Solar Wind Acceleration: Puzzles, Progress, & (DKIST) Prospects

Steven R. Cranmer

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1. Where are we? What's going on?
2. Origins: theory overview, model results
3. Waves & turbulence: how can observations constrain the physics?

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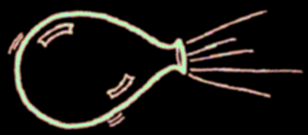
The solar corona

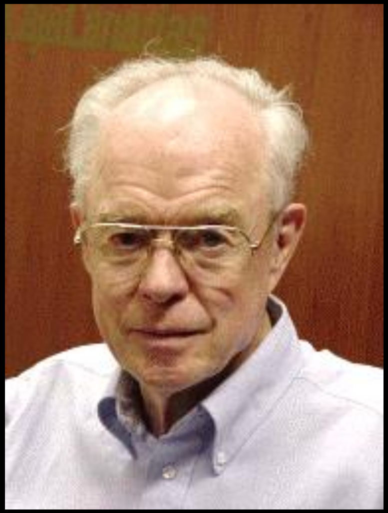
- 1870s: First off-limb solar spectroscopy: unknown emission lines ("coronium?")
- 1930s: Atomic physics identified lines: Fe^{+9}, Fe^{+13} (T needs to be > 1 million K).
- Of course, UV & X-ray observations sealed the deal . . .

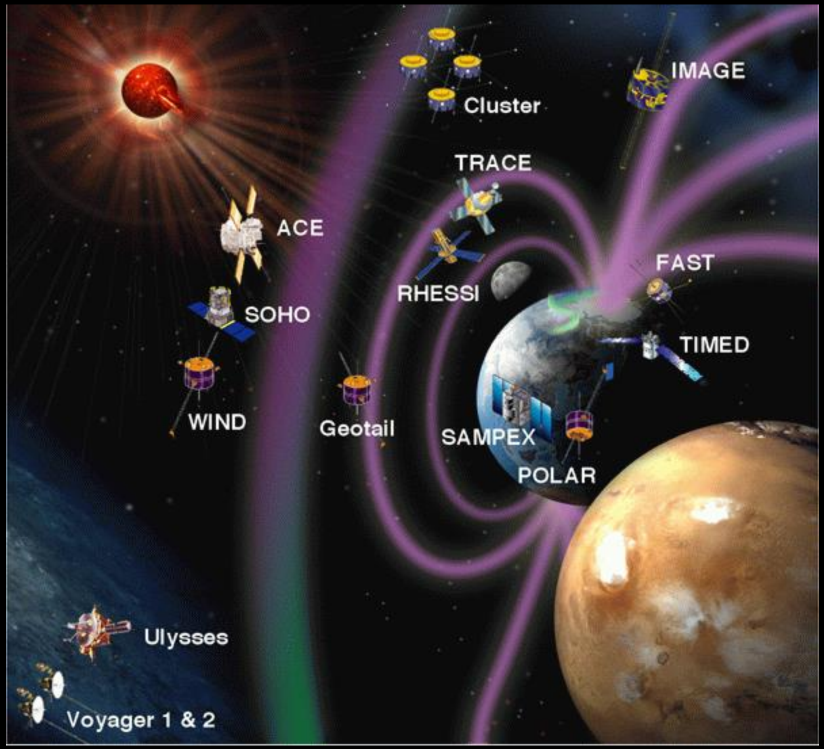
The solar wind: prediction & discovery

- 1958: Parker proposed that the **hot corona** provides enough gas pressure to counteract gravity and accelerate a steady outflow.

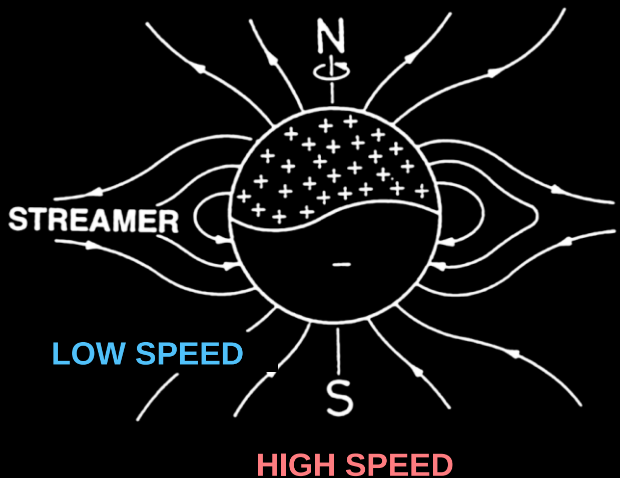


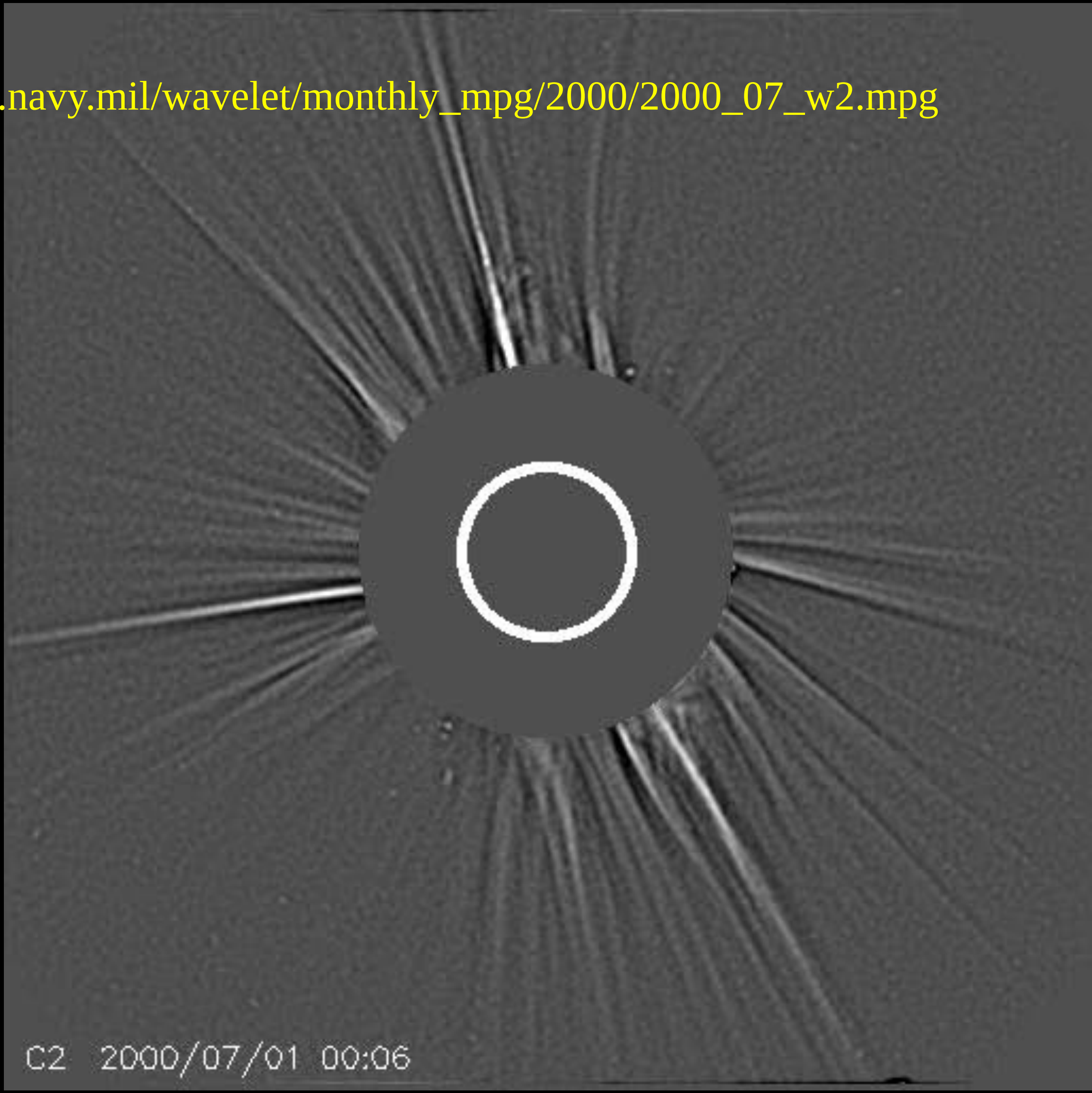
- 1962: ***Mariner 2*** exited Earth's magnetosphere & provided direct confirmation!
- 1970s-1990s: ramp-up of a golden age of combined exploration & observation…





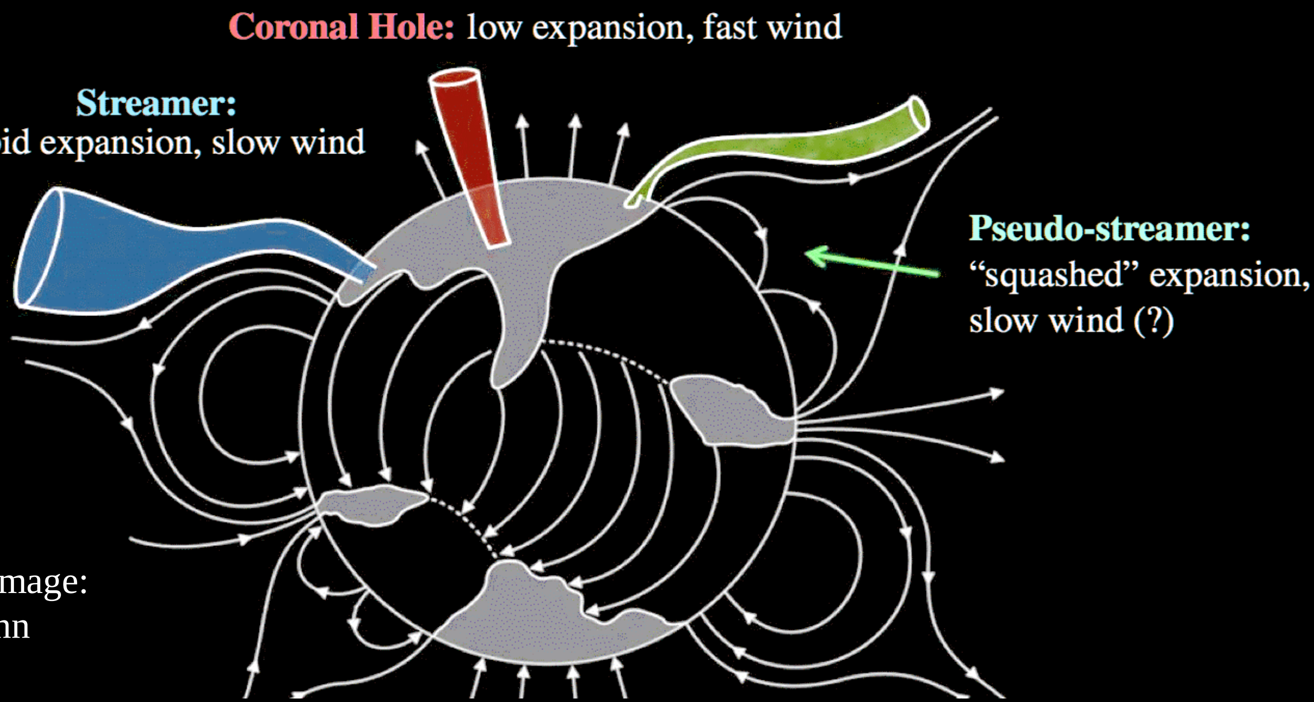
MOVIE LINK:
http://lasco-www.nrl.navy.mil/wavelet/monthly_mpg/2000/2000_07_w2.mpg





Fast versus slow wind

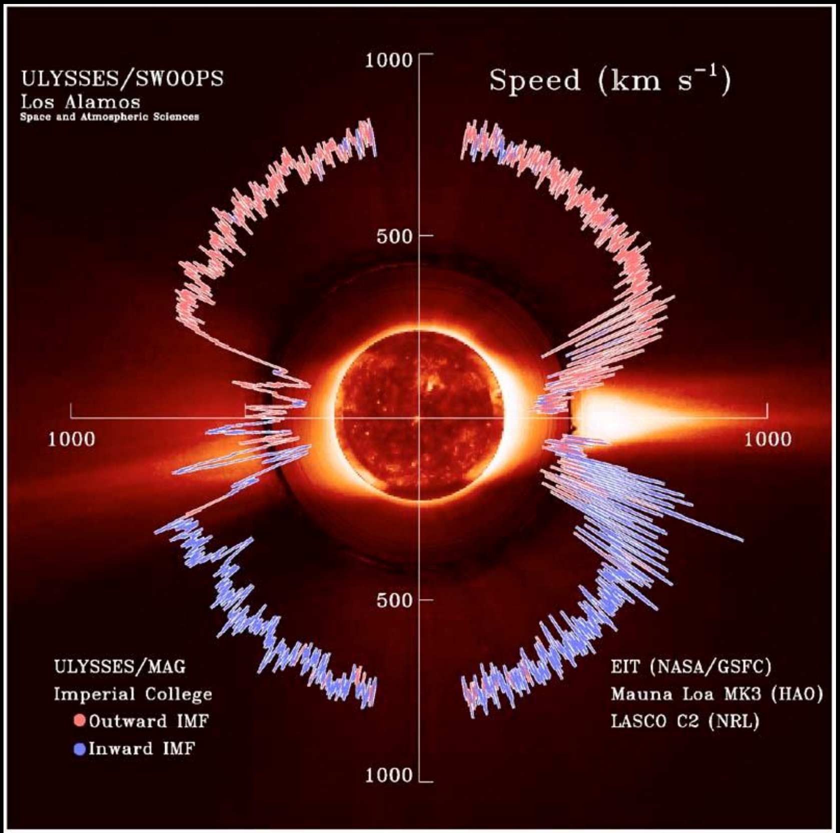
- **High-speed wind:** strong connections to the largest coronal holes
- **Low-speed wind:** still no agreement on the full "census" of coronal sources:
  - hole/streamer boundary regions
  - plasmoids from streamer cusps
  - small coronal holes / jets
  - active region outflows
  - pseudo-streamers

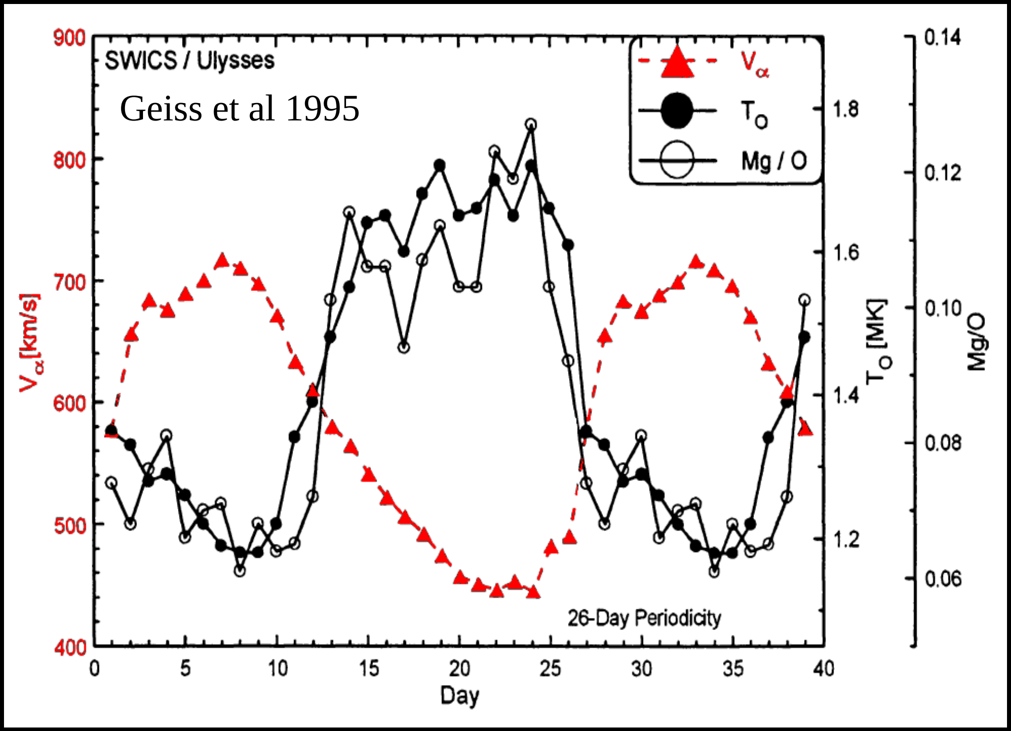


Original image:
J. Luhmann

Fast versus slow wind

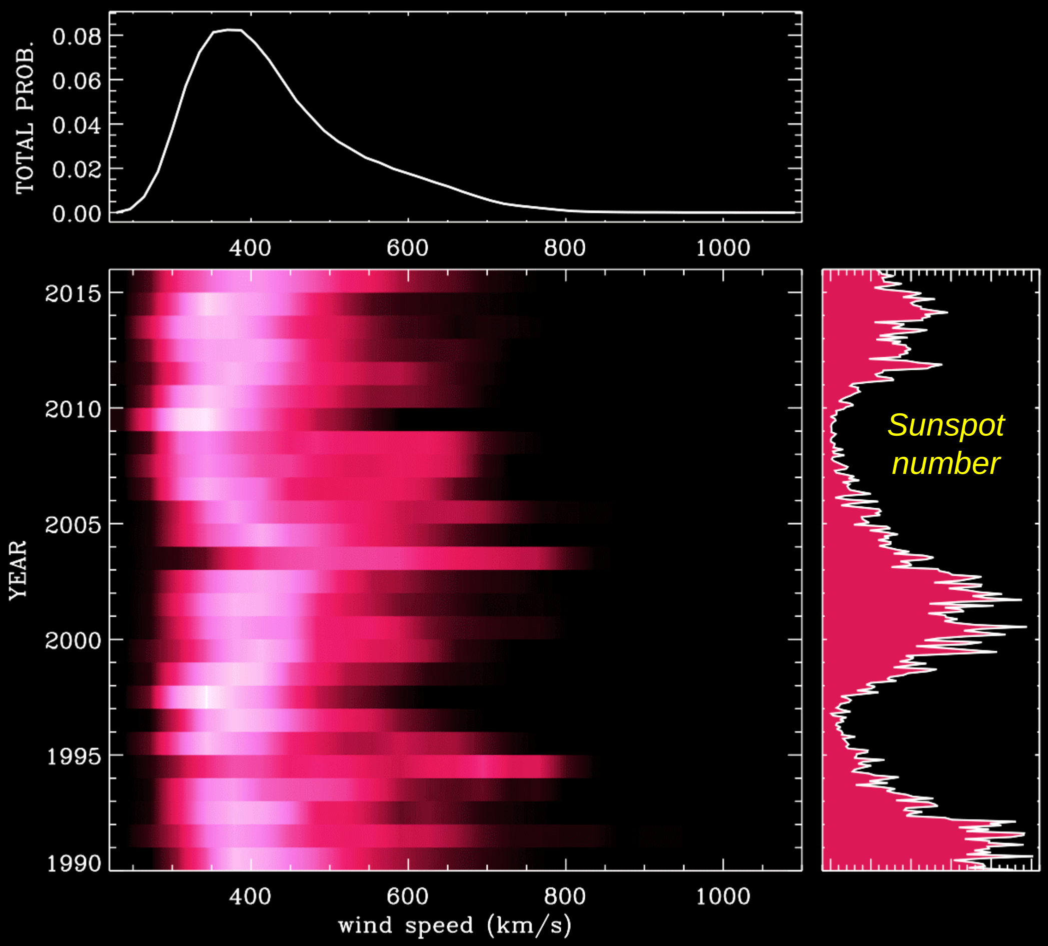
- Is it a "bimodal" distribution?   It sometimes looks that way…

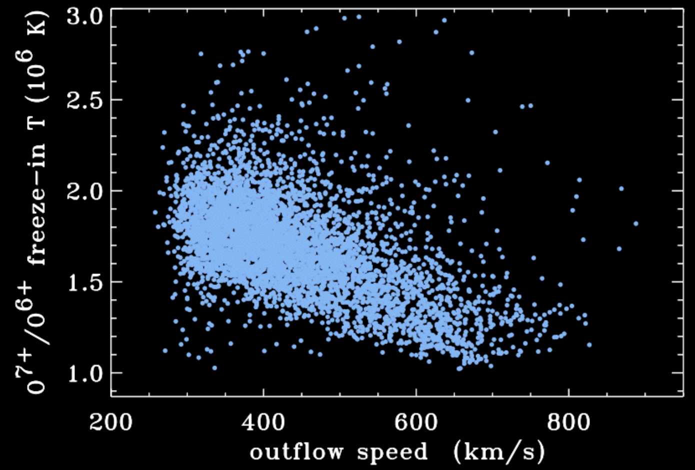


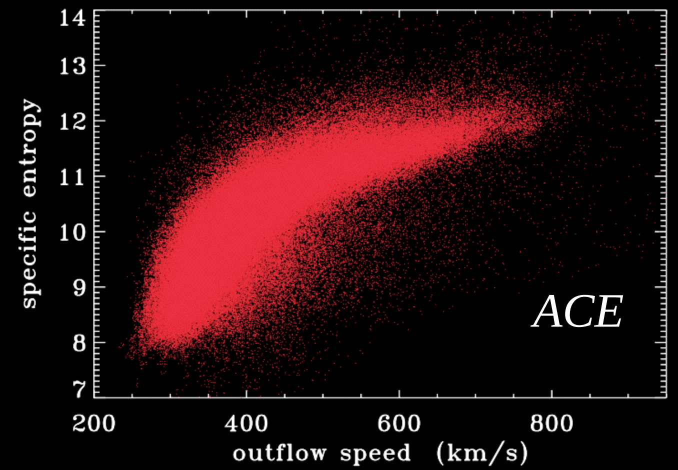


Fast versus slow wind

- Is it a "bimodal" distribution? In the ecliptic at 1 AU…. ***no!***







One mechanism for both?

- Should that be the default (Occam's razor) point of view?
- At least 2 pieces of evidence point to a single mechanism.

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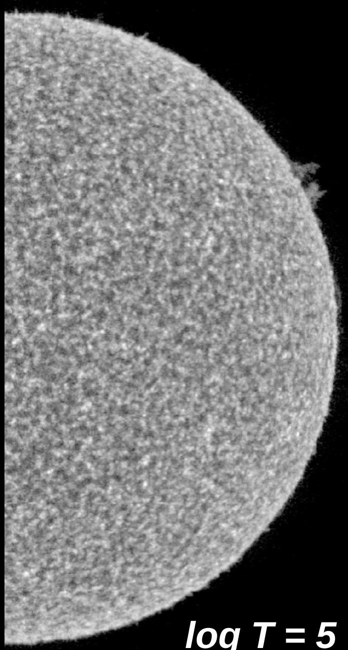
  - Plasma in the chromosphere/TR doesen't seem to "care" about overlying large-scale MHD.
  - In many models, wind mass/energy flux is set $\leq$ TR.



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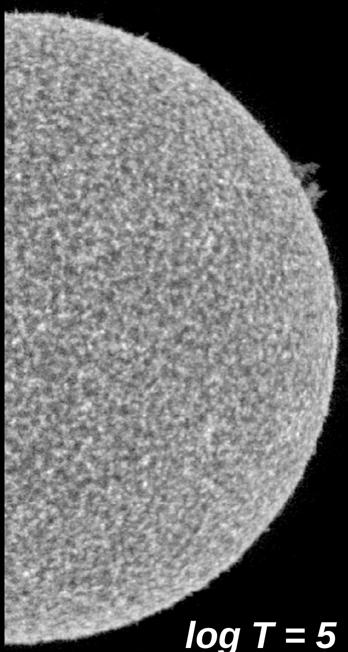
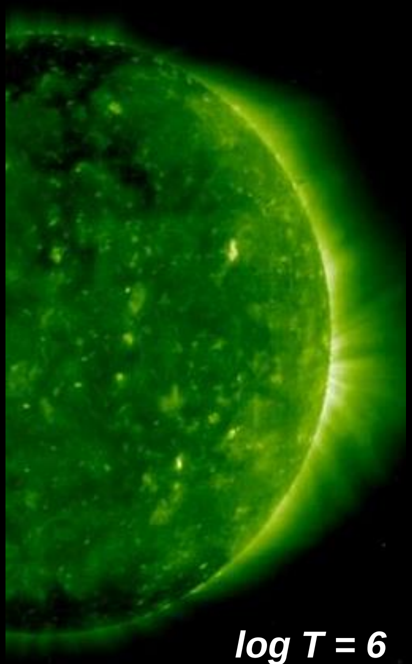
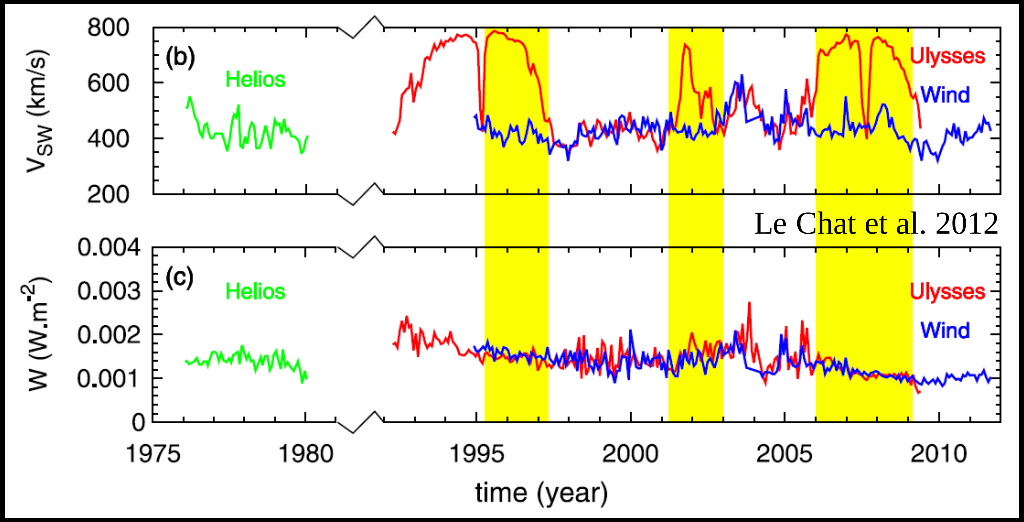




- Mass flux is roughly constant.
- Kinetic energy flux is roughly constant.



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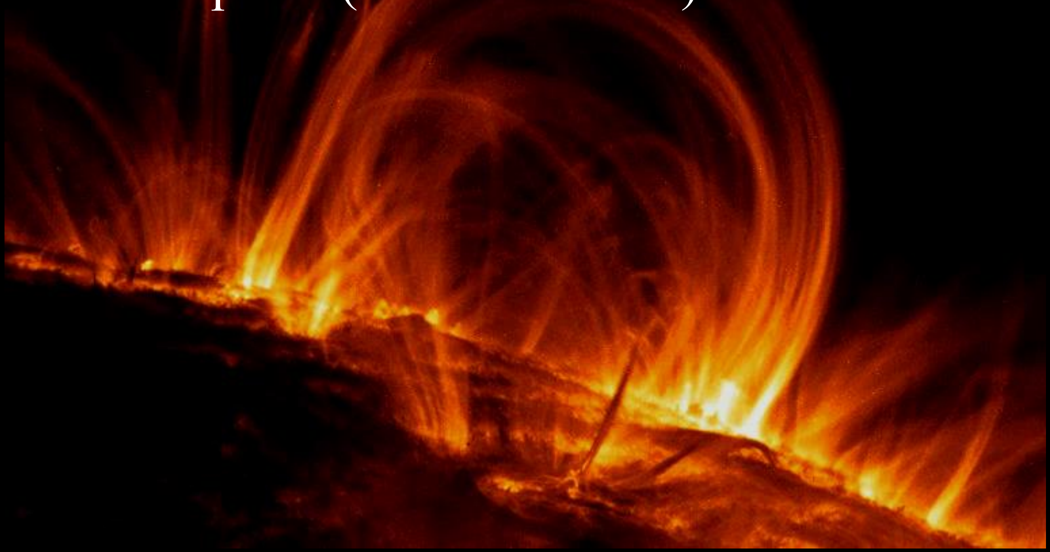
Solar wind acceleration 101

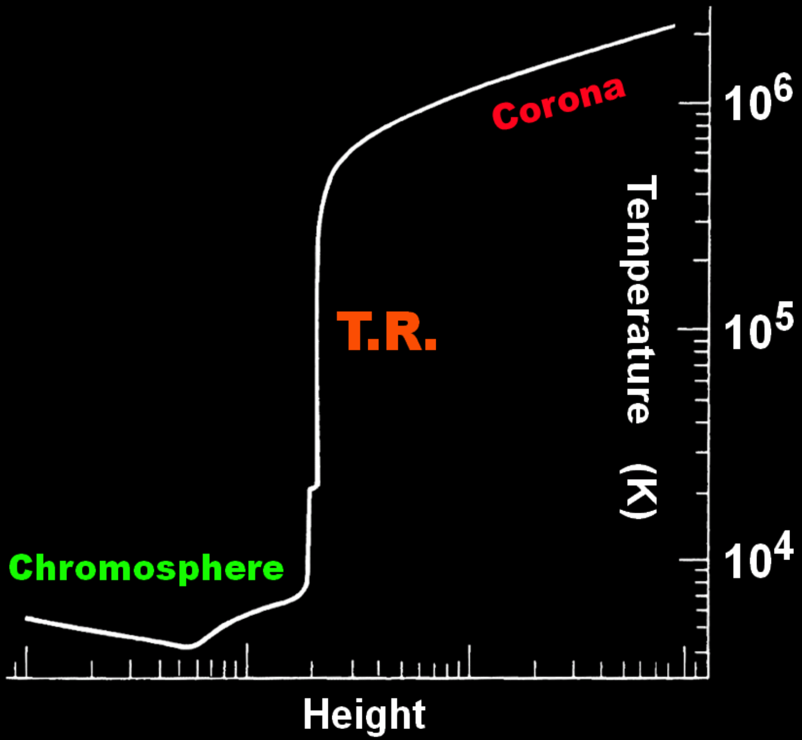
- The original (Parker 1958) model is still valid [more or less], but the coronal heating problem is still unsolved [more or less].
- Nearly everyone agrees that there is more than enough energy in the subsurface **convection** to heat the corona. But…

Solar wind acceleration 101

- The original (Parker 1958) model is still valid [more or less], but the coronal heating problem is still unsolved [more or less].
- Nearly everyone agrees that there is more than enough energy in the subsurface **convection** to heat the corona. But how does a fraction (~1%) of that energy get:

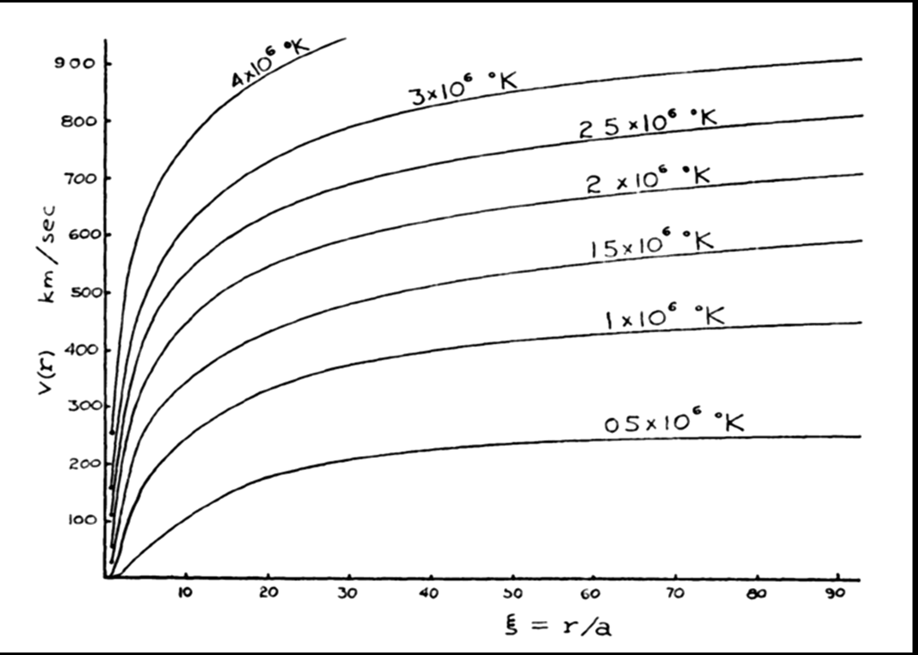
  a. transported up to the corona,
  b. temporarily stored in magnetic field,
  c. dissipated ("randomized?") as heat ?





Is coronal heating enough?

- The Parker (1958) theory says that a higher-temperature corona accelerates a faster wind.
- Do observations of the coronal source regions back this up?



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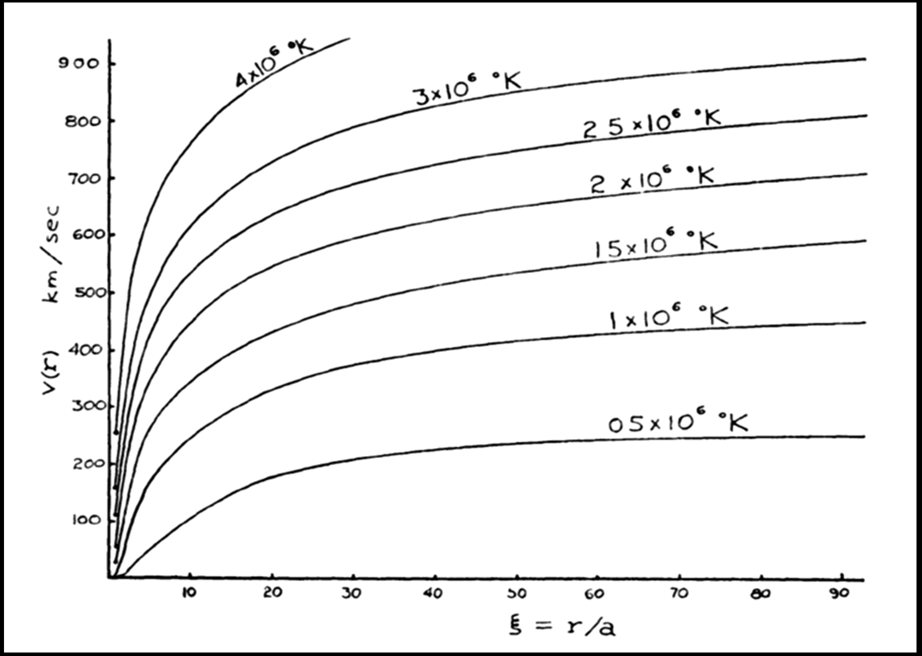


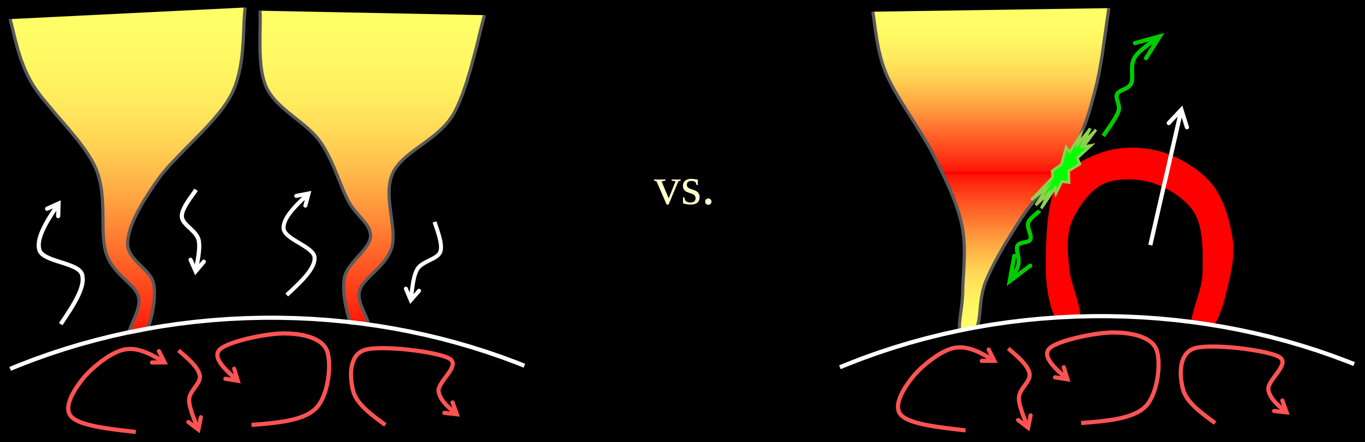
Red: low T_e

Blue: high T_e

- No! (see also measurements of ion charge states in the solar wind)
- It is clear the fast wind needs something **besides** gas pressure to accelerate so fast.

Debates: 1 of N

- How long do open field lines stay open? Does mass get injected from closed loops?



Long lifetime: everything must propagate up from below: **waves/turbulence?**

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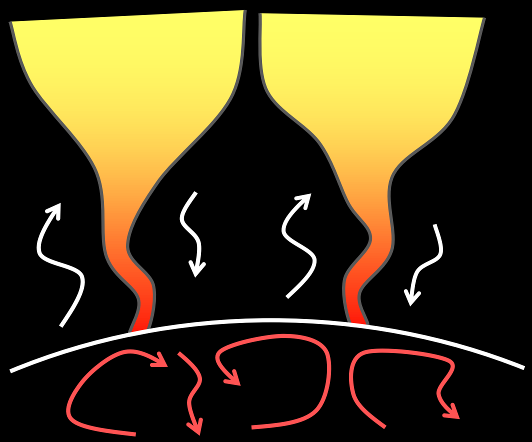

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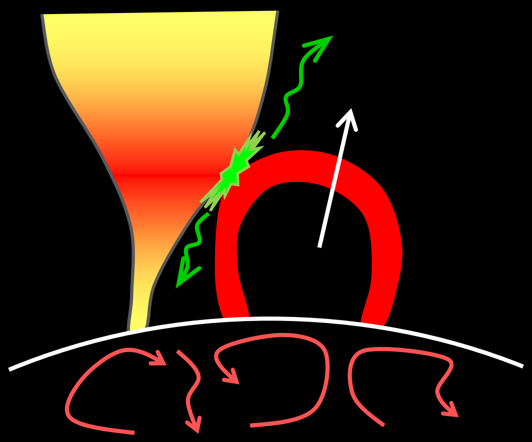

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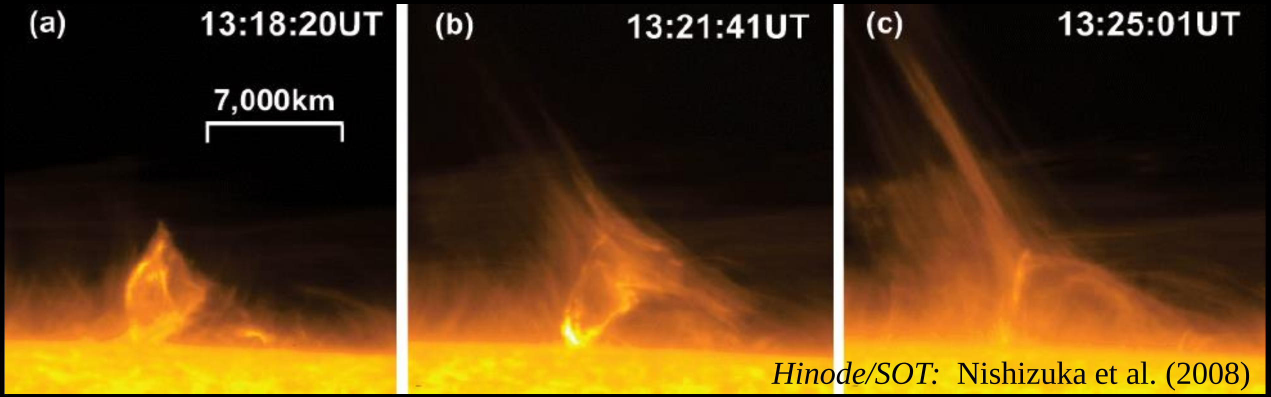
There's a natural appeal to "loop-opening"

- Open-field regions show frequent jet-like reconnections!
- *In situ* slow wind abundances ≈ closed loop abundances.



Hinode/SOT: Nishizuka et al. (2008)

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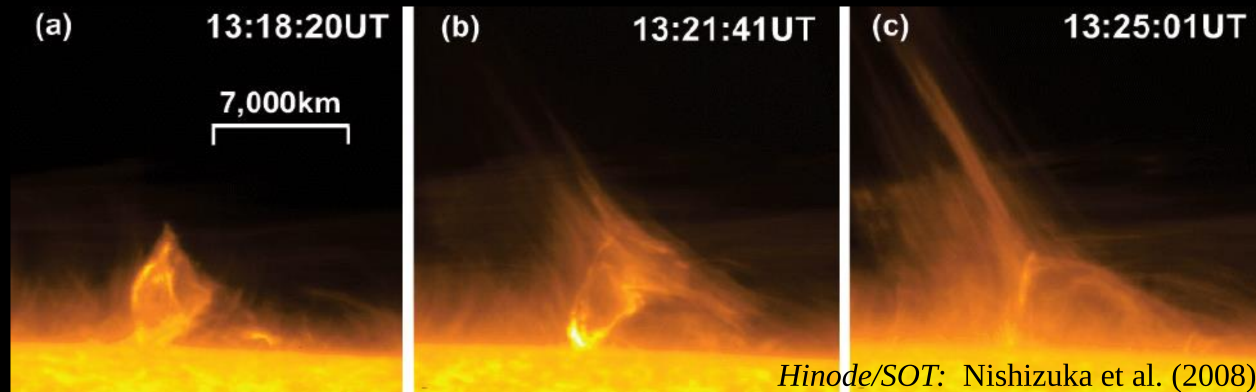
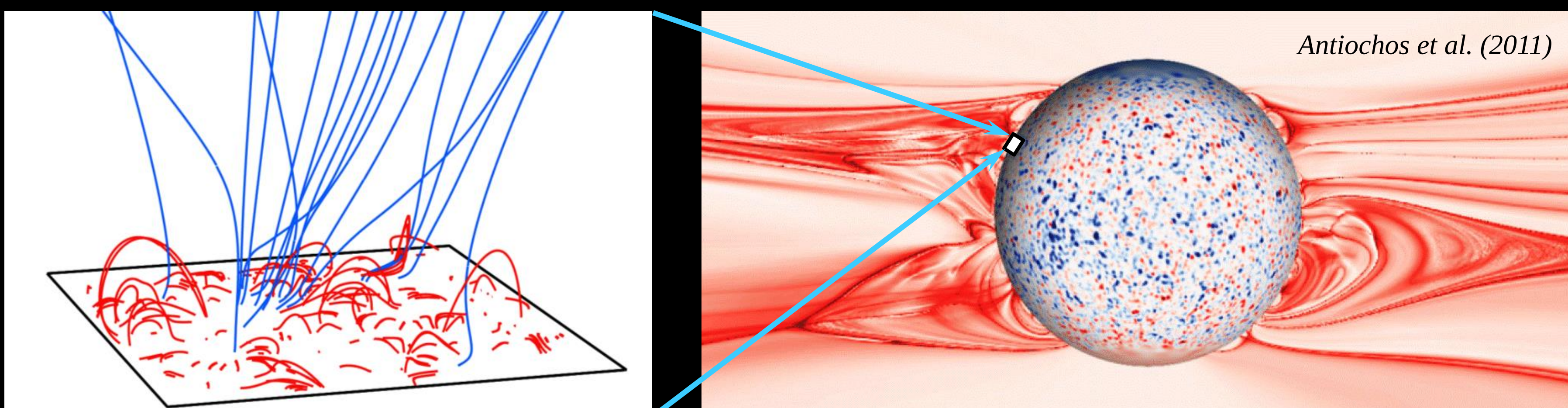
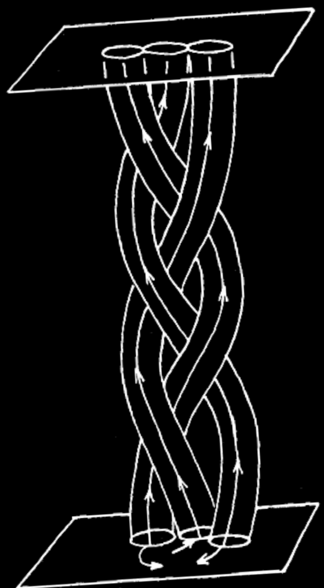


- But is there **enough** mass & energy released (in the subset of reconnection events that turn closed fields into open fields) to *heat/accelerate the entire solar wind?*



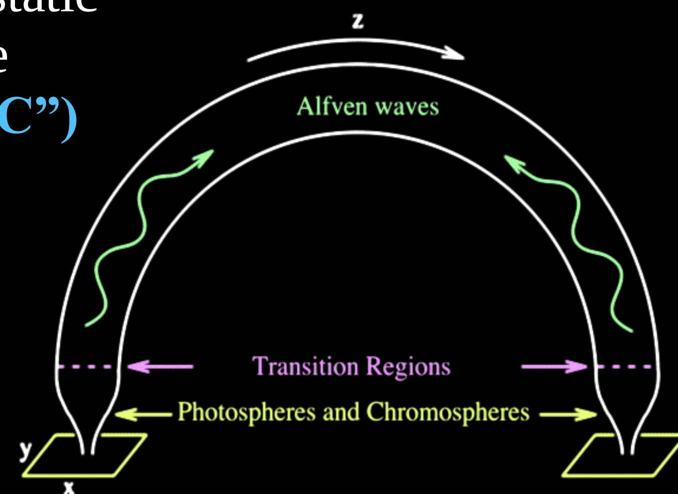
Debates: 2 of N

- Can the corona "keep up" with rapid changes in the convective lower boundary?



Slow footpoint motions ($\tau_{ph} > L/V_A$) cause the field to twist & braid into a quasi-static state; electric currents build up and are released via bursty reconnection. **("DC")**

Rapid footpoint motions ($\tau_{ph} < L/V_A$) propagate through the field as waves, which are eventually dissipated. **("AC")**



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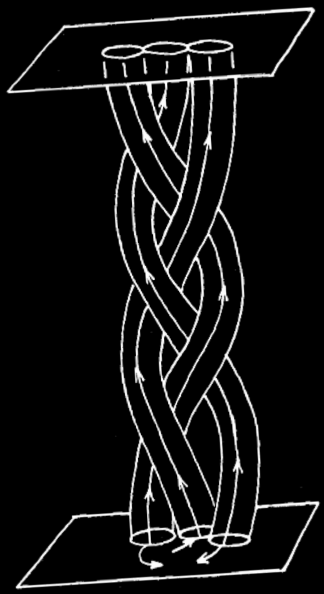

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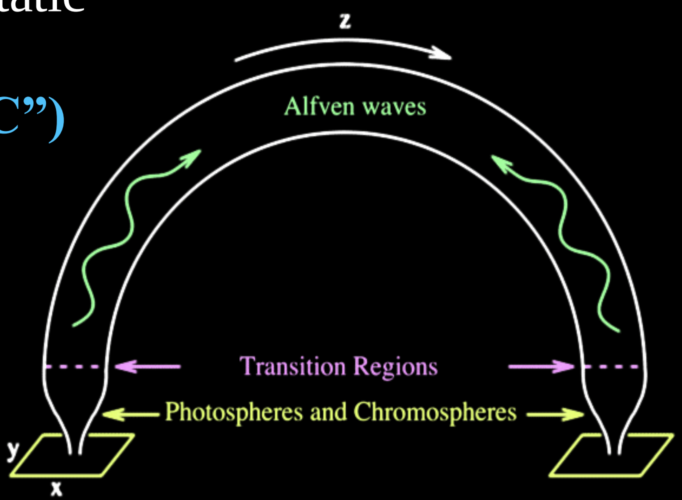


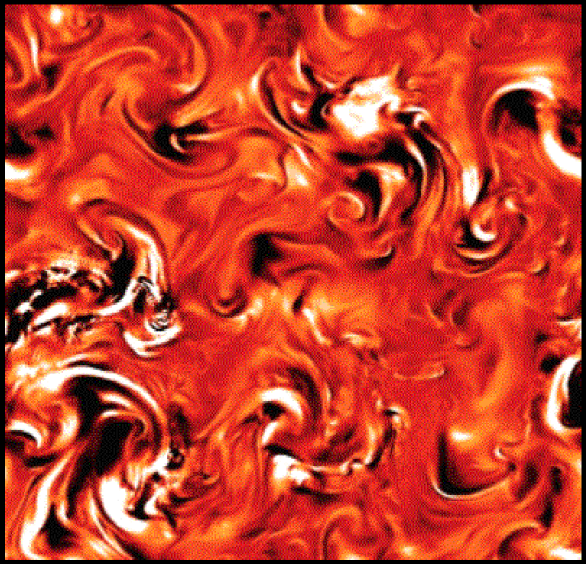
However . . .

- The Sun's atmosphere exhibits a continuum of time scales bridging AC/DC limits.
- "Braiding" is observed, but is highly dynamic. (see: Hi-C sounding rocket!)

Waves go along with reconnection

To complicate things even more . . .

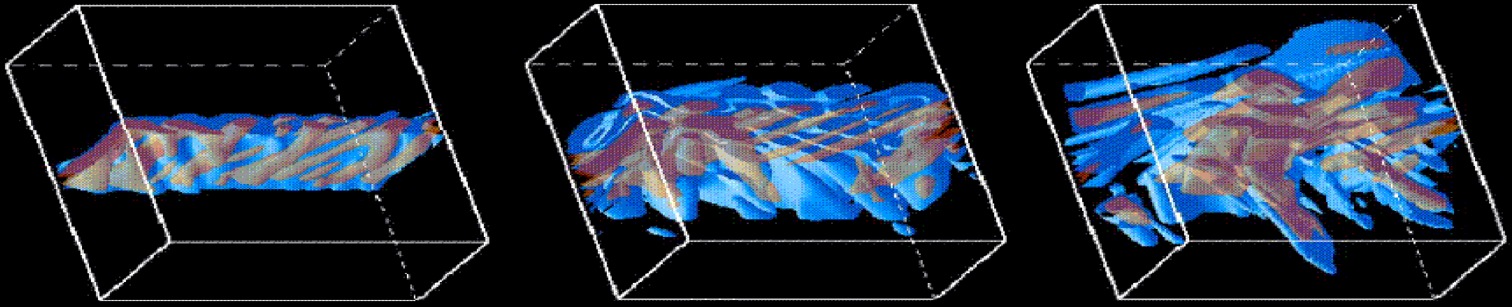
- Waves cascade into MHD turbulence (eddies), which tends to:
  - ➢ break up into thin **reconnecting** sheets on its smallest scales.
  - ➢ accelerate electrons along the field and generate **currents.**



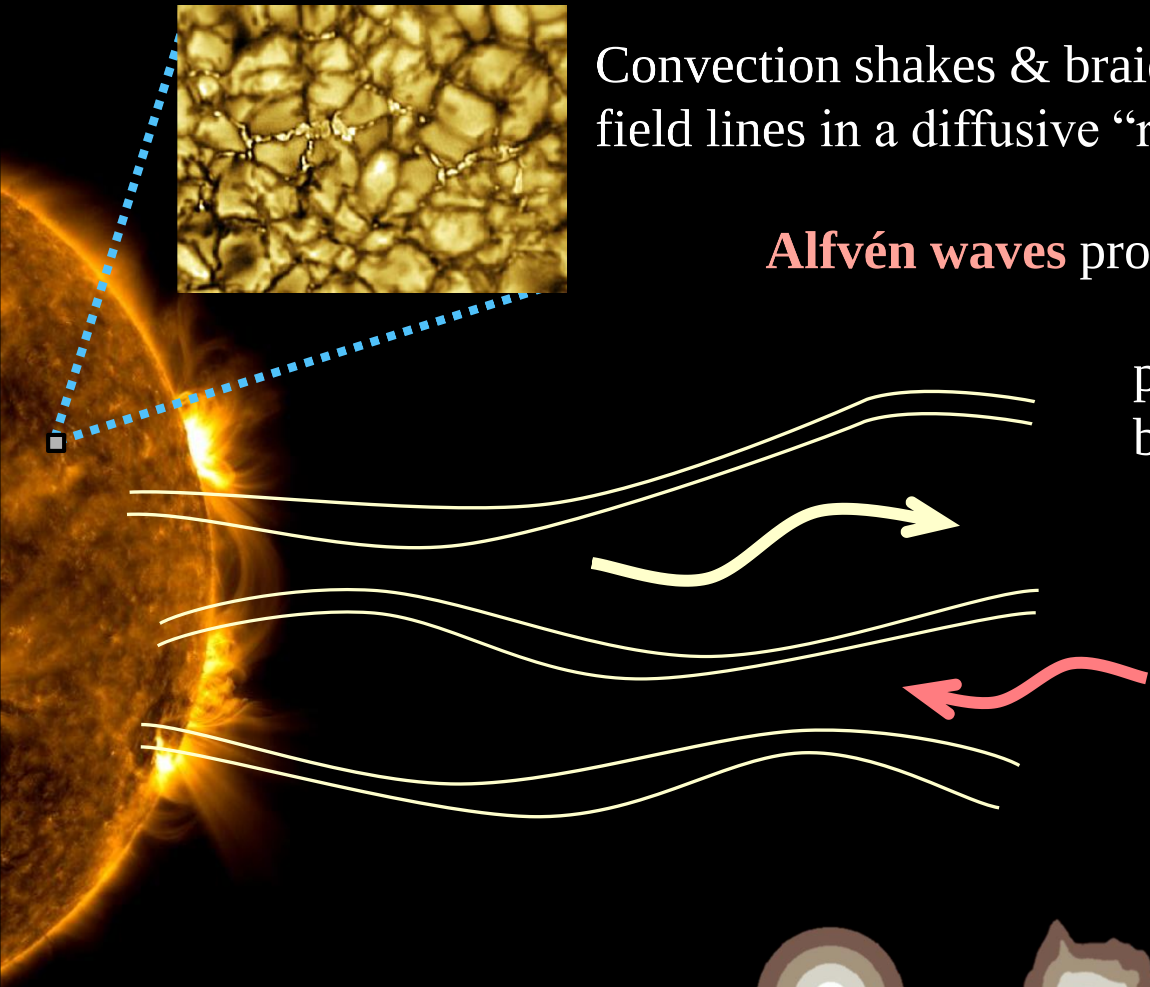
e.g., Dmitruk et al. (2004)

- Coronal current sheets can emit **waves,** and can be unstable to growth of **turbulent motions** which may dominate the energy loss & particle acceleration.

Onofri et al. (2006)



Conjecture: turbulence is a unifying "language"



Convection shakes & braids magnetic field lines in a diffusive "random walk"

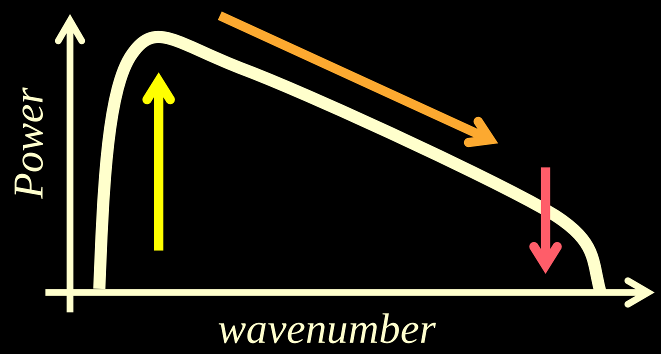
Alfvén waves propagate up...

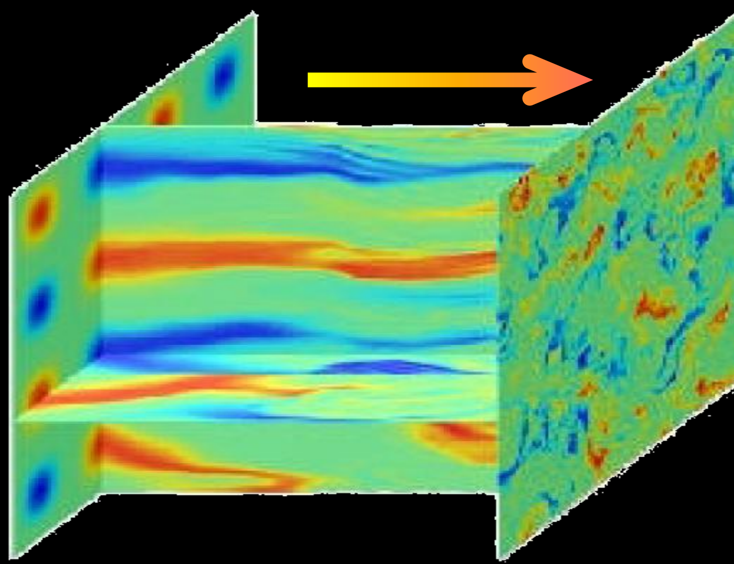
partially reflect back down...

...and cascade from large to small eddies, eventually dissipating (via tiny **reconnections**) to heat open-field regions.

Anisotropic MHD turbulence

- With a strong background field, it is easier to **mix** field lines (perp. to ***B***) than it is to **bend** them (parallel to ***B***).





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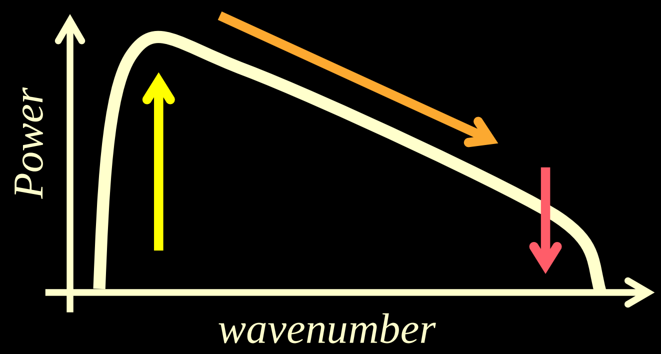
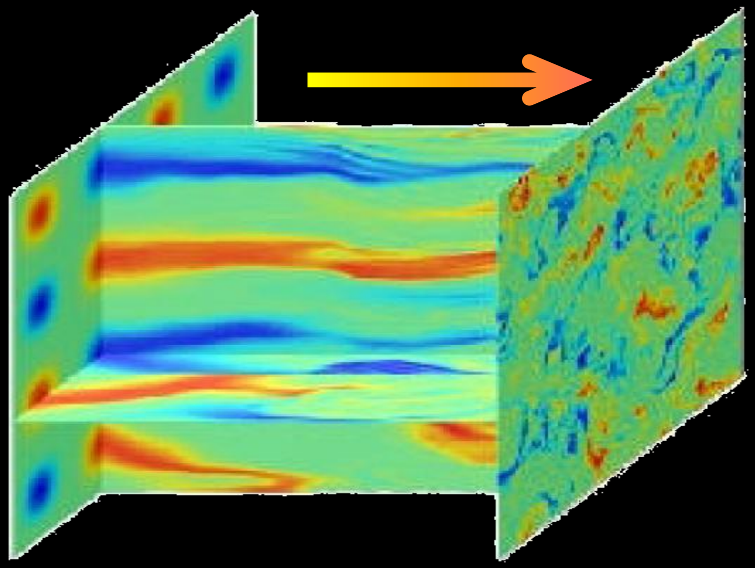




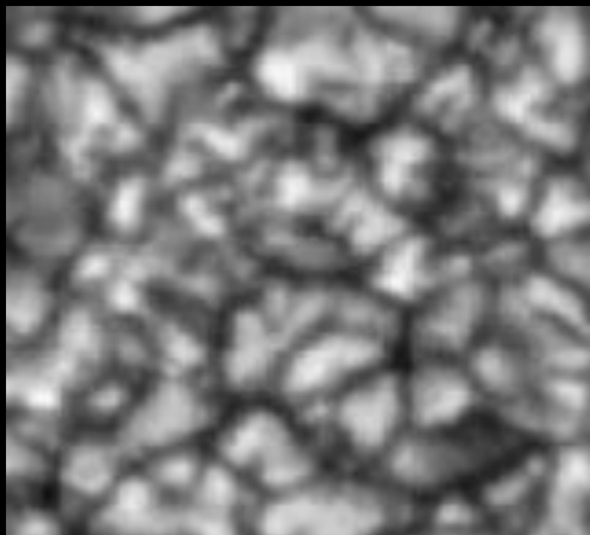
- MHD simulations inspire phenomenological scalings for the cascade/heating rate:

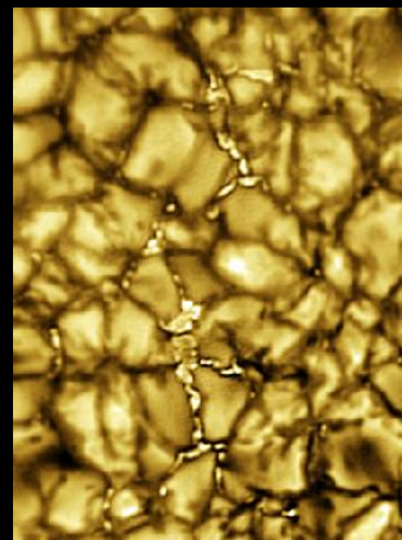
$$Q_{\text{heat}} \approx \frac{\rho\, v^3}{\ell} \approx \frac{\varepsilon\, \rho\, \left(v_+^2 v_- + v_-^2 v_+\right)}{\ell_\perp}$$

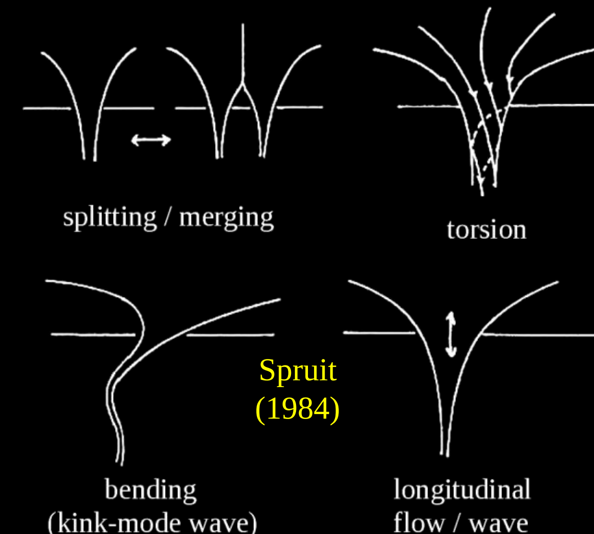
(e.g., Iroshnikov 1963; Kraichnan 1965; Strauss 1976; Shebalin et al. 1983; Hossain et al. 1995; Goldreich & Sridhar 1995; Matthaeus et al. 1999; Dmitruk et al. 2002; Chandran 2008)

What's the lower boundary condition?

- Inter-granular bright points appear to be the "roots" of *ALL* coronal magnetic field.

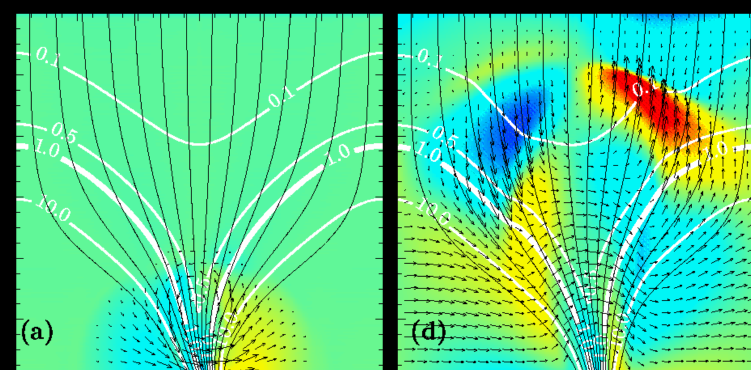






Spruit (1984)

- It's important to measure horizontal motions of small (sub-arcsecond) footpoints of the large-scale field.
- Sam Van Kooten (CU) is comparing **power spectra** from existing data with MURAM & other simulations.



Hasan et al. (2005)

Other physical processes

- To explain everything from the photosphere to the heliosphere, one needs…
- Radiative losses (op. thick → op. thin)
- Heat conduction (strong → weak coll.)

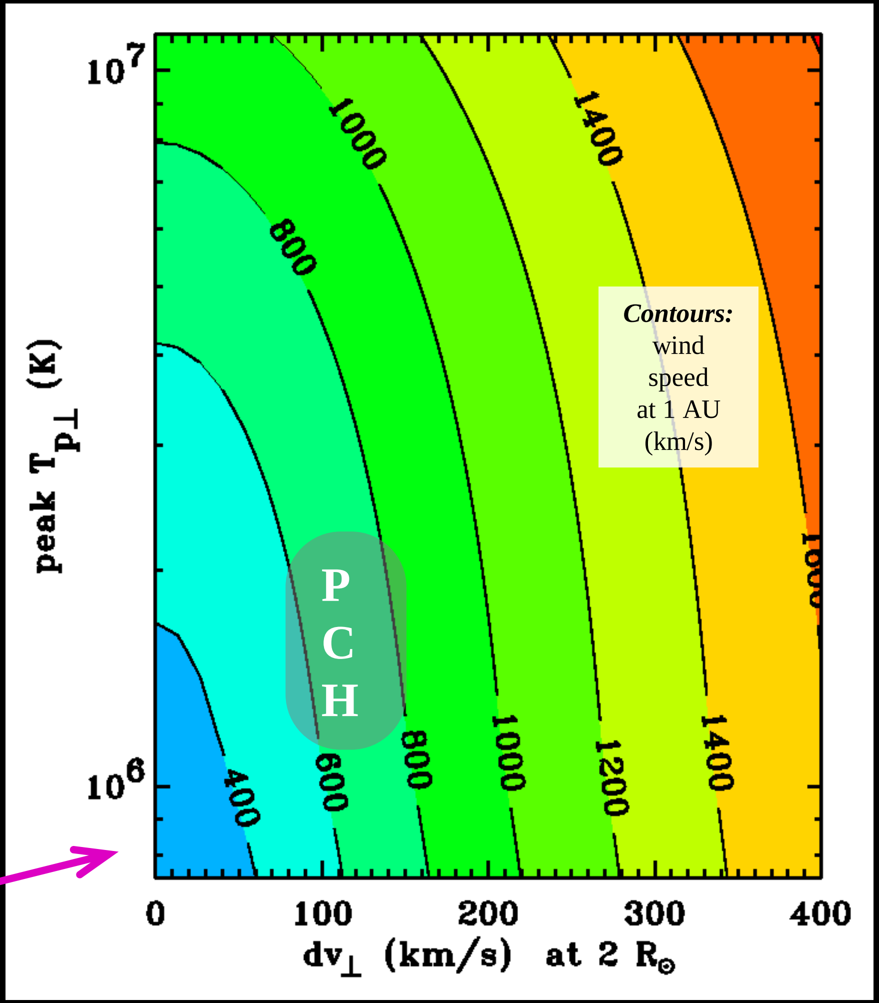
Other physical processes

- To explain everything from the photosphere to the heliosphere, one needs…

- Radiative losses (op. thick → op. thin)
- Heat conduction (strong → weak coll.)
- **Wave pressure!** Just as E&M waves carry momentum and exert pressure on matter, MHD waves do work on the gas via similar net stress terms:

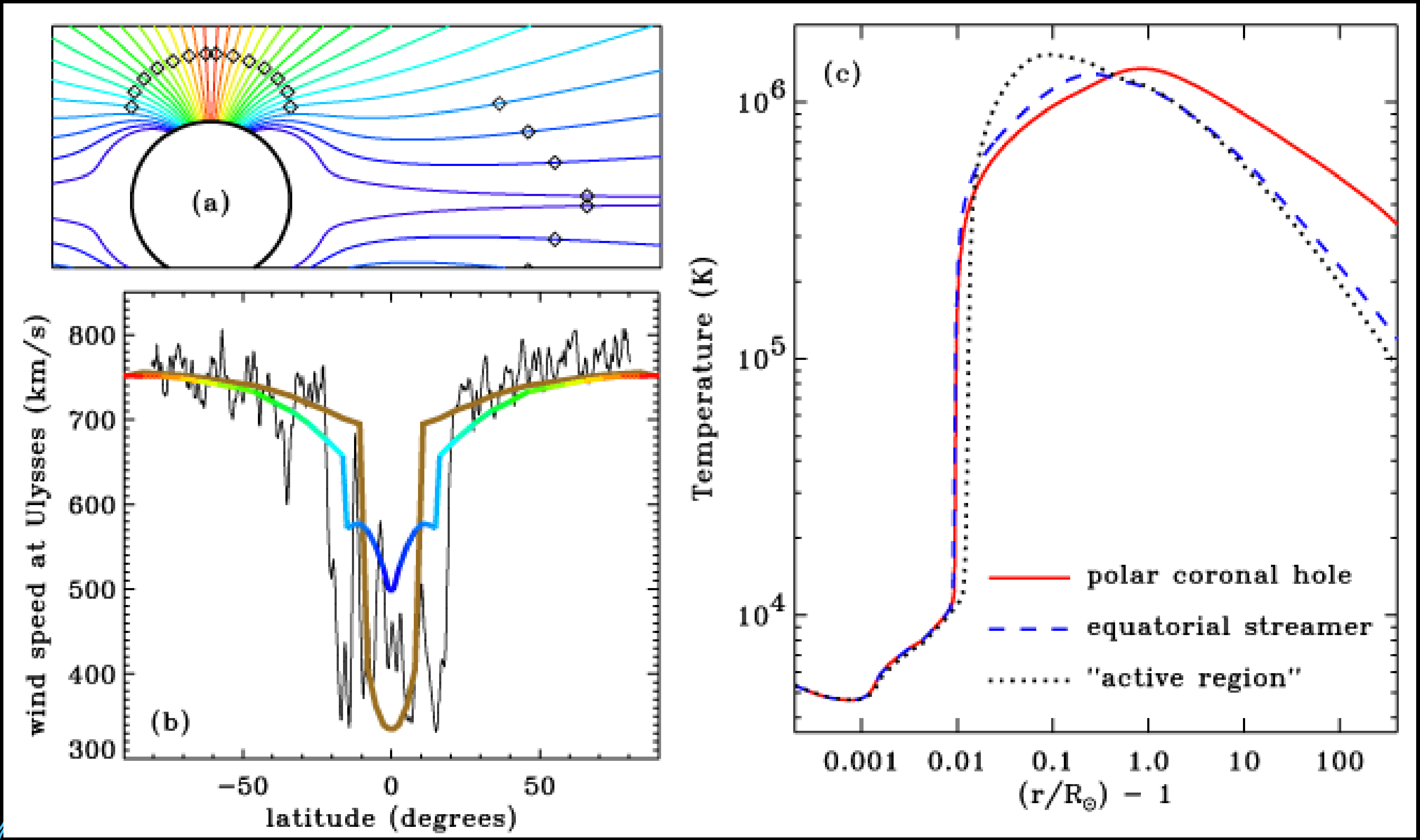
$$\rho a_{\mathrm{wp}} = -\nabla \cdot \mathbb{P}_{\mathrm{wp}} \approx -\frac{\partial}{\partial r}\left(\frac{\delta B_{\perp}^{2}}{8\pi}\right)$$

- **Example parameter study:** Wave pressure & gas pressure work together to produce high-speed wind.
- Each point in this grid represents a solution to the Parker critical pt. eqn.



MHD turbulence appears to work

- MHD turbulence heating rates – plus the rest of the kitchen sink – were built into the *ZEPHYR* code (Cranmer et al. 2007, 2013; Woolsey & Cranmer 2014).



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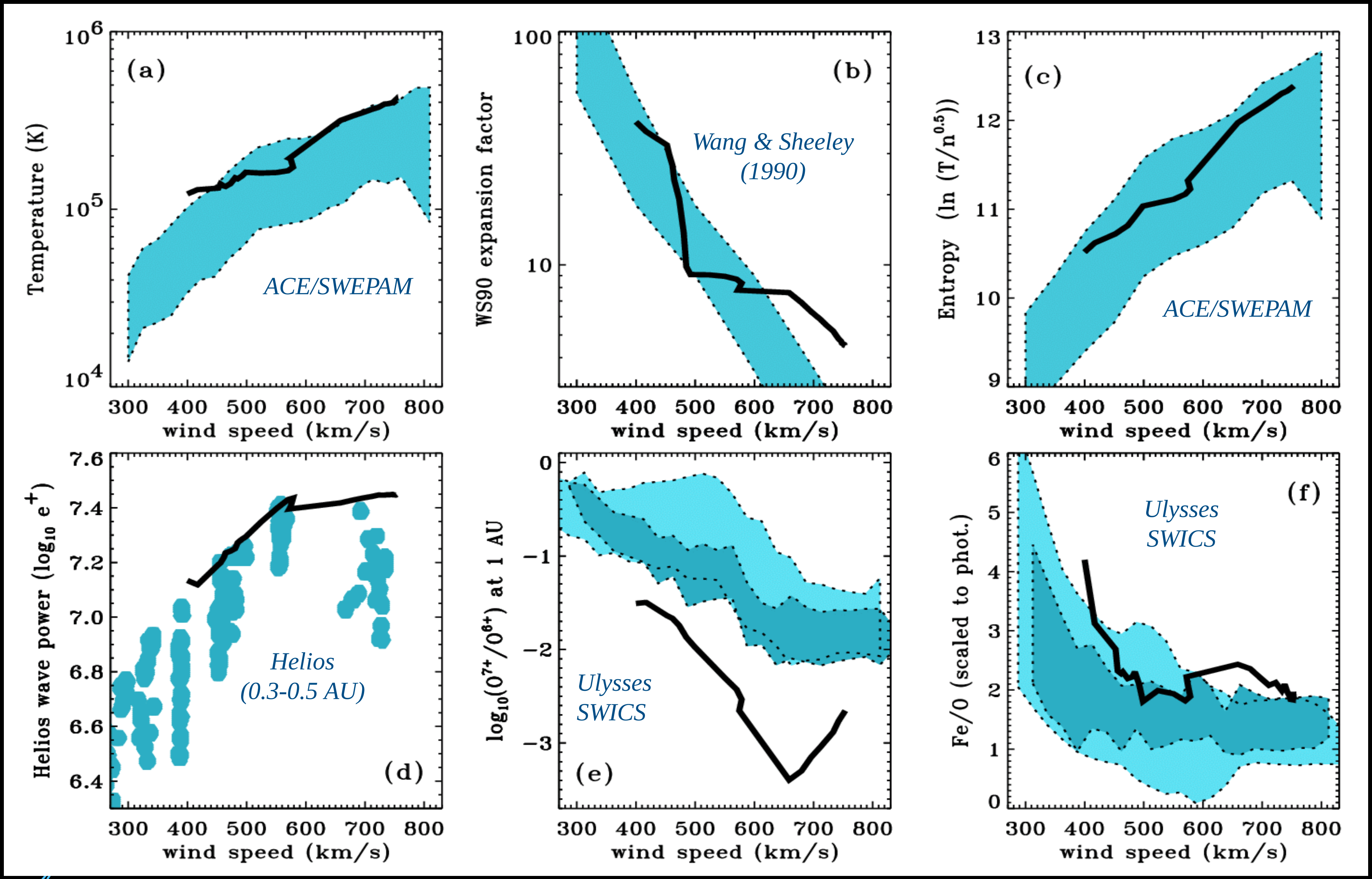

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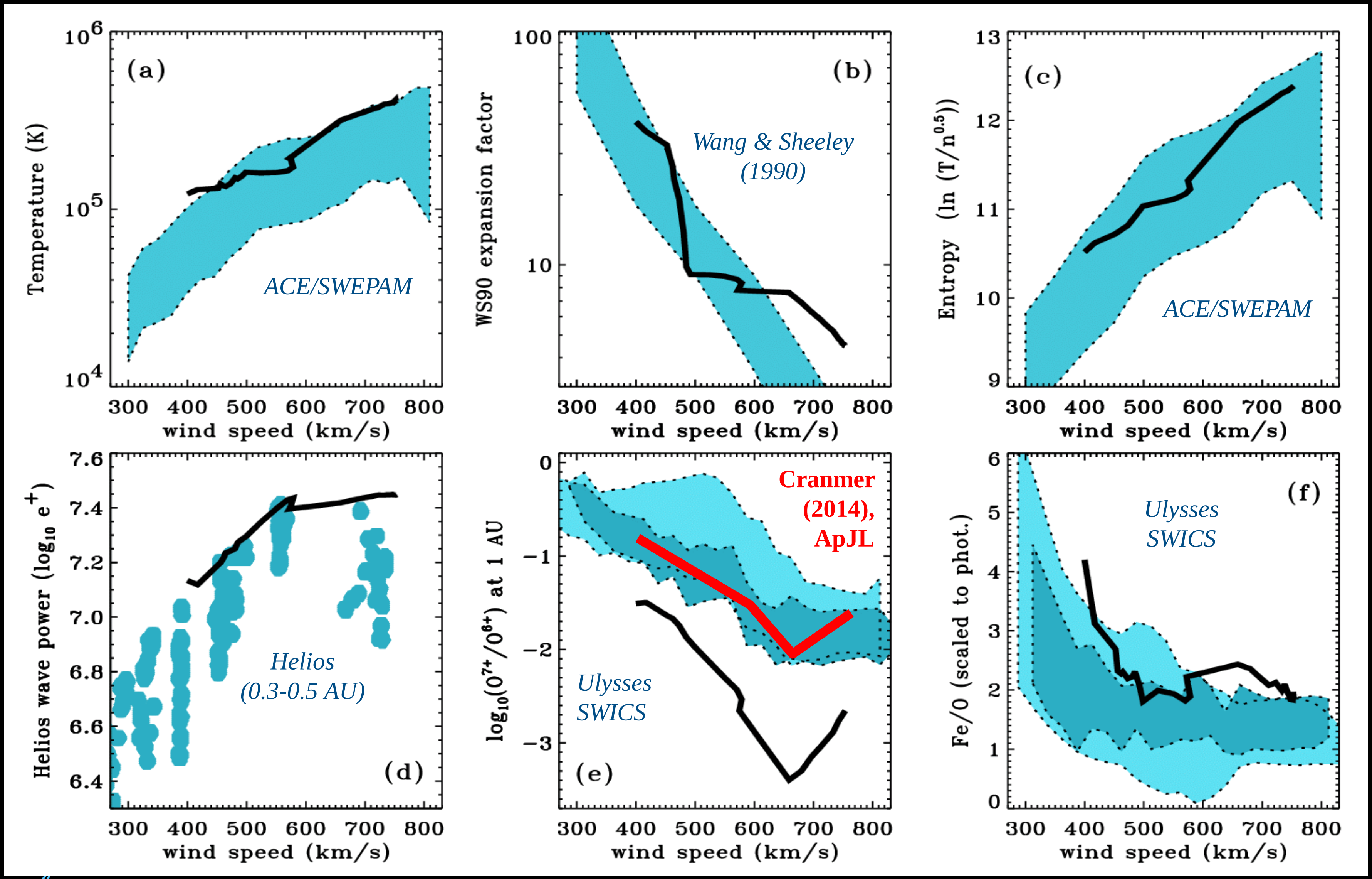
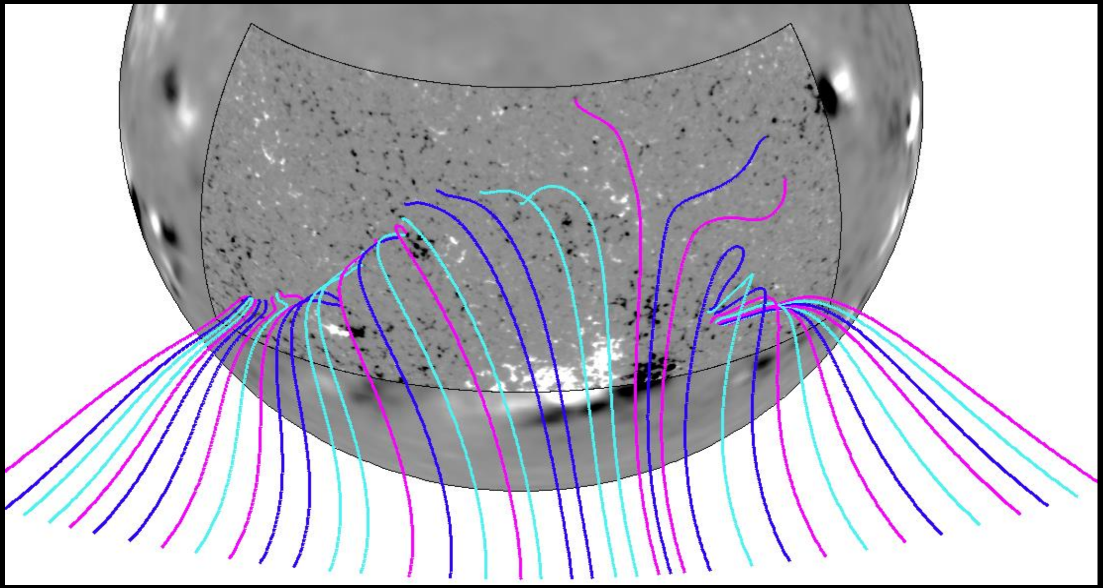
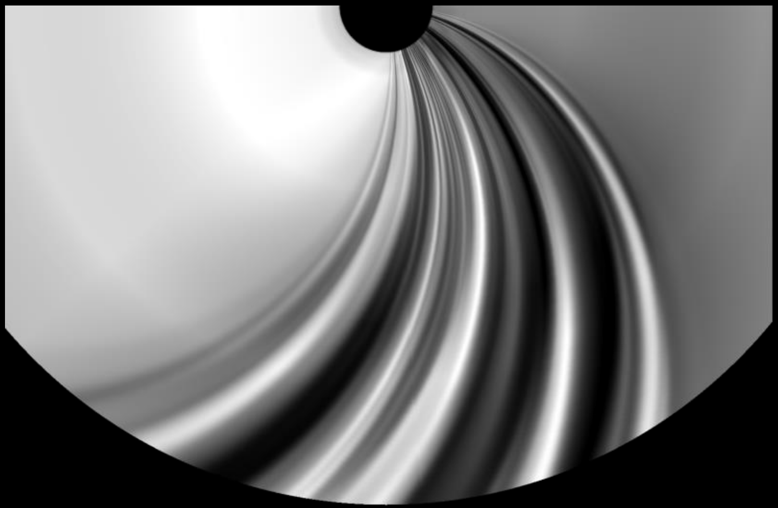


High resolution needed for CIRs…

- Cranmer et al. (2013) ran *ZEPHYR* models on flux tubes mapped from SOLIS magnetograms.
- **Low-latitude Quiet Sun →**
- In-ecliptic evolution modeled with full MHD: much more CIR structure than in low-res models!





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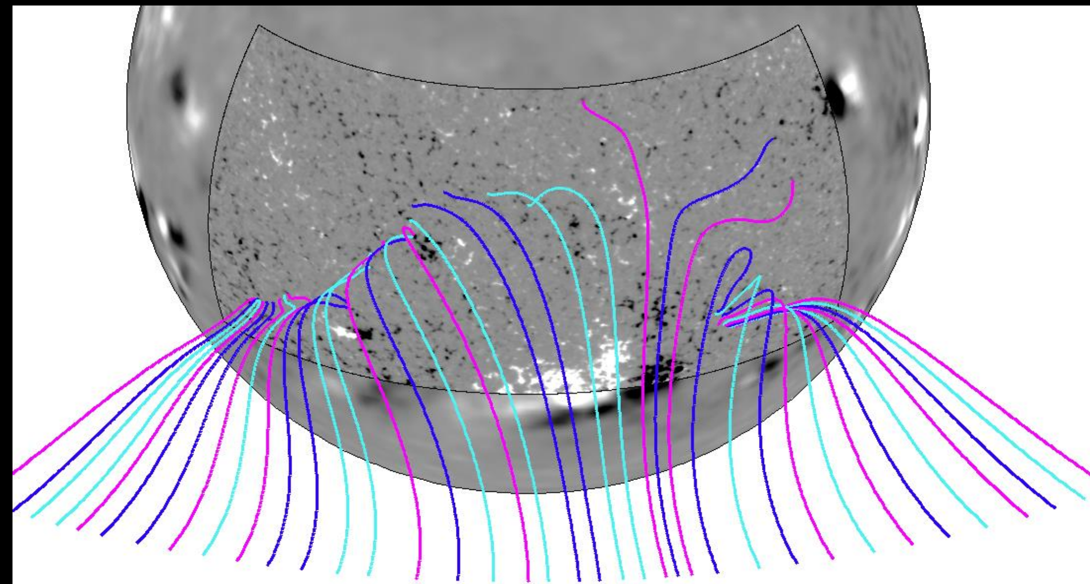

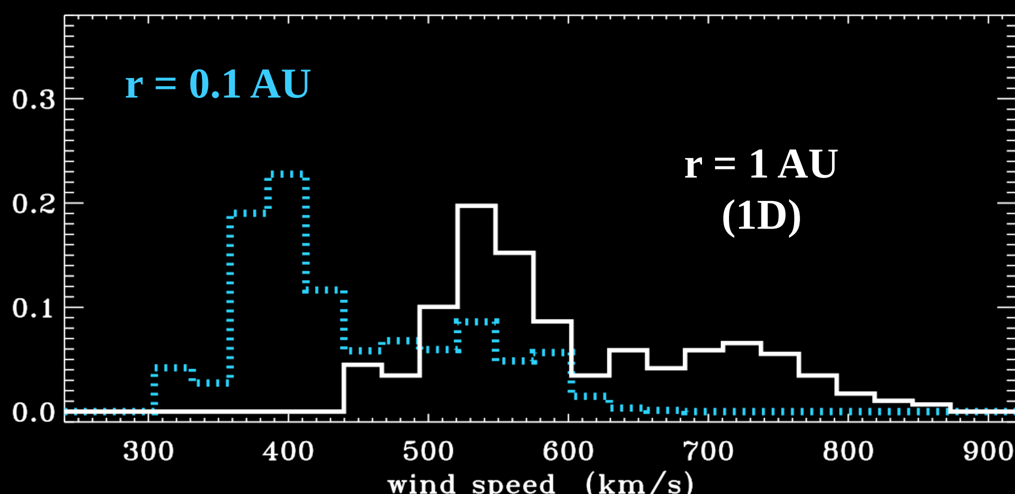

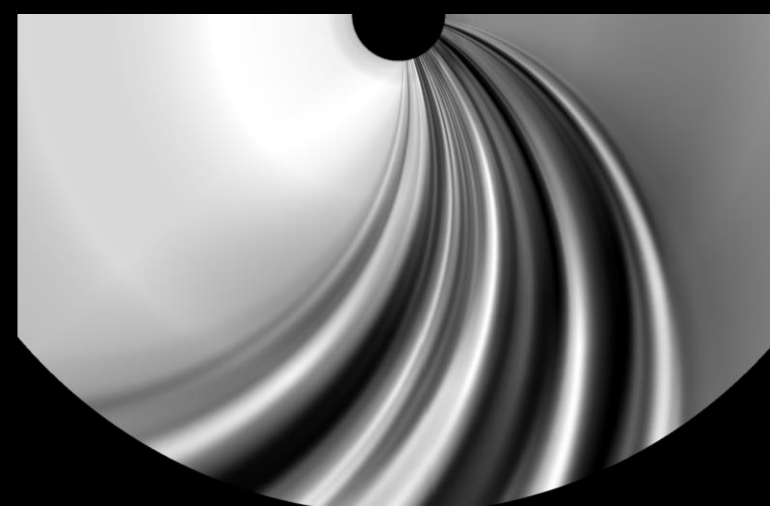

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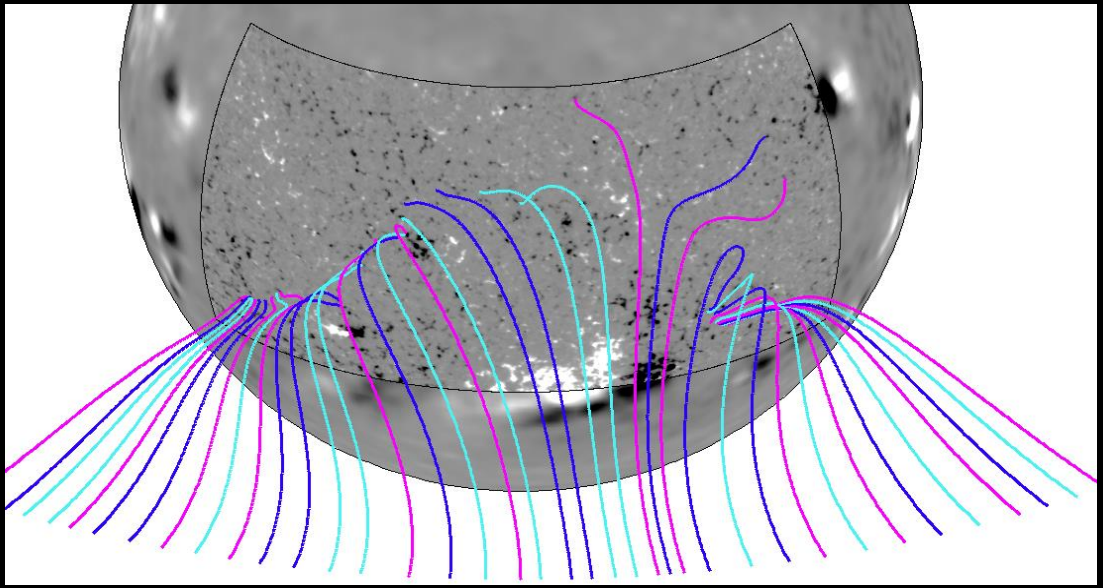
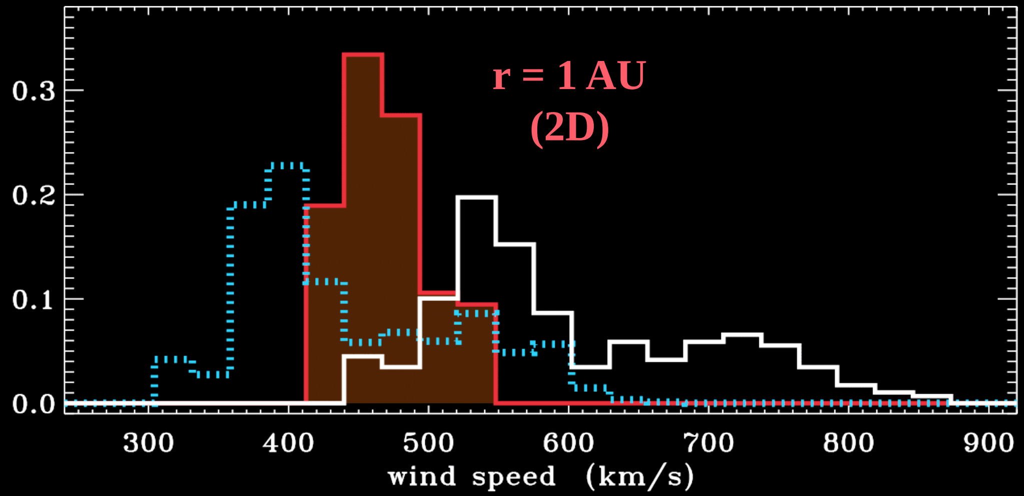
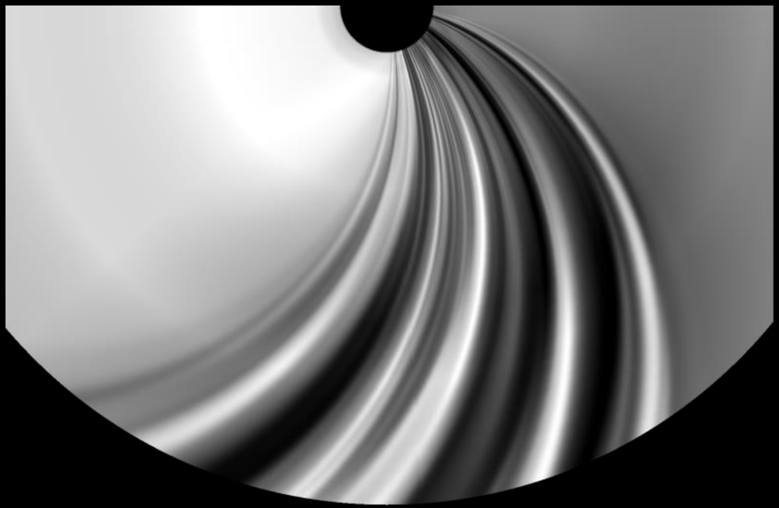
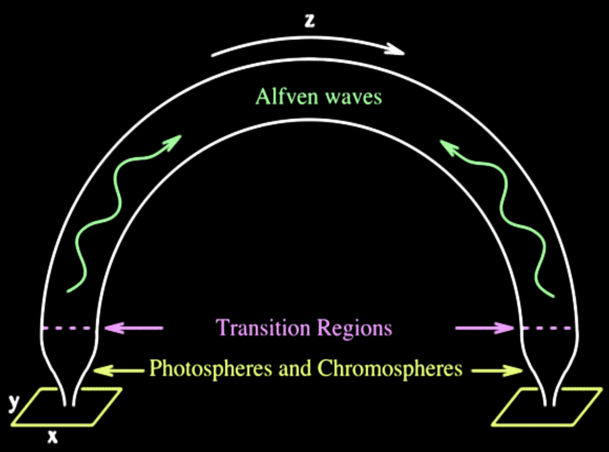


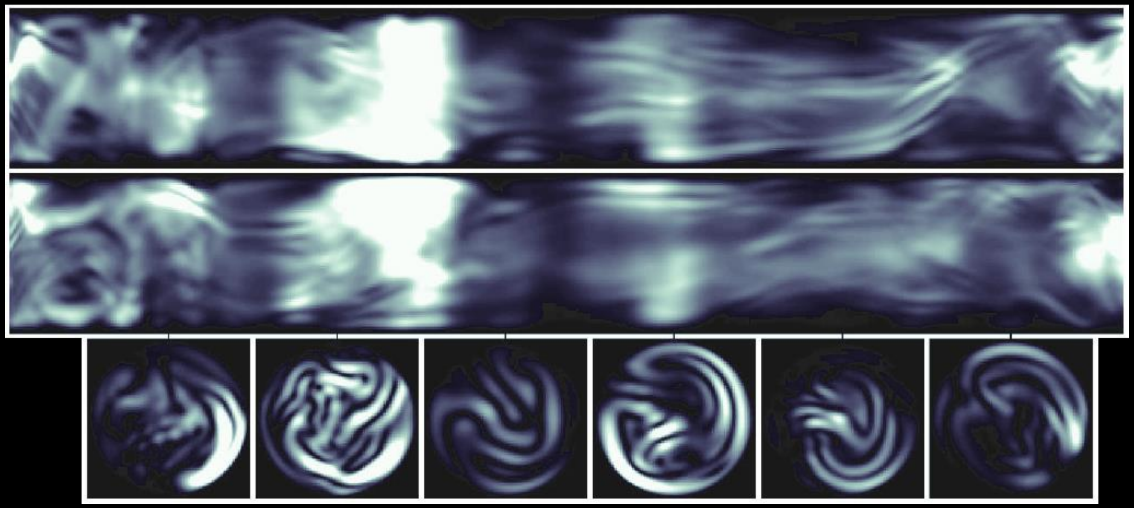


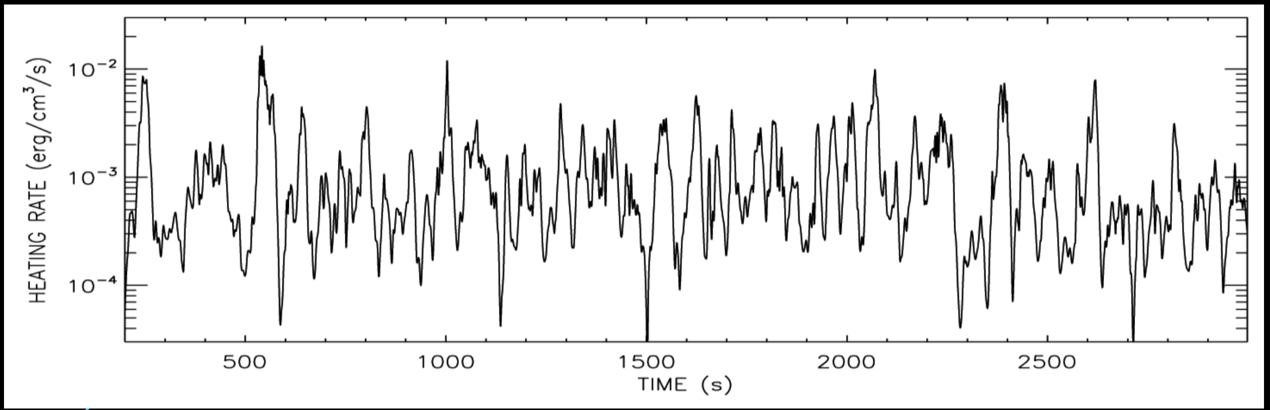


Turbulence is "nanoflare-like"

- van Ballegooijen et al. (2011); van Ballegooijen & Asgari-Targhi (2014, 2016) modeled the turbulence as fully time-dependent reduced MHD…



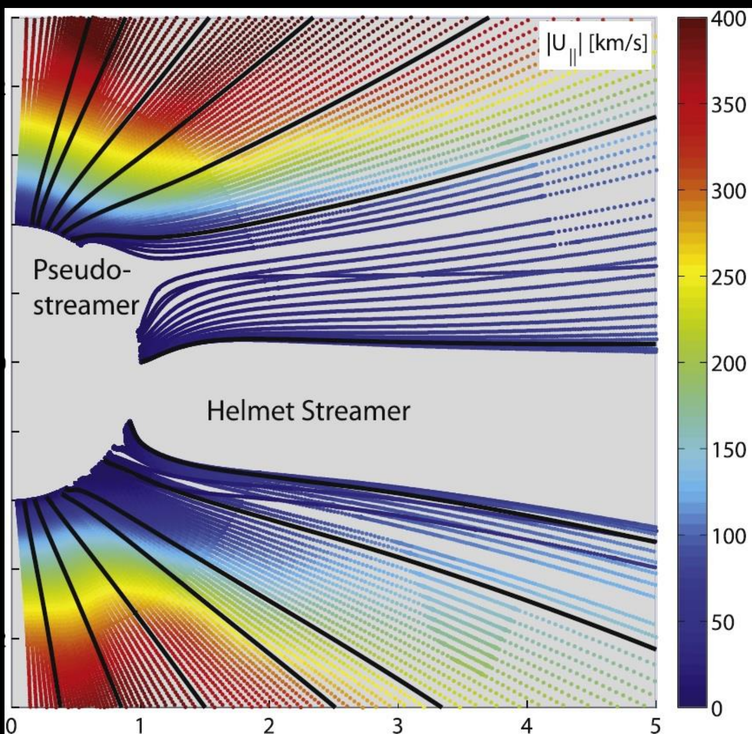




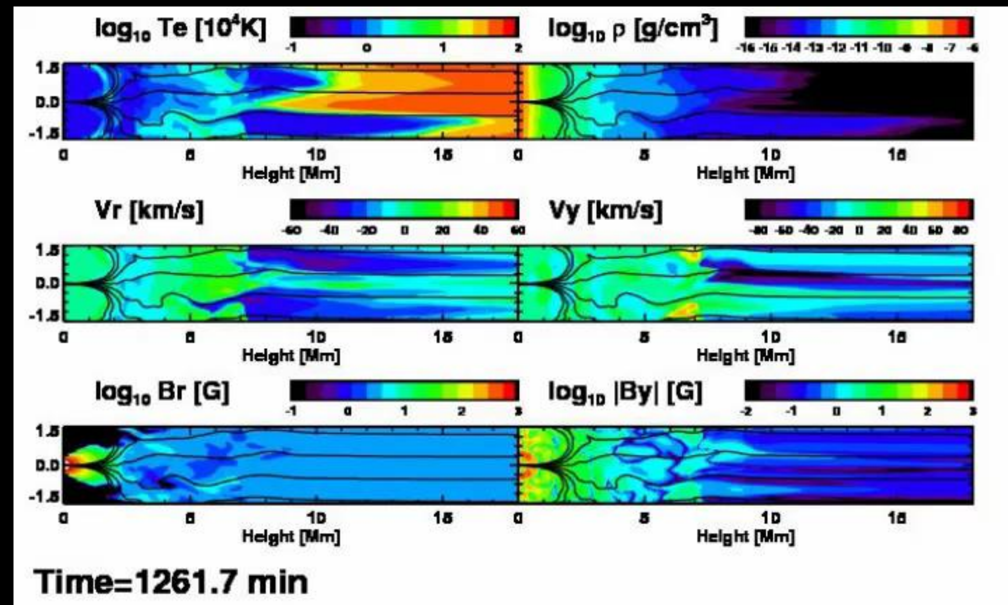
Woolsey & Cranmer (2015) showed that variable *T* makes a "DEM" with realistic properties

It's a world-wide effort

U. Michigan's **AWSoM** code (e.g., Oran et al. 2015) applies Alfvénic turbulence model in 3D; correctly predicts slow ("closed") ioniz. states!



At U. Tokyo (e.g., Matsumoto & Suzuki 2014), time-dependent models of more restricted domains pinpoint more physics…



- A missing piece in most models: **multi-wave "mode coupling!"** (Alfvén ↔ acoustic)
- Avery Schiff (CU) is exploring mode coupling in a wide range of coronal heating models.

1. Where are we? What's going on?
2. Origins: theory overview, model results
3. **Waves & turbulence: how can observations constrain the physics?**

Remote sensing of MHD waves

With good instrumentation, **imaging & spectroscopy** can resolve wave-like fluctuations:

- Intensity modulations . . .

$$\delta I \;\propto\; (\delta\rho)^{1-2}$$

- Motion tracking in images . . .

$$\delta V_{\rm POS}$$

- Doppler shifts . . .

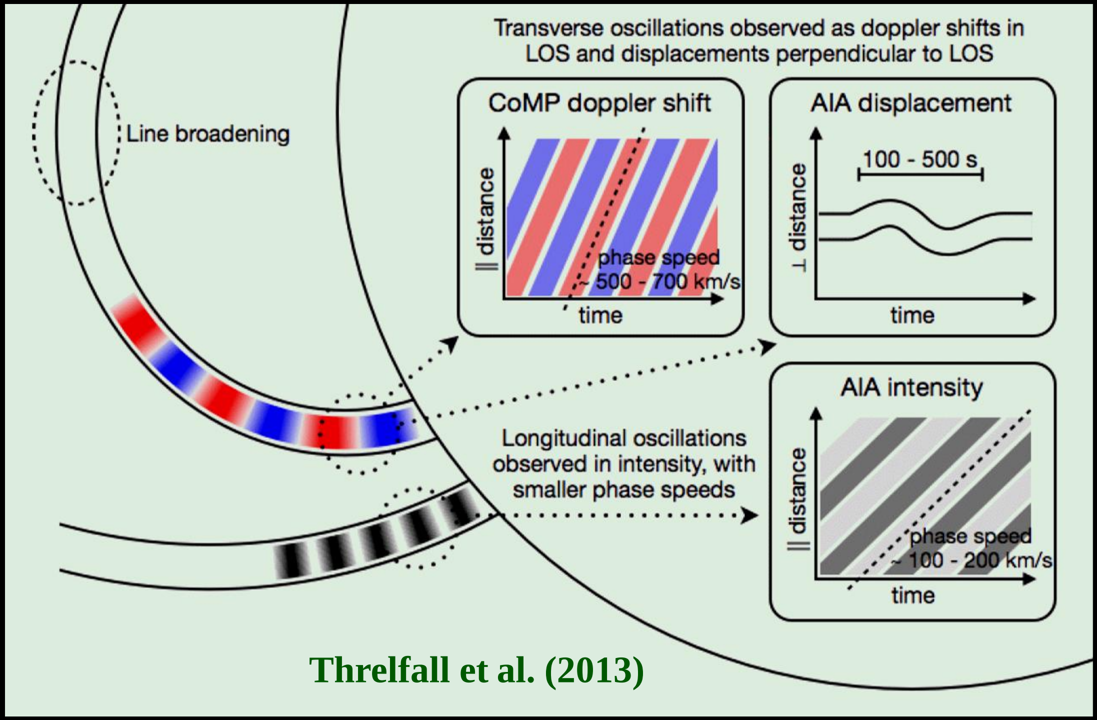
$$\delta\lambda \;\propto\; \delta V_{\rm LOS}$$

- Doppler broadening . . .

$$\delta\lambda \;\rightarrow\; <\delta V_{\rm LOS}>$$

- Radio sounding . . .

$$\delta\tilde{n} \;\rightarrow\; \delta\rho\,,\delta B \;\rightarrow\; \delta V$$

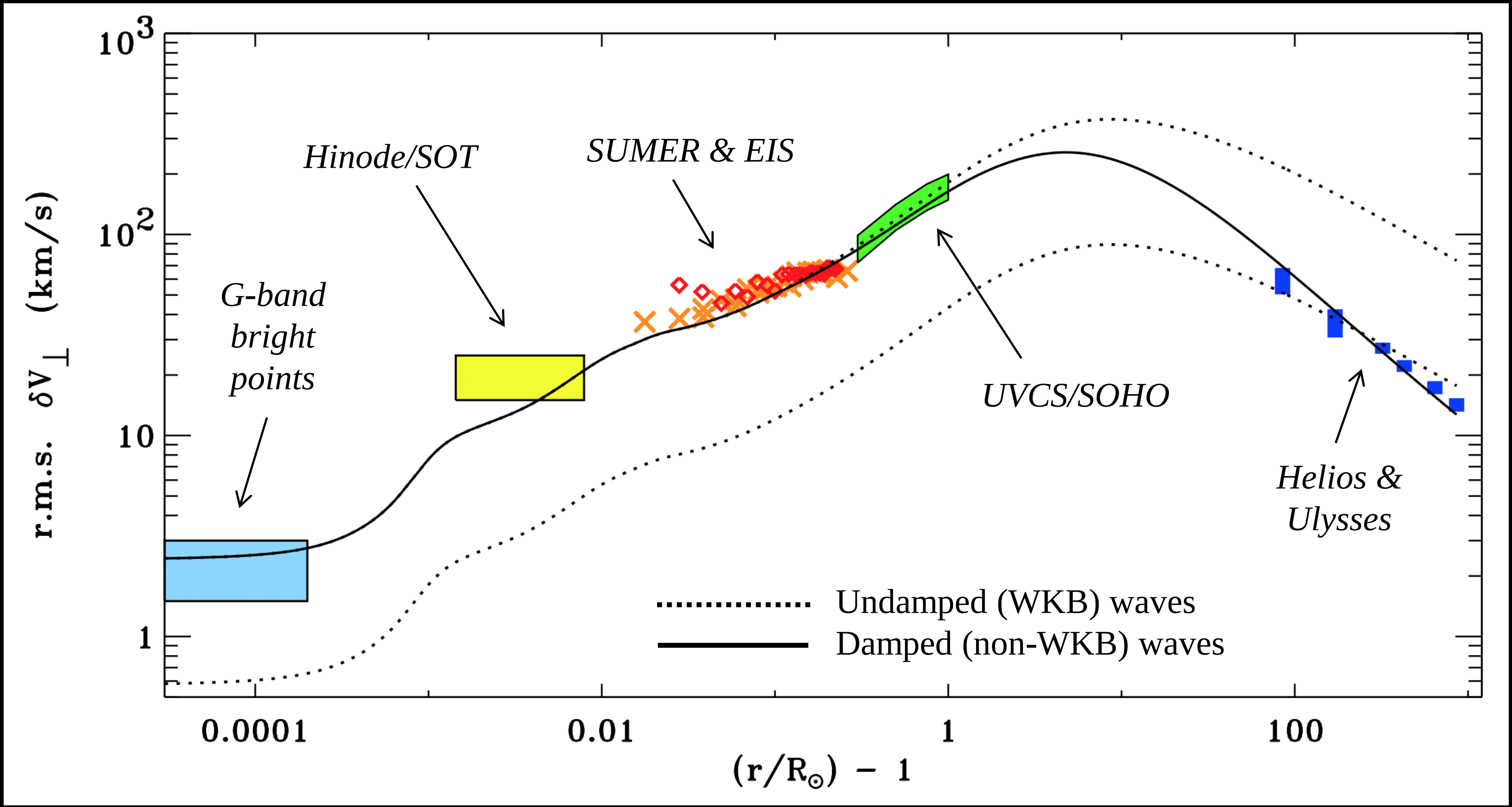


Threlfall et al. (2013)

- ***Results:*** Alfvén-like waves seem to have periods of order 3-5 minutes; compressive waves have periods of order 10-20 minutes.

Measured Alfvénic fluctuations

- Cranmer & van Ballegooijen (2005) collected a range of observational data…



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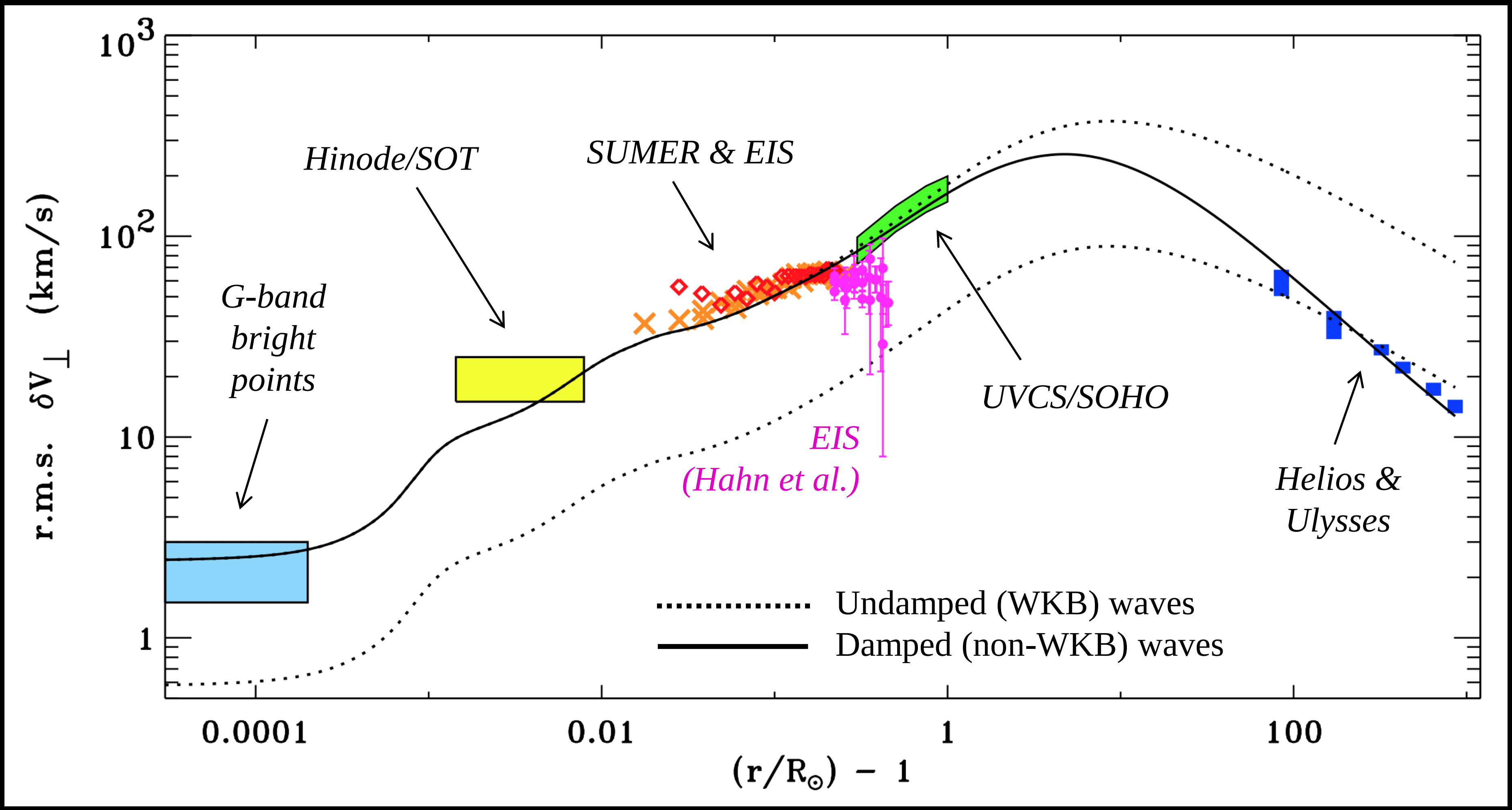
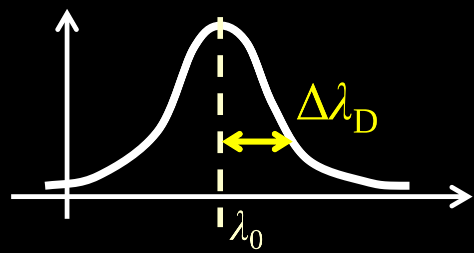


Off-limb complications

- At large *r*, one must integrate over tens of minutes (hours?) for good profiles.
- Can we separate the 2 components of the **width?**



$$\frac{\Delta\lambda_D}{\lambda_0} = \frac{v_{\mathrm{th,eff}}}{c} = \frac{1}{c}\sqrt{\frac{2k_B T_{\mathrm{ion}}}{m_{\mathrm{ion}}} + \xi^2}$$

thermal width

nonthermal width (waves?)

- Observed quantities depend on integration over an optically thin line of sight.
- Chris Gilbert (CU) is working on 3D forward modeling to better do “inversions.”

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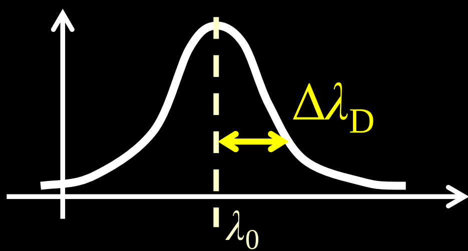

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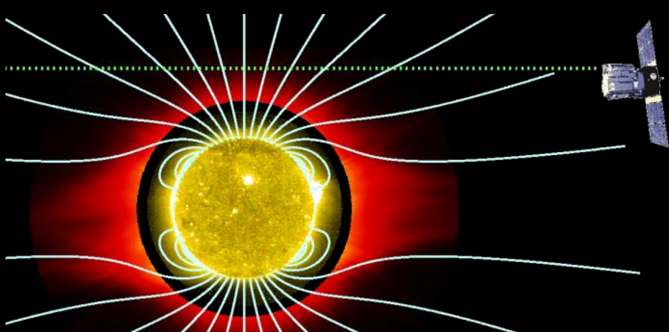
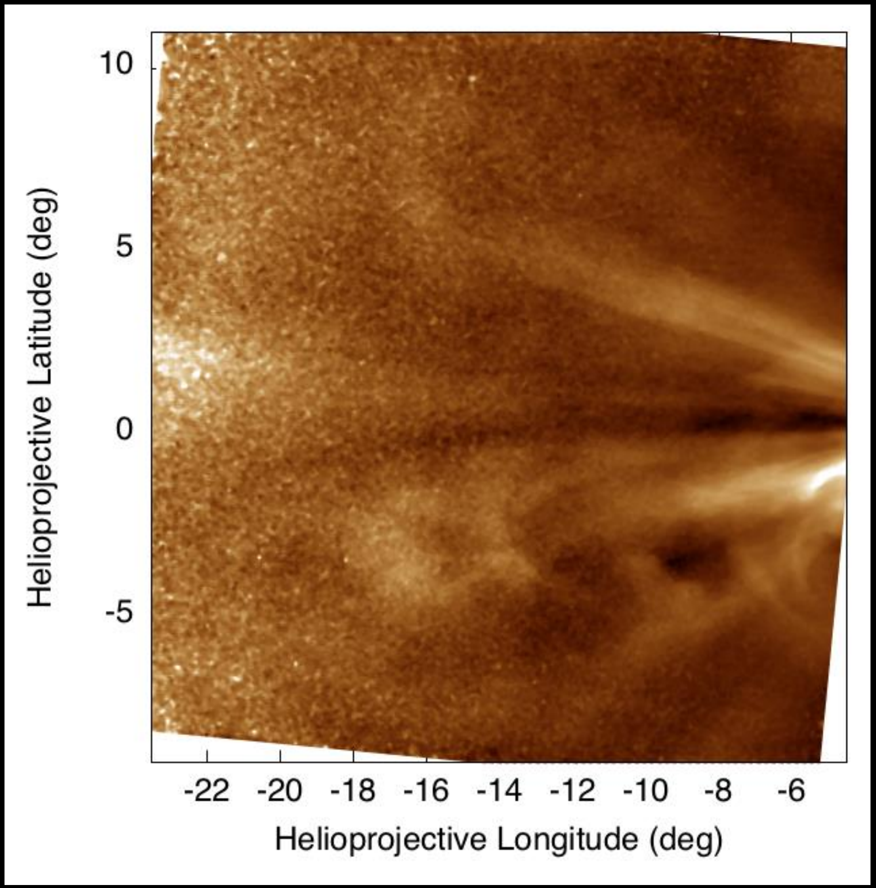


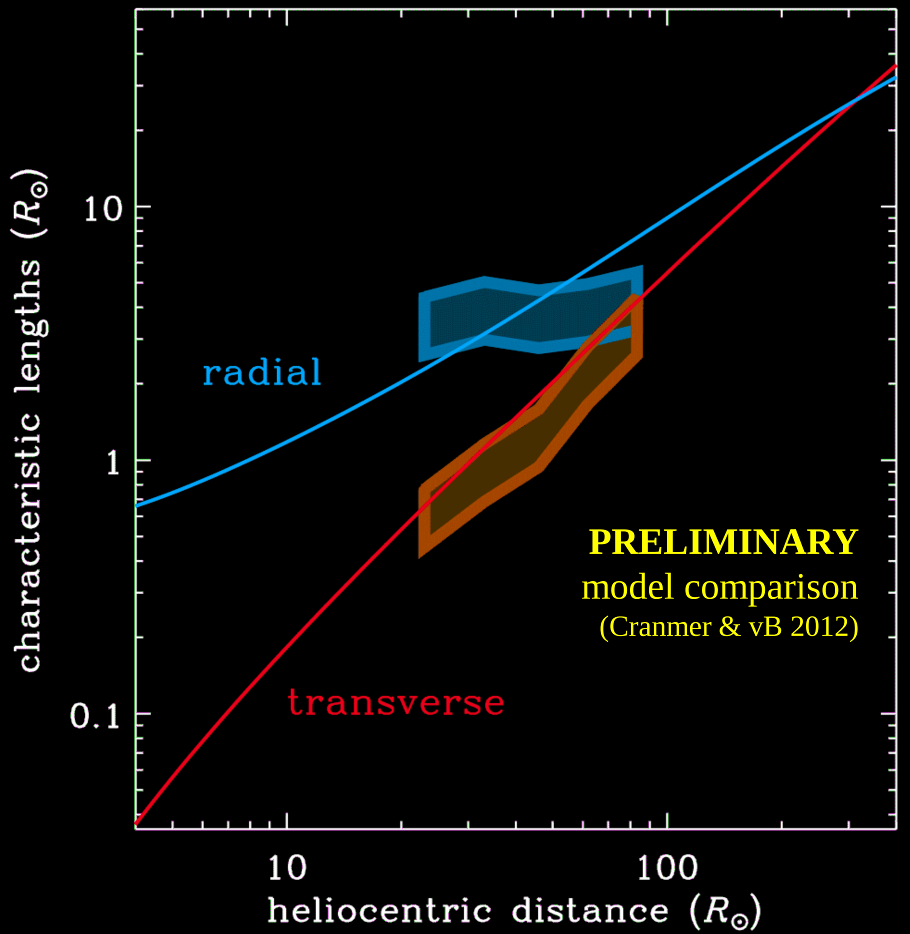
Observing even higher up (e.g., UVCS/SOHO) reveals indirect information about waves, via how their dissipation heats the particles . . .

$$T_{\rm ion} \gg T_{\rm p} \gtrsim T_{\rm e} \;,\quad T_\perp > T_\parallel \;,\quad \mathbf{v}_{\rm ion} > \mathbf{v}_{\rm p}$$

Turbulence loses its anisotropy

- DeForest et al. (2016) processed STEREO/HI-1 data to find that radial "striations" near the Sun (r < 40 R_s) give rise to isotropic "flocculation" further out (r > 60 R_s)





What can DKIST do?

On-disk diagnostics:

- DKIST can extend the bright point kinetic energy power spectrum to both **higher** freq's (cadence) & **lower** freq's (sensitivity)
- Flux-tube distortions (not just centroids) can be measured!

Off-limb diagnostics: (DL-NIRSP & Cryo-NIRSP)

- "How much" of each wave mode is present in various regions?
- Do different modes correlate with one another? With background properties?
  - Total intensity (line or continuum) . . . . $\delta\rho$
  - Narrow feature position ("swaying strands") . . $\delta v_\perp$ (maybe $\delta v_\parallel$)
  - Doppler velocity . . . . $\delta v_\perp$ (maybe $\delta v_\parallel$)
  - Line intensity ratios . . . . $\delta\rho$, δT
  - Line width . . . . $\delta v_\perp$, δT
  - Magnetically sensitive polarization? . . . . δB **? !**

Conclusions

- Although the "problems" are not conclusively solved, we're including more and more real physics (e.g., MHD turbulence) in models that are doing better at explaining the heating & acceleration of solar wind plasma.

- However, we still do not have complete enough observational constraints to be able to choose between competing theories . . .

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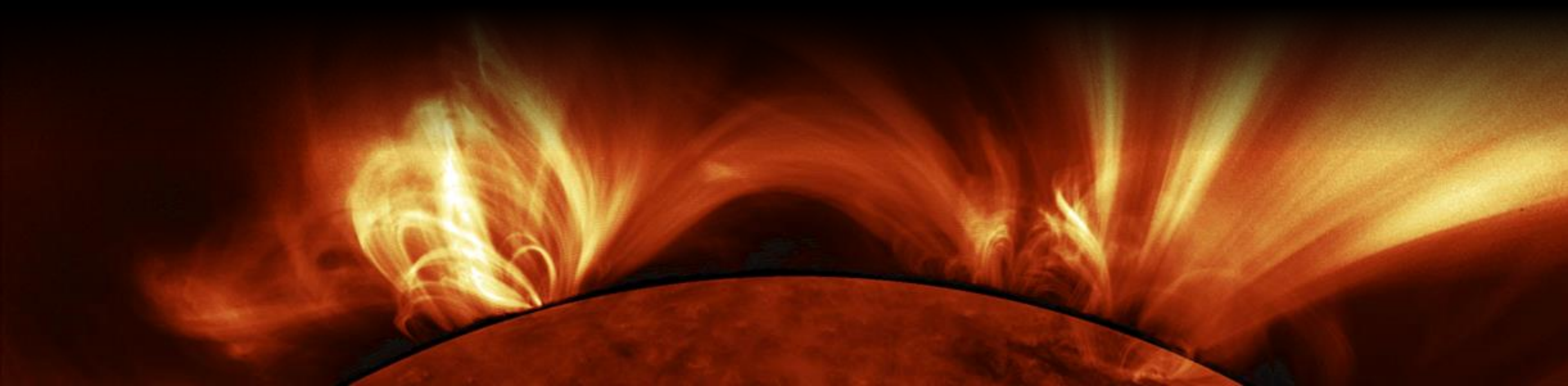
DANIEL K. INOUYE SOLAR TELESCOPE

COSMO

esa
Solar Orbiter

EXPLORERS
GODDARD SPACE FLIGHT CENTER



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Solar Probe Plus
A NASA Mission to Touch the Sun

Solar Orbiter

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GODDARD SPACE FLIGHT CENTER

DKIST CRITICAL SCIENCE PLAN

Title: Coronal Waves and Turbulence: Energy Fluxes, Dispersion Relations, and Mode Coupling

Prepared by: Steven R. Cranmer

Team: Ineke De Moortel, Sarah Gibson, Michael Hahn, Hui Tian, Steve Tomczyk

Date: October 20, 2014

http://tinyurl.com/cranmer–dkist