

# Evolution of the polar outflow from the Earth's cusps

K.G. Kislyakova<sup>1</sup>, C.P. Johnstone<sup>1</sup>, M. Scherf<sup>2</sup>, H. Lammer<sup>2</sup>,  
M. Holmström<sup>3</sup>, M. Khodachenko<sup>2</sup>, M. Güdel<sup>1</sup>

<sup>1</sup>University of Vienna, Department of Astrophysics, Vienna, Austria

<sup>2</sup>Space Research Institute, Austrian Academy of Sciences, Graz, Austria

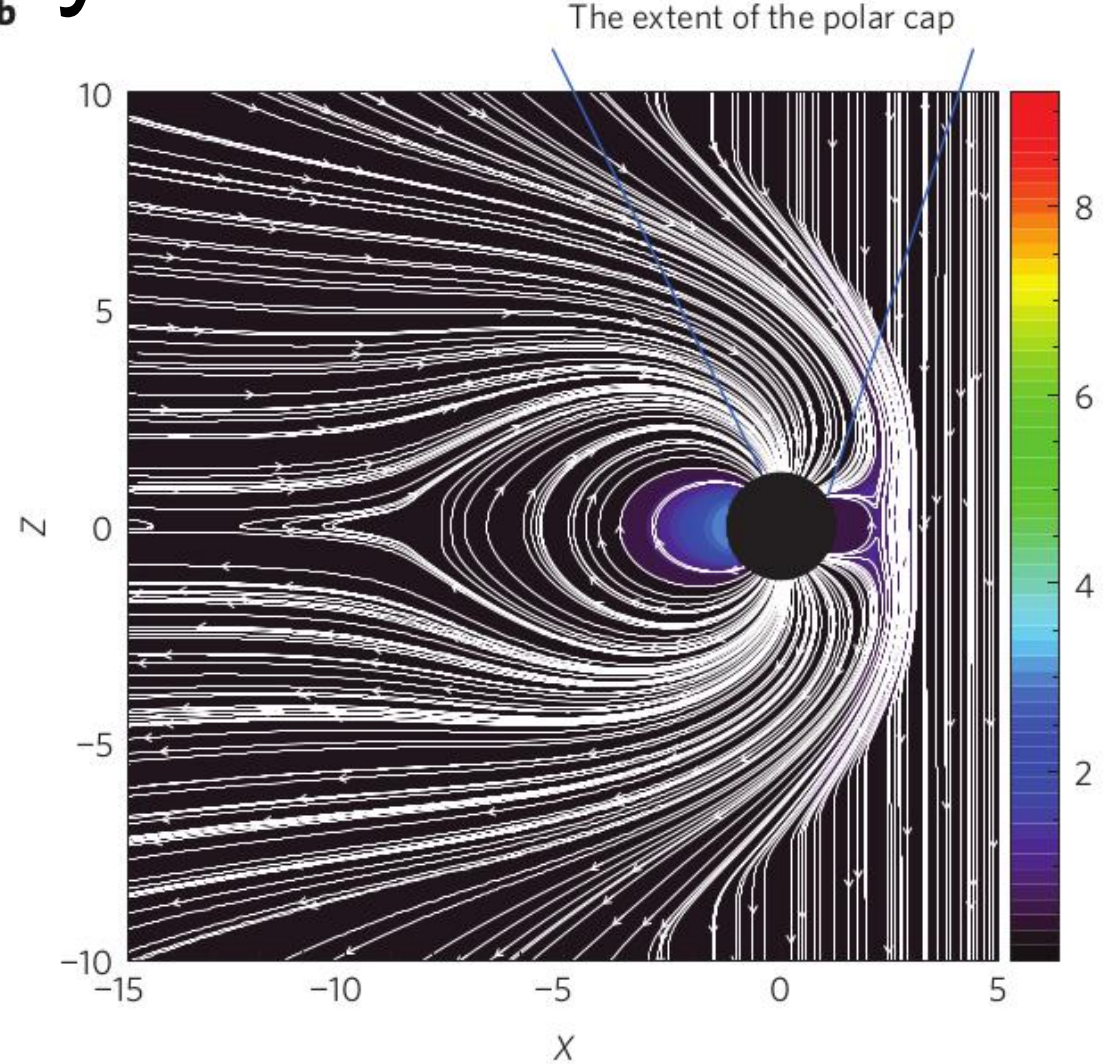
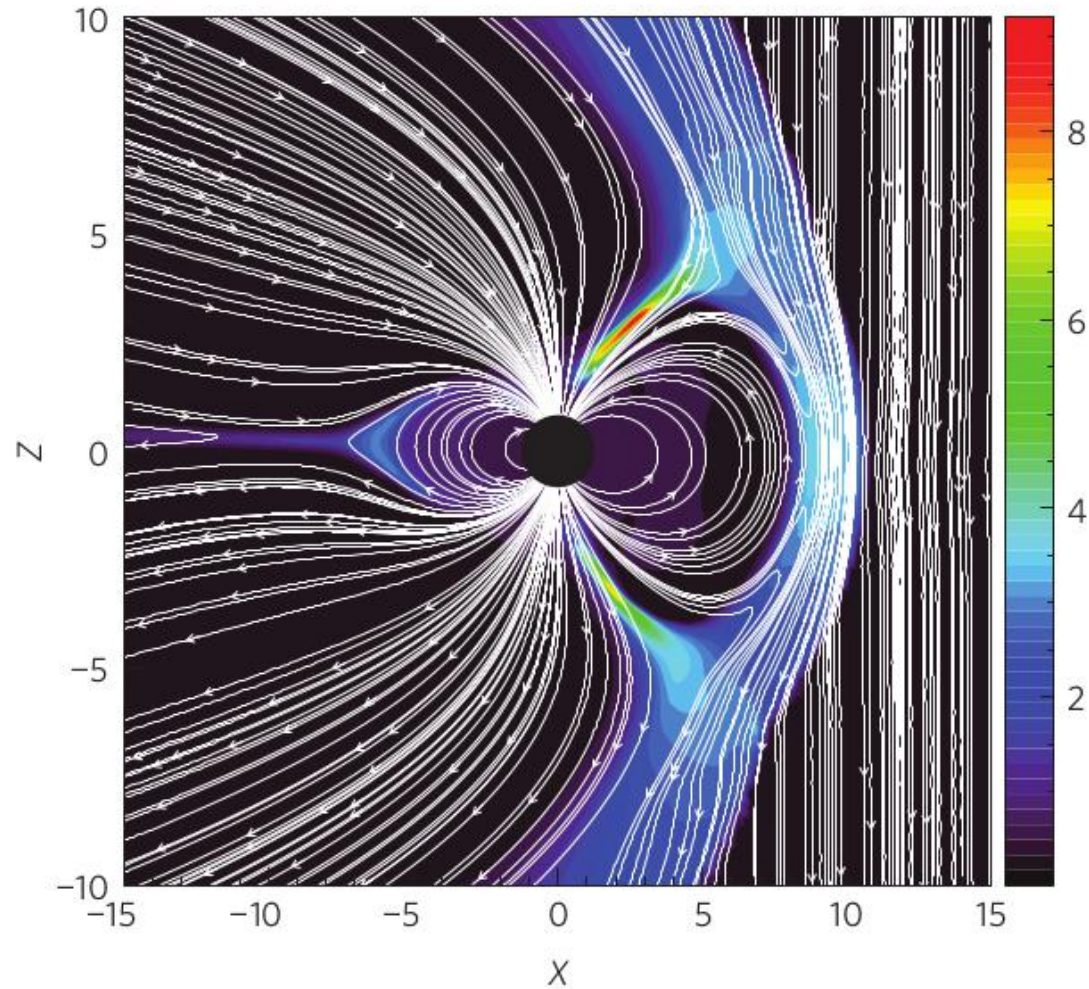
<sup>3</sup>Swedish Institute of Space Physics, Kiruna, Sweden



# Motivation for the study

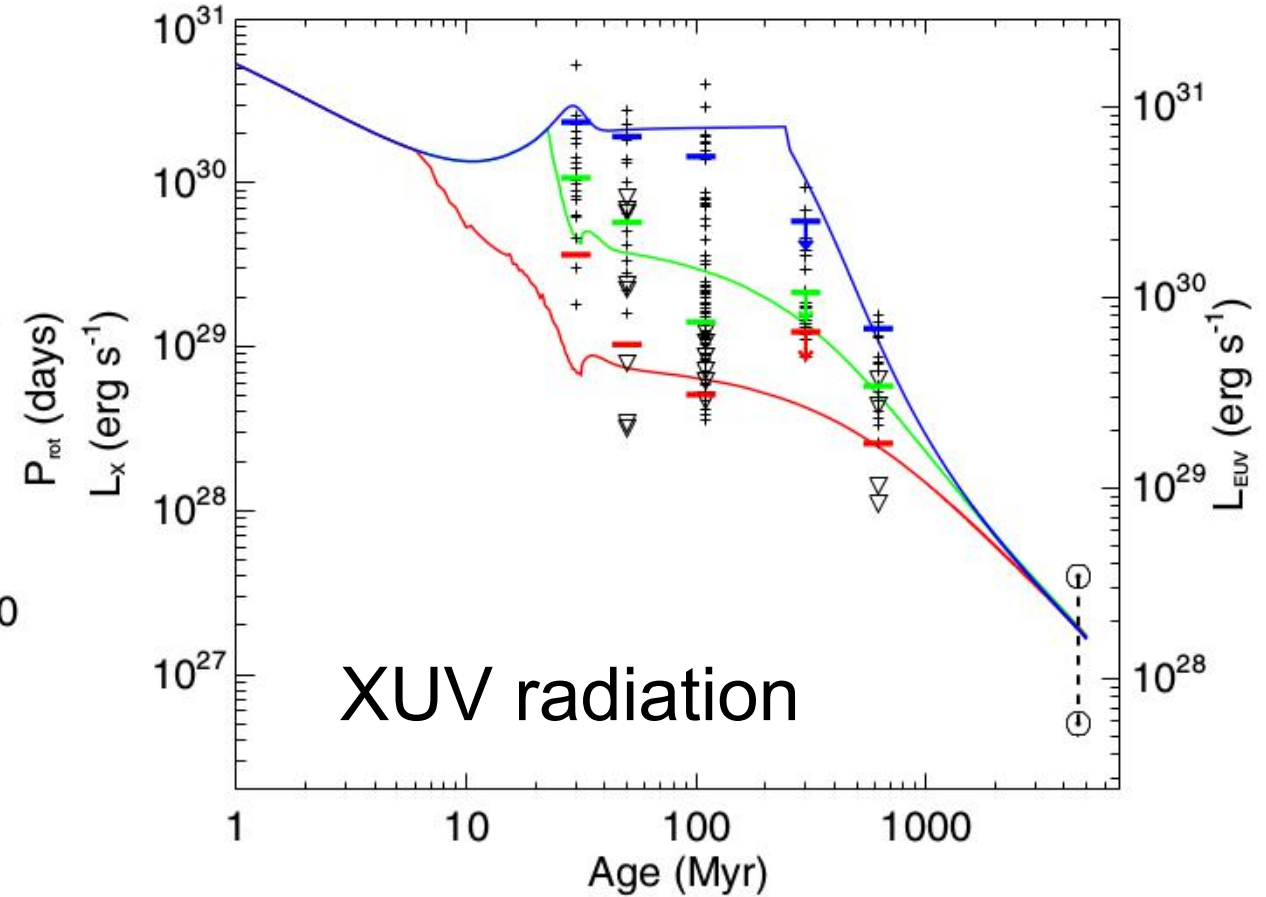
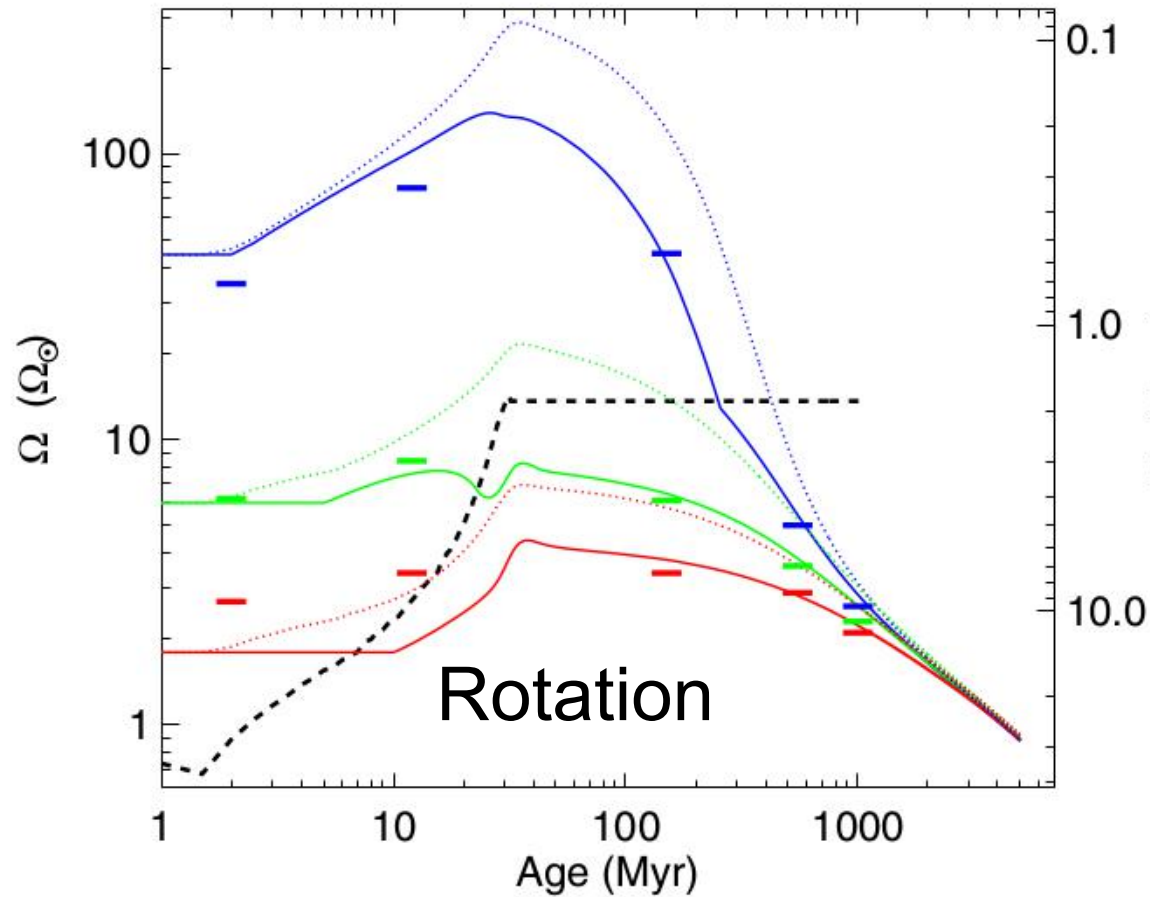
a

b



Airapetian et al. 2016

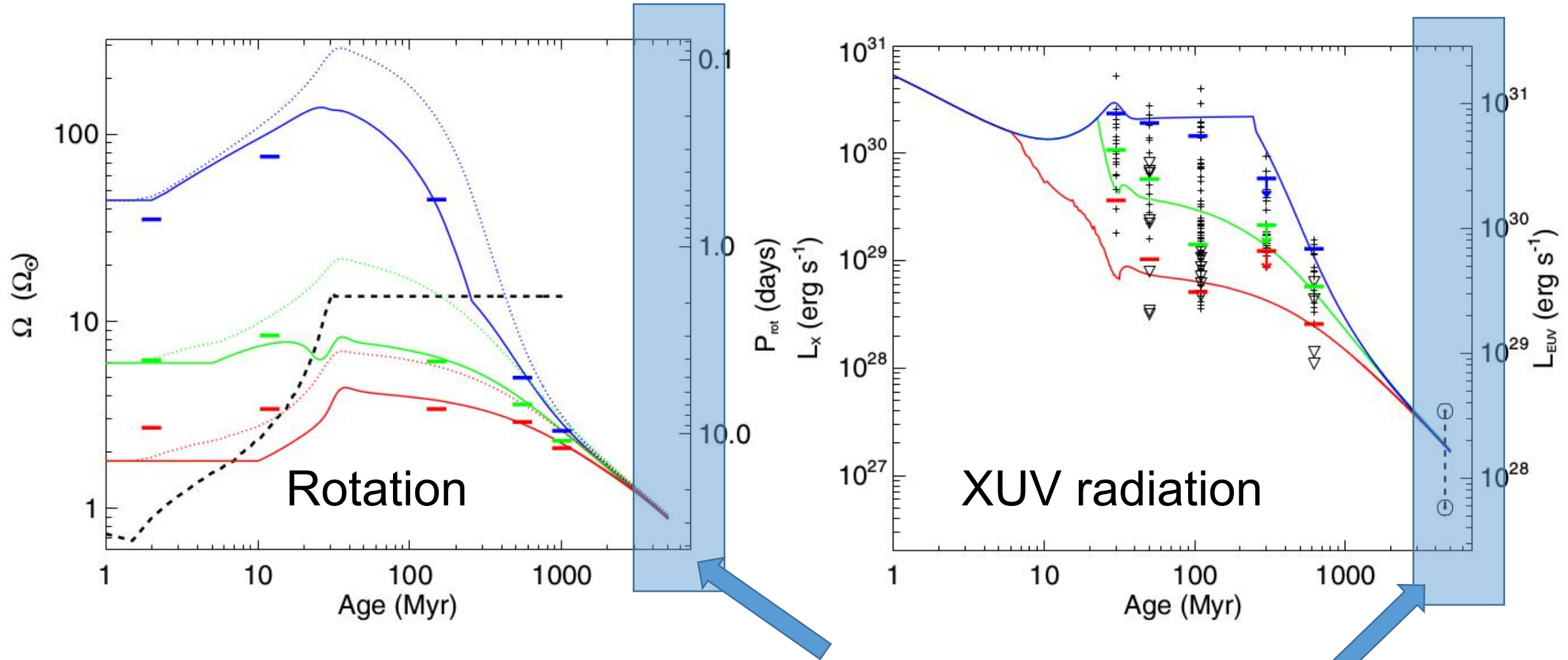
# Evolution of the Sun and its XUV (X-ray + EUV) output



Tu et al. 2015



# Evolution of the Sun and its XUV (X-ray + EUV) output

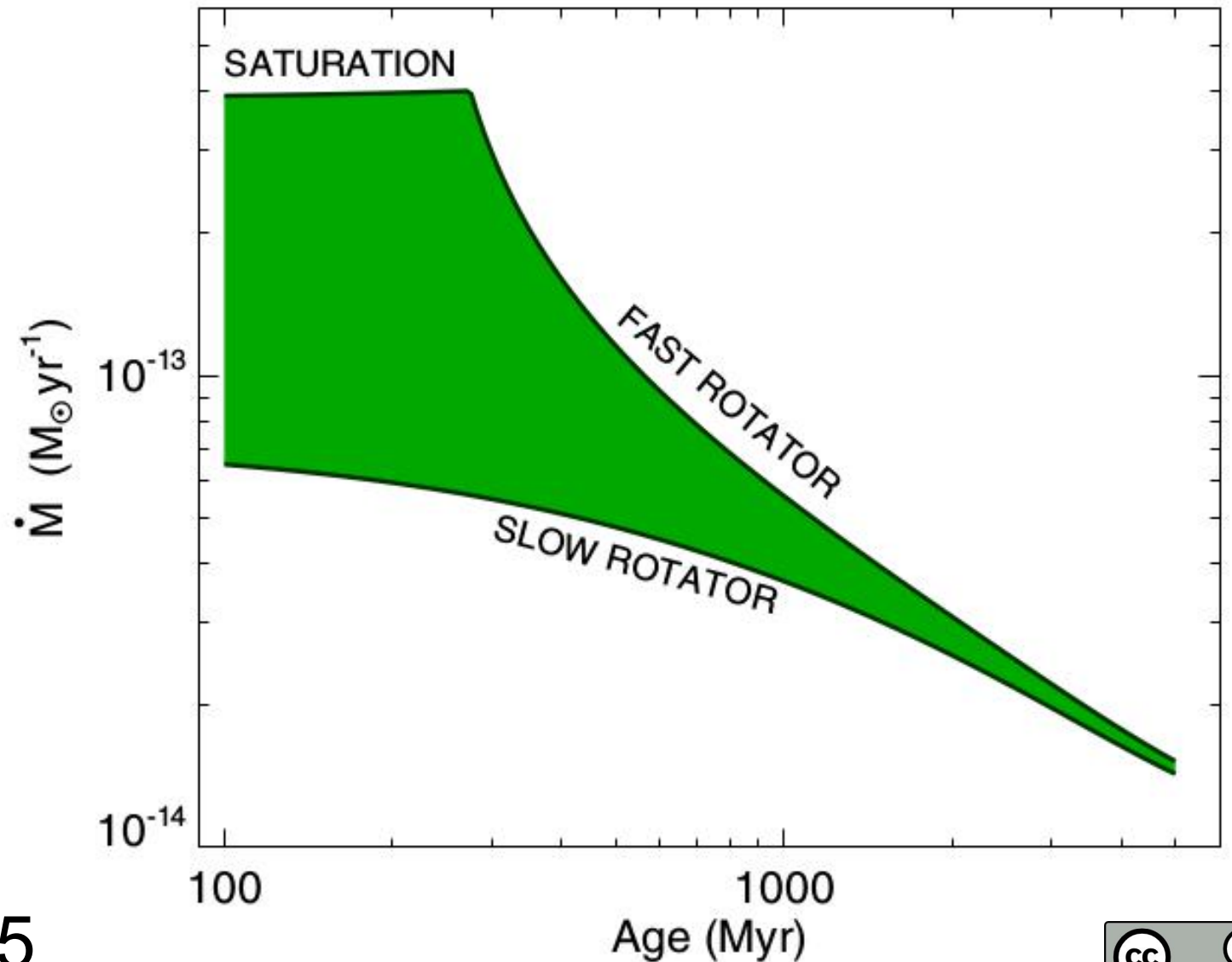


Tu et al. 2015

Mid-Archean and later

# Evolution of the solar wind

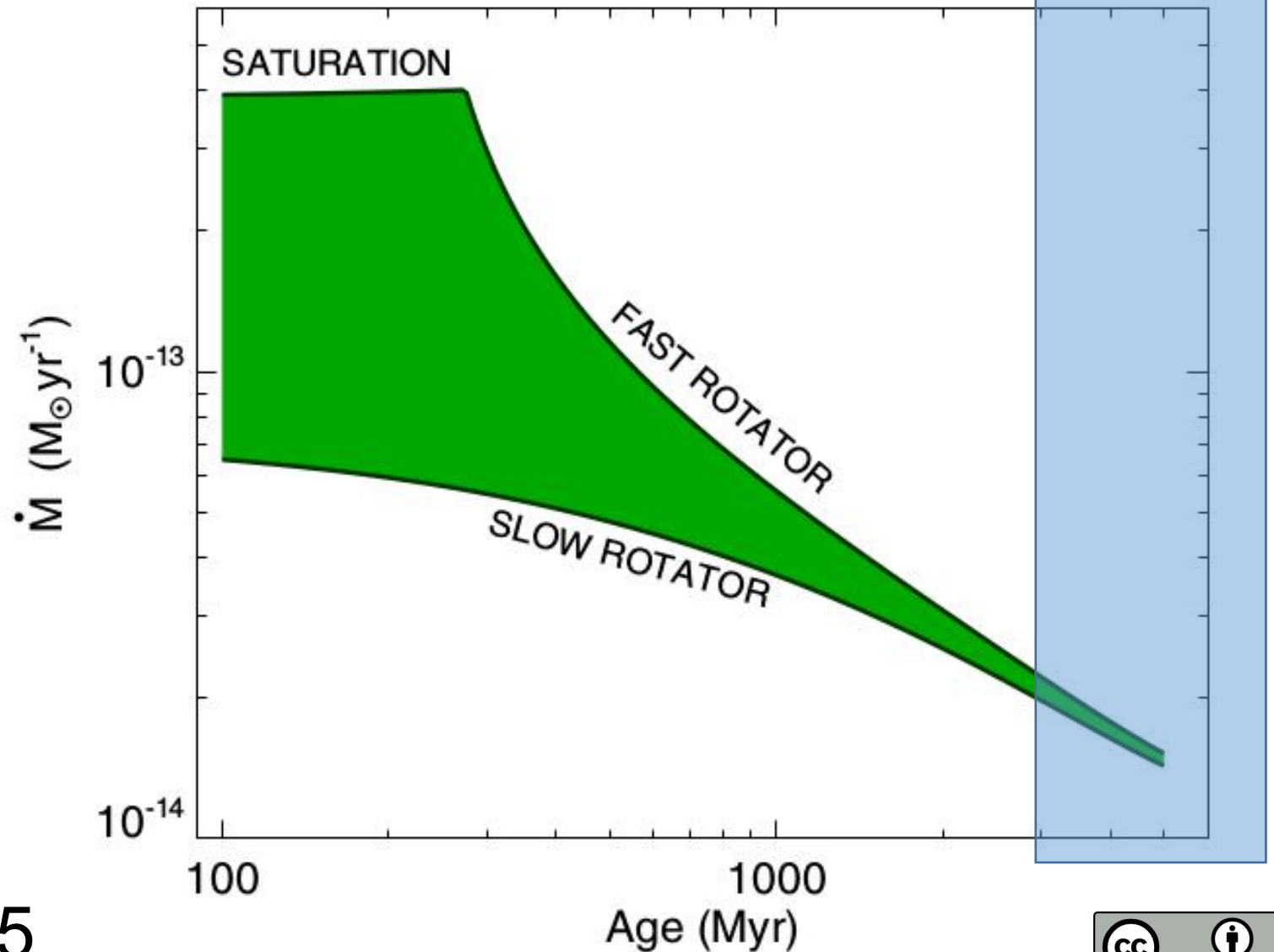
The evolution of the solar wind also depends on the solar rotation evolution



Johnstone et al. 2015

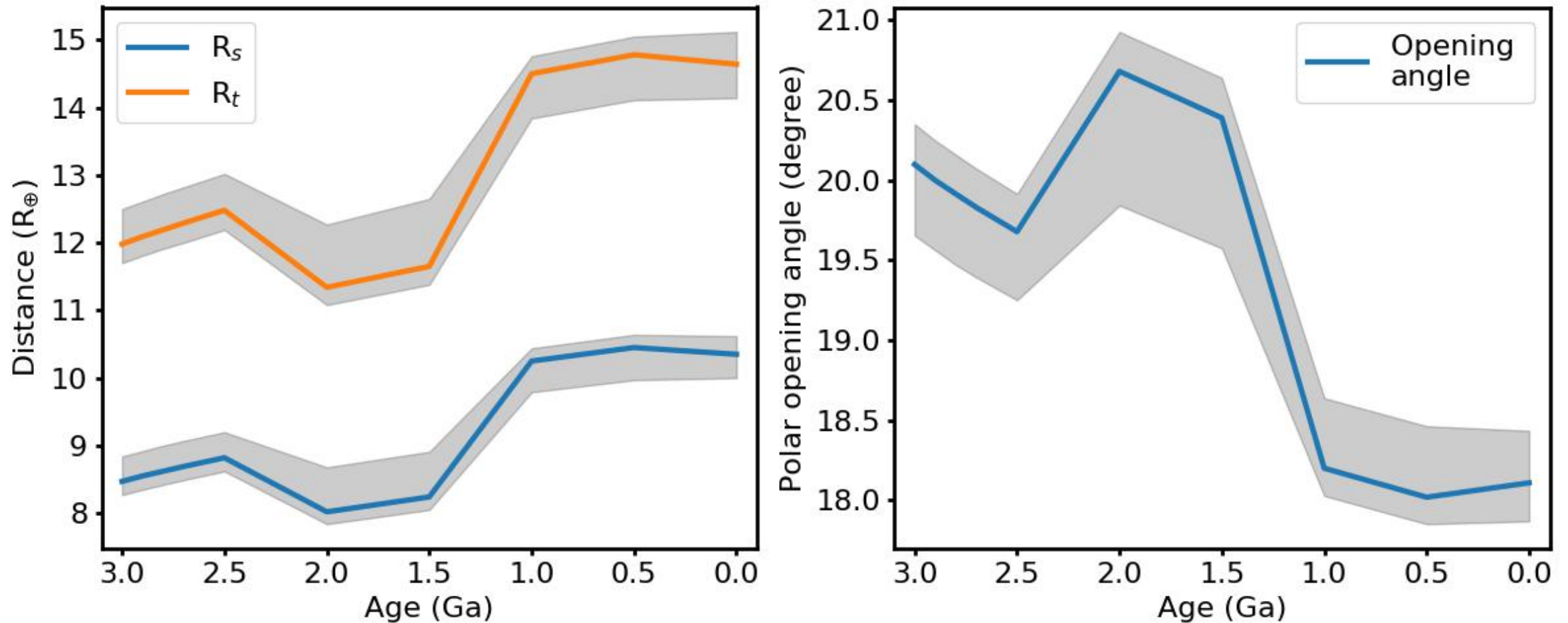
# Evolution of the solar wind

The evolution of the solar wind also depends on the solar rotation evolution



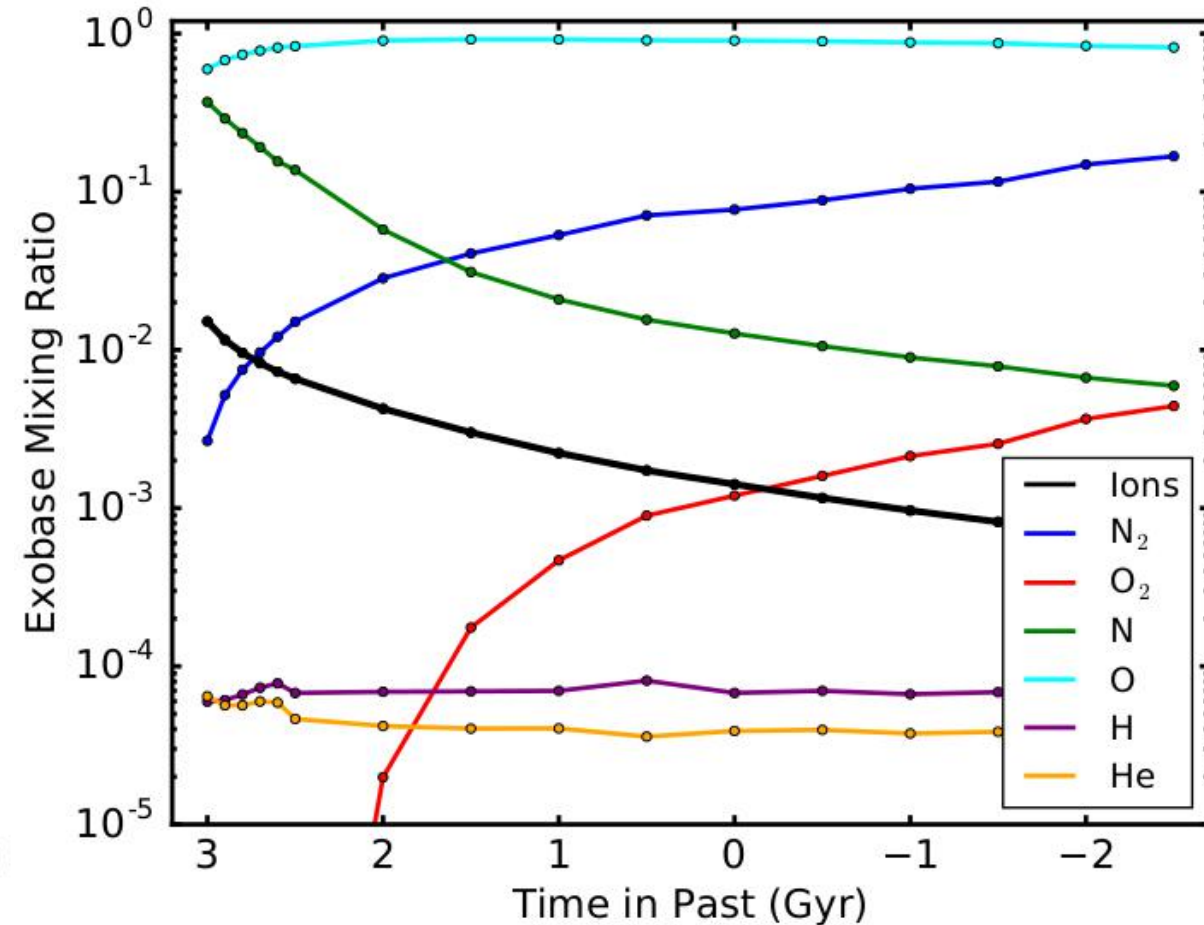
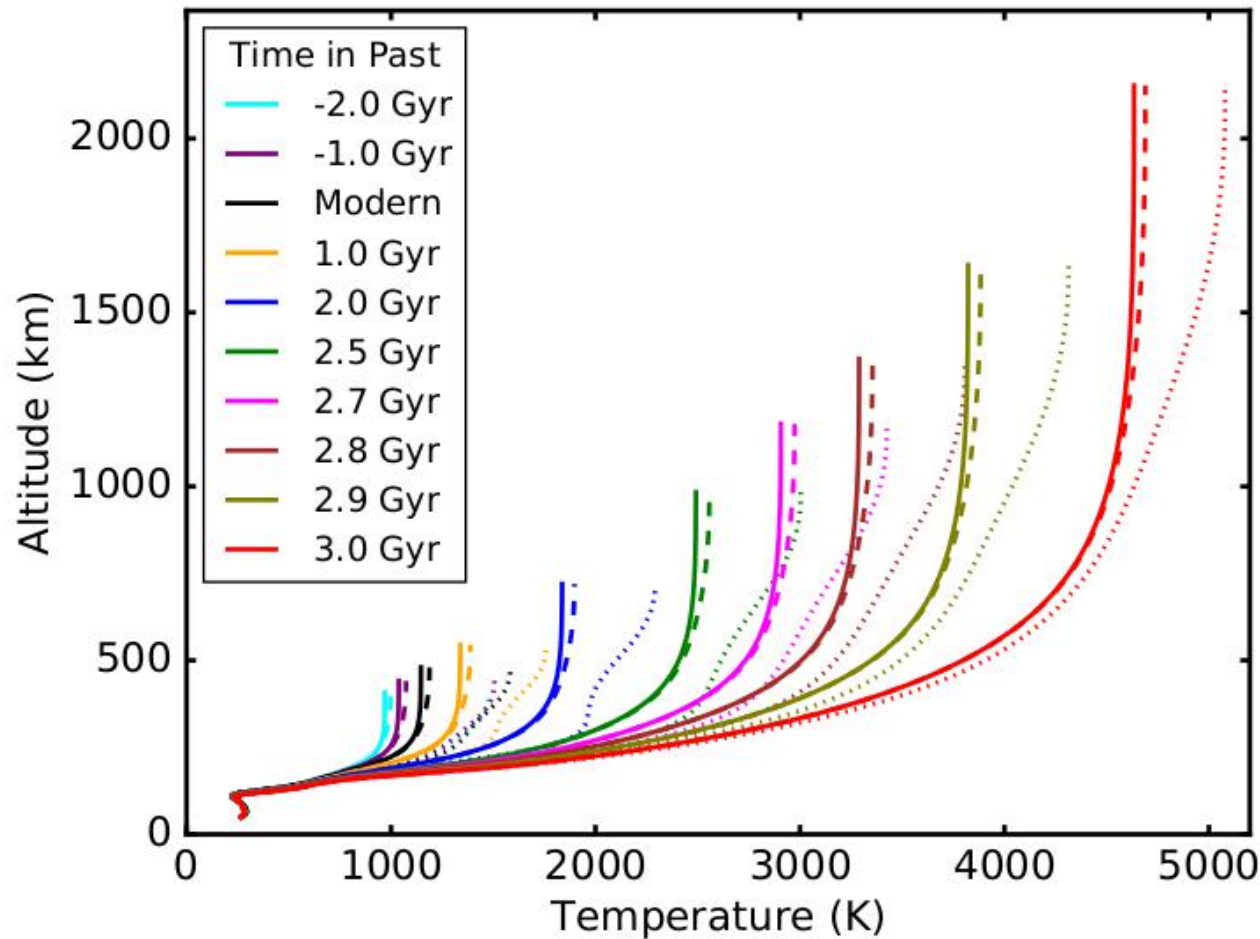
Johnstone et al. 2015

# Evolution of the Earth's dynamo



Magnetic moment evolution following Biggin et al. 2015

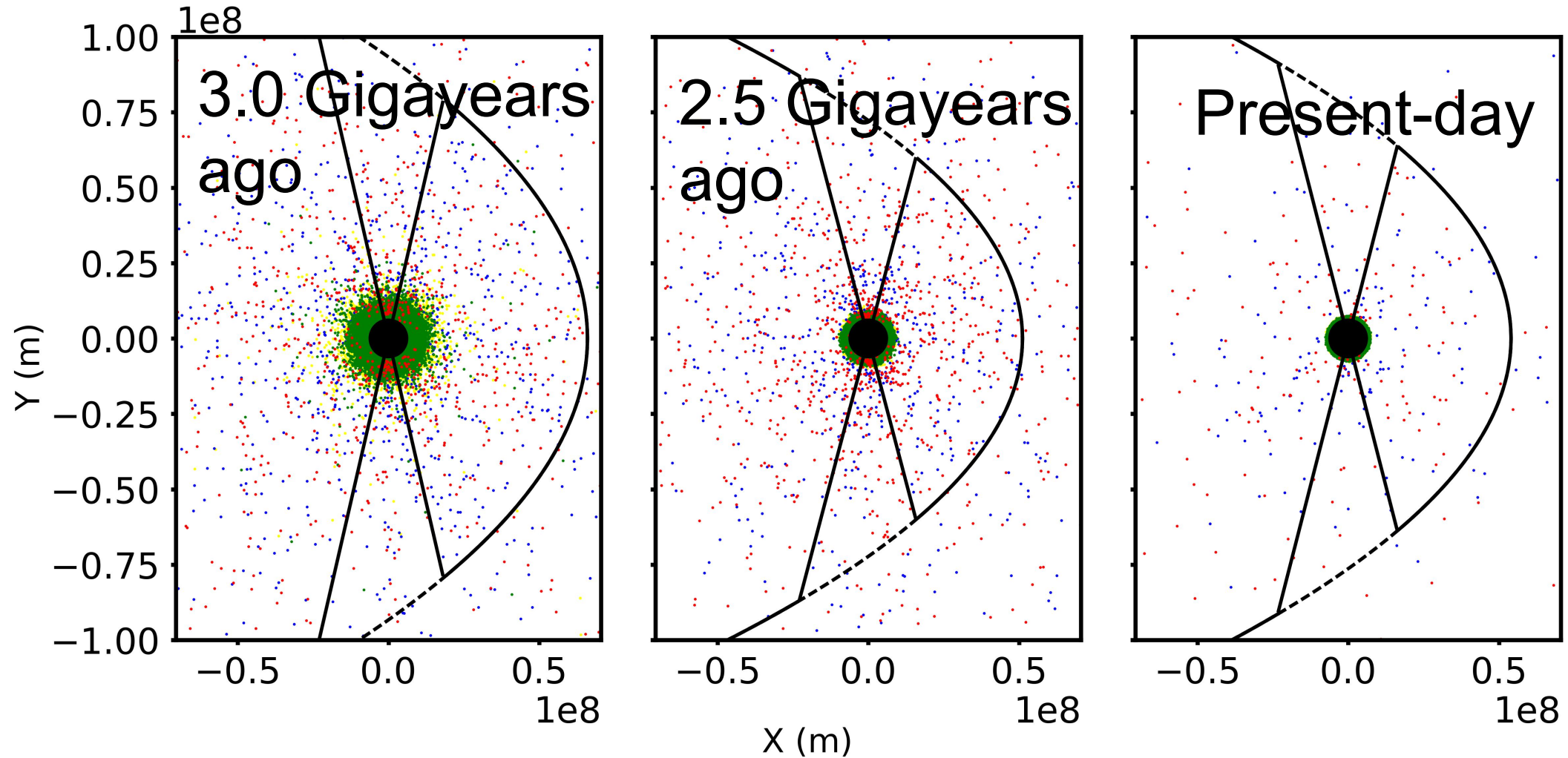
# Evolution of the Earth's atmosphere



Johnstone et al. 2018



# Upper atmosphere structure

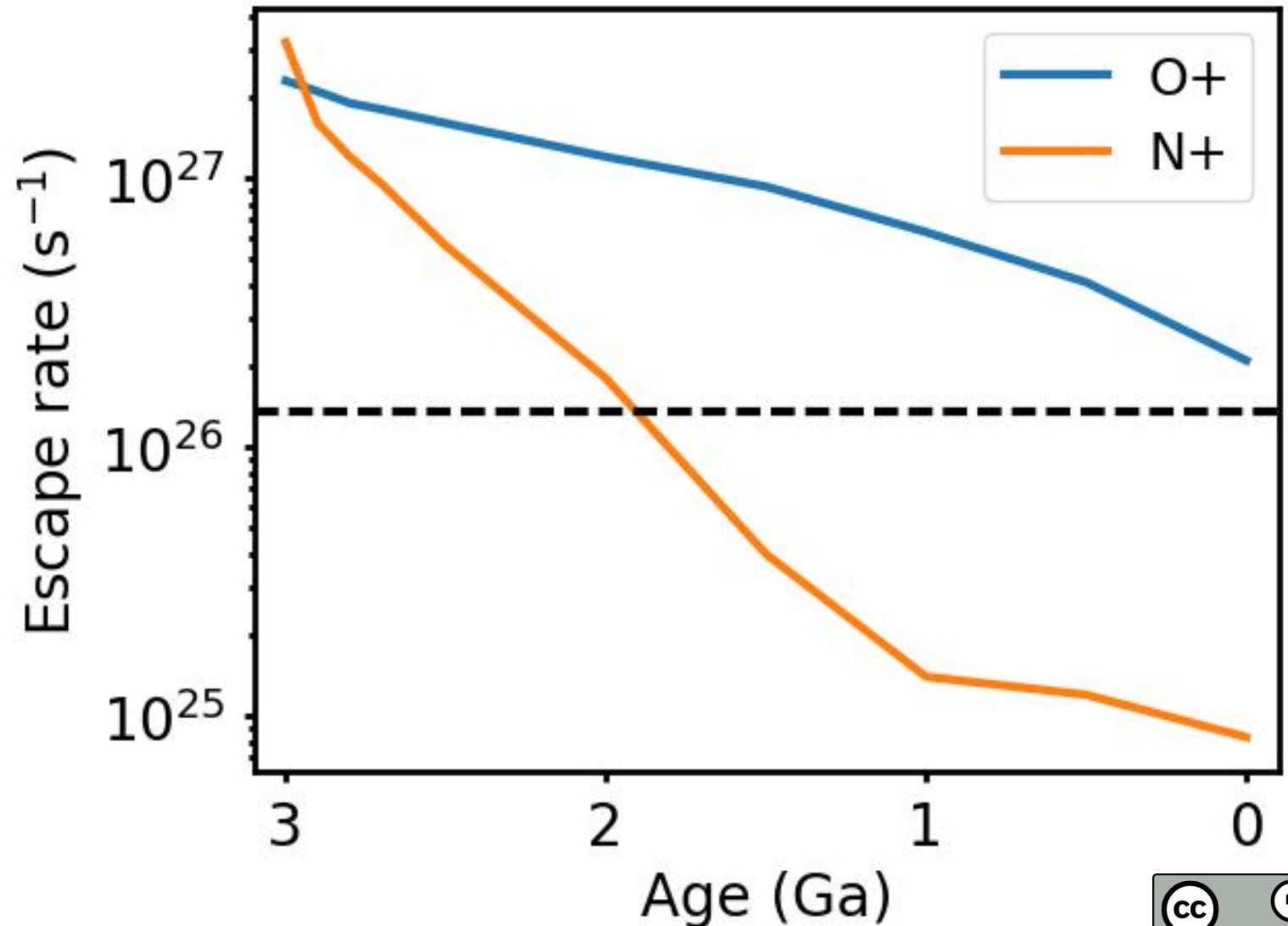


Kislyakova et al. submitted

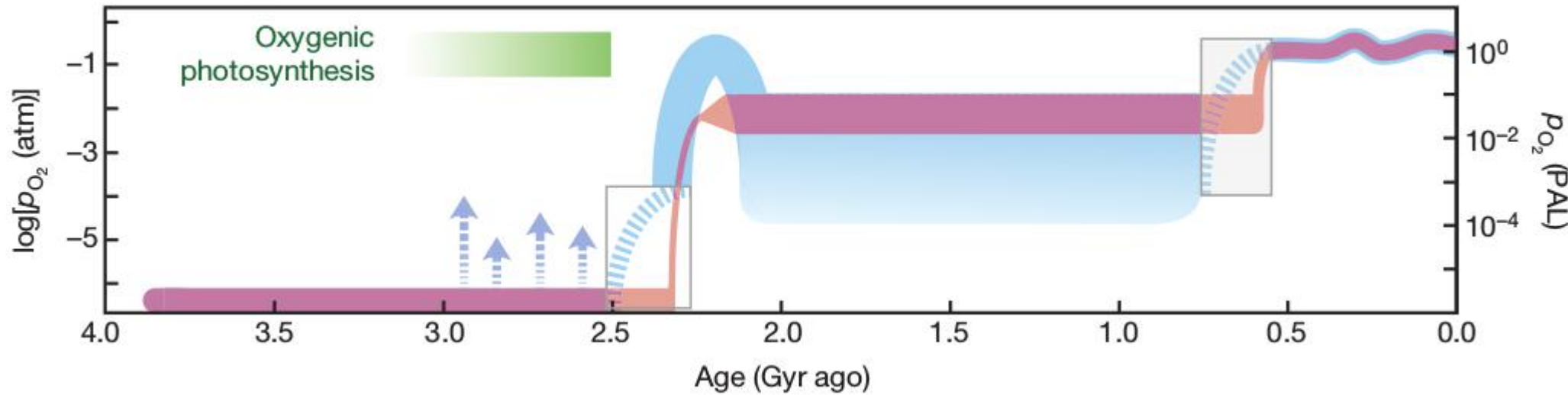
# Evolution of the polar outflow

The outflow is assumed to be source limited

We assume the modern-day composition of the atmosphere



# The Great Oxidation Event (GOE) and the polar outflow



Lyons et al.  
2014

Simulation 2.5 Ga with modern composition:  $\text{O}^+$  escape =  $1.6 \times 10^{27} \text{ s}^{-1}$ ,  $\text{N}^+$  escape =  $5.6 \times 10^{26} \text{ s}^{-1}$

Simulation 2.5 Ga with 1% oxygen:  $\text{O}^+$  escape =  $2.0 \times 10^{26} \text{ s}^{-1}$ ,  $\text{N}^+$  escape =  $2.9 \times 10^{27} \text{ s}^{-1}$



# Conclusions

- Polar outflow of the nitrogen ions three gigayears ago increases by two orders of magnitude compared to its present value.
- Polar outflow of oxygen ions from the Earth's open field line regions varies greatly depending on the oxygen mixing ratio
- Polar outflow escape is governed primarily by the evolution of the solar short-wavelength radiation and the atmosphere's composition

→ Kislyakova et al., JGR, under review