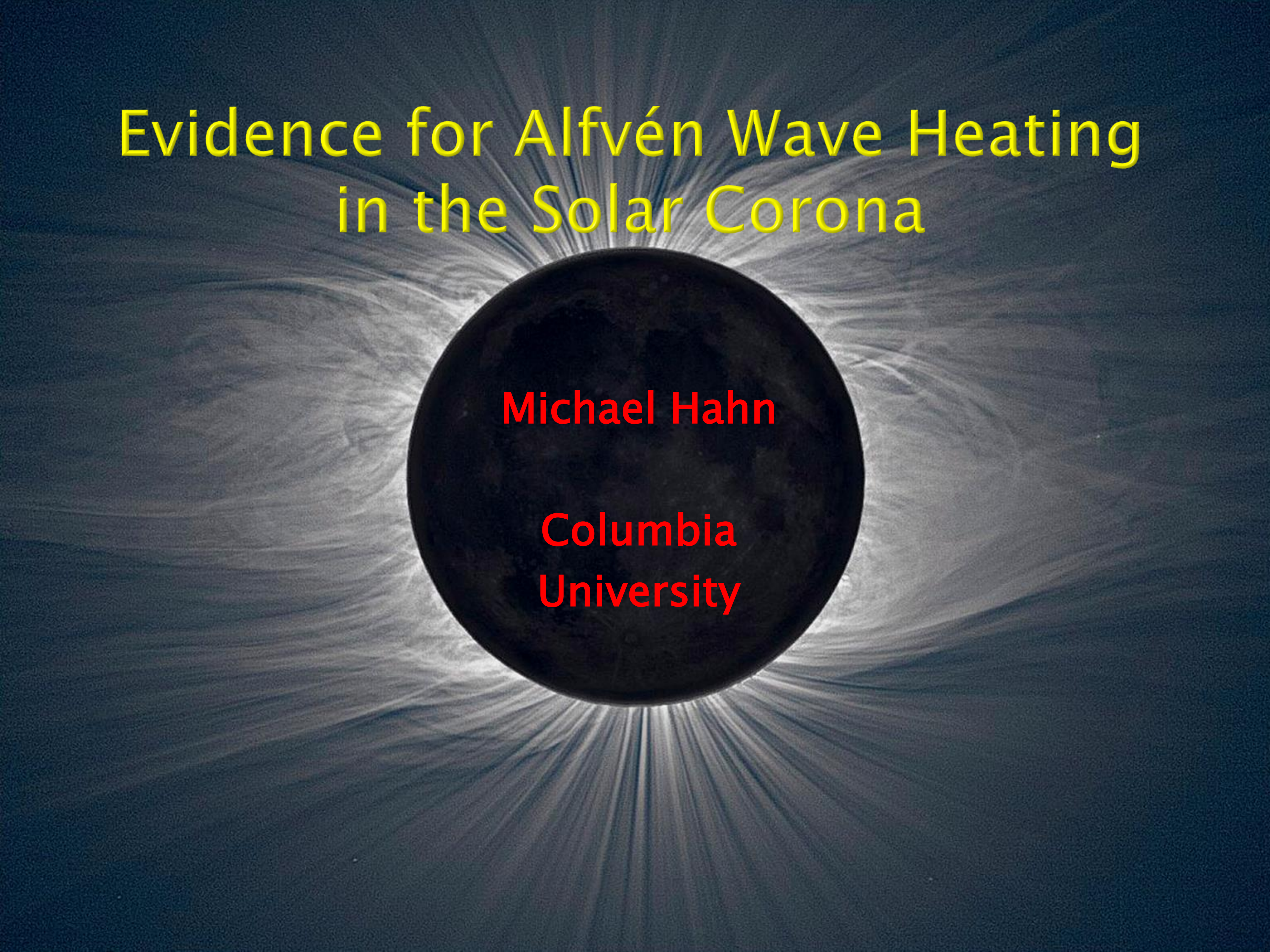

Evidence for Alfvén Wave Heating in the Solar Corona

Michael Hahn

Columbia University

Acknowledgements

Daniel Wolf Savin (Columbia)

Enrico Landi (Michigan)

NSF Solar Heliospheric and Interplanetary Environment (SHINE)

Outline

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  - The Coronal Heating Problem.
  - Reconnection.
  - Waves.
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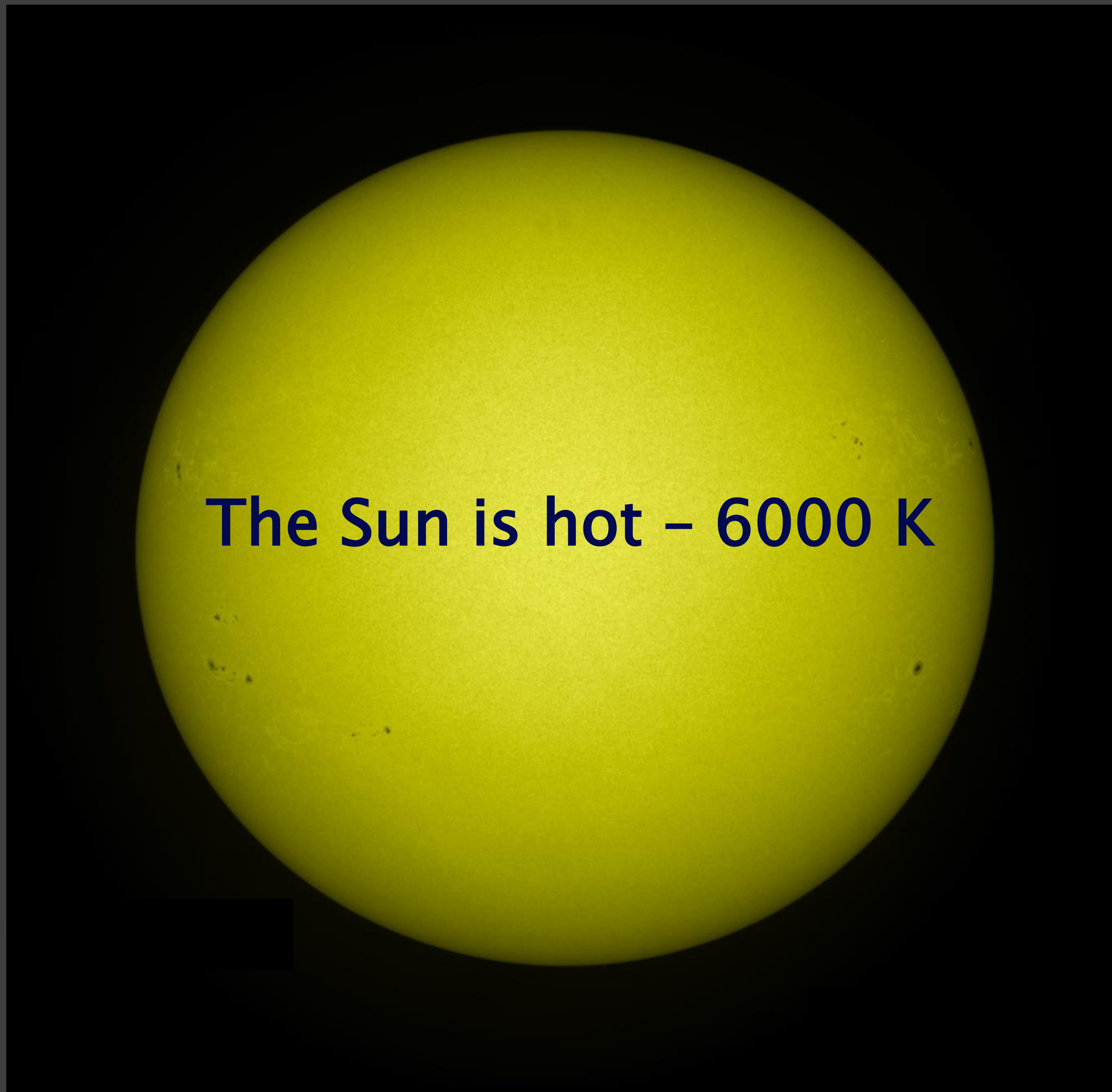
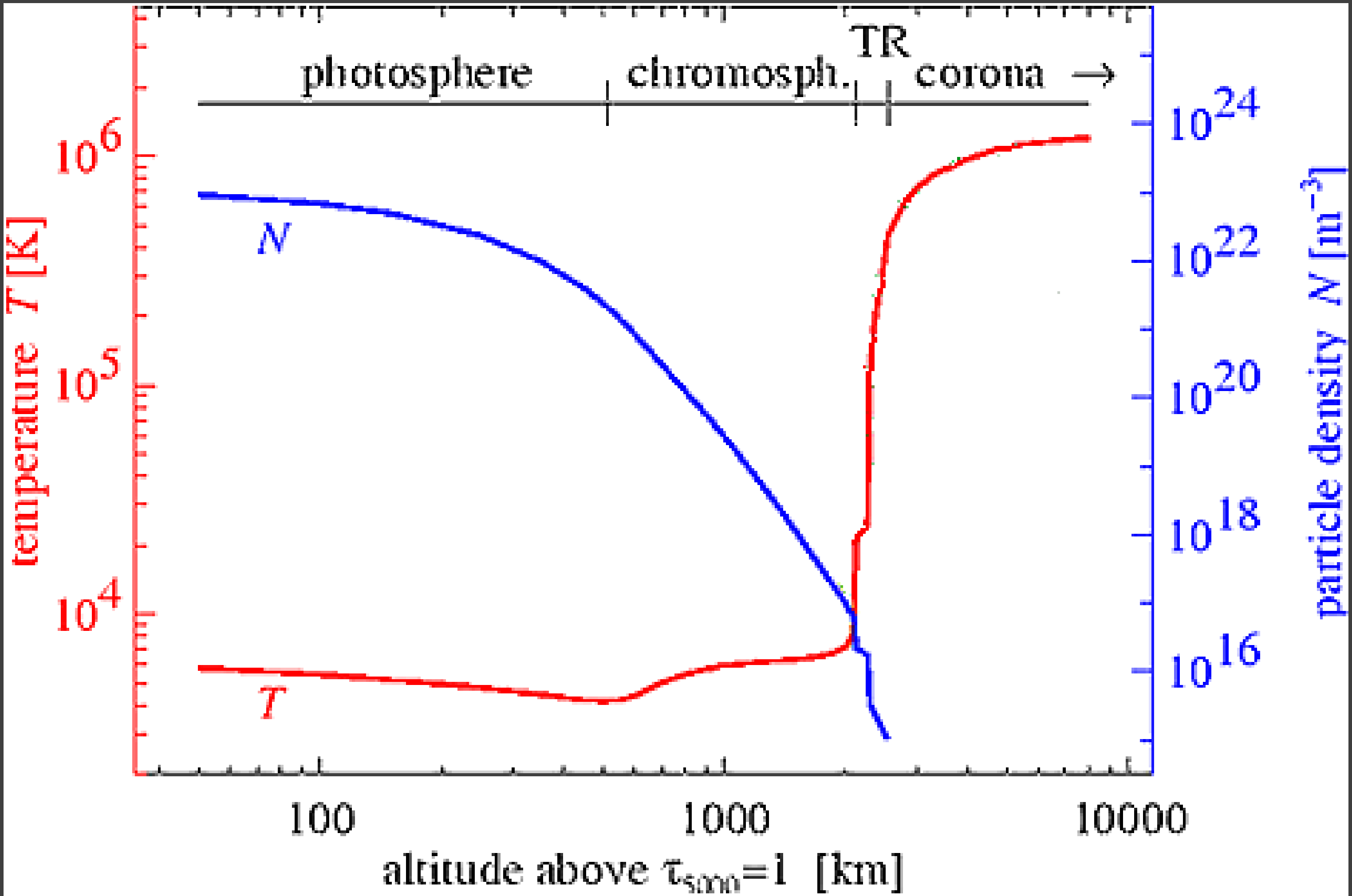
The Coronal Heating Problem



The Coronal Heating Problem

The Coronal Heating Problem



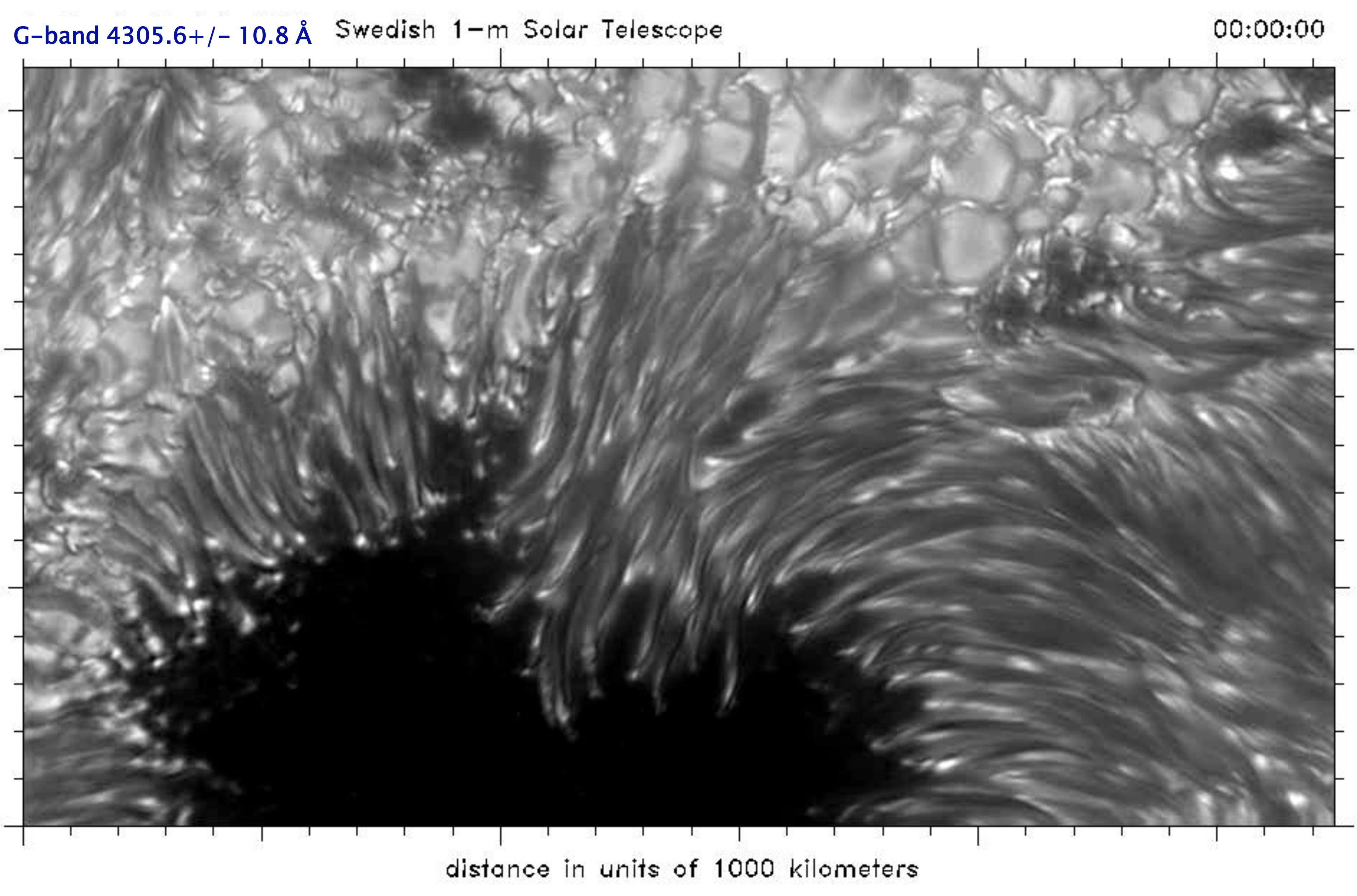
Wilhem et al. (2007)

Driving the Solar Wind

Coronal Heating

- Only 0.01% of Sun's energy output required.
- Energy source is fluid motion in outer convection zone.

Convection Near a Sunspot



Coronal Heating

- Only 0.01% of Sun's energy output required.
- Energy source is fluid motion in outer convection zone.
- Jostling of field lines gives energy to corona via:
  - Magnetic reconnection
  - Waves

So is it Reconnection?

THE ASTROPHYSICAL JOURNAL, 720:824–847, 2010 September 1 doi:10.1088/0004-637X/720/1/824

CAN THE SOLAR WIND BE DRIVEN BY MAGNETIC RECONNECTION IN THE SUN'S MAGNETIC CARPET?

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Received 2010 May 25; accepted 2010 July 13; published 2010 August 13

ABSTRACT

The physical processes that heat the solar corona and accelerate the solar wind remain unknown after many years of study. Some have suggested that the wind is driven by waves and turbulence in open magnetic flux tubes, and others have suggested that plasma is injected into the open tubes by magnetic reconnection with closed loops. In order to test the latter idea, we developed Monte Carlo simulations of the photospheric "magnetic carpet" and extrapolated the time-varying coronal field. These models were constructed for a range of different magnetic flux imbalance ratios. Completely balanced models represent quiet regions on the Sun and source regions of slow solar wind streams. Highly imbalanced models represent coronal holes and source regions of fast wind streams. The models agree with observed emergence rates, surface flux densities, and number distributions of magnetic elements. Despite having no imposed supergranular motions in the models, a realistic network of magnetic "funnels" appeared spontaneously. We computed the rate at which closed field lines open up (i.e., recycling times for open flux), and we estimated the energy flux released in reconnection events involving the opening up of closed flux tubes. For quiet regions and mixed-polarity coronal holes, these energy fluxes were found to be much lower than that which is required to accelerate the solar wind. For the most imbalanced coronal holes, the energy fluxes may be large enough to power the solar wind, but the recycling times are far longer than the time it takes the solar wind to accelerate into the low corona. Thus, it is unlikely that either the slow or fast solar wind is driven by reconnection and loop-opening processes in the magnetic carpet.

Key words: magnetic fields – magnetohydrodynamics (MHD) – plasmas – solar wind – Sun: corona – Sun: photosphere

Or Waves?

THE ASTROPHYSICAL JOURNAL, 711:1044–1050, 2010 March 10 doi:10.1088/0004-637X/711/2/1044

DEMONSTRATIONS THAT THE SOLAR WIND IS NOT ACCELERATED BY WAVES OR TURBULENCE

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Received 2009 July 14; accepted 2010 January 21; published 2010 February 22

ABSTRACT

The present work uses observations and theoretical considerations to provide both qualitative and quantitative arguments that hydromagnetic waves, whether turbulent or not, cannot produce the acceleration of the fast solar wind and the related heating of the open solar corona. Waves do exist, and can play a role in the differential heating and acceleration of minor ions, but their amplitudes are not sufficient to power the wind, as demonstrated by extrapolation of magnetic spectra from Helios and *Ulysses* observations. Dissipation mechanisms invoked to circumvent this conclusion cannot be effective for a variety of reasons. In particular, turbulence does not play a strong role in the corona as shown both by observations of coronal striations and other features, and by theoretical considerations of line tying to a nonturbulent photosphere, nonlocality of interactions, and the nature of the kinetic dissipation. We consider possible "ways out" of the arguments presented, and suggest that in the absence of wave or turbulent heating and acceleration, the chromosphere and transition region become the natural source, if yet unproven, of open coronal energization through the production of nonthermal particle distributions.

Key words: magnetic fields – solar wind – Sun: corona

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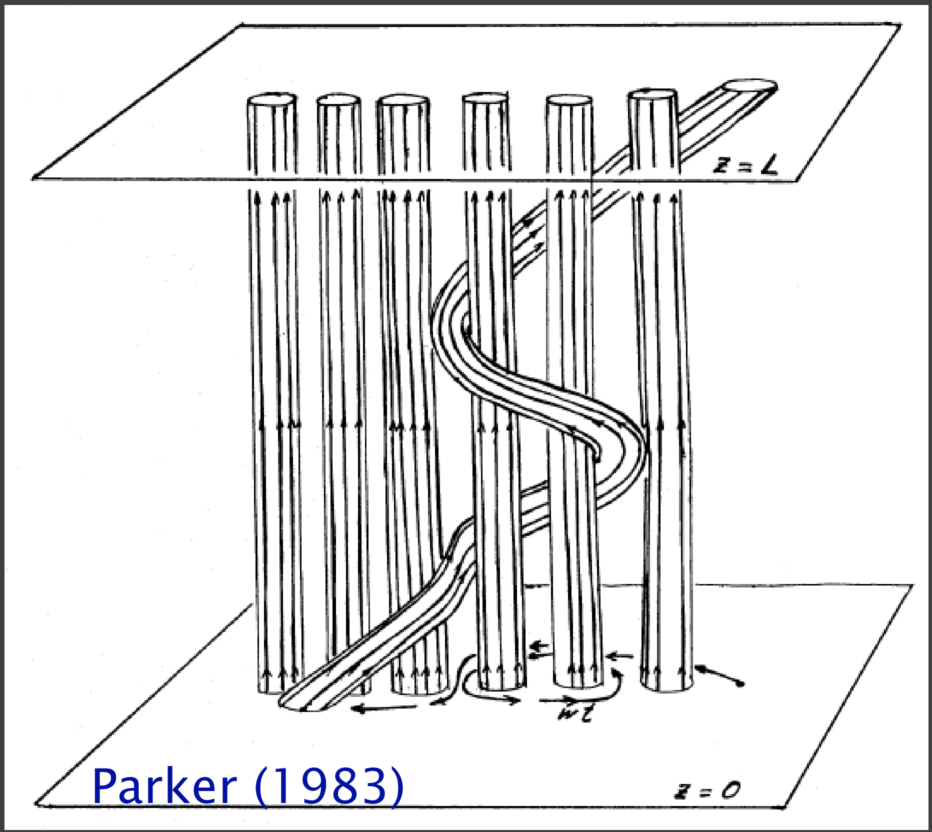
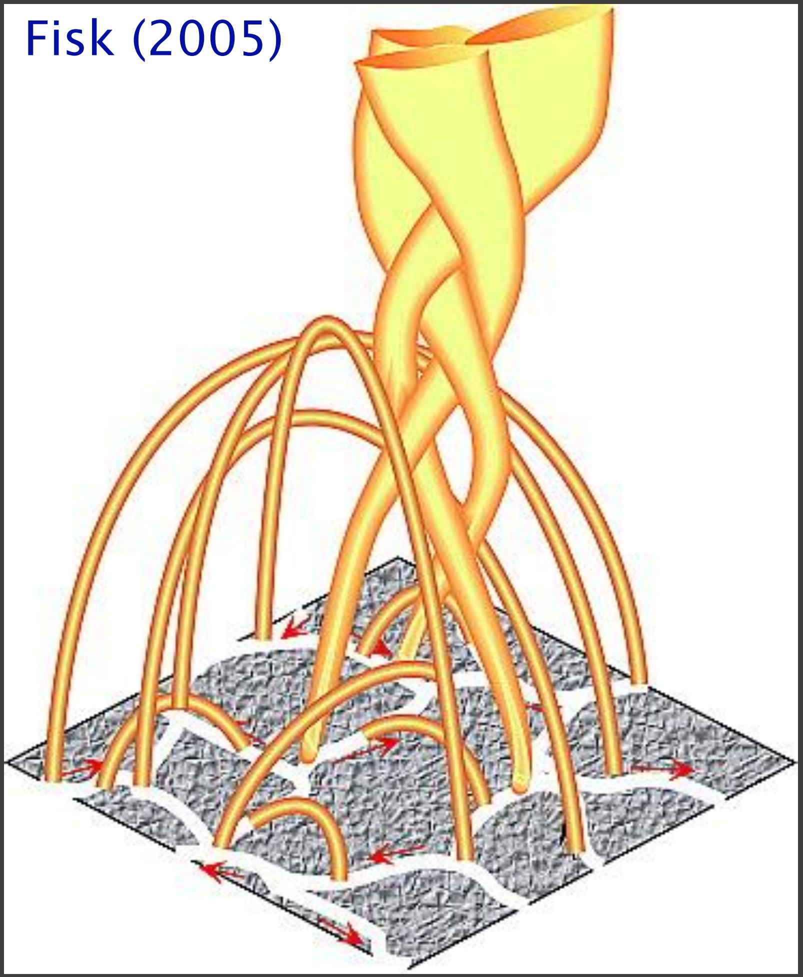
  - due to transverse structure of the magnetic field.
  - due to wave reflection along the field.

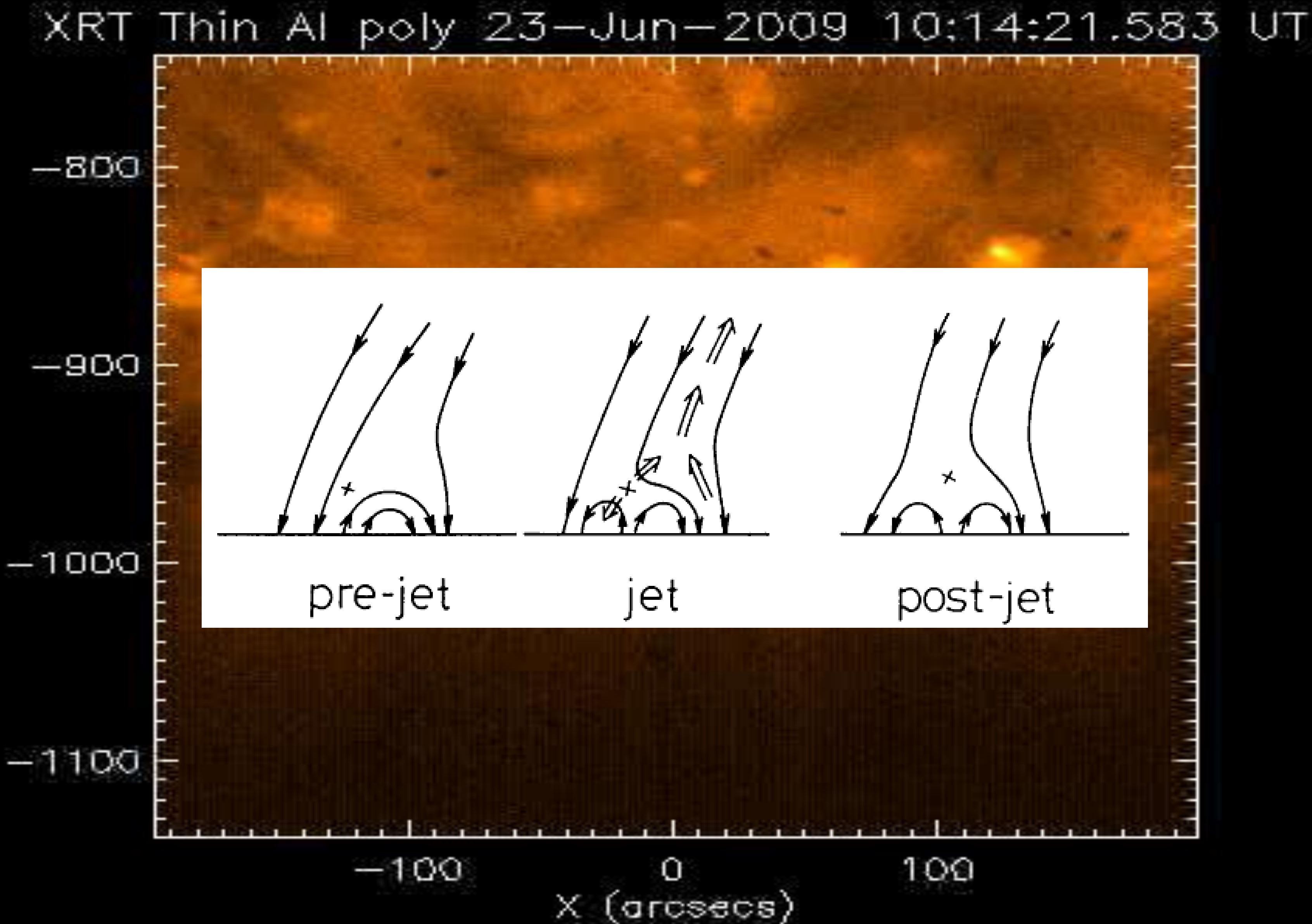
- Conclusions.

Convection tangles magnetic field





Reconnection Example: X-ray Jets



Problems with Reconnection?

- Heating looks constant, not epsiodic.
- Are there a large enough number of small reconnection events to provide effectively continuous energy input?

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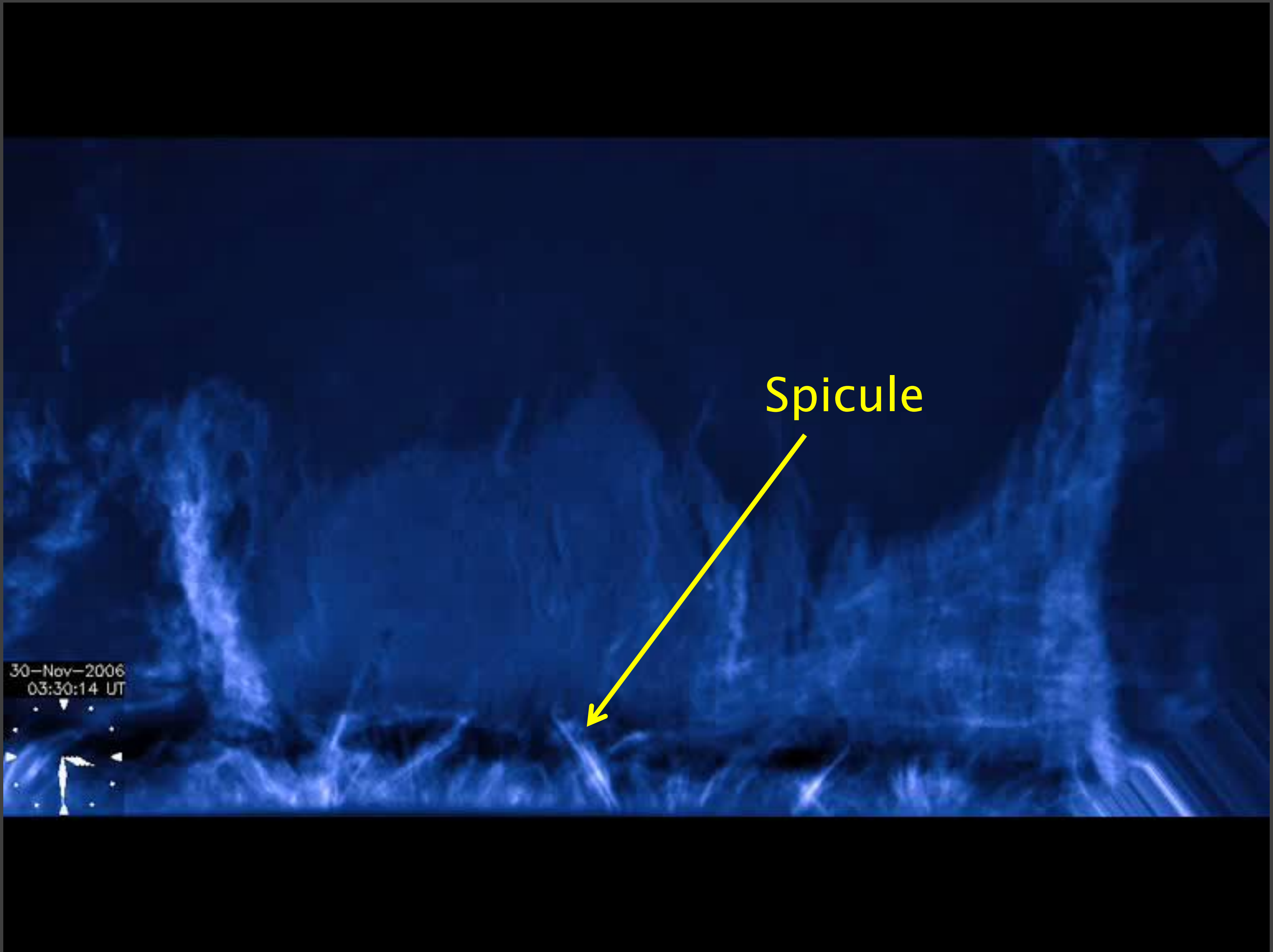
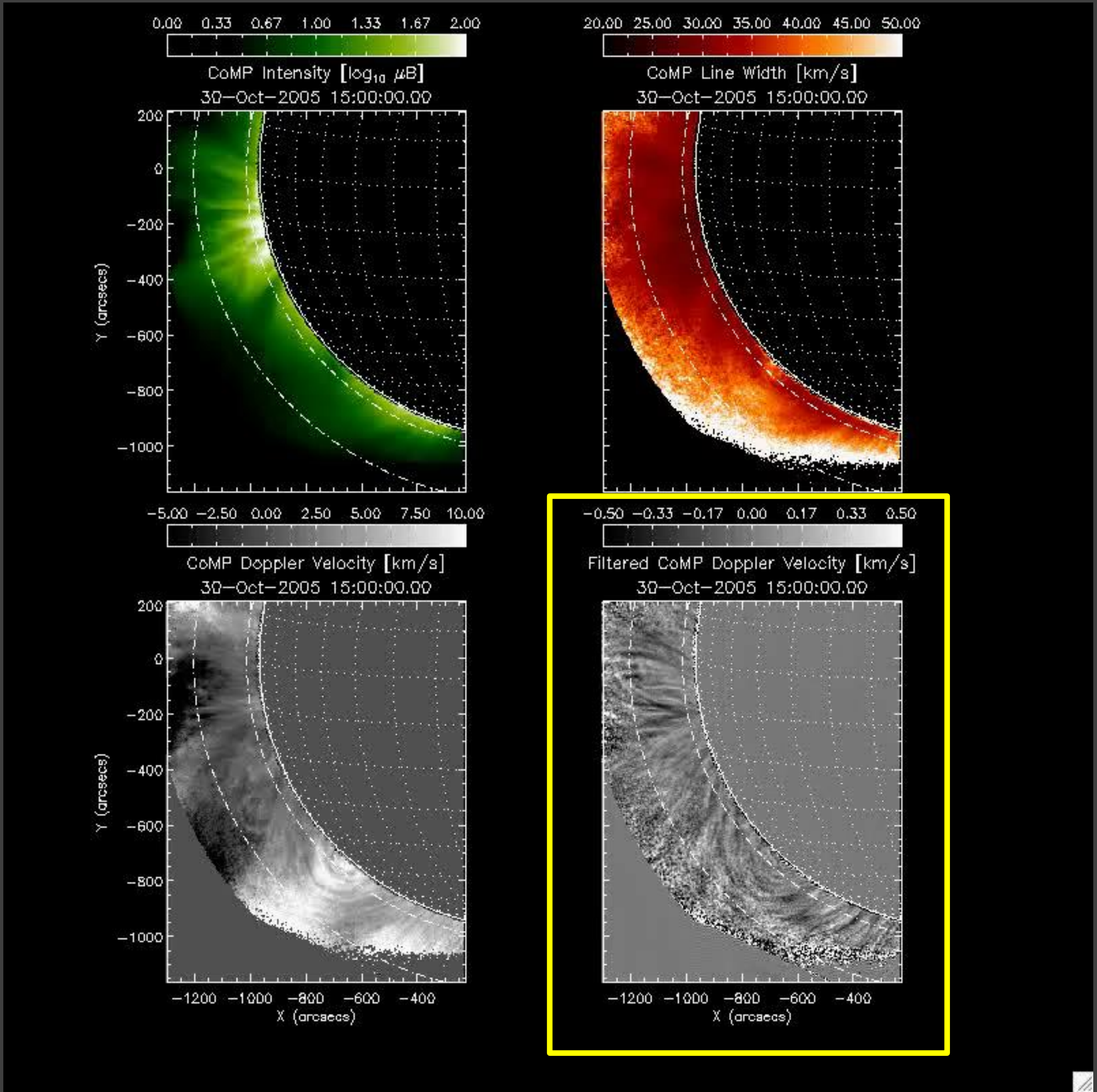
Alfvén Waves : Chromosphere

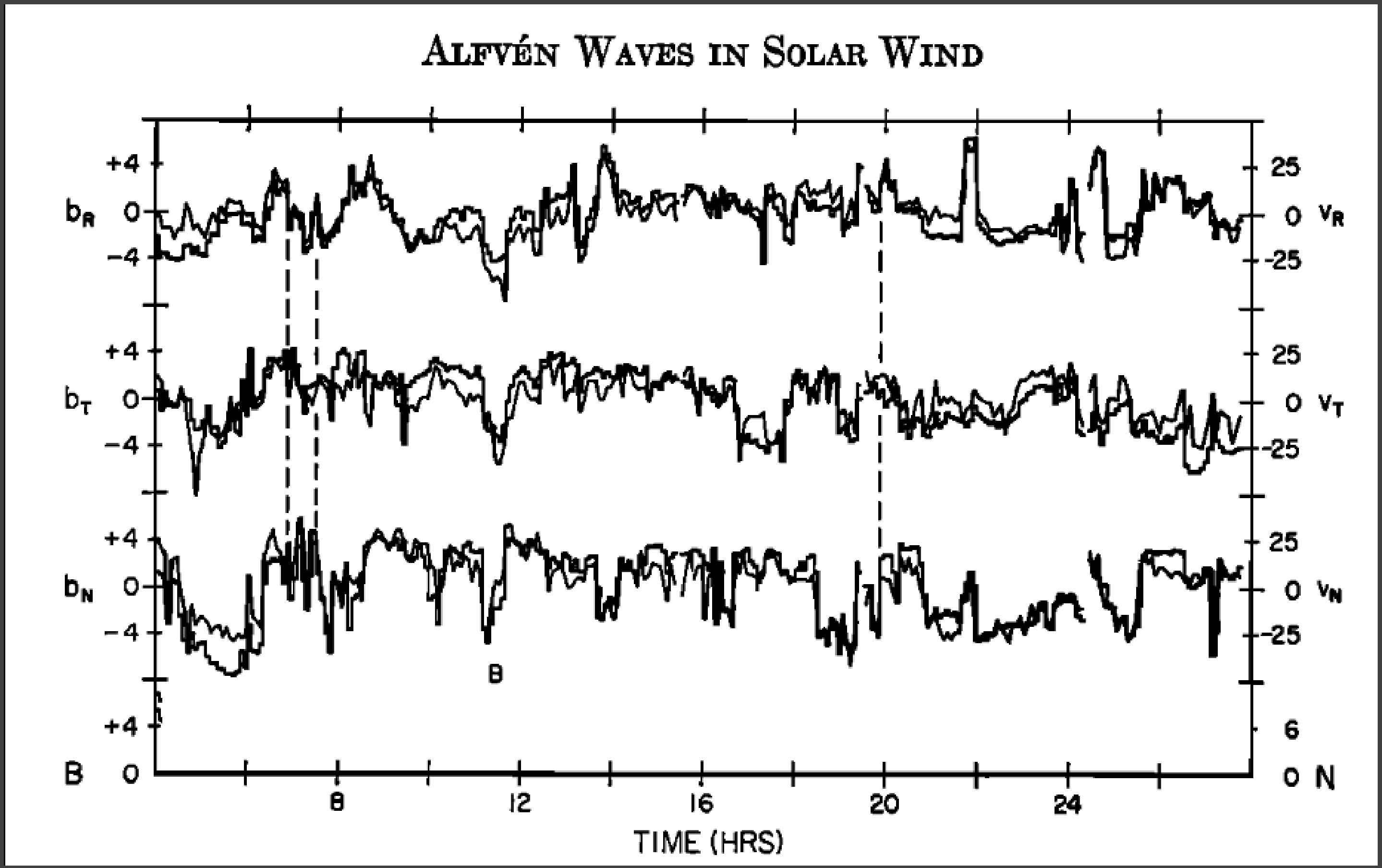


Alfvén Waves : Corona



Solar Alfvén Waves

$\vec{B}$



$\vec{V}$

Belcher & Davis (1971)

Alfvén waves from Mariner 5 at Venus.

Wave Heating

- Waves are found throughout the corona and solar wind.
- If the waves are damped then they can heat the plasma.
- Collisions (viscosity, resistivity) damp waves but require length scales of ~3 $R_\odot$
- Above ~2 $R_\odot$ low density and supersonic solar wind make heat conduction inefficient.

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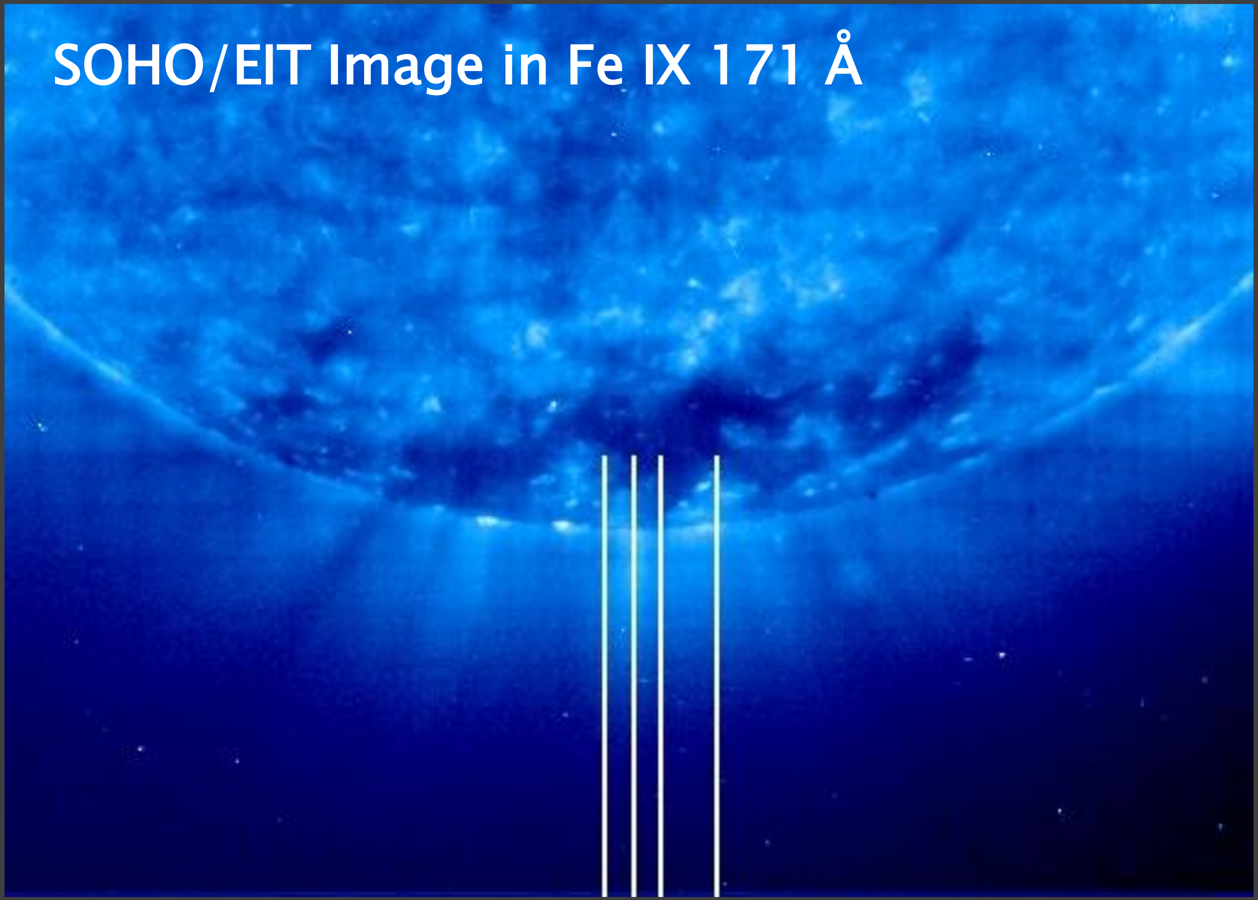
Extreme Ultraviolet Imaging Spectrometer (EIS)

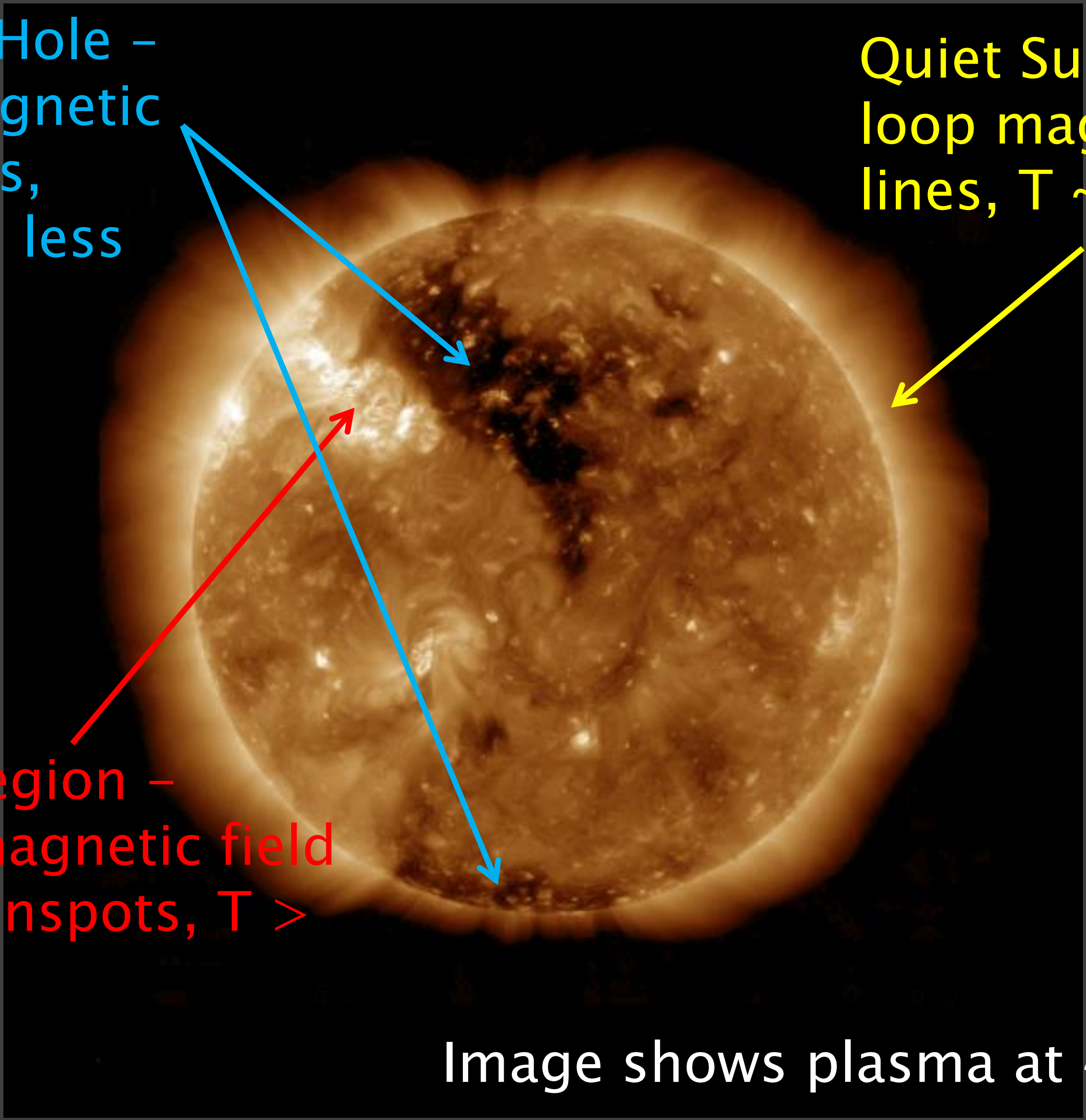
- Hinode launched 2006
- 171–211 Å & 245–291 Å
- 0.022 Å/pixel
- 1" and 2" slits

Observation

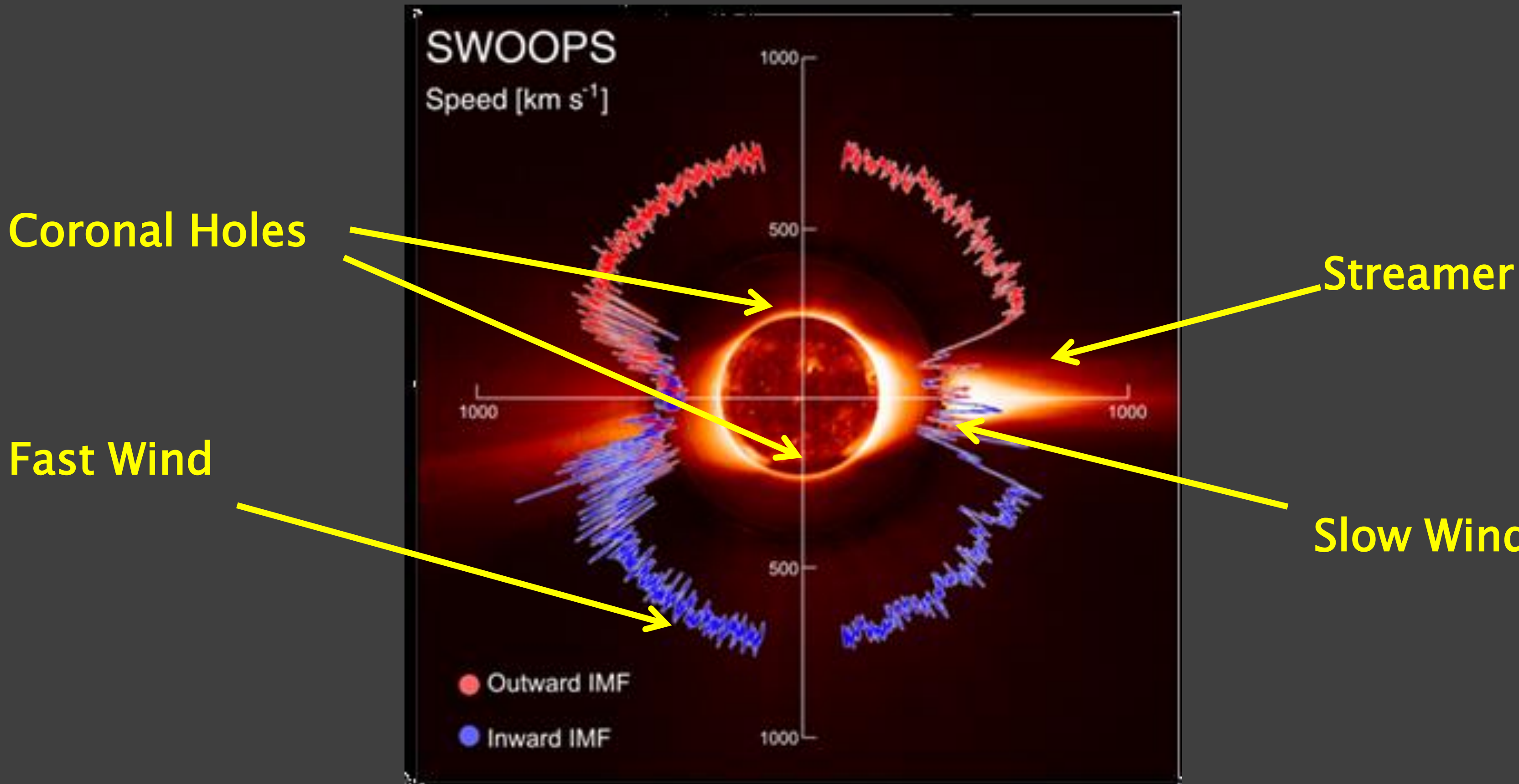


- Polar coronal hole from April 2009

The Solar Corona



Fast solar wind comes from coronal holes

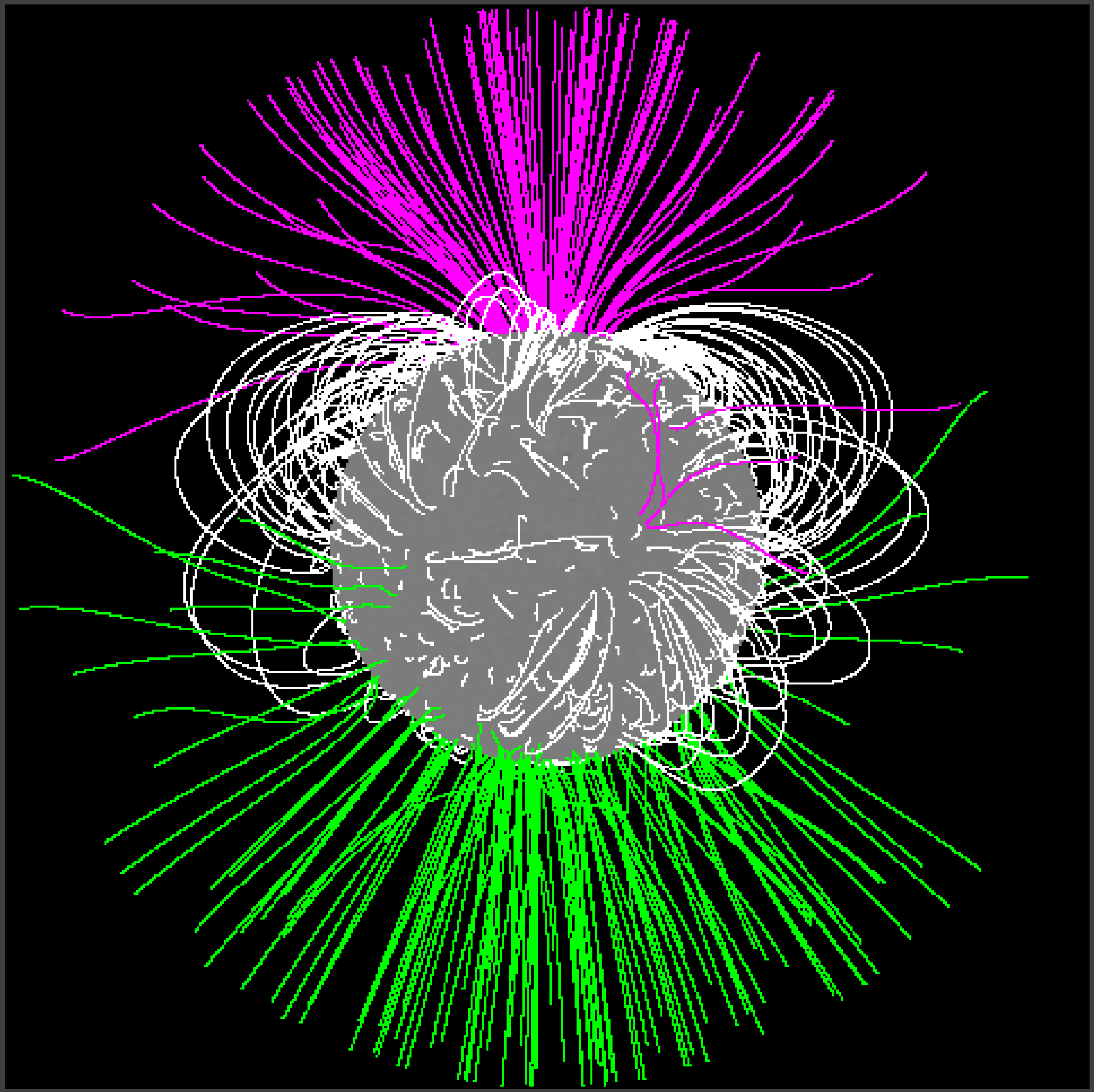


McComas et al. (2008)

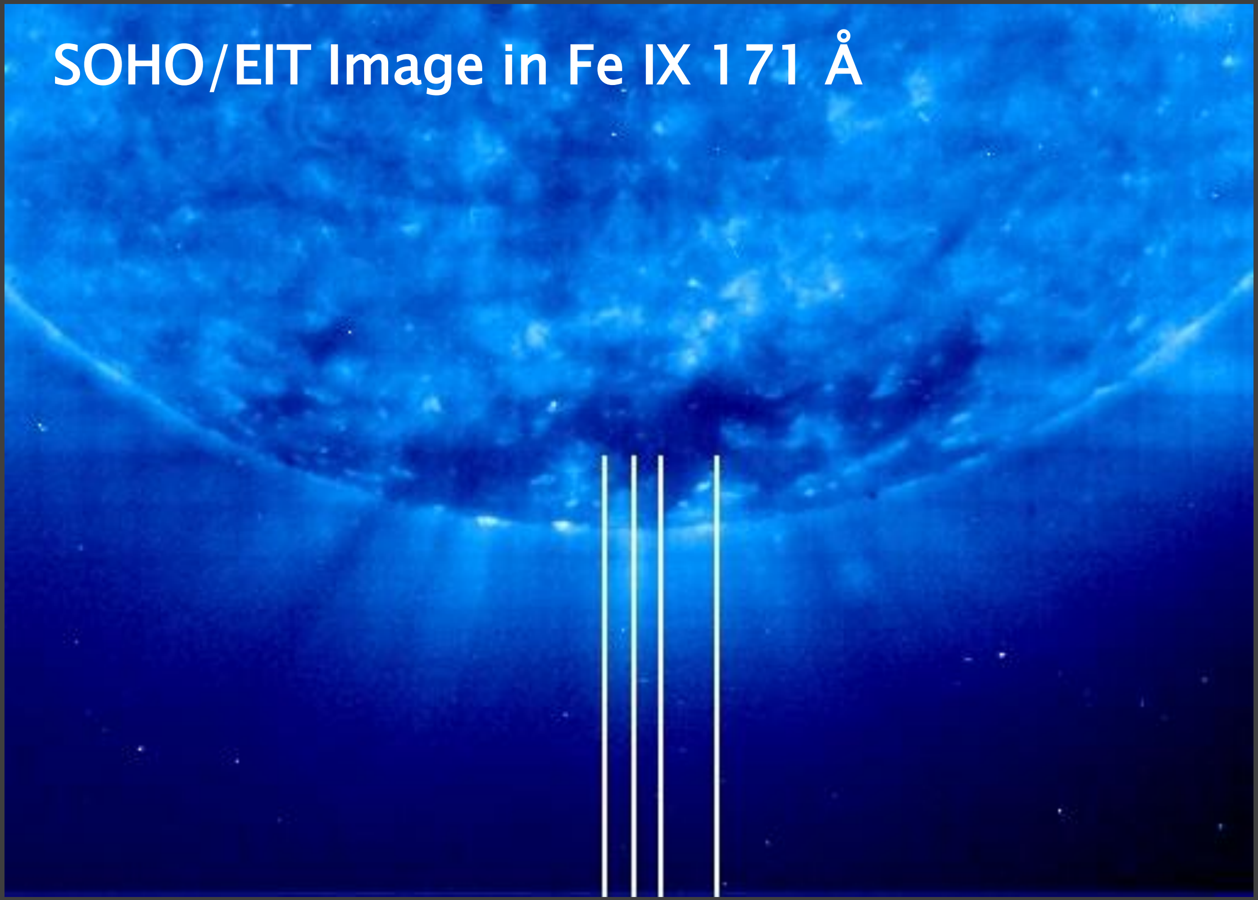
Ulysses – polar orbit of the Sun at ~1 AU.

SWOOPS = Solar Wind Plasma Experiment

Solar Magnetic Fields

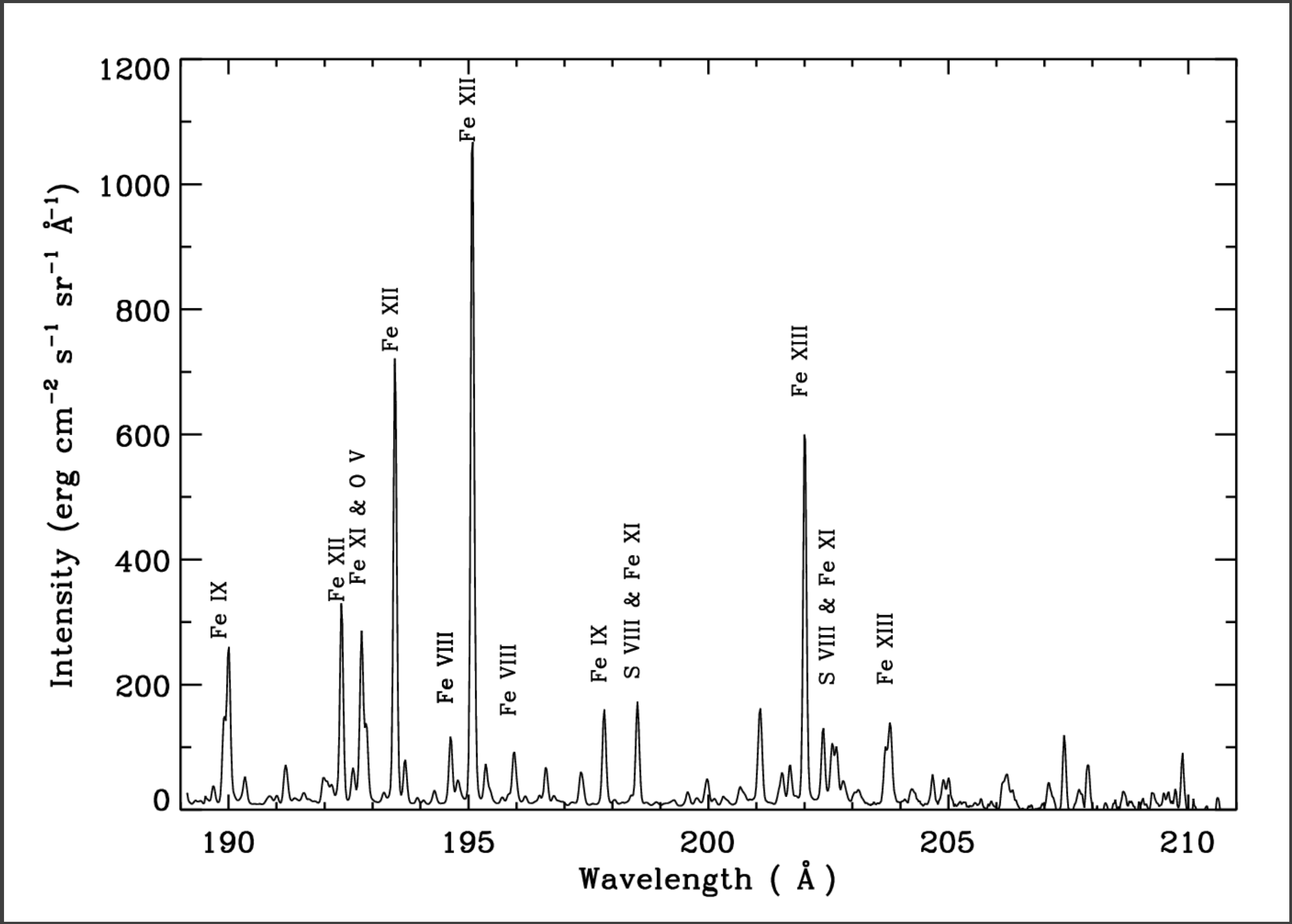


Observation



- Polar coronal hole from April 2009
- Sum of 4 observations of 30 min. each
- Observed up to 1.44 $R_{\odot}$

Observation



Portion of a typical EIS spectrum.

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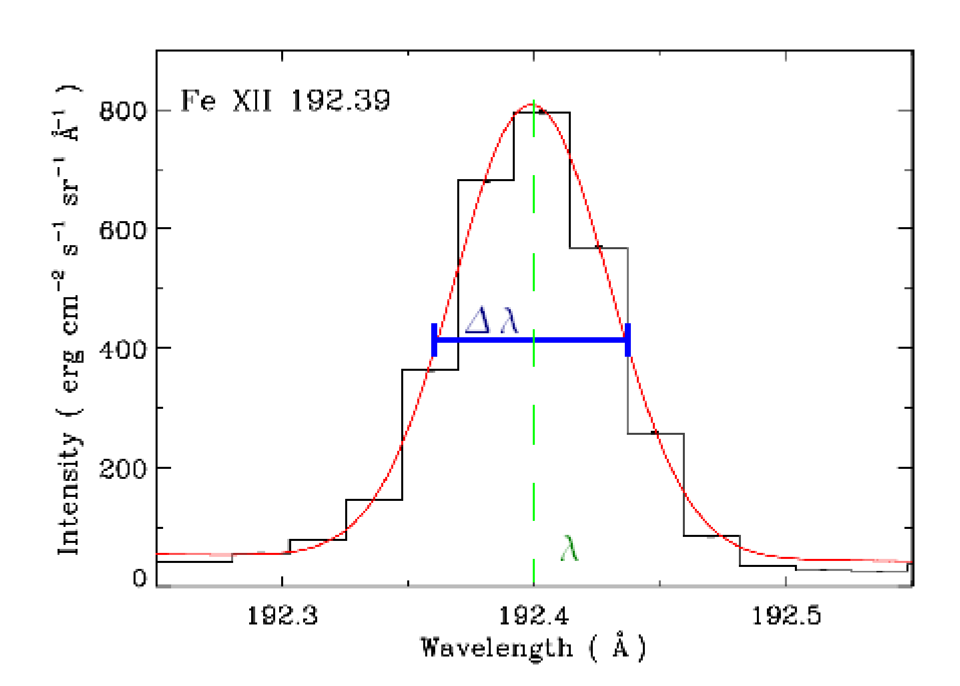
Spectroscopic Signature of Waves



$$\Delta\lambda = \sqrt{\left(\frac{\lambda}{c}\right)^2\left(\frac{2k_B T_i}{M} + v_{nt}^2\right)}$$

M – Ion Mass

v_{nt} – Nonthermal velocity

T_i – Ion temperature

Subtract instrumental width

Wave amplitude δv from $\langle \delta v^2 \rangle = 2\, v_{nt}^2$.

T_i affected by ion cyclotron resonance heating.

Energy Conservation

Wave energy flux is $$F = 2\rho v_{nt}^2 V_A$$ $$V_A = \frac{B}{\sqrt{4\pi\rho}}$$

If undamped then *FA* is constant.

$$FA = \frac{1}{\sqrt{\pi}} \rho^{1/2} v_{nt}^2 BA$$

Flux tube $BA =$ constant, thus : $v_{nt} \sim \rho^{-1/4}$

If waves are undamped since ρ decreases with height v_{nt} must increase.

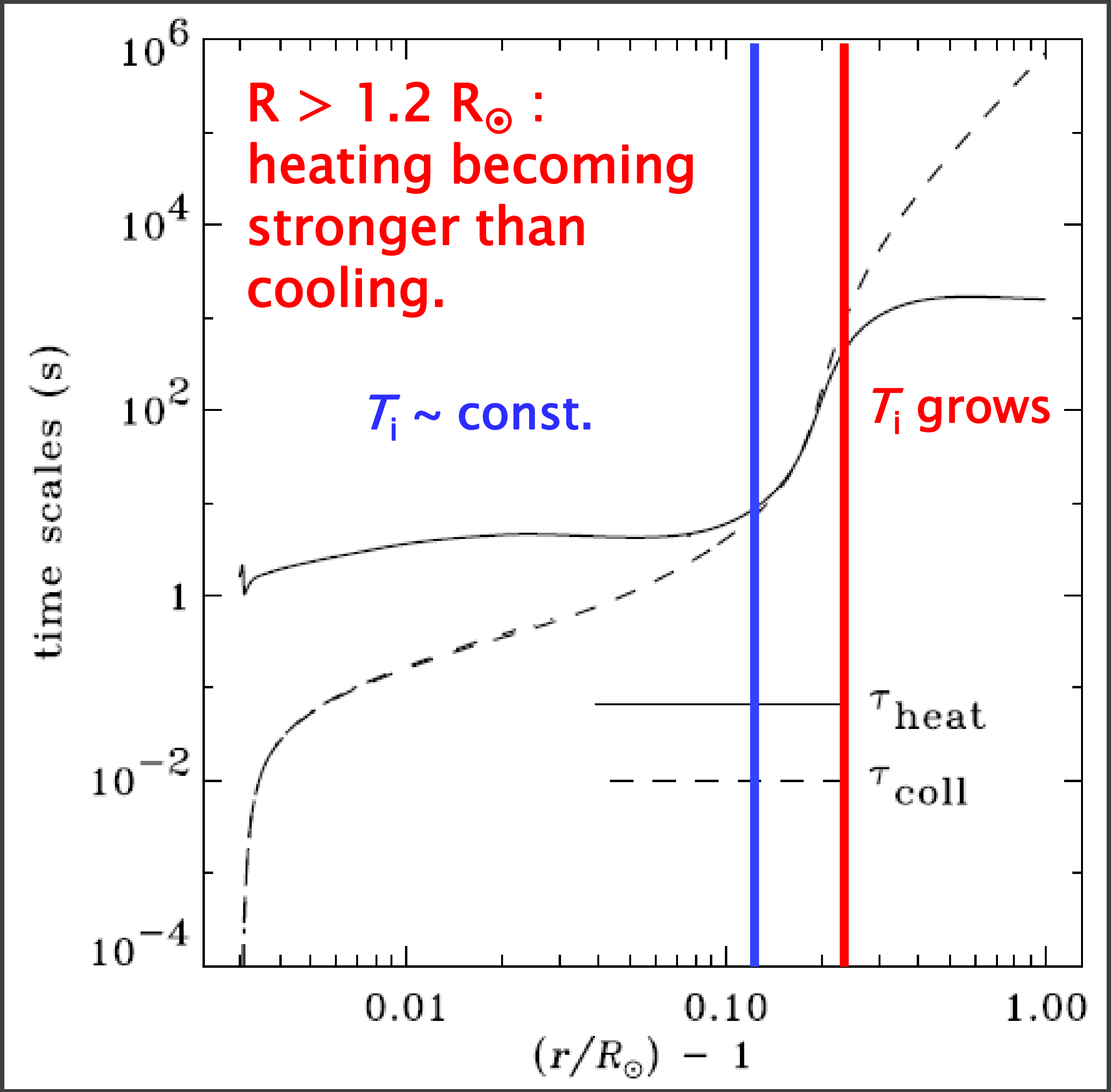
Separate Thermal and Nonthermal

$$v_{\text{eff}}^2 = \sqrt{\frac{2k_{\text{B}}T_{\text{i}}}{M} + v_{\text{nt}}^2} = \sqrt{v_{\text{th}}^2 + v_{\text{nt}}^2}$$

1. Assume T_{i} constant with height.

$$v_{\text{eff}}^2(R_1) - v_{\text{eff}}^2(R_2) = v_{\text{nt}}^2(R_1) - v_{\text{nt}}^2(R_2)$$

Collision vs. Heating times



Landi & Cranmer (2009)

Separate Thermal and Nonthermal

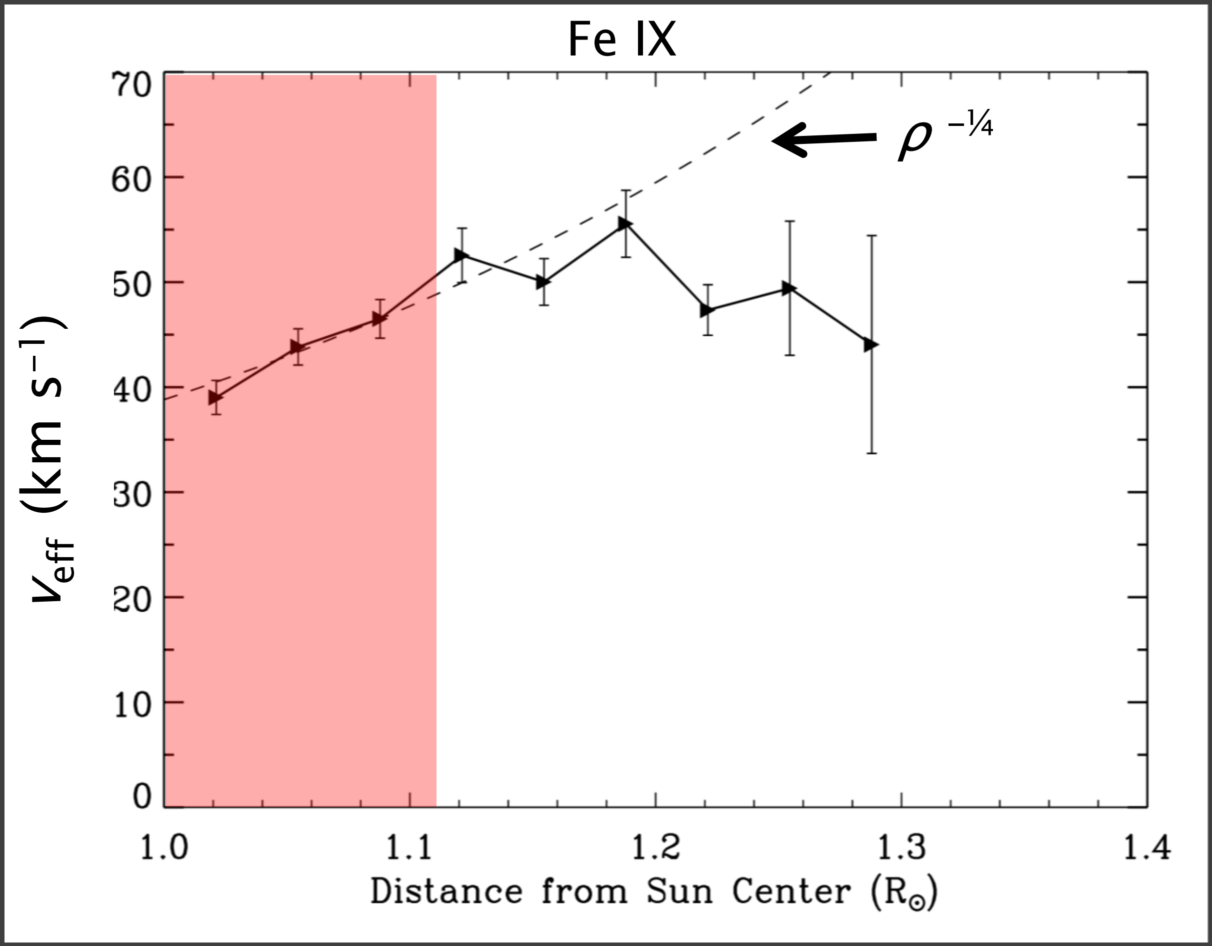
$$v_{\mathrm{eff}}^{2} = \sqrt{\frac{2k_{\mathrm{B}}T_{\mathrm{i}}}{M} + v_{\mathrm{nt}}^{2}} = \sqrt{v_{\mathrm{th}}^{2} + v_{\mathrm{nt}}^{2}}$$

1. Assume T_{i} constant with height.

$$v_{\mathrm{eff}}^{2}(R_1) - v_{\mathrm{eff}}^{2}(R_2) = v_{\mathrm{nt}}^{2}(R_1) - v_{\mathrm{nt}}^{2}(R_2)$$

2. Assume waves undamped at low heights.

Waves undamped at lowest heights



Undamped R < 1.15 $R_\odot$ found by Banerjee et al. (1998, 2009), Dolla & Solomon (2008), Doyle et al. (1998)...

Separate Thermal and Nonthermal

$$v_{\mathrm{eff}}^2 = \sqrt{\frac{2k_{\mathrm{B}}T_{\mathrm{i}}}{M} + v_{\mathrm{nt}}^2} = \sqrt{v_{\mathrm{th}}^2 + v_{\mathrm{nt}}^2}$$

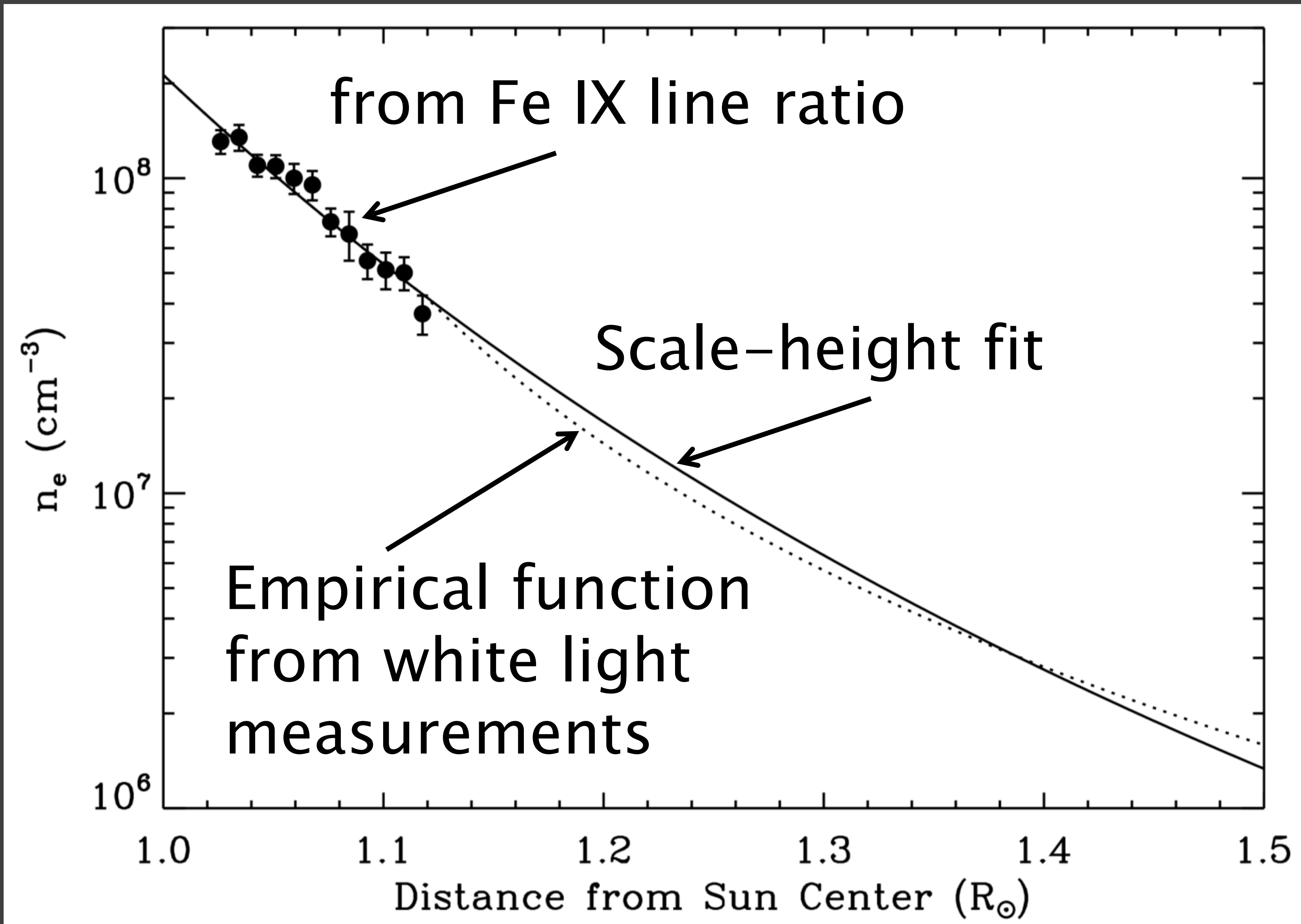
1. Assume T_{i} constant with height.

$$v_{\mathrm{eff}}^2(R_1) - v_{\mathrm{eff}}^2(R_2) = v_{\mathrm{nt}}^2(R_1) - v_{\mathrm{nt}}^2(R_2)$$

2. Assume waves undamped at low heights.

$$\frac{v_{\mathrm{nt}}(R_1)}{v_{\mathrm{nt}}(R_0)} = \left[\frac{n_{\mathrm{e}}(R_1)}{n_{\mathrm{e}}(R_0)}\right]^{-1/4}$$

Measured Density



Separate Thermal and Nonthermal

$$v_{\text{eff}}^2 = \sqrt{\frac{2k_B T_i}{M} + v_{\text{nt}}^2} = \sqrt{v_{\text{th}}^2 + v_{\text{nt}}^2}$$

1. Assume T_i constant with height.

$$v_{\text{eff}}^2(R_1) - v_{\text{eff}}^2(R_2) = v_{\text{nt}}^2(R_1) - v_{\text{nt}}^2(R_2)$$

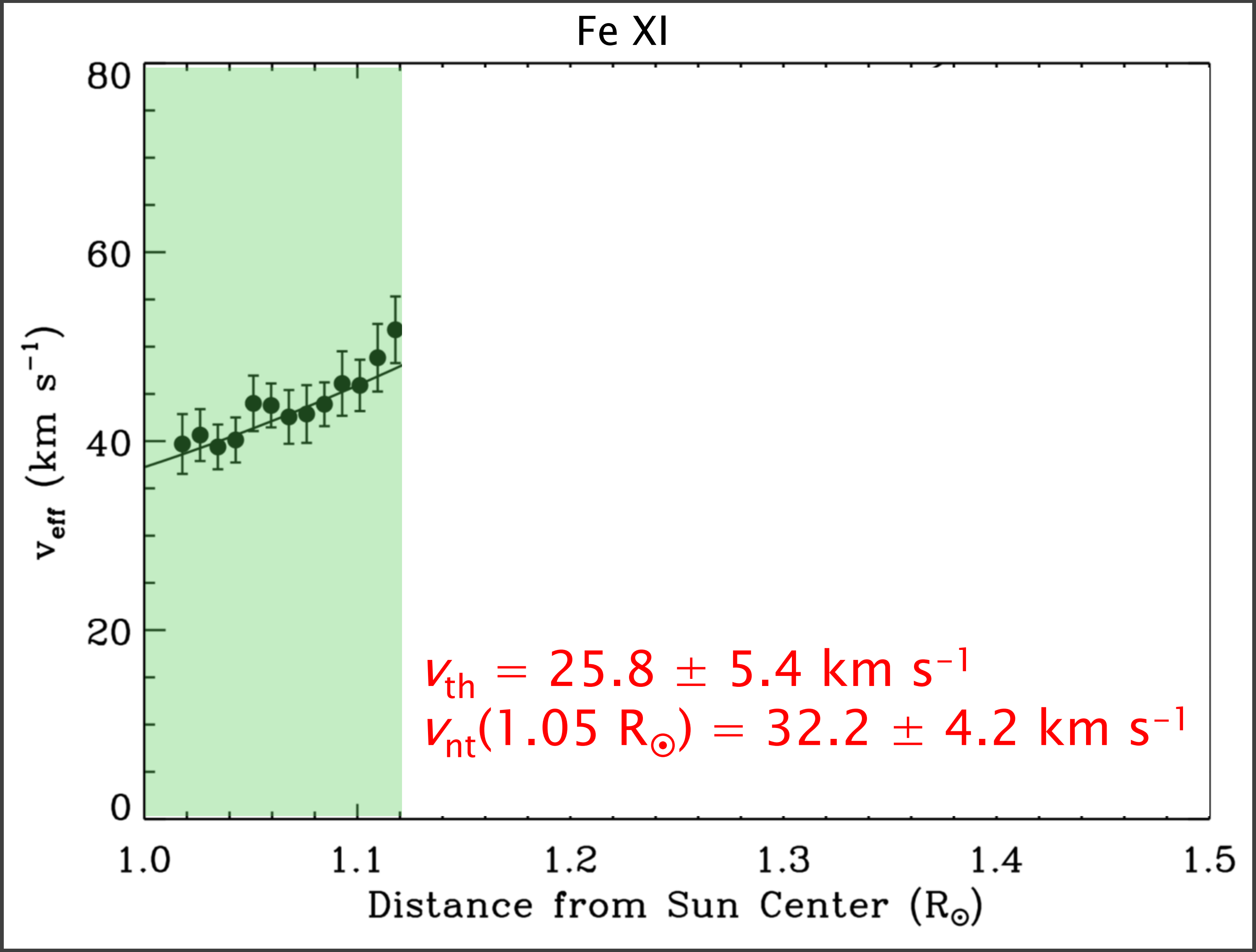
2. Assume waves undamped at low heights.

$$\frac{v_{\text{nt}}(R_1)}{v_{\text{nt}}(R_0)} = \left[\frac{n_e(R_1)}{n_e(R_0)}\right]^{-1/4}$$

3. Fit data with v_{th} and $v_{\text{nt}}(R_0)$ free parameters.

$$v_{\text{eff}}(R) = \sqrt{v_{\text{th}}^2 + v_{\text{nt}}^2(R_0)\left[\frac{n_e(R)}{n_e(R_0)}\right]^{-1/2}}$$

Example Fit



Fe XI
80
60
40
20
0
v_{eff} (km s^{-1})
1.0
1.1
1.2
1.3
1.4
1.5
Distance from Sun Center ($R_\odot$)
v_{th} = 25.8 ± 5.4 km s^{-1}
v_{nt}(1.05 $R_\odot$) = 32.2 ± 4.2 km s^{-1}

Extend to larger heights

The fit used up to 1.12 $R_\odot$.

To extend, assume T_i remains constant.

In reality, T_i increases at large heights.

In deriving v_{nt}, not subtracting enough v_{th}.

We may underestimate the actual damping.

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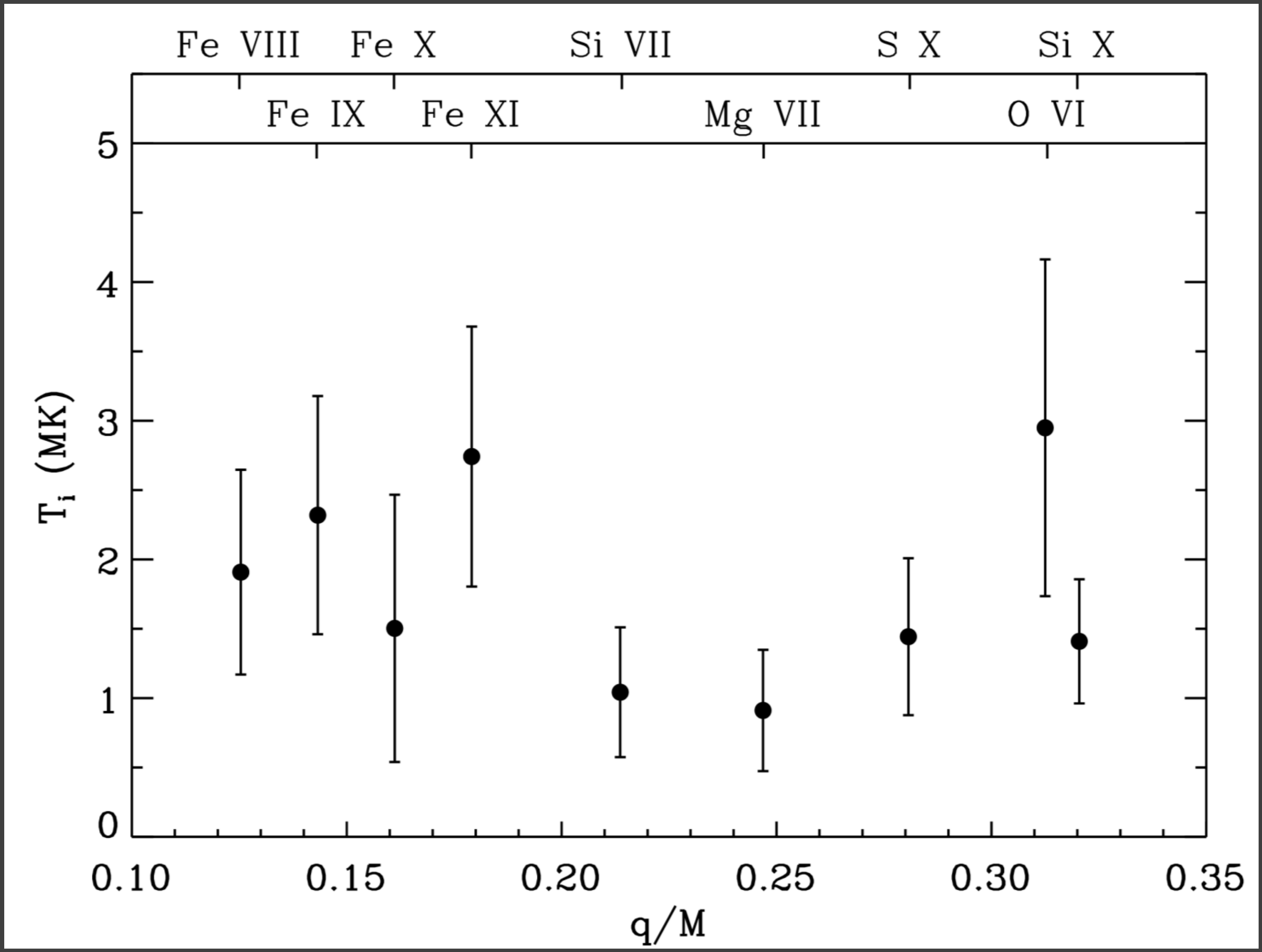
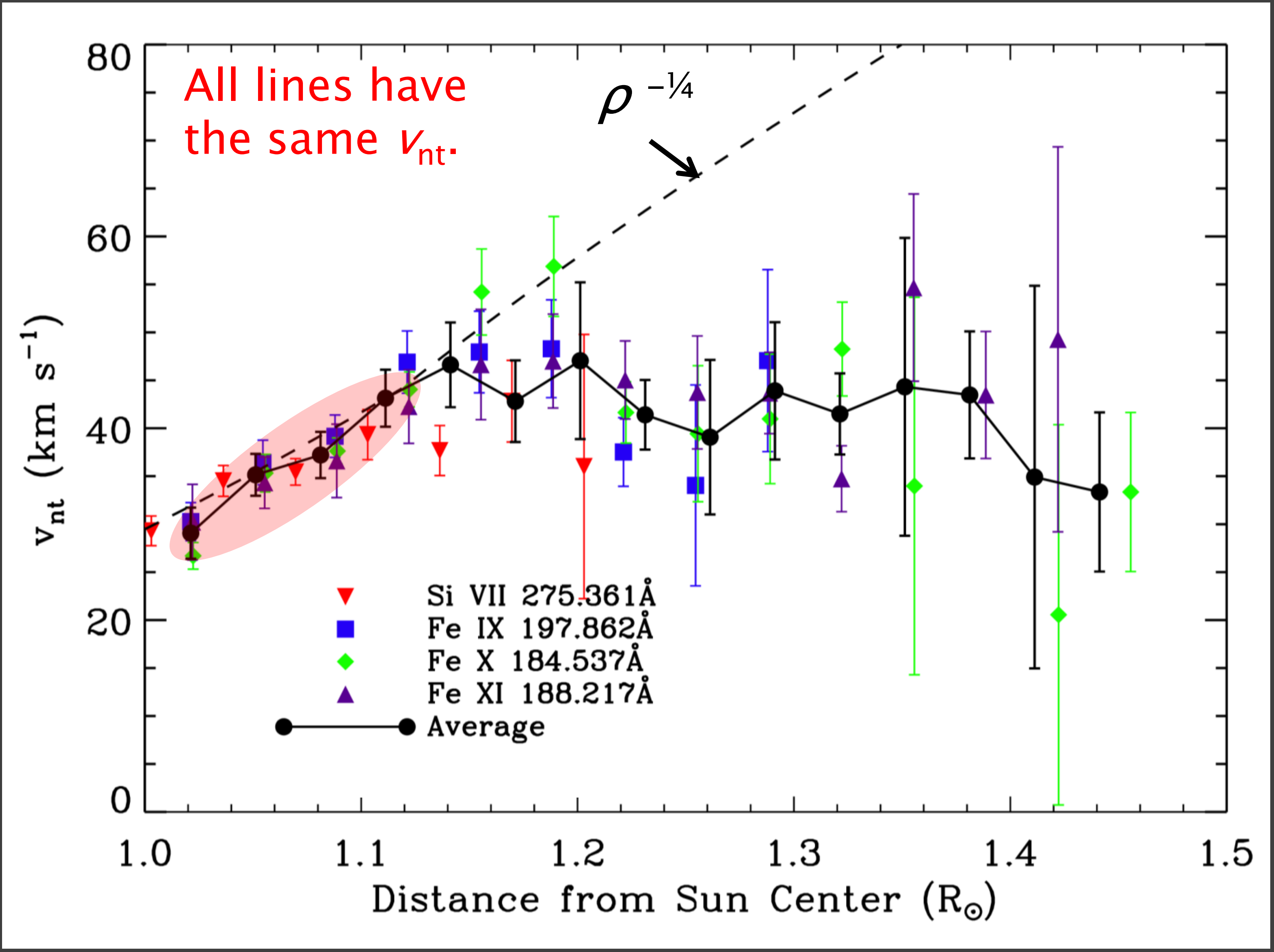
Ion Temperature



Damping begins about 1.15 $R_\odot$



Wave Energy Flux

$$F = 2\rho v_{nt}^2 V_A$$

$$V_A = \frac{B}{\sqrt{4\pi\rho}}$$

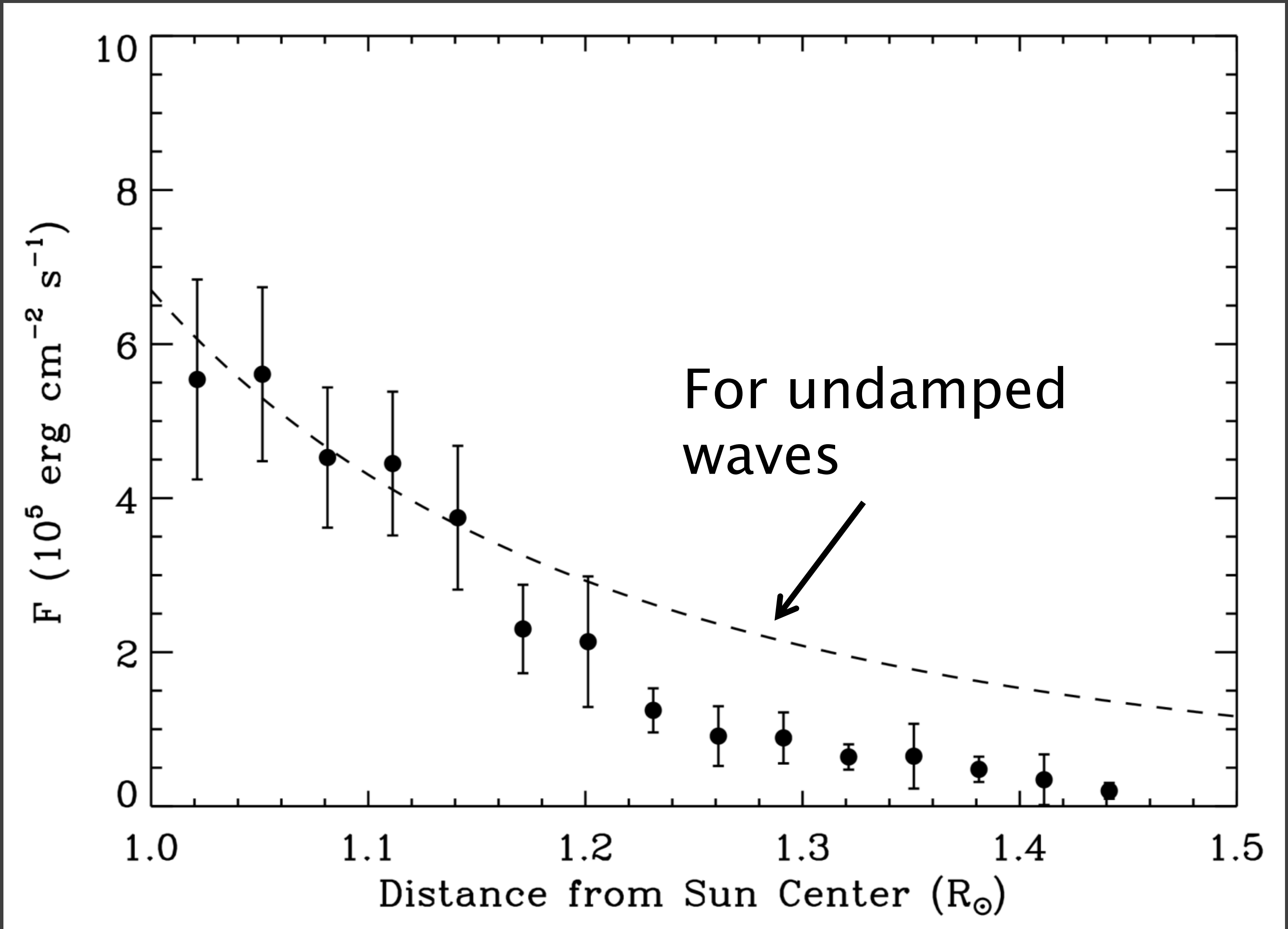
$$\rho \sim 1.15\, m_p n_e$$

For *B* use empirical model (Cranmer et al. 1999) .

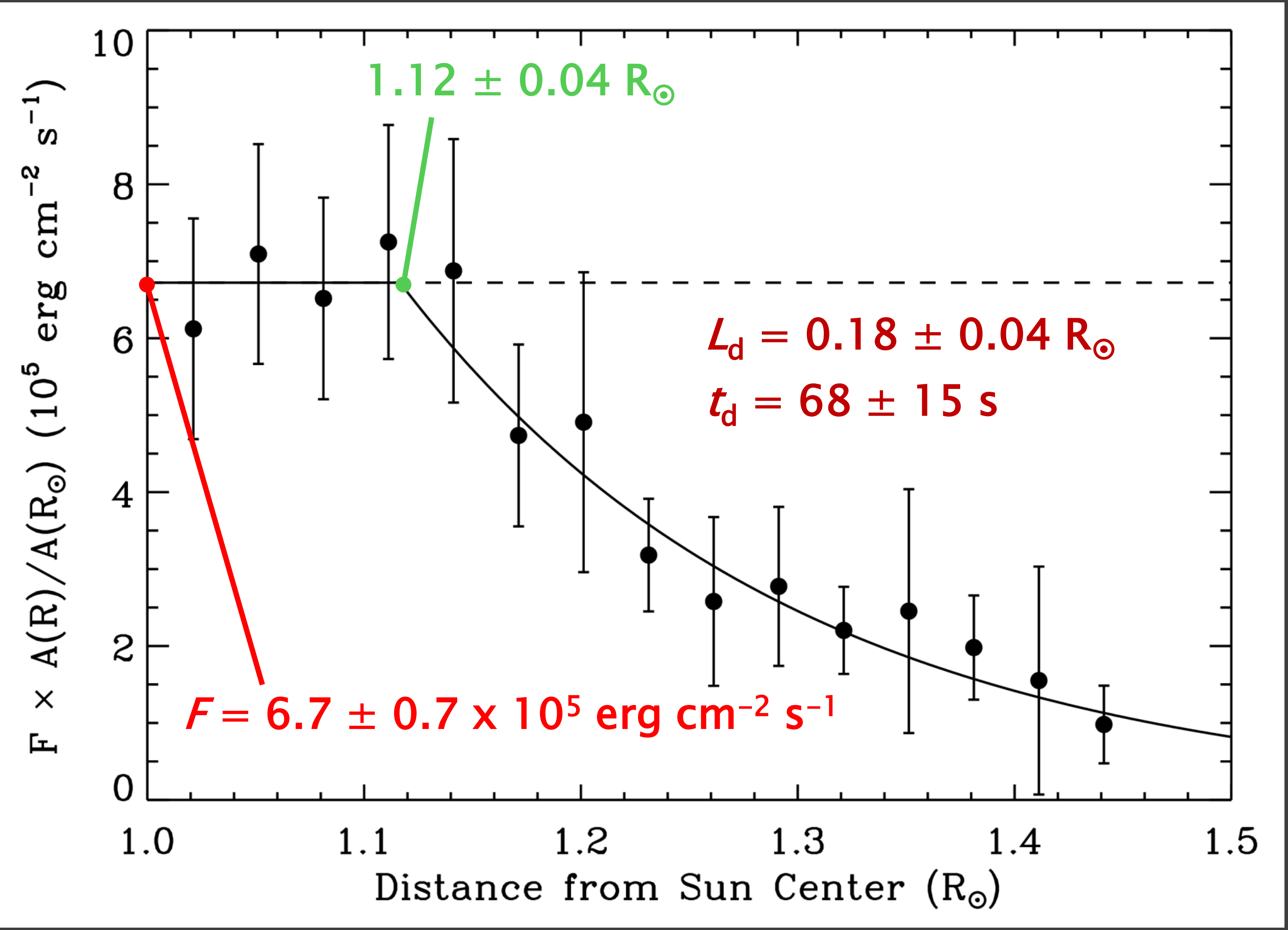
$$B(R)/B(R_\odot) = A(R_\odot)/A(R)$$

$$B(R_\odot) = 7.3 \pm 1 \text{ G} \quad \text{(Wang 2010)}$$

Wave Energy Flux *F*



F Corrected for Area Expansion



Energy Required

To heat coronal hole and accelerate solar wind $\sim 6 \times 10^5$ erg cm^{-2} s^{-1} required during this time.

Measured $6.7 \pm 0.7 \times 10^5$ erg cm^{-2} s^{-1}

Waves carry and dissipate enough energy at low enough heights to heat coronal holes and accelerate the fast solar wind.

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Damping Mechanisms

- The structure of the real solar magnetic field is not homogeneous – allows additional damping mechanisms:

- Gradients across the magnetic field:
  - E.g. Phase mixing

- Gradients along the field:
  - E.g. Wave reflection & turbulence

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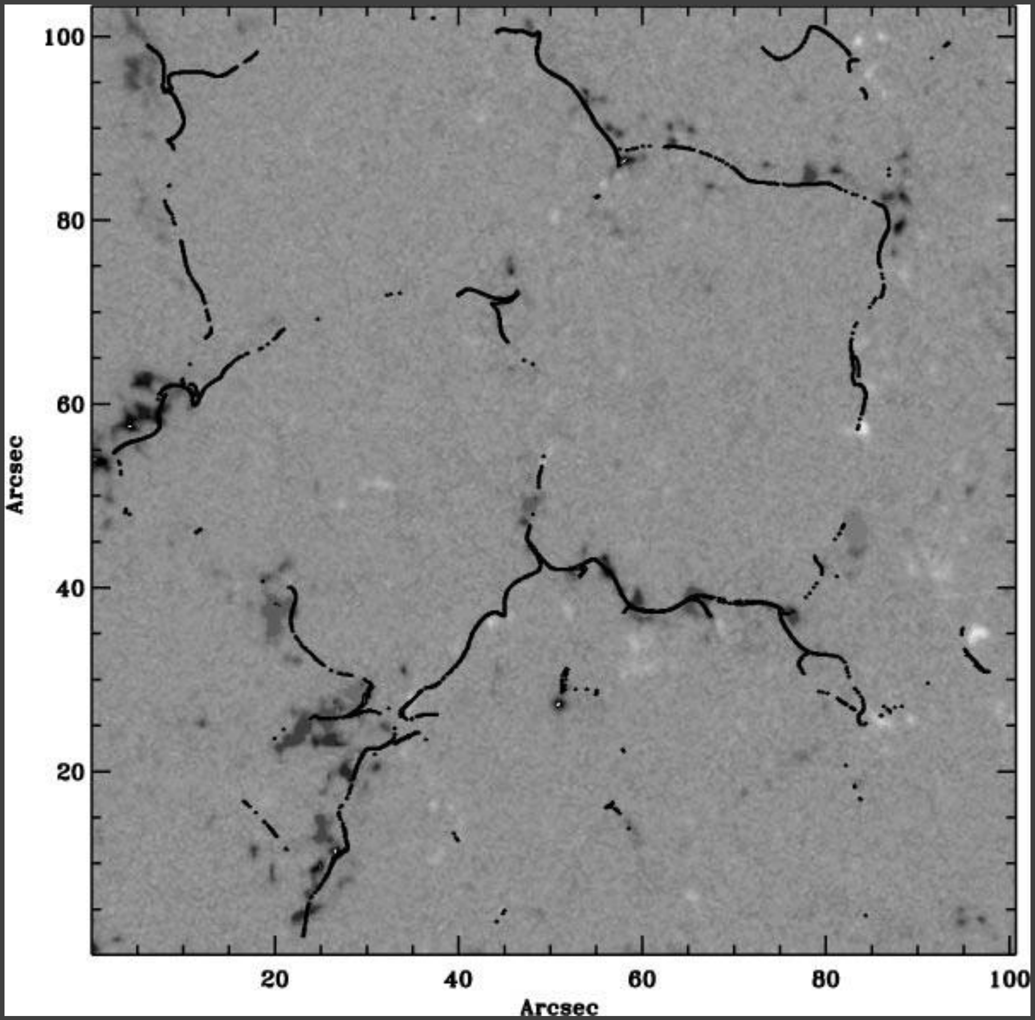
Structure of Surface Magnetic Field



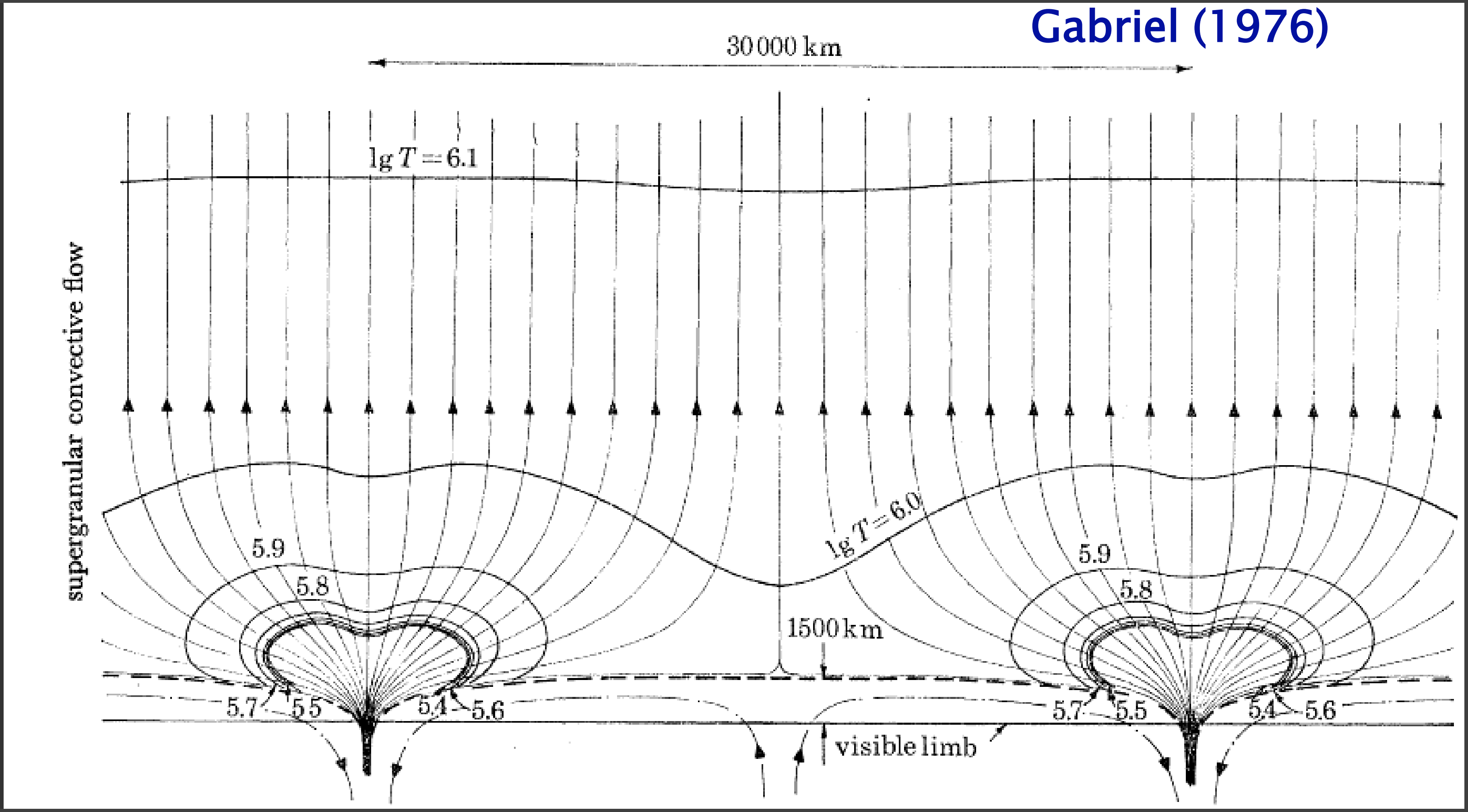
Roudier et al. (2009)

Greyscale is magnetic field, white = positive, black = negative, grey = neutral.

Black lines outline edges of convection cells (supergranules).

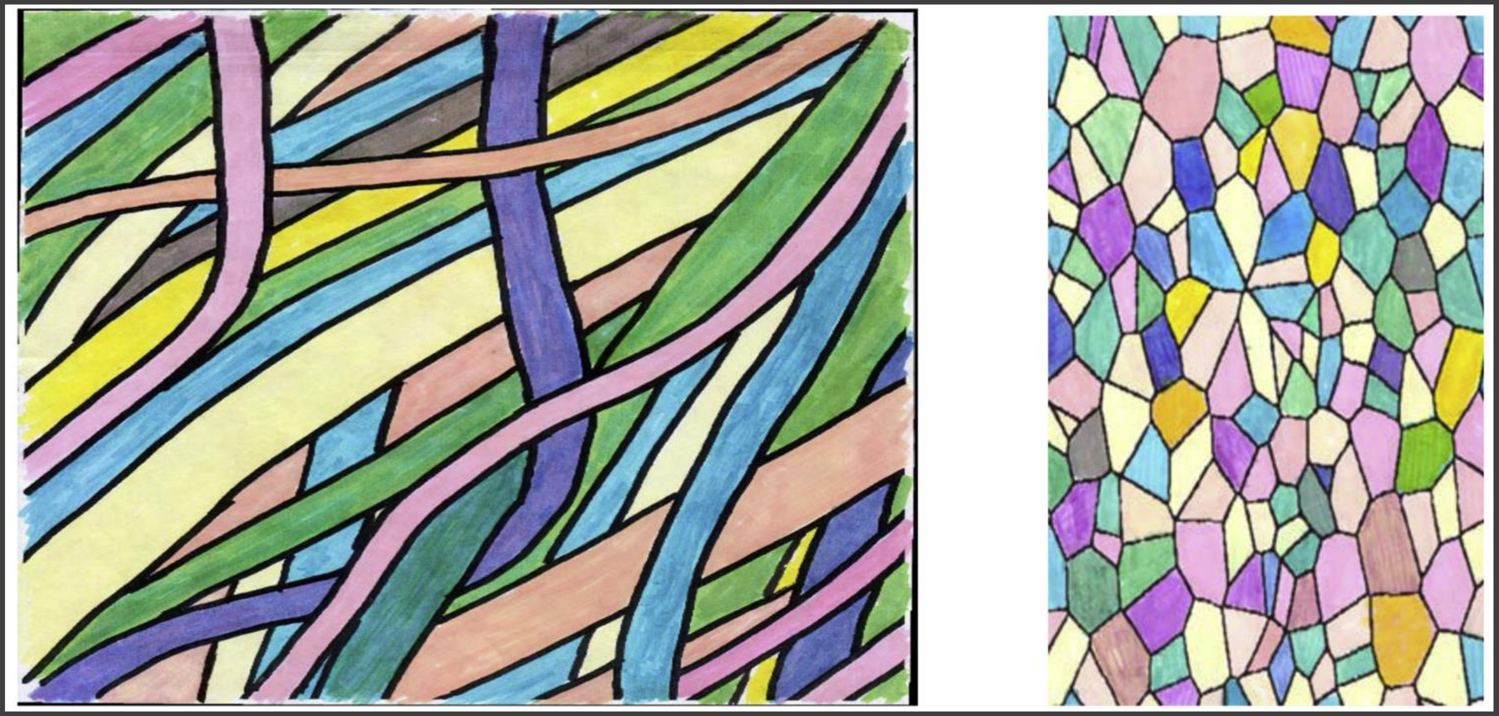
Magnetic network.

Structure of Solar Magnetic Field



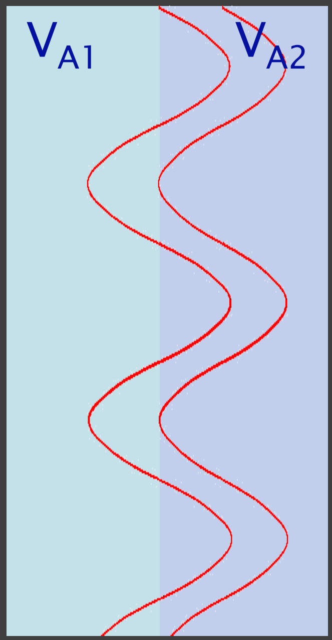
Structure of Solar Magnetic Field

Sketch of flux tubes at 1 AU

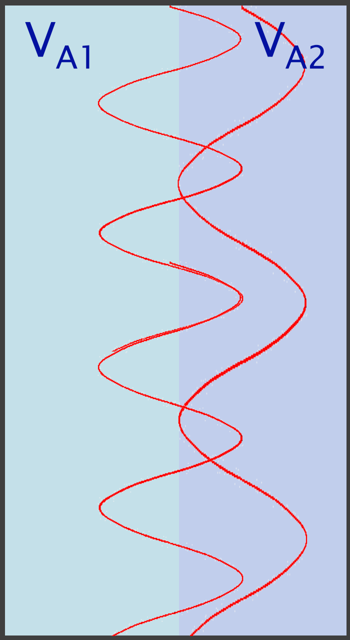


Borovsky (2008)

Phase Mixing



Footpoint oscillations generate waves at same frequency, initially in-phase.



Due to different V_A (phase velocity) waves become out of phase.

Increases viscous damping (friction)

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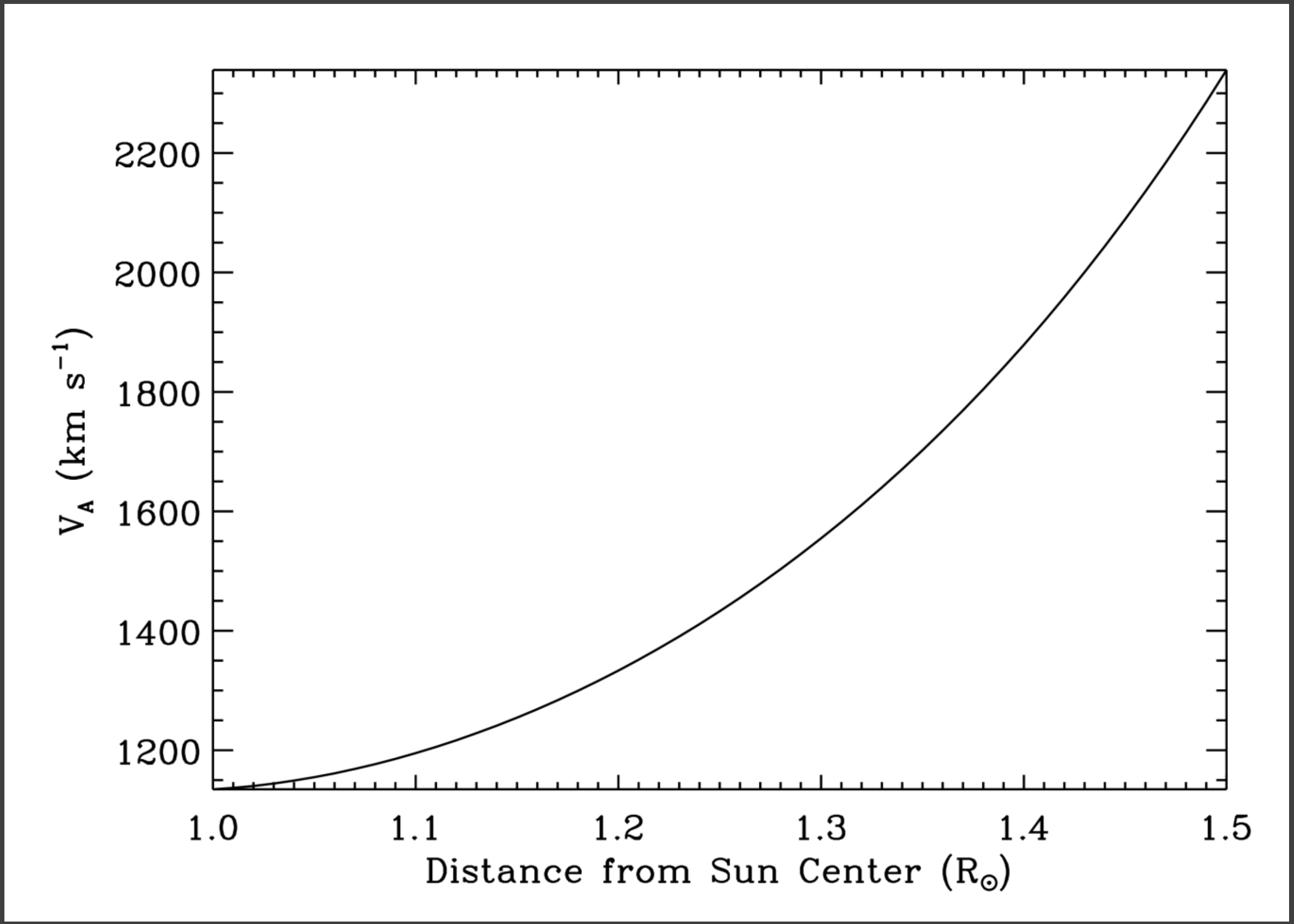
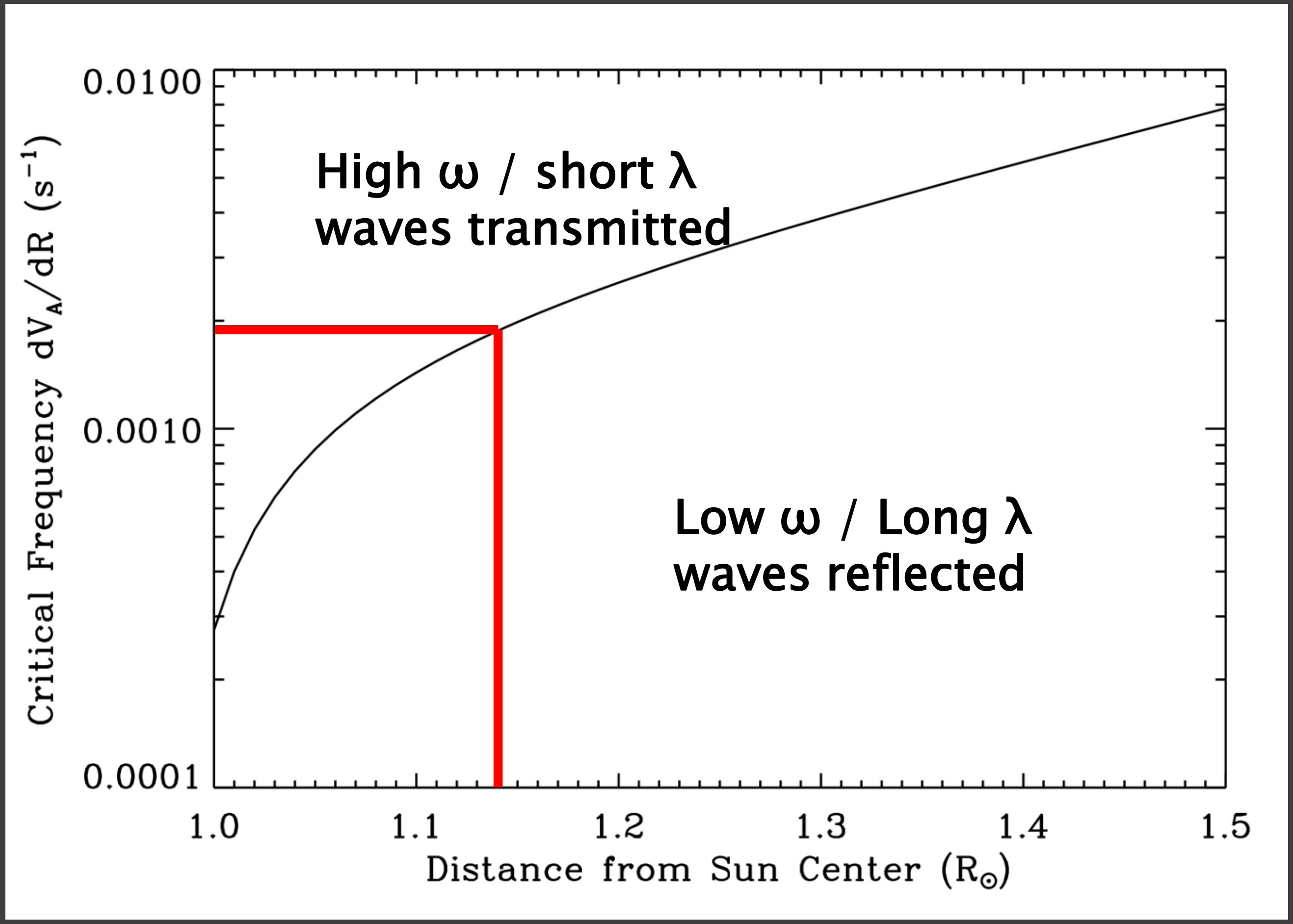
Wave Reflection and Turbulence



Strong wave reflection if V_A changes over scales shorter than the wavelength

Wave Reflection & Turbulence

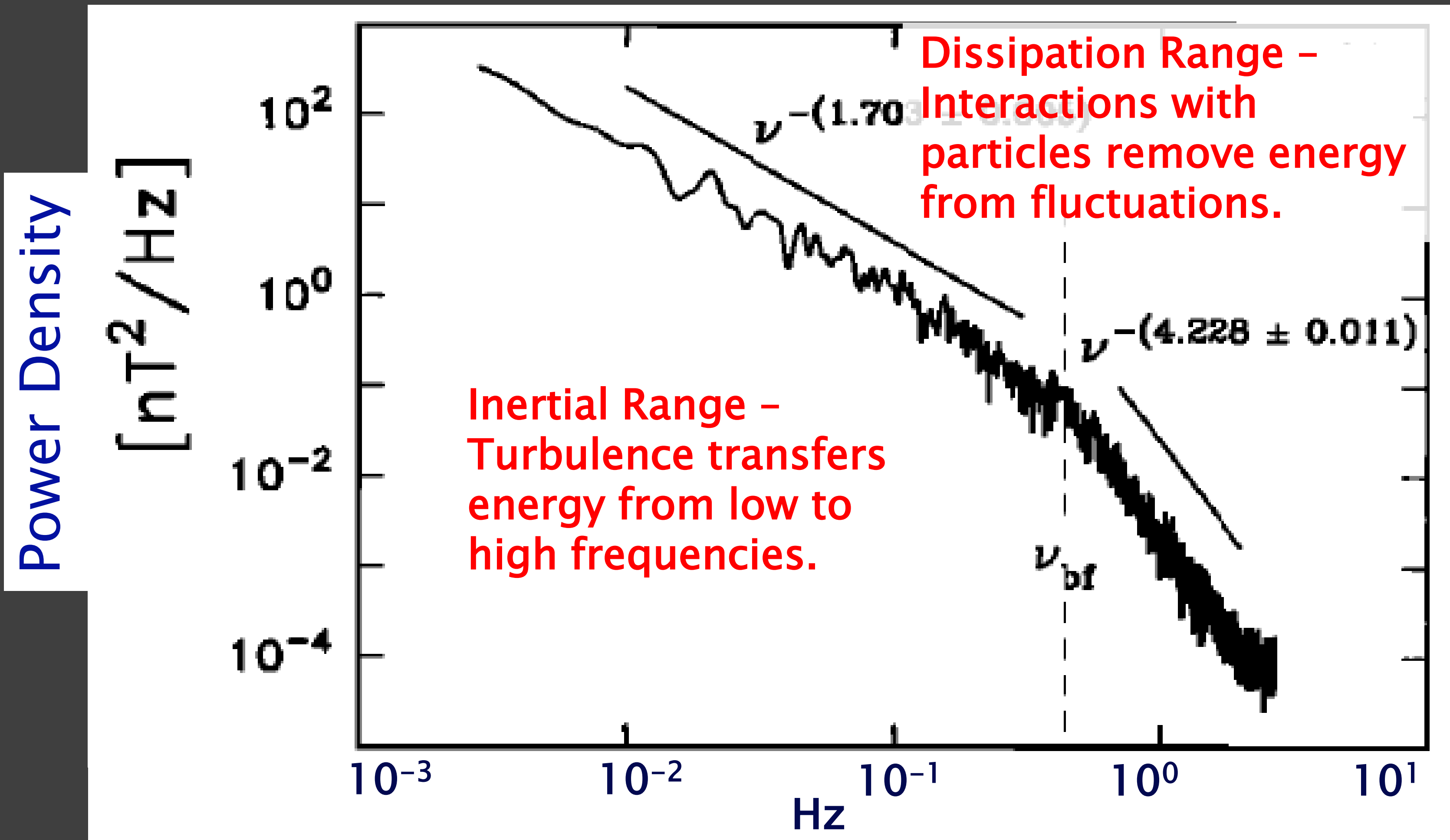


Waves reflected if $\omega < \omega_{critical} \sim dV_A/dr$

Photospheric source $\omega \sim 0.05\text{–}0.005 s^{-1}$

Turbulence in the Solar Wind

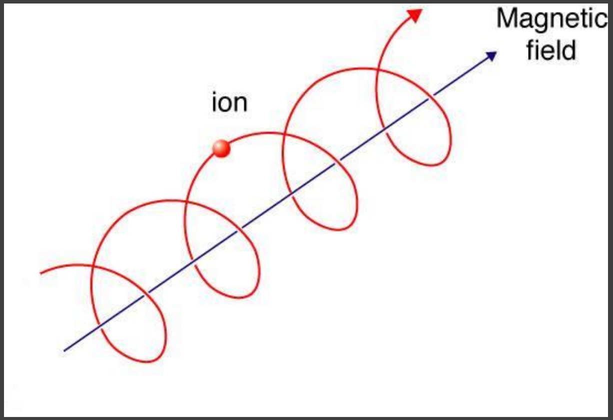
Leamon et al. (1998) – Measurements at 1 AU



Interaction of the outward propagating and reflected waves generates turbulence.

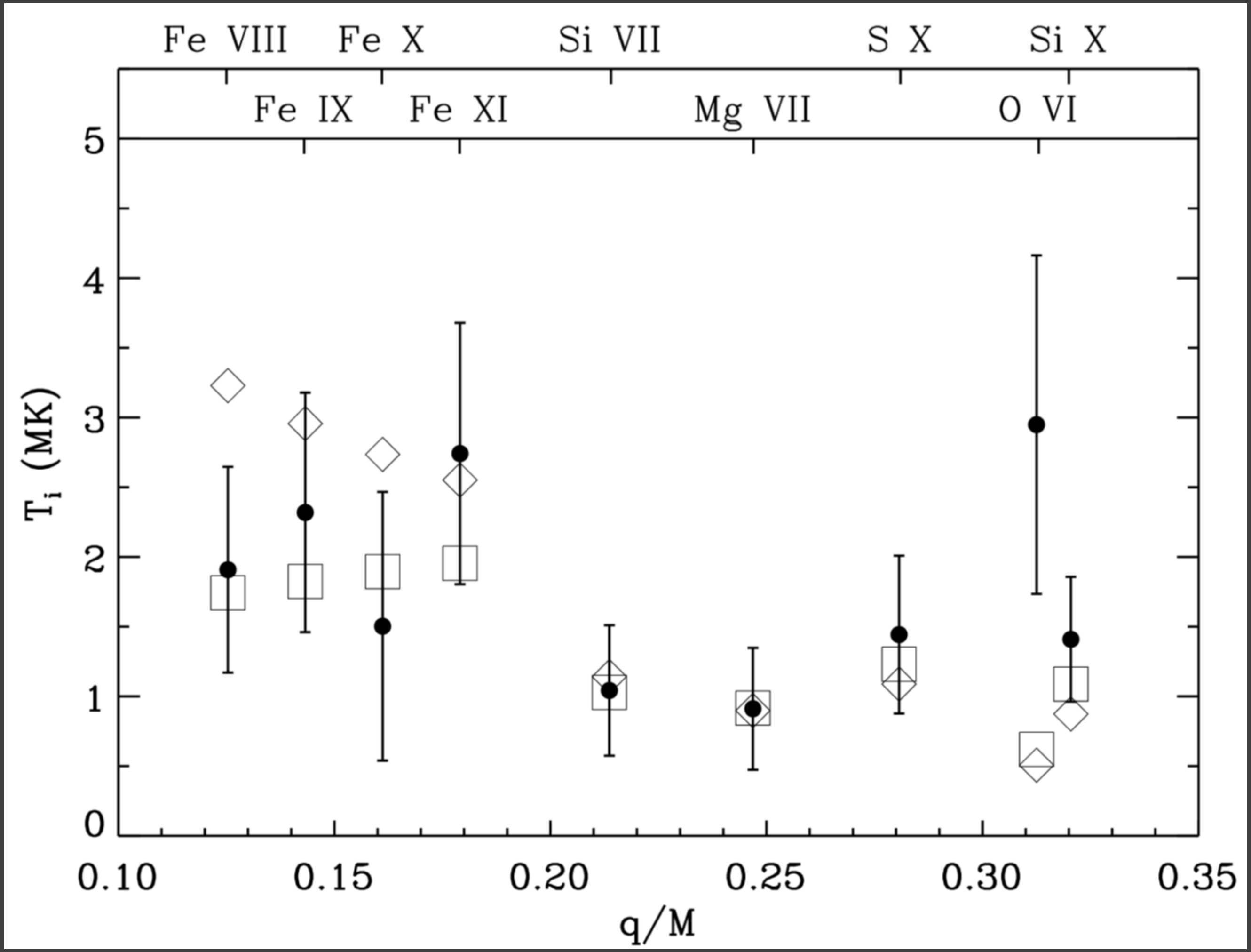
Ion Cyclotron Resonant Heating

- Ion cyclotron frequency $\Omega_i = qB/M$.



- If wave frequency close to Ω_i then waves can efficiently transfer energy to the ions.
- Expect more power at low frequencies, so heating depends on q/M.
- Measure T_i vs. q/M to look for evidence of resonant heating.

Ion Temperature



Measured T_i compared to predicted trends for turbulence-driven heating

Conclusions and Open Questions

- Waves carry and dissipate enough energy at low enough heights to heat coronal holes and accelerate the fast solar wind.

- What causes the wave damping?
  - Magnetic structure allows damping processes.
  - Laboratory experiments are planned to study these.

- What heats other structures of the corona?
  - Models and some measurements suggest quiet Sun could also be heated by waves.
  - Currently applying this type of analysis to quiet Sun.