The Fundamentals: Physical Origins of Particles in Circumstellar Space

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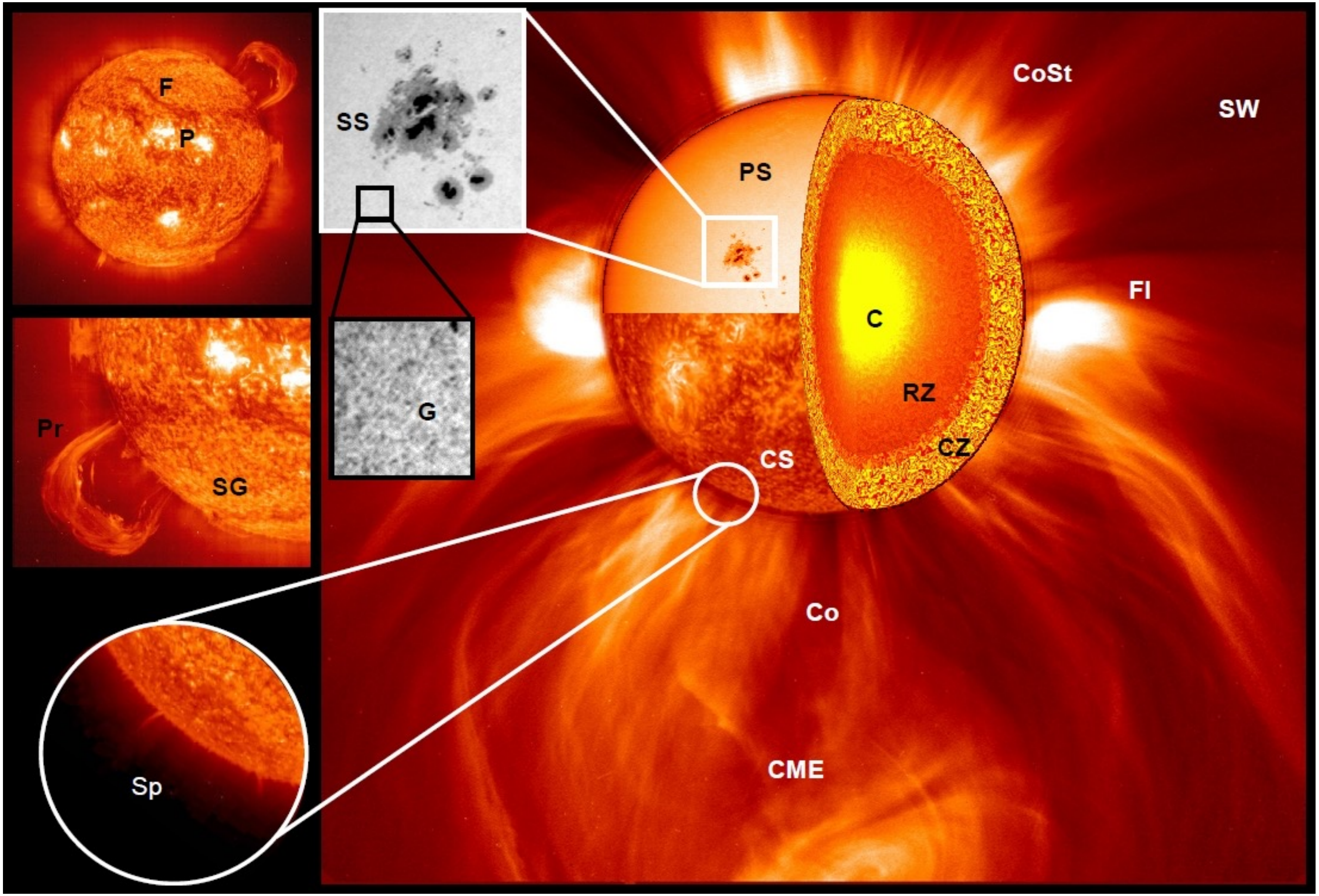
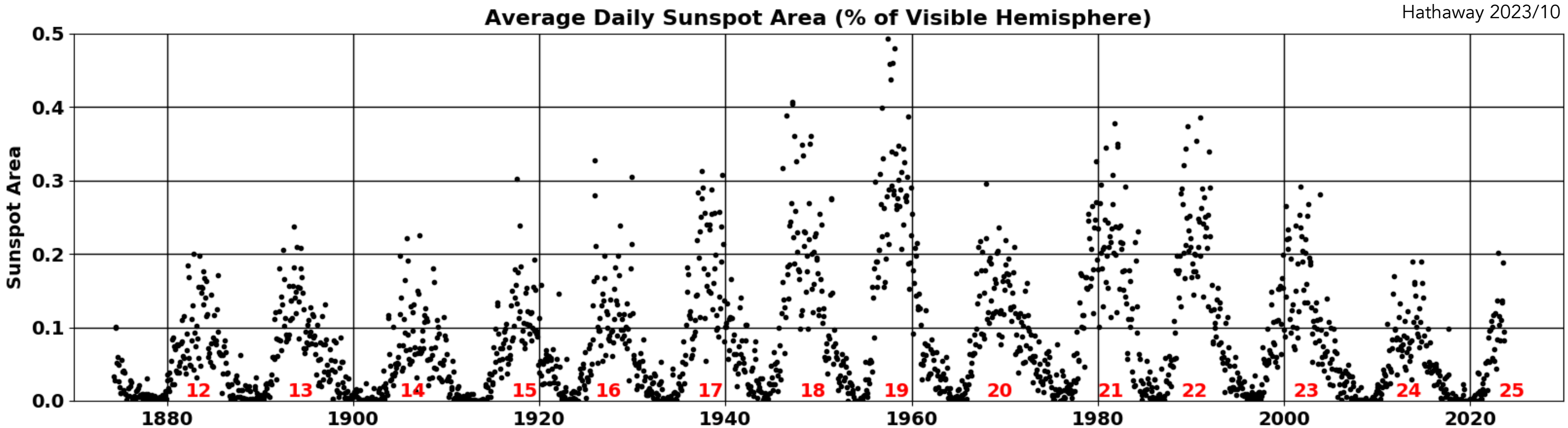
Different manifestations of the Sun's magnetic field

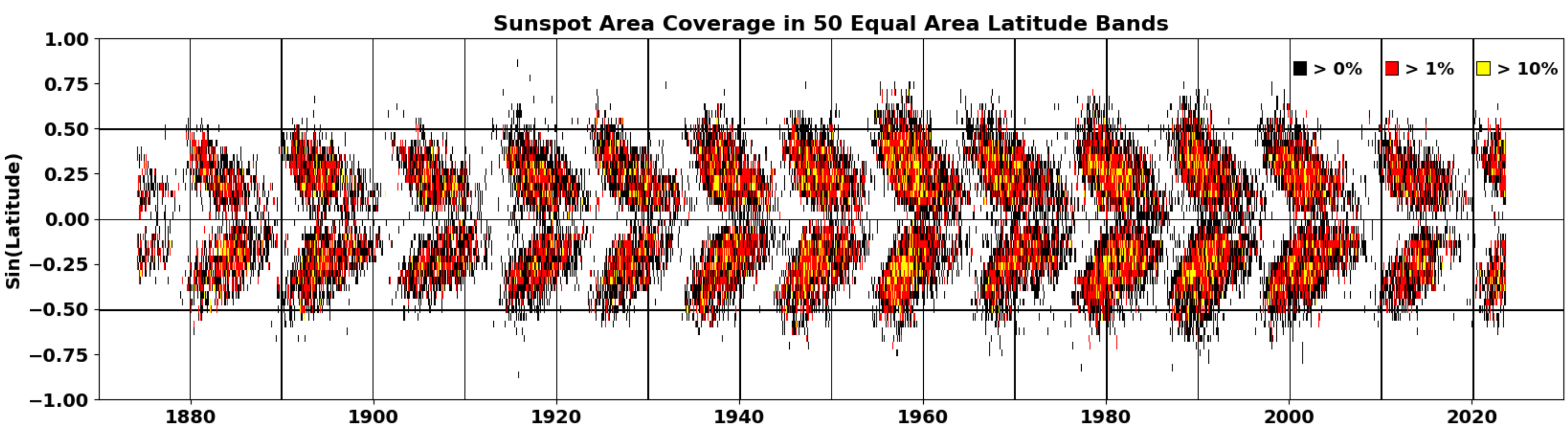


Temporal evolution

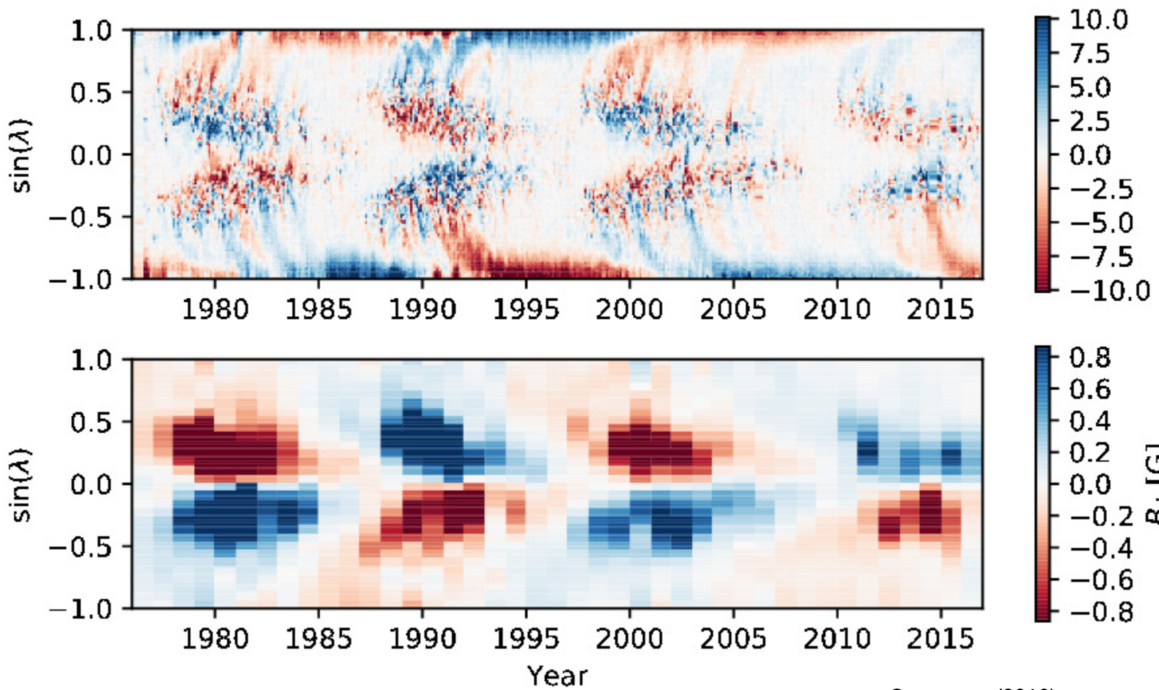
Sunspots (active regions) appear and disappear with a period of approximately 11 years (solar activity cycle).



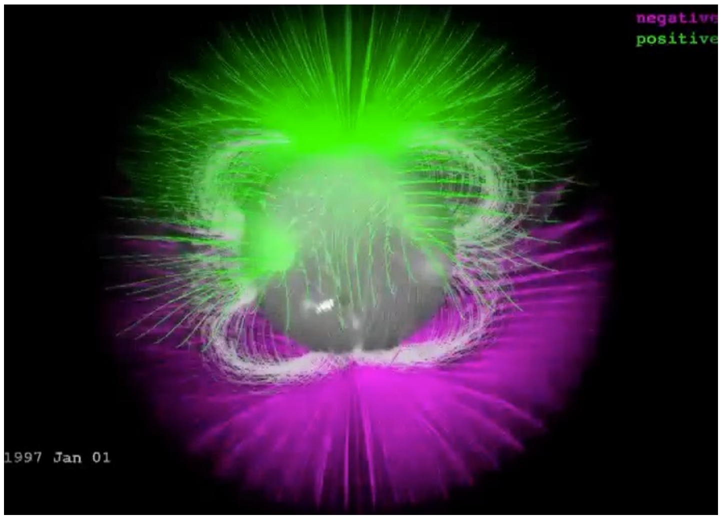
Sunspots migrate progressively toward the Solar equator (butterfly diagram).



Over the course of the activity cycle, the solar magnetic field reverses its **polarity** (Hale's Law).



Cameron+ (2018)



NASA Scientific Visualization Studio (SVS)

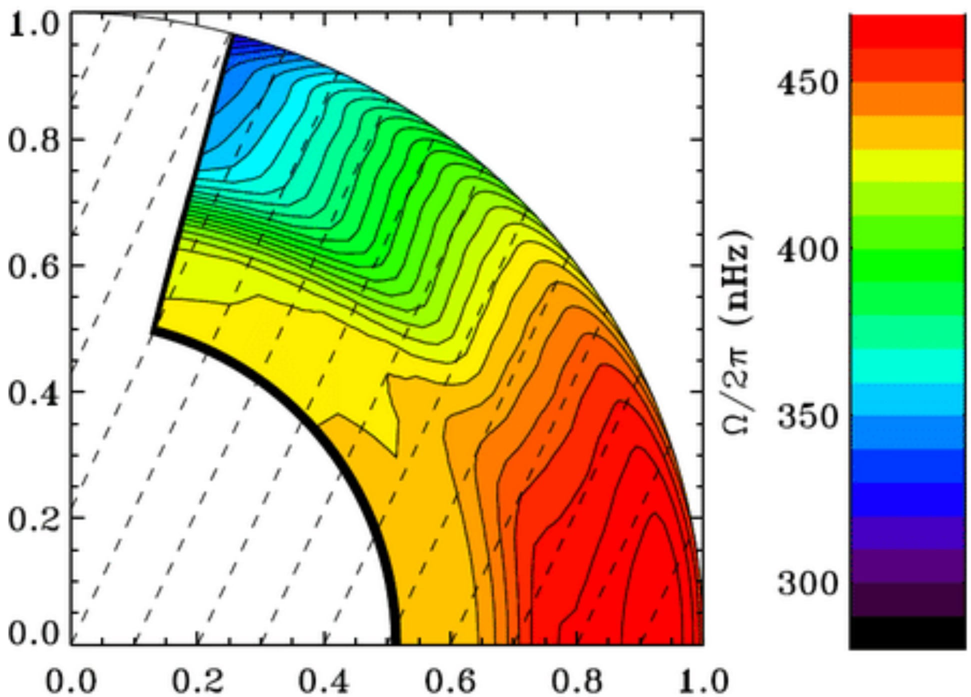
Magnetic Solar Cycle: Period required for the magnetic field to emerge with the same polarity (~22 years).

Solar (differential) rotation:

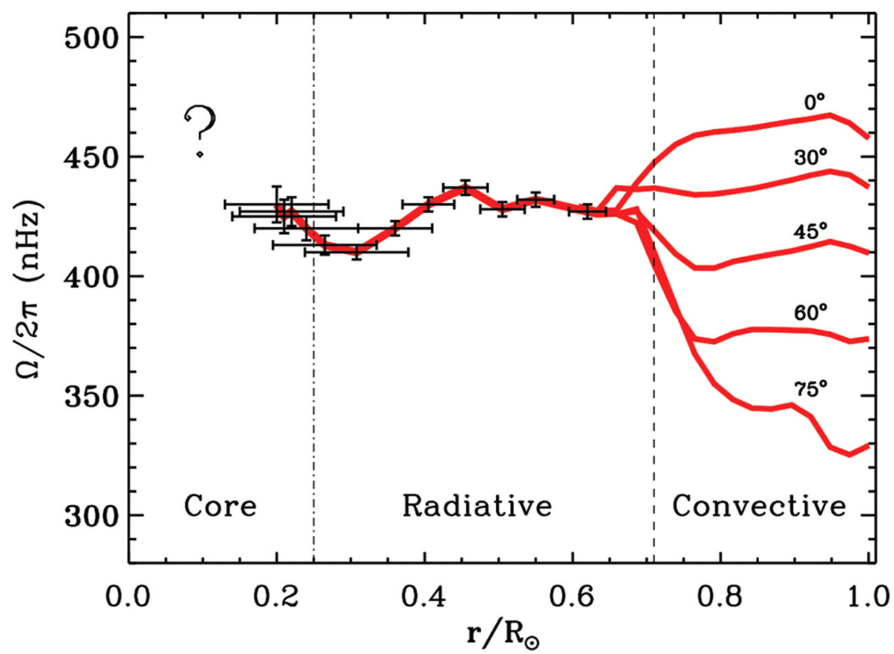
Surface: Latitudinal differential rotation (Equator: ~25 days, Poles: ~35 days)

Interior:
- Down to the base of the Convection Zone (~30% in depth): Radial differential rotation
- Radiative Zone: Solid body rotation (with a speed equivalent to 30° latitude)
- Core: Recent studies indicate faster rotation (~4x the RZ rotation rate; Fossat+2017)

Tachocline: Layer between the Radiative and Convective regions of the Sun



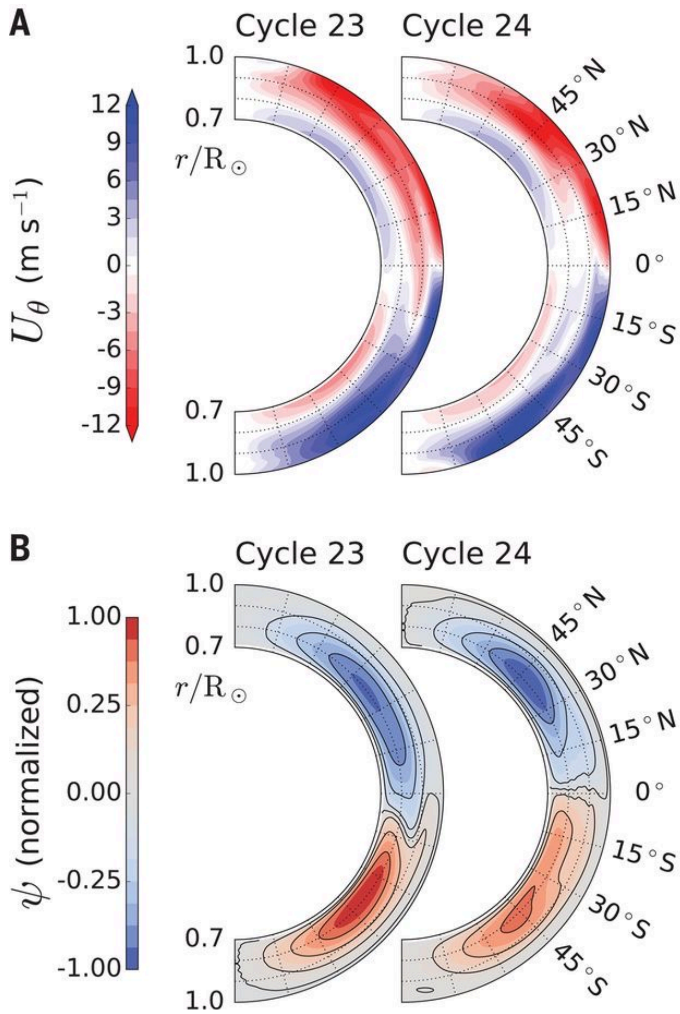
Howe (2009)



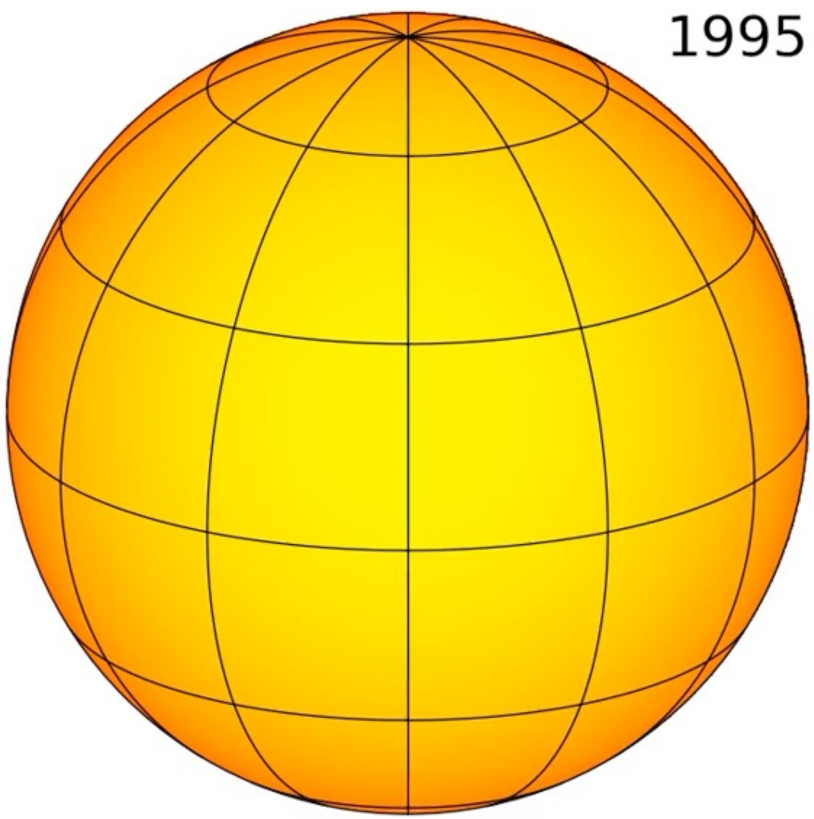
García+ (2007)

Solar meridional circulation:

Large-scale axisymmetric surface flow carrying material from the solar Equator to the poles. An internal return flow brings the material back to low latitudes (circulation cell).



Gizon+ (2020)



Credit: MPS (Z.-C Liang)

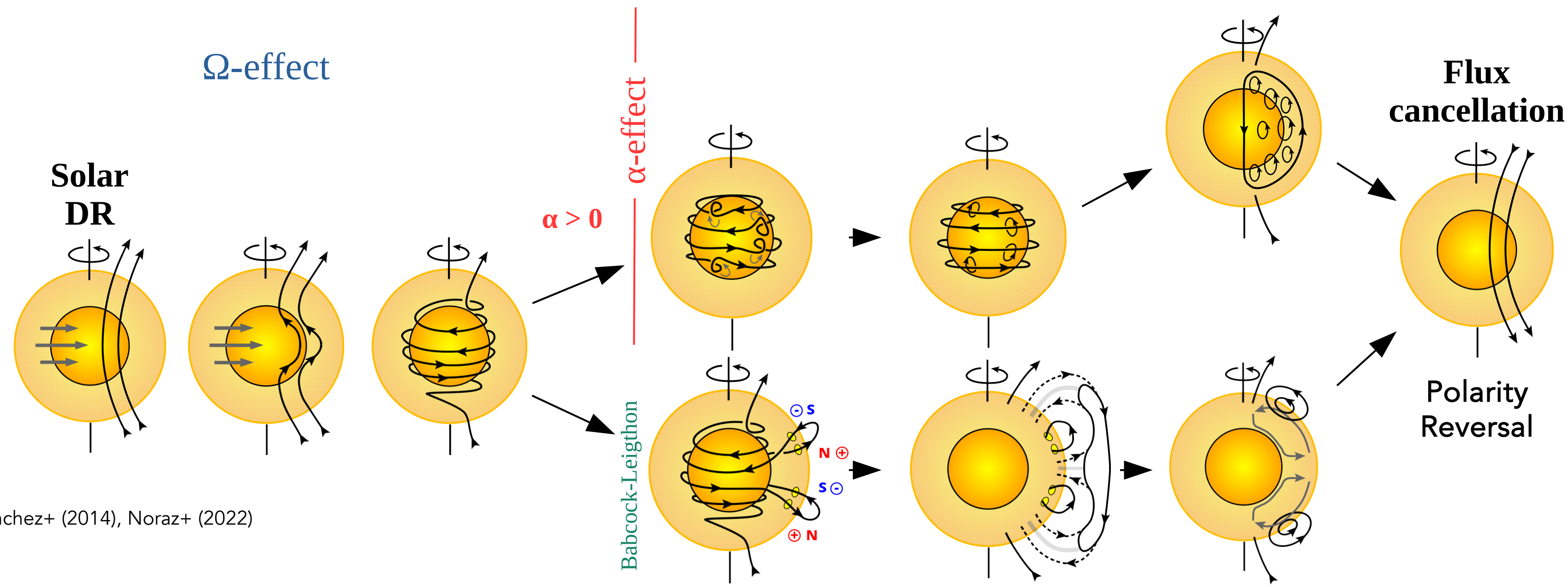
The meridional flow is believed to strongly influence the magnetic cycle time-scale (Hathaway 2003)

The solar dynamo

Models of the generation/evolution of the solar magnetic field should fulfill the following minimal requirements (Charbonneau 2020):

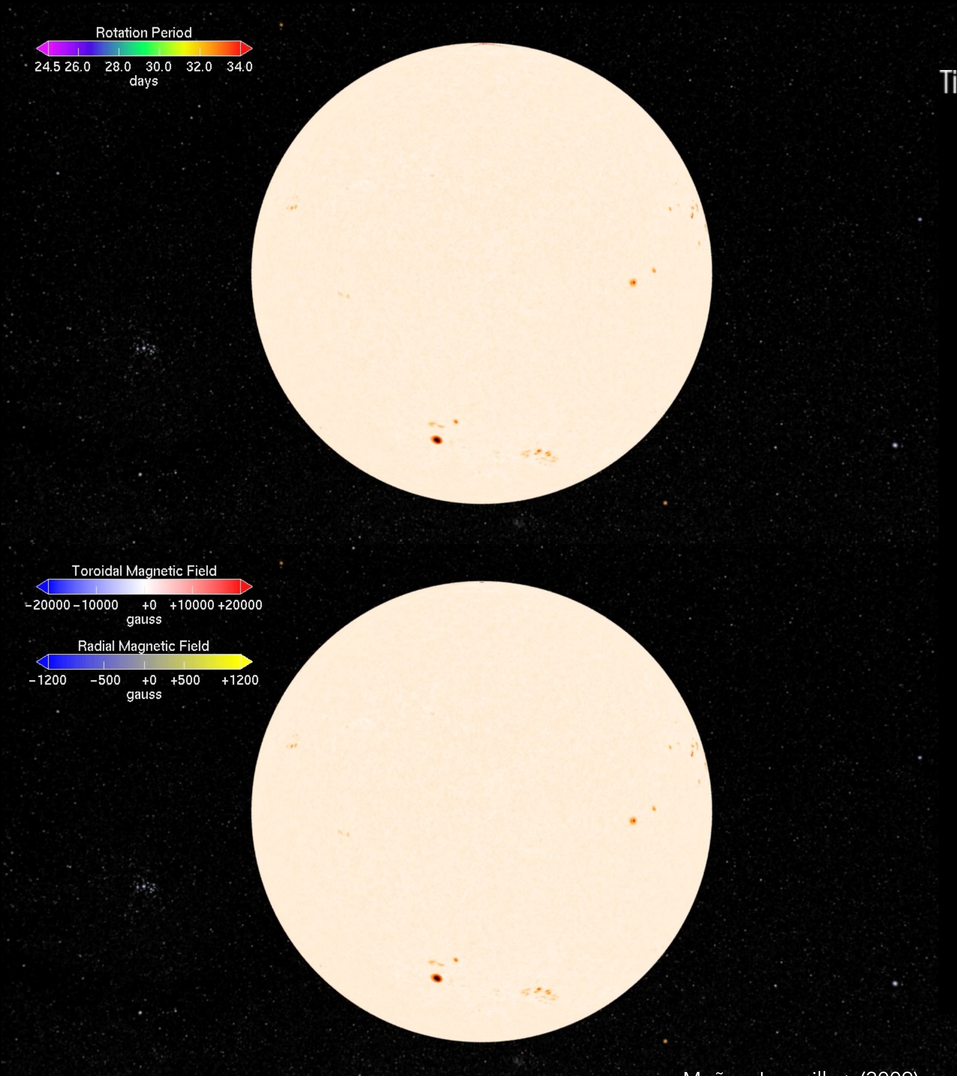
- Cyclic polarity reversals with a decadal half-period.
- Equatorward migration of the sunspot-generating deep toroidal field and its inferred strength.
- Poleward migration of the diffuse surface field.
- Observed π/2 phase lag between poloidal and toroidal components.
- Polar field strength.
- Observed antisymmetric equatorial parity.
- Predominantly negative (positive) magnetic helicity in the Northern (Southern) solar hemisphere.

The Parker (α-Ω) and Babcock-Leigthon (BL) mechanisms



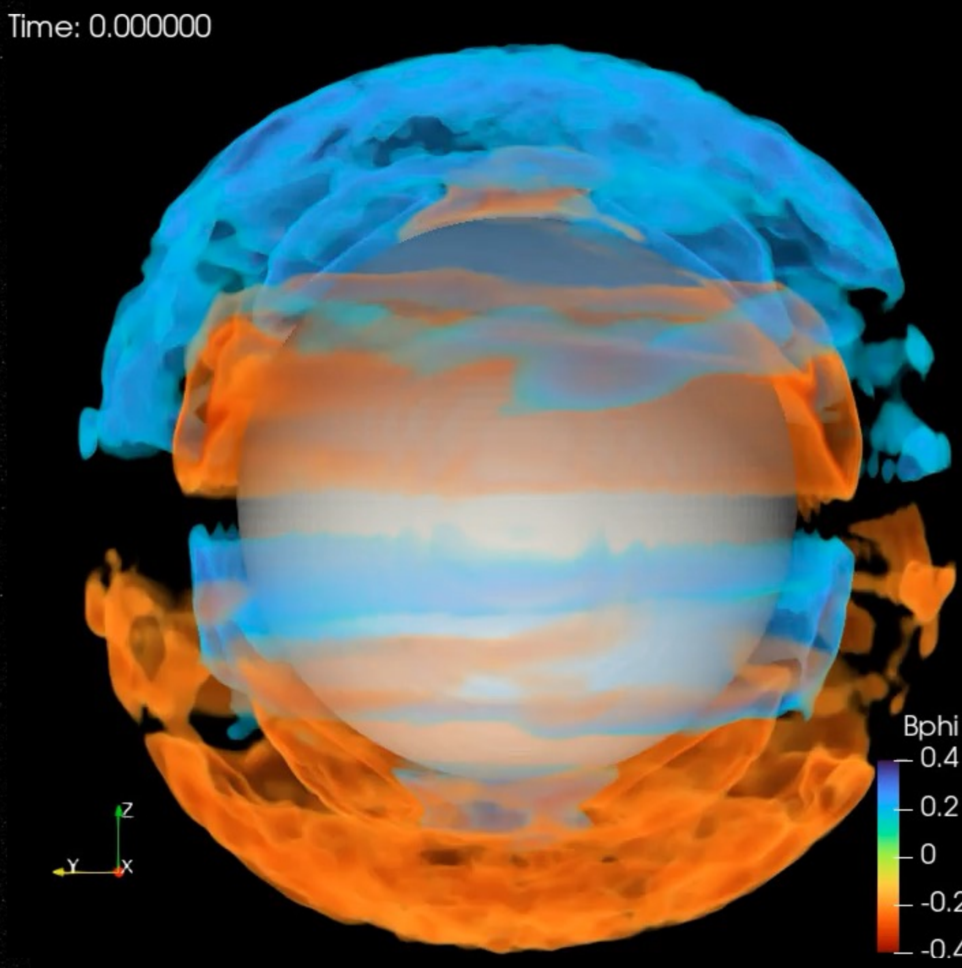
Sanchez+ (2014), Noraz+ (2022)

Examples of numerical solar dynamo models



Muñoz-Jaramillo+ (2009)

Kinematic BL Dynamo



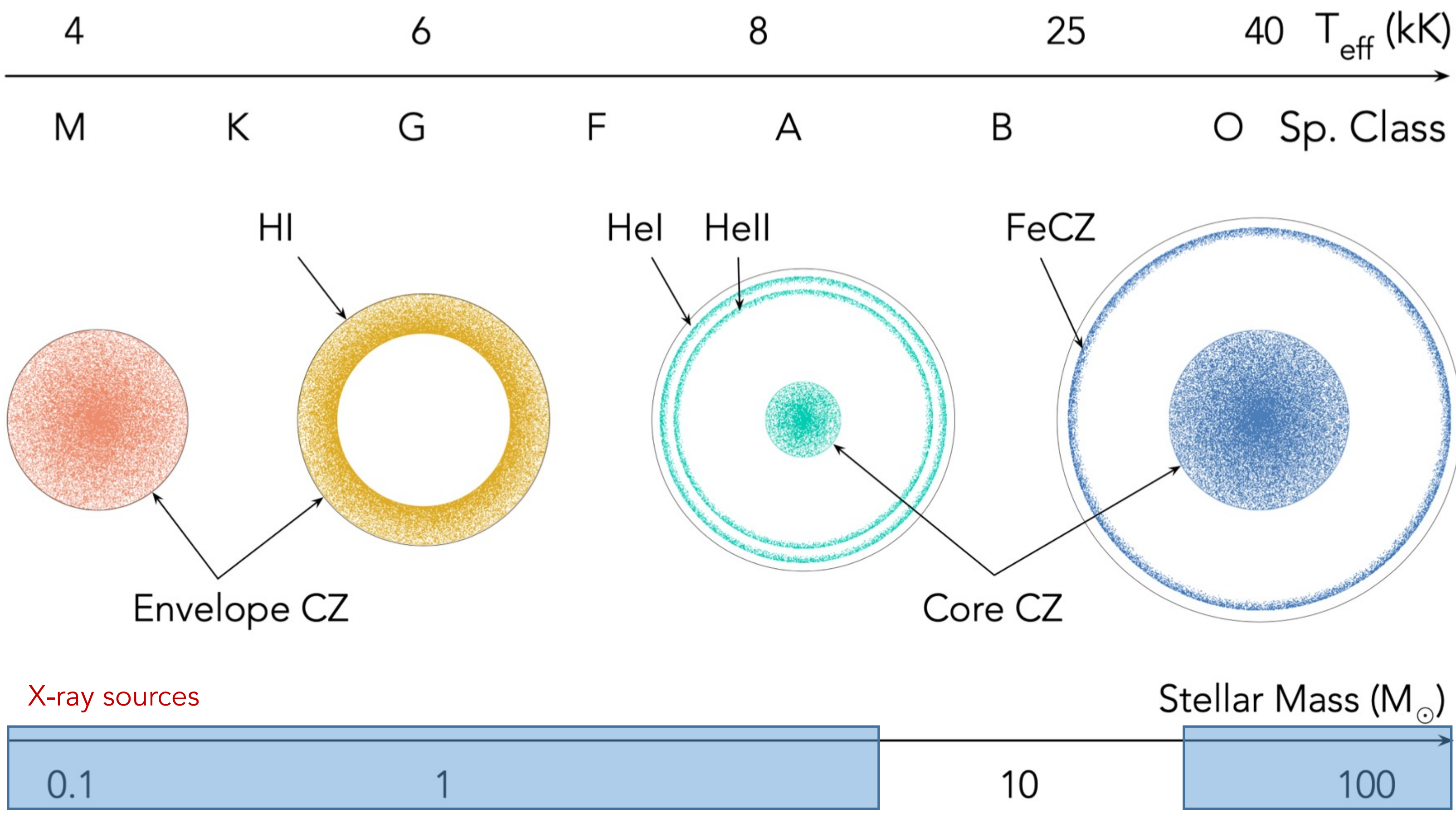
Guerrero+ (2023)

Convective Global Dynamo
(EULAG Code | 3D Anelastic MHD)

Magnetic field generation (Sun and other stars):

Dynamo action:

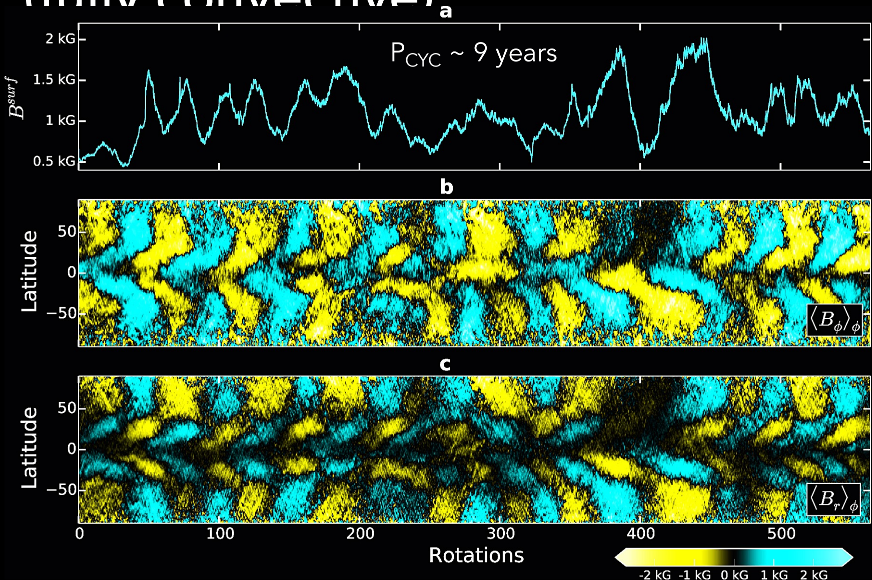
- A process converting a source of free energy (e.g., differential rotation, convection, turbulence) into magnetic energy.
- It continuously regenerates magnetic fields against decay/dissipation
- The field displays variability on relatively short time-scales

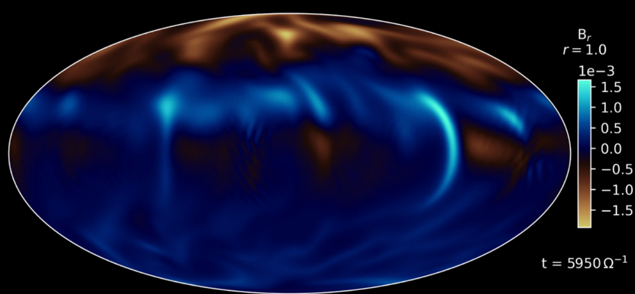


Credit: M Cantiello (MIAPbP: Stellar Magnetism)

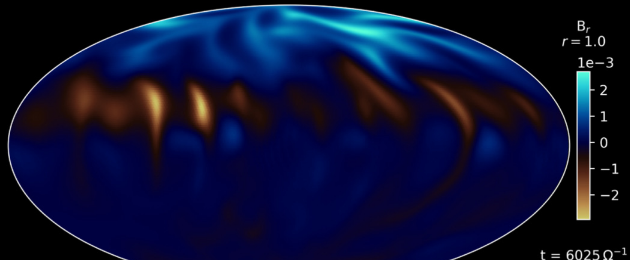
Dynamo simulations of Proxima Centauri (fully convective)

$M_\star \simeq 0.122\ M_\odot$
$R_\star \simeq 0.154\ R_\odot$
$P_{ROT} \simeq 83$ days

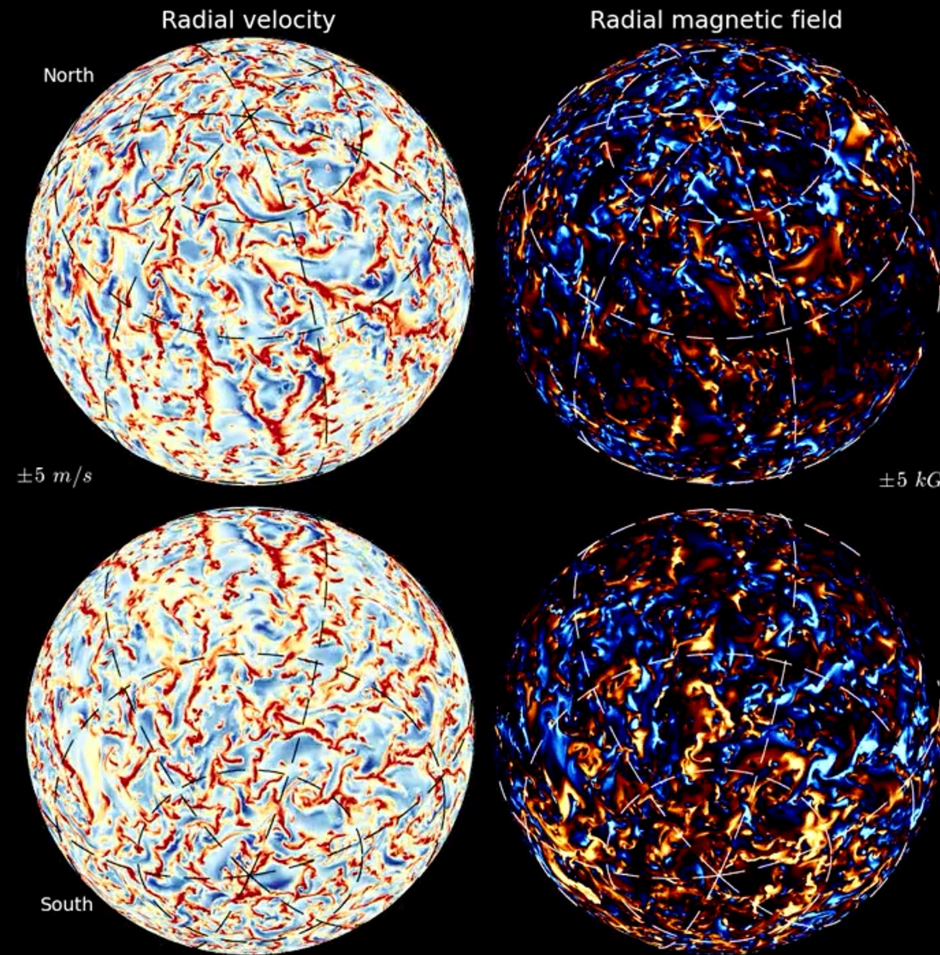




Brown+ (2020)



Turbulent Convection Dynamo
(Dedalus Code | 3D Anelastic MHD)



Yadav+ (2016)

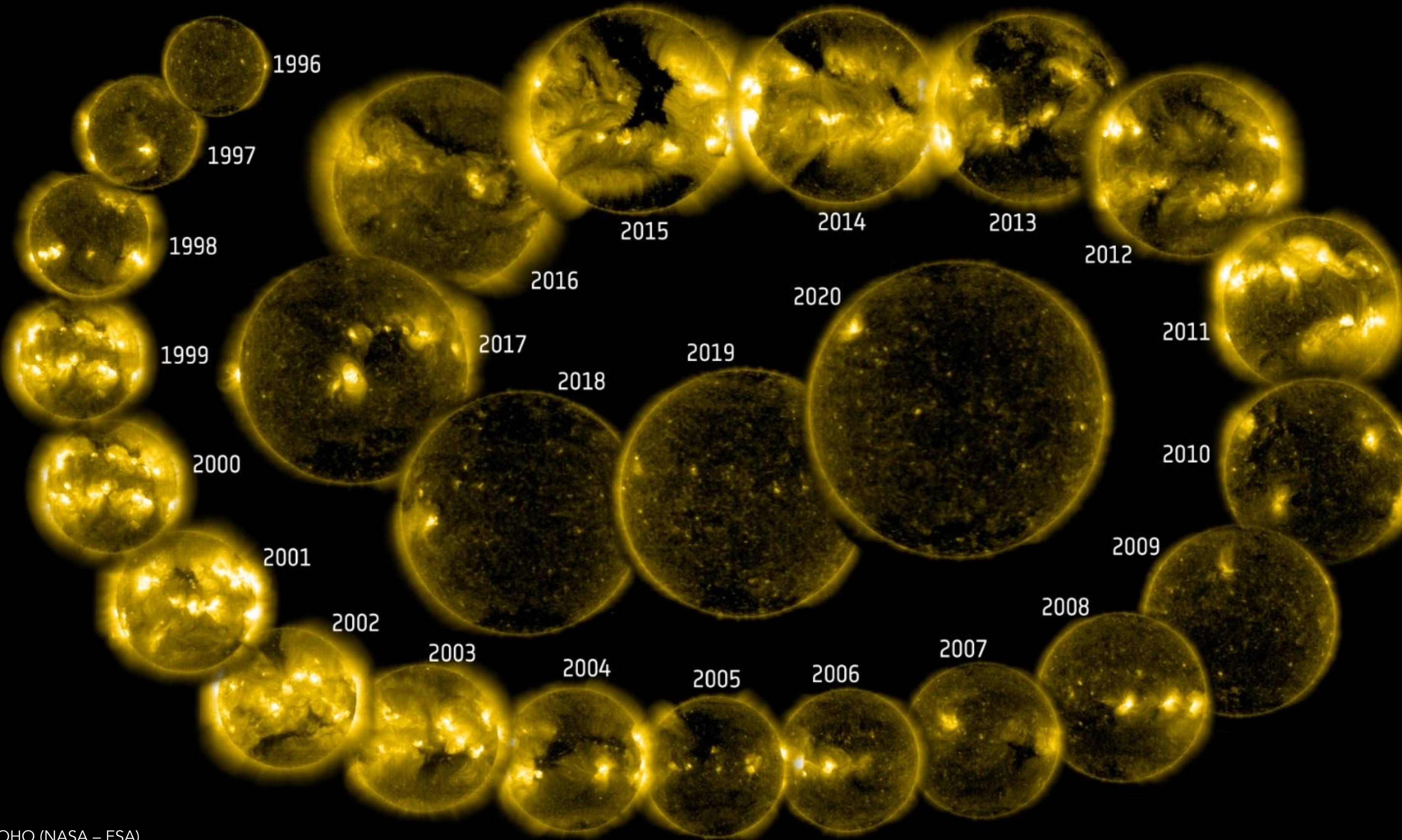
Turbulent Convection Dynamo
(MagIC Code | 3D Anelastic MHD)

The solar corona

Outermost part of the solar atmosphere.
Consists of a rarefied (~10^8 - 10^9 cm^{-3}) and hot (~10^6 K) plasma.

Emission centered around the Extreme Ultraviolet (EUV) and X-ray wavelengths.
Constitutes the base of the solar wind.

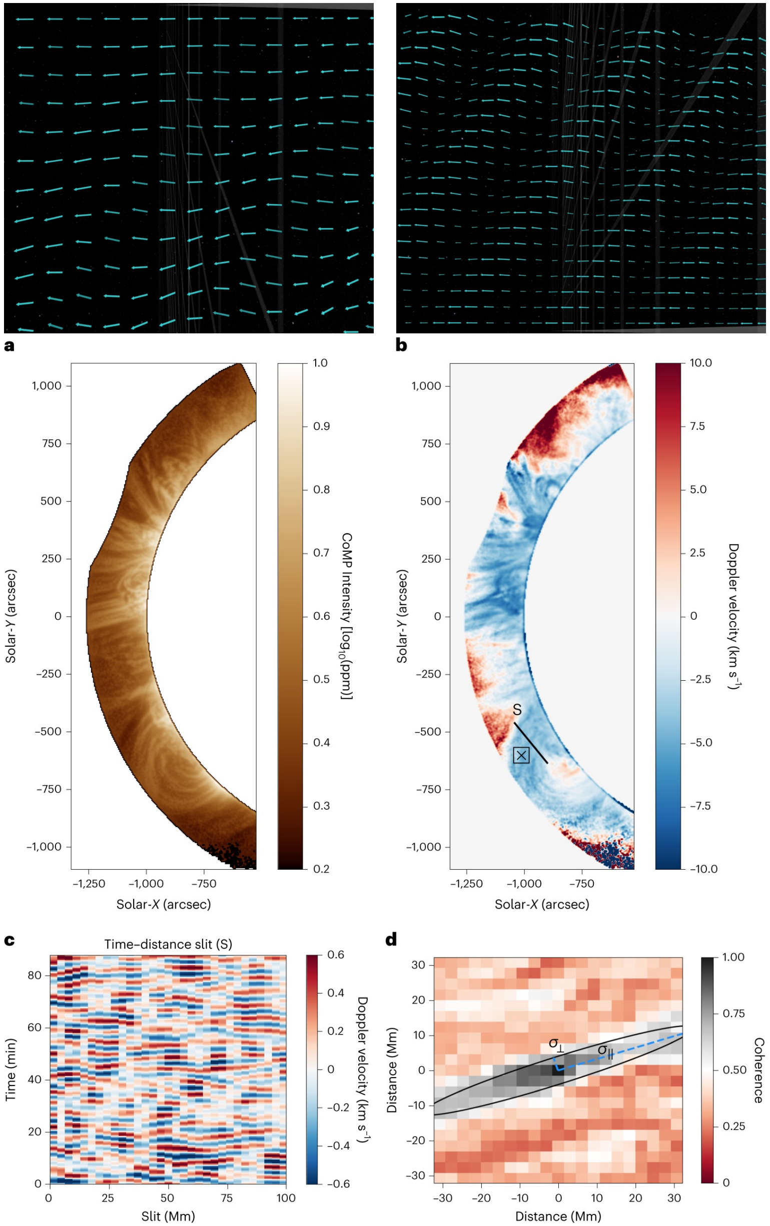
Coronal heating problem: unsolved but with consensus on a magnetic origin.



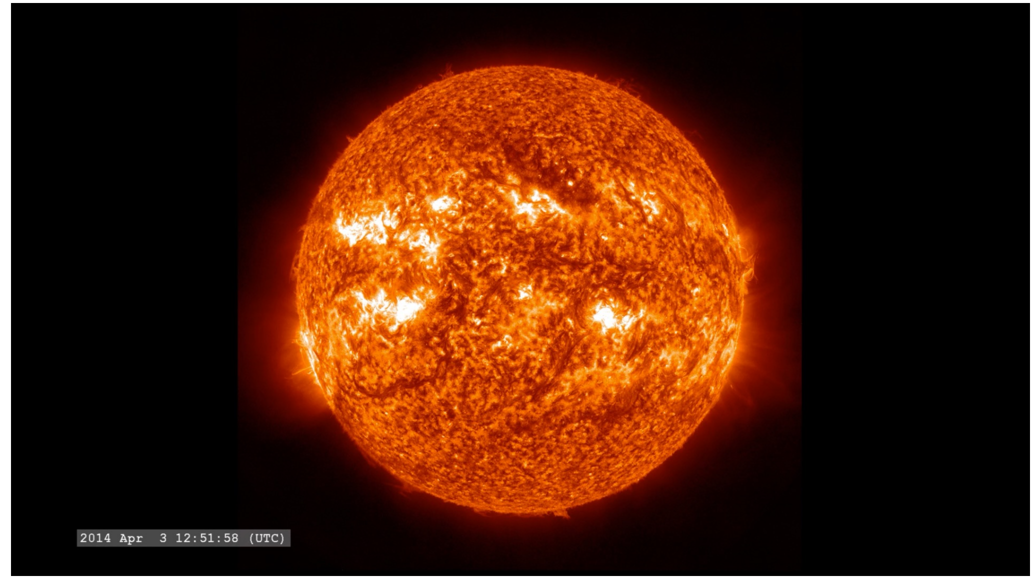
SOHO (NASA – ESA)

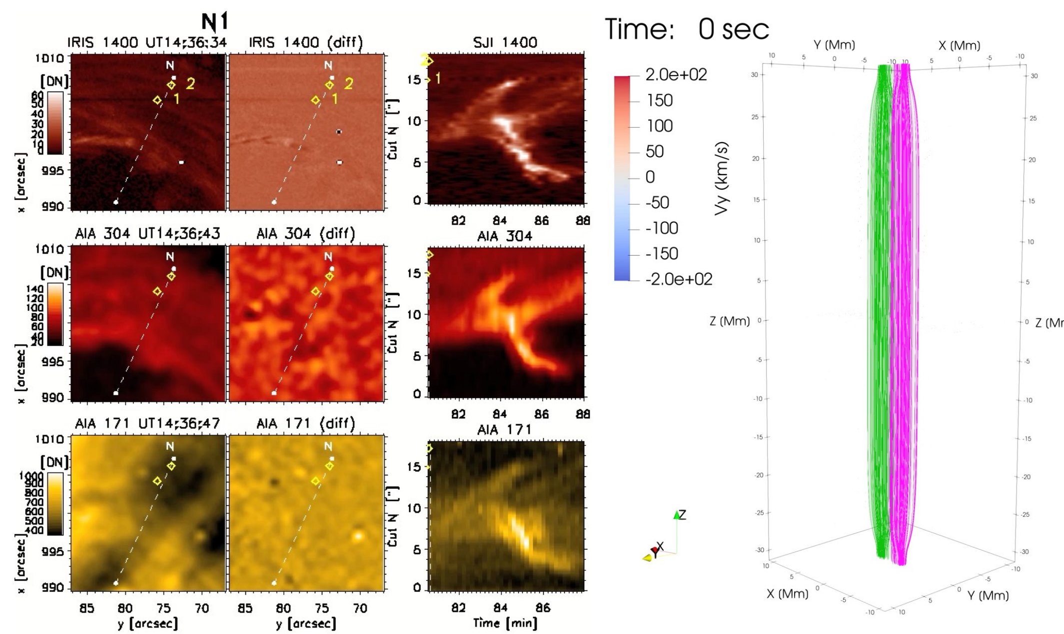
EUV images of the Solar Coronal Cycle
(Fe XV filter at 284 Å | T ~ 2.0×10^6 K).

Alfvén waves & Nanoflares (steady & impulsive heating)



Sharma & Morton (2023)



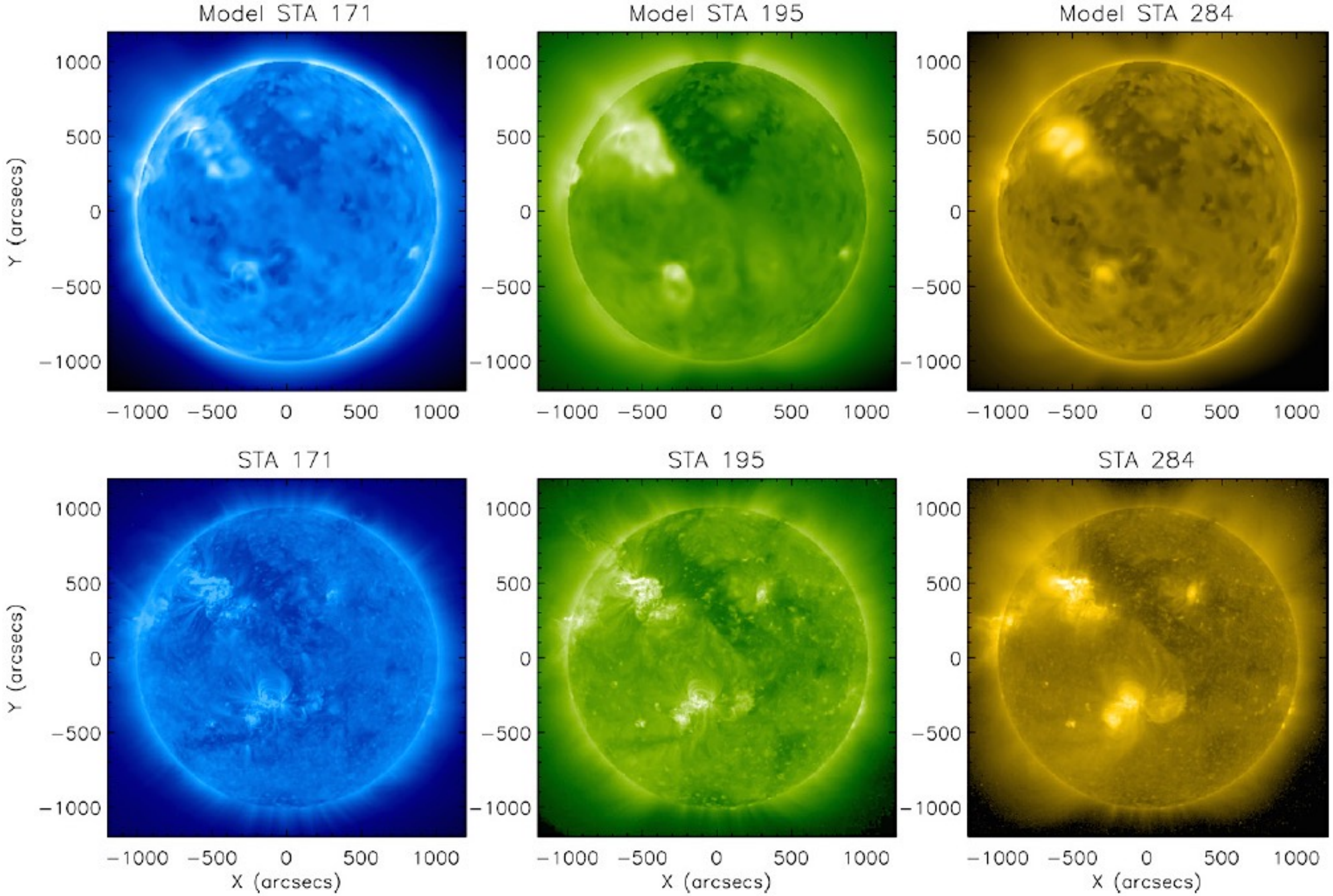


Antolin+ (2021)

The Alfvén Wave Solar Model (AWSoM)

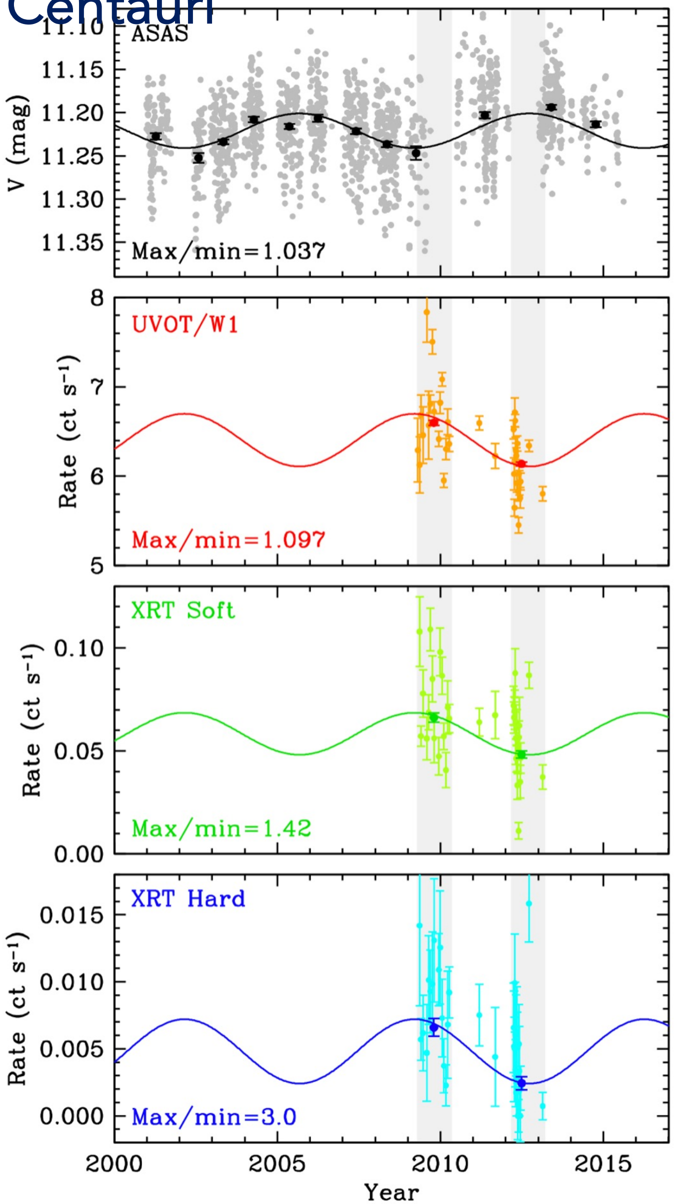
State-of-the-art 3D MHD code incorporating Alfvén wave turbulence dissipation + radiative cooling + electron heat conduction… Driven by the surface magnetic field.

Part of the Space Weather Modelling Framework – SWMF (Gombosi+ 2018)

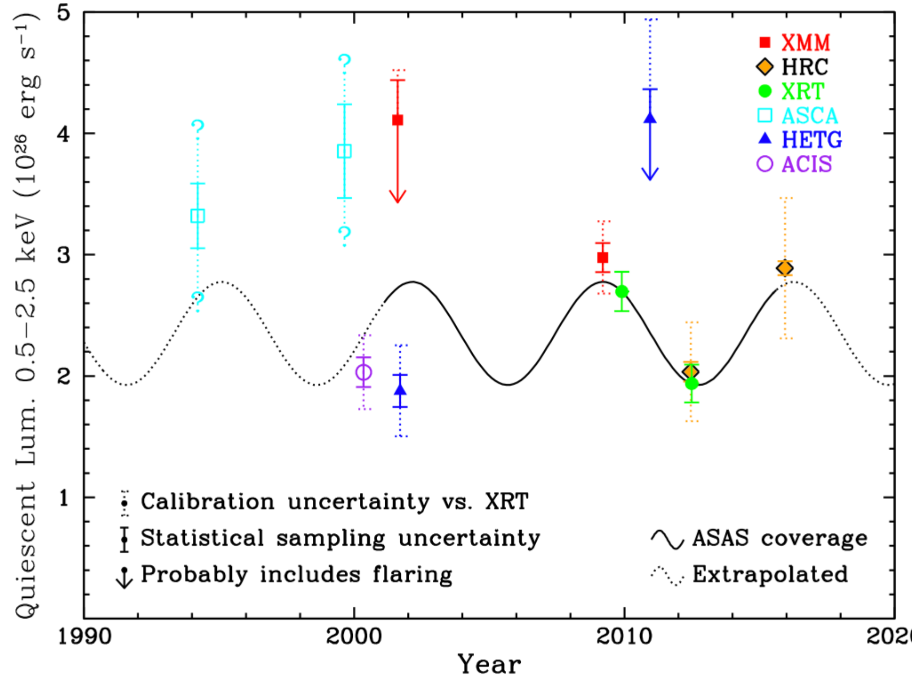


van der Holst et al. (2014)

The Activity Cycle of Proxima Centauri



Wargelin+ (2017)



The X-ray Stellar Cycle of Proxima Cen

Show affiliations

Wargelin, Bradford ; Saar, Steven ; Do Nascimento, José-Dias

Stellar cycles in fully convective M stars were generally thought to be impossible until a few years ago, when ~8 examples were discovered from analysis of ASAS photometric monitoring data. Proxima Cen (dM5.5) was one of those stars, and also had (limited) supporting evidence for a cycle from Swift observations in the X-ray and UV, where emission is more directly tied to magnetic activity cycles (in contrast to spot/plage countereffects in photometry) and displays much larger cycle amplitudes. With several additional years of data, now spanning 8 epochs over more than 12 years, we find that an ~8-year cycle is clearly apparent in both X-rays and the UVOT/W1 band, and provide an update on the previously suggested association of X-ray cycle amplitude with Rossby number.

Publication: AAS High Energy Astrophysics Division meeting #20, id. 116.64. Bulletin of the American Astronomical Society, Vol. 55, No. 4 e-id 2023n4i116p64

Pub Date: September 2023

Bibcode: 2023HEAD...2011664W

The solar wind

Persistent flow of plasma (protons, electrons, magnetic field) propagating (radially) outward from the hot solar corona into interplanetary space. Proposed by E. Parker (1927-2022) in 1958.

NASA Scientific Visualization Studio (SVS)

Defines the structure of the Heliosphere

Classically divided in two components:

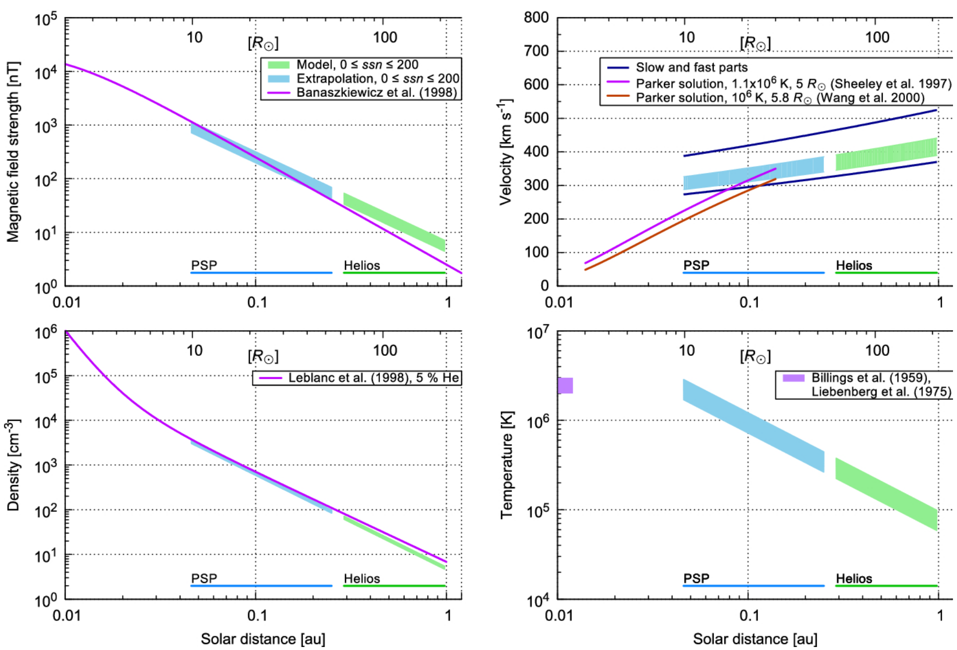
Fast (~400 – 800 km/s) | Slow (~250 – 400 km/s) [at 1au]

Differences extend well beyond their speeds:

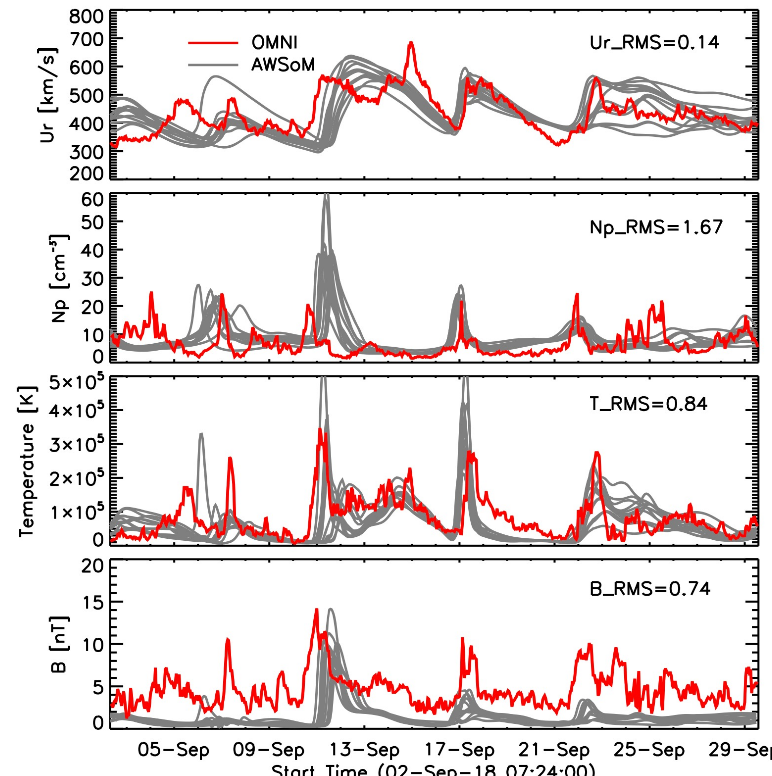
- Origin Fast: Coronal holes | Slow: Streamers near the current sheet [?]
- Densities Fast: low [a few cm^{-3} at 1 au] | Slow: high [tens of cm^{-3} at 1 au]
- Composition: Fast: (nearly) Photospheric | Slow: ↑ low-FIP elements [x3-4]
- Kinetic properties

AWSoM Validation [1 au]

Radial profiles

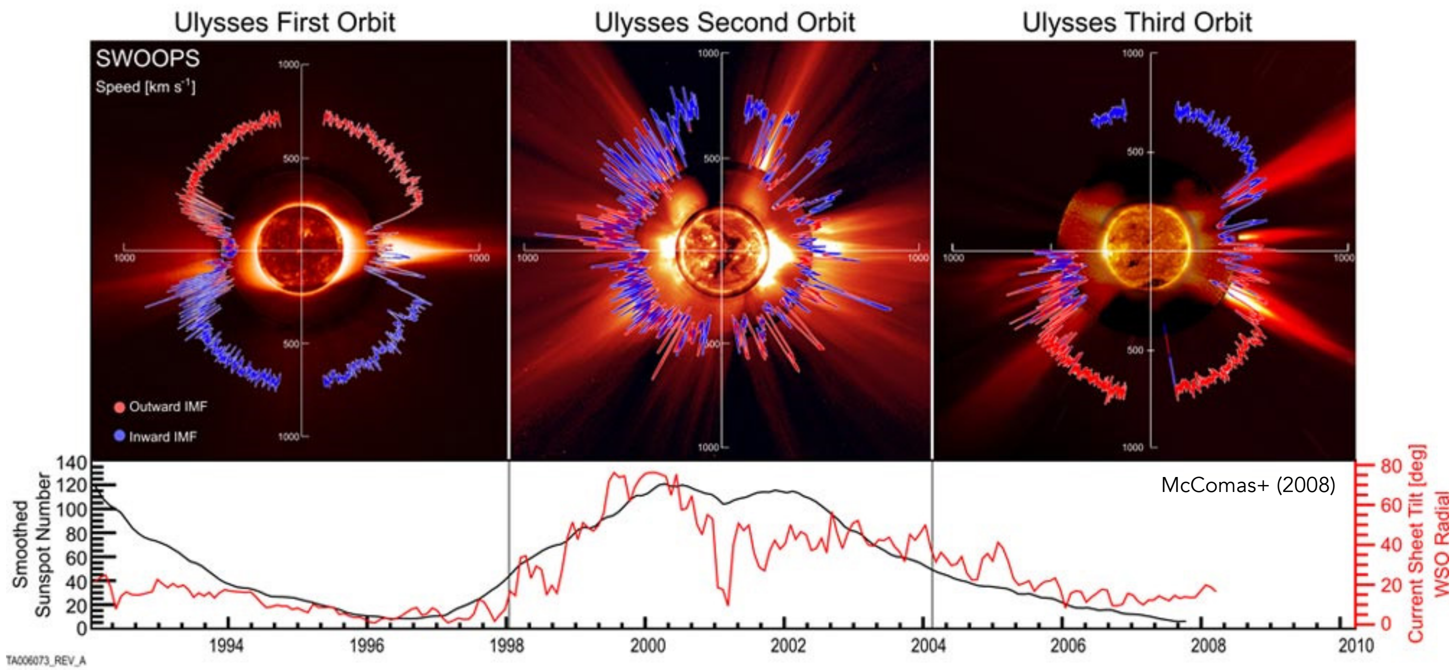


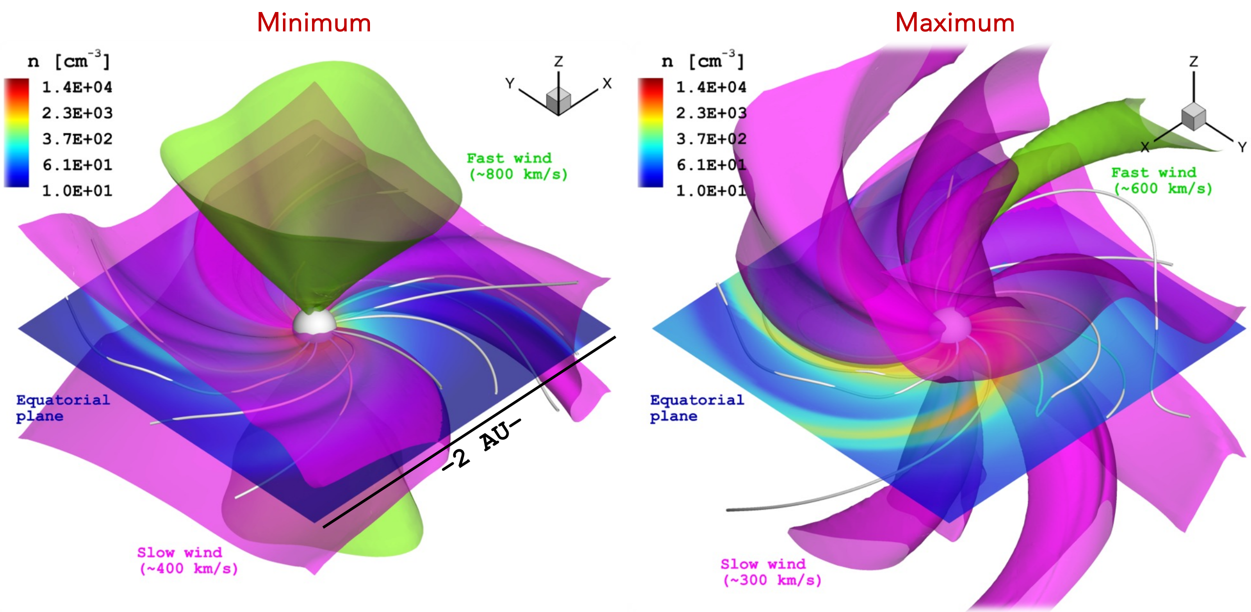
Temmer (2021)



Sachdeva+ (2019)

The structure of the solar wind is dictated by the solar (large-scale) magnetic field.

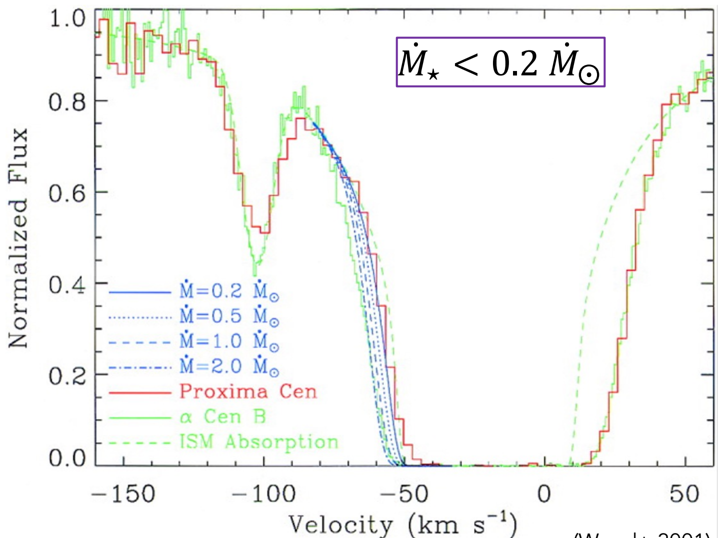




Alvarado-Gómez+ (2016)

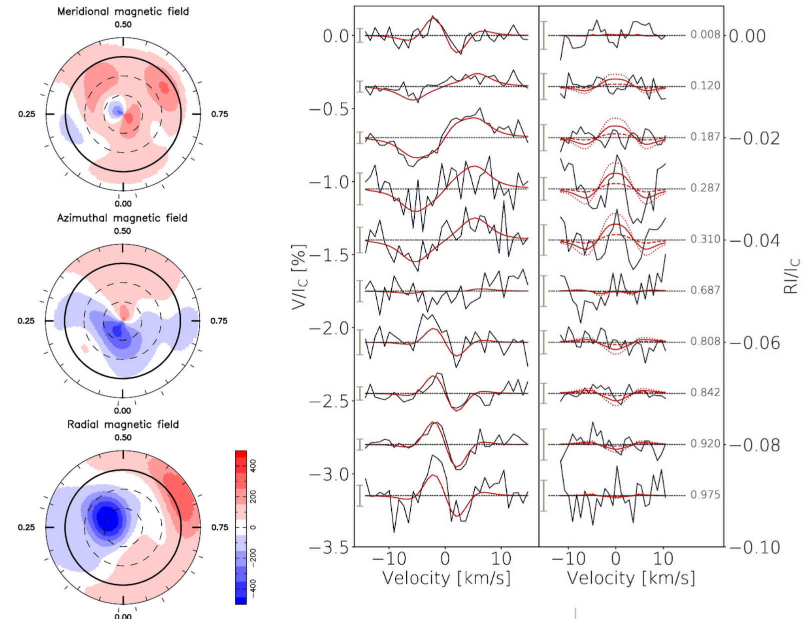
The stellar wind of Proxima Centauri

Lyman-α Astrosphere (STIS/HST)

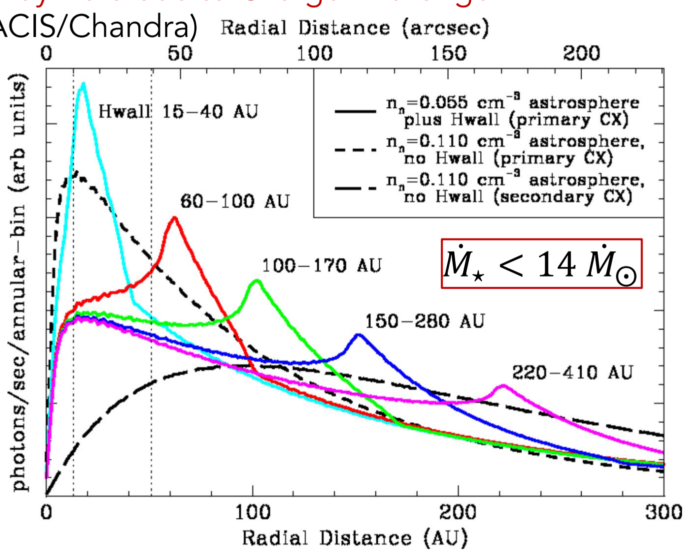


(Wood+ 2001)

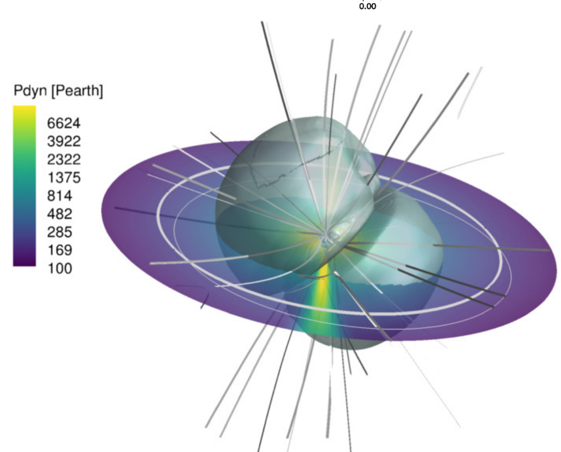
Large-Scale Magnetic Field Reconstruction
(HARPSpol + ZDI | Klein+ 2021)



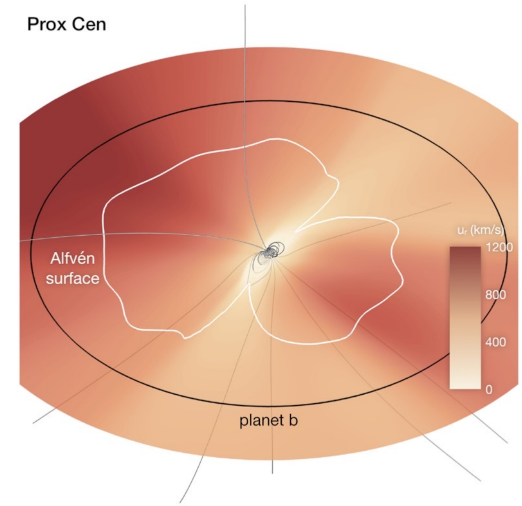
X-ray Halo due to Charge-Exchange
(ACIS/Chandra)



(Wargelin & Drake 2002)



(Garraffo+ 2016, 2022)



(Kavanagh+ 2021)

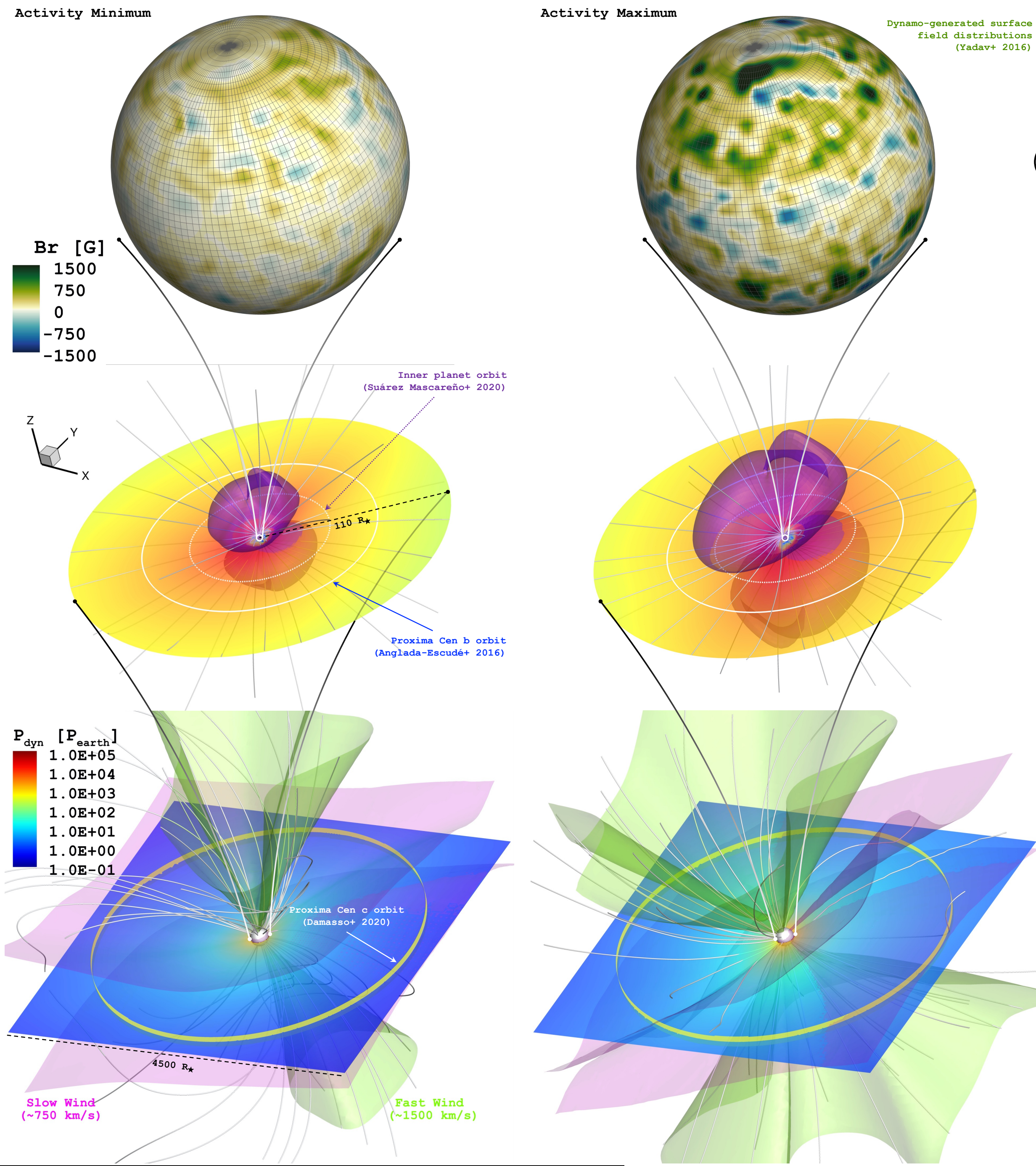
Stellar Wind Models
(AWSoM/SWMF | 3D MHD)

Julián D. Alvarado-Gómez | KISS Workshop | 06.11.23

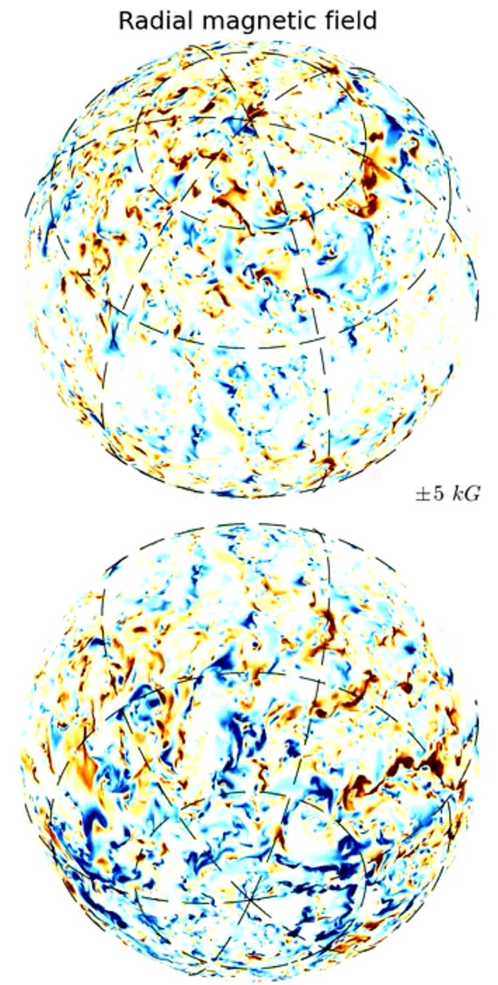
Stellar Wind Variability (Magnetic Cycle)

(AWSoM/SWMF | Alvarado-Gómez+ 2020)

$\Delta|B_R| = 65\%$ $\Delta\dot{M}_\star = 3$



(Alvarado-Gómez+ 2020a)



(Yadav+ 2016)

Energetic transient events:

Explosive phenomenon in the corona where a large amount of energy is suddenly released (heating, radiation, particle acceleration, plasma motions…)

Flares | Coronal Mass Ejections (CMEs) | Energetic Particles (EPs)

Examination of the possible energy sources shows that the magnetic field is the only plausible driver of these events.

Energy sources (solar flare)

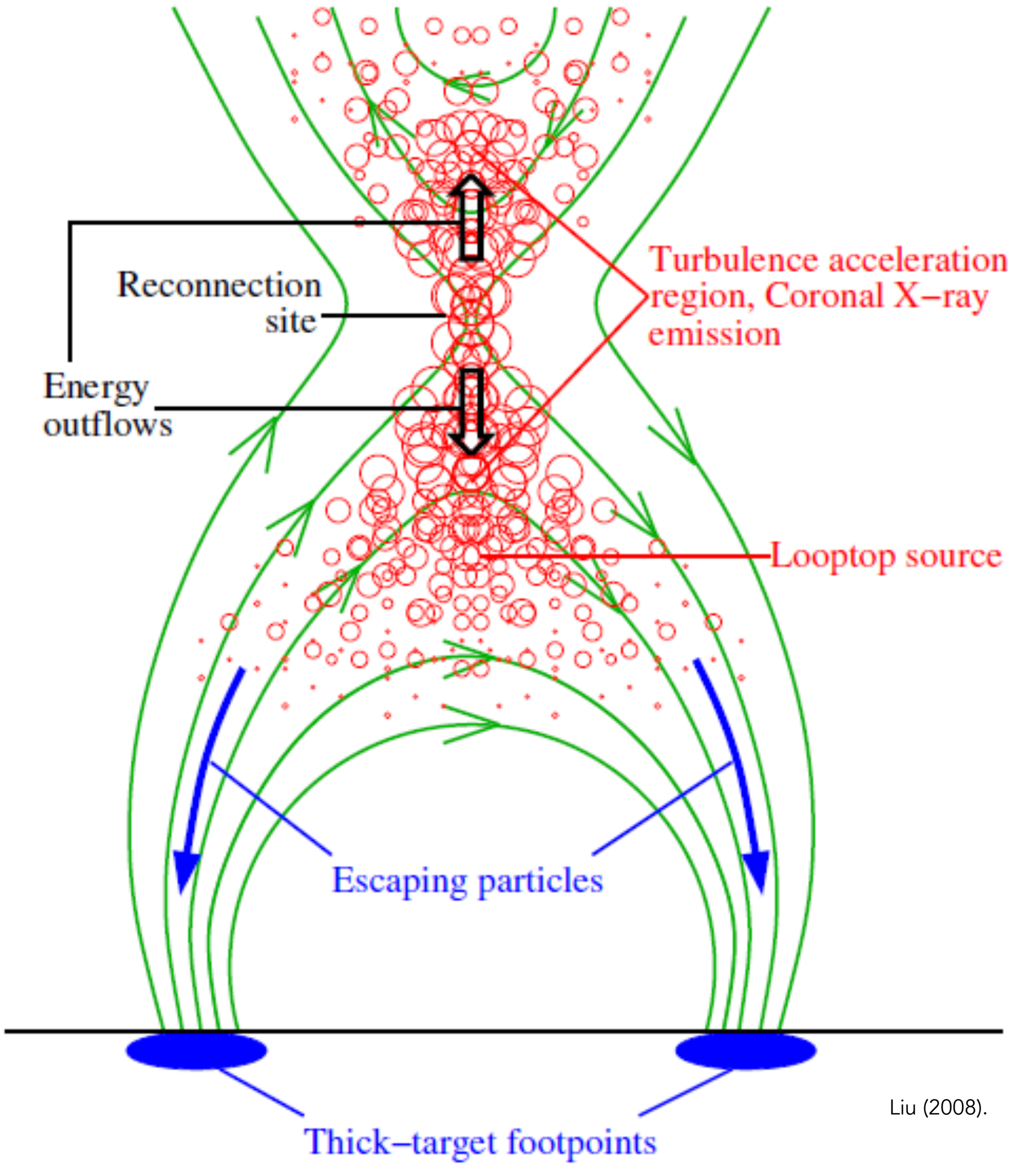
Typical values:

$$\left.\begin{aligned} E &\sim 10^{32}\mathrm{erg} \\ V \sim d^3 &\sim 10^{30}\mathrm{cm}^3 \end{aligned}\right\} 100\ \mathrm{erg}\ \ \mathrm{cm}^{-3}$$

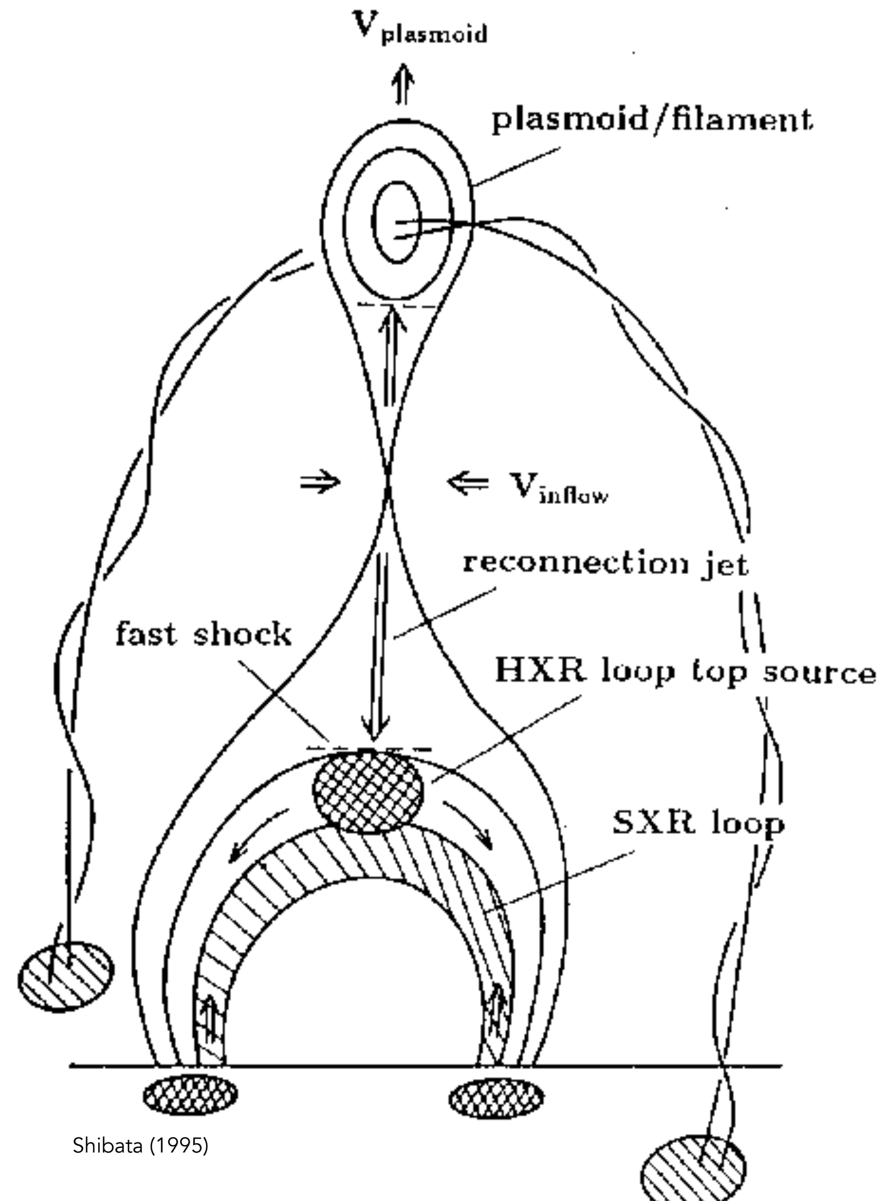
Energy source	Average observed values	Energy density [erg cm^{-3}]
Kinetic (~ $m_p n v^2/2$)	n ~ 10^9 cm^{-3} v ~ 10 km/s	~ 10 $^{-3}$
Thermal (~ $n k_b T$)	T ~ 10^6 - 10^7 K	~ 0.1 – 1.0
Gravitational (~ $m_p g H$)	H ~ 10^5 km	~ 0.4
Magnetic (~ $B^2/8\pi$)	|B| ~ 100 G	~ 400

Solar flares and CMEs are the most energetic phenomena in the solar system.

``Standard" model of a solar flare / CME



Liu (2008).

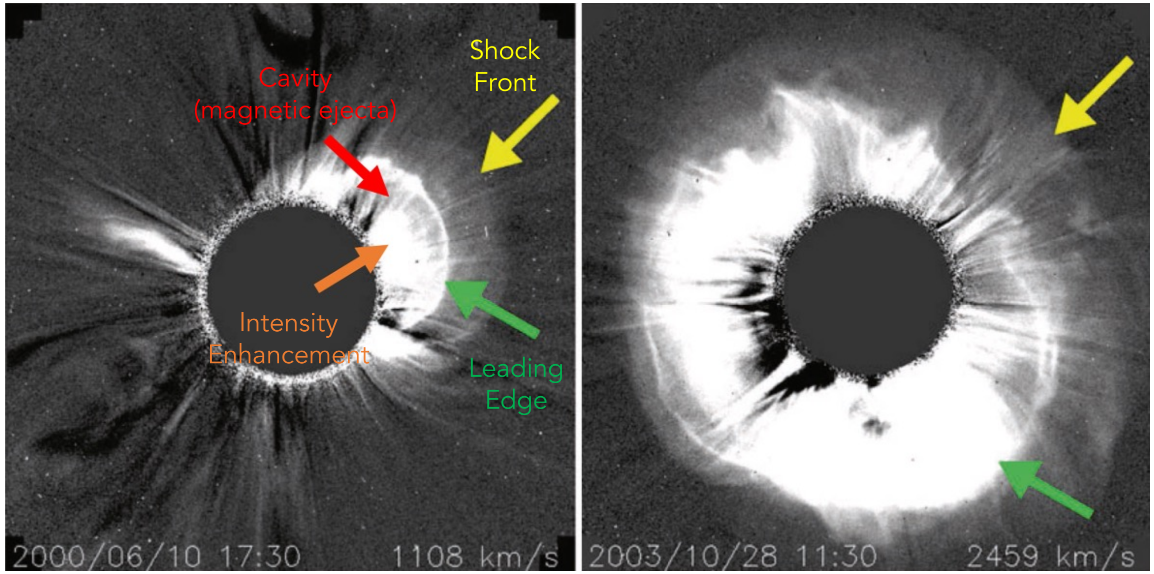


Shibata (1995)

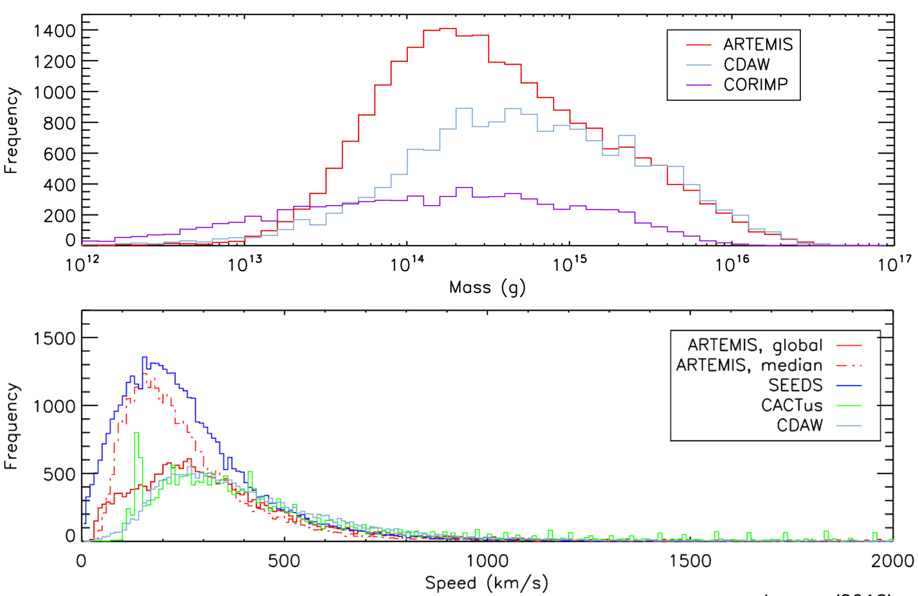
Grand archive of flare & CME cartoons:
https://www.astro.gla.ac.uk/cartoons/index.html

CME: General Properties

Vourlidas+ (2013).

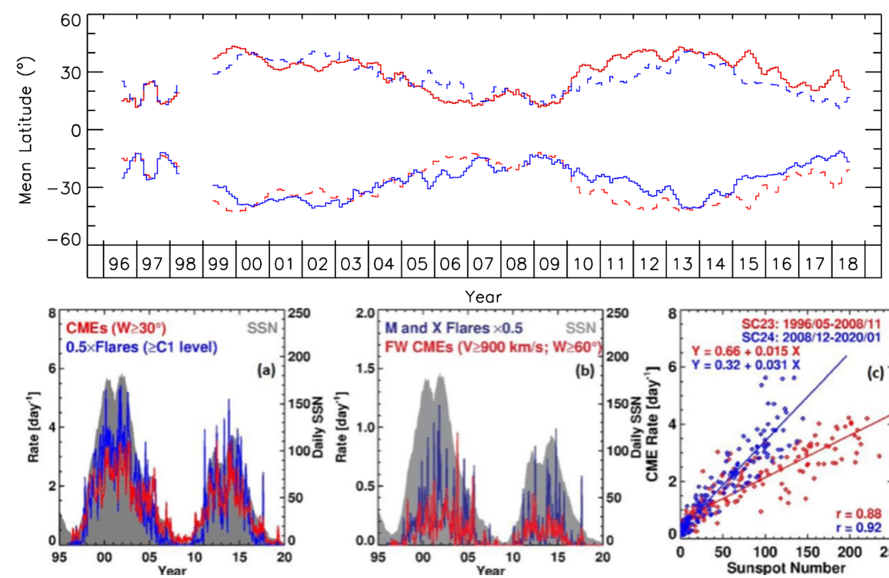


Mass and Velocity



Lamy+ (2019).

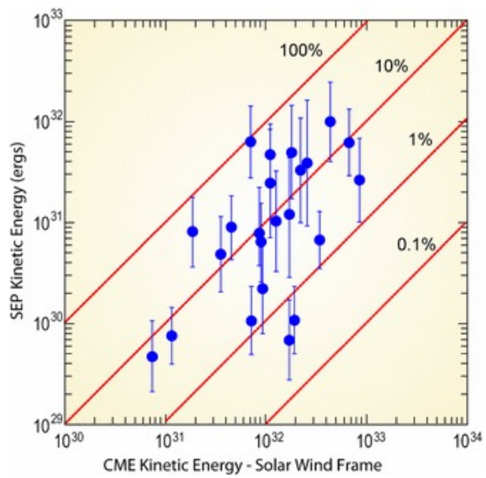
Connection with the (magnetic) activity cycle



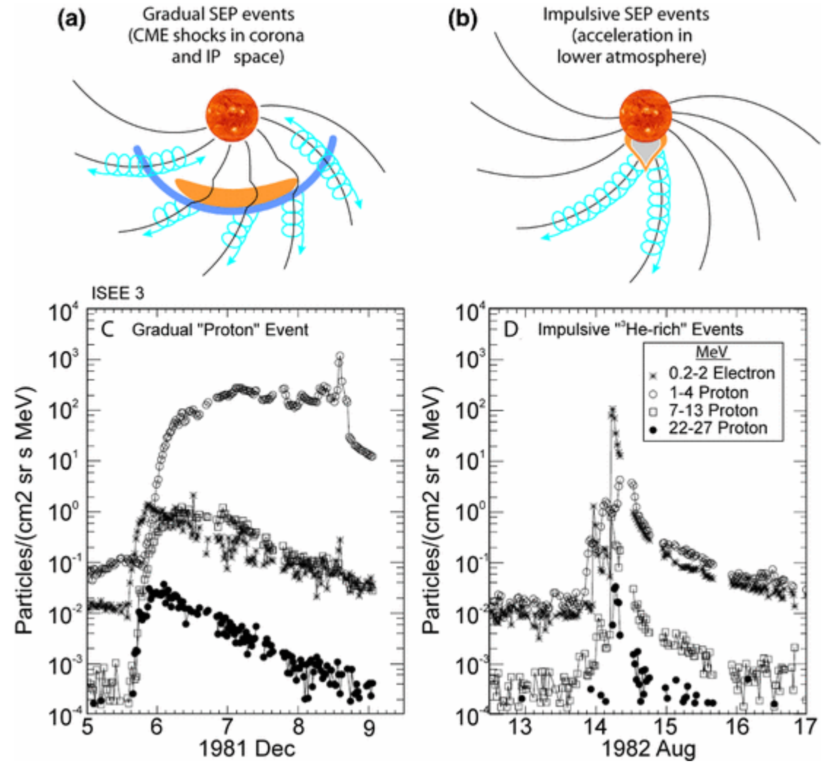
Zhang+ (2021).

Solar Energetic Particles (SEPs)

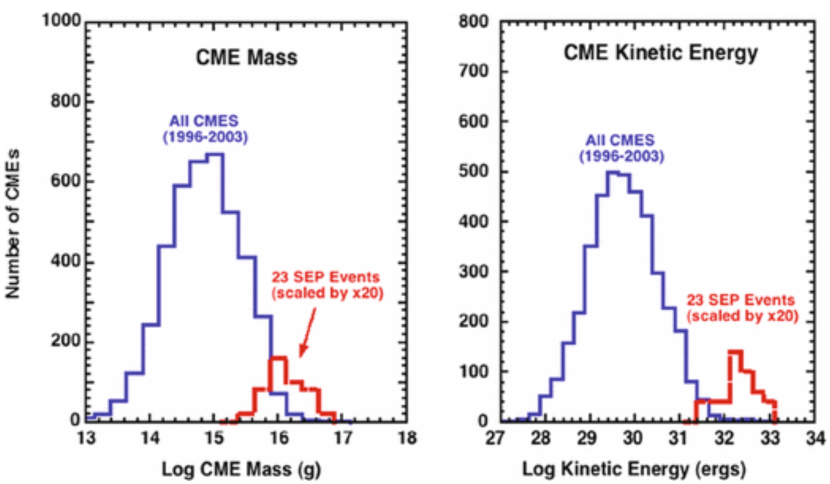
Property	Impulsive	Gradual
Electron/proton	$\sim 10^2 - 10^4$	$\sim 50 - 100$
$^3He/^4He$	~ 1	$\sim 4 \times 10^{-4}$
Fe/O	~ 1	~ 0.1
H/He	~ 10	~ 100
Q_{Fe}	~ 20	~ 14
SEP duration	$<$1–20 h	$<$1–3 days
Longitude cone	$<30°$	$<100° - 200°$
Seed particles	Heated Corona	Ambient Corona or SW
Radio type	III	II
X-ray duration	$\sim$10 min–1 h	$\gtrsim$1 h
Coronagraph	N/A	CME
Solar eind	N/A	IP shock
Events/year	~ 1000	~ 10



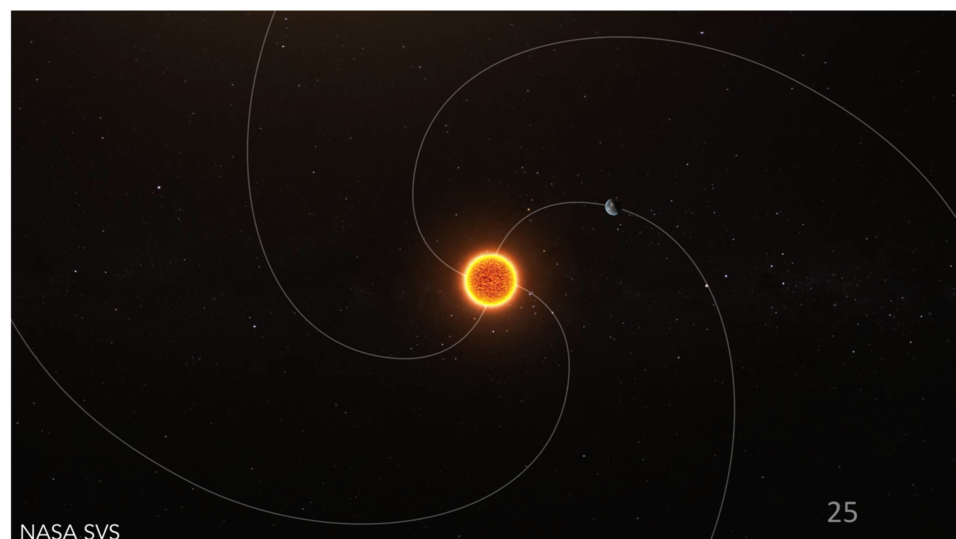
Desai & Giacalone (2016).



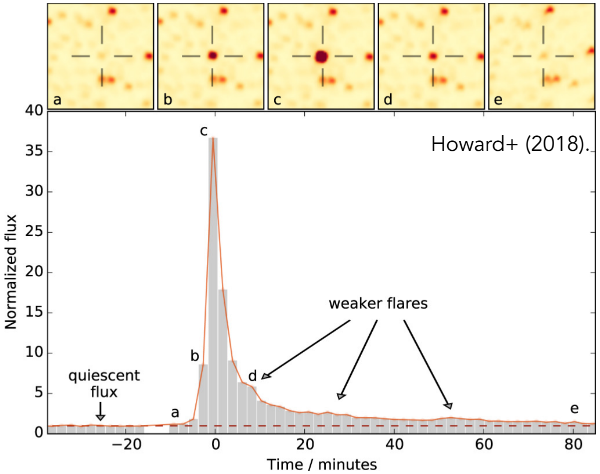
Reames (1999).

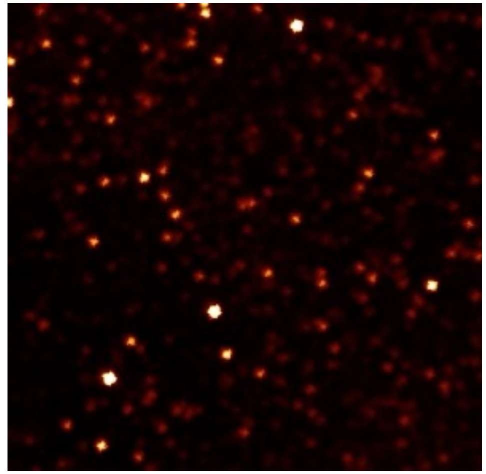


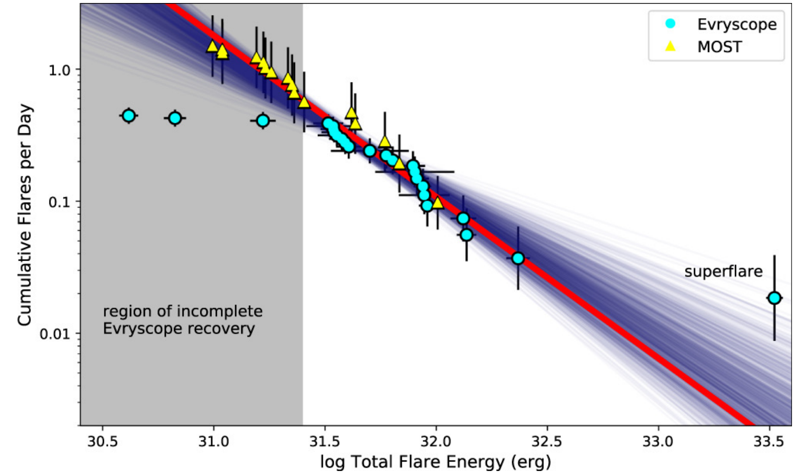
Mewald (2008).

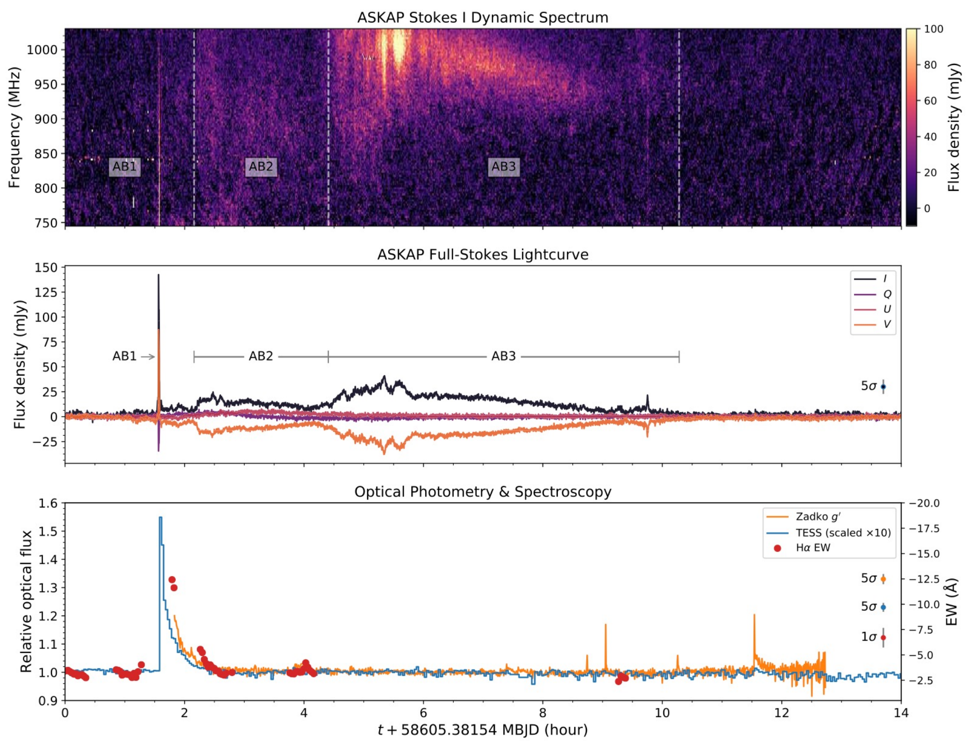


Flares and CMEs/EPs (?) from Proxima Centauri

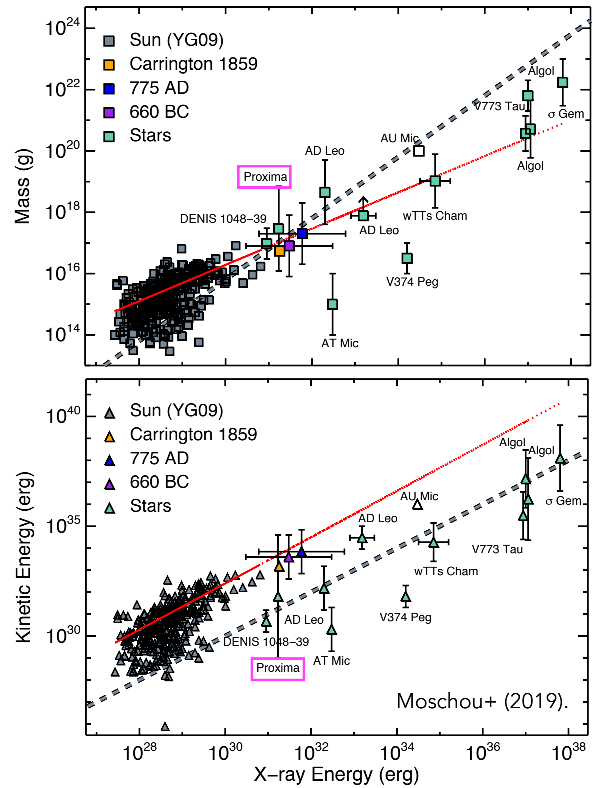






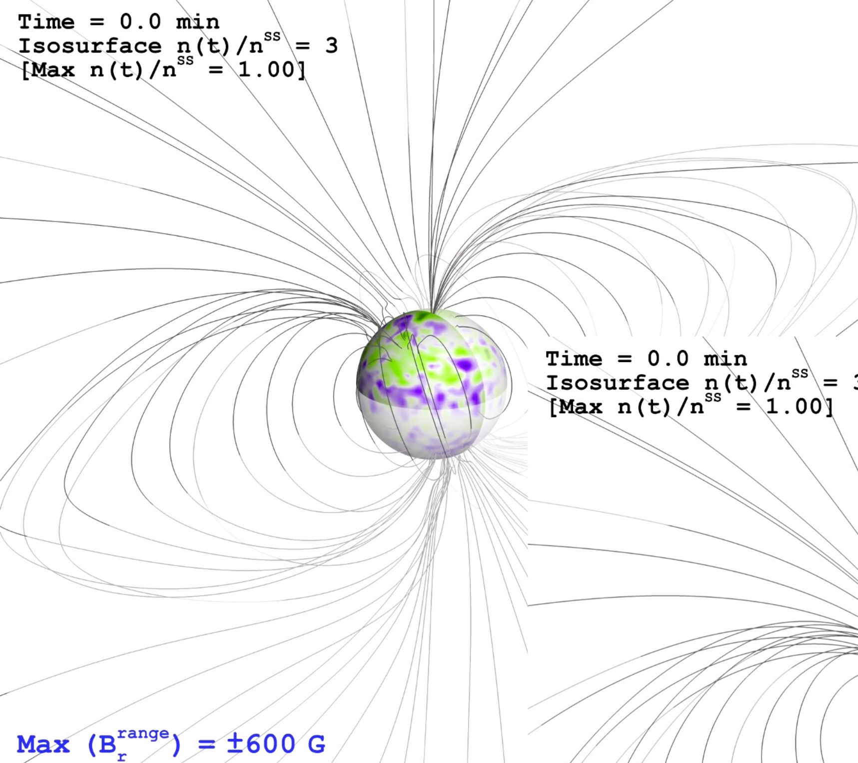


Zic+ (2020).

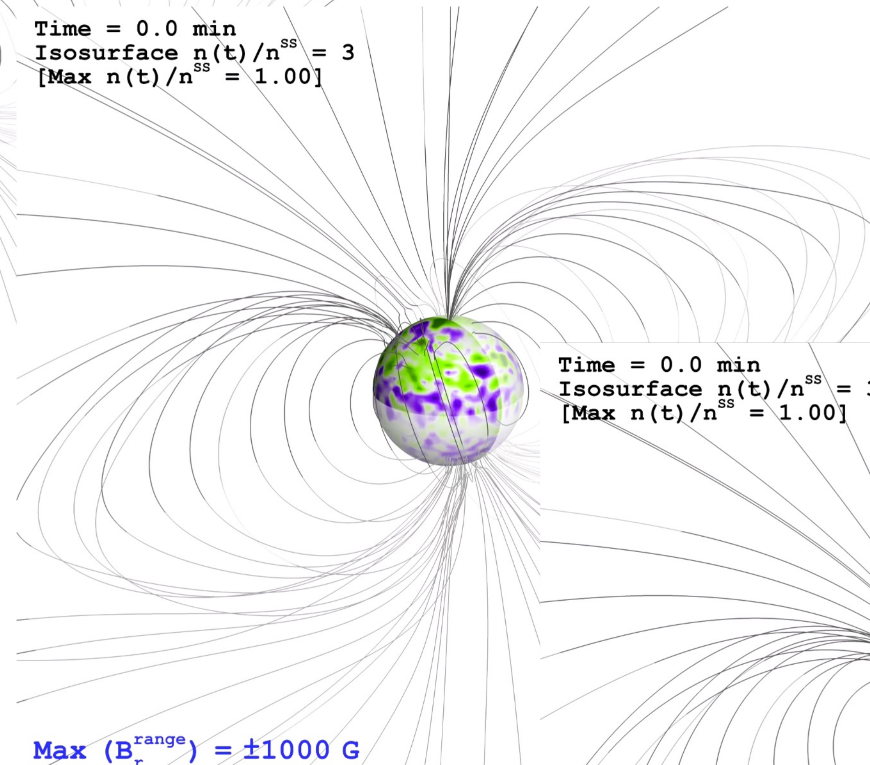


Magnetic Connection: Suppression of CME in Active Stars (M-dwarf simulations)

M_{CME} ~ 4 x 10^{14} g
$E_{B\text{-}Free}$ ~ 6.5 x 10^{34} erg

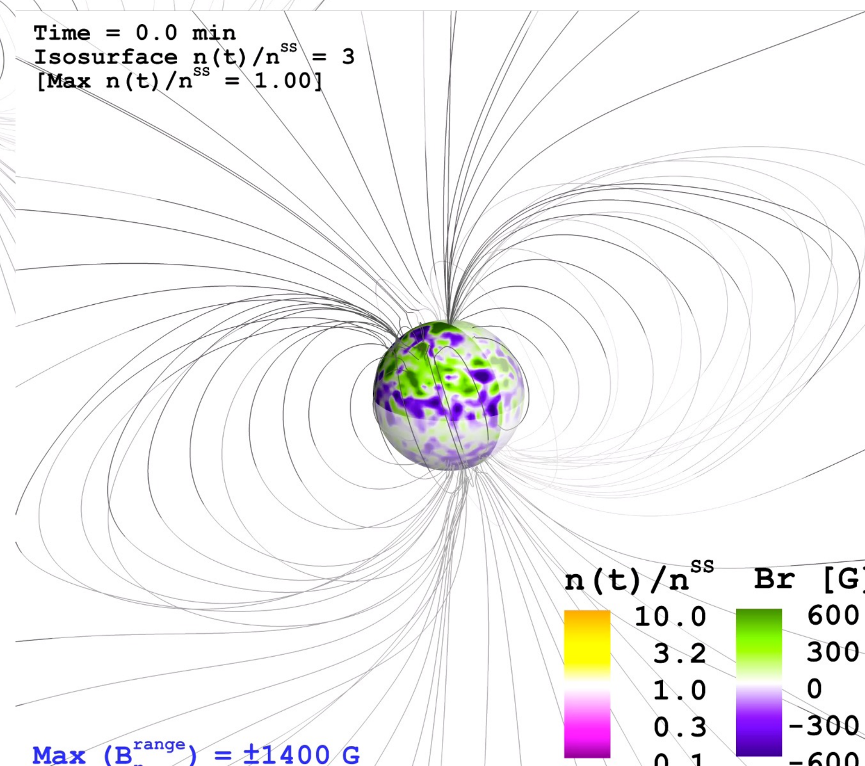


Weak



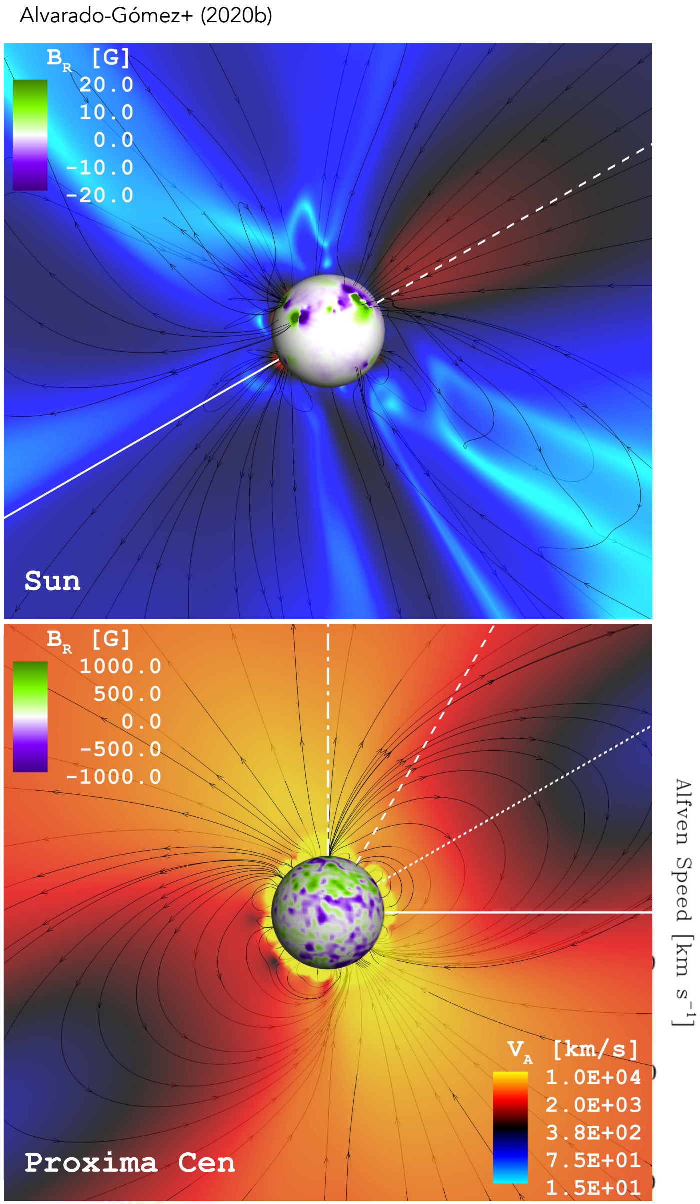
Partial

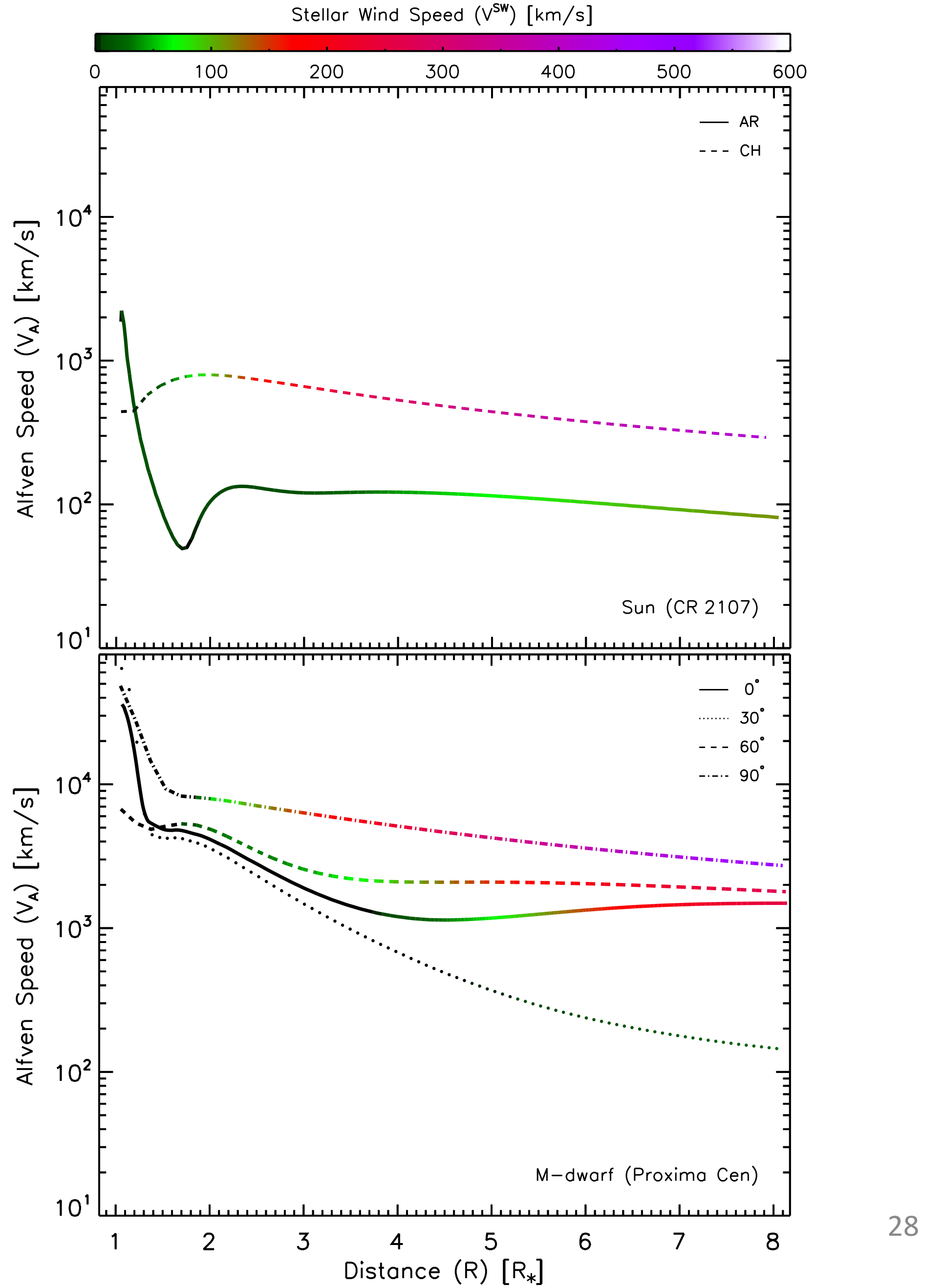
Strong



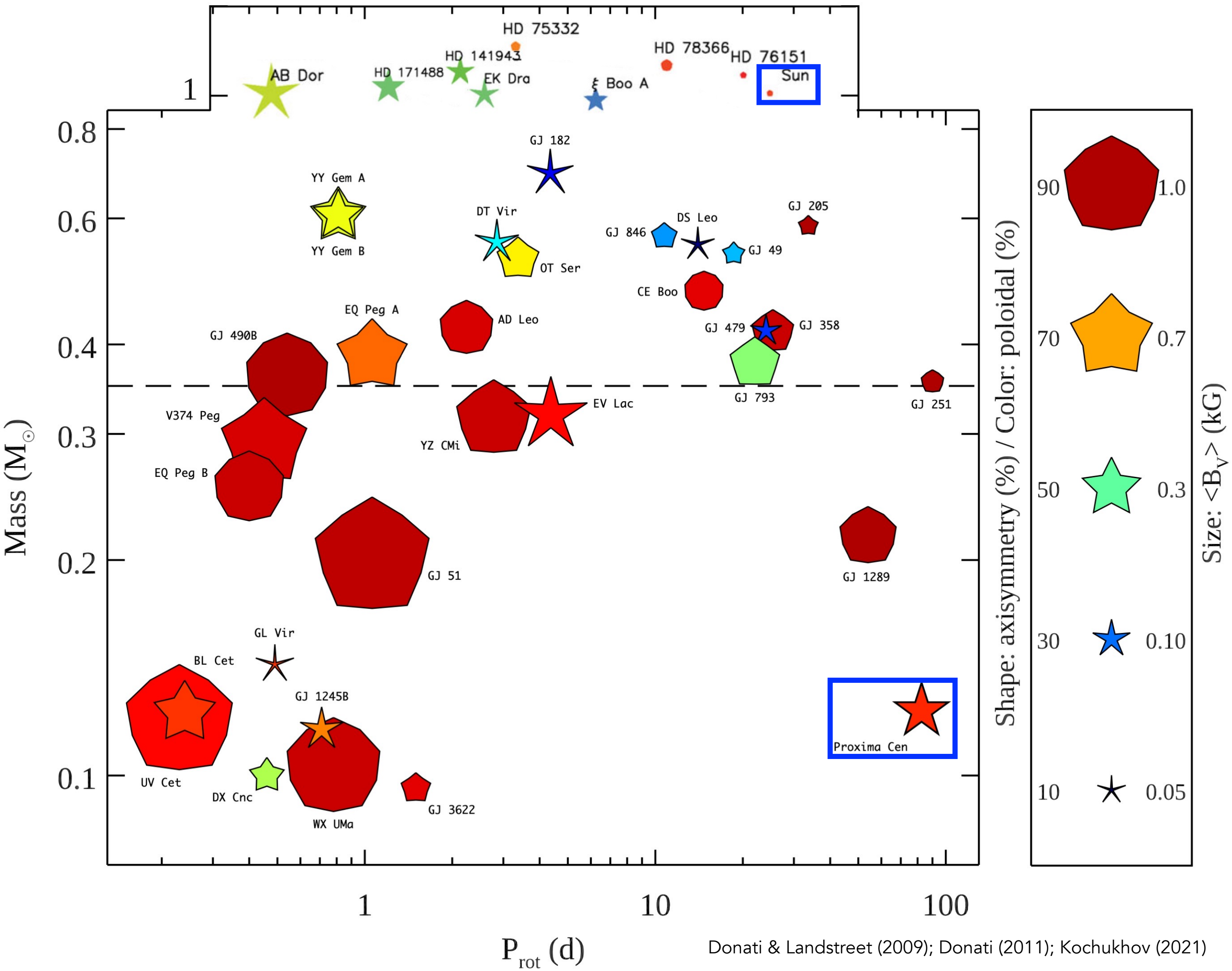
CME simulations (Flux-rope eruption models)
(AWSoM/SWMF I Alvarado-Gómez+ 2019)

The stellar magnetic field in M-dwarf stars could hamper the generation of CME-shocks due to relatively large Alfvén speeds in the corona + magnetic suppression of CMEs





Magnetism in cool main sequence stars: The "Confusogram"
(derived from Zeeman Doppler Imaging reconstructions)



Donati & Landstreet (2009); Donati (2011); Kochukhov (2021)

Sizes: Field Strength
(3 – 1000 G)

Color: Main Geometry
(Red: Poloidal | Blue: Toroidal)

Shapes: Symmetry
(Decagons: Axisymmetric
Stars: Non-Axisymmetric)

Concluding Remarks

- It is now possible to study the properties of magnetic fields of stars other than the Sun (observationally/numerically). The wide parameter space on the stellar domain is fundamental for our understanding of how magnetism is generated on the Sun and stars.

- The study of stellar activity in any context (e.g., "noise" for exoplanet studies) can only be complete via knowledge of its relationship with the magnetic field.

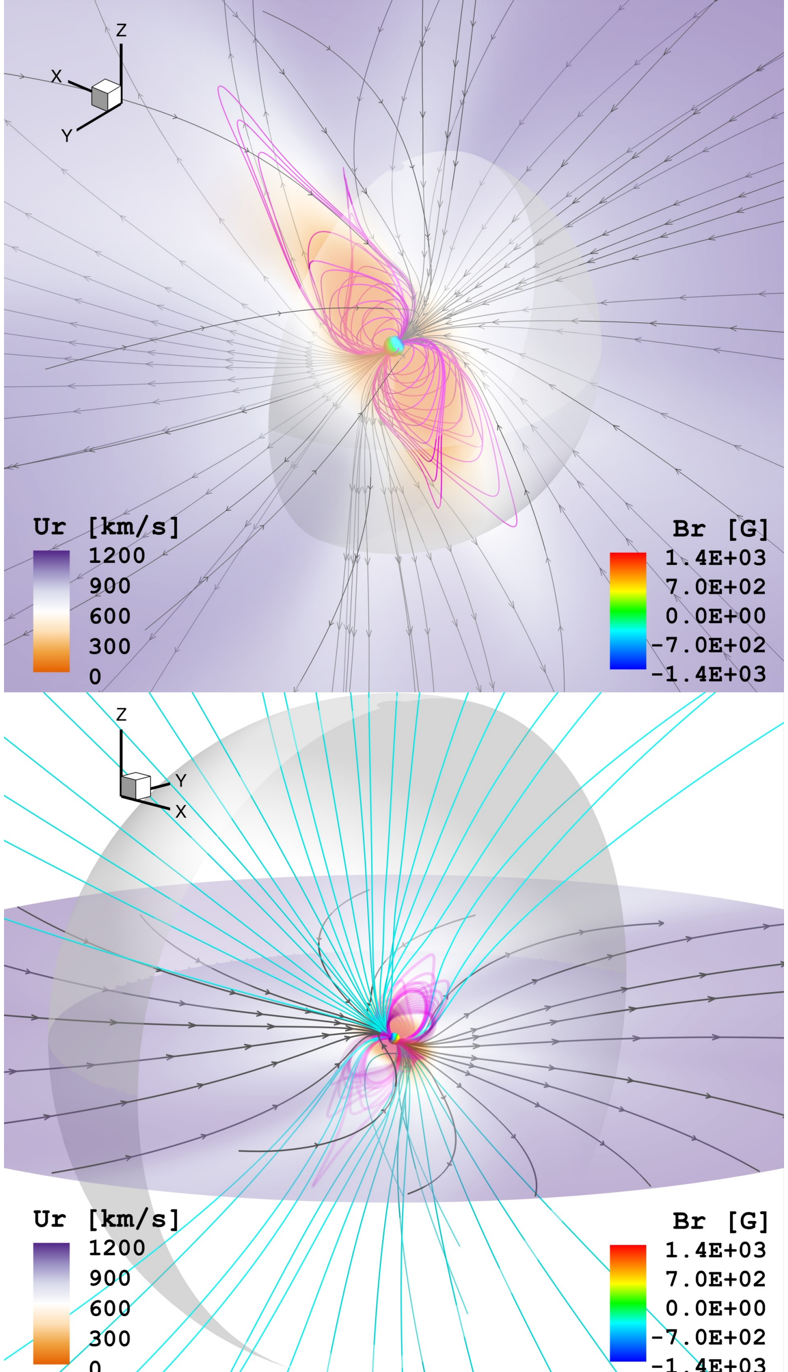
- Current exoplanet characterization efforts must include the influence due to the magnetized environment generated by the star (e.g., corona, stellar wind, flares/CMEs, EPs).

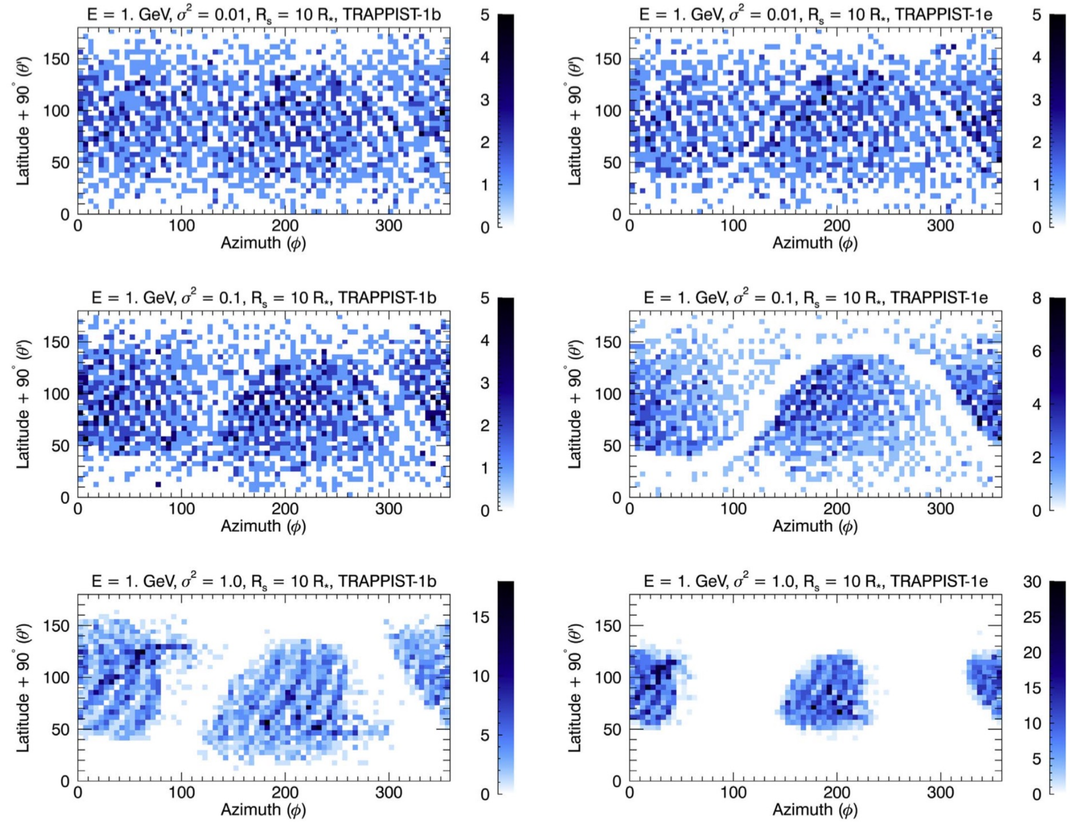
- Even the best data of stellar particle environments would be almost impossible to interpret without complementary information on the stellar magnetic field and its variability (short- and long-term).

- While the Sun serves as the best possible guide, in the realm of stars and exoplanets our minds must always remain open to possibilities (specially those rarely or never observed in the solar system).

Energetic particles in the TRAPPIST-1 System

(Garraffo+2017, Fraschetti+ 2019)





Only a few percent of particles injected within half a stellar radius from the stellar surface escape.

The escaping fraction increases strongly with increasing injection radius.

Escaping particles are increasingly deflected and focused by the ambient spiraling magnetic field (two caps in the fast wind region).