Multi-Dimensional Description of Ion-Driven Instabilities in the Inner Heliosphere

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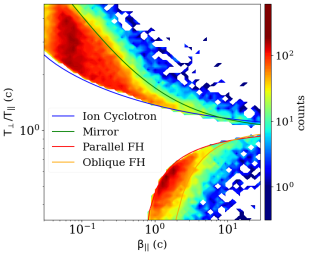

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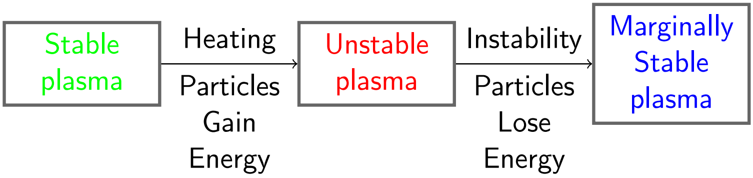
Objectives

- Intent - Provide a comprehensive description of linear kinetic plasma instabilities in the inner helisophere
  - Determine stability of measured Velocity Distribution Function (VDFs)
  - Describe intensities and types of instabilities throughout both physical and phase space
- Why? Determine which physical quantities tailor the solar wind dynamic behavior
  - Find how various instabilities tend to reshape the VDF
  - Estimate the levels of the energy "returned" from particles to waves as a complementary process to solar wind heating



Outline

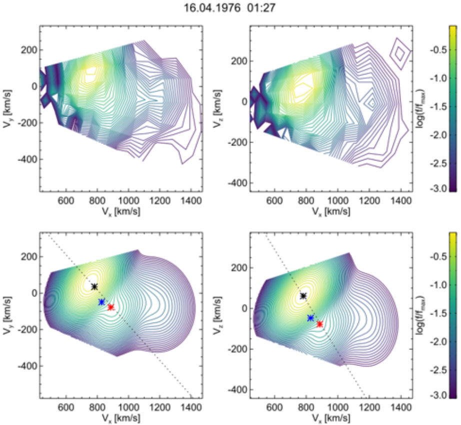
- Part I - Statistical Analysis of *Helios* observations
  - Analyze linear stability of ∼1.5M VDFs observed by *Helios I & II*
  - Understand the behavior of unstable modes with regard to various plasma and spatial parameters
    - and instrumental effects too
- Part II - Map the important physical processes acting in different conditions in the solar wind
  - Train Stability Analysis Vitalizing Instability Classification (`SAVIC`) algorithm to recognize the instability types in a automatized fashion
  - Use `SAVIC` to sort the multidimensional phase space of VDF and instability parameters to reveal trends in the solar wind
- Part III - `SAVIC` resources and short tutorial
  - SAVIC makes the power of complicated solvers accessible to a wide community of users who are not necessarily experts in linear instabilities

Part I

Part I - Stability analysis of *Helios* observations survey

Helios Observations of VDFs

- Helios I (1974 – 1985) & II (1975 - 1980)
  - 0.3 – 1 au; 6 month periods
  - 40s cadence; $\sim$ 1.5M observations
- Three populations fitted as anisotropic drifting Maxwellians [Ďurovcová et al., 2019]
  - proton core
  - proton beam
  - α particles

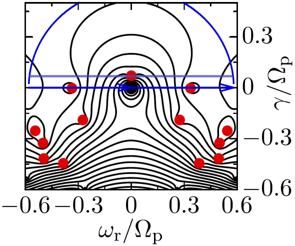


core	core + beam	core + α	core + beam + α
315,755 (22.3%)	352,414 (24.9%)	253,779 (18.0%)	490,830 (34.7%)

Analysis of Plasma Stability Applied to Helios Observations

- PLUME dispersion solver [Klein and Howes, 2015] predicts wave modes $det[\mathcal{D}(\omega, \mathrm{k}, \mathcal{P})] = 0$
- PLUMAGE [Klein et al., 2017] numerically evaluates contour integral

$$W_n(\mathrm{k}, \mathcal{P}) = \frac{1}{2\pi i} \oint \frac{\mathrm{d}\omega}{det[\mathcal{D}(\omega, \mathrm{k}, \mathcal{P})]}$$

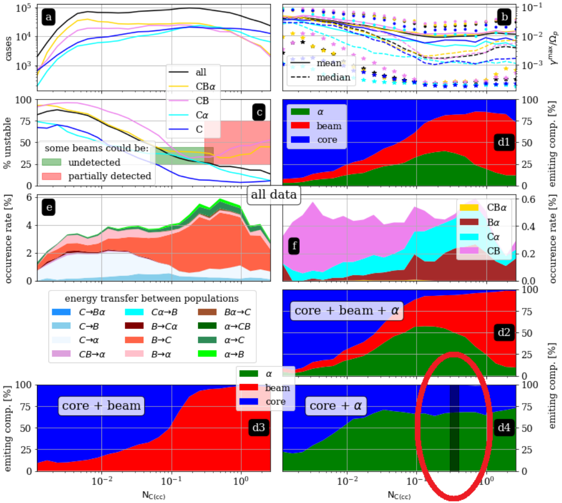


$$\mathcal{P}_0 = \left(\beta_{\parallel,c}, \frac{v_{the\parallel,c}}{c}\right); \quad \mathcal{P}_j = \left(\frac{n_j}{n_c}, \frac{T_{\perp,j}}{T_{\parallel,j}}, \frac{T_{\parallel,j}}{T_{\parallel,c}}, \frac{\Delta v_{j,c}}{v_{Ac}}, \frac{m_j}{m_p}, \frac{q_j}{q_p}\right) \quad (1)$$

- For each Most Unstable Mode (MUM), we find
  - frequency $\omega_r + i\gamma$
  - wavenumber $\mathrm{k}_{\max}$
  - field fluctuations $\delta\mathrm{B}, \delta\mathrm{E}$
- and for each population
  - power emitted (absorbed) P_j
  - parameter fluctuations $\delta n, \delta \mathrm{v_j}$
- and set label $\mathcal{W}$ for PLUME output

First Look at the Results - Something is Off...

- Results are Classified by Coulomb Number $N_{C(cc)} = \nu_{cc} r / v_{sw,c}$
- Every subset is shown separately in panels *d1-d4*
- A "steady state" for the emitting population is reached very early in the solar wind propagation
  - a very suspicious result
  - we investigate 77,000 intervals in grey shade



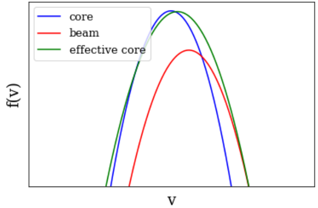
Digression - Beam Detection on Helios I1

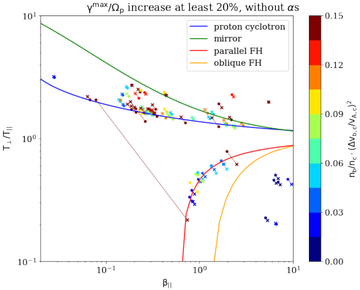
- Beam can be mistaken as part of the core due to I1 instrument limited resolution
  - the issue is emphasized for low drifts (older wind far from the Sun)
- We indroduce "effective" core

$$T_{\mathrm{eff}\|,b} = T_{\|,b} + \frac{m_p(\Delta v_{b,c})^2}{2k_b} \qquad (2)$$

$$T_{\mathrm{eff}\|} = \frac{n_c T_{\|,c} + n_b T_{\mathrm{eff}\|,b}}{n_c + n_b}, \qquad (3)$$

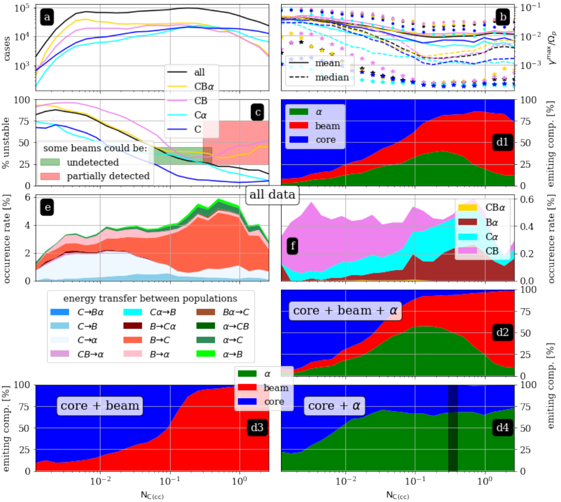
- Two possible scenarios
  - Beam not detected: $T_{\|,c}$ increases
  - Beam partially detected: artificially increased beam anisotropy – seen as highly unstable





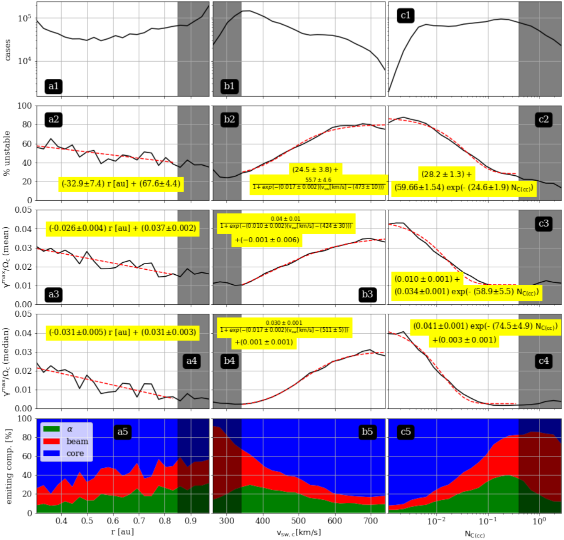
Second Look at the Results - With More Clarity

- Beam stability trends are not reliable for old wind *(c)*
- Fraction of emitted energy can be *absorbed* by another component *(e)*
- More than one component can emit power at the same time *(f)*
- Core free energy dominates the young solar wind *(d)*



Solar Wind Instability Statistics

- Radial trend is **linear**
- Speed and Coulomb Number trends are **exponential**
- proton core (beam, α) dominantly drives instabilities in collisionally young (intermediate, old) wind
- Beams—seemingly not strongly affected by collisions—carry more free energy in older wind

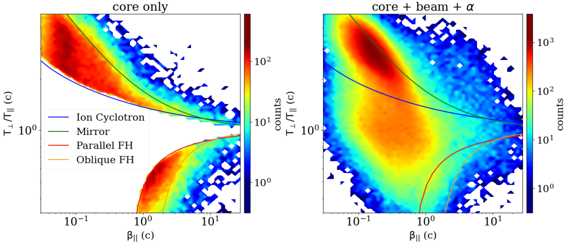


Part II

Part II - Characterisation and Multidimensional Mapping of Plasma Instabilities

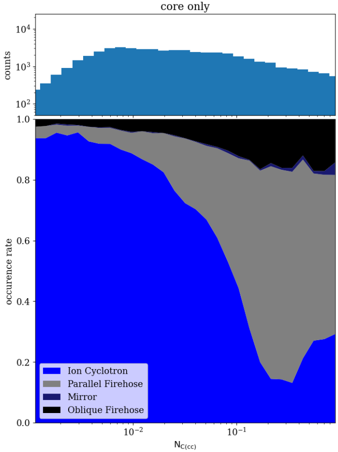
Towards Mapping of Plasma Instabilities

- A fairly simple basic concept:
  - identify the type of instability
  - understand its role in solar wind dynamics based on $\mathcal{P}$ and $\mathcal{W}$



EASY IMPOSSIBLE

- This task is straight-forward only for a single (core) population



Understanding Multi-Dimensional Phase Space - Introducing Machine Learning

- The number of $\mathcal{P}$ and $\mathcal{W}$ parameters increases with number of identified components
  - some may vary up to 4 orders of magnitude

Components	# $\mathcal{P}$	# $\mathcal{W}$
C	5	20
CB	9	25
Cα	9	25
CBα	13	30

- Major problem 1: Tabulation of $\mathcal{W}$ for all feasible $\mathcal{P}$s is not possible

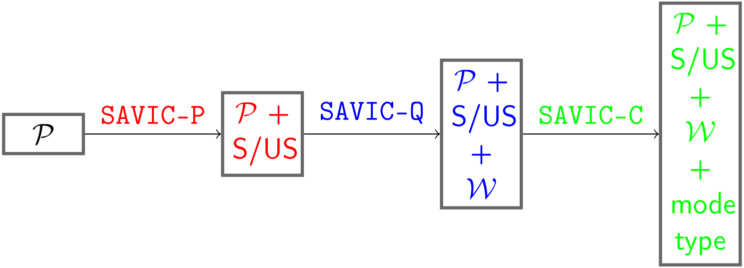
$$\mathcal{P} = \left(\beta_{\parallel,c}, \frac{v_{the\parallel,c}}{c}, \frac{n_j}{n_c}, \frac{T_{\perp,j}}{T_{\parallel,j}}, \frac{T_{\parallel,j}}{T_{\parallel,c}}, \frac{\Delta v_{j,c}}{v_{Ac}}, \frac{m_j}{m_p}, \frac{q_j}{q_p}\right) \quad (4)$$

$$\mathcal{W} = (\omega_r, \gamma, \mathrm{k}_{\mathrm{max}}, \delta \mathrm{B}, \delta \mathrm{E}, P_j, \delta n, \delta \mathrm{v}_\mathrm{j}) \quad (5)$$

- Major problem 2: Even if Problem 1 was resolves, extracting a complete set of conclusions about all aspects of underlying physics from 30+ dimensional data set is not realistic
  - We turn to Machine Learning (ML) for additional insight

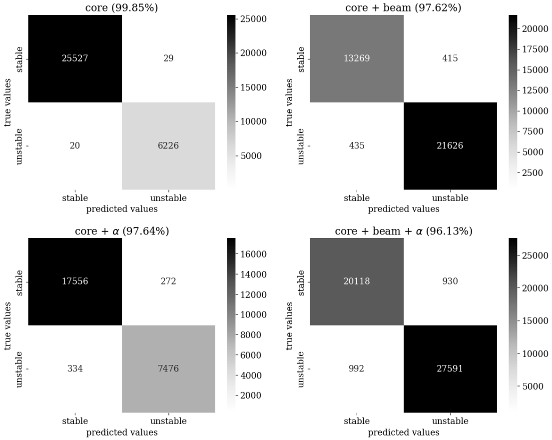
SAVIC Software Setup

- We train Stability Analysis Vitalizing Instability Classification — SAVIC chain of Machine Learning Algorithms that
  - Predict if a given VDF is stable (95.5 - 99.9%) - SAVIC-P
  - Quantify the instability parameters (92.1 - 98.9%) - SAVIC-Q
  - Cluster into groups that represent different types of instabilities - SAVIC-C



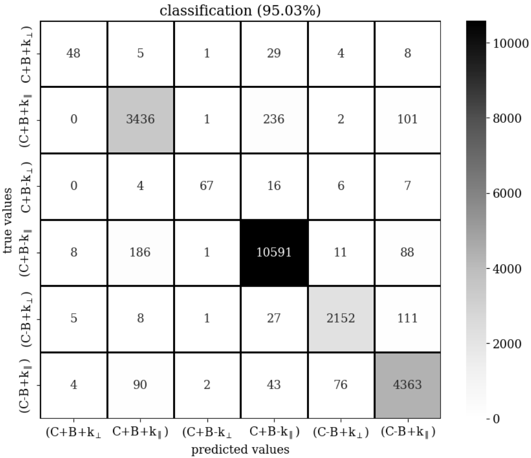
SAVIC-P - Predicting Stability

- Every subset of data works on its own classifier that determines of the VDf is stable or unstable
  - Accuracy varies between 96.1 - 99.9%
- Using parametric curves for core instabilities *decreases* precision of SAVIC-P



SAVIC-Q - Quantifying Instability Parameters

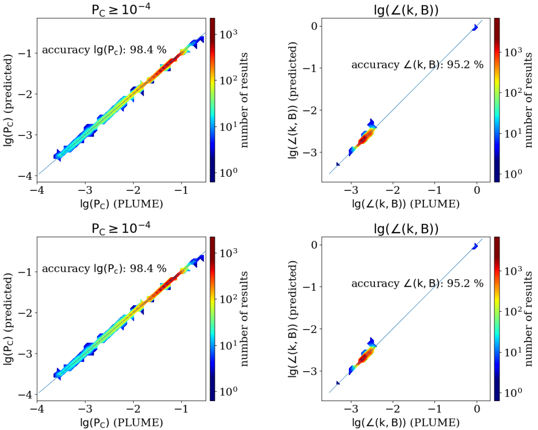
- Every subset (except **C**) of data has an additional classifier that predicts:
  - which mode emits energy (C, B, α, or any combination of the three)
  - angle of propagation k_{max} and the magnetic field
- some groups do not have statistically meaningful number of intervals, and cannot train a follow-up $\mathcal{W}$ regressor



SAVIC-Q - Quantifying Instability Parameters

- Some of the regressors, such as CB C+B- are trained from two groups, using wider parameter range

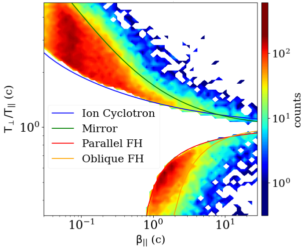
Set	max	groups	reg
C	2	1	1
CB	6	6	4
Cα	6	6	4
CBα	14	8	8

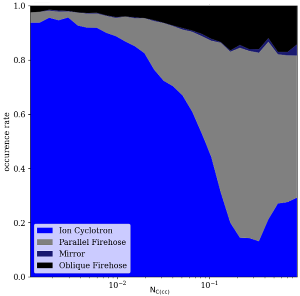


SAVIC-C - Classifying Unstable Modes

- $\mathcal{P}$ and $\mathcal{W}$ (obtained either from PLUMAGE or SAVIC) describe predicted unstable modes, but are just sets of numbers
- Understating the type of instability in question requires understating subtitles of linear theory and a "trained eye"
- For the first time, we automatize the unstable mode detection - recognizing from the textbook lists of linear instabilities
- This new feature enables us to follow *not statistical, but physical* trends in the inner heliosphere

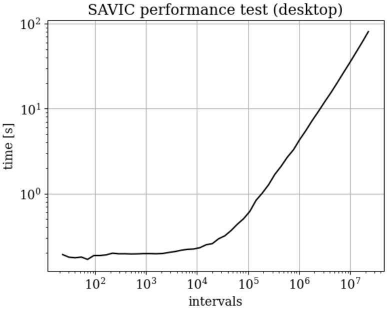
	C	CB	Cα	CBα
# Clusters	4	8	6	12

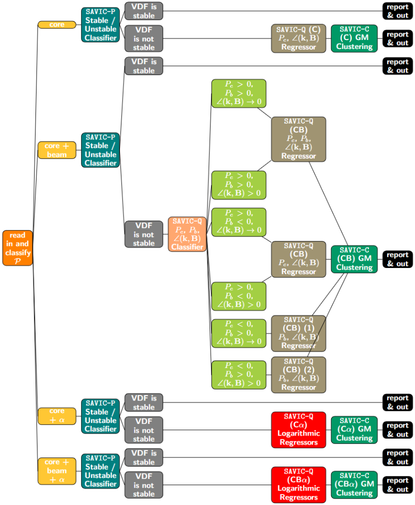




SAVIC Software Overview

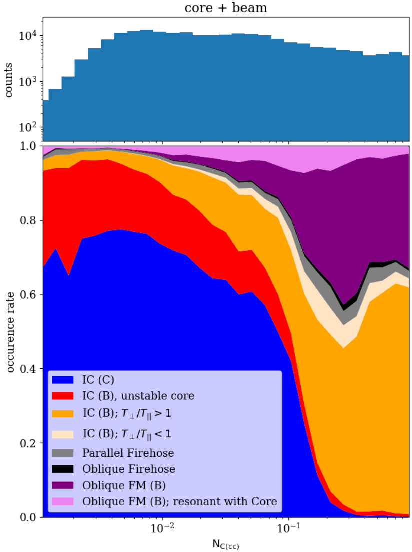
- SAVIC automatically recognizes subsets within the input files and assigns adequate processing chains
- The code is able to process millions of intervals in seconds





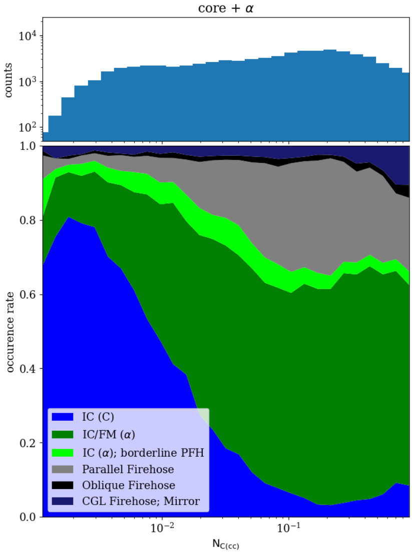
Core + Beam Results

- Sorting by Coulomb number gives expected core to beam transition
    - energy emitted by the core dominates / notably contributes to modes in the young wind
- Parallel (oblique) beam-induced modes are mostly caused by beam anisotropy (drift)
    - at specific drift values, core can absorb part of the energy emitted by the beam
- Old wind (low densities, low drifts) tests limits of Helios instrumentation



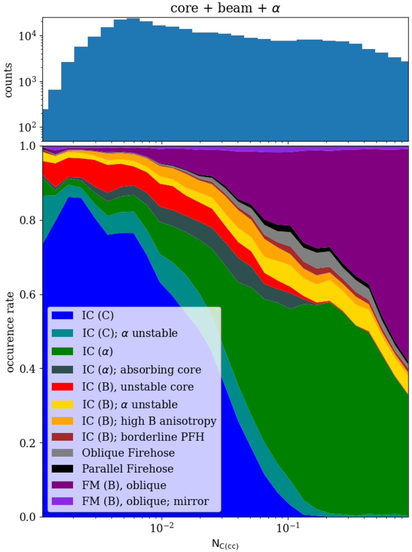
Core + α Results

- 6 clusters instead of 8, α fitted as single Maxwellian - oblique modes are rare
- *Green:* About a third of the parallel modes are FMs induced by the excess parallel pressure of the α component
- *Dark blue:* Identified CGL Firehose can come from undetected beams and increased $T_{\mathrm{eff}\|}$
- *Light green:* Core protons close to FH threshold but are anisotropic enough to resonate with mildly drifted αs



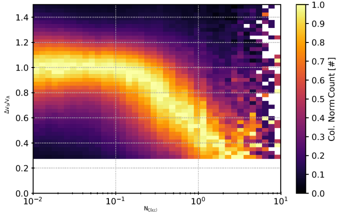
Core + Beam + α Results

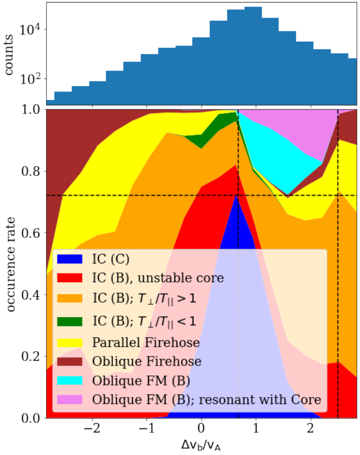
- *Bright purple:* Non-negligible mirror mode
  - sampled in younger wind with high anisotropy
- *Reds:* Beams maintain constant contribution to instability distribution
  - drift makes beams less prone to collisions compared to $C\alpha$
- *Purples:* Oblique FM is still present in the old wind
- *Grey:* Notably lower abundance of Firehose instabilities compared to $C\alpha$ - predicted due to undetected beams



Exploring $\mathcal{P}$ - $\mathcal{W}$ "Multiverse" — Oblique Fast Mode

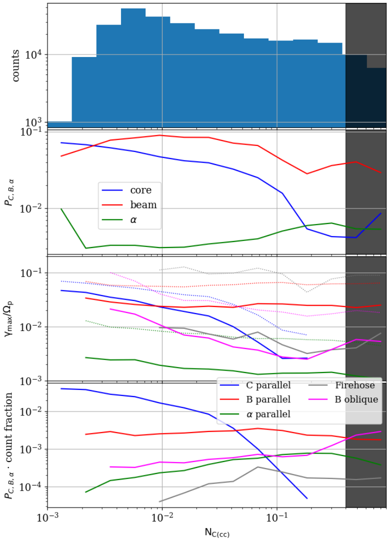
- Oblique Fast Mode (OFM) remains ubiquitous and becomes MUM when other sources of free energy are exhausted
- OFM ensures $\Delta v_b / v_A \to 1$
  - as $v_A \sim r^{-0.65}$, beam drifts of $\sim v_A$ are constantly marginally (un)stable—OFM constantly reduces drift to subafvénic value





Exploring $\mathcal{P}$ - $\mathcal{W}$ "Multiverse" — Emitted Power

- We group 12 CBα clusters in 5 categories
  - The beams seem to emit the most power *per interval*
  - However, the core IC instability is ubiquitous in the young wind - it determines the *total* emitted power
  - deviations of $\gamma_{\max}$ are very large - individual cases can significantly defer from overall statistical description



Part III

Part III - `SAVIC` resources - Access and Usage

How to Use SAVIC? User's Approach

- Short way to use it (works as well as the long way):
  - 1) `pip install savic`
  - 2) `from savic import SAVIC`
  - 3) `SAVIC.SAVIC(<your_input_file>)`
  - that's all!

	beta_par_core	alph_c	tau_b	alph_b	D_b	vv_b	unstable	group	Pow_core	Pow_beam	kB_angle	ins_type
0	1.0	1.0	NaN	NaN	NaN	NaN	False	NaN	NaN	NaN	NaN	NaN
1	0.5	3.2	NaN	NaN	NaN	NaN	True	NaN	0.171887	NaN	0.001113	Ion Cyclotron
2	1.0	0.4	NaN	NaN	NaN	NaN	True	NaN	0.000287	NaN	0.002231	Parallel Firehose
3	12.0	1.2	NaN	NaN	NaN	NaN	True	NaN	0.001800	NaN	0.001649	Ion Cyclotron
4	1.0	1.0	1.0	1.0	0.05	0.5	False	NaN	NaN	NaN	NaN	NaN
5	1.5	2.5	0.8	1.0	0.05	0.5	True	3.0	0.193271	0.000000	0.004137	IC (B), unstable core
6	0.5	1.0	1.0	3.5	0.10	1.5	True	5.0	0.000000	0.123028	0.003983	IC (B); $T_{\perp}/T_{\|\|} > 1$
7	0.8	1.1	1.0	1.2	0.05	1.8	True	5.0	0.000000	0.004923	0.001414	IC (B); $T_{\perp}/T_{\|\|} > 1$
8	0.5	0.7	0.8	0.8	0.01	0.2	False	NaN	NaN	NaN	NaN	NaN

So, what happens in the background?

How to Use SAVIC? More Details

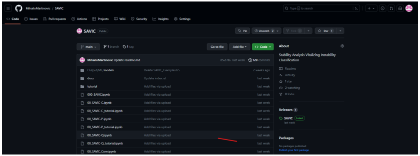
- SAVIC sort the input and calls one of the four chains:
  - SAVIC_Core, SAVIC_CoreBeam, SAVIC_CoreAlpha, SAVIC_CoreBeamAlpha
  - Each chain calls its own versions of SAVIC-P, SAVIC-Q, and SAVIC-C
- Each sub-algorithm has its own internal input and output and can be called separately if needed
- Each sub-algorithm contributes to the final output

	beta_par_core	alph_c	tau_b	alph_b	D_b	vv_b	unstable	group	Pow_core	Pow_beam	kB_angle	ins_type
0	1.0	1.0	NaN	NaN	NaN	NaN	False	NaN	NaN	NaN	NaN	NaN
1	0.5	3.2	NaN	NaN	NaN	NaN	True	NaN	0.171887	NaN	0.001113	Ion Cyclotron
2	1.0	0.4	NaN	NaN	NaN	NaN	True	NaN	0.000287	NaN	0.002231	Parallel Firehose
3	12.0	1.2	NaN	NaN	NaN	NaN	True	NaN	0.001800	NaN	0.001649	Ion Cyclotron
4	1.0	1.0	1.0	1.0	0.05	0.5	False	NaN	NaN	NaN	NaN	NaN
5	1.5	2.5	0.8	1.0	0.05	0.5	True	3.0	0.193271	0.000000	0.004137	IC (B), unstable core
6	0.5	1.0	1.0	3.5	0.10	1.5	True	5.0	0.000000	0.123028	0.003983	IC (B); $T_\perp/T_\parallel > 1$
7	0.8	1.1	1.0	1.2	0.05	1.8	True	5.0	0.000000	0.004923	0.001414	IC (B); $T_\perp/T_\parallel > 1$
8	0.5	0.7	0.8	0.8	0.01	0.2	False	NaN	NaN	NaN	NaN	NaN

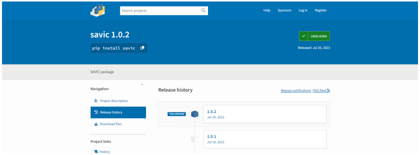
input data (beta_par_core … vv_b) — SAVIC-P (unstable) — SAVIC-Q (group … kB_angle) — SAVIC-C (ins_type)

How to Use SAVIC? For Developers

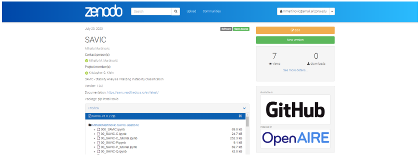
Explore *Jupyter* Notebooks



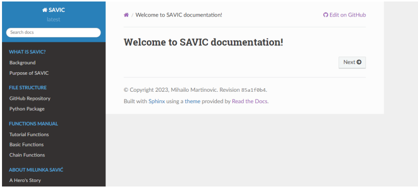
Explore Version History



Download the Source Code



Read detailed documentation



Conclusions

- Stability analysis of $\sim$1.5M of Helios VDF measurement reveals *linear* trends with radial distance in both occurrence rate and intensity, while the trends are *exponential* with Coulomb number
- We are able, for the first time, to provide a comprehensive mapping of solar wins instabilities using ML algorithms
- Young solar wind plasma emits unstable waves mostly due to proton *core* anisotropy; proton *beam* and α particles are more important in the older solar wind
- *Beam* stability is less affected by collisions than other components
- *Oblique Fast Mode* acts as a “guardian” of the *beam* drift stability
  - this mode is probably dominant in 2-4 AU range

Public Repository Info

Article I in *ApJ*
[Martinović et al., 2021]

Article II in *ApJ*
[Martinović and Klein, 2023]

`SAVIC` code on *GitHub*

`SAVIC` Python Package on *PiPy*

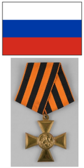
`SAVIC` Tutorial on *ReadTheDocs*

`SAVIC` *Zenodo* Release

THANK YOU

Milunka Savić (1889 - 1973)

- Volunteered for World War I, disguised as a man
- First exception to send a women to the front lines
  - after being awarded Karađorđe star in hospital
- Moved on to become the most decorated female warrior in history



- Declined French military pension to stay in Serbia
  - Raised over 30 wartime orphans and children from her home village
- `SAVIC` code went public 50 years after Milunka's death

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