Into the Fire: Plasma Physics of the Turbulent Solar Corona

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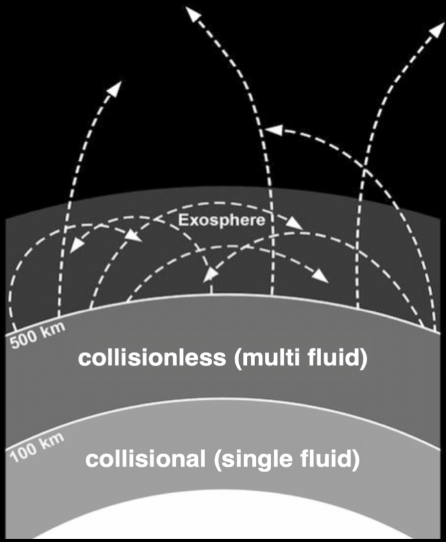
Image credit: M. Druckmüller

Into the Fire: Plasma Physics of the Turbulent Solar Corona

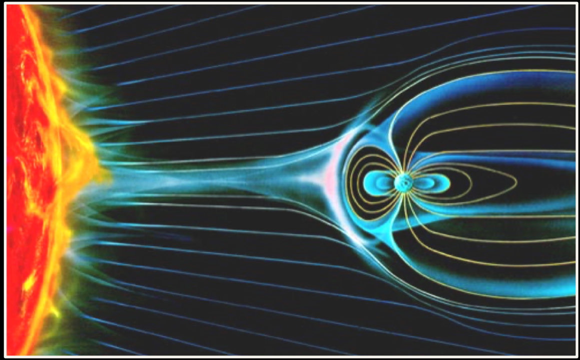
Outline:

1. Intro & brief history
2. PSP, PUNCH, and the Alfvén surface
3. Collisionless coronal heating
4. Turbulence & the "helicity barrier" 

Stellar winds



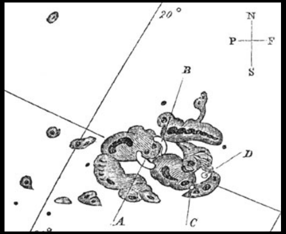
- Every gravitationally bound object with a gaseous atmosphere must *lose* some of that atmosphere due to some particles with $v_r > V_{esc}$.
- In addition, nearly all stars exhibit additional processes that give rise to gradual outward acceleration of that gas → a steady stellar wind.
- Stellar winds affect how the stars themselves evolve… and how they contribute "recycled" gas back to their galaxy's ecosystem.



- Stellar winds affect the formation & habitability of planets, too.
- Closer to home, **space weather** affects technology & society.

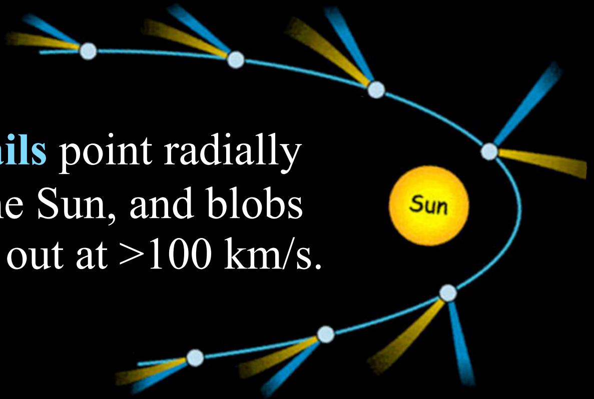
Early observational hints . . .

There must be some kind of "flow" from the Sun to the Earth. **Solar flares** are often followed by geomagnetic storms & aurora...

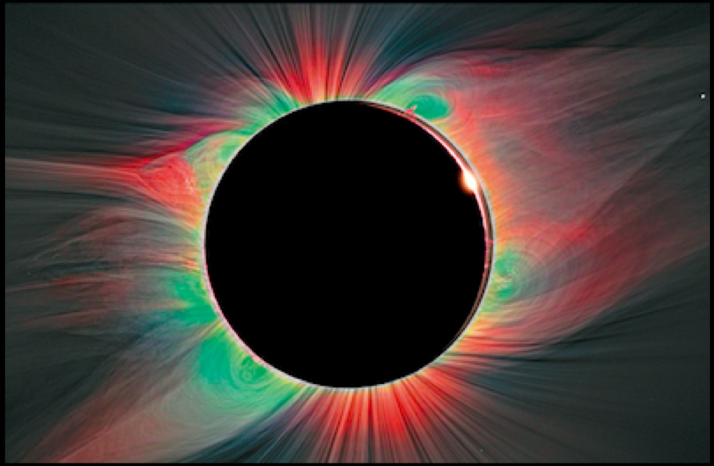


2 to 3 days

Comet **ion tails** point radially away from the Sun, and blobs in them flow out at >100 km/s.



There's something very odd about the Sun's **corona** that one sees during total eclipses.



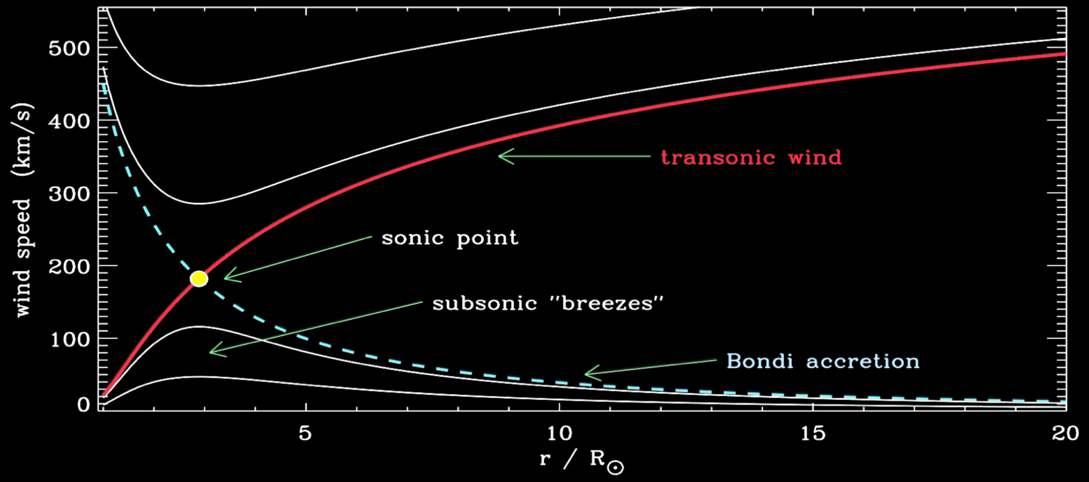
1860s: unknown lines... "coronium?"

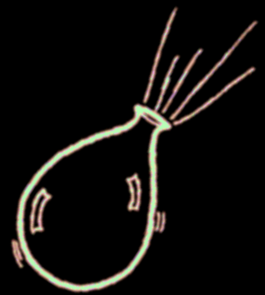
1930s: quantum mech FTW: **Fe X, Fe XIV**

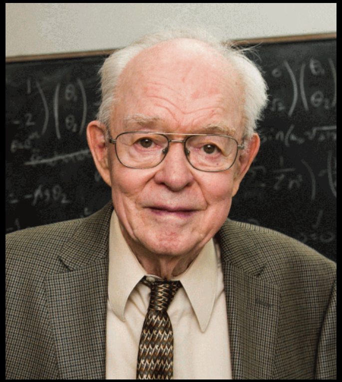
But this implies the corona has $T > 10^6$ K !

Prediction & discovery

- 1958: Eugene Parker proposed the hot corona has such a high **gas pressure** that it must naturally expand as a steadily accelerating outflow…



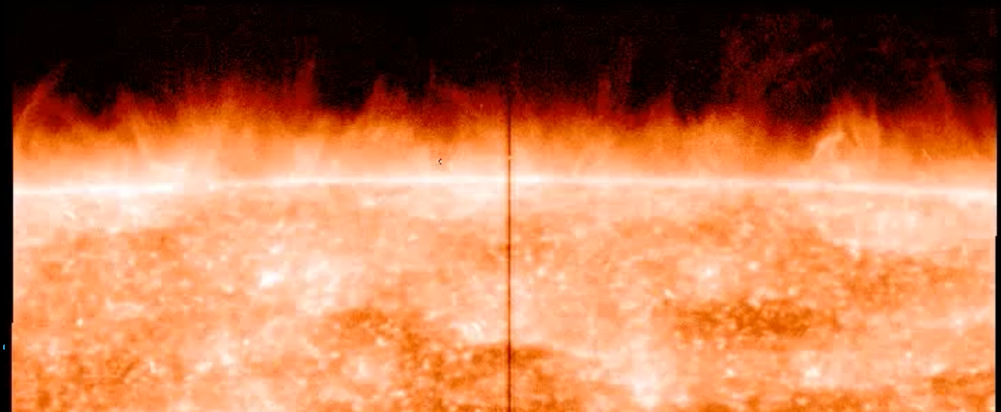


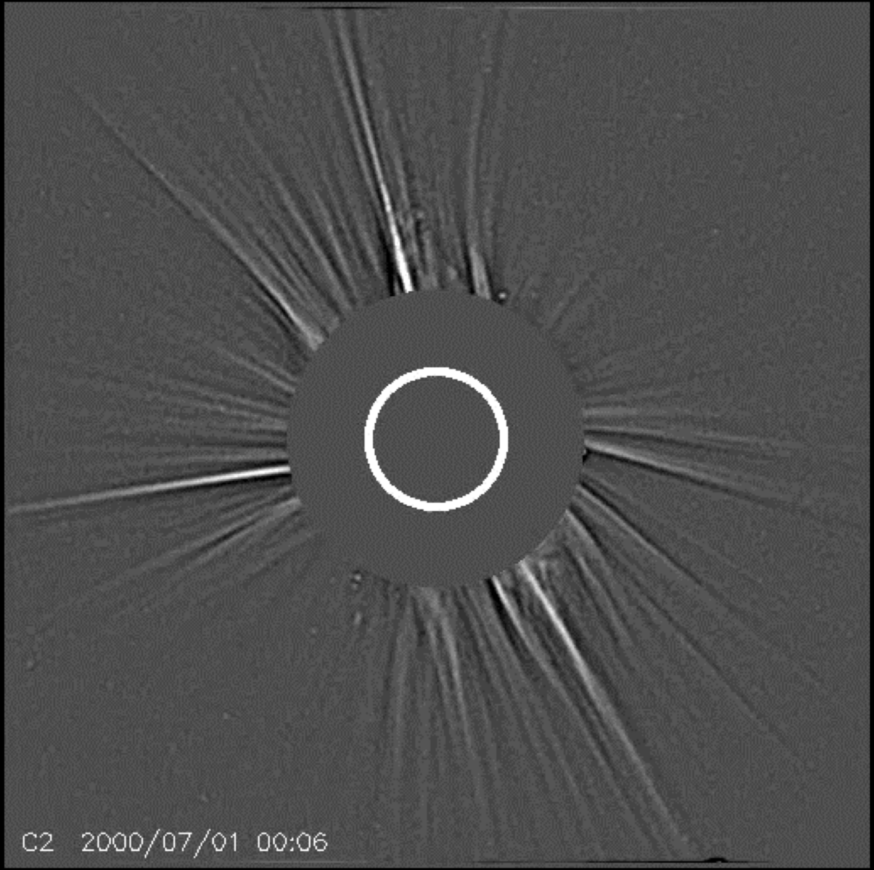


- 1959-1961: Intermittent detections: *Lunik, Venera, & Explorer 10.*
- 1962: Marcia Neugebauer & colleagues got **continuous** data from *Mariner 2* on its journey to Venus. The solar wind fills the solar system!

Observing the solar wind

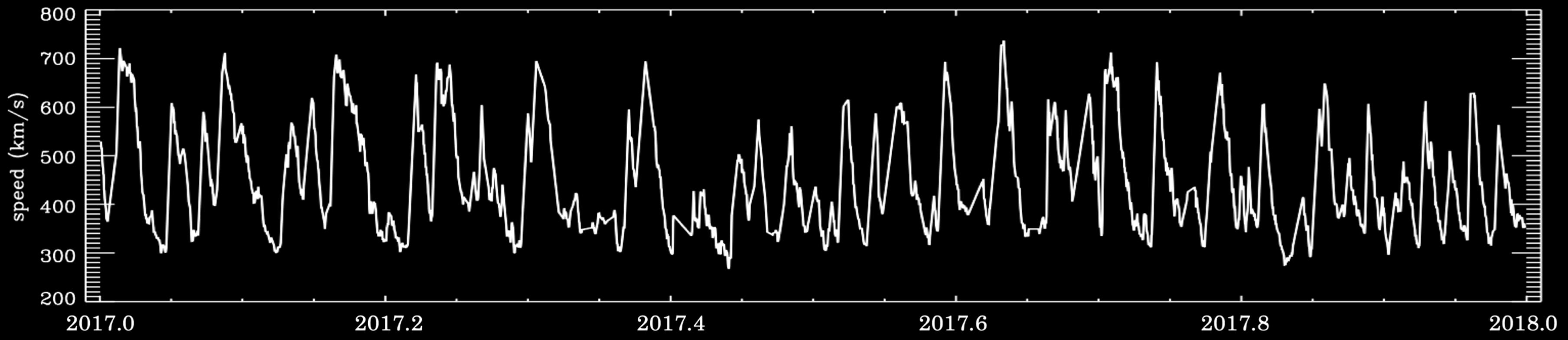
- It's observable with a **coronagraph** (i.e., a telescope with an occulter to generate an "artificial eclipse").
- LASCO coronagraph on *SOHO* has been operating since 1996. Wavelet filtering (Stenborg & Cobelli 2003) enhances details. →
- High-resolution imaging of the chromosphere & corona highlights chaotic up (and down!) flows near the surface...



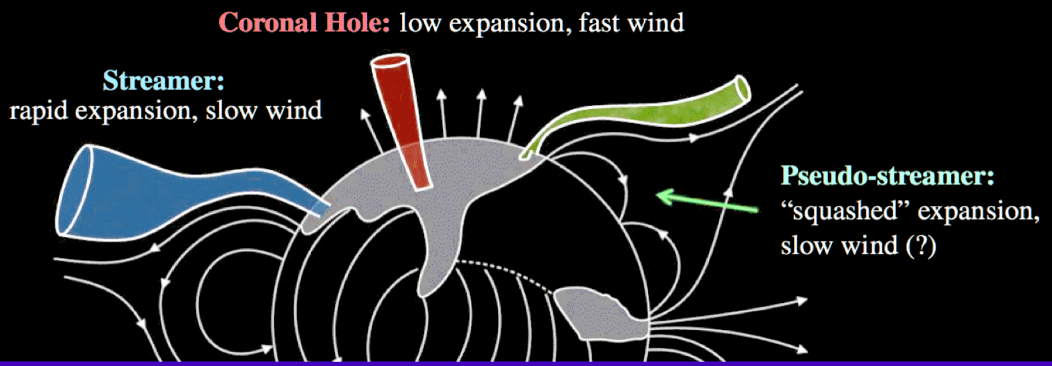


Fast wind vs. slow wind

- Speeds at 1 AU range from 250 to 800 km/s… sometimes seems "bimodal"



Wind speeds are decided *somewhat* by the magnetic geometry of **"superradial" flux-tube expansion,** but that's not the whole story.



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The goal is to get closer . . .

Is there a boundary between the corona and the solar wind?

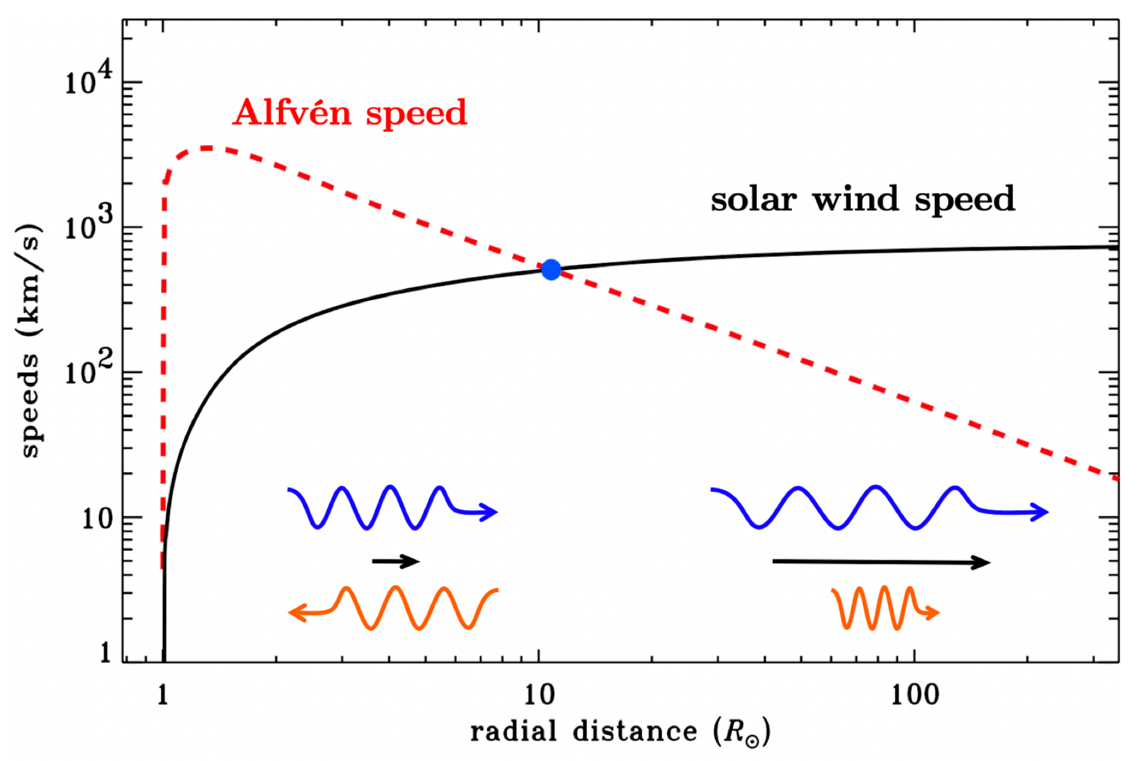
A boundary between the corona & solar wind?

- The Alfvén surface (or Alfvén radius, or Alfvén zone) is a useful place to draw this distinction.

- Below r_A, information (waves) can propagate both in & out. Above r_A, the solar wind drags out both inward & outward modes, and information doesn't propagate back down to the Sun.

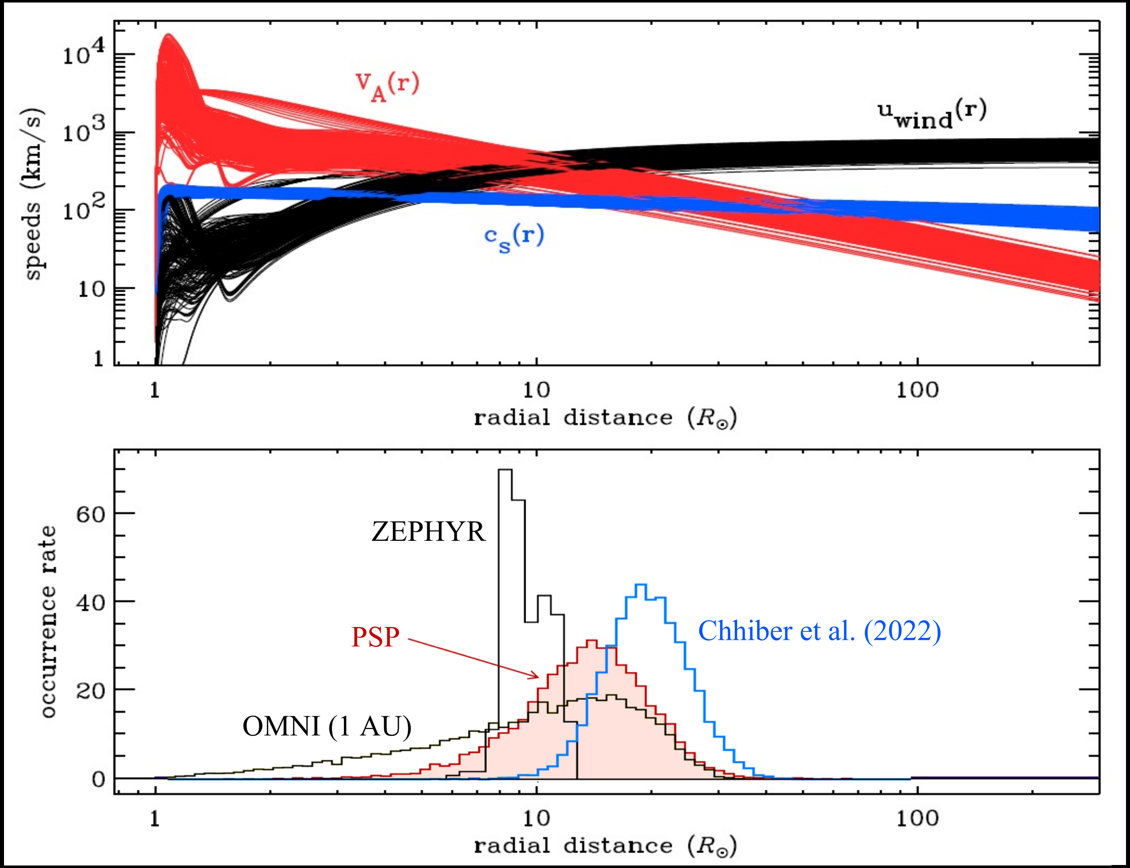
- It's the angular momentum "lever-arm" of the corona (Weber & Davis 1967).

- Measuring the wind speed at r_A gives $V_A \rightarrow B$ there, too.

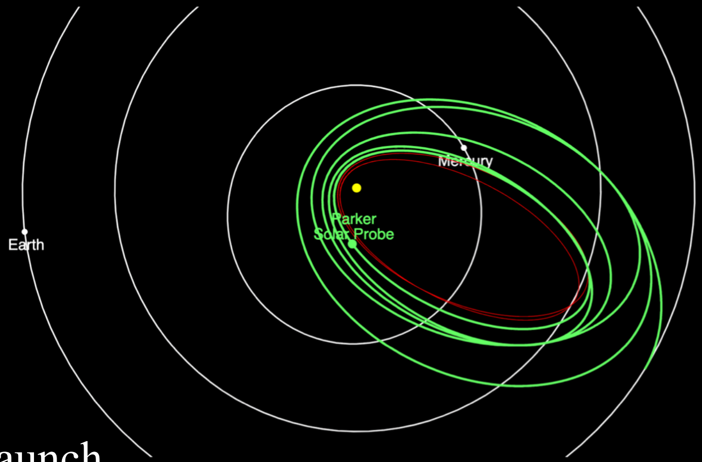


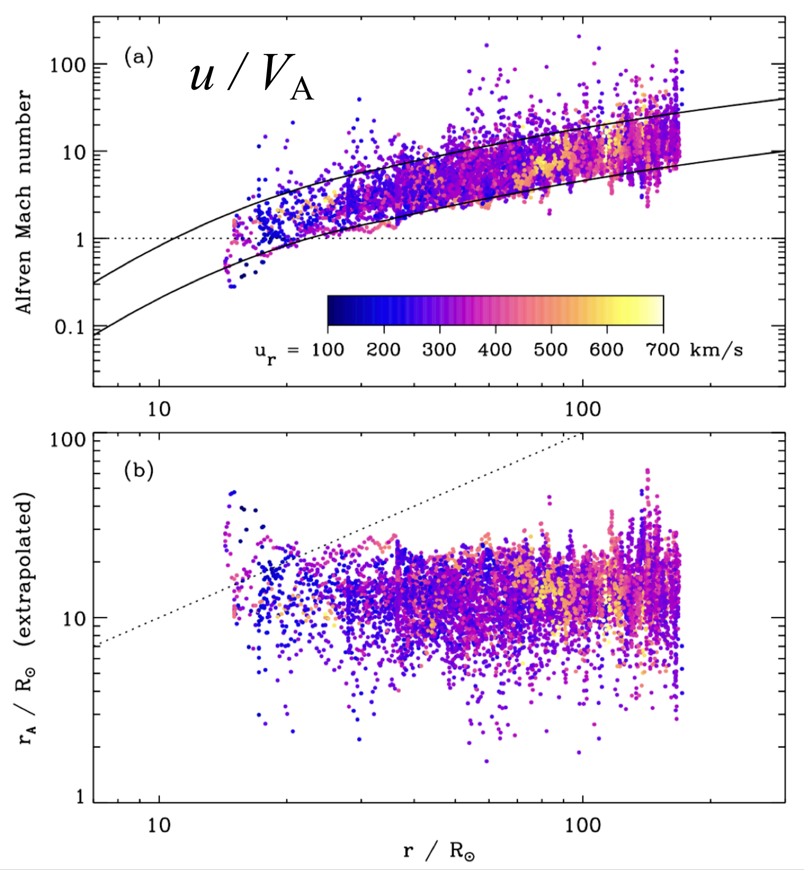
In reality, there's a range of critical radii

- Models: 318 runs of ZEPHYR for various types of magnetic flux configurations & wind speeds (Cranmer et al. 2007, 2013).
- Weber & Davis (1967) found that the Parker "sonic point" is the point beyond which slow-mode MHD waves cannot reach the Sun.
- There are separate radii for Alfvén & fast-mode MHD waves, but they differ in location by < 0.01 R_{sun} .
- Additional estimates of r_A come from **other simulations** and from extrapolating *in situ* data →



Parker Solar Probe has been to the other side!

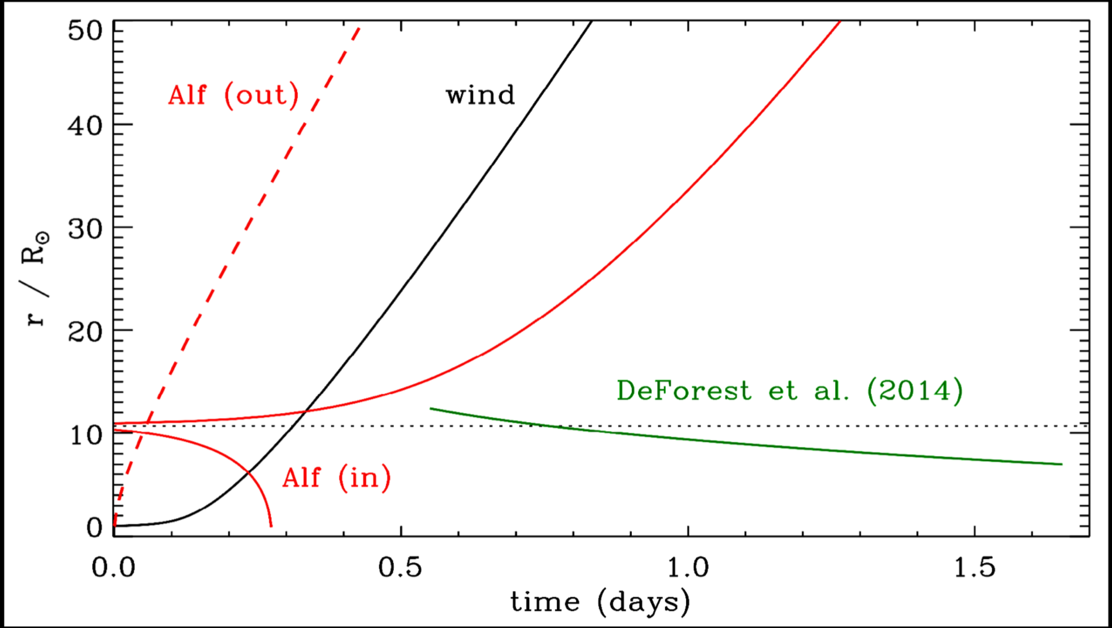




- Aug. 2018: Launch
- Nov. 2018: Perihelion 1 (36 R_{sun})
- Apr. 2021: Perihelion 8 (16 R_{sun}); **first crossing** of the Alfvén surface
- Mar. 2023: Perihelion 15 (13.3 R_{sun})
- Dec. 2024: Perihelion 22 (9.9 R_{sun})

Coronagraph imaging can see inflows, too

- The corona is full of small density inhomogeneities (“blobs”) that flow in & out.
- Tracking outflowing blobs with off-limb imaging has helped probe solar-wind dynamics.
- DeForest et al. (2014) saw one example of **inflow** (12 to 7 R_{sun}), but the kinematics didn’t really match MHD-wave expectations:



- Theoretical models abound (see Tenerani et al. 2016; Cranmer et al. 2021) but we need more examples!
- PUNCH will launch in 2025 to provide higher sensitivity & cadence in a larger field-of-view.

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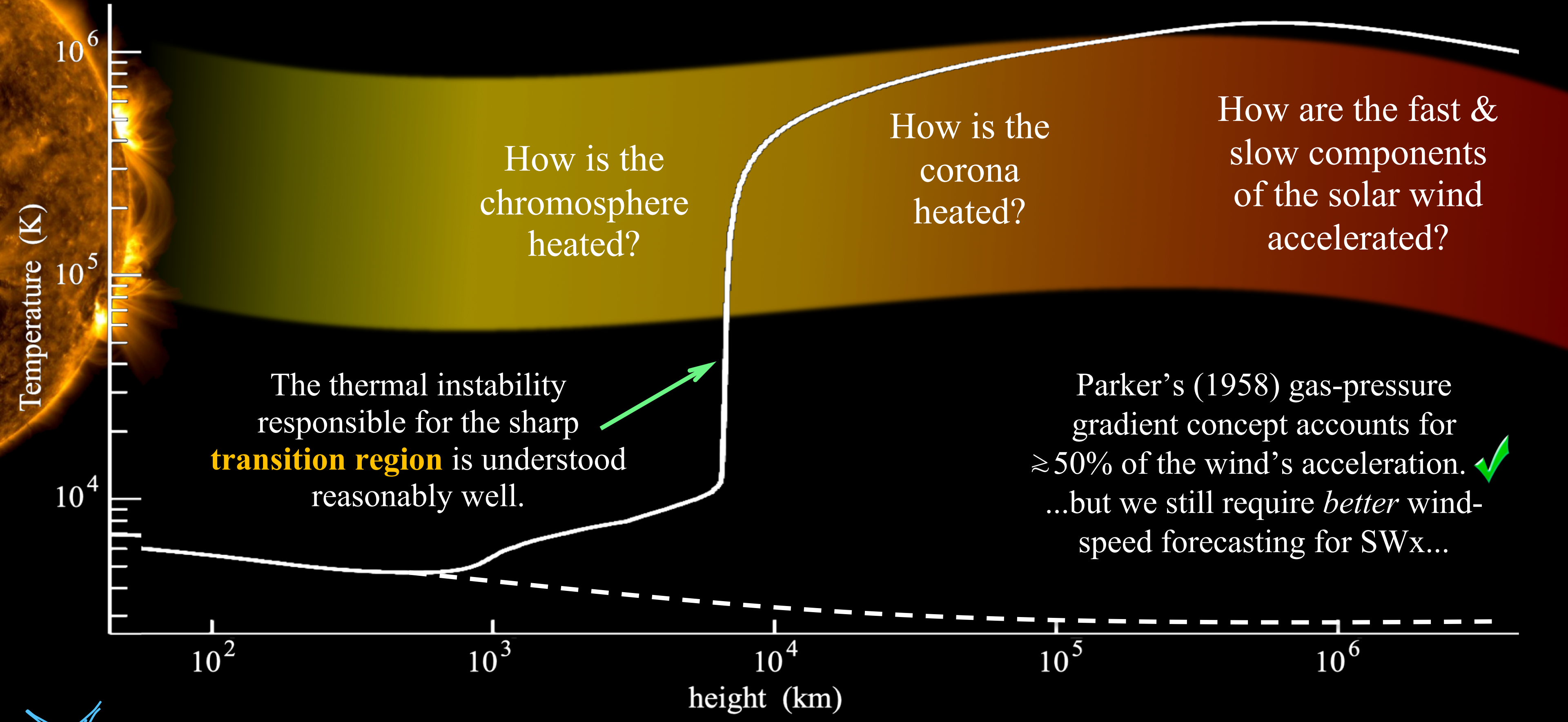
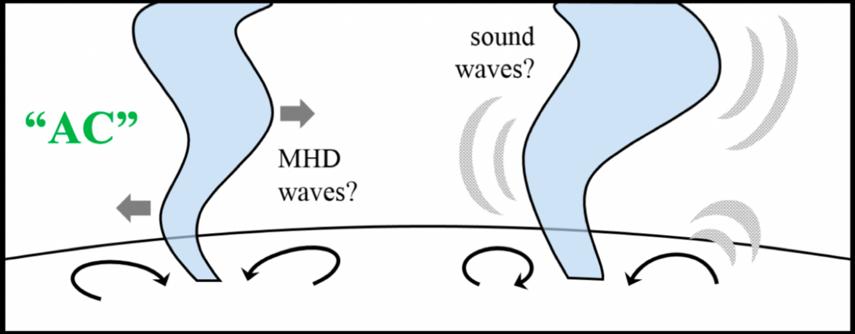
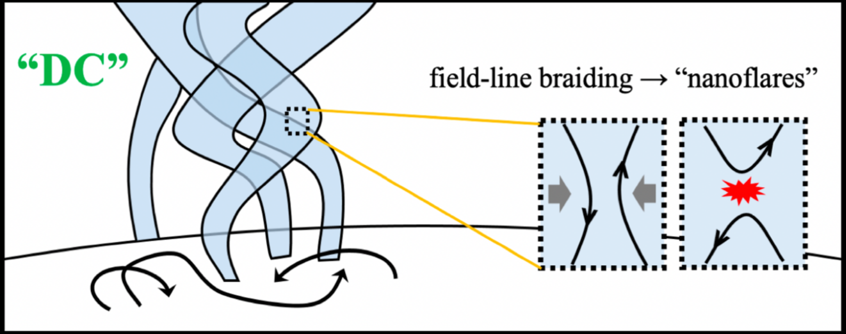
Unanswered questions

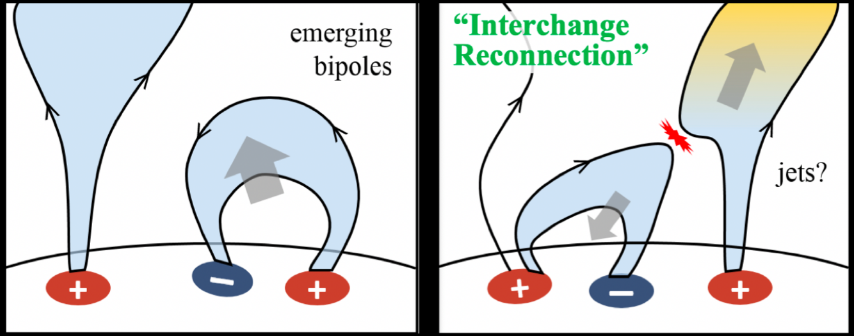


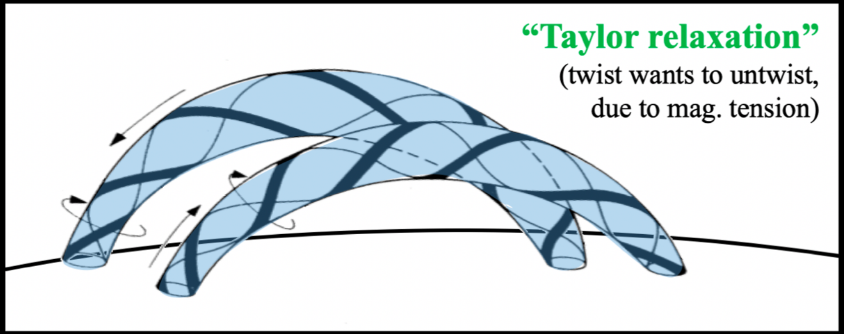
One-slide summary of proposed heating processes

- A successful mechanism must explain how energy is **transported** up from the photospheric convection, how it **couples** with the magnetic field, and how it **dissipates** to heat particles. Four flavors:



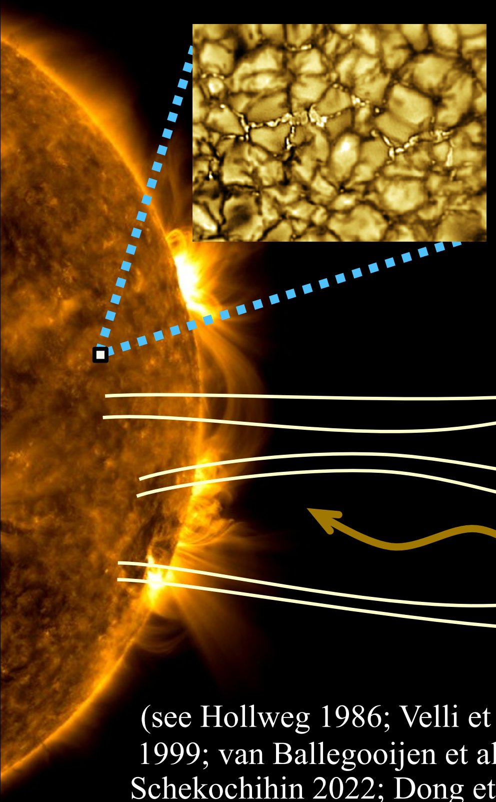






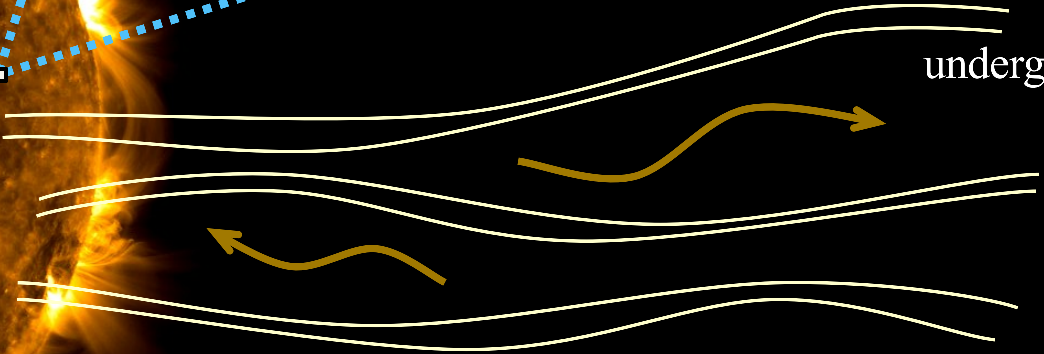
see Cranmer & Winebarger 2019, *Ann. Rev. Astron. Astrophys.*, 57, 157, arXiv: 1811.00461

MHD turbulence: a unifying language?

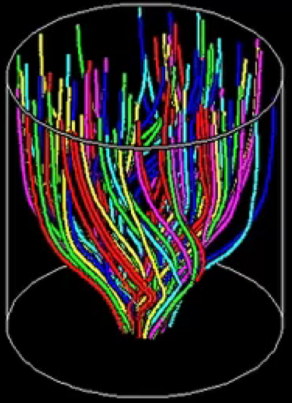


Convection shakes & twists magnetic field lines in a diffusive "random walk"

Alfvén waves propagate up...



undergo partial reflection...

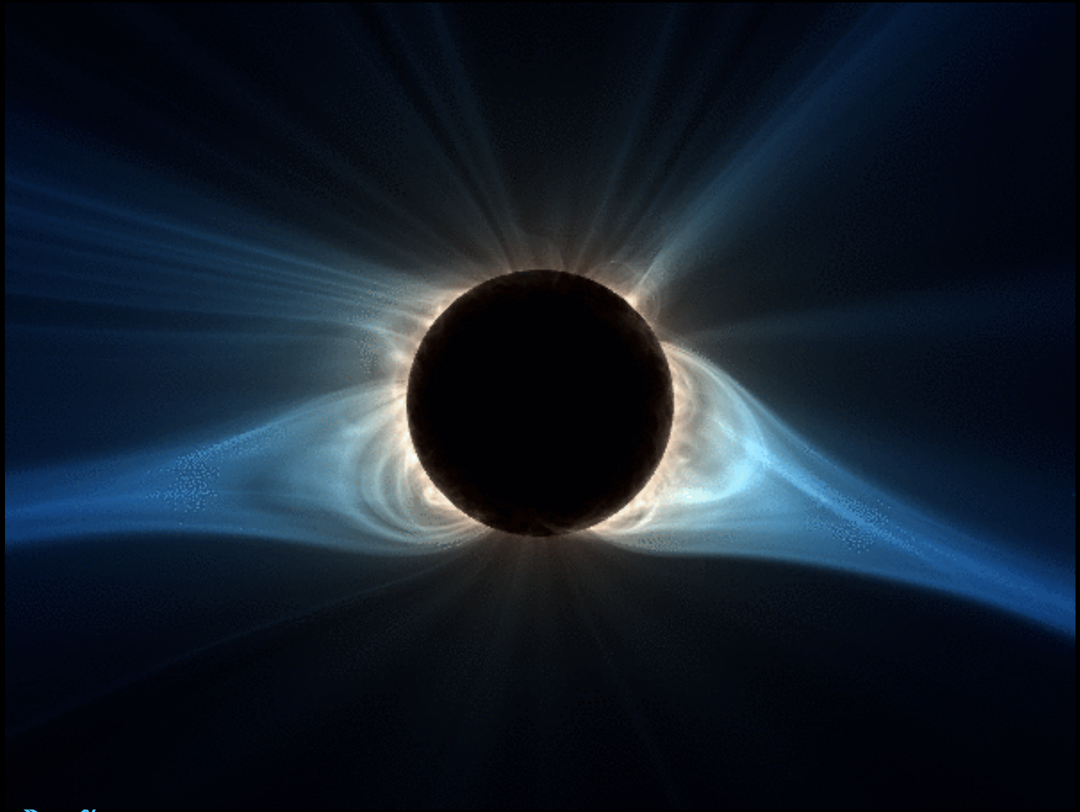


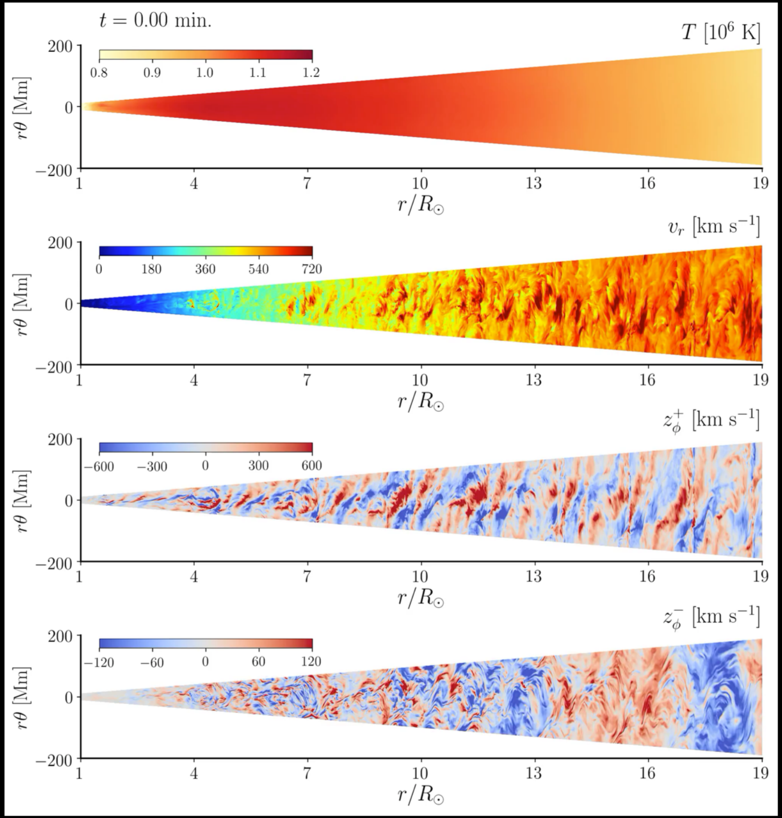
...then undergo a rapid turbulent cascade, eventually dissipating in intermittent (**nanoflare-ish!**) sites of magnetic reconnection.

(see Hollweg 1986; Velli et al. 1991; Matthaeus et al. 1999; van Ballegooijen et al. 2011; Shoda et al. 2019; Schekochihin 2022; Dong et al. 2022; and many more)

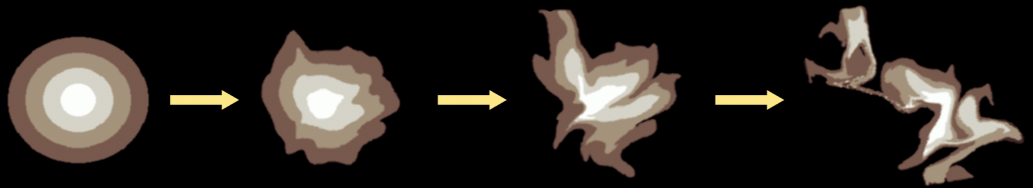
MHD turbulence: successful ingredient in simulations

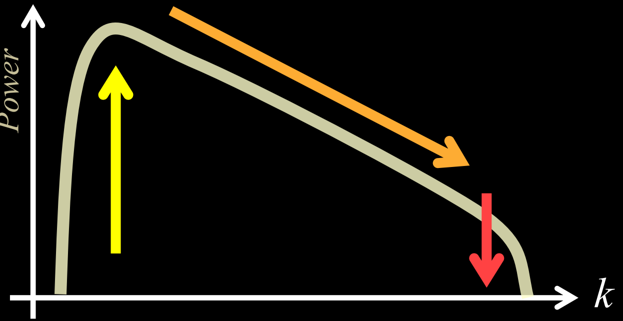
3D & time-steady (Mikić et al 2018) vs. evolving turbulence in restricted geometry (Shoda et al 2019):





Cascade → dissipation → heating





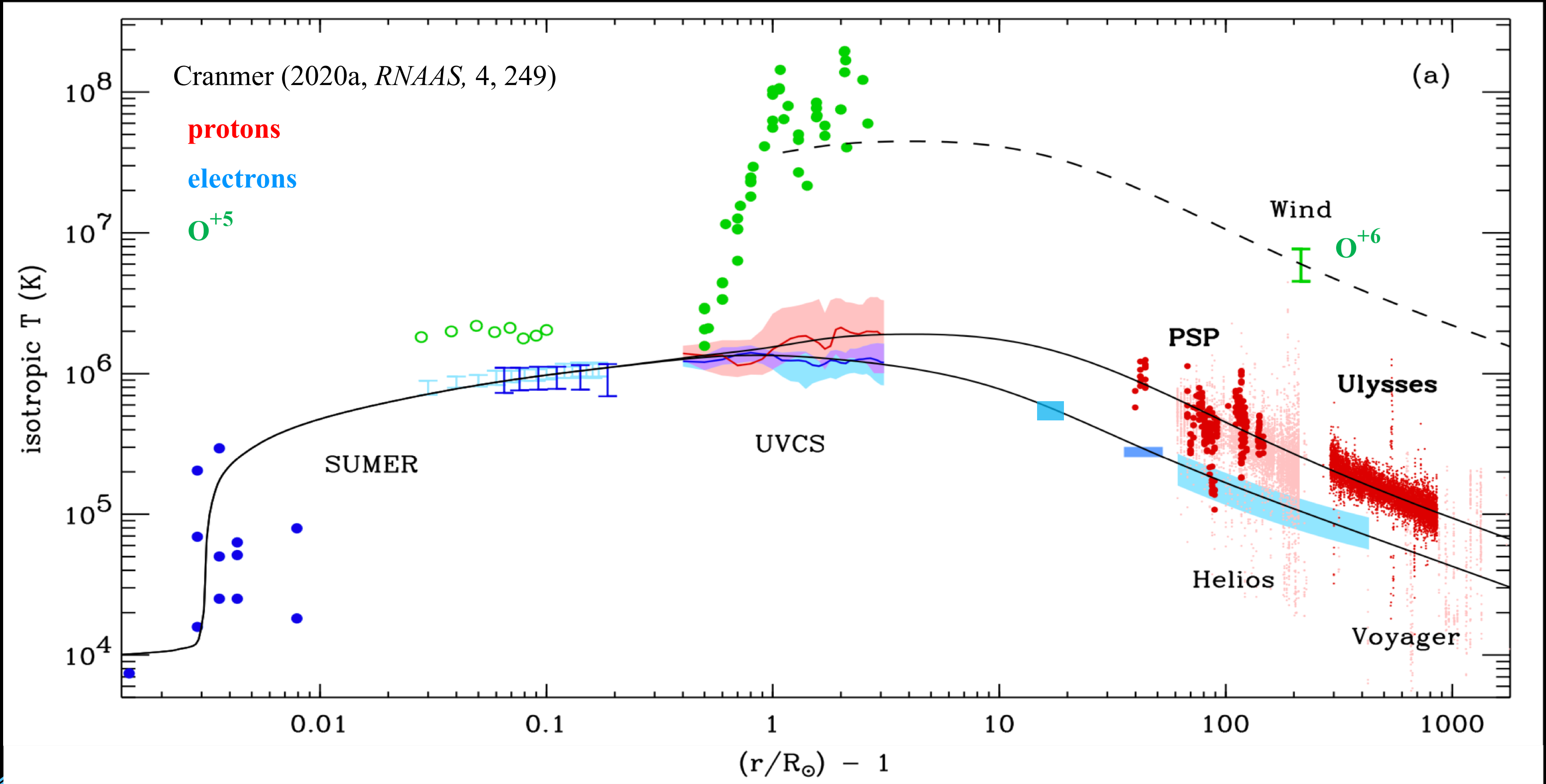
- It's traditional to think of turbulence as a 'pipeline' of energy transfer from large scales (low k) to small scales (high k).
- When dissipation happens at high k in a **low-density plasma,** particle-particle collisions are infrequent, so we can see how the heat is distributed **unevenly** between...

$T_p \neq T_e \neq T_{ion}$

$T_\perp \neq T_\parallel$

Spoiler alert: *EVERY* model has trouble matching the observed non-equilibrium "partitioning"

Temperature smörgåsbord (fast solar wind)



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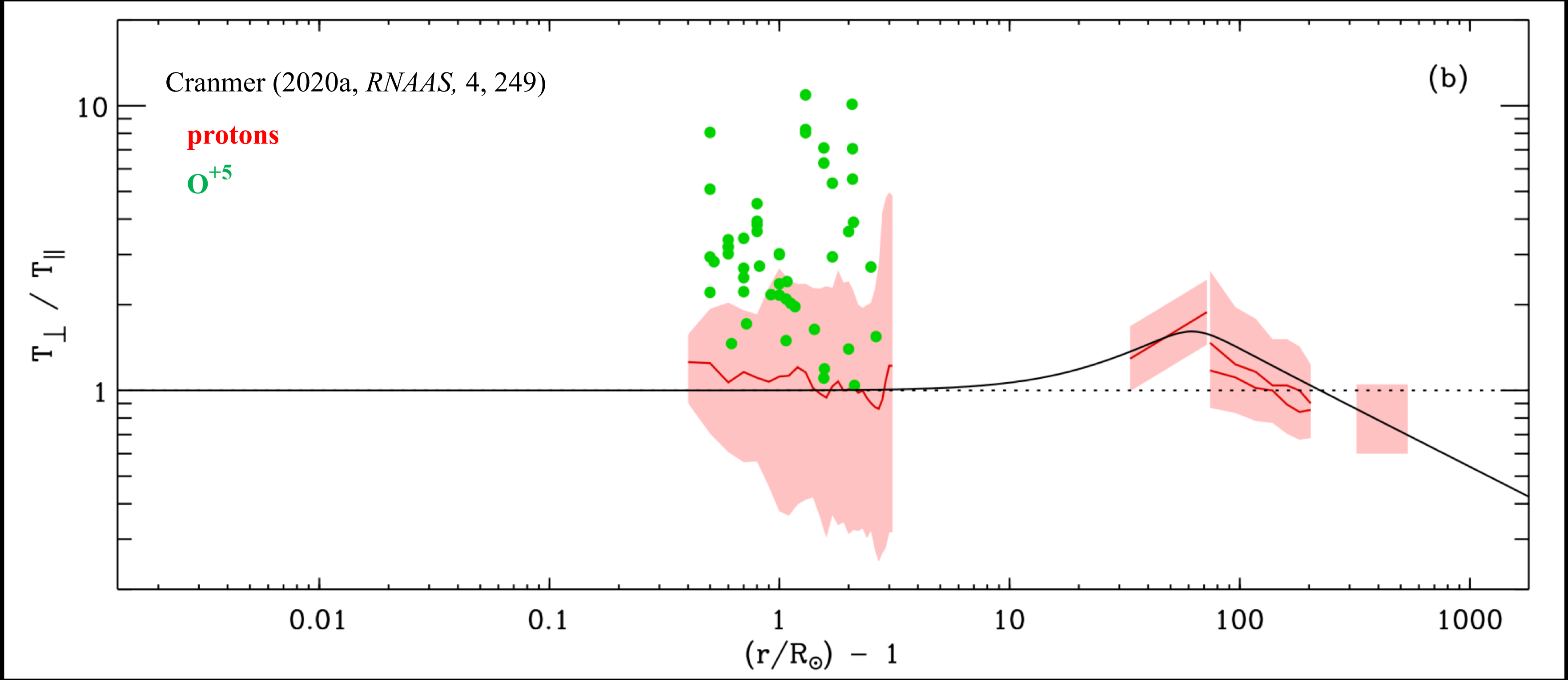


From T's to Q's

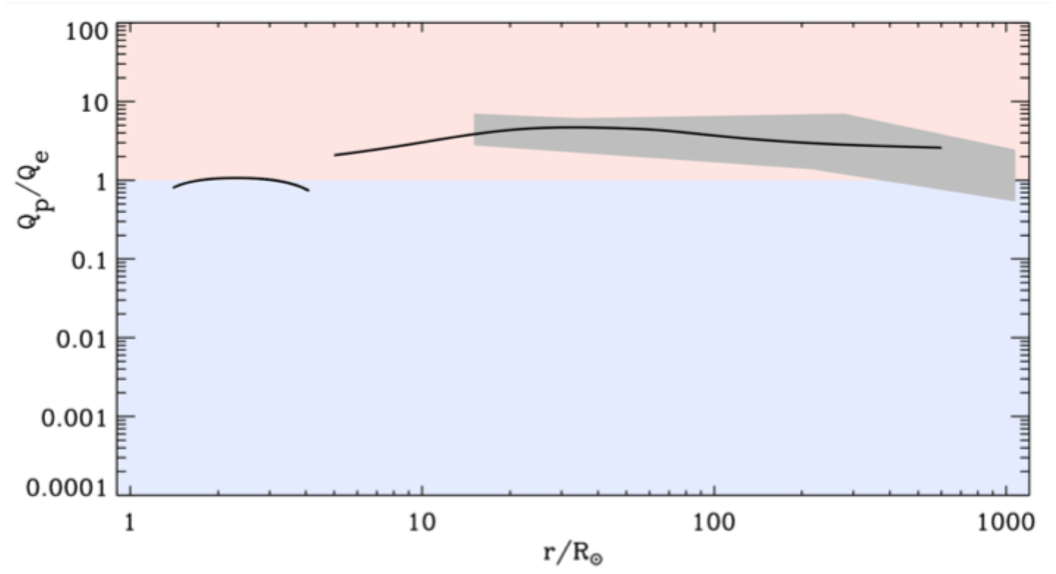
- Once we know **plasma temperatures** (and densities, flow speeds, etc.) it becomes possible to back-engineer **heating rates** required to maintain the plasma in its assumed steady state... e.g.,

$$\frac{3}{2} n_e u_p k_B \frac{\partial T_e}{\partial r} - u_p k_B T_e \frac{\partial n_e}{\partial r} = Q_e - \frac{1}{A}\frac{\partial}{\partial r}(A q_e) + C_{\parallel ep}(T_{p\parallel} - T_e) + C_{\perp ep}(T_{p\perp} - T_e) + m_p (J_{\parallel ep} + J_{\perp ep})$$

- The total rate (say, $Q_e + Q_p$) does a good job matching what's required for the overall coronal heating problem, and for how much turbulence ought to be dissipated from the Sun to 1 AU. ✓

  (Leamon et al. 1999; Cranmer et al. 2009; Cranmer 2020b; Bandyopadhyay et al. 2023)

- The ratio (Q_p / Q_e) is another story... →



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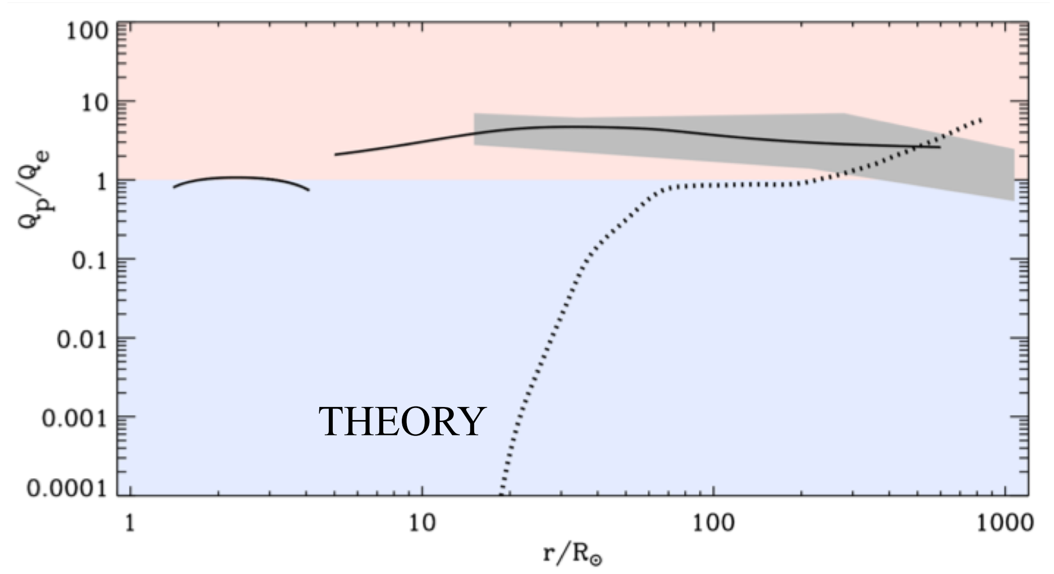

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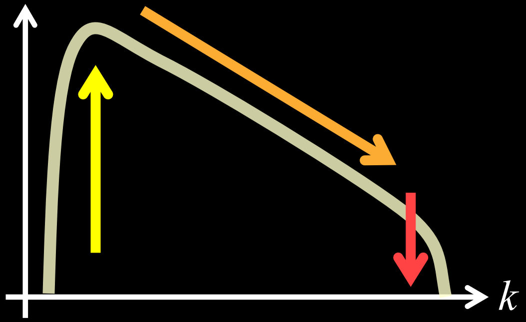
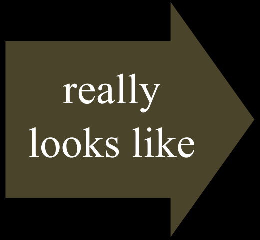
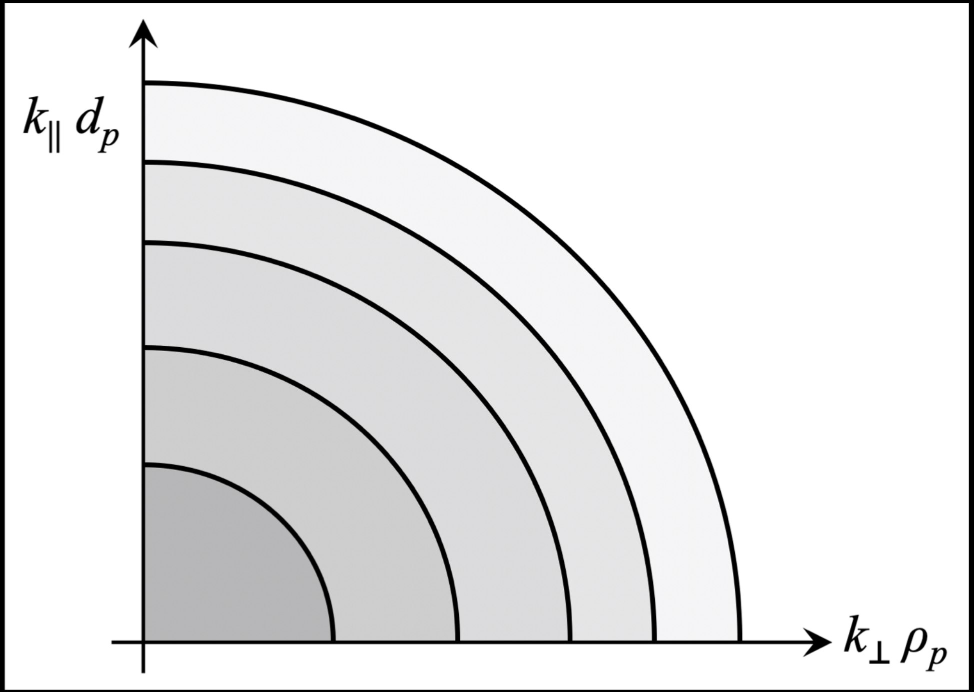
Spaghetti or pancakes?

- So *WHY* does the theory say electrons should receive nearly all of the heating in the corona?
- In this region, the cascade is anisotropic. It's no longer just about ***k*,** but about $k_\perp$ and $k_{||}$







- Key collisionless length scales:

$$d_p = \frac{V_A}{\Omega_p} \qquad \rho_p = \frac{v_{\mathrm{th},p}}{\Omega_p}$$

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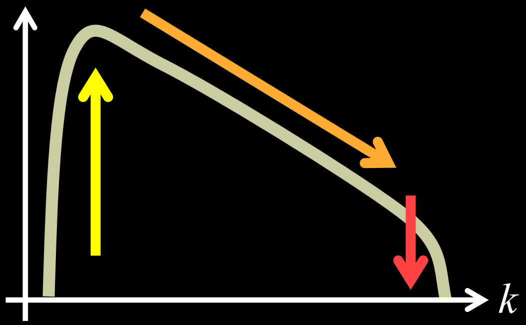

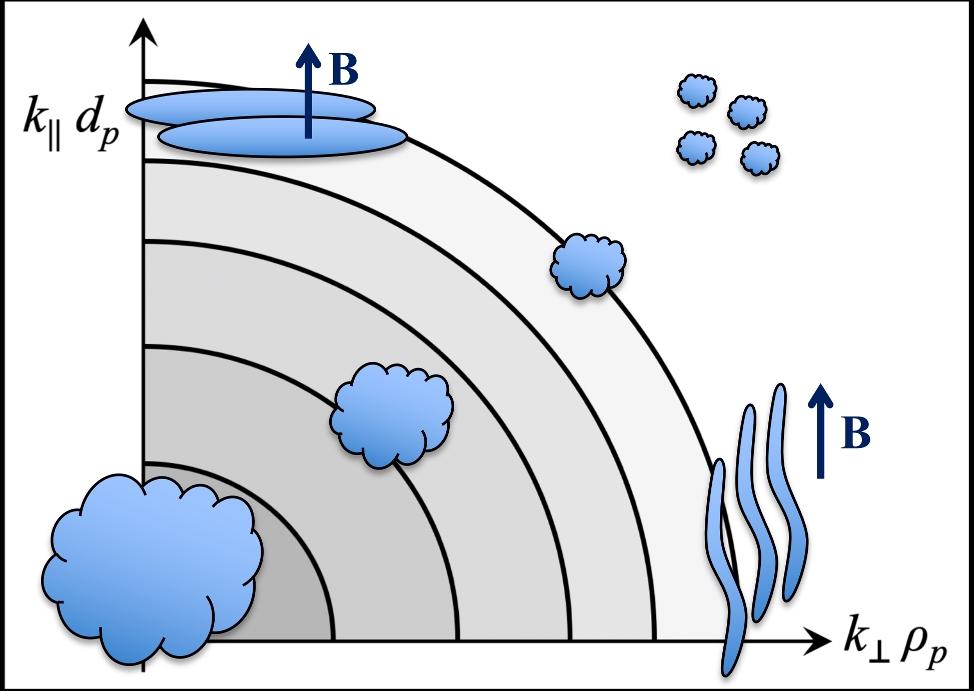

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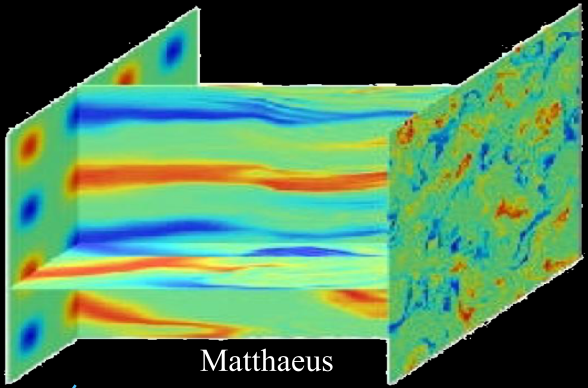
MHD turbulence

- Because magnetic fields have **tension,** most of the cascade happens perpendicular to the background vector field. (It's easier to shuffle dried spaghetti than it is to bend it…)

"strong field"

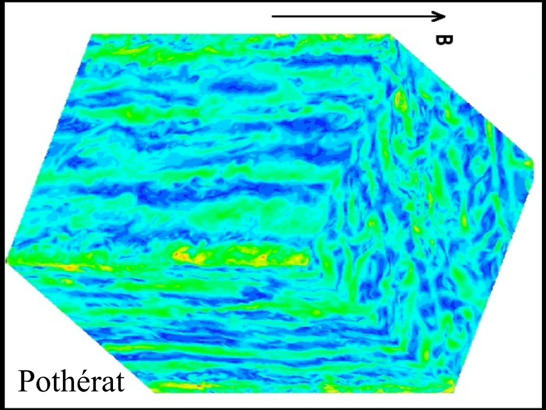
"weak field"

- Simulation snapshots courtesy of...



Matthaeus

Rappazzo



Pothérat

MHD turbulence

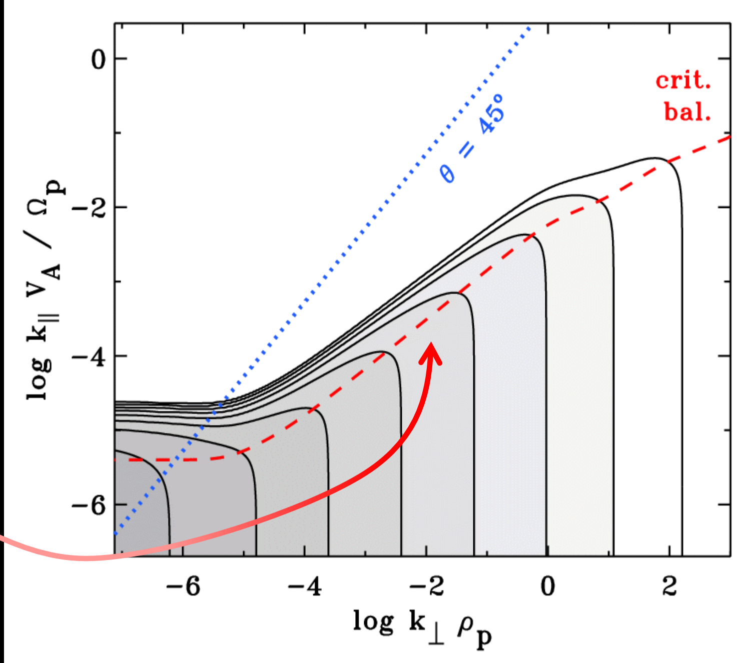
- Although the cascade is **mostly** "left to right" in our ($k_\perp$, $k_{||}$) diagram, it's not purely so.
- Goldreich & Sridhar (1995) determined that there must be a **"critical balance"** between the two primary time-scales of the system:

$$\tau_{\rm nonlin} = \frac{\ell_\perp}{v_\perp} \sim \frac{1}{k_\perp v_\perp} \qquad \tau_{\rm Alf} = \frac{\lambda_{||}}{V_{\rm A}} \sim \frac{1}{k_{||} V_{\rm A}}$$

- The rapid left-to-right cascade occurs mostly for eddies with $\chi << 1$, where

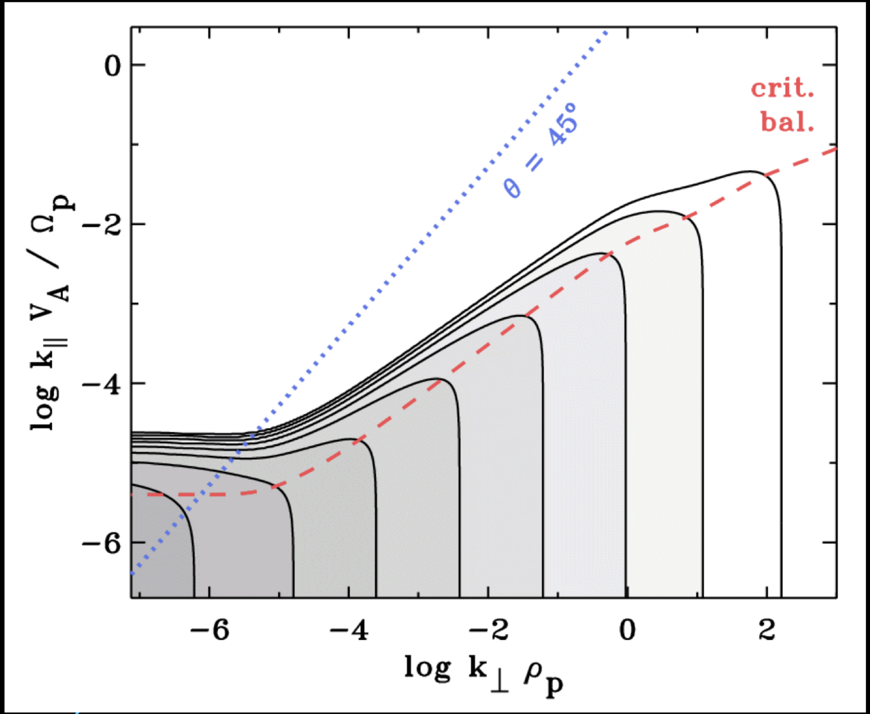
$$\chi = \frac{k_{||} V_{\rm A}}{k_\perp v_\perp}$$

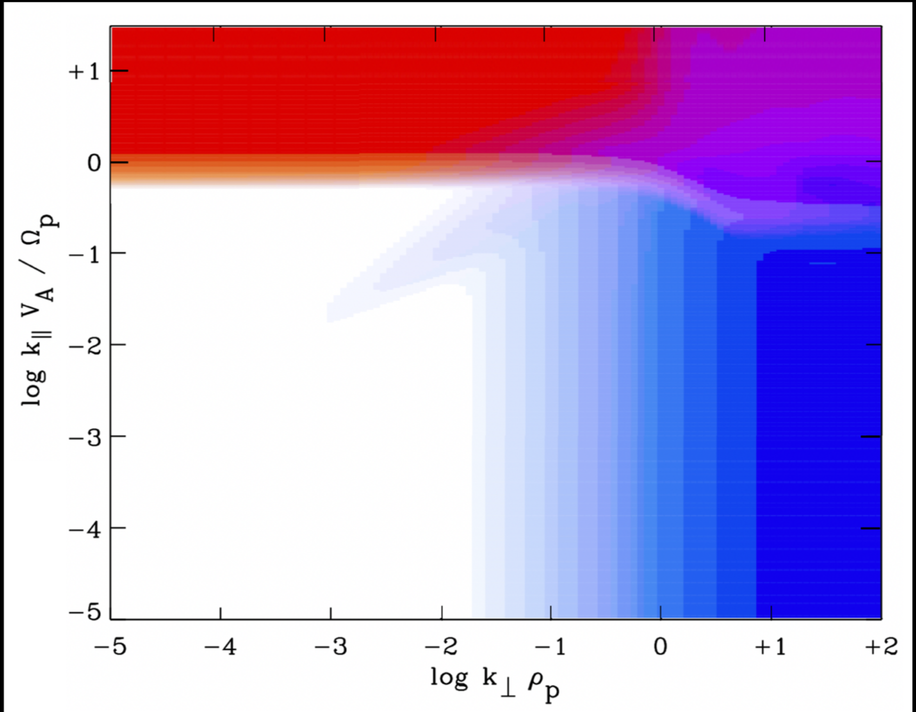
- Note that $v_\perp \propto k_\perp^{-0.3}$, so the $\chi \approx 1$ curve is **oblique**
- The region with $\chi >> 1$ is "empty" of turbulent energy.



Why does this matter?

- For the magnetically dominated plasma in the corona, the collisionless dissipation mechanisms (at high k) favor **protons** in some places, and **electrons** in other places:





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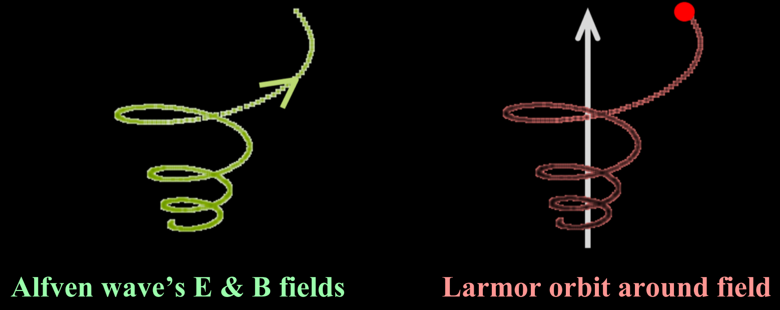
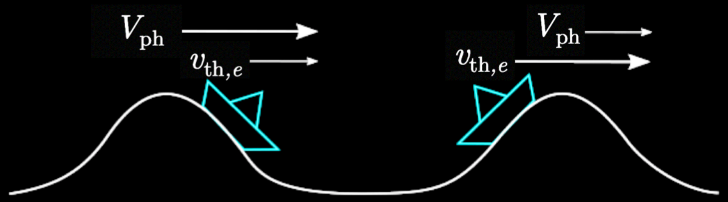
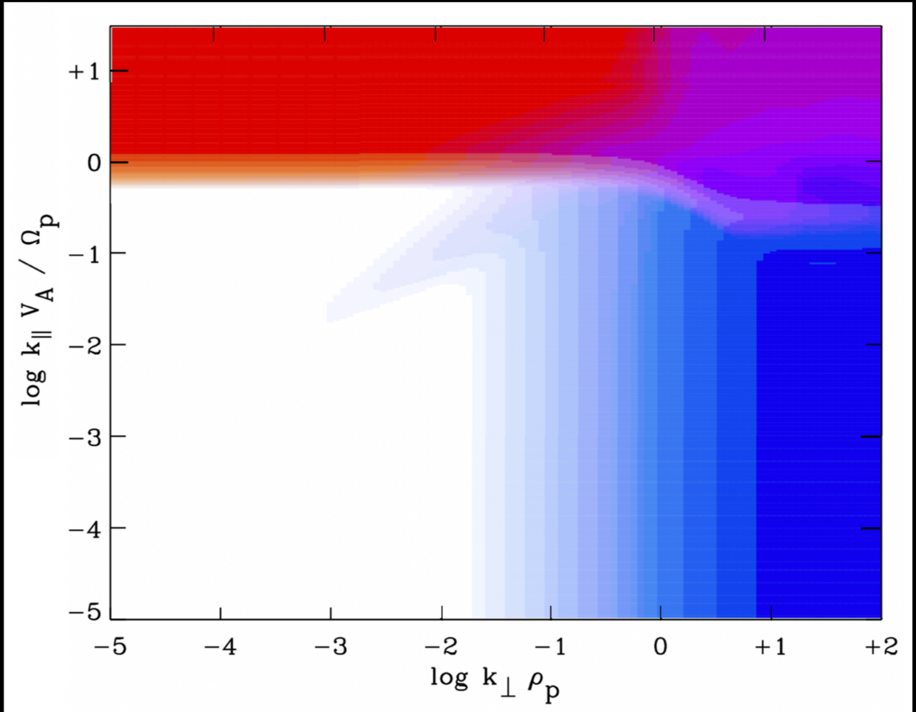
- Ion-cyclotron resonance:



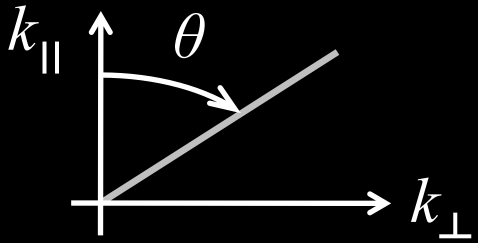
- Landau damping:

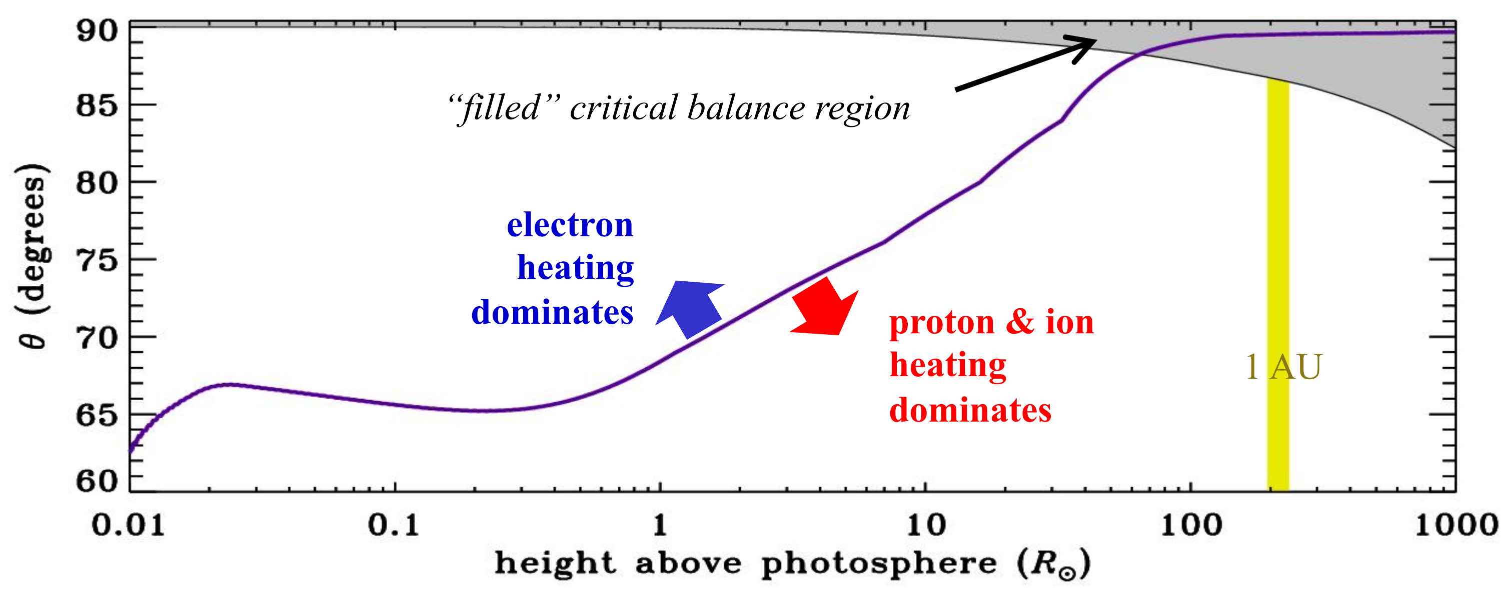




How bad is the "mismatch" from Sun to 1 AU ?

- According to Goldreich & Sridhar, what wavenumber angles should be "filled" by turbulence in the solar wind? **(gray region)**
- What is the angle that separates ion/proton heating from electron heating? **(purple curve)**





Something else must be going on . . .

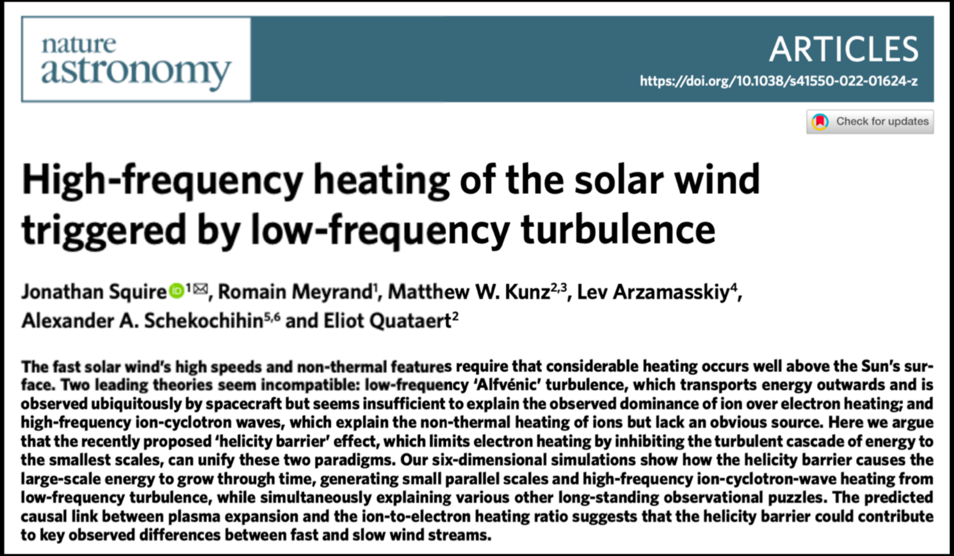
- Alfvénic turbulence may induce some kind of **"parallel cascade"** in non-critical-balance ways that gradually produce ion cyclotron waves in the corona and solar wind.
- When MHD turbulence cascades to small perpendicular scales, the small-scale **shearing motions** may be unstable to generation of cyclotron waves (Markovskii et al. 2006).
- Dissipation-scale **current sheets** may preferentially spin up ions (Dmitruk et al. 2004; Servidio et al. 2015).
- If MHD turbulence exists for both Alfvén and fast-mode waves, the two types of waves can **nonlinearly couple** with one another to produce high-frequency ion cyclotron waves (Chandran 2005; Cranmer & van Ballegooijen 2012).
- If **nanoflare-like reconnection events** in the low corona are frequent enough, they may fill the extended corona with electron beams that would become unstable and produce ion cyclotron waves (Markovskii 2007).
- If kinetic Alfvén waves reach large enough amplitudes, they can damp via wave-particle interactions and heat ions **stochastically** (Voitenko & Goossens 2006; Chandran 2010; Martinović et al. 2020).
- Kinetic Alfvén wave damping in the extended corona could lead to electron beams, Langmuir turbulence, and Debye-scale **electron phase space holes** which could scatter off ions & heat them perpendicularly (Matthaeus et al. 2003; Cranmer & van Ballegooijen 2003).

Recall spoiler alert? *every* model seems to have trouble matching observed T_p, T_e, T_{ion}, $T_\perp$, $T_\parallel$

Something else must be going on . . .

- Alfvénic turbulence may induce some kind of **“parallel cascade”** in non-critical-balance ways that gradually produce ion cyclotron waves in the corona and solar wind.

Update: a promising new idea (Meyrand et al. 2021; Squire et al. 2022) may point to a way that **this** happens!



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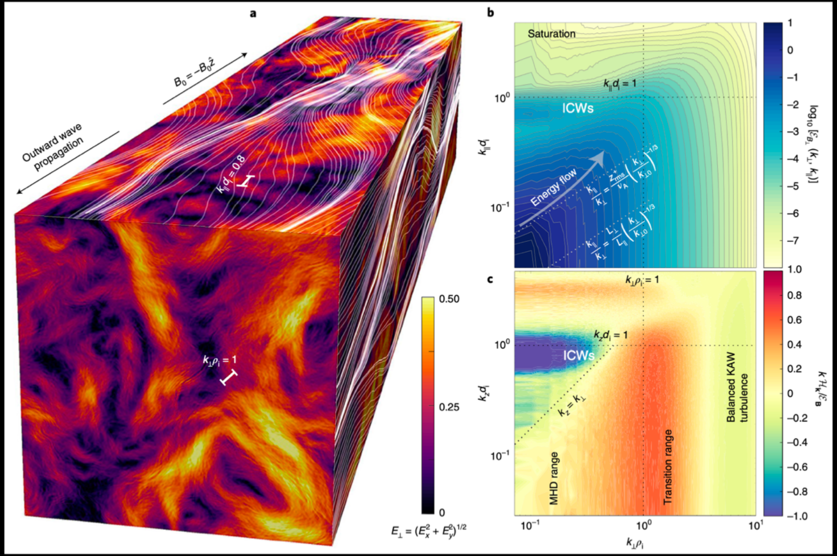
Check for updates

High-frequency heating of the solar wind triggered by low-frequency turbulence

Jonathan Squire[1], Romain Meyrand[1], Matthew W. Kunz[2,3], Lev Arzamasskiy[4], Alexander A. Schekochihin[5,6] and Eliot Quataert[2]

The fast solar wind’s high speeds and non-thermal features require that considerable heating occurs well above the Sun’s surface. Two leading theories seem incompatible: low-frequency ‘Alfvénic’ turbulence, which transports energy outwards and is observed ubiquitously by spacecraft but seems insufficient to explain the observed dominance of ion over electron heating; and high-frequency ion-cyclotron waves, which explain the non-thermal heating of ions but lack an obvious source. Here we argue that the recently proposed ‘helicity barrier’ effect, which limits electron heating by inhibiting the turbulent cascade of energy to the smallest scales, can unify these two paradigms. Our six-dimensional simulations show how the helicity barrier causes the large-scale energy to grow through time, generating small parallel scales and high-frequency ion-cyclotron-wave heating from low-frequency turbulence, while simultaneously explaining various other long-standing observational puzzles. The predicted causal link between plasma expansion and the ion-to-electron heating ratio suggests that the helicity barrier could contribute to key observed differences between fast and slow wind streams.



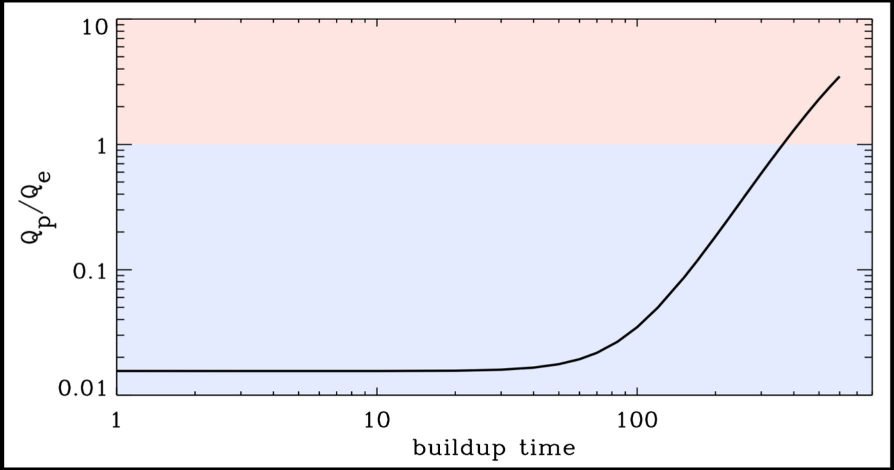
"The Helicity Barrier"

- Simulations show that imbalanced MHD turbulence cascades less strongly than balanced, and that when $k_\perp \rho_p \approx 1$, it essentially stops cascading altogether!
- Instead, fluctuation power builds up over time... $v_\perp$ gets bigger at all $k_\perp$!

- The spectrum is "filled" up to $\chi \approx 1$, but the critical-balance curve must now increase in $k_\parallel$ over time, too! Eventually, it saturates when the curve reaches the **proton-cyclotron resonant region,** and it dissipates.

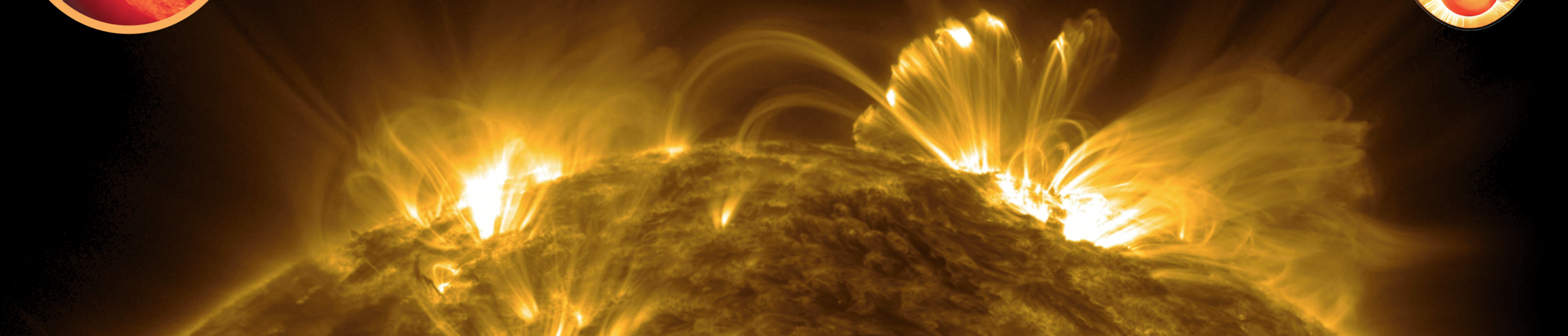
$$\chi = \frac{k_\parallel V_A}{k_\perp v_\perp}$$

- Example time evolution, for coronal conditions **($r = 4\ R_{sun}$),** showing how a buildup in $v_\perp$ (mocked up to resemble the spectra seen in simulations!) moves the critical-balance locus up enough to reach $Q_p/Q_e \approx 1$.
- However, the required buildup is too much: $\delta v_{rms} > 10{,}000$ km/s, vs. observed (< 200 km/s)



Conclusions

- Advances in MHD turbulence theory & collisionless plasma physics continue to help improve our understanding of coronal heating & solar wind acceleration.
- We still have more theories than observational constraints, but we now know better *which* new observations can best answer the remaining questions . . .



Some references

- Online seminar course on coronal heating & solar wind (YouTube videos, Python codes): https://stevencranmer.bitbucket.io/ASTR_6000_2022/
- Coronal heating review (Cranmer & Winebarger 2019, *ARA&A,* 57, 157)
- Observed temperatures (Cranmer 2020a, *RNAAS,* 4, 249; Cranmer 2020b, *ApJ,* 900, 105)
- Inflowing blobs near the Alfvén surface (Cranmer, DeForest, & Gibson 2021, *ApJ,* 913, 4)
- Earlier results about ion cyclotron heating & low-beta anisotropic turbulence (Cranmer & van Ballegooijen 2012, *ApJ,* 754, 92; Cranmer 2014, *ApJ Suppl.,* 213, 16)

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