コロナ加熱・太陽風駆動機構でこれまで分かったことと，未解明問題
Solved & Unsolved Problems in the Coronal Heating & the Solar Wind Acceleration

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Sep.13th, 2014

What to be clarified

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Energy/Momentum/Mass transfer
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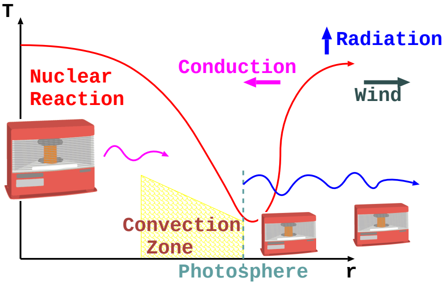
3. The energy dissipates at appropriate locations



In Situ Heating in the Corona & Wind

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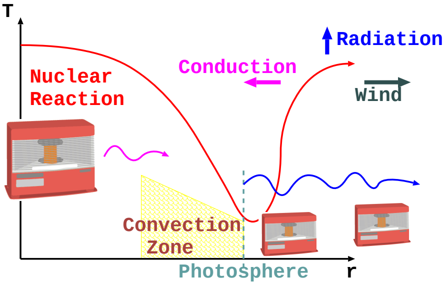

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"Type II spicule" (De Pontieu+ 2011): Direct supply of hot gas

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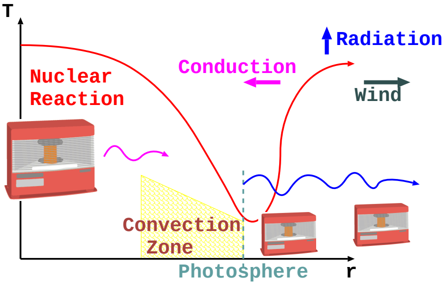

In Situ Heating
in the Corona & Wind

"Type II spicule" (De Pontieu+ 2011): Direct supply of hot gas
: negligible contribution

- need heating against the adiabatic loss (e.g. Klimchuk 2011)
- IRIS observed falling back of Type II spicules (Pereira+ 2014)

Energy Transfer

Energy Flux

$$= \rho v_{||}\left(v^2/2 + h - GM/r\right) + v_{||}B_{\perp}^2/8\pi - B_{||}v_{\perp}B_{\perp}/4\pi$$

h: enthalpy

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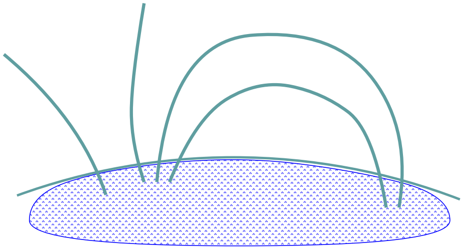

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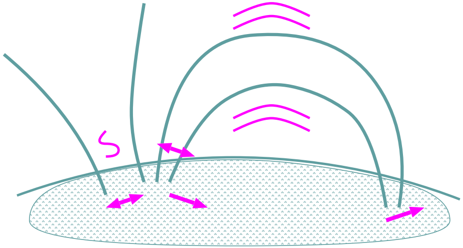

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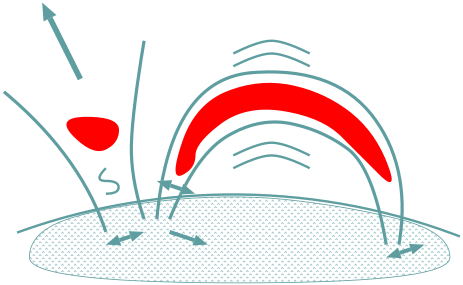

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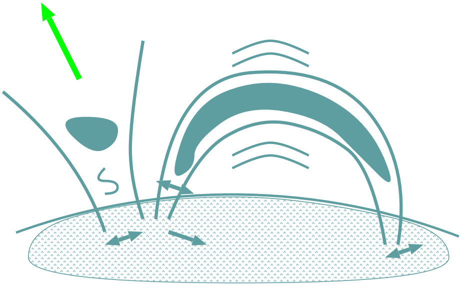

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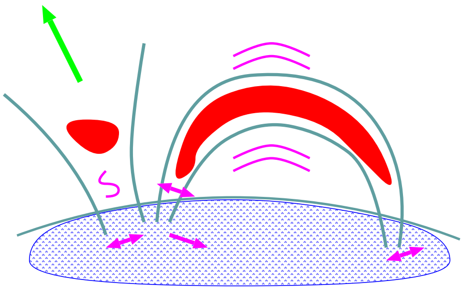

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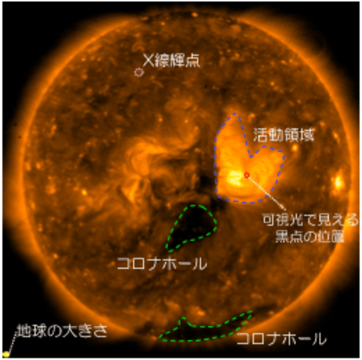

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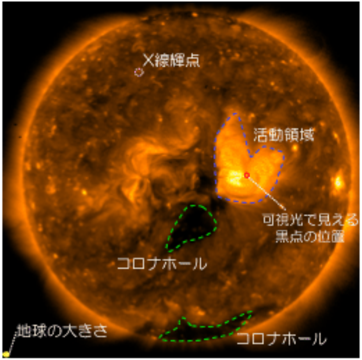

Classification of Regions

Withbroe & Noyes (1977)

Region	CH	QS	AR
Loss(erg/cm^{2}s)	8×10^5	3×10^5	10^7
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Open ⇐ ⇒ Closed ?

CH=Coronal Holes; QS=Quiet Regions; AR=Active Regions

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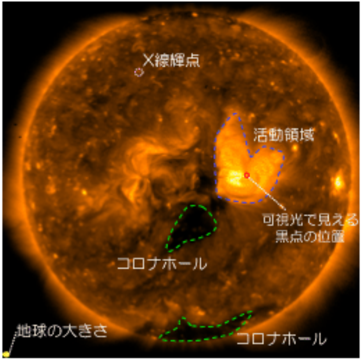

Classification of Heating

- Reconnection (DC)
- Wave (AC)

τ_{motion} > or < τ_{Alf}

The difference is vague

–e.g. waves with short duration.

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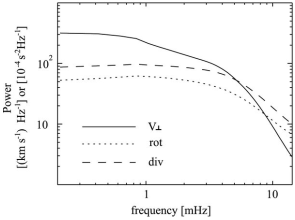

Matsumoto & Kitai 2010

$$\langle \delta v_\perp \rangle = 1.1 \text{km/s}$$

$$F = 10^8 \text{(erg/cm}^2\text{s)} \left(\frac{\rho}{10^{-7}\text{g/cm}^3} \right) \left(\frac{\delta v}{1\text{km/s}} \right)^3$$

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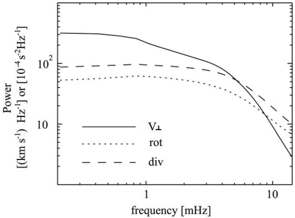

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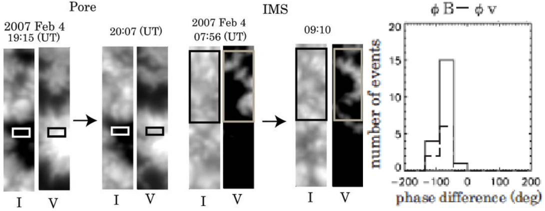
Fujimura & Tsuneta 2009

IMS=intergranular magnetic structure



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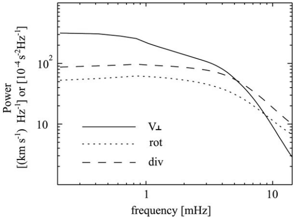

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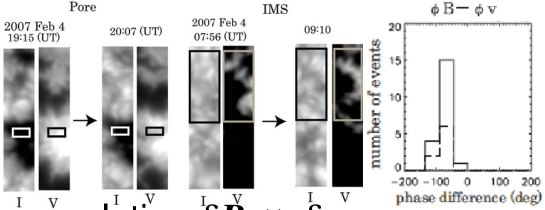

Phase correlation $\delta B \Leftrightarrow \delta v$

$\Rightarrow$ direction of Alfvénic wave

see also Ulrich 1996

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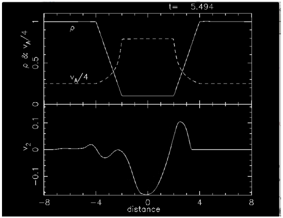
- But, most of energy ($\gtrsim$ 90%) is reflected back.
  - Consistent with numerical simulations.
    Suzuki & Inutsuka 2005; Cranmer+ 2007; Verdini & Velli 2007



Reflection test

Energy Transfer in Chromosphere

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HINODE/SOT

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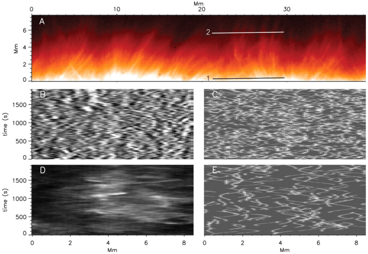

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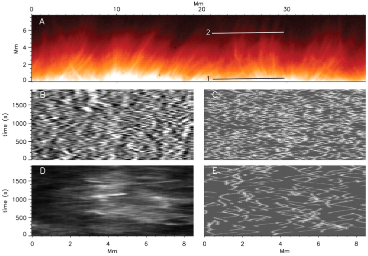

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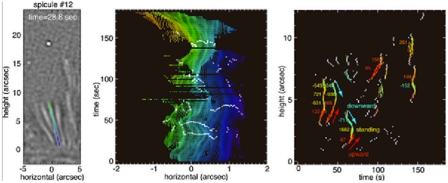

OBS: waves with short period ($\lesssim$100 s)

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Each event seems nice, but spatial (⇔ filling factor) & time (⇔ lifetime) integration ?

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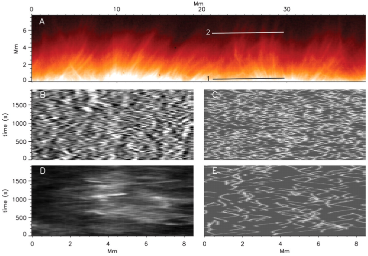

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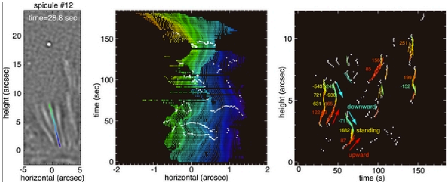

OBS: waves with short period (≲100 s)

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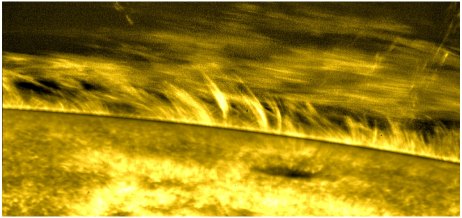
Alfvénic waves in prominence

(Okamoto+ 2007)



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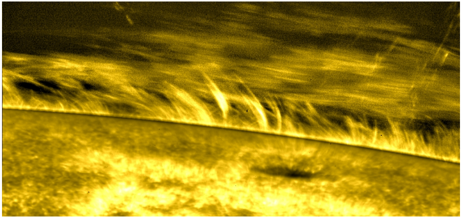
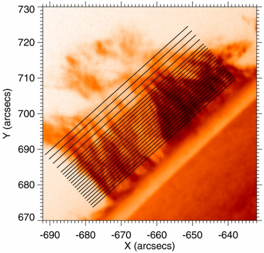


Hiller+ 2013



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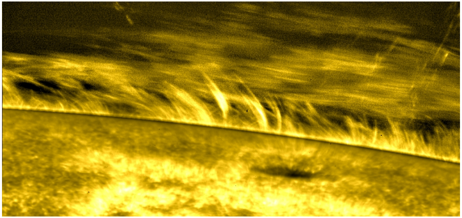

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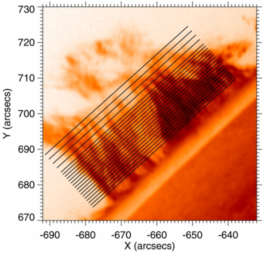
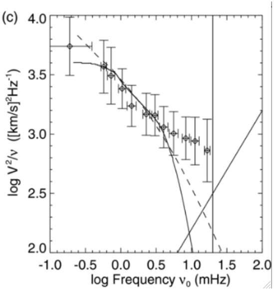


Lines: $\boldsymbol{P(v)}$ at Photosphere

- Solid: Matsumoto & Kitai 2010
- Dashed: Chitta+ 2012

$\boldsymbol{P(v)}$: Chromosphere – Photosphere



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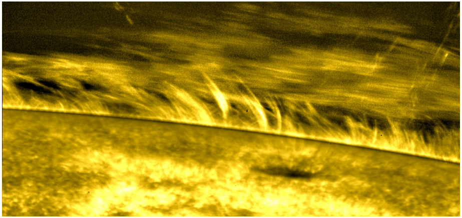

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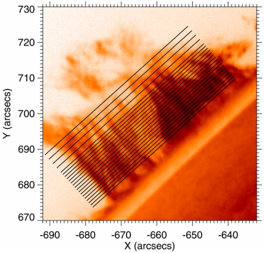

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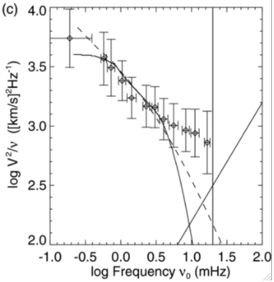
Turbulent cascade to higher-frequency from photosphere to chromosphere ?

$P(v)$: Chromosphere – Photosphere



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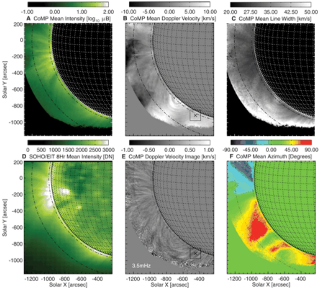
  e.g. 10(erg/cm^{2}s) Tomczyk+2007

CoMP/NSO Tomczyk+ 2007



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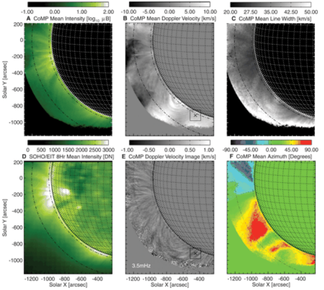

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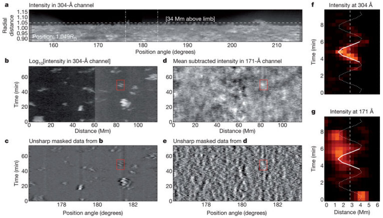

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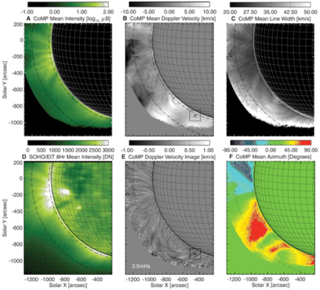

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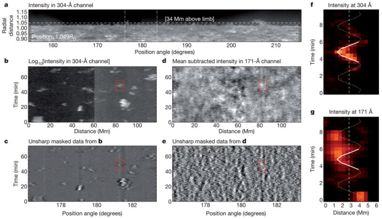

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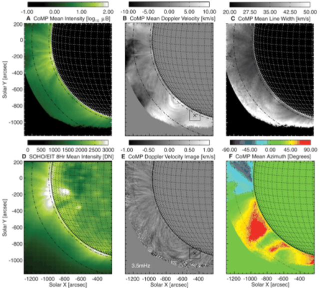

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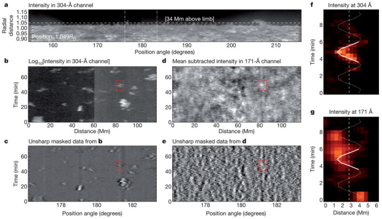

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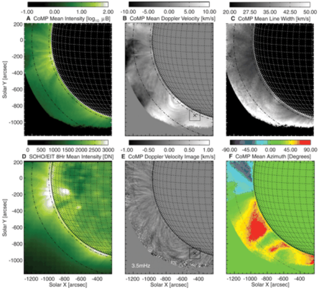

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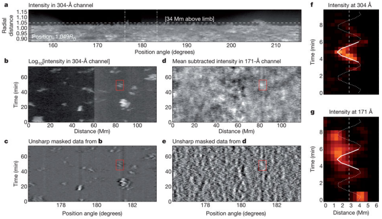

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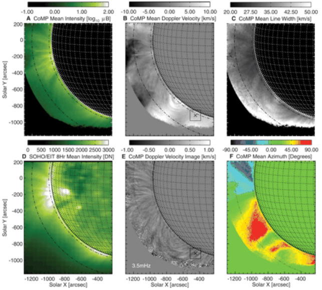
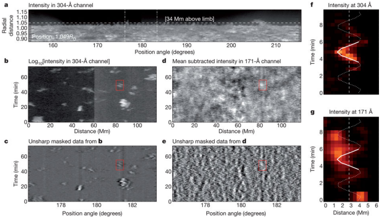
    Pure OBS by the same method gives
    $(0.9-2.4)\times 10^4$(erg/cm^{2}s)

Thurgood+ 2014

CoMP/NSO Tomczyk+ 2007

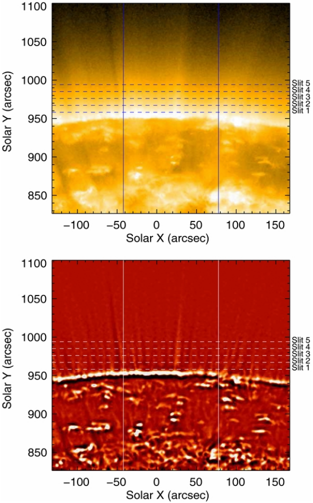


SDO/AIA McIntosh+ 2011

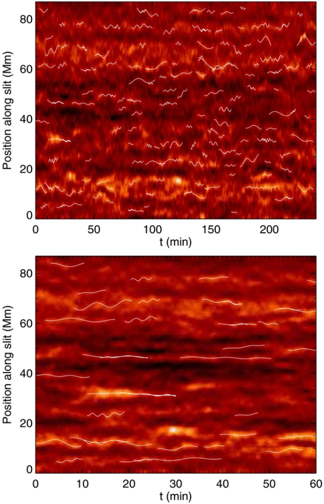


Transverse Waves in Corona –contd.

SDO/AIA obs (Thurgood+ 2014)



Time-Position at Slit 1



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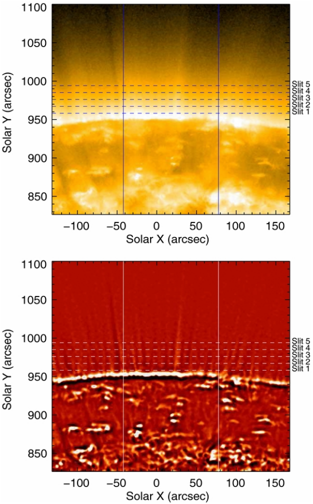

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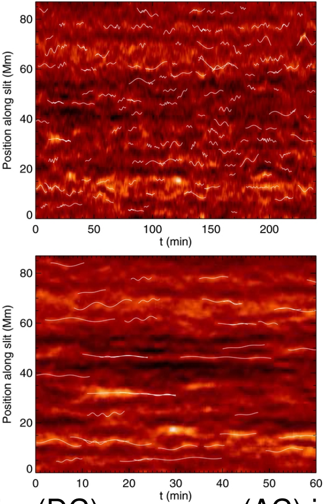
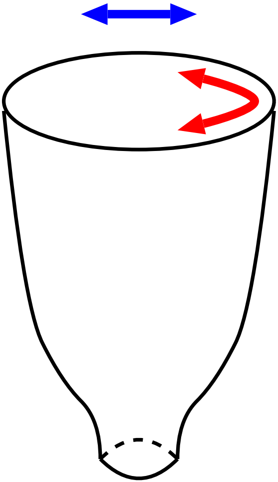


- The concept of reconnection(DC) vs. waves(AC) is not reasonable.

Observable Transverse Waves ??



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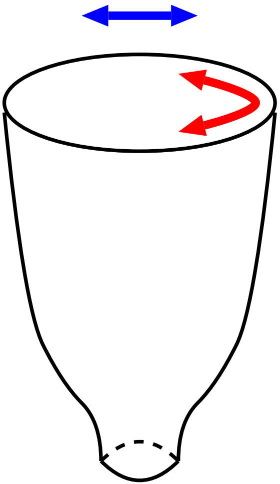

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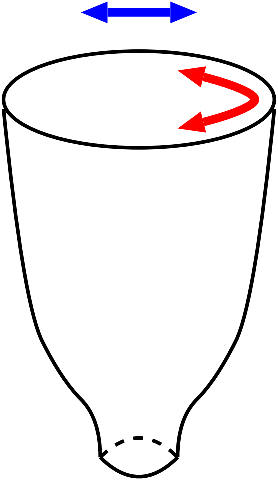

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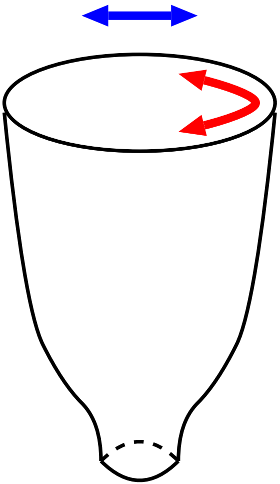

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Hidden energy flux in torsional waves in fine-scale tubes ???

⇔ Observation of helicity in the corona Curdt & Tian 2011

Longitudinal Waves in Corona

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Plenty of Observations

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- Reconnections or motion of loops
  Sturrock 1999; Nishizuka+ 2009; Kigure+ 2010

Outflows near ARs

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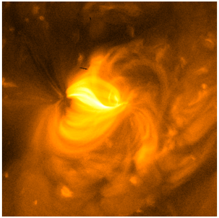
XRT obs (Sakao+ 2007)



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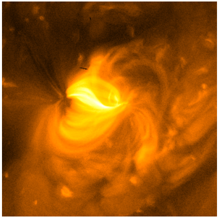
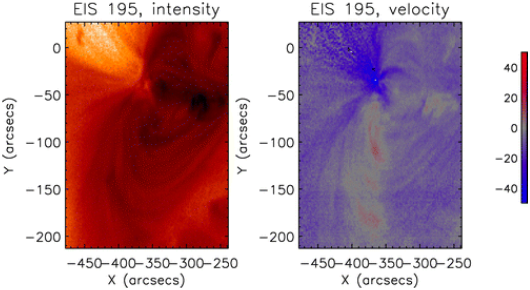


Harra+ 2008



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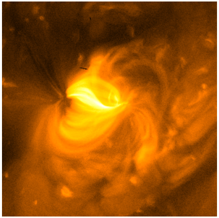

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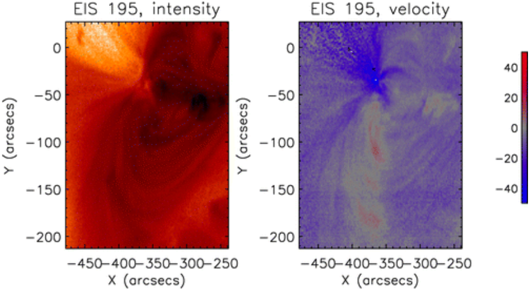

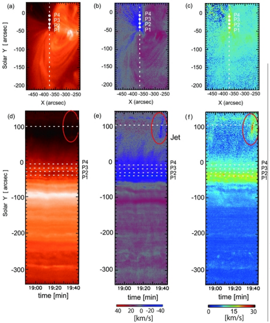

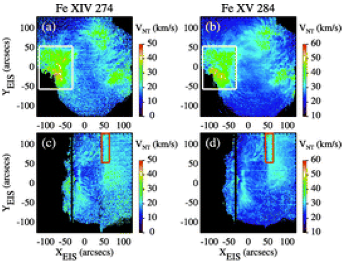

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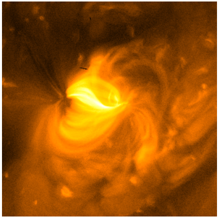

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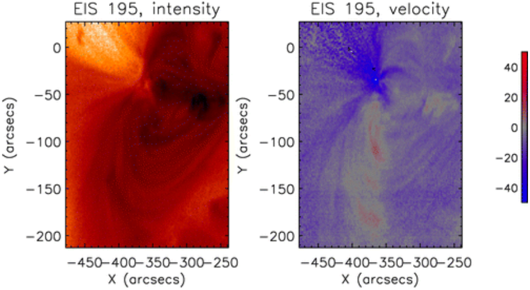

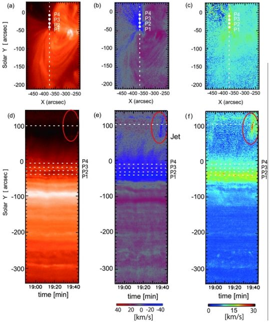

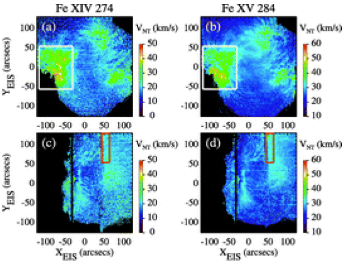

Blue-shifted (outflow) regions

= large non-thermal δv

⇐ Impulsive Heating?

Nishizuka & Hara 2011; Hara+ 2008

T dependent flows

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EIS obs of a CH near an AR

(Imada+ 2007; 2011)

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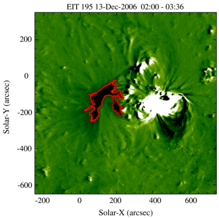

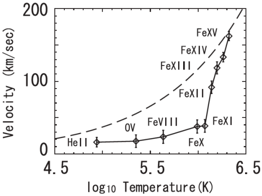

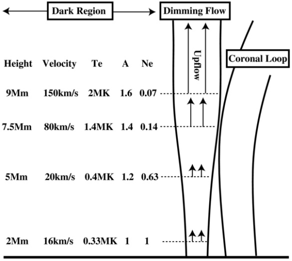

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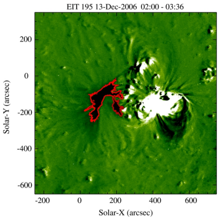
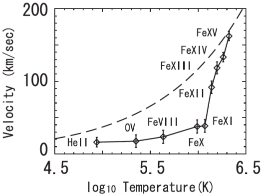
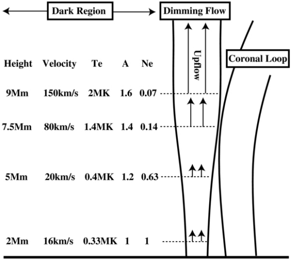
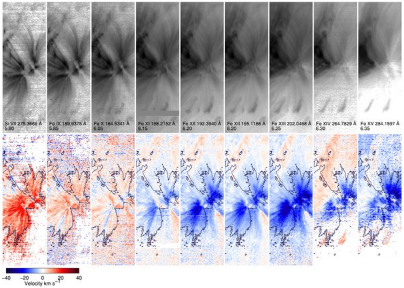






Warren+ 2010 see also Brooks & Warren 2012



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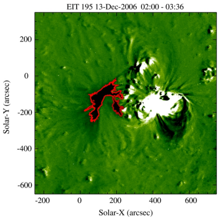

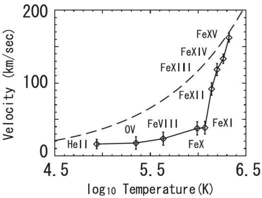

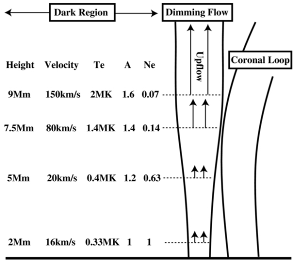

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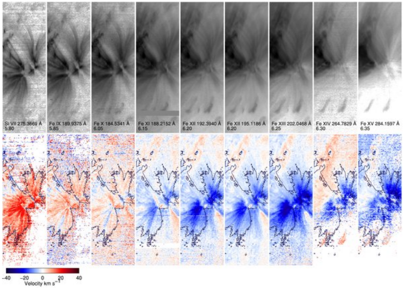

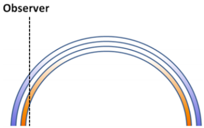

Taroyan & Bradshaw 2014

can be explained by OBS of
multiple unresolved loops

- Heated loops = upflows
- Cooled loops = downflows

Outflows in CHs

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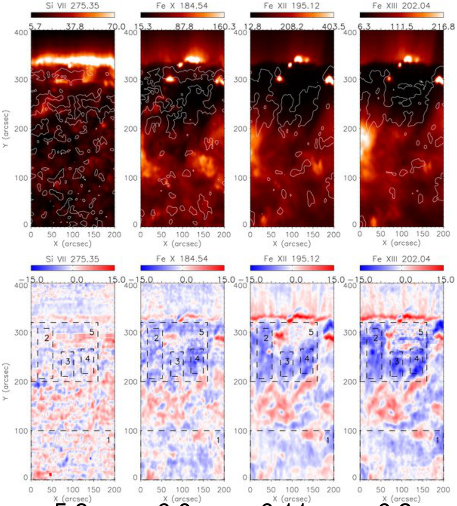
Tian+ 2010



5.8 6.0 6.11 6.2

$\log T$

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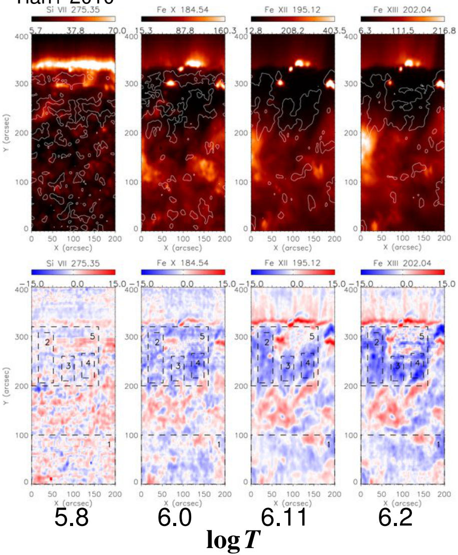

Blue-shifted (outflow) regions gradually dominate with T ⇑

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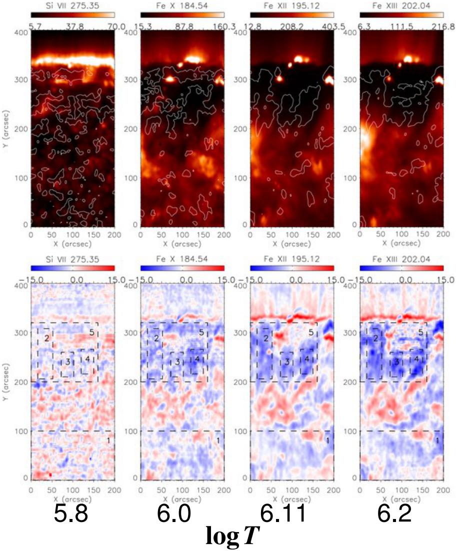
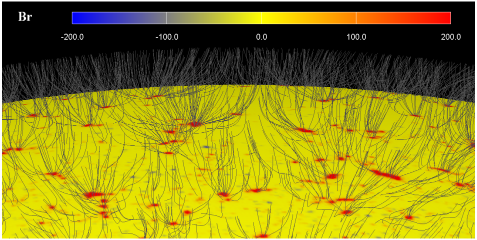


Shiota+ 2012



Blue-shifted (outflow) regions gradually dominate with $T \Uparrow$

$\Leftarrow$ Merging of super-radially open flux tubes

Heating in CHs

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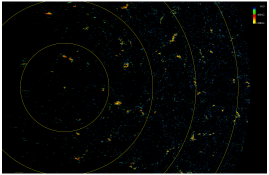
Tsuneta+ 2008



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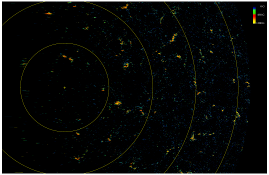
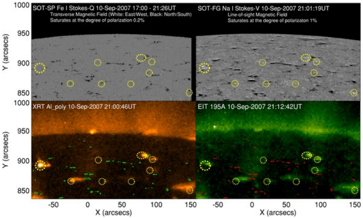


Shimojo & Tsuneta 2009



- kG-patches (Tsuneta+ 2008; Ito+ 2010)
  ⇔ X-ray bright points
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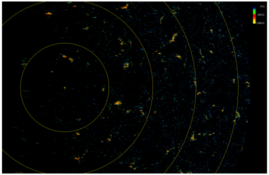

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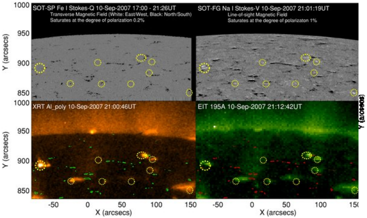

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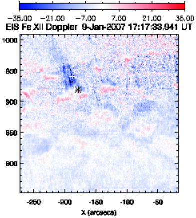

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  - Triggered by reconnection events?
  - Excite Alfvénic waves (Cirtain+ 2007)
- Contribute to $\sim 10\%$ of $\dot{M}$ of the solar wind (Cirtain+ 2007)

  ⇐ Estimated occurrence rate of X-ray jets

Heating in AR Corona

Heating in AR Corona

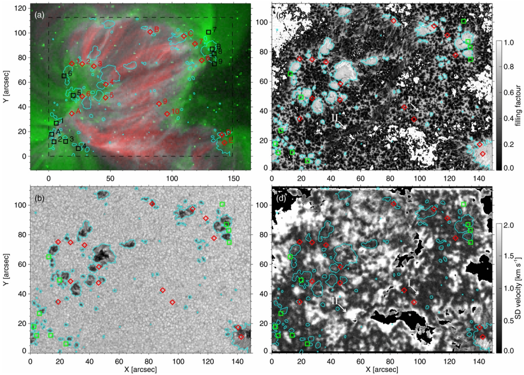
Filling factor – δv

Heating in AR Corona

Filling factor – δv

Kano+ 2014

XRT(red)/TRACE(green) filling factor



Continuum Intensity δv from SOT/SP

Heating in AR Corona

Filling factor – δv

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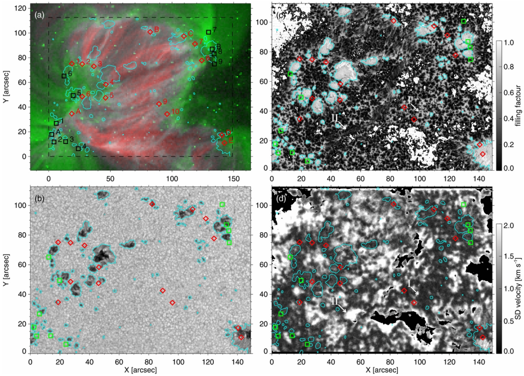

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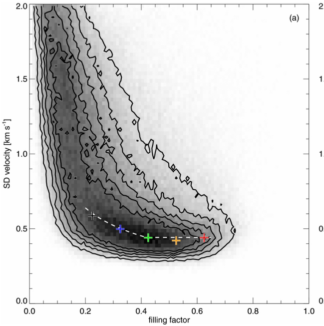

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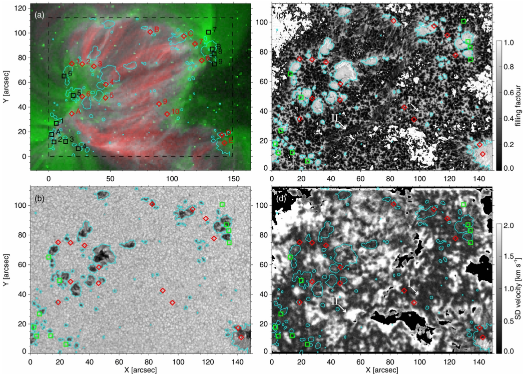

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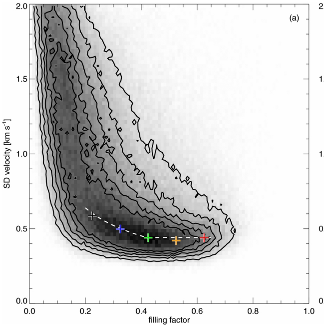
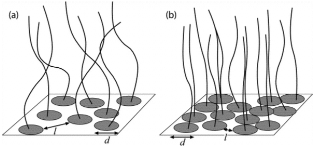




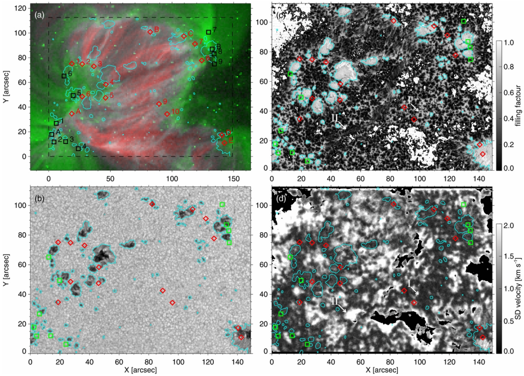
Inconsistency/Consistency with

Katsukawa & Tsuneta (2005)?

Heating in AR Corona

Filling factor – δv

XRT(red)/TRACE(green)   filling factor



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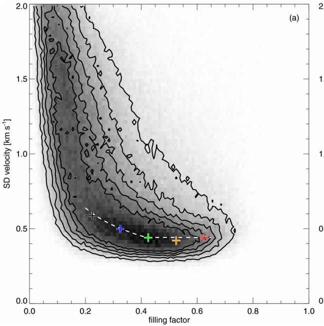
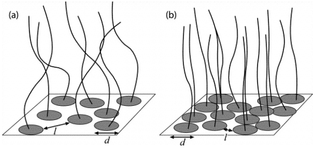




Inconsistency/Consistency with Katsukawa & Tsuneta (2005)?

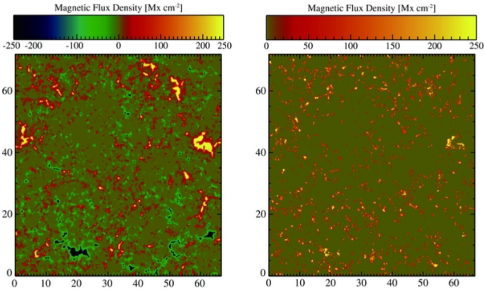
Similar studies for QS & CH are important.

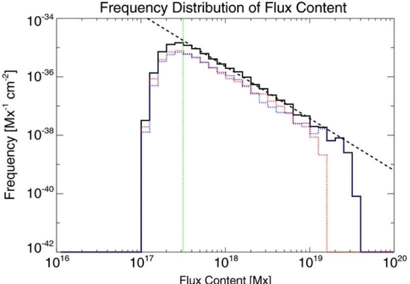
Other Issues should be Addressed

- $\boldsymbol{B}$ at Photosphere ⇔ Injection of Poynting Flux

Magnetic Field at Photosphere

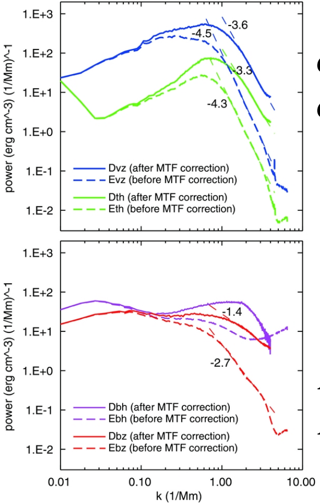
Φ_h & Φ_z in QS (Ishikawa & Tsuneta 2011)





Katsukawa & Orozco Suárez 2012

Iida+ 2012



δT
δv

B_h
B_z

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- $\boldsymbol{B}$ at Photosphere $\Leftrightarrow$ Injection of Poynting Flux

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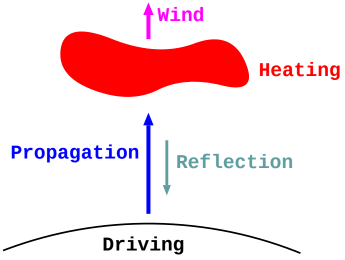
  - Stellar Flare – Stellar Corona – Stellar Wind – Protoplanetary Disks

Summary –Individual Events



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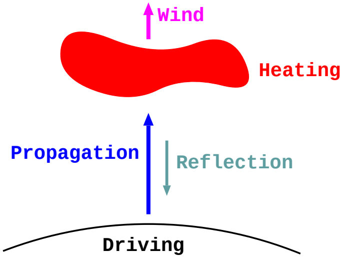

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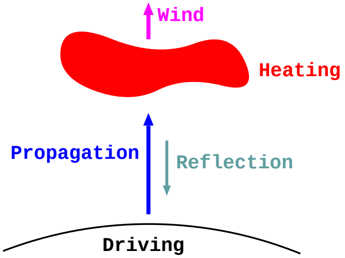

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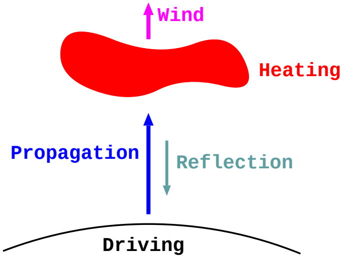

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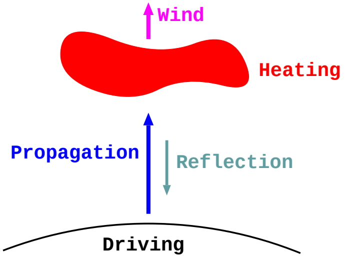

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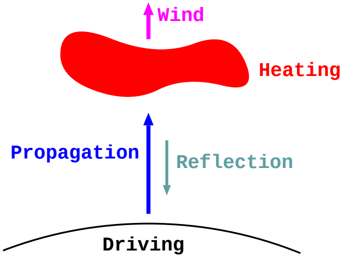

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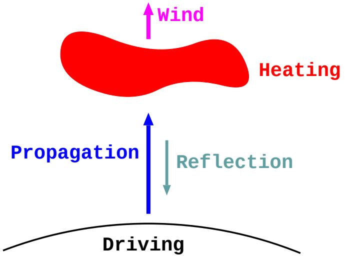

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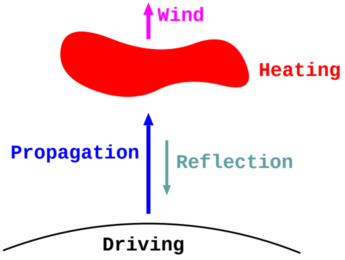

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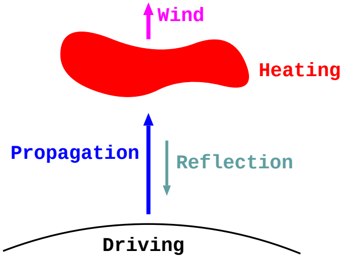

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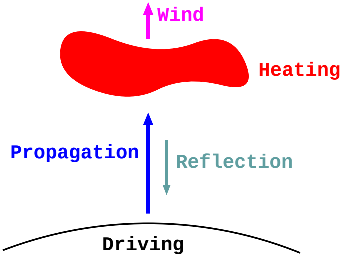

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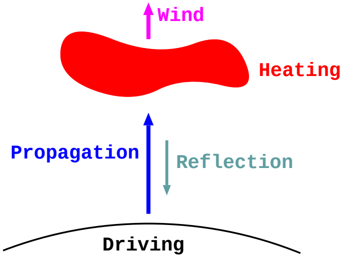

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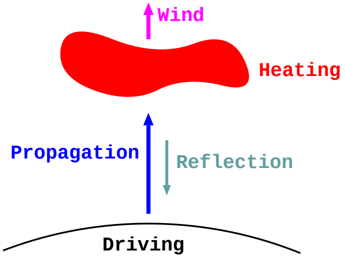

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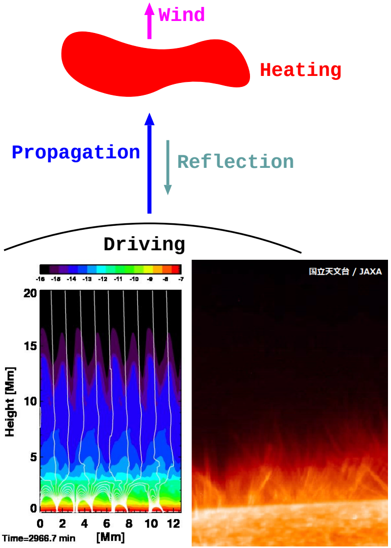

based on Matsumoto & Suzuki 2012

⇔ Forward-type Numerical Simulations

Summary –Integration

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Want to know Integrated Energy Input.

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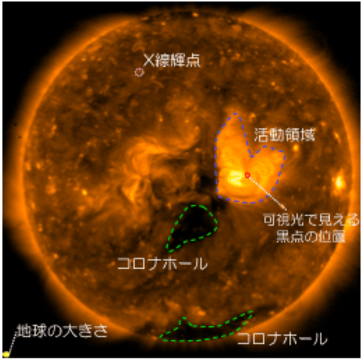

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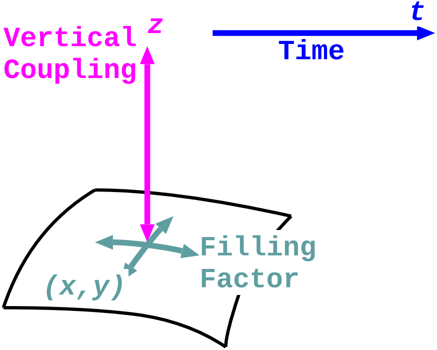

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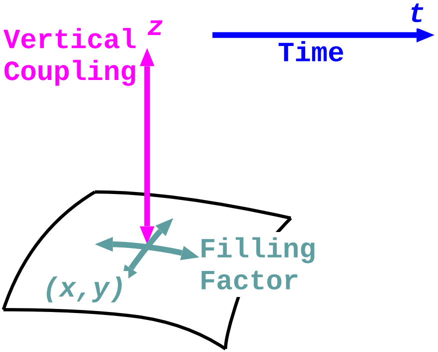

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  particularly in QSs & CHs

Photosphere – Corona Coupling ?

Coordinate observation in comparison with numerical simulation

Reconnection-triggered

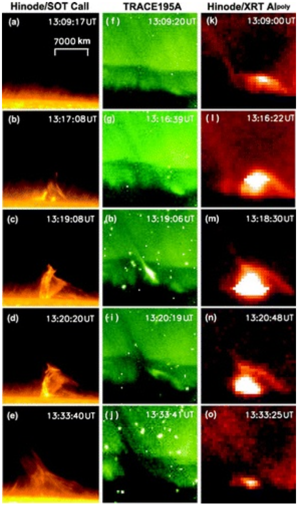
- Ca II jet
- Propagating Alfvénic waves
- X-ray jet

Need quantitative arguments.

HINODE – IRIS coordinate observation.

An example observation of an AR

Nishizuka+ 2008



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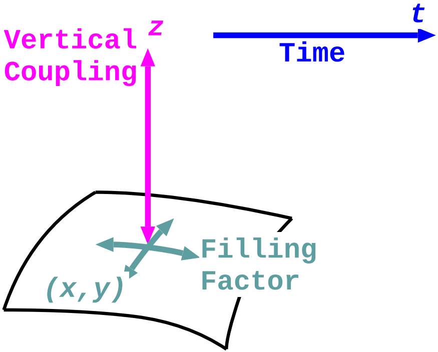

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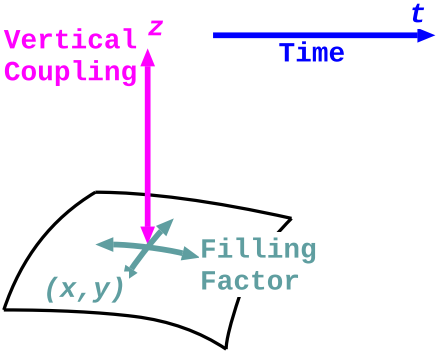

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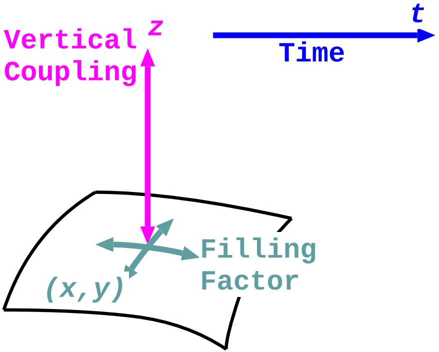

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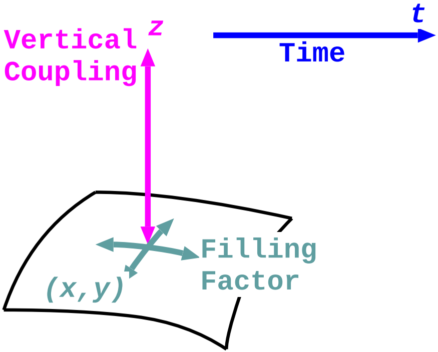

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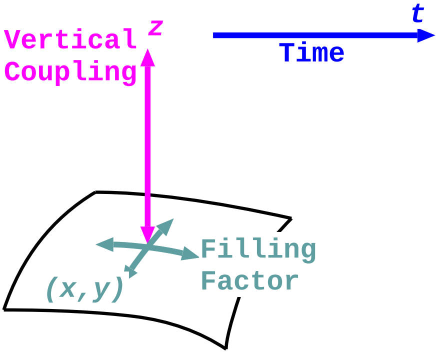

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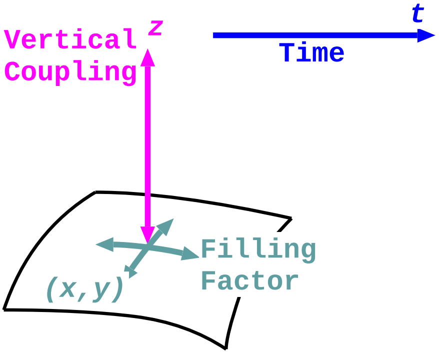

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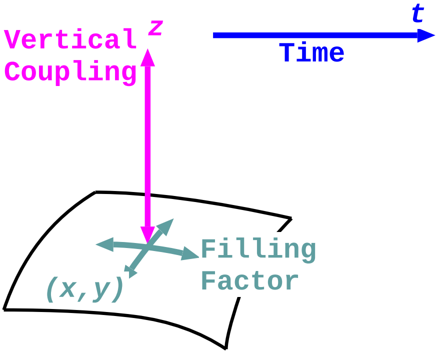

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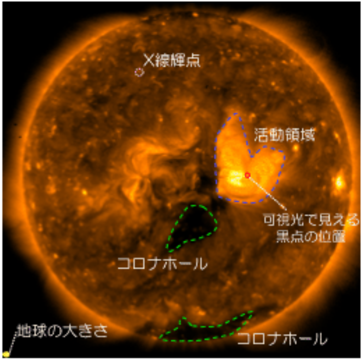

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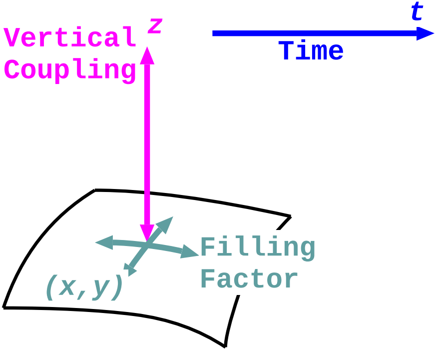

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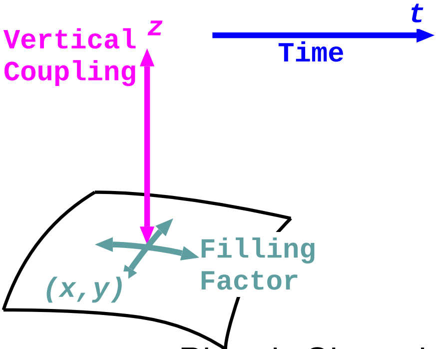

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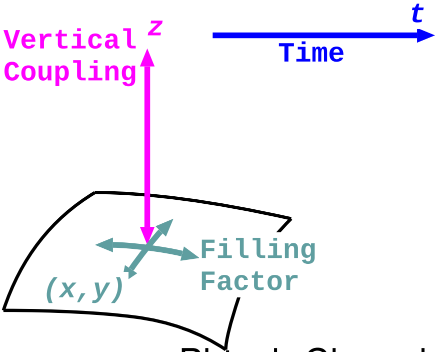

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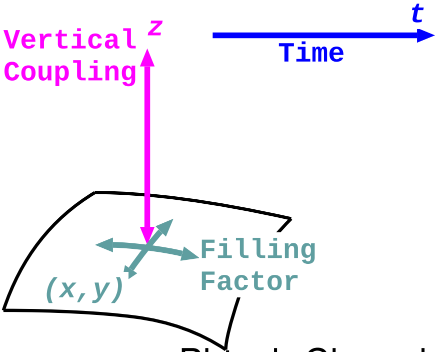

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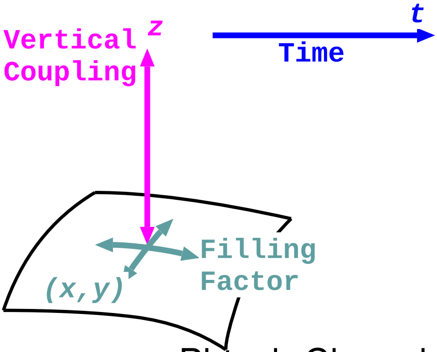

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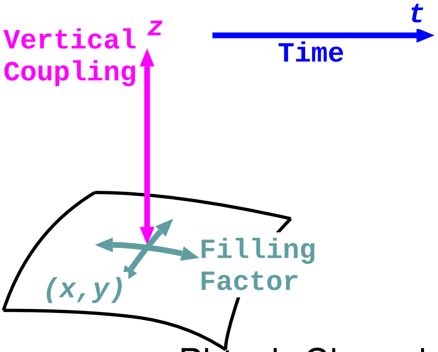

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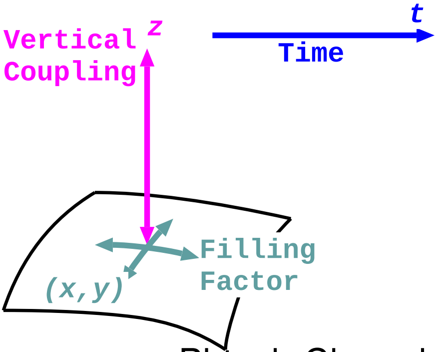

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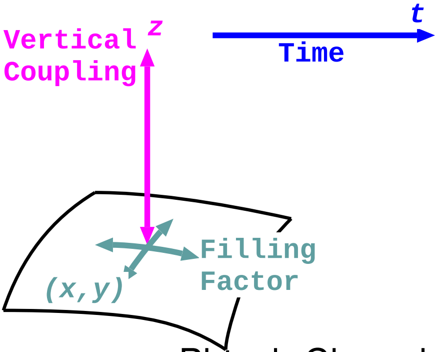

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Summary

- Vertical Direction
  Photosphere – Chromosphere – Corona & Wind: Our understandings are decoupled at the moment
  ⇒ Coordinate Observations
- Horizontal Direction
  Filling Factor of energy flux / tubes / magnetic elements
  ⇒ Smaller scale
- Time Direction
  Heating in time integration ??
  ⇒ Need compiling works with present observational data

Energy Transfer

$$F = \rho v_{||}\left(v^2/2 + h - GM/r\right)$$
$$+ v_{||}B_{\perp}^2/8\pi - B_{||}v_{\perp}B_{\perp}/4\pi$$

h: enthalpy

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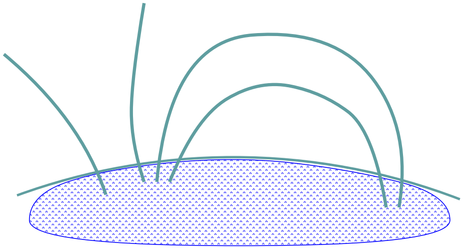

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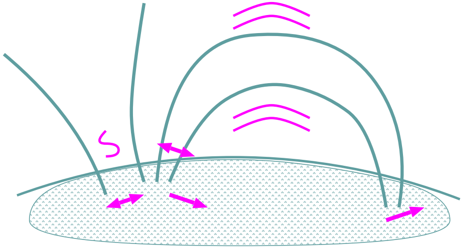

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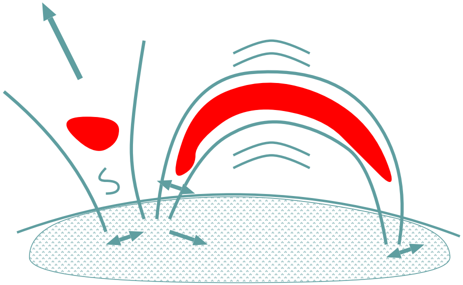

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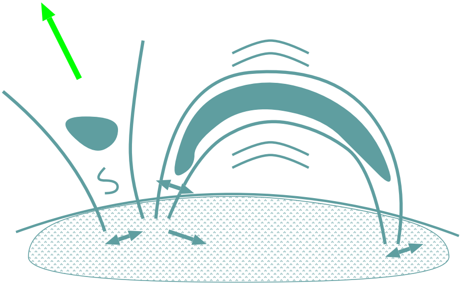
   $\Rightarrow \rho v_{||} h$
4. $v_{||}B_{\perp}^2/8\pi -$
   $B_{||}v_{\perp}B_{\perp}/4\pi + \rho v_{||} h$
   $\Rightarrow \rho v_{||} v^2/2$

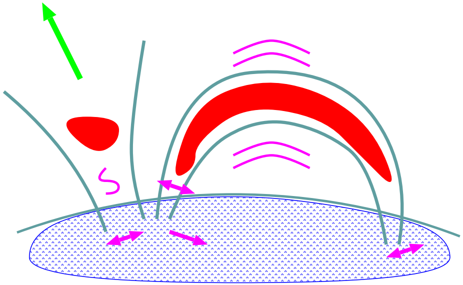


Energy Transfer

$$F = \rho v_{||}\left(v^2/2 + h - GM/r\right)$$
$$+v_{||}B_{\perp}^2/8\pi - B_{||}v_{\perp}B_{\perp}/4\pi$$

h: enthalpy

1. $\rho v_{||}v^2/2$
2. $\rho v_{||}v^2/2$
   $\Rightarrow$
   $v_{||}B_{\perp}^2/8\pi - B_{||}v_{\perp}B_{\perp}/4\pi$
3. $v_{||}B_{\perp}^2/8\pi - B_{||}v_{\perp}B_{\perp}/4\pi$
   $\Rightarrow \rho v_{||}h$
4. $v_{||}B_{\perp}^2/8\pi -$
   $B_{||}v_{\perp}B_{\perp}/4\pi + \rho v_{||}h$
   $\Rightarrow \rho v_{||}v^2/2$



Input & Response in TR & Corona

- Direct (spectroscopic/imaging) OBS of transverse waves
- Direct (spectroscopic/imaging) OBS of longitudinal waves
- Indirect OBS –Non-thermal broadening– Propagation & Dissipation of Alfvénic waves
- OBS of outflows
  Ubiquitous in open flux tubes near ARs
- X-ray bright points