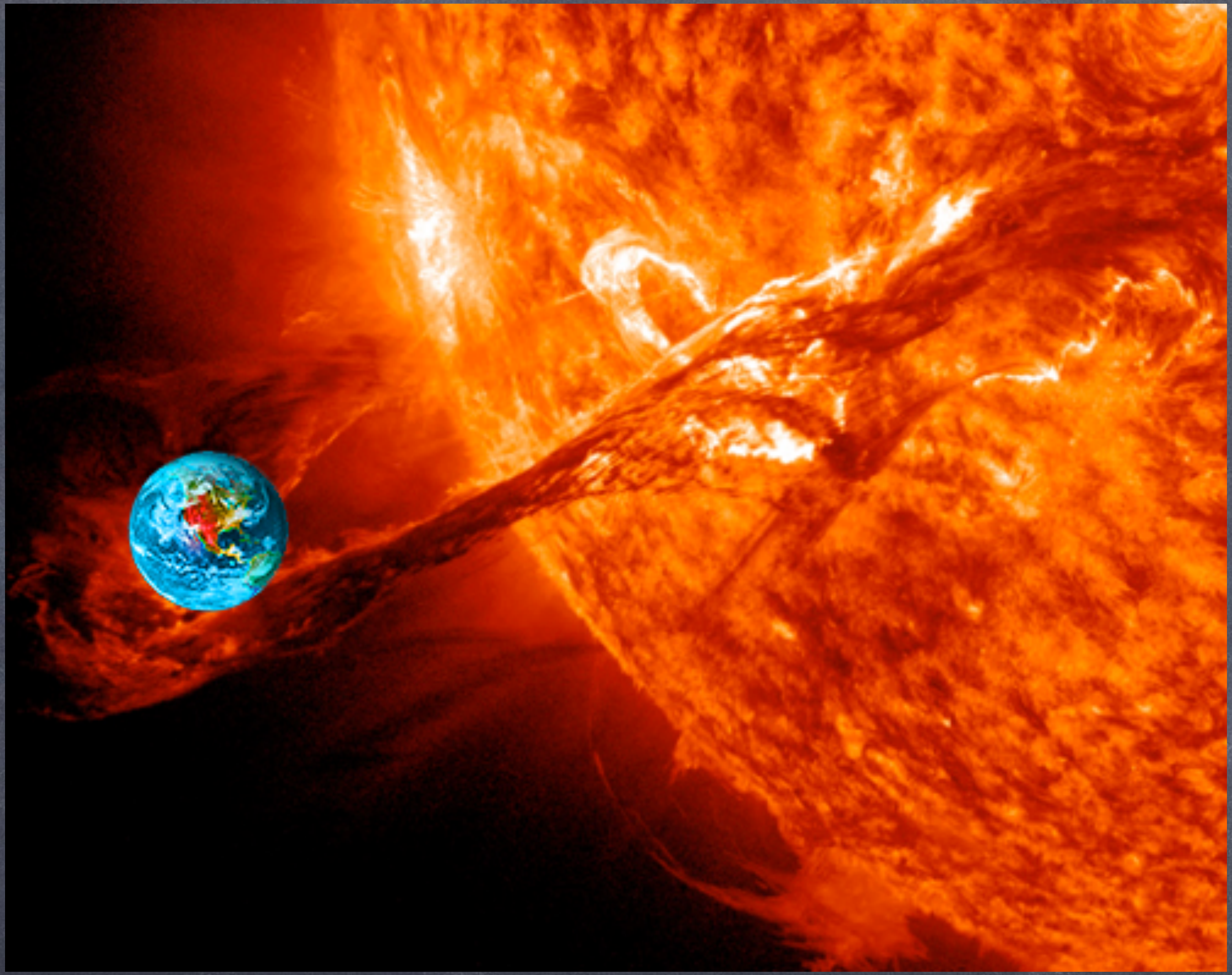
Comparative Heliophysics



Credit: NASA

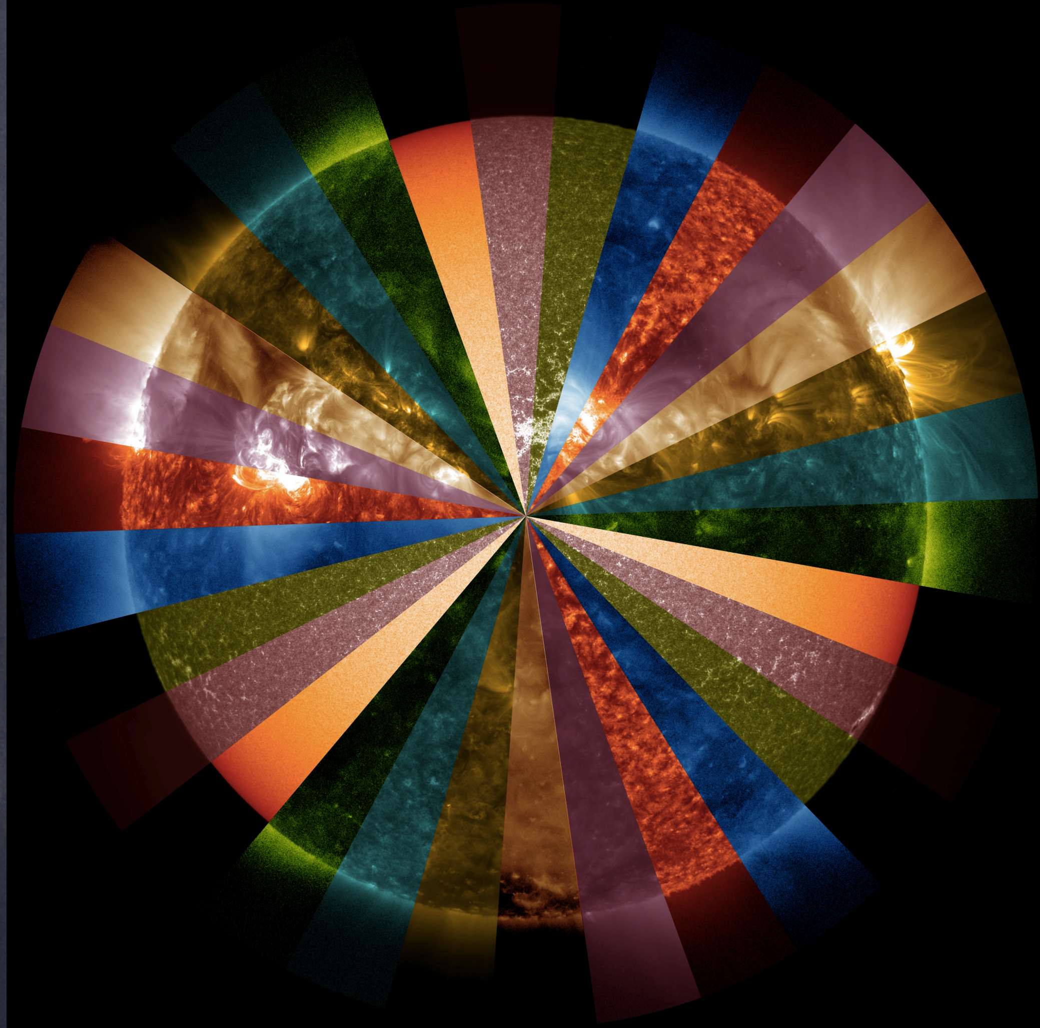
Heliophysics Summer School, Boulder CO, 2017

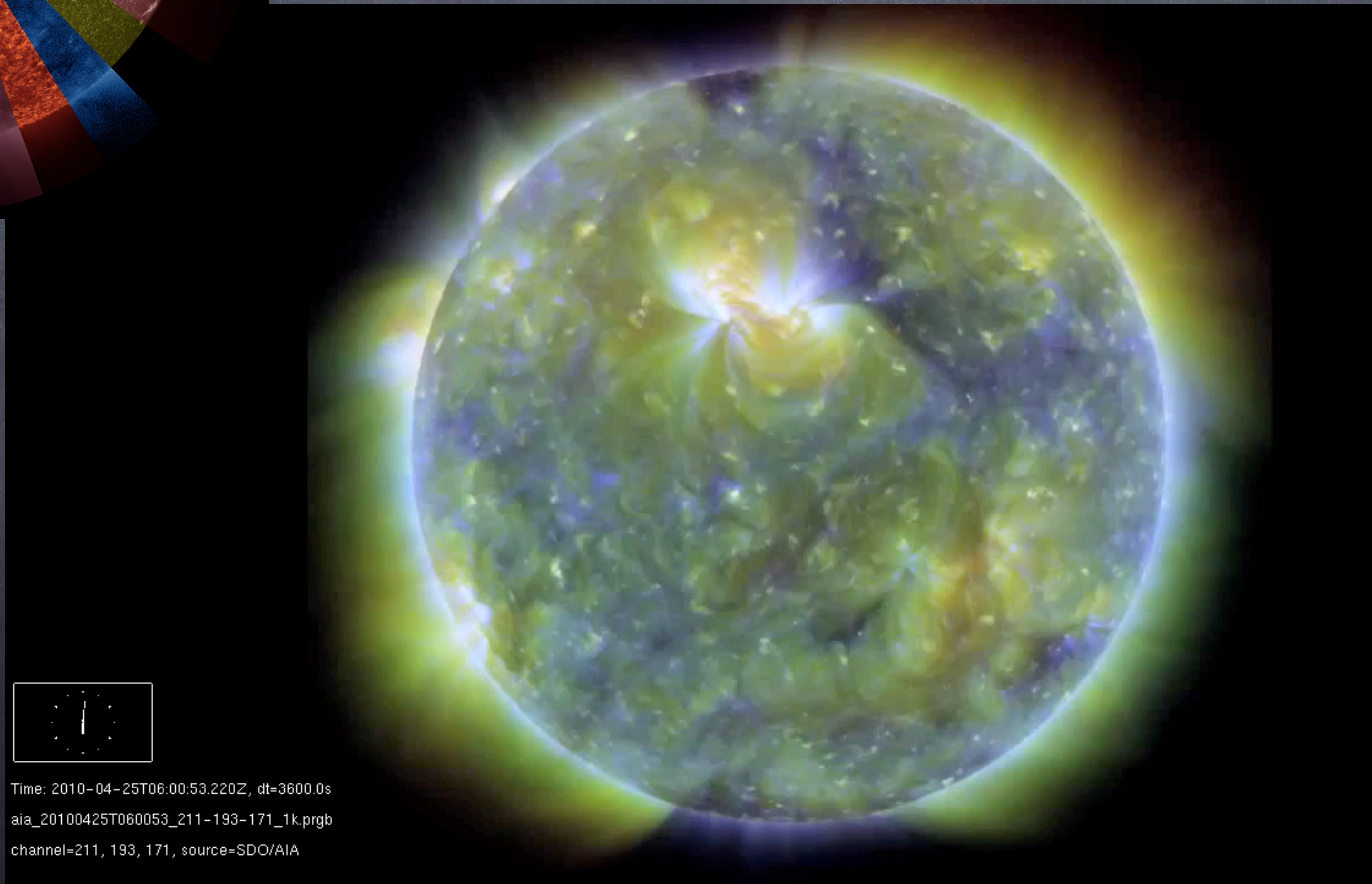
Outline

1. Solar-stellar connection:
   I. Stellar evolution
   II. Solar Vs. stellar physics
   III. Ways to relate the two
   IV. Astrospheres - stellar environments
   V. CMEs on other stars
2. Planet habitability:
   I. The importance of the stellar environment
   II. The case of close-orbit M-dwarf planets

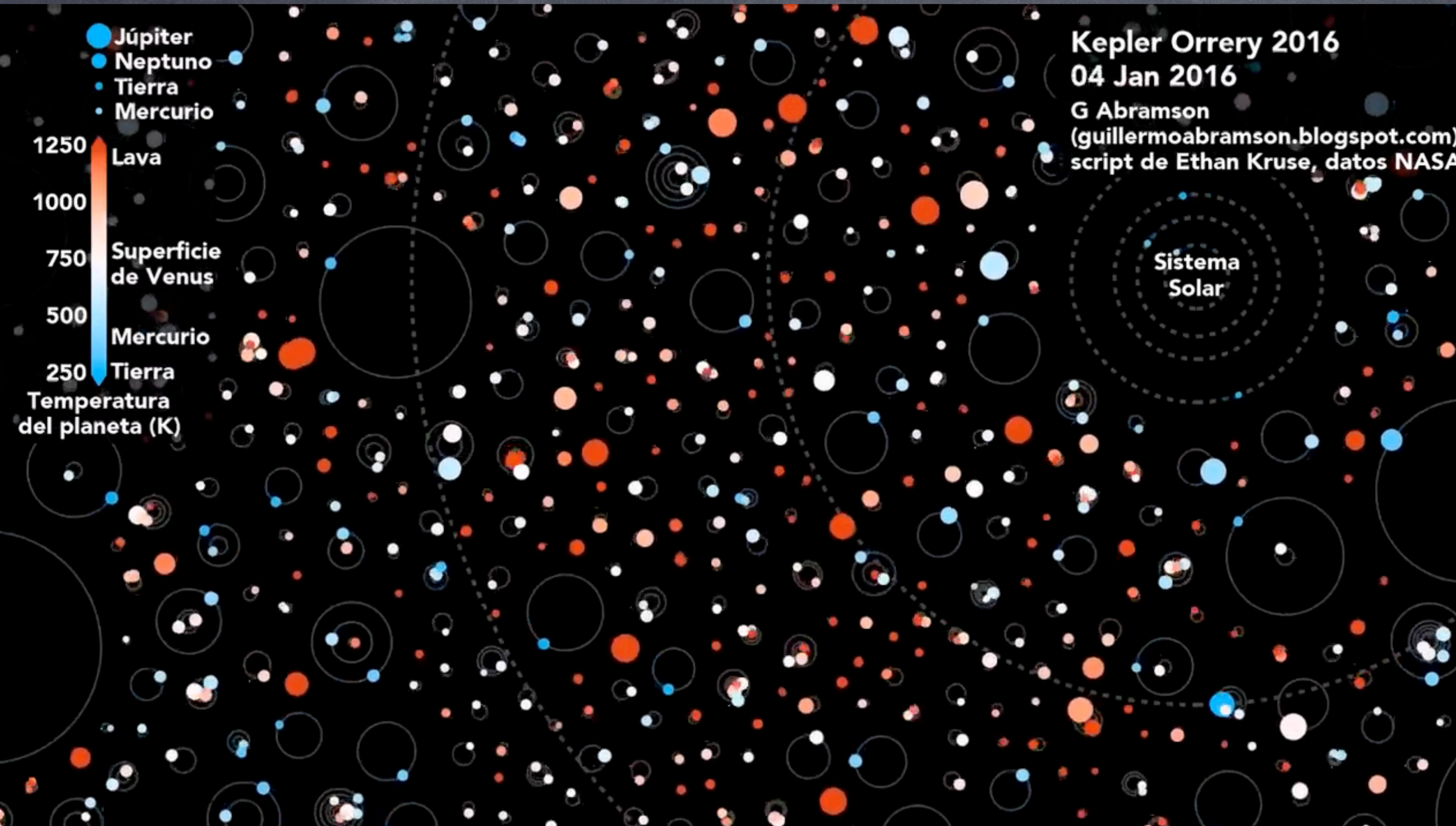
The Solar-stellar connection

SDO observations of the Sun



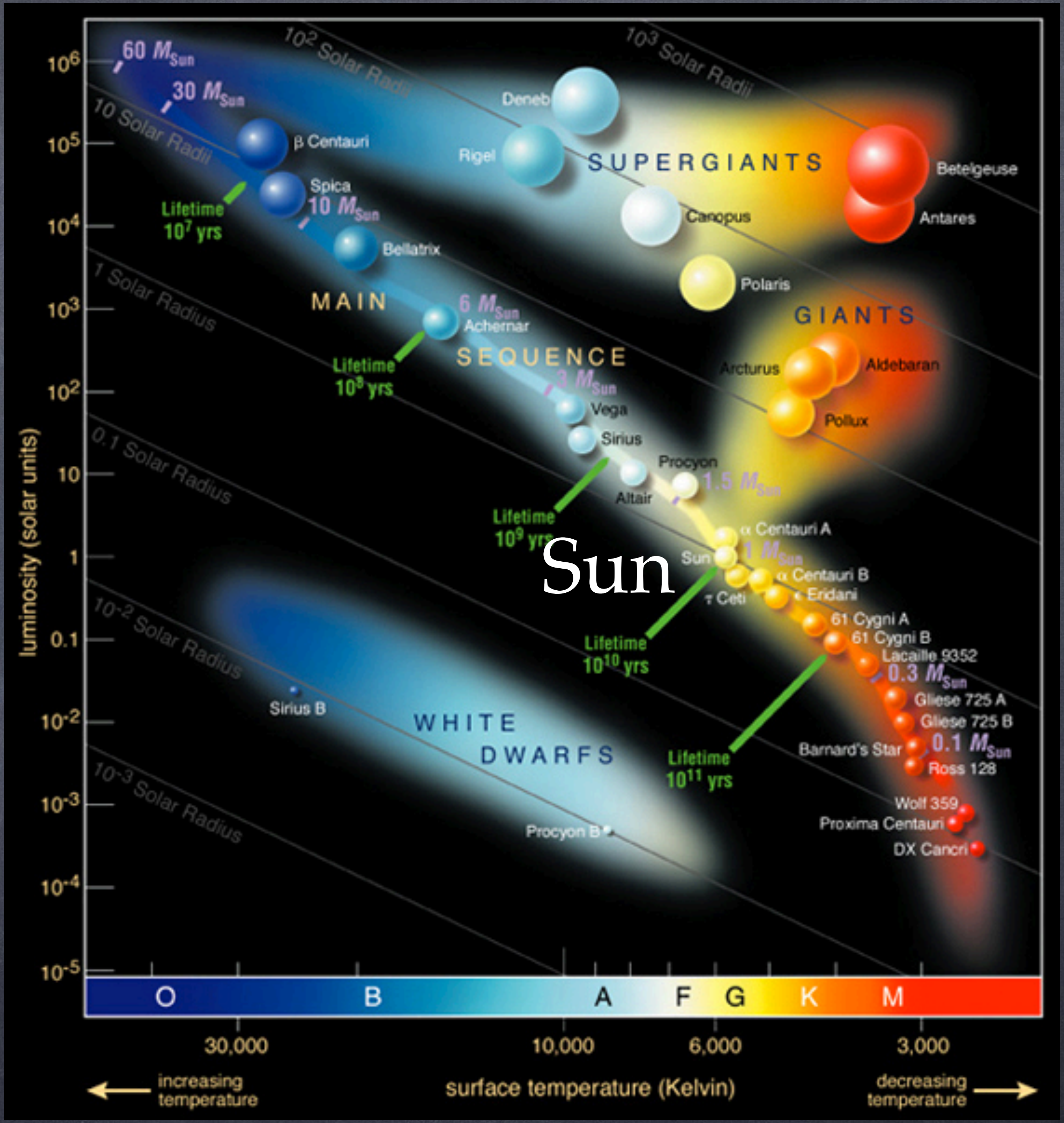


Kepler systems observed as of Jan 2016



Stellar Evolution

Class	Temperature (kelvins)	Conventional color	Apparent color
O	≥ 33,000 K	blue	blue
B	10,000–30,000 K	blue to blue white	blue white
A	7,500–10,000 K	white	white to blue white
F	6,000–7,500 K	yellowish white	white
G	5,200–6,000 K	yellow	yellowish white
K	3,700–5,200 K	orange	yellow orange
M	≤ 3,700 K	red	orange red



Credit: ESO

Solar Physics:

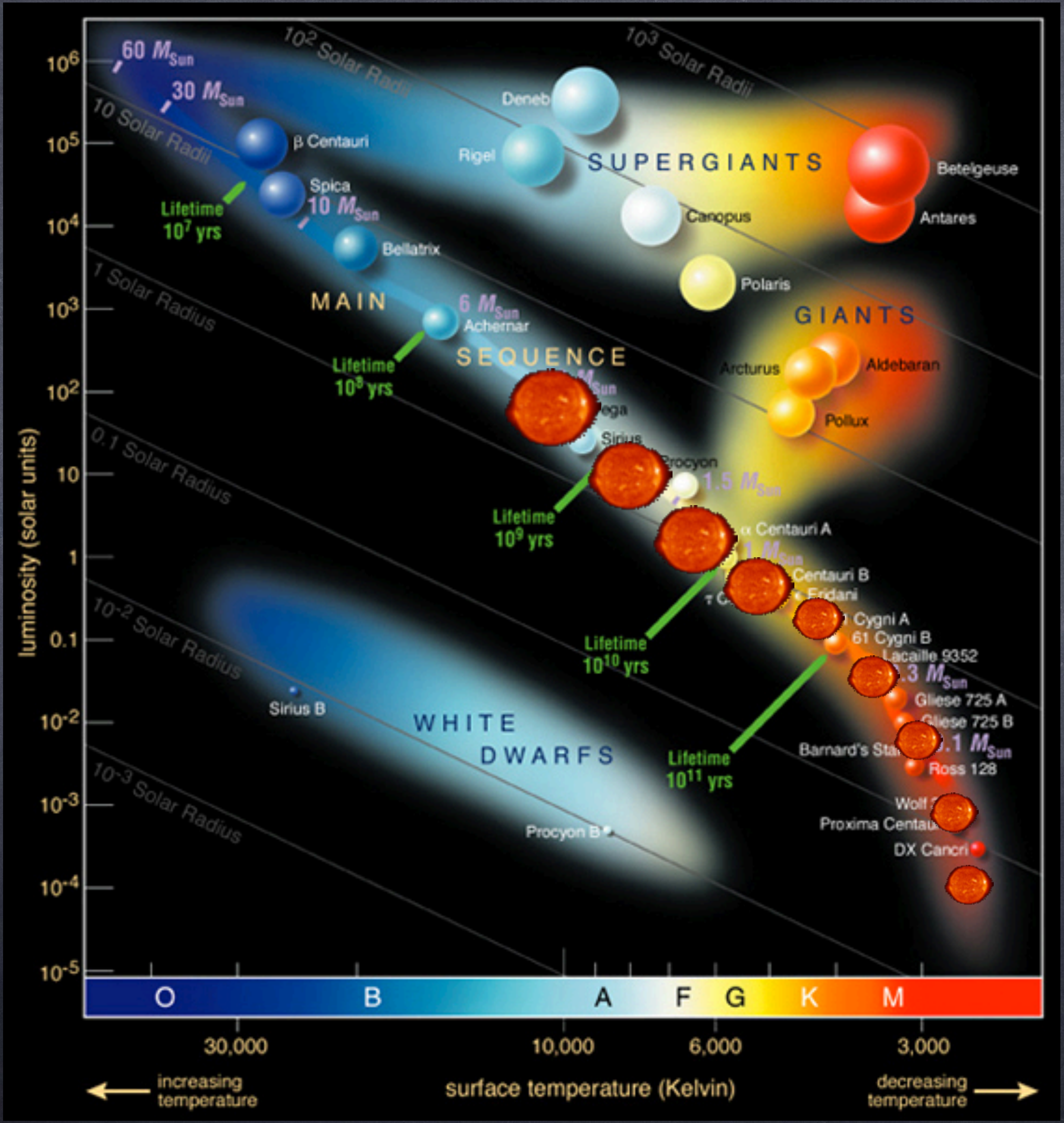
1. High-resolution global observations
2. High-cadence observations of temporal evolution
3. Multi-wavelength observations
4. In-situ observations of the interplanetary environment
5. Detailed and constrained models
6. Information only about one star

Stellar Astrophysics:

1. Statistical information on many stars
2. Data on different spectral types
3. Data on stellar evolution of each type, including solar analogs
4. Information about planetary systems
5. Limited knowledge about specific parameters
6. Limited knowledge about stellar winds and interplanetary environments
7. Unconstrained models

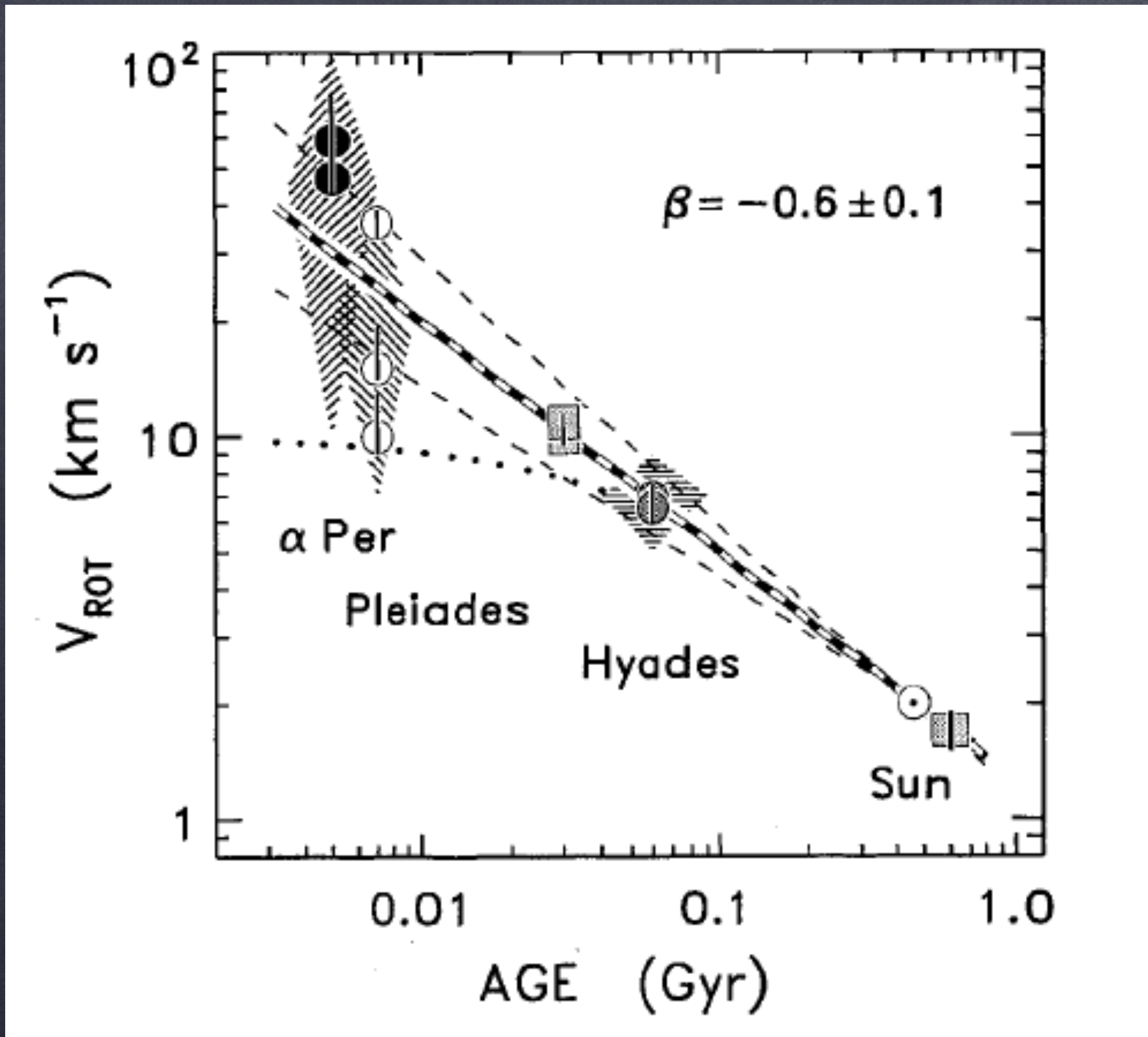
History of the Sun over time - solar system evolution and the evolution of the Earth (beginning of life)

More details and constrains about:
Fundamental parameters
Evolution
Magnetic fields
Stellar winds
Planetary environments
Planet formation

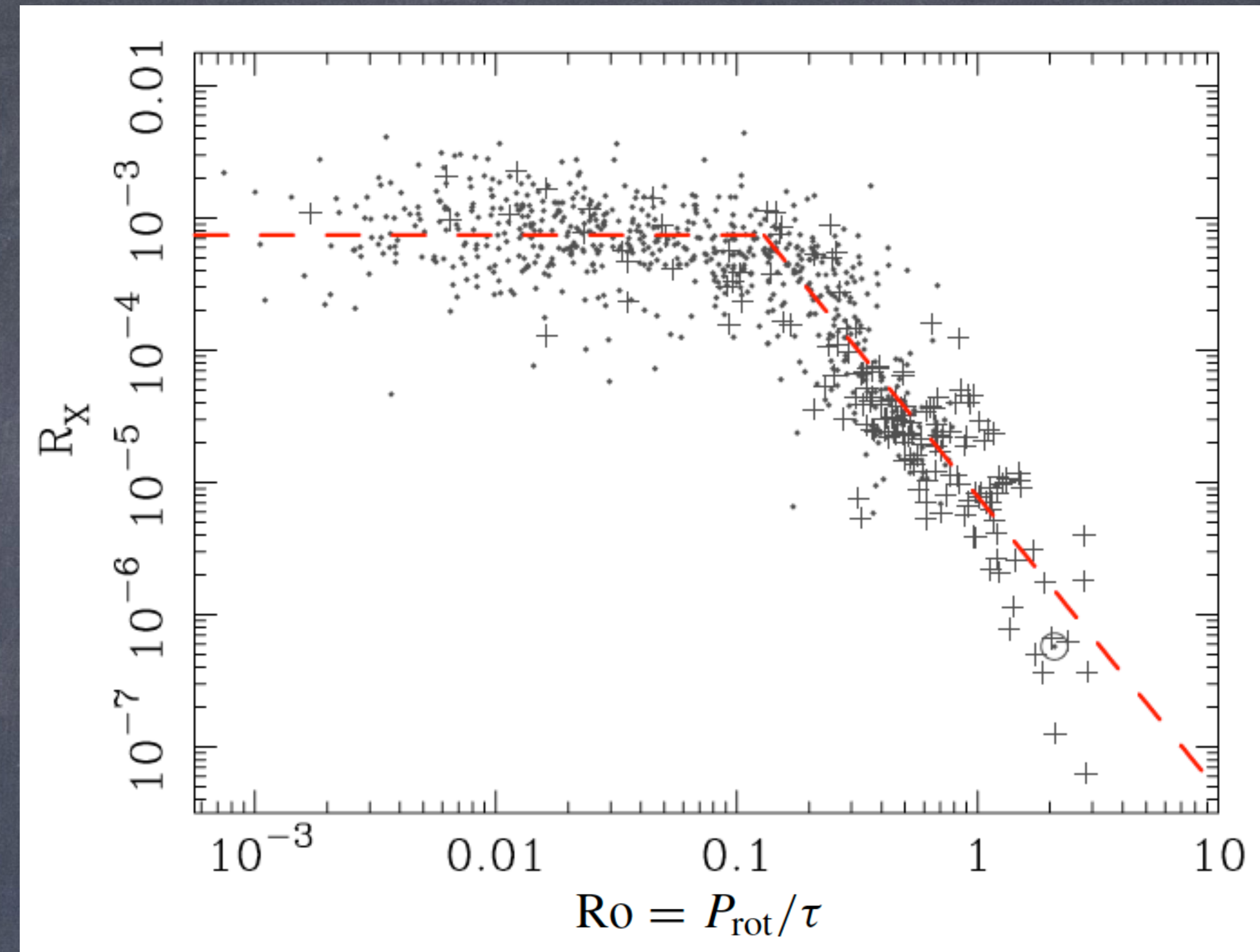


luminosity (solar units)
surface temperature (Kelvin)
increasing temperature
decreasing temperature
30,000
10,000
6,000
3,000
O
B
A
F
G
K
M
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
1.5 M_Sun
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
β Centauri
Spica
Bellatrix
Achernar
Arcturus
Aldebaran
Pollux
Sirius
Procyon
α Centauri A
Centauri B
Eridani
Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Sta
Ross 128
Proxima Centau
DX Cancri
Sirius B
Procyon B

Astrospheres & Stellar Evolution



Ayres 1997



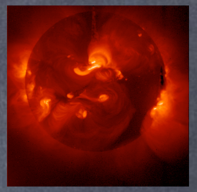
Wright et. al 2011

Skumanich Law:

$\Omega \propto \tau^{-1/2}$

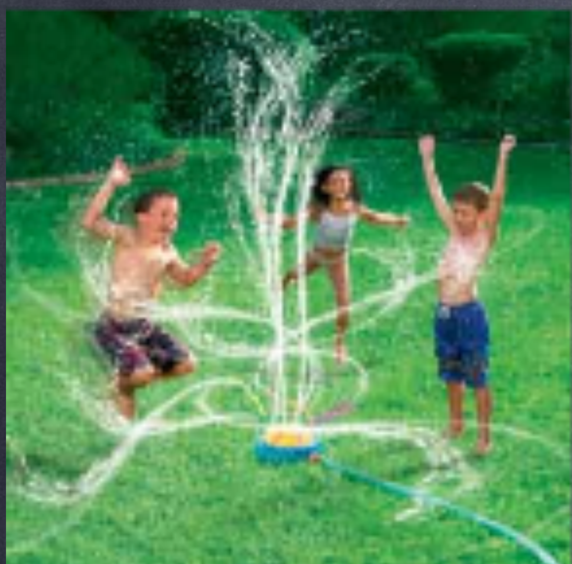
Rotation 

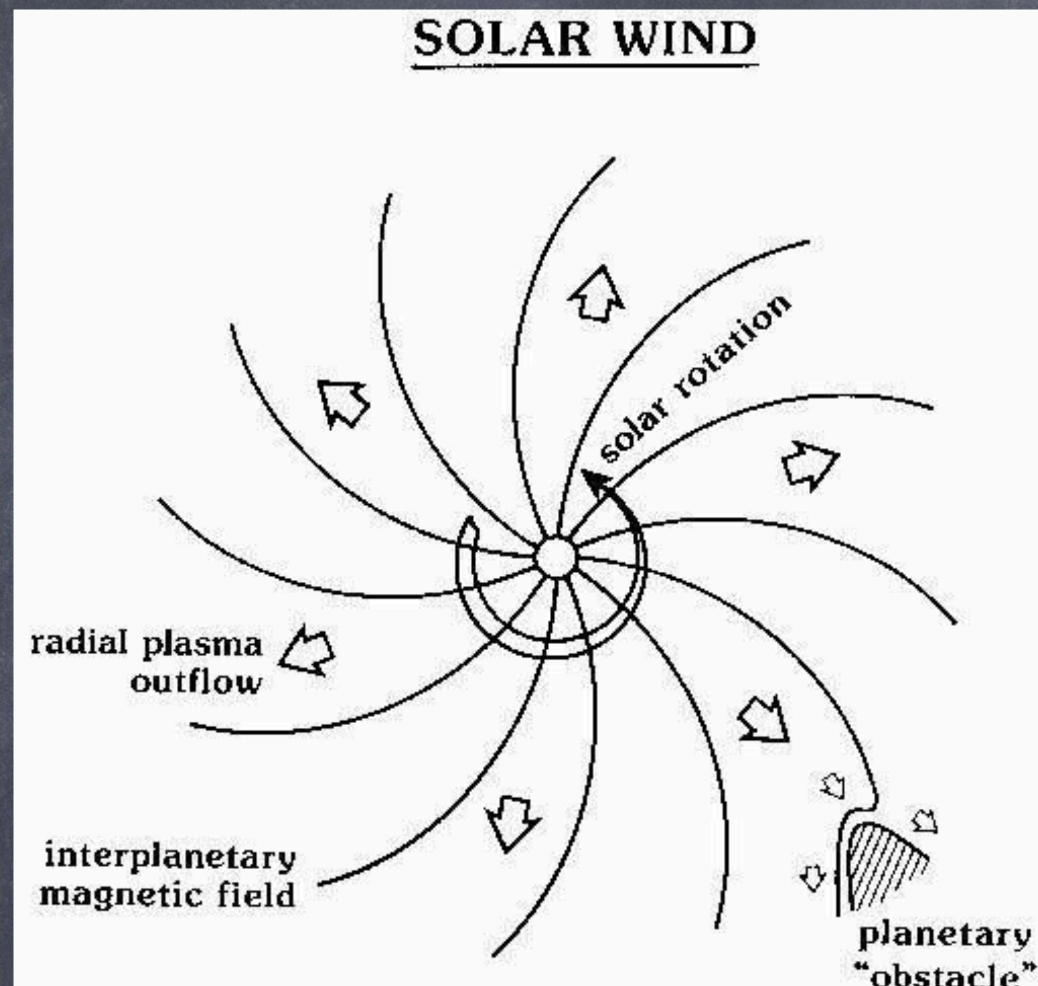
Age 

Stellar activity 

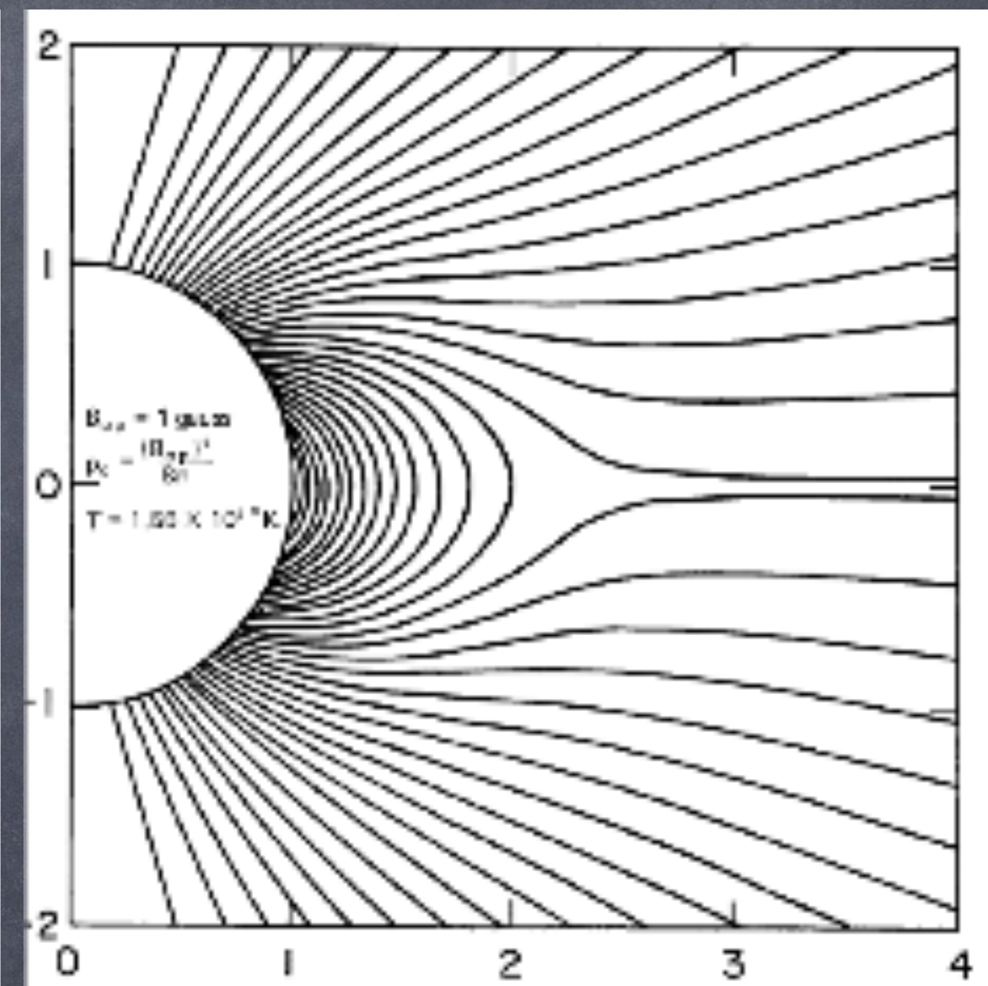
Magnetic field 

The structure of the Astrospheric Magnetic Field (AMF):





By J. Luhmann



Pneumann & Kopp 1971
HAO!!!

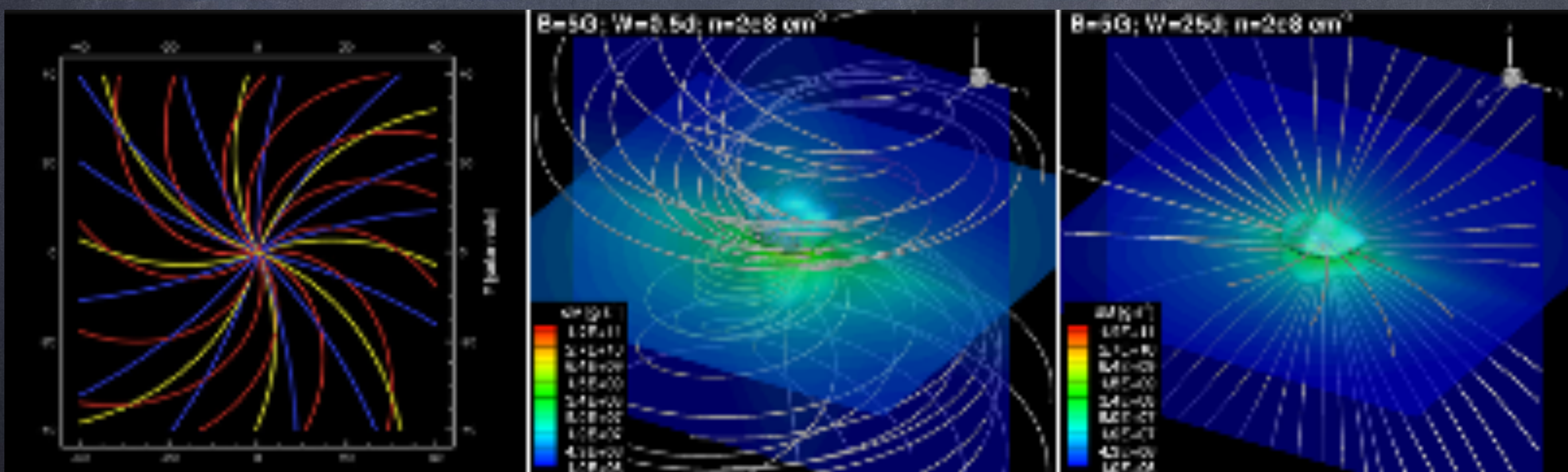
for $r \gg r_0$

$$\mathbf{B}(\mathbf{r}) = B_s \left(\frac{r_0}{r}\right)^2 \left[\hat{r} - \frac{r\Omega_\odot \sin\theta}{u_{sw}}\hat{\phi}\right]$$

The effect of stellar rotation:

$$\mathbf{B}(\mathbf{r}) = B_s \, \Omega_{\odot} \, \frac{\Omega_{\odot} \sin\theta}{u_{sw}} \hat{\phi}]$$

For faster rotations, the azimuthal component dominates the AMF:



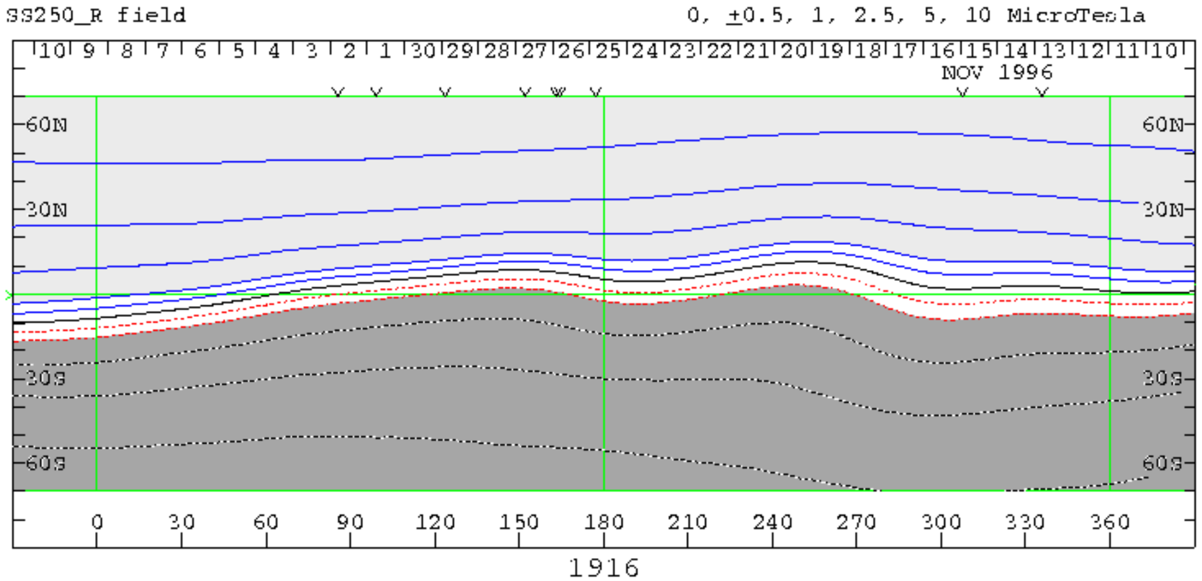
Cohen, drake & Kota, 2012; Cohen & Drake 2014

The effect of B_s:

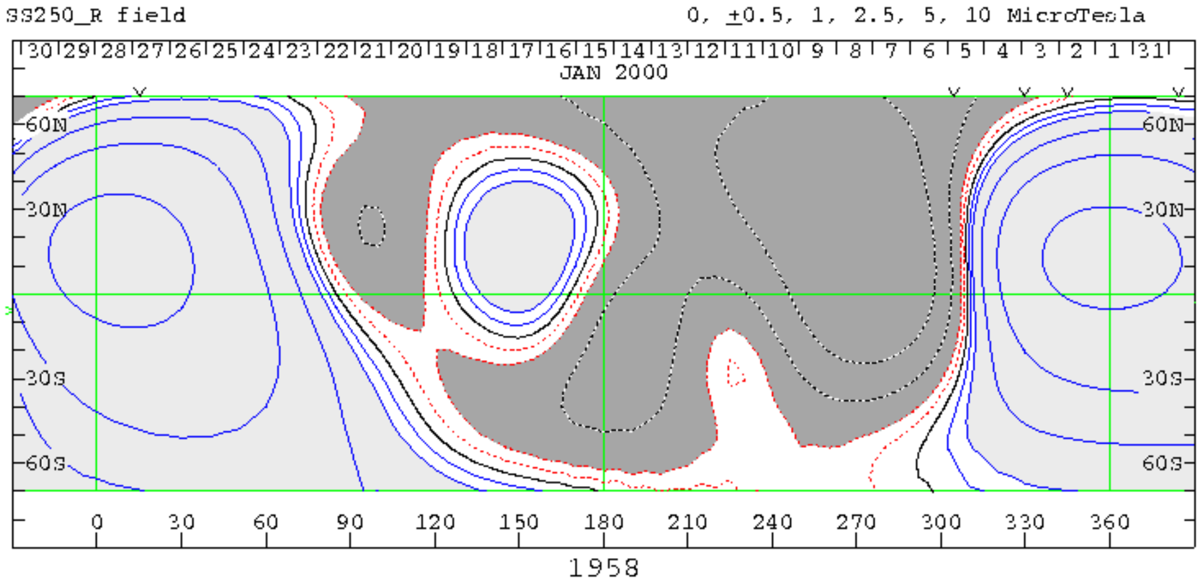
$$\mathbf{B}(\mathbf{r}) = B_s \Big(\cdots \; B_s \; \cdots \frac{r\Omega_\odot \sin\theta}{u_{sw}}\hat{\phi} \Big]$$

B_s is not uniform and $u_{sw}(B_s)$.

Solar Minimum



Solar Maximum

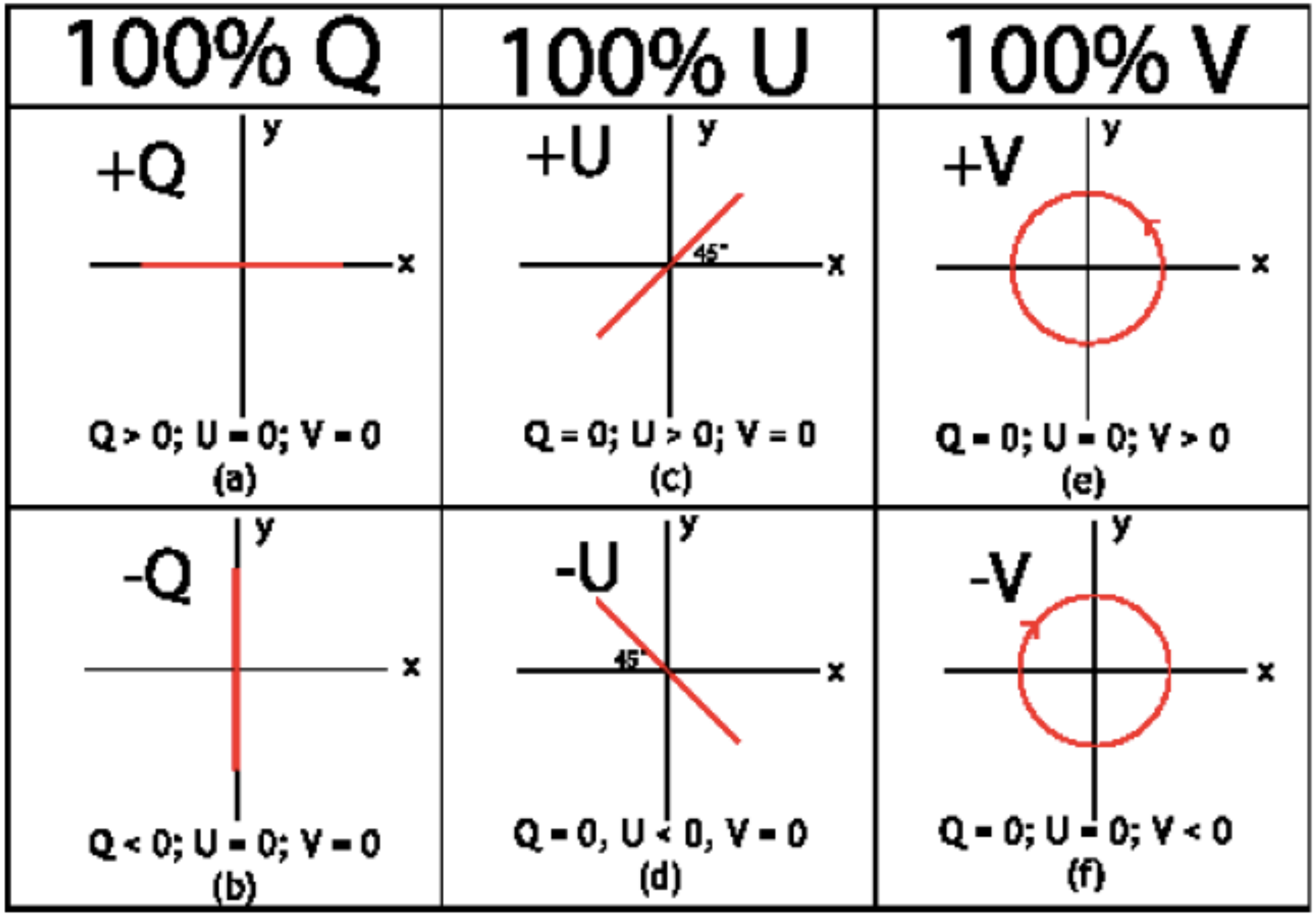


Wilcox Solar Observatory data

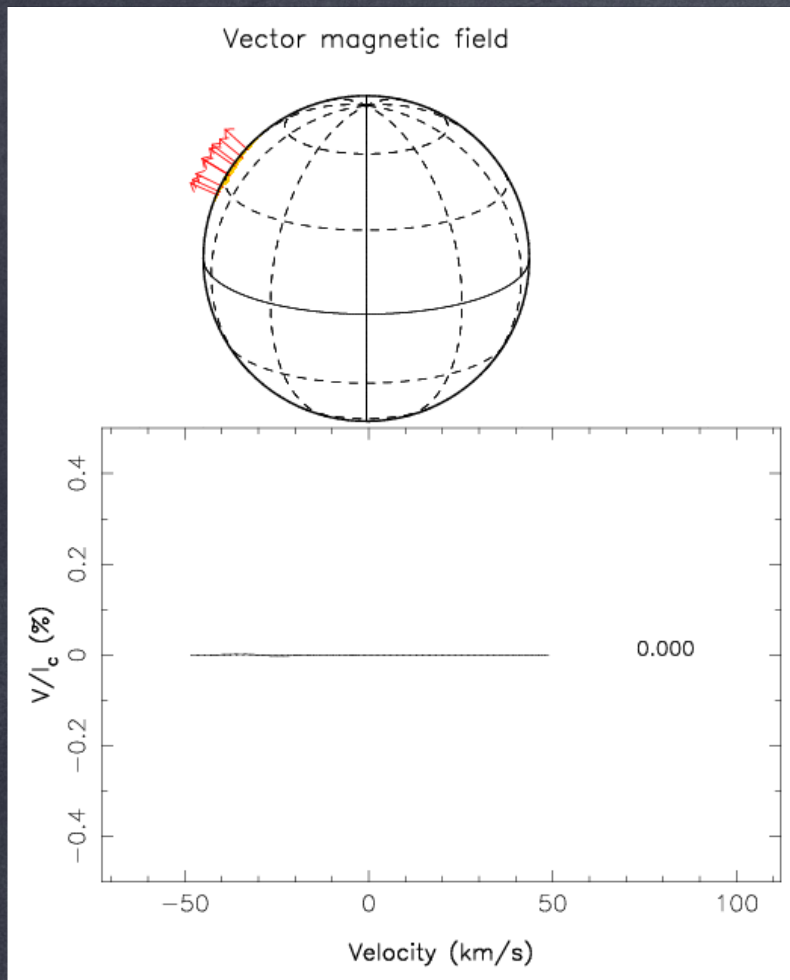
Magnetic field and light polarization

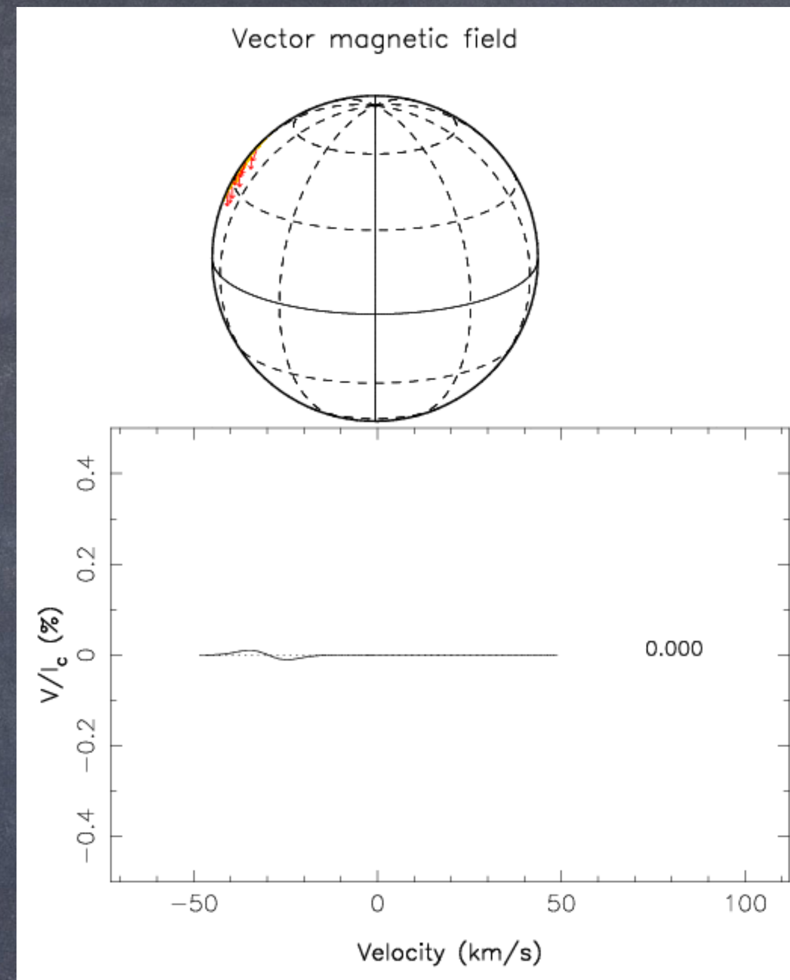
Linear polarisation of a line   Q and U give the transverse field components

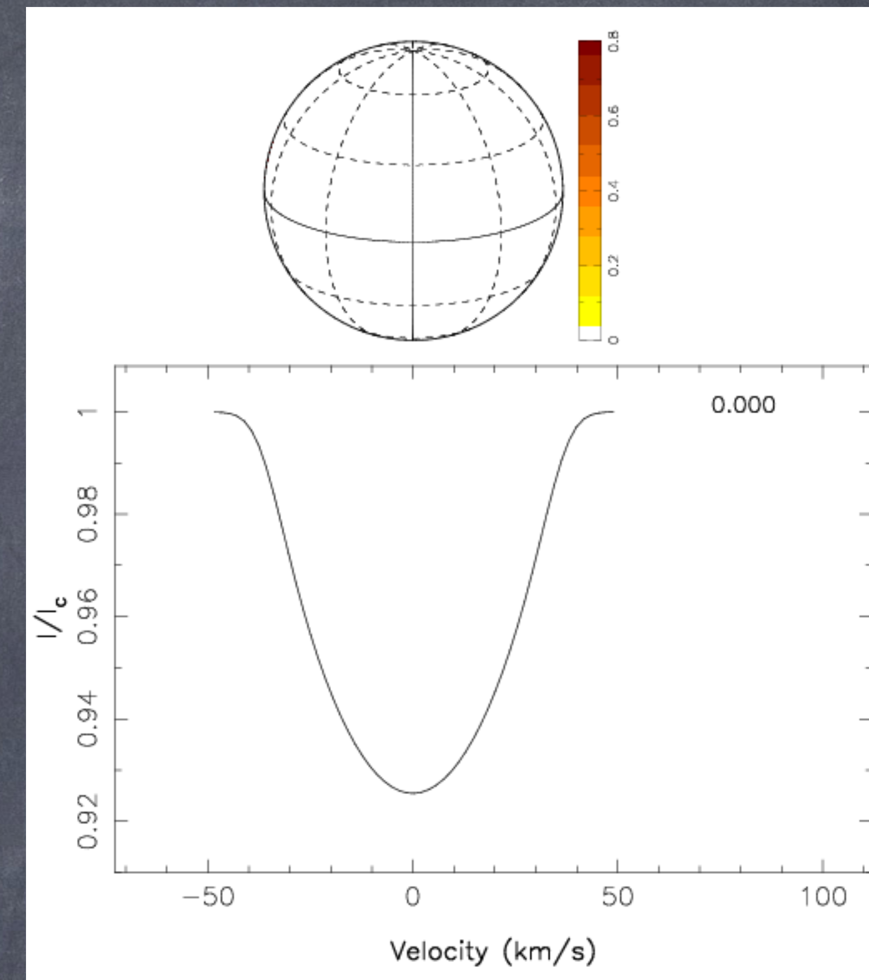
Circular polarisation   V gives the line-of-sight components

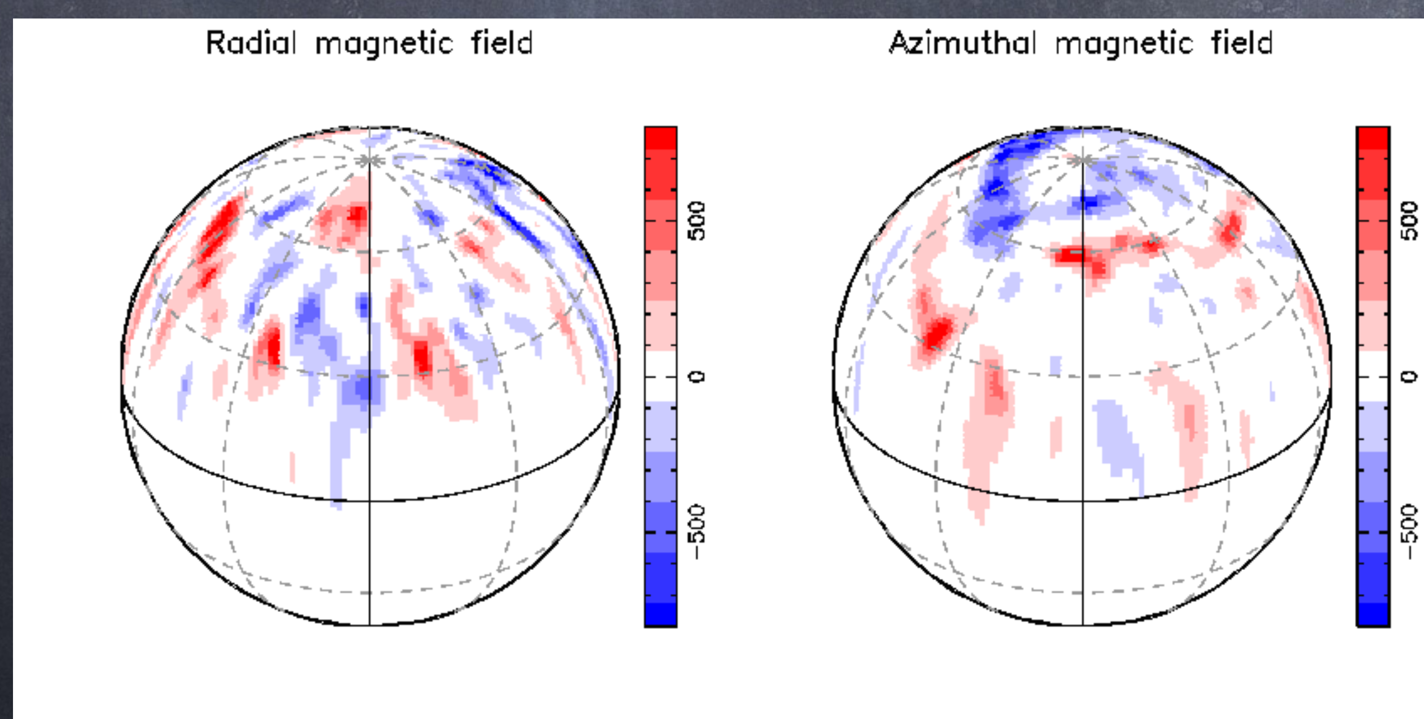


Zeeman–Doppler imaging (ZDI)



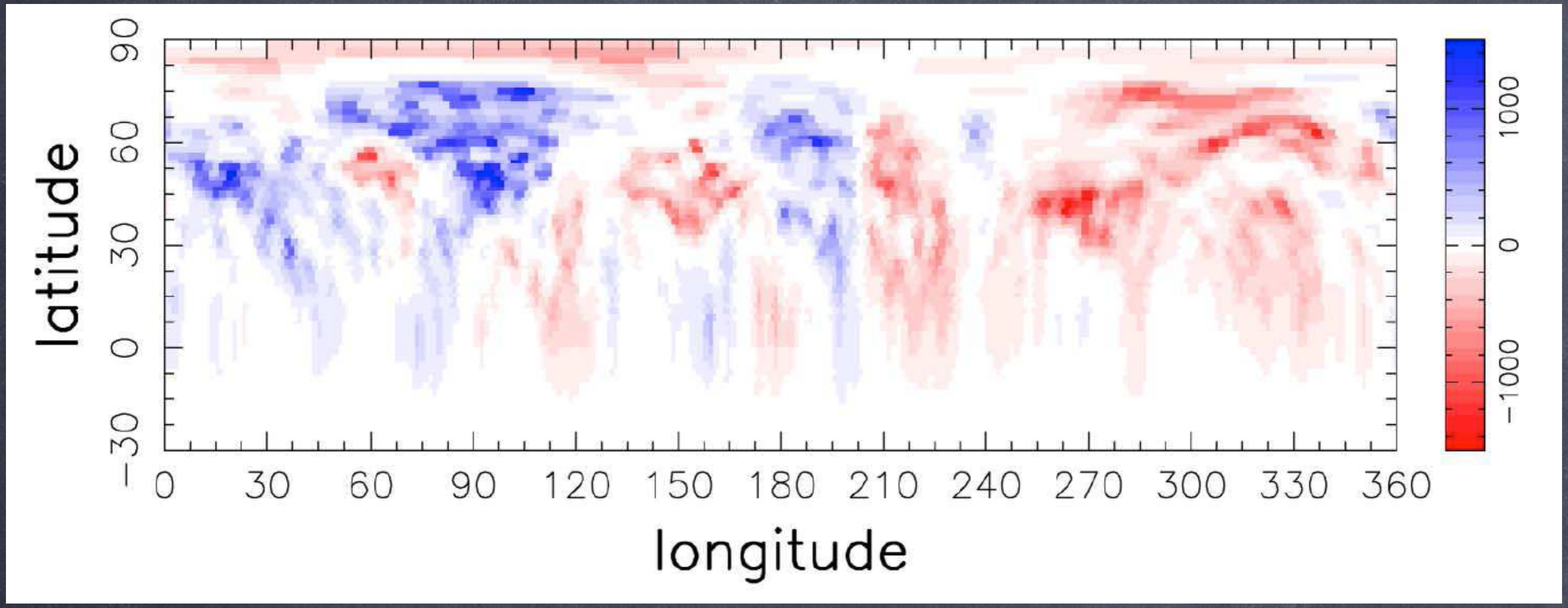




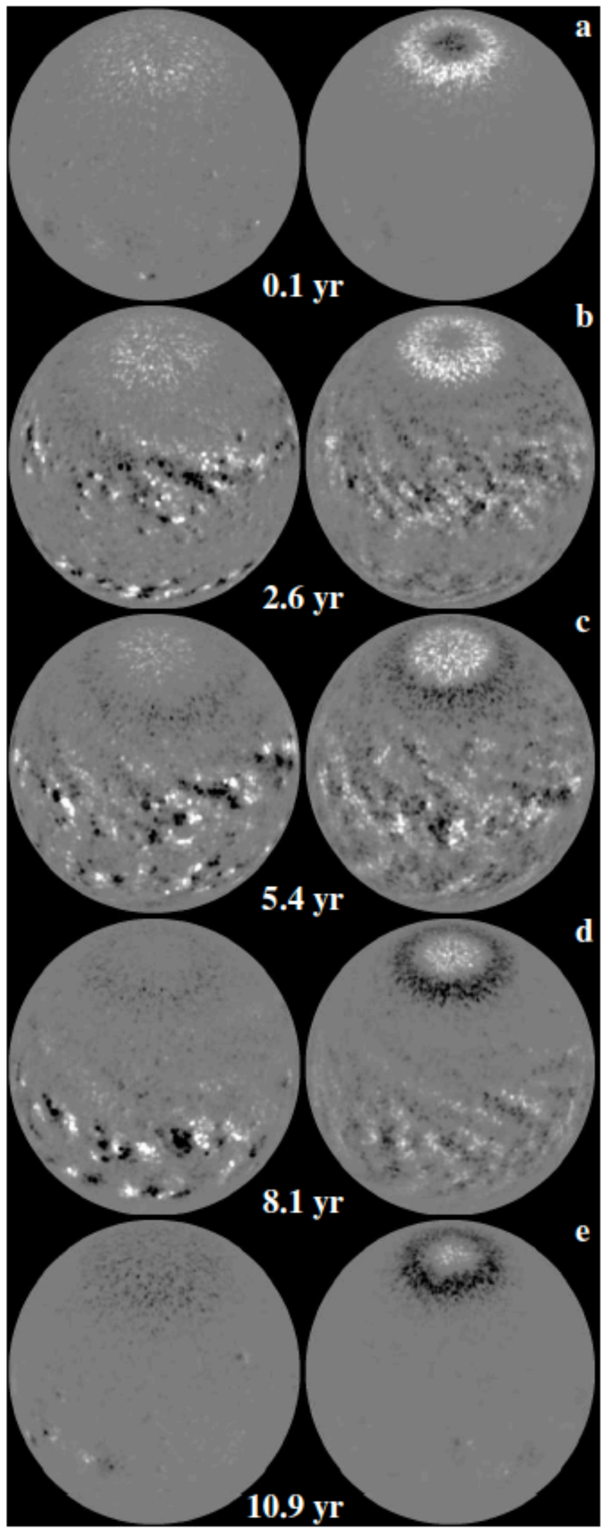


Young, active, fast-rotating stars seem to have their magnetic activity concentrated at high latitudes.

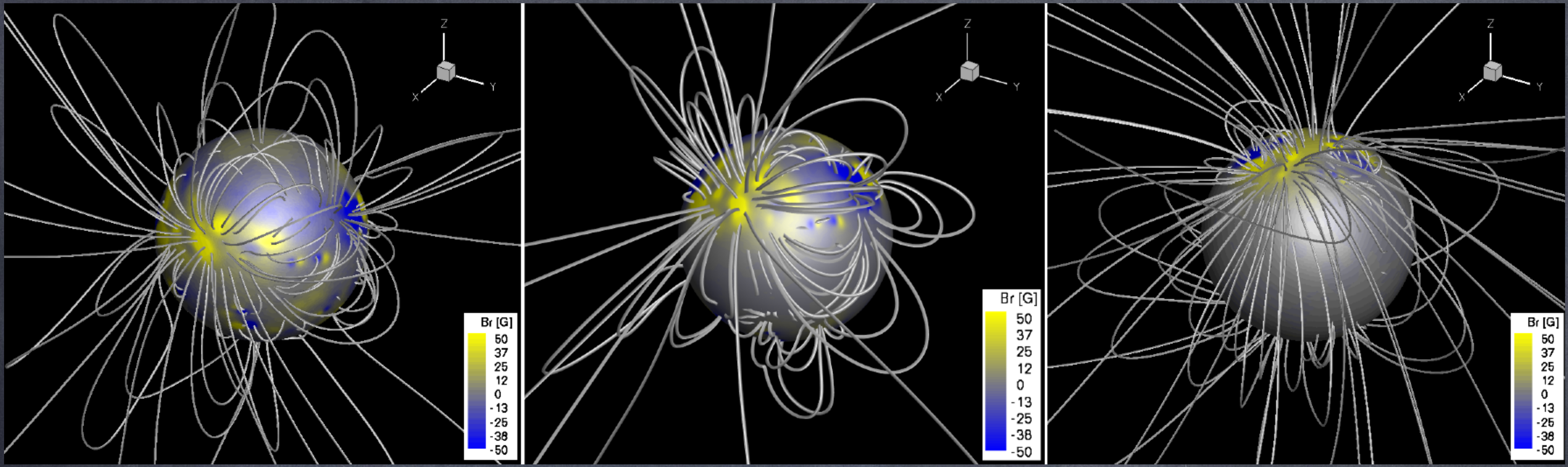
AB Doradus - young active Sun (P=0.5 days):



Hussain et. al 2007

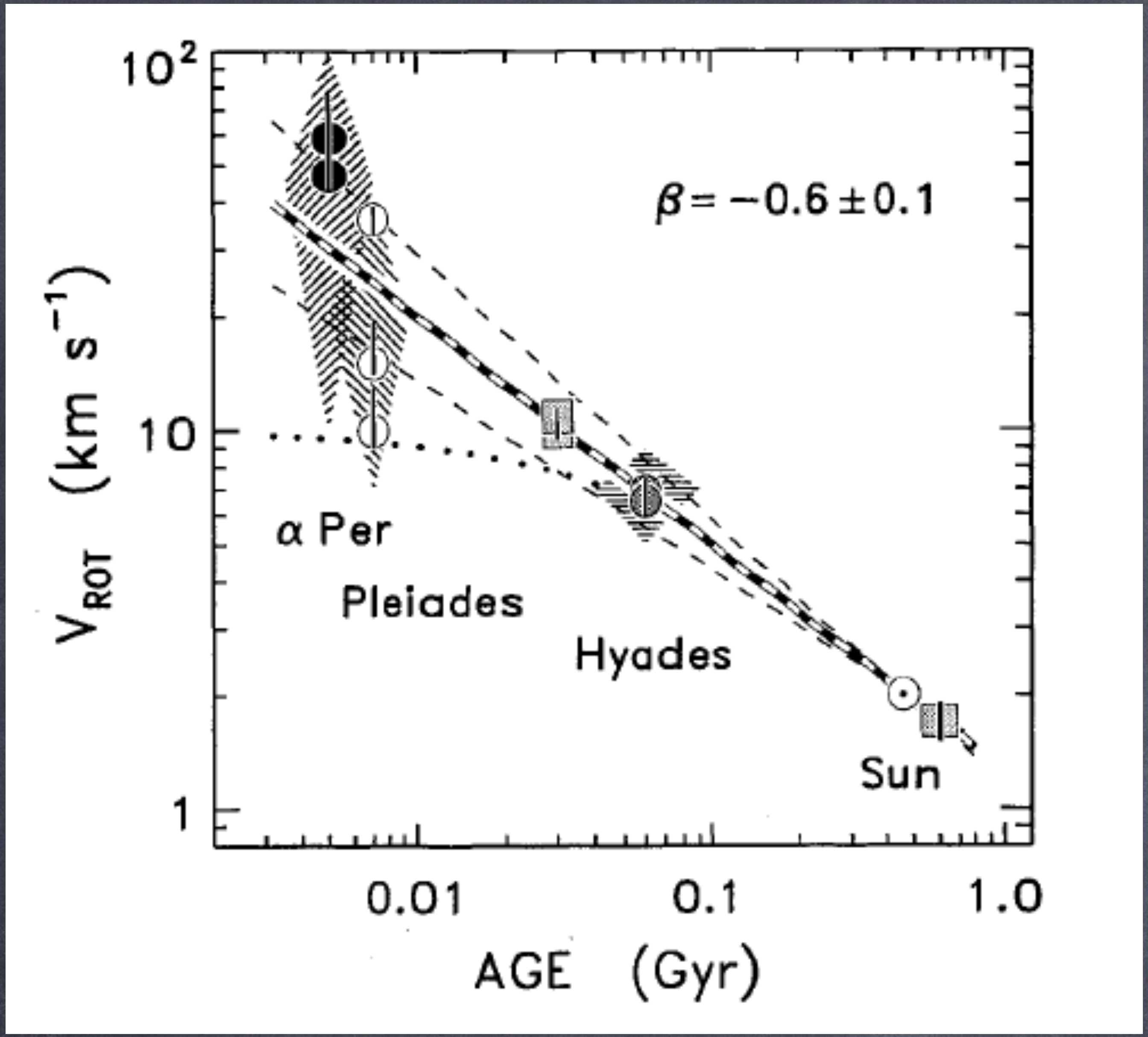


Schrijver & Title 2001



Cohen, Drake & Kota, 2012

Stellar Mass-loss and Stellar Spindown



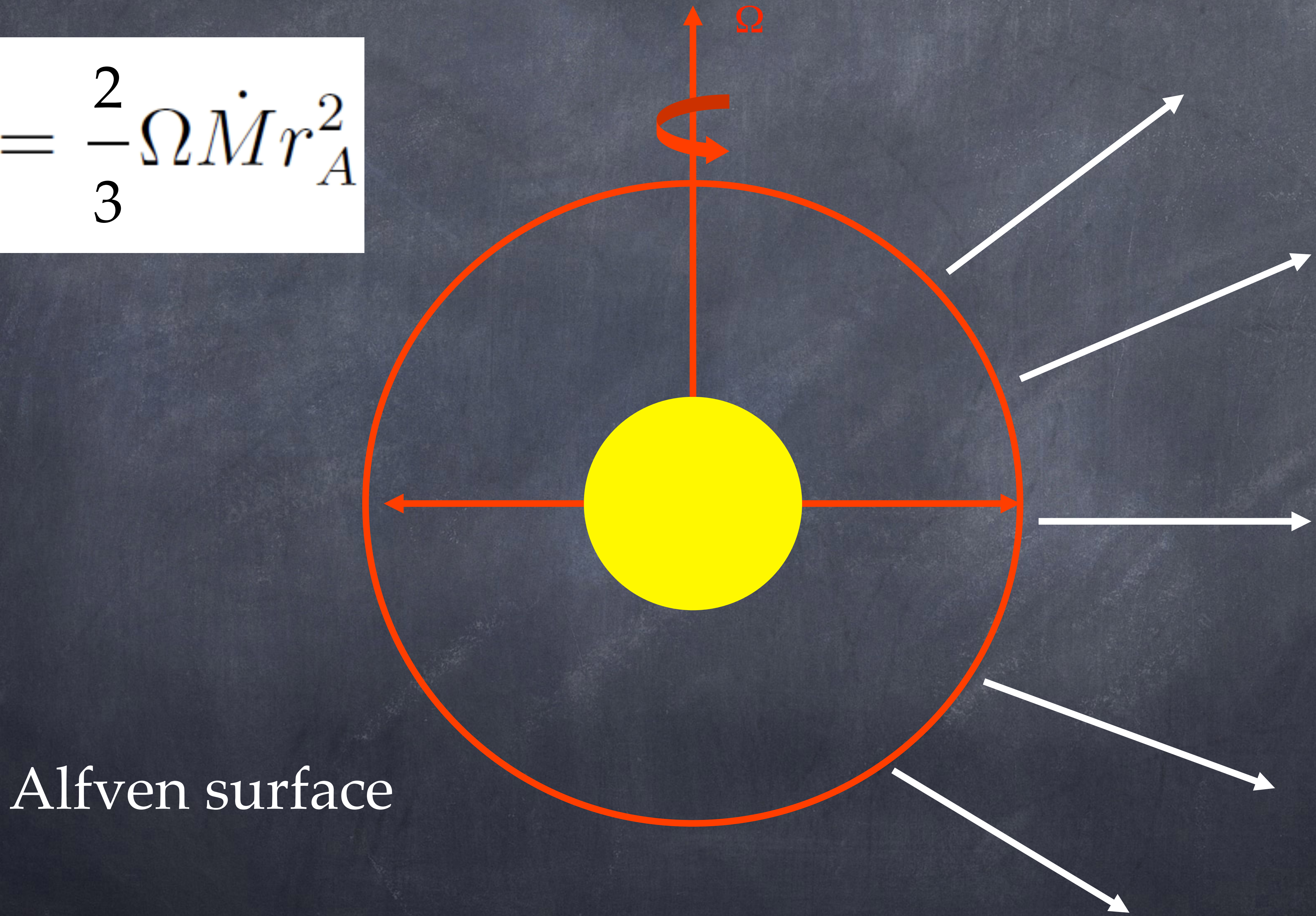
Ayres 1997

Skumanich Law:
$\Omega \propto \tau^{-1/2}$

We need a mechanism explain stellar loss of angular momentum over time.

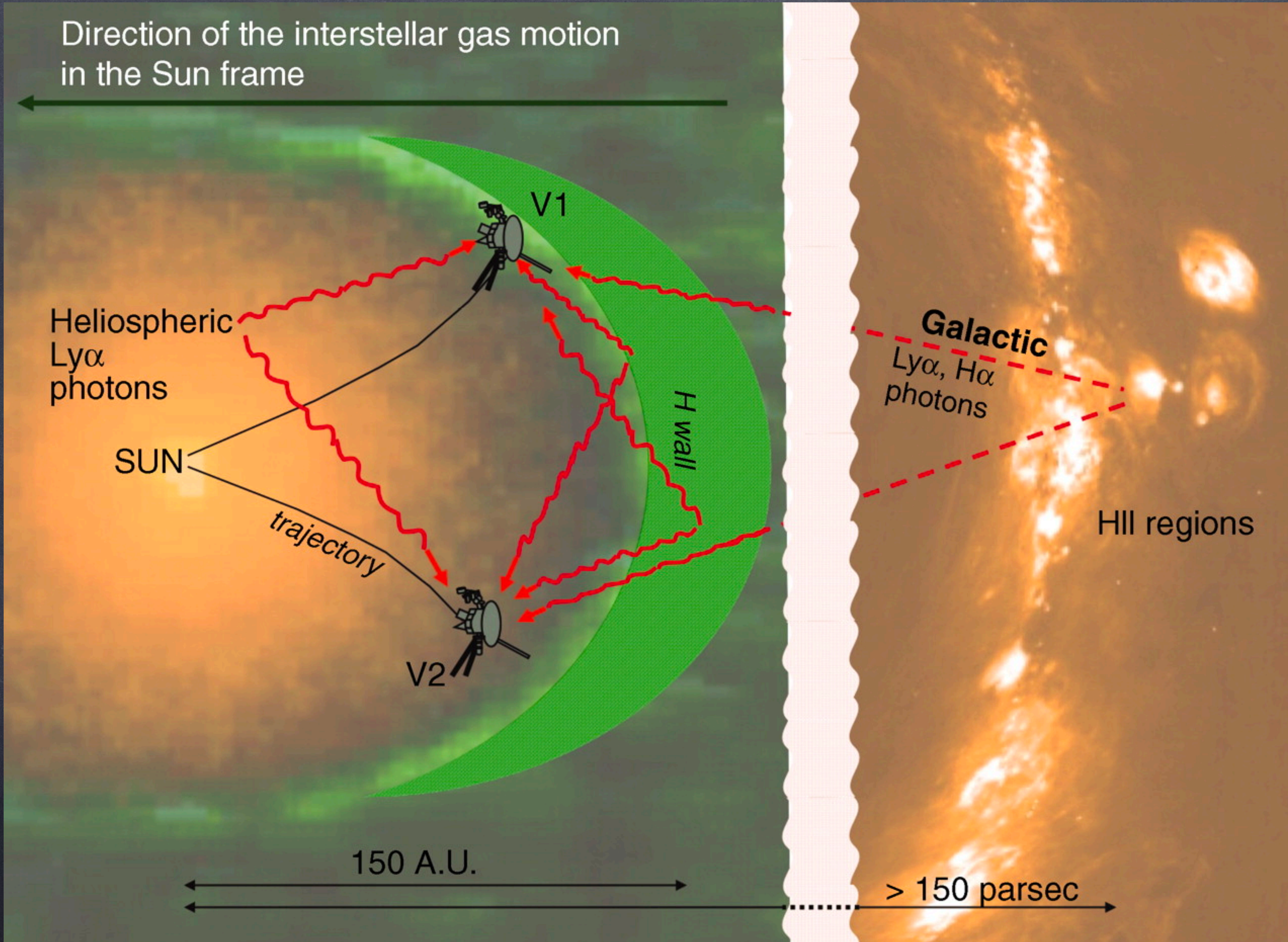
Stellar angular momentum loss to the magnetized wind ("magnetic breaking" - Weber-Davis, 1967):

$$\dot{J} = \frac{2}{3}\Omega \dot{M} r_A^2$$



$$\frac{\dot{\Omega}}{\Omega} \propto \frac{\dot{M}}{M} \left(\frac{R_{\mathrm{A}}}{R_{\odot}} \right)^{m}$$

Defining stellar mass-loss rates is a key for understanding stellar evolution!!!

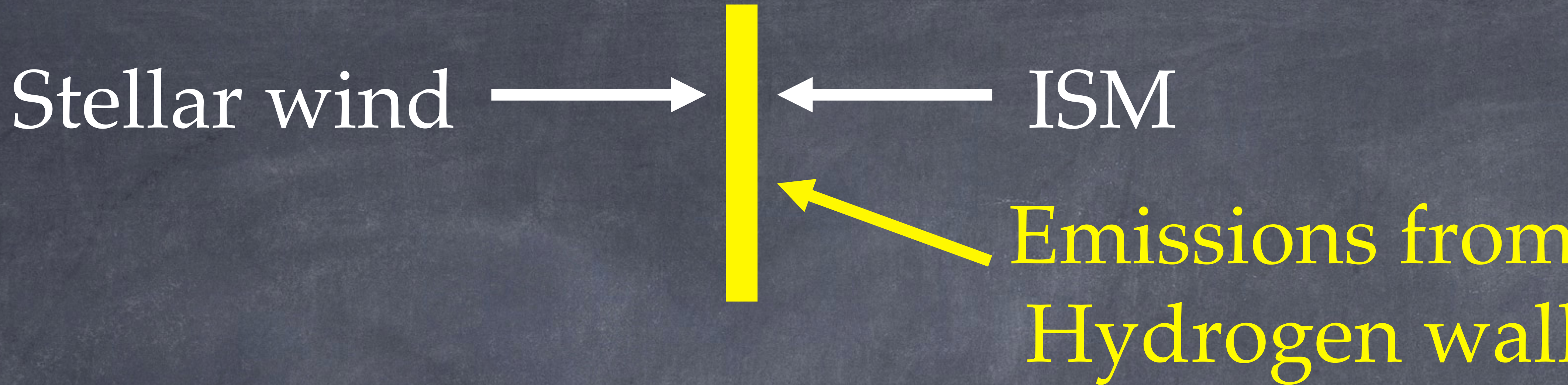


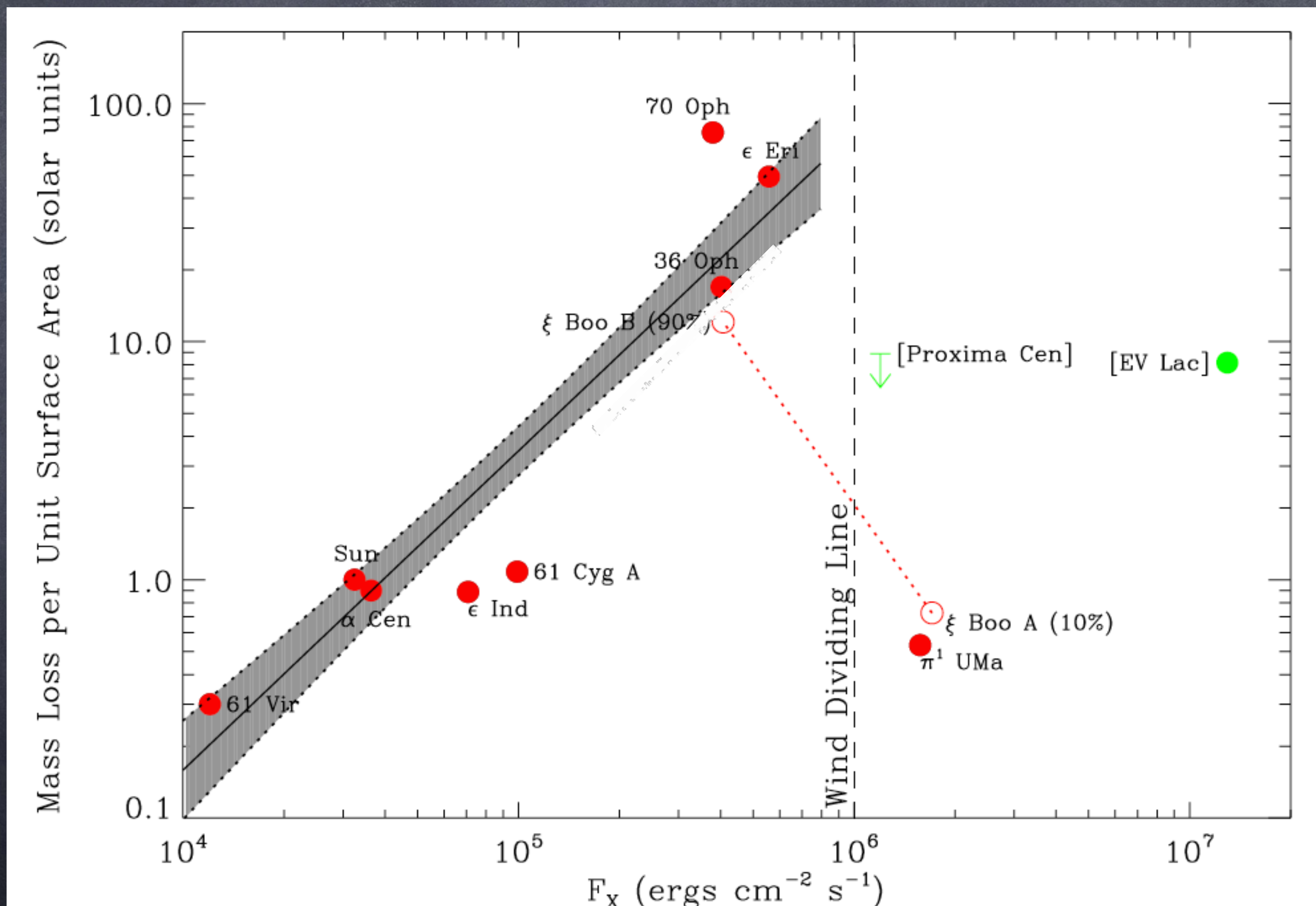
sciencemag.org

Image courtesy of
R. Caslegno, C.
Conselice et al.,
WIYN NOAO

Other images from
HubbleSite.org

Closeup of IRS8,
resolving the bow shock
of a fast-moving star





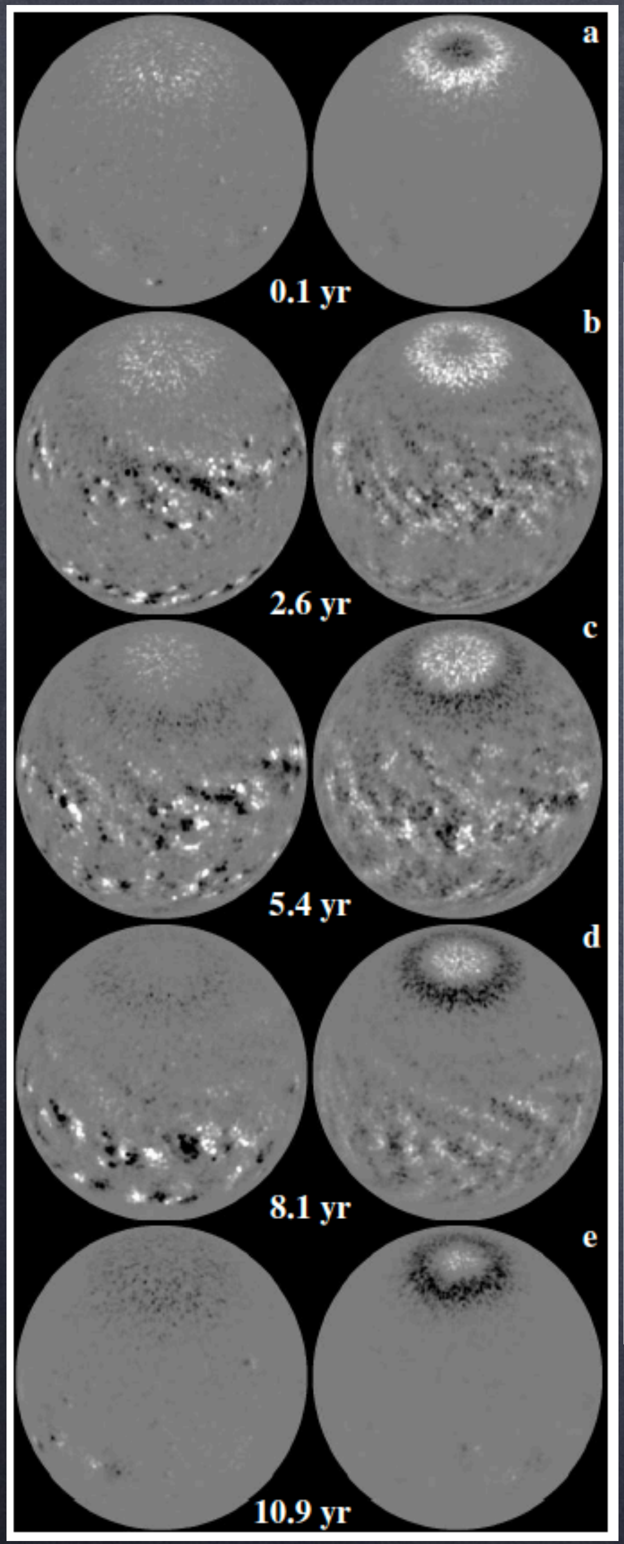
Wood et. al 2014

How do CMEs change with stellar evolution and change in activity level?

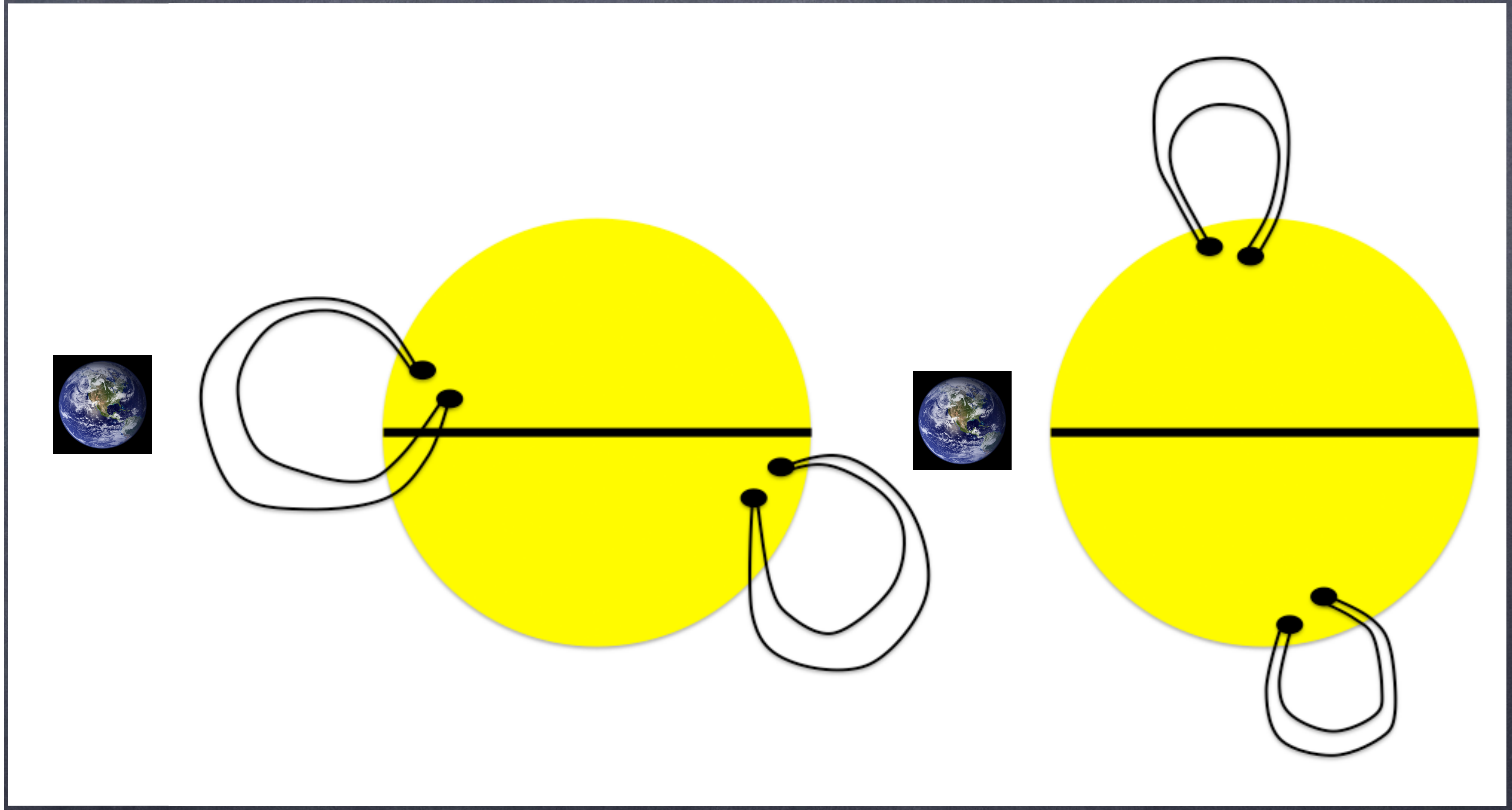
- Impact on CME initiation.
- Impact on propagation & evolution.

Observations:
Stellar flares...

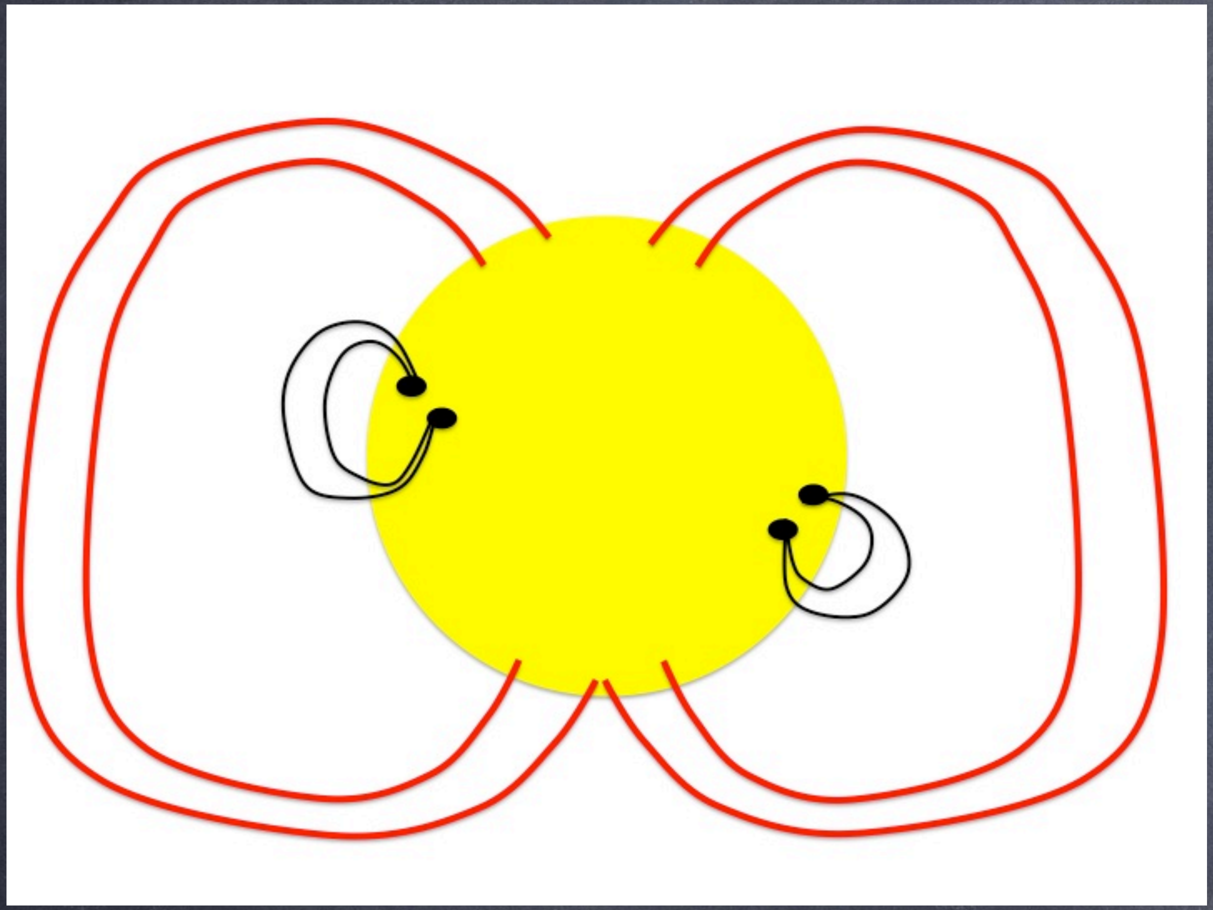
Impact on CME initiation:

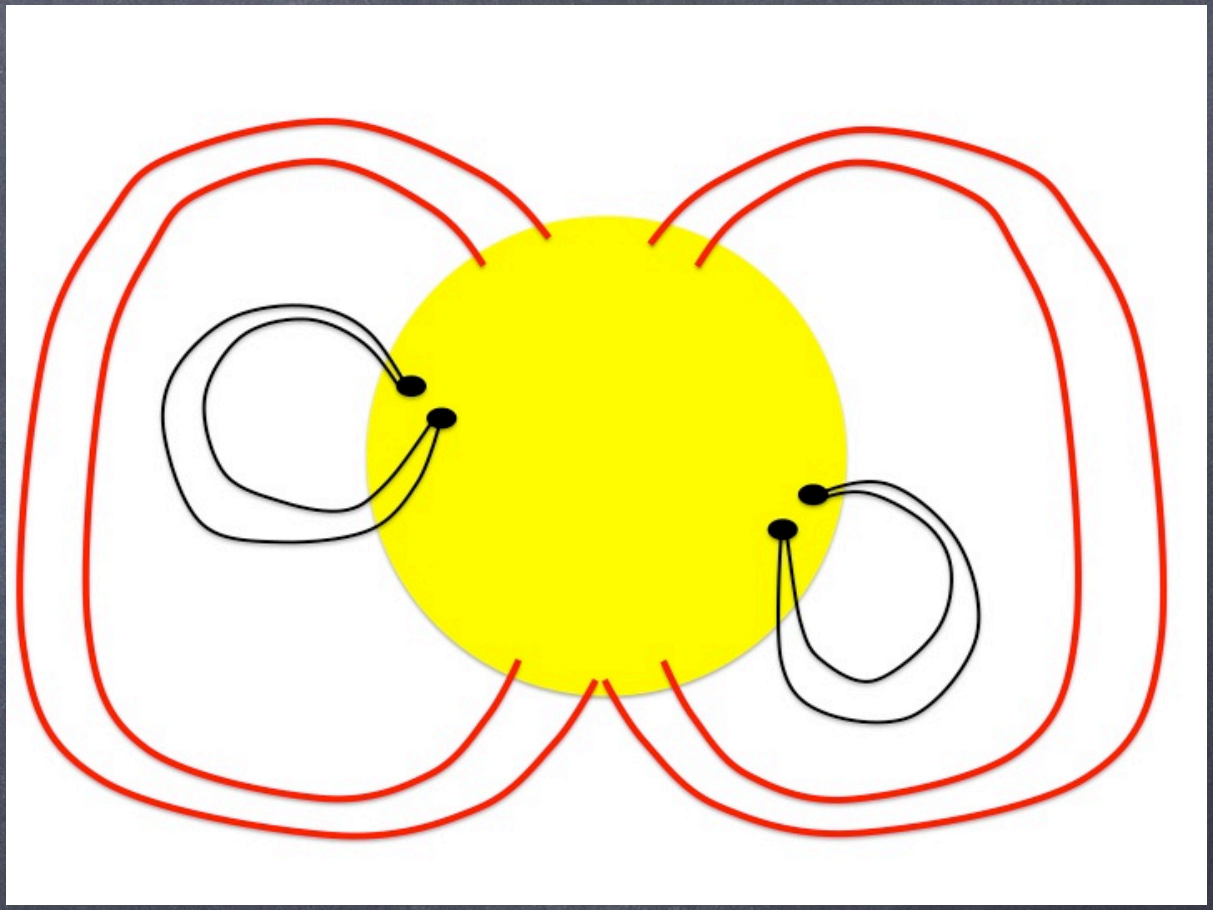


Schrijver & Title 2001



Do stellar CMEs scale with the overall increase in magnetic energy?

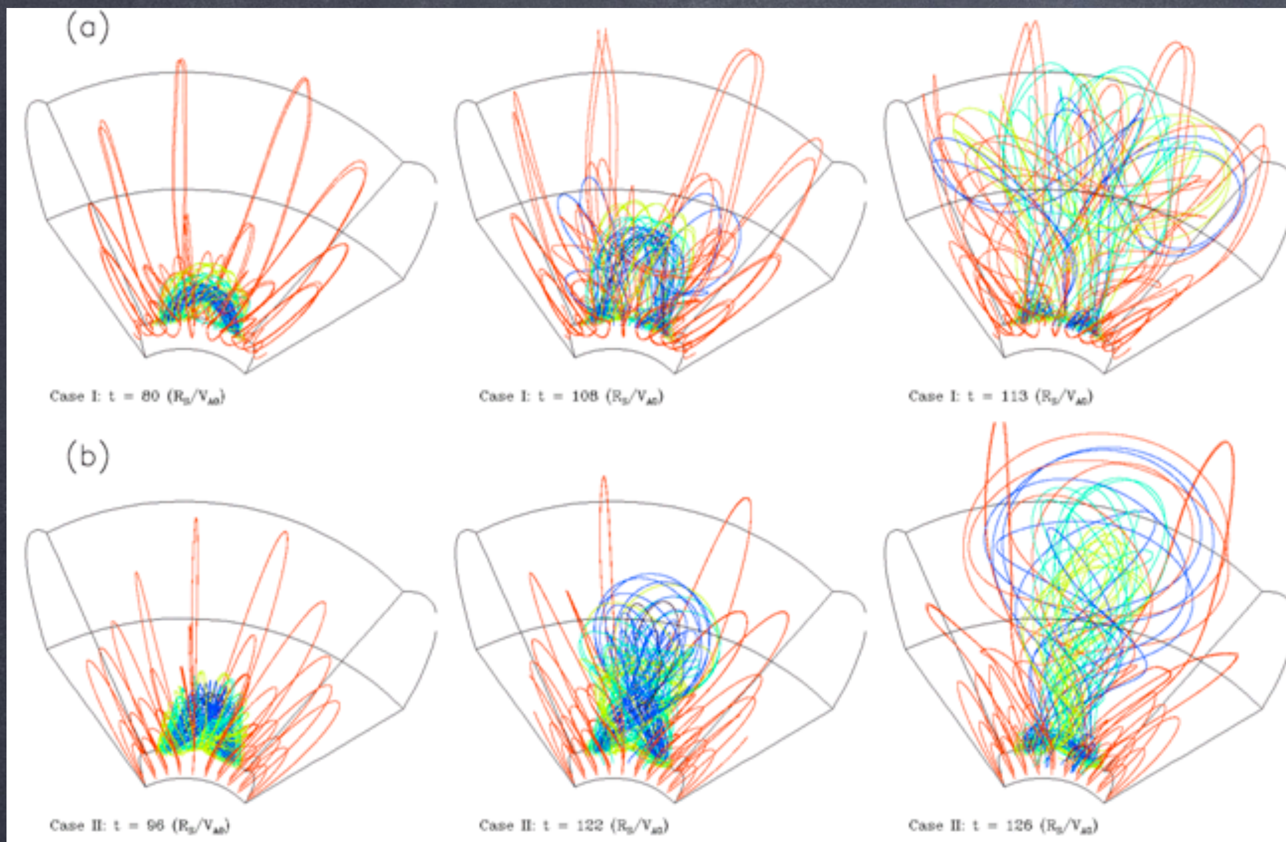




Open question...

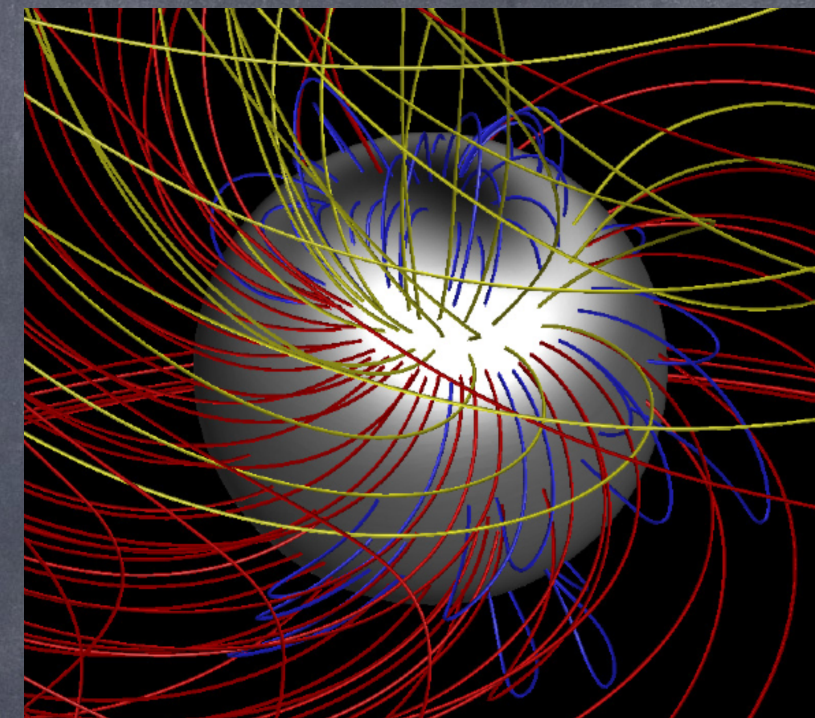
Different initiation mechanism?

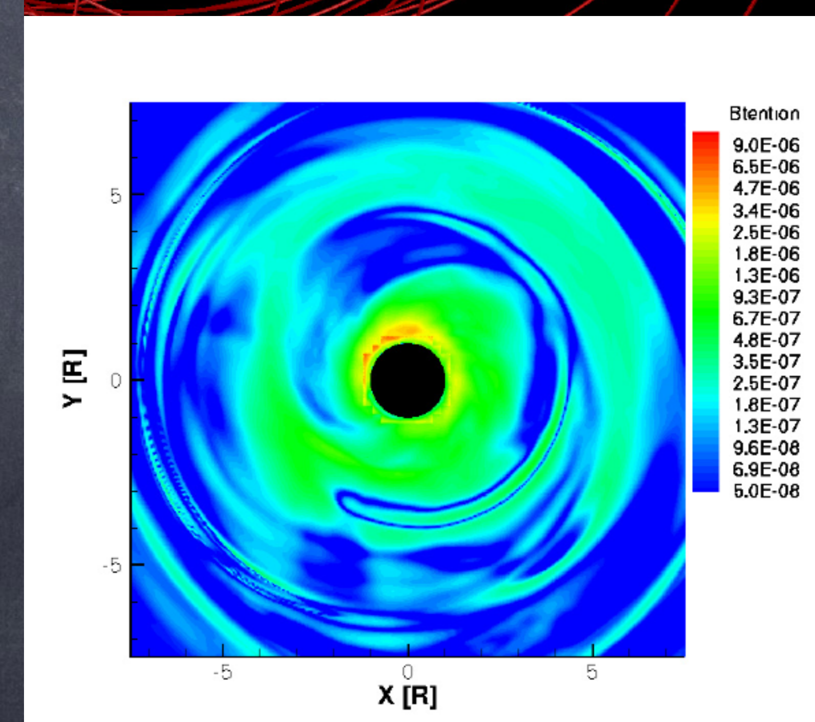
Solar CME



Fan & Gibson 2007

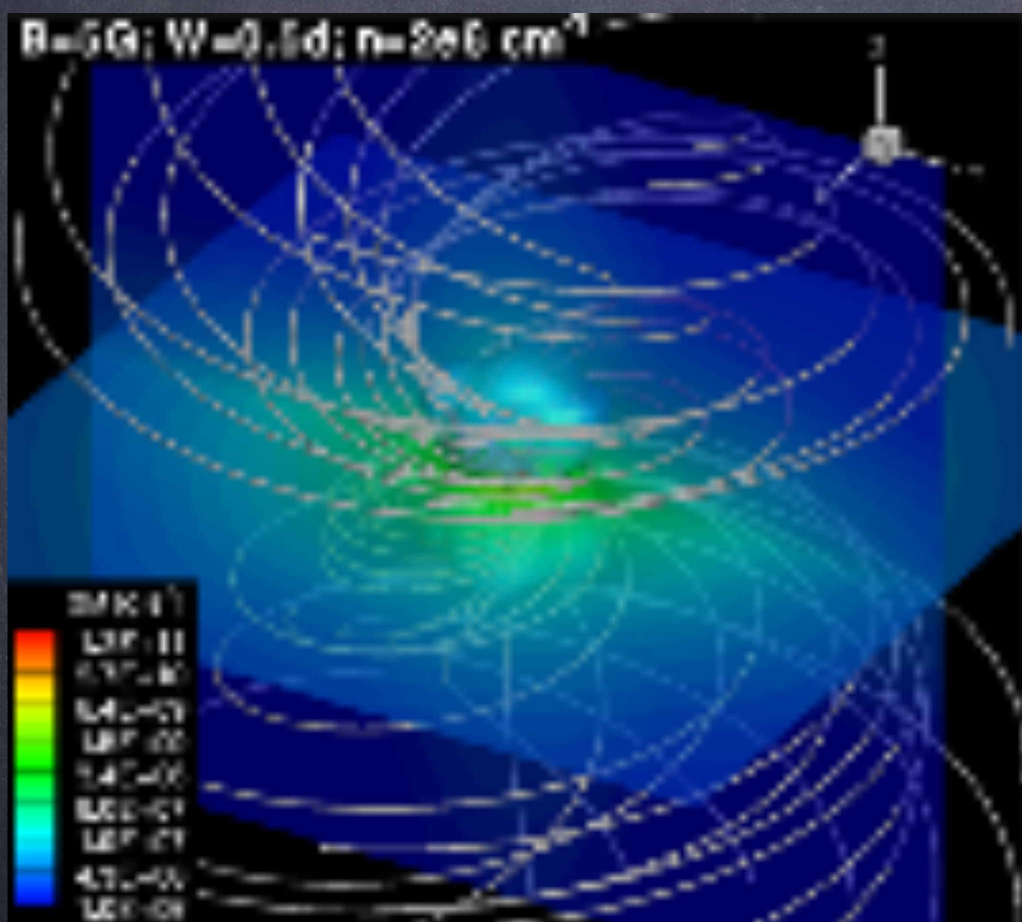
FK Comae



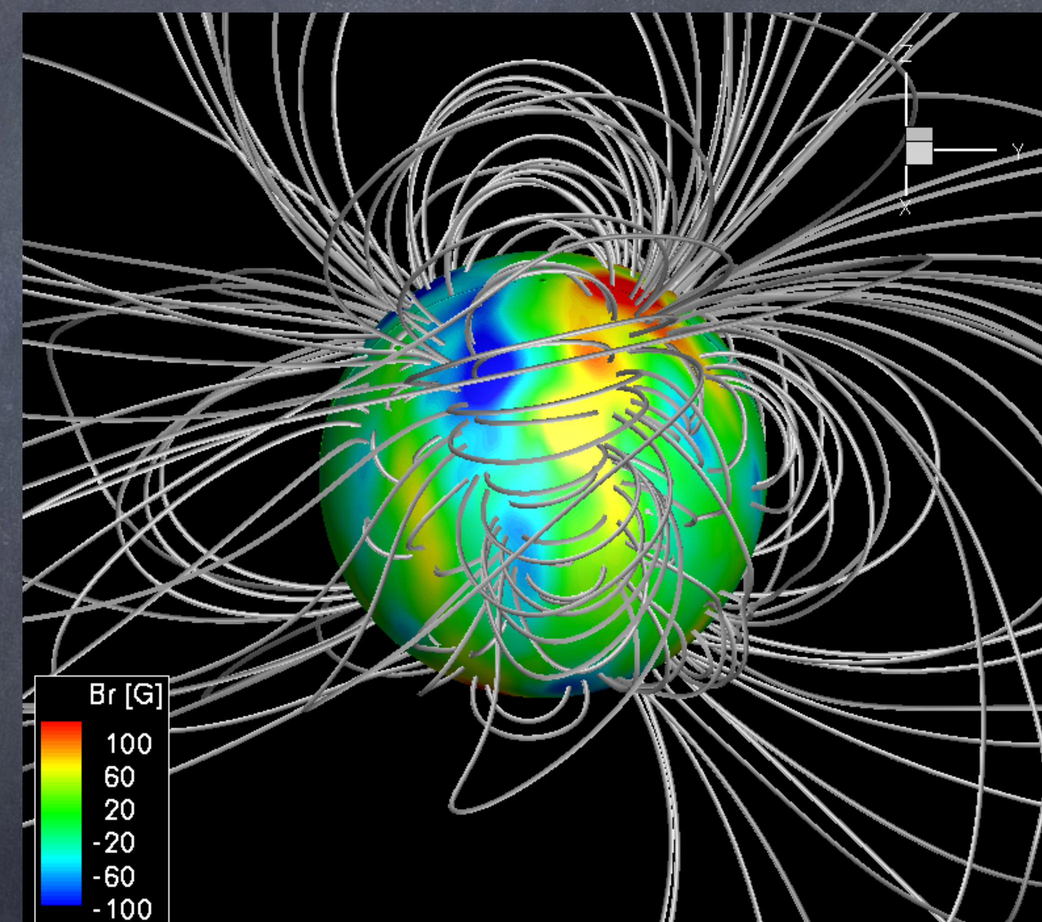


The propagation and evolution of CMEs depend on the Astrospheric field.

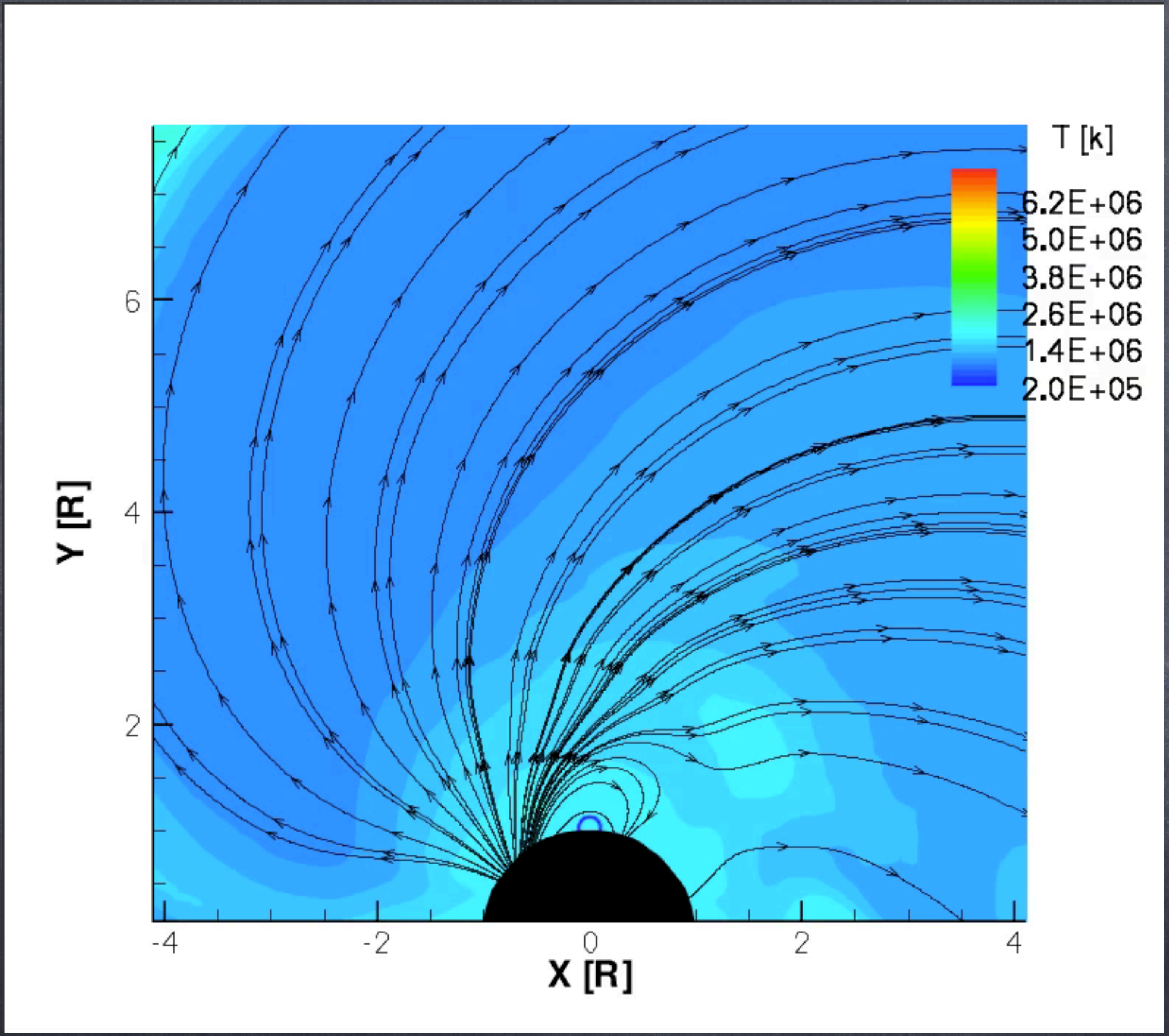
Strong azimuthal field close to the star



Strong field strength



A toy simulation of a CME on AB Doradus



Winds mass-loss rates of cool stars - 10^{-15}-10^{-12} Msun/yr.

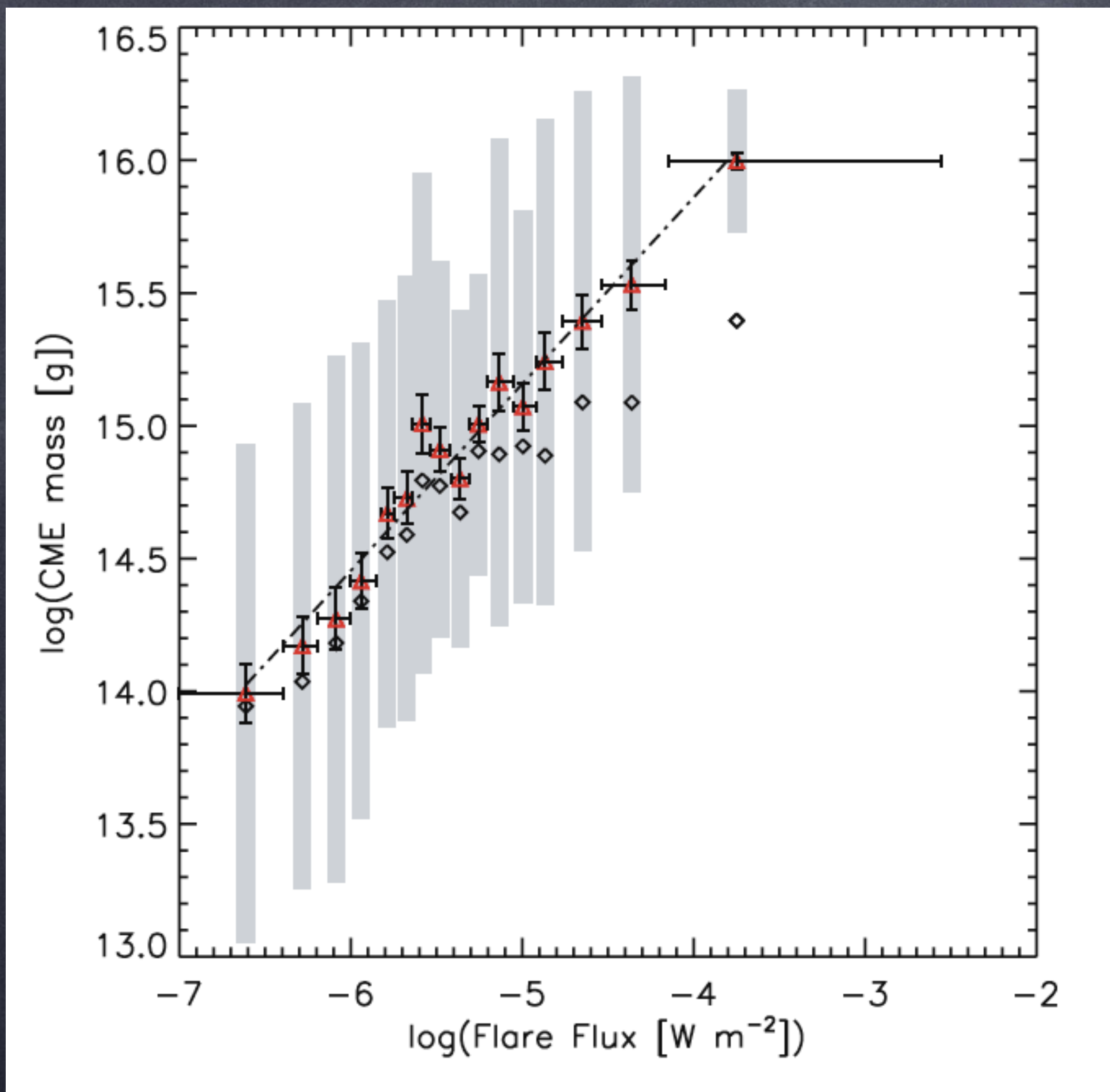
Solar wind mass-loss rate:
rho_{SW}*u_{SW}*$4\pi(1AY)^2$ = 2* 10^{-14} Msun/yr.

Mass-loss rate due to CME:
CMEs carry 10^{13}-10^{17} g
Over the solar cycle - 0.5-4 CMEs per day,
Average of 2-3 CMEs per day.
2-3*10^{15} g / 86400 sec (per day) = 2-3*10^{10} g/s
Mass-loss rate of about 5*10^{-16} Msun/yr

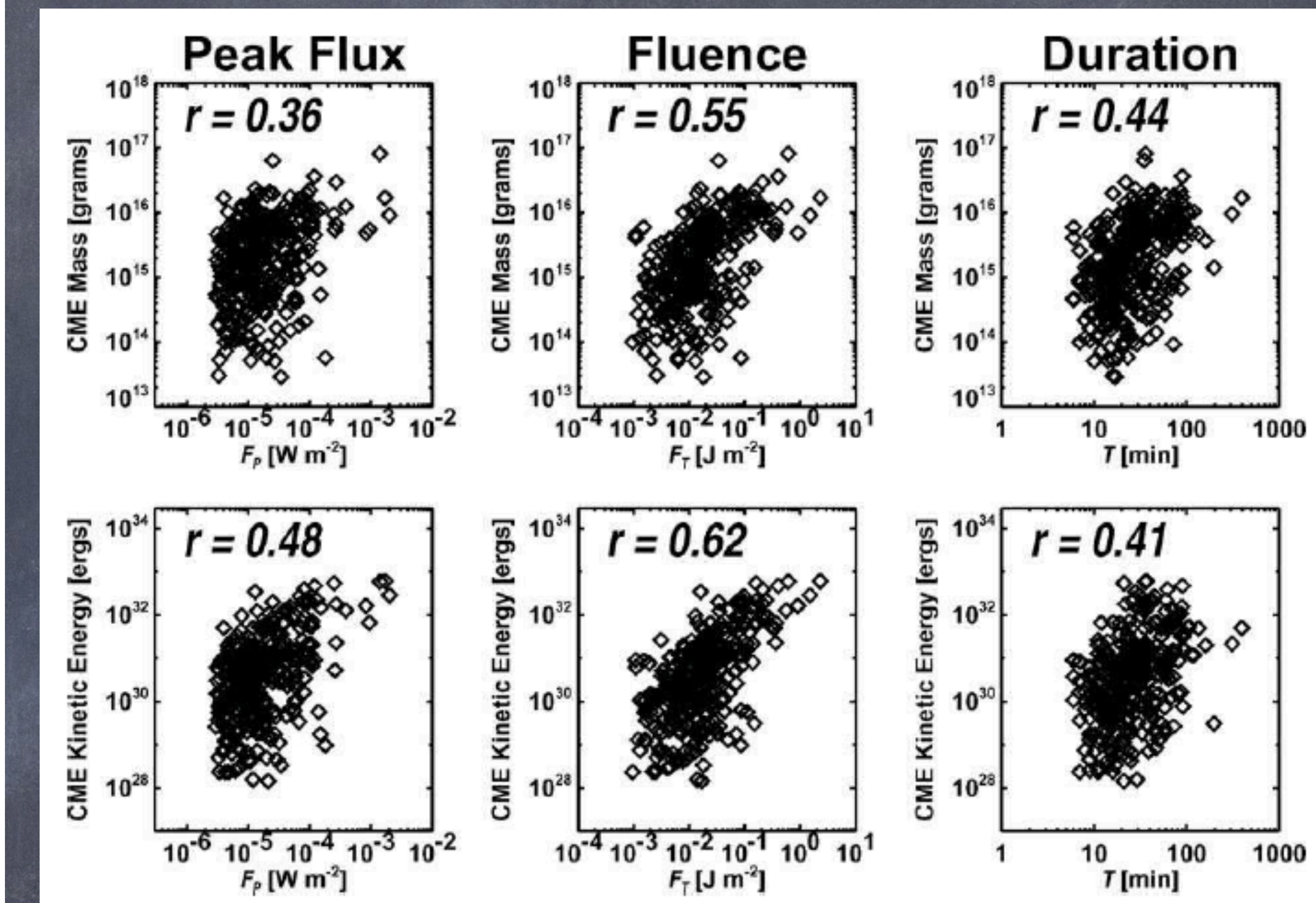
Few percents of the SW mass-loss rate

What if the CME rate is much higher?
How to scale CMEs to other stars?

Scaling solar CMEs with solar flares (LASCO & GOES 1-8A):



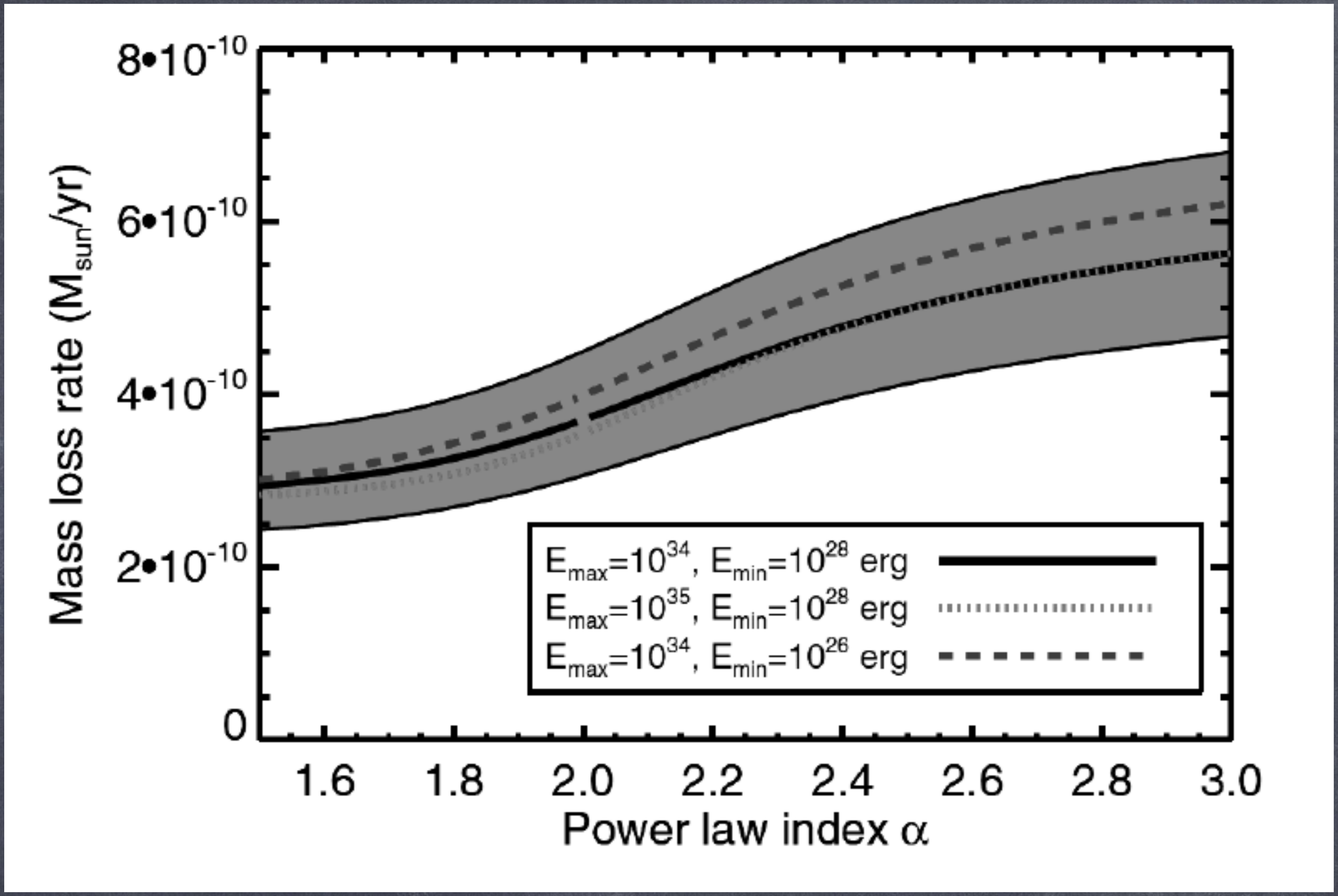
Aarnio et. al 2012



Yashiro & Gopalswamy 2009

$$\log(\text{CME mass}) = (18.67 \pm 0.27) + (0.70 \pm 0.05) \times \log(\text{flare flux})$$

CME mass-loss rate:



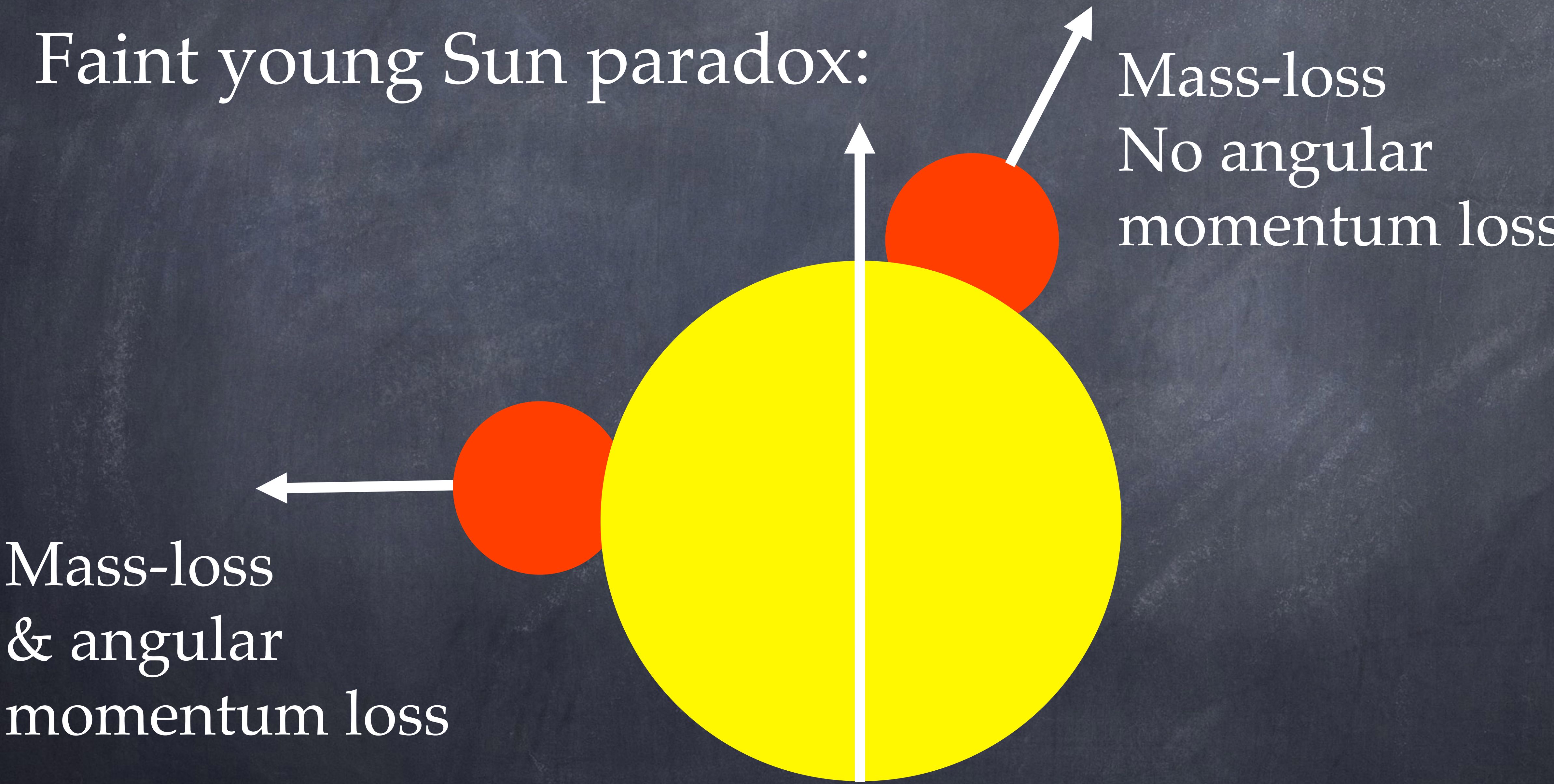
Drake et. al 2013

Drake et. al 2013: 10^{-11} - 10^{-10} Msun/yr (1% - 10% L_{bol})
Aarnio et. al 2012: 10^{-11} - 10^{-9} Msun/yr

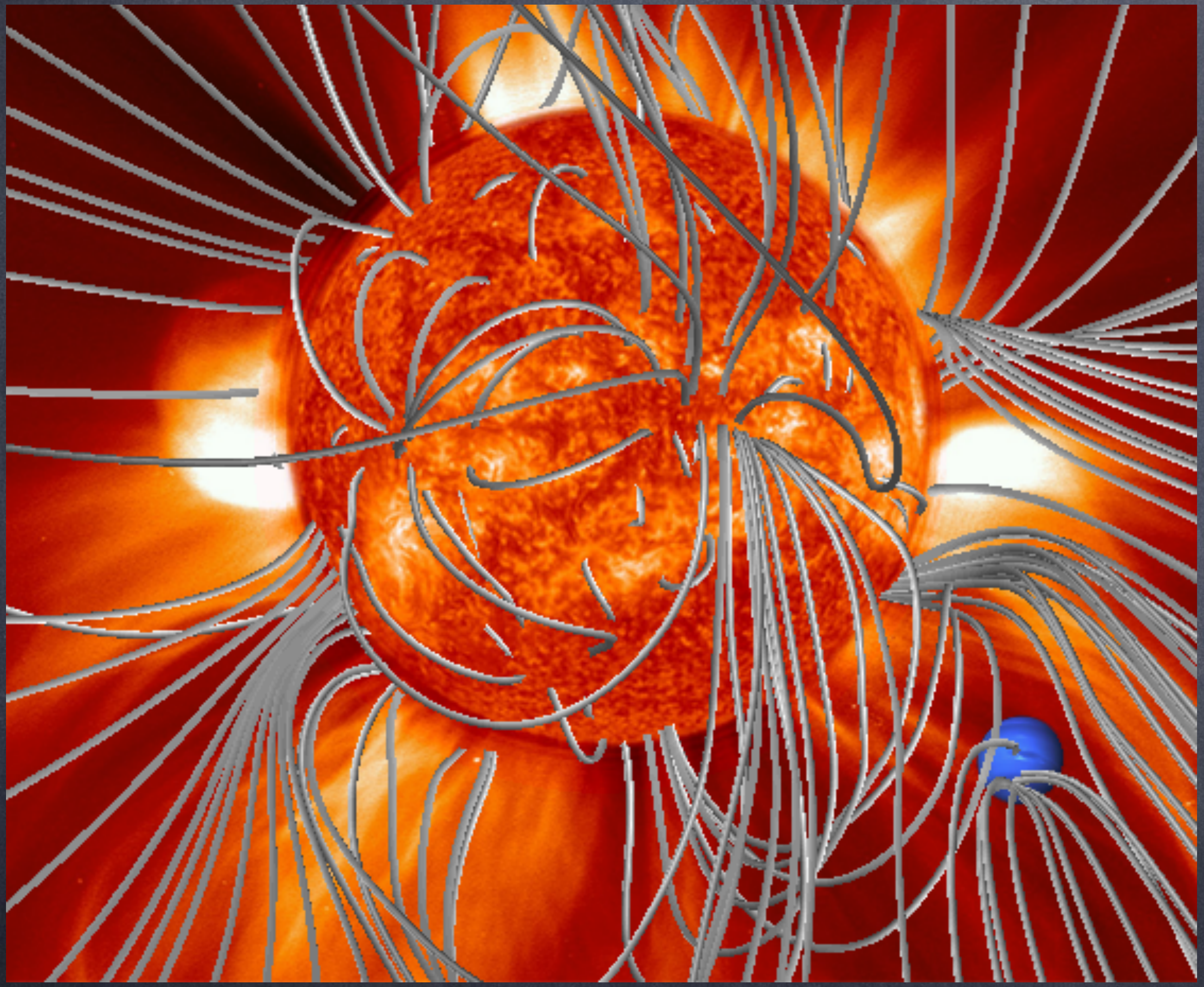
Impact on stellar spindown (Aarnio et. al 2012):

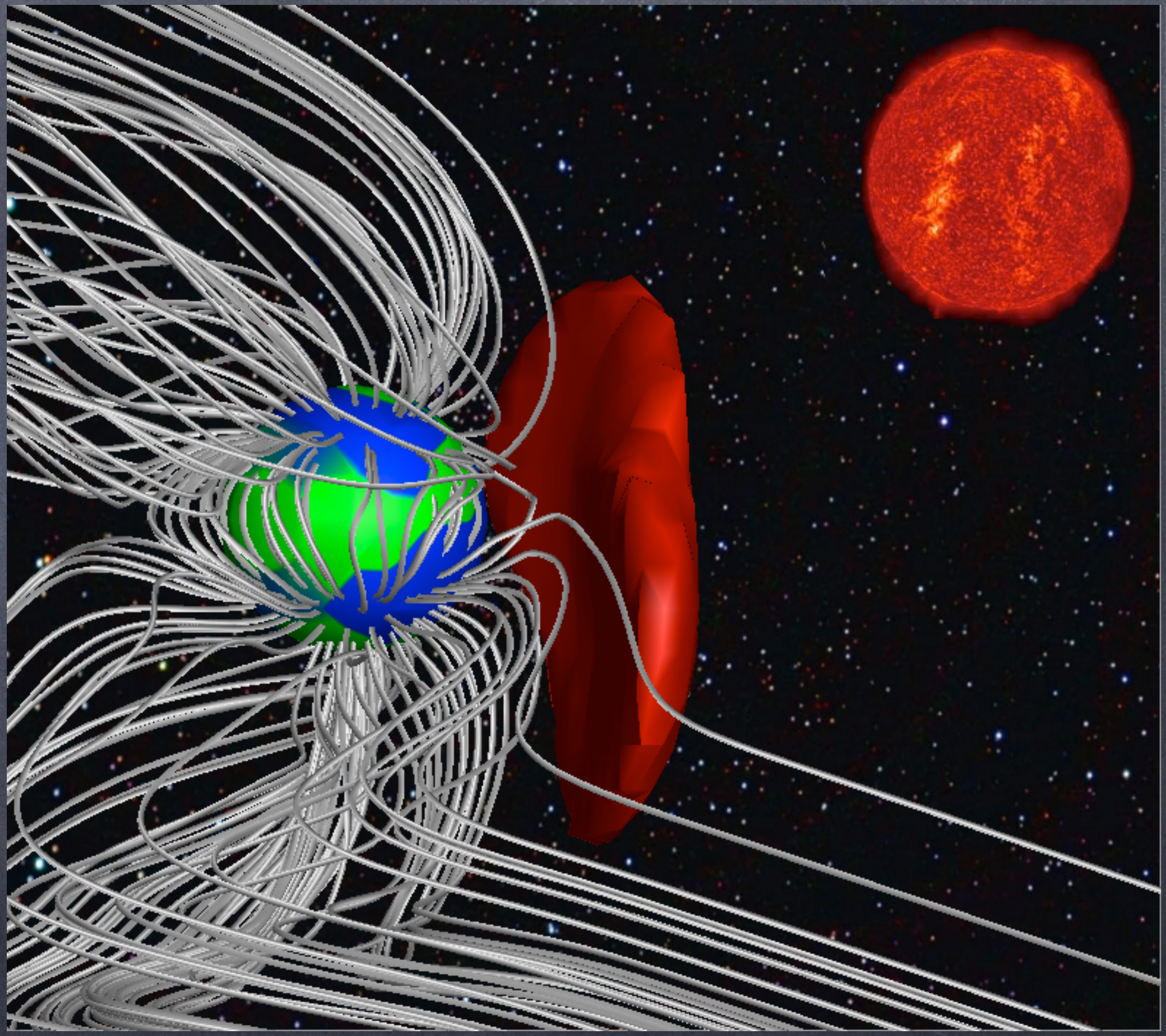
$$\tau = k^2 \left(\frac{M_\star}{\dot{M}_{CME}} \right) \left(\frac{R_\star}{r_A} \right)$$

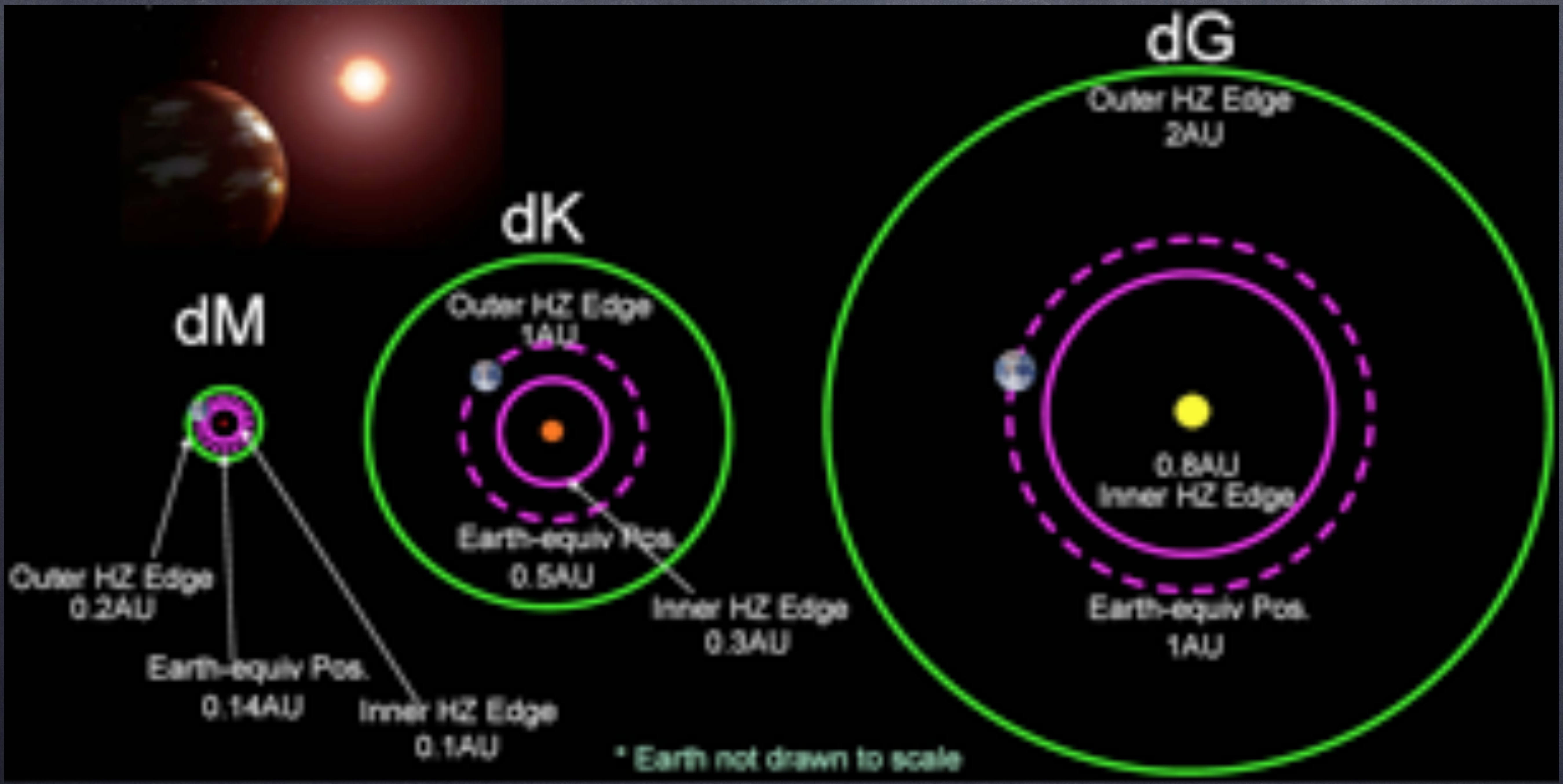
Faint young Sun paradox:



Planet Habitability

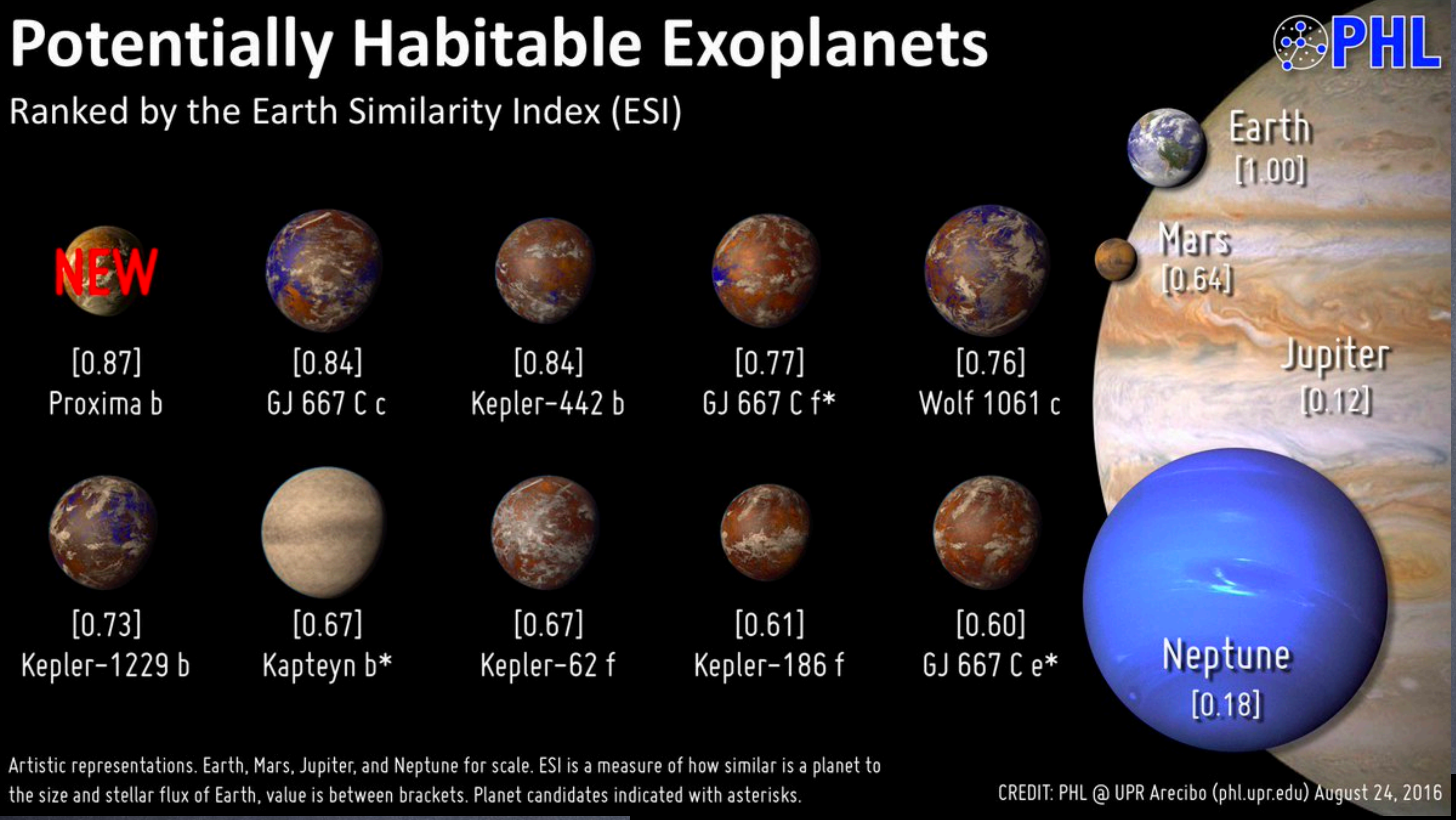


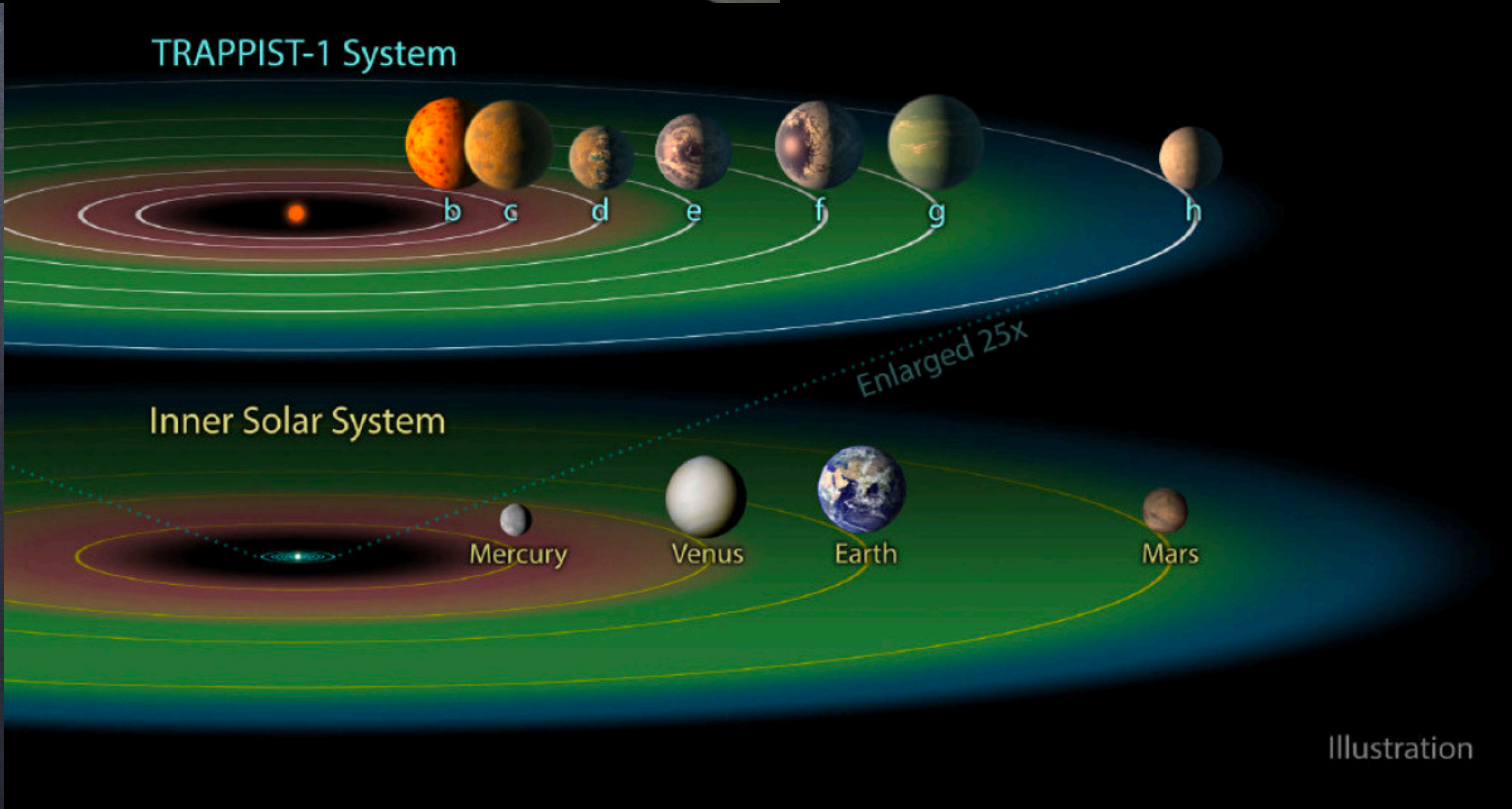




From the Living with a Red Dwarf project
http://astronomy.villanova.edu/livingwithareddwarf

M-dwarf planets





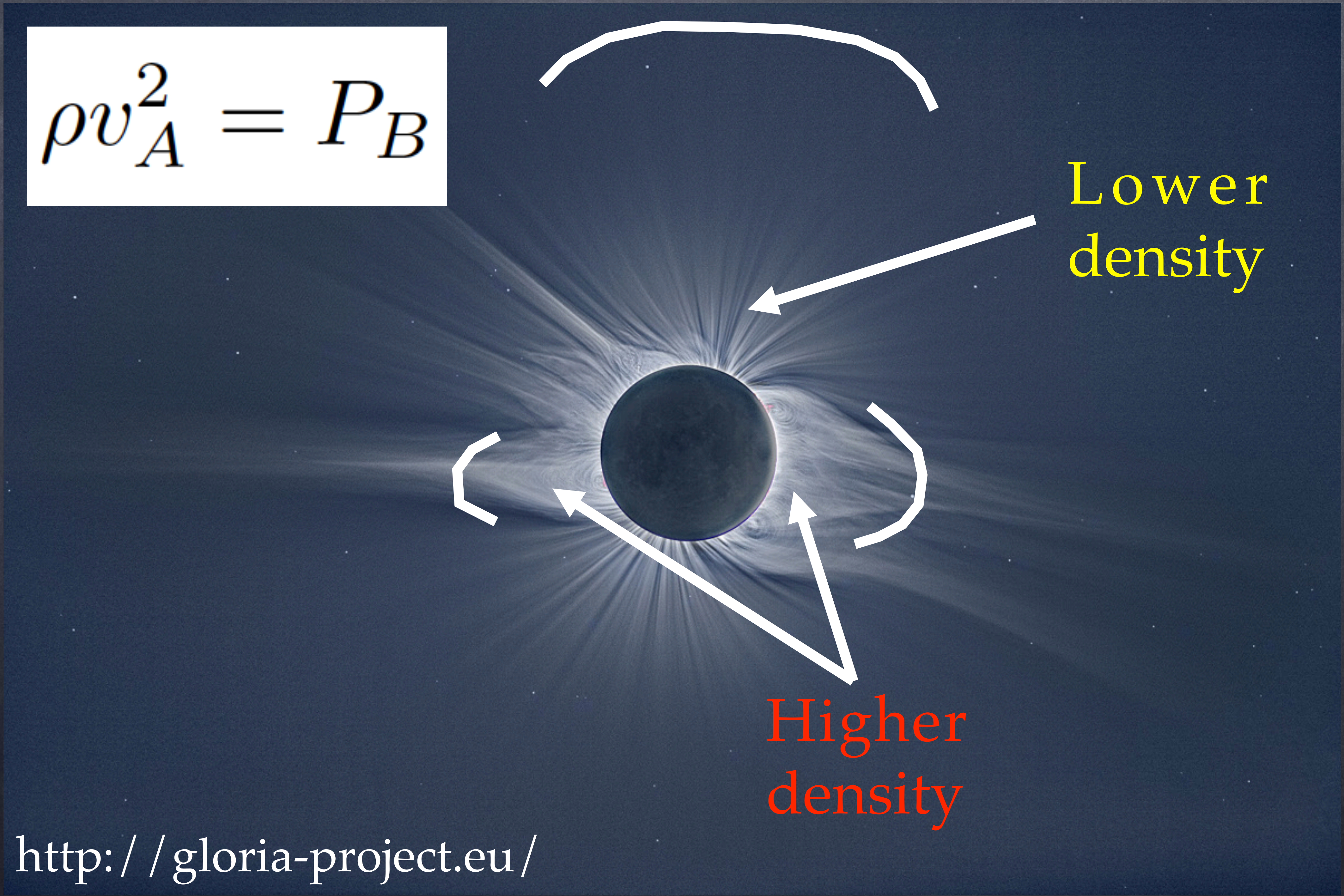
What is the Alfven point/surface?

$$v^2_A = \frac{B^2}{4\pi\rho} = \frac{p_B}{2\rho}$$

$$c^2_s = \frac{\gamma p}{\rho}$$

$$M_A = v/v_A$$

$$\rho v_A^2 = P_B$$

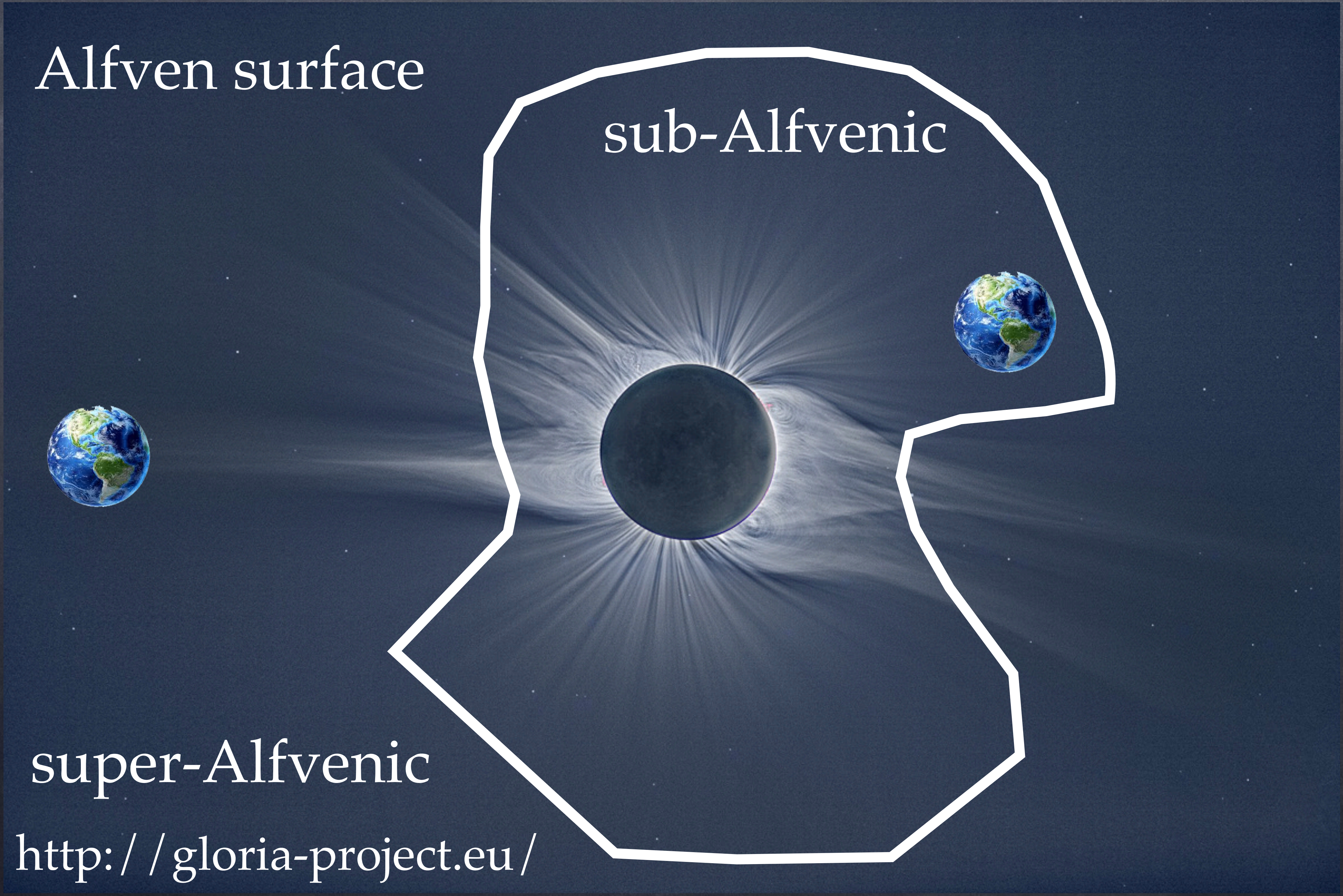


What is the Alfven point/surface?

$$v_A^2 = \frac{B^2}{4\pi\rho} = \frac{p_B}{2\rho}$$

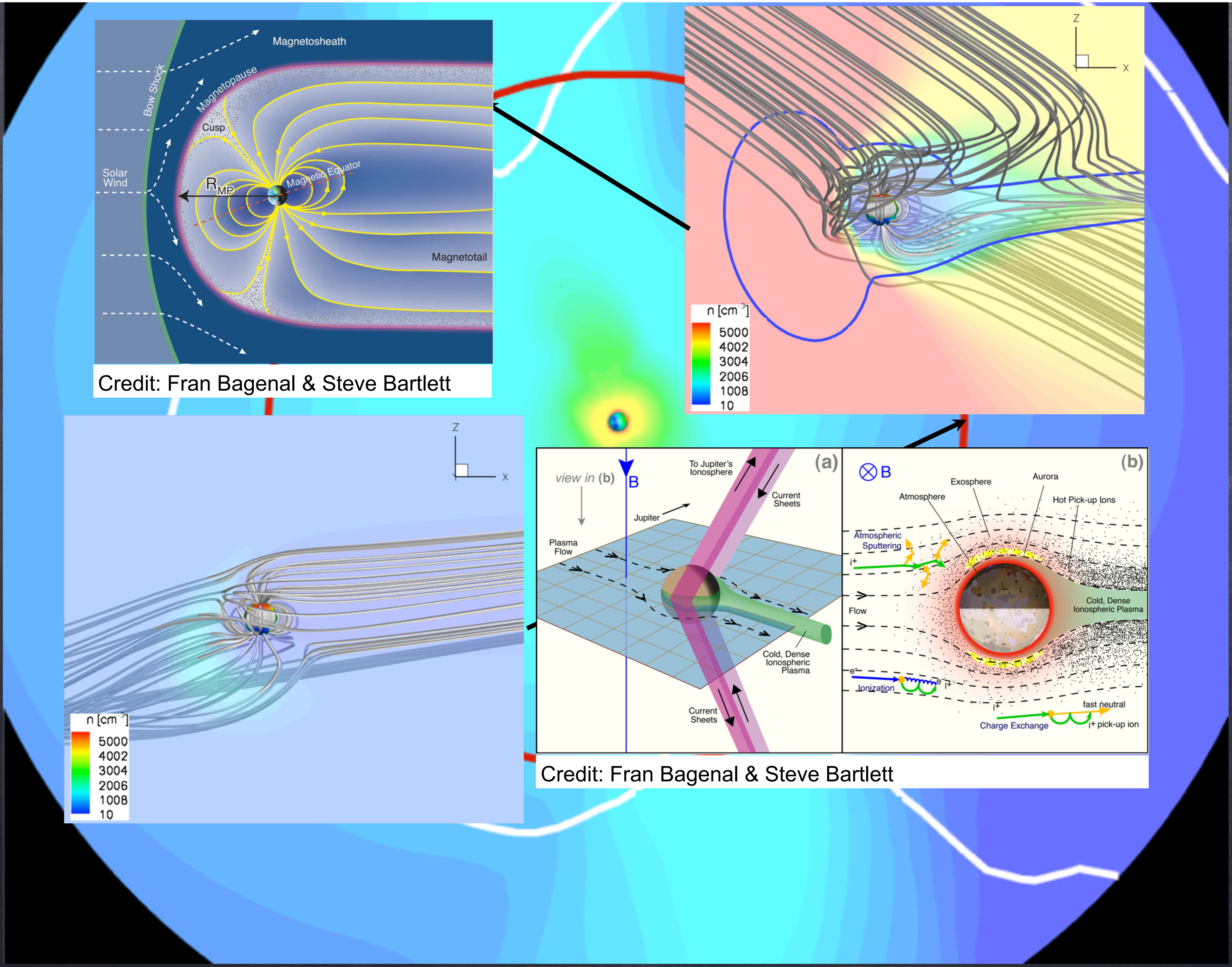
$$c_s^2 = \frac{\gamma p}{\rho}$$

$$M_A = v/v_A$$

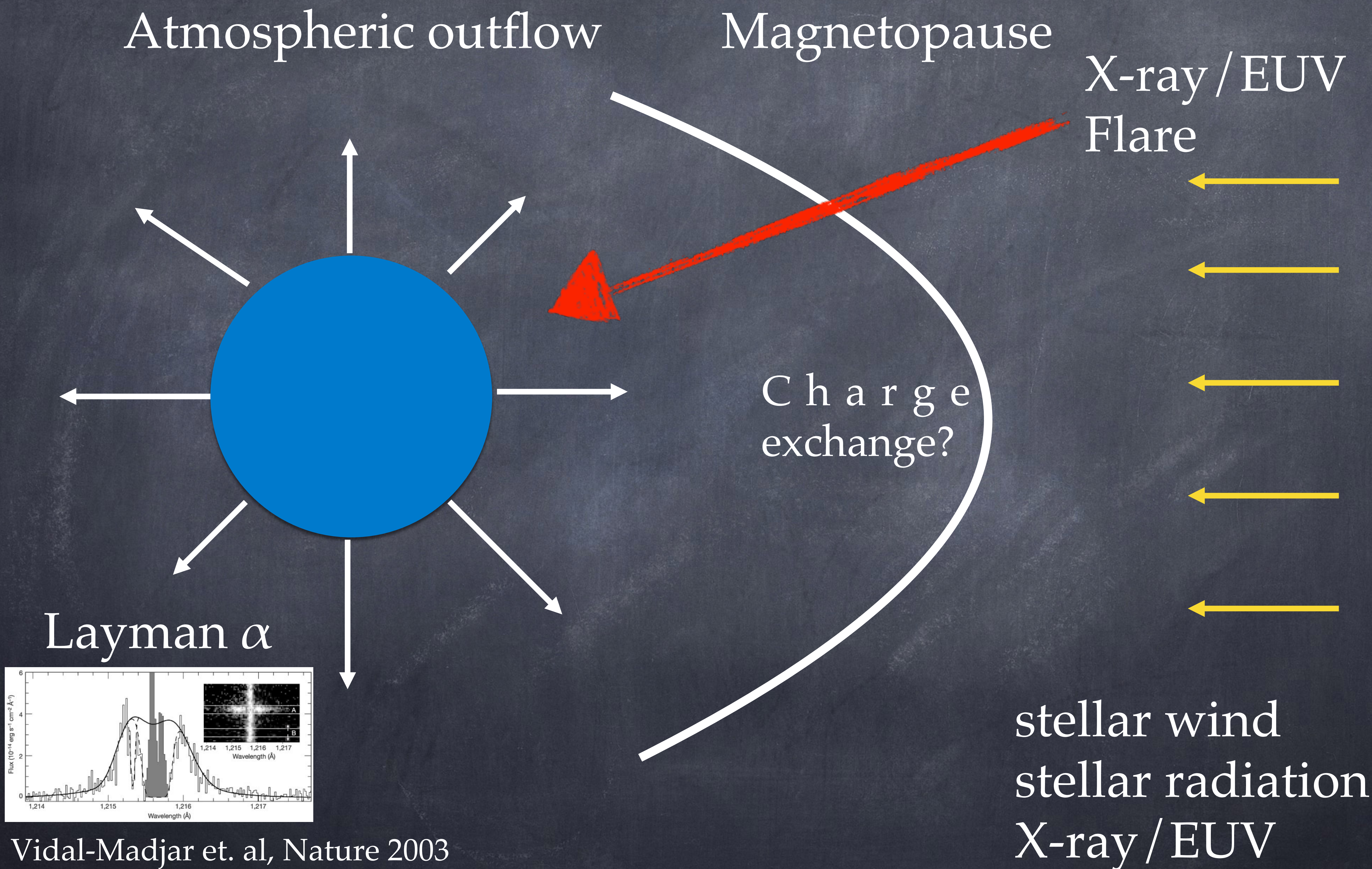


http://gloria-project.eu/

Possible unique conditions in a nearly sub-Alfvenic stellar wind regime:



Impact on the upper atmosphere:

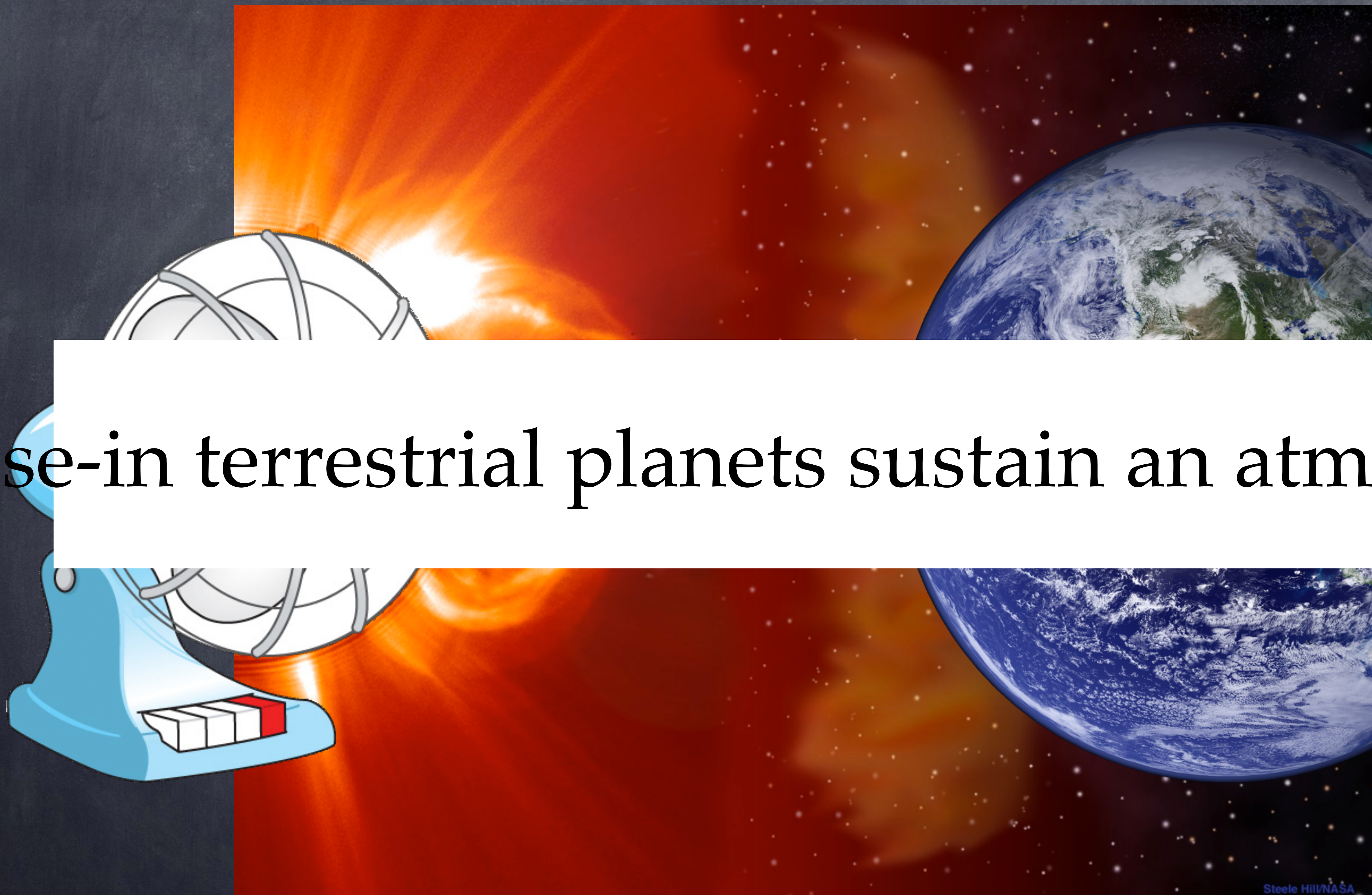


Vidal-Madjar et. al, Nature 2003

Extreme space weather:

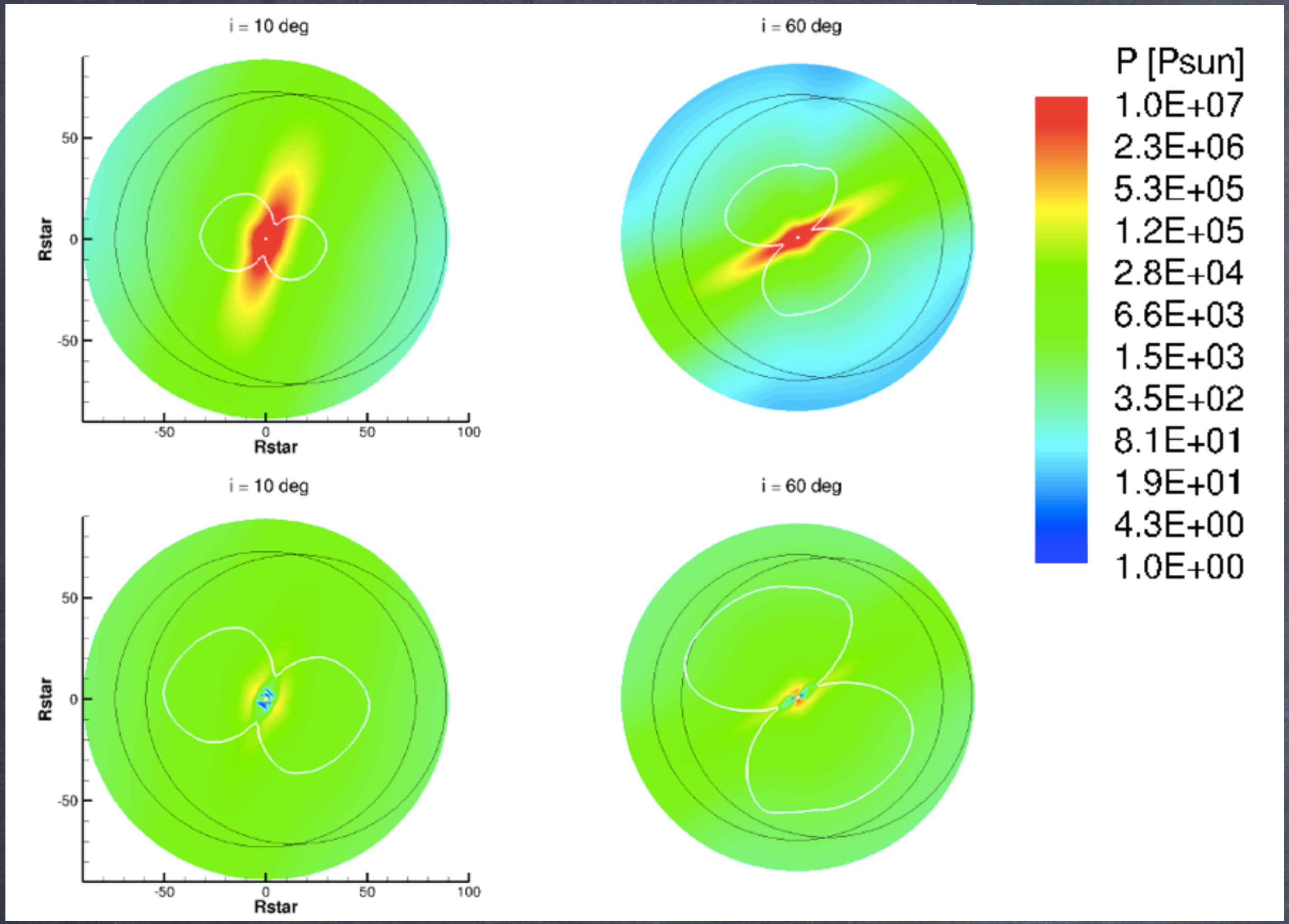
1. Extreme stellar radiation (EUV/Xray) - photoevaporation of atmospheres
2. Extreme stellar wind
3. Coronal background temperature - 1MK
4. High ambient density/pressure - 1000x1AU
5. High ambient magnetic field - >1000nT
6. Possible star-planet interaction
7. Fast orbital motion (3d=150 km/s)

Atmospheric stripping by the stellar wind:

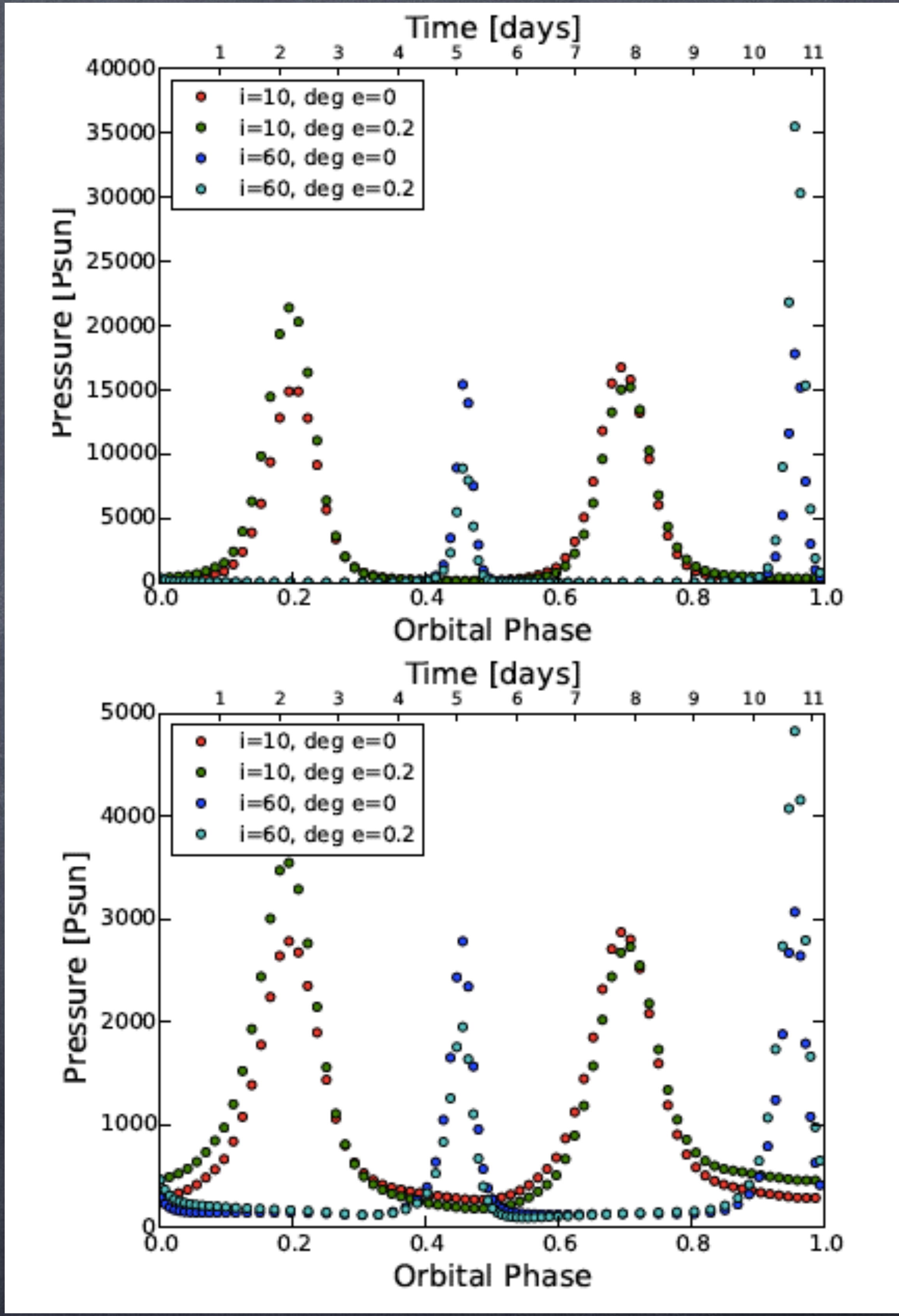


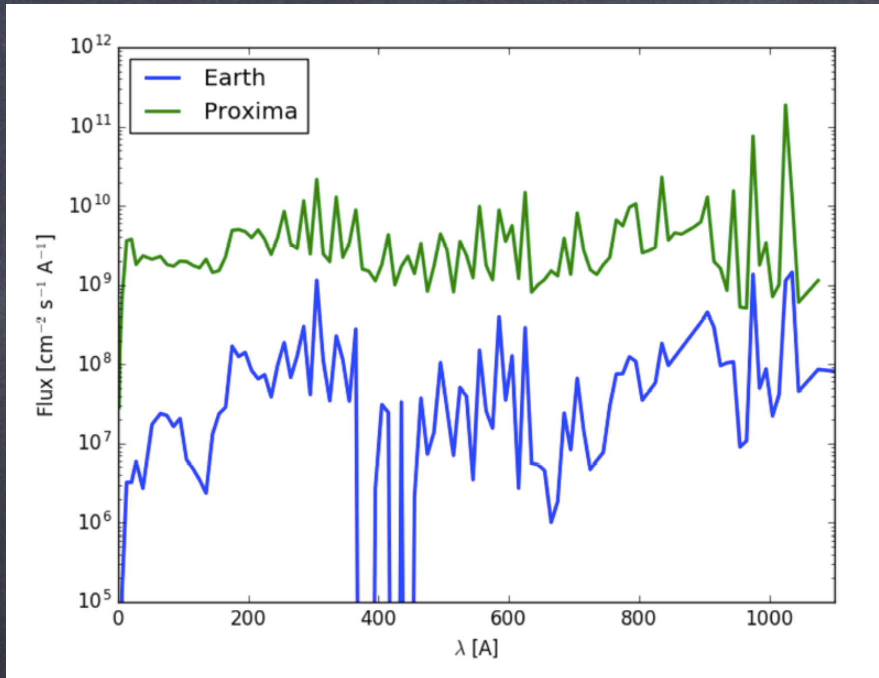
se-in terrestrial planets sustain an atmosphere

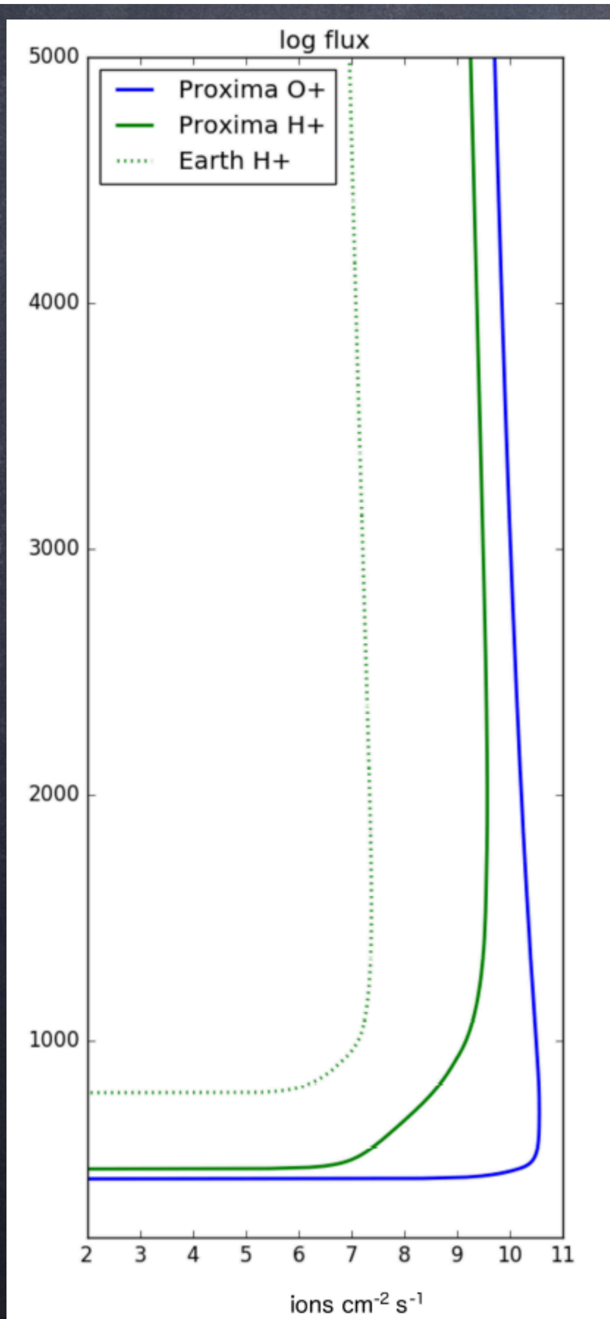
Proxima Centauri b

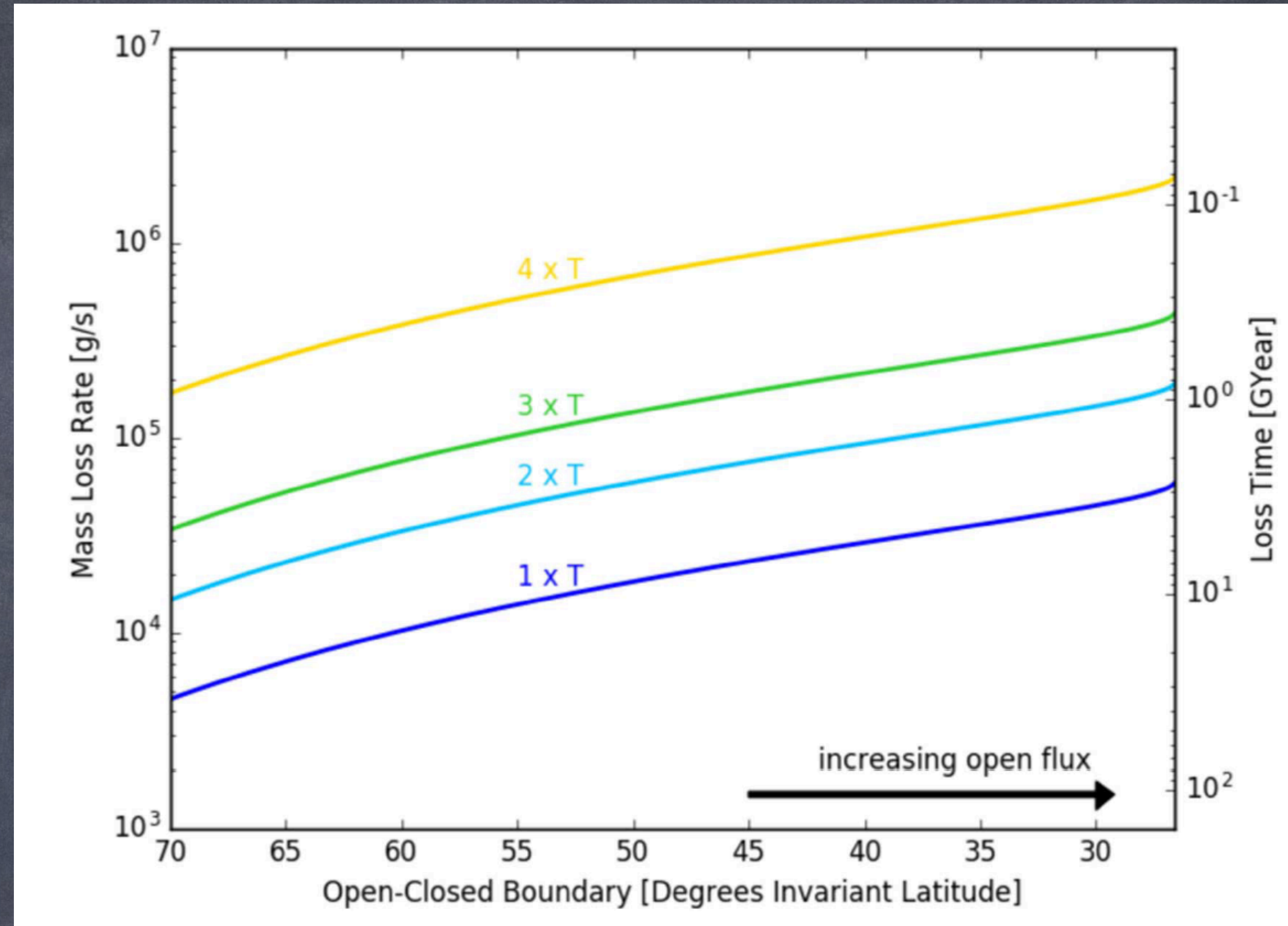


Garraffo et. al 2016

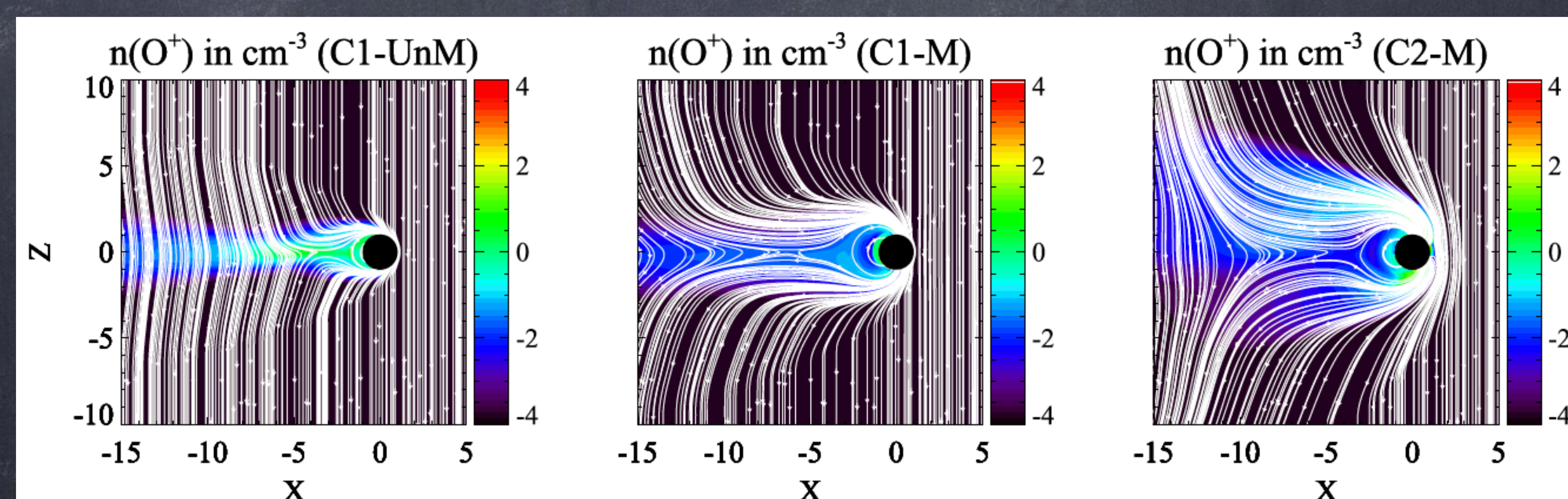






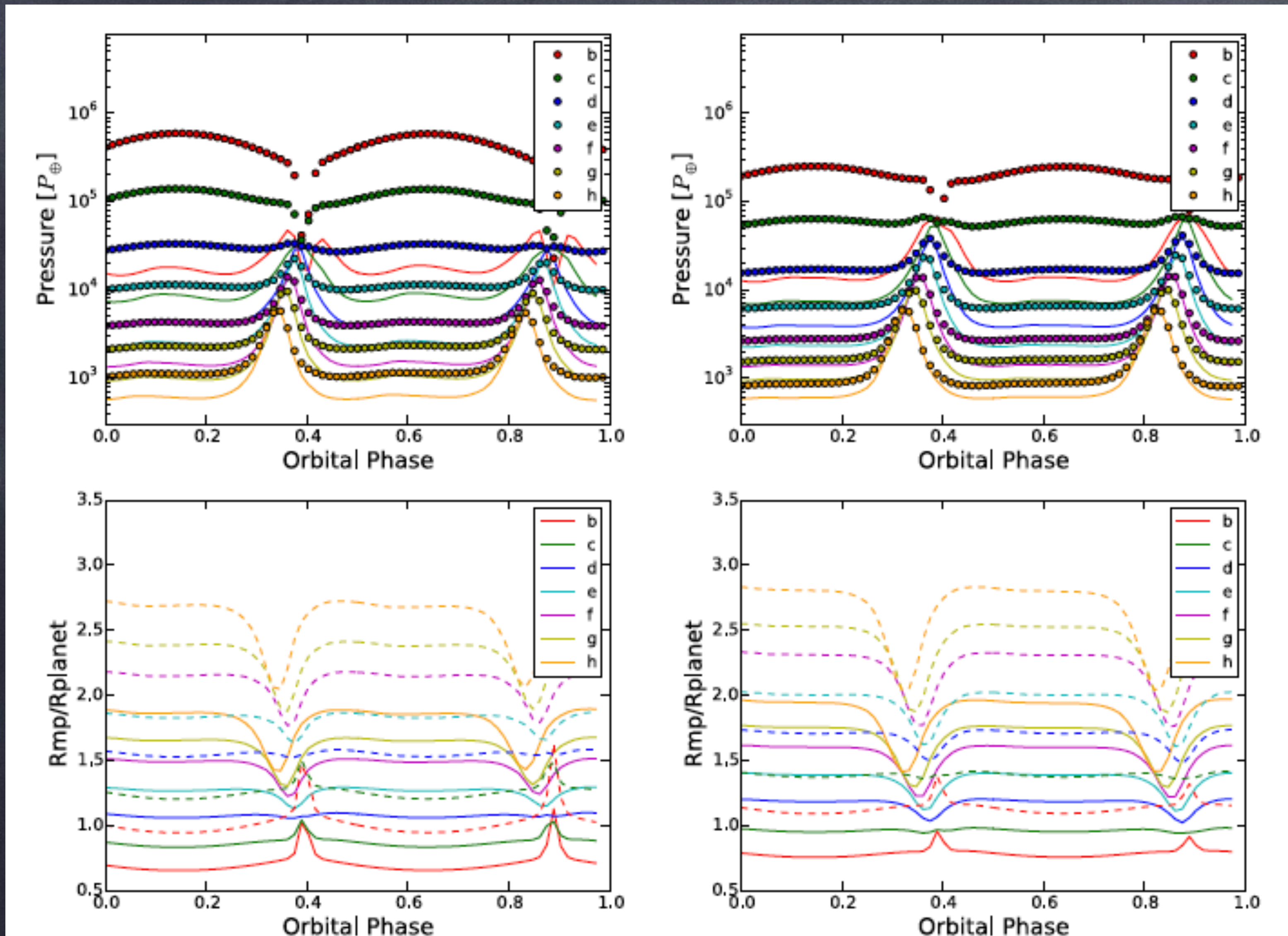


Garcia-Sage et. al 2017

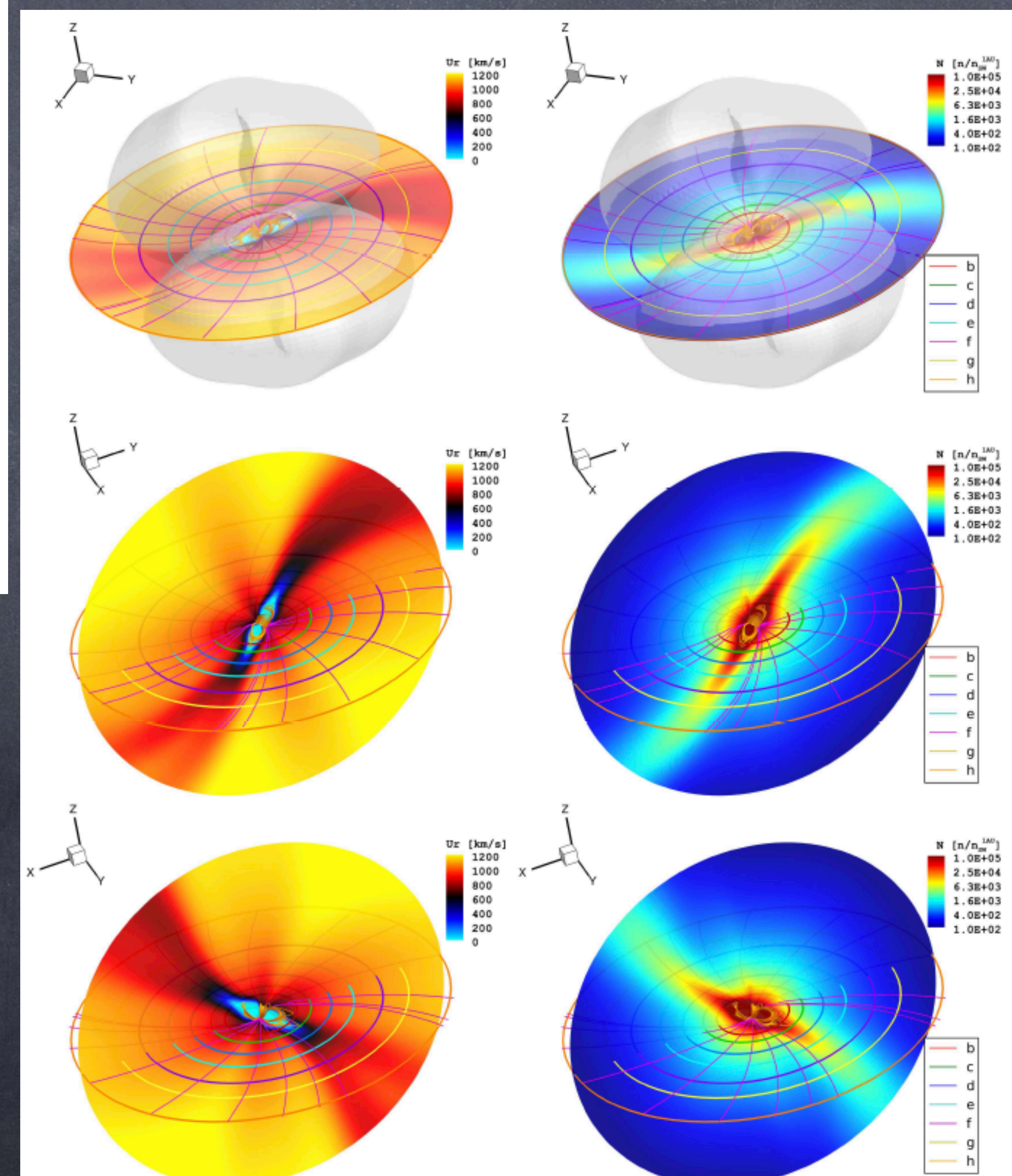


Dong et. al 2017

Trappist-1

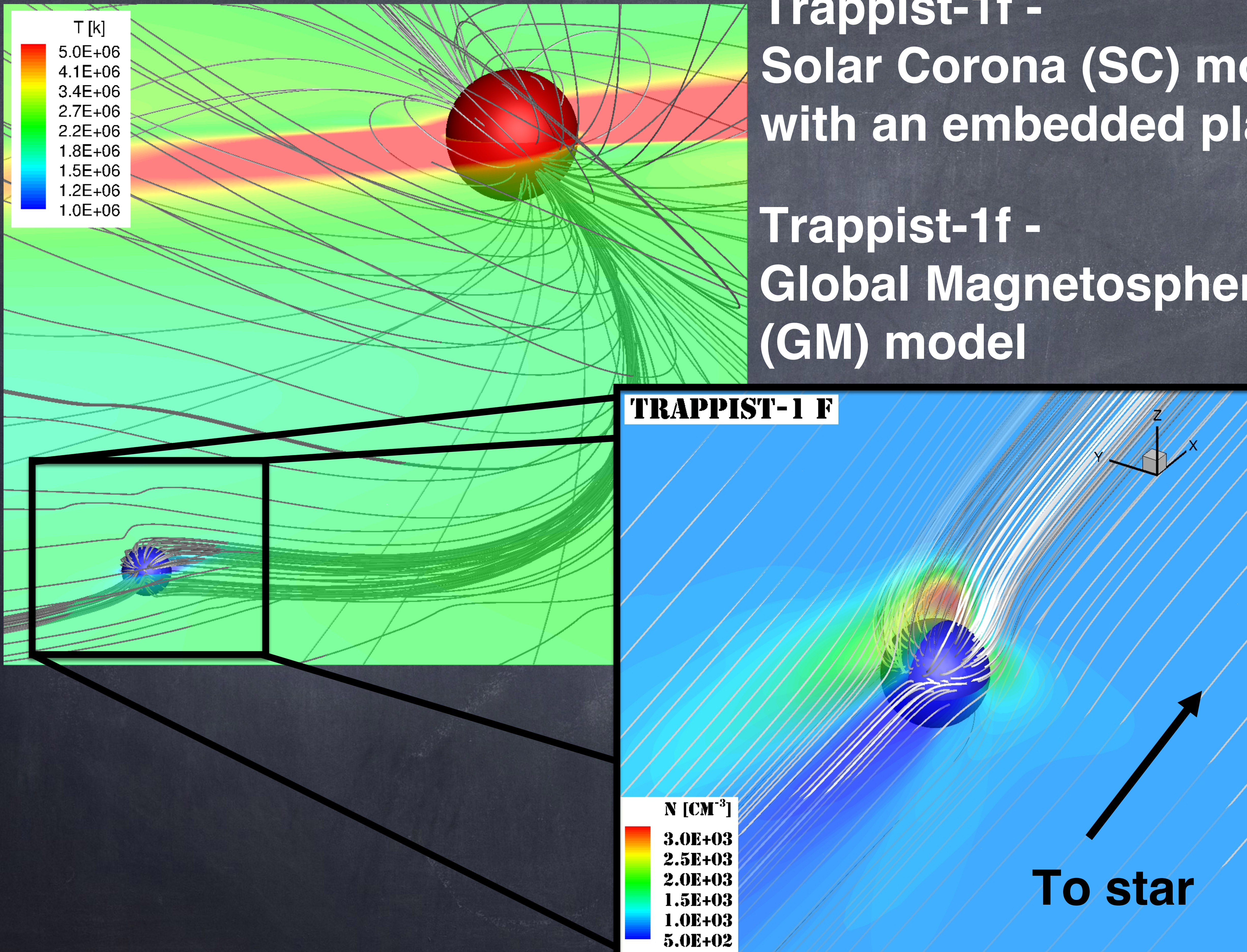


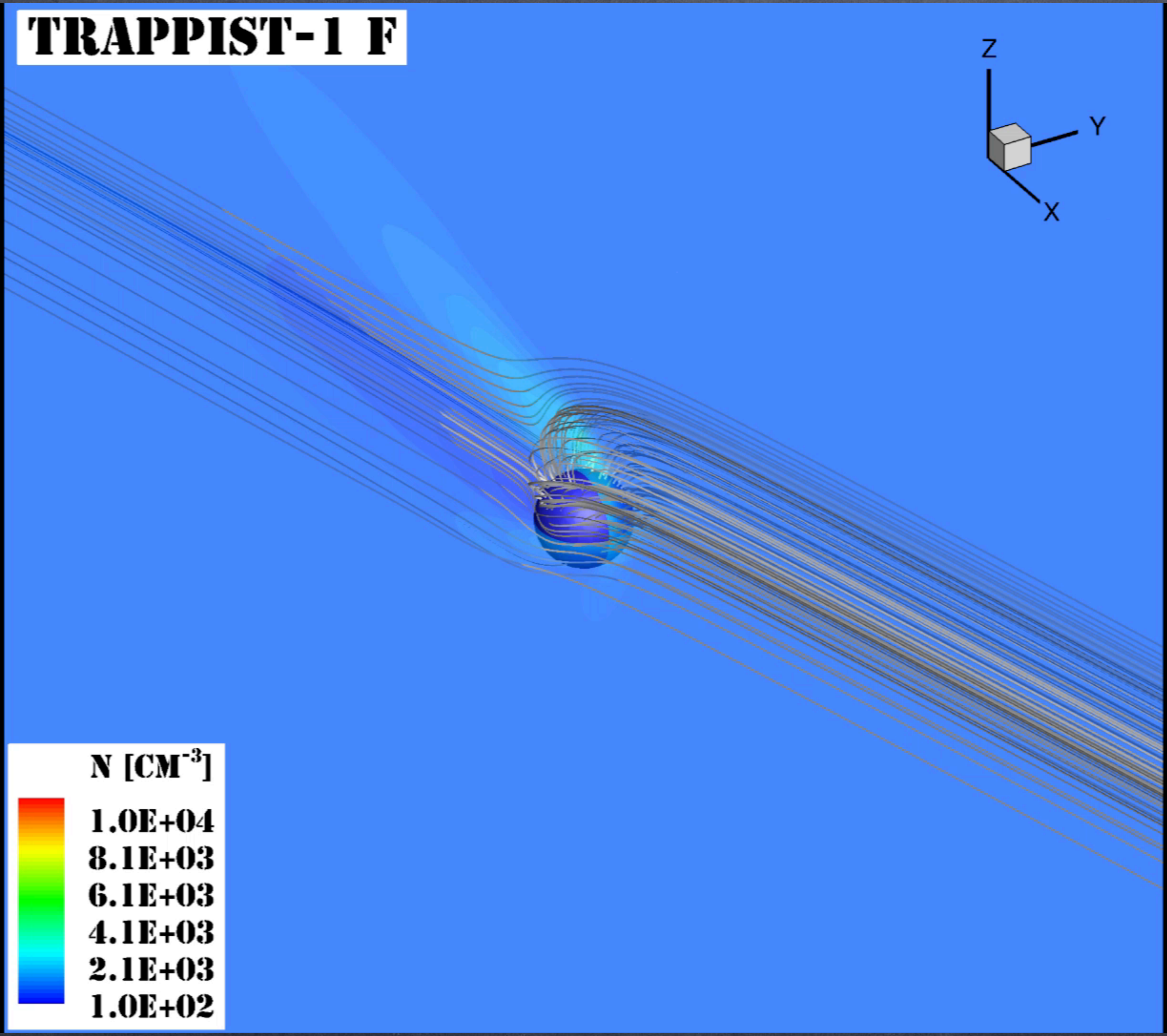
Garraffo et. al 2016



Trappist-1f - Solar Corona (SC) model with an embedded planet

Trappist-1f - Global Magnetosphere (GM) model




TRAPPIST-1 F
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Y
X
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1.0E+02

To wrap things up...

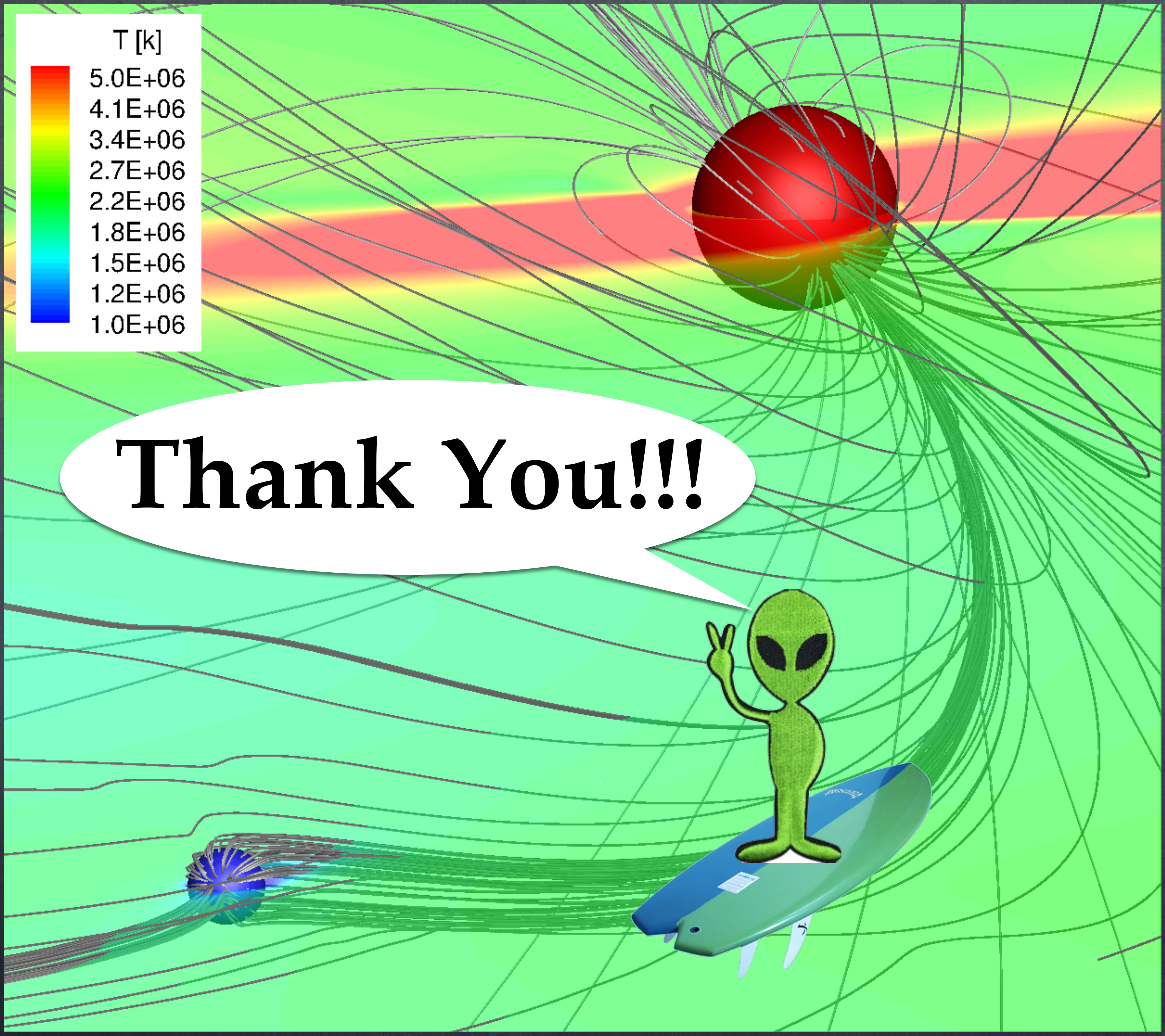
Astrophysics has limited data and the Sun has detaile

Connecting the two can improve our understanding about the Sun as a star and the physics of solar analogs

For very active stars, CMEs can take over the ambient state

Planet habitability should take into account the stellar environment

Close-orbit, M-dwarf planets may not sustain their atmosphere over a long time.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1.0E+06
Thank You!!!