Coronae, Heliospheres and Astrospheres

Heliophysics Summer School, Boulder CO, 2018

Outline

Part I:
- I. Solar Vs. stellar physics
- II. Stellar evolution
- III. Coronae and winds
- IV. Stellar environments - astrospheres

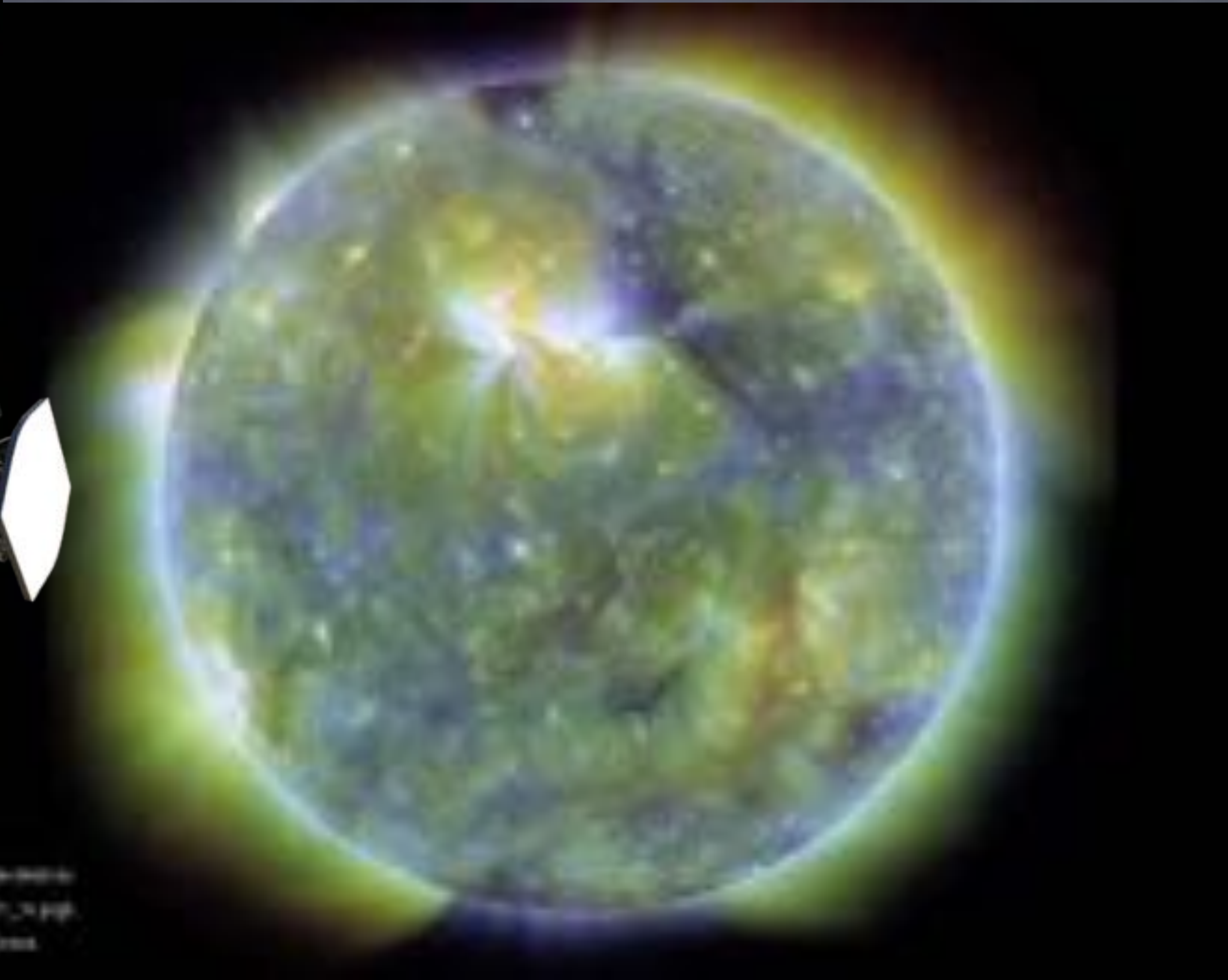
Part II
- V.Stellar evolution and magnetized winds
- VI. Stellar mass-loss rates and stellar spin-down
- VII. Flares
- VIII.Exoplanets and planet habitability

Material mostly based on Volume IV chapters 2,3,4

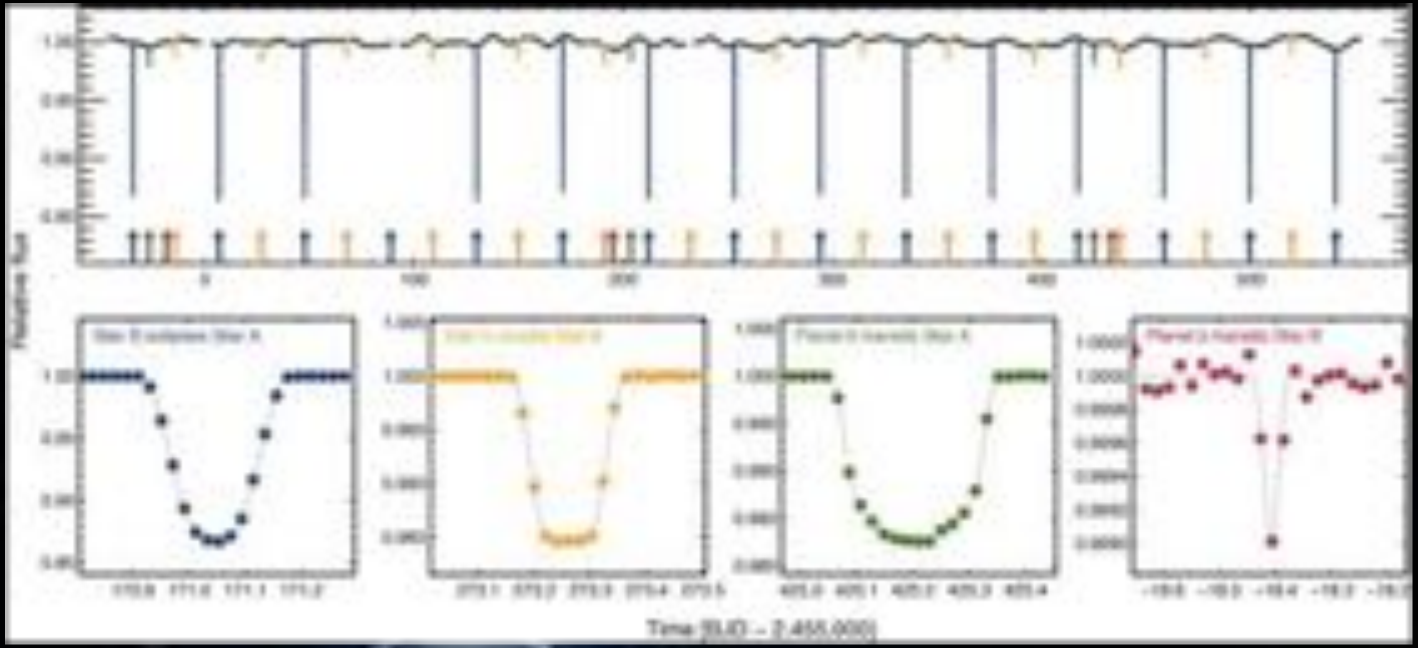
Part I

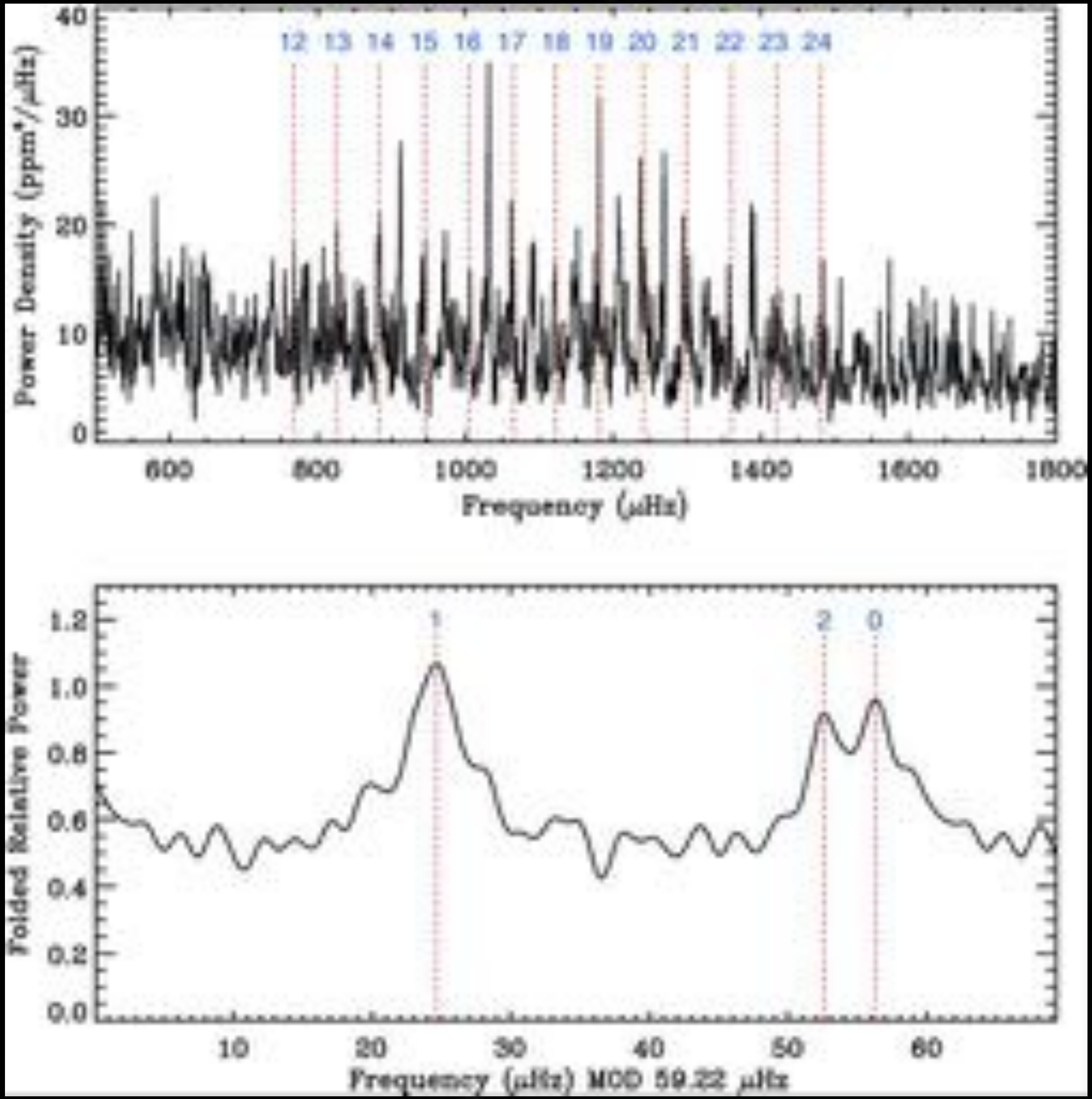
The Solar-stellar connection

SDO observations of the Sun

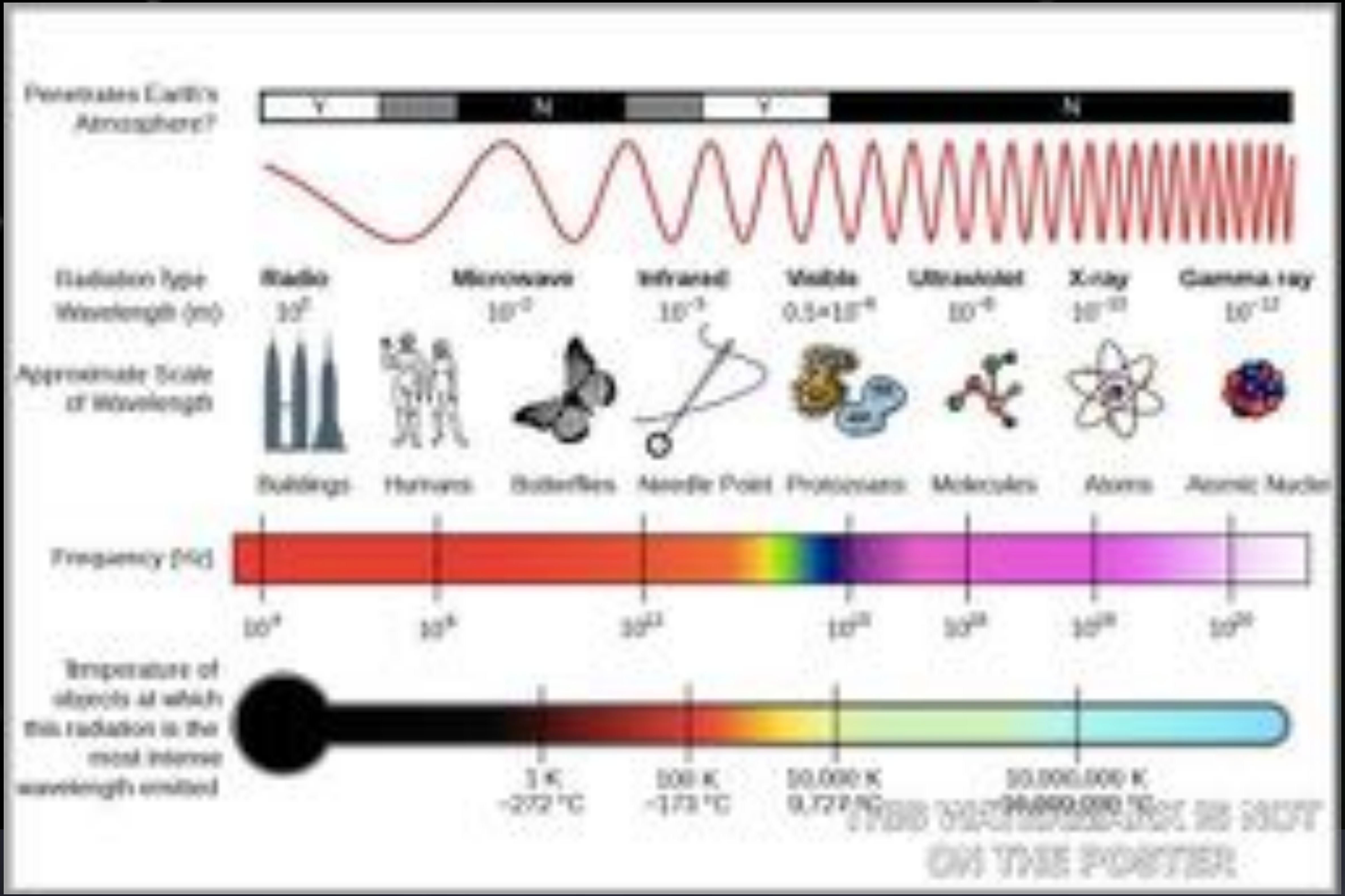


Photometry - measuring the intensity of the light

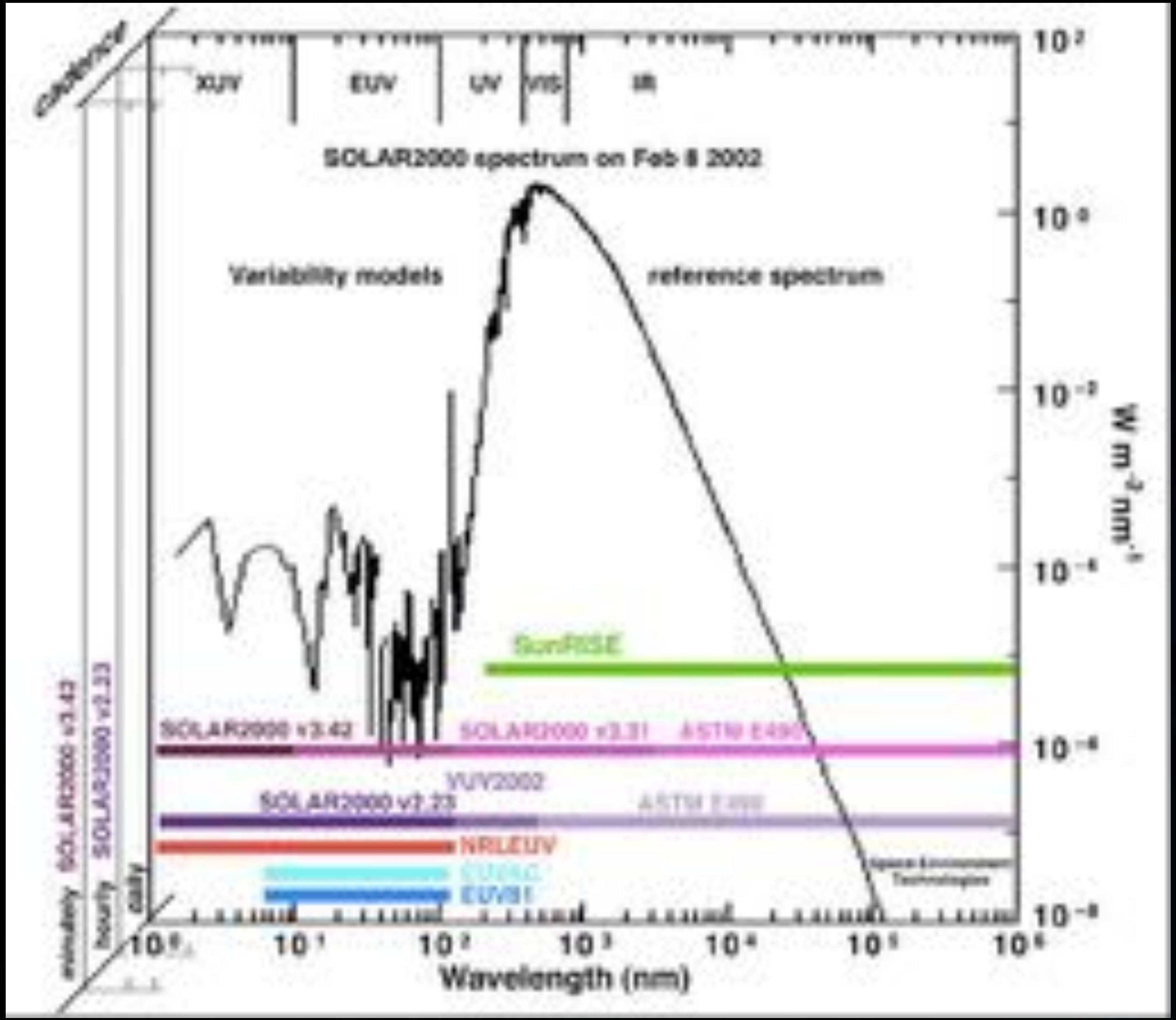


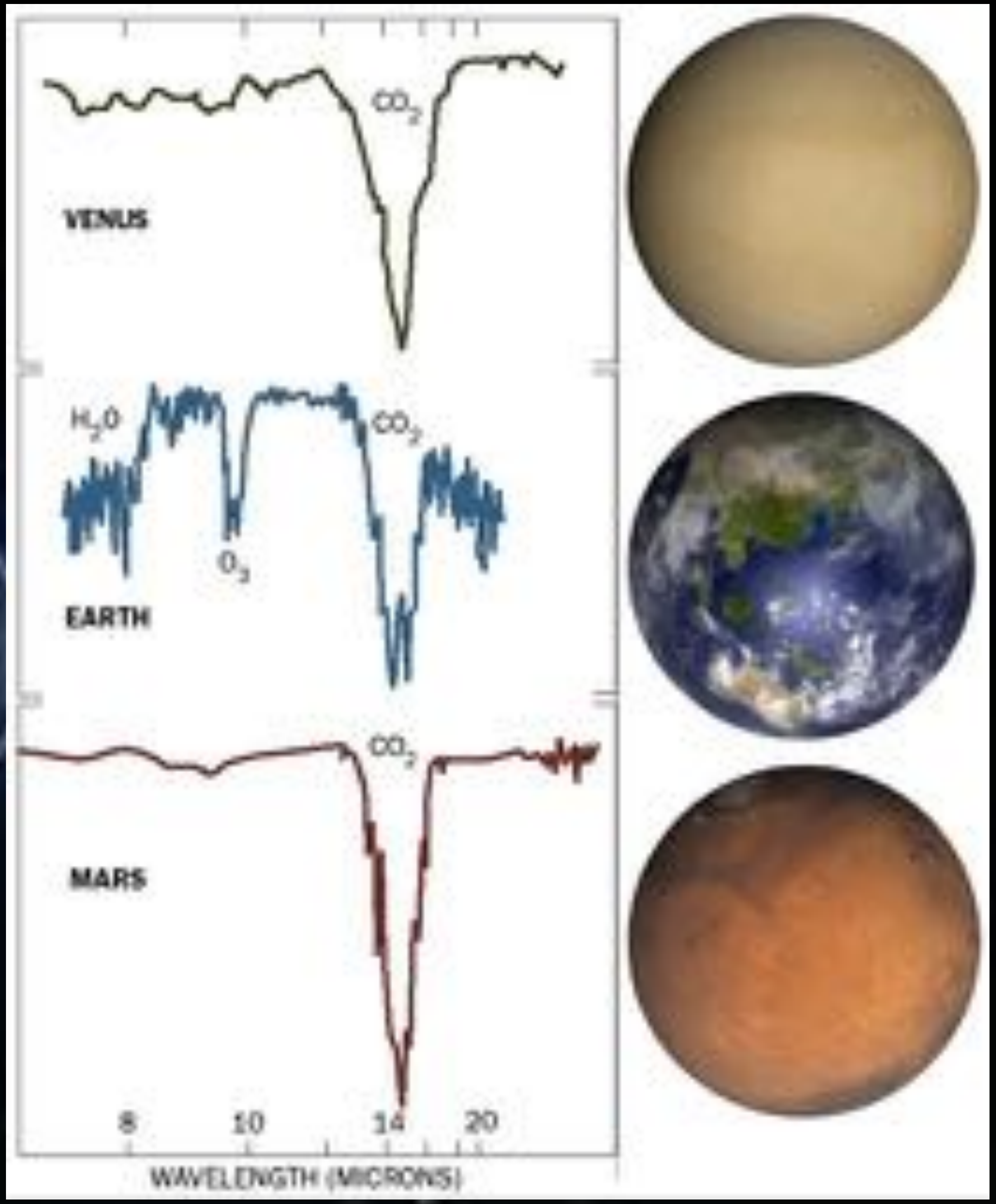


Spectrometry - measuring the intensity of particular

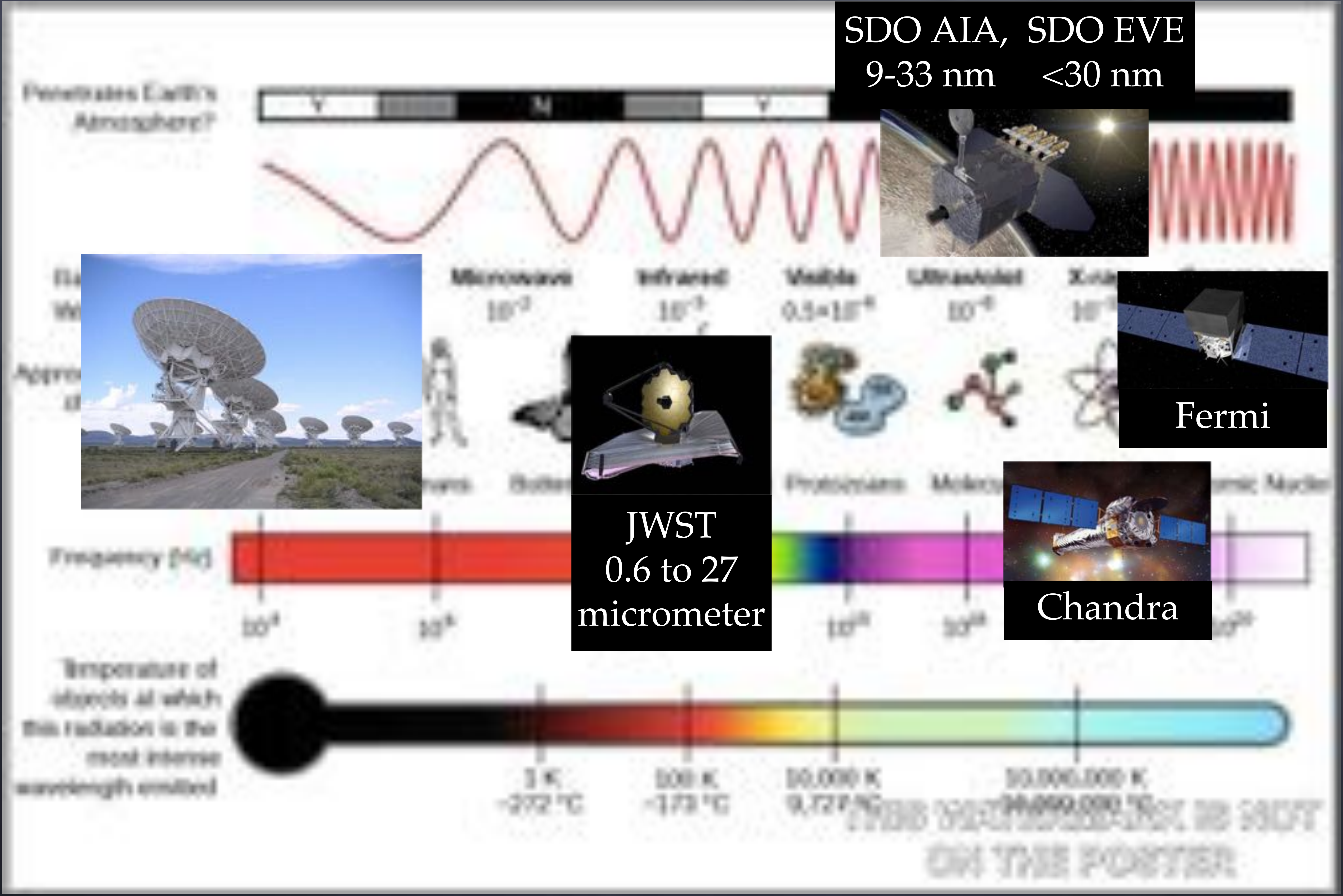


Transmission spectra - E=hv





How many photons with certain energy (thus wavelen



SDO AIA, 9-33 nm

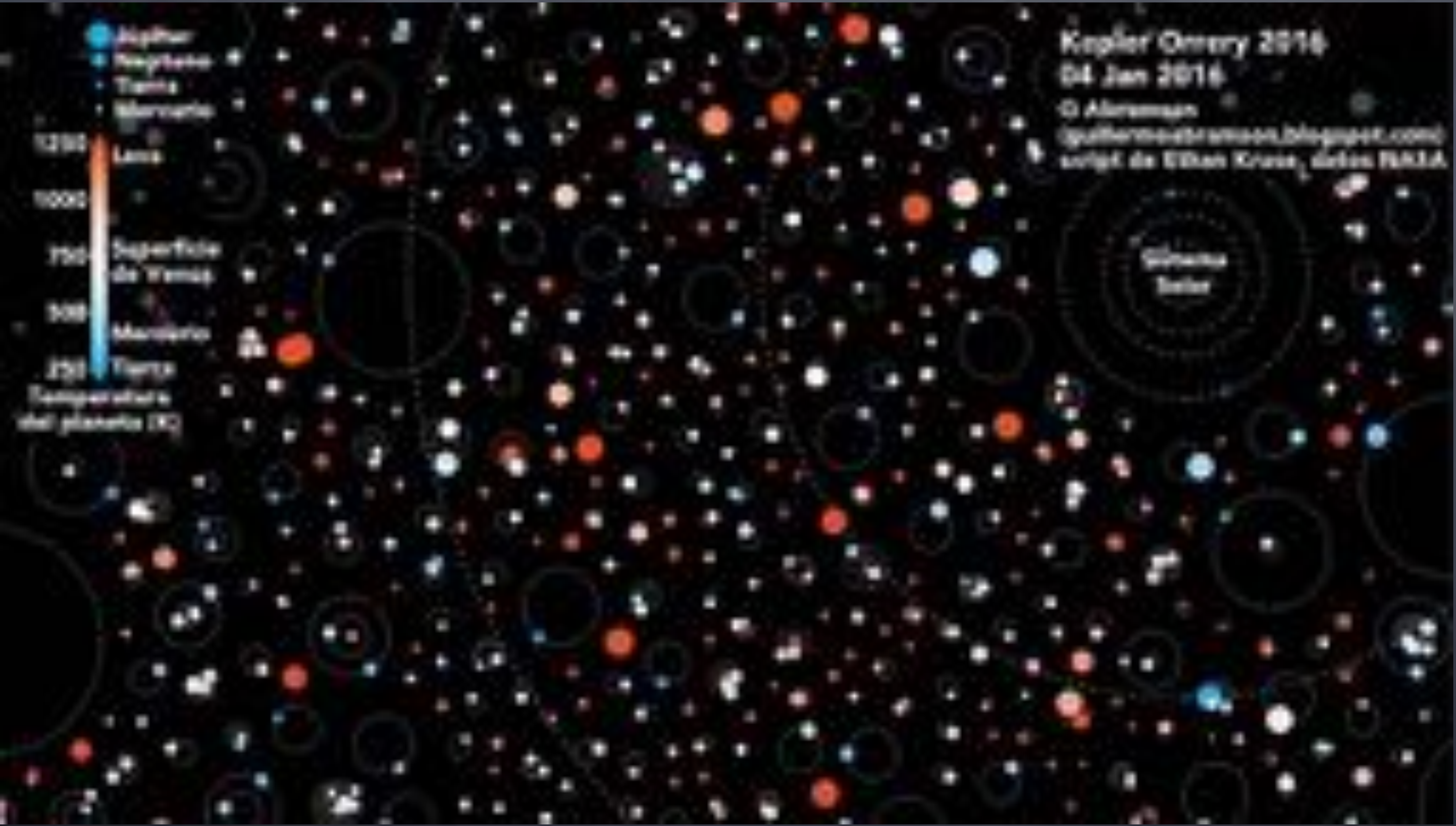
SDO EVE <30 nm

JWST 0.6 to 27 micrometer

Fermi

Chandra

Kepler systems observed as of Jan 2016



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

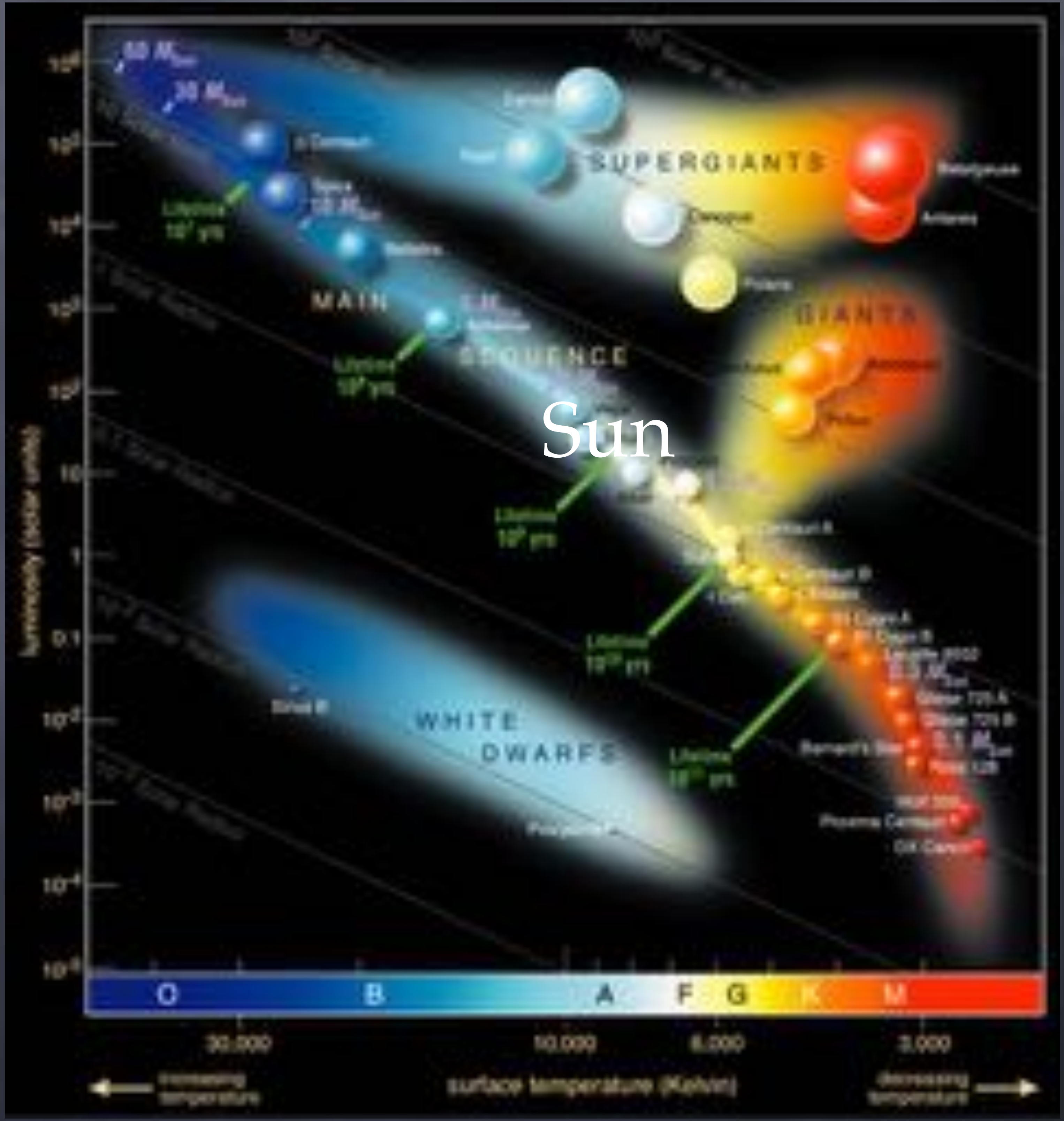
Stellar Astrophysics:

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

Stellar Evolution

Stellar Evolution (yes, some figures are from Wikipedia…)

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



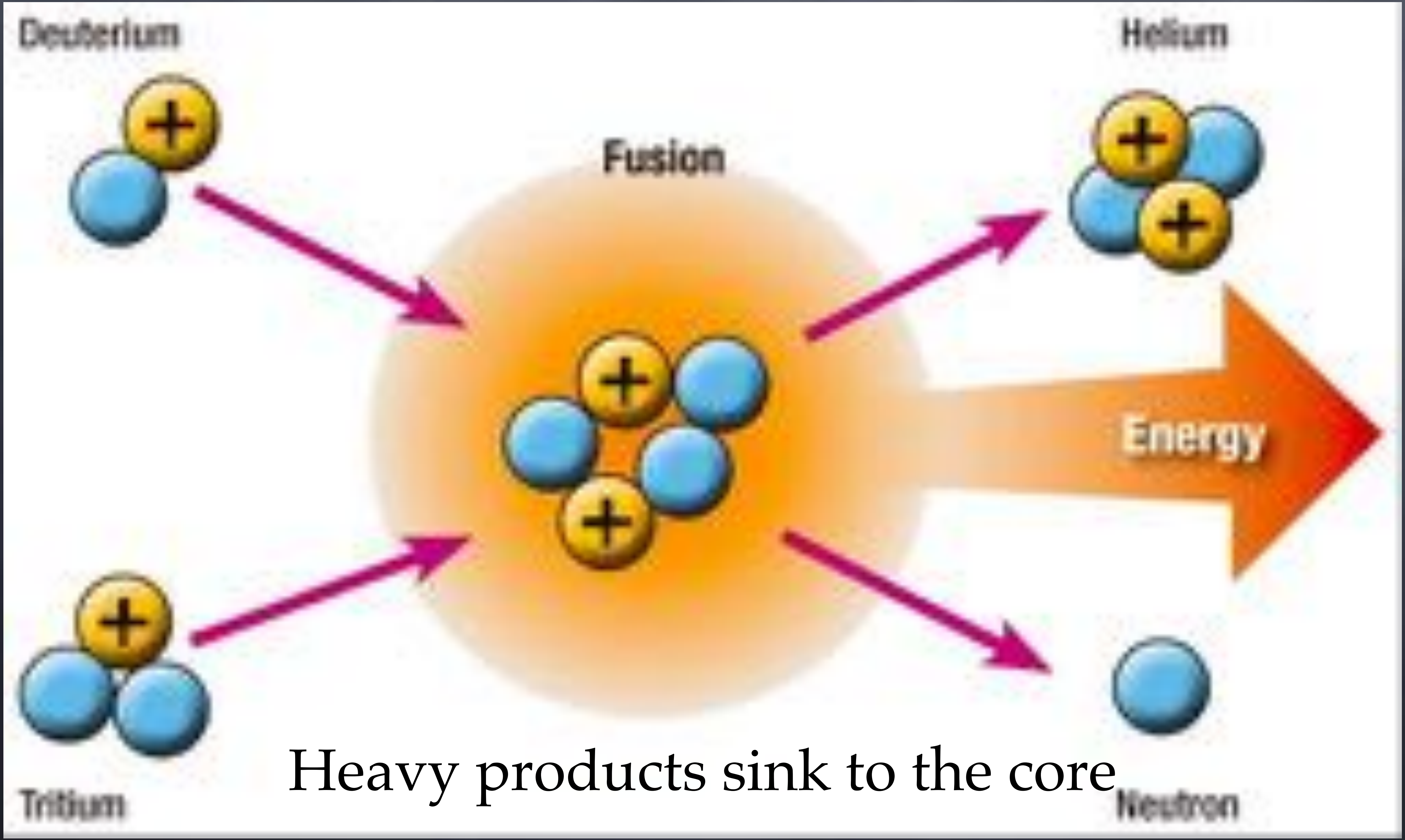
Credit: ESO

Star-forming regions - molecular clouds

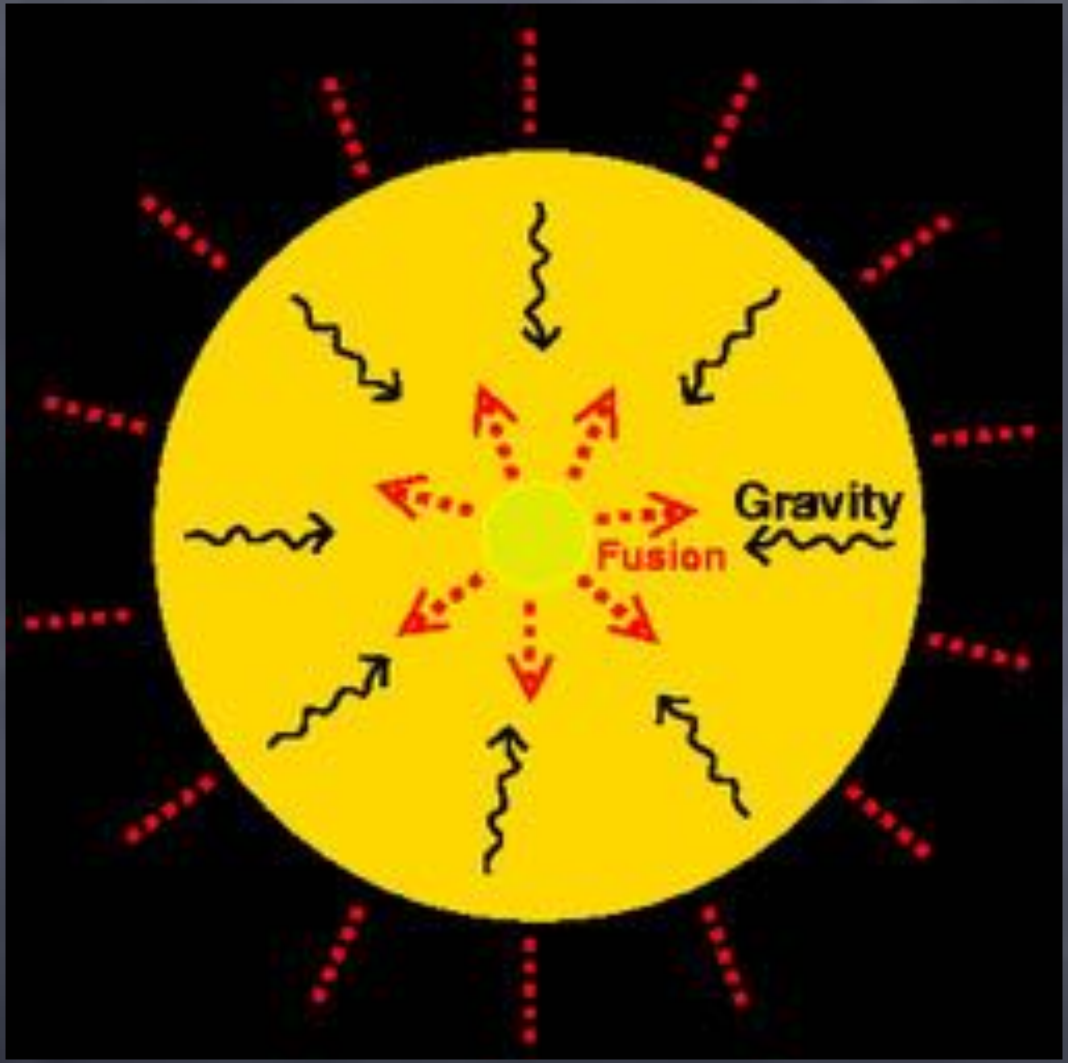
Protoplanetary disk

What drives stars?

Nuclear Fusion



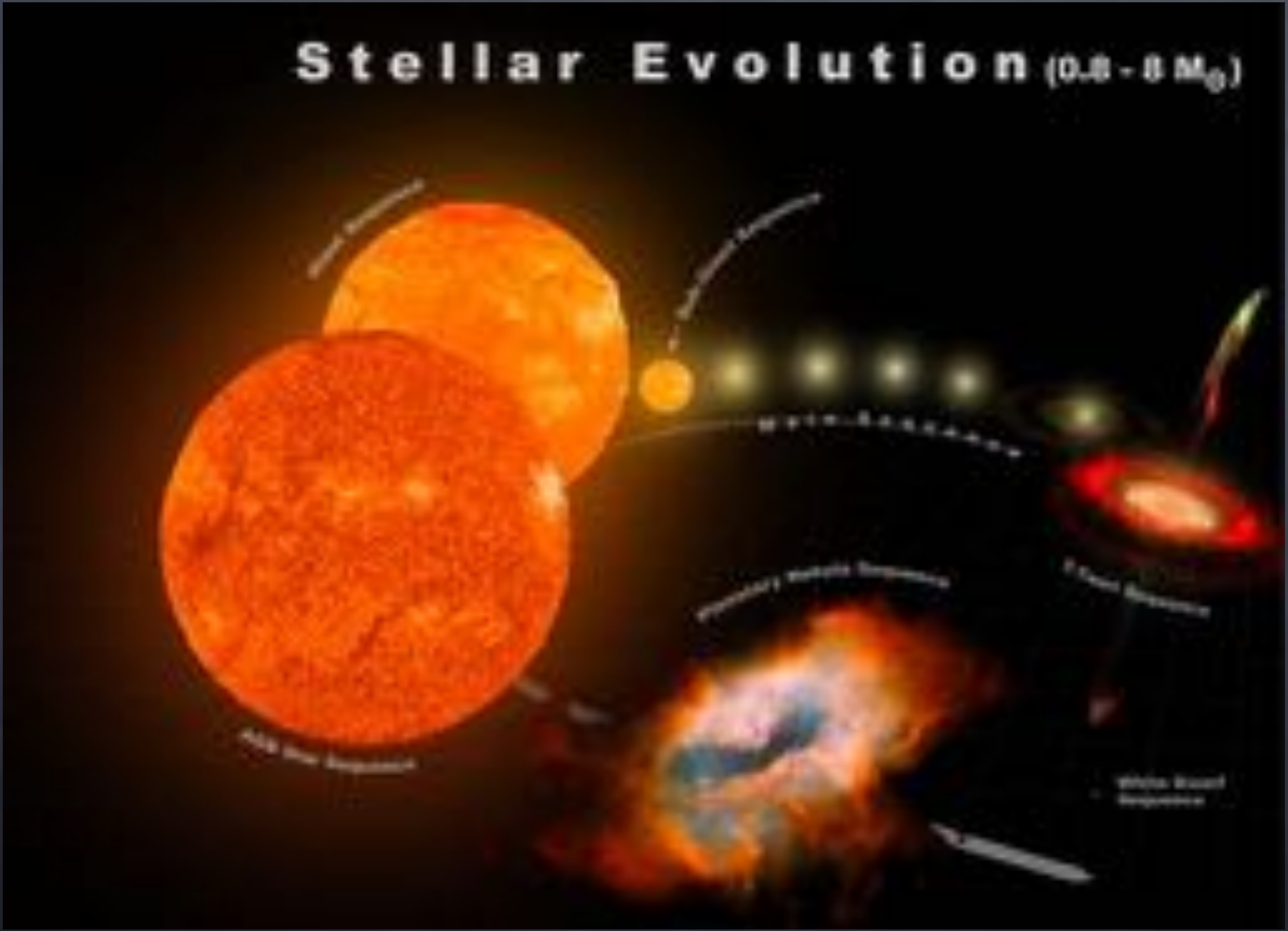
Heavy products sink to the core


Gravity
Fusion

Main Sequence: H—> He

Post-main Sequence:

Mid-size stars
1. sub-giant phase - H burning in the H shell
2. red-giant phase - He burning with H shell
3. Asymptotic-giant-branch phase - H,He shell burning, C,O core
4. Planetary nebula —> white dwarf —> black dwarf

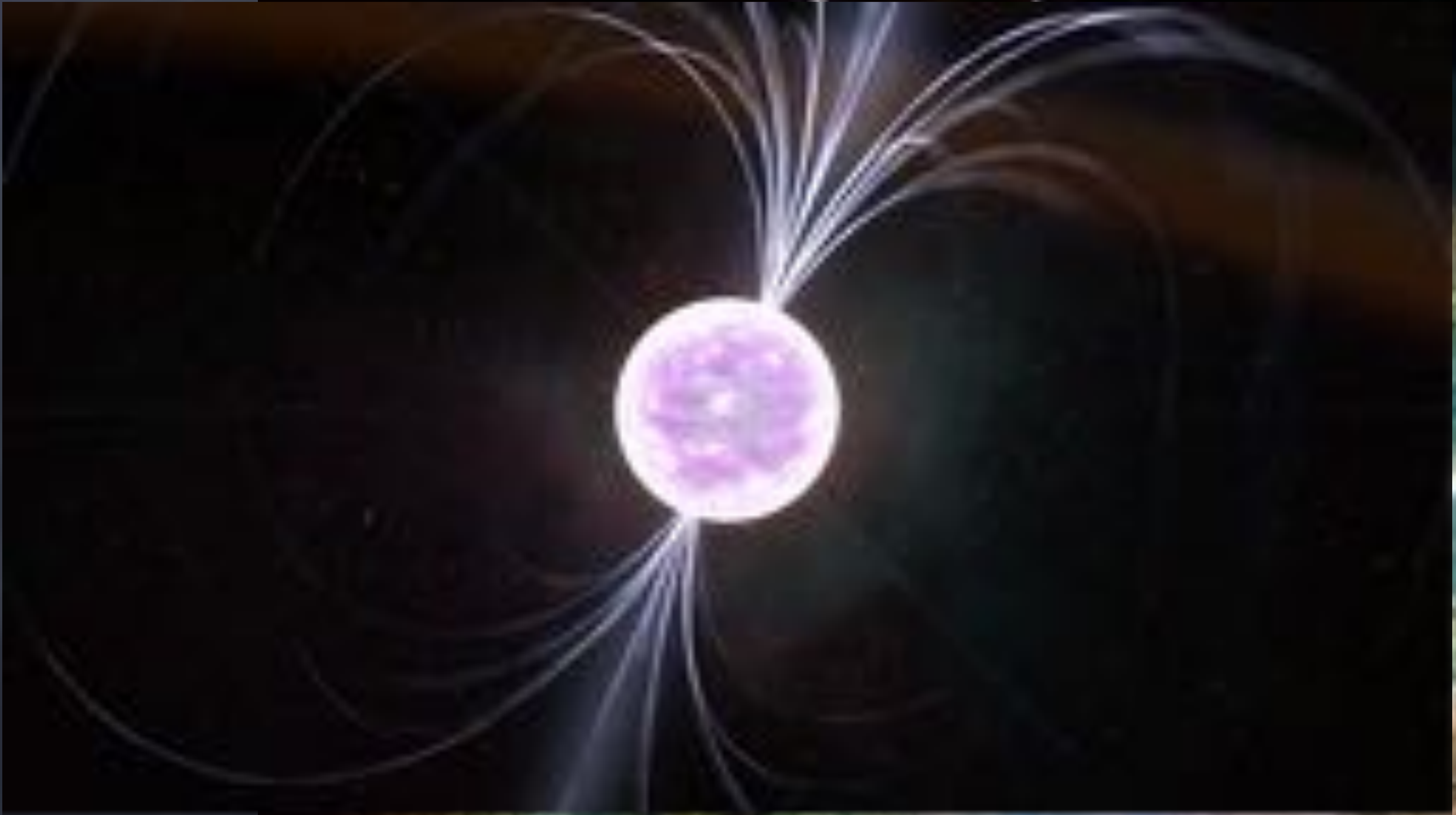

Stellar Evolution (0.8 - 8 $M_\odot$)
Main Sequence
Planetary Nebula Sequence
AGB Star Sequence
White Dwarf Sequence

Main Sequence: H—> He

Post-main Sequence:

Massive stars:
A chain-reaction of nuclear reactions that create heavier elements in the core.

Temperature (and luminosity) ↑ → Creation of heavier elements ↓



When
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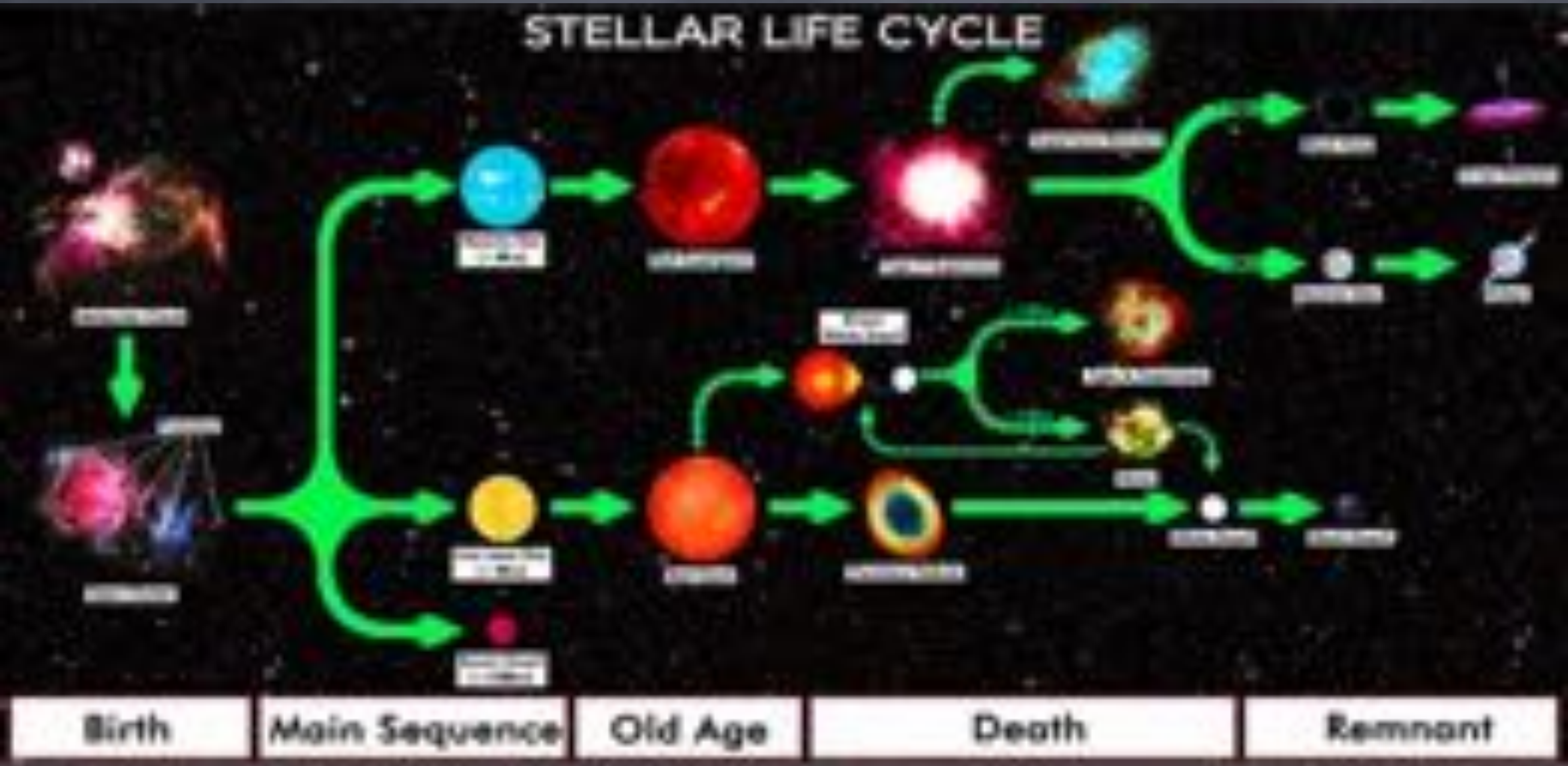
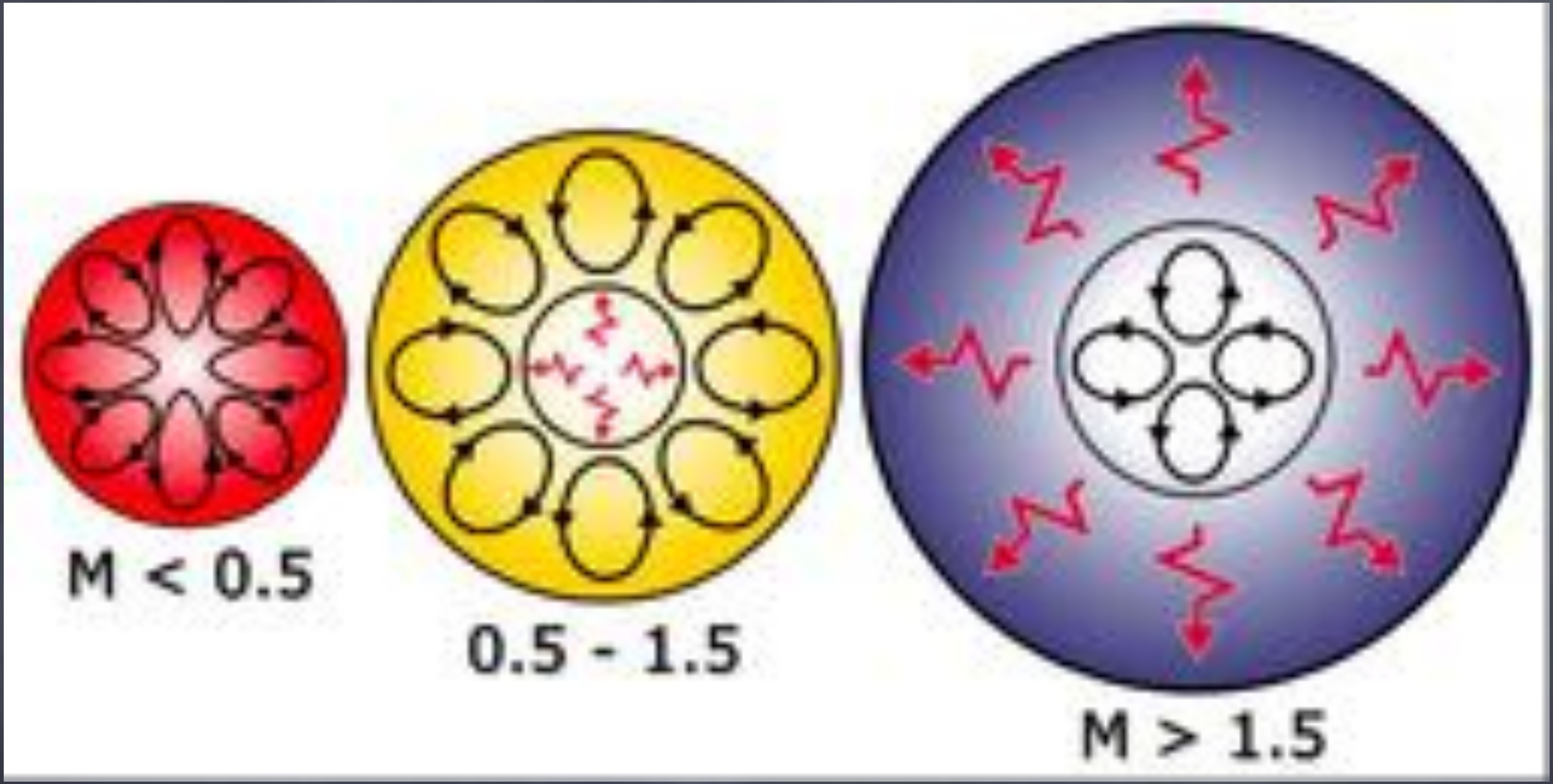
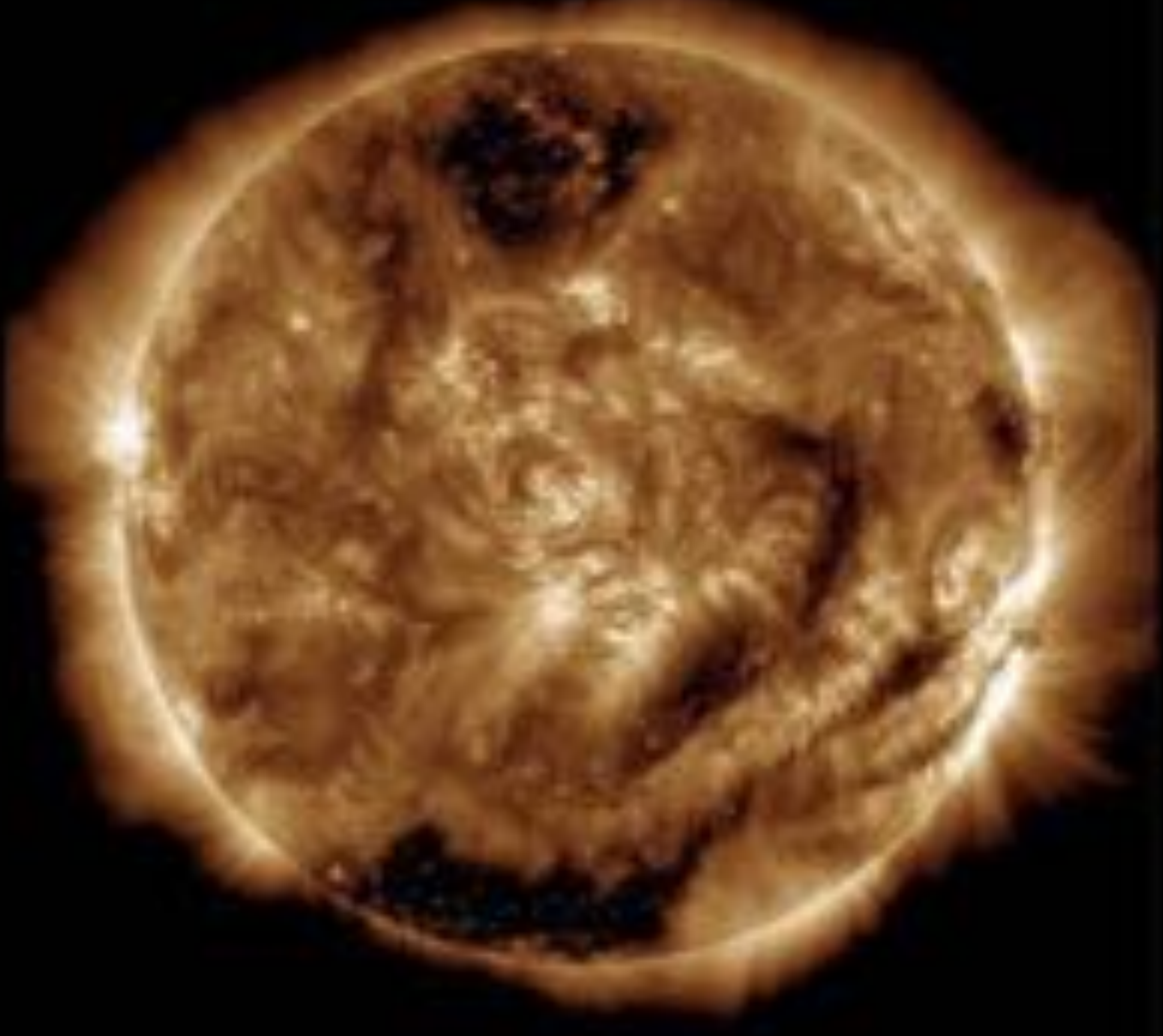

STELLAR LIFE CYCLE
Birth
Main Sequence
Old Age
Death
Remnant

Internal structure



Different dynamo mechanism to generate stellar magn

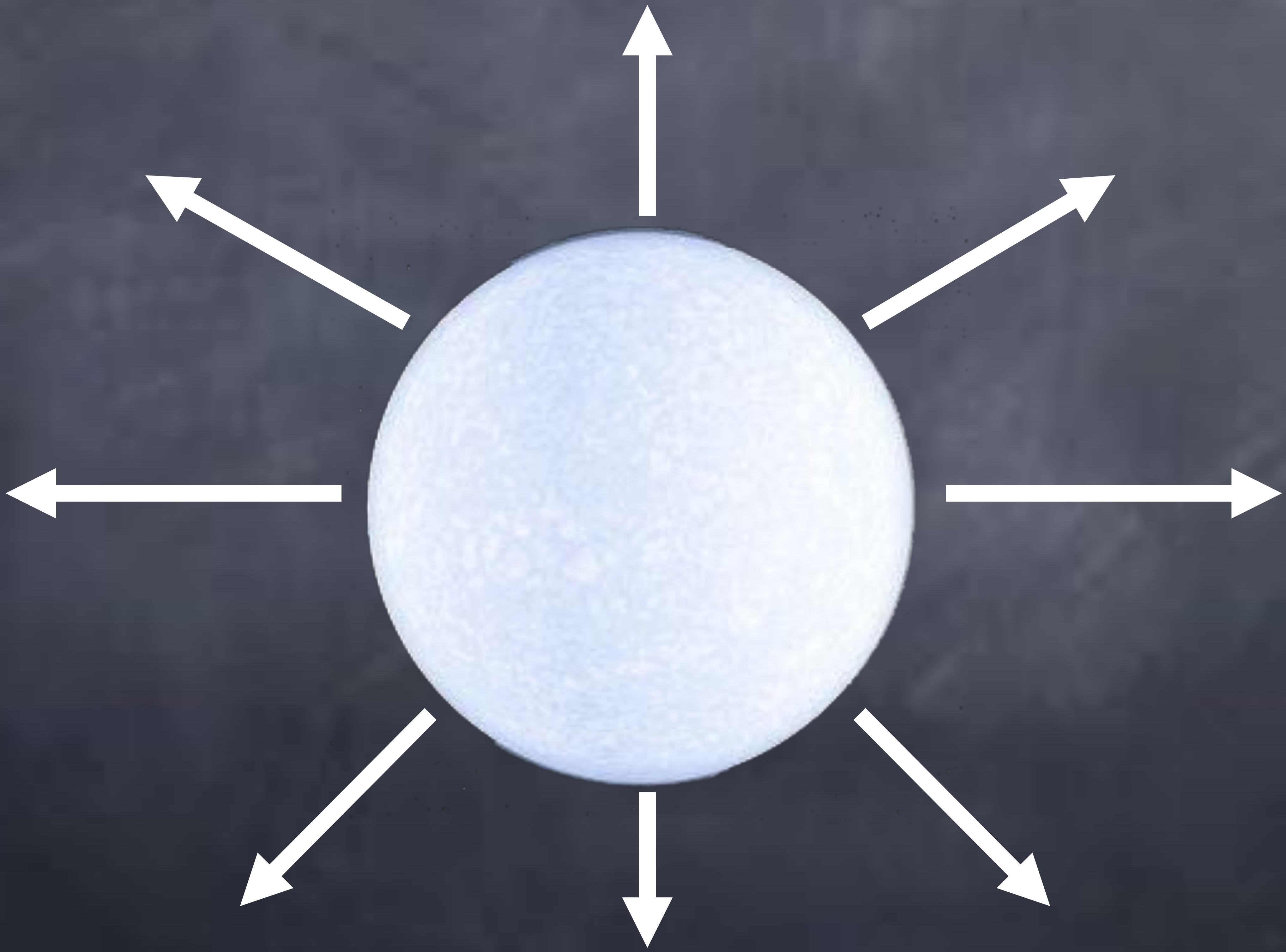
Stellar Coronae and Winds



Hot stars radiation driven winds:

7000-8000K and above
Full radiative envelop
Relatively cold corona
(10,000-50,000K)
Winds become supersonic
almost at the surface

Radiation pressure drives powerful winds (10000km/s) and strong mass-loss rate (10^{-6} Msun/yr, solar is 10^{-14} Msun/yr)



Low-mass, cool stars -

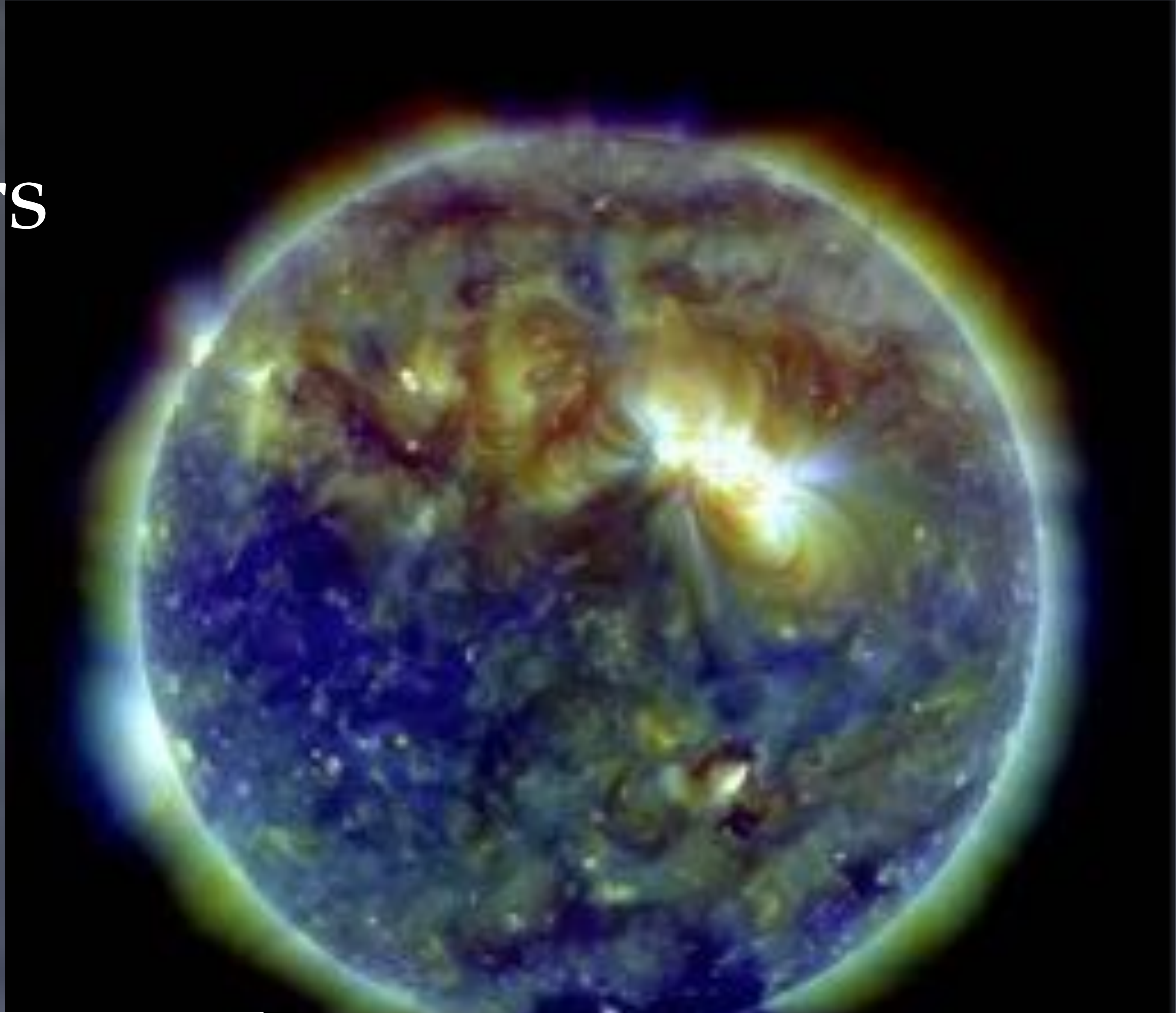
solar analogs, Sun-like stars

Cool stars - hot coronae

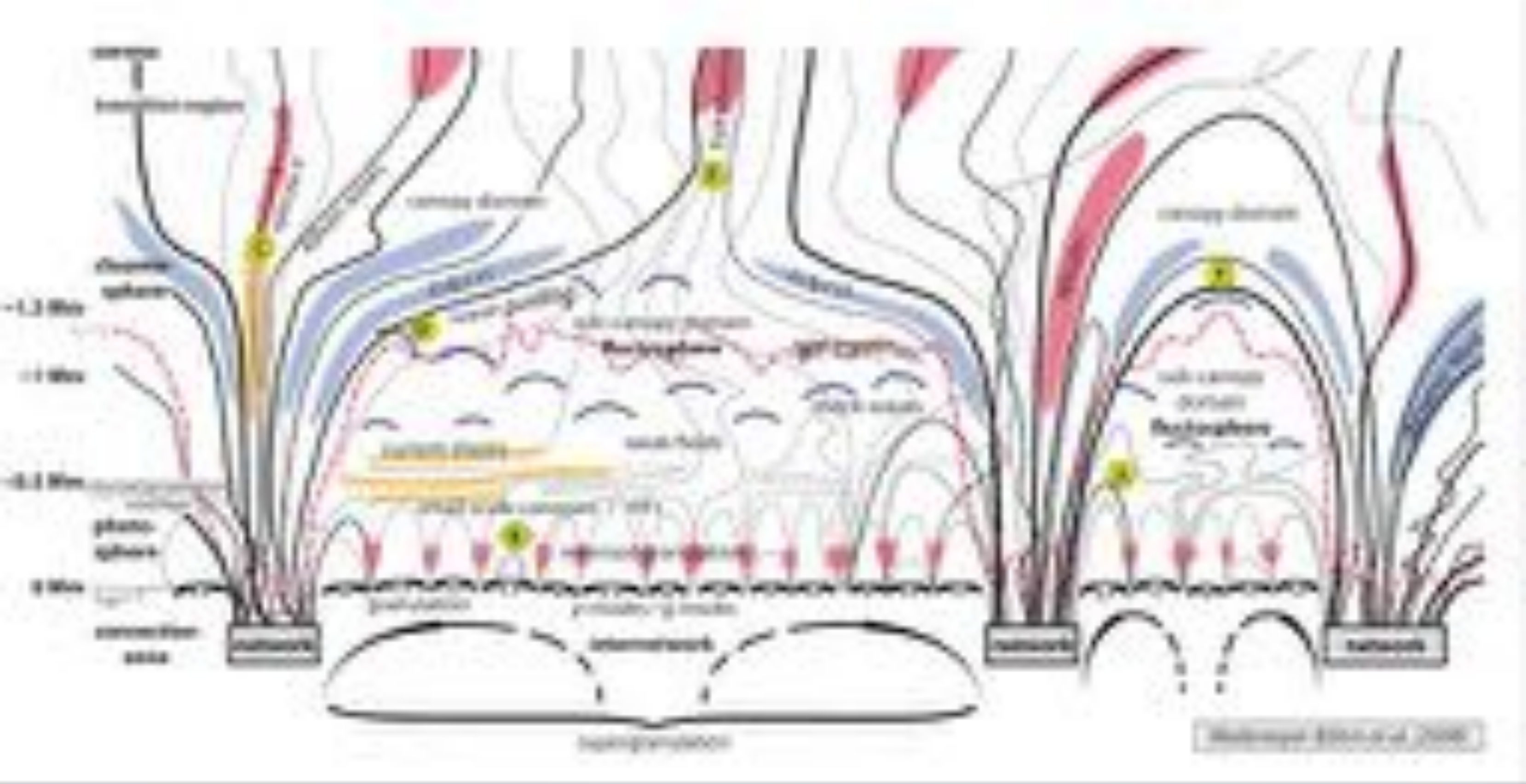
corona is heated and how does the solar

Low-mass, cool stars -
solar analogs, Sun-like stars

Cool stars - hot coronae

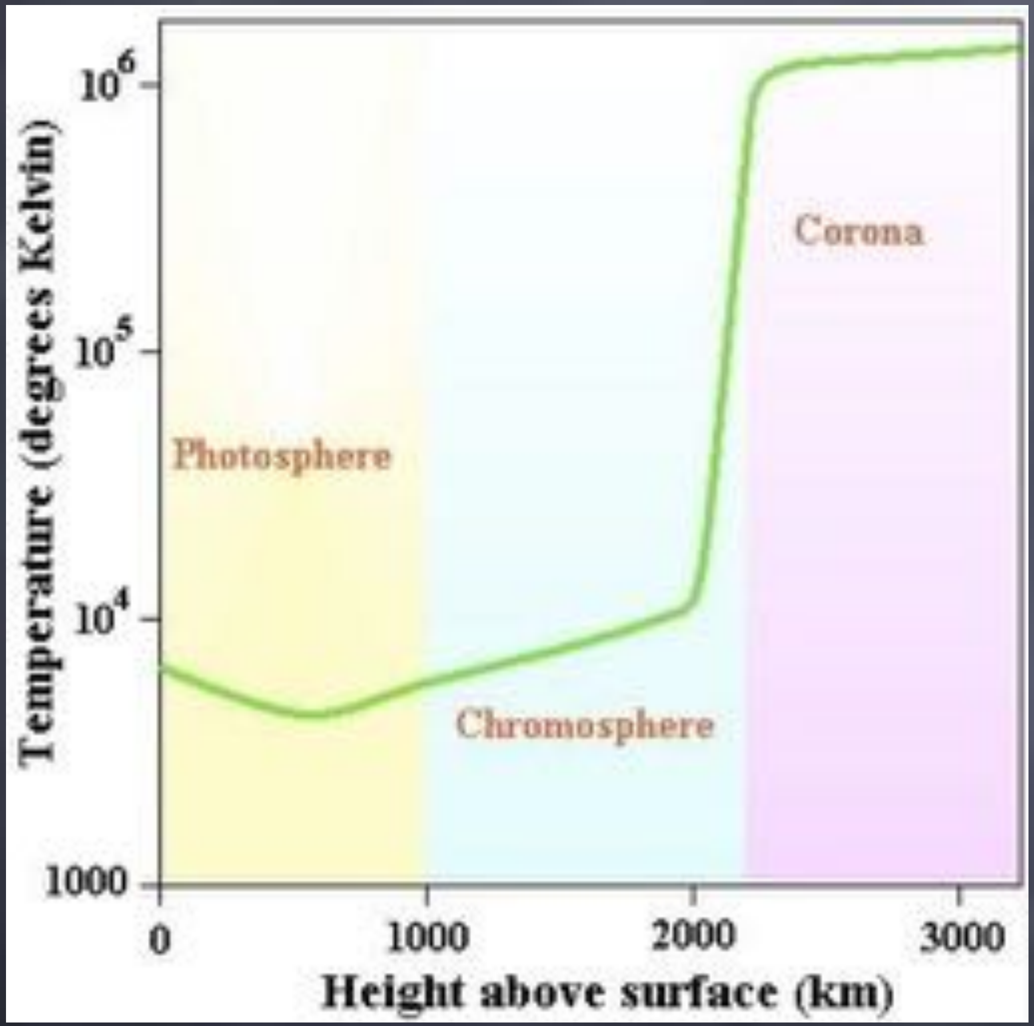


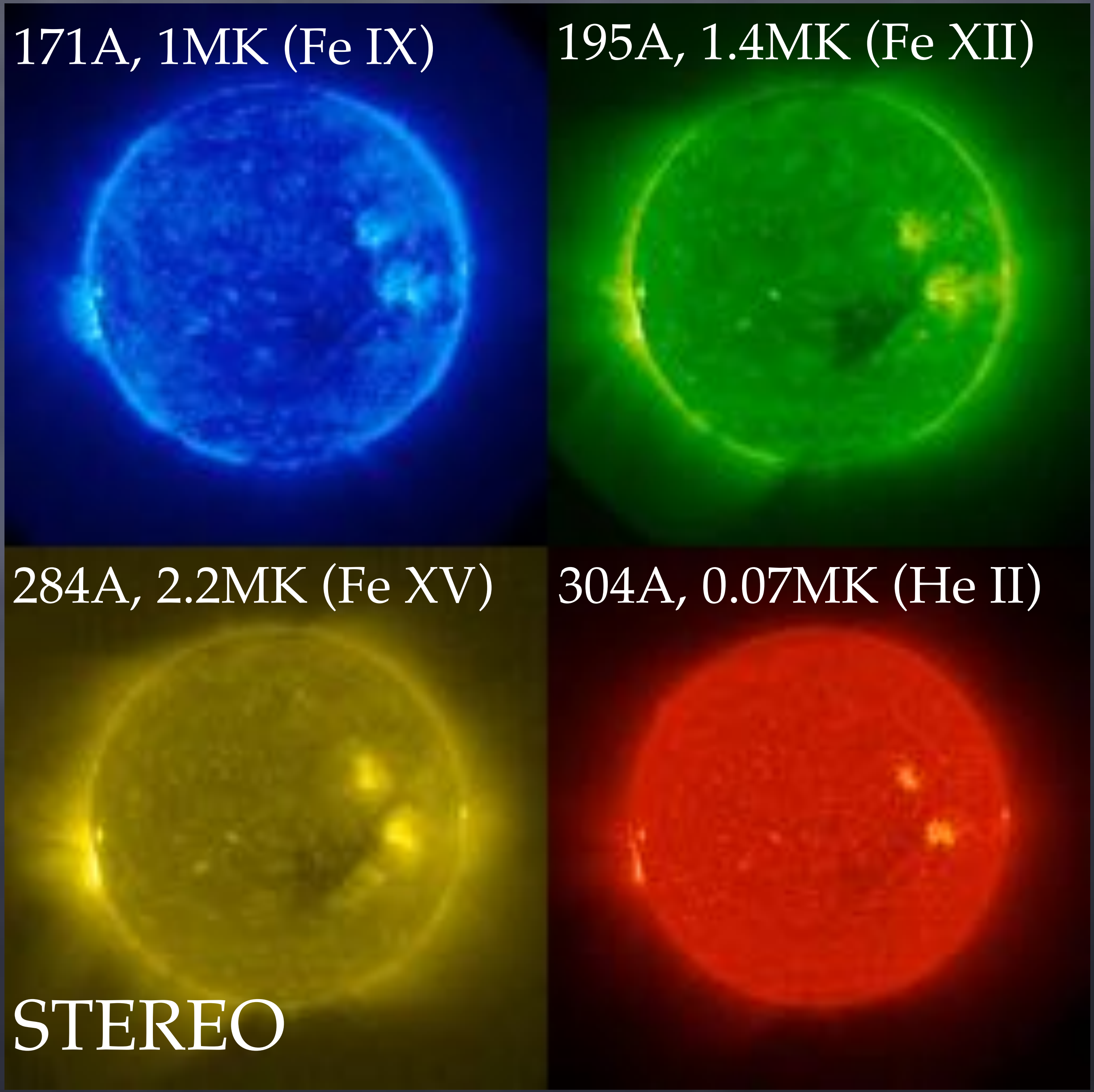
SDO/AIA



The problem of coronal heating:

The temperature of the solar (and stellar) corona is over a million degrees Kelvin (5000K at the photosphere).




171A, 1MK (Fe IX)

195A, 1.4MK (Fe XII)

284A, 2.2MK (Fe XV)

304A, 0.07MK (He II)

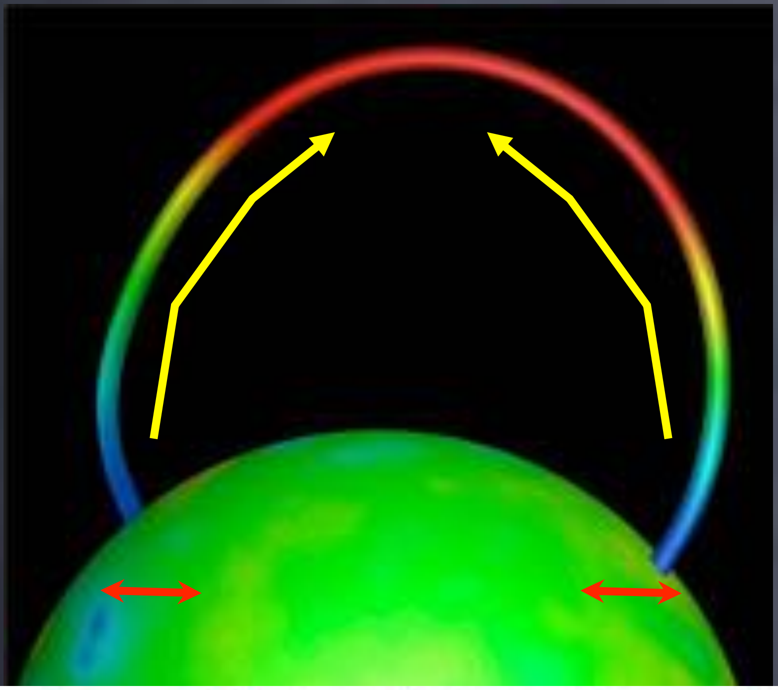
STEREO

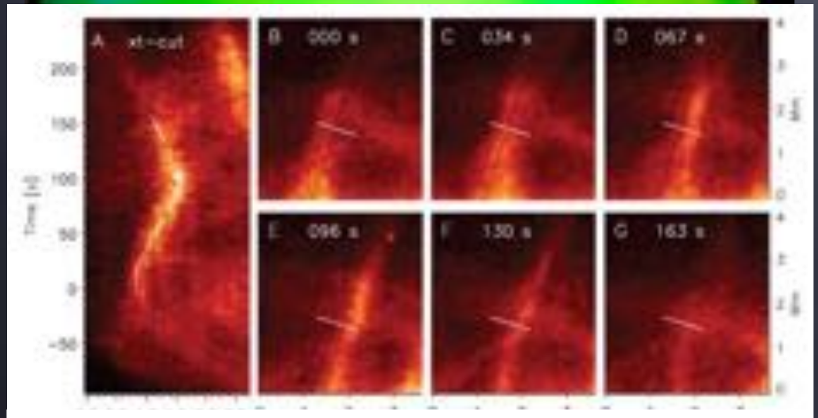
Possible mechanisms to heat the corona:

AC (waves)

DC

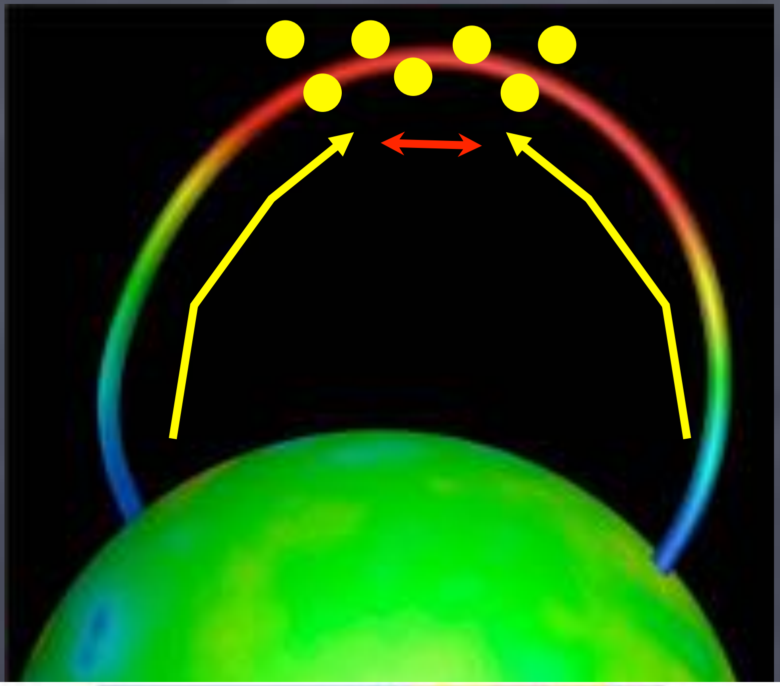
Wave dissipation

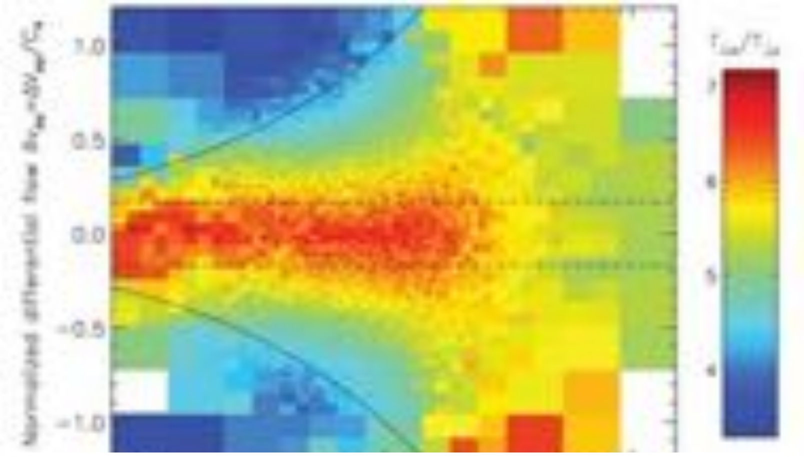




De Pontieu et al, Science 2007

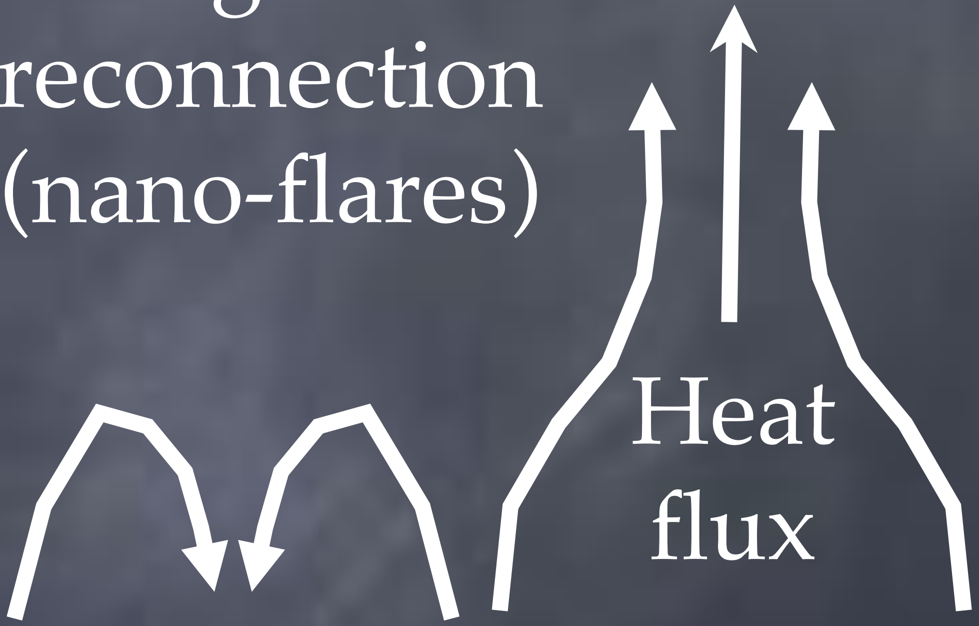
Wave turbulence resonance





Kasper et al. PRL, 2013

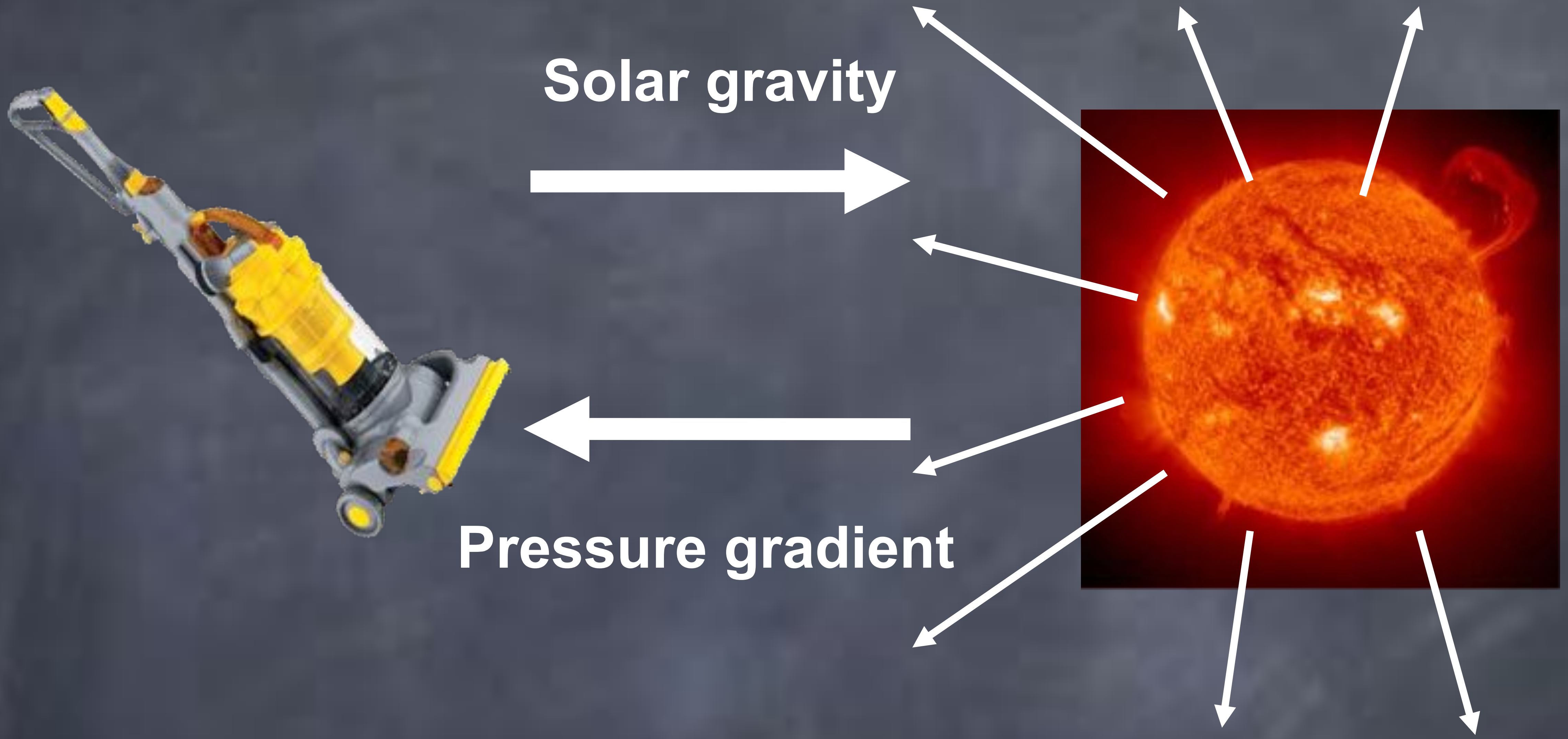
Magnetic reconnection (nano-flares)



Heat flux

High-Resolution Coronal Imager (Hi-C)
Cirtain et al., Nature, 2013

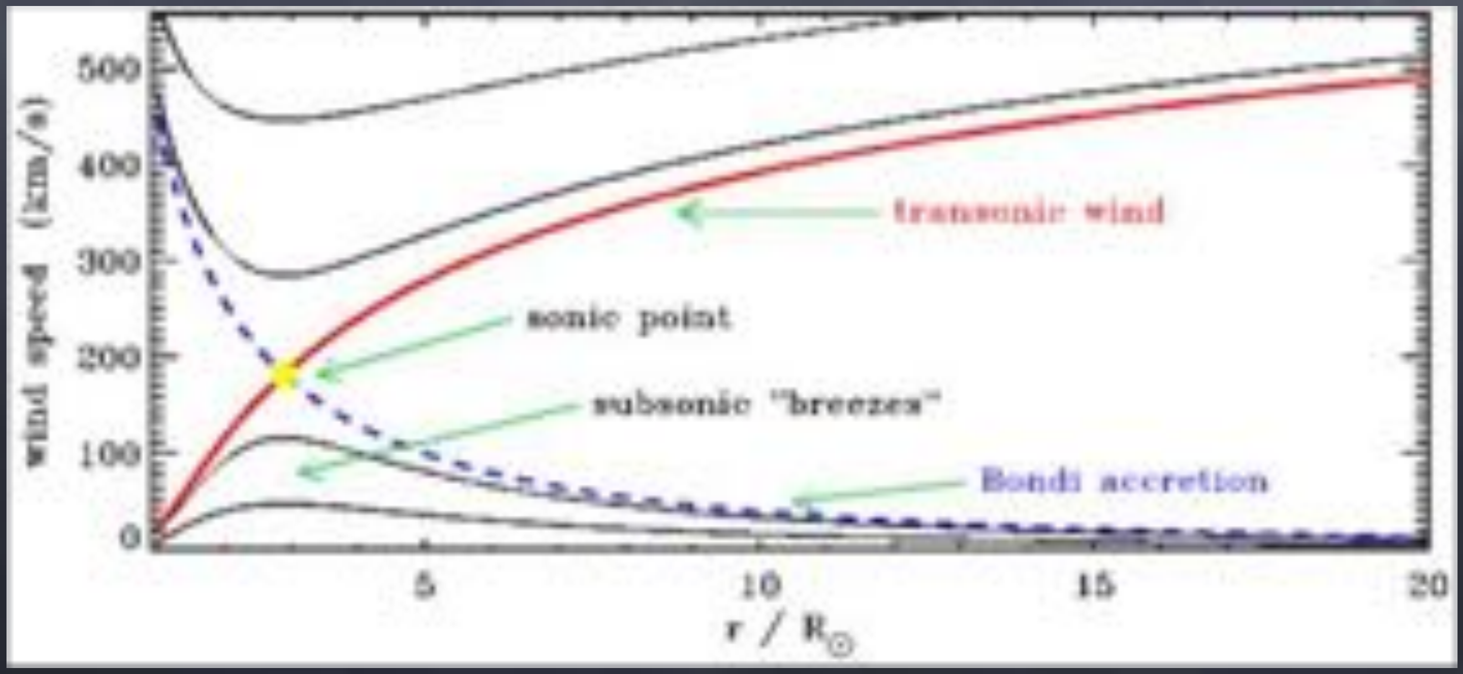
The origin and evolution of the solar wind

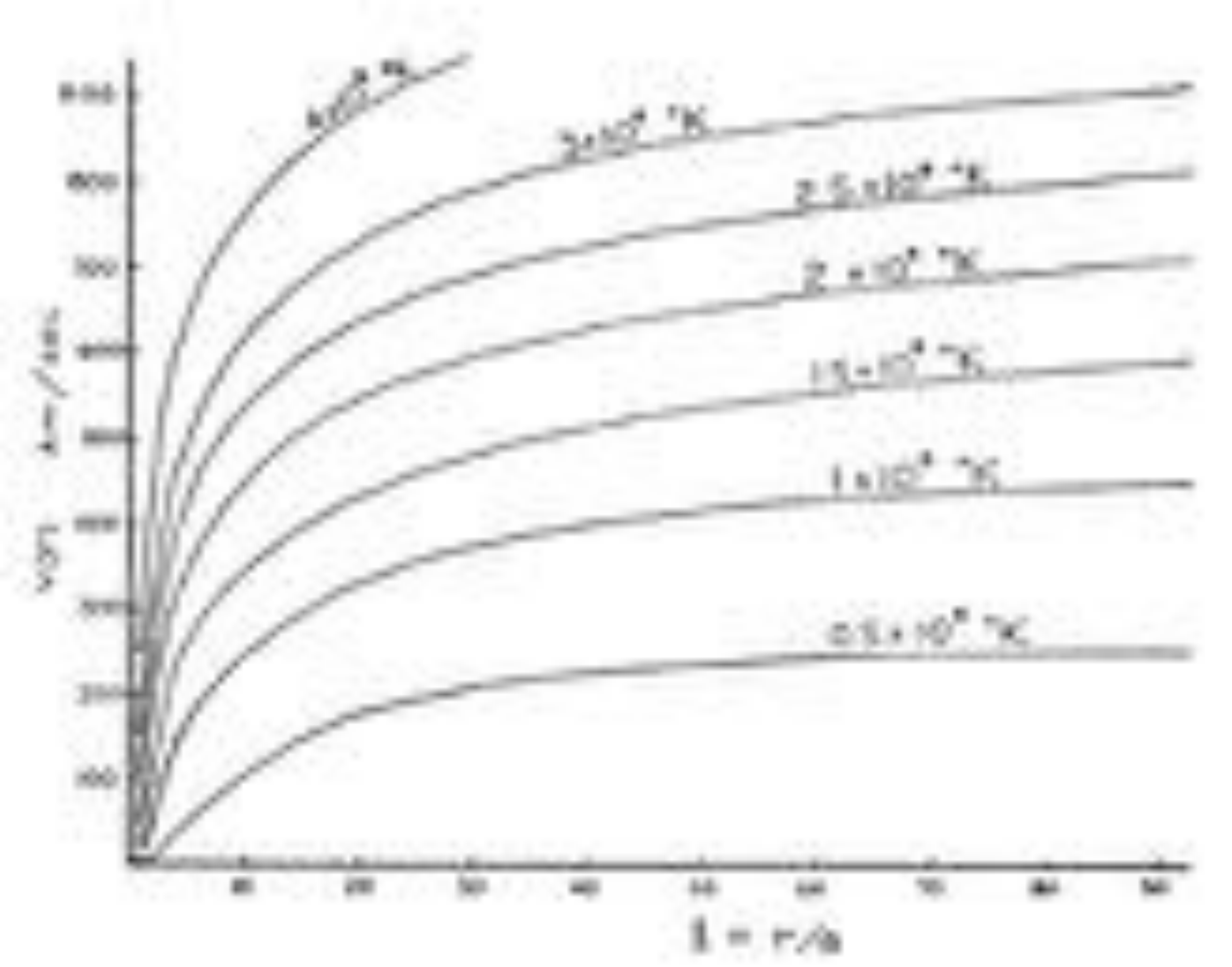


Solar gravity

Pressure gradient

E. Parker
1958





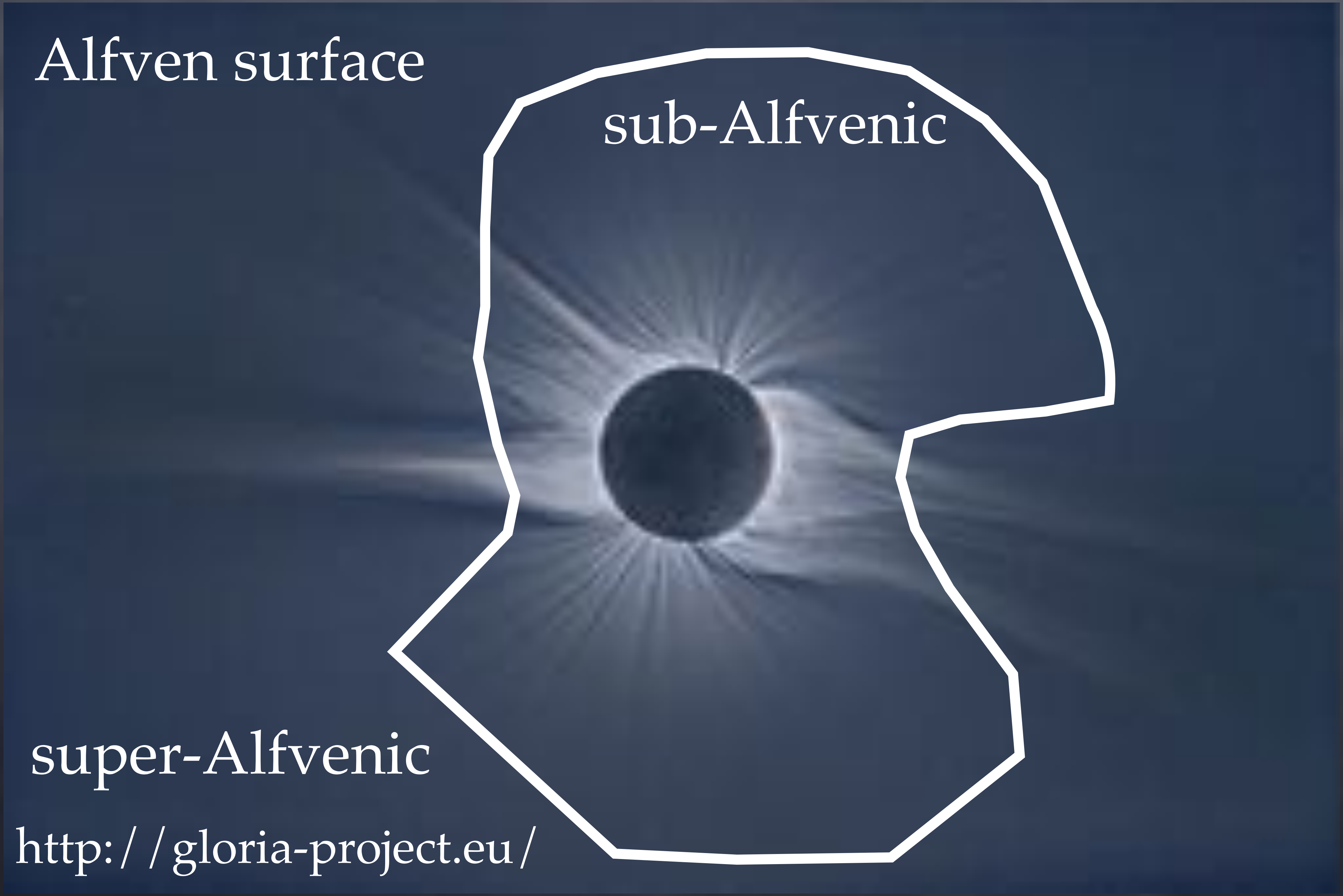
1. Bimodal - cooler, less dense, fast wind and hotter, more dense, slow wind populations.
2. Faster than predicted by the hydrodynamic model .
3. Inverse relations between wind speed and electron temperature - contradicts hydrodynamic model.

The Alfven point/surface

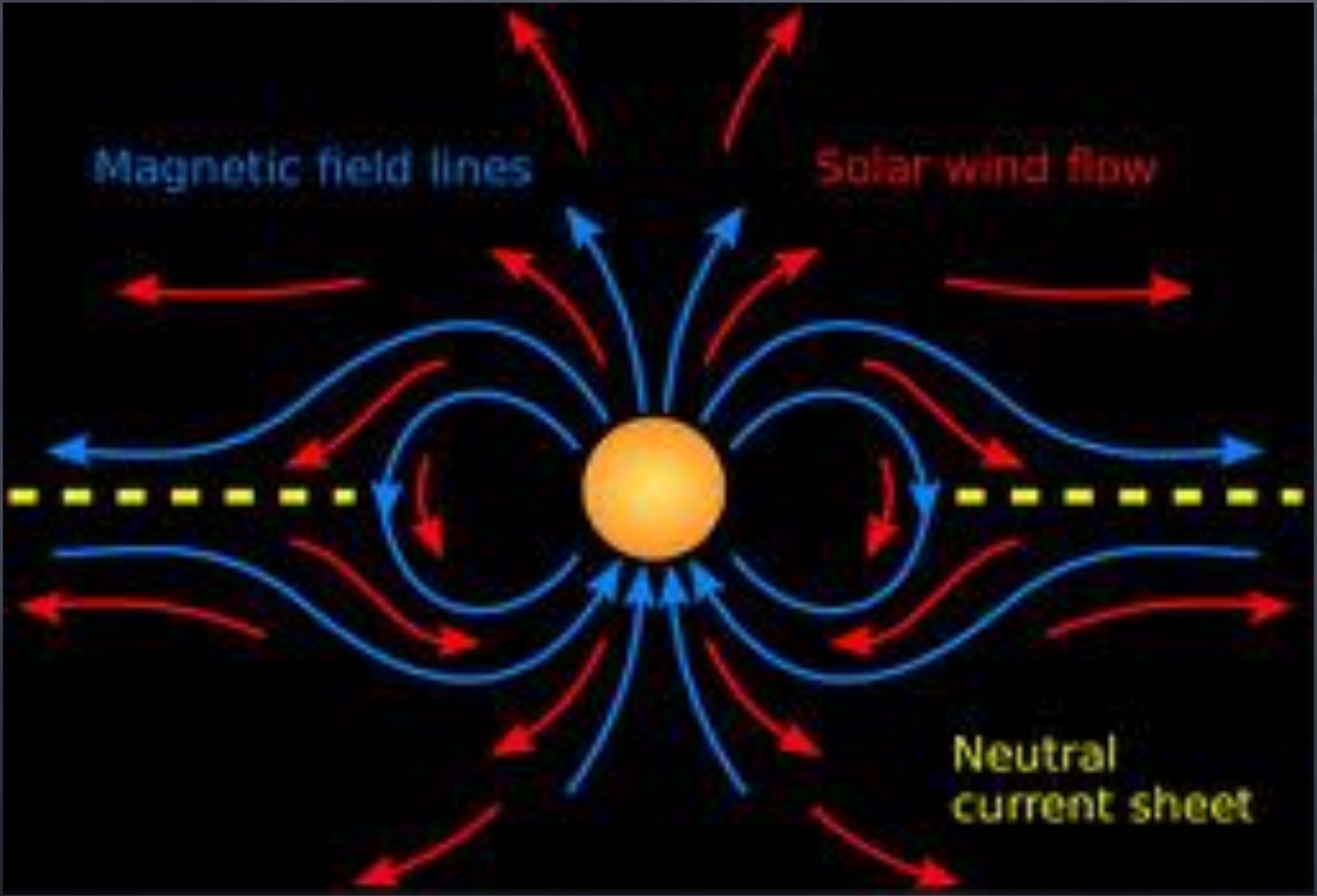
$$v_A^2 = \frac{B^2}{4\pi\rho} = \frac{p_B}{2\rho}$$

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

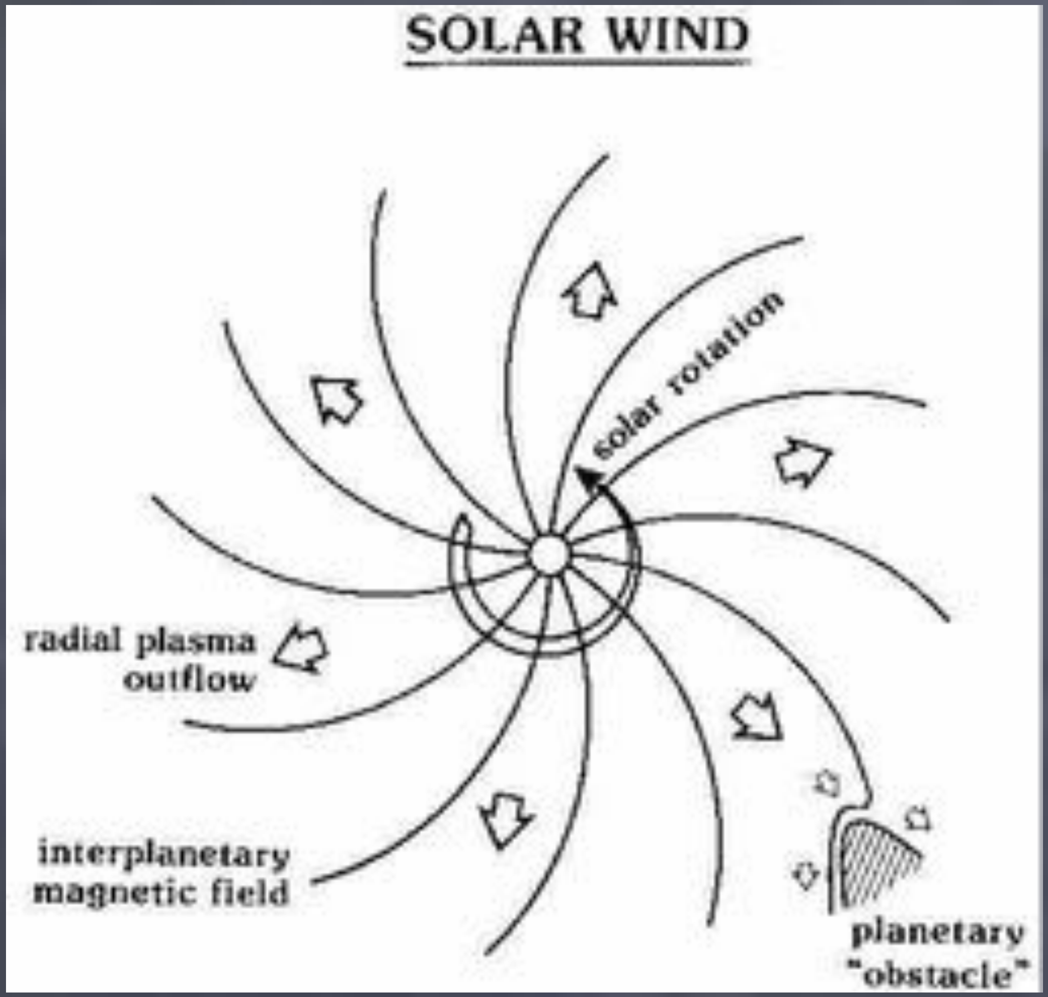
$$M_A = v/v_A$$



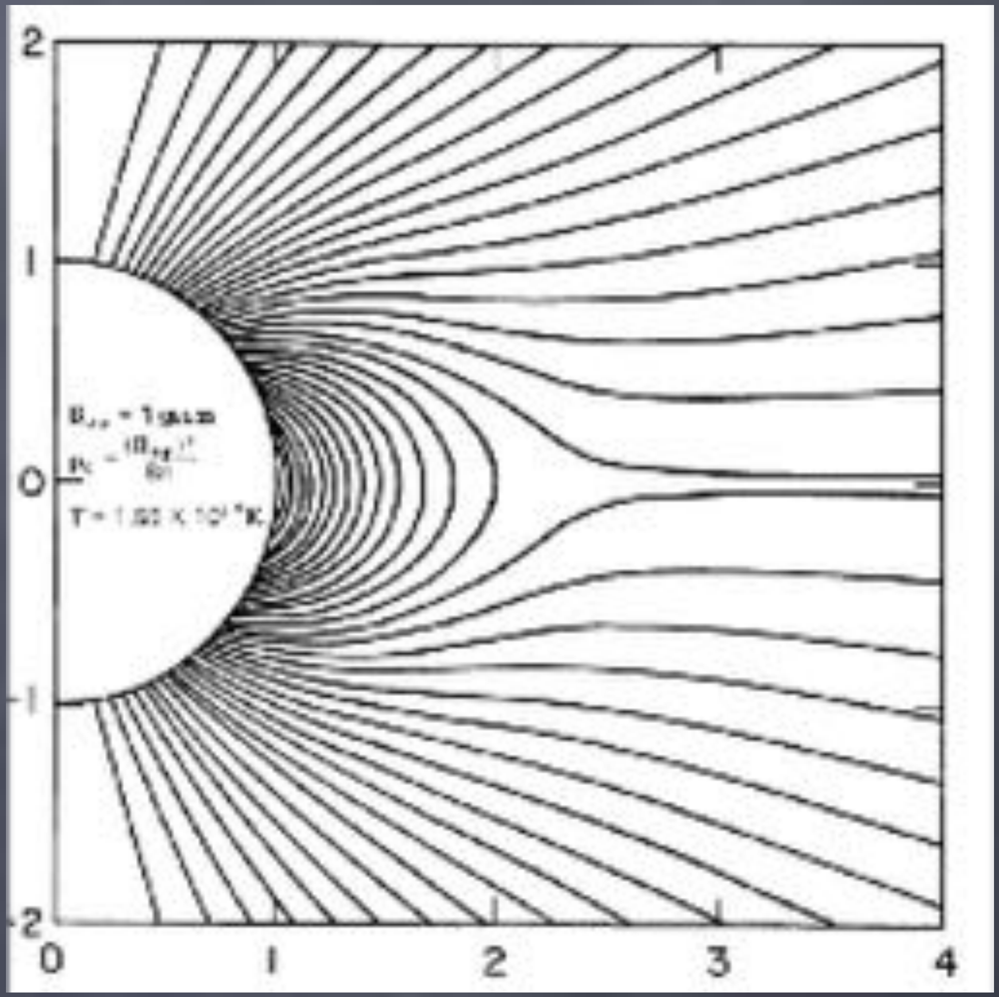
http://gloria-project.eu/


Magnetic field lines
Solar wind flow
Neutral current sheet

The structure of the Heliospheric Magnetic Field (IMF):



By J. Luhmann



Pneumann & Kopp 1971

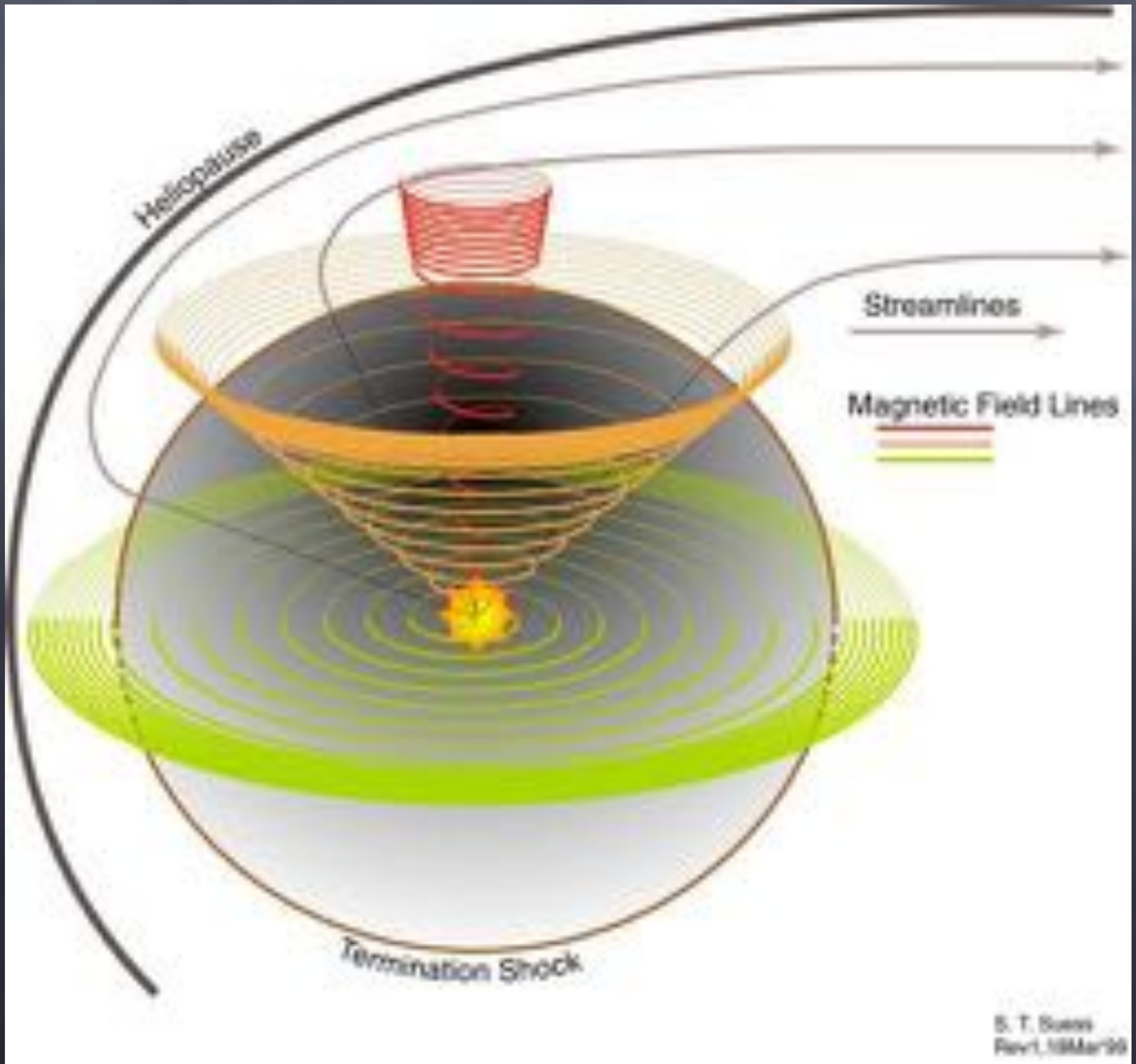
The IMF - Parker spiral:

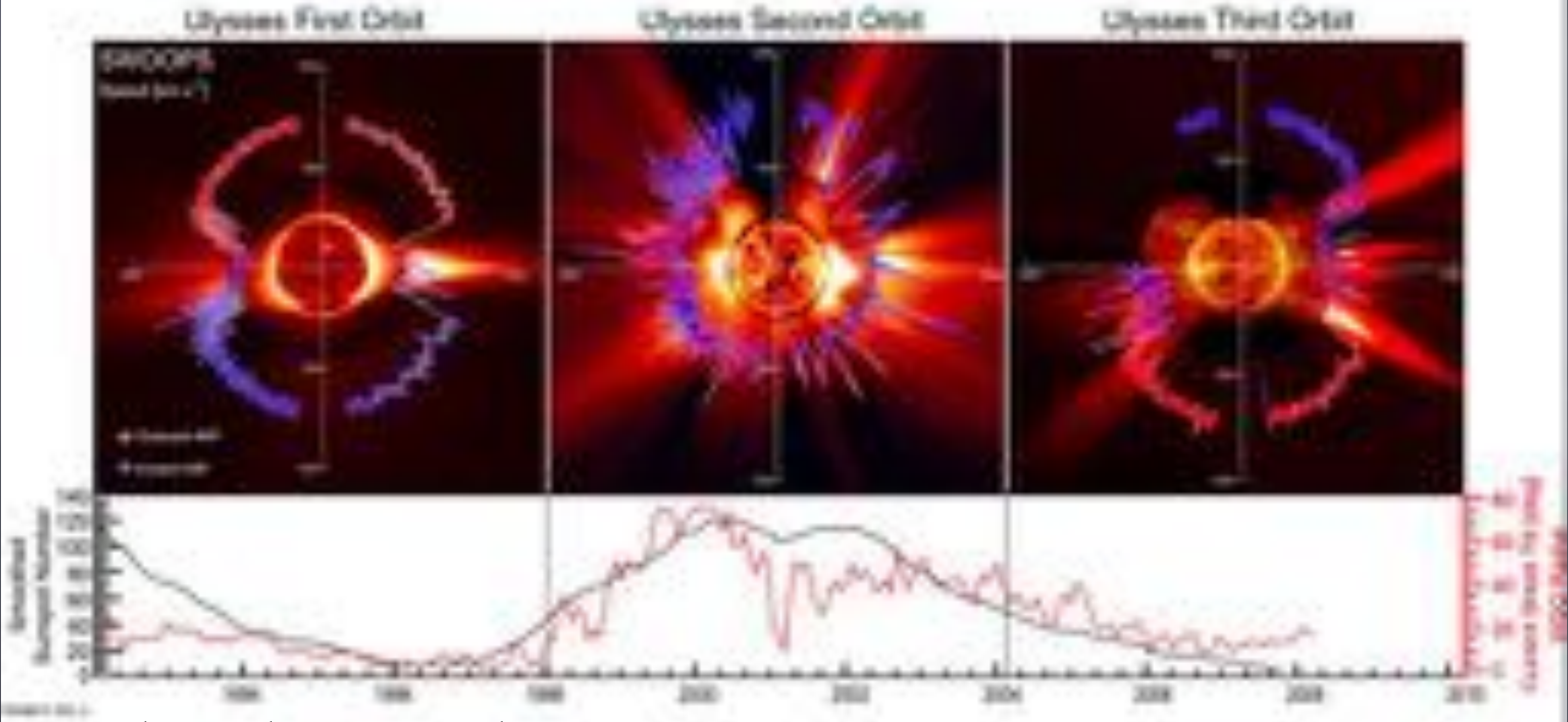
Heliospheric latitude

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

Magnetic field at r_0

Solar rotation

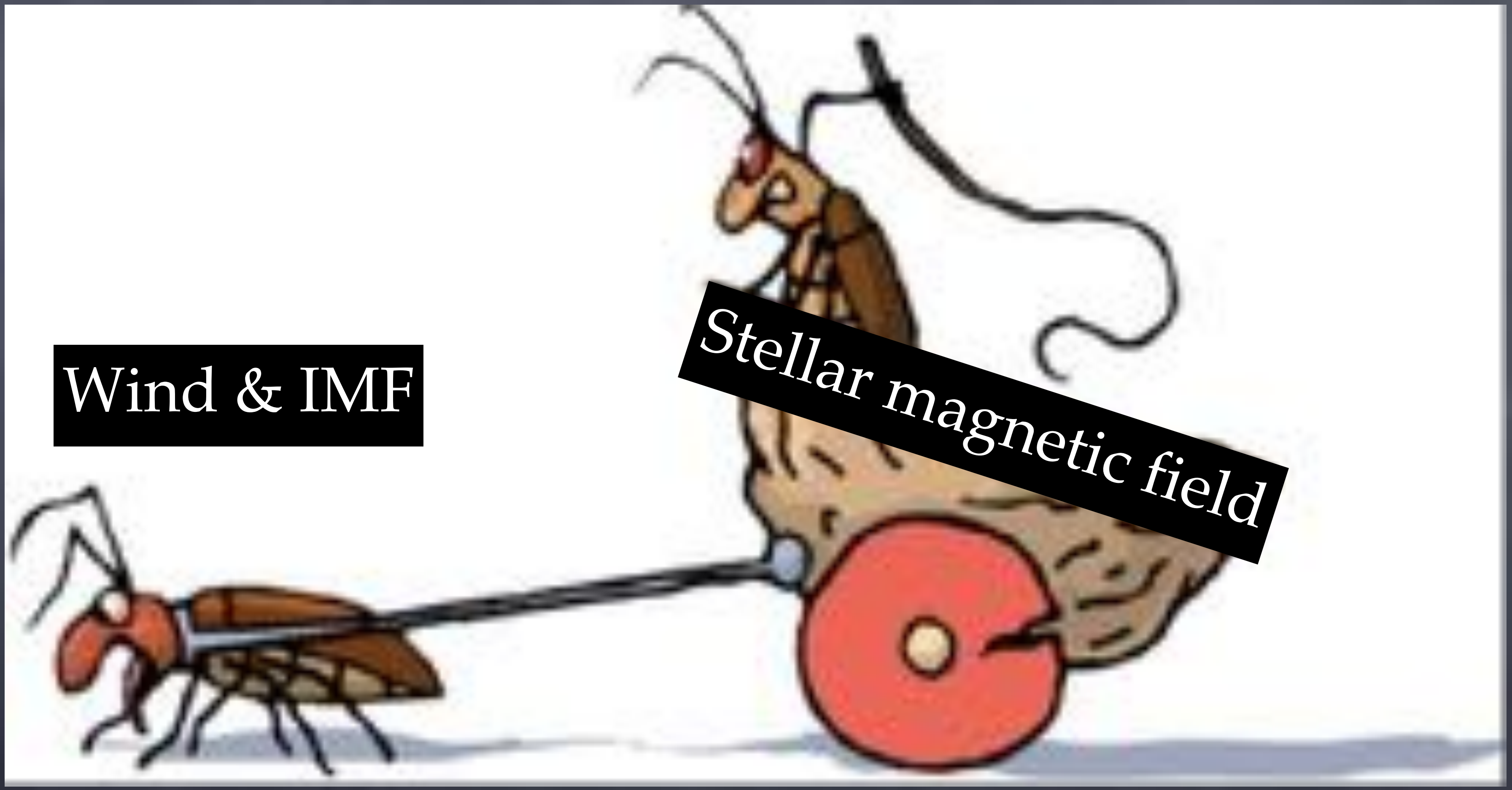




Solar minimum (dipole) - equatorial slow wind (dense), polar fast wind (less dense), lower IMF

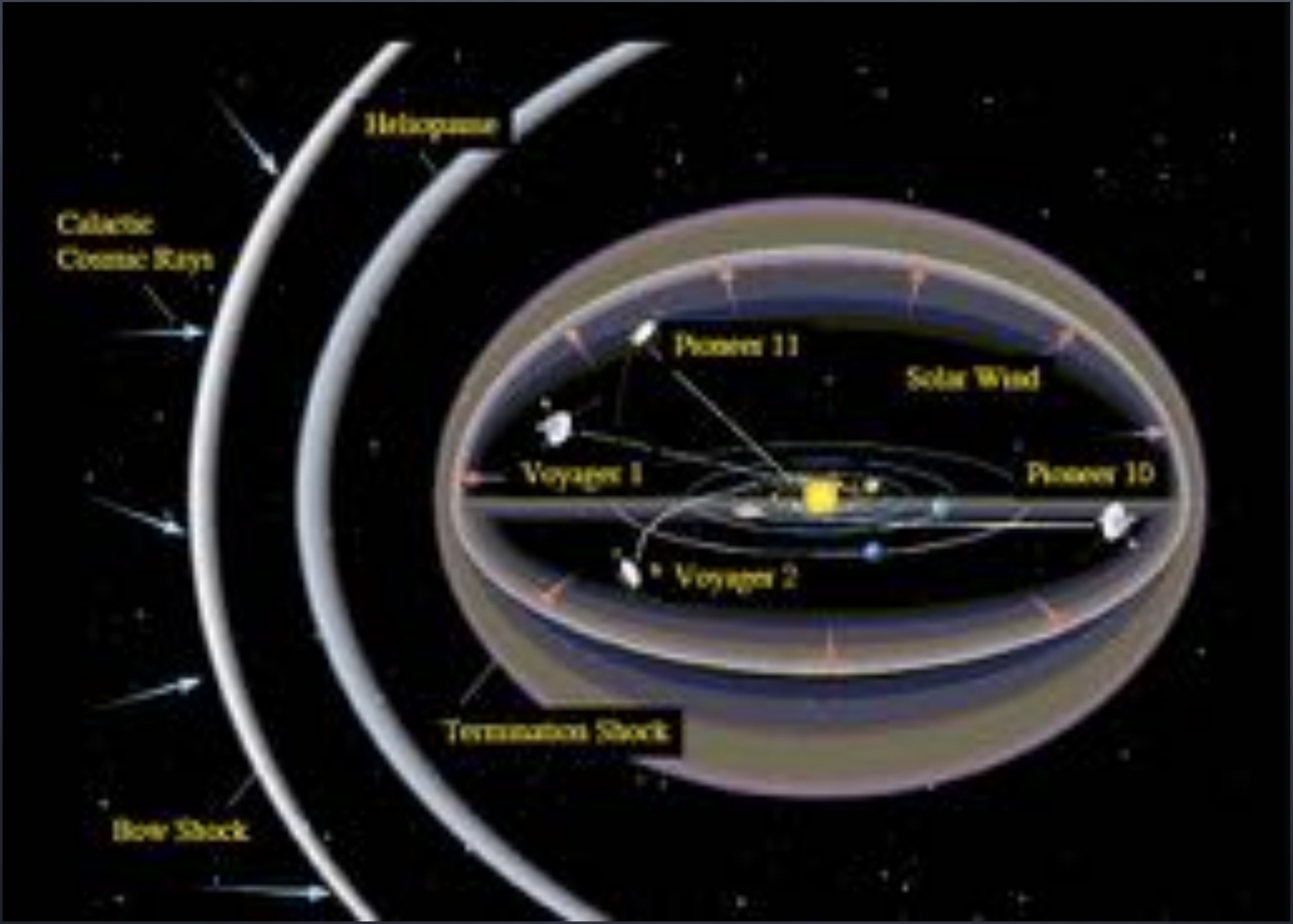
Solar max (multipole) - mostly slow wind, unstructured, increased IMF

The structure of the solar wind and the interplanetary space is controlled by the structure of the solar/stellar magnetic field!!!



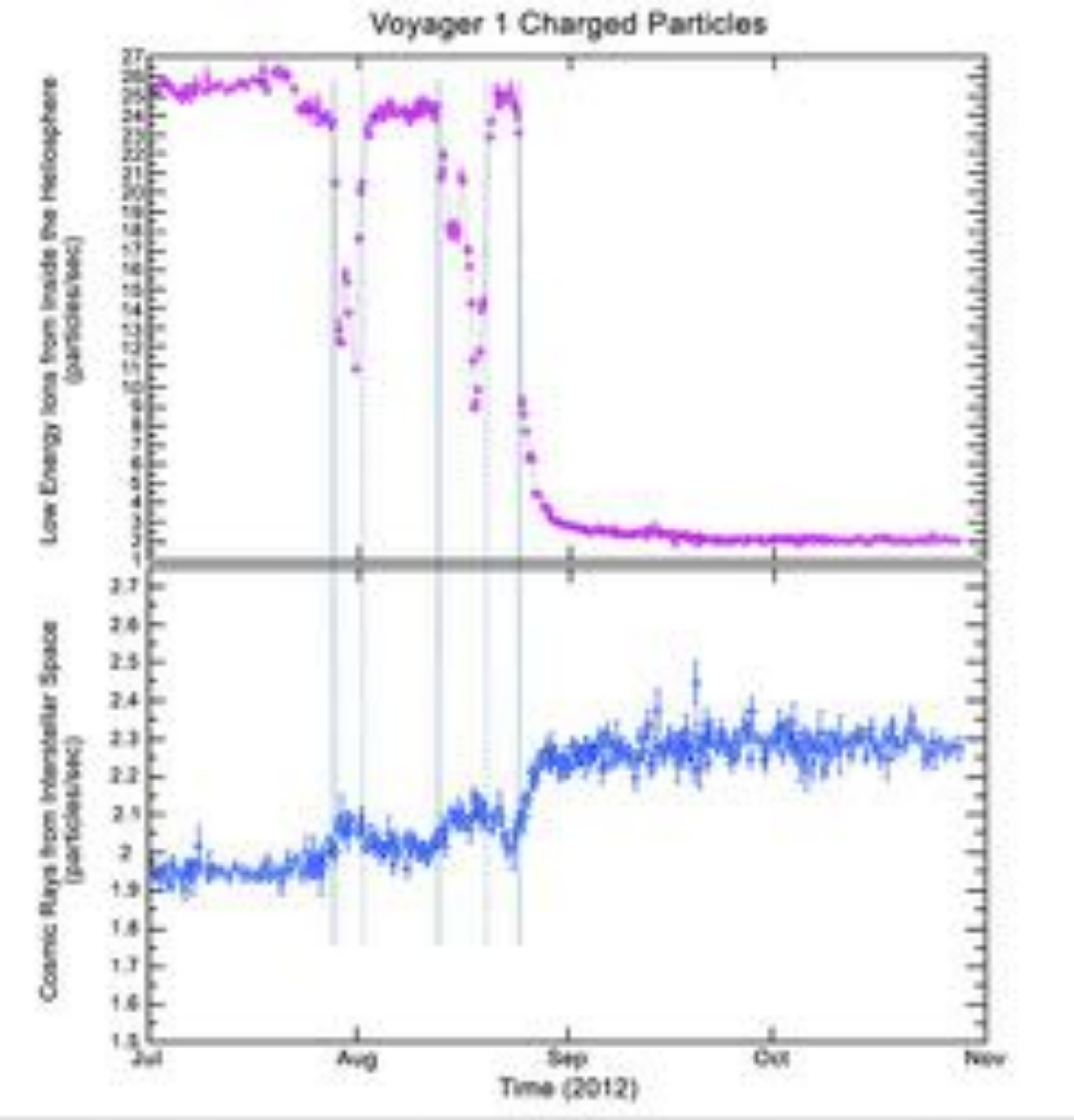
v does this relation changes in other st

Astospheres


Heliopause
Galactic Cosmic Rays
Pioneer 11
Solar Wind
Voyager 1
Pioneer 10
Voyager 2
Termination Shock
Bow Shock

Solar wind

Cosmic rays



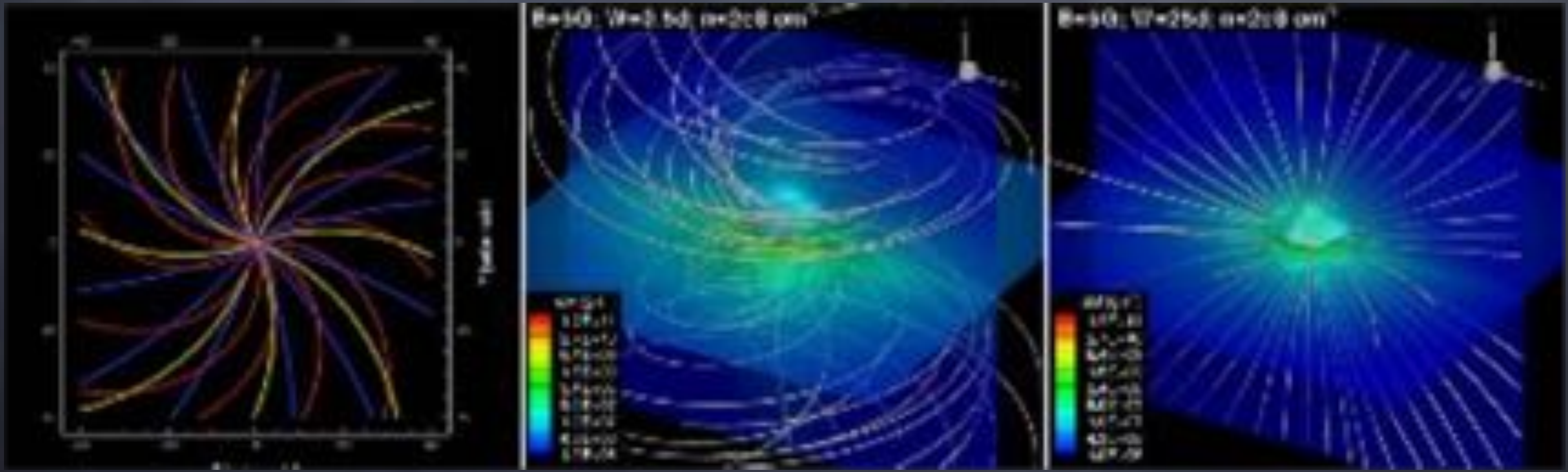
for $r>>r_0$

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

The effect of stellar rotation:

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

For faster rotations, the azimuthal component dominates the AMF:



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

The effect of B

$$\mathbf{B}(\mathbf{r}) = B_s \left(\right.$$

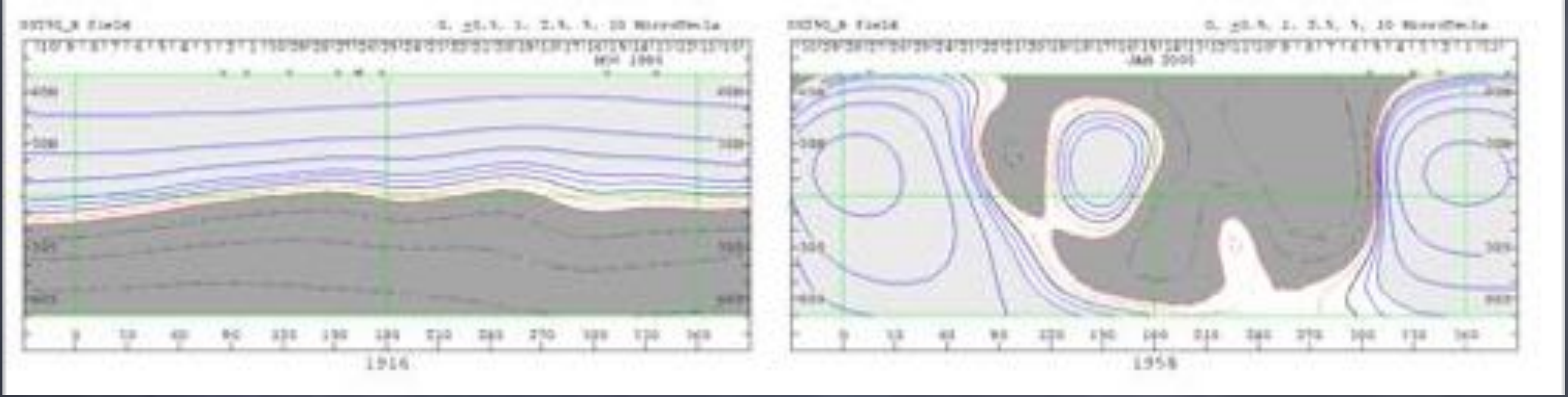
$$B_s$$

$$\left. \frac{r\Omega_\odot \sin\theta}{u_{sw}}\hat{\phi} \right]$$

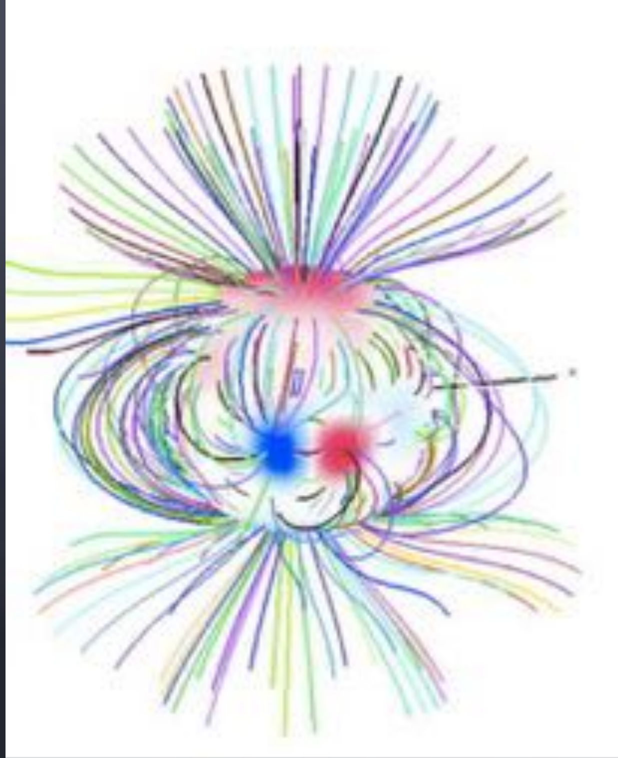
B_s is not uniform and $u_{sw}(B_s)$.

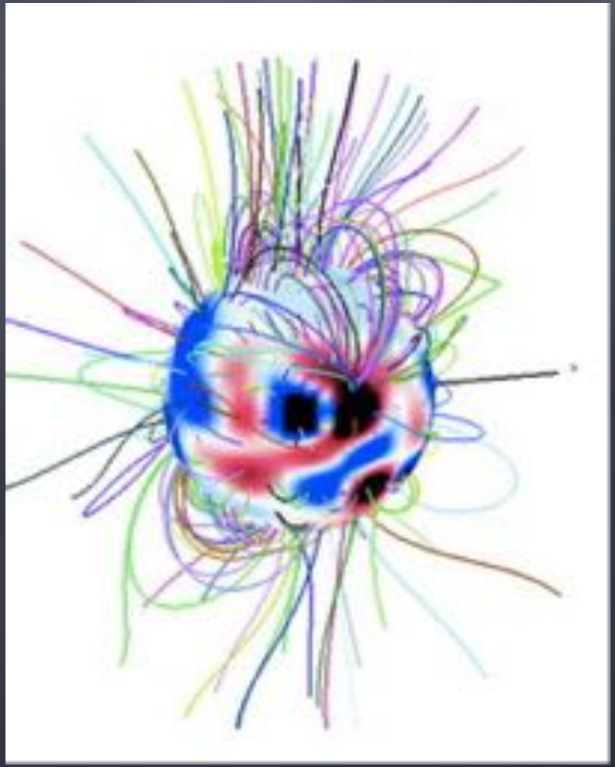
Solar Minimum

Solar Maximum



Wilcox Solar Observatory data

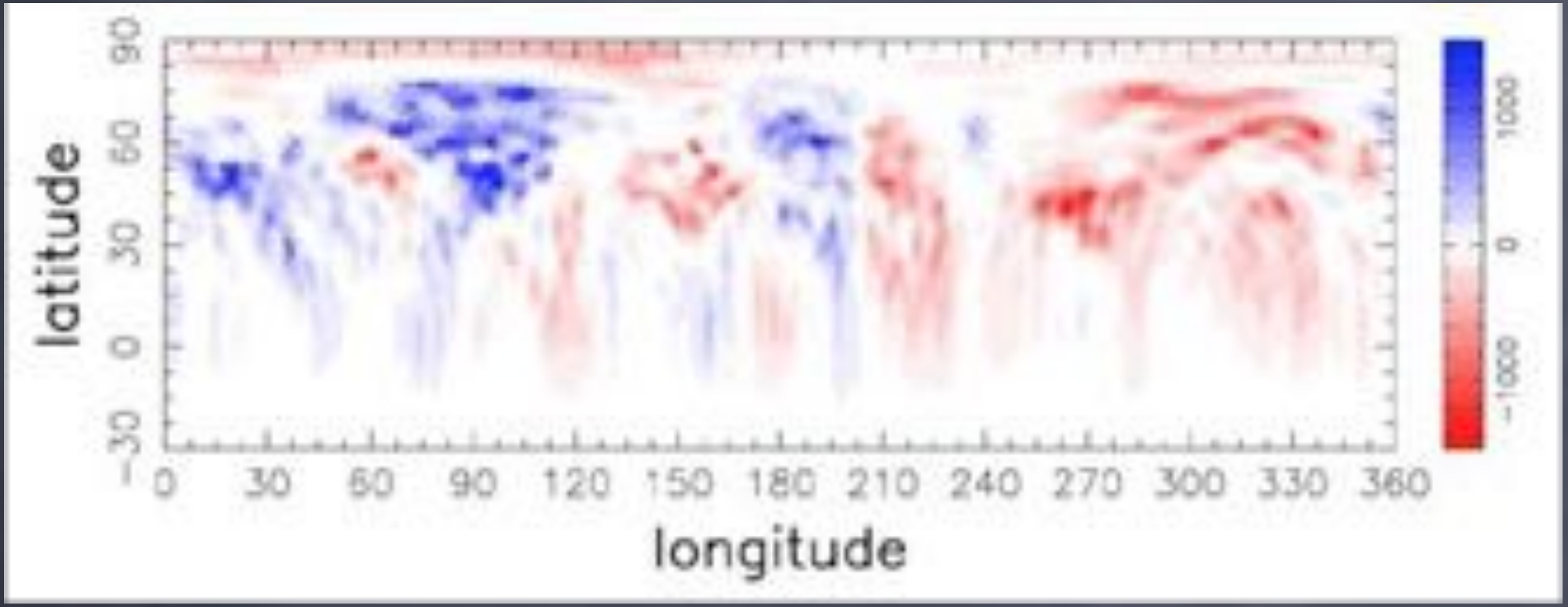




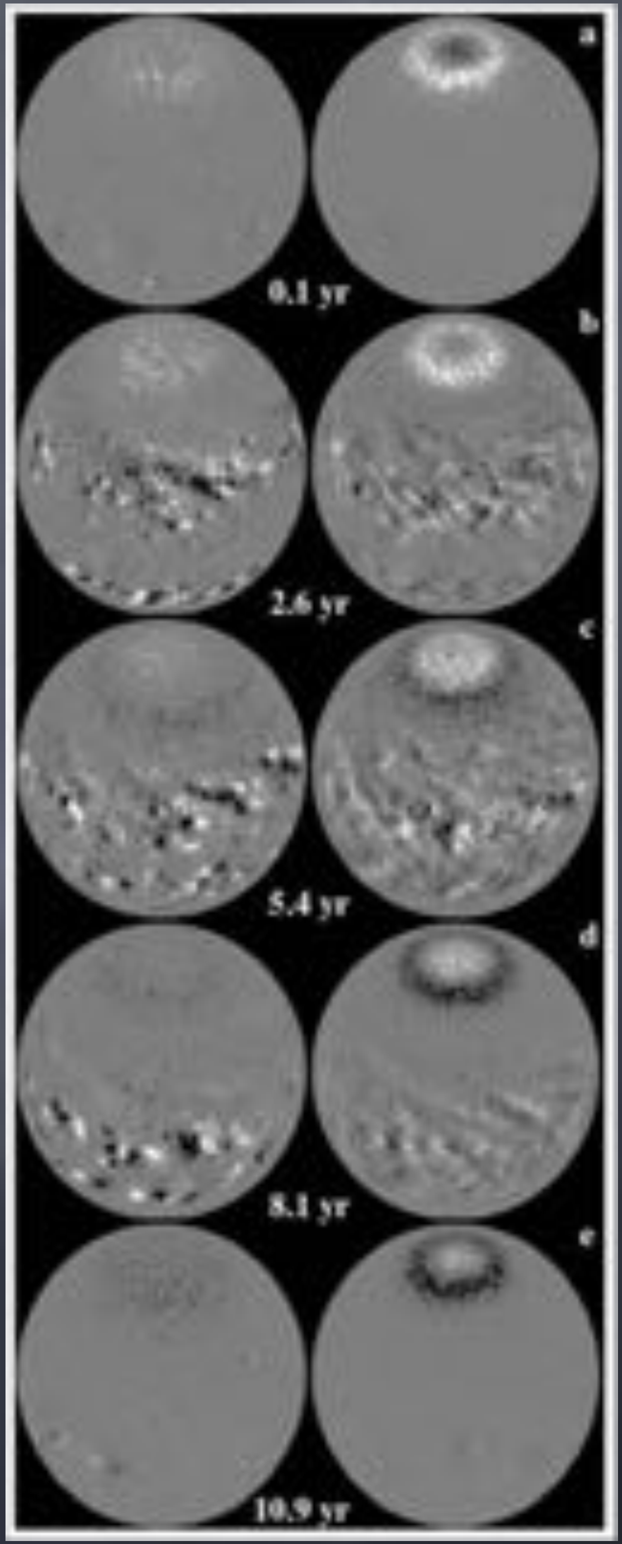
PFSSM - Riley et. al 2006

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

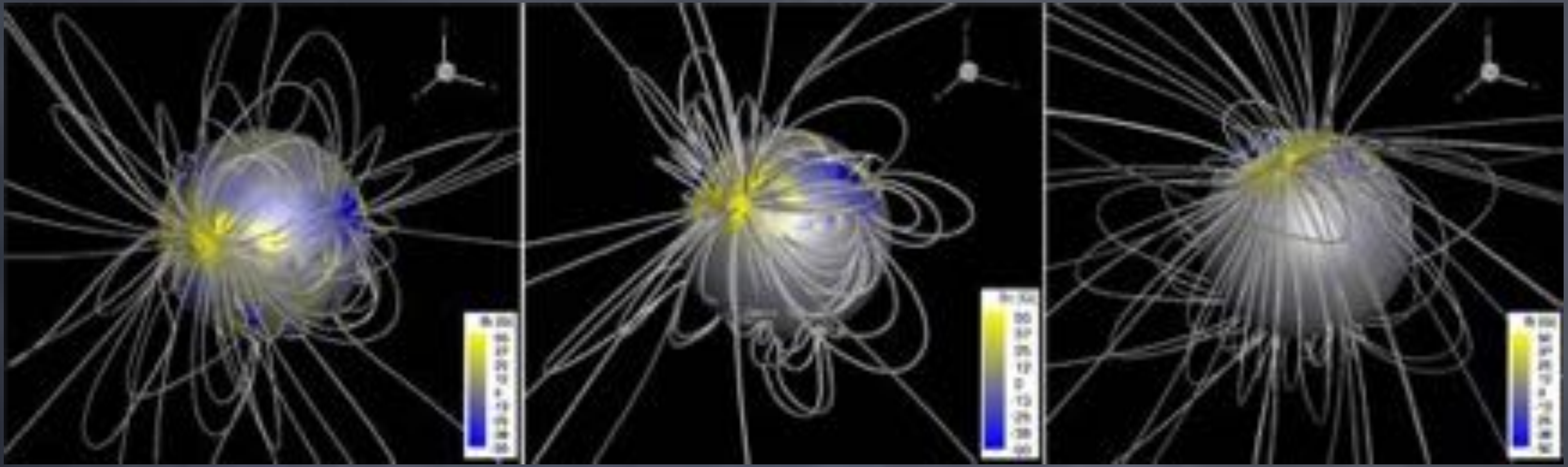
AB Doradus - young
active Sun (P=0.5 days):



Hussain et. al 2007



Schrijver & Title 2001

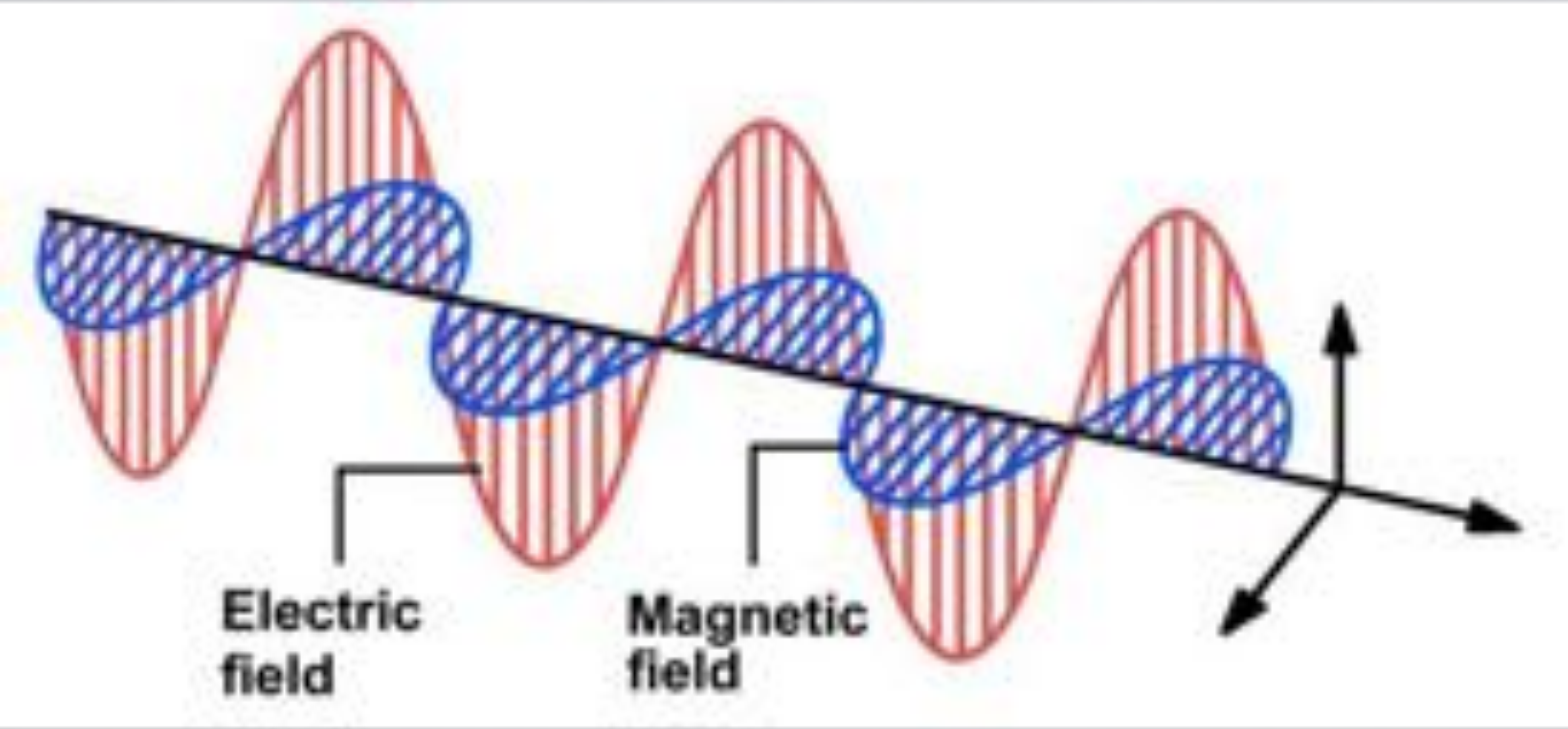


Cohen, Drake & Kota, 2012

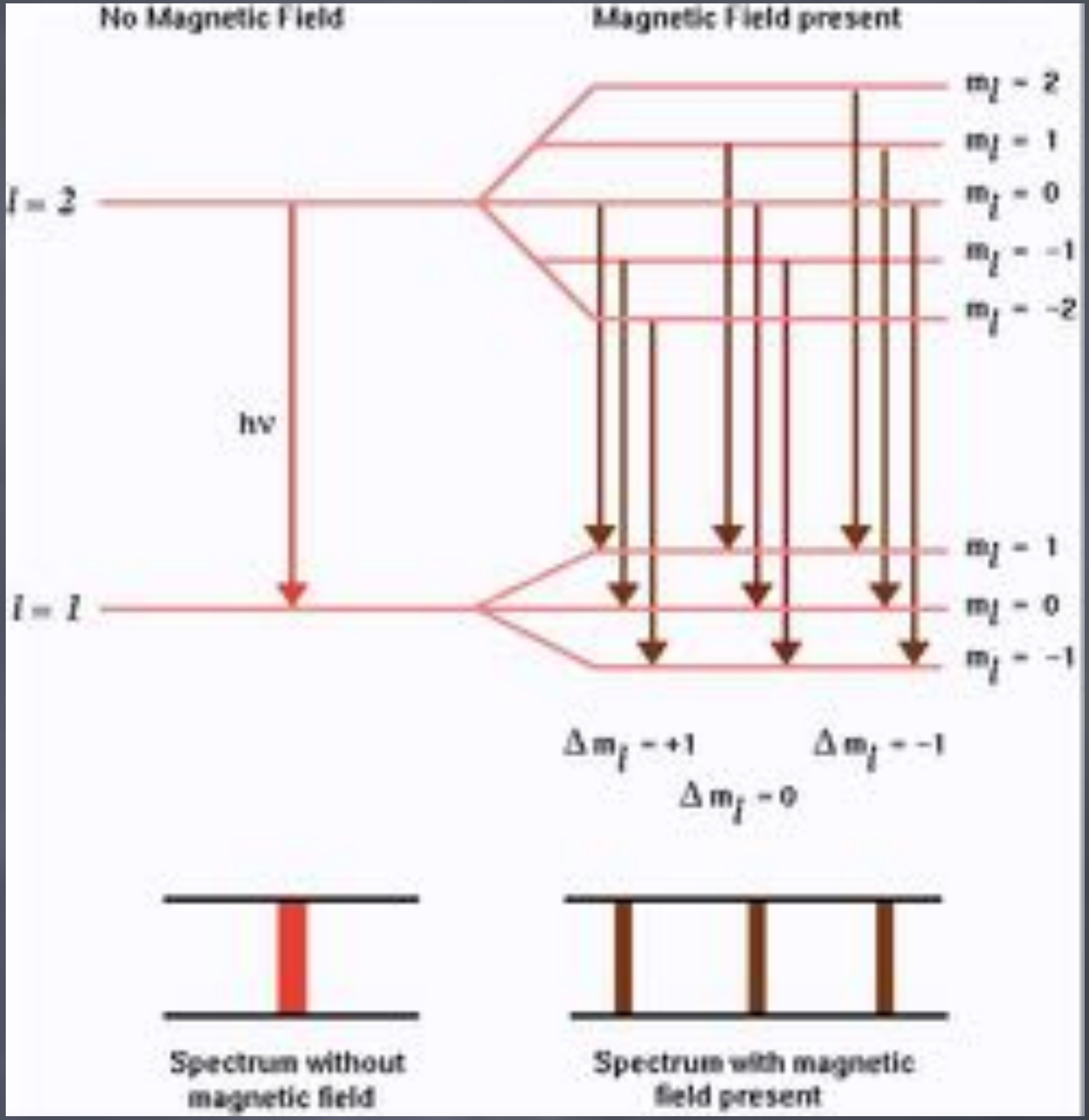
IMF quantities with strong latitudinal dependence should be affected by the latitudinal location of the active regions.

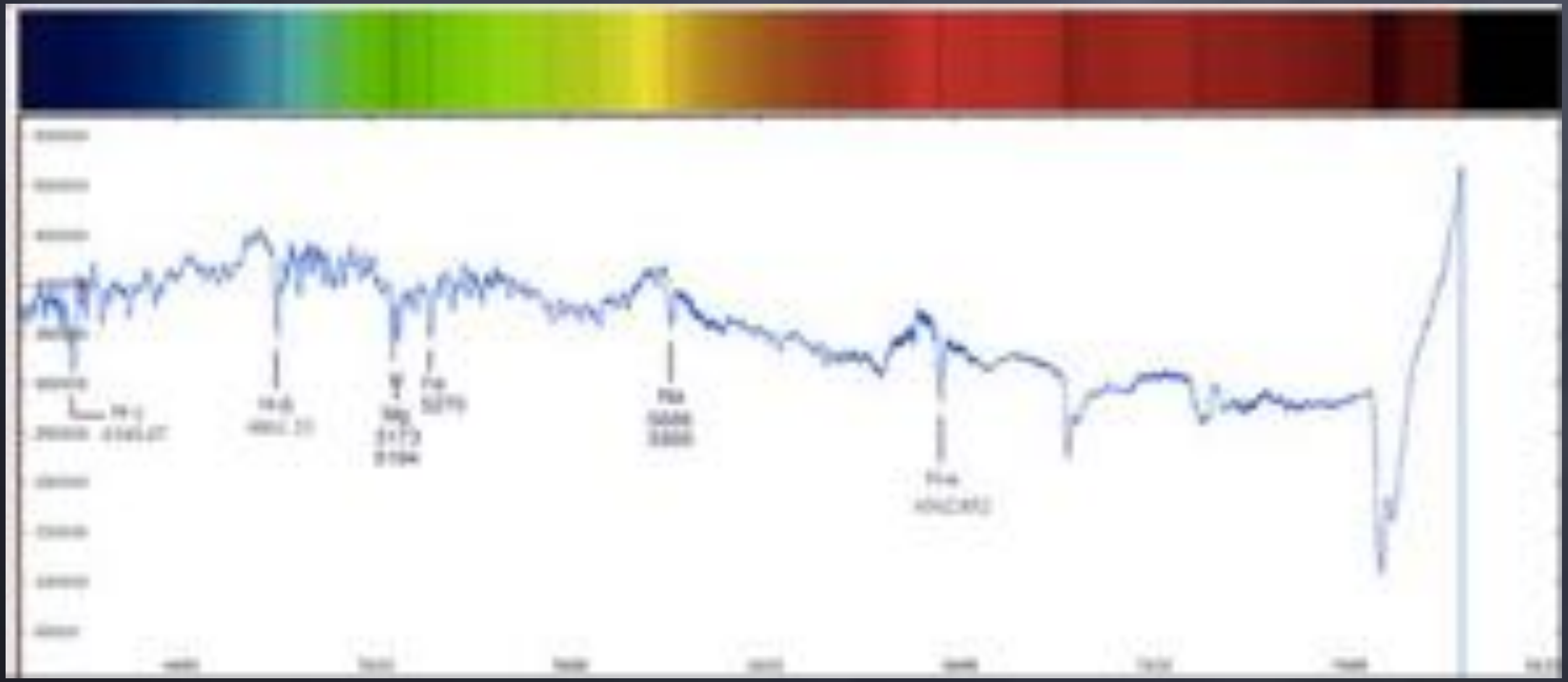
How to observe magnetic fields in other stars?

Light - Electromagnetic wave

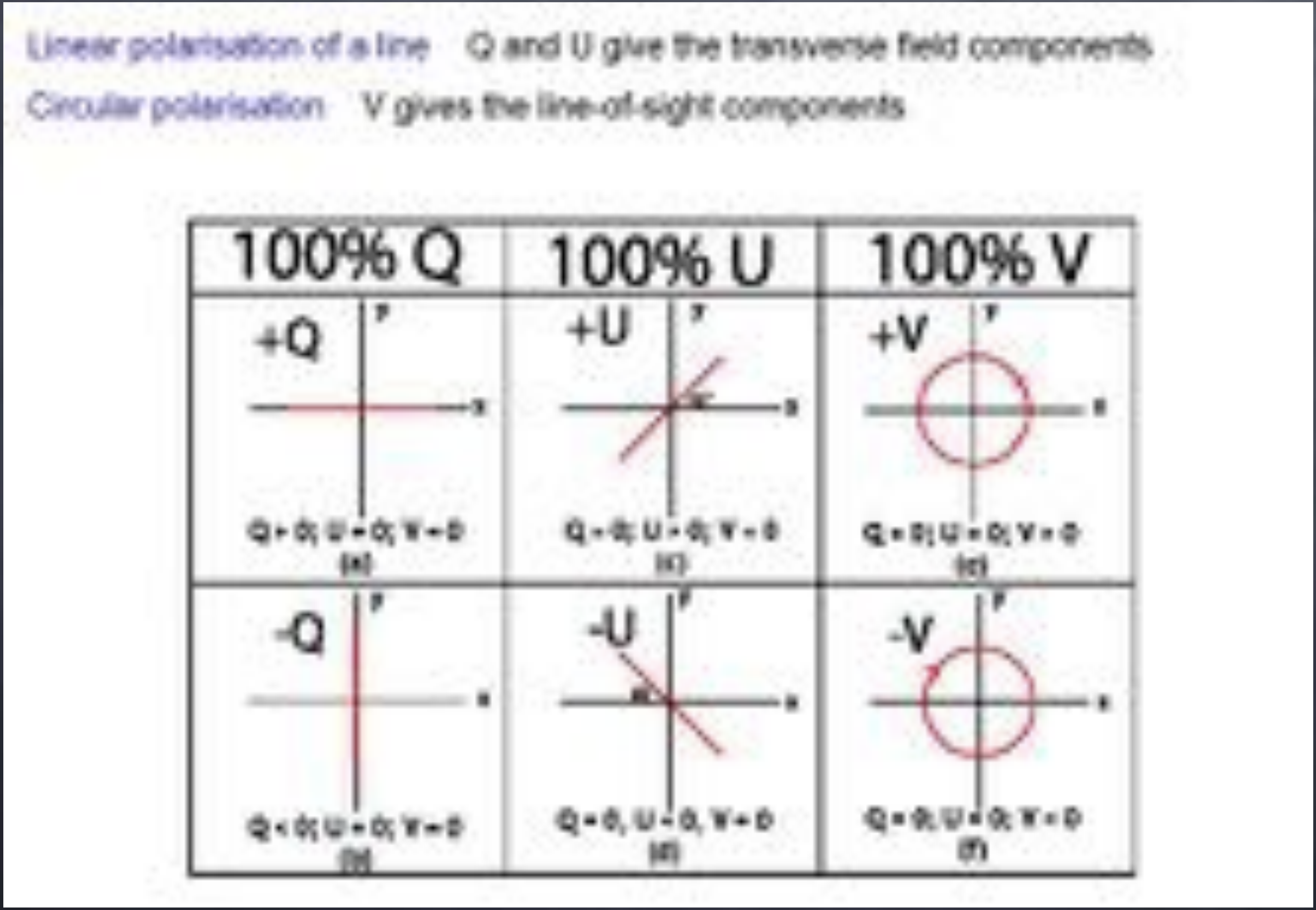


Zeeman splitting





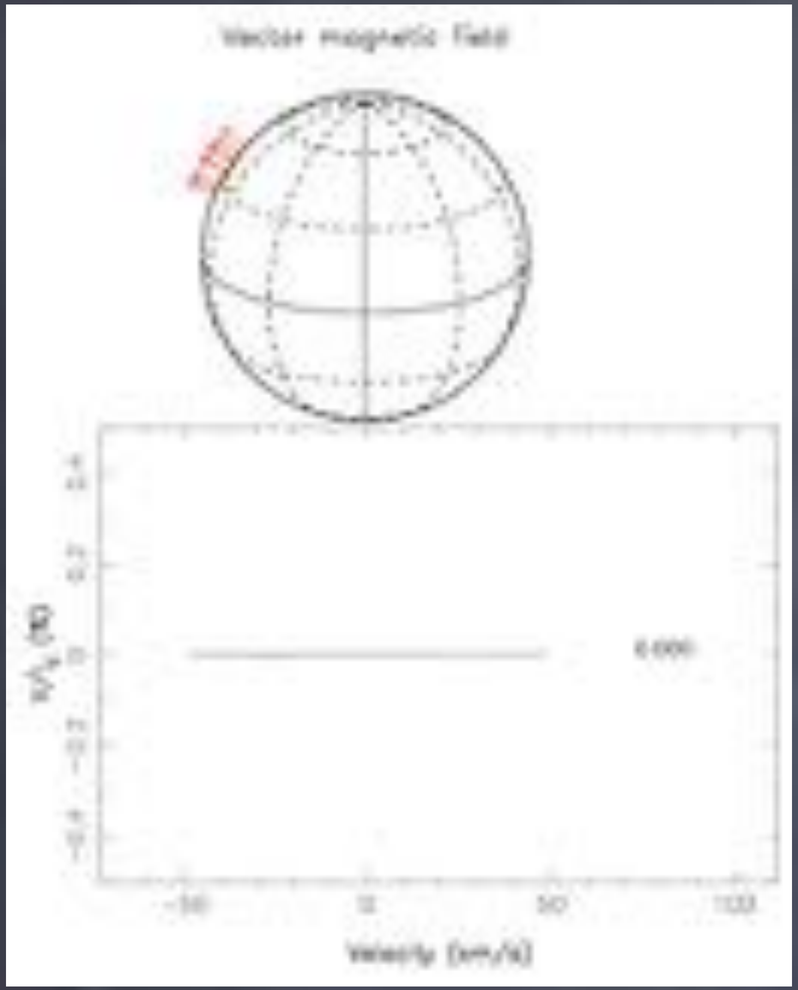
Polarimetry - Observing light polarization Give insight about magnetic fields

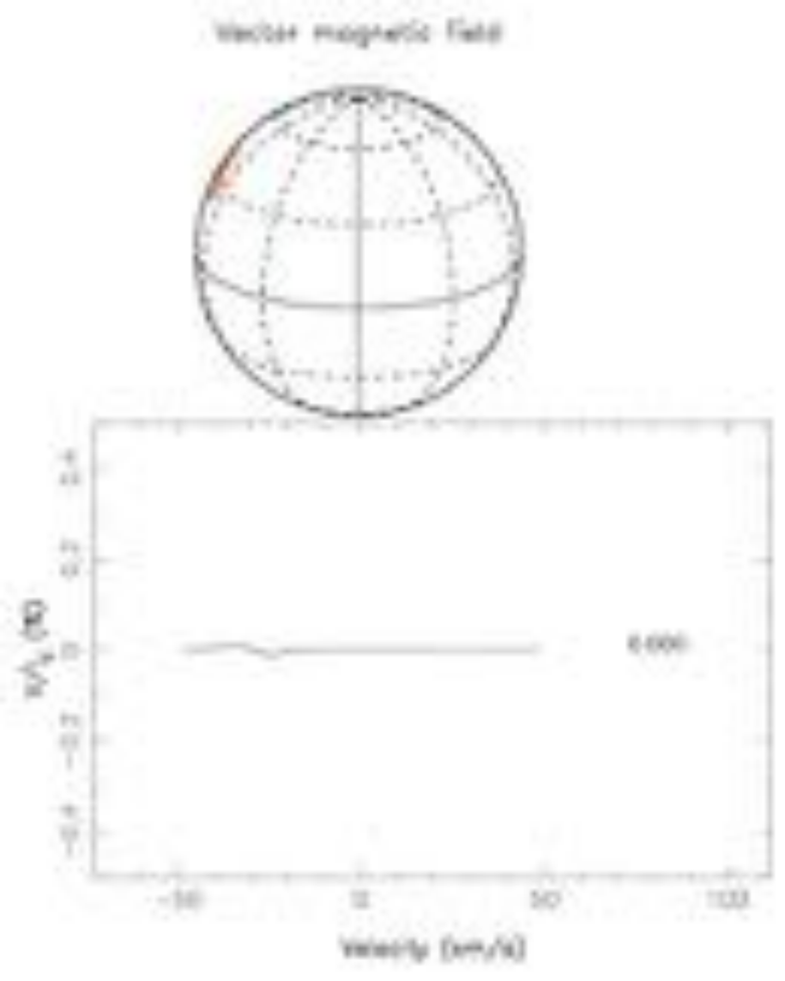


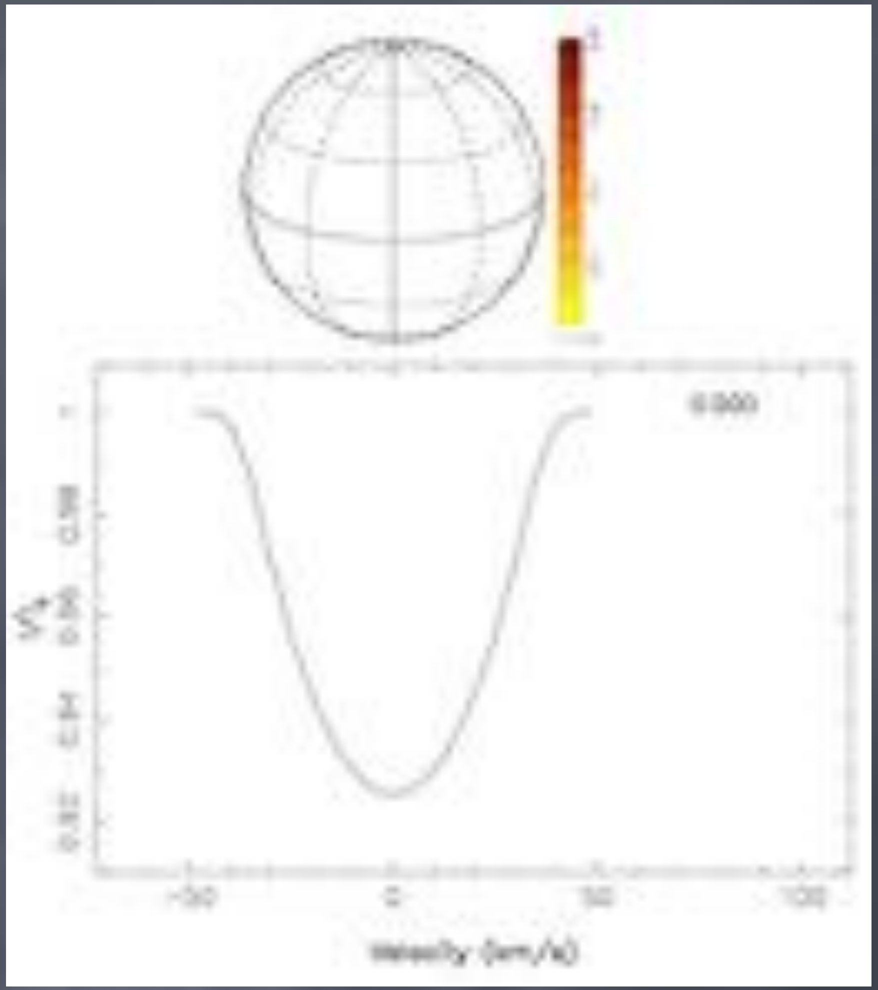
Linear polarisation of a line Q and U give the transverse field components

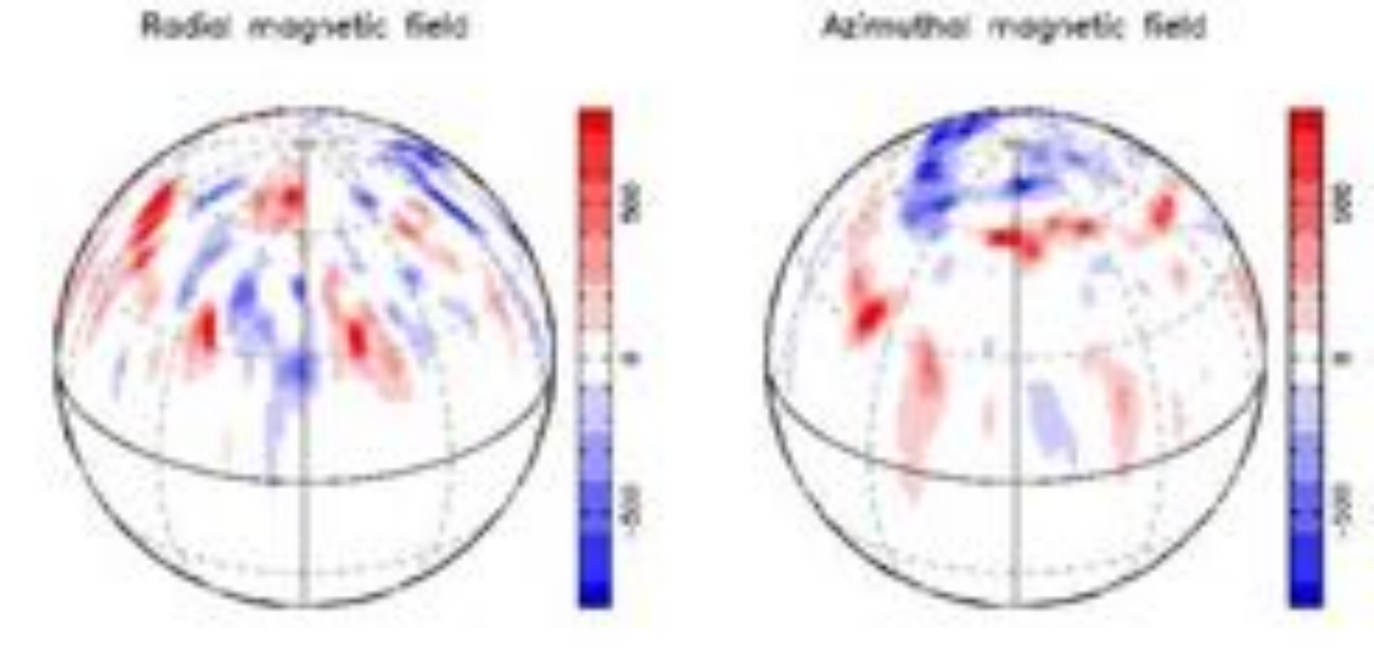
Circular polarisation V gives the line-of-sight components

Zeeman–Doppler imaging (ZDI)

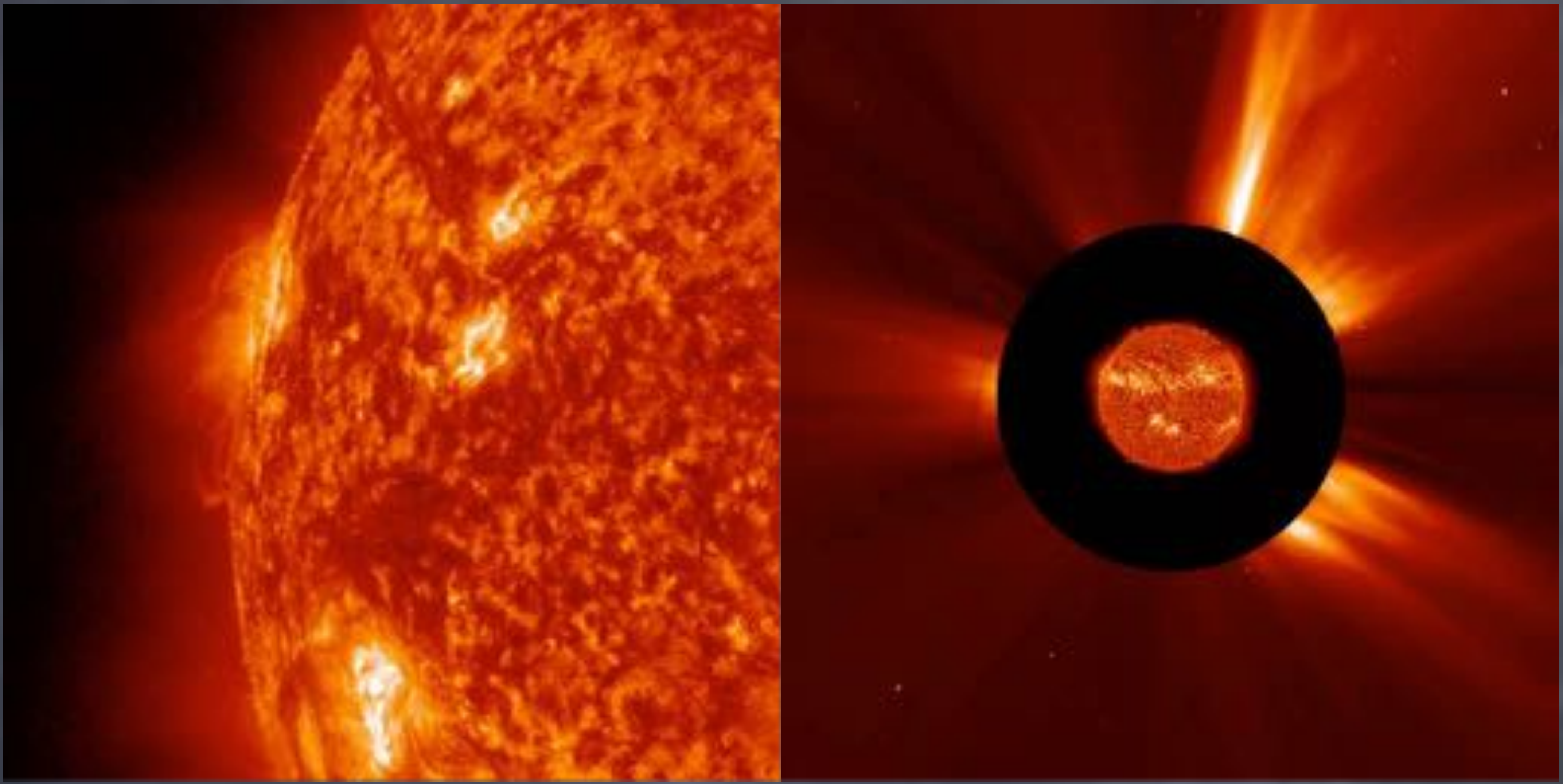








Coronal Mass Ejections (CMEs):



10^{12} kg (mt. Everest)
10^{15} ergs (magnitude 9 earthquake)
Speed of 500-1500 km/s (takes 2-4 days to travel to the Earth)

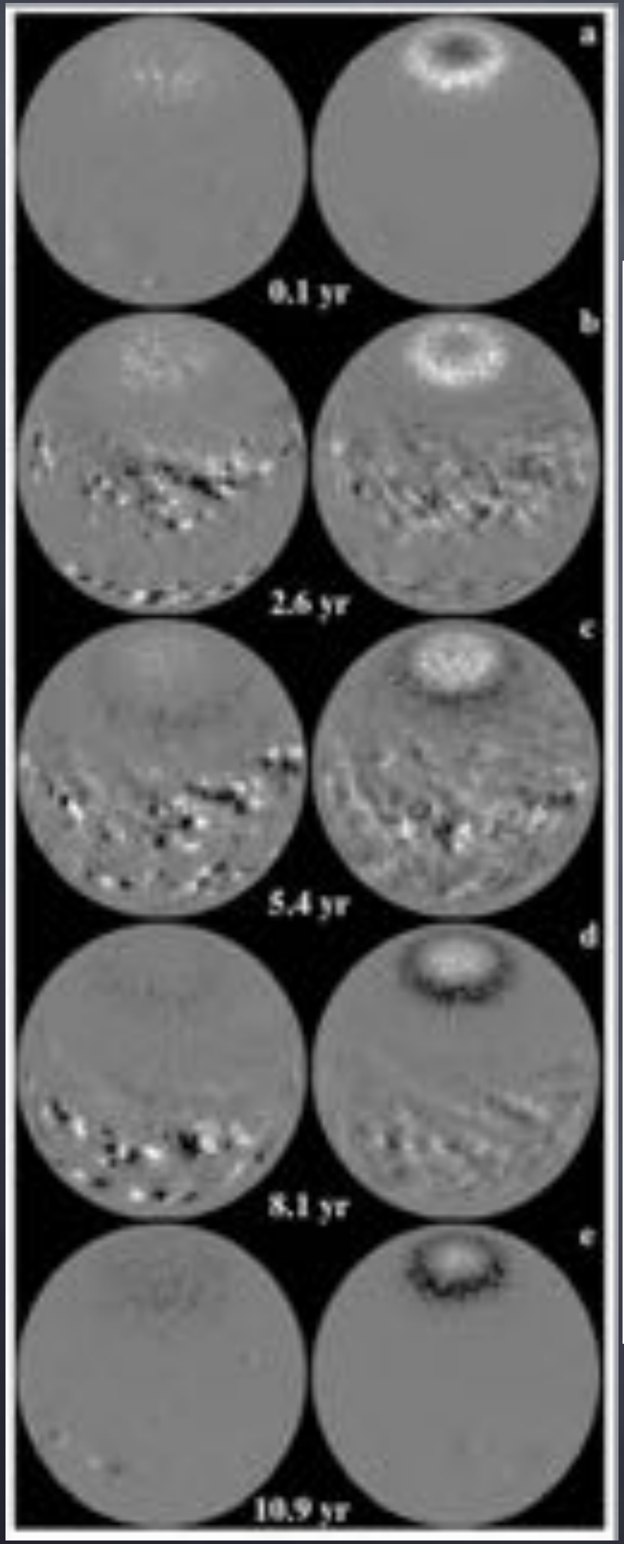
CMEs also take mass from the Sun…

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

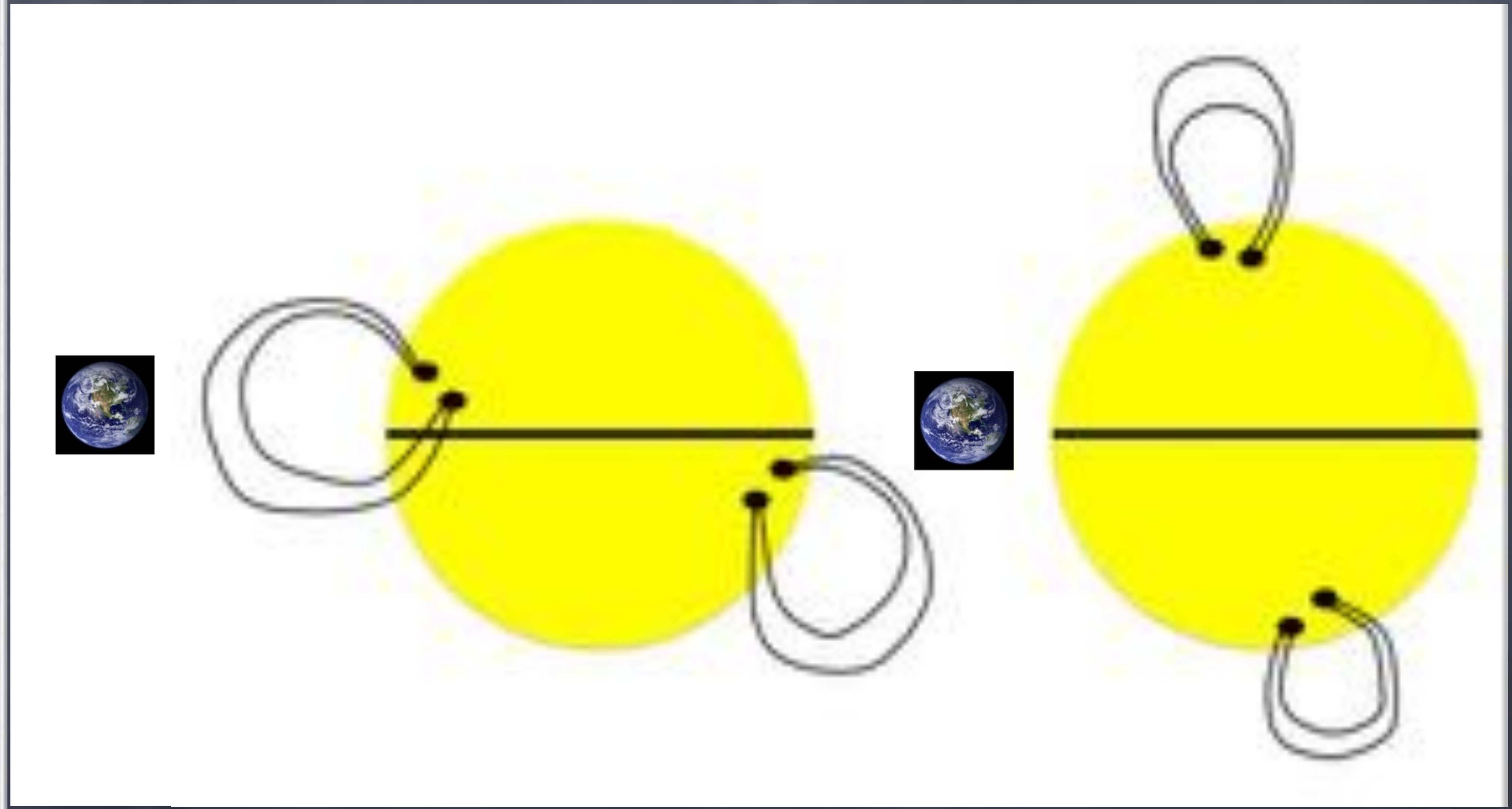
- Impact on CME initiation.
- Impact on propagation & evolution.

Observations:
Stellar flares...

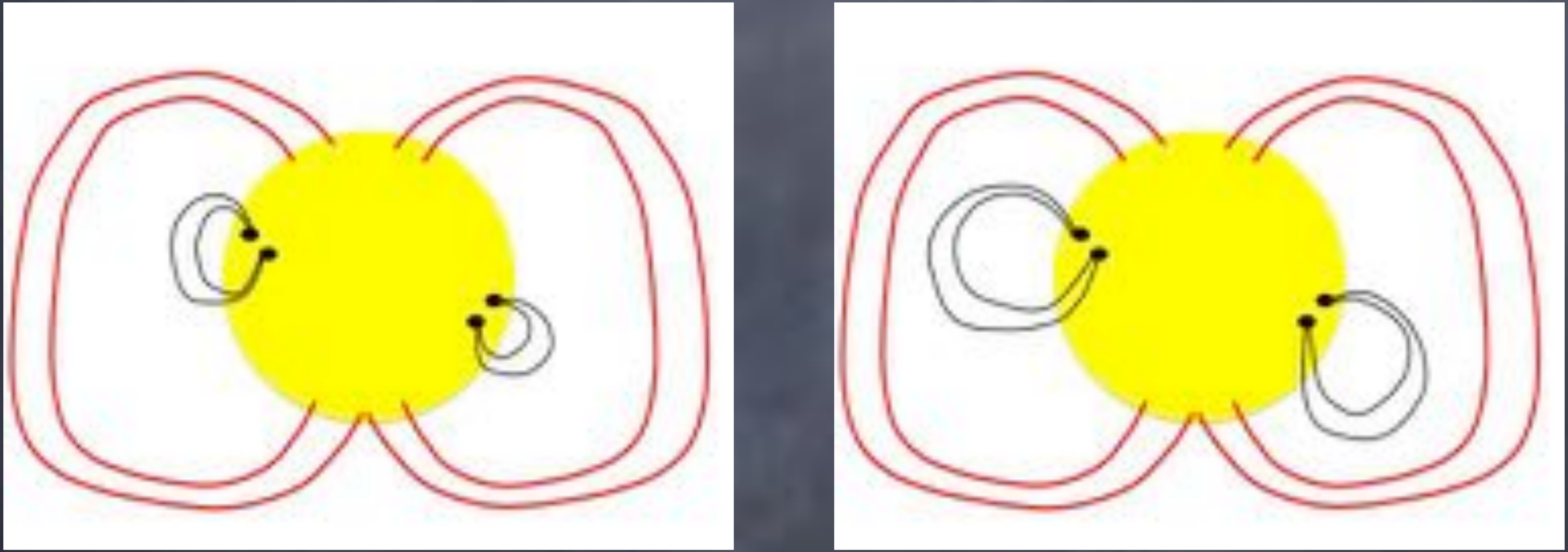
Impact on CME initiation:



Schrijver & Title 2001



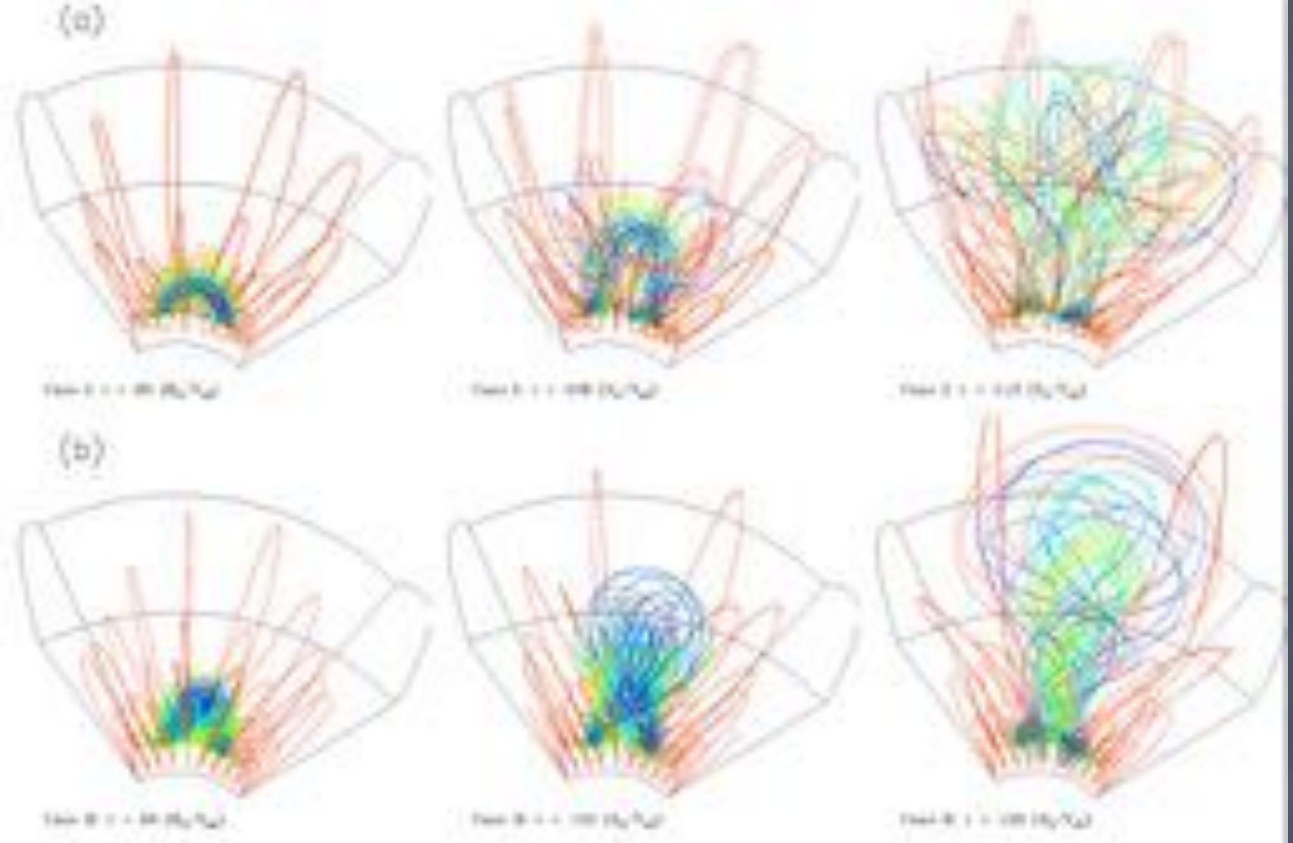
Do stellar CMEs scale with the overall increase in magnetic energy?



Open question...

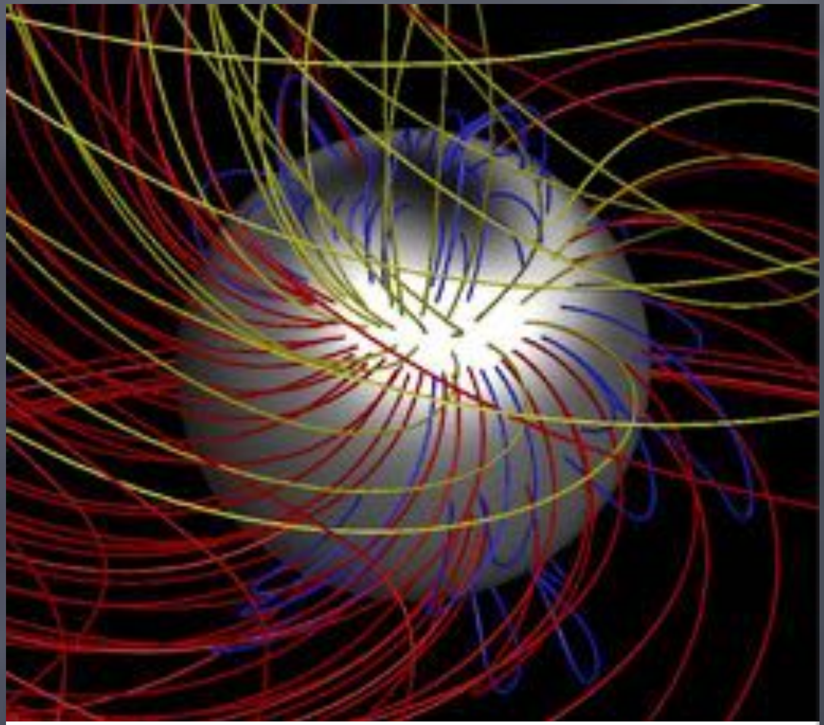
Different initiation mechanism?

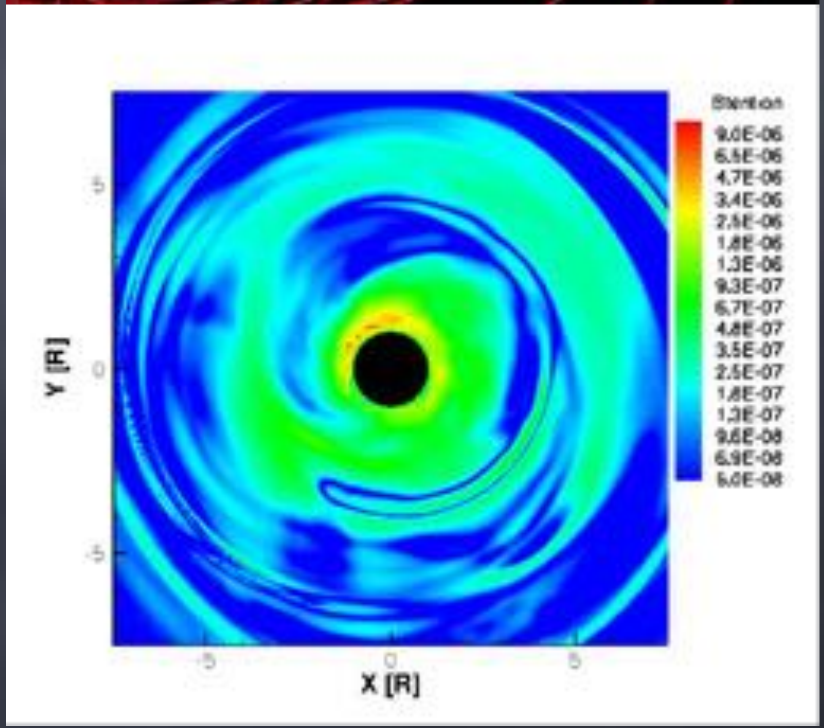
Solar CME



Fan & Gibson 2007

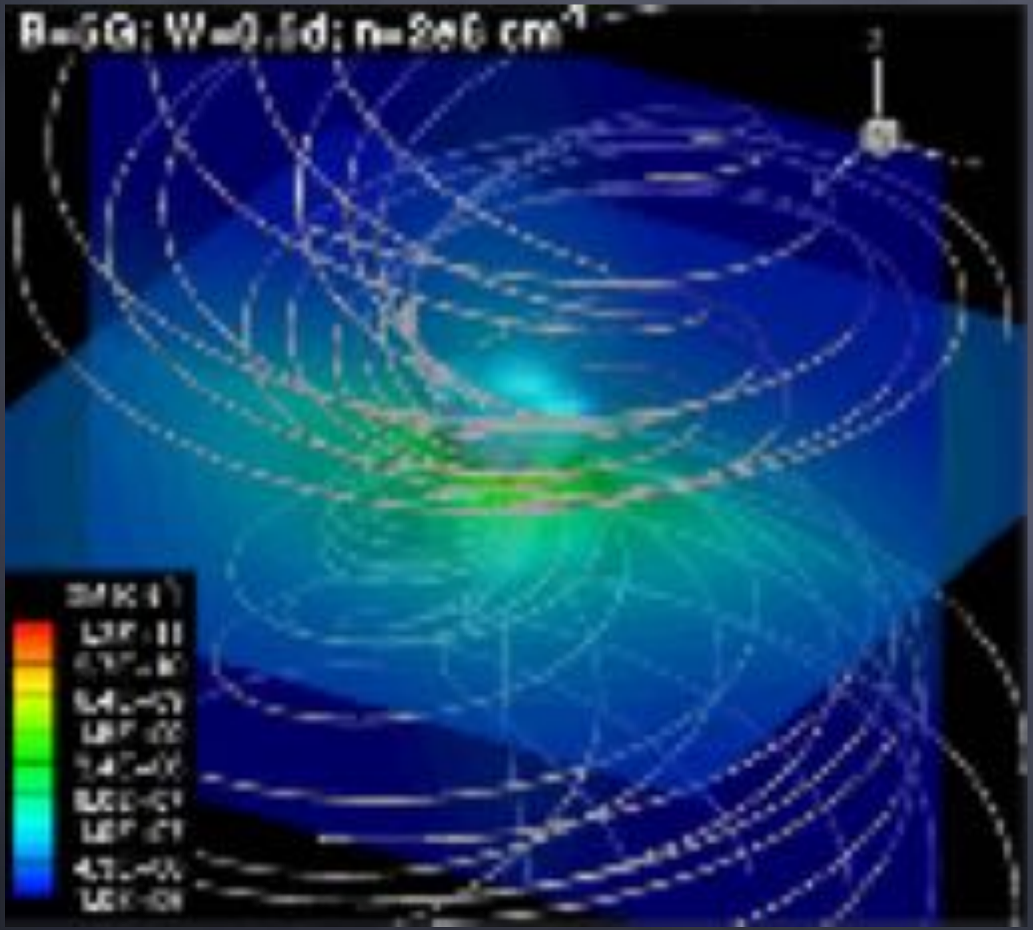
FK Comae



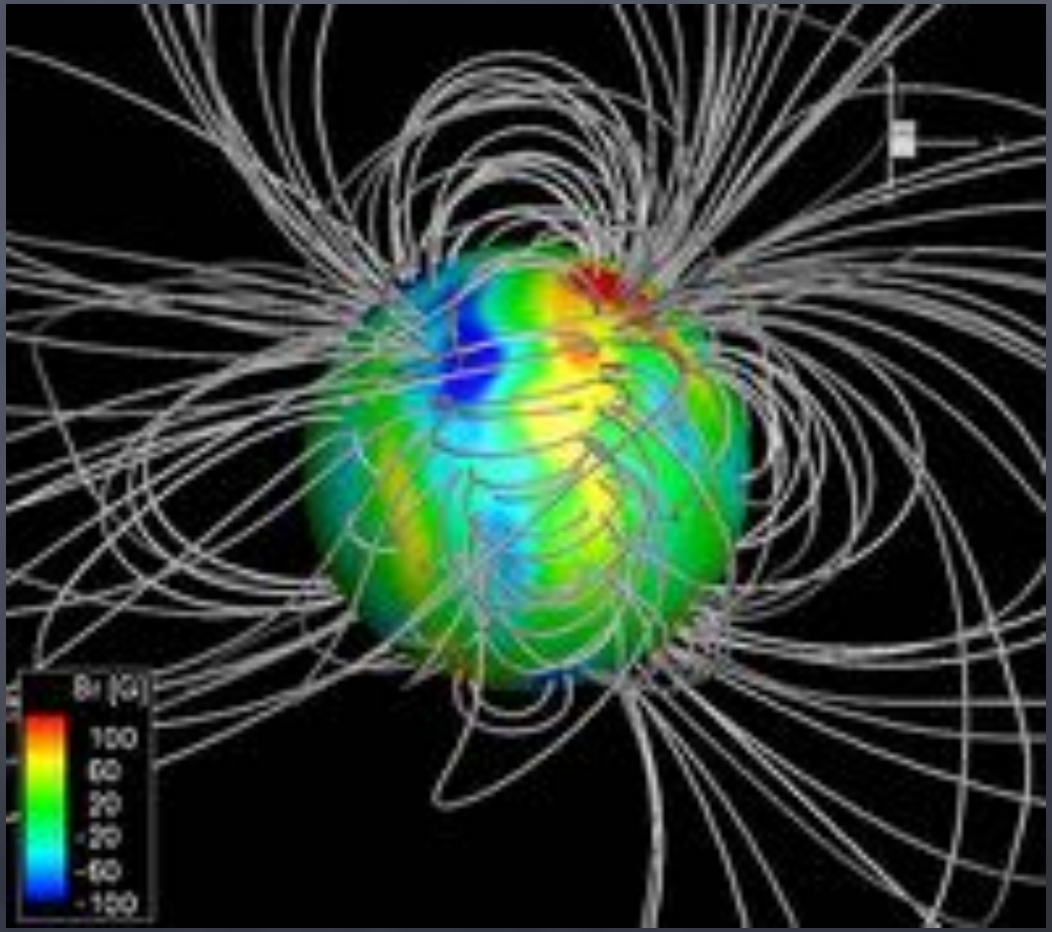


The propagation and evolution of CMEs depend on the Astrospheric field.

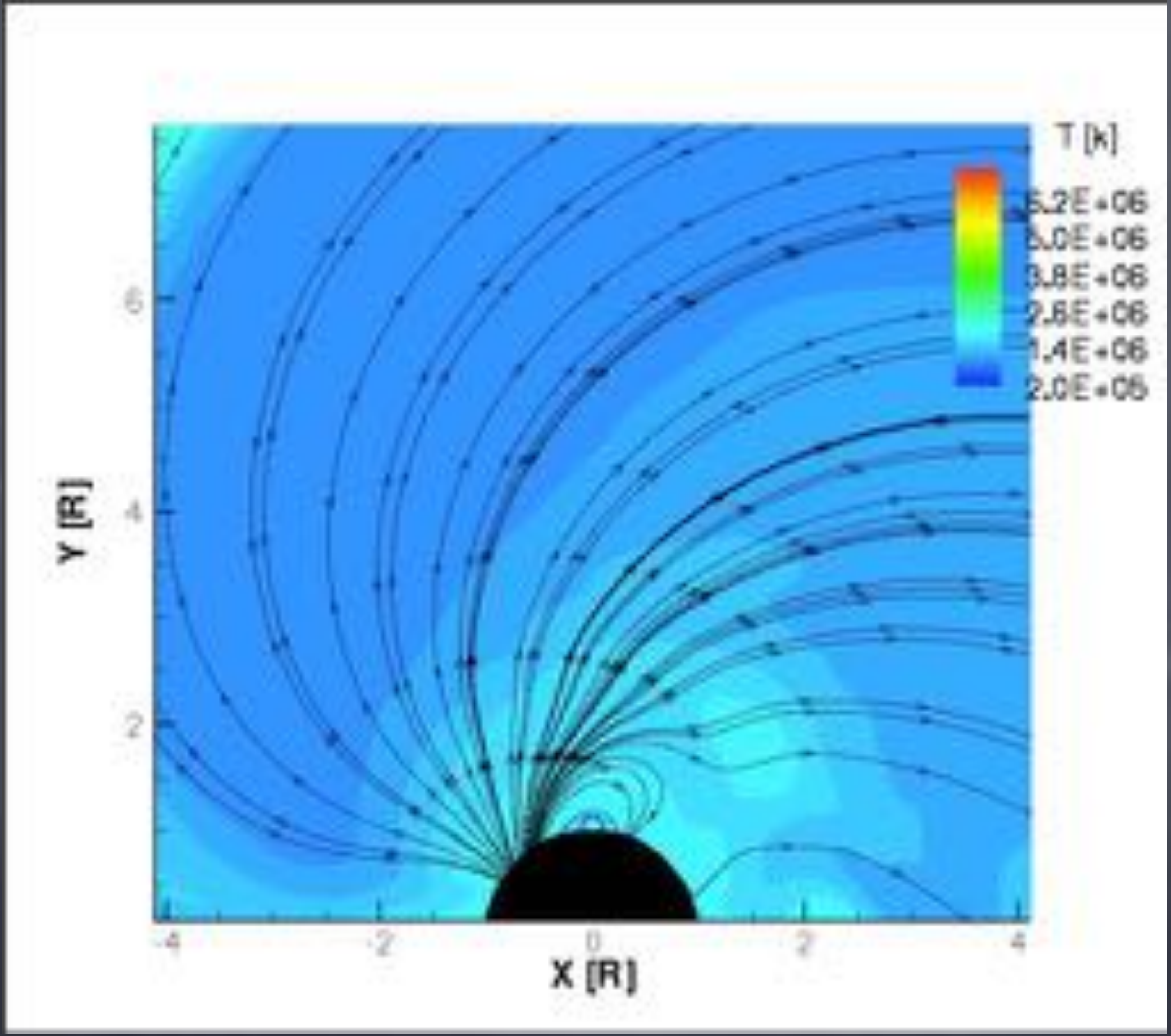
Strong azimuthal field close to the star

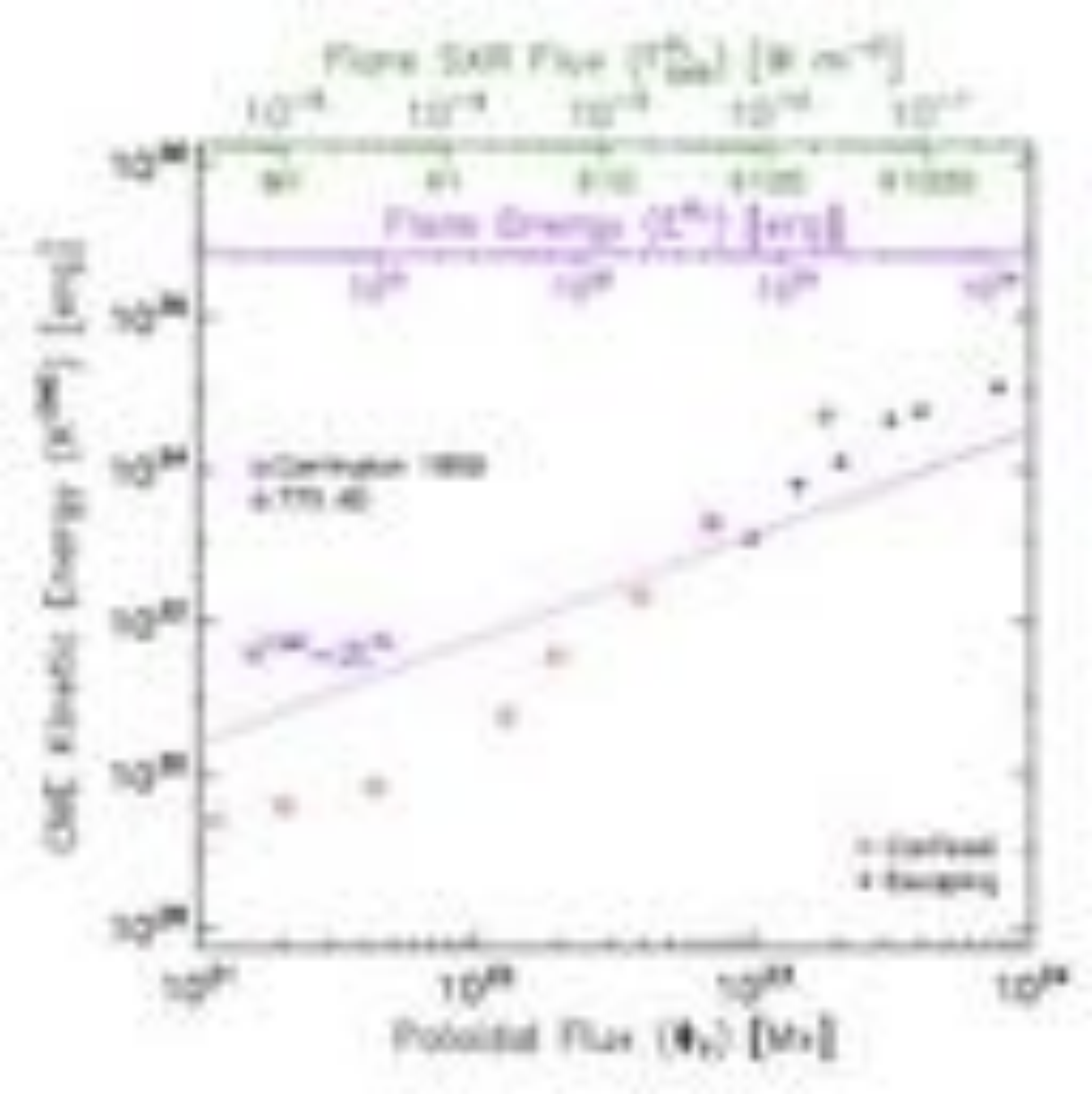


Strong field strength



A toy simulation of a CME on AB Doradus





Alvarado-Gomez et. al 2018

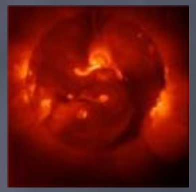
Part II

Stellar Evolution and Magnetized Winds

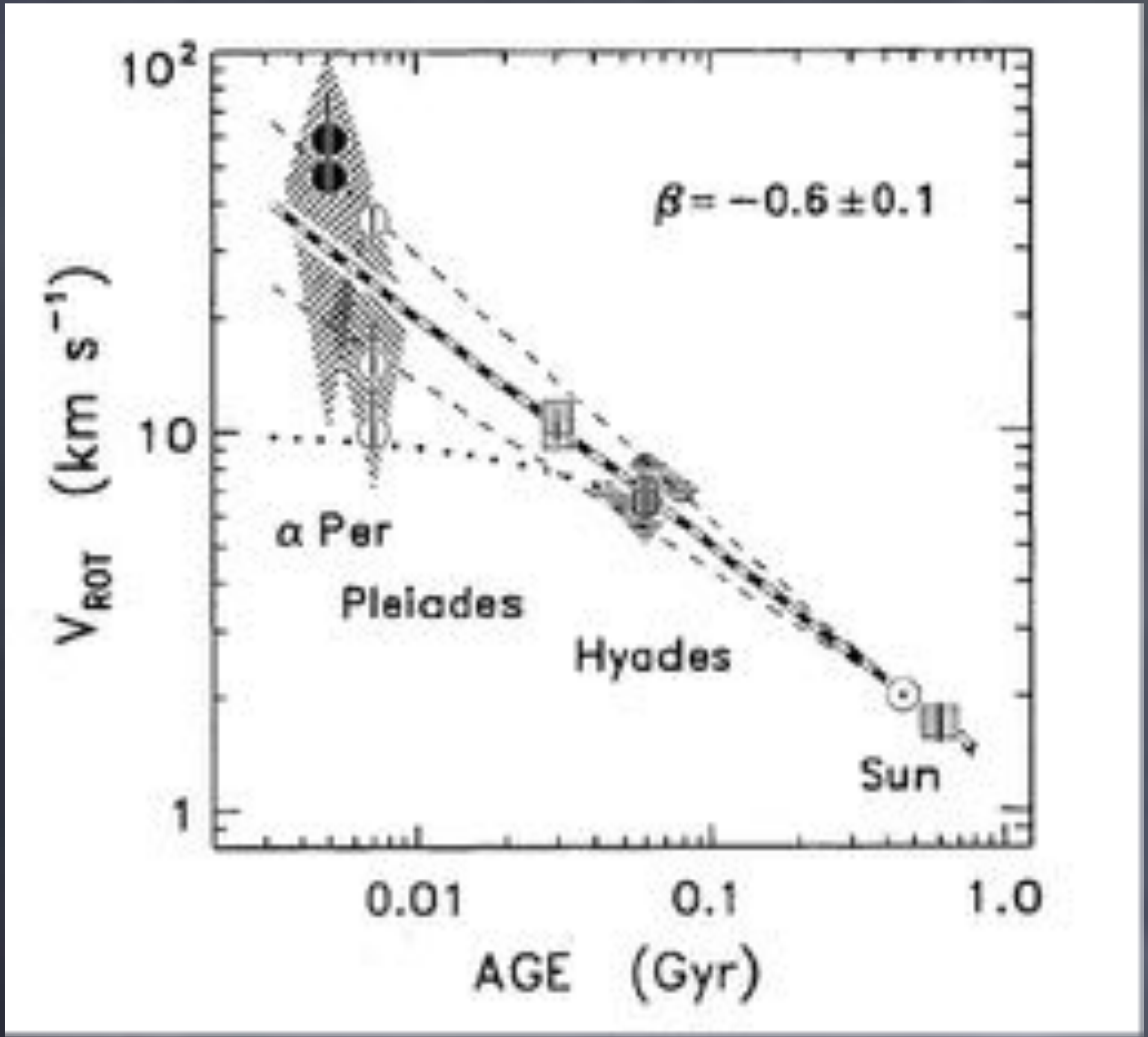
Rotation

Age

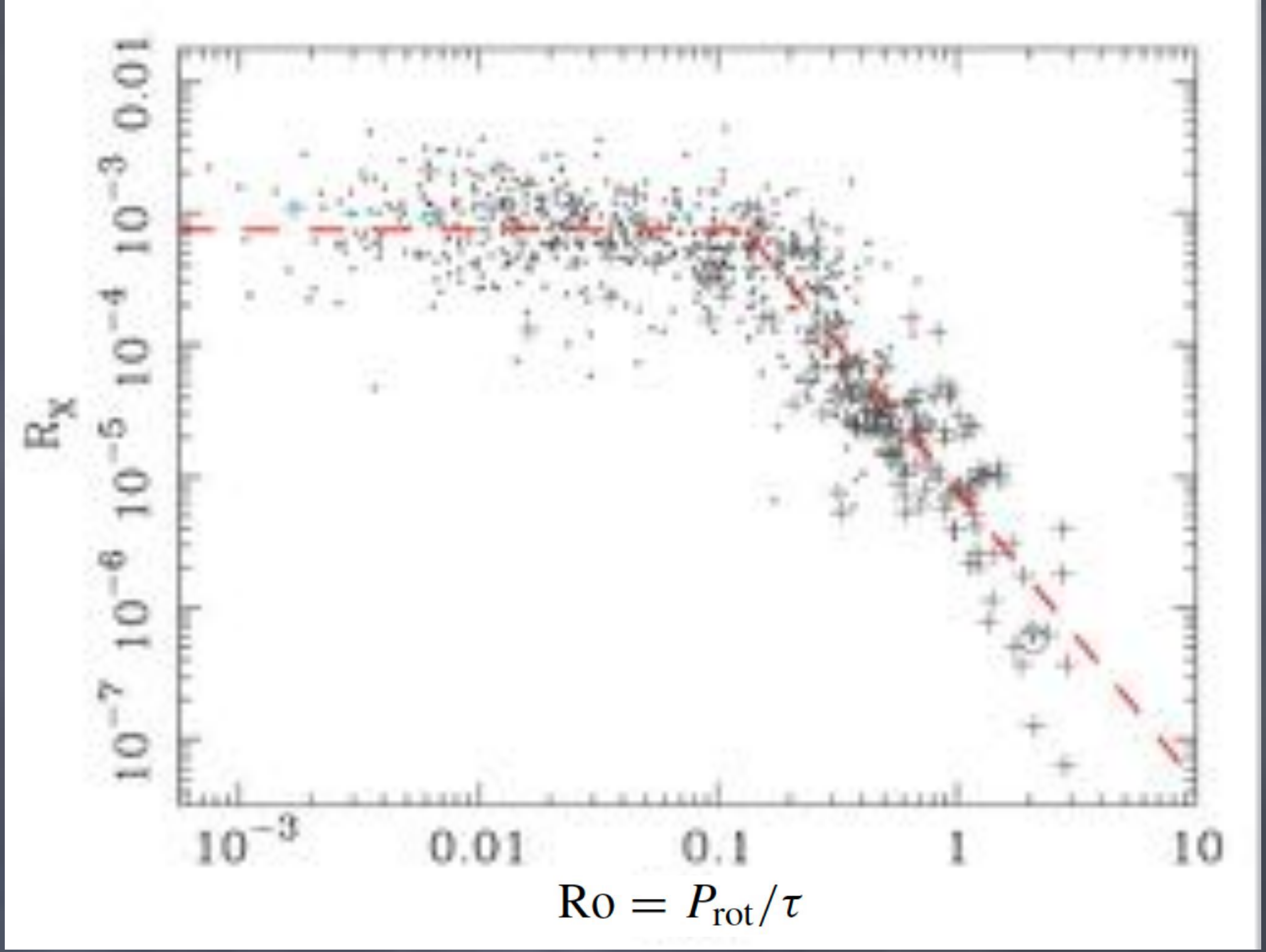
Stellar activity



Magnetic field



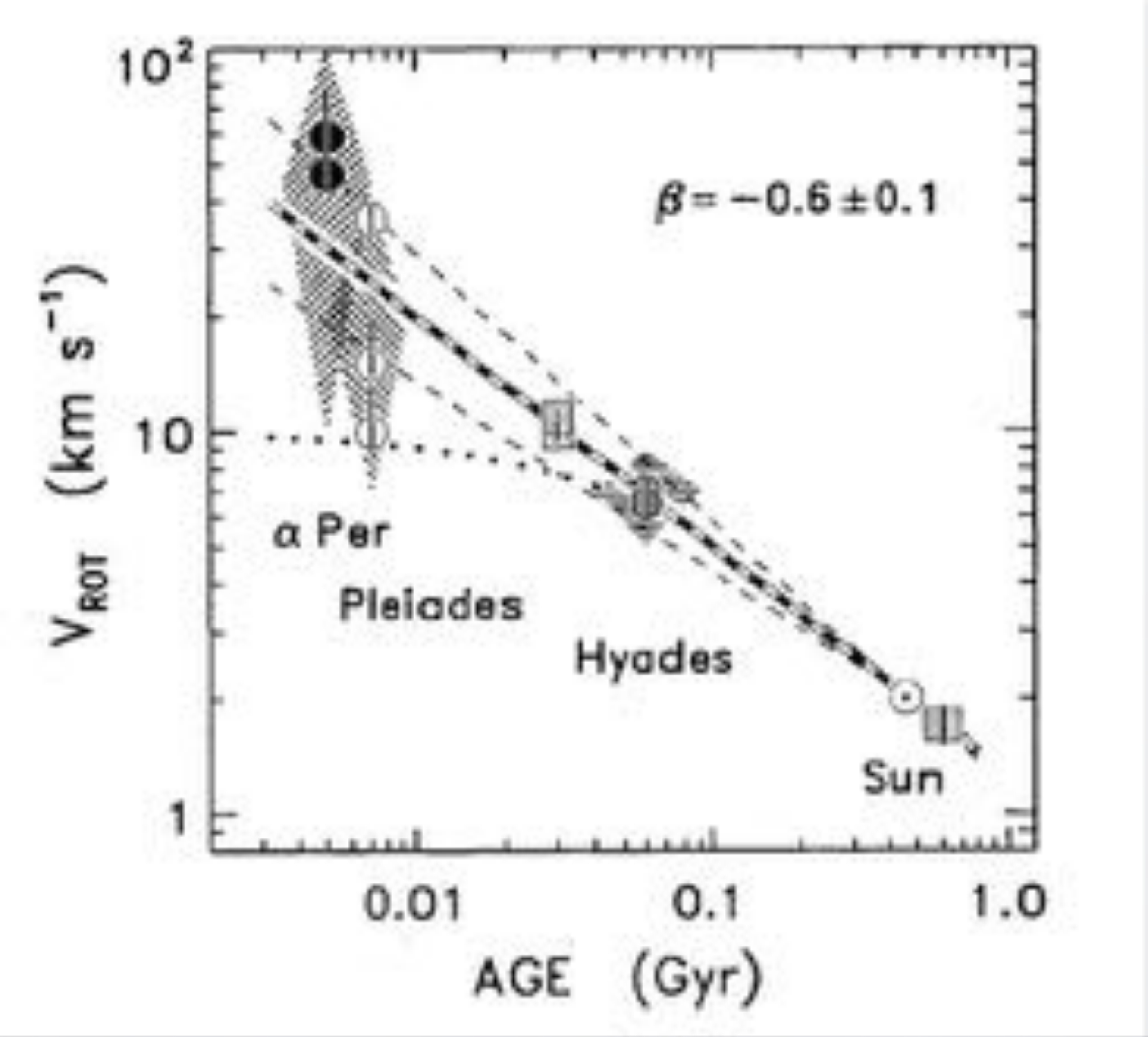
Ayres 1997



Wright et. al 2011

Skumanich Law:

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



Ayres 1997

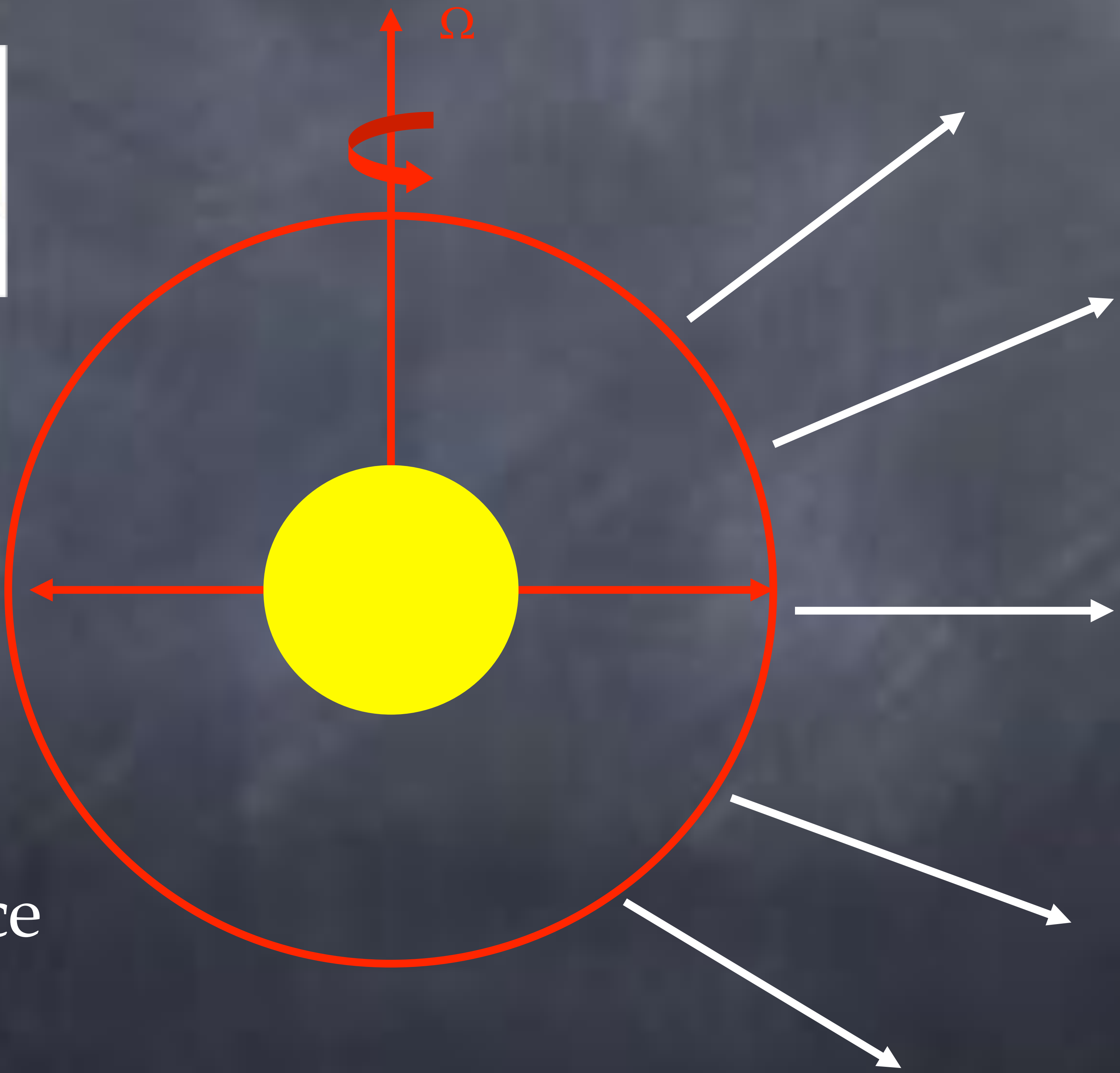
Skumanich Law:

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

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

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

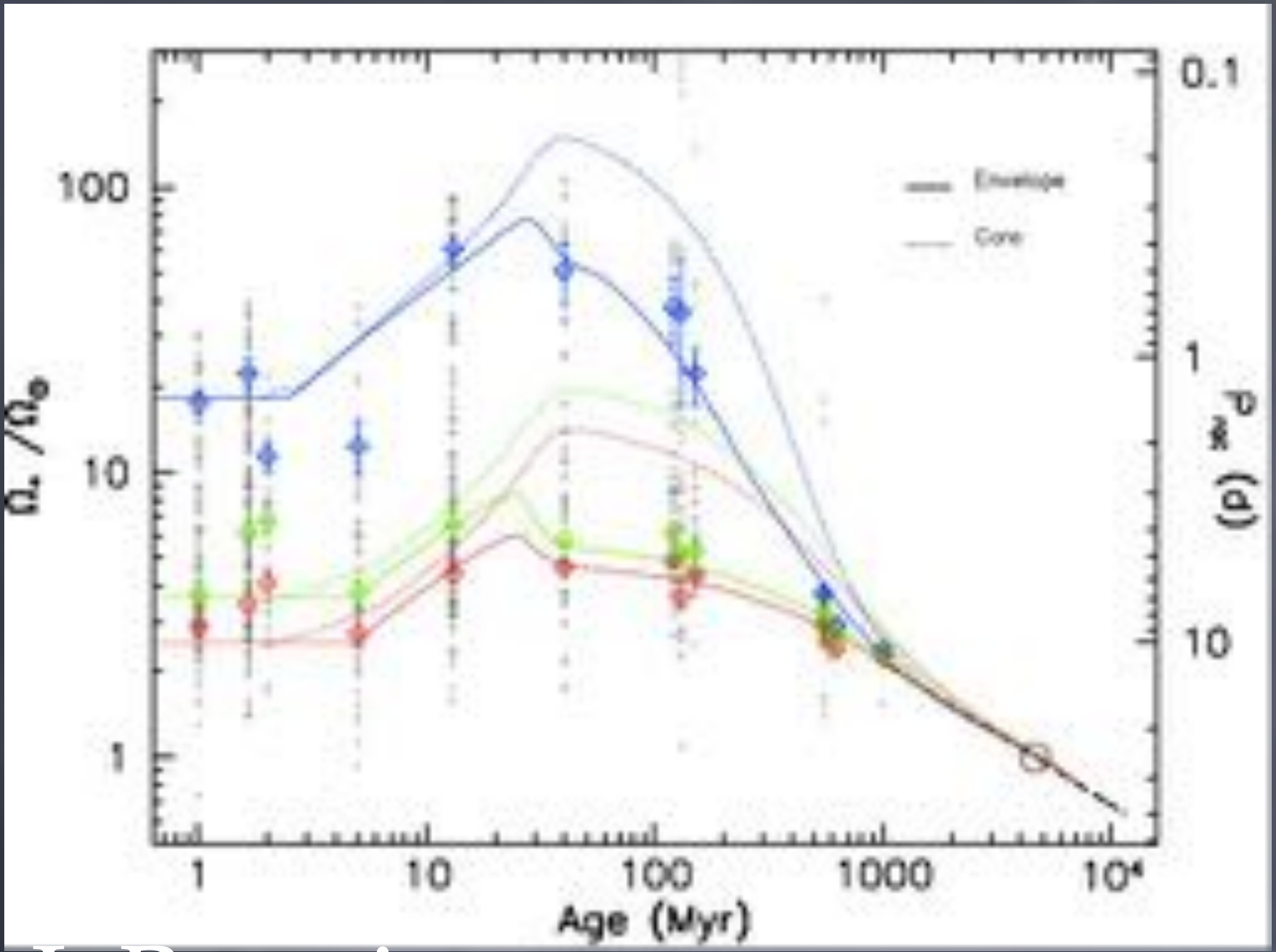
$$\dot{J} = \frac{2}{3}\Omega\dot{M}r_A^2$$



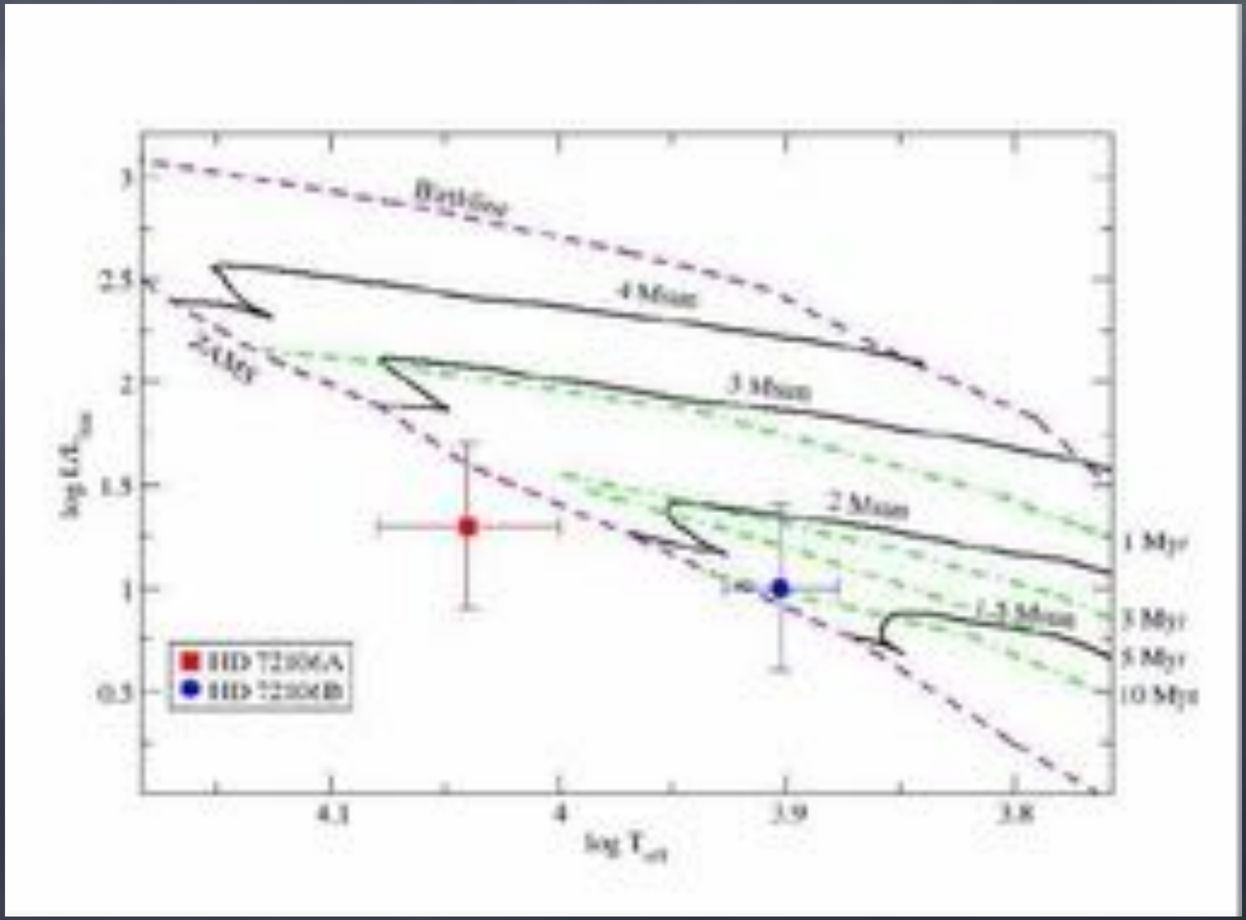
Alfven surface

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

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



J. Bouvier



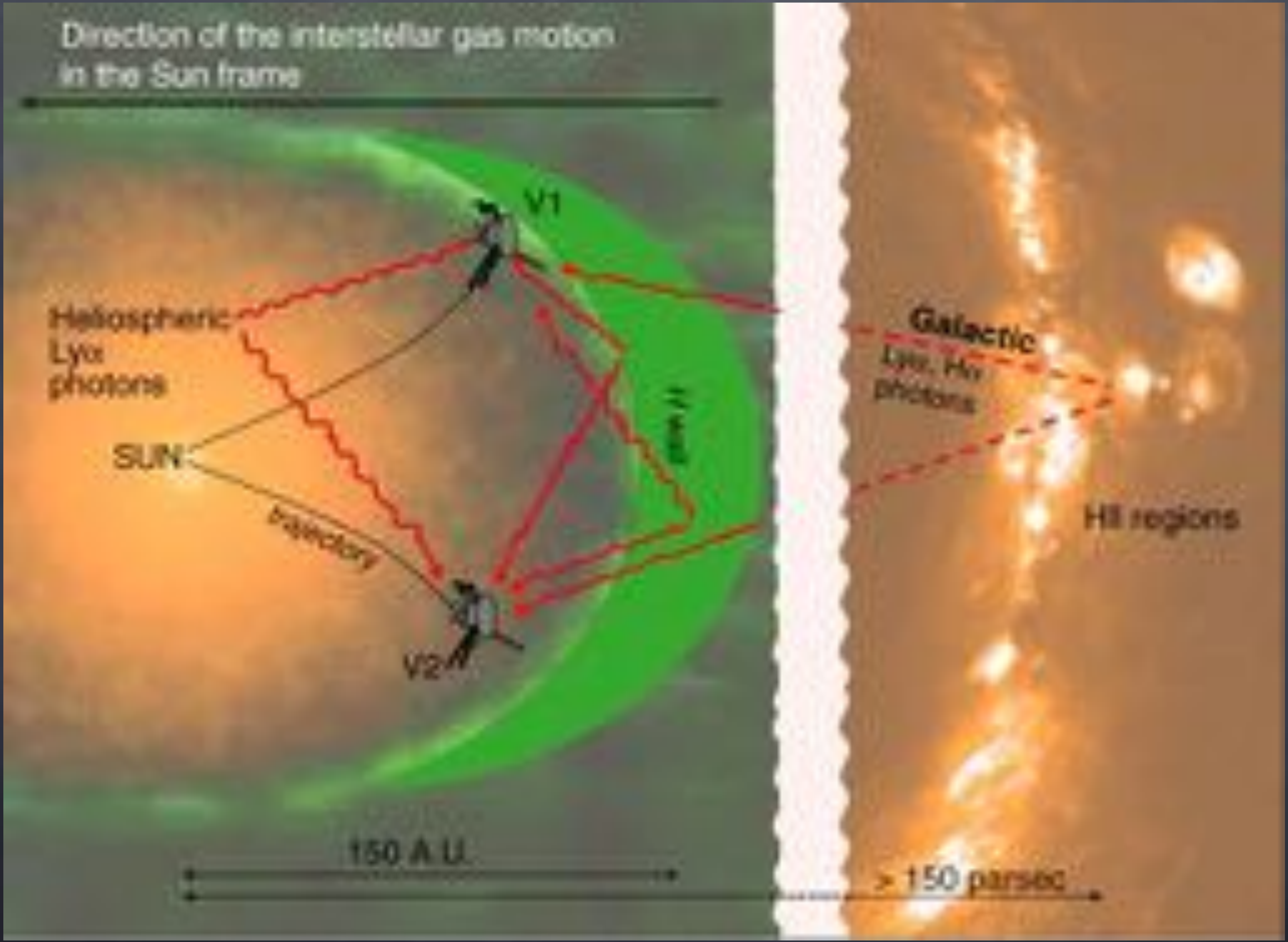
C. Folsom

The faint young Sun paradox (Sagan & Mullen 1972):

- The luminosity of the young Sun was about 30% lower than the current luminosity.
- Therefore, the surface temperature of the Earth should have been bellow freezing.
- Geological record shows the existence of liquid water on the surface.... A paradox!!!
- If the young Sun was slightly more massive and the solar mass loss rate was high - solar luminosity isn't that low... No paradox!!!

Can we observe winds of cools stars and define their m

Kind of…

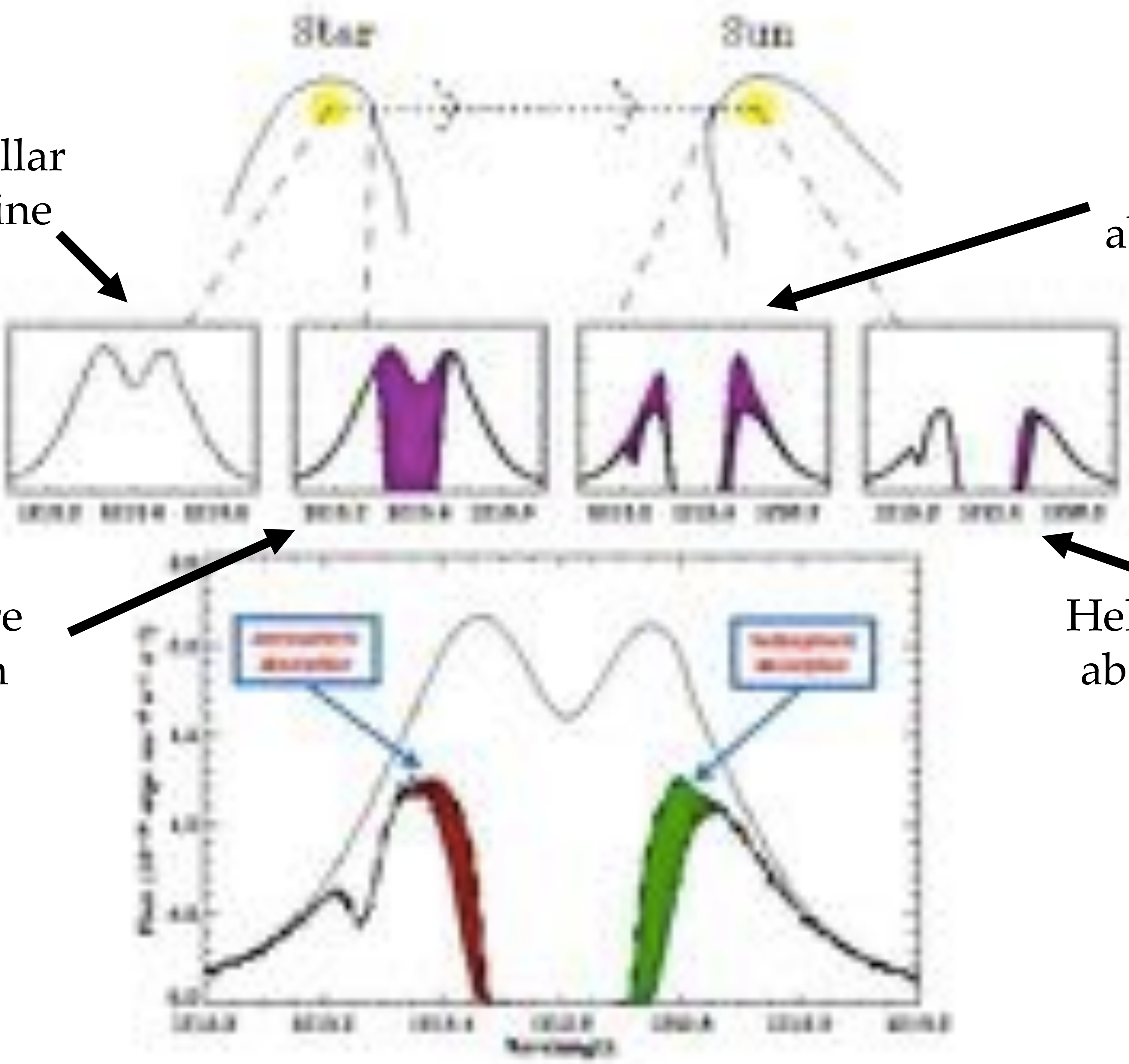


sciencemag.org

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

Other images from
HubbleSite.org

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

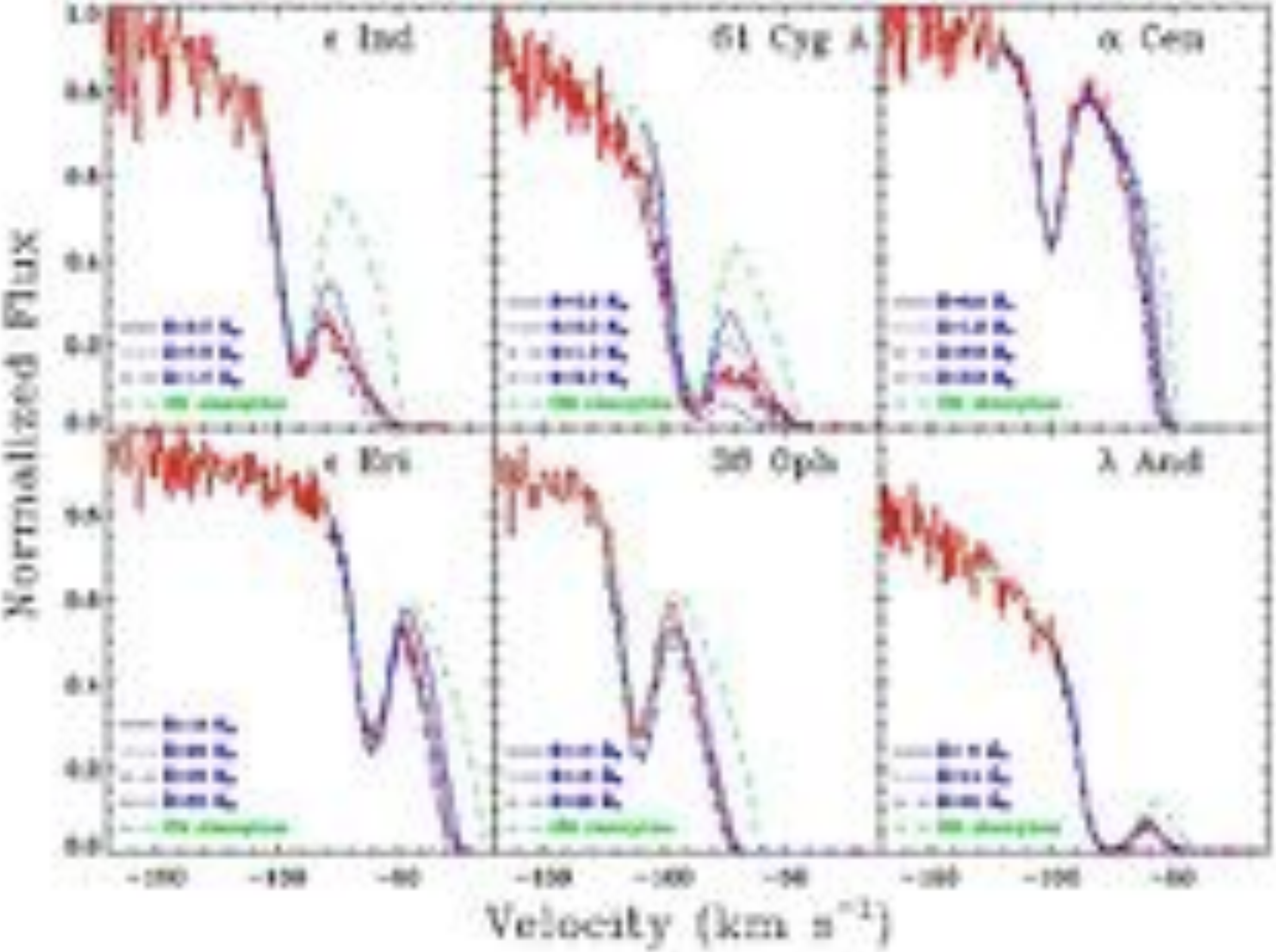


Original stellar
Ly alpha line

ISM
absorption

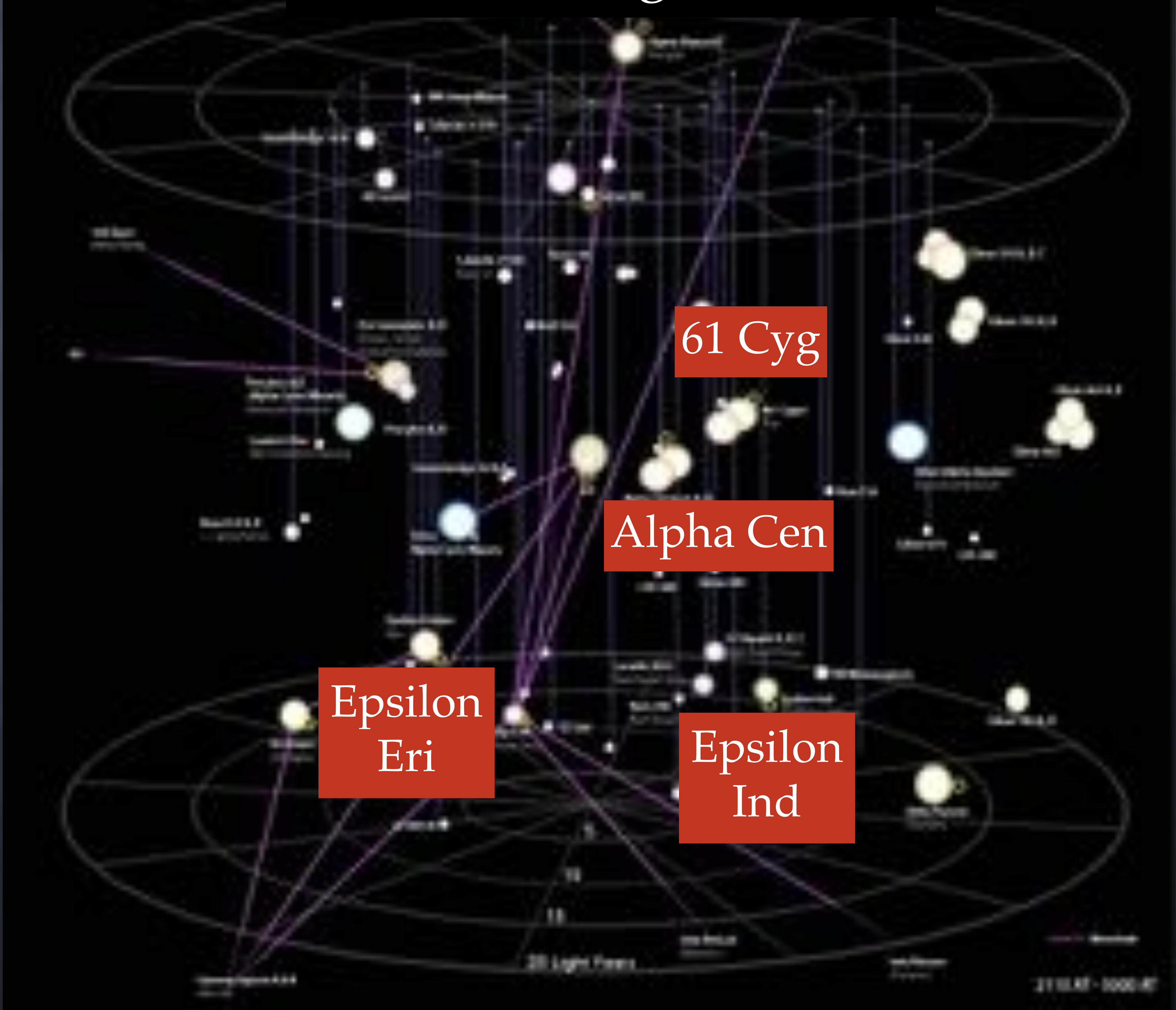
Astrosphere
absorption

Heliosphere
absorption



Wood et al. 2002, ApJ, 574, 412

The Solar neighborhood

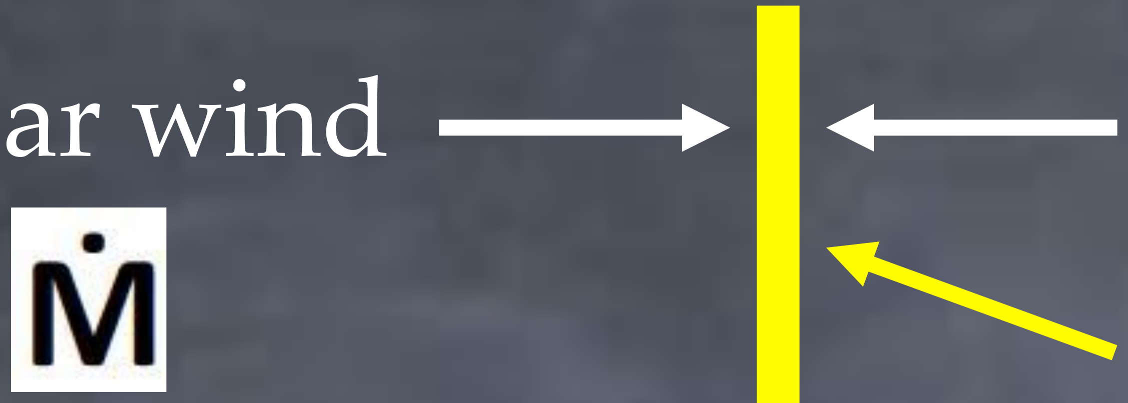


61 Cyg

Alpha Cen

Epsilon Eri

Epsilon Ind

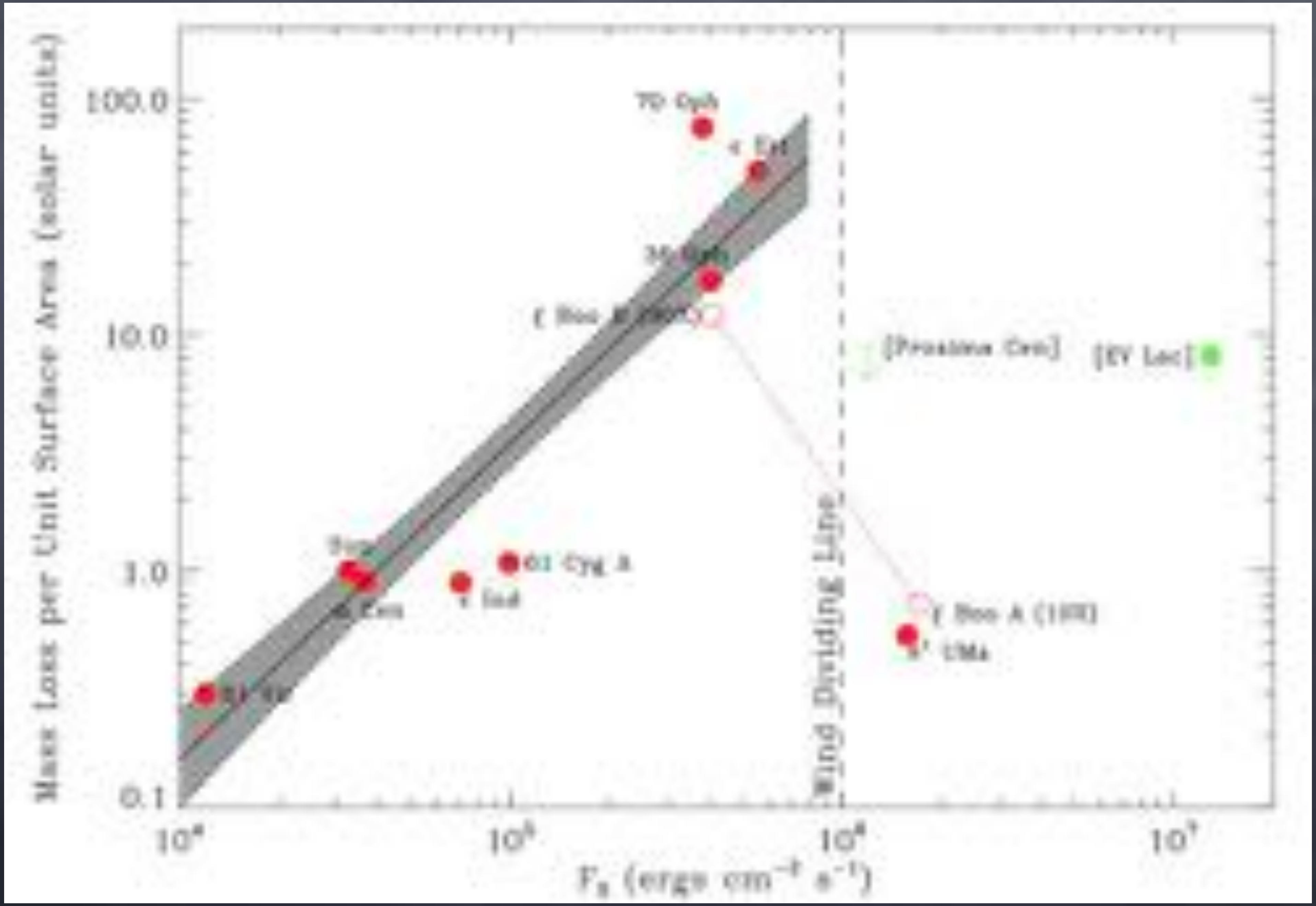


Stellar wind

$\dot{M}$

ISM

Emissions from Hydrogen wall



Wood et. al 2014

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

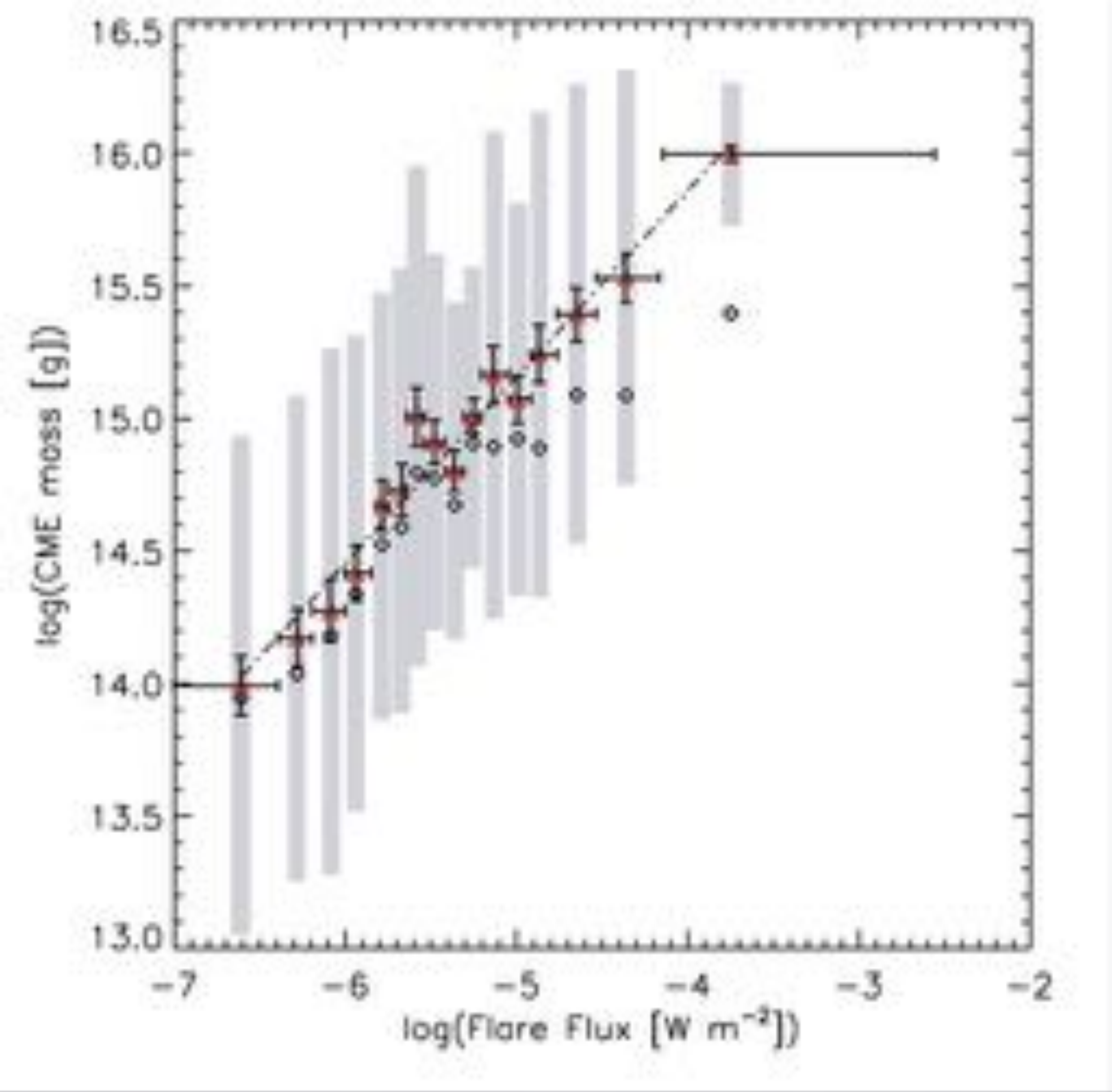
Solar wind mass-loss rate:
$\mathrm{rho}_{\mathrm{SW}}*u_{\mathrm{SW}}*4\pi(1\mathrm{AY})^2 = 2*\ 10^{-14}$ Msun/yr.

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.
$2\text{-}3*10^{15}$ g / 86400 sec (per day) = $2\text{-}3*10^{10}$ g/s
Mass-loss rate of about $5*10^{-16}$ Msun/yr

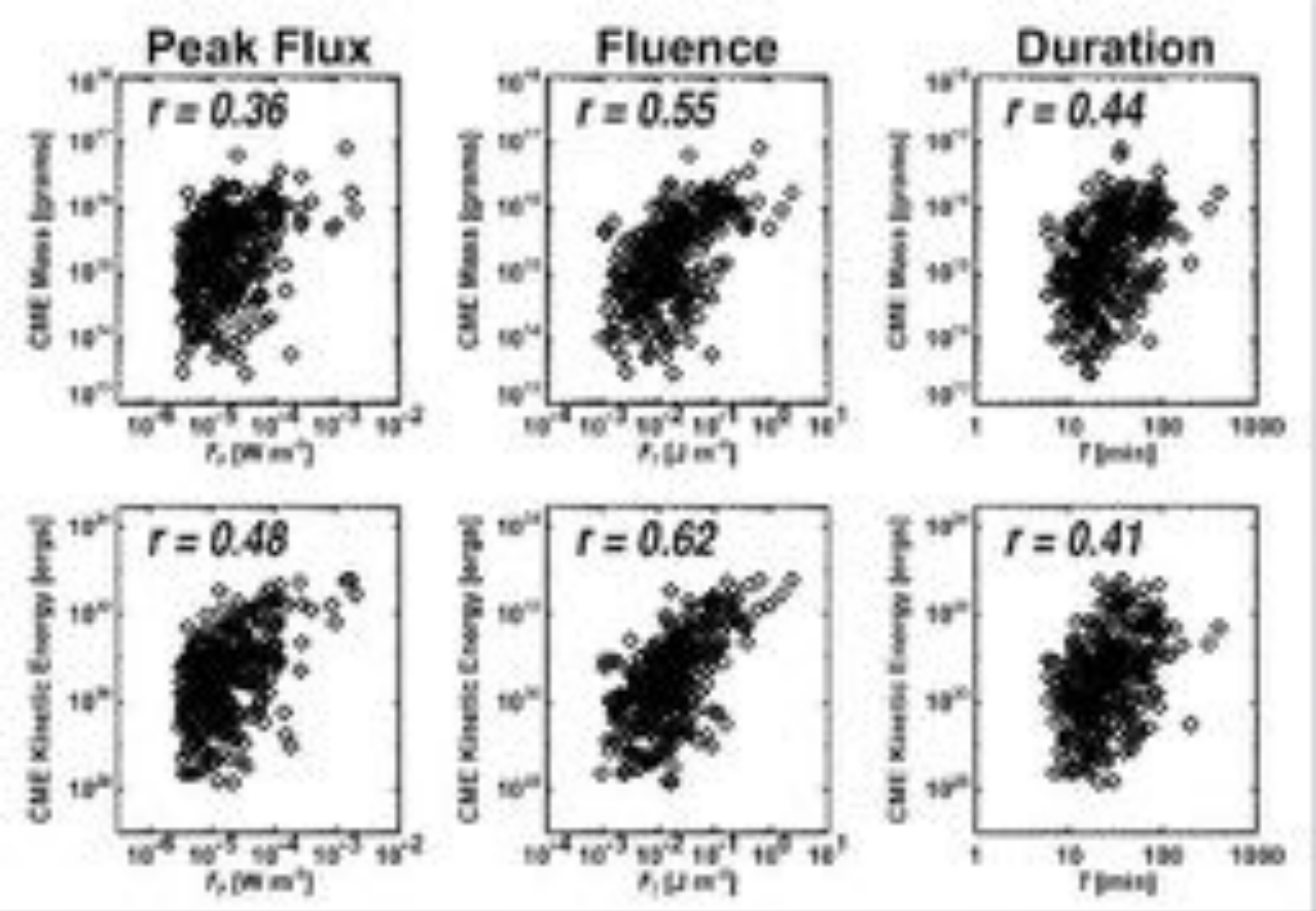
Few percents of the SW mass-loss rate

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):



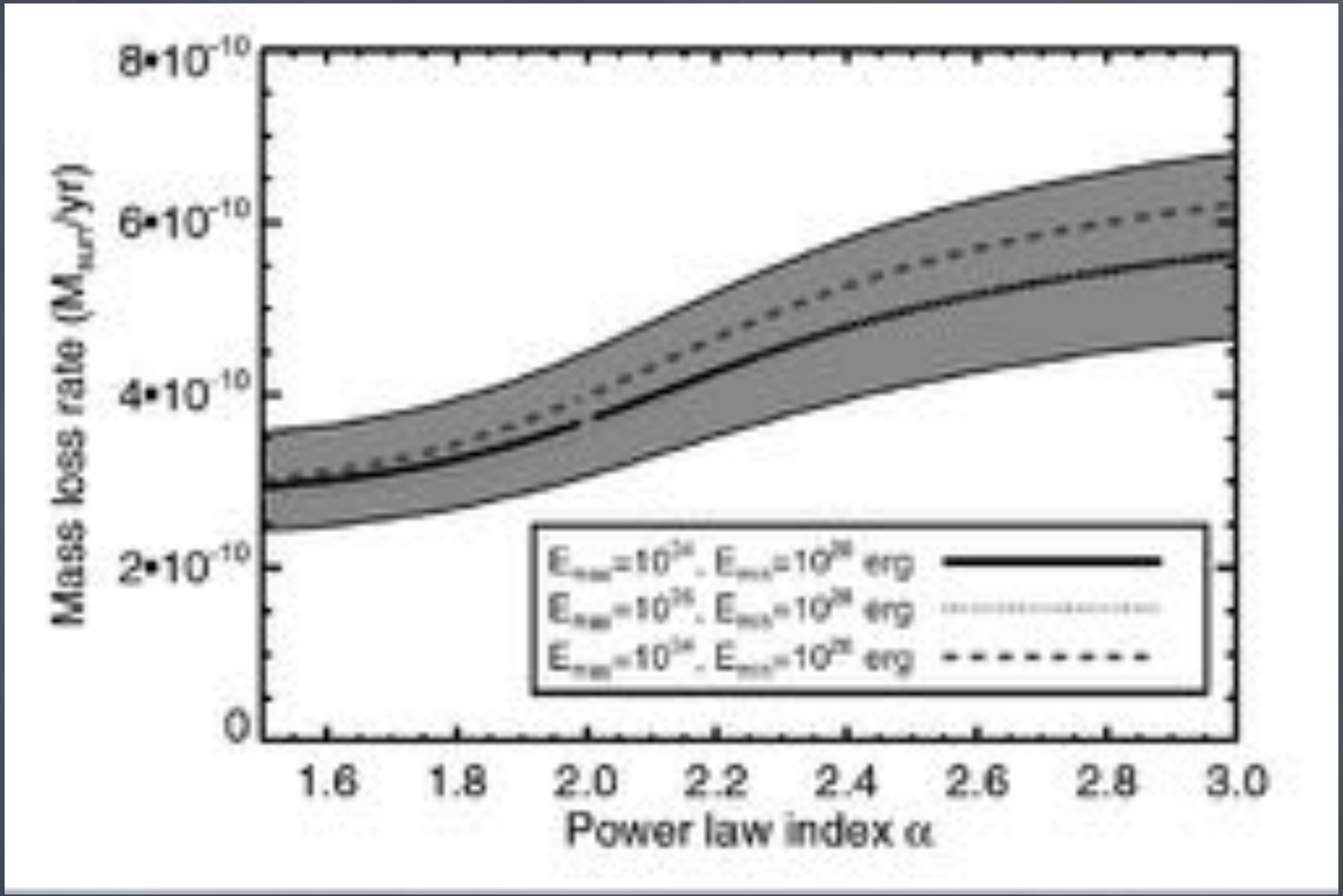
Aarnio et. al 2012



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:



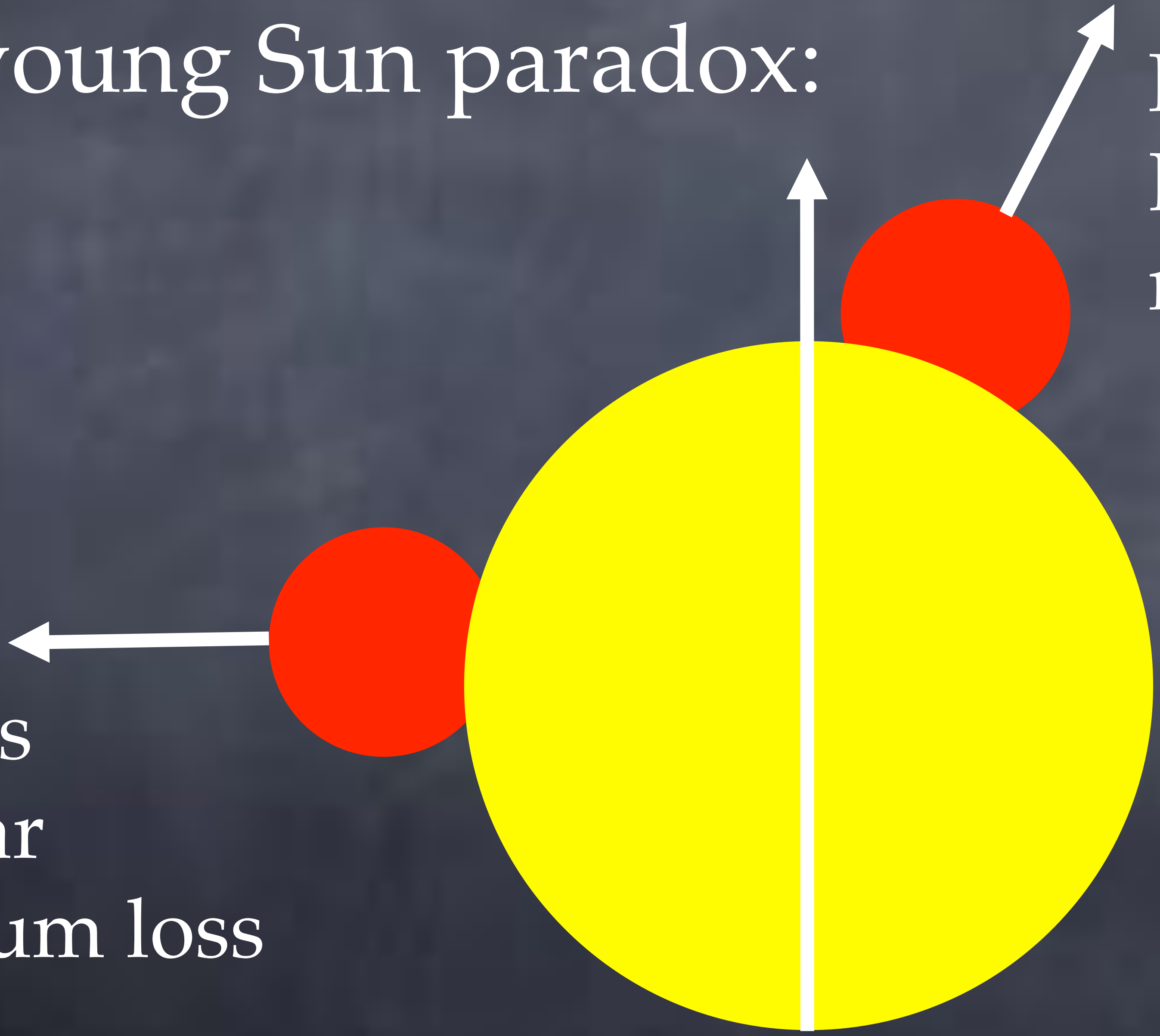
Drake et. al 2013

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:



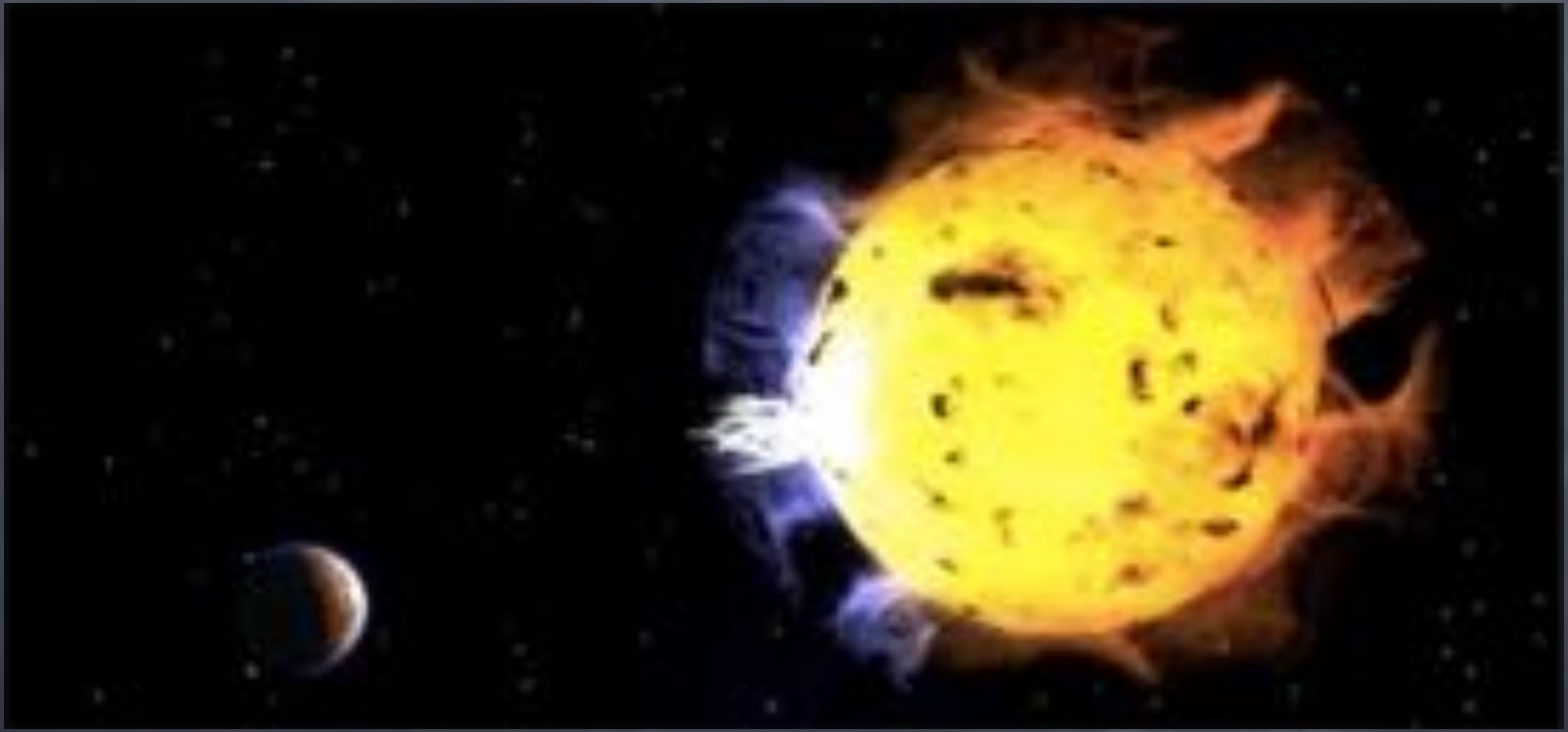
Mass-loss
No angular
momentum loss

Mass-loss
& angular
momentum loss

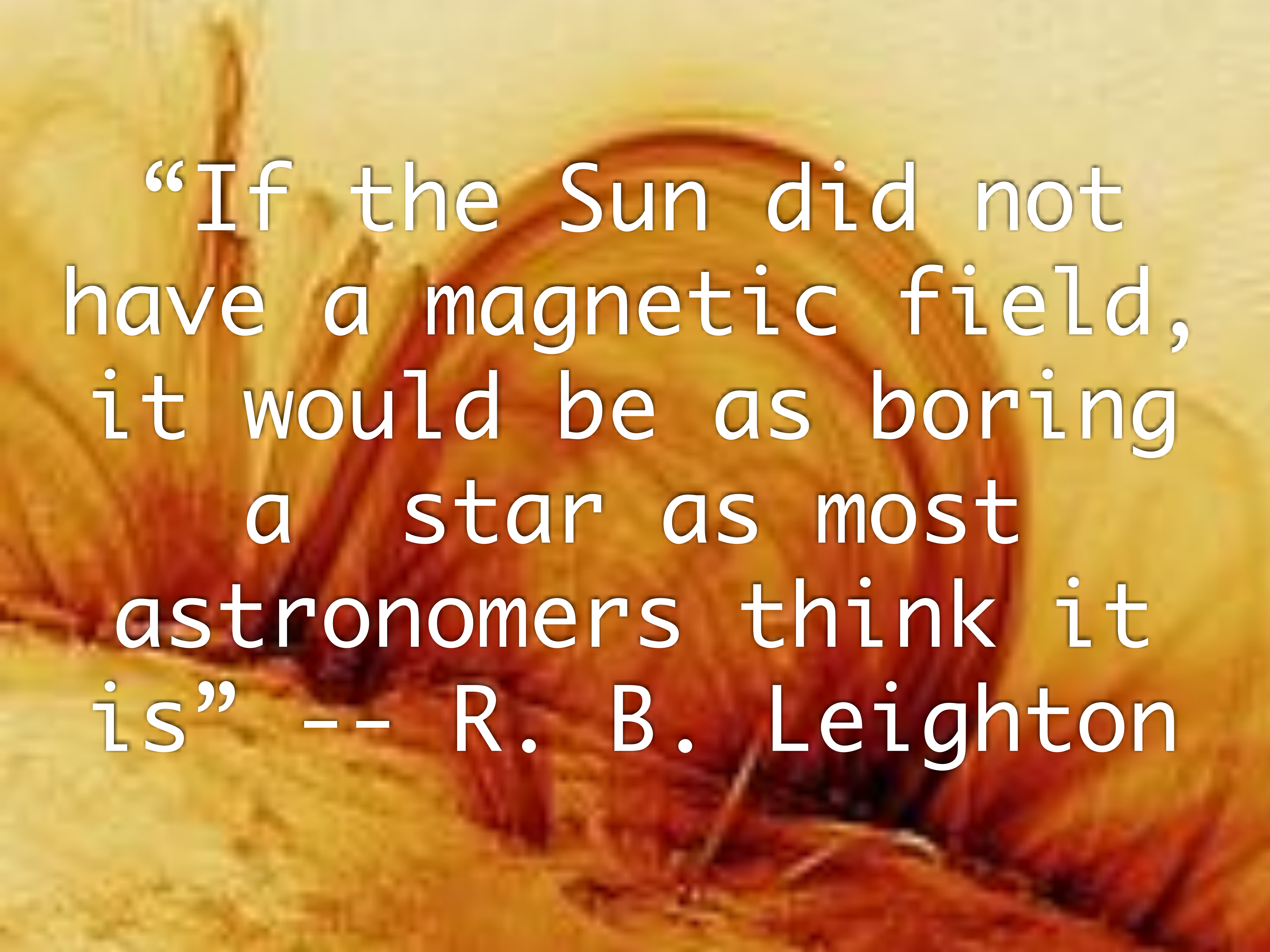
The Sun could lose large mass without lose angular m

The Sun have been 10% more massive - the faint youn

Flares

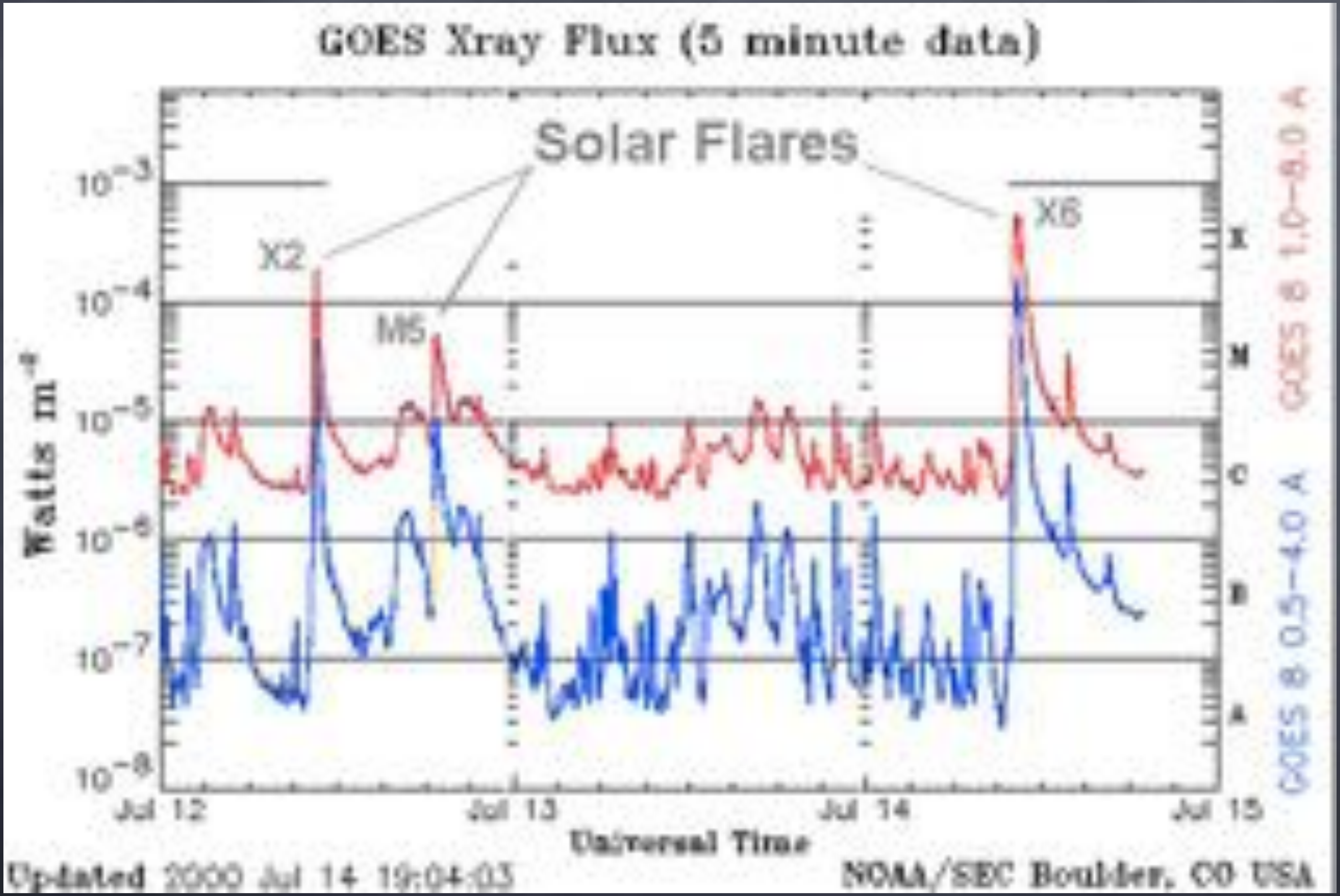


Thanks to Rachel Osten



“If the Sun did not have a magnetic field, it would be as boring a star as most astronomers think it is” -- R. B. Leighton

Flare - a (large) bump

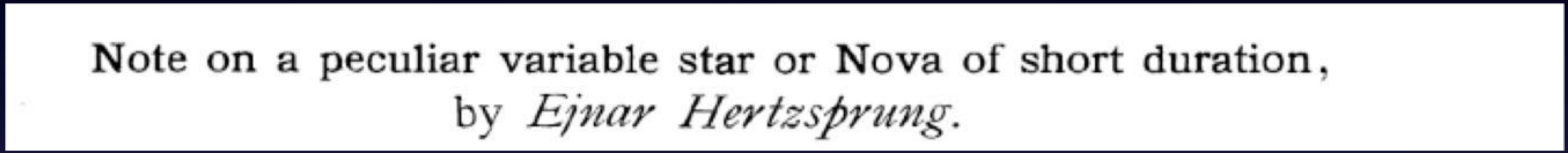


What is an explosive event?

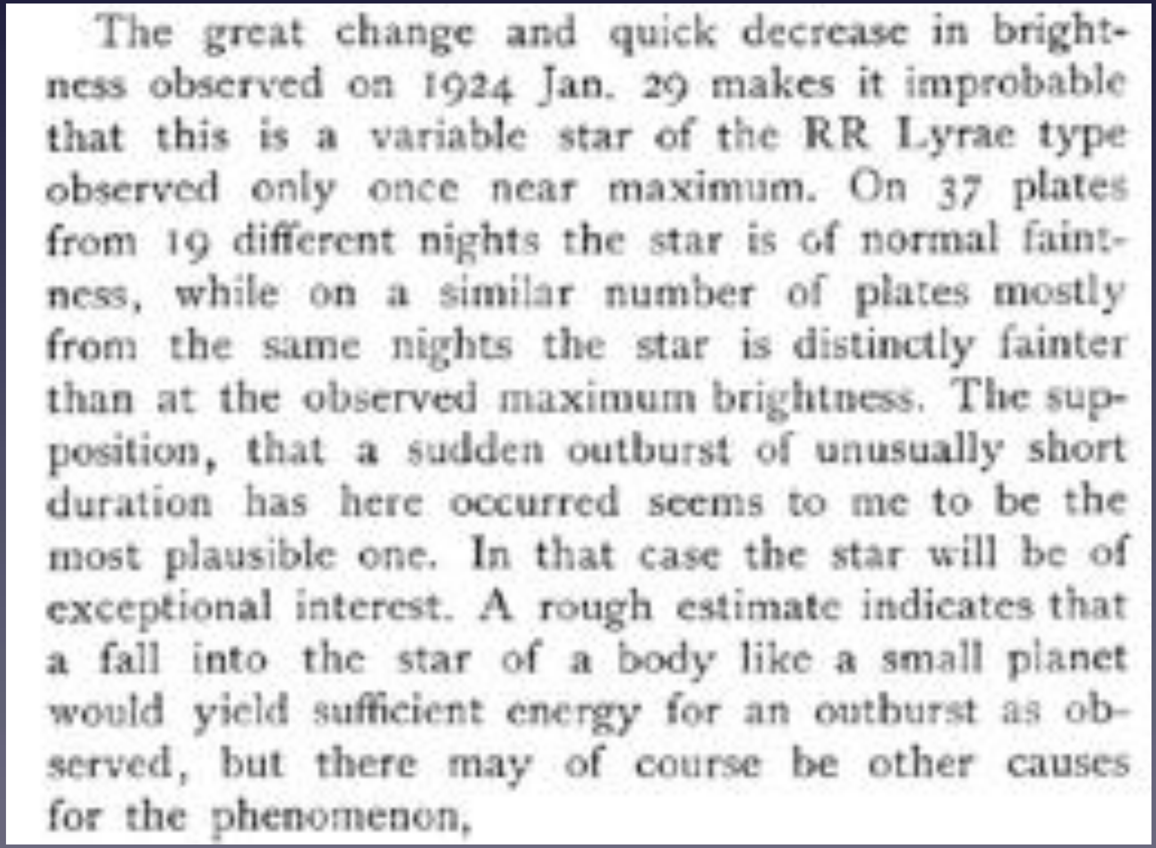
stellar astronomers only see the radiative manifestation of the explosive event - the flare

- Involves particle acceleration, plasma heating, and mass motions
  - particles get accelerated up to GeV energies
  - plasma heated to temperatures of 10^6 K or larger
  - mass motions up to a few thousand km/s
- Is a consequence of magnetic reconnection occurring high in the corona
- Involves all atmospheric layers, from the photosphere through the chromosphere & into the corona (even the heliosphere)
- Produces emissions across the EM spectrum
- Has different components: flare, coronal mass ejection, solar energetic particles

Early Stellar Flare Observations



Note on a peculiar variable star or Nova of short duration,
by *Ejnar Hertzsprung.*



The great change and quick decrease in brightness observed on 1924 Jan. 29 makes it improbable that this is a variable star of the RR Lyrae type observed only once near maximum. On 37 plates from 19 different nights the star is of normal faintness, while on a similar number of plates mostly from the same nights the star is distinctly fainter than at the observed maximum brightness. The supposition, that a sudden outburst of unusually short duration has here occurred seems to me to be the most plausible one. In that case the star will be of exceptional interest. A rough estimate indicates that a fall into the star of a body like a small planet would yield sufficient energy for an outburst as observed, but there may of course be other causes for the phenomenon,

To Start

- Stellar flares show many commonalities with solar flares which belies a common (perhaps not identical) physical mechanism.
- Stellar flare observations are necessarily limited in completeness and wavelength regimes compared to solar flare observations, but compensates in the rich variety of stars which can be studied.
- This enables the study of flares on stars of different ages to inform the range of conditions that the Sun may have experienced in the past.

Flares - temporal increase variations of some ambient s

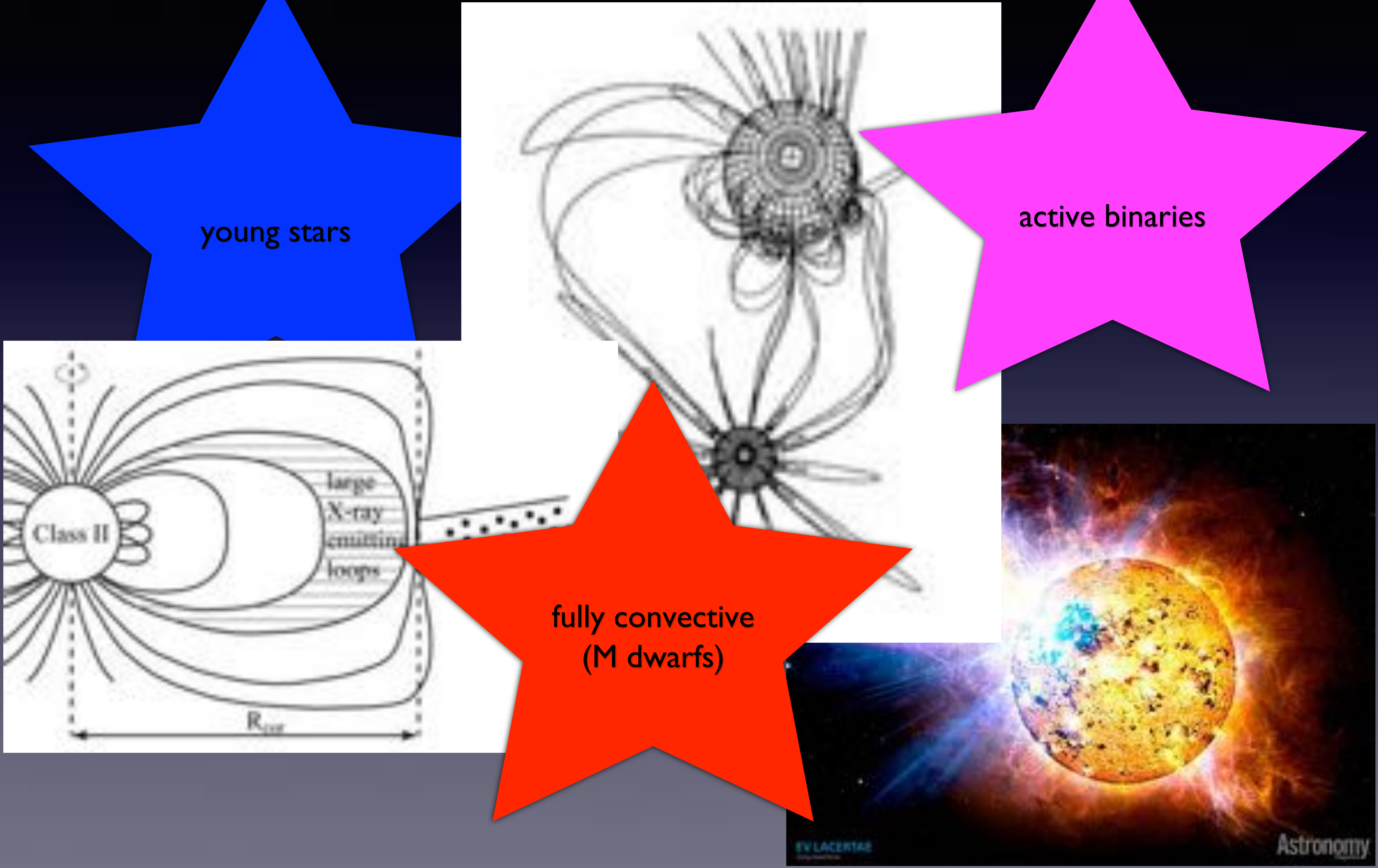
We should consider a situation where flares are so freq

The ambient state in that case is described by a whole

Comparing large solar and stellar flares

	energy	max. duration	intensity increase (visible)	intensity increase (X-ray)
Sun	10^{32} ergs	~5 hours	1.00027	6000
young stars	10^{36} ergs	~1 day	small	50
single stars	10^{35} ergs	several days	1000	1000
binary stars	10^{38} ergs	~ 1 week	1.2	120

THE KINDS OF STARS TYPICALLY TARGETED FOR FLARE STUDIES

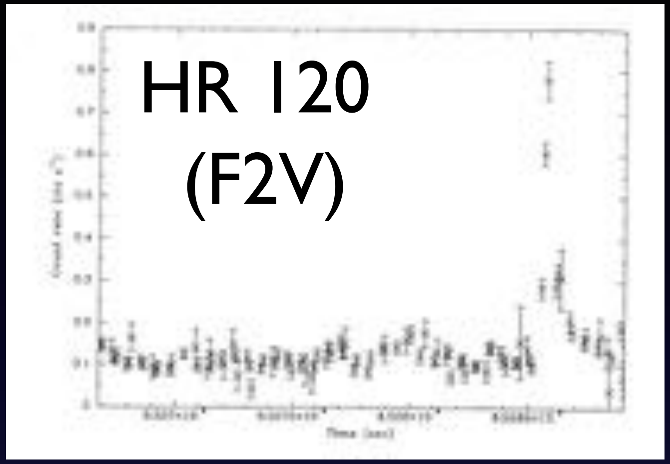


young stars

active binaries

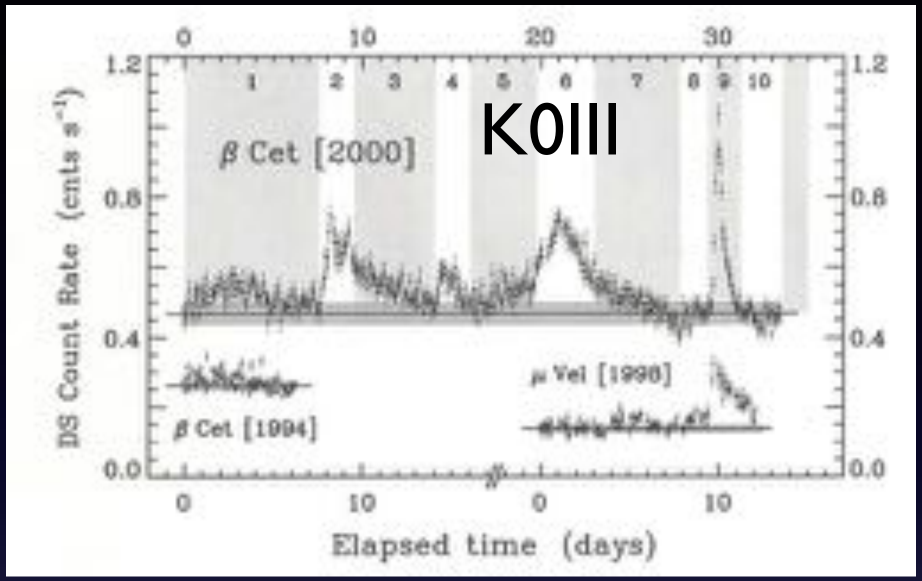
fully convective
(M dwarfs)

Demographics of Flaring Stars Seen at X-ray Wavelengths



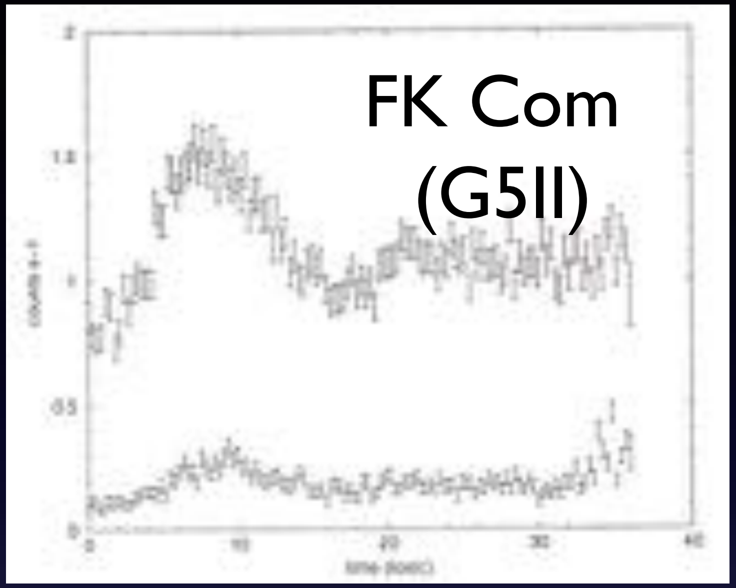
HR 120
(F2V)

Mullan & Mathioudakis 2000



K0III

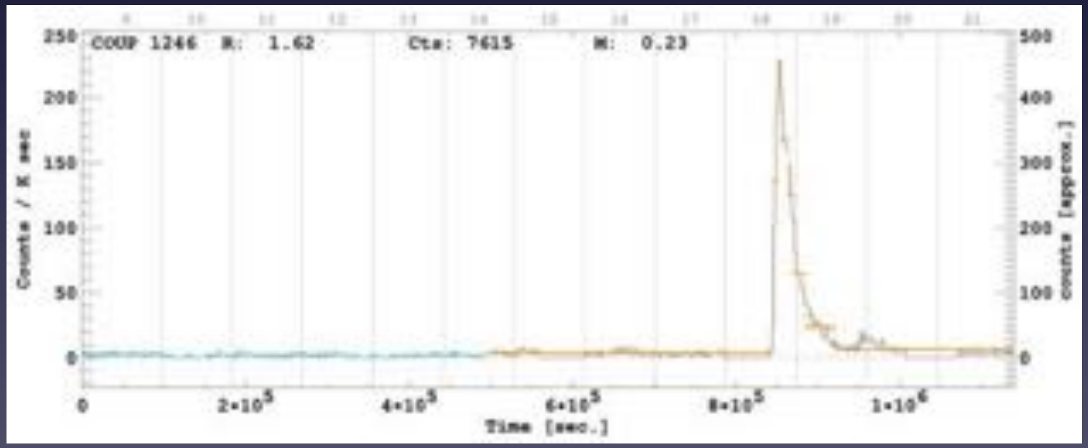
Ayres et al. 2001



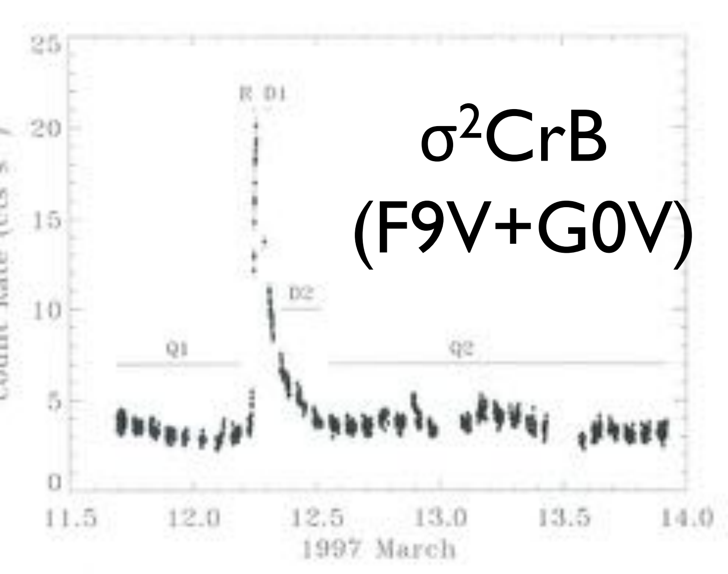
FK Com
(G5II)

Gondoin et al. 2002

Favata et al. (2005)
young star in ONC

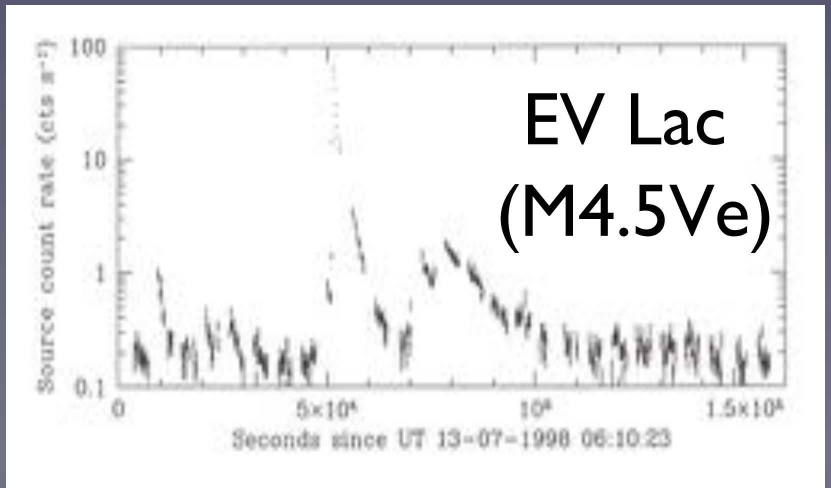


Osten et al. 2000



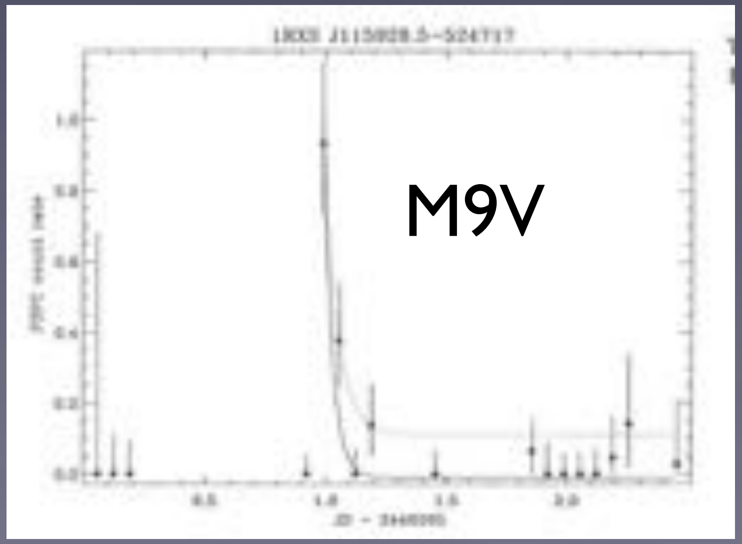
σ^{2}CrB
(F9V+G0V)

Favata et al. 2000



EV Lac
(M4.5Ve)

Hambaryan et al. 2004



M9V

Holistic approach finds agreement in manifestations of solar/stellar Flares

Flare Observational Signature	Solar Flares	Stellar Flares*
EUV/soft X-ray emission (corona)		
optical emission lines (chromosphere)		

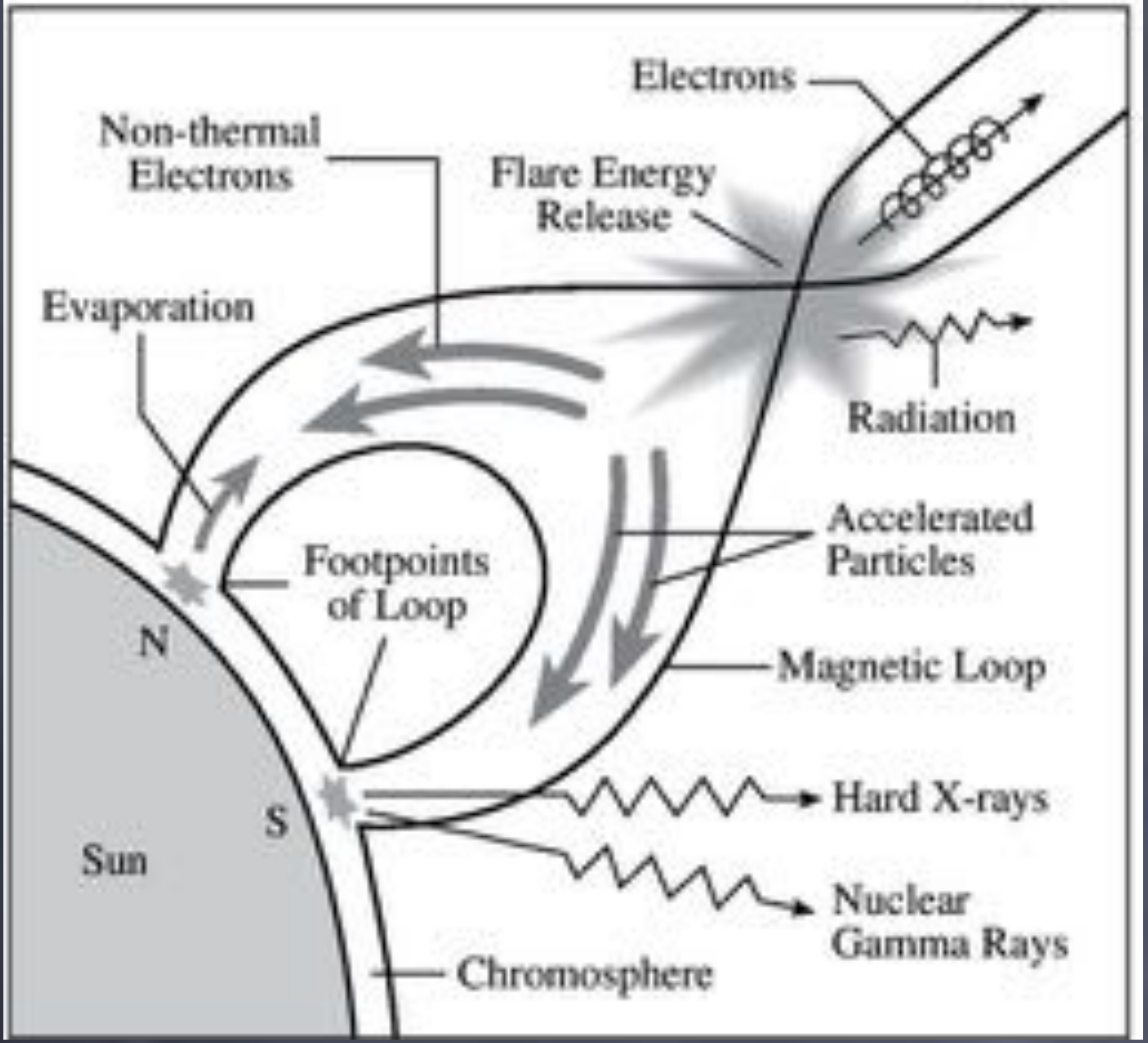
cyan=impulsive phase, orange=gradual phase

* across different kinds of stars

In stars we see the flare but not the CME!!!

Multi-Wavelength Stellar Flare Studies

λ range	instruments	info
radio (mm-m)	ALMA, JVLA, ATCA, MERLIN, LOFAR, GMRT	flux, polarization: gyrosynchrotron, coherent emission
optical (3000-7000 Å)	spectra, photometry	white light flares photosphere, chromosphere
UV 900-3000 Å	IUE, HST, FUSE, GALEX	chromosphere, TR: flux, redshift, density
EUV 80-350 Å	EUVE, Chandra/LETGS	corona: density, temperature, EM
SXR 1.8-30 Å	ASCA, RXTE, BeppoSAX, Chandra, XMM-Newton, Swift	corona: temp., EM, abundance densities
HXR 10-100 keV	Swift, BeppoSAX, Suzaku	corona: thermal/nonthermal

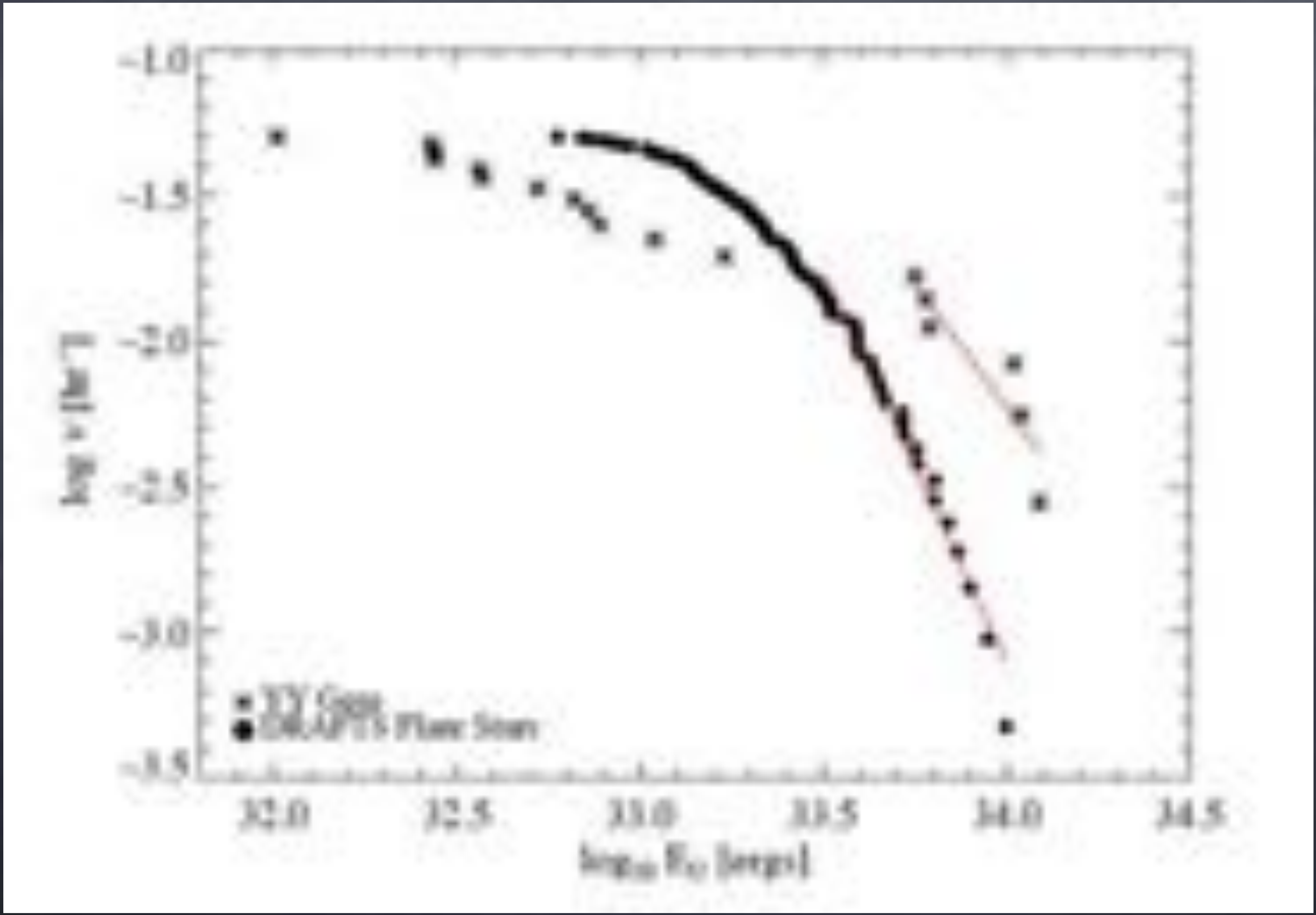


Kenneth R. Lang, Tufts University

Particle acceleration is manifested in different bands and energies:
High energy: Soft/hard X-ray, EUV
Low energy: radio

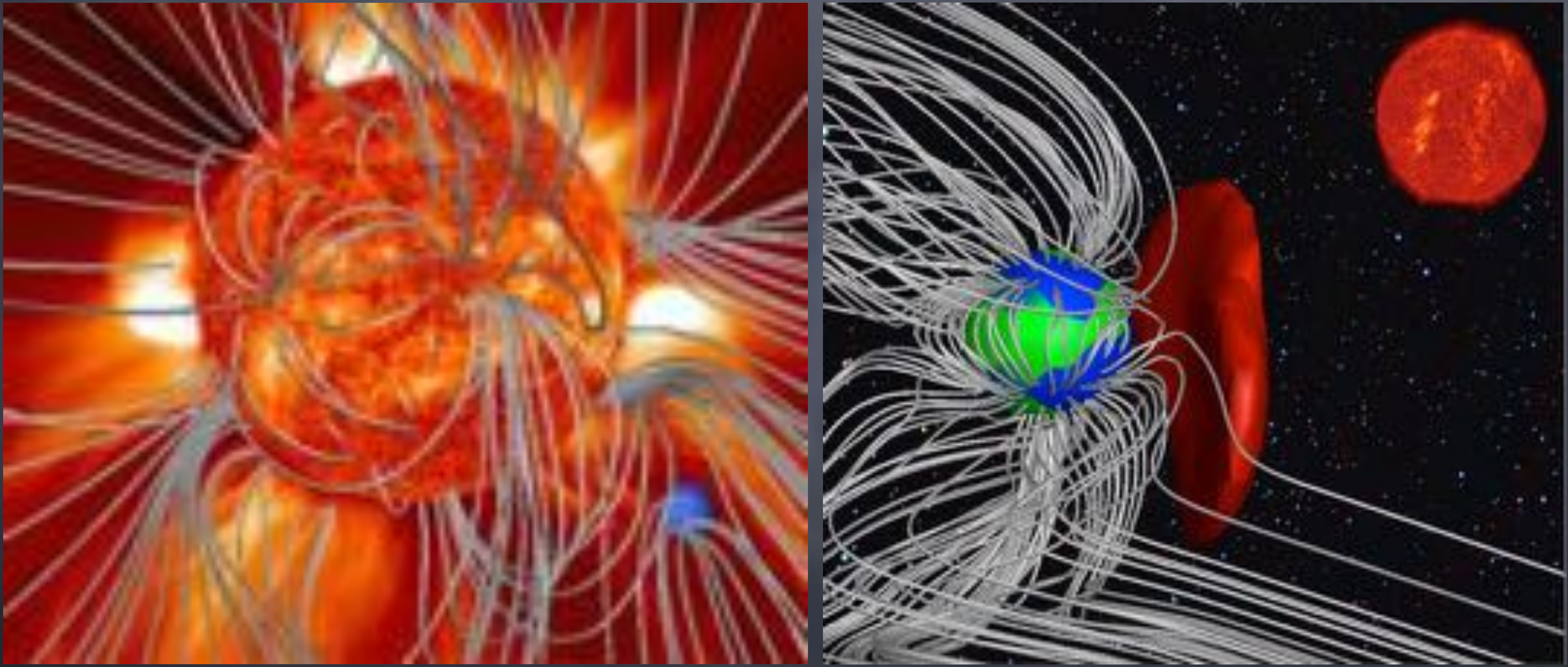
Emissions are the results of

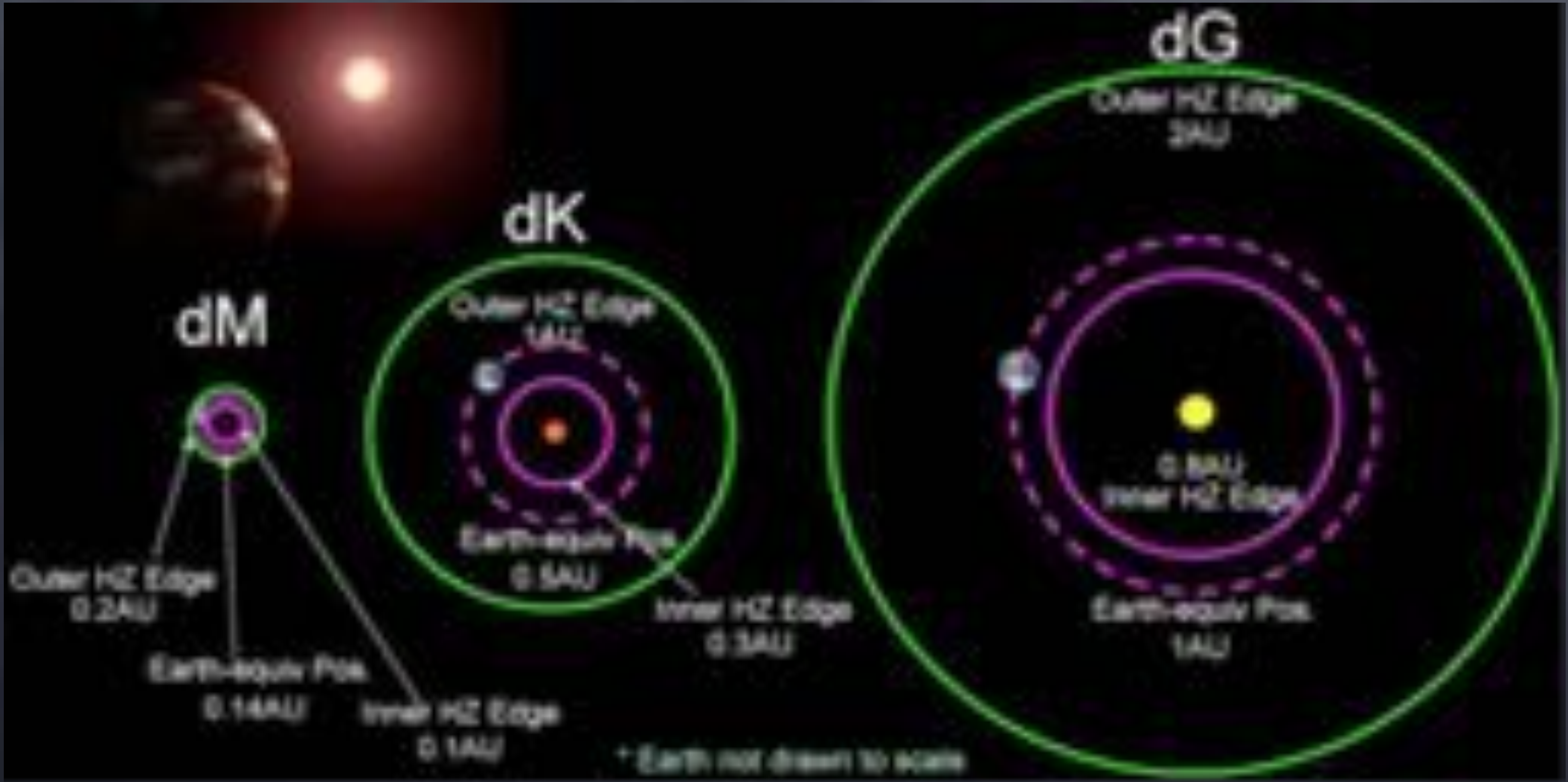
1. Accelerated particles interaction with coronal/chromospheric/photospheric material
2. Accelerated electrons



Osten et. al 2012

Planet Habitability





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

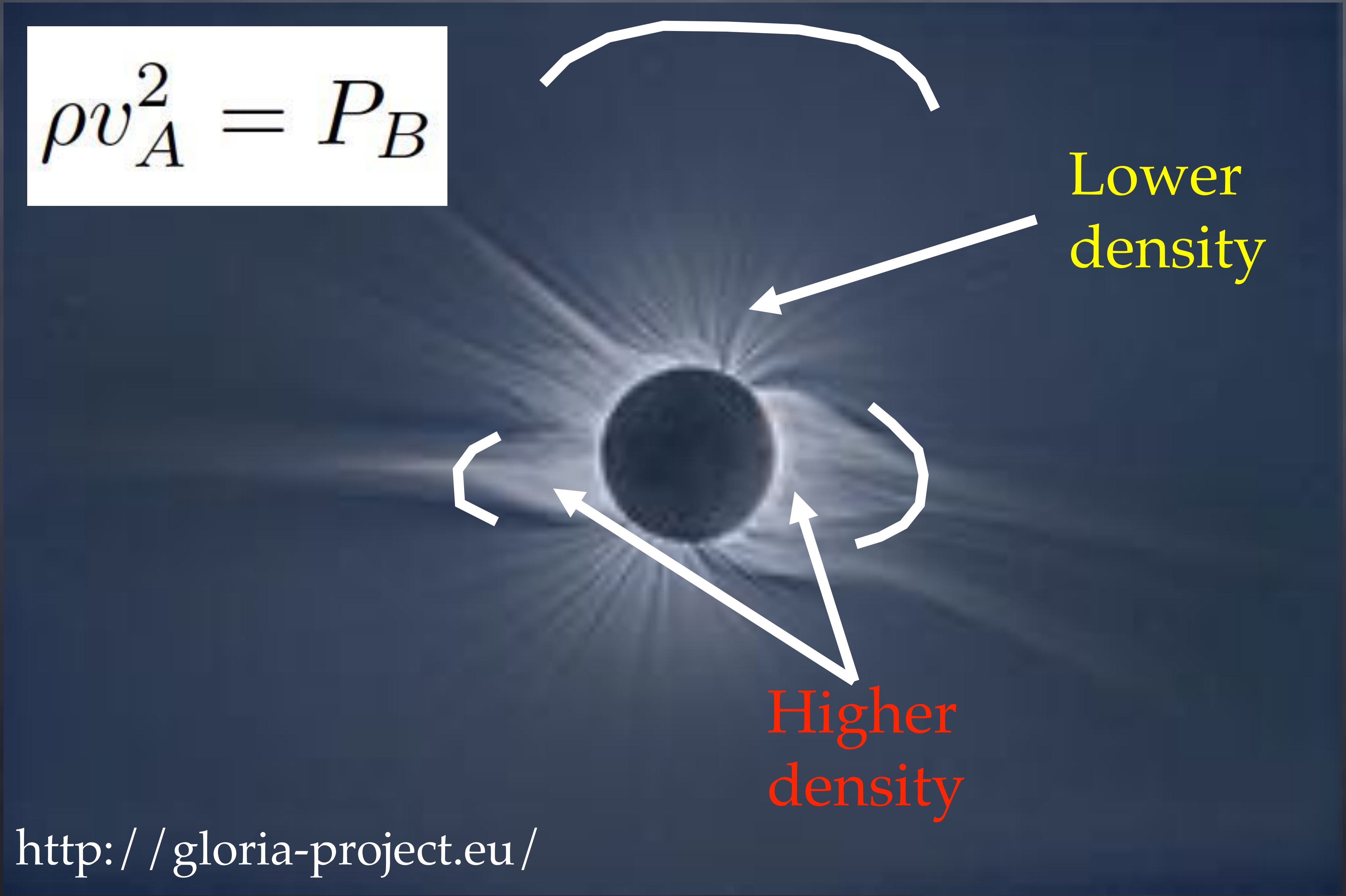
M-dwarf planets

What is the Alfven point/surface?

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

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

$$M_A = v/v_A$$



$$\rho v_A^2 = P_B$$

Lower density

Higher density

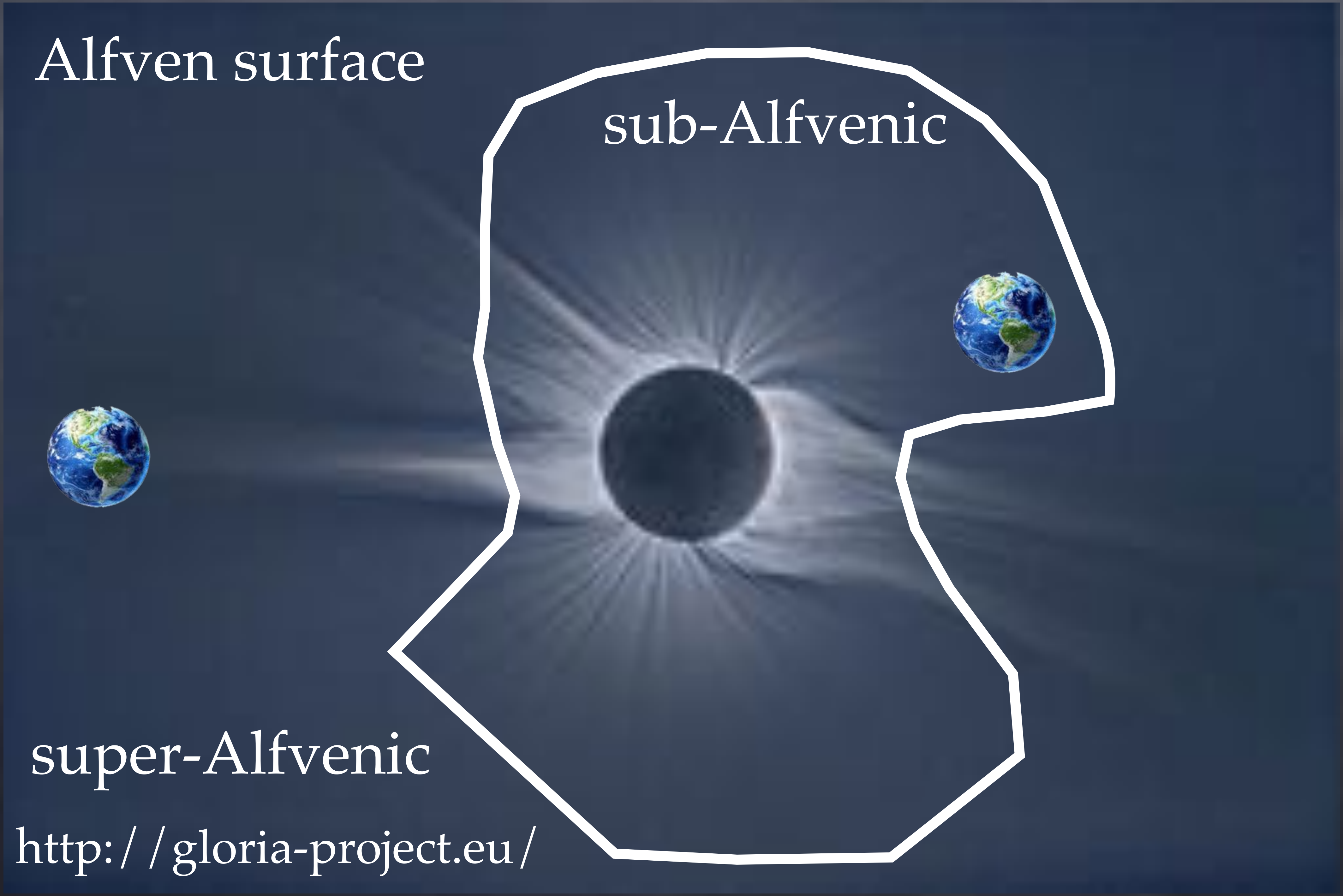
http://gloria-project.eu/

What is the Alfven point/surface?

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

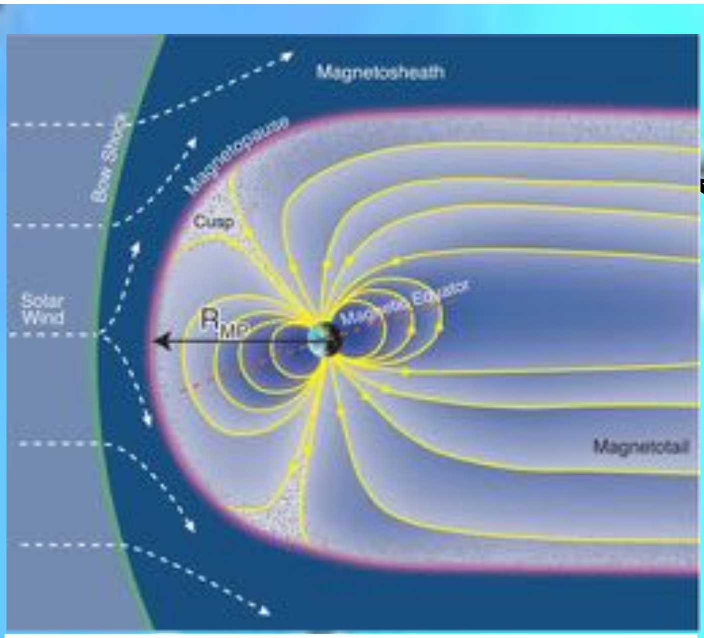
$$c^2_s = \frac{\gamma p}{\rho}$$

$$M_A = v/v_A$$

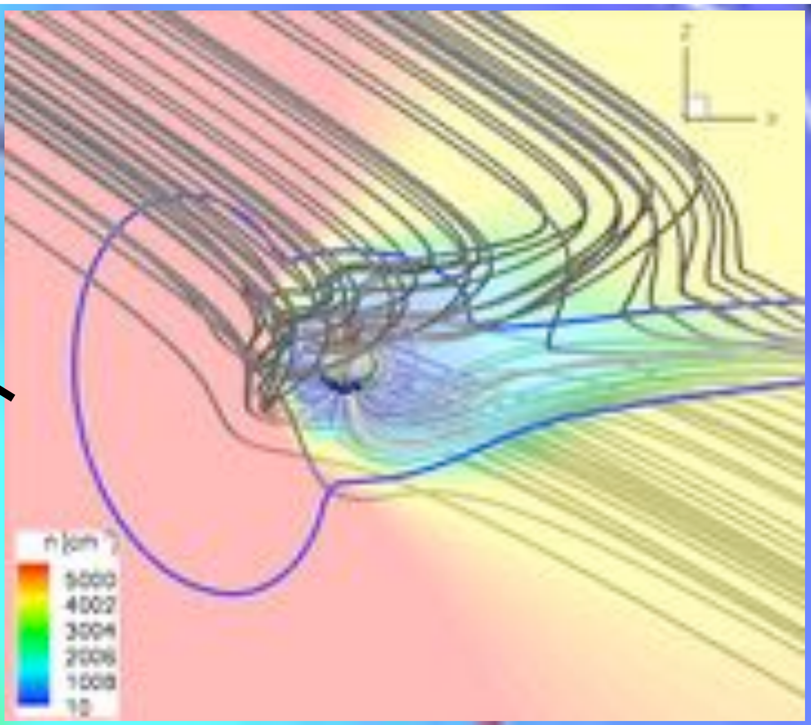


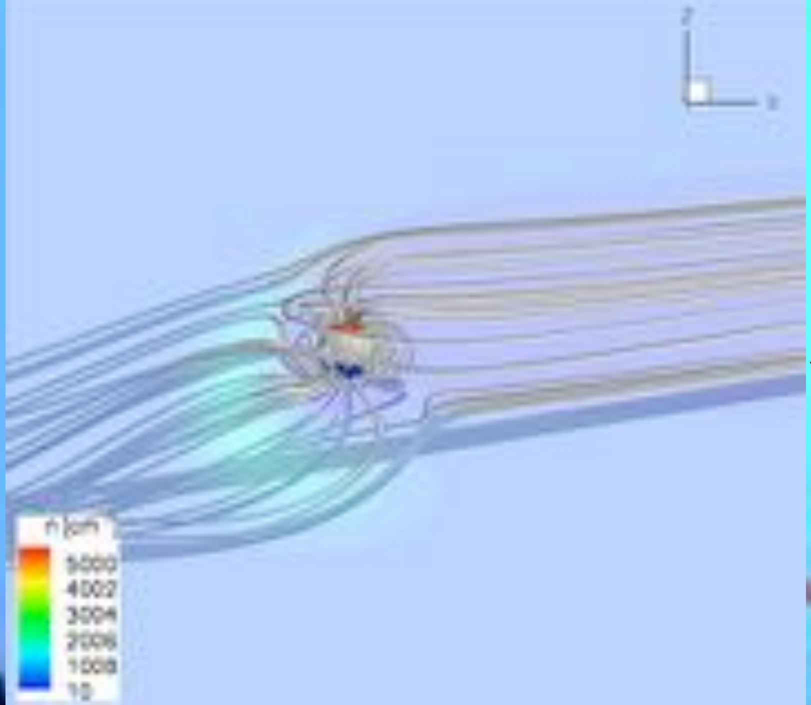
http://gloria-project.eu/

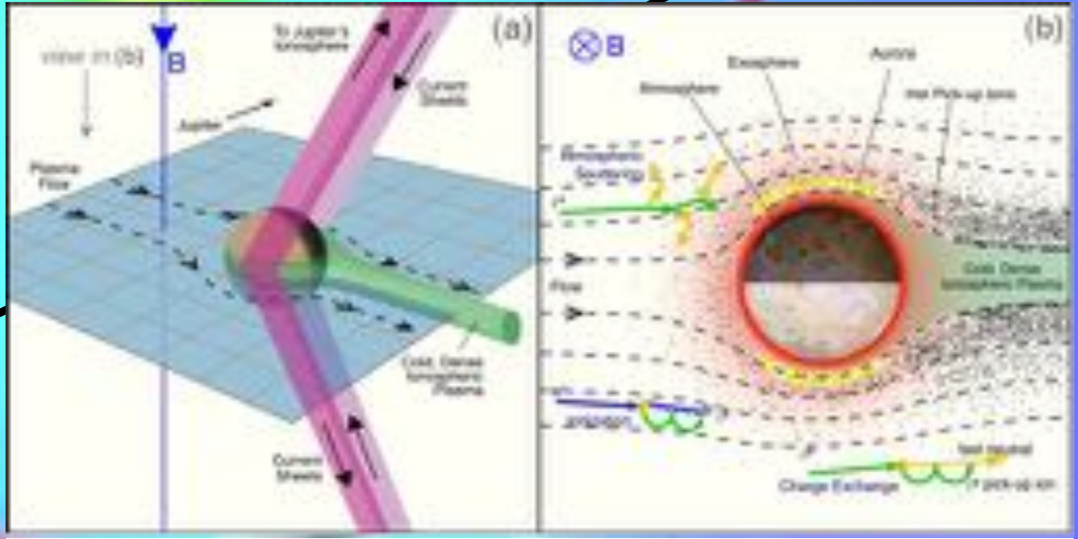
Possible unique conditions in a nearly sub-Alfvenic stellar wind regime:



Credit: Fran Bagenal & Steve Bartlett

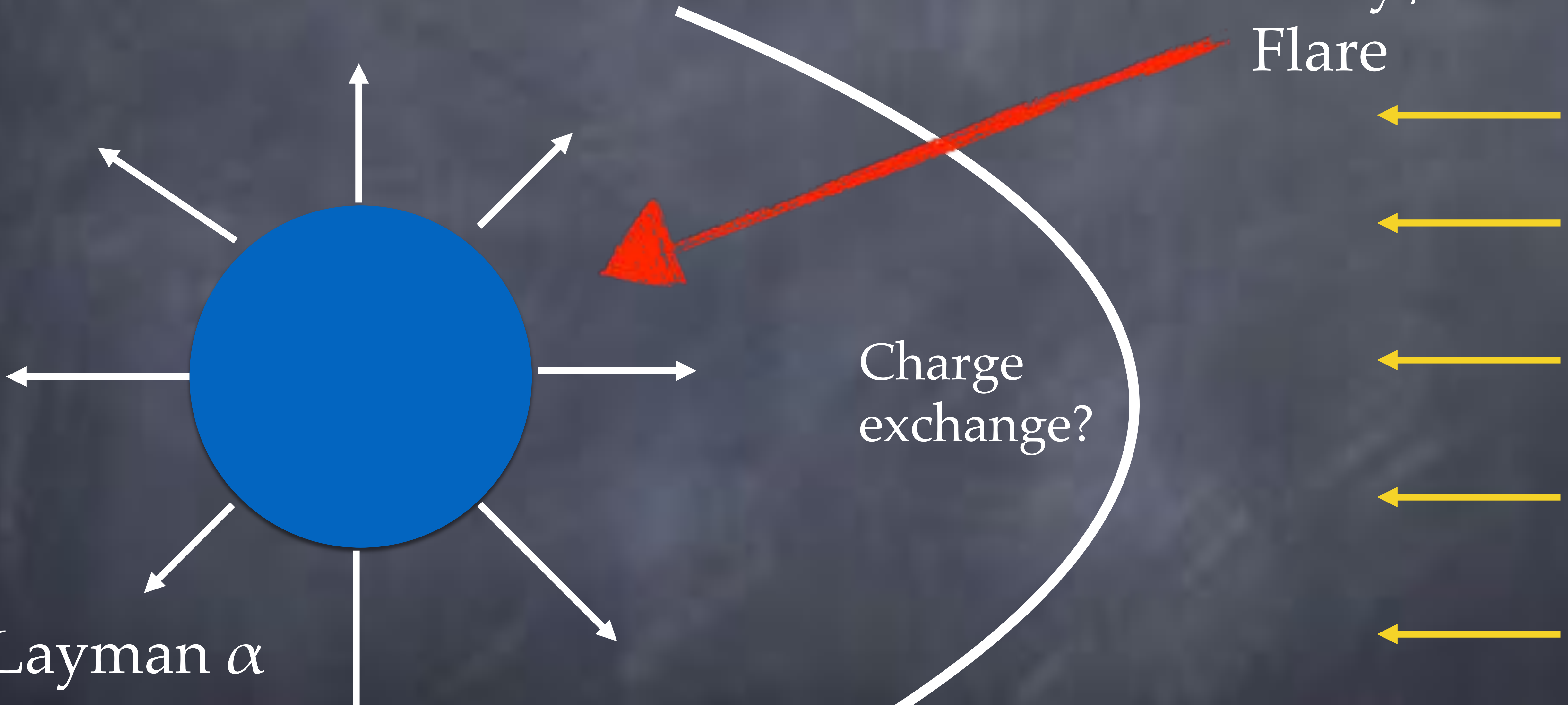






Credit: Fran Bagenal & Steve Bartlett

Impact on the upper atmosphere:



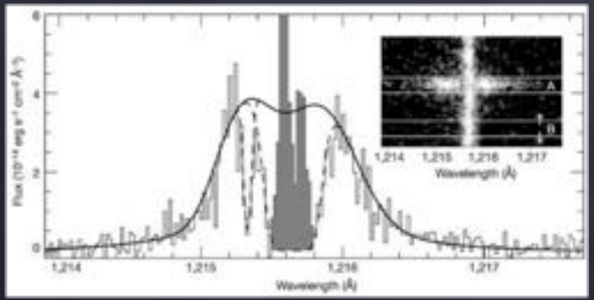
Atmospheric outflow

Magnetopause

X-ray/EUV
Flare

Charge
exchange?

Layman α



Vidal-Madjar et. al, Nature 2003

stellar wind
stellar radiation
X-ray/EUV

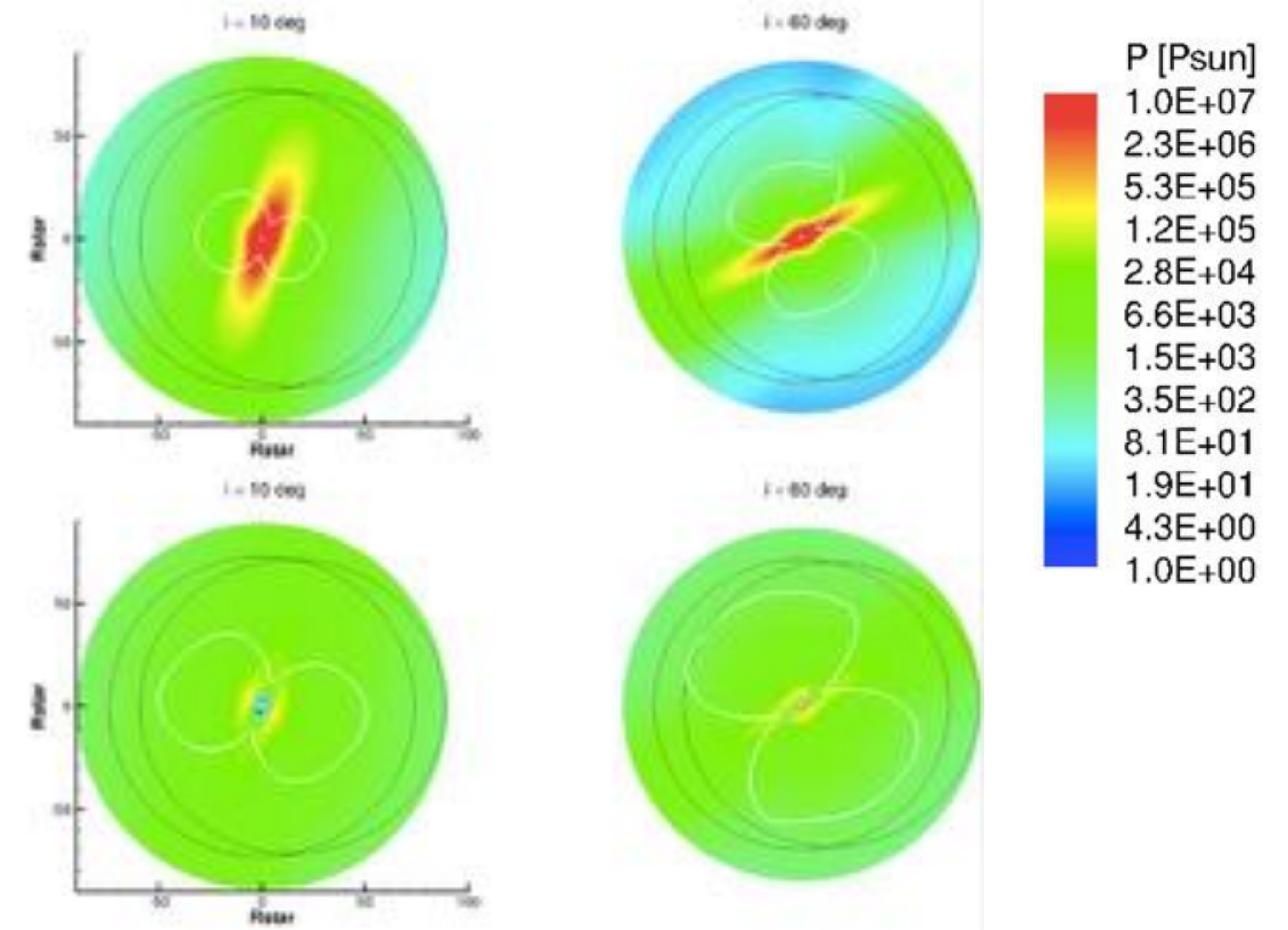
Extreme space weather:

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)

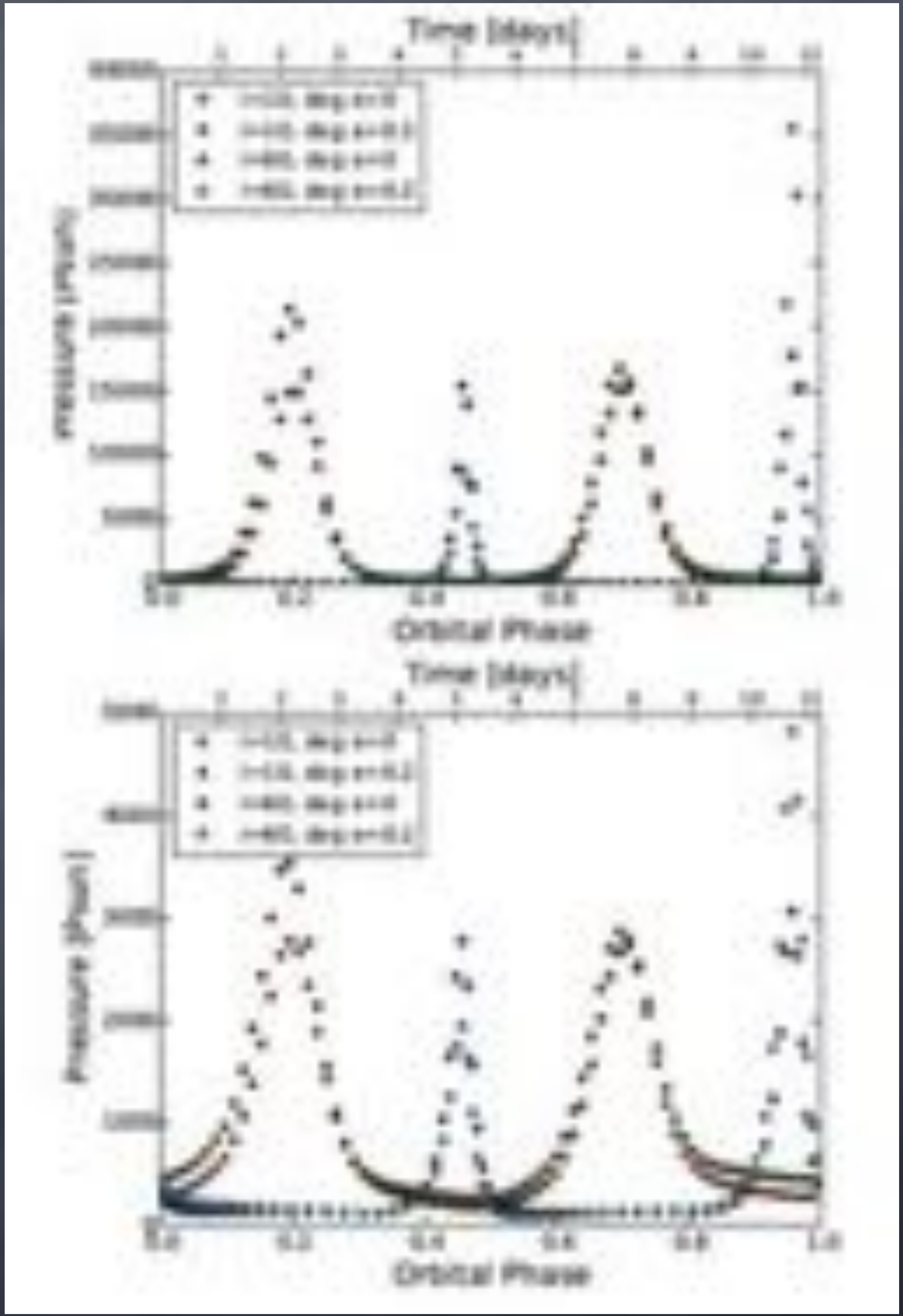
Atmospheric stripping by the stellar wind:

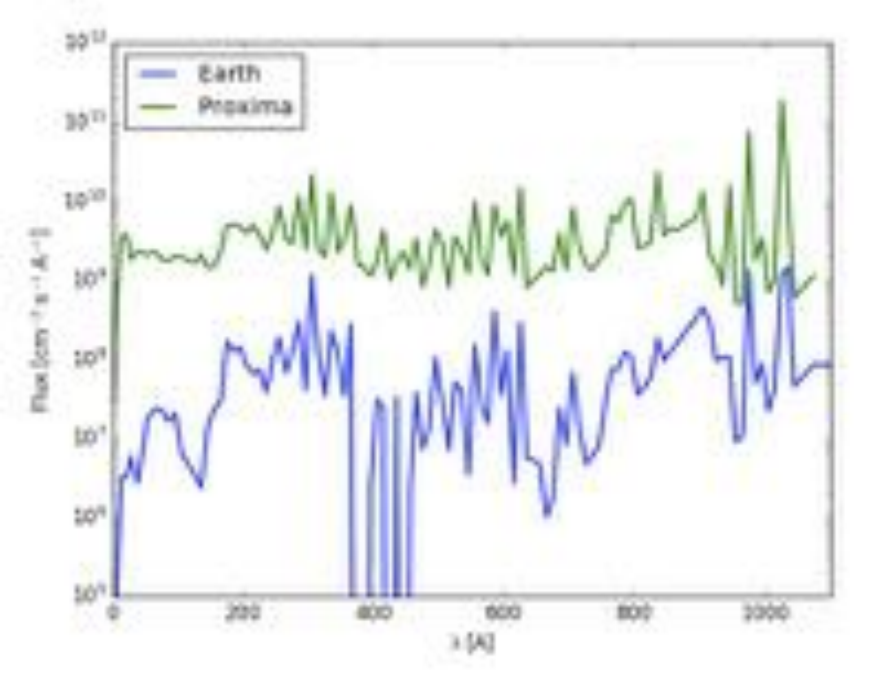
ose-in terrestrial planets sustain an atmosphere

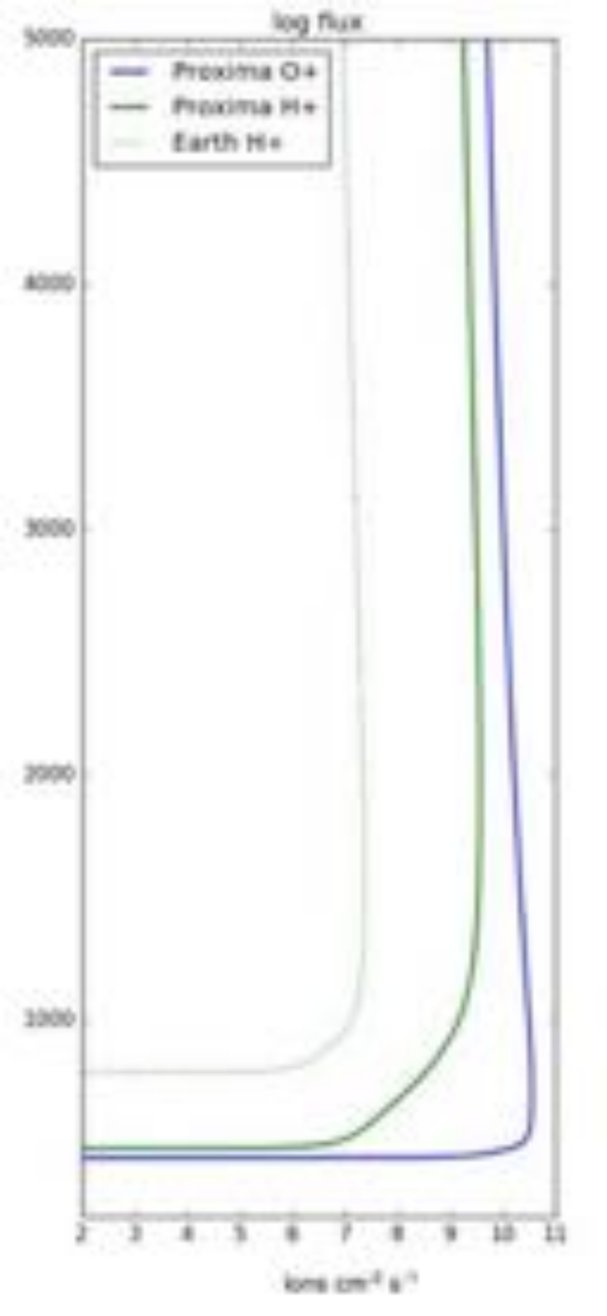
Proxima Centauri b

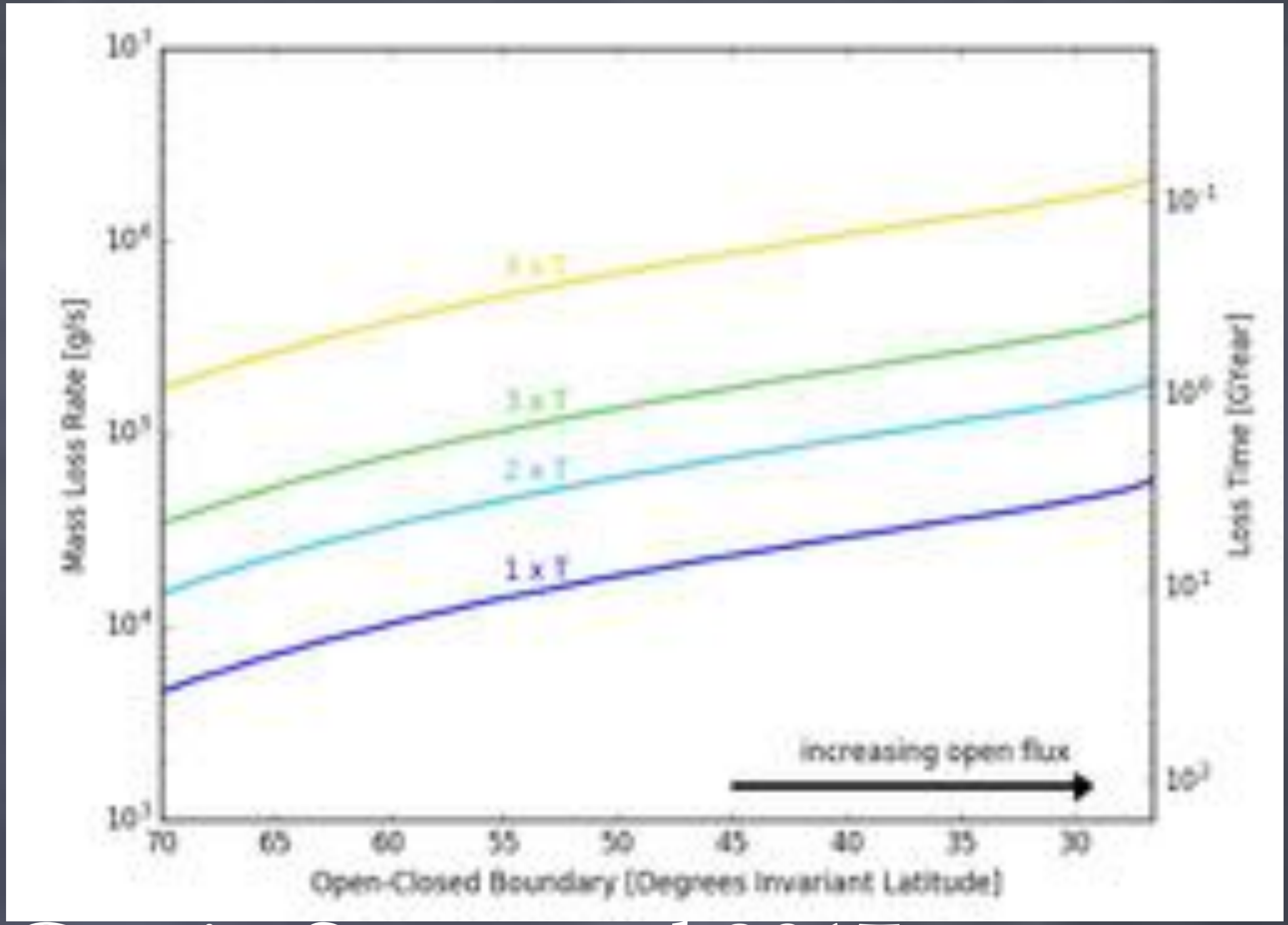


Garraffo et. al 2016

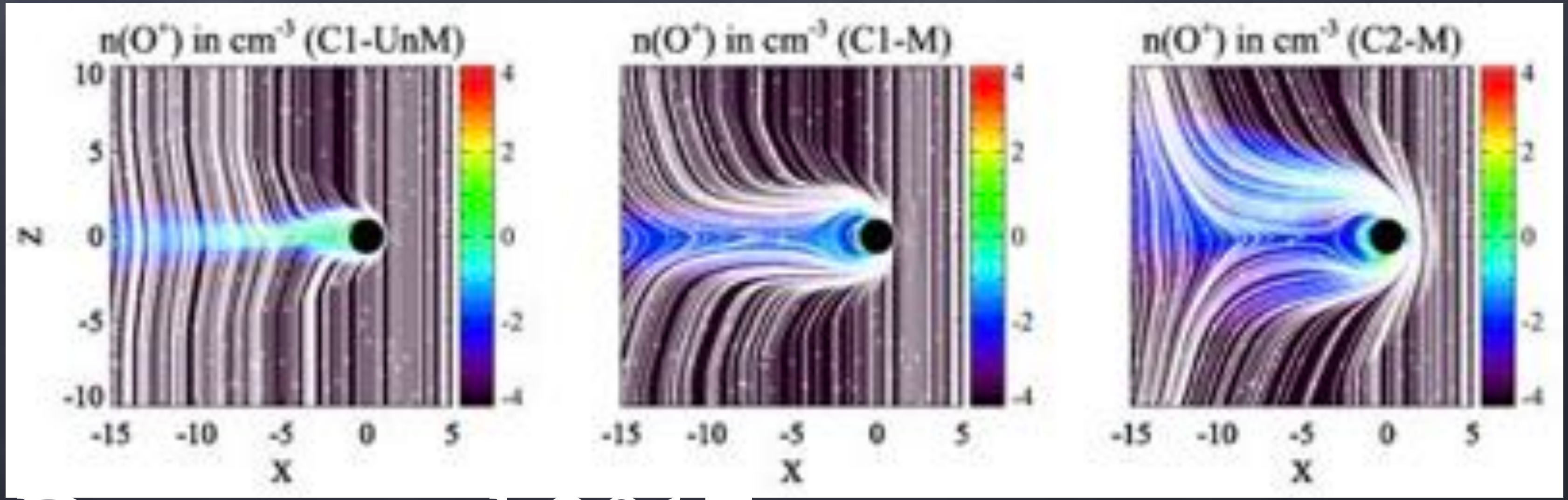






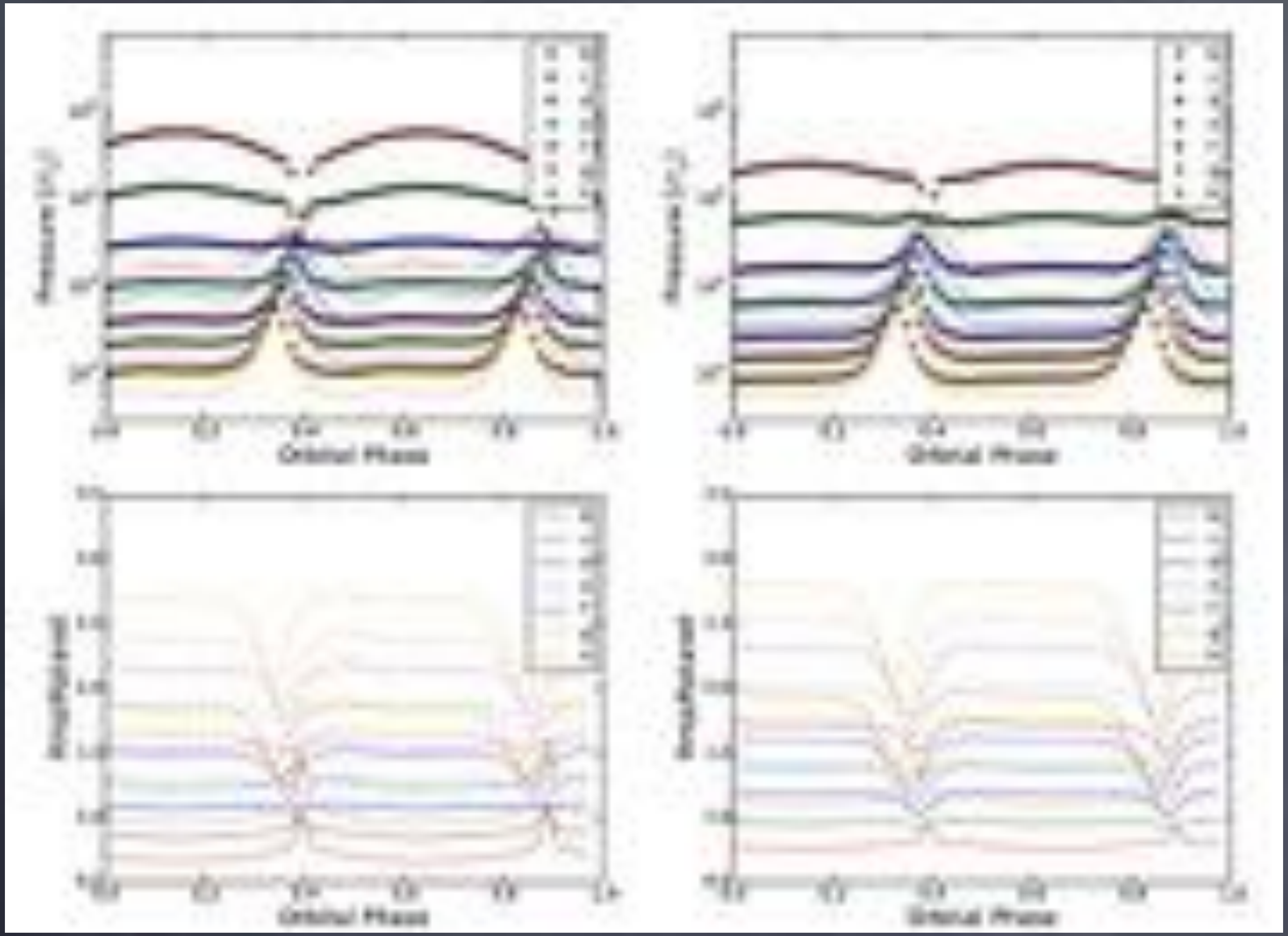


Garcia-Sage et. al 2017

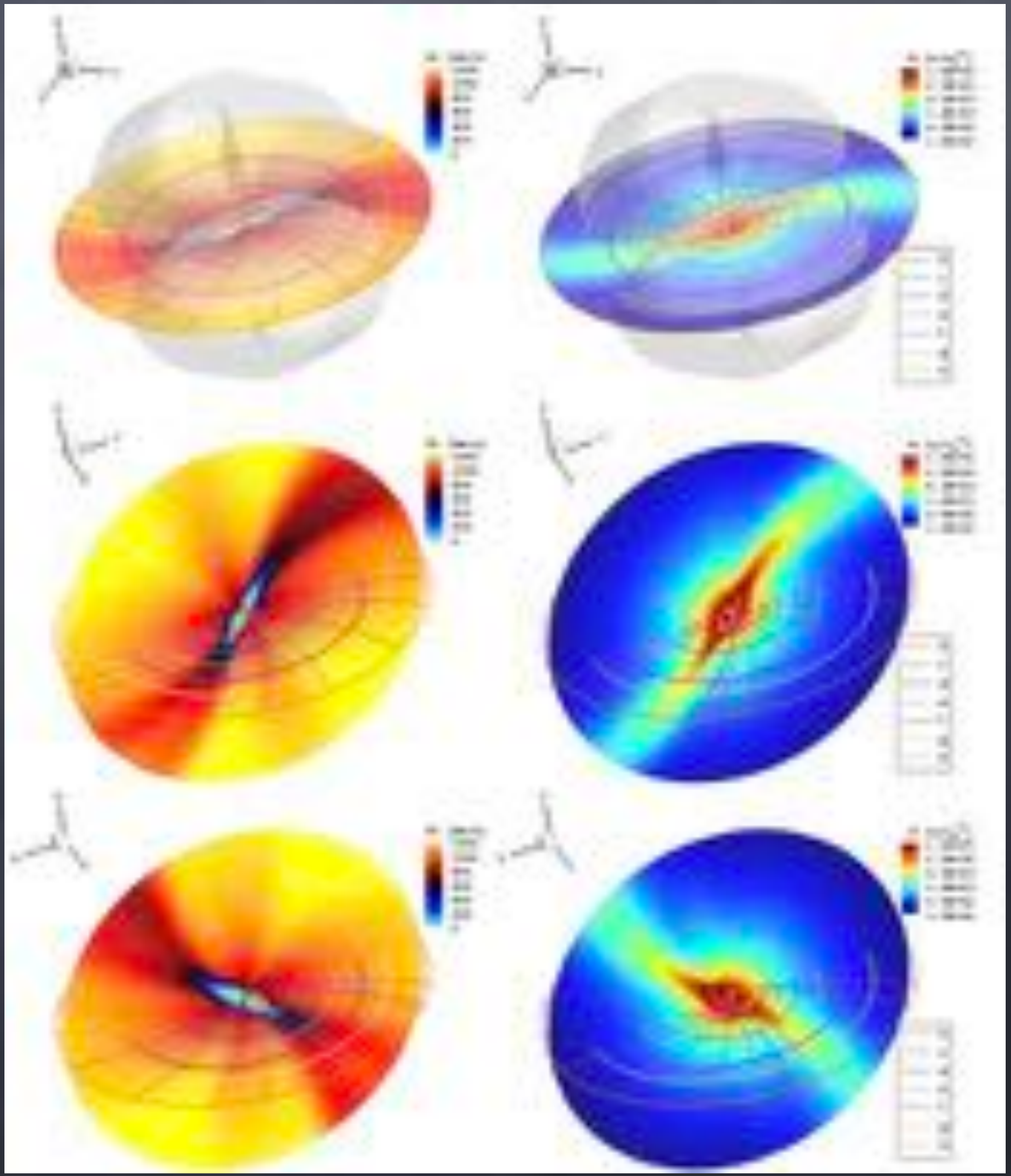


Dong et. al 2017

Trappist-1

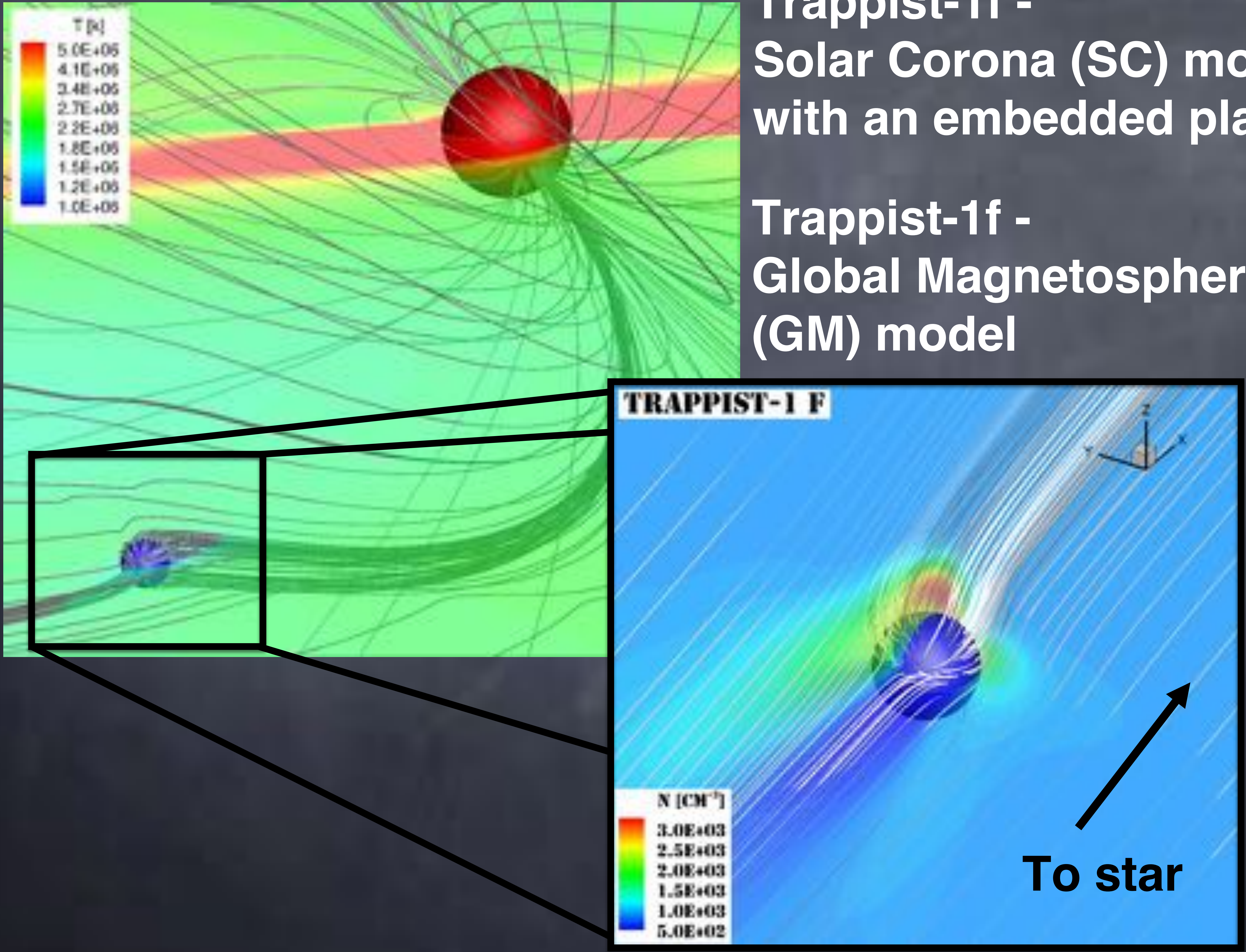


Garraffo et. al 2016

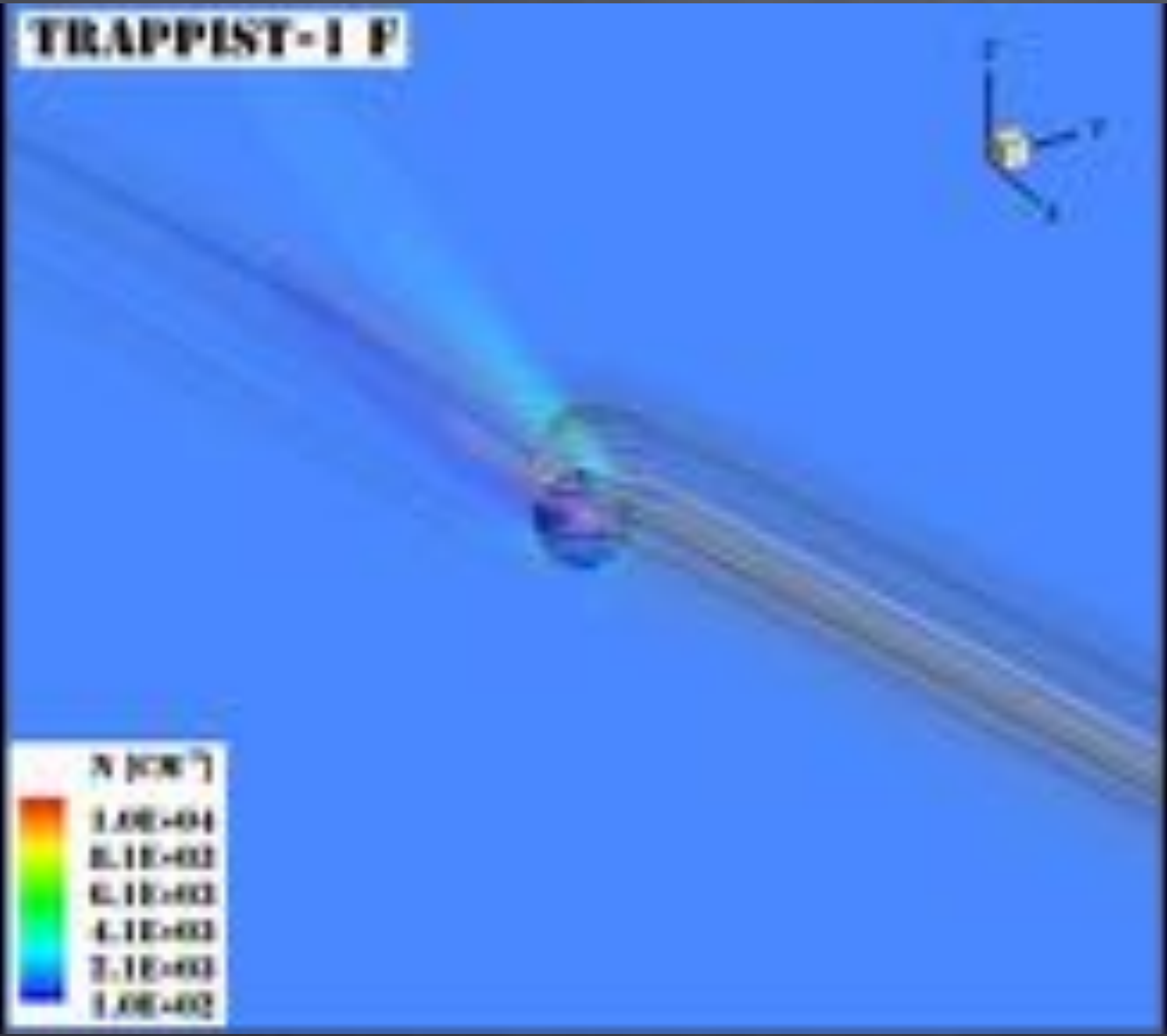


Trappist-1f - Solar Corona (SC) model with an embedded planet

Trappist-1f - Global Magnetosphere (GM) model

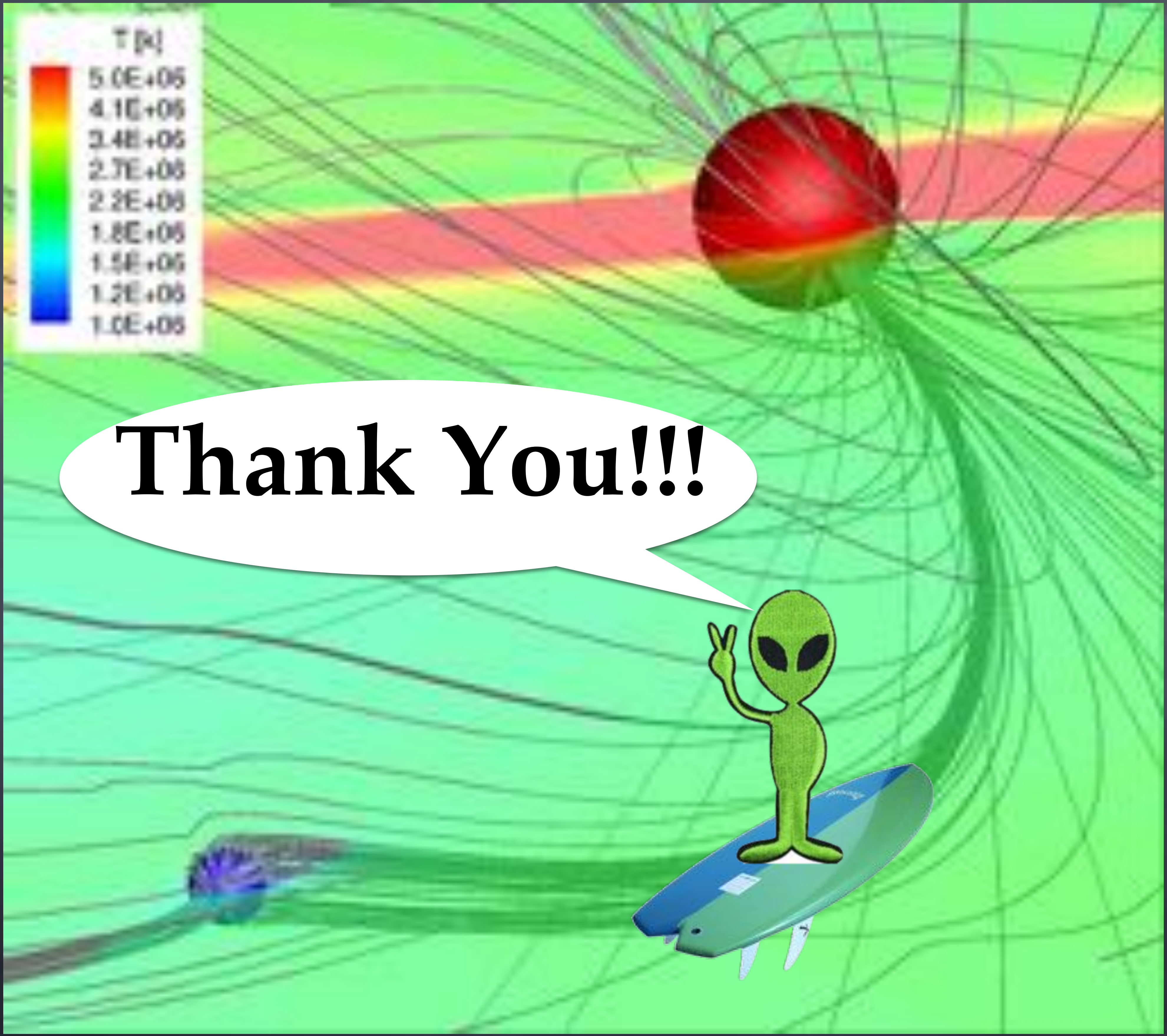


To star


TRAPPIST-1 F
z
y
x
N [cm⁻³]
1.0E+04
8.1E+03
6.1E+03
4.1E+03
2.1E+03
1.0E+02

To wrap things up...

I.Solar Vs. stellar physics
II. Stellar evolution
III. Coronae, winds, and astrosphers- in the context of the Sun and extrapolation to stars
IV. Stellar evolution and magnetized winds and their role in stellar mass-loss rates and stellar spin-down
V. Solar Vs. stellar Flares
VI.Exoplanets and planet habitability


T [k]
5.0E+06
4.1E+06
3.4E+06
2.7E+06
2.2E+06
1.8E+06
1.5E+06
1.2E+06
1.0E+06
Thank You!!!