# Plasma Mechanisms Behind Hammerhead Proton Populations Observed by Parker Solar Probe

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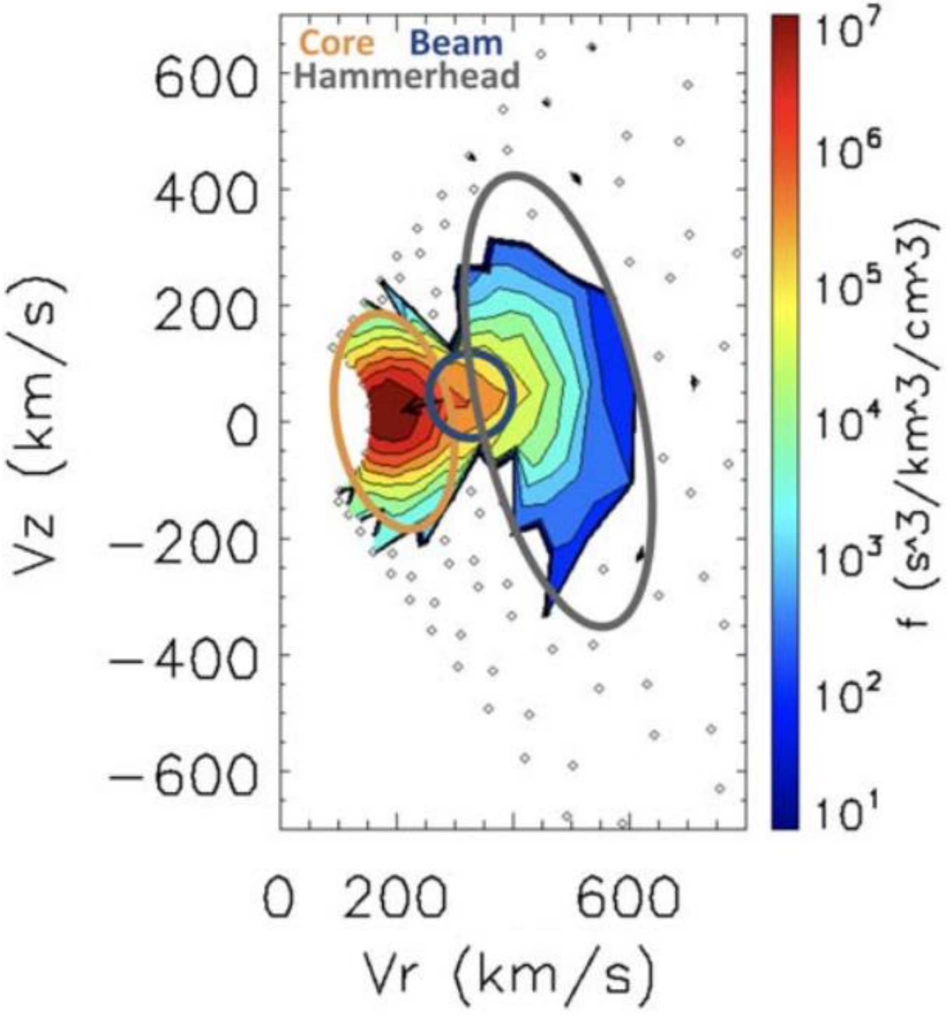
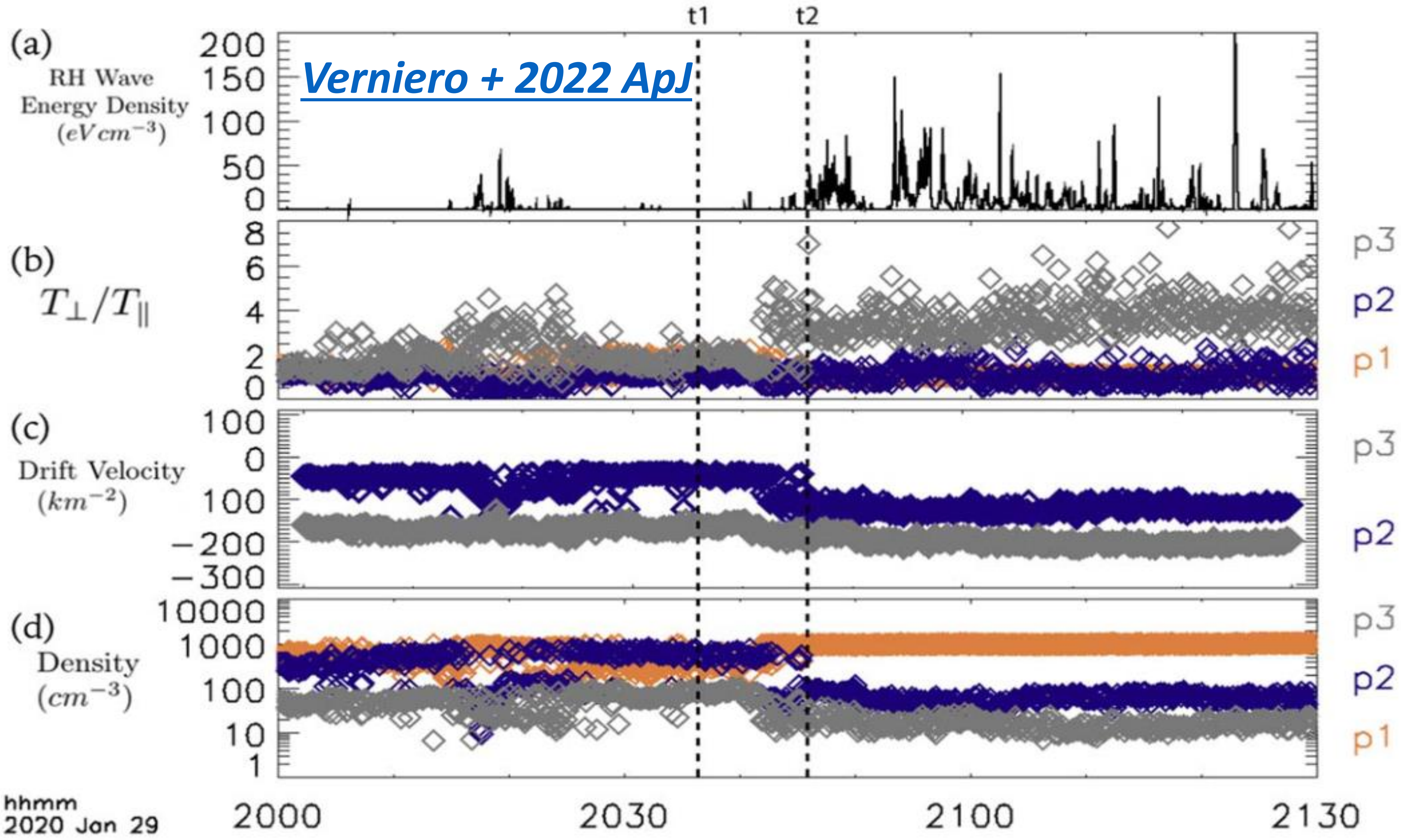
# Motivations

- Proton beams (PBs) affect solar wind heating.
- PSP observed hammerhead-shaped VDs (Verniero + 2022 *ApJ*).
- Need to identify physical mechanisms behind these features.
- We propose a QL firehose-like instability as the driver.




An example proton VDF in SPAN-I instrument coordinates during E4 quiescent solar wind period. Adapted from [Verniero + 2022 ApJ]

# Growth of PB temperature anisotropy coincides with enhanced RH wave power



# Theoretical Framework

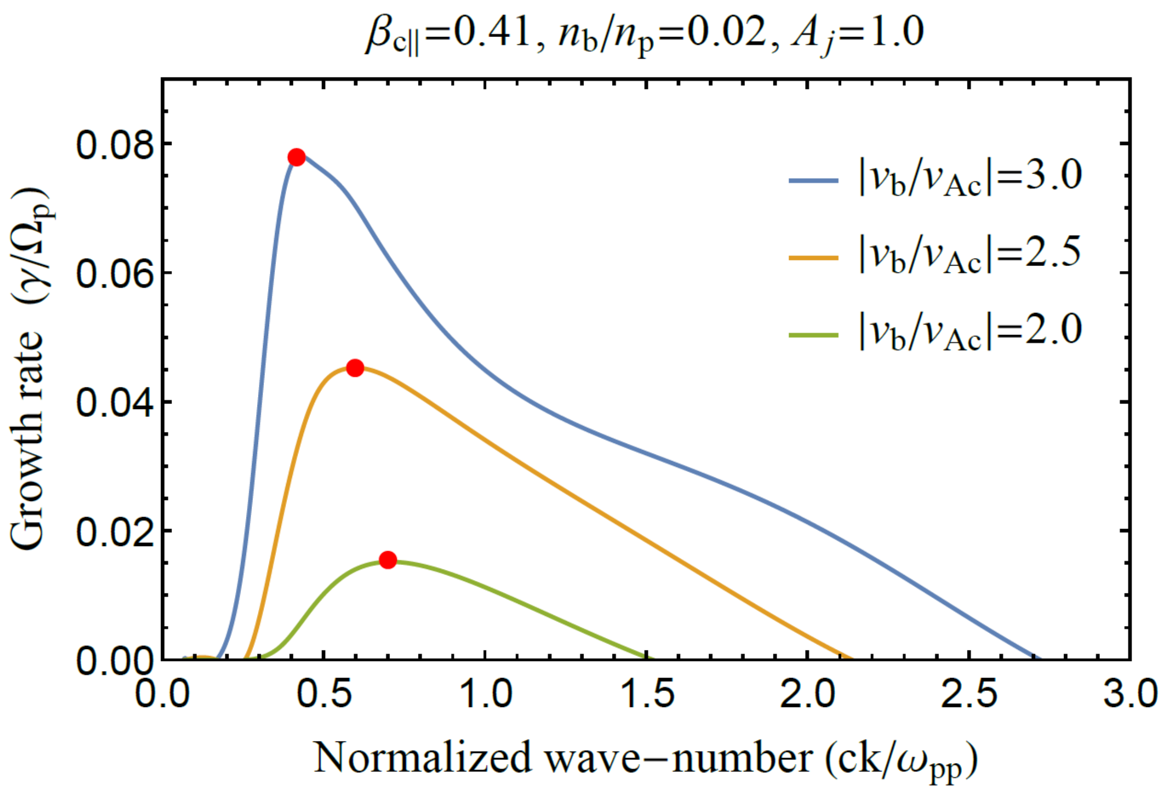
Detailed description can be found in Shaaban + 2024 A&A.

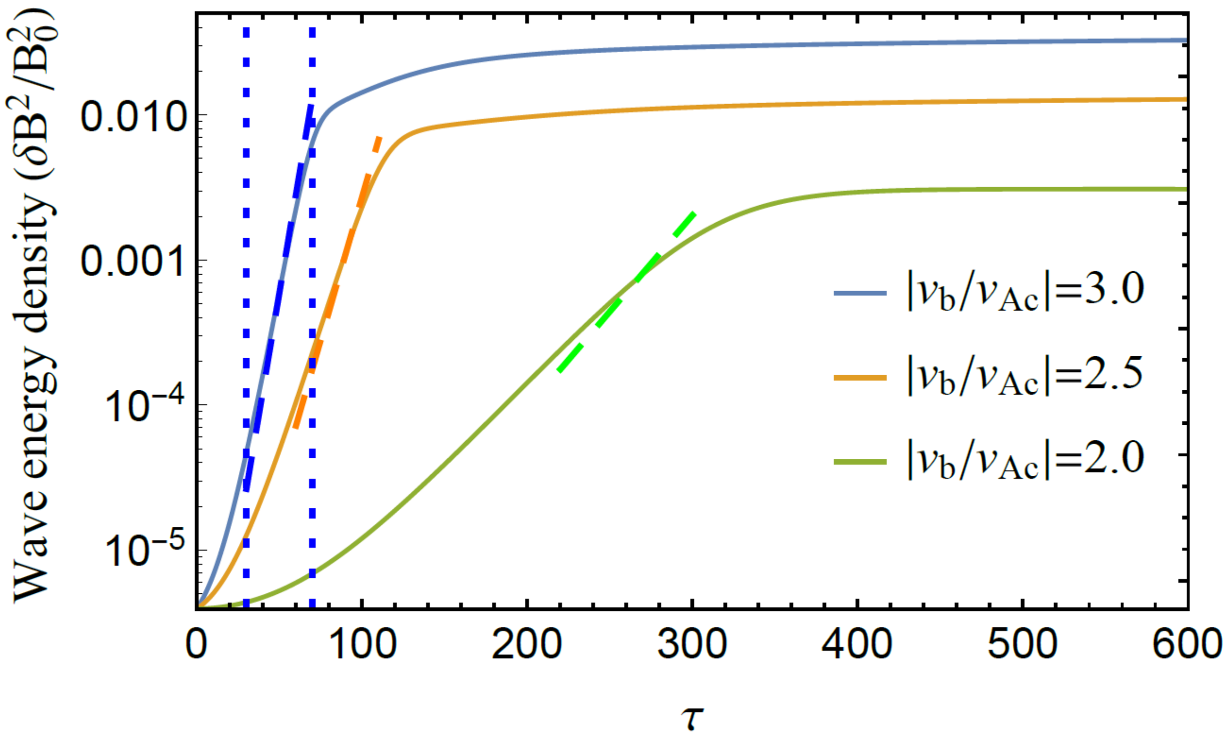
- Drifting bi-Maxwellian proton populations.
- No net current: $n_b\, v_b + n_c\, v_c = 0.$
- Instability: RH polarized transverse waves.
- Dispersion Relation: Growth rate depends on

  - Beam drift velocity $v_b/v_{Ac}$.
  - Beam density $n_b/n_p$
  - Beam anisotropy $A_b = T_{b\perp}/T_{b\parallel}$
  - Plasma beta $\beta_\parallel$

- Quasi-Linear (QL): temporal evolution of the plasma parameters:
  - $\beta_\perp,\ \ \beta_\parallel,\ \ v_b,\ \ A_b$
  - Wave energy $\delta B^2/B_0^2$
  - Captures energy exchange between particles and waves.

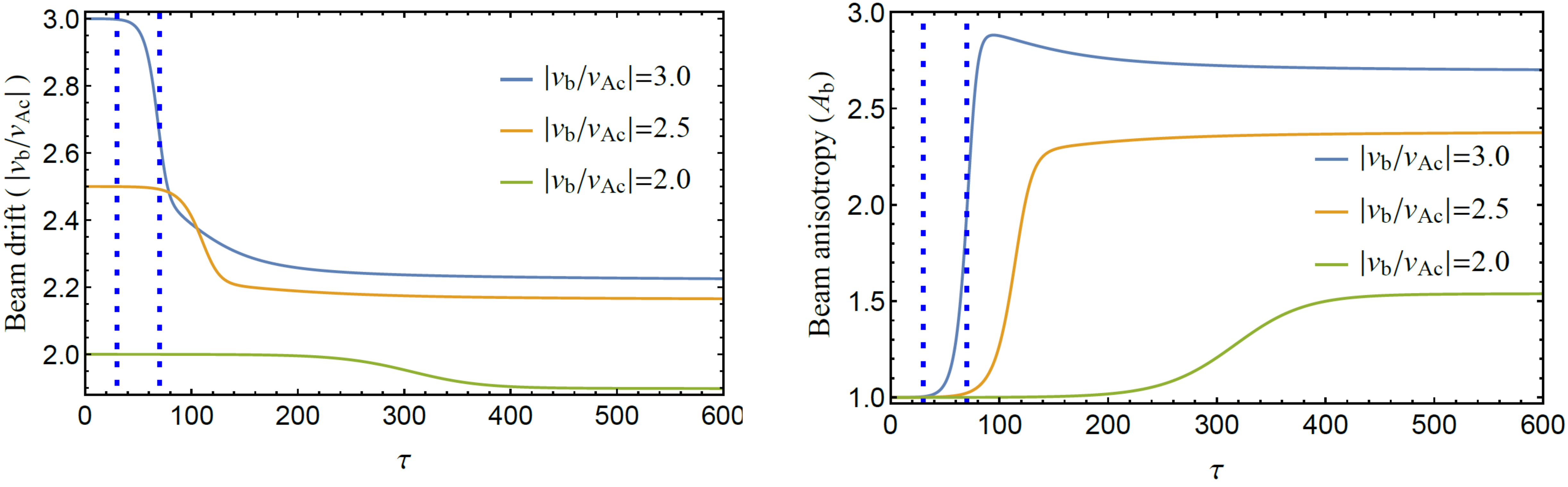
# RH proton-beam (RHPB) instability



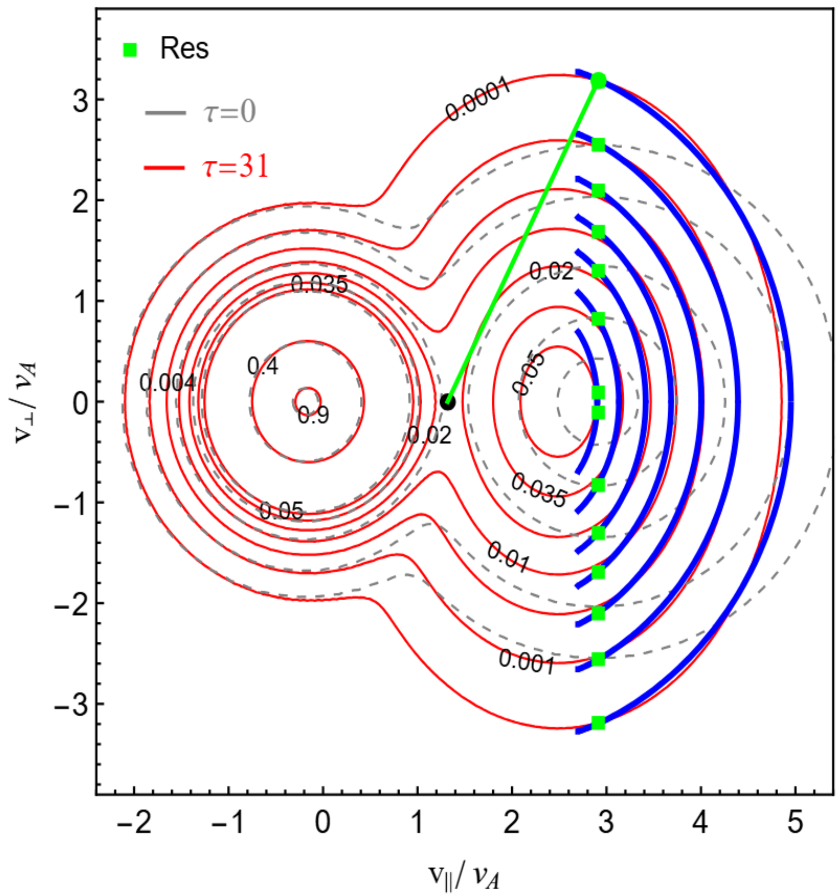

*Growth rates obtained from linear theory (left) and the enhanced wave energy density of the RHPB fluctuations obtained from the QL analysis (right) for different drift. Adapted from* **Shaaban + 2024 A&A**.

# Relaxation of $v_b$ and the induction of $A_b$

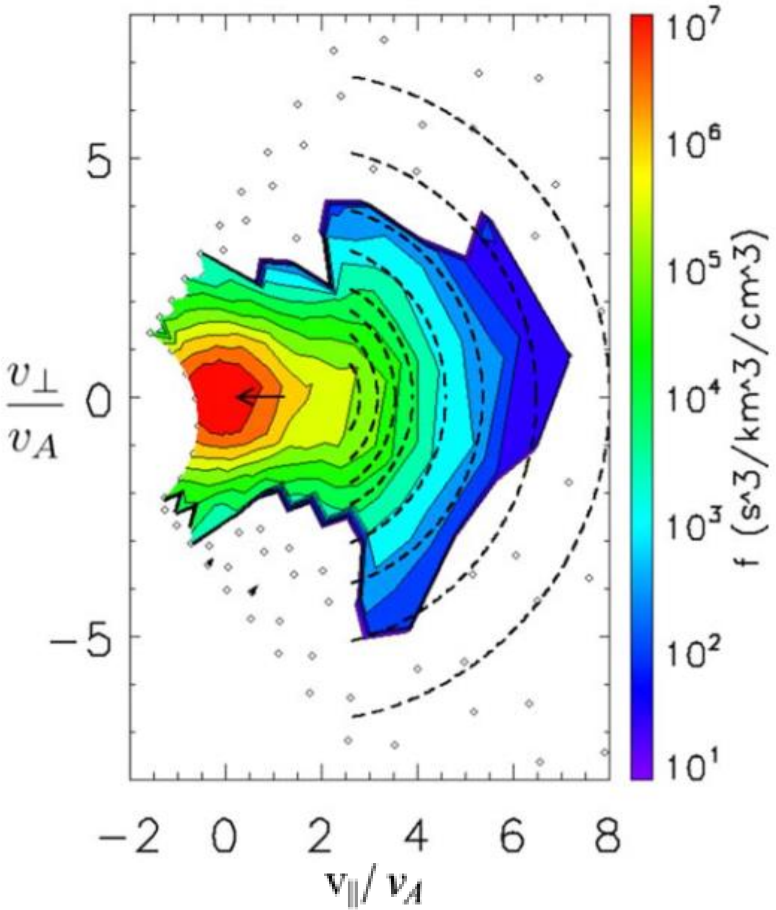



*The relaxation of the drift velocity (left) and the induced perp temperature anisotropy (right). Adapted from* **Shaaban + 2024 A&A**.

# VDF: theory vs. observation



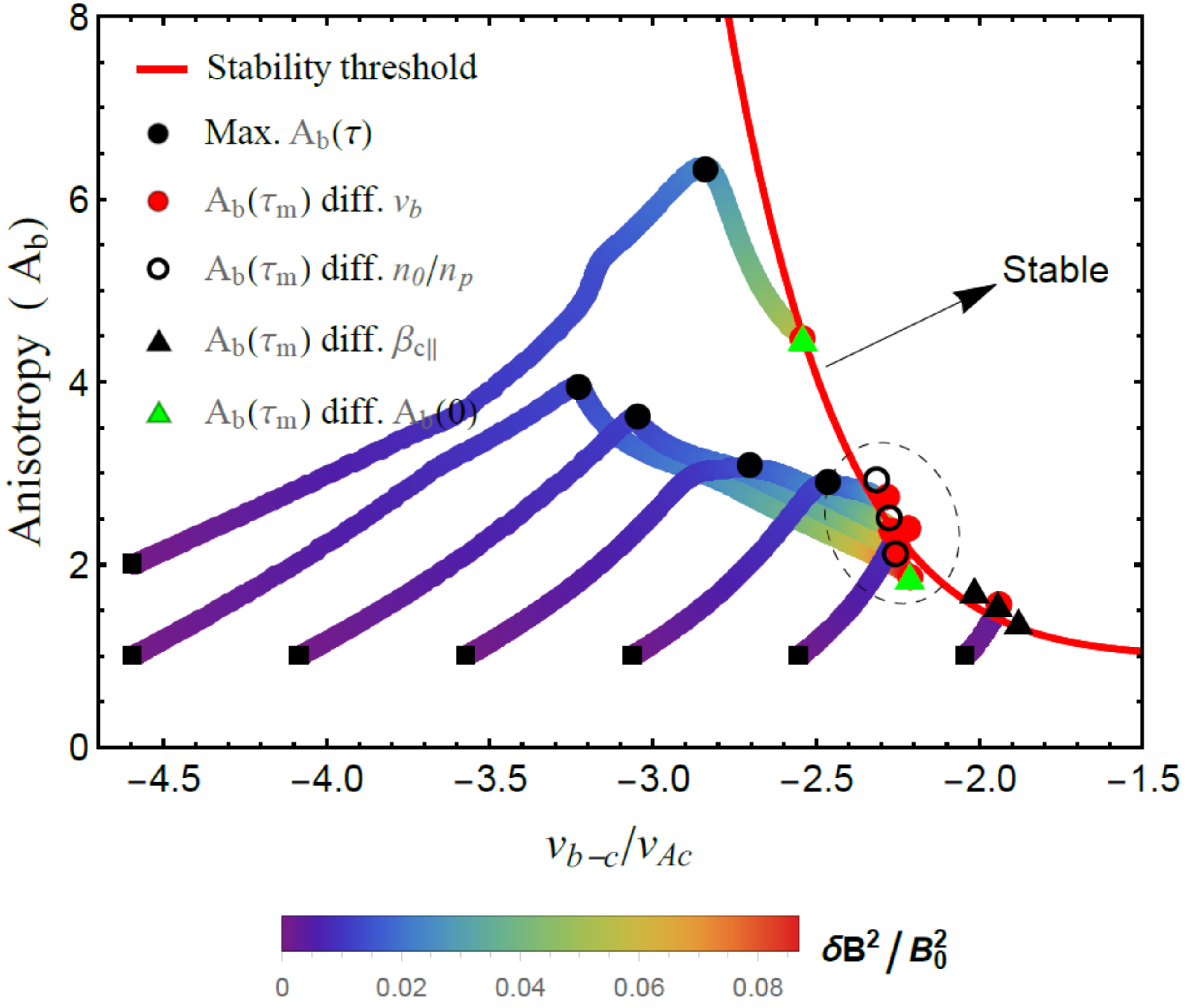

Shaaban + 2024 A&A




Verniero + 2022 ApJ

Left panel shows the QL temporal evolution beam development (with $\tau = \Omega_p\ t$). The forward half of the VDF is shaped by the kinetic shells (blue), which are relevant to the hammerhead populations reported by PSP in the right panel.

# QL dynamical paths of 12 runs



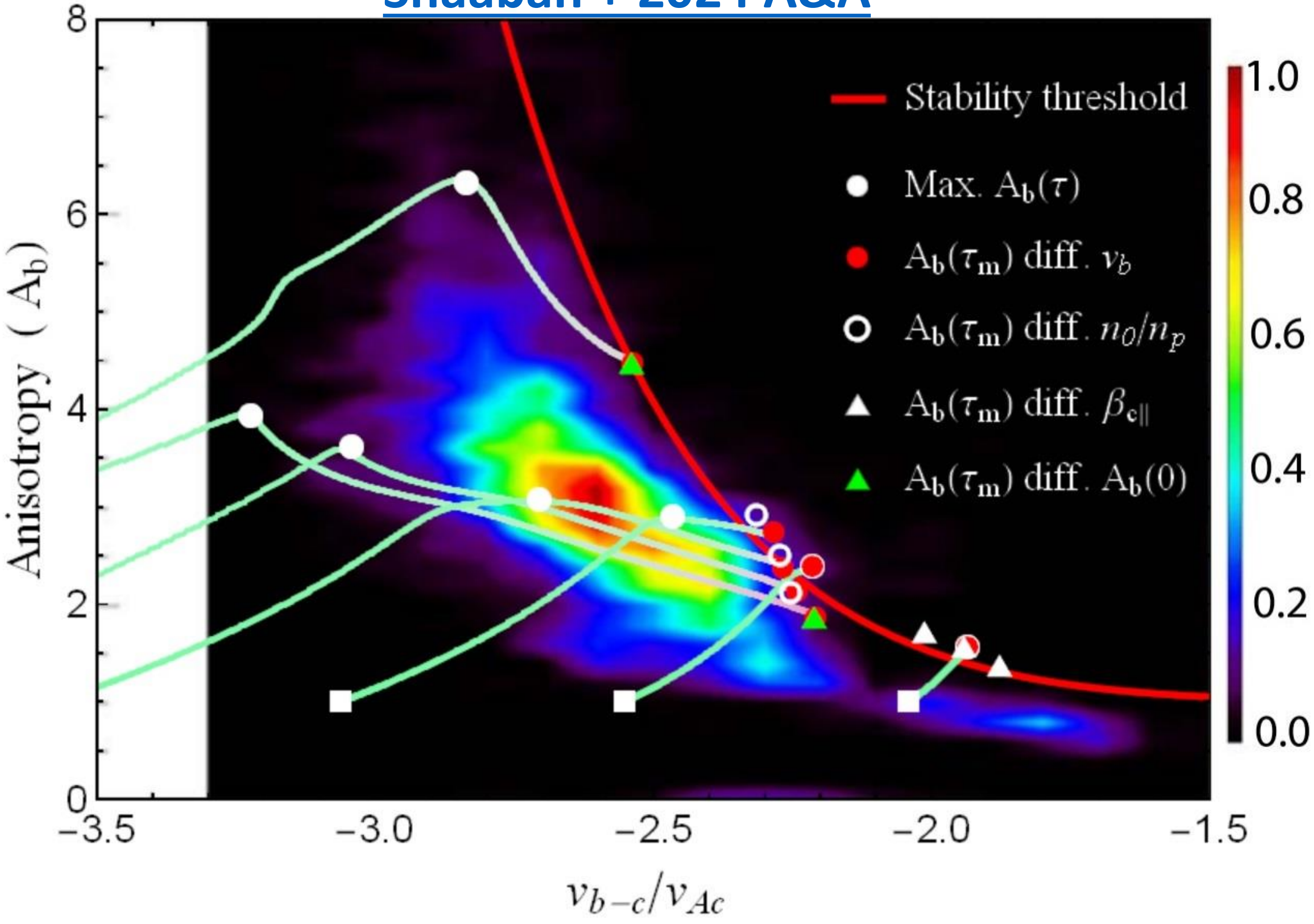

QL dynamical paths of temperature anisotropy ($A_b$) vs. beam-core drift velocity ($v_{b-c}/v_{Ac}$). Black squares are initial states, and the magnetic wave energy level is color-coded. Adapted from **Shaaban + 2024 A&A**.

Final states follow the stability threshold (red line):

$$A_b = 1 + 0.0019(-v_{b-c}/v_{Ac})^{8.04}$$

# Constraints on the observed hammerhead populations

Shaaban + 2024 A&A




Same as left panel but superimposed on PSP observations, with color-coded (normalized) number of events with hammerhead populations (adapted from Verniero + 2022 ApJ)

# Key Conclusions

- This study demonstrates that the RHPB instability provides a viable mechanism for the formation of hammerhead populations observed by PSP.
- As the instability grows, it transfers energy from the drifting beam into electromagnetic wave fluctuations. This process reduces the relative drift between beam and core populations and leads to preferential heating of the beam in the perpendicular direction.
- The resulting anisotropy, with $T_{b\perp} > T_{b\parallel}$, matches the distinctive shape of the observed hammerhead distributions.
- The QL model effectively reproduces key features seen in PSP data, including resonant velocity-space diffusion and the statistical bounds of observed events.