Bayesian inference of β-meteoroid parameters with Solar Orbiter

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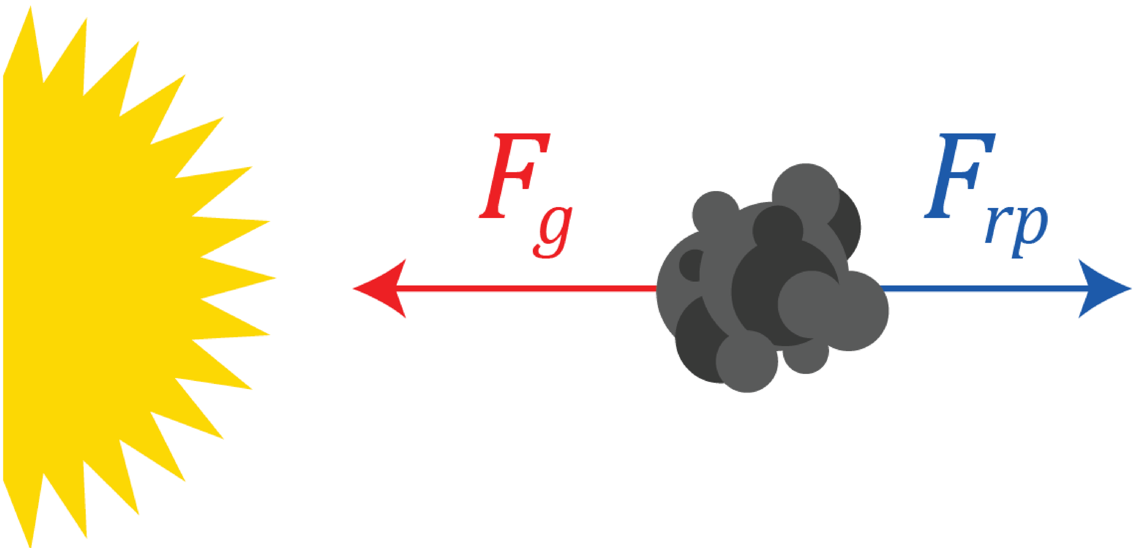
Solar Orbiter's Radio and Plasma Waves instrument is capable of detecting **hypervelocity dust impacts** onto the spacecraft through the fast electrical phenomena that accompany the process. Solar Orbiter operates within 1AU, in the environment with high density of β-meteoroids – dust grains escaping from the proximity of the Sun due to radiation pressure force counteracting gravity. Recently, Convolutional Neural Network (CNN) classified data were made available[1], analyzing all available data and providing us with the highest quality dataset of the impact events to date.

We **present a model** for the in-situ impact rate on Solar Orbiter, assuming **β-meteoroids** are the main component of the detections. We fit the model to the highest quality available CNN data assisted by Integrated Nested Laplace Approximation (INLA) for Bayesian inference with informative priors[2].

Taking into account spacecraft's position and its velocity vector, we are able to infer mean radial velocity of the detected dust grains to be **63 ± 7 km/s**. We are also able to constrain **β-meteoroid predominance** and dust's mean acceleration and by extension constrain its mean β-parameter. The procedure is general enough to be used in a different setting for Solar Orbiter, or by a different spacecraft in the future.

Dust dynamics



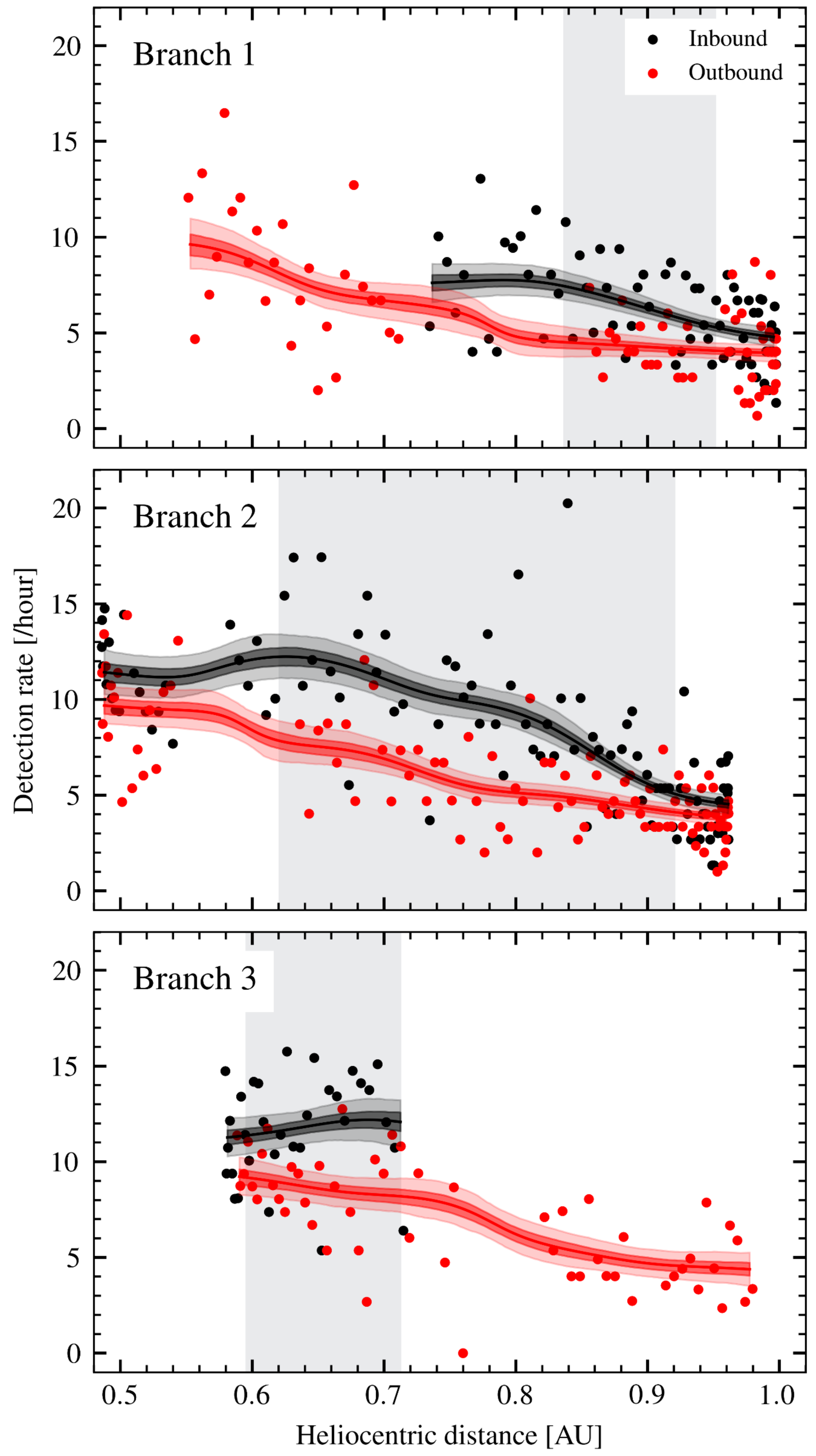
Two forces act on a dust grain:

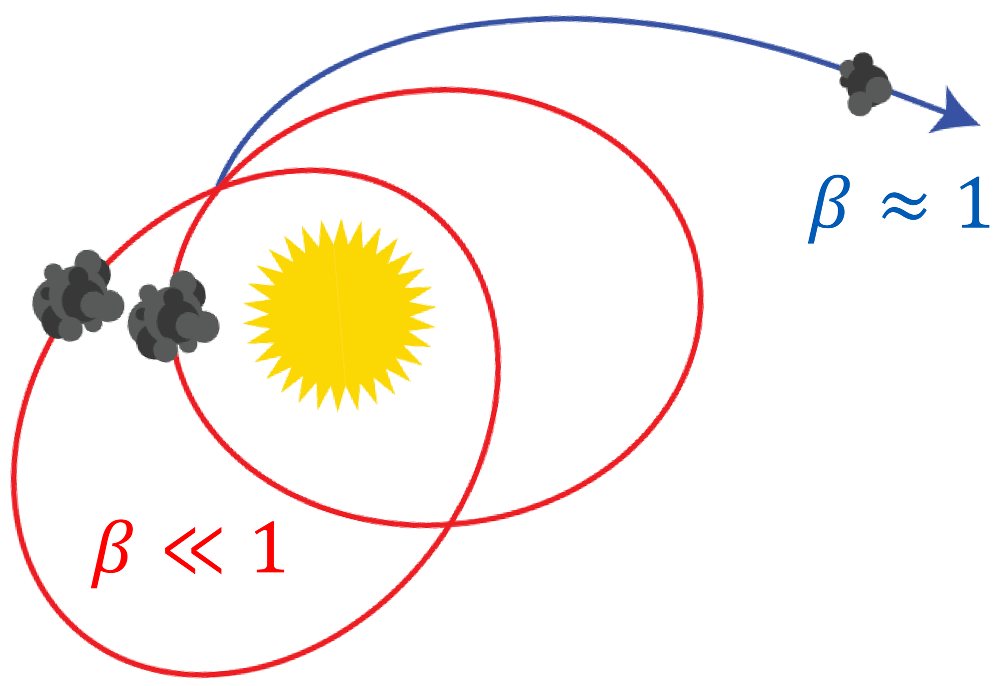
- gravity F_g
- radiation pressure F_{rp}

β-number describes the relative importance of F_{rp} compared to F_g and is highest for $\lesssim \mu m$ grains, known as β-meteoroids.

$$\beta = \frac{F_{rp}}{F_g}$$

More dust detected in the inbound part of each branch implies outward motion of the dust - consistent with β-meteoroids. →





Radial velocity v_r (used in the Bayesian model) estimated from in/outward difference, assuming:

- Background rate λ_{bg}
- Dust size distribution and material ($\alpha\delta$)
- Dust's origin (initial heliocentric distance)

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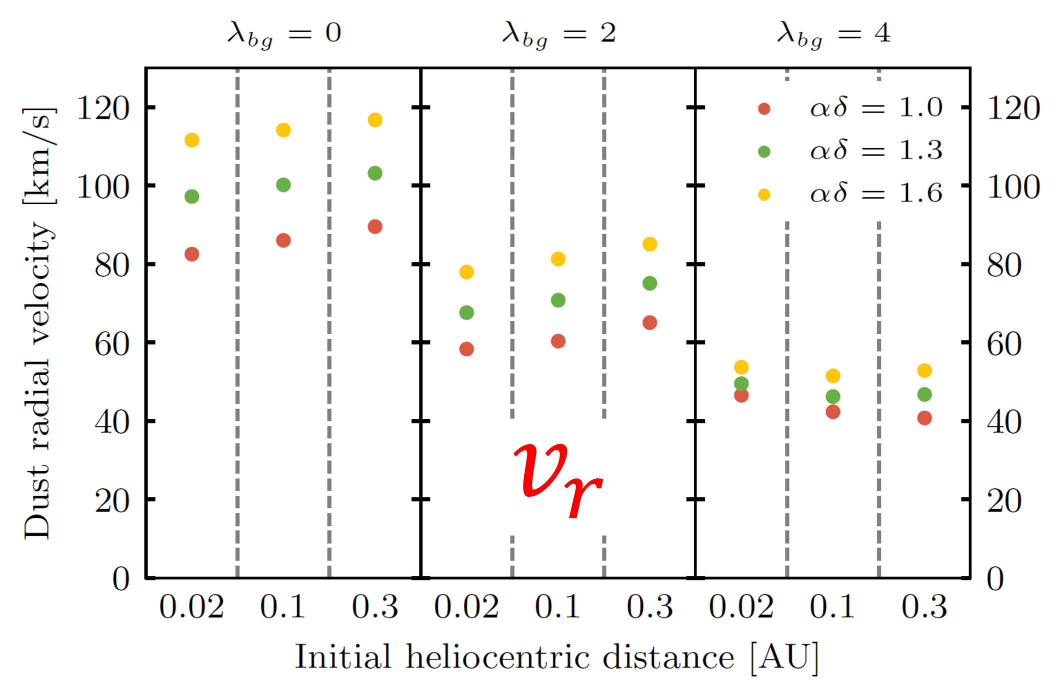


The Bayesian model

Bayesian models use ambiguous prior knowledge of parameters and the available data to produce sharper, posterior knowledge. The present model accounts for both dust velocity and acceleration.

The dust flux model:

$$N|\lambda,\theta \sim Poisson\big(E \cdot \lambda(\theta)\big)$$

$$\lambda(\theta) = \lambda_\beta \cdot v_{impact}^{\epsilon_v} \cdot r^{\epsilon_r} + \lambda_{bg}$$

$$v_{impact} = \frac{|\boldsymbol{v_{sc}} - \boldsymbol{v_{dust}}|}{50 km/s}$$

$$\boldsymbol{v_{dust}} = v_r \cdot e_r + v_a \cdot e_\phi$$

$$v_a = 12 km/s \cdot \frac{0.75 AU}{|\boldsymbol{r}|}$$

Acceleration:

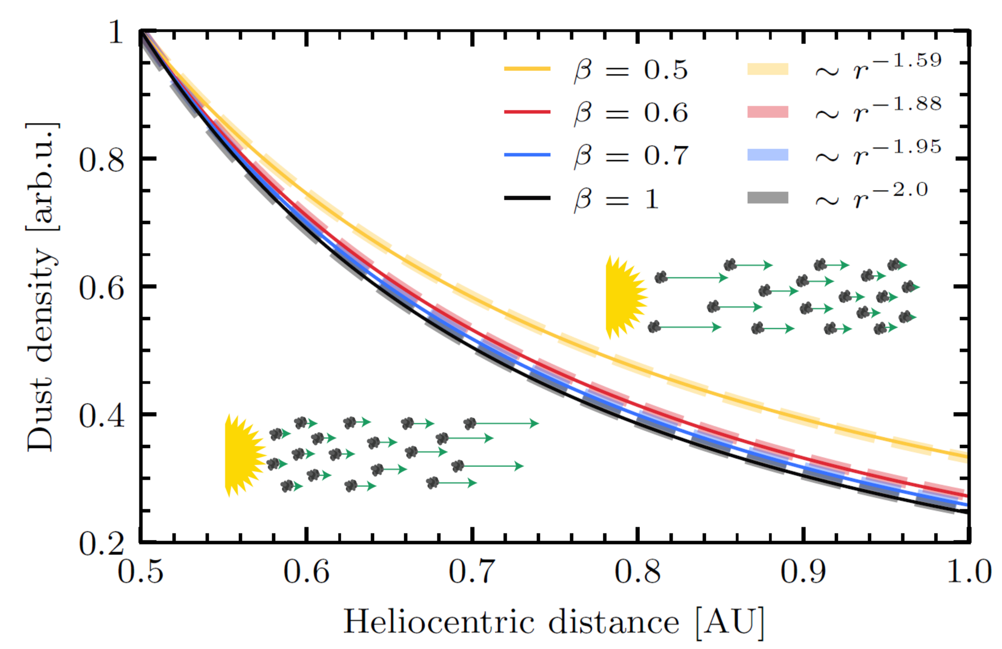
$$\tilde{R} \propto r^{-2} \cdot \frac{v_{impact}}{v_r} \cdot v_{impact}^{\alpha\delta}$$

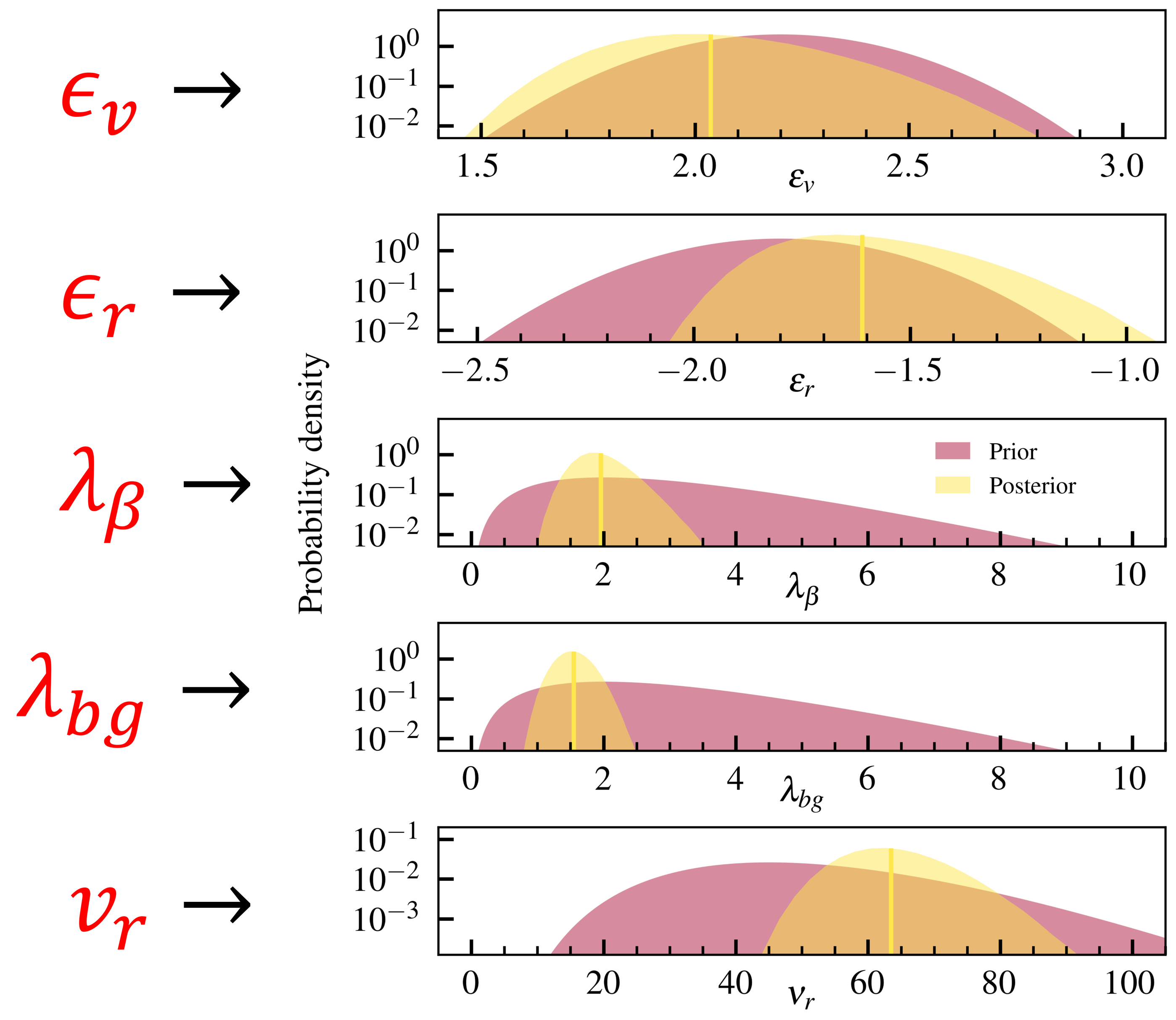
$$assume: v_r \propto r^{\xi}$$

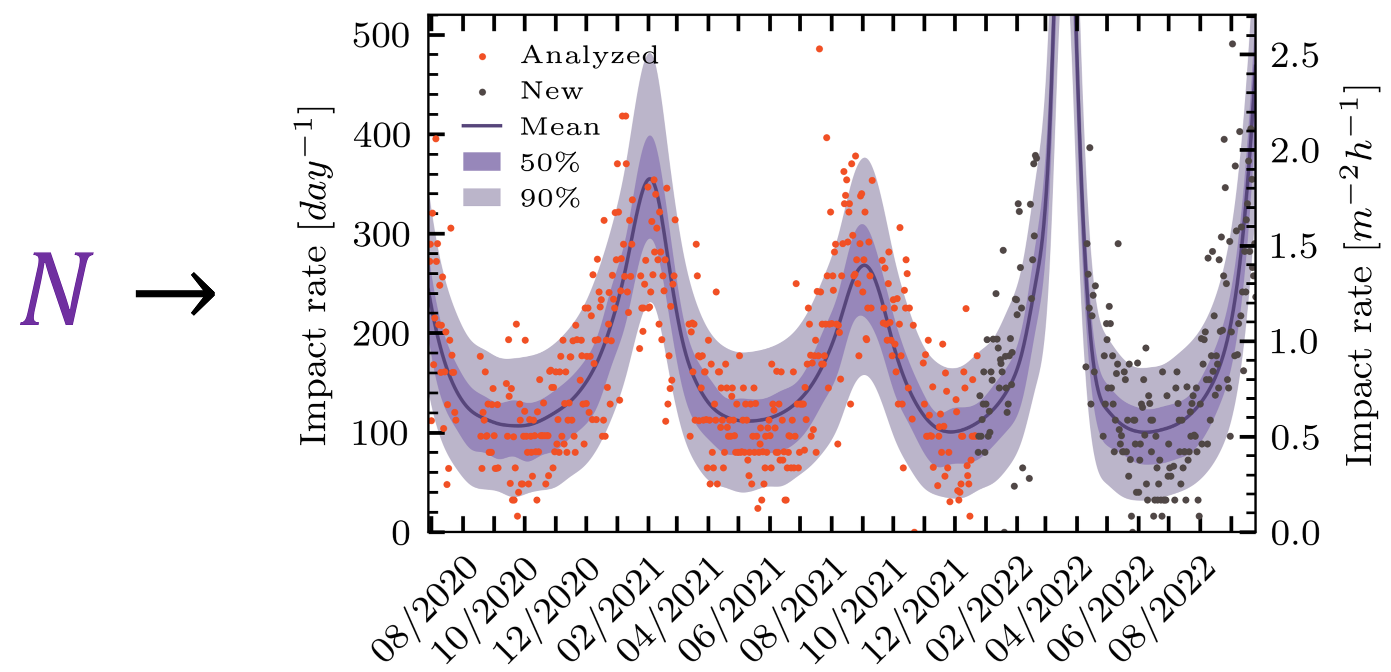
$$\tilde{R} \propto r^{-2} \cdot r^{-\xi} \cdot v_{impact} \cdot v_{impact}^{\alpha\delta}$$

$$\tilde{R} \propto r^{-2-\xi} \cdot v_{impact}^{1+\alpha\delta} = r^{\epsilon_r} \cdot v_{impact}^{\epsilon_v}$$

↓







Conclusions:

- The model represents the data well.
- The β-meteoroids account for ≈ 78% of detections.
- The dust mean radial speed is $v_r \approx 63 \pm 7\ km/s$.
- The dust notably decelerates, which implies $\beta < 1$.

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[1] Kvammen, Andreas, et al. "Machine learning detection of dust impact signals observed by the Solar Orbiter." Annales Geophysicae. Vol. 41. No. 1. Copernicus GmbH, 2023.
[2] Kočiščák, Samuel, et al. "Modeling Solar Orbiter dust detection rates in the inner heliosphere as a Poisson process." Astronomy & Astrophysics 670 (2023): A140.

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