# The "Missing Stellar CME Conundrum": Lessons from the Sun

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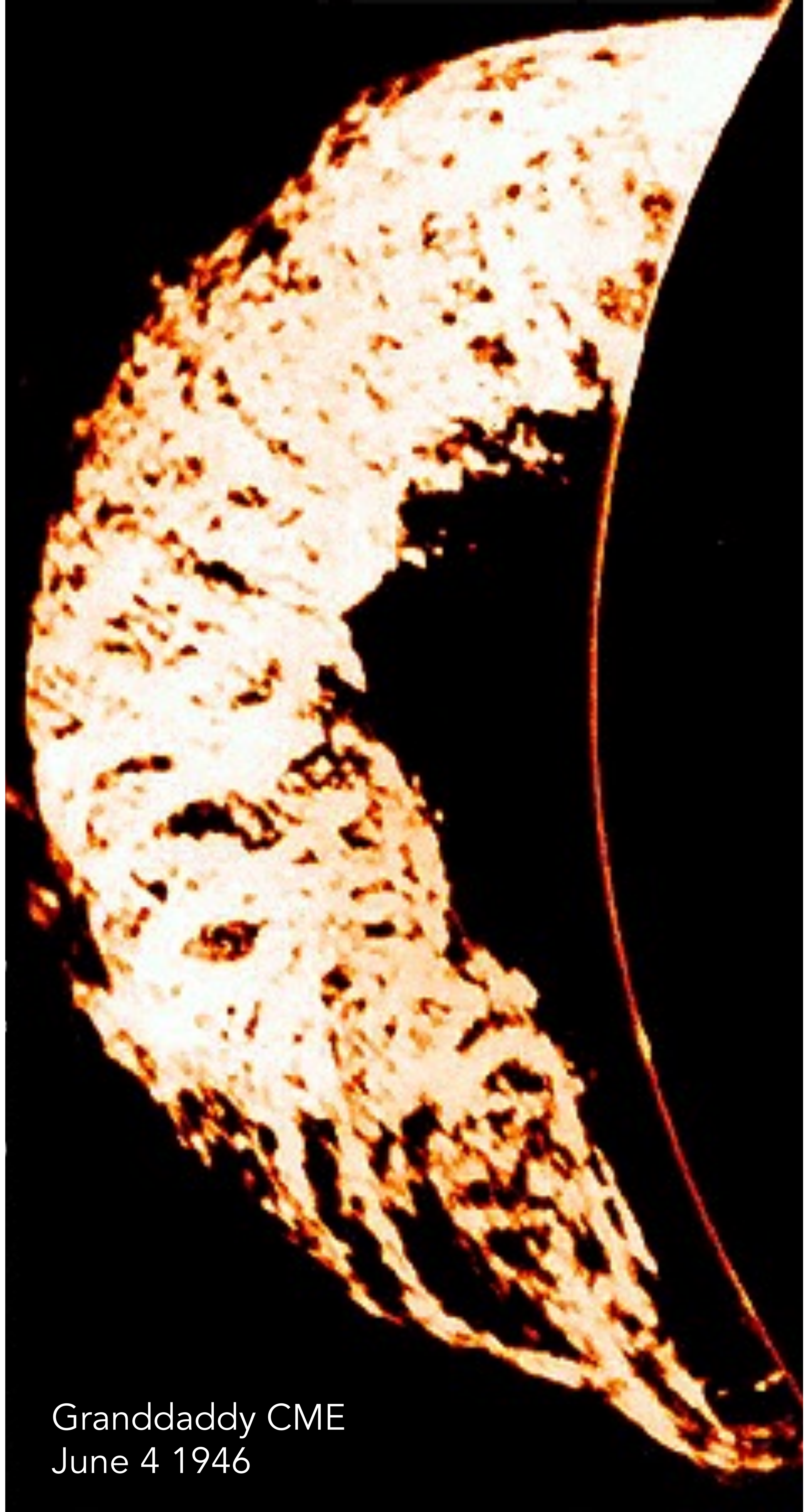
# Outline

- Introduction: "missing stellar CME conundrum"
- Lessons from the Sun: "failed eruptions" [Sun+ 2015]
- Proposal: suppression of the Torus Instability [Sun, Török, & DeRosa 2022]
- Outlook: data-constrained simulations

HAO



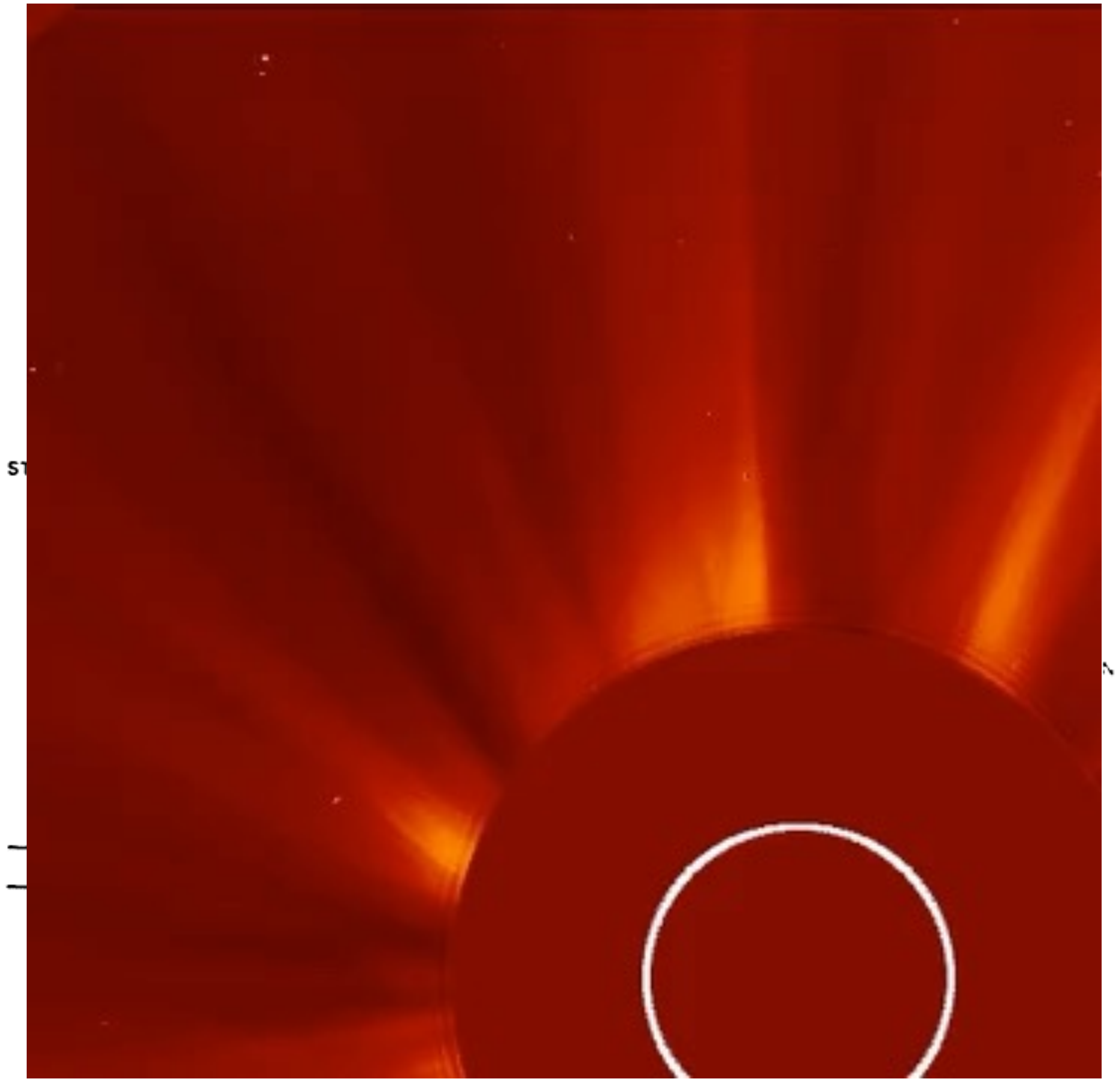
Granddaddy CME
June 4 1946

# Solar Flare & CME as magnetic phenomena

- Magnetic energy is gradually stored in coronal magnetic field, and released rapidly

- **Magnetic flux rope** becomes CME; reconnection powers flare; both can drive energetic particles

- Two aspects of a same process, but one can occur without another

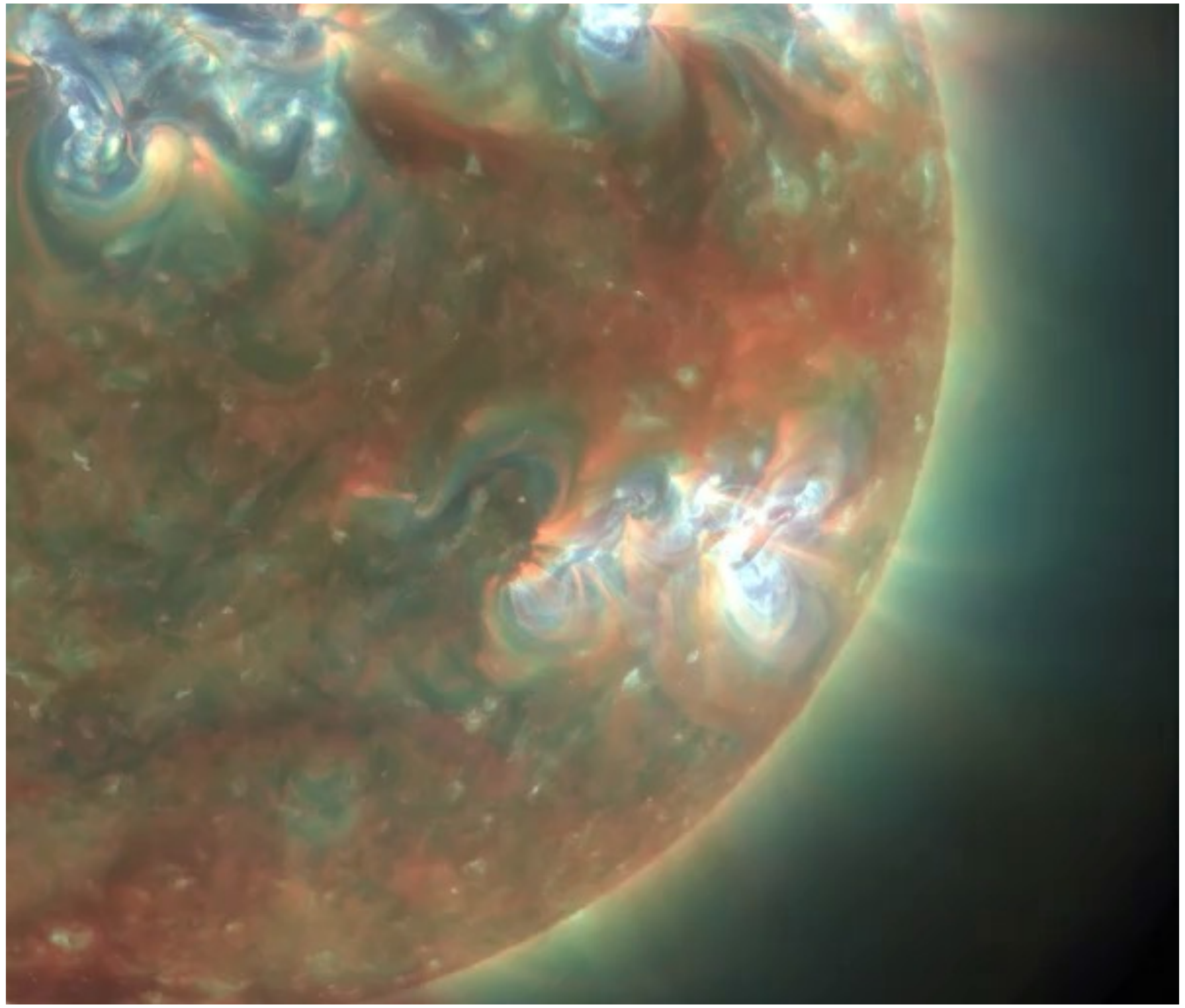


SoHO/LASCO

Martens & Kuin (1989)

# Flare & CME in Broader Context

- **Plasma physics:** magnetic reconnection, particle acceleration …
- **Stellar astrophysics:** accretion, loss of angular momentum …
- **Exoplanet habitability:** UV/X-ray & hi-energy particle flux; atmospheric loss …



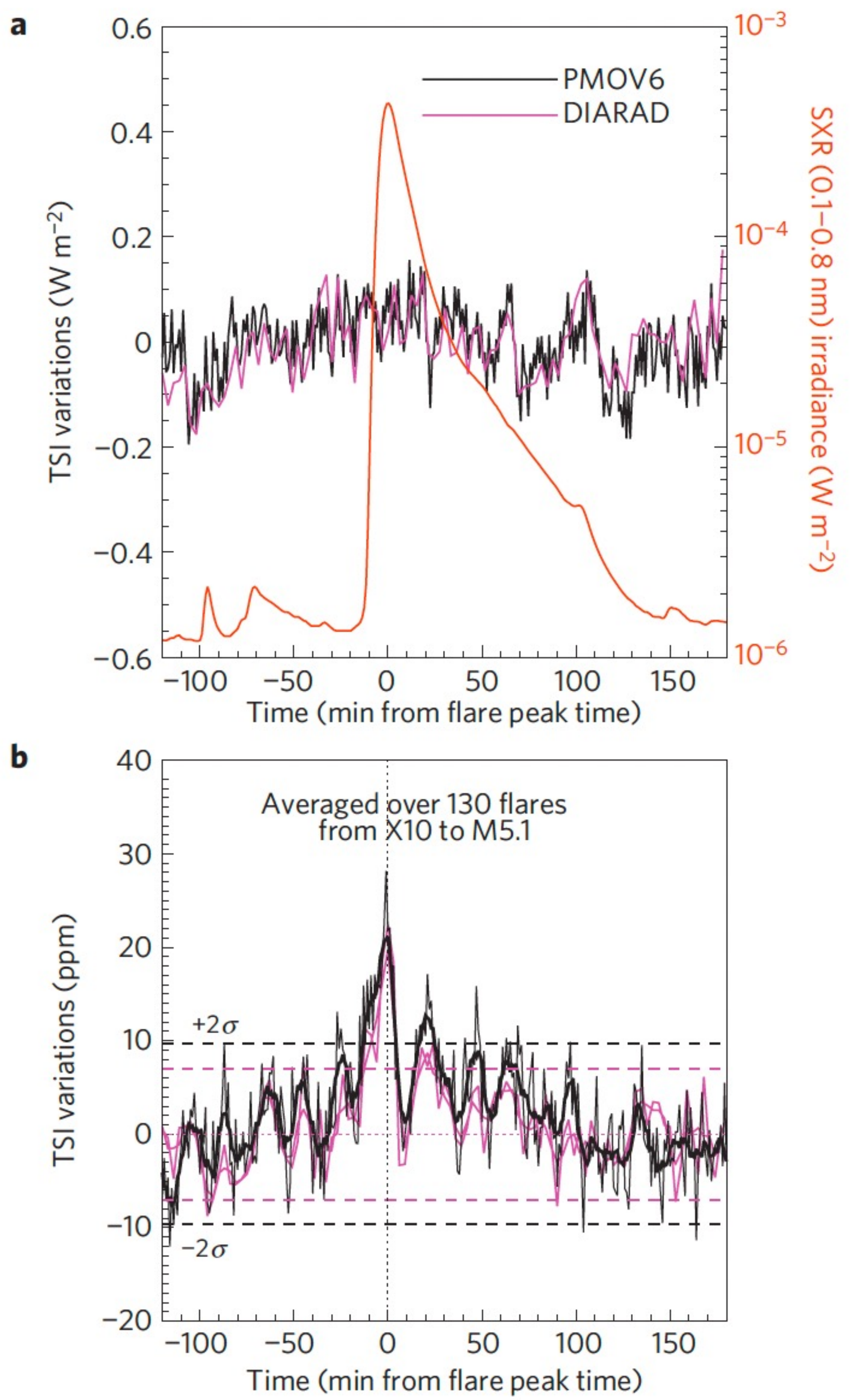
SDO/AIA

# Flare on Cool Stars

- Optical survey found thousands of "super flares" on G/K/M stars with energy $10^{34}$-$10^{36}$ erg [Schaefer+ 2000; Maehara+ 2012; Davenport 2016; Howard+ 2019; Günther+ 2020]

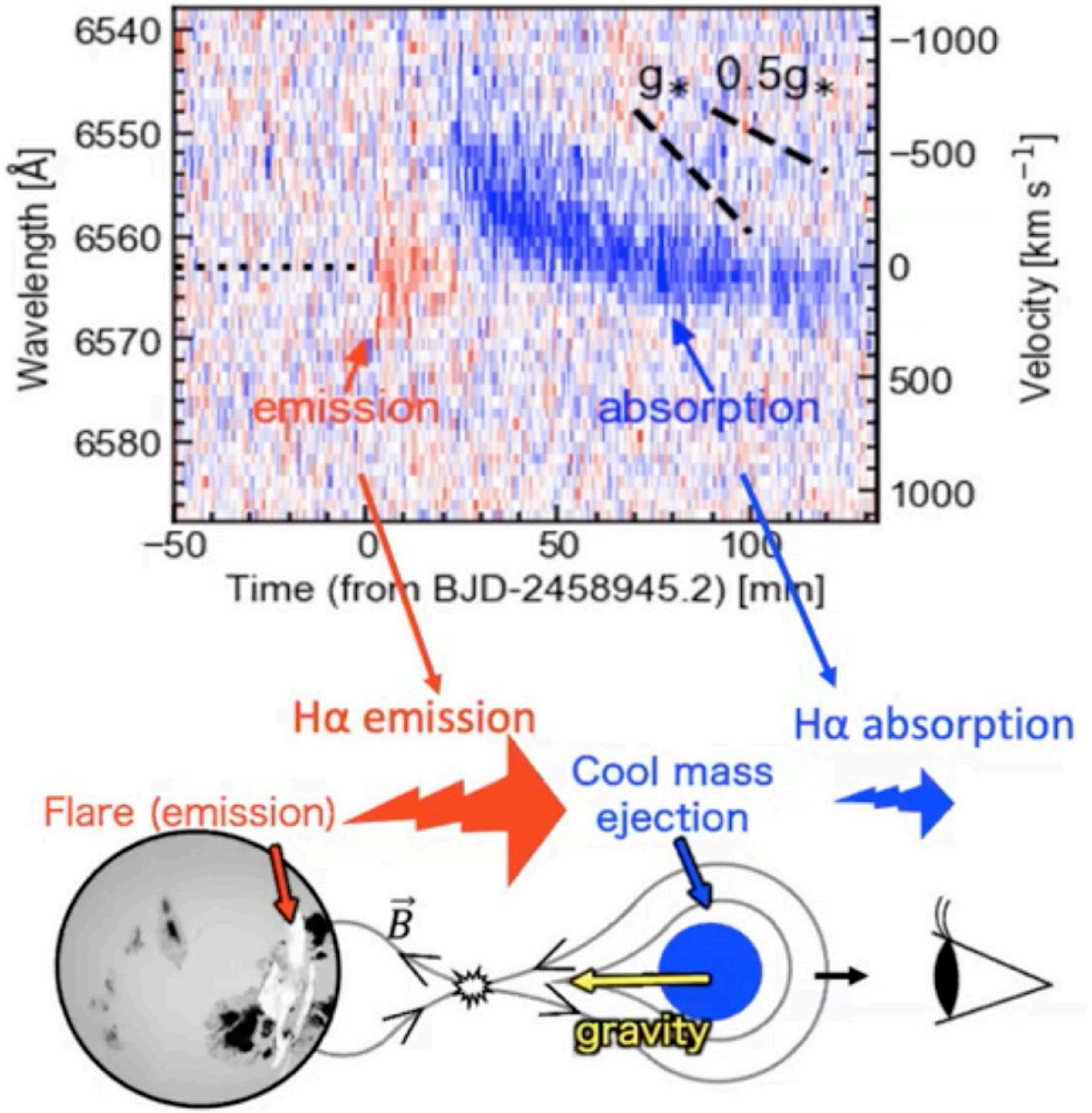
- Likely same physics: statistics follow the same power law as solar flares

- Likely also magnetically driven: stronger flares occur on stars that rotate faster, have larger spots [Notsu+ 2019]



# CME on Cool Stars

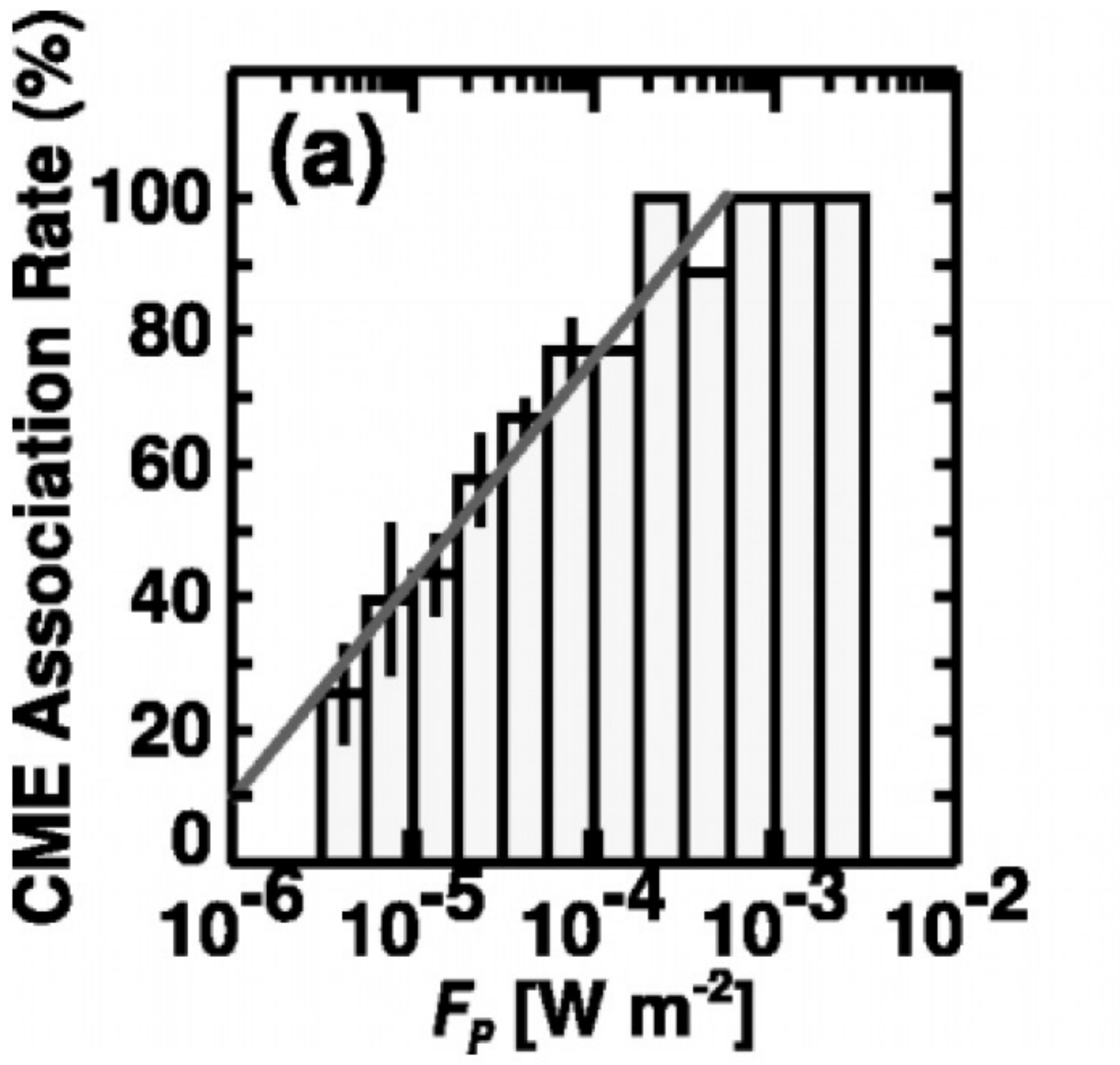
- CME detection is difficult for other stars: requires high-sensitivity spectral monitoring
- Detections are rare: only ~40 candidates via Doppler shift of Balmer lines, X-ray absorption, EUV/X-ray dimming [e.g. Moschou+ 2019; Argiroffi+2019; Veronig+ 2021]
- Recent dedicated optical + radio monitoring gave negative results [e.g. Crosley & Osten 2018; Villadsen & Hallinan 2019]




Namekata et al. (2022)

# The “Missing Stellar CME Conundrum”

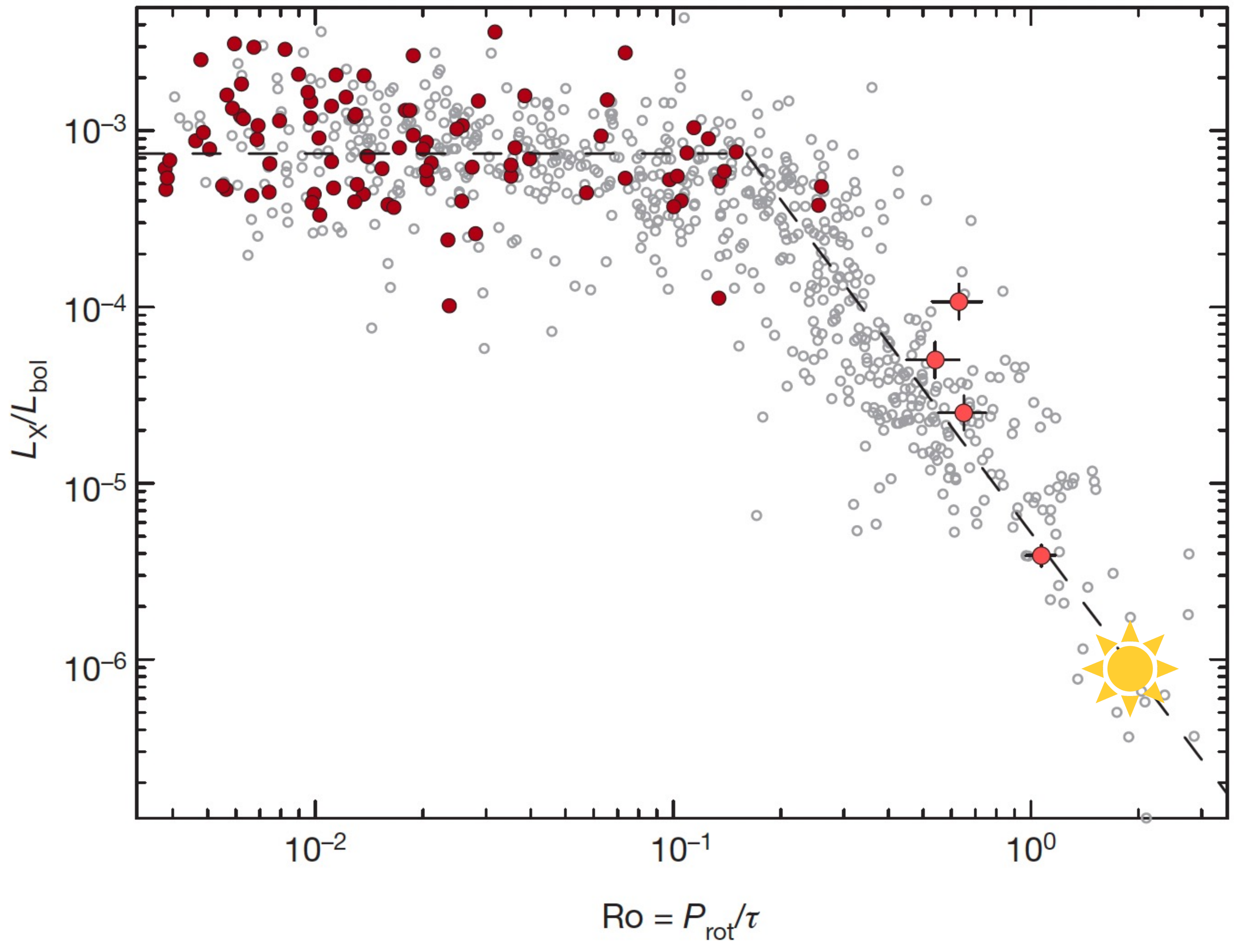
- Solar flare-CME association rate increases with flare energy: for large flares ~100% [Andrews 2003; Yashiro+ 2006]
- **Too few stellar CMEs** detection based on solar flare-CME association rate
- **Detected CME velocity too low** based on solar X-ray scaling [Aarnio+ 2011; Drake+ 2013; Moschou+ 2019]




Yashiro et al. (2006)

# Solution to the Conundrum?

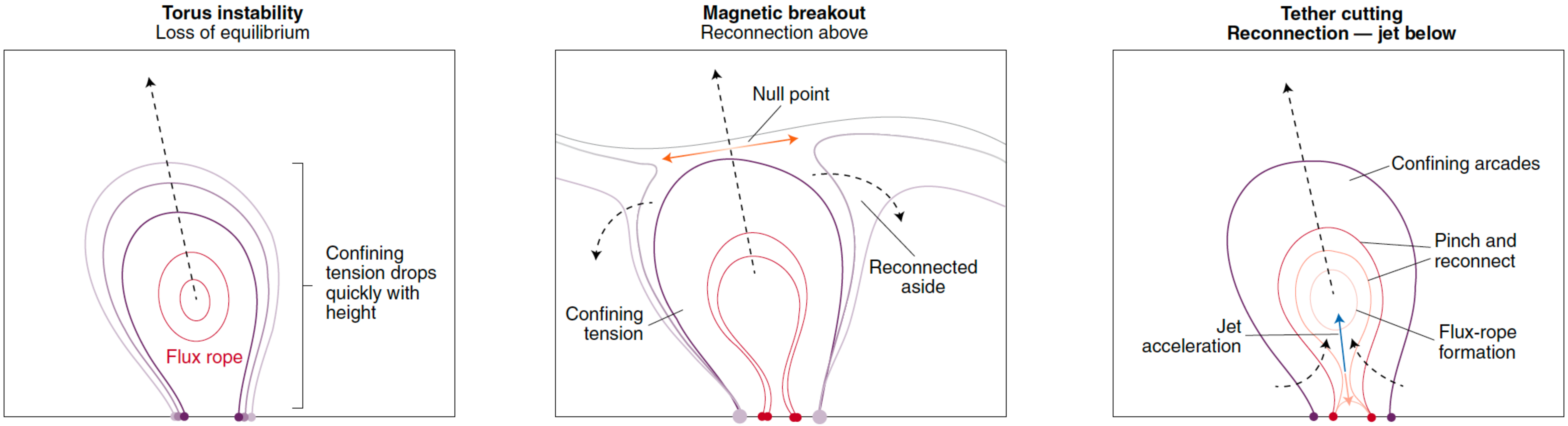
- Unlikely: observational bias
- Unlikely: Eruption due to different physics
- Possible: **Different magnetic environments**
- Sun is relatively inactive with weak magnetic field




Wright & Drake (2016)

# Theories of Solar CME

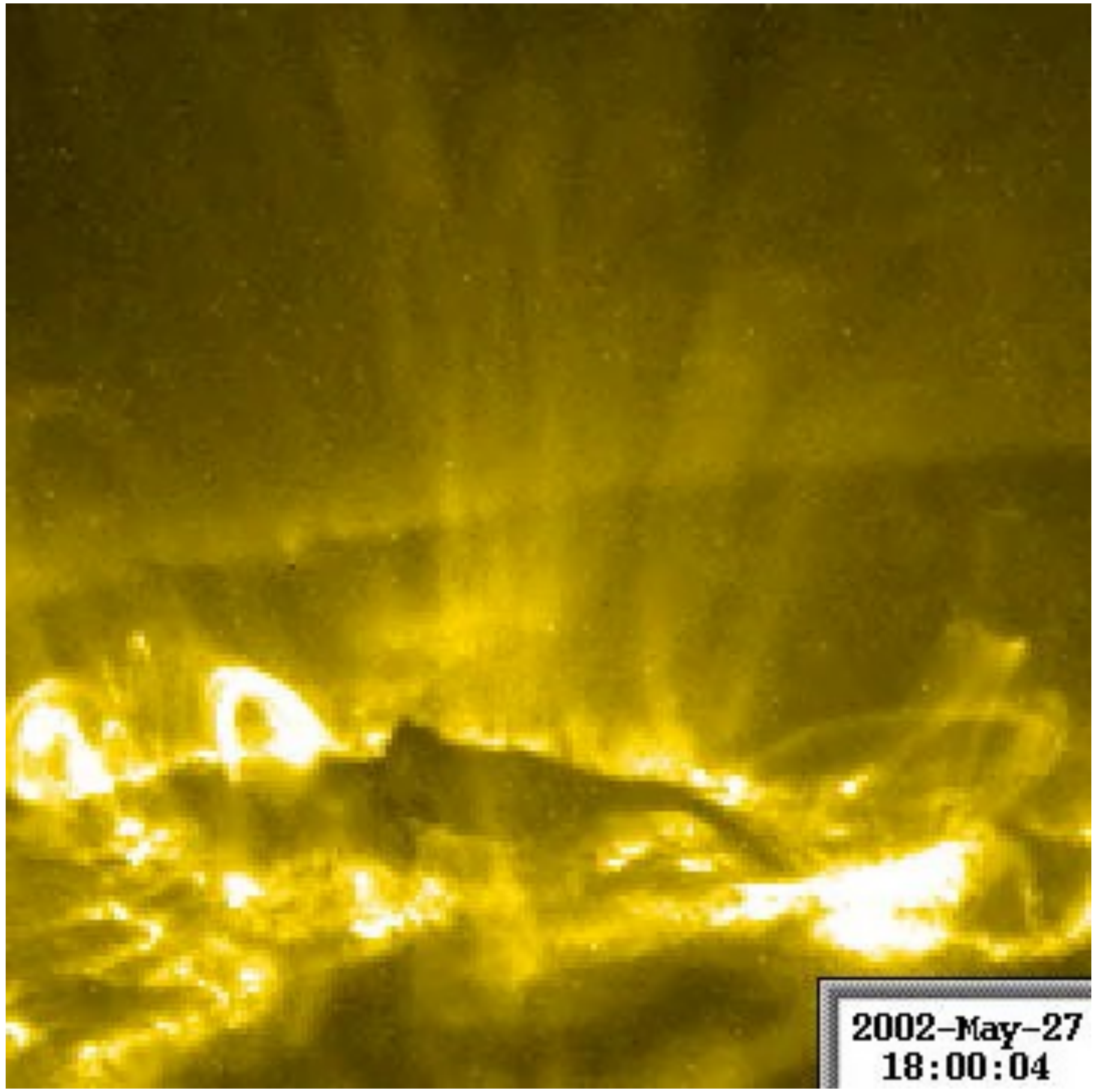
- Consensus: MFR is at the core CME; formation/driving mechanism under debate [e.g., Patsourakos+ 2020]
- **Expanding MFR** v.s. **confining background magnetic field** [e.g., Green+ 2019]




Aulanier (2021)

# "Failed Eruption"

- Most solar CMEs start with slow expansion, followed by impulsive acceleration [e.g., Zhang+ 2001]
- **Failed eruption:** some MFR starts to accelerate, but then decelerates and comes to a halt [e.g., Ji+ 2003; Green+ 2017; Zhou+ 2019]
- Intense magnetic reconnection still creates flare, but no CME ensuing [e.g., Liu+ 2018]

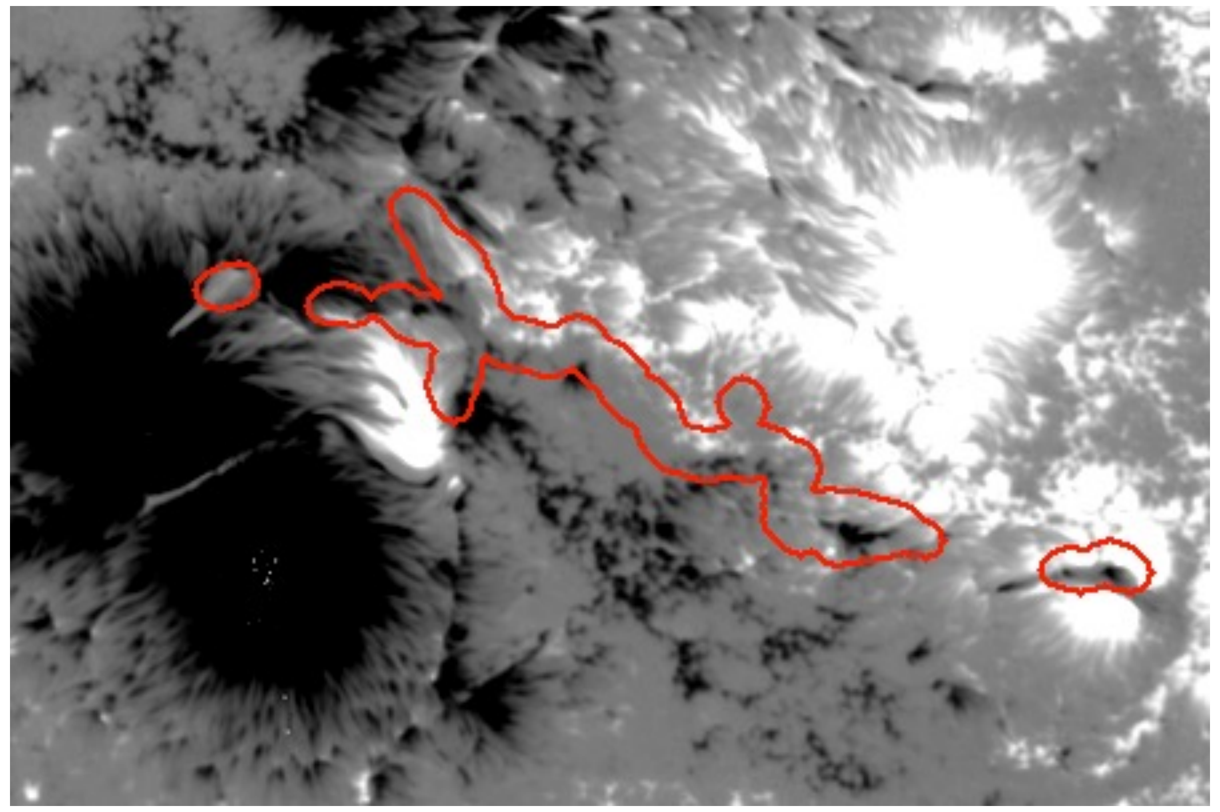



TRACE

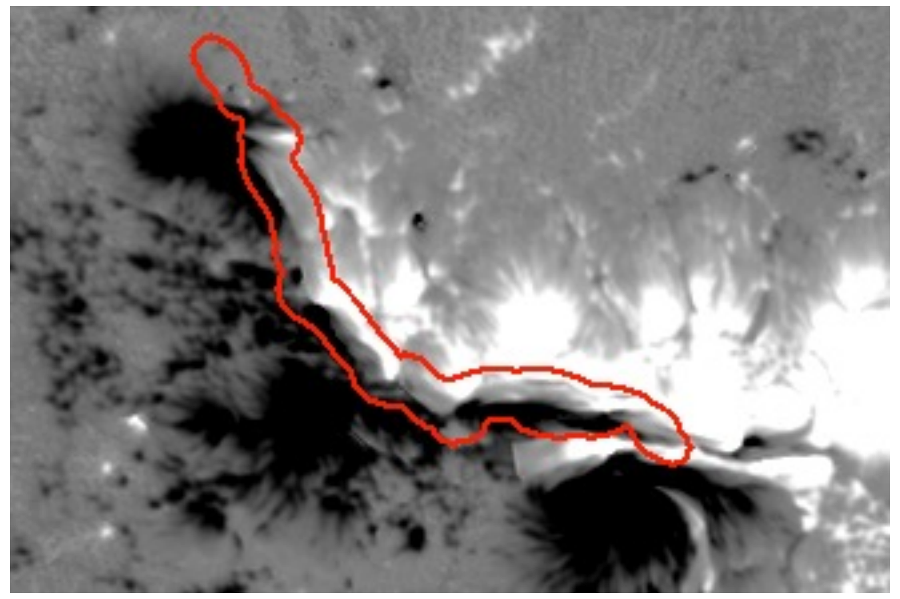
# The Gentle Giant: Active Region 12192

- AR 12192 (Oct 2014) hosted the largest sunspot group since 1990; most flare productive AR of cycle 24
- Extreme outlier: six X-class flares, but **no CME**!
- Comparison with other flare-CME-productive ARs: **less energetic MFR** + **stronger background field** [Sun+ 2015, using NLFFF by Wiegelmann+ 2012]

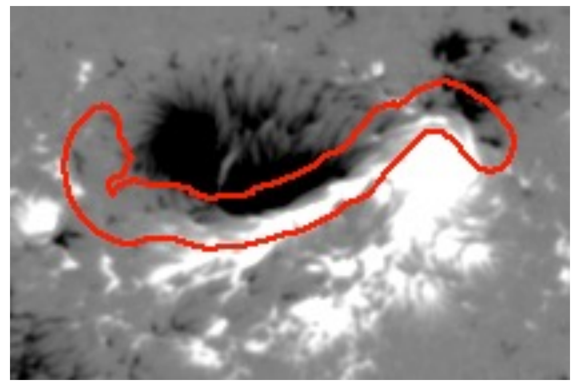
AR 12192



AR 11429



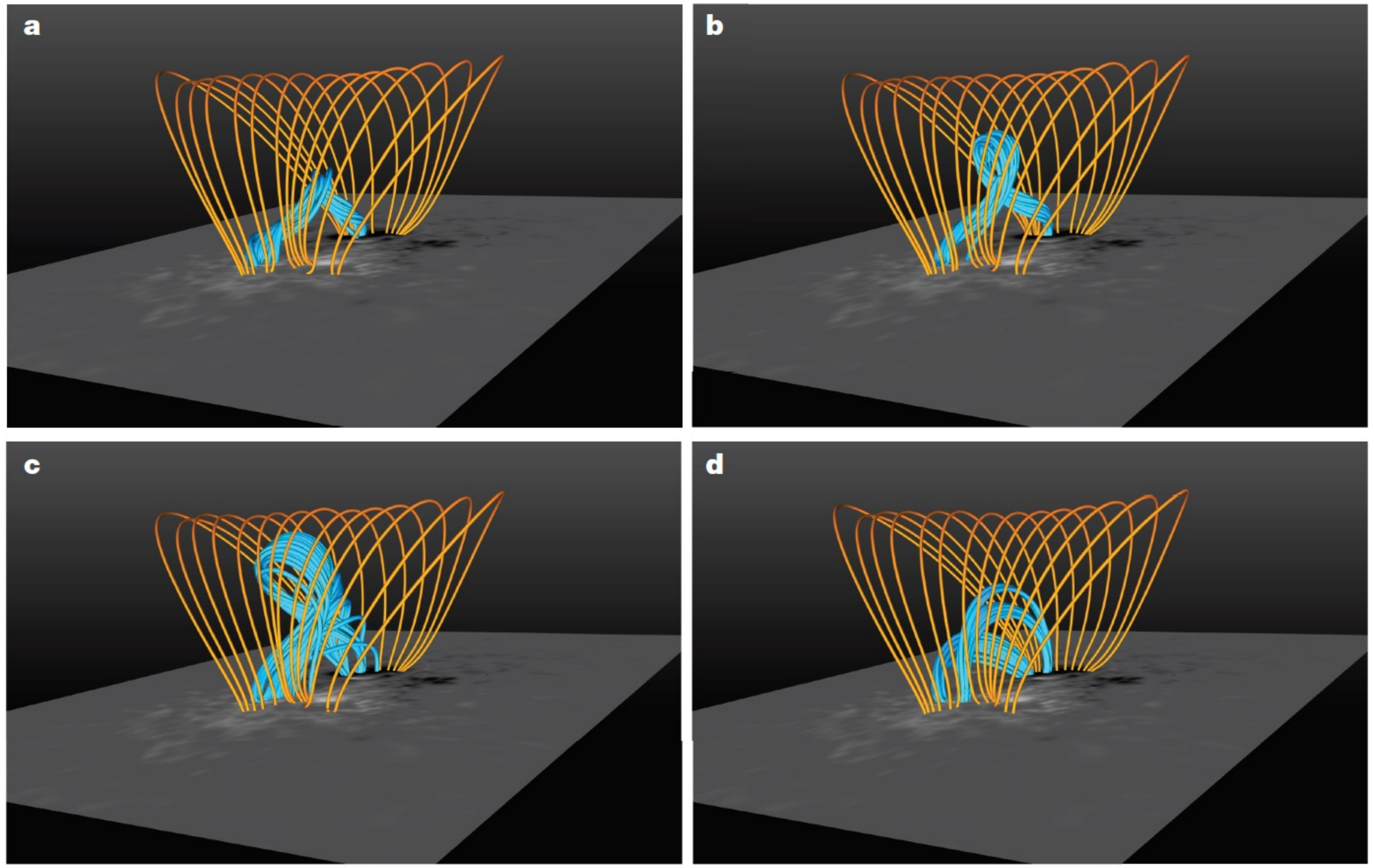
AR 11158



SDO/HMI

# Background Field Causes Failed Eruption

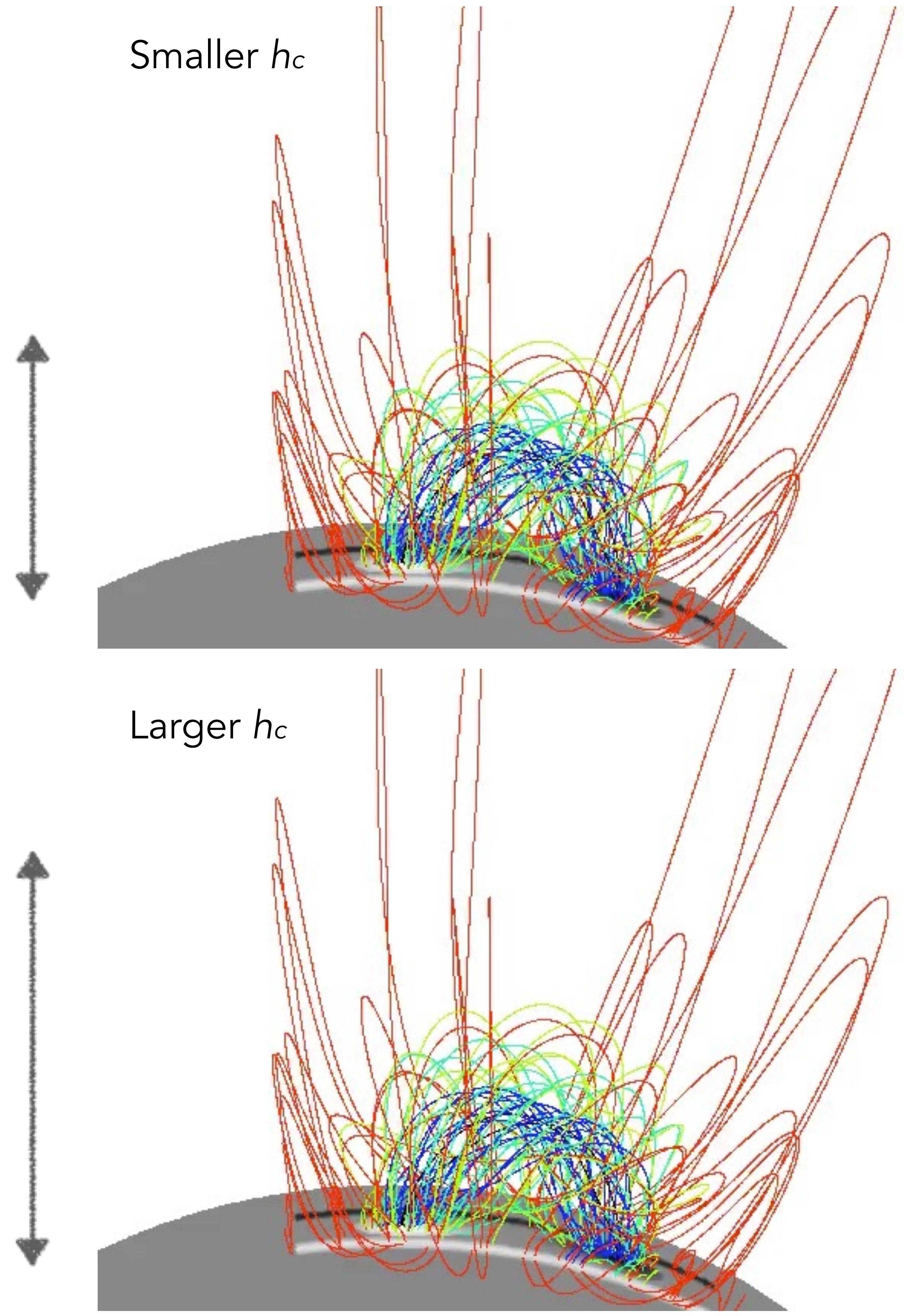
- AR 12192 serves as a "solar analogue" for stellar CME-less flares [Drake+ 2016; Olsten & Wolk 2017]
- Large solar ARs with $>10^{23}$ Mx magnetic flux produce exclusively CME-less flares! [Li+ 2021, 2022]
- Solar MHD code in stellar regime: efficacy of strong dipole verified [Alvarado-Gómez+ 2018, 2020]




Amari et al. (2018)

# Torus Instability (TI)

- Torus instability [Bateman 1978; Chen & Krall 2003; Kliem & Török 2006]
    - Expanding instability of toroidal magnetic flux rope
    - Suppressed by overlying magnetic field: failed eruption
- Background field decay index: $n = -\frac{\partial \ln B_p}{\partial \ln h} < n_c = 1.5$
- **Torus-stable zone (TSZ)**: $h < h_c|_{n=n_c}$



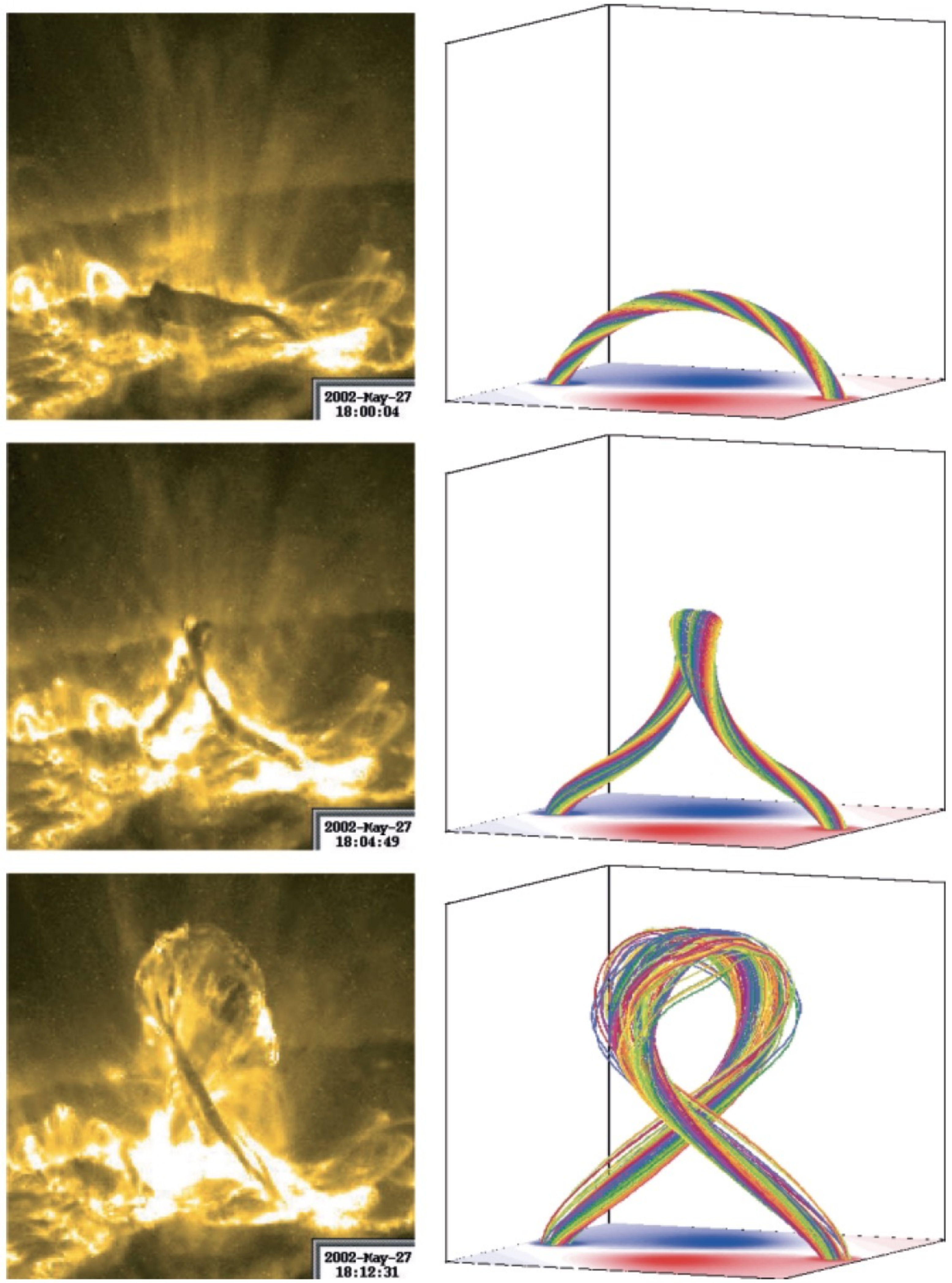

Fan (2010)

# Failed Eruption in Torus-Stable Zone

- Failed eruption can simultaneously explain flare emission and lack of CME detection

- **Mode 1:** in an extended TSZ, eruption can triggered by other mechanism (e.g. kink instability) [e.g. Ji+ 2003; Török & Kliem 2005]

- **Mode 2:** with a secondary TSZ at higher altitude, eruption can be triggered by TI or other mechanism at the torus-unstable layer at lower altitudes [cf. Wang+ 2017]



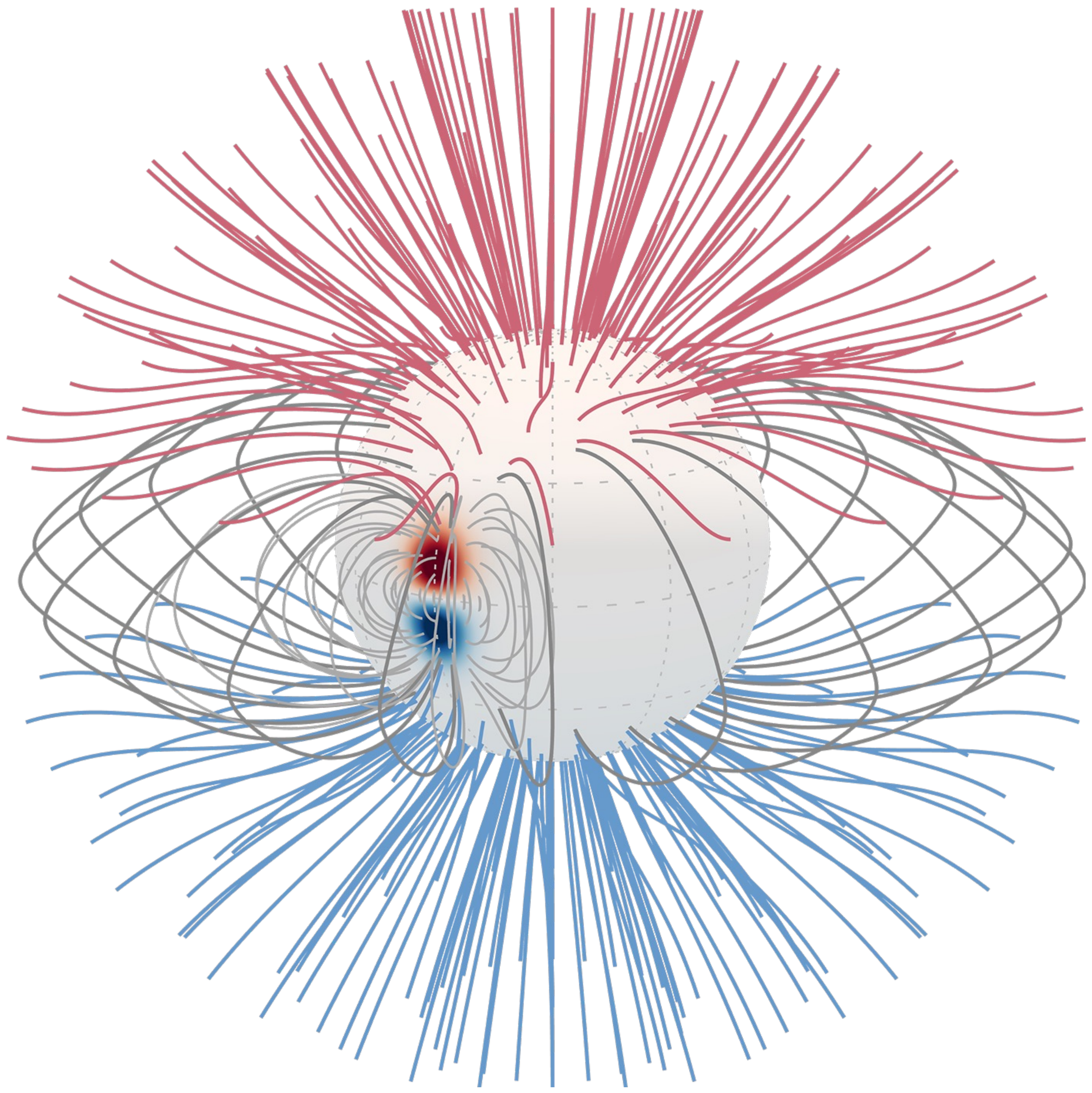

Török & Kliem (2005)

# An Idealized coronal field model

- Potential field source surface (PFSS) model
  - Axial dipole field
  - Magnetic bipole as a pair of starspots [Yeates 2020]

- Free parameters: larger for more active stars
  - Starspot (bipole) size $\rho \in [3°, 25°]$
  - Dipole strength $g_{10} \in [0, 1000]\mathrm{G}$
  - Source surface radius $R_s \in [2, 20] R_\star$

- Evaluate decay index profile $n(h)$ and critical height $h_c$



Sun, Török, & DeRosa (2022)

# Parameter 1: Starspot Size

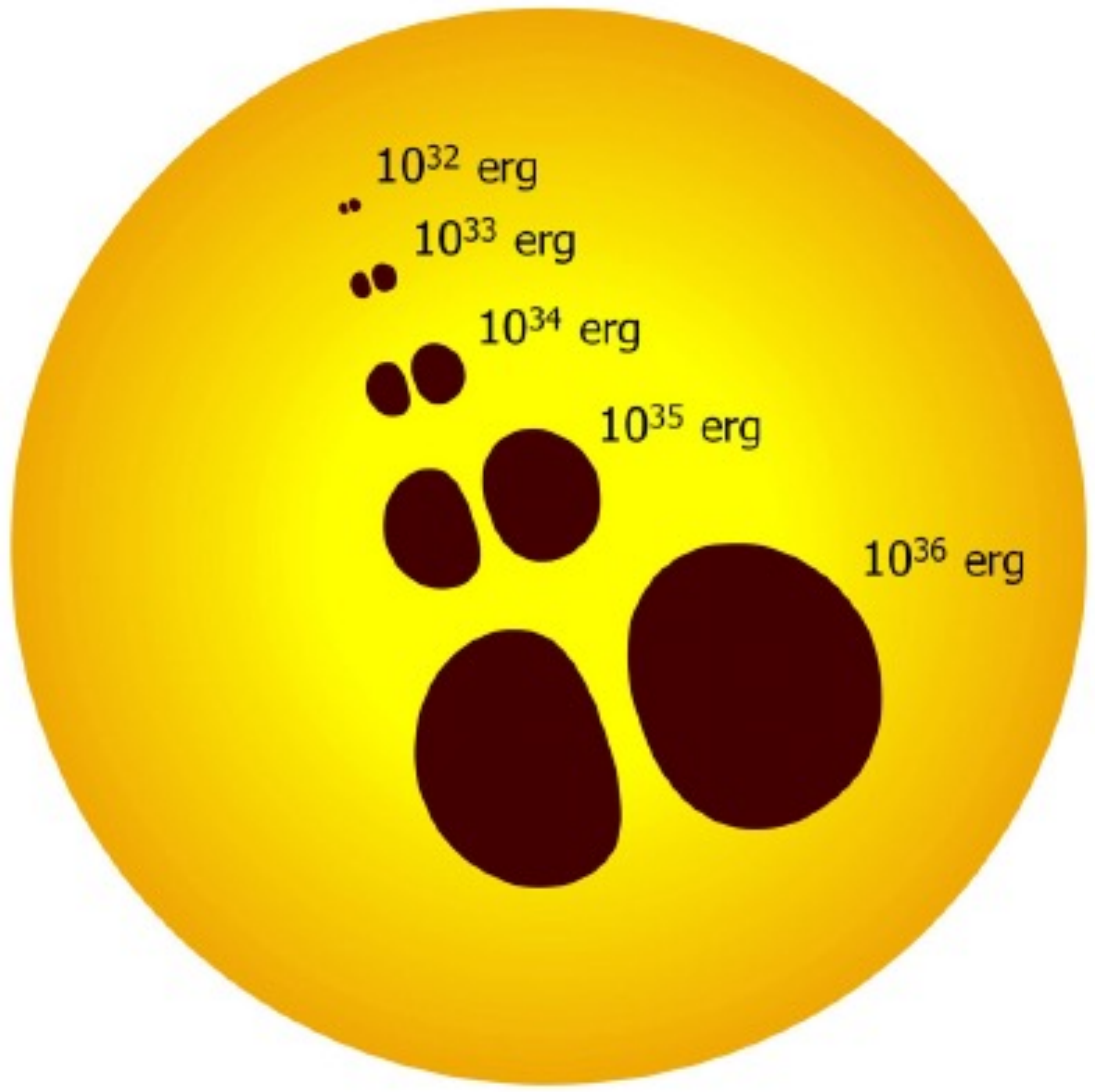
- Filling factor (size) / temperature inferred via: Doppler imaging, molecular band modeling; exoplanet transit; optical interferometry, etc.

- Magnetic field Field: Zeeman broadening; Zeeman Doppler imaging

- Spots on cool stars can be large; magnetic field strength similar to sunspots (a few kG)

…the spot's size is approximately… 60 times the extension of the largest ever observed sunspot group or 10,000 times its areal coverage. Such dimensions may have an impact on the local hydrostatic equilibrium because a sunspot-like Wilson depression would make the star look like the logo of a well-known computer company.

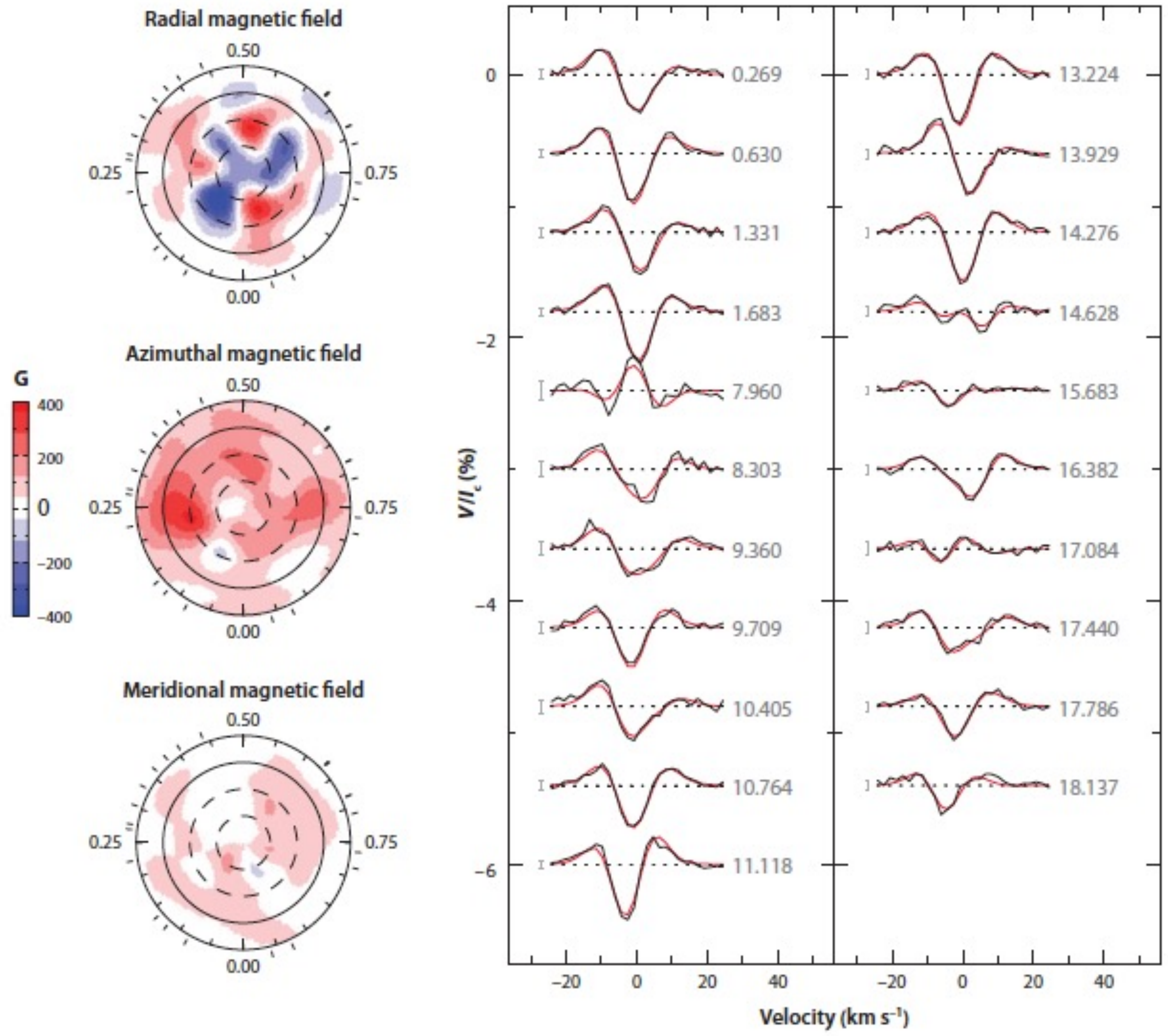
Strassmeier (2005)




Aulanier et al. (2013)

# Parameter 2: Large-Scale Magnetic Field

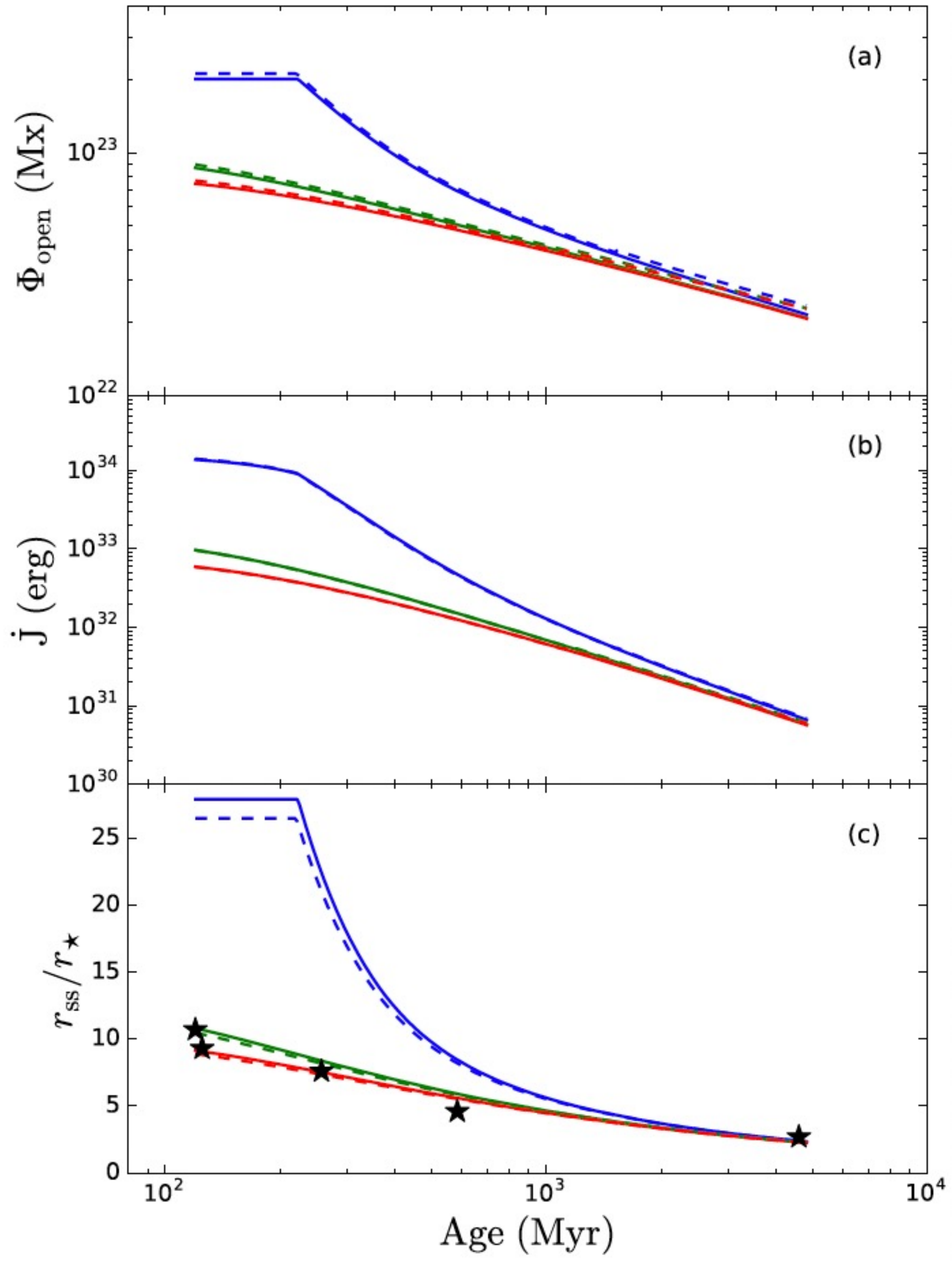
- Zeeman Doppler Imaging (ZDI): from modulation of *I*, *V* to spatial maps of ***B***
- Recovers $l \lesssim 5$ & 10% of magnetic energy; **insensitive to starspots** [Lehmann+ 2019]
- Inversely correlated with Rossby number ($\mathrm{Ro}$); saturates at $\mathrm{Ro} \approx 0.1$ [e.g., Wright+ 2011]
- M-dwarfs can have kG dipole field




Donati & Landstreet (2009)

# Parameter 3: Source Surface Radius

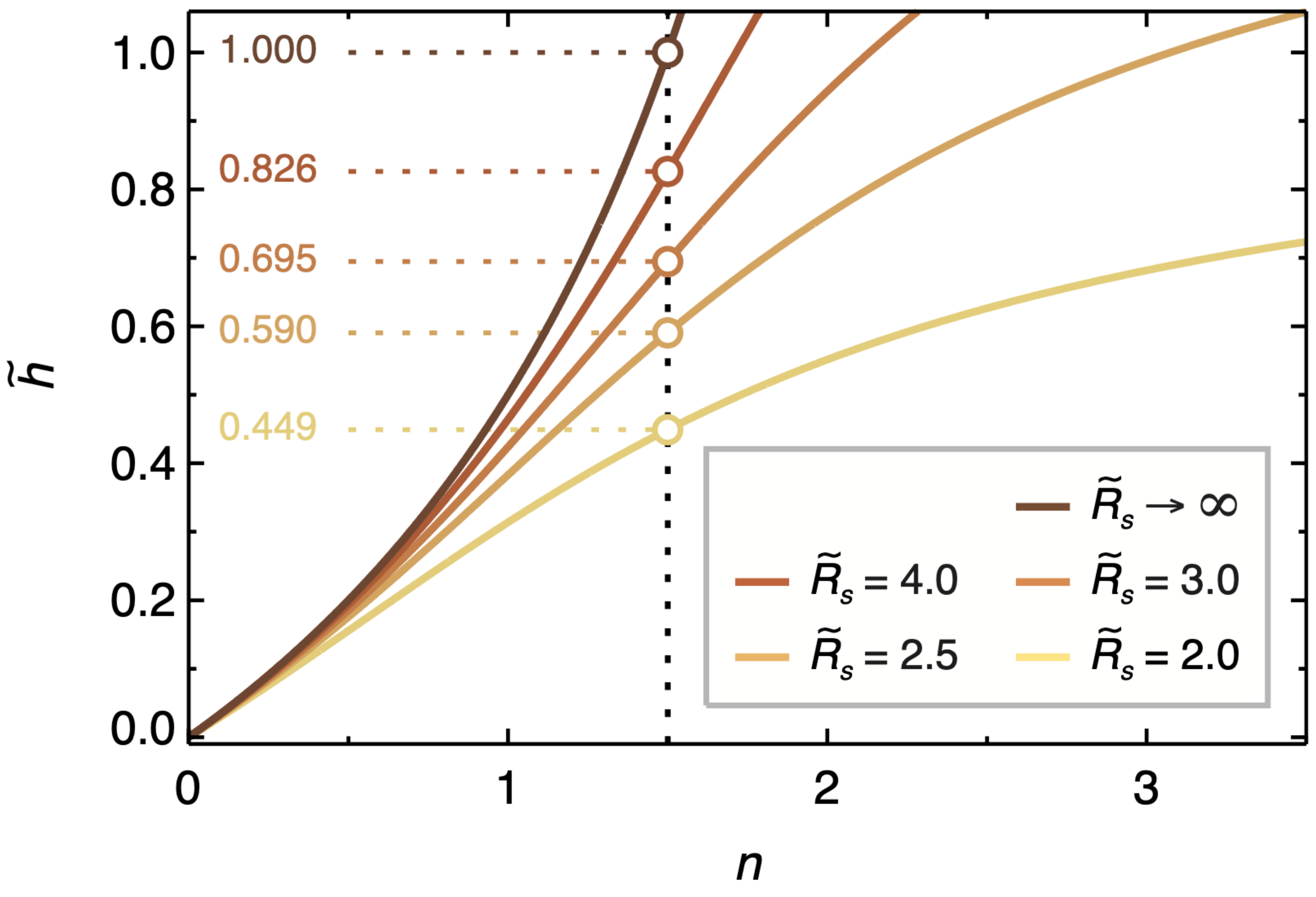
- Height where coronal field opens to stellar wind: larger $R_s$ leads to more closed magnetic topology
- For the Sun, $R_s$ can be determined by comparing model results with coronal observations
- For cool stars, $R_s$ increases with surface activity to reproduce observed spin-down rate, or to match open flux from *ab initio* stellar wind MHD [Shcrijver+ 2003; Reville+ 2015, 2016; See+ 2017, 2018]

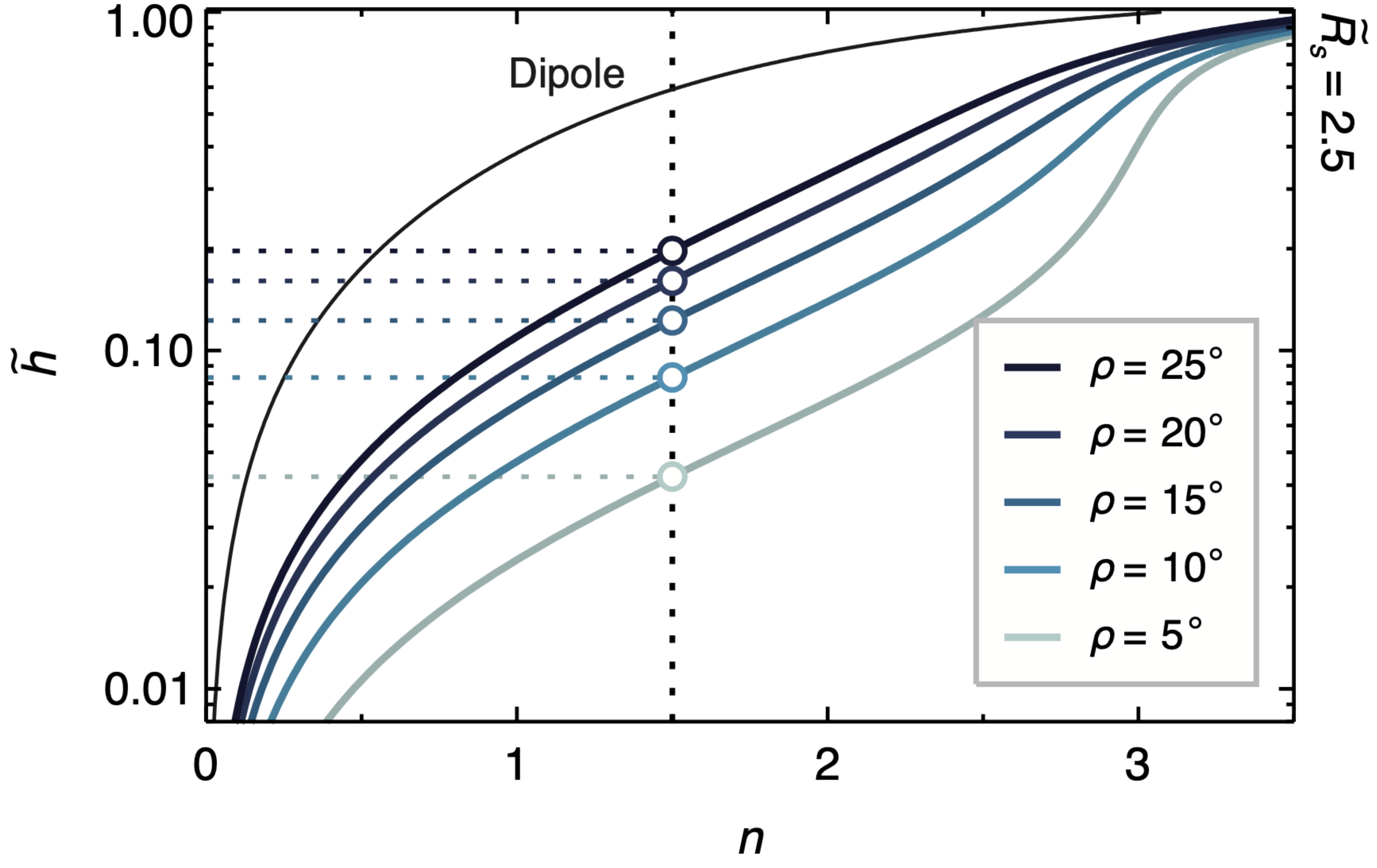



See et al. (2018)

# TSZ for dipole or spots

- For dipole, $h_c \in [0.45, 1]R_\star$ depends on $R_s$ alone
- For starspots, $h_c \approx 0.5\rho R_\star < 0.2R_\star$ (half bipole size)

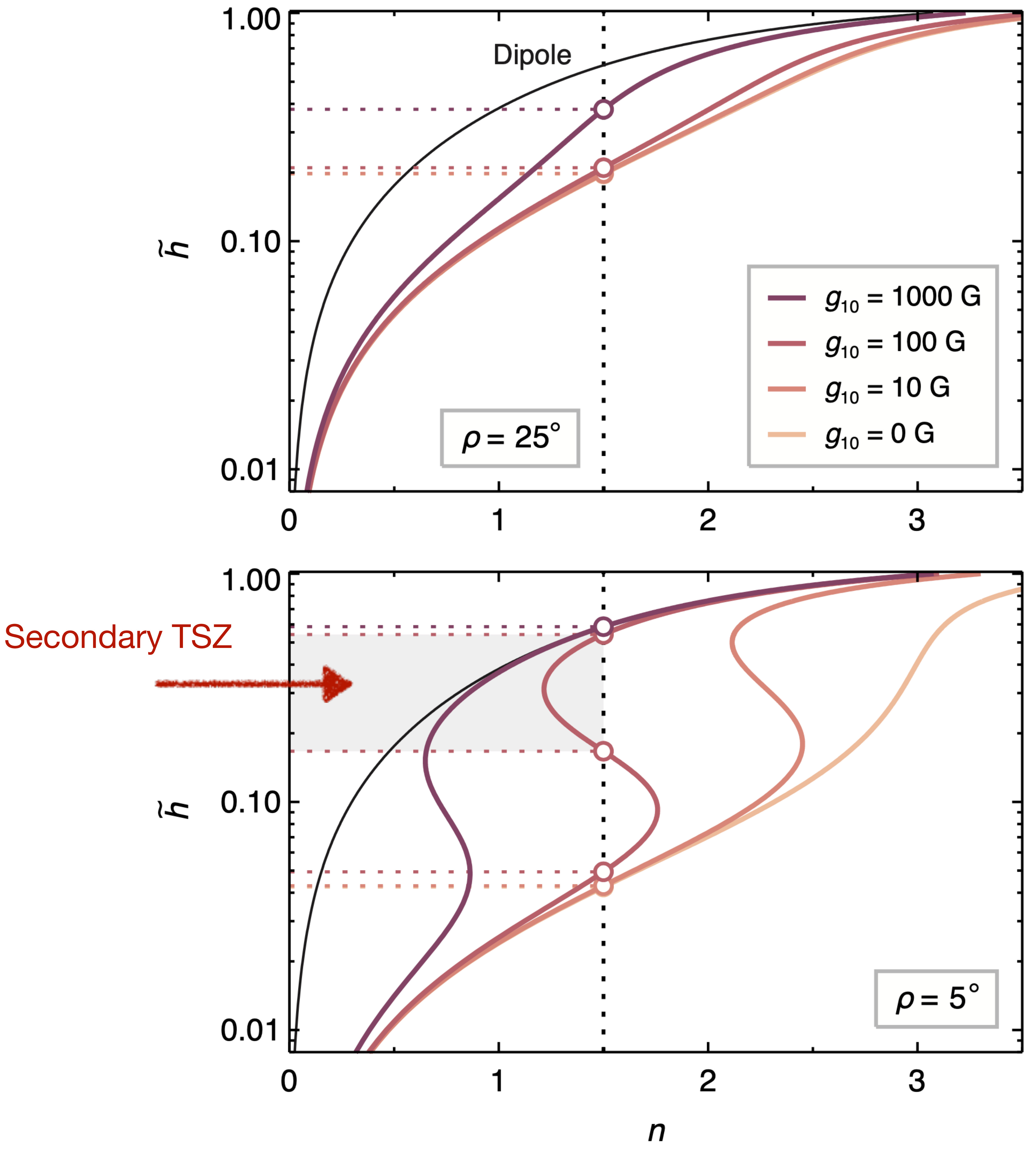



Sun, Török, & DeRosa (2022)

# TSZ for dipole + spots

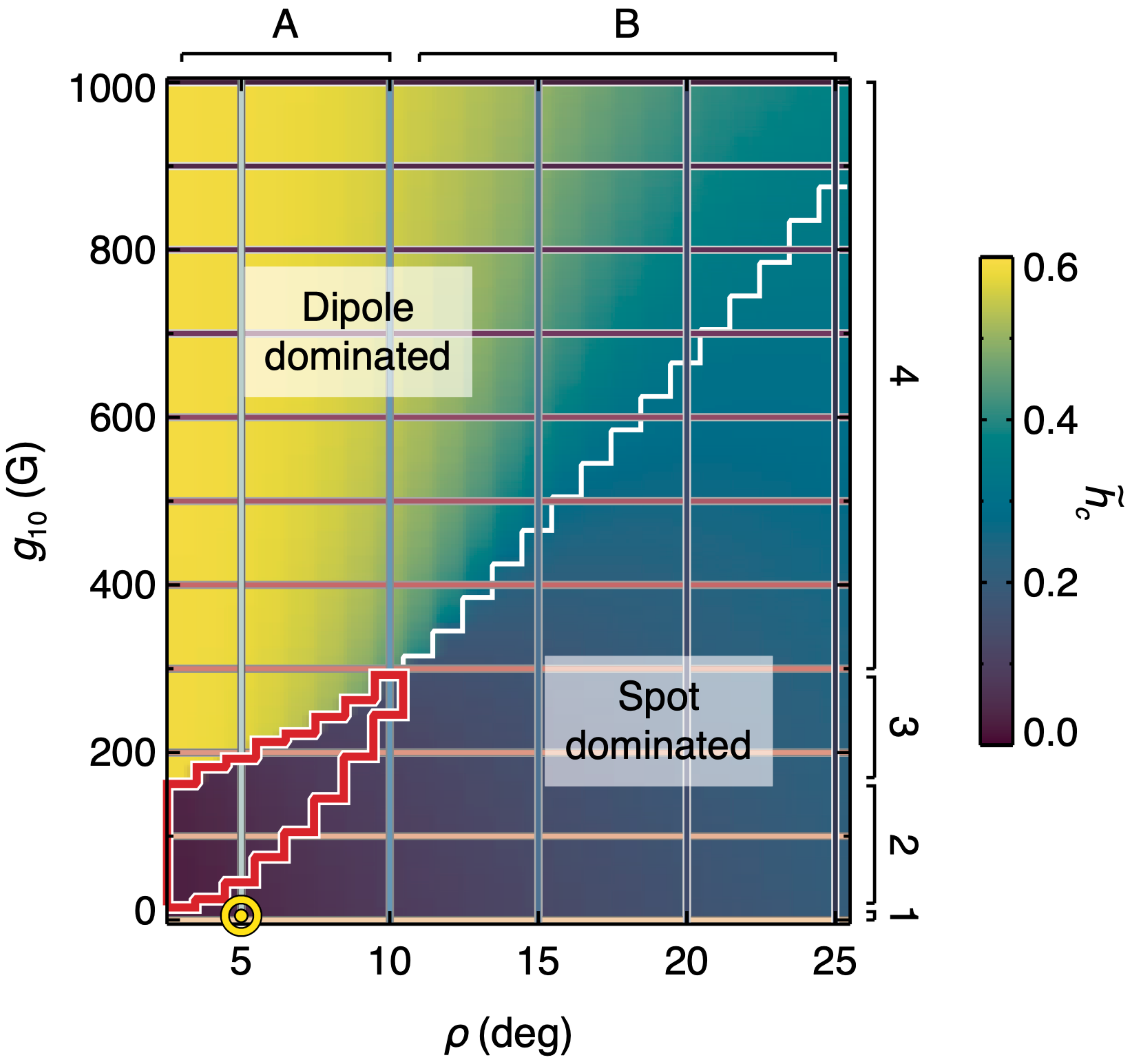
- For large starspots ($\rho = 25°$), dipole field boosts $h_c$ by tens to a hundred percent
- For typical solar spots ($\rho = 5°$), 1000 G dipole increases $h_c$ by 10 times
- For typical solar spots ($\rho = 5°$), 100 G dipole creates a secondary TSZ: ideal for failed eruptions
- TSZ depends on interplay between starspots & dipole: **local- vs global-scale confinement**




Sun, Török, & DeRosa (2022)

# TSZ for dipole + spots

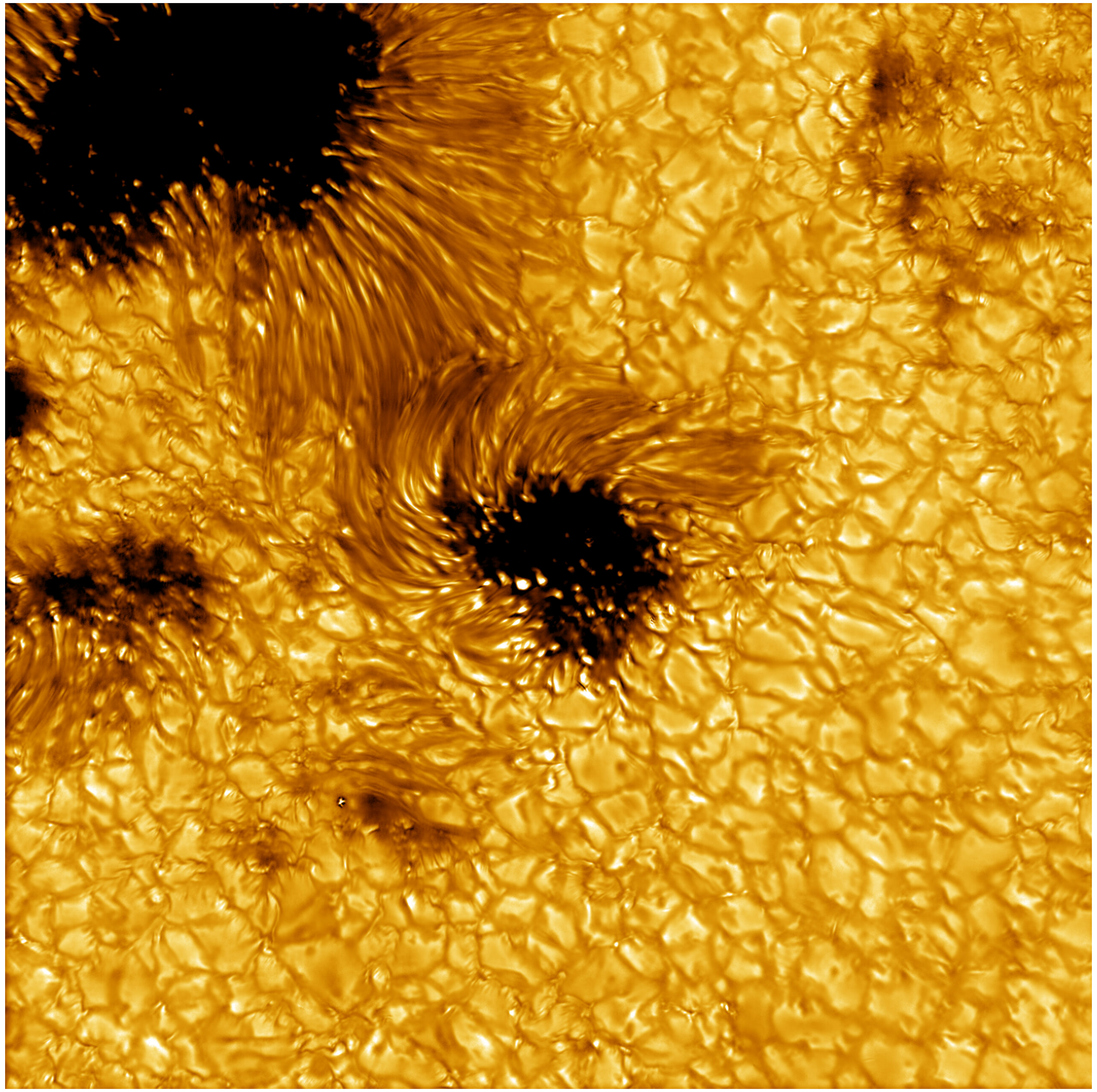
- The $(\rho, g_{10})$ plane can be divided to dipole- and spot-dominated regimes
- The solar eruption is controlled by spots alone; it occupies a tiny fraction of the parameter space!
- Only smaller spots and intermediate dipole leads to secondary TSZ
- Larger $R_s$ leads to higher TSZ




Sun, Török, & DeRosa (2022)

# Caveat

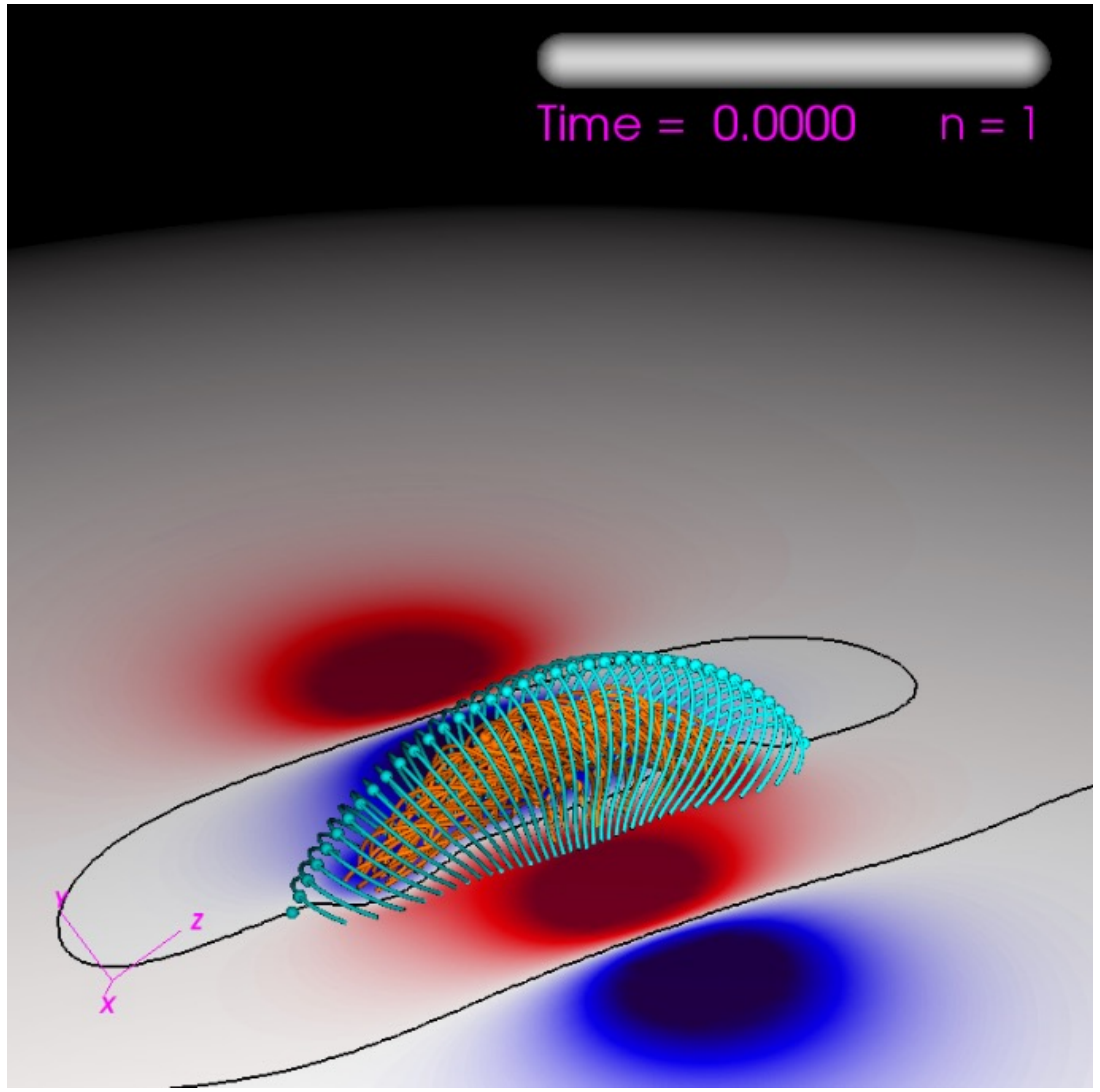
- First-order estimate: realistic case can be much more complicated
  - Spots & dipole are likely not aligned
  - High-latitude, fragmented, nested spots
  - Quadrupolar & octupolar components
- Static model, no MFR, no dynamics
- Alternative scenarios: flare without MFR? CME without flare?



NSF/DKIST

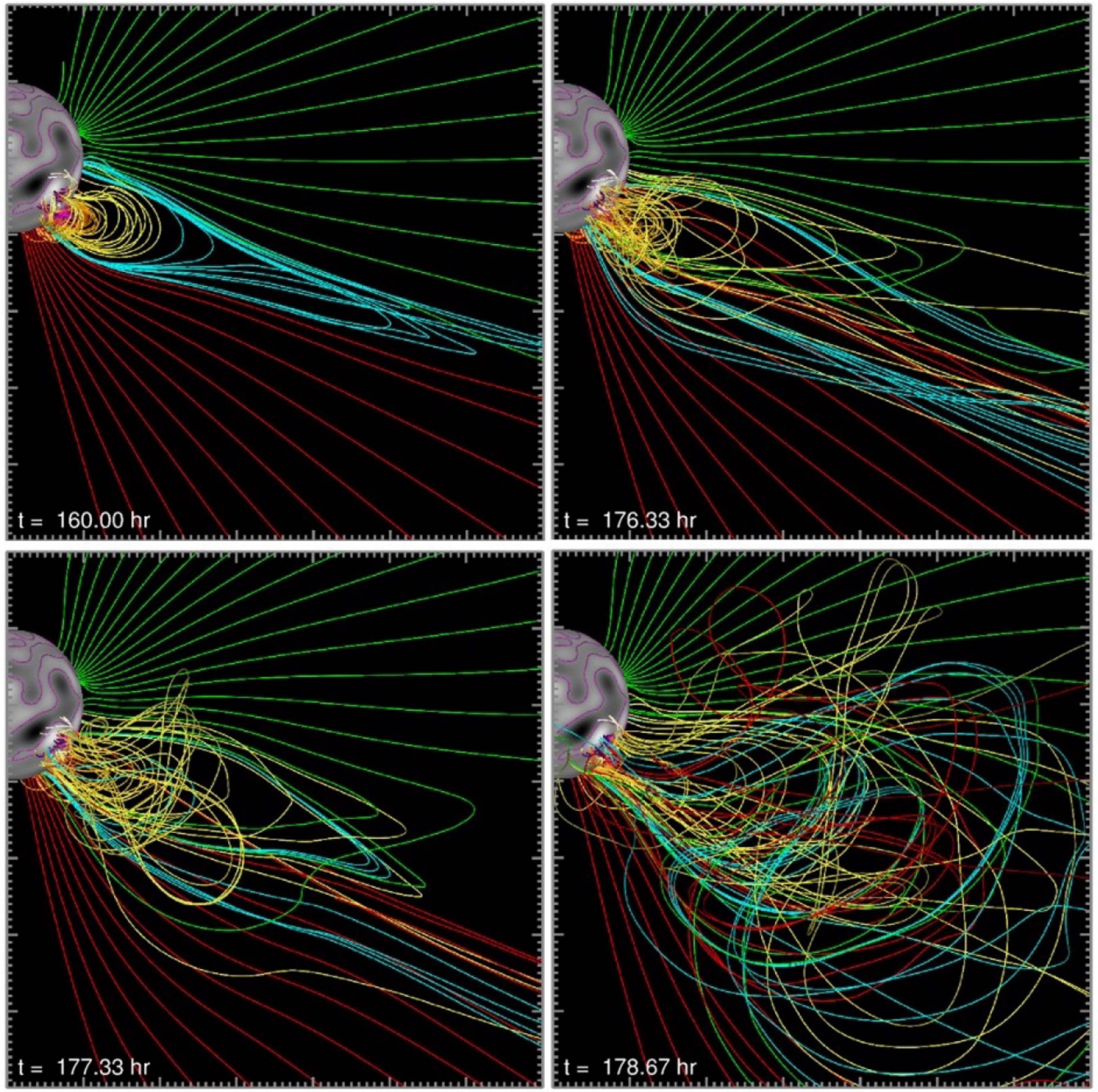
# Outlook: MHD Simulations

- Idealized MHD simulation for parameter study




Courtesy E. Avallone

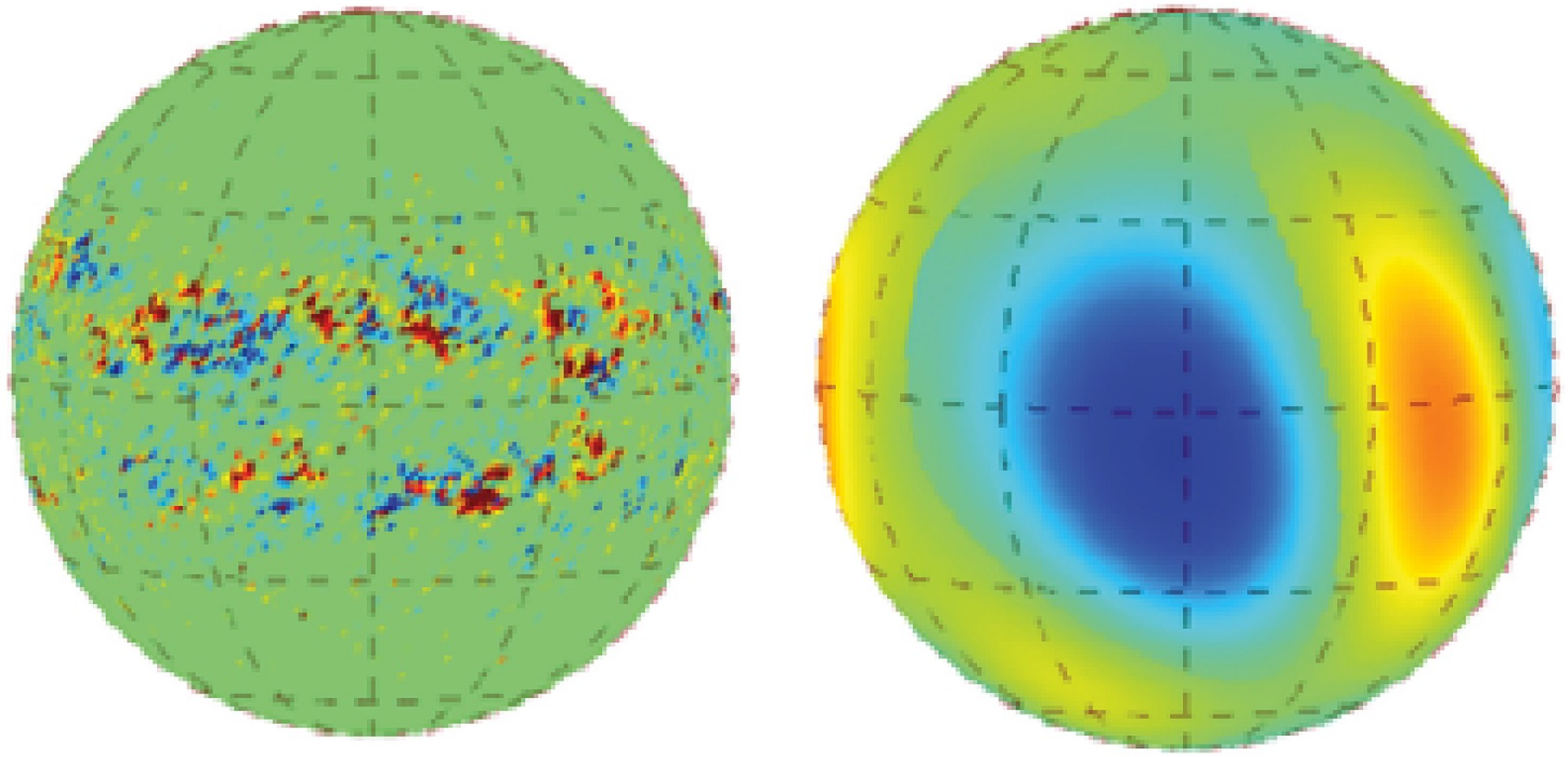
- Driving stellar CME with known solar CME mechanisms



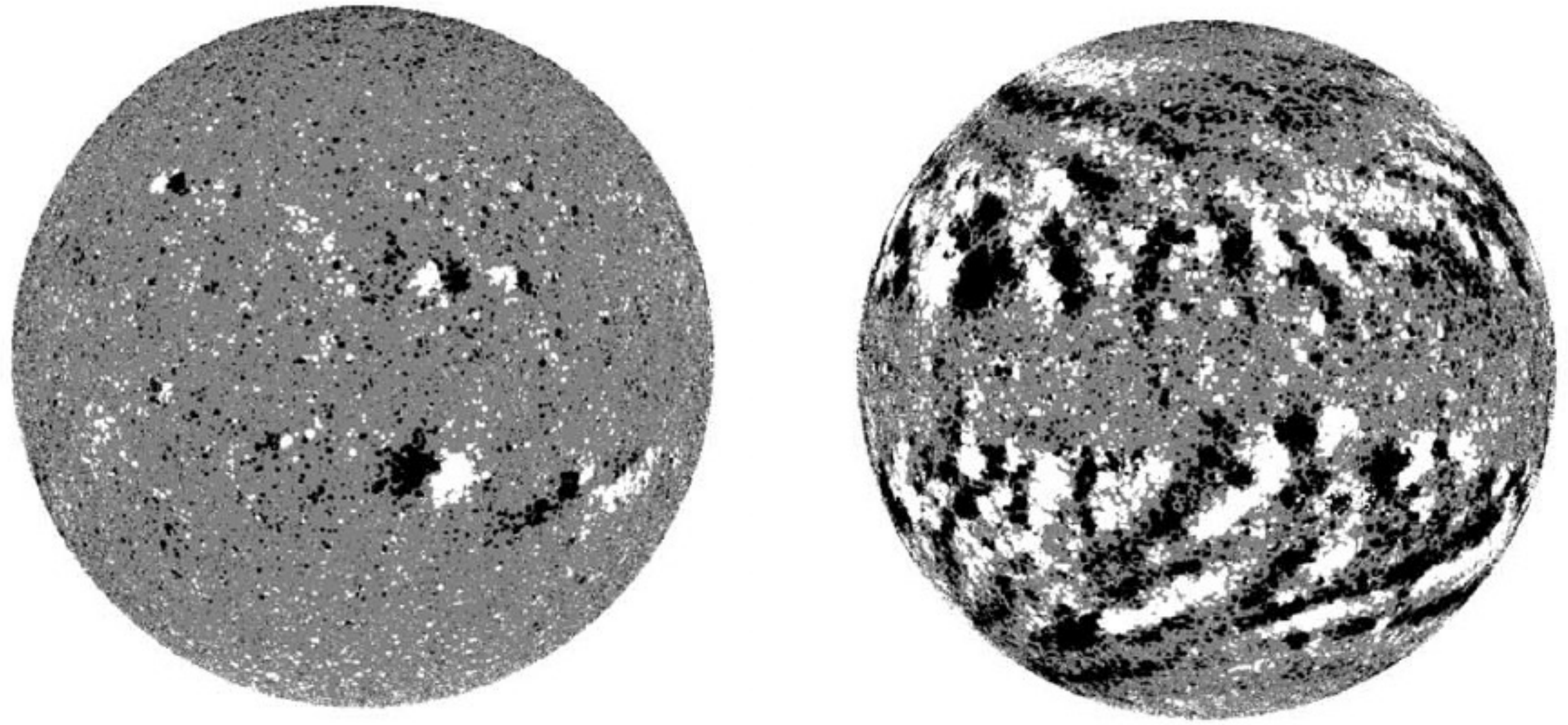

Lynch et al. (2021)

# Outlook: Surface Flux Transport Model

- ARs follow know patterns/statistics: butterfly diagram, log-normal size distribution, etc.
- Surface field results from dispersion of AR magnetic flux by surface flow
- SFT model creates ensemble surface magnetic maps, successfully reproduced many observed stellar features [e.g. Schrijver & Title 2001; Mackay+ 2004; Işik+ 2018; Farrish+ 2019]
- Bonus: light curves for rotation studies! [e.g. Claytor+ 2022]



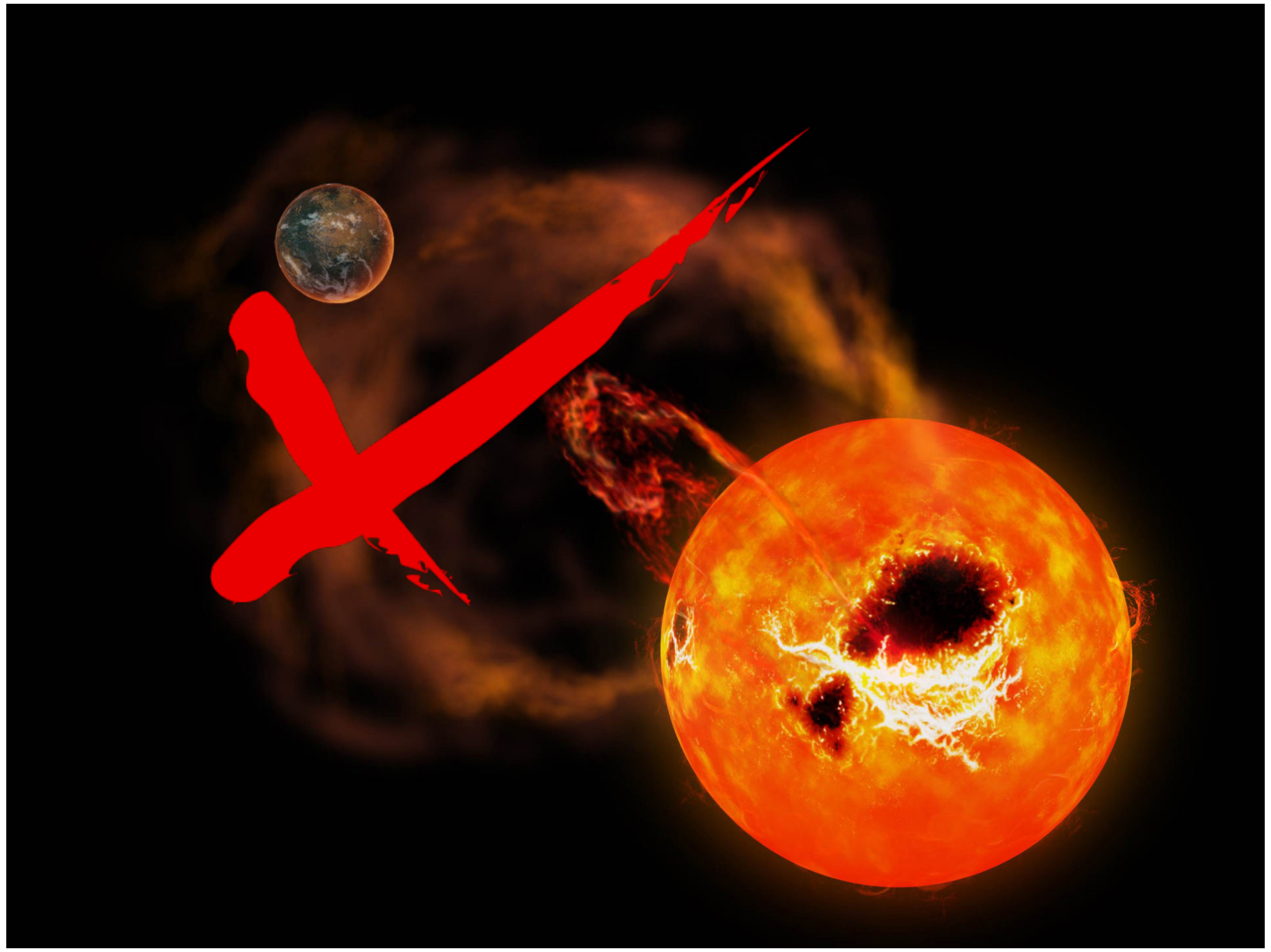
Kochukov et al. (2017)



Farrish et al. (2019)

# Summary

- Stellar CME detections are rare, in stark contrast with stellar flares
- Observation & theory of solar eruption suggest large-scale magnetic field plays a crucial role
- Larger spots, stronger dipole, more closed magnetic topology all act to confine CME
- Suppression of the torus instability may contribute to the lack of stellar CME detection



Courtesy NAOJ