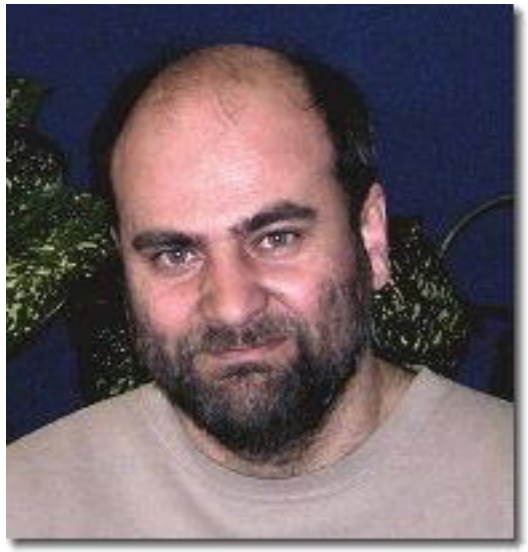
Recovering 3D Magnetic Turbulence from a Single Polarization Map

One map. One band. Full turbulence slope.

A. Melnichenka

A. Lazarian



D. Pogosyan

Problem & Payoff

Observations often have one band or two adjacent bands; RM synthesis requires broad λ-coverage.

Goal: recover inertial-range magnetic turbulence from a single polarization map.

Payoff: a robust, interferometer-friendly statistic that preserves the slope even with missing short spacings.

Polarization Angle Directional Correlation (PADC)

New measure (compute from one map):

$$S(R) = \langle \cos[2(\chi(x) - \chi(x+R))] \rangle$$

Directional spectrum (2-D Fourier power):

$$P_{dir}(k) = |FFT(\cos(2\chi)|^2 + |FFT(\sin(2\chi)|^2$$

Why it works:
no angle unwrapping
robust to filtering
directly maps to power spectrum

Emission vs. Faraday Screen: who dominates?

Polarization model (external screen or mixed):

$$P(x,\lambda) = e^{2i\,[\,\psi_{emit}(x) + \lambda^2\, RM(x)}$$

Transition criterion (at scale k):

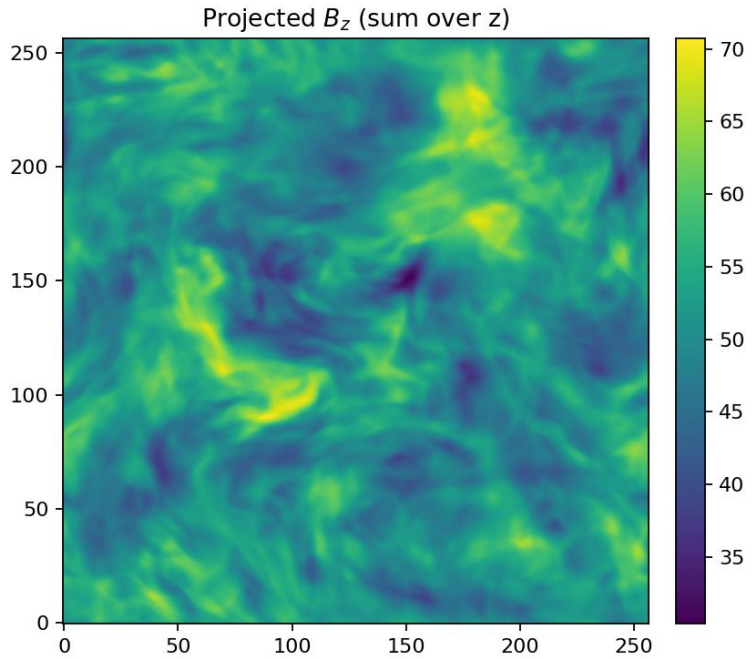
$$\lambda^2 \cdot \sigma_{RM}(k) \approx 1$$

defines crossover $k_\times\,(\lambda)$

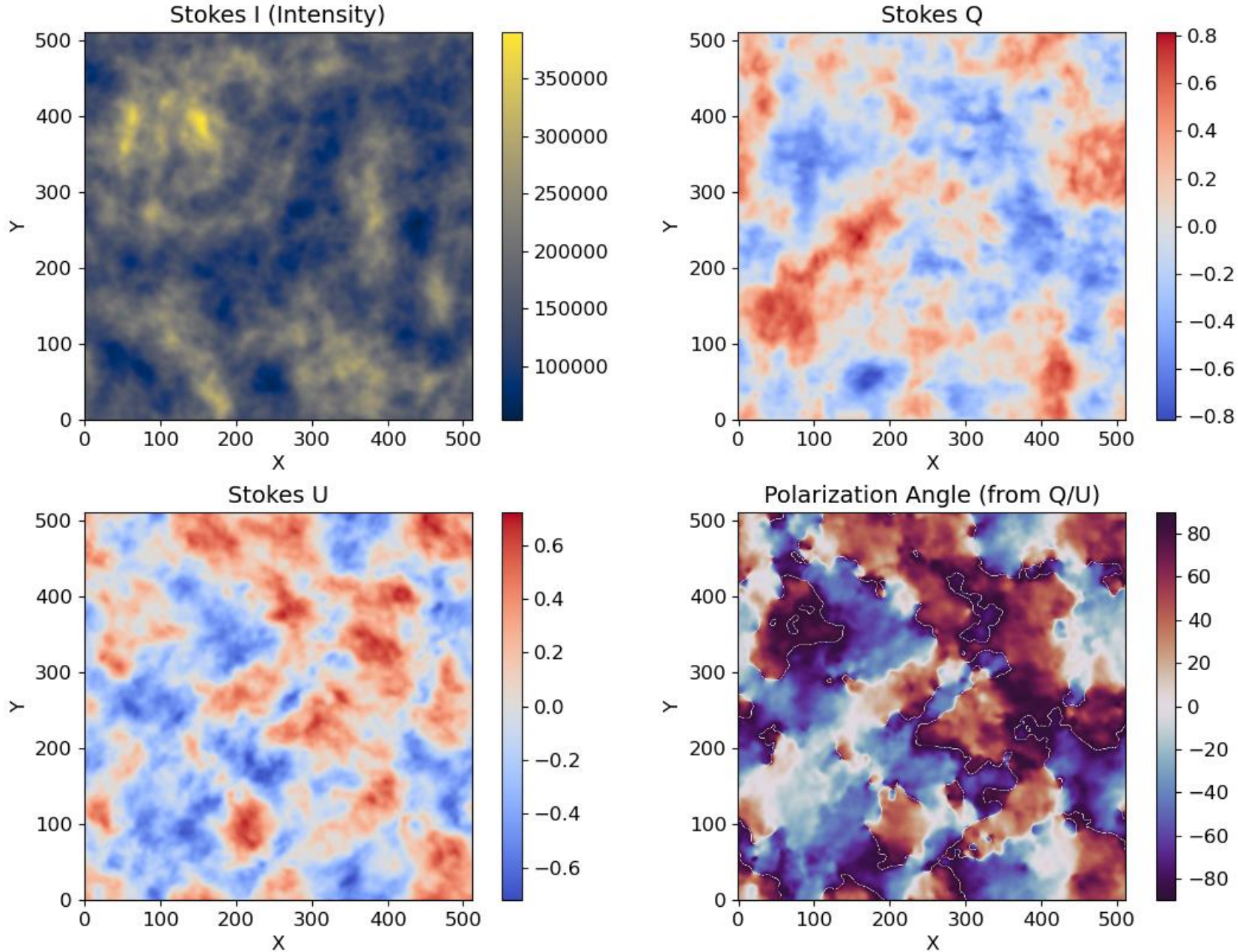
Short λ : synchrotron emission angles dominate.
Long λ : Faraday screen ($n_e B_\parallel$) dominates.

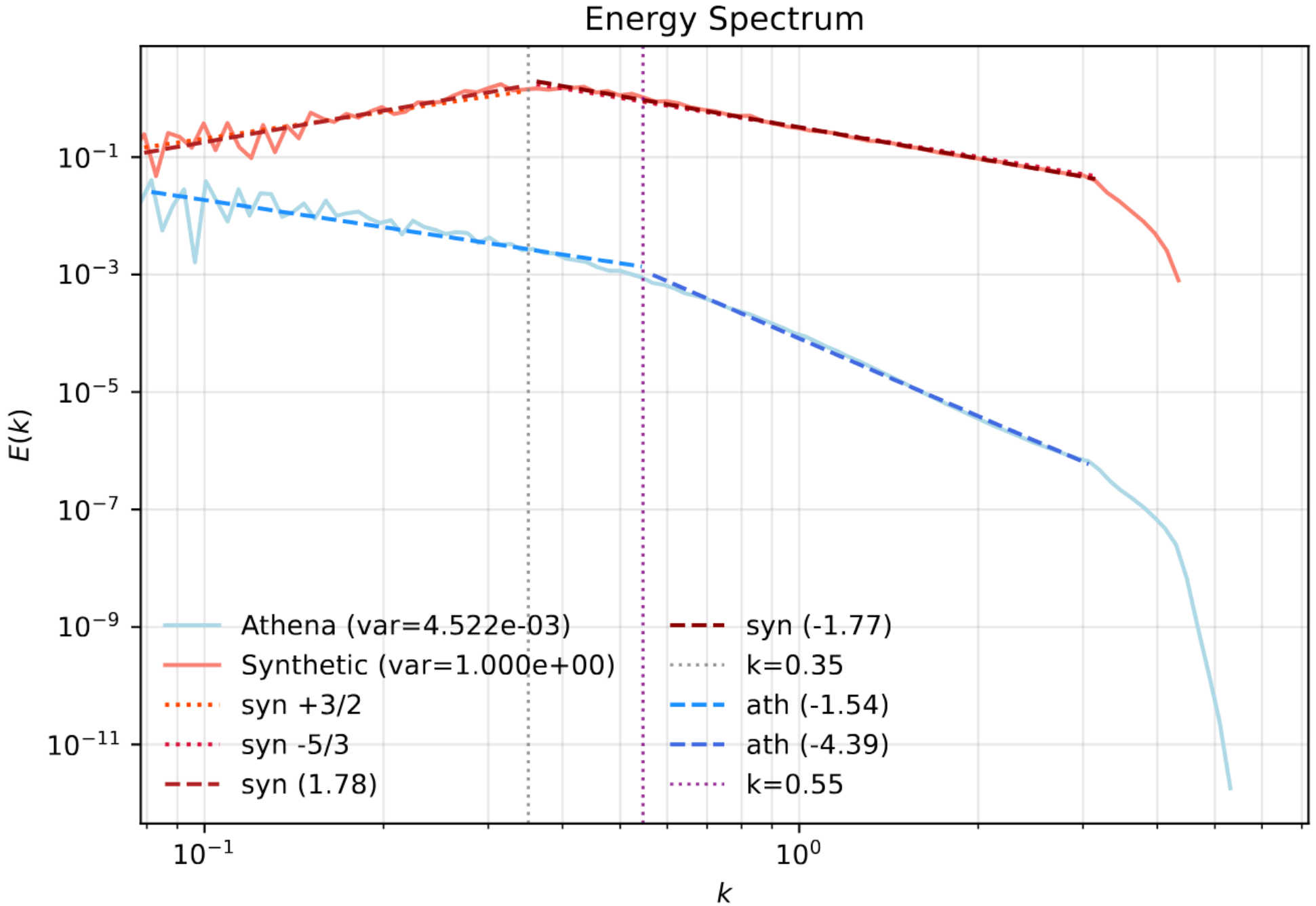
Simulation design

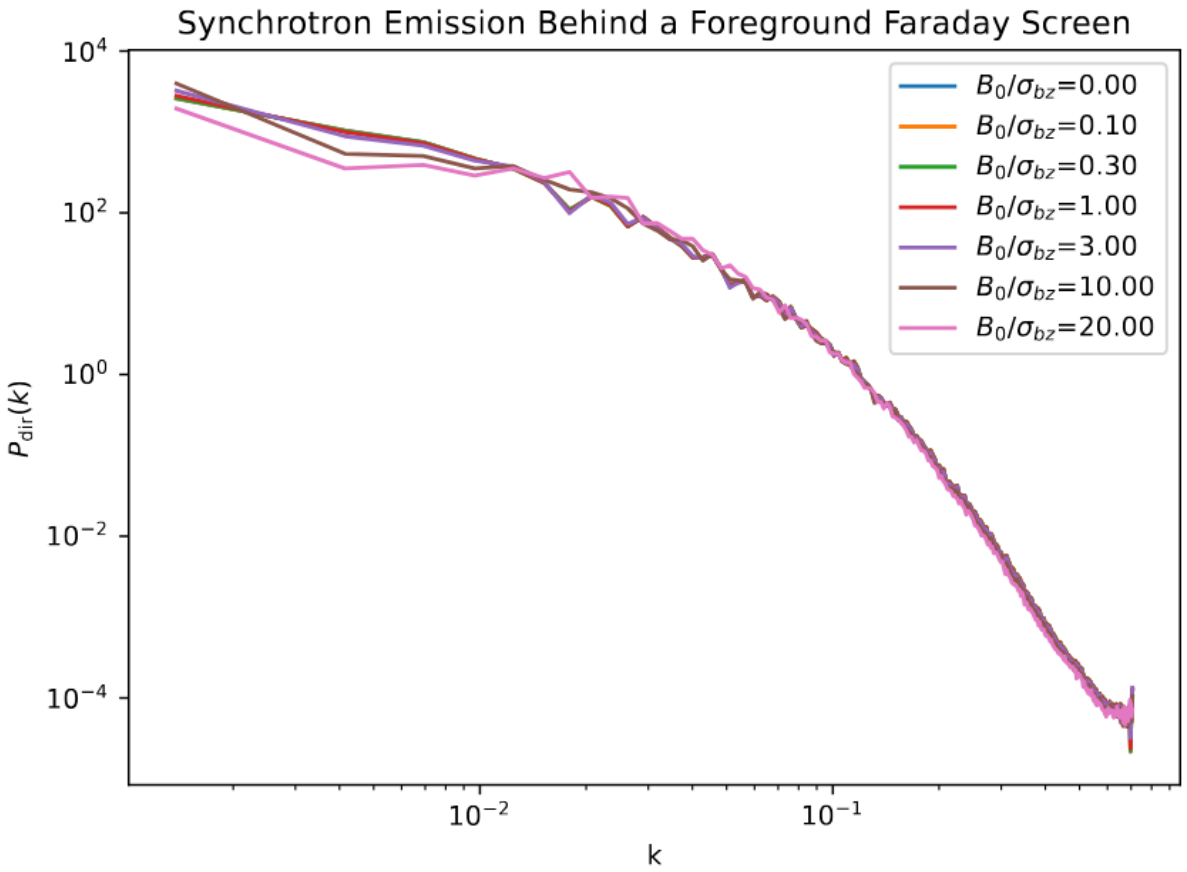
- Synthetic fields with controlled slopes (density & magnetic)
- ATHENA MHD snapshots (sub- and super-Alfvénic)
- Geometries: External screen; Mixed emission and screen; Two-screen tests
- Outputs: $S(R), P_{dir}(k)$, crossover $k_{\times}$ (λ)

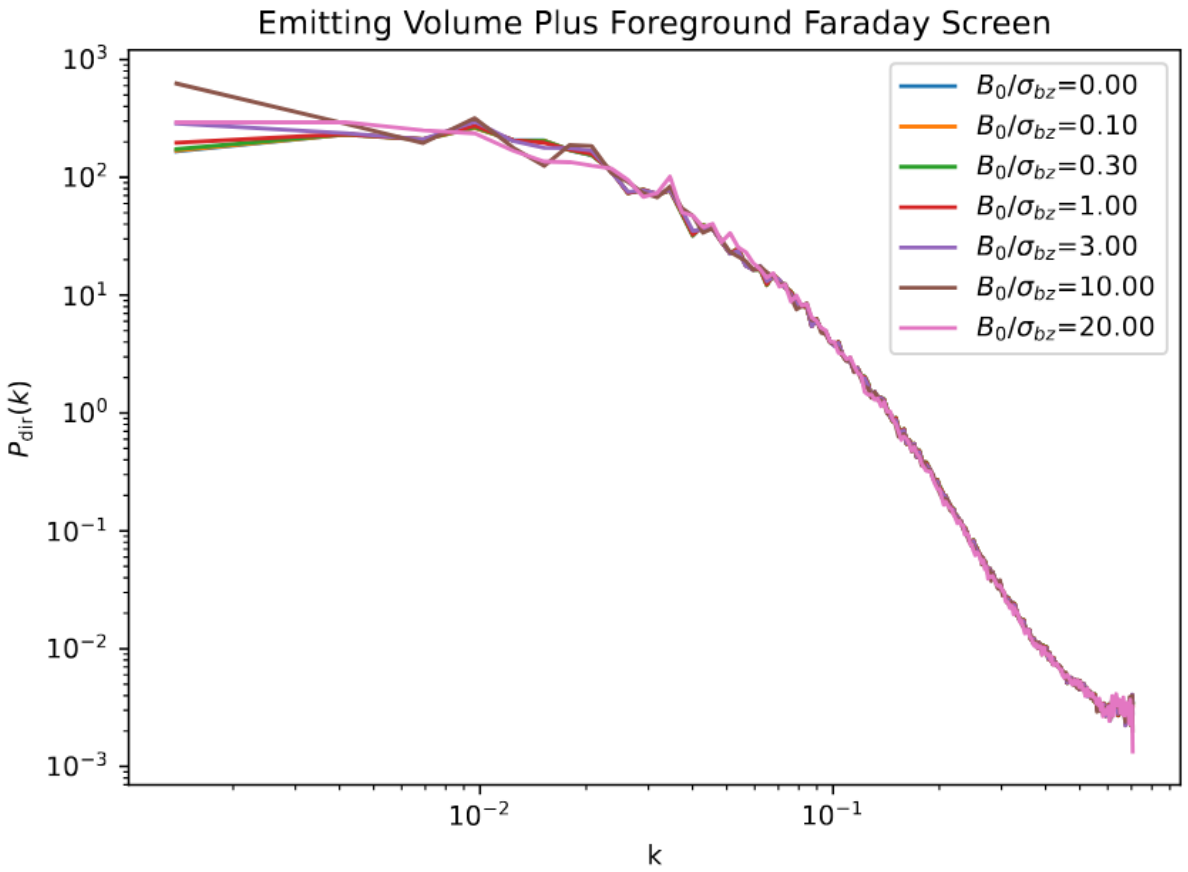


Polarization Maps

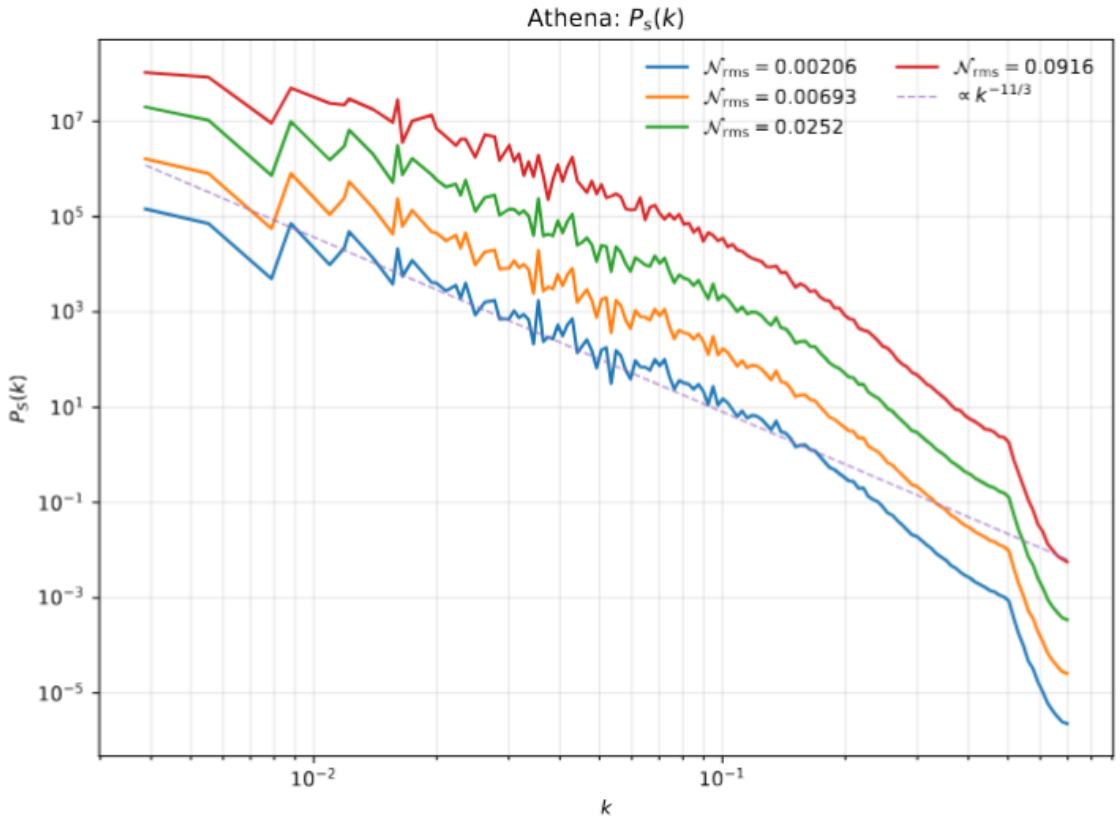


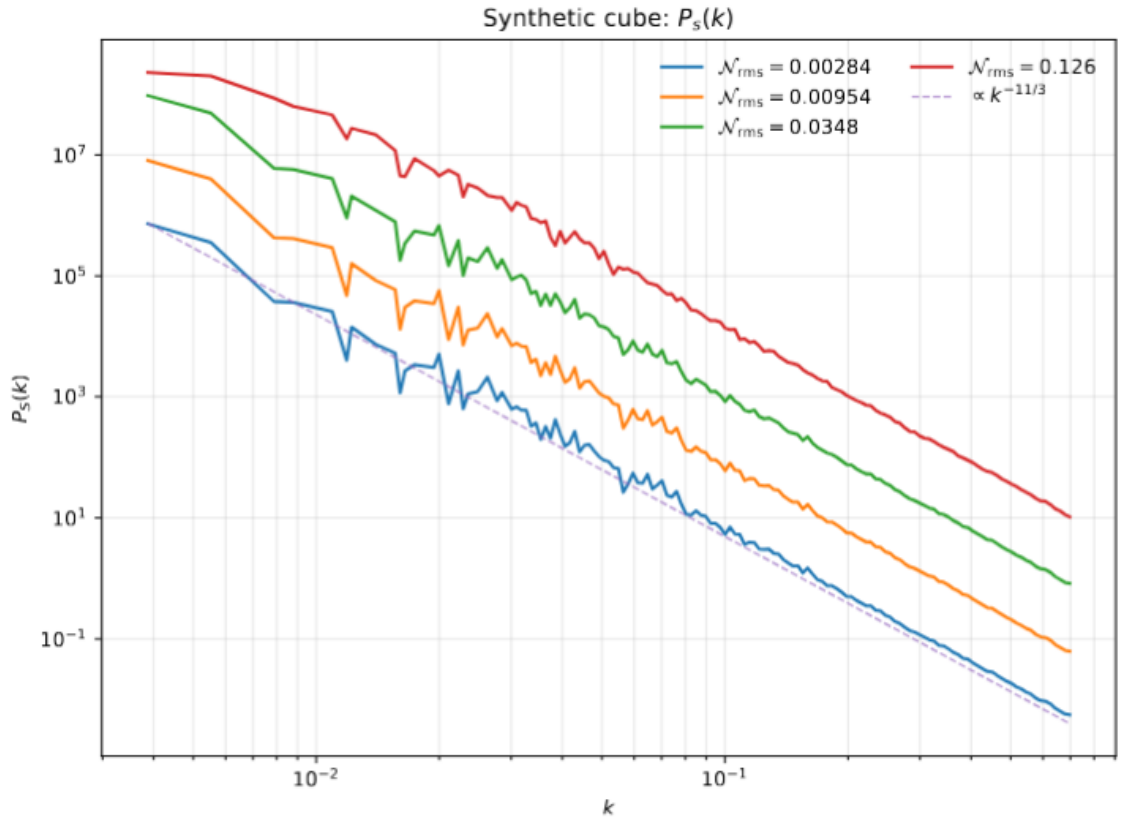

Energy Spectrum
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
$E(k)$
10^{-1}
10^{0}
k
Athena (var=4.522e-03)
Synthetic (var=1.000e+00)
syn +3/2
syn -5/3
syn (1.78)
syn (-1.77)
k=0.35
ath (-1.54)
ath (-4.39)
k=0.55

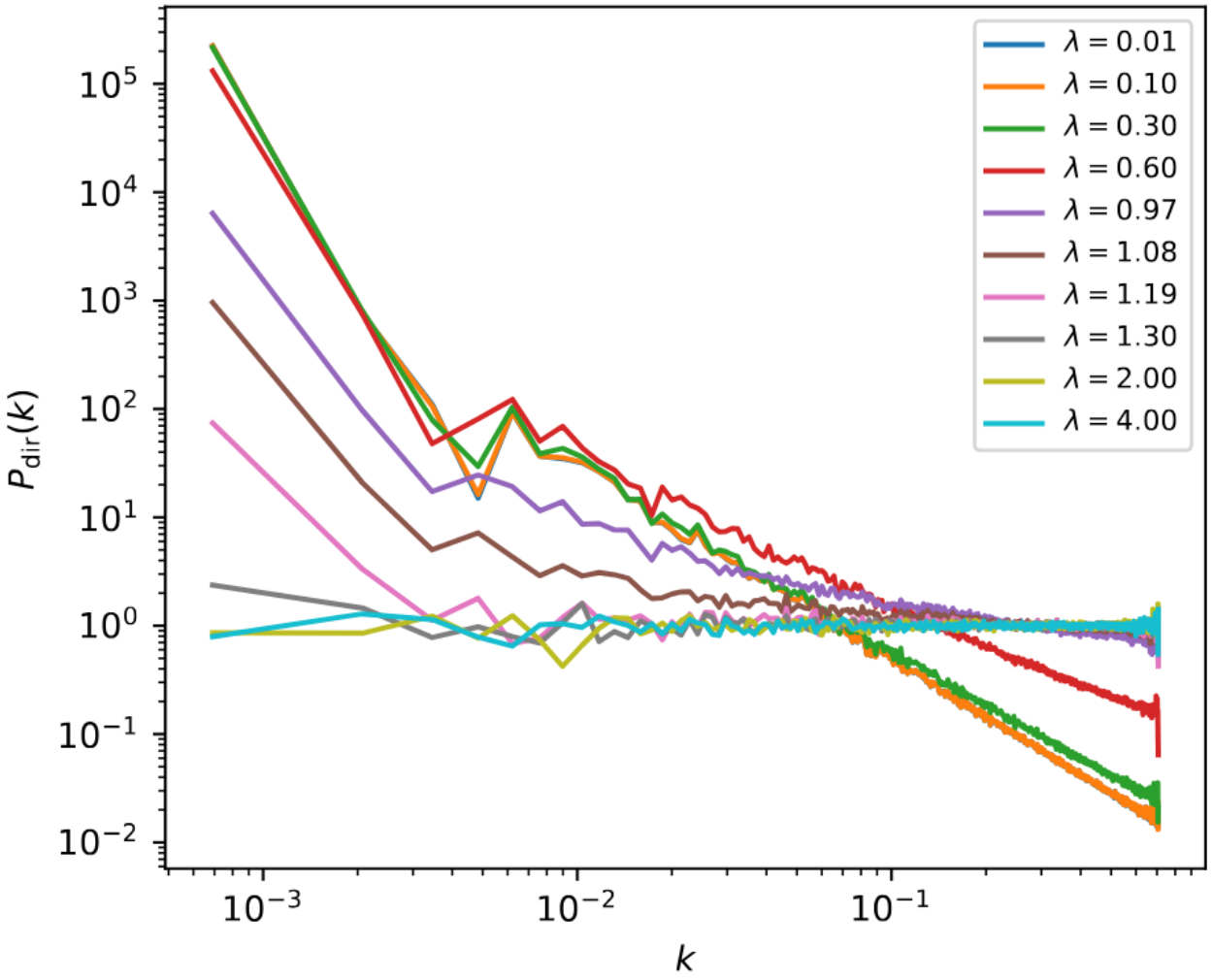


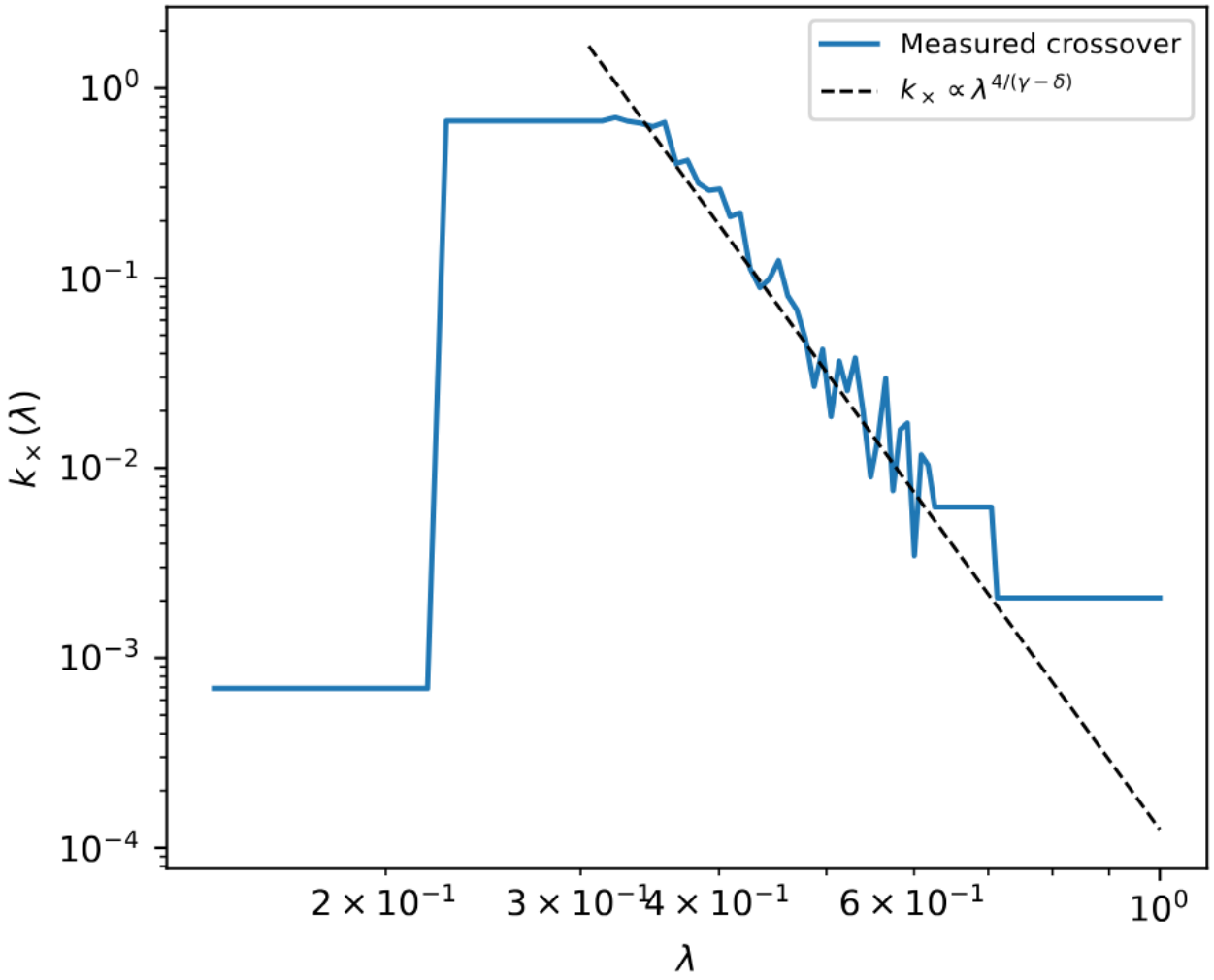


The emitting volume both emits and internally rotates; a foreground screen adds rotation.
Despite competition, the same crossover criterion holds and separates regimes cleanly.


Athena: $P_s(k)$
$\mathcal{N}_{\rm rms} = 0.00206$
$\mathcal{N}_{\rm rms} = 0.00693$
$\mathcal{N}_{\rm rms} = 0.0252$
$\mathcal{N}_{\rm rms} = 0.0916$
$\propto k^{-11/3}$
$P_s(k)$
k

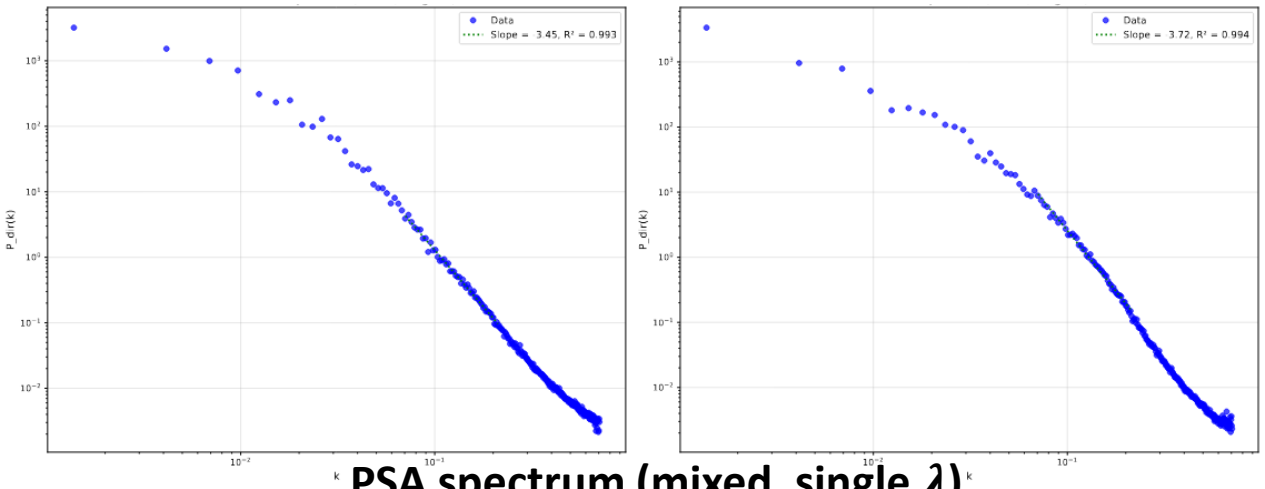

Synthetic cube: $P_s(k)$
$\mathcal{N}_{\rm rms} = 0.00284$
$\mathcal{N}_{\rm rms} = 0.00954$
$\mathcal{N}_{\rm rms} = 0.0348$
$\mathcal{N}_{\rm rms} = 0.126$
$\propto k^{-11/3}$
$P_s(k)$
k



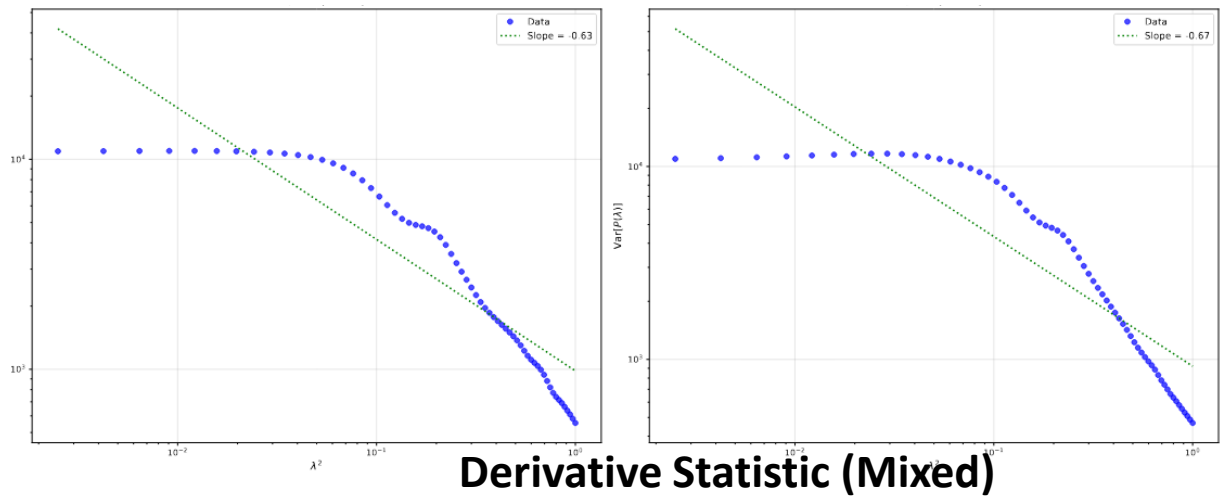


At small λ, $P_{dir}(k)$ follows the background angle field.
At large λ, $P_{dir}(k)$ follows RM statistics ($n_e B_\parallel$).
Crossover observed where $\lambda^2\,\sigma_{RM}(k_\times) \approx 1$.

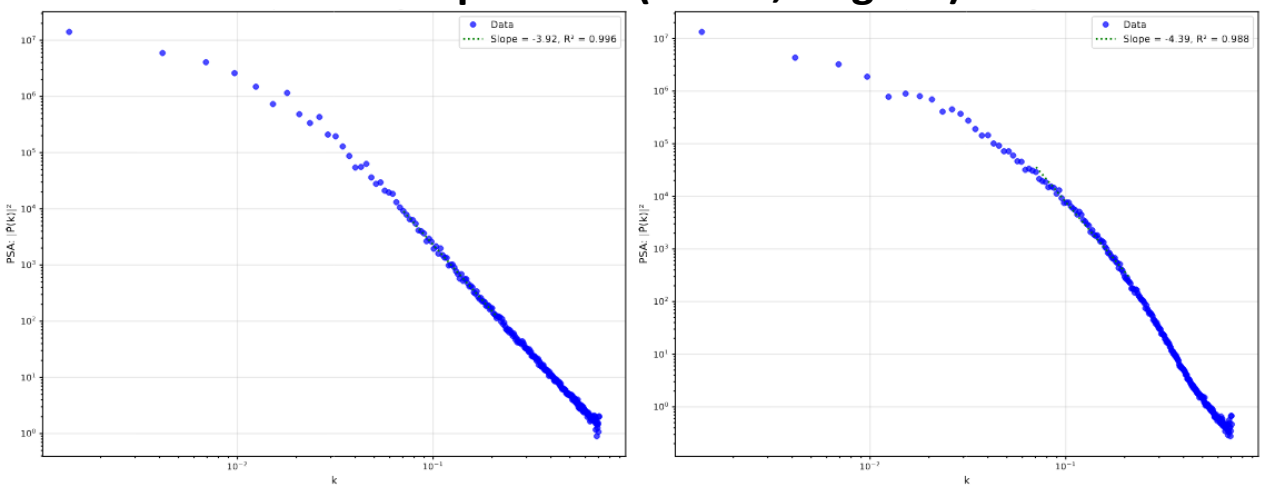
Directional spectrum (mixed, single λ)



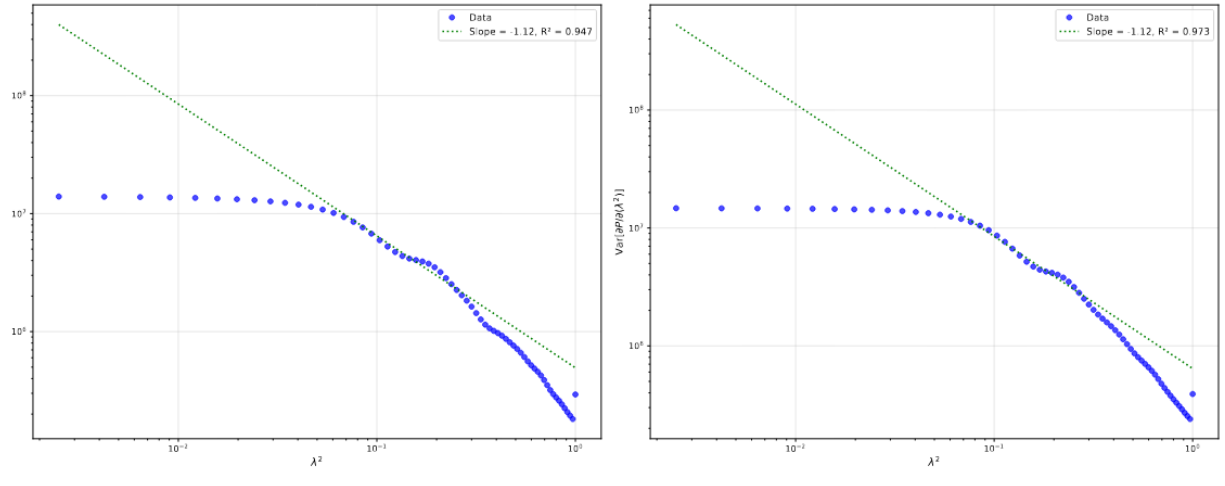
PFA/PVA (mixed)



PSA spectrum (mixed, single λ)

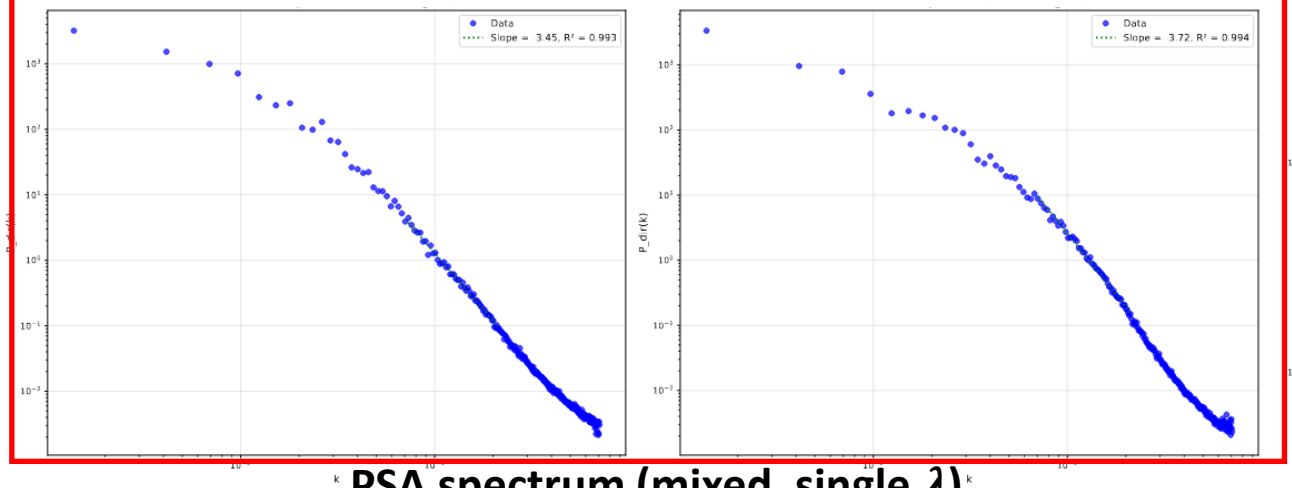


Derivative Statistic (Mixed)



Comparison PADC with other known measures

Directional spectrum (mixed, single λ)



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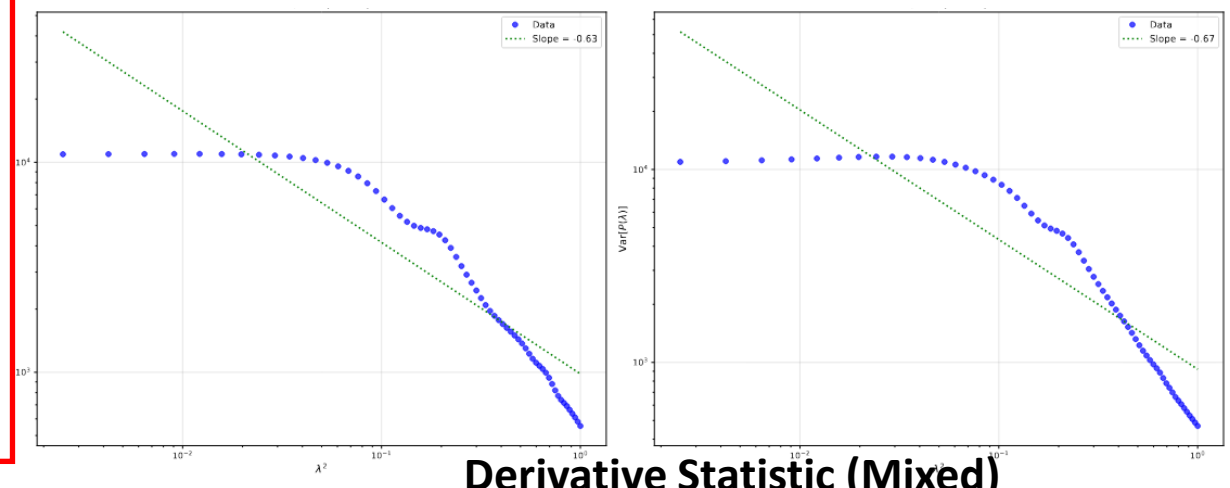

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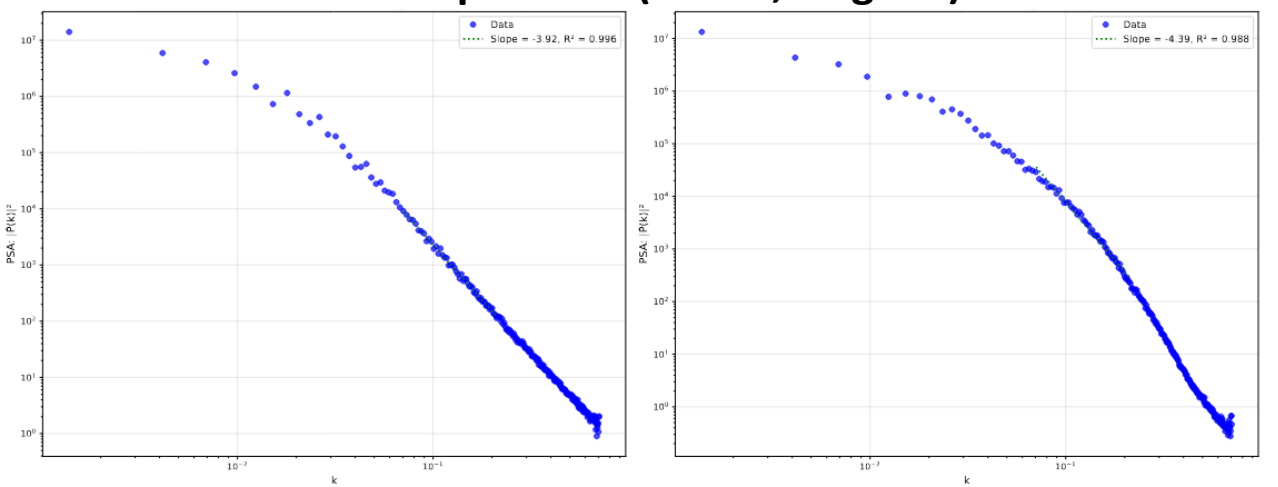

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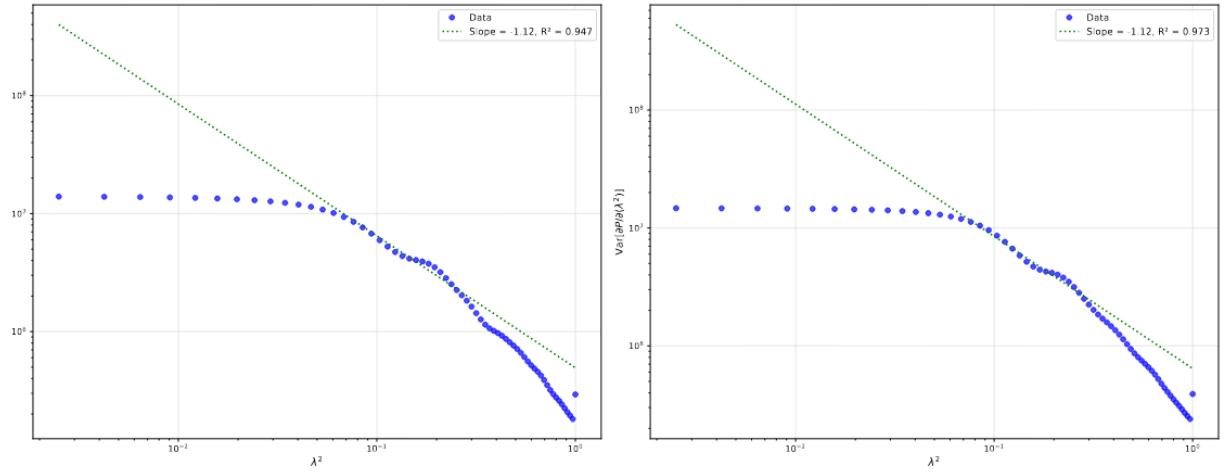

Comparison PADC with others known measures

Take-home & outlook

- Single-frequency polarization already encodes turbulence: $S(R)$ and $P_{dir}(k)$ recover slopes.
- Crossover $k_{\times}$ (λ) operationalizes separation of emission vs. screen with minimal bandwidth.
- Ready for LOFAR/MeerKAT/VLA archives; sets the stage for SKA when spectral coverage is sparse.

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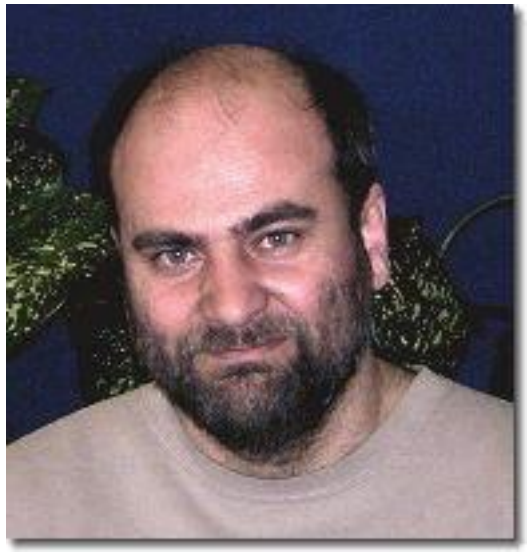

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