Space Weather Beyond the Solar System

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Cool Stars 20 | Aug 2 2018

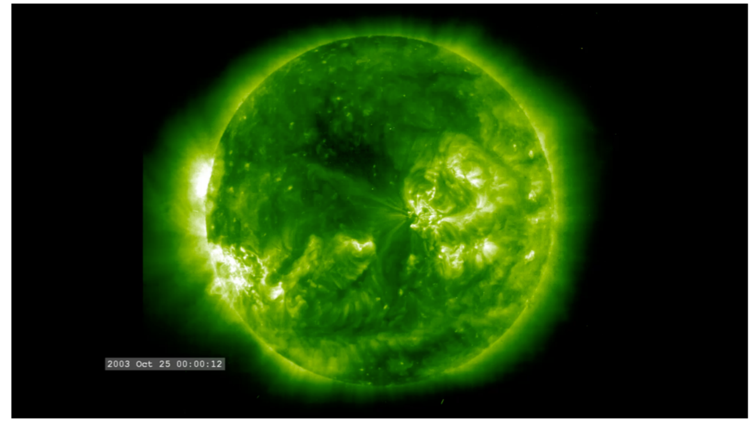
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

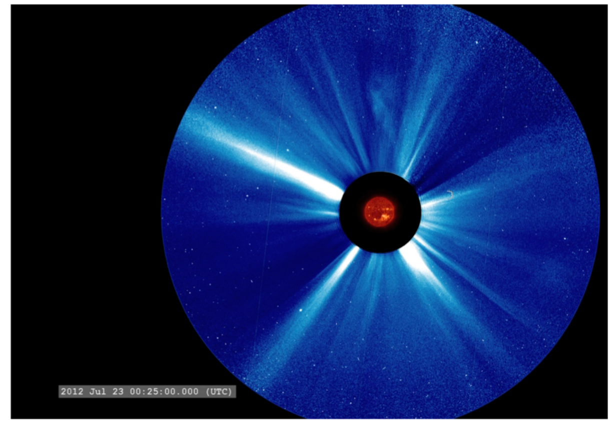
Suppression of Coronal Mass Ejections (CMEs) in Active Stars

Alvarado-Gómez et al. 2018b
(ApJ 862, 93)

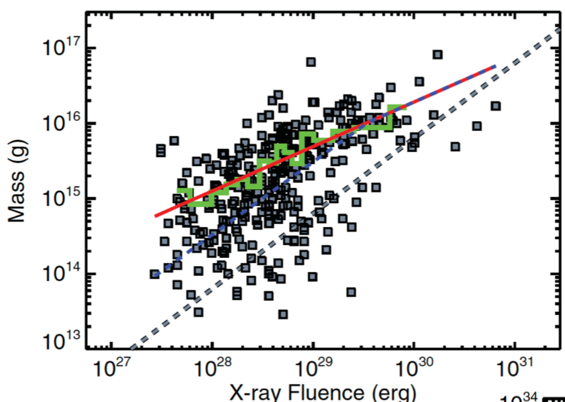
Solar Flares – CMEs: generalities and association

- Flares: Sudden energy release in the corona involving particle acceleration, radiation, and plasma heating.
- CMEs: "Localized" release of plasma and magnetic field into the solar/stellar wind (plasmoids/filament eruptions).
- Solar statistics: Large flares (GOES X Class) are nearly always accompanied by a CME (Yashiro & Gopalswamy 2009).



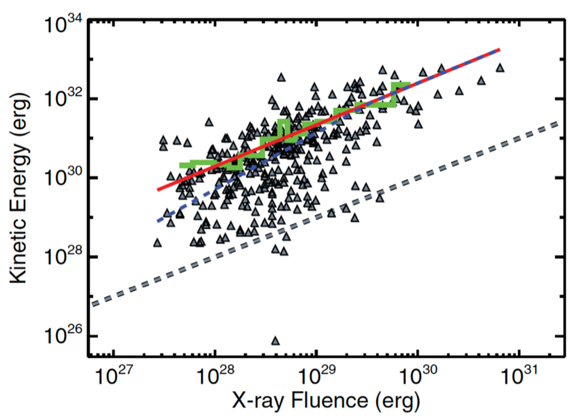


Extension to more active stars?



Study of Drake et al. (2013):

(see also Aarnio et al. 2012)



Consequences of extrapolating the observed mass and kinetic energy of CMEs associated with solar flares to more active stars.

A saturated Sun-like star (L_X ~ 10^{30} erg/s) would have:

CME-Mass loss rate: $\dot{M} \sim 5 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$

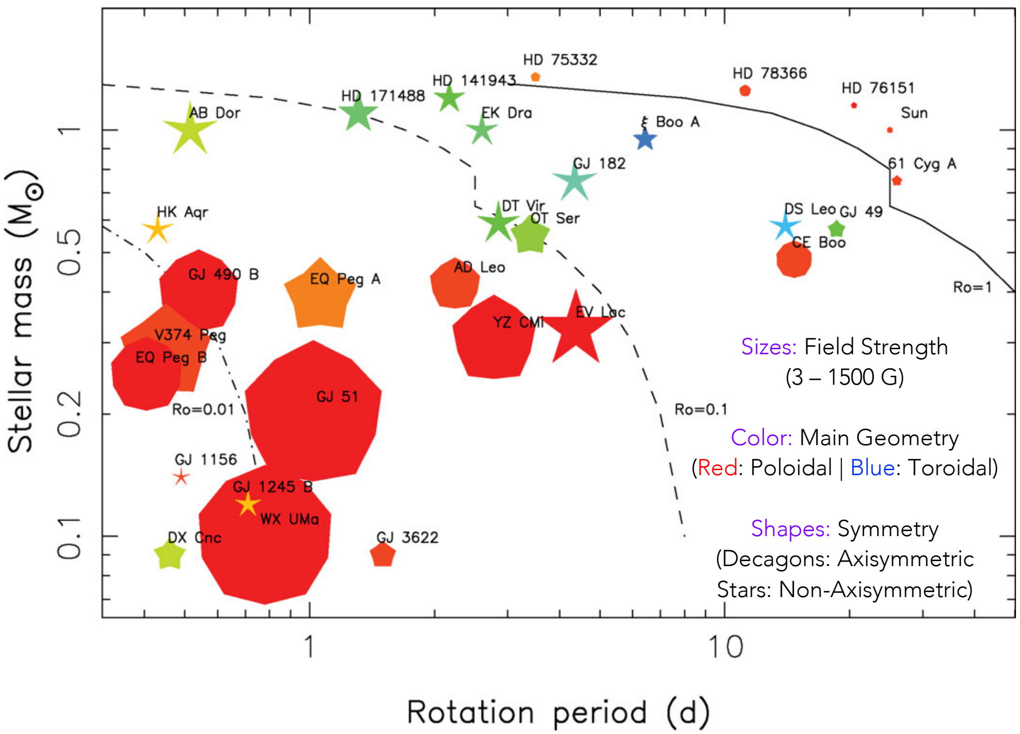
CME-Kinetic energy requirement: $\dot{E}_{ke} \sim 0.1 L_{\odot}$

Conclusion: The flare-CME relations (mass/energy) must flatten out for large energies (≥ 10^{31} ergs).

Possible solution: Suppression of CMEs by overlying magnetic field

Stellar observations

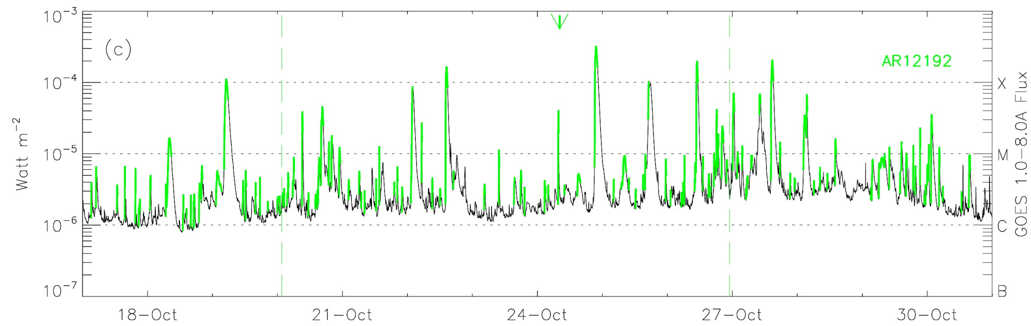
Donati (2011); Donati & Landstreet (2009)

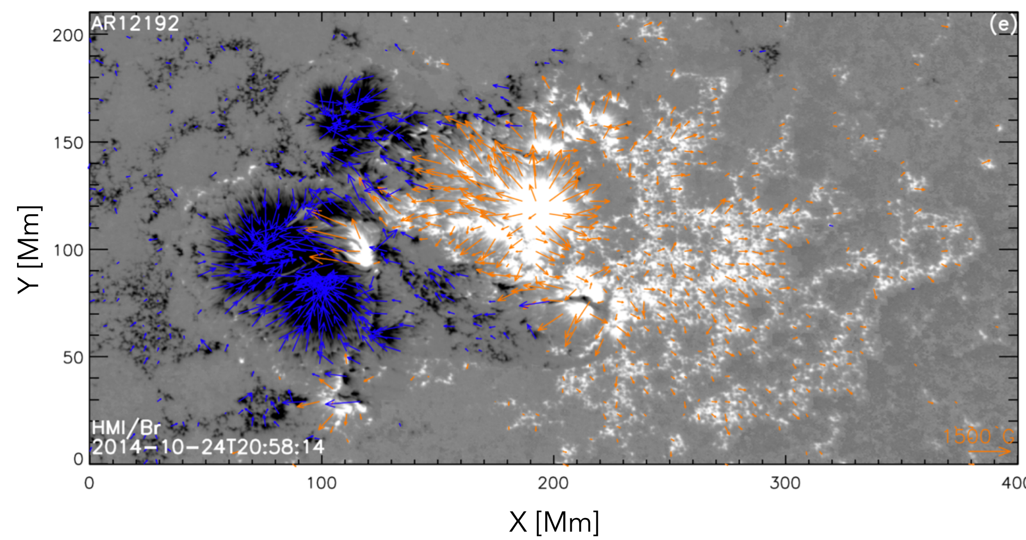


(This plot is known as the "Confusogram" so don't worry if you are confused now).

Solar observations

Lin et al. (2016)





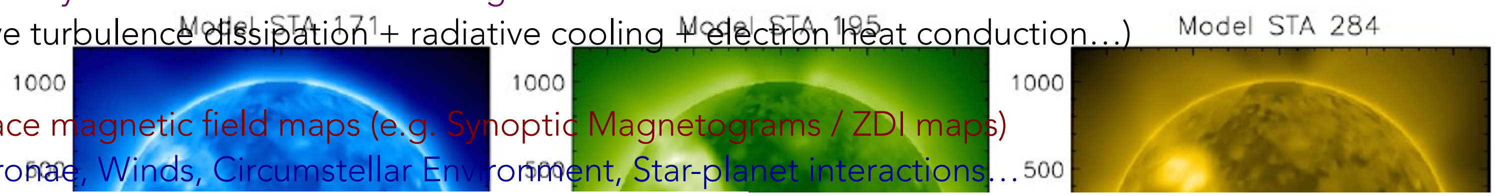
Space Weather Modeling Framework (SWMF)

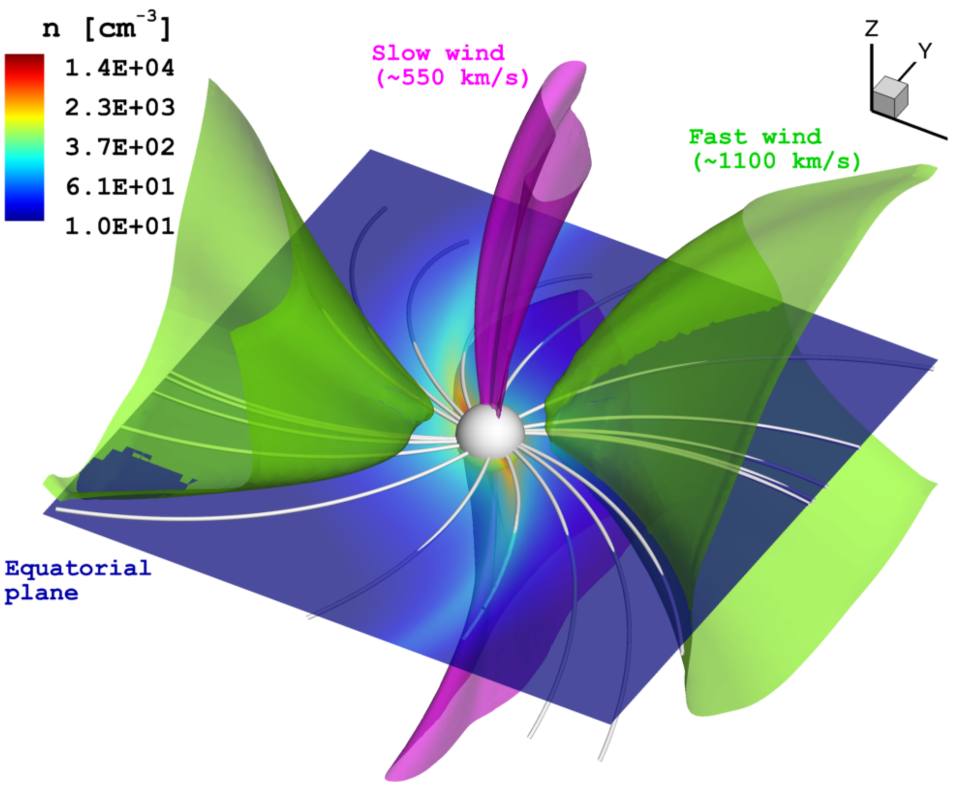
State-of-the-art 3D MHD code used and validated in different Heliophysics domains

Physics-based space weather simulations:
Self-consistently calculated: Coronal heating / stellar wind acceleration
(Alfven wave turbulence dissipation + radiative cooling + electron heat conduction…)

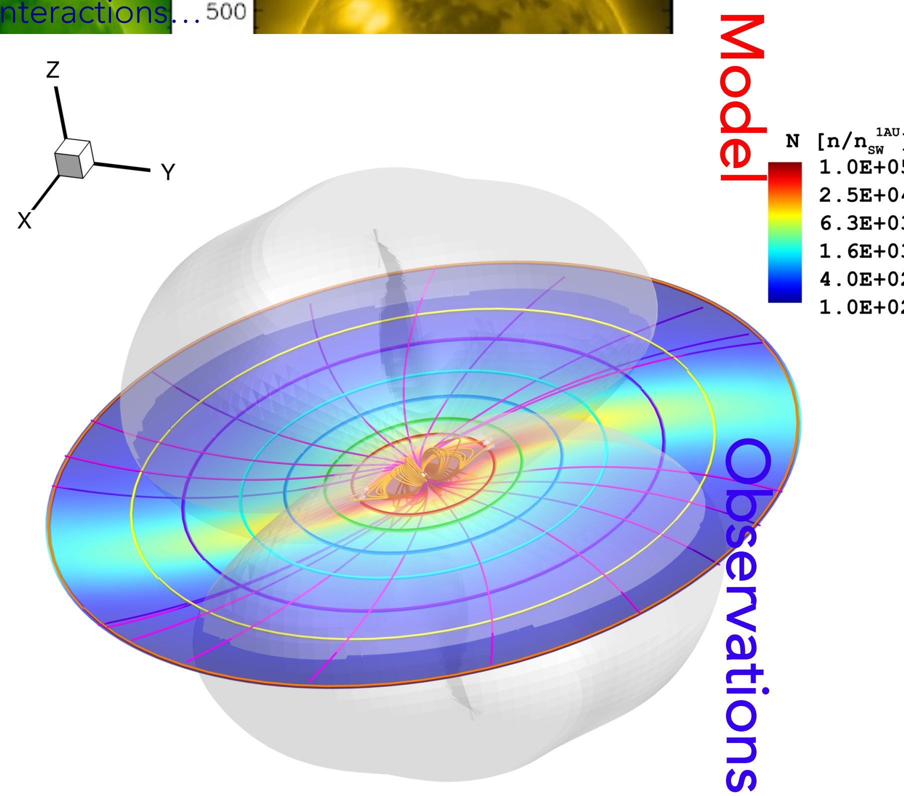
Input: Surface magnetic field maps (e.g. Synoptic Magnetograms / ZDI maps)
Model: Coronae, Winds, Circumstellar Environment, Star-planet interactions…

van der Holst et al. (2014)





Alvarado-Gómez et al. (2016b)

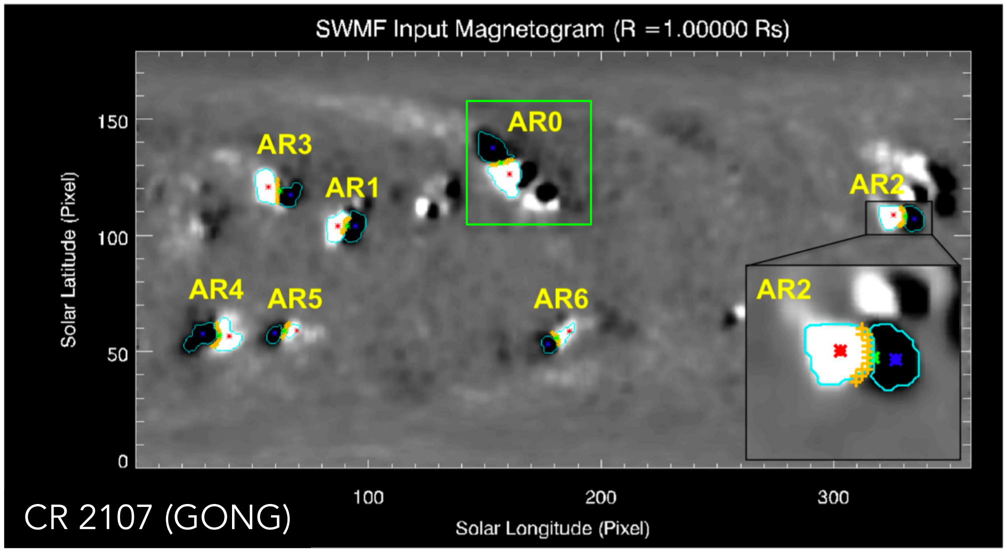


Garraffo et al. (2017)

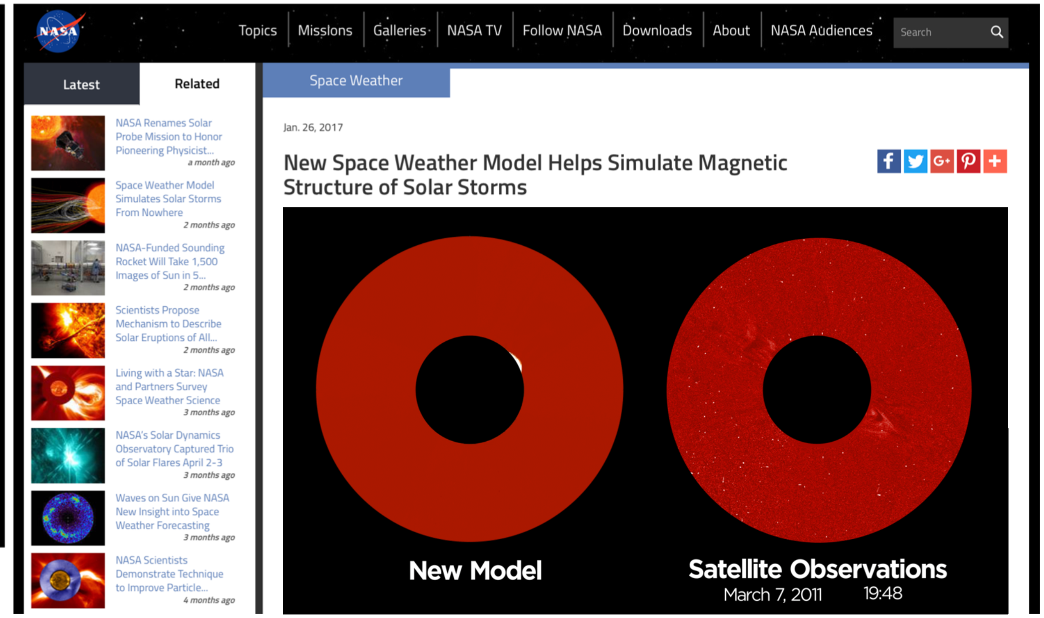
A set of MHD simulations: Gibson & Low (1998) flux rope CME model

Eruption of a twisted flux rope starting from the steady-state corona/wind solution (Afvén Wave Solar Model)

Validated against Solar CME observations (Jin et al. 2017)



Jin et al. (2017)



Parameters from the calibration study of the CME model applied on a "younger Sun".

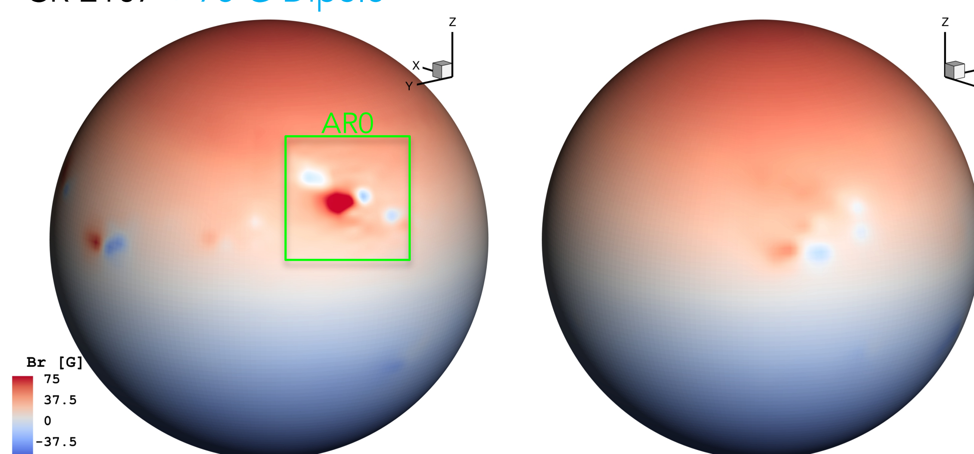
Simulation domain: 1 – 50 $R_\odot$

Grid: Spherical + High-res spherical wedge (25 $R_\odot$).

1 hour wall-clock time for each CME simulation.

~1 million core hours of supercomputing time (+post-processing).

CR 2107 + 75 G Dipole

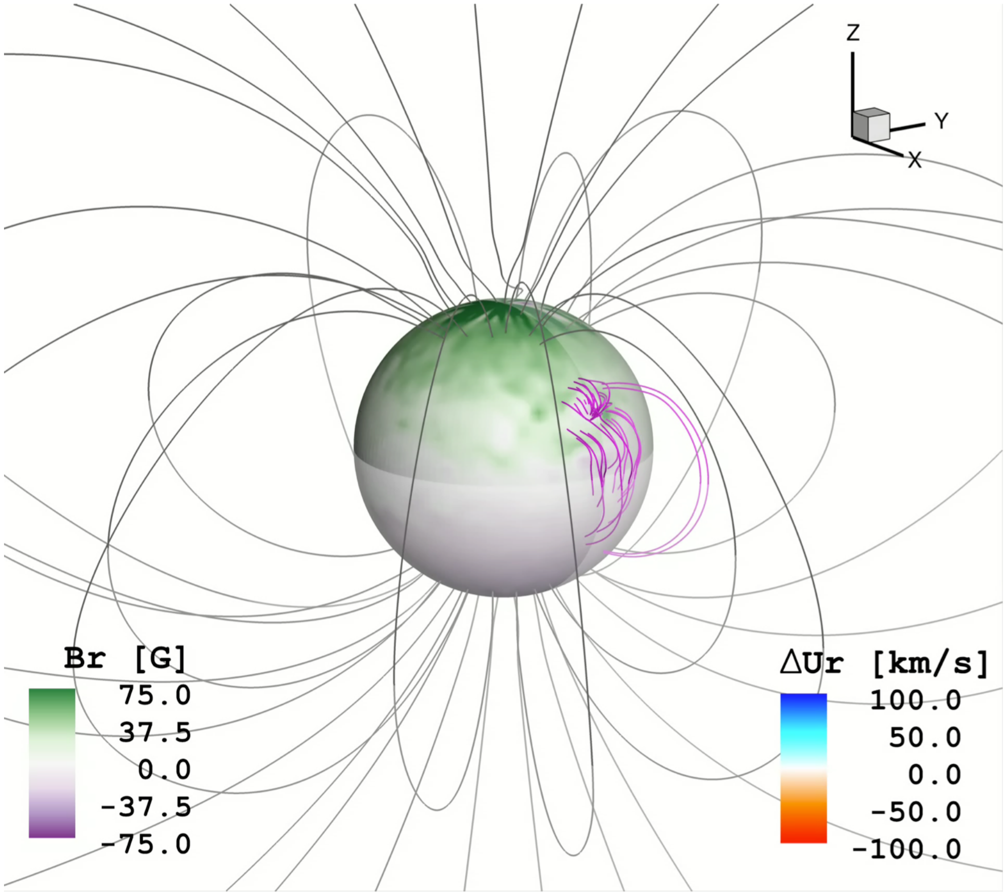


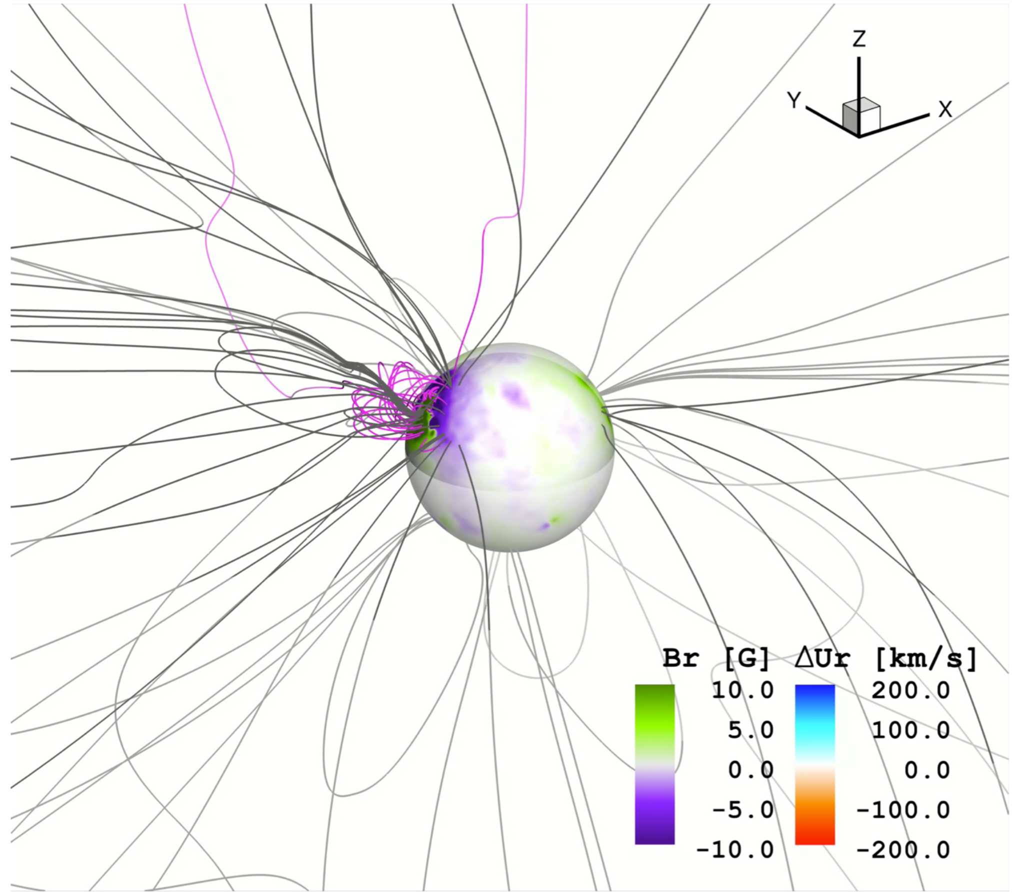
Alvarado-Gómez et al. (2018b)

Results:

Confined CMEs

Alvarado-Gómez et al. (2018b)





Φ_P = 1.94 x 10^{22} Mx
(Equivalent GOES Class Flare: X5.0)

Solar CME simulation

The coronal material rises following the overlying field lines.

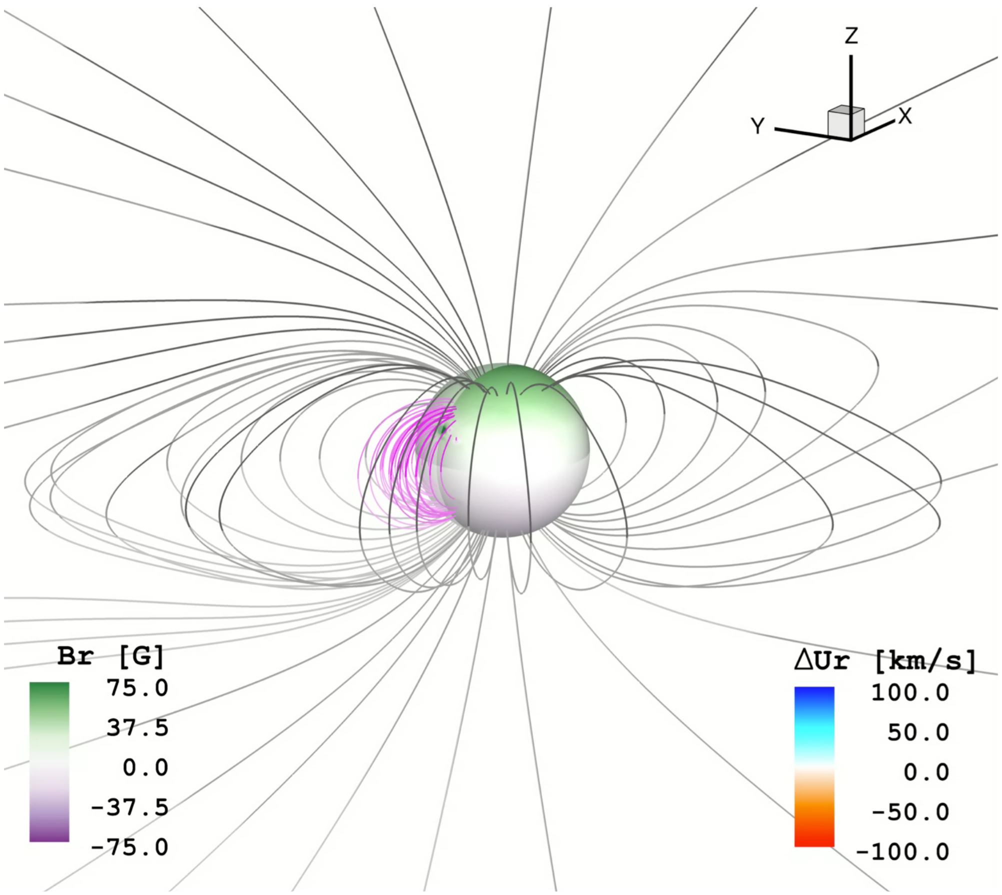
The perturbed plasma remains confined within the region of the lower corona.

Solar simulations: ~2500 – 3000 km/s
(CME-Speed – Φ_P Relation; Jin et al. 2017)

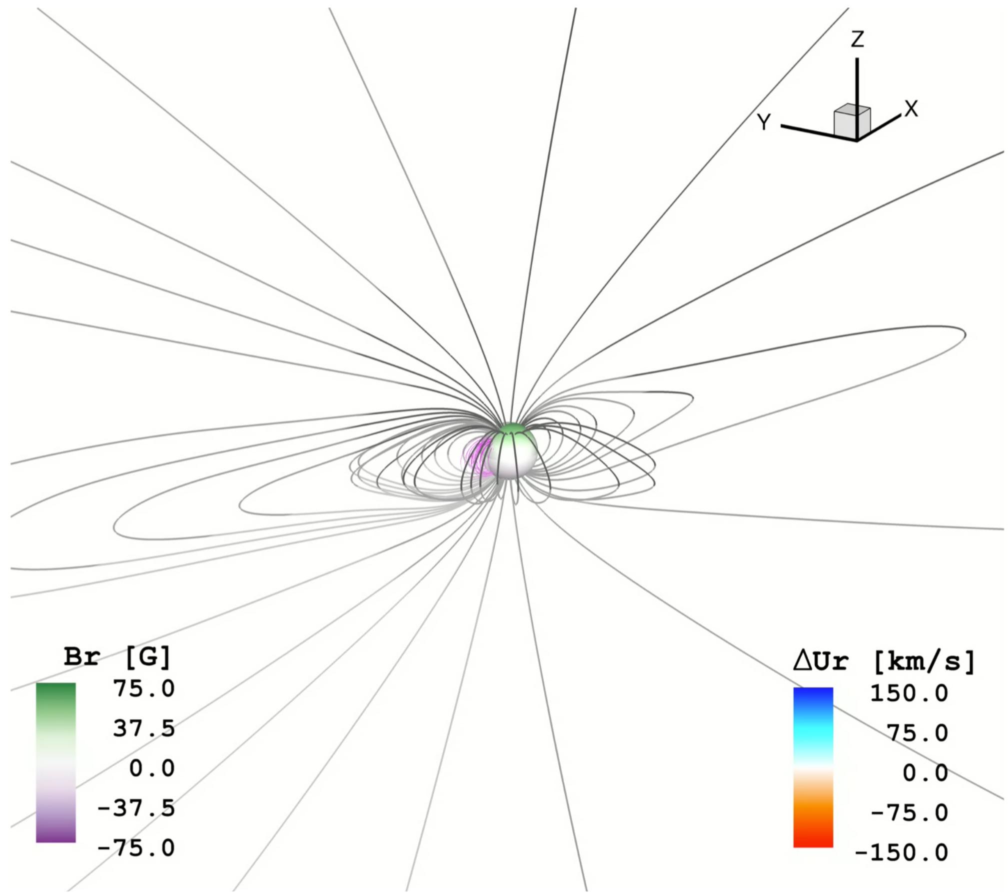
Results:

Partially confined & "Monster" CMEs

Alvarado-Gómez et al. (2018b)



Φ_P = 1.44 x 10^{23} Mx
(Equivalent GOES Class Flare: X170.0)



Φ_P = 3.99 x 10^{23} Mx
(Equivalent GOES Class Flare: X900.0)

CME-speed: ~1700 km/s

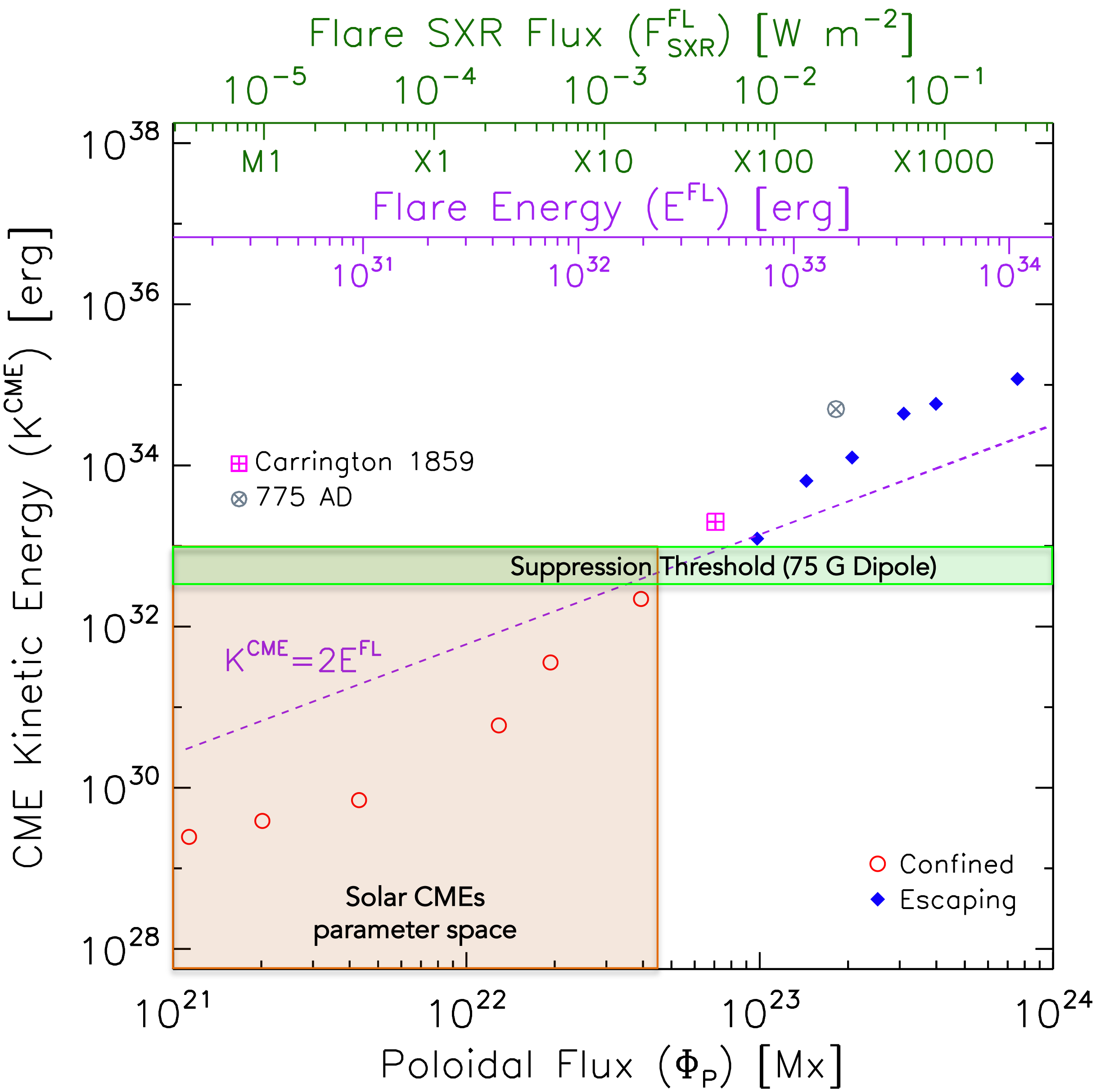
M_{CME} ~ 4 x 10^{17} g
E_{KIN} ~ 10^{33} erg

CME-speed: ~3200 km/s

M_{CME} ~ 1 x 10^{18} g
E_{KIN} ~ 10^{34} erg

Results: CME Suppression threshold

Alvarado-Gómez et al. (2018b)



The large-scale magnetic field tends to slow down the CMEs.

Escaping CMEs are **less energetic** than expected; The candidate stellar CME observed so far show this!
(Poster 214 – S. Moschou et al.)

Magnetic suppression would mitigate small/moderate CMEs in active stars.

Only "monster" CMEs would be able to escape (c.f. Moschou et al. 2017).

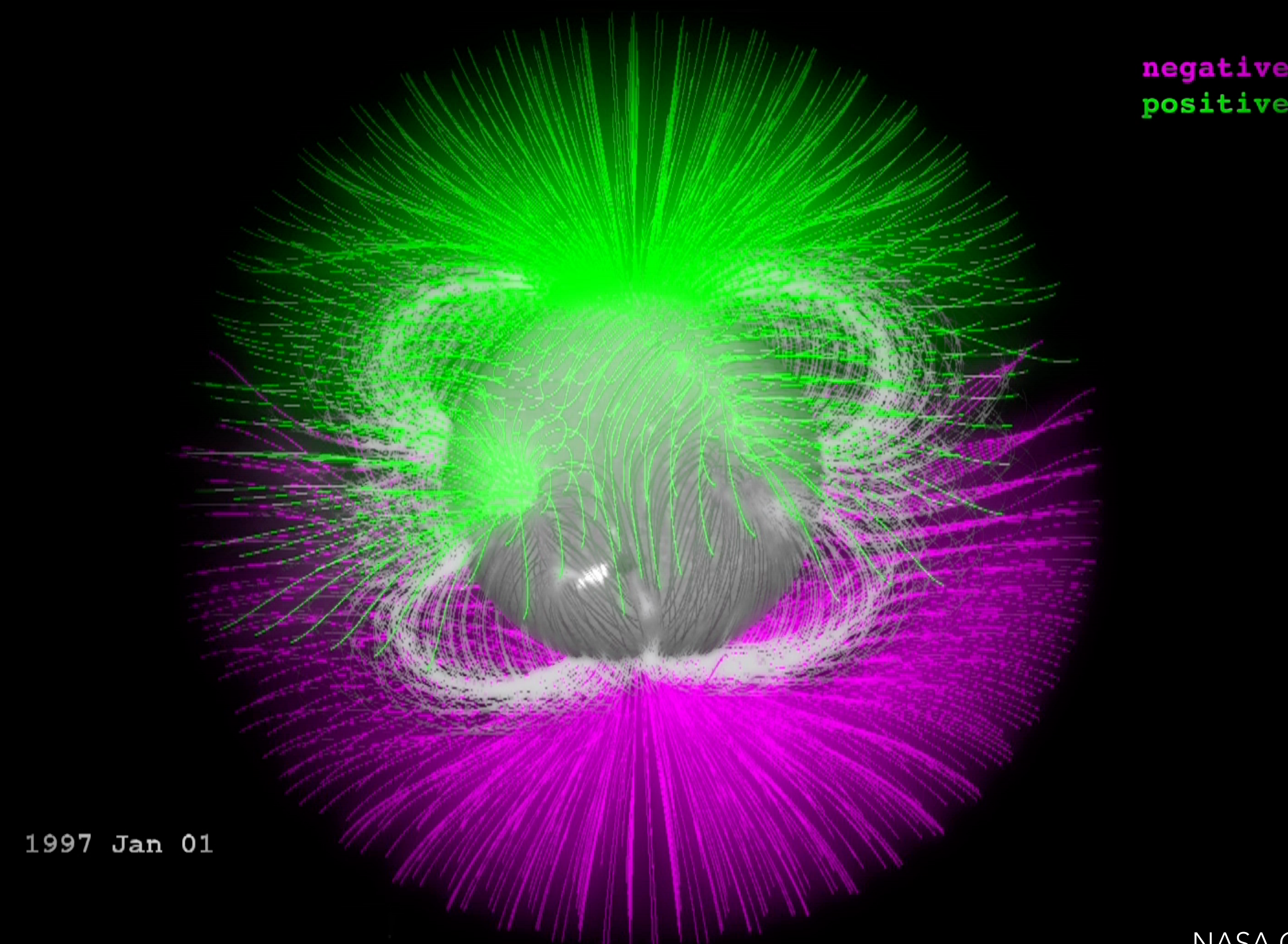
Work in progress:

Large-scale field complexity
Observable signatures (EUV/X-rays)
Connection with super-flares (Kepler WLF)?

The Changing Space Weather of a Young Sun

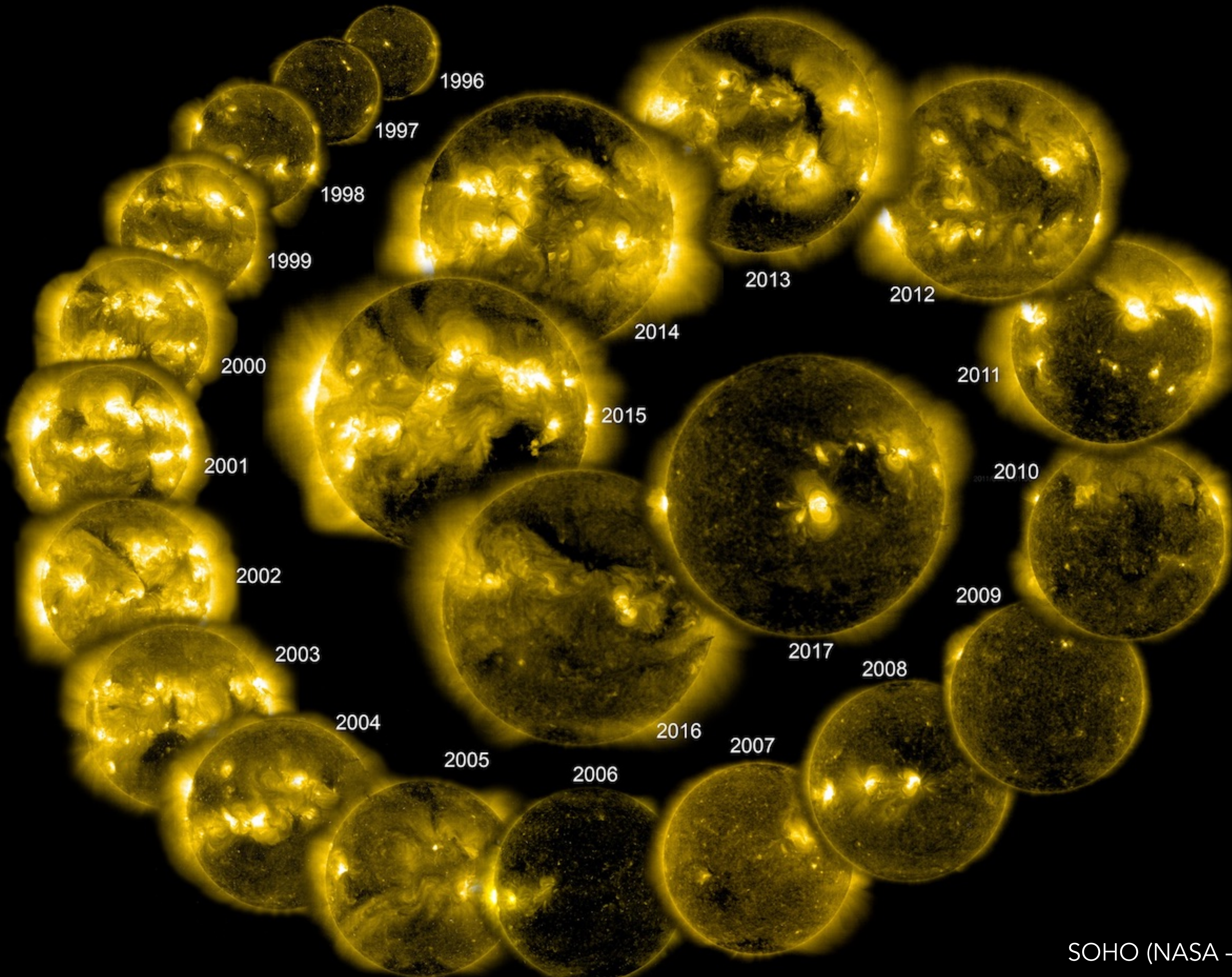
Alvarado-Gómez et al. 2018a
(MNRAS 473, 4326)

Changing Space Weather: Global magnetic field



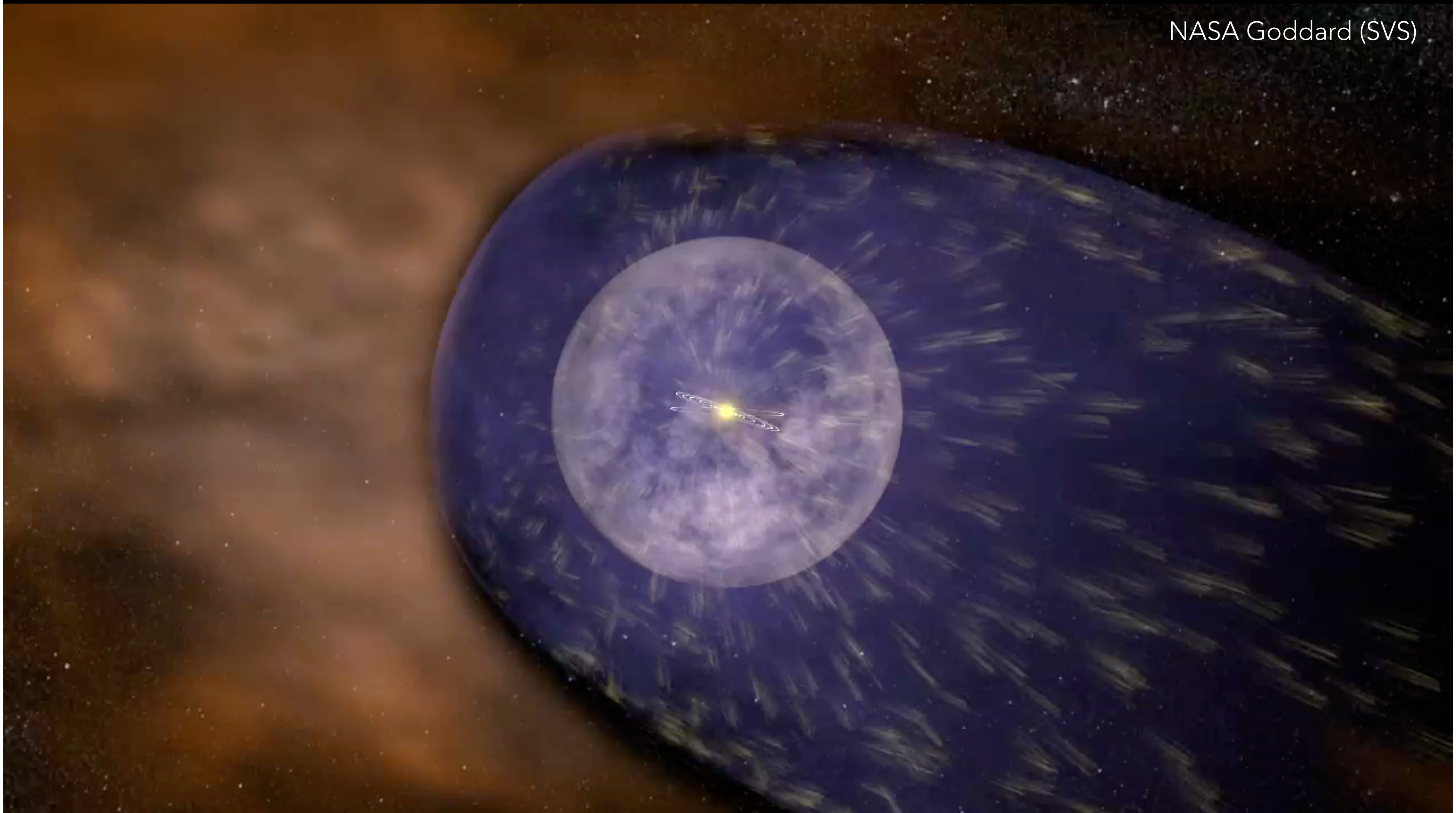
NASA Goddard (SVS)

Changing Space Weather: Corona (EUV/X-ray)



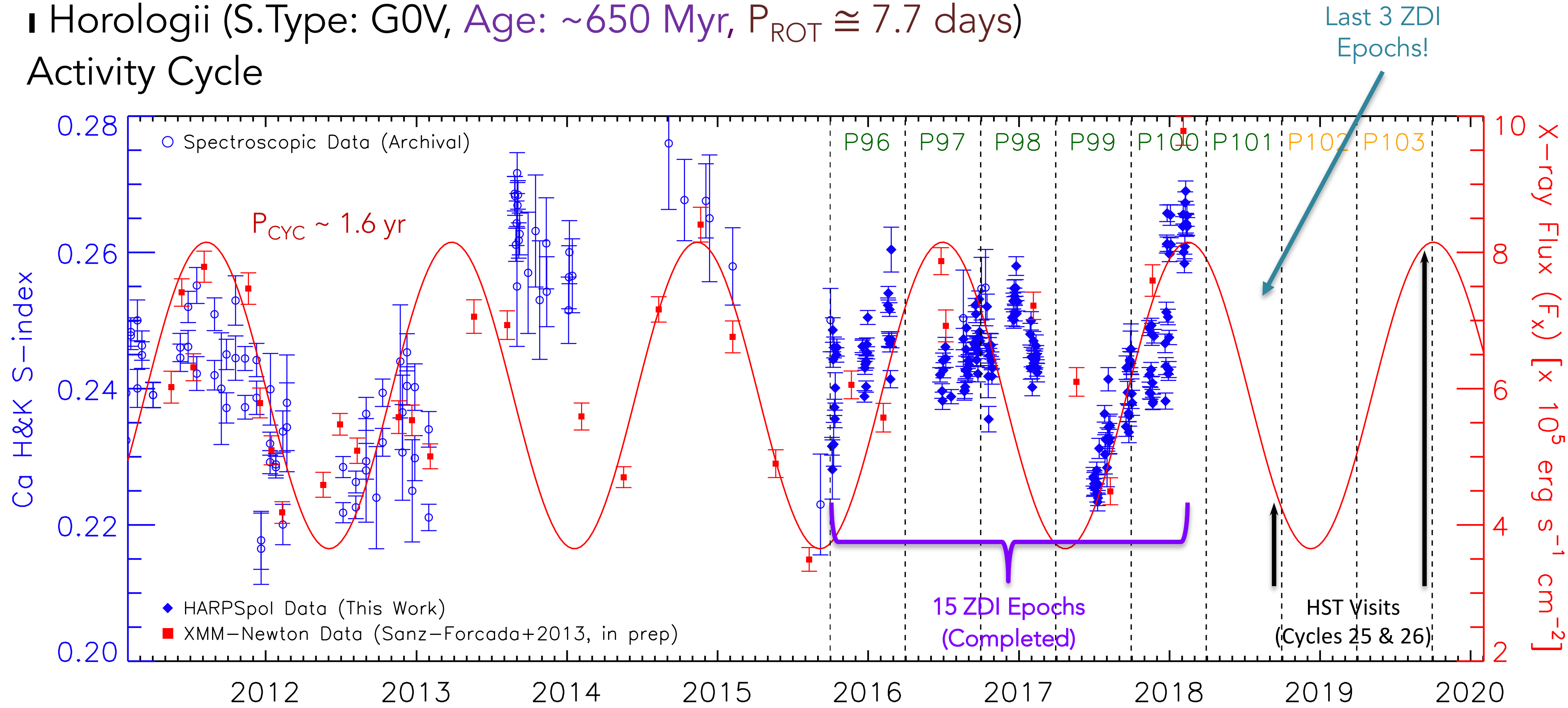
SOHO (NASA – ESA)

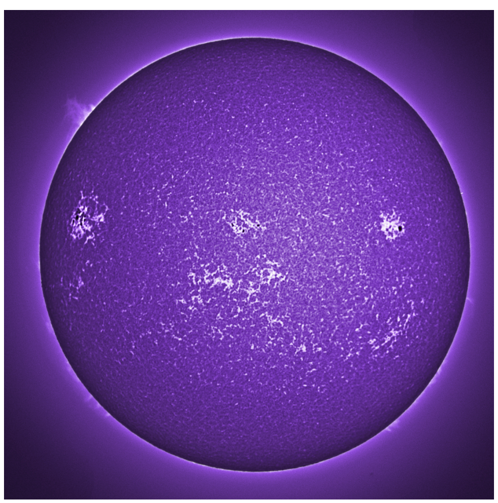
Changing Space Weather: Heliosphere/Astrospheres



ι Horologii (S.Type: G0V, Age: ~650 Myr, $P_{ROT} \cong 7.7$ days)

Activity Cycle





"Far Beyond the Sun" Campaign

HARPSpol (ESO3.6m)

✓ 096.D-0257 ✓ 097.D-0420
✓ 098.D-0187 ✓ 099.D-0236.
✓ 0100.D-0535 ▶ 0101.D-0465

PI: Alvarado-Gómez

EPIC (XMM-Newton)

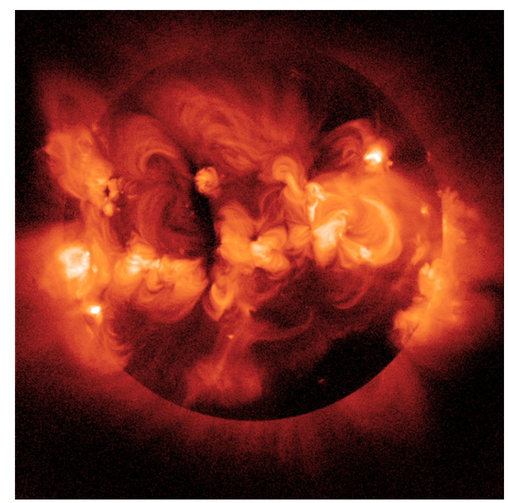
✓ 07638301
✓ DDT–94656
✓ 80338

PI: Sanz-Forcada

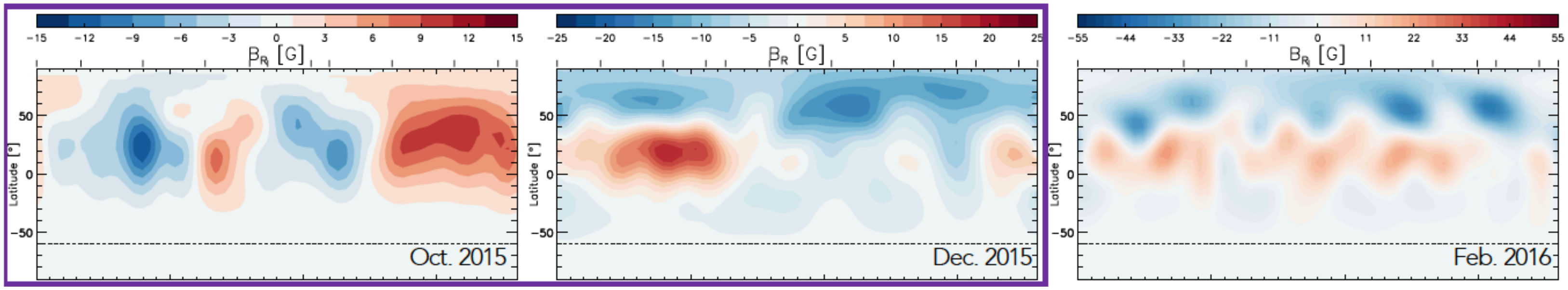
STIS (HST – Cycles 25 & 26)

▶ GO15299 ‖ GO15512

PI: Alvarado-Gómez

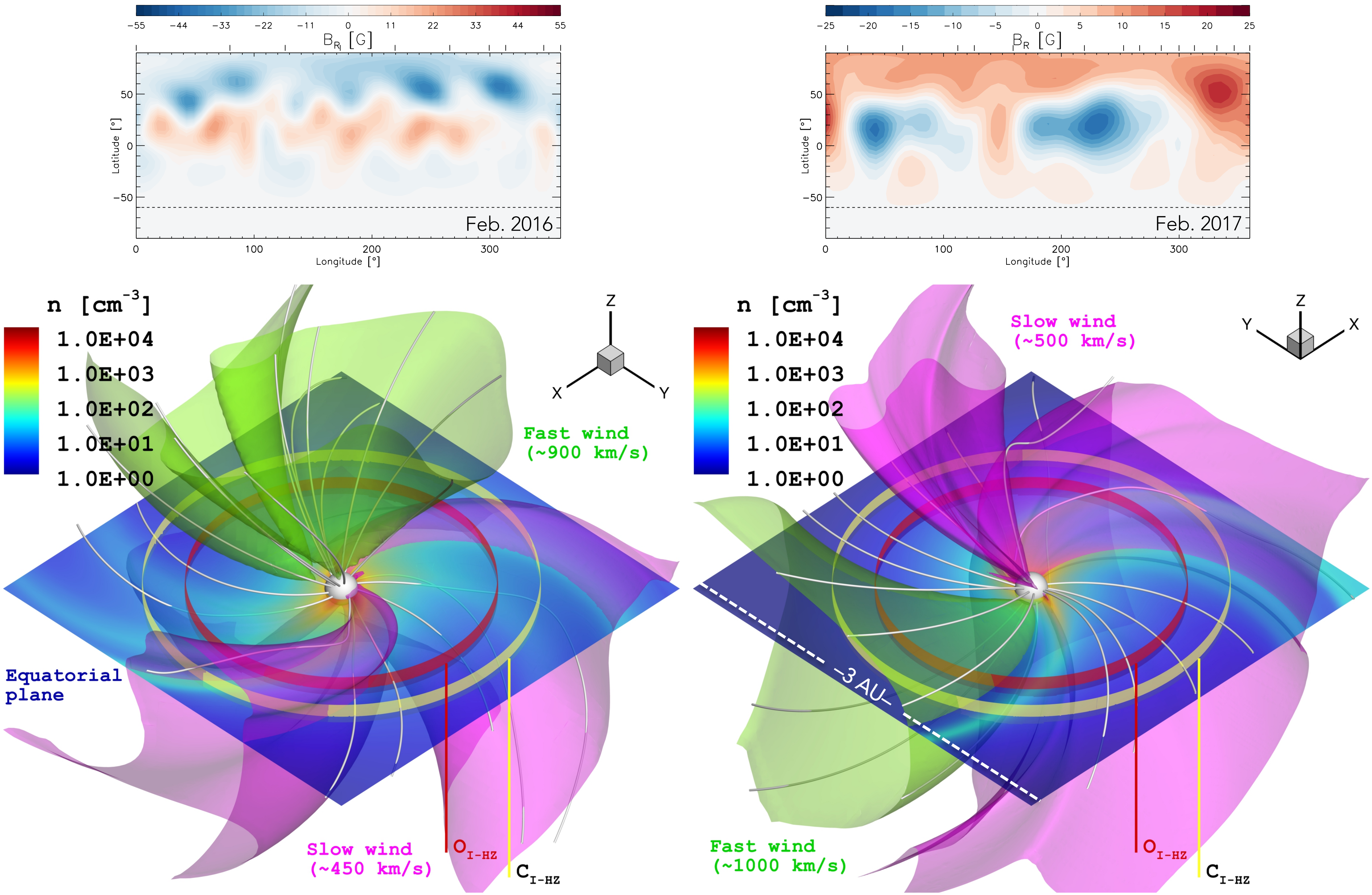


ι Horologii: Radial Magnetic Field Evolution

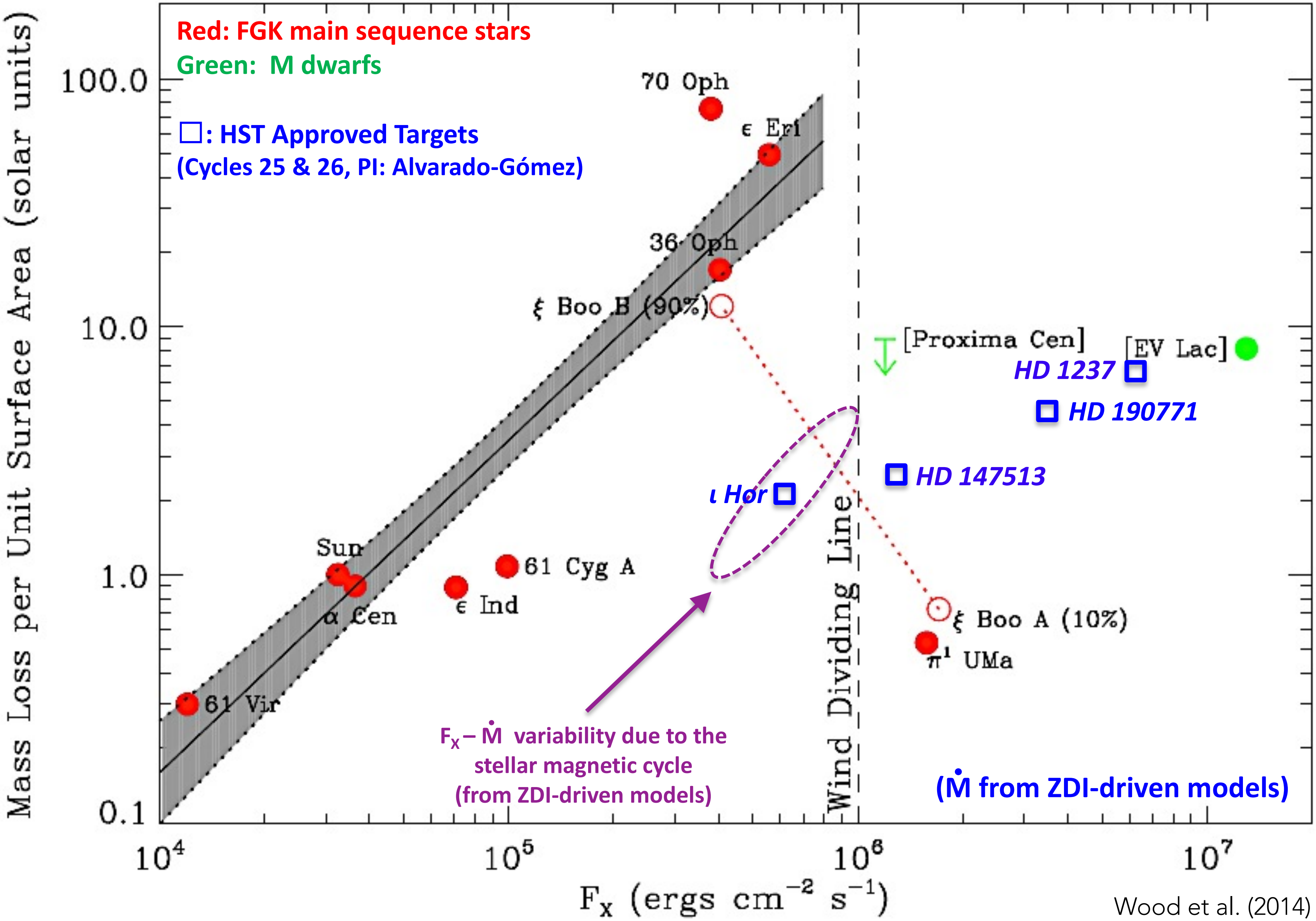


The space weather of ι Horologii through its magnetic cycle

Alvarado-Gómez et al. (in prep)



Mass loss and Astrospheres: Variability and the "dividing line" of stellar winds



Wood et al. (2014)

Concluding remarks:

- Magnetic suppression is a viable mechanism for reducing the flare-CME association rate in active stars. The large-scale field tends to reduce the speed and energy of the CMEs.

- Our 75 G dipole simulations are idealized but still plausible conditions for ~0.6 – 0.8 Gyr old F-G-K main-sequence stars.

  The complexity of the large-scale magnetic field needs to be considered.

- Influence from CME suppression in the mass loss budget in active stars?

  Will depend on whether small or large flares dominate the properties of the corona.

- Activity cycles detected in cool stars? Many. Magnetic cycles? Only a handful. Do they behave like the solar one? Not really. Need more systems? Yes please!

- Variability in the large-scale field should modify the space weather conditions significantly (e.g. corona, stellar wind, astrosphere).

- The era of exo-space weather is here.

  Stay tuned for more results from the "Far Beyond the Sun" campaign!