Kinetic Effects in Coronal Holes & High-Speed Streams: A Roundup of Observational Constraints

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With tons of
gratitude to
the SOHO
UVCS team

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Introduction

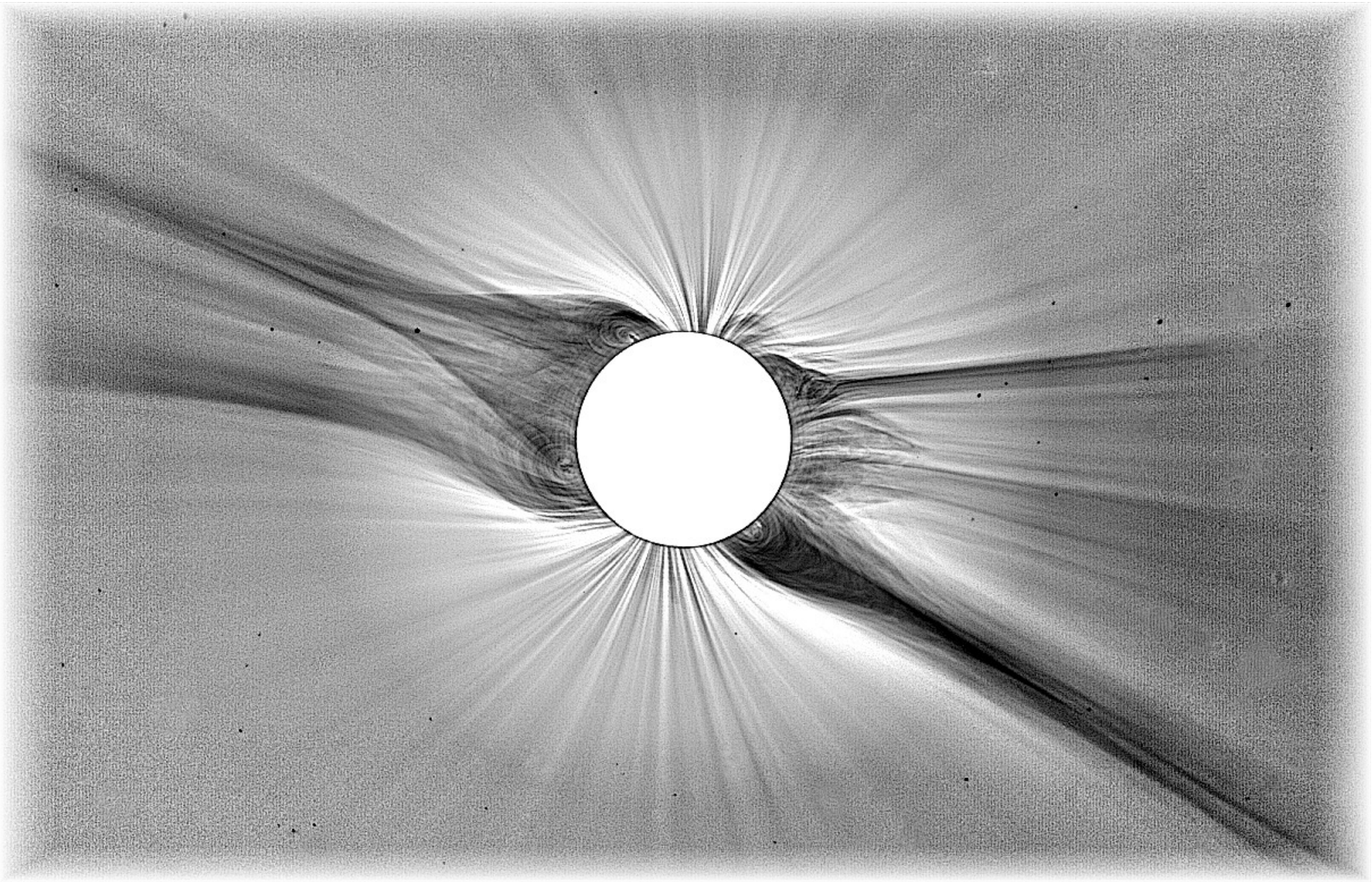
- Although we have come to understand many links in the chain of events that produces the hot solar corona and the supersonic solar wind, it is still the case that the final links – i.e., the actual dissipation processes that act on the smallest scales – remain elusive.

- Different proposed processes act on particles of different charge & mass in different ways. However, some regions of the corona and heliosphere are so dense that Coulomb collisions are frequent enough to wipe out these unique charge/mass signatures.

- Thus, theorists tend to look to the **lowest-density regions** (e.g., coronal holes & fast wind streams) to have the best chance to identify these kinetic clues.

- In this poster, I summarize the observational data (remote-sensing & *in situ*) and discuss the laundry list of proposed **collisionless mechanisms** that have been proposed to explain them.

- Hopefully collecting this stuff all in one place will help prod the theorists (including myself!) to find the best ways to move forward.

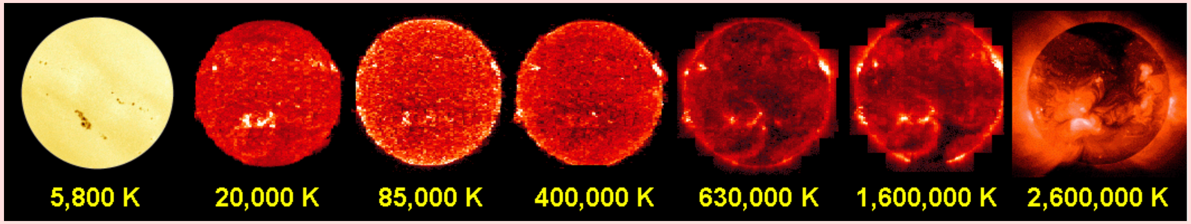


Looking forward to next month . . .   Image credit: M. Druckmüller (2008), with some processing by SRC

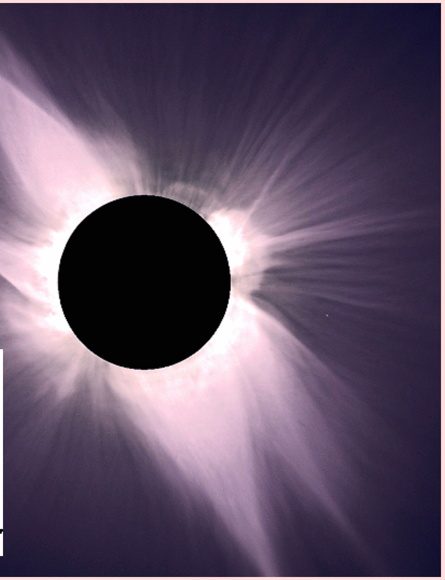
Remote sensing

- Probing coronal holes with photons is a challenge: (1) Low densities = low photon counts. (2) Difficult to interpret optically-thin emission over long lines of sight.

- On-disk measurements help reveal **basal** coronal heating & lower boundary conditions for solar wind.

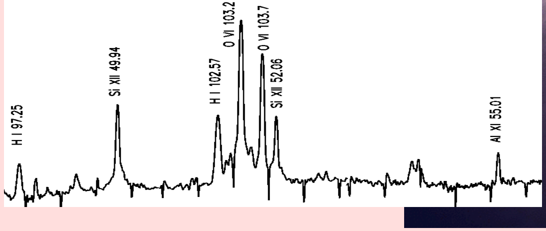


- Off-limb measurements (in the **solar wind “acceleration region”**) allow dynamic non-equilibrium plasma states to be followed as the asymptotic conditions at 1 AU are gradually established.



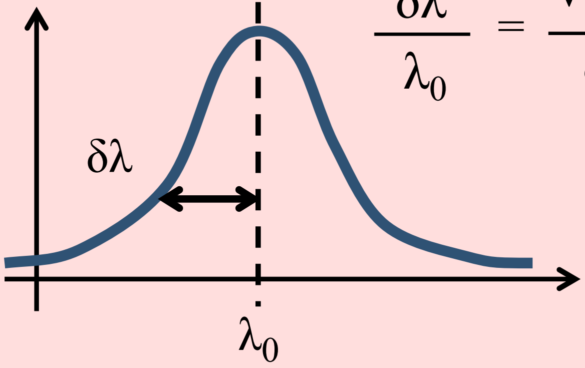
Occultation is required because extended corona is 5 to 10 orders of magnitude less bright than the disk!

Spectroscopy provides detailed plasma diagnostics that imaging alone cannot.



The power of UV coronagraph spectroscopy

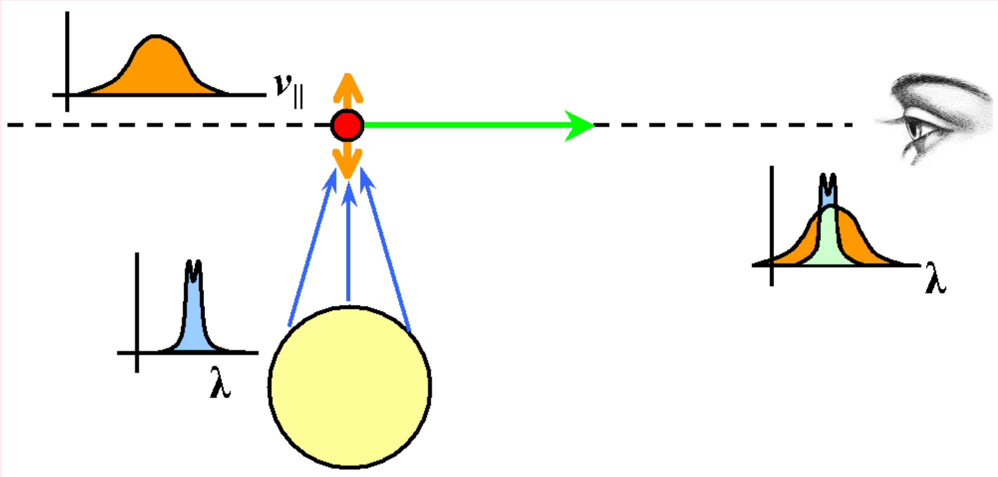
- Spectral lines are the true powerhouse of plasma diagnostics, and ultraviolet wavelengths are key because that’s where most emission at ~10^6 K happens.



$$\frac{\delta\lambda}{\lambda_0} = \frac{V_{LOS}}{c}$$

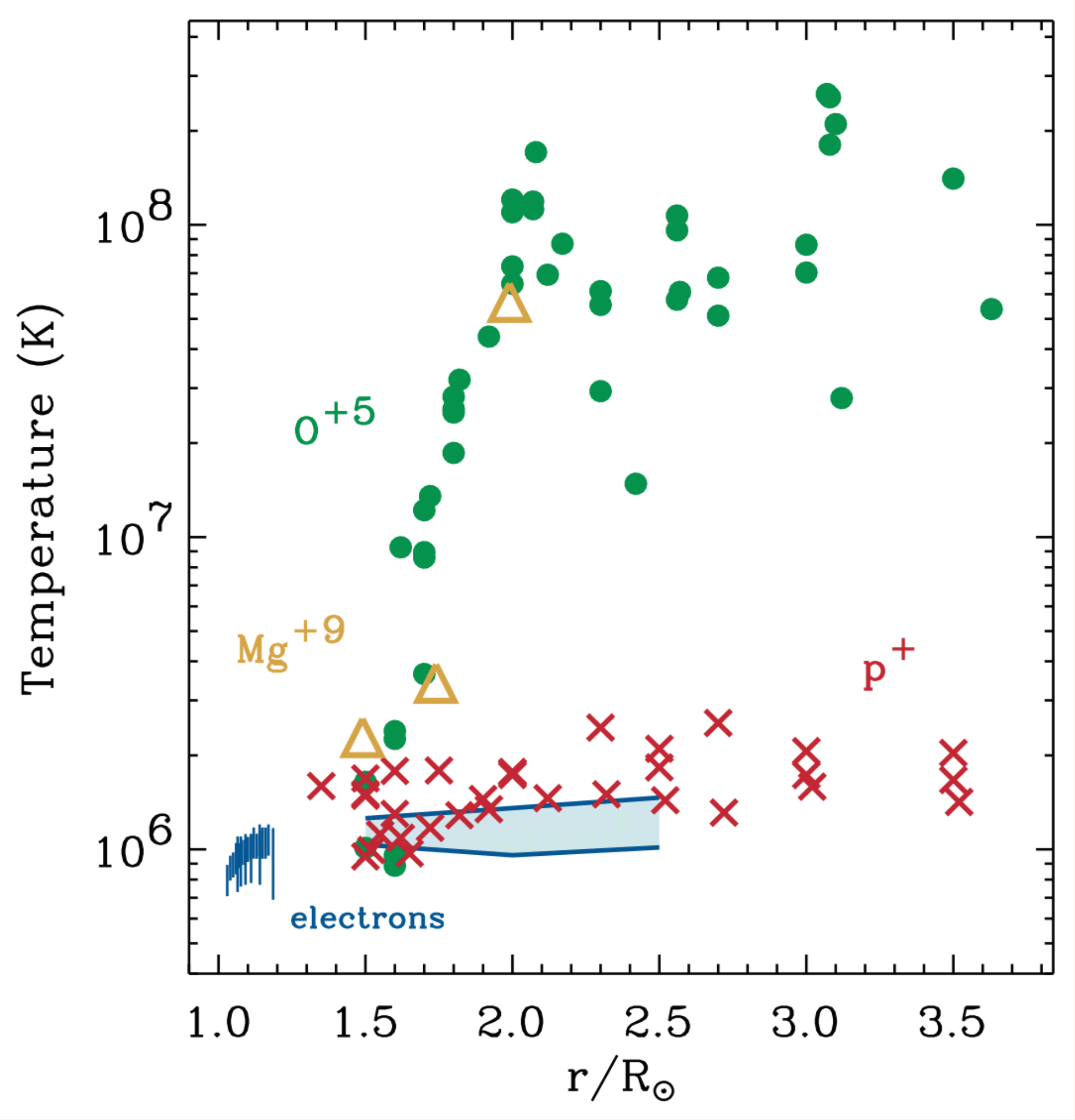
- If line profiles are Doppler shifted up or down in wavelength (from known rest wavelength), this gives **bulk flow speed** along line of sight.
- The widths of the profiles tell us about unresolved (“random?”) motions along the line of sight: **temperatures & MHD waves.**

- For scattering lines, the total # of photons scattered depends on how well the radial velocity distribution lines up with the narrow source of photons.
- “Doppler dimming” can help tell us about **velocities transverse to the line of sight.**

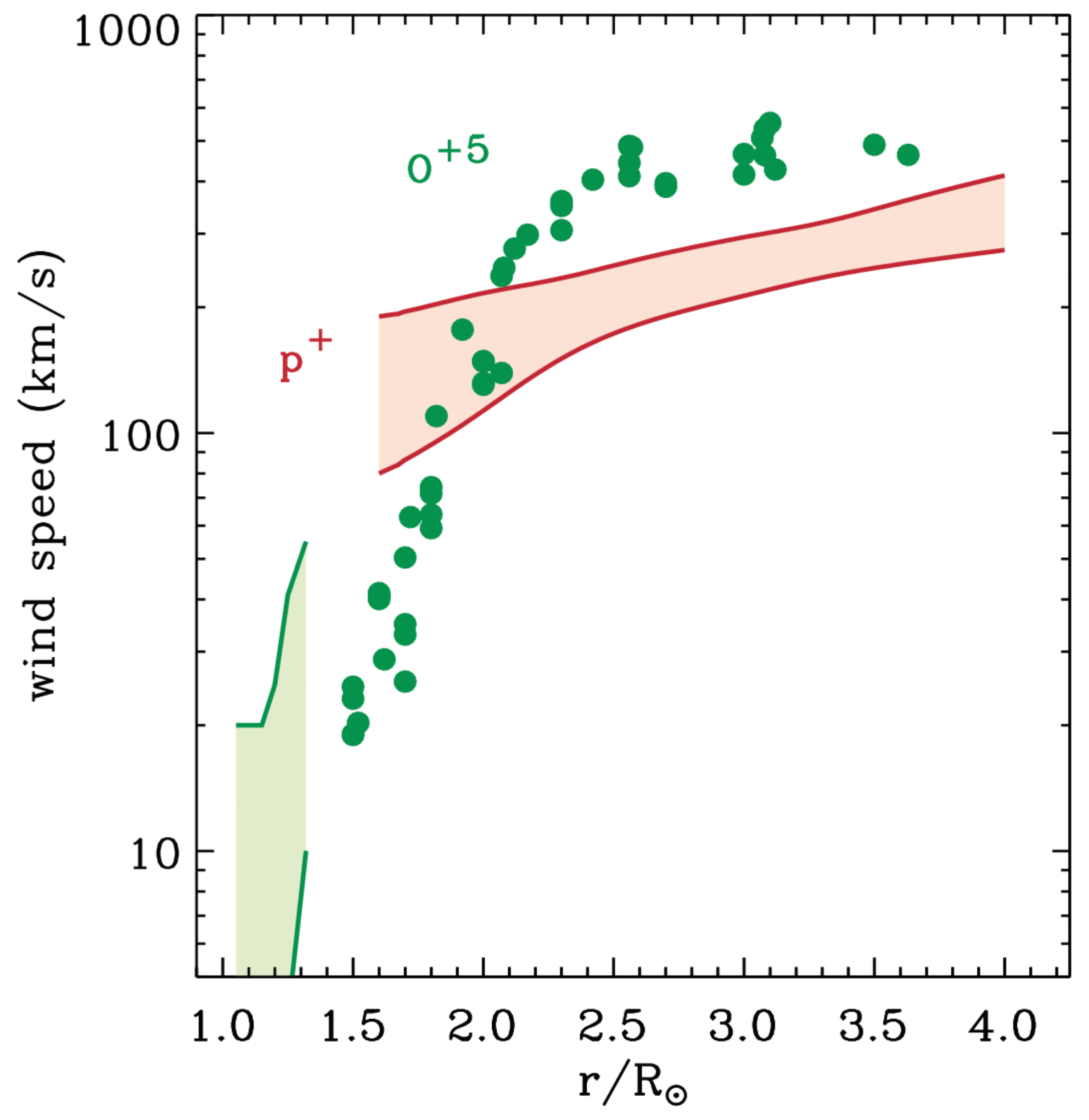


UVCS preferential ion heating & acceleration

- The *SOHO* Ultraviolet Coronagraph Spectrometer (UVCS) (Kohl et al. 1995, 1997, 2006) probed ion properties at large heights in coronal holes.
- Most surprisingly, O^{+5} ions have temperatures >100 MK **(hotter than the solar core!)**
- Mg^{+9} data in coronal holes are preliminary; higher-sensitivity measurements are needed to confirm.
- Ion temperatures shown: $T_\perp$ (from line widths), with modeled "wave sloshing" subtracted out.



UVCS preferential ion heating & acceleration



- UVCS also found that O^{+5} ions flow out with bulk speeds ~double that of the proton/electron plasma.

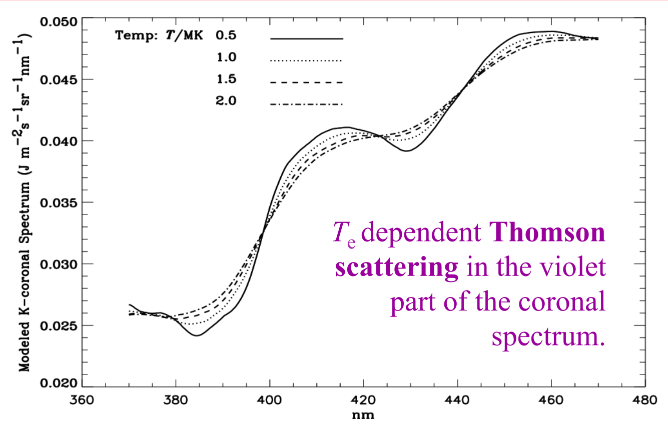
- Similar O^{+5} properties were also found in **helmet streamers** at larger heights ($r > 5\ R_s$), which is presumably where that plasma becomes collisionless.

- In general:

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

Proton vs. electron heating

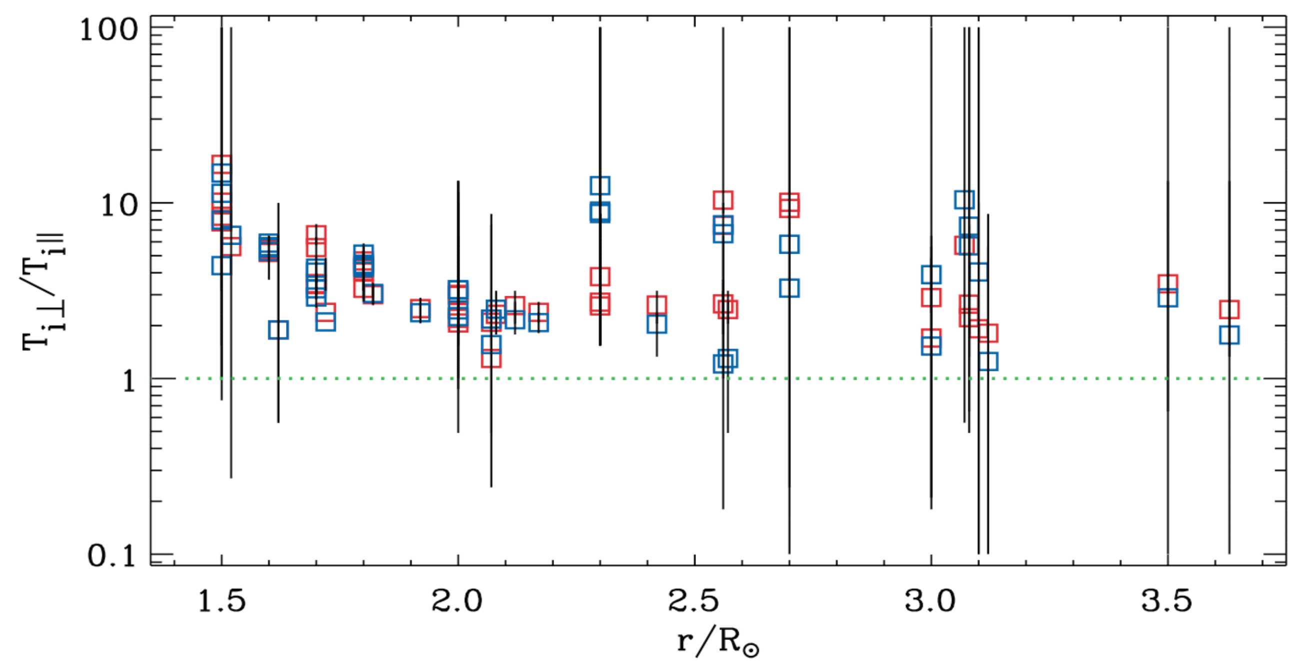
- The above figure shows that $T_{\perp p}$ is *slightly* bigger than T_e, which is similar to what's seen *in situ* in high-speed streams (see below).
- Electron temperatures are difficult to measure in the extended corona!
- The blue T_e region shown above was estimated via the **dynamical scale height technique** – i.e., solving an empirical version of the momentum equation for T_e, given observations for all other terms (see, e.g., Guhathakurta et al. 1992, 1999; Zidowitz 1999; Lemaire & Stegen 2016).
- This also required a more involved Doppler-dimming analysis for the UVCS H I Lyα data, which used mass-flux conservation to put better constraints on the proton anisotropy ratio $T_{\perp p} / T_{\parallel p}$ (Cranmer et al. 201?, in prep).
- Better T_e measurements may come from narrow-band-filter coronagraphs (e.g., Reginald et al. 2000, 2011, 2014).



T_e dependent **Thomson scattering** in the violet part of the coronal spectrum.

Heavy ion temperature anisotropy

- The early (pre-2000) UVCS data analysis indicated O^{+5} temperature anisotropy ratios $T_\perp/T_\parallel$ of order 10 to 100.
- There were also claims that the data were compatible with no anisotropy at all (Raouafi & Solanki 2004).
- Like with many things, the real answer turned out to be in between the extremes. These disagreements spurred much more rigorous data analysis (Cranmer et al. 2008) that found the data definitely incompatible with isotropy, but also incompatible with extreme anisotropy ratios of order 100…



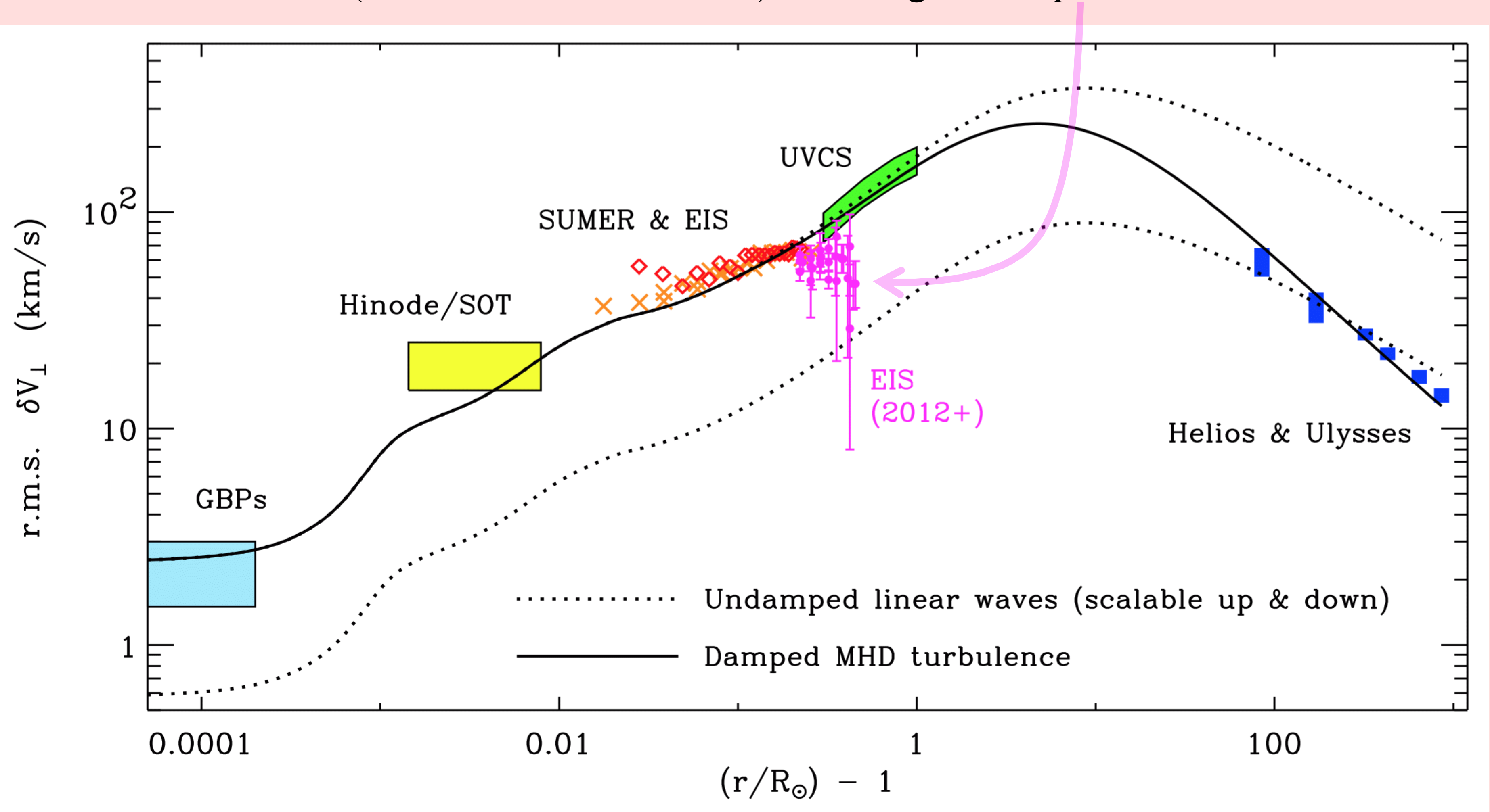
Error bars are large, but $T_\perp/T_\parallel$ really seems to hover around values of

~3 to 10

with not much discernible radial dependence

Alfvénic turbulence: combined remote & in situ

- Additional information from kinematic motions, line broadening, and direct particle/field detection puts constraints on the velocity amplitude of MHD waves.
- Cranmer & van Ballegooijen (2005) found evidence for large-scale wave damping, but Hahn & Savin (2012, 2013; and others) challenged this picture; still unresolved.



In situ particle & field detection

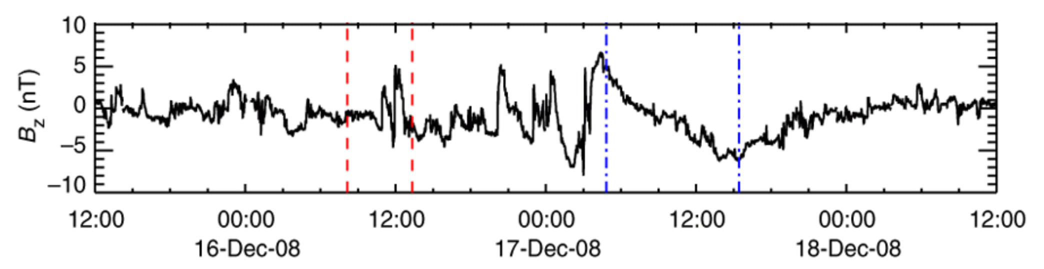
- Direct measurement of E & B fields & particles (speed, density, temperature, etc.)

- Particles: { mass spectrometers
Faraday cups
electrostatic analyzers } ... collect charged particles (from a given solid angle, in a certain kinetic energy range) & convert them to currents.

- If enough energies & angles collected, one gets the velocity distribution function.
- Collisionless space plasmas show **departures** from equilibrium Maxwellians.

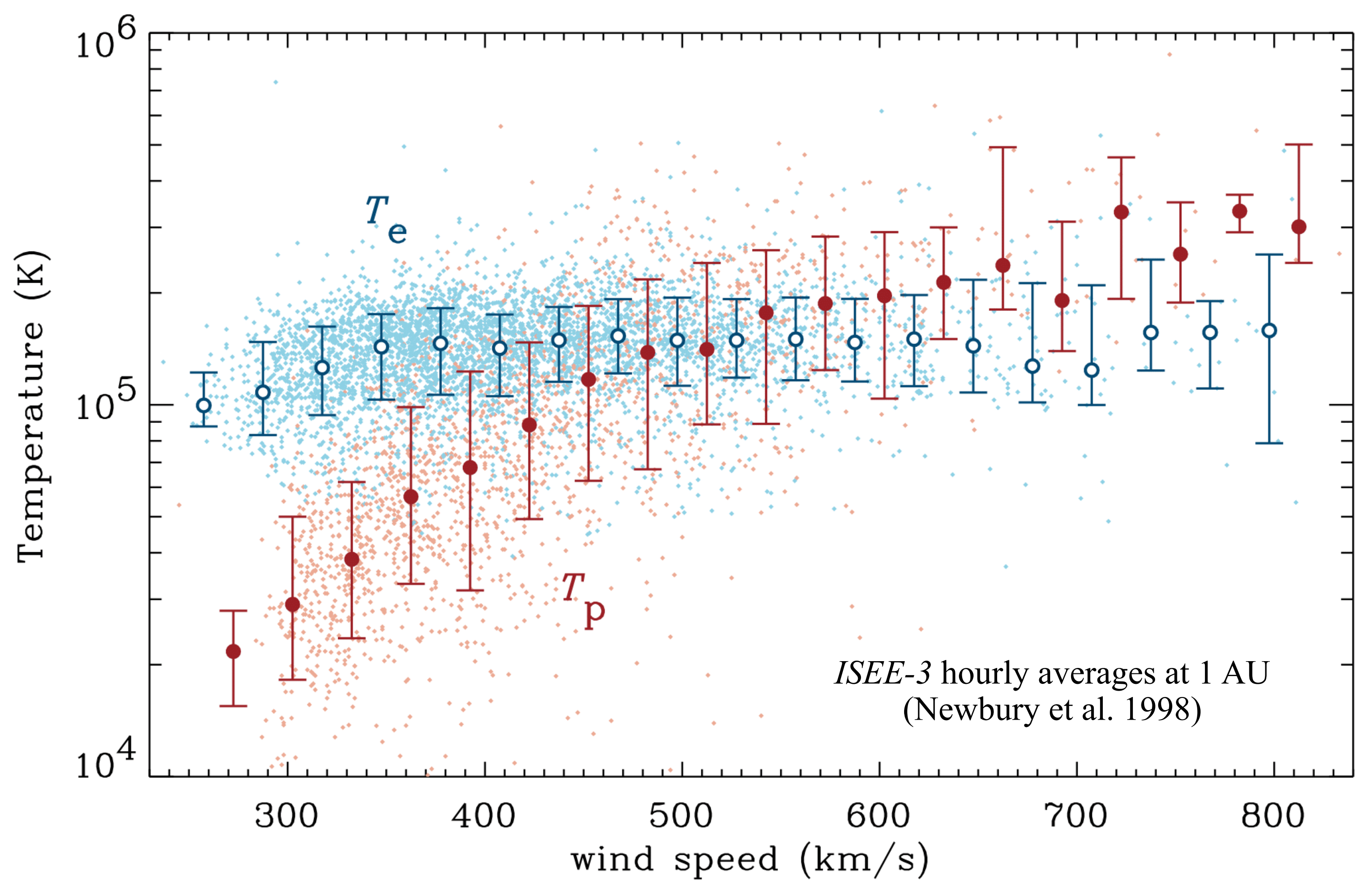
- **Challenge:** how to disentangle spatial/time fluctuations in single-point data?

- **Taylor's hypothesis:** "eddies" flow past spacecraft much more rapidly than they evolve (i.e., ~all variation is spatial)



Proton & electron heating

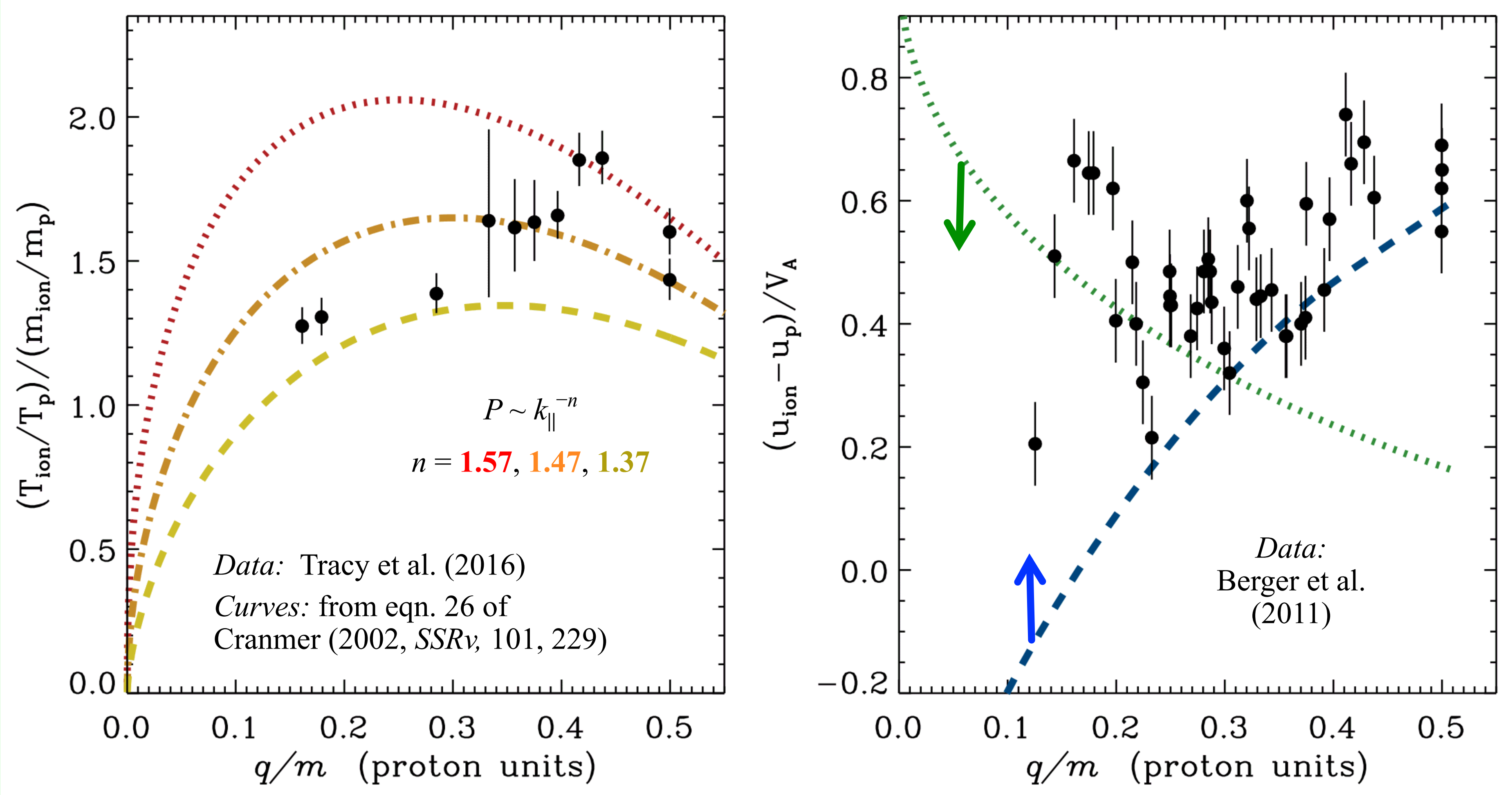
- In slow wind, strong electron heat conduction keeps T_e high (closer to its coronal origins), while weaker proton conduction allows them to cool off rapidly.
- In fast wind, there must be additional proton heating to enable $T_p > T_e$ (see also Freeman 1988; Stawarz et al. 2009; Elliott et al. 2012).



ISEE-3 hourly averages at 1 AU
(Newbury et al. 1998)

Heavy ions: preferential heating & acceleration

- Data from SWICS & SWEPAM on *ACE*. Model curves illustrate difficulties in explaining data with a single kinetic theory (see Cranmer et al. 2017 for details). (a) Heating-rate prediction from a turbulent power spectrum in ion cyclotron resonance. (b) Min/max ion-cyclotron resonant speeds for **$k_{\|}>0$** and **$k_{\|}<0$**.

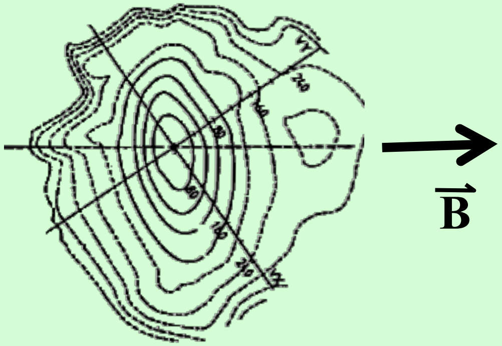


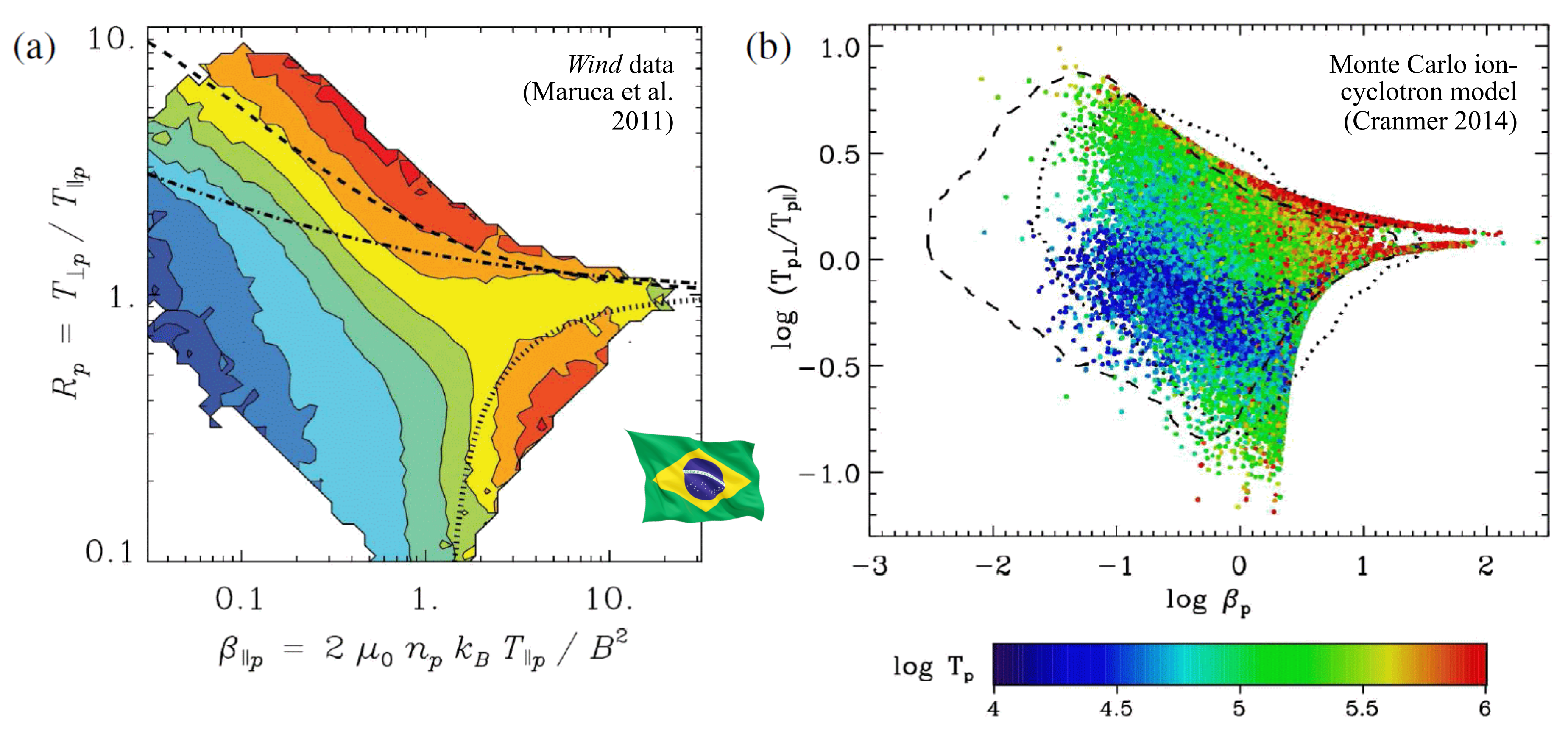
Data: Tracy et al. (2016)
Curves: from eqn. 26 of Cranmer (2002, *SSRv,* 101, 229)

Data:
Berger et al.
(2011)

Proton temperature anisotropy

- *Helios* probed $T_\perp \neq T_\parallel$ close to the Sun (Marsch 1991).
- *Wind* & other 1 AU spacecraft gathered much better data to show what regions of parameter space are occupied.
- Plasma instabilities create boundaries on the right; coronal history creates boundaries on the left…



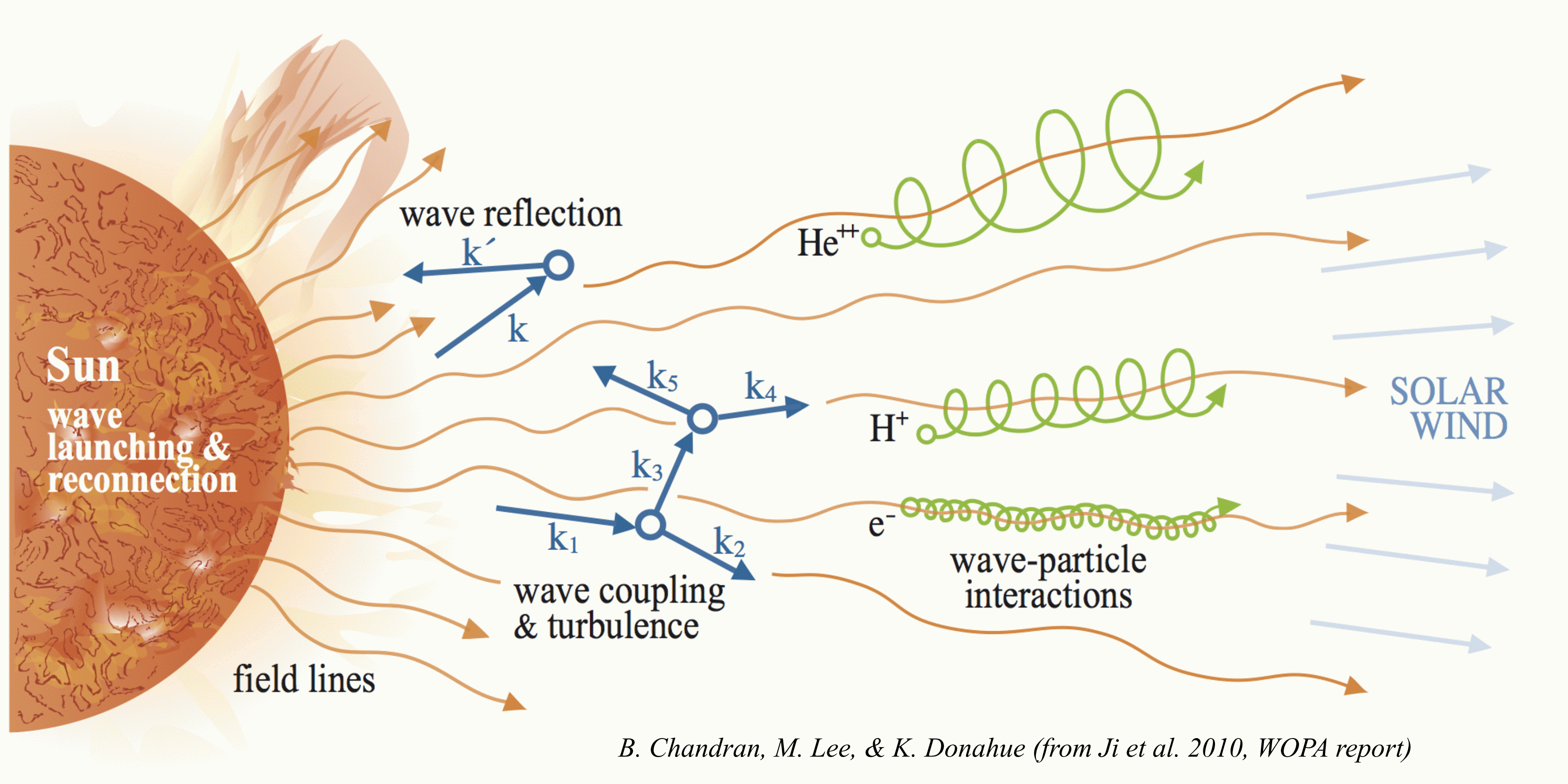


Wind data (Maruca et al. 2011)

Monte Carlo ion-cyclotron model (Cranmer 2014)

Proposed theoretical explanations

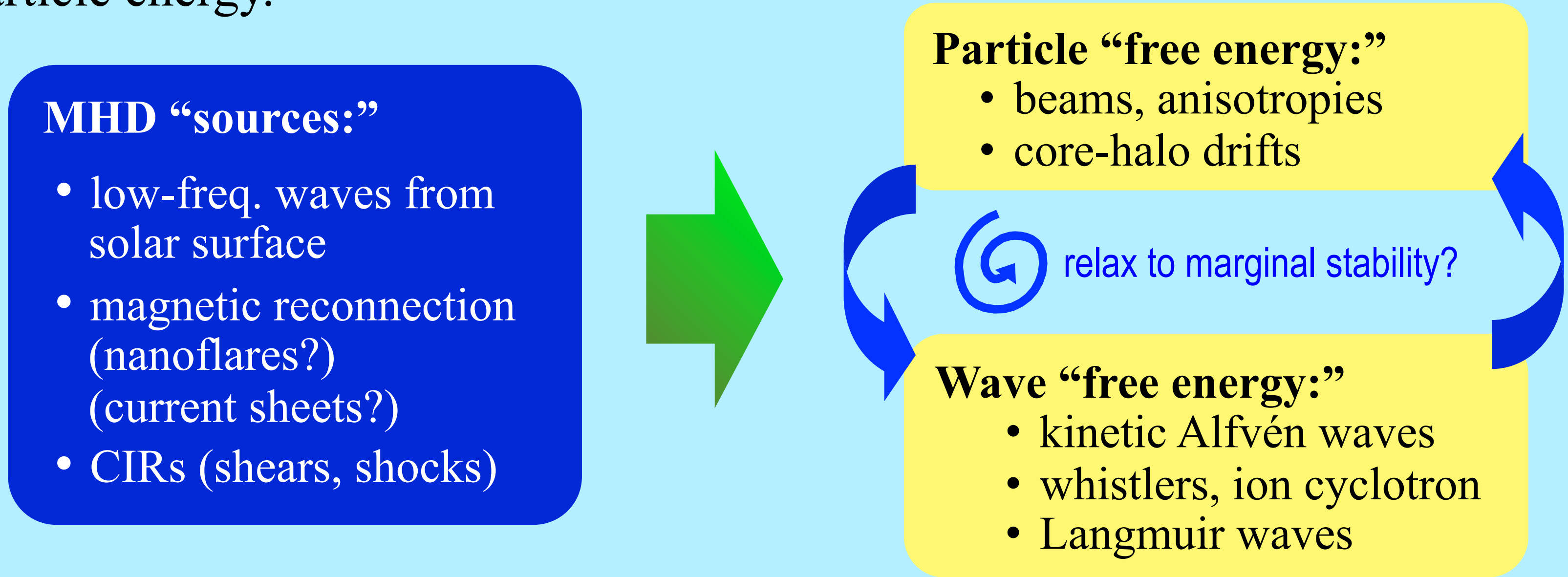
- There are quite a few mechanisms that can energize ions up to “equal thermal speeds” (i.e., $T_{\rm ion}/m_{\rm ion} = T_p/m_p$), but it’s more difficult to identify processes that give $T_{\rm ion}/m_{\rm ion} > T_p/m_p$.
- Nevertheless, since the 1970s, many ideas have been explored that involve Sun-generated fluctuations being **damped,** & their energy going into particles...



B. Chandran, M. Lee, & K. Donahue (from Ji et al. 2010, WOPA report)

Proposed theoretical explanations

- Most proposed "wave dissipation" mechanisms are stronger when the damped fluctuations have higher frequencies and/or smaller wavelengths.
- This points to turbulent cascade (big eddies make small eddies...) as a natural way to make the small scales.
- In collisionless regions, **wave-particle resonances** can act like quasi-collisions to provide a (statistically averaged) transfer from wave energy to "thermal" particle energy.



MHD "sources:"

- low-freq. waves from solar surface
- magnetic reconnection (nanoflares?) (current sheets?)
- CIRs (shears, shocks)

Particle "free energy:"

- beams, anisotropies
- core-halo drifts

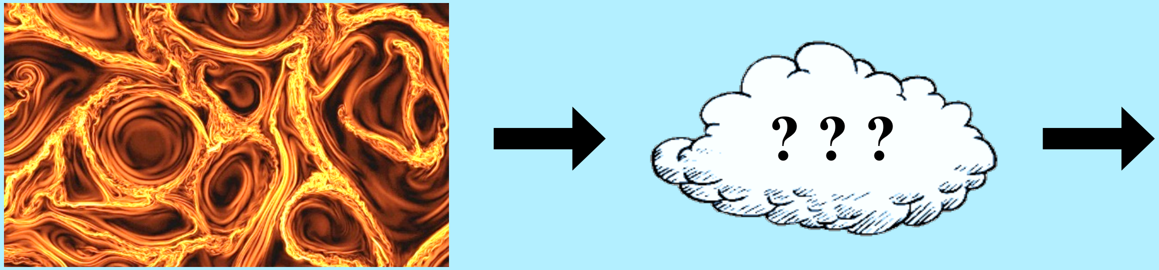
relax to marginal stability?

Wave "free energy:"

- kinetic Alfvén waves
- whistlers, ion cyclotron
- Langmuir waves

- **Problem:** In the low-β corona, the most straightforward models of MHD turbulence predict a cascade toward KAWs that linearly damp to provide parallel electron heating. We see the exact opposite: perpendicular ion heating!

Can turbulence account for the kinetic data?



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Maybe, but there must be some nonlinear / intermediary processes...

- If **ion cyclotron waves** somehow propagate up into the corona & solar wind (e.g., parallel cascade?) they can efficiently heat ions (Hollweg & Isenberg 2002; Marsch 2006; Cranmer 2001, 2014; Isenberg & Vasquez 2015).
- 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, they may fill the extended corona with electron beams that become unstable and produce other modes that heat ions (Markovskii 2007; Che et al. 2014).
- If kinetic Alfvén waves reach large enough amplitudes, they can damp via **stochastic heating** to energize ions (Voitenko & Goossens 2006; Wu & Yang 2007; Chandran 2010).
- Kinetic Alfvén wave damping in the extended corona could lead to electron beams, Langmuir turbulence, and Debye-scale **electron phase space holes** which could heat ions perpendicularly (Matthaeus et al. 2003; Cranmer & van Ballegooijen 2003).

Conclusions

- There's no shortage of theoretical ideas for explaining how particles are heated in the ~collisionless parts of the corona and heliosphere.

- We still do not have complete enough **observational constraints** to be able to choose between competing theories, but hopefully this poster has helped to serve as a reference point for the observations we do have.

- Apologies about not including a reference list. Contact me, or see:

  Kohl, J. L., et al. 2006, *A&A Review,* 13, 31
  Cranmer, S. R. 2009, *Living Reviews in Solar Phys.,* 6, 3
  Cranmer, S. R. 2014, *ApJ Suppl.,* 213, 16
  Cranmer, S. R., Gibson, S. J., & Riley, P. 2017, *SSRv,* under review

SOLAR HELIOSPHERIC & INTERPLANETARY ENVIRONMENT

SHINE

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