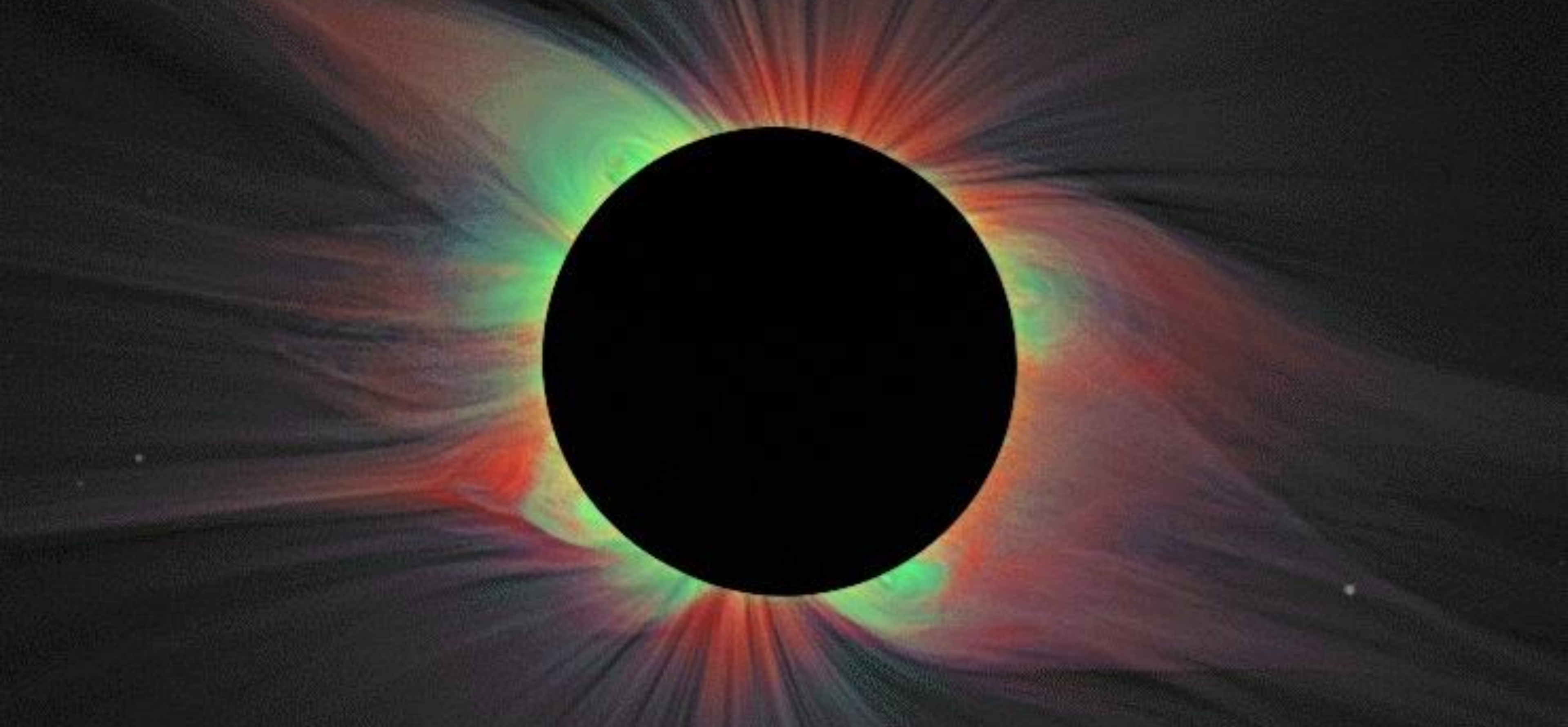
Coronal Science: Preparing for the DKIST Era



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Outline

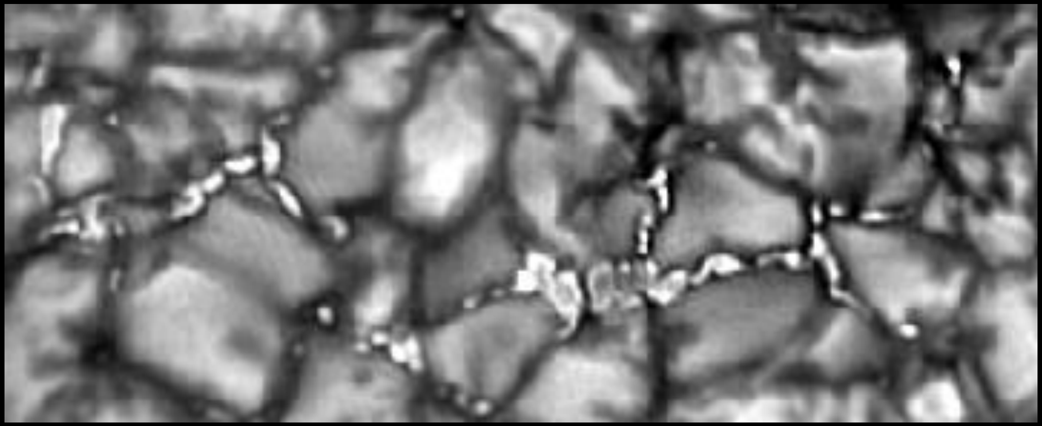
6 x { Topics with burning questions (personally biased!)
Paths forward (what can DKIST do?)

More information…

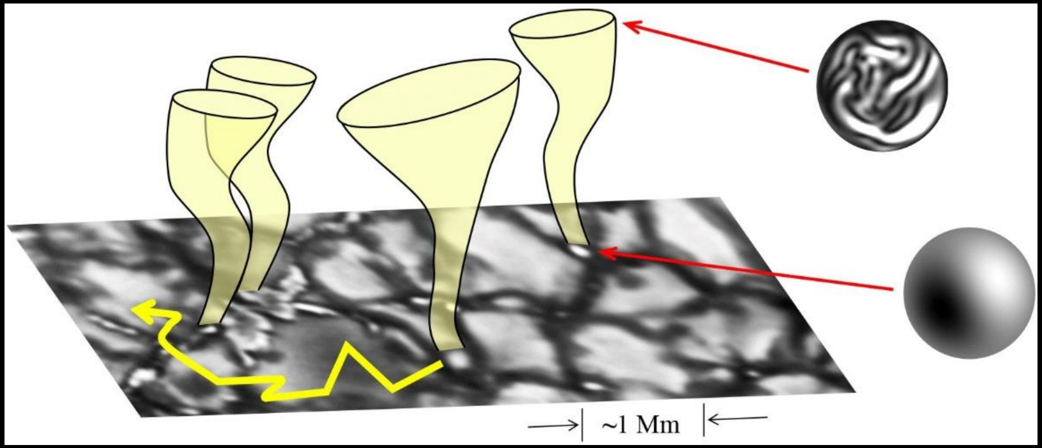
- Two 2015 themed issues of *Phil. Trans. Roy. Soc. A:*
  - v. 373, issue 2042, **"Recent Advances in Coronal Heating,"** ed. De Moortel & Browning
  - v. 373, issue 2041, "Dissipation & Heating in Solar Wind Turbulence," ed. Kiyani et al.
- Just a selection of last 2 years of *Living Reviews in Solar Physics:*
  - Warmuth (2015), global coronal waves
  - Laming (2015), FIP effect in solar/stellar coronae
  - van Driel-Gesztelyi & Green (2015), active regions
  - Reale (2014), coronal loops
  - Penn (2014), infrared solar physics

1. Photosphere: flux tube motions

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



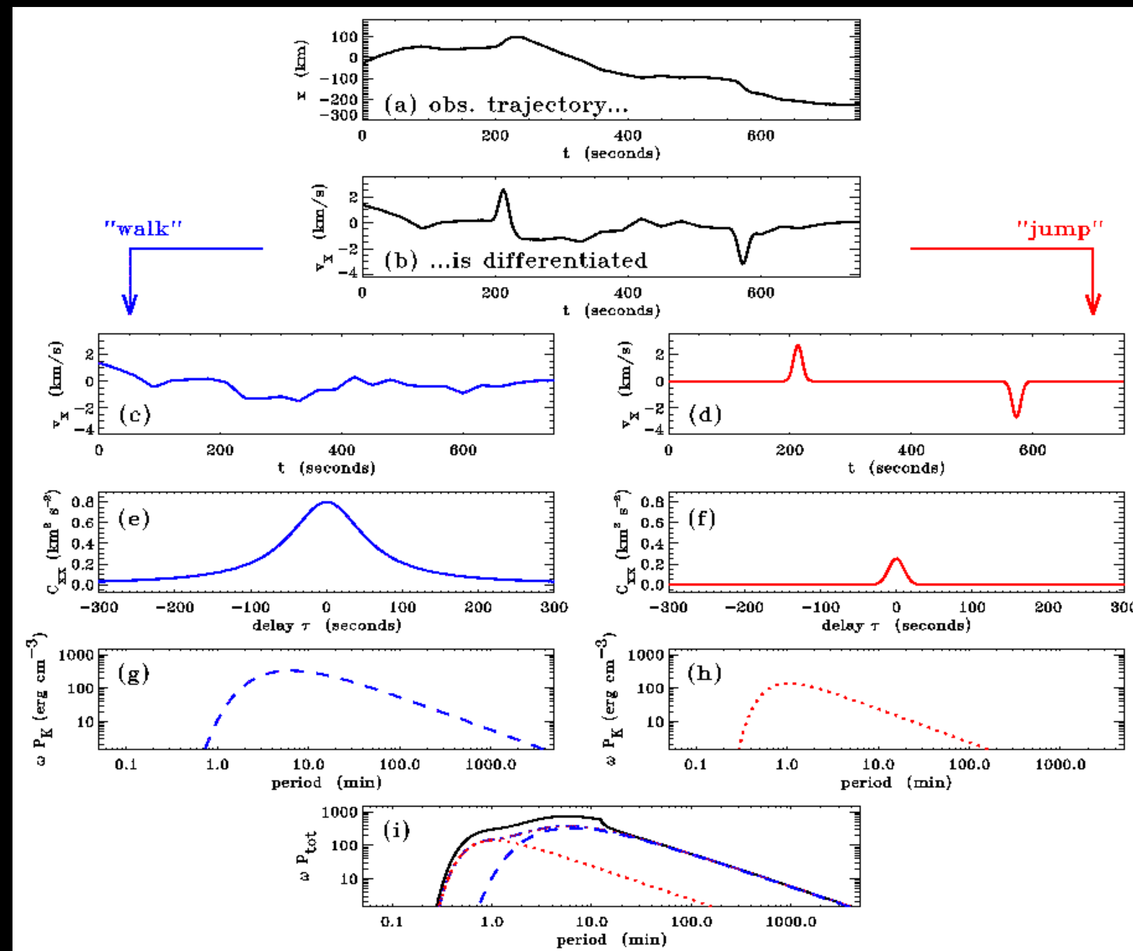
- Over the last 20 years, we've begun to characterize BP
  - magnetic fluxes (*B* ~ 1 kG)
  - lifetimes
  - random walk horiz. velocities
  - departures from cylindrical "flux tube" shapes
  - formation mechanisms (flux emergence? convective collapse?)
- Above: used ≤ 1.5 m telescopes



1. Photosphere: flux tube motions

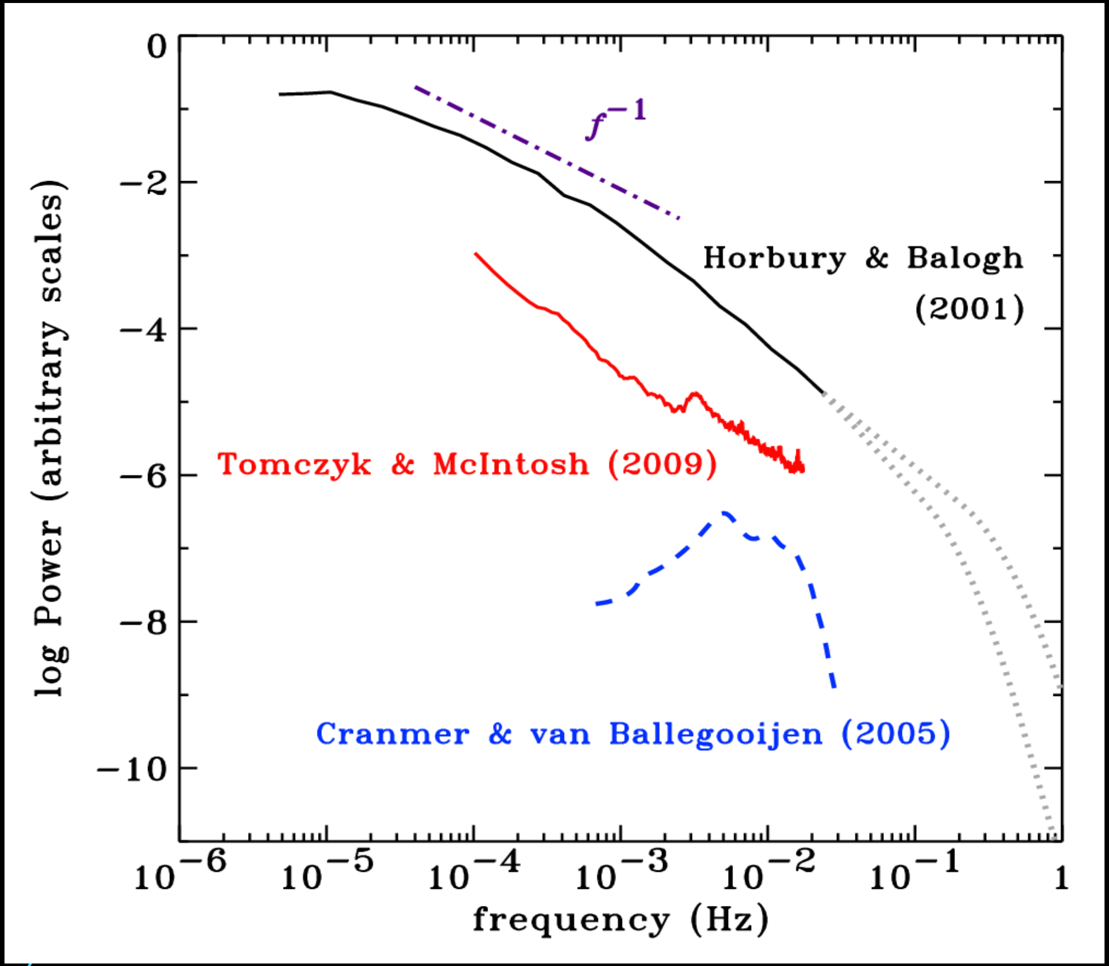
- Simple things have been done to convert horizontal motions to a "lower boundary condition" (power spectrum) of MHD waves…

- There seem to be 2 components of BP motion:
- **"random walk"** (e.g., Nisenson et al. 2003);
- **"intermittent jumps:"** assoc. with mergers, fragmenting, reconnection? (Berger et al. 1998).
- Derived power spectrum feeds corona/wind models (Cranmer & van Ballegooijen 2005) →
- P_{kin} not necessarily = P_{mag}



1. Photosphere: flux tube motions

- So far, the kinetic energy power spectrum obtained from BP measurements has been limited in several ways.   (most recent: Chitta et al. 2012, ApJ, 752, 48)

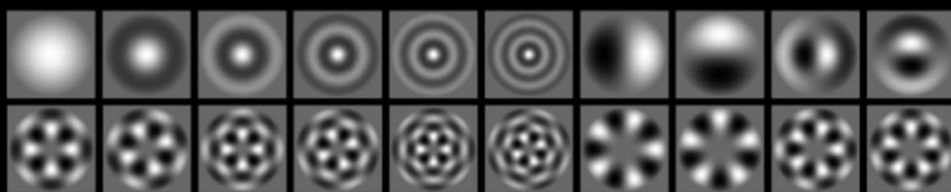


- Basic limitations on cadence prevented going to **higher frequencies.**
- Finite (apparent) lifetimes of BPs prevented going to **lower frequencies.**

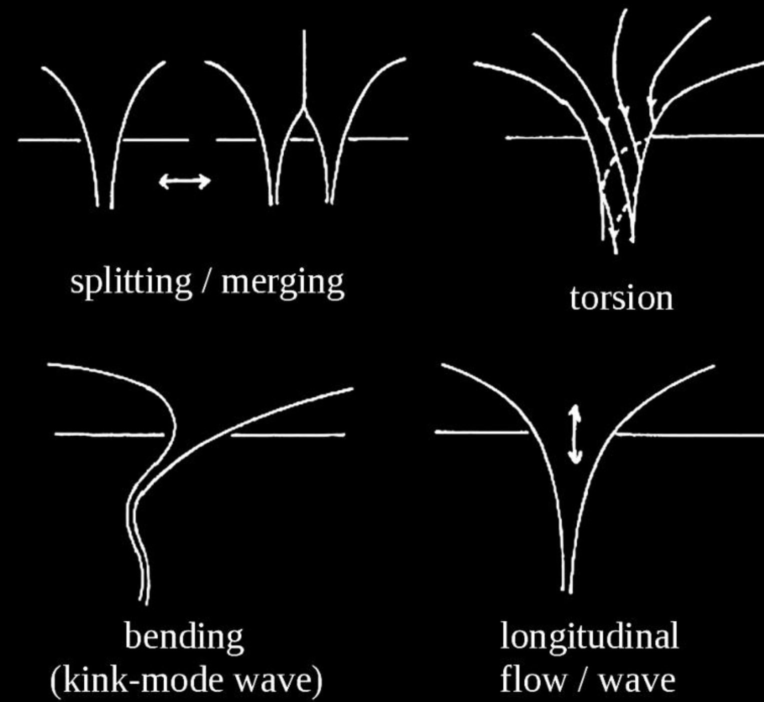
  (Is BP birth/death just due to dispersal of flux below detection limit? Is reconnection destroying flux?)

1. Photosphere: flux tube motions

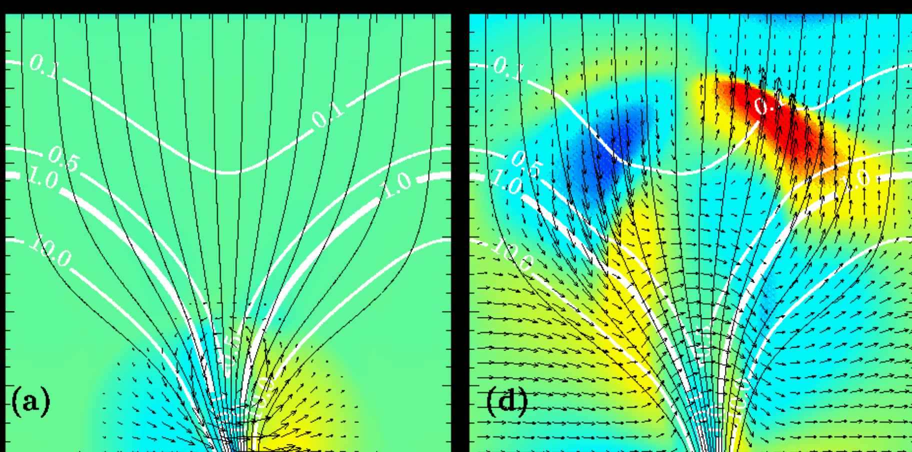
- In addition to "centroid" motion, the flux tubes undergo many other kinds of **distortion** that can propagate up into the corona.



van Ballegooijen et al. (2011)



Spruit (1984)



The surroundings matter, too (e.g., Hasan et al. 2005)

1. Photosphere: flux tube motions

What should DKIST do? (mostly VBI?)

In prep for first light:

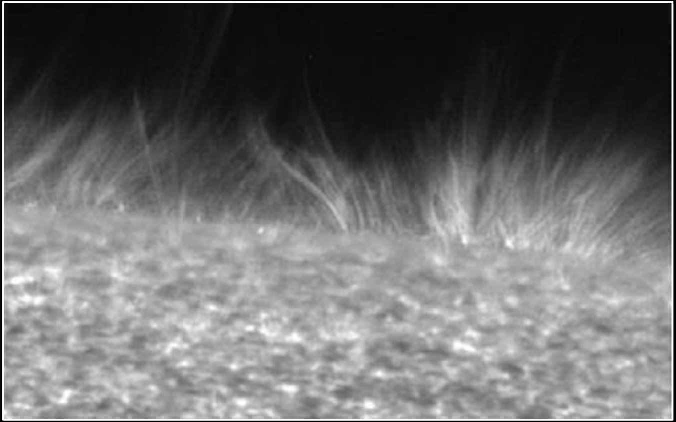
- With "perfect" data (Rempel's simulations?) we should figure out
  - whether the idea of a 2-phase medium (kG flux tubes + weak-field granules) needs to be broadened
  - whether there's a straightforward quantitative way to take a movie of a distorted/squishy flux tube and characterize its MHD oscillation energy
  - whether or not these oscillations are thin-tube normal modes, we should work out ***how*** each mode transits energy up into the corona

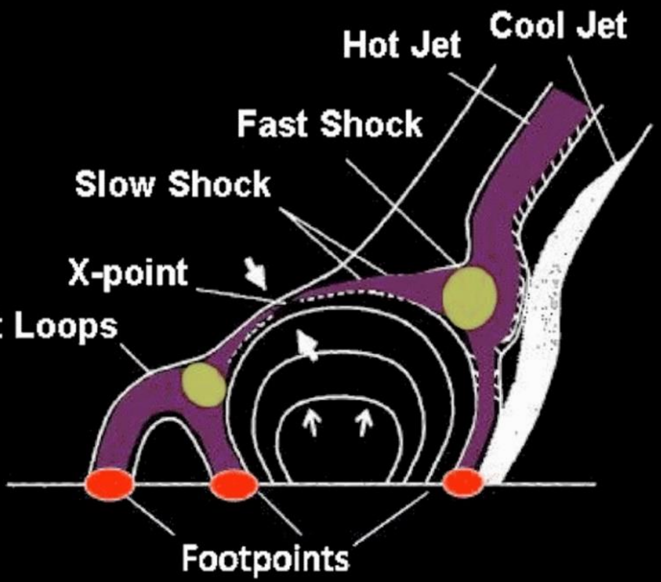
Observations:

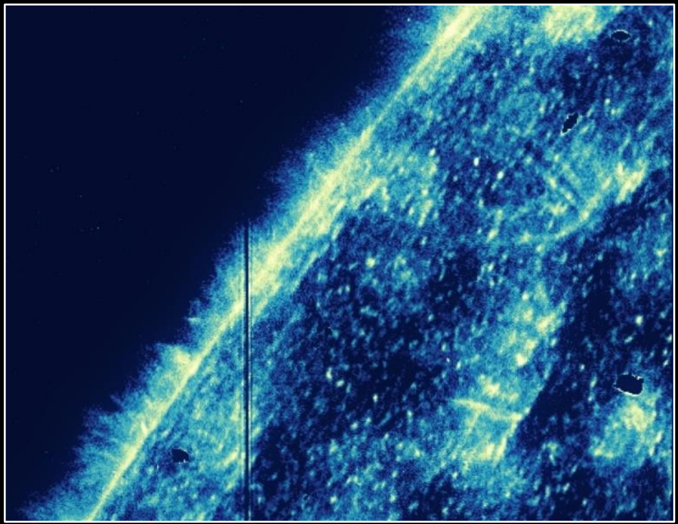
- Repeat BP centroid motion-tracking, with better cadence & sensitivity.
- Implement above squishy flux tube analysis on real data to derive full range of MHD wave power spectra.
- For all of the above, characterize differences in **CH / QS / AR** (*B* imbalance?)

2. Chromo/corona: *jets & spicules*

- Already likely discussed by Scott…
- Do they feed mass/momentum/energy into the corona and/or solar wind?
- Largest events (X-ray jets) are surely driven by reconnection, but are the smallest ones?

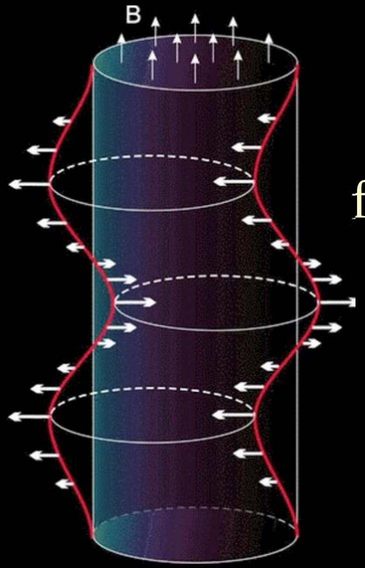

Hinode SOT image: M. Carlsson




IRIS; Narang et al. (2015)

2. *Chromo/corona: jets & spicules*

- Cranmer & Woolsey (2015) followed up on the Kudoh & Shibata (1999) idea of Alfvén-wave driving of jets. (Replace sinusoidal waves w/ turbulence)
- No reconnection needed; works in ~unipolar coronal hole network regions.



mode conversion

↓

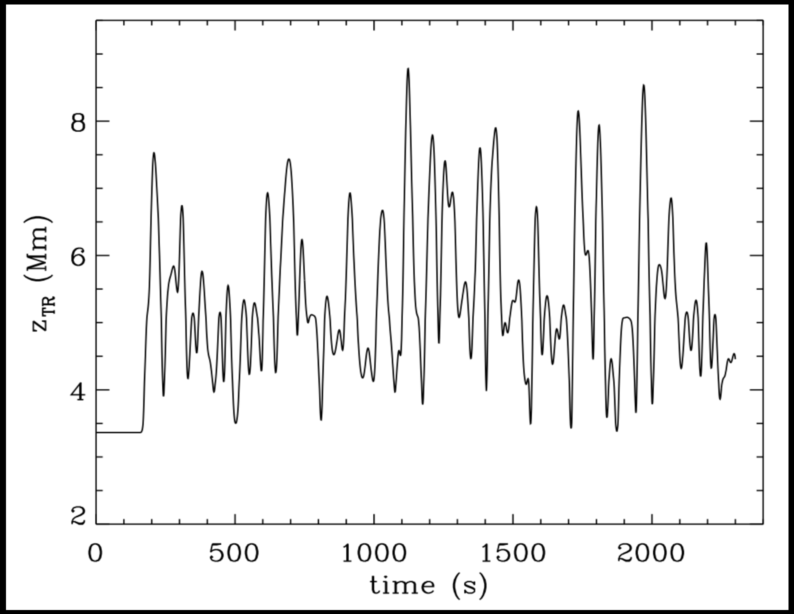
fast/slow (compressive) waves

↓

shocks

↓

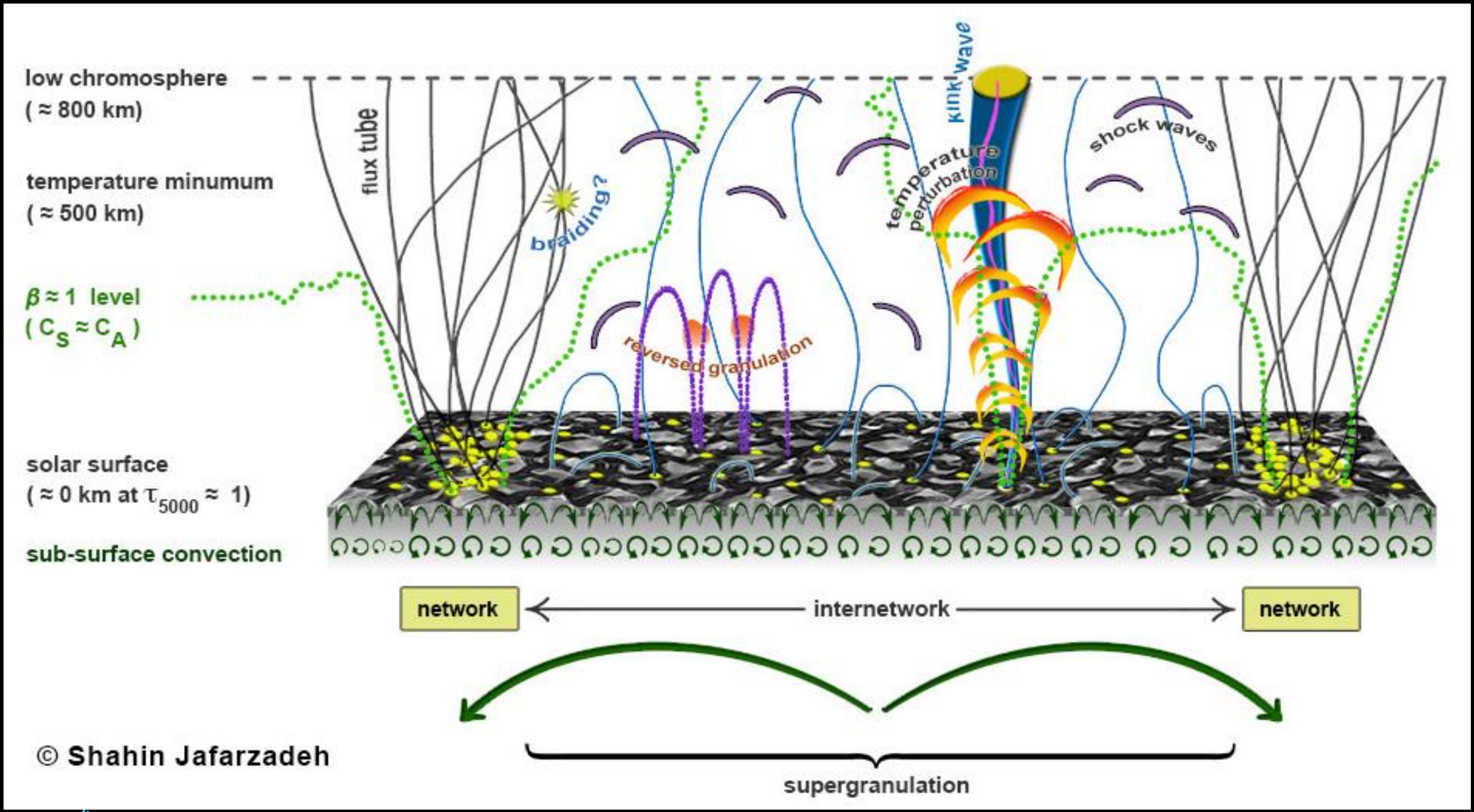
transient pressure "support"



Are these up/down motions of TR true "flows?"

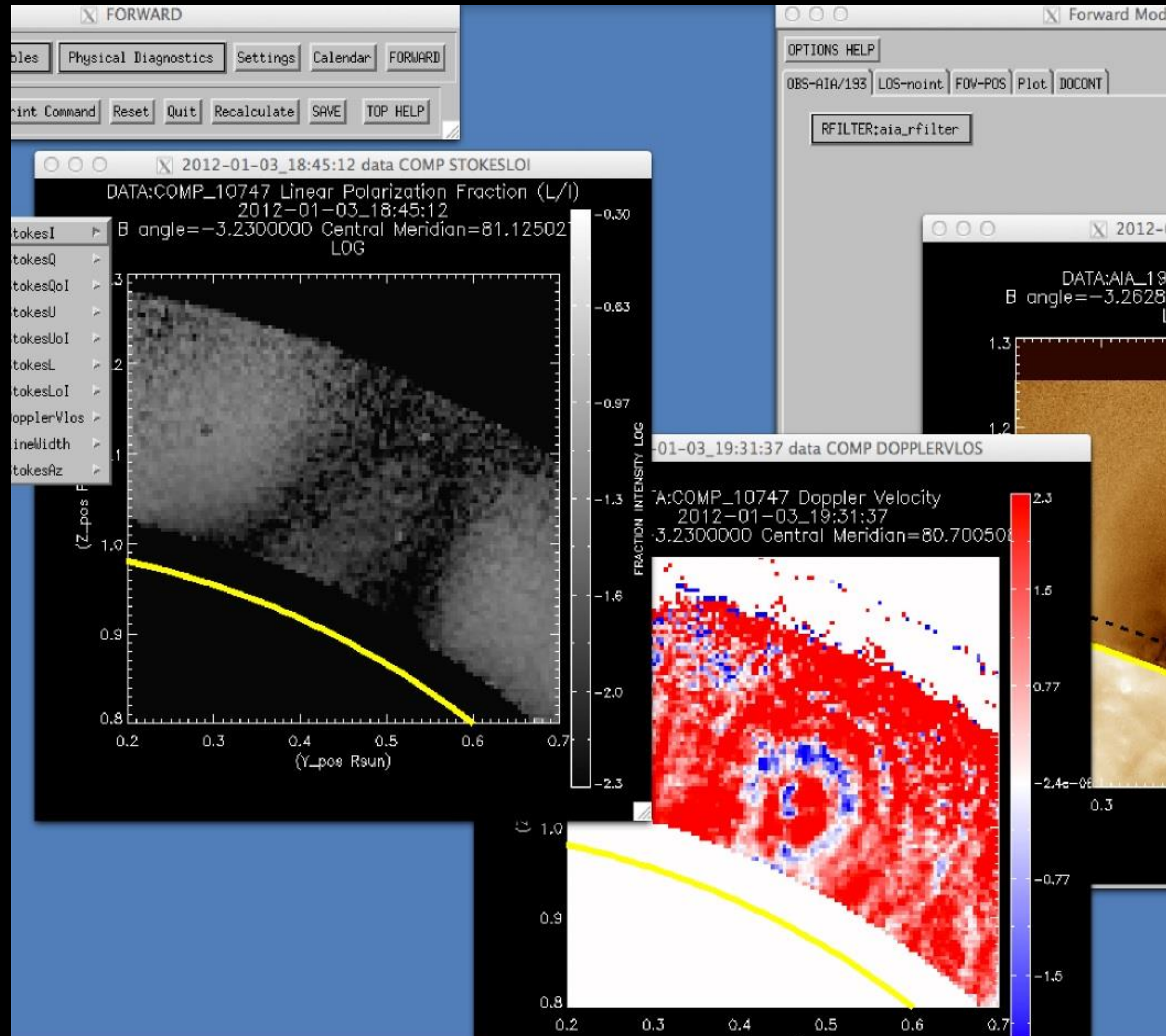
Aside 1…

When searching for explanations, we should be prepared for **both/and,** not either/or.



Aside 2…

- Most off-limb measurements (not just spicules/jets!) integrate through a long, optically thin, **line of sight.**
- CoMP Doppler oscillation velocities are ~0.5–1 km/s, but that's reduced by $1/\sqrt{N}$ from 20–40 km/s (?) in each feature.
- Much more **forward modeling** is needed to reliably "convert" between observations and models.



2. Chromo/corona: *jets & spicules*

What should DKIST do?   (mostly Cryo-NIRSP?)

In prep for first light:

- We need to ~~fully explore~~ ***science the s**t out of*** the line-of-sight integration problem.
- Hold models to the grindstone (spicule mass supply vs. "classical" RTV-ish) and figure out where they differ in terms of what we can observe!

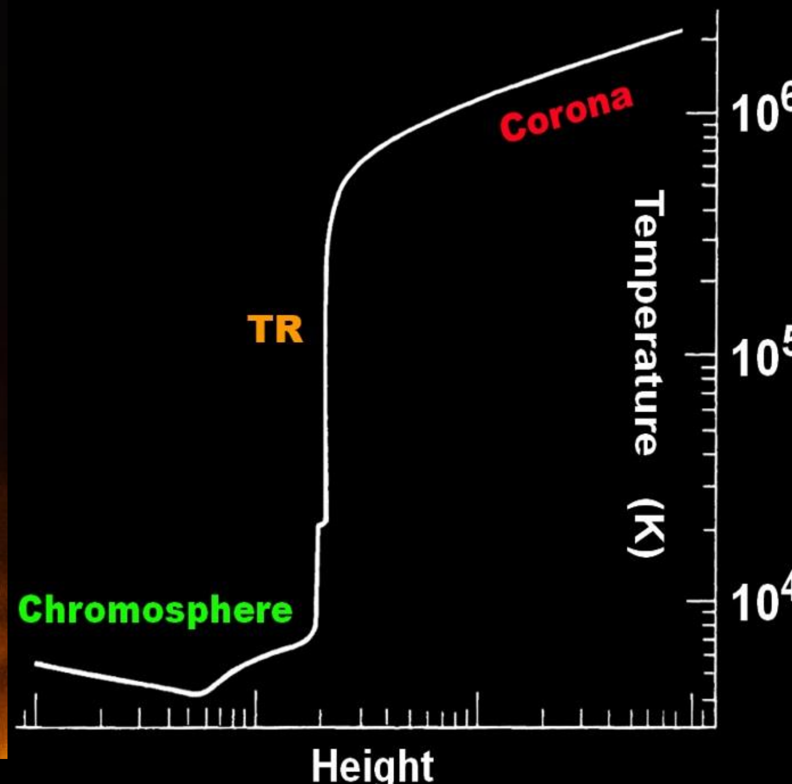
Observations:

- See "Spicule physics" & "Chromo-corona connection" use-case groups.
- How do the (short!) ***lifetimes*** of off-limb swaying structures compare to predictions of, e.g., Goldreich-Sridhar turbulence?

3,4,5. Coronal heating mechanisms

- First, we should clarify what we mean; e.g., “nanoflares” is not an actual physical heating mechanism!
- (Nearly!) everyone agrees that there is more than enough kinetic energy in the 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 ?

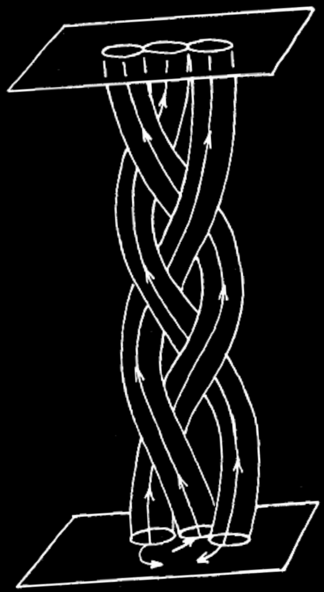


3,4,5. Coronal heating mechanisms

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

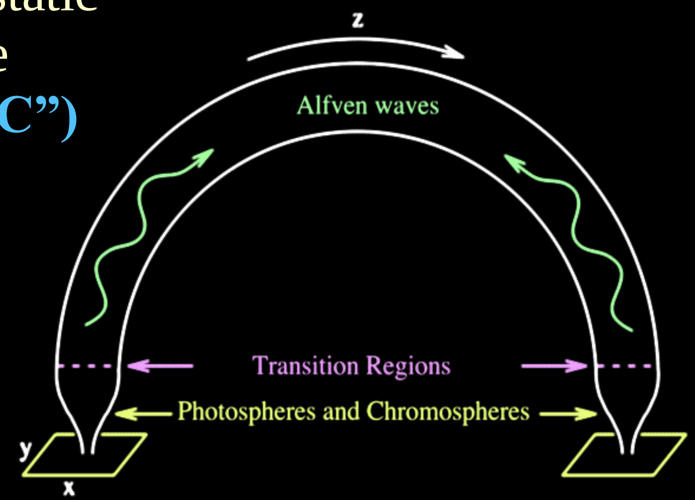
3. Large-scale, time-averaged coronal heating problem
4. Spatial inhomogeneities (importance of "interfaces")
5. Waves/shocks/eddies (rapid time & space variability)

3. *Big-picture coronal heating*



Slow footpoint motions ($\tau_\odot > L/V_A$) 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 ($\tau_\odot < L/V_A$) propagate through the field as waves, which are eventually dissipated. **(“AC”)**

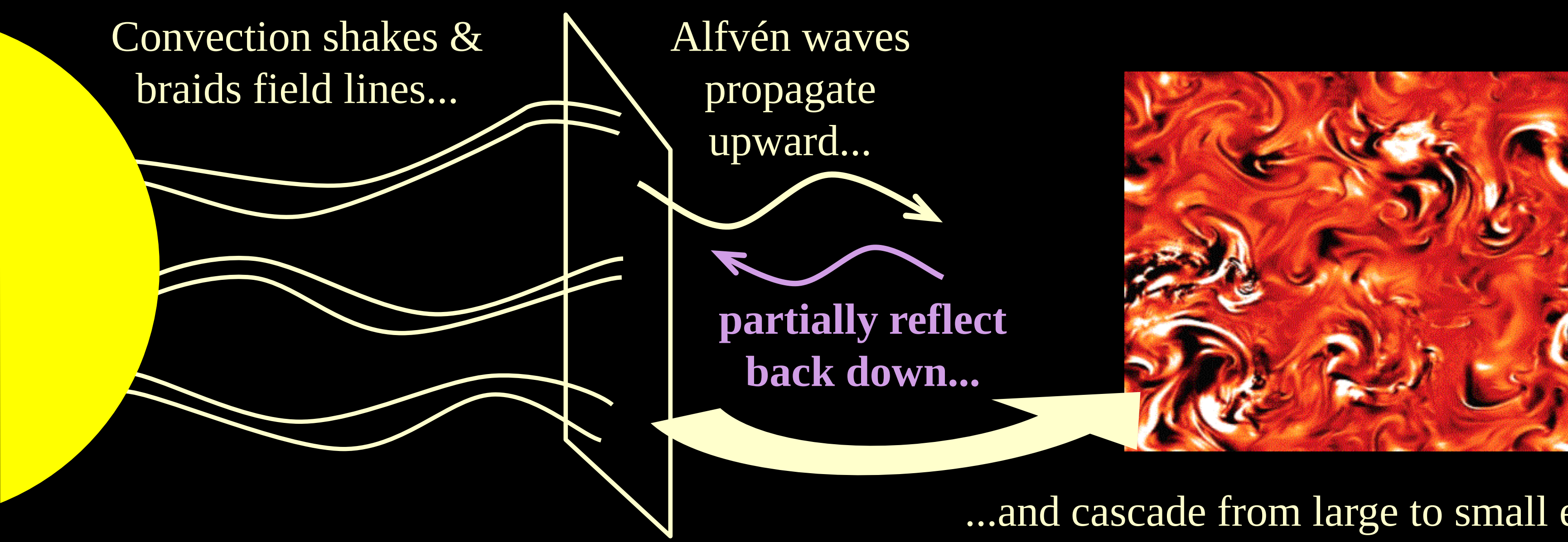


However . . .

- The Sun’s atmosphere exhibits a continuum of time scales bridging AC/DC limits.
- “Waves” in the real corona aren’t just linear oscillations.
  (amplitudes are large) (fluctuations damp after only ~few periods)
- “Braiding” in the real corona is highly dynamic. (see: Hi-C sounding rocket!)

3. Big-picture coronal heating

- I'm partial to **MHD turbulence** as a unifying "language" to describe what's going on in the corona & solar wind.
- Turbulence seems to explain many of the observations (ask me later).



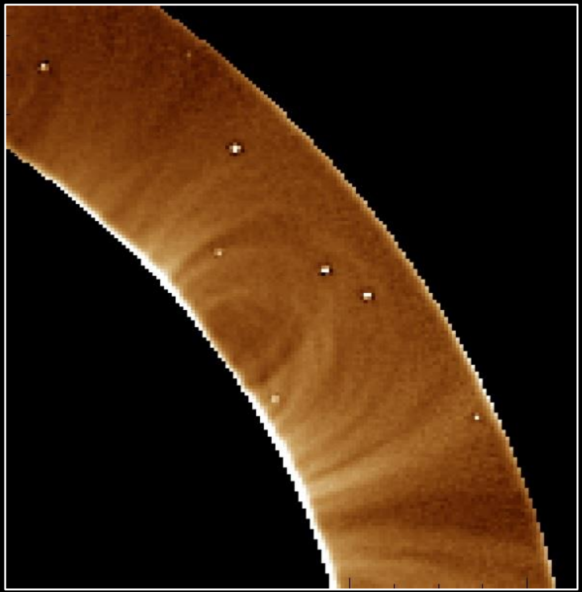
...and cascade from large to small eddies, eventually dissipating (in the form of tiny reconnection **current sheets**) to heat the plasma.

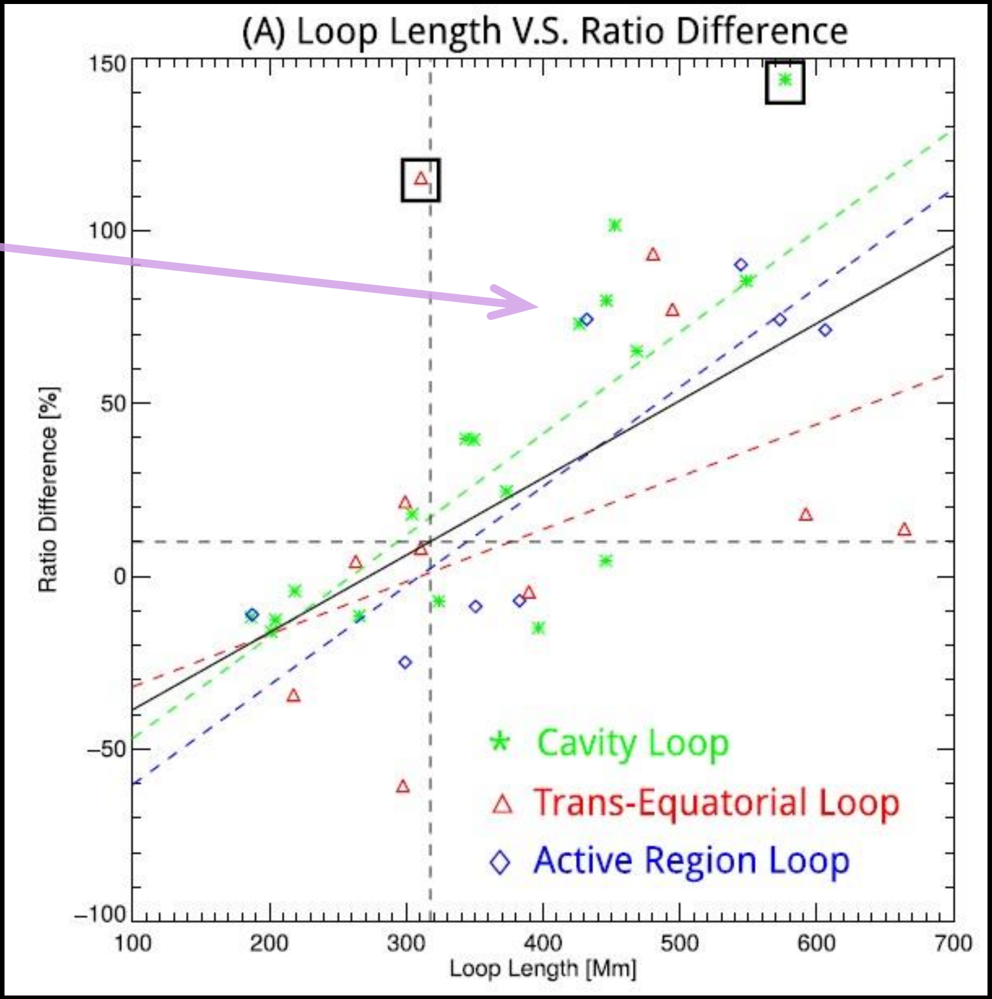
3. Big-picture coronal heating

- Recent evidence for turbulence in coronal loops from CoMP (Liu et al. 2014):

- Alfvénic wave power always grows with height, but does high-freq. power grow **faster** or slower than low-freq. power?

- Without cascade, high-freq. power should preferentially damp out.





3. Big-picture coronal heating

What should DKIST do? (mostly Cryo-NIRSP)

In prep for first light:

- Continue sciencing the line-of-sight integration problem. We want intrinsic ("plane of sky?") quantities.
- Determine how DEM width ($\neq 0$ even in "isothermal" regions) varies between different models. A good discriminator?

Observations:

- If multiple emission lines can give us DEM(T,r), can we use that to back out radial dependence of heating rates Q in different structures?
- Dependence of Q on B & L has been studied (Schrijver), but what about dependence on underlying magnetic topology, imbalance fractions, etc.?

4. Spatially inhomogeneous heating

- How does the known **cross-field structure** of the corona affect its heating?

$\nabla_\perp V_A$:   phase mixing, surface-wave generation, filamentation instability

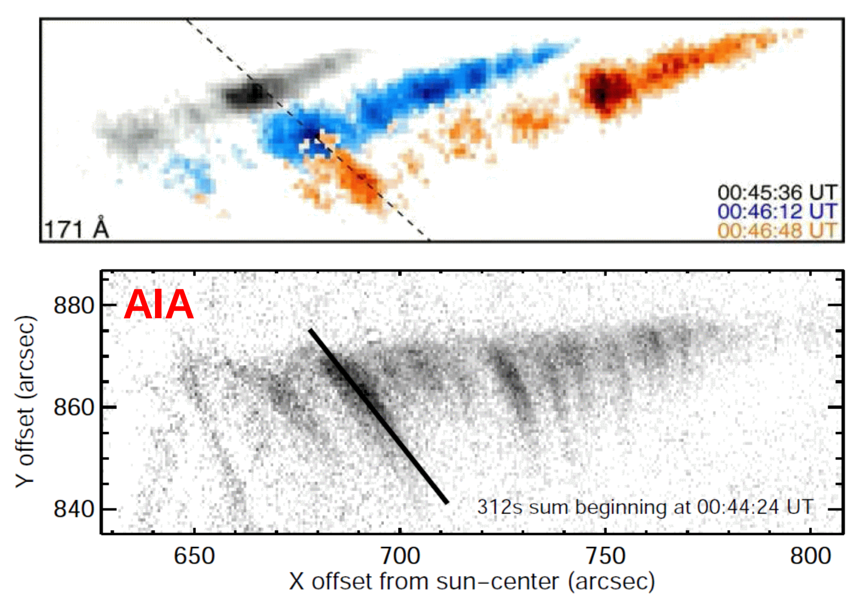
→ don't forget **quasi-separatrix layers** (S-web; Antiochos et al. 2011)

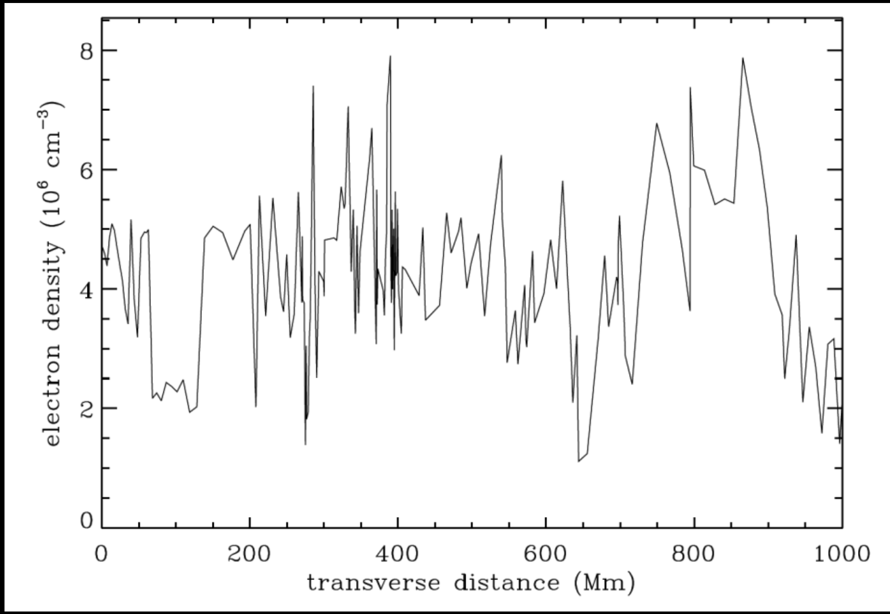
$\nabla_\perp \rho$:   drift-wave instability, radio IPS "inner scale" fluctuations?

$\nabla_\perp v_{flow}$:   shear-driven wave mode transformation

4. Spatially inhomogeneous heating

- One example: Raymond et al. (2014) used the passage of **Comet Lovejoy** through the low corona to measure properties of small-scale density striations.
- The detected fluctuations were found to have transverse spatial scales of ~4 Mm (at r ≈ 1.3 R_s), very similar to predicted correlation lengths of MHD turbulence.
- Measurements also agree with predicted amplitudes of solar wind density variations between flux tubes extrapolated from a high-res SOLIS magnetogram.





4. Spatially inhomogeneous heating

What should DKIST do? (mostly Cryo-NIRSP)

Observations:

- How do coronal properties vary as a function of the local cross-field inhomogeneity?
  - Are locations with high V_A shear (for surface waves; see Evans et al. 2012) coincident with high-squashing-factor QSLs?

- To better constrain inhomogeneity, use “new” combinations of collisional & radiative emission lines to put limits on $\langle n^2 \rangle / \langle n \rangle^2$

5. A census of coronal waves

- Caveat: “waves” = shorthand for repeating or quasi-repeating oscillations, including eddies, pulses, shocks, solitons, …
- There’s decades of growing evidence that MHD waves of all flavors exist in the corona, but
  - How much energy of each type is present?
  - What’s generated at the photosphere, and what’s generated “gradually?”
  - How much does each type contribute to coronal heating?
  - What survives out into the solar wind?

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

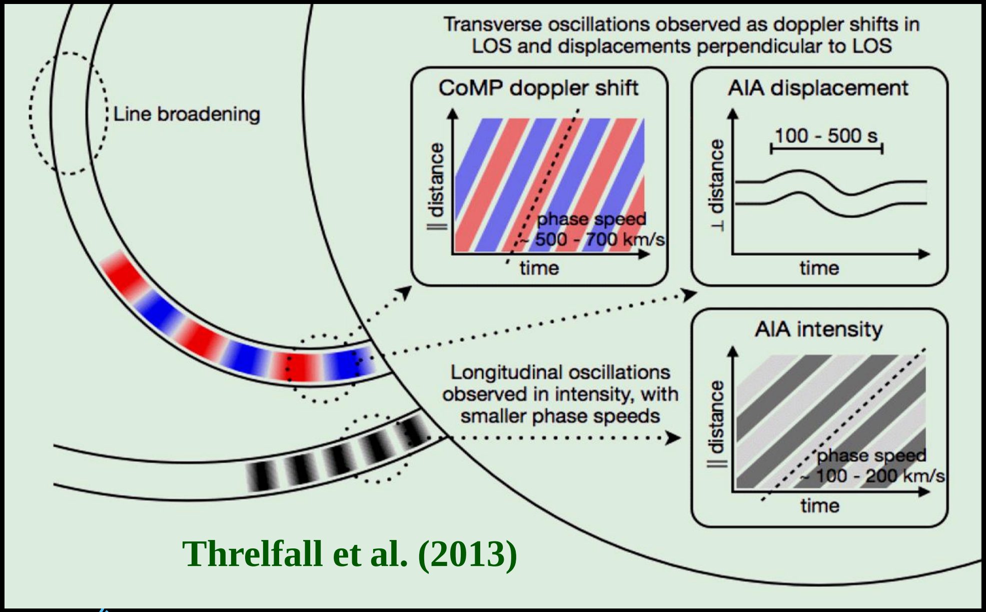
Date: October 20, 2014

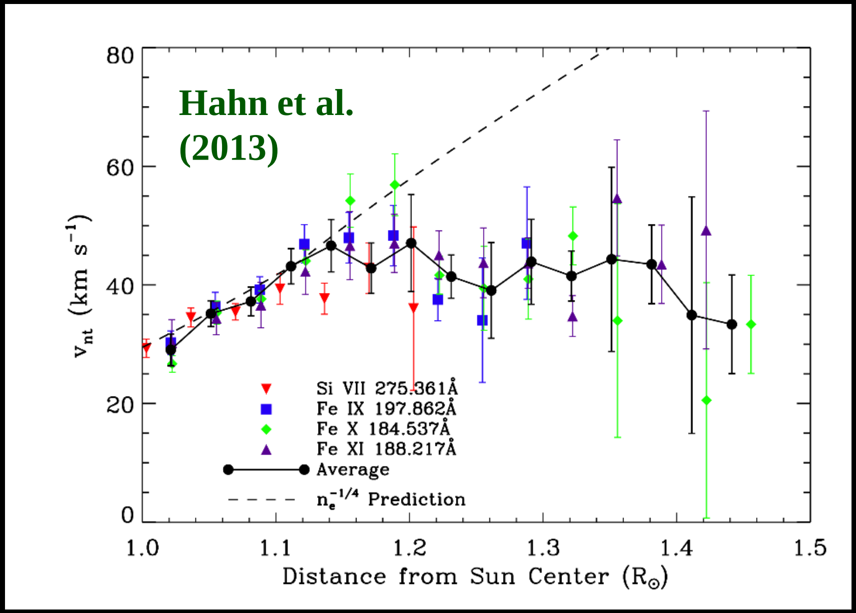
http://tinyurl.com/cranmer-dkist

5. A census of coronal waves

Diagnostics: fluctuations in…

- 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 →





5. *A census of coronal waves*

What should DKIST do? (mostly Cryo-NIRSP)

In prep for first light:

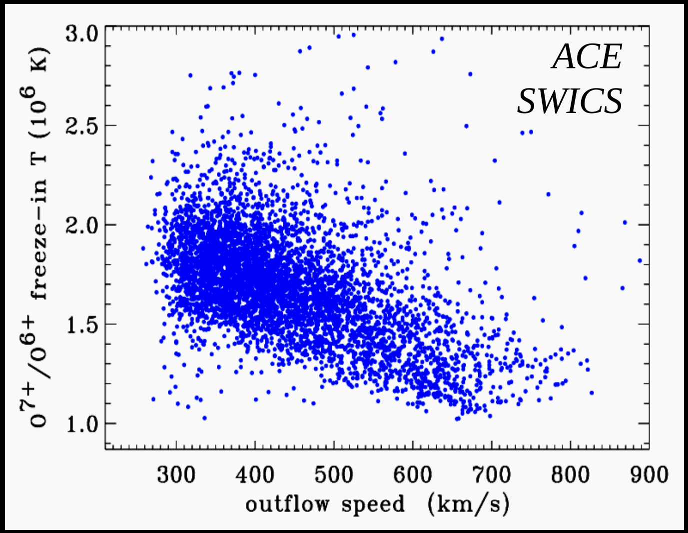
- Nail down how DKIST's line & continuum diagnostics will best complement (i.e., fill in gaps of) space-based UV spectroscopy.
- Optimize multi-slit rastering (radial offsets, dwell times, raster-cycle times) to best capture full range of likely phase speeds.
- Yes, more ~~Matt Damon~~ line-of-sight forward modeling.

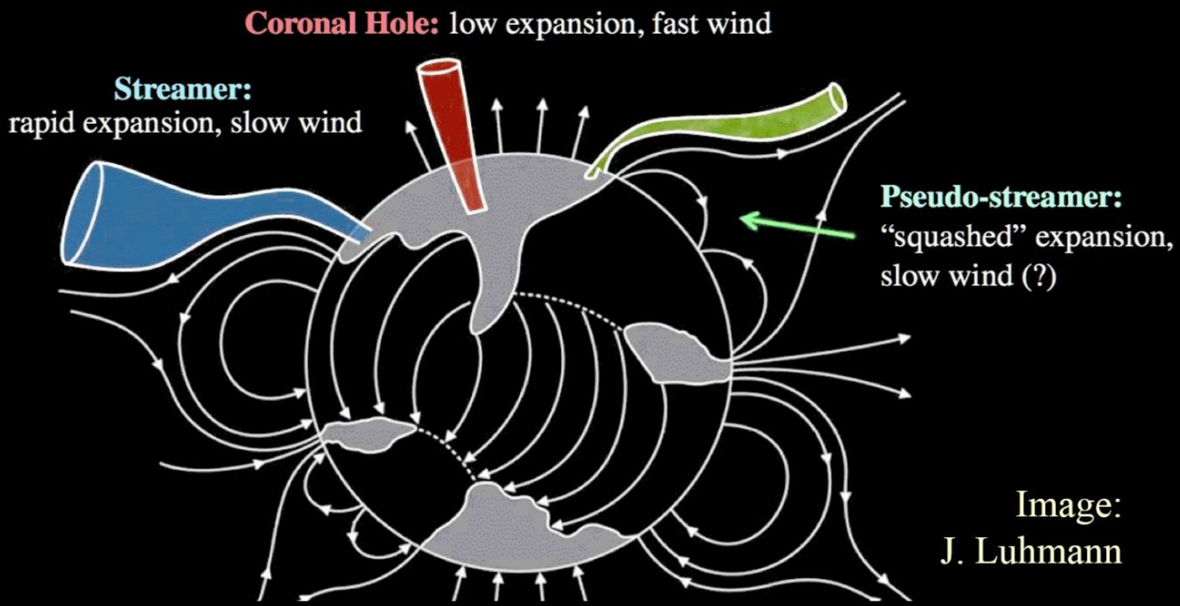
Observations:

- In addition to high-cadence wave measurements, make sure to do "deep" context maps of local background properties (like flats; before & after).
- How do the different oscillating parameters correlate with one another?

6. *Solar wind: origins near the surface*

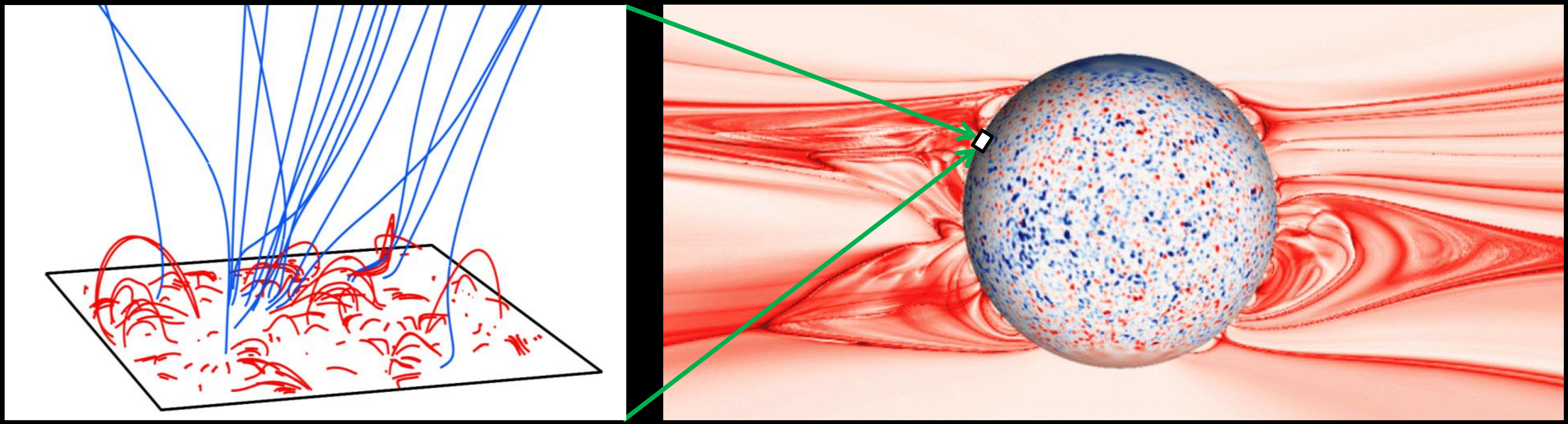
- Much of what we learn about the inner corona is "open/closed agnostic."
- Basic structure: fast vs. slow wind (+ CMEs), but how bimodal is the steady wind?
- **High-speed wind:** strong connections to the largest coronal holes
- **Low-speed wind:** still no agreement on the full range of coronal sources:
  - hole/streamer boundary region
  - small coronal holes
  - active regions (some with streamer cusps)
  - pseudo-streamers





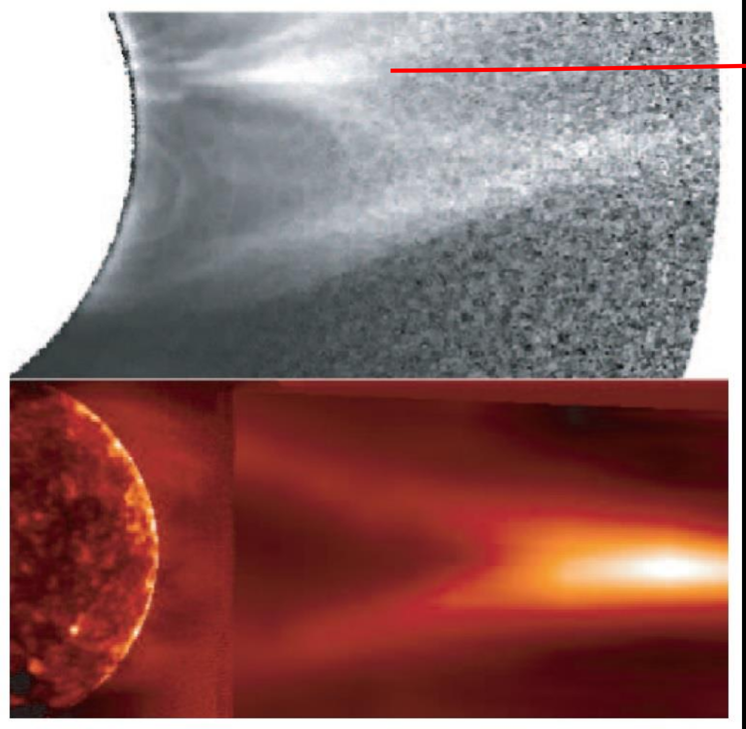
6. Solar wind: origins near the surface

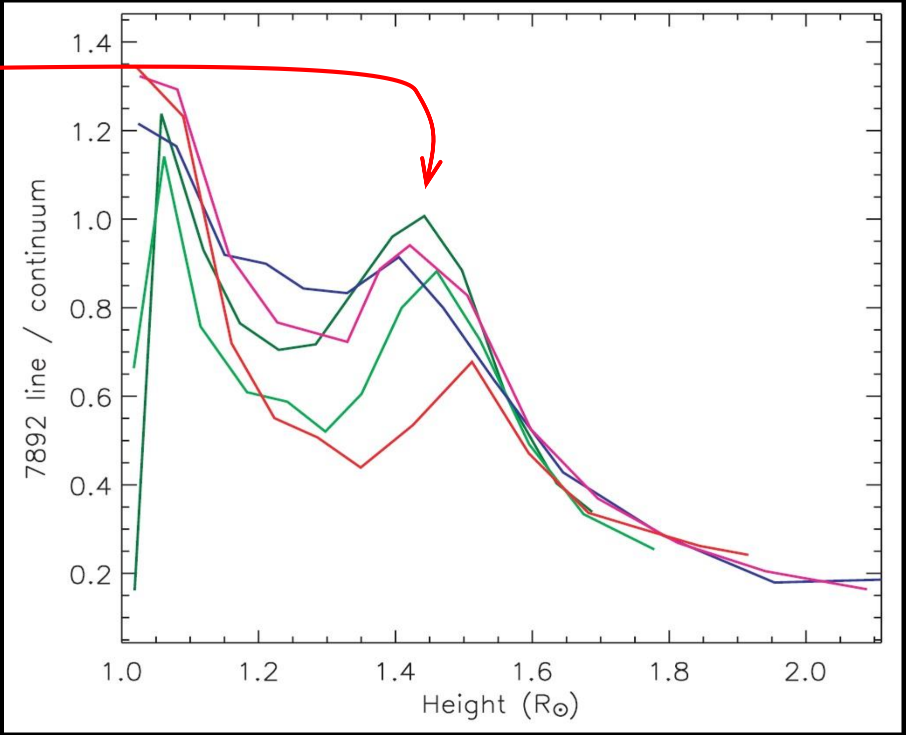
- Big question: how much of the solar wind plasma comes from the opening up of closed loops?
- Many invoke heavy ion composition data: slow wind looks “loop-like.”
- The magnetic carpet is always churning & “replacing” the coronal field on time scales of 2–20 hours. Some **interchange reconnection** is inevitable.
- Does the mass/energy released by reconnection feed a significant fraction of the wind (Fisk), or does the reconnection merely shuffle around footpoints to launch MHD waves (Lynch) or organize large-scale web of connectivity (Antiochos)?



6. *Solar wind: origins near the surface*

- Solar wind particles are **kinetic…** they deviate from collisionally coupled MHD.
- Habbal et al. (2007, 2011) found Fe XI 789.2 nm abundance anomalies that *may* be probes of preferential ion heating/acceleration, or nonclassical transport coefficients.
- Similar to UVCS O VI 103.2,103.7 nm streamer core/leg abundance differences?





6. Solar wind: origins near the surface

What should DKIST do? (mostly Cryo-NIRSP)

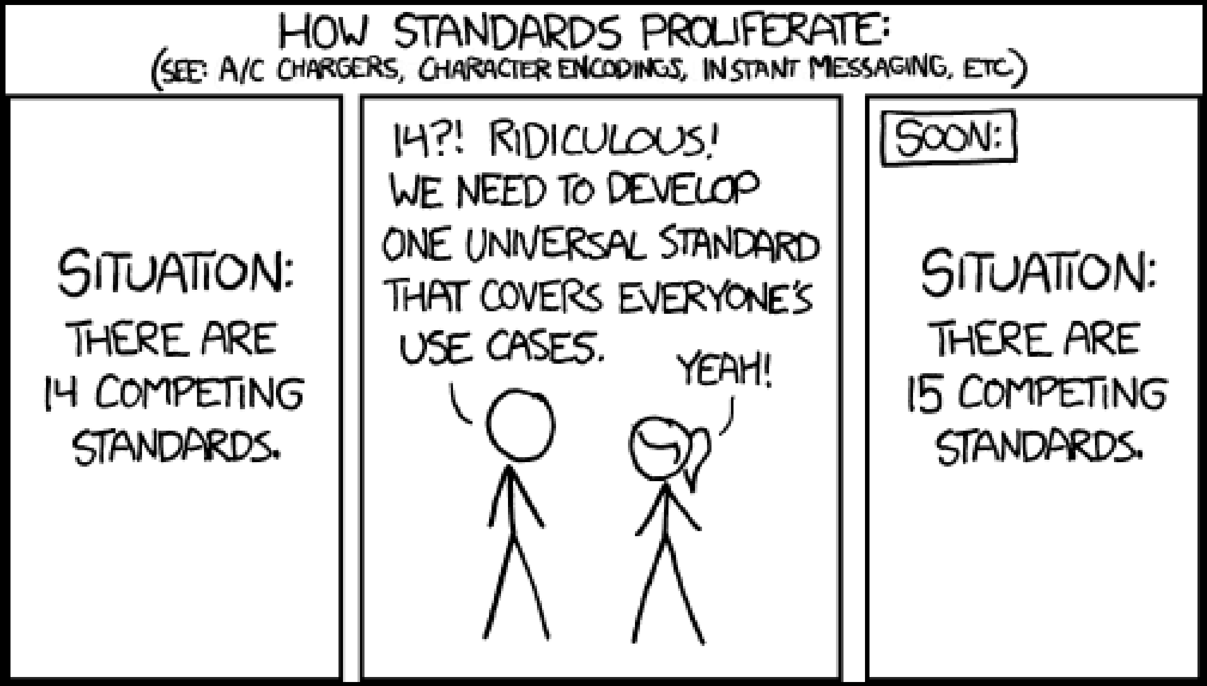
In prep for first light:

- Determine how well ion abundances (FIP ratios; ionization fractions) can be measured with DKIST's unique selection of diagnostics.
- What are the observations that can distinguish between flows and waves at, e.g., the edges of active regions?

Observations:

- Push sensitivity limits to do as much of the (active region) **coronal heating** science in coronal holes & quiet Sun regions, too!
- Catalog abundance anomalies: how depend on B, ρ, wind speed?
- Can we reach heights where $T_e \neq T_p \neq T_{ion}$? (line width ≠ ioniz bal.)
- Find signatures of interchange reconnection ***away from*** classical jets.

Conclusions



http://xkcd.com/927/

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