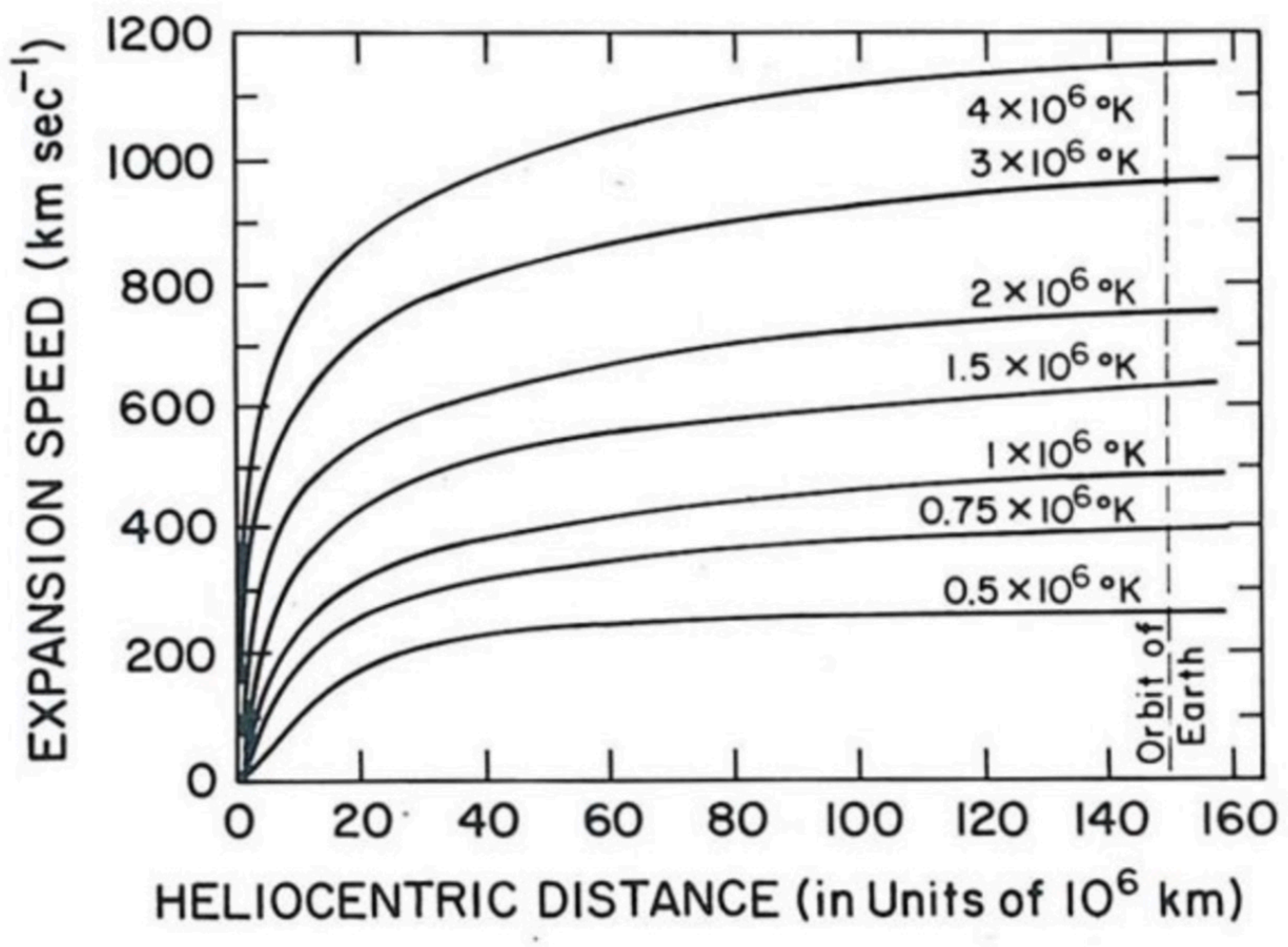
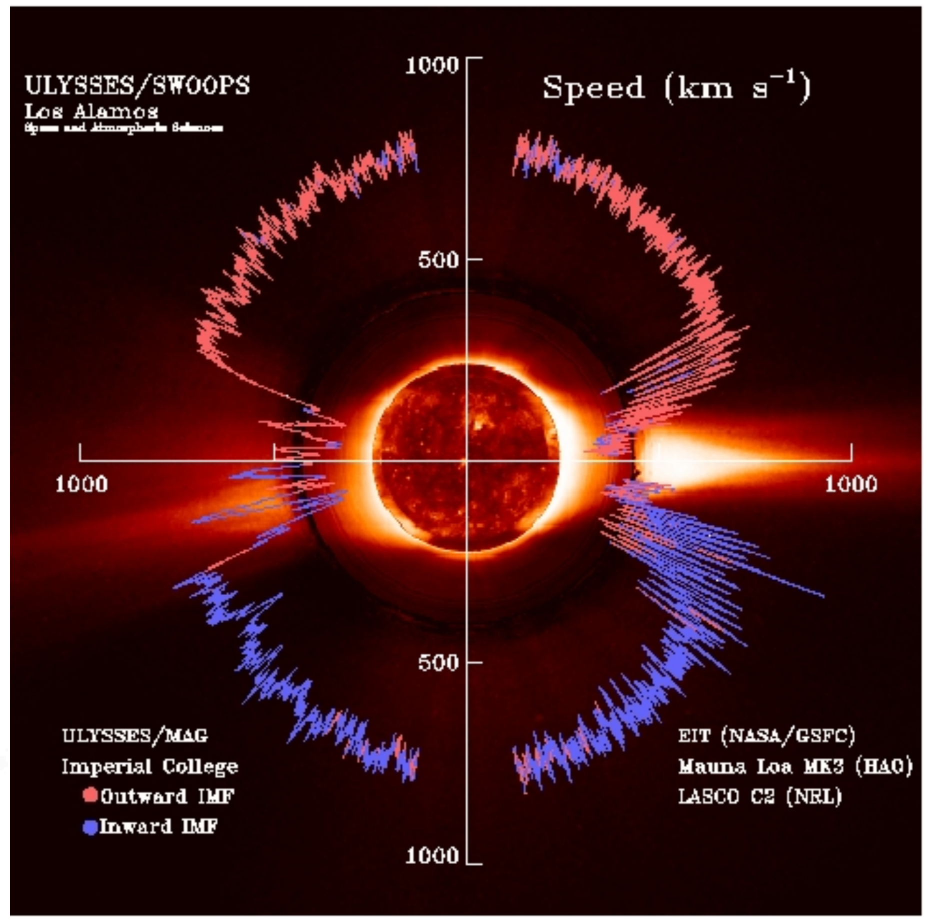
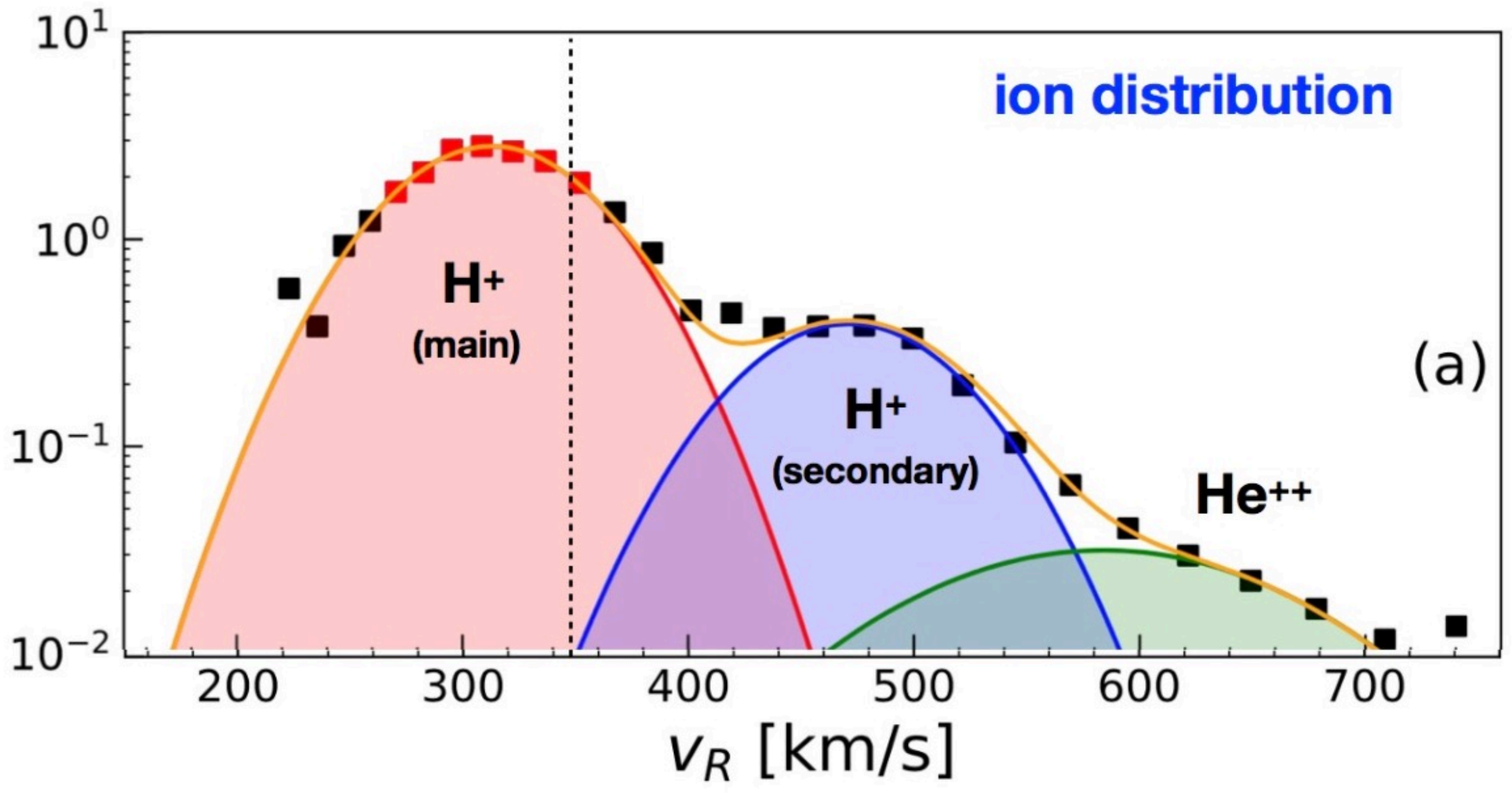
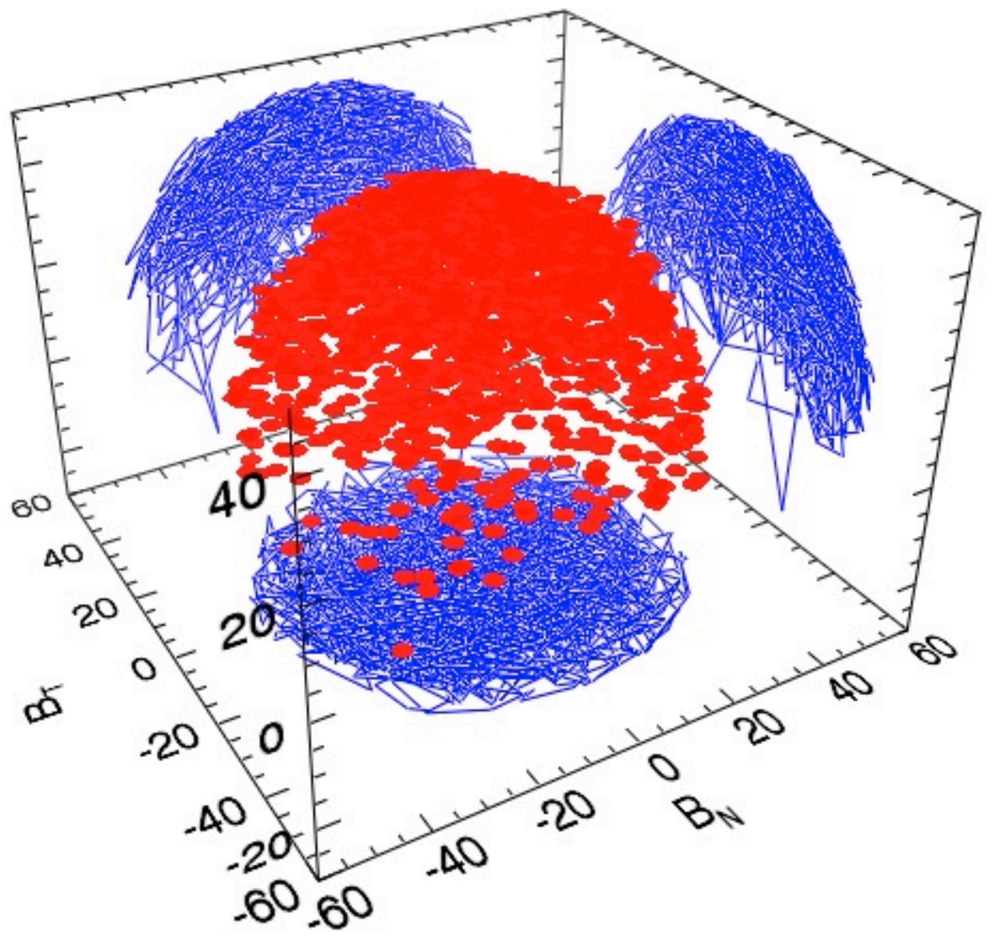
Multi-scale nature of the solar wind

Lorenzo Matteini
Imperial College London









Introduction

About me

Research interests: space plasmas, kinetic physics, MHD waves, turbulence and wave-particle interactions

Applications: solar wind, magnetospheres (magnetosheath), cometary environments

Methodology: numerical simulations (kinetic-hybrid), in situ data analysis (PSP, Solar Orbiter, Helios, Ulysses)

About the lecture

1. Part I: Large scale fluctuations in solar wind – fluid/MHD description
2. Part II: Small scales – Kinetic physics

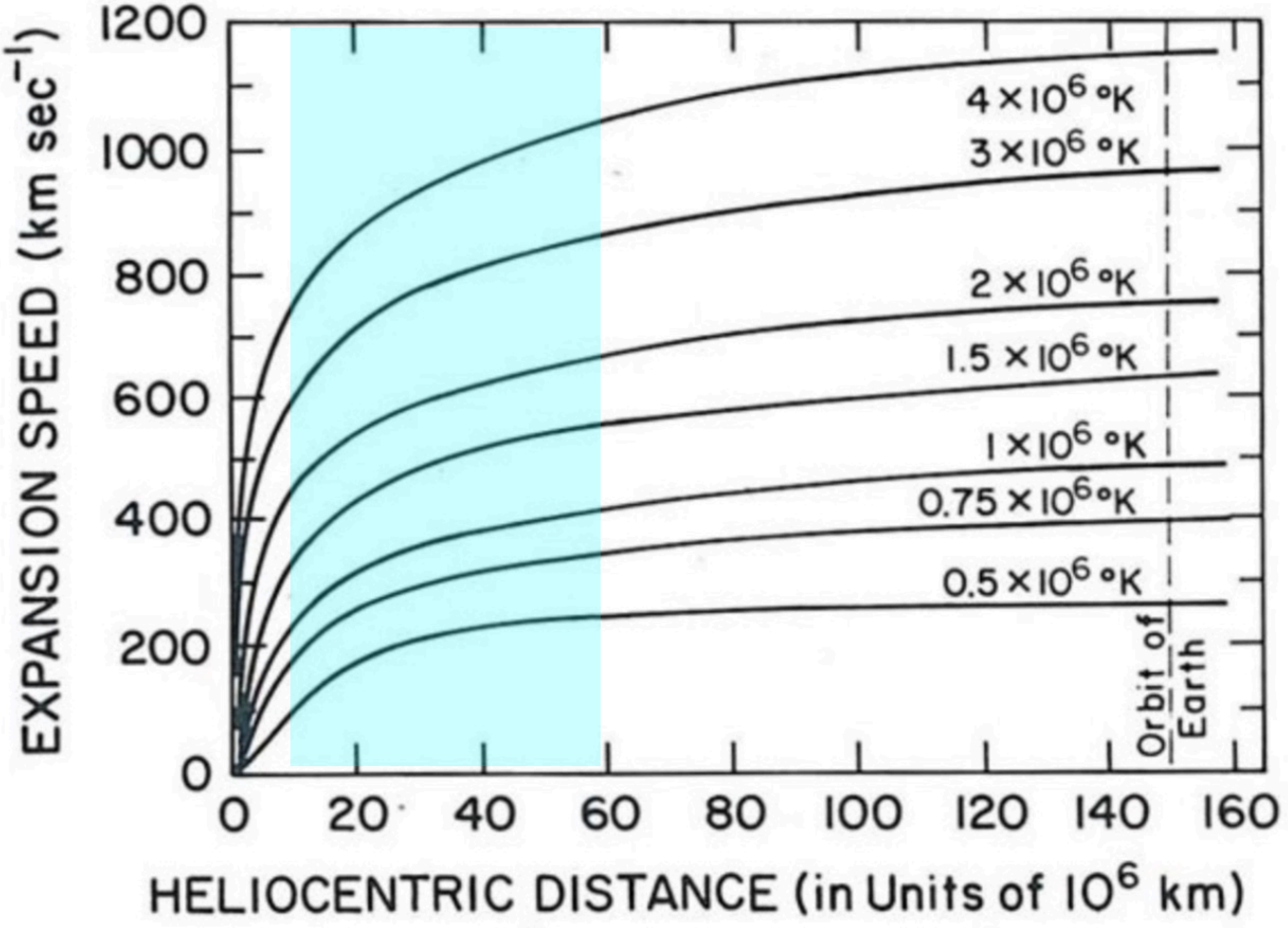
About you

Keywords:

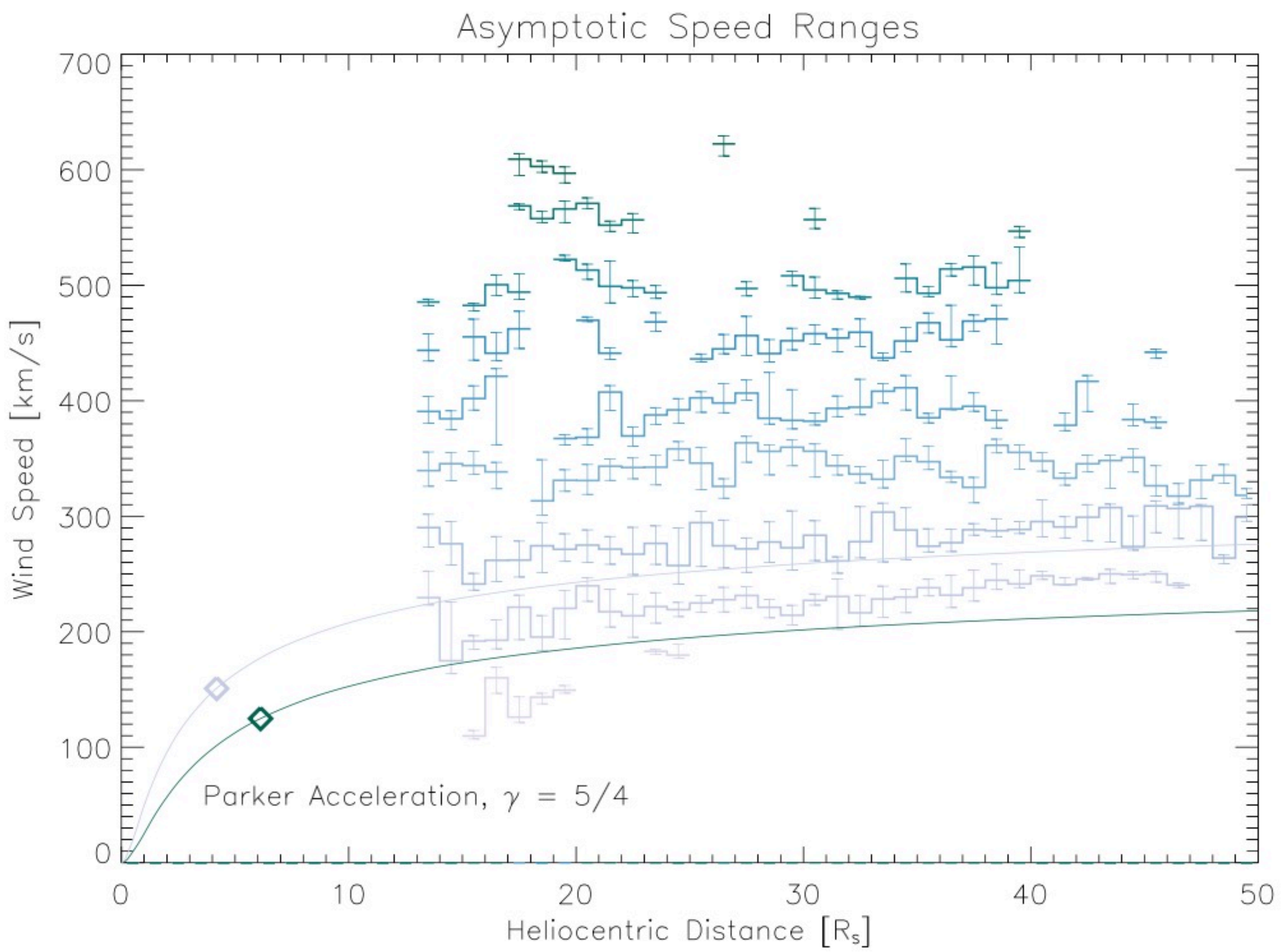
Alfvén waves, Turbulence, Switchbacks, Kinetic physics, wave-particle interactions, non-thermal distributions, micro-instabilities, SW in situ data

Solar wind – Parker model

The Parker solar wind model (*Parker 1958*)

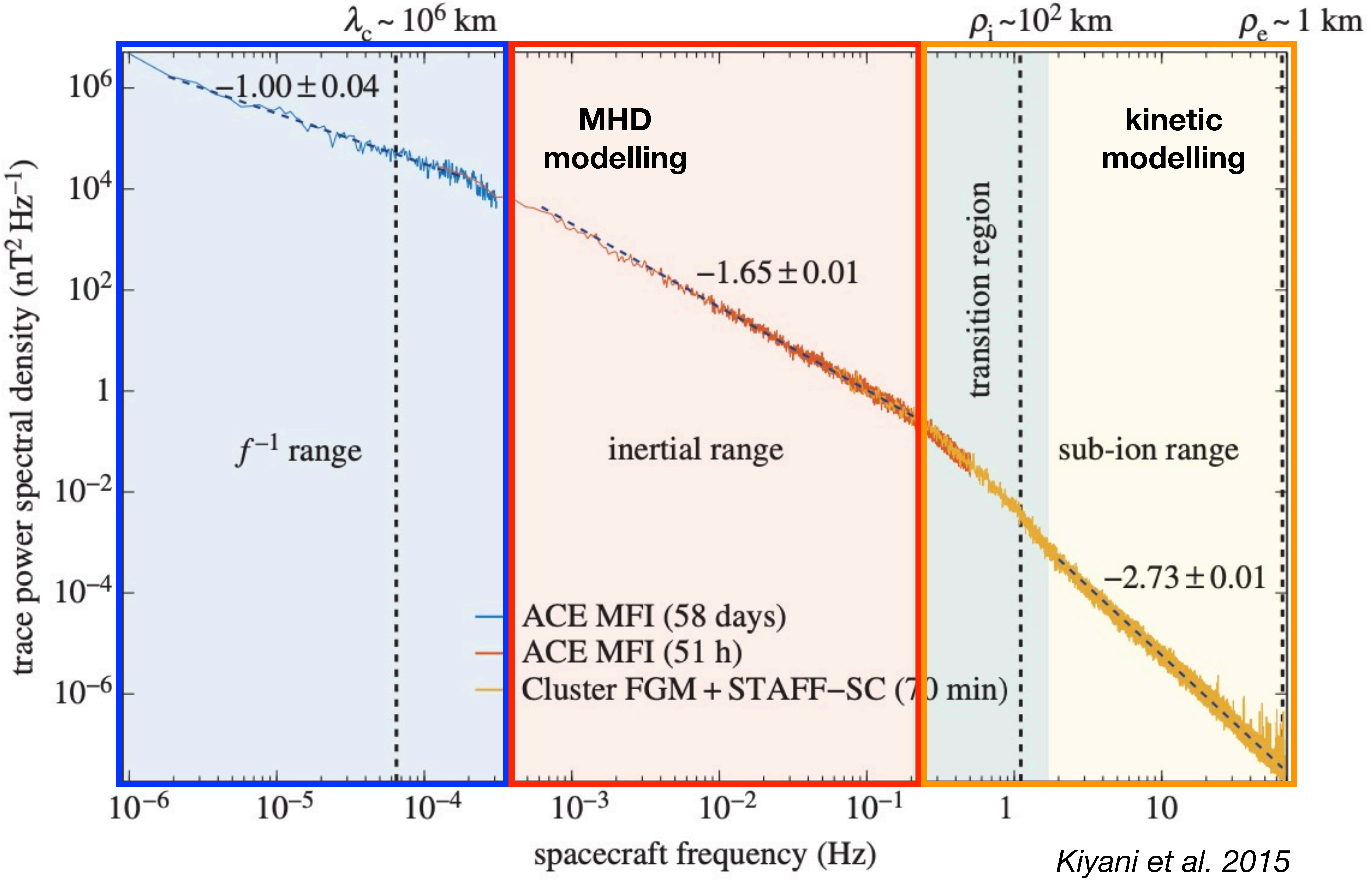


PSP data *(Halekas et al. ApJ 2022)*



The Parker model (fluid, wind pushed by Coronal high pressure) can account for the acceleration of the slow solar wind (2-300 km/s), but not of the fast solar wind (~700km/s). The acceleration mechanism of fast solar wind, which is originating from open field regions at the Sun (coronal holes) is still unknown! An additional source of energy/momentum is needed.

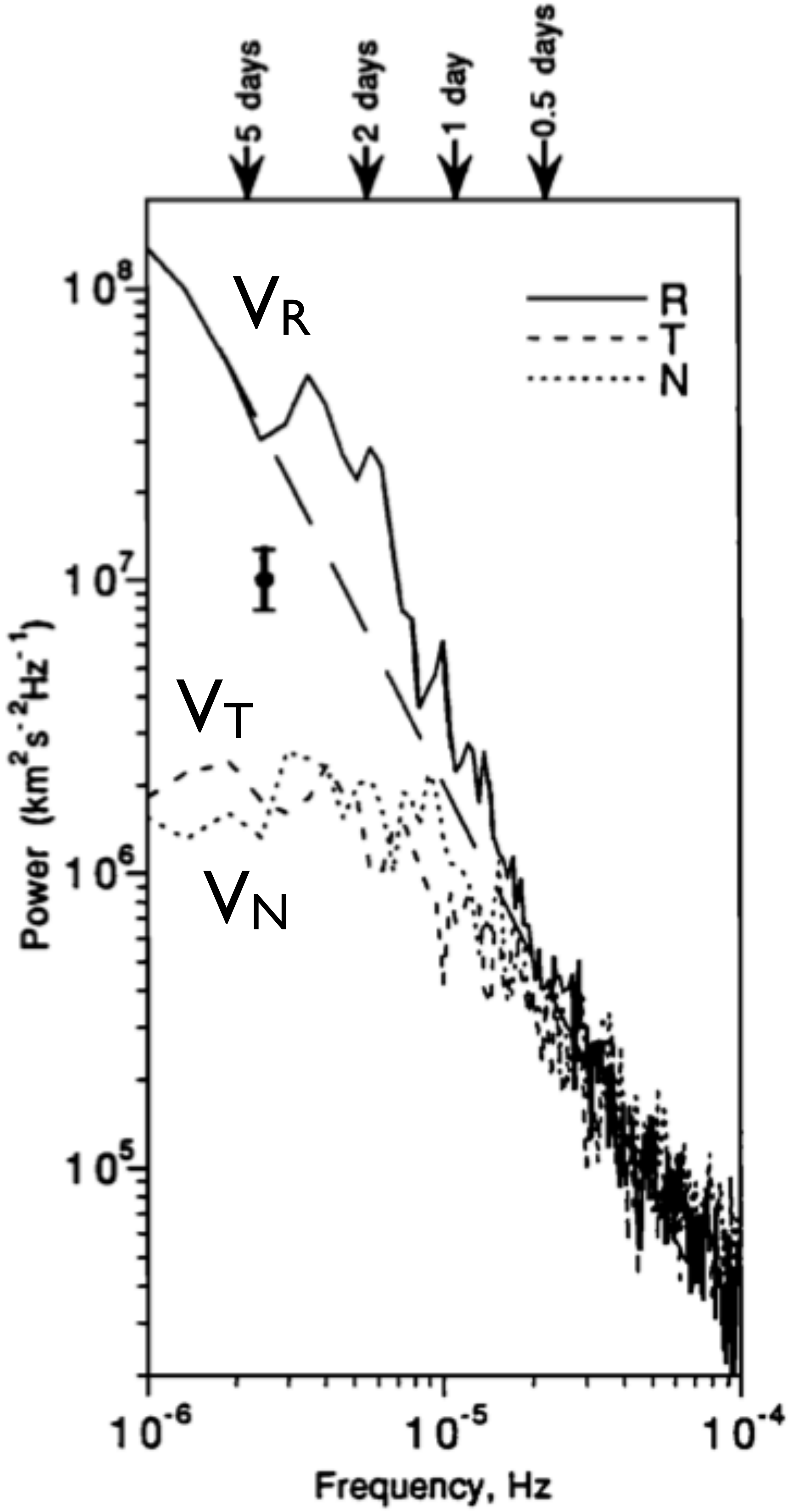
The multi-scale solar wind: Magnetic field spectrum

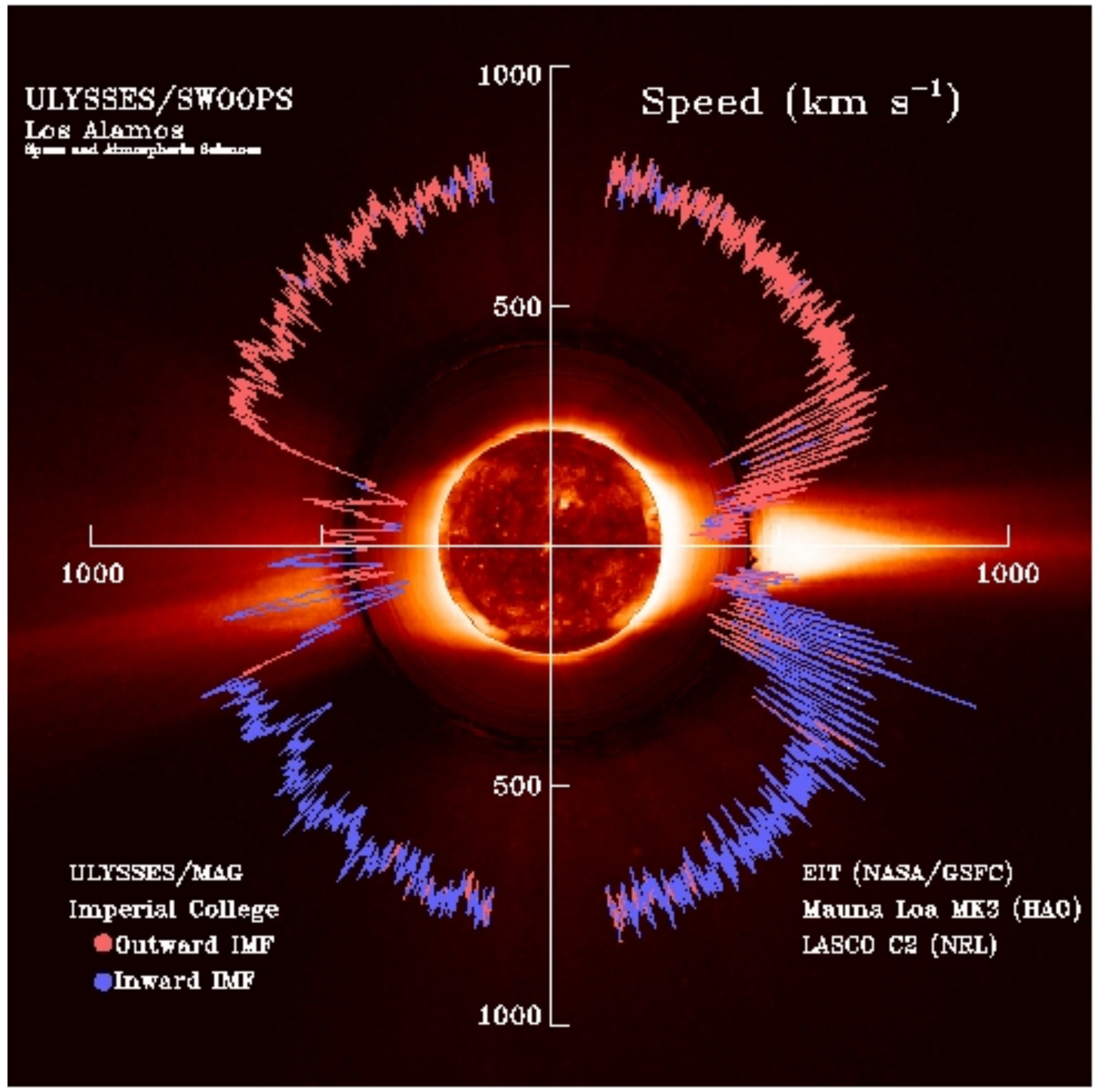


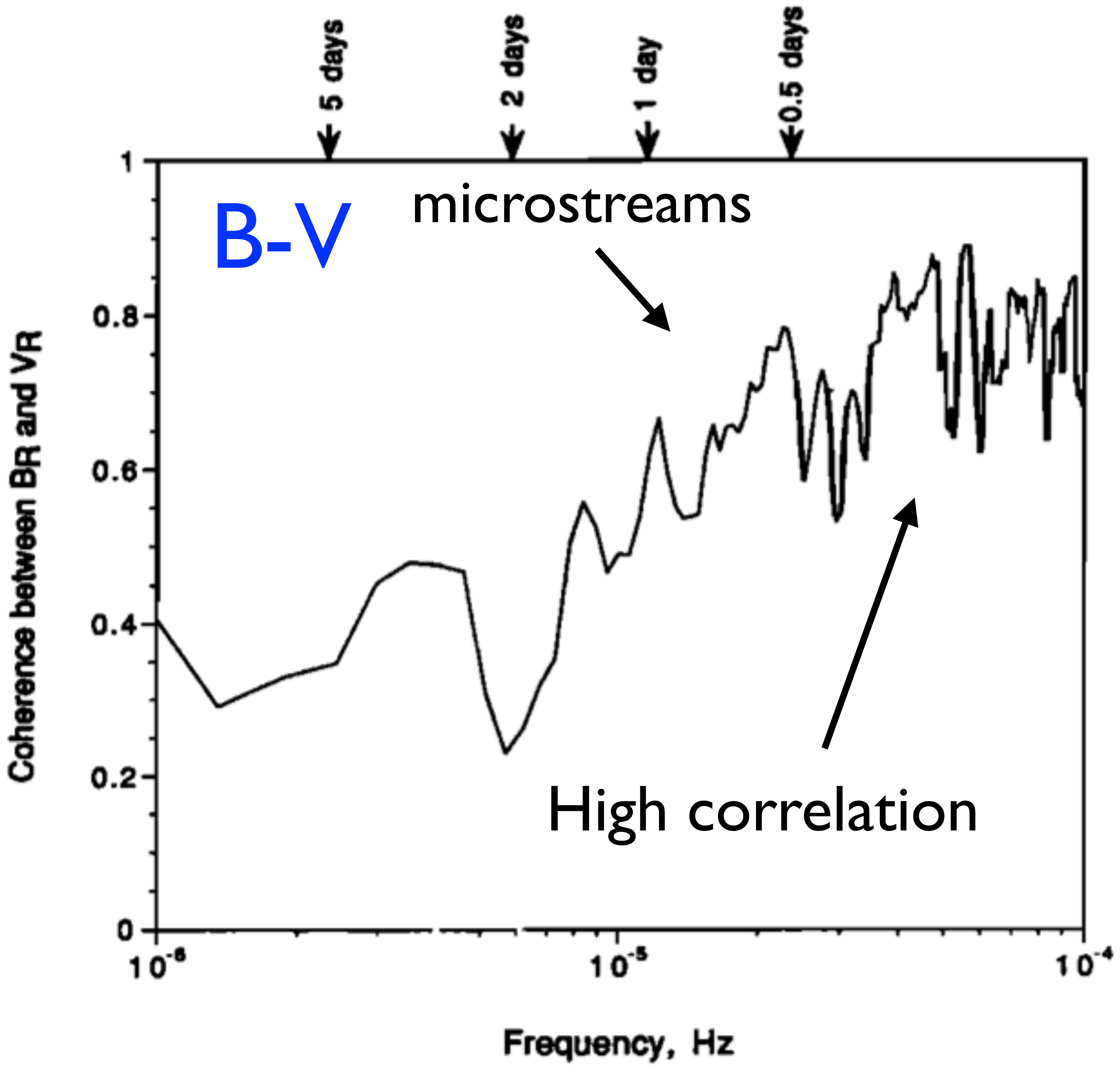
See also the review: “The multi-scale nature of the solar wind”, *Verscharen et al. 2019*

Solar wind velocity fluctuations

Ulysses observations, high latitude fast SW (*Neugebauer et al, 1995*)

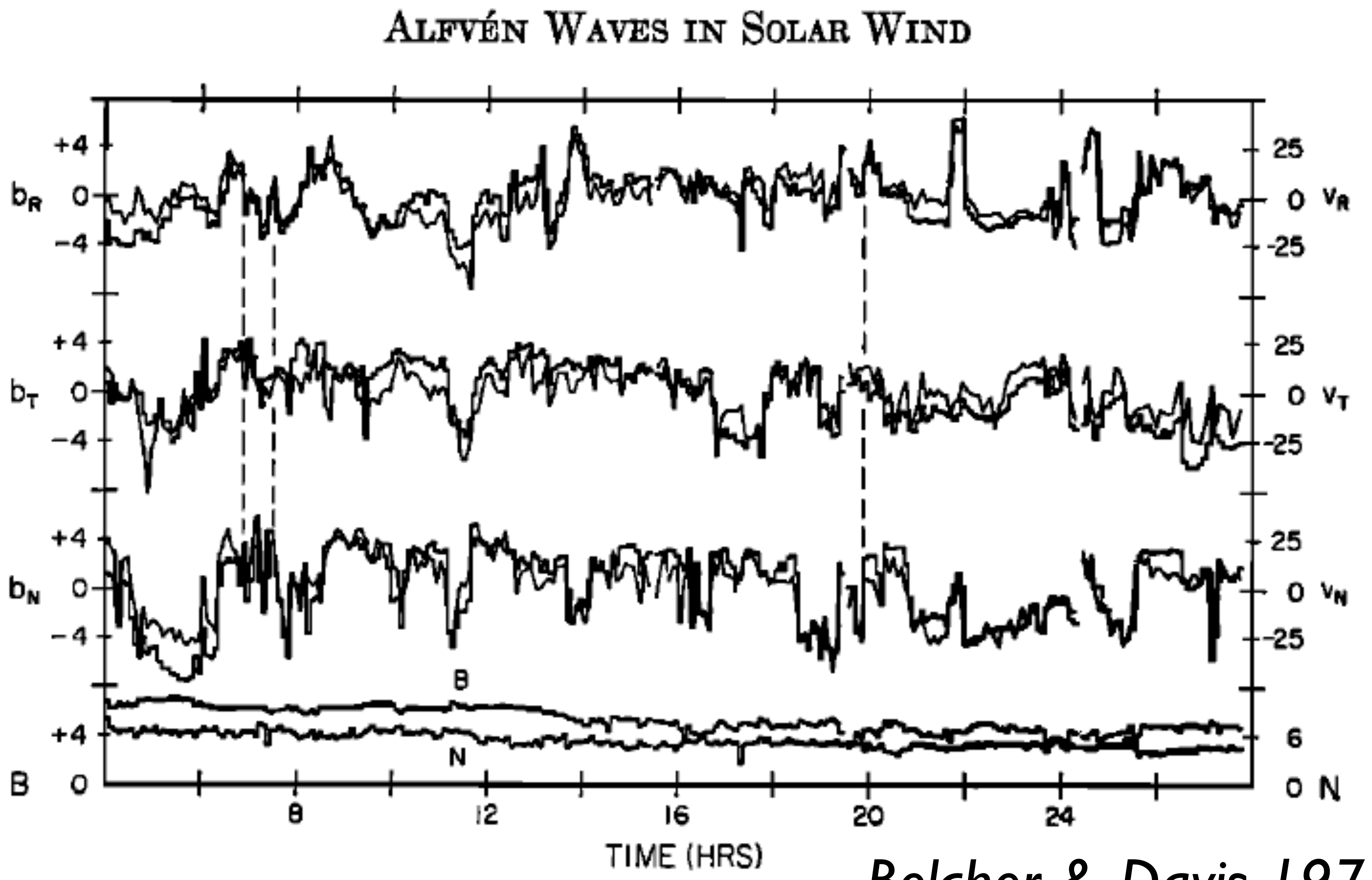






At smaller scales (less than a day) all velocity components become comparable in amplitude and highly coupled with magnetic field fluctuations

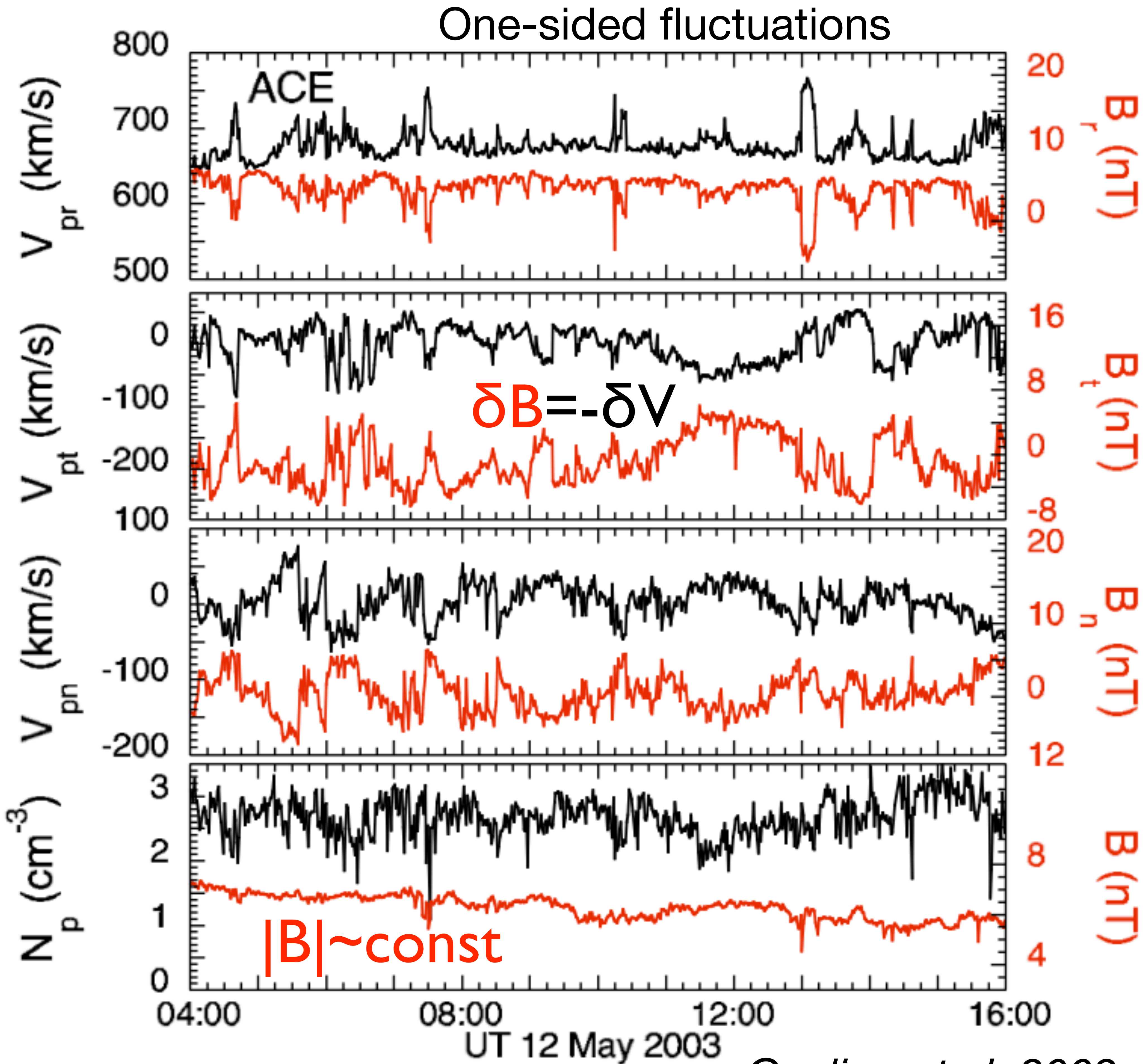
Alfvénic fluctuations in fast wind



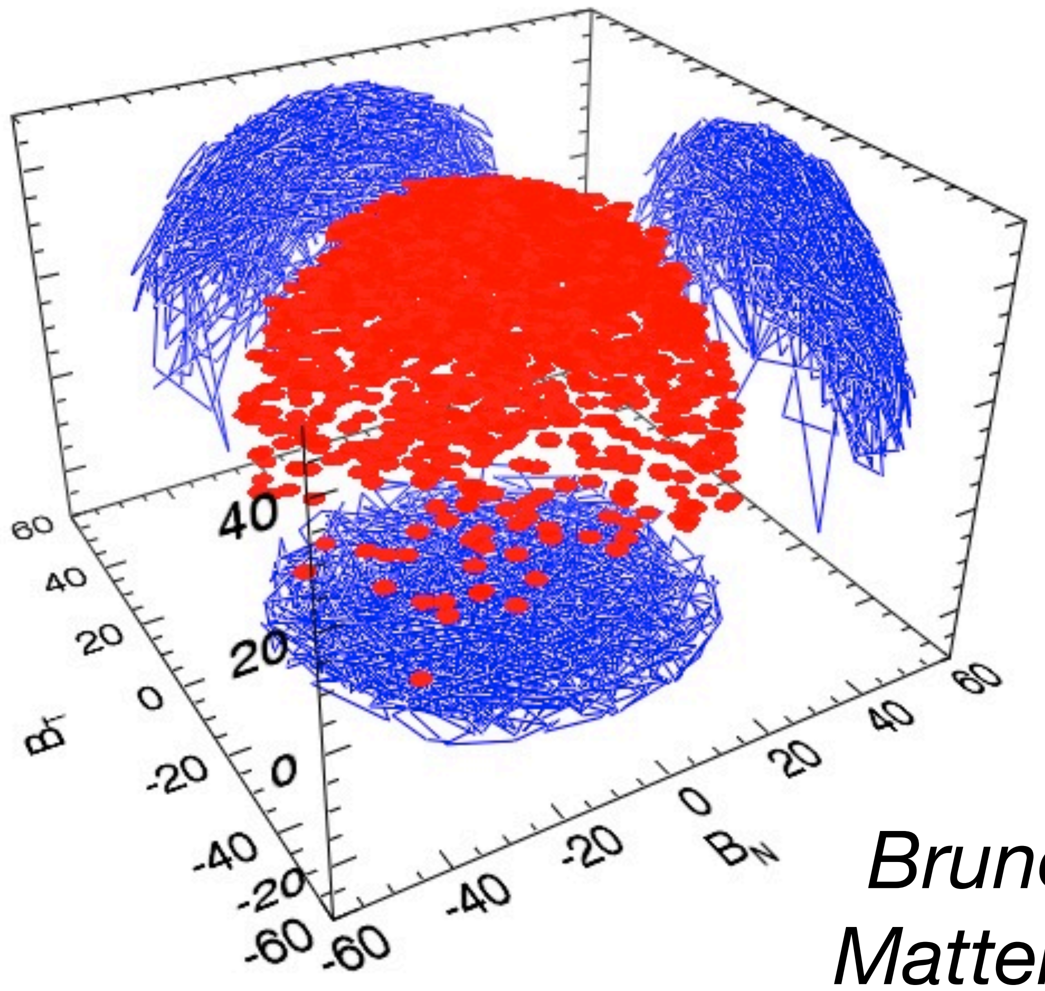
Belcher & Davis 1971

Correlation between magnetic and velocity fluctuations: $\delta\mathbf{B}/B_0=\pm\delta\mathbf{V}/V_A$

Anti-sunward waves propagating at the Alfvén speed V_A



Gosling et al. 2009



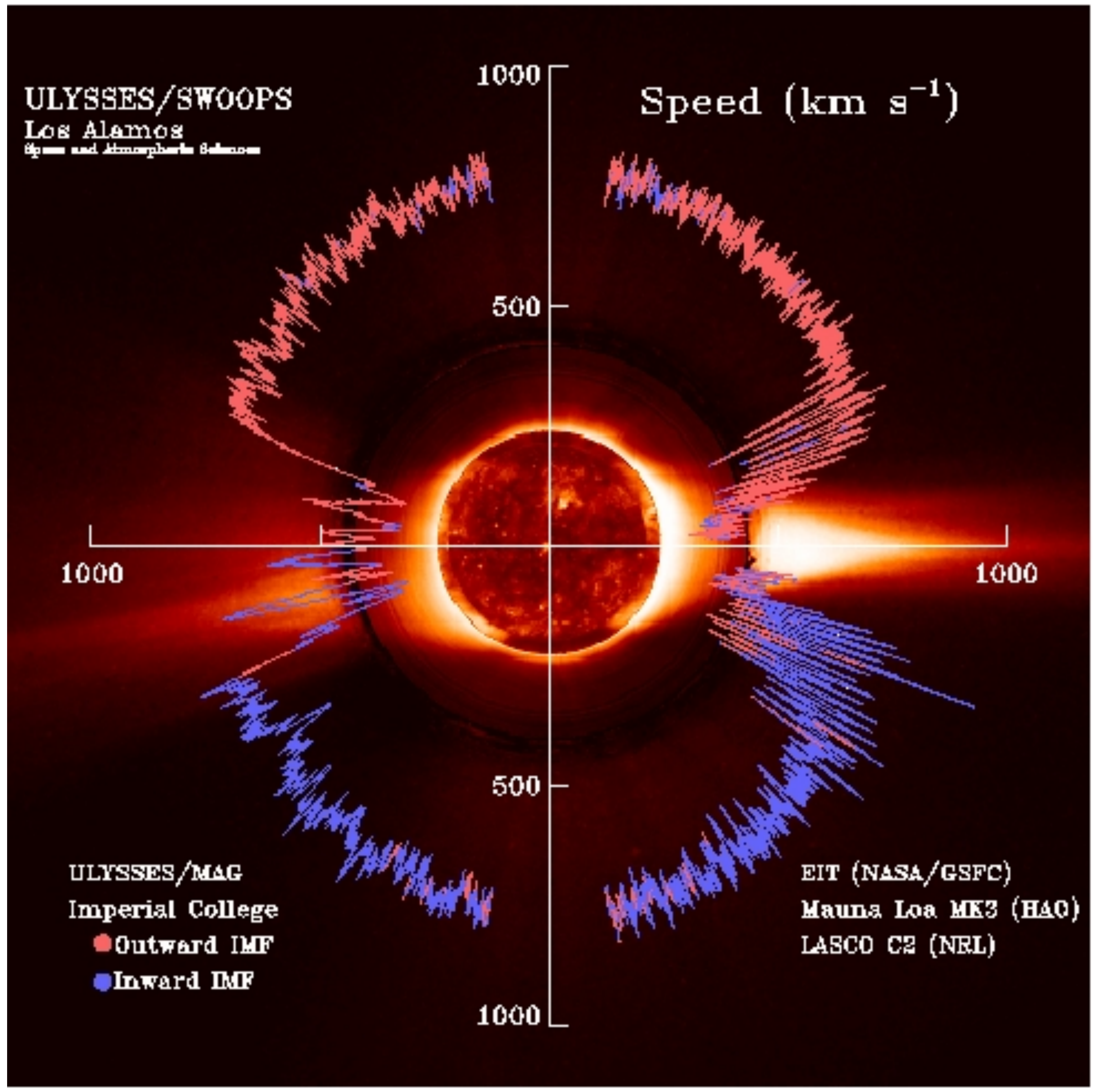
Bruno et al. 2004
Matteini et al. 2015

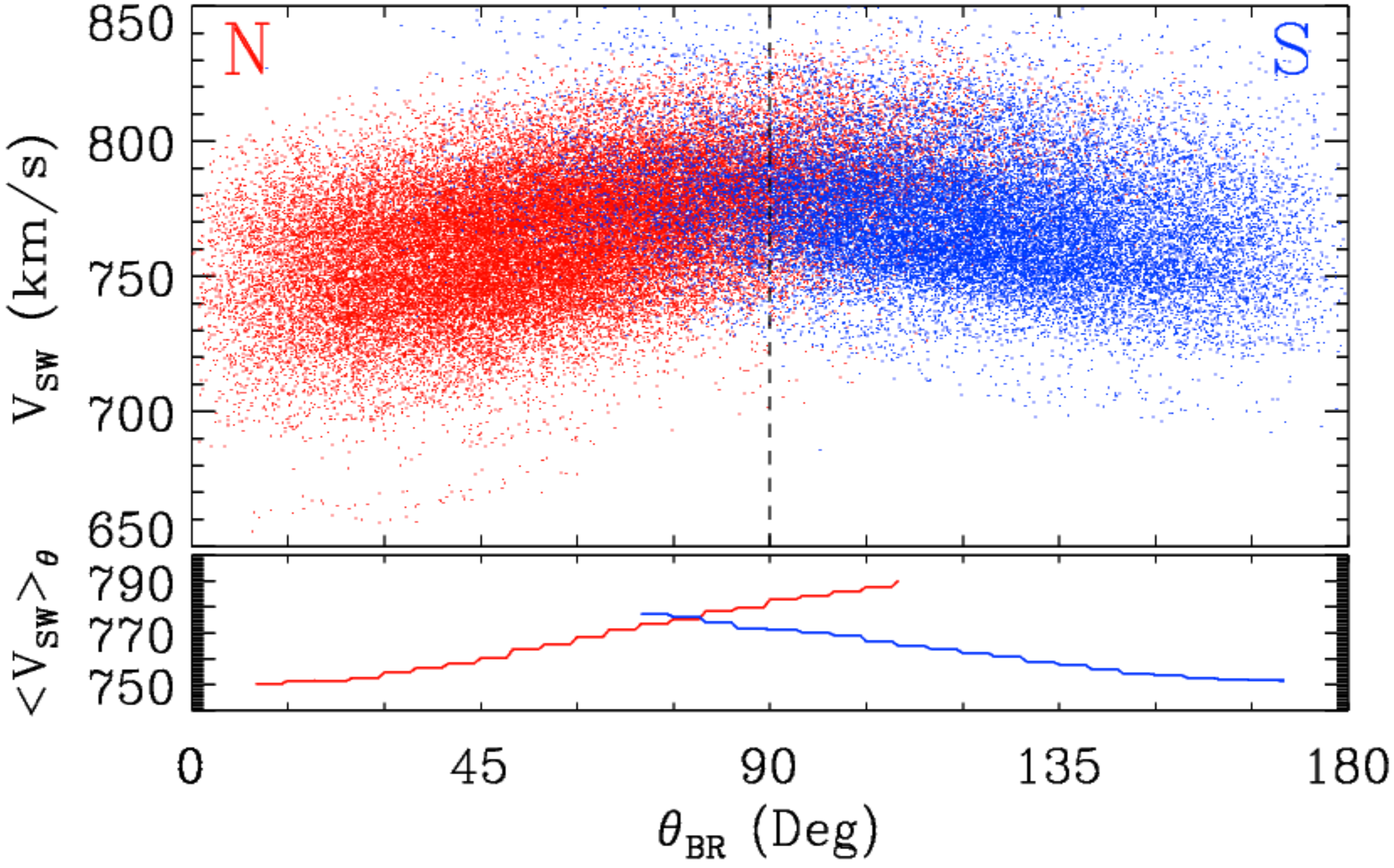
$\mathbf{B^2 = (B_x^2+B_y^2+B_z^2) = const.}$

Magnetic field vector is constrained on a sphere

Solar wind speed vs. θ_{BR}

Speed is larger when θ_{BR}~90 than when the field is parallel (N) or antiparallel (S) – why??

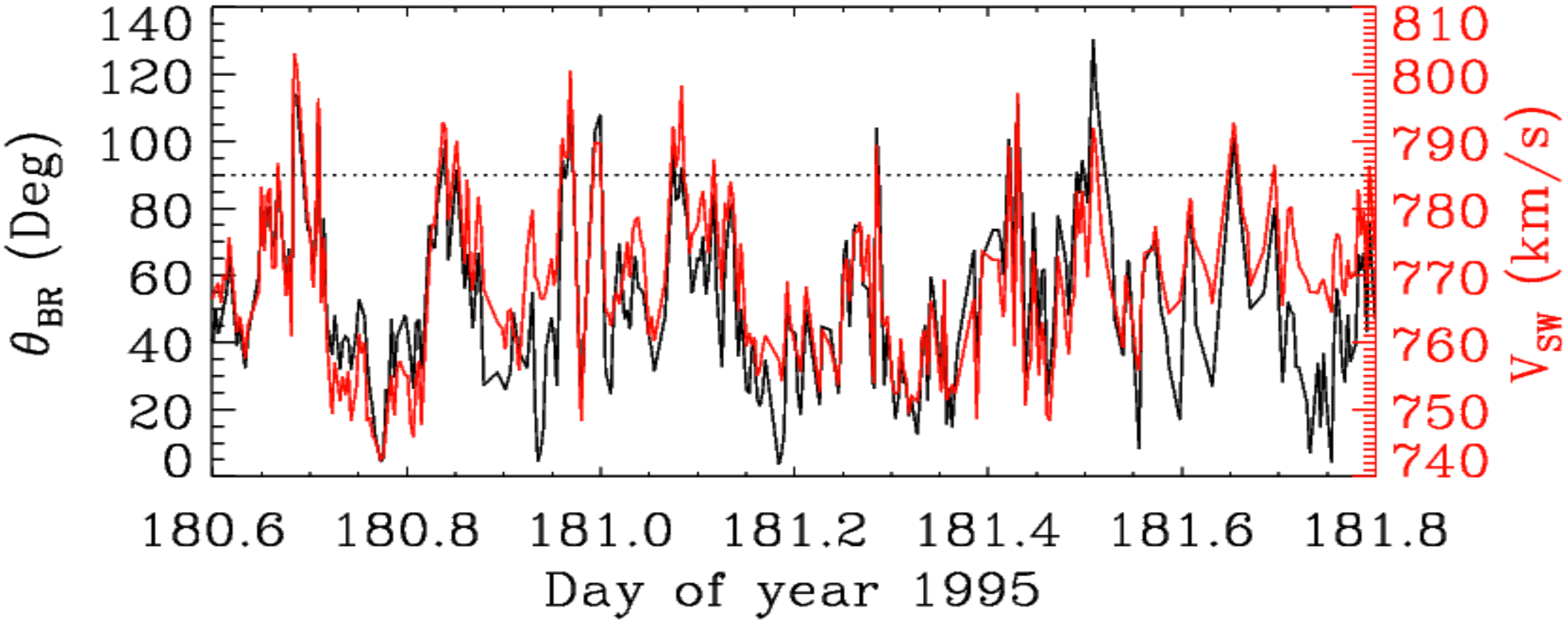




Ulysses polar passes (1994/1996)

Matteini et al, GRL 2014

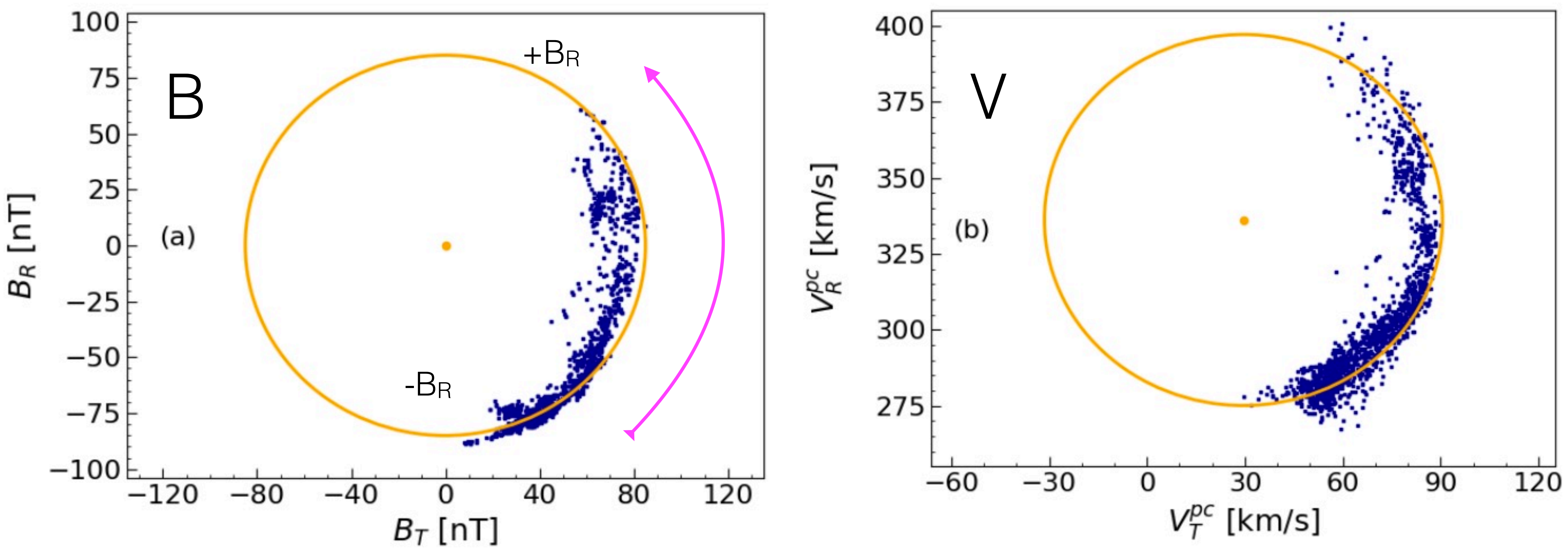
Closer look at the correlation between θ_{BR} and speed - 1 Day



Very good correlation: same trend in θ_{BR} and V_{SW} !

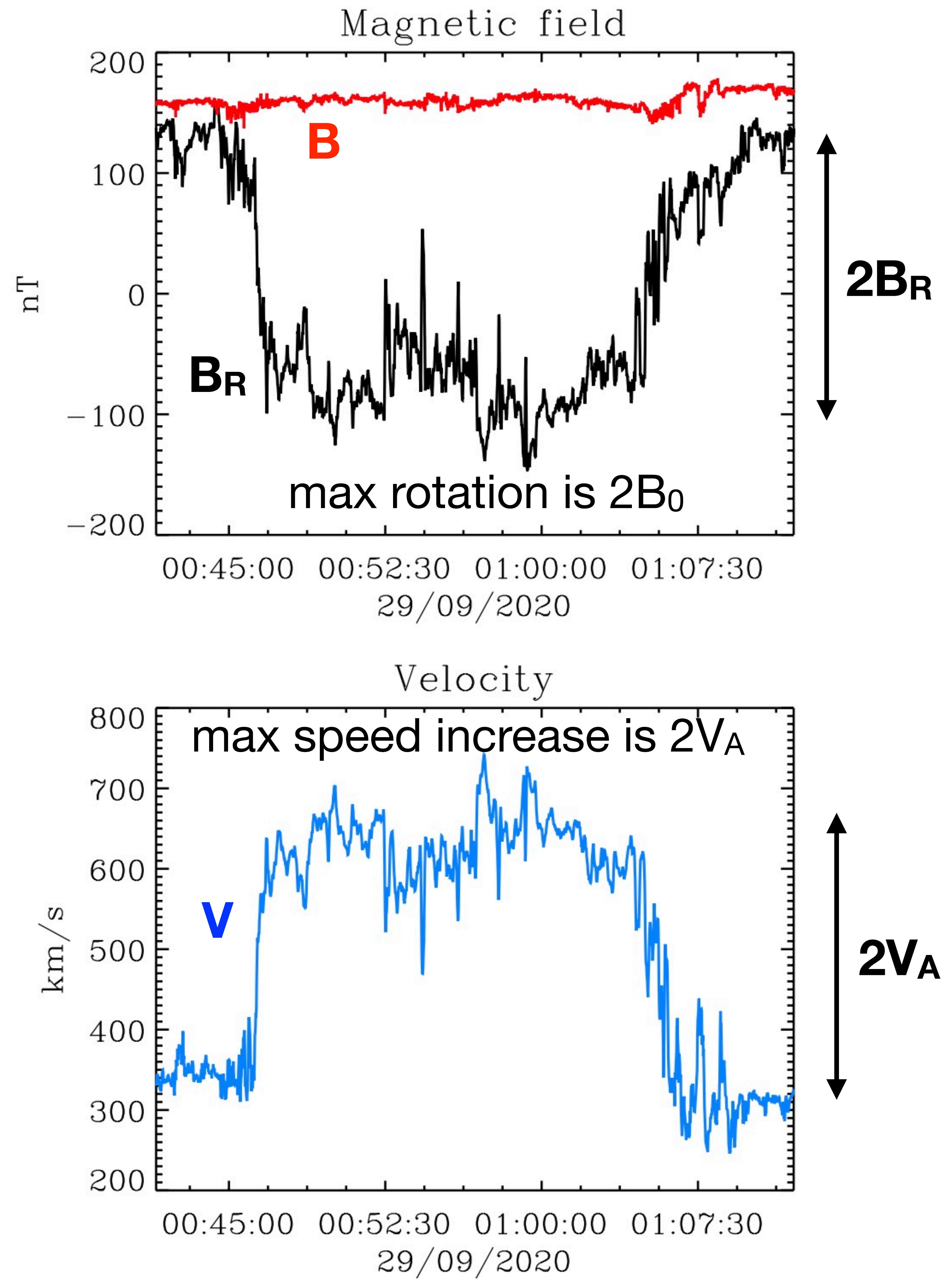
Rotations of **B** beyond θ=90° – “switchbacks”– correspond to peaks in speed

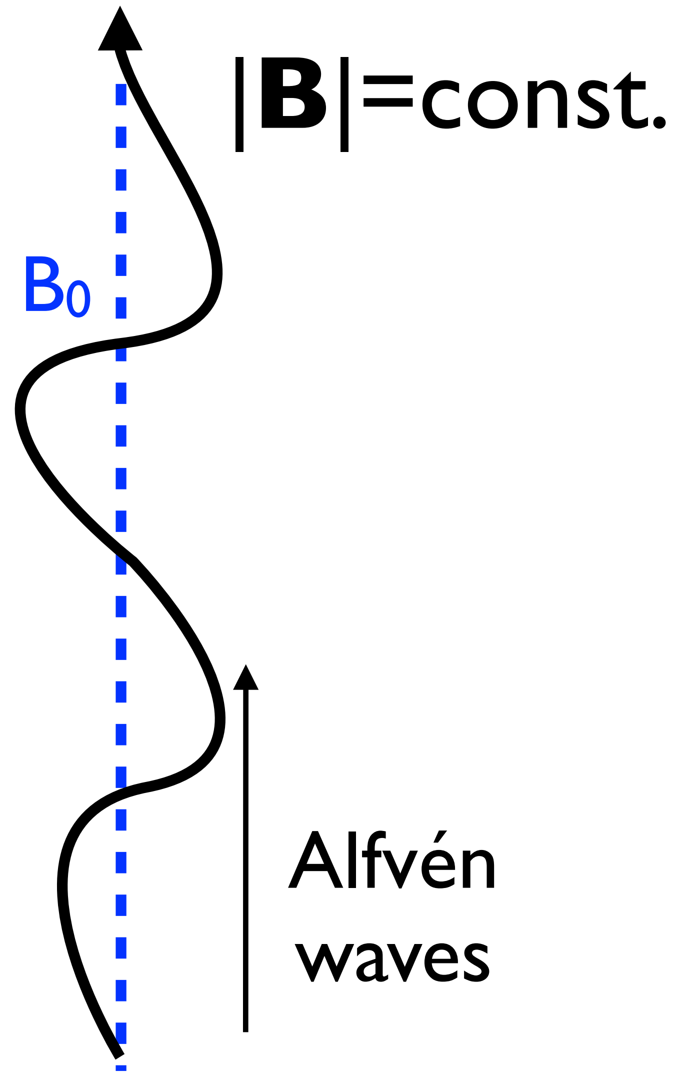
Switchbacks explained - the role of Alfvénicity: $\delta V/V_A=\delta B/B_0$

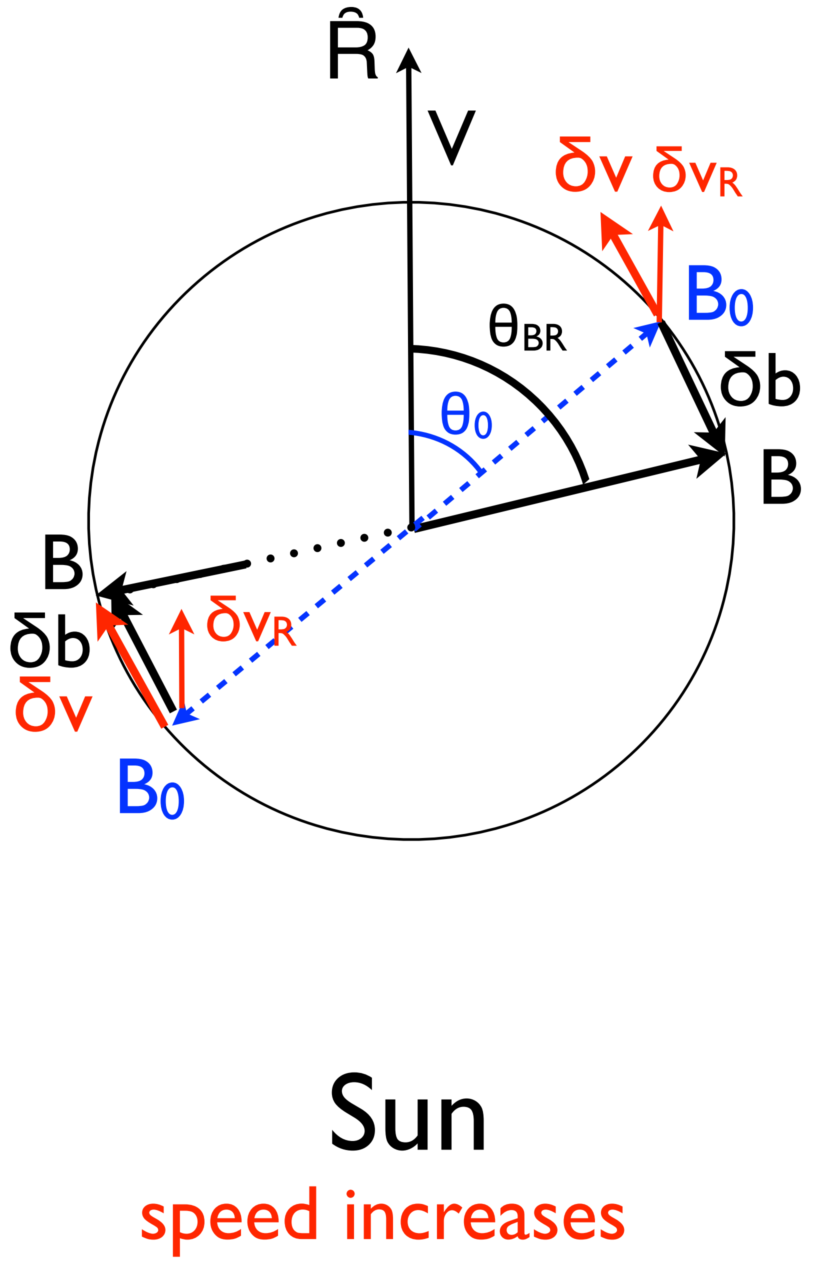


Woolley et al., MNRAS 2020

N.B. it implies centre of mass motion







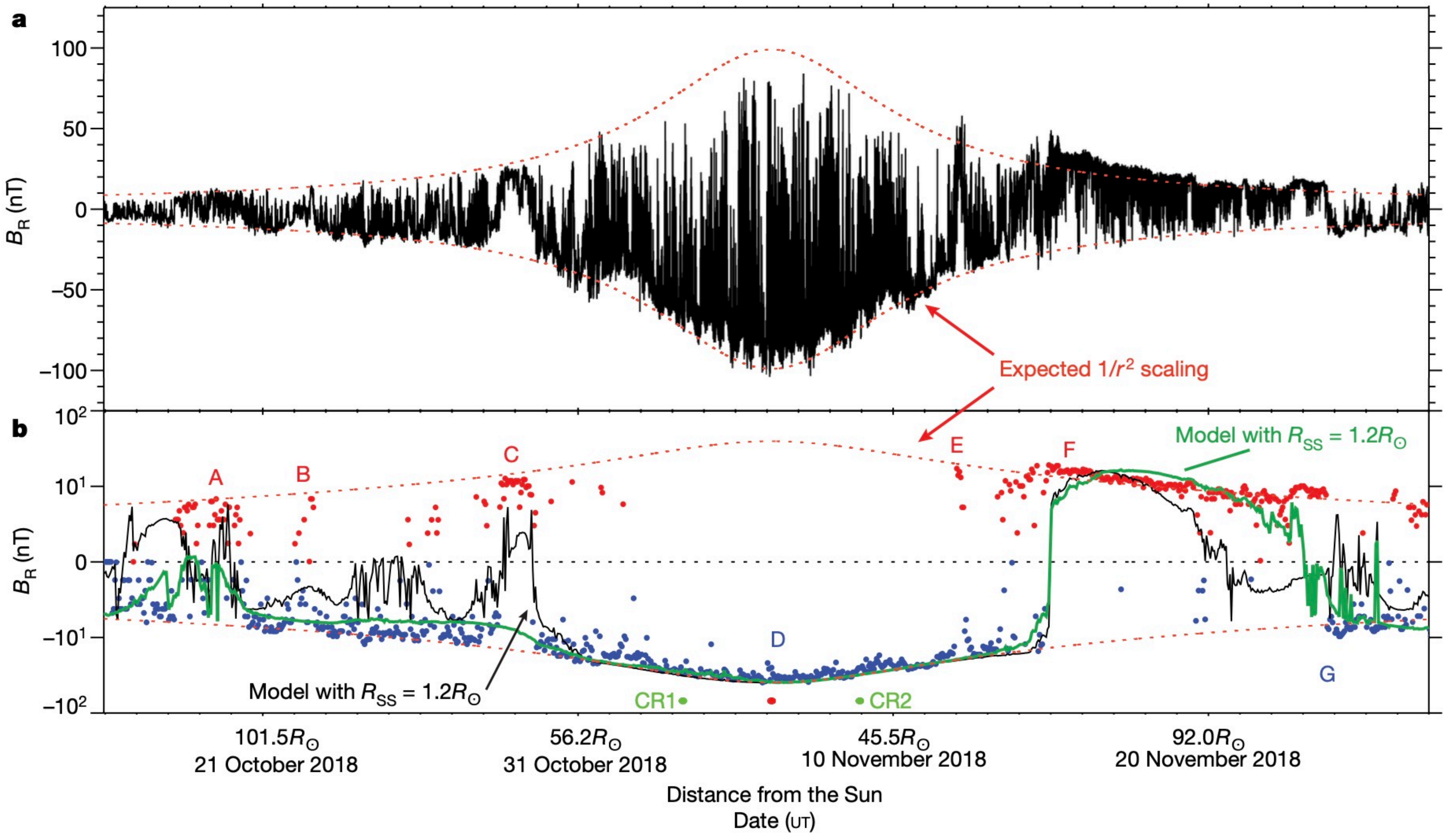
B rotations on a sphere + Alfvénic correlation = speed correlated with B angle!

Switchbacks have always velocity enhancements, regardless of the polarity of the underlying interplanetary magnetic field (Matteini et al., GRL 2014)

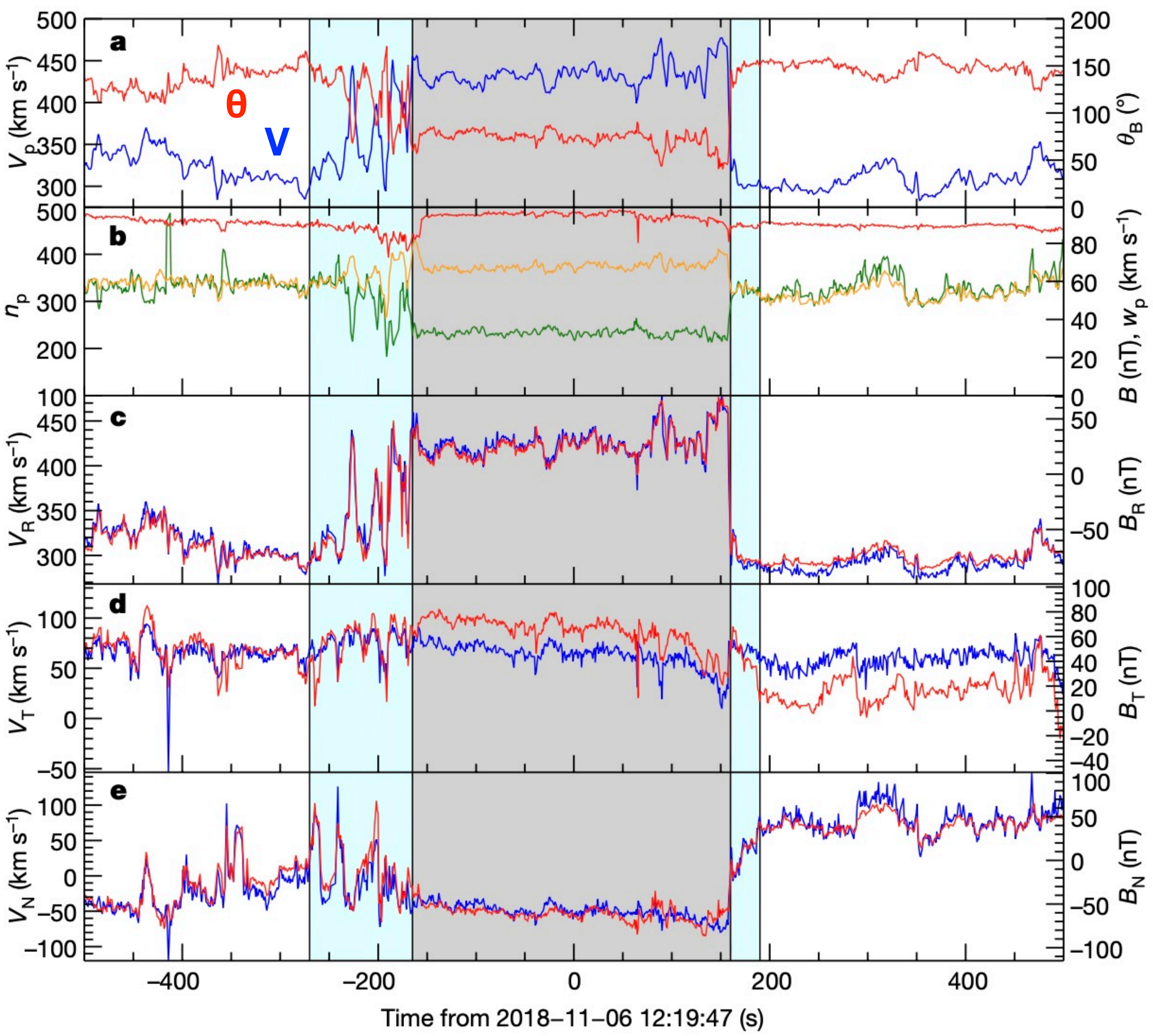
$$V = V_0 + V_A[1+\cos(\theta_{BR})]$$

$$V_{max} = V_0 + 2V_A$$

Switchbacks near the Sun with Parker Solar Probe



Bale et al., Nature 2019

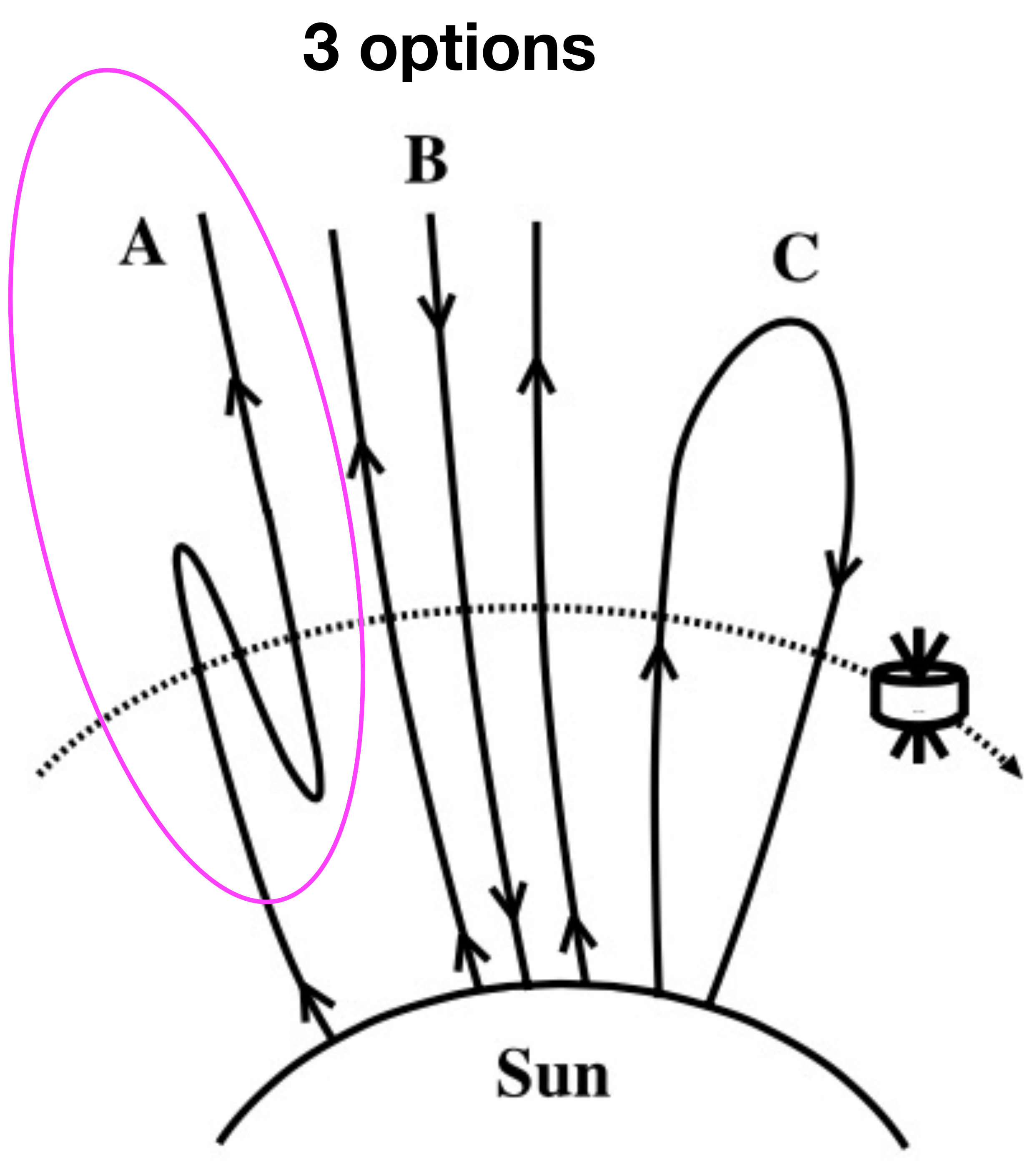


Kasper et al., Nature 2019

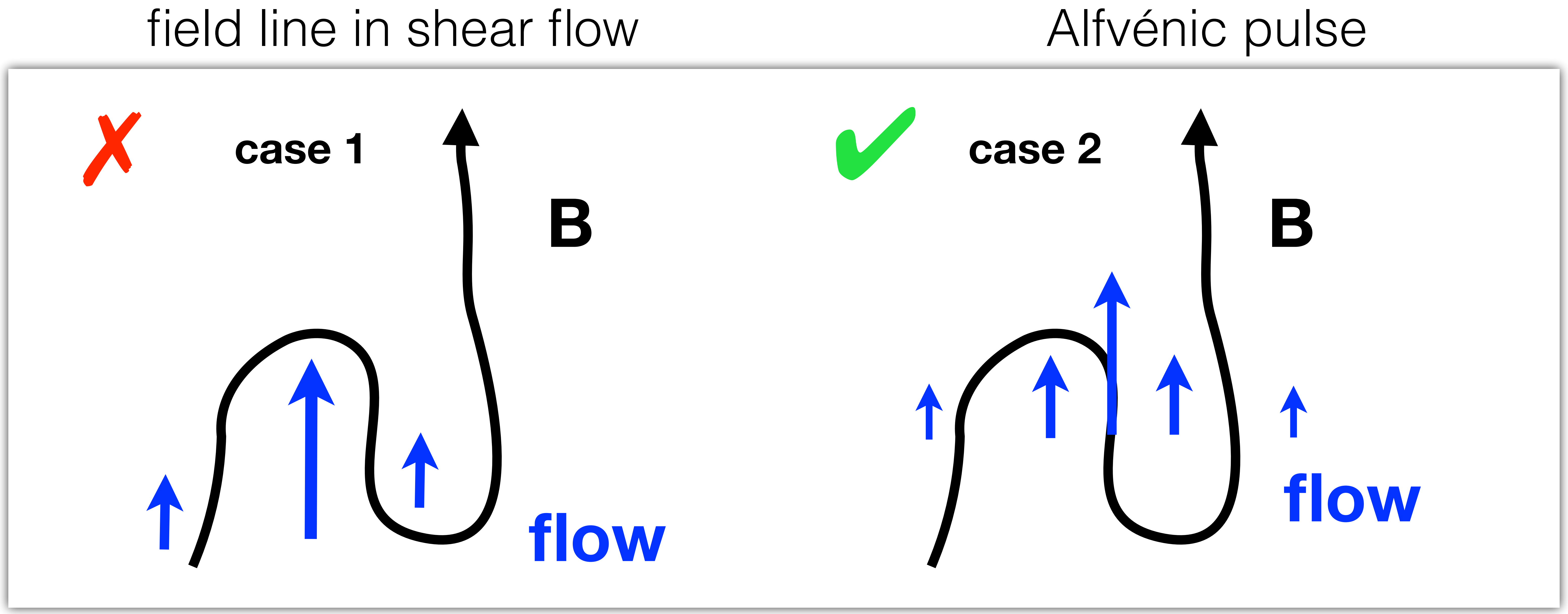
Switchbacks ubiquitous close to the Sun, in slower and faster solar wind (always Alfvénic!)

A key ingredient of solar wind dynamics?

Switchbacks are kinks in the field



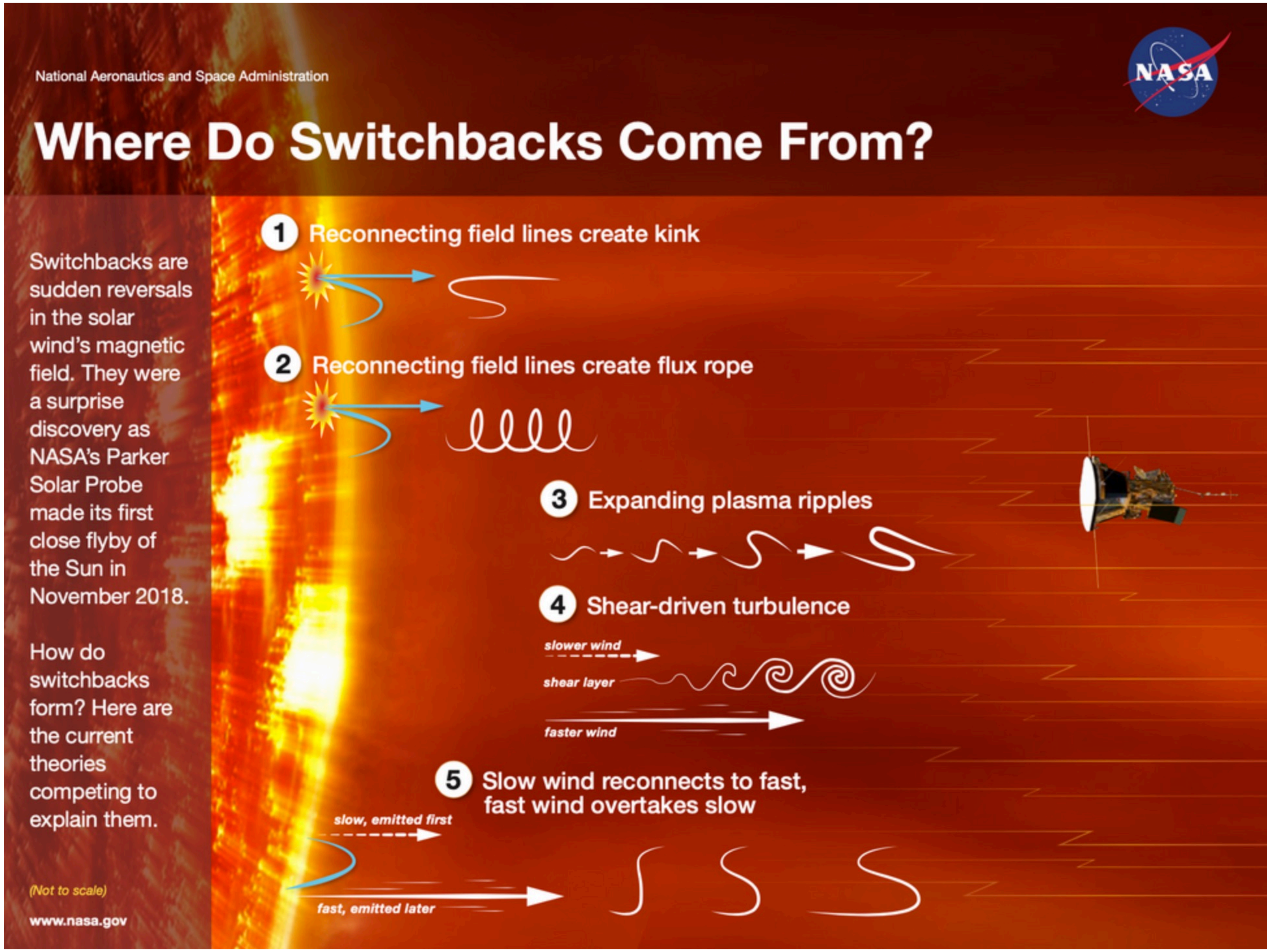
Yamauchi et al. 2004



Local fold supported by:

- Electron heat flux (strahl) (*Khaler et al. 1996*)
  "…about half the IFRs are due to <u>folds in the fields</u> with no change of polarity from that of the surrounding sector."
- Alfvén waves (*Balogh et al. 1999*)
  "The inversions therefore correspond to a <u>folded structure</u> in the magnetic field…"
- Alpha particles (*Yamauchi et al. 2004*)
  *"…local reversals in B_r in PBSs are commonly due to kinks in the magnetic field, **magnetic switchbacks**…"*
- Proton core-beam (*Neugebaur&Goldstein 2013*)
  *"… reversed double-proton beams are best explained as **switchbacks** of the interplanetary field…"*

Some switchbacks models



- Generation in corona
- Generation by expansion
- Kink driven by velocity shears
- Role of tangential flows
- Role of flux ropes
- Role of magnetic reconnection

But also

- stability with distance
- erosion by reconnection
- Kinetic processes at boundaries
- Statistics and waiting time
- Impact on turbulence

…

It is very likely that more of these effects contribute together in shaping switchbacks as observed by PSP

General consensus that occurrence rate is a common issue in models

Why are switchbacks important?

- They dynamical contribute to the solar wind acceleration
  Switchbacks imply a motion of the ion centre of mass and carry net outward momentum. Do they contribute to the flow acceleration?

- They are energetically important for solar wind heating during expansion
  Switchbacks carry extra kinetic energy and Poynting flux and could release them during expansion, leading to plasma heating directly (internal energy redistribution) or indirectly (turbulence-mediated)

- They are signatures of the processes that heat and accelerate the plasma close to the Sun
  Switchbacks are generated by mechanisms in the Solar atmosphere (e.g. interchange reconnection) and bring essential information about these processes

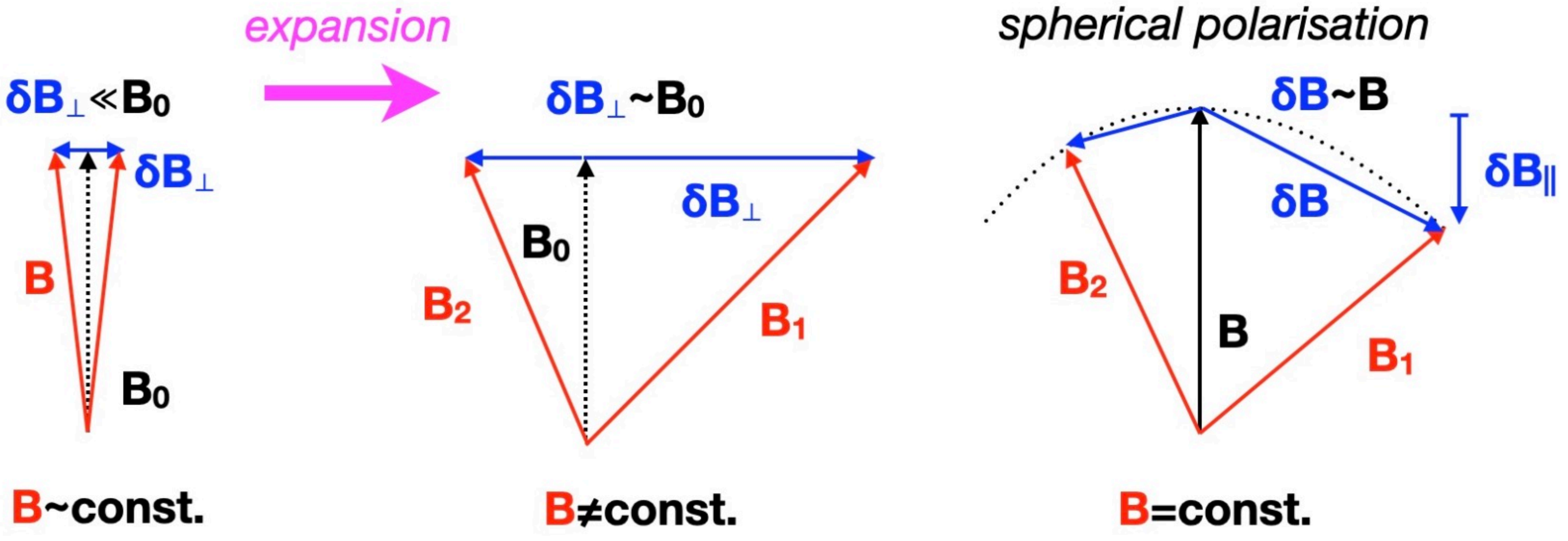
- They are tracers of the underlying source imprints in the flow
  Switchbacks are ubiquitous and act like passive tracers in the flow, making possible to identify flow sources and capture their variability (e.g. patches and link with super-granulation and/or plumes)

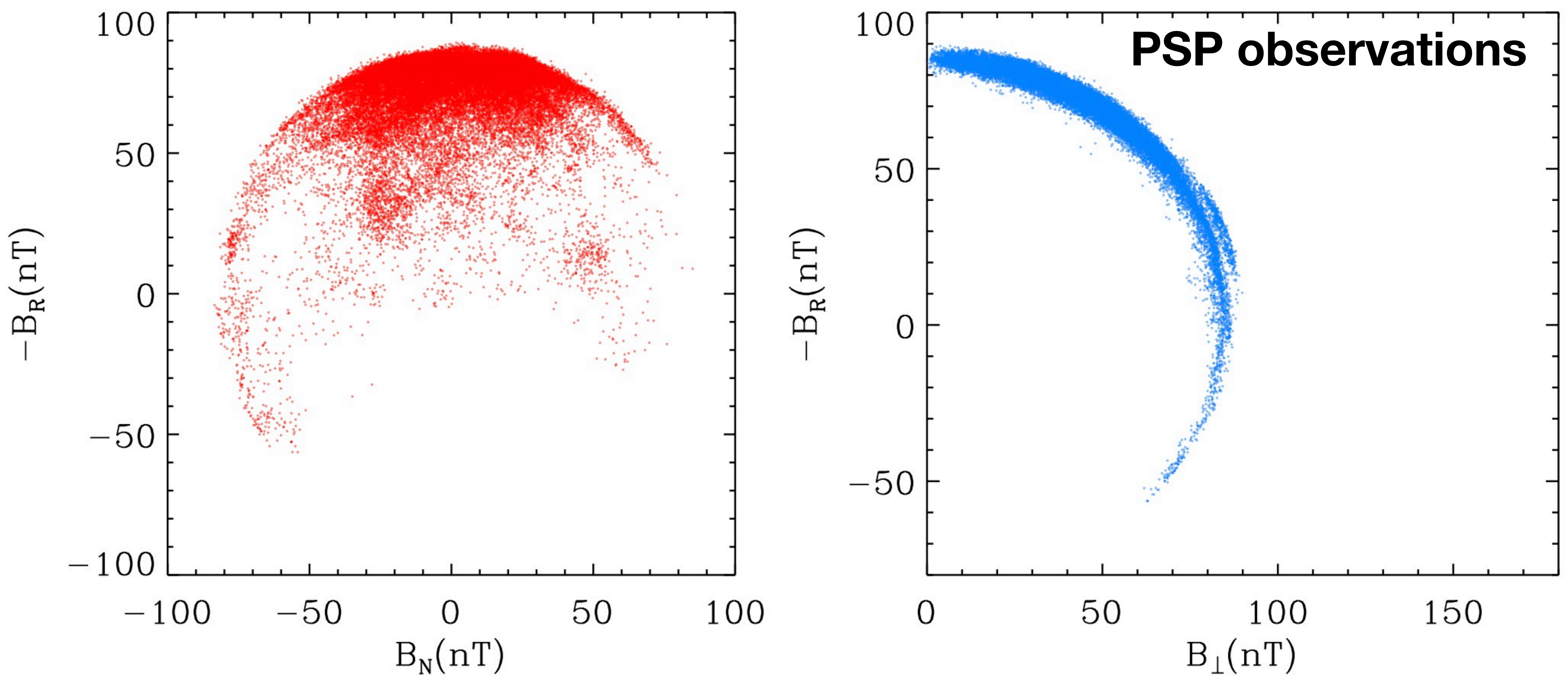
A note on the generation of spherical polarisation

start with small transverse δB fluctuations close to the Sun

fluctuations grow relative to the background field (geometrical expansion scaling), so that reach $\delta B \sim B_0$ with distance

in order to maintain **constant |B|** a field-aligned component $\delta B_{\|}$ is formed, leading to spherical polarisation

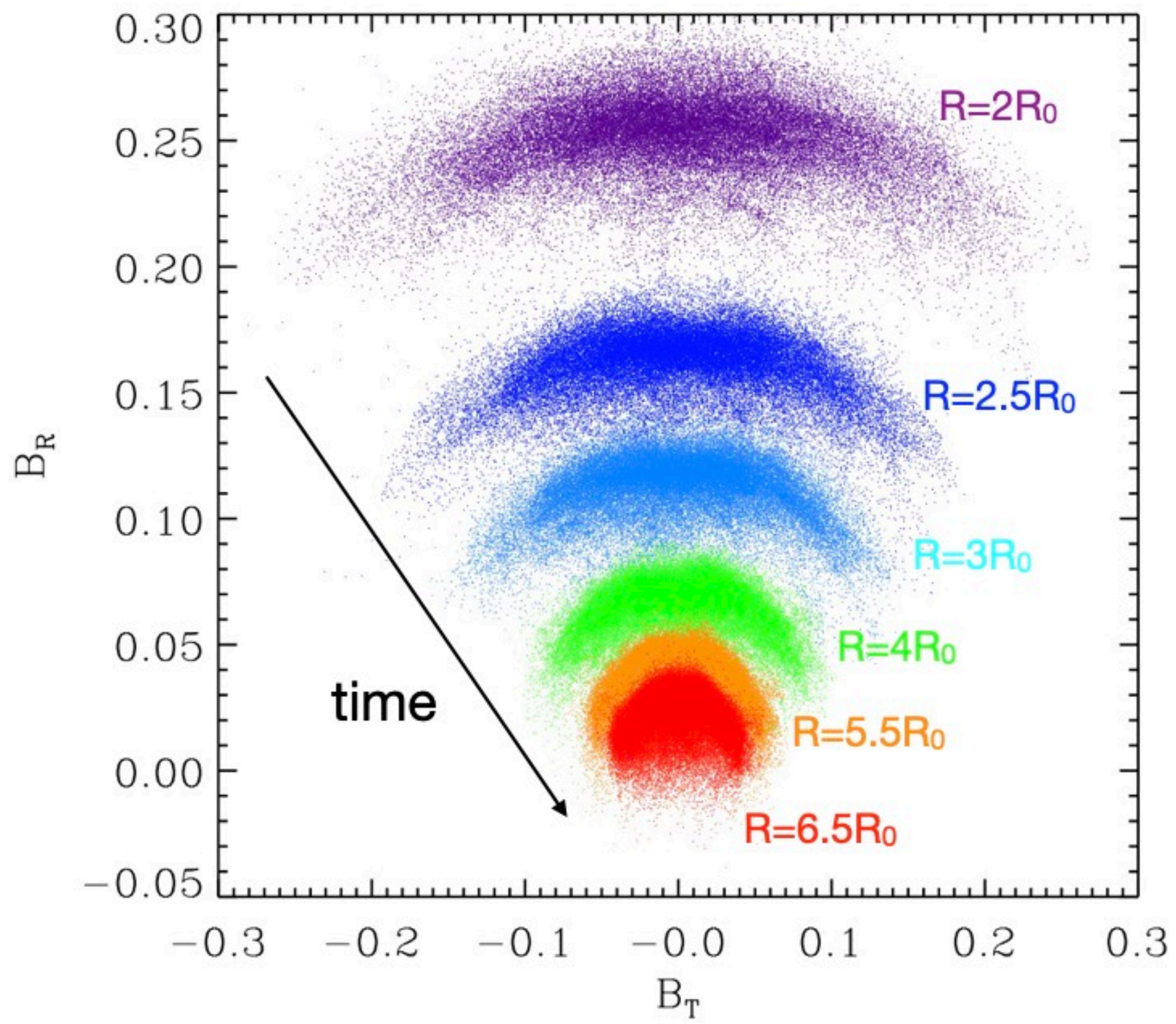


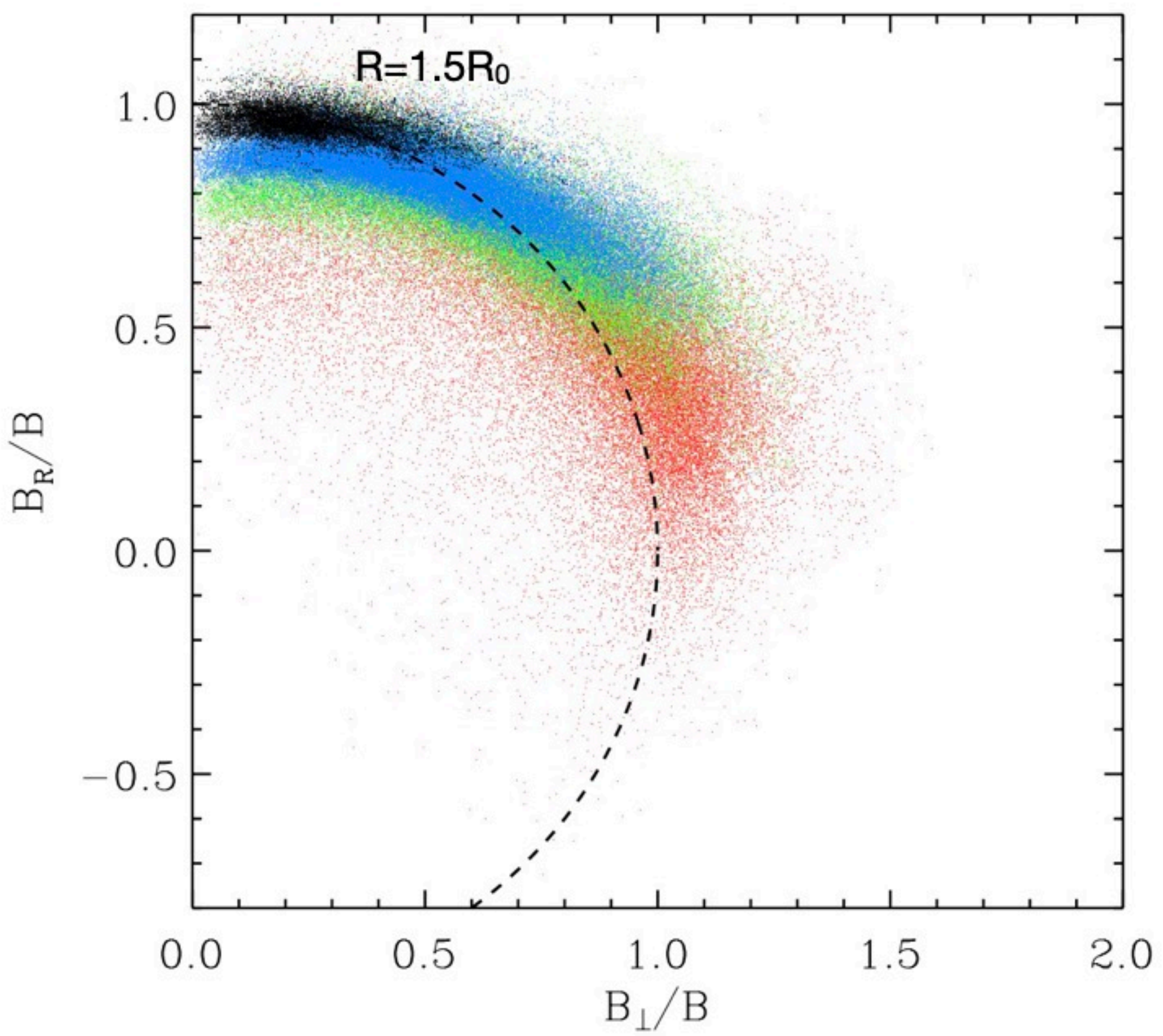


Next slide: Hybrid simulations
(kinetic ions, fluid electrons)
with expansion to investigate generation and radial evolution of spherical polarisation

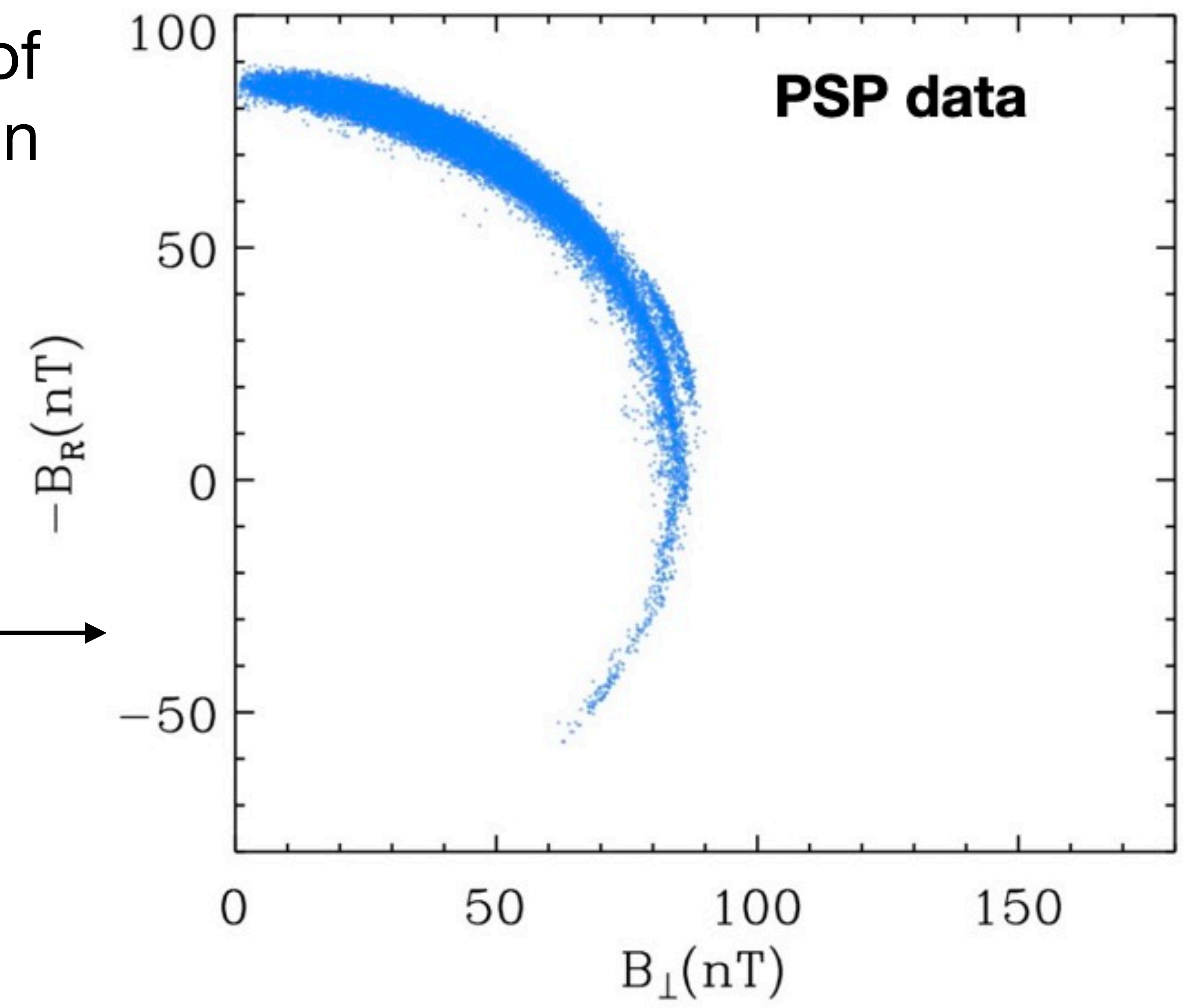
See also MHD modelling by:
Squire et al. 2020, 2021, Mallet et al. 2021, Shoda et al. 2021, Johnston et al. 2022

2D simulations of Alfvénic fluctuations with expansion (Matteini et al. PoP 2024)

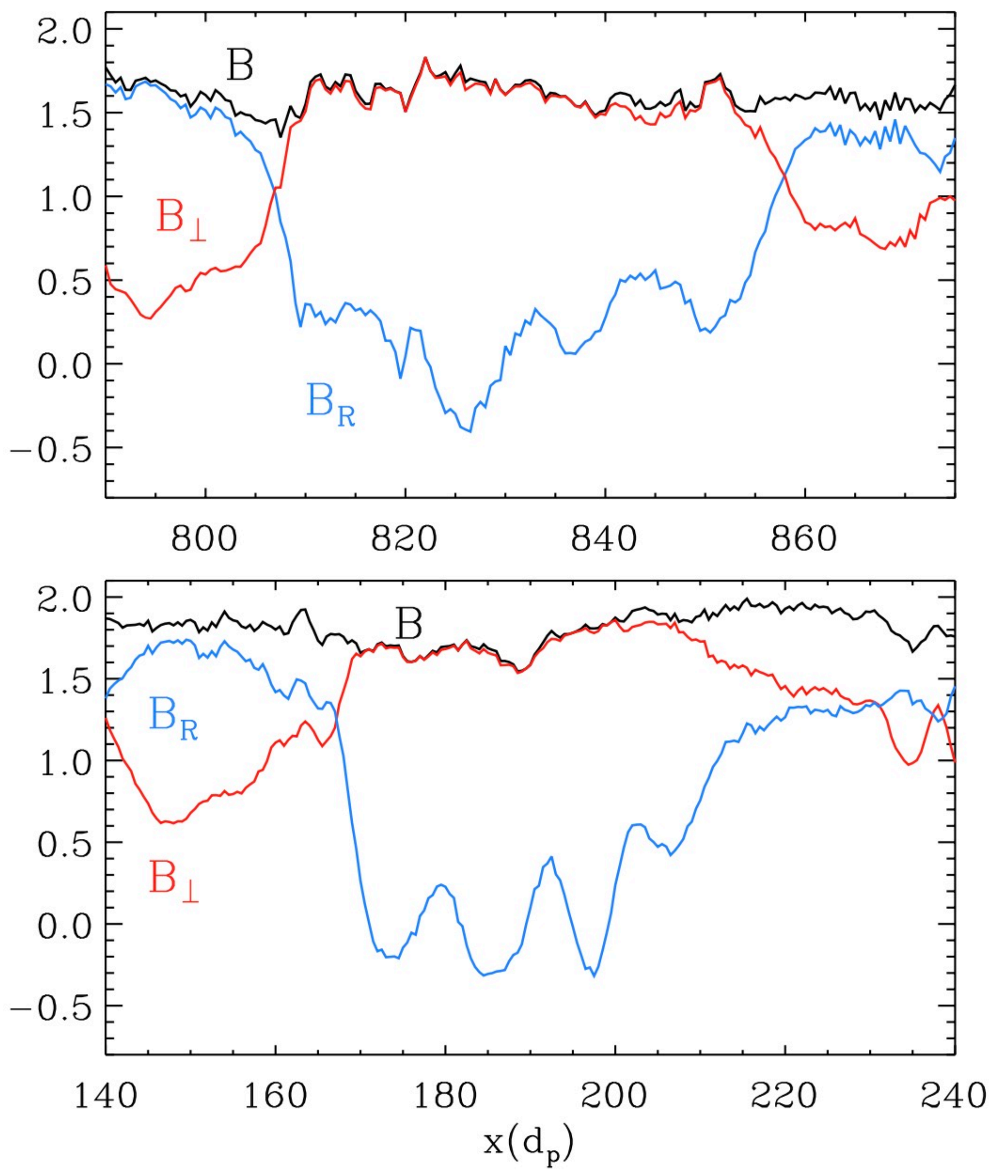




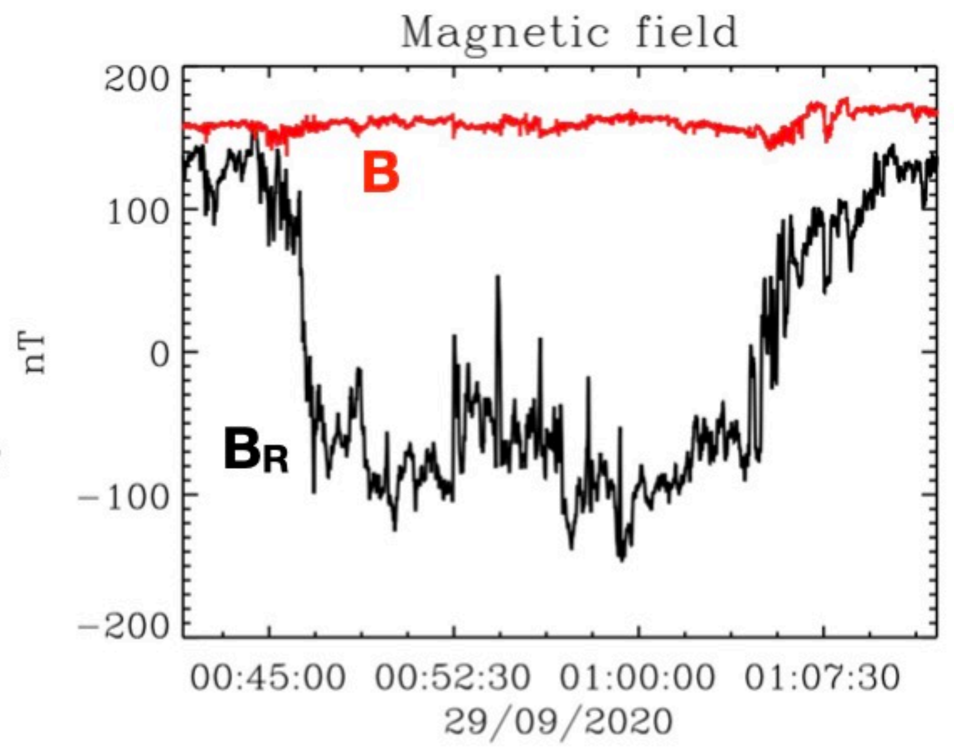
gradual generation of spherical polarisation



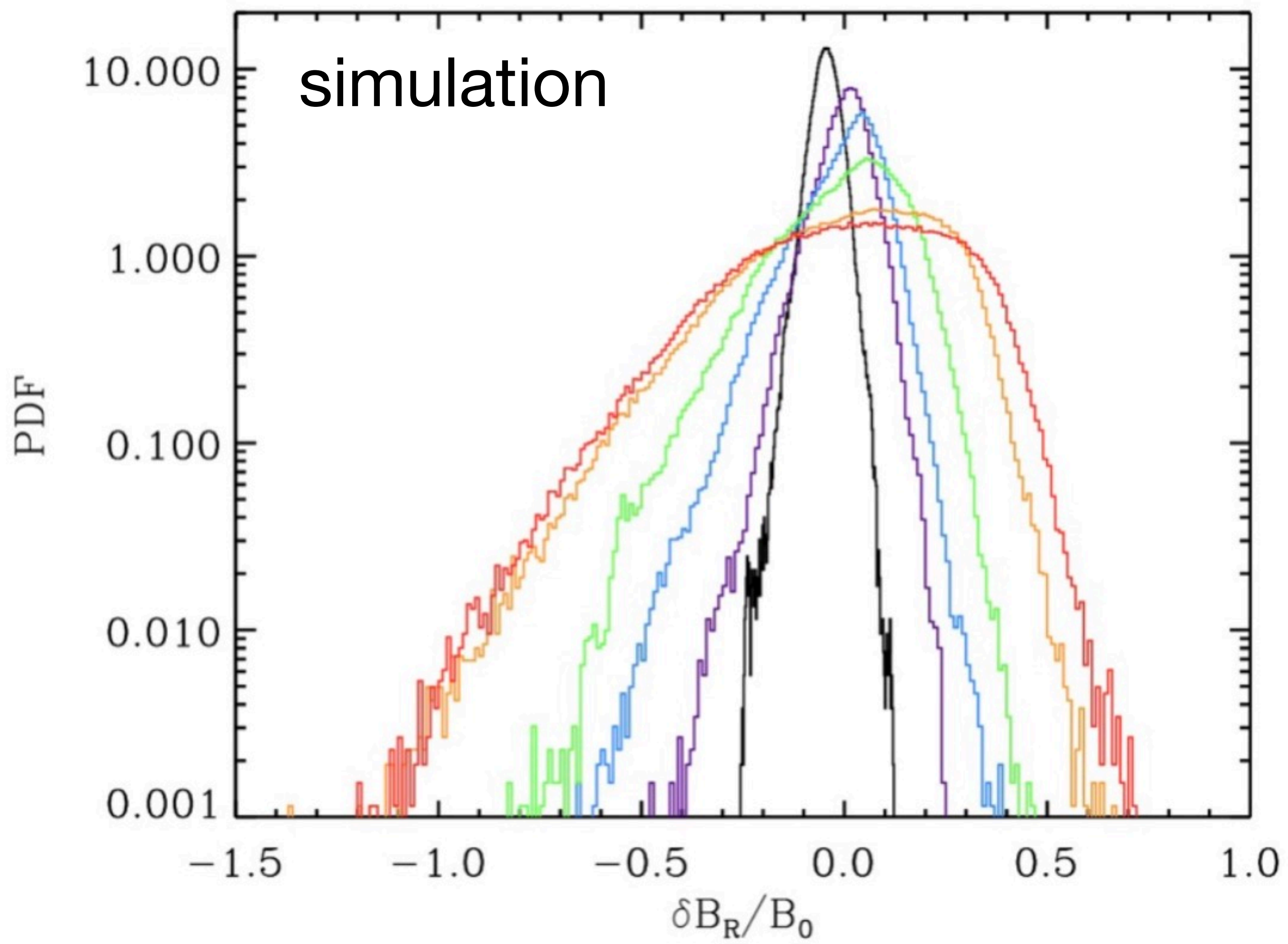
similar to in situ observations

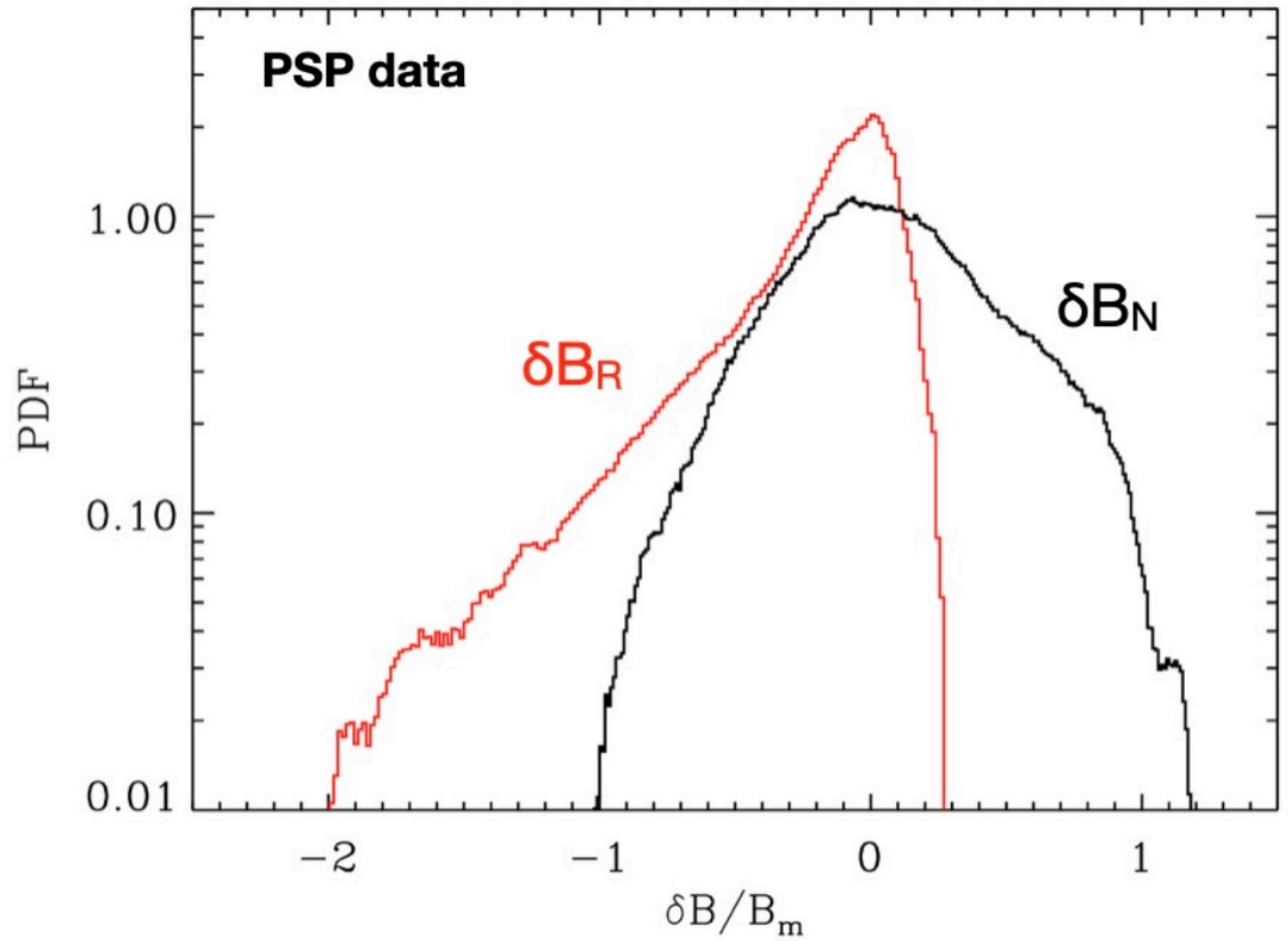


switchback-like magnetic field reversals are formed



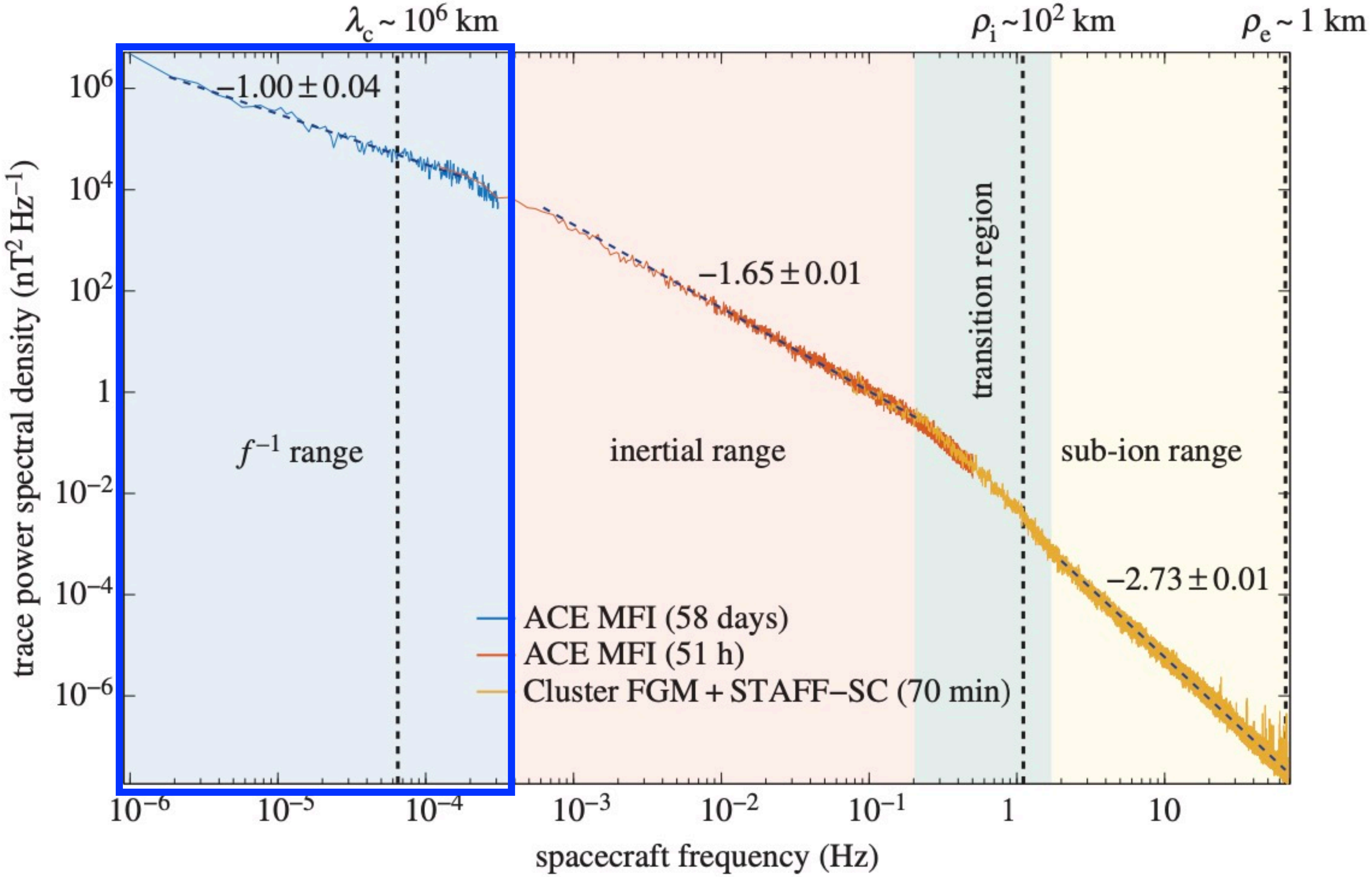
fluctuations in B_R are one-sided



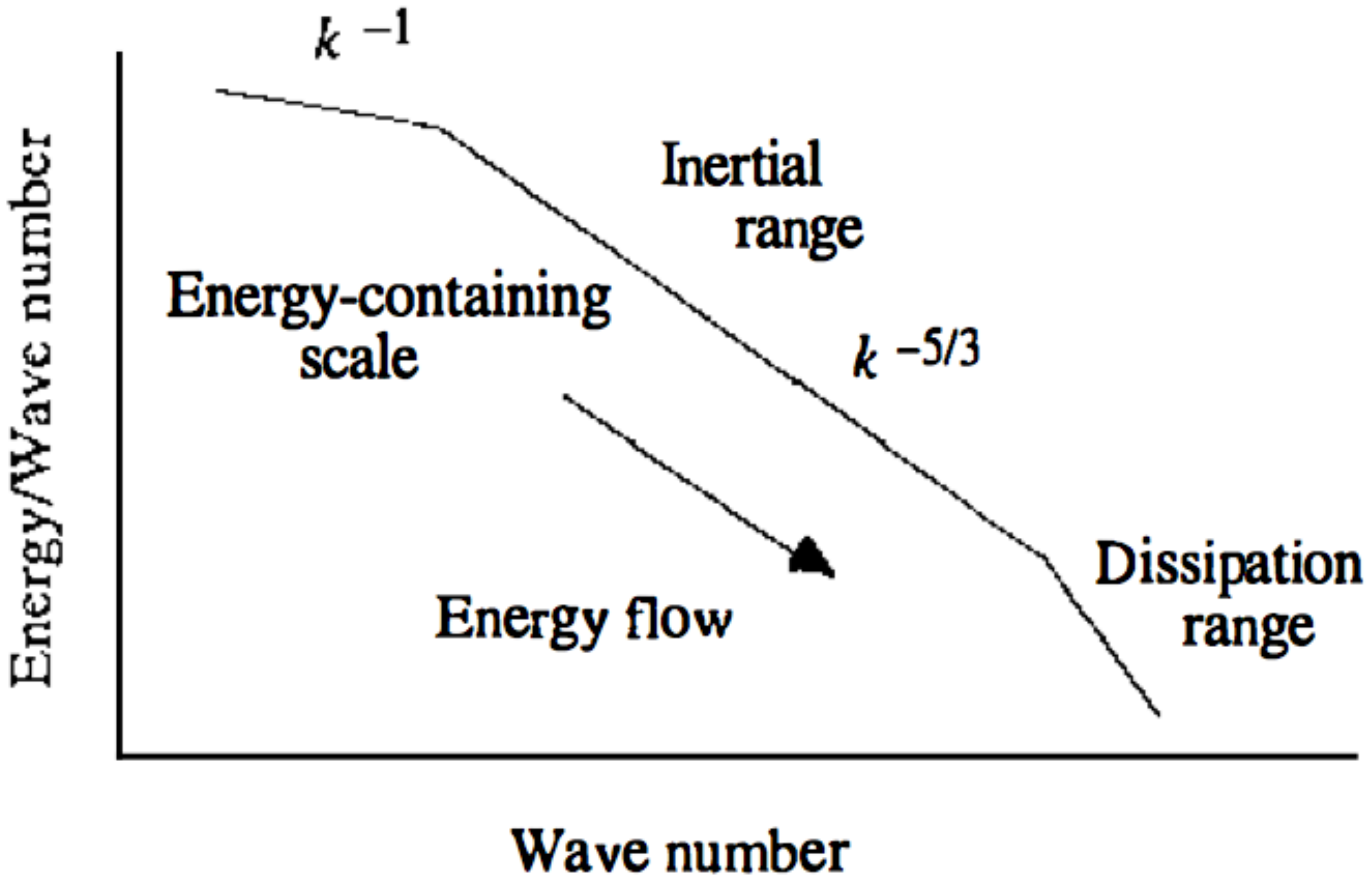


Summary of large-scale range

- Large scale, Alfvénic, spherical polarisation (one-sided)
- dB/B~1, including switchbacks (V_R enhancements)
- Spectral slope close to -1 => same dB at all scales
- Decay as a function of distance as WKB – weakly-interacting fluctuations
- Energy reservoir for smaller scales?



Some basics of fluid turbulence

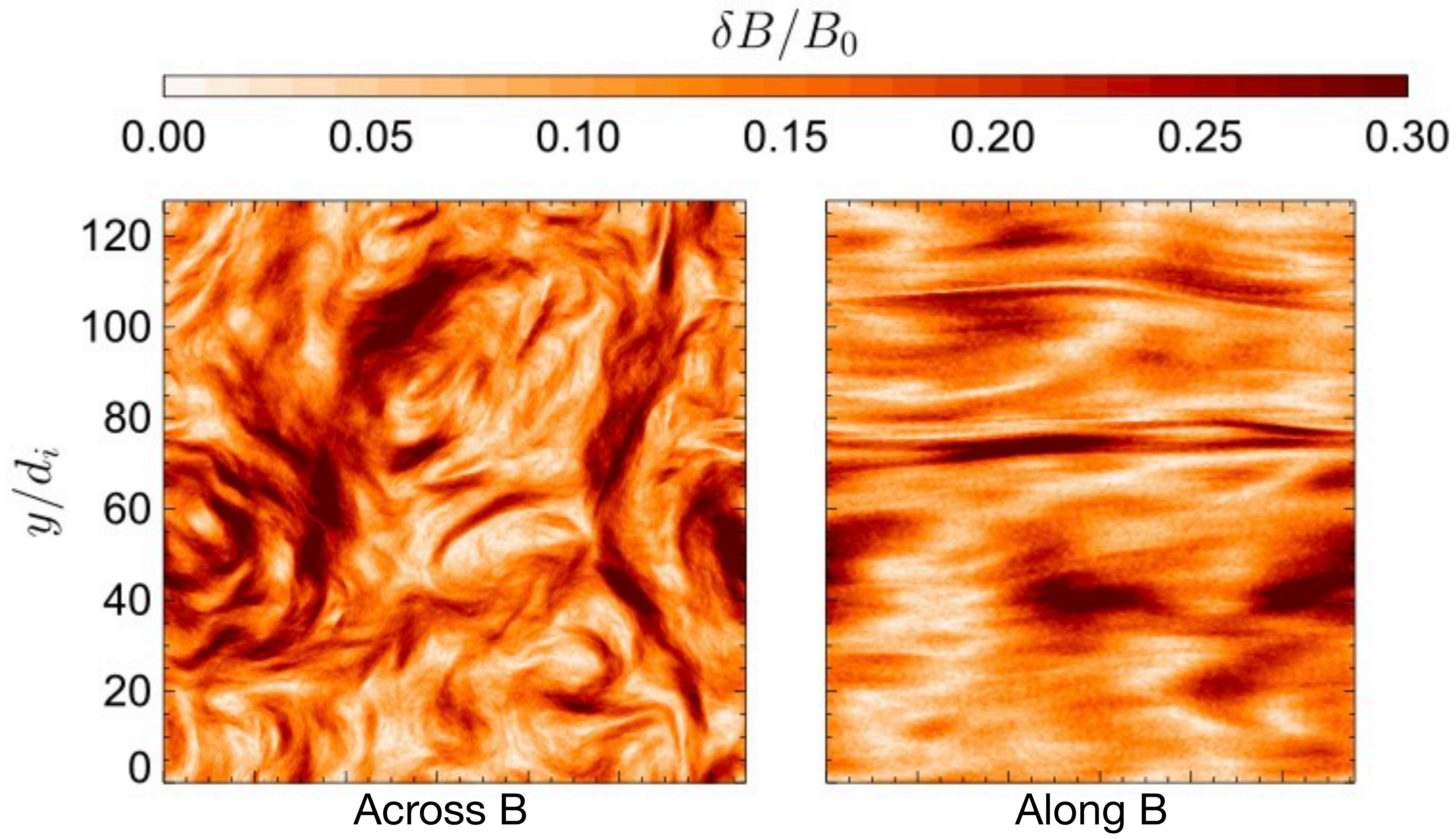


Energy "cascades" from large to small scales, at constant rate.
Turbulent eddies of smaller and smaller sizes are formed, until they reach the dissipative scale.

Plasma turbulence is more complicated

$\delta B_\perp > \delta B_{||}$ variance anisotropy

$\delta B(k_\perp) > \delta B(k_{||})$
k-vector anisotropy

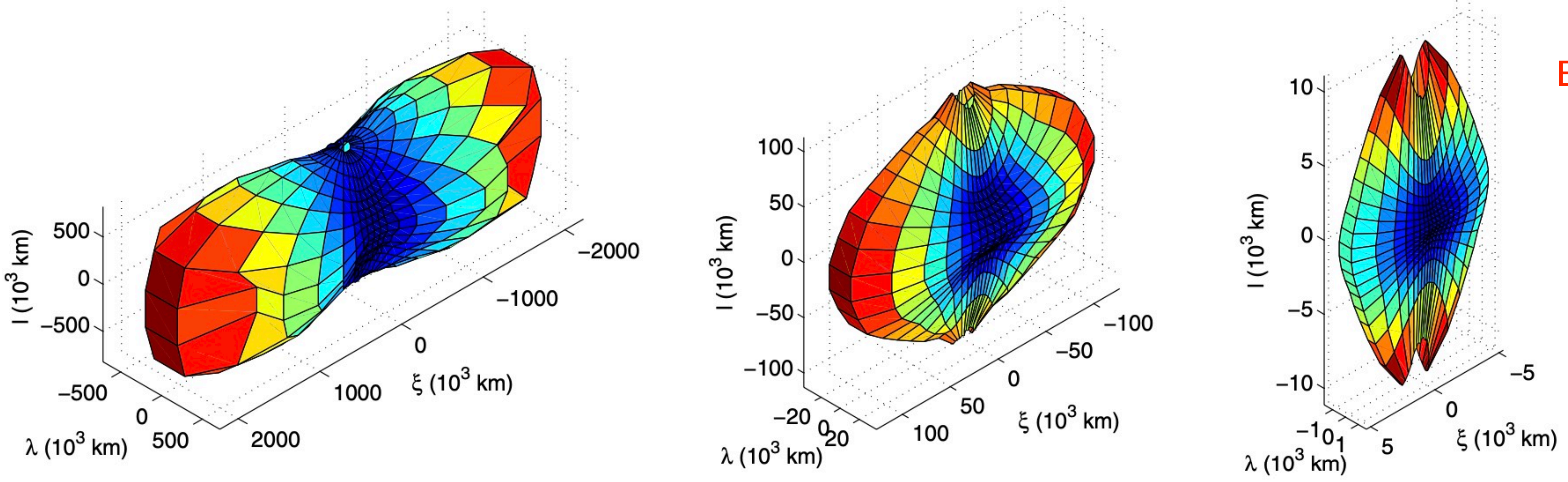


3D simulations of magnetised plasma turbulence (*Hellinger et al. 2019*)

Scale-dependence of turbulent eddies shape

Large scales | intermediate scales | small scales

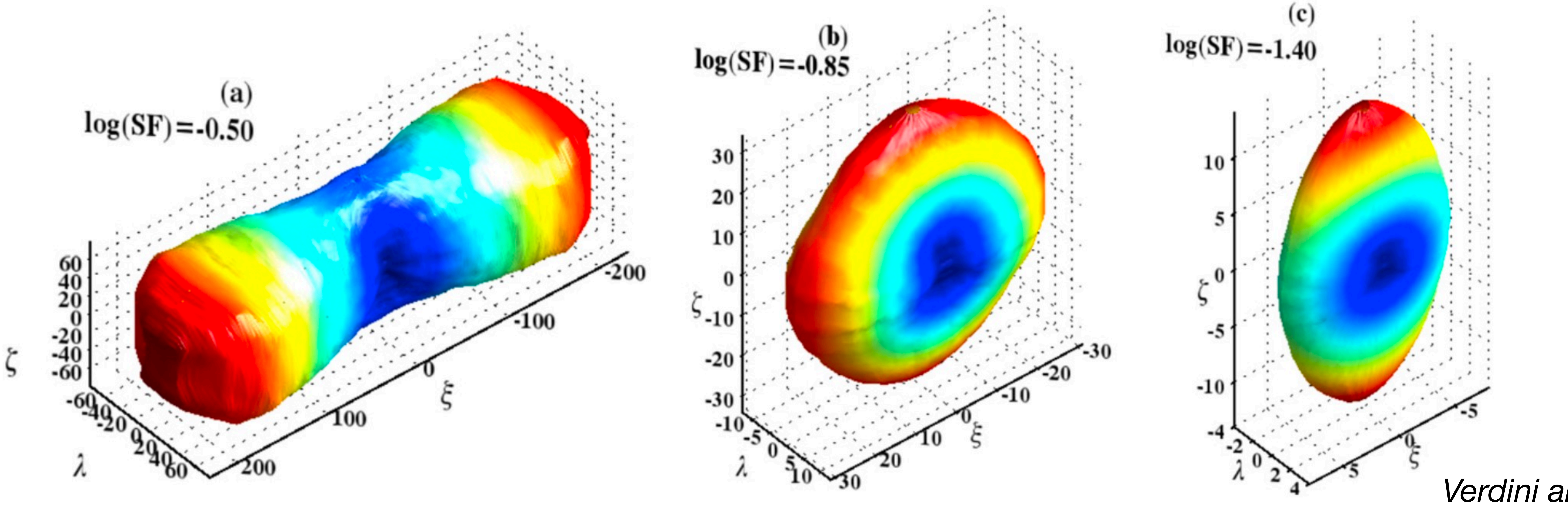
Solar wind data (Ulysses)



Eddies become more elongated along the magnetic field at smaller scales

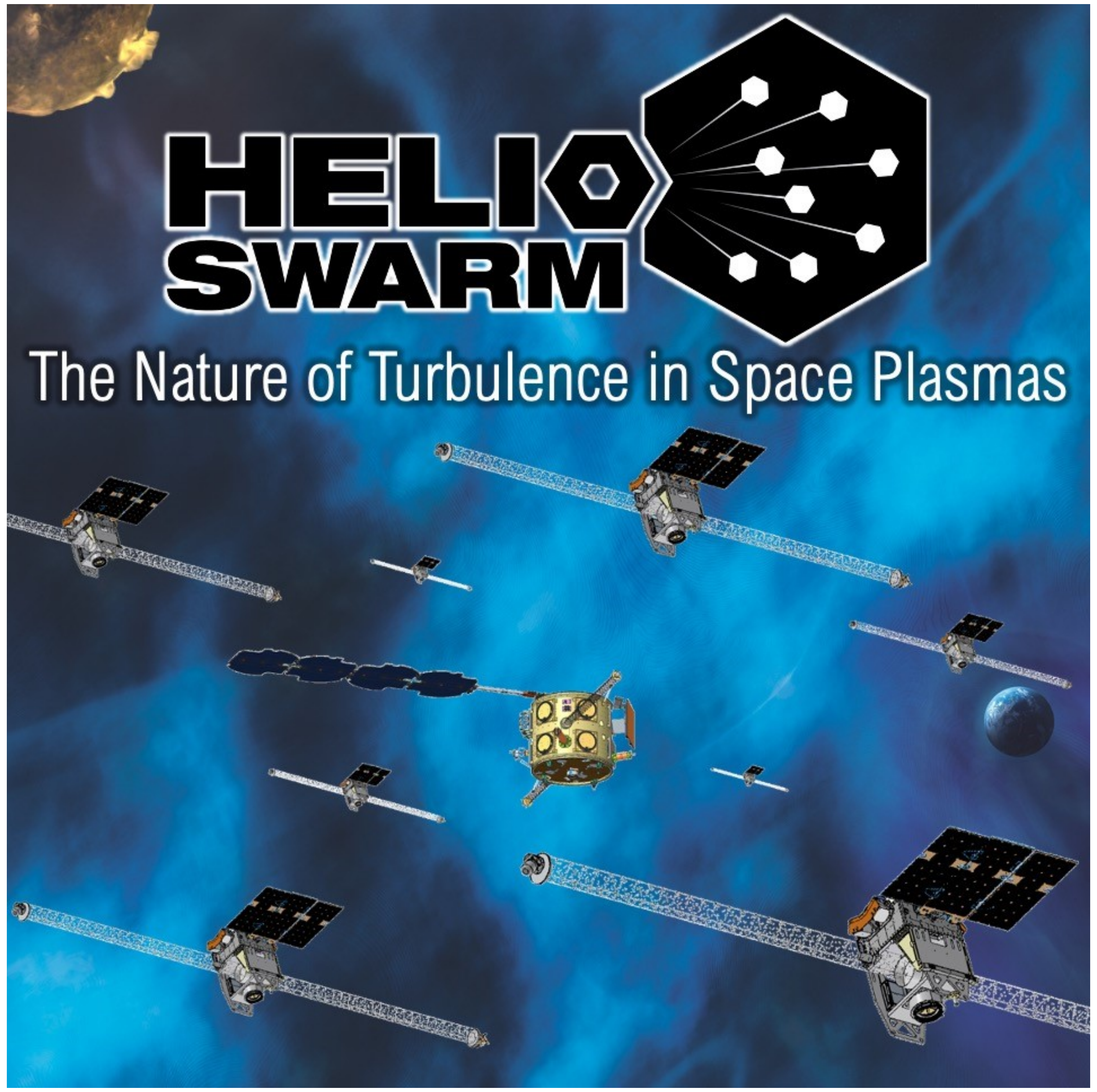
Chen et al., ApJ 2012

MHD Simulations including expansion effects



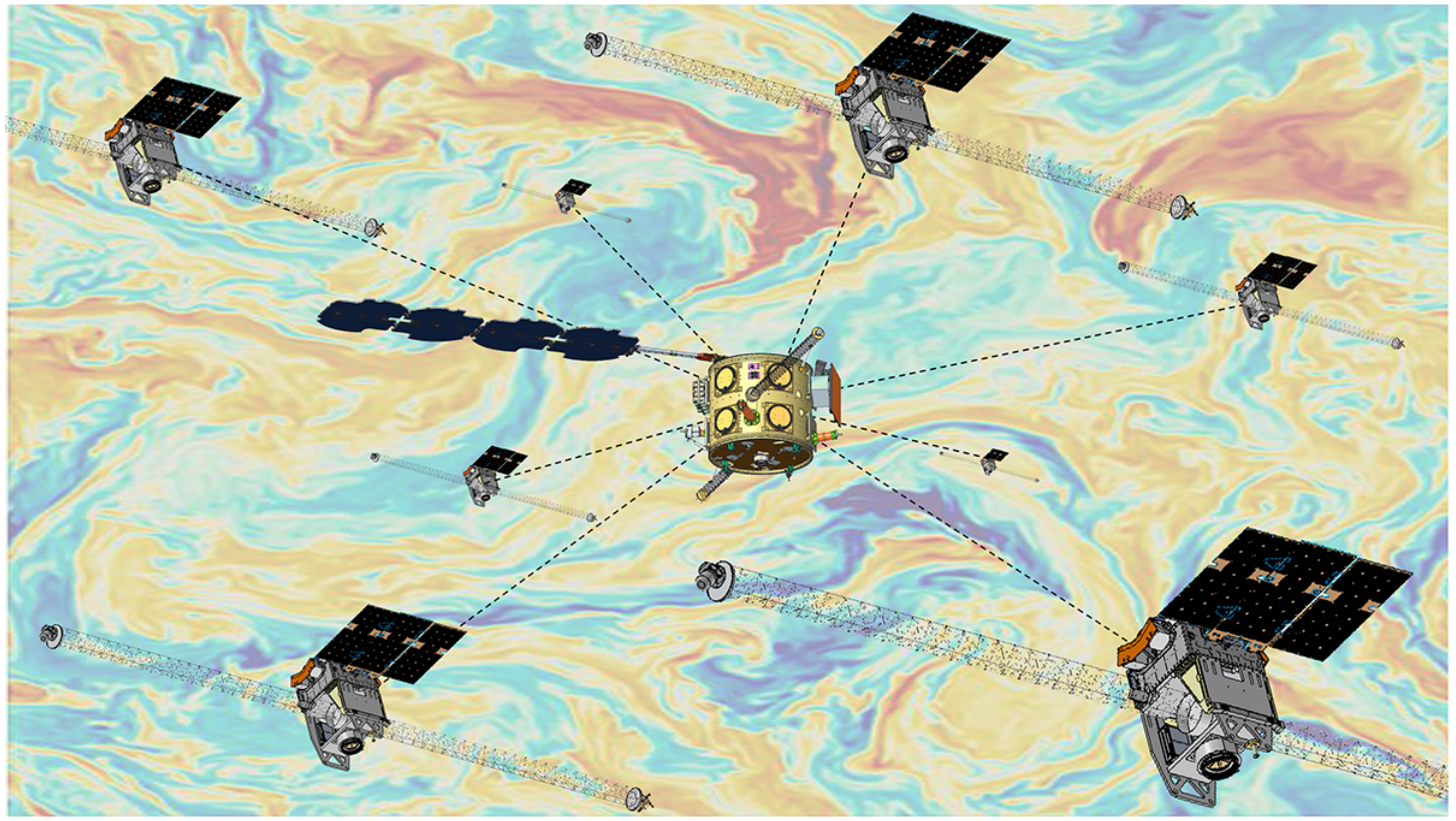
Verdini and Grappin, ApJ 2012

NASA HelioSwarm – launch in 2029



9 spacecraft investigating plasma turbulence in the solar wind plasma, to:

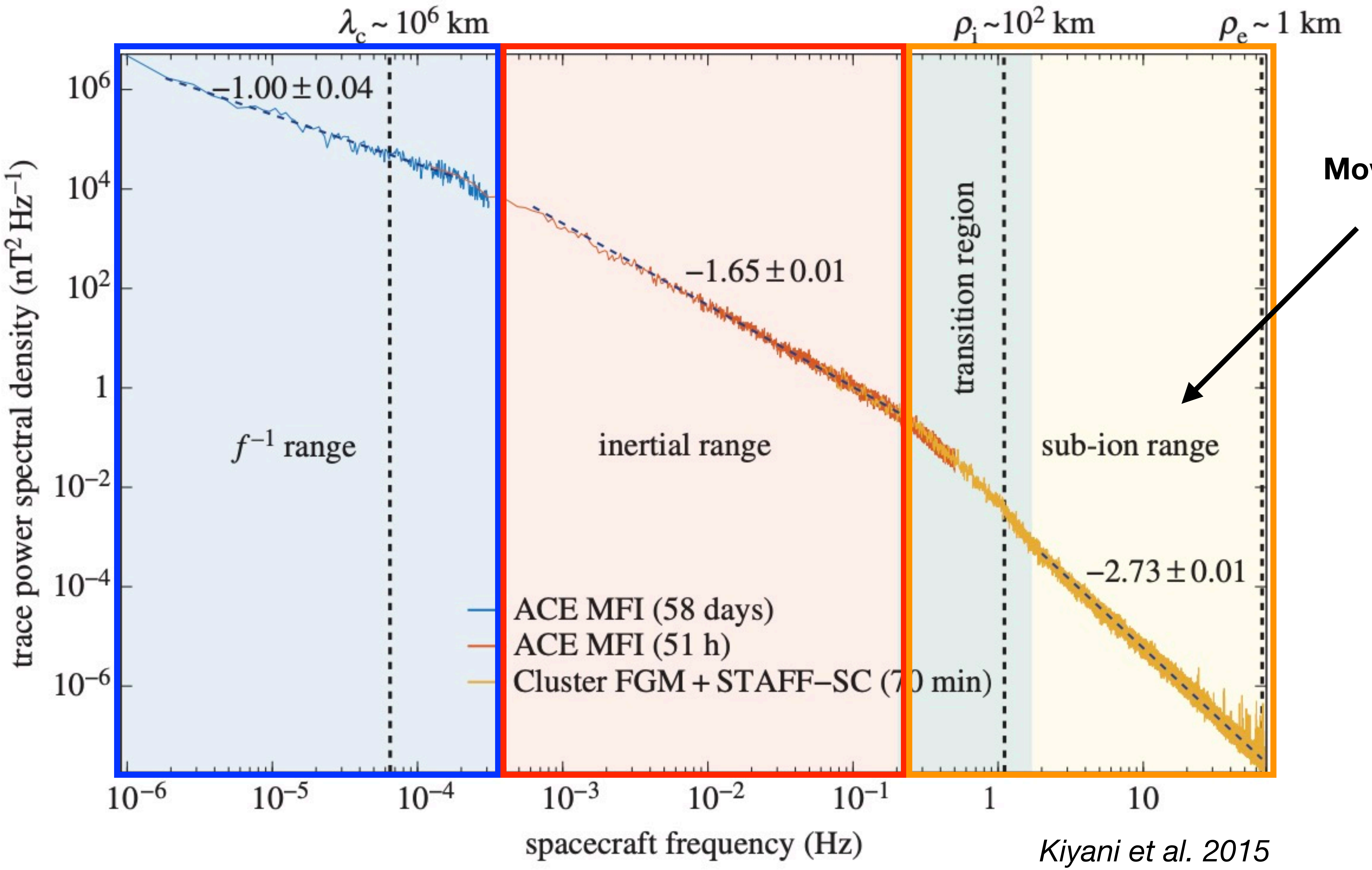
1) reveal the 3D spatial structure and dynamics of turbulence in a weakly collisional plasma
2) ascertain the mutual impact of turbulence near boundaries and large-scale structures



Science and orbit complementary to another proposed constellation to fly in the Earth's magnetosphere, Plasma Observatory, an ESA mission proposal currently under consideration for launch in 2037

Part 2

The multi-scale solar wind: Magnetic field spectrum



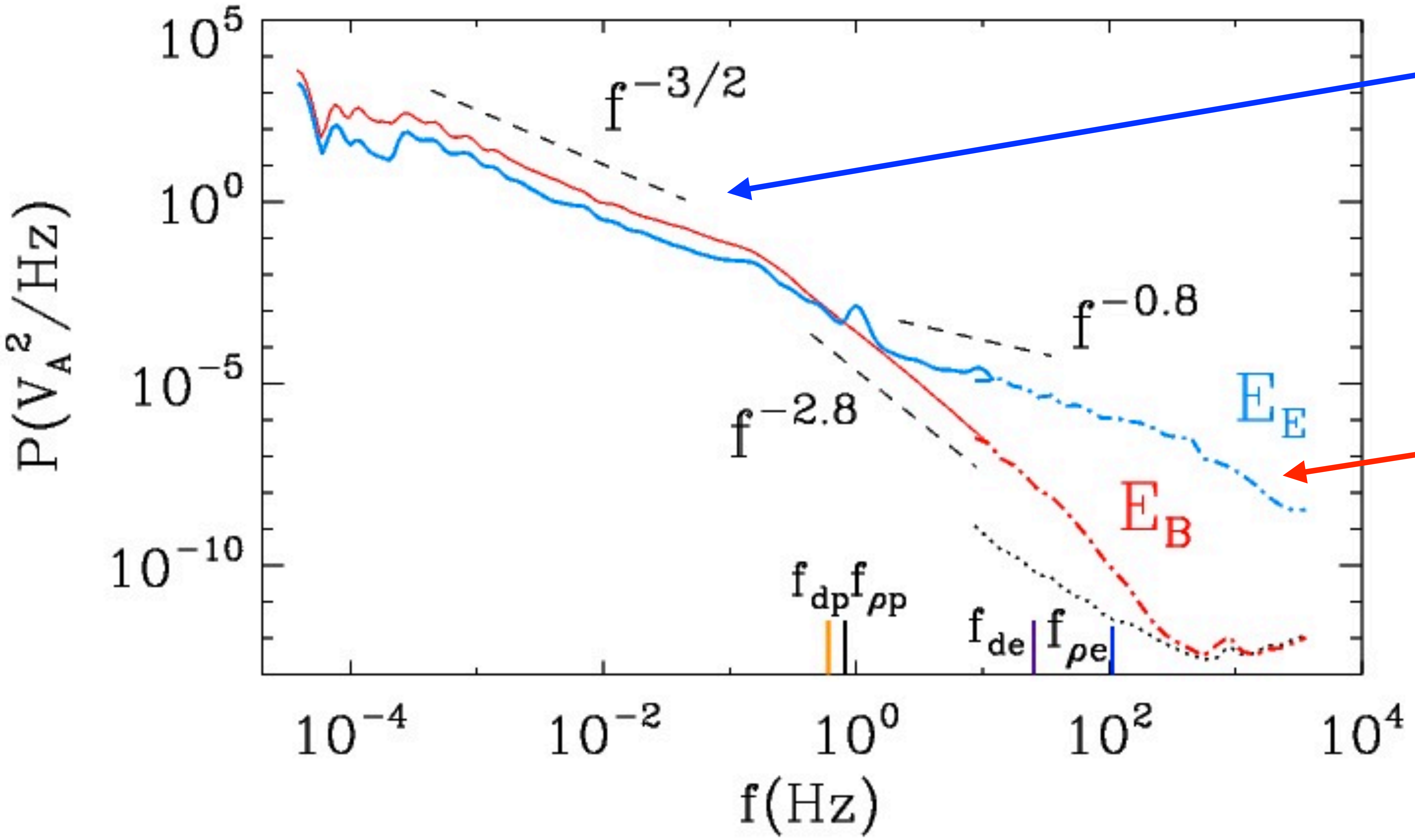
Moving towards smaller scales

Kiyani et al. 2015

See also the review: "The multi-scale nature of the solar wind", *Verscharen et al. 2019*

Electric and magnetic turbulent spectra

Characterisation of magnetic field fluctuations from fluid to electron scales (merging MAG and SCM)



MHD/fluid scales: E=-VxB => $\delta E \sim \delta V * B_0$

for Alfvénic fluctuations: $\delta B \sim \delta V$

then: $\delta B^2 \sim \delta E^2$

At ion scales, VxB=>0 and electric field dominated by Hall effect:

E~JxB => $\delta E \sim k * \delta B * B_0$

for ion-scale fluctuations: $\delta E \sim k * \delta B$

then: $\delta E / \delta B \sim k$

Cluster observations in the magnetosheath (*Matteini et al. MNRAS 20216*)

E_E = electric field spectrum
E_B = magnetic field spectrum

sub-ion spectra:

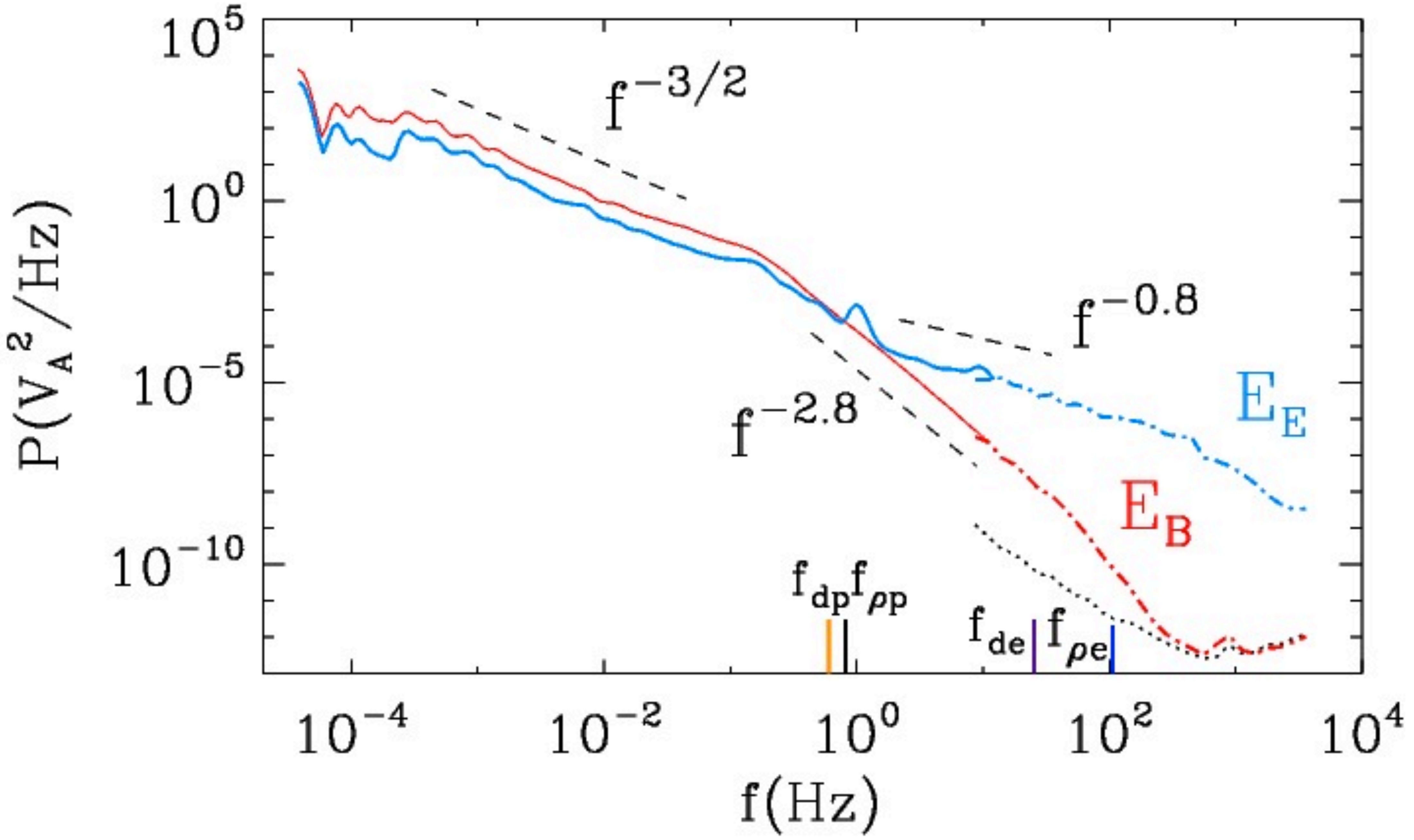
$$\delta E^2 \propto k^2 \delta B^2$$

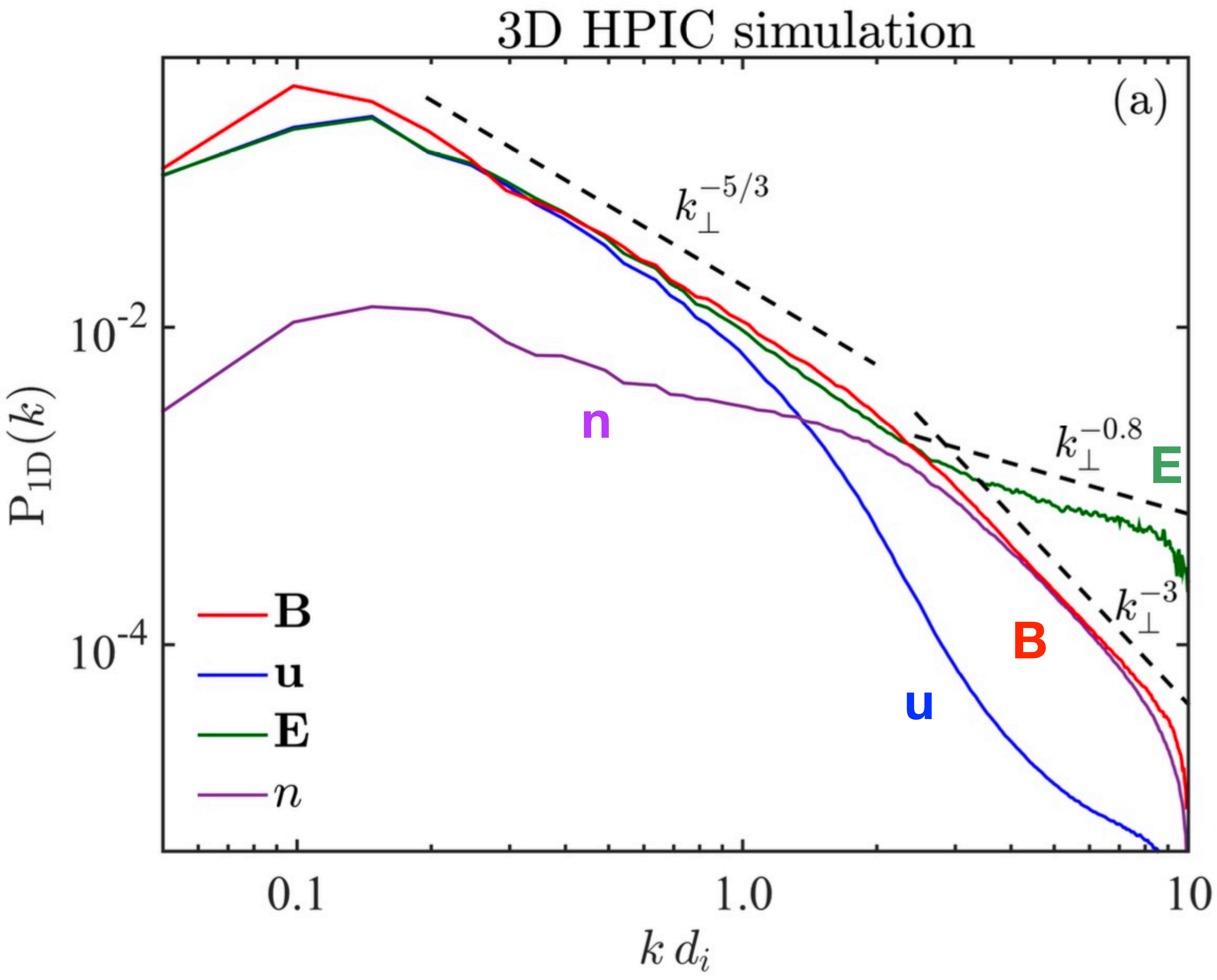
Modelling sub-ion turbulence

The hybrid approximation: kinetic ions + fluid electrons

hybrid-PIC methods
(see also *Valentini et al. 2008* for hybrid-Vlasov)

see also Minna's talk on Thursday for more discussion on numerical models and a hybrid code version suitable for global simulations (Vlasiator)

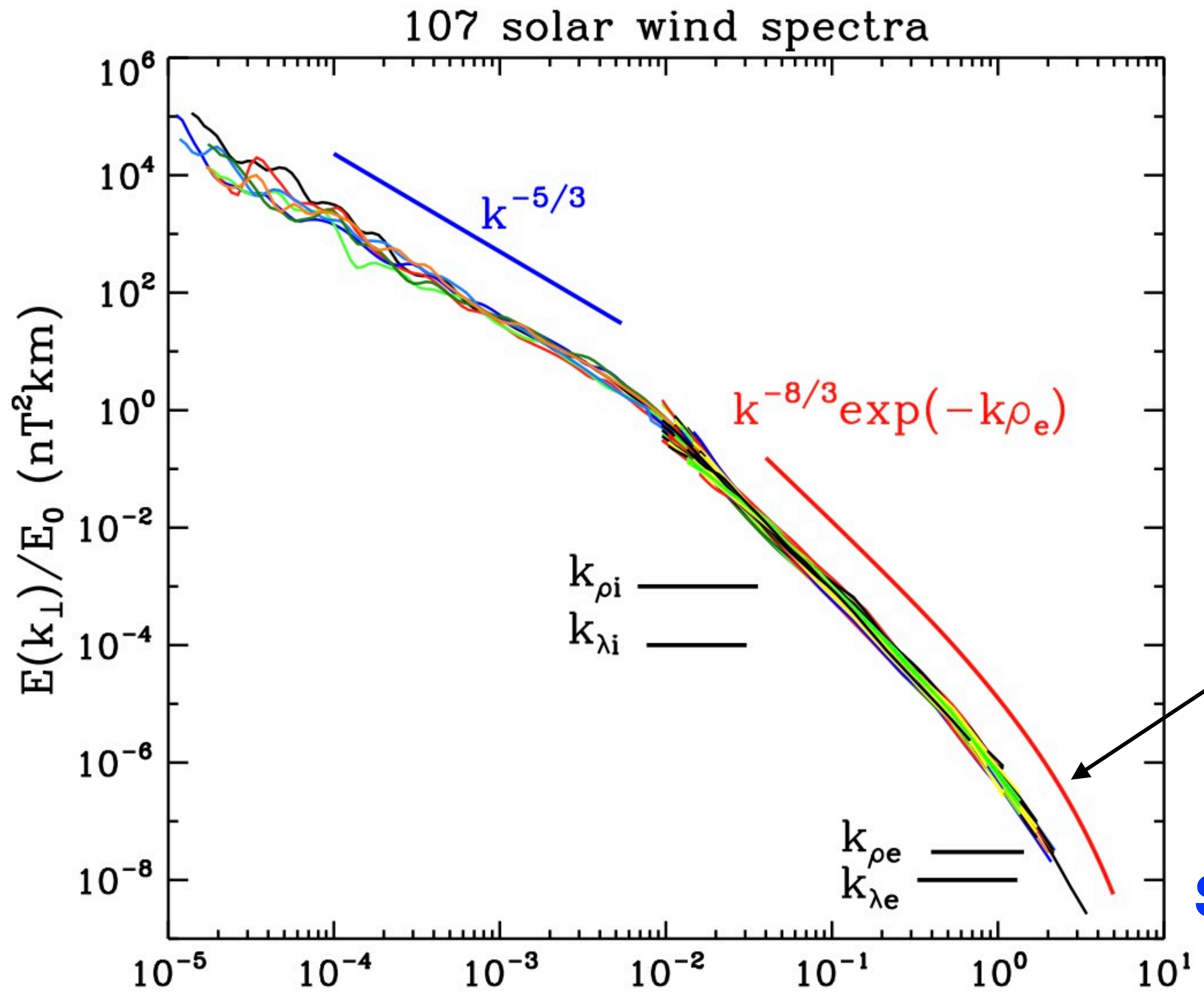




Franci et al., 2015, 2018
See also: Valentini 2014, Cerri 2017, Groselji 2018

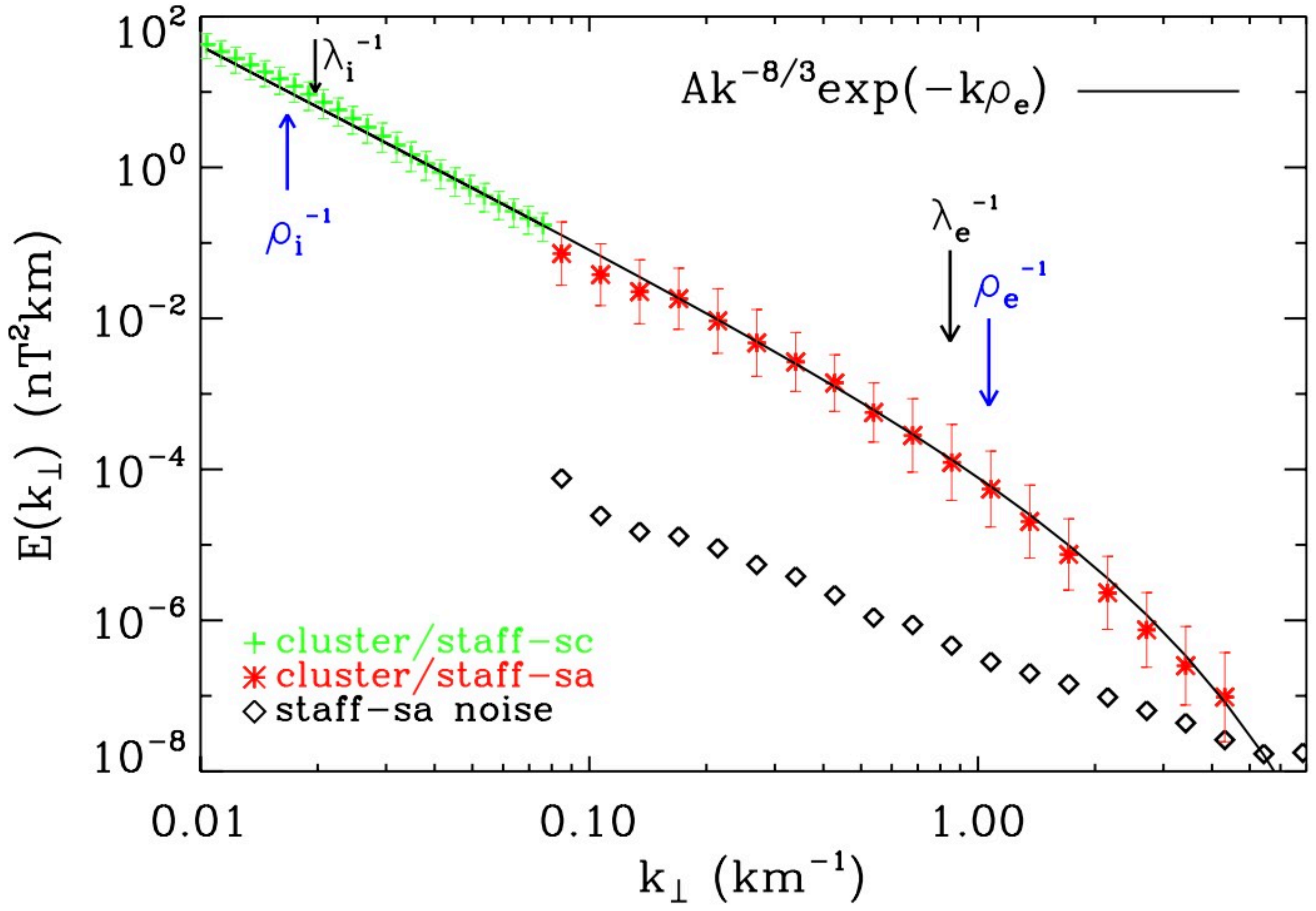
Hybrid models, including ion kinetics, are able to reproduce the observed spectral properties of plasma turbulence at sub-ion scales

Turbulence at electron scales



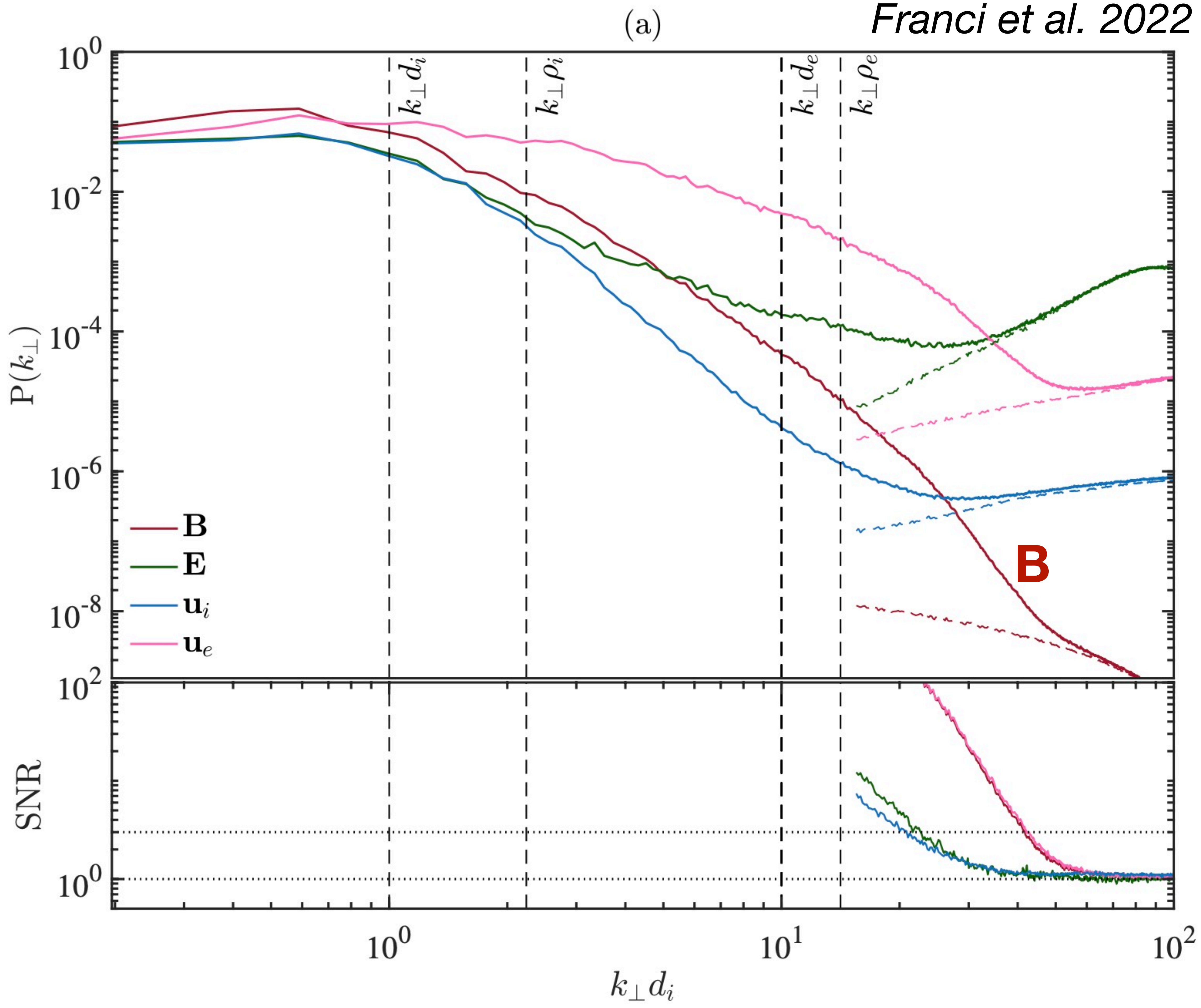
Alexandrova et al. 2009, 2012
see also Sahraoui 2009, 2013

Further change in the spectrum at electron scales.
Exponential cut-off?
Signature of dissipation?



Capturing electron-scale dynamics in the cascade require full-PIC simulations

Franci et al. 2022

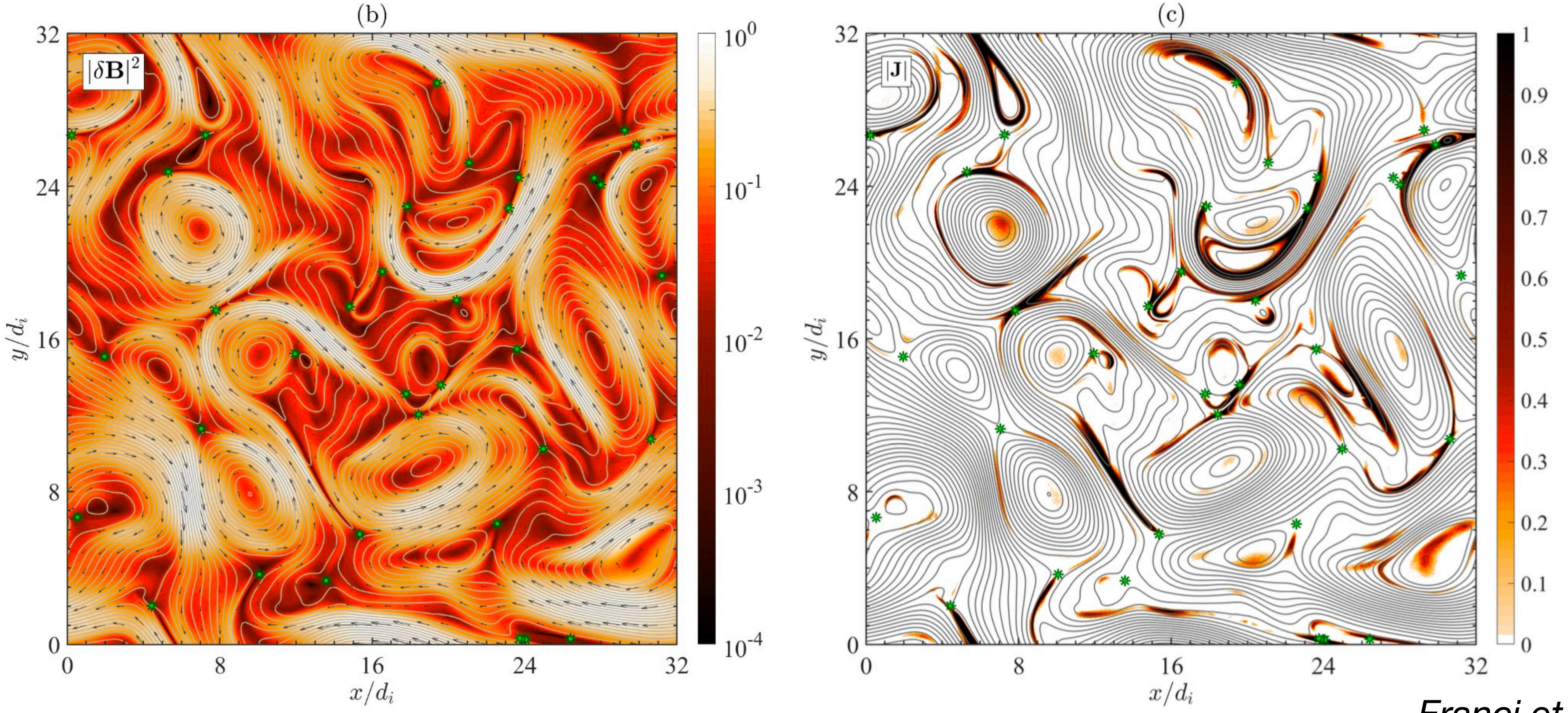


ion scales **electron scales**

Turbulent cascade is further modified when approaching electron scales

Energy dissipation at electron scales

In a turbulent regime small-scale current sheets form and disrupt via magnetic reconnection



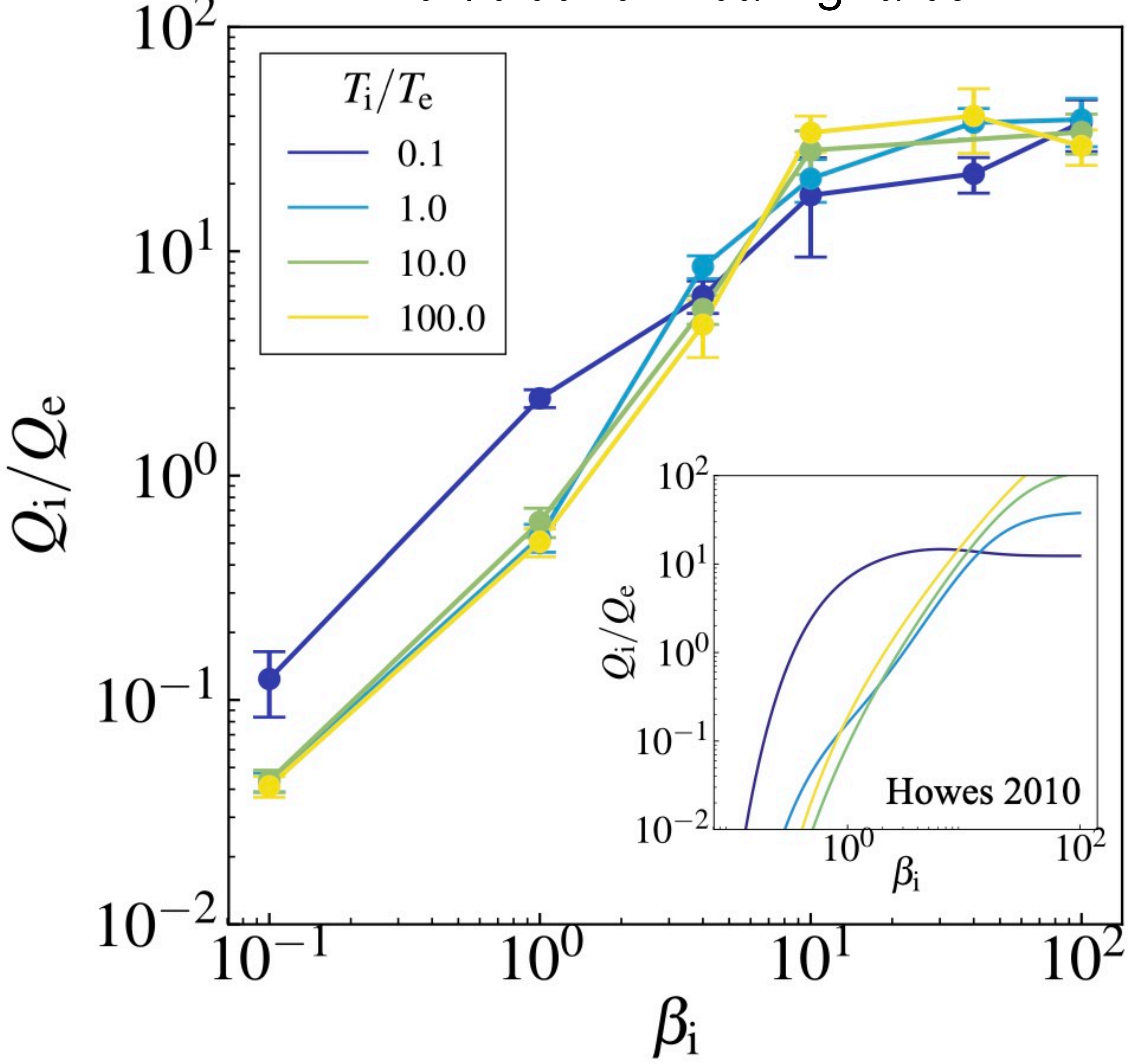
Franci et al. 2022,

Is reconnection the ultimate dissipation in space plasmas?
reconnection-mediated turbulence: e.g. *Loureiro&Boldyrev 2017, Mallet et al. 2017*
Also Ion-Cyclotron resonances and/or Landau damping? *Chen et al. 2019, Bowen et al. 2024*

Summary on kinetic turbulence and open questions

- MHD cascade continues into kinetic range, through sub-ion scales, down to electron scales
- fluctuations remain mostly electromagnetic, at least until sub-electron scales
- Dissipation by reconnection or waves?
- Is a (large?) fraction of the energy dissipated already at ion scales? What is the heating partition between electrons and ions in collisionless plasmas? (important for astrophysical sources - depends on plasma beta)

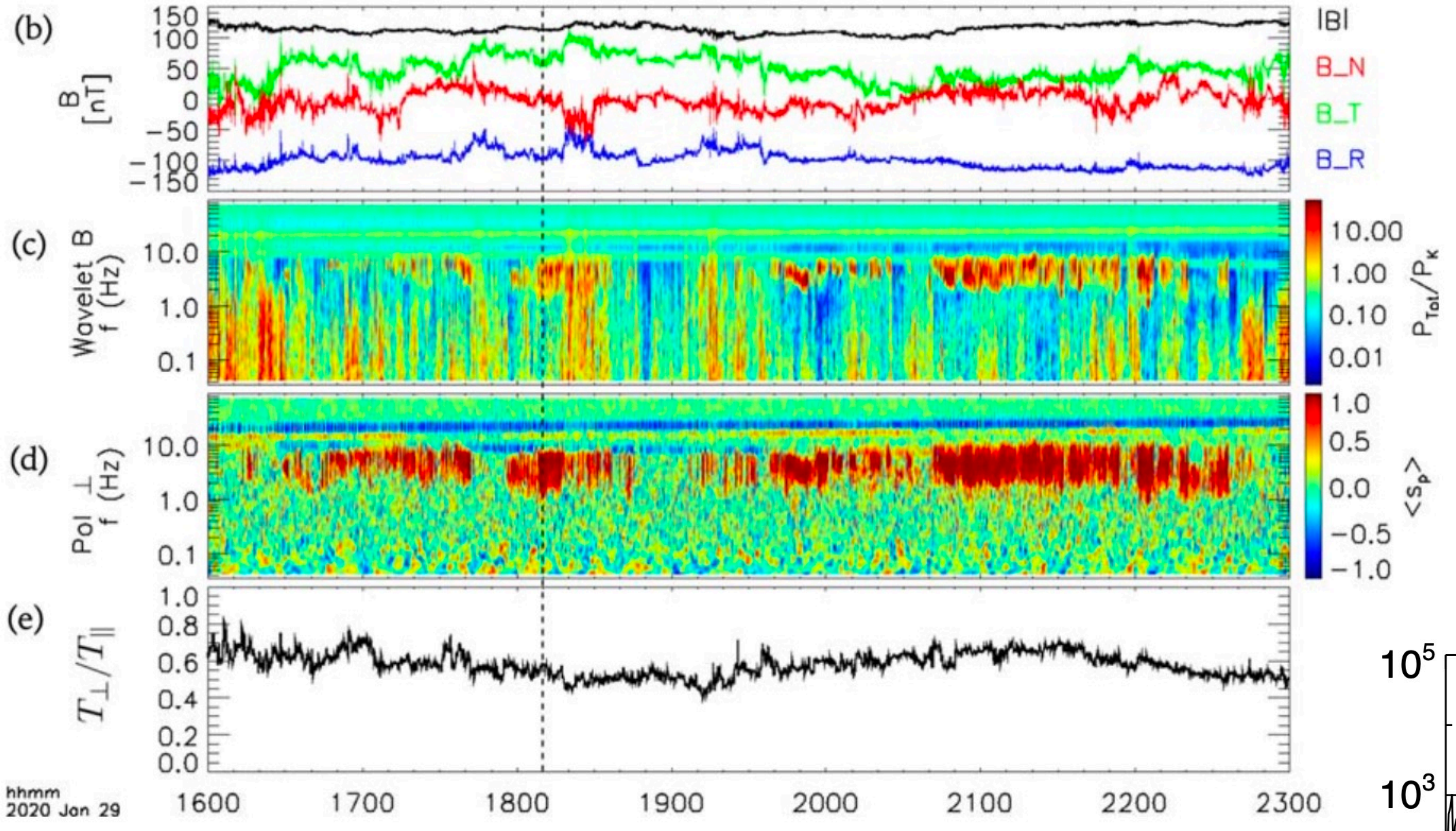
ion/electron heating rates



Kawazura et al., 2019

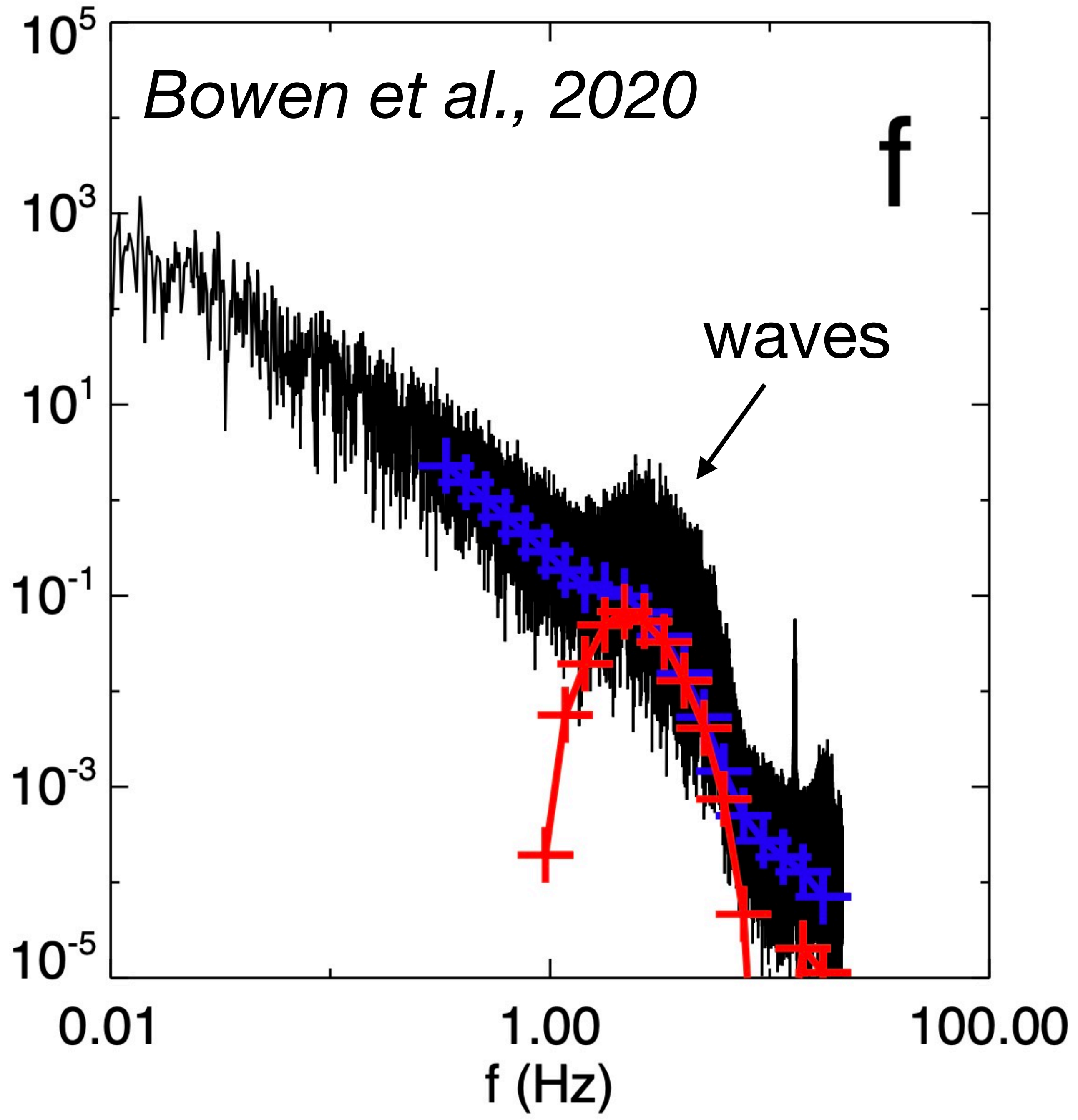
Not only turbulence in the wind…

ion scale waves observed by PSP



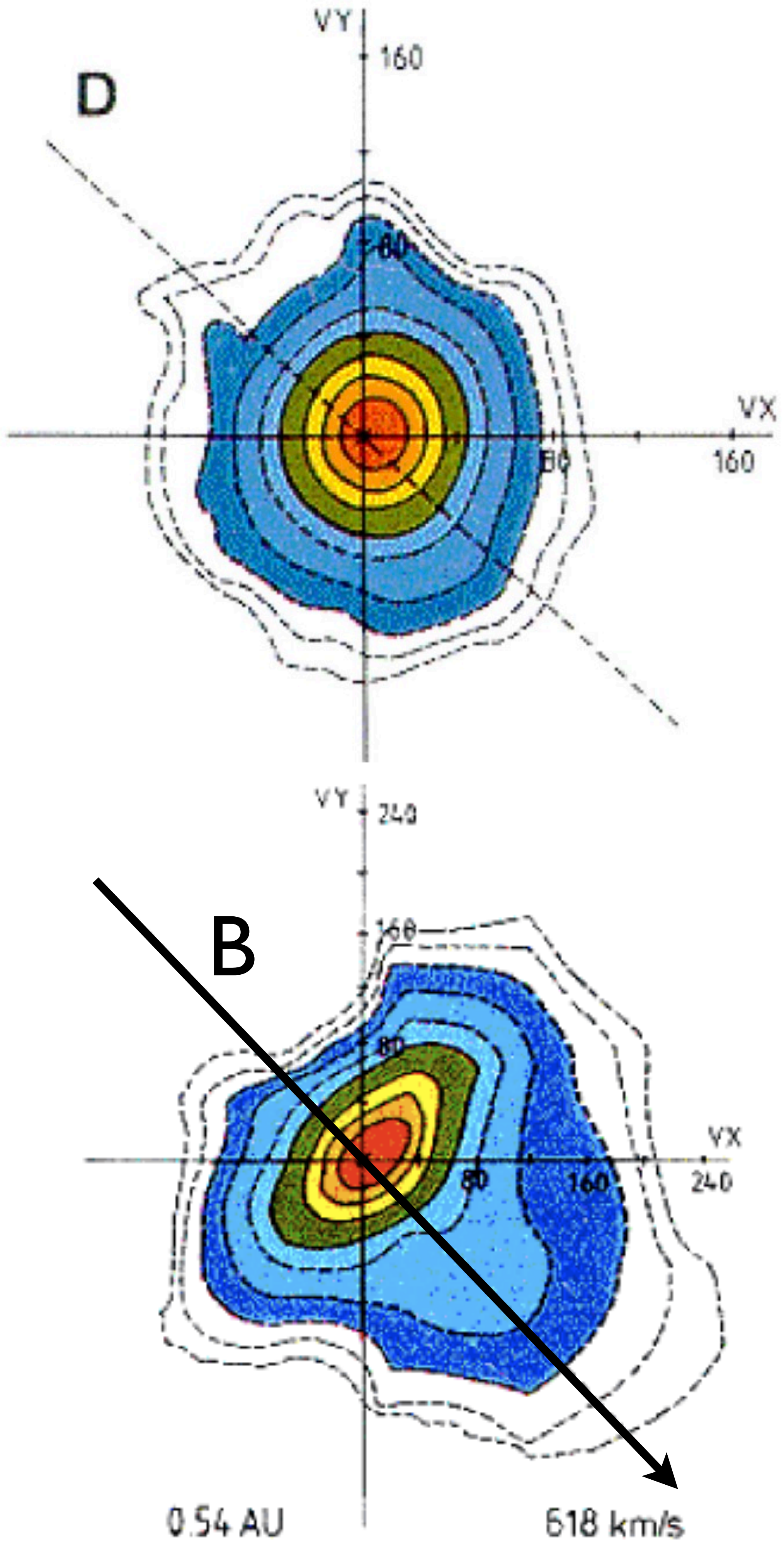
Verniero et al., 2022

spectral bump at ion scale



magnetic spectra for (random) turbulence
and polarised signals – waves

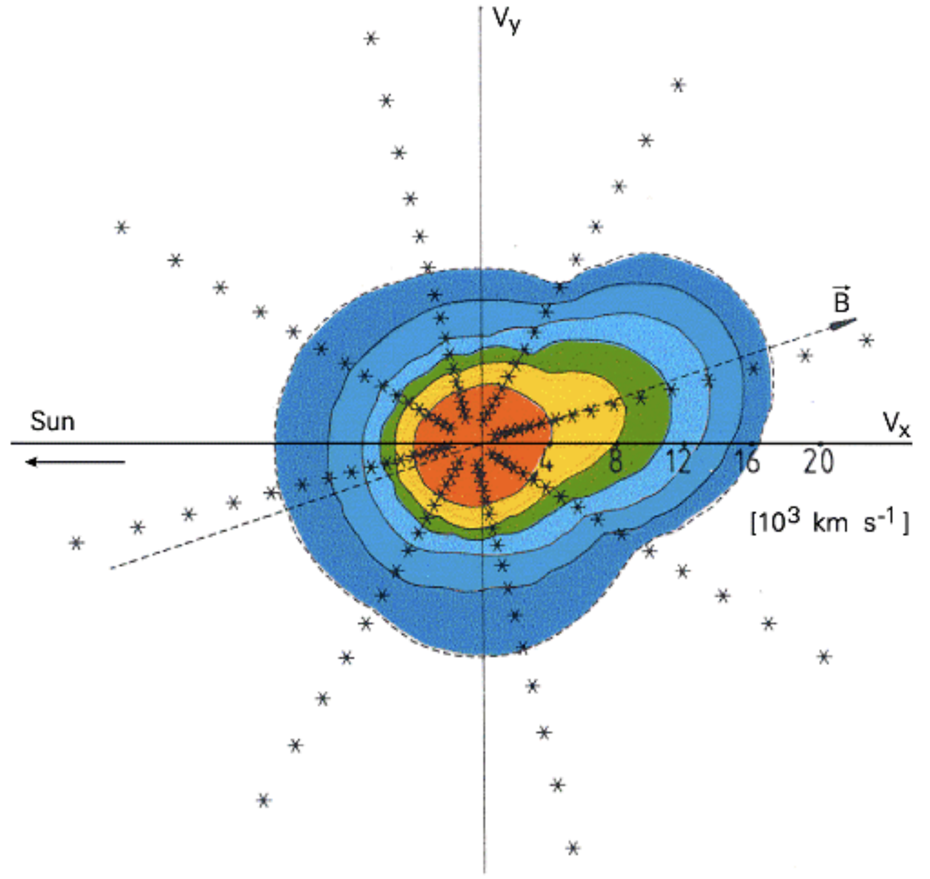
Velocity distributions are not Maxwellian
not at local thermodynamic equilibrium



Helios observations (*Marsch et al. 1982*)

Evolution of expanding distribution functions

Initial Maxwellian isotropic population expanding at constant speed in a radial magnetic field



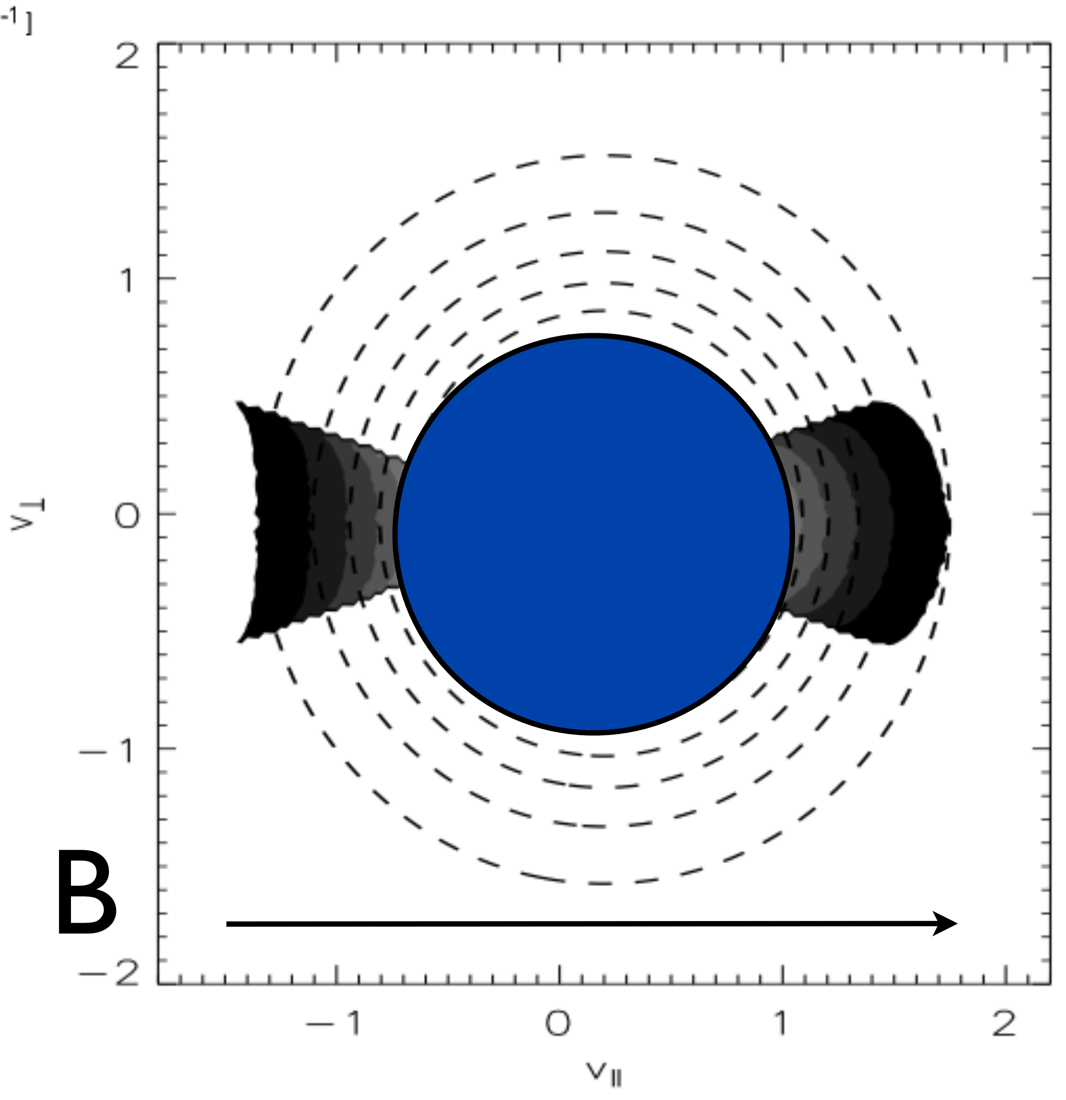
the electron Strahl population forms via collimation due to magnetic moment conservation

No interactions:

Kinetic energy: $E_{kin} = v_\parallel^2 + v_\perp^2$

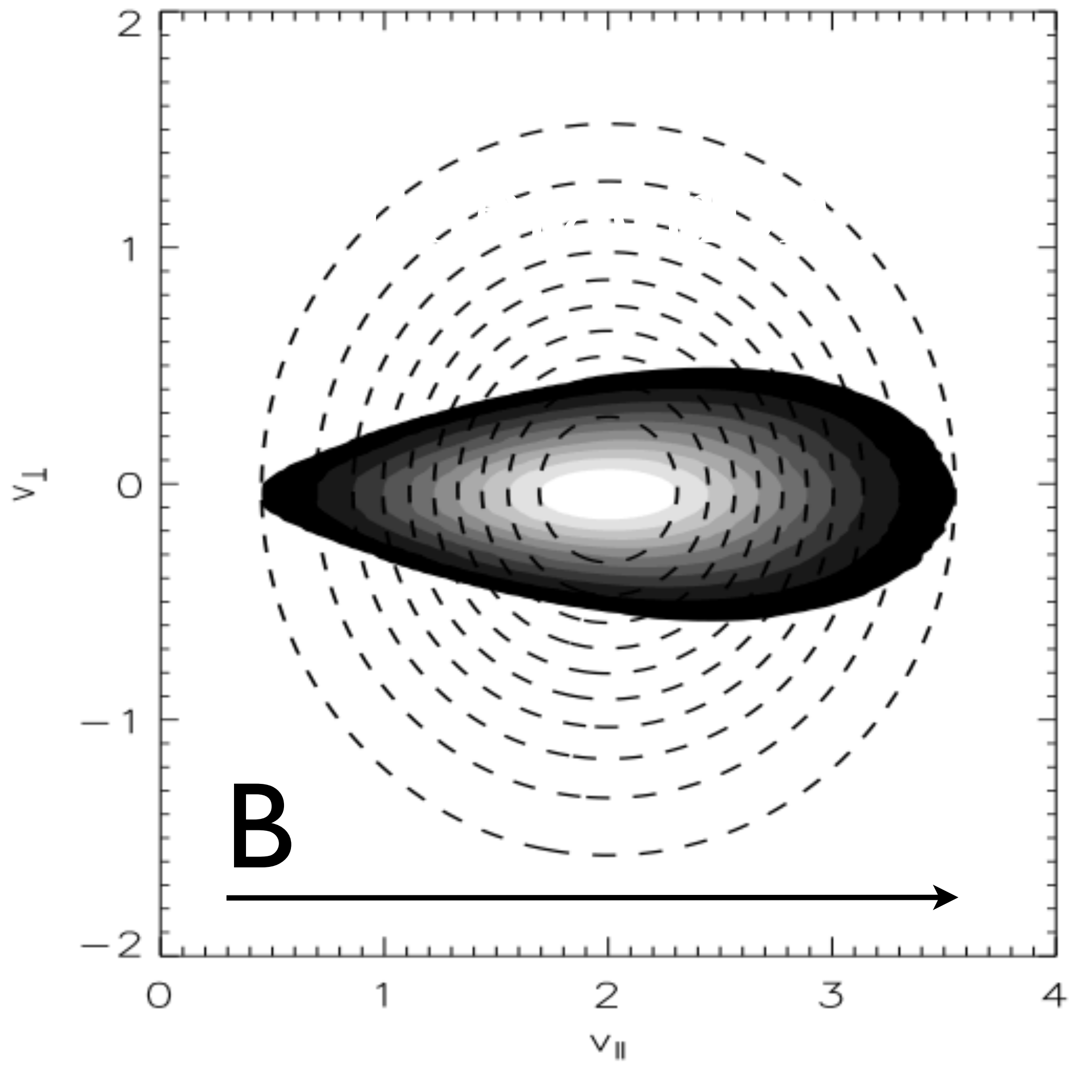
Magnetic moment: $\mu = {v_\perp}^2/B$

for a radial B ∝ R^{-2} $v_\perp \propto r^{-1}$



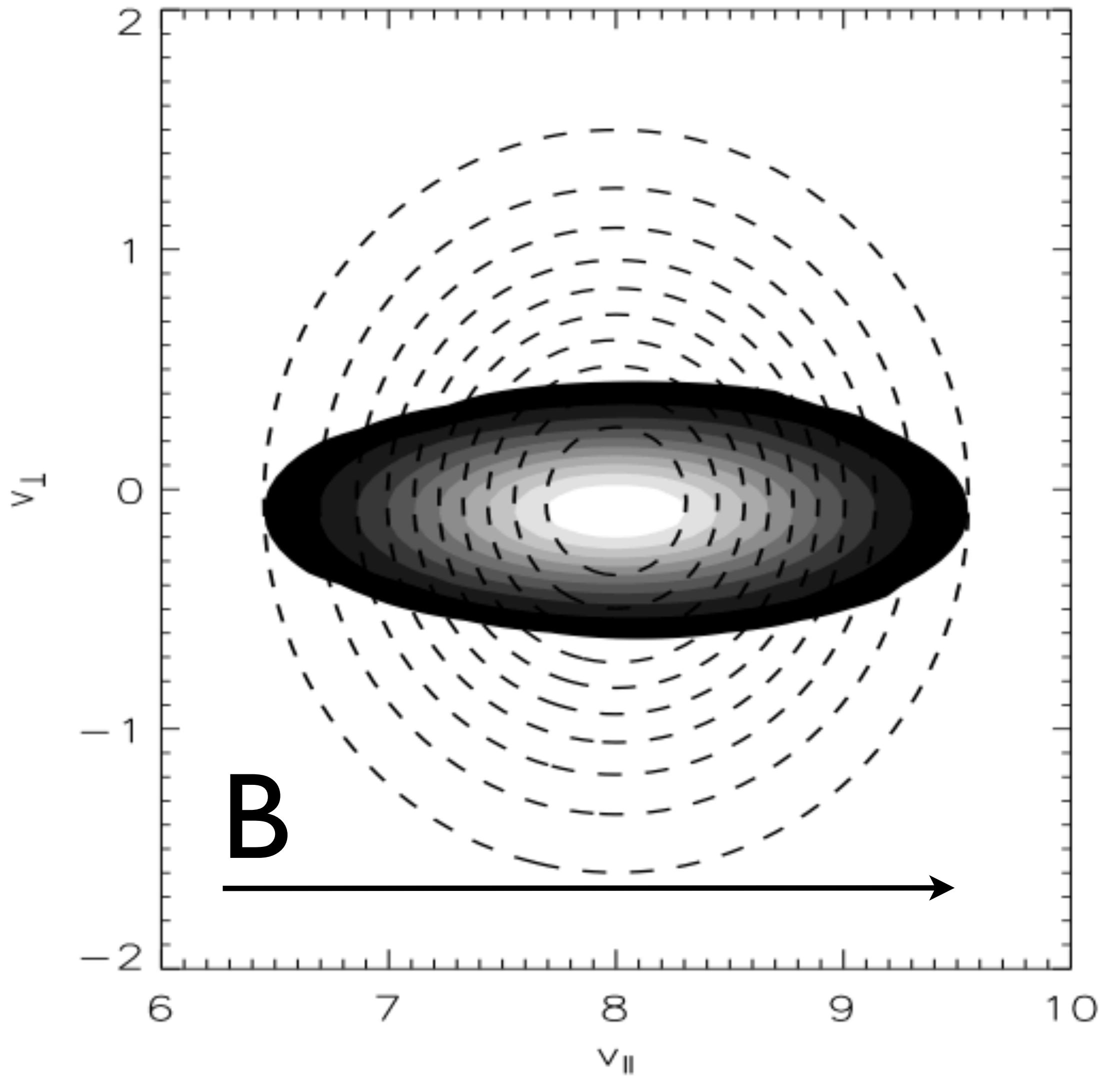
Subsonic

electrons



Supersonic

protons
close to the Sun



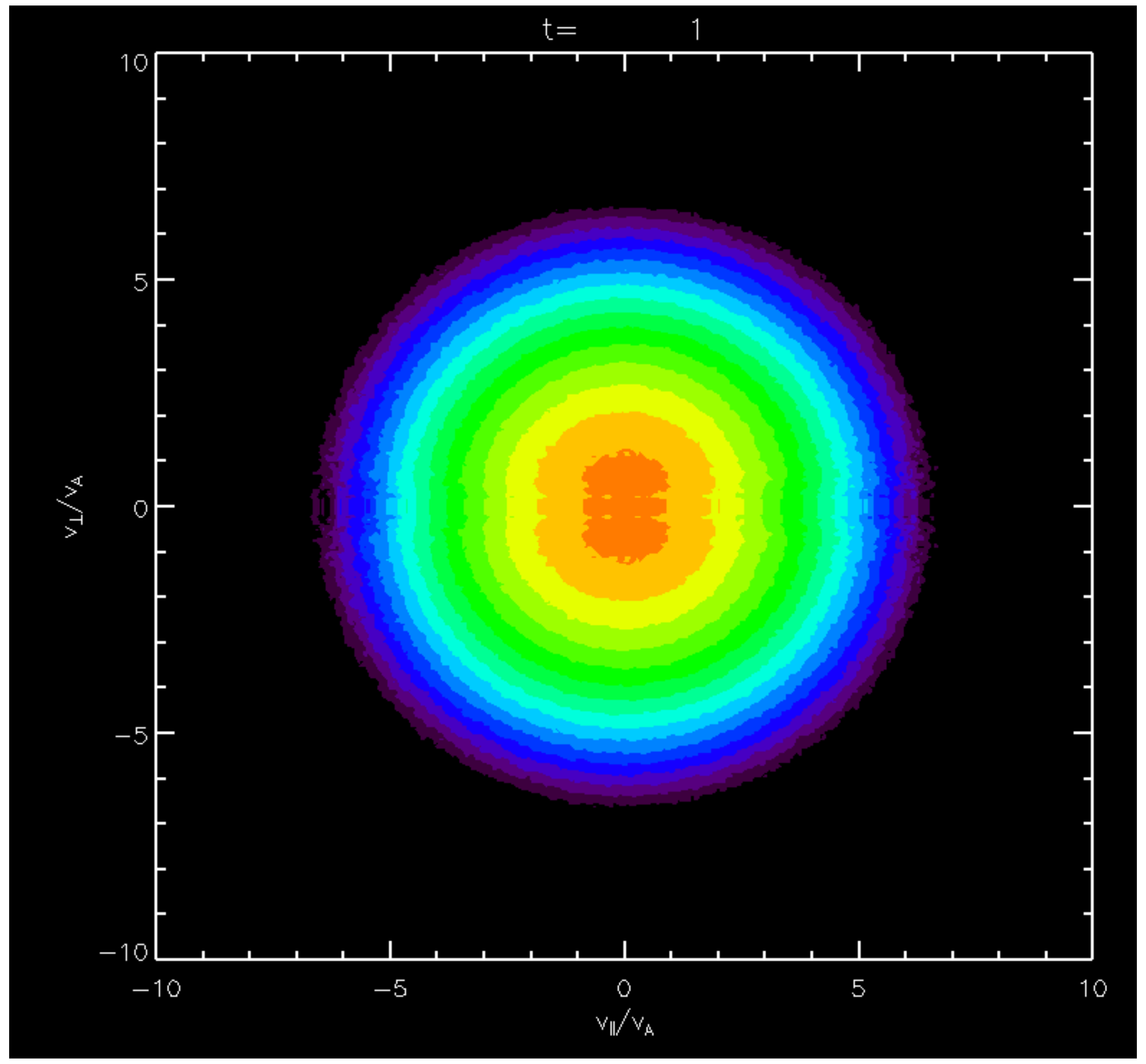
Highly supersonic

protons in the expanding solar wind

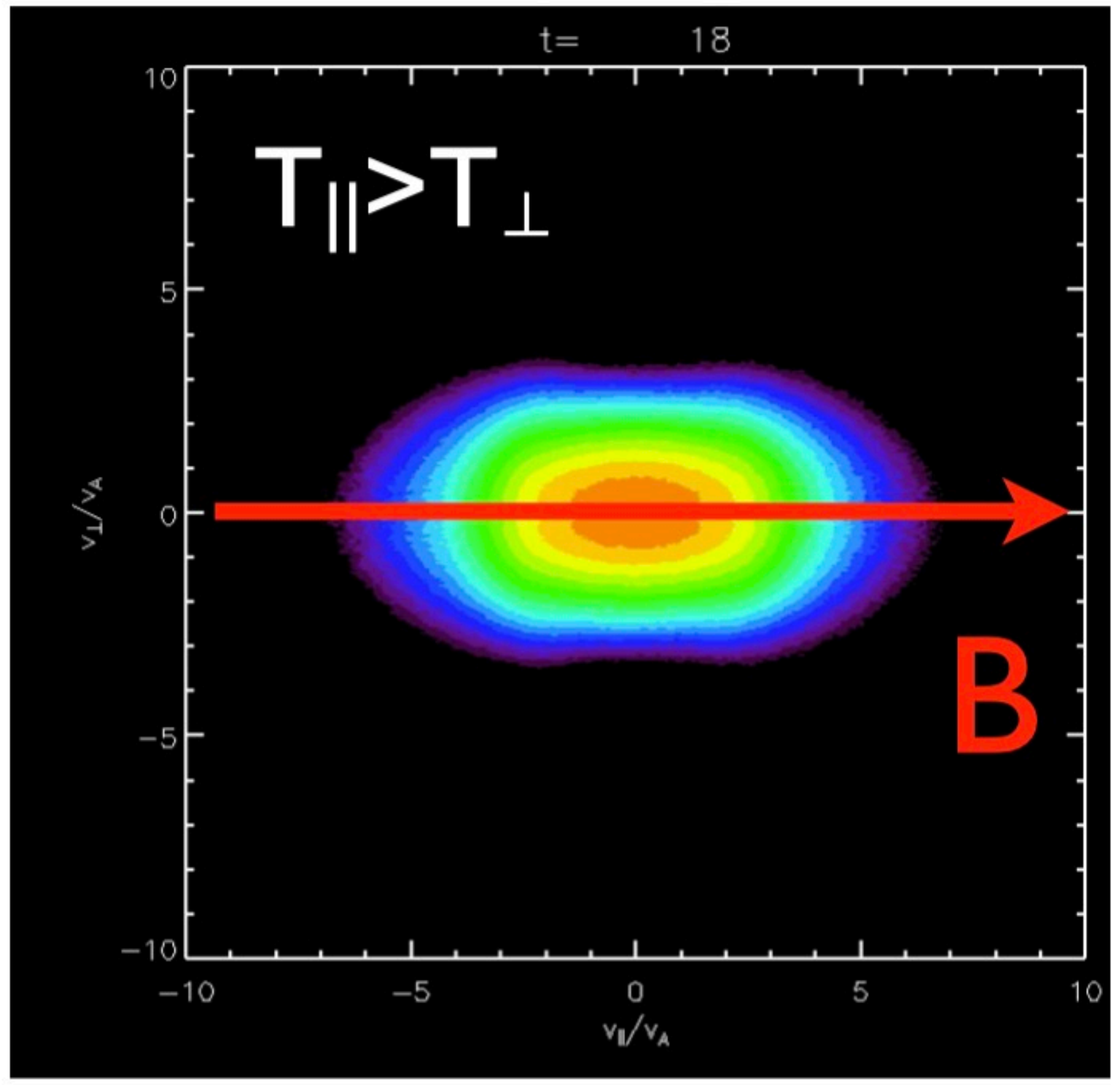
Landi, Matteini and Pantellini 2012

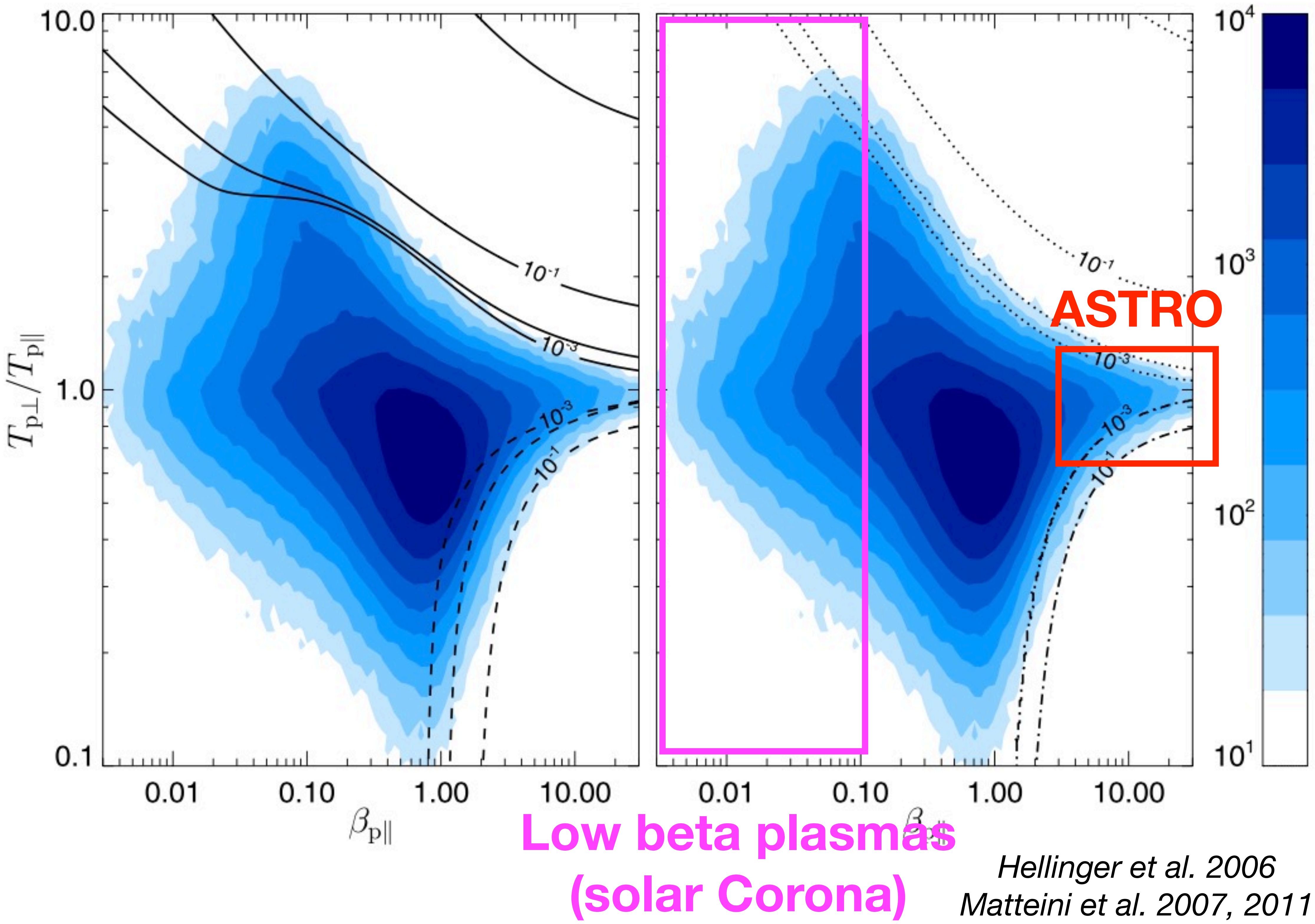
In the absence of collisions, particle properties are shaped by collisions with waves

Proton distribution



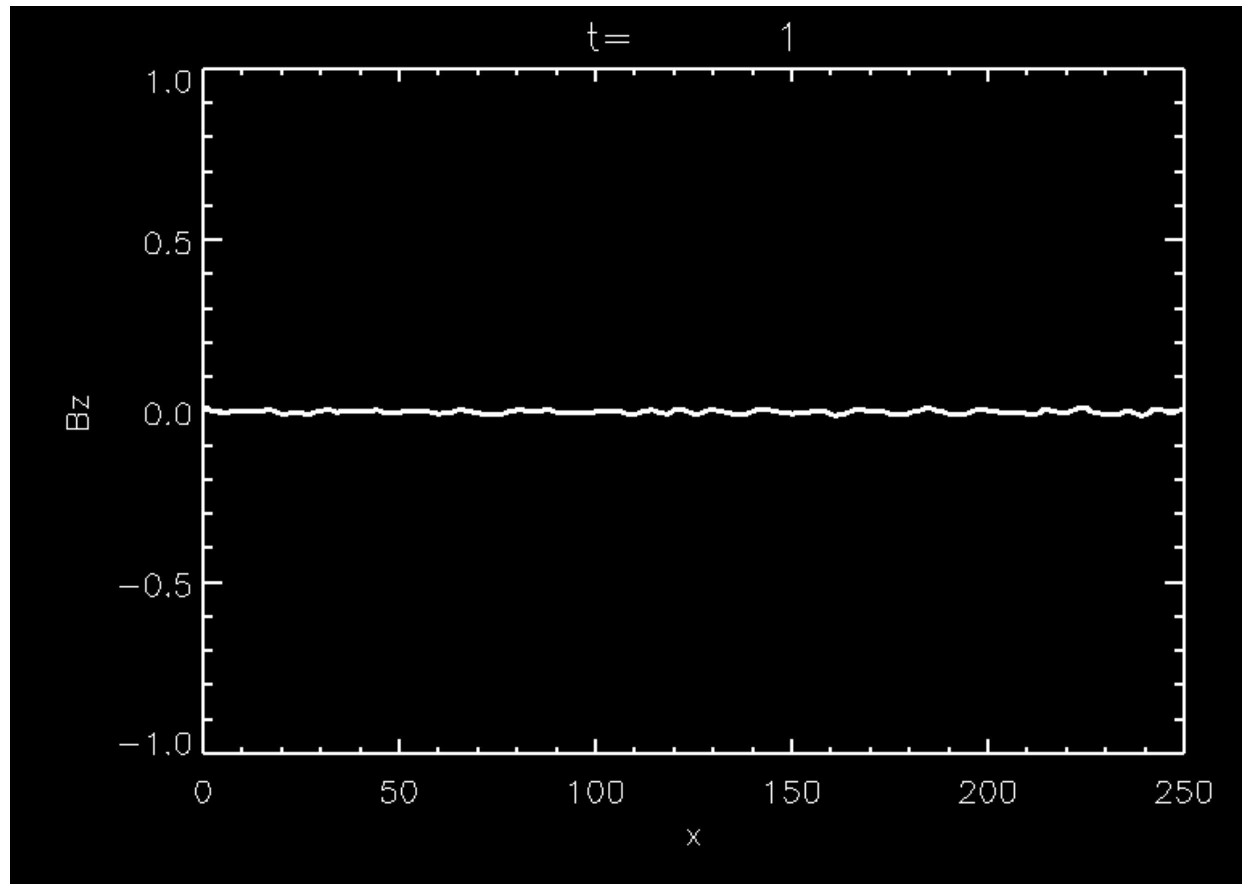
Proton distribution



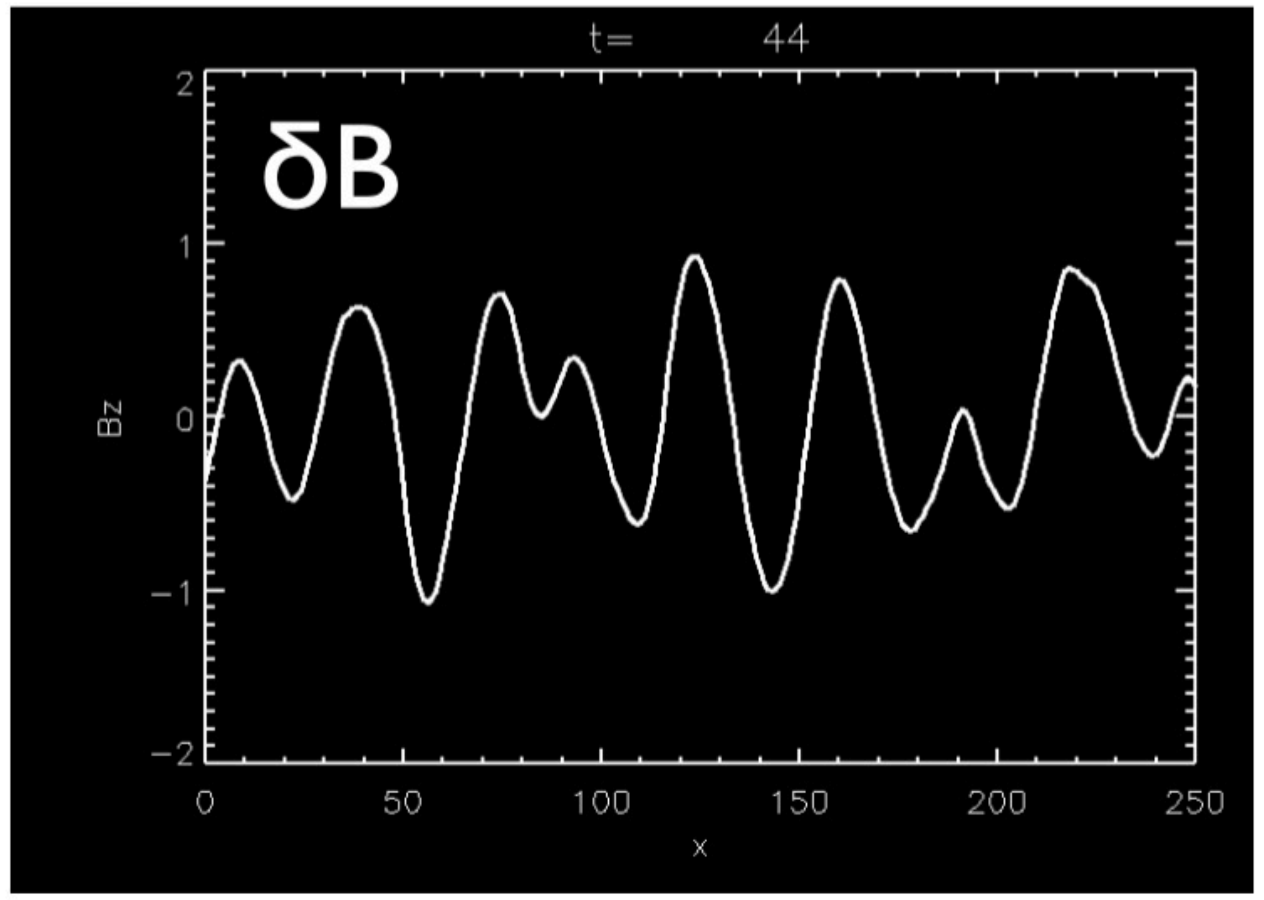


Hellinger et al. 2006
Matteini et al. 2007, 2011

Magnetic fluctuations



Magnetic fluctuations



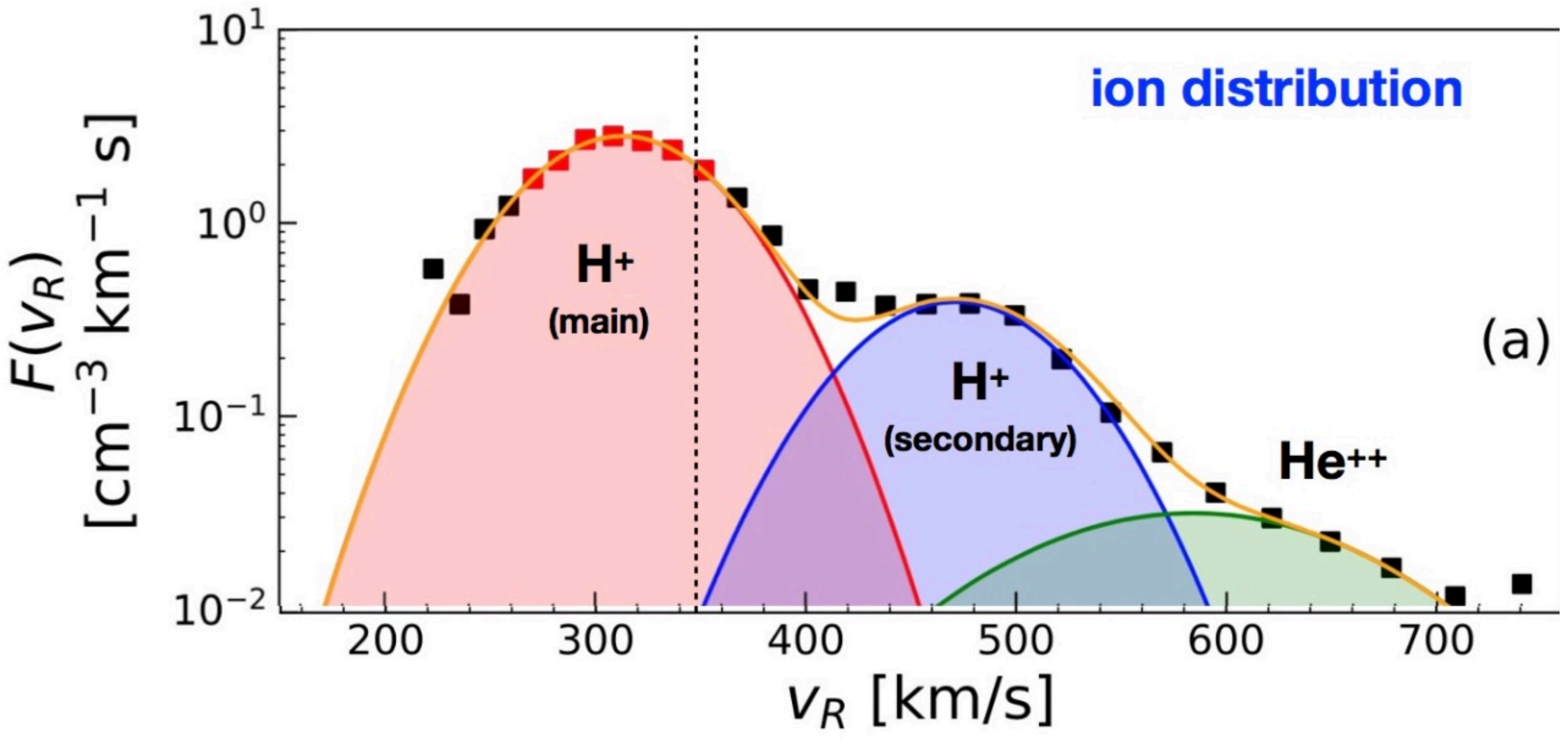
- Kinetic instabilities (Mirror, Ion-cyclotron, Fire-hose) constrain the anisotropy via wave-particle scattering.
- Instabilities are regulated by the plasma beta

Wave-particle scattering induced by microinstabilities replaces collisions in weakly collisional plasma

Introduce an effective (enhanced) collisionality, important for e.g. accretion disks (Kunz et al. PRL 2014)

Ion differential streaming in the solar wind

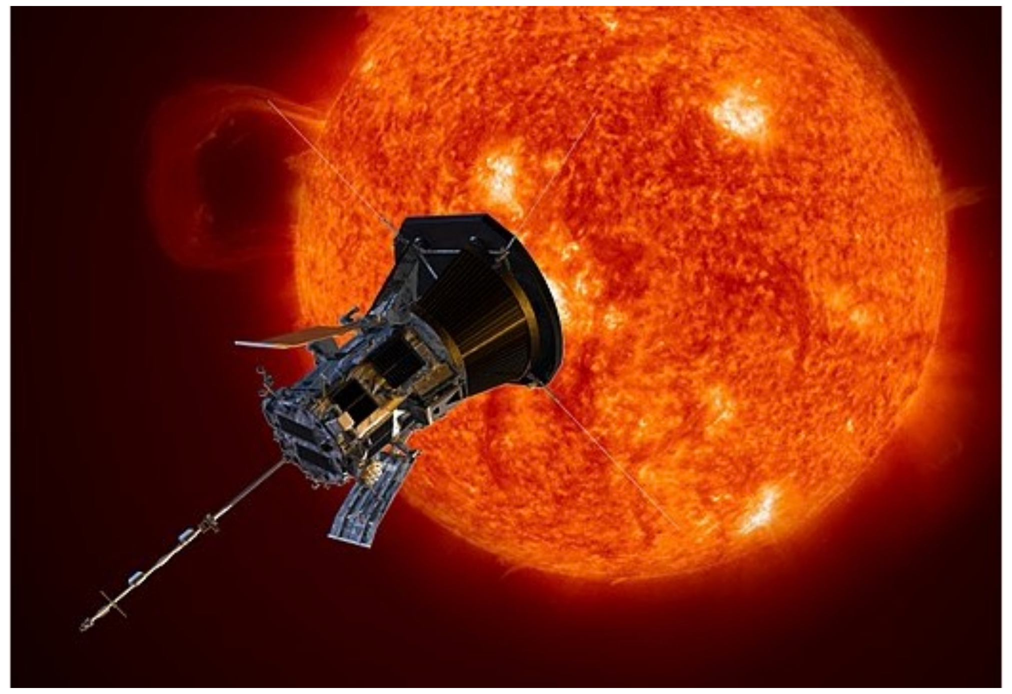
near-Sun PSP observations

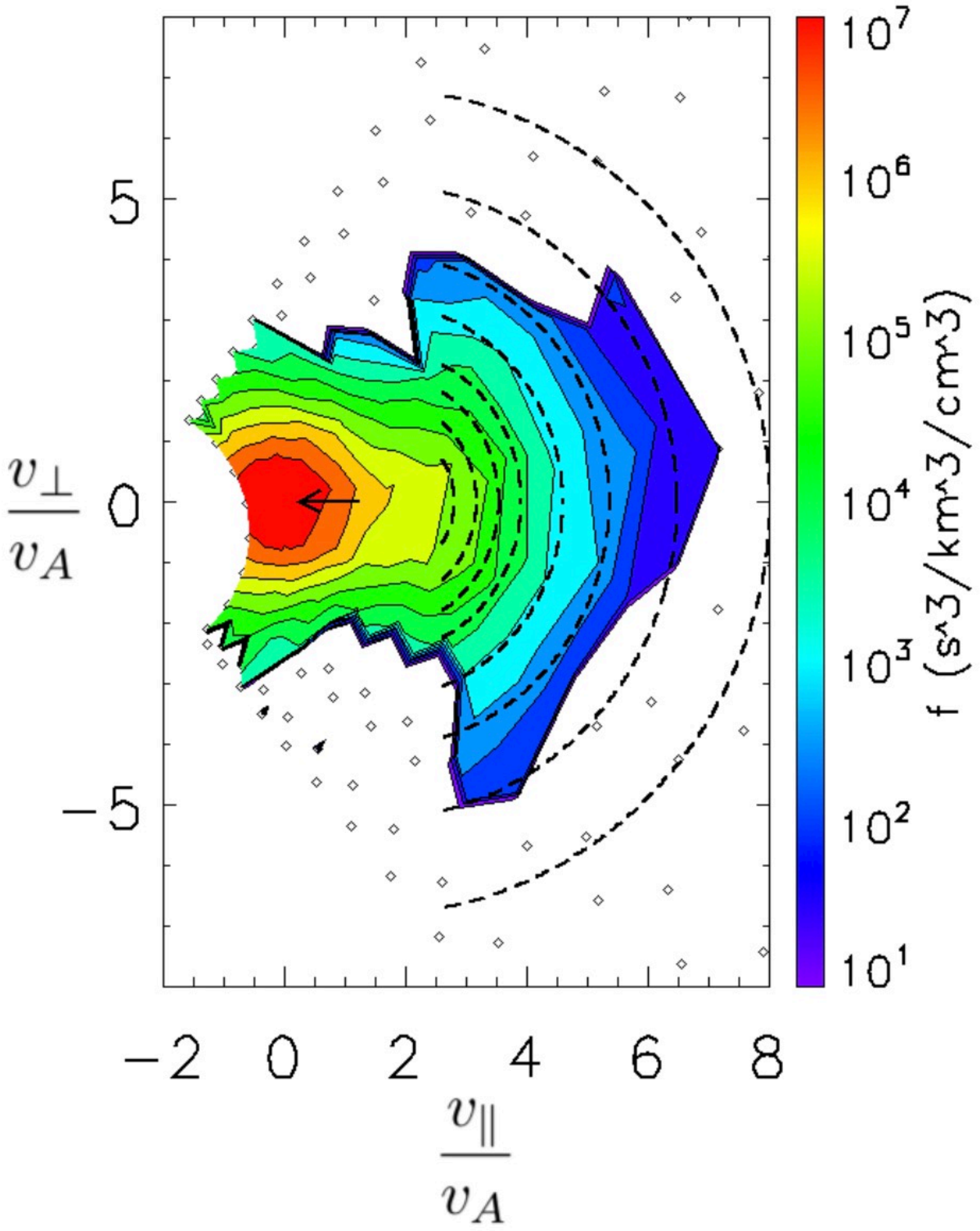


Woolley et al. MNRAS 2020

Large relative speeds along the local magnetic field between all ion populations:

- proton core
- proton beam
- alphas

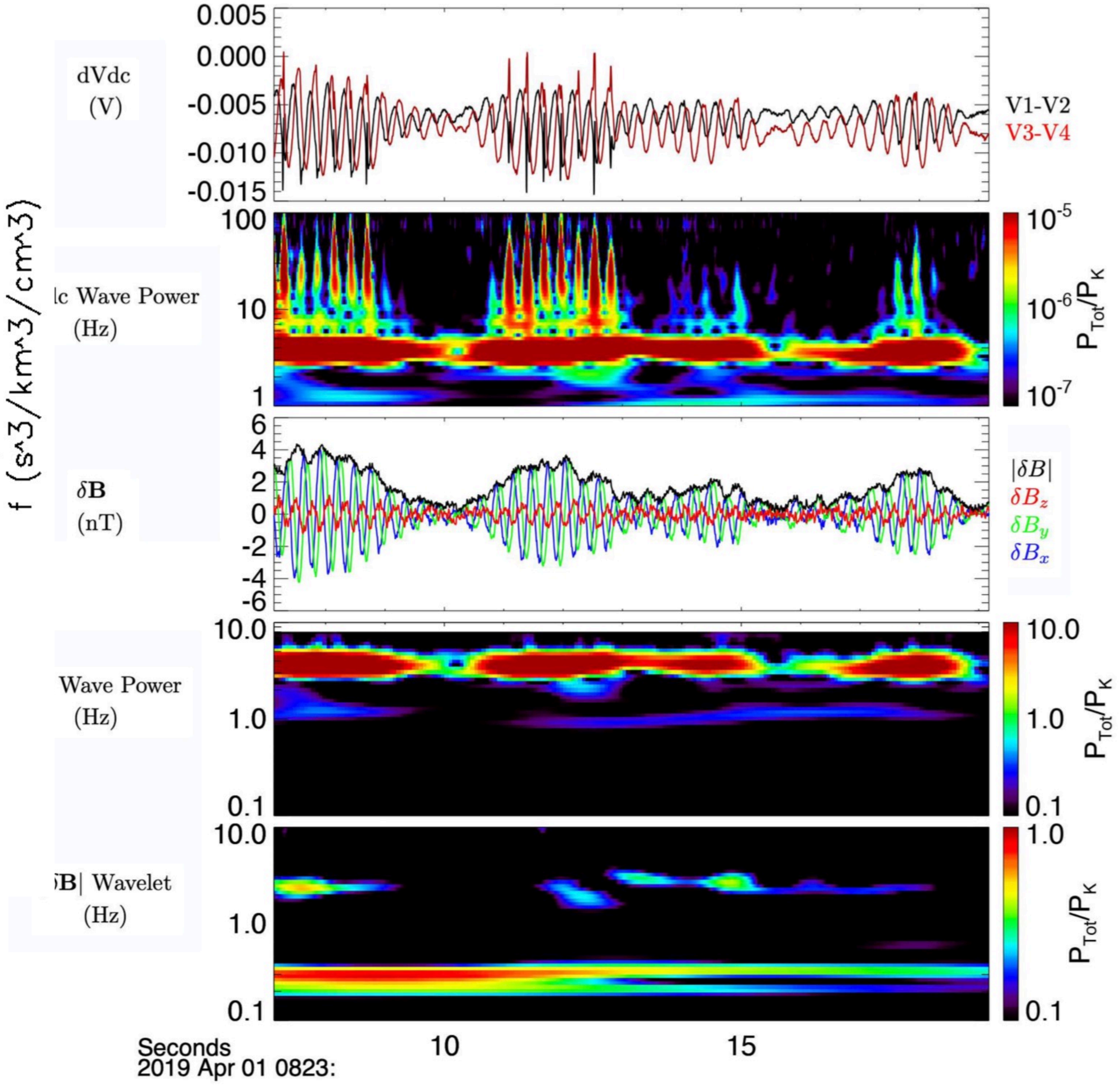




Verniero et al. 2021

Scattering contours.
Signatures of wave-particle interactions?

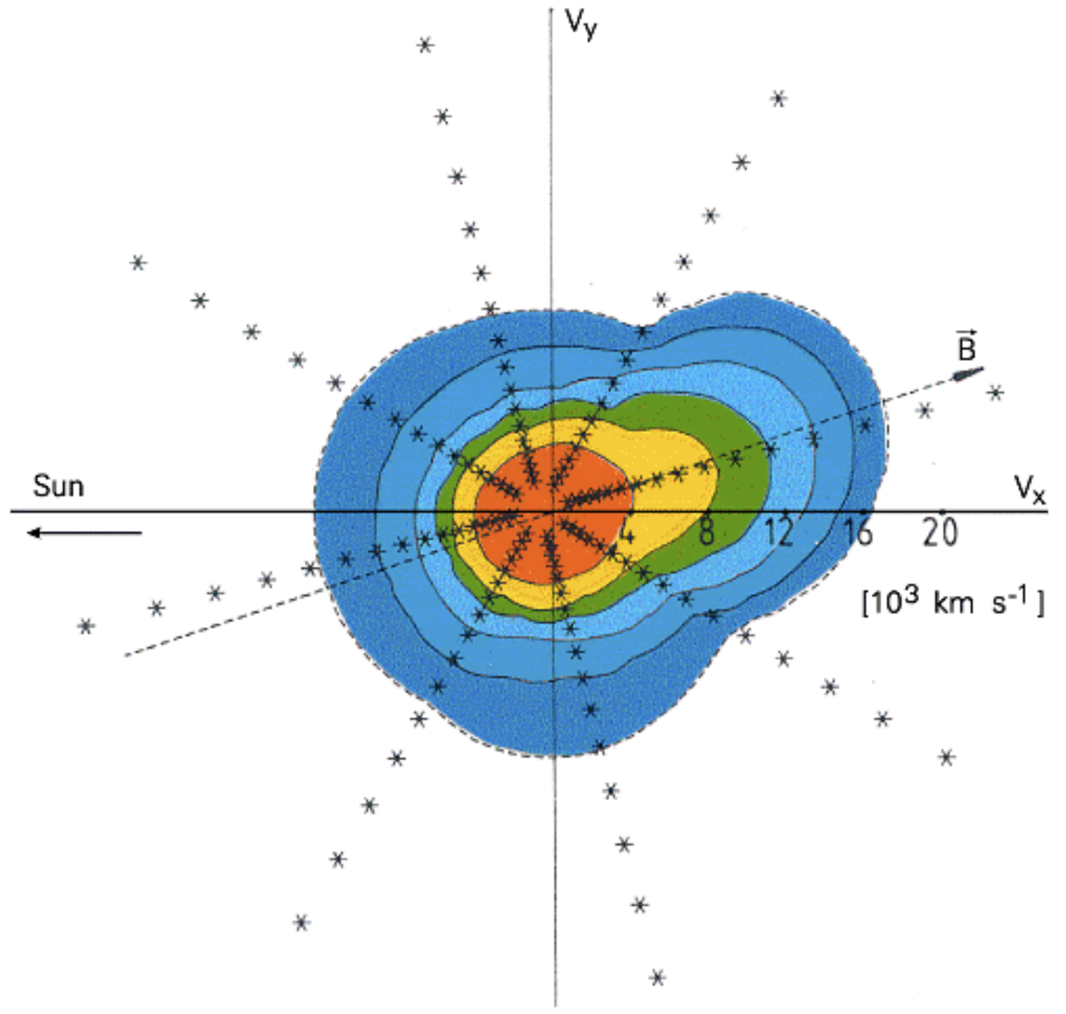
Verniero et al. 2020



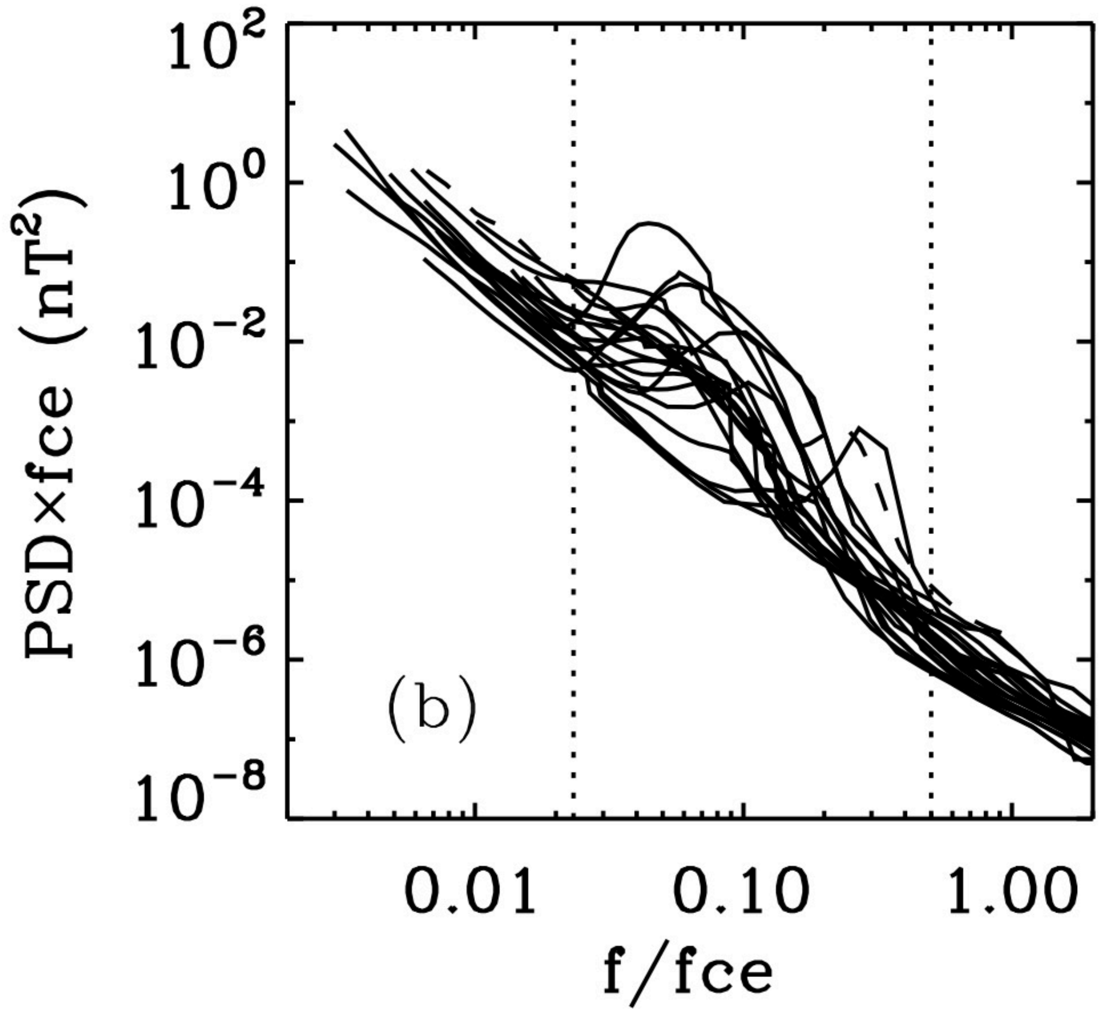
Small scale electro-magnetic waves observed.
Generated by beams?
Responsible for scattering?

...and what about electrons?

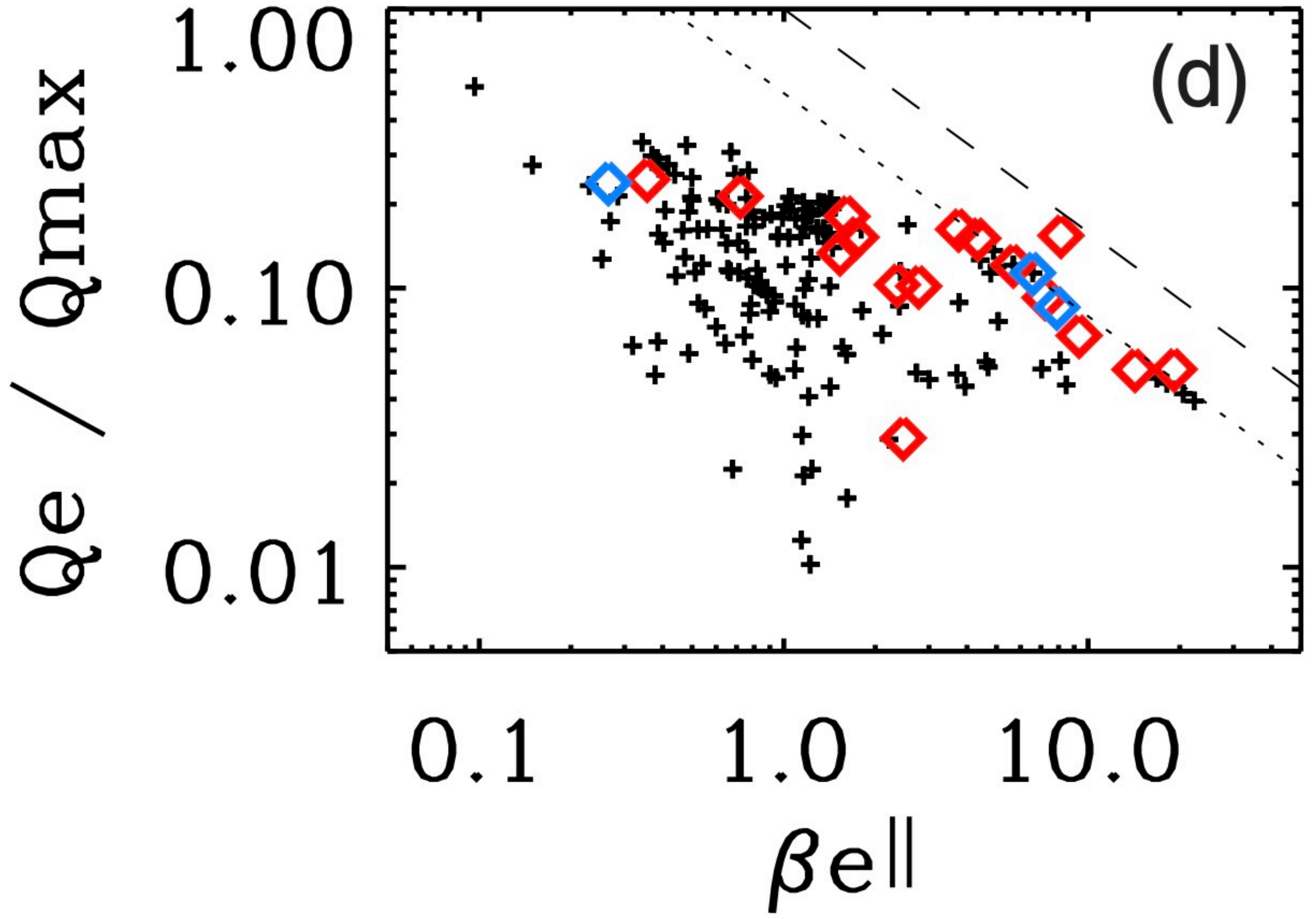
Electron distributions are characterised by field-aligned “Strahl” fast population, carrying significant heat flux (important for solar wind energy budget!)



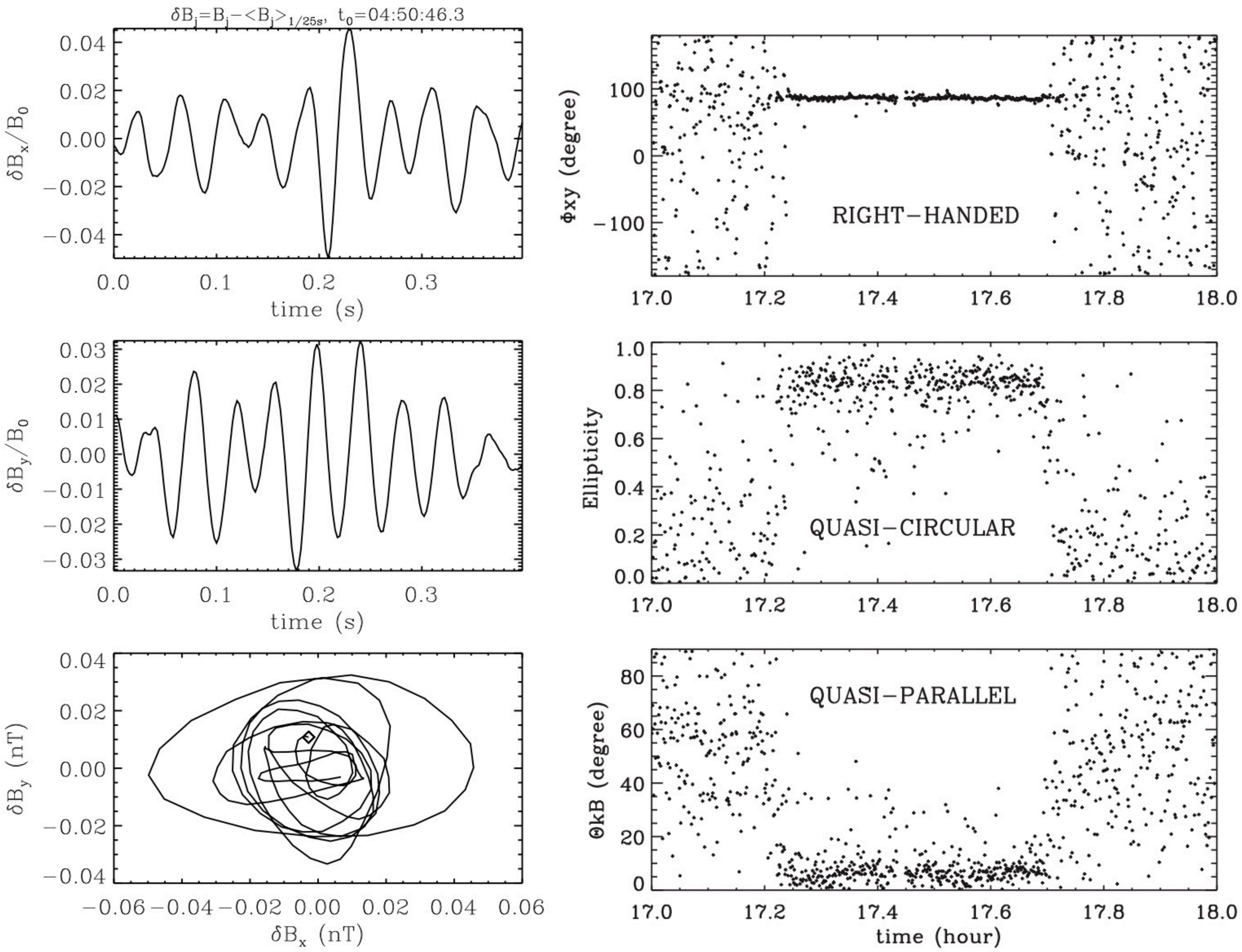
spectral bump at electron scales



heat-flux instabilit



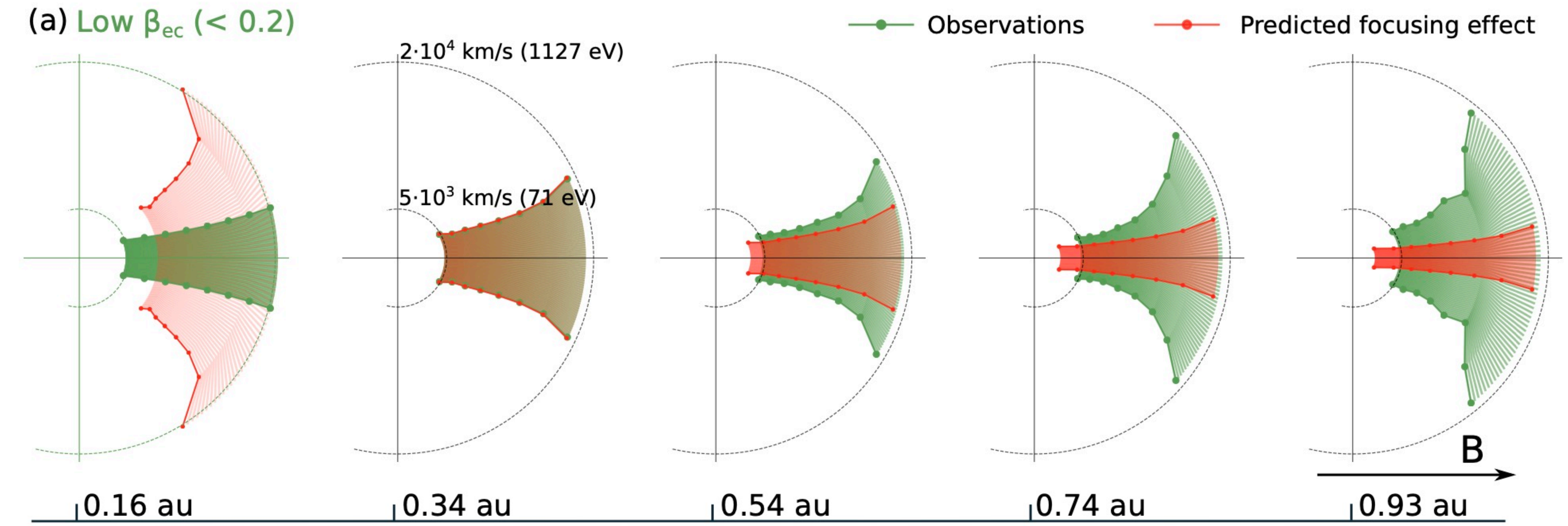
Observation of whistler waves in the solar wind (*Lacombe et al. 2014*)



whistler waves interact with electrons and constrain their thermodynamic properties

Signatures of electron strahl scattering

Electron strahl evolution with distance

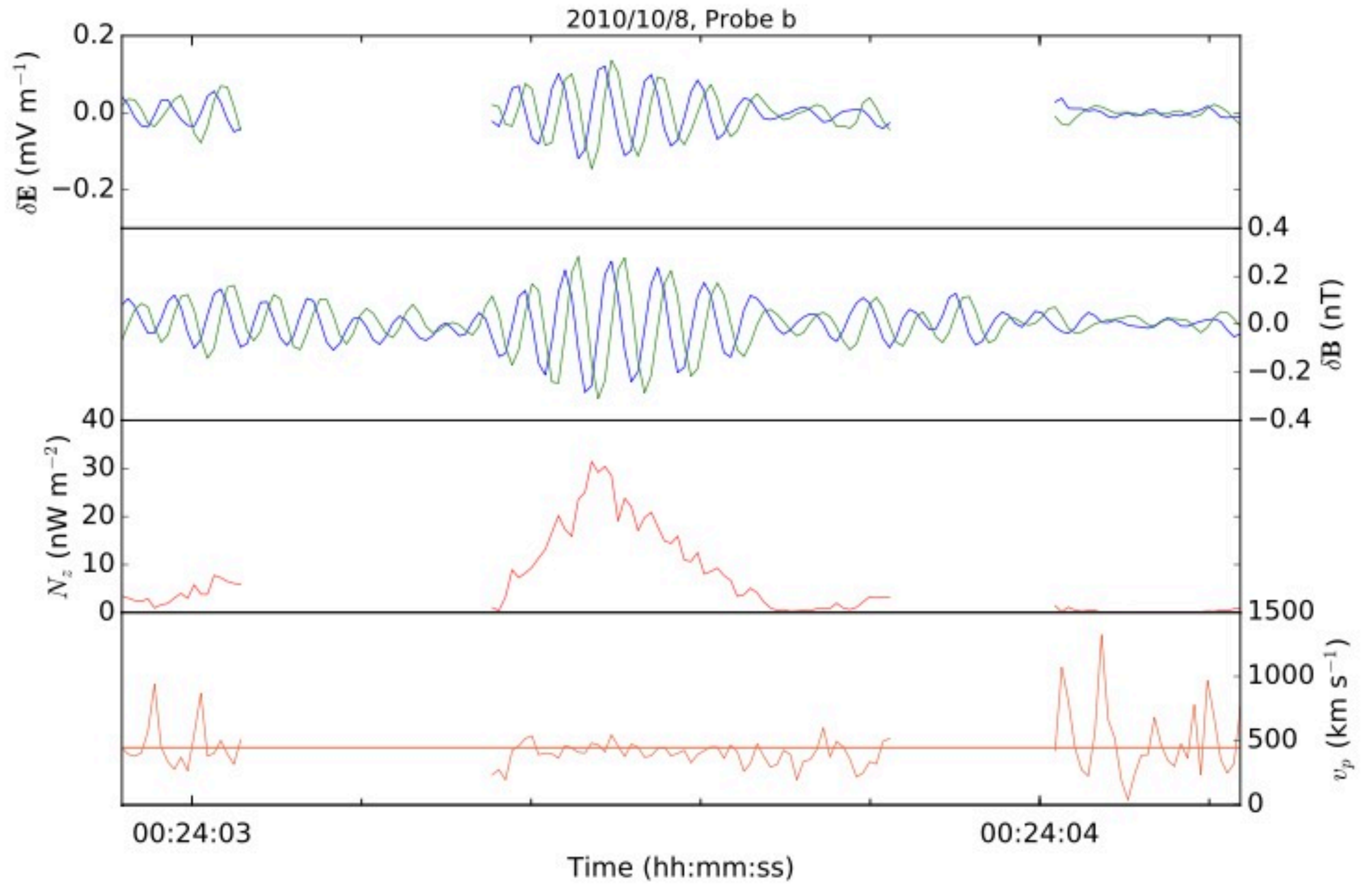


Bercic et al. MNRAS 2019

Theory predicts that the electron strahl becomes narrower with distance from the Sun, but observations show the opposite: it becomes broader!
indication of electron scattering?
waves generated by heat-flux instability?

Observation of whistler waves

Measuring E and B we can identify the direction of propagation



Stansby et al. 2016

- Whistler waves detected in the solar wind are found to propagate anti-sunward: consistent with heat-flux instability, but not effective for strahl scattering…
- Possible solution: instability generates oblique waves, making scattering possible, then evolving into parallel waves (*Micera et al. 2020*)

Closing the loop

Solar wind modelling:

1. **Fluid models: Parker 1958, 1960… ; Leer & Axford 1972…**
2. **Kinetic - exospheric models: Lemaire-Scherer 1970, Jockers 1970**

the two approaches are ultimately equivalent!

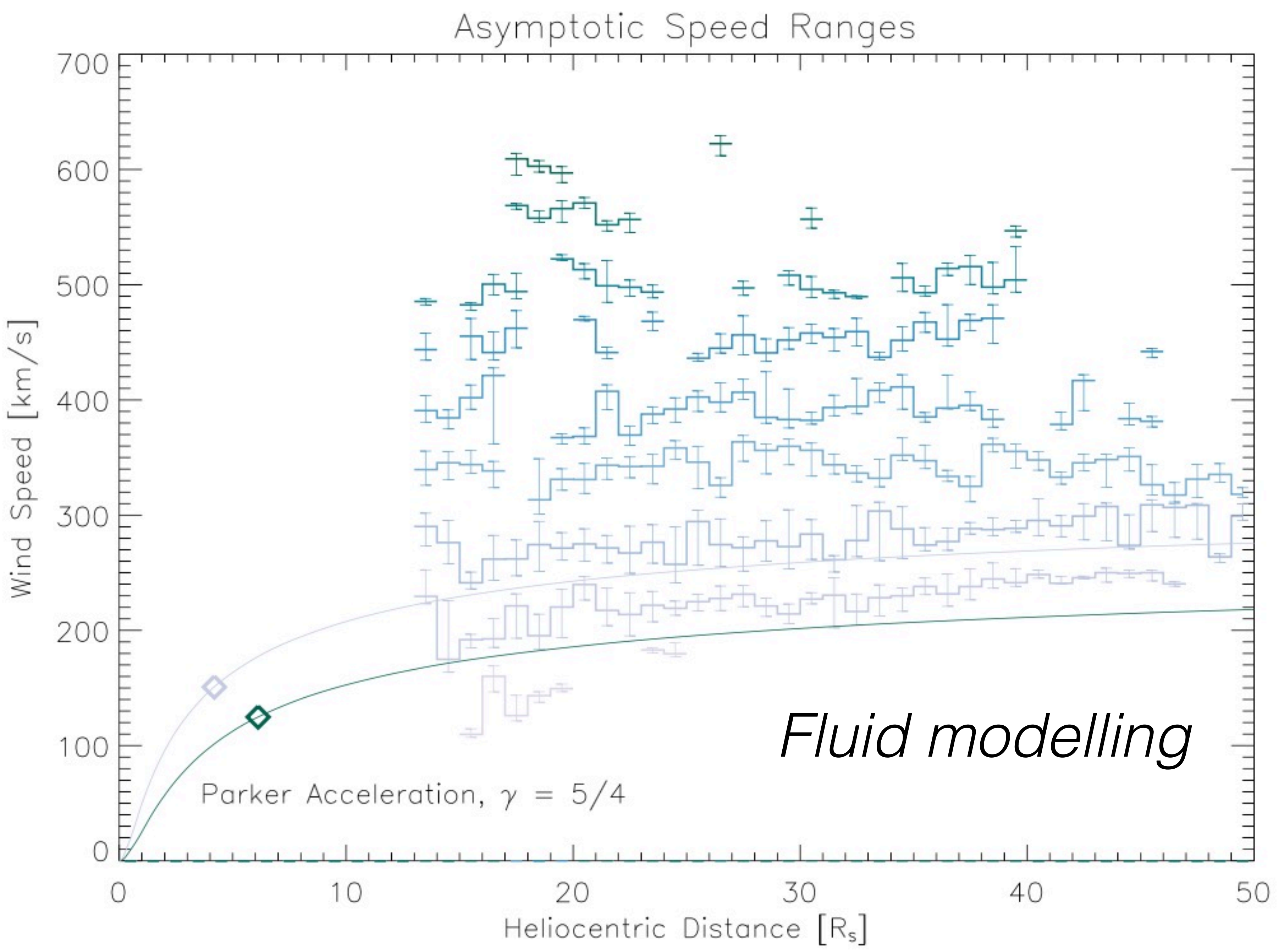
Kinetic and Hydrodynamic Representations of Coronal Expansion and The Solar Wind

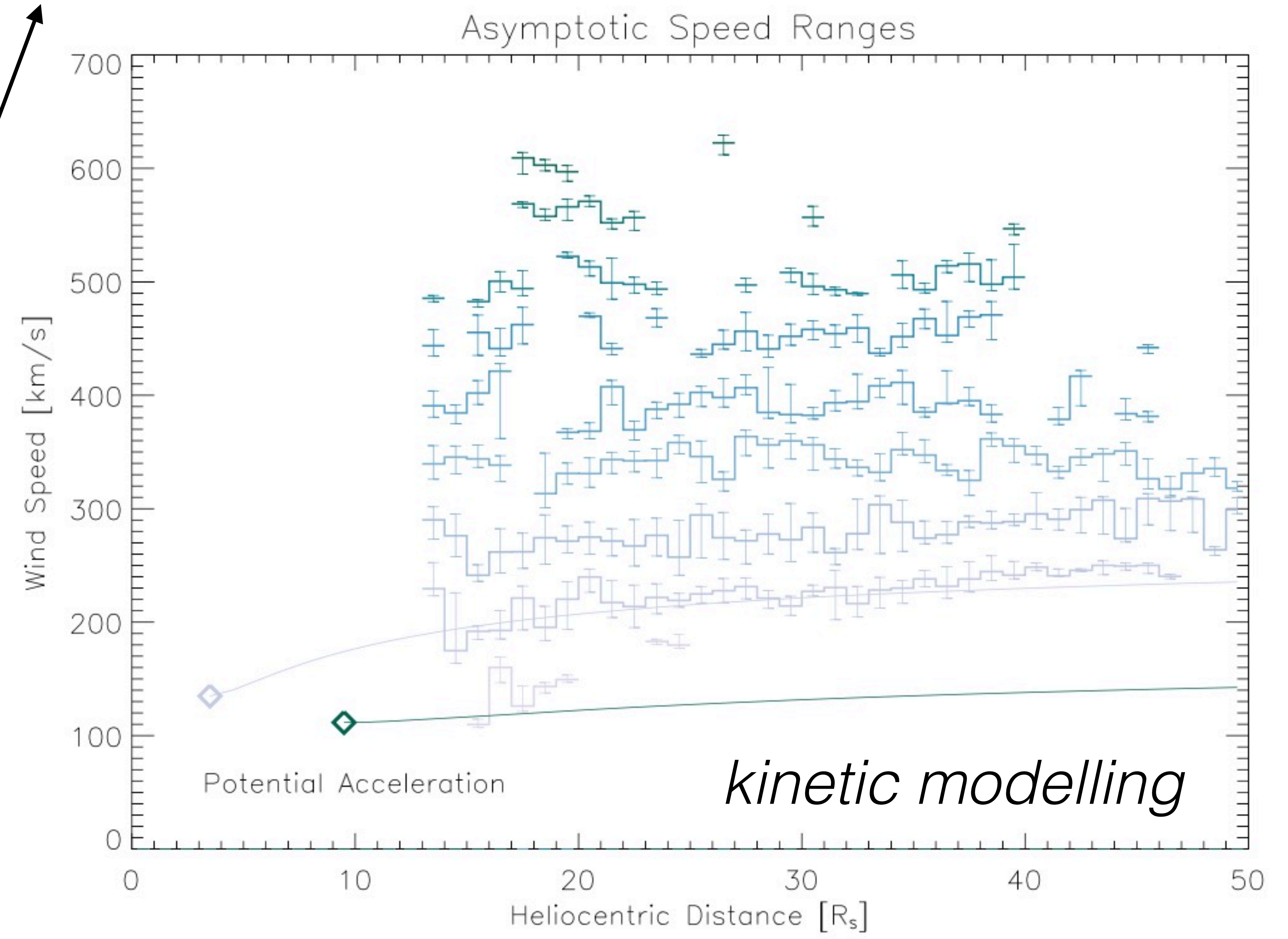
E. N. Parker

Department of Physics
University of Chicago
Laboratory for Astrophysics
933 East 56th Street
Chicago, IL 60637
USA

Abstract. We consider the Lemaire-Scherer construction of the supersonic solar wind as the kinetic escape of a collisionless (scatter-free) plasma from an exosphere near the Sun. The radial electric field enforces equality of the electron and ion densities and also equality of the electron and ion fluxes. Consequently, the electrons form an electrostatically confined atmosphere with the temperature declining outward only slowly from the exosphere and becoming the work horse that lifts and accelerates the ions to supersonic velocity.

Solar wind 12 conference proceeding





… but both fluid and kinetic (exospheric) models fail in reproducing the large speeds of the fast solar wind!

Halekas et al. ApJ 2022

Some take-home messages

- PSP measurements near the Sun, coordinated with Solar Orbiter remote and in situ observations offer the unique opportunity for understanding solar wind acceleration and its energy budget

- Current models – either fluid or kinetic – are not able to self-consistently accelerate a fast solar wind from a ~1MK Corona. Some additional energy source is needed: waves, turbulence, reconnection?, non-thermal distributions in the Corona?

- PSP observations suggests that Alfvén waves (switchbacks) may play a key role in the acceleration – relevant for all stellar wind from hot Coronae?

- Energy in the large-scale Alfvénic fluctuations undergo a turbulent cascade, leading to energy transport down to small-scale. At ion scale, properties of the turbulence change and some energy is likely dissipated to heat the ions, however the responsible physical processes have not beed constrained yet (ion-cyclotron resonance, reconnection?). The cascade continues to electron scales – are electrons significantly heated?

- Wave-particle interactions play a key role in the way energy is dissipated and exchanged between fields and particles. Interactions are controlled by the non-Maxwellian shape of distributions. Wave-particle interactions replace collisions and control the plasma temperature anisotropies, relative drifts between ion populations and electron heat-flux. It's likely necessary to take these processes into account to model solar wind acceleration and expansion