ISTITUTO PER LA SCIENZA E TECNOLOGIA DEI PLASMI
Consiglio Nazionale delle Ricerche

Queen Mary University of London

On universality in turbulence through the study of vector increments probability density functions

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Motivation

- Kolmogorov 1962: the probability density function (pdf) of increments of the velocity in the inertial range are dependent only on the Reynolds number (R_e) and for large R_e they become independent of R_e, therefore **universal**

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- Zhdankin+2012 showed that the magnetic field increments in the solar wind at 1AU can be rescaled to a universal pdf, which is **log-normal.** A model of the rotations can be obtained from it.

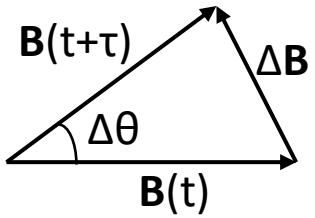
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- Zhdankin+2012 showed that the magnetic field increments in the solar wind at 1AU can be rescaled to a universal pdf, which is **log-normal.** A model of the rotations can be obtained from it.
- What is the radial evolution of the increments and rotations distribution? Is universality preserved? What are the implications for switchbacks? Does universality and/or log-normality hold for different solar wind conditions?

Methods & Data

We work with two quantities:

Magnetic increments:
$\Delta B/B = |\mathbf{B}(t+\tau) - \mathbf{B}(t)|/|\mathbf{B}(t)|$



$\Delta\theta$ = angle between B(t+ τ) and B(t)

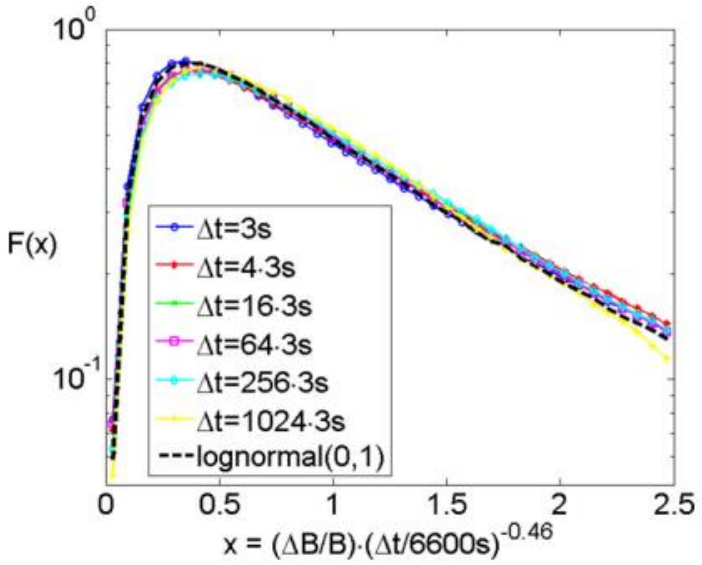
NB: $\Delta B/B = 2\sin(\Delta\theta/2)$ for pure rotations

PSP data **First 11 orbits**, below 0.5 AU, magnetic field data with 4 samples per cycle cadence. **Enc 14** full cadence for sub-Alfvenic wind

Electron pitch angle distribution to remove HCS crossings. Other transients like CME removed.

WIND data (30 years) slow and fast Alfvénic (Courtesy of N. Sioulas)

Distribution of **B** increments 1 AU



Lognormal

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2\sigma^2}(\log x - \mu)^2\right)$$

Universal Lognormal σ=1

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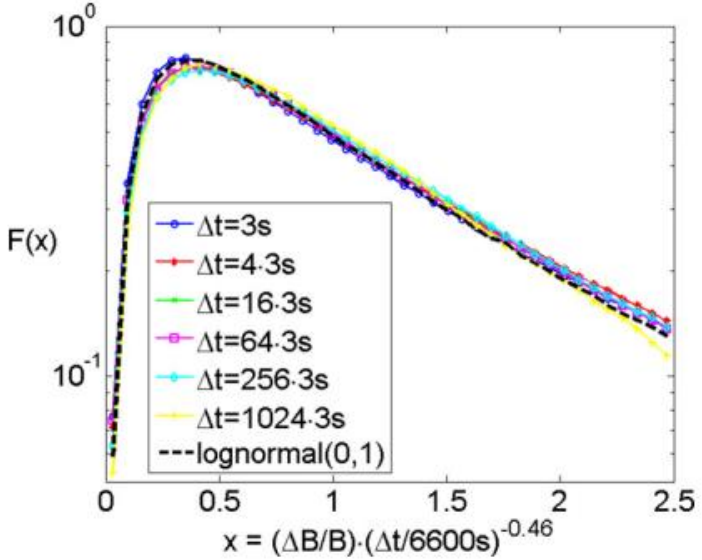
1) The increments of the magnetic field ($\Delta B/B = |\mathbf{B}(t+\tau) - \mathbf{B}(t)|/|\mathbf{B}(t)|$) can be rescaled to an universal Lognormal distribution function. **Provided that σ=1 at all scales**.

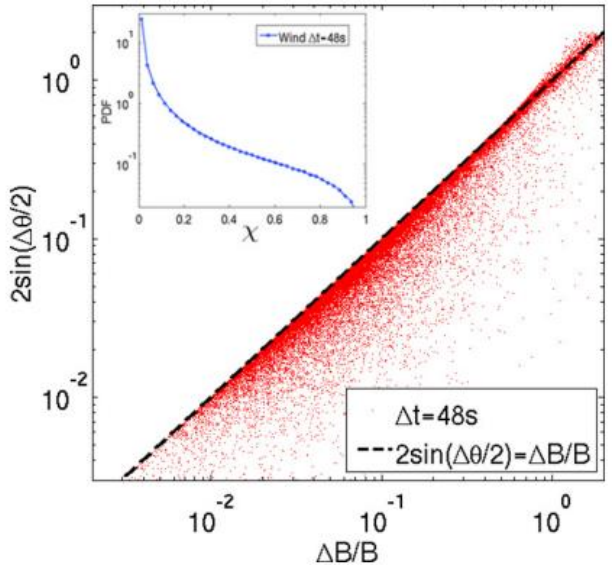
Rescaling of the ΔB/B (t, τ)

$$P\left(\frac{\Delta B}{B}; \Delta t\right) = \left(\frac{\Delta t}{\Delta t_0}\right)^{-\alpha} F\left(\frac{\Delta B}{B}\left(\frac{\Delta t}{\Delta t_0}\right)^{-\alpha}\right)$$

Zhdankin+2012, WIND data

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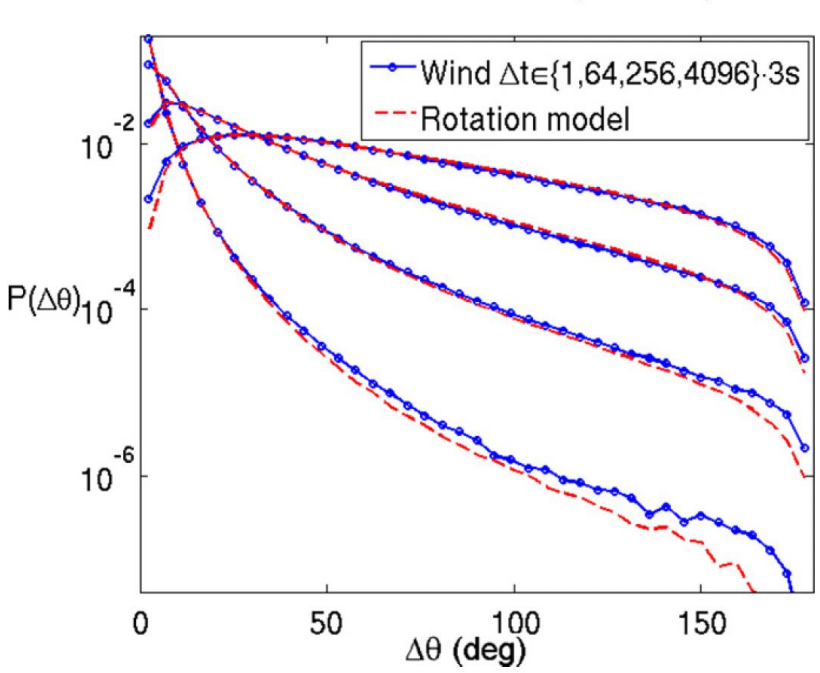
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2) The magnetic field mostly undergoes pure rotation between two different times:
$\Delta B/B = 2\sin(\Delta\theta/2)$

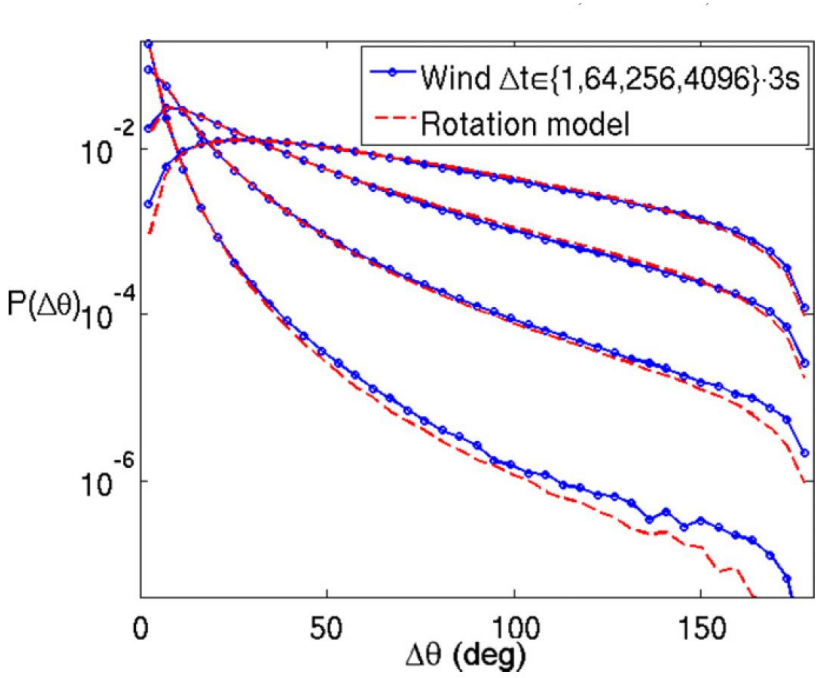
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Rotations distributions in the solar wind

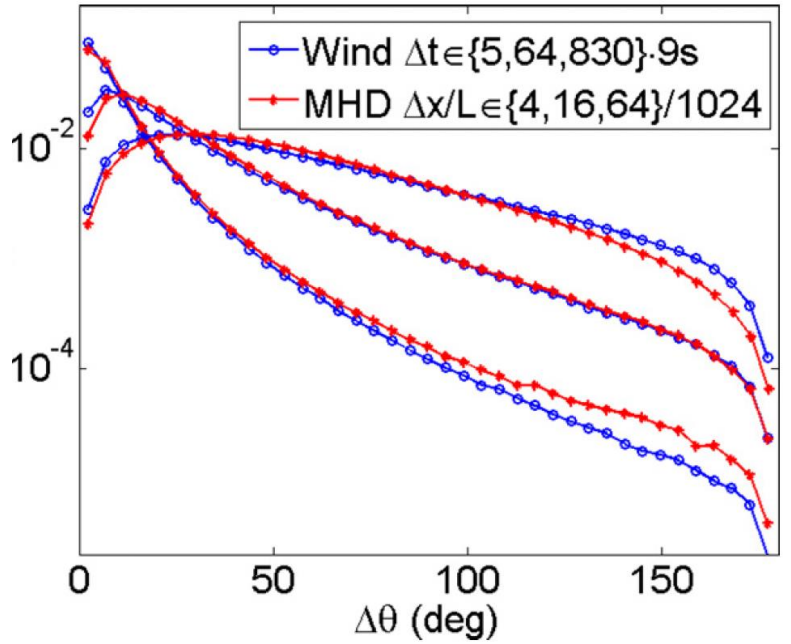


Zhdankin+2012, WIND data
and rotation model

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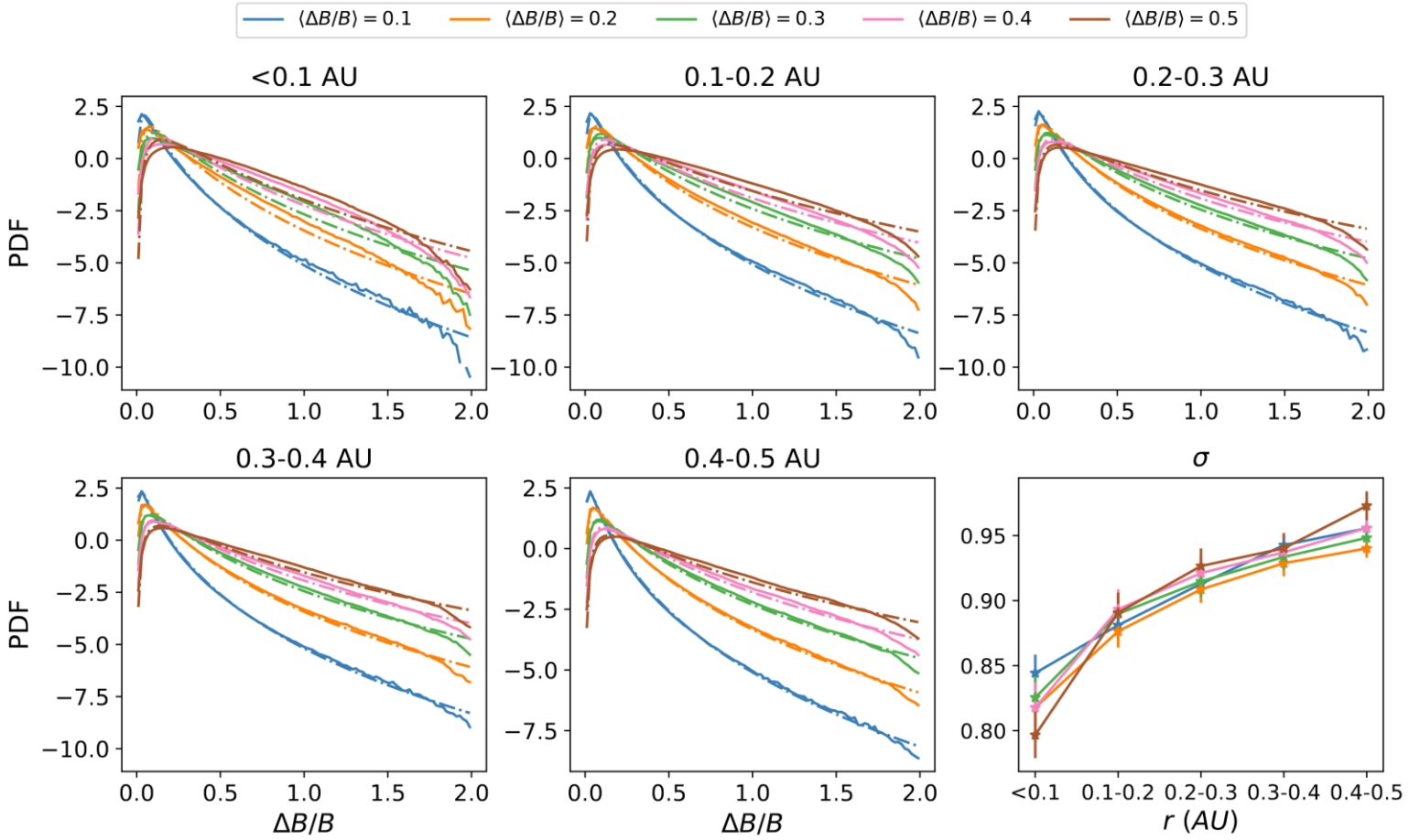
Zhdankin+2012, WIND data and rotation model



Zhdankin+2012, simulations of three-dimensional incompressible strong MHD turbulence

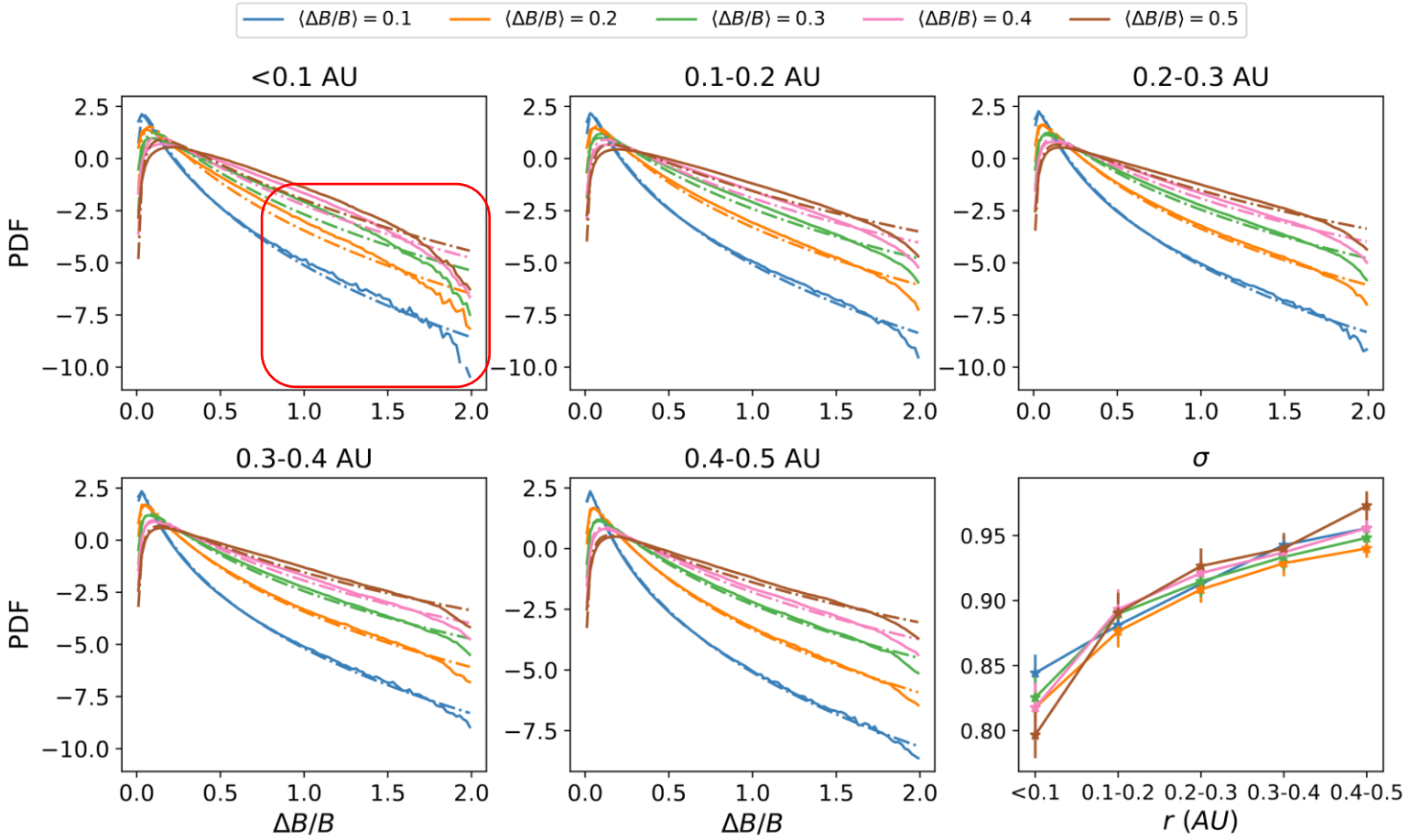
PSP data

Log-normal fit (dash dotted) vs R vs Scale



The lognormal fit improves with distance but at the closest distances there is a discrepancy between the fit and the data except at the small scales (blue)

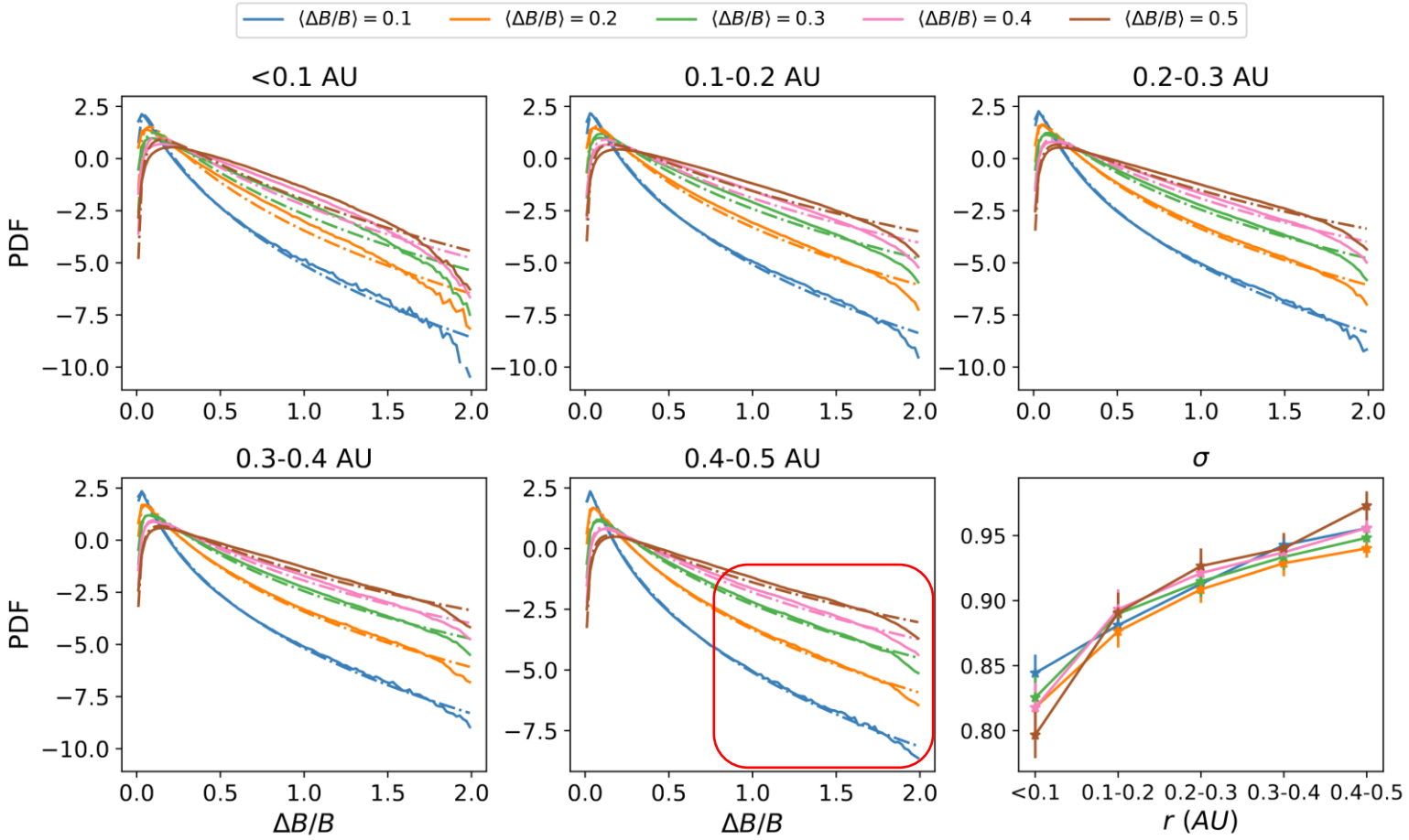
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Scale dependence highly suggestive of a turbulent evolution of the distributions.

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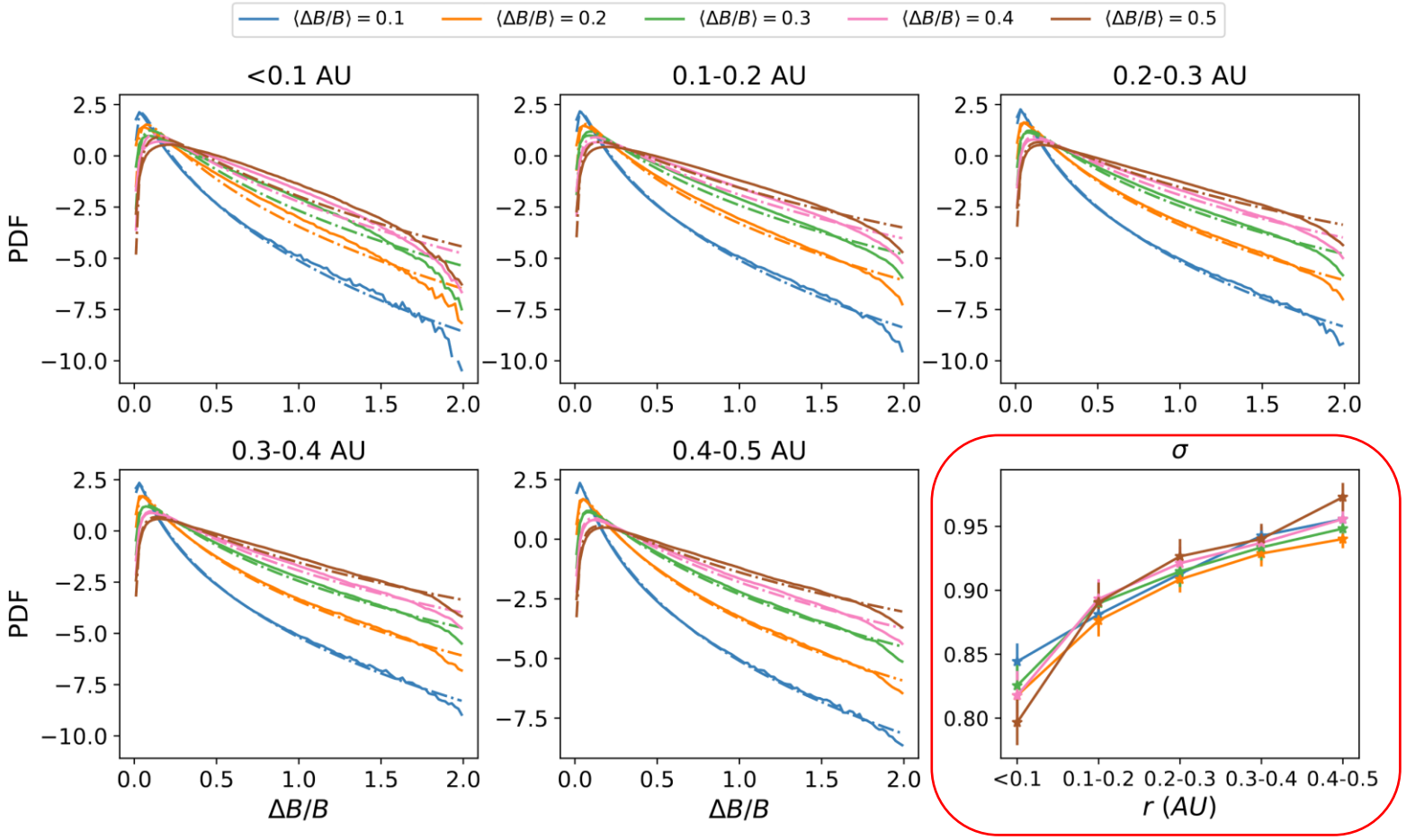
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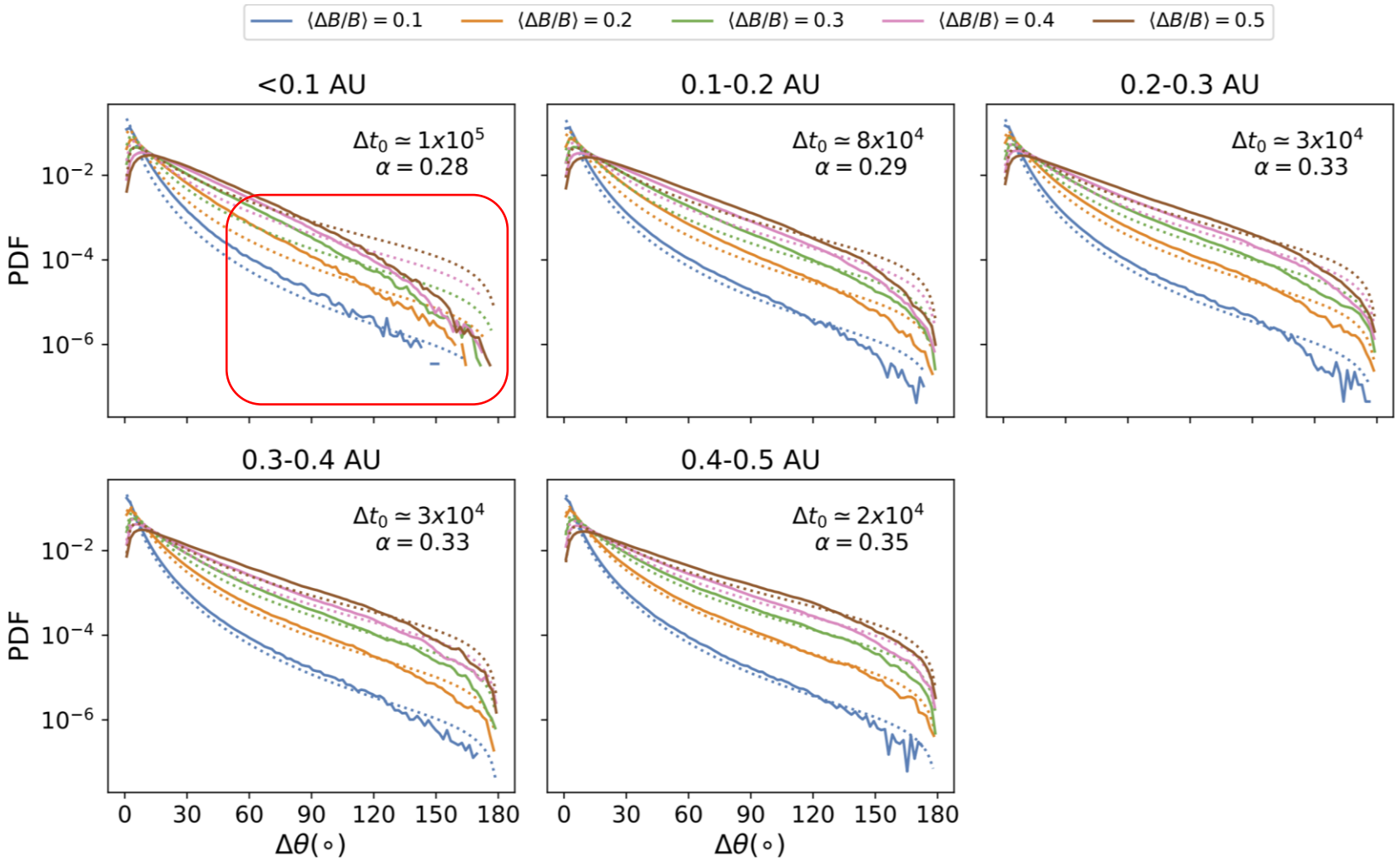
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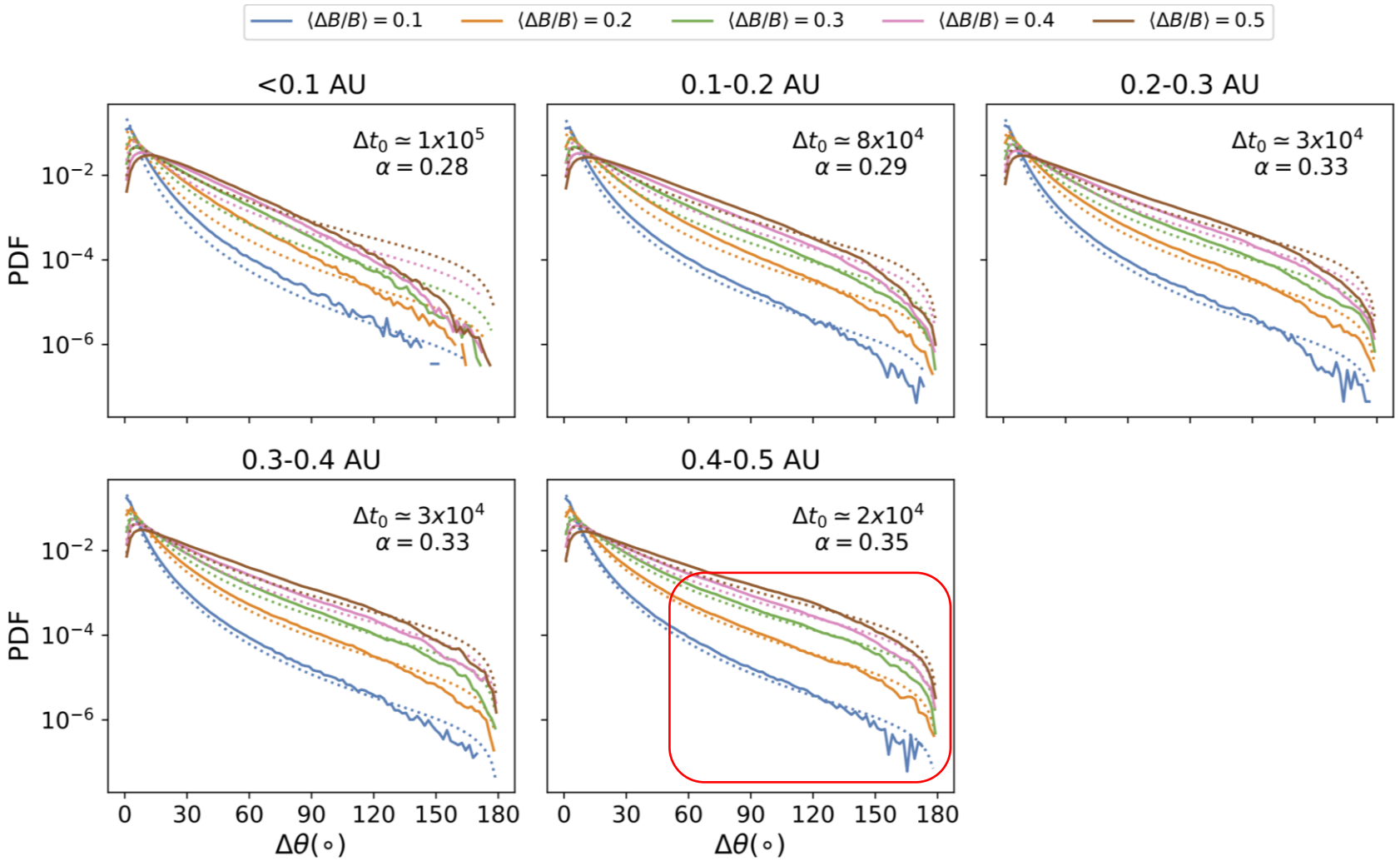
Sigma increases with distance, becoming closer and closer to one. This result support the idea that these distributions are still evolving towards the universal lognormal

Rotation model fit (dotted)



At the closest distances the rotation model fit does not work.

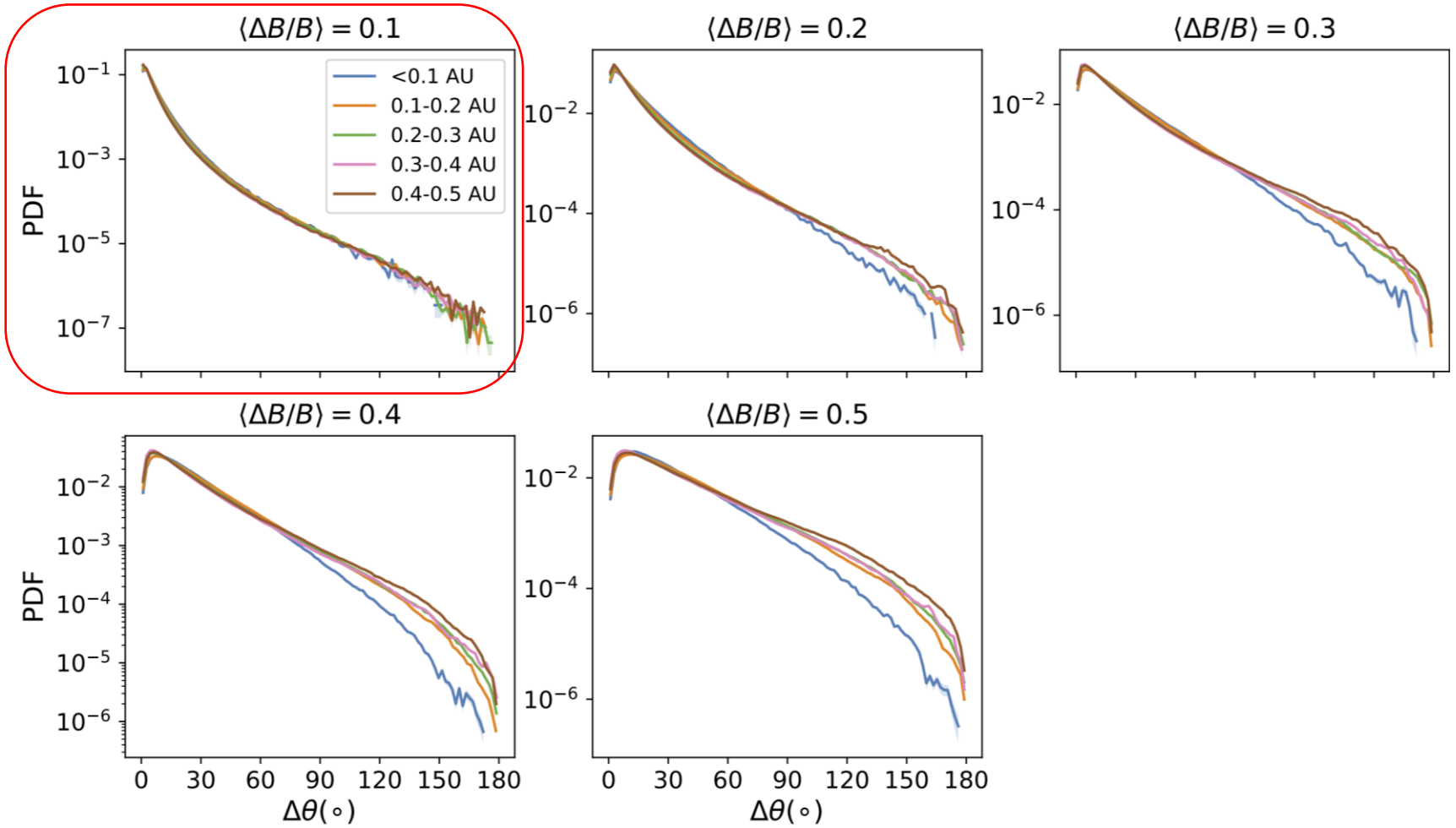
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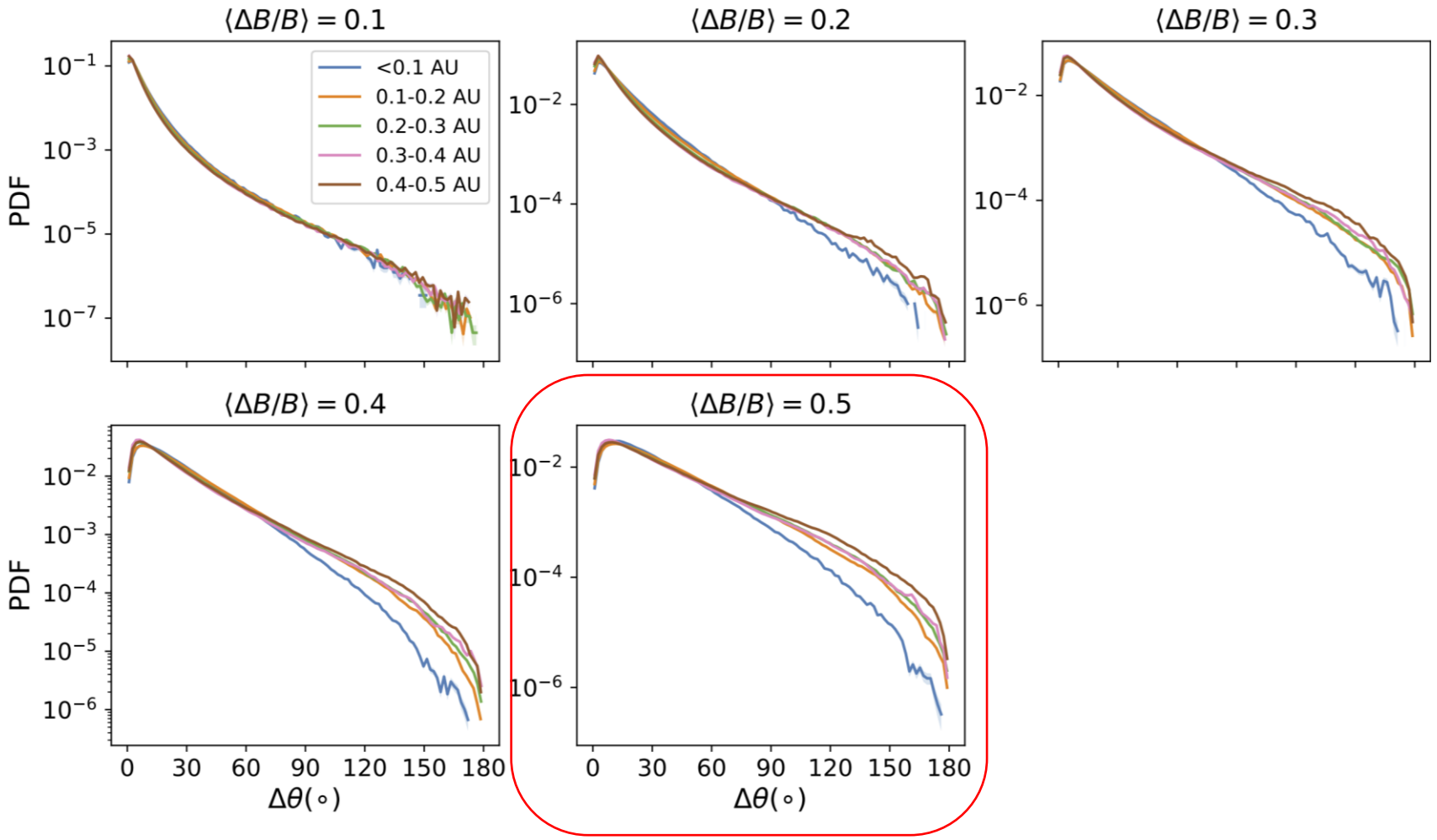
At 0.4-0.5 AU the rotation model is able to capture the full distribution without the necessity of splitting into different population of rotations

About Switchbacks



At small scales the distributions collapse one on top of the other.

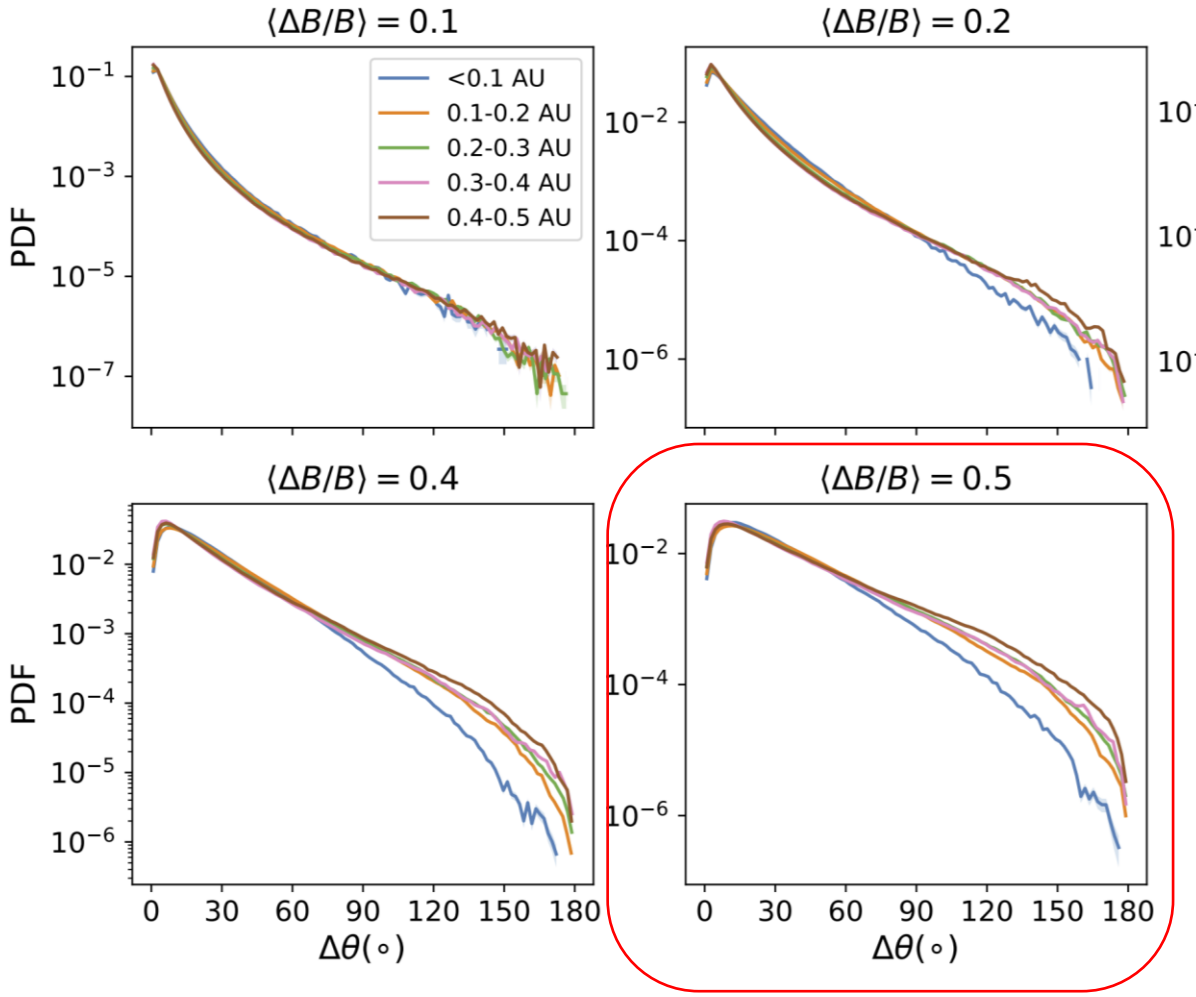
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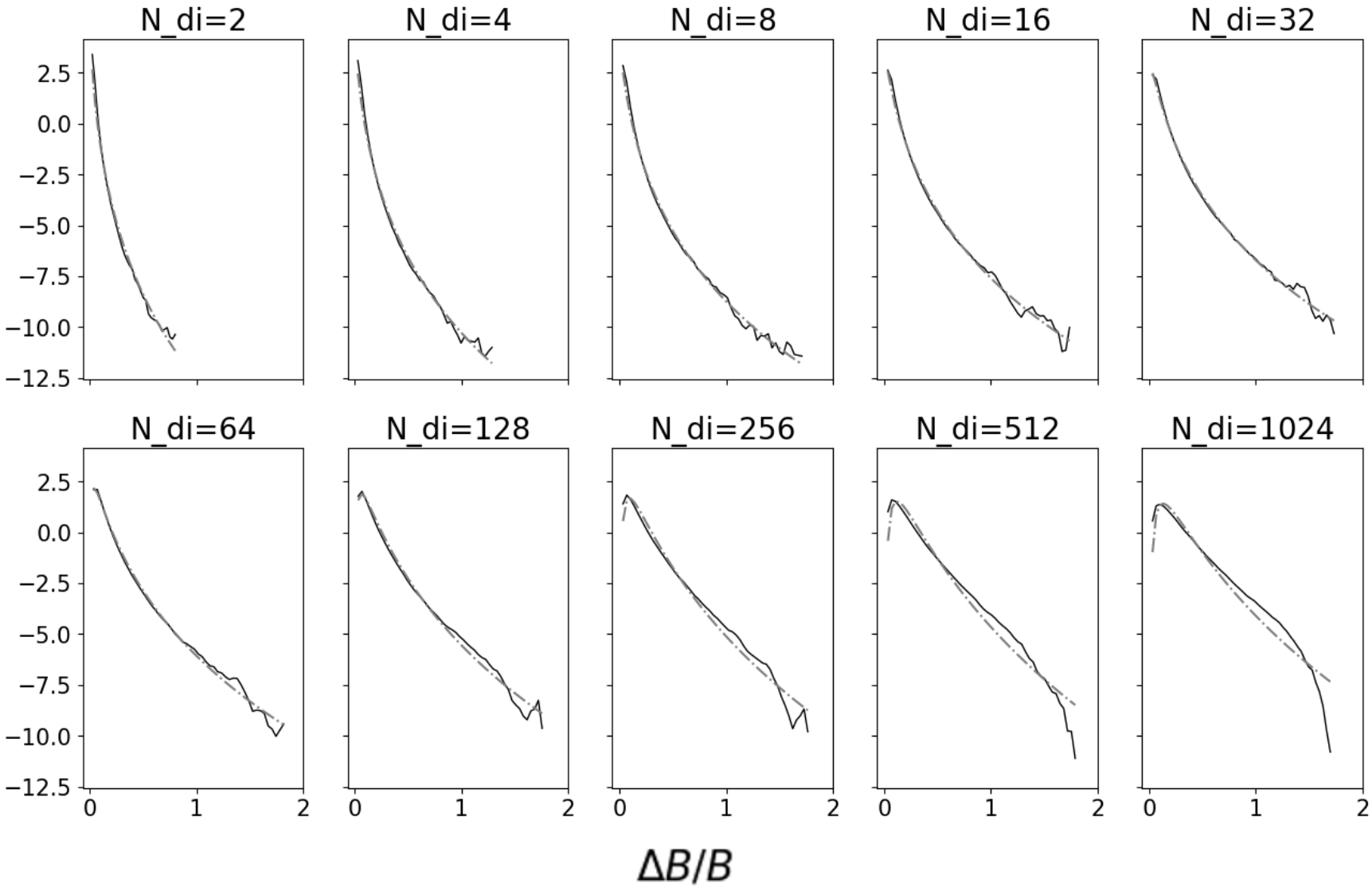
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The scale dependence and the change in shape are highly suggestive of a turbulent evolution of the rotation distributions.

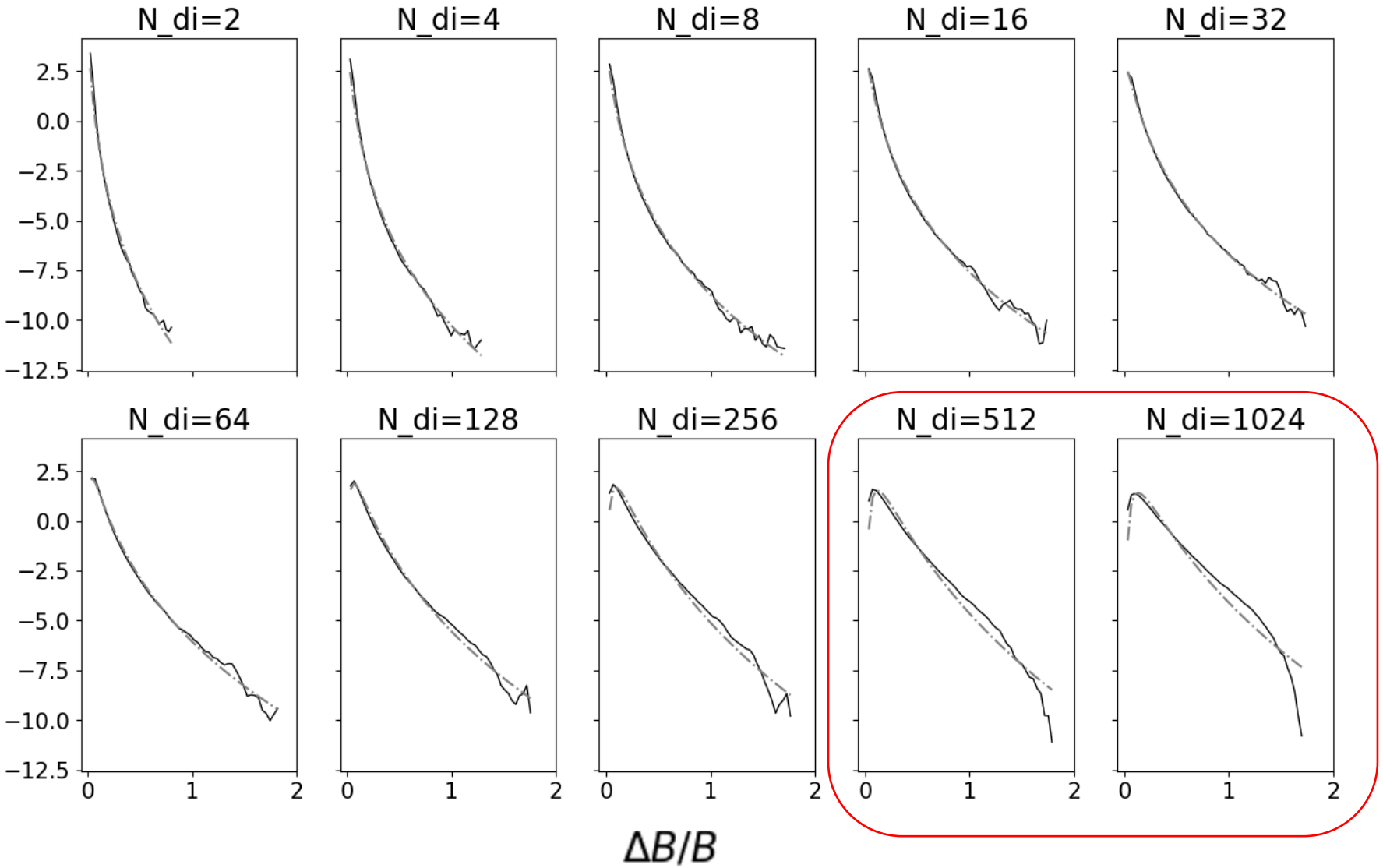
Different solar wind conditions

Sub-Alfvénic interval (Enc 14)



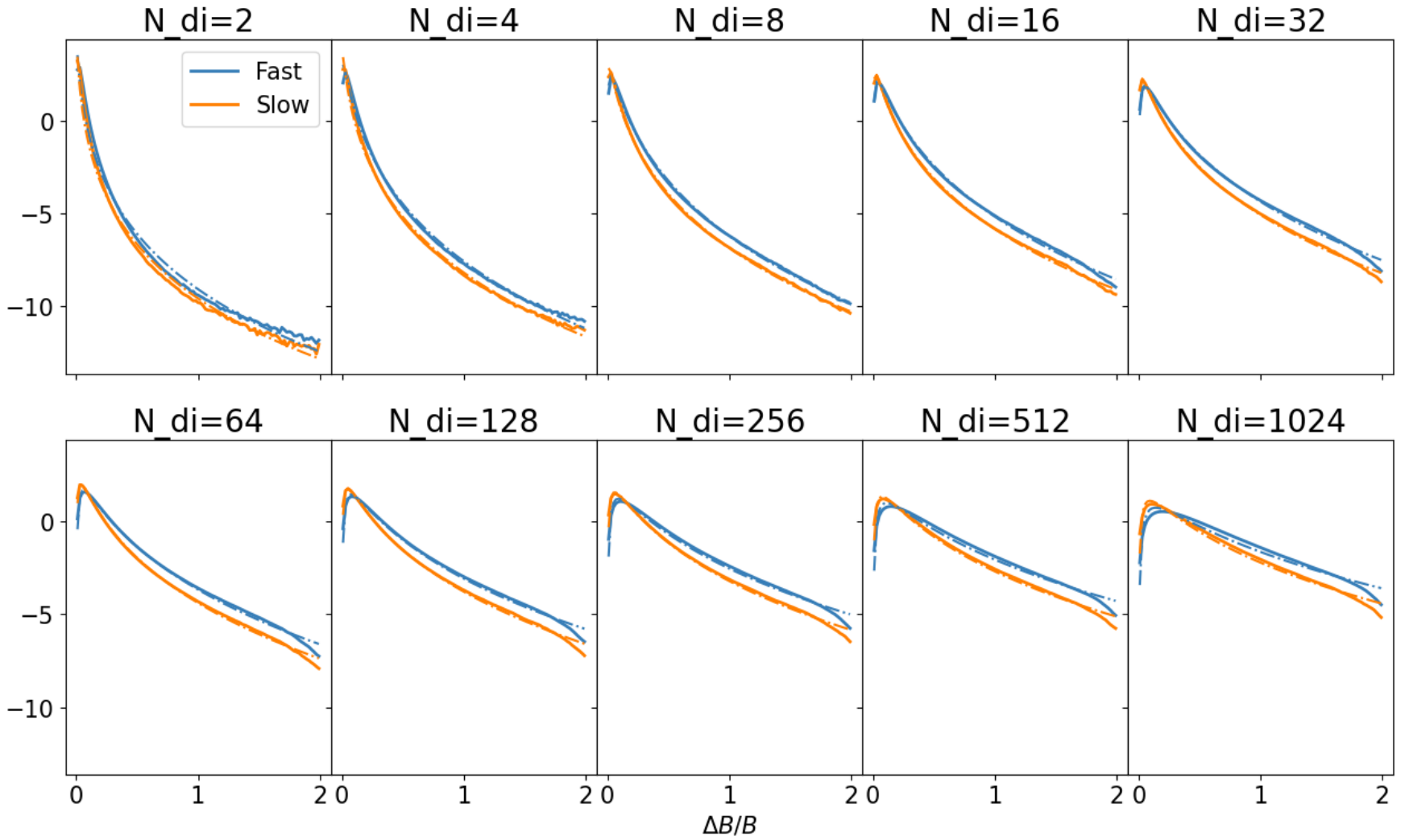
The log-normal is not an accurate description for sub-alfvenic wind. At large scales the fit is poorer due to the lack of large rotation. Keep in mind that this could be due to looking at CME affected regions (Jagarlamudi+2024 in prep)

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Dependence on speed (Fast and Slow Alfvenic, WIND 1 AU)



The lognormal is a good fit at all scales

But the rescaling into the universal lognormal does not work when the data are split in different streams.

See also Perrone+2020

Conclusions

- Log-normality is valid at small scales independently of the solar wind conditions, but not at large scales. For these scales the fit is poor for sub-Alfvénic wind. Log-normality is valid at 1 AU for both fast and slow wind.
- The Zhdankin rotation model fits the data well for R>0.4 AU, suggesting that a single function can capture the rotation distributions without invoking an arbitrary distinction between turbulent and non turbulent fluctuations (as done in Borovsky+2008)
- The possibility to rescale everything into a universal lognormal seems lost with different solar wind conditions
- The scale dependent behavior, the consistency with numerical simulations and the log-normality are highly suggestive of a turbulent processing of the medium independently of the rotation amplitude.