Stellar and solar winds…

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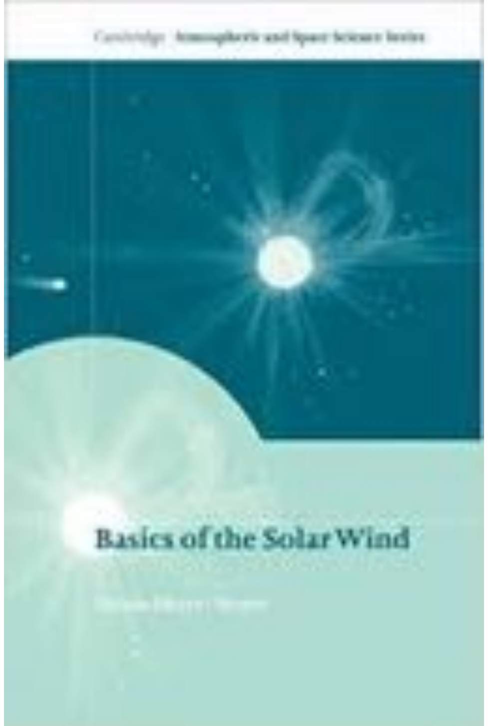
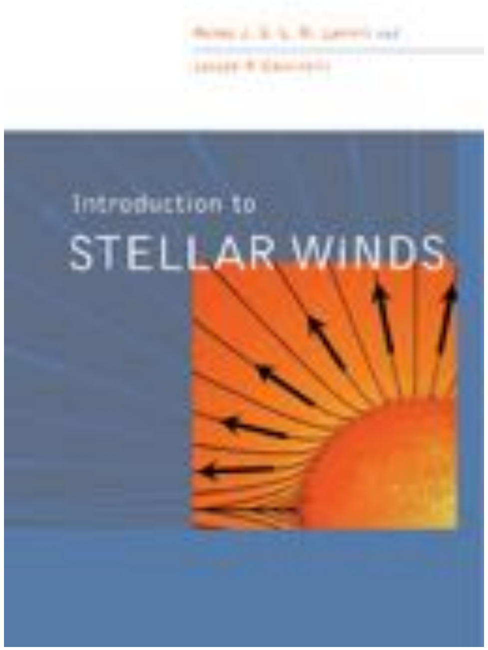
Basics of the Solar Wind, Meyer-Vernet

Intro to Stellar Winds, Lamers & Cassinelli





Solar Wind Kinetic Physics and the NASA Parker Solar Probe mission

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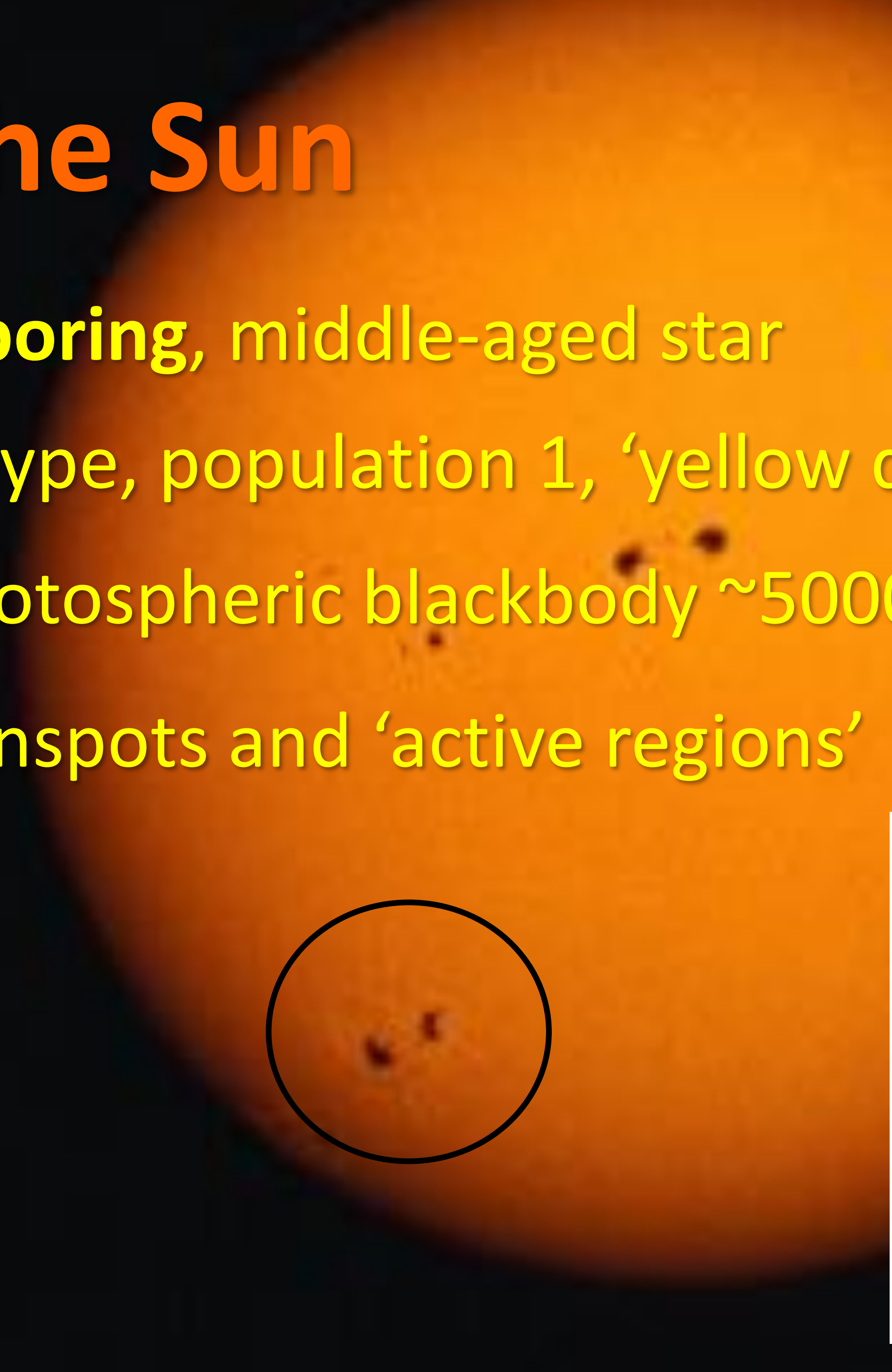
Berkeley
UNIVERSITY OF CALIFORNIA

Outline

1. Some solar wind history and concepts
2. A little bit about turbulent heating
3. The solar wind at 1 AU and beyond is more thermalized by collisions
4. As we go closer to the Sun, we should see more ‘plasma physics’ and intermittency
5. NASA Parker Solar Probe (PSP) will launch this summer (!) and enter the corona

The Sun

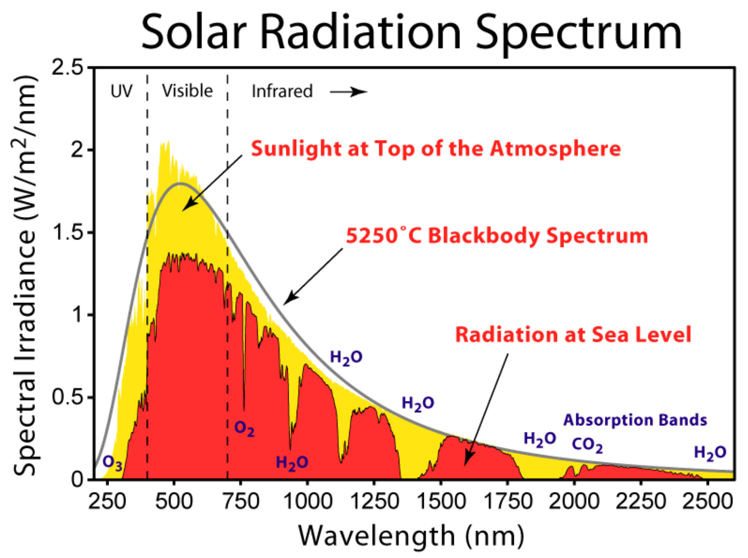


A **boring**, middle-aged star

G type, population 1, 'yellow dwarf'

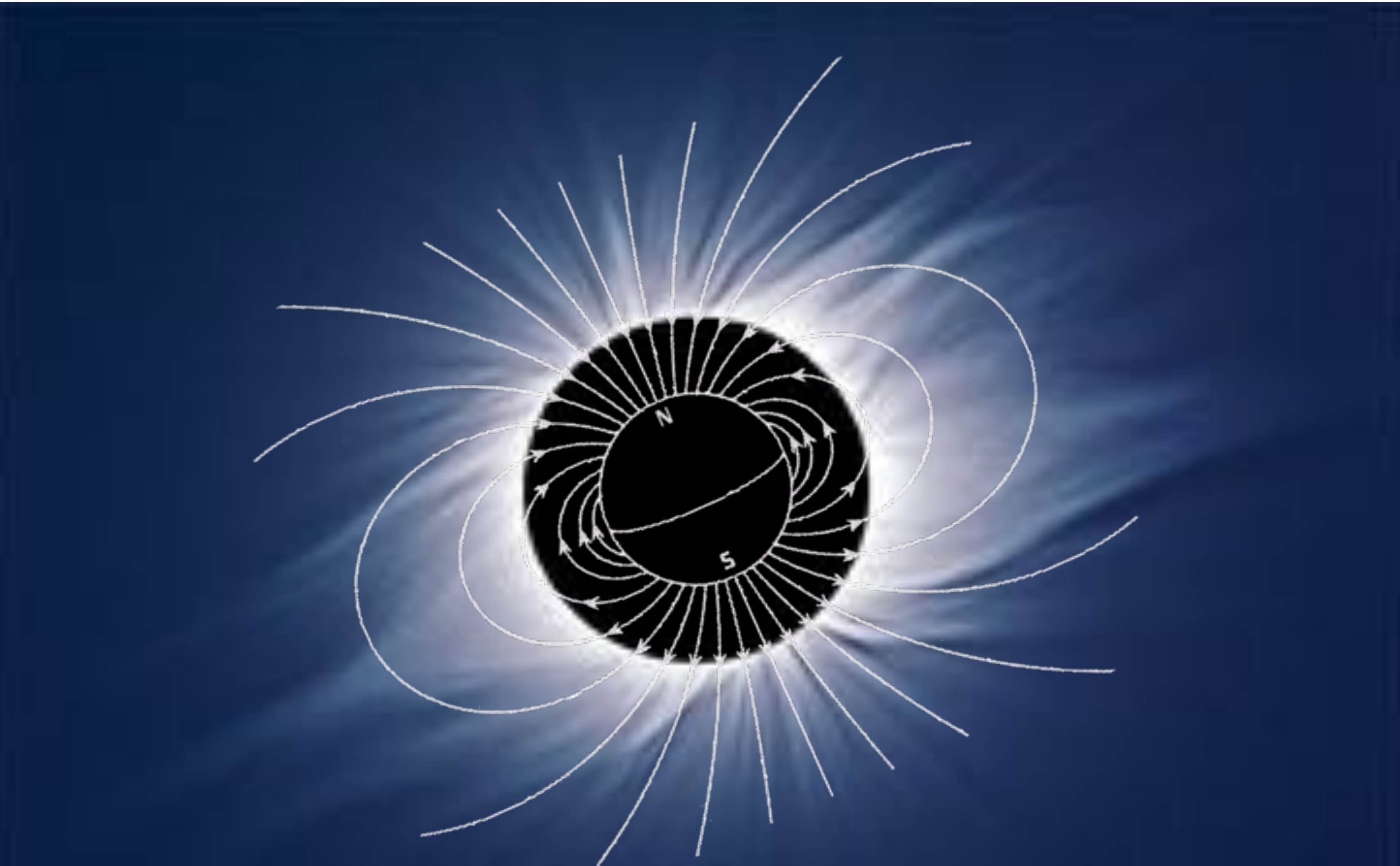
Photospheric blackbody ~5000-6000K

Sunspots and 'active regions'



The solar corona

The solar corona



The corona is very hot and magnetized

Scale height (H ~ kT/mg) is not consistent with simple hydrostatic equilibrium
- Using 6000 degrees C as a temperature, if the atmosphere is hydrogen then H = 175 km (110 miles)
- Instead, from the eclipses the scale height is clearly comparable to the radius of the Sun, or H = 695,500 km (430,000 miles)
- So the corona is very hot *or* we have some new, lighter elements ‘ coronium’

Alfvén (1941) estimated coronal brightness scale height (~2 R_s) and suggested hot ‘atmosphere’

Edlén (1942) identified line emission with highly ionized Fe implying electron temperatures of T >10^6 C – *temperature inversion!*

E corona – emission lines from ionized, heavy elements in the corona – UV-soft x-ray

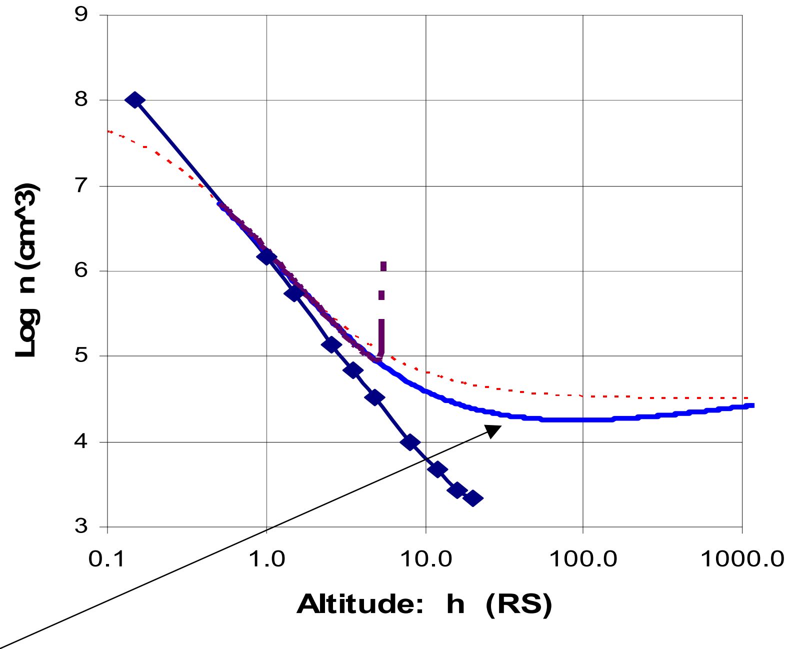
  - H and He are fully ionized – no emission
  - Minor ions are partially ionized
  - Polarization of emission lines gives line-of-sight magnetic field

Chapman’s solar ‘atmosphere’

Chapman (1957) assumed a static ‘atmosphere’ as a ideal gas in hydrostatic equilibrium

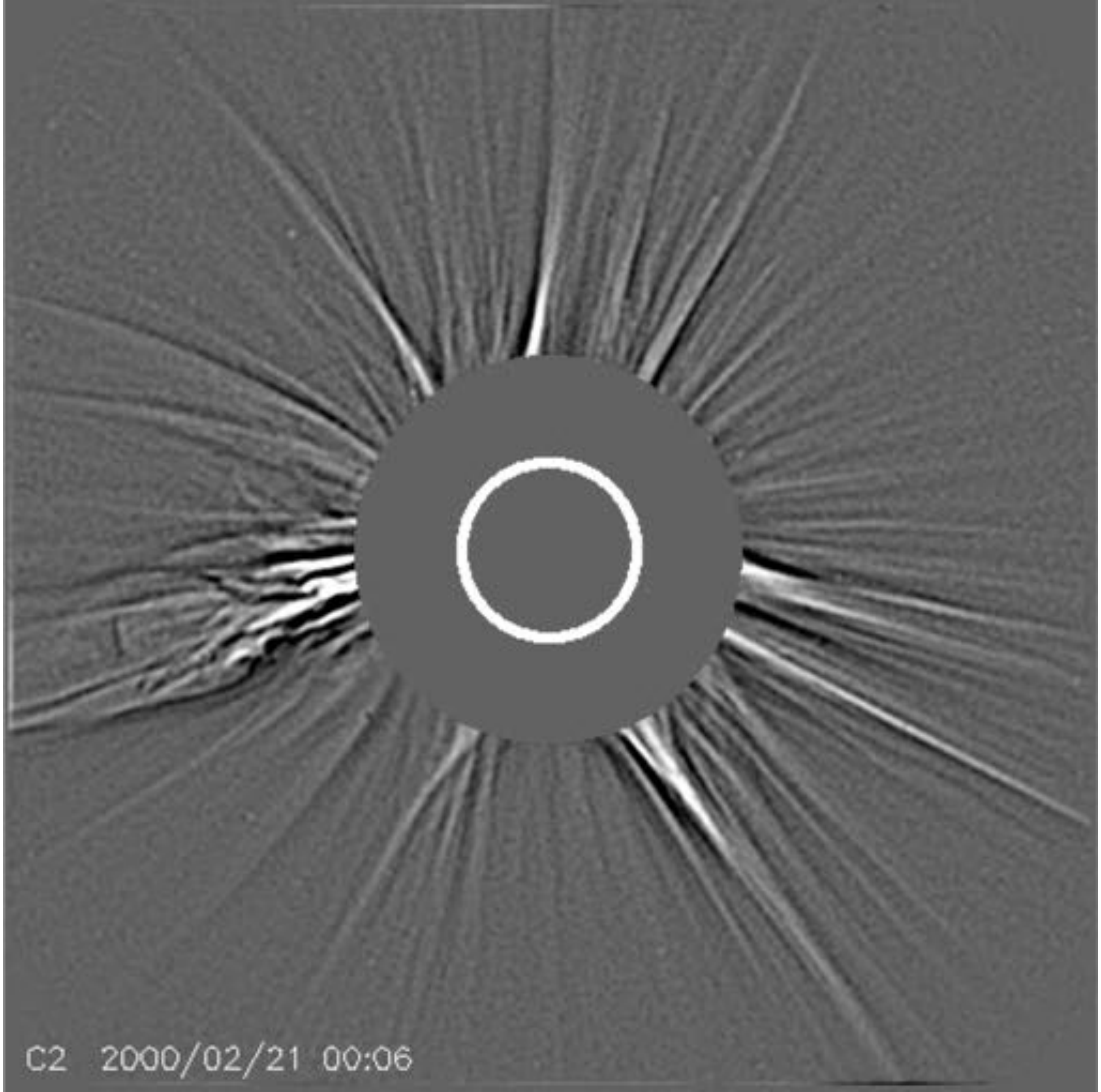
$$\frac{dp}{dr} = -\rho \frac{GM_s}{r^2}$$

Collisional heat flux and $\nabla \cdot q = 0$



This gives a density profile with a minimum at ~100 R_s which would be convectively unstable! The system is dynamic… Also too much pressure at heliopause

(figure: Lemaire)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Parker’s solar wind model

(Comet tails and boundary conditions)

$$\rho U r^2 = \dot{\mathrm{M}} \qquad p = c^2 \rho$$

$$U \frac{\partial U}{\partial r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{gR_s}{r^2}$$

$$\left(M - \frac{1}{M} \right) M' = \frac{2}{r} - \frac{gR_s}{r^2 c^2}$$

Can be integrated…(isothermal)

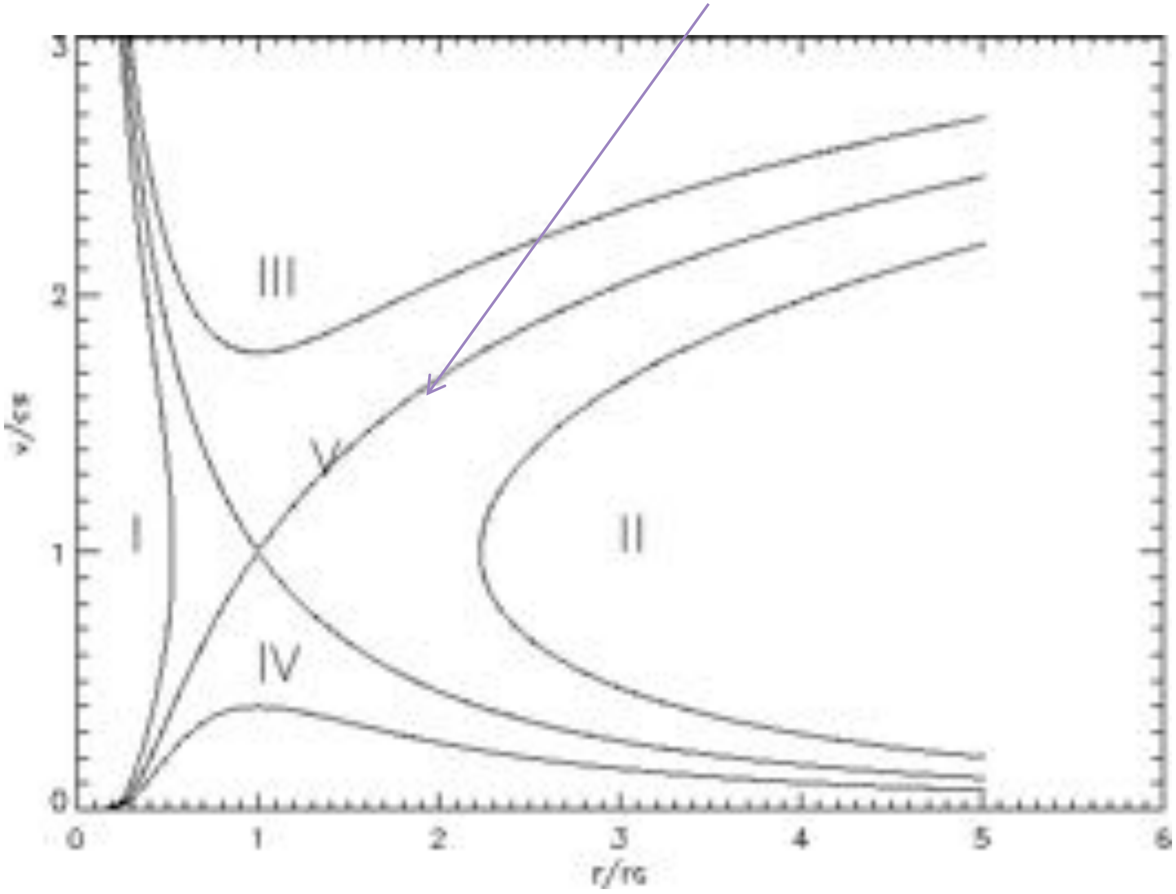
$$\frac{1}{2}\left(M^2 - M_0^2 \right) - \log\left(\frac{M}{M_0} \right) = 2\log r + \frac{gR_s}{c^2}\left(-1 + \frac{1}{r} \right)$$

$$\frac{1}{2}\left(M^2 - M_0^2 \right) + \log\left(\frac{p}{p_0} \right) = \frac{gR_s}{c^2}\left(-1 + \frac{1}{r} \right)$$

where M = U/c

Parker’s solar wind model

- Hydro solution (like Bondi accretion)
- Predicts a supersonic atmosphere ‘wind’
- Similar to ‘de Laval nozzle’ or a jet engine
- Requires energy input (gas pressure) at the base. kT_{ph} is not nearly enough!
- ‘Alfven point’ in magnetized plasma determines extent of corona - corotation


A ‘solar wind’ is accelerated from the corona

de Laval nozzle !

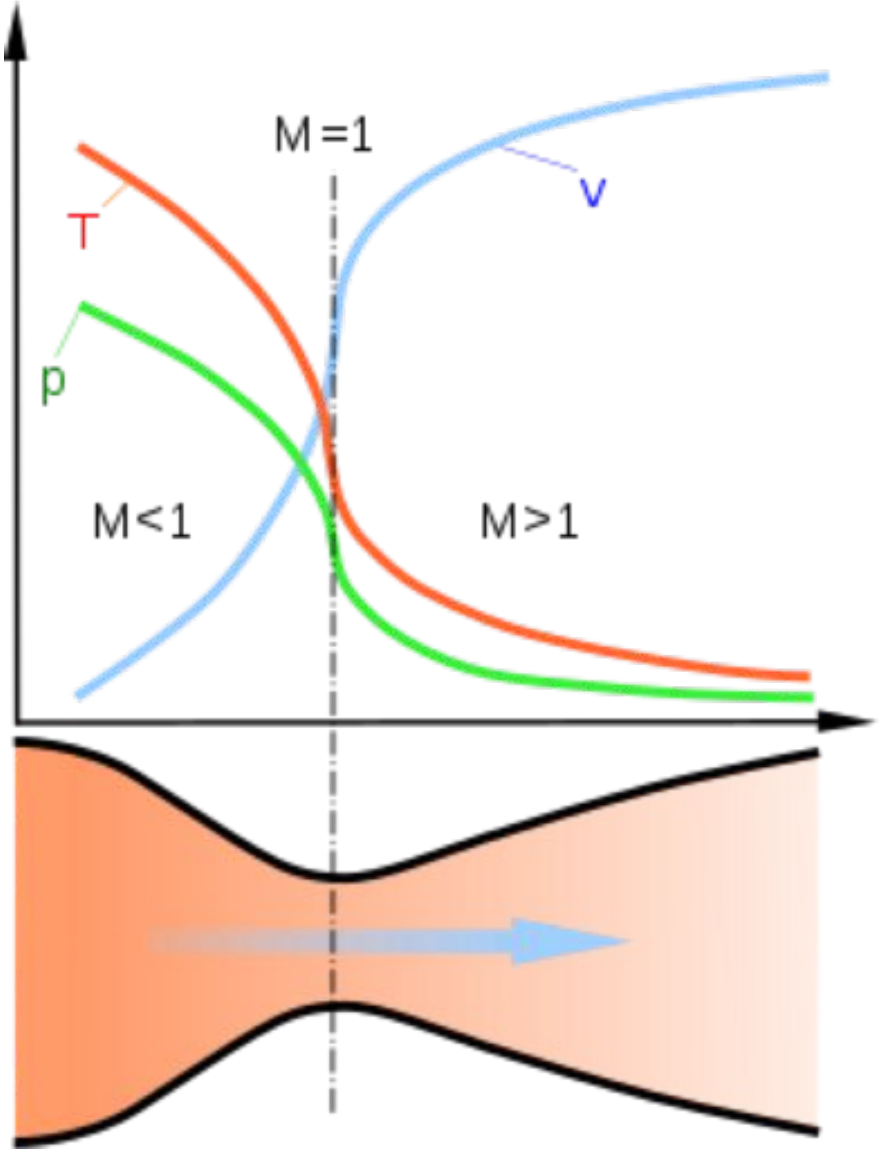
$$\rho \sigma w = const$$

$$\frac{d\rho}{\rho} + \frac{d\sigma}{\sigma} + \frac{dw}{w} = 0$$

$$\frac{dp}{d\rho} = c_s^2$$

$$\frac{d\sigma}{\sigma} + (1 - \frac{w^2}{c^2})\frac{dw}{w} = 0$$

with $\sigma = \sigma(x)$



Mariner 2 measurements

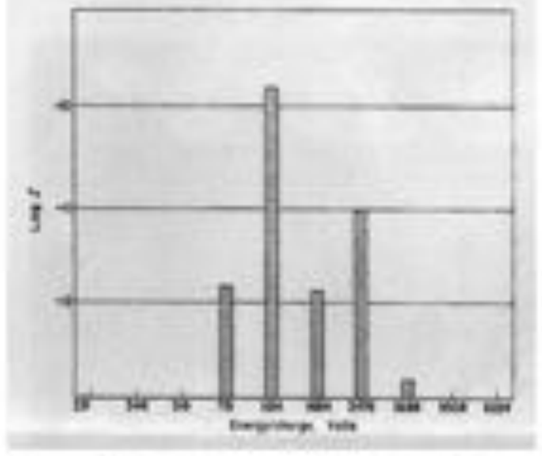


Figure 1. One of the better spectra obtained by the Mariner 2 solar wind spectrometer. The current I is given in amperes.

4476 NEUGEBAUER AND SNYDER

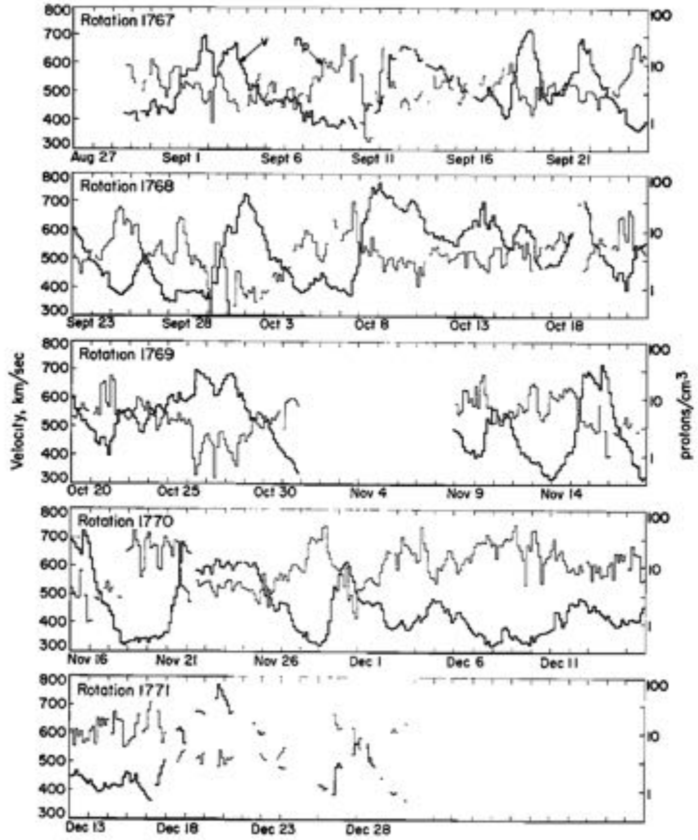


Fig. 5. 3-hour average values of plasma velocity v and proton number density n_p (logarithmic scale) versus time. The time base is chosen to show the 27-day-recurrence features associated with solar rotation.

Parker's solar wind is confirmed

The solar wind is highly variable

Solar wind acceleration profiles

'Fast' and 'slow' profiles

Fast wind is relatively uniform

Slow solar wind is impulsive

Minor ions show enhanced acceleration – field-aligned flow

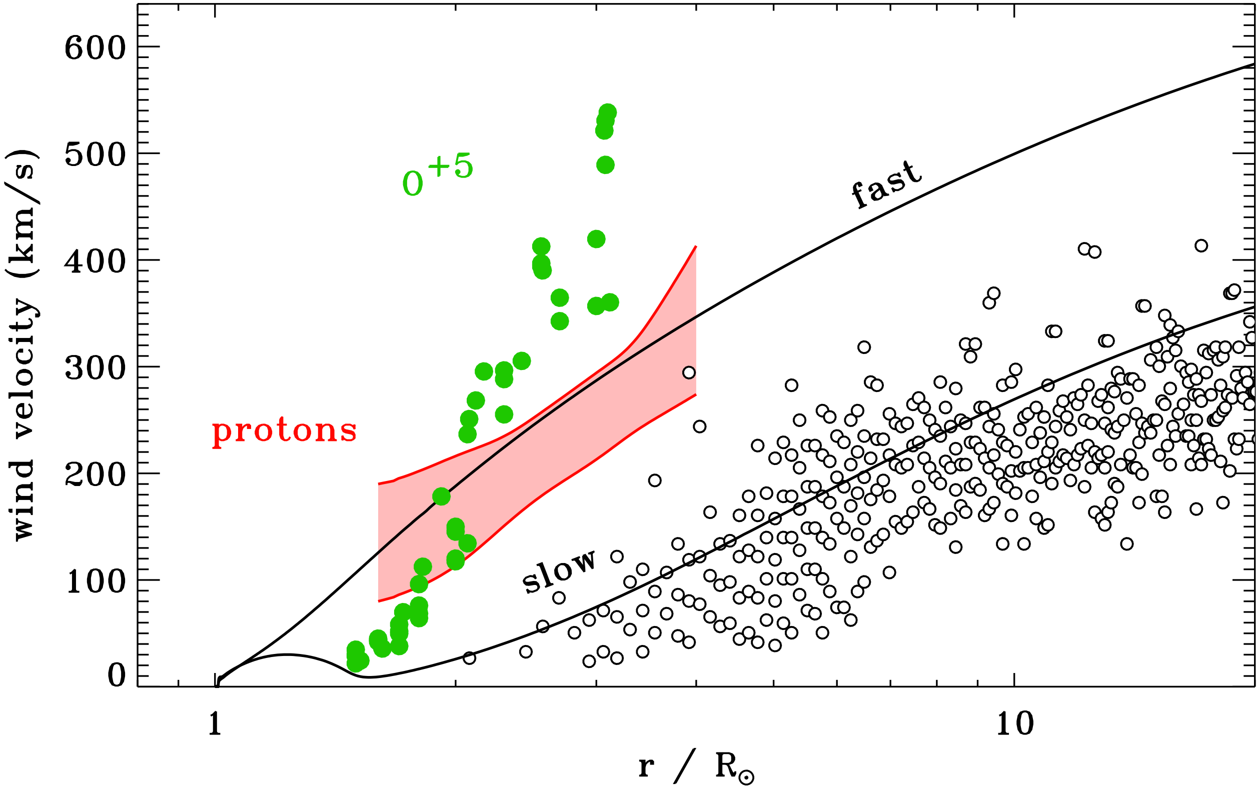


Figure 8: Radial dependence of solar wind outflow speeds. UVCS Doppler dimming determinations for protons (red; Kohl *et al.*, 2006) and O^{+5} ions (green; Cranmer *et al.*, 2008) are shown for polar coronal holes, and are compared with theoretical models of the polar and equatorial solar wind at solar minimum (black curves; Cranmer *et al.*, 2007) and the speeds of "blobs" measured by LASCO above equatorial streamers (open circles; Sheeley Jr *et al.*, 1997).

(Cranmer, 2009)

Solar wind temperature profiles

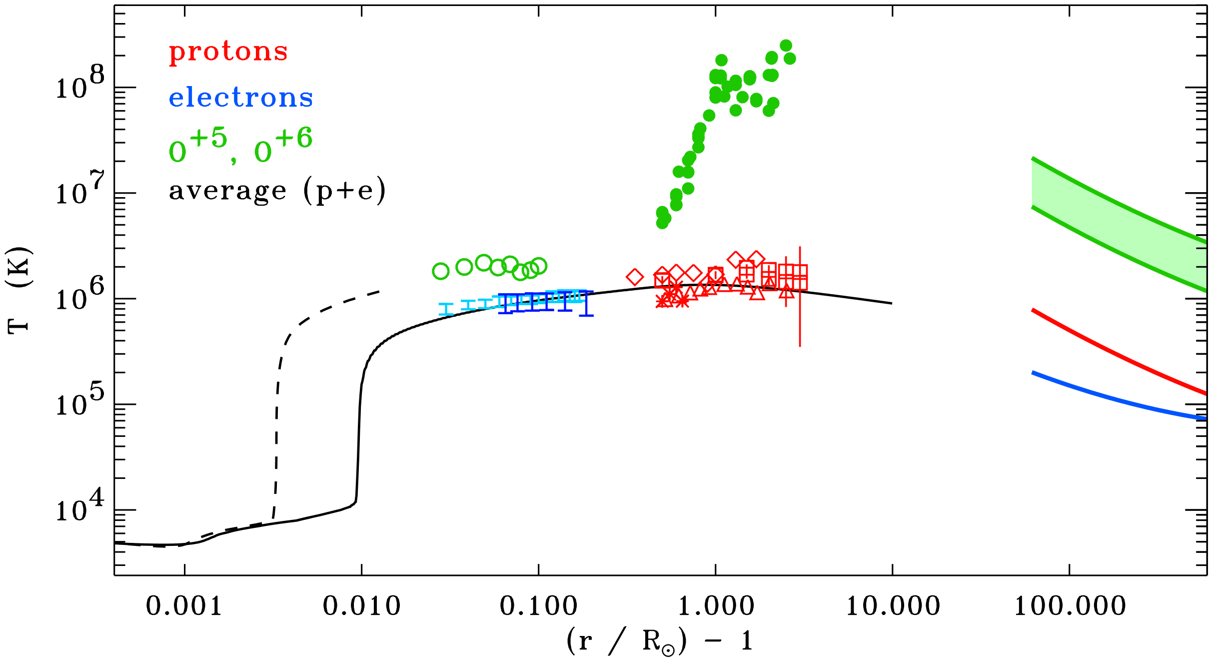
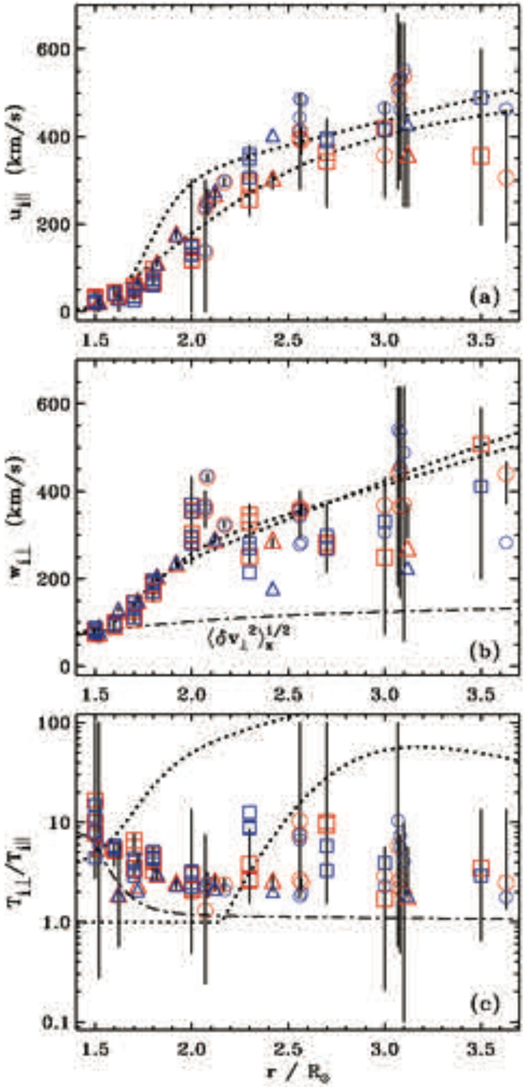


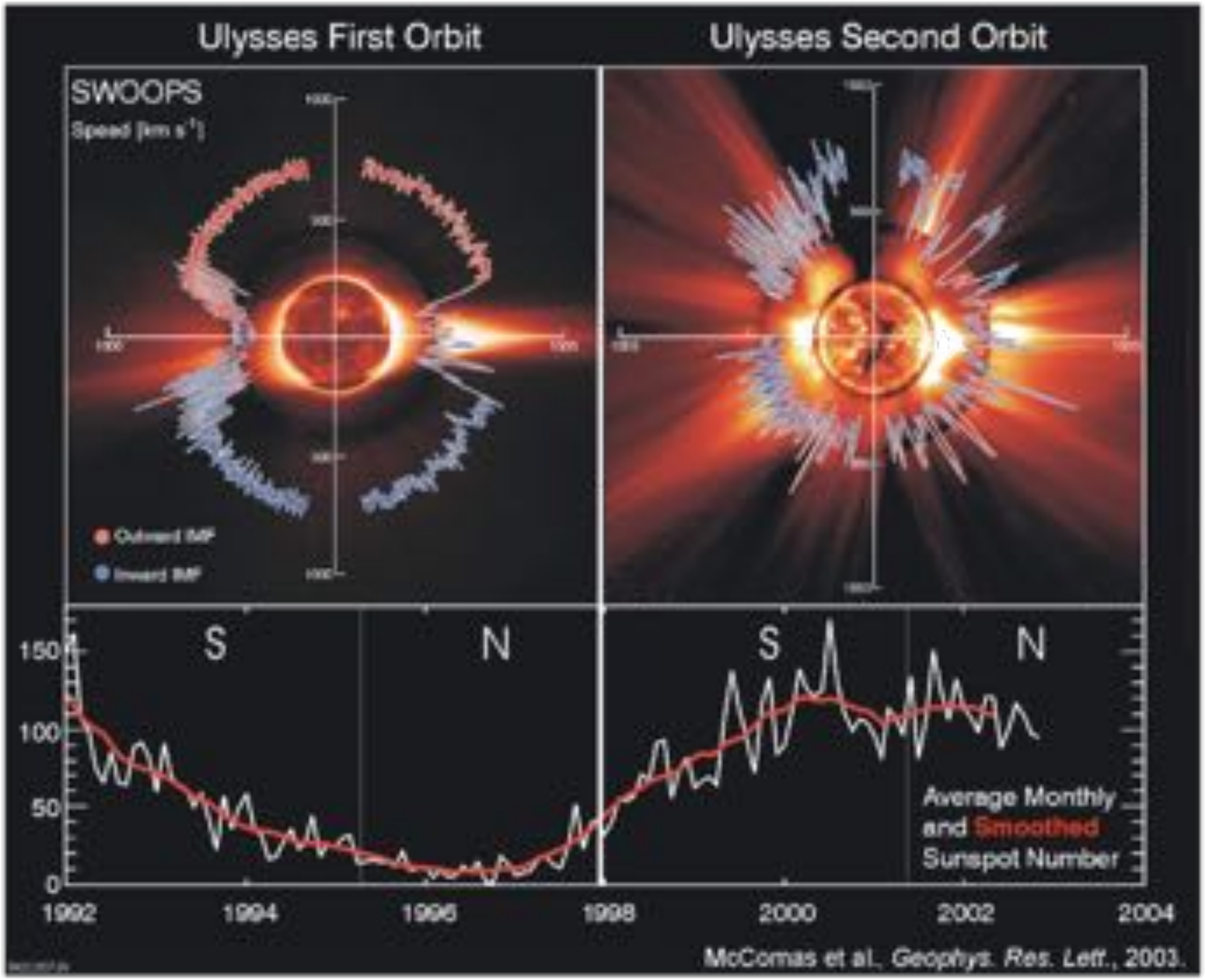
Figure 6: Radial dependence of empirical and model temperatures in polar coronal holes and fast w streams. Mean plasma temperatures from a semi-empirical model (dashed black curve; Avrett and Loe 2008) and from a turbulence-driven coronal heating model (solid black curve; Cranmer *et al.*, 2007). from off-limb SUMER measurements made by Wilhelm (2006) (dark blue bars) and Landi (2008) (li blue bars), T_p from UVCS measurements assembled by Cranmer (2004b) (see text), and perpendicular (ion temperatures from Landi and Cranmer (2009) (open green circles) and Cranmer *et al.* (2008) (fi green circles). In situ proton and electron temperatures in the fast wind ($r > 60\, R_\odot$) are from Cranı *et al.* (2009).



(Cranmer et al., 2008)

Minor ions are heated strongly and are primarily perpendicular to B (cyclotron res?). T/T of 10+ is huge!

The solar wind is bimodal



McComas et al., *Geophys. Res. Lett.*, 2003.

Fast wind (1 AU)

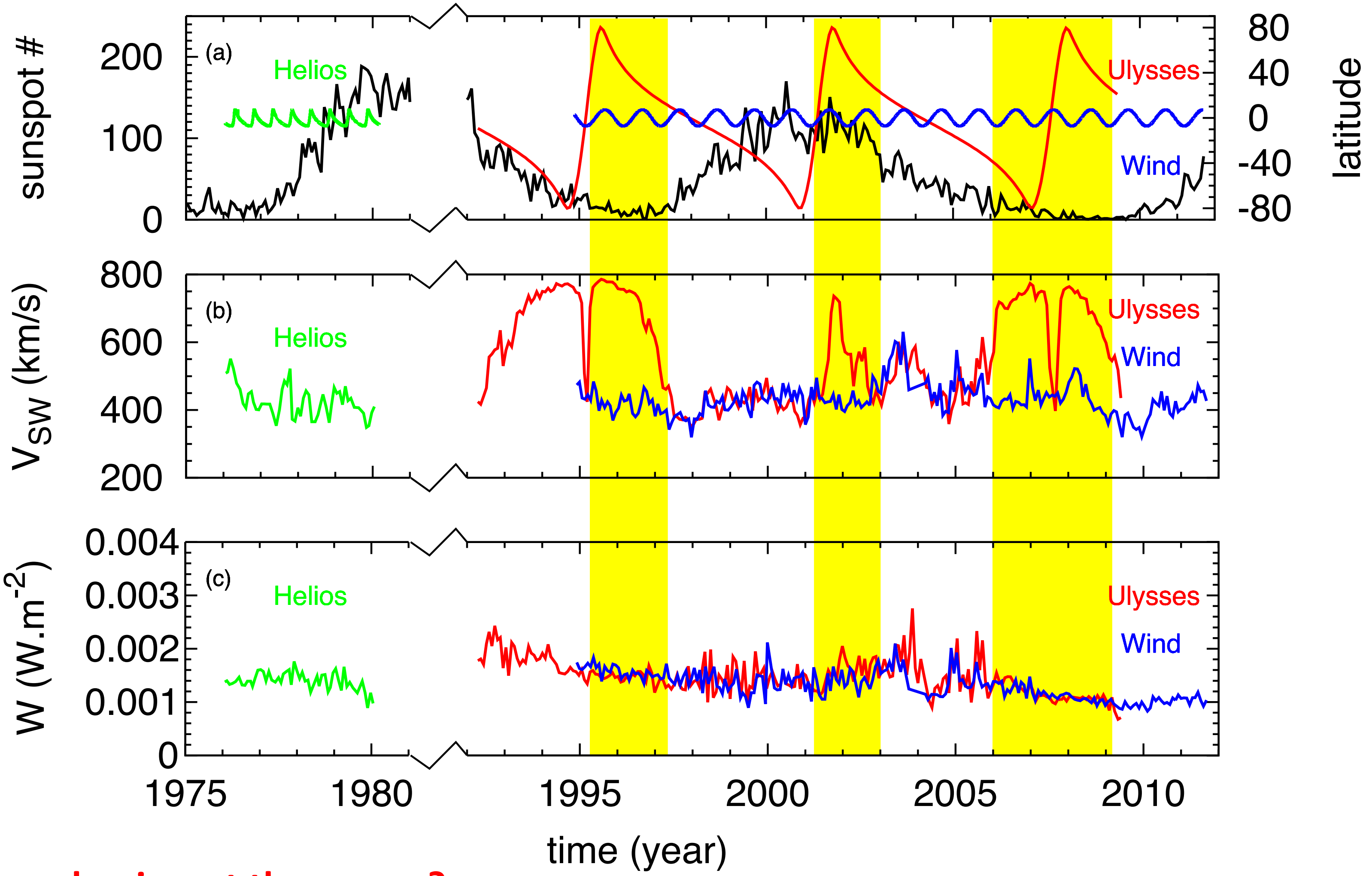
V_{sw} ~ 500-1000 km/s
T_p ~10-20 eV
T_e ~ 5-20 eV
n ~ 1-10 cm-3
B ~ 5 nT, δB is larger
β ~ 1

Slow wind (1 AU)

V_{sw} ~ 250-500 km/s
T_p ~5-20 eV
T_e ~ 5-20 eV
n ~ 5-25 cm-3
B ~ 5 nT
β ~ 1

Fast wind emerges from **coronal holes**, slow wind from **streamer belt**

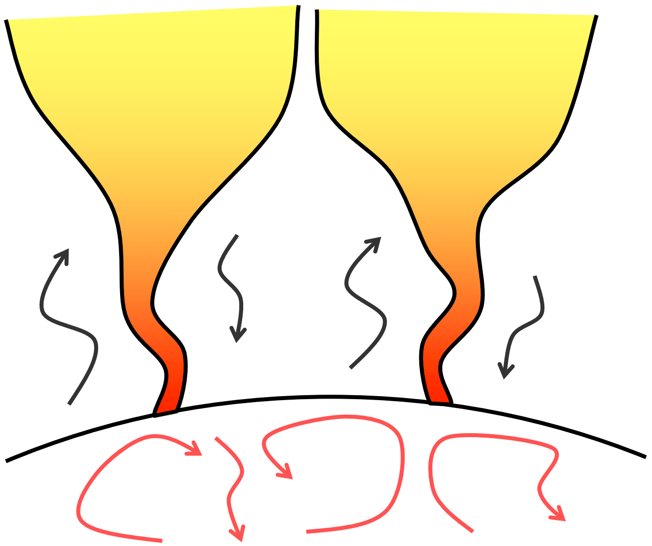
But energy flux is constant…

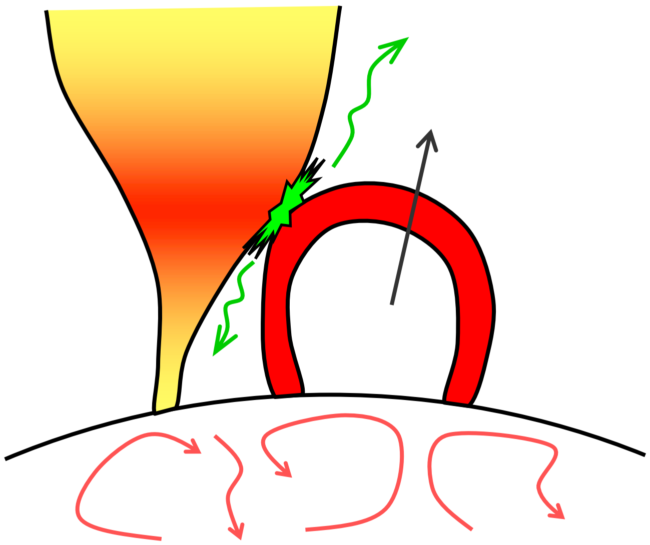


One mechanism at the source?

Le Chat et al. 2012

What is the energy source? Waves/turbulence vs reconnection





Footpoint shuffling of open field lines generates Alfven waves. Waves propagate upward and damp – “somehow”

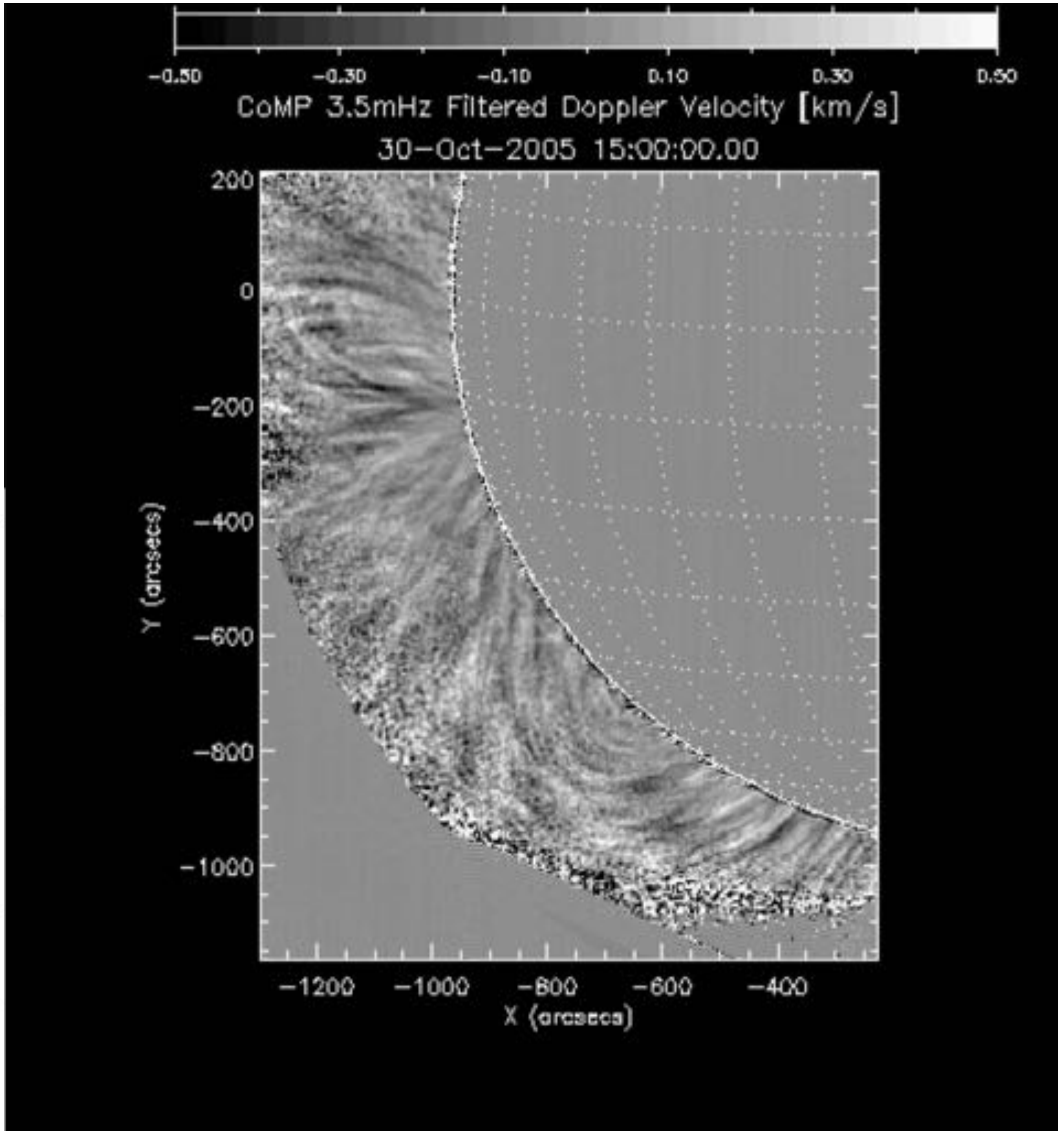
Reconnection injects energy from closed field regions

(Cranmer cartoon)

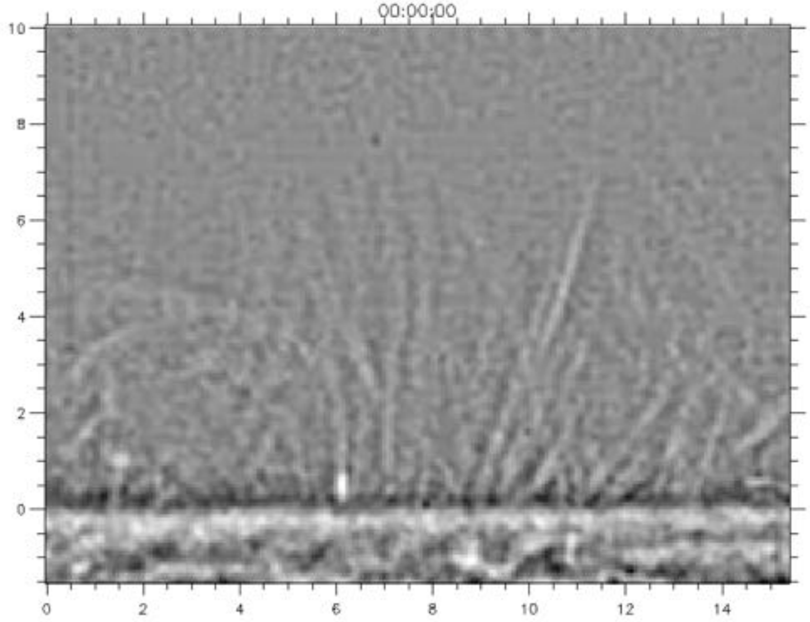
Alfven waves

CoMP at NSO
FeXIII at 1074.7 nm

- ‘Waves’ are faster than sound
- Propagate along magnetic field
- Low intensity

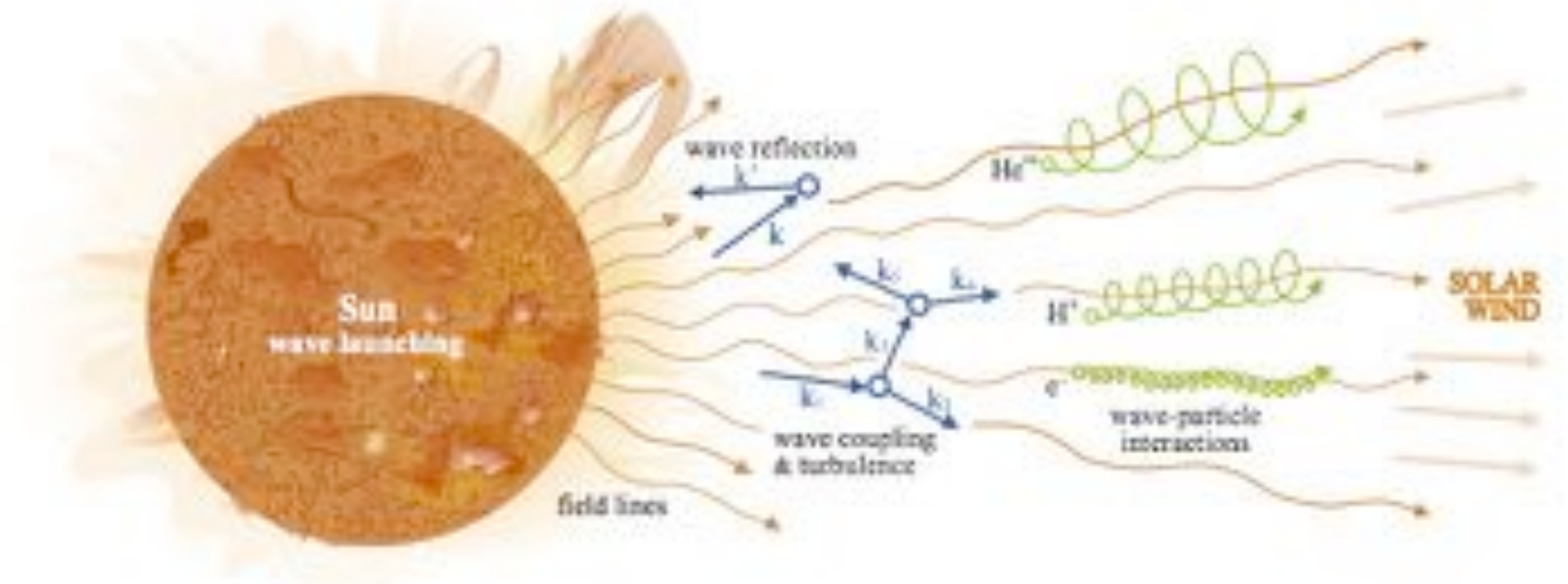


Hinode (JAXA) CaII measurements



Plasma wave launching

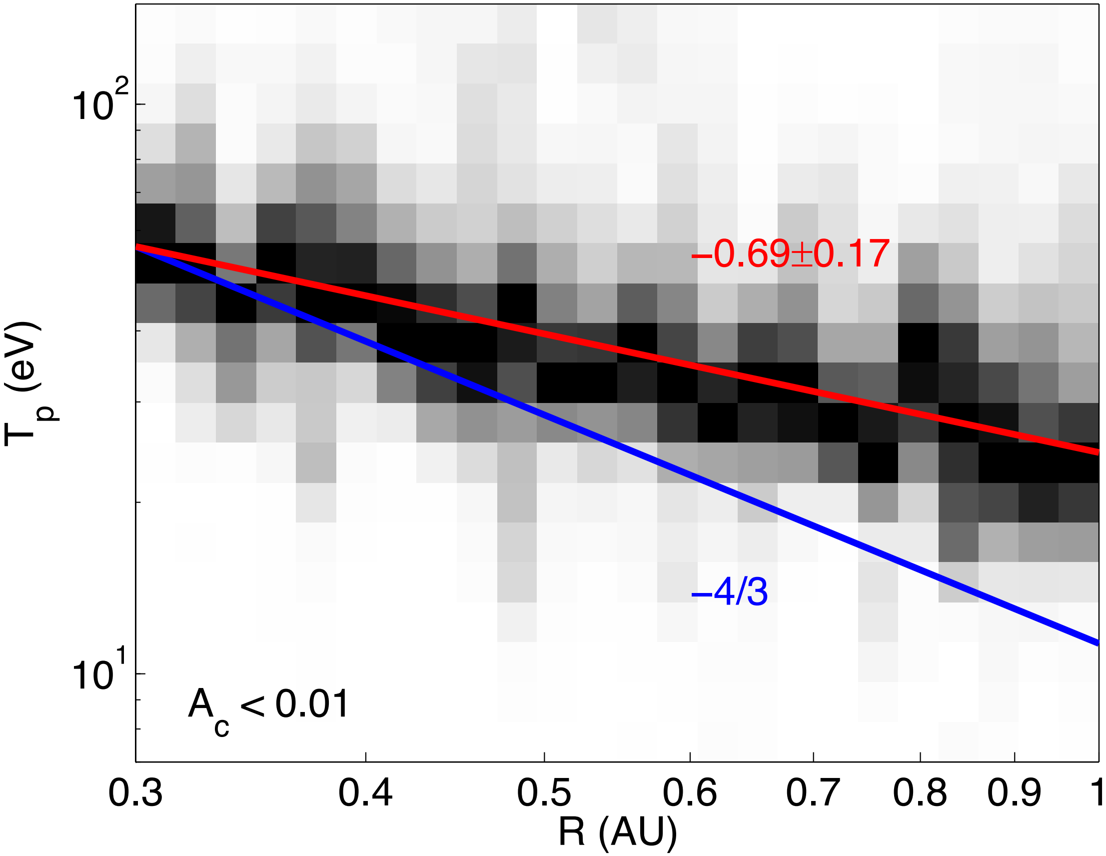
- 1) Footpoint ‘shuffling’ generates currents, magnetic fields
- 2) Alfven waves propagate upward, some reflect
- 3) Produce a turbulent cascade that terminates in damping
- 4) Damping (Landau and transit-time) or heating (cyclotron, stochastic) heats the plasma or maybe form current sheets and reconnect?



(Chandran cartoon)

The solar wind is heated continuously

- Helios spacecraft measurements from 0.3 – 1 AU
- Voyager spacecraft measurements outward
- $T_p \sim 1/r$
- Adiabatic cooling predicts a much more rapid decay
- Requires continuous, distributed energy input



The solar wind is heated continuously

Helios observations $0.3 < R < 1.0$ AU,

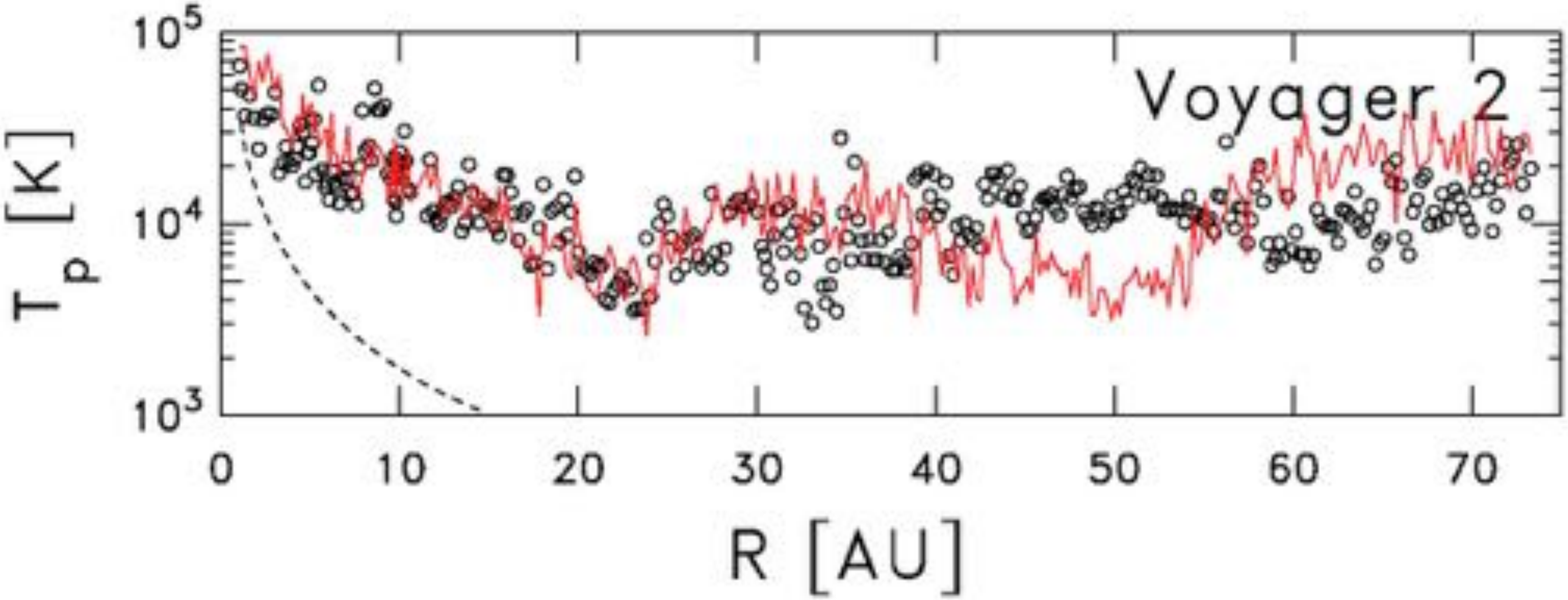
$400 < V_{SW} < 500$ km/s, $T \sim R^{-1.0 \pm 0.10}$

$500 < V_{SW} < 600$ km/s, $T \sim R^{-0.8 \pm 0.10}$

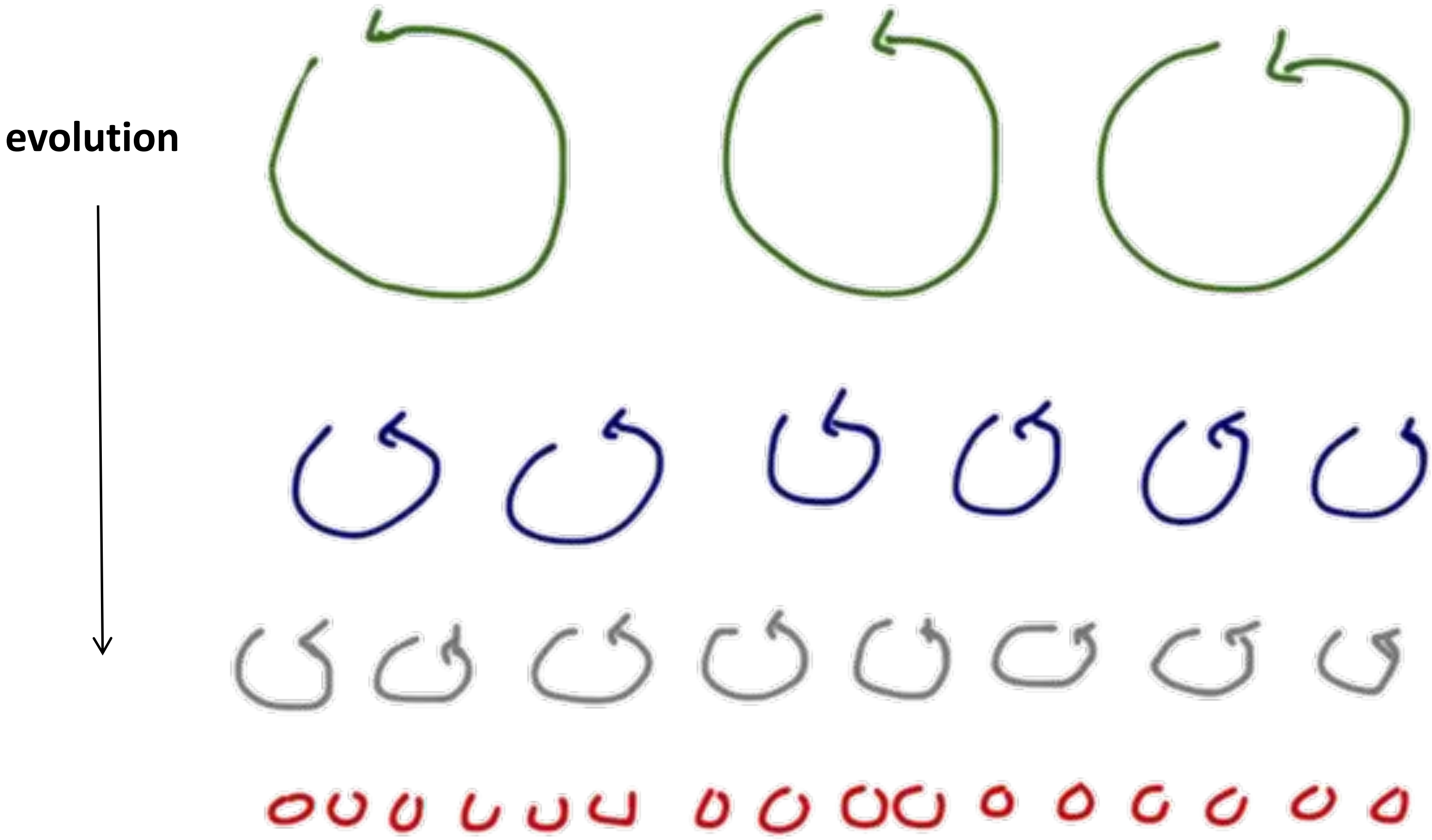
$600 < V_{SW} < 700$ km/s, $T \sim R^{-0.8 \pm 0.09}$

$700 < V_{SW} < 800$ km/s, $T \sim R^{-0.8 \pm 0.17}$

Turbulent transport theory attempts to describe the rate energy cascades to small scales and the evolution of the large- and intermediate-scale fluctuations. It does **not** describe the actual dissipation processes.



Turbulent ‘eddies’



viscous damping

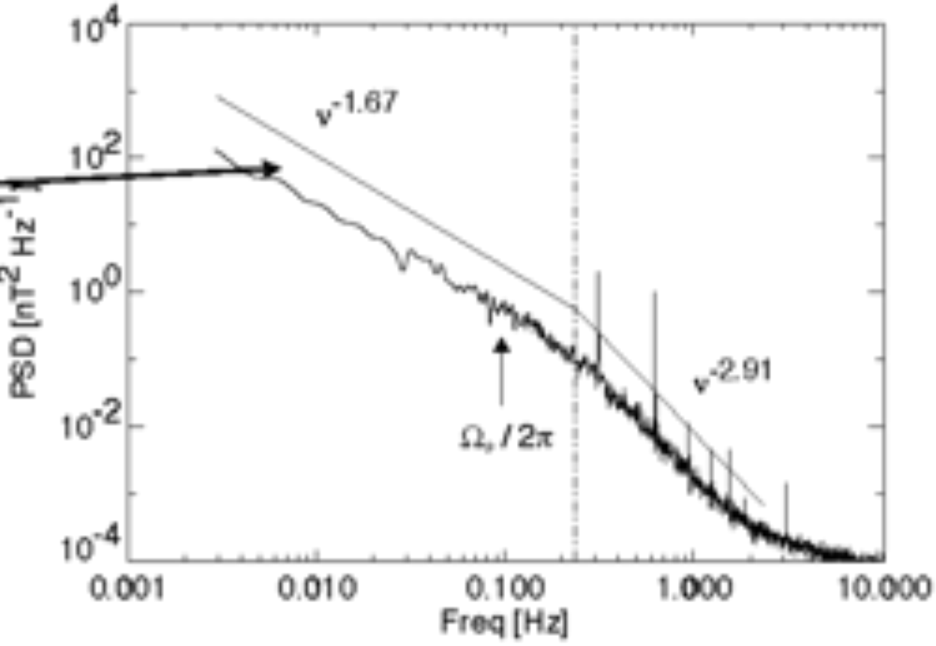
Fluid turbulence

- Kolmogorov (isotropic, hydro) turbulence - scale free inertial range

$$\epsilon \sim \frac{u^2}{\tau} = const \qquad \tau \sim \lambda/u$$

$$\epsilon \sim u^3/\lambda \qquad u \sim (\epsilon\lambda)^{1/3}$$

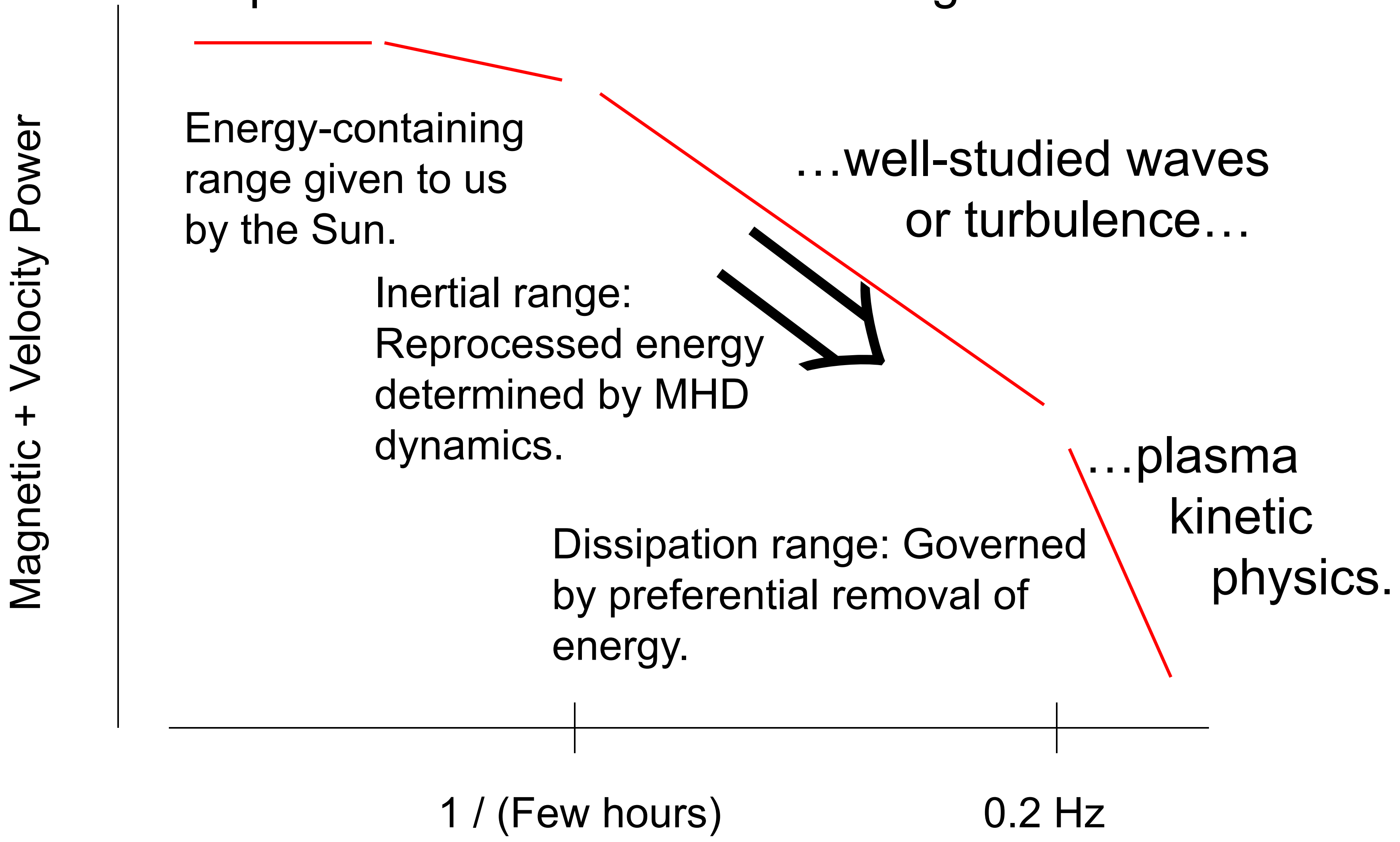
$$P \sim \lambda u^2 \sim \epsilon^{2/3}\lambda^{5/3}$$



(Leamon et al., 1998)

The total field |B|, field components, density, temperature, and velocity *all* show evidence of $k^{-5/3}$ behavior (sometimes)

The Cascade ‘Paradigm’



Unprocessed features of solar origin…

Energy-containing range given to us by the Sun.

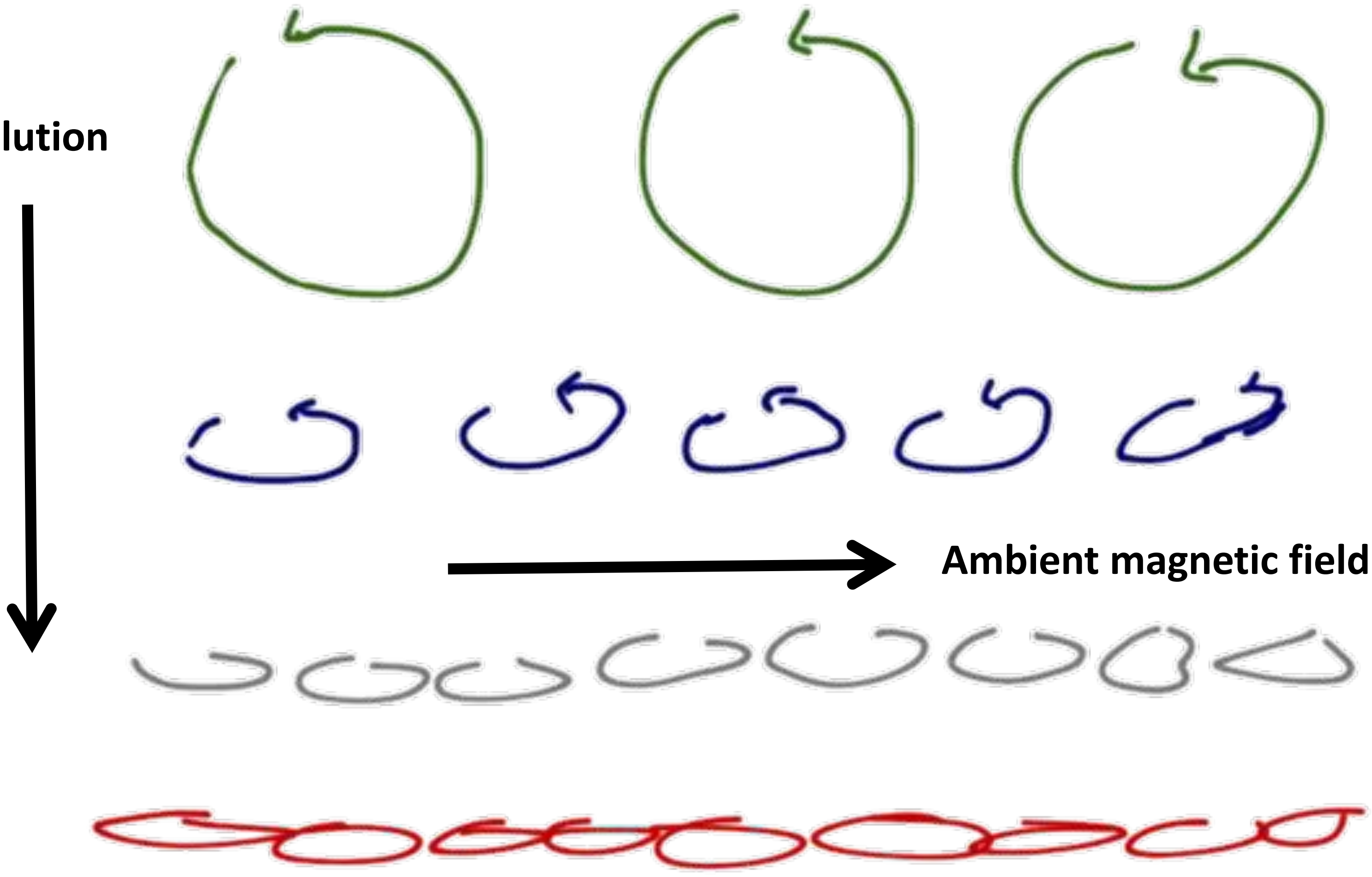
…well-studied waves or turbulence…

Inertial range: Reprocessed energy determined by MHD dynamics.

…plasma kinetic physics.

Dissipation range: Governed by preferential removal of energy.

Magnetized turbulent 'eddies'



evolution

Ambient magnetic field

collisionless damping

Magnetized Turbulence

- Goldreich-Sridhar (anisotropic) turbulence - also scale free, ‘strong’

perpendicular cascade $k_{||} \ll k_{\perp}$

critical balance $\omega \sim k_{||} v_A \sim k_{\perp} v_{\perp}$

$$\epsilon \sim \frac{v_{\perp}^2}{\tau} = const \qquad \tau \sim \lambda / v_{\perp} \sim l_{||} / v_A$$

$$\epsilon \sim v_{\perp}^3 / \lambda \qquad v_{\perp} \sim (\epsilon \lambda)^{1/3}$$

$$P \sim \lambda u_{\perp}^2 \sim \epsilon^{2/3} \lambda^{5/3} \qquad P_{||} \sim l^2$$

$$k_{||} \sim k_{\perp}^{2/3}$$

evolution is primarily in perpendicular wavenumber

Anisotropic MHD turbulence

- Goldreich-Sridhar (anisotropic) turbulence - also scale free

perpendicular cascade $k_{||} \ll k_{\perp}$

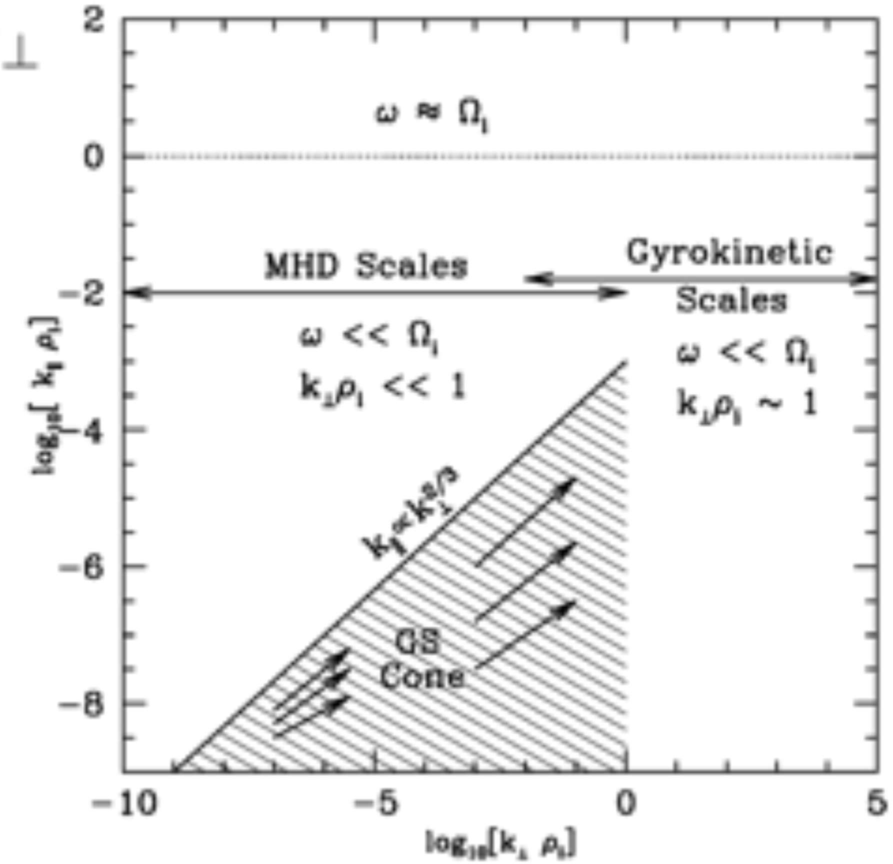
critical balance $\omega \sim k_{||} v_A \sim k_{\perp} v_{\perp}$

At $k_{\perp}\rho_i \approx 1$

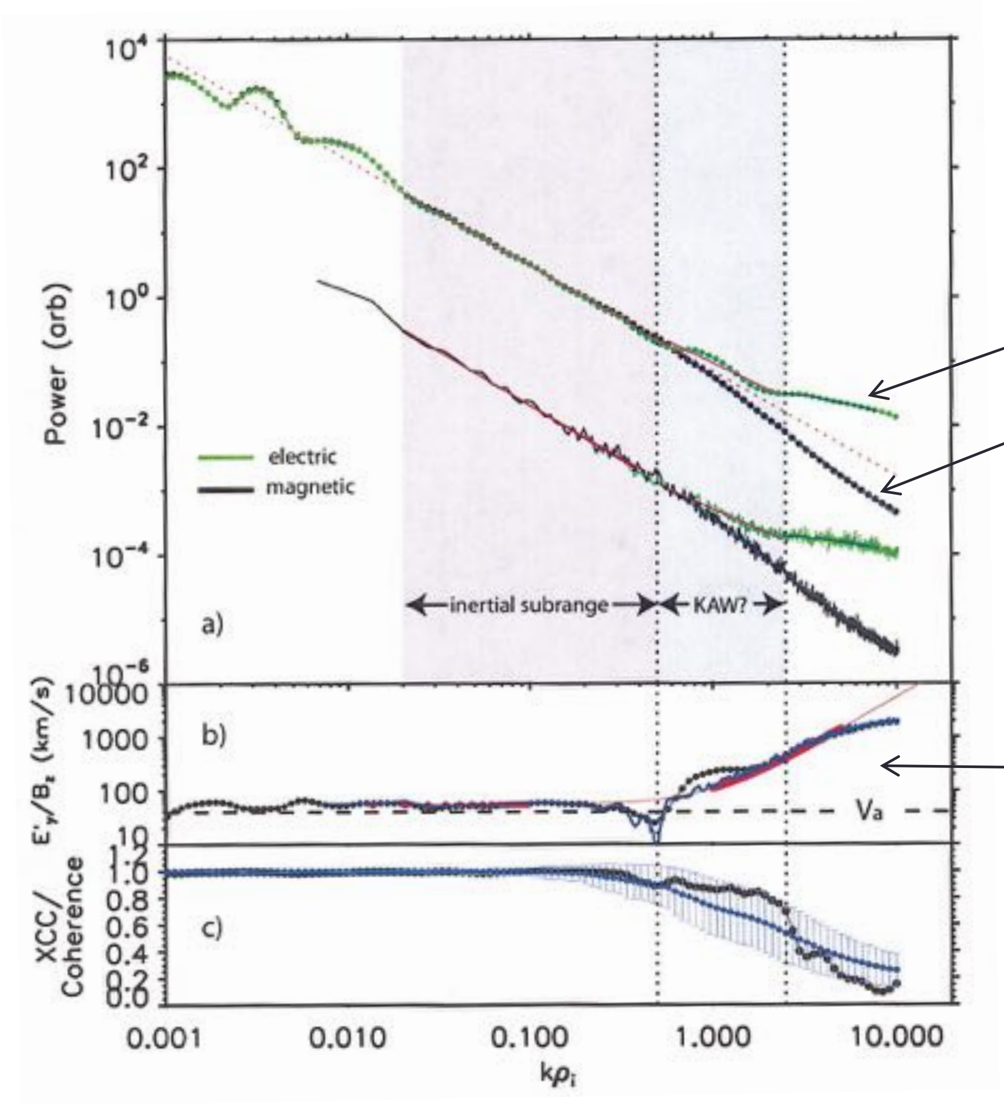
$$\omega/\Omega_i \approx (\rho_i/L)^{1/3}\beta_i^{-1/2}$$

is very small. Far from cyclotron resonance! So we think that ω = k v_{sw} is pretty good.

Heating is by Landau damping or transit-time damping



Alfvenic fluctuations and KAW at 1 AU



Phase speed is ~Alfven speed
Dispersion at short wavelength is like Kinetic Alfven Wave

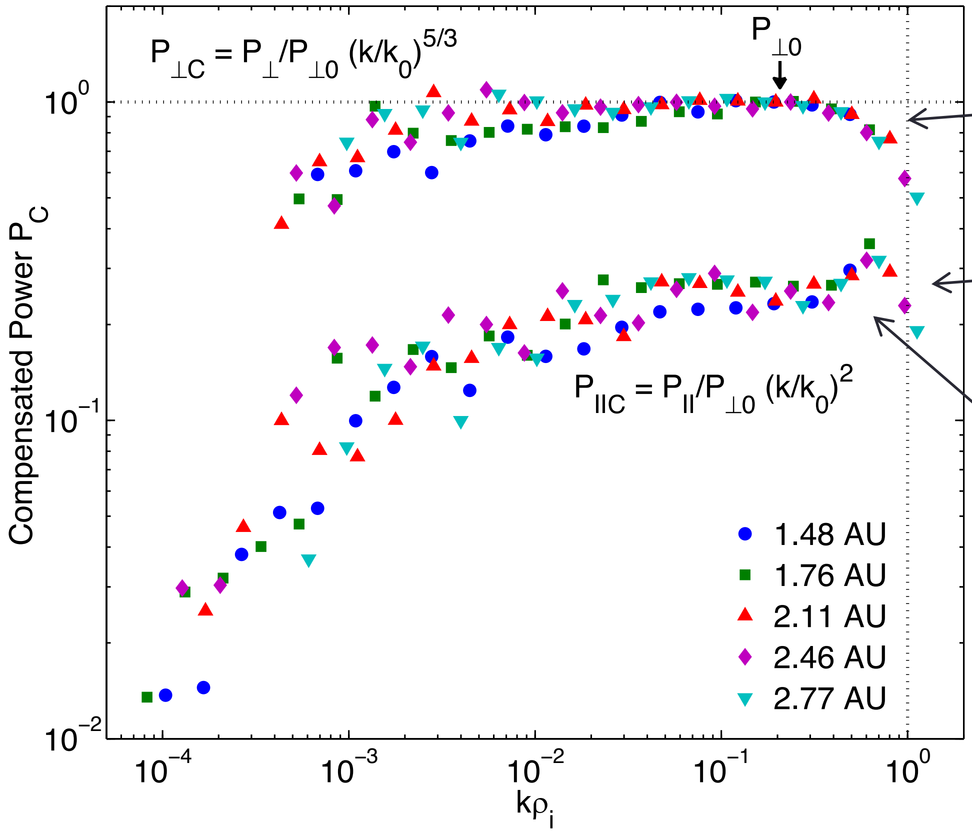
Electric field spectrum

Magnetic field spectrum

E/B ~ phase speed

(Bale et al., 2005)

Perpendicular (GS) cascade



$$P \sim \lambda u_\perp^2 \sim \epsilon^{2/3}\lambda^{5/3}$$

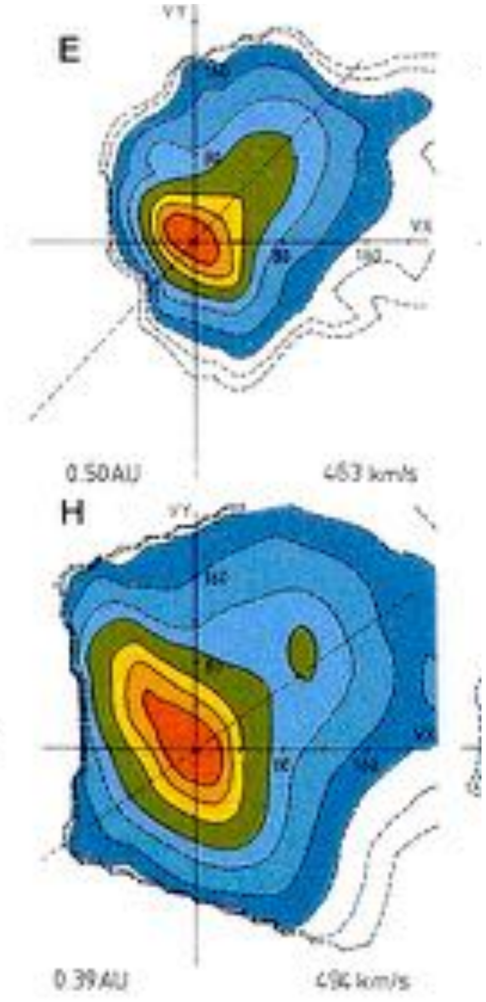
$$P_{||} \propto l_{||}^2$$

Bump – instability?

Figure 4. Perpendicular and parallel power for each of the five periods in Table 1, compensated to remove a spectral gradient of $-5/3$ from the perpendicular power and -2 from the parallel.

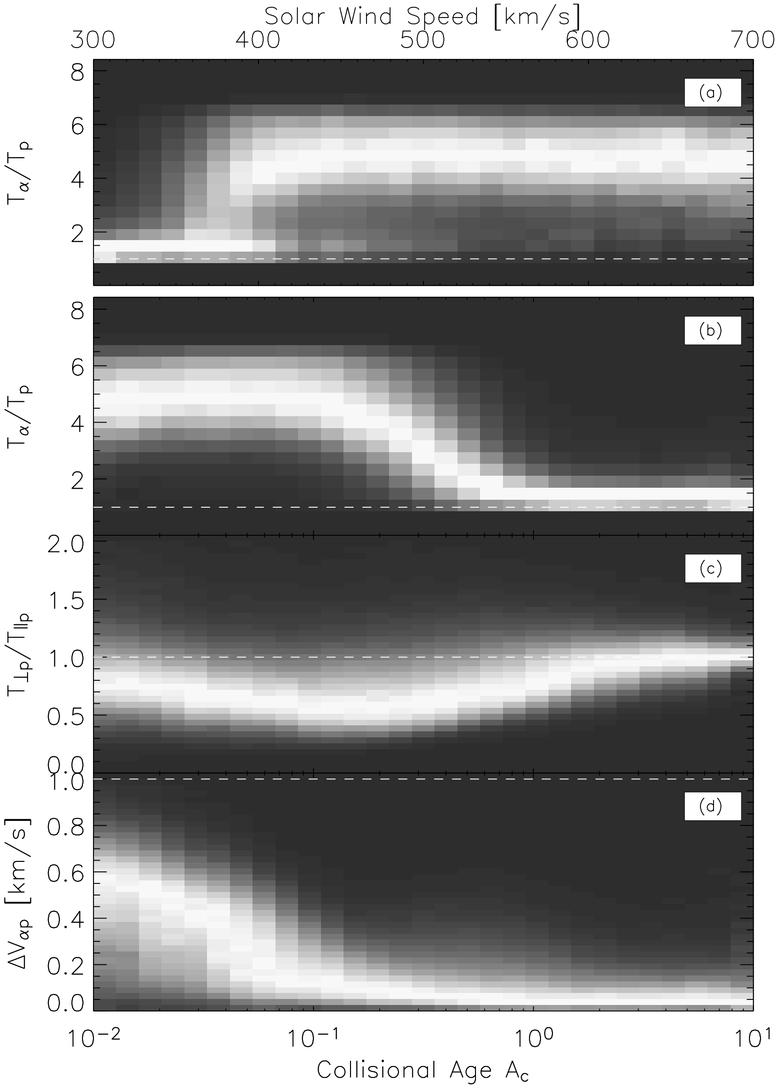
(Wicks et al., 2010)

Solar wind ion kinetics



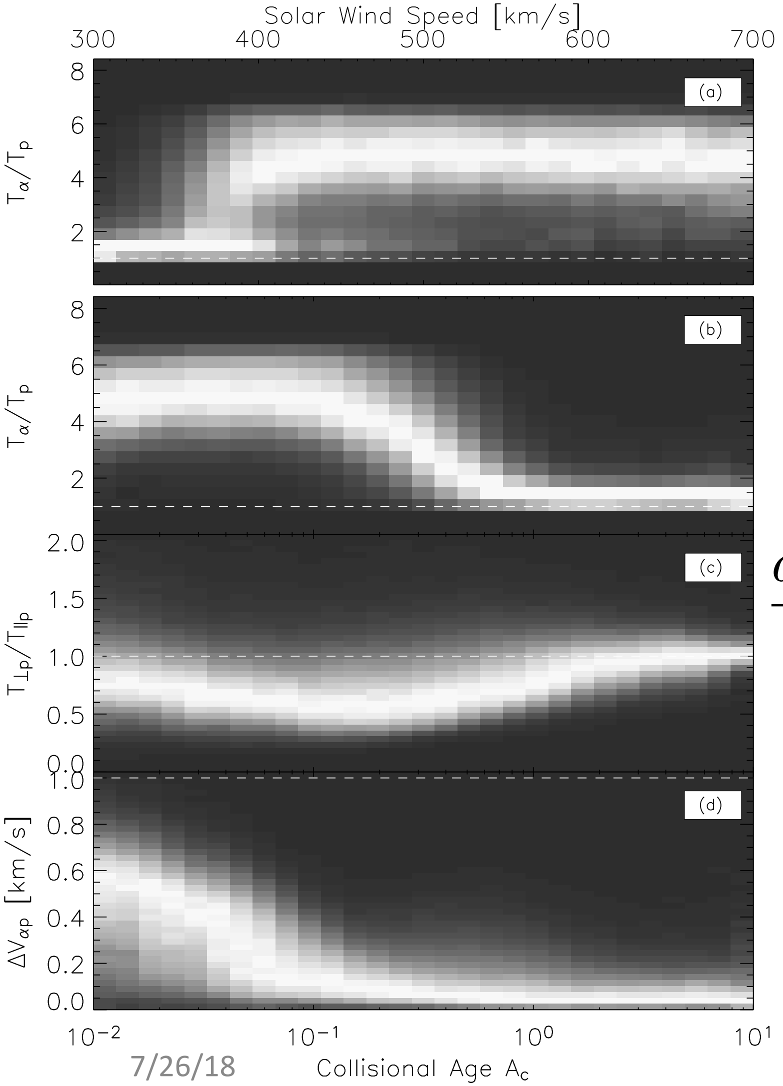
(Marsch et al)

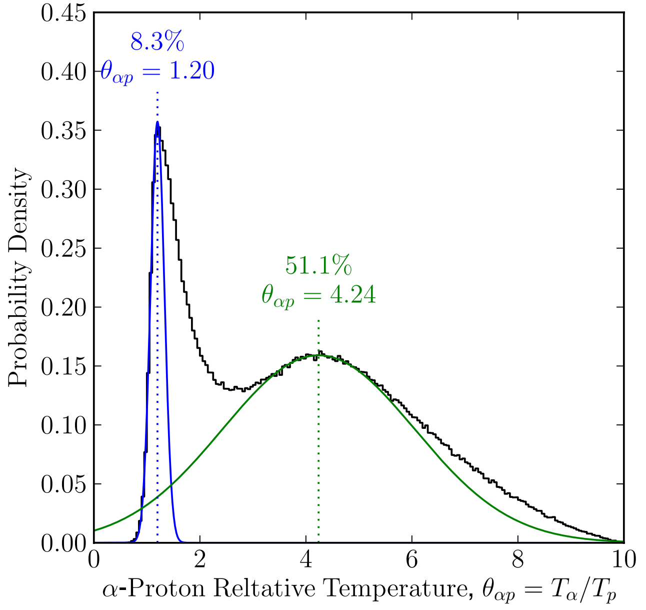
- Core protons, proton beams, alphas
- Not generally thermal equilibrium
- relative drifts, finite/large temperature anisotropies
- collisionality – A ~ $\nu\ \tau$



(Kasper et al)

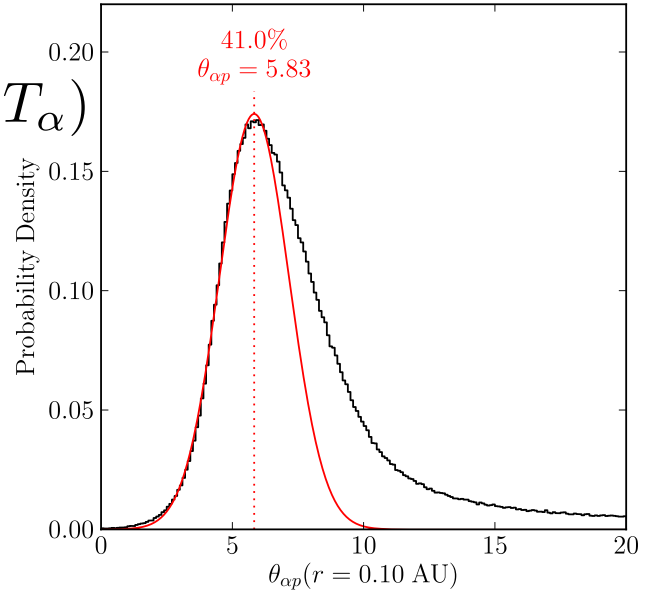
Collisional evolution





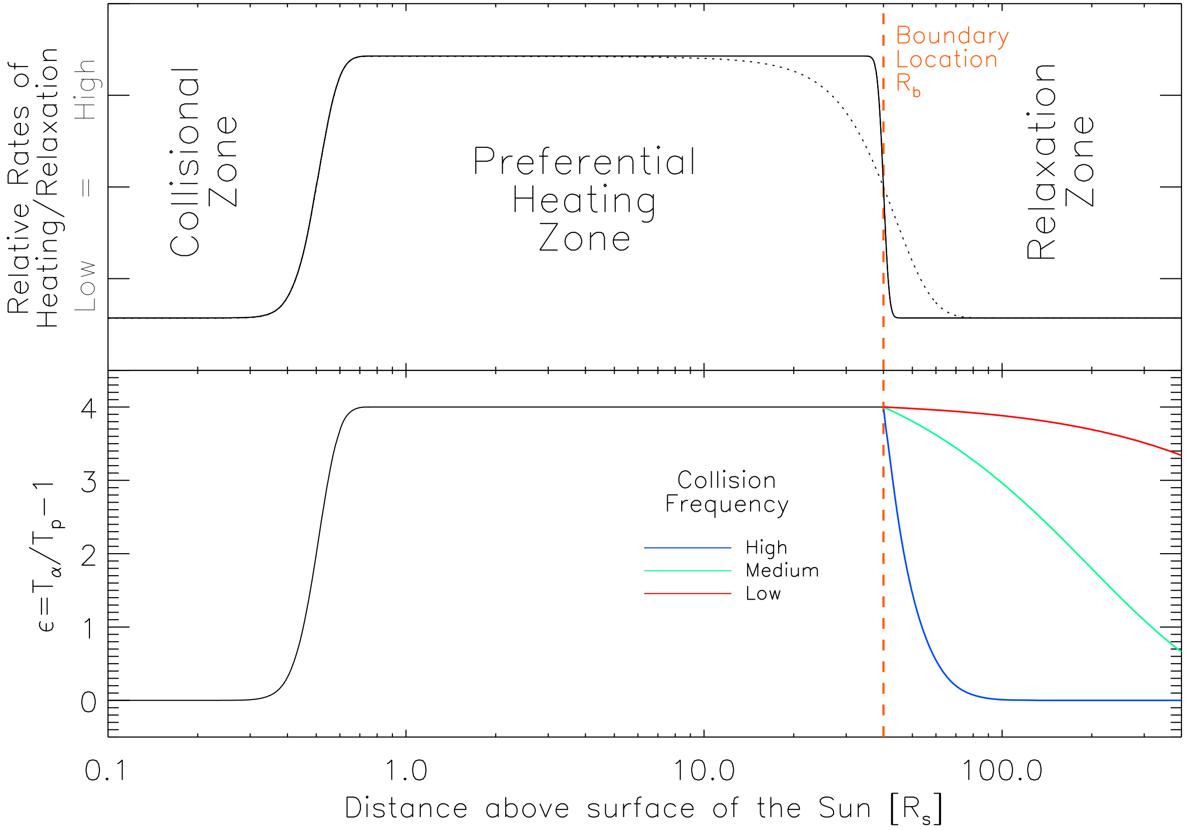
Extrapolating collisional evolution back to the inner heliosphere

$$\frac{dT_\alpha}{dt} = \nu^{\alpha/\beta}(T_\beta - T_\alpha)$$



(Maruca et al, 2013, Kasper et al, 2017)

A ‘zone’ of ion heating



(Kasper et al., 2017)

The collisional evolution equation

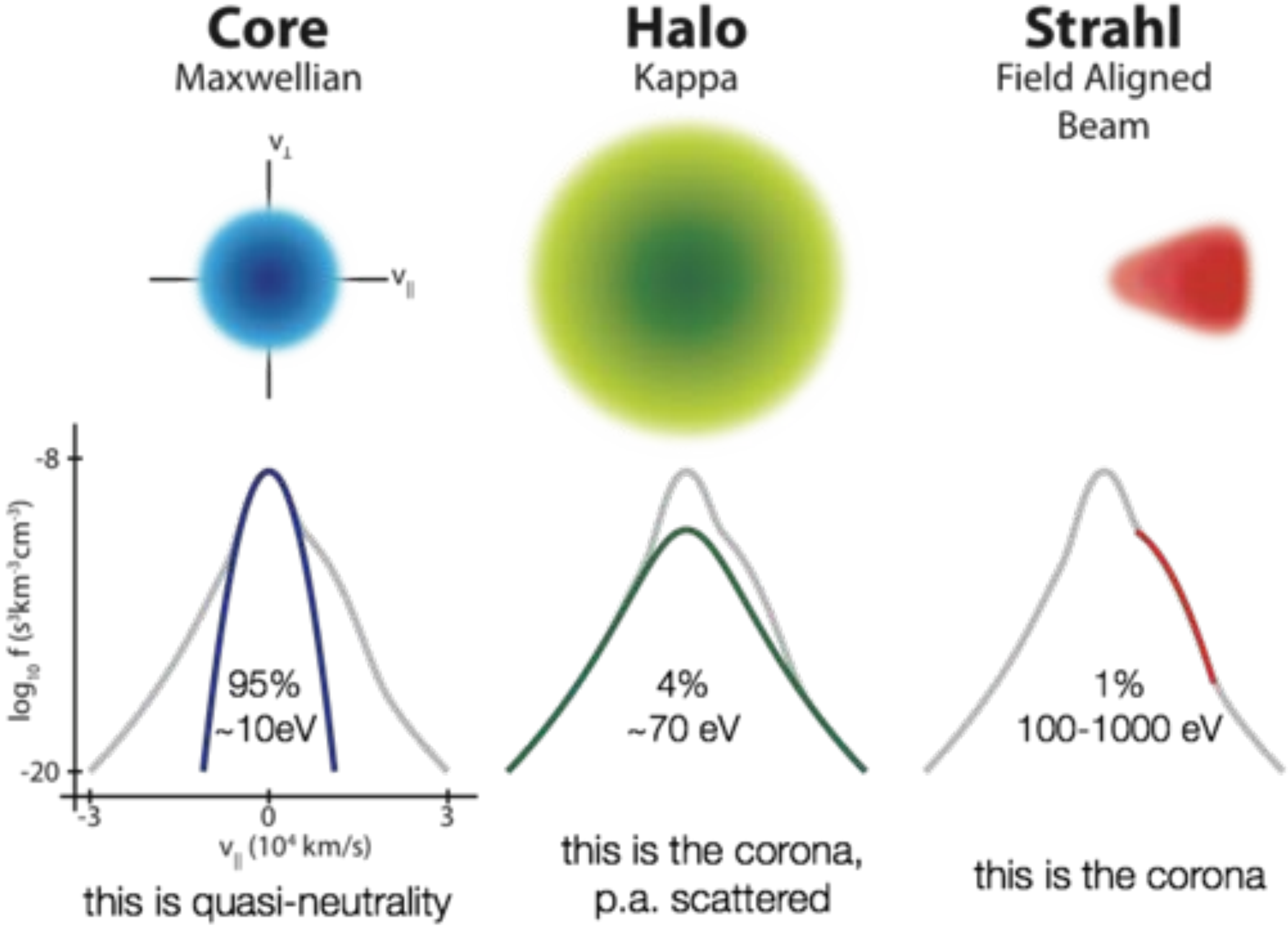
$$\frac{dT_\alpha}{dt} = \nu^{\alpha/\beta}(T_\beta - T_\alpha)$$

Can be integrated back to a starting point in the inner heliosphere.

This starting point seems to be related (equal?) to the Alfven radius!

And the Alfven radius moves around with solar cycle.

Electron velocity distributions



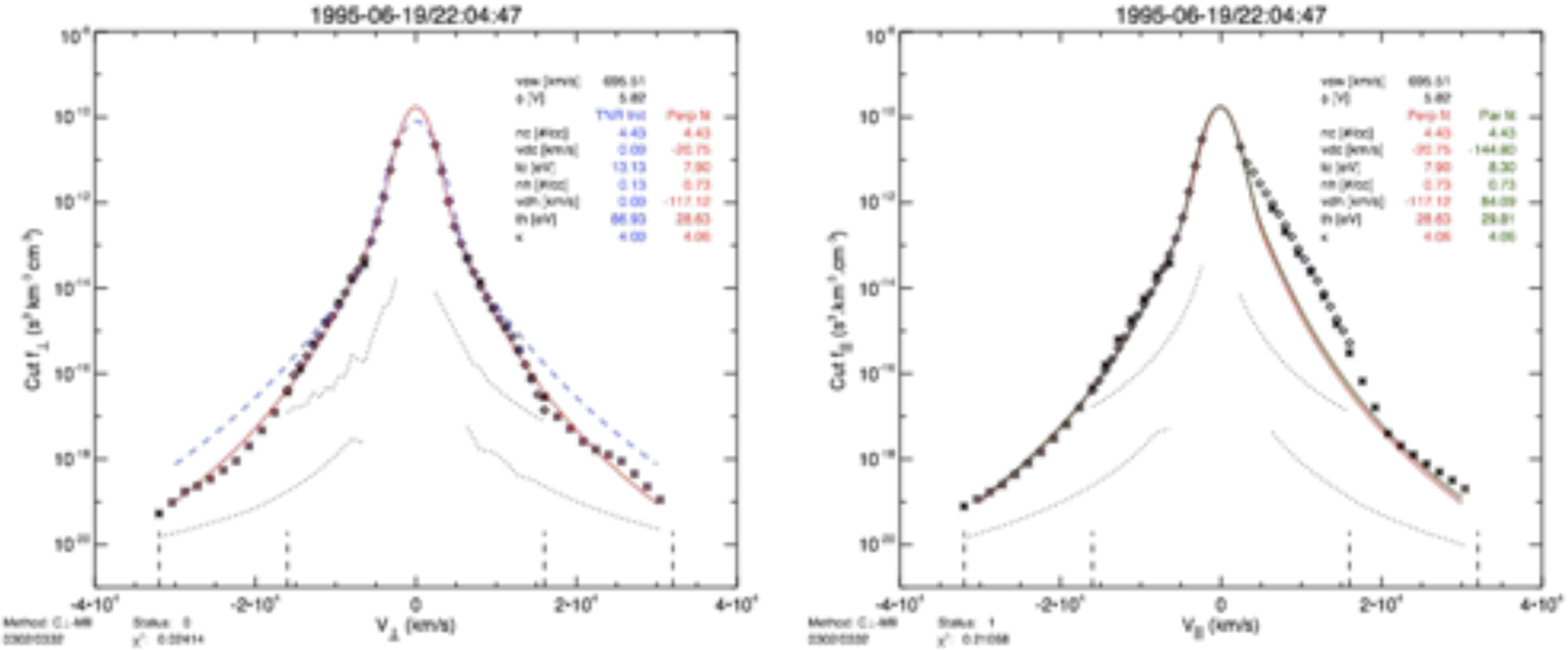
this is quasi-neutrality

this is the corona, p.a. scattered

this is the corona

electron distribution function fits - ‘fast wind’

Wind/3DP electron measurements



- use drifting bi-Maxwellian core and drifting bi-Lorentzian halo, integrate strahl

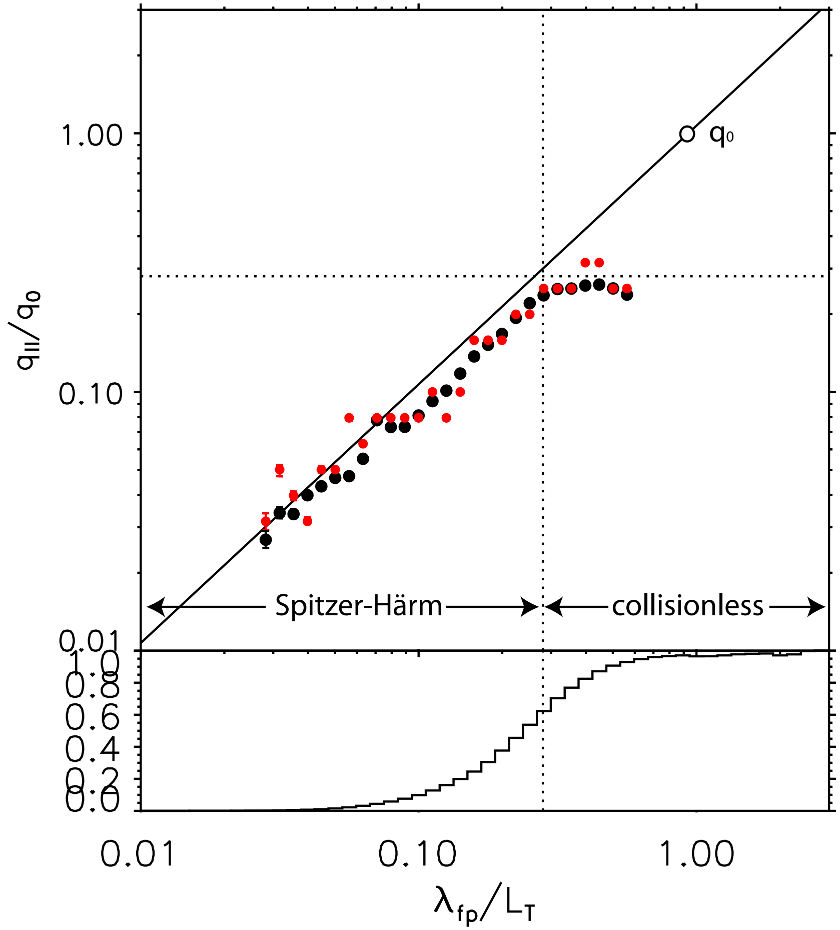
0) correct f(v) for s/c potential

1) fit f(v) perpendicular to core and halo - use QTN initial values

2) fit f(v) parallel to core and halo - use QTN and f(v) perp initial values

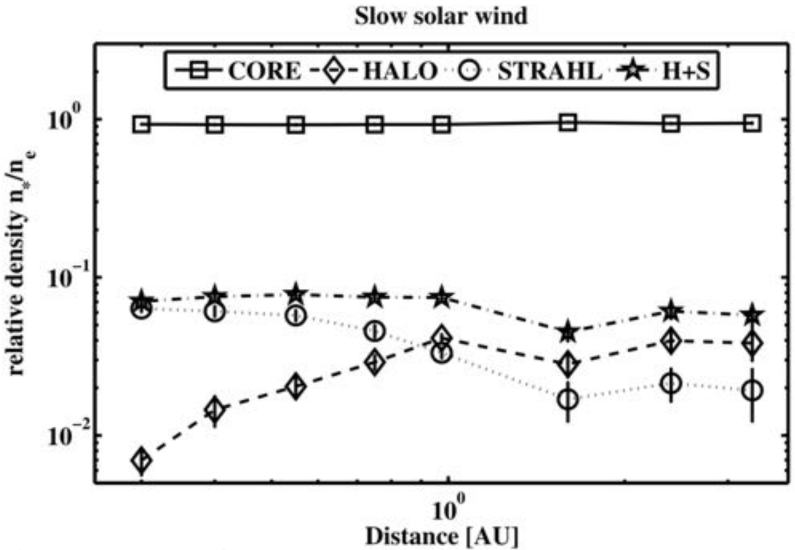
3) subtract f(v) core and halo, fit strahl, and compute strahl moments

Electron heat flux

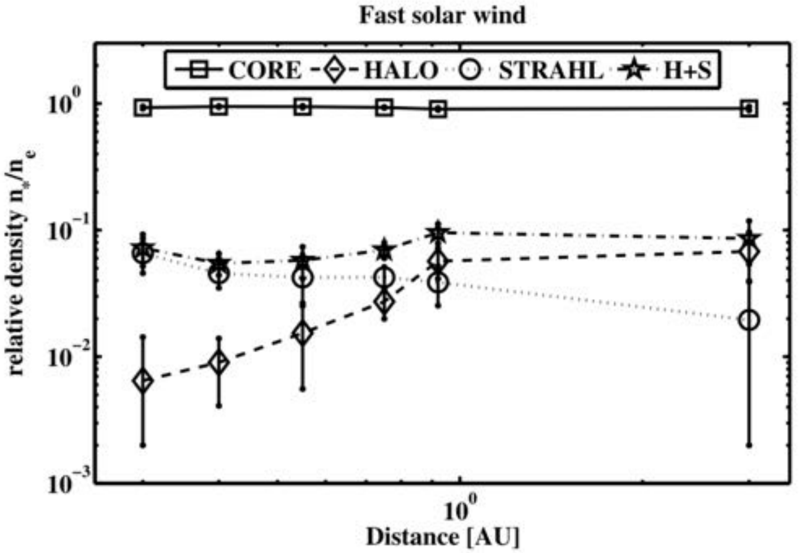


Into the corona ->

(Bale et al., 2013)

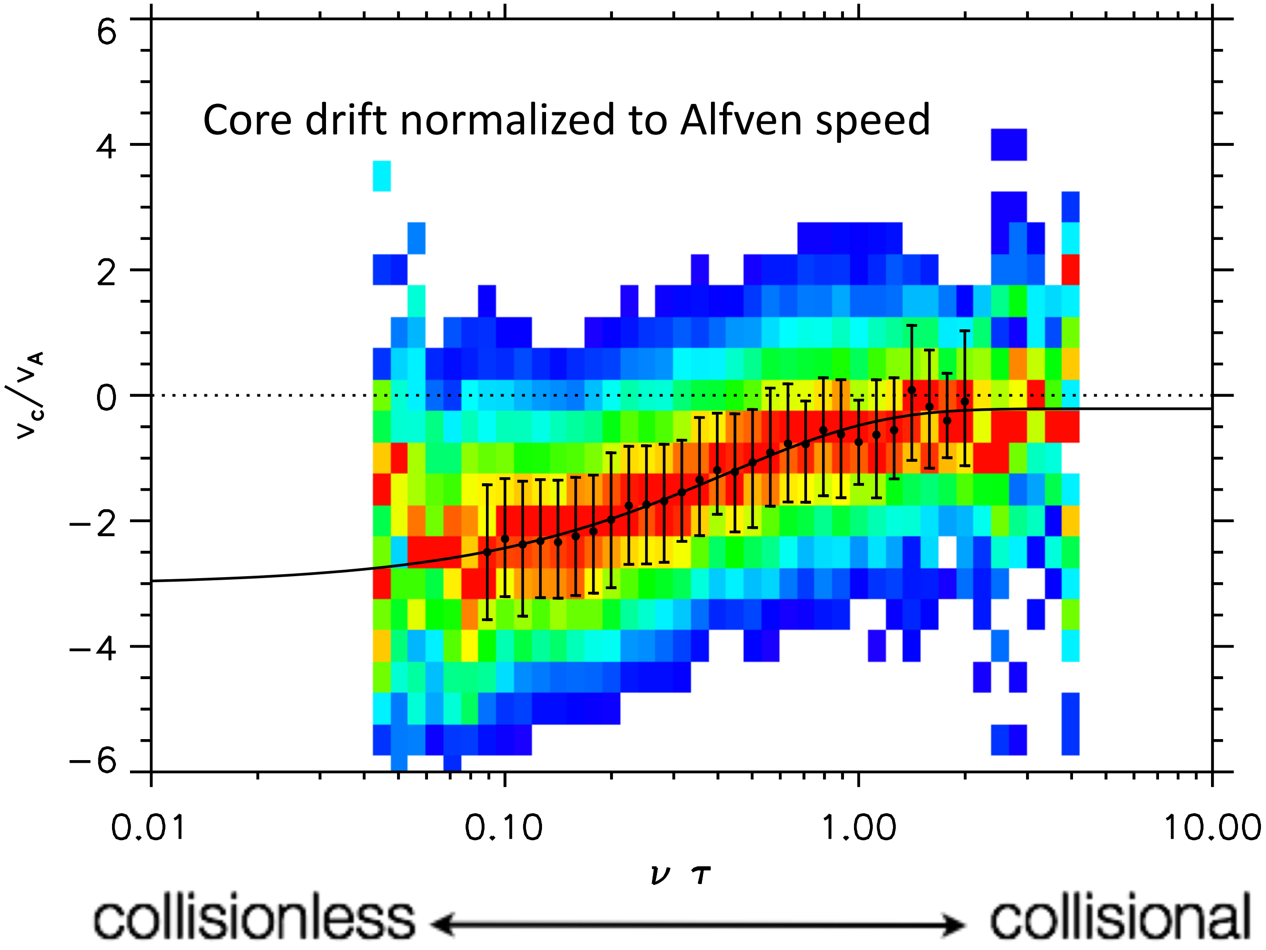


Stverak et al., JGR, 2009



Strahl dominates the suprathermal electron population in the corona…

Electron core drift to v_A



frictional slowing!

$$\frac{dv}{dt} = -\nu v$$

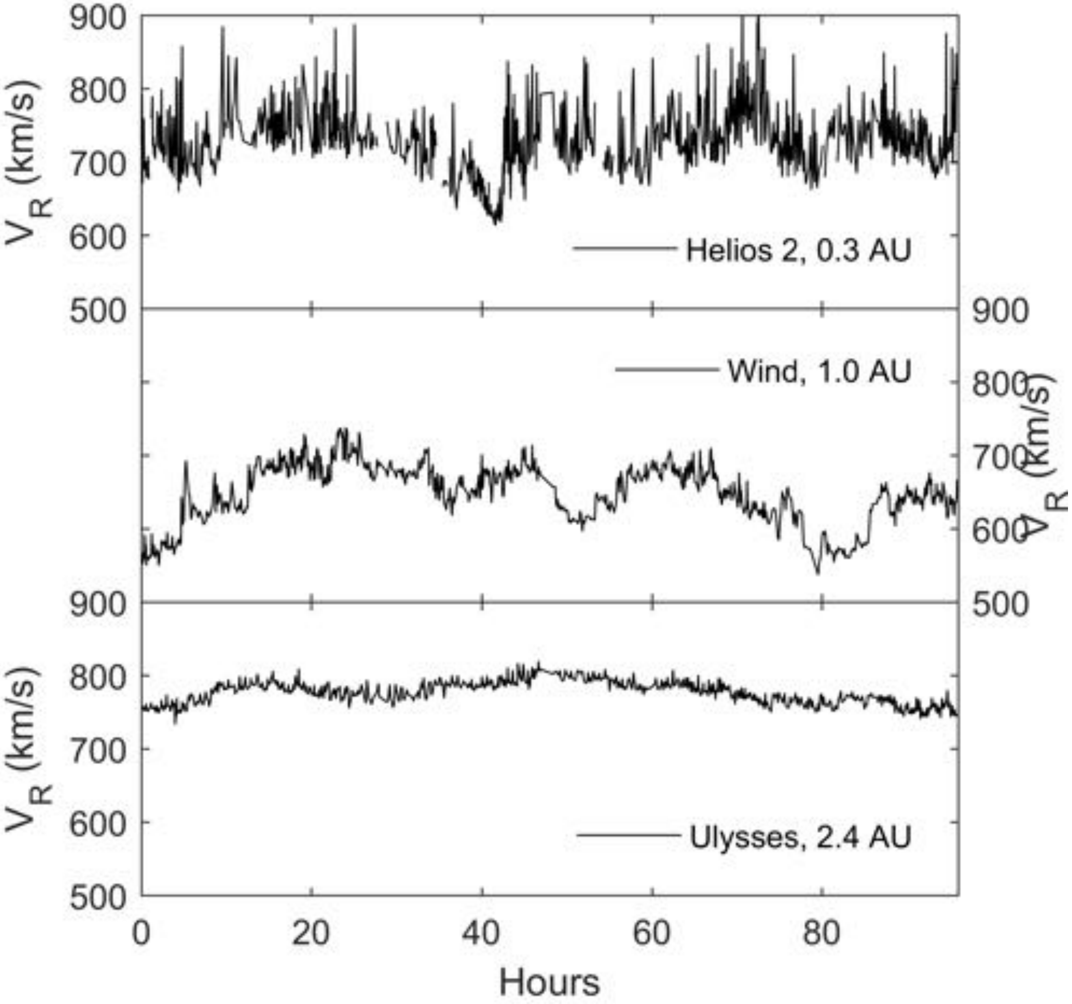
Large core drift rates exceed the Alfven and sound speeds!

This should be unstable and/or modify wave damping (heating) rates

Solar wind velocity

Helios spacecraft measurements at 0.3 AU show that the radial velocity of the solar wind is very impulsive.

This effect is reduced as the wind evolves out to 1 AU (Wind) and 2.4 AU (Ulysses)



(Horbury et al, 2018)

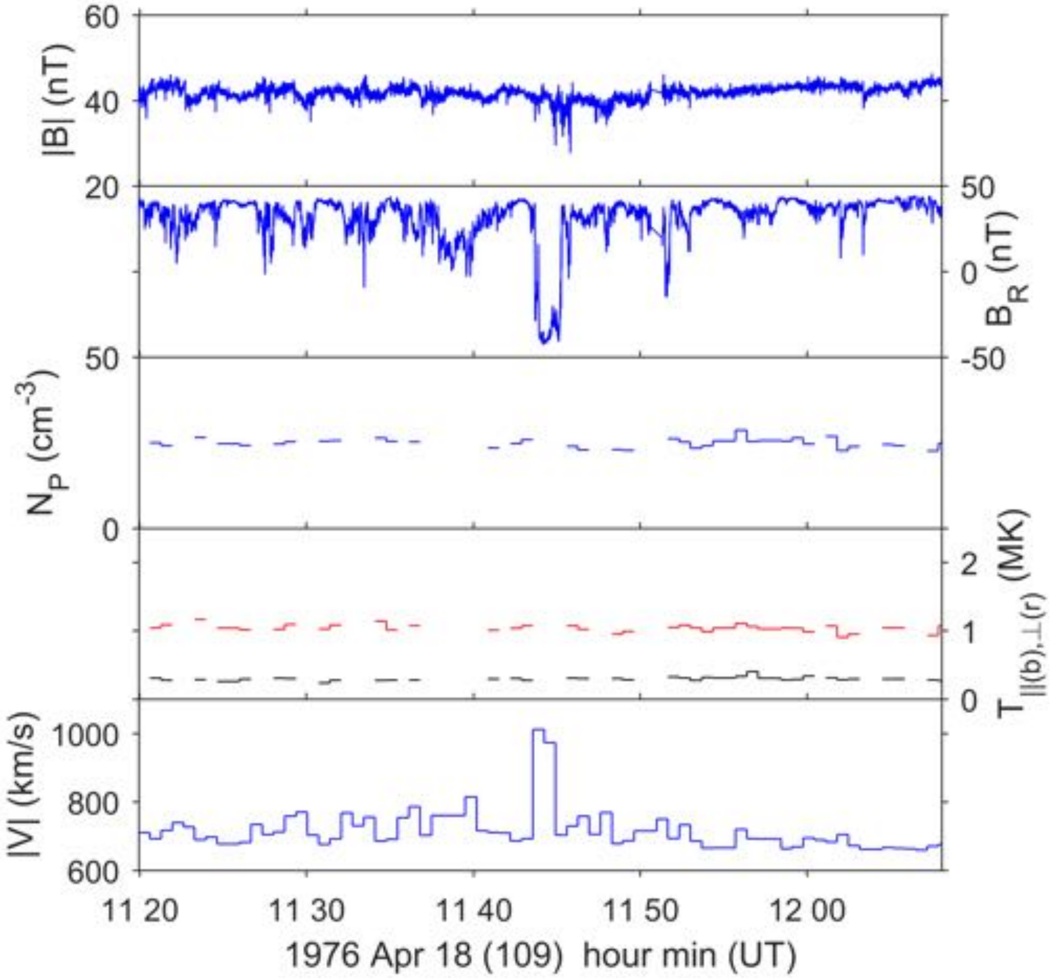
Solar wind speed

The velocity ‘spikes’ can be as large at 1000 km/s (2x the ambient speed)

The radial velocity spikes correspond to radial magnetic field spikes.

The spikes are **Alfvenic** in nature.

Remnants of coronal ’jets’?

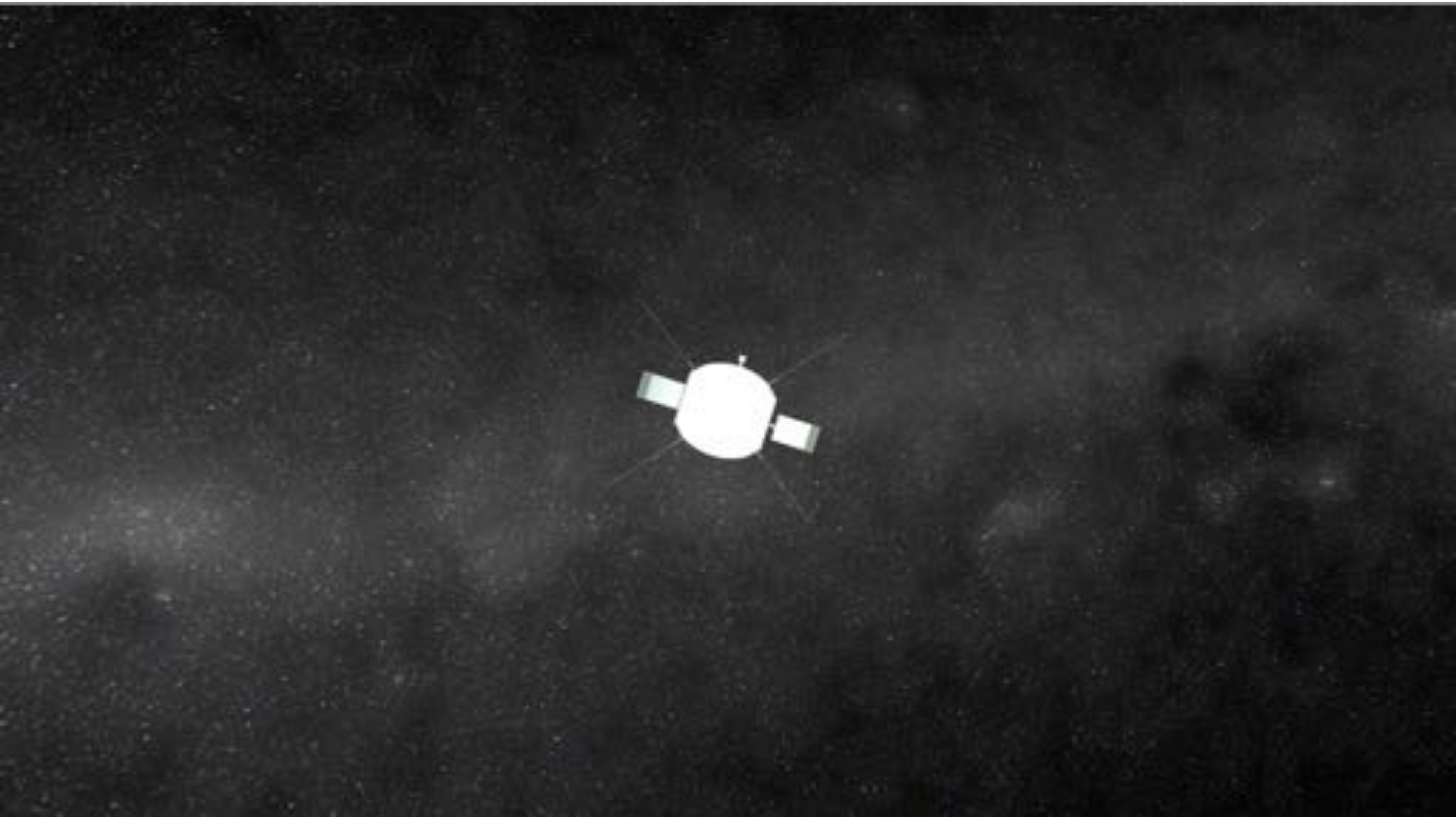


(Horbury et al, 2018)

What can we expect to measure in the corona?

1. Large pressure/temperature anisotropies
2. Active ion heating – mass proportional?
3. Nonthermal electron and ion populations (beams, tails, strahl)
4. Impulsive Alfvenic structures and waves
5. Little collisional processing

NASA Parker Solar Probe (PSP)



PSP Level 1 Science Objectives

L1 Science Objectives	Sample Processes	Needed Measurements	Instruments
1. Trace the flow of energy that heats and accelerates the solar corona and solar wind. 2. Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind. 3. Explore mechanisms that accelerate and transport energetic particles.	- heating mechanisms of the corona and the solar wind; - environmental control of plasma and fields; - connection of the solar corona to the inner heliosphere. - particle energization and transport across the corona	- electric & magnetic fields and waves, Poynting flux, absolute plasma density & electron temperature, spacecraft floating potential & density fluctuations, & radio emissions - energetic electrons, protons and heavy ions - velocity, density, and temperature of solar wind e-, H+, He++ - solar wind structures and shocks	FIELDS - Magnetic Field - Electric Field - Electric/Mag Wave ISOIS - Energetic electrons - Energetic protons and heavy ions - (10s of keV to ~100 MeV) SWEAP - Plasma e-, H+, He++ - SW velocity & temperature WISPR - White light measurements of solar wind structures

The PSP Plasma Environment

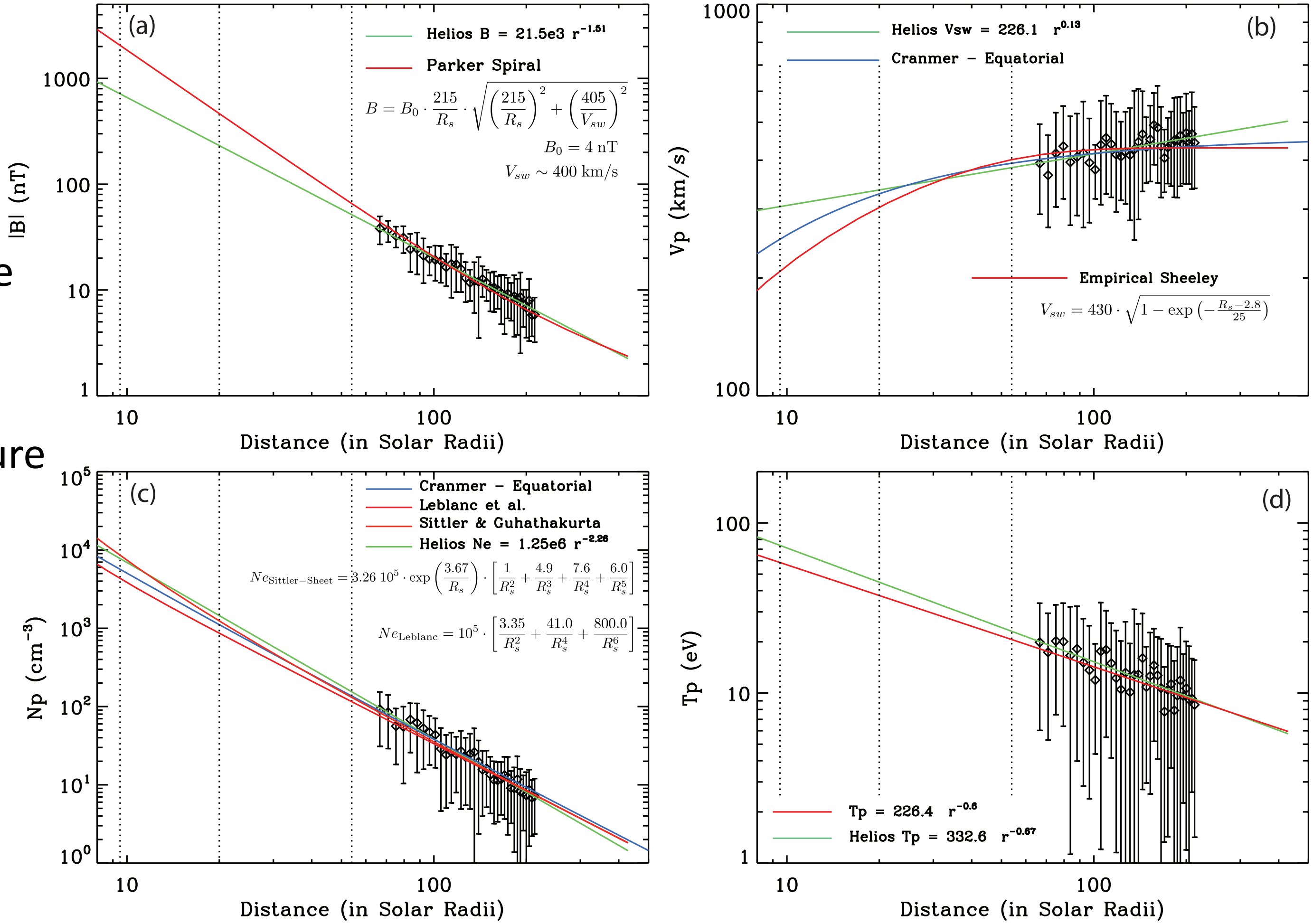
Helios (0.29 AU), 1 AU, and remote sensing measurements extrapolated into 10 Rs

Helios

- Magnetic field
- Velocity
- Proton density
- Proton temperature

Helios + models

- Electron temperature



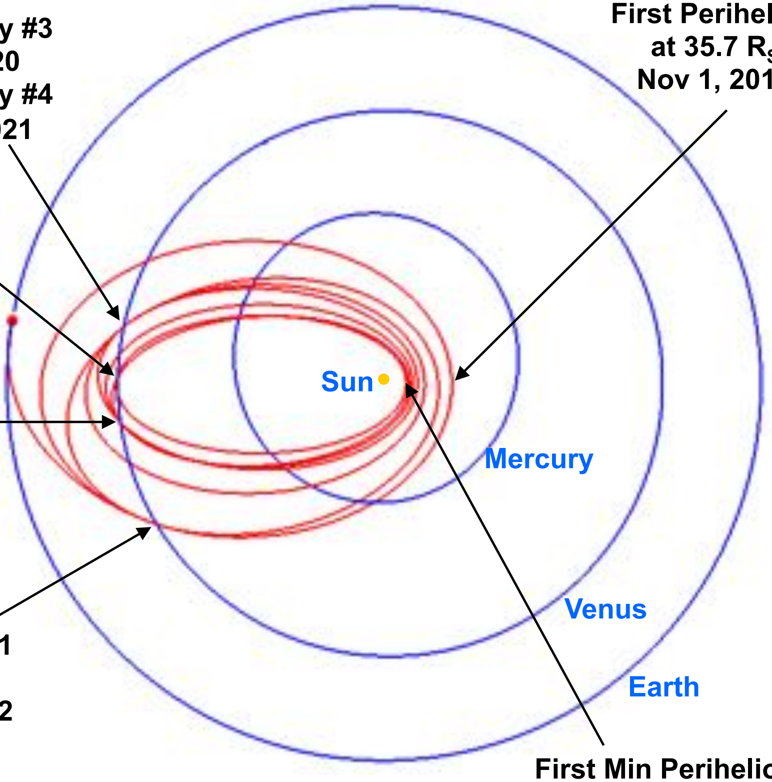
Plasma environment…

- High cadence sampling
- Burst memory system
- Floating voltage preamps
- Large dynamic range

Parameters		**~10 R_s Typical**	**55 R_s Typical**	**1 AU Typical**
Magnetic Field	$\lvert B_0 \rvert \sim \delta B$	2000 nT	70 nT	6 nT
Electric Field	$\lvert E \rvert \sim v_{sw} B_0$	100 mV/m	30 mV/m	3 mV/m
Density	$n_e \sim \delta n_e$	7000 cm^{-3}	120 cm^{-3}	7 cm^{-3}
Electron Temperature	T_e	85 eV	25 eV	8 eV
Solar Wind Speed	v_{sw}	210 km/s	400 km/s	450 km/s
Alfven Speed	v_A	500 km/s	125 km/s	45 km/s
Plasma Frequency	f_{pe}	750 kHz	100 kHz	24 kHz
Electron Gyrofrequency	f_{ce}	60 kHz	2 kHz	160 Hz
Proton Gyrofrequency	f_{ci}	32 Hz	1 Hz	0.1 Hz
Convected Debye Scale	v_{sw}/λ_D	250 kHz (4 μs)	125 kHz (8 μs)	45 kHz (22 μs)
Convected Electron Inertial Length	$v_{sw}/(c/\omega_{pe})$	3.5 kHz (0.3 ms)	825 Hz (1.2 ms)	180 Hz (5.5 ms)
Convected Ion Inertial Length	$v_{sw}/(c/\omega_{pi})$	75 Hz (13 ms)	20 Hz (50 ms)	4 Hz (250 ms)
Convected Ion Gyroradius	v_{sw}/ρ_i	300 Hz (3 ms)	35 Hz (30 ms)	5 Hz (200 ms)
DC/LF Electric Fluctuations	$\delta E_A \sim v_A \, \delta B_A$	1 V/m	10 mV/m	1 mV/m
Kinetic Electric Fluctuations	δE_L	1 V/m	70 mV/m	10 mV/m

2018 Baseline Mission Design
Mission Trajectory

Venus-Venus-Venus-Venus-Venus-Venus-Venus-Gravity-Assist (V^7GA) Trajectory



Venus Flyby #3
Jul 6, 2020
Venus Flyby #4
Feb 16, 2021

Venus Flyby #7
Nov 2, 2024

Launch
July 31, 2018

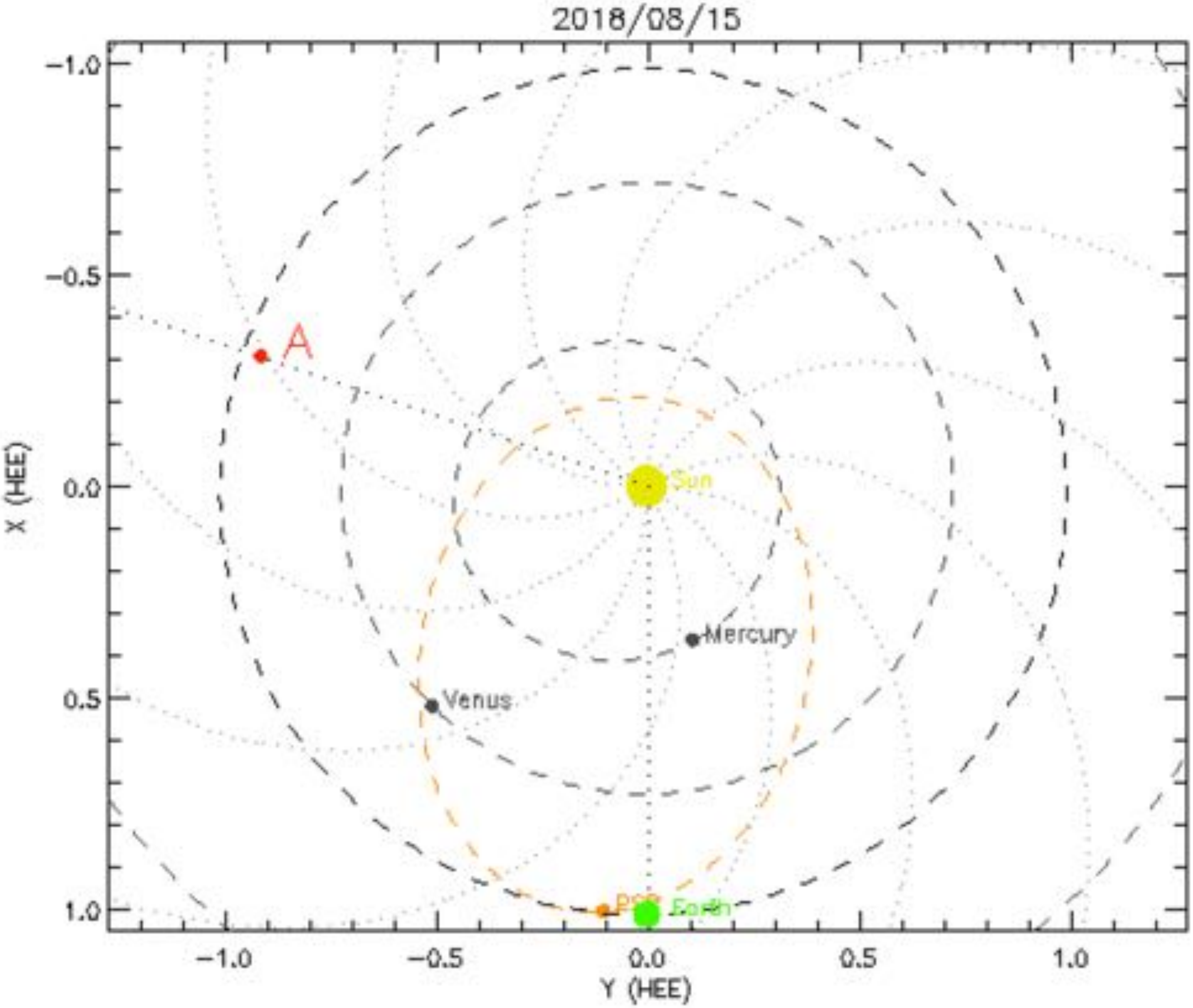
Venus Flyby #5
Oct 11, 2021
Venus Flyby #6
Aug 16, 2023

Venus Flyby #1
Sept 28, 2018
Venus Flyby #2
Dec 22, 2019

First Perihelion
at 35.7 R_S
Nov 1, 2018

First Min Perihelion
at 9.86 R_S
Dec 19, 2024

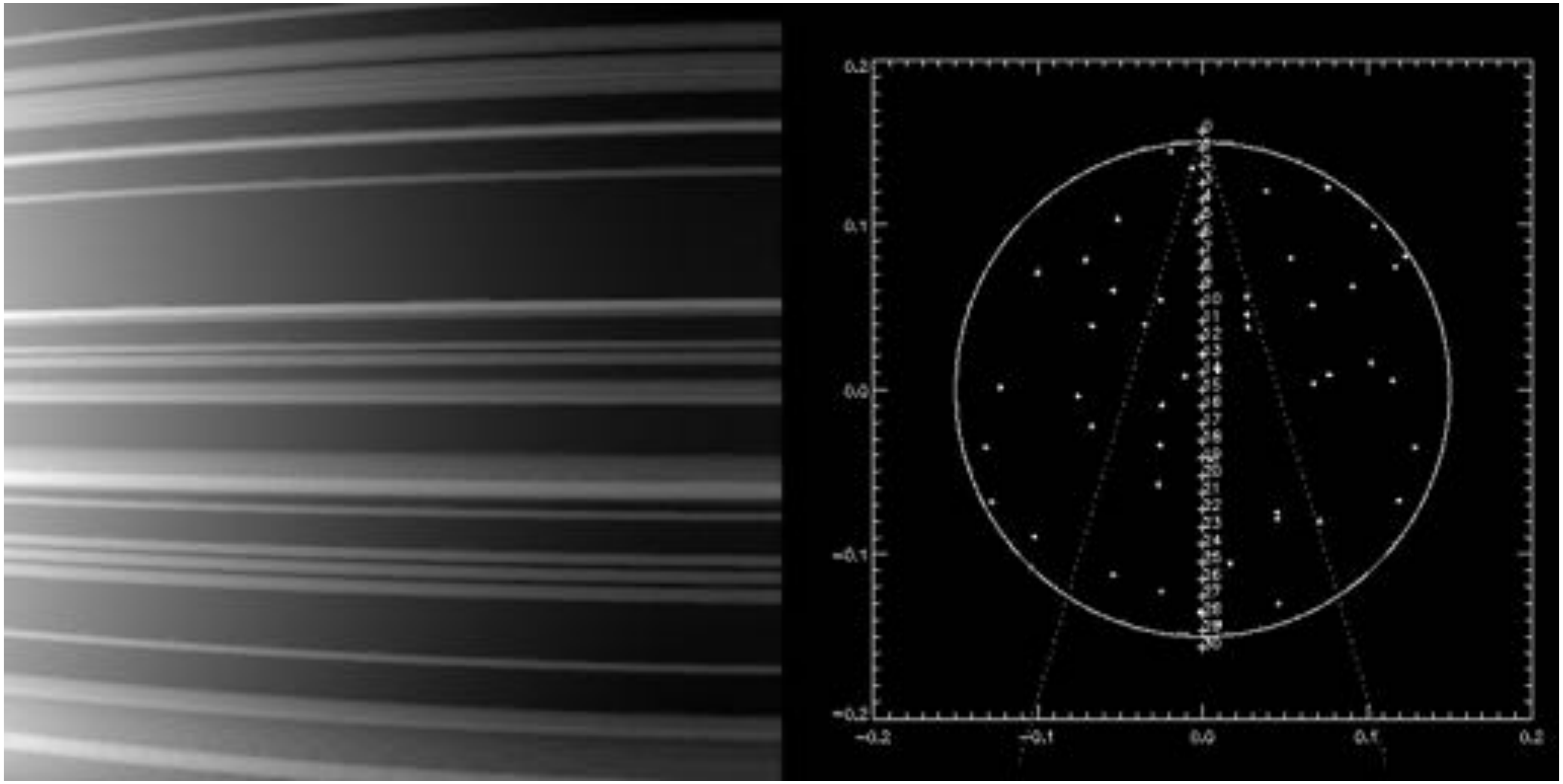
- Repeated 7 Venus gravity assists to lower orbit to reach the Sun
- Switching between resonant and non-resonant Venus encounters to minimize mission duration
- Orbit phasing matched between flybys so that no deep space maneuvers are required
- Multiple solar encounters at various distances
- Solar distances not beyond Earth for a solar powered spacecraft


2018/08/15
A
Sun
Mercury
Venus
PSP
Earth
X (HEE)
−1.0
−0.5
0.0
0.5
1.0
Y (HEE)
−1.0
−0.5
0.0
0.5
1.0

Investigation Overview

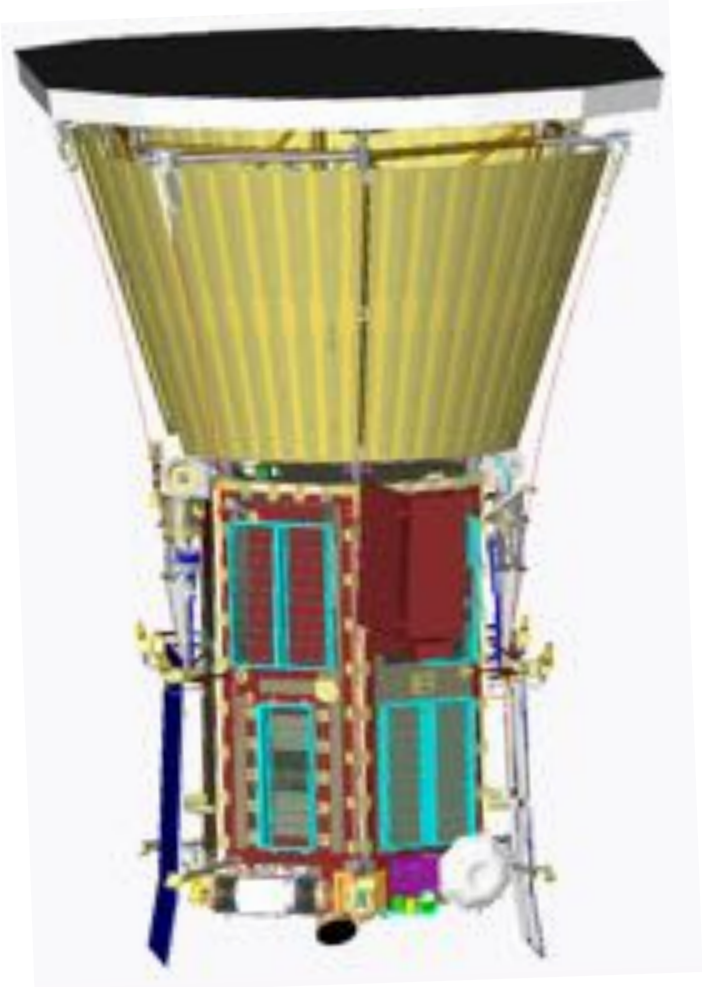
Investigation	Instruments	Principal Investigator
Fields Experiment (FIELDS)	5 x Electric Antennas 2 x Fluxgate Magnetometer (MAG) 1 x Search Coil Magnetometer (SCM)	Prof. Stuart D. Bale, University of California Space Sciences Laboratory, Berkeley, CA
Integrated Science Investigation of the Sun ~~(ISIS)~~	High energy Energetic Particle Instrument (EPI-Hi) Low energy Energetic Particle Instrument (EPI-Lo)	Prof ~~D~~r. David J. McComas, ~~Southwest Research Institute, San Antonio, TX~~ Princeton Univ
Solar Wind Electrons Alphas and Protons (SWEAP)	Solar Probe Cup (SPC) 2 Solar Probe ANalyzers (SPAN)	Prof ~~D~~r. Justin Kasper, University of Michigan, Ann Arbor, MI & Sm~~ithsonian Astrophysical Observatory~~, Cambridge, MA
Wide-field Imager for Solar PRobe (WISPR)	White light imager	Dr. Russ Howard, Naval Research Laboratory, Washington, DC
Heliospheric Origins with Solar Probe Plus (HeliOSPP)	Observatory Scientist - addresses SPP science objectives via multi-instrument data analysis to optimize the scientific productivity of the mission	Prof ~~D~~r. Marco Velli, ~~Jet Propulsion Laboratory, Pasadena~~, CA UCLA

PSP remote sensing – ‘WISPR’



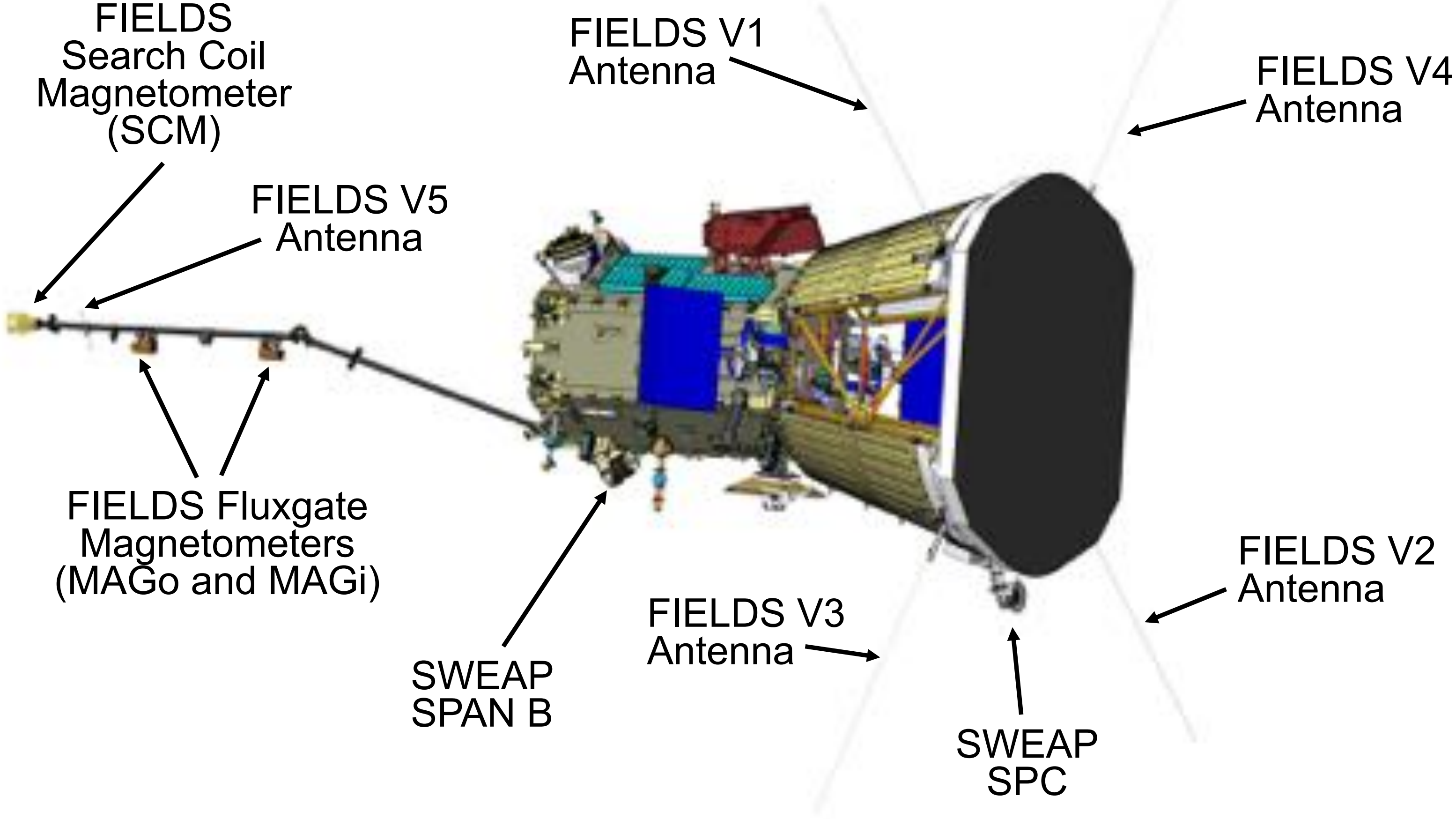
Simulated WISPR Observation during 9.8Rs perhelion passage. Fly-through a Streamer Stalk of 0.15Rs radius with fine-scale structure (filaments are **1400 km-wide**).
Movie duration = **30 min**.

Spacecraft Overview

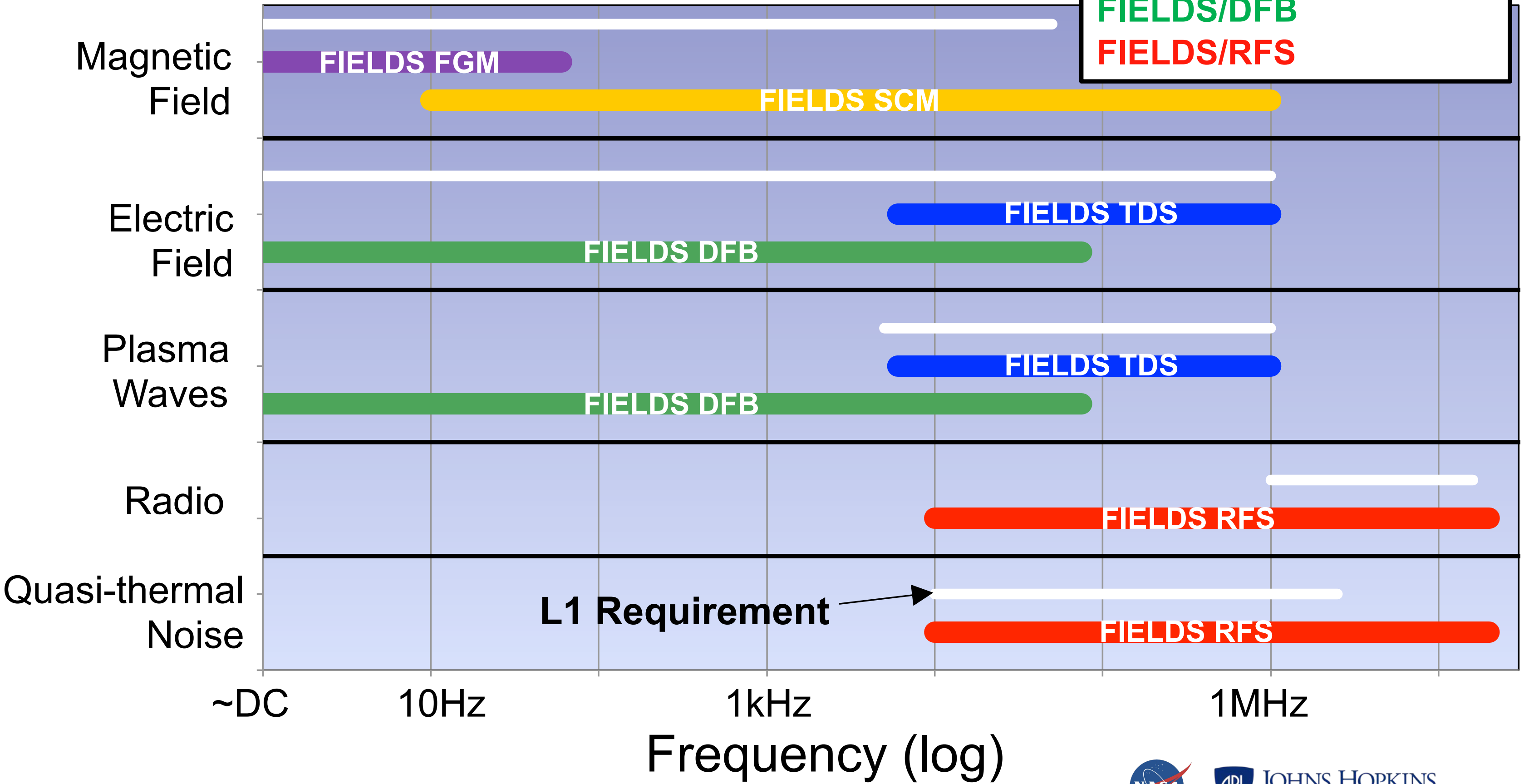


- NASA selected instrument suites
- 685kg max launch wet mass
- Reference Dimensions:
    - S/C height: 3m
    - TPS max diameter:2.3m
    - S/C bus diameter: 1m
- C-C Thermal protection system
- Hexagonal prism s/c bus configuration
- Actively cooled solar array
    - 388W electrical power at encounter
    - Solar array total area: 1.55m^2
    - Radiator area under TPS: 4m^2
- 0.6m HGA, 34W TWTA Ka-band science DL
- Science downlink rate: 167kbps at 1AU

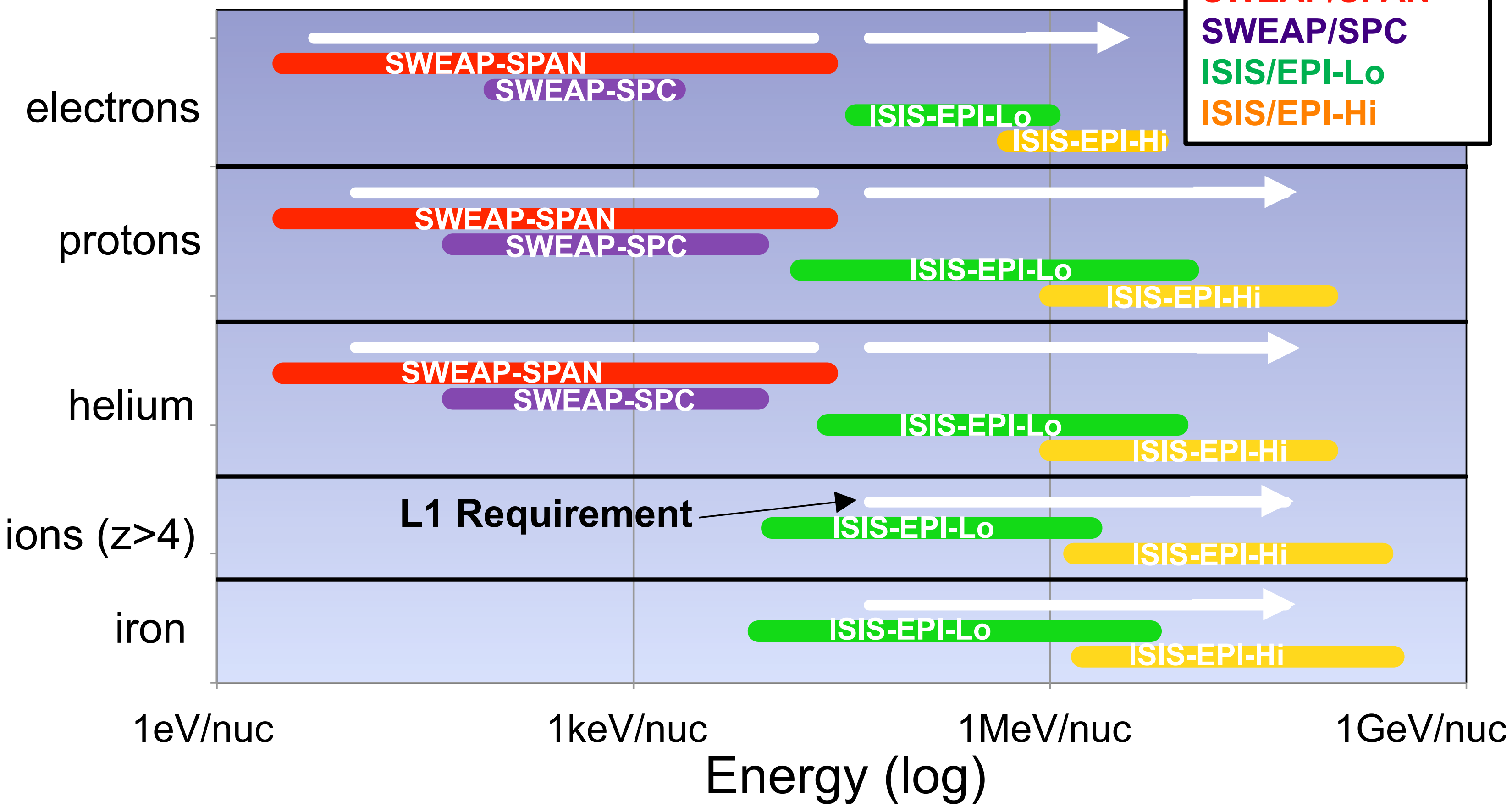
Payload Accommodation on S/C (1/3)



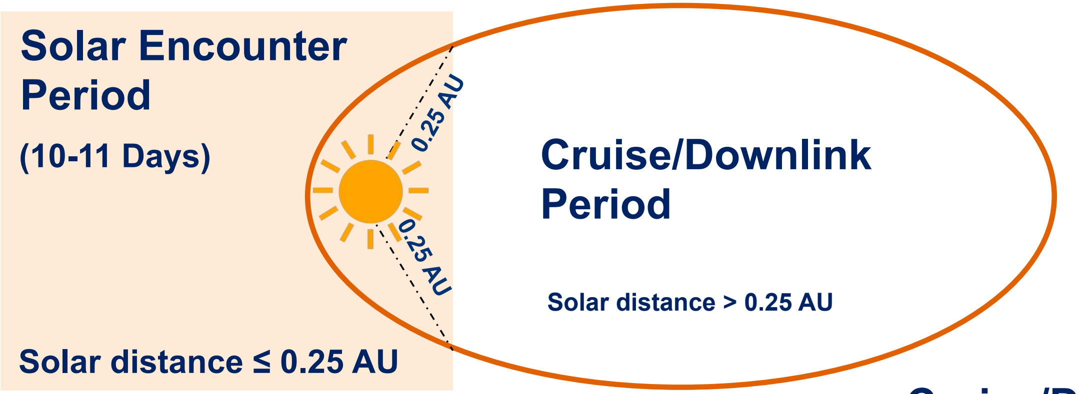
Fields & Waves Instrument capabilities meet Level 1 requirements with margin



Particle Instrument capabilities meet Level 1 requirements with margin



Payload Overview - Operations



24 Solar Encounter Orbits

Orbital Periods Vary (168 to 88 days)

Solar Encounter Period

- **Encounter Operations**
  - Primary science data collection phase – All instruments powered on
  - LGA or Fanbeam antenna periodically available for comm & nav data
  - No recorded data playback

Cruise/Downlink Period

- **Cruise Operations**
  - Instruments Powered On (Sun distance < 0.82 AU)
  - Instruments may be off during special activities
  - Fanbeam for comm – HSK data only; LGA during maneuvers
  - Commanding as needed to support S/C maintenance
- **Science Downlink Operations**
  - All instruments powered off
  - HGA for comm – recorded data playbacks
  - Commanding as needed to support S/C maintenance

Status

Launch window opens July 31, 2018!
Delayed to NET August 11
Spacecraft is fully integrated
Being integrated to 3rd stage
Move to Complex 37 in one week

Summary/End

- The inner heliosphere is the birthplace of the solar wind
- The plasma conditions are likely to be very ‘kinetic’ and transient: large plasma pressure anisotropies, nonthermal particle populations, inter-species drifts, structured turbulence, etc
- NASA Parker Solar Probe will go to within the Alfven surface and make the first *in situ* measurements of this environment
- Solar Orbiter, DKIST, SKA, and other assets come online in the same timeframe: **a golden age for coronal and solar wind physics!**