Exoplanetary Habitability: Radiation, Particles, Plasmas, and Magnetic Fields

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FWF Der Wissenschaftsfonds.

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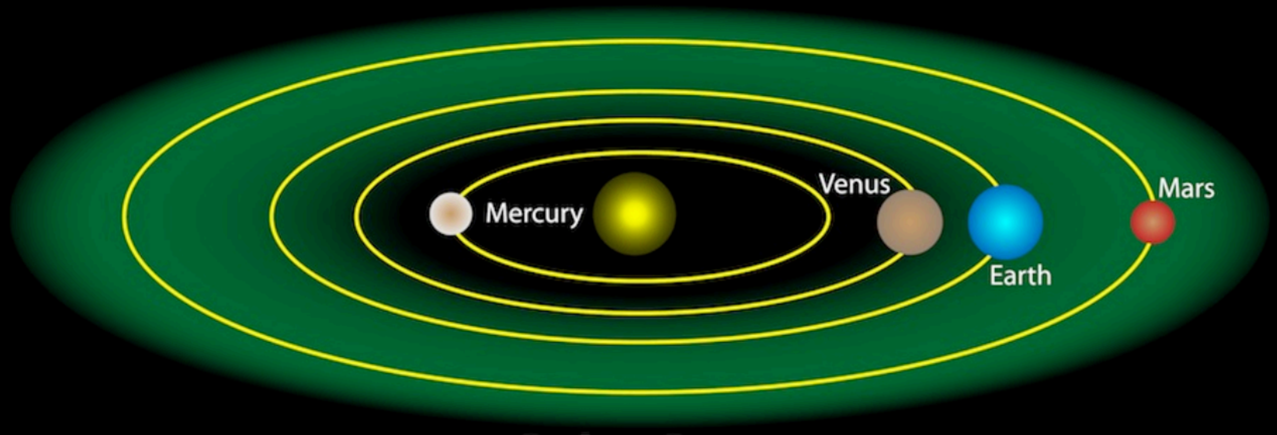
Outline

- Habitability
- Thermal and non-thermal atmospheric loss
- Rotational evolution of star
- Stellar winds
- Stellar particles
- Summary

The Liquid Water Habitable Zone



NASA

Habitable planet a priori requires a rocky planet with an atmosphere.

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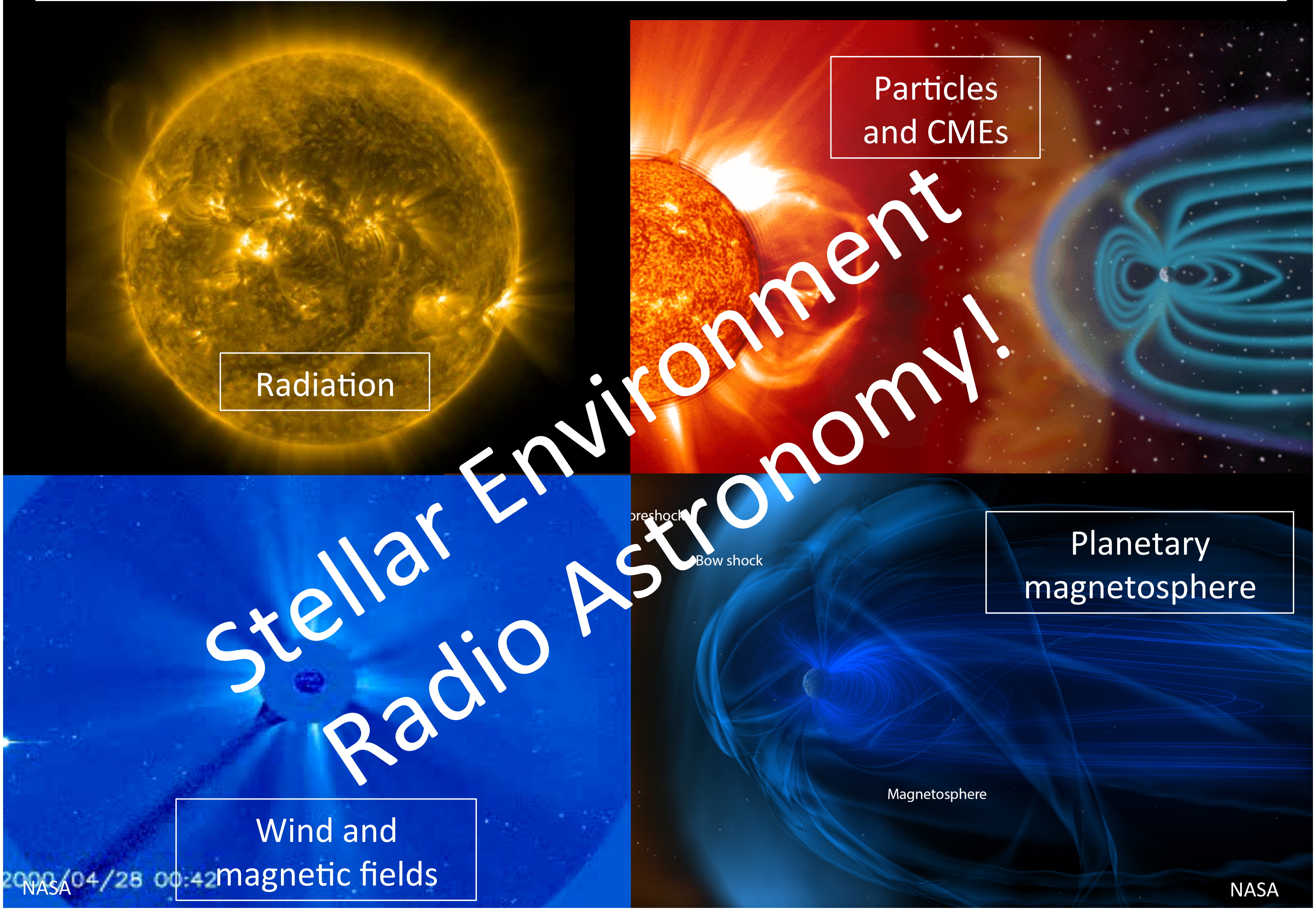
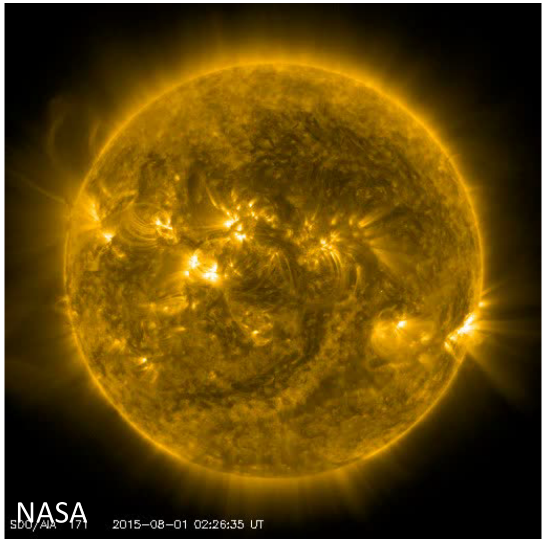
NASA

But to establish and sustain habitability, many *astrophysical* factors must be right!



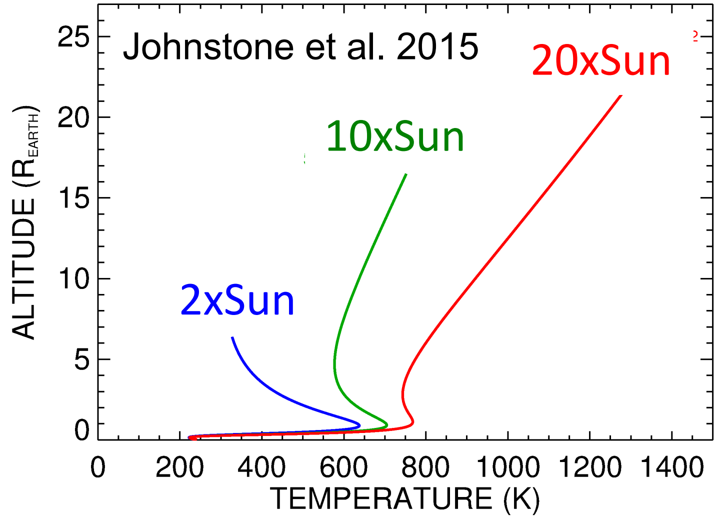
Motivation: Atmospheric Processing and Erosion



Extreme-UV & X-rays:

→

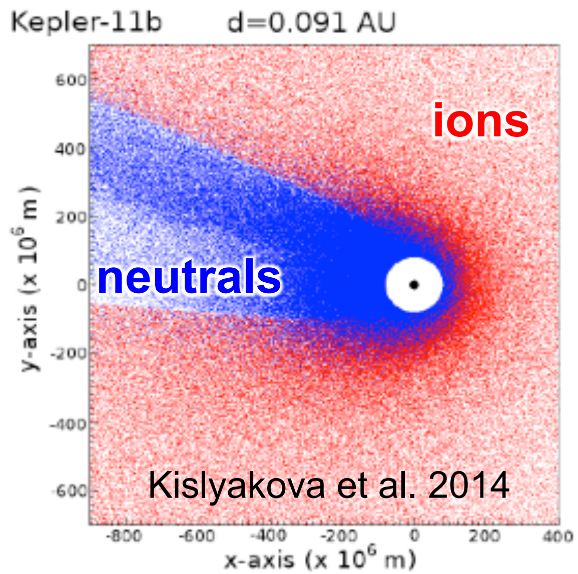
chemistry, thermal loss
(evaporation)



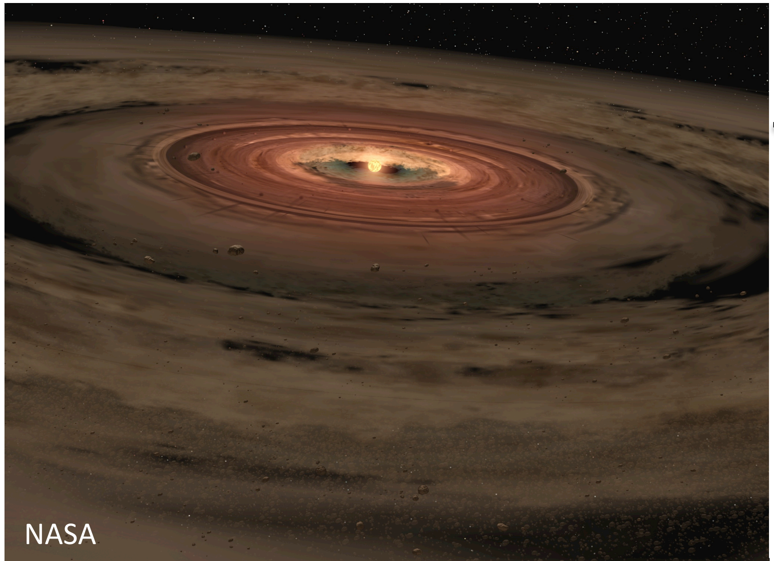
Ionized winds:

→

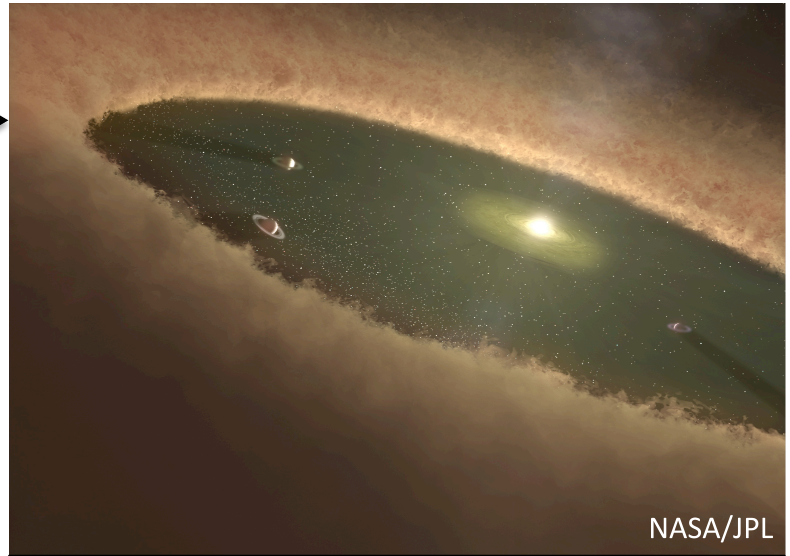
non-thermal loss



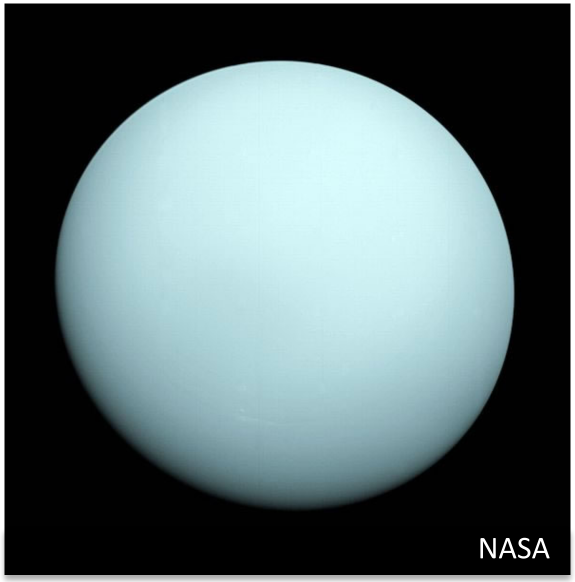
Atmospheric Accretion and Erosion

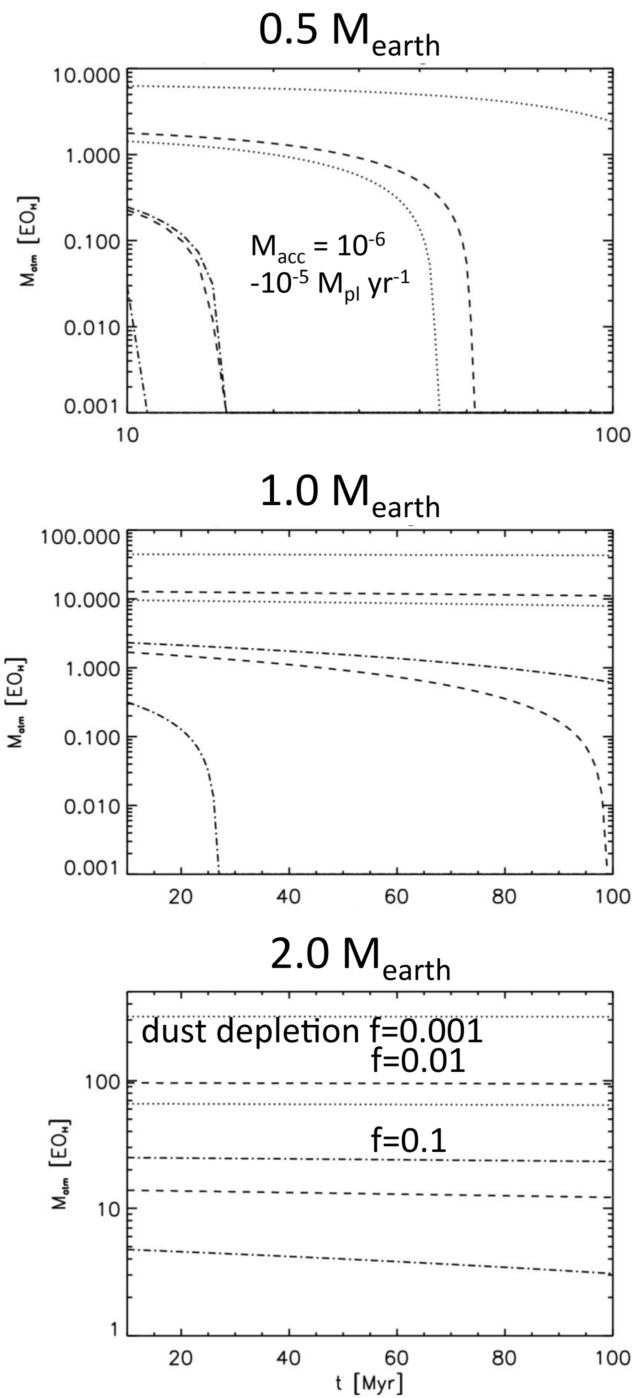


Gas envelope **accretion**



Loss due to **pressure release**





... followed by thermal loss:

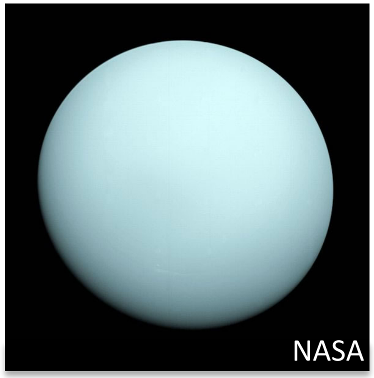
(Lammer et al. 2014)

Small (<1 M_{Earth}) planets lose captured H envelopes after a few 10 Myr

< 1.5 M_E

Earth-sized planet loses envelope *possibly*

> 1.5 M_E

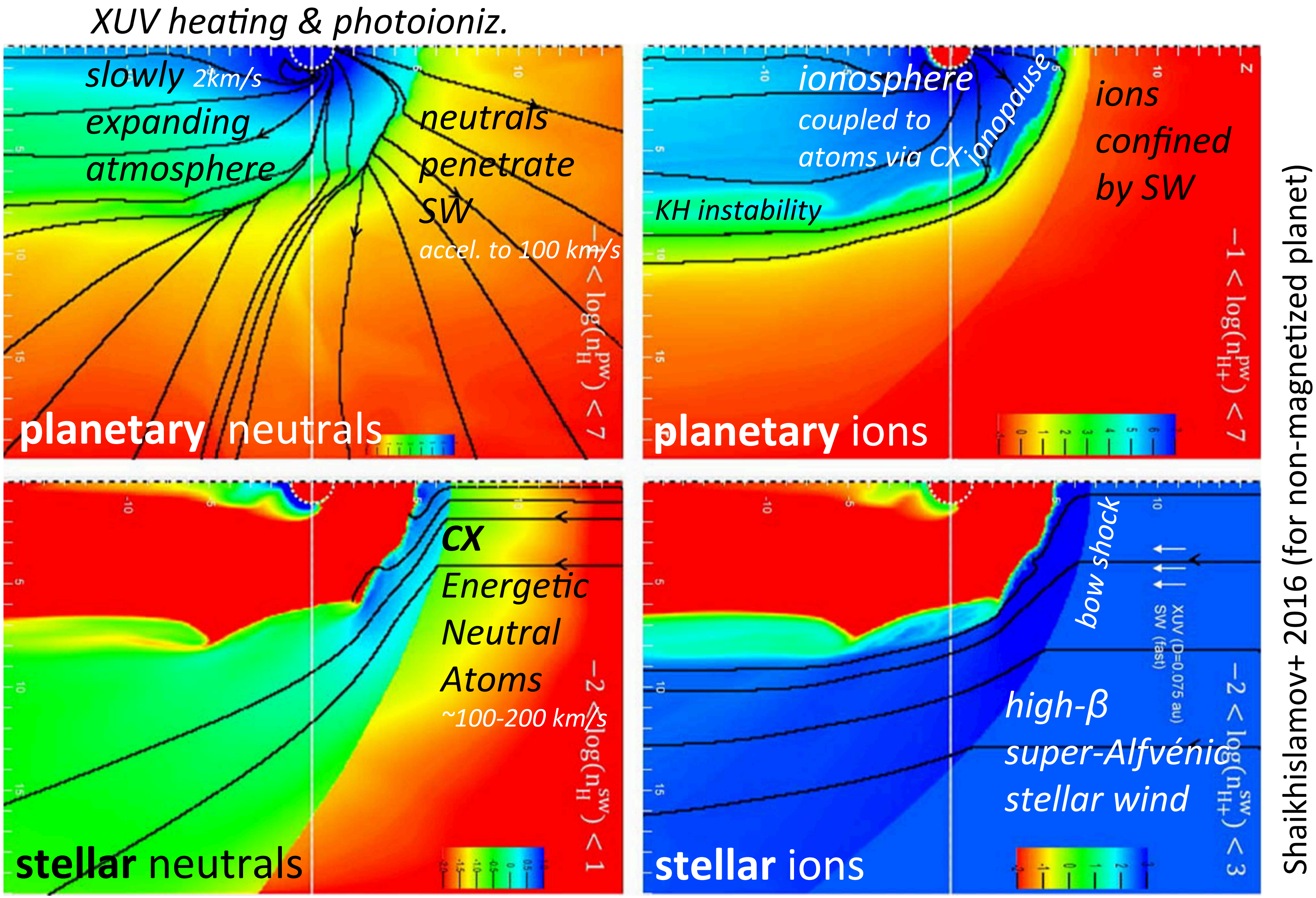


"Super-Earths" *can't lose captured - very dense! – envelopes at all!*

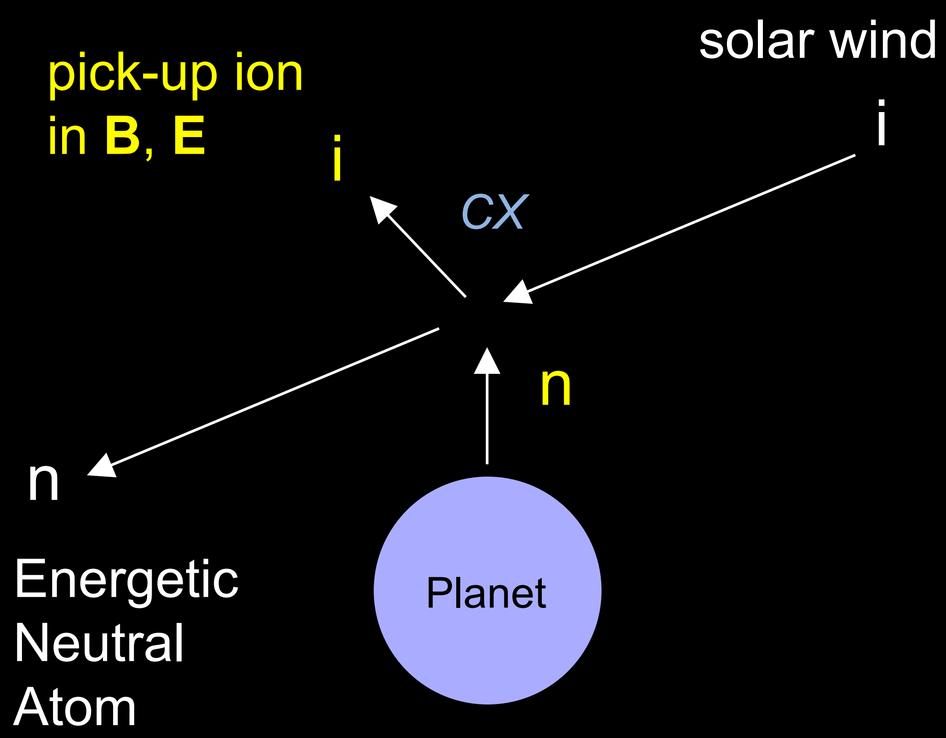
(Erkaev+ 2013 for entire MS)

Planetary Wind Processed by Stellar Wind and Radiation:

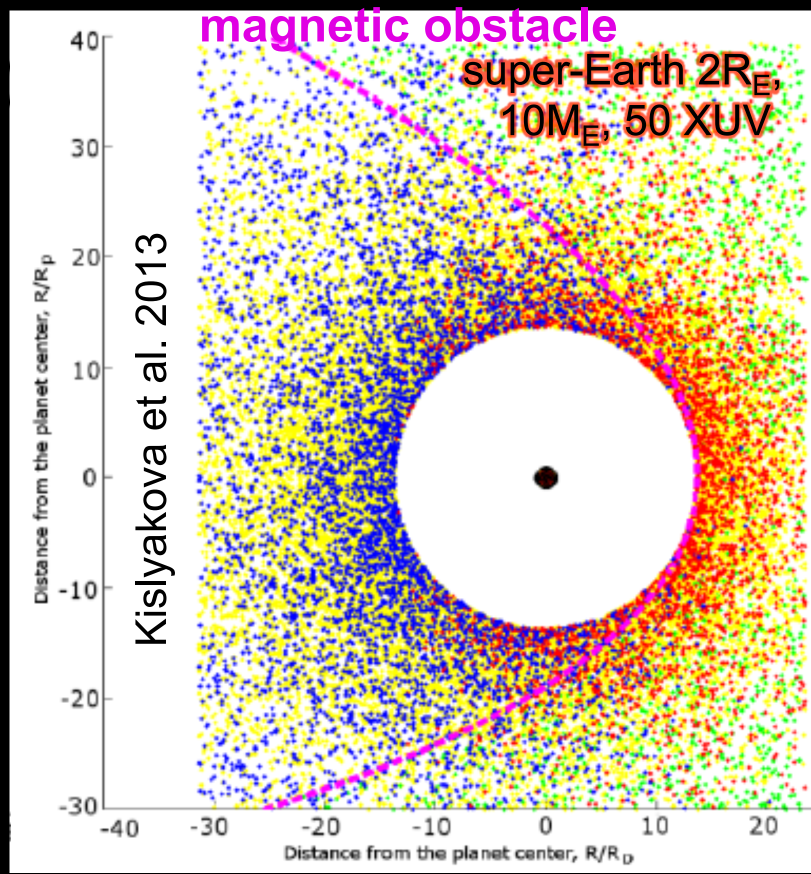
Heating, expansion, radiation pressure, charge exchange, ion pick-up



Ions Get Picked Up By Stellar Wind



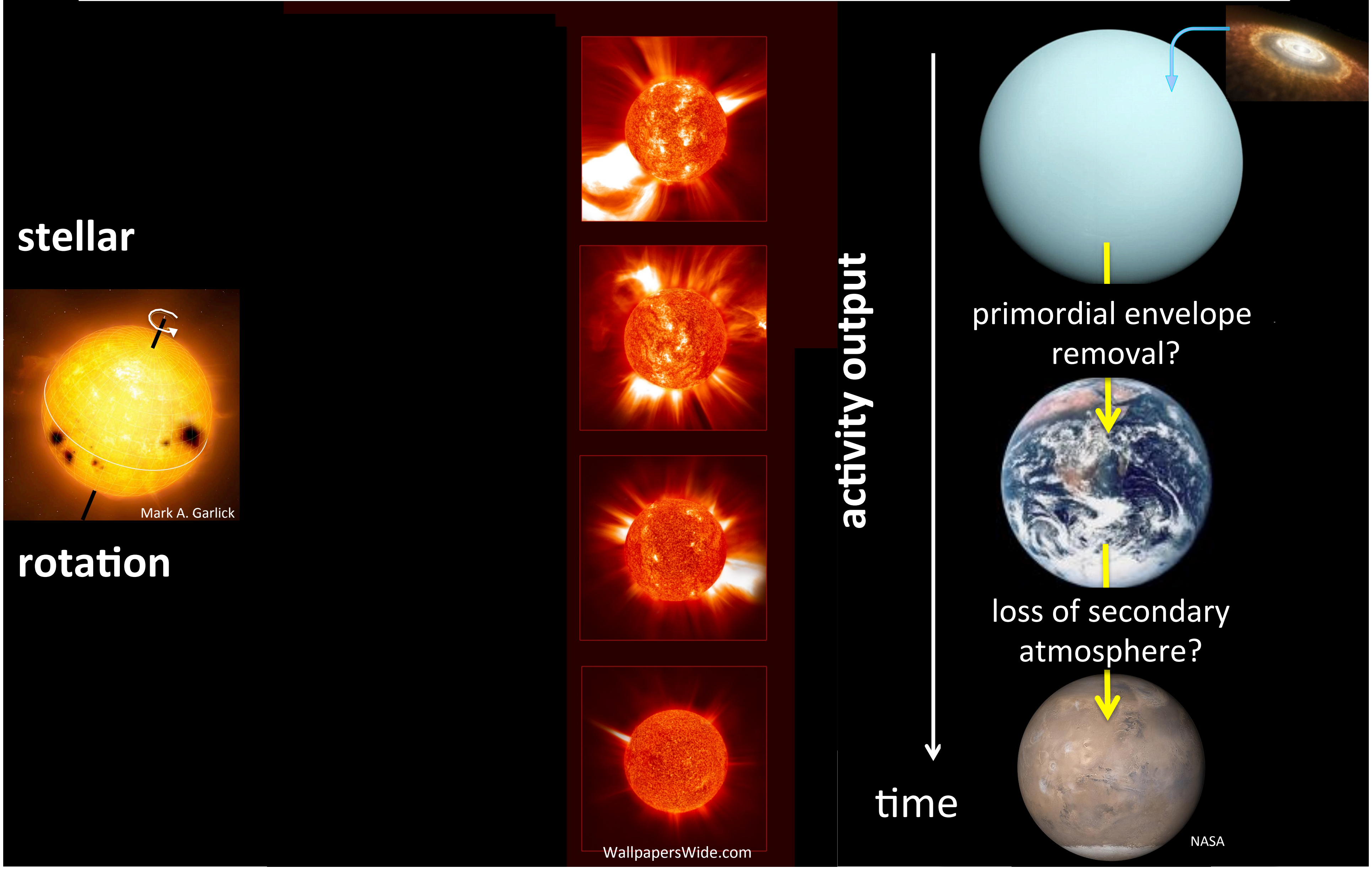
+photo- and impact ionization



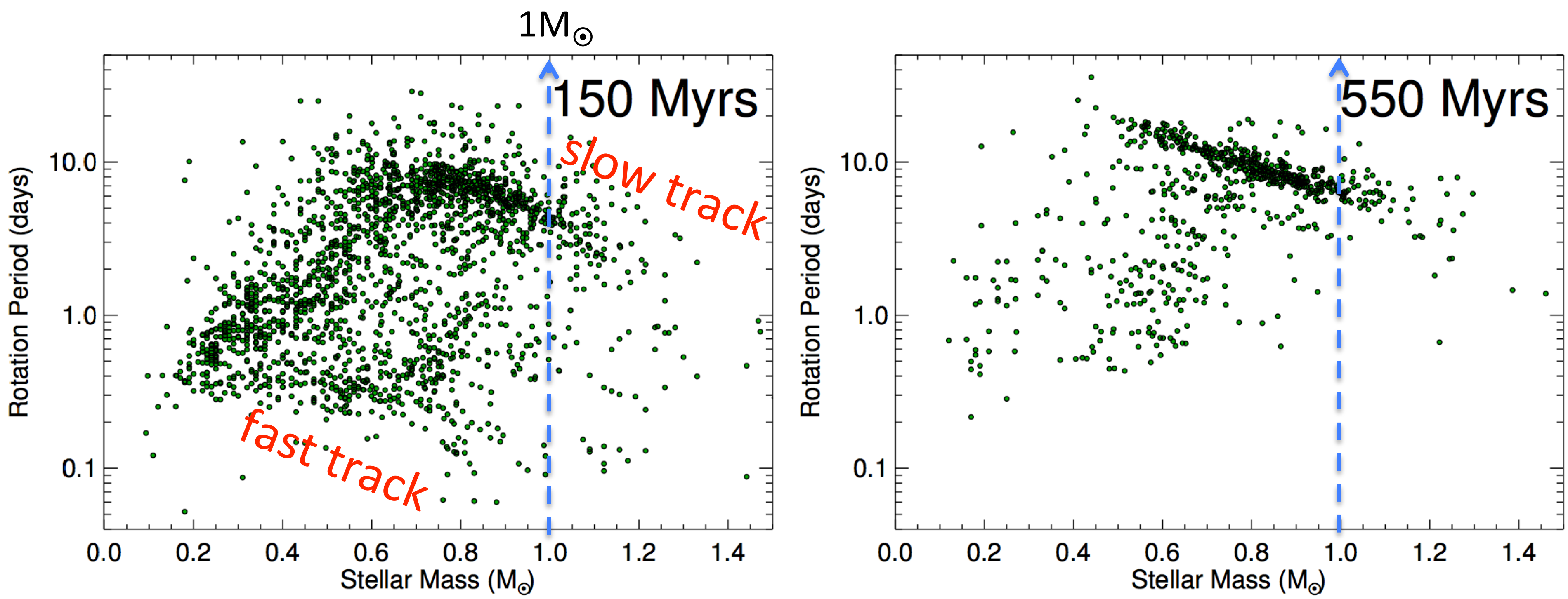
stellar wind protons planetary H atoms
ENAs moving away from / towards the star

- Massive H atmosphere in Habitable Zone around M dwarf, 1-100 x XUV:
- Ion pick-up by the stellar wind/CME wind ~10-30% of thermal escape
- Difficult to get rid of it! (~1-10 EO_H thermal for Earth in M dwarf HZ; Kislyakova+ 2013)

To understand a planet and its habitability, the entire evolution of the stellar/planetary environment must be known!

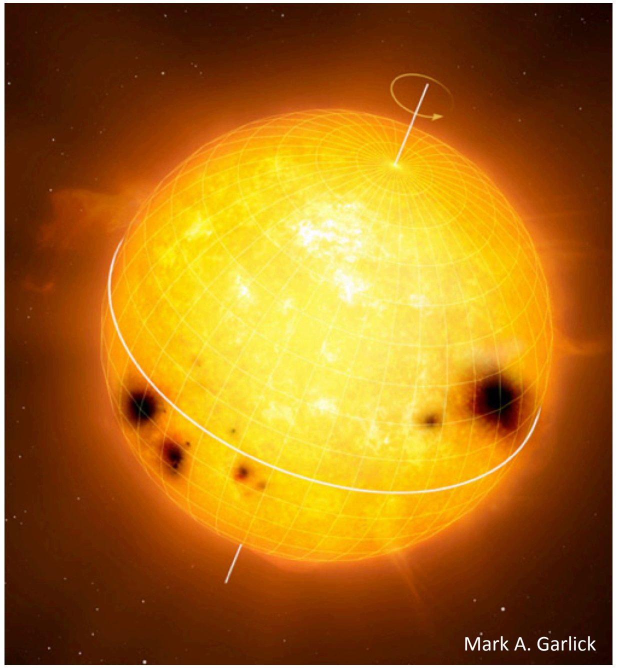


Mass Loss and Rotation: Introducing Rotational Distributions



(Johnstone, Güdel+ 2015; see also Gallet & Bouvier 2013)

Stellar Rotational Evolution: Torques in Magnetized Wind



Plan of attack:

1 Rotation rate Ω*(age)*: from observations of clusters

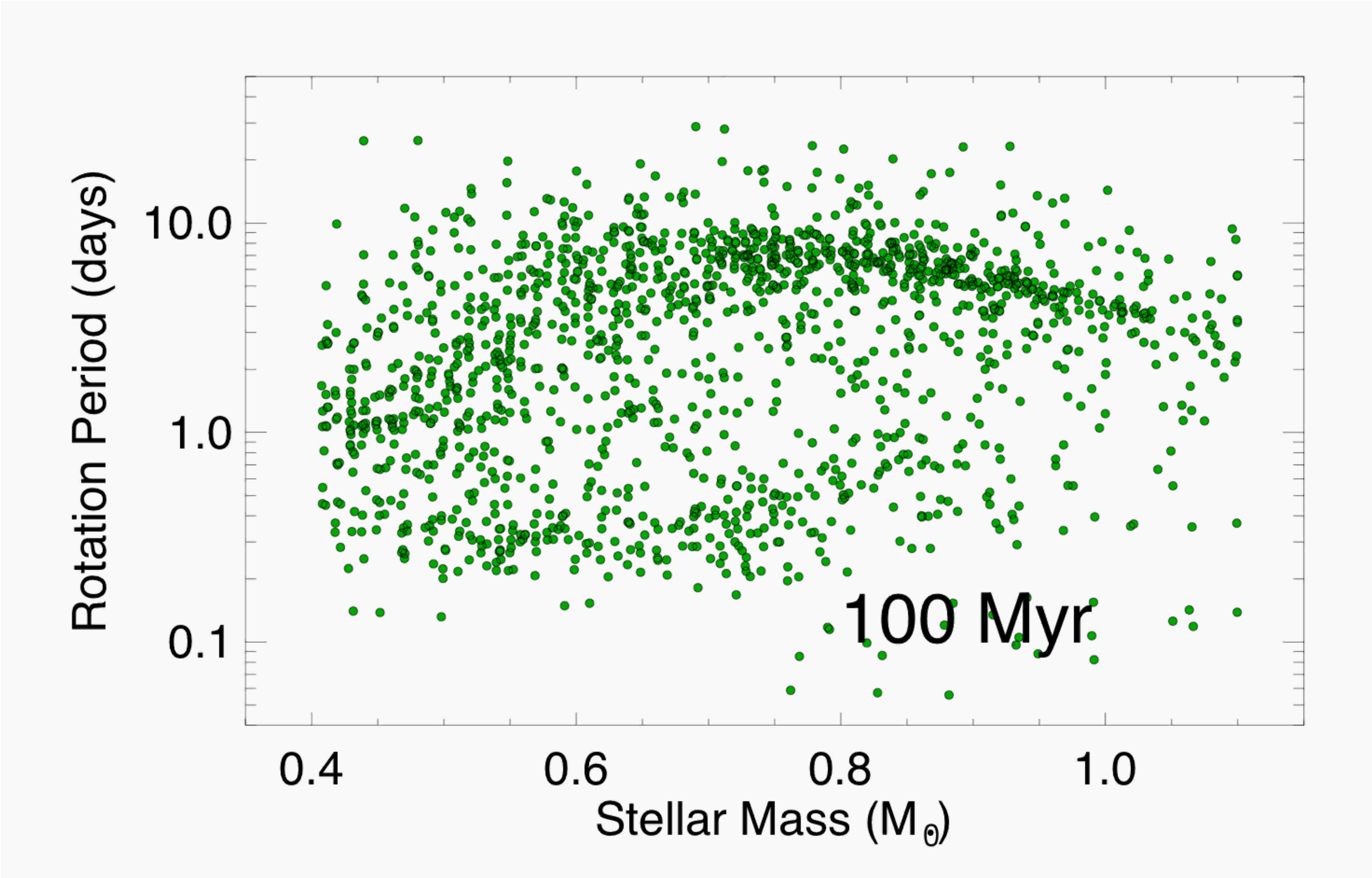
2 spin-down rate $d\Omega/dt$ = torque/moment of inertia

3 torque = $f(B, \dot{M}, \Omega)$ from hydro simulations

4 $B = f(\Omega)$ (dipole) from observations

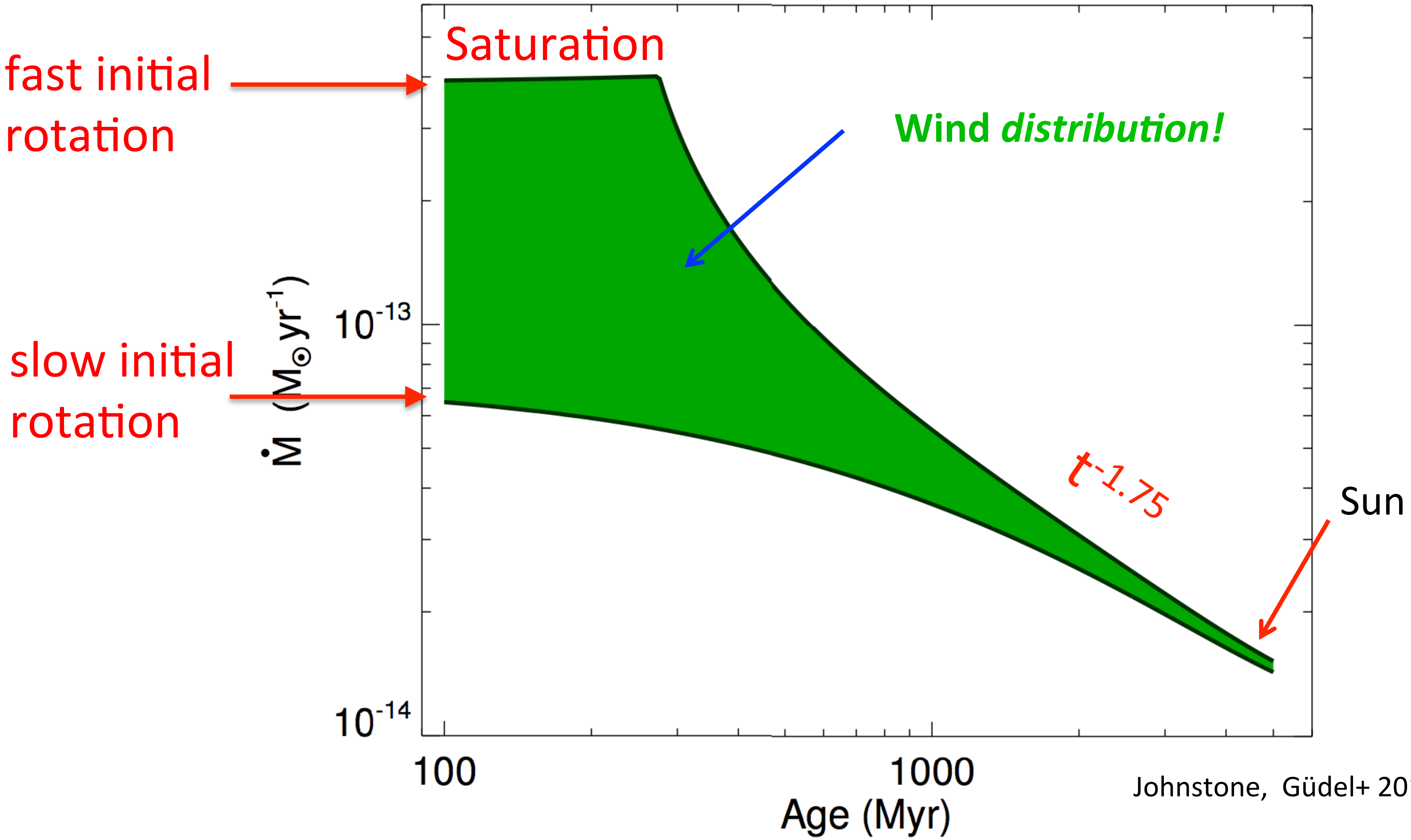
5 $\dot{M} = f(\Omega)$ Mass loss rate

(Johnstone, Güdel+ 2015)



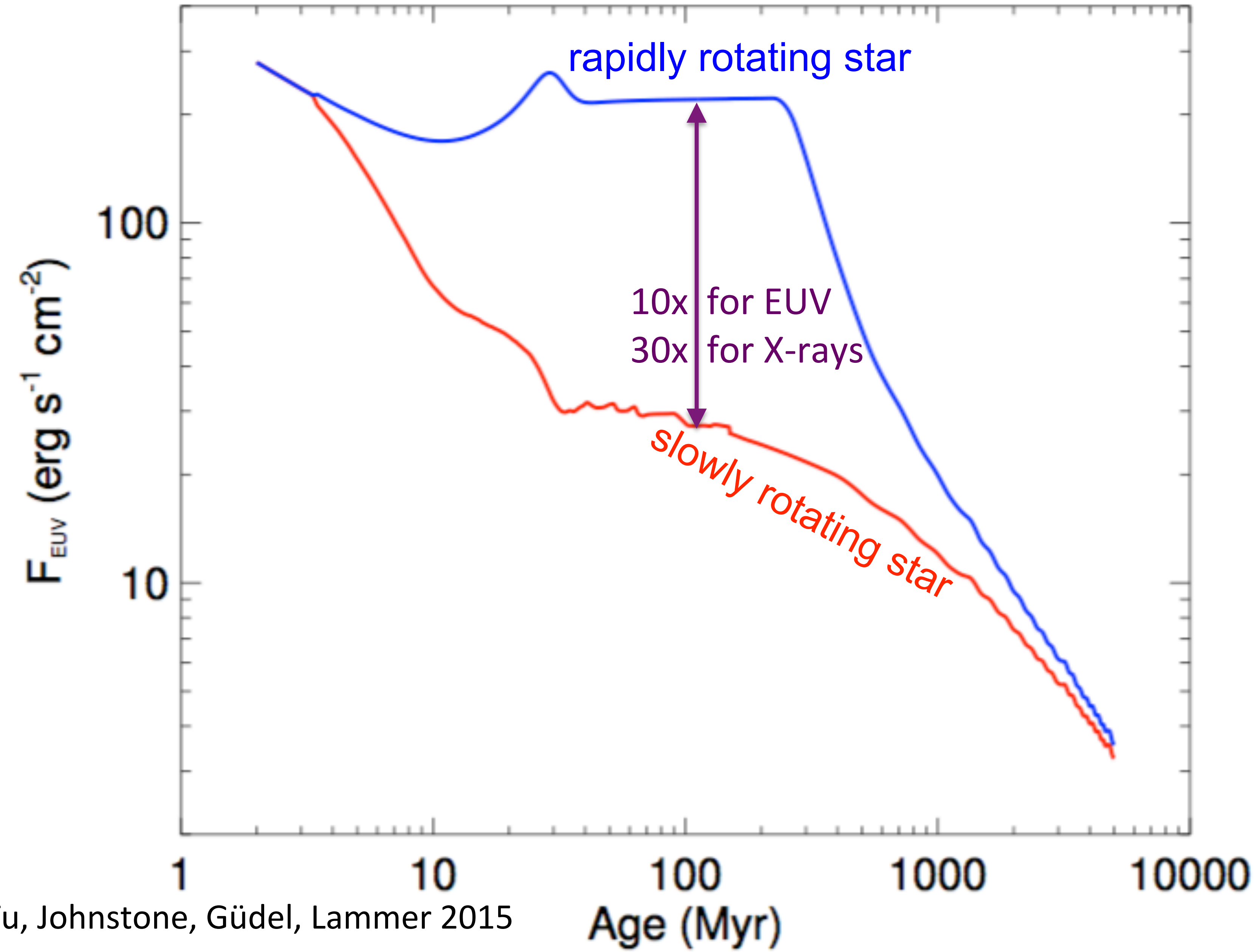
Johnstone, Güdel+ 2015

The 'Solar' Wind in Time ($1M_\odot$) – Non-Unique!



Johnstone, Güdel+ 2015

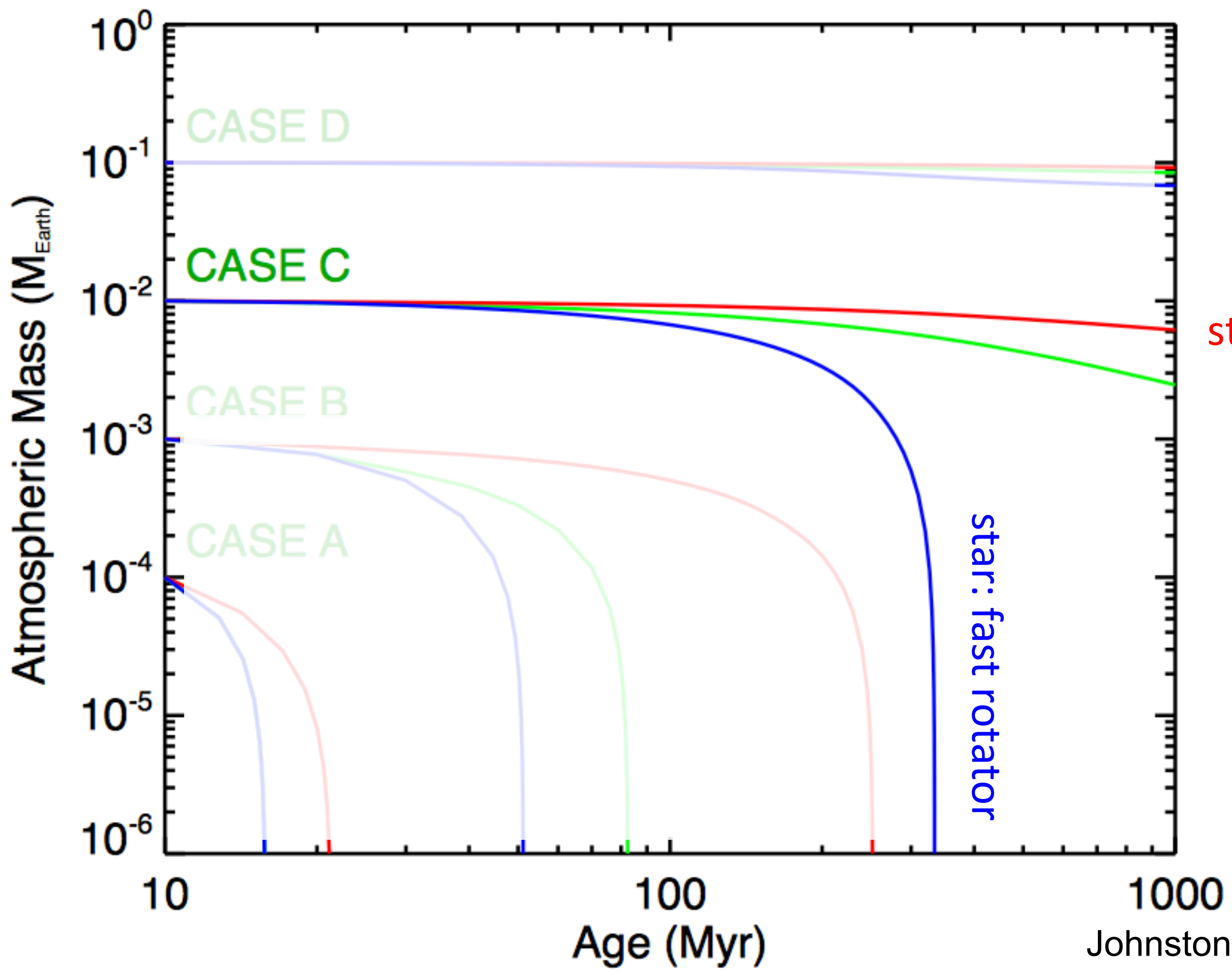
The High-Energy Sun in Time



Tu, Johnstone, Güdel, Lammer 2015

Thermal Escape for H/He protoatmospheres:

atmospheric evolution depends strongly on
initial atmospheric mass and *initial stellar rotation!*



$1M_E$
planet

Johnstone, Güdel et al. 2015c

Stellar Winds from Exoplanet Lyα Observations

Hot Jupiter HD 209458b in transit:
8.9±2.1 % excess blue/red Lyα absorption

(Vidal-Madjar et al. 2003, Ben-Jaffel 2007;
HD 209458: 1.15$M_\odot$, 4±2 Gyr)

Model: H envelope escaping due to

- Lyα radiation pressure
- line broadening due to v distribution
- photo- and e^- impact ionization
- exospheric energetic charge-exchange H

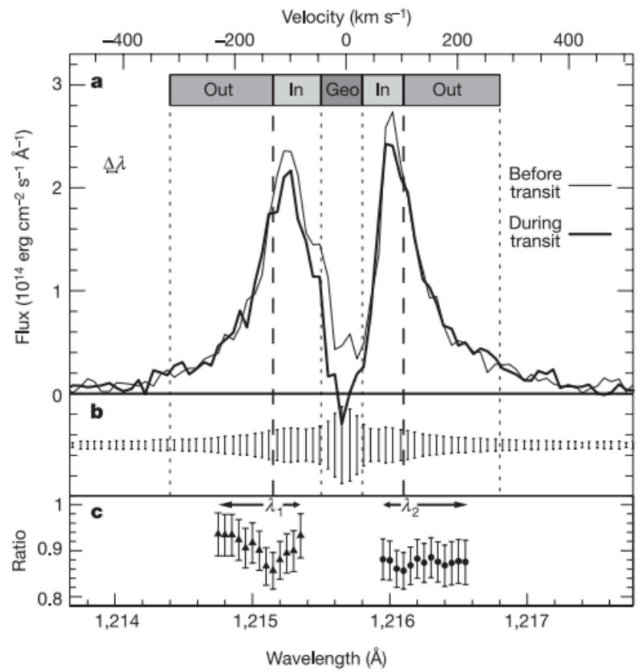
(*not* thermal evaporation!)

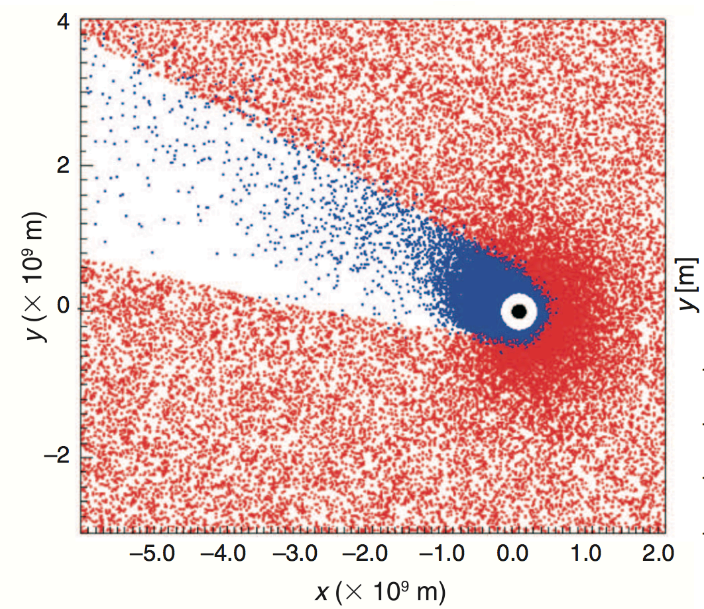
Best-fit energetic H @ 0.047 AU:

v_{wind}=400 km s^{-1}, n=5x10^3 cm^{-3} , T=1.1x10^6 K

and: *planetary magnetic moment ~0.1 M_{jup}!*

Kislyakova et al. 2014

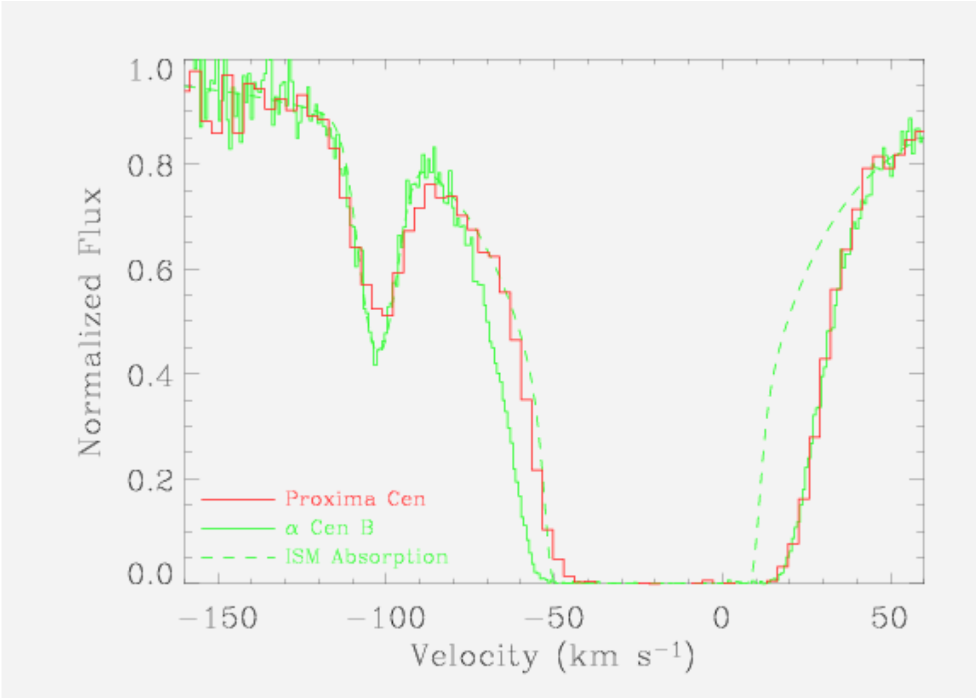


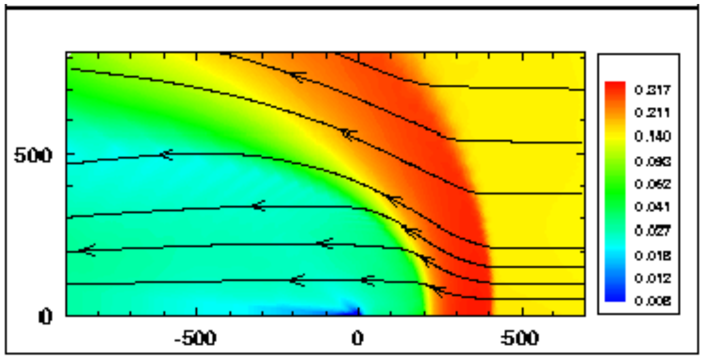


Stellar Ionized Winds: Indirect Evidence

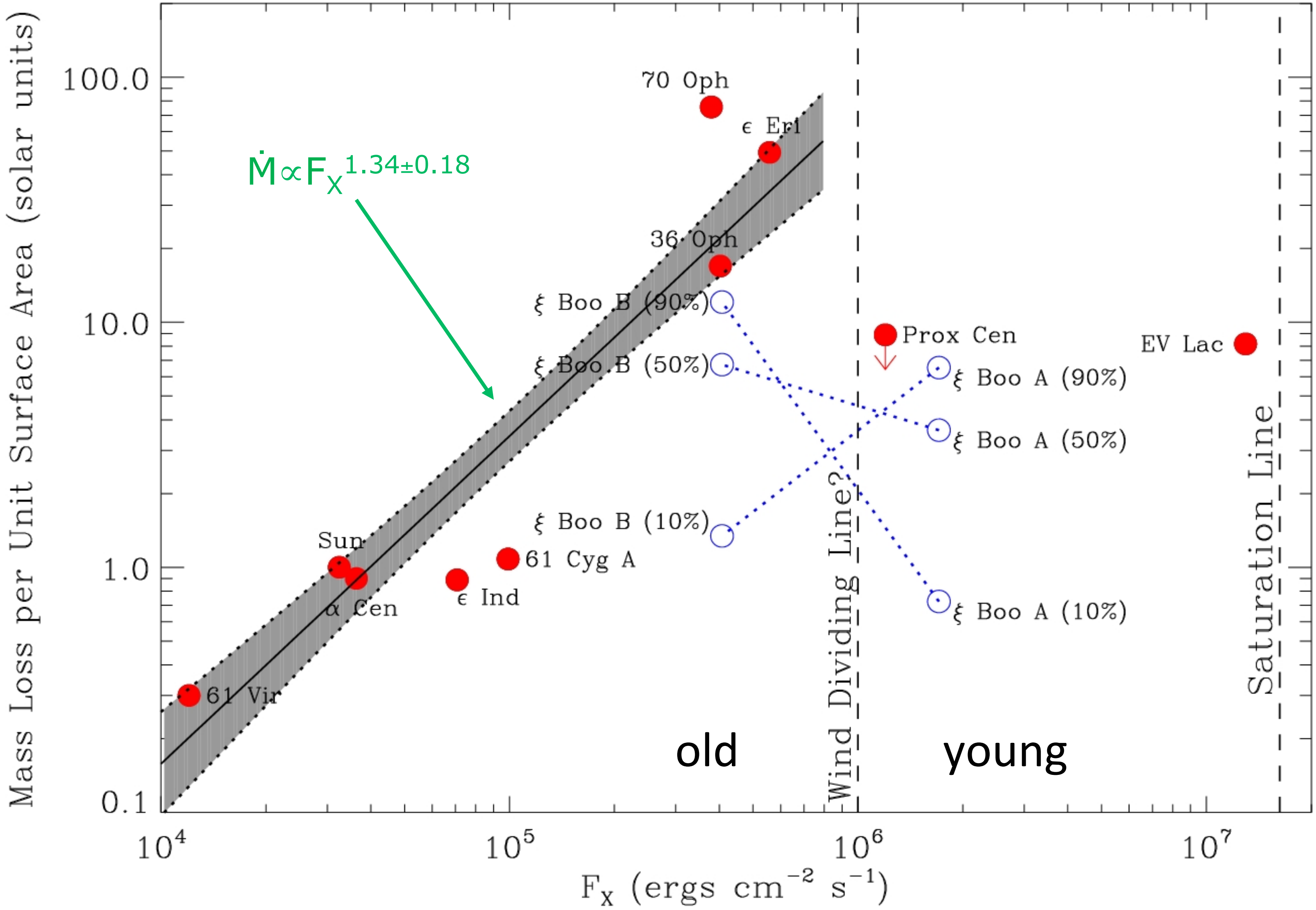
- Wind-ISM collision: astrospheric H walls
- Observation of Lyα absorption (HST)
- Hydrodynamic modeling: absorption ⇔ mass loss

(Wood et al. 2005)





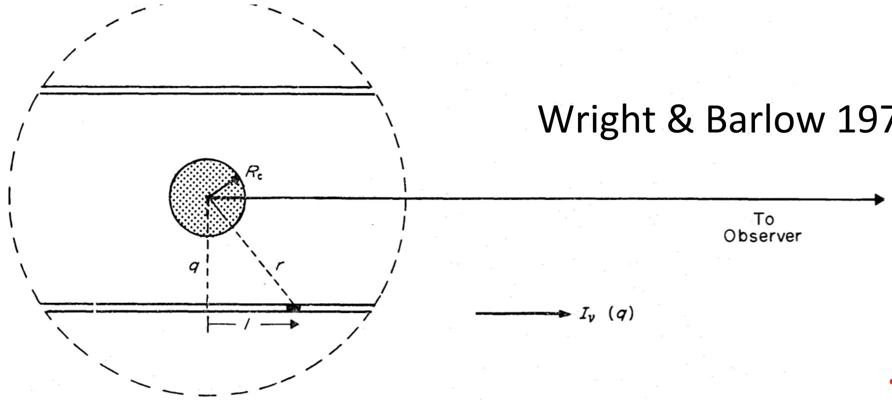
Semiempirical mass-loss estimates



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

Ionized Stellar Winds from Radio Bremsstrahlung

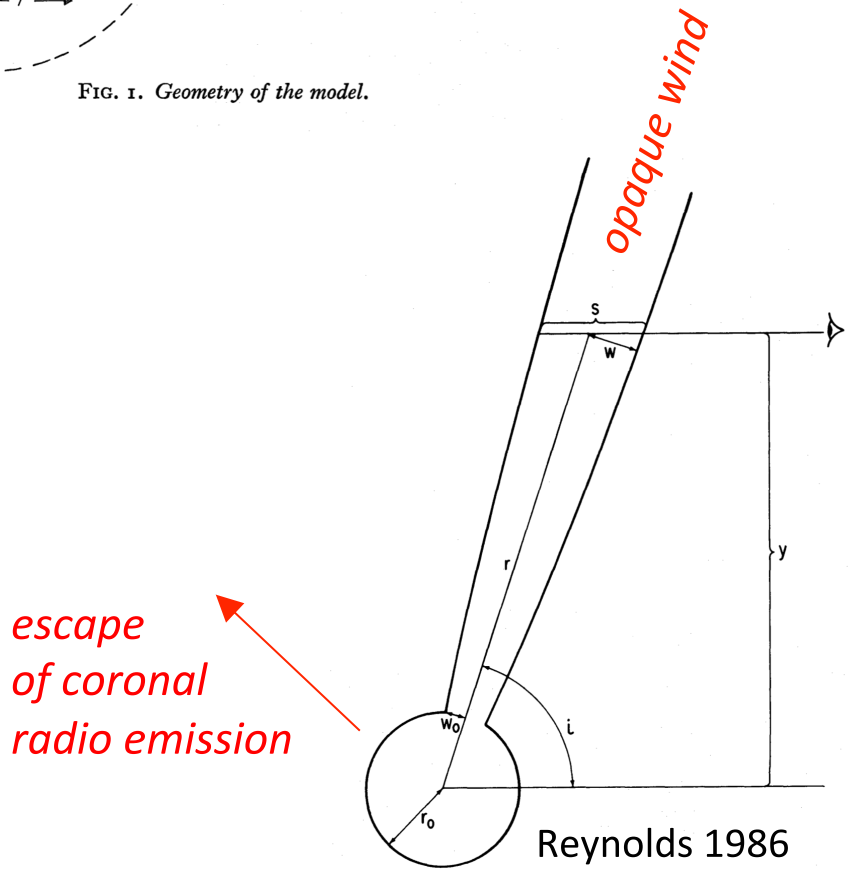
Radiative transfer for
spherical wind:



Wright & Barlow 1975

FIG. 1. *Geometry of the model.*

Polar outflows:
same wind mass loss rate
→ higher *density*
→ more radio emission



Reynolds 1986

Flux density (if optically thick):

spherical:

$$S_\nu = 8.3 \times 10^{-4}\ \text{mJy} \left(\frac{\dot{M}}{10^{-10} M_\odot/\text{yr}}\right)^{4/3} \left(\frac{v}{400\ \text{km/s}}\right)^{-4/3} \left(\frac{T}{10^6\ \text{K}}\right)^{0.1} \left(\frac{d}{10\ \text{pc}}\right)^{-2} \nu_{\text{GHz}}^{0.6}$$

polar:

$$S = 5.1 \times 10^{11} \left(\frac{\dot{M}}{v}\right)^{4/3} \frac{T^{0.1}}{\theta d^2} (\sin i)^{1/3} \nu^{0.6} \quad [\text{mJy}]$$

Optically thick radius:

spherical:

$$R_{\text{thick}} = 3.2 \times 10^{11}\ \text{cm} \left(\frac{\dot{M}}{10^{-10} M_\odot/\text{yr}}\right)^{2/3} \left(\frac{v}{400\ \text{km/s}}\right)^{-2/3} \left(\frac{T}{10^6\ \text{K}}\right)^{-0.45} \nu_{\text{GHz}}^{-0.7}$$

New JVLA campaign on solar analogs

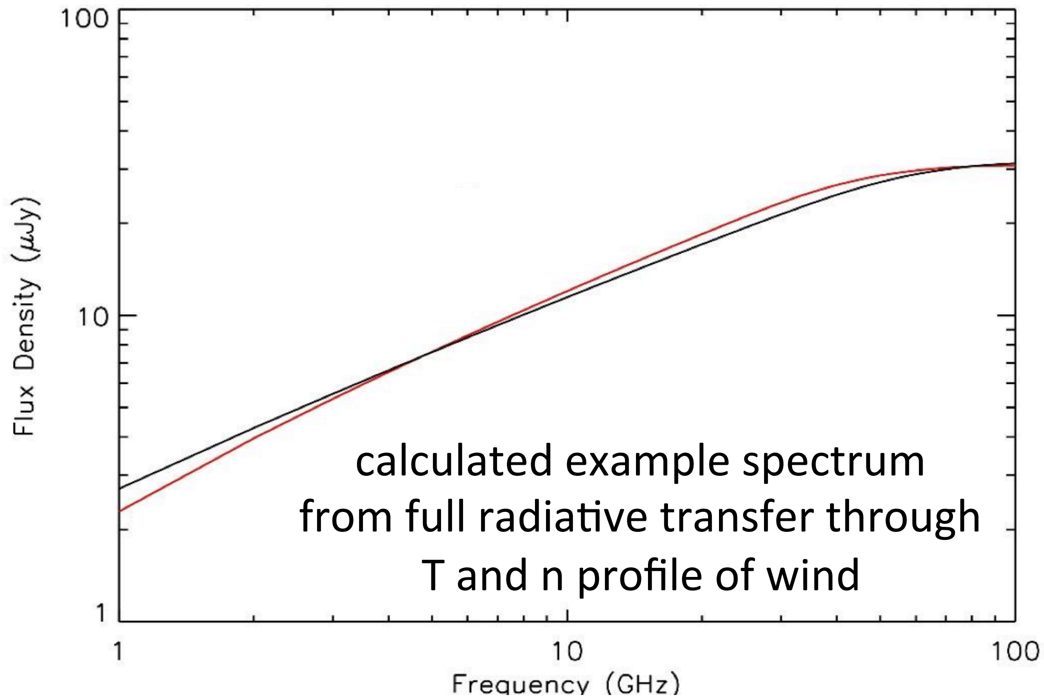
(Fichtinger et al. 2017)

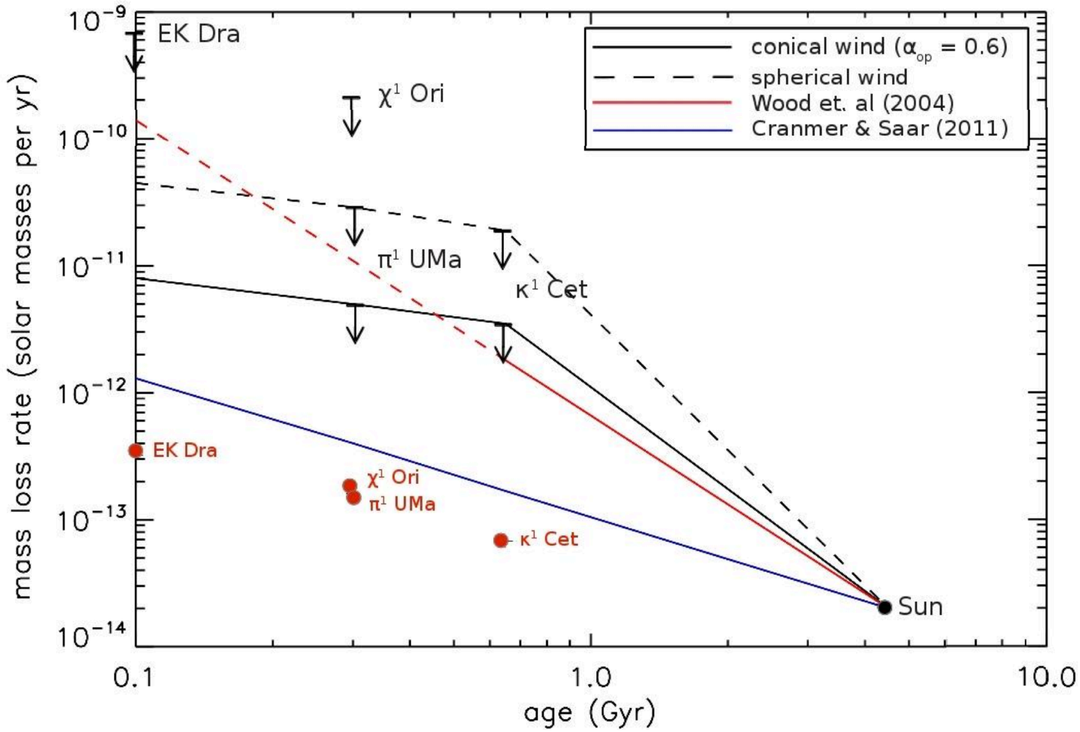
Maximum mass of ZAMS Sun:

1.02$M_\odot$ for spherical wind

Sun still too faint to solve "Faint Young Sun Paradox"

(require 1.03-1.07$M_\odot$, Sackmann & Bootroyd 2003





An estimate for T Tauri stars

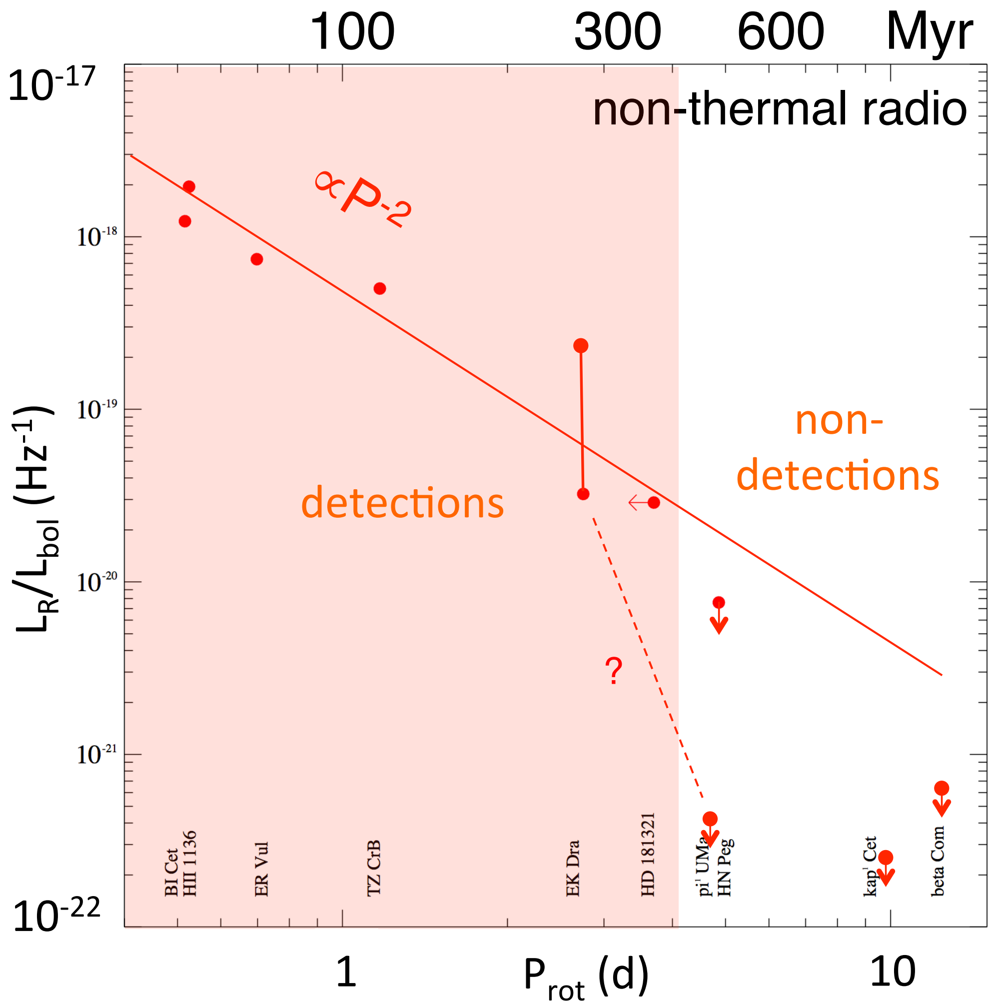
<u>*X-ray flares on T Tau stars in Orion, 1 Myr*</u> *(Feigelson et al. 2002):*

X-ray peak luminosity	1.5 dex	x largest solar flares
Flare frequency	2.5 dex	x largest solar flares
Non-linearity X vs. protons	1.0 dex	for 2 dex in X ampl.
time averaged:	**10^5 times higher <u>proton</u> flux**	
radio observations:	**10^5 times more coronal <u>electrons</u>** *(Güdel +...)*	

- *Overlapping events from many flares: near-continuous stream of 10^7 protons (>10 MeV)/cm^2/s @ 1AU*
- *Similar values for other saturated stars including ZAMS*

The Radio Sun in Time

Solar analogs:



Güdel et al. 1998
Fichtinger et al. 2017

High production rate of accelerated particles in young Sun;
but *very rapid decay* with time

What Could be Expected from Radio Emission? (Vidotto et al. 2017)

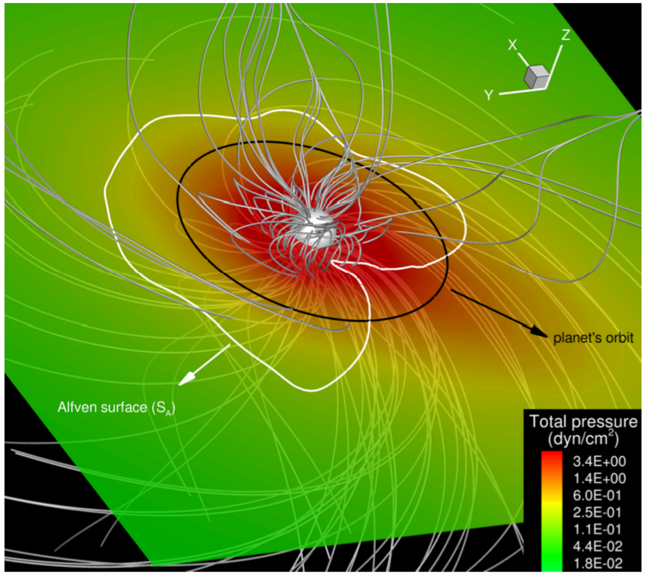
- V830 Tau b: 2 Myr hot Jupiter, 0.77 M_{jup} ,0.057 au
- MHD wind simulations using stellar magnetic map
- Wind: base $T=10^6$ K, $n=10^{12}$ cm^{-3}, $\dot{M}=3x10^{-9}$ $M_\odot$ yr^{-1}

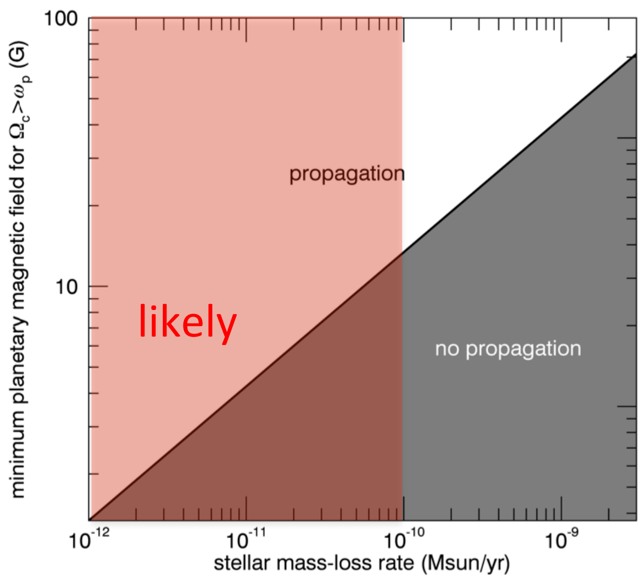
Radio power ∝ magnetic (and kinetic) energy flux
hitting planetary magnetosphere

Stellar wind radio < 0.1 mJy for ν < 6 GHz
With Bower et al. (2016): $\dot{M} <$ $3x10^{-9}$ $M_\odot$ yr^{-1}

Planetary radio: 1-12 mJy @ 4-40 MHz, B_p=1.3-13 G
for wave propagation above plasma frequency

Planet marginally outside optically thick wind region





Summary

- Early phases of planet evolution subject to (for G star)

5-30	x wind mass loss rate
10-100	x EUV
30-1000	x X-rays
up to 10^5	x high-energy particles

but evolution is *non-unique* in first few 100 Myr for a G star.

- Radio astronomy promising for detecting winds, CMEs, and high-energy particles in planetary magnetospheres.

END