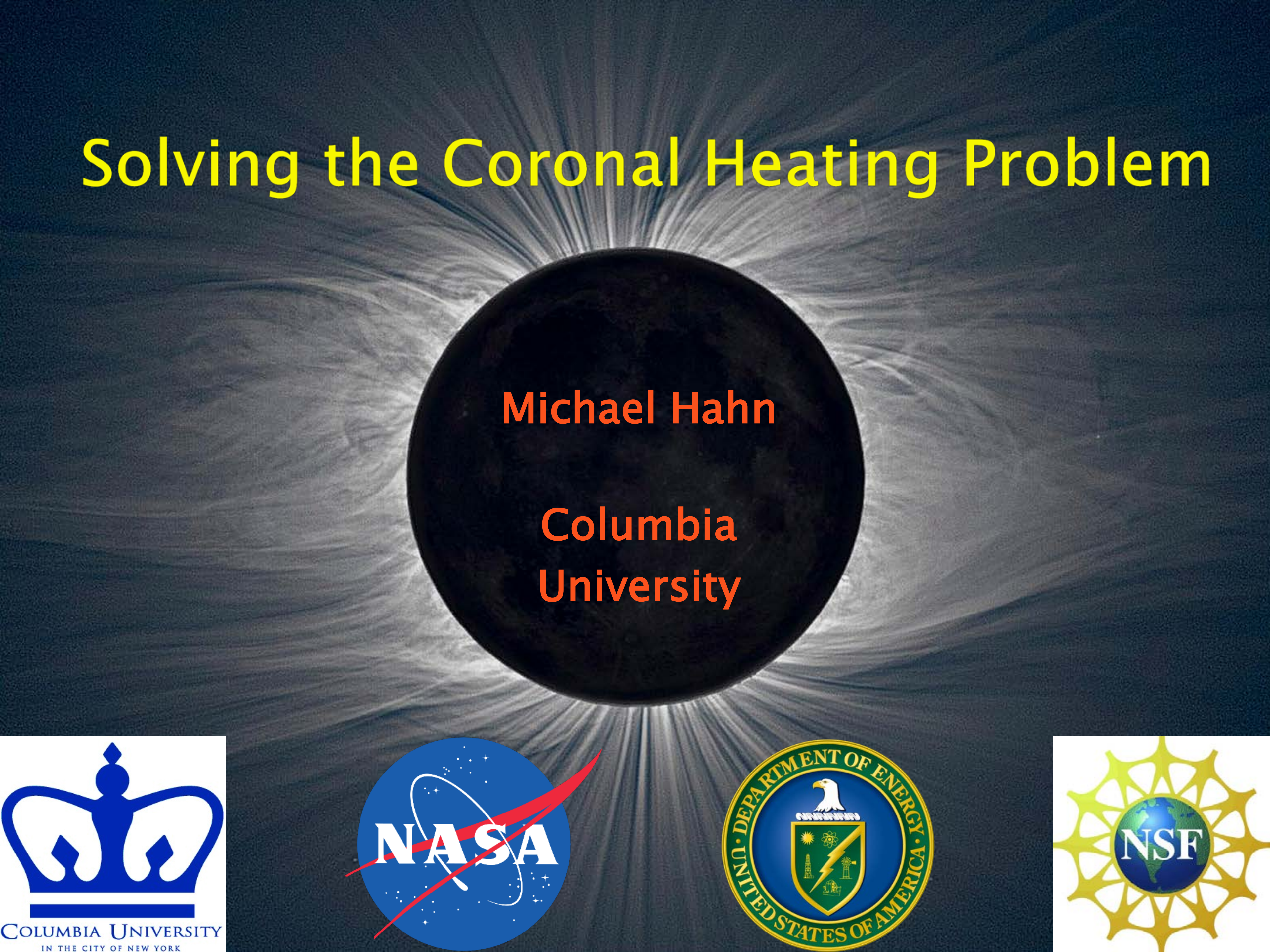

Solving the Coronal Heating Problem

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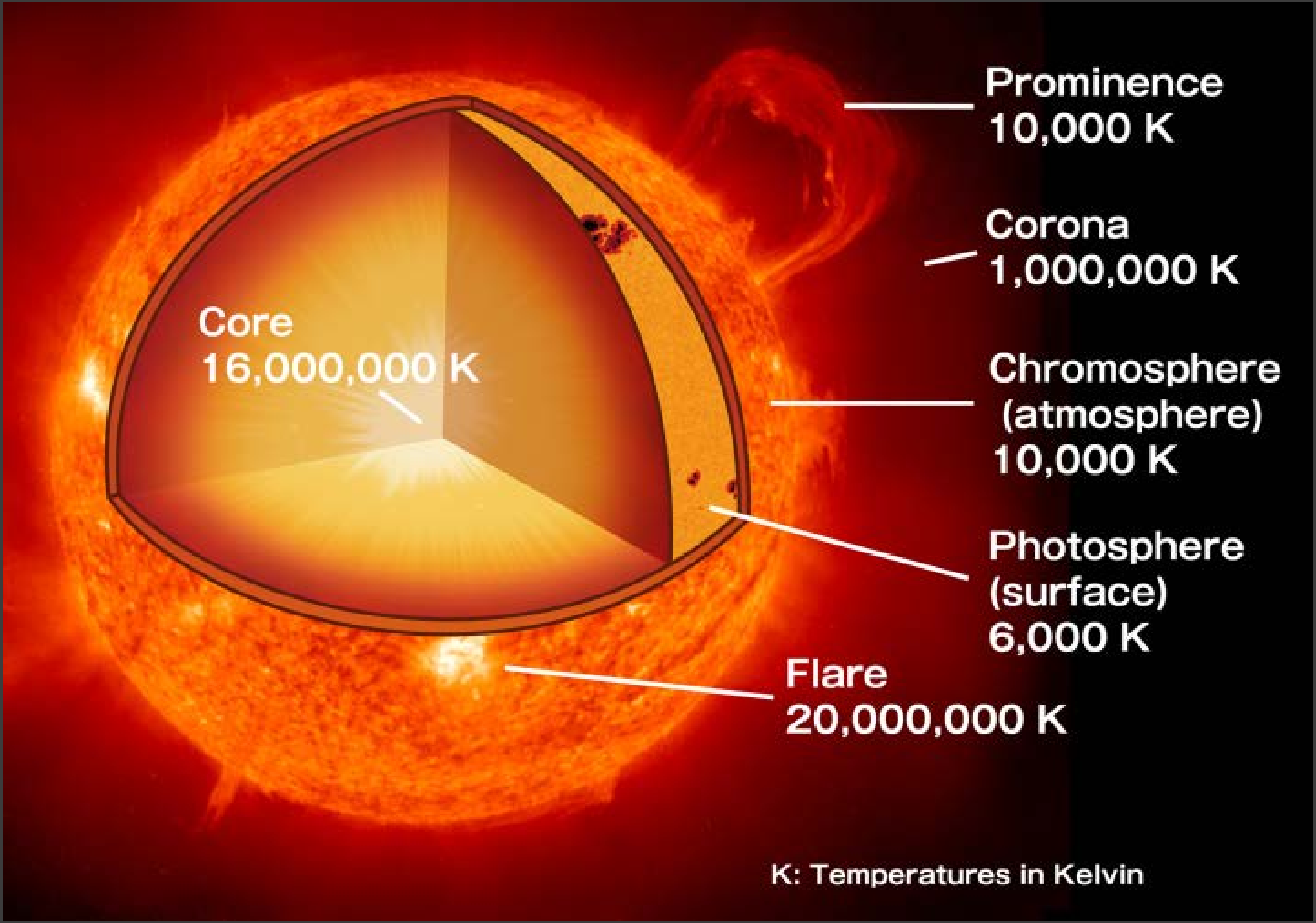
UNITED STATES OF AMERICA

NSF

Outline

- Introduction
- Observations
- Models
- Laboratory Experiments
- Summary

The Coronal Heating Problem



Coronal heating

- Energy source is turbulent fluid motion in outer convection zone.

- Jostling field lines gives energy to corona via:
  - Magnetic reconnection
  - Waves

Questions about wave heating

- Where and how are waves generated?
- How is wave energy transmitted through the transition region?
- What wave modes are there in the corona?
- How much energy do these waves carry?
- How and where are the waves dissipated?

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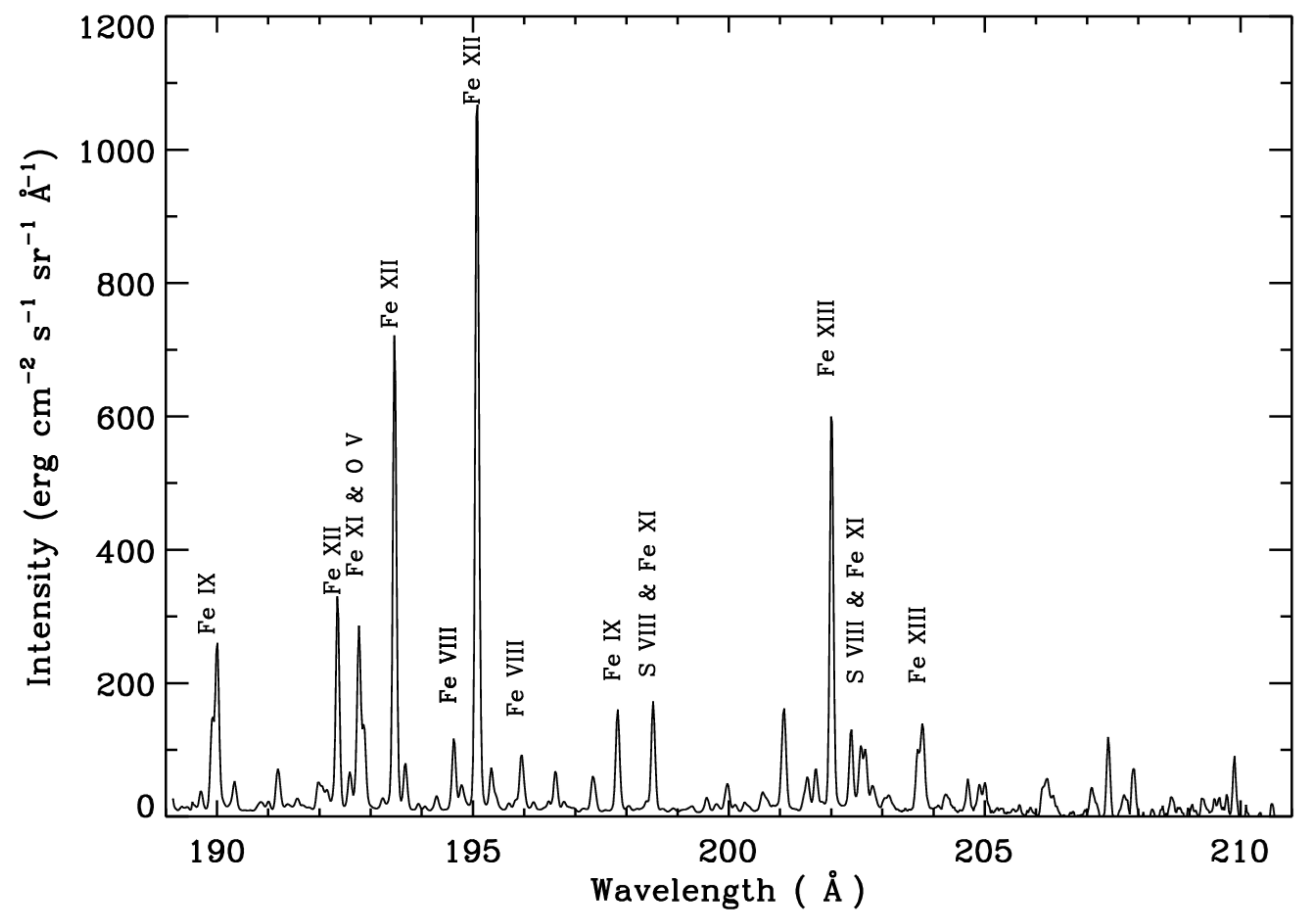
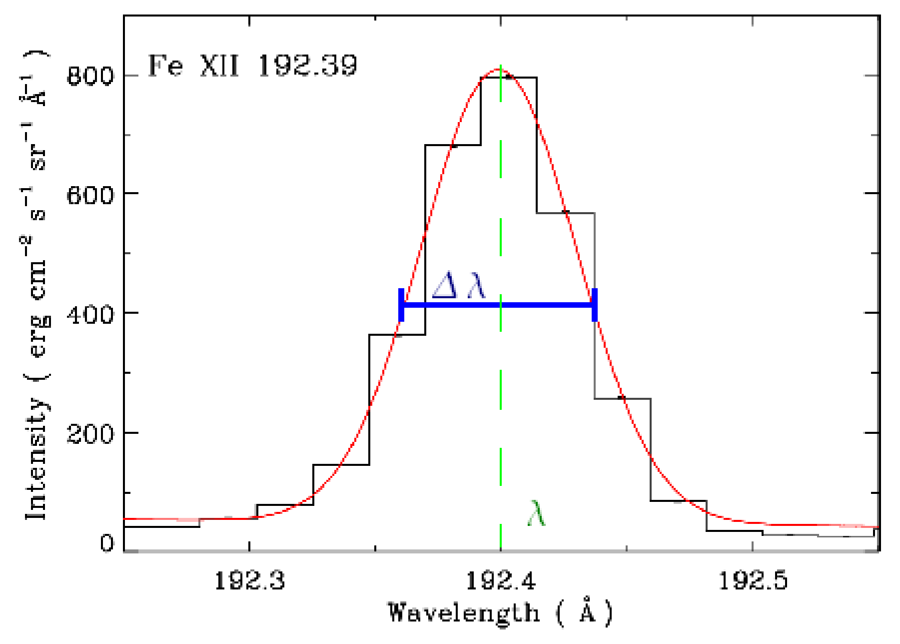
Typical solar spectrum



Temperature, density, Doppler shifts, Line profiles

Line widths reflect wave amplitudes



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

M – Ion Mass

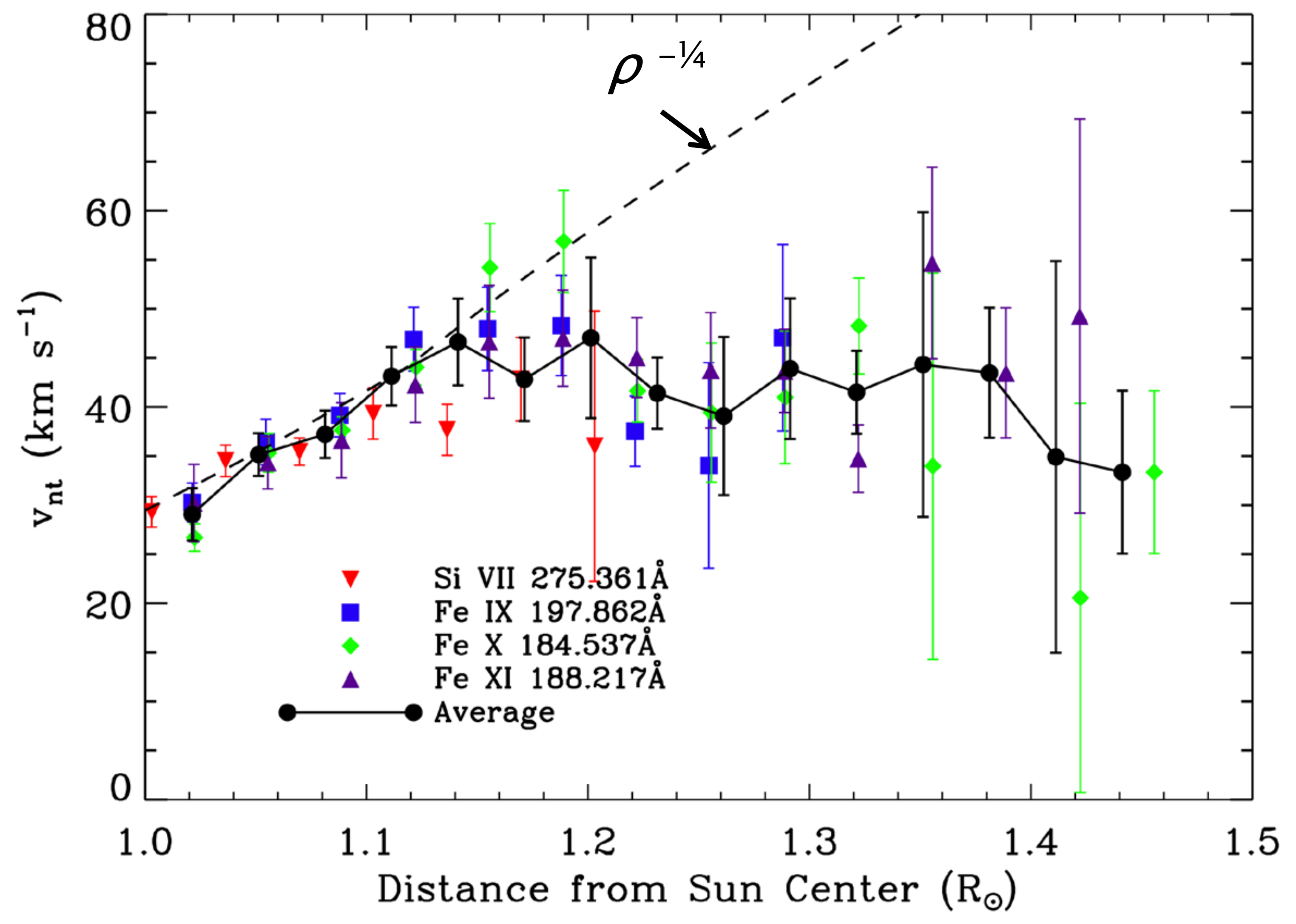
v_{nt} – Nonthermal velocity

T_i – Ion temperature

Subtract instrumental width

Wave amplitude δv from $<\delta v^2> = 2 v_{nt}^2$.

Evidence for wave damping in corona

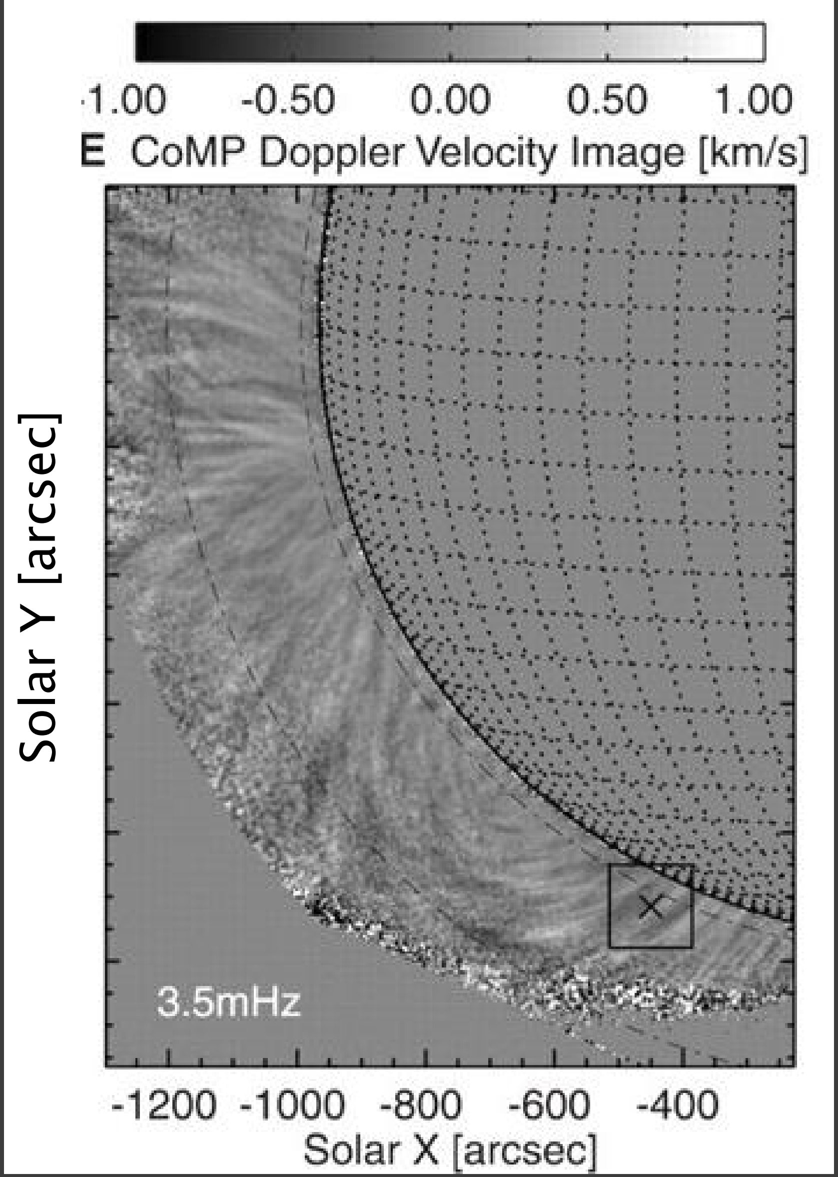


Similar results found by Bemporad & Abbo (2012)

Doppler shifts also show waves

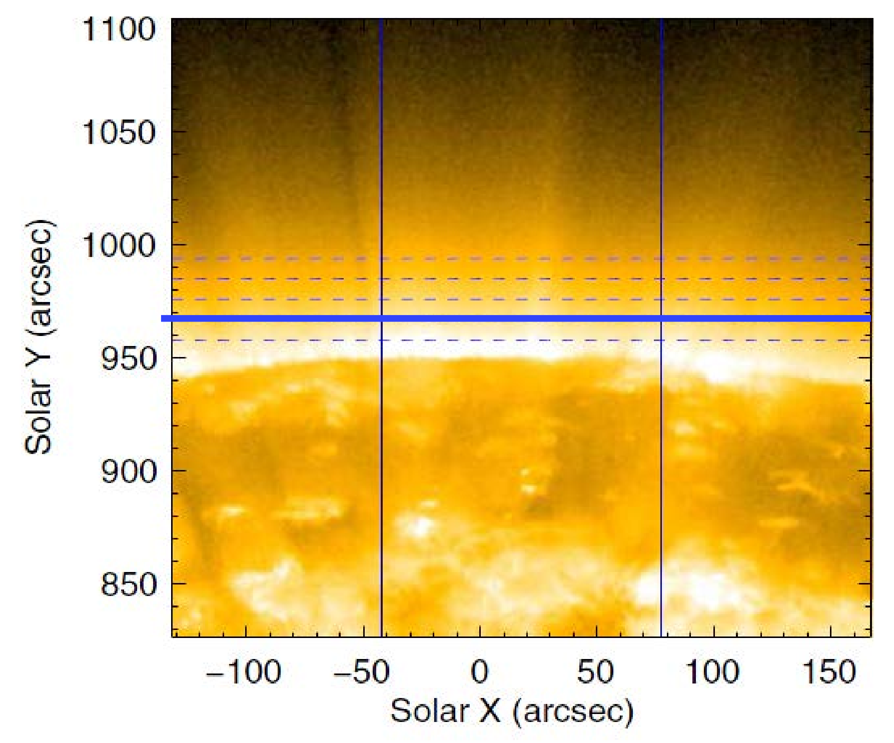
These waves travel along coronal magnetic field lines.

However, line-of-sight integration washes out the apparent amplitude.
– No energy estimate.

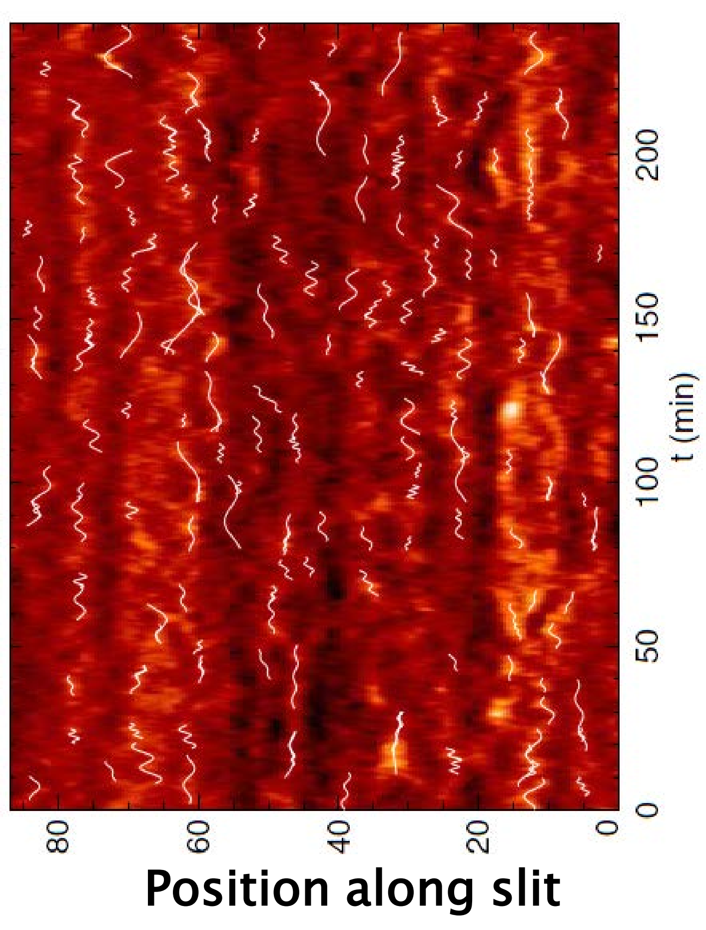


Tomczyk et al. (2007)

Imaging observations can see waves



Thurgood et al. (2014)



Only large amplitudes – need cross several pixels.
Acoustic modes observed as intensity fluctuations.

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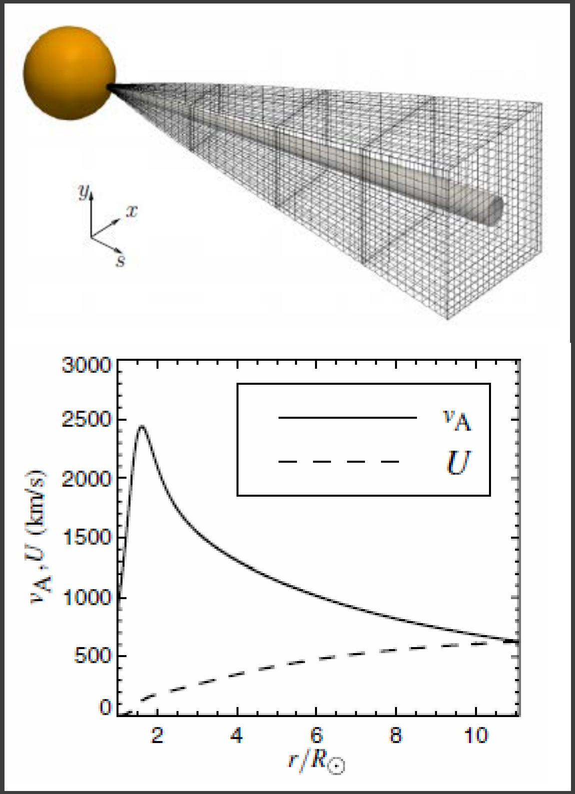
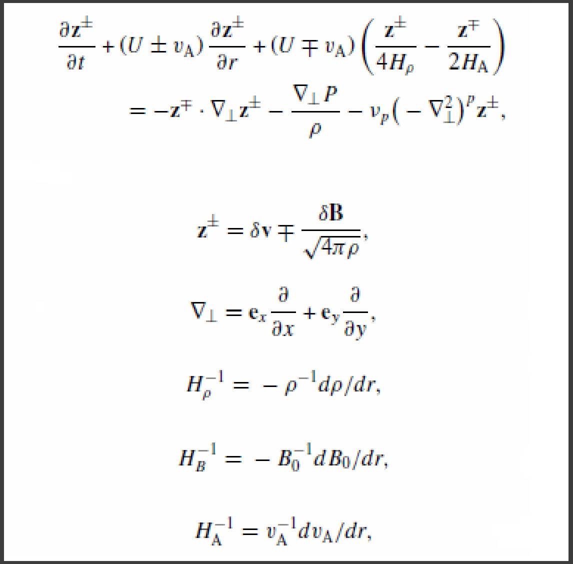
Models of physical processes

Reduced MHD simulations of turbulence.(Perez & Chandran 2013)



Relatively simple computational geometry and physical parameters.



$$\frac{\partial \mathbf{z}^\pm}{\partial t} + (U \pm v_A)\frac{\partial \mathbf{z}^\pm}{\partial r} + (U \mp v_A)\left(\frac{\mathbf{z}^\pm}{4H_\rho} - \frac{\mathbf{z}^\mp}{2H_A}\right)$$

$$= -\mathbf{z}^\mp \cdot \nabla_\perp \mathbf{z}^\pm - \frac{\nabla_\perp P}{\rho} - \nu_p\left(-\nabla_\perp^2\right)^p \mathbf{z}^\pm,$$

$$\mathbf{z}^\pm = \delta\mathbf{v} \mp \frac{\delta\mathbf{B}}{\sqrt{4\pi\rho}},$$

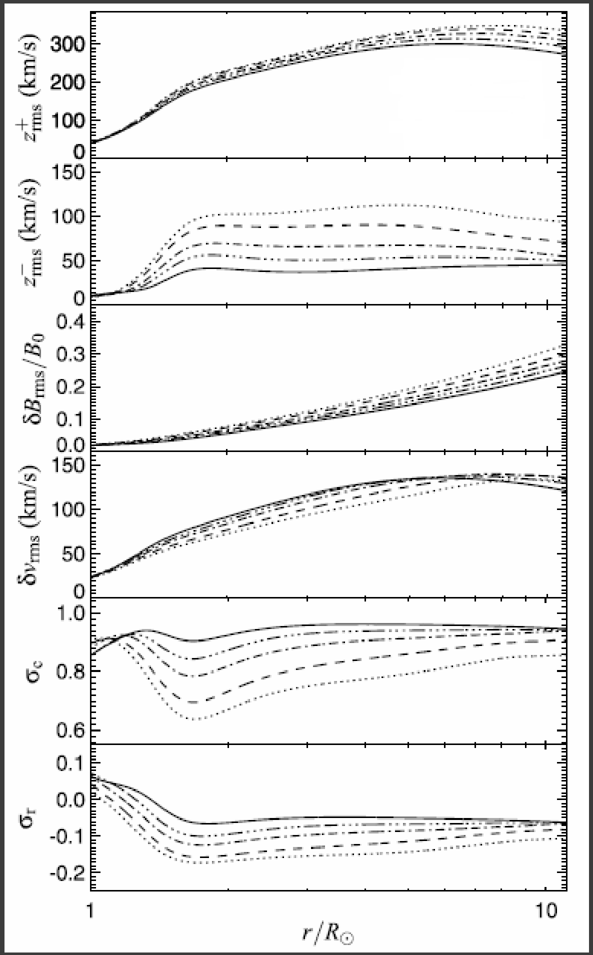
$$\nabla_\perp = \mathbf{e}_x\frac{\partial}{\partial x} + \mathbf{e}_y\frac{\partial}{\partial y},$$

$$H_\rho^{-1} = -\rho^{-1} d\rho/dr,$$

$$H_B^{-1} = -B_0^{-1} dB_0/dr,$$

$$H_A^{-1} = v_A^{-1} dv_A/dr,$$

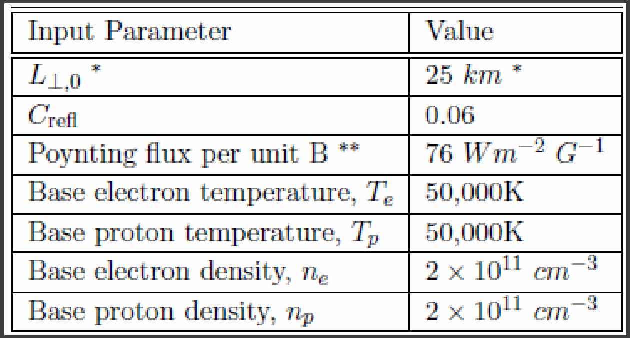
Solve the RMHD equations.



Variables of theoretical interest, but not directly related to observeables.

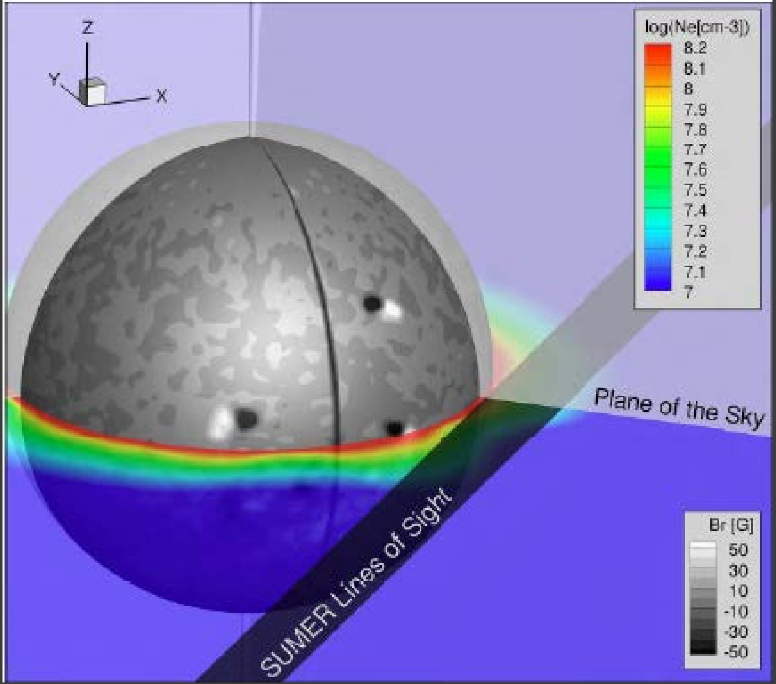
Models of the Sun

3D model of the corona with parameterized heating driven by wave turbulence (Oran et al. 2013).

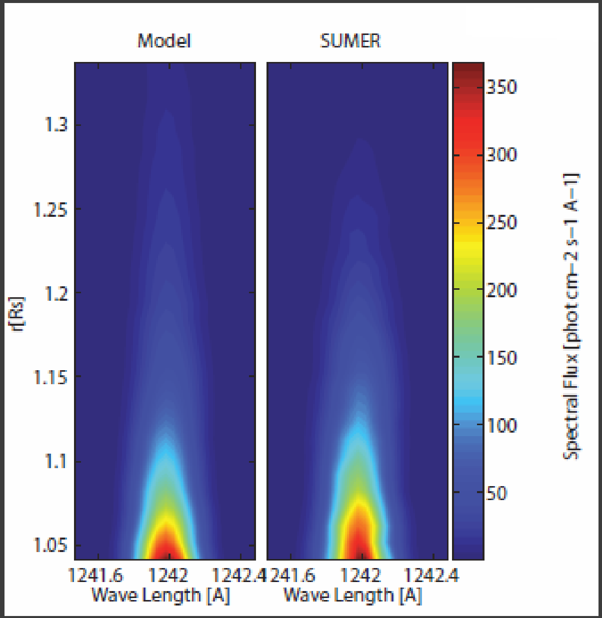


Input Parameter	Value
$L_{\perp,0}$ *	25 km *
C_{refl}	0.06
Poynting flux per unit B **	76 $W m^{-2} G^{-1}$
Base electron temperature, T_e	50,000K
Base proton temperature, T_p	50,000K
Base electron density, n_e	$2 \times 10^{11}\ cm^{-3}$
Base proton density, n_p	$2 \times 10^{11}\ cm^{-3}$

Input parameters.



3-D solution for wave amplitudes, density, temperature.



Integrate along a line-of-sight to simulate observation.

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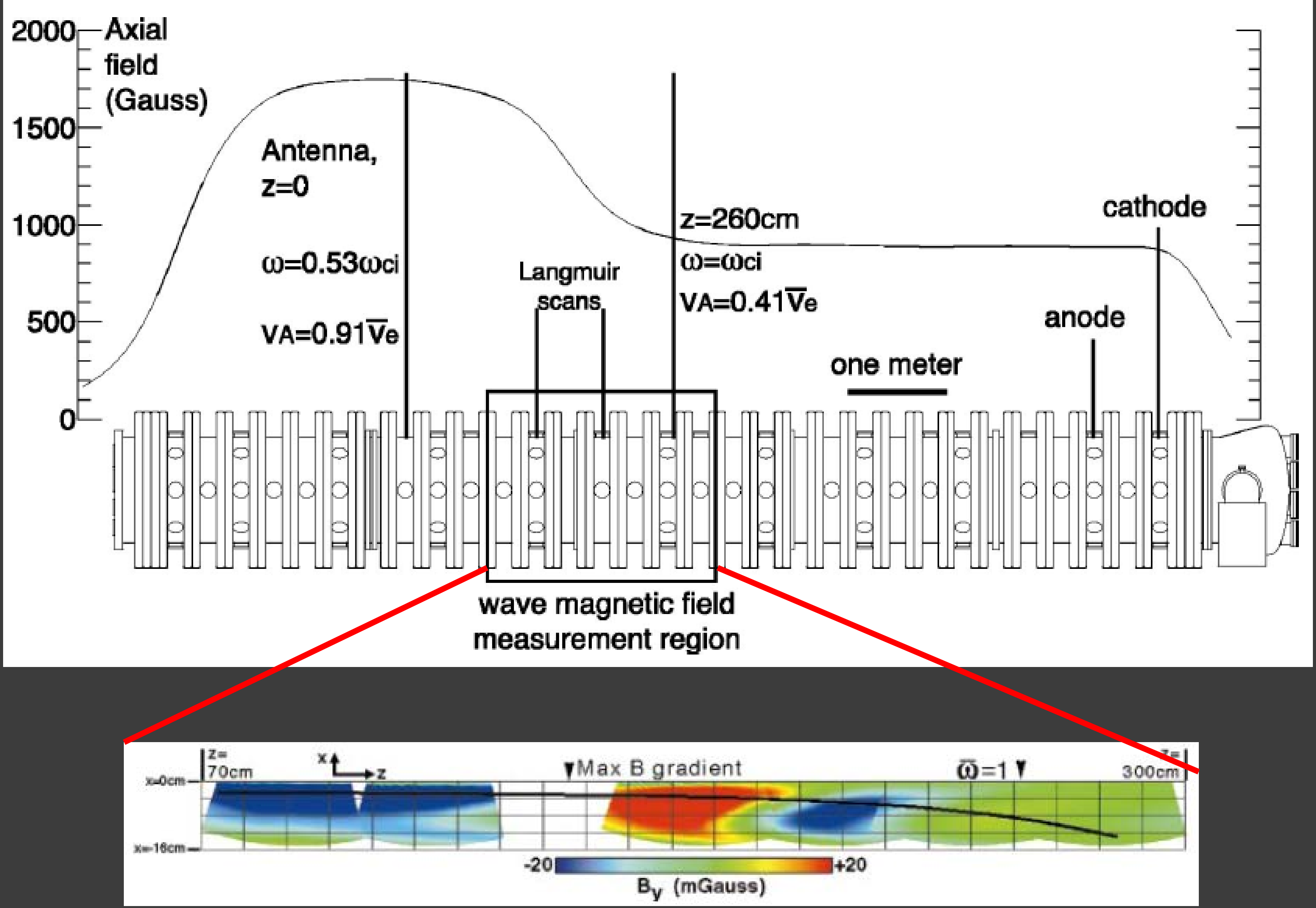
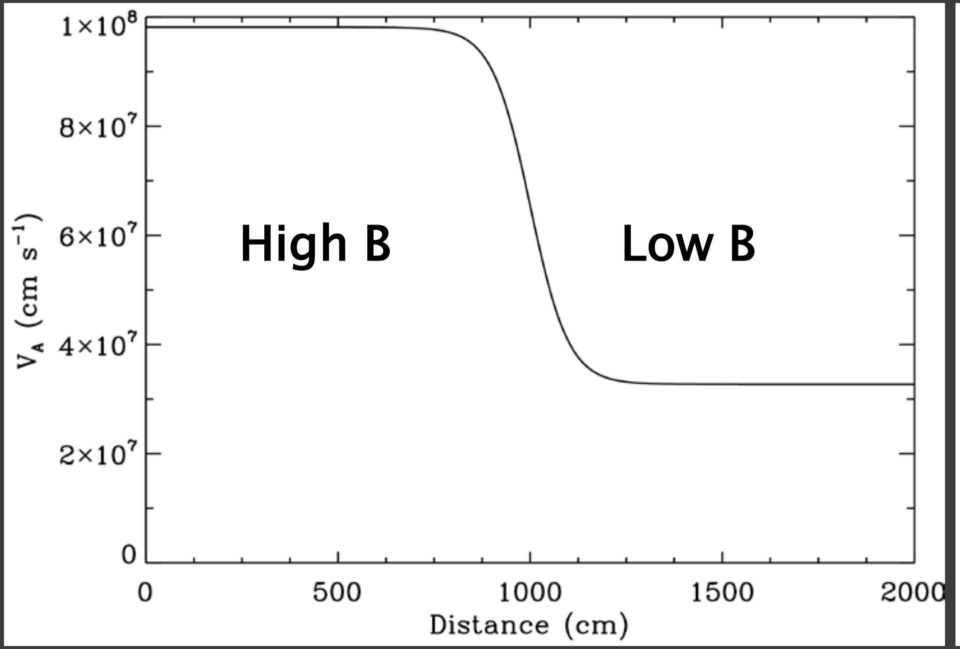
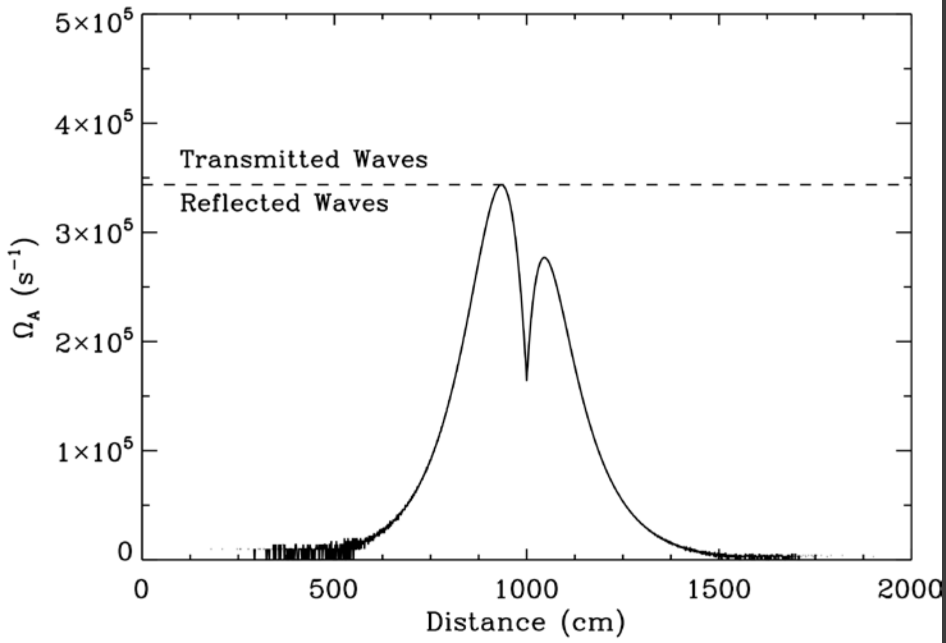
Large Plasma Device – Schematic



Vincena et al. (2001)

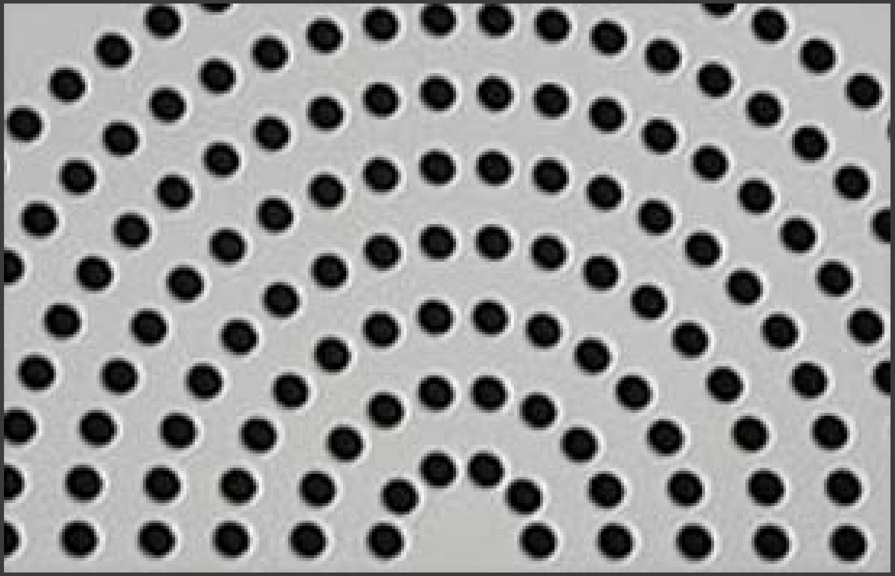
Wave reflection from a gradient in V_A

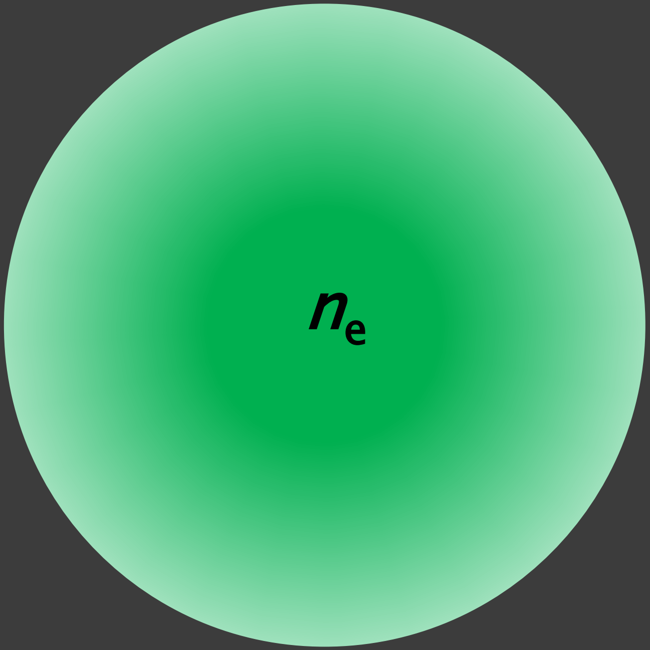




- Systematic measurements of Alfven wave reflection from a gradient.
- Determine reflection/transmission efficiencies and compare to theory.

Phase mixing in a radial density gradient





- Determine phase mixing dissipation length and compare to theoretical predictions.

- Do additional waves excited by phase mixing lead to greater dissipation than predicted?

Summary

- Remote solar observations lack enough detail for unambiguous interpretation.

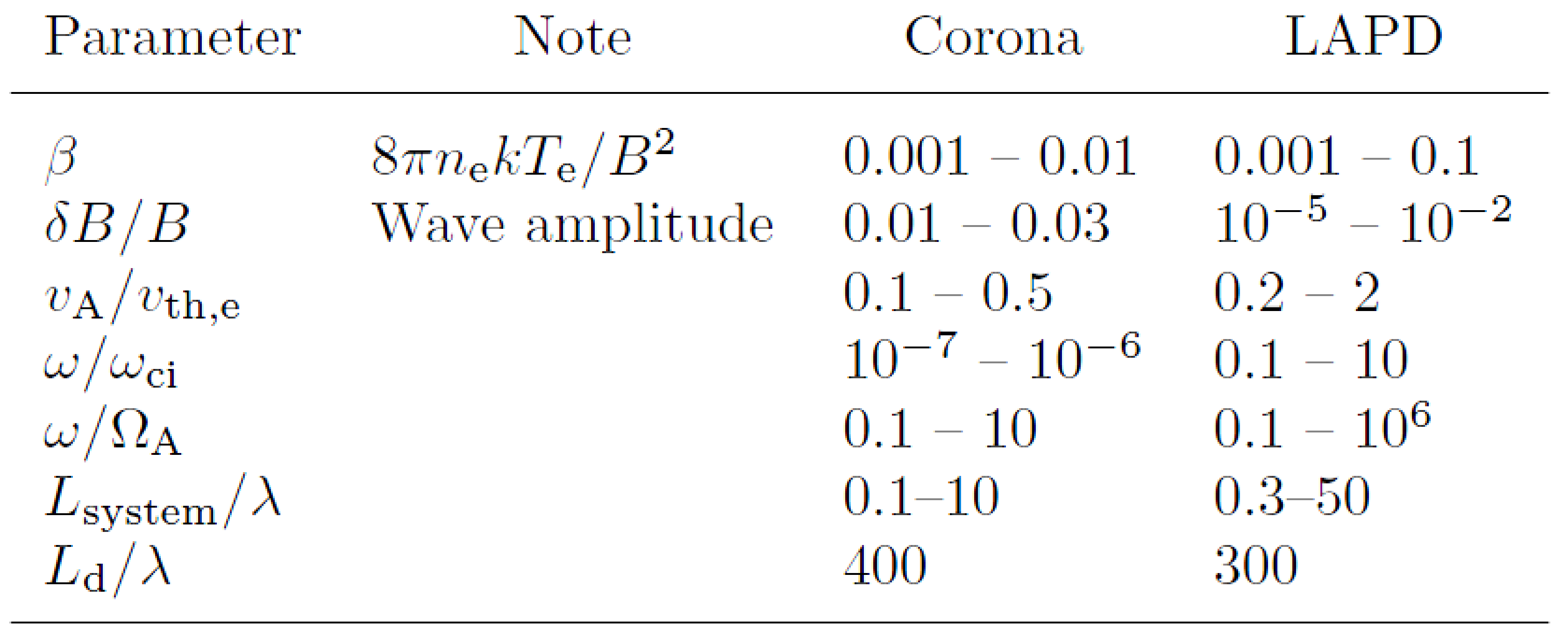
- Detailed physical models hard to relate to observables.

- Model–generated synthetic observations may not use correct physics.

- Laboratory experiments are measured well and (more) tractable to model.

- Need to know which processes are relevant, and how to distinguish one process from another.

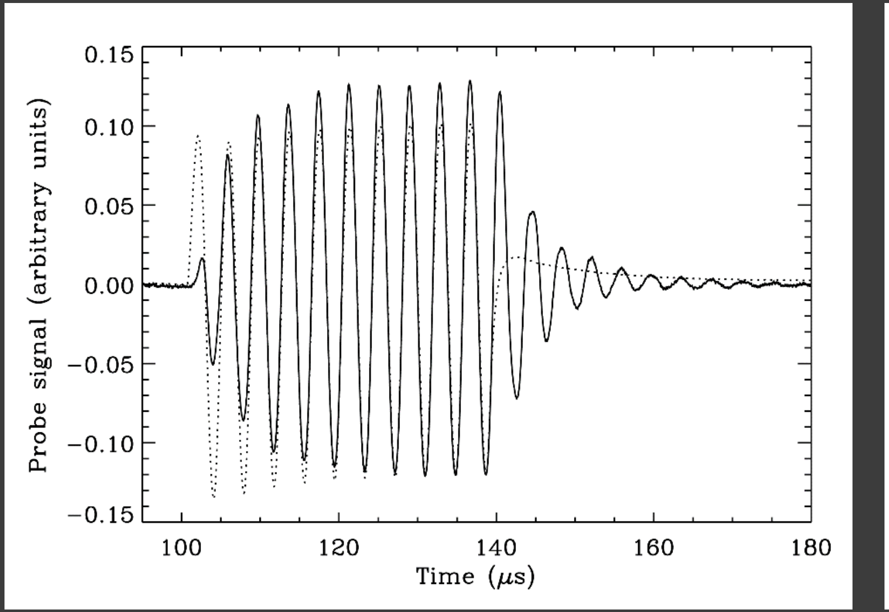
LAPD conditions can match coronal holes.

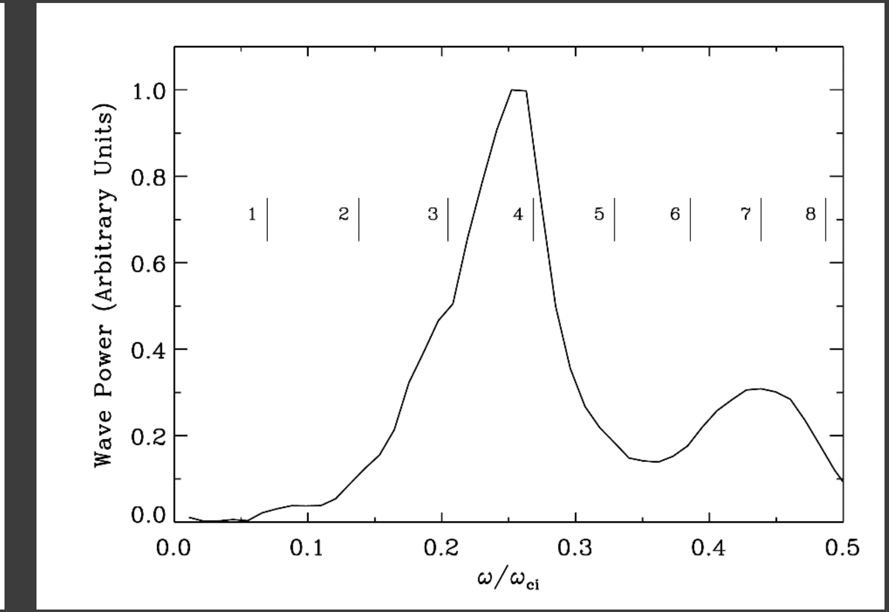


Parameter	Note	Corona	LAPD
β	$8\pi n_e k T_e / B^2$	0.001 – 0.01	0.001 – 0.1
$\delta B / B$	Wave amplitude	0.01 – 0.03	10^{-5} – 10^{-2}
$v_A / v_{th,e}$		0.1 – 0.5	0.2 – 2
ω / ω_{ci}		10^{-7} – 10^{-6}	0.1 – 10
ω / Ω_A		0.1 – 10	0.1 – 10^6
L_{system} / λ		0.1–10	0.3–50
L_d / λ		400	300

Wave reflection in a cavity

Magnetic mirror with 600 G at the antenna and 1600 G at the ends





f=200 kHz ~ 0.2 f_{ci}

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.

Wave Energy Flux

$$F = 2\rho v_{nt}^{2} V_{A}$$

$$V_{A} = \frac{B}{\sqrt{4\pi\rho}}$$

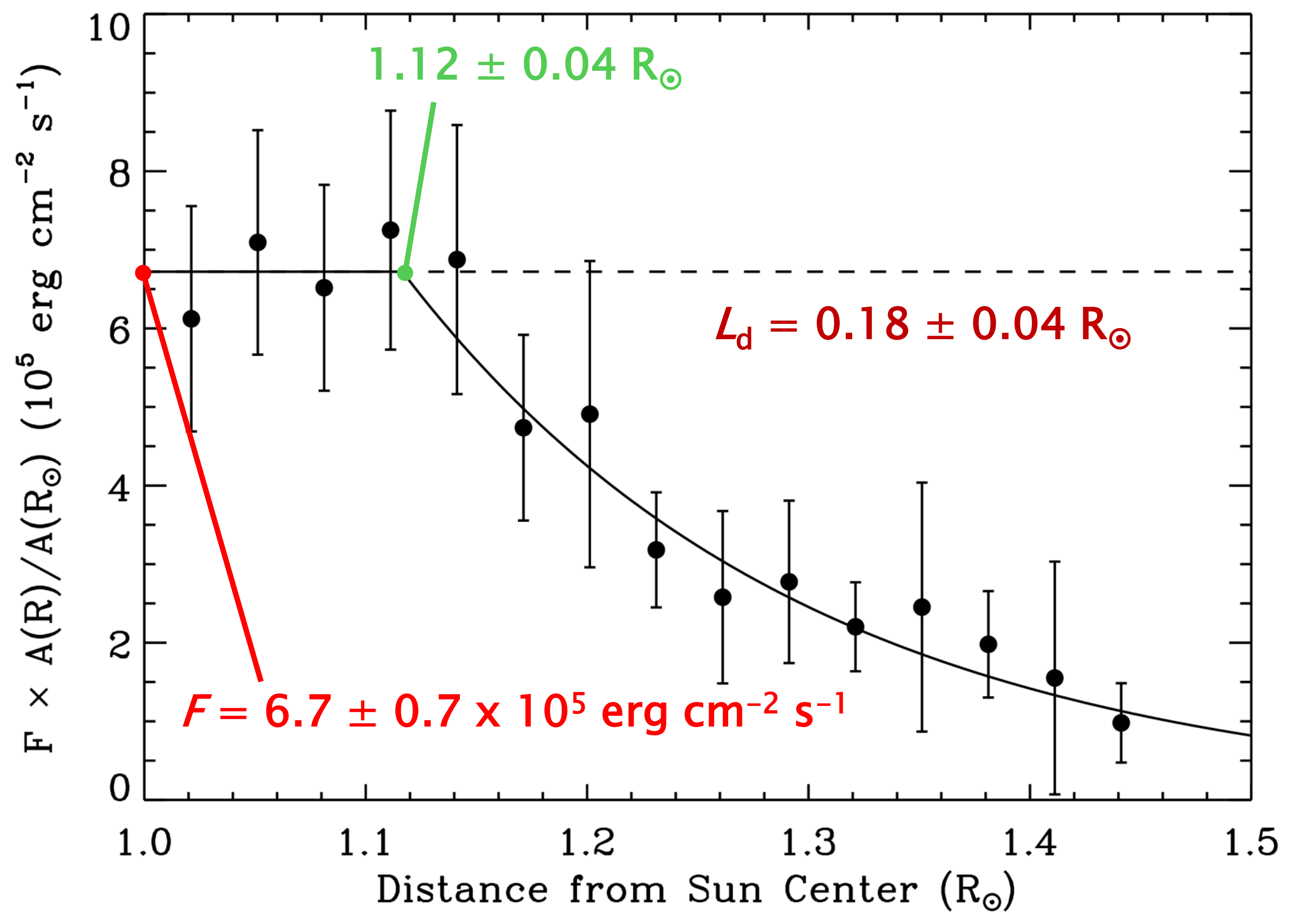
$$\rho \sim 1.15\, m_{\mathrm{p}} n_{\mathrm{e}}$$

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

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

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

F Corrected for Area Expansion



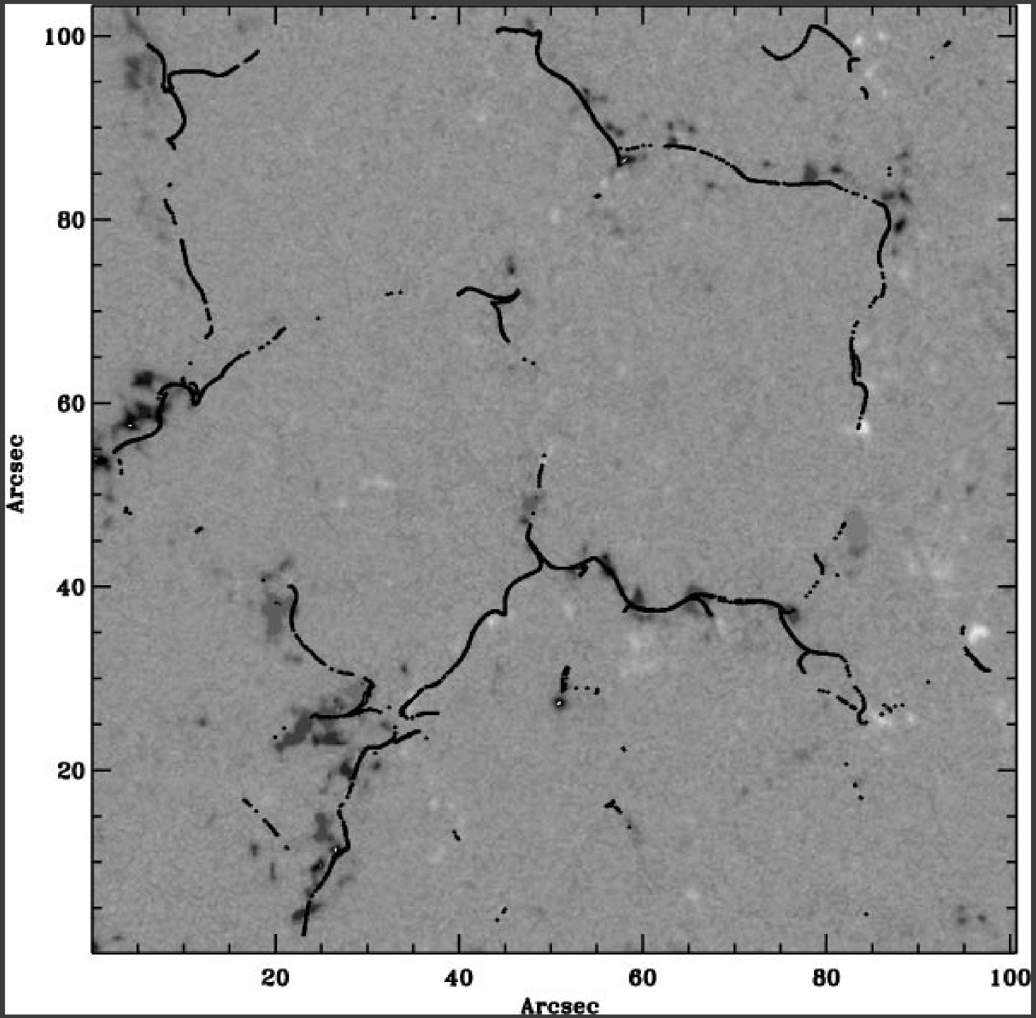
Energy Required

Need ~6×10^5 erg cm^{-2} s^{-1} this solar minimum.

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

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

Structure of Surface Magnetic Field



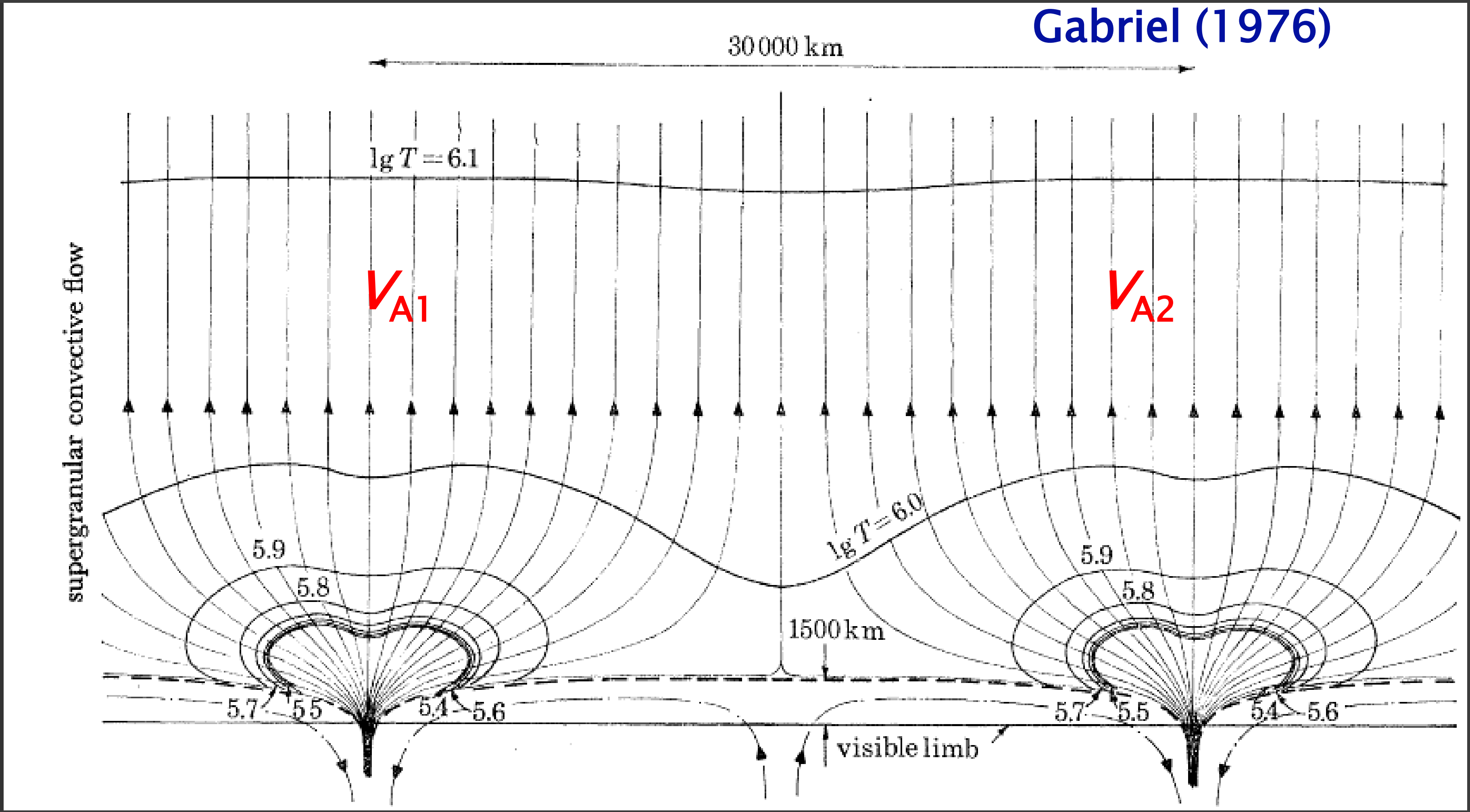
Roudier et al. (2009)

Convection cells (supergranules) Outlined by black lines

Magnetic field shown in greyscale white = positive, black = negative, grey = neutral.

Magnetic network.

Structure of Solar Magnetic Field



Gabriel (1976)