Alfvén wave heating of the solar chromosphere

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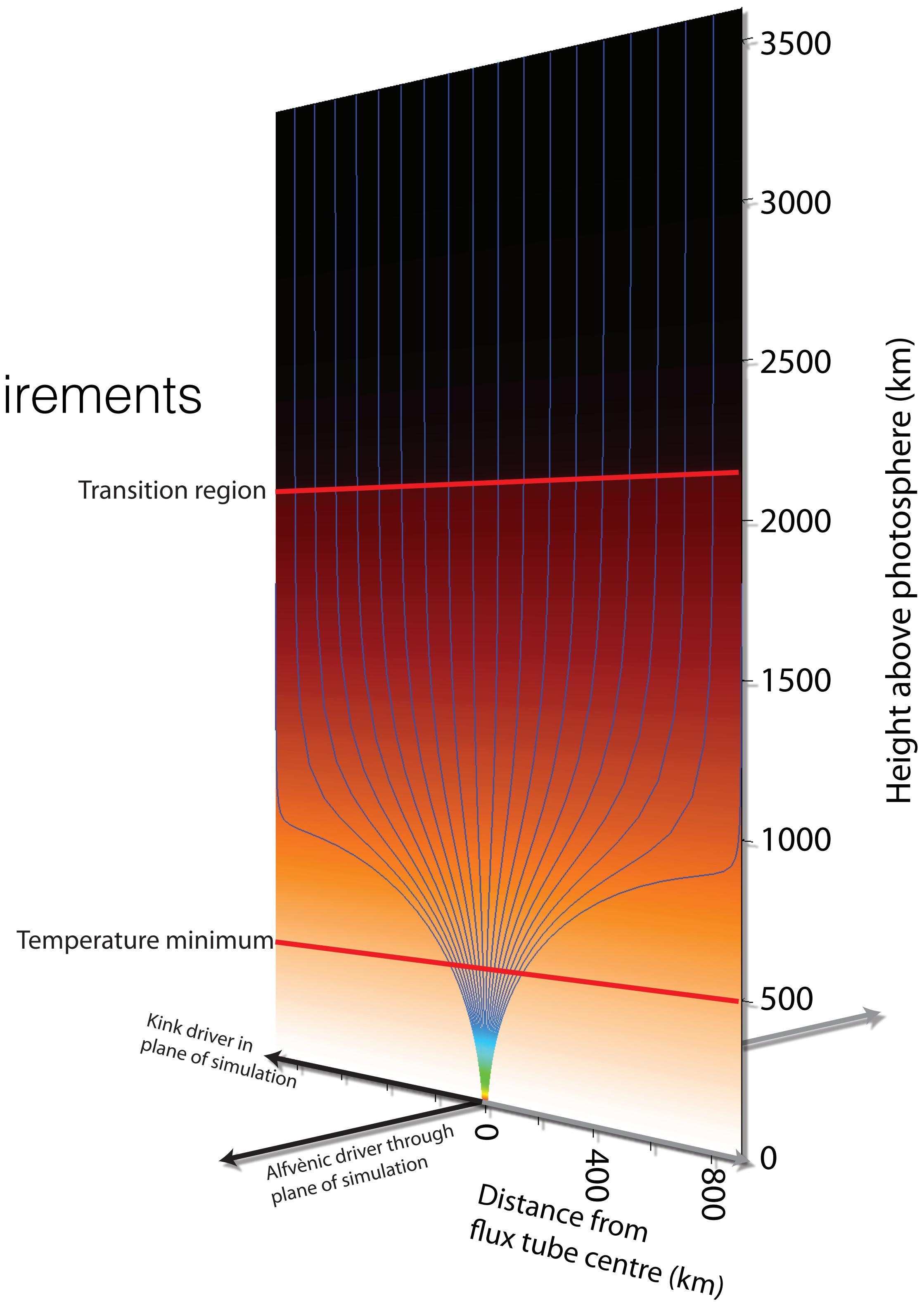
Solarnet 4, Lanzarote, 16-20 January 2017

Start at the end

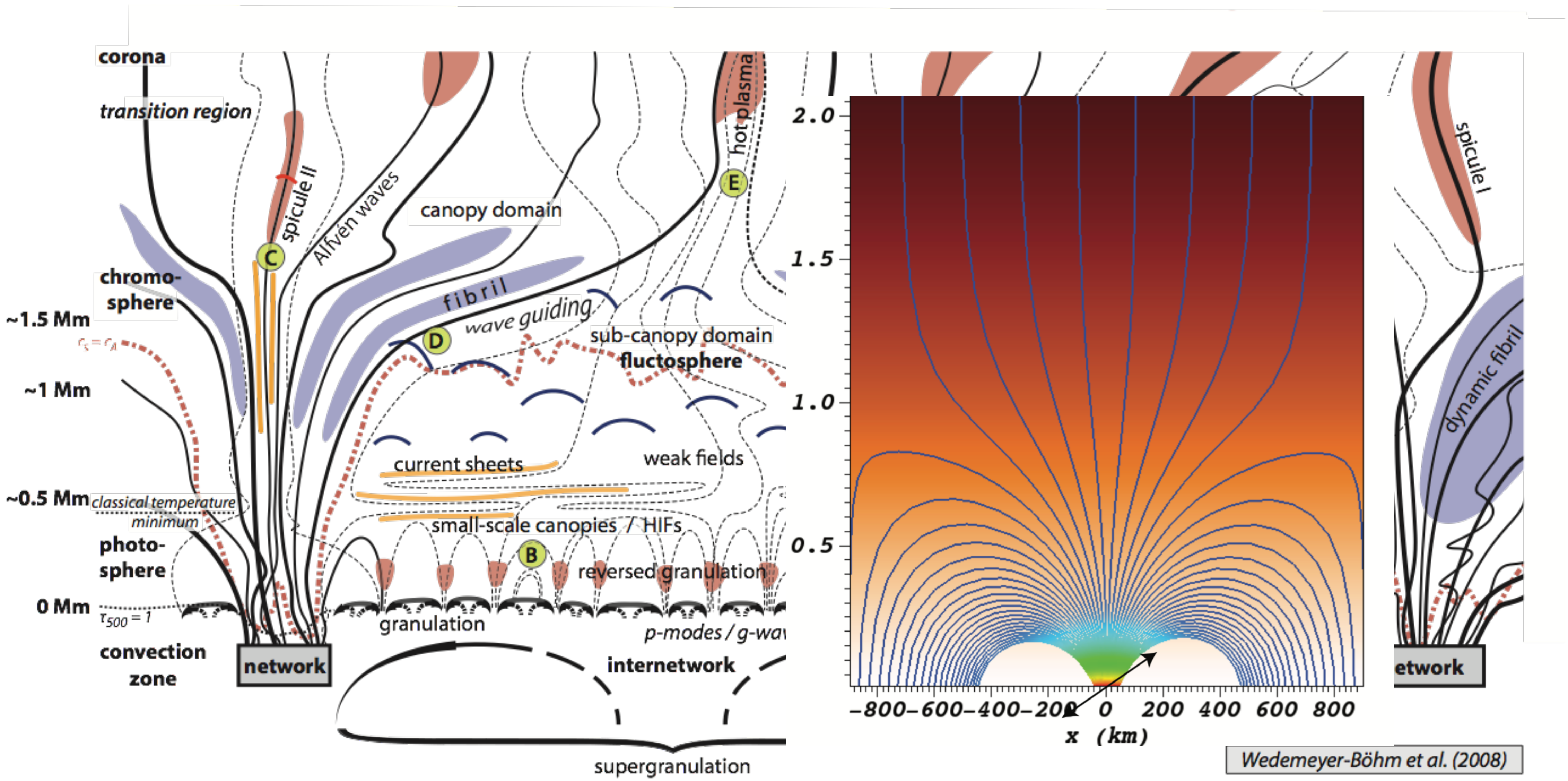
Shake an expanding 2D flux tube at photosphere

- Broad spectrum MHD driver
- Ponderomotively couple to slow modes
- Slow modes shock low in atmosphere
- Shock dissipation leads to heating
- Shock heating matches estimates of heating requirements
- Shocks also lift chromospheric material
- Velocities match observations of Type-I spicules



Model Setup is highly idealized and only 2D

Chromospheric Heating & Spicules



Chromospheric Heating

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

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

Spicules

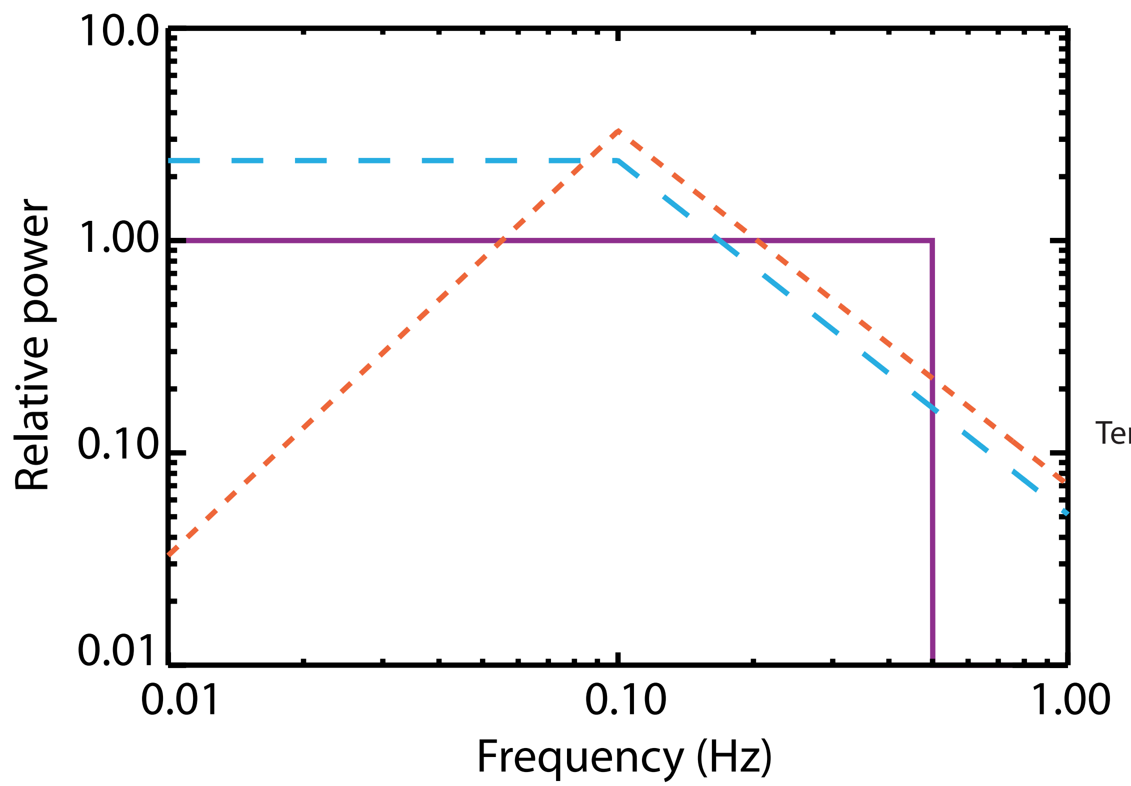
Type-I spicule rise speed ~15 km s^{-1}

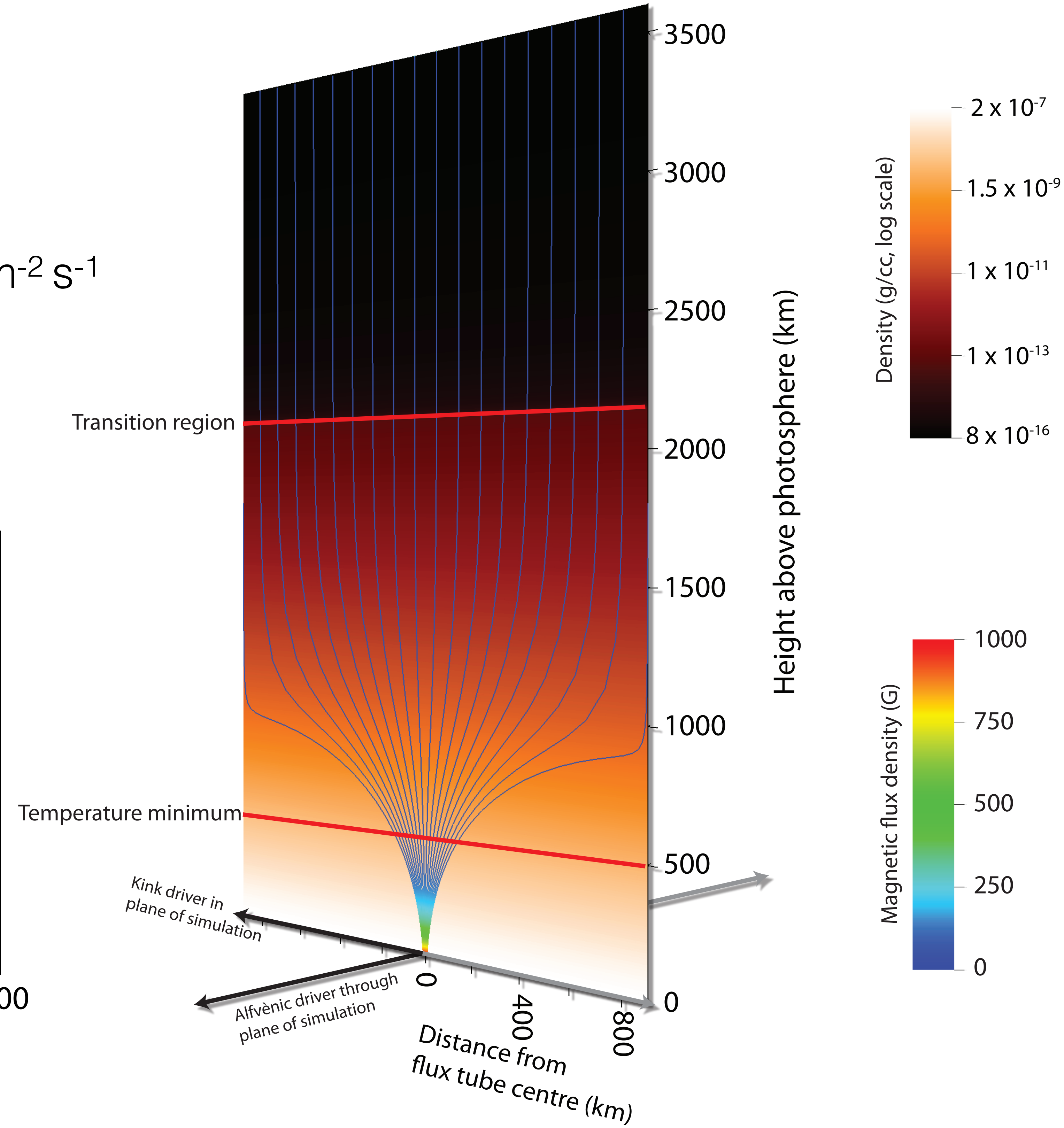
Transverse r.m.s. speeds ~4-7 km s^{-1}

MHD Driving of Flux Concentration

Model Setup

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





Work follows from previous theory/simulation, e.g.
Hollweg (Solar Physics 1978-82) **Hollweg** (1982)
Matsumoto & Suzuki (ApJ, 2012 and MNRAS, 2014) **van Ballegooijen et al.** (2011, ApJ)

Resistive MHD with Neutrals

Pedersen resistivity

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

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

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

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

Cooling term

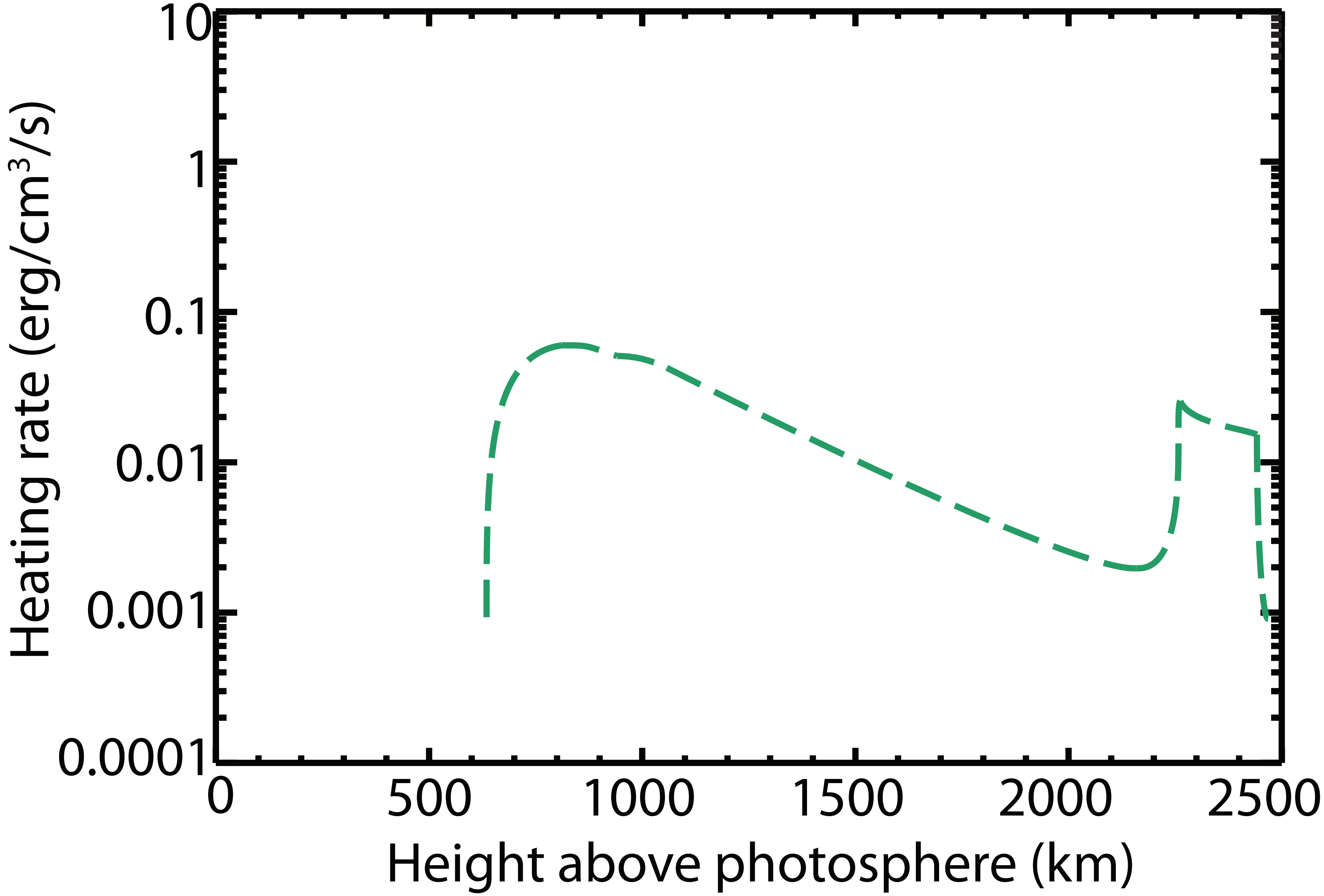
$$H_{cooling}(\mathbf{r},t) = \frac{1}{\tau}\int_{t-\tau}^{t} H_{visc}(\mathbf{r},t')\ dt'$$

Simulations

- 4000x8000 resolution (~1km x 2km)
- 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)….

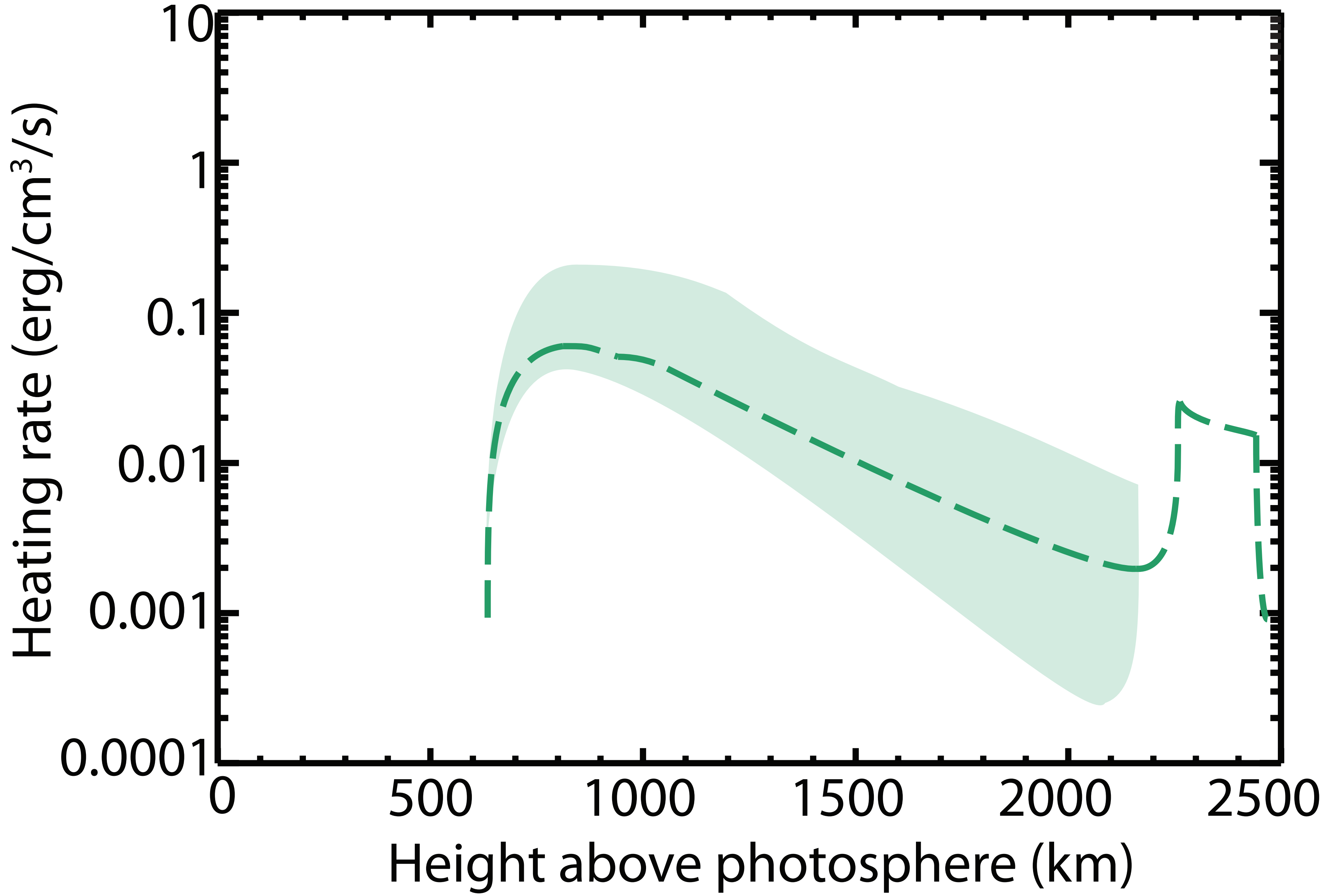
Estimated heating requirement



Estimate of local cooling due to chromospheric radiation from Avrett (1981) Model C for the quiet chromosphere

Avrett, Solar Phenomena in Stars and Stellar Systems, 1981

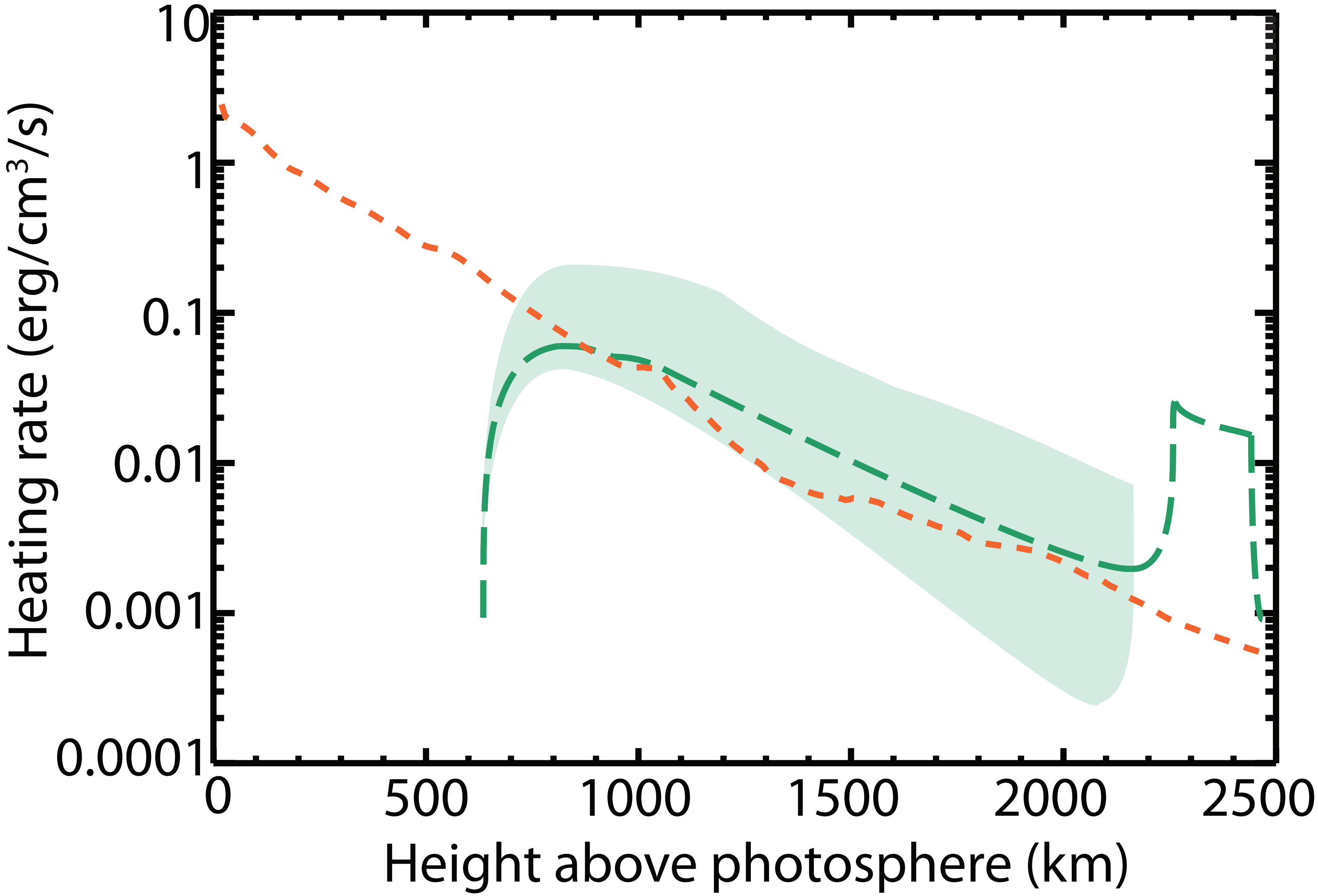
Estimated heating requirement



Shaded area is bounded by Avrett Model A (dark network region) and Avrett Model F (very bright network element)

Avrett, Solar Phenomena in Stars and Stellar Systems, 1981

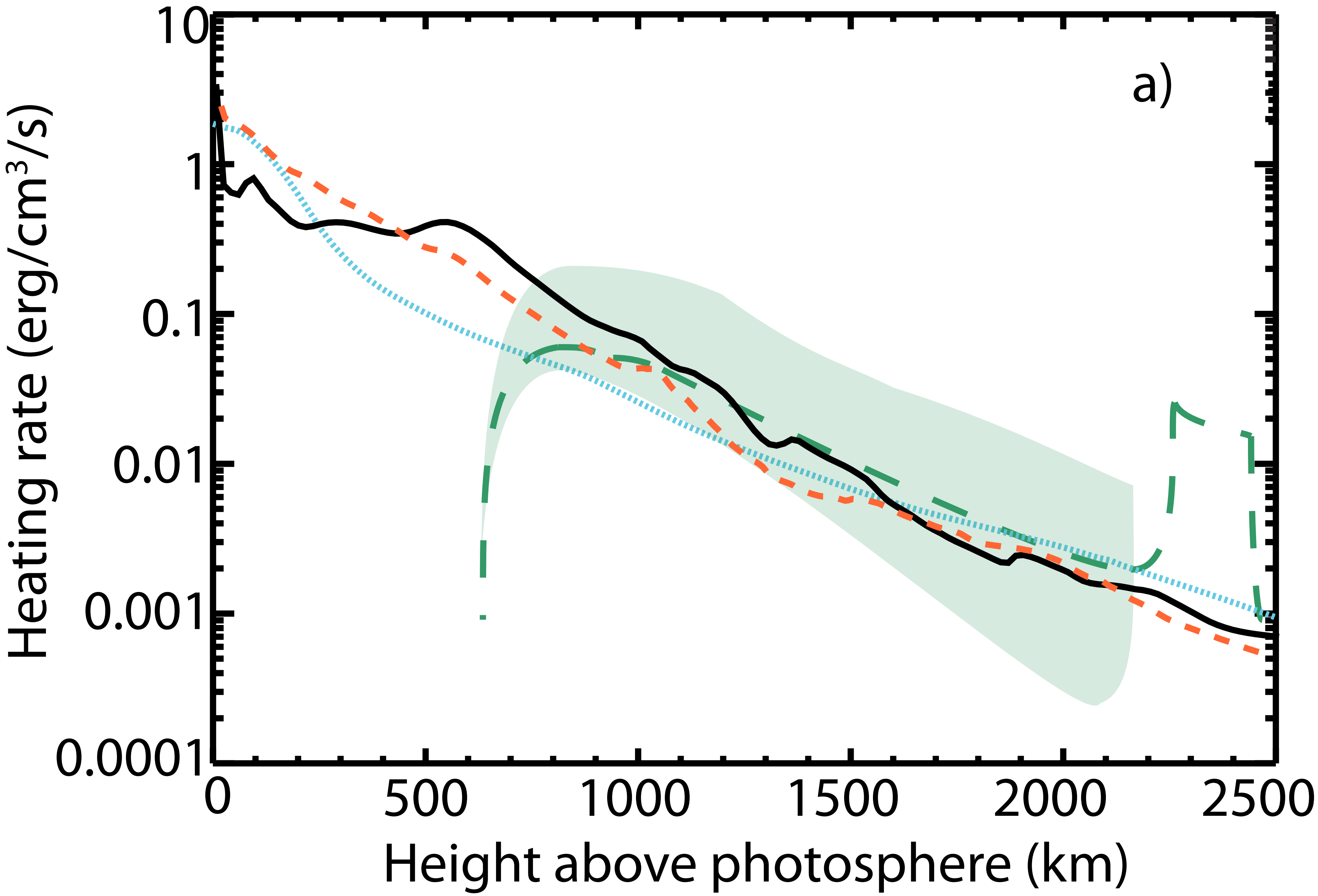
Average shock heating



Short dashed line from simulations with mixed driver and local cooling term in energy equation

Avrett, Solar Phenomena in Stars and Stellar Systems, 1981

Average shock heating



Solid line without cooling term
Dotted line is pure Alfvenic driver

Avrett, Solar Phenomena in Stars and Stellar Systems, 1981

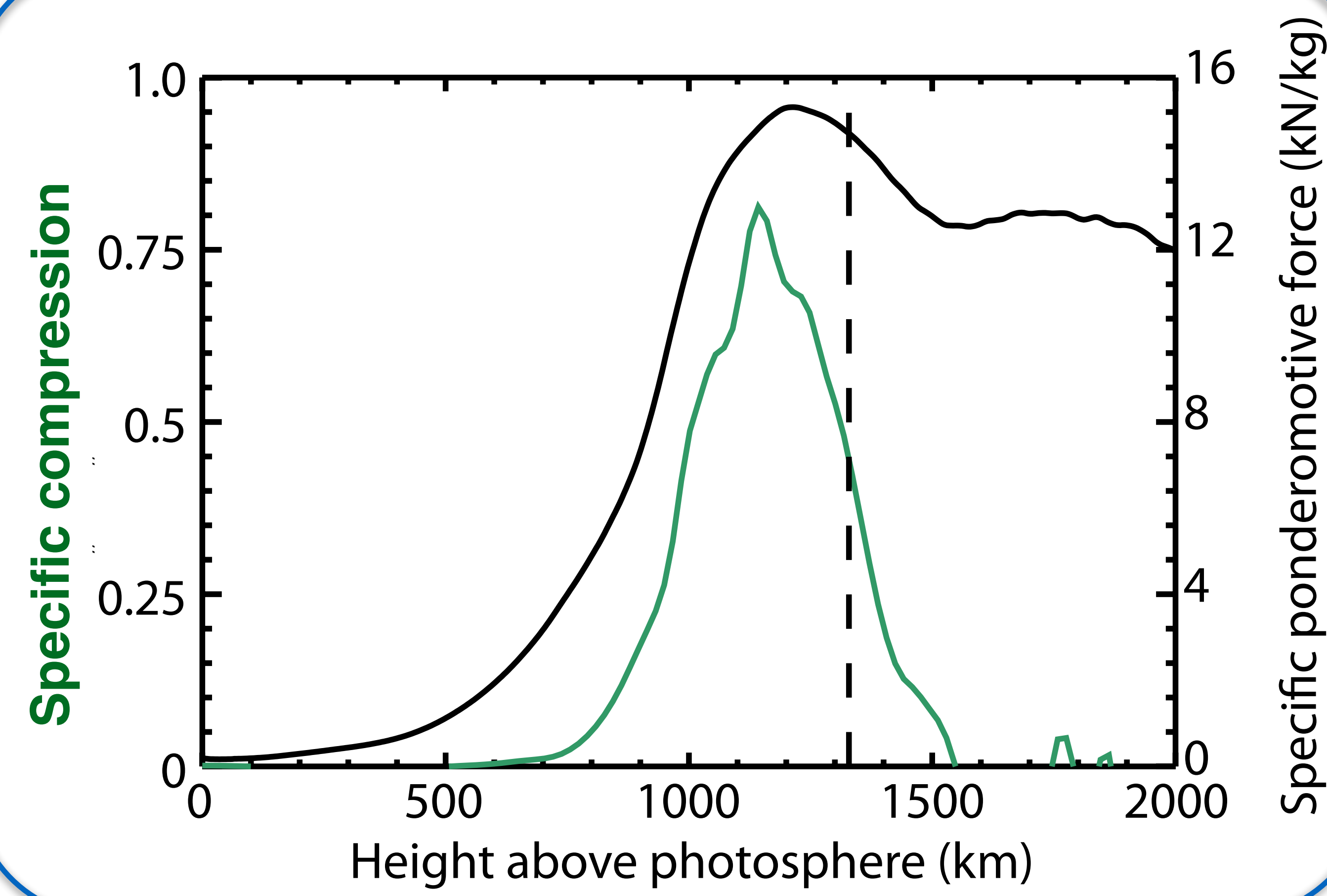
Where do the shocks come from?

No acoustic mode driver

Generated by ponderomotive MHD

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

…or geometric mode coupling due to field expansion

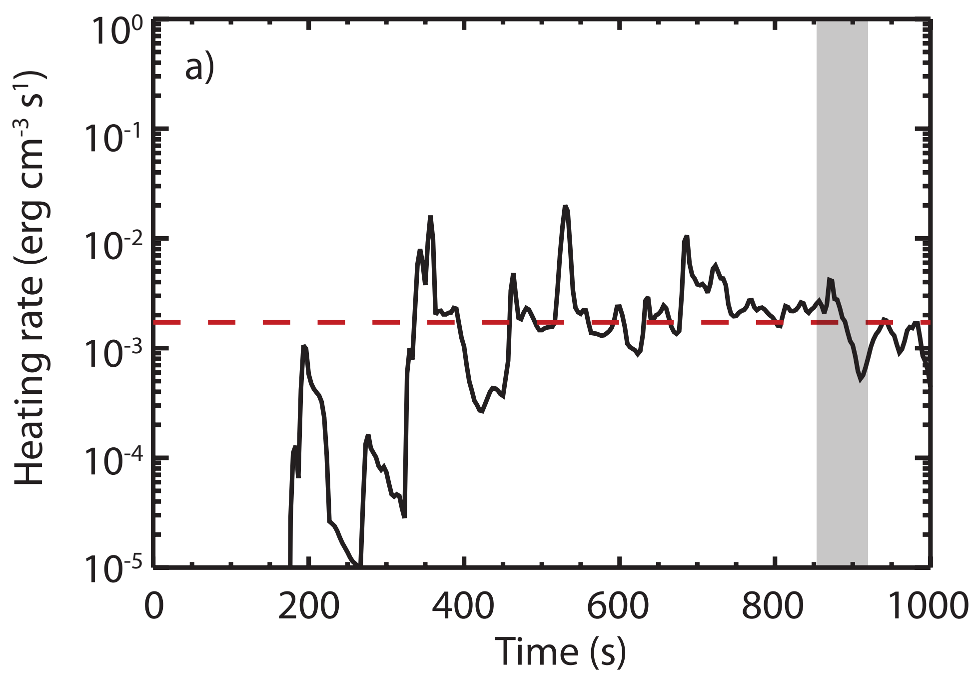


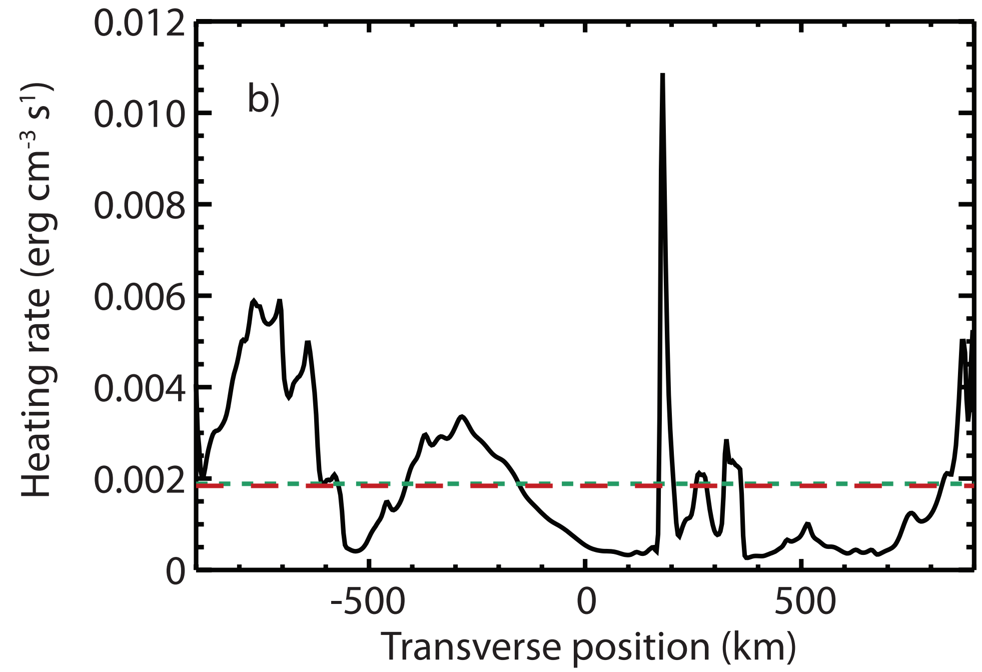
Sound waves generated in chromosphere from MHD waves

Coupling not at β=1 (vertical dashed line)

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

Time & spatial heating profiles

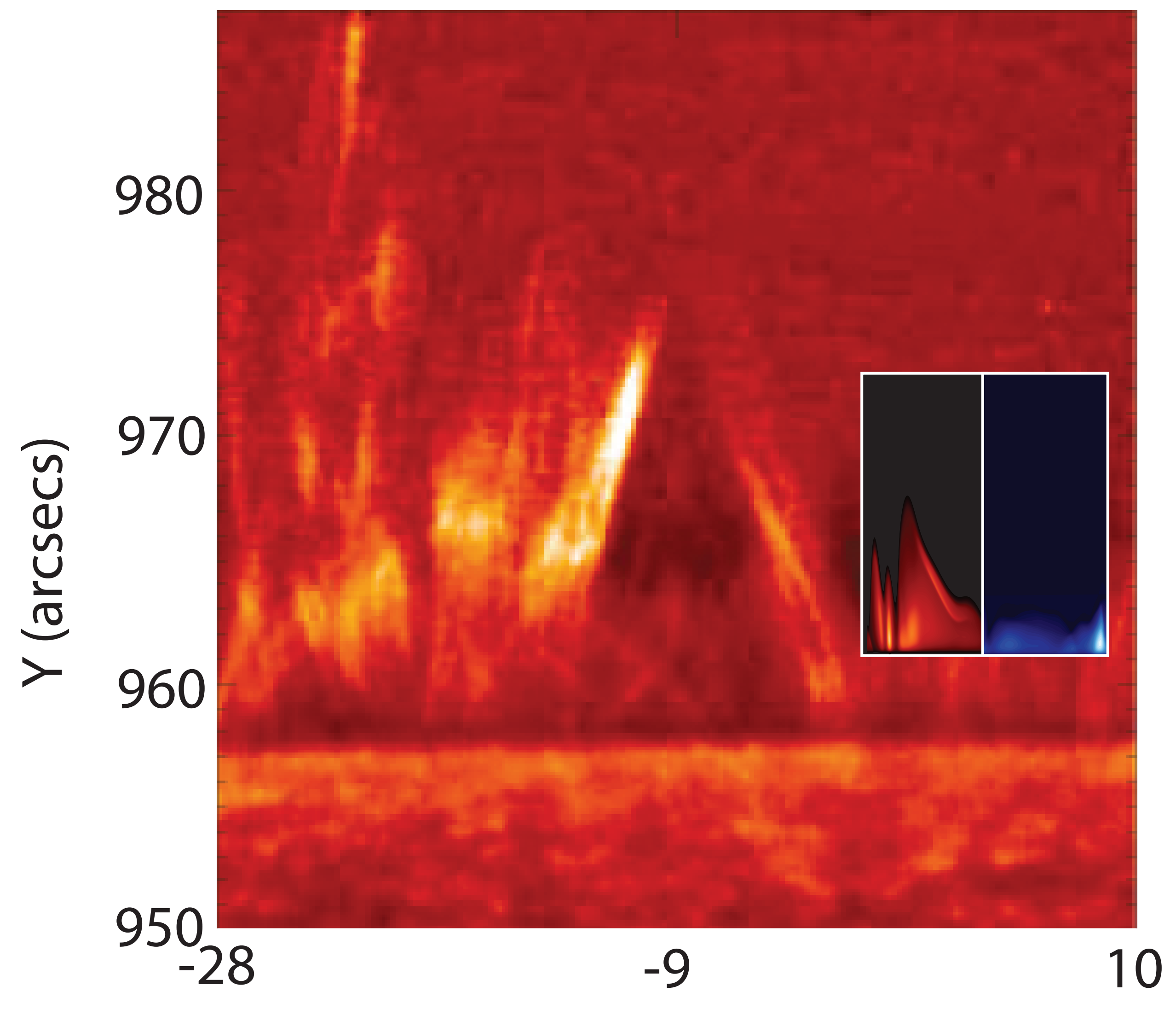




The observation is from an Hinode SOT Ca II H image from Tsiropoula.

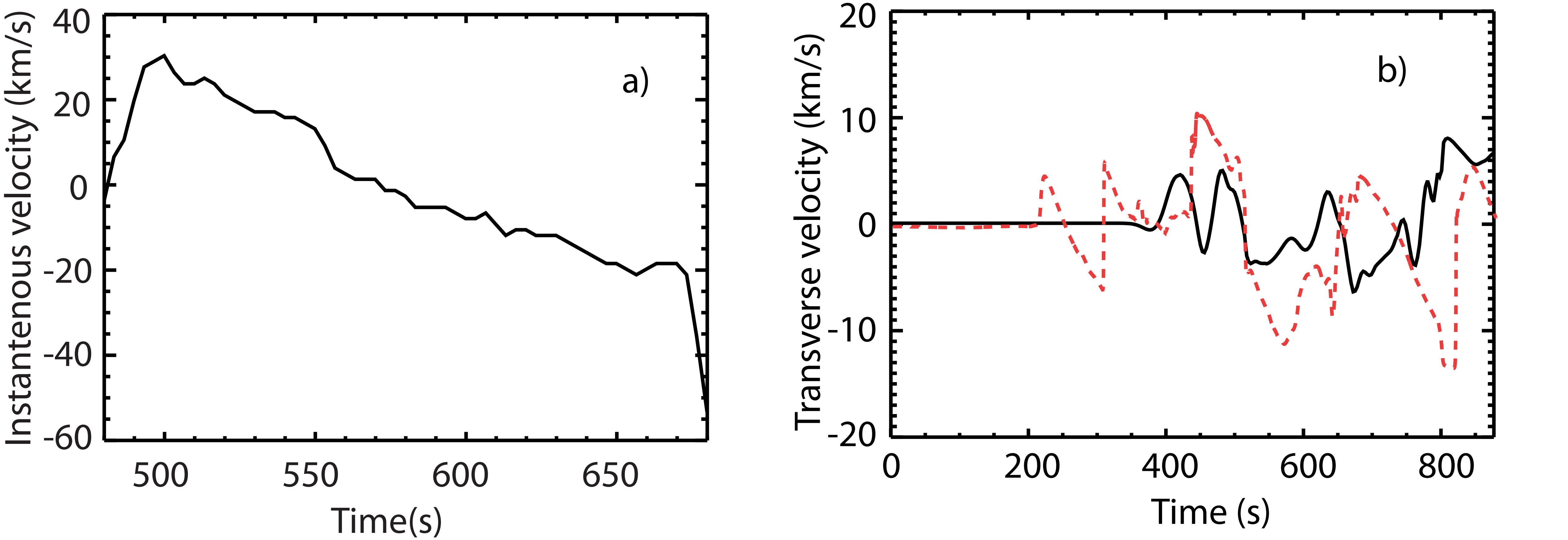
Red - mixed mode

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}

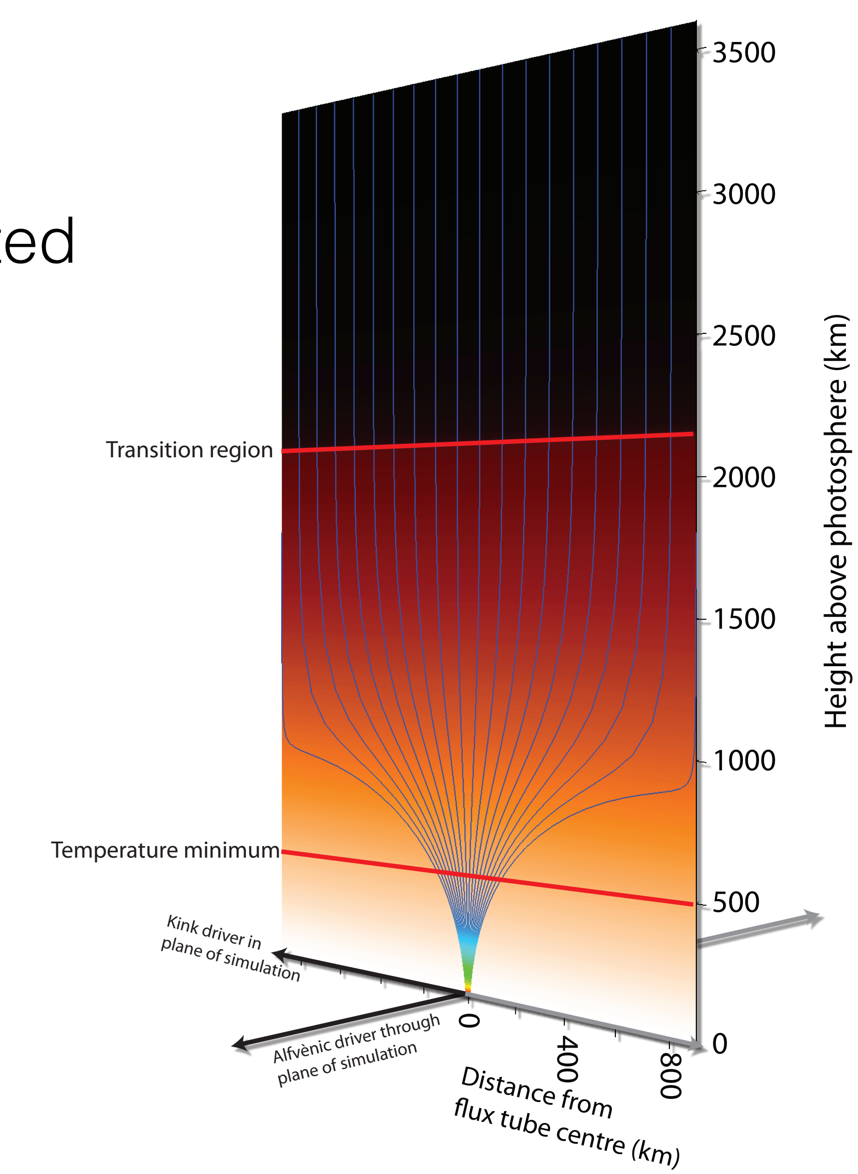
Beckers, Solar Physics, **3**, 367 (1968)
De Pontieu et al. Science, **318**, 1574 (2007)

Summary

- 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 …
- Simulations not compared with correct Avrett model…
- Sensitivity to driver, field structure, atmospheric model…



Brady & Arber, ApJ, **829**, 80 (2016)