Imperial College London

What scatters the electron strahl in the solar wind?

David Stansby
david.stansby14@imperial.ac.uk

- PhD student at Imperial College London

- Here for 2 weeks, working on Helios data
  (say Hi, and come ask me questions if interested!)

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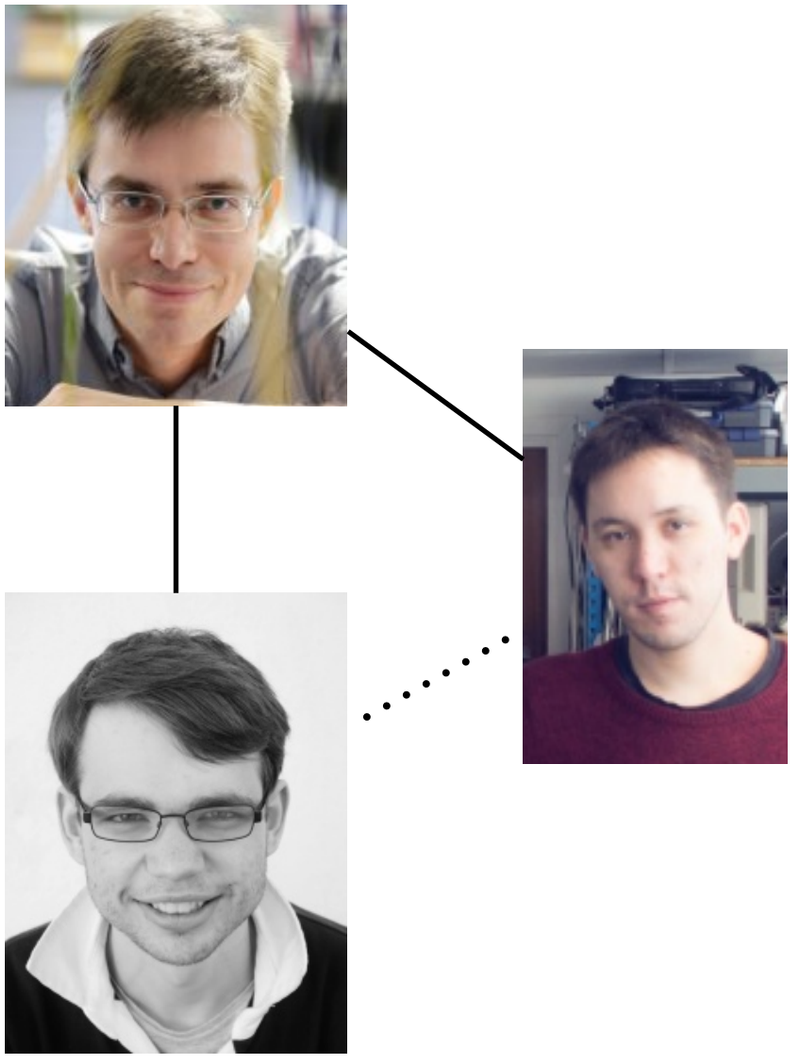
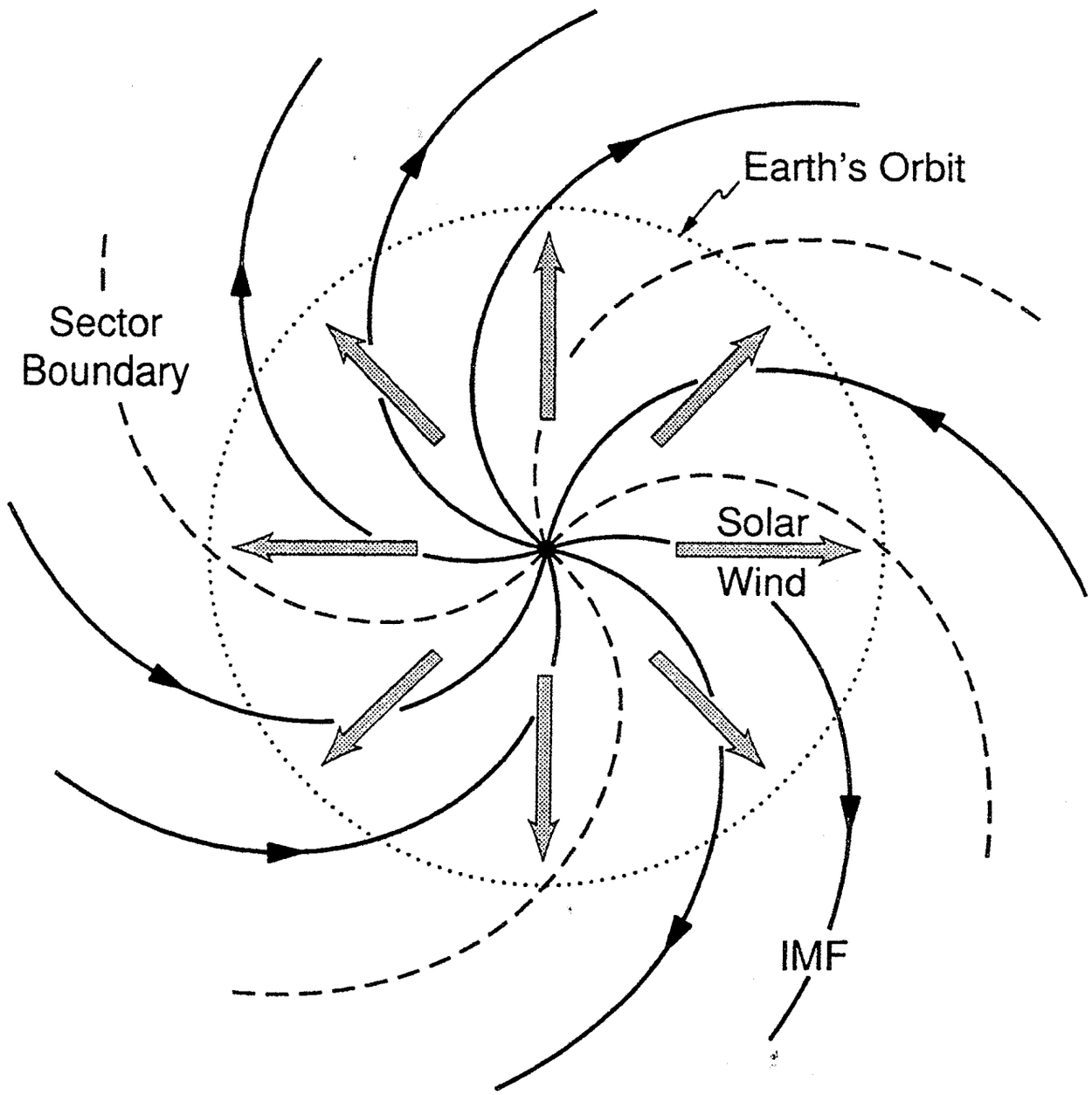
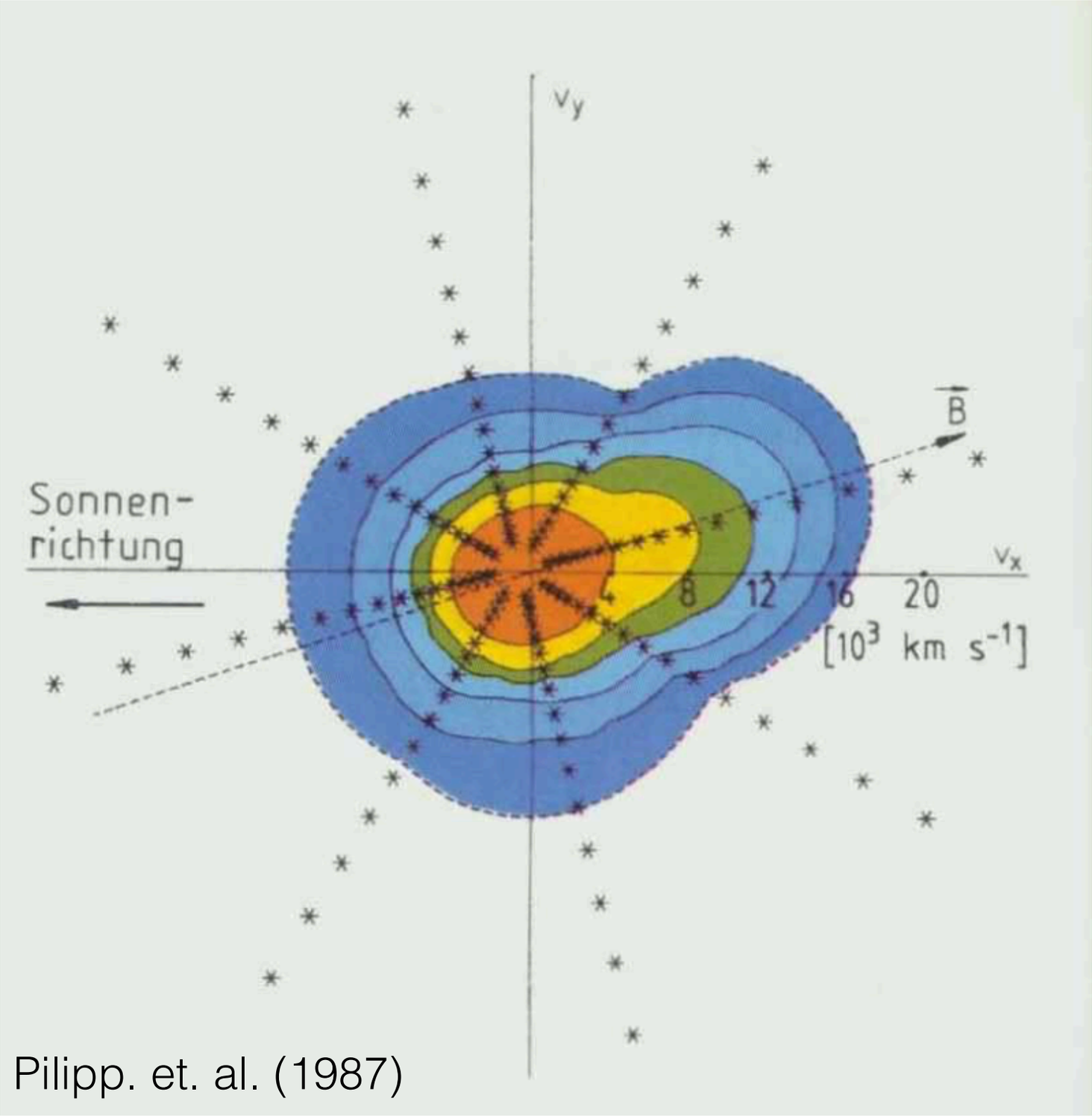


The Solar Wind



Electrons in the solar wind



Pilipp. et. al. (1987)

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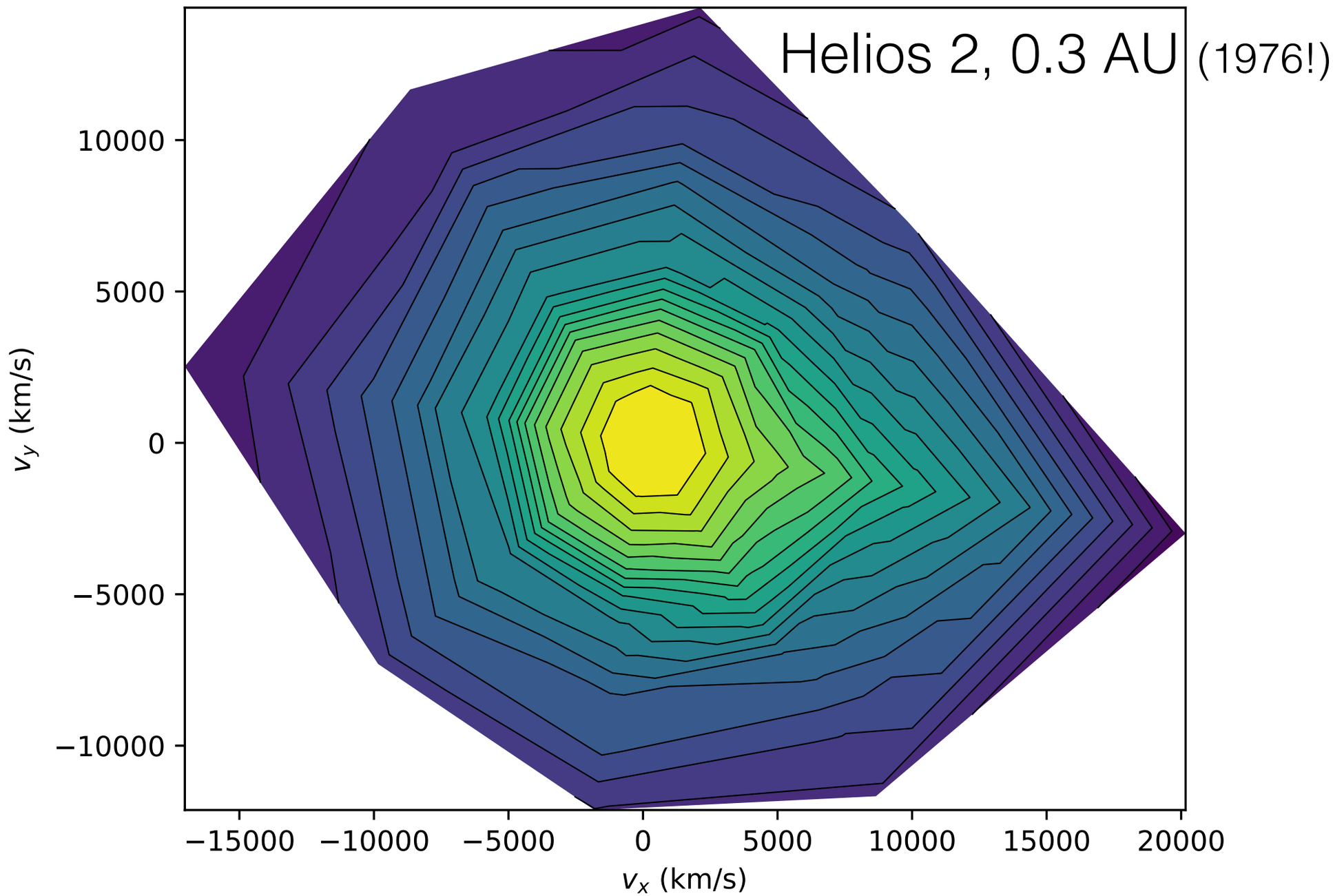

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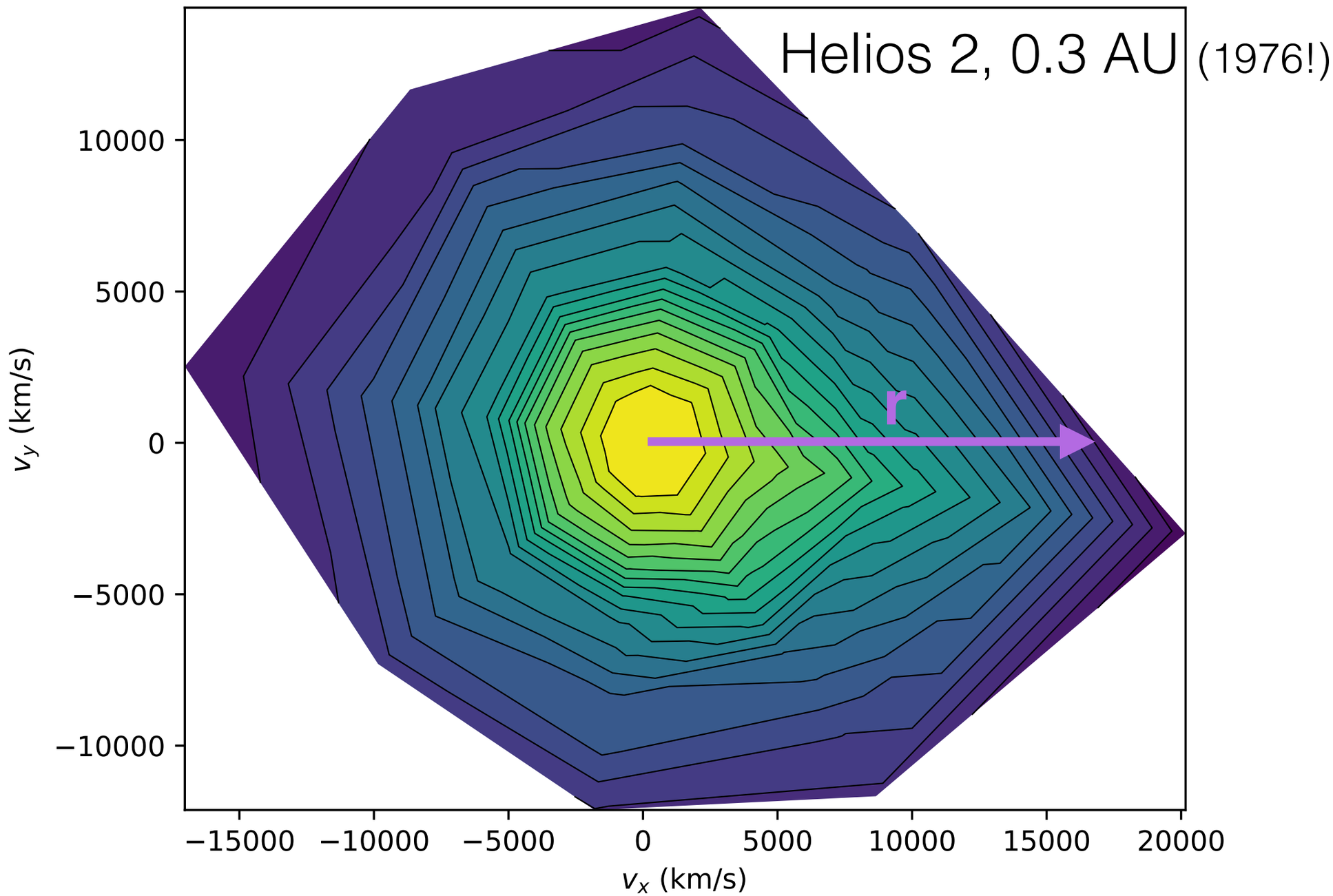

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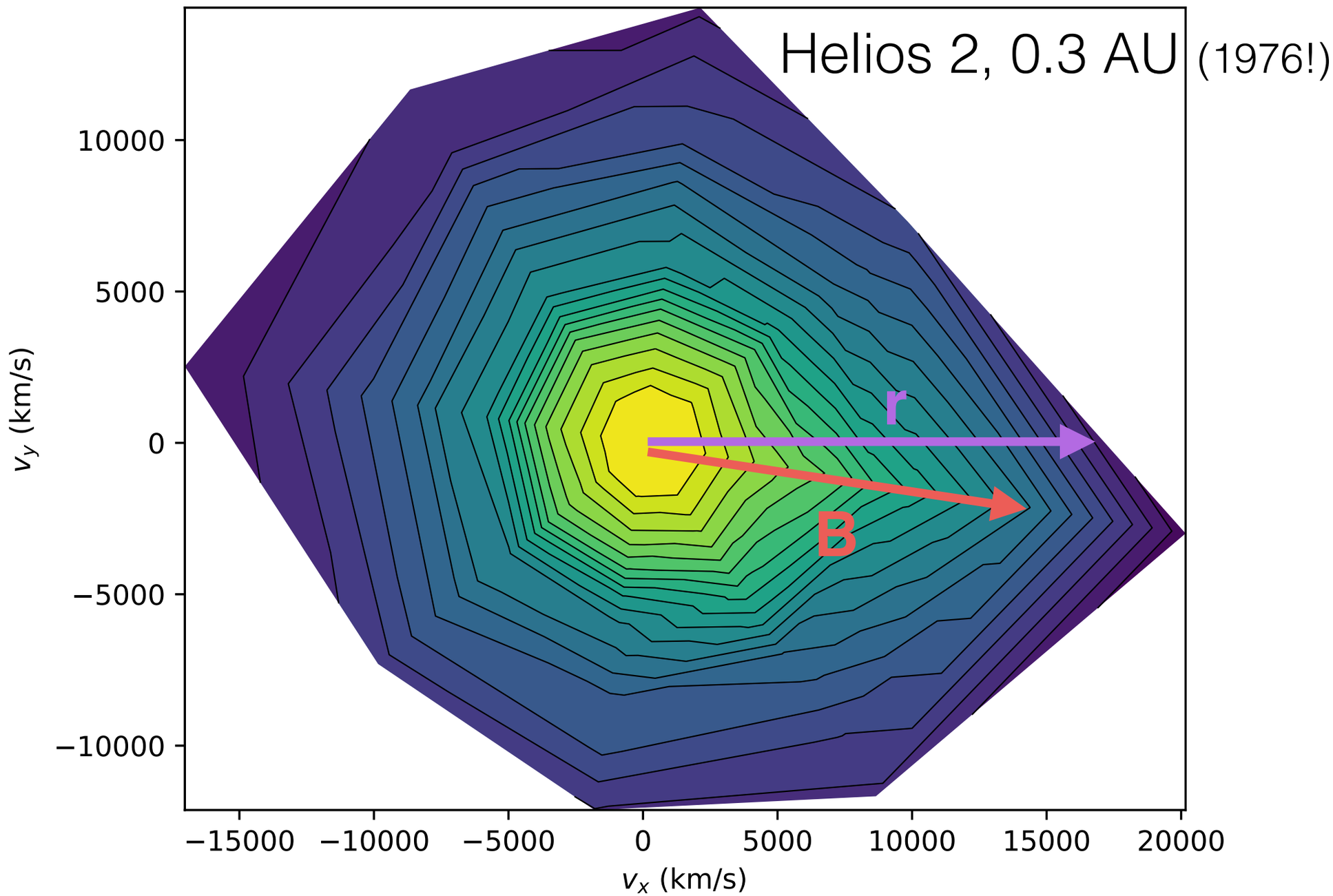
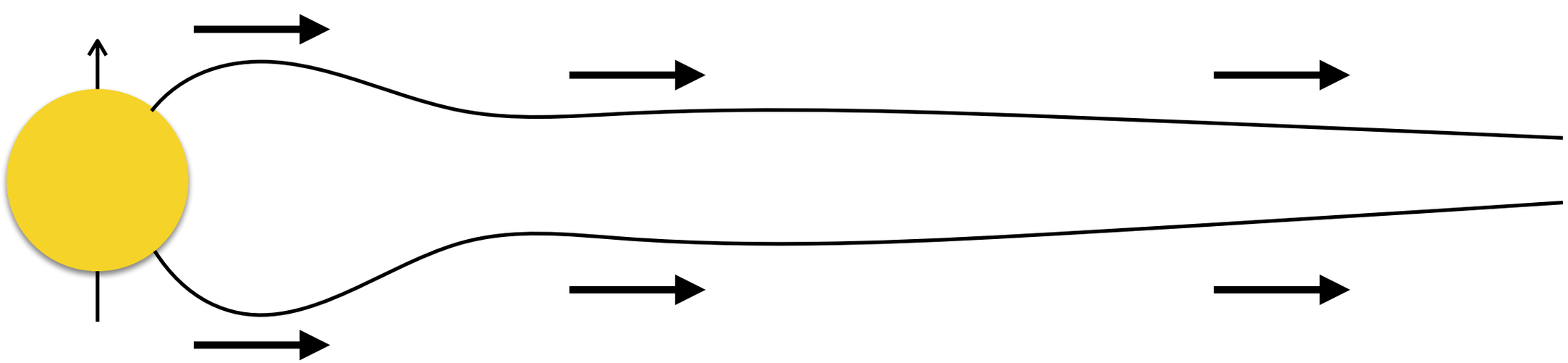


Electron strahl

- Travels anti-sunward, along magnetic field
- Typical speed ~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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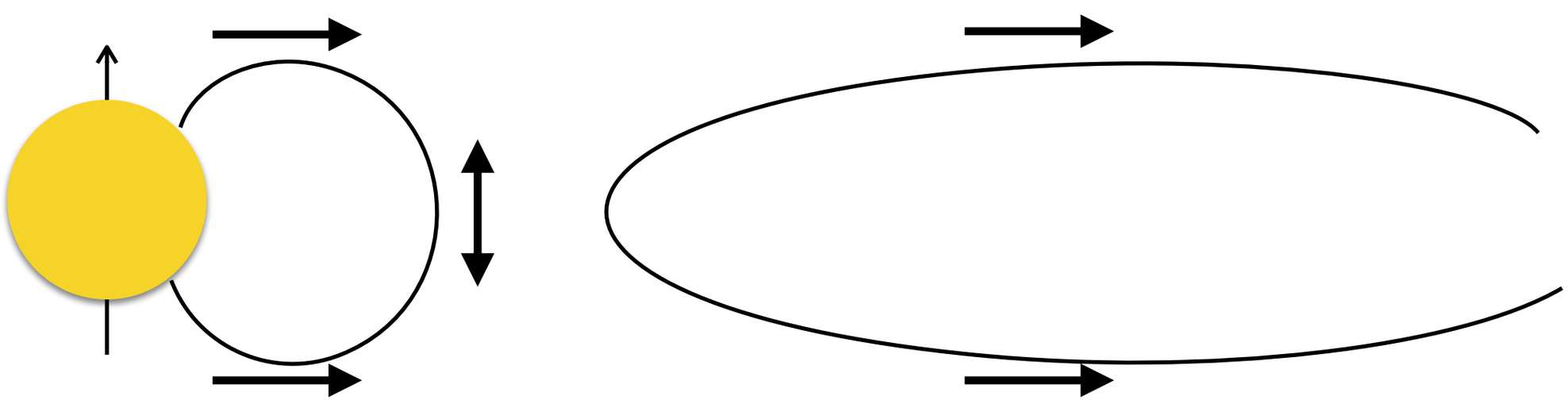

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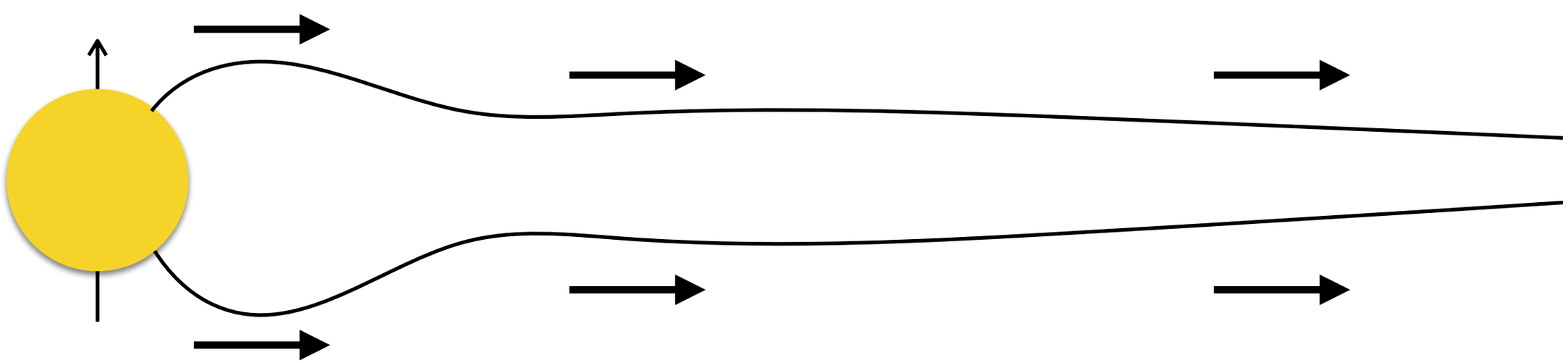
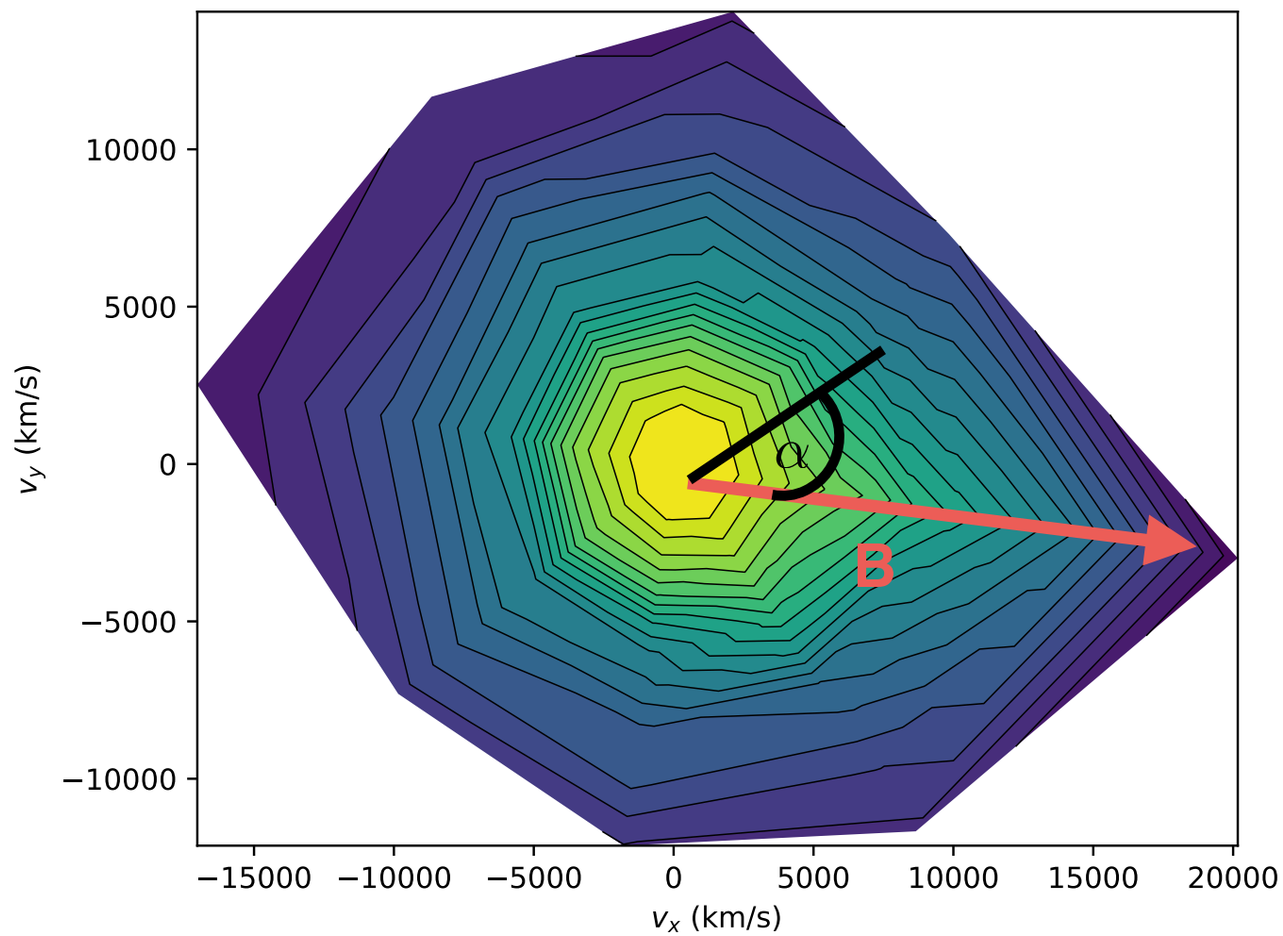


How should the strahl evolve?

- In a collisionless plasma, particles should conserve magnetic moment

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



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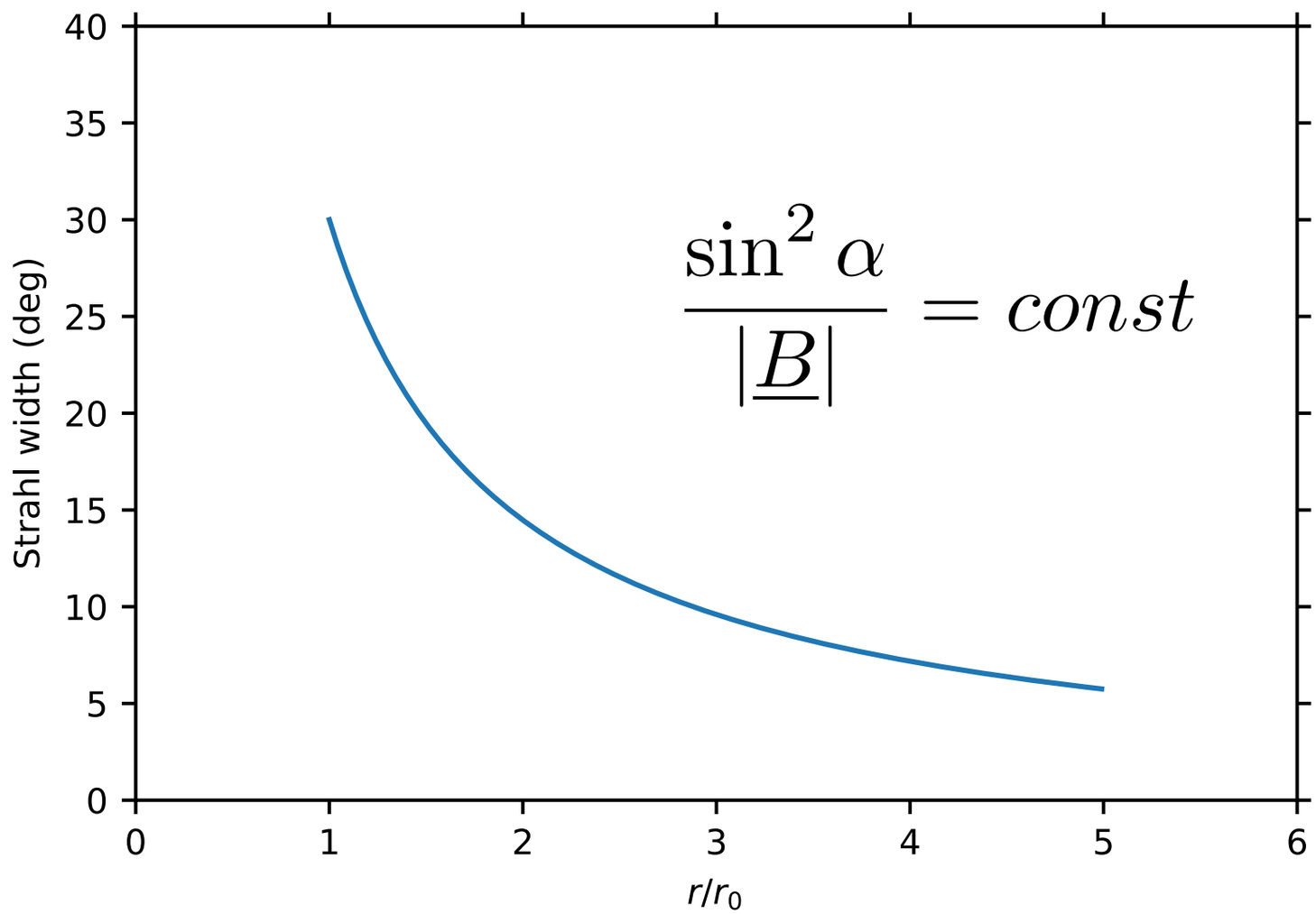
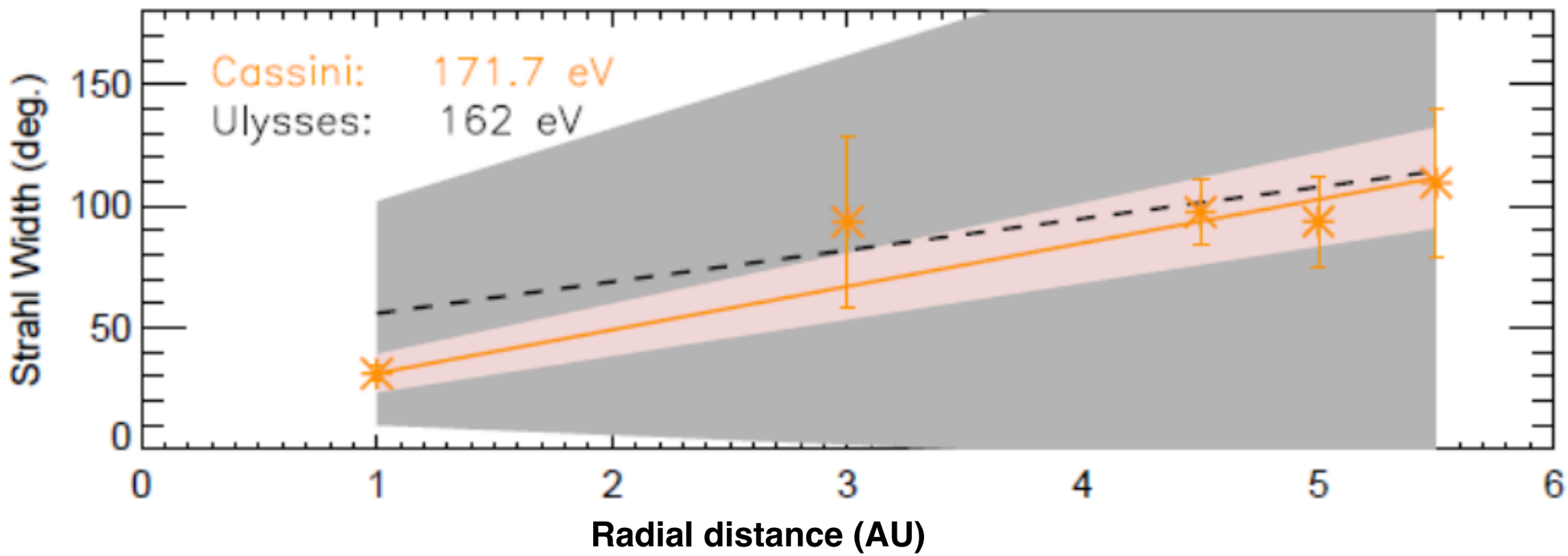


- Theoretically, expect strahl to narrow with distance

How does the strahl evolve?

Graham et. al. 2017



- But observationally, strahl widens with distance!

There must be a mechanism to scatter the strahl

How does the strahl evolve?

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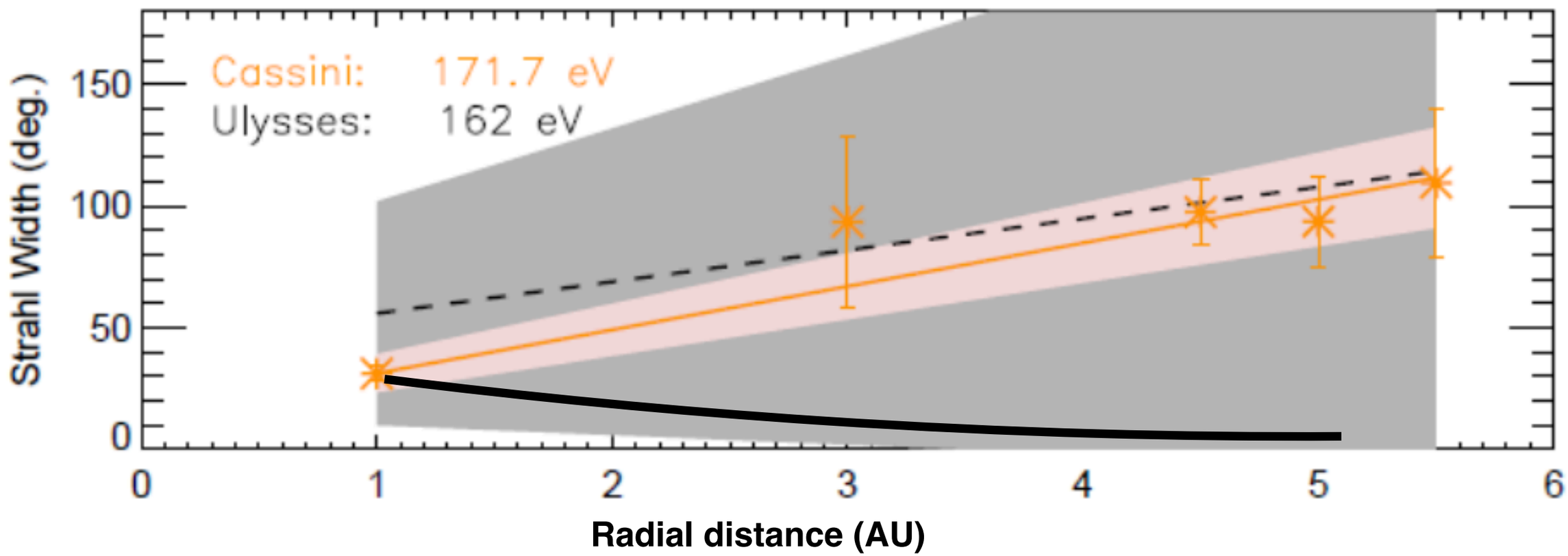

- But observationally, strahl widens with distance!

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]*

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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?

Imperial College London

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

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

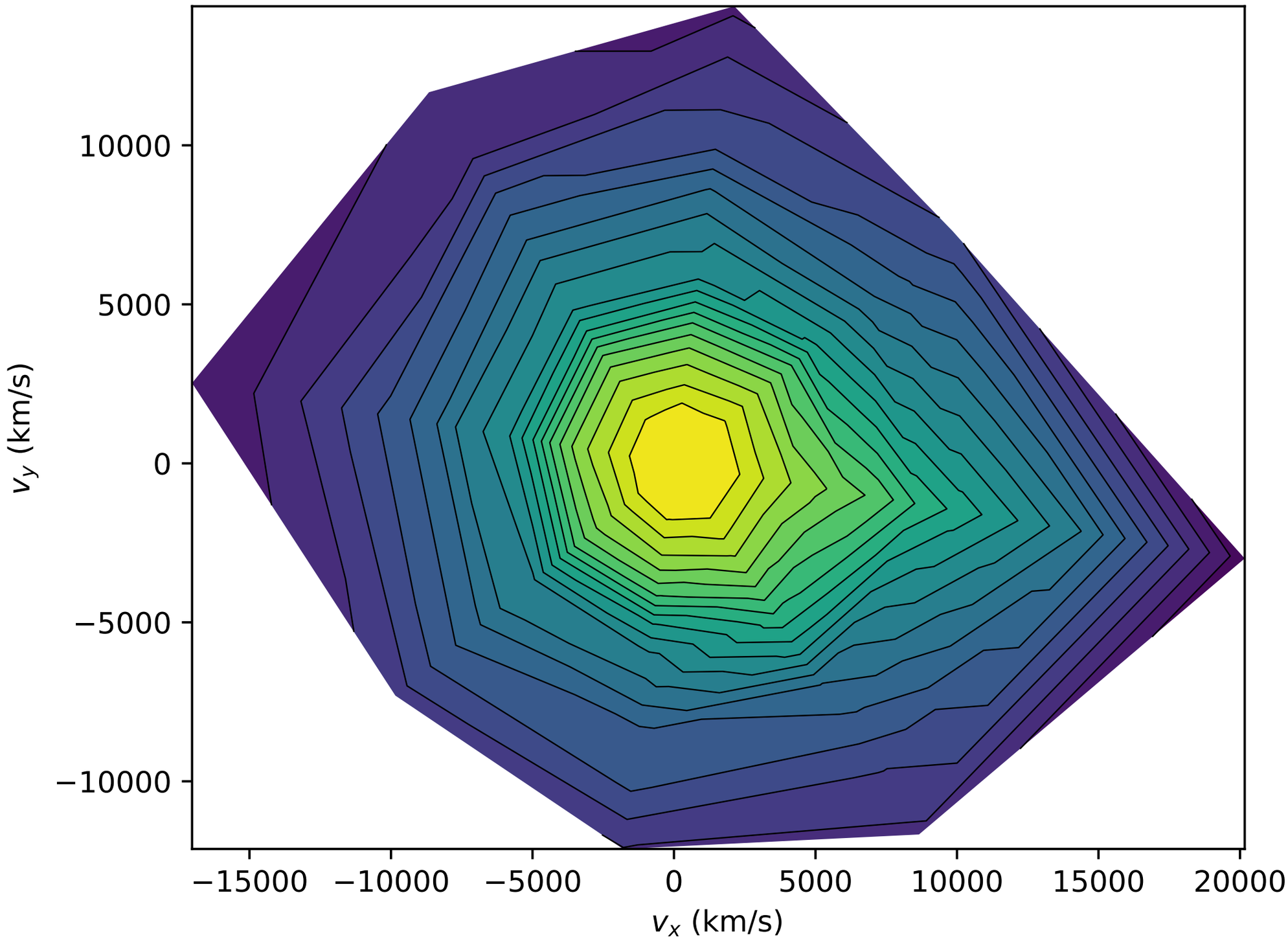
Parallel wave vector

Parallel electron velocity

Wave frequency

Electron gyro-frequency

Can whistler waves scatter the strahl?



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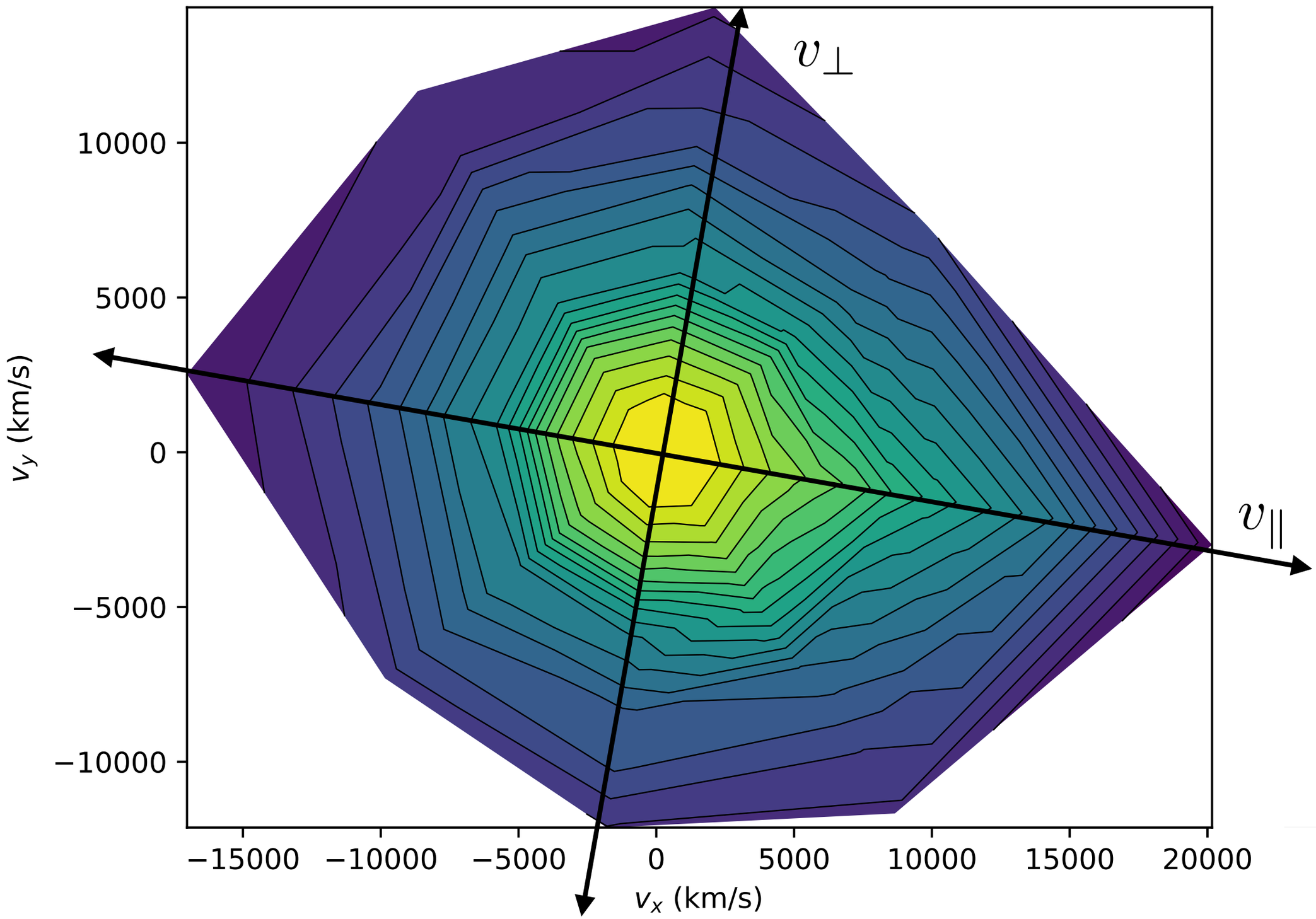

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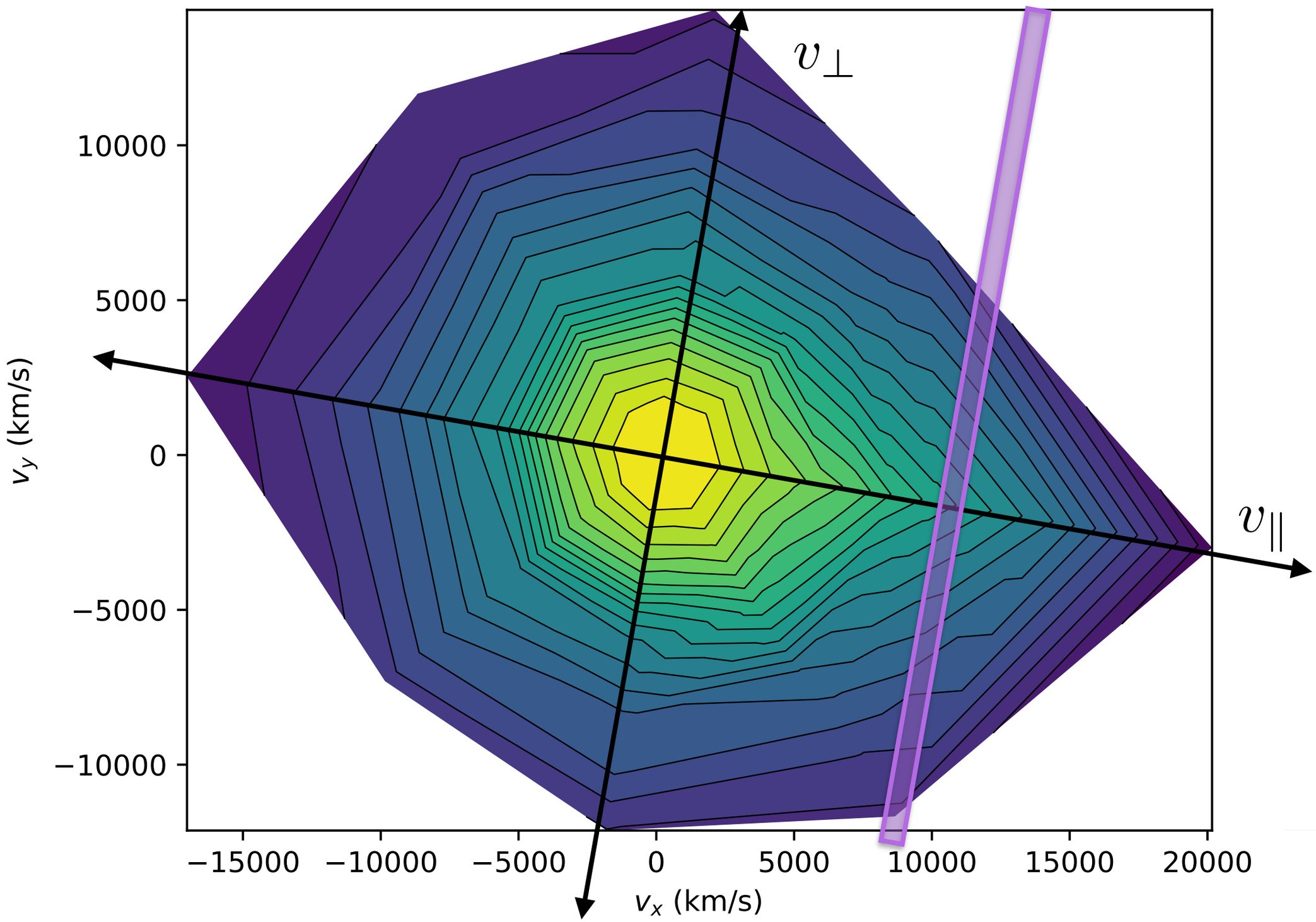

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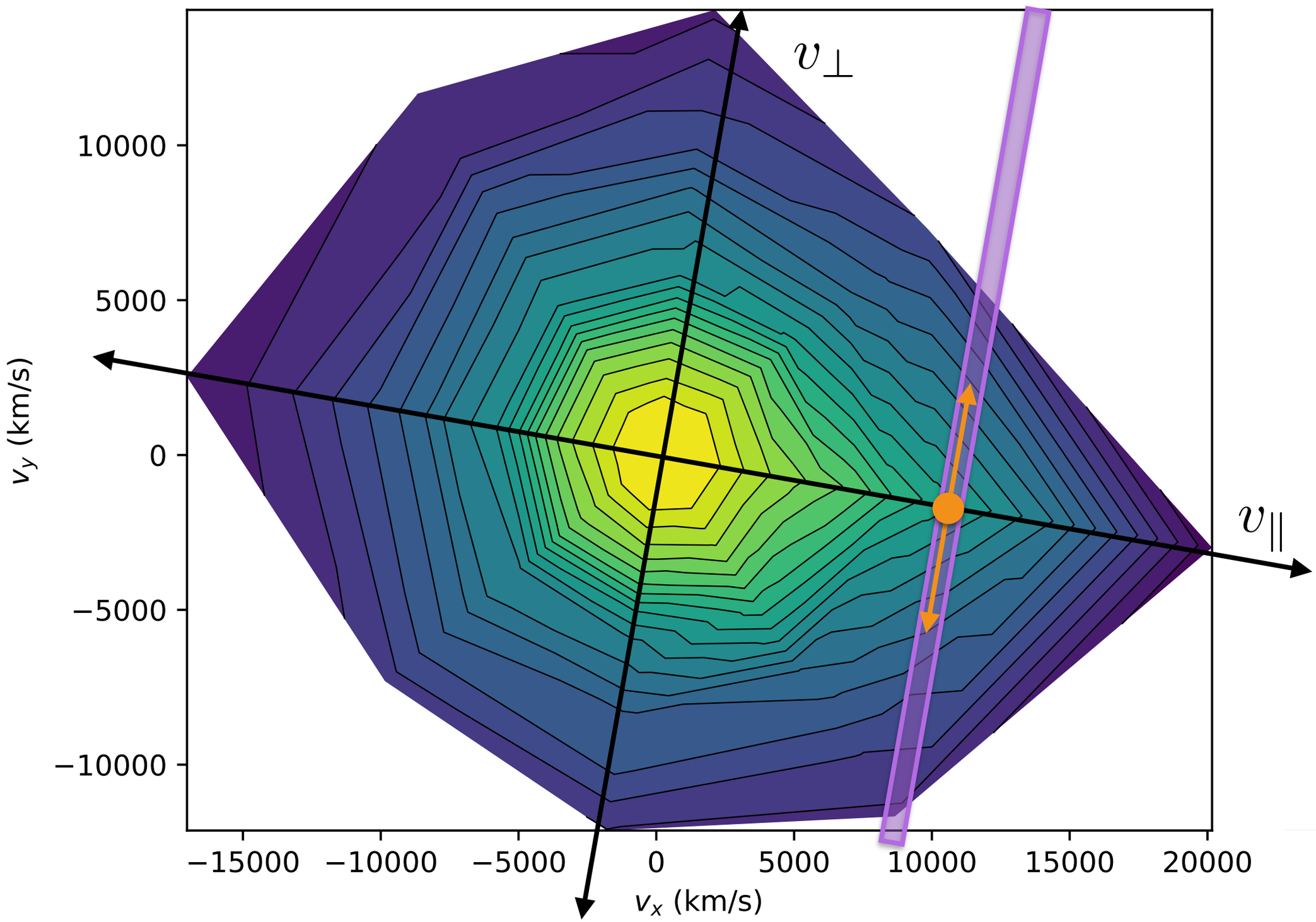


Can whistler waves scatter the strahl?

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

- 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

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

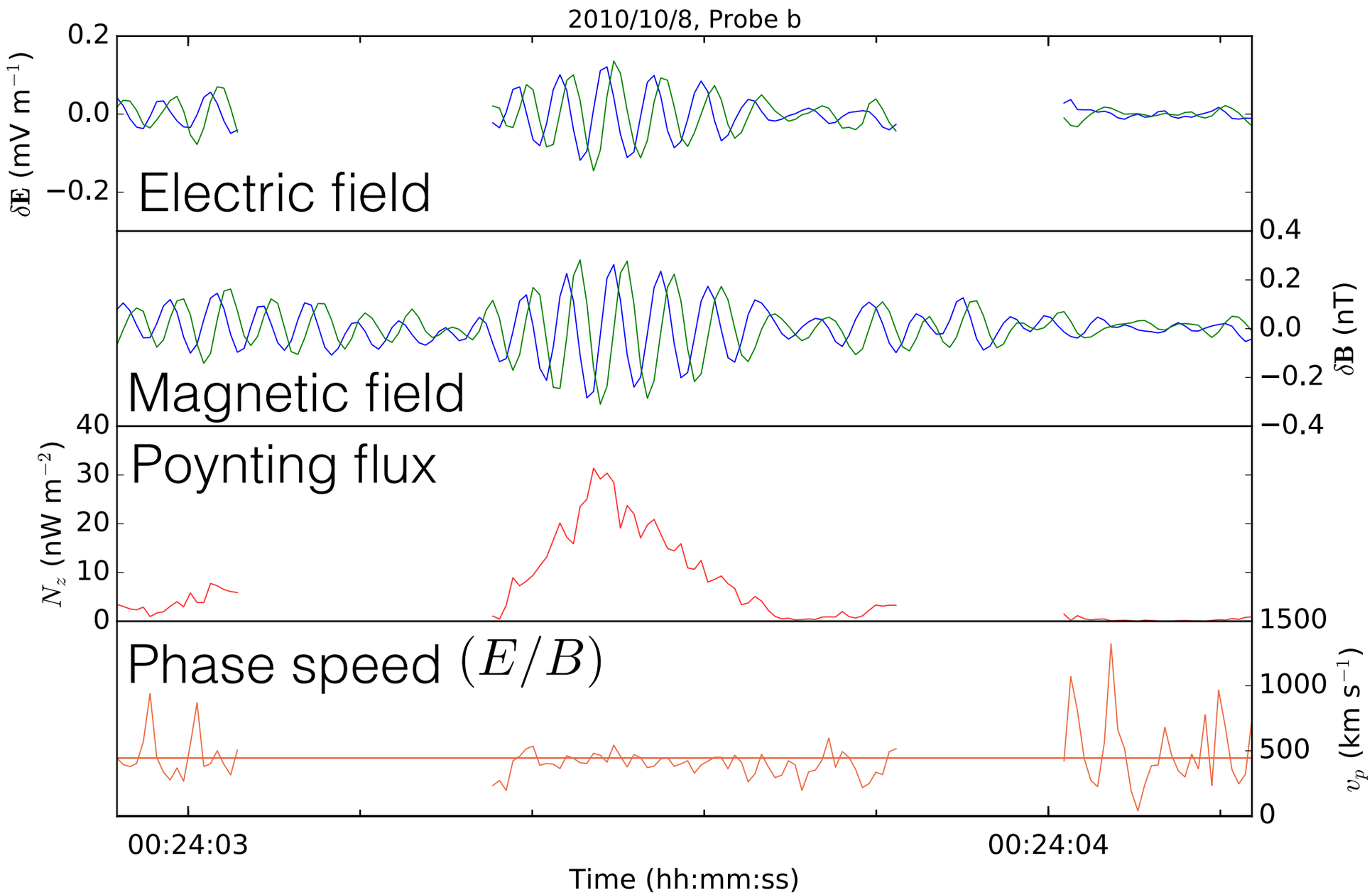
- **P** points in the direction of wave propagation

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, over 3 independent intervals



Aside - dispersion relations

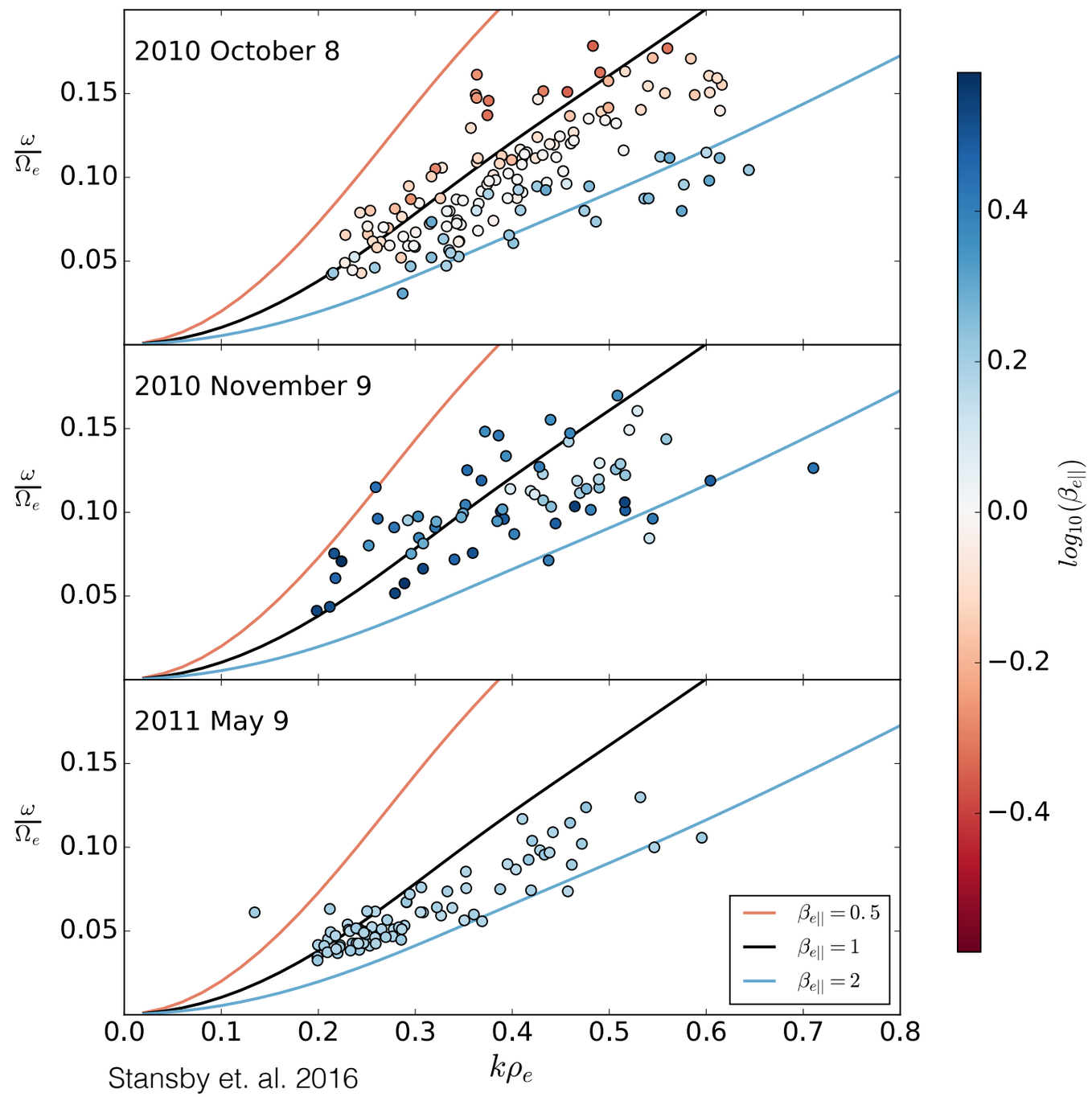
- How to identify a wave mode from observations?
- Wave mode defined by a dispersion relation

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

➡ Measure frequency and wavevector, compare to theoretical wave mode predictions

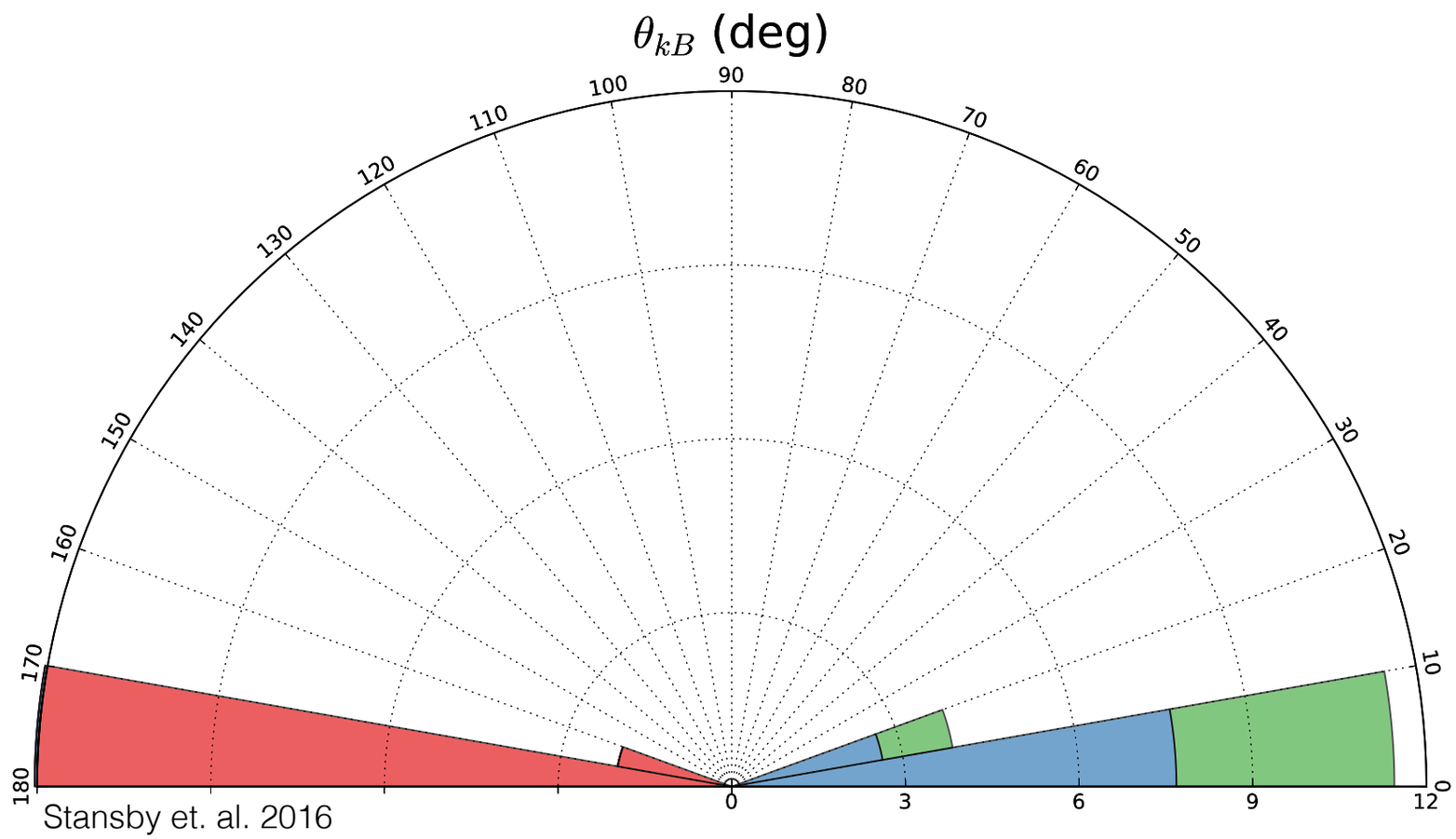
Aside - dispersion relations

$$\omega = f\left(\mathbf{k}; \beta_{e\parallel}, \ldots\right)$$



Stansby et. al. 2016

Direction results 1

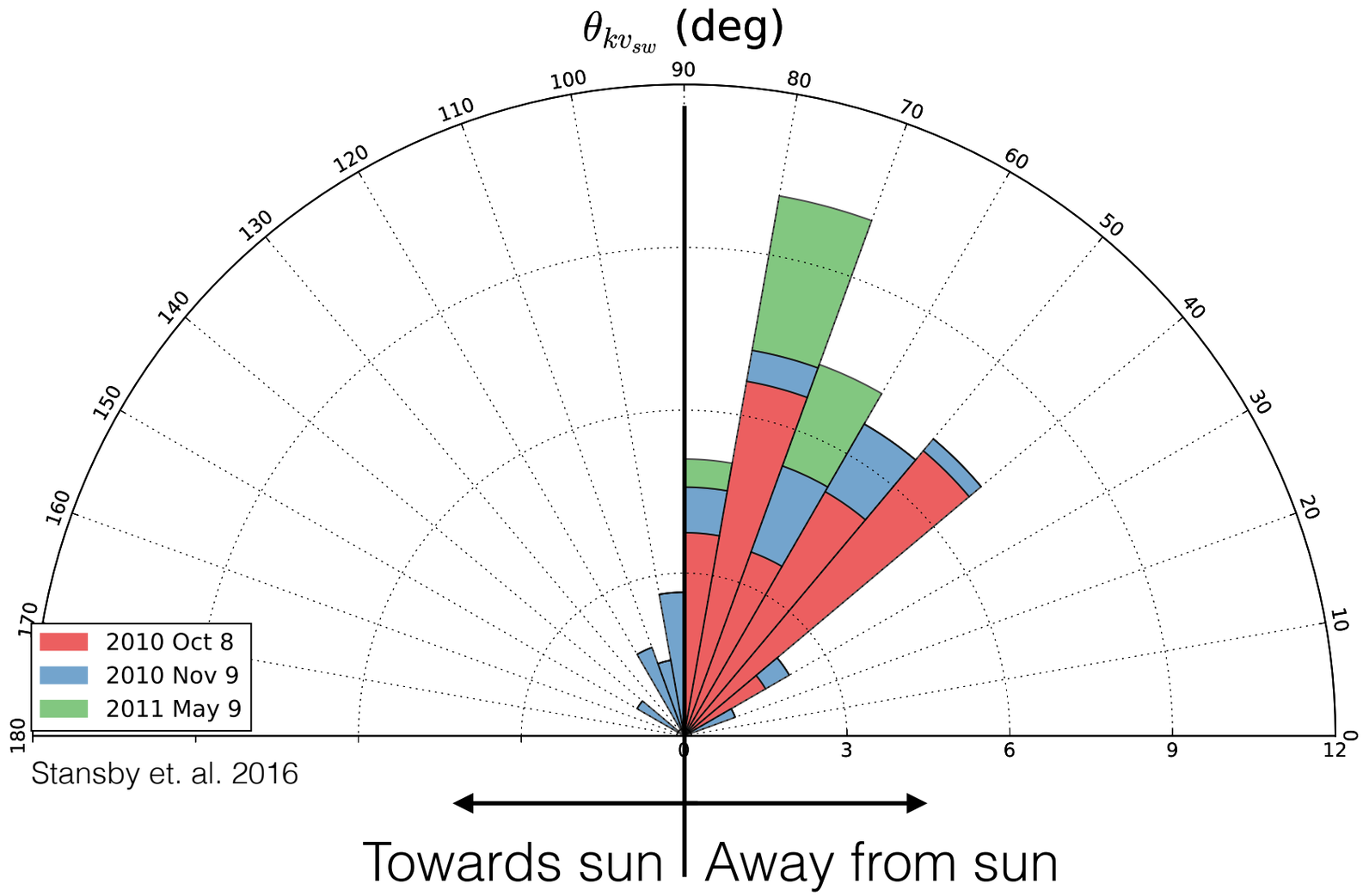


Stansby et. al. 2016

$\mathbf{B}_0$

Whistler waves travel along background magnetic field

Direction results 2



Whistler waves **travel anti-sunward**

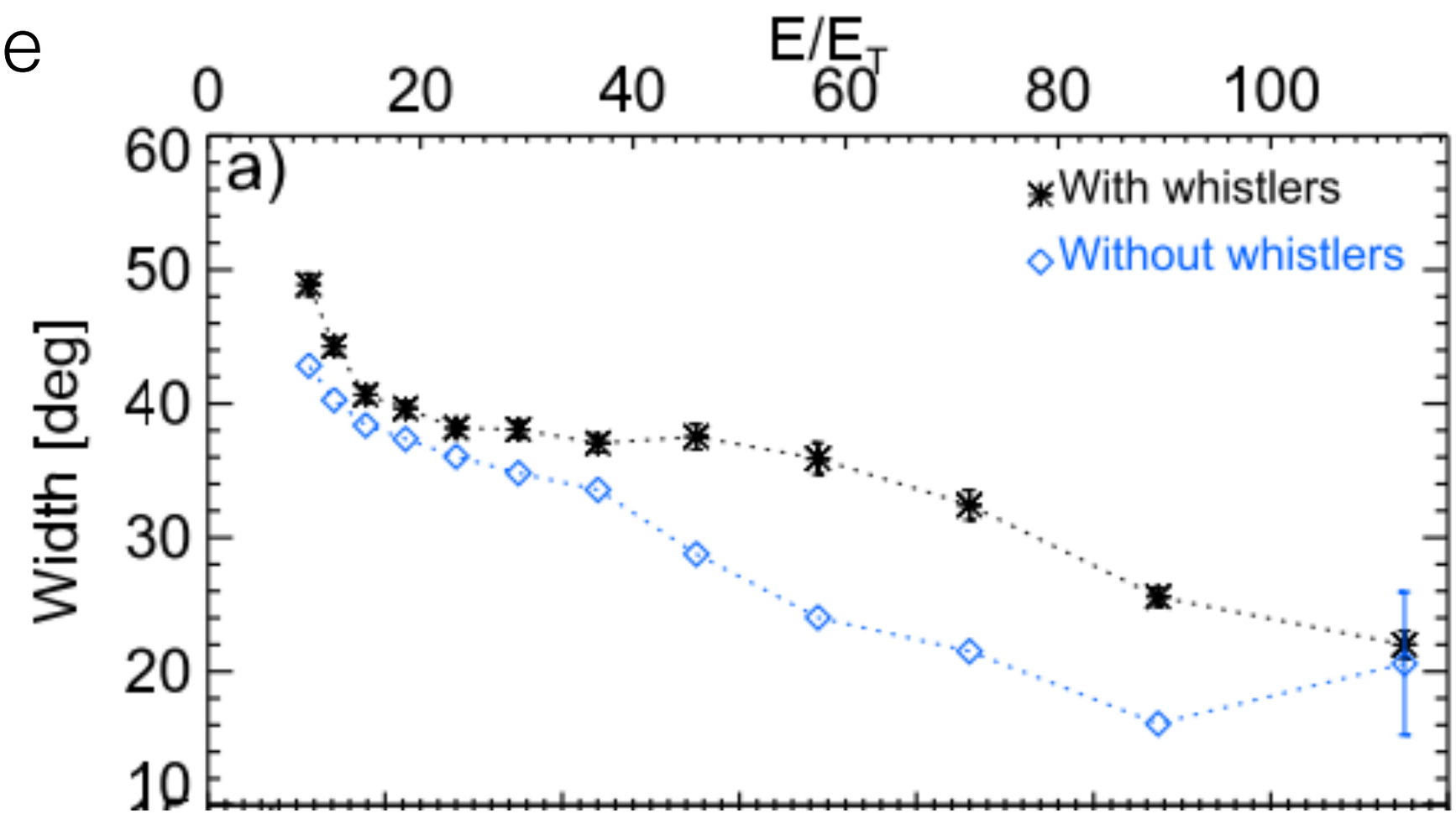
Part II conclusions

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

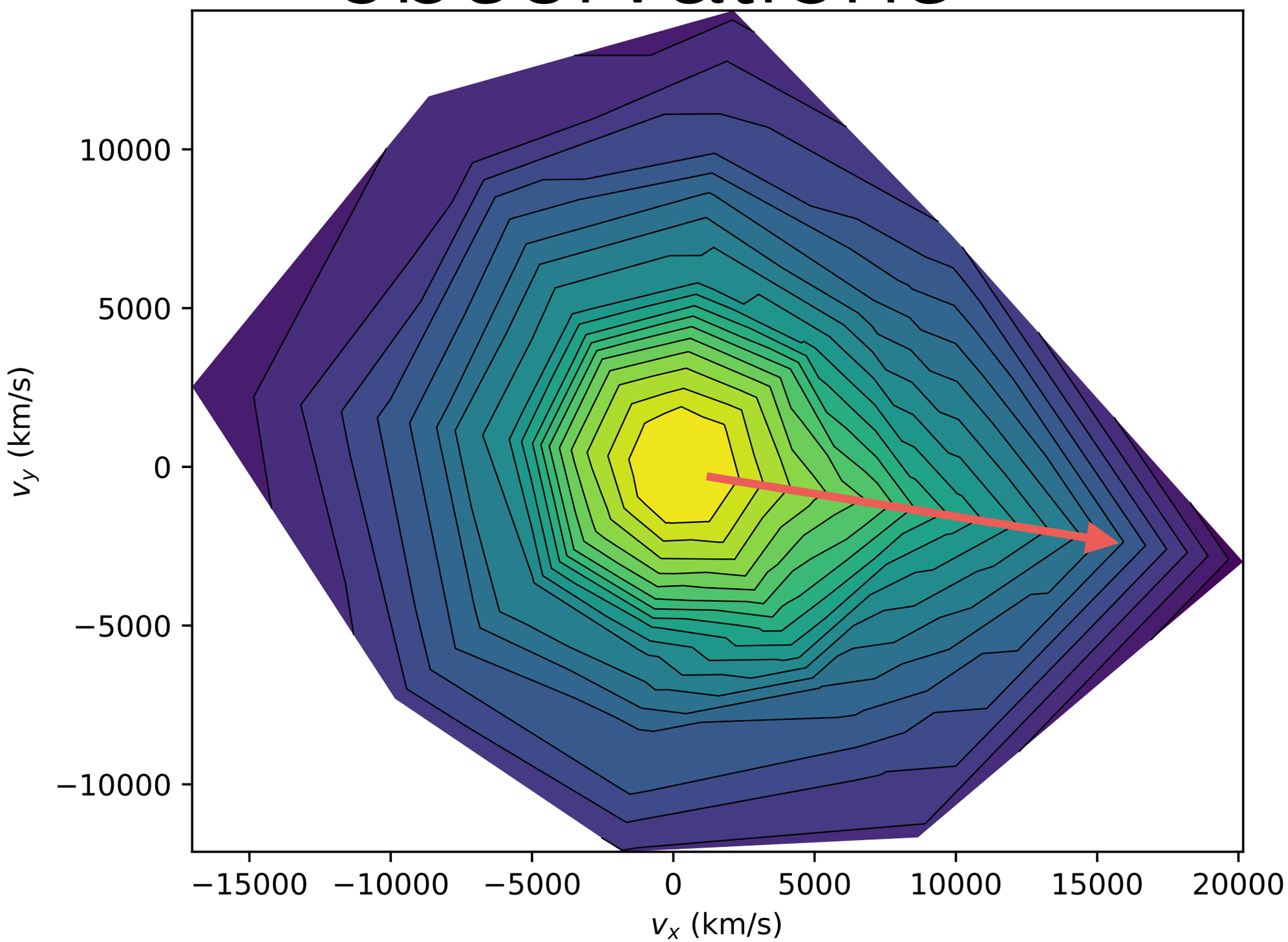


Kajdič et. al. 2017 [see also Pagel et. al. 2007]

‘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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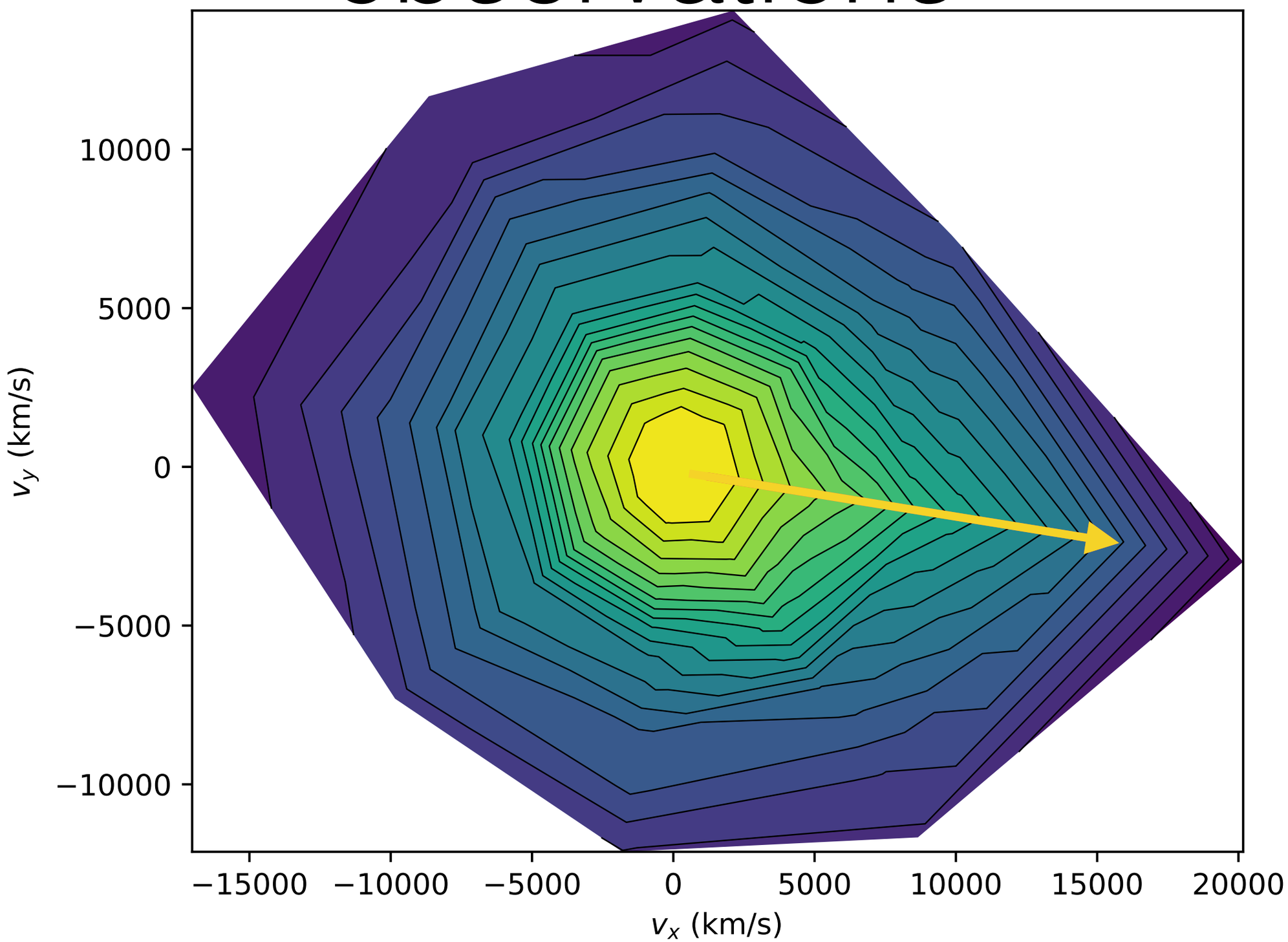

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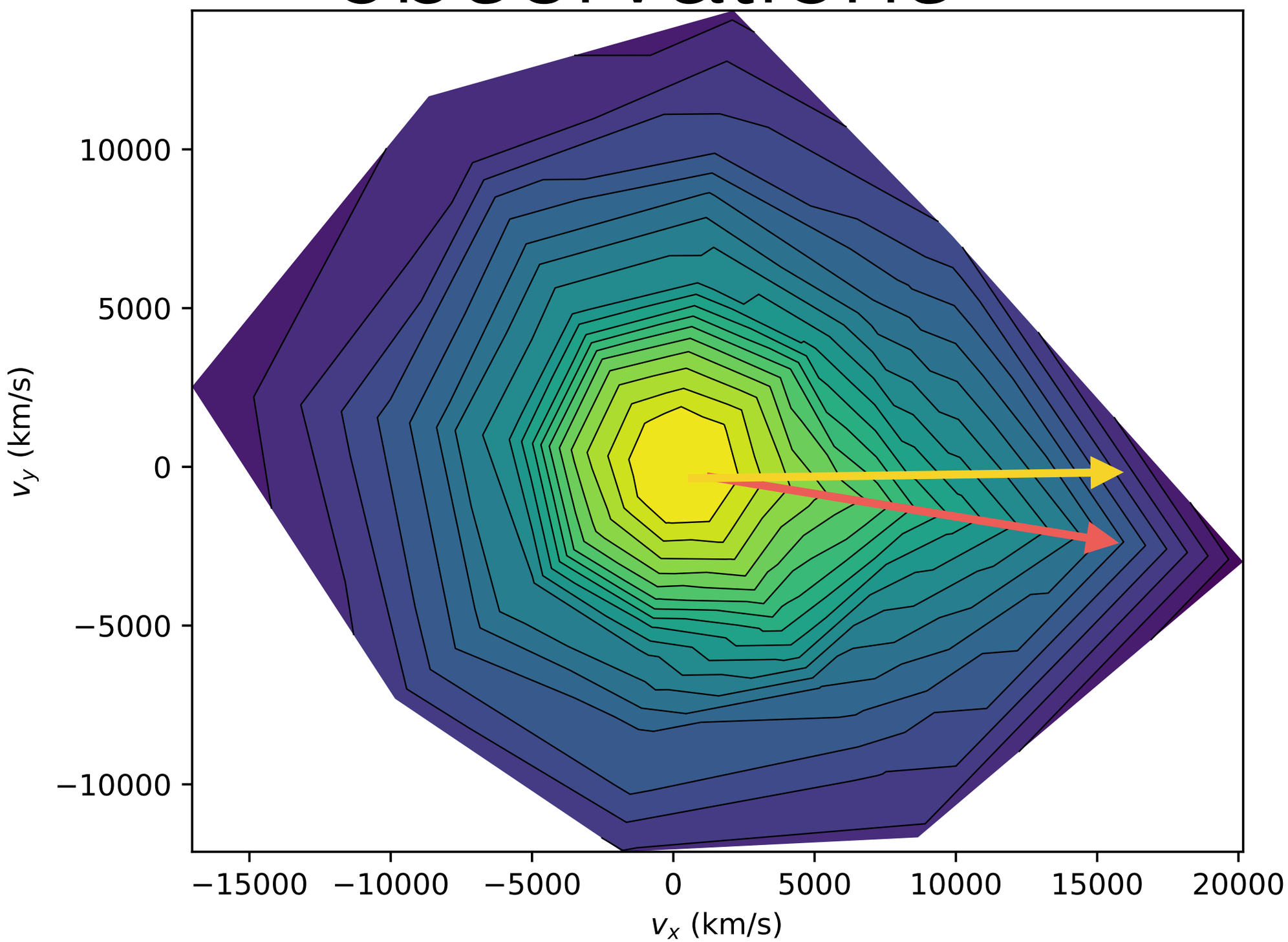

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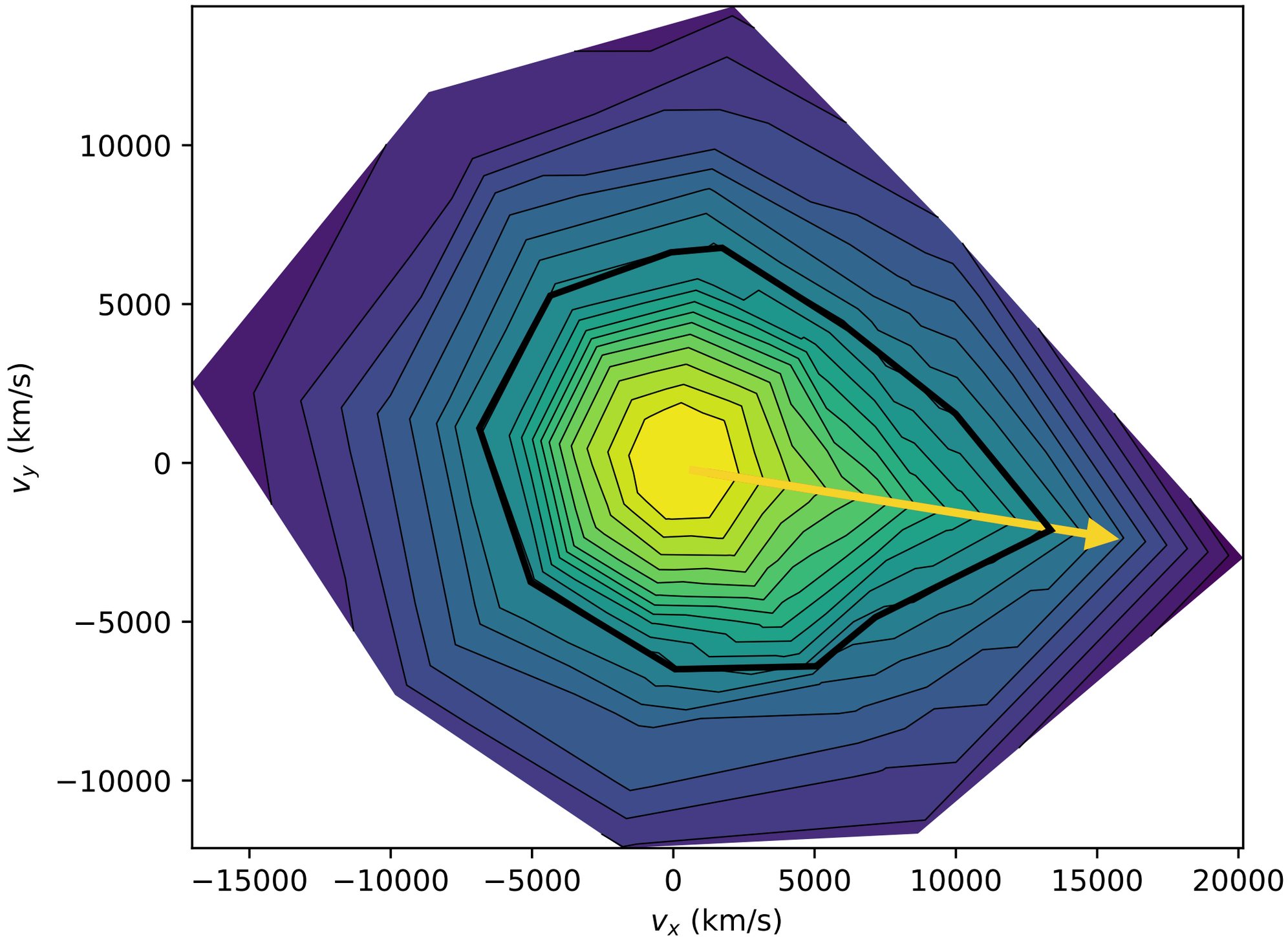

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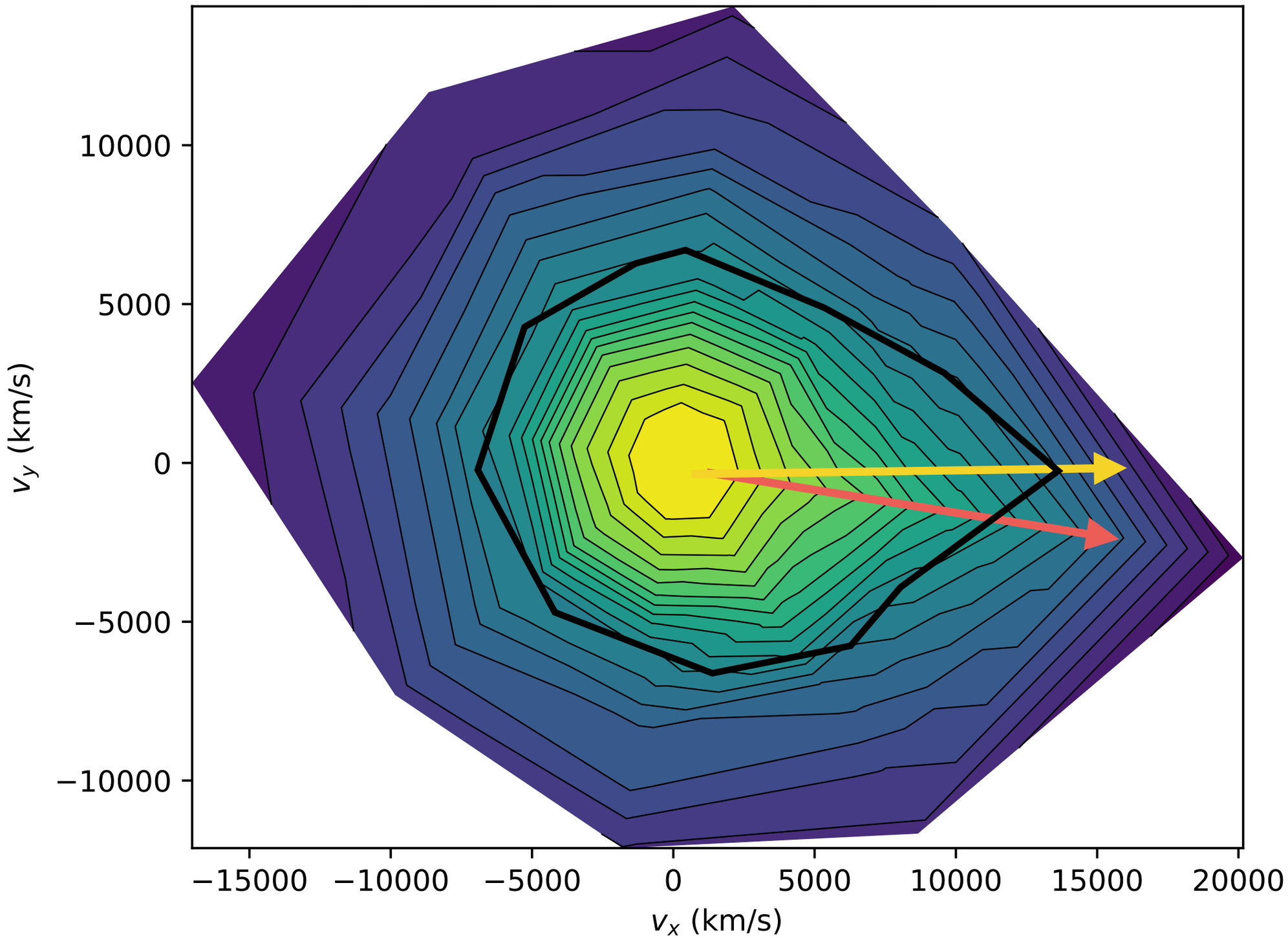

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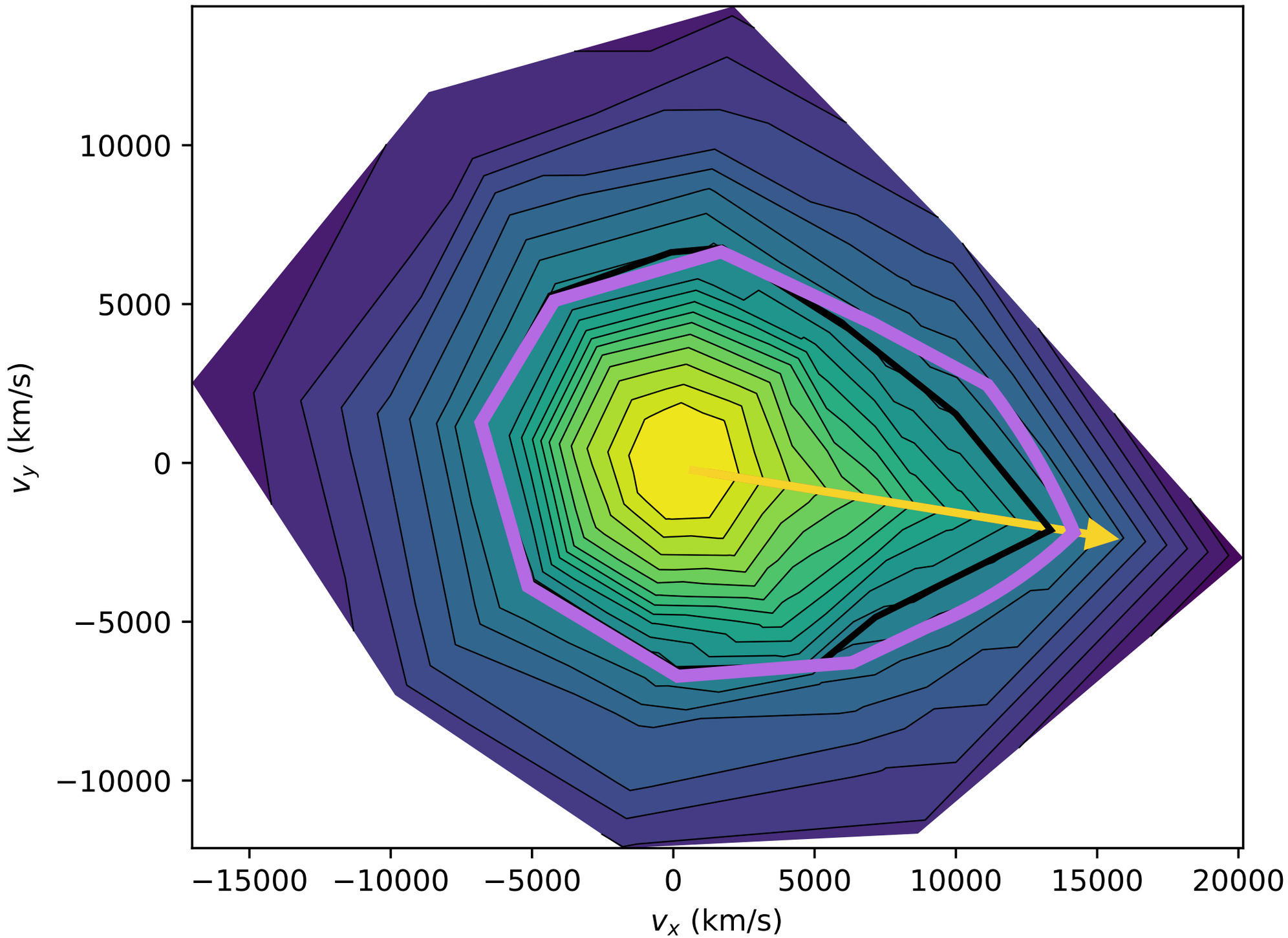

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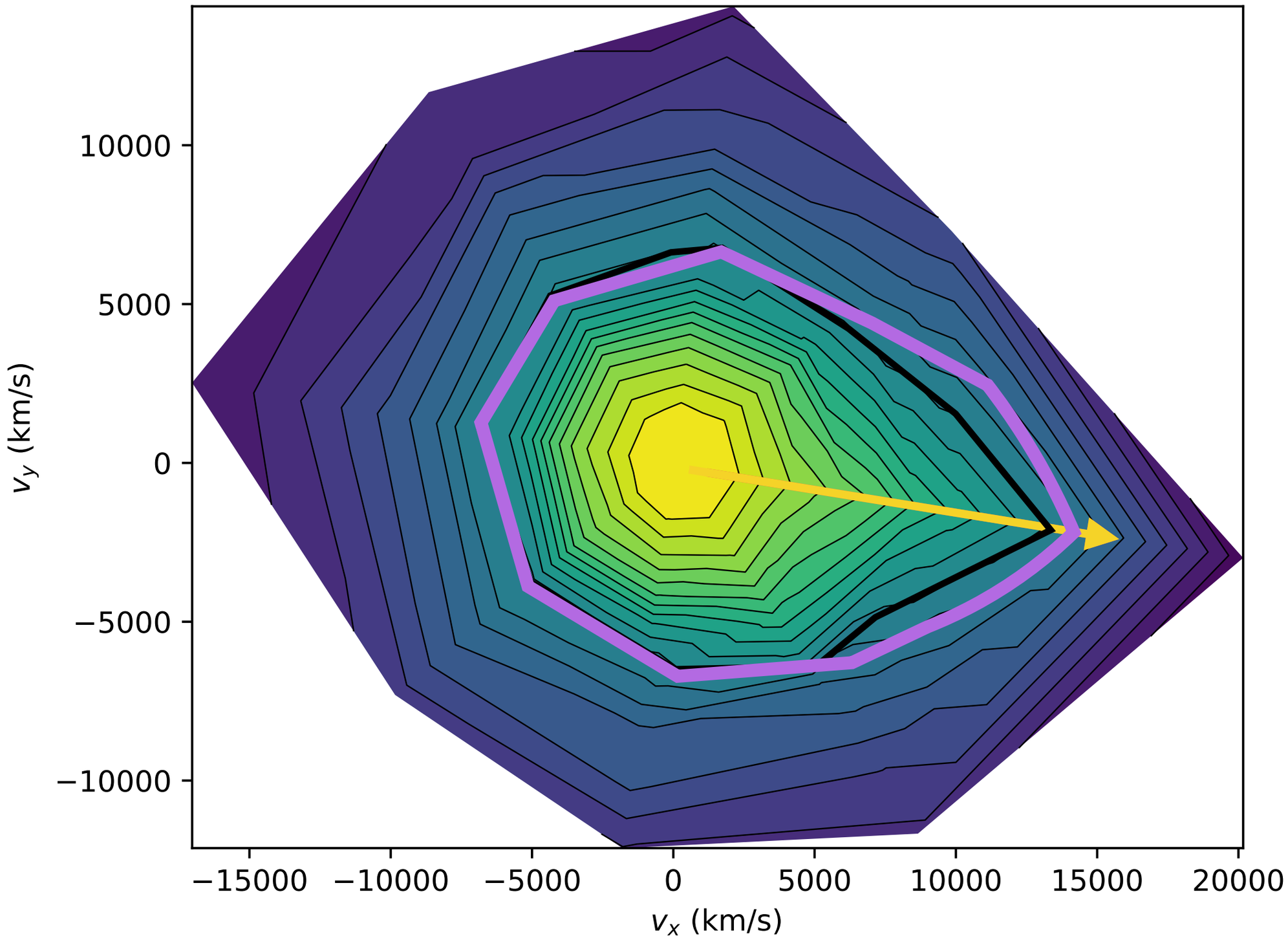

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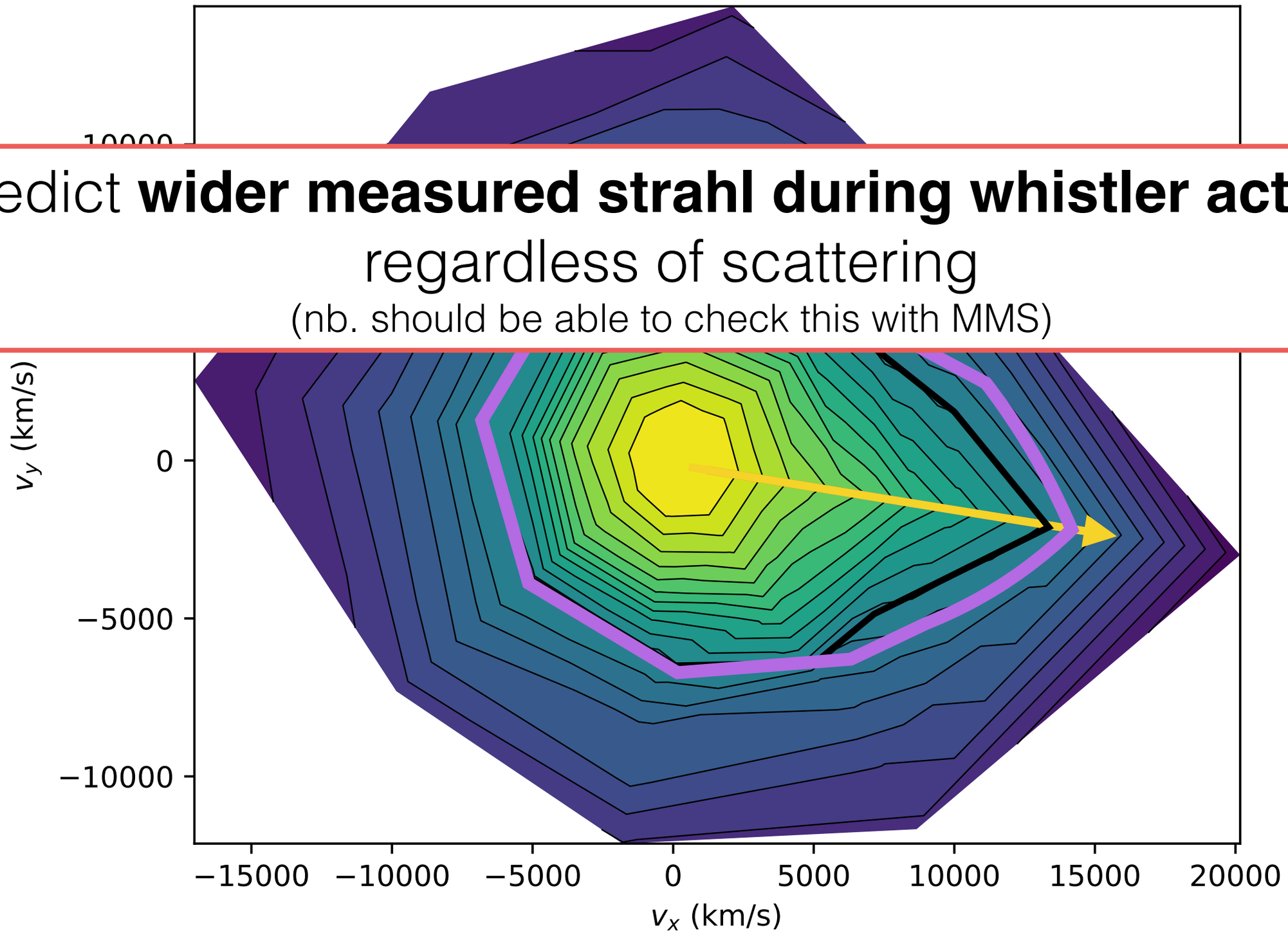


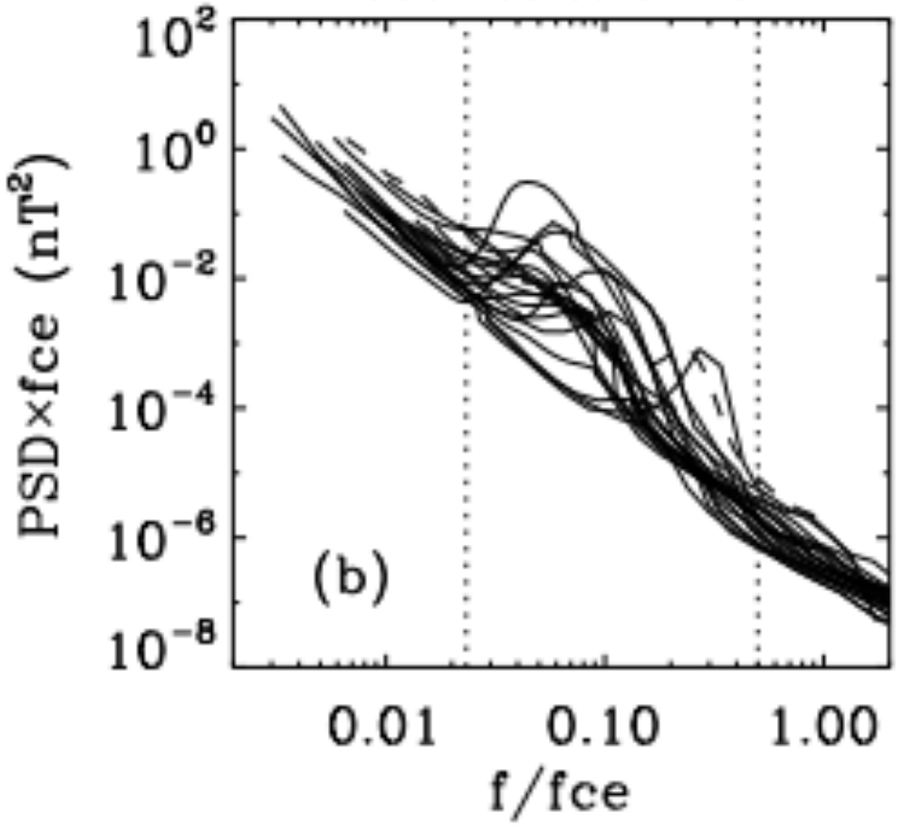
Predict **wider measured strahl during whistler activity** regardless of scattering

(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



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- Opinion still divided as to whether electron scale turbulence is whistlers or kinetic Alfvén waves

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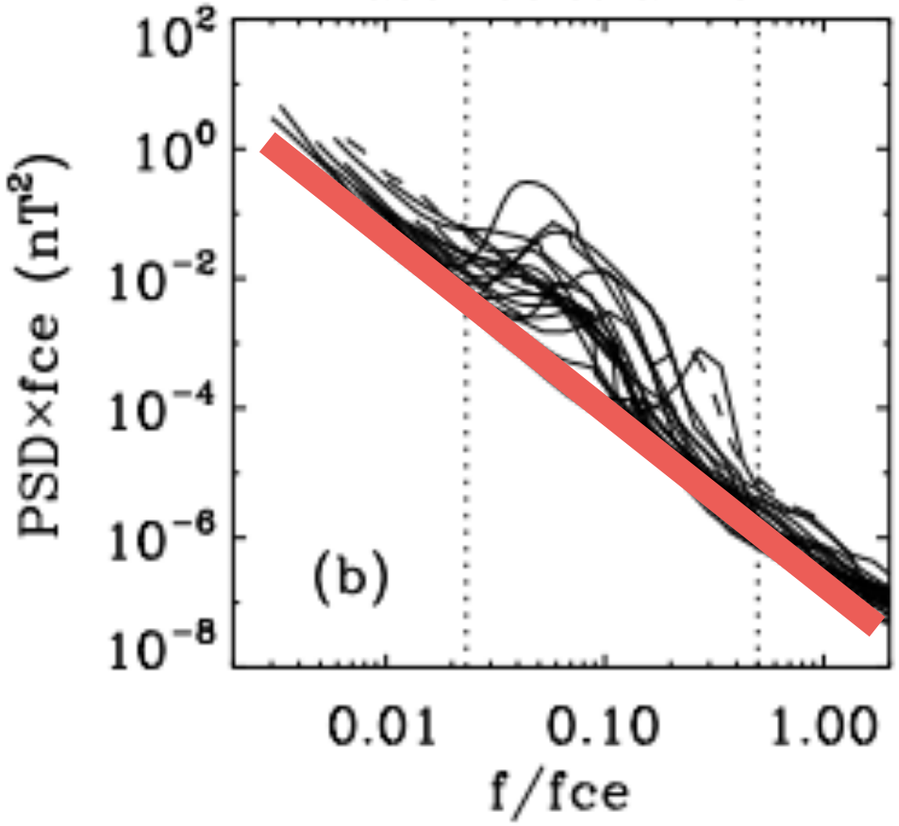

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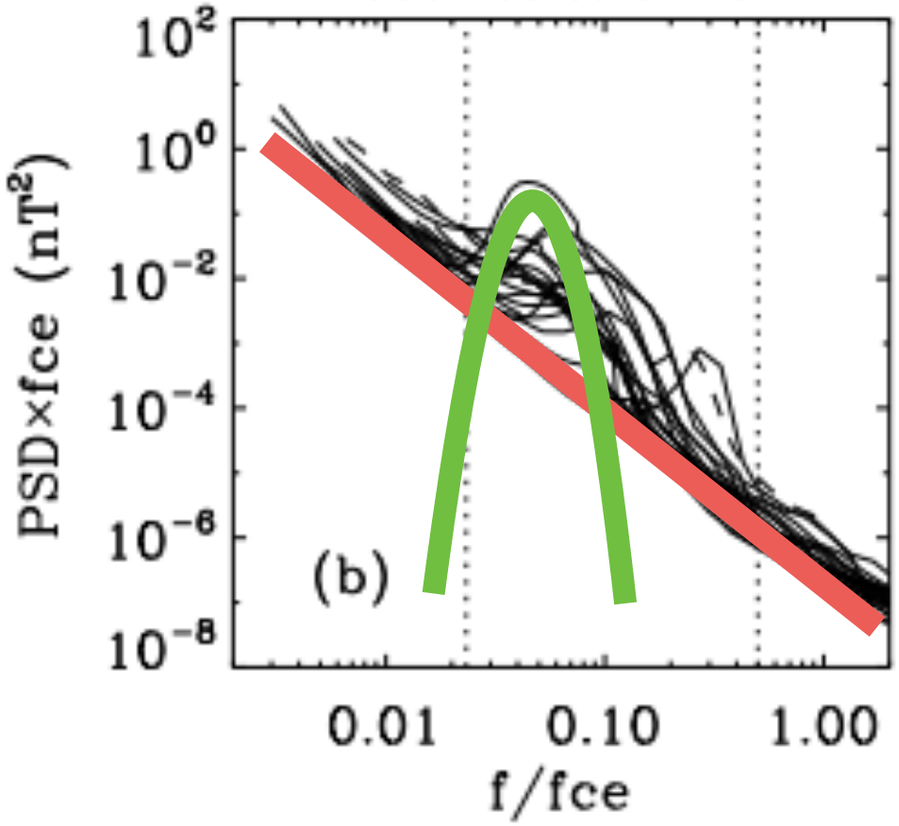

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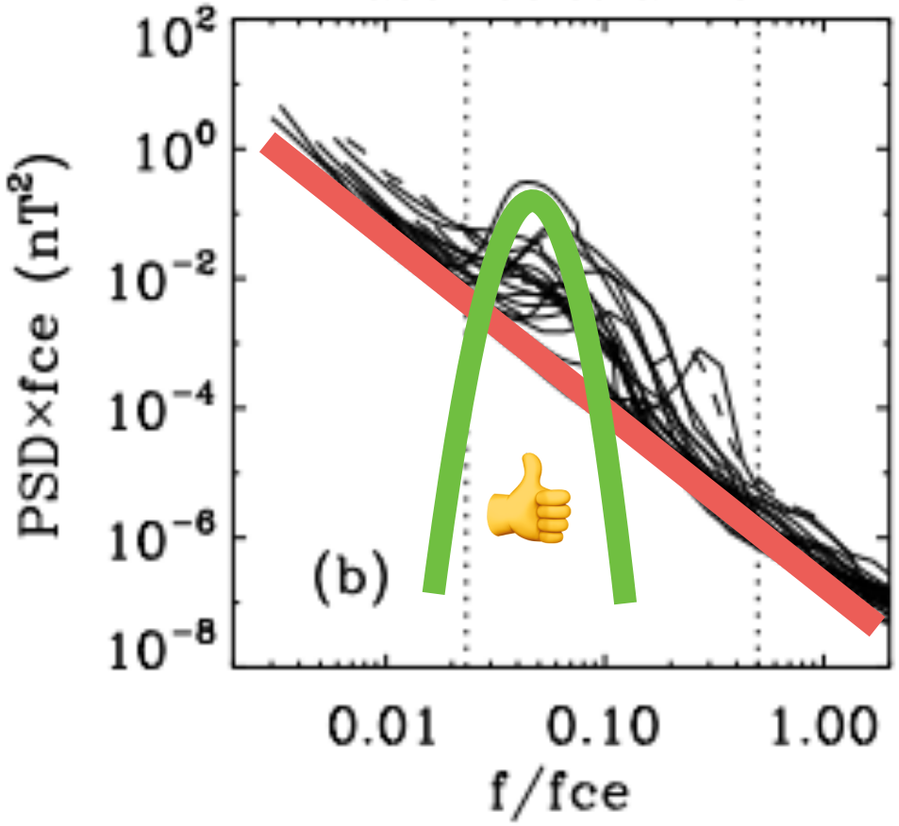

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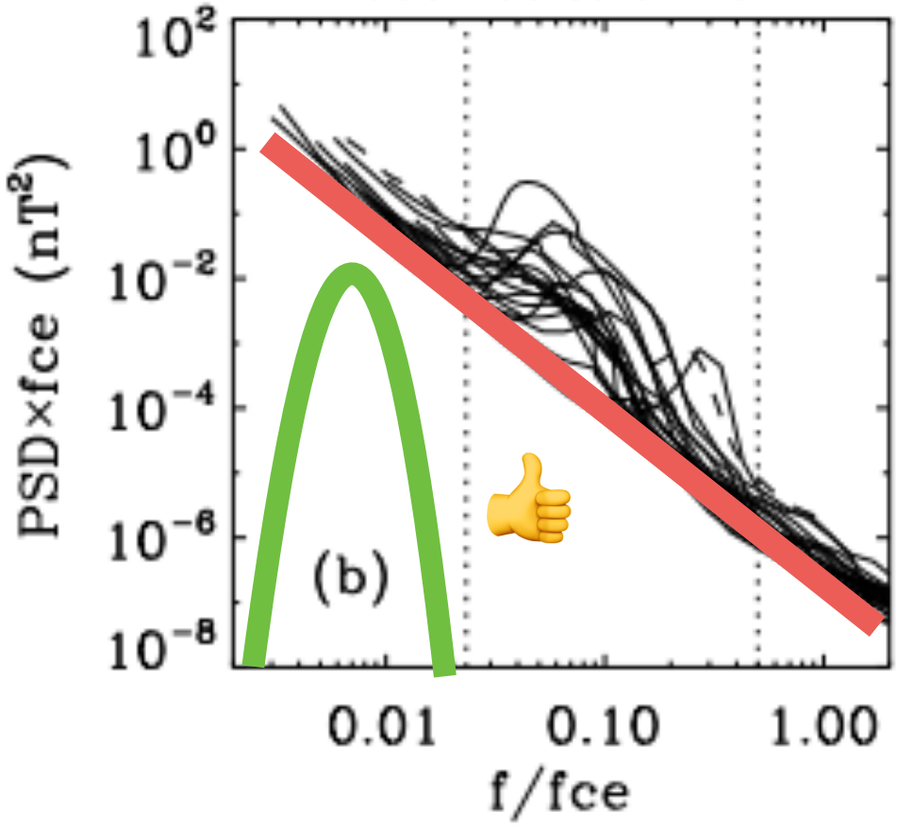

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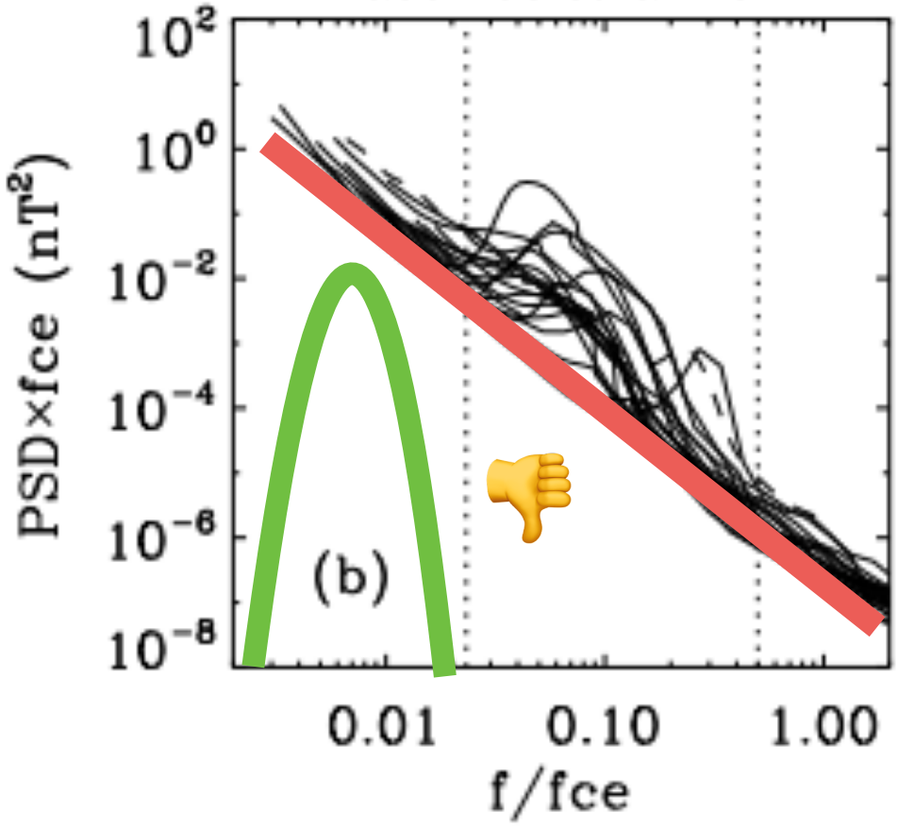

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Caveats II

- Only looked at waves visible above turbulence
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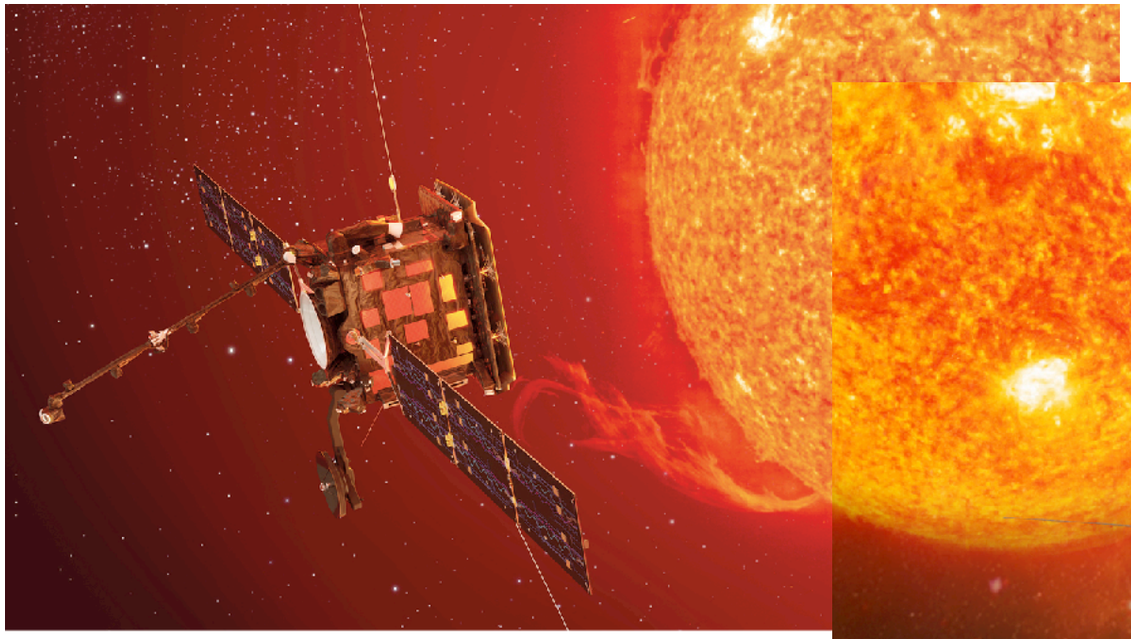

Caveats III

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- "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?

Caveats IV

- Waves that do scatter the strahl could have been generated and absorbed on very short timescales

- Would expect interactions to happen on timescales of the order of $\tau \sim 1/\gamma = const/\Omega_e$

- In the solar wind, this is microseconds, so maybe we will never see the waves responsible

➡ Need theory or simulation

Conclusions I

- Electron strahl widens with radial distance

➡ Needs a wave-particle mechanism to achieve this

- Whistler wave scattering is a proposed mechanism

- Using single spacecraft measurements, we have shown that observed whistler waves cannot linearly scatter the strahl

Conclusions II

- Both **E** and **B** measurements allow construction of experimental dispersion relations for coherent waves
- This can be used to predict wave-particle interactions

dstansby.github.io/talks