SOHO–15: Coronal Heating, 6–9 September 2004,
University of St. Andrews, Scotland

Coronal Heating “versus” Solar Wind Acceleration

Steven R. Cranmer
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA

- **Background and brief history**
- **Fast wind: coronal heating**
  - ⟶ Basal heating vs. extended heating
  - ⟶ MHD turbulence as a heat source
- **Fast wind: wave–particle acceleration:**
  - ⟶ Alfvén waves: results from a non–WKB reflection model
  - ⟶ What about fast-mode magnetosonic waves?
- **Slow wind: how similar/different from fast wind?**
- **Conclusions and future missions**

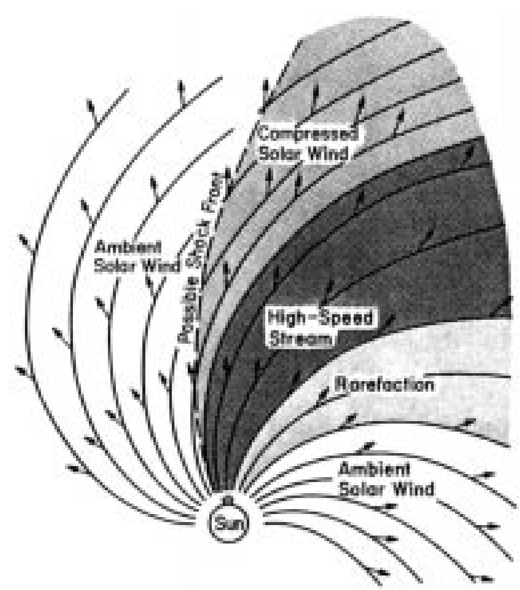
Exploring the Solar Wind (pre–SOHO)

- ⋆ 1958: Eugene Parker proposed that the hot corona provides enough **gas pressure** to counteract gravity.

- ⋆ 1962: *Mariner 2* provided first direct confirmation of the continuous, supersonic solar wind **. . .** in two relatively distinct modes:

high-speed (500–800 km/s)	low density	∼laminar flow
low-speed (300–500 km/s)	high density	variable, filamentary

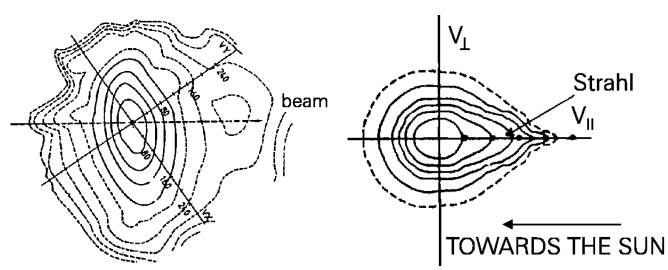
- ⋆ Uncertainties about which type is “ambient” persisted because measurements were limited to the ecliptic plane **. . .**



- ⋆ **Ulysses** left the ecliptic; provided 3D view of wind’s **source regions.**

- ⋆ By ∼1990, it was clear that the fast wind needed something besides gas pressure to accelerate so fast!

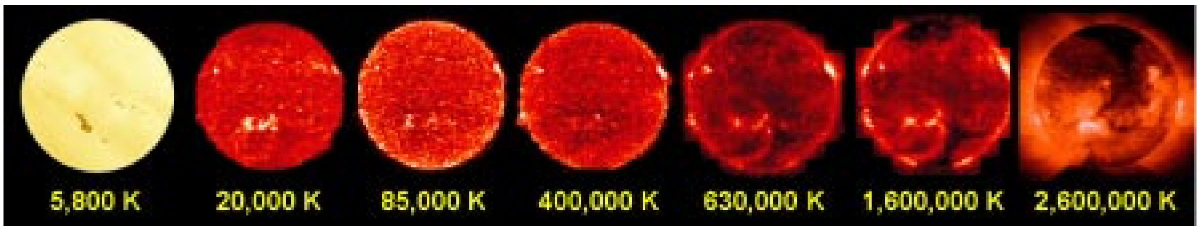
- ⋆ **Helios** explored the inner solar wind (0.3–1 AU); saw strong **departures from Maxwellian** velocity distributions:



We still have not uniquely identified the physical processes that heat the corona and accelerate the solar wind . . . .

Heating the Extended Corona

Most of this meeting is devoted to studying the heat deposited at the **"base"** of the corona, e.g.,

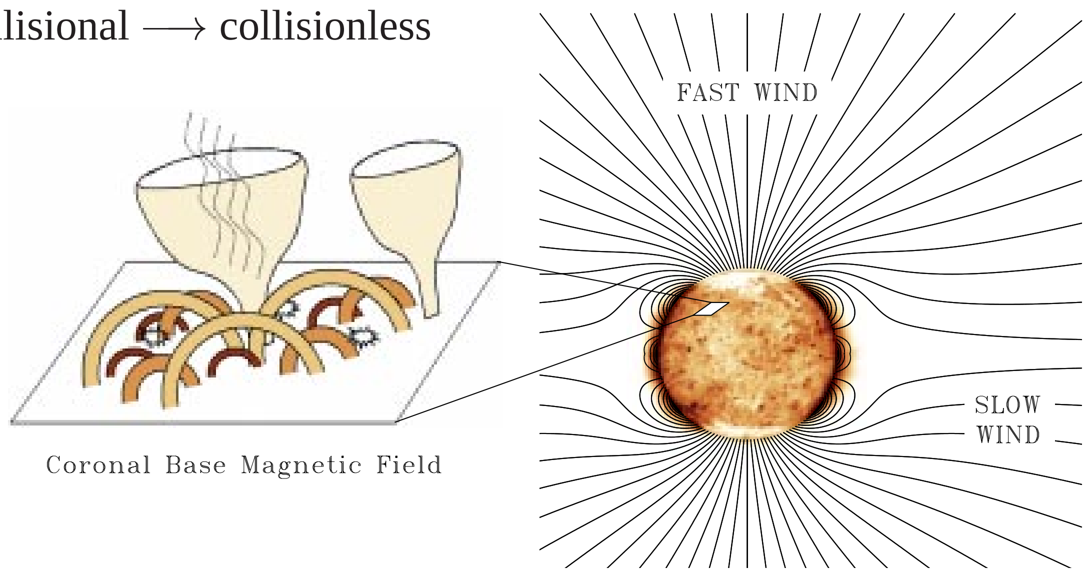


Above 2 $R_\odot$, additional energy deposition is required in order to . . .

- ⋆ accelerate the high-speed ($v > V_{\rm esc}$) component of the solar wind;
- ⋆ produce the proton & electron temperatures (and gradients!) measured in interplanetary space;
- ⋆ produce the strong preferential heating ($T_\perp > T_\parallel$) of heavy ions (in the wind's acceleration region) seen with UV spectroscopy.

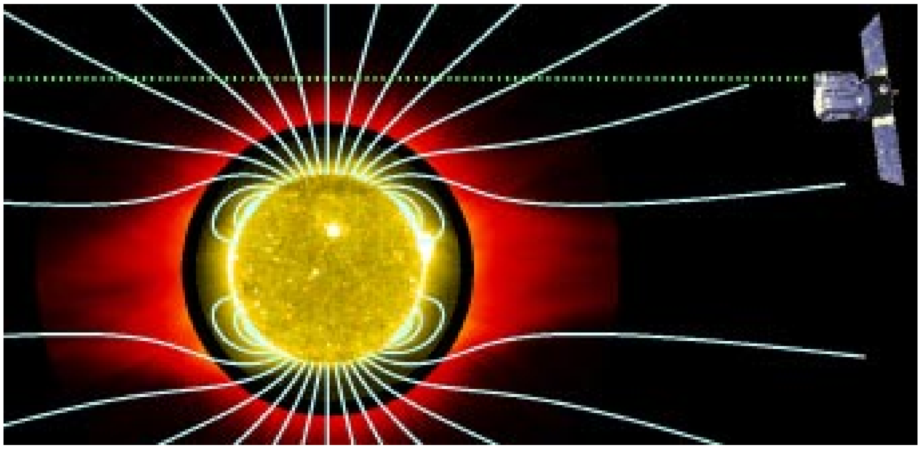
It's a very different environment from the base . . .

- ⋆ Collisional $\longrightarrow$ collisionless



UVCS results: solar minimum (1996–1997)

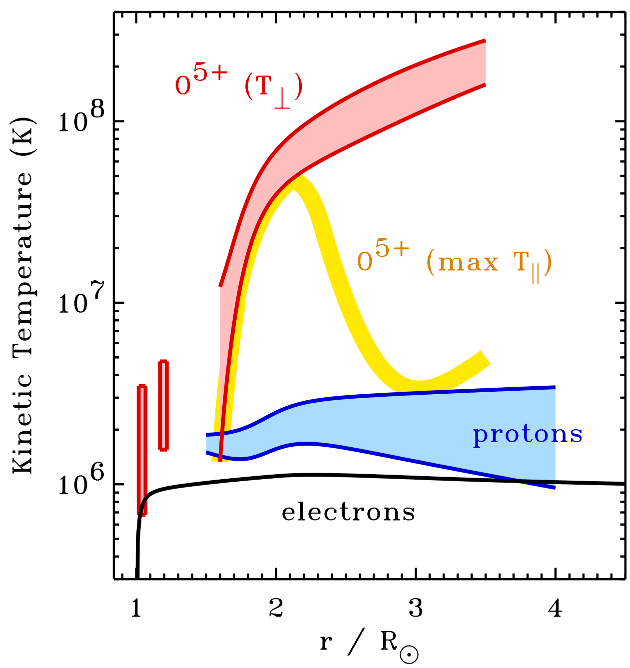
- UVCS/SOHO has measured the properties of protons and heavy ions in the wind's acceleration region:



- O^{5+} exhibits an anisotropic velocity distribution above $\sim 2\, R_\odot$ in coronal holes: $(T_\perp / T_\parallel \approx 10 \text{ to } 100)$

- For O^{5+}, $T_\perp$ approaches **200 million K** at $3\, R_\odot$. The kinetic temperatures of O^{5+} and Mg^{9+} are much greater than mass-proportional when compared with hydrogen.

- **Outflow speeds** for O^{5+} are greater than those for the bulk proton-electron plasma by as much as a factor of 2.



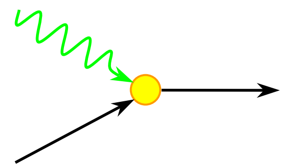
$$\left\{ \begin{array}{ccc} T_{\text{ion}} \gg & T_{\text{p}} & > T_{\text{e}} \\ (T_{\text{ion}}/T_p) & > & (m_{\text{ion}}/m_p) \\ T_\perp & \gg & T_\parallel \\ u_{\text{ion}} & > & u_p \end{array} \right\}$$

These observations have led to a resurgence of interest in theories of **ion cyclotron wave dissipation** in the extended solar corona.

Wave Generation & Damping

- ⋆ Much effort has gone into "working backwards" from the UVCS and SUMER data—i.e., identifying the ultimate **kinetic wave damping mechanisms.**

- ⋆ Quasi-linear wave-particle resonances:

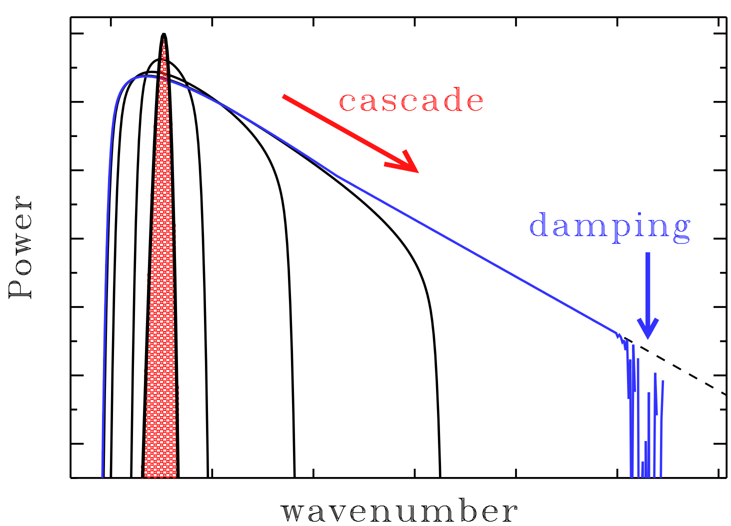


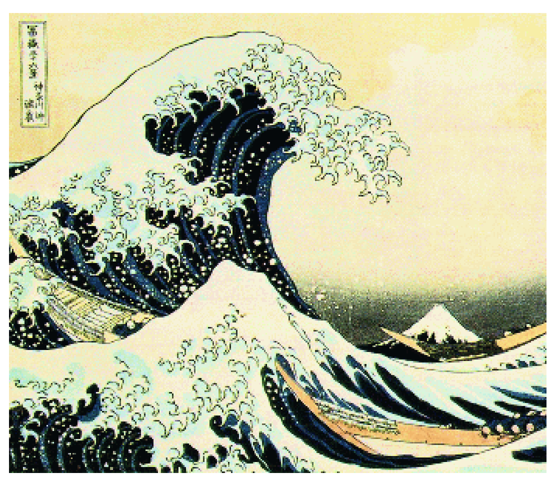
Landau damping	**Ion cyclotron damping**
$\omega - u_{\parallel} k_{\parallel} = 0$	$\omega - u_{\parallel} k_{\parallel} = \pm n \Omega_{\rm ion}$
$T_{\rm e} > T_{\rm p}$ **(low-β)**	$T_{\rm ion} \gg T_{\rm p} > T_{\rm e}$
$T_{\parallel} > T_{\perp}$	$T_{\perp} > T_{\parallel}$

- ⋆ But how are these tiny-wavelength fluctuations generated?

- ⋆ Many suspect a **turbulent cascade** from the dominant large-scale (granular / supergranular) waves emitted in the low atmosphere:

$$\mathcal{E}_{\rm out} = \frac{\rho\, v_{\rm eddy}^3}{\ell_{\rm eddy}} \quad \rightsquigarrow \rightsquigarrow \rightsquigarrow \quad Q_{\rm heat} \approx \mathcal{E}_{\rm out}$$

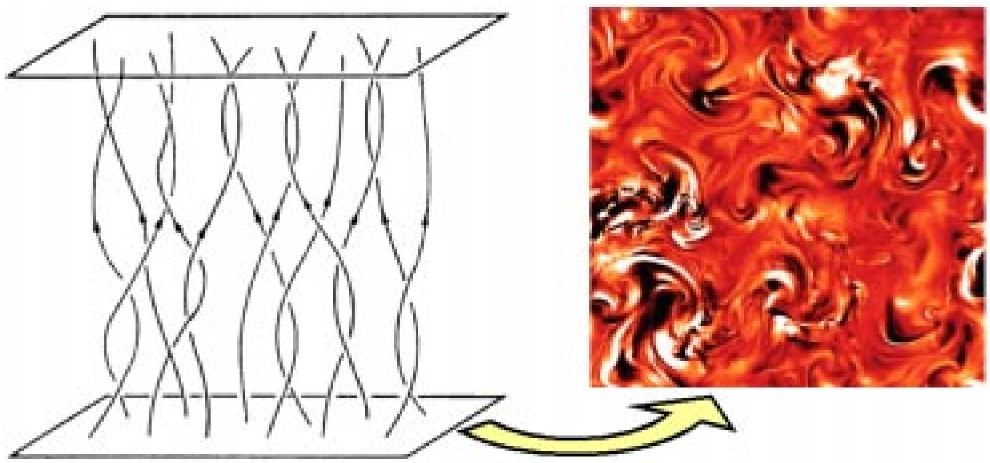




Anisotropic MHD Turbulence

- ⋆ The Kolmogorov heating rate ($\rho v^3/\ell$) has been used in many coronal and solar wind models (1986–present).

- ⋆ However, in the low-β corona (i.e., mag. pressure $\gg$ gas pressure), it is easier to **mix** field lines in directions perp. to **B** than it is to **bend** them parallel to **B**.



$\boldsymbol{k_{\parallel}}$**:** Alfvén waves travel up and down; they damp weakly and **reflect** because $\nabla V_{\mathrm{A}} \neq 0$.

$$\Downarrow$$

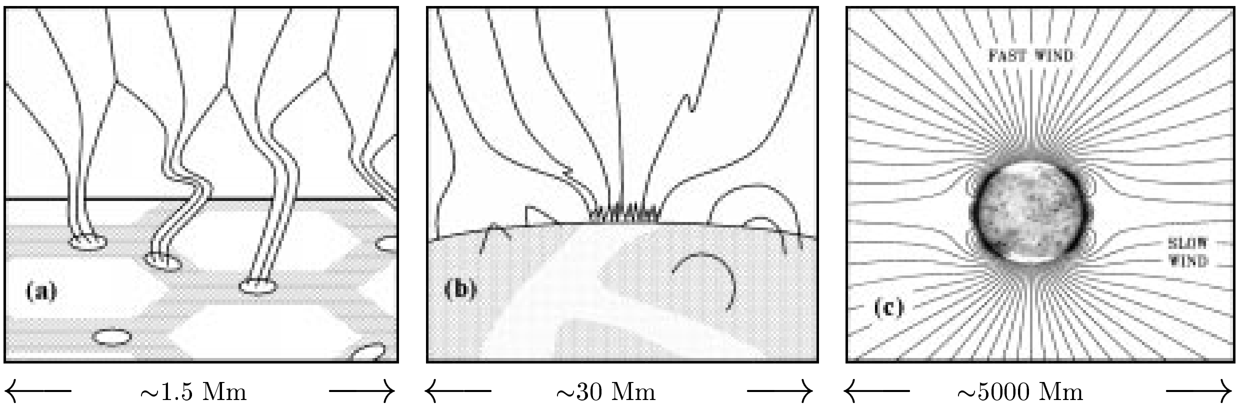
$\boldsymbol{k_{\perp}}$**:** cascade proceeds rapidly . . . but not to high-freq.?

- ⋆ Because the turbulence is far from isotropic, the energy injection rate (and thus the **heating rate**) is modified:

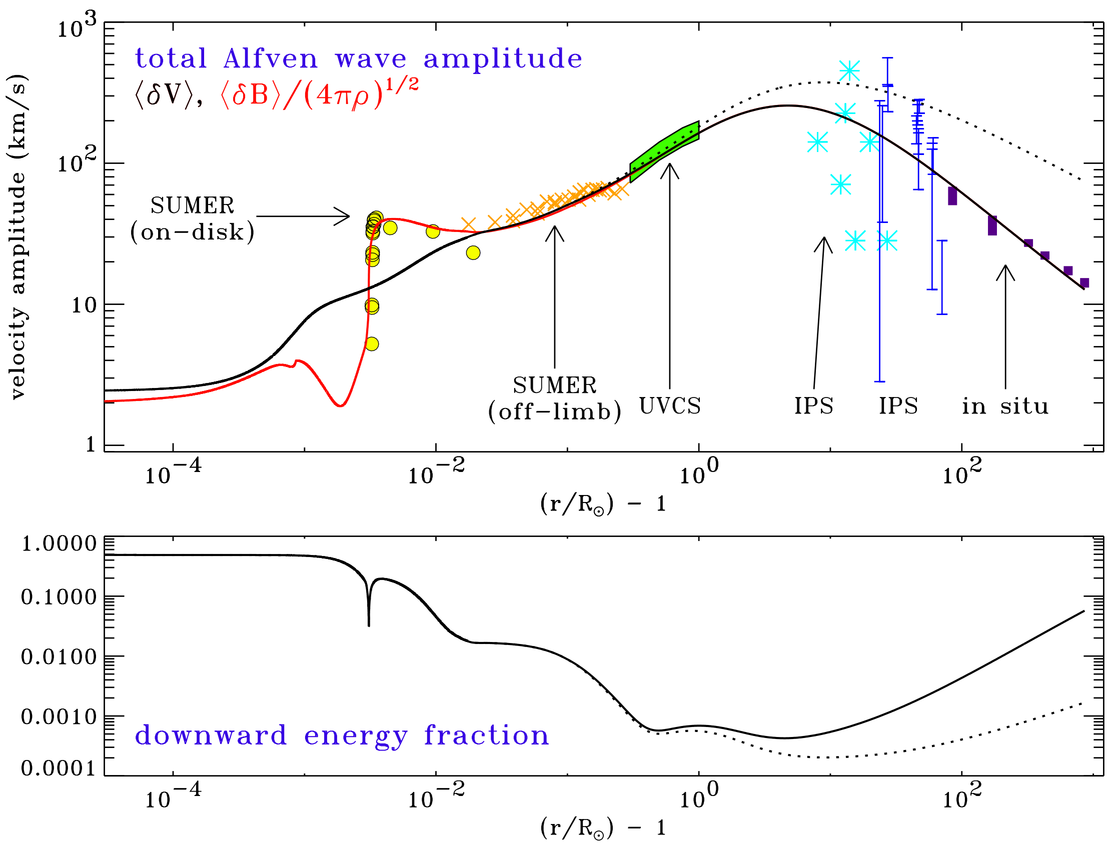
$$\mathcal{E}_{\rm out} = \frac{\rho\, \mathbf{v}^3_{\rm eddy}}{\ell_{\rm eddy}} \quad \longrightarrow \quad \frac{\rho\,(v^2_{\perp\,\rm up} v_{\perp\,\rm down} + v_{\perp\,\rm up} v^2_{\perp\,\rm down})}{2\,\ell_{\perp\,\rm eddy}}$$

Alfvén wave reflection in coronal holes

- Cranmer & van Ballegooijen (2004) built a model of the global properties of Alfvén waves in an open coronal-hole flux tube. Note successive **merging** of flux tubes on granular & supergranular scales:

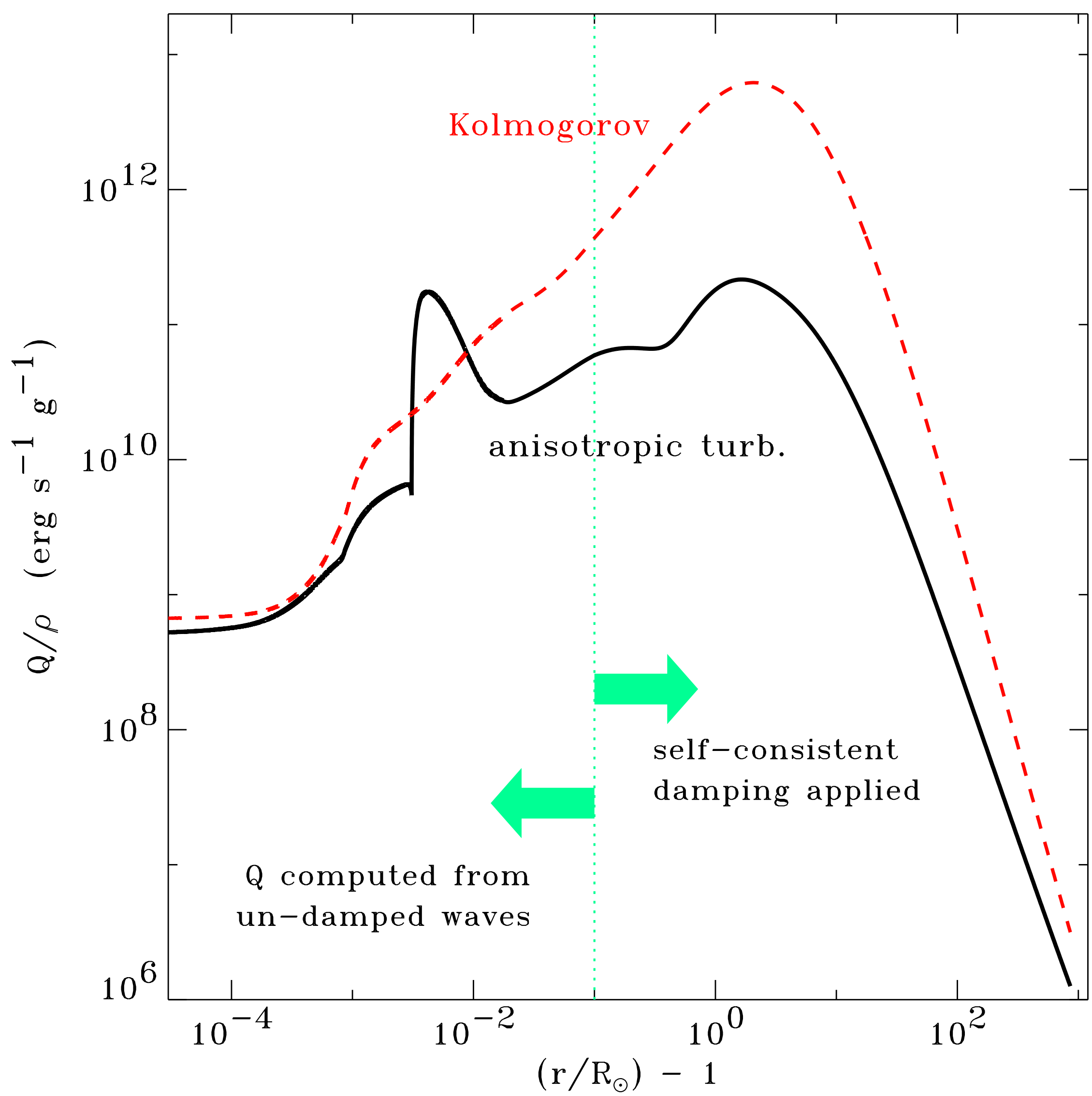


- Non-WKB wave reflection was modeled for individual frequencies comprising an empirical power spectrum. $\ell_{\perp \mathrm{eddy}} \propto B_0^{-1/2}$ normalized to produce correct damping at 1 AU.



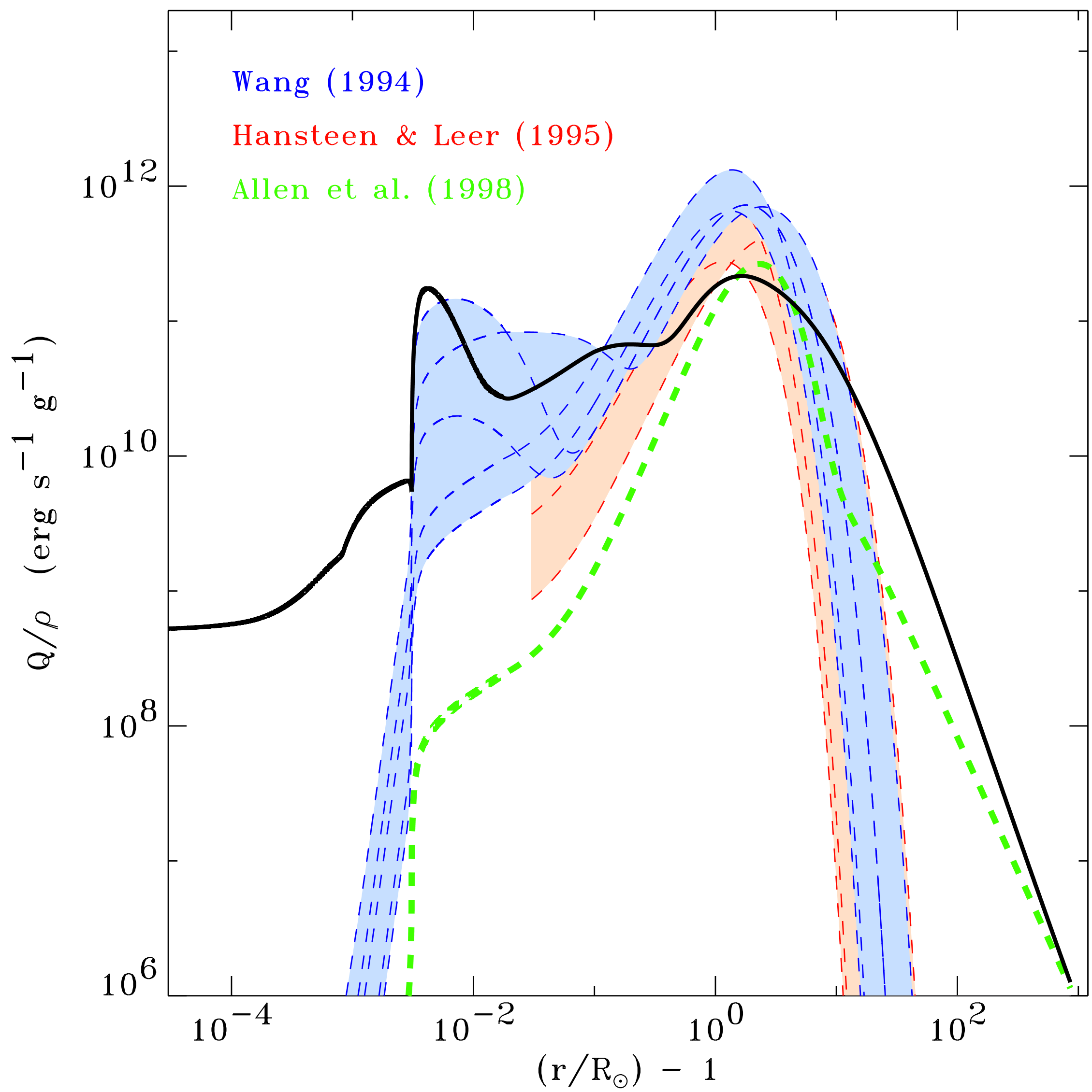
Turbulent Heating Rate (1)

⋆ The isotropic Kolmogorov formula **overestimates** the heating in regions where $v_{\perp\mathrm{up}} \neq v_{\perp\mathrm{down}}$ . . . by as much as a factor of 30.



Turbulent Heating Rate (2)

⋆ Dmitruk et al. (2002) predicted that this anisotropic heating rate may account for much of the expected (i.e., empirically constrained) coronal heating in open magnetic regions . . .

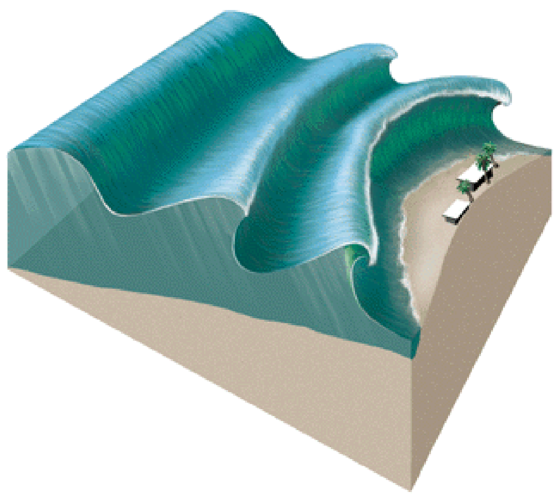


Wave-particle acceleration ("pummeling")

- ⋆ Just as E/M waves carry momentum and exert pressure on matter, acoustic and MHD waves **do work on the gas** via similar net stress terms:

$$\rho\, \boldsymbol{a}_{\rm wp} = -\nabla \cdot \mathcal{P}_{\rm wp}$$

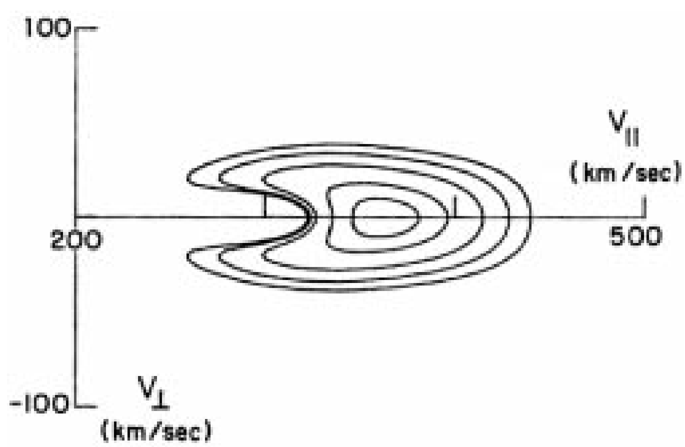
$$\approx -\frac{\partial}{\partial r}\left(\frac{\delta B_{\perp}^{2}}{8\pi}\right)$$



- ⋆ When $v_{\perp \rm up} \gg v_{\perp \rm down}$, the above simple WKB expression is valid. However, Laming (2004) suggests that non-WKB departures from the above may give rise to the **FIP effect** in loops.

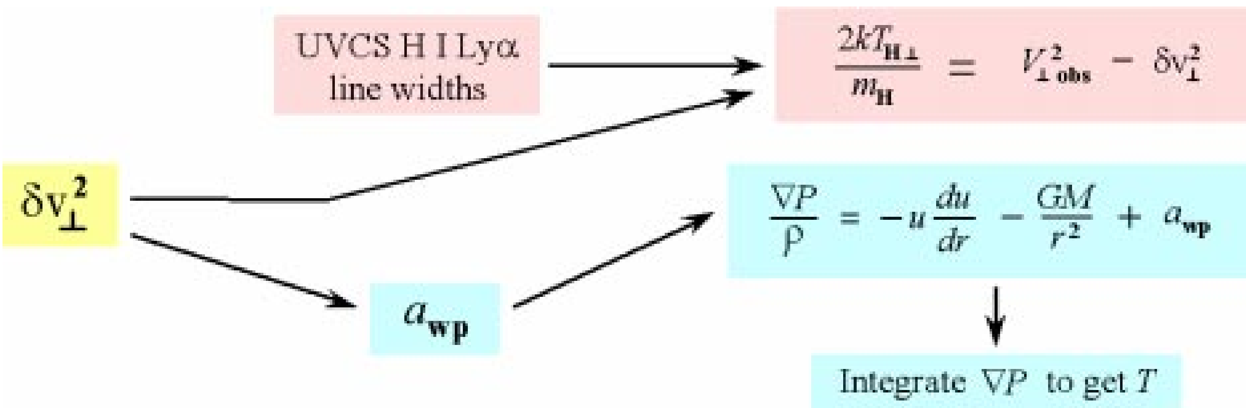
- ⋆ In the extended corona, $a_{\rm wp} \approx |g|$ (at $r \sim 2\, R_{\odot}$), and can exceed $|g|$ by a factor of 3 at larger heights.

- ⋆ Goodrich (1978) derived the detailed "microscopic" velocity-space response of particles to $a_{\rm wp}$ in the collisionless solar wind. **Kinetic models should include this!**

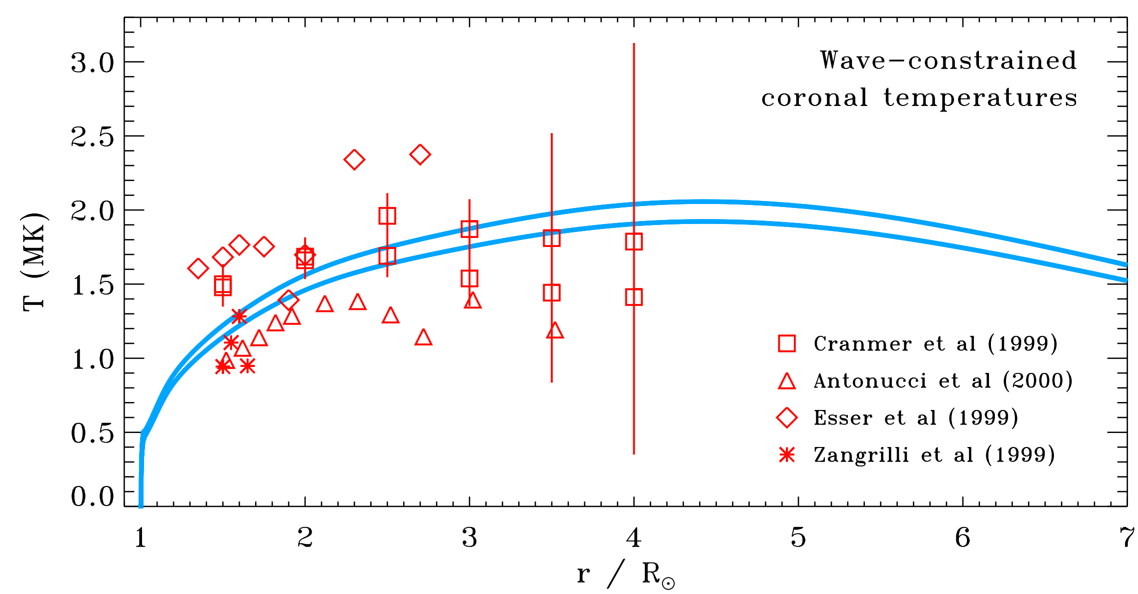


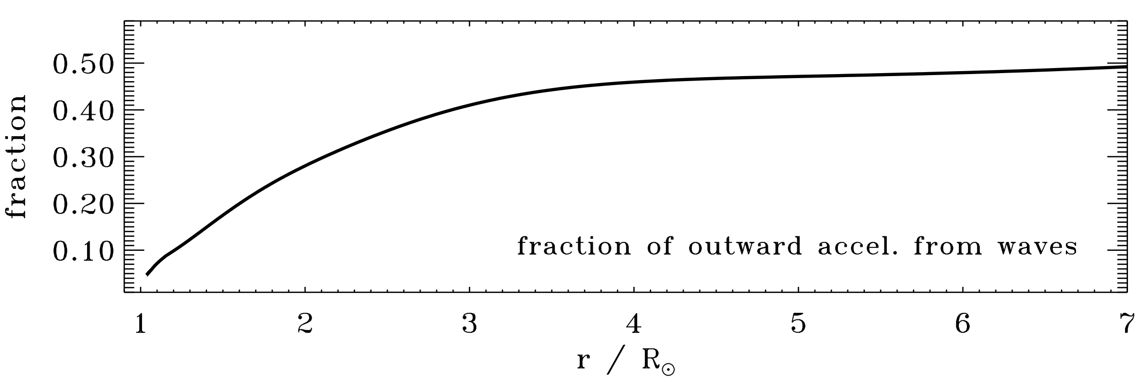
Wave pressure ⟶ Temperature?

★ There are two semi-empirical ways of using a "known" $\boldsymbol{\delta v_\perp}$ and $\boldsymbol{a_{\rm wp}}$ to put constraints on the temperature in the extended corona:



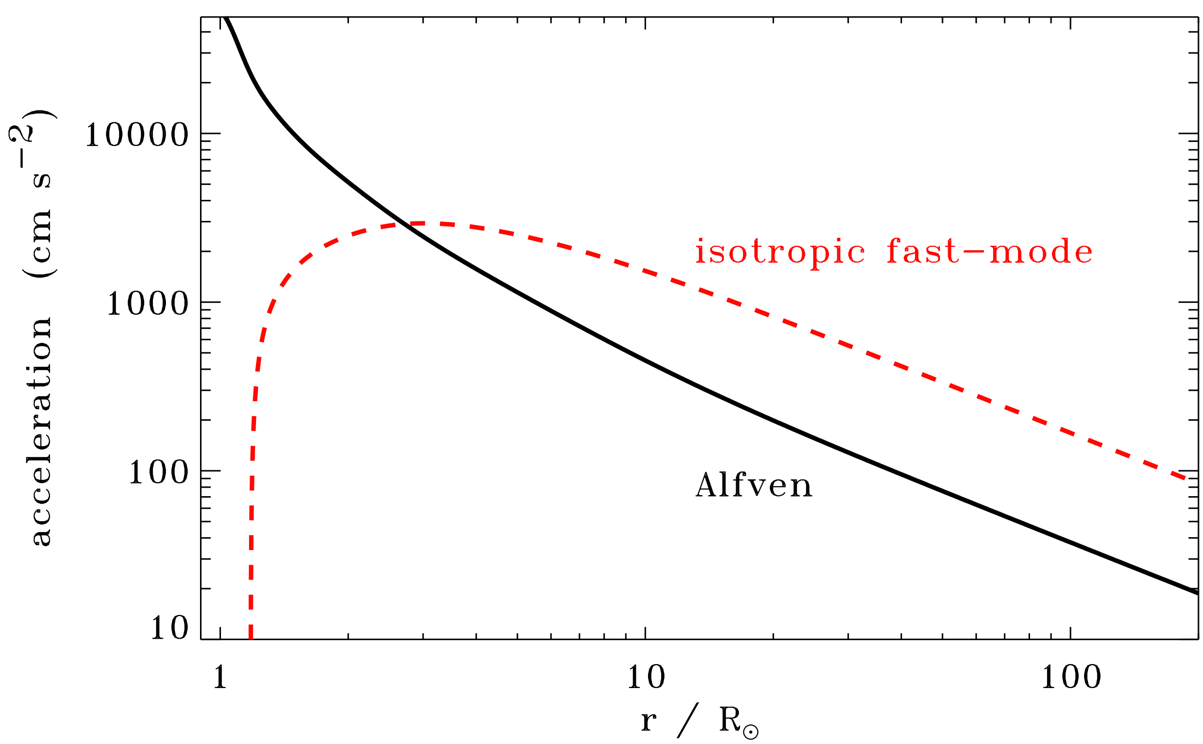
★ Do the two methods give the same answer?





Fast-mode wave pressure?

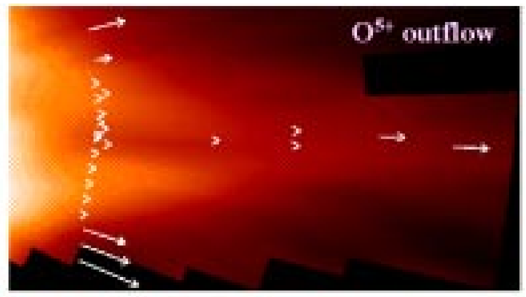
- ⋆ Most solar wind models with $\boldsymbol{a}_{\text{wp}}$ include only Alfvén waves (incompressible; no linear steepening).
- ⋆ Fast and slow magnetoacoustic waves are probably generated in the solar atmosphere with similar fluxes as Alfvén waves . . .
  - ⇒ **slow-mode** waves steepen into shocks and damp mostly in the chromosphere;
  - ⇒ **fast-mode** waves may also steepen ($\theta \neq 0$), but their collisional damping rates are comparable to those of Alfvén waves! (Whang 1997)
- ⋆ For undamped Alfven and fast-mode waves obeying wave-action conservation (and equal in energy density at 2 $R_{\odot}$), we can compare their respective wave-pressure accelerations (Jacques 1977):

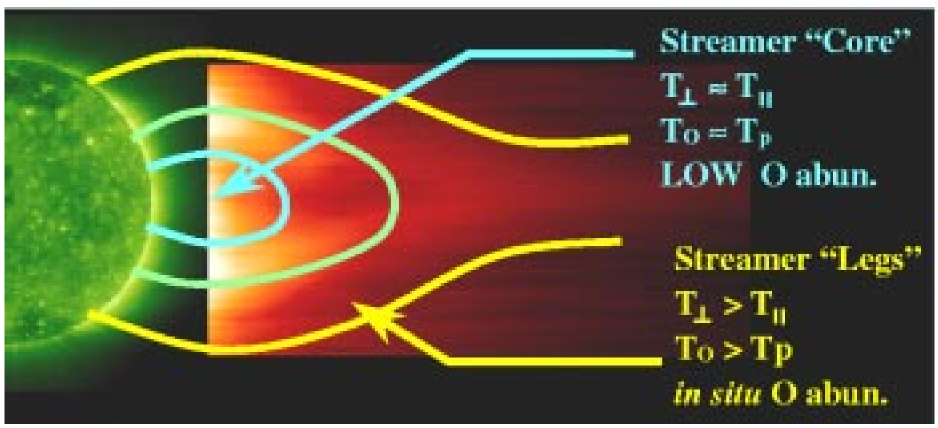


The slow solar wind: brief summary

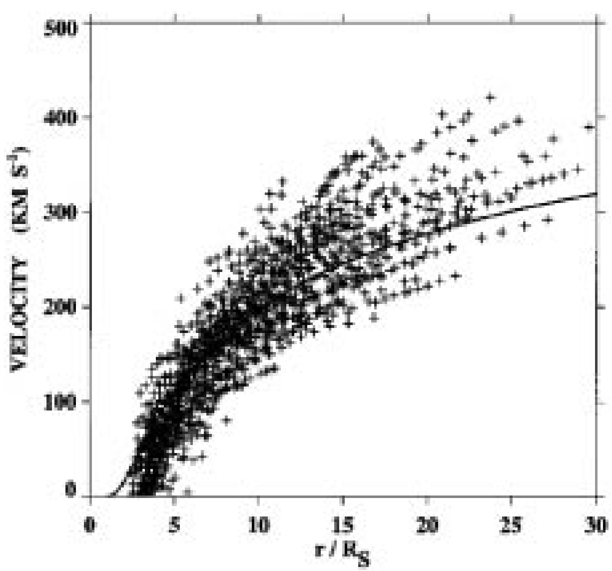
★ The visible corona is dominated by bright **streamers** known for decades to be associated with the slowest solar wind streams. But what is the magnetic topology of these regions?

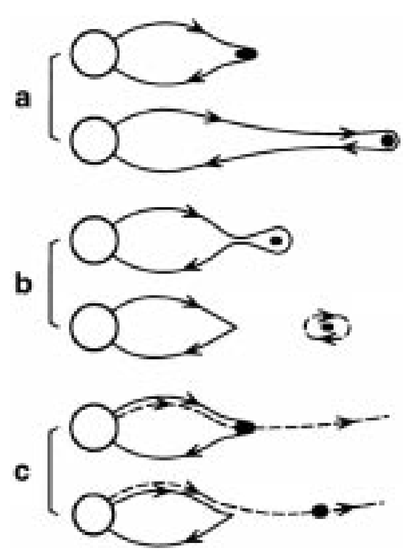
★ **UVCS spectroscopy** found outflows consistent with slow wind **only along the edges** of streamers at solar minimum:





★ **LASCO movies** spotlighted low-contrast "blobs" continually ejected from streamer cusps . . .





Conclusions

- ⋆ Our understanding of the dominant physics in the acceleration region of the solar wind is progressing rapidly . . . but so is the complexity!

What should future missions do?

- ⋆ We still don't know several basic plasma parameters (e.g., $T_{\rm e}$ and $T_{\rm p}$) with sufficient accuracy in the acceleration region of the wind.
- ⋆ Only by better "filling out" our knowledge of **heavy ion** properties (vs. q and m) can we uniquely identify the ultimate kinetic damping mechanisms.

  ⇒ **Spectroscopy is key!**

- ⋆ The power spectrum $P(k_{\parallel}, k_{\perp}, r)$ of MHD fluctuations (near the Sun) is a strong driver of solar wind physics, but we have only very indirect constraints on its properties.

  ⇒ ***in situ* co-rotation may be key! (Solar Orbiter)**

- ⋆ The origin of coronal waves in **jostled photospheric flux-tube motions** needs to be pinned down in order to put better empirical constraints on the "lower boundary condition."

  ⇒ **sub-arcsec (∼100 km), sub-sec resolution is key!**
  (near future: ground-based only . . .)