

# Coronal Heating And Acceleration of the High- And Low-Speed Solar Winds by MHD waves

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# Outline

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We focus on

- heating of **main body (p & e)** of the plasma
  - We neglect heavy ions though they are also important.
- heating in **open field regions**
  - ⇒ **Solar Wind** is inevitably taken into account.
- a role of **MHD waves**.
  - MHD effects could be essential in p & e as waves with periods of a few minutes are expected to contain sizable energy.
  - c.f. Kinetic effects seems to be important for heavy ions.

Anyway, we still have a lot of things to be done on MHD waves in spite of plenty of works so far.

We show results of 1-dimensional

- Steady-state modelling
  - 2 fluids, focusing on MHD shock trains.
- Numerical simulations from upper chromosphere to  $\sim 30R_{\text{sun}}$ 
  - 1 fluid, but **detailed wave dissipation** is taken into account. c.f. Ofman & Davila

# MHD Waves along Field Line (low-B)

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## Longitudinal (Slow or Sound) Waves

- Dissipation is (too) easy
  - Those only excited in the corona can contribute to the heating.

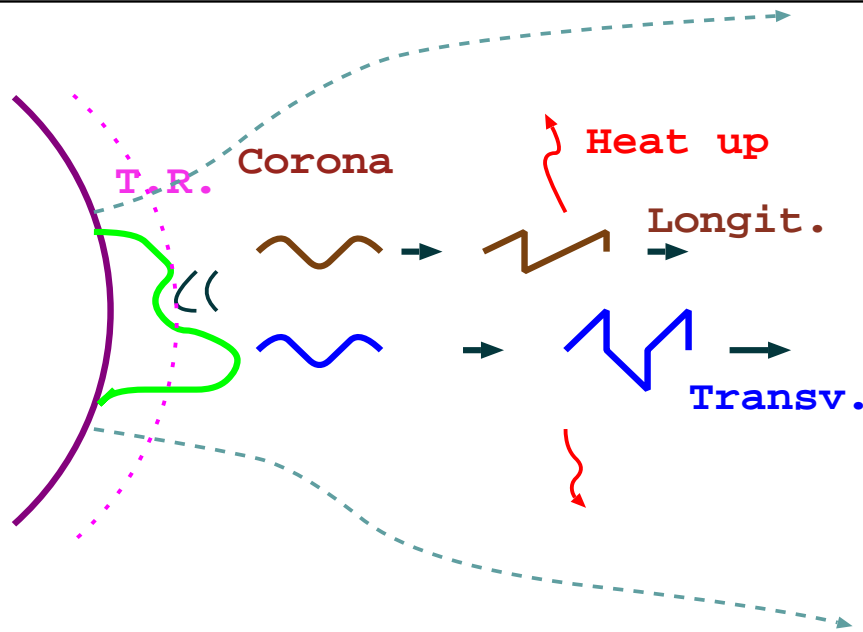
## Transverse (Alfven & Fast) Waves

- Dissipation is difficult.
  - Once they dissipate, they can heat the corona.
- Various processes have been explored.
  - Linear Polarization => Fast Shocks Hollweg 1982
  - Mode Conversion (Generation of Slow Waves)
  - Interaction between In & Out-going Waves  
/ Turbulent Cascade / Parametric Decay Instability
  - Phase Mixing (2-d resistive MHD) Heyvaerts & Priest 1983
  - Ion-cyclotron Resonance (Kinetic) e.g. Tu & Marsch 1980; Cranmer et al. 1999 \_

Blue : in Steady-State Model

Blue & Red : in Numerical Simulation

# Steady-State Model

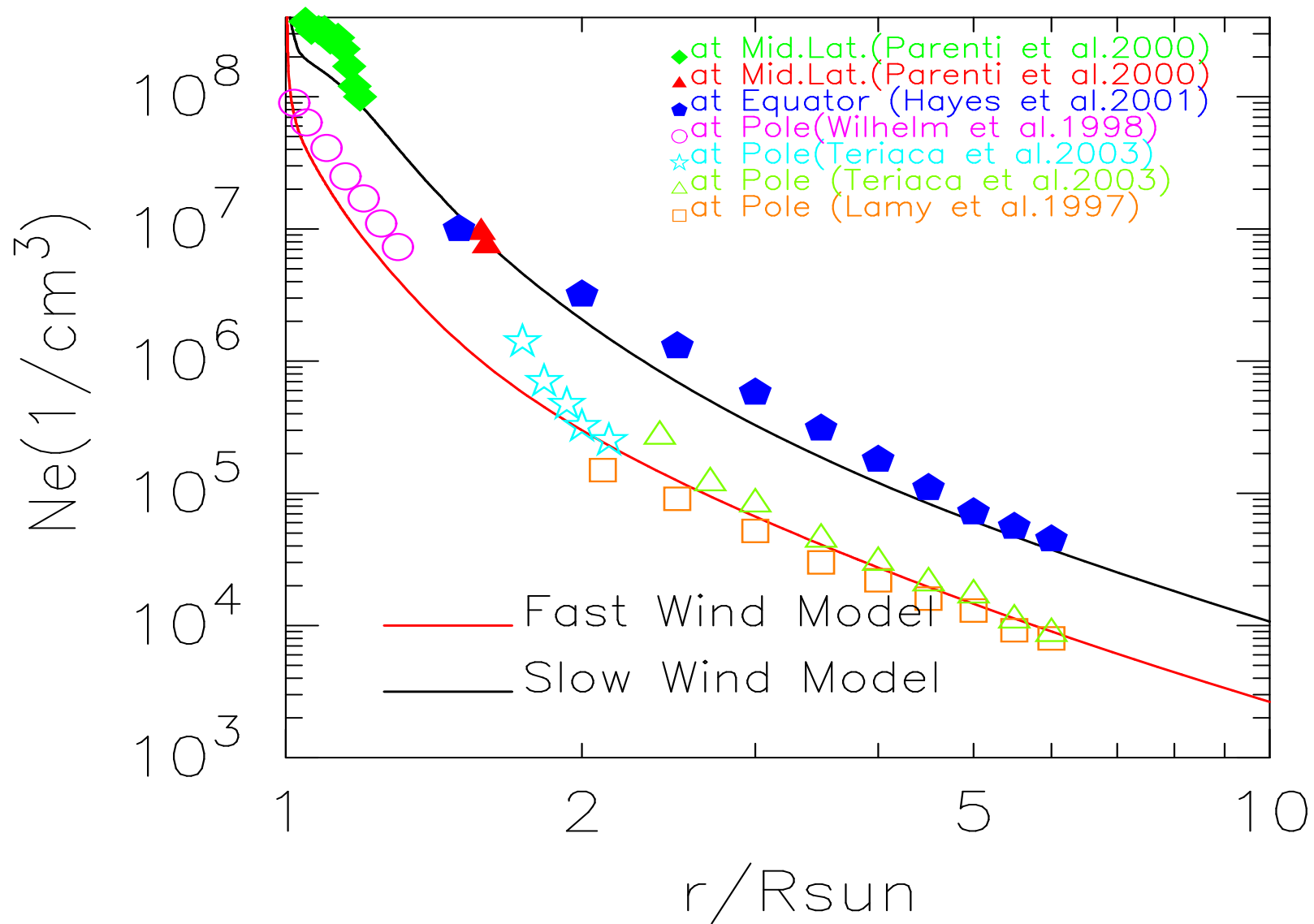


Suzuki, T. K. 2002, ApJ, 578, 598

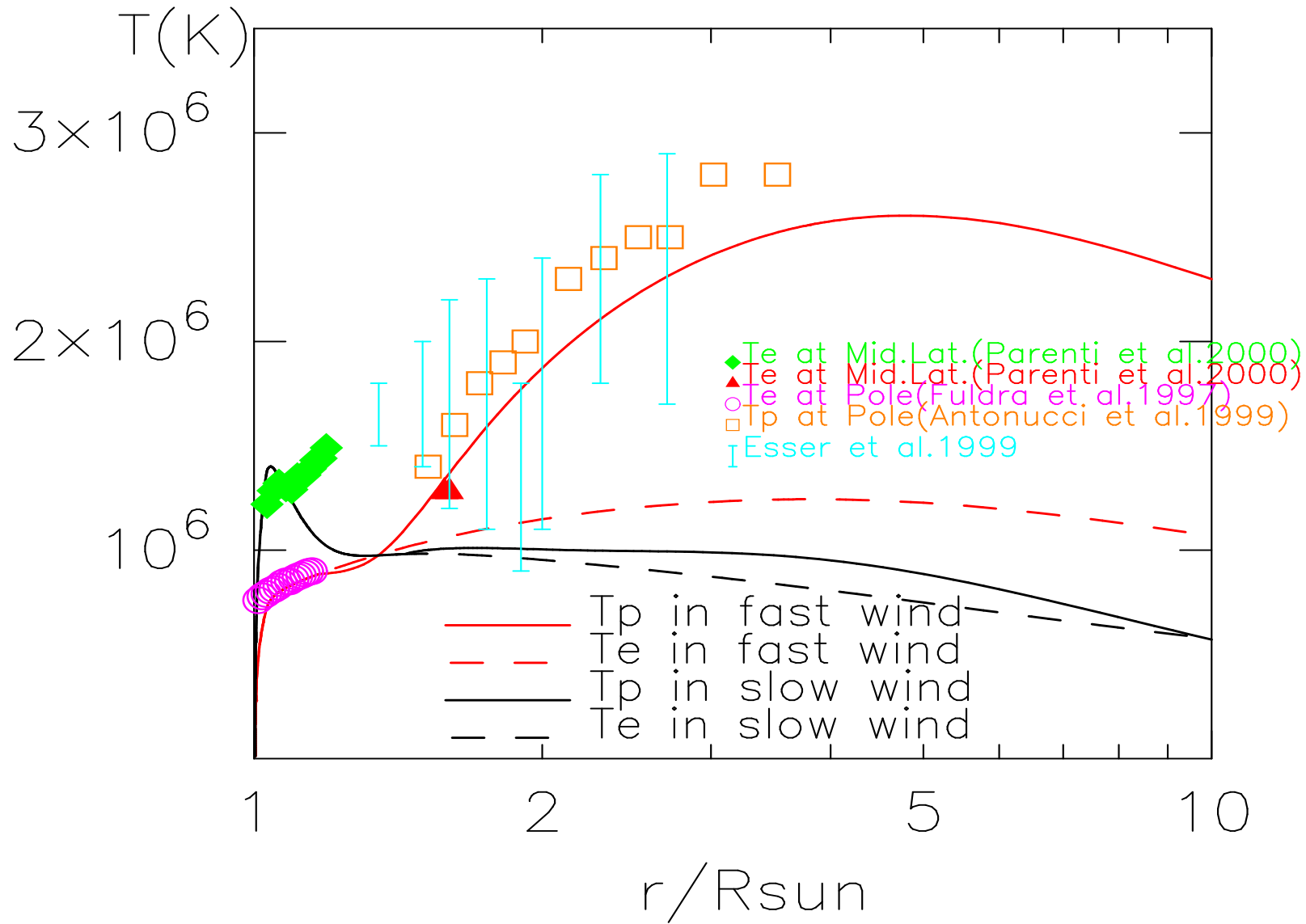
Suzuki, T. K. 2004, MNRAS, 349, 1227

- Calculation region : Upper Chromosphere => 1AU
- **Input Parameters** :  $F_{w,\perp,0}$ ,  $F_{w,\parallel,0}$ ,  $B_0$ , and  $f_{\max}$   
 $\tau = 2\text{mins.}$  (weak dependence on  $\tau$ )
- Solve evolutionary equations for shock train amplitudes derived from heating (jump conditions) at each shock.  
**No ad hoc parameters such as dissipation length**

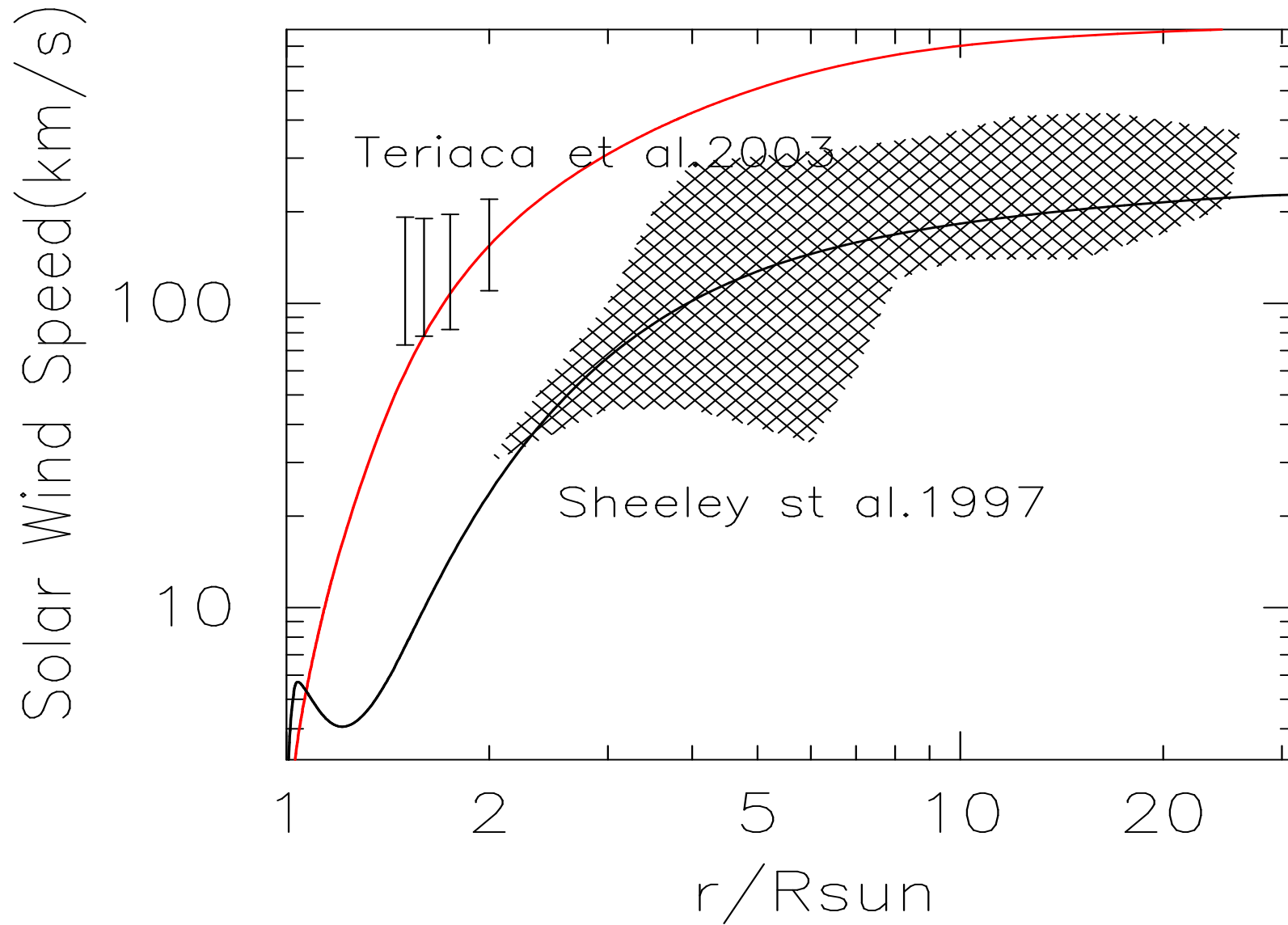
# Results (Ne)



# Results (Temperature)



# Results (Solar Wind Speed)



# Input & Main Points

## Input Parameters

Model	$F_{w,\perp}$ (erg cm <sup>-2</sup> s <sup>-1</sup> )	$F_{w,\parallel}$ (erg cm <sup>-2</sup> s <sup>-1</sup> )	$B_0$ (G)	$f_{\max}$
High-Speed	$2.4 \times 10^5$	$0.36 \times 10^5$	2	1
Low-Speed	$4.4 \times 10^5$	$7.2 \times 10^5$	10	8

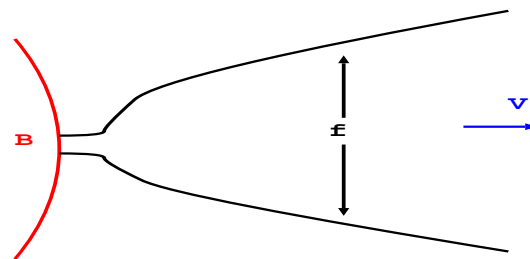
## Main Results

### ■ Fast Winds from flux tubes with large $B_0/f_{\max}$

- Consistent with recent results Kojima et al.(2004)
- One of Explanations

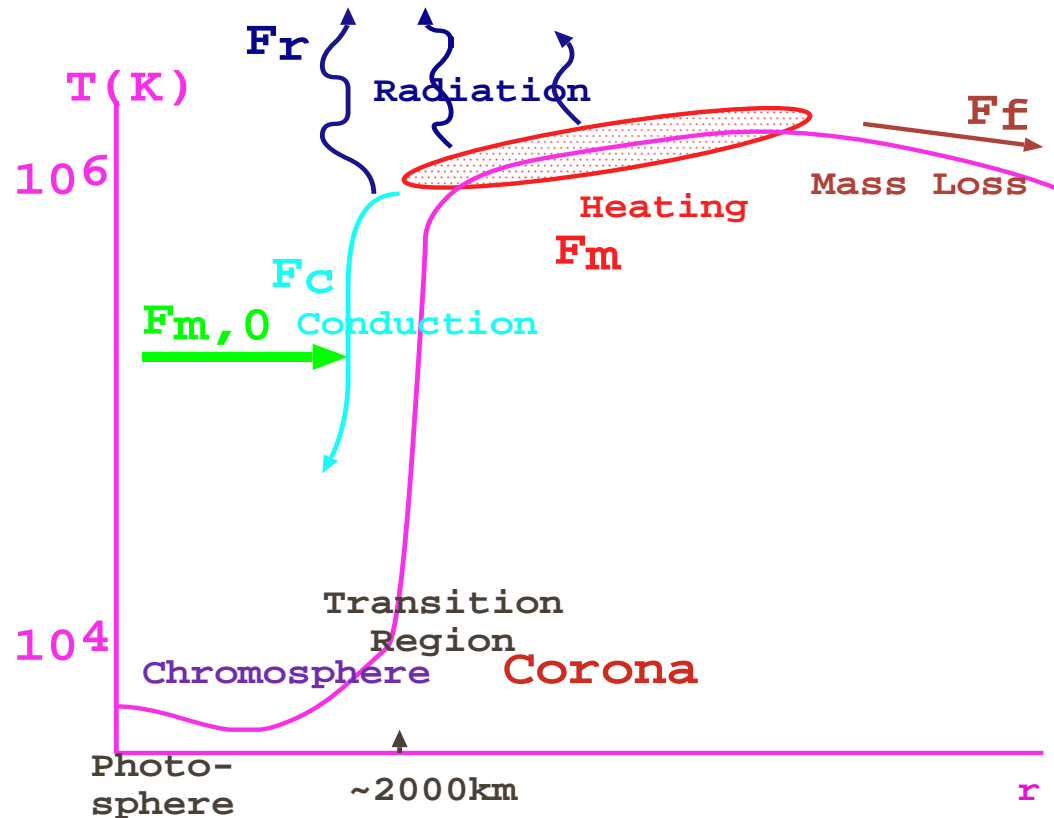
$$\text{Energy flux of Alfvén waves} = \frac{1}{8\pi} \delta B_{\perp} \delta v_{\perp} B \propto B_0 / f_{\max}$$

$(B f r^2 = B_0 r_0^2)$



- Sound waves, or generally **heating sources in the low corona**, makes slower but denser winds.

# Low Coronal Heating $\Leftrightarrow$ Slow Wind



Heat in the low corona

=> Downward thermal conduction

=> Chromospheric Evaporation

=> Increase Density at the Transition Region

It can raise density in the inner corona to form the dense slow wind.

# Numerical Simulations

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Simulation studies are highly desired because

- first of all, Corona is dynamical.
- Complicated wave dissipation cannot be treated in detail in steady-state models.

## On Our Simulations

Modification of Sano & Inutsuka 2001

- 1 dim. with 2nd & 3rd components of  $B$  &  $v$
  - Spherical coordinate with super-radial expansion
  - 2nd Order Godunov Method(MHD extension of van Leer 1979)
    - Compressive Waves
      - : Non-linear Riemann Solver with  $B_{\perp}$
    - Incompressive Waves
      - : Method of Characteristics for Alfvén Waves
  - Radiative Cooling and Conduction
    - added by operator split with implicit time-step
  - Outgoing Boundary Condition
    - use only outgoing characteristics out of 7 MHD waves
- Long Time-Simulation without unphysical wave reflections

# Demonstration

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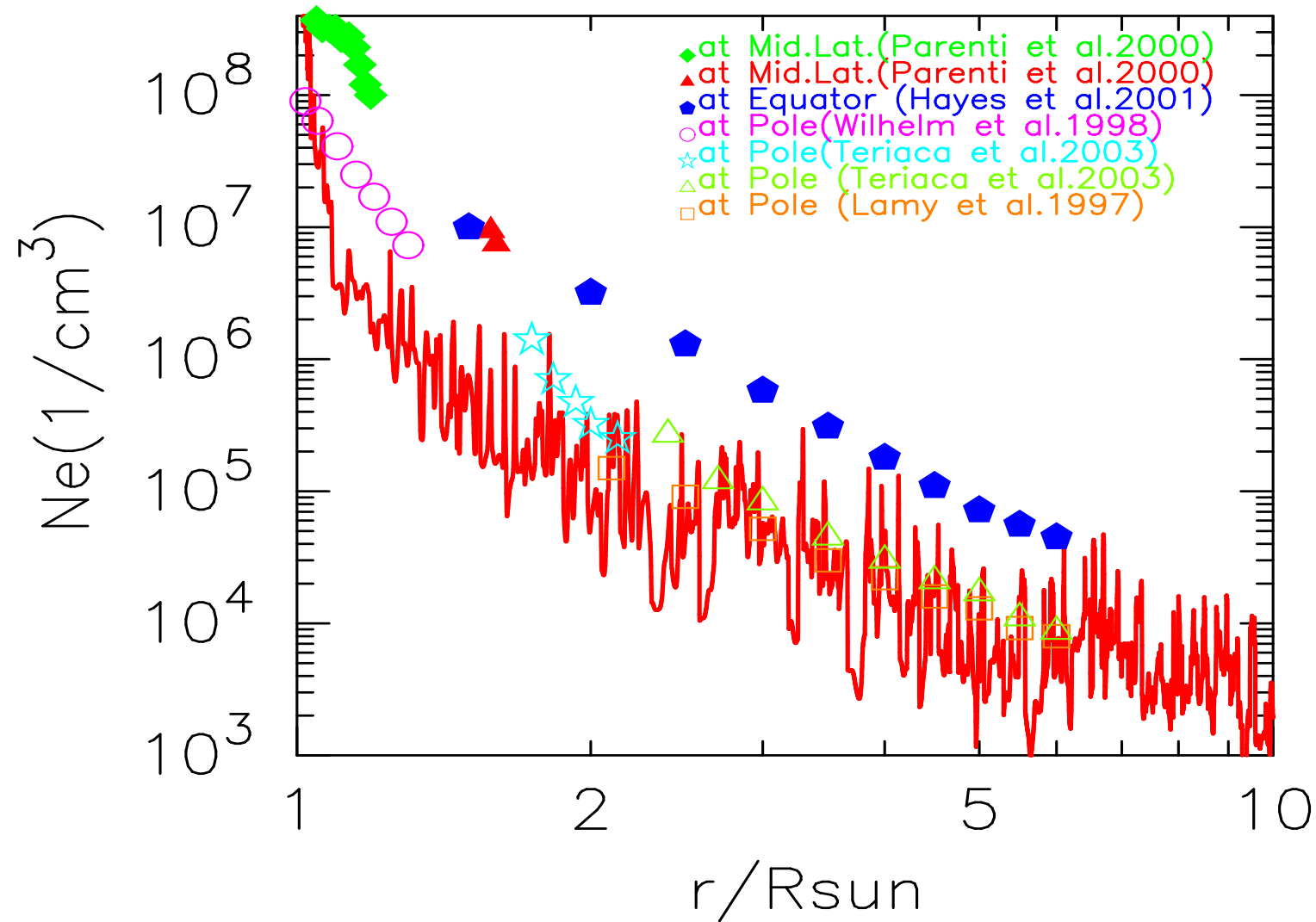
Although we have not completed parameter search yet, we demonstrate an example of the simulations.

## Set-up

- **Inner Bound. : Upper Chromosphere**  
 $\rho = 10^{-13} \text{g cm}^{-3}$ ,  $T = 10^4 \text{K}$ ,  $B = 8 \text{G}$
- **Outer Bound. :  $\sim 30R_{\odot}$ , Outgoing Boundary for 7 MHD waves**
- **Initial :  $T = 10^4 \text{K}$  in the entire region,  $f_{\text{max}} = 5$**   
**Inner Region : Hydrostatic  $\rho$  profile**  
**Outer Region : larger  $\rho$  than hydrostatic with random  $\delta v_{\perp}$**
- **Input Waves : White noise with  $\tau > 2\text{s}$  (resolution limit)**  
 $\delta v_{\perp} \simeq 25 \text{km/s}$  at the inner boundary  
(Corresponding to  $\delta v_{\perp} \sim 0.5 - 1 \text{km/s}$  at the photosphere for undamped Alfvén waves,  $\delta v_{\perp} \propto \rho^{-1/4}$ )
- **Number of grids : 27,000;  $dr \simeq 5 \text{km}(\text{inner}) \Rightarrow 500 \text{km}(\text{outer part})$**
- **Time :  $\simeq 20 \text{hr} \leftarrow \sim$  twice of sound crossing time.**

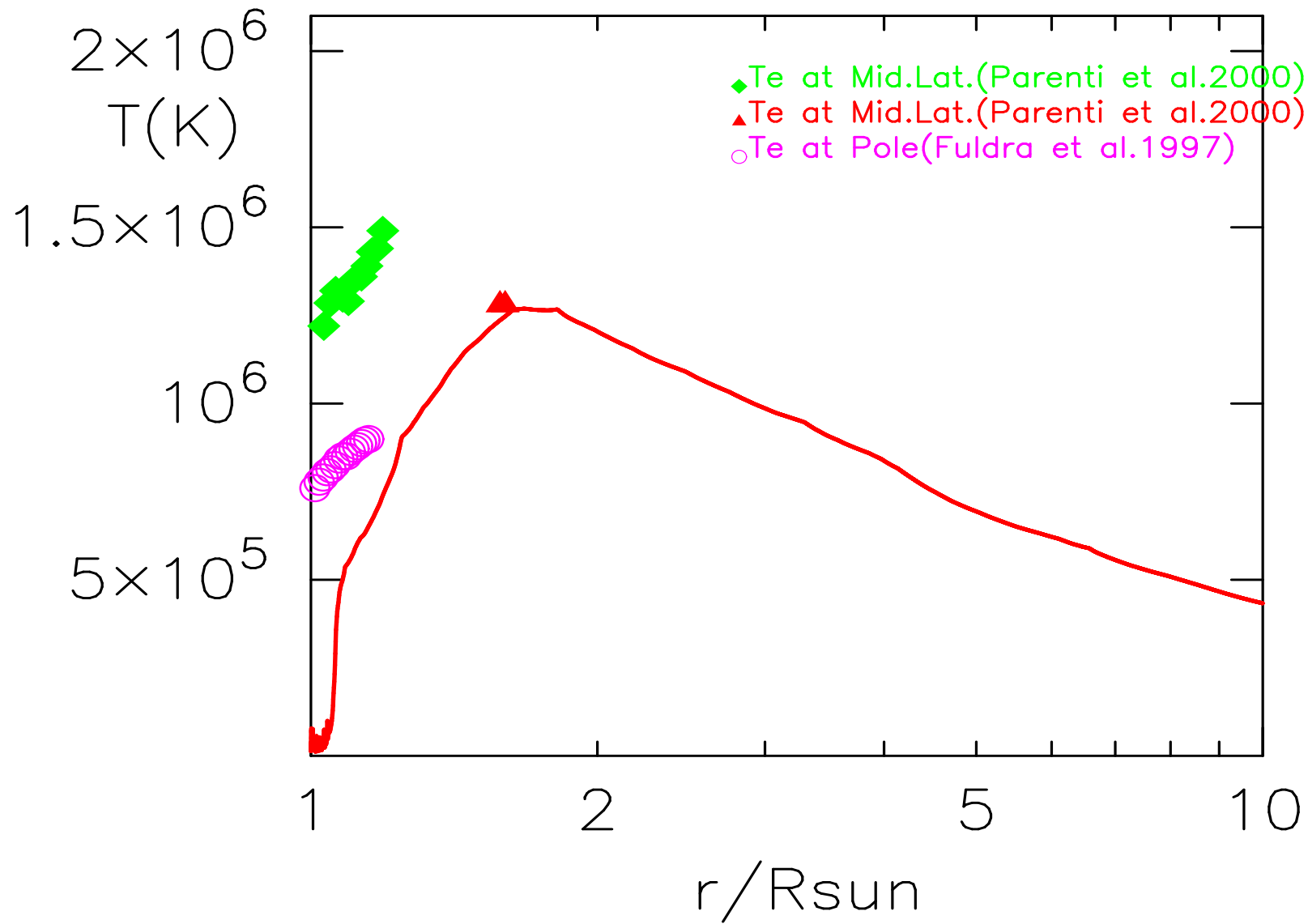
**Please enjoy a movie.**

# Result(Ne)

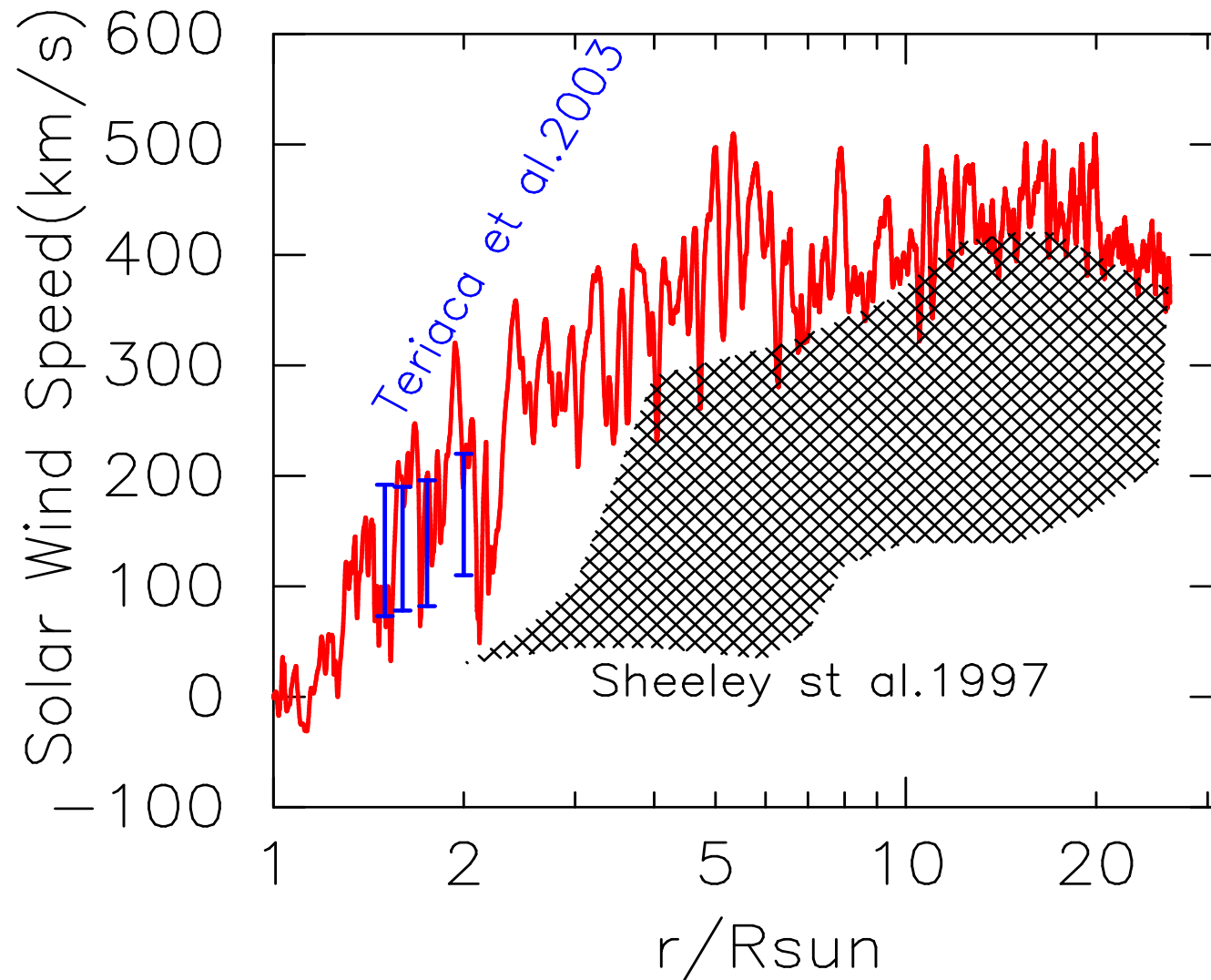


- A Lot of (Both Fast & Slow) Shocks
- More like high-speed wind.

# Result(T)



# Result(Wind Speed)



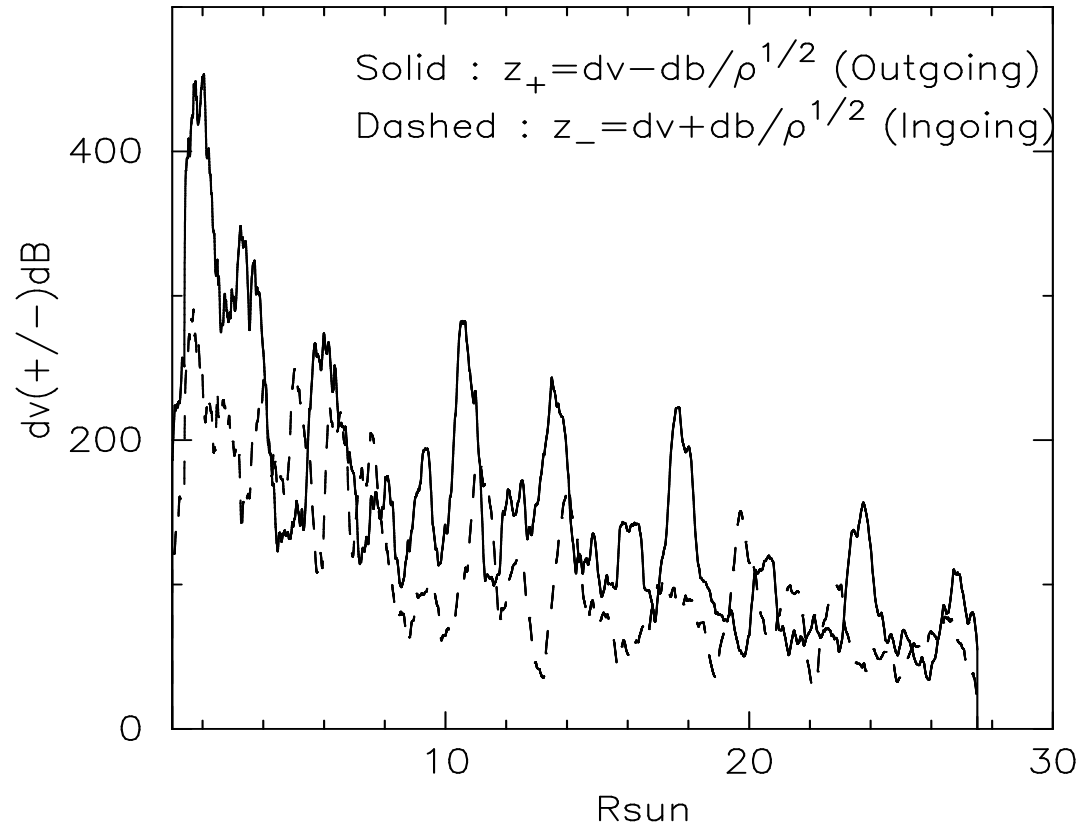
- Rapid acceleration of fast wind is recovered.
- But terminal speed is a little slow (~500km/s)

# Generation of Ingoing Mode

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Besides shocks, ingoing waves play a role in heating.

In/Out-going Alfvén waves



Density Fluctuation => (Decay Instability)

=> Ingoing Alfvén waves (+Outgoing sound waves)

=> Wave Dissipation through wave-wave interactions

# Problematic $\Delta v$

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Wave amplitudes exceed observed non-thermal broadening of spectral lines.

- Our results : 50~100 km/s
- Observations (Banerjee et al.1998; Doyle et al.1999) :  $\sim < 50 \text{ km/s}$

Most of wave models suffer from this problem. (I guess)

Reasons of the discrepancy ?

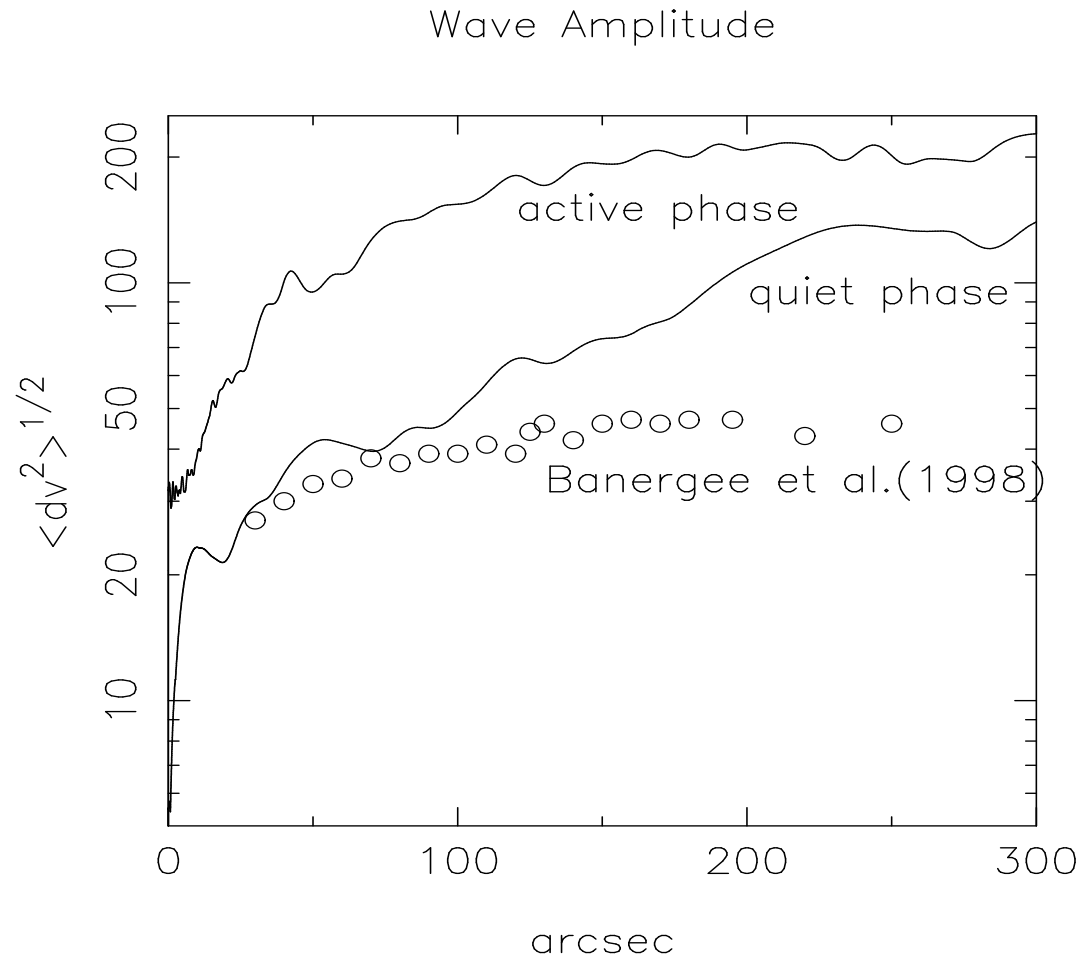
- Additional heating is working ?
  - Inner corona might be heated by reconnection events,  
But how to heat outer corona ( $\sim > 100 \text{ Mm}$ ) without waves ?
- How about the projection effects in Obs?
  - Of course, I respect observations.
- **Intermittent wave activities ?**
  - If waves are generated by transient events...
  - If observations are carried out during quiet phase...

=> Simulation

# Intermittent Wave Activities

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10min. Wave Injection + 10 min. Rest



Although quiet case still exceeds OBS.,  $dv$  shows large difference.

- Other cases should be examined, say 1hr active + 3hr Rest.

# Summary

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We have investigated coronal heating and solar wind acceleration by MHD waves both by steady-state model and simulation.

- They seem successful.

Steady-state Results :

- Fast Winds from Large  $Bo/f_{max}$
- Low Coronal Heating in Slow Wind

Simulations :

- Million K Corona and 500km/s Solar Wind is formed from gas with 10000K.
- $dv$  exceeds nonthermal broadening for continuous wave injection. Intermittency might be important.

We wish direct observation of Alfvén waves by the future missions.

- It may be difficult due to incompressible mode, but
- If they propagate in fluctuating media, they can be observed.