Simulations of Alfvén wave driving of the solar chromosphere

Efficient heating and spicule launching

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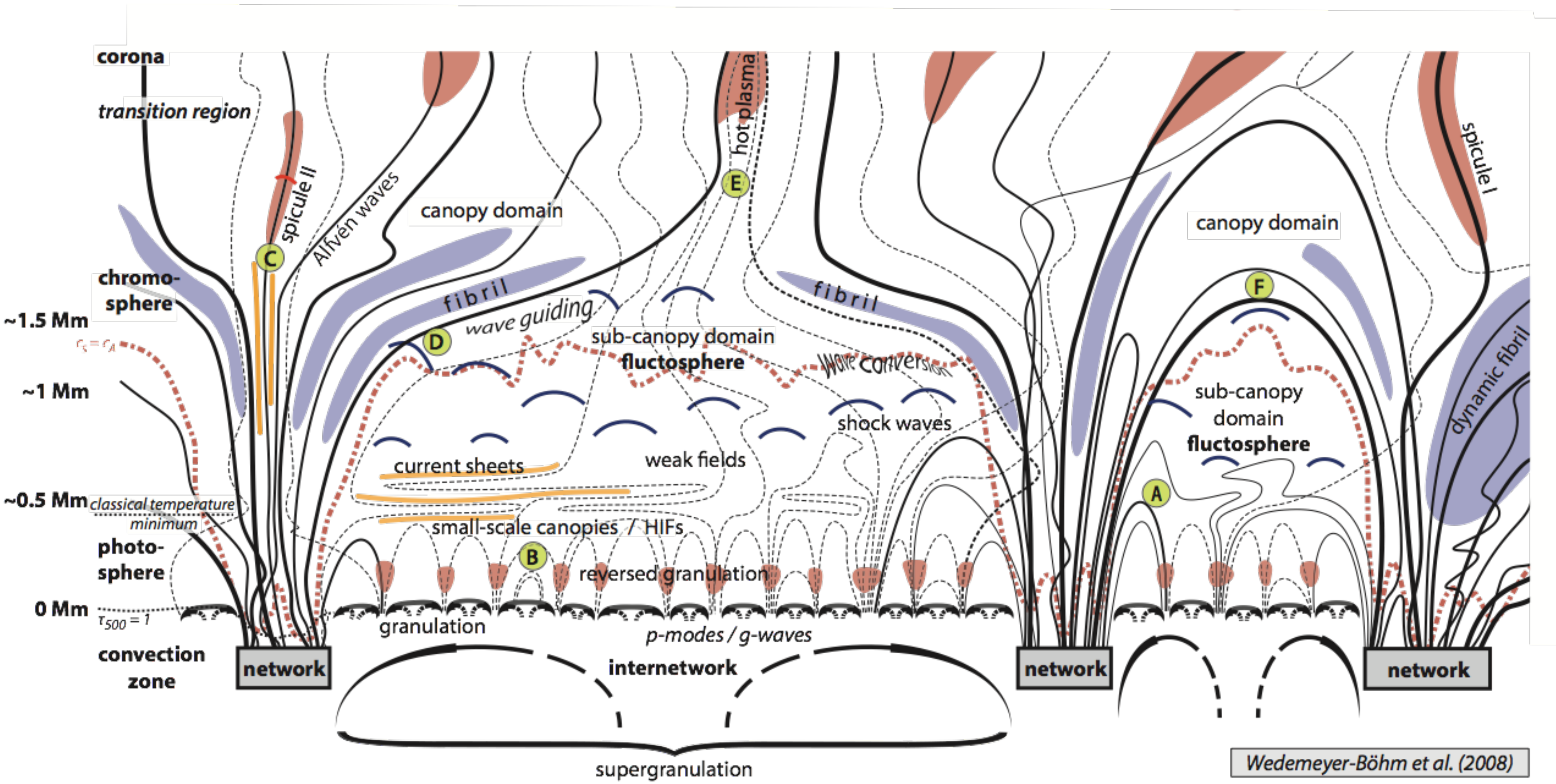
IRIS-6, Stockholm 2016

Chromospheric Heating & Spicules



Chromospheric Heating

Lower ~ 0.1 erg cm^{-3} s^{-1}

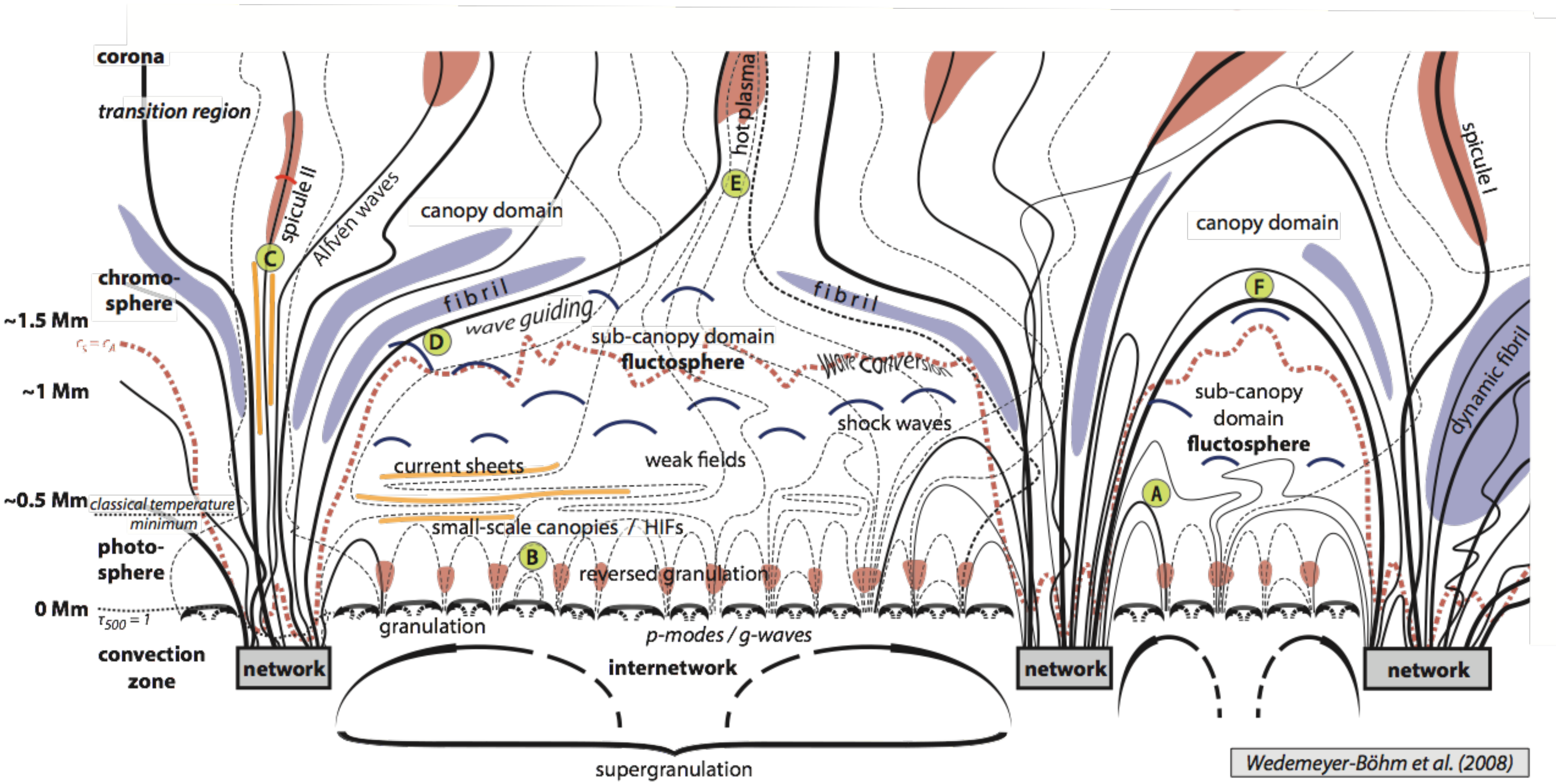
Upper~ 10^{-3} erg cm^{-3} s^{-1}

Spicules

Type-I spicule rise speed ~15 km s^{-1}

Transverse r.m.s. speeds ~4-7 km s^{-1}

Chromospheric Heating & Spicules



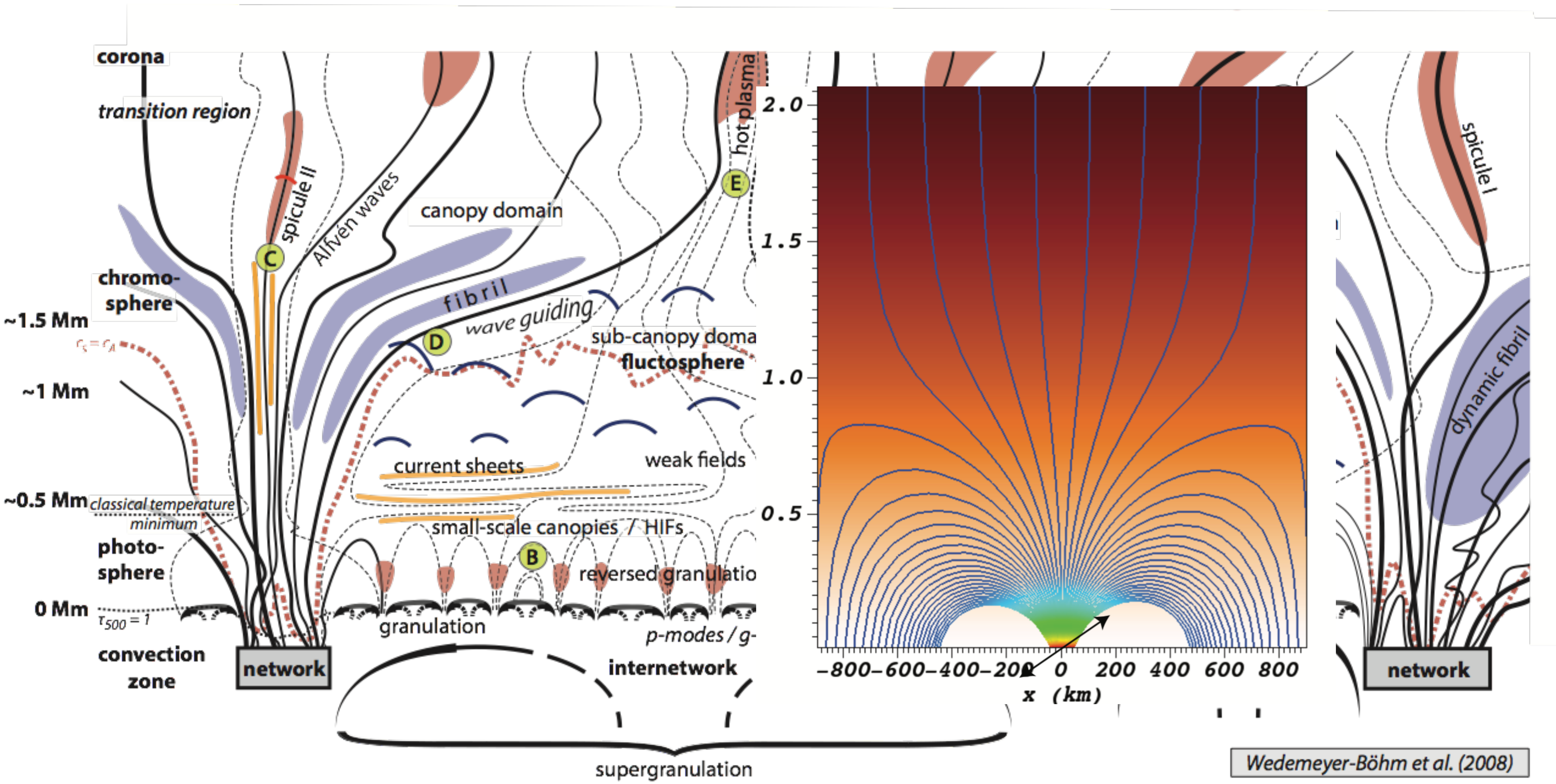
Hollweg (Solar Physics 1978-82) Alfvén waves → ponderomotive force → shocks

Hollweg (1982) suggested that the shocks are spicules

Matsumoto & Suzuki (ApJ, 2012 and MNRAS, 2014) - chromosphere + corona + solar wind

van Ballegooijen et al. (2011, ApJ) reduced MHD turbulence chromospheric heating

Chromospheric Heating & Spicules



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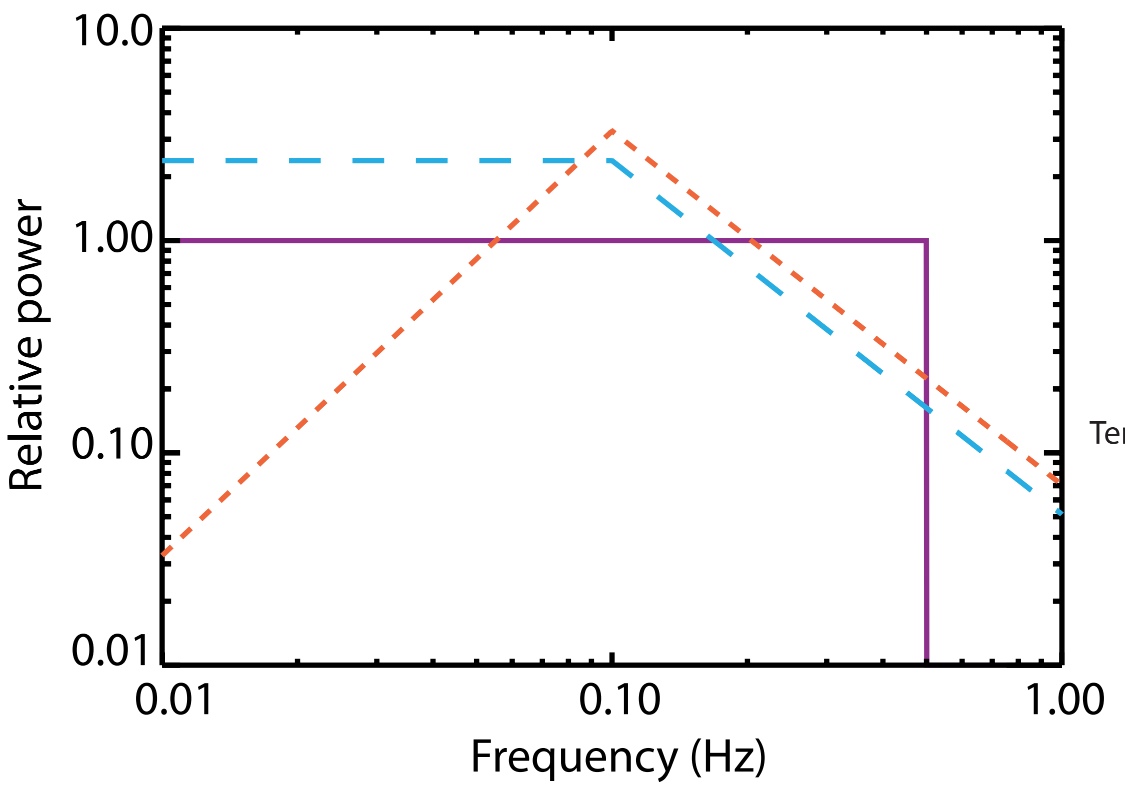
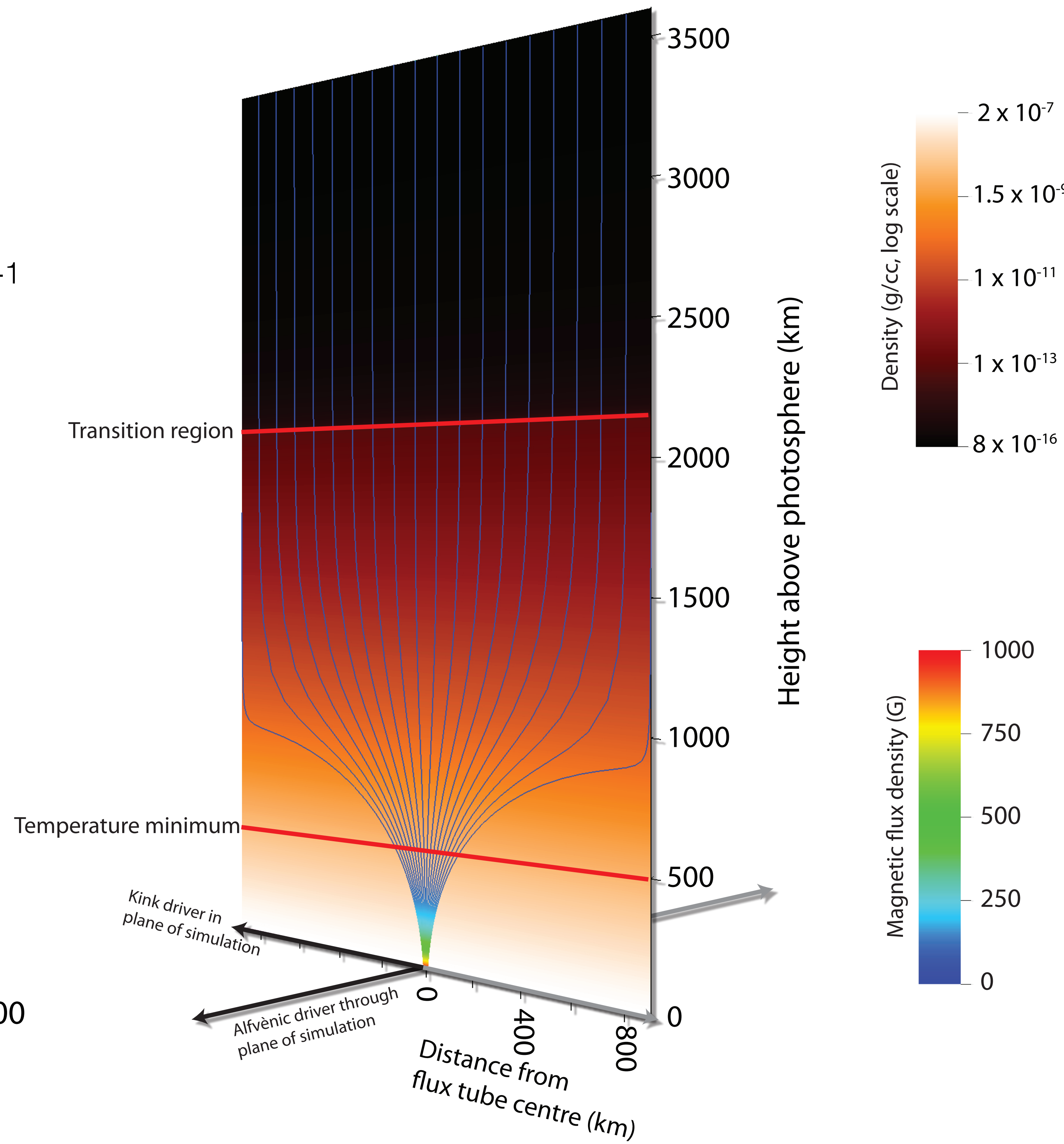
MHD Driving of Flux Concentration

Model Setup

- Expanding flux tube
- Drive Alfvén or kink waves in 2.5D
- Total Poynting flux 2×10^7 erg cm^{-2} s^{-1}
- Flat spectrum or K41





Resistive MHD with Neutrals

Pedersen resistivity

$$\eta_P = \eta + \frac{\xi_n^2 B^2}{(1-\xi_n)}\frac{1}{\rho}\tau_{in}$$

$$\xi_n = \rho_n/\rho - \text{neutral fraction}$$

$$\tau_{in} - \text{ion-neutral collision time}$$

$$\begin{aligned}
\frac{D\rho}{Dt} &= -\rho\nabla.\mathbf{v} \\
\rho\frac{D\mathbf{v}}{Dt} &= \mathbf{j}\times\mathbf{B} + \rho\mathbf{g} - \nabla P + \mathbf{F}_{shock} \\
\frac{\partial\mathbf{B}}{\partial t} &= -\nabla\times\mathbf{E} \\
\frac{D\epsilon}{Dt} &= -\frac{P}{\rho}\nabla.\mathbf{v} + \frac{H_{\rm visc}}{\rho} + \frac{H_{\rm Ohmic}}{\rho} \\
\mathbf{j} &= \frac{1}{\mu_0}\nabla\times\mathbf{B} \\
\mathbf{E} &= -\mathbf{v}\times\mathbf{B} + \eta\mathbf{j}_{||} + \eta_p\mathbf{j}_{\perp}
\end{aligned}$$

Cooling term

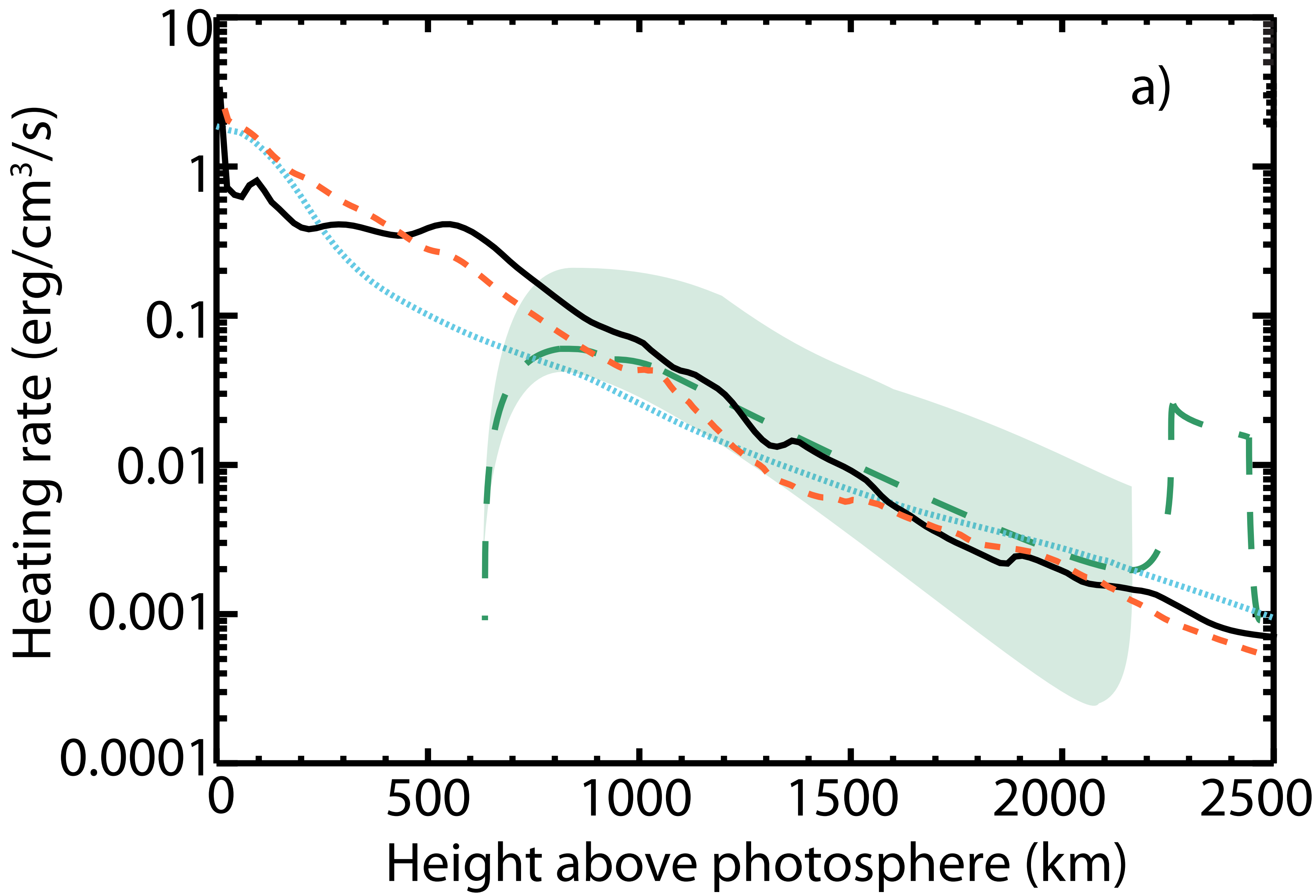
$$H_{cooling}(\mathbf{r},t) = \frac{1}{\tau}\int_{t-\tau}^{t} H_{visc}(\mathbf{r},t')\;dt'$$

Simulations

- 4000x8000 resolution
- Run to t = 1000 s (~15 Alfvén transits)
- Cooling averaged over 16 s

Papers from Piddington (1956), Goodman (2011), Leake (2006), De Pontieu (2001), Khomenko (2012), Martinez-Sykora (2012)….

Average shock heating



Black - shock heating for mixed driver

Blue - shock heating Alfvén driver

Orange - mixed mode driver and cooling

Green - cooling rate from Avrett 1981 Model C (quiet)

Shaded - bounded by the Model A (dark network region) and Model F (very bright network element)

Avrett, Solar Phenomena in Stars and Stellar Systems, 1981

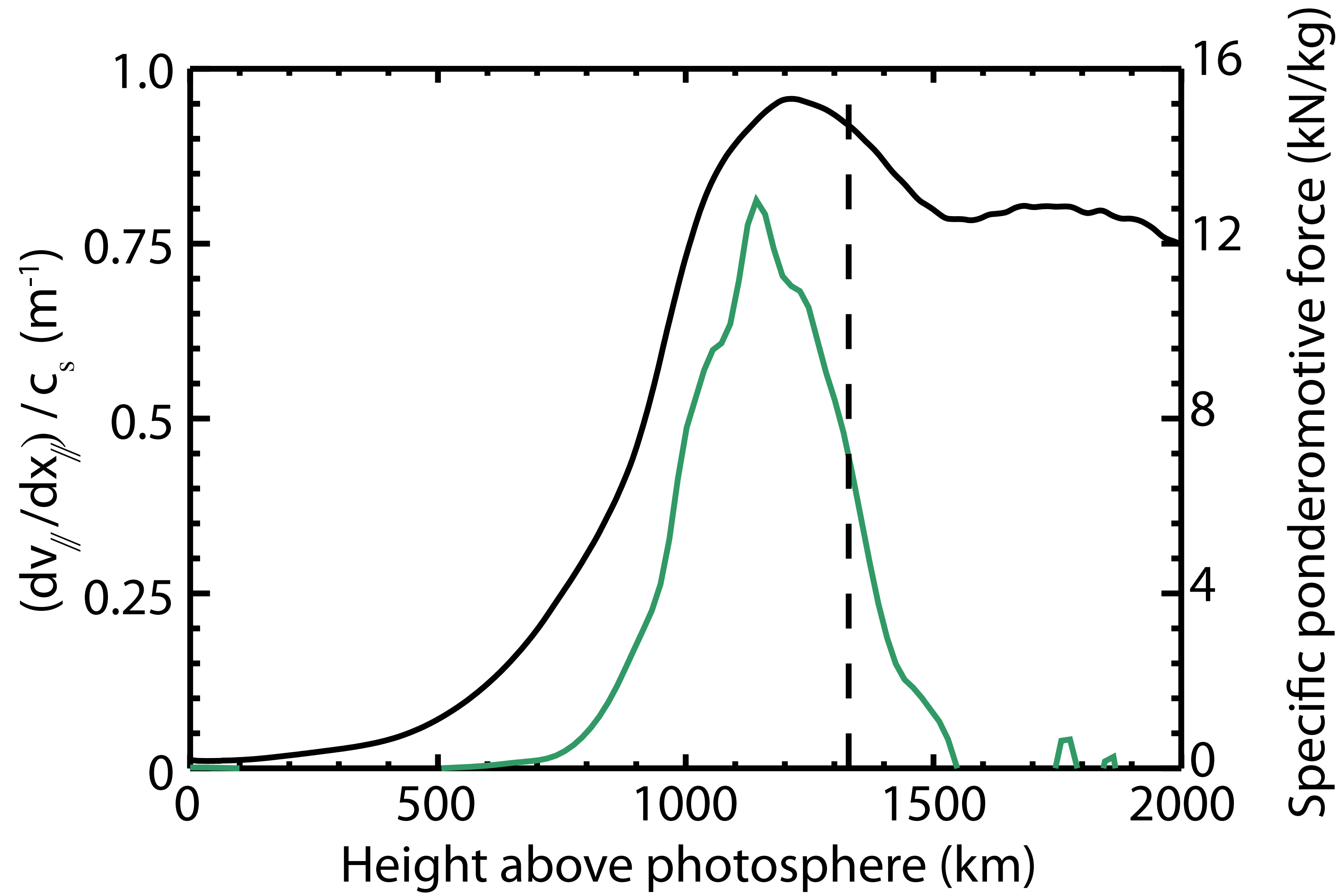
Ponderomotive Force

Heating from acoustic/slow modes

No acoustic mode driver

Generated by ponderomotive MHD

$$\rho \frac{dv_{\parallel}}{dt} \sim -\nabla B_{\perp}^2$$



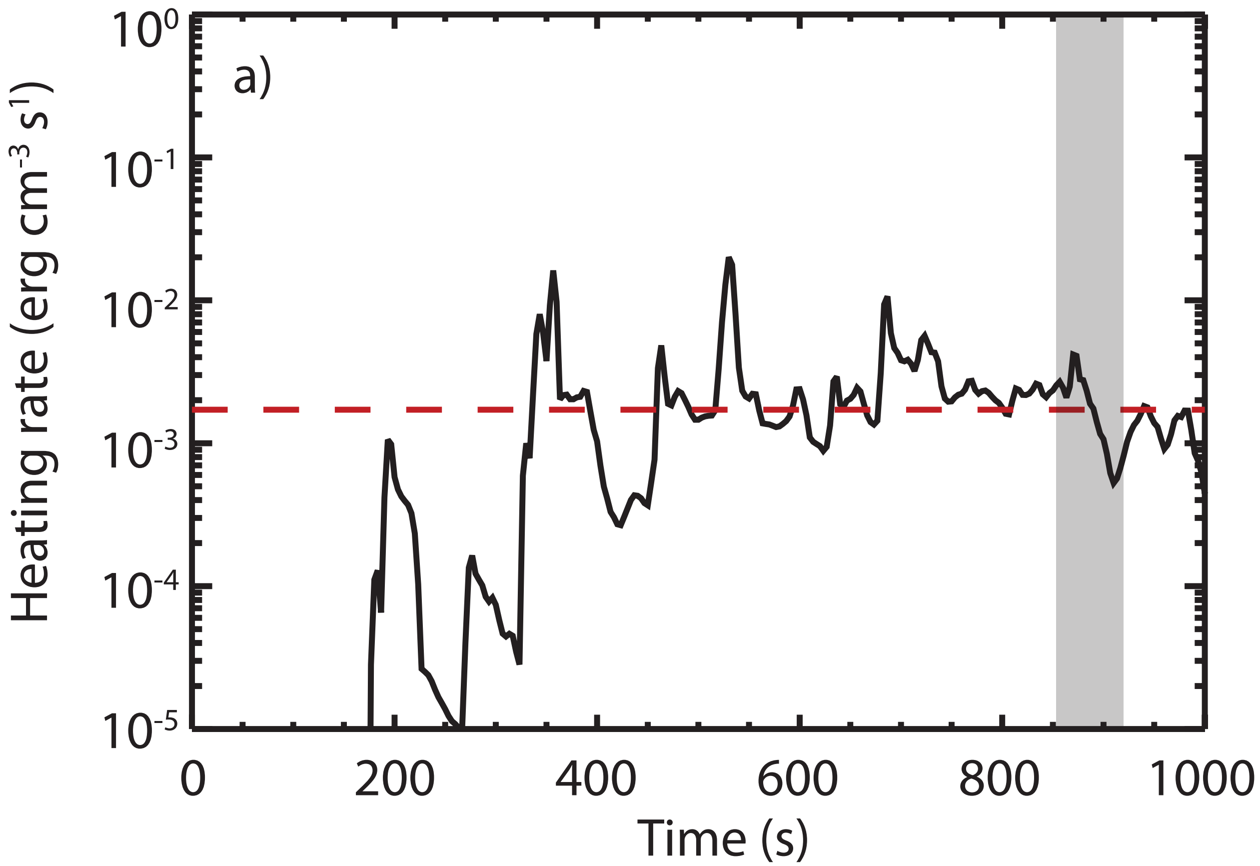
Sound waves generated in chromosphere from MHD waves

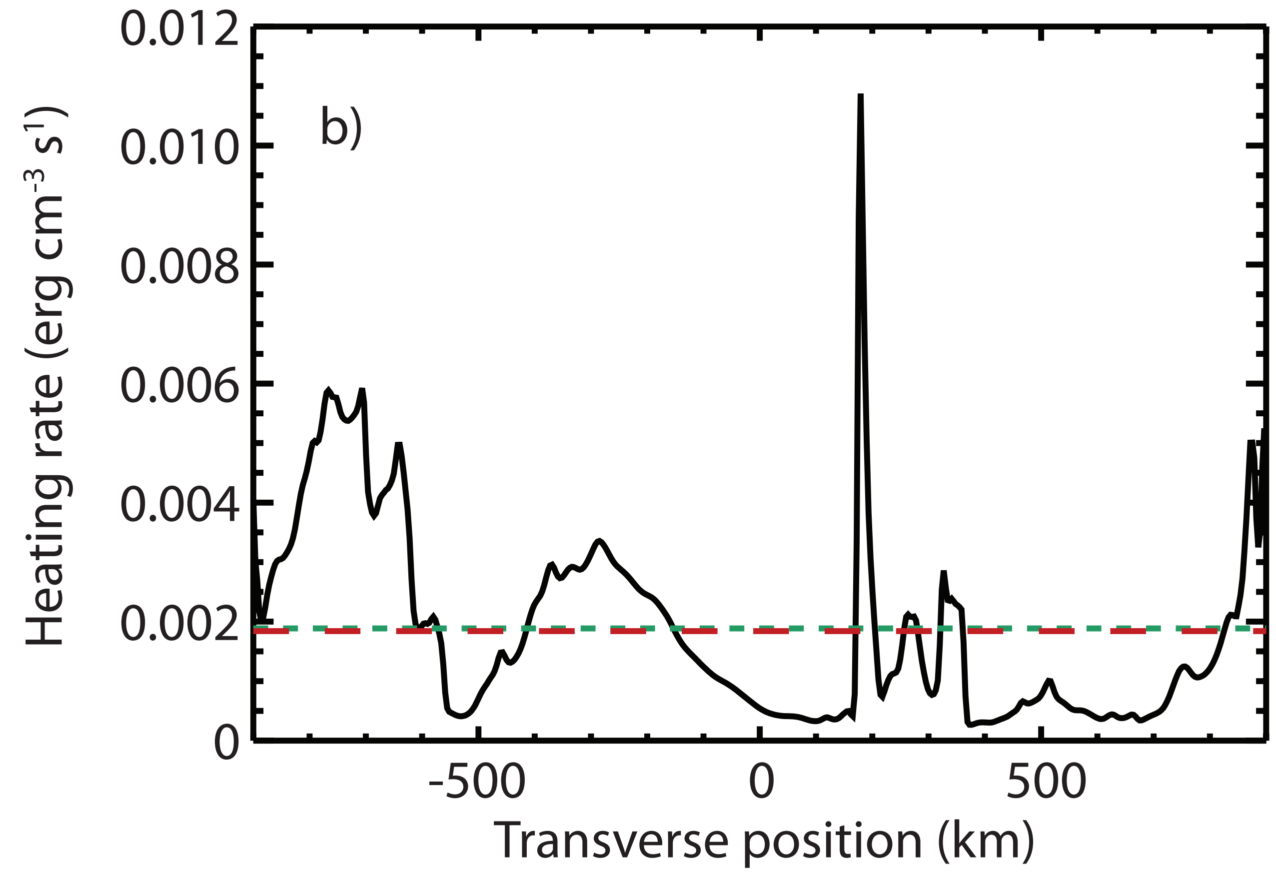
Coupling not at β=1 (vertical dashed line)

Ponderomotive robust - just B-field and mass density

Arber, Brady & Shelyag, ApJ, **187**, 94 (2016)

Time & spatial heating profiles





Black - Heating averaged over 30 seconds

Red - Average over whole simulation

Spicules?

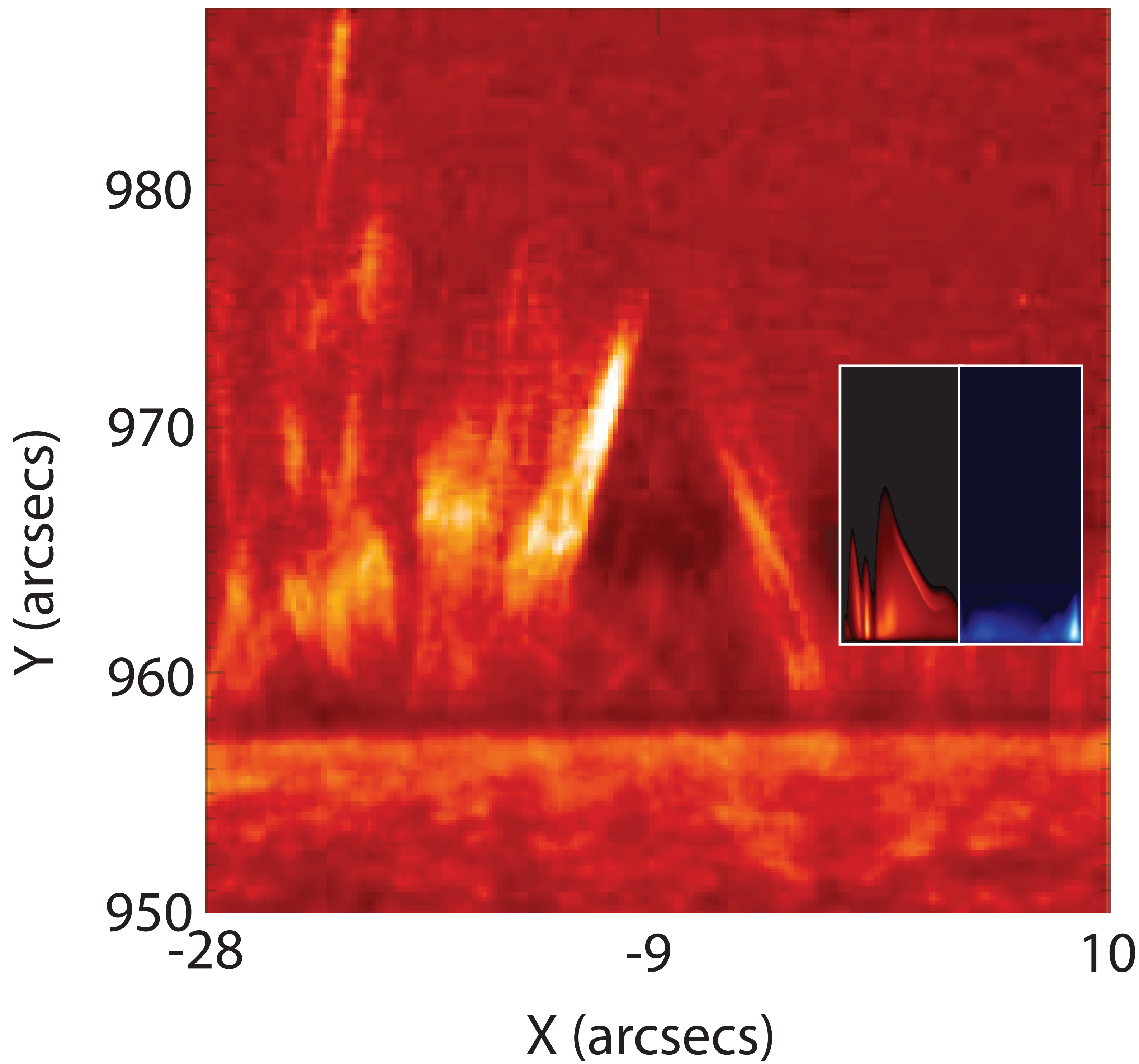
Acoustic shocks lift dense material

The observation is from an Hinode SOT Ca II H image from Tsiropoula.

The insert plots the relative change in density from the initial conditions of the coronal part of a simulation at the same height and scale.

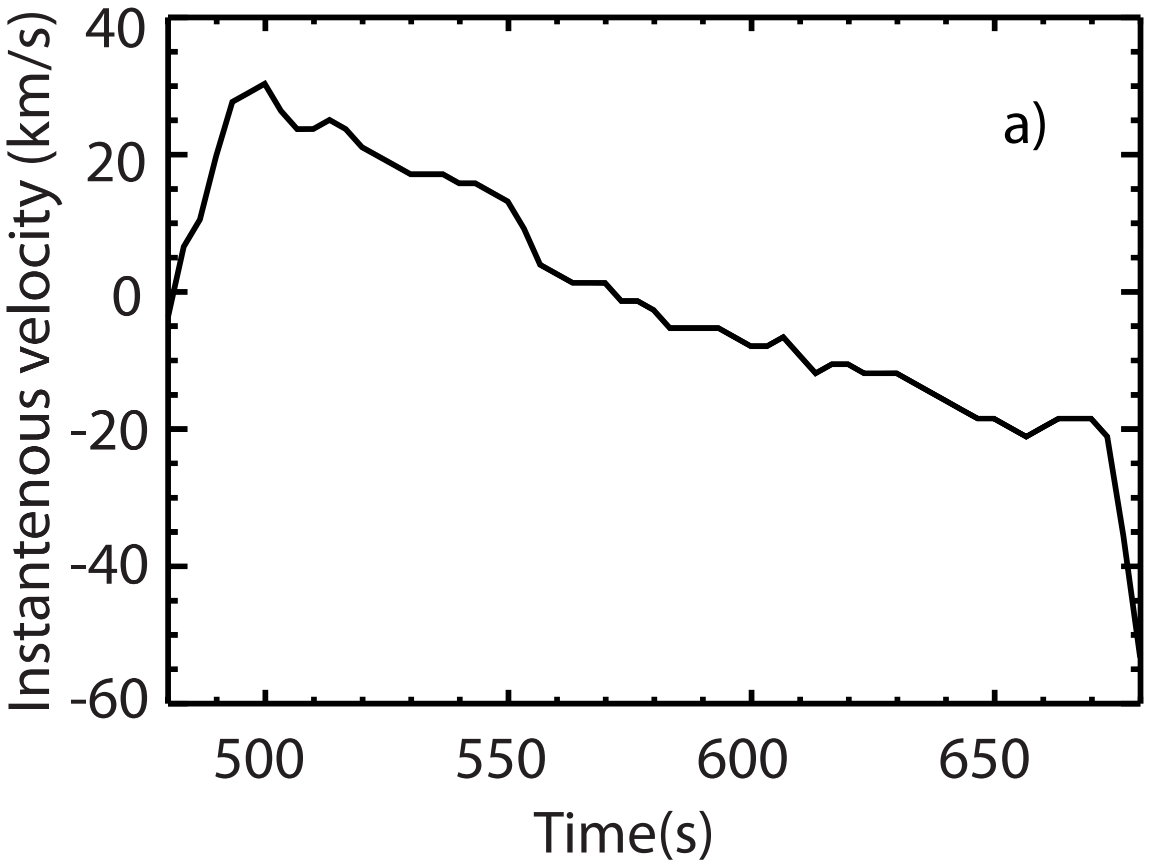
Red - mixed mode

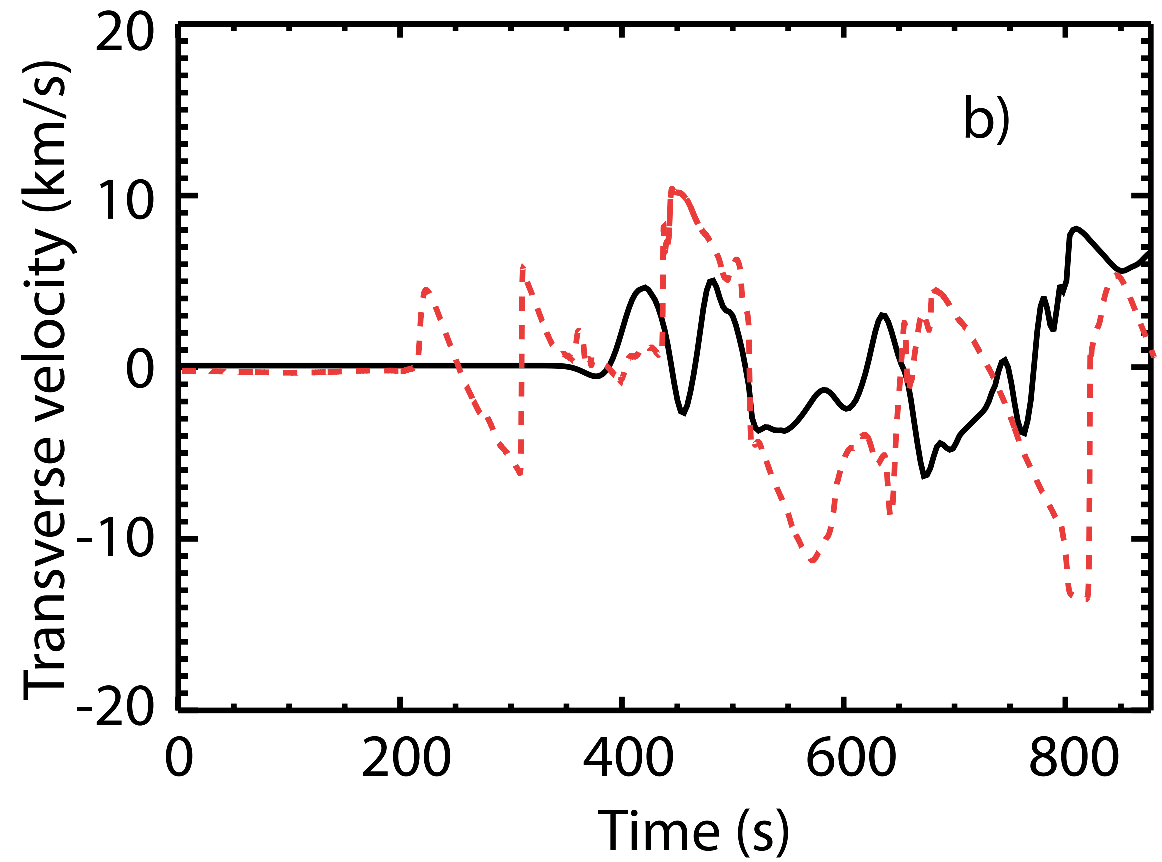
Blue - Alfvén only



Tsiropoula, et al. Space Science Reviews, 169 (2012)

Spicule velocity





Black - mixed Alfvén and kink driver. **Red** - Alfvén only driver.

Simulations

Typical rise speeds at TR ~12 km s^{-1}

Transverse speeds ~9 km s^{-1}

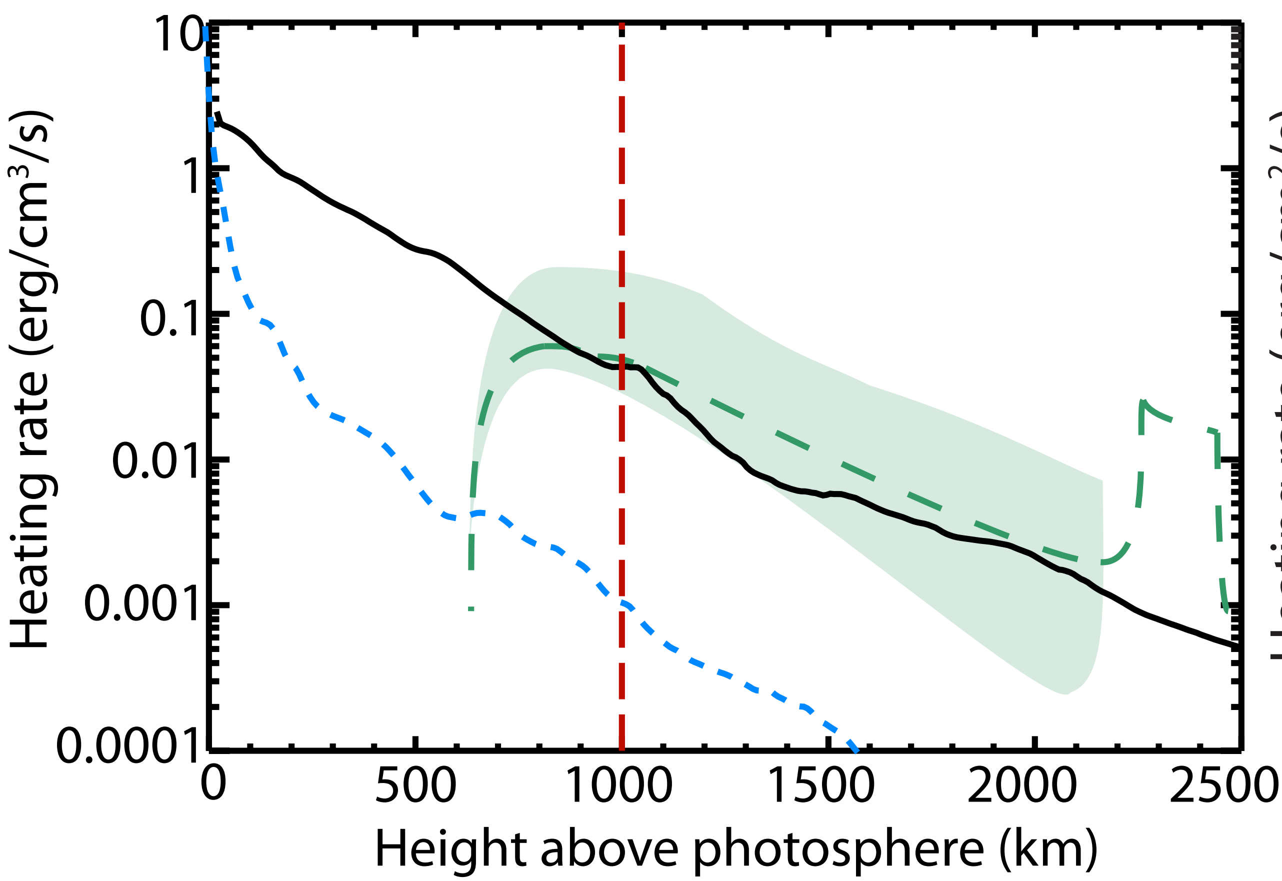
Observations

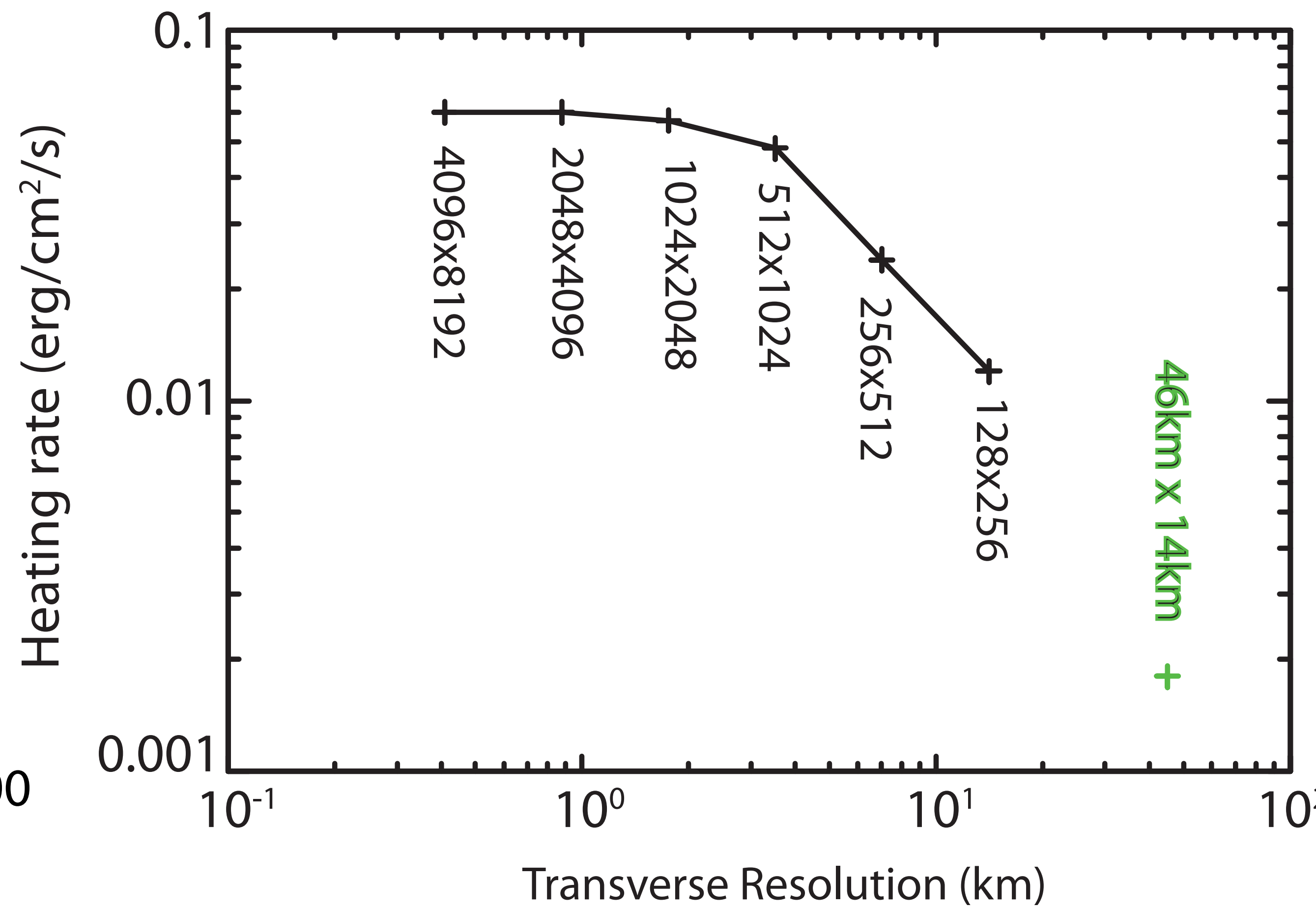
Type-I spicule rise speed ~15 km s^{-1}

Transverse r.m.s. speeds ~4-7 km s^{-1}

Beckers, Solar Physics, **3**, 367 (1968)
De Pontieu et al. Science, **318**, 1574 (2007)

Resolution and Convergence





Black - converged result with ~1km resolution

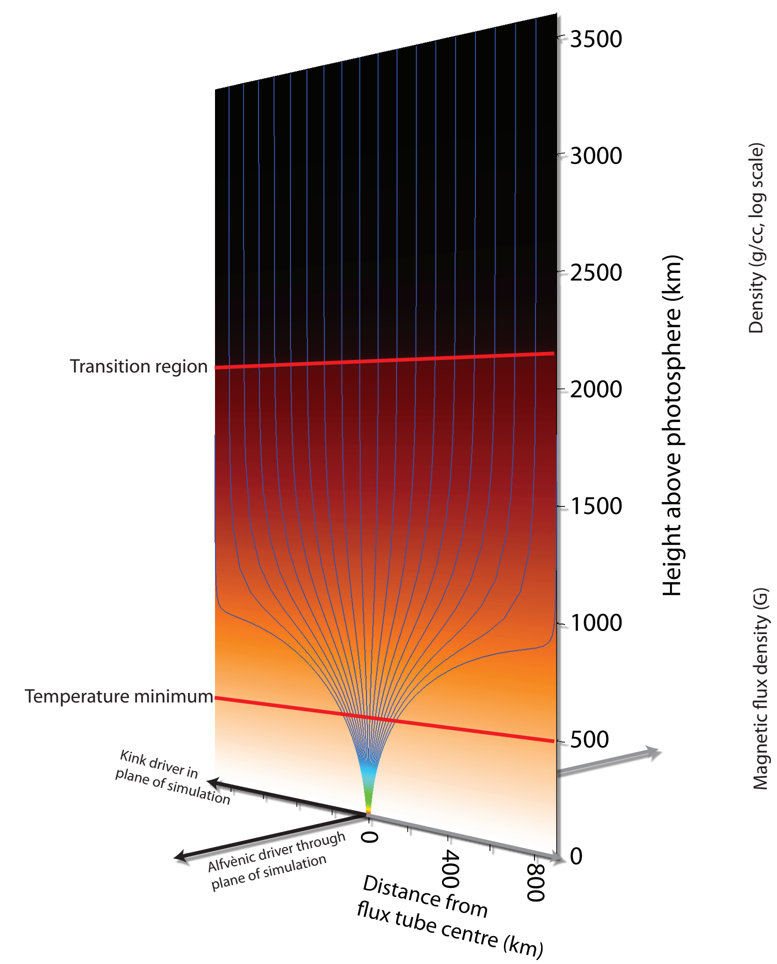
Blue - typical photospheric simulation with ~40km resolution

Summary

- Hollweg was right in 1980
- Broad spectrum MHD driver generates slow modes - ponderomotive coupling
- Slow modes shock low in atmosphere
- Shock heating matches estimates of heating requirements
- Shock rise and transverse velocities match observations of Type-I spicules

But…

- In 3D Alfvén cascade to turbulence is faster
- Only limited range of, rather extreme, model flux tubes tested
- No reconnection or flux emergence …
- No acoustic (p-mode) driving …



Brady & Arber, ApJ, in review (2016)