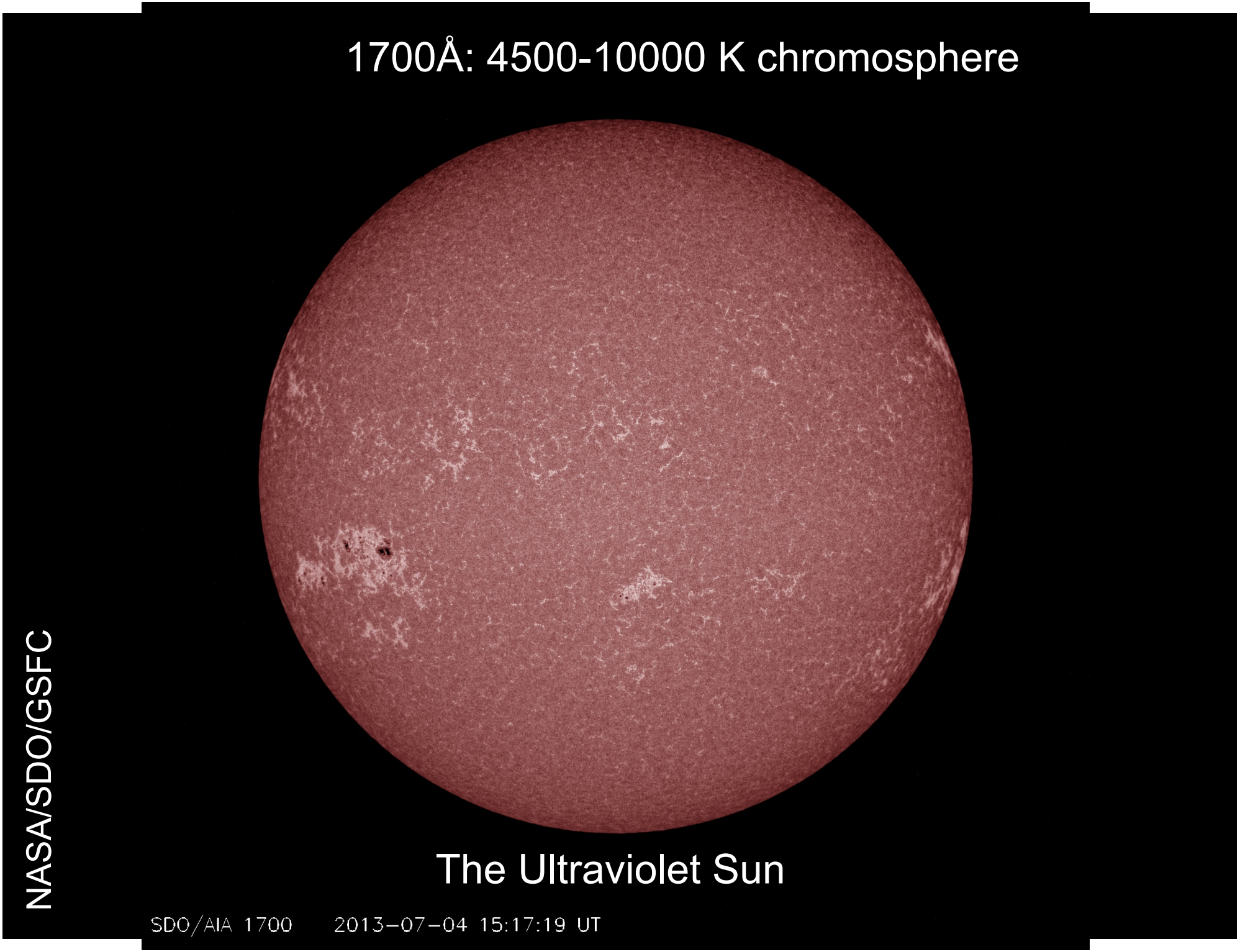
Kasting et al. 1991, Icarus, 94, 1-13

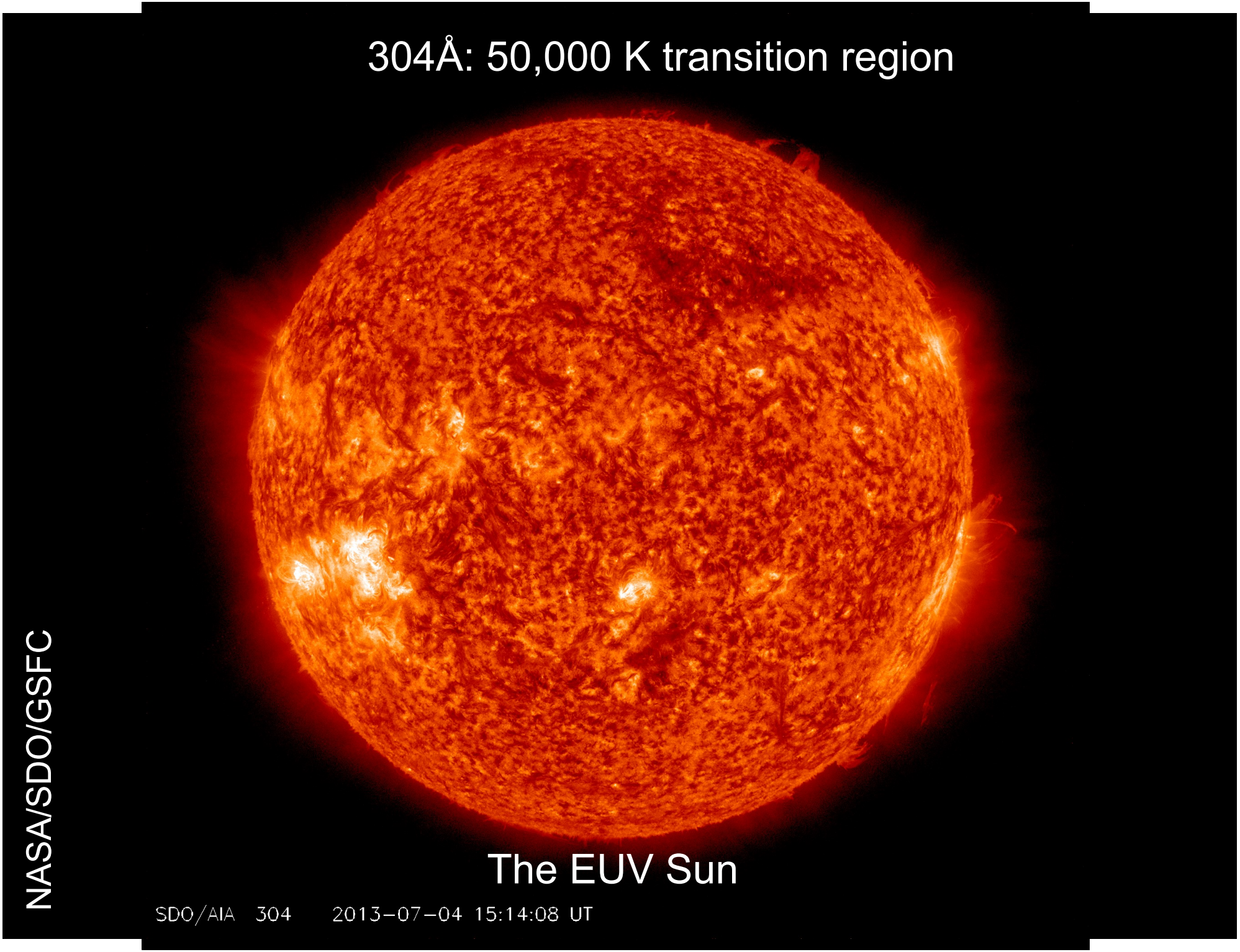
Lower Albedo

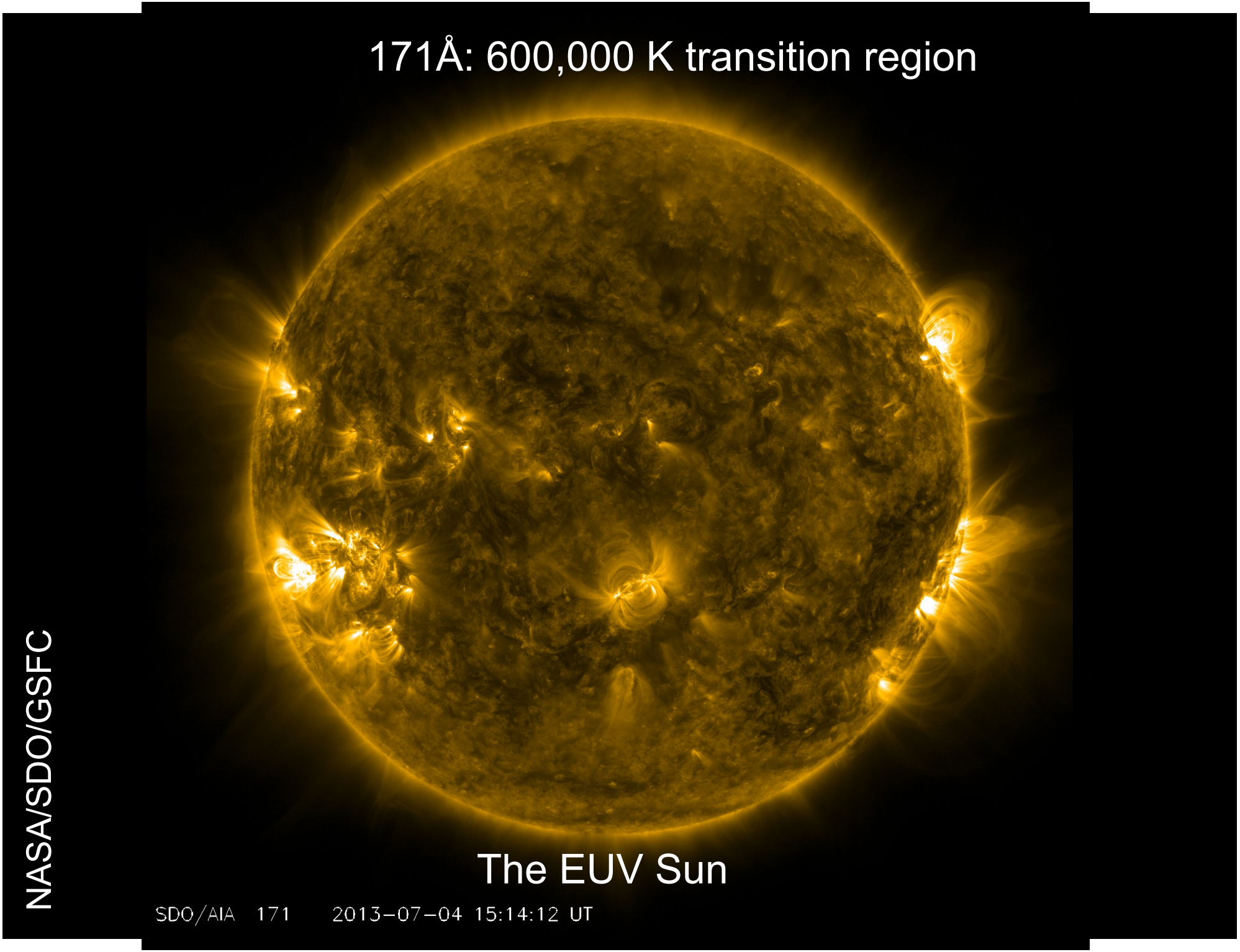
- need high ice clouds (low clouds reflect): but very thick layer required (Goldblatt & Zahnle 2011)
- fewer cloud condensation nuclei for low clouds (Rosing et al. 2010 - debated)

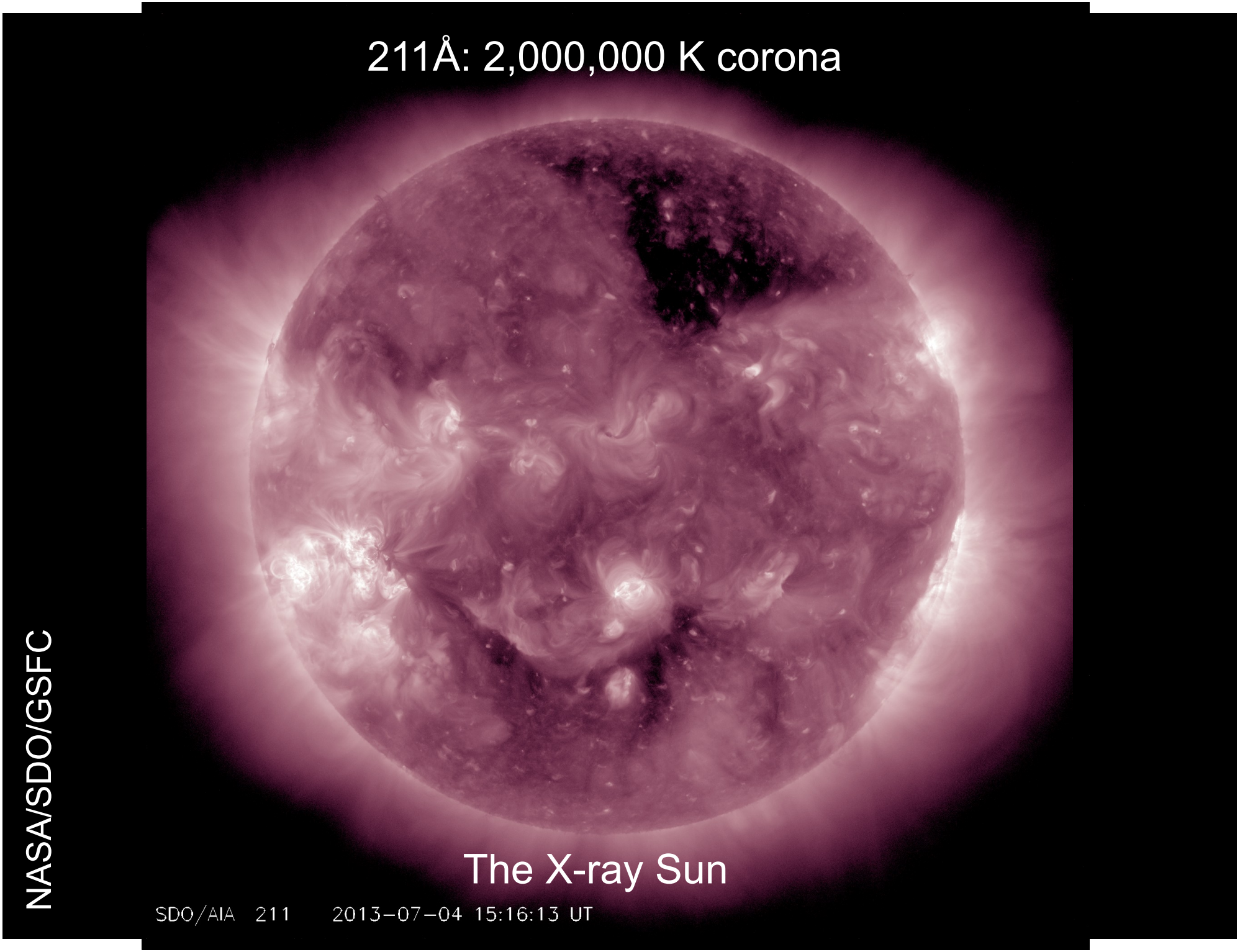
http://www.space4case.com/mmw/

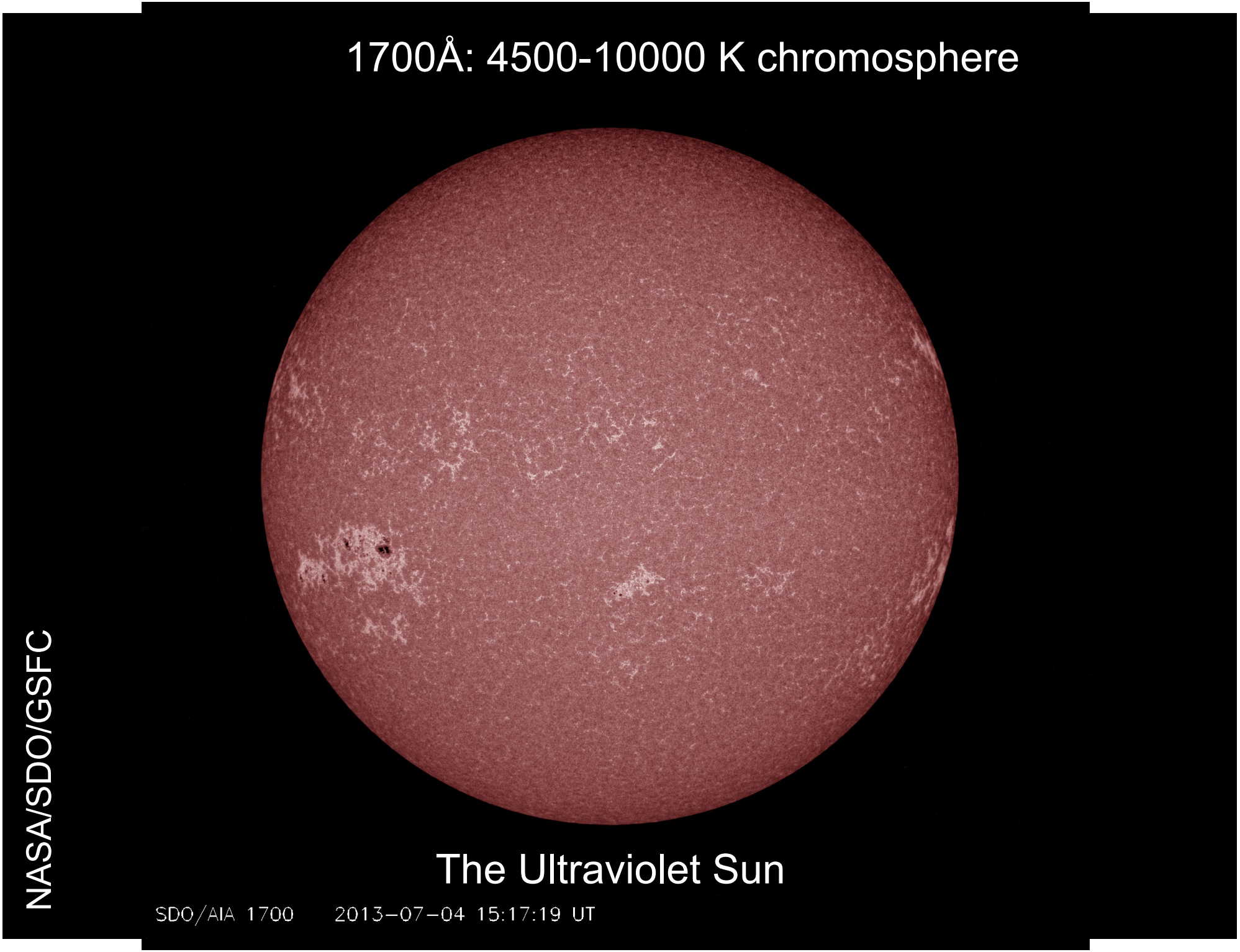

4500Å: 6000 K photosphere
SDO/HMI Quick-Look Continuum: 20130704_150000
NASA/SDO/GSFC
The optical Sun


1700Å: 4500-10000 K chromosphere
NASA/SDO/GSFC
The Ultraviolet Sun
SDO/AIA 1700 2013-07-04 15:17:19 UT

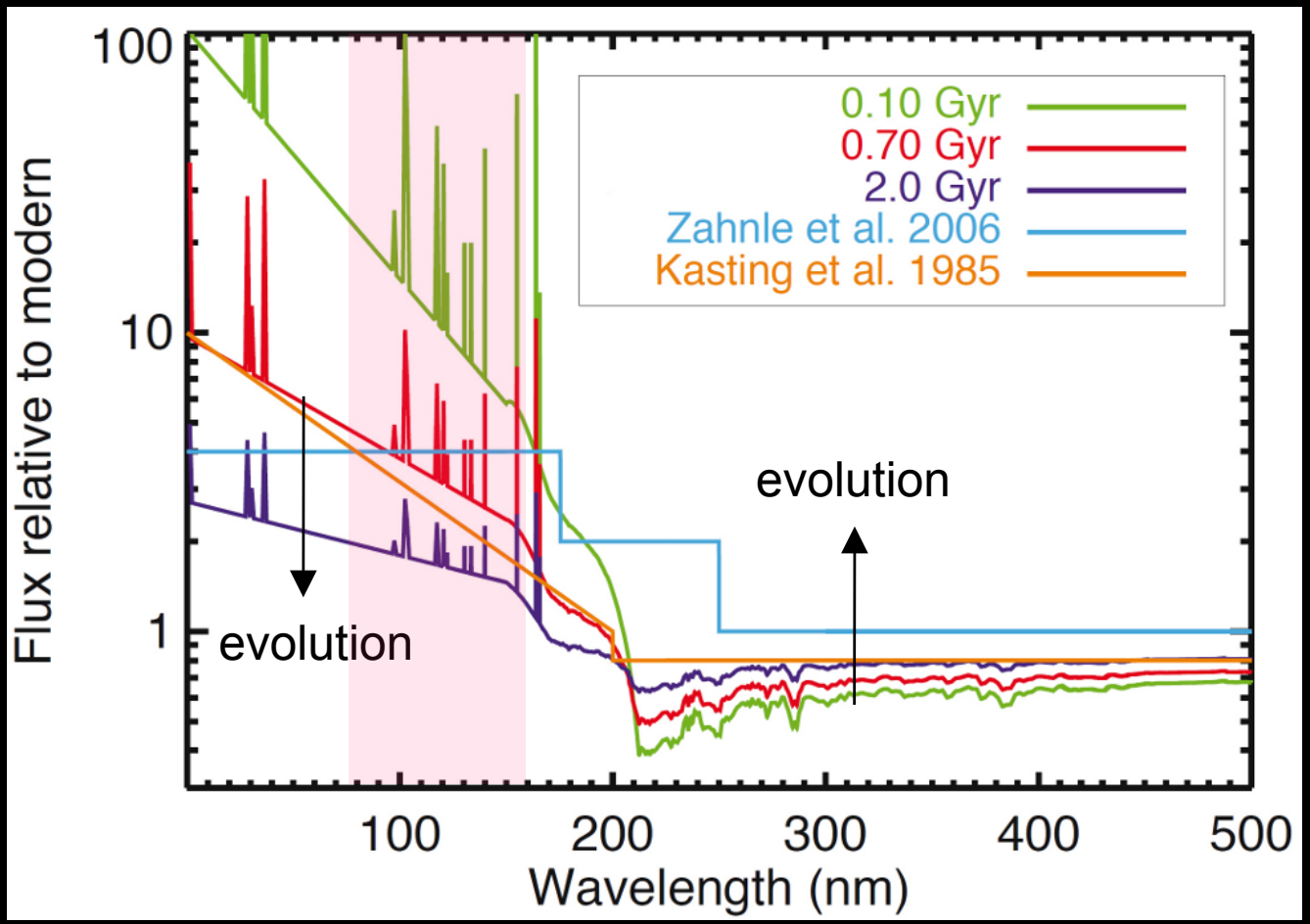

304Å: 50,000 K transition region
The EUV Sun
SDO/AIA 304 2013-07-04 15:14:08 UT
NASA/SDO/GSFC


171Å: 600,000 K transition region
The EUV Sun
SDO/AIA 171 2013-07-04 15:14:12 UT
NASA/SDO/GSFC


211Å: 2,000,000 K corona
The X-ray Sun
SDO/AIA 211 2013-07-04 15:16:13 UT
NASA/SDO/GSFC


1700Å: 4500-10000 K chromosphere
NASA/SDO/GSFC
The Ultraviolet Sun
SDO/AIA 1700 2013-07-04 15:17:19 UT

Ultraviolet Radiation



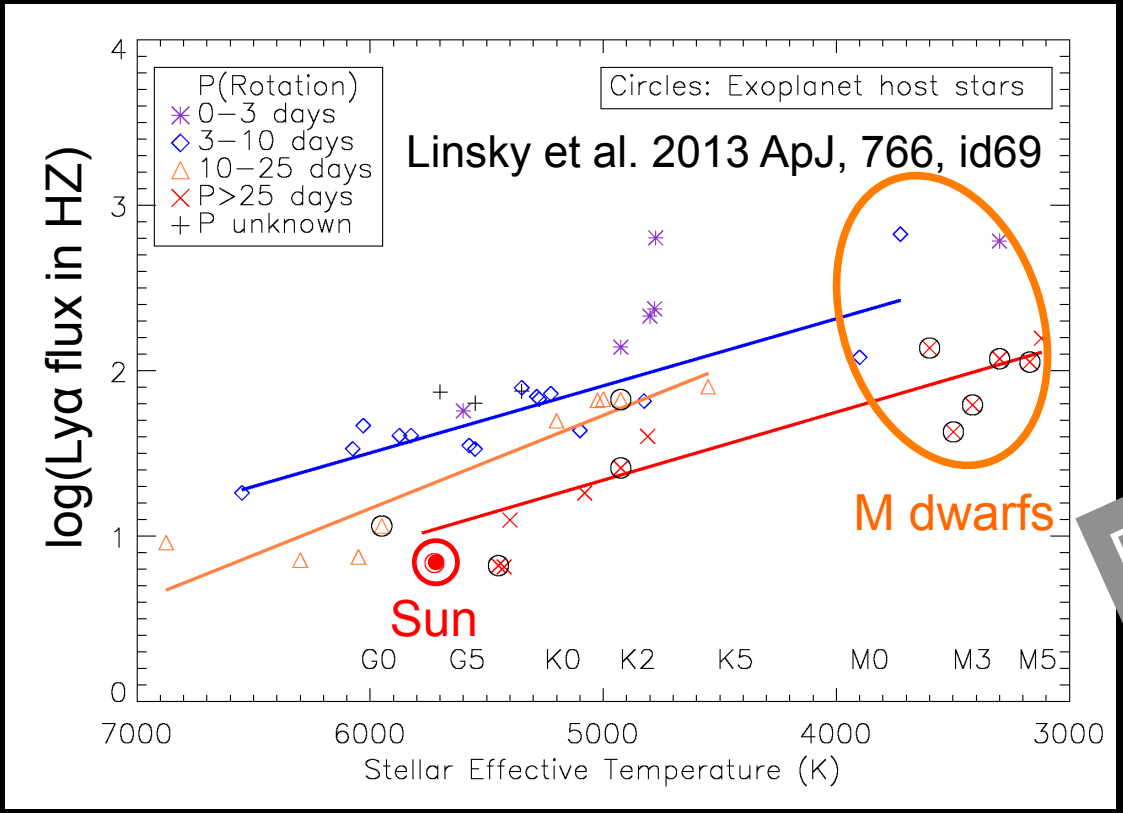
from Claire et al. 2012, ApJ, 757, 95

Young stars: stronger magnetic activity → more **FUV** active;
shorter wavelength → stronger evolutionary **decay**

Ultraviolet Matters: M Dwarfs

M dwarfs photospherically NUV faint, but magneticlly FUV strong:

large f(FUV)/f(NUV) ratio (France+ 2013), **strong Lyα** (Linsky+ 2013)



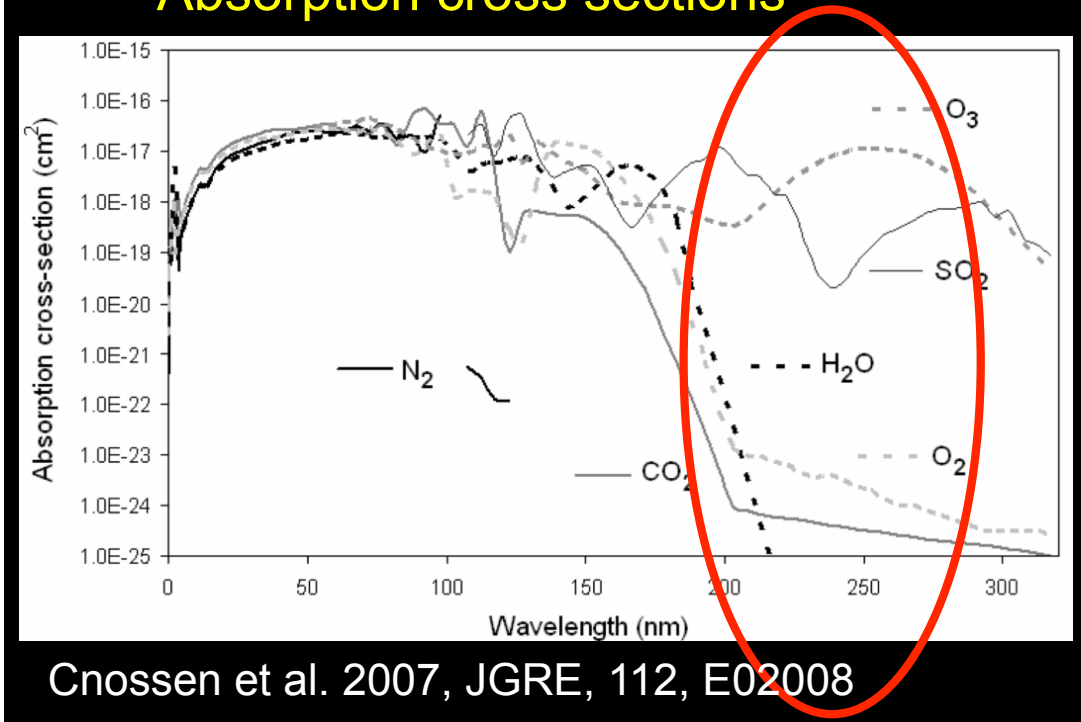
Poster 2G017
Feng Tian

CO_2 photodissociation → abiotic O_2 (+O_3) atmospheres in HZ (Tian+ 2012)

→ *O_2, O_3 dubious biomarkers for HZ planets!* (France+ 2013)

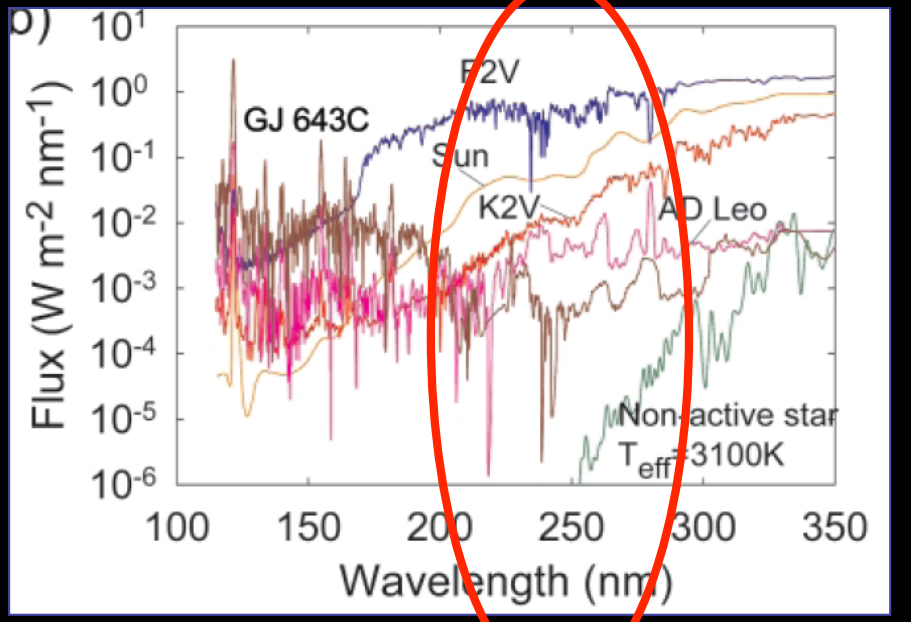
Ultraviolet Radiation: Why Important?

Absorption cross sections



Cnossen et al. 2007, JGRE, 112, E02008

Stellar flux



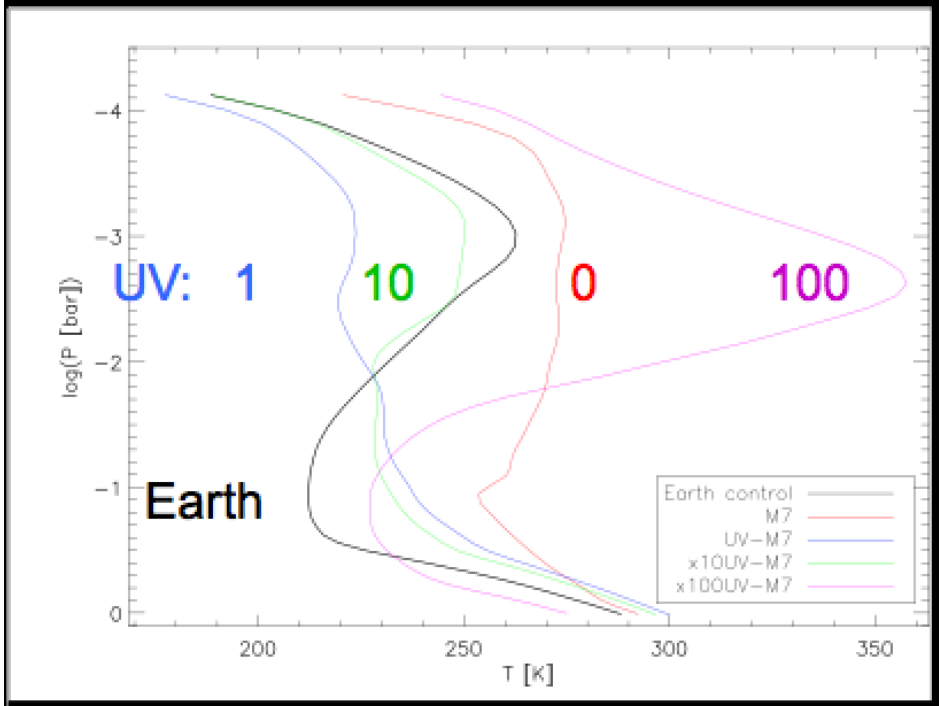
Segura et al. 2005, Astrobiology, 5, 706

- Stellar UV flux important for stratospheric heating due to ozone.
- stellar types and activity matter!
- High UV flux for active M dwarfs can be much higher *(in HZ)*

Chapter N. Madhusudhan

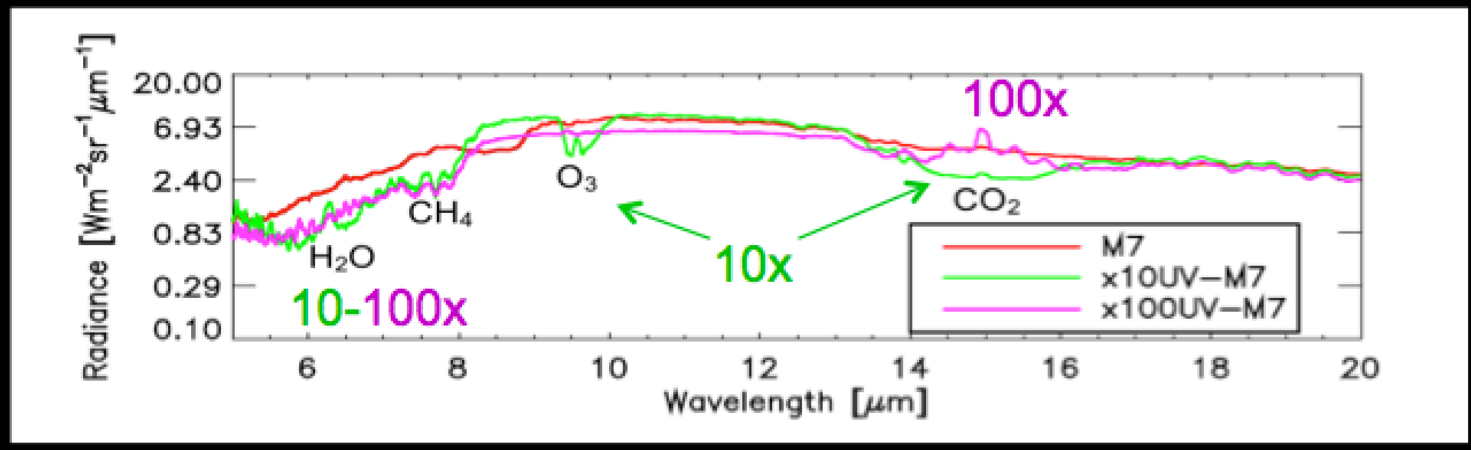
Earth-like planets: Structure of Protoplanetary Atmospheres and Spectral Signal

Temperature profile



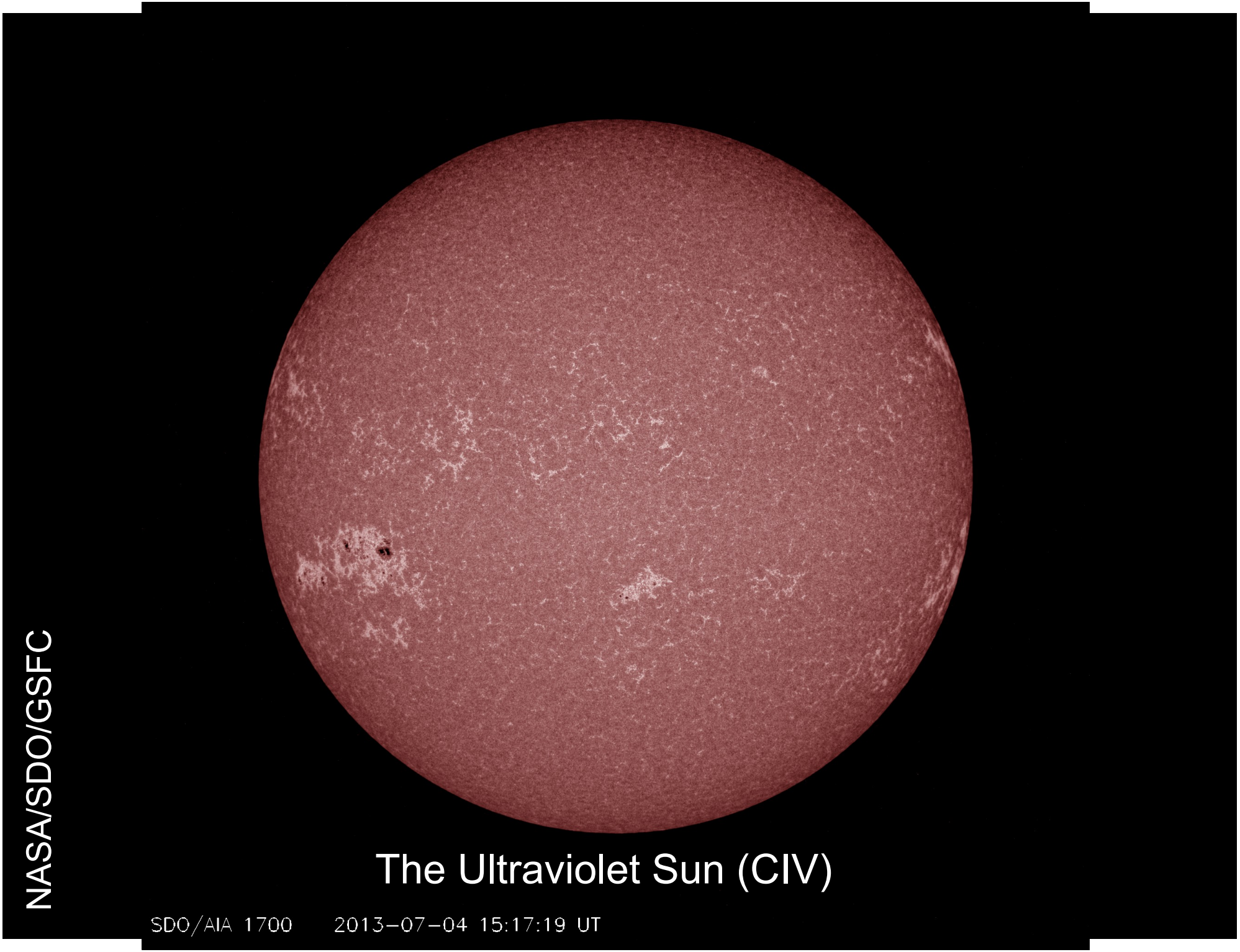
- UV flux → stratospheric temperature inversion
- affects atmospheric chemistry and abundances
- Different T-profiles and abundances affect e.g. ozone absorption bands

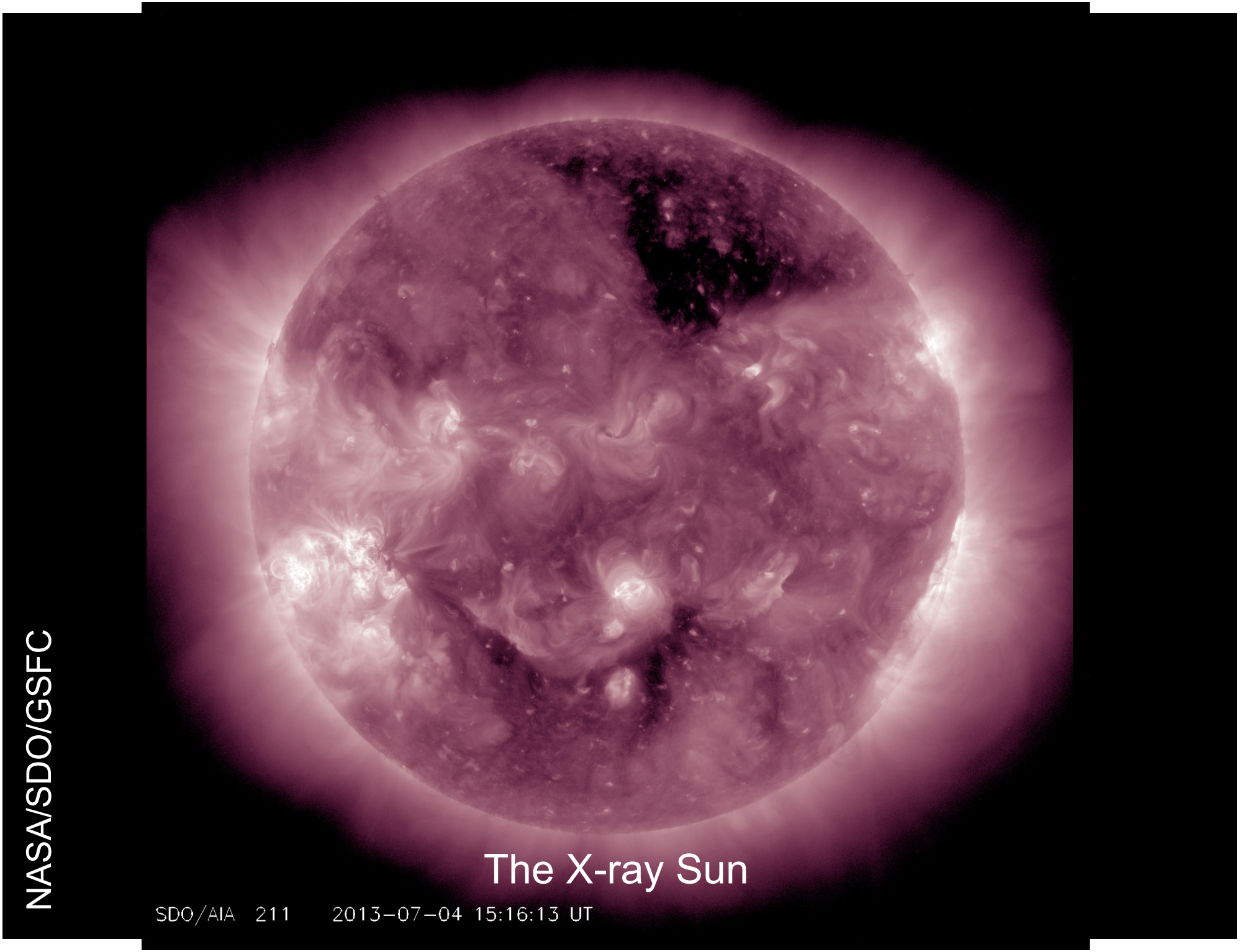
Emission spectrum



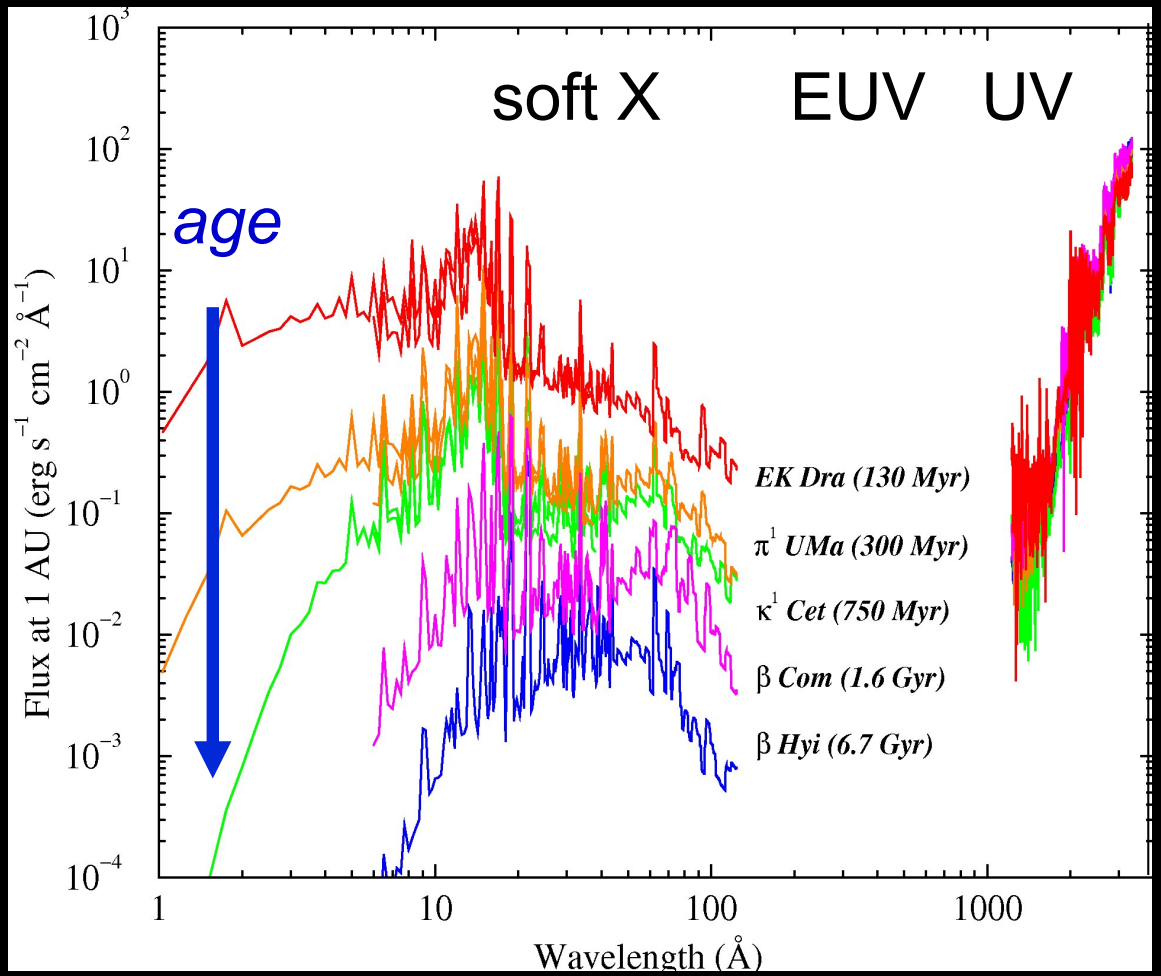
Grenfell et al., 2013, submitted

Rauer+2011, Segura+ 2005, Hedelt+ 2013


NASA/SDO/GSFC
The Ultraviolet Sun (CIV)
SDO/AIA 1700 2013-07-04 15:17:19 UT


NASA/SDO/GSFC
The X-ray Sun
SDO/AIA 211 2013-07-04 15:16:13 UT

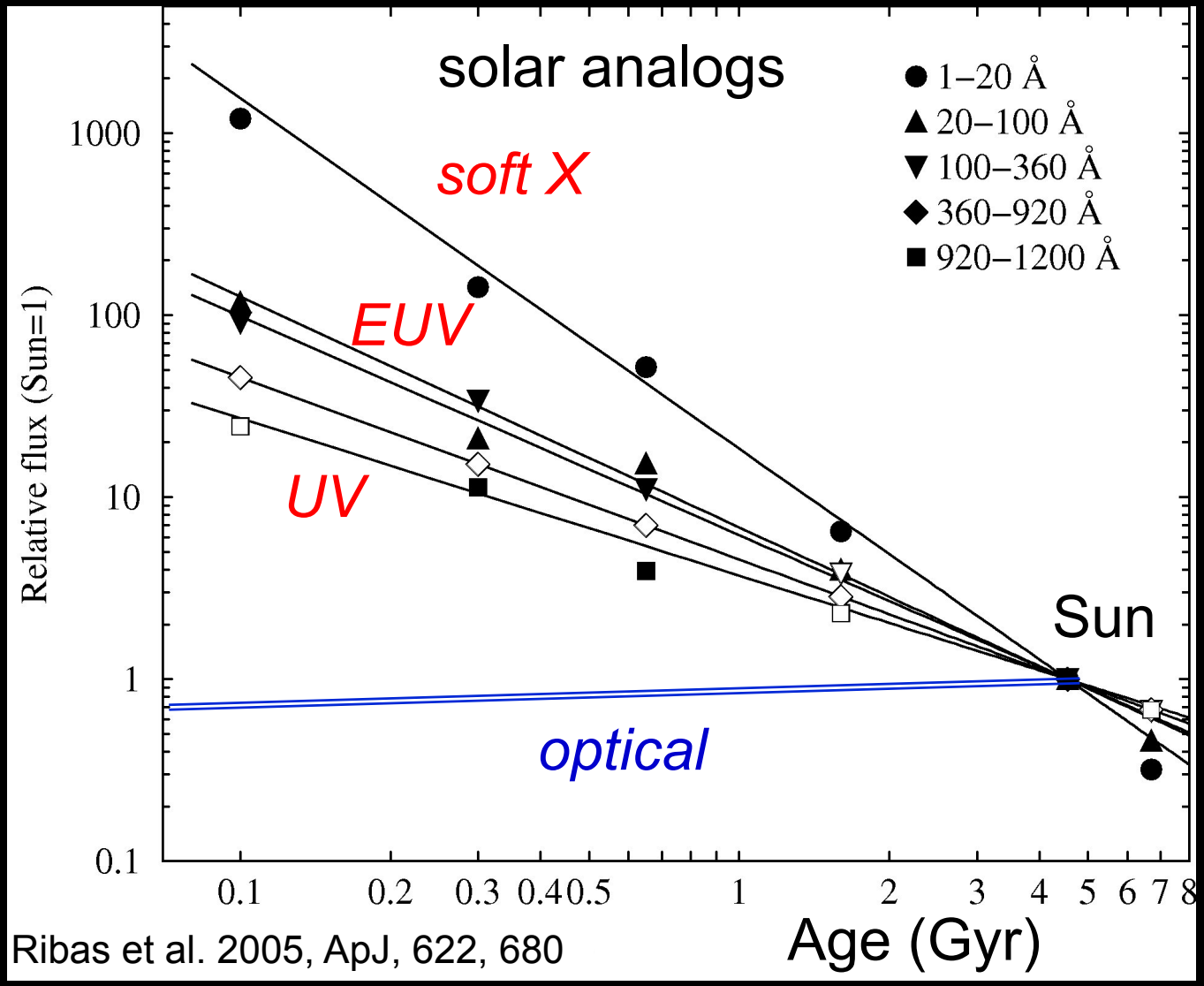
The EUV and X-Ray Sun in Time



Guinan & Ribas 2002, ASP Conference Proceedings, Vol. 269, 85
also Ribas et al. 2005, APJ, ApJ, 622, 680; Claire et al. 2012, ApJ, 757, 95

Luminosity (and hardness!) decay
more rapidly over much larger scale in X-ray than in UV

Magnetic Activity Decays



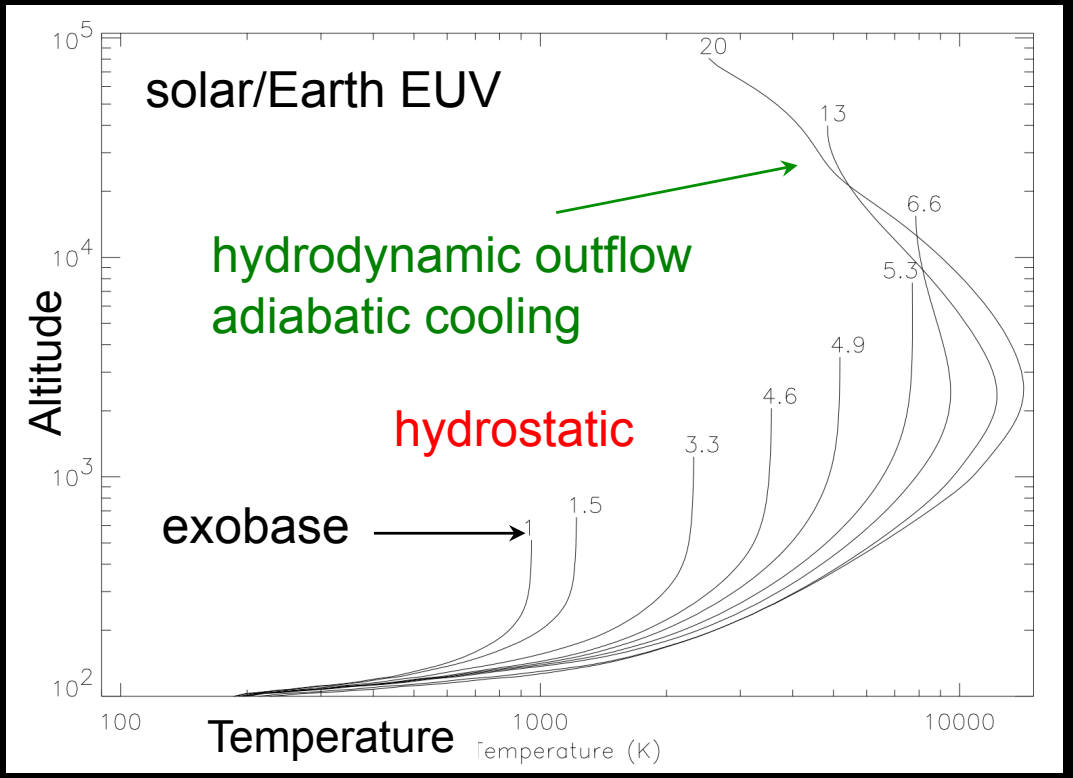
Luminosity decay larger and steeper at shorter wavelengths

Upper Atmospheres Respond to XUV Radiation

heating
ionization
dissociation

Tian et al. 2008,
JGR, 113, E05008

Tian+ 2005, 2008, 2009,
Kulikov+ 2007, Penz+ 2008,
Lammer+ 2011, 2013etc

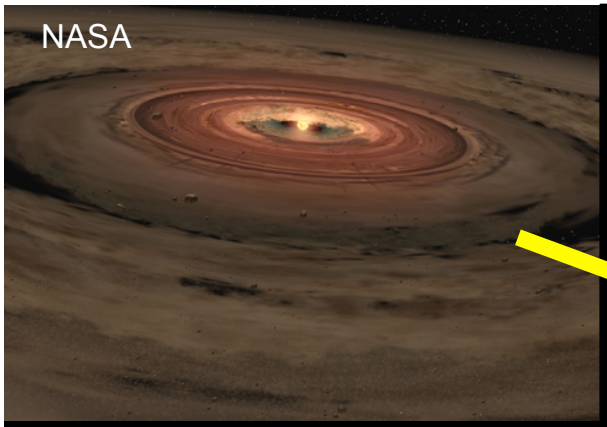


Hydrostatic: ***Jeans escape:*** high-energy Maxwellian tail escapes

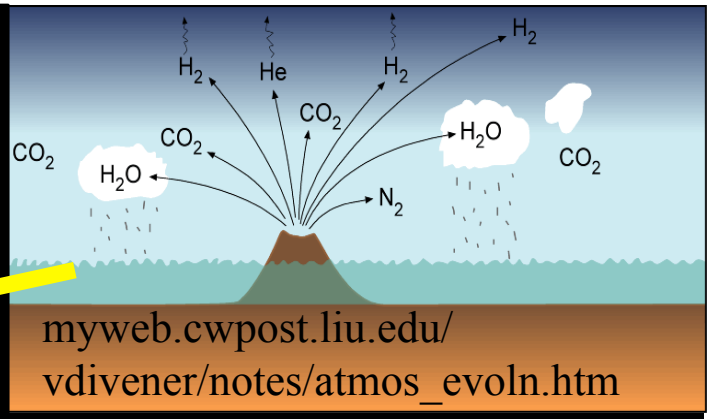
Hydrodynamic: ***Controlled outflow:*** not all exobase atoms reach escape velocity
Depends on: host star activity, planetary parameters, atmospheric composition

Uncontrolled blow-off: mean thermal energy of upward flowing bulk gas exceeds gravitational energy at exobase

need hydro simulations for correct mass loss rates!
(loss overestimate by 1-2 orders of magnitude easy!)



Protoatmospheres Matter



Accumulation of massive protoatmospheres during planet formation:

- disk H/He gas envelope: 10s-100s of EO_H (super-Earths: -10^4)
- CO_2 + H_2O outgassing: few EO H_2O ~500 bar

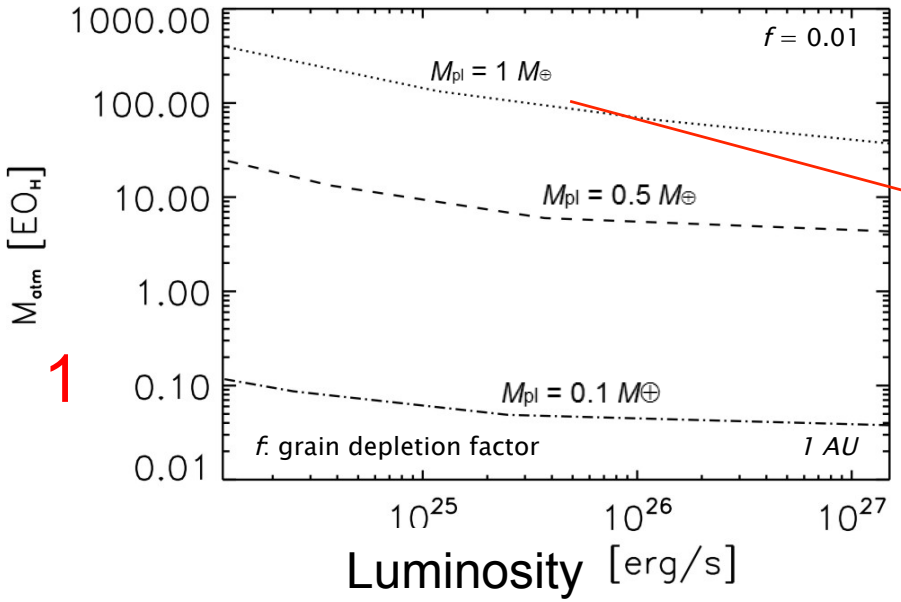
e.g., Adams 2008, Rogers & Seager 2010, Rogers+ 2011; Elkins-Tanton 2008, Lebrun+ 2013)

Good: protect N_2 atmosphere from evaporation; still present on Earth!

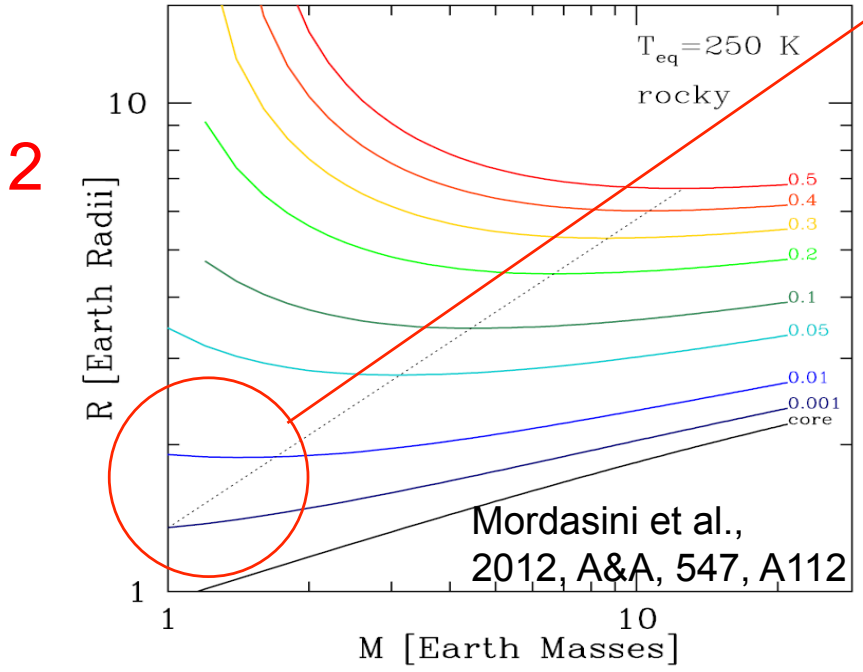
Challenge: How to get rid of protoatmospheres? Earth does not have it!

Protoatmosphere: Accretion and Loss

1



2



1. H protoatmosphere capture in nebula for 1 Earth-mass core:

   ~ 50 – 500 EO_H

   (Stoekl et al., 2013, in prep., in agreement with Ikoma & Genda, Icarus, 2006; Rafikov, ApJ, 2006)

2. Thermospheric radii as function of **H** envelope mass fraction (Mordasini+ 2012)

3. Loss of protoatmosphere by EUV:

   100x XUV, 1 AU, first 100 Myr:

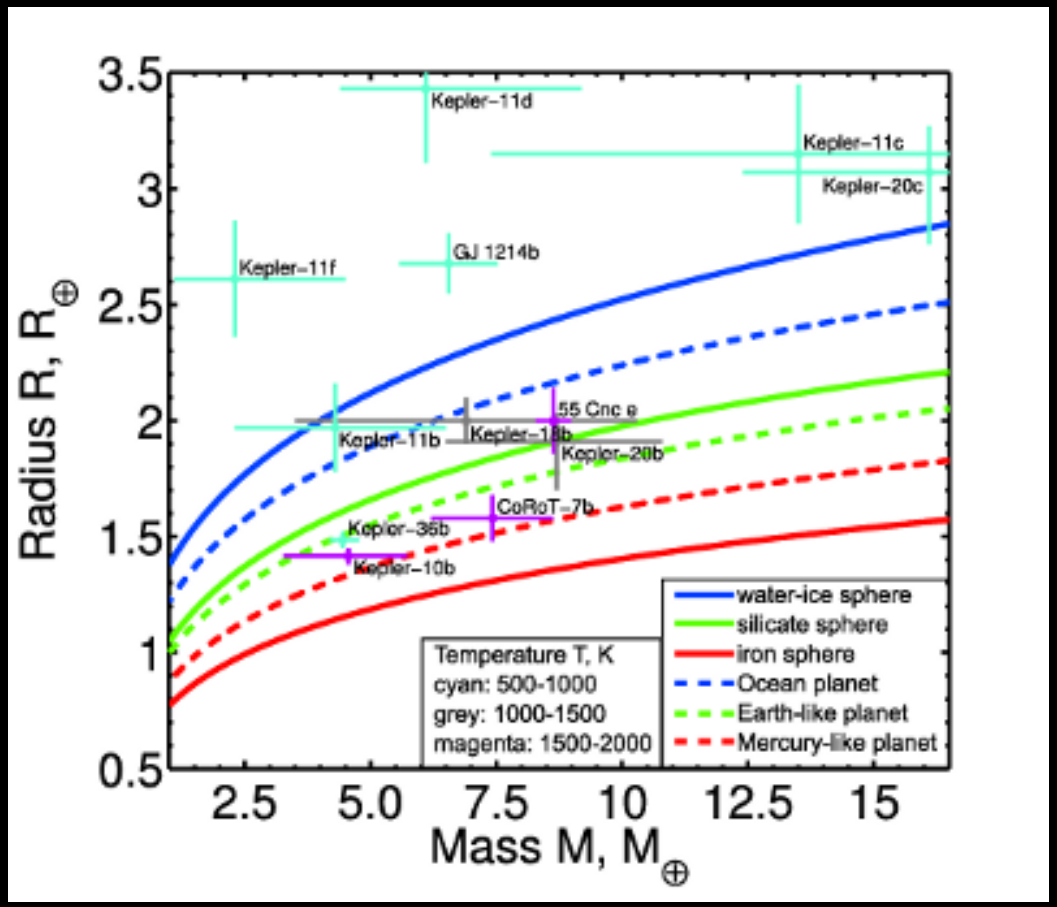
   For $2R_\oplus$ H loss ~ 15 – 30 EO_H
   For ~$1R_\oplus$ H loss ~ 1 – 1.85 EO_H

   less for super-Earths!

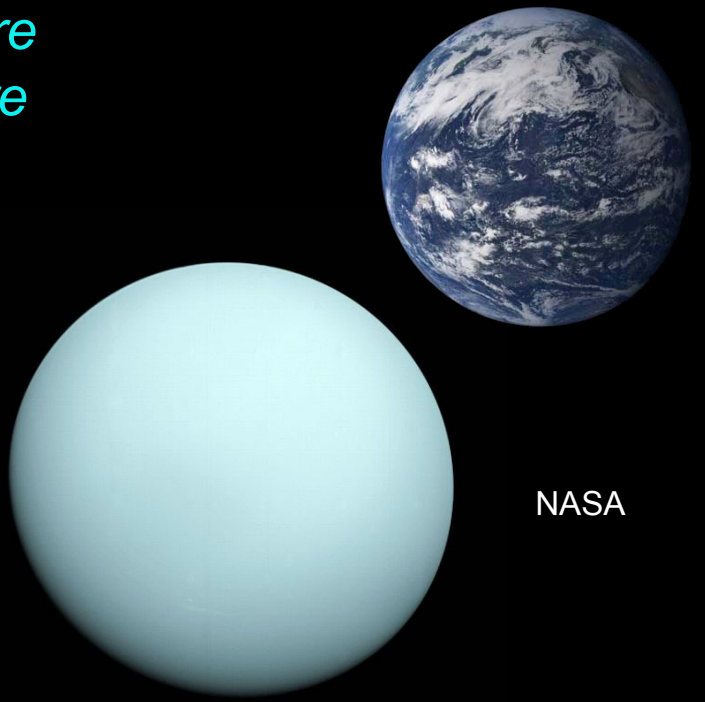
   (Lammer et al., in preparation, 2013)

so: much of the initial outgassed or accreted atmosphere may remain!

⇒
- *mini-Neptune: dense initial atmosphere*
- *remaining dense abiotic O atmosphere*
- *or water world*



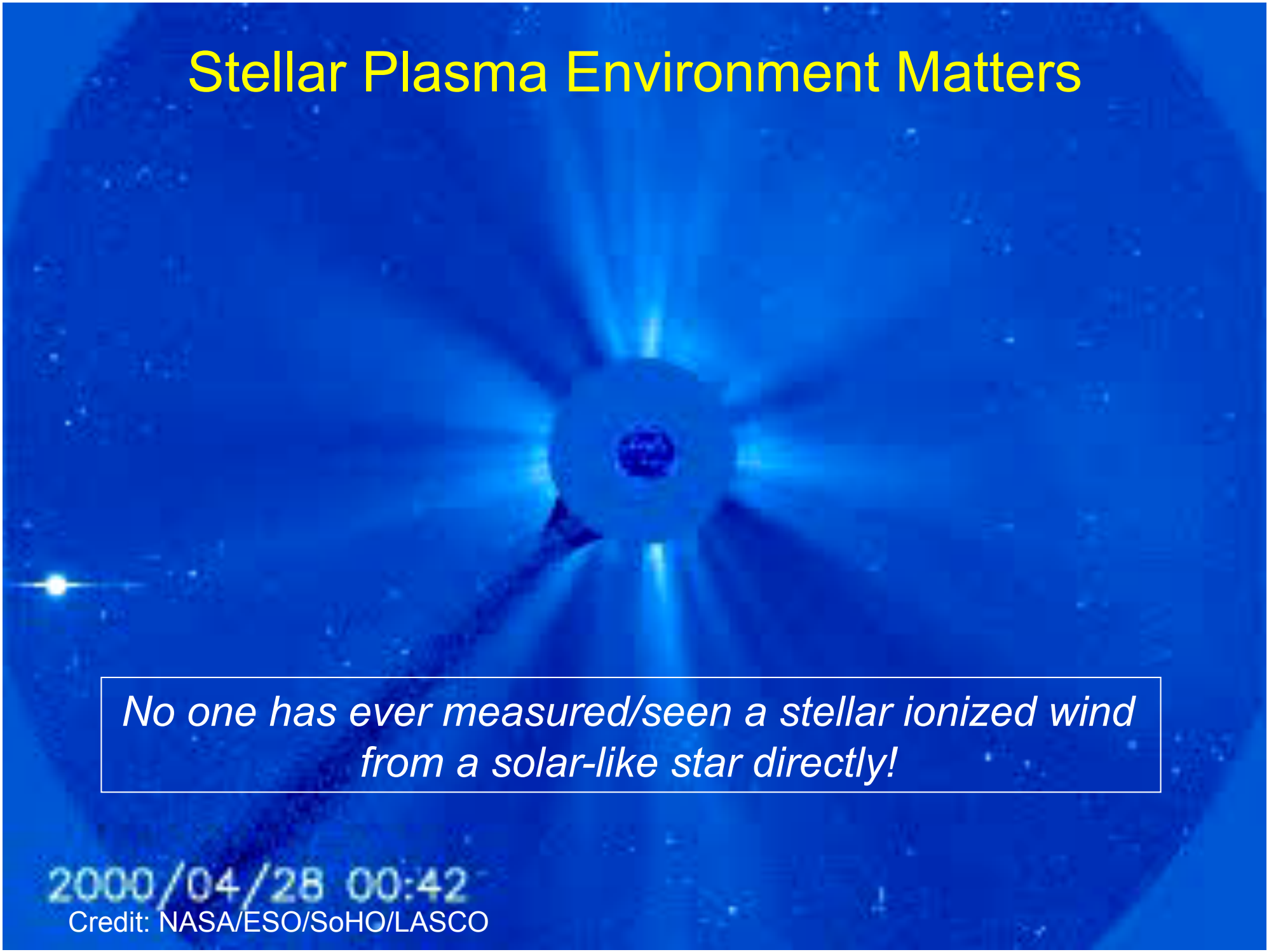
(Wagner et al. 2011, Icarus 214, 366-376)



NASA

- *Possibly realized in exoplanets*
- *got it "just right" for Earth?*
- *Or final assembly of Earth after disk dispersal!*

Stellar Plasma Environment Matters



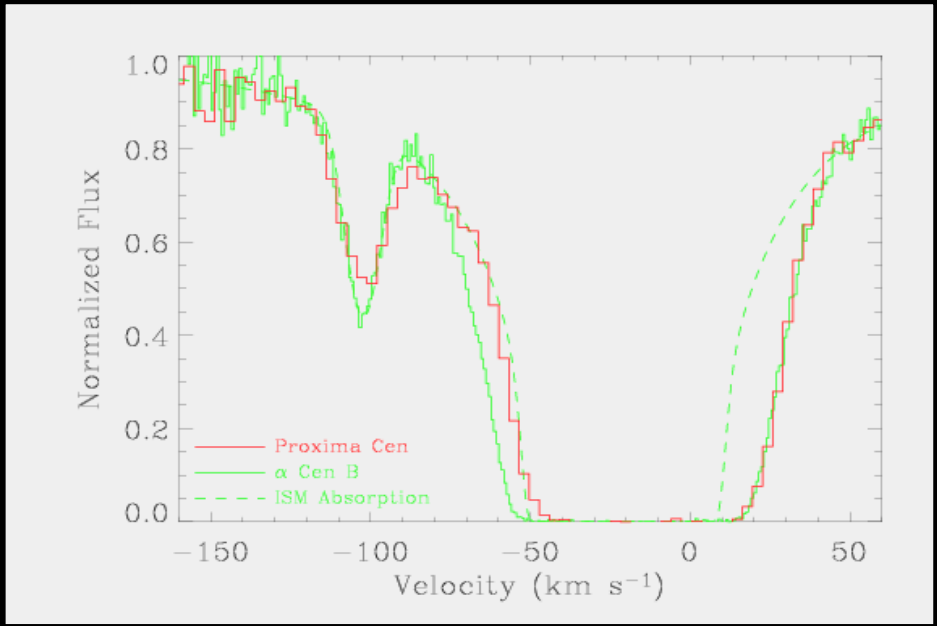
No one has ever measured/seen a stellar ionized wind from a solar-like star directly!

Credit: NASA/ESO/SoHO/LASCO

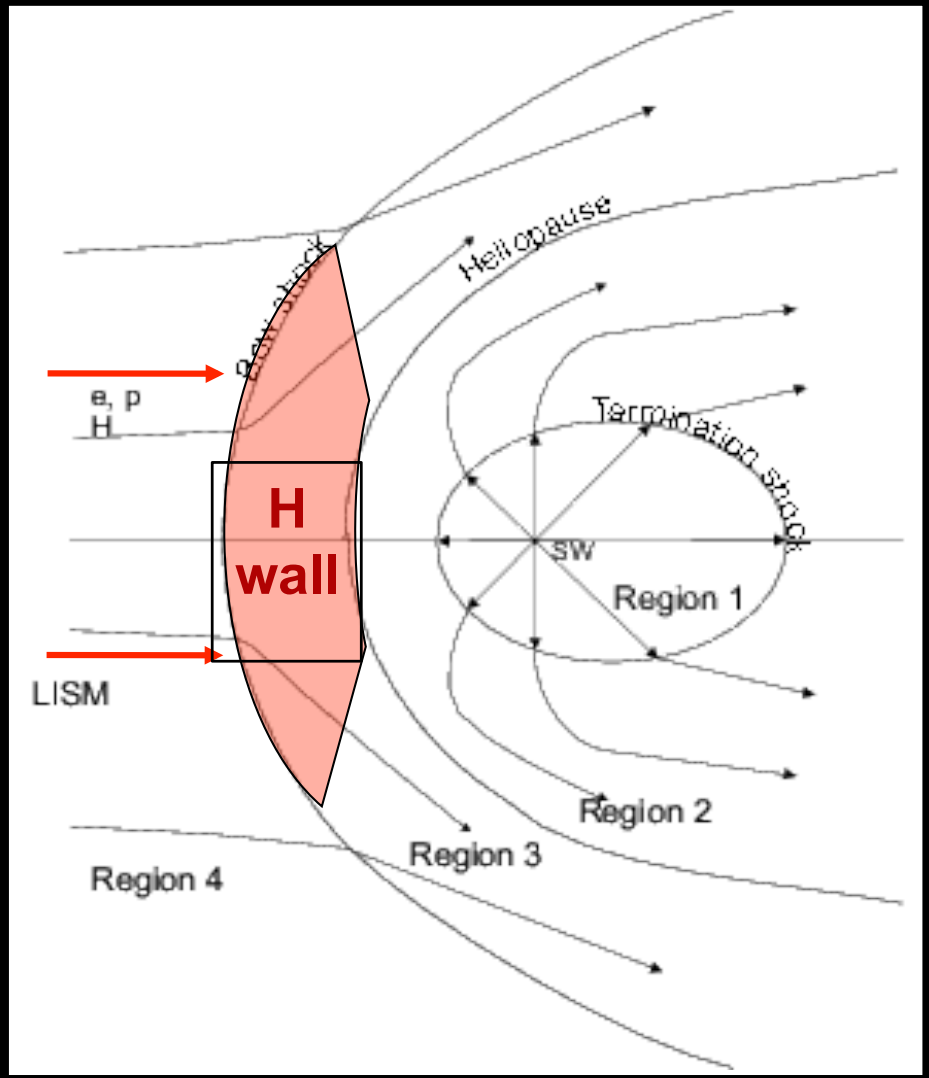
Stellar Winds Matter

Leading indirect method uses blueshifted Lyα absorption in hydrogen wall around "astrosphere" to estimate wind ram pressure

(Linsky & Wood 1996; Gayley et al. 1997, Wood et al. 2002, 2005)

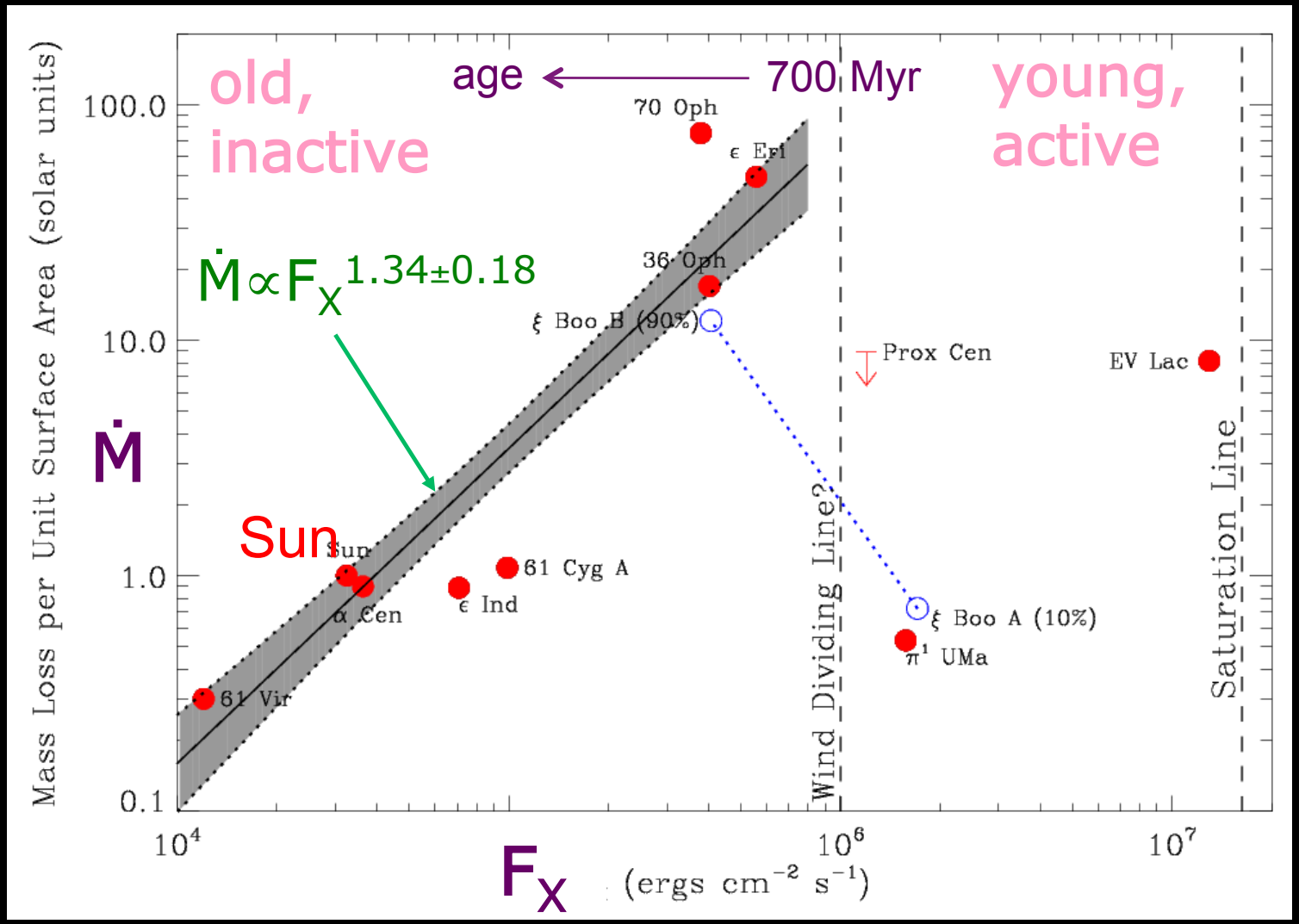


(Wood et al. 2005, ApJ, 628, L143)



(Wood 2004, Lin. Rev. Solar Phys., 1, 2)

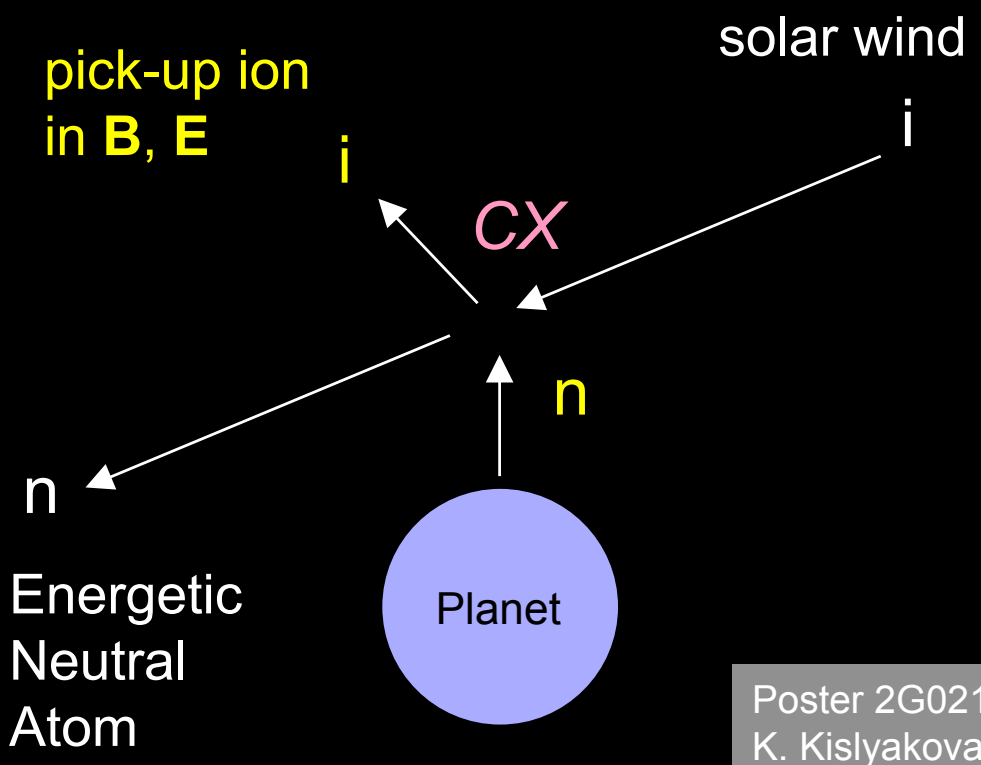
Winds Decay in Time

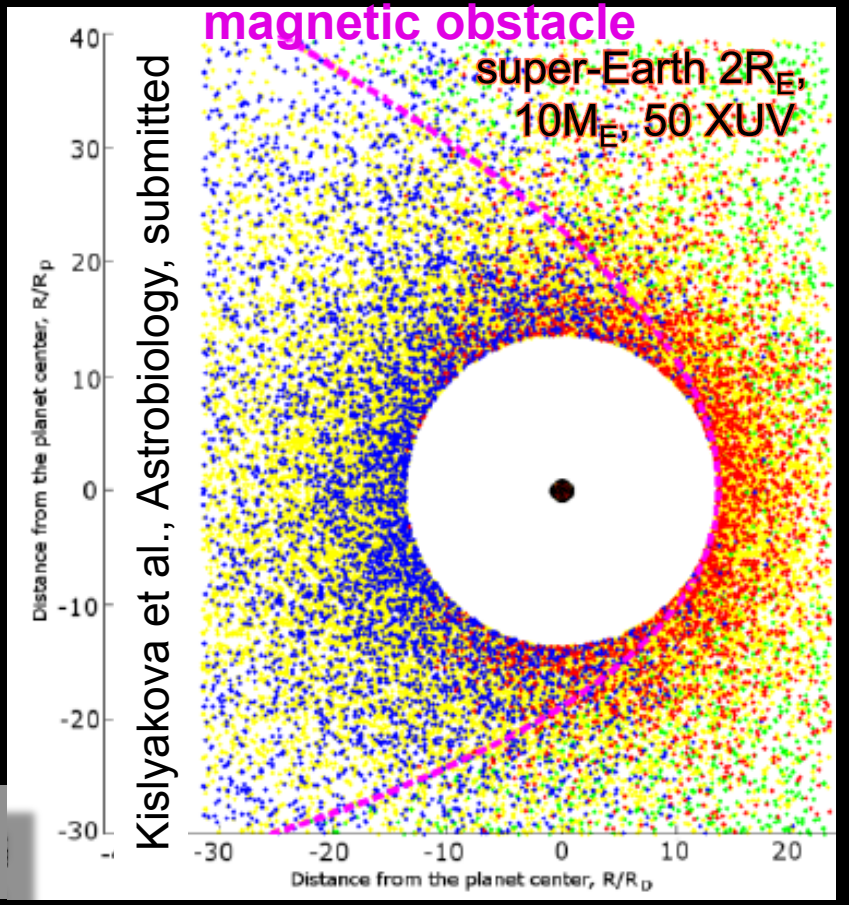


Wood et al. 2005, ApJ, 628, L143; Wood et al. 2010, ApJ, 717, 1279

$\dot{M} \propto t^{-2.33\pm0.55}$ for ages > 700 Myr

But Ions Get Picked Up





Poster 2G021
K. Kislyakova

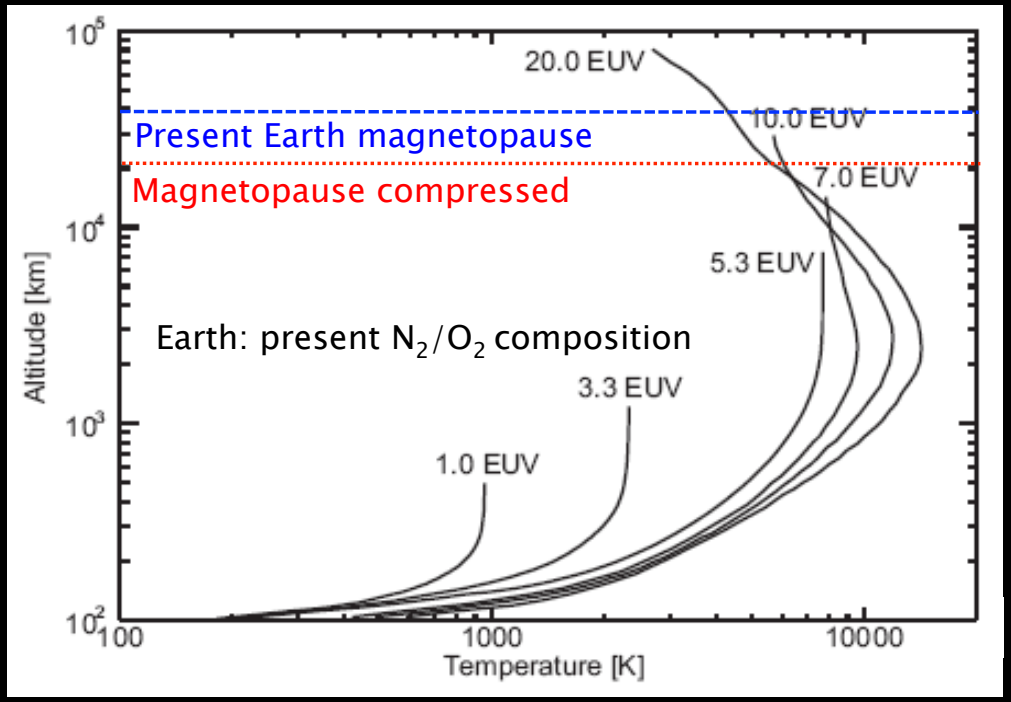
stellar wind protons planetary H atoms
ENAs moving away from / towards the star

Lundin et al. 2007, Kulikov+ 2007, Lammer+ 2003 etc.

Massive H atmosphere in HZ around M dwarf:

- Ion pick-up by the stellar wind ~10x lower than thermal escape
- Difficult to get rid of it! (~1-10 EO$_H$ for Earth in M dwarf HZ; Kislyakova+ 2013)

Stability Problems of N_2 Atmospheres



much worse for HZ of M dwarfs!

get more CO_2 !!

Tian et al. JGR, 200, 113, E05008

XUV	$t_{\rm Earth}$[Myr]	$\Delta t^{\rm w}$=10Myr	$\Delta t^{\rm w}$=100Myr	$\Delta t^{\rm st}$=10Myr	$\Delta t^{\rm st}$=100Myr
20	350	1 bar	10 bar	5 bar	50 bar
10	650	0.4 bar	4 bar	3 bar	30 bar
7	850	0.2 bar	2 bar	1 bar	10 bar

N_2-rich Earth-like atmosphere for wind exposure time t, Earth @ 1AU:

weak wind 30x stronger wind

Lichtenegger et al., Icarus, 2010; Lammer et al. OLEB, 2011

My obligatory ALMA slide...

Alma, NM, USA (pics by MG)

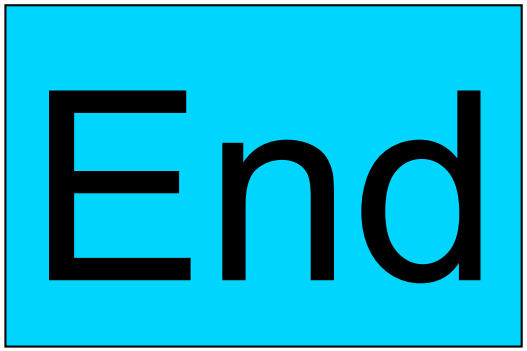
Concluding Remarks

We are only at the beginning of understanding the complex interactions between astro-physical factors and a forming and evolving planet.

Some “fine tuning” is needed to get habitability right! (star, spectrum, activity, atmosphere, magnetosphere).

Care should be taken as conditions for *life* are poorly understood!

VLA Site, New Mexico (pic by MG)


End