Recent progress in plasma turbulence, heating, and related processes, from solar wind observations

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Outline

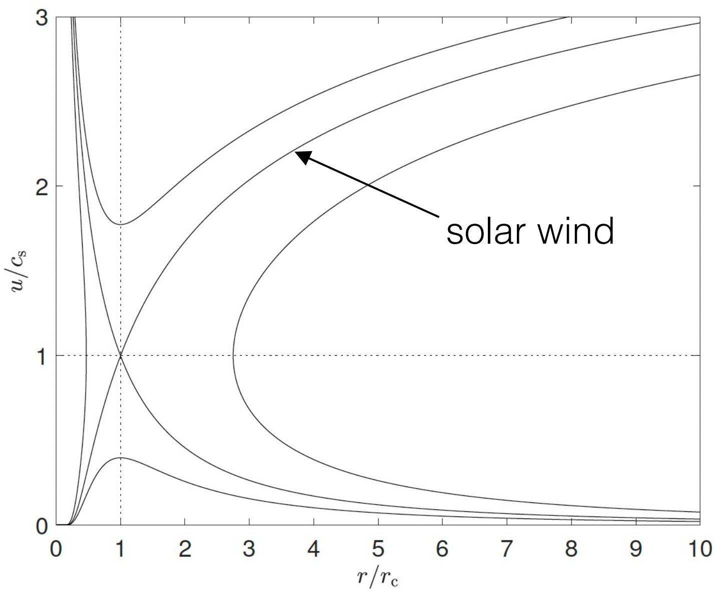
1. Introduction to the solar wind
2. Solar wind turbulence and dissipation
3. Pressure anisotropy instabilities
4. Effective collisionality
5. Possible links to ICM

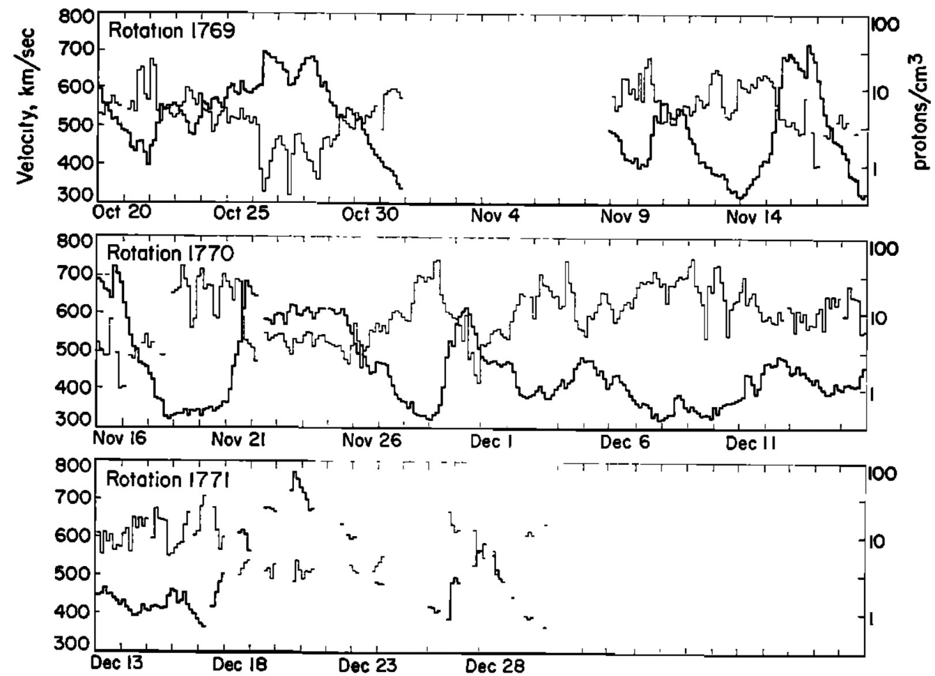
1. Introduction to the Solar Wind

Discovery of the Solar Wind

- Existence not known until ~60 years ago (previously only hints of connection)
  - predicted by Eugene Parker in 1958
  - observed by Luna & Mariner spacecraft in 1960s
- Steady-state hydro + isothermal + radial symmetry → supersonic wind

$$\frac{1}{u}\frac{du}{dr}\left(u^2 - \frac{2k_{\mathrm{B}}T}{m}\right) = \frac{4k_{\mathrm{B}}T}{mr} - \frac{GM_\odot}{r^2},$$

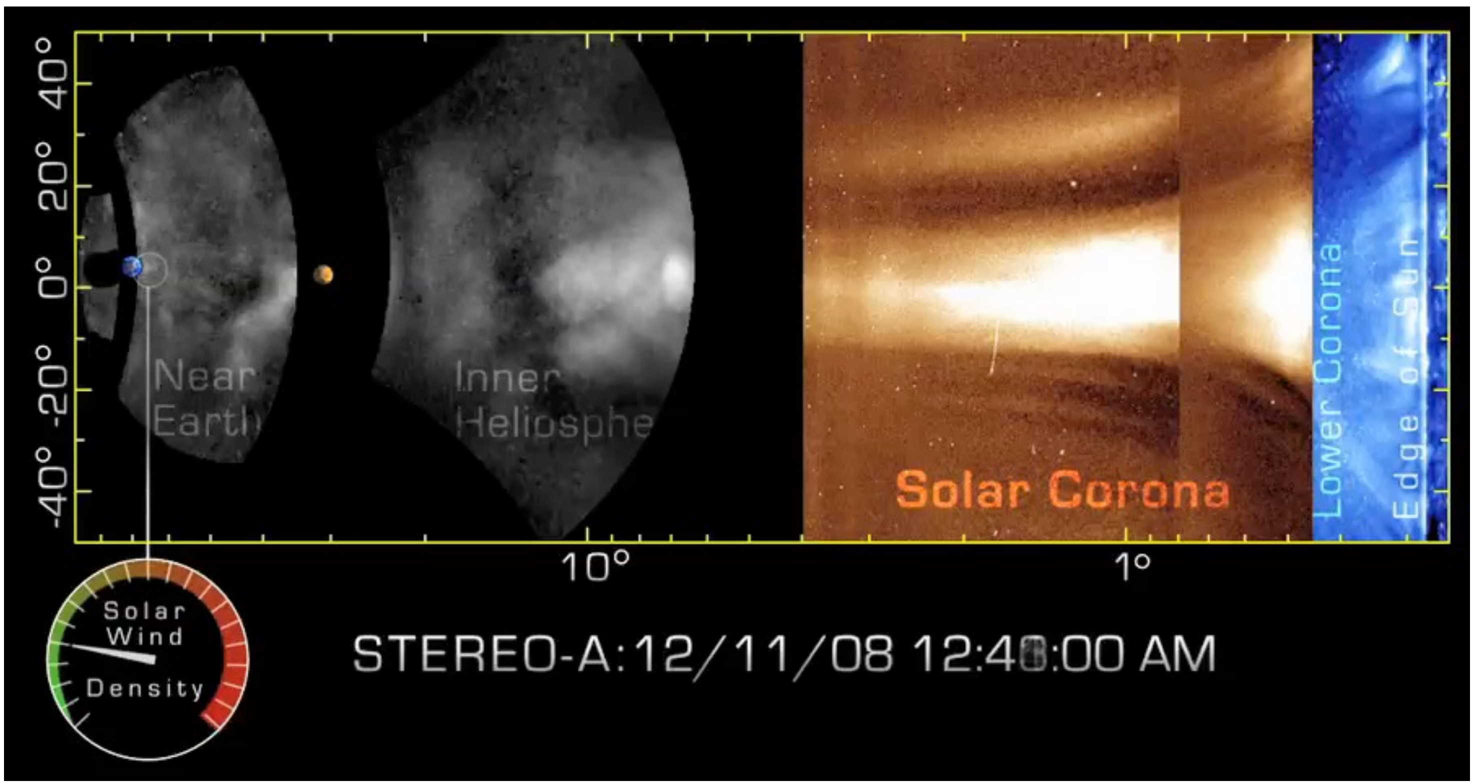




Neugebauer et al. 1966 JGR

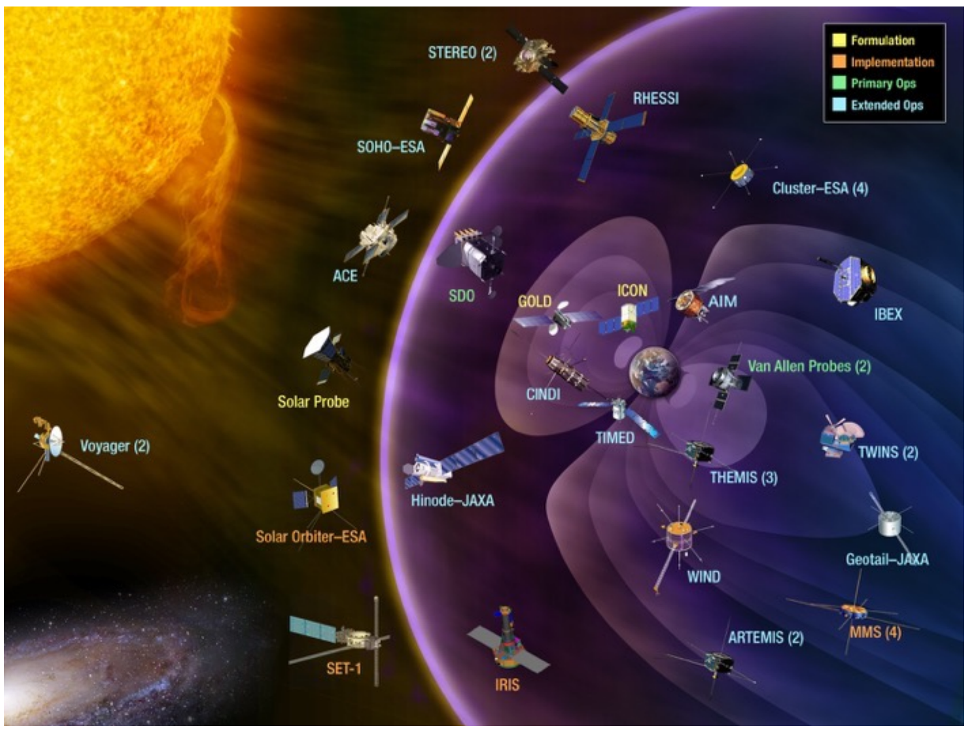
The Solar Wind Imaged Now

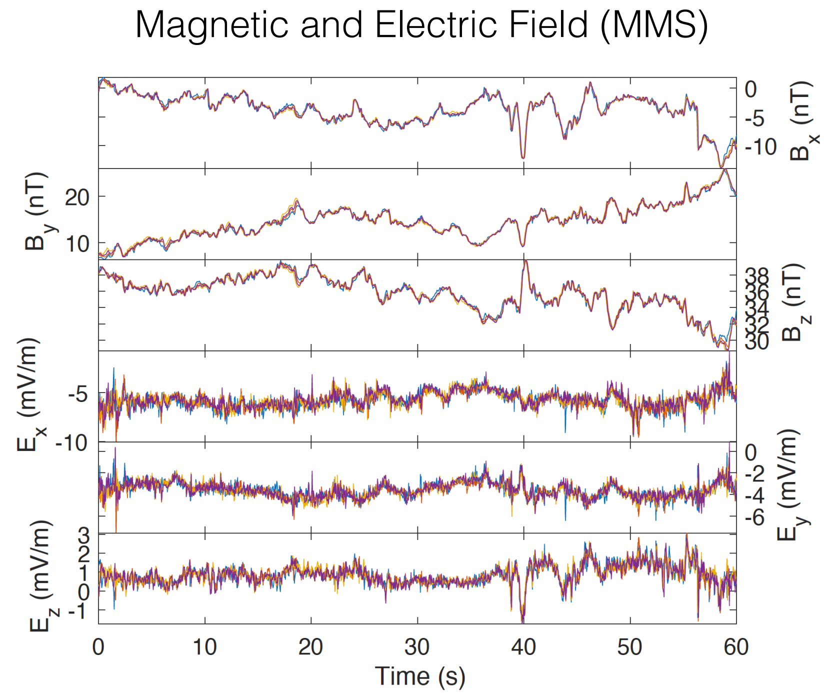
- Full extent of the solar wind <1AU now imaged by STEREO
- Complex, structured on all measured scales, contains any plasma process imaginable (well, maybe not, but almost!)

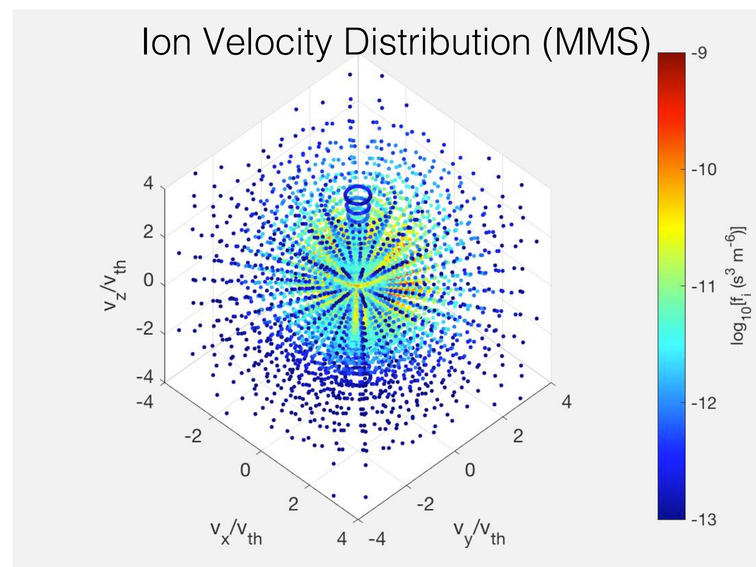


In Situ Measurements

- Large number of spacecraft making in situ measurements
- Everything you need to characterize a plasma





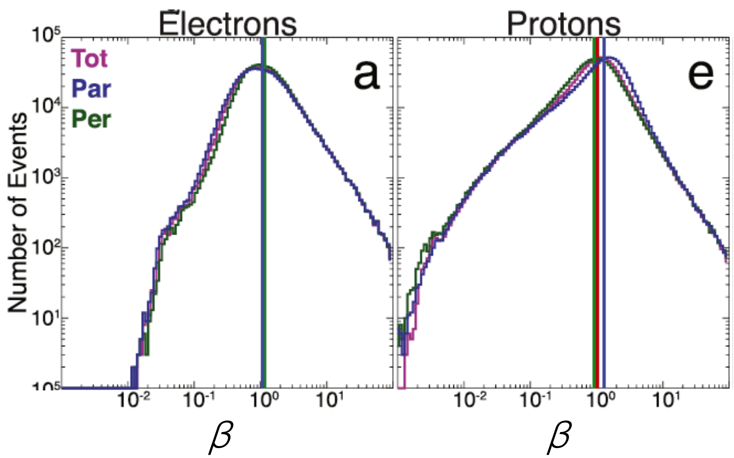


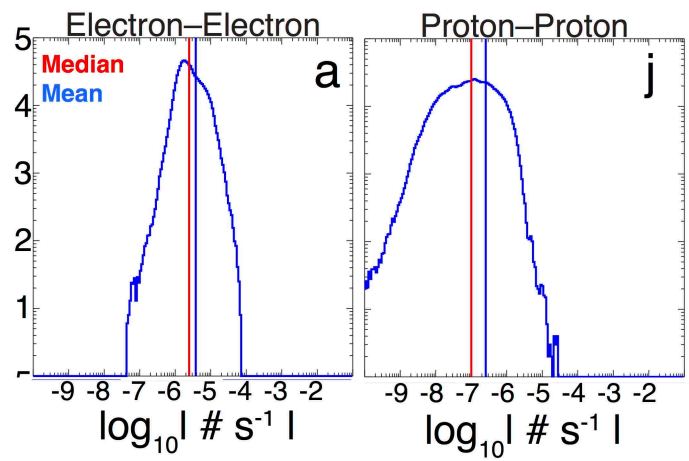
Solar Wind Parameters

- "Typical" parameters at 1 AU
  - Mainly H^+ (95%) and He^{2+} (5%), + some minor ions (O, C, N, etc.)
  - Speed ~ 400 km/s, n ~ 10 cm^{-3}, B ~ 10 nT
  - $T_i \sim T_e \sim 10$ eV → $\beta \sim 1$
- Typical scales
  - $L \sim 1$ AU $\gg \rho_i \sim 100$ km $\gg \lambda_D \sim 10$ m
  - $\omega_p \sim 10^5\ s^{-1} \gg \Omega_i \sim 1\ s^{-1} \gg \nu_{ee} \sim 10^{-5}\ s^{-1}$
- Great for studying turbulence
  - large volume, scale separation, relatively undisturbed, fast flowing, long data sets with variety of conditions

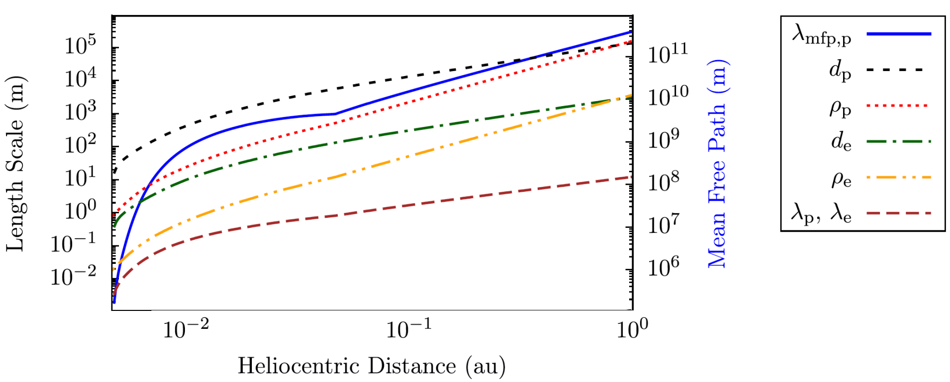
Solar Wind Parameters – Variability

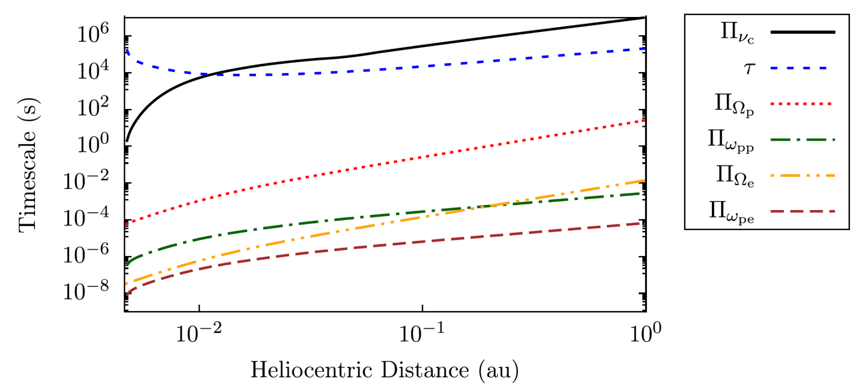
- Variability at 1AU (Wilson et al. 2018 ApJS)





- Variability with distance (Verscharen et al. 2019 LRSP)

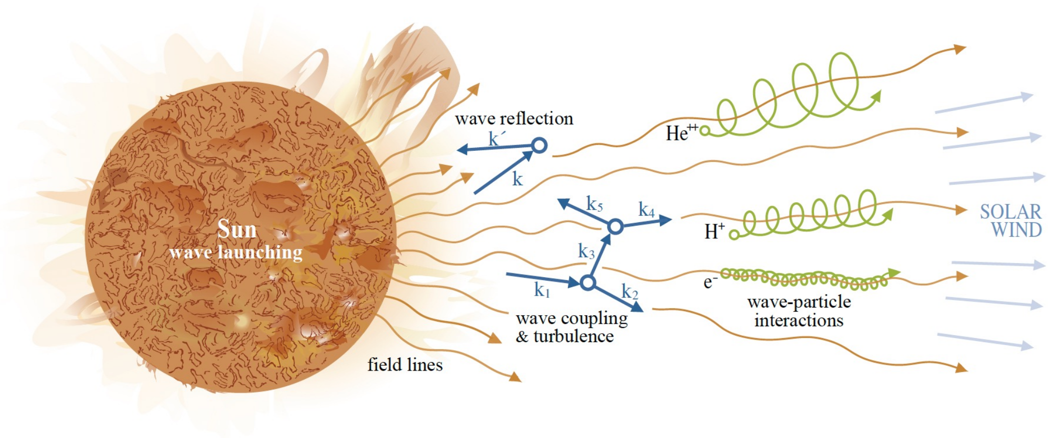


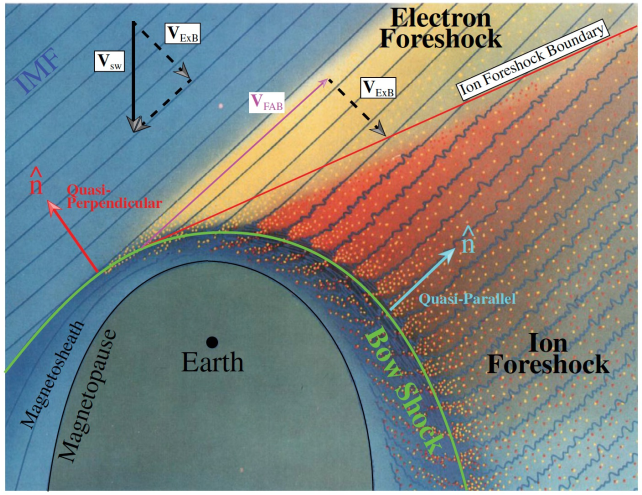


- Some might say a natural laboratory for plasma (astro)physics (albeit one in which we can't control the conditions)

Solar Wind Physics

- Many processes studied (e.g., Wilson et al. 2021 RevGeo)
  - waves, turbulence, reconnection, shocks, particle acceleration, instabilities, plasma kinetics, CMEs, large-scale structures, solar cycle





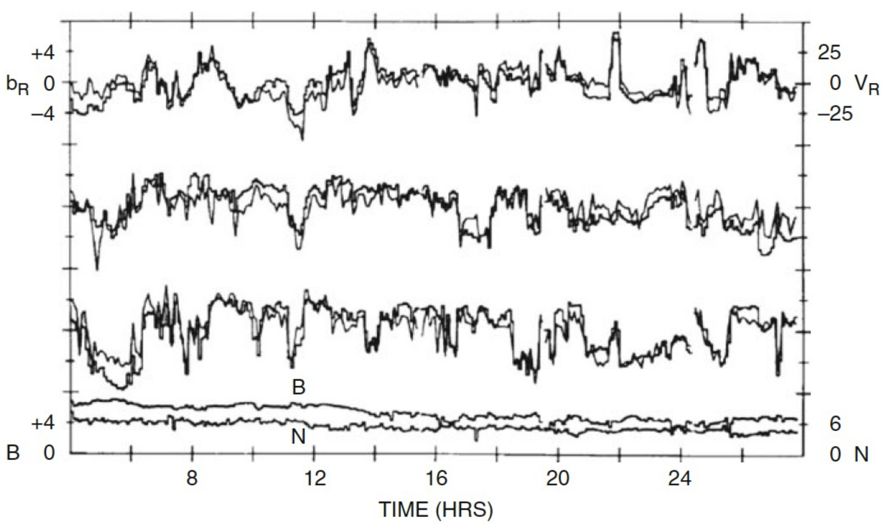
- Open questions:
  - plasma physics: nature of turbulence/reconnection/shocks/acceleration
  - heliophysics: coronal heating, solar wind origin/acceleration, ISM interaction, space weather prediction
  - astrophysics: compare (inform/learn from) other astrophysical plasmas

2. Solar Wind Turbulence and Dissipation

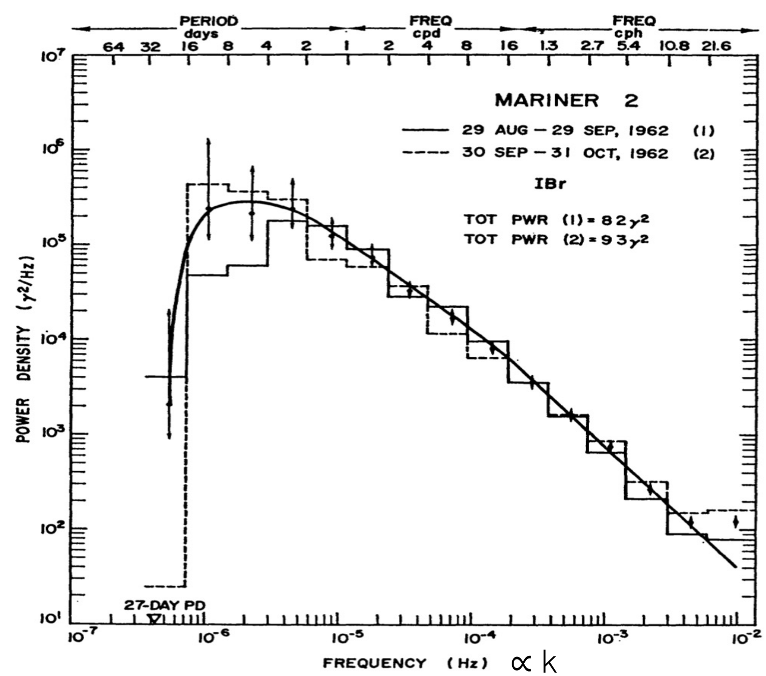
[see Chen 2016 JPP for a review]

Solar Wind Turbulence

- Early measurements showed
  - Alfvénically polarized fluctuations much of the time
  - power law spectrum of fluctuations over many decades
- Large scale Alfvén waves drive cascade of Alfvénic turbulence

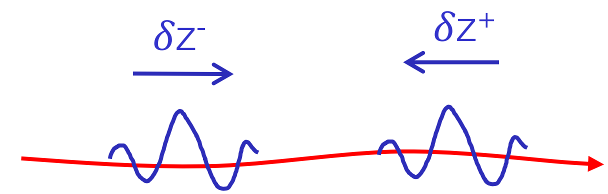


Belcher & Davis 1971 JGR



Coleman 1968 ApJ

Alfvénic Turbulence Models

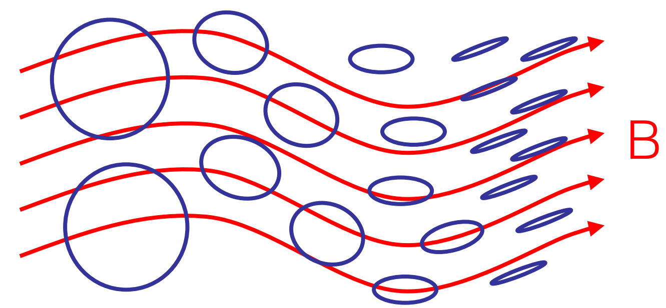


counter-propagating wavepackets
(Irosknikov 1963; Kraichnan 1965)

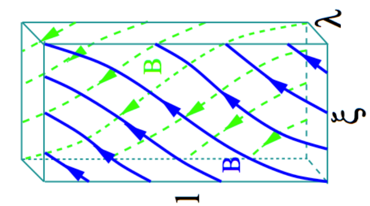
- MHD in Elsasser variables $\mathbf{z}^{\pm} = \mathbf{u} \pm \mathbf{b}$,

$$\frac{\partial \delta \mathbf{z}^{\pm}}{\partial t} \mp v_A \frac{\partial \delta \mathbf{z}^{\pm}}{\partial z} + \delta \mathbf{z}^{\mp} \cdot \nabla \delta \mathbf{z}^{\pm} = -\nabla p_t,$$

linear nonlinear



- Strong MHD turbulence (Goldreich & Sridhar 1995)
  - critical balance: $\tau_A \sim \ell_{||}/v_A$ and $\tau_{nl} \sim \ell_{\perp}/\delta b$
  - $E(k_{\perp}) \sim k_{\perp}^{-5/3}$, $k_{||} \sim k_{\perp}^{2/3}$
  - scale-dependent anisotropy
- With alignment (Boldyrev 2006 PRL)
  - δv & δb, align to scale-dependent angle $\sim \ell_{\perp}^{1/4}$
  - $E(k_{\perp}) \sim k_{\perp}^{-3/2}$

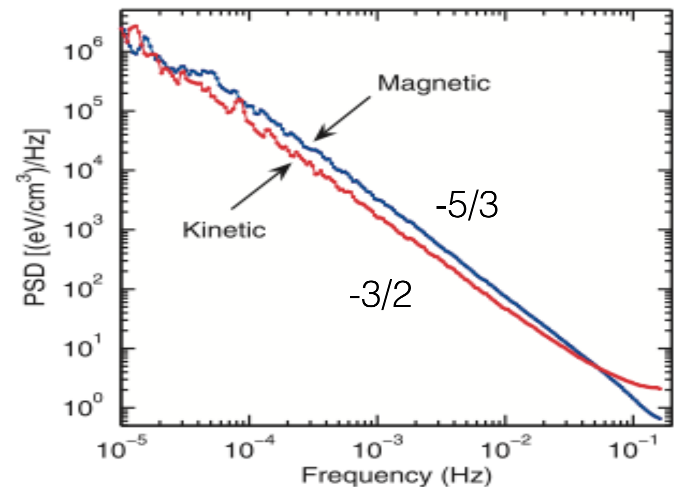


- Imbalanced (Lithwick/Goldreich/Sridhar, Beresnyak/Lazarian, Chandran, Perez/Boldyrev, …)
- Intermittent (Chandran/Schekochihin/Mallet, Mallet/Schekochihin, …)
- Reconnecting (Louriero/Boldyrev, Mallet/Schekochihin/Chandran, …)

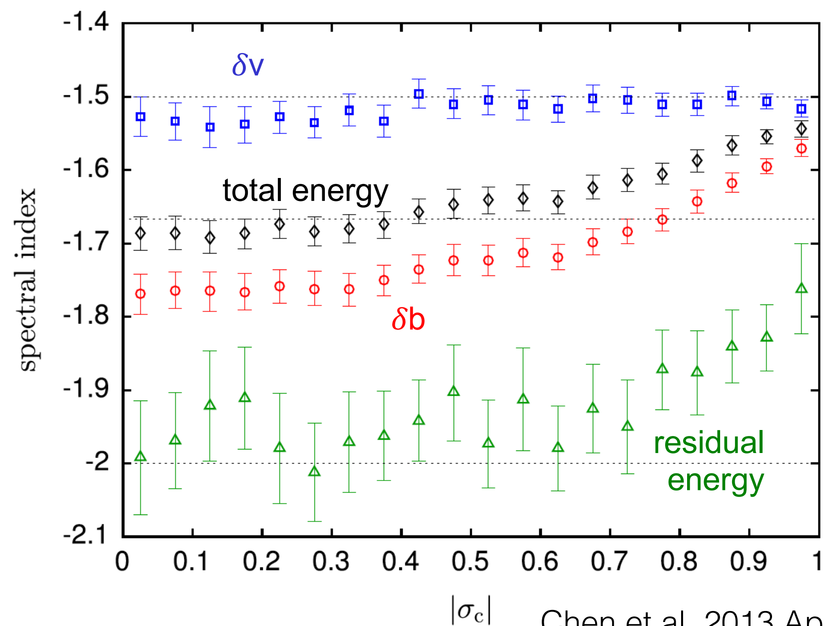
[see Schekochihin 2022 JPP for a review]

Solar Wind Spectra

- Velocity and magnetic field scale differently (-3/2 vs -5/3)
- Magnetic energy dominates (residual energy), indicating polarisations are not totally linear
- $\sigma_c = (E^+ - E^-)/(E^+ + E^-)$ = imbalance of Alfvénic fluxes
- E_v constant, E_b varies with σ_c
- Total energy varies from -5/3 to -3/2 (not predicted by any model)
- But for large σ_c, residual energy is low, -3/2 favours Boldyrev alignment model



Podesta et al. 2007 JGR

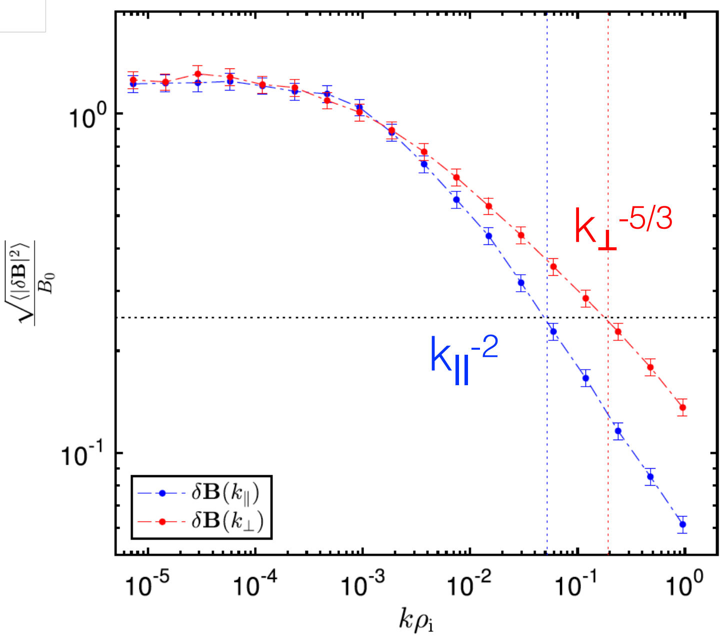


Chen et al. 2013 ApJ
Chen 2016 JPP

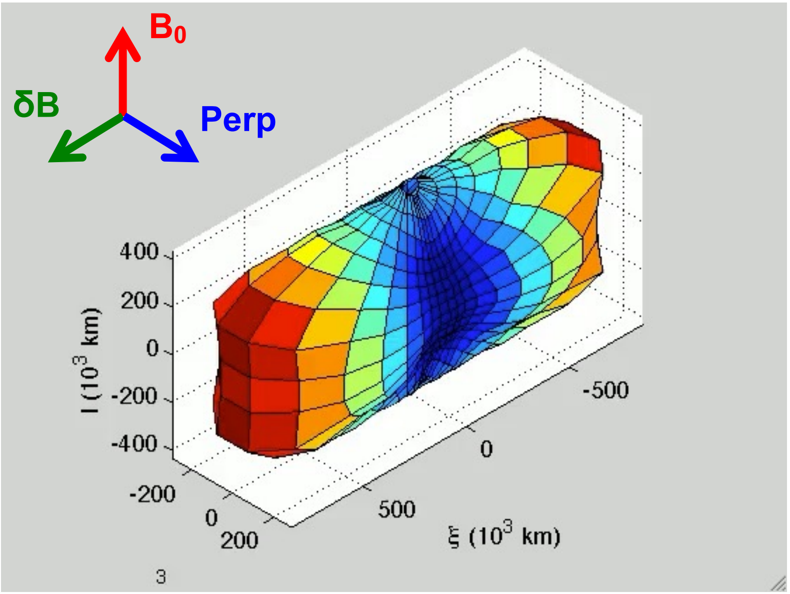
Anisotropy

- Split spectra into local par and perp
  - Critical balance predicts a $k_{||}^{-2}$ spectrum, this is found (Horbury et al. 2008 PRL)
  - Also found by many others since (Podesta/Luo/Wicks/Chen/He/…)

- Can also measure full 3D anisotropy
  - see 3D-anisotropic eddies
  - change with scale
  - may be several causes (Mallet et al. 2016, 2017, Verdini et al. 2018, 2019)



Chen 2016 JPP



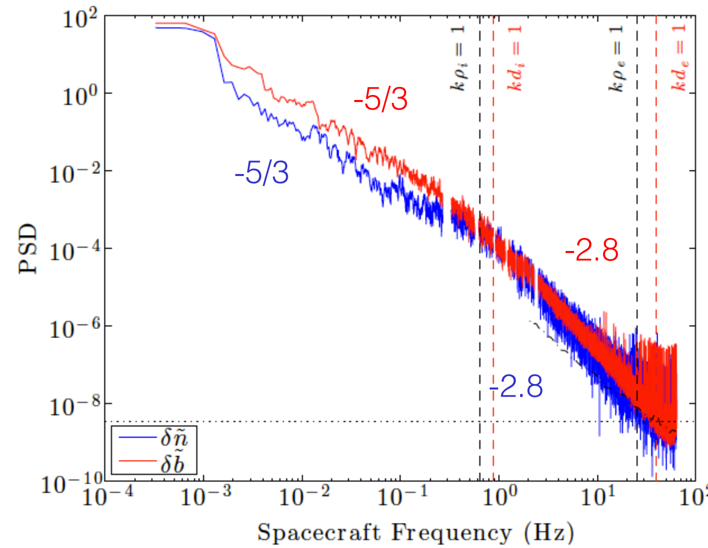
Chen et al. 2012 ApJ

Sub-Ion-Gyroscale Range

- Further cascade expected, $k_\perp^{-7/3}$ or $k_\perp^{-8/3}$
- B & n spectra steepen, index ~ -2.8
  - closer to -8/3 prediction (2D sheets) (Boldyrev & Perez 2012 ApJL)
  - But other possibilities: e.g., electron Landau damping (Howes et al. 2011 PRL)
- KAW or whistler turbulence?
  - KAW: $\delta\tilde{n} = \delta\tilde{b}_\perp$
  - whistler: $\delta\tilde{n} << \delta\tilde{b}_\perp$
- Data shows kinetic Alfvén turbulence
- Low frequency → implications for heating

KAW: $\omega \ll k_\perp v_{\mathrm{th},i}$

Whistler: $\omega \gg k_\perp v_{\mathrm{th},i}$



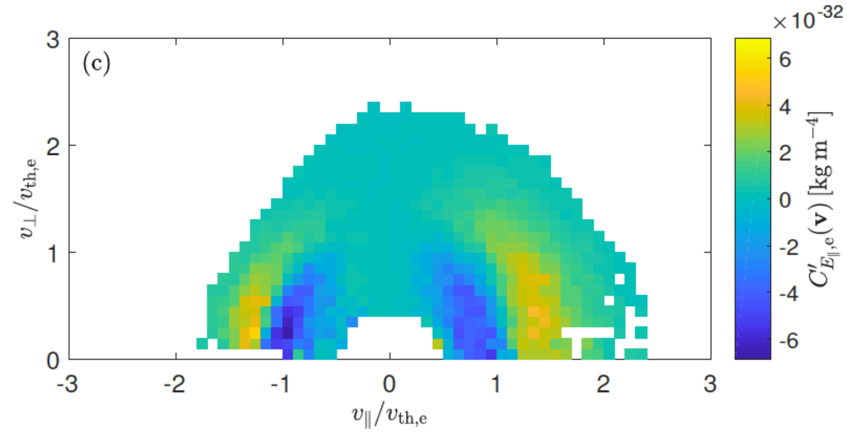
Chen et al. 2013 PRL

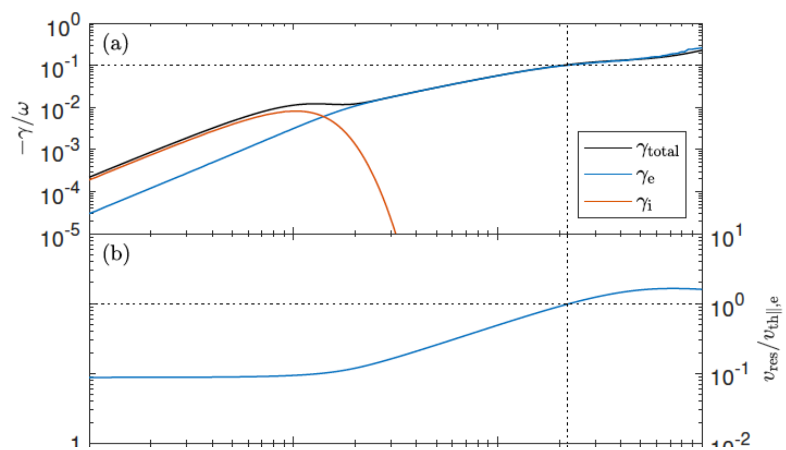
Landau Damping

- How is turbulent energy dissipated?
- Method: correlating f_e and $E_\parallel$ gives field-particle energy transfer
  - symmetric bi-polar signatures
  - at resonant expected velocity
  - consistent with Landau damping
- Total integrated energy transfer

$$C_{E_\parallel,\mathrm{e}} \approx 3.4 \times 10^{-12}\,\mathrm{kg\,m^{-1}\,s^{-3}}$$

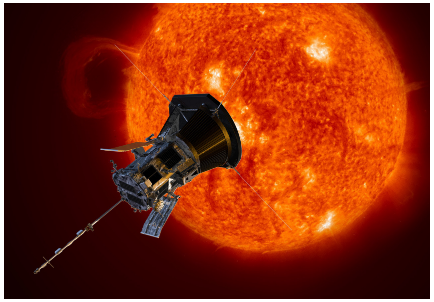
  - comparable to cascade rate
  - significant energy conversion



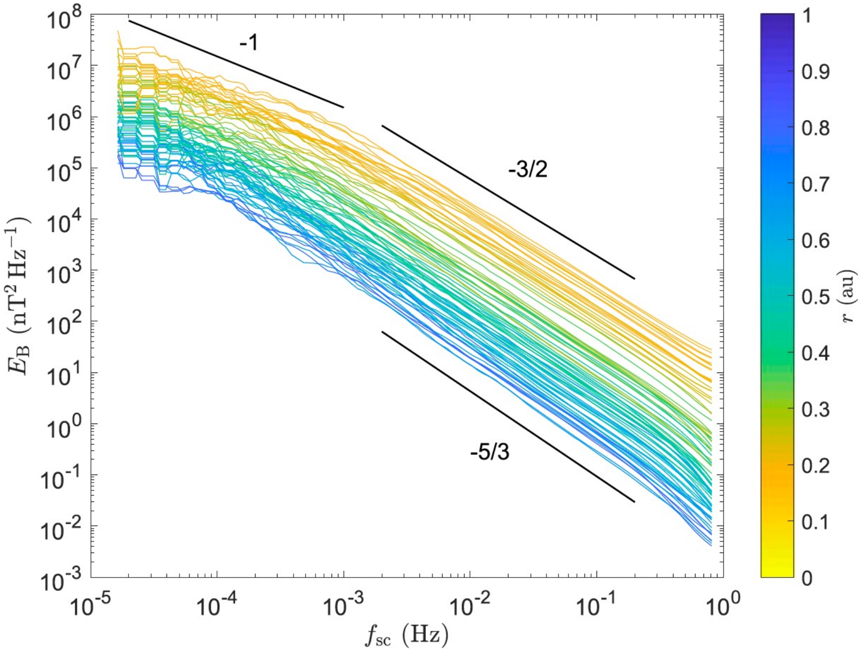


Chen et al. 2019 Nat Comm

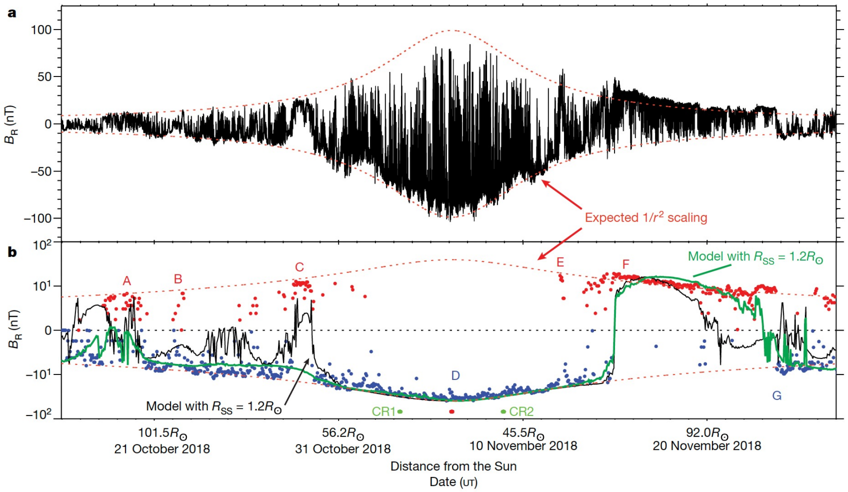
Parker Solar Probe



- Closer to Sun than ever before
- Now in the solar corona
  (Kasper et al. 2021 PRL)
- Turbulence changes – TBC
- Switchback structures – TBC



Chen et al. 2020 ApJ



Bale et al. 2019 Nature

Jack McIntyre
Near-Sun turbulence

Andrea Larosa
What are these switchbacks?

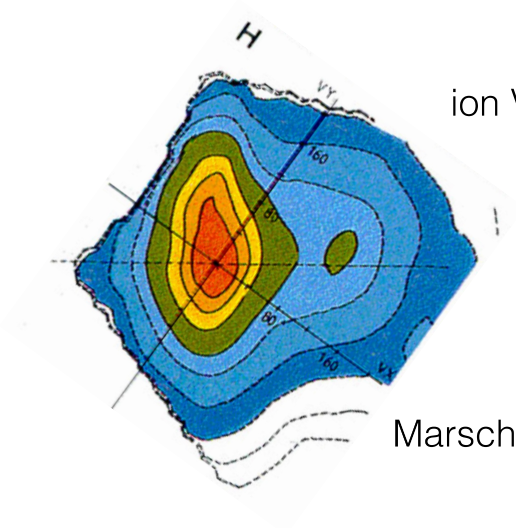
3. Pressure Anisotropy Instabilities

Pressure Anisotropy Instabilities

- Plasma is weakly collisional
  → non-thermal distributions
  → instability, simplest due to pressure-anisotropy (but many others too)

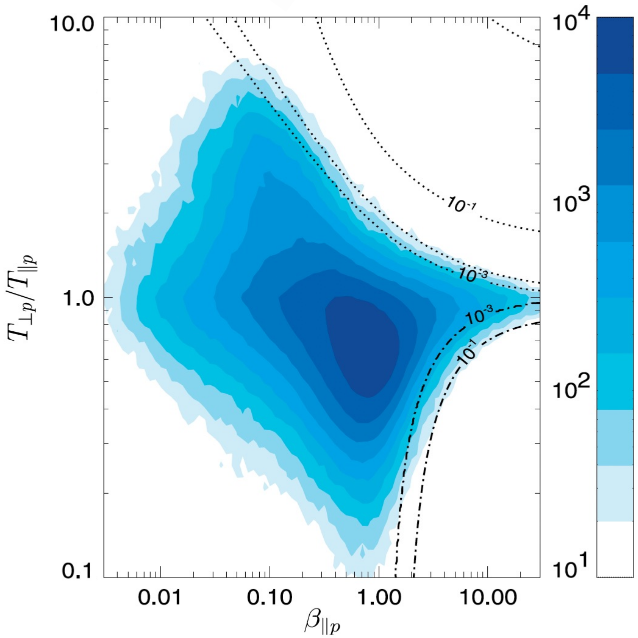
- Important for
  - understanding non-linear instability
  - plasma transport properties
  - affect turbulence/reconnection/dynamo
  - evolution of global dynamics (sw)

- Studied many years, iconic Hellinger plot
  - many years of solar wind data
  - appears to be constrained/shaped by firehose/mirror thresholds



ion VDF

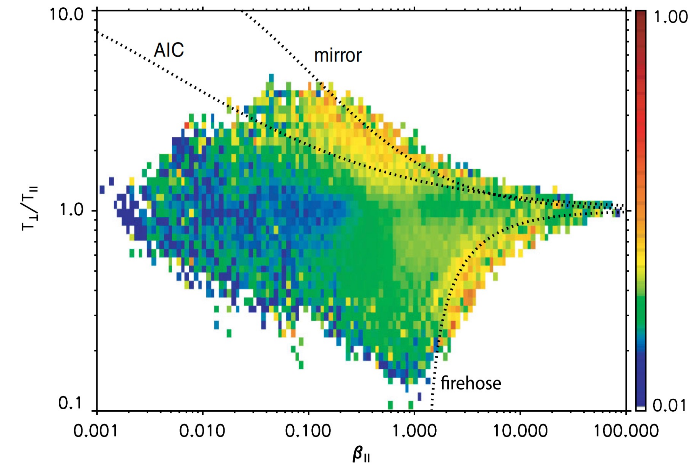
Marsch 2012 SSR



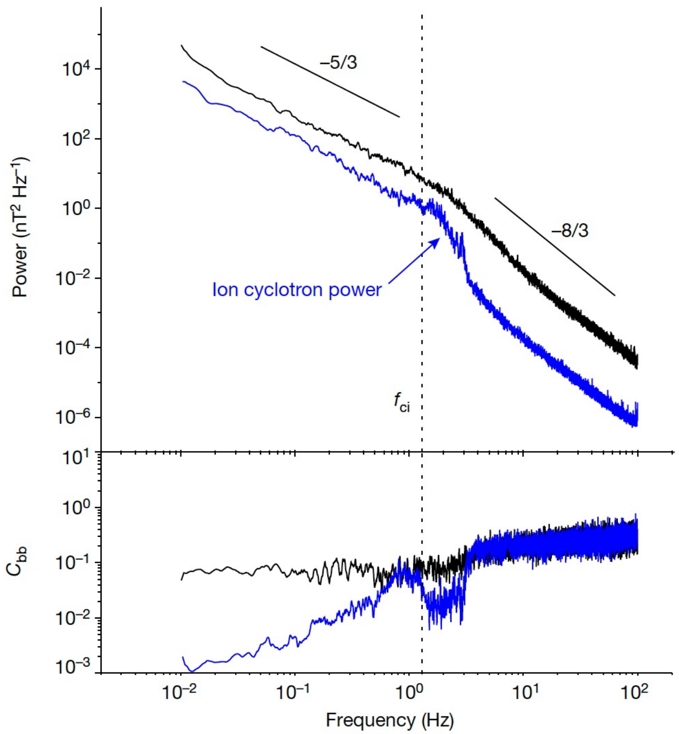
Hellinger et al. 2006 GRL

Instabilities – Fluctuations

- Evidence that instabilities are acting
  - enhanced fluctuations near thresholds
  - cyclotron waves, mirror modes seen
- Simulations show effects on many processes

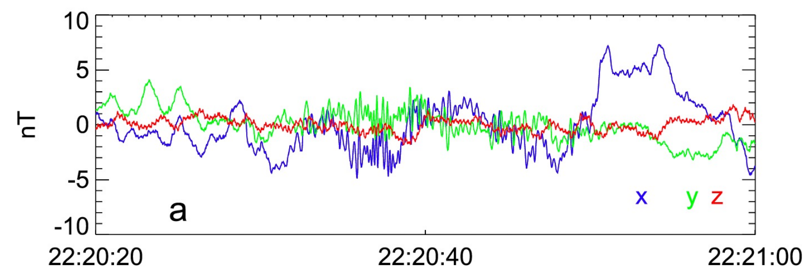


Bale et al. 2009 PRL



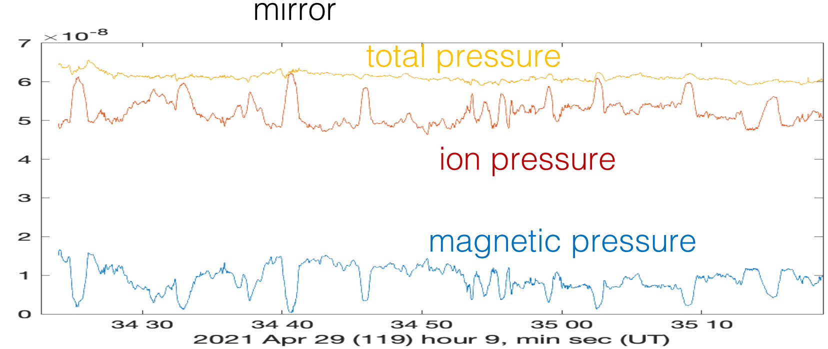
Bale et al. 2019 Nature

ion cyclotron



Bowen et al. 2020 ApJS

mirror



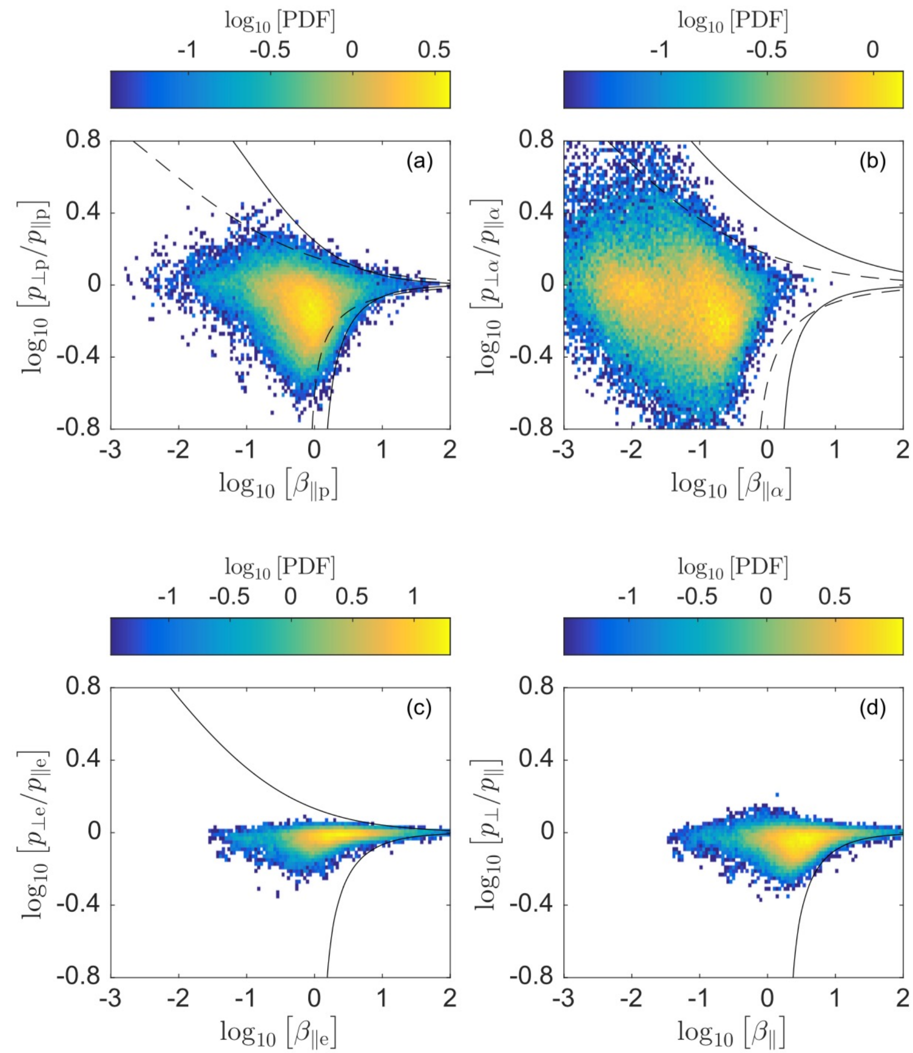
Chen, unpublished

Instabilities – Multi-Species

- Previously, only single species studied separately
  - not complete
  - plasma stability depends on all species
- Combine proton (H+), alpha (He++) and electron data
  - fluid-firehose well constrained

$$\frac{\beta_{\|} - \beta_{\perp}}{2} > 1$$

  - non-resonant firehose many be important in solar wind



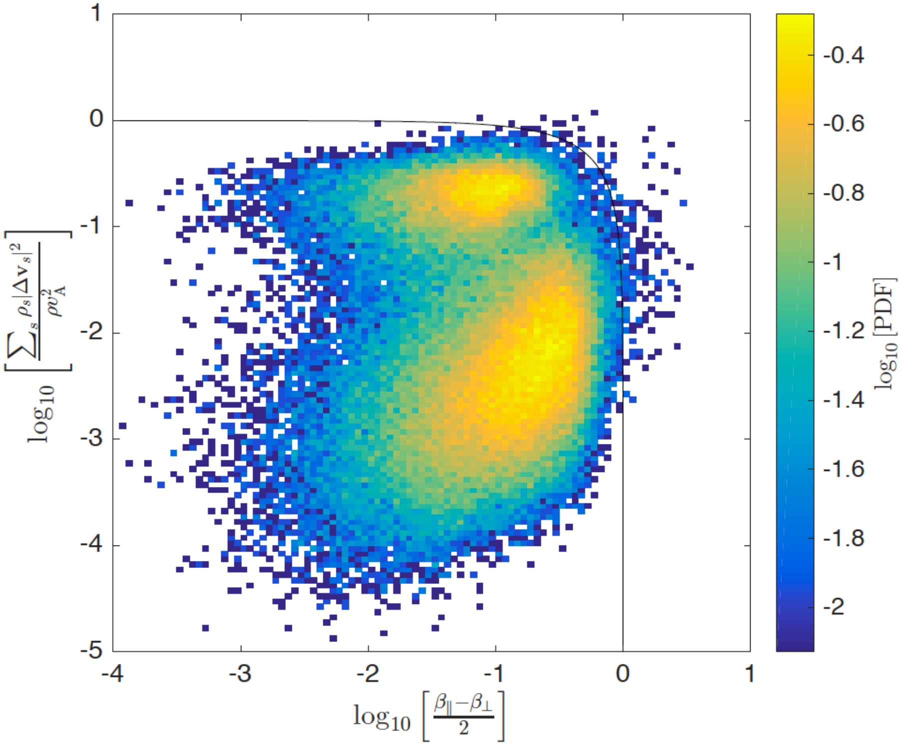
Chen et al. 2016 ApJL

Instabilities – Multi-Species with Drifts

- There are also “drifts” between species
  - contribute to parallel pressure

$$\frac{\beta_{||} - \beta_{\perp}}{2} + \frac{\sum_s \rho_s |\Delta \mathbf{v}_s|^2}{\rho v_A^2} > 1$$

- Plot shows how each term constrains distribution
- 2 populations
  - times with proton beam
  - times without
- Both anisotropies and drifts important for long-wavelength firehose



Chen et al. 2016 ApJL

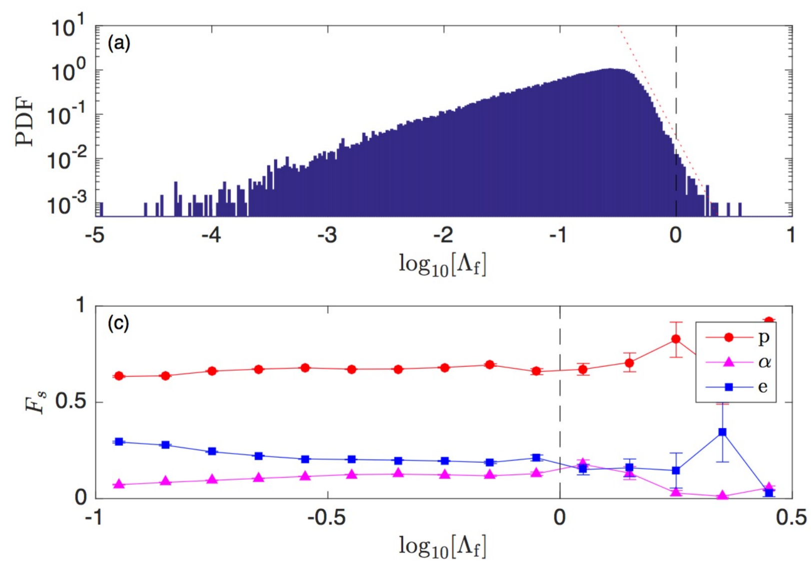
Instabilities – Multi-Species Contributions

- Combined thresholds constrain data well
- Protons dominate instability (~2/3), but other species are significant (~1/3)
- Can use these thresholds for astro modelling (Chandran et al. 2011, Sharma et al. 2006)
- Open question: role of long-wavelengths vs kinetic (resonant) instabilities

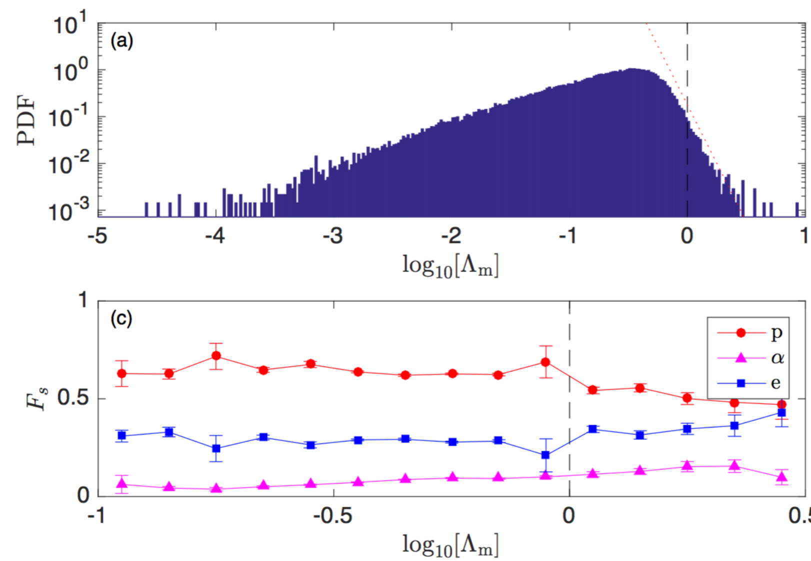
$$\Lambda_\mathrm{f} \equiv \frac{\beta_\parallel - \beta_\perp}{2} + \frac{\sum_s \rho_s |\Delta \boldsymbol{v}_s|^2}{\rho v_\mathrm{A}^2} > 1$$

$$\Lambda_\mathrm{m} \equiv \sum_s \beta_{\perp s} \left(\frac{\beta_{\perp s}}{\beta_{\parallel s}} - 1 \right) - \frac{\left(\sum_s q_s n_s \frac{\beta_{\perp s}}{\beta_{\parallel s}} \right)^2}{2 \sum_s \frac{(q_s n_s)^2}{\beta_{\parallel s}}} > 1$$

Firehose

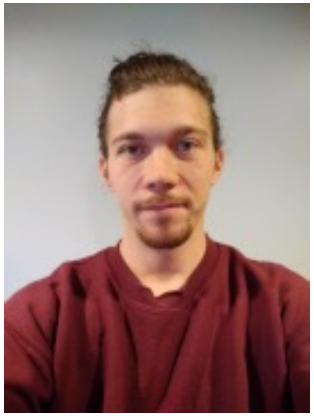


Mirror



Chen et al. 2016 ApJL

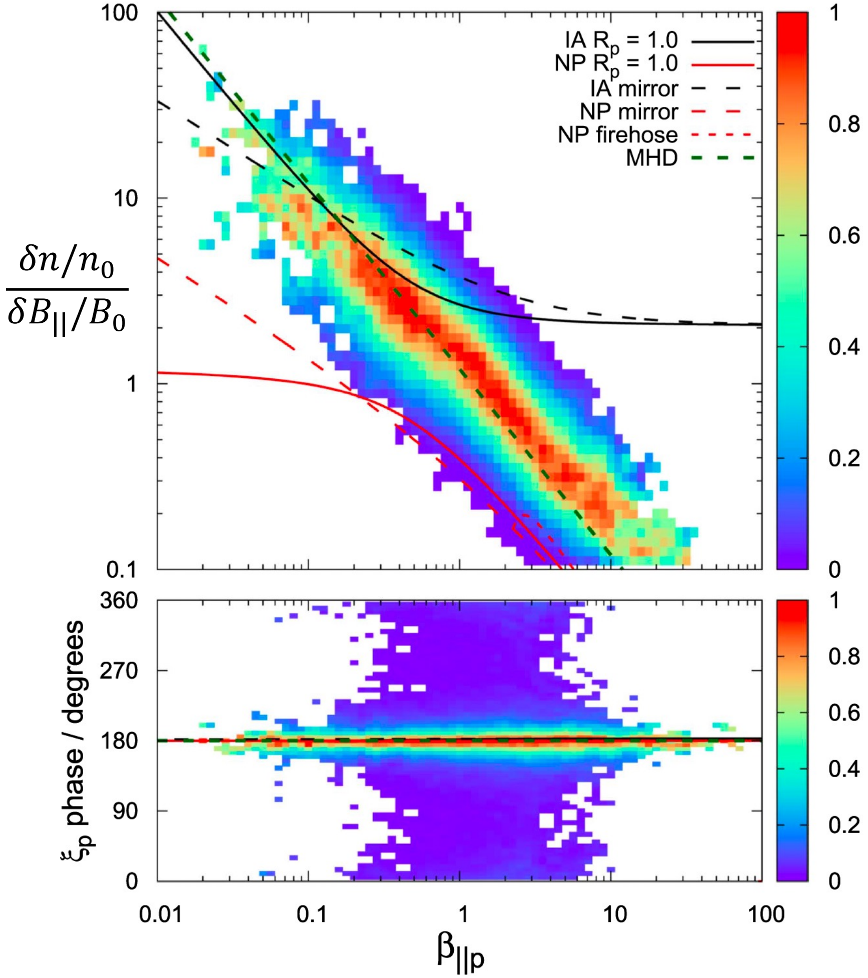
4. Effective Collisionality



work from Jesse Coburn

Effective Collisionality – The Question

- Why does the solar wind behave in a more fluid way than it should?
  - Alfvén modes as expected
  - Compressive fluctuations follow MHD modes
- Many solar wind phenomena are modelled with MHD
  - why does it work so well?
  - at what scales is it valid?
- First step is to characterize the effective collisionality



Verscharen, Chen & Wicks 2007 ApJ

Effective Collisionality – Technique

- Technique
  - measure correlations based on CGL invariants to see how broken by heat fluxes and/or effective collisions
  - fit to find $\lambda_{\text{mfp,eff.}}$

$$n_{\rm p} B \frac{\rm d}{{\rm d}t}\left(\frac{p_\perp^{\rm p}}{n_{\rm p} B}\right) = -\boldsymbol{\nabla}\cdot(q_\perp^{\rm p}\hat{\boldsymbol{b}}) - q_\perp^{\rm p}\boldsymbol{\nabla}\cdot\hat{\boldsymbol{b}} + \frac{\nu_{\rm eff}}{3}(p_\parallel^{\rm p} - p_\perp^{\rm p}).$$

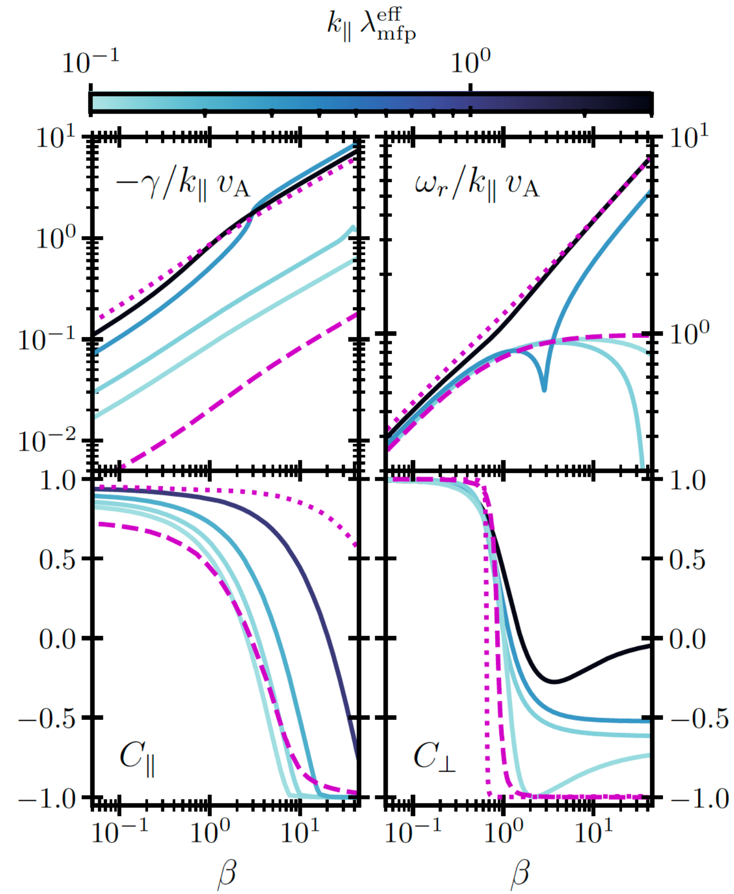
$$\frac{n_{\rm p}^3}{2B}\frac{\rm d}{{\rm d}t}\left(\frac{p_\parallel^{\rm p} B^2}{n_{\rm p}^3}\right) = -\boldsymbol{\nabla}\cdot(q_\parallel^{\rm p}\hat{\boldsymbol{b}}) + q_\perp^{\rm p}\boldsymbol{\nabla}\cdot\hat{\boldsymbol{b}} + \frac{2\nu_{\rm eff}}{3}(p_\perp^{\rm p} - p_\parallel^{\rm p})$$

$$C_\parallel = \frac{\langle \delta p_\parallel^{\rm p}\, \delta(n_{\rm p}^3/B^2)\rangle}{\langle|\delta p_\parallel^{\rm p}|^2\rangle^{1/2}\langle|\delta(n_{\rm p}^3/B^2)|^2\rangle^{1/2}},$$

$$A_\parallel = \frac{\langle|\delta(n_{\rm p}^3/B^2)|^2\rangle^{1/2}}{\langle n_{\rm p}^3/B^2\rangle}\frac{\langle p_\parallel^{\rm p}\rangle}{\langle|\delta p_\parallel^{\rm p}|^2\rangle^{1/2}},$$

$$C_\perp = \frac{\langle \delta p_\perp^{\rm p}\, \delta(n_{\rm p}B)\rangle}{\langle|\delta p_\perp^{\rm p}|^2\rangle^{1/2}\langle|\delta(n_{\rm p}B)|^2\rangle^{1/2}},$$

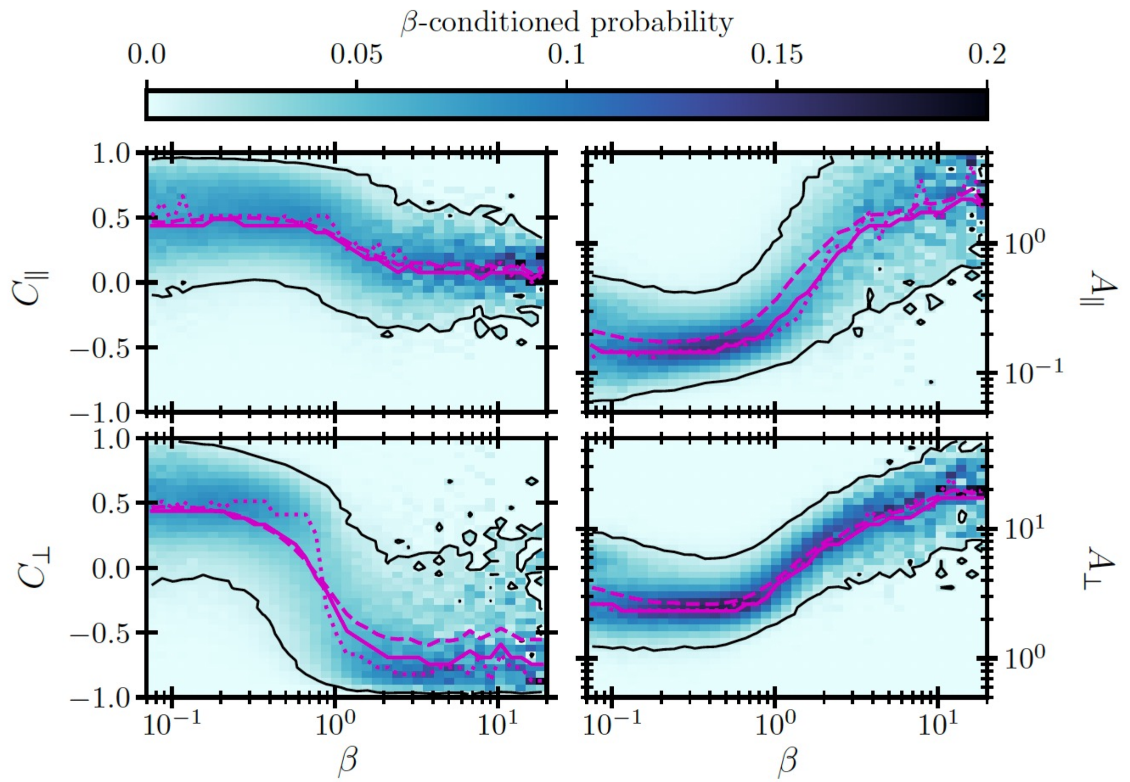
$$A_\perp = \frac{\langle|\delta(n_{\rm p}B)|^2\rangle^{1/2}}{\langle n_{\rm p}B\rangle}\frac{\langle p_\perp^{\rm p}\rangle}{\langle|\delta p_\perp^{\rm p}|^2\rangle^{1/2}},$$



Coburn, Chen & Squire 2022 arXiv:2203.12911

Effective Collisionality – Solar Wind

- Many years of compressive (slow mode) data in the solar wind at 1AU
  - clear deviations from unity
  - CGL is not appropriate (both invariants)
  - fit to model to determine parameters

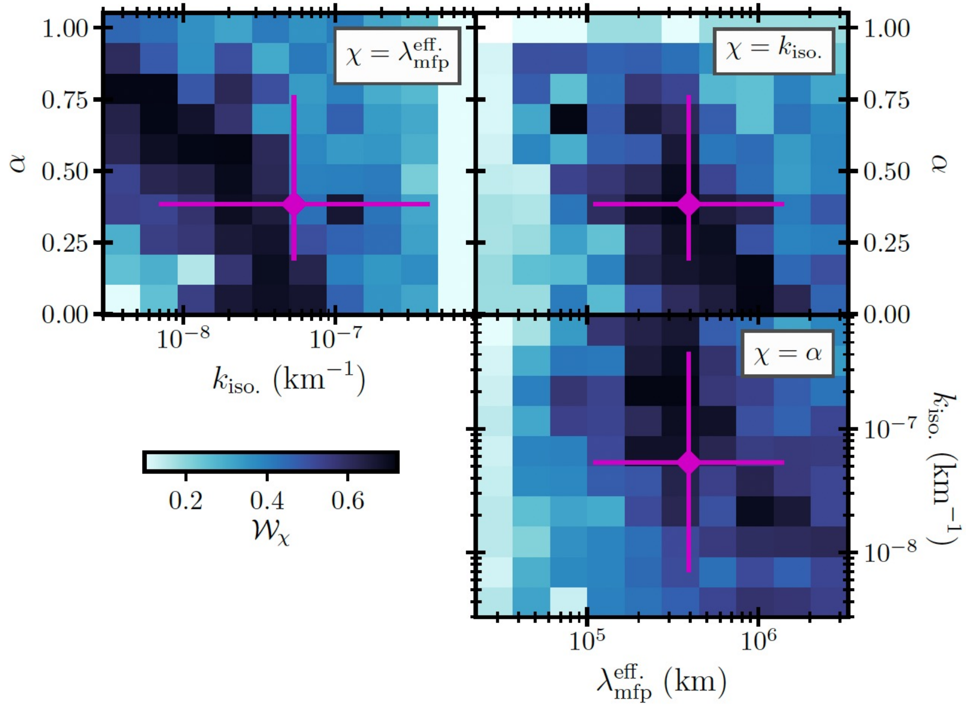


Coburn, Chen & Squire 2022 arXiv:2203.12911

Effective Collisionality – Solar Wind

- 3 model fit parameters
  - k_{iso} = isotropic outer scale
  - α = anisotropy exponent
  - $\lambda_{mfp,eff.}$ = effective mfp
- k_{iso} and α consistent with previous findings
- $\lambda_{mfp,eff.} = 4\times10^5$ km

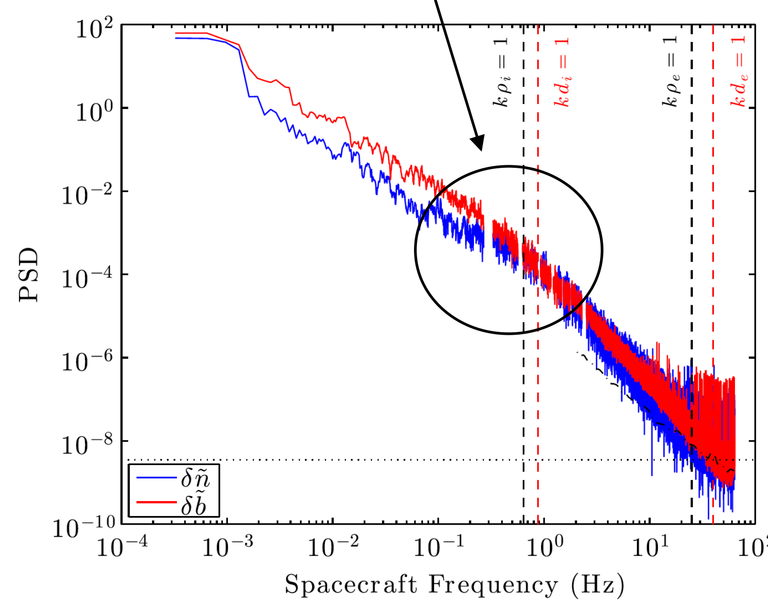
λ_{mfp} is ~10^3 times smaller than classical (Spitzer-Harm) estimate!



Coburn, Chen & Squire 2022 arXiv:2203.12911

Mechanisms & Links to Astro

- In the solar wind at 1AU, $k_{||}\lambda_{mfp,eff.} \sim 1$ corresponds to $k_{\perp}\rho_i \sim 1$
- Related to ion gyroscale processes?
  - pressure anisotropy instabilities? (Bale et al. 2009, Kunz et al. 2020)
  - other kinetic processes? (Kellogg 2000, Bale et al. 2005, Schekochihin et al. 2016, Meyrand et al. 2019)
  - answer TBC
- Consistent(?) with galaxy cluster observations (Zhuravleva et al. 2019)
- If $k_{||}\lambda_{mfp,eff.} \sim k_{\perp}\rho_i$ is a general property of weakly collisional plasmas, this could be used to parametrize their effective collisionality…



Chen et al. 2013 PRL

5. Summary

Summary

- Solar wind is great for studying various plasma physics
- Links to ICM?