Imperial College London

Science & Technology Facilities Council

Preparing to re-visit the inner heliosphere

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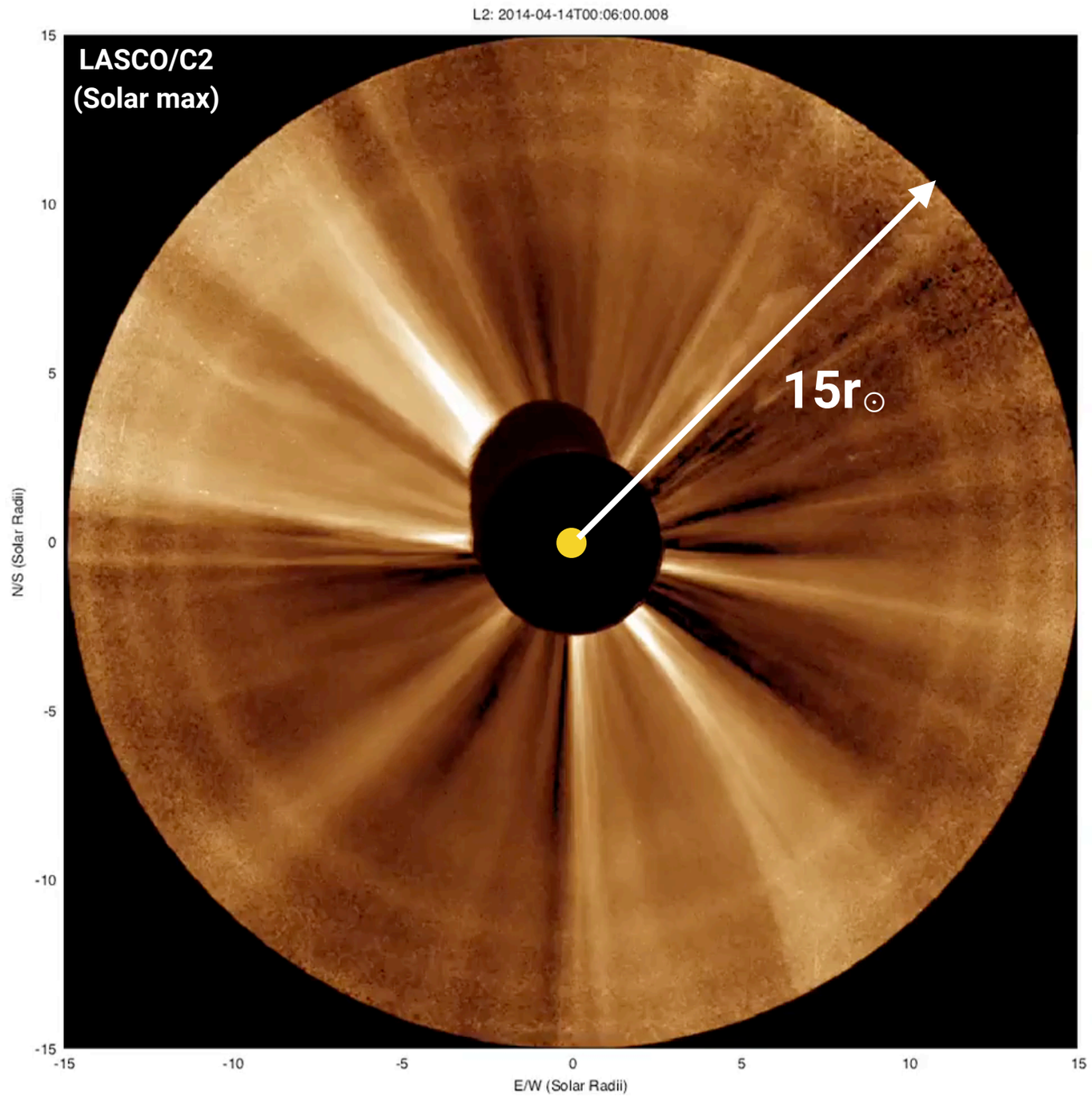
The Solar Wind



DeForest et al. 2018

Open questions

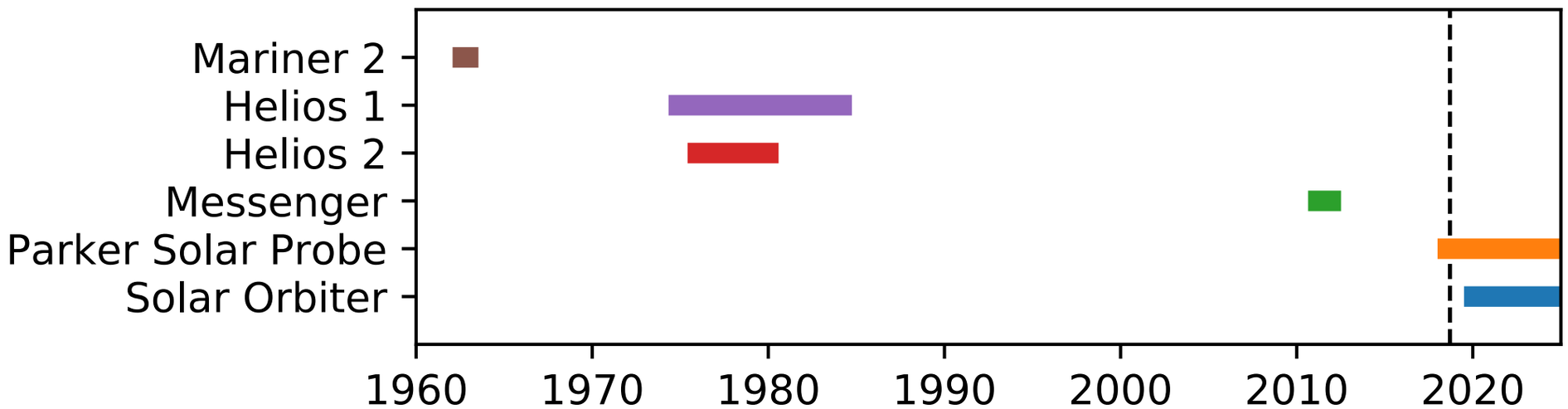
3.1.1. What Are the Source Regions of the Solar Wind and the Heliospheric Magnetic Field?

3.1.2. What Mechanisms Heat and Accelerate the Solar Wind?

- In-situ measurements at 1 AU limited by processes that erase information on source regions during transit
- To mitigate this, get close to the Sun → SO and PSP
- But we have been to the inner heliosphere before!

"Trying to answer Solar Orbiter and Parker Solar Probe science objectives before they launch"

Measurements inside 1 AU



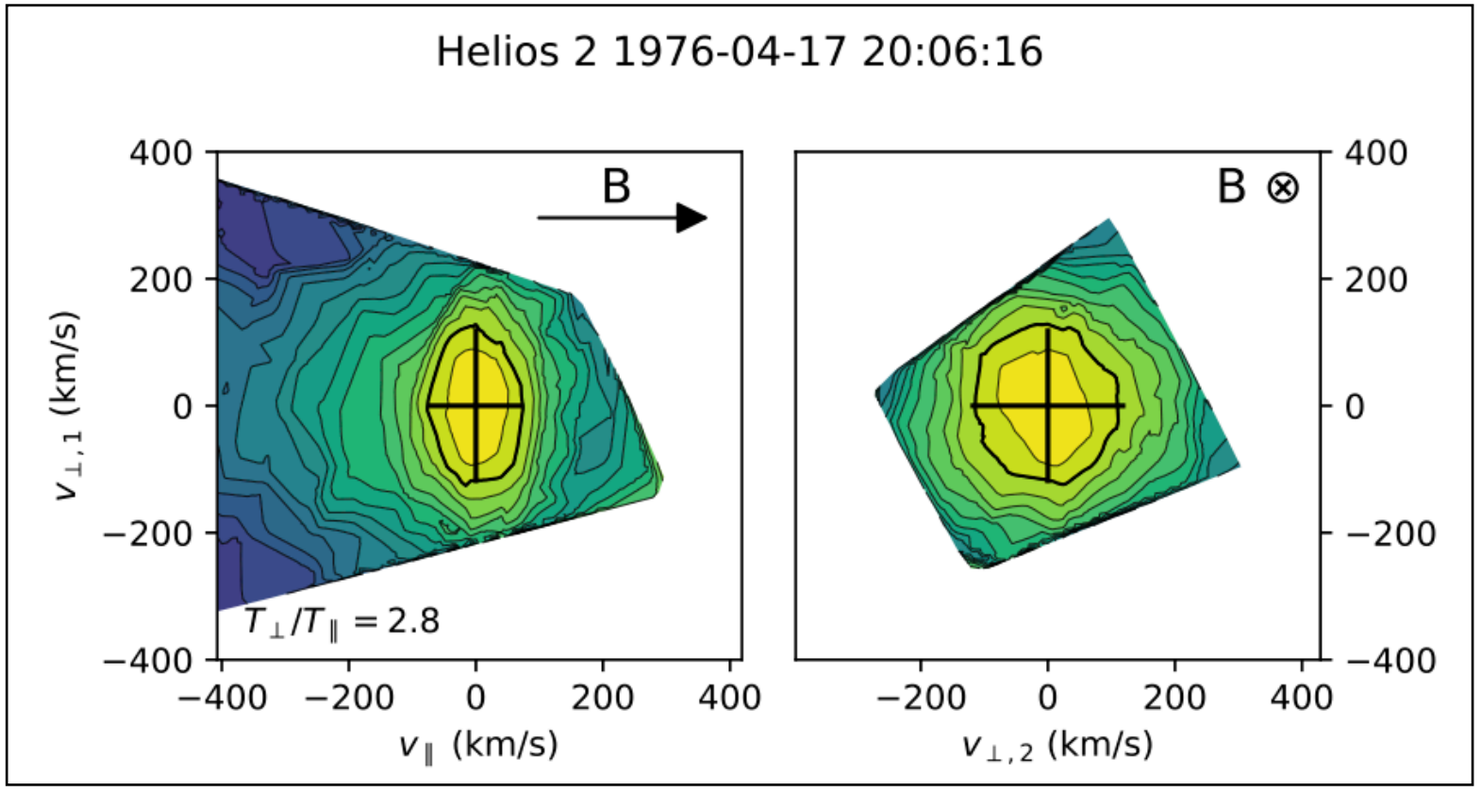
- Helios have the only comprehensive, archived in-situ measurements of the inner heliosphere to date
- Reprocessed to provide reproducible + reliable proton number densities, speeds, and temperatures (*Stansby 2018, arXiv*)

Mariner 2: *Neugebauer et al. 1962;* ***MESSENGER:*** *Gershman et al. 2012*

In-situ measurements

- All in-situ spacecraft typically measure
  magnetic field & **proton velocity distribution function**

- **Derive** number density, velocity, and temperatures



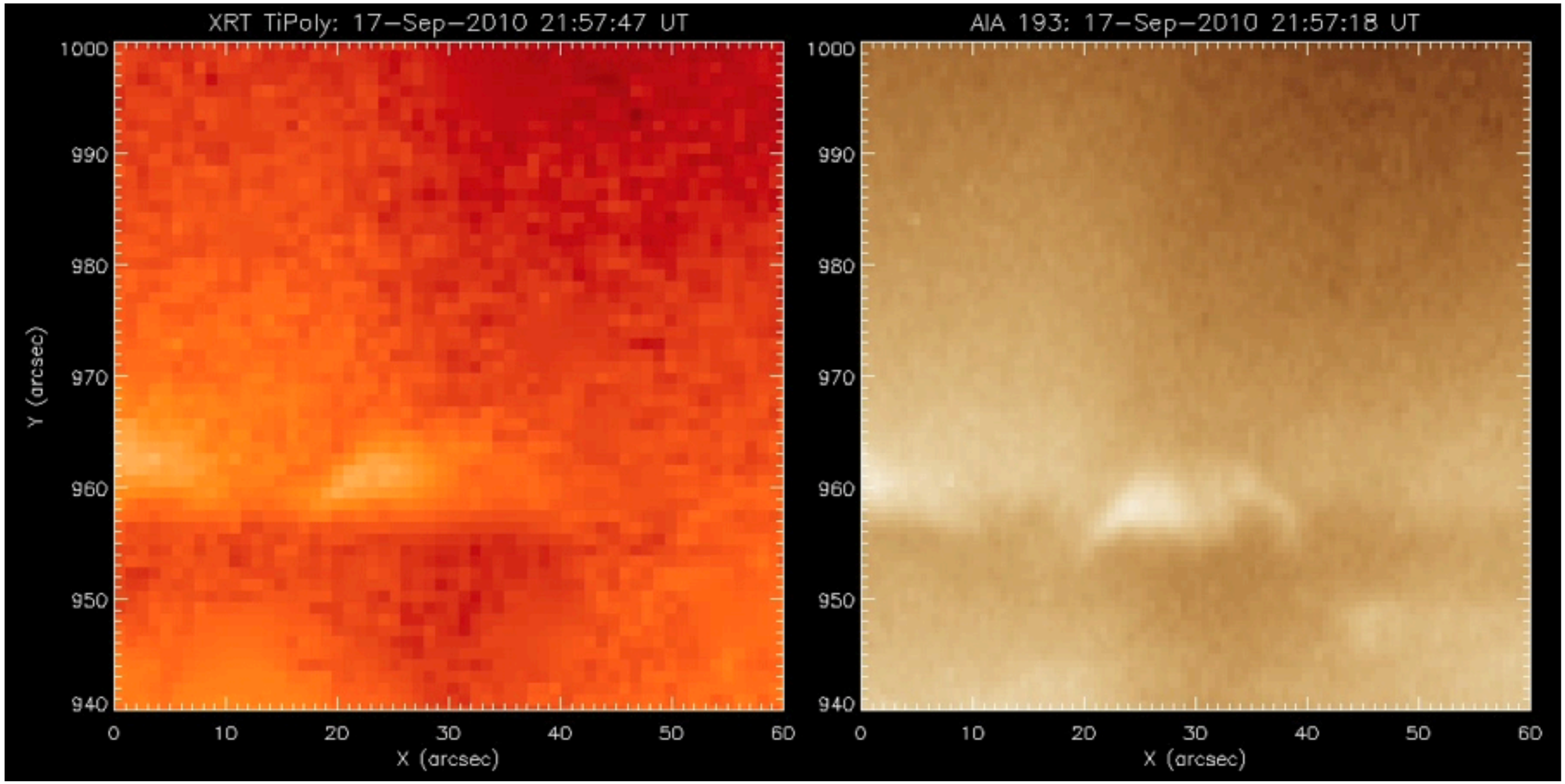
(times 2,000,000)

Stansby et al. 2018

Rest of talk structure

- For each topic I'll give
  - Overview of relevant remote sensing measurements
  - What we have learnt from Helios measurements
    1. Coronal hole jets
    2. Solar wind source regions
    3. Coronal heating mechanisms

Solar coronal jets



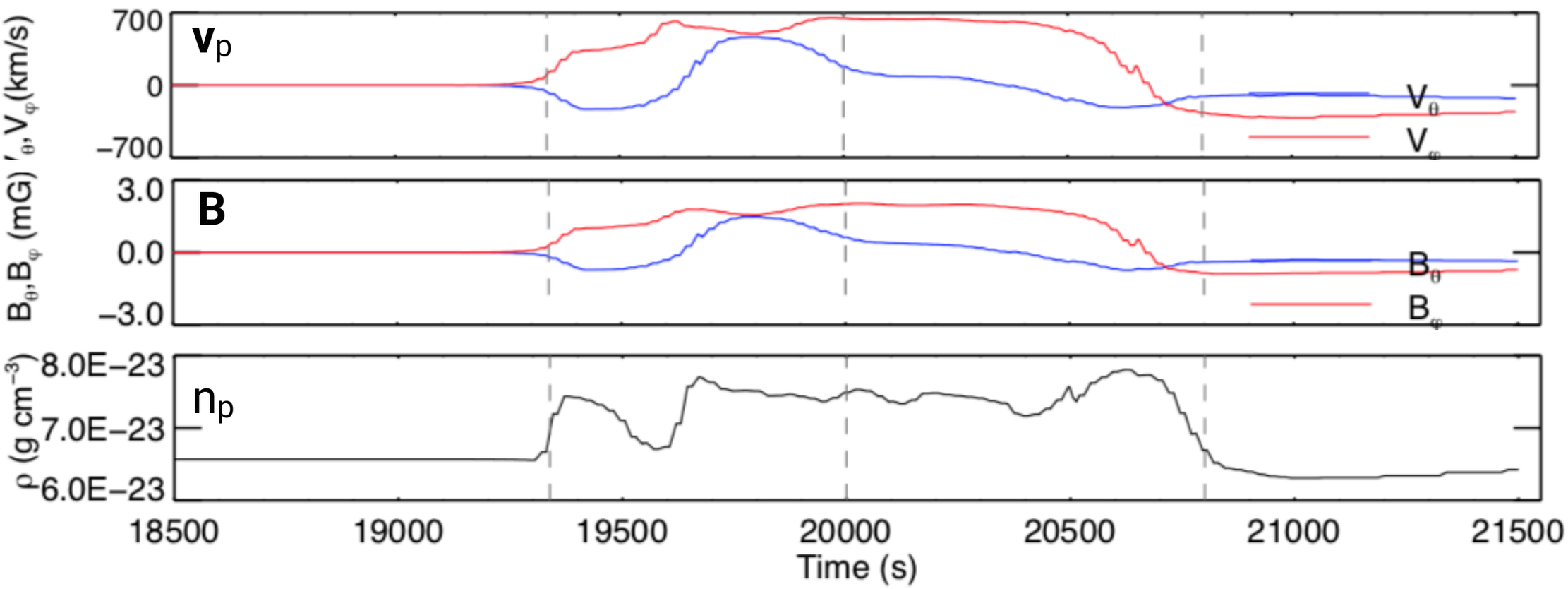
Sterling et al. 2015

See *Raouafi et al. 2016 for a review*

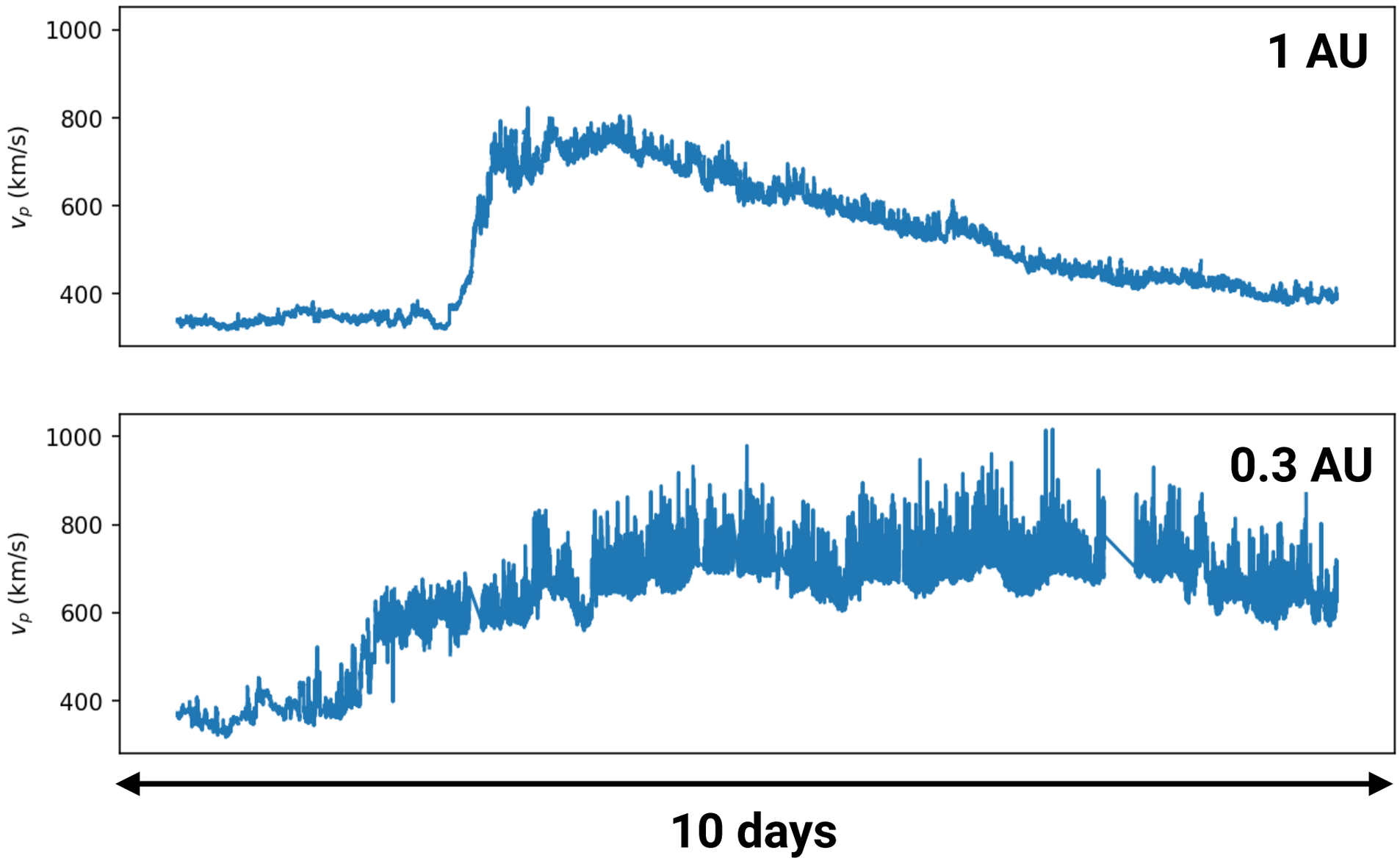
Solar coronal jets

- Occur almost everywhere
- Easy to spot in coronal holes due to dark background
- Are there signatures of jets in the solar wind?

Roberts et al. 2018



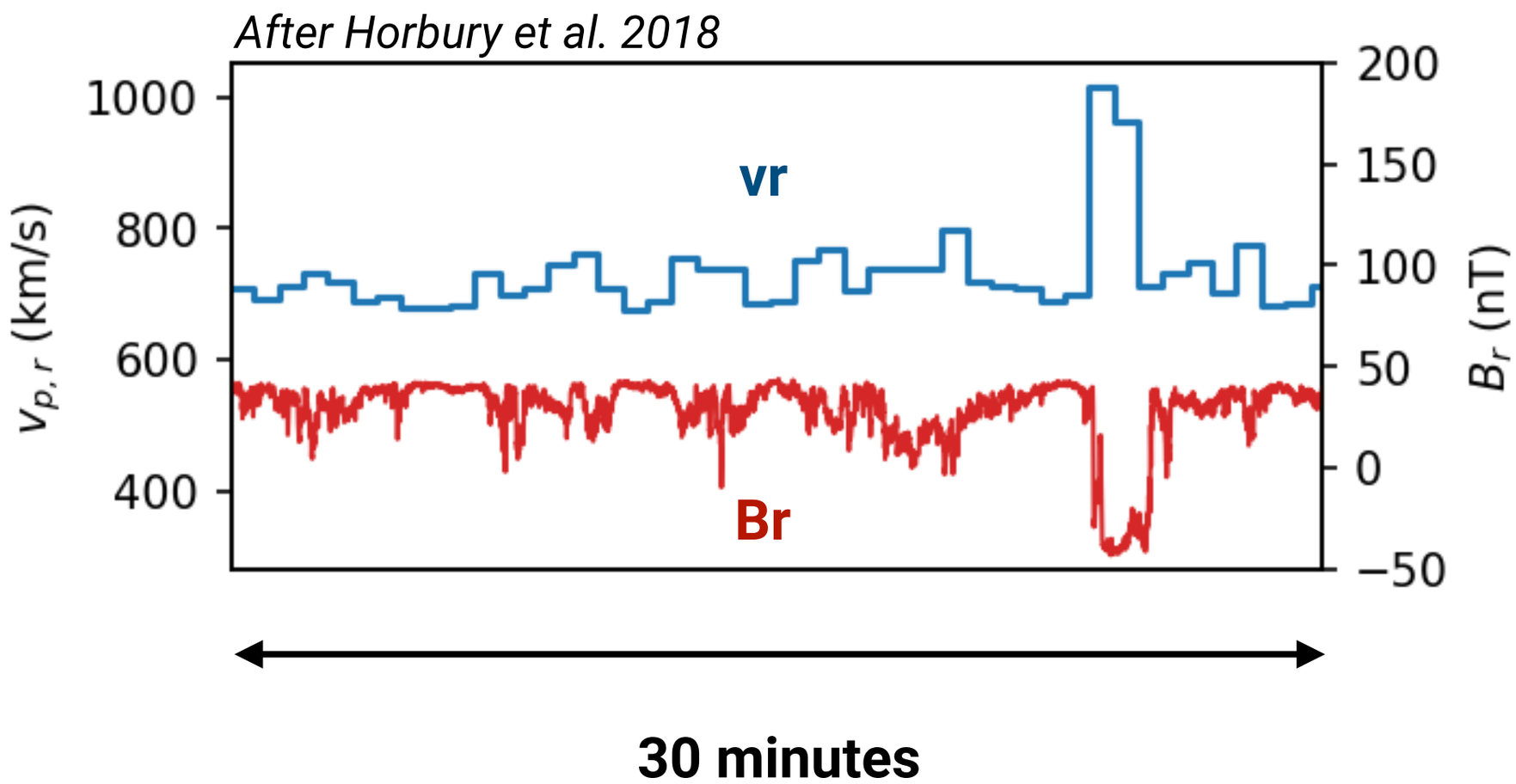
Fast solar wind



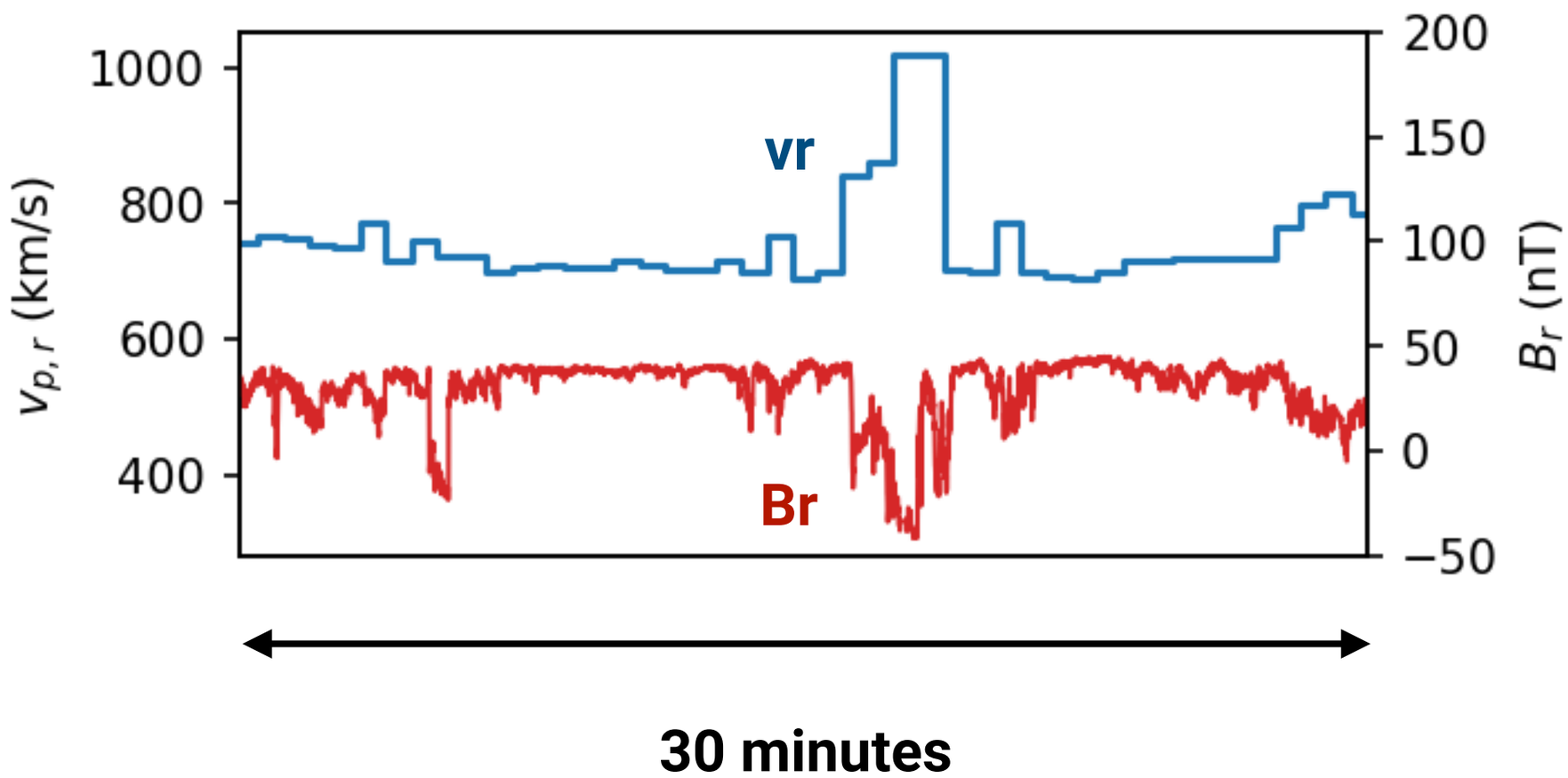
$$\mathbf{v}_p = \mathbf{v}_0 + \delta\mathbf{v} \qquad \delta\mathbf{v} = \pm v_A \frac{\delta\mathbf{B}}{B}$$

(See *Matteini et al. 2015* for details)

Fast solar wind



Fast solar wind



- Alfvénic ‘jets’ occur almost everywhere in the fast solar wind
- Much faster closer to the Sun $(\delta \mathbf{v} \propto v_A)$

Jet conclusions

- Jets may have important role in heating coronal hole wind
- No in-situ indications of heating/density enhancements
- See *Horbury et al. 2018* for more details on Helios work

Table 1. Mean properties inside spikes compared to the entire stream. Error values are standard deviations.

	Spikes	Stream
Proton core speed (km s^{-1})	852 ± 43	724 ± 54
Proton core number density (cm^{-3})	25.1 ± 3.2	25.5 ± 2.8
Proton core $T_{\|\|}$ (10^5 K)	2.6 ± 0.6	2.5 ± 0.5
Proton core $T_{\perp}$ (10^5 K)	9.6 ± 1.4	9.5 ± 1.3
Proton beam fraction	0.14 ± 0.04	0.14 ± 0.04
Magnetic field magnitude (nT)	42 ± 3	43 ± 3

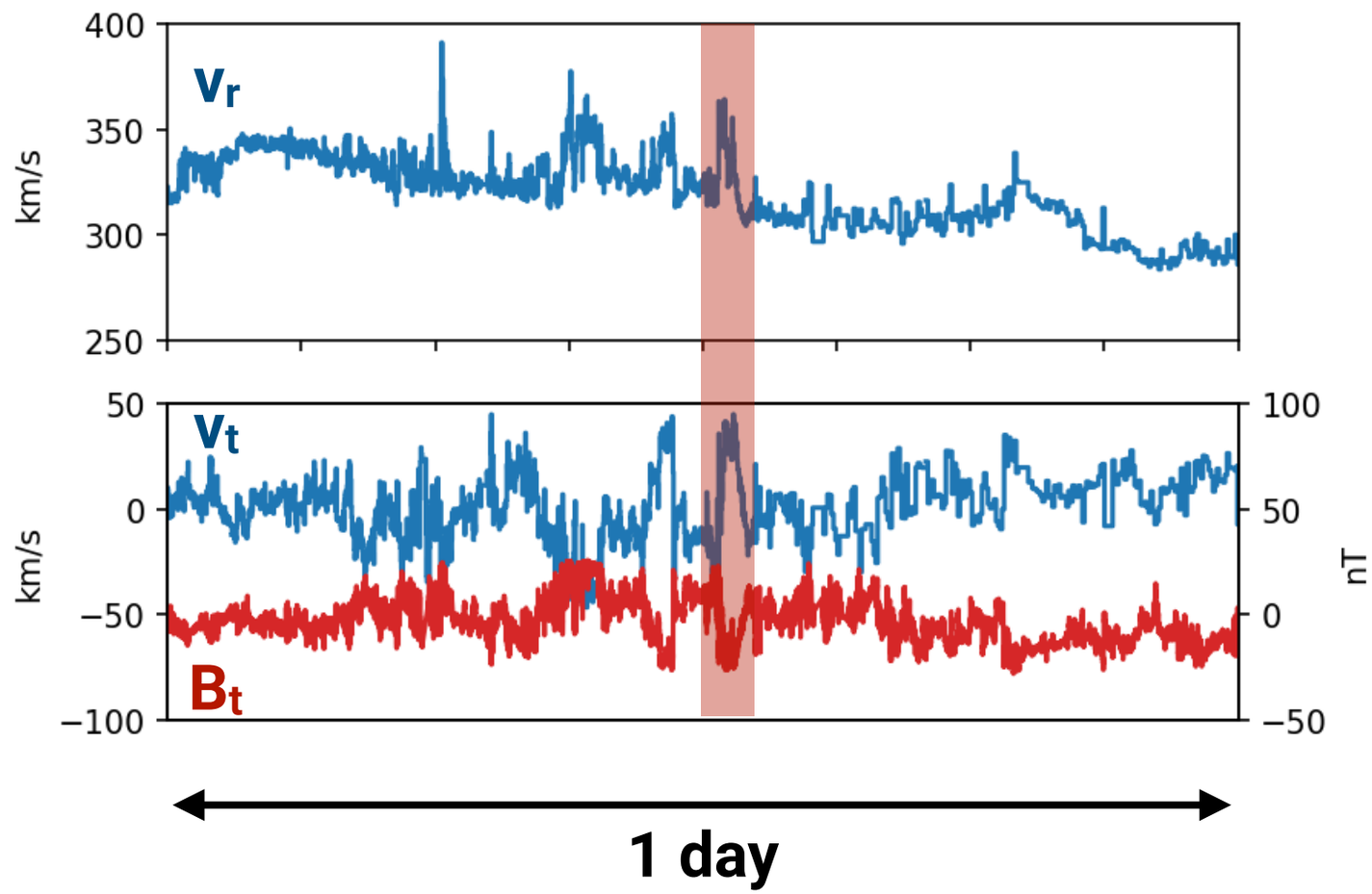
Solar wind sources

3.1.1. What Are the Source Regions of the Solar Wind and the Heliospheric Magnetic Field?

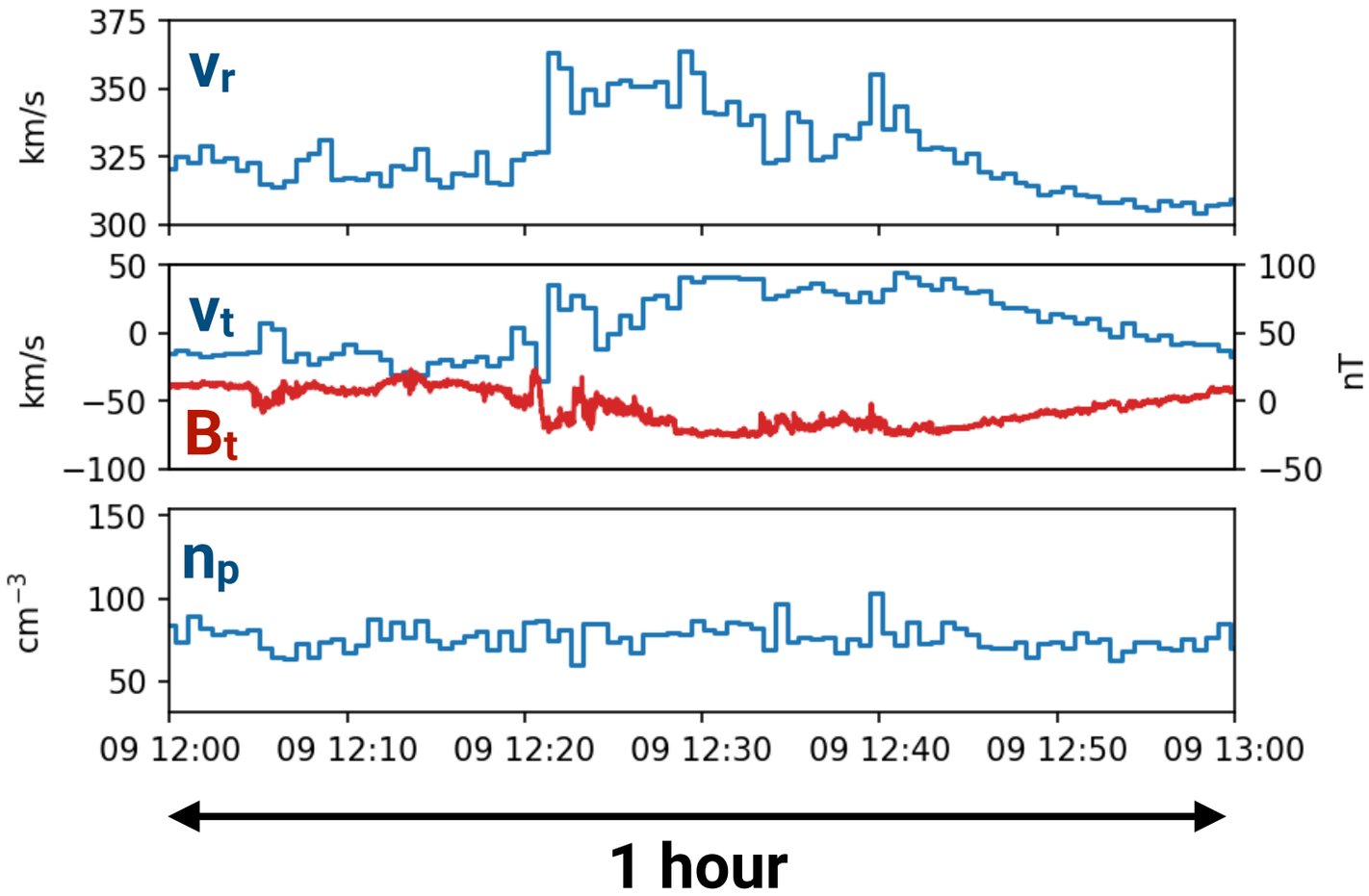
- Try to categorise in-situ solar wind measurements into different sources
- Been attempted before (e.g. Neugebauer et al. 2017), but only with 1 AU data
- Possible sources are
  - Coronal holes (centre + edges)
  - Active regions (e.g. *Harra et al. 2017*)
  - Small transients (e.g. *Sheeley et al. 1997*)

Cutting by speed doesn't work

- All fast solar wind is a smooth flow + Alfvén waves
- Recent work has found similar (lack of) structure within slow wind *(D'Amicis et al. 2015, 2016)*

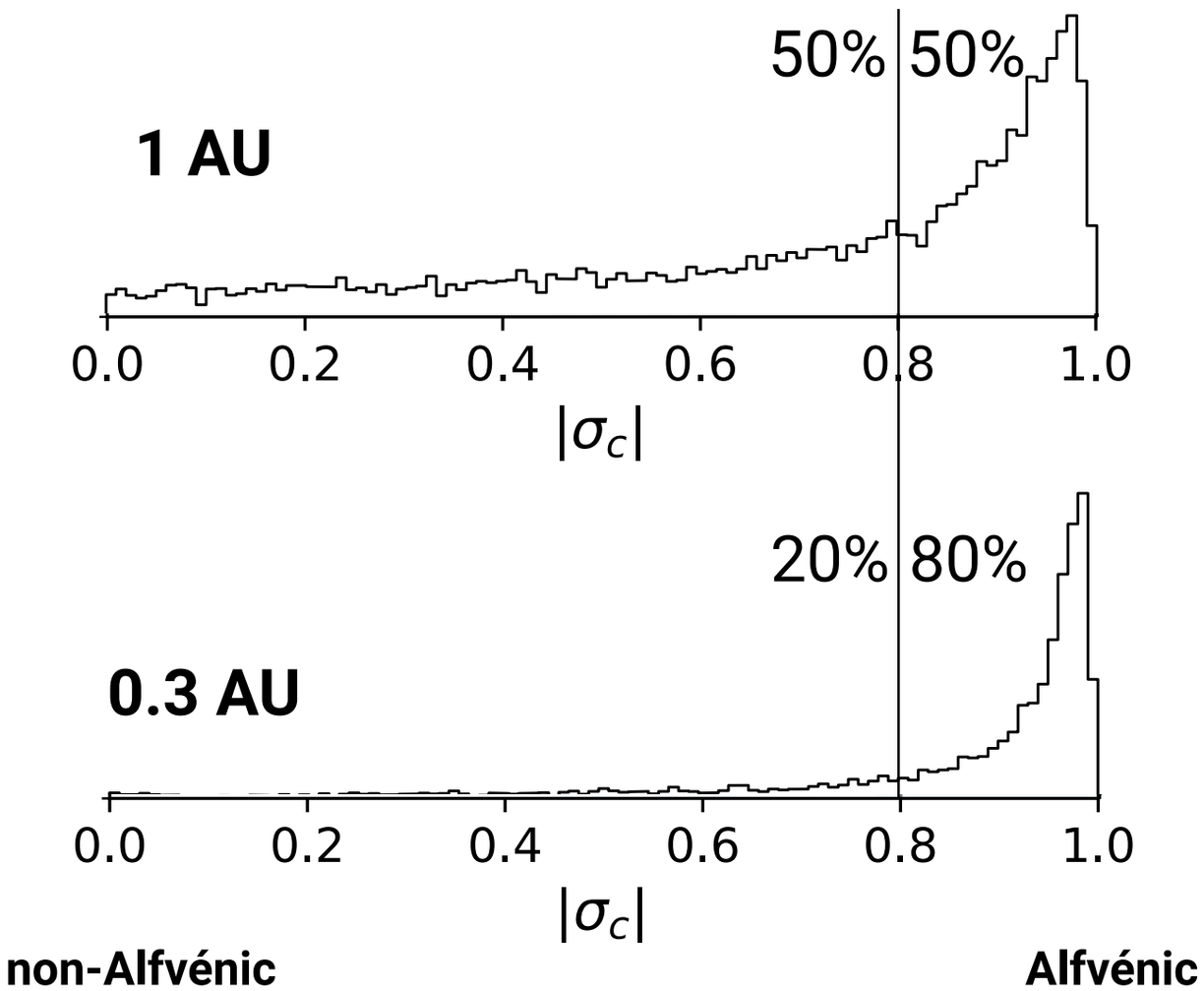


Cutting by speed doesn't work



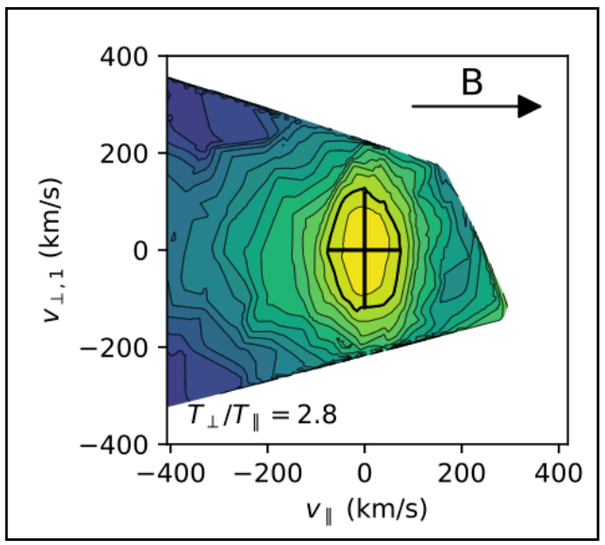
- Alfvénicity might be a more fundamental variable (related to open/closed field)

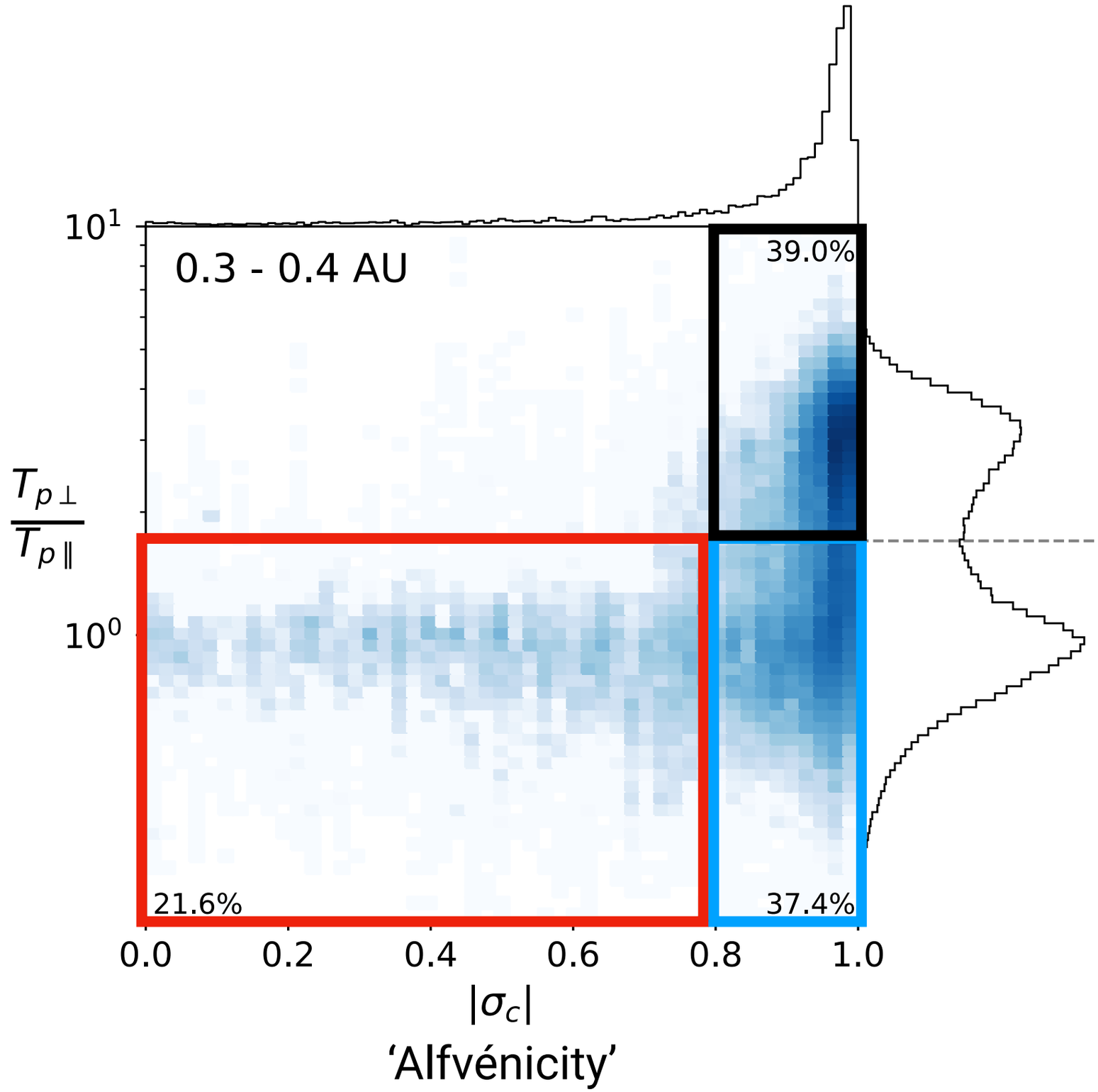
Radial variation of Alfvénicity



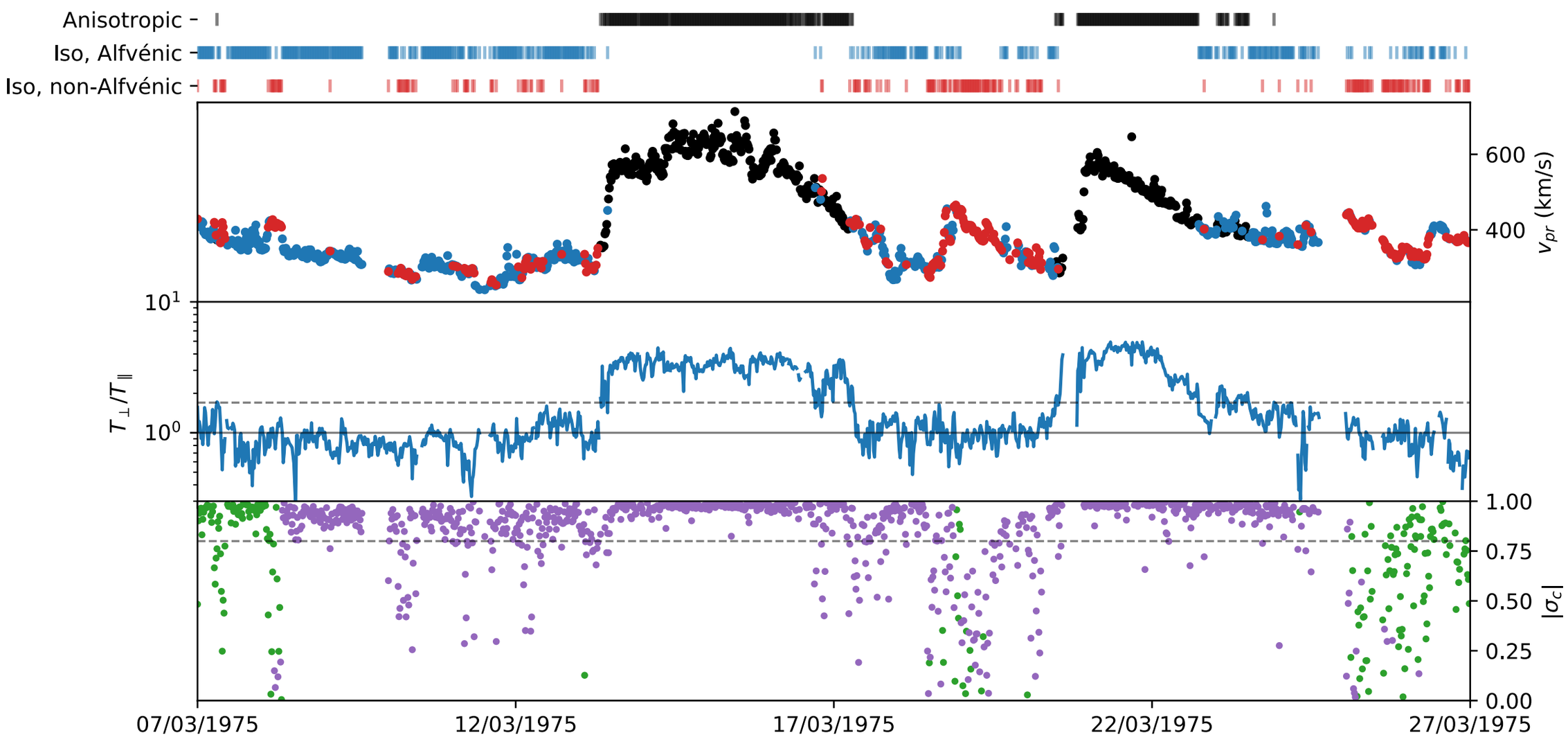
- All Helios data at solar minimum
- Properties at 1 AU not reflective of solar source properties!

Alfvénic wind at 0.3 AU



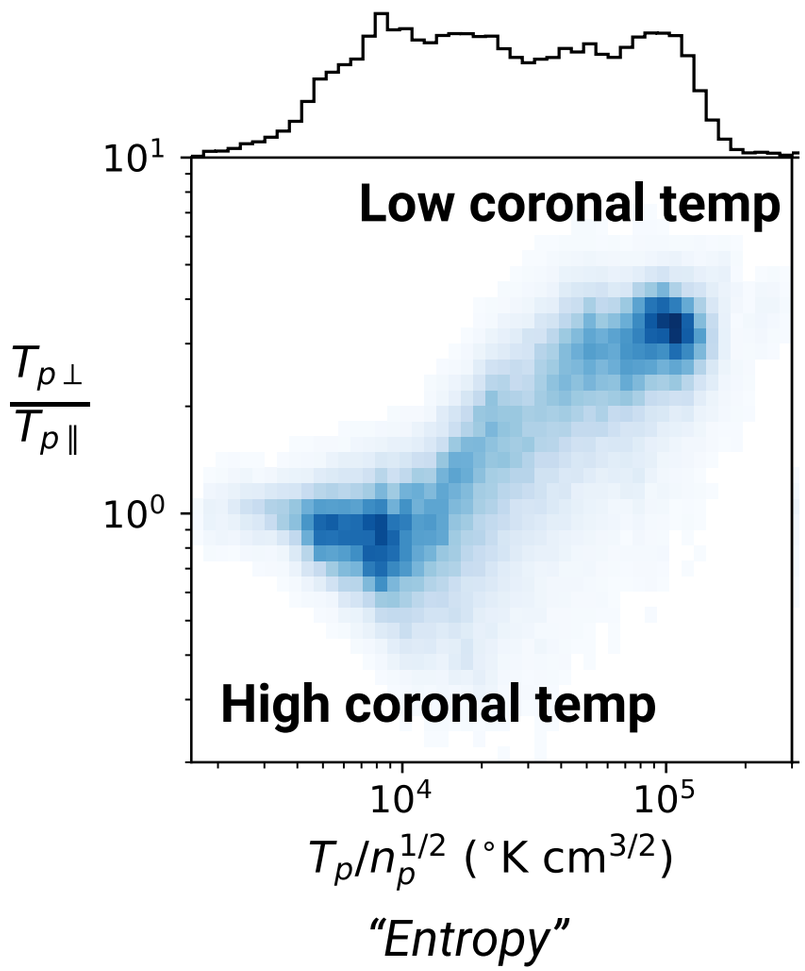


Classification timeseries



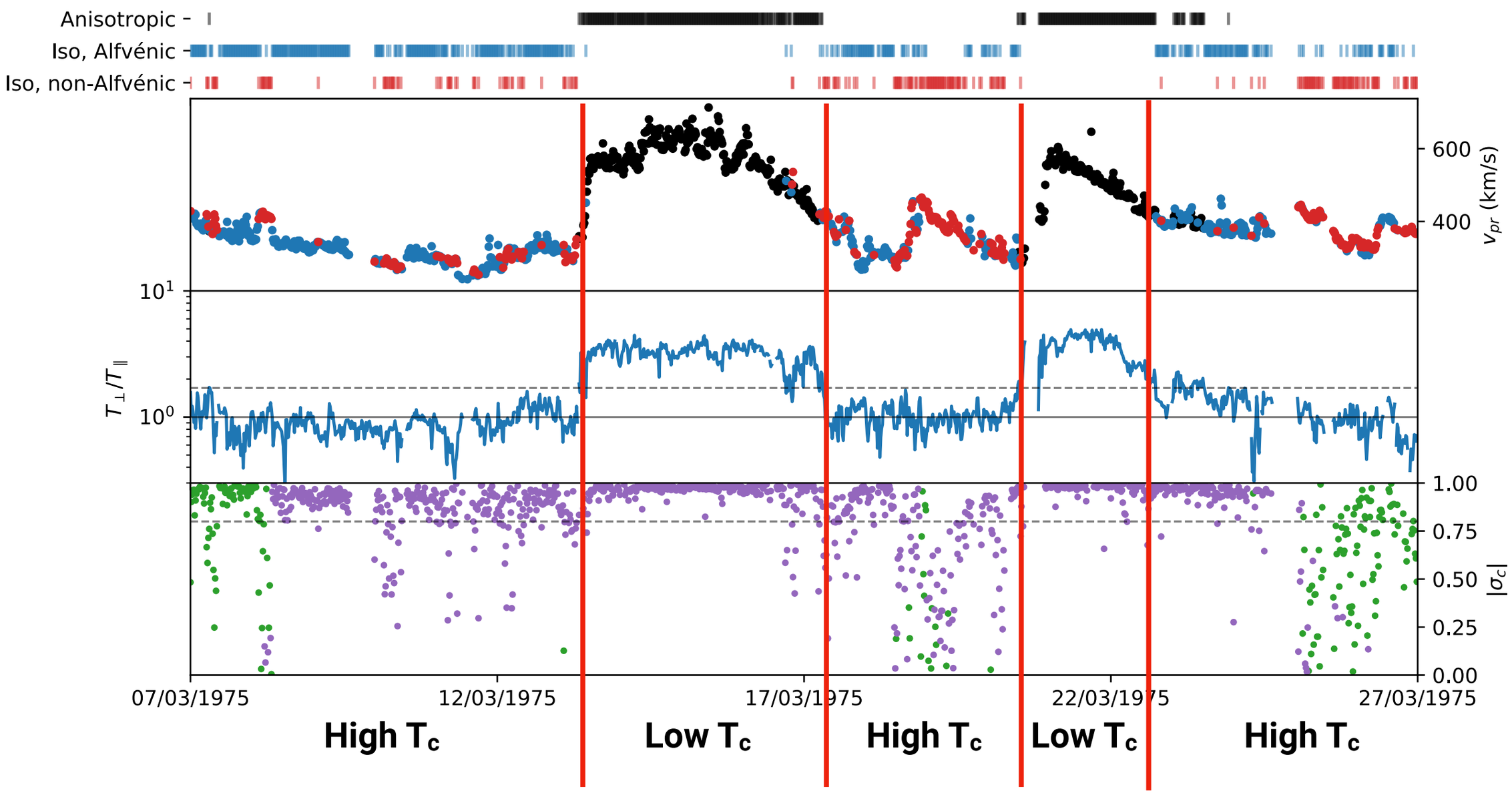
20 Days

Using $T_\perp/T_\parallel$ to infer composition



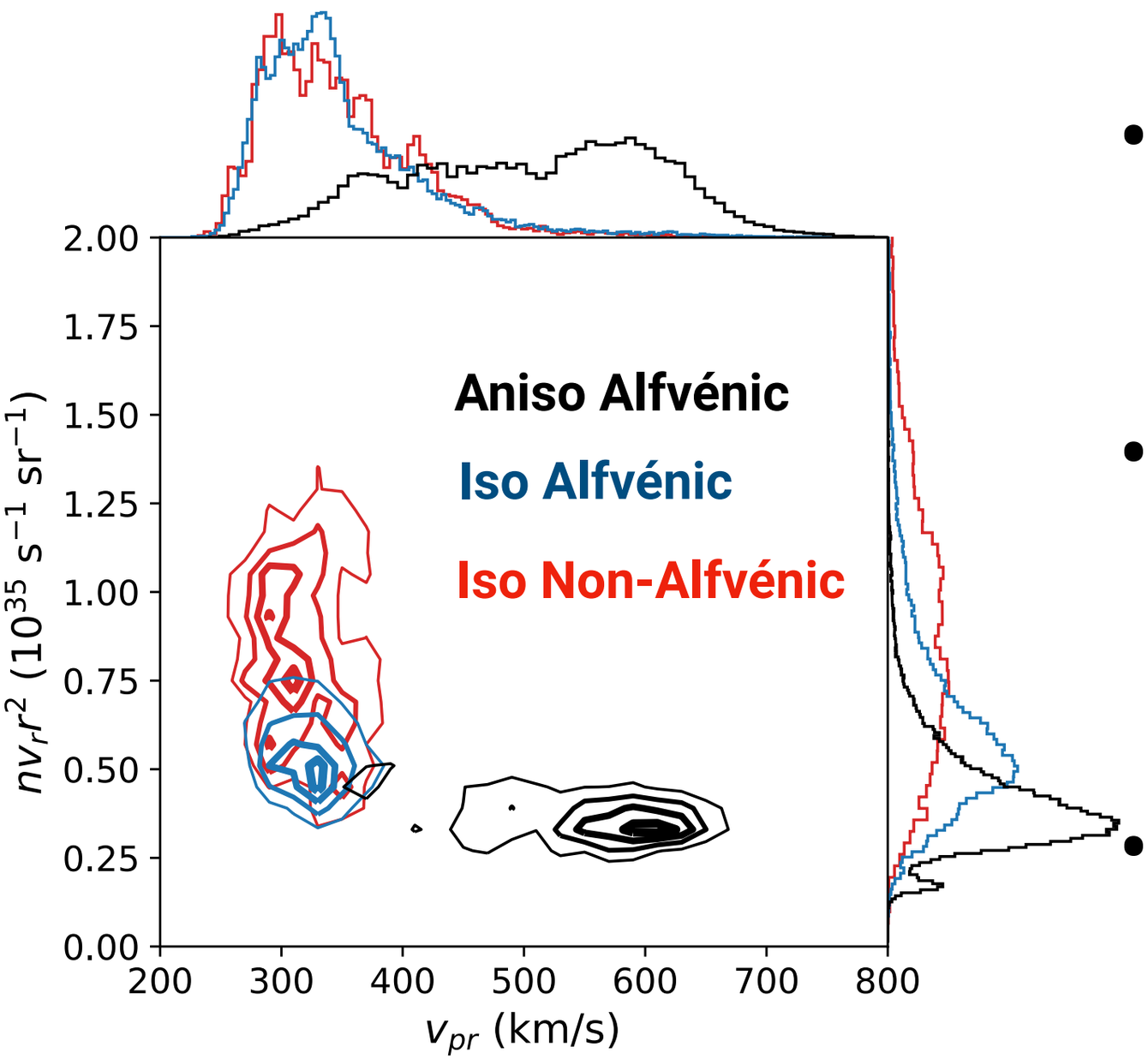
- Ulysses and ACE show entropy and O^{7+}/O^{6+} are statistically correlated
  [Pagel et. al. 2004, Stakhiv et. al. 2015, 2016]
- Also sharp O^{7+}/O^{6+} boundaries at leading + trailing edges of high speed streams
  [Burton et. al. 1999, Borovsky et. al. 2016]
- Helios saw **sharp anisotropy boundaries** in the **leading and trailing edges** at 0.3 AU

Classification timeseries



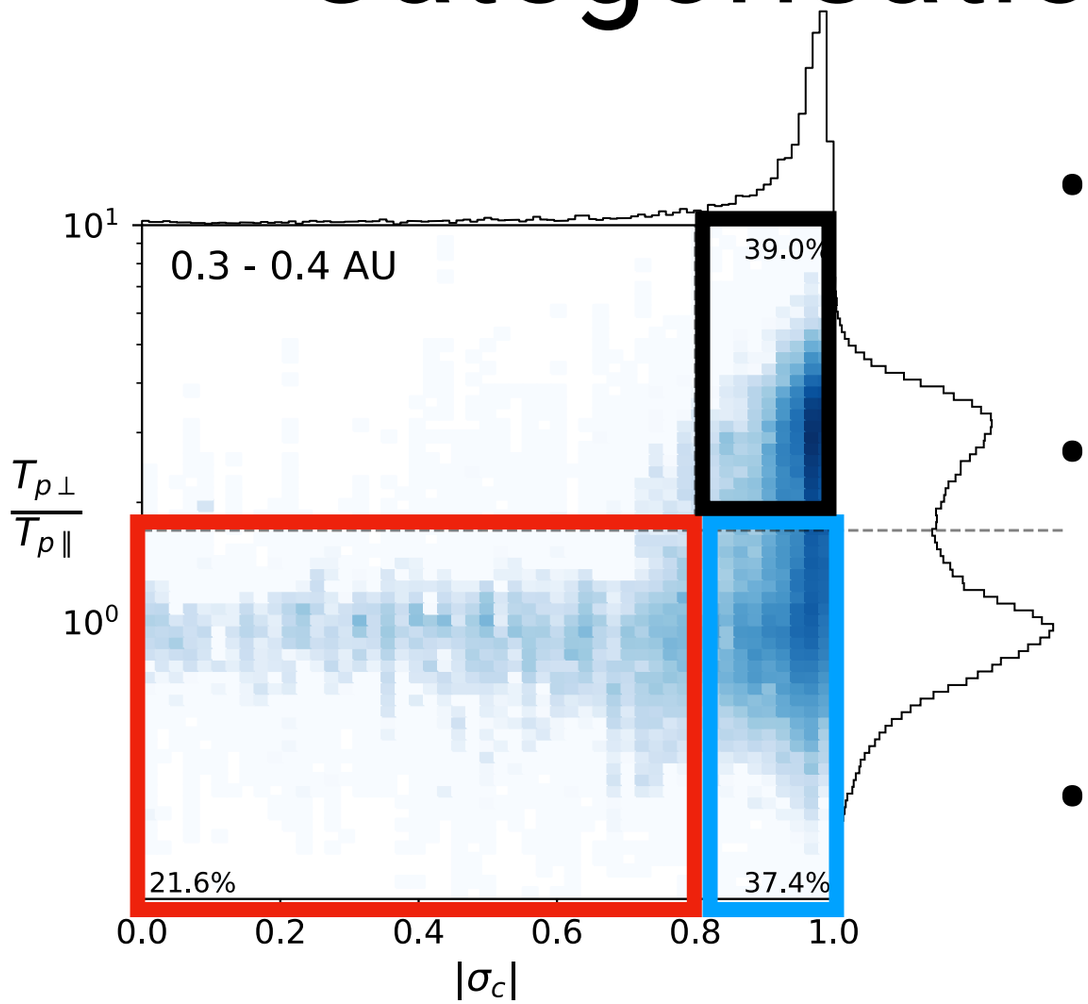
20 Days

Speed + mass flux of the 3 categories



- Distinction between slow/fast blurred at intermediate speeds
- Alfvénic wind has steady mass flux → continuous release on open field lines
- Non-Alfvénic wind has varying mass flux → transient release on closed lines

Categorisation conclusions



- Lots (~80 %) of slow wind is Alfvénic at 0.3 AU
- Solar wind at looks significantly different at 0.3 AU compared to 1 AU
- A **prediction** of contributions of different sources to the solar wind (at solar minimum)

Coronal holes
- Low coronal temp
- Constant mass flux
- Includes high speeds

Active regions/CH edges
- High coronal temp
- Alfvénic + constant mass flux

⇒ quasi-steady open flux

Small transients
- High coronal temp
- non-Alfvénic + variable mass flux

⇒ intermittent source

Stansby et al. in prep

Coronal heating

3.1.2. What Mechanisms Heat and Accelerate the Solar Wind?

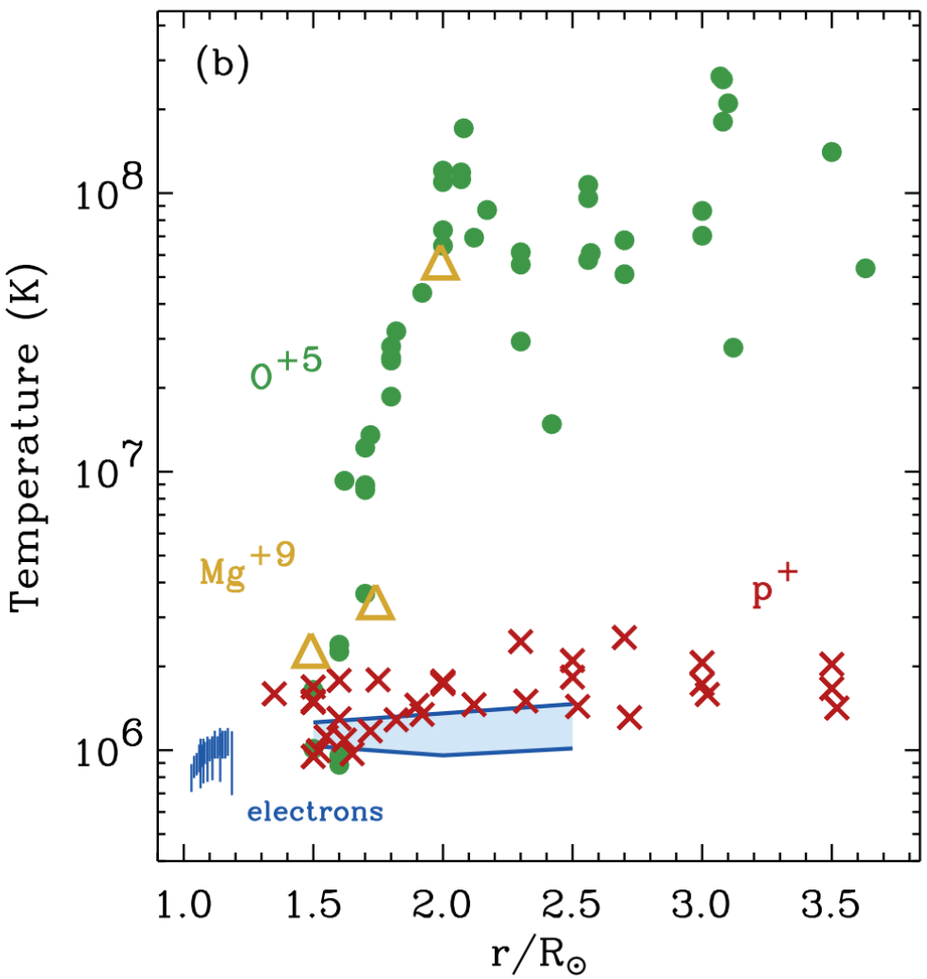
- One line of attack: see how heating affects different ions

- In-situ measurements of heavy ions only at > 1 AU (until SO) (e.g. *Tracey et al. 2016*)

- Remote sensing of lots of different ions (SOHO/UVCS, Hinode/EIS, e.g. Hahn et al. 2013, Cranmer et al. 2008)

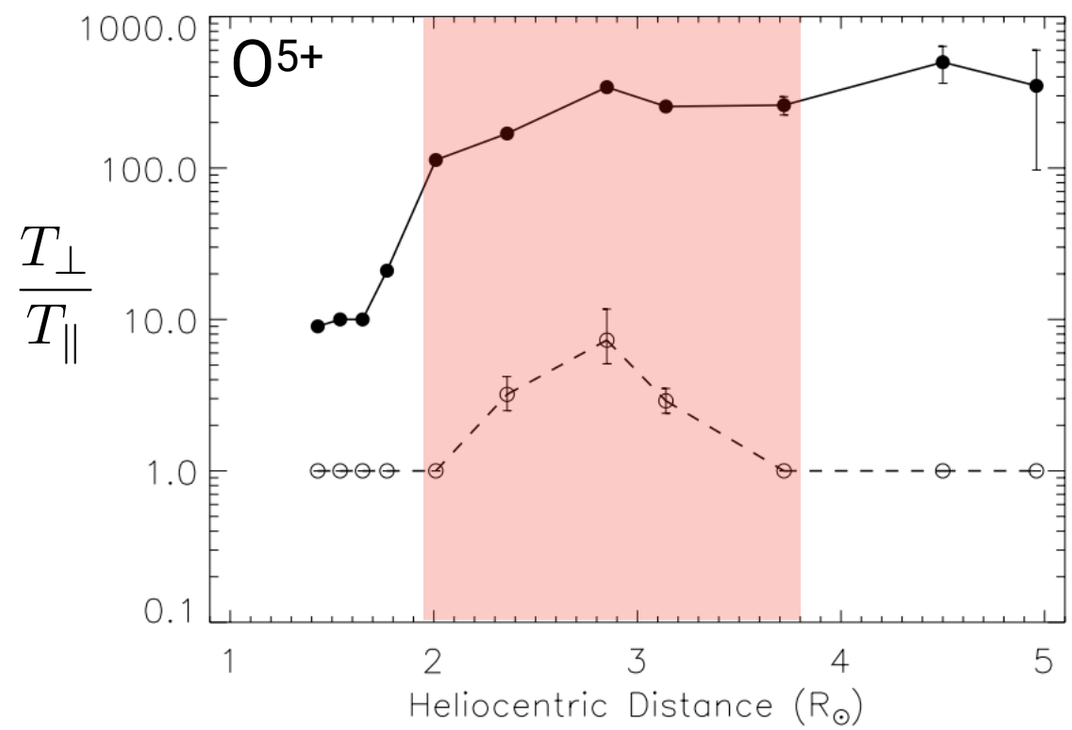
Preferential heating

Heaving ion heating



SOHO/UVCS; *Cranmer et al. 2017*

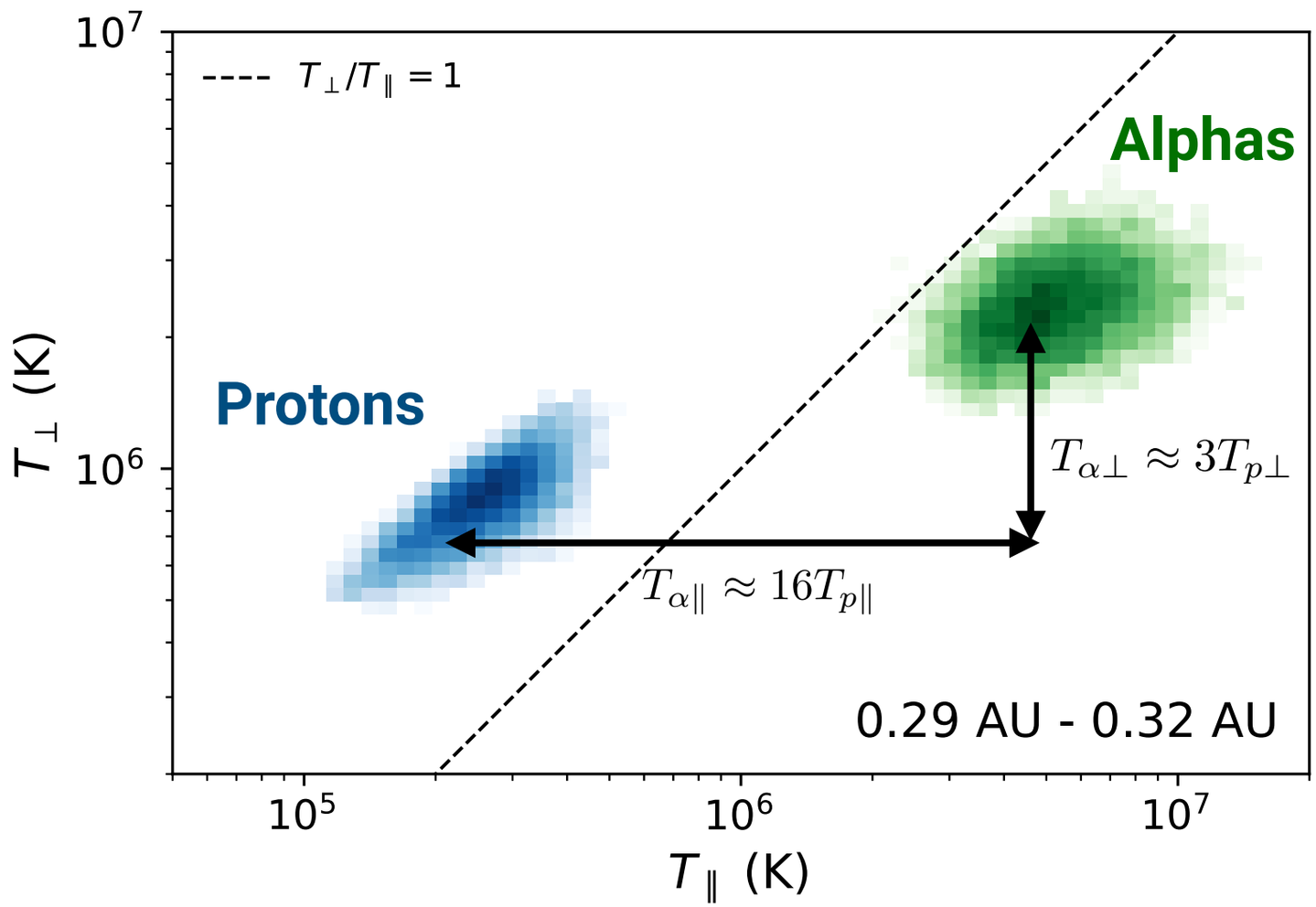
Perpendicular heating



SOHO/UVCS; *Telloni et al. 2007*

Fast wind He^{2+} at 0.3 AU

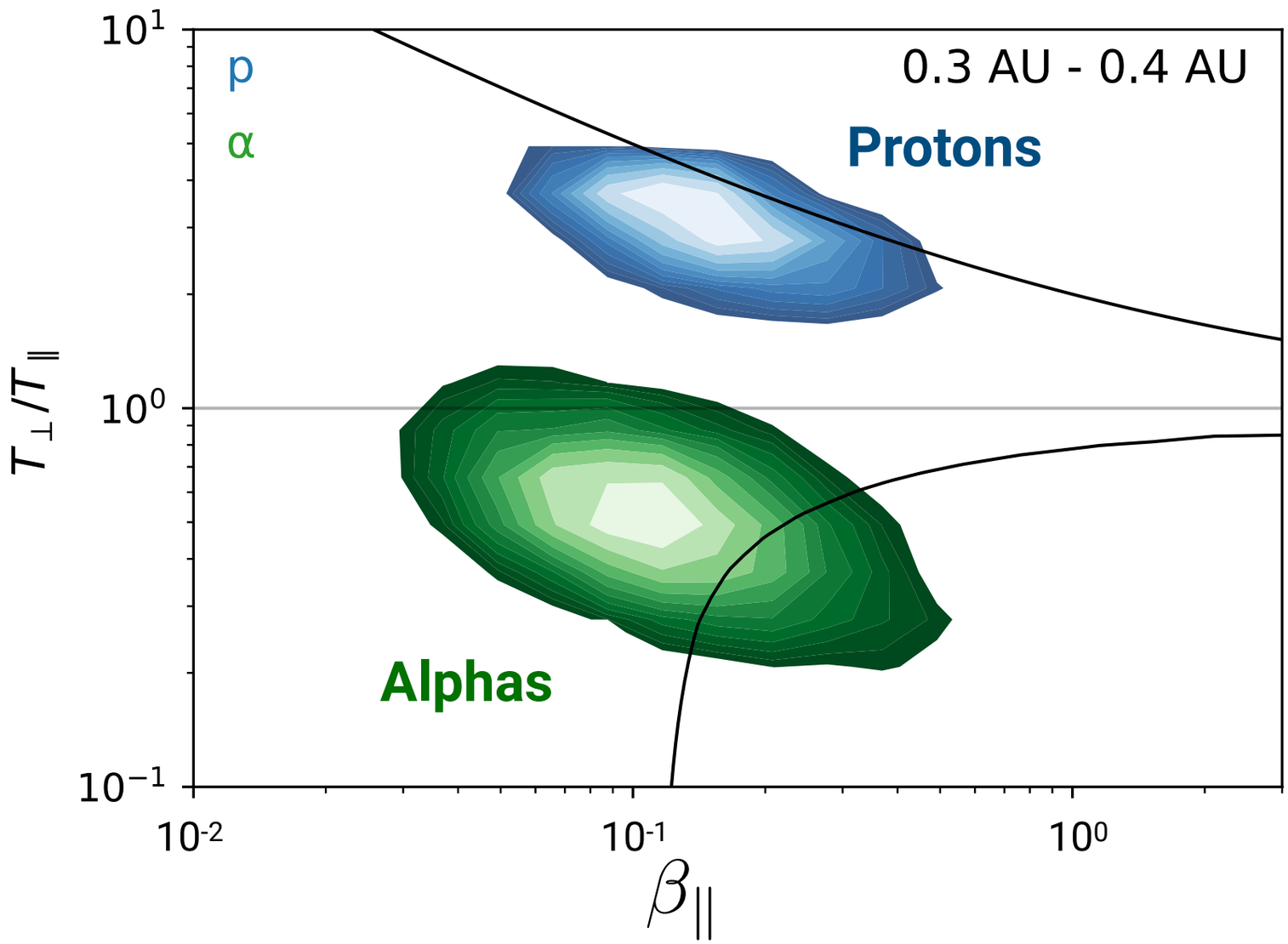
Work in progress



- He^{2+} does undergo preferential heating…
- … but is **less** anisotropic than protons
- An important new constraint for coronal heating theories?

Fast wind He^{2+} at 0.3 AU

Work in progress

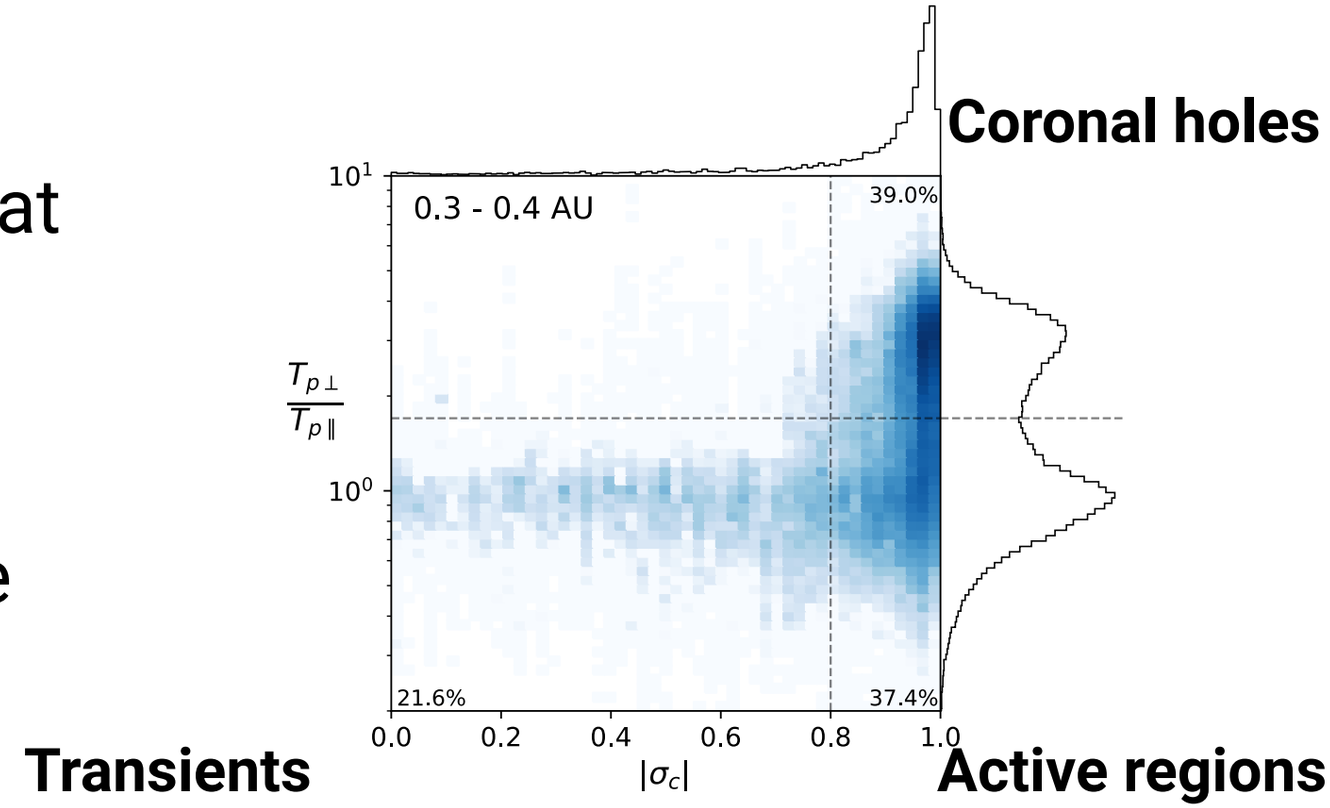


- He^{2+} anisotropy << proton anisotropy
- He^{2+} becomes unstable ~ 0.3 AU
- He^{2+} properties at 1 AU very strongly influenced by transit effects

Conclusions

- Properties measured in-situ at 1 AU may **not** reflect solar sources

- Helios data are very valuable and still returning surprises



- Developed **testable** scheme for categorising solar sources

- Trying to do science w/ Helios data has been excellent preparation for Parker Solar Probe and Solar Orbiter

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davidstansby.com/talks

Bibliography

- **New Helios data** - Stansby 2018 (http://arxiv.org/abs/1807.04376)
- **MESSENGER solar wind** - Gershmann 2012 (http://doi.wiley.com/10.1029/2012JA017829)
- **Coronal jet review** - Raouafi+ 2016 (http://link.springer.com/10.1007/s11214-016-0260-5)
- **In-situ jets** - Horbury+ 2018 (https://academic.oup.com/mnras/article-abstract/478/2/1980/4987231)
- **Solar wind movies** - DeForest+ 2018 (http://iopscience.iop.org/article/10.3847/1538-4357/aac8e3)
- **Alfvénic slow wind** - D'Amicis+ 2015 (http://stacks.iop.org/0004-637X/805/i=1/a=84)