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Coronal Turbulence Driven from the Photosphere: Opportunities for DKIST

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The big picture

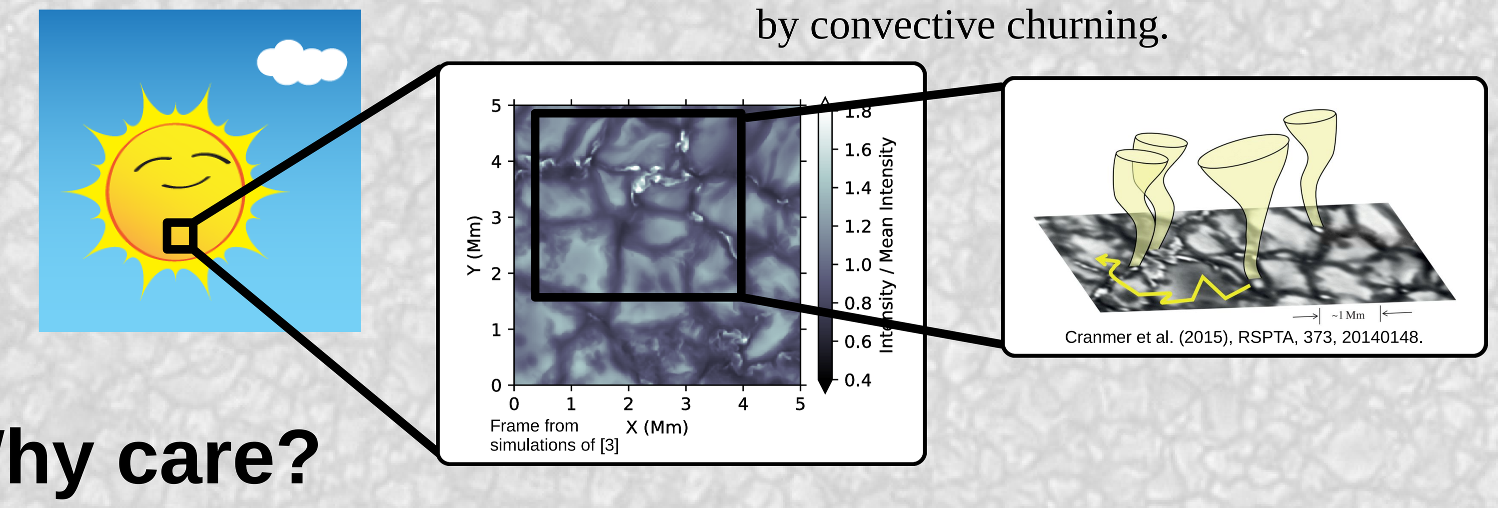
Shaken bright points are a suspected driver of coronal heating, but the closer you look at them, the harder they are to measure.

What's a bright point?

Photospheric bright points are small (~100 km) regions of concentrated (~1 kG), vertical magnetic flux. They appear in the lanes between granules on the solar surface (**center panel below**) and are shaken about by convective churning.

Flux tubes

Bright points are the bases ("footpoints") of magnetic flux tubes reaching up to the corona. Illustrated to left (rightmost panel), these tubes widen as gas pressure decreases with height. **Waves propagate up the tubes** from the convective shaking of the tube bases. At the photosphere, the tubes' magnetic pressure offsets gas pressure. This reduces the gas density and lets photons escape from deeper, hotter depths. This makes the footpoint look like a bright point at the tube's base, and is the only easily-observable feature of the flux tube.



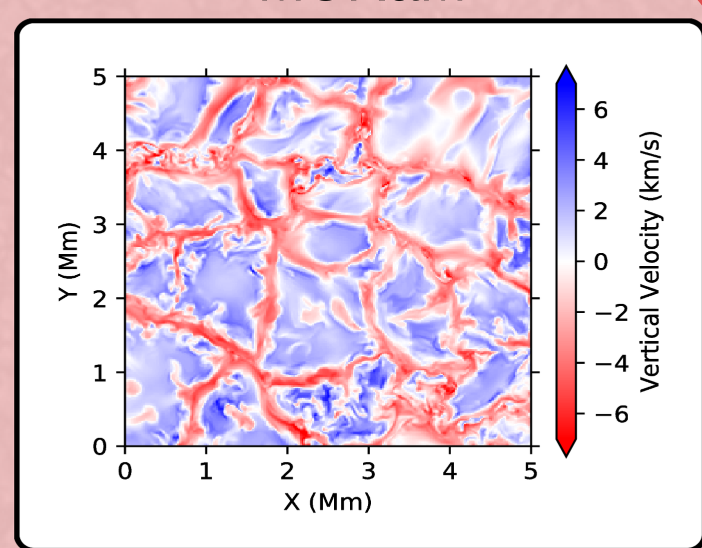
Why care?

Convective churning shakes the flux tubes (seen as motion in the bright point), exciting waves. These waves are believed to dissipate in the corona and deposit energy—**contributing to coronal heating**. The power spectrum of bright point motion provides the spectrum of the waves launched and serves as input to models of MHD wave propagation through the corona and heliosphere [1].

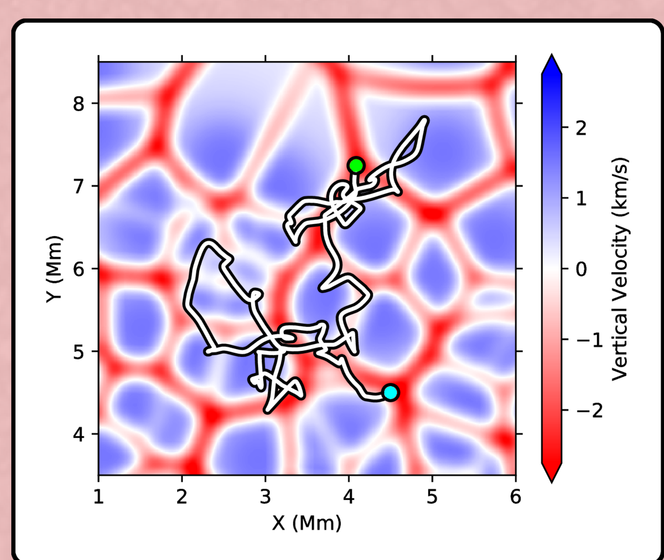
What we've finished

In past work [2], we compared the motions of bright points and bright point analogues across **two simulations, with spatial resolution comparable to DKIST** and surpassing current observations. **MURaM** is a realistic, 3D, full-MHD simulation [3] containing bright points. We developed a second simulation, called **ROUGH**. It is a phenomenological model that produces reasonable but turbulence-free granulation and allows direct control of granular properties.

MURaM

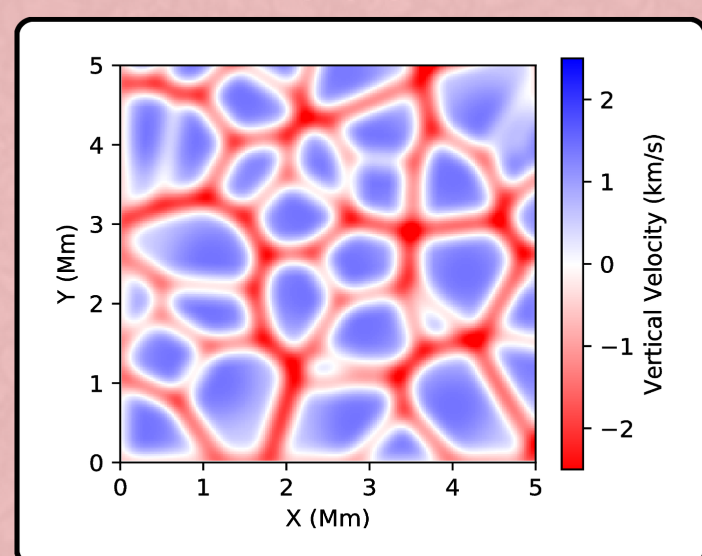


ROUGH emulates bright points as **passive tracers, or "corks"**, that simply follow the plasma flow. They realistically remain in and move with the downflow lanes, where horizontal flows converge. In MURaM, we automatically identified and tracked bright points. We also tracked passive traces for an apples-to-apples comparison with ROUGH.



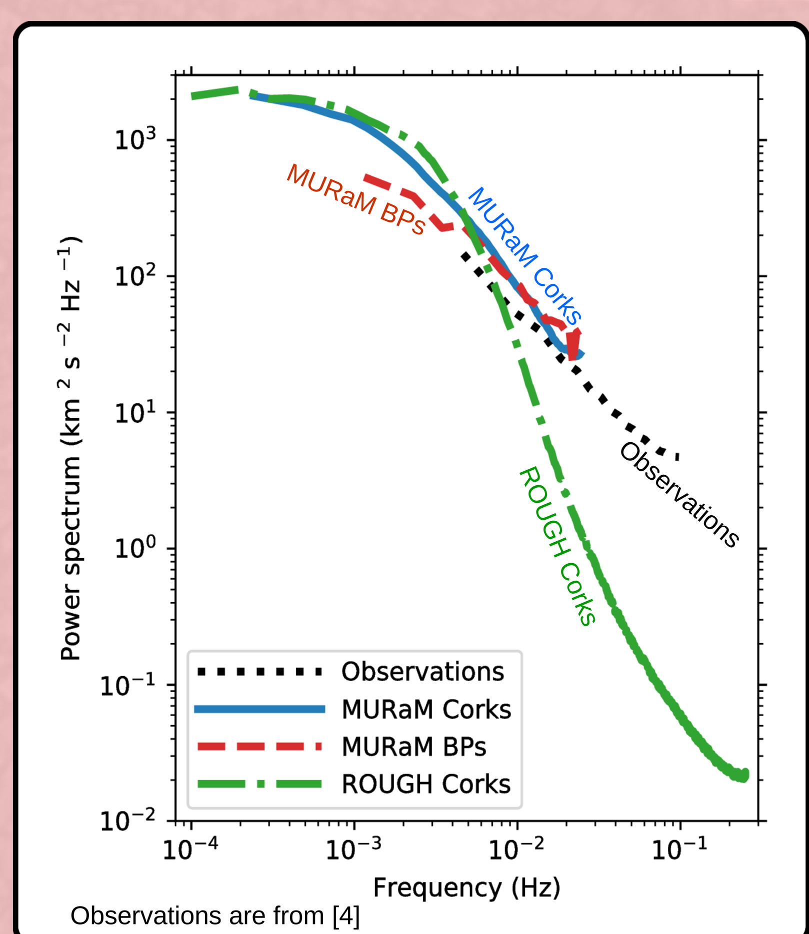
Above: The motion path of a ROUGH cork over a few hours

ROUGH



Results

- MURaM bright points show **more power than observations**
  - Does higher resolution resolve more motion? Is it an observational effect? Are MURaM bright points too active? We'll check with DKIST!
- ROUGH corks' velocity power spectra fall off at high frequencies, suggesting:
  - High-frequency bright point motion is driven by turbulence (absent in ROUGH)
  - Low-frequency motion is driven by large-scale granule flow (present in ROUGH)
- MURaM corks show more power than bright points at low frequencies
  - Bright points have a physical depth into the photosphere; corks don't. This may provide **anchoring** against long-term motion.



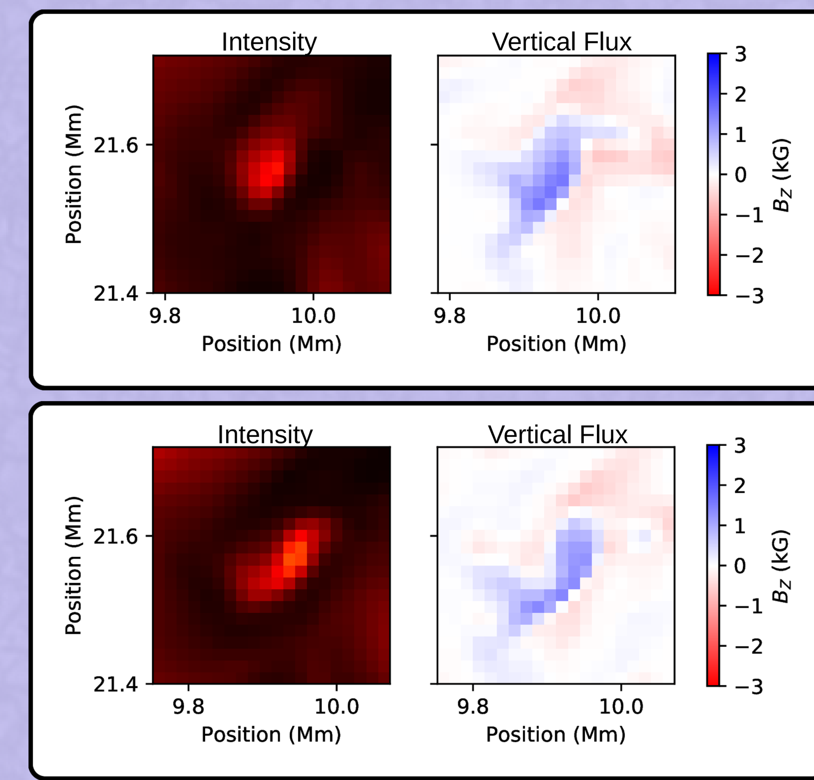
Above: The velocity power spectra discussed to the left

A warning

We used centroid tracking, similar to others' work [4, 5]. But bright points change shape and have fuzzy edges, complicating centroid analysis. This causes **centroid jitter** [6] which can distort power spectra. As shown in [2], we believe the above spectra are unaffected but **DKIST power spectra** will likely be **contaminated** by jitter. We aim to address this in the following section.

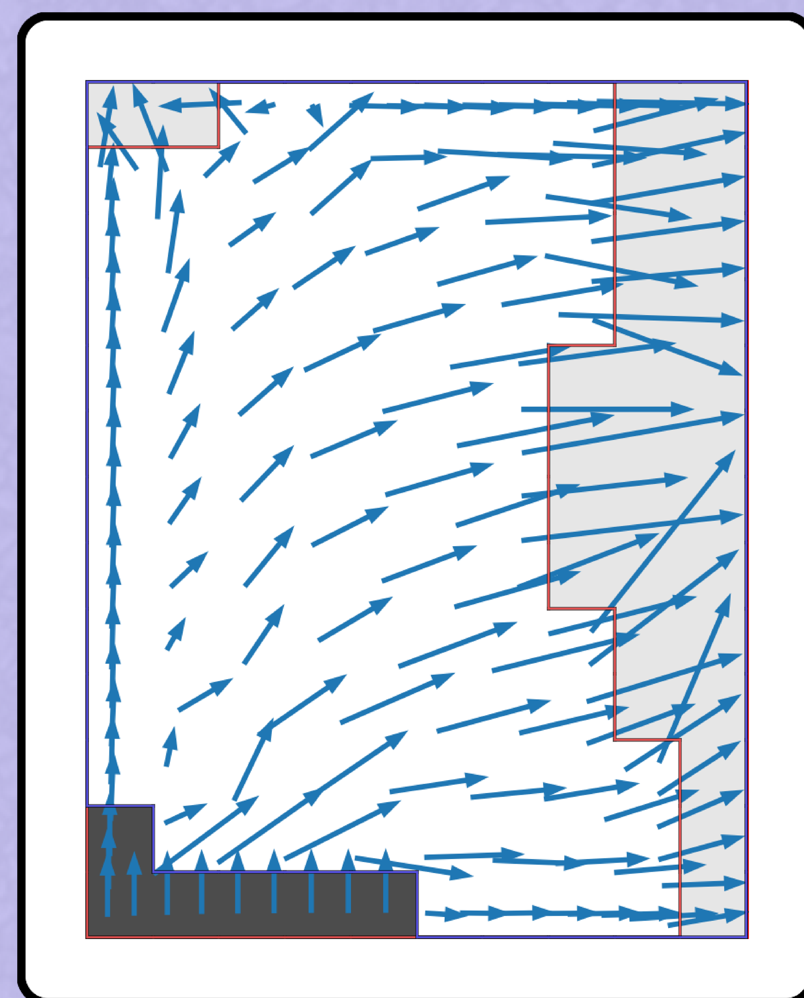
What we're working on

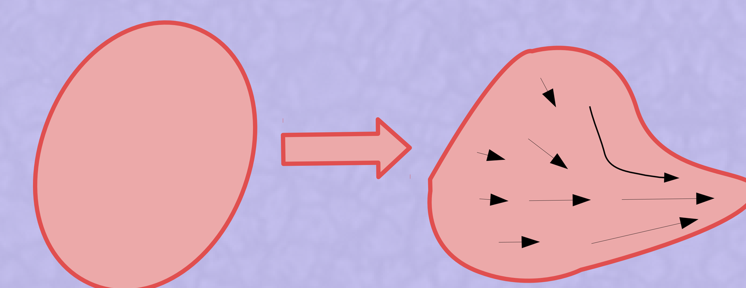
Beyond the bulk, centroid motion that produces kink-mode waves, bright points bend, twist, grow and shrink (**"internal motions"**), and this is **expected to excite sausage-mode and higher-order waves** which can carry energy to the corona. **DKIST will be the first telescope to substantially resolve these shape and size changes.** However, this complex motion will **confound traditional centroid tracking** of bright points (described lower left, "A Warning"). We're trying to both avoid this pitfall and explore the non-kink-mode waves by inferring the internal motions (see cartoon below) as bright points change shape.



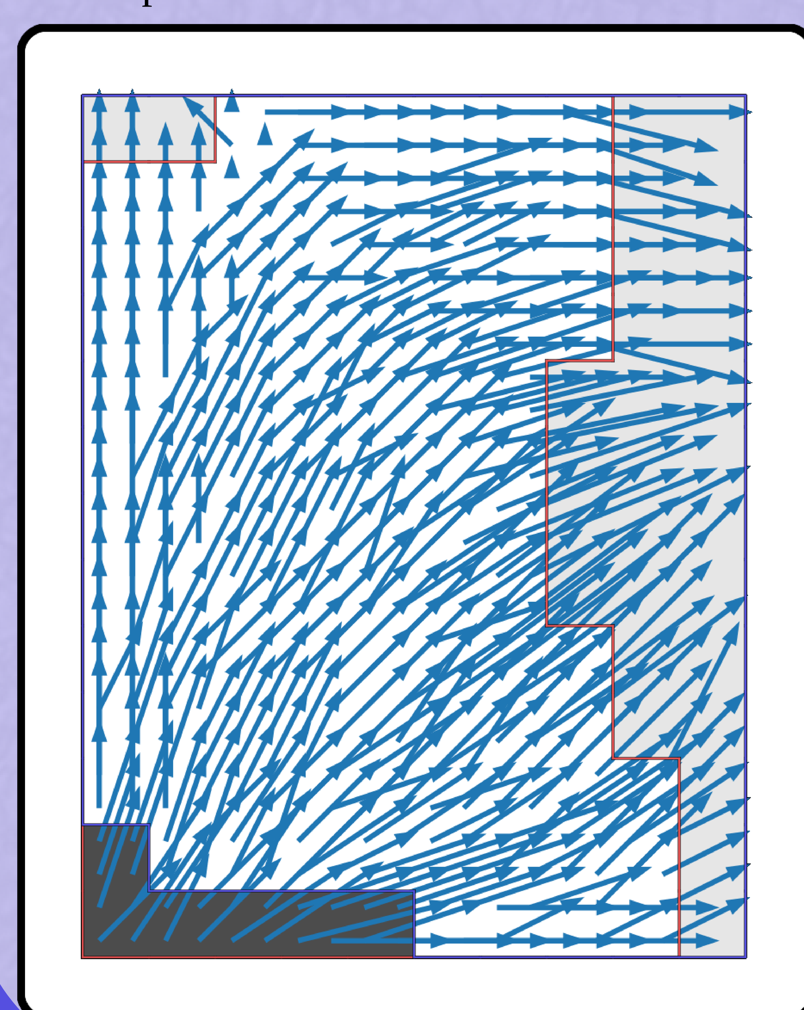
Right: A bright point in two successive frames (20s apart) from the MURaM simulations of [3]. The shape change is significant.

Lower Right: Cartoon of the flow fields we're seeking to produce in the algorithm below.





Initial results from our prototype mutually-repulsive-particle (**above**) and earth mover's distance (**below**) algorithms. In both, arrows connect particles' initial and final positions after the artificial bright point changed shape. Dark gray areas were removed from the feature during the shape change, and light gray areas were added. (The corresponding borders are marked.) The velocity fields are reasonable but not yet perfect. The different densities of arrows only reflect varied levels of algorithm development.



We're evaluating different ways to infer these complex internal motions:

We developed a technique that fills the 2D area of each bright point with **mutually-repulsive test particles** (like electrons). These particles are evenly spaced throughout a bright point in one frame and then allowed to redistribute themselves to fill that bright point's area as identified in a subsequent frame. Connecting particles' initial and final positions provides velocity samples throughout the bright point (demoed to the left), and the composite velocity field characterizes the bright point's inferred motion. This field approximates a plasma flow that maintains pressure equilibrium, assuming a bright-point shape change is a simple, horizontal re-arrangement of plasma and field lines.

We recently encountered the **earth mover's distance** (or the Wasserstein metric, or optimal transport). Similar to the above approach, we can seed a bright point in one image with test particles. If we independently seed the bright point in a second frame, **off-the-shelf algorithms** will produce a one-to-one mapping between particle locations in the two frames, so that if each particle in the first frame is moved to the identified location in the second frame, the total motion is minimized. As above, each location pair provides a velocity field sample (demoed to the left).

The velocity fields produced by either algorithm will not be unique solutions, but we believe they will be reasonable. This approach will handle the limited resolution of DKIST bright point observations, unlike more common techniques such as correlation tracking.

From the photosphere to the corona

To analyze the waves excited by the motions we measure, we plan to feed velocity map sequences and corresponding magnetic flux measurements from many bright points into MHD simulations, simulate the MHD waves propagating to the lower corona, and study these waves' statistics. The results will serve as an improved form of the power spectra produced by traditional centroid tracking of bright points, and will serve in turn as lower boundary conditions for waves simulated through the full corona and into the heliosphere.

We are currently developing these tracking and simulation techniques using simulated photospheric images from [3] of DKIST-comparable resolution, and will be prepared to **repeat the analysis on DKIST data** when it becomes available in the coming few years.

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References: [1] Cranmer & van Ballegooijen (2005), ApJ, 156, 265. [2] Van Kooten & Cranmer (2017), ApJ, 850, 64. [3] Rempel (2014) ApJ, 789, 132. [4] Chitta et al. (2012), ApJ, 752, 48. [5] Keys et al. (2011), ApJL, 740, L40. [6] Agrawal et al. (2018), Apj 854, 118.