UiT The Arctic University of Norway

Double-peaked dust impact electrical signatures partially explained

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RPW meeting 2023, Praha

Outline

- Introduction
  - Interplanetary dust
  - Impact ionization
- What we found with RPW
  - New signals observed
  - Unsurprising
  - Surprising

Introduction

Solar system‘s dust cloud

- Dynamic
- Sources
  - Comets
  - Interstellar dust
- Sinks
  - P-R drag
  - Ejection

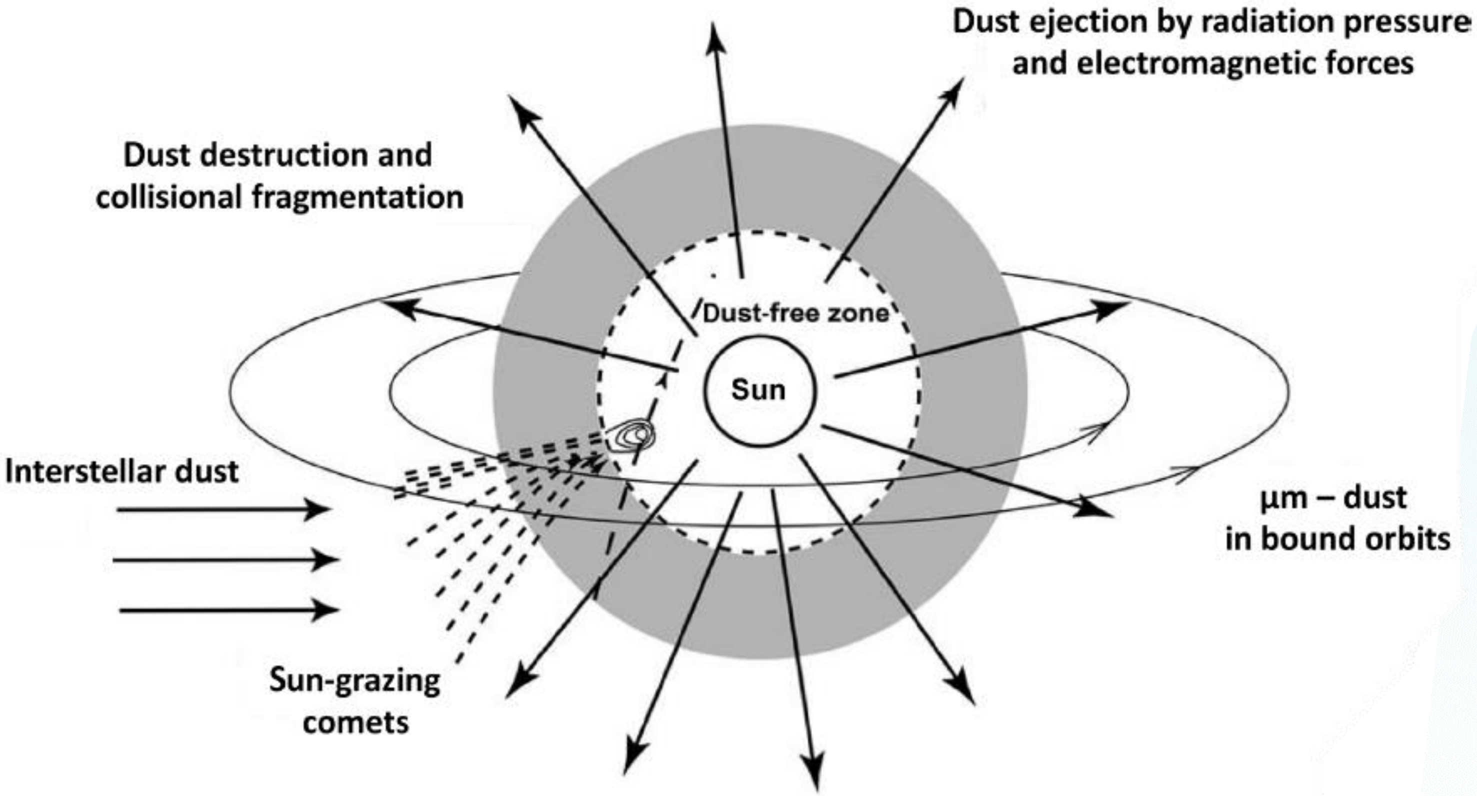


Fig. 1 from Mann et al. (2019)

Hypervelocity collisions

Material strength $\ll$ inertial stress

Melting steel: $1\frac{MJ}{kg} \Rightarrow 700m/s$

Burning coal: $24\frac{MJ}{kg} \Rightarrow 3{,}5km/s$

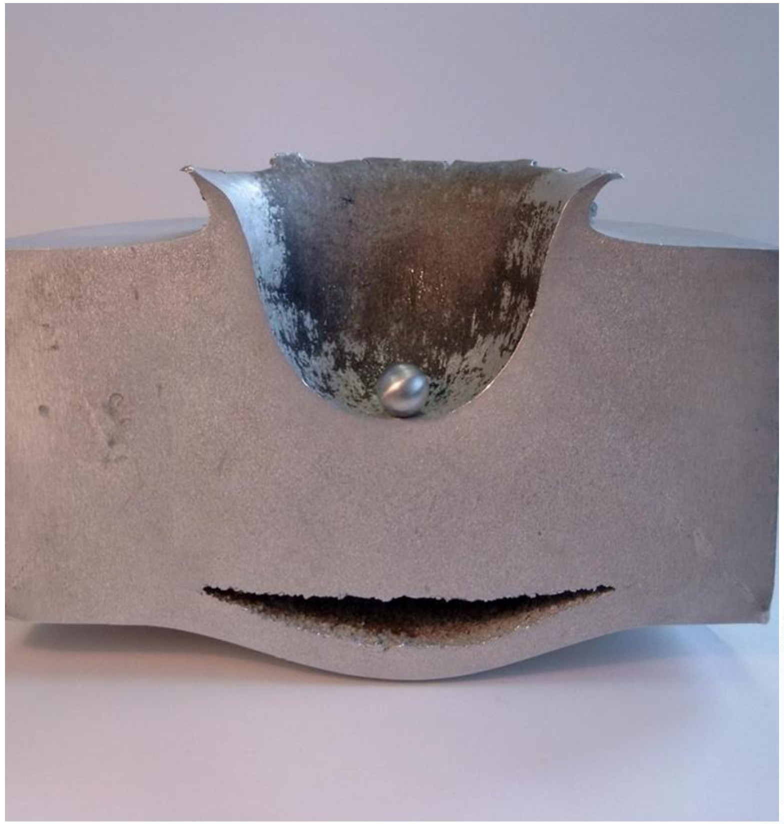
Ionizing Na: $21\frac{MJ}{kg} \Rightarrow 3{,}2km/s$

Ionizing H: $0.55\frac{GJ}{kg} \Rightarrow 18km/s$

Speeds in space

Earth‘s orbital speed $\approx 30km/s$

Sun relative to ISM $\approx 25km/s$



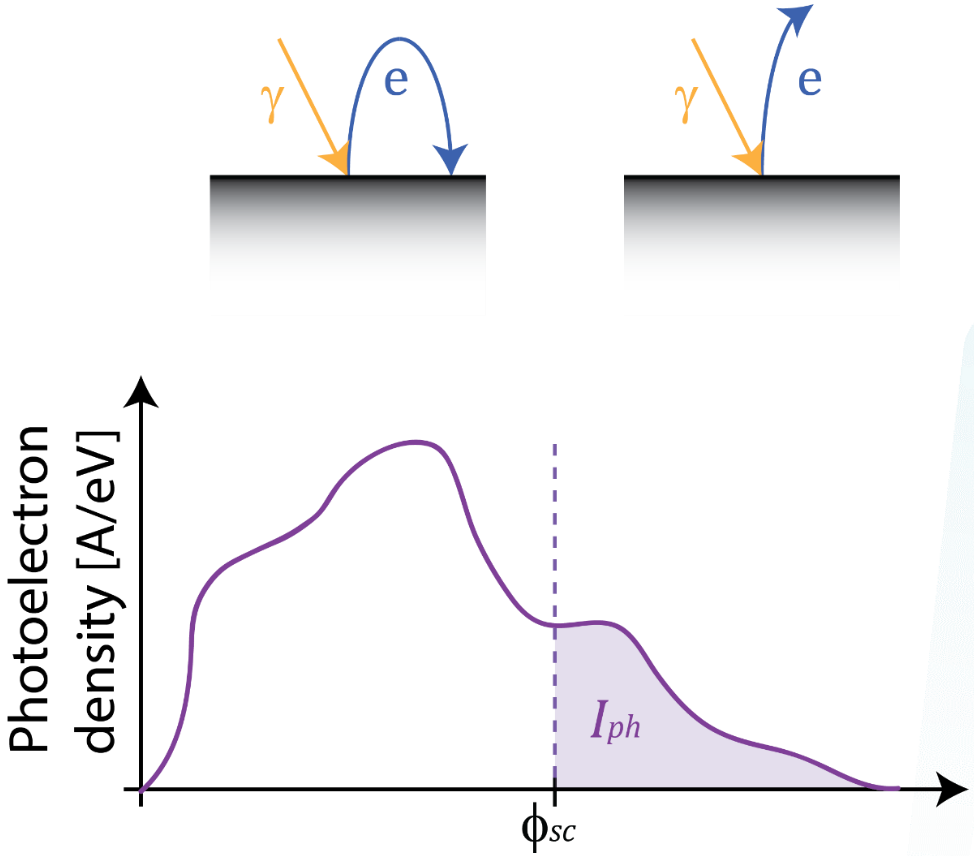
Spacecraft's floating potential

$$0 = I^{+}_{SW}(\phi) - I^{-}_{SW}(\phi) + I^{-}_{ph}(\phi)$$

Solar wind ≪ Photocurrent

$$\phi_{sc} > 0$$

Attraction ⊖ ⊕ **Repulsion**

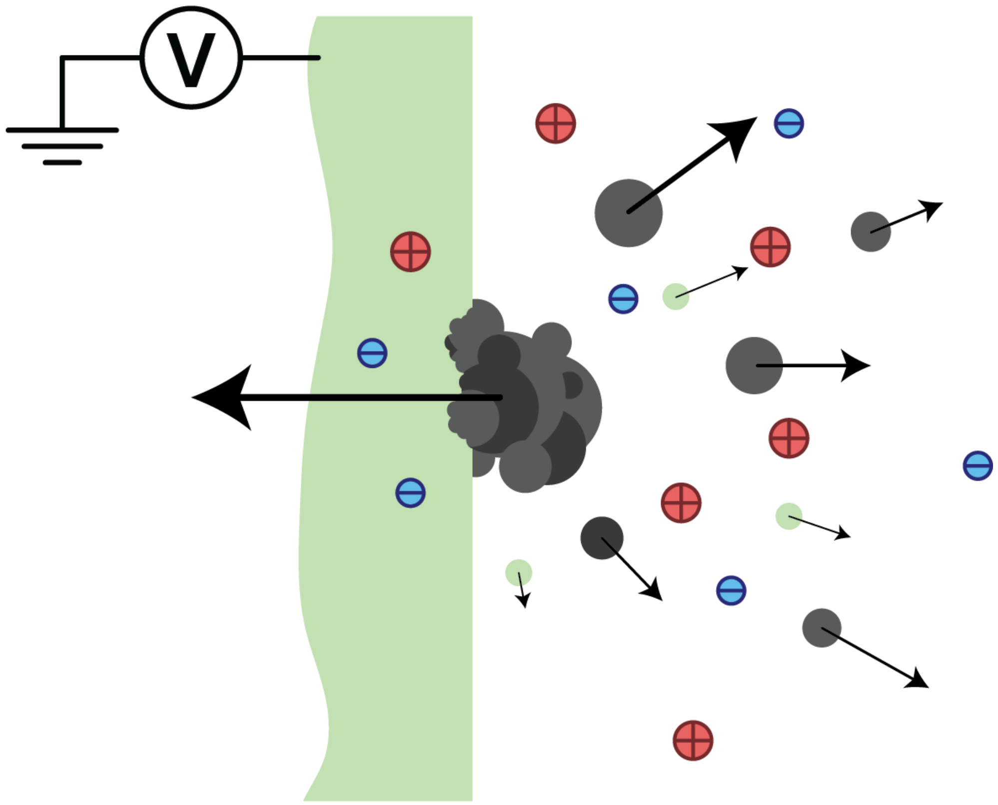


Impact ionization

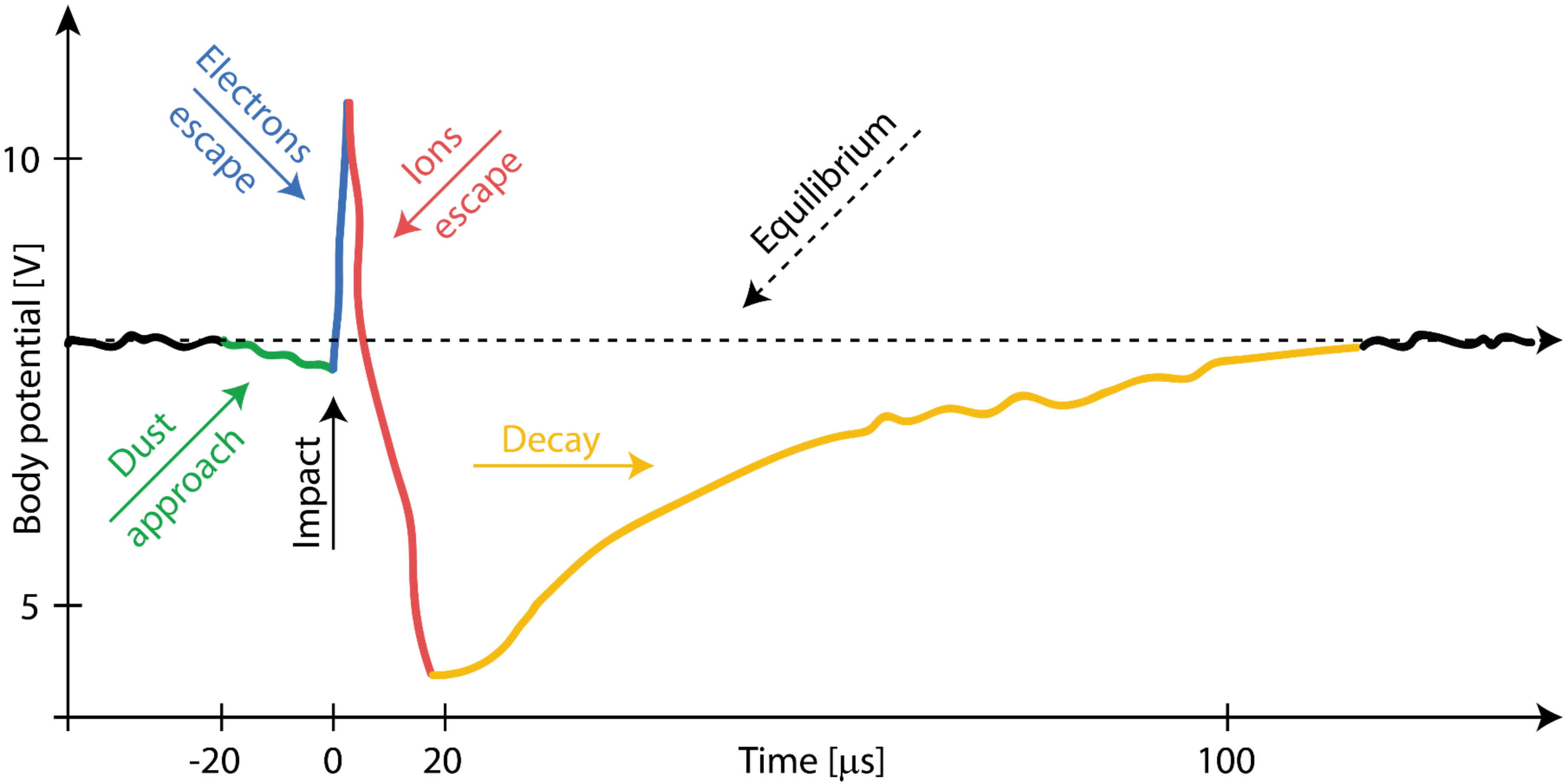
Impact cloud:

- Neutrals ○ ○
- Electrons ⊖
- Ions ⊕
- Partial thermalization

$$v_{electrons} \gg v_{ions}$$



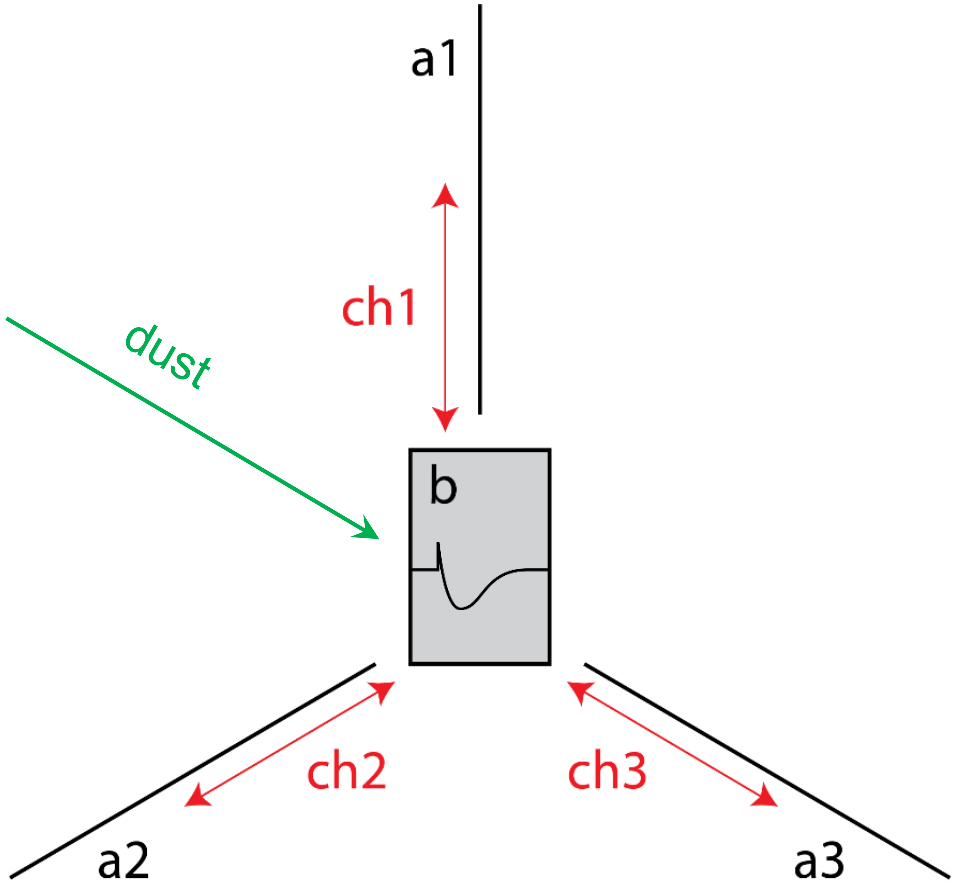
Dust impact signature - potential

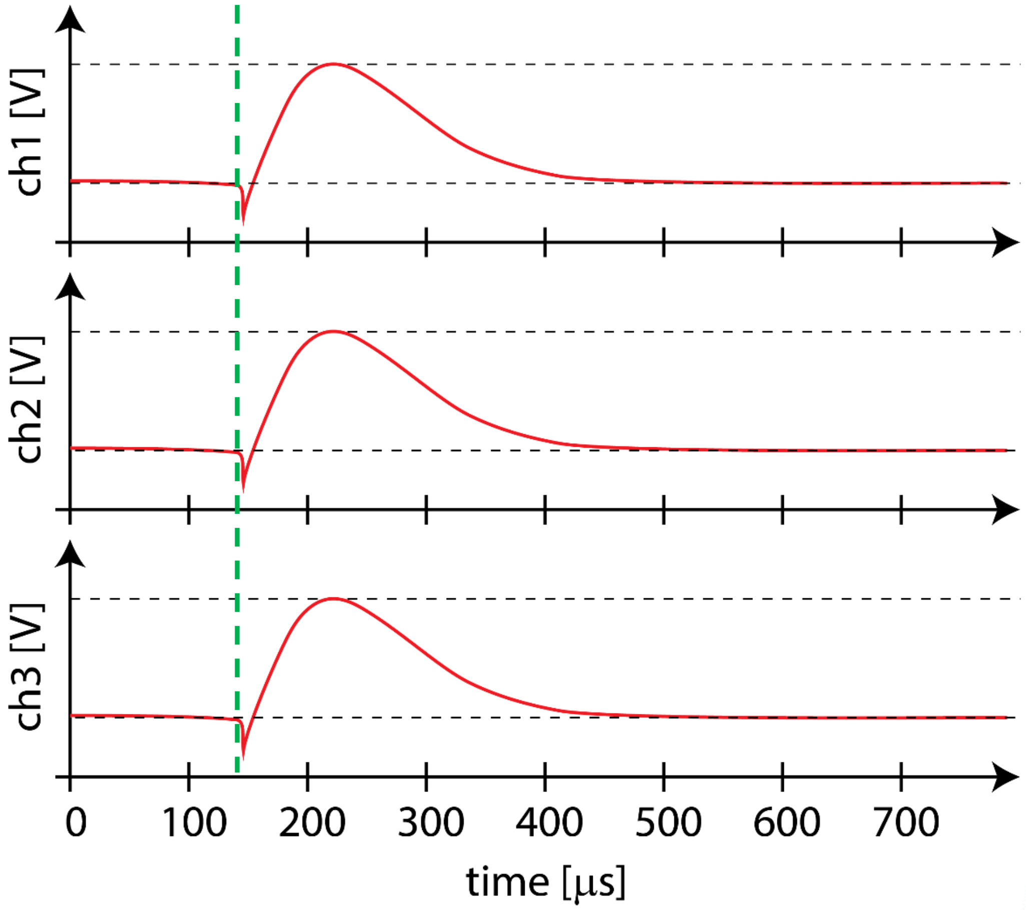


What we found in RPW data

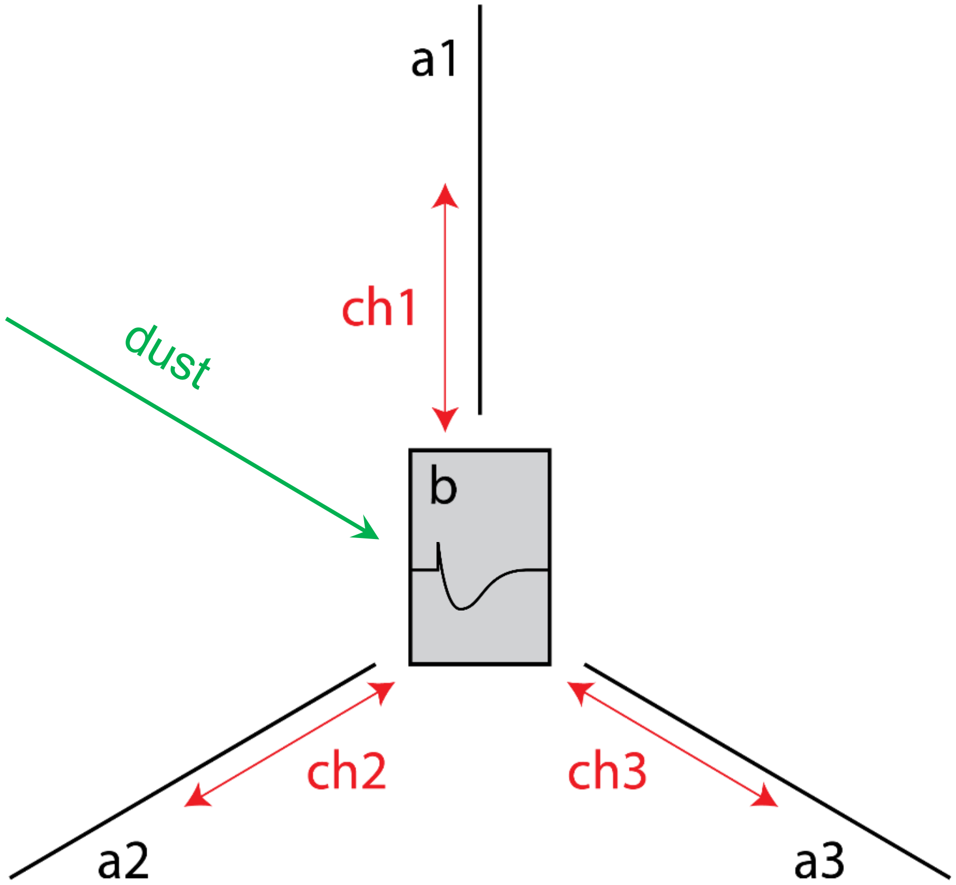
(solo_L2_rpw-tds-surv-tswf-e_YYYYMMDD_V0X.cdf)

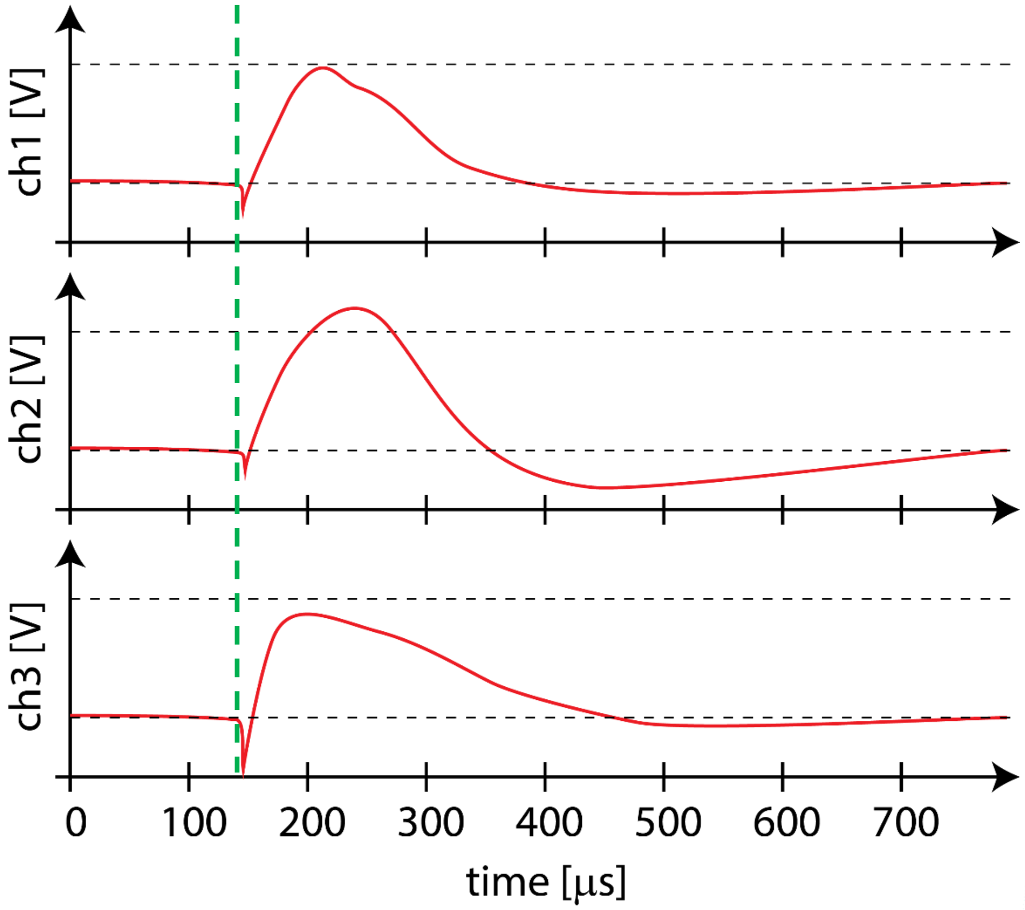
3x monopole (ideal)





3x monopole (more realistic)



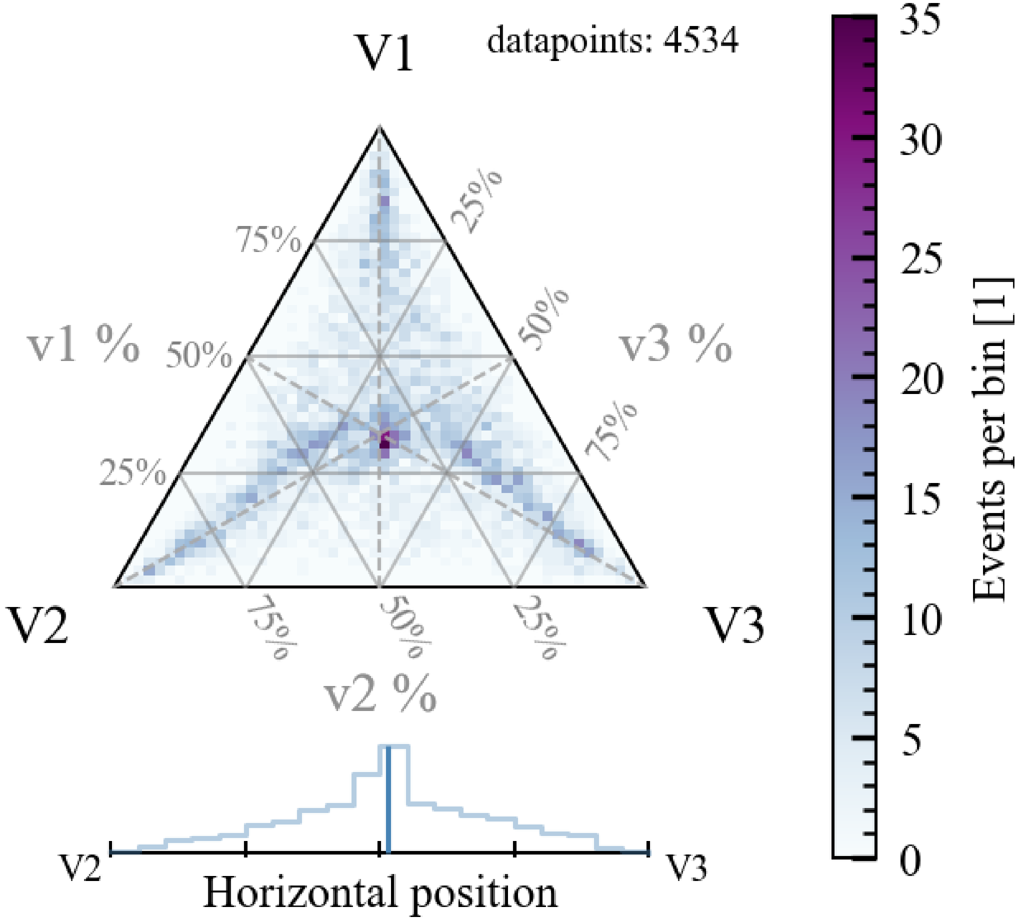


Antennas compared

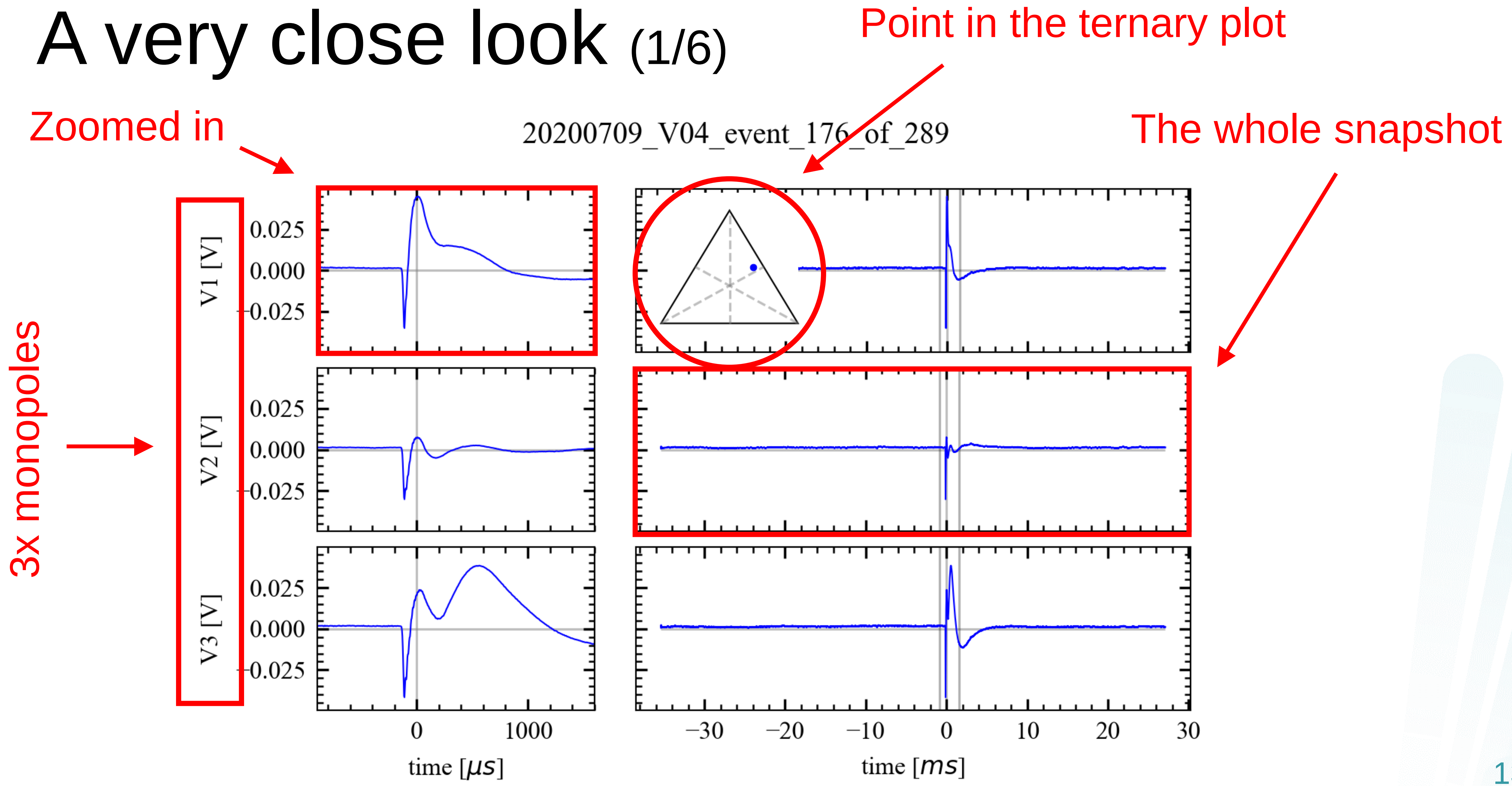
- Technically: monopoles reconstructed from XLD1
- Ternary plot of maxima:

$$V1 + V2 + V3 = 100\%$$

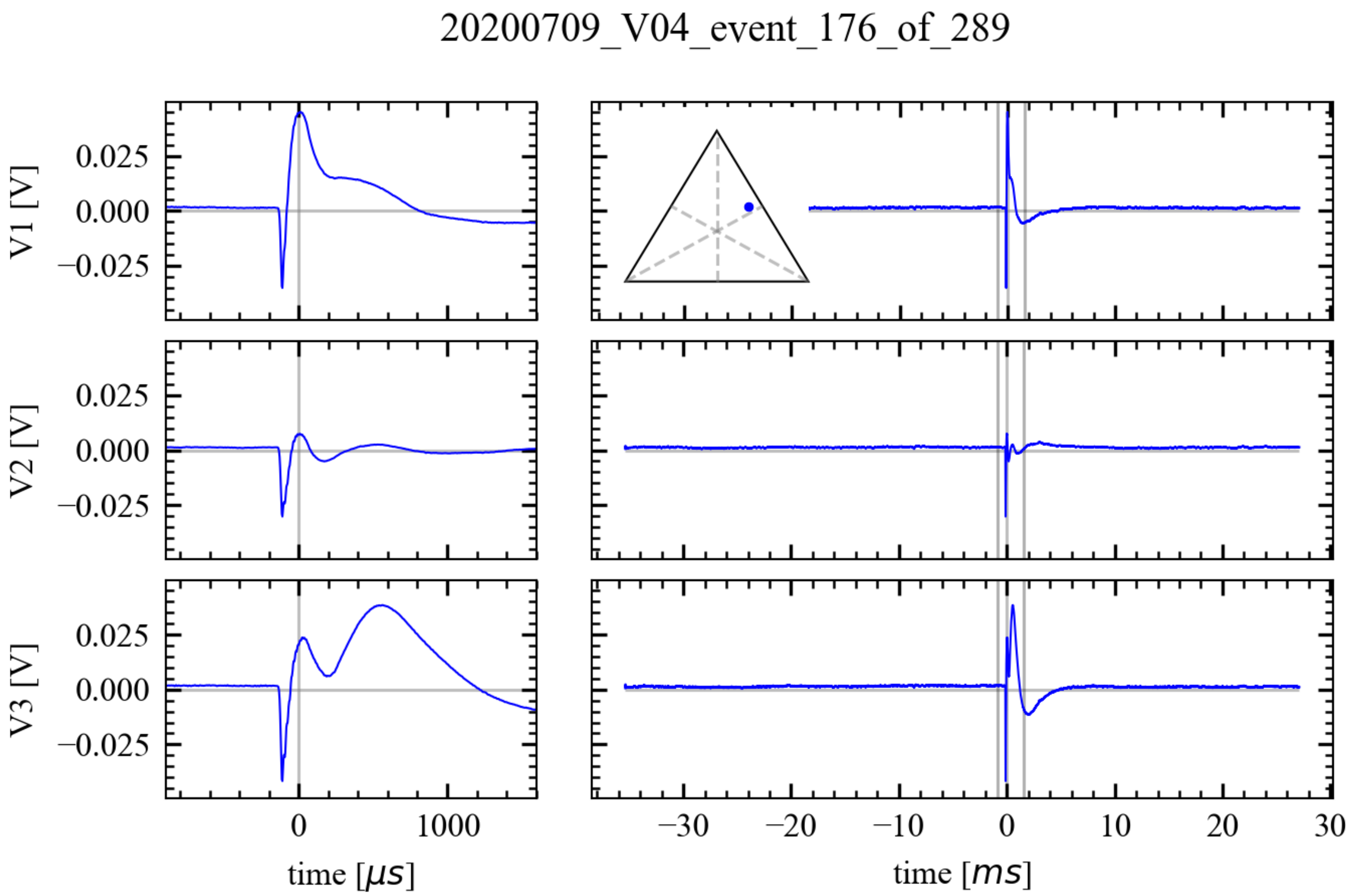
- 3 antennas show **different amplitudes**



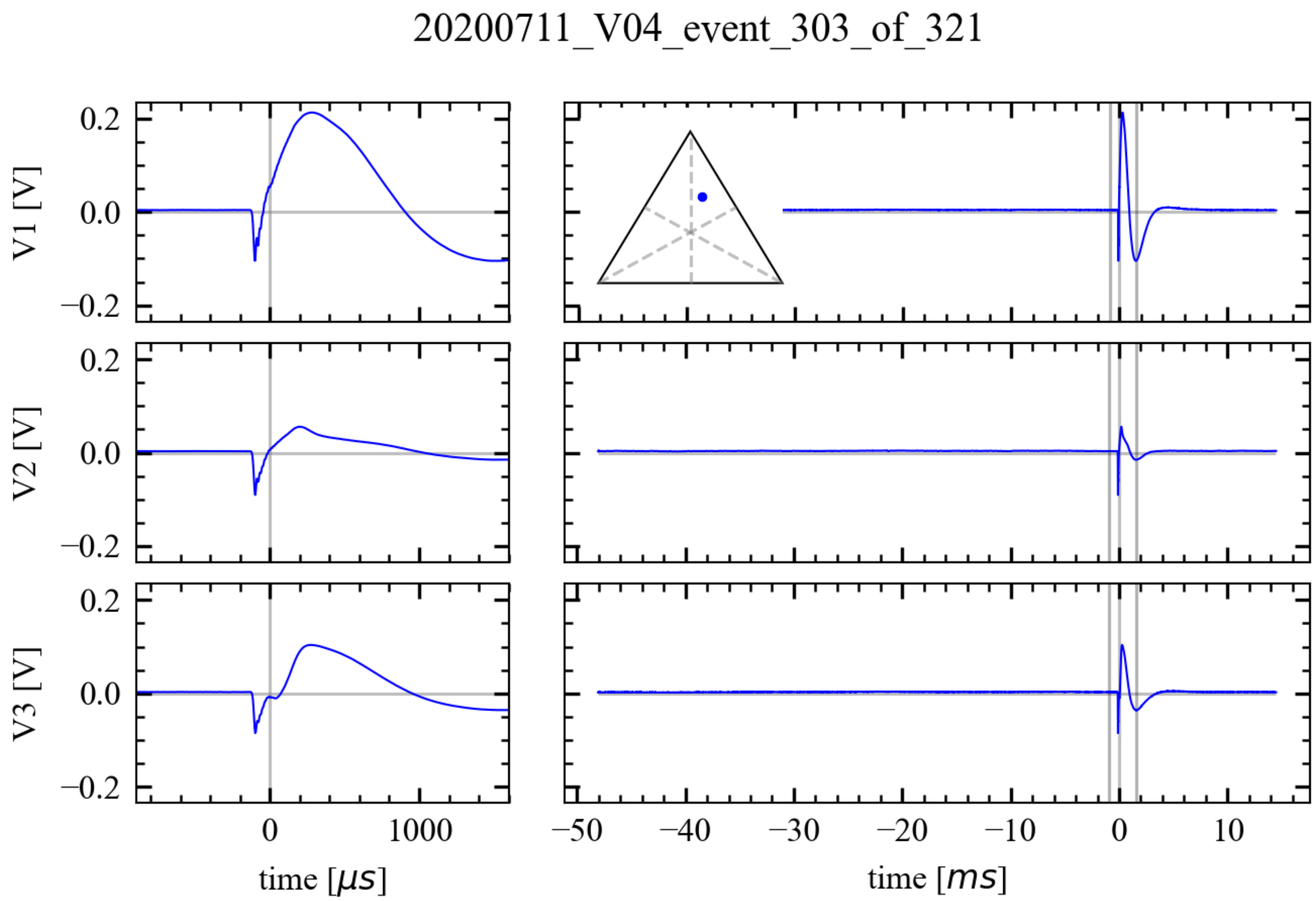
A very close look (1/6)



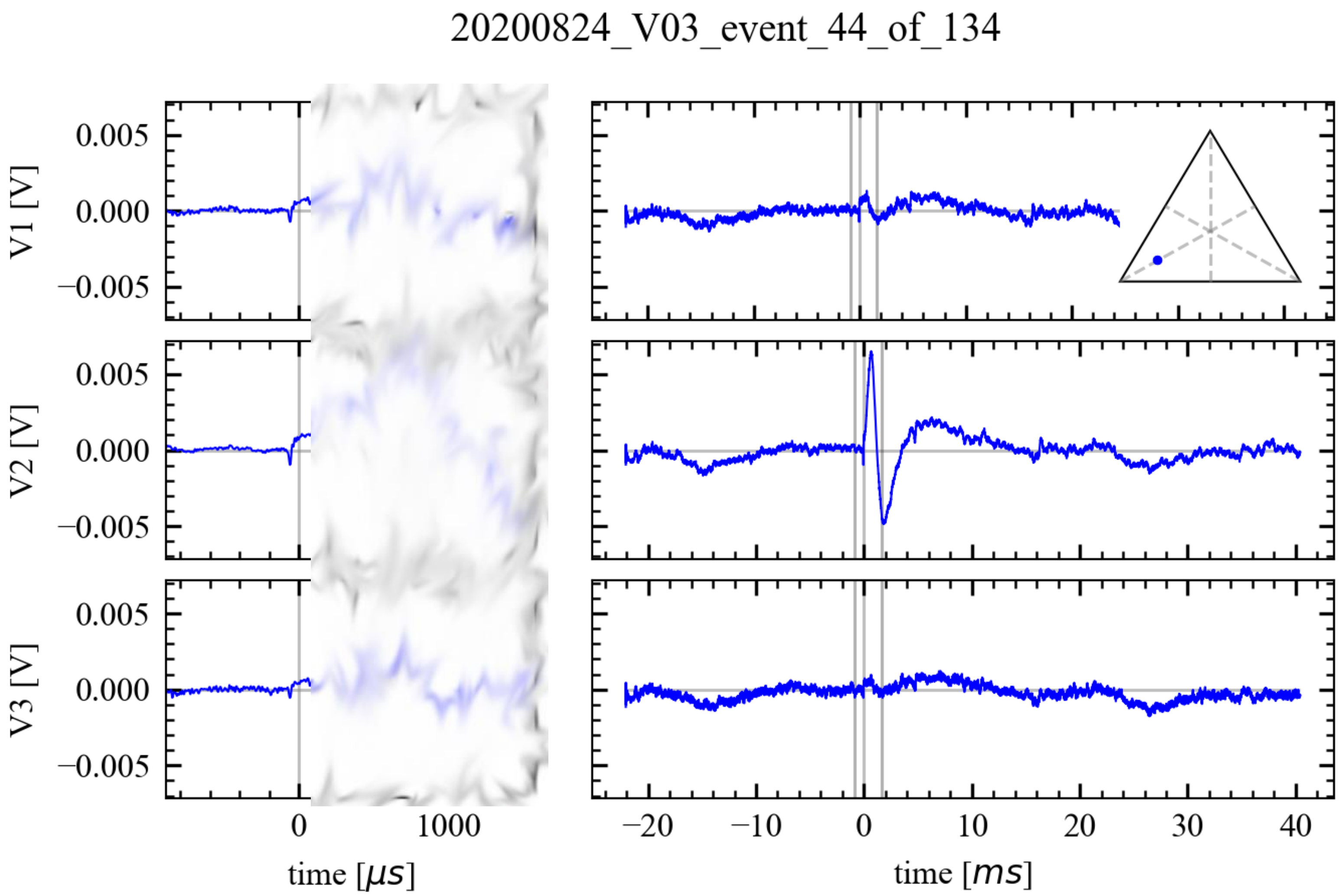
A very close look (1/6)



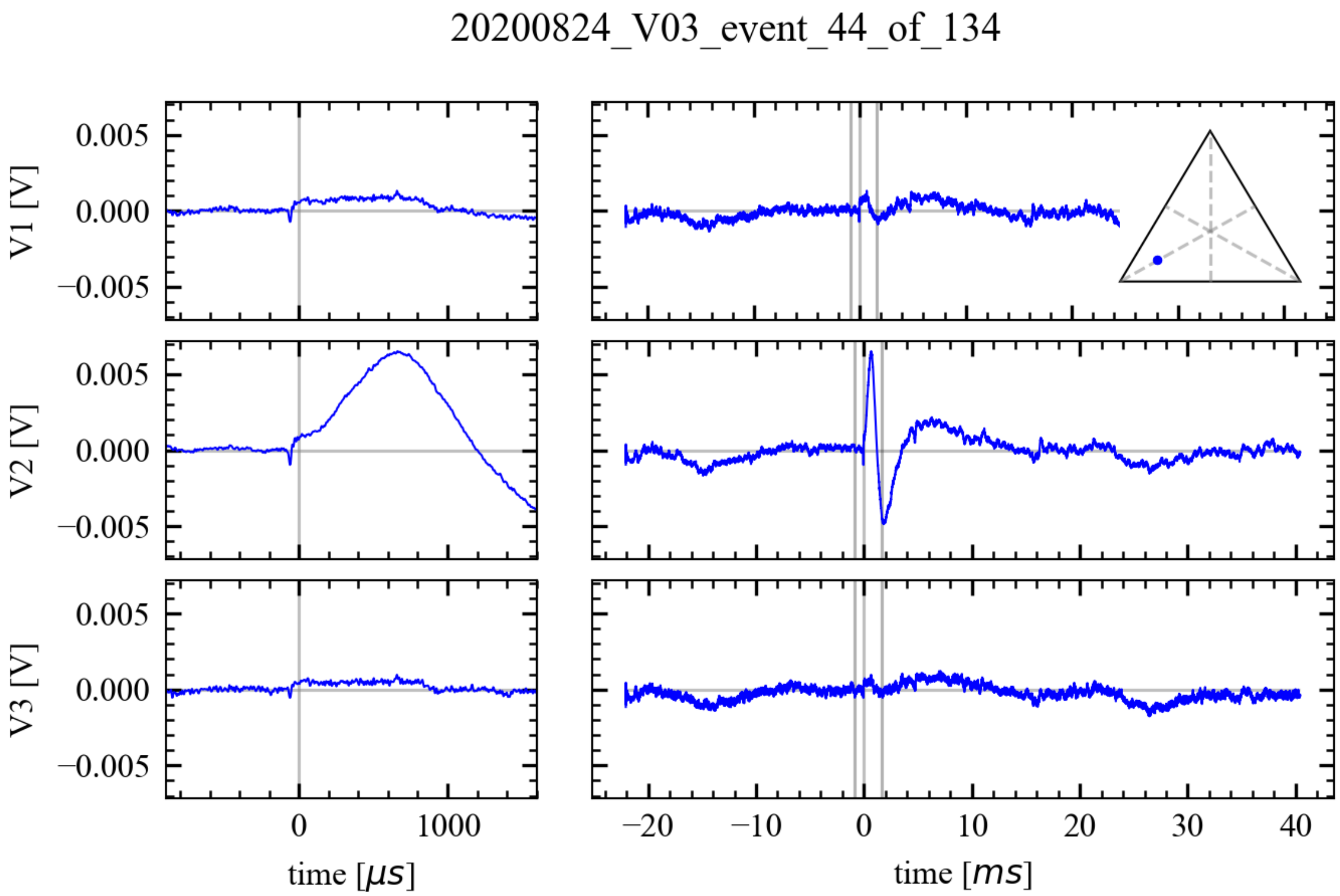
A very close look (2/6)



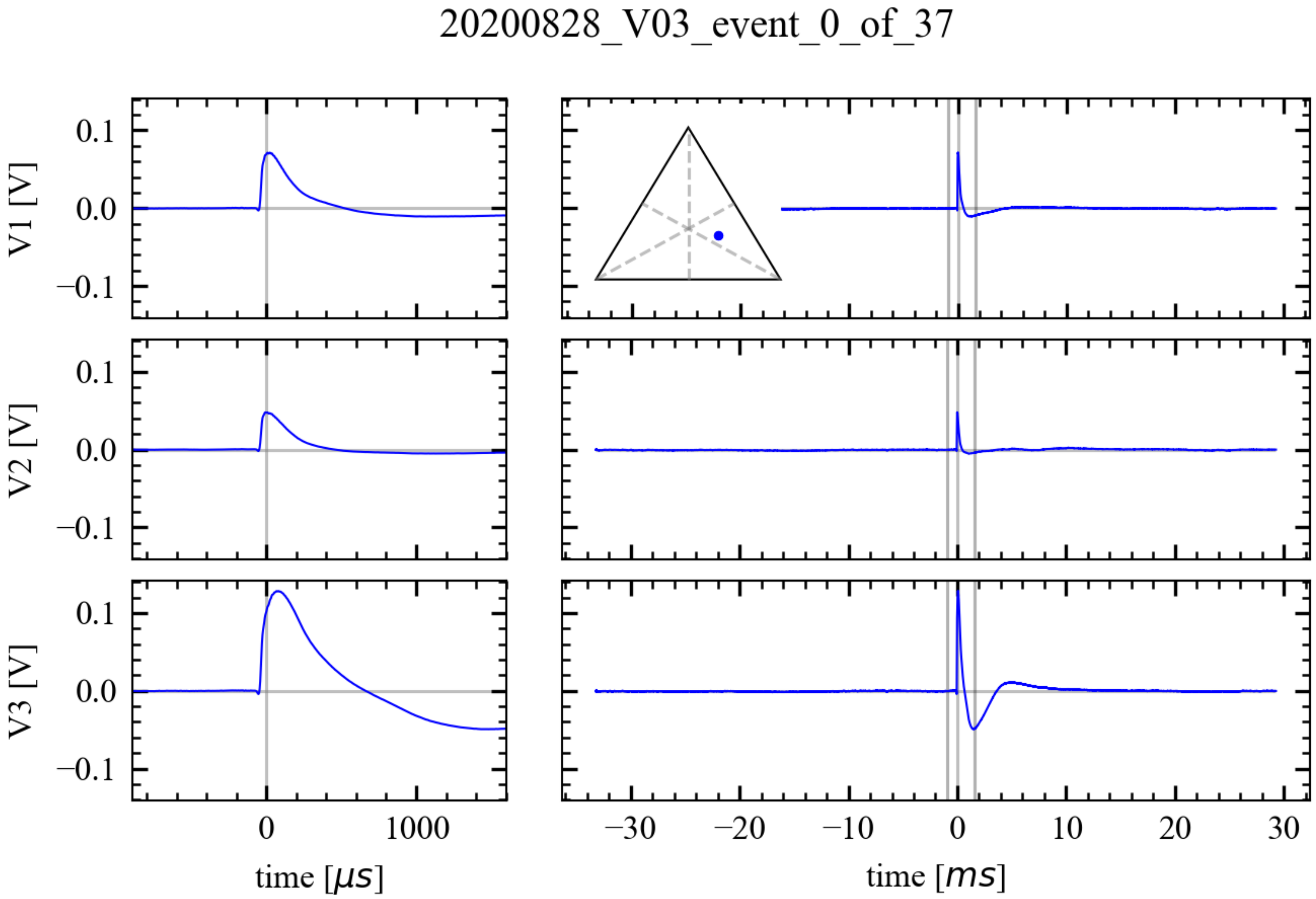
A very close look (3/6)



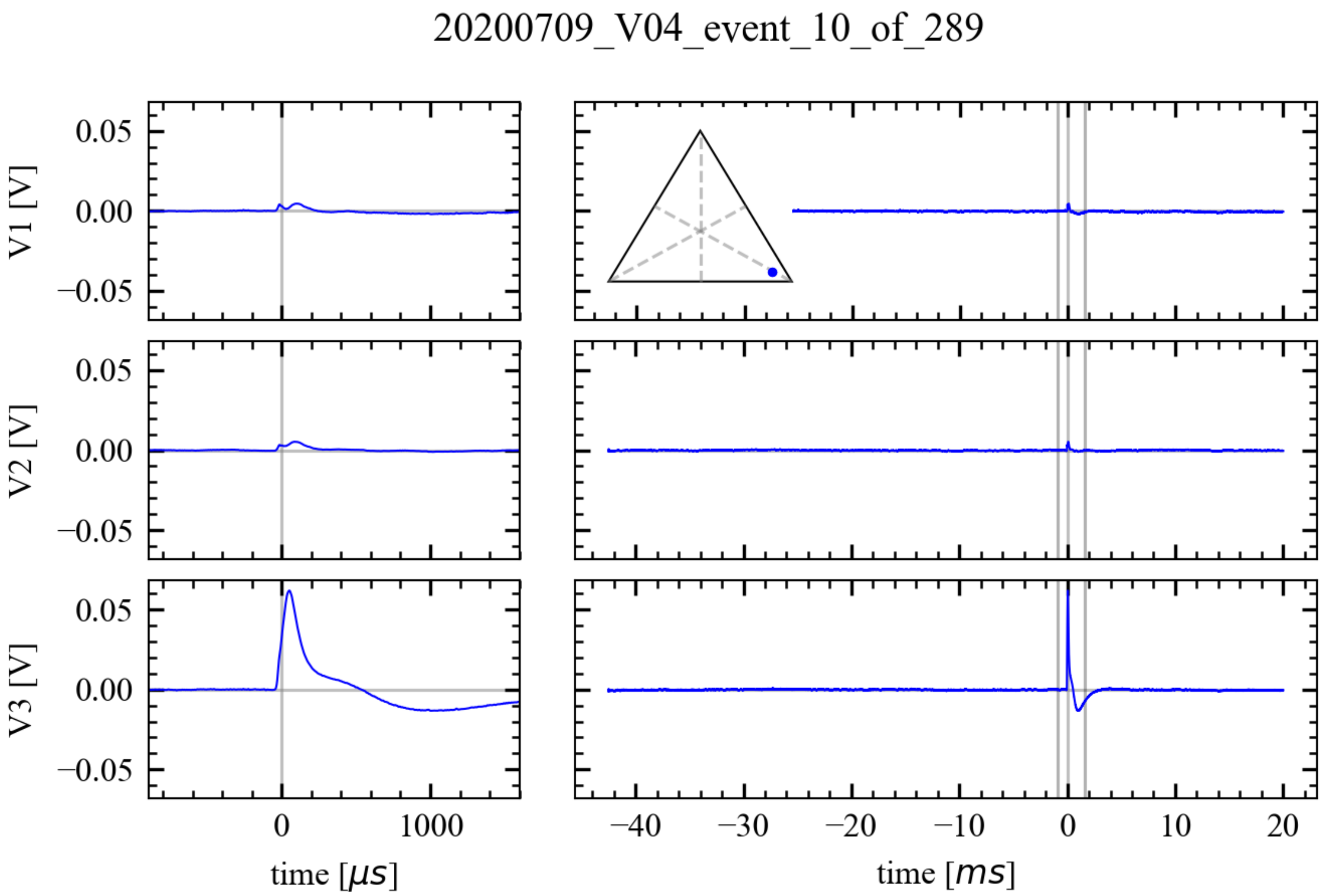
A very close look (3/6)



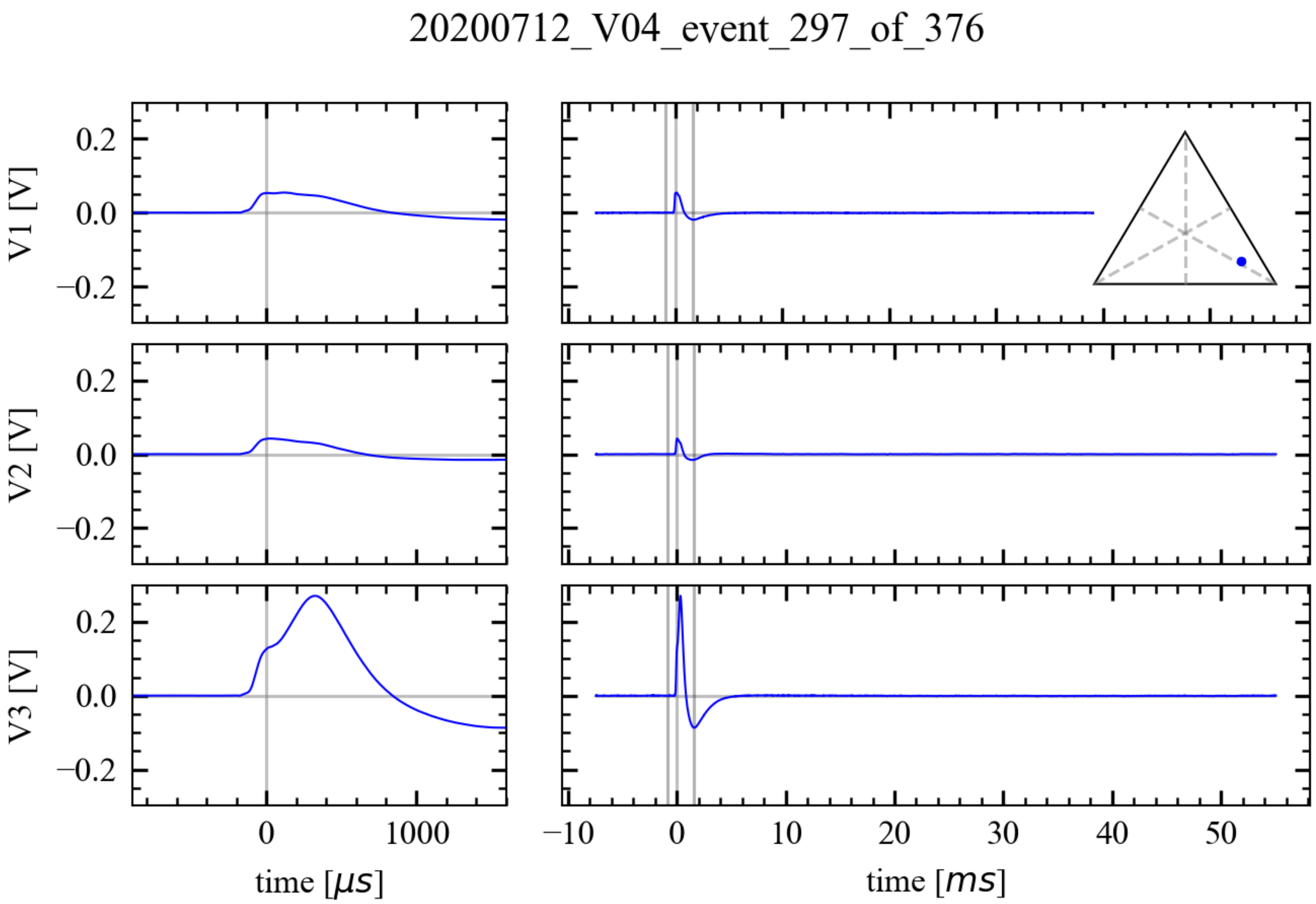
A very close look (4/6)



A very close look (5/6)



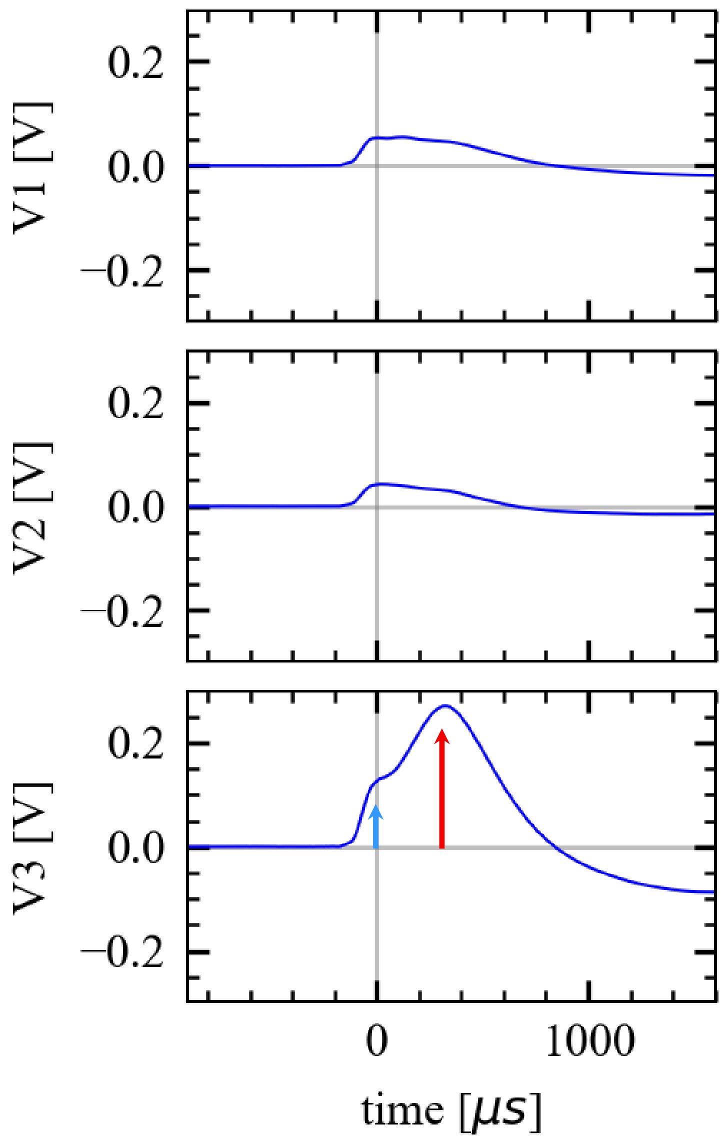
A very close look (6/6)



An observation

2 peaks of the same polarity

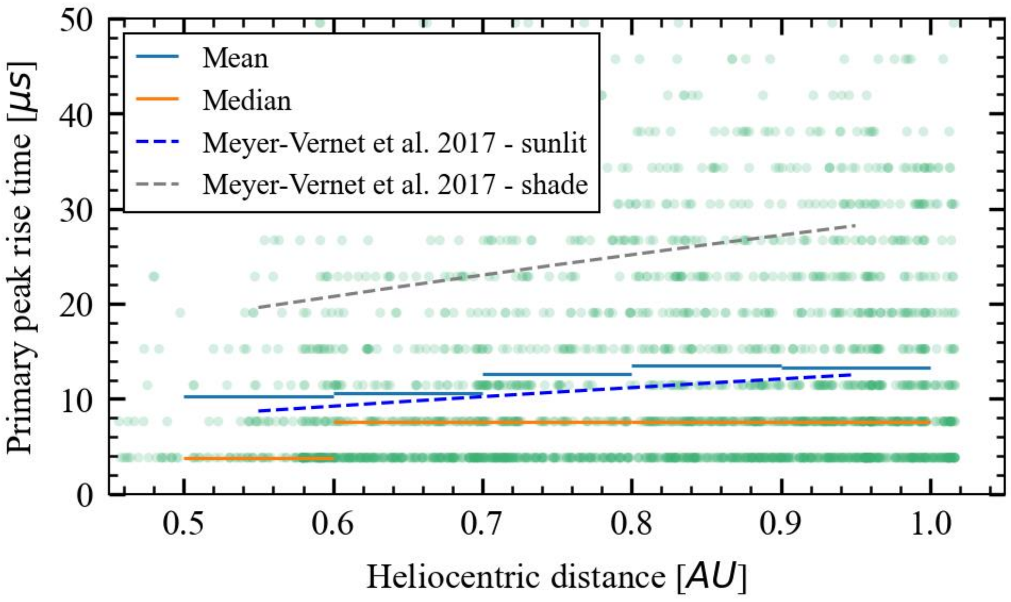
- Primary (first in time)
  - Consistent ⇒ body
  - Irregularities $\pm 50\%$
- Secondary (second in time)
  - Inconsistent ⇒ antenna



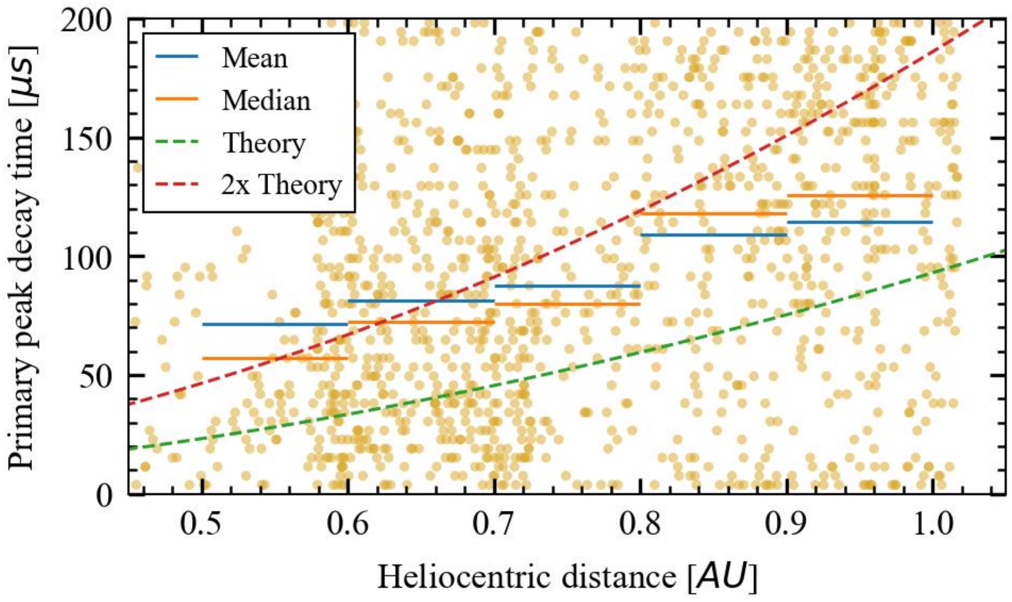
Primary peak

Mean primary peak – understood!

Rise time ✓



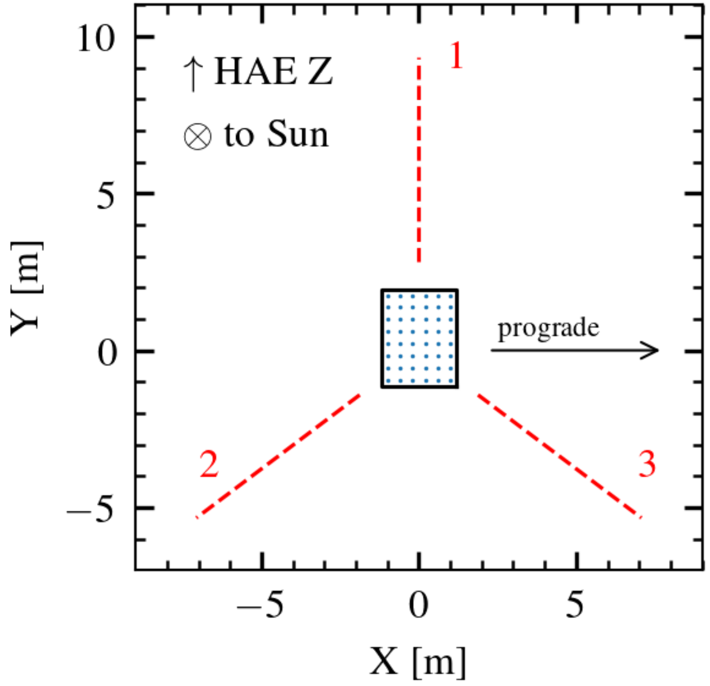
Decay time ✓



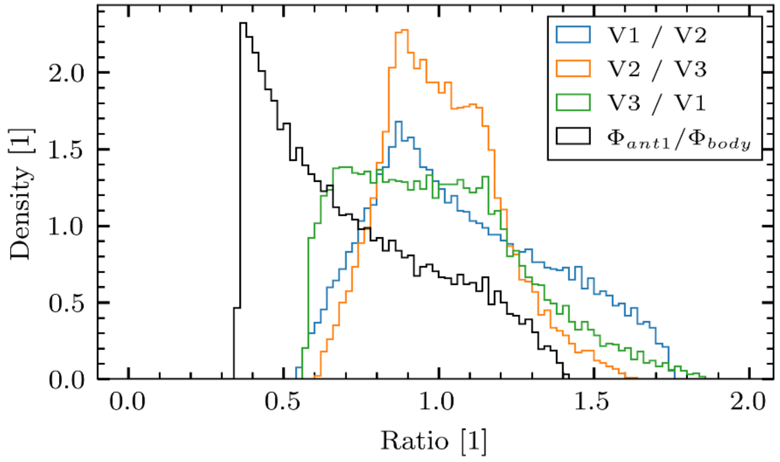
Expected, understood!

Asymmetry of the primary peak

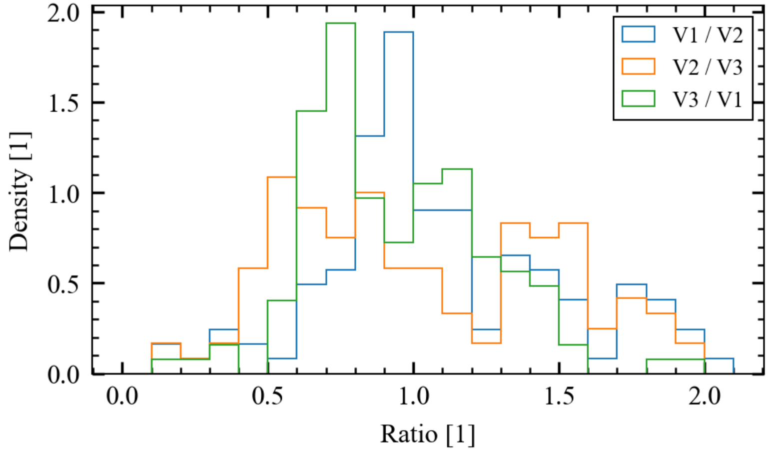
Ion leftover: induction on the antennas



MC model



data



✓

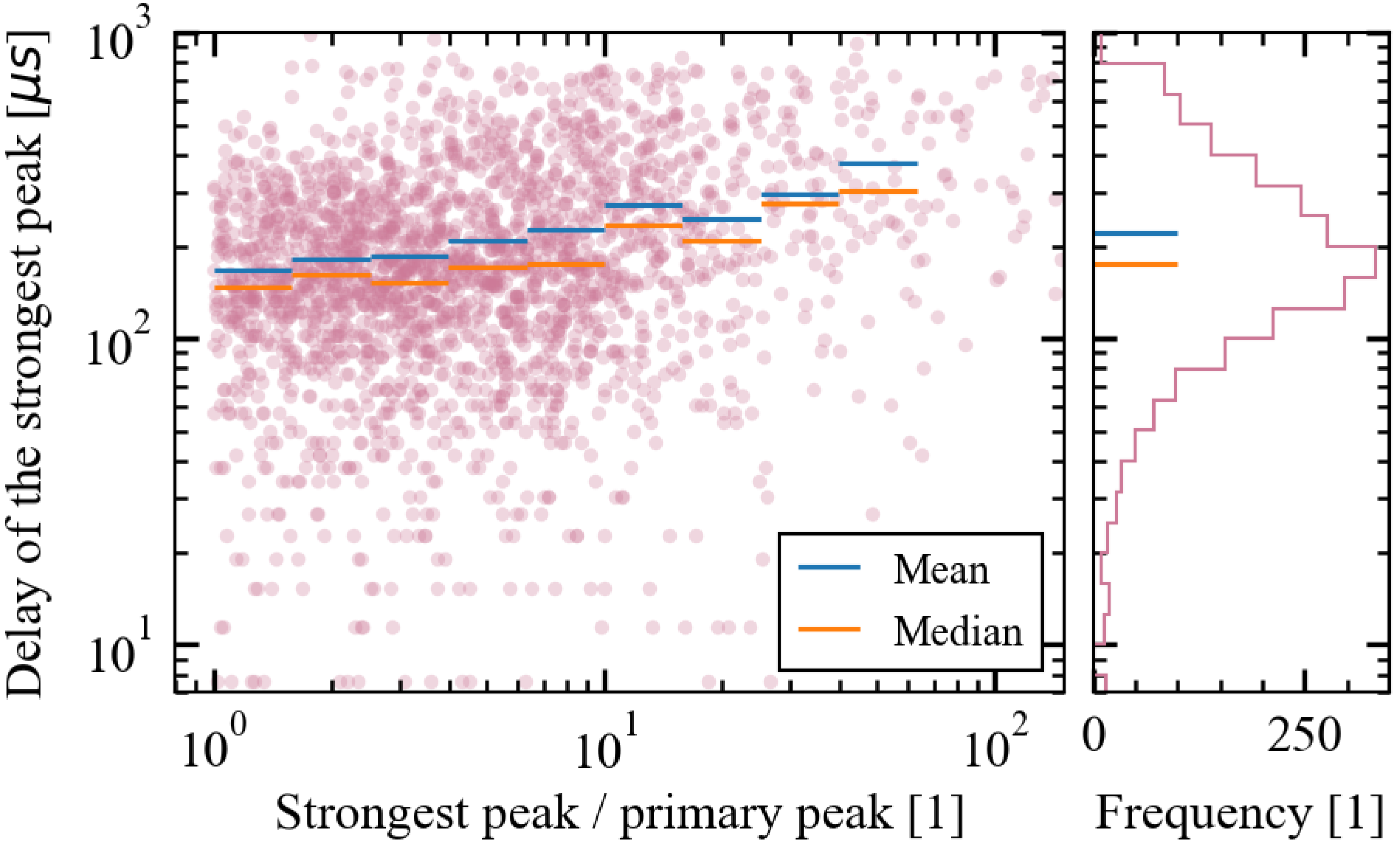
Secondary peak

Secondary peak‘s delay

$100 - 300\ \mu s$

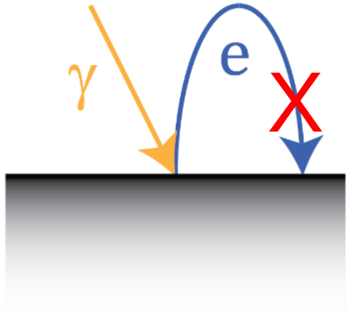
Ion motion timescale!

Relative amplitude - important?



Pantellini effect for cylindrical antennas

Photoelectron return current blocked



Possible current towards the body? Opinions?

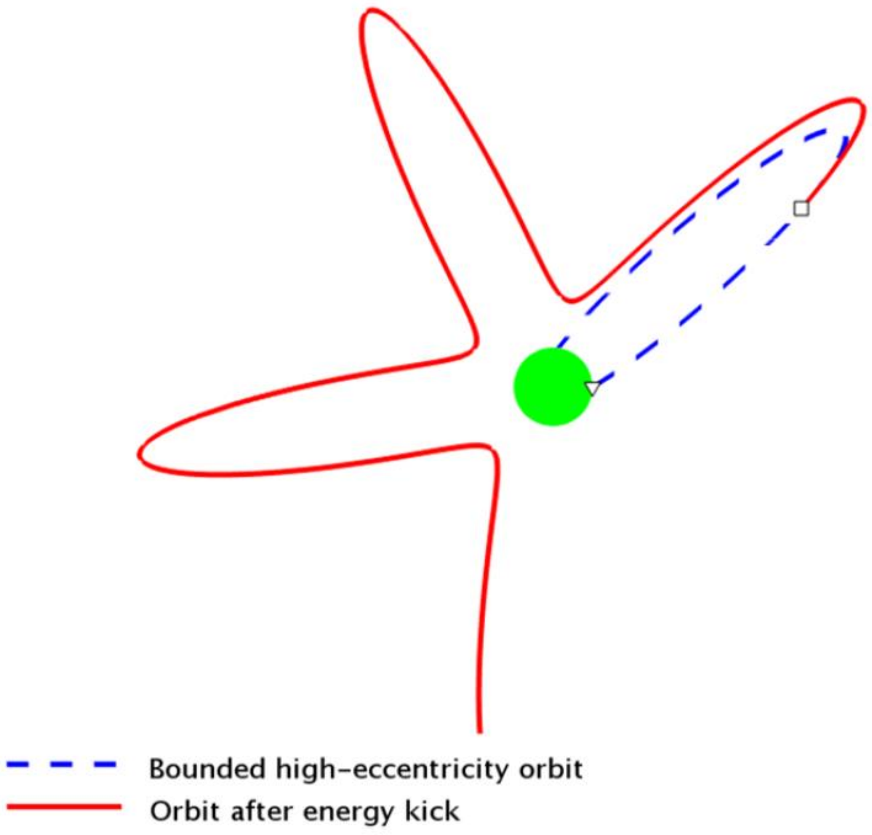


Fig. 2 from [1]

[1] Pantellini, F., Belheouane, S., Meyer-Vernet, N., & Zaslavsky, A. (2012). Nano dust impacts on spacecraft and boom antenna charging. *Astrophysics and Space Science*, *341*, 309-314.

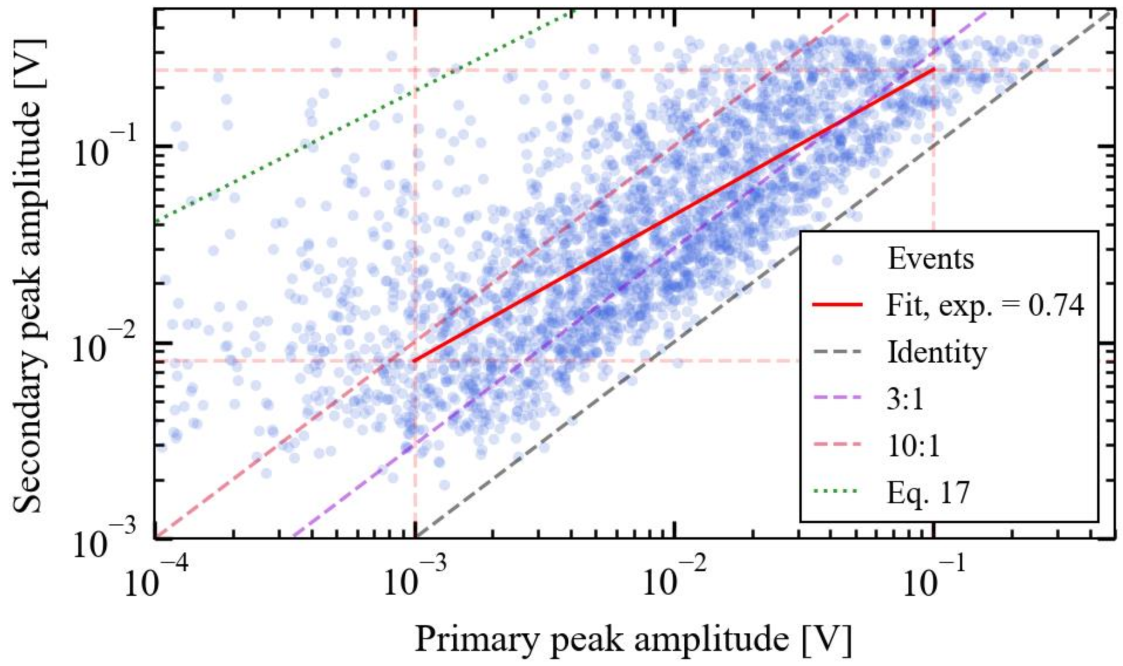
Secondary amplitudes

Electrostatic induction can‘t explain

Additional amplification must be present!

Adapted Pantellini:

$$V_{sec} \propto V_{pri}^{\frac{2}{3}}$$



Conclusions

1. We observed double-peaked dust impact signatures for the first time. Tricky to use MAPM data.

2. Primary peak is found consistent with expectations

3. Secondary peak is new!
   - Time-scale consistent with ion motion
   - Possibly explained with Pantellini process

Kočiščák, S., Mann, I., Meyer-Vernet, N., Theodorsen, A., Vaverka, J., and Zaslavsky, A.:
Impact Ionization Double Peaks Analyzed in High Temporal Resolution on Solar Orbiter,
EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-2067, 2023.

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CNN dust classification – higher sampling rate

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RPW meeting 2023, Praha

Big thanks to

the RPW & TDS team for their work and support.

We highly appreciate the nice data structure, even though we might complain time-to-time, we love the data.

CNN classification

TDS dust recognition performance

- Golb. average: 15 000 TDS triggers
  - 2 000 TDS dust -> 1 640 +, 360 –
    ⇒ **82% spec.**
  - 13 000 TDS no-dust -> 918 +, 12 082 –
    ⇒ **64% sens.**
- FEB-APR/2022: 17 842 TDS triggers
  - 712 TDS dust -> 420 +, 290 –
    ⇒ **59% spec.**
  - 17 130 TDO no-dust -> 94 +, 17 036 –
    ⇒ **82% sens.**

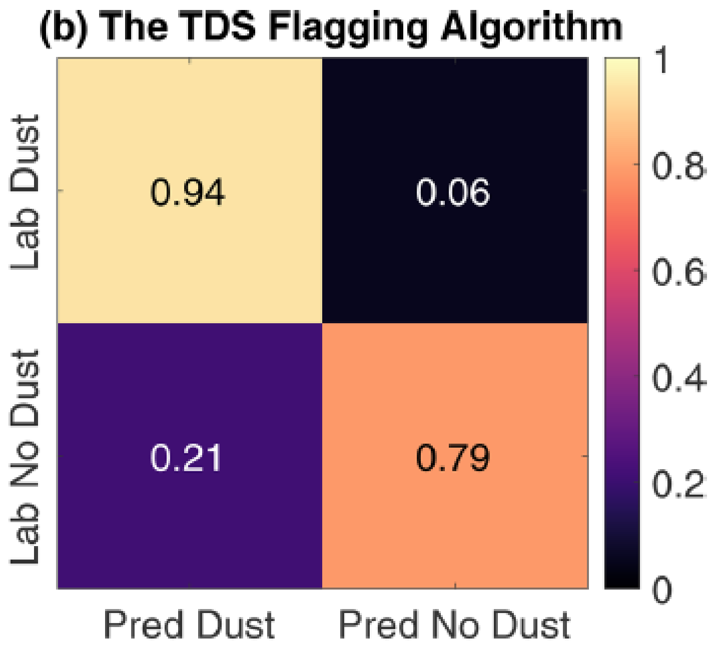
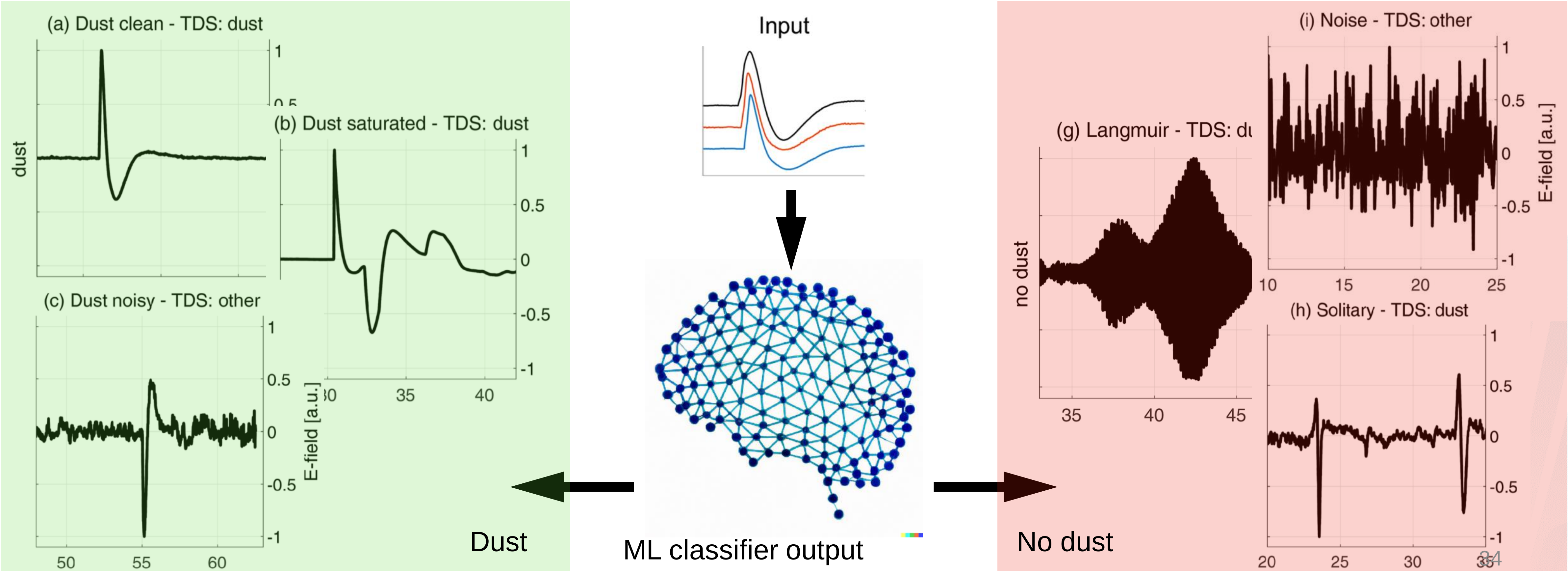


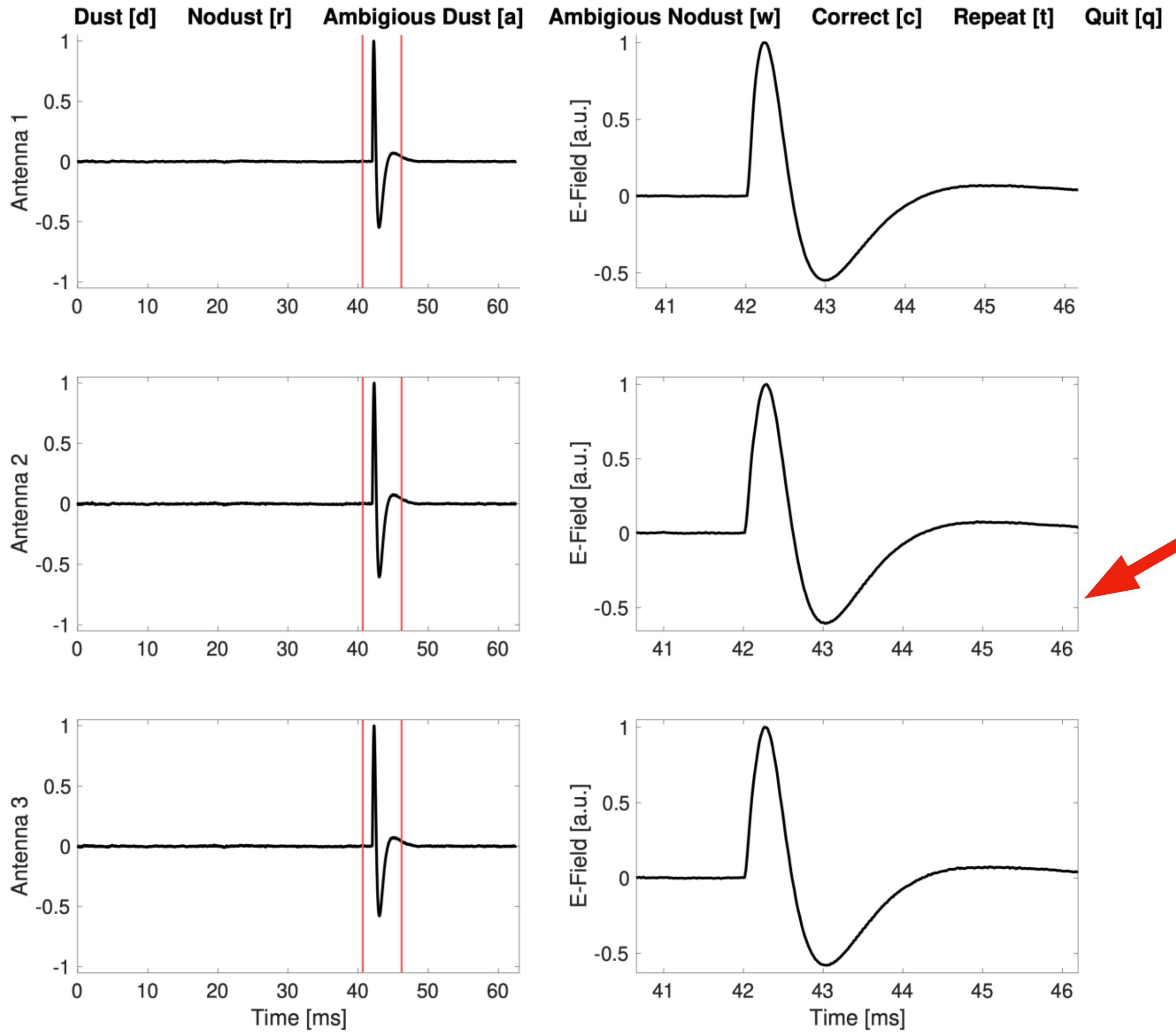
Fig. 10 from Kvammen et al. (2023)

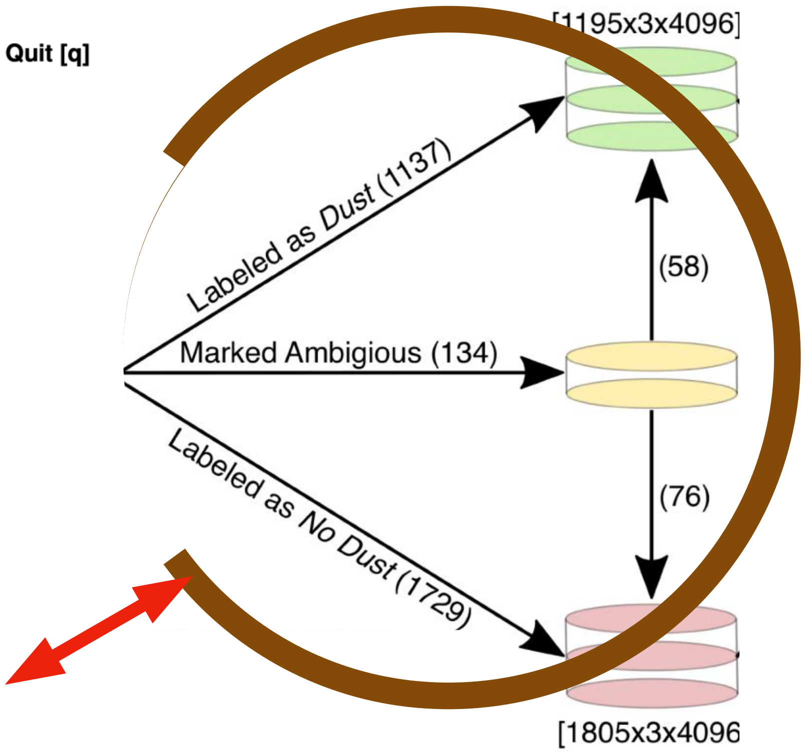
Project Objective and Methodology

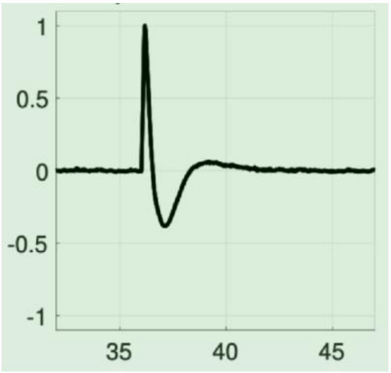
- **Project Objective** — Develop a fully automated dust detection tool with a high (≥ 95%) accuracy
- **Methodology** — Classification using supervised machine learning techniques
  Input: Observed signal — **Output**: Binary label (Dust or No Dust)
- **Supervised learning** — Manually labeled observations are used to train and test the machine learning classifiers

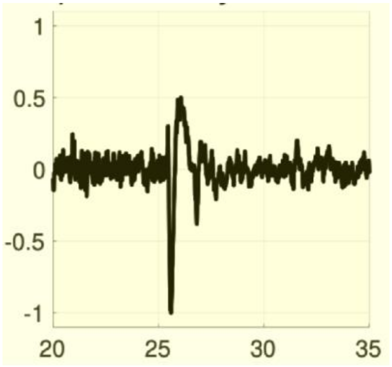


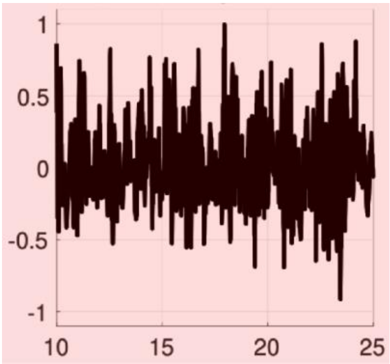
Manual labeling











Code and data availability

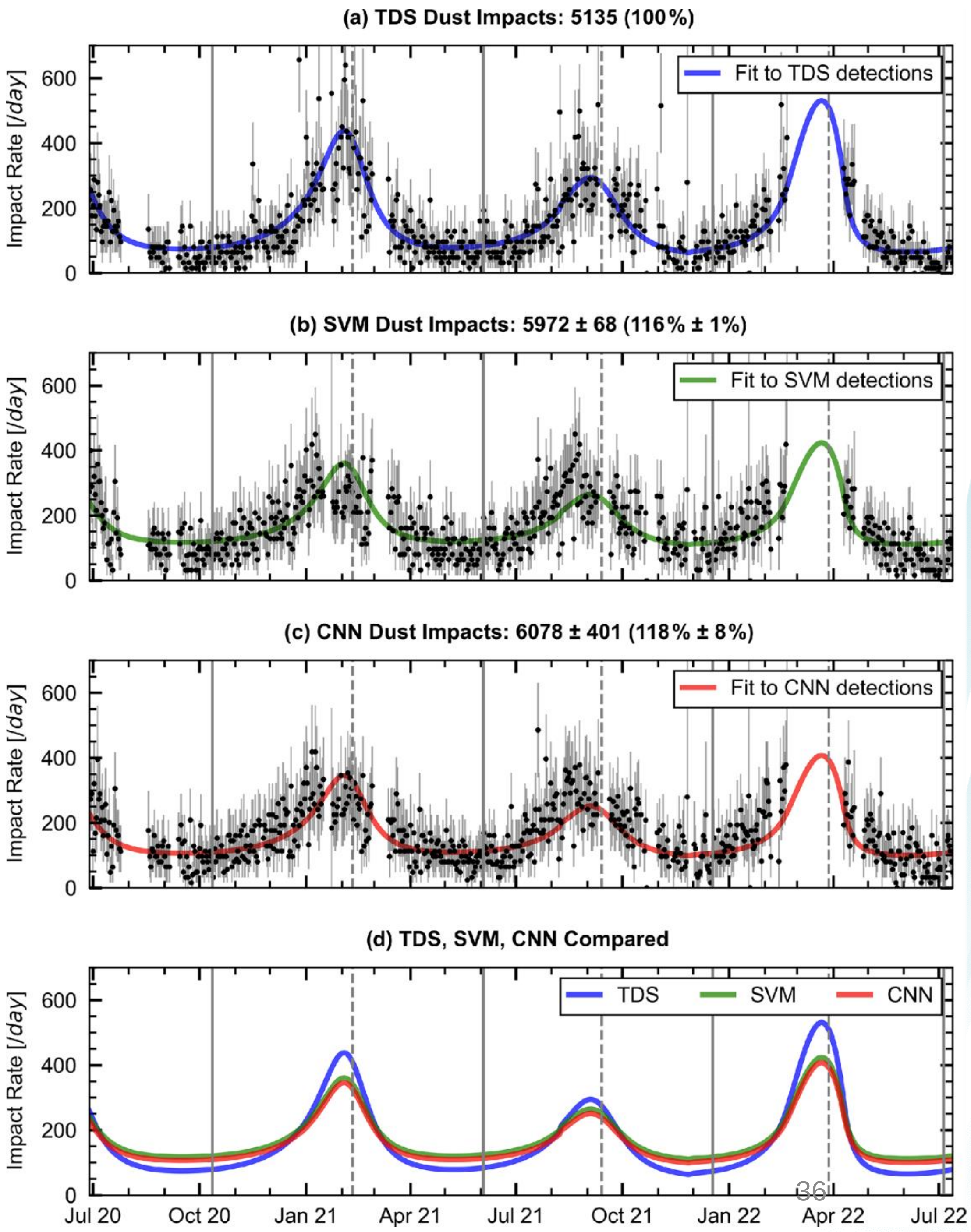
- **RPW data**— Solar Orbiter data are made available by LEISA Observatory at: https://rpw.lesia.obspm.fr/roc/data/pub/solo/rpw/data/L2/tds_wf_e/
- **Code, Training, Testing** — The trained classifiers, the code and manually labelled data sets are available at: https://github.com/AndreasKvammen/ML_dust_detection with included user instructions
- **Article** — For more details, see our article titled **Machine learning detection of dust impact signals observed by the Solar Orbiter**, published at Annales Geophysicae: https://angeo.copernicus.org/articles/41/69/2023/
- **Contact** — If you have trouble using these tools or other requests, please contact me at: Andreas.kvammen@uit.no
- **References**

Mann, I., Nouzák, L., Vaverka, J., Antonsen, T., Fredriksen, Å., Issautier, K., ... & Zaslavsky, A. (2019, December). Dust observations with antenna measurements and its prospects for observations with Parker Solar Probe and Solar Orbiter. In Annales Geophysicae (Vol. 37, No. 6, pp. 1121-1140). Copernicus GmbH.

Zaslavsky, A., Mann, I., Soucek, J., Czechowski, A., Píša, D., Vaverka, J., ... & Vaivads, A. (2021). First dust measurements with the Solar Orbiter Radio and Plasma Wave instrument. Astronomy & Astrophysics, 656, A30.

Maksimovic, M., Bale, S. D., Chust, T., Khotyaintsev, Y., Krasnoselskikh, V., Kretzschmar, M., ... & Zouganelis, I. (2020). The solar orbiter radio and plasma waves (RPW) instrument. Astronomy & Astrophysics, 642, A12.

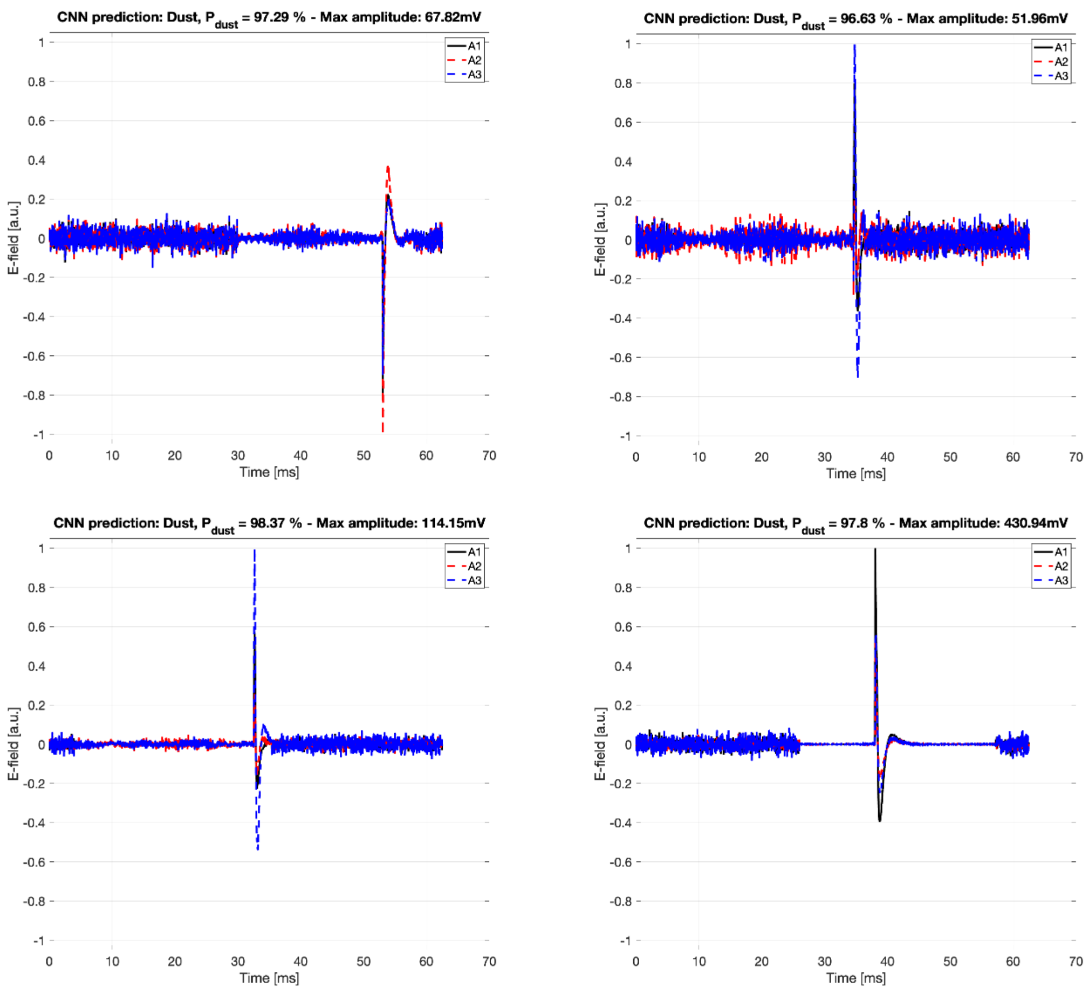
Kočiščák, S., Kvammen, A., Mann, I., Sørbye, S. H., Theodorsen, A., & Zaslavsky, A. (2023). Modeling Solar Orbiter dust detection rates in the inner heliosphere as a Poisson process. Astronomy & Astrophysics, 670, A140.



Higher sampling rate data

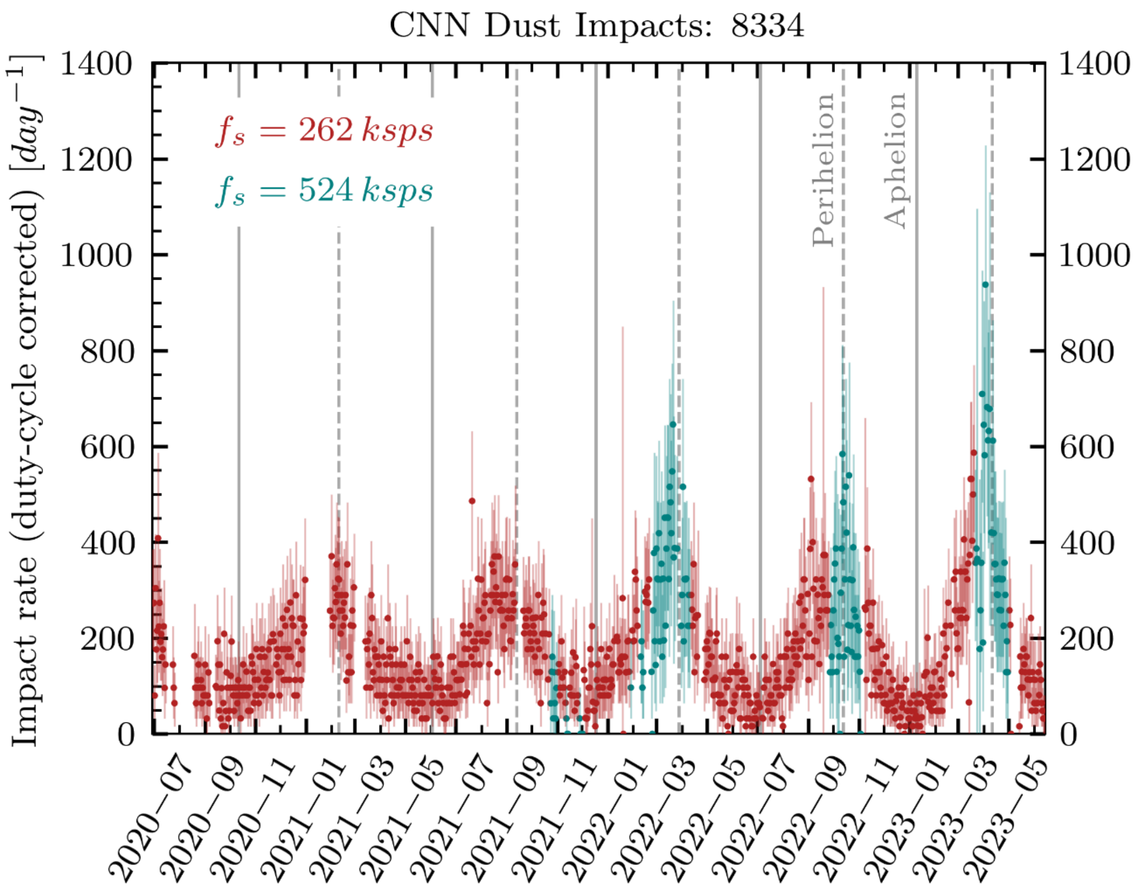
Higher sampling rate inclusion

- Before 2/2022:
  - $f_s = 262\ ksps$
- After 2/2022 variable:
  - $f_s = 524\ ksps$
    - While $R \lesssim 0.5AU$
- The detection algorithm trained on $f_s = 262\ ksps$
- Padding + subsampling



New observed flux

- The flux seems quite continuous
- We now have nearly 3 years, i.e. 8334 grains
- Possibility to make this an L3 product?

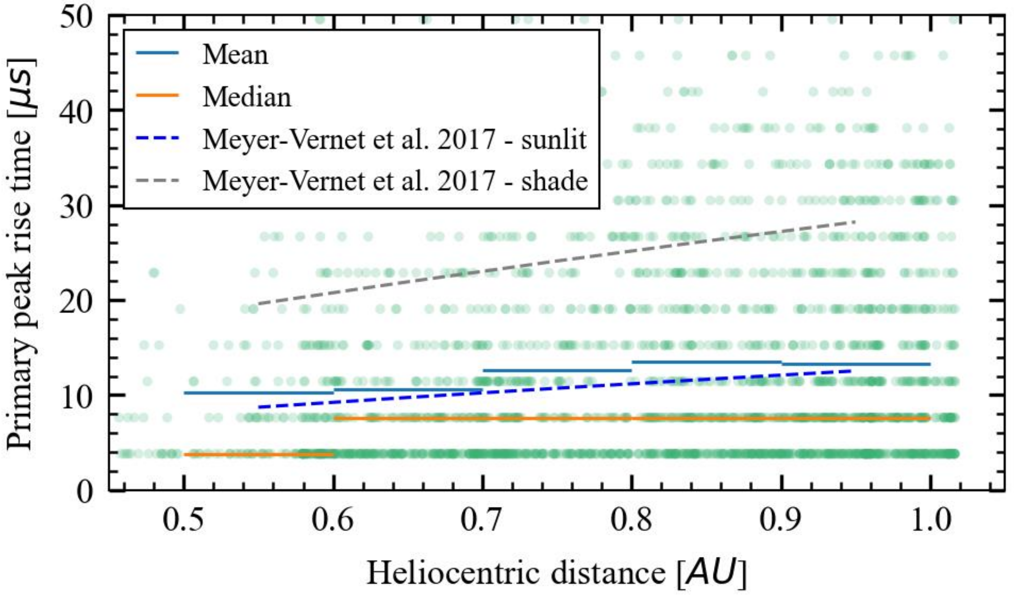


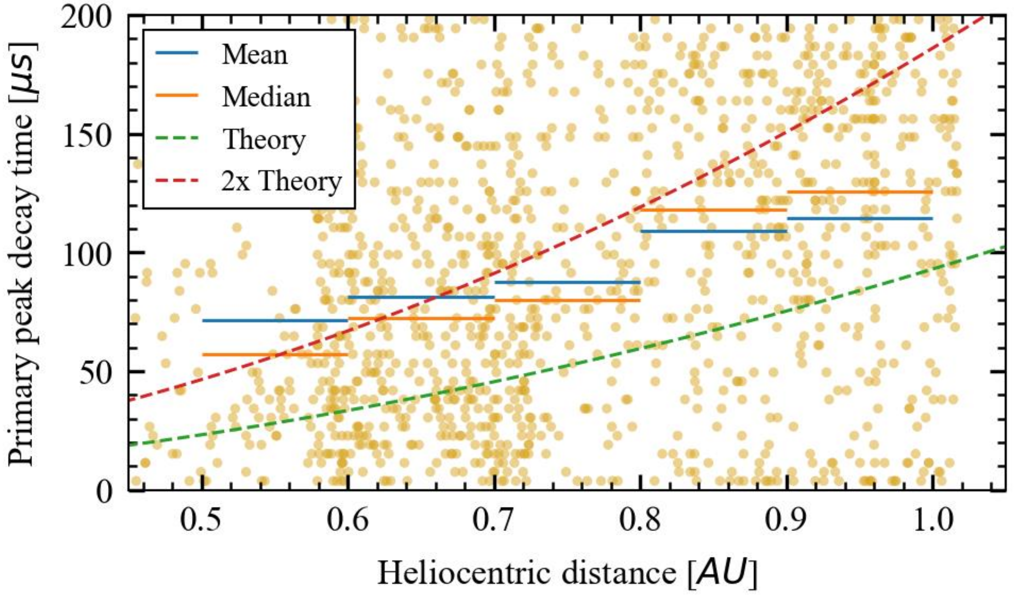
Thank you for your questions!

Backup

Mean primary peak – understood!

✓ ✓





$$\tau_{rise} \approx \left(\frac{3Q}{2\pi e n v_E^2 v_e}\right)^{\frac{1}{3}}$$

Expected, understood!

$$\tau_{RC} \approx \frac{C_{sc} k_B T_{ph}}{e^2 n_e v_e S_{sc}}$$

Adapted Pantellini effect

$$V_{sec} \propto Q_{ant} \propto j_{ph} w L_{submerged} \tau$$

$$L_{submerged} \propto \left(\frac{V_{pr}}{n_{sw}}\right)^{\frac{1}{3}}$$

$$\tau \propto \frac{L_{submerged}}{v_{ion}}$$

$$V_{sec} \propto \frac{j_{ph} w}{v_{ion}} \left(\frac{V_{pr}}{n_{sw}}\right)^{\frac{2}{3}}$$

$$V_{sec} = \frac{\Gamma}{C_{ant}} Q_{ant}$$

$$Q_{ant} = \int_0^{\tau} j_{ph} w L(t)\, dt \approx \frac{1}{2} j_{ph} w L_{sub} \tau$$

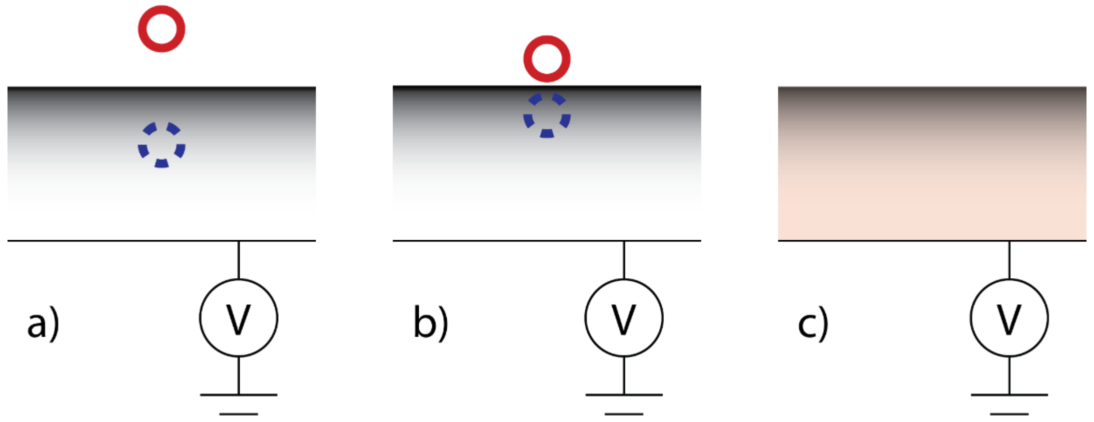
$$\mathrm{n}_{cloud} = \frac{3\mathrm{Q}}{4\pi \mathrm{e} \mathrm{L}_{\mathrm{sub}}^{3}} \Rightarrow L_{sub} = \left(\frac{3Q}{4\pi e n_{sw}}\right)^{\frac{1}{3}}$$

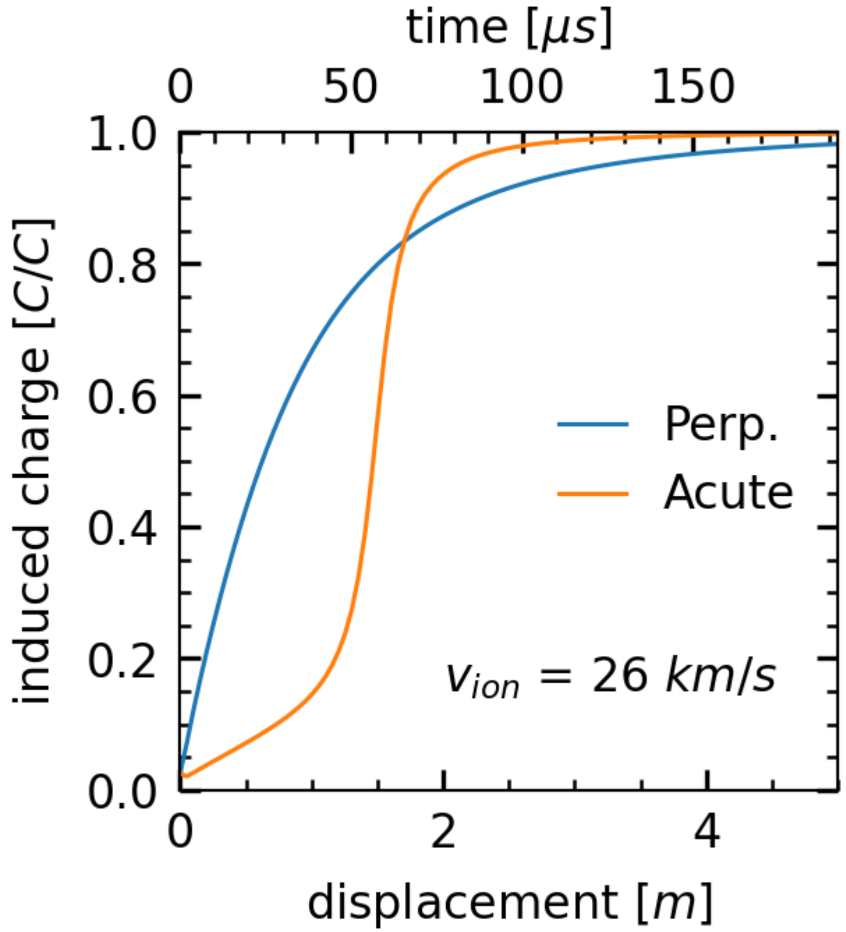
$$\tau = \frac{L_{max}}{v_{ion}}$$

$$V_{sec} \approx \frac{\Gamma^{\frac{1}{3}} j_{ph} w}{2 C_{ant} v_{ion}} \left(\frac{3 V_{pr} C_{sc}}{4\pi e n_{sw}}\right)^{\frac{2}{3}}$$

The image charge

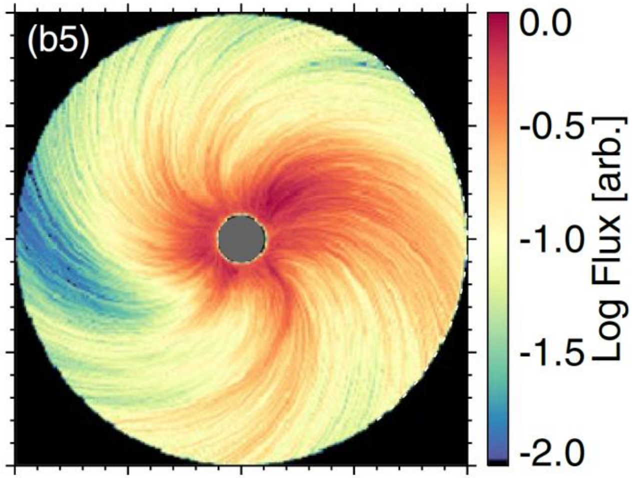
- No difference between „close“ and „touching“
- We only see the change once the charge gets far



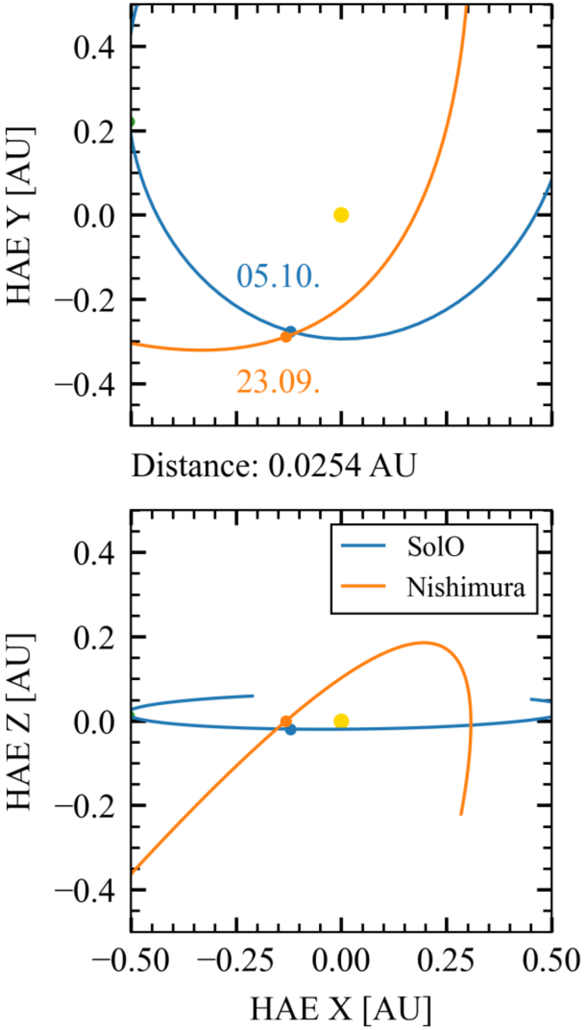


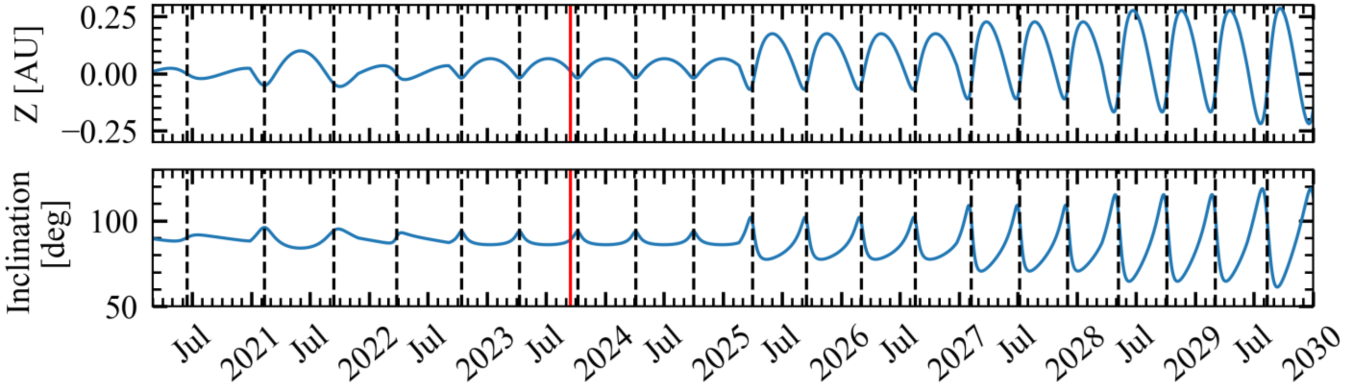
Outlook

- Nanodust
- Comet nishimura
- Inclination



20 nm @ solar max.,
Fig. 3 from Poppe & Lee (2022)





Spatial distribution

Solar attraction

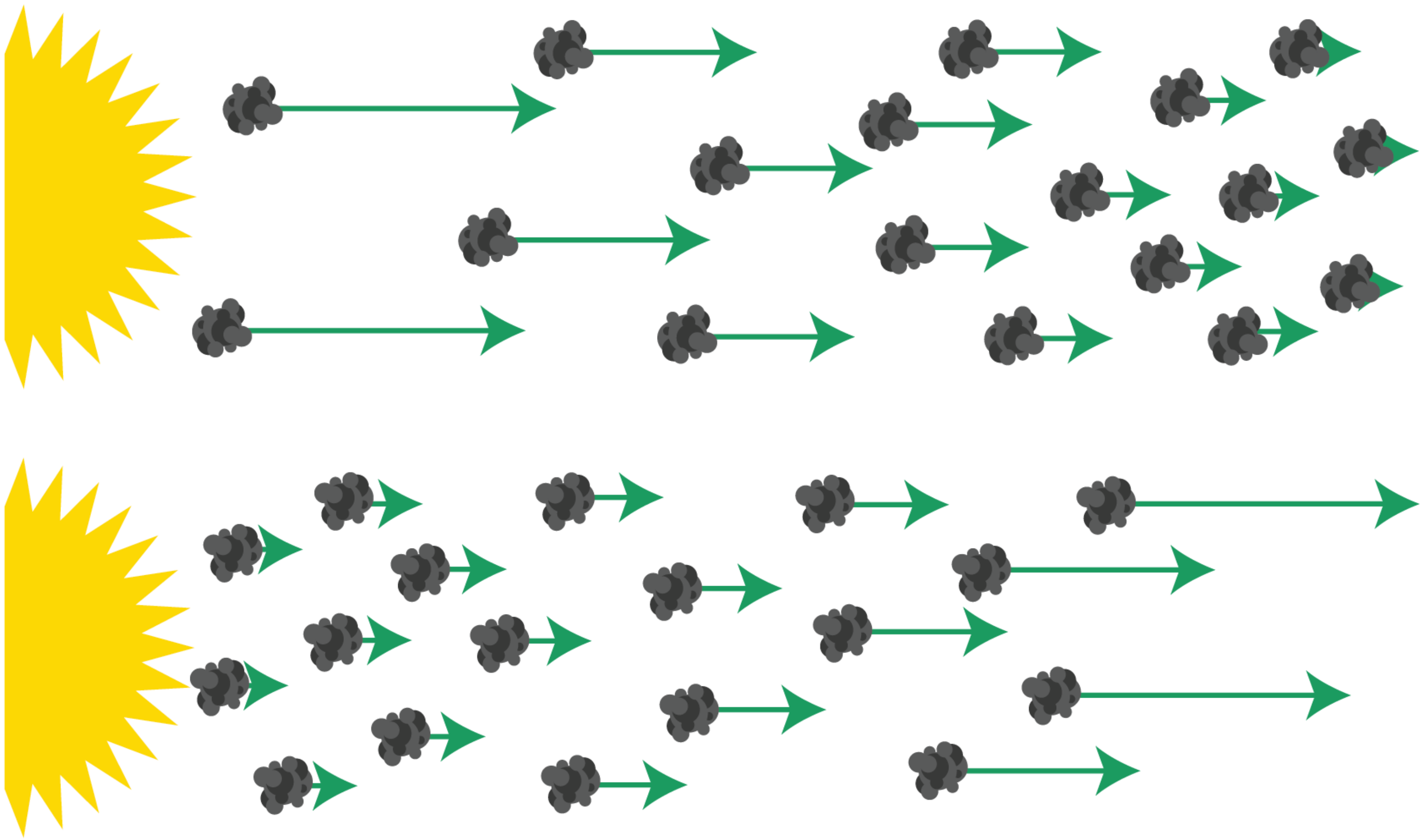
⇓

Accumulation

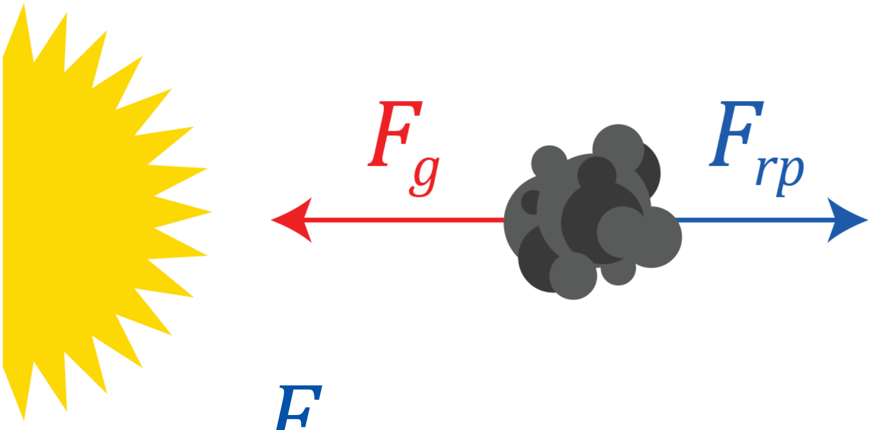
Solar repulsion

⇓

Depletion

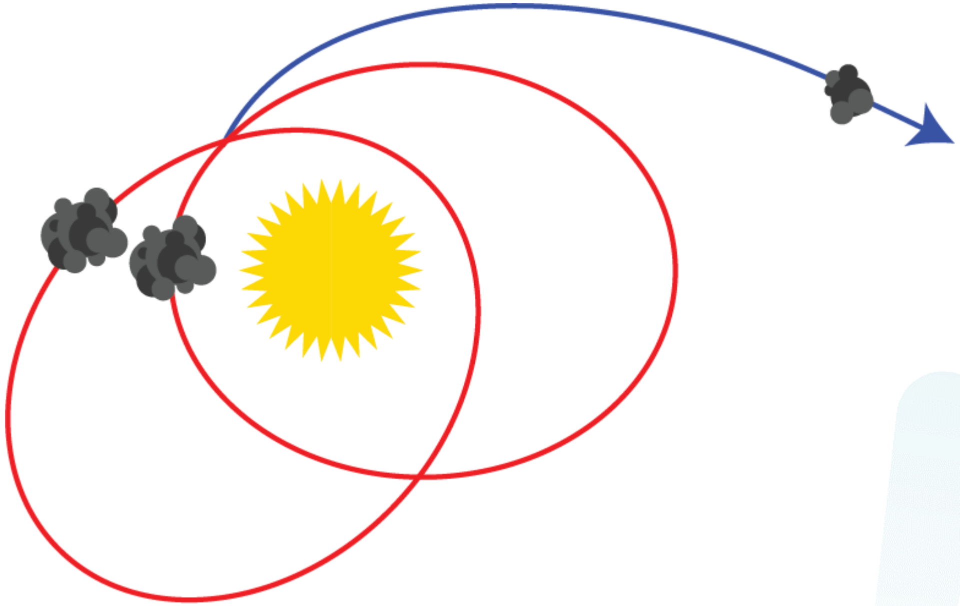


β-meteoroids



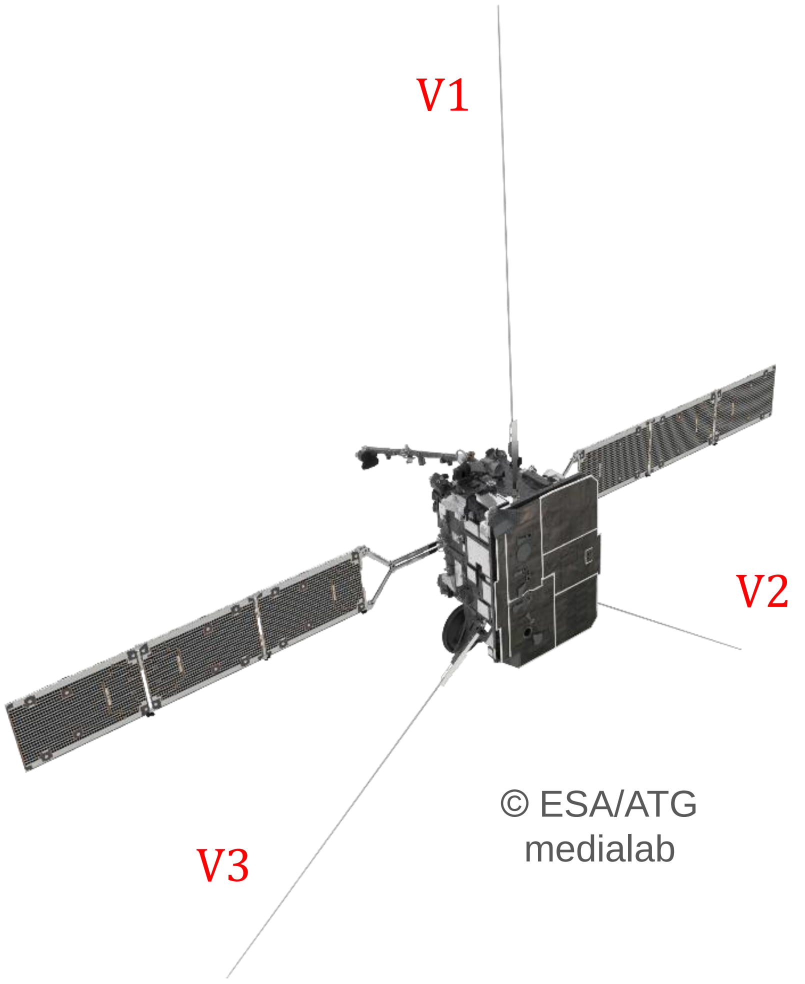
$$\frac{F_{rp}}{F_g} = \beta \neq f(r)$$

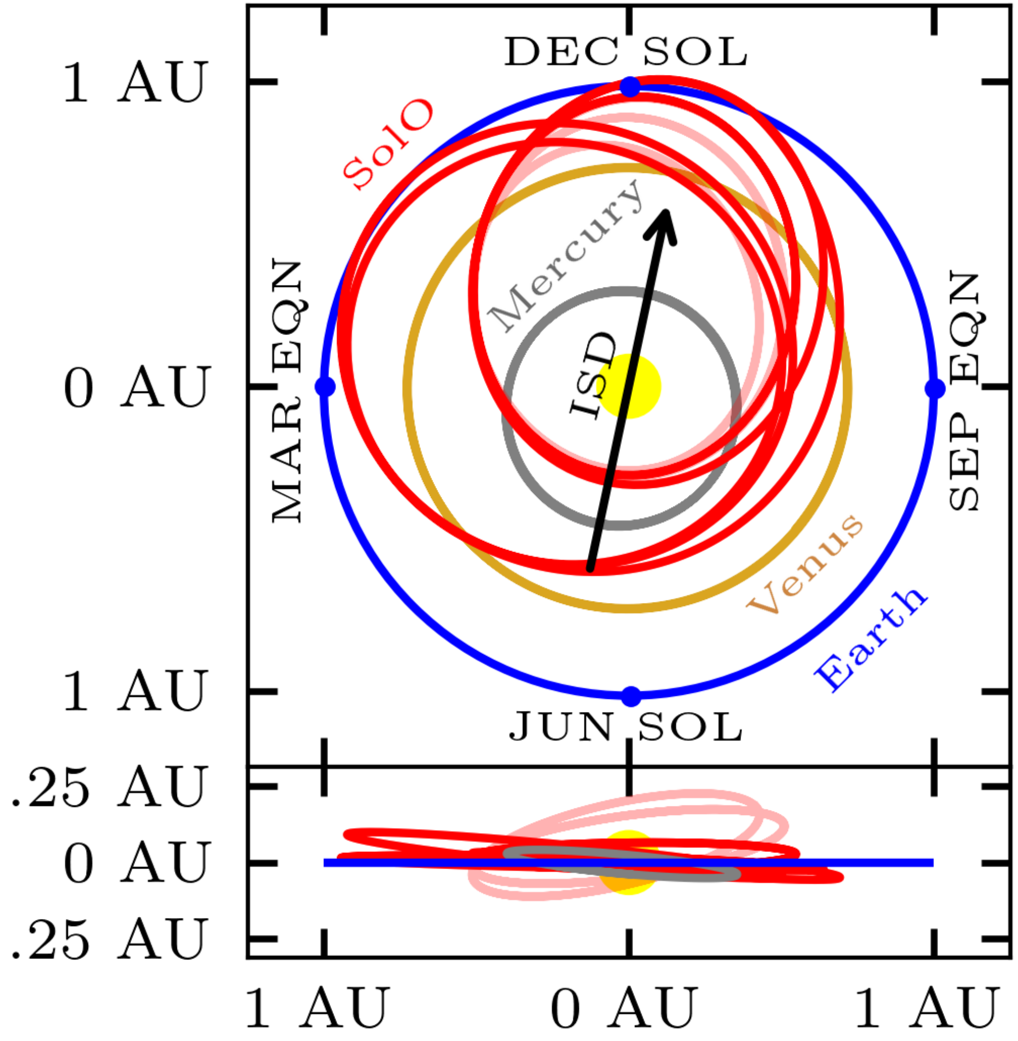
$$F_{effective} = (1 - \beta) \cdot F_g$$



$$v_{escape} = f(\beta)$$

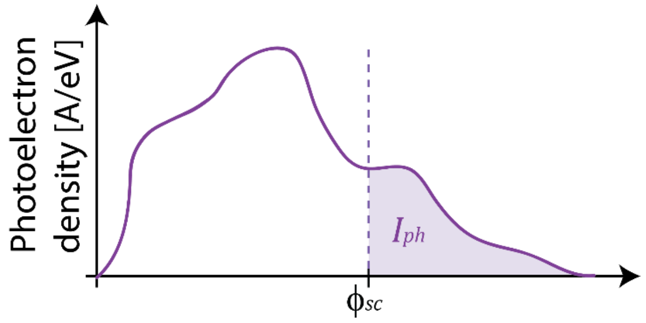
Solar Orbiter





RC decay

$$RC_{sc} = C_{sc}\left(\frac{dI}{d\phi_{sc}}\right)^{-1} \approx C_{sc}\left(\frac{dI_{ph}}{d\phi_{sc}}\right)^{-1} \nparallel \phi_{sc}$$



Assuming Boltzmann distribution:

$$\left.\frac{dI_{ph}}{d\phi_{sc}}\right|_{\phi_{sc}} = \frac{eI_{ph}(\phi_{sc})}{k_B T_{ph}} =^* \frac{eI_e(\phi_{sc})}{k_B T_{ph}}$$

$$I_{ph}^{-}(\phi_{sc}) \approx I_{SW}^{-}(\phi_{sc})$$

$$\tau_{sc} = RC_{sc} \approx \frac{C_{sc} k_B T_{ph}}{e^2 n_{SW}^{-} S v_{th}^{-}}$$

$$\left.\begin{array}{l} C_{sc} \approx 350pF \\ k_B T_{ph} \approx \mathrm{E}(\lambda_{UV}) - W \approx 3eV \end{array}\right\} \tau_{sc} \approx 50\mu s$$

Spacecraft currents at $\phi = 0$

$$I_{tot} = I_{SW}^{+} - I_{SW}^{-} + I_{ph}^{-} + I_{se}$$

$$I_{SW}^{+} \approx e\, n_{SW}^{+}\left(S_{front} v_{SW} + S v_{th}^{+}\right)$$
$$I_{SW}^{-} \approx e\, n_{SW}^{-}\left(S_{front} v_{SW} + S v_{th}^{-}\right)$$
$$I_{ph}^{-} \approx e\, \phi_{ph}^{UV} S_{front} Y$$

$S \approx 30m^2$; $S_{front} \approx 6m^2$

$n_{SW}^{+} \approx n_{SW}^{-} \approx 10cm^{-3} \approx 10^7 m^{-3}$

$v_{SW} \approx 400\ km/s$
$v_{th}^{+} \approx 15\ km/s$
$v_{th}^{-} \approx 600\ km/s$
$v_{\oplus} \approx 30\ km/s$

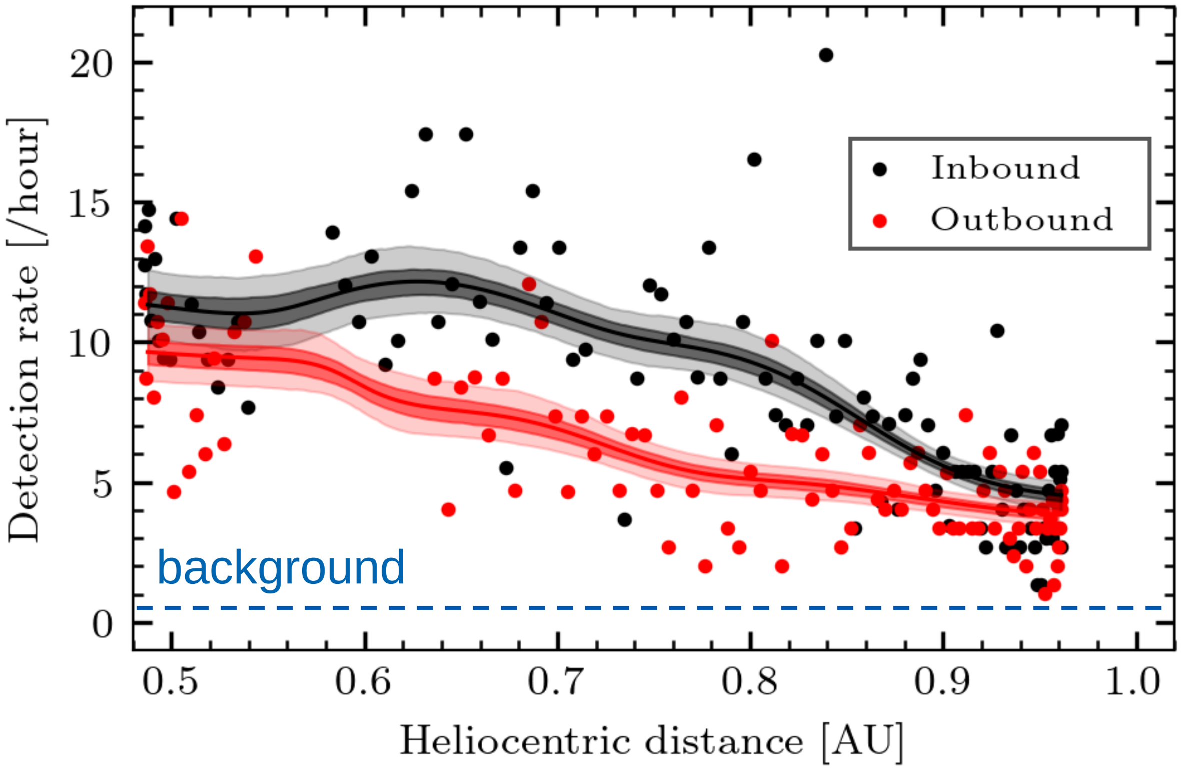
$\phi_{ph}^{UV} \approx 4 \cdot 10^{14}\ m^{-2}s^{-1}$
$Y \approx 1$

Detection rate – inbound and outbound

- Hypothesis: dust is moving outward
  - ➢ $R \sim v_{rel} = |v_{SolO} - v_{dust}|$

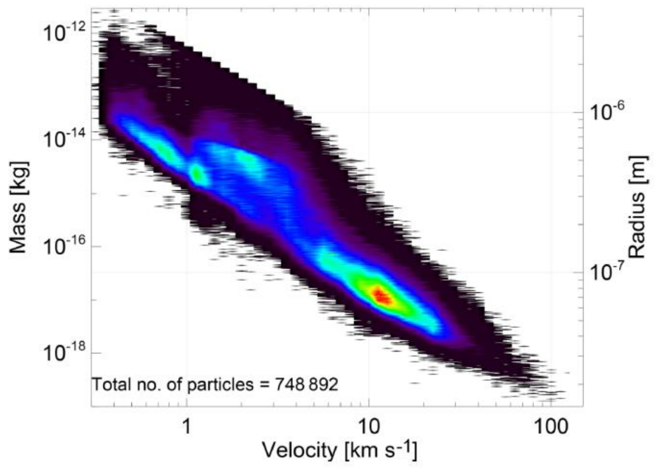
- Non-parametric regression
  - Bootstrap

- Background?

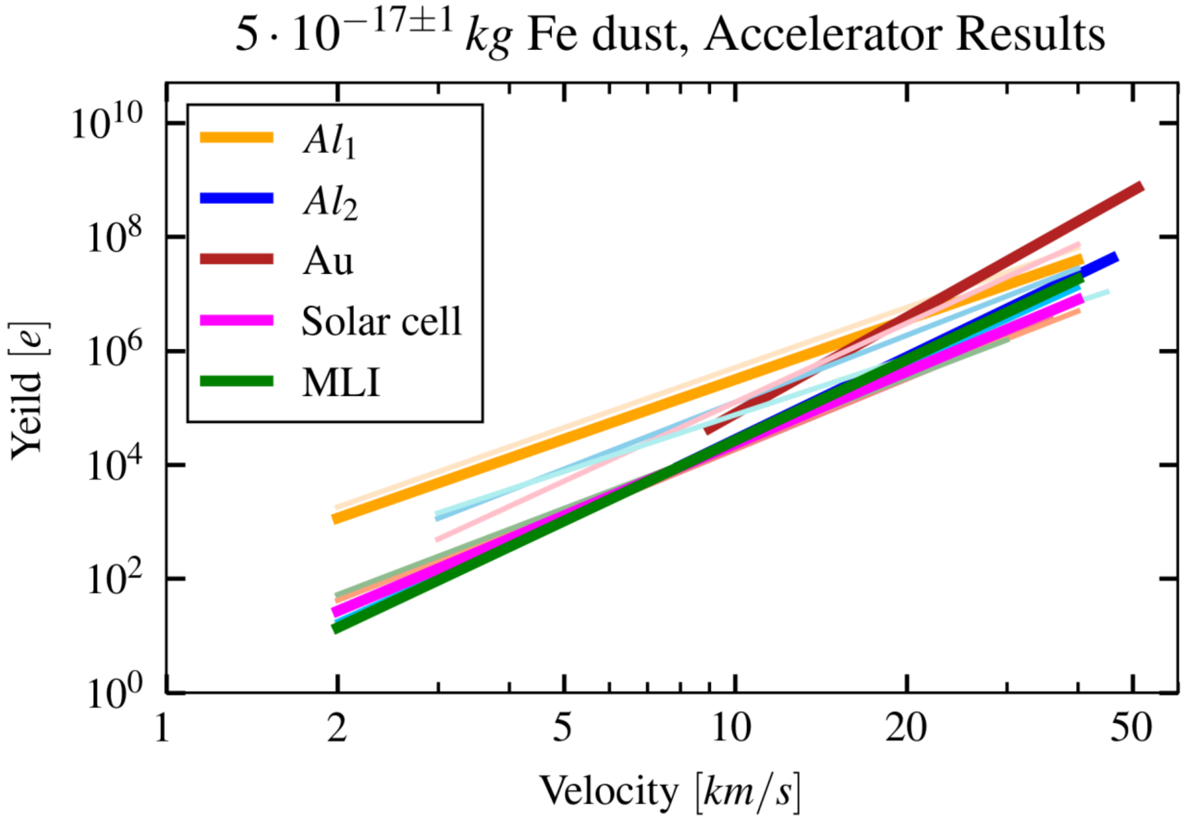


Charge yield

- $Q \propto mv^4$
  - Ionization degree ↗ v
- Need to measure charge
- Hard to separate $m; v$



from Mann et al. (2019)



Based on Colette et al. (2014)

Spacecraft floating potential

PLASMA	Earth	Venus	Mercury Aph	Mercury Peri	SO peri	SP+ 1st Peri	0,11 UA	SP+ Sci ops	0,067 UA	SP+ Last Peri
CASE (AU)	1	0,72	0,46	0,3	0,25	0,162	0,11	0,093	0,067	0,044
CURRENTS on SC (A)										
Thermal electrons net	-2,55E-05	-4,98E-05	-1,30E-04	-2,68E-04	-4,76E-04	-9,39E-04	-2,63E-03	-3,78E-03	-6,41E-03	-2,46E-02
Ions net	1,52E-06	3,08E-06	8,05E-06	2,07E-05	2,93E-05	6,61E-05	1,73E-04	2,37E-04	4,00E-04	1,56E-03
Photoelectrons										
Collected	-7,89E-05	-1,53E-04	-3,73E-04	-9,00E-04	-1,25E-03	-3,16E-03	-7,01E-03	-9,89E-03	-1,96E-02	-4,52E-02
Emitted	1,01E-04	1,94E-04	4,75E-04	1,12E-03	1,61E-03	3,83E-03	8,31E-03	1,16E-02	2,24E-02	5,19E-02
Net	2,17E-05	4,05E-05	1,02E-04	2,17E-04	3,54E-04	6,75E-04	1,30E-03	1,73E-03	2,77E-03	6,75E-03
2nd electrons										
Collected	-1,19E-05	-2,59E-05	-8,18E-05	-2,11E-04	-3,89E-04	-1,07E-03	-3,16E-03	-5,01E-03	-8,71E-03	-4,62E-02
Emitted	1,41E-05	3,18E-05	1,02E-04	2,40E-04	4,82E-04	1,26E-03	4,24E-03	6,74E-03	1,29E-02	6,14E-02
Net	2,27E-06	5,97E-06	1,99E-05	2,86E-05	9,26E-05	1,87E-04	1,08E-03	1,73E-03	4,15E-03	1,52E-02
All populations										
Collected	-1,15E-04	-2,26E-04	-5,77E-04	-1,36E-03	-2,09E-03	-5,10E-03	-1,26E-02	-1,84E-02	-3,43E-02	-1,14E-01
Emitted	1,15E-04	2,26E-04	5,77E-04	1,36E-03	2,09E-03	5,08E-03	1,25E-02	1,84E-02	3,53E-02	1,13E-01
Net	-3,60E-09	-1,75E-07	1,31E-07	-1,55E-06	-2,46E-07	-1,02E-05	-8,67E-05	-7,72E-05	9,09E-04	-1,07E-03
Recollection (%)										
Photoelectrons	78,44	79,11	78,54	80,59	77,99	82,38	84,39	85,08	87,61	86,99
2nd electrons	83,97	81,24	80,40	88,09	80,79	85,07	74,59	74,34	67,74	75,24
POTENTIALS										
Spacecraft (V)	13,53	13,89	13,39	7,91	6,29	5,21	1,22	-0,69	-4,26	-16,23
Ram min position (m)	NA	NA	NA	3,02	1,66	0,99	0,56	0,44	0,37	0,23
Wake min position (m)	NA	NA	NA	3,41	2,93	2,16	1,65	1,52	1,13	0,84
Ram min value (V)	NA	NA	NA	-0,23	-1,13	-2,84	-7,23	-8,88	-13,13	-25,42
Wake min value (V)	NA	NA	NA	-0,47	-1,07	-3	-7,06	-9,39	-14,01	-31,3
Potential barriers for secondaries (V)										
Ram	13,53	13,89	13,39	-8,14	-7,42	-8,05	-8,45	-8,19	-8,87	-9,19
Wake	13,53	13,89	13,39	-8,38	-7,36	-8,21	-8,28	-8,70	-9,75	-15,07
OTHER VALUES										
Rate 2nd-emission/the-coll	-0,56	-0,64	-0,78	-0,90	-1,01	-1,34	-1,61	-1,78	-2,00	-2,50
Coll-The/Coll-ALL (%)	22,21	22,01	22,51	19,70	22,78	18,42	20,85	20,48	18,68	21,49
Coll-2nd/Coll-ALL (%)	10,35	11,44	14,17	15,55	18,62	20,95	25,02	27,17	25,36	40,40
Coll-photo/Coll-ALL (%)	68,77	67,91	64,71	66,27	60,00	61,92	55,50	53,63	57,13	39,48

from Guillemant et al. (2013)