[movie courtesy of Marc DeRosa]

Convective Flux Emergence Simulations of the Generation of Flare-prolific Active Regions

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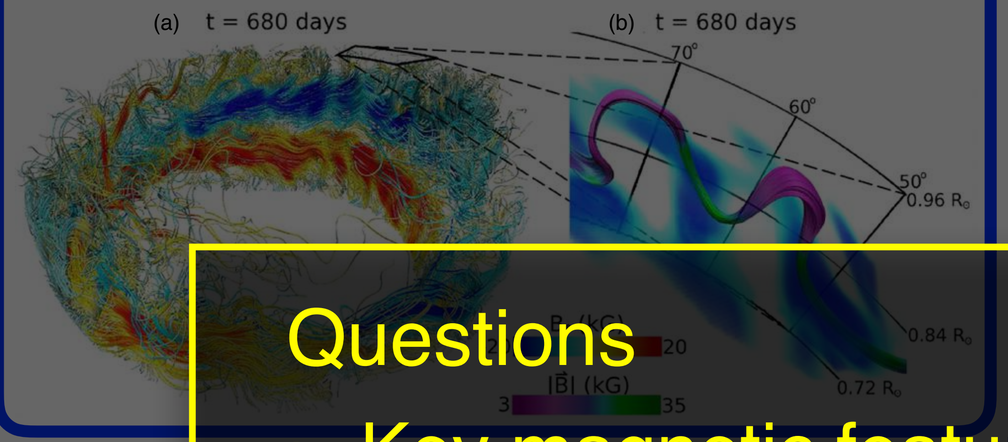
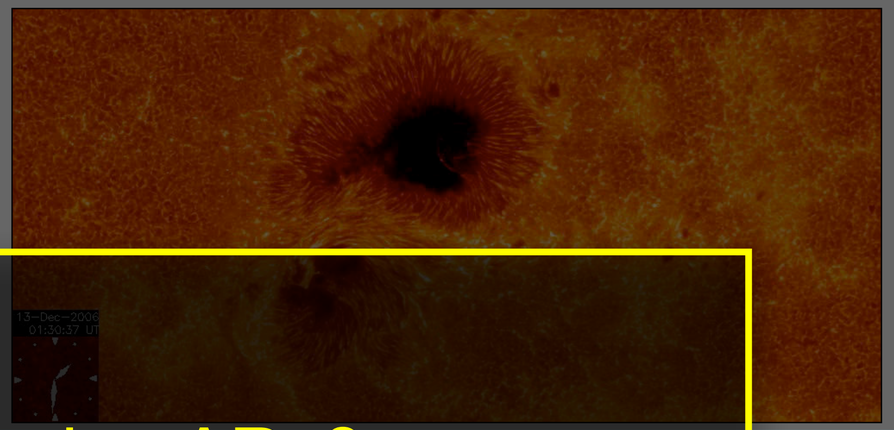
Helicity 2020 (2020 Dec 3)

1. Introduction

Solar dynamo[1]



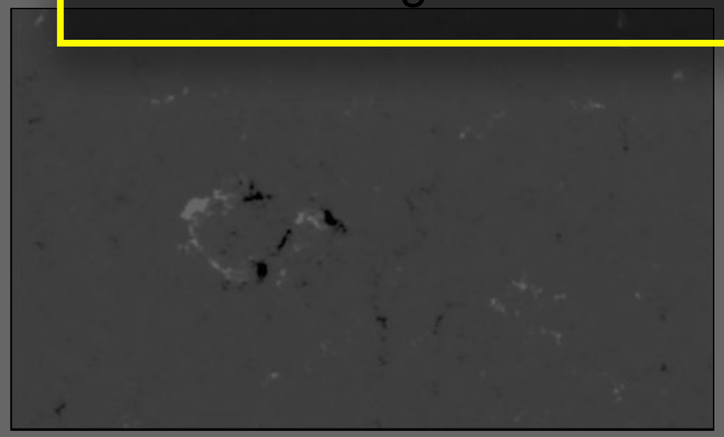
Flares & CMEs[4]



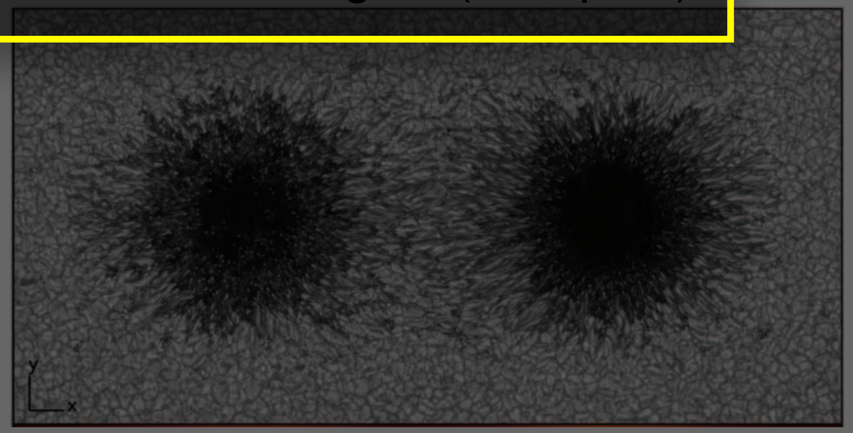
Questions

- Key magnetic features of flaring ARs?
- How these features created?

Flux Emergence[2]



Active region (sunspots)[3]



[1: Nelson+ 2013; 2: Toriumi+ 2013; 3: Rempel+ 2009; 4: courtesy of J. Okamoto]

[Toriumi & Wang 2019]

Living Reviews in Solar Physics (2019) 16:3
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REVIEW ARTICLE

Check for updates

Flare-productive active regions

Shin Toriumi[1,2] · Haimin Wang[3,4]

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Abstract
Strong solar flares and coronal mass ejections, here defined not only as the bursts of electromagnetic radiation but as the entire process in which magnetic energy is released through magnetic reconnection and plasma instability, emanate from active regions (ARs) in which high magnetic non-potentiality resides in a wide variety of forms. This review focuses on the formation and evolution of flare-productive ARs from both observational and theoretical points of view. Starting from a general introduction of the genesis of ARs and solar flares, we give an overview of the key observational features during the long-term evolution in the pre-flare state, the rapid changes in the magnetic field associated with the flare occurrence, and the physical mechanisms behind these phenomena. Our picture of flare-productive ARs is summarized as follows: subject to the turbulent convection, the rising magnetic flux in the interior deforms into a complex structure and gains high non-potentiality; as the flux appears on the surface, an AR with large free magnetic energy and helicity is built, which is represented by δ-sunspots, sheared polarity inversion lines, magnetic flux ropes, etc; the flare occurs when sufficient magnetic energy has accumulated, and the drastic coronal evolution affects magnetic fields even in the photosphere. We show that the improvement of observational instruments and modeling capabilities has significantly advanced our understanding in the last decades. Finally, we discuss the outstanding issues and future perspective and further broaden our scope to the possible applications of our knowledge to space-weather forecasting, extreme events in history, and corresponding stellar activities.

- Flare-productive active regions
  - S. Toriumi & H. Wang 2019
  - Living Reviews in Solar Physics, 16, 3
    https://doi.org/10.1007/s41116-019-0019-7

[Eberhardt Hall, NJIT]

2. ARs and Solar Flares

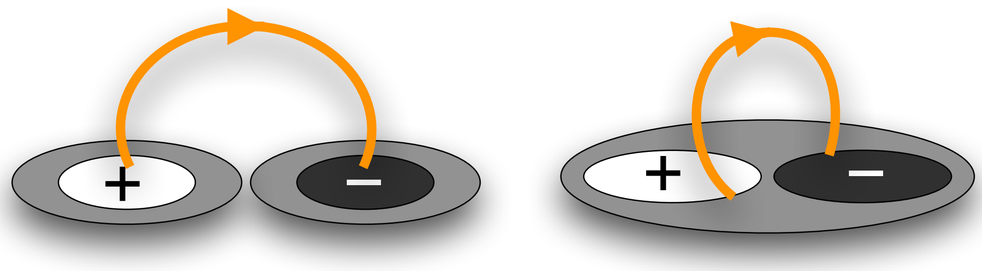
[Toriumi & Wang 2019]

- Solar flares
  - Releasing of free magnetic energy

$$\Delta E_{\mathrm{mag}} = \int \frac{B^2}{8\pi}\, dV - \int \frac{B_{\mathrm{pot}}^2}{8\pi}\, dV$$

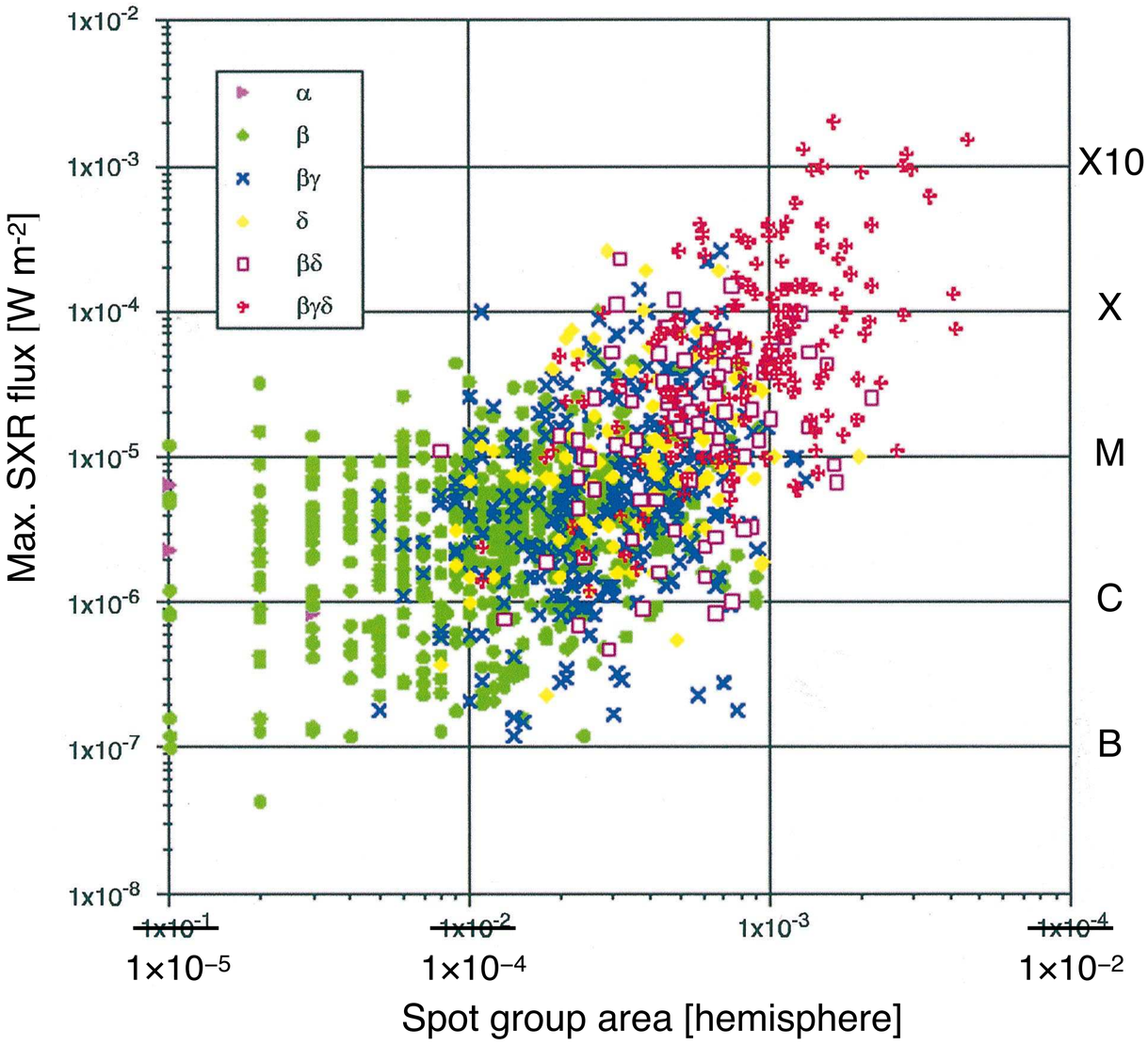
Free mag energy — Mag energy — Potential mag energy

- Key factors for ARs
  1. **Size**…… amount of accumulated energy
  2. **Complexity**… non-potentiality
  3. **Evolution**… energy storage dominates dissipation



β-spots
Simple bipolar region

δ-spots
Umbrae of opposite polarities share a common penumbra

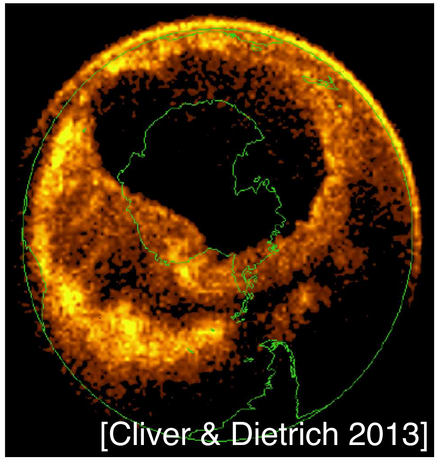


[Sammis+ 2000]

2. ARs and Solar Flares

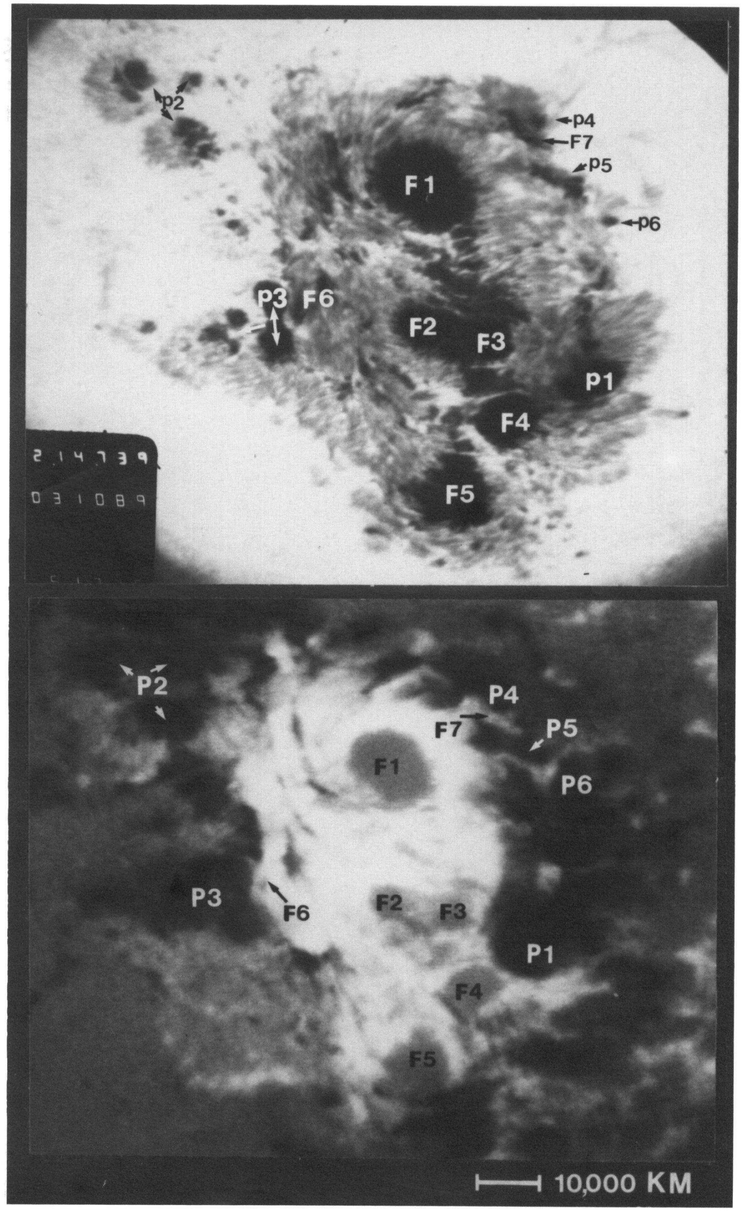
- δ-sunspot and flare activity
  - Mt. Wilson classification: magnetic complexity
  - **δ-spots** are known to be flare-productive
    [Künzel 1960; Sammis+ 2000; Toriumi+ 2017]
  - Strongest flares are almost all from δ-spots

March 1989 geomagnetic storm



NOAA 5395 produced >200 flares including the X15 event. The strong geomagnetic storm caused blackout in Quebec and damaged transformer in Salem, NJ.

[Toriumi & Wang 2019]



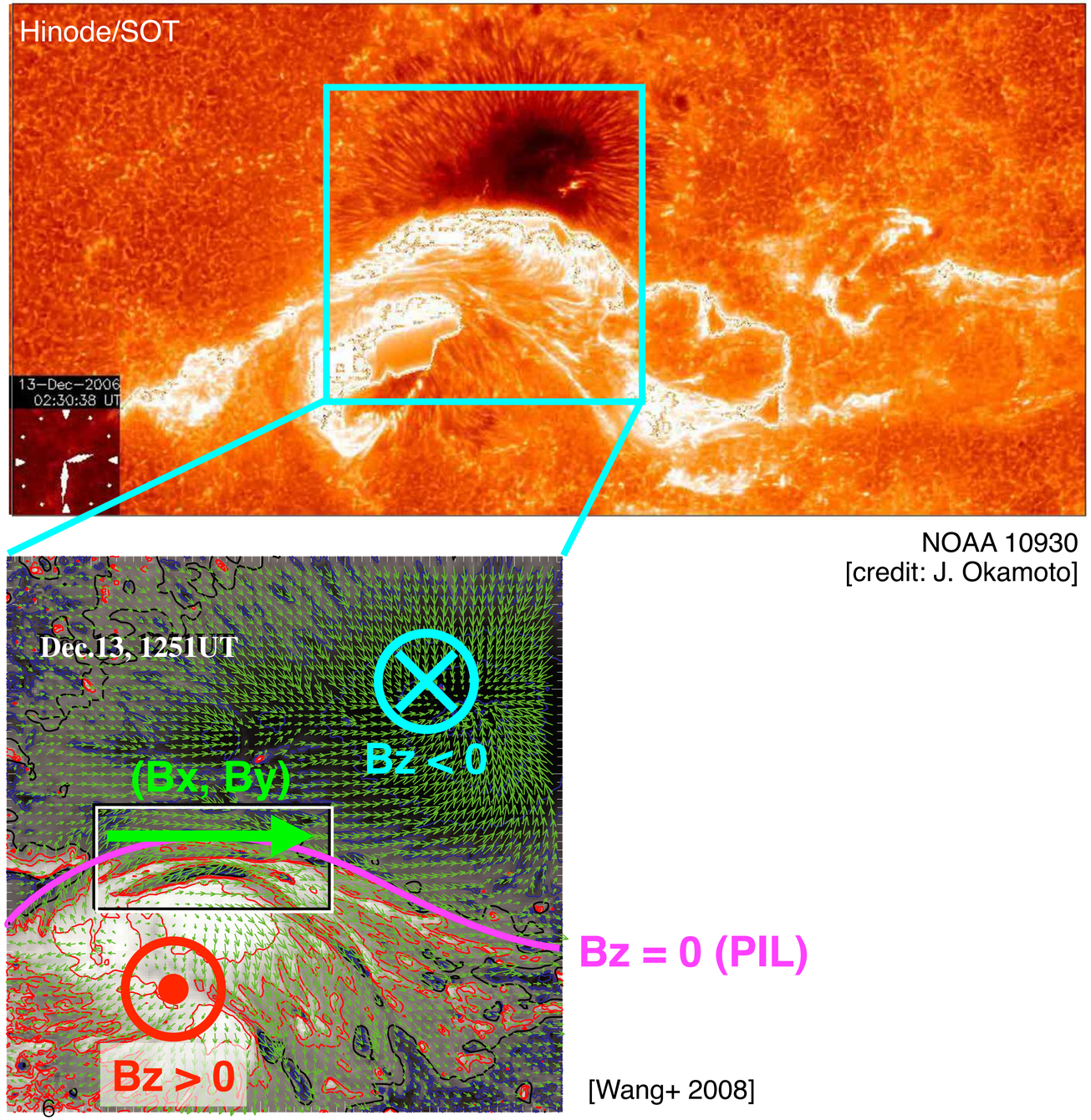
[NOAA 5395: Wang+ 1991]

[Sammis+ 2000]

2. ARs and Solar Flares

- Key observational features
  - Flaring **polarity inversion lines (PILs)**
    - Strong horizontal fields: > 4000 G
    - Strong Bz gradient: ~100 G Mm^{-1}
    - Strong magnetic shear: 80°—90°
      [Severny 1958; Hagyard+ 1984; Schrijver 2007]
    - "Magnetic channel" and flare-triggering fields
      [Zirin & Wang 1993; Wang+ 2007; Kusano+ 2012]
    - "Magnetic tongues" and helicity
      [Lopez Fuentes+ 2000; Mandrini+ 2014; Poisson+ 2015]

[Toriumi & Wang 2019]



NOAA 10930
[credit: J. Okamoto]

[Wang+ 2008]

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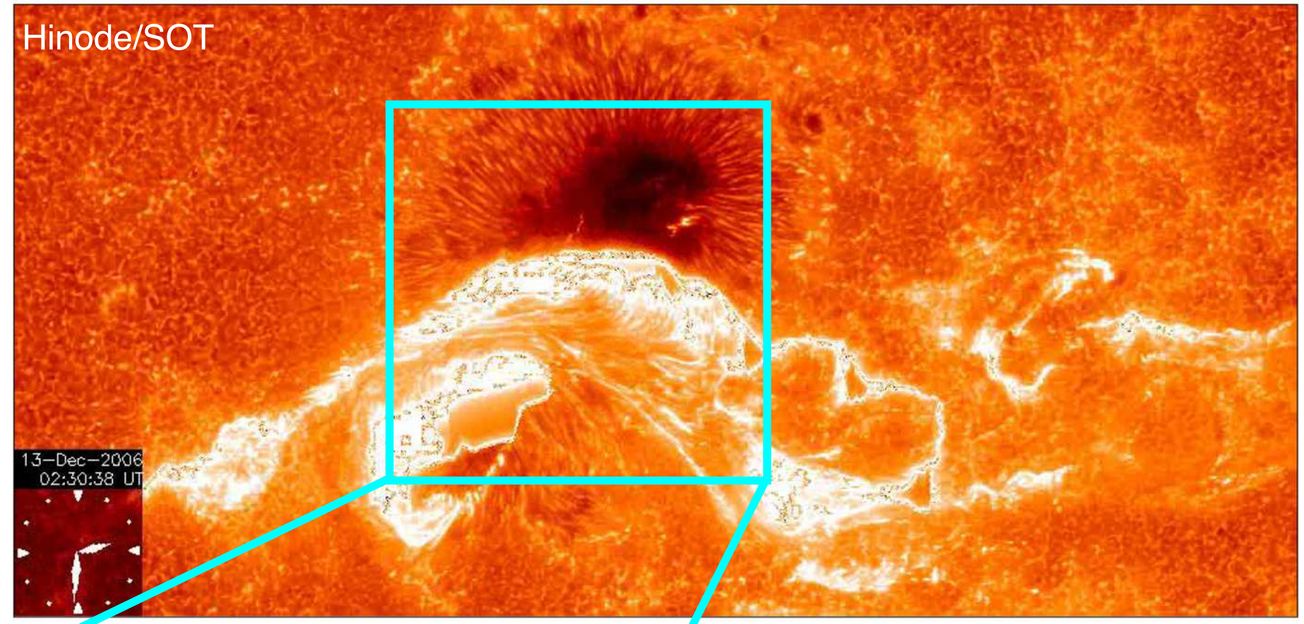
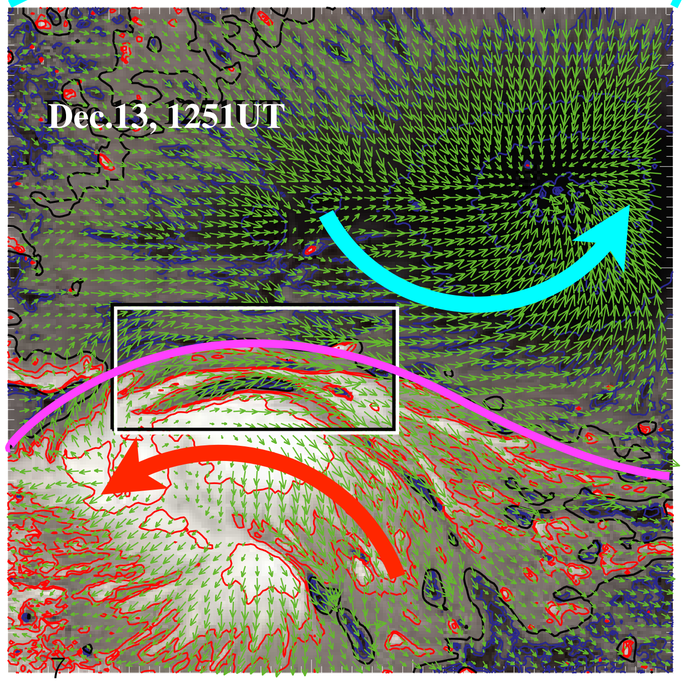
  - Velocity fields
    - **Spot rotation** (self and mutual)
      [Krall 1994; Min & Chae 2008; Brown+ 2003]

[Toriumi & Wang 2019]



NOAA 10930
[credit: J. Okamoto]



Bz = 0 (PIL)

[Wang+ 2008]

2. ARs and Solar Flares

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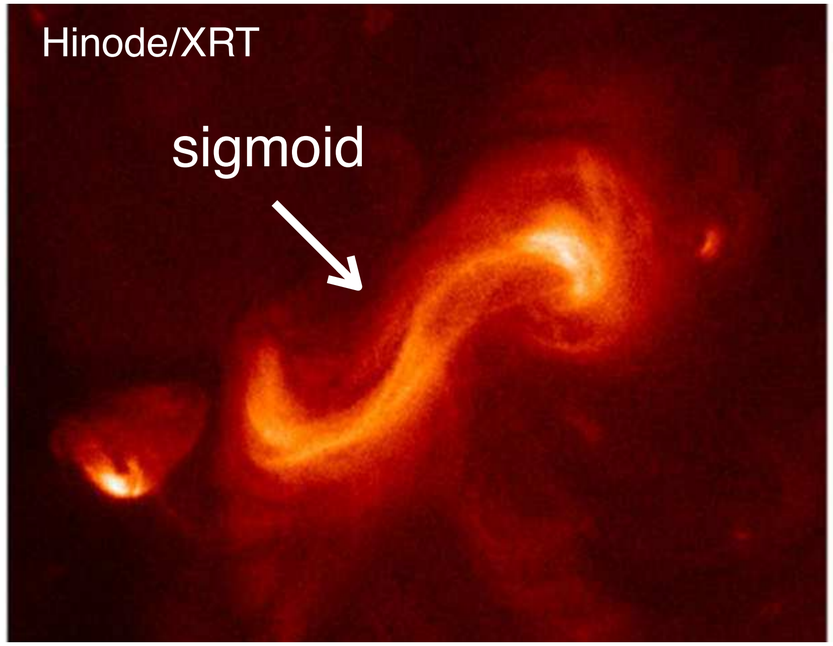
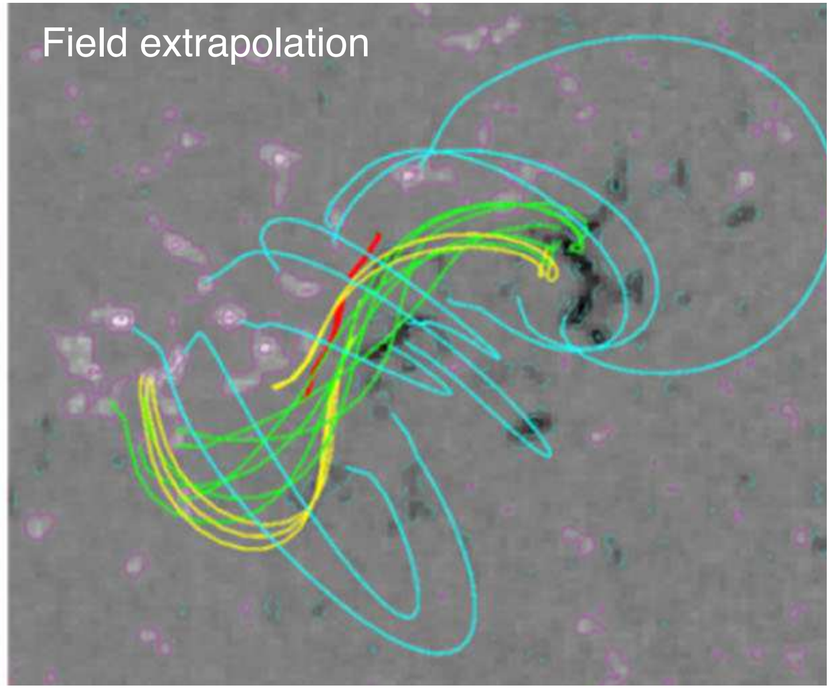
  - Velocity fields
    - **Spot rotation** (self and mutual)
      [Krall 1994; Min & Chae 2008; Brown+ 2003]
  - Magnetic **flux rope**
    - Sigmoids in soft X-ray and filaments in Hα
      [Rust & Kumar 1996; Canfield+ 1997; Pevtsov+ 2002]



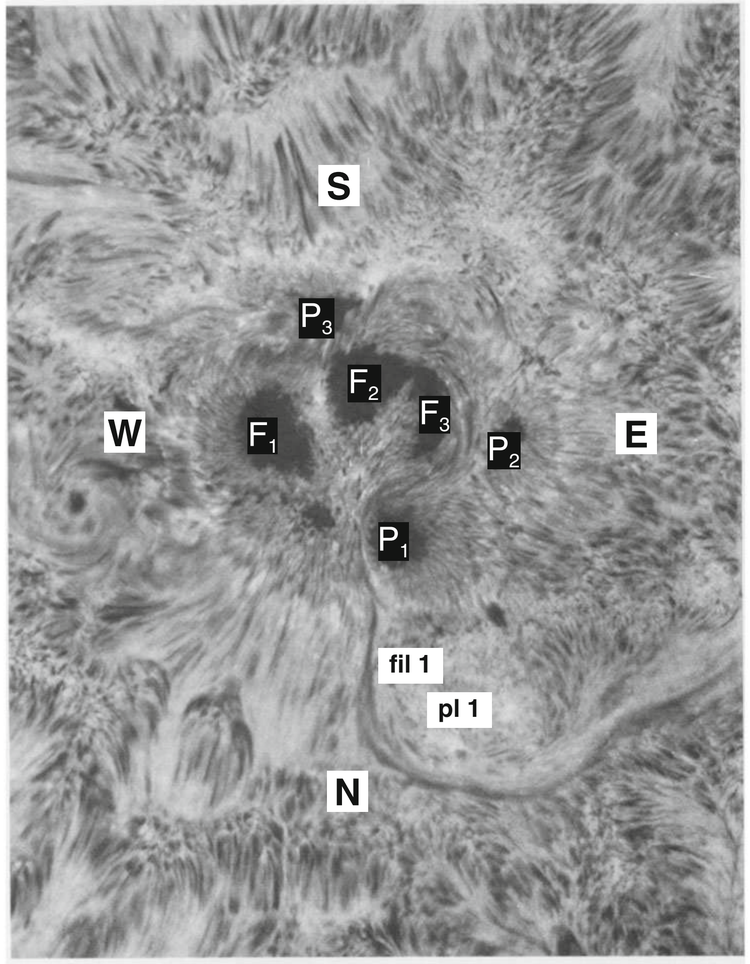


[Savcheva+ 2012]

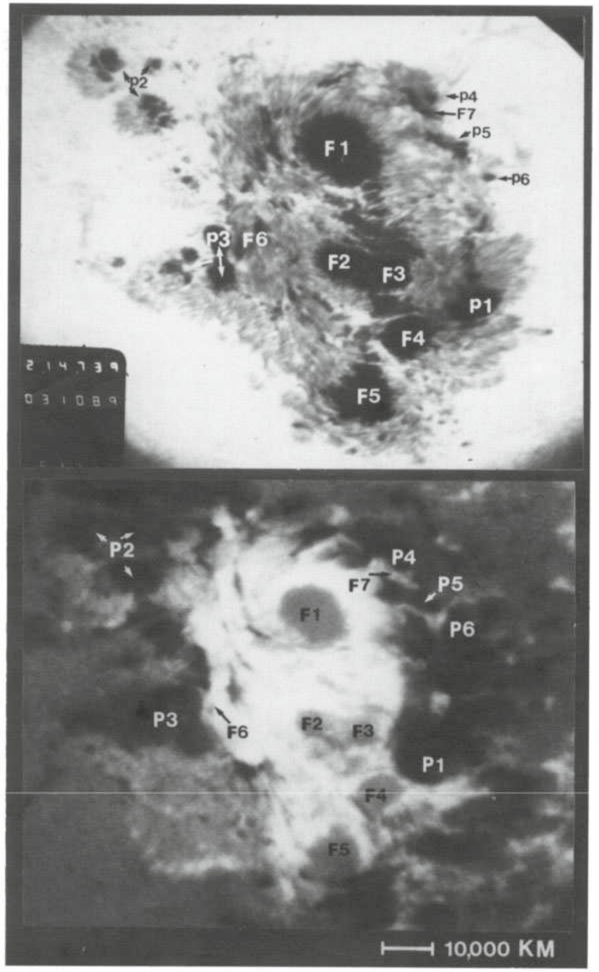
2. ARs and Solar Flares

- Evolution of δ-spots
  - Classification by Zirin & Liggett (1987)
    Type I: spots emerging all at once, intertwined
    Type II: satellite spots near larger older spots
    Type III: collision of two bipoles

(a) McMath 11976



(b) NOAA 5395



[Zirin & Tanaka 1973; Wang+ 1991]

2. ARs and Solar Flares

- Evolution of δ-spots
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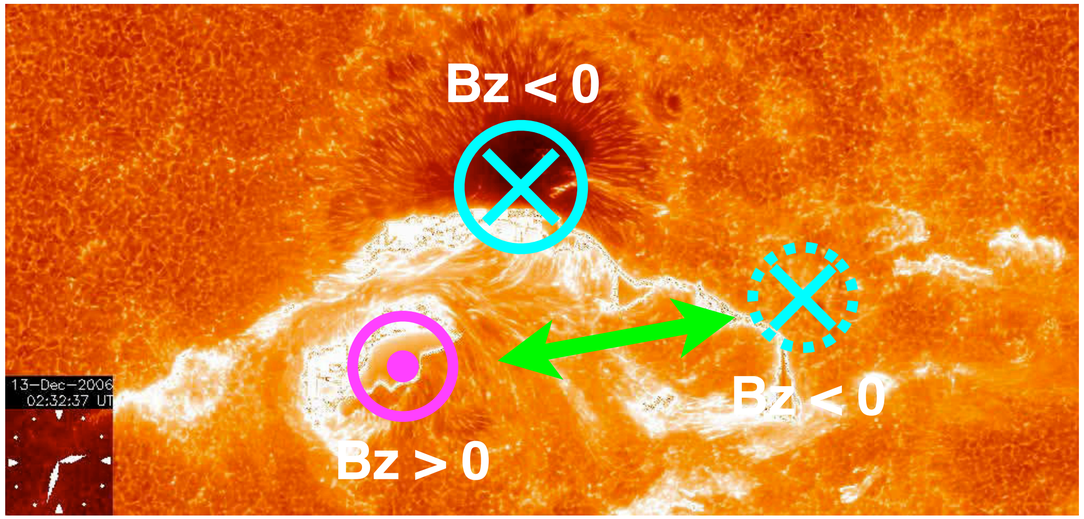
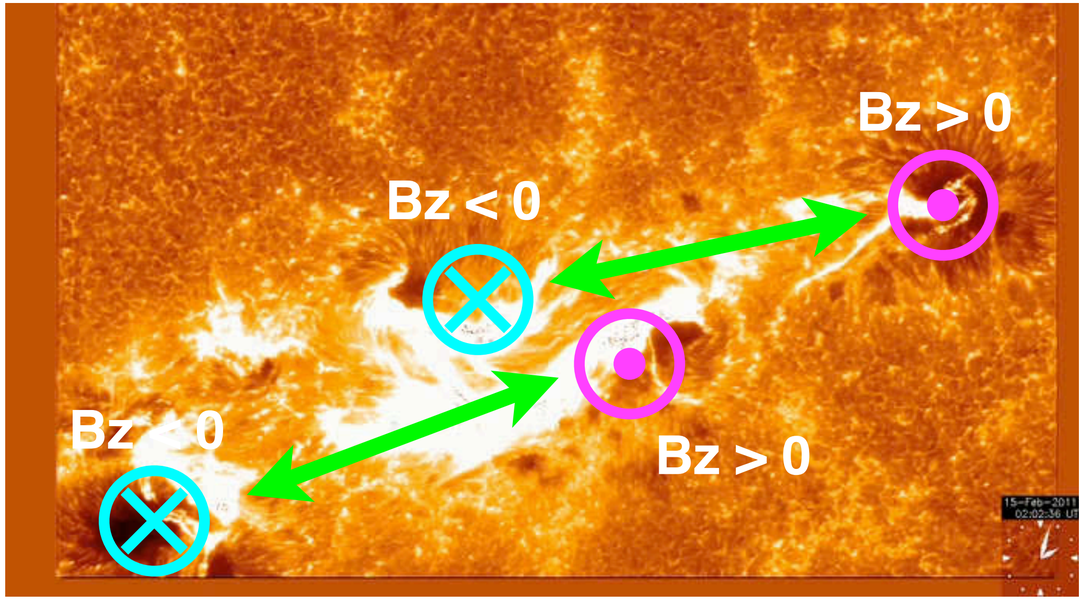
    Type I: spots emerging all at once, intertwined
    Type II: satellite spots near larger older spots
    Type III: collision of two bipoles

Numerical experiments (1990s-)

Type II: NOAA 10930



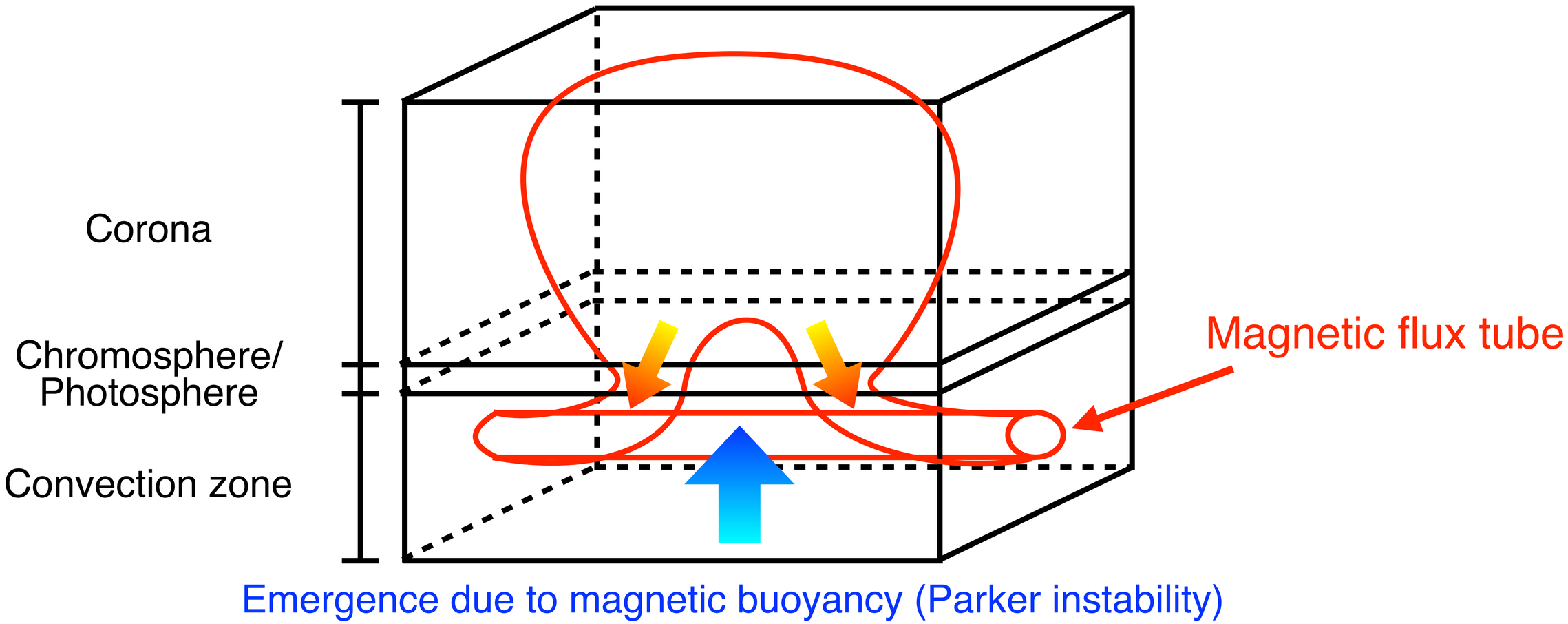
Type III: NOAA 11158



[movies by J. Okamoto]

3. δ-spot Modeling

- **MHD flux emergence simulations**
  - Mimic emergence of magnetic flux tubes from the convection zone
  - Solve regular MHD equations over computational box

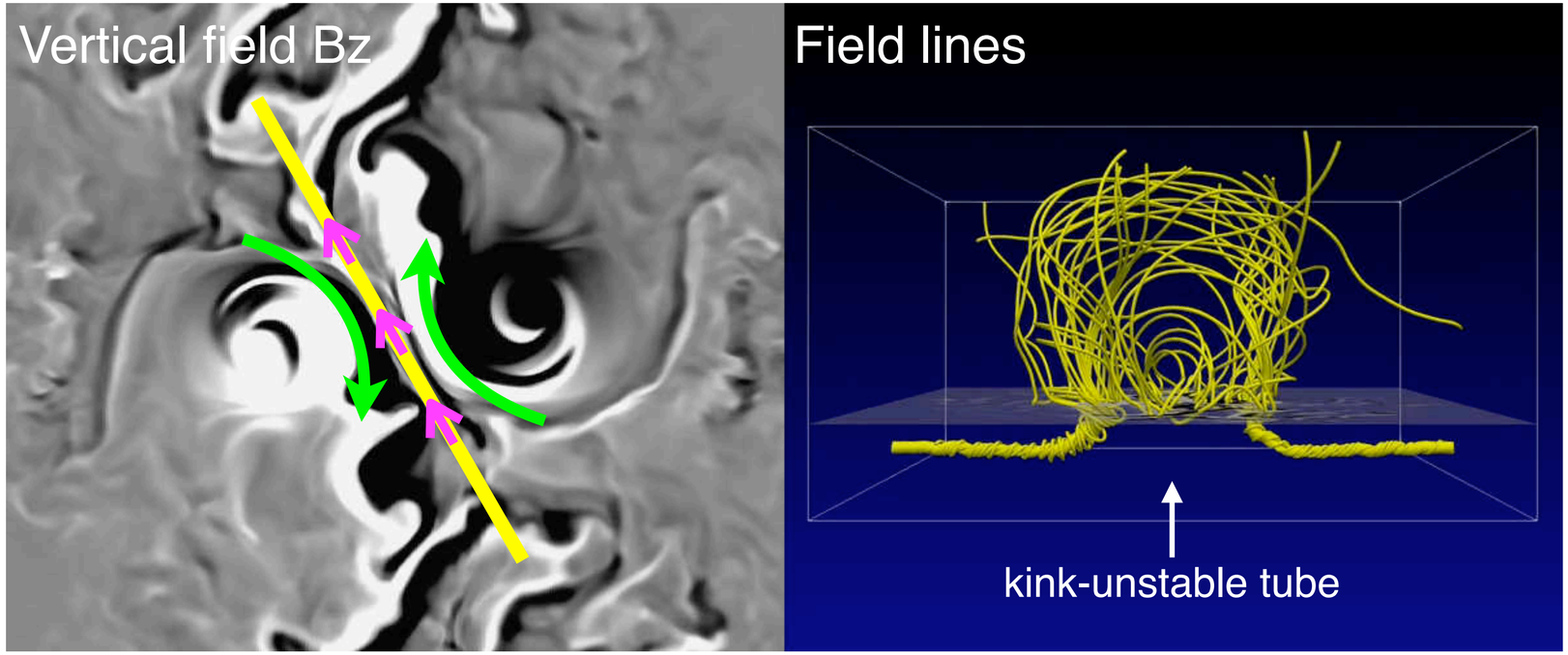


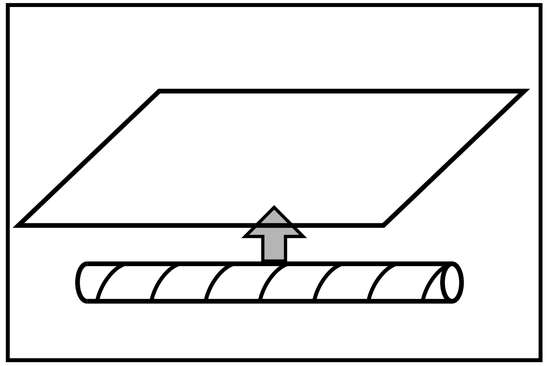
[see e.g. Archontis (2008), Fan (2009), Schmieder+ (2014), Cheung & Isobe (2014) for reviews]

3. δ-spot Modeling

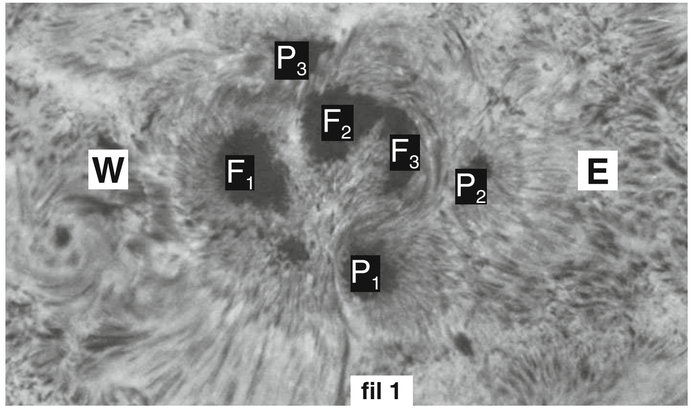
- Kinked-tube model
  - Strongly twisted tube
  - Emergence due to buoyancy and the kink instability
  - Well reproduce rotating spots

[Toriumi & Takasao 2017]





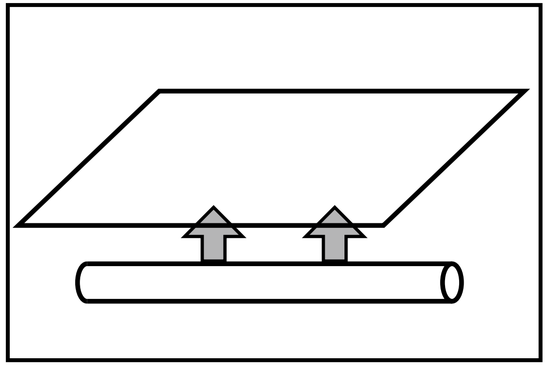
may explain Type I δ-spots



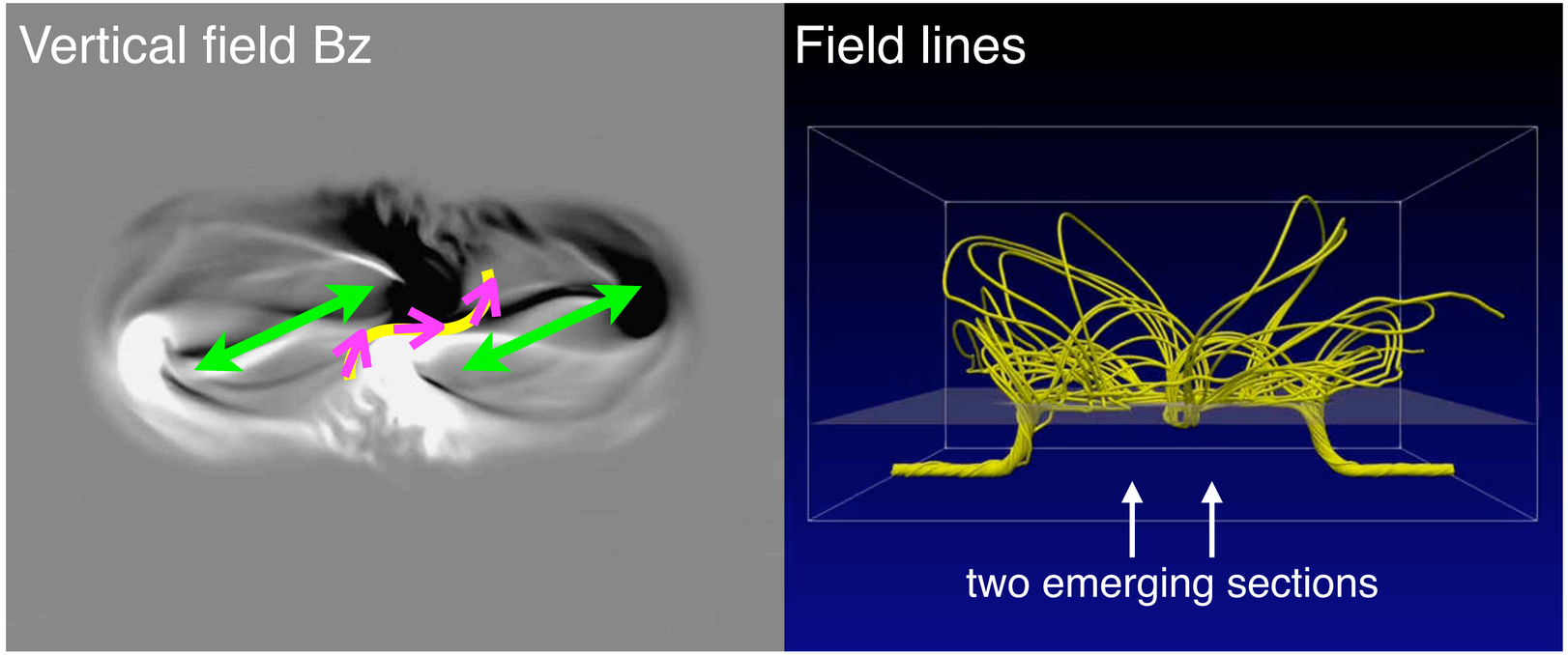
[Linton+ 1996; Matsumoto+ 1998; Linton+ 1998; Fan+ 1999; Takasao+ 2015; Kniznik+ 2018]

3. δ-spot Modeling

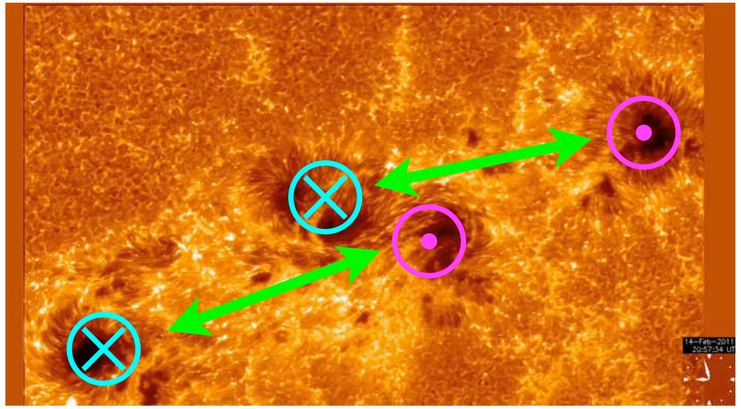
- Multi-buoyant segment model
  - Tube is elevated at two density reduction points
  - Two emerging bipoles appear and collide at the middle
  - Well reproduce δ-spots with sheared PIL



[Toriumi & Takasao 2017]



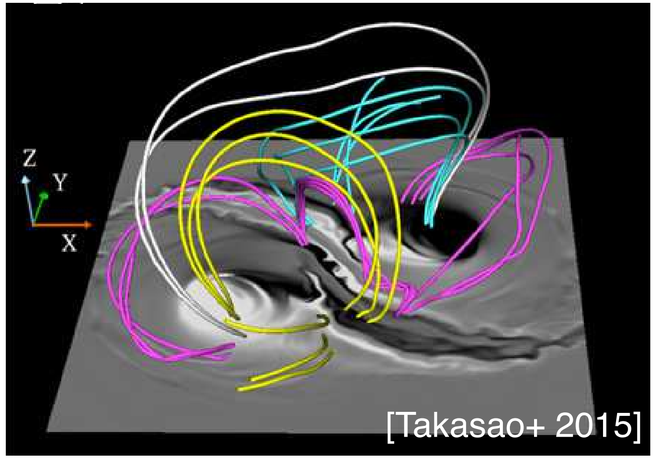
⇨ may explain Type III δ-spots

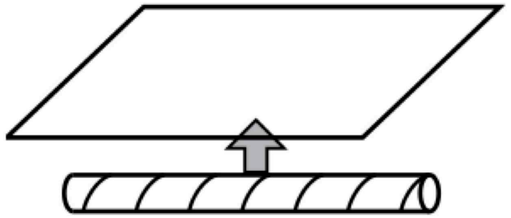


[Toriumi+ 2014; Fang & Fan 2015; Oi 2017; Syntelis+ 2019]

3. δ-spot Modeling

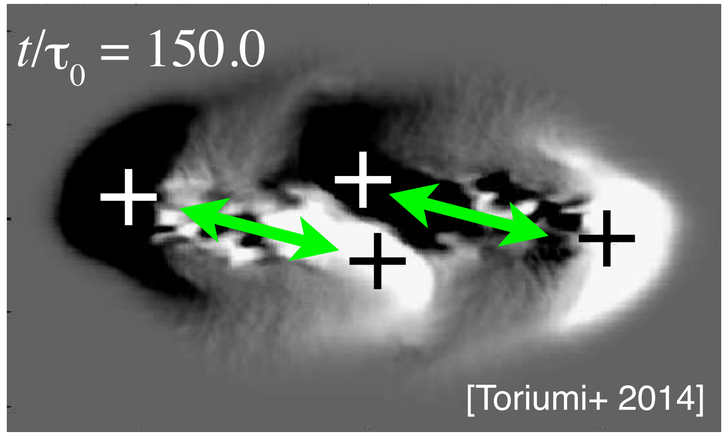
Kinked-tube model

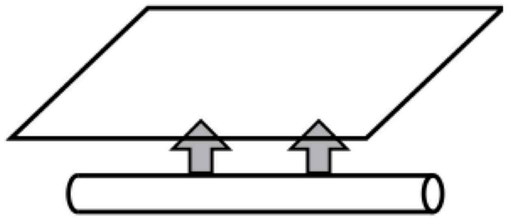




[Linton+1996; Matsumoto+1998; Linton+1998; Fan+1999; Kniznik+2018]

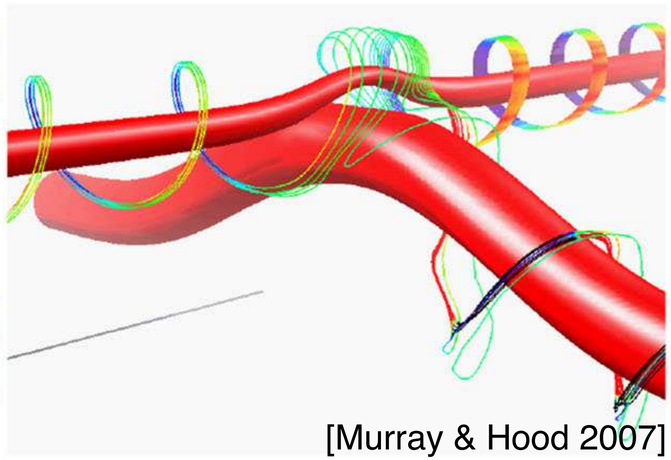
Multi-buoyant segment model

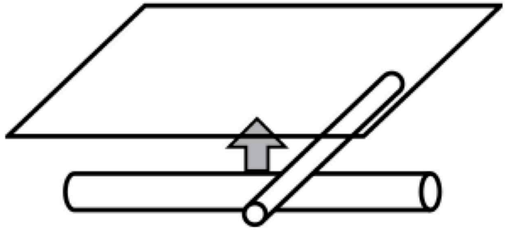




[Fang & Fan 2015; Toriumi & Takasao 2017]

Interacting-tube model





[Fan+ 1998; Jouve+ 2018; Cheung, Rempel+ 2019]

Highly idealized…

- Convection zone is adiabatically stratified **without** convection
- Emerging flux is forcibly (kinematically) **injected** in to domain

[Other proposed models include the breakup of flux sheet and collision of spots (Chatterjee et al. 2016) and NEMPI-based scenario (Mitra et al. 2014)]

4. The New Twist

[Toriumi & Hotta 2019]

- Realistic background convection
  - R2D2: Radiation and RSST for Deep Dynamics
    [Hotta+ 2019; Hotta & Iijima 2020]

$$\frac{\partial \rho_1}{\partial t} = -\frac{1}{\xi^2}\nabla\cdot(\rho\boldsymbol{V})$$

$$\frac{\partial}{\partial t}(\rho\boldsymbol{V}) = -\nabla\cdot(\rho\boldsymbol{V}\boldsymbol{V}) - \nabla p_1 - \rho_1\boldsymbol{g}$$

$$\rho T\frac{\partial s_1}{\partial t} = -\rho T(\boldsymbol{V}\cdot\nabla)s + Q_{\rm rad}$$

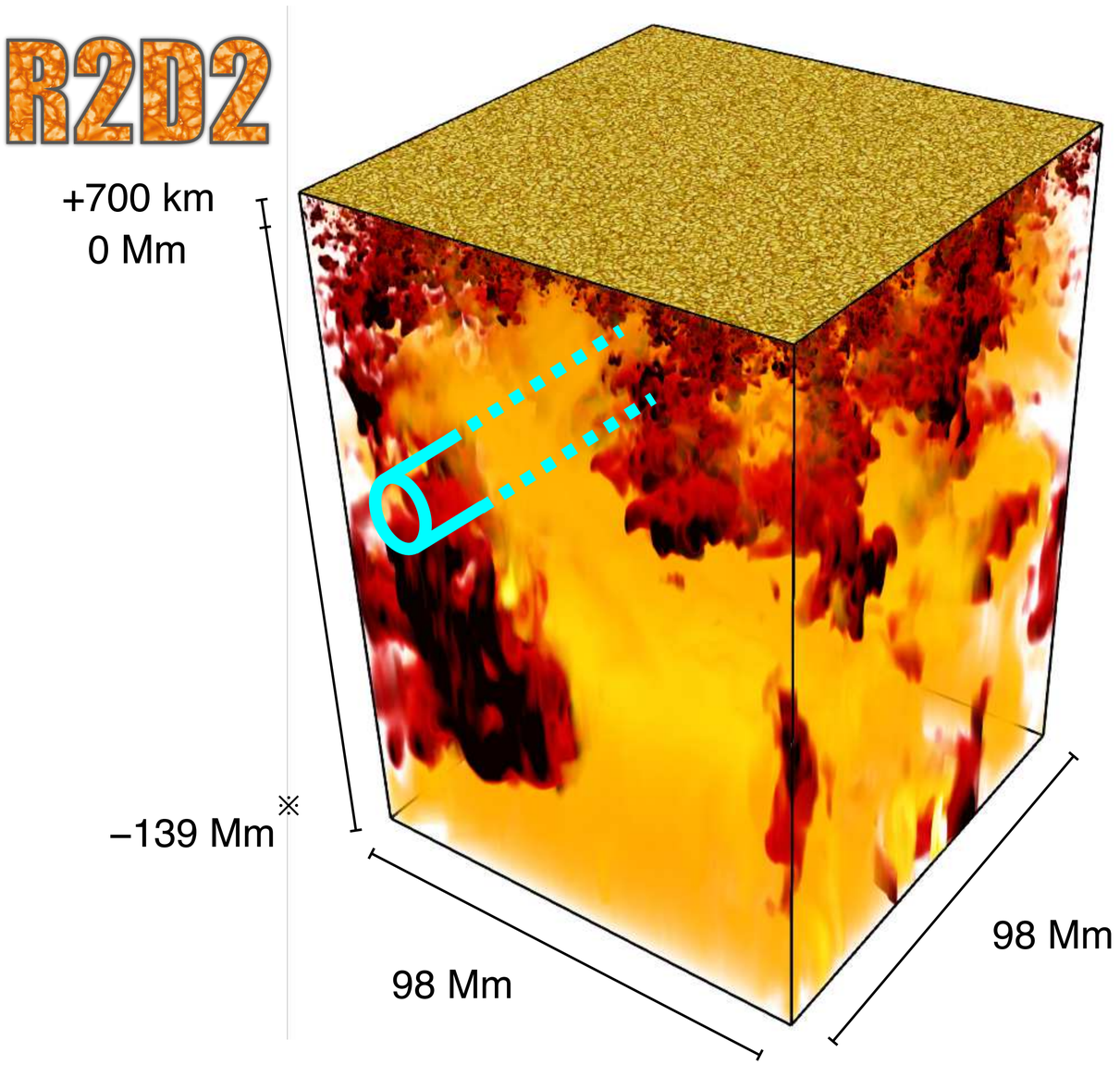
ξ: reduction factor for sound speed
Q_{rad}: diffusion approx. for deep layer, LTE around surface

  - V = 98 Mm × 98 Mm × 140 Mm
  - N = 1024 × 1024 × 256
  - performed on K computer

- Twisted force-free flux tube
  - Inserted at –16.7 Mm with **no** artificial buoyancy

$$B_x = B_{\rm tb}J_0(\alpha r)$$

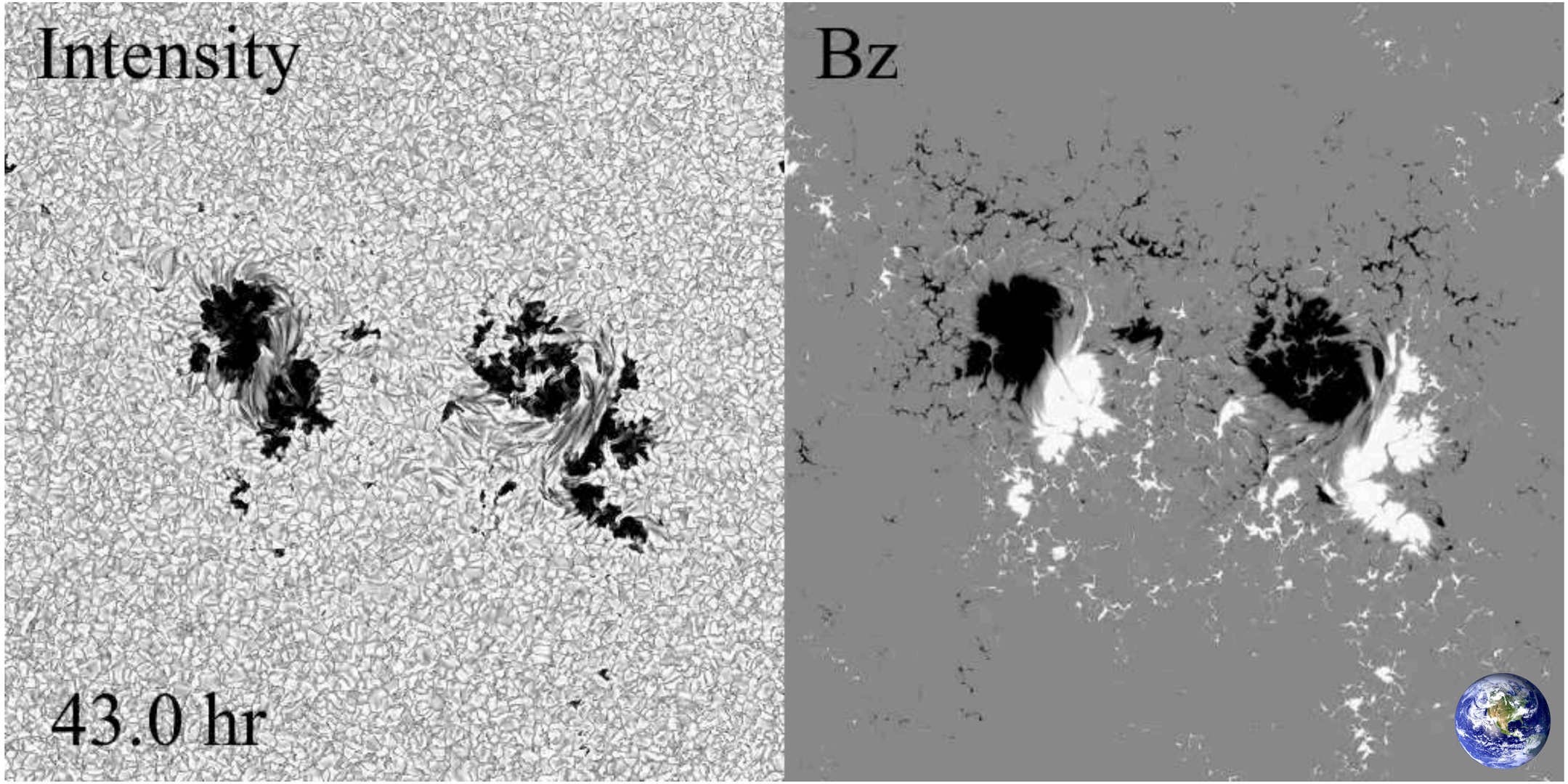
$$B_\phi = B_{\rm tb}J_1(\alpha r)$$



※ Thickness of the solar CZ is ~200 Mm. Previous convective simulations are down to about –30 Mm [Cheung+ 2010; Stein+ 2012; Rempel+ 2014; Chen+ 2017].

4. The New Twist

[Toriumi & Hotta 2019]

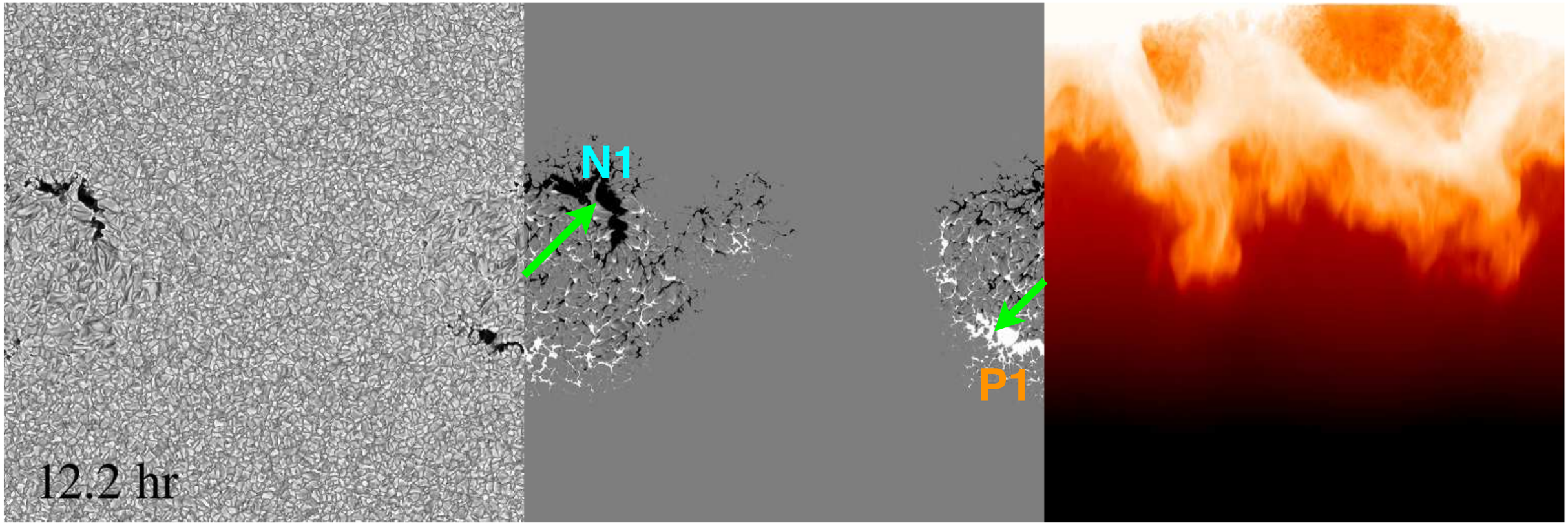


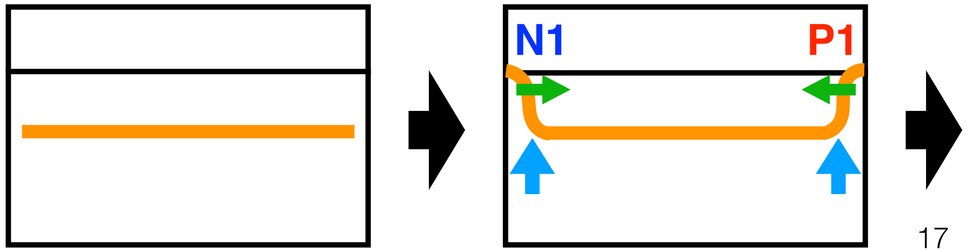
98 Mm

4. The New Twist

[Toriumi & Hotta 2019]

Intensity | Bz | |B| on x-z plane





4. The New Twist

[Toriumi & Hotta 2019]

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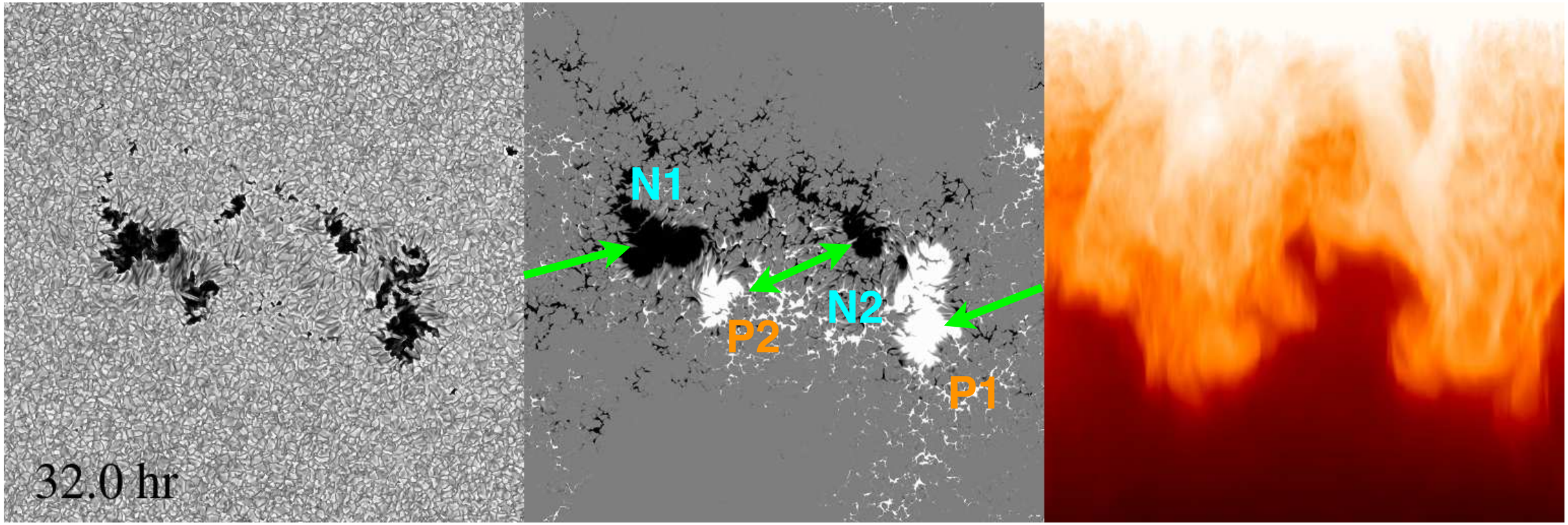

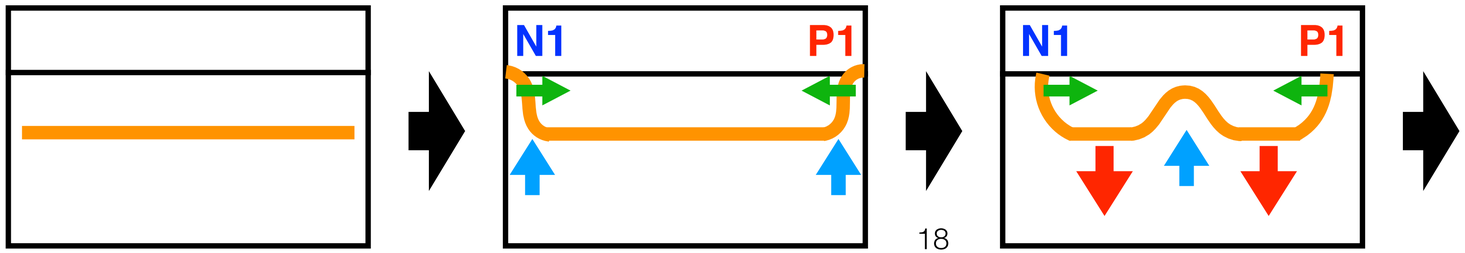

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[Toriumi & Hotta 2019]

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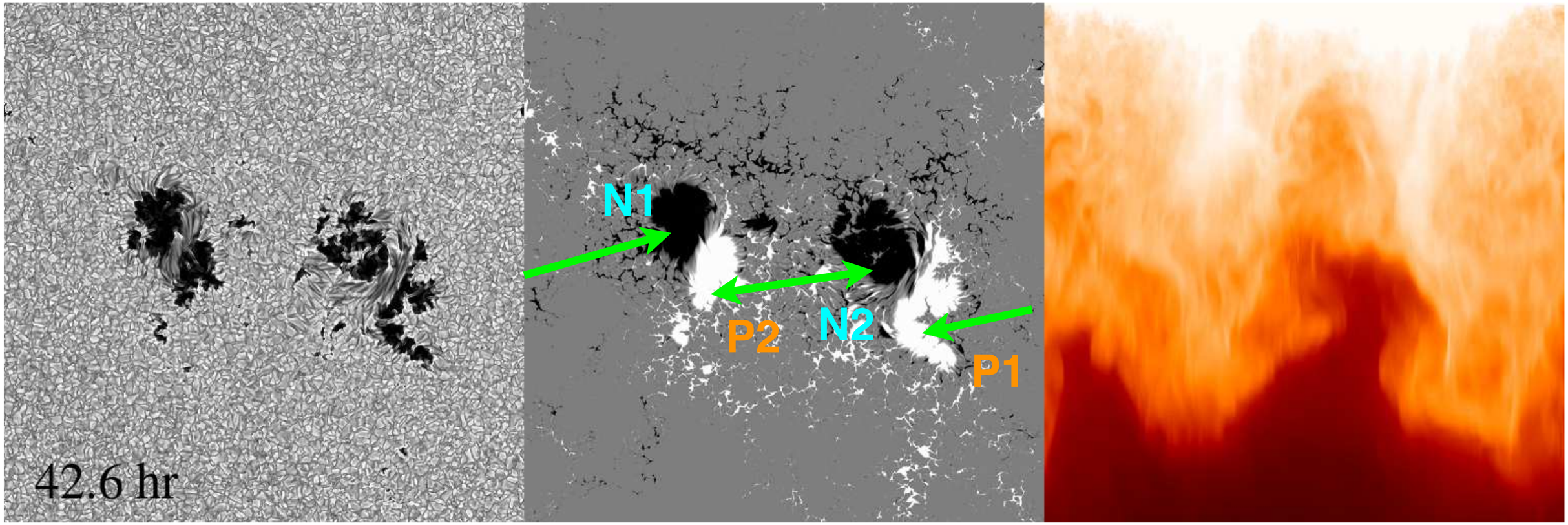

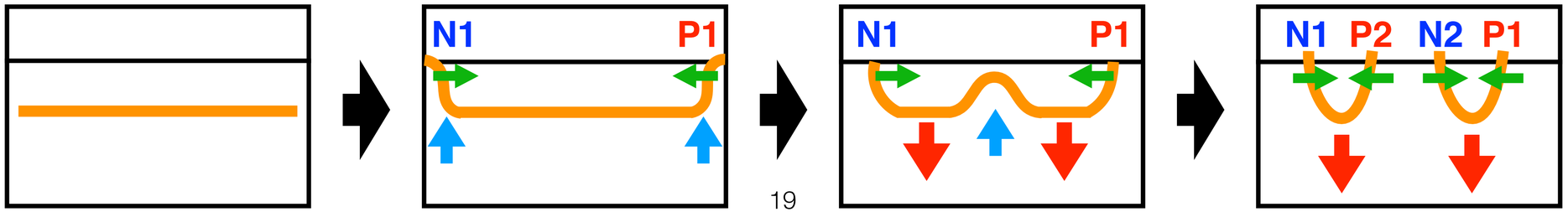

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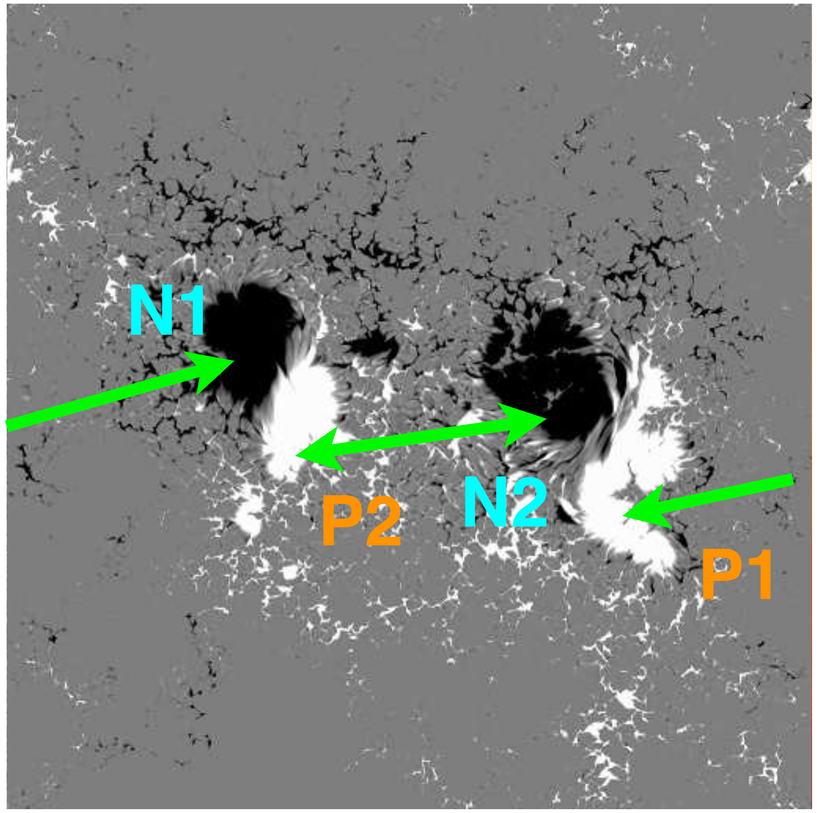
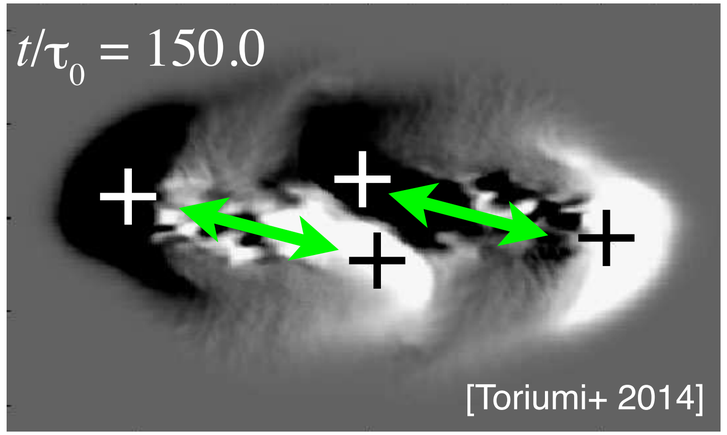
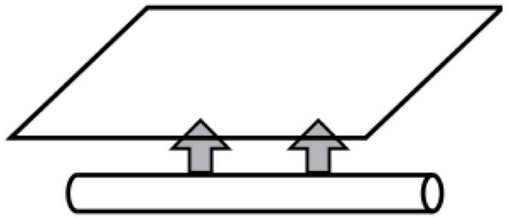
[Toriumi & Hotta 2019]

Bz

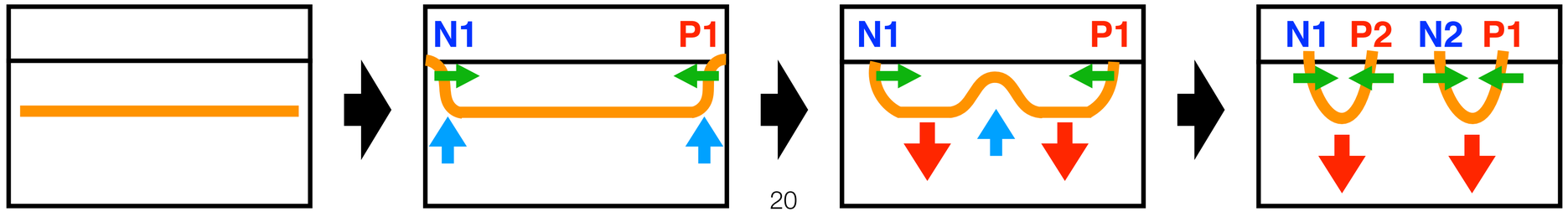


Multi-buoyant segment model



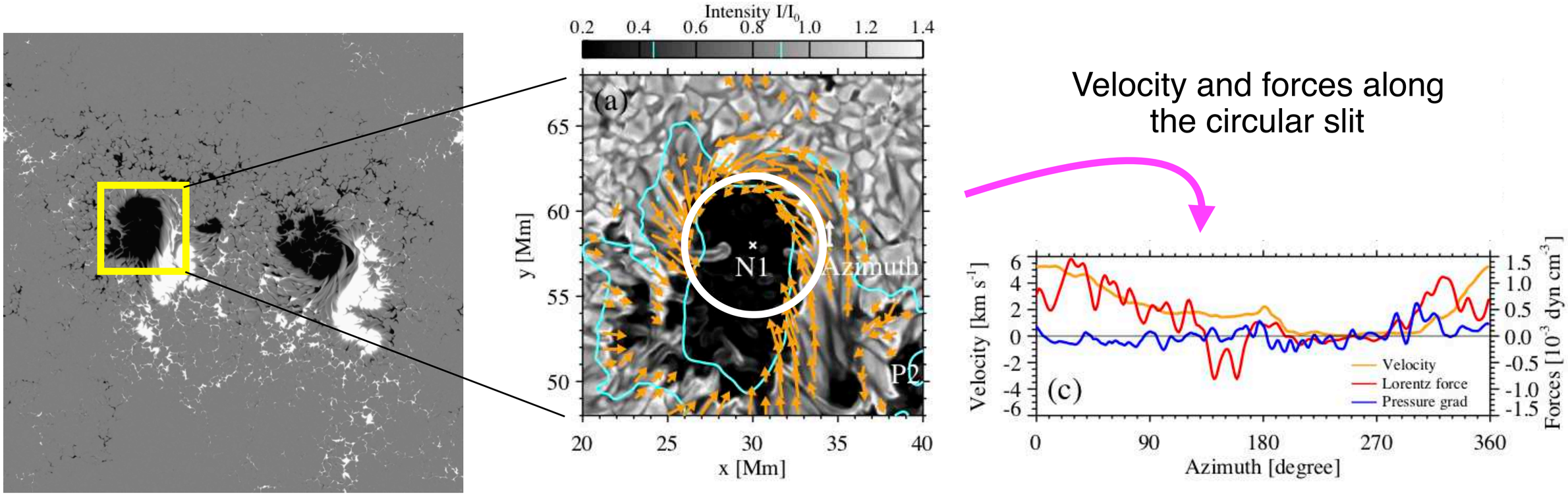


[Fang & Fan 2015; Toriumi & Takasao 2017]



4. The New Twist

[Toriumi & Hotta 2019]

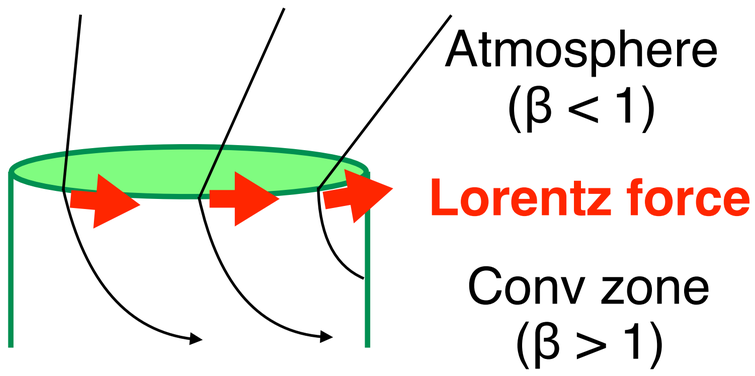


- Spot rotation
  - Driving force: Lorentz force dominates the pressure grad.

$$\frac{1}{4\pi}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} > -\nabla p$$

→ Spot rotates due to releasing of tube's twist

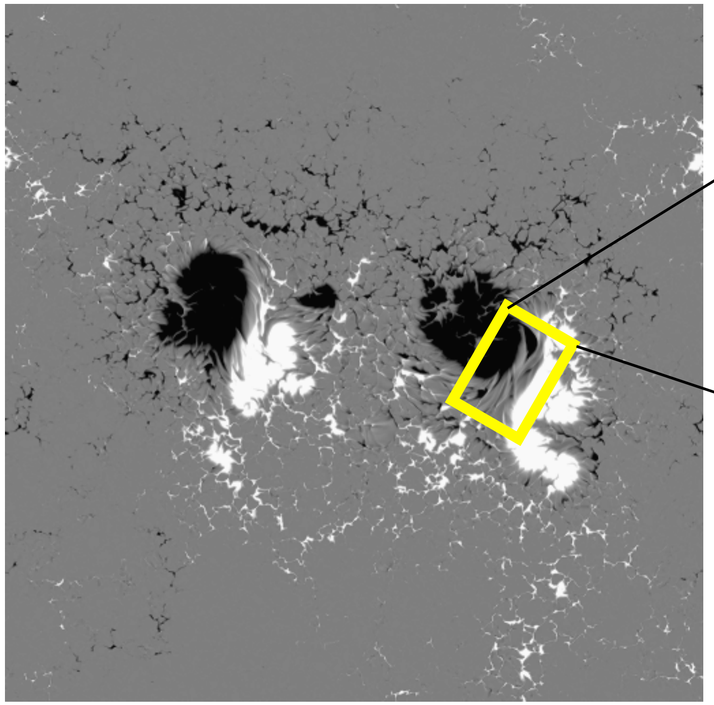
[Longcope & Welsch 2000; Manchester+ 2004; Fan 2009; Leake+ 2013; Sturrock+ 2015]

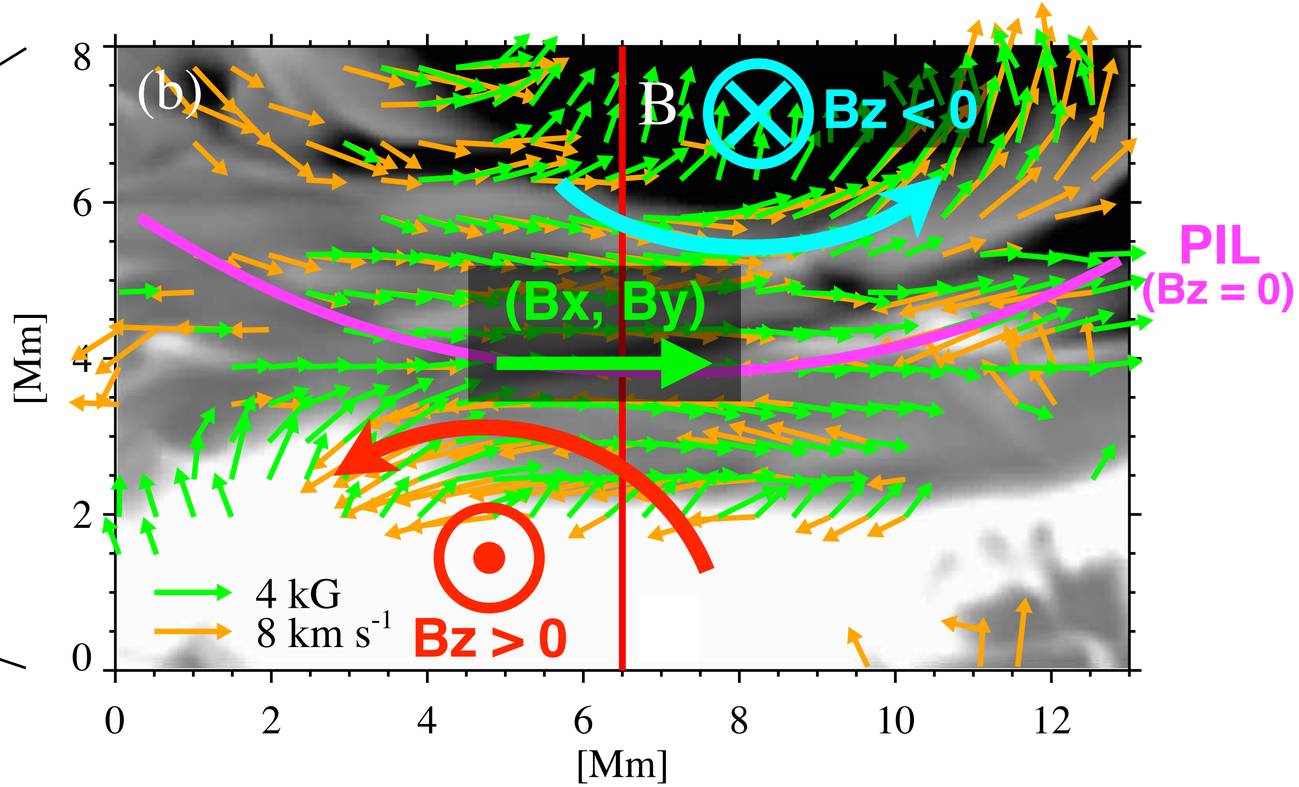


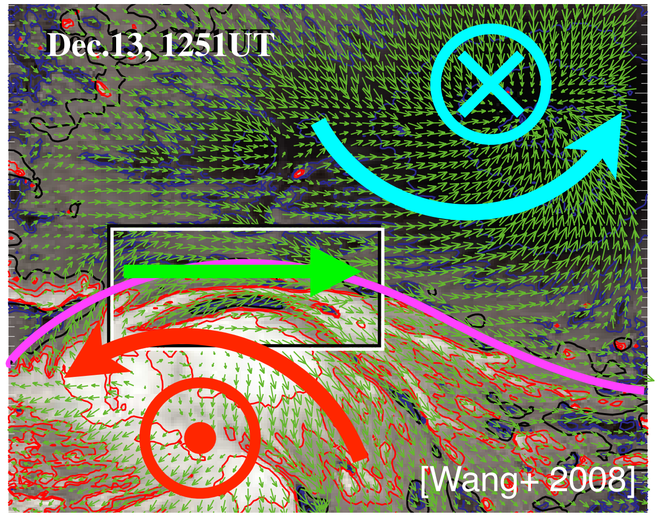
Field lines have left-handed twist.

4. The New Twist

[Toriumi & Hotta 2019]



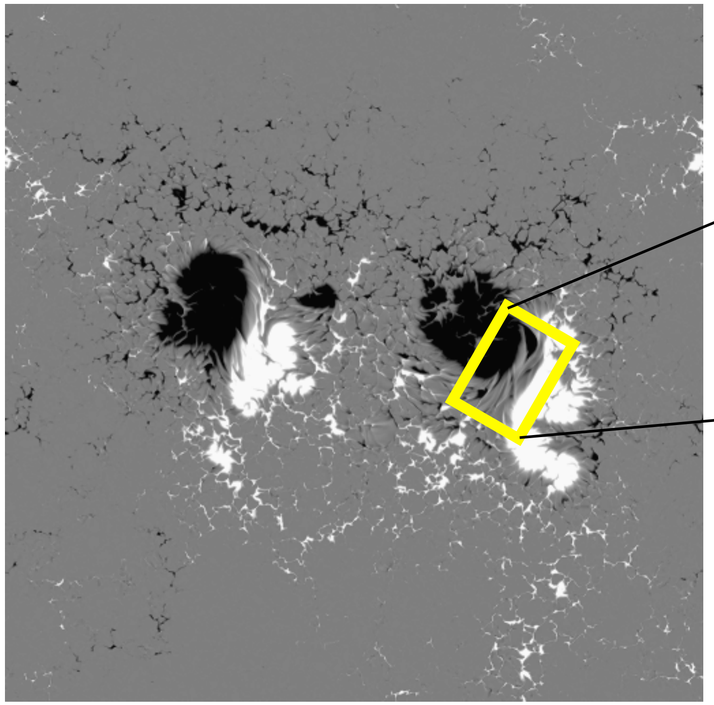


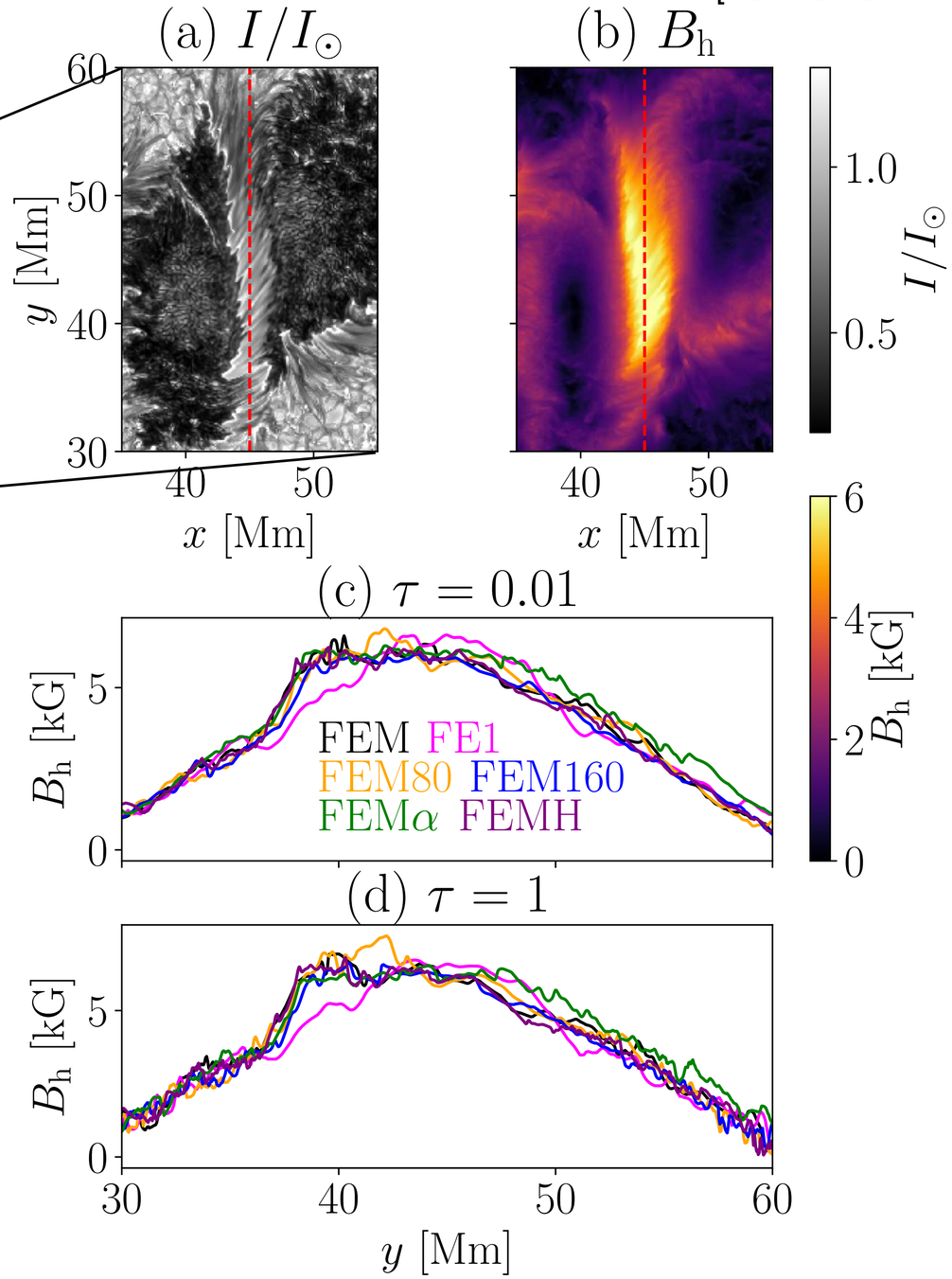


- PIL in δ-spots
  - Strong horizontal field with strong shear (~90 deg)
    ← produced by Lorentz force + convective motion
    $$(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}/(4\pi)$$
  - "Magnetic channel" or candidate flare-triggering field
  - Consistent with the observed flaring PILs →

4. The New Twist

[Hotta & Toriumi 2020]

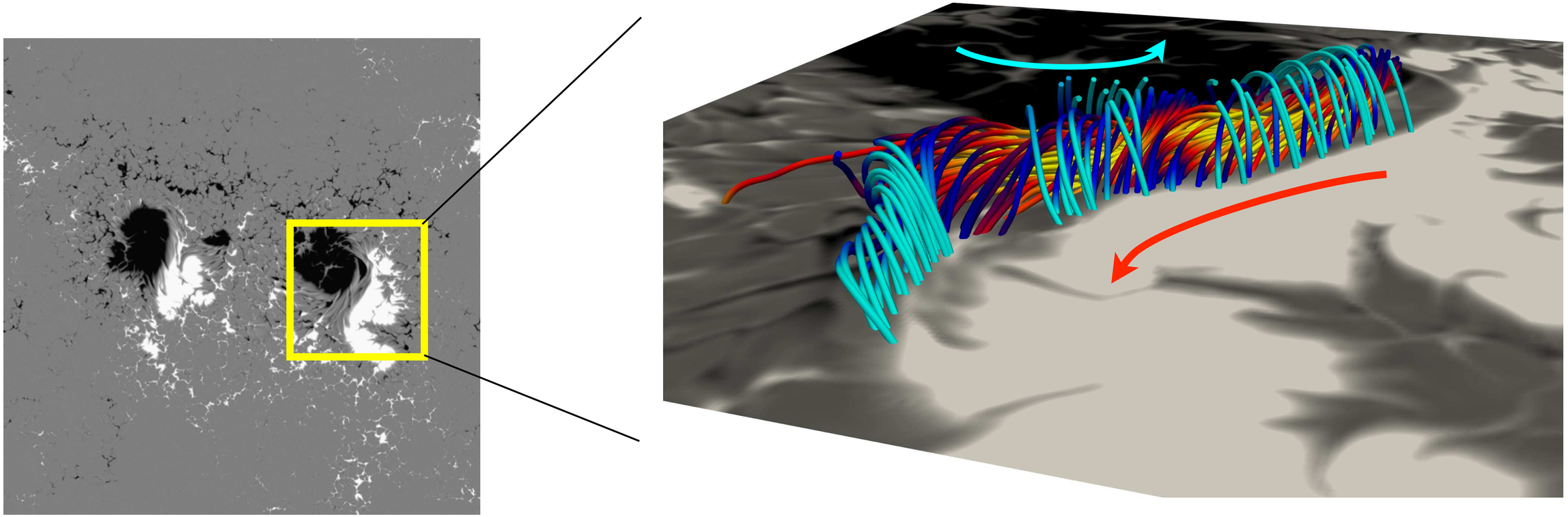




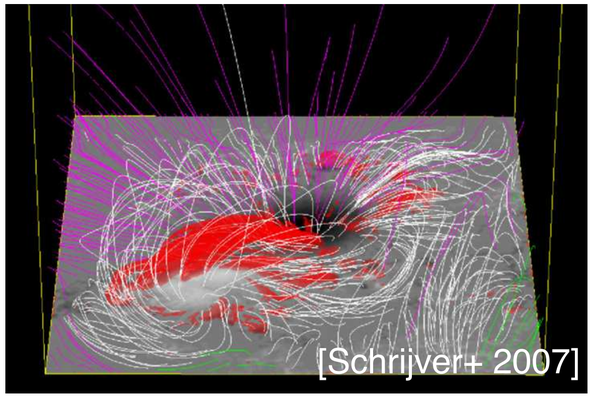
- PIL in δ-spots
  - Super-strong field of > 6 kG is detected by Hinode/SOT [Okamoto & Sakurai 2018; Castellanos Durán+ 2020]
  - > 6 kG field is reproduced in the follow-up simulations [Hotta & Toriumi 2020], due to stretching by strong shearing and suppression by arcade fields

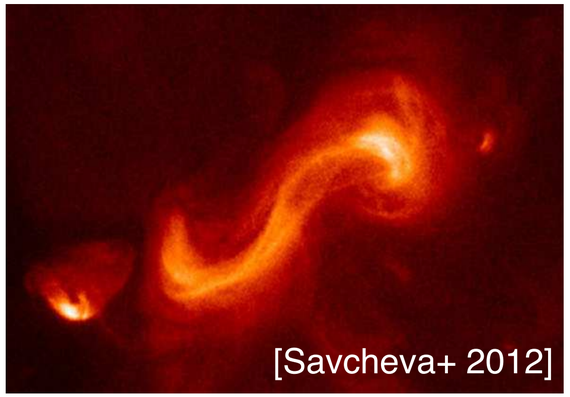
4. The New Twist

[Toriumi & Hotta 2019]



- Field line structure
  - Helical magnetic flux rope with overlying arcade
  - Consistent with NLFFF extrapolations and soft X-ray sigmoids →



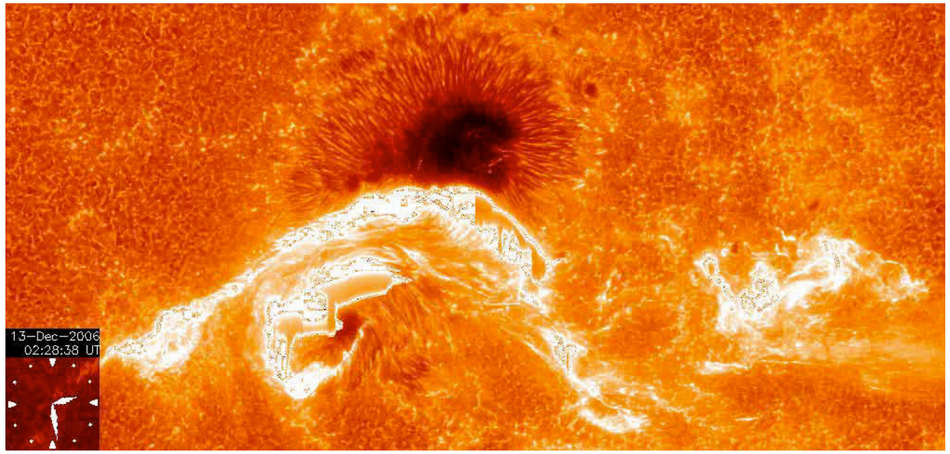


5. Summary and Discussion

Flare-productive ARs?

Observations

- Sheared polarity inversion lines
- Coronal field extrapolations
- X-ray sigmoids
- Non-thermal line broadening
- etc.



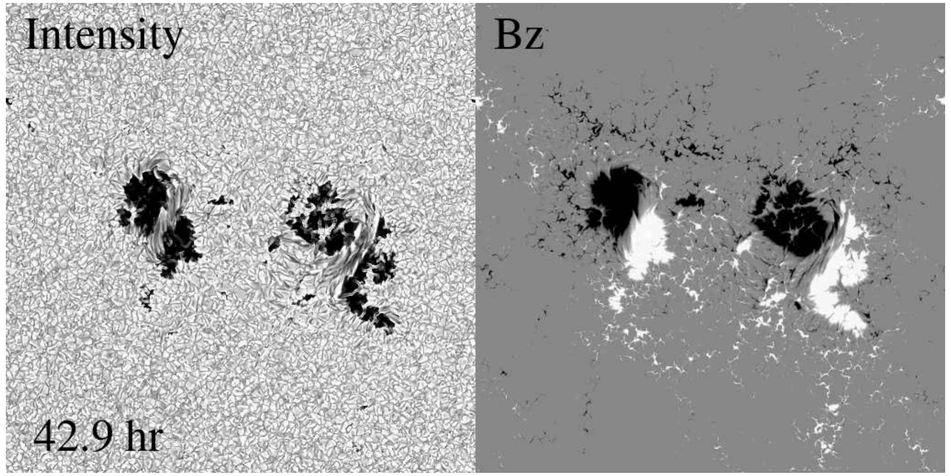
[credit: J. Okamoto]

MHD models

- Ideal and realistic simulations

→ coupling of mag flux and convection

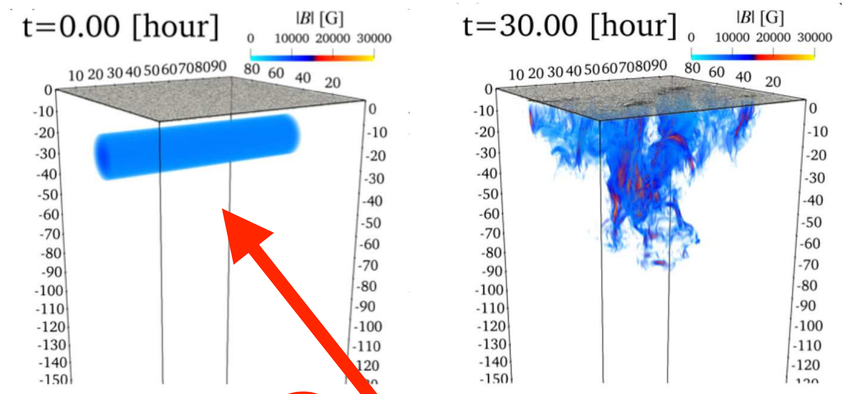
- Sheared PILs, flare-triggering fields
- Helical flux rope, overlying arcade



[Toriumi & Hotta 2019]

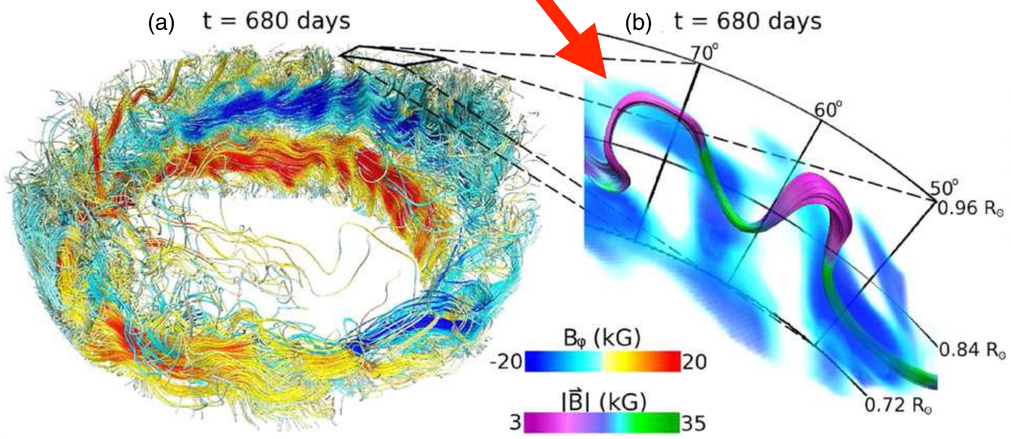
5. Summary and Discussion

- Global and local models
  - How the two regimes are combined?



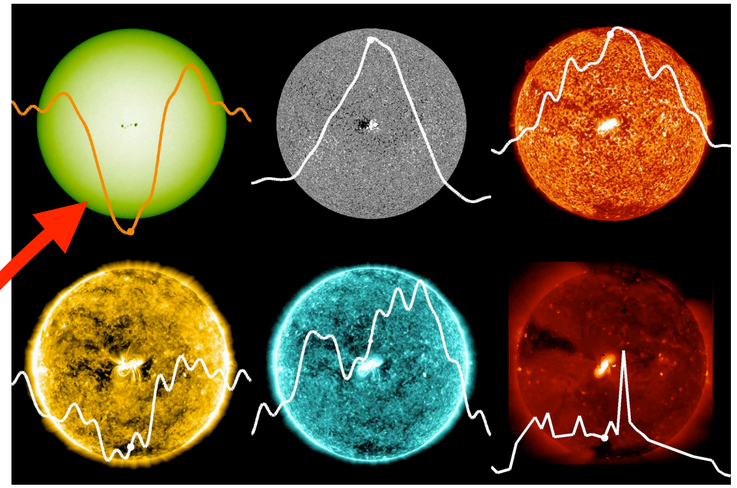
[Hotta & Toriumi 2020]

?



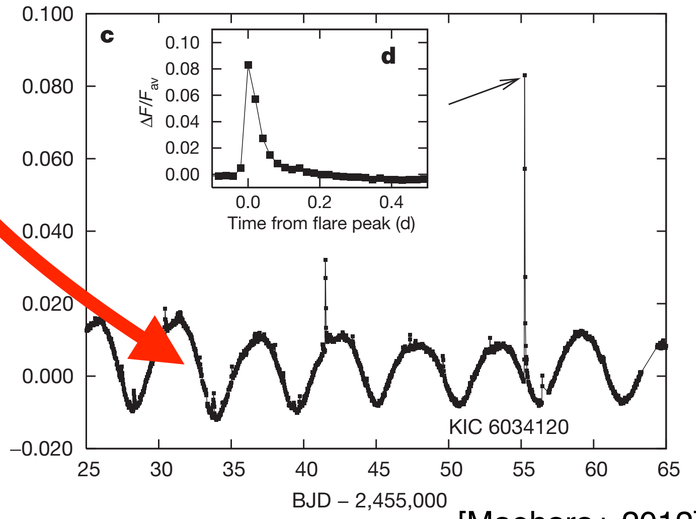
[Nelson+ 2013]

- Solar-stellar connection
  - Starspot evolution and flare occurrence?



[Toriumi+ 2020]

?



[Maehara+ 2012]

Thank you for your attention!

Send feedback to toriumi.shin@jaxa.jp