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Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

STILES: the Impact of stellar XUV radiation on exoplanetary atmosphere evolution

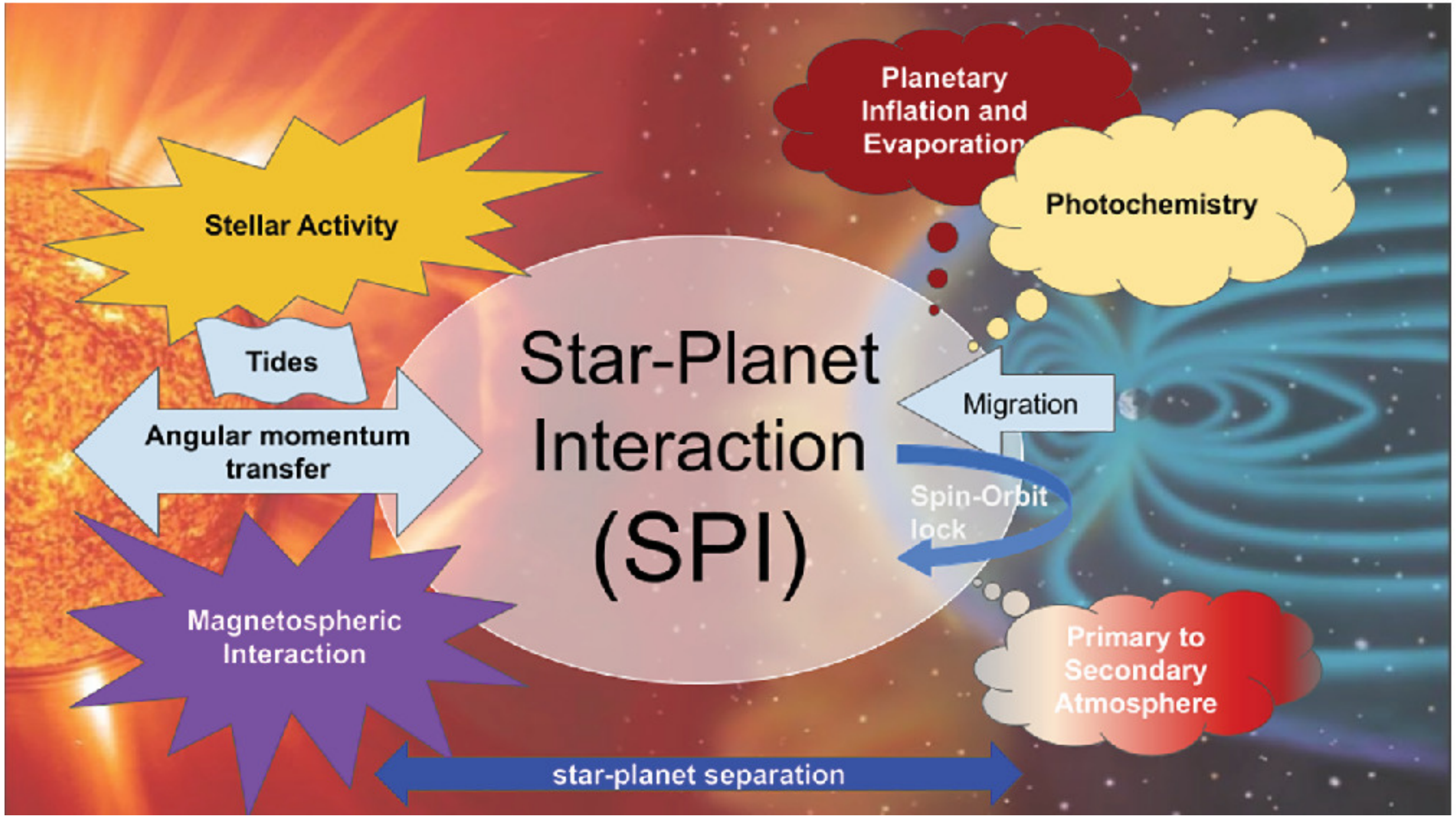
Daniele Locci[1]

Molecules and planets in the outer Galaxy: is there a boundary of the Galactic Habitable Zone? Workshop

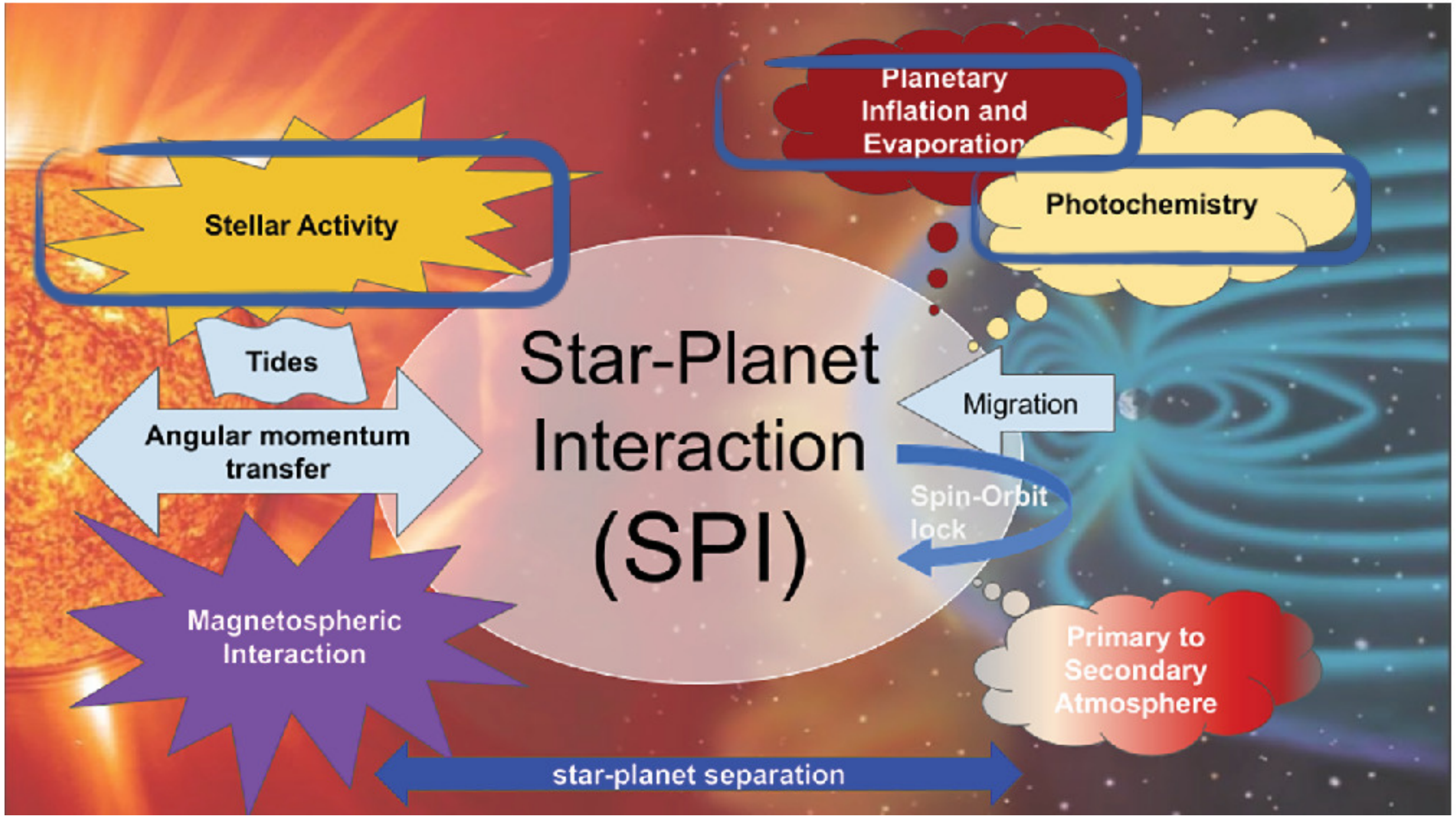
Florence, novembre 12-14, 2024

1 INAF-OAPa

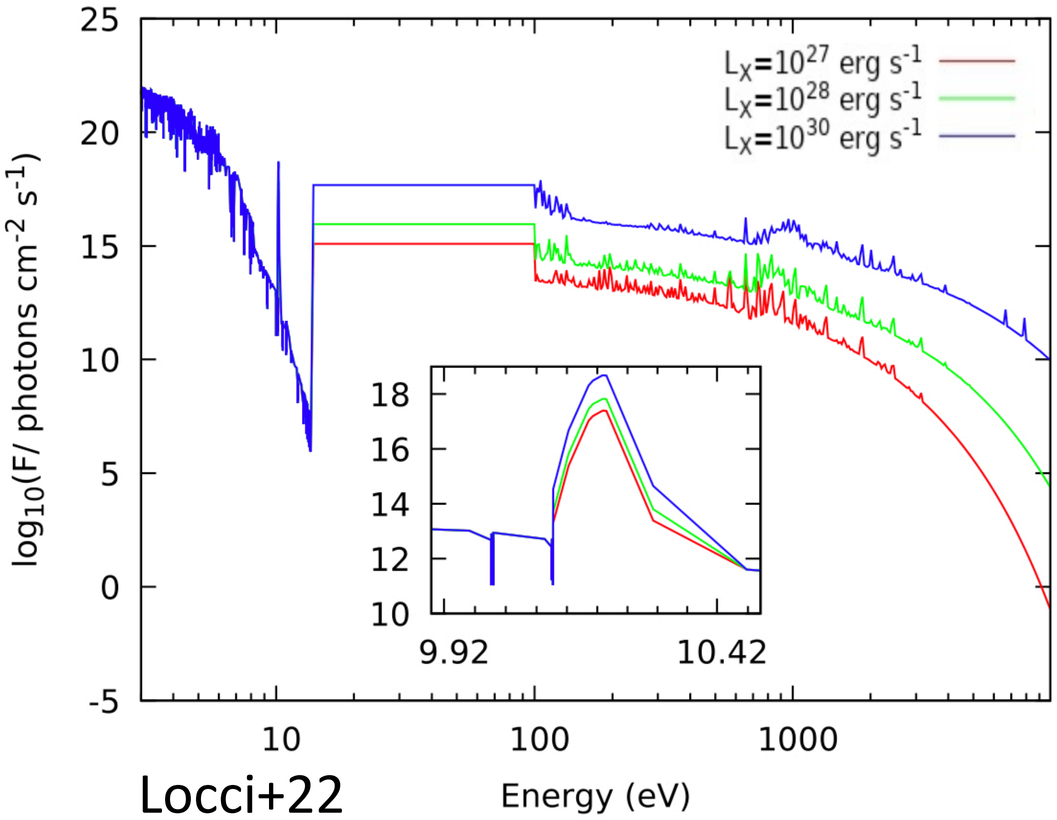
Introduction



Introduction



Photochemistry



Locci+22

UV (3 - 13.6 eV)

Stellar spectrum from Phoenix

Lyman-α from *Linsky+20*

EUV (13.6 - 100 eV)

Spectral constant shape

$$L_{EUV} = 10^{6.5} L_X^{0.8}$$

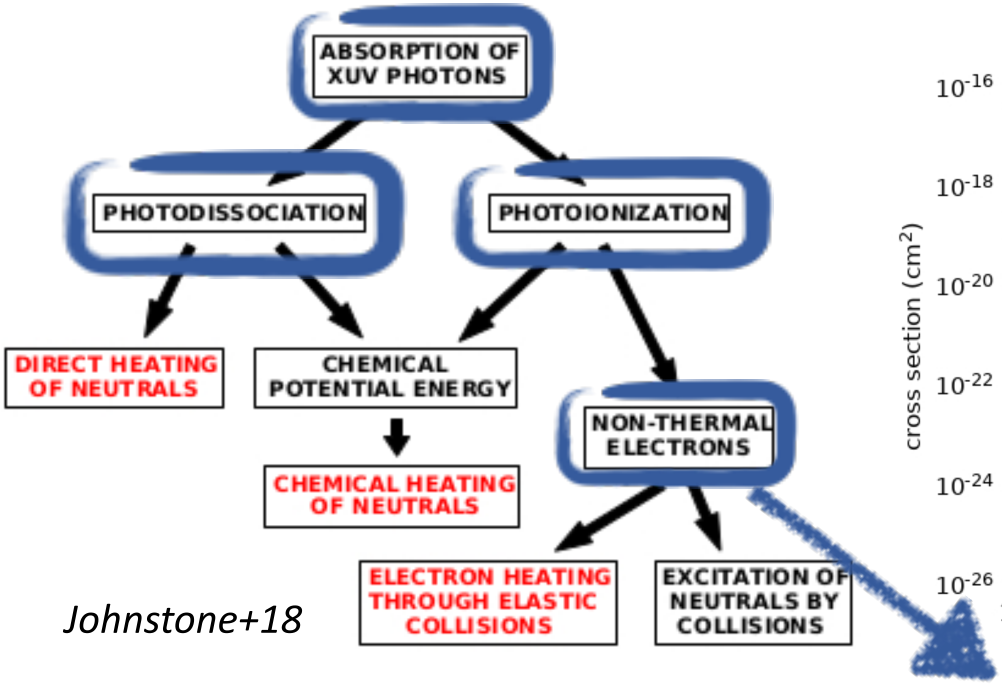
Sanz-Forcada+22

X-rays (0.1 - 10 keV)

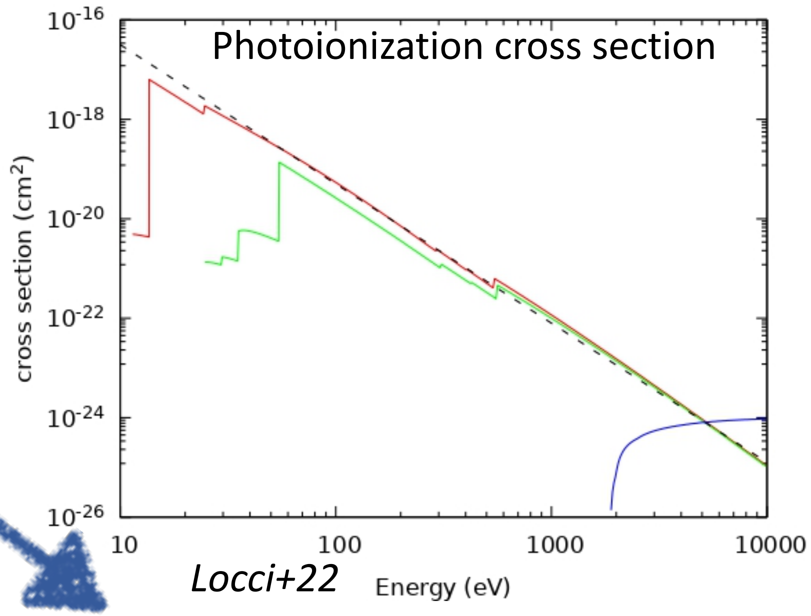
Emission from a optically thin plasma *Raymond & Smith+77*

L_x is an input parameter

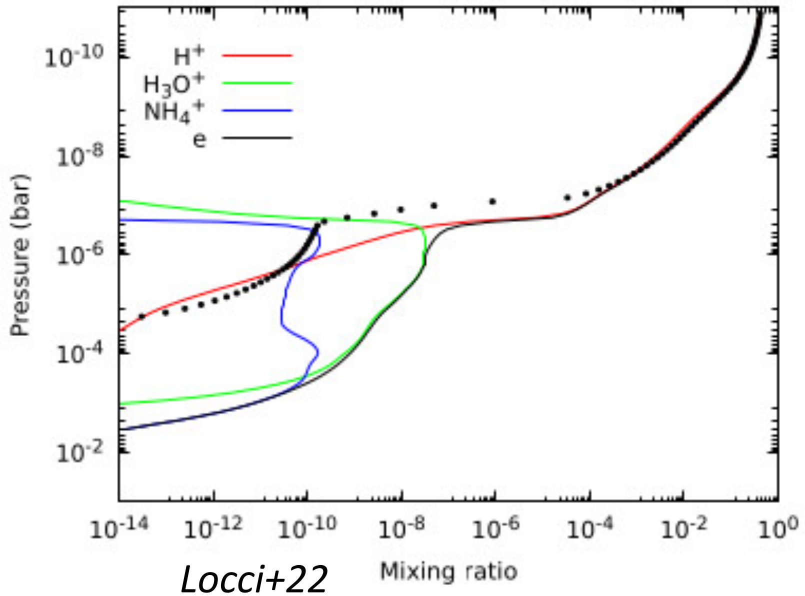
Photochemistry



Johnstone+18



Locci+22



Locci+22

Secondary ionization

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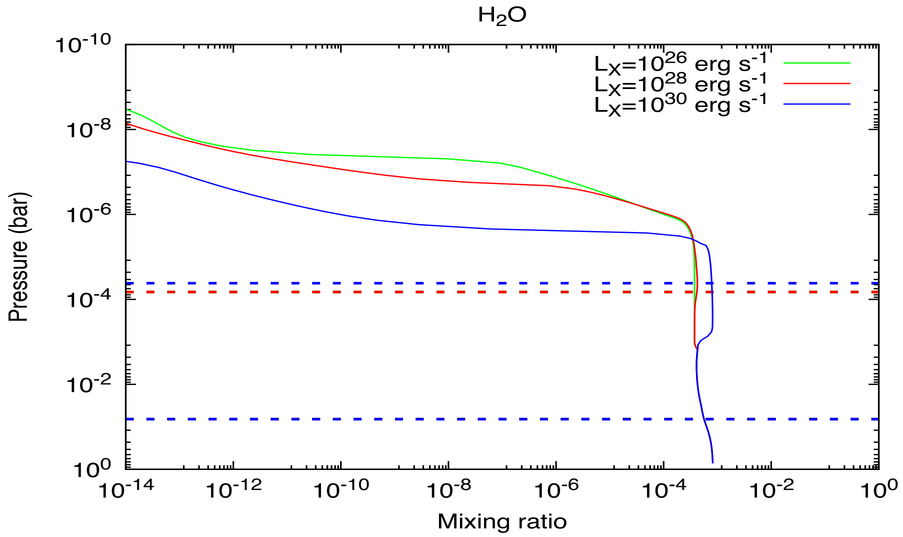
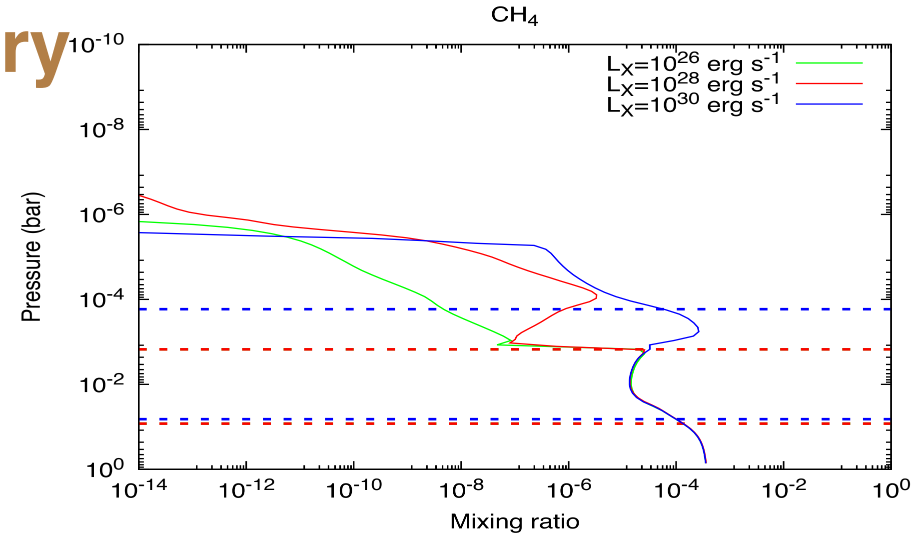
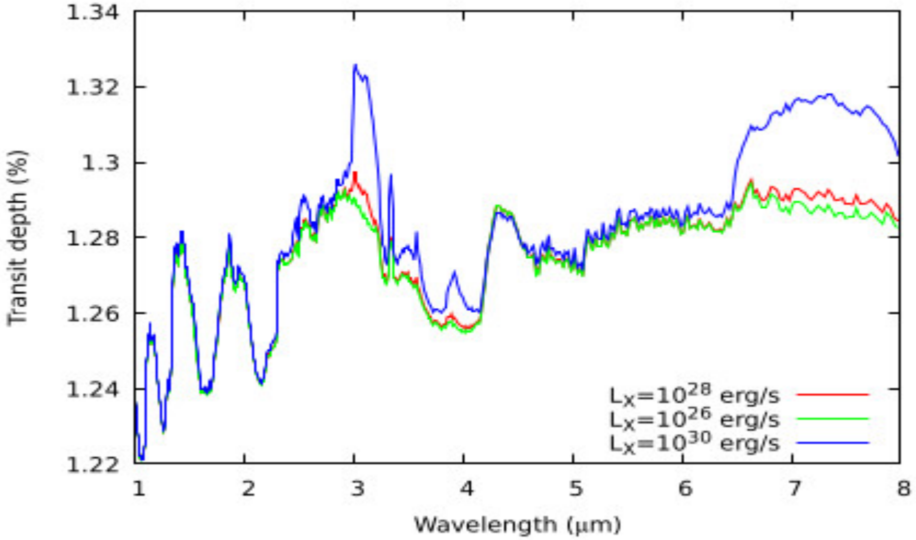
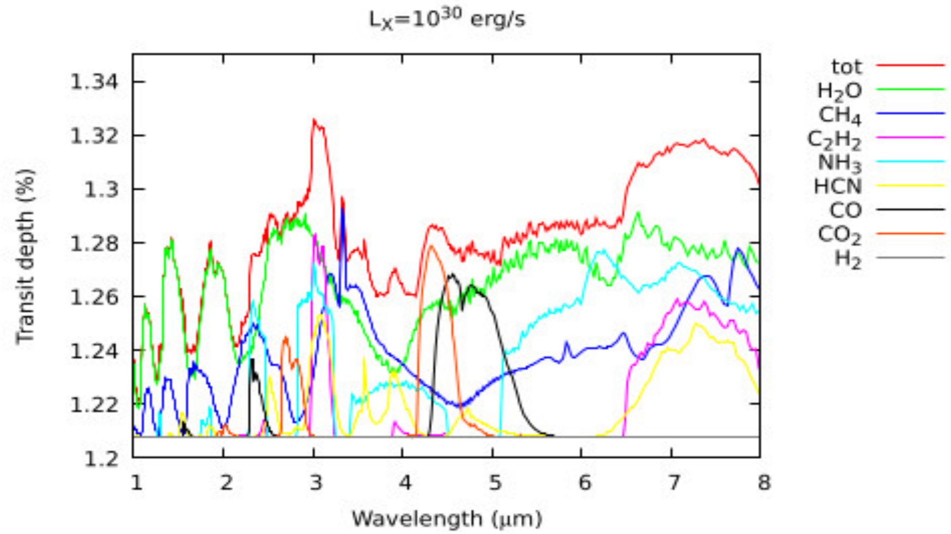
Photochemistry



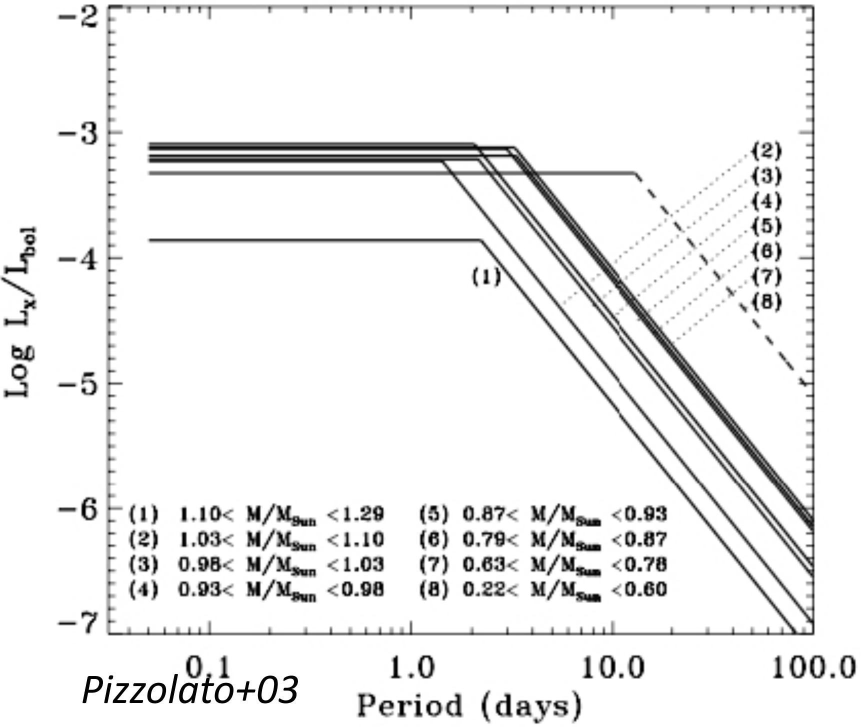




Locci+24



Activity temporal evolution

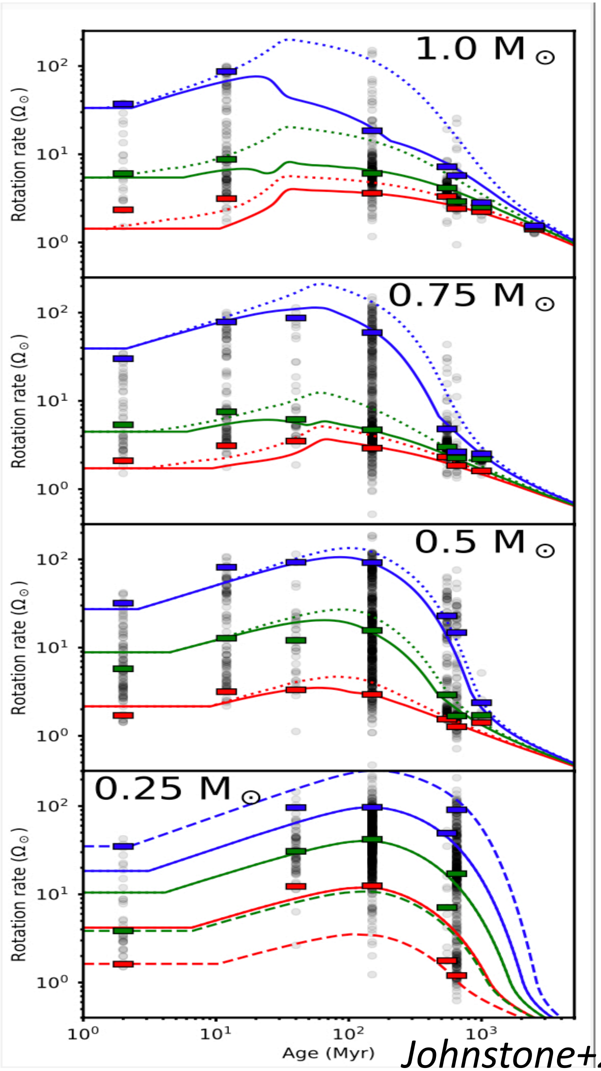


Pizzolato+03

$$L_X/L_{bol} \sim 10^{-3}$$

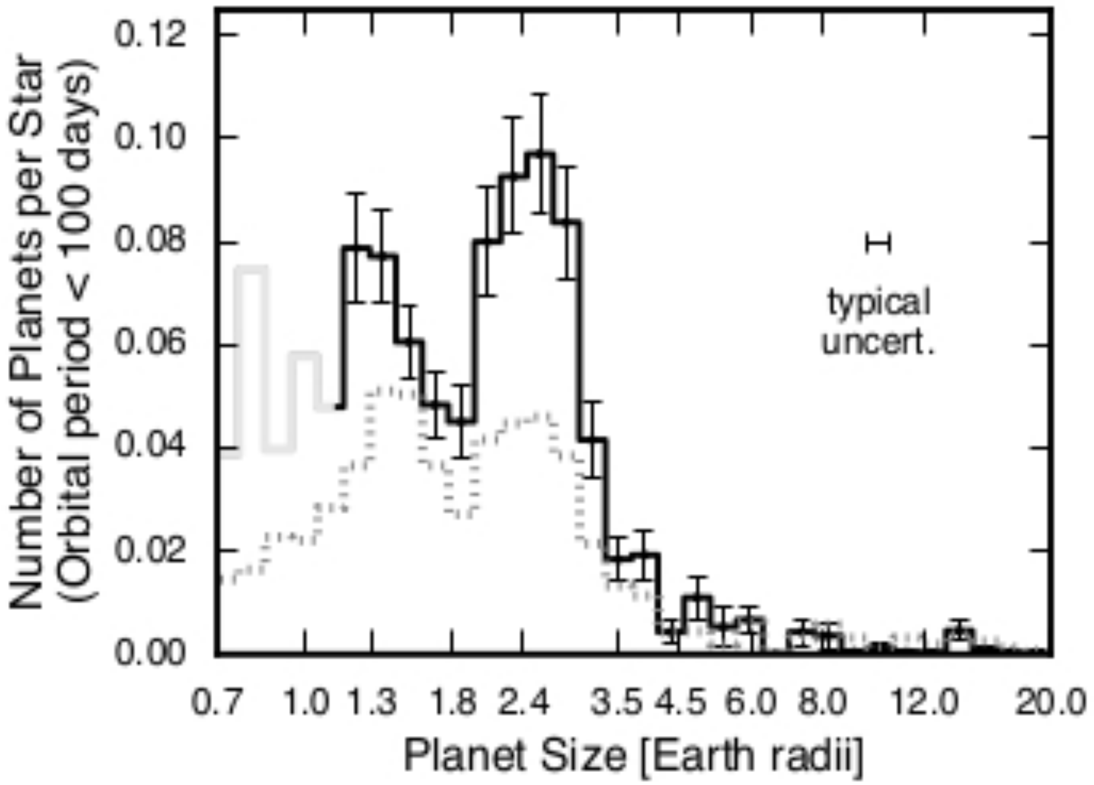
$$\Omega_{sat} \propto M_\star Age_\star$$

With the same received bolometric flux, a planet orbiting a less massive star receives a larger integrated XUV flux.

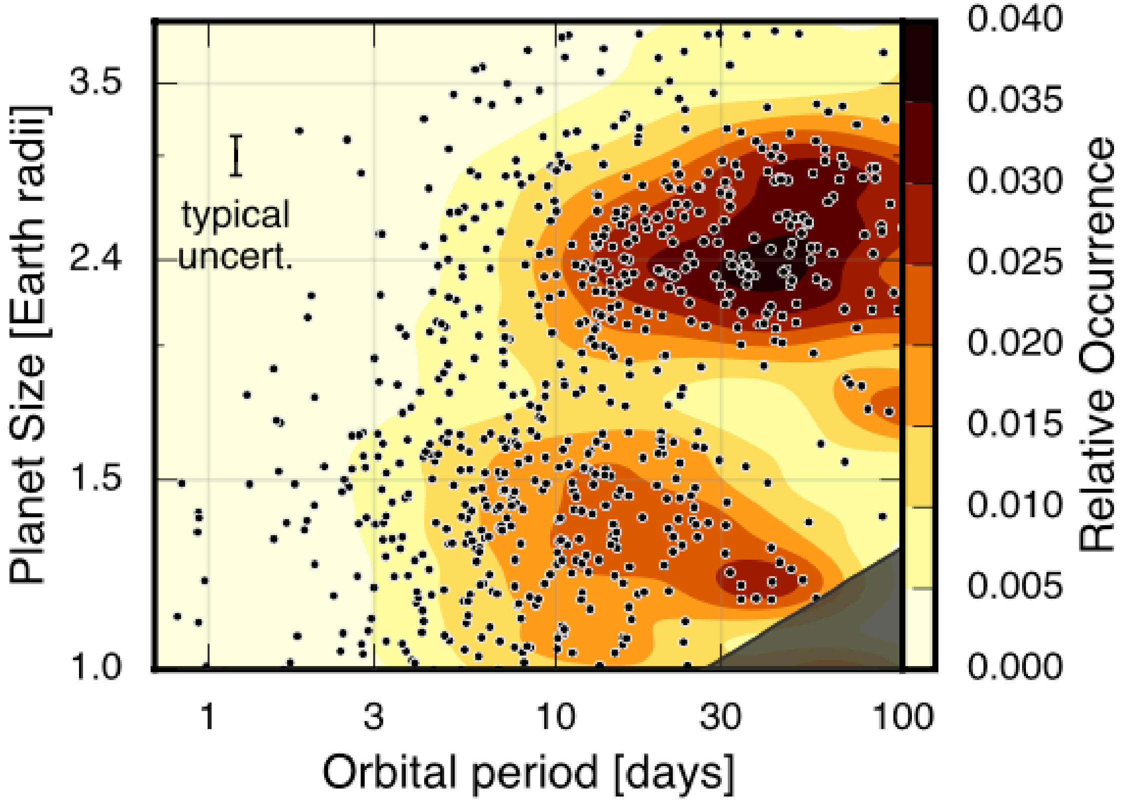


Johnstone+22

Bimodal distribution

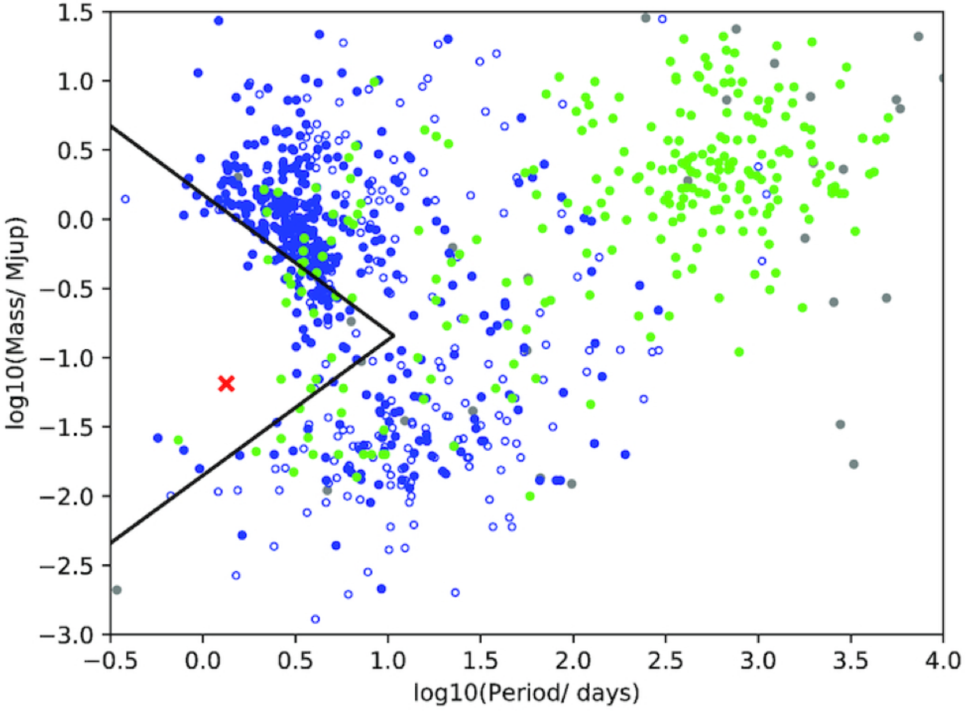


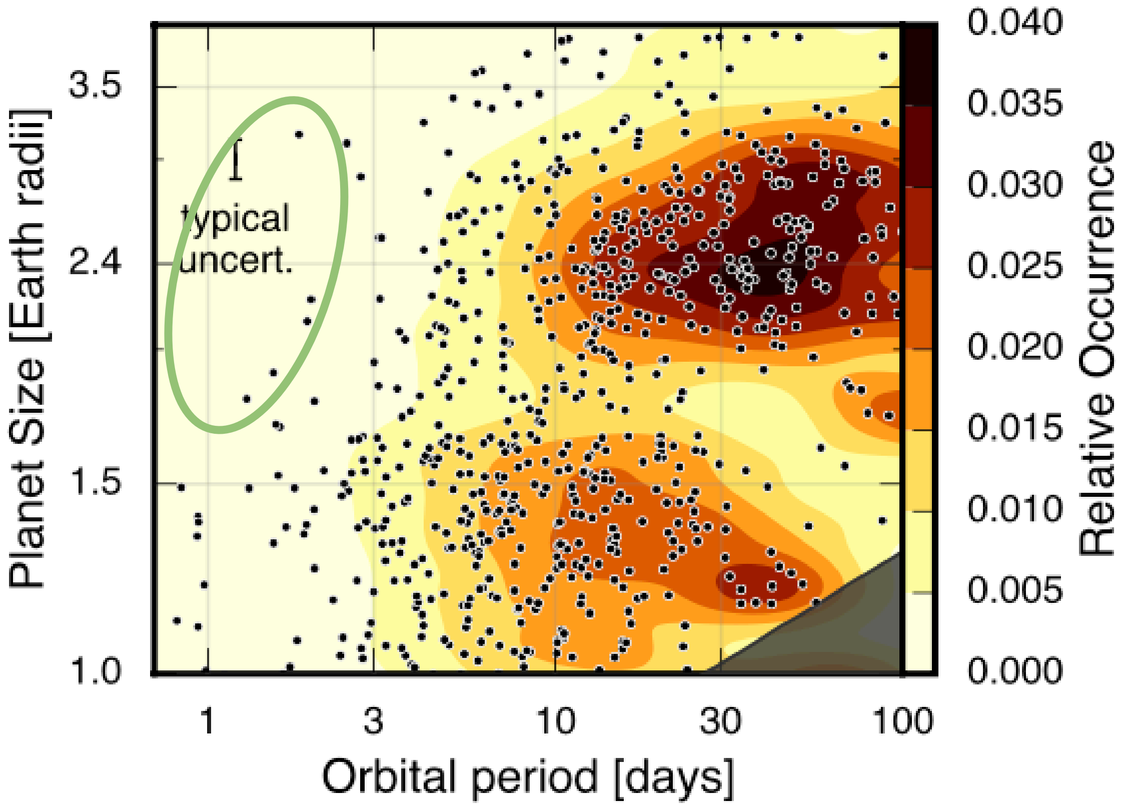
Fulton+18



Fulton+18

Sub-Jovian desert





Fulton+18

Photoevaporation

Hydrodynamic equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v r^2)}{r^2 \partial r} = 0\,,$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial[r^2(\rho v^2 + P)]}{r^2 \partial r} = -\frac{\partial U}{\partial r} + \frac{2P}{r}\,,$$

$$\frac{\partial[\frac{1}{2}\rho v^2 + E + \rho U]}{\partial t} + \frac{\partial v r^2[\frac{1}{2}\rho v^2 + E + P + \rho U]}{r^2 \partial r} = Q_{\rm XUV} - Q_{\rm Ly-\alpha} + \frac{\partial}{r^2 \partial r}\left(r^2 \chi \frac{\partial T}{\partial r}\right) - Q_{\rm H_3^+}\,.$$

Analytic approximations

Hydro-based approximation

$$\dot{M}_{\rm HBA} = e^{\beta}\,(F_{\rm XUV})^{\alpha_1}\left(\frac{d_0}{\rm au}\right)^{\alpha_2}\left(\frac{R_{\rm pl}}{R_\oplus}\right)^{\alpha_3}\Lambda^K.$$

ATES analytical fit, Energy limited

$$\dot{M} = \eta_{\rm eff}\frac{3F_{\rm XUV}}{4GK\rho_{\rm p}},$$

Evolutionary model: Planetary structure

Envelope radius equation

$$R_{\rm env} = R_{\rm p} - R_{\rm core} - R_{\rm atm} = 2.06\, R_{\oplus} \left(\frac{M_{\rm p}}{M_{\oplus}}\right)^{-0.21} \times \left(\frac{f_{\rm env}}{5\%}\right)^{0.59} \left(\frac{F_{\rm p}}{F_{\oplus}}\right)^{0.044} \left(\frac{age}{5\,{\rm Gyr}}\right)^{-0.18}$$

Lopez & Fortney 2014

Relation mass core - radius core

$$R = (0.0592{\rm imf} + 0.0975)(\log M)^2 + (0.2337{\rm imf} + 0.4938)\log M + (0.3102{\rm imf} + 0.7932),$$

$$R = (0.0912{\rm rmf} + 0.1603)(\log M)^2 + (0.3330{\rm rmf} + 0.7387)\log M + (0.4639{\rm rmf} + 1.1193)$$

Fortney+07

Atmospheric mass fraction equation

$$f_{env} = (M_p - M_{core})/M_P$$

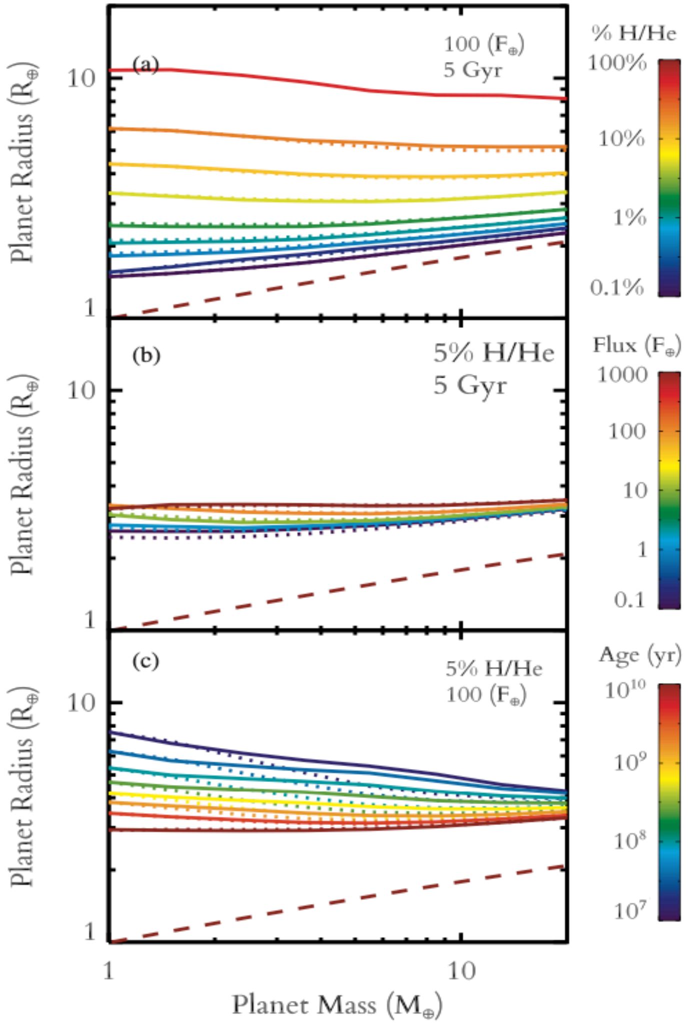
Radii relation

$$R_P = R_{core} + R_{env}$$

Evolutionary model: Radius evolution

$$R_{\rm env} = R_{\rm p} - R_{\rm core} - R_{\rm atm} = 2.06\, R_{\oplus} \left(\frac{M_{\rm p}}{M_{\oplus}}\right)^{-0.21} \times \left(\frac{f_{\rm env}}{5\%}\right)^{0.59} \left(\frac{F_{\rm p}}{F_{\oplus}}\right)^{0.044} \left(\frac{age}{5\,\rm Gyr}\right)^{-0.18}$$

Lopez & Fortney 2014



Evolutionary model: Radius evolution

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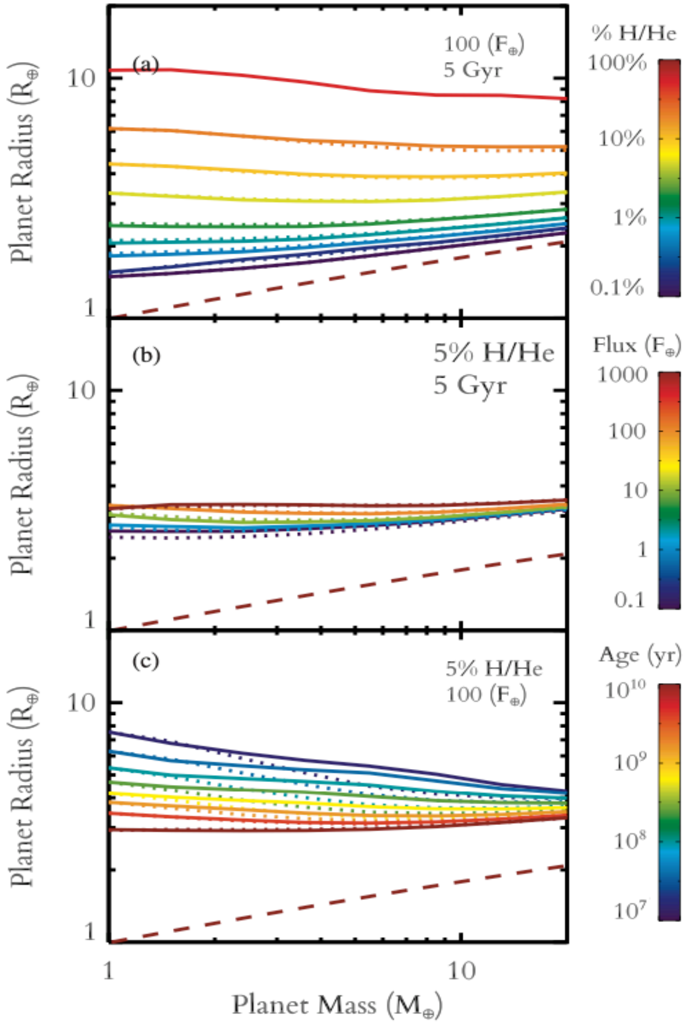
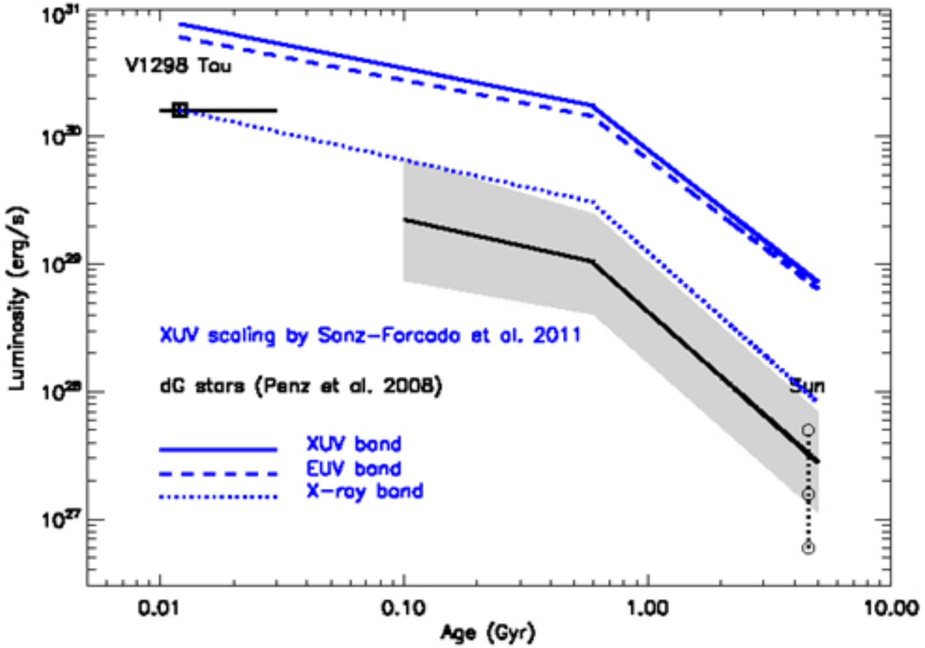
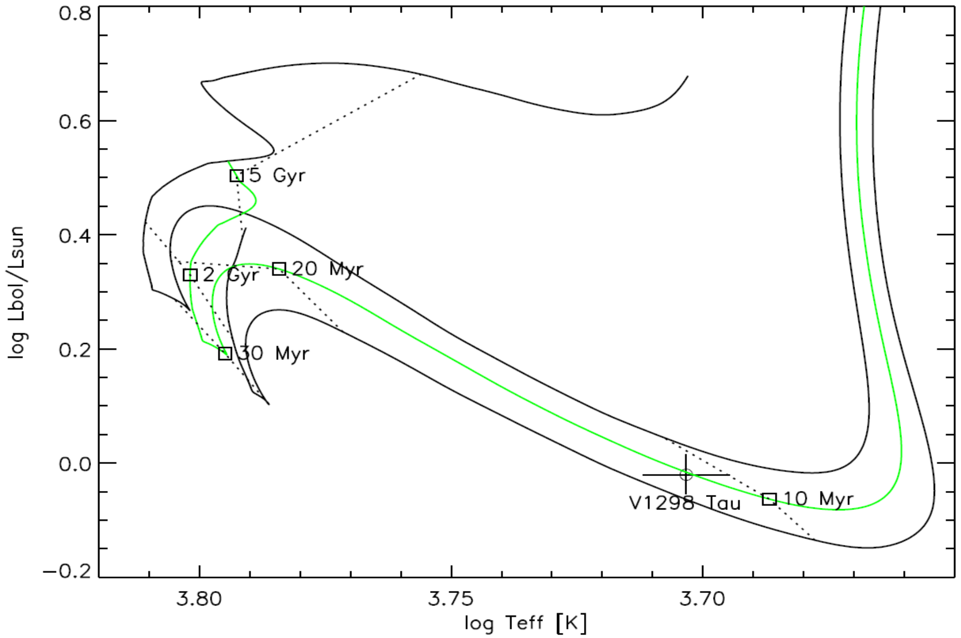
Depends on the metallicity



Lopez & Fortney 2014

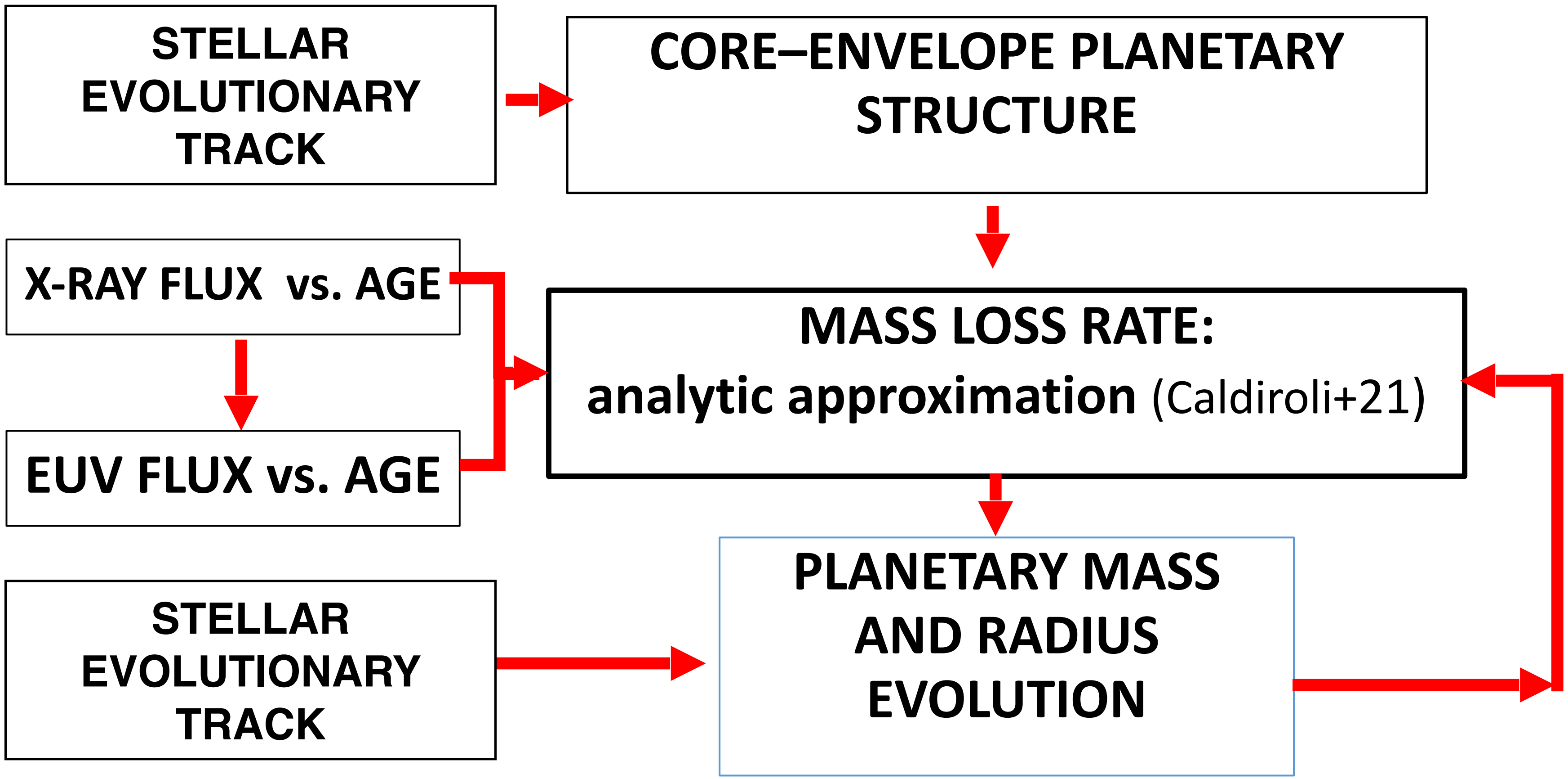
Evolutionary model: Luminosity evolution



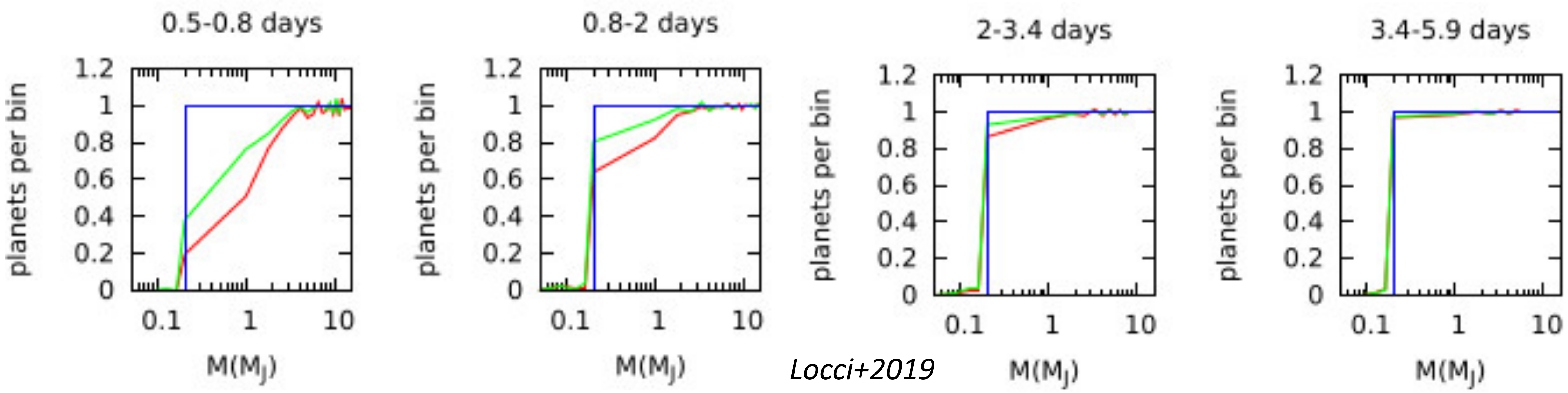


Maggio+22

Evolutionary model



Population studies



Locci+2019

Initial distribution
Planets around dG stars
Planets around dM stars

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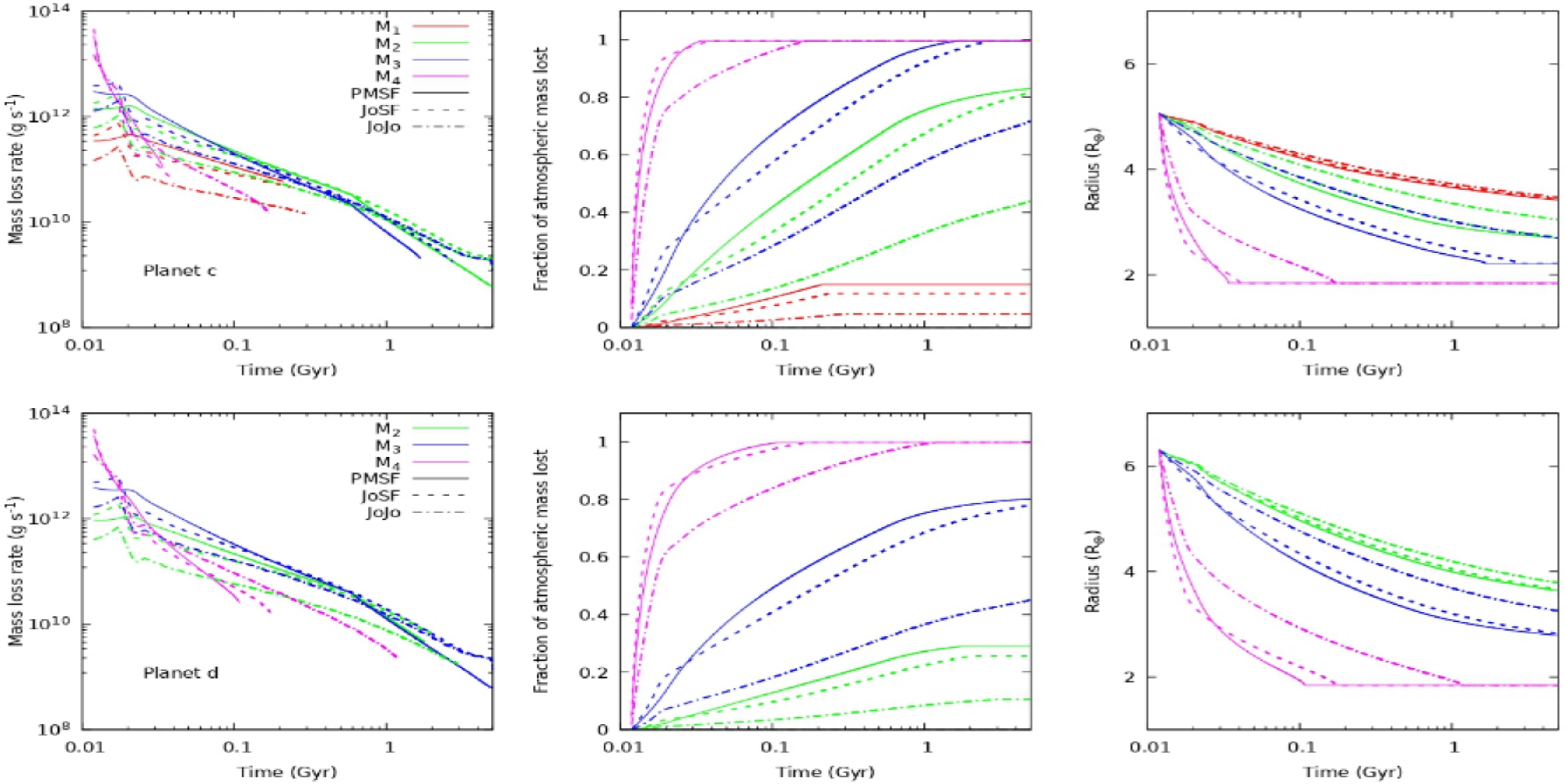
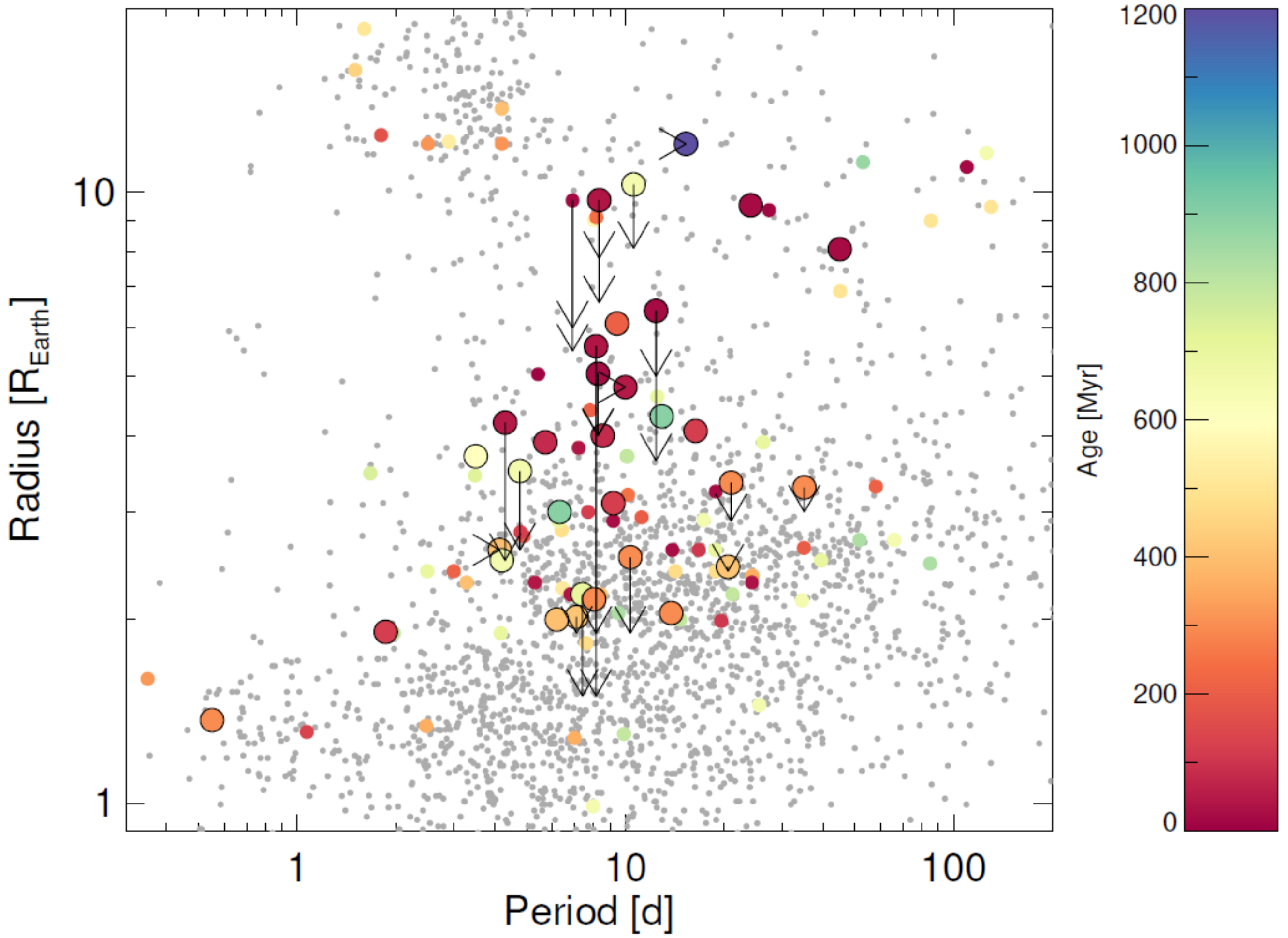
Single system studies

V1298 Tau system



Maggio+22

GAPS collaboration



TOI-1430 b (Nardiello+ 2024)

TOI 5398 b,c (Mantovan+ 2024)

HD 63433 b,c (Damasso+ 2023)

TOI 179 b (Desidera+ 2023)

TOI-2076 b,c,d (Damasso+ 2024)

TOI 837 b (Damasso+ 2024)

DS Tuc A b (Benatti+ 2021)

V1298 Tau b,c,d,e (Maggio+ 2022)

HIP 67522 b (Maggio+ 2024)

Take home messages

Stellar high energy emission affects the planet evolution:

- High-energy radiation drives planetary atmospheres out of chemical equilibrium

- The photoevaporation process sculpts the shape of planetary populations

- Photoevaporation could lead to the loss of primordial atmospheres, promoting the formation of secondary atmosphere