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What scatters the electron strahl in the solar wind?

David Stansby
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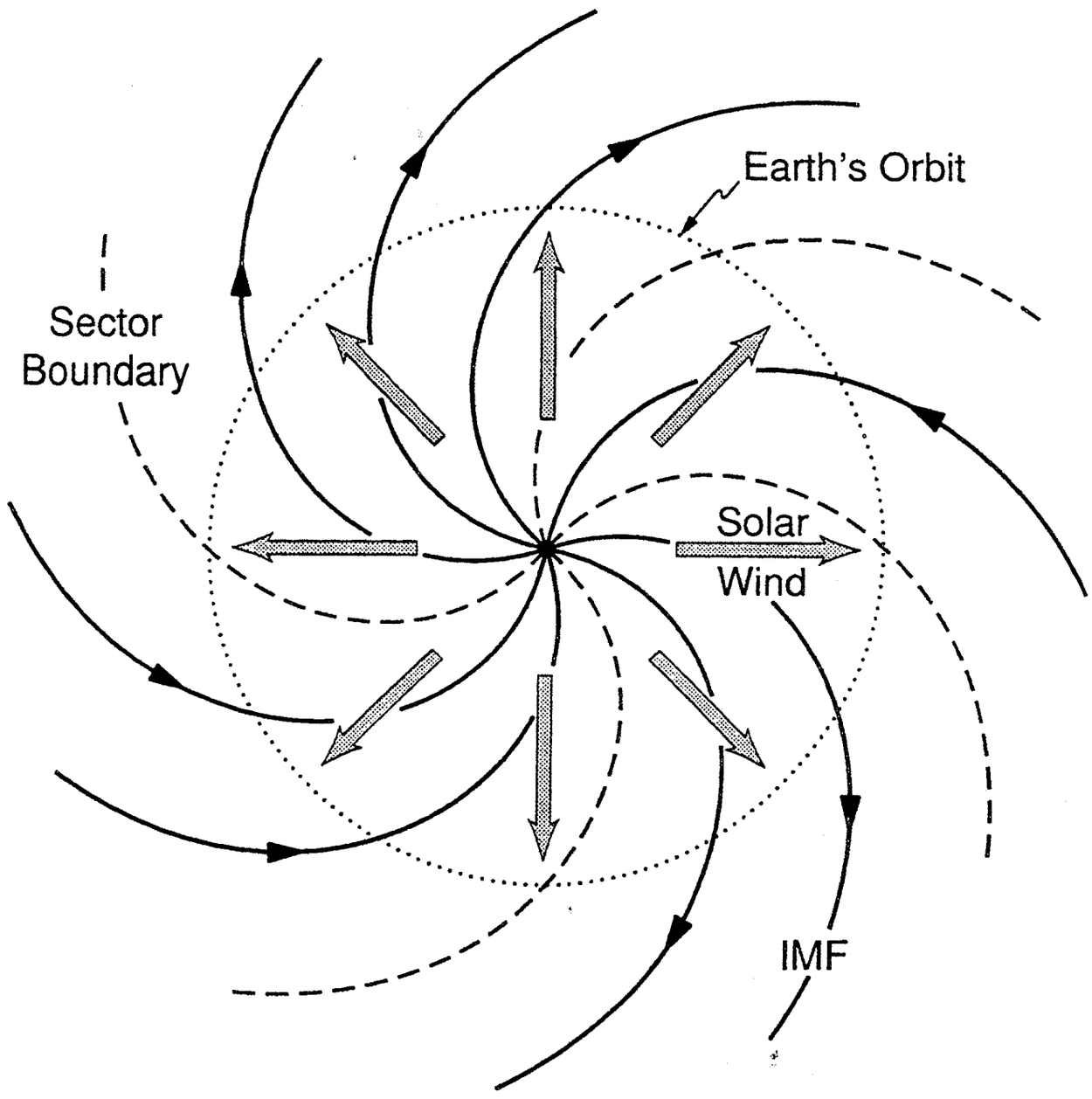
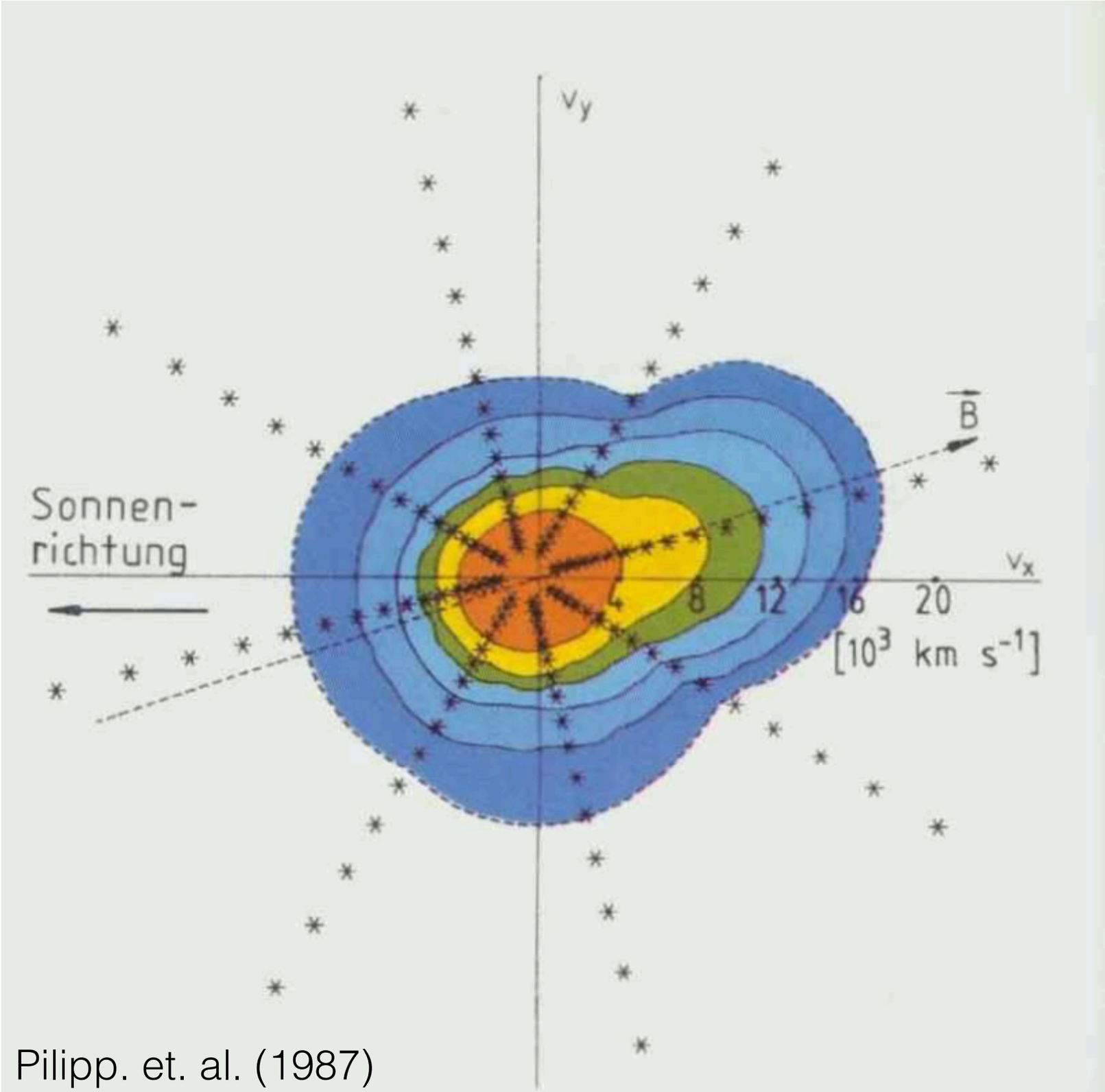
The Solar Wind

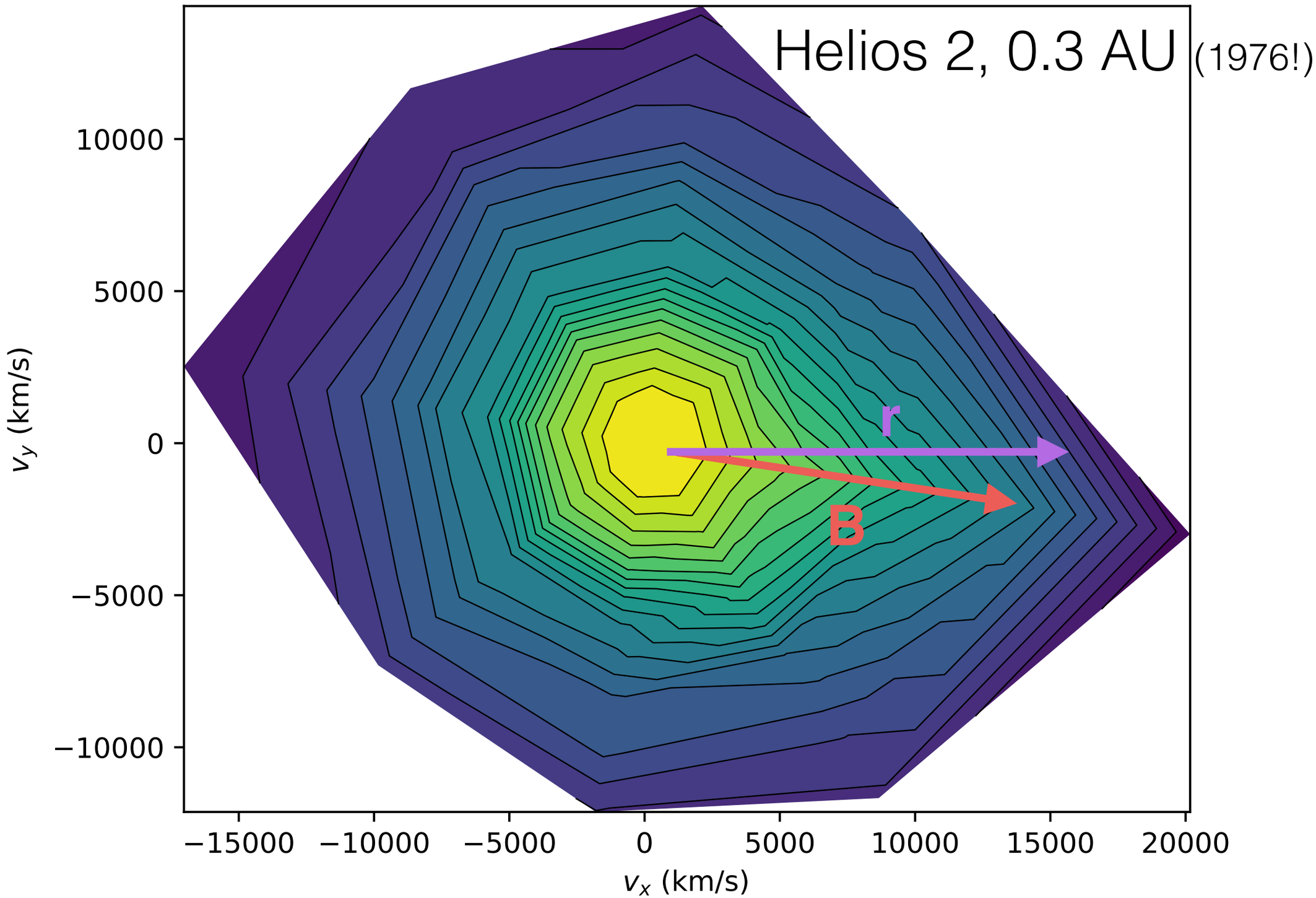


Electrons in the solar wind



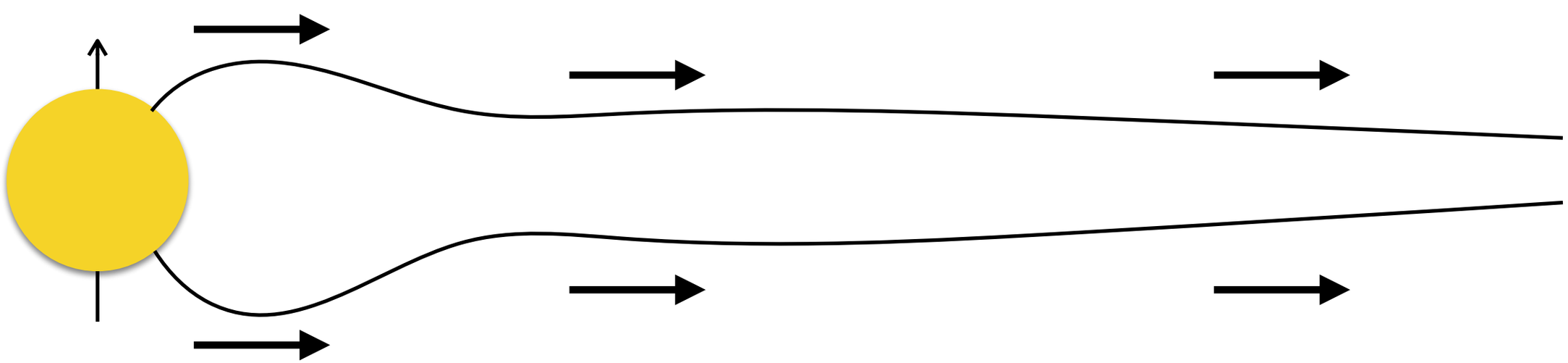
Pilipp. et. al. (1987)

Electrons in the solar wind



Electron strahl

- Travels anti-sunward, along magnetic field
- Typical speed of ~10,000 km/s (20x faster than protons)
- Propagation time ~1hr from Sun to 0.3 AU
- Gives information about magnetic connectivity



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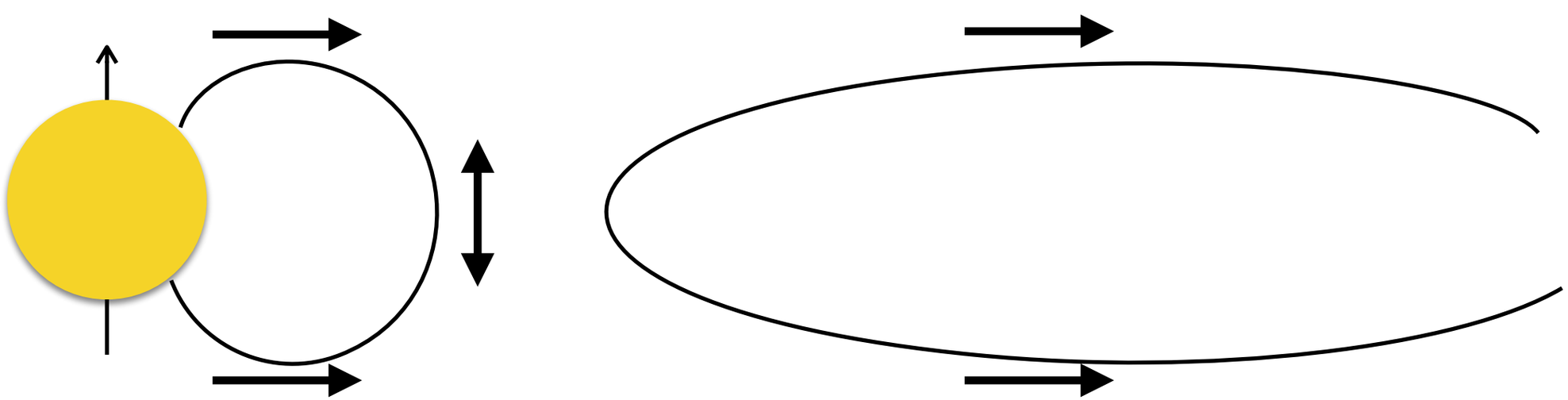

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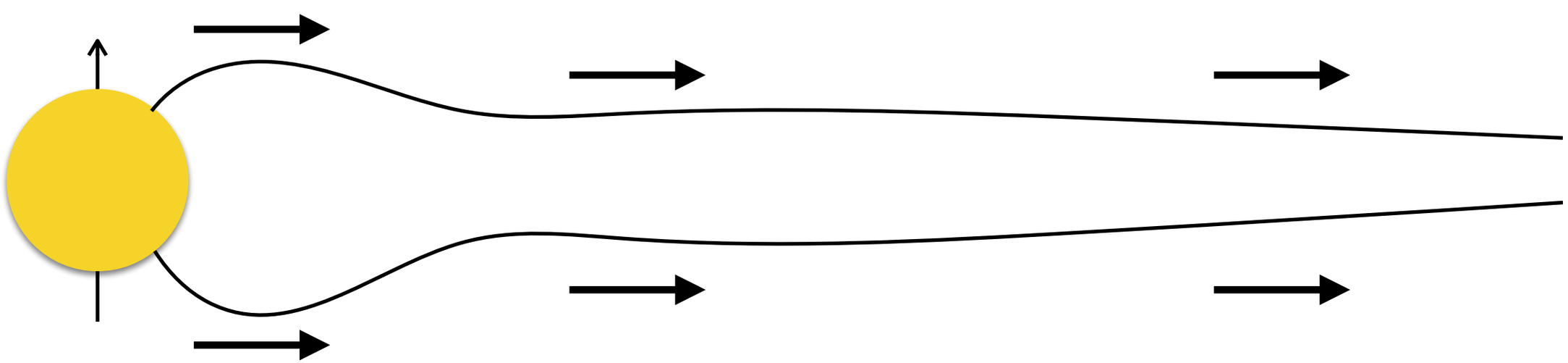
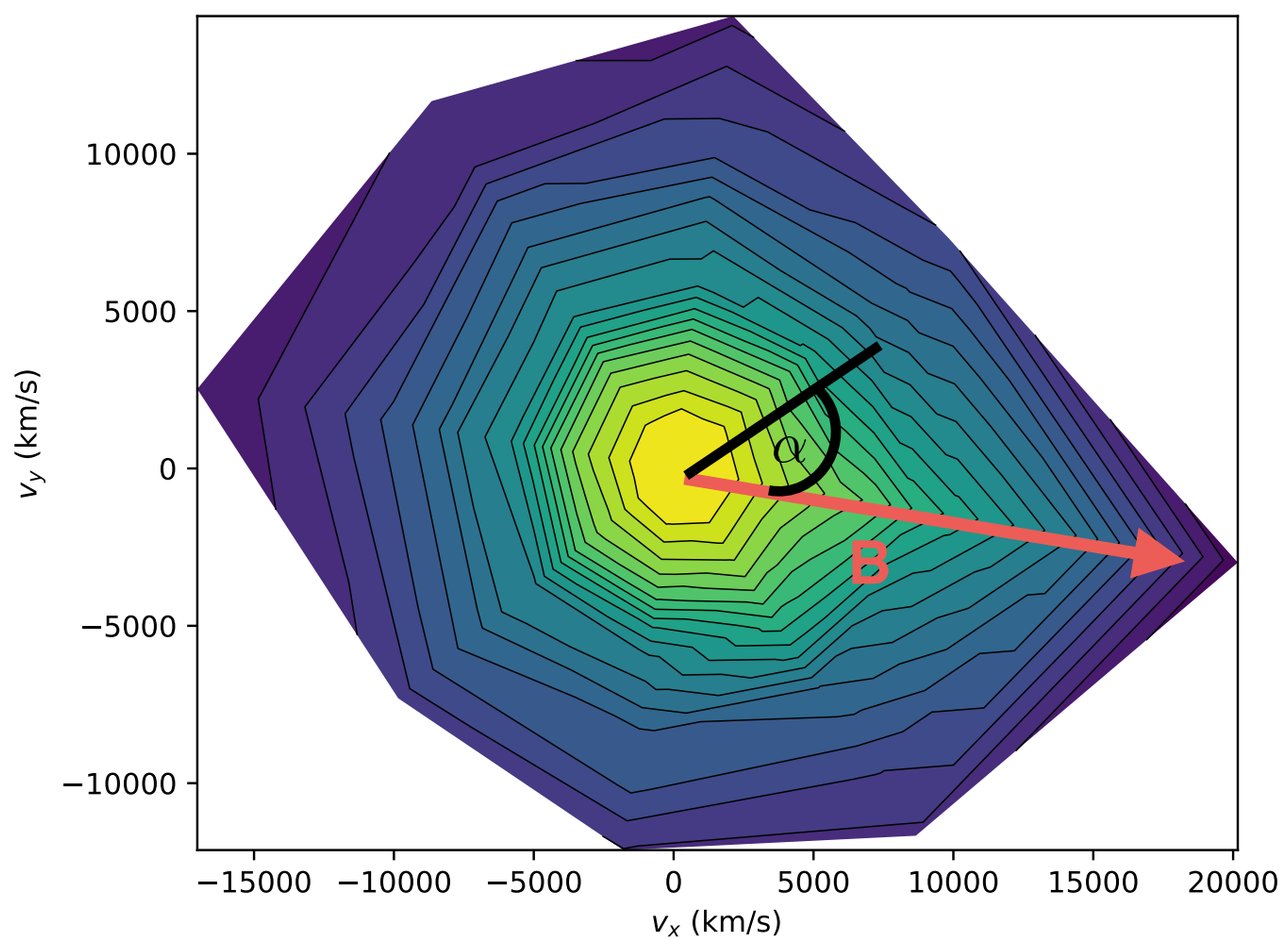


How should the strahl evolve?

- In a collisionless plasma, particles should conserve magnetic moment

$$\frac{\sin^2 \alpha}{|\underline{B}|} = const$$



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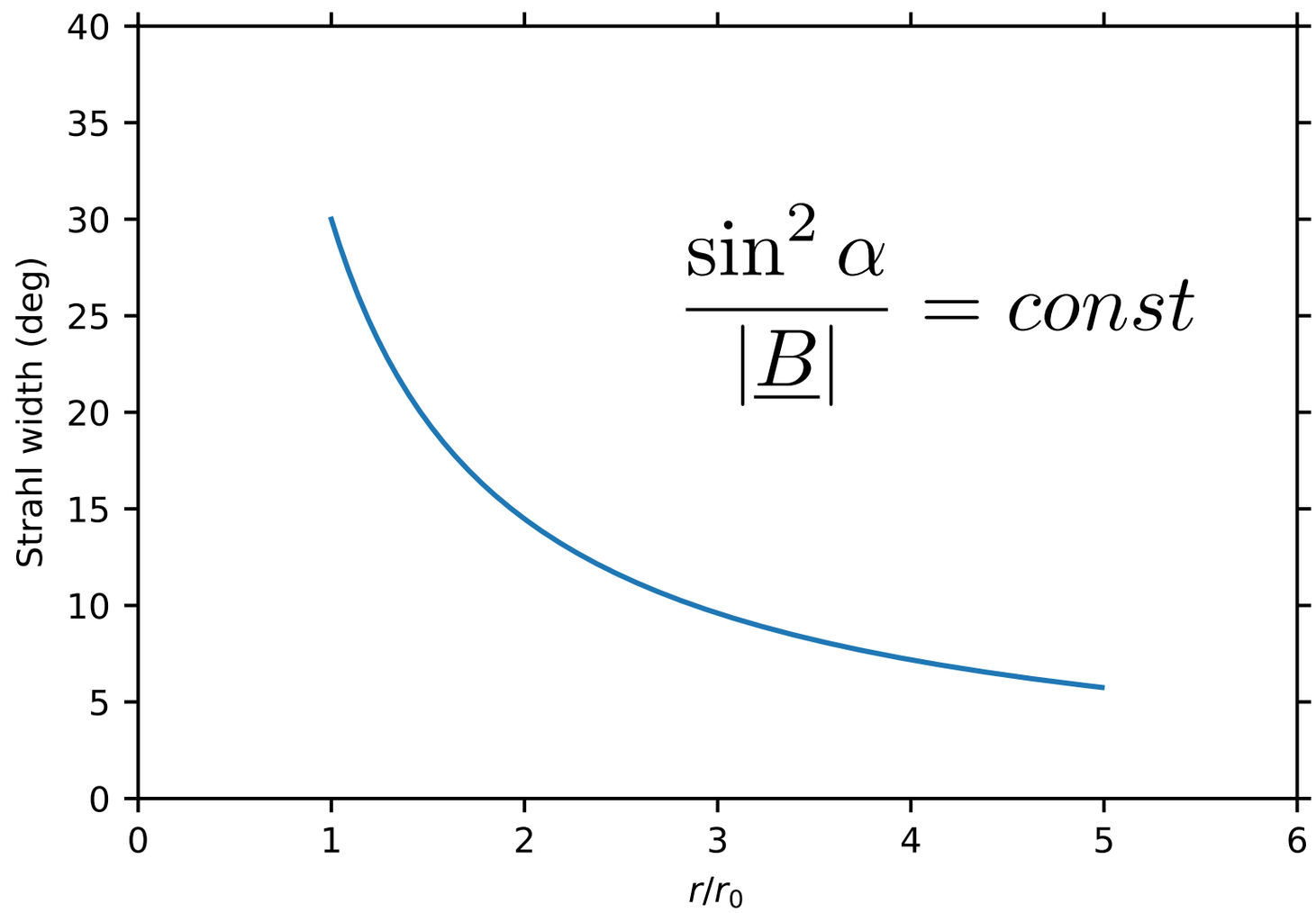
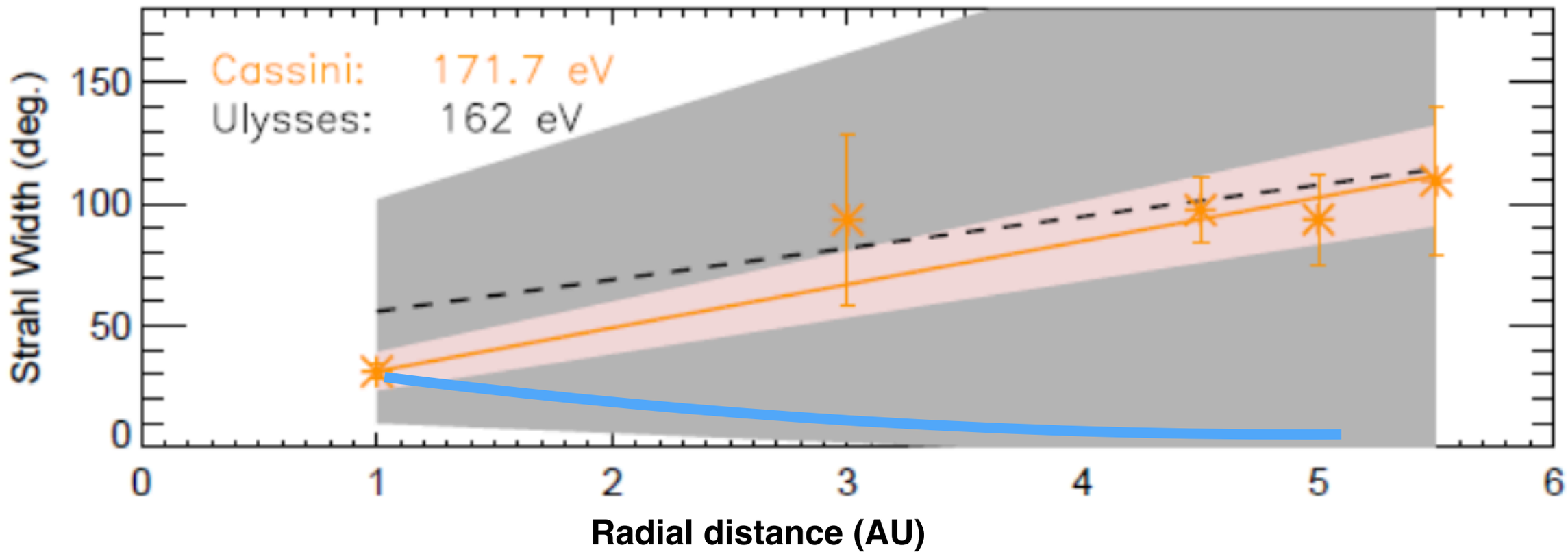


- Theoretically, expect strahl to narrow with distance

How does the strahl evolve?

Graham et. al. 2017



- But observationally, strahl widens with distance!

There must be a mechanism to scatter the strahl

Proposed scattering mechanisms

- Electrons not collisional enough to account for scattering (mean free path ~ 1 AU) *[Hammond et. al. 1996]*

➡ Need a wave-particle interaction

- Whistler waves *[Vocks et. al. 2005, Saito et. al. 2007, Seough et. al. 2015]*

- Langmuir waves *[Pavan et. al. 2013]*

Proposed scattering mechanisms

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- **Whistler waves** *[Vocks et. al. 2005, Saito et. al. 2007, Seough et. al. 2015]*

- Langmuir waves *[Pavan et. al. 2013]*

Part I conclusions

- Expect a collisionless strahl to narrow as it travels away from the sun
- In contrast, the strahl widens with radial distance

➡ Need a wave-particle interaction to scatter electrons

- Can observed whistler waves perform this scattering?

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Can whistler waves scatter the strahl?

David Stansby
Tim Horbury, Chris Chen, Lorenzo Matteini

"Experimental determination of whistler wave dispersion relation in the solar wind"
ApJ Letters, 2016
http://tinyurl.com/solarwindwhistlers

Can whistler waves scatter the strahl?

- Plasma waves can scatter charged particles
- Scattering condition for electrons and whistler waves is given by

$$k_{\|} v_{\|} = \omega - \Omega_e$$

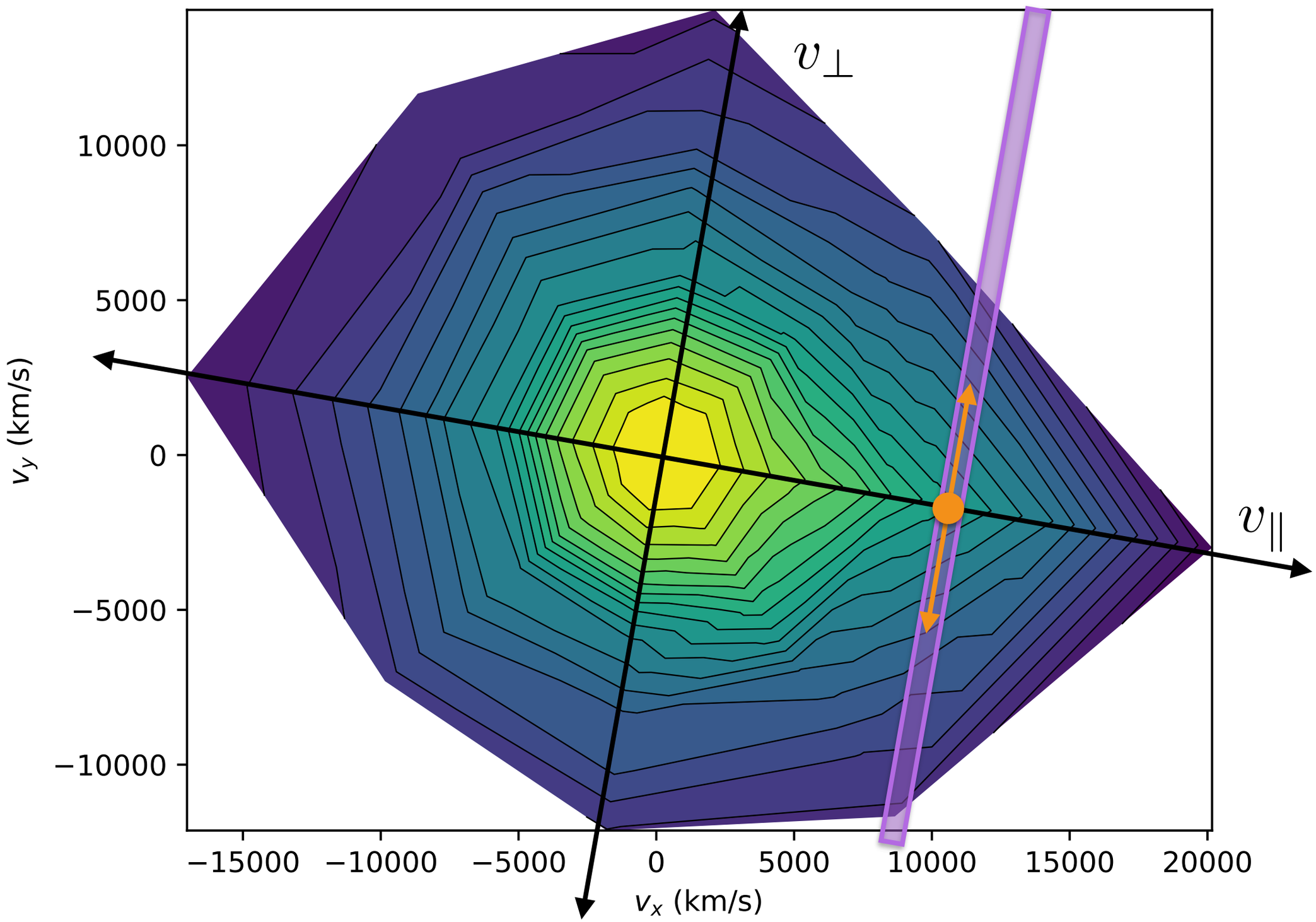
Parallel wave vector

Parallel electron velocity

Wave frequency

Electron gyro-frequency

Can whistler waves scatter the strahl?



Can whistler waves scatter the strahl?

$$k_{\|} v_{\|} = \omega - \Omega_e$$

- For whistler waves, $\omega - \Omega_e < 0$
- This means $k_{\|} v_{\|} < 0$
- Key observation:

Whistlers and strahl must be travelling in opposite directions to interact

Whistler wave direction

- For an EM wave, Poynting vector is $\mathbf{P} = \dfrac{\mathbf{E} \times \mathbf{B}}{\mu_0}$
- This works for whistler waves too, if we consider the fluctuating fields

$$\mathbf{P} = \frac{\delta\mathbf{E} \times \delta\mathbf{B}}{\mu_0}$$

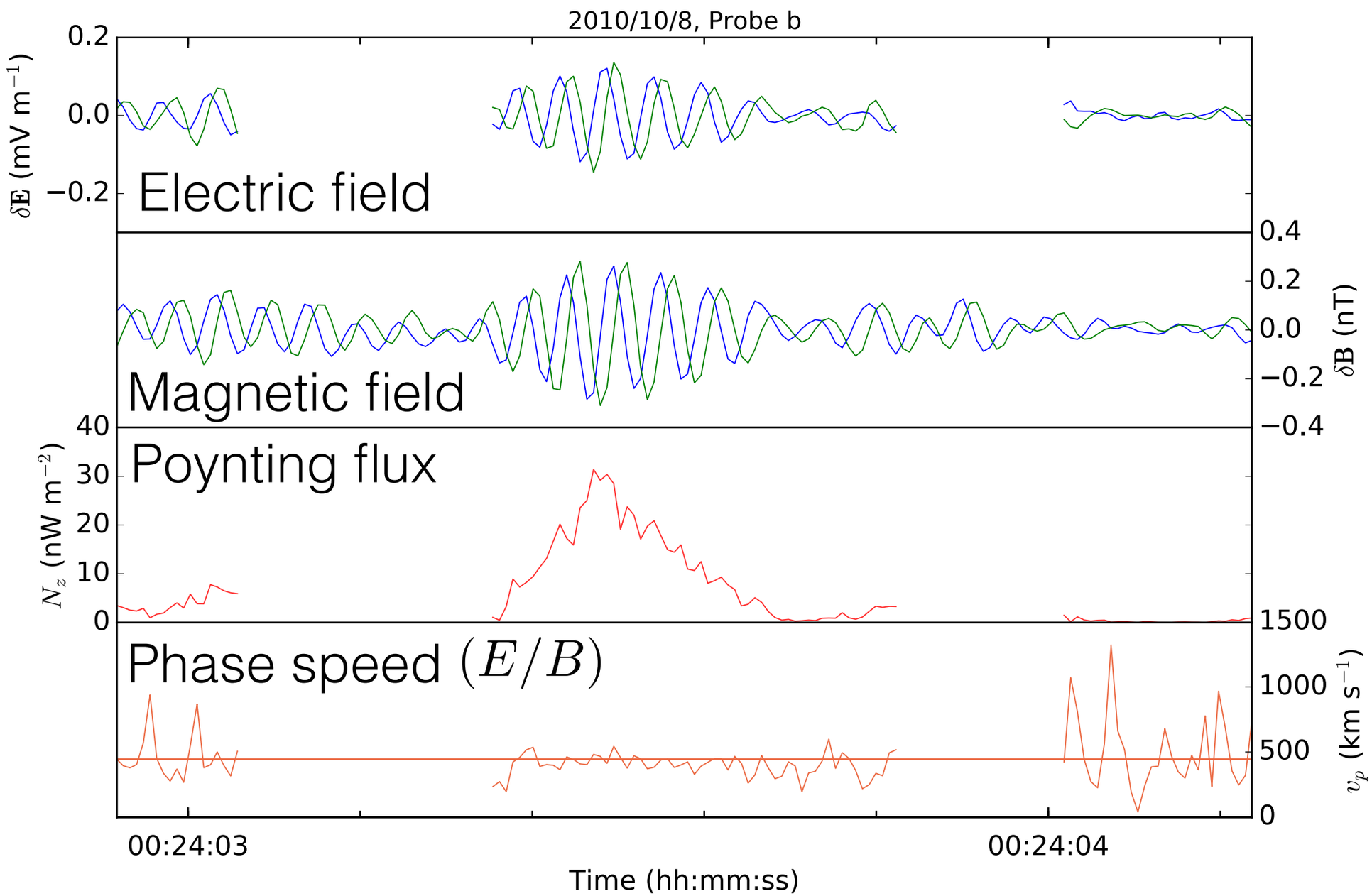
- **P** points in the direction of wave propagation

Measuring **E**/**B** in the solar wind

- Need high frequency (> 4Hz) measurement cadence
  - Use *ARTEMIS* Spacecraft
    (10 minute bursts at 128 samples/second)
- **B** fairly easy; **E** much harder!
  - No details here, but ask me later if interested

Wave packets

- 289 individual wave packets with plasma properties



Aside - dispersion relations

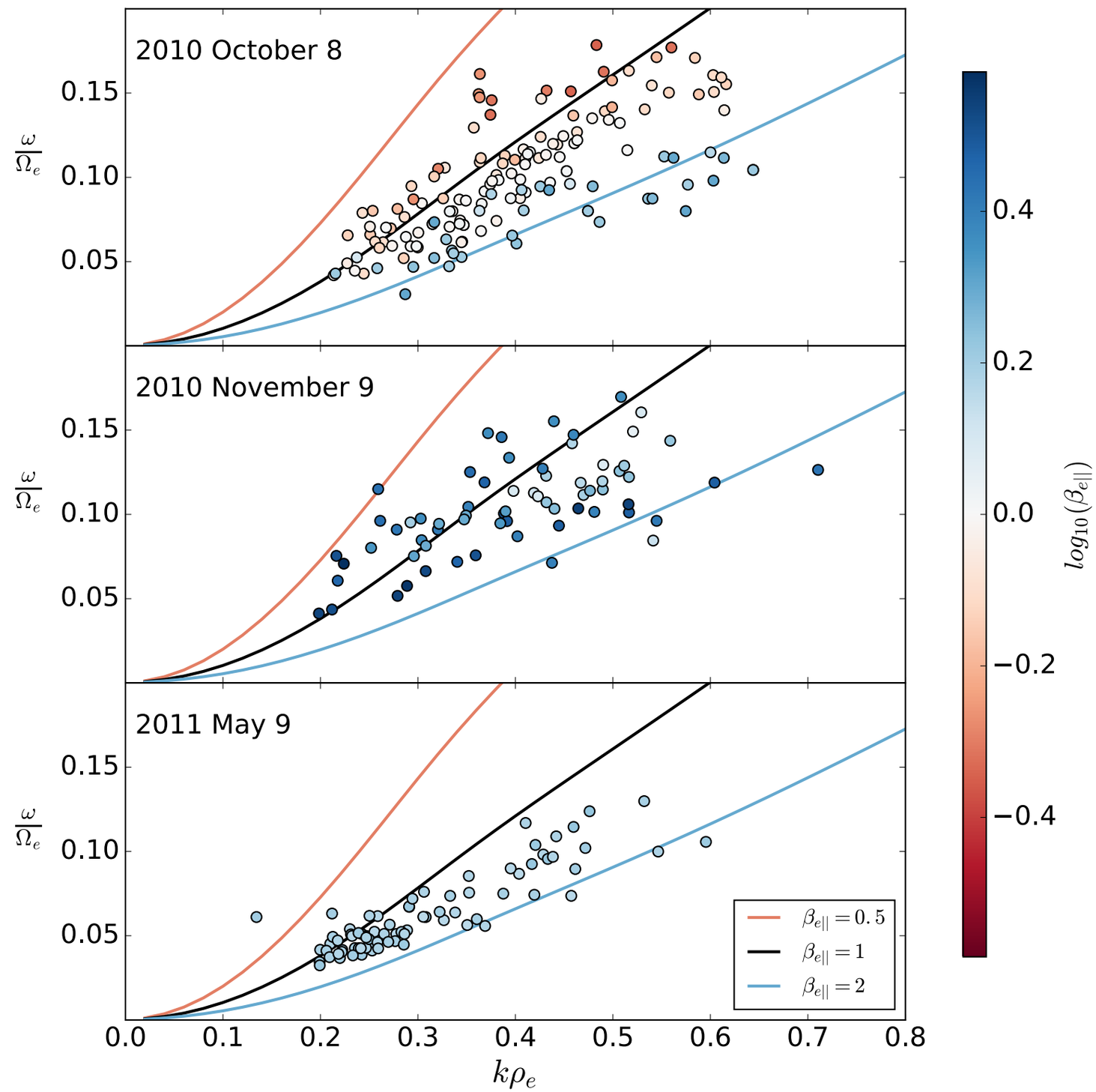
- How to identify a wave mode from observations?
- Wave mode defined by a dispersion relation

$$\omega = f\left(\mathbf{k}; T_e, n_e....\right)$$

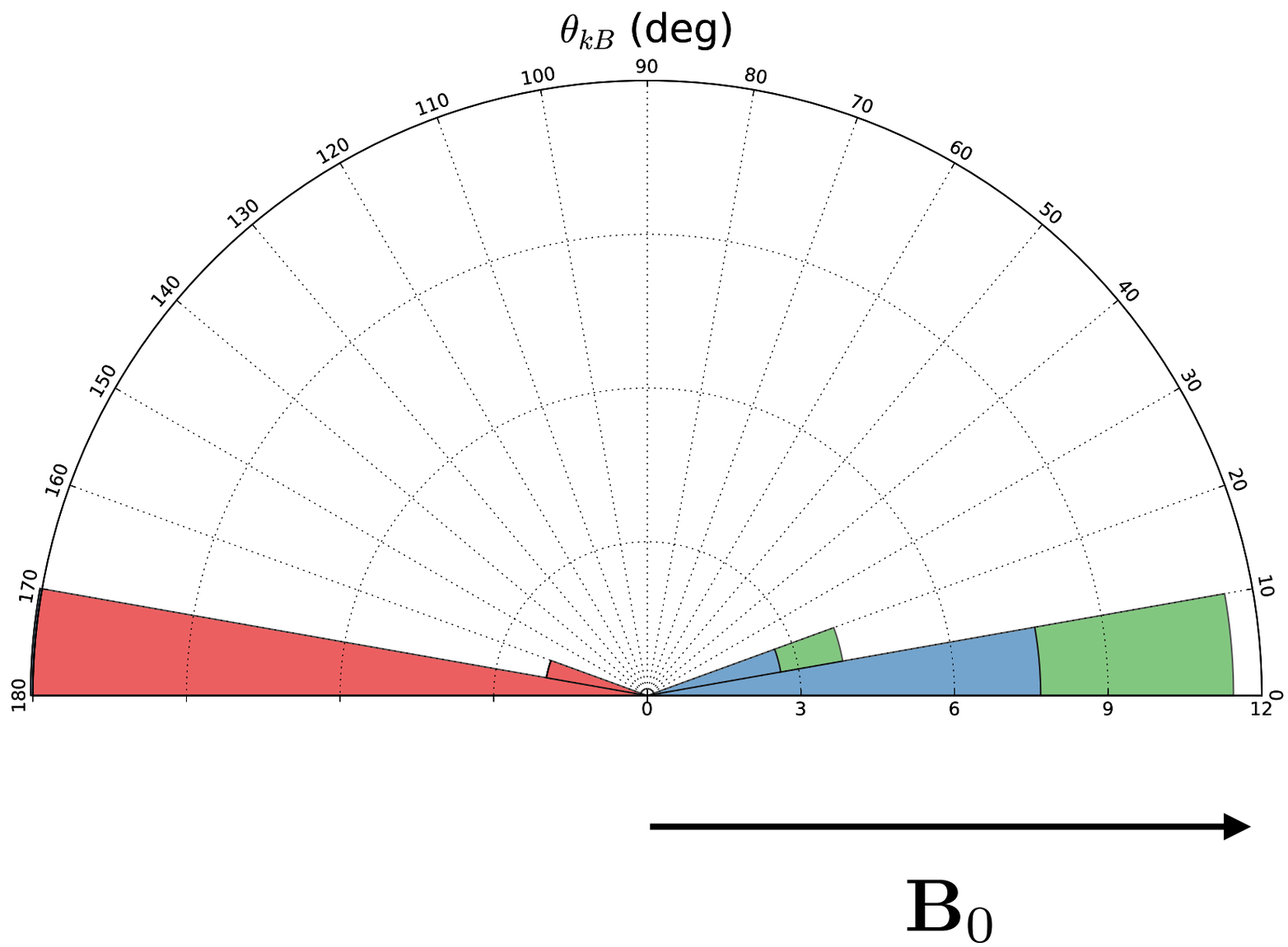
➡ Measure frequency and wavevector, compare to theoretical predictions

Aside - dispersion relations

$$\omega = f\left(\mathbf{k}; T_e, n_e ....\right)$$

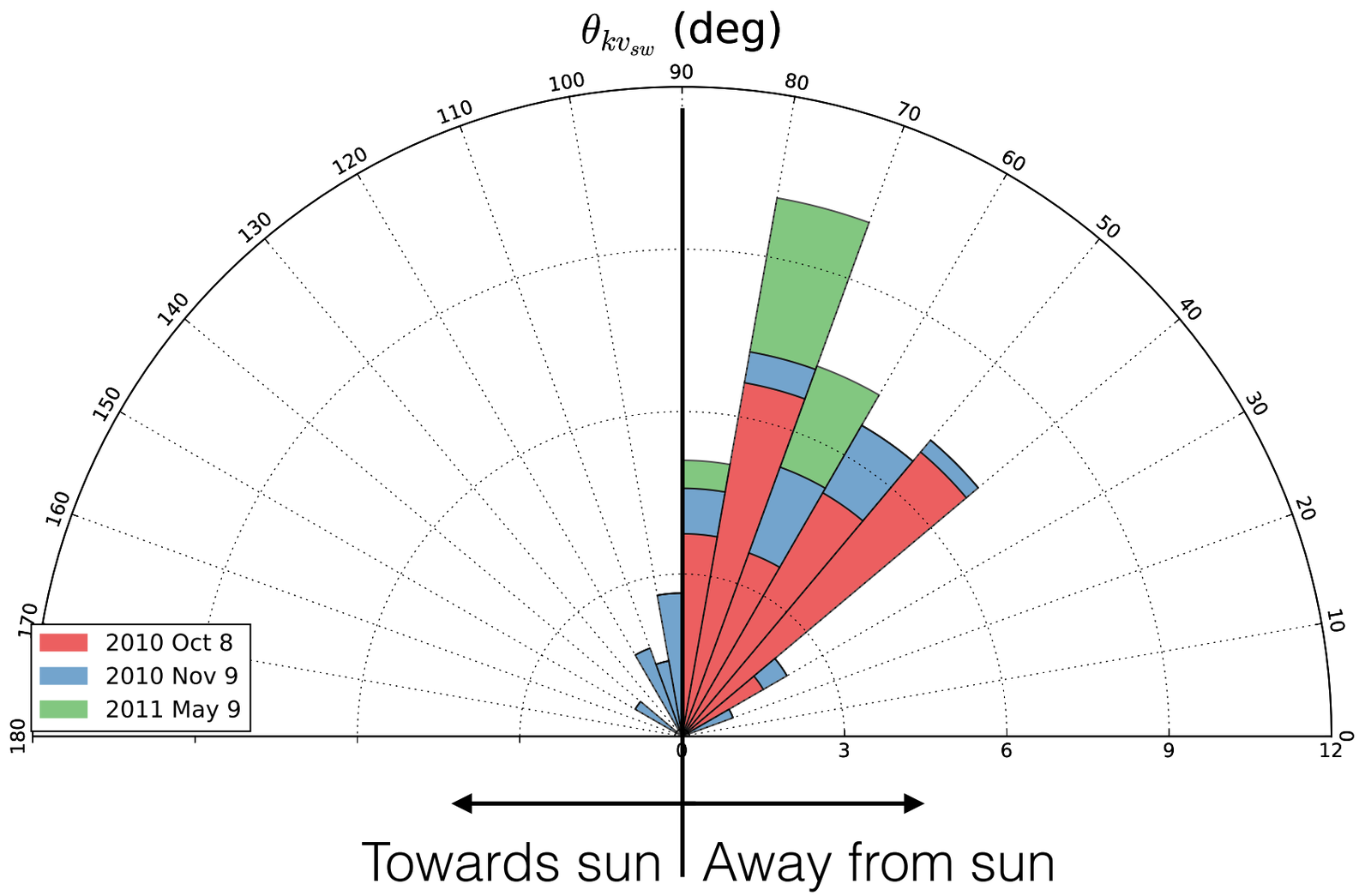


Direction results 1



Whistler waves travel along background magnetic field

Direction results 2



Whistler waves **travel anti-sunward**

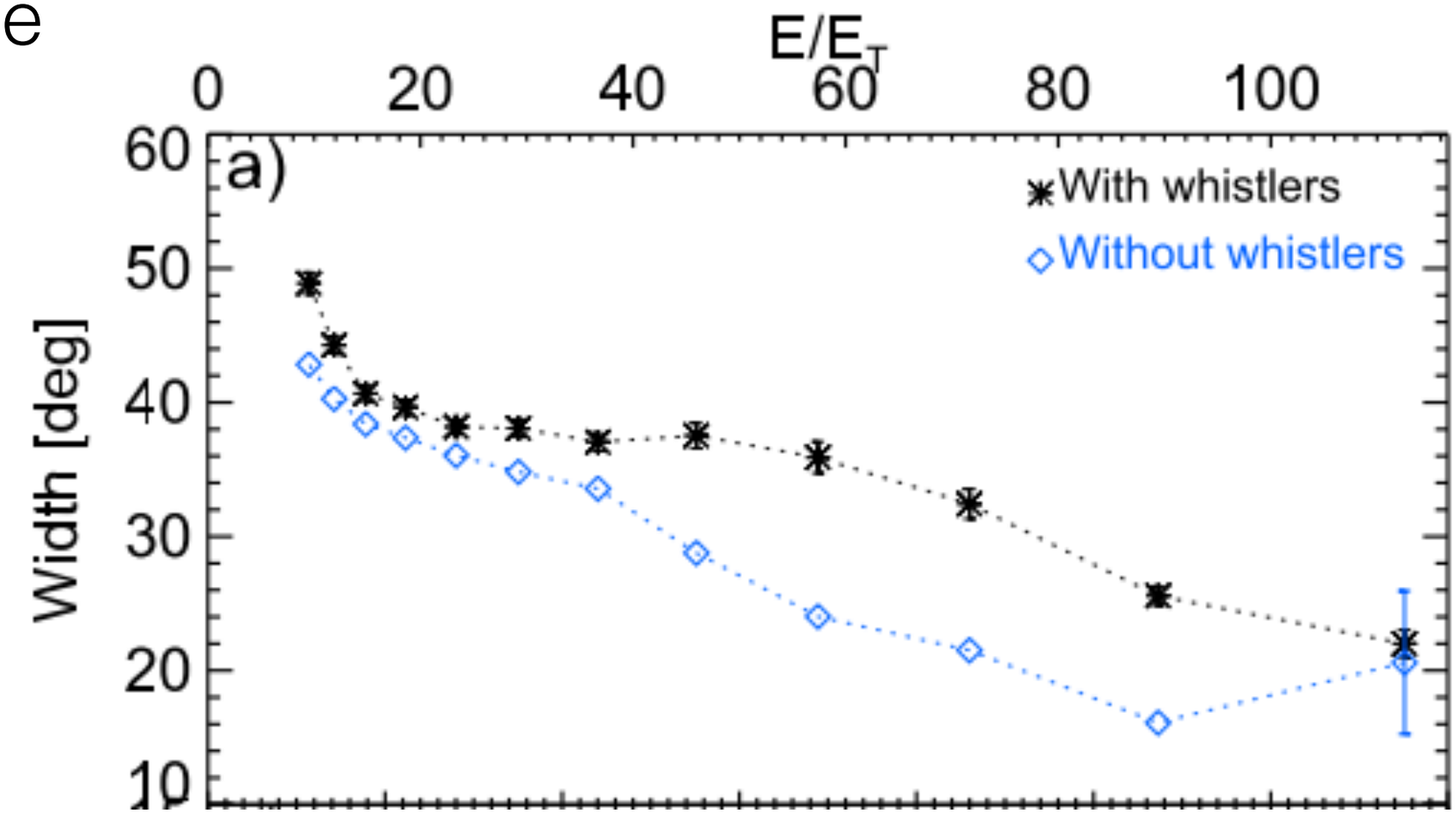
Part II conclusions

Observed whistler waves cannot scatter the strahl

- Caveats:
  - Only looked at waves visible above turbulence
  - Only looked at 1AU
  - Only considered linear interaction
- But what about observations claiming to directly observe scattering?

‘Direct scattering’ observations

- One way to approach problem is to look at particle distributions and wave measurements at the same time

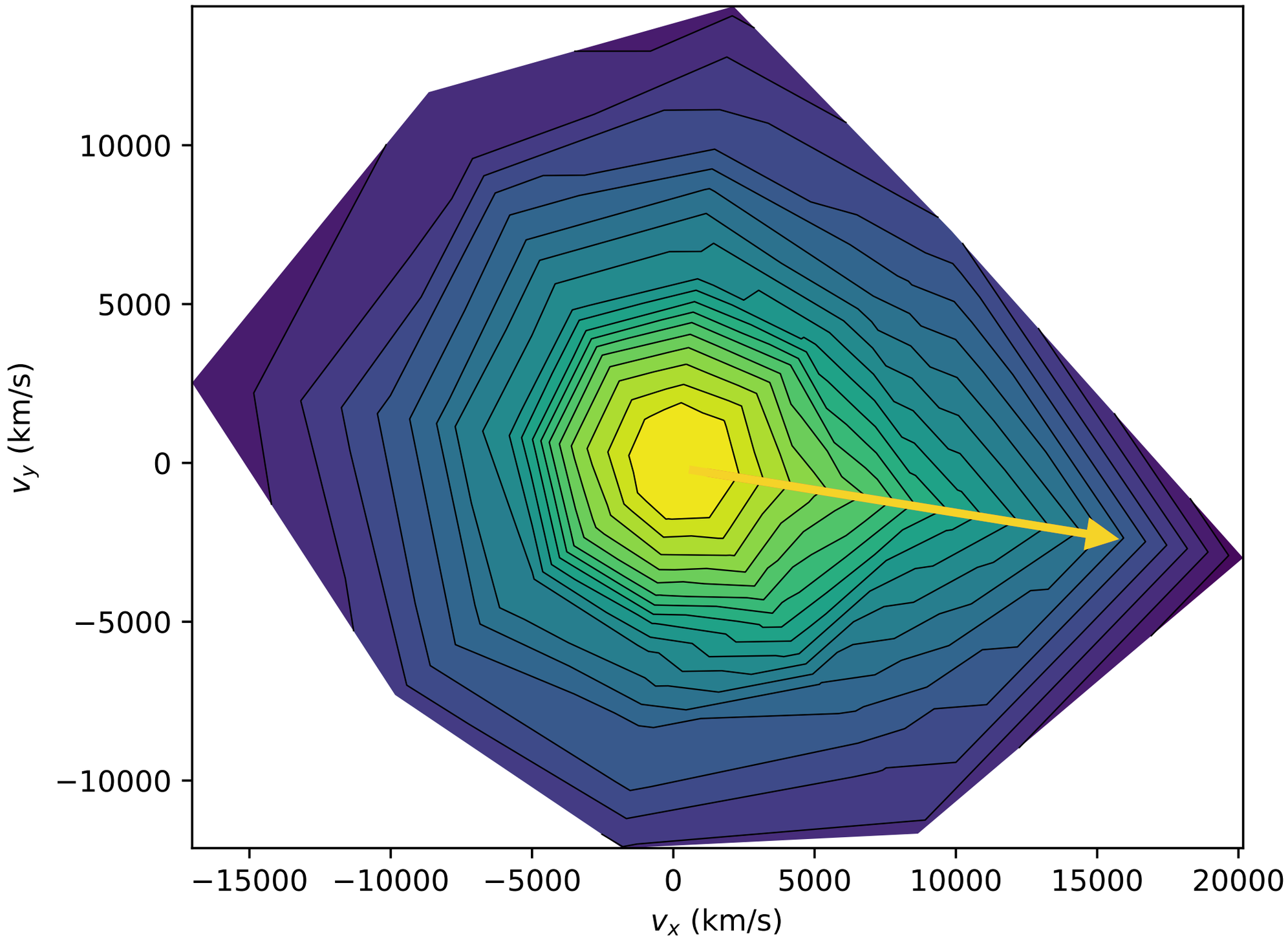


Kajdič et. al. 2017 [see also Pagel et. al. 2007]

‘Direct scattering’ observations

- One way to approach problem is to look at particle distributions and wave measurements at the same time
- Have to be very careful however, as magnetic field variations can affect particle distributions

‘Direct scattering’ observations



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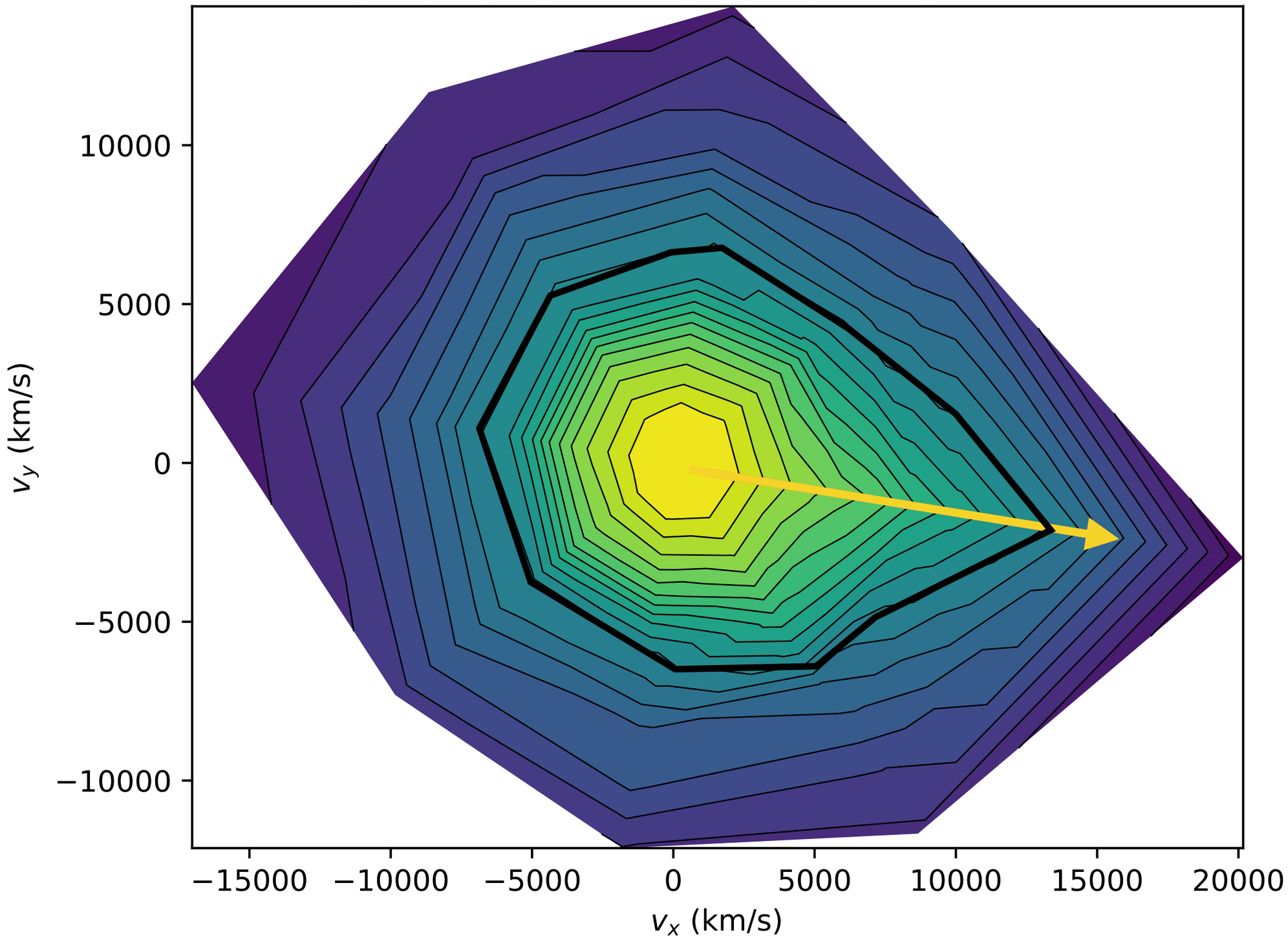
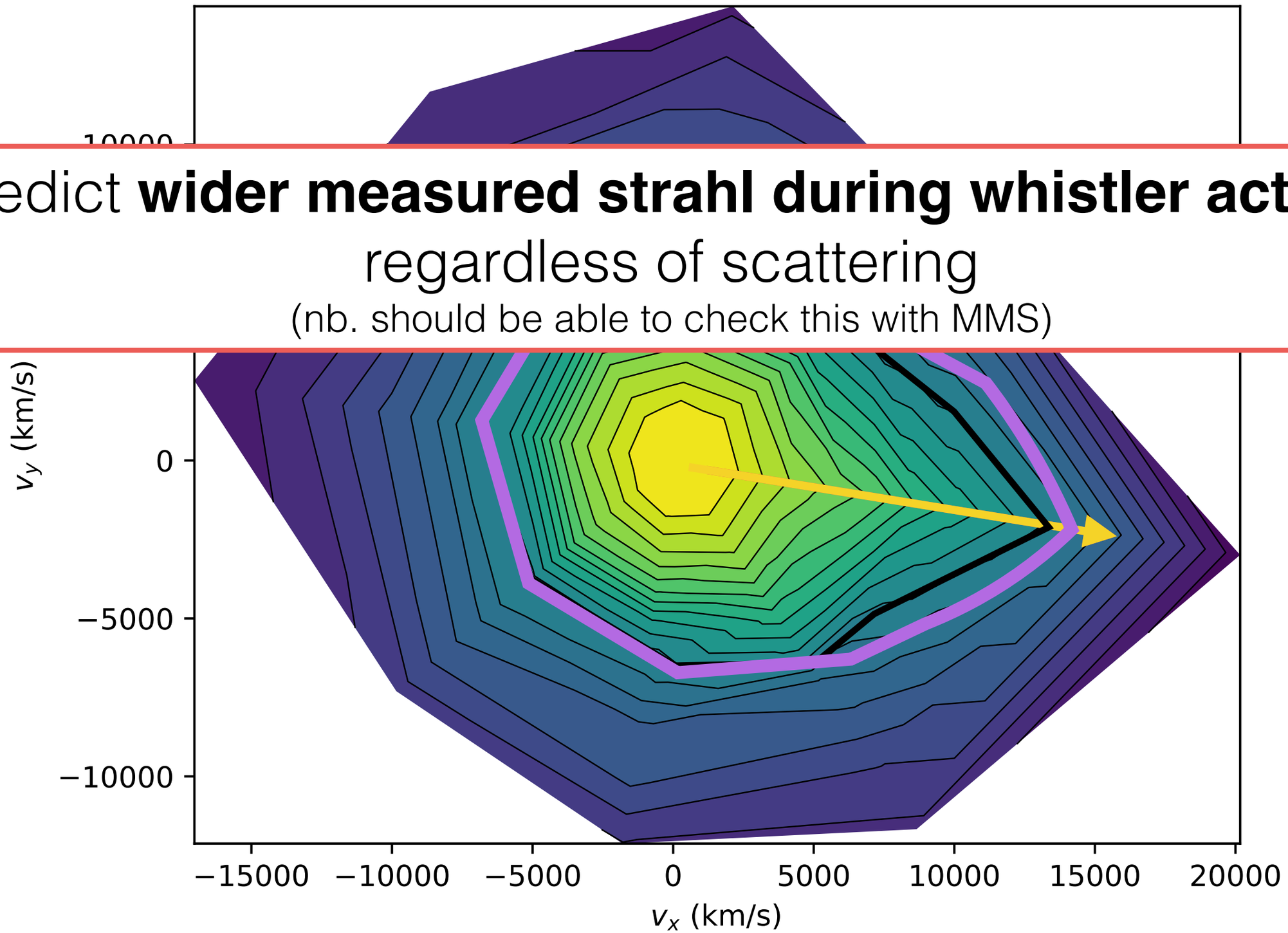


‘Direct scattering’ observations



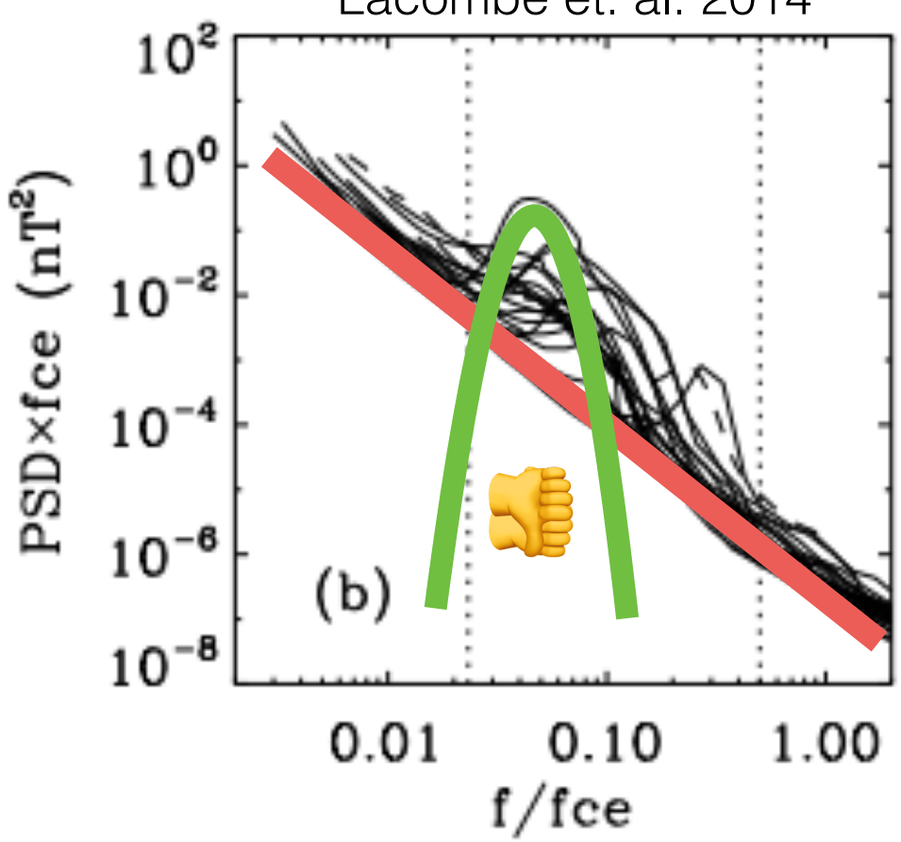
Predict **wider measured strahl during whistler activity** regardless of scattering

(nb. should be able to check this with MMS)

Caveats I

- **Only looked at waves visible above turbulence**
- Only looked at 1AU
- Only considered linear interaction

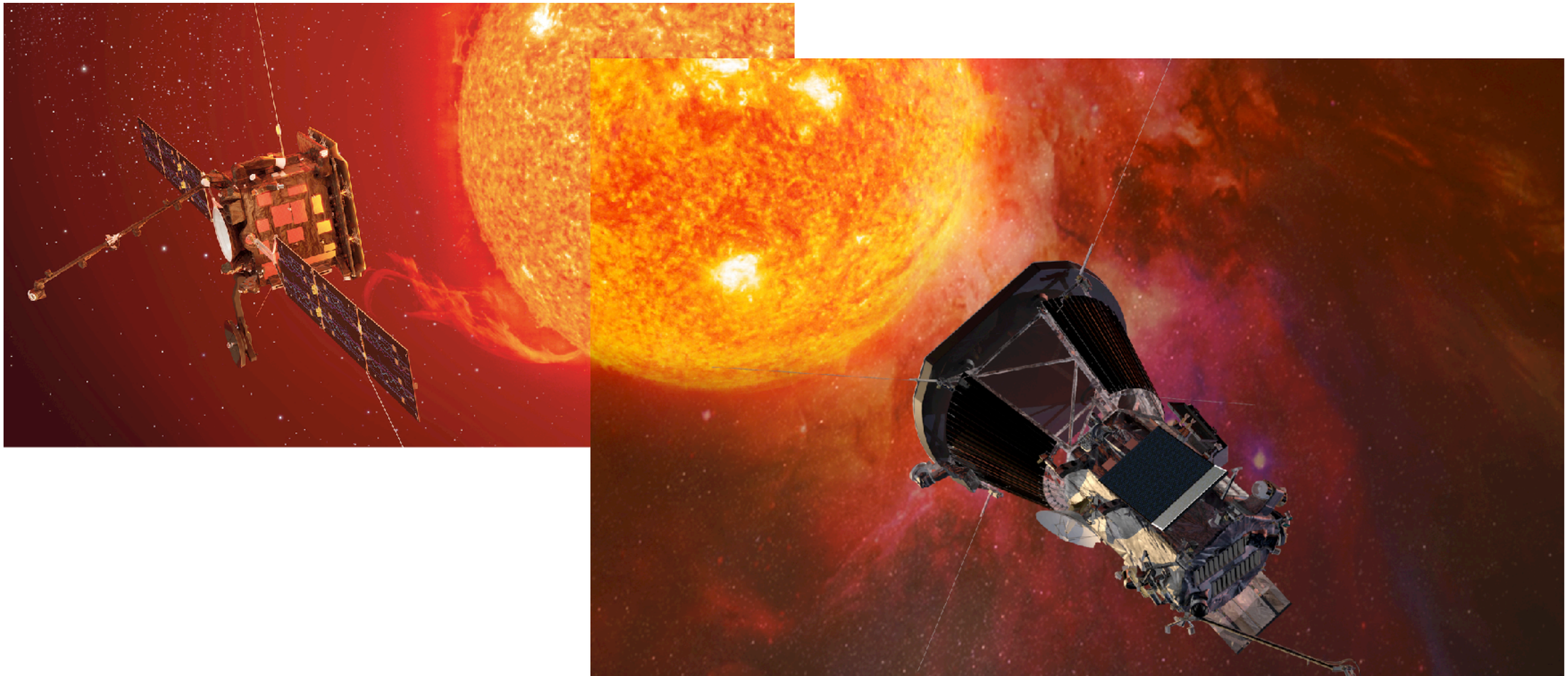
Lacombe et. al. 2014



- Arguably any wave power below turbulent background *is* the turbulence
- Opinion still divided as to whether electron scale turbulence is whistlers or kinetic Alfvén waves

Caveats II

- Only looked at waves visible above turbulence
- **Only looked at 1AU**
- Only considered linear interaction



Caveats III

- Only looked at waves visible above turbulence
- Only looked at 1AU
- **Only considered linear interaction**

- "Particle scattering off of right-handed dispersive waves" *[Schreiner et. al. 2017]*
- (non-linear scattering of electrons by whistler waves)

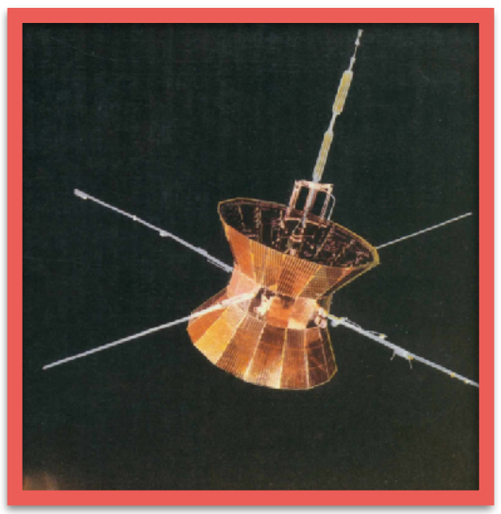
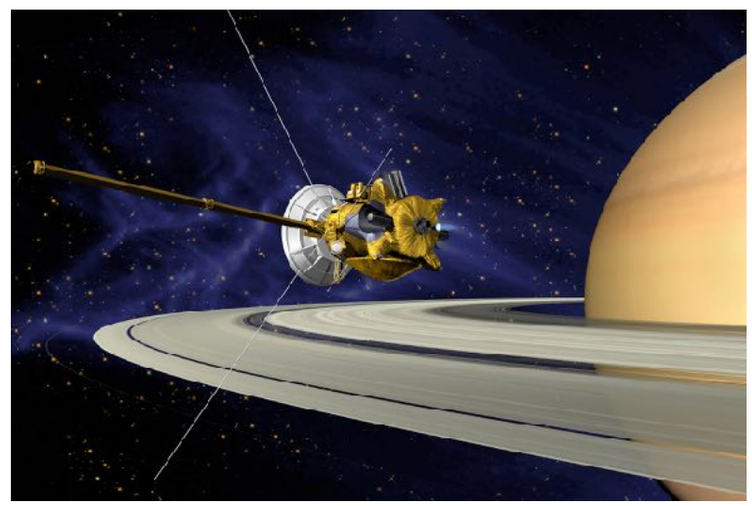
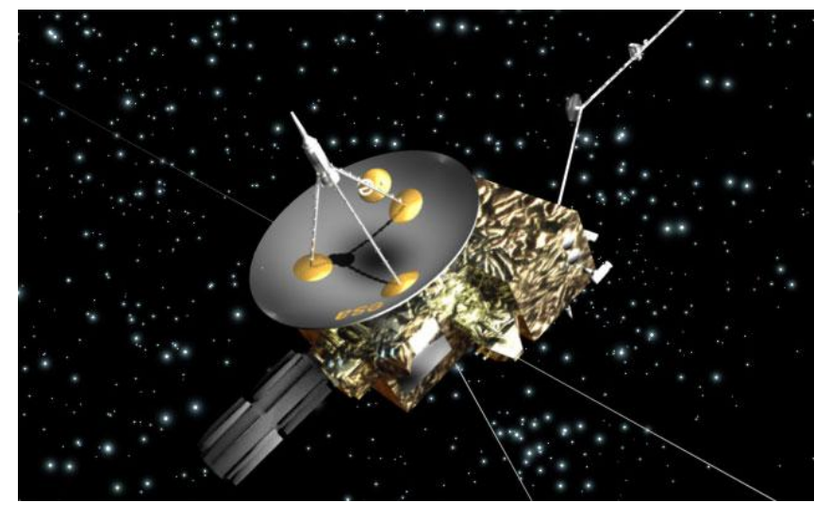
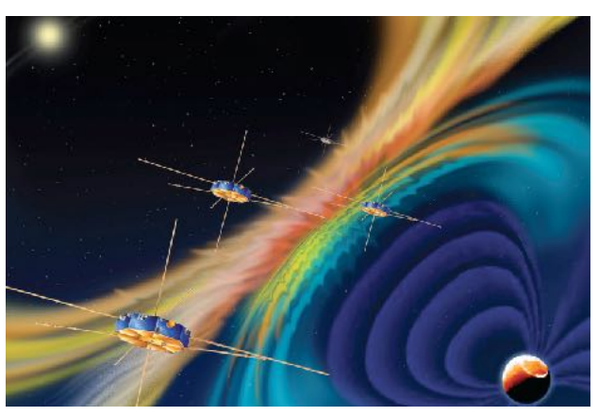
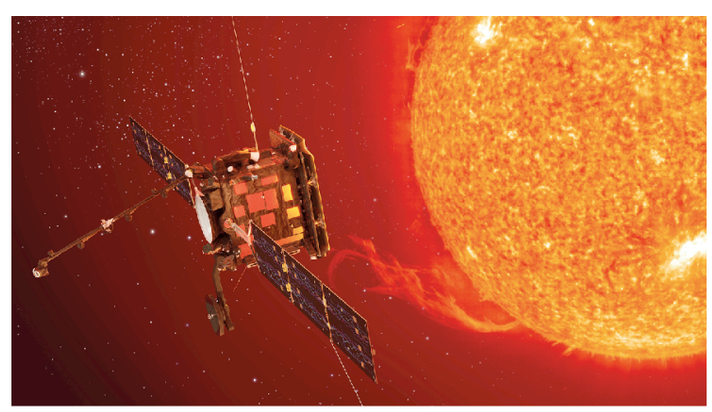
➡ Could observed whistlers non-linearly scatter strahl?

Conclusions

- Observed whistlers cannot linearly scatter the strahl
- What does scatter the strahl?
  - ➡ Non-linear whistler wave interactions?
  - ➡ Another wave mode?
  - ➡ Interaction with magnetic/electric field turbulence?
- What observations can we make to answer this question?
- What simulations and theory work can we do to answer this question?

What scatters the electron strahl in the solar wind?

- Lots of work still to be done on legacy data sets (**Helios**, Cassini, Ulysses)…





- …and exciting times ahead with MMS (in solar wind), Solar Orbiter, and Solar Probe Plus!