Advances in the study of solar multi-scale magnetic activity

Guiping Zhou

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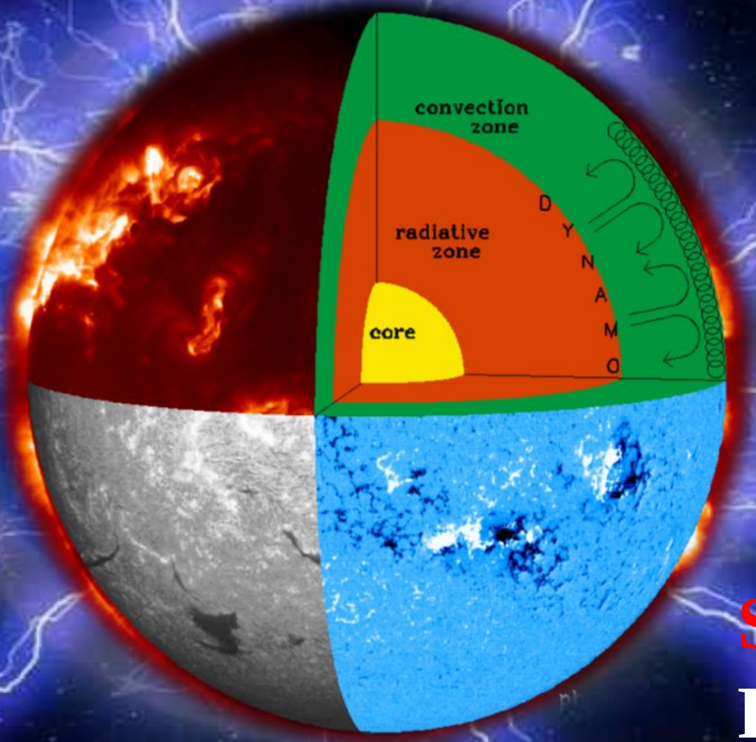
OUTLINES

- Why study Solar Physics
- Basic physical problems of solar activity research
- Progress in understanding multi-scale magnetic activity of the sun (star)

Sun as a natural plasma laboratory

Weakest
Range – infinite
Gravitational

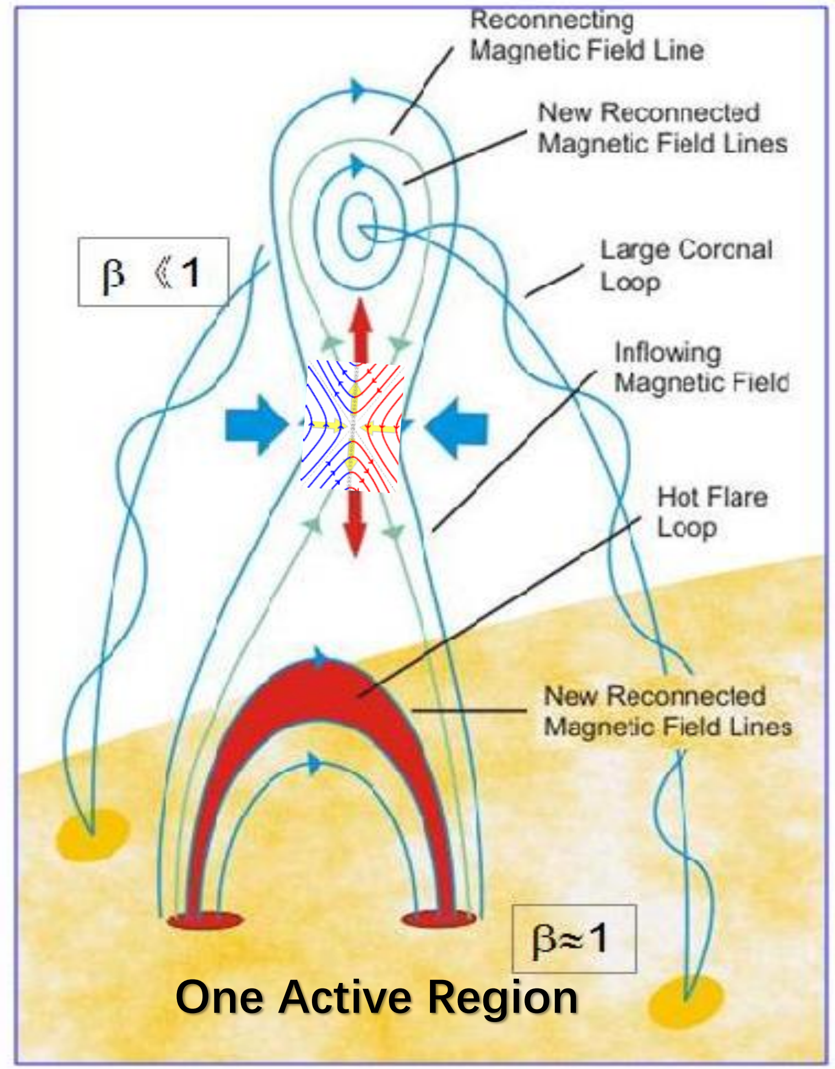
2nd strongest
Range – infinite
Electromagnetic

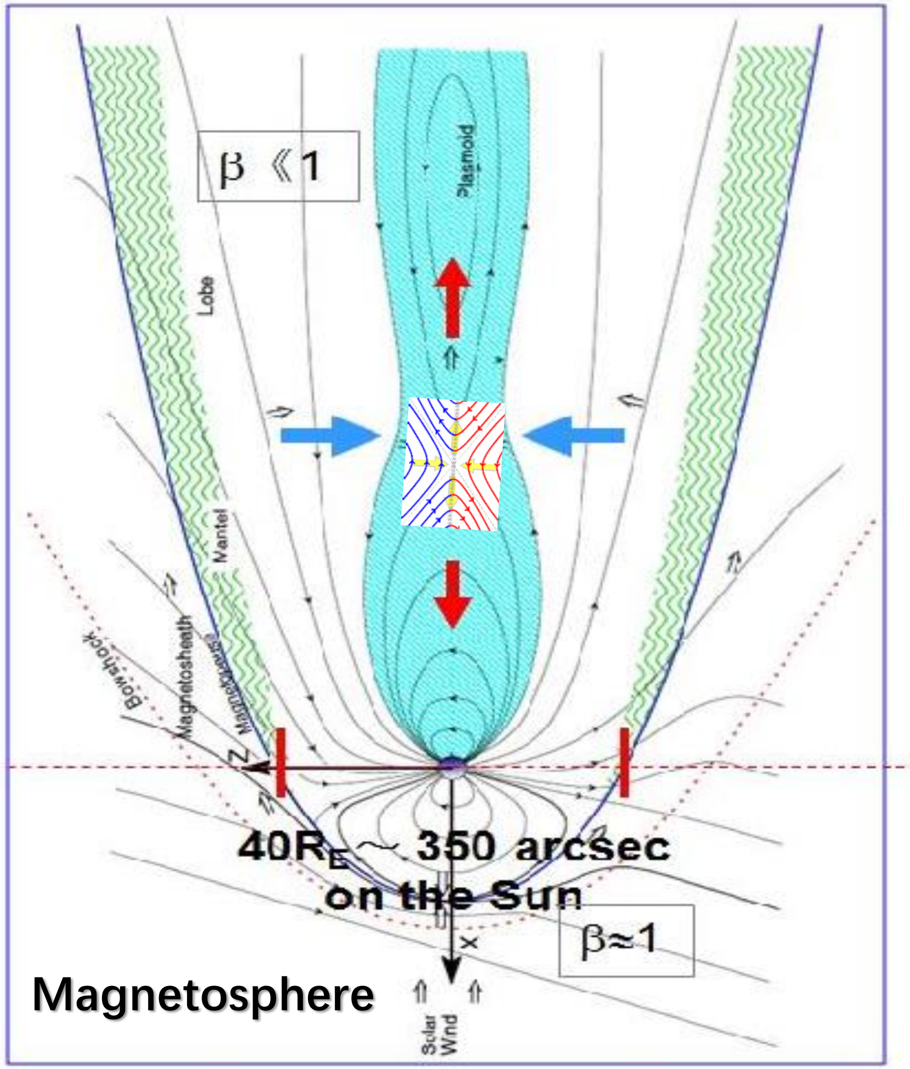


3rd strongest
Range – 10^-18 m
Weak Nuclear

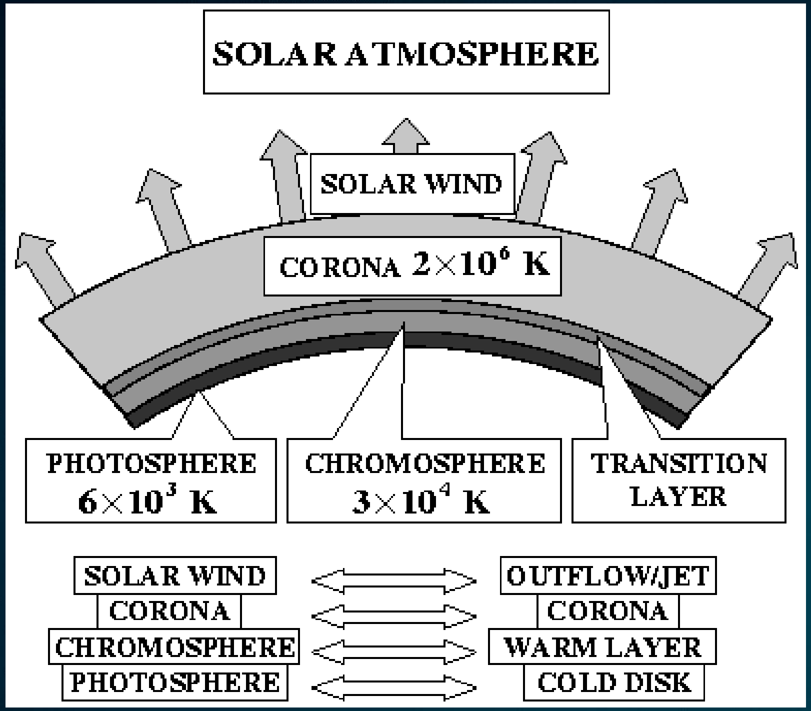
Strongest
Range – 10^-15 m
Strong Nuclear

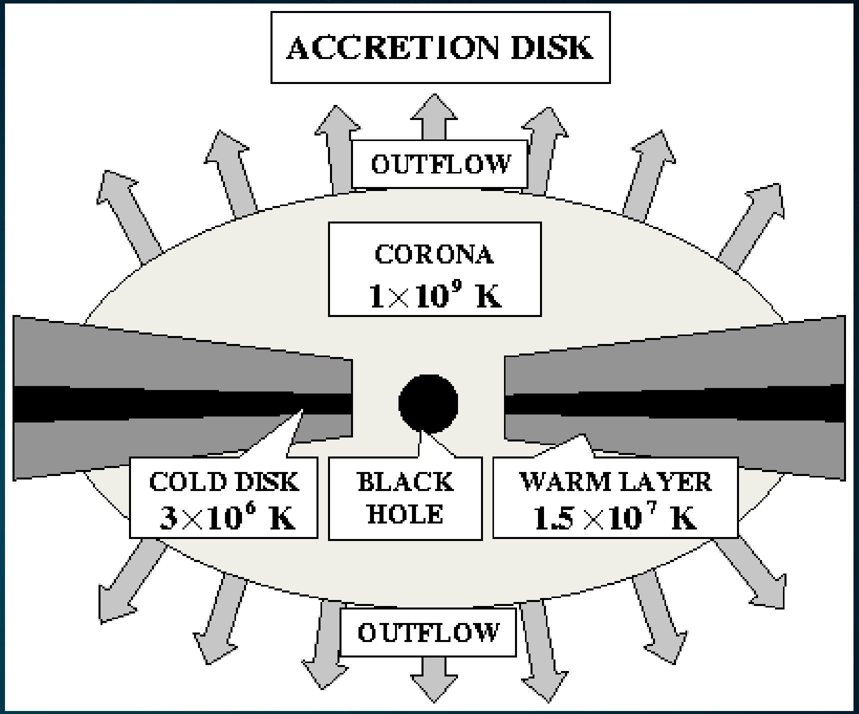
Standard Models of Solar Flares & Geomagnetic Storms — amazing similarities in the universe





Solar atmosphere and accretion disks around BHs

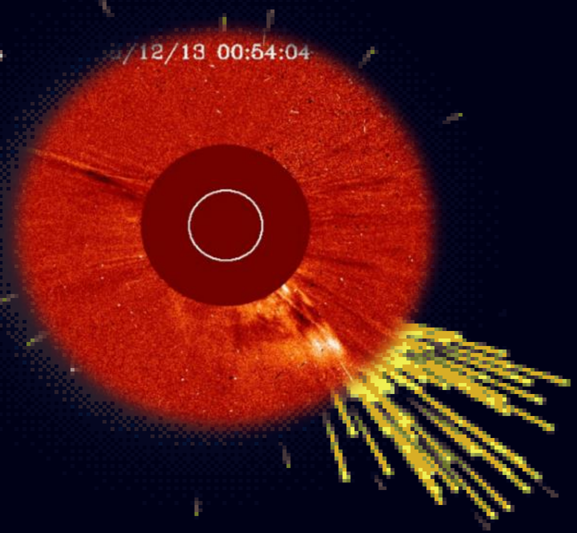




500 × Temperatures of Solar Atmosphere = Temperatures of Accretion Disk

$$T \propto E^{1/4} \propto B^{1/2} \Rightarrow \frac{T_{DISK}}{T_{SUN}} \approx \left(\frac{B_{DISK}}{B_{SUN}}\right)^{1/2} \approx \left(\frac{10^8\ G}{500\ G}\right)^{1/2} \approx 500$$

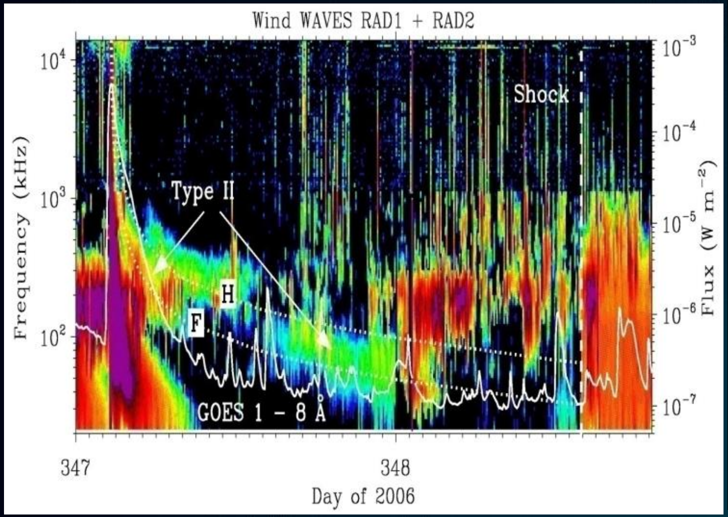
Magnetic energy release dominates.
(Zhang et al, Science, 2001)

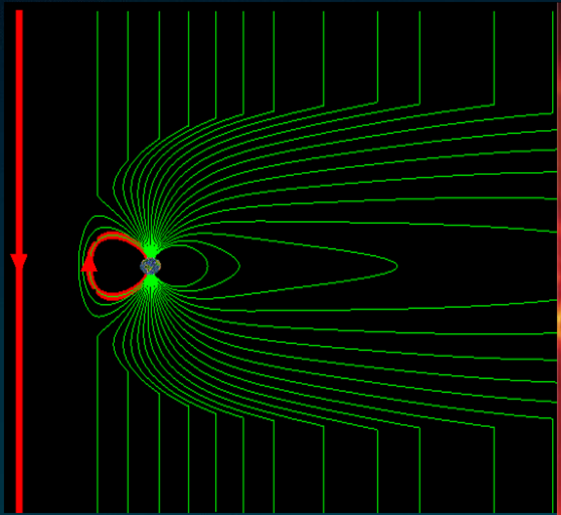


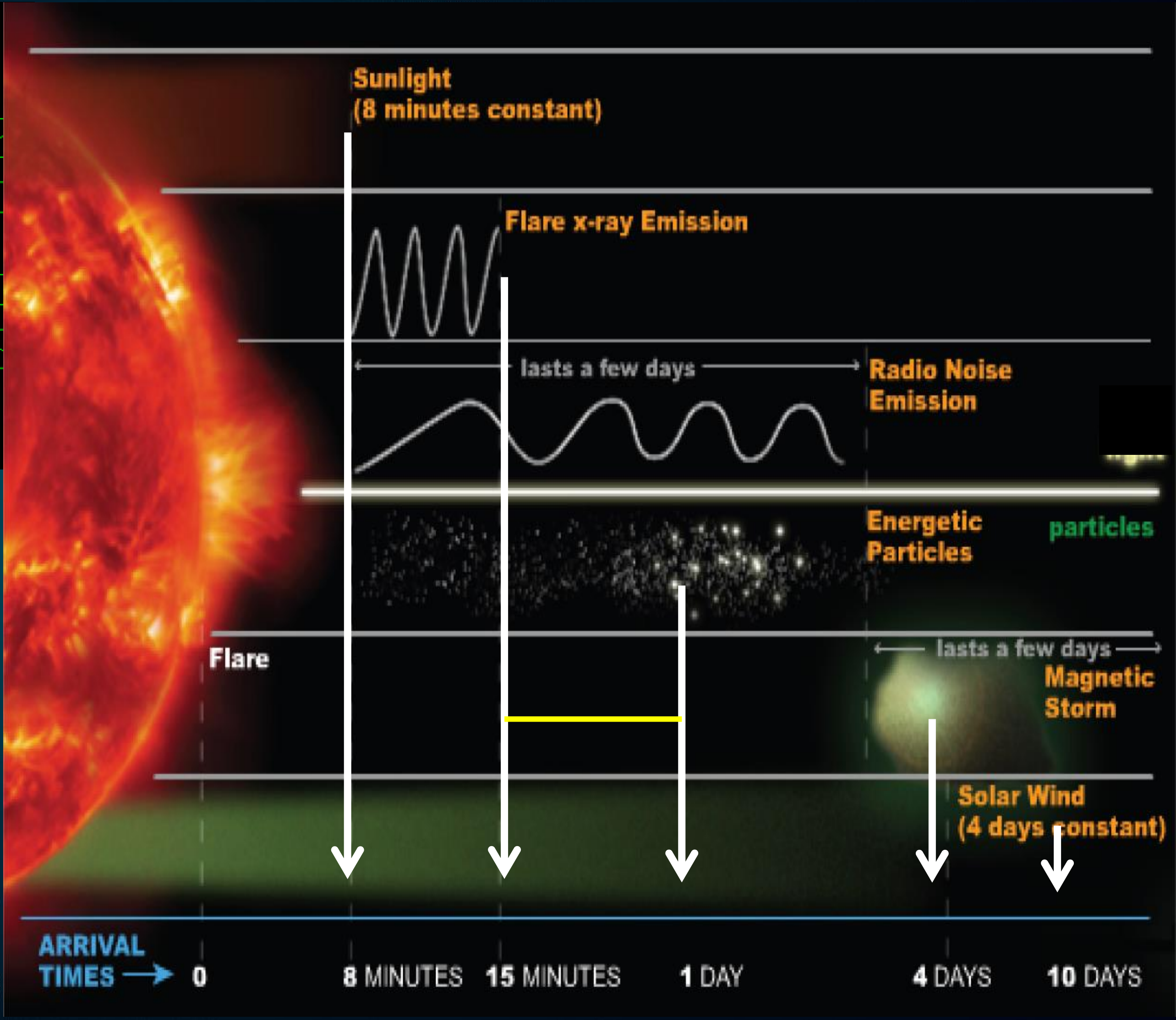
Solar activity & space weather

- Solar eruption - a violent electromagnetic storm represented by solar flares/coronal mass ejections (CME), flare, fil. eru
- Natural disasters faced by mankind: violent solar eruption (flare>X1.0) —"super strong solar storm and abnormal behavior of the solar cycle", heavily impact on Sun-terrestrial environment, and technological sys.
- Forecast —basic scientific research, urgent and significant needs, challengers to sci. cognitive ability

Coronal mass ejections, radio storms, particle accelerations and geomagnetic storms associated with flares

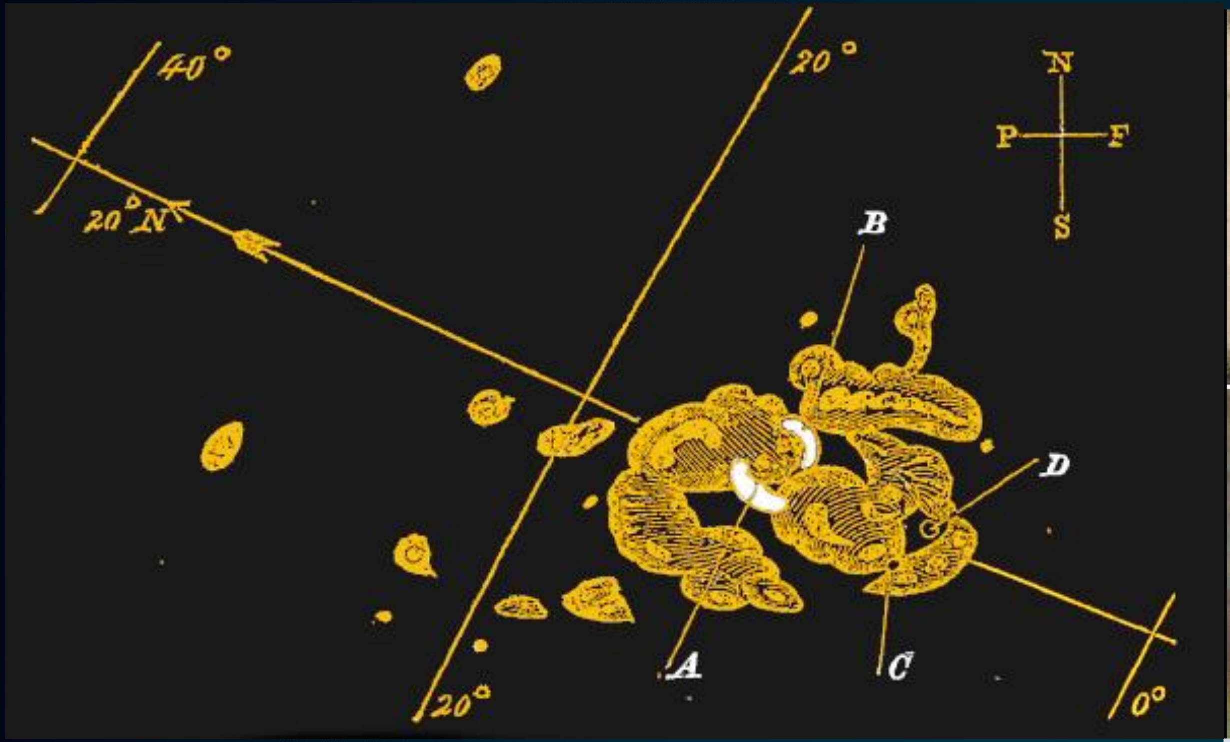


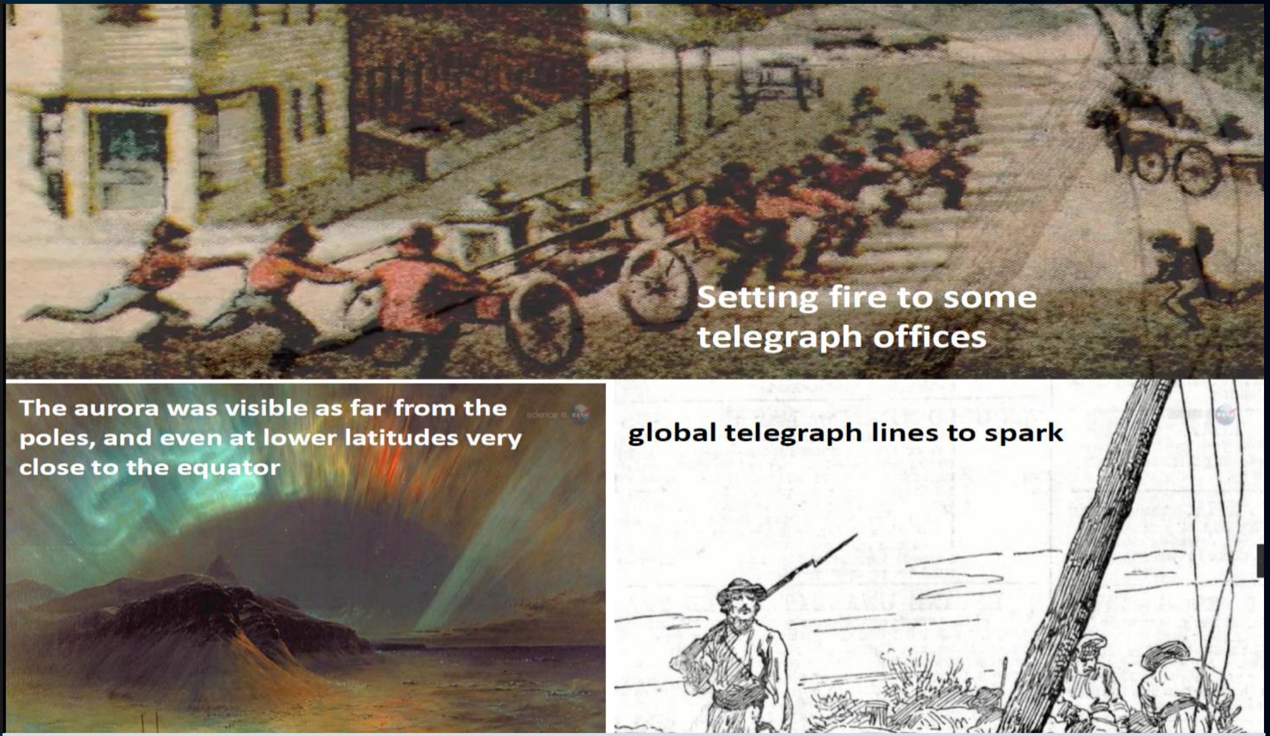




- ✓ CMEs are often associated with a sustained southward magnetic field, which allows a strong coupling between solar wind and magnetosphere;
- ✓ Fast CMEs can generate interplanetary shocks, a key source of energetic particles and radio bursts.

The strongest solar storm in history - the Carrington event on September 1, 1859

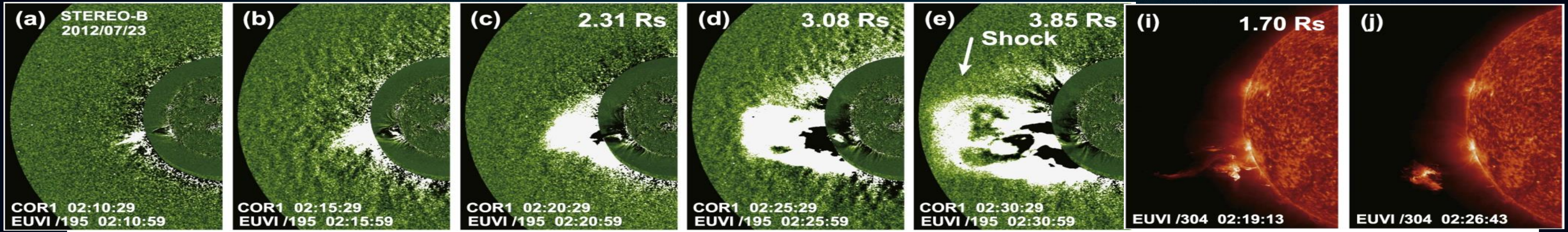


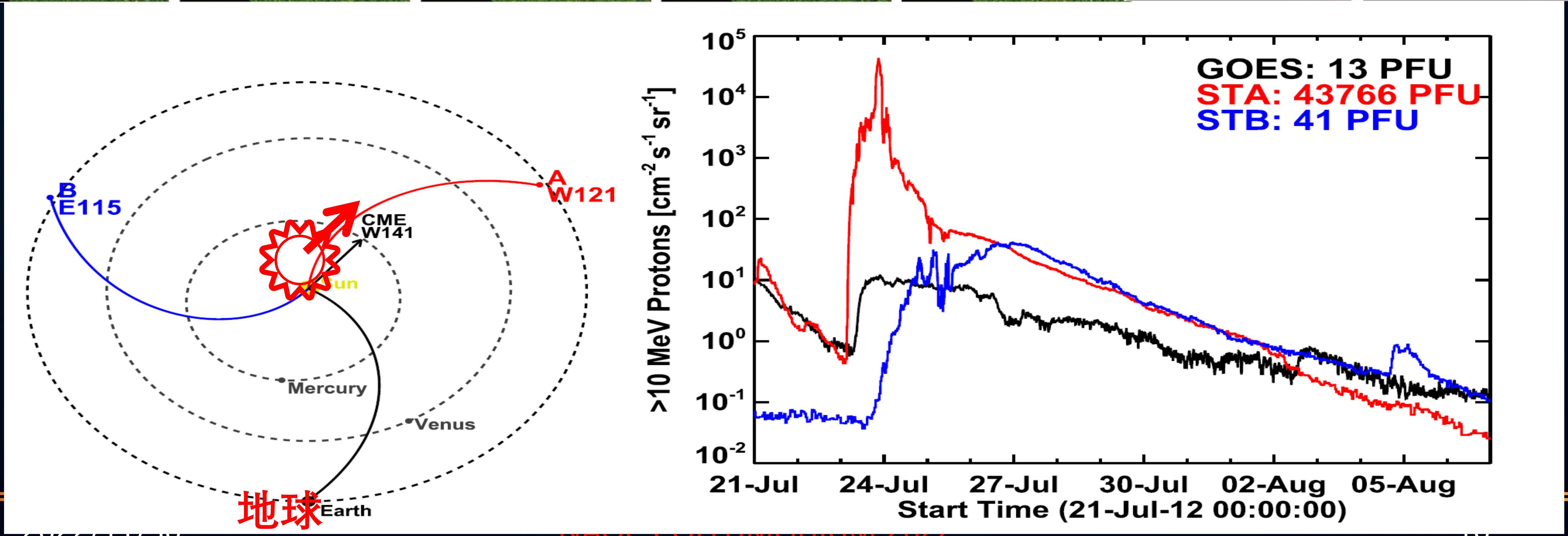


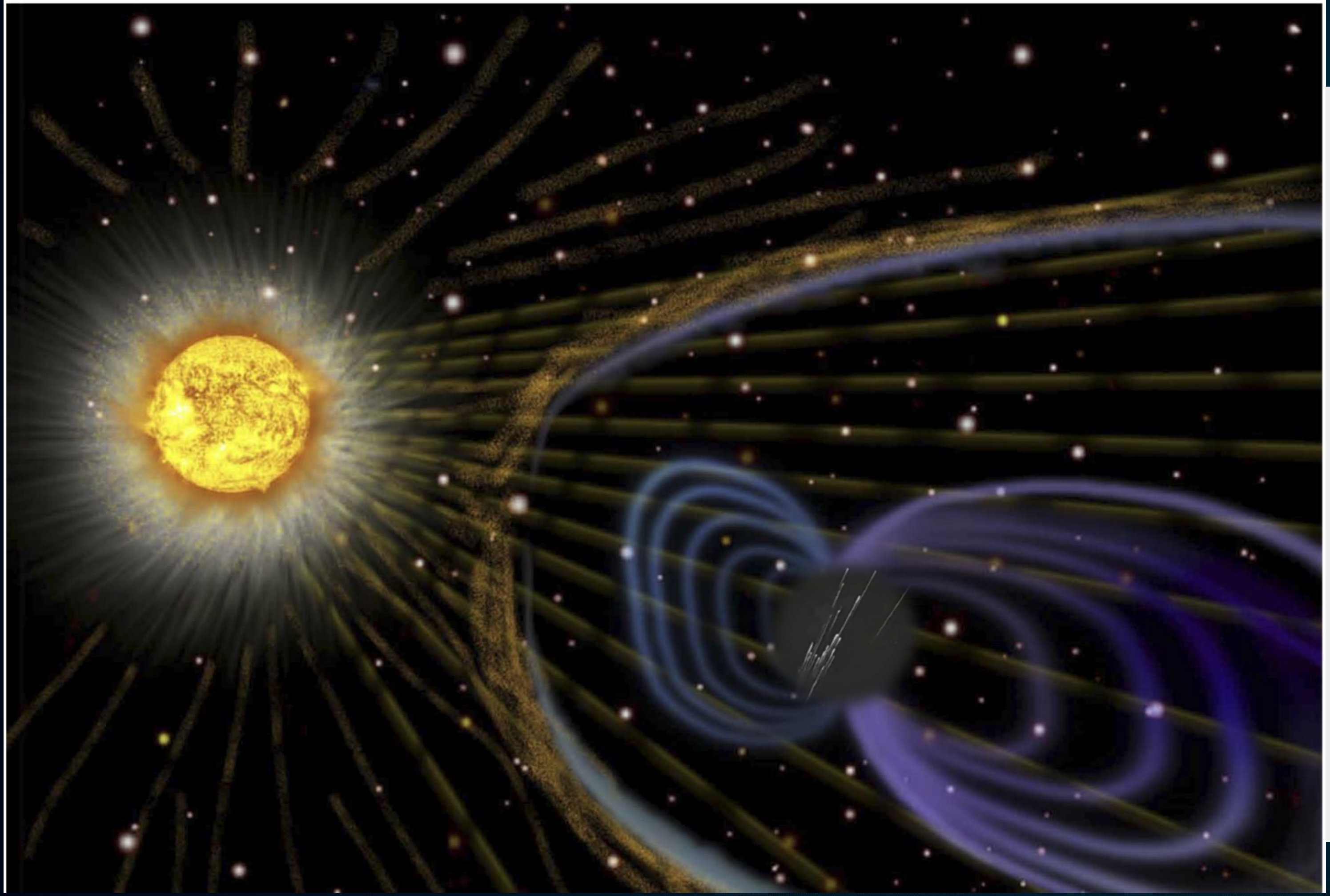
(Carrington, 1859, MNRAS, 20, 13)

- The global aurora
- The transoceanic telegraph system in Europe and North America failed

The strongest solar storm in the weakest solar cycle in recent century (backside events)—Carrington-like solar storm on 2012. 7. 23



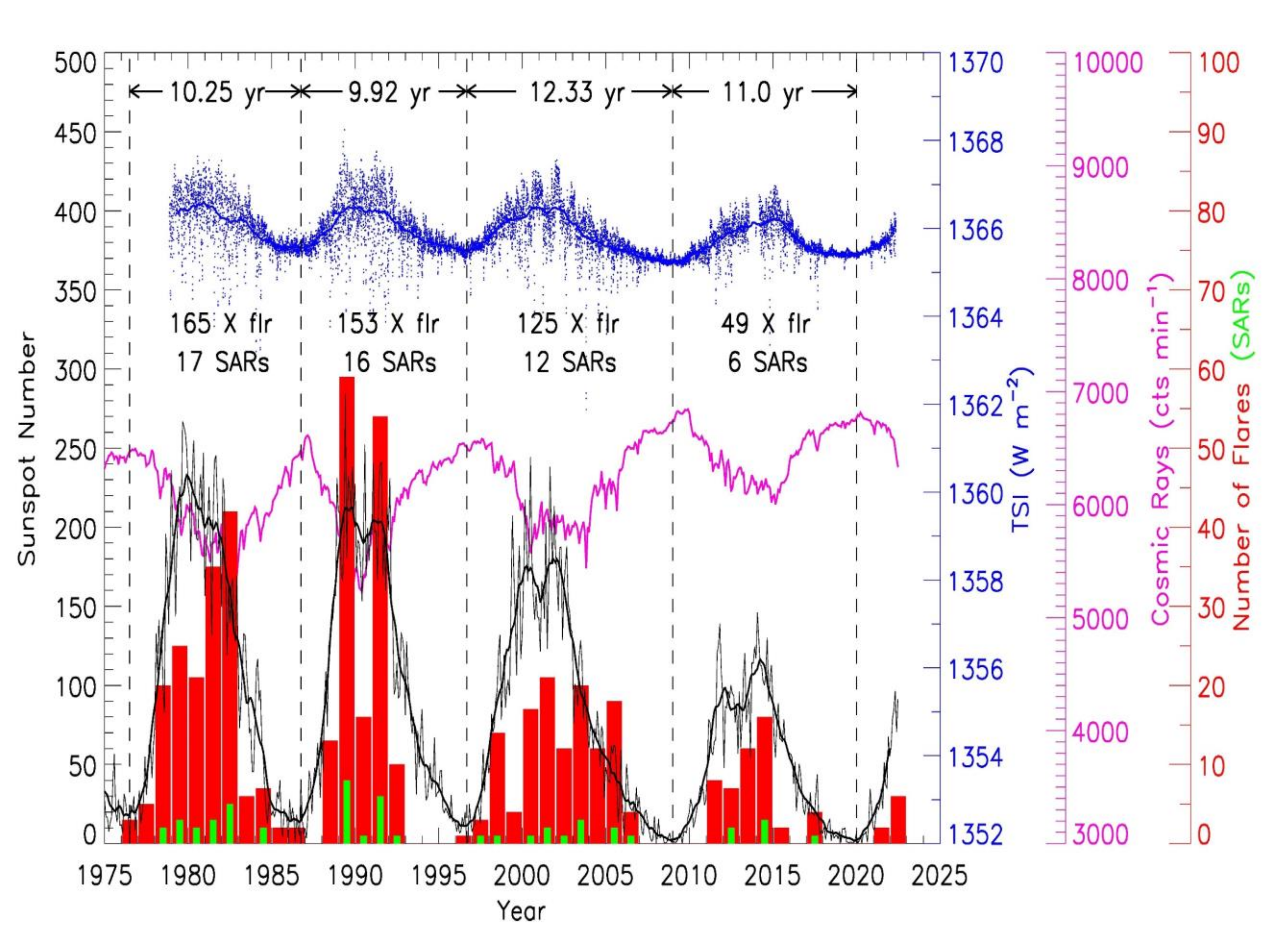




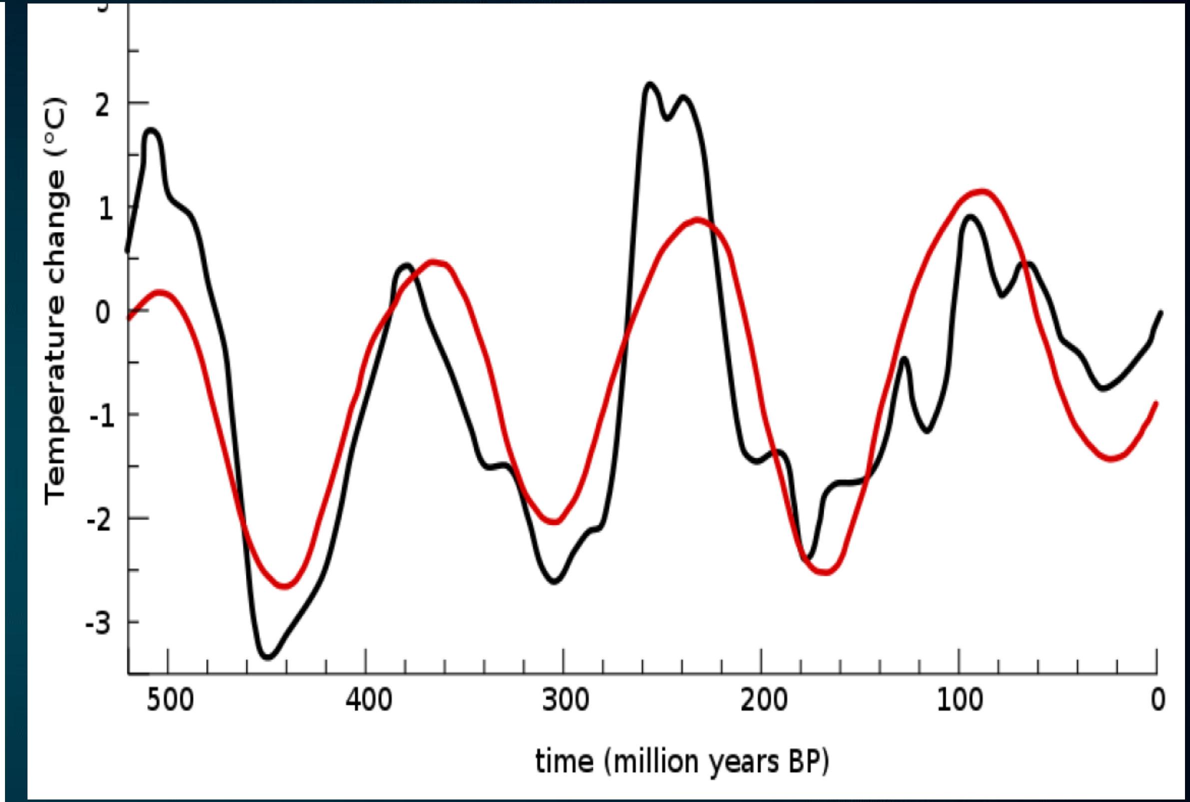
- ☐ **Three Rounds of Attacks:**
- ✓ **Coronal Mass Ejection**
- ✓ **Energetic Particles**
- ✓ **UV、EUV、X-rays**
- ☐ **SpaceX: Space storm destroys 40 of Elon Musk’s Starlink satellites on 2022.02. 03**

(张宇宗，2022，国家天文)

Solar mag. Activity & space weather and climate



- Sunspot number, super solar active regions, X-class flares, total solar radiation and cosmic ray intensity in the past 5 solar cycles (Chen, AQ, Wang, JX+ 2022)



- sea temperature & cosmic ray inten.

(Shaviv N J, Veizer J. Celestial driver of Phanerozoic climate?, GSA today, 2003)

Fields affected by solar activity and space weather

- Spacecraft safety
- Space and aviation activity safety
- communication
- Navigation and positioning
- national defense
- geological prospecting
- Long distance pipe network system
- Meteorological Operation and Research
- biology

…

Why we should study solar physics?

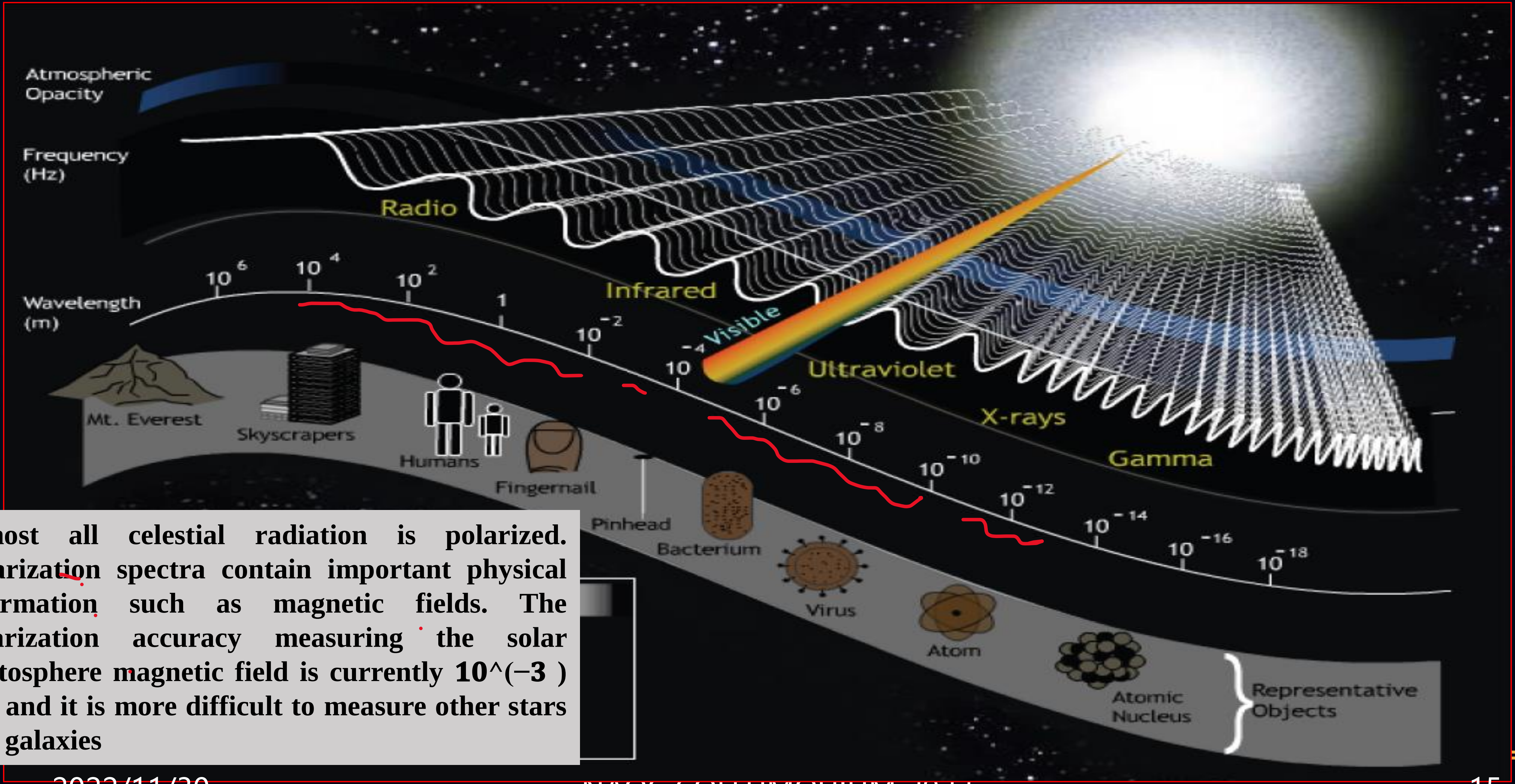
- Understand the position and living environment of human beings in the universe
- Understand the basic scientific laws in the universe, especially the ubiquitous electromagnetic interaction in the universe

  —Solar interior - productivity mechanism, dark matter particles, gravitational wave modes

  —Solar atmospheric structure and solar activity - origin of magnetic field and solar activity - fluid, magnetohydrodynamics, plasma physics, high-energy physics, three-dimensional radiation magnetohydrodynamics numerical experiment

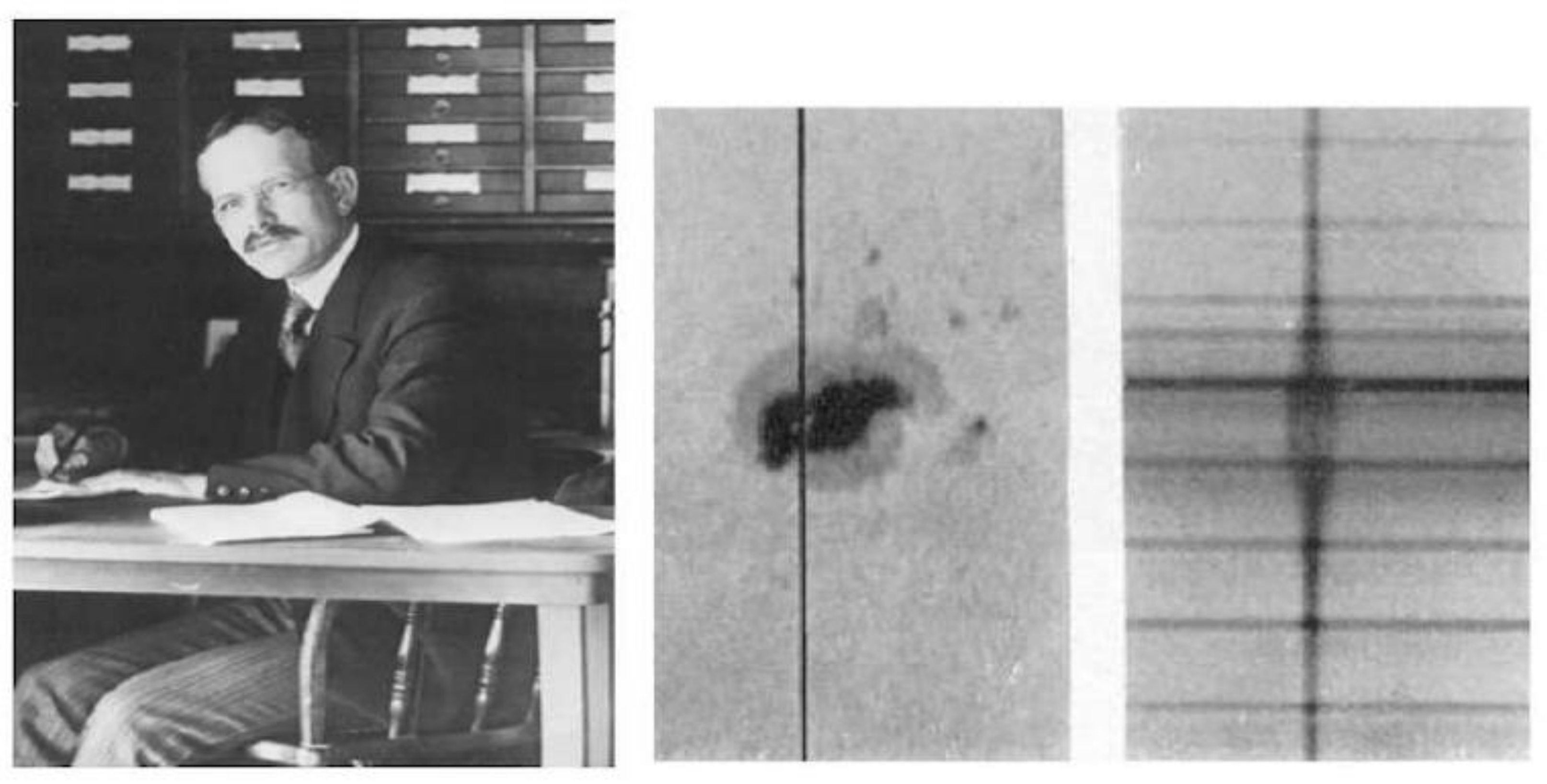
  —The influence of the sun on the Earth, solar system objects, heliospheric space and life processes - multidisciplinary and interdisciplinary
- Applied research: prediction of space weather and space climate
- Search for universe neighbors and migration to habitable exoplanets

The sun—an astronomical object that covers almost the entire spectrum of electromagnetic radiation



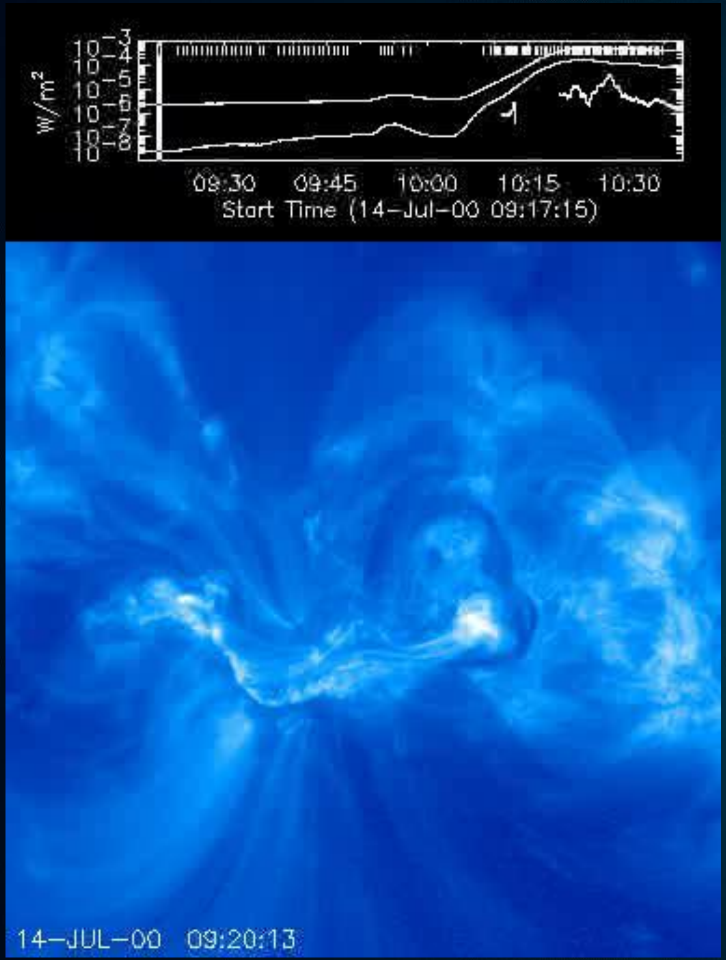
Almost all celestial radiation is polarized. Polarization spectra contain important physical information such as magnetic fields. The polarization accuracy measuring the solar photosphere magnetic field is currently 10^(−3) I_c, and it is more difficult to measure other stars and galaxies

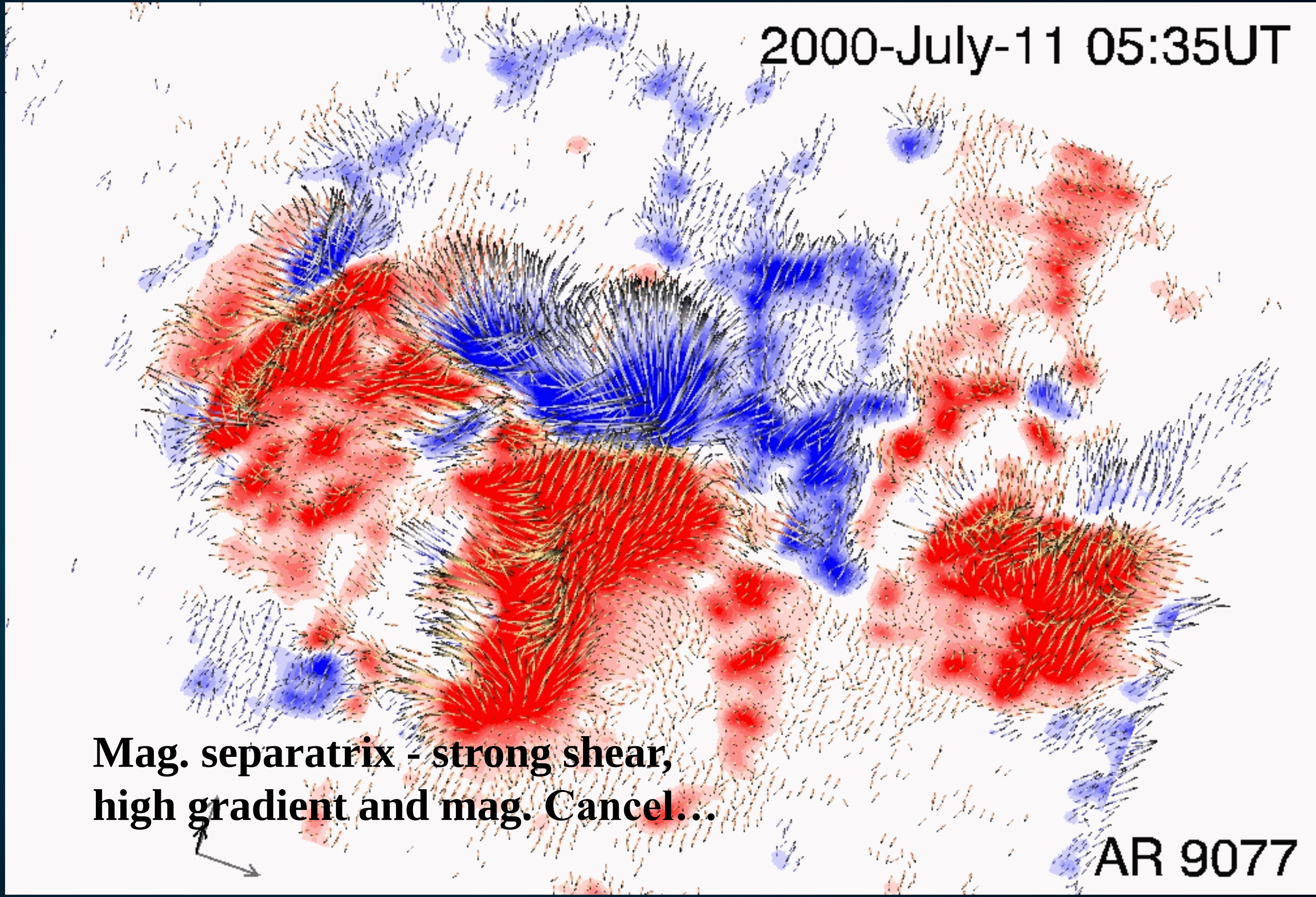
magnetic field in sunspot discovered in 1908



The Zeeman effect was discovered in 1897 and won the Nobel Prize in Physics. Hale discovered the strong magnetic field of sunspots based on the Zeeman effect in 1908, which was the first to use physical methods to study celestial objects, marking the birth of solar physics or astrophysics

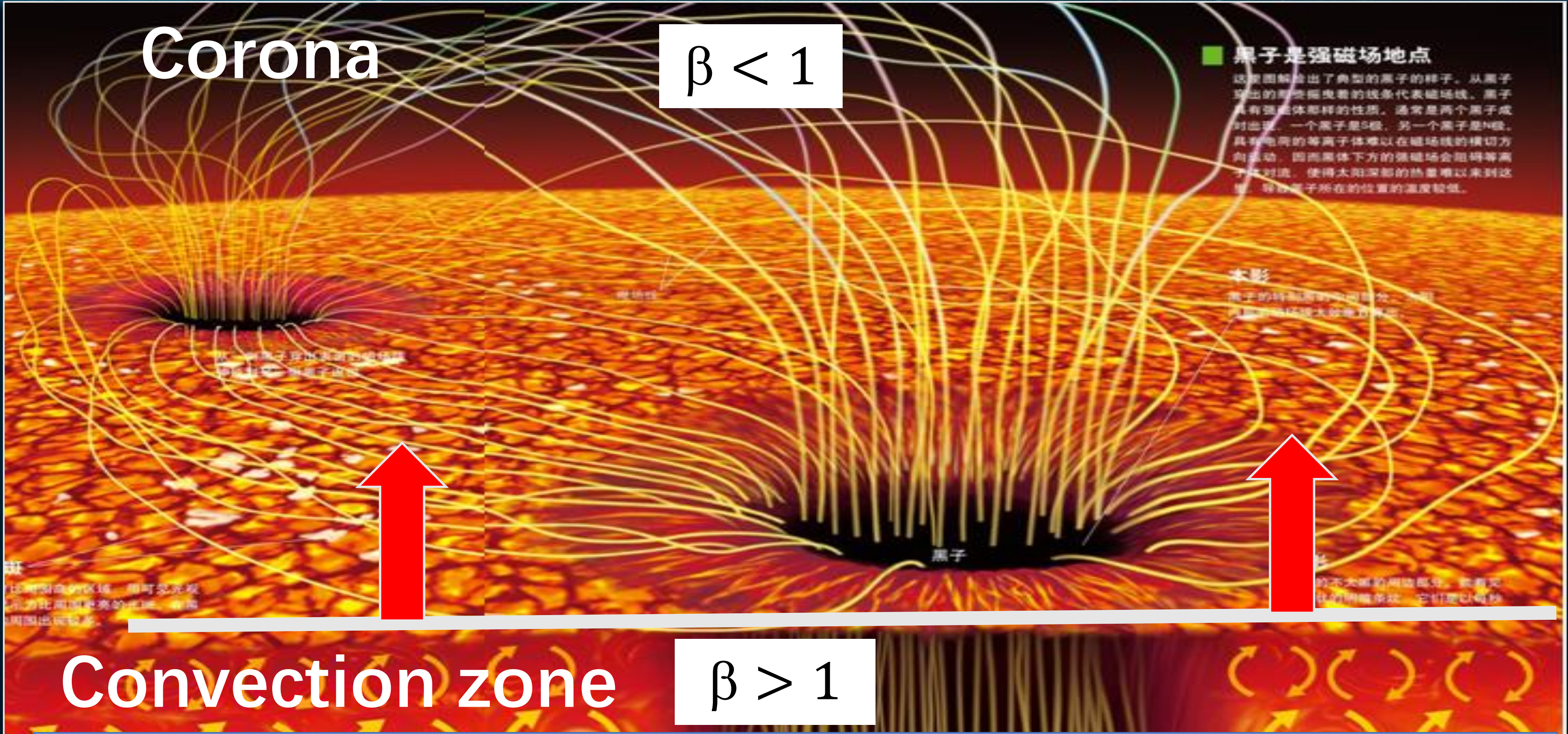
Solar Activity of Bastille Event -- Evolving Vec. Mag. Field





(e.g., Zhang et al.2001; Deng et al. 2001; Wang et al. 2004)

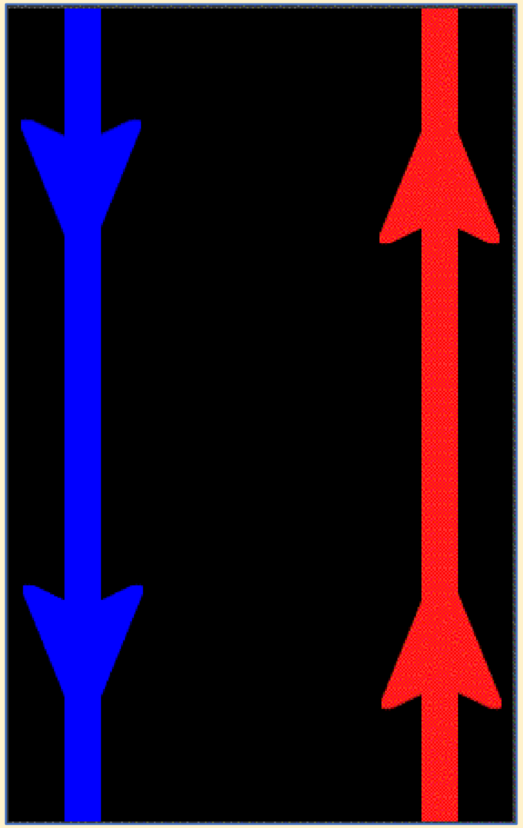
Mag. energy accumulation processes in the solar atmosphere (partially ionized plasma)

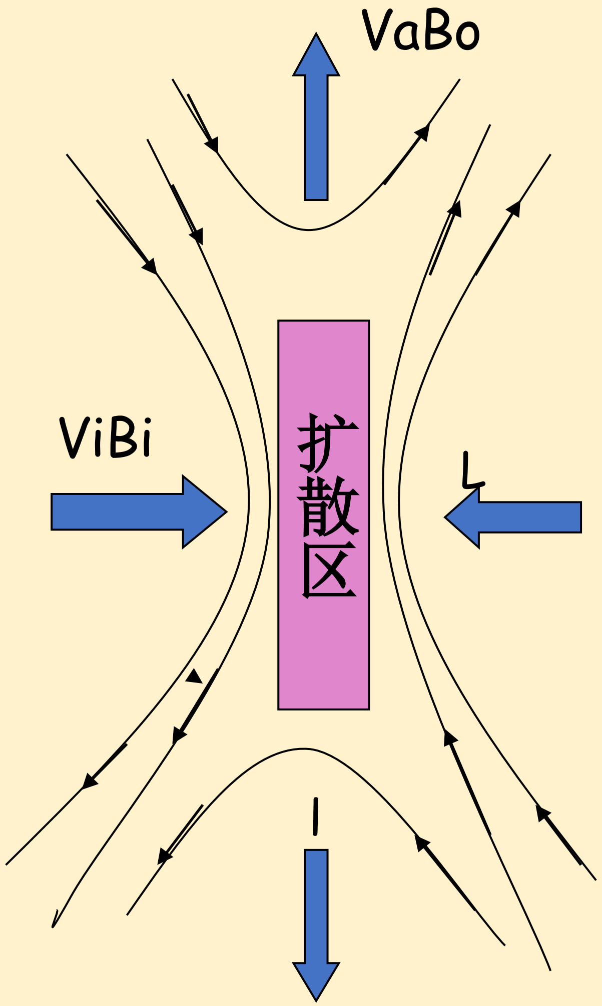


$$\frac{\partial W_m}{\partial t} = \oiint_s \left\{ [B_\perp^2 V_z - (\vec{V}_\perp \bullet \vec{B}_\perp) B_z] + \eta \vec{B}_\perp \bullet \left(\nabla B_z - \frac{\partial \vec{B}_\perp}{\partial z} \right) \right\} ds \quad (1)$$

Mag. emerging　　Mag. shear　　Mag. Cancel

Mag. Reconn. — Mag. energy release process accompanied by topological change of mag. field





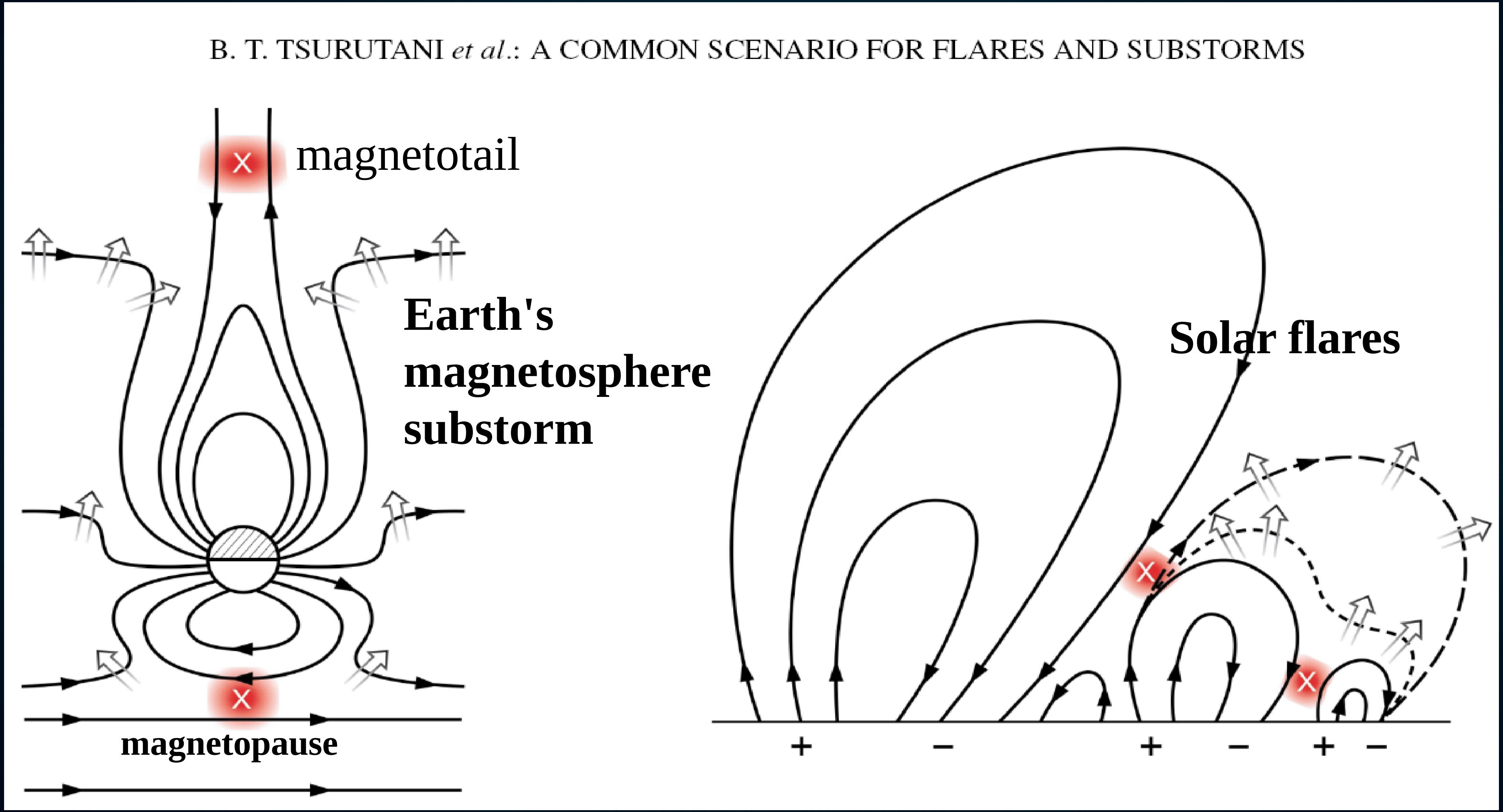
For Sweet—Parker slow mag. Recon.

$$v_i = \frac{v_a^*}{\sqrt{R_m}} = \frac{B_i}{\sqrt{\mu \rho_c R_m}}$$

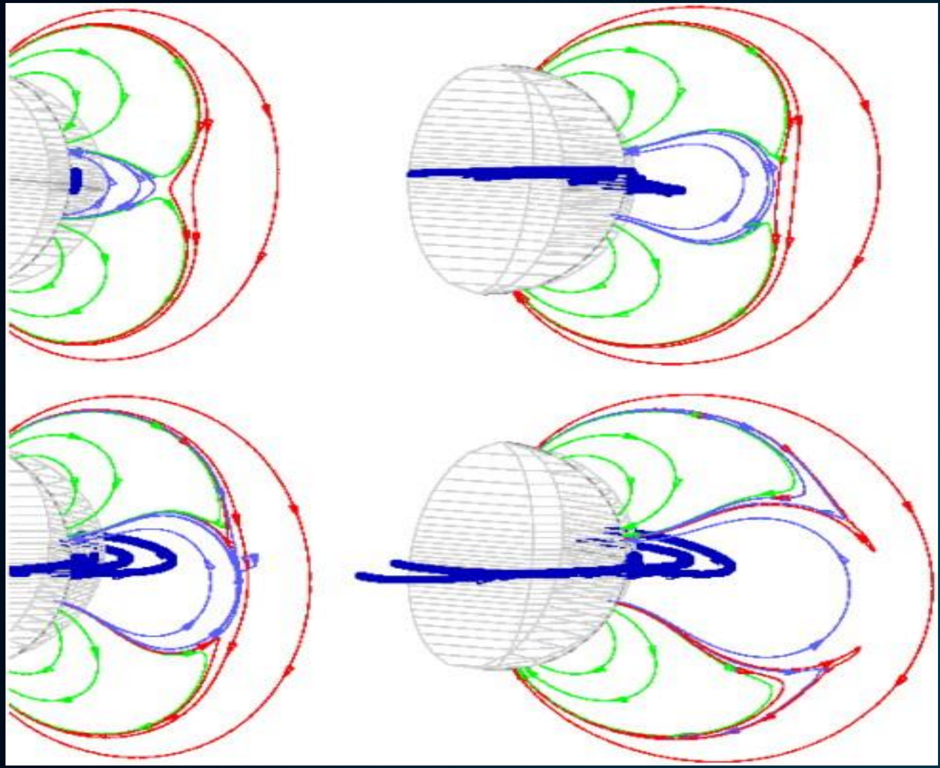
For Petschek fast mag. Recon.

$$v_i \propto \frac{v_a}{\ln R_m}$$

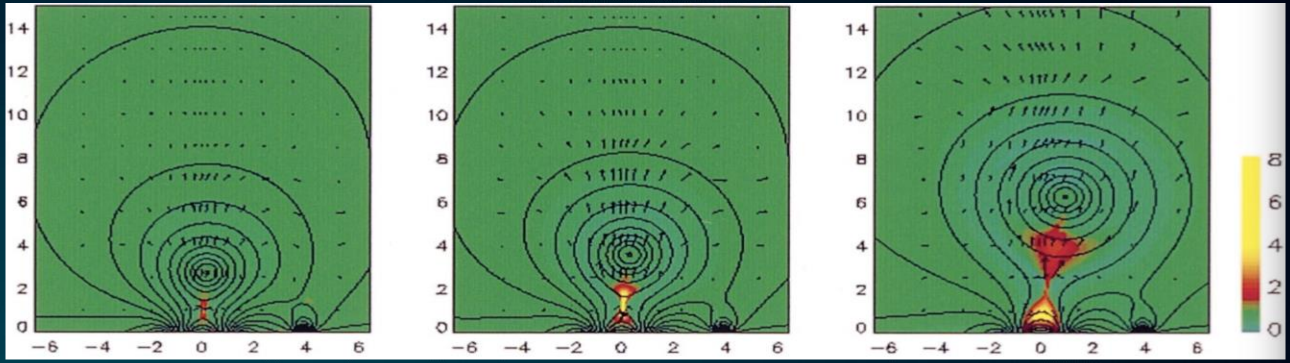
Two-stage mag. Recon. Model (e.g., Wang & Shi, 1993）



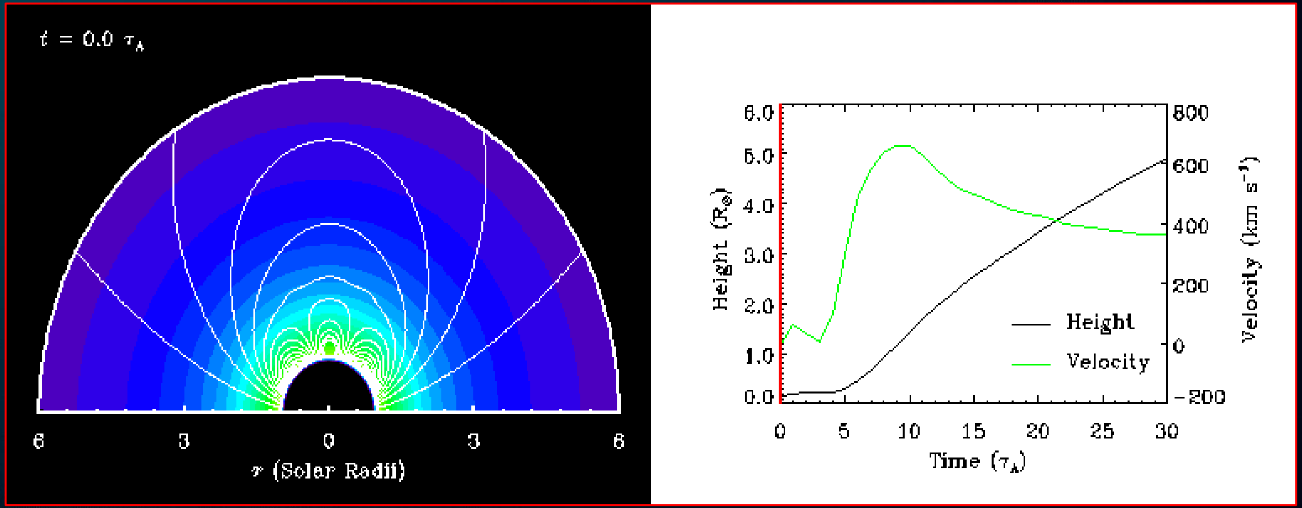
Mag. Recon. in multi-poles mag. topological sys.



breakout model
(Antiochos et al. 1999; Karpen et al. 2012)

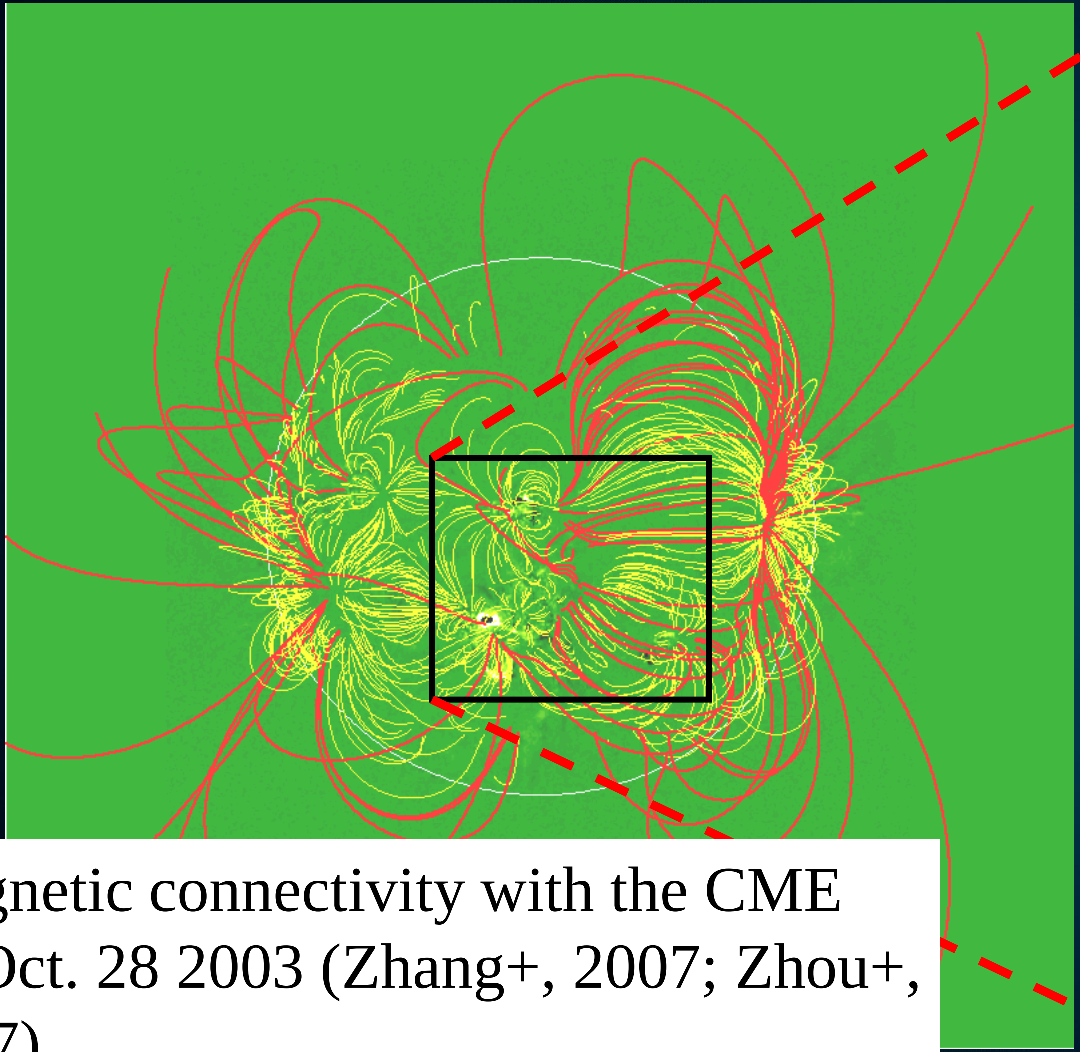


“flux emergence model” (Chen & Shibata 2000)



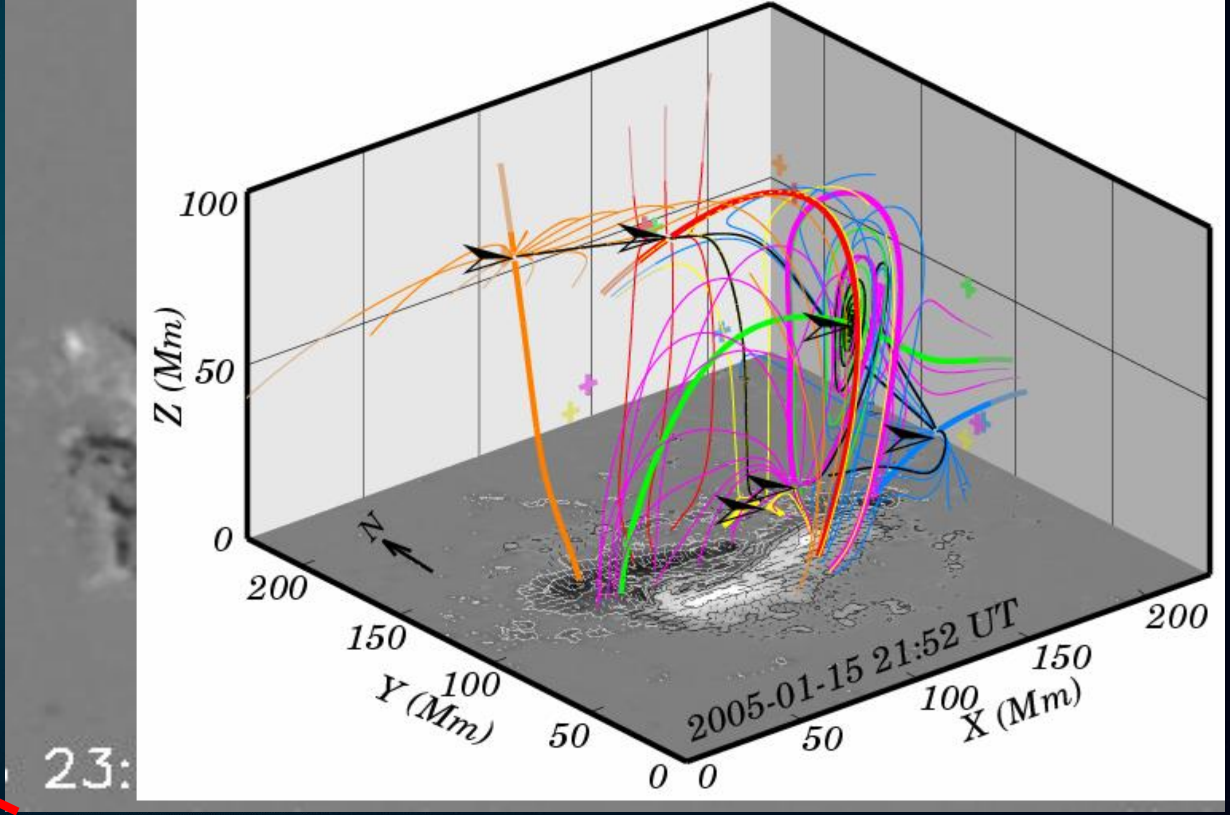
TWO CURRENT (Zhang，Hu & Wang. 2006)

Global magnetic connectivity in CMEs



Magnetic connectivity with the CME on Oct. 28 2003 (Zhang+, 2007; Zhou+, 2007)

3D Mag. null points and Mag. Topology (Zhao et al. 2005, 2008)



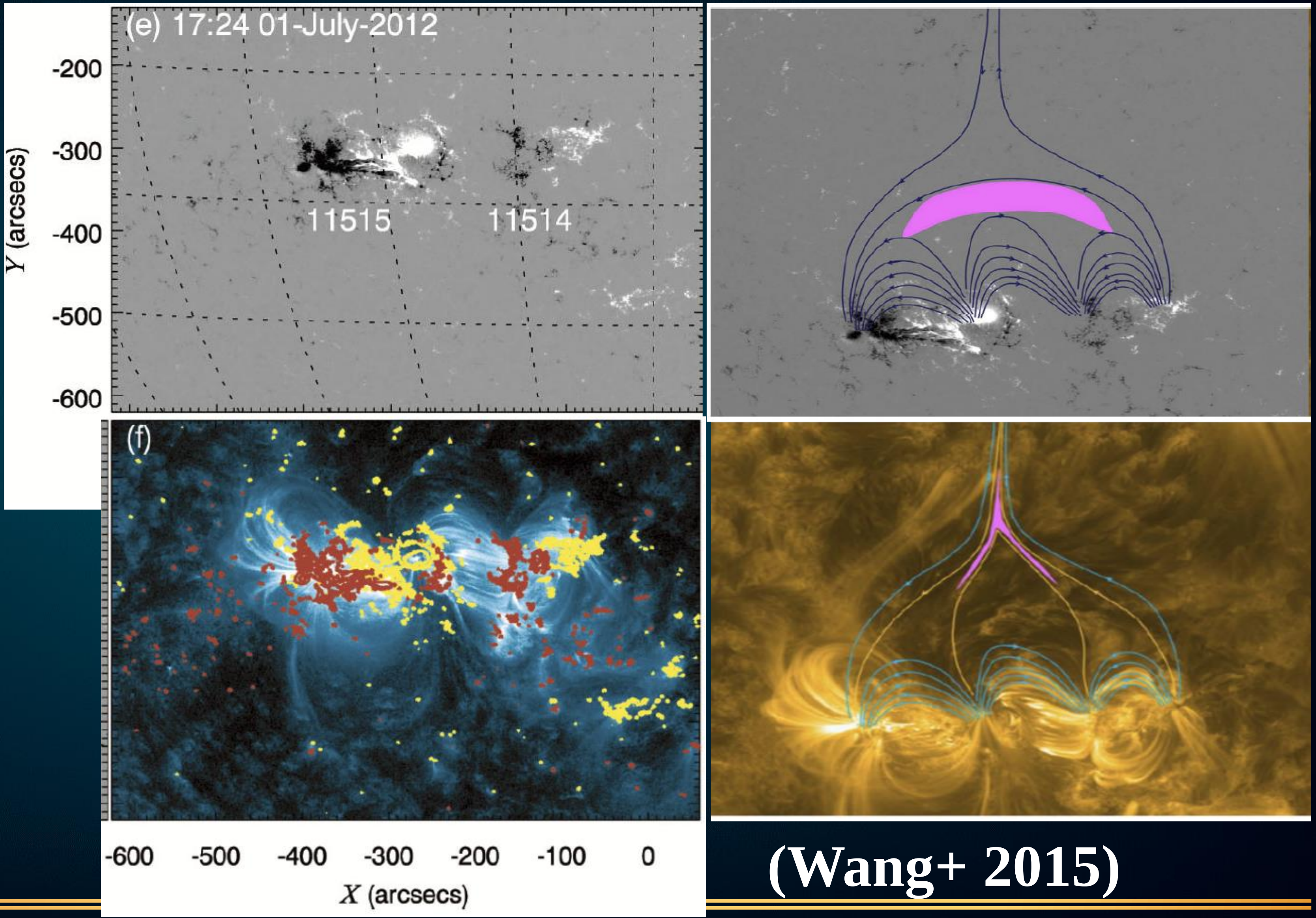
Mag. Synoptic Meteorology & essential elements

- Basic Phys. Para. — Vector Magnetic Field
- Leading Physical Theory — RMHD
- Weather Sys. Carrier — isolated Mag. Flux Sys. (Mag. Rope or Mag. Loop) frozen with Plasma
- Common mag. field environ. — dense driving layer and thin corona
- Basic Topological Constraints — mag. Connectivity and Complexity
- Core Physics Concept — Mag. Topology Interface
- Main physical process — Interaction of independent mag. flux sys. & mag. Recon. with topological tearing or topological collapse
- Initiations of weather processes — near the 3D magnetic singularity and its associated topology
- • • • • •

（Wang JX & Liu ZX， 2000, Science of China）

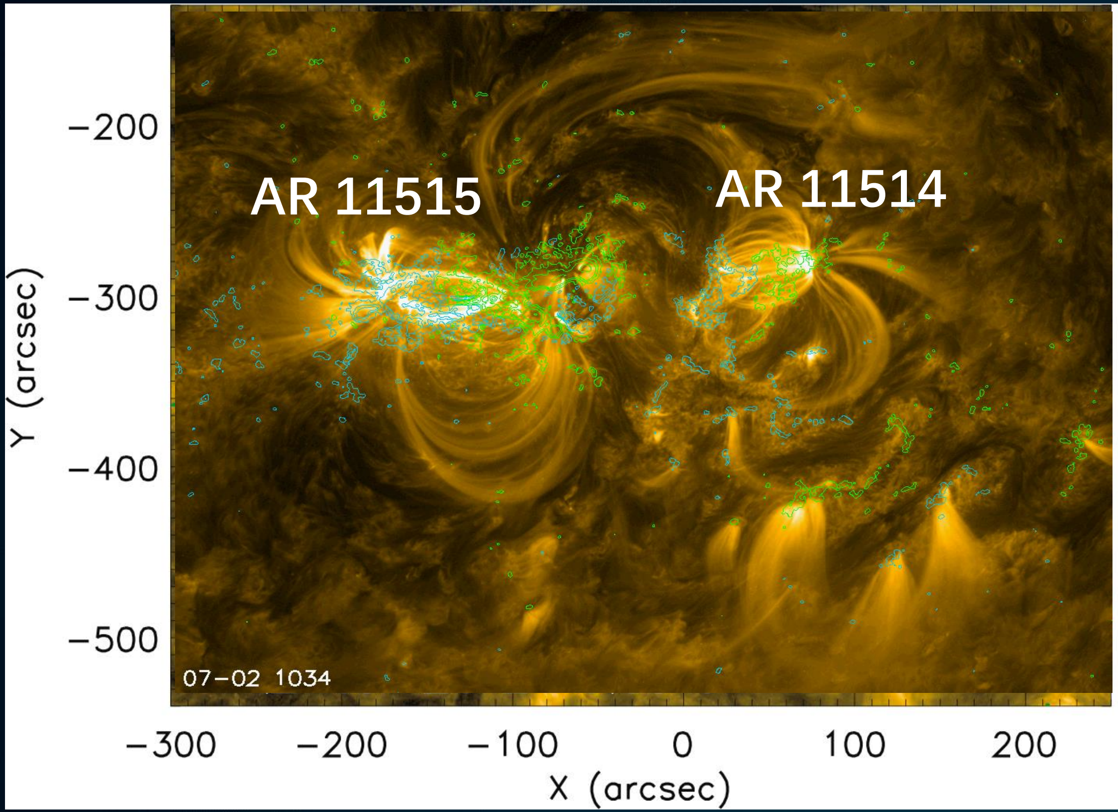
Active Region Entity (Activity Nest)

- Consists Of One Or More Complex Activity Regions That Are Interconnected

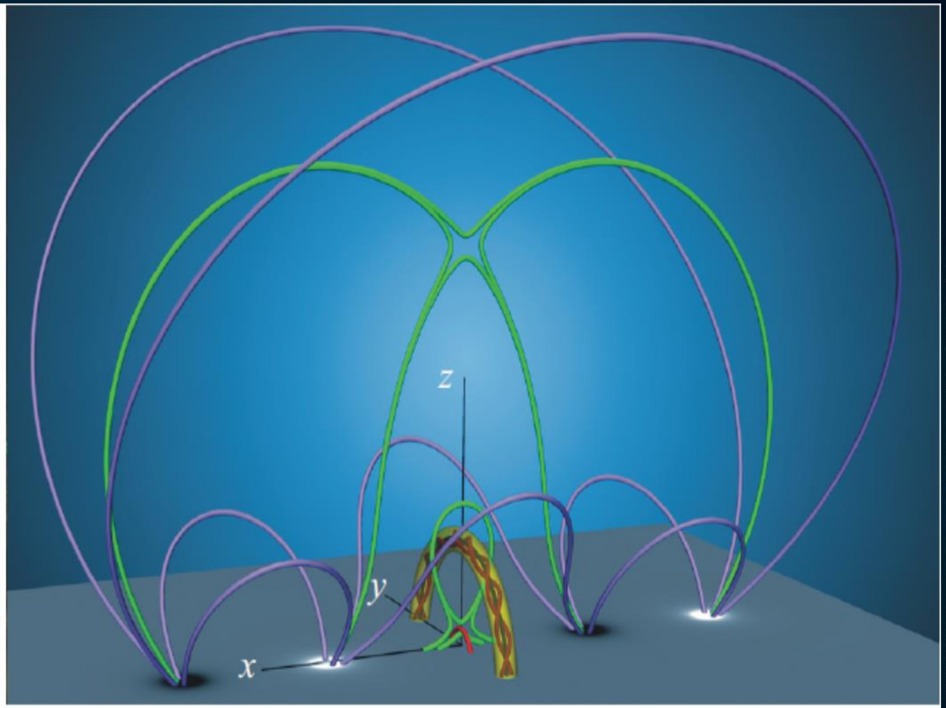


(Wang+ 2015)

Observation and MHD description of multi-polarity mag. field config.



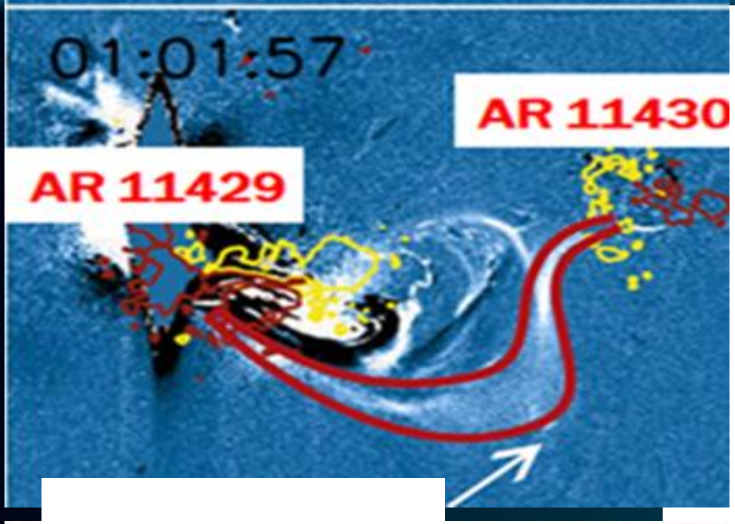
(Wang+ 2015)

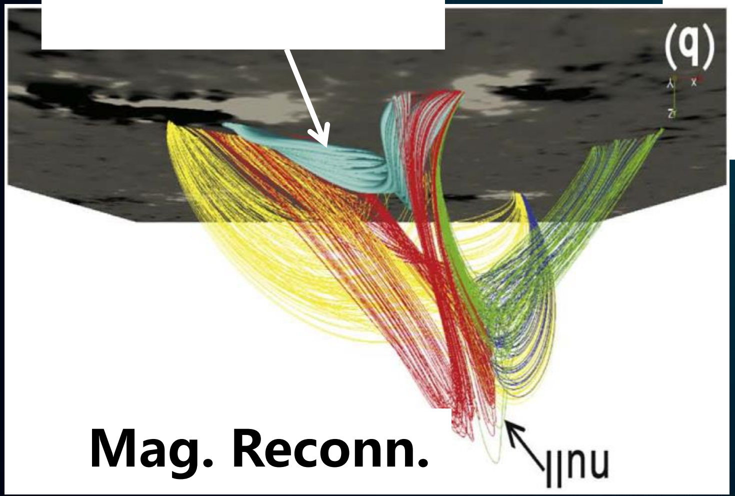


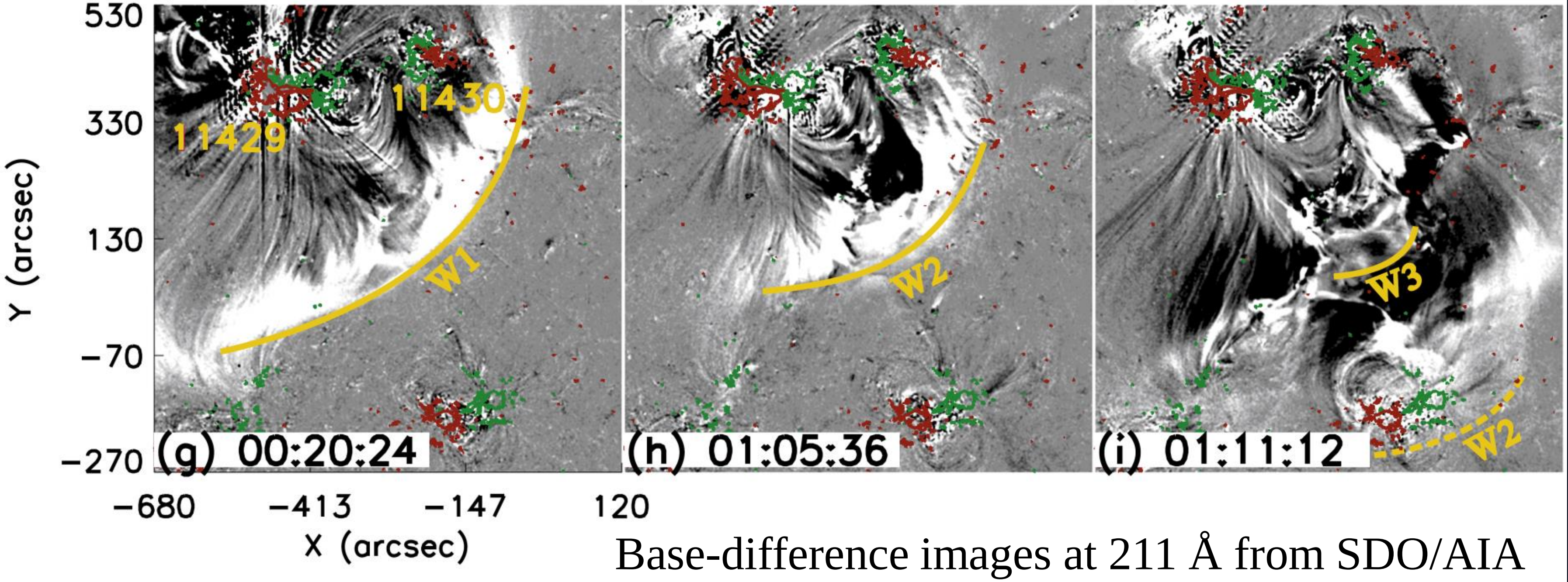
(Kliem et al. 2014 ApJ)

- A major flare/CME: brokenout first then followed successive reconnections in the cluster

Unveiling Large-scale magnetic ropes & multiple mag. Recon.





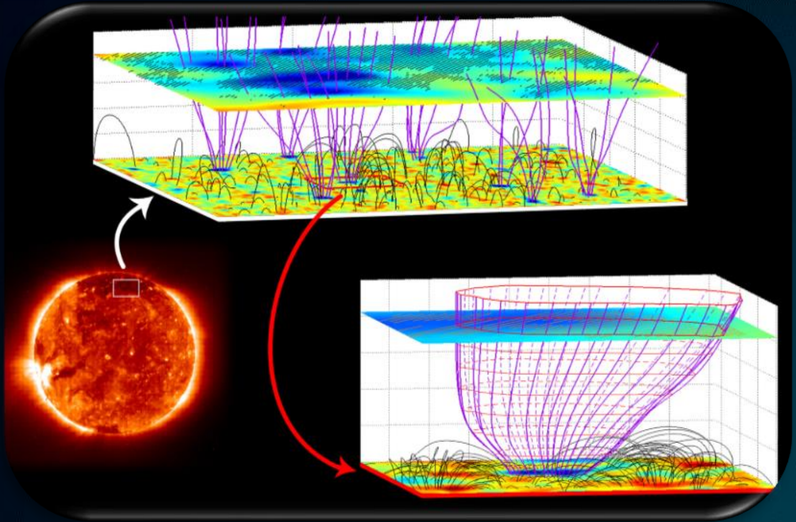


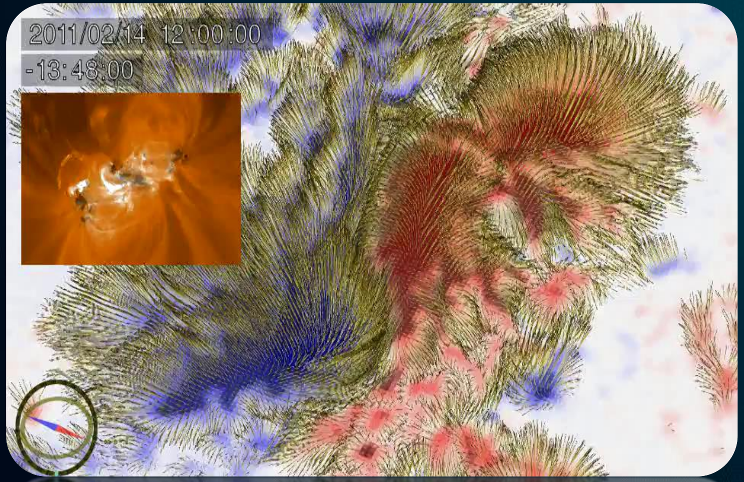
Base-difference images at 211 Å from SDO/AIA

- **Identifying a Large-scale mag. ropes between active regions**
- **fast (magnetoacoustic) shock driving mag. rope instability & external mag. recon. above**
- **Unveiling a new physical mechanism for coronal mass ejections**

- (Zhou+, ApJ, 2019, 2020)

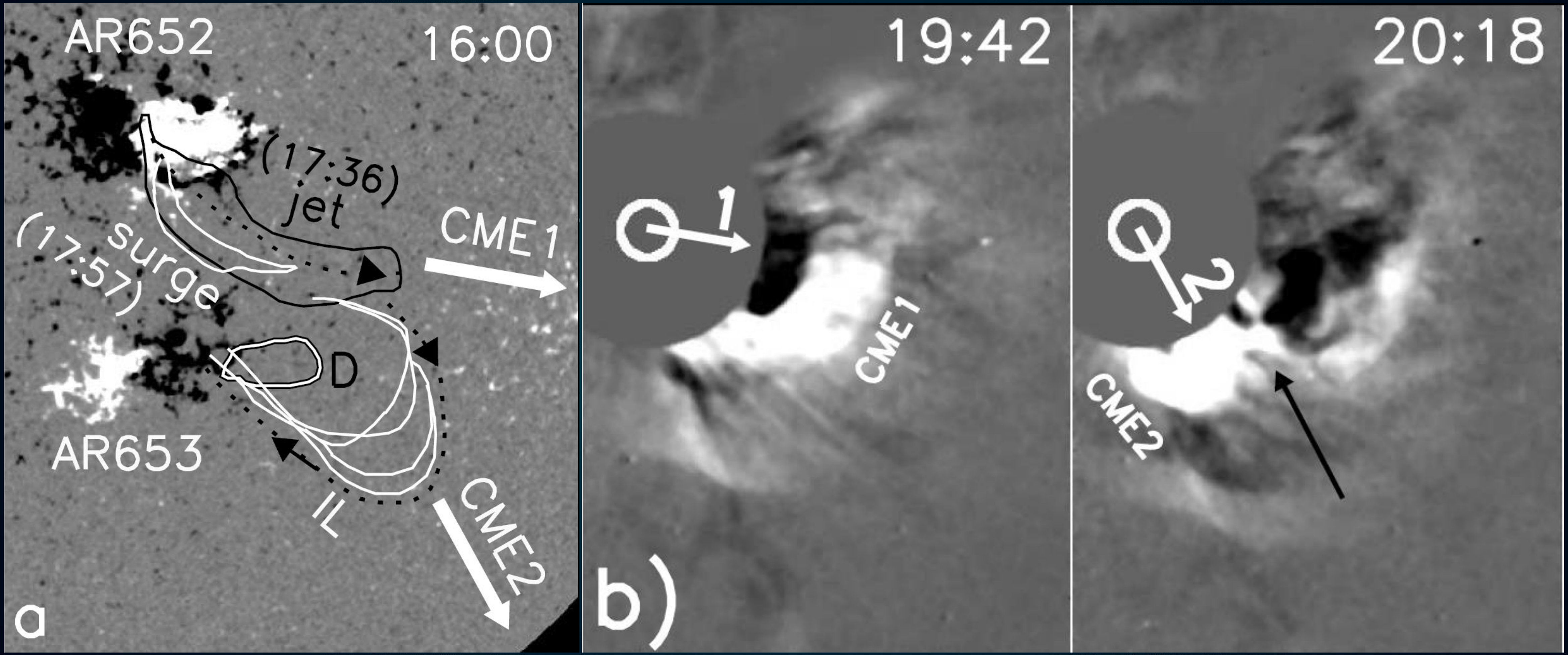
Magnetic Interfaces—Rich Physical Processes



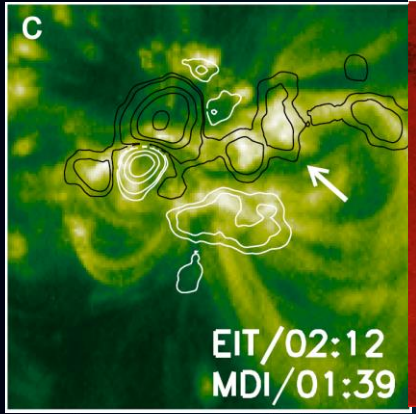


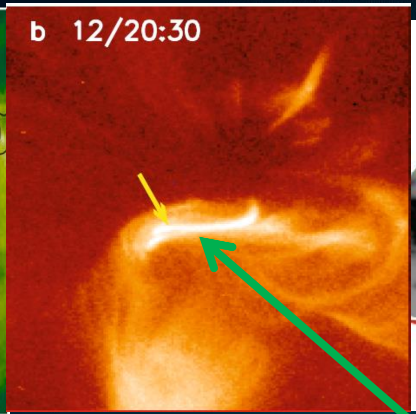
- Magnetic cancellation and CME triggering (Zhang, J. et al. 2001 ApJ)
- Dynamic activity of flare rings (Ji et al.2007 ApJ)
- Super solar active regions (Wang et al. 2010 IAUS 273
- Solar Wind Modeling (Tu et al. 2005 Science)
- Multiple Magnetic Clouds (Wang, Y. et al. 2003 JGR)
- Magnetic cloud boundary layer (Wei et al. 2003a,b, JGR, GRL)
- The magnetopause component and reverse reconnection (Pu et al.2007 GRL)

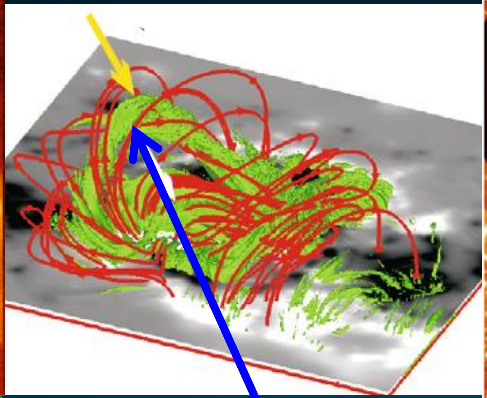
Magnetic Interactions: Transequatorial Jets and Coronal Loops (Jiang et al. 2008)

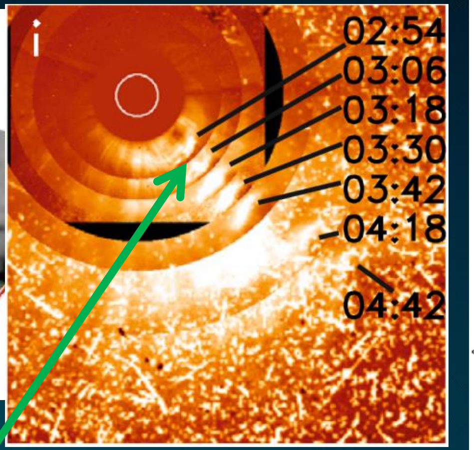


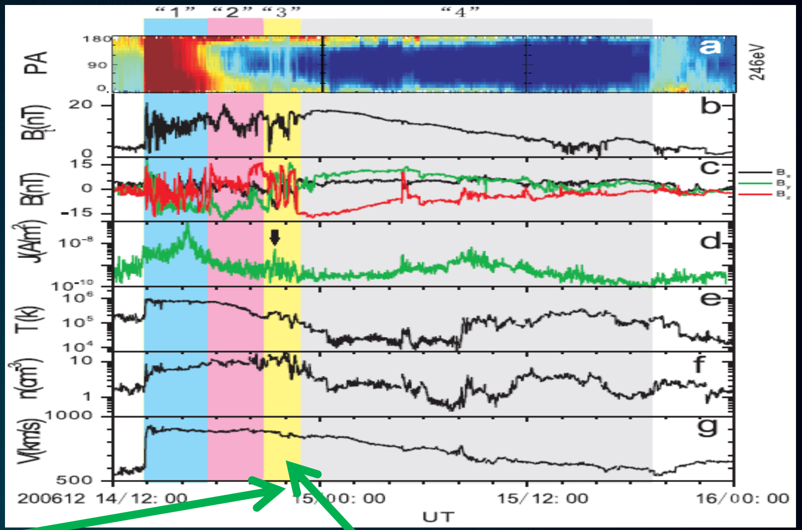
Tracing large-scale transverse current sheets at the violent CME front from the source to the interplanetary space on 2006. 12. 13

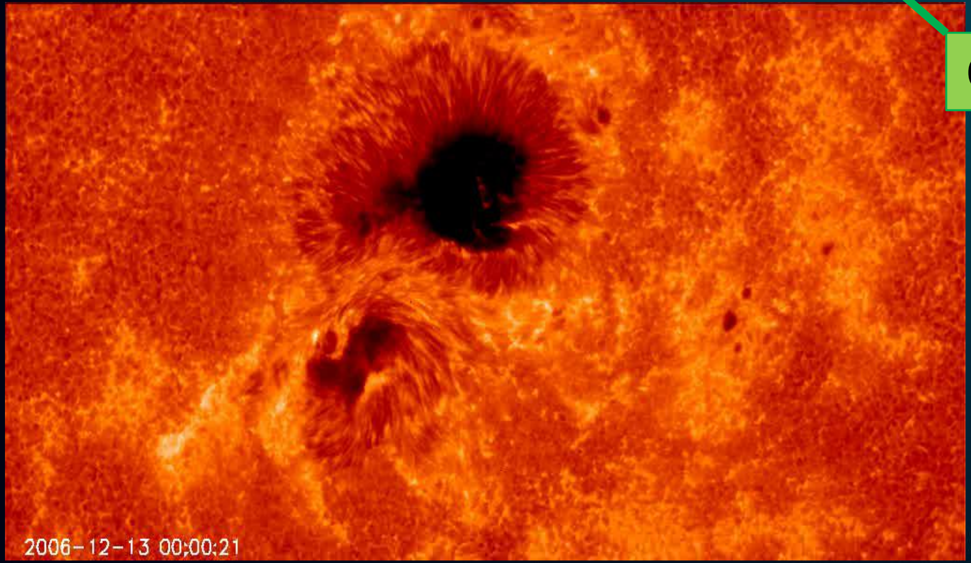






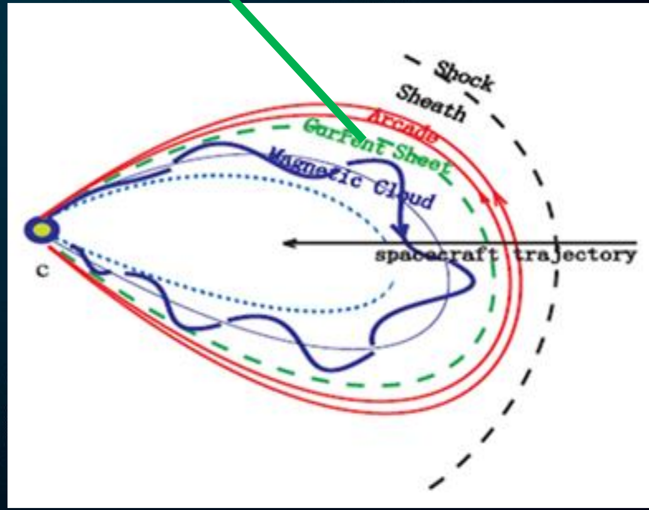






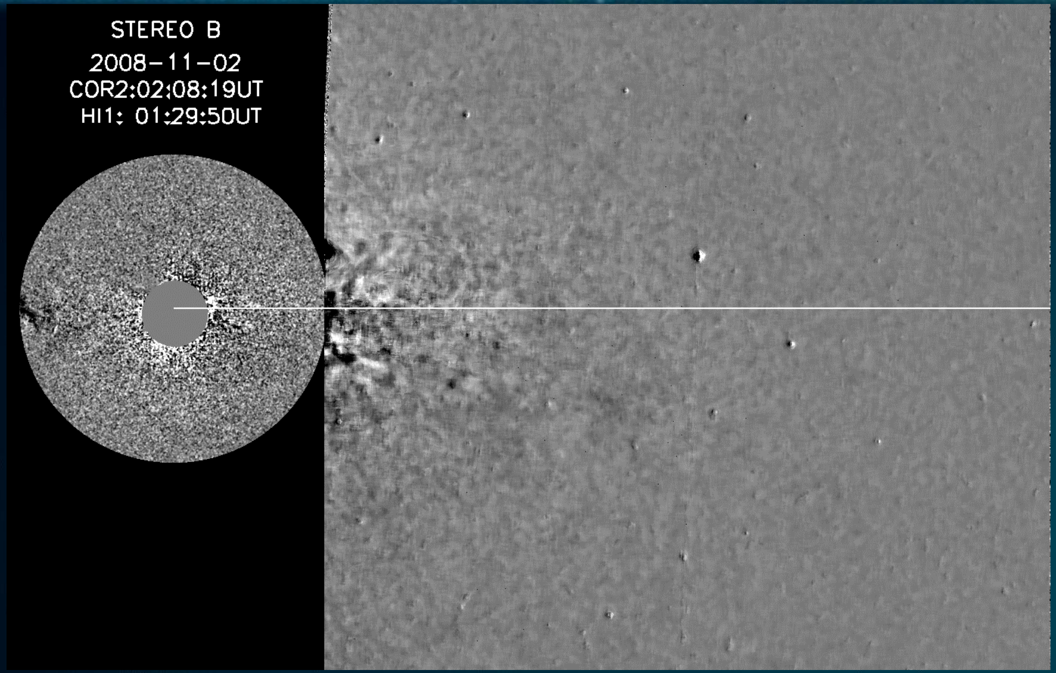
Current sheet

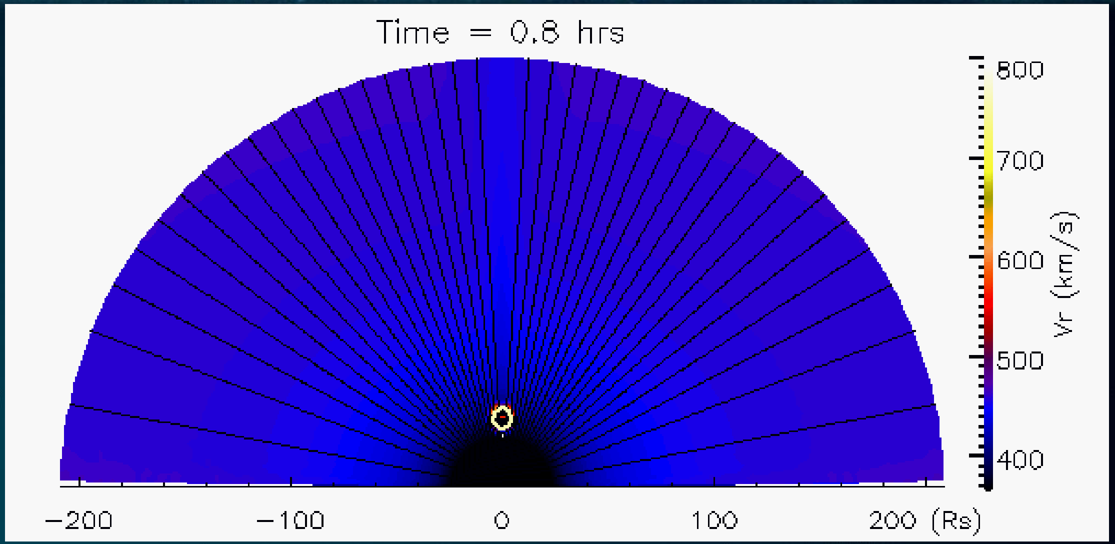
- Verifying a large-scale transverse current sheet from above the active region to the interplanetary space
- It is essential for the triggering, propagation, geomagnetic effects, and modeling of CMEs

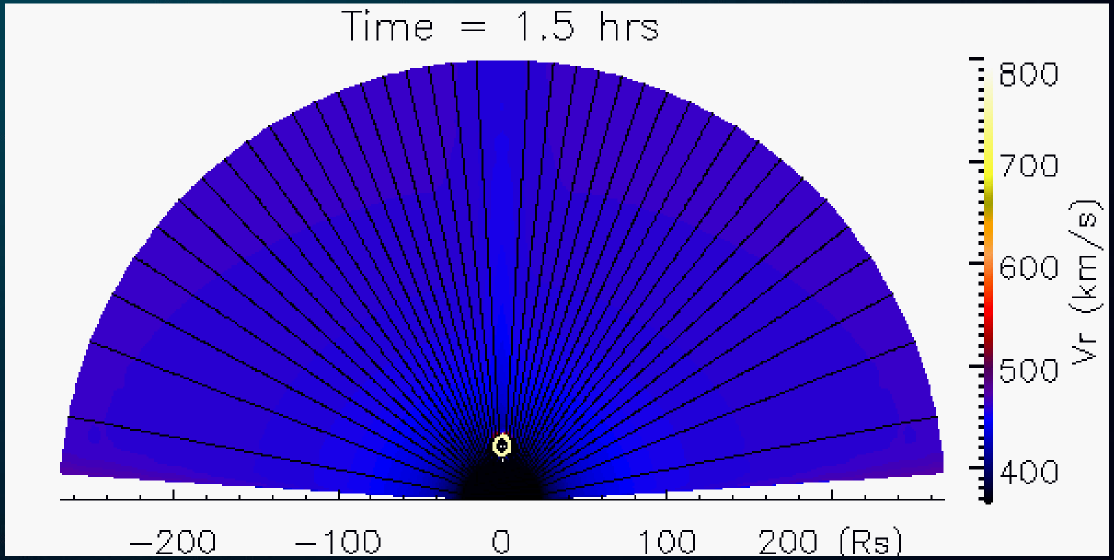


(Zhou+2011)

Interplanetary Interaction







Major Interplanetary Sources of Disaster Space Weather

- ✓Collision of multiple CMEs (Shen et al. 2012)
- ✓Shock wave propagates through mag. cloud
- ✓Interacting mag. cloud

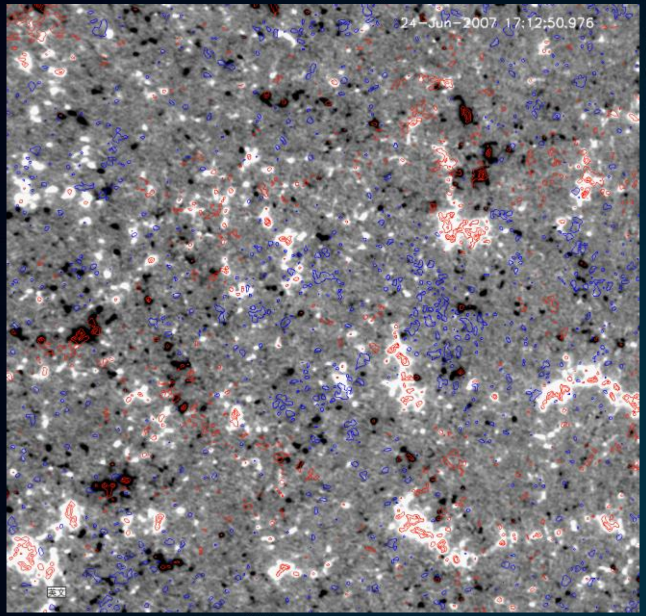
OUTLINES

- Why study Solar Physics
- Basic physical problems of solar activity research
- Progress in understanding multi-scale magnetic activity of the sun (star)

Basic physical problems in the study of solar activity

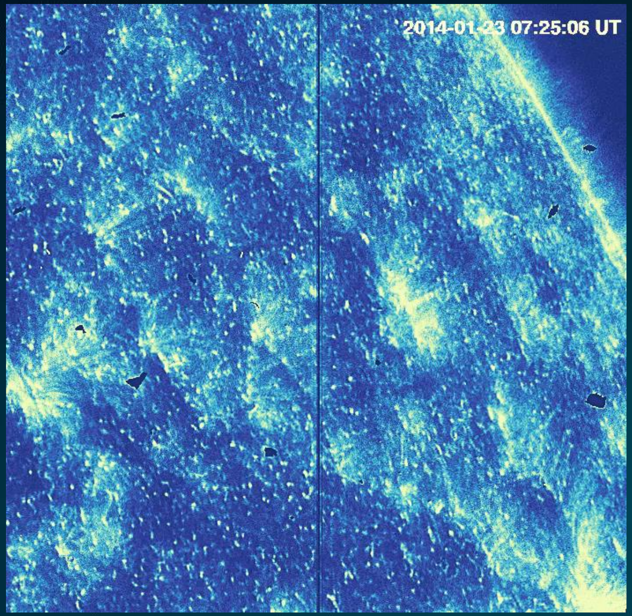
- Magnetic energy accumulation in the solar atmosphere
- Explosive release of magnetic energy in the corona
- Acceleration of high energy particles in solar electromagnetic storms
- General characteristics of solar electromagnetic storms - solar cycle and dynamo (astronomical and physical methods and theories)
- Prediction of solar electromagnetic storms

Ubiquitous small-scale magnetic fields on the Sun



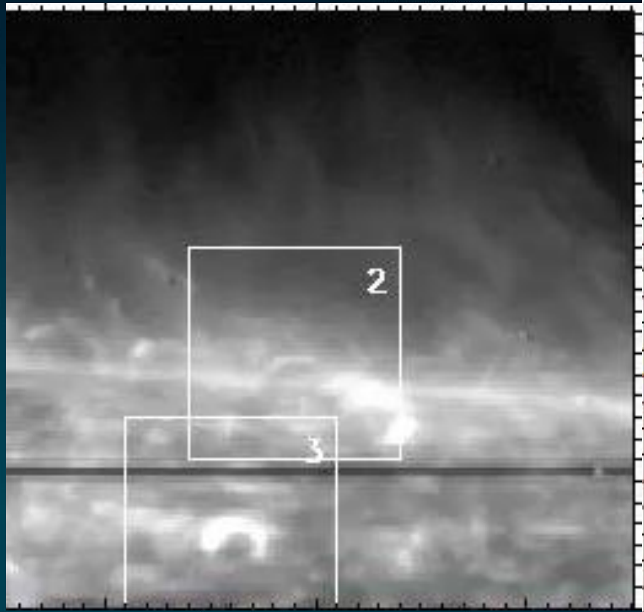
Wang et al.， 2012， Solar Phys.

- **The Sun's surface is an ocean of small-scale magnetic activity**



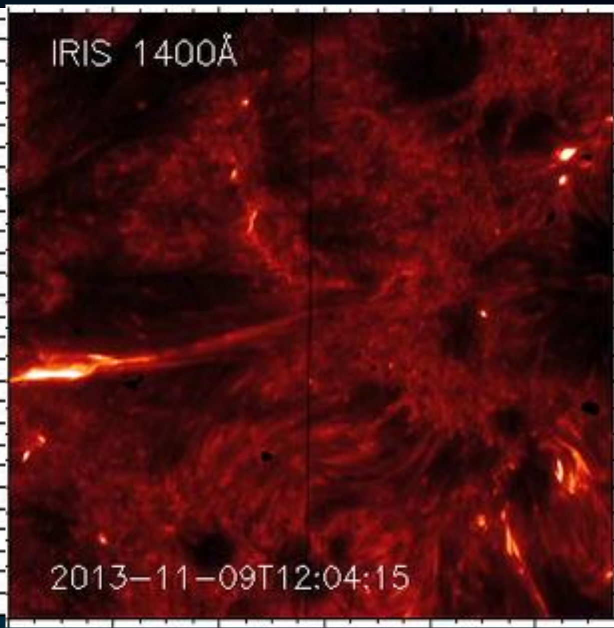
Tian et al.， 2014， Science

- **A highly dynamic and extremely inhomogeneous transition reg.**



Hansteen et al. 2014, Science

- **High speed intermittent jet in coronal hole/quiet Sun**

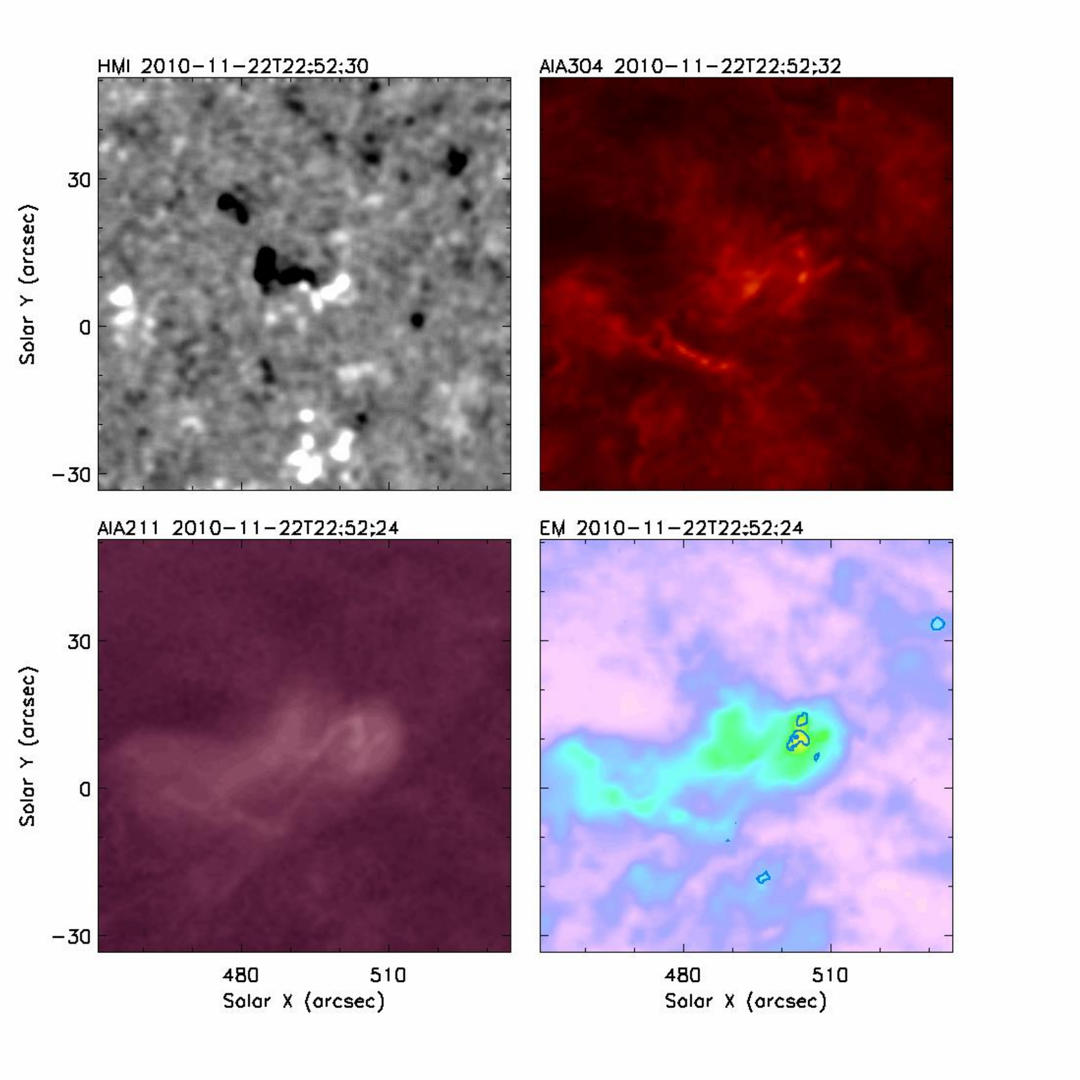


(Testa et al. 2014, Science; Tian et al. 2014, ApJL)

- **Flare-like brightening in transition reg.**

Nanoflare heating corona ?

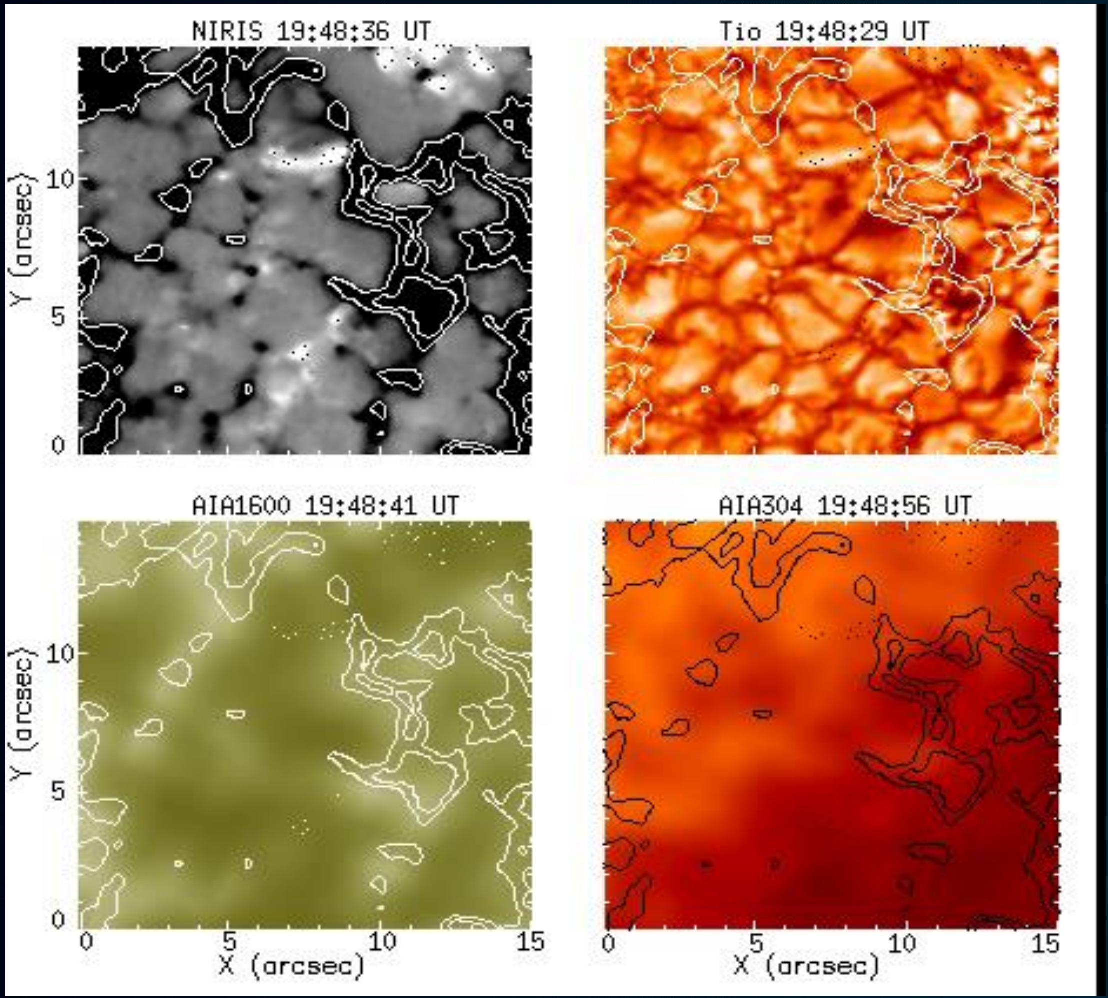
Homologous Microflares related to Mass Ejection and Plasma Heating on the Quiet Sun



- Microflares related wtih major mag. Recon in the chromosphere
- Related mass ejections , velocity up to 160 km/s
- Heating the corona in the quiet Sun up to 5.8 MK

(Jin et al. ApJL, 2021)

Magnetic outbreak associated with exploding granulations



1. A new form of flux appearance: magnetic outbreak, which refers to an early growth of unipolar magnetic flux and its later explosion into fragments.

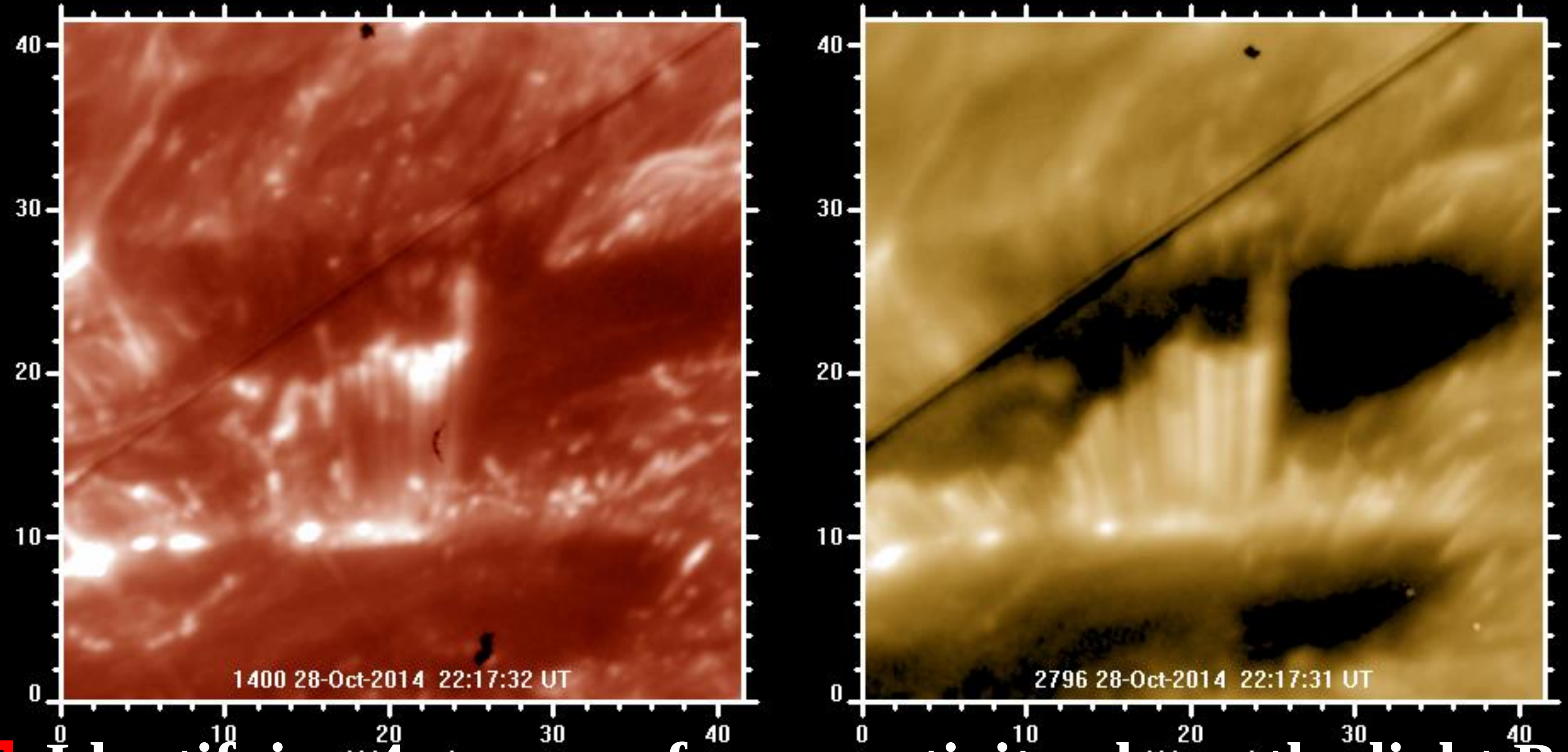
2. The magnetic phenomenon is associated with plasma upflow and exploding granulations

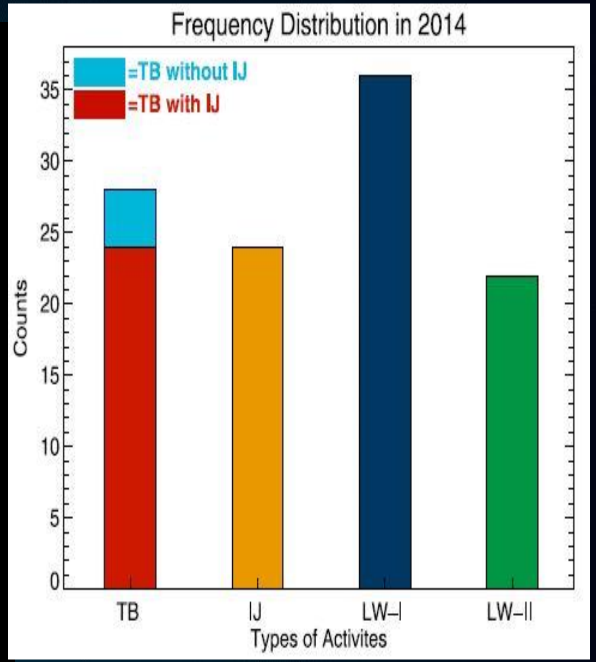
3. The newly discovered magnetic outbreak might be the first evidence of the long-anticipated convective blowup.

(Jin et al., 2022, to be accepted)

Understanding various activity phenomena above the light Bridge of sunspots

Coronal surge in light bridge observed by IRIS

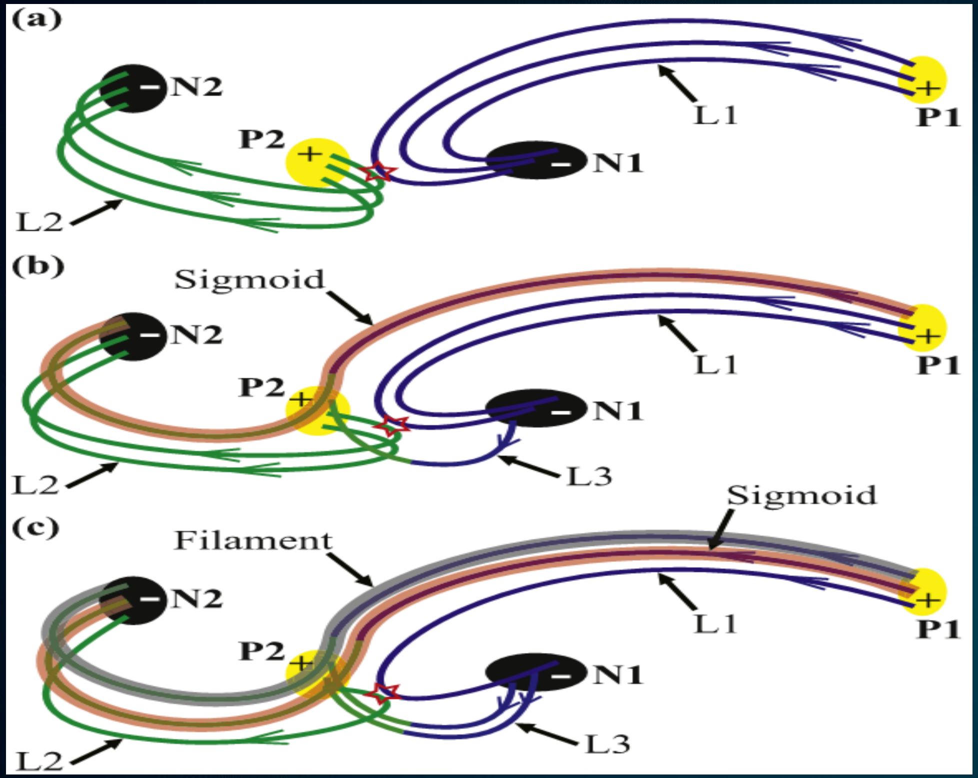


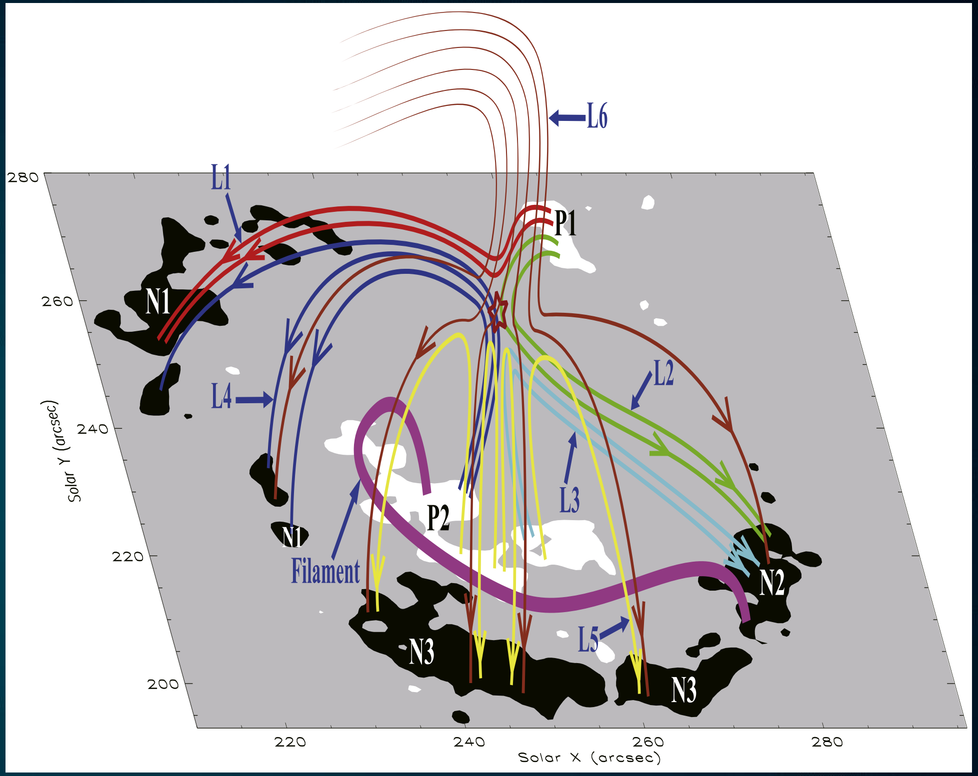


(Hou et al. 2022)

- Identifying 4 groups of mag. activity above the light Bridge of sunspots
- Decided by mag. convection, mag. Recon., & leakage of P-mode wave

New observations of Mag. Recon.

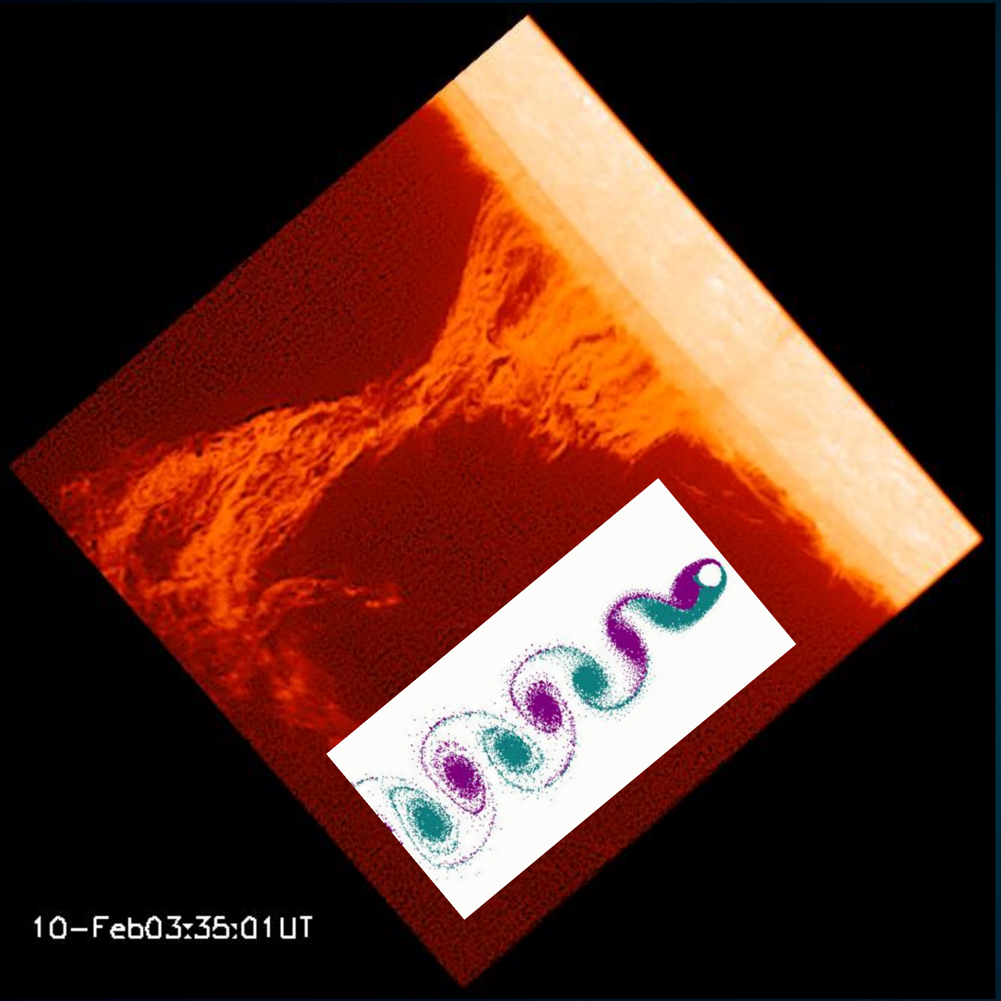


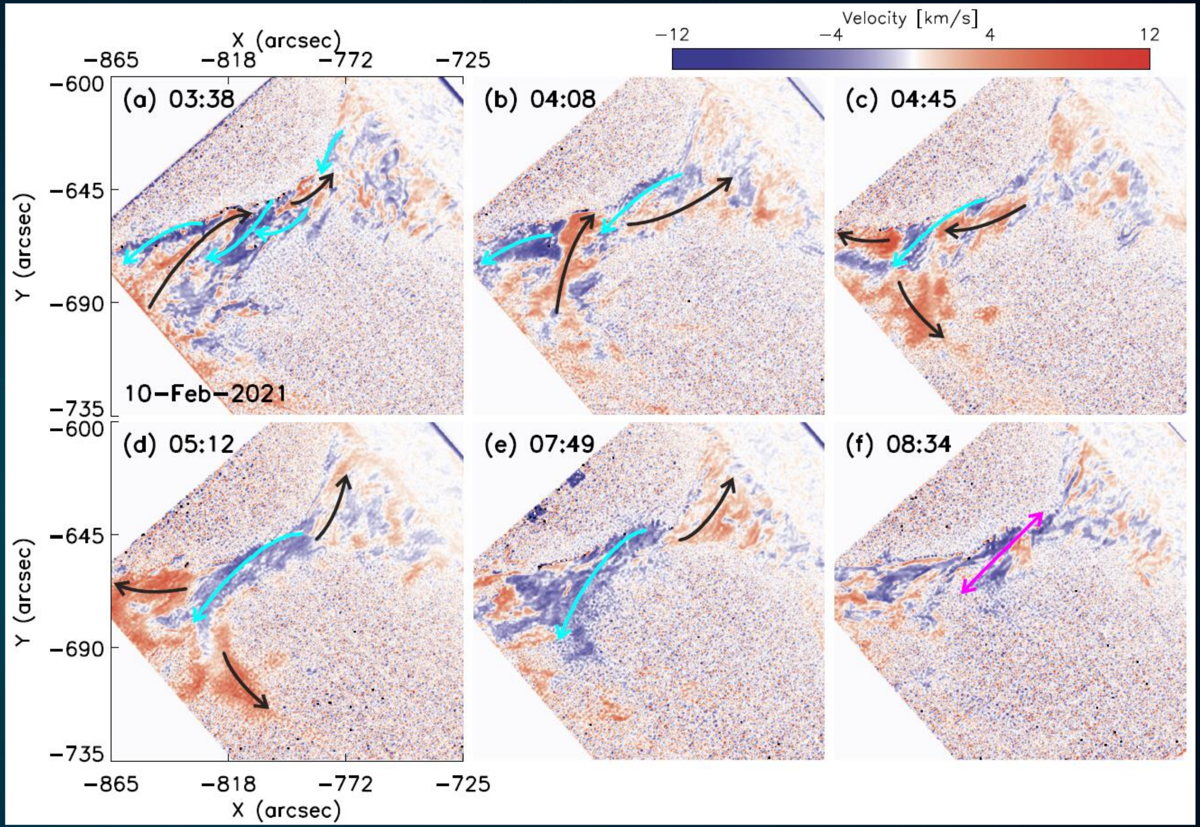


- Mag. Recon. Play key role in filament formations (Li et al. 2021a),, filament eruptions by mag. emerging (Li et al. 2022), and producing coronal rain (Li et al. 2021c, d, Chen et al. 2022)

- fast-mode magneto acoustic waves accelerate the magnetic recon. (Li et al. 2021b)

Karman vortex effect in a twisted prominence





- *Strach number St=L/Pv =0.215*
- *[0.20, 0.25] (e.g., Buchholz, 2008)*

(Zhang X.F. +， in preparing)

Observations of a magnetic dip in a quiescent prominence foot

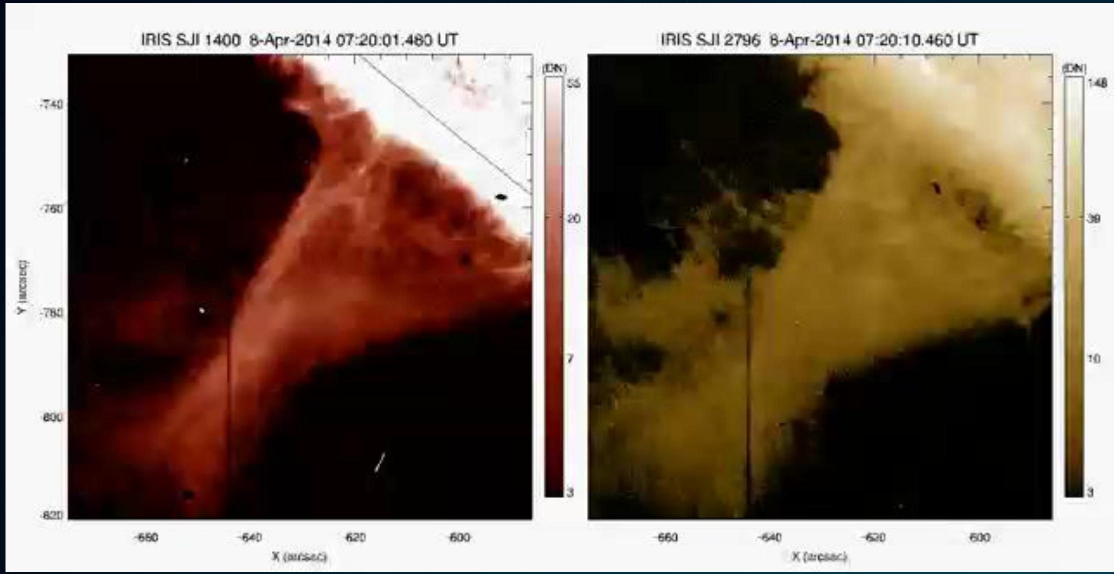


Fig.1 Magnetic dip observed in IRIS SJI 1400 Å

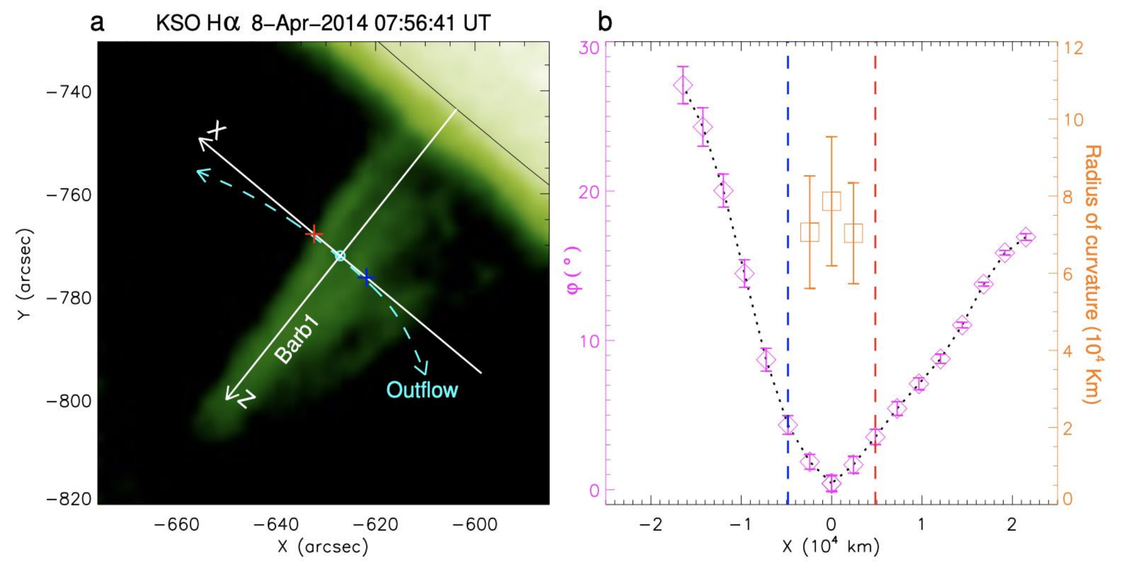


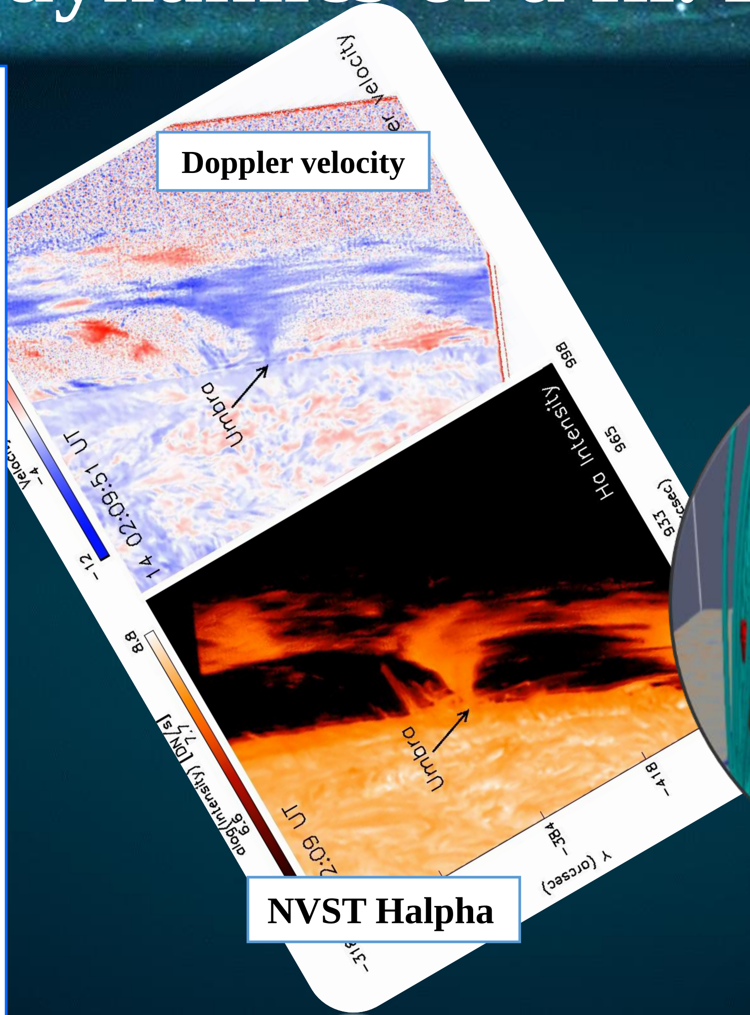
Fig.2 The field orientation of the magnetic dip

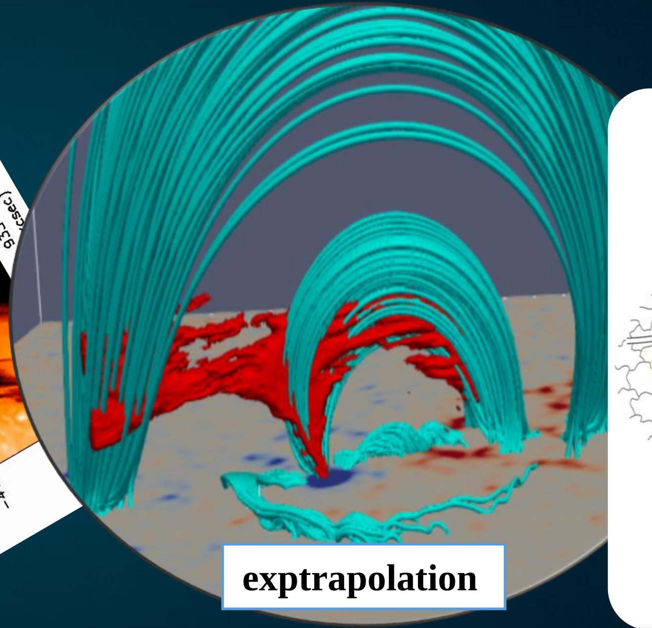
- Filament material is always suggested to situated in a proposed dip structure
- Using high-resolution imaging and spectral data from IRIS and SDO, a magnetic dip structure is demonstrated in a quiescent prominence foot.

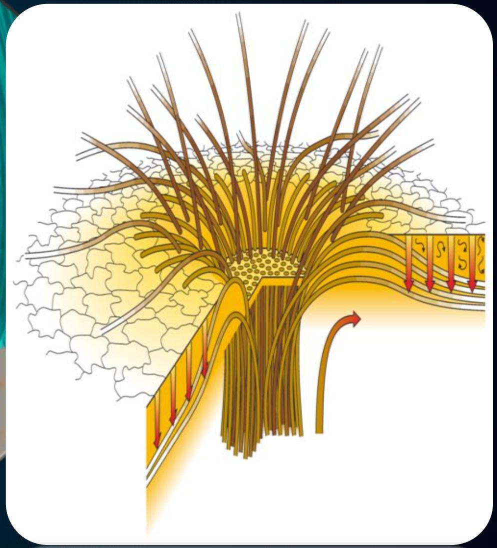
(Chen H. D. +, in revising)

Formation & dynamics of a fil. rooted in sunspot umbra

- The filament formed in the sunspot umbra
- The original material of the filament is likely to come from below the umbra, rather than from the corona
- Newly understanding of the origin of the filament material



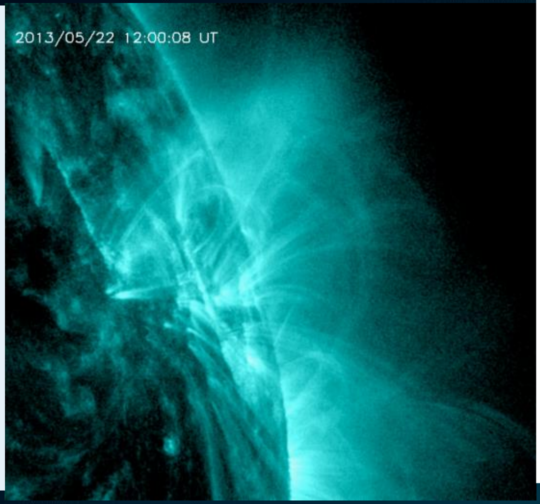


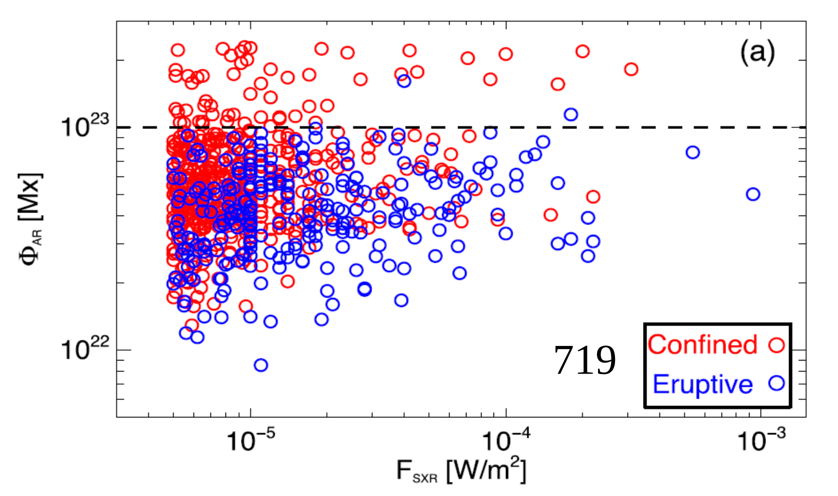


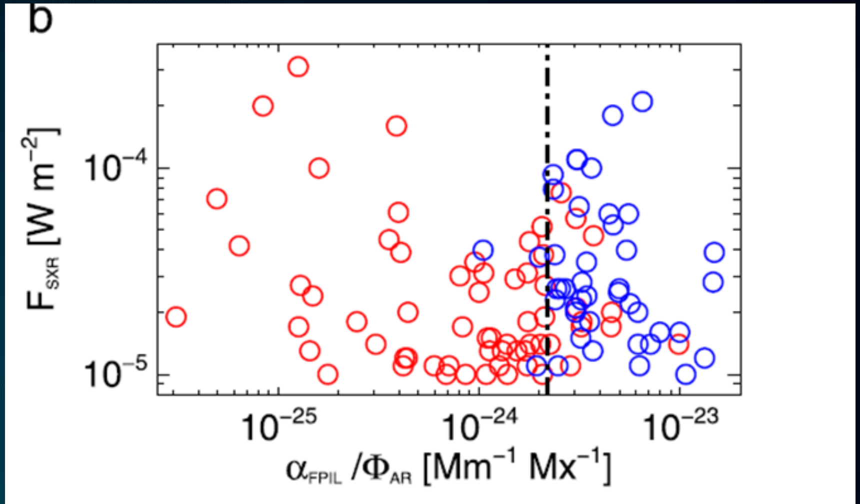
- **Zhou +， in revision**

Mag. Flux suggested as an important parameter to divide two types of flares

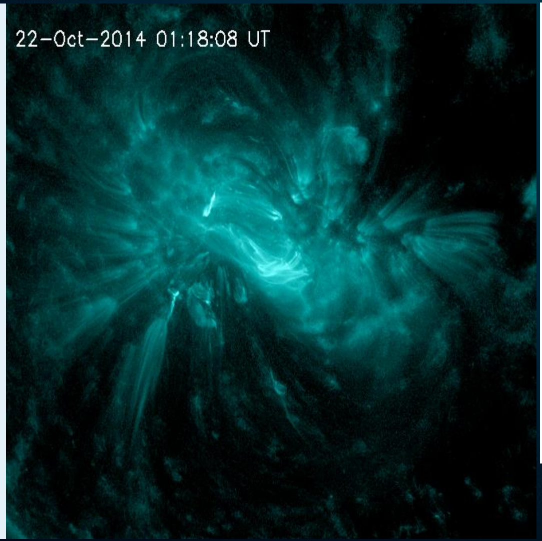
Eruptive flares related to CMEs

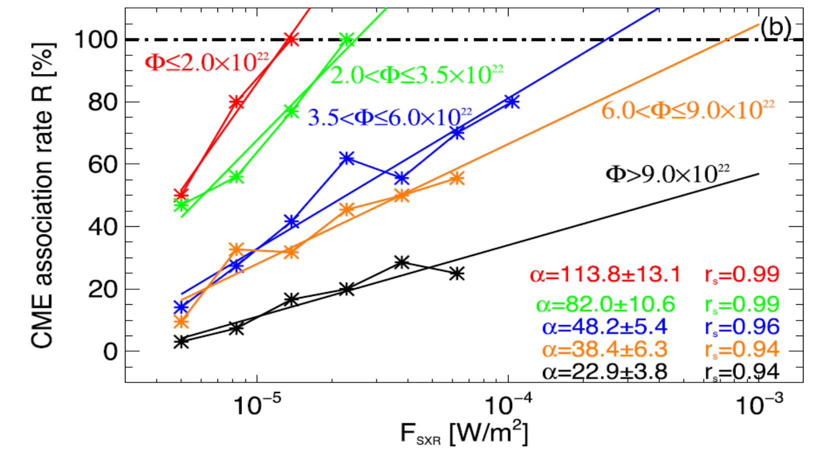






Confined flare without relating CMEs





- **Mag. Flux is important in determining the occurrence of eruptive flares**
- **A new parameter (mag. field twist number/mag. flux) is proposed to distinguish two types of flares**

(李婷 等，2021, 2022)

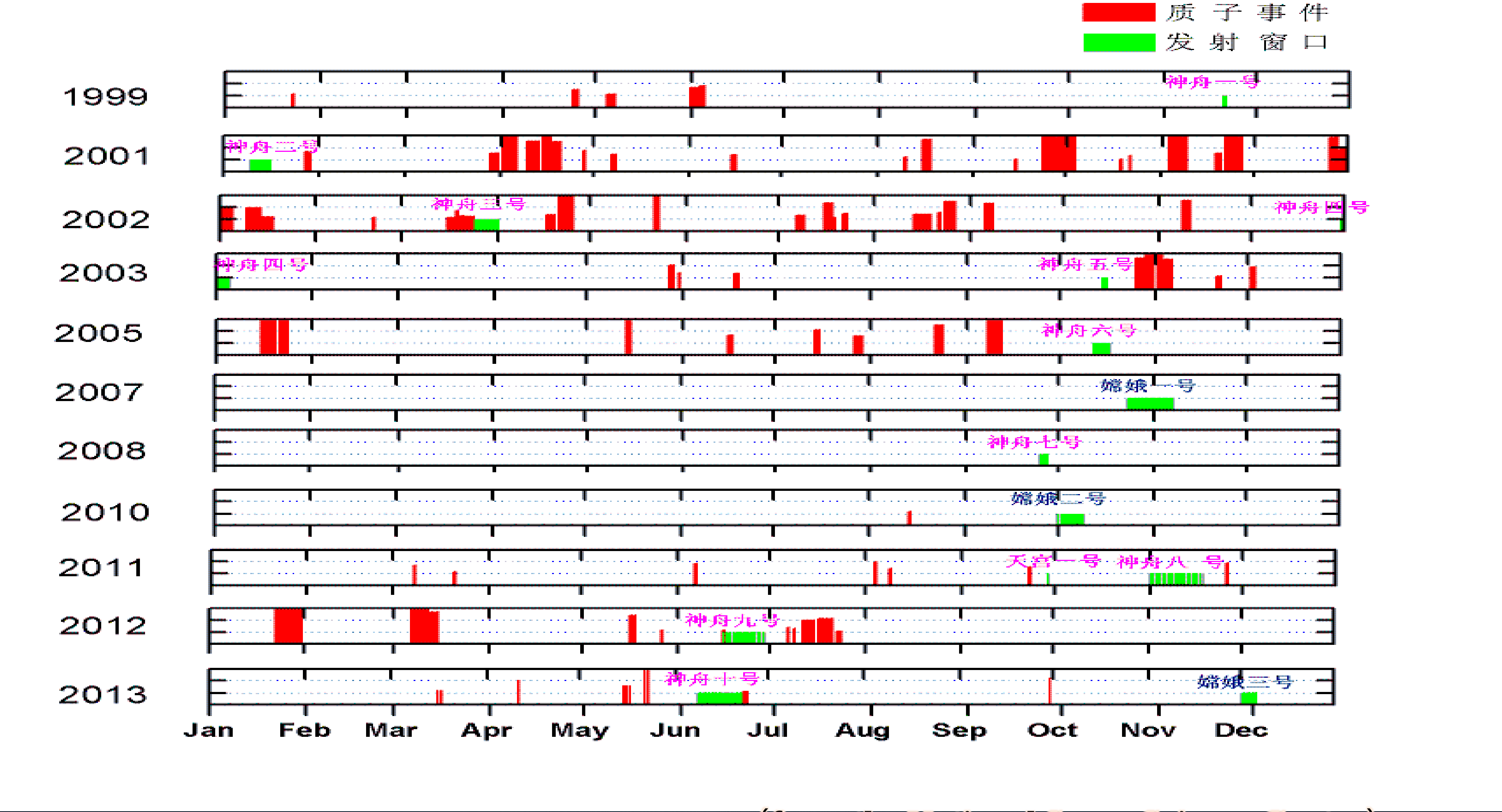
Predicting Solar flares and CMEs based on vector magnetic fields

Parameter	Description	Unit	Formula
$\|\Phi_{tot}\|$	Total unsigned magnetic flux	Mx	$\Phi_{tot} = \sum \|B_z\| dA$
$\|\Phi_{net}\|$	Net magnetic flux	Mx	$\|\Phi_{net}\| = \|\sum B_z dA\|$
ρ_{free}	Free magnetic-energy density	$erg\, cm^{-3}$	$\rho_{free} = \|\mathbf{B_o} - \mathbf{B_p}\|^2/8\pi$
E_{free}	Total free magnetic-energy density	$erg\, cm^{-1}$	$E_{free} = \sum \rho_{free}\, dA$
Ψ	Shear angle	degree	$\Psi = \cos^{-1}(\mathbf{B_o} \cdot \mathbf{B_p}/B_o B_p)$
A_Ψ	Area with $\Psi \geq 80°$	Mm^2	$A_\Psi = \sum dA$
$\nabla_h B_z$	Horizontal gradient of B_z	$G\, Mm^{-1}$	$\nabla_h B_z = \sqrt{(\frac{\partial B_z}{\partial x})^2 + (\frac{\partial B_z}{\partial y})^2}$
L_{NL}	Length of magnetic-neutral line	Mm	$L_{NL} = \sum dL$
J_z	Vertical electric current density	$mA\, m^{-2}$	$J_z \propto \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}$
α	Twist parameter	Mm^{-1}	$\alpha \propto \frac{\sum J_z B_z}{\sum B_z^2}$
α_{best}	Best force-free parameter	Mm^{-1}	$\alpha_{best} = \frac{\nabla \times \mathbf{B}}{\mathbf{B}}$

Notes: B_x and B_y represent the horizontal components, and B_z represents the vertical component of the photospheric vector magnetic field **B**. B_o and B_p are the observed and the potential magnetic field, respectively.

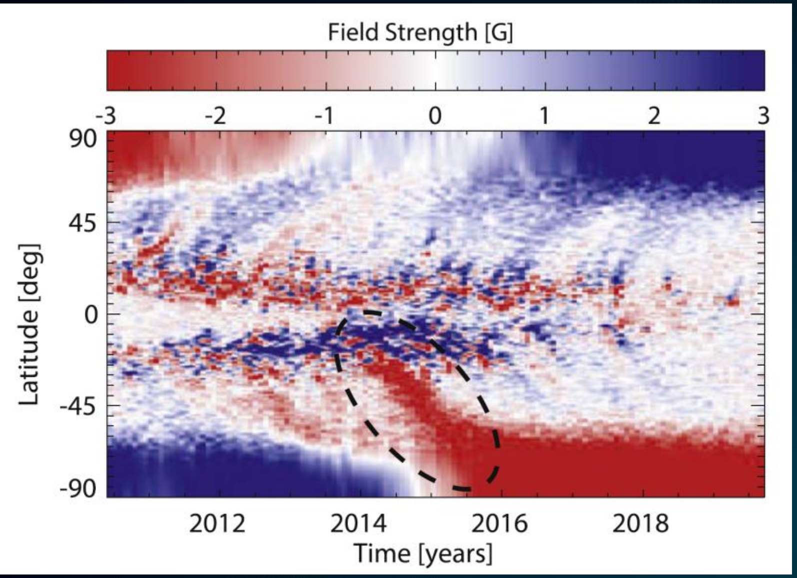
（Chen, A. Q.+ 2022）

Great achievements in space weather forecasting. All space launch missions planned have avoided solar proton events (from 1999-2013)

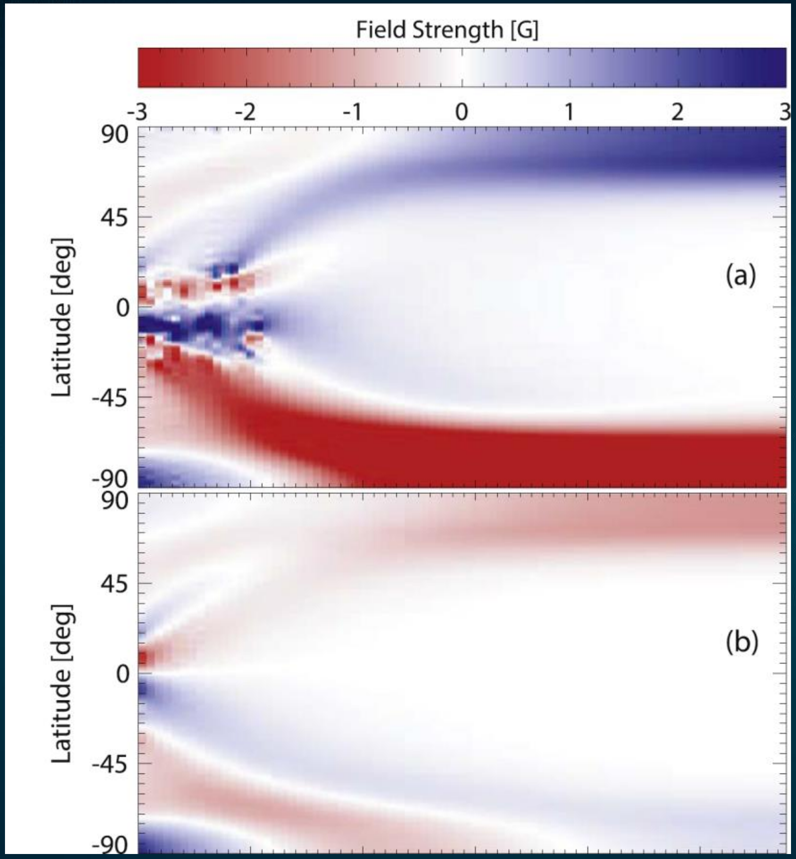


(from the National Space Science Center)

Making progress in well understanding Solar Dynamo



- Magnetic butterfly diagram from SDO/HMI. poleward surge in the southern hemisphere.



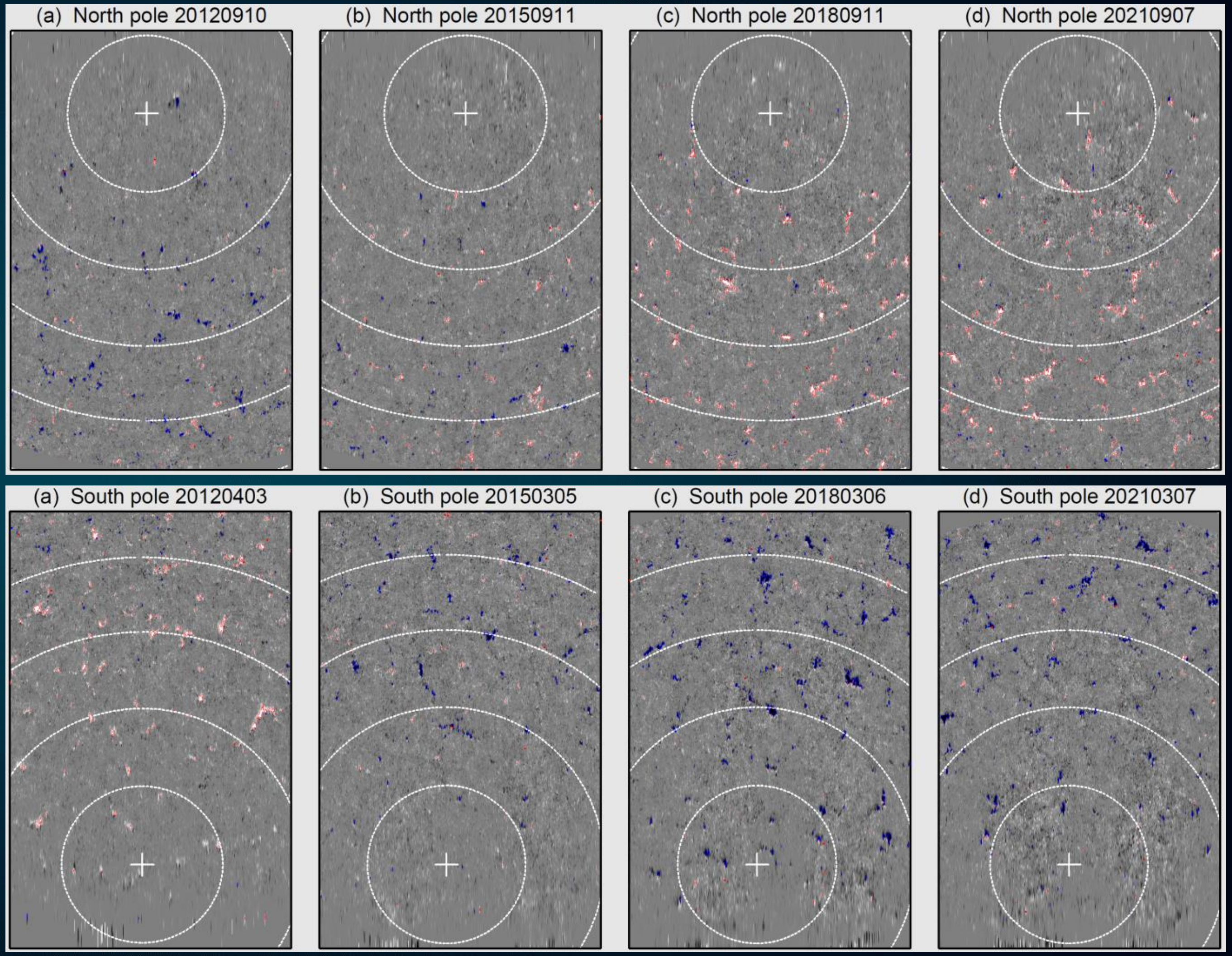
Simulation with/without the activity complexes.

Activities complexes— a key parameter in solar cycle evolution

- **Observation & Simulation Model**— Simulation shows great contribution of activity complexes on forming the surge, Without the surge, polar field cannot perform reverse. (Wang, Z.-F.+ 2020, ApJ)
- **Analysis Model—**Algebraic quantification of an active region contribution to the solar cycle (Wang, Z.-F.+, 2021, A&A)
- **Statistic Model—**Nonuniformity of poleward flux transport on the solar surface (Wang, Z.-F+, ApJ, 2022)

The long-term evolutions of magnetic fields in solar polar regions

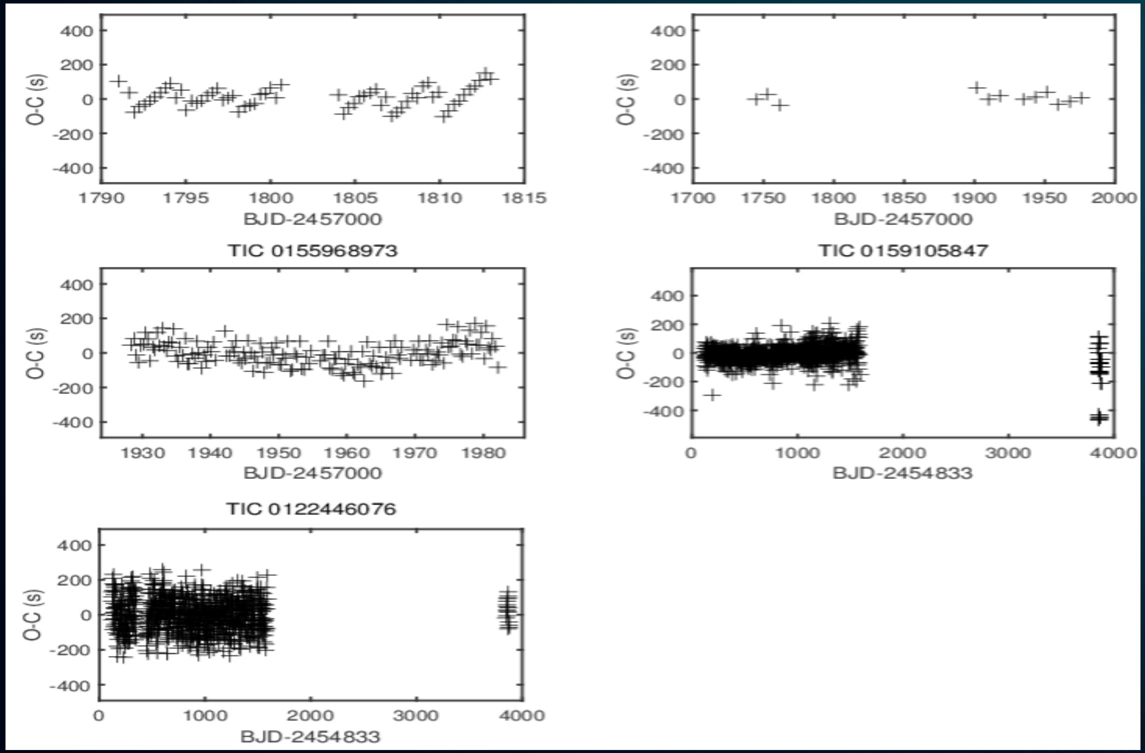
- High-altidude vector magnetic fields from hinode over 10 years
- structure、distribution、polarity reversal of magnetic fields in the solar poles
- Provide important preliminary investigations for project of solar polar-orbiter observatory

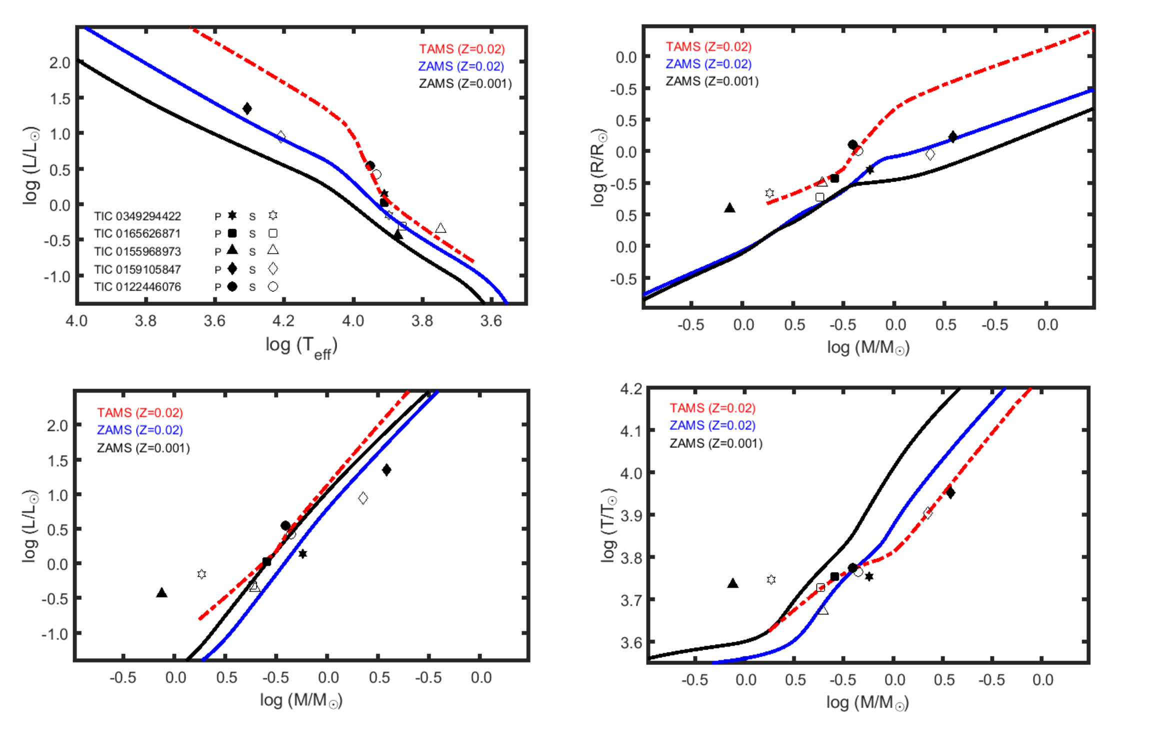


(Yang shuhong +, in preparation)

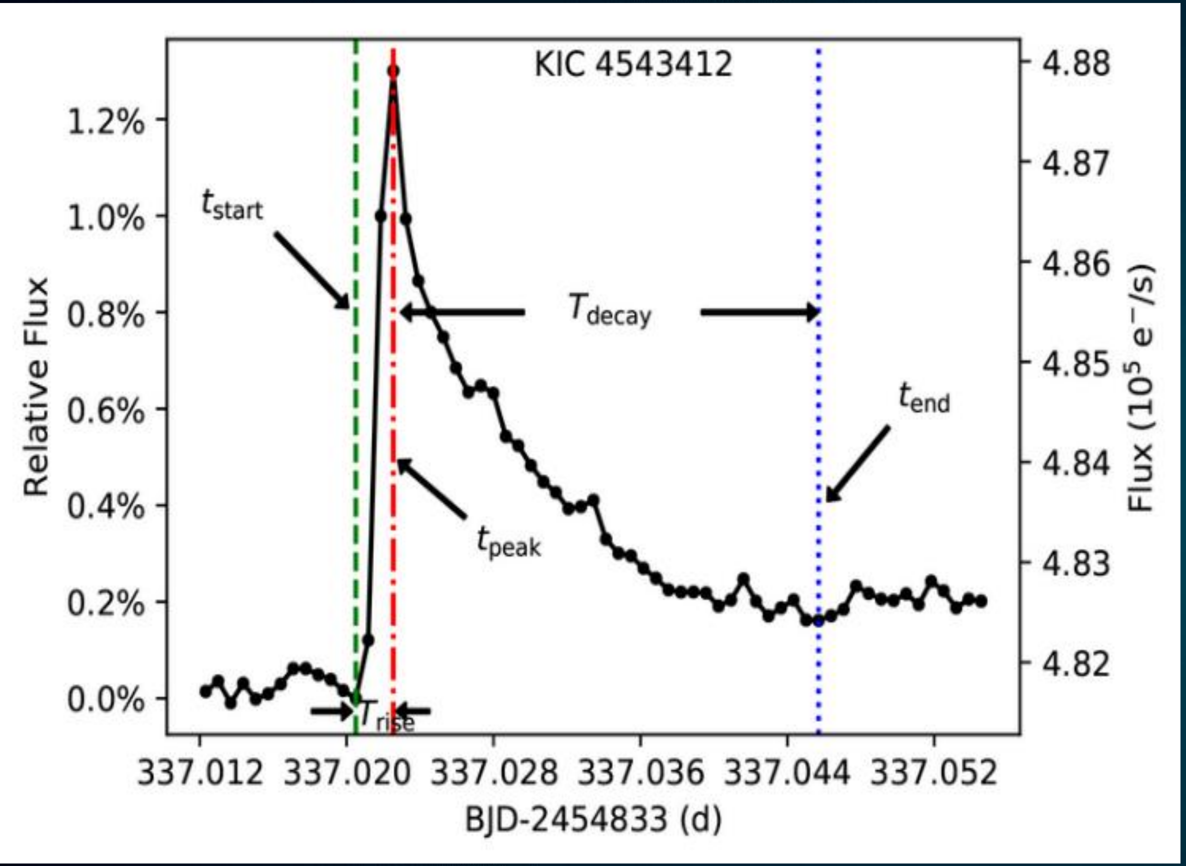
Turning on Stellar explorations

- **Based on photometric and spectral data, e.g. from TESS, LAMOST, and others instruments, double-line binary star systems were studied with emphasis on obtaining their accurate system parameters and understanding their evolutions.**





Characteristic time of Solar-like stellar flares



✓ A flare light curve from *Kepler* SC mode.

Statistics of T_{rise} & T_{decay}

	Median	Mean	Q1	Q3	Min	Max	Std
T_{rise}	5.9	8.8	3.9	9.1	1.0	152.0	13.2
T_{decay}	22.6	33.7	15.7	37.3	4.9	216.8	32.4

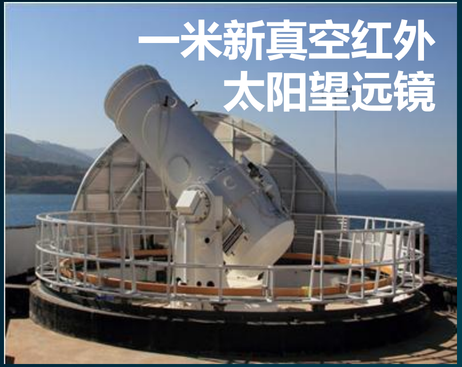
Two Phases For Stellar Flares

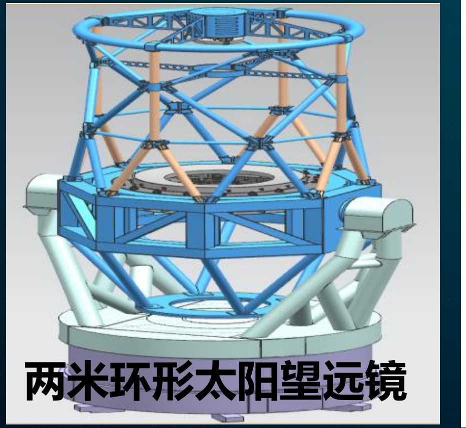
- **rise time T_{rise} ~5.9 min**
- **decay time T_{decay} ~ 22.6 min.**

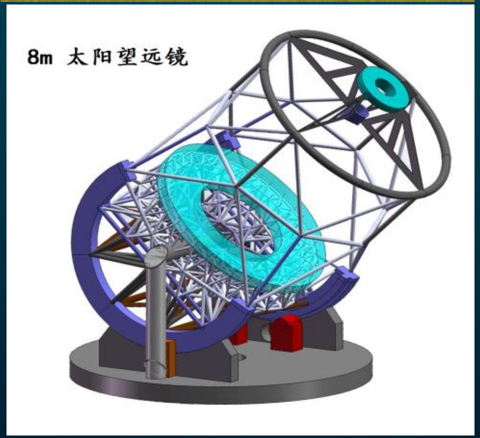
(Yan et al., 2021, MNRAS)

A science driven by observation discoveries

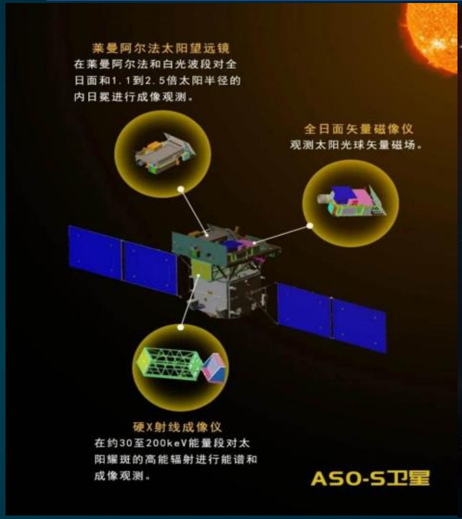
Ground-based

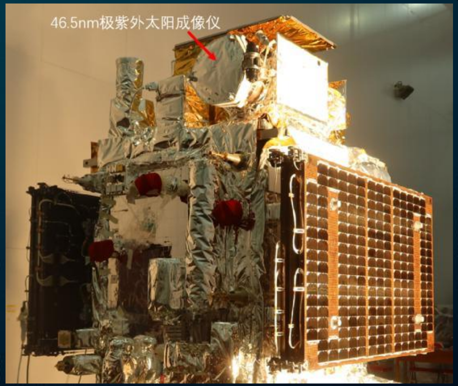






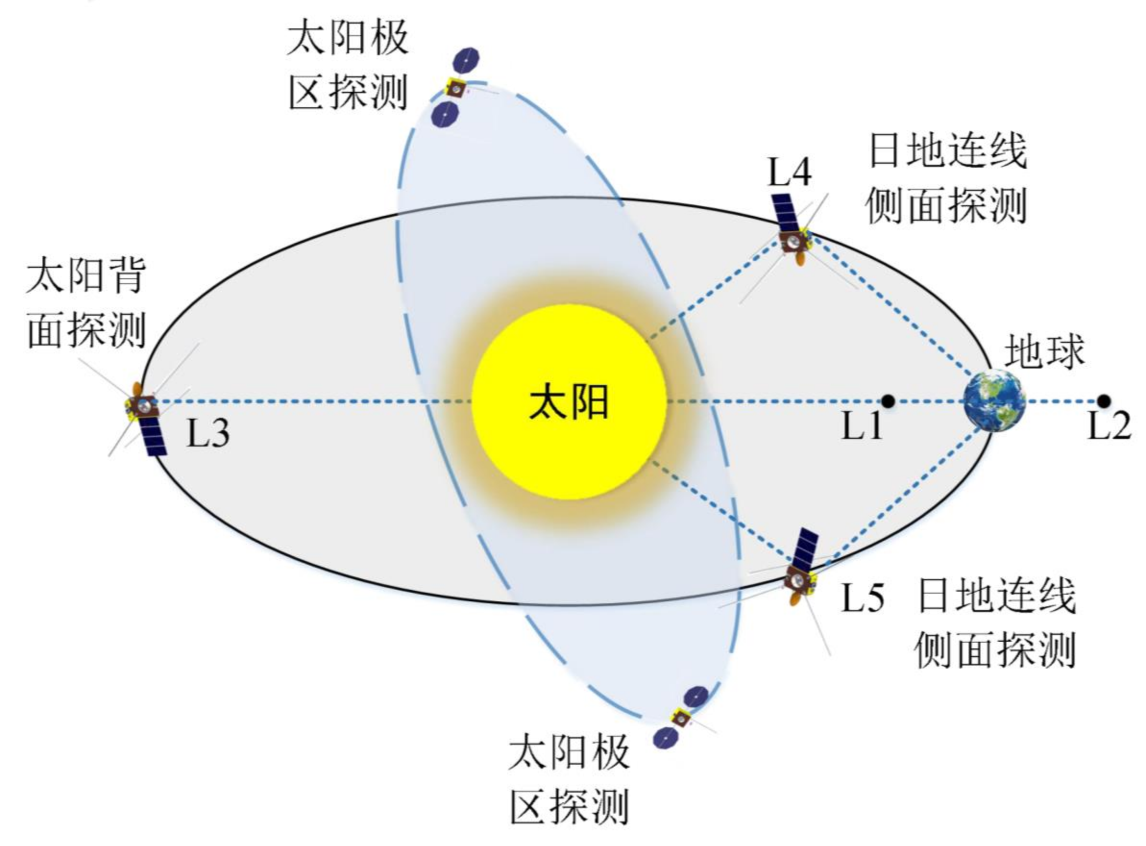
Space-based

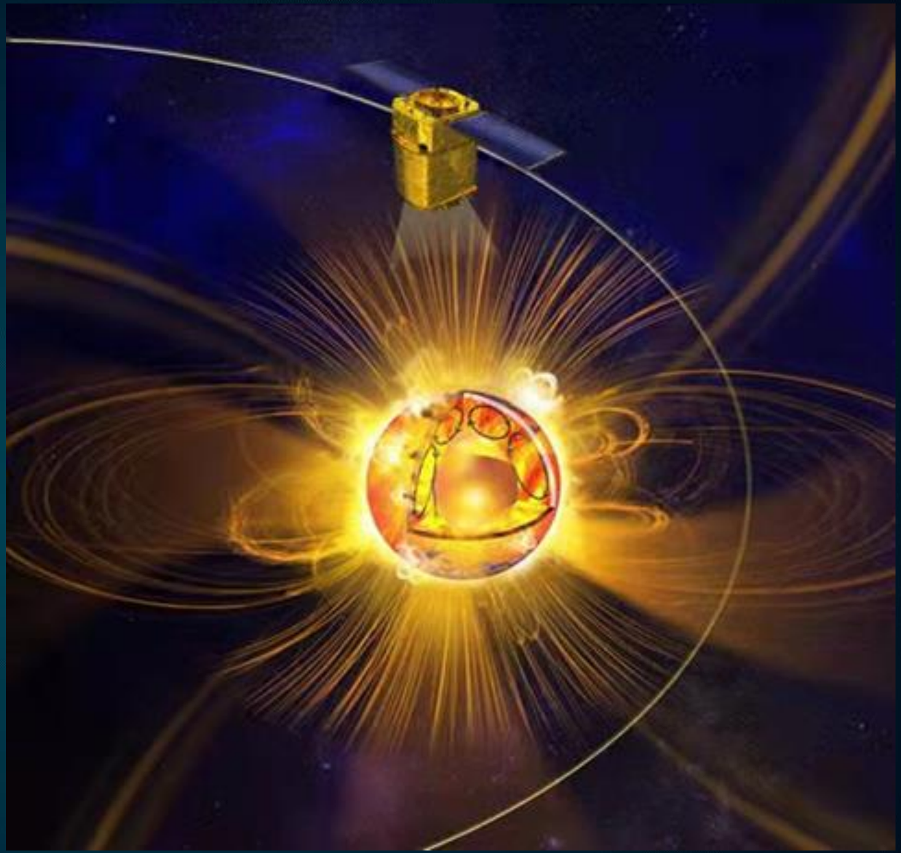




46.5 nm极紫外太阳成像仪

Expecting future advanced domestic observations





- 杨孟飞、汪景琇 等 ,太阳立体探测任务设想，2022，科学通报
- 邓元勇、周桂萍 等 ,太阳极轨天文台，2022， 科学通报

Collaborations of different fields

Major Unsolved Fundamental Issues in Solar Activity

- Solar (Stellar) Activity mechanisms
- Solar dynamo—origin of solar mag. cycle
- corona (stellar and galactic corona) Heating
- The Evolution of the Sun as a Star and Its Influence on the Celestial Bodies & Life Processes in the heliosphere·····
- Solar Pridictions—synthesize all the knowledge gained to establish a new methodology of solar prediction

谢谢大家恳请批评指正！

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