MONOFRACTALITY IN THE SOLAR WIND AT ELECTRON SCALES

Insights from kinetic Alfvén waves turbulence

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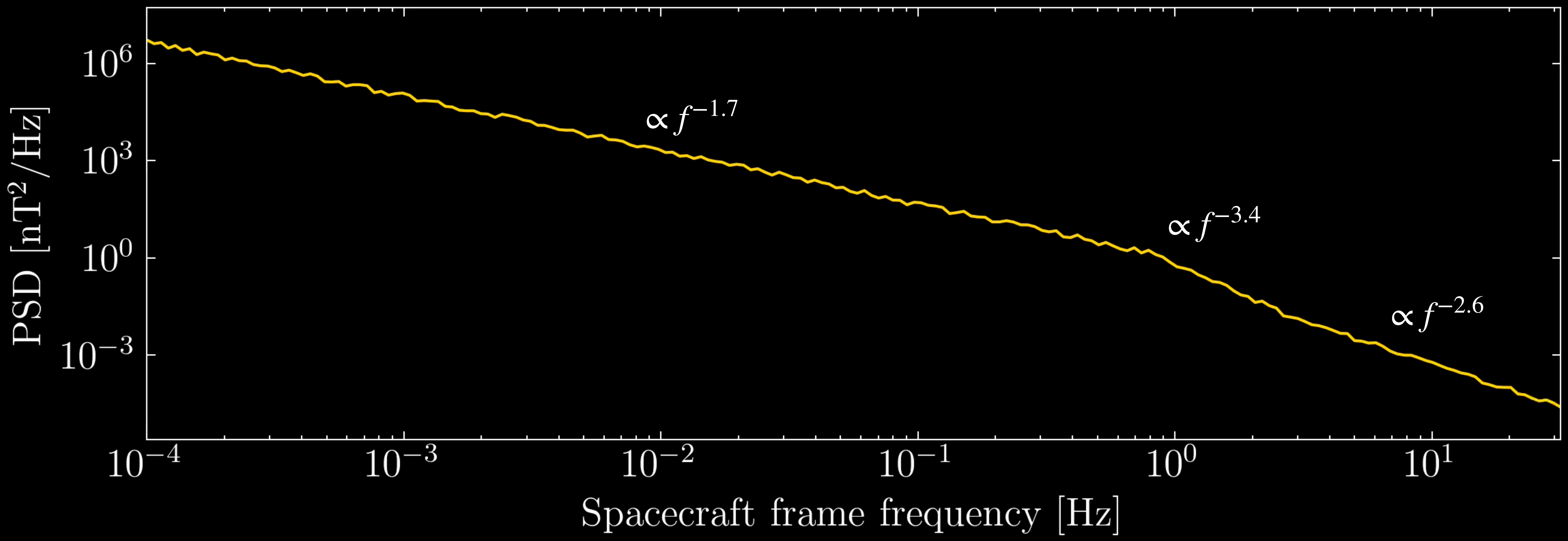
LPP

How do electrons behave when ions are motionless?



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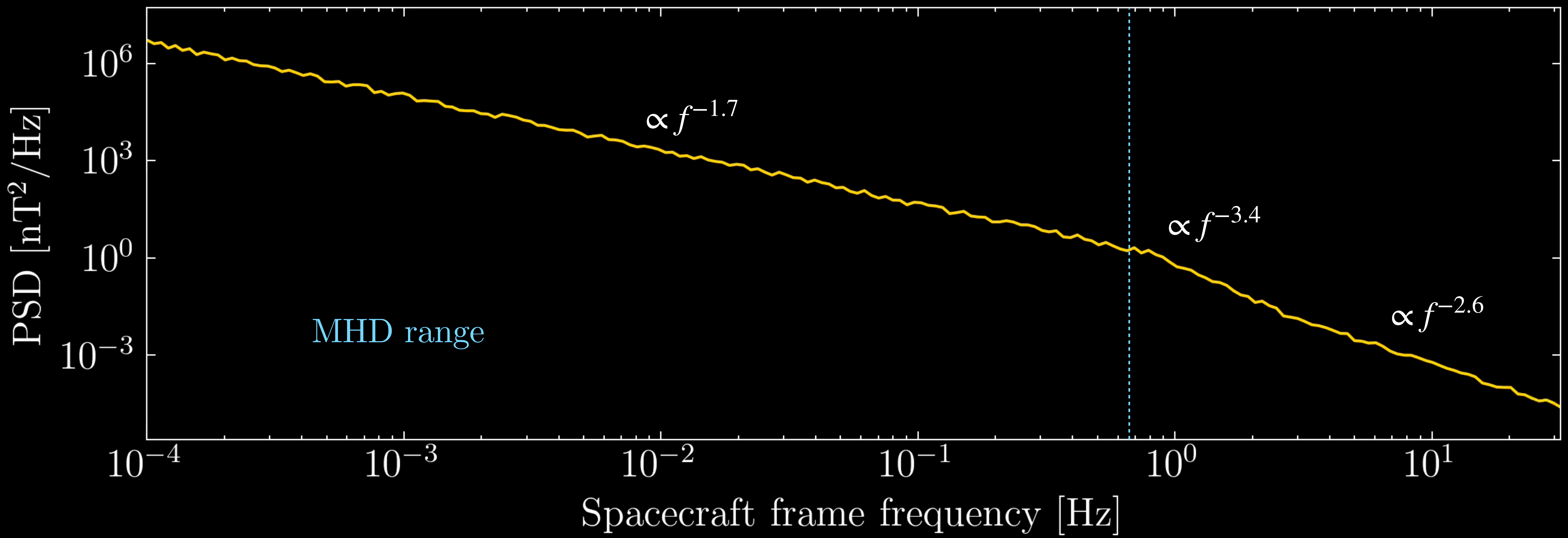

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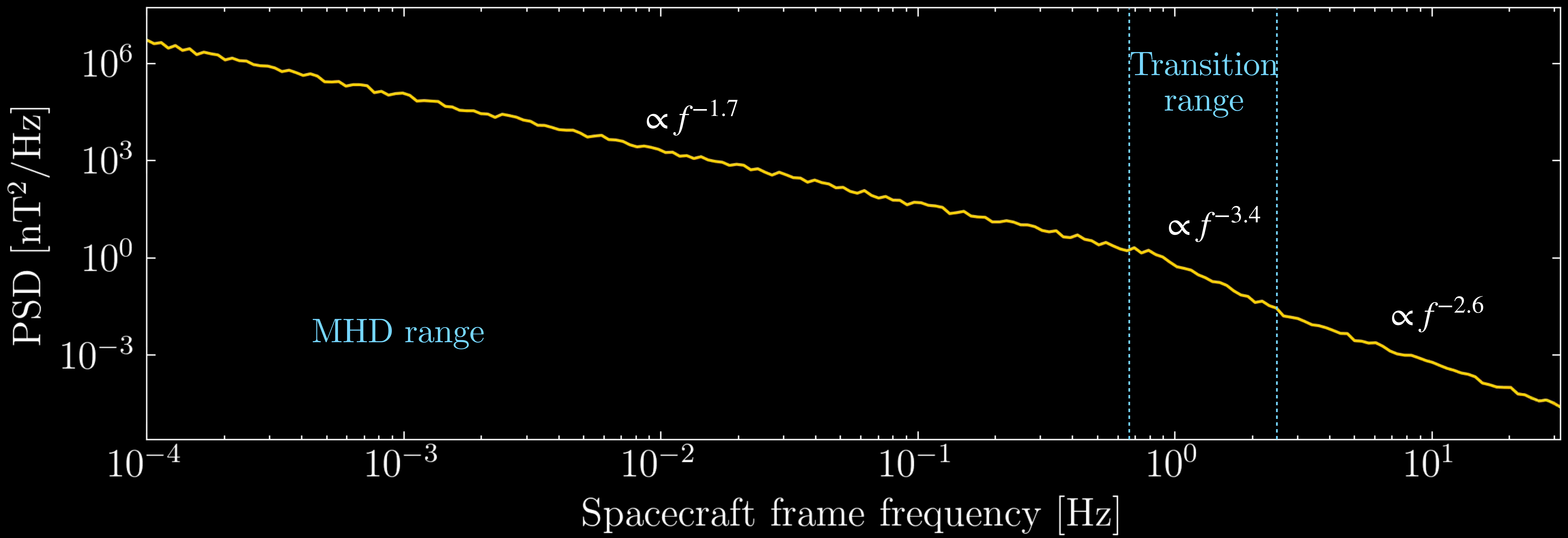

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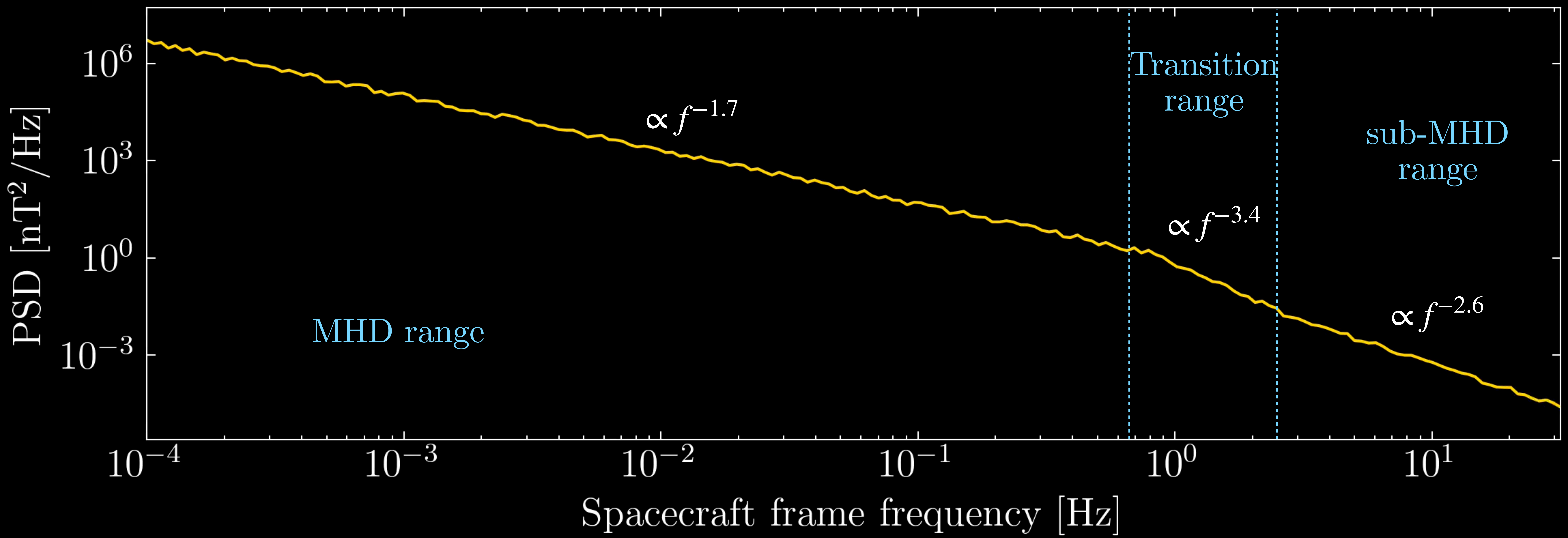

Electron reduced MHD

Assumptions:

- strong guide field $\vec{b}_0$
- weakly compressible plasma
- $\vec{b}(\vec{x}, t) = \left(b_0 + b_z\right) \hat{e}_z + \hat{e}_z \times \vec{\nabla}_\perp \psi$

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$d_i \sim 100\,\text{km}$

ERMHD $\longrightarrow$

$$\frac{\partial \psi}{\partial t} = d_i \left\{\psi, b_z\right\} + d_i b_0 \frac{\partial \psi}{\partial z} \qquad \frac{\partial b_z}{\partial t} = -\frac{d_i}{\kappa} \left\{\psi, \nabla_\perp^2 \psi\right\} + \frac{d_i b_0}{\kappa} \frac{\partial}{\partial z} \left(\nabla_\perp^2 \psi\right)$$

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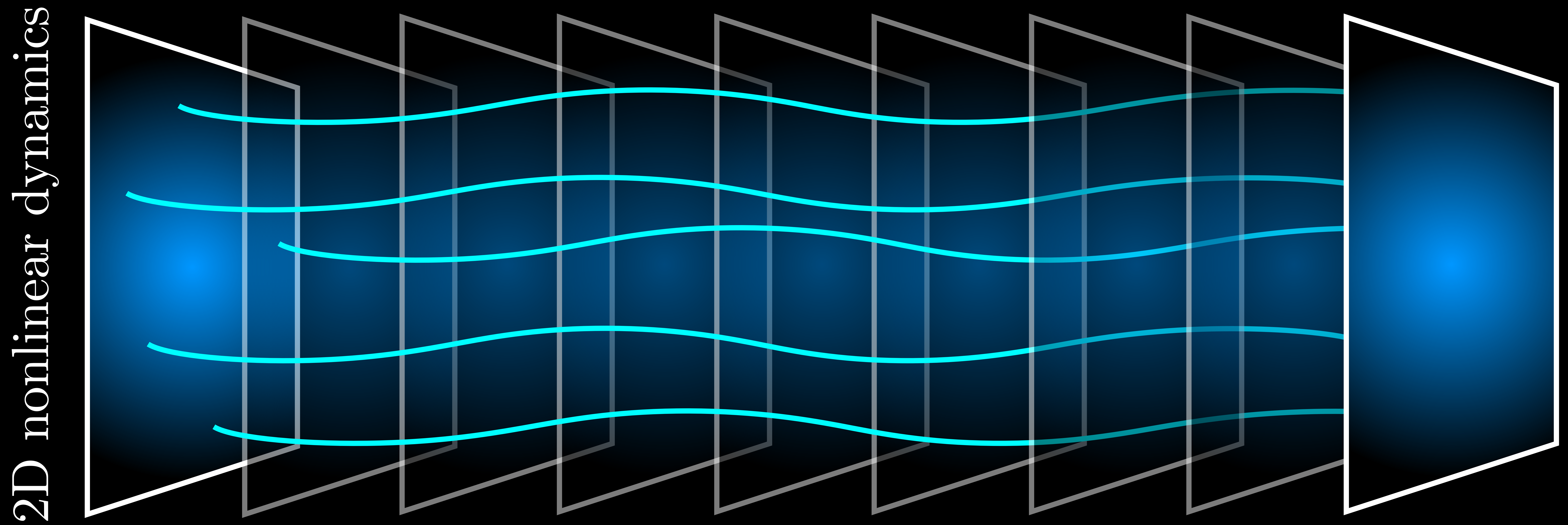
$$\Longrightarrow \boxed{\omega_k = \frac{d_i b_0}{\kappa} k_\perp k_\parallel}$$

kinetic Alfvén waves

— gradient along the guide field $\vec{b}_0$

— gradient along the local field $\vec{b}(\vec{x}, t)$

Electron reduced MHD



Kinetic Alfvén Waves carrying information

Phenomenology

Two timescales from the equations: $\tau_{\text{lin}} \sim \dfrac{\kappa}{d_i b_0 k_\perp k_\parallel}$ $\quad \tau_{\text{nl}} \sim \dfrac{\kappa}{d_i k_\perp^2 b_k}$ $\longrightarrow$ $\chi \equiv \dfrac{\tau_{\text{lin}}}{\tau_{\text{nl}}}$

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χ ~ 1 $\longrightarrow$ Strong turbulence ($\tau_{\text{lin}} \sim \tau_{\text{nl}}$) $\longrightarrow$ $E_k \sim k_\perp^{-7/3} k_\parallel^{-1}$

χ $\ll 1$ $\longrightarrow$ Weak turbulence ($\tau_{\text{lin}} \ll \tau_{\text{nl}}$) $\longrightarrow$ $E_k \sim k_\perp^{-5/2} k_\parallel^{-1/2}$

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Hardly distinguishable through their perpendicular spectra.

[S. Nazarenko & A. Schekochihin, 2011, JFM] [J. Cho & A. Lazarian, 2004, ApJL] [S. Galtier & A. Battacharjee, 2003, PoP]

Energy spectra

Two decades, 20% of noise

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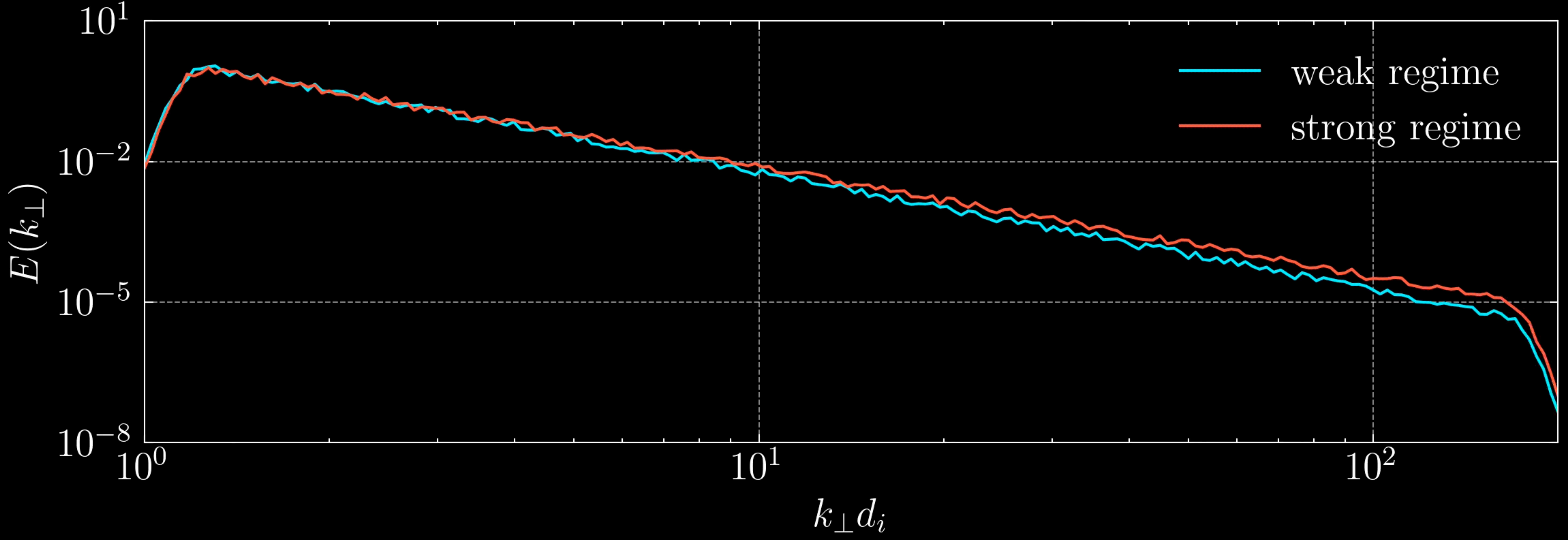

Energy spectra

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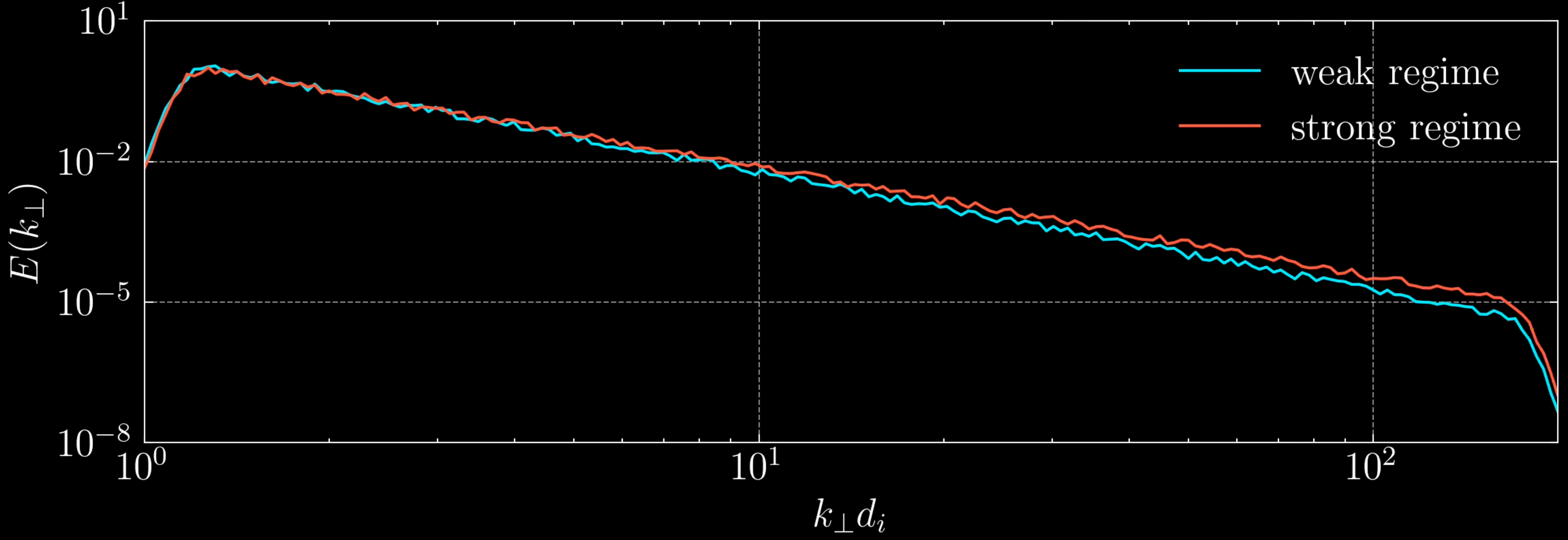

Another diagnostic is required to clearly differentiate the two regimes.

Intermittency

What does quantify intermittency?

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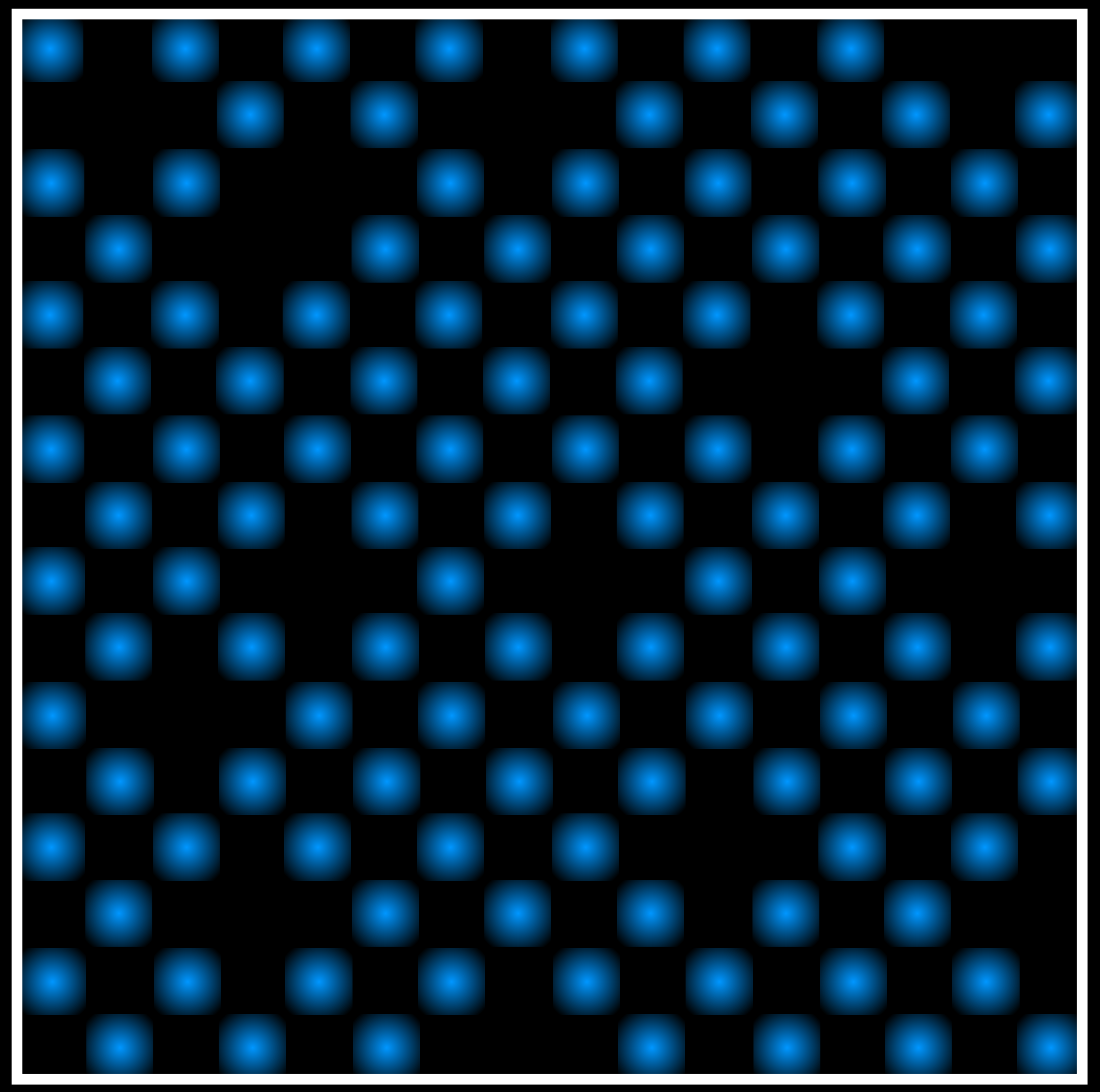

Even repartition

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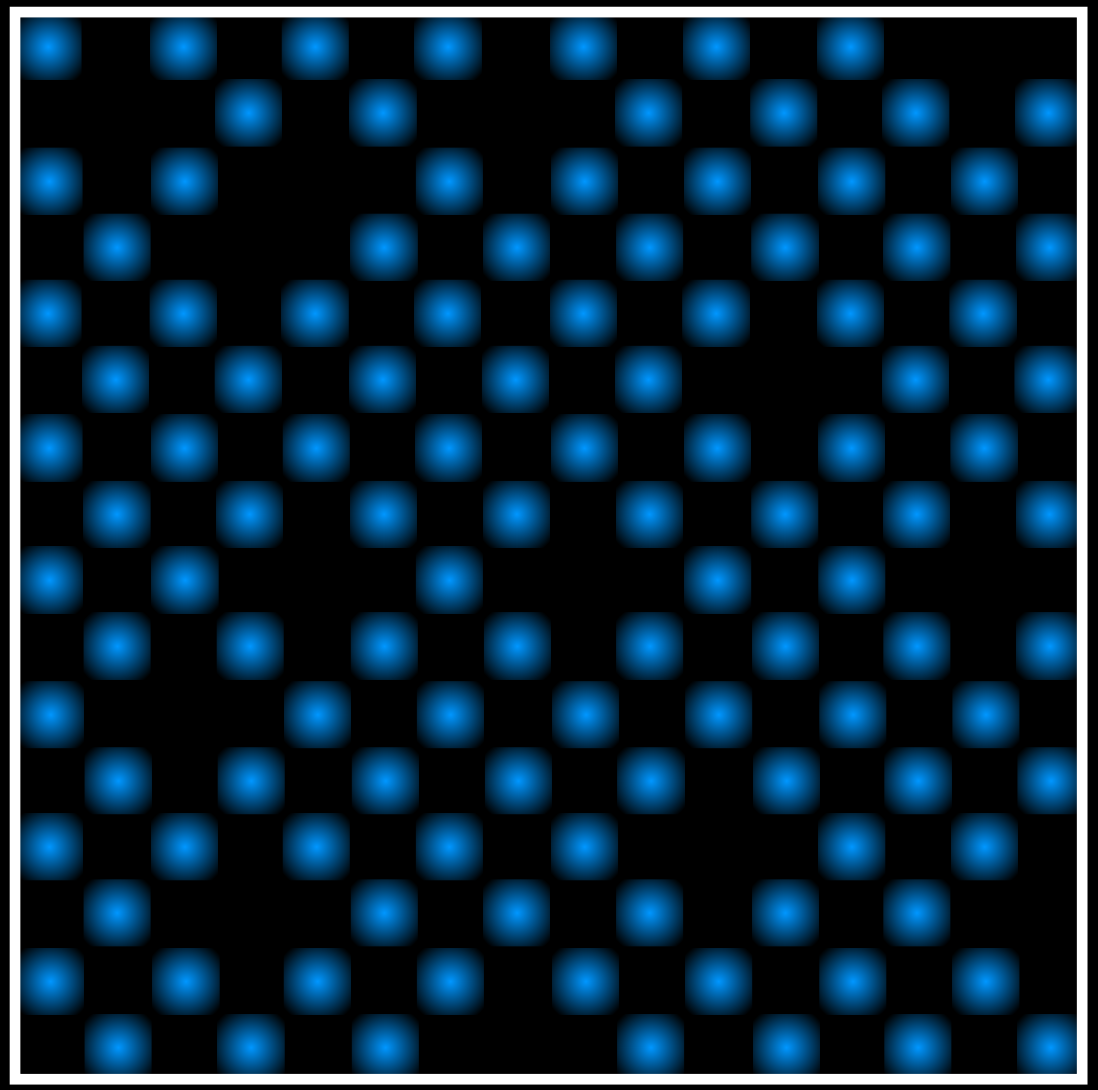

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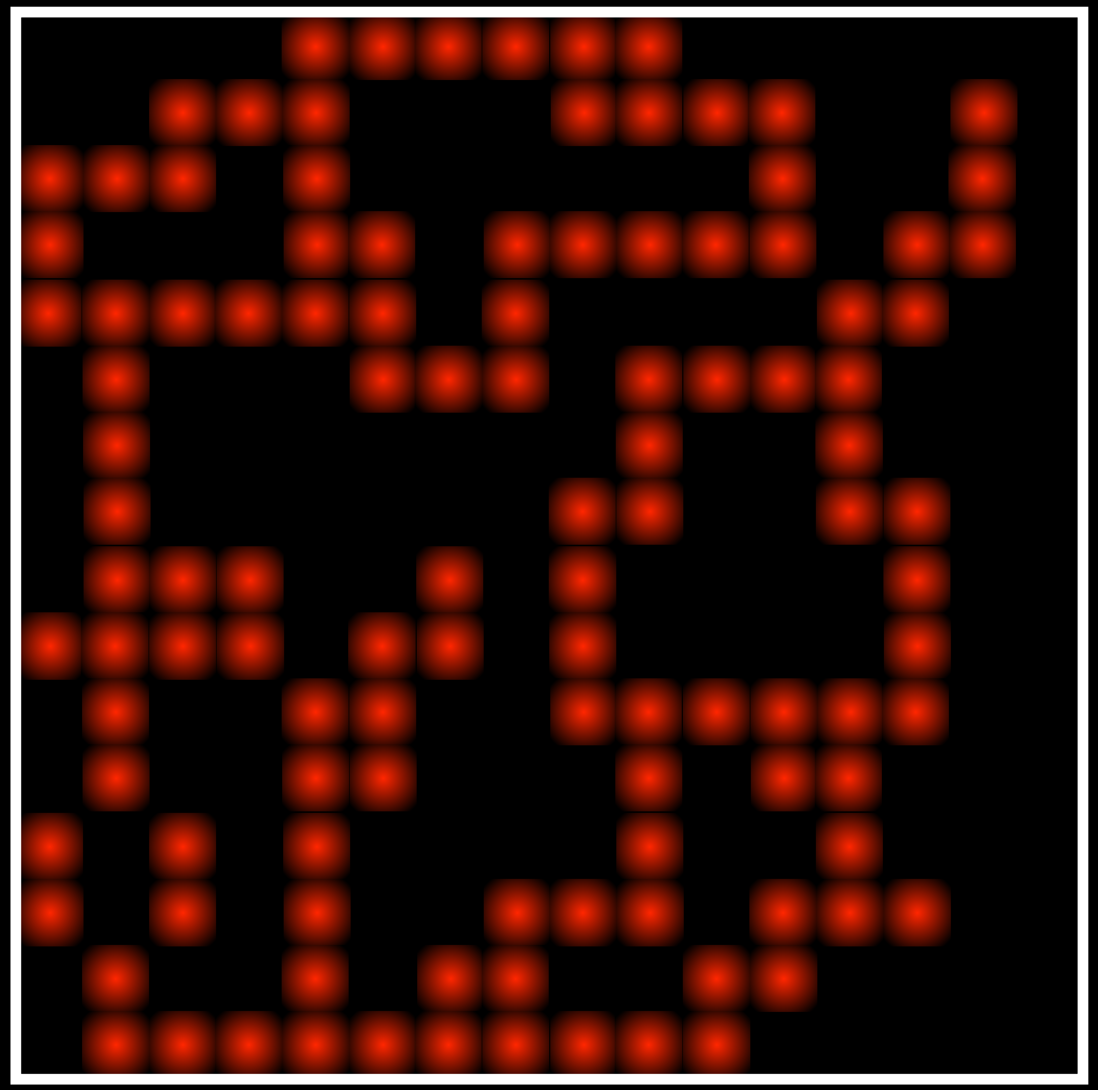

Sparse repartition

Intermittency

Recipe:

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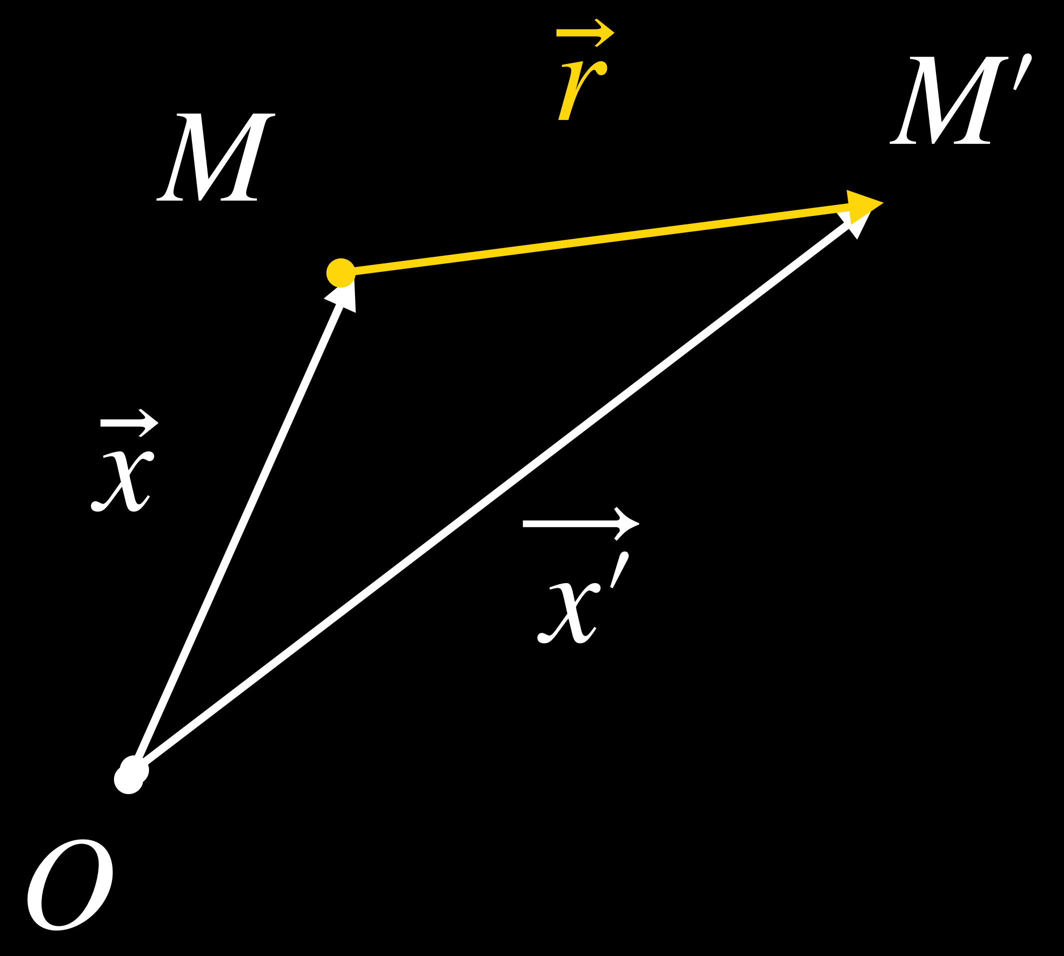
- Compute the magnetic field increments $\delta\vec{b}$.

$$\delta\vec{b} \equiv \vec{b}(\overrightarrow{x'}) - \vec{b}(\vec{x})$$



<u>Recipe:</u>

- Compute the magnetic field increments $\delta\vec{b}$.
- Raise its absolute value to a power $p \geq 1$.

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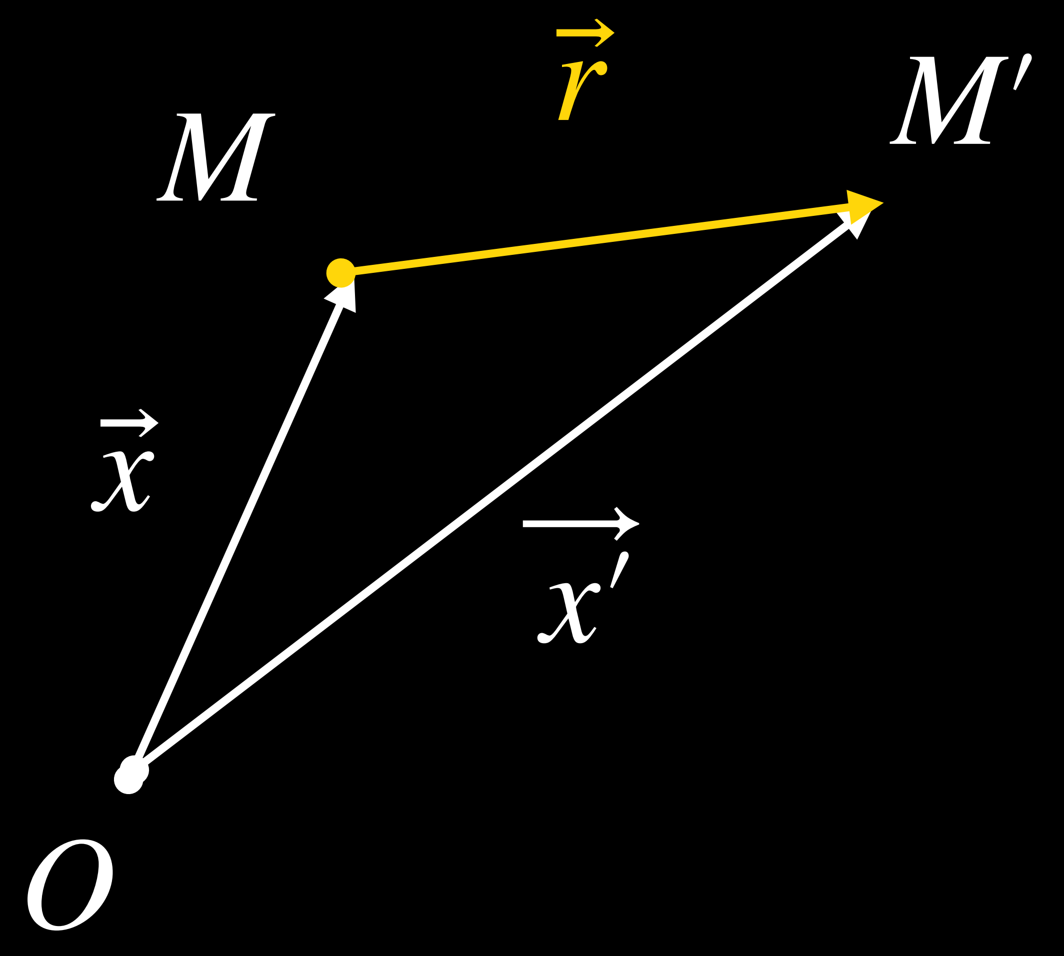

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Recipe:

- Compute the magnetic field increments $\delta\vec{b}$.
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- Compute its ensemble average $\left\langle \left|\delta b\right|^{p} \right\rangle$.

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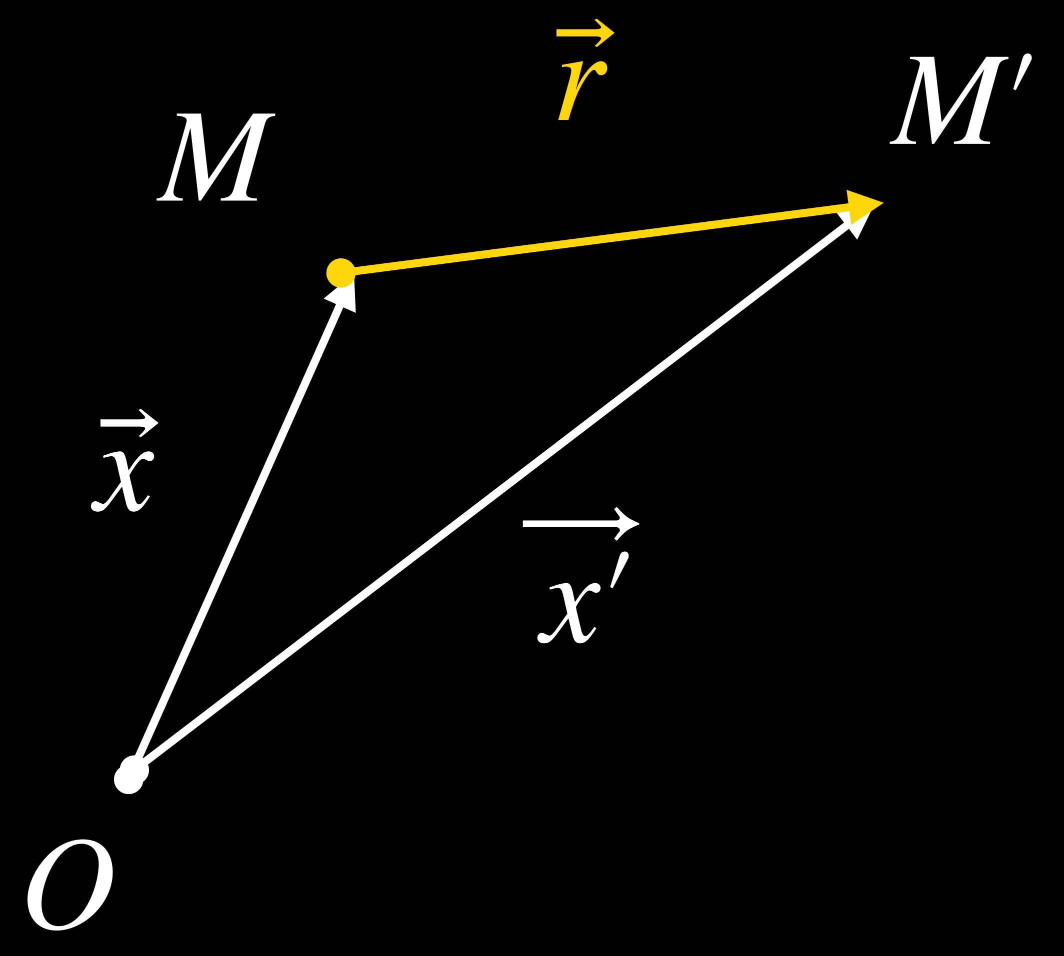

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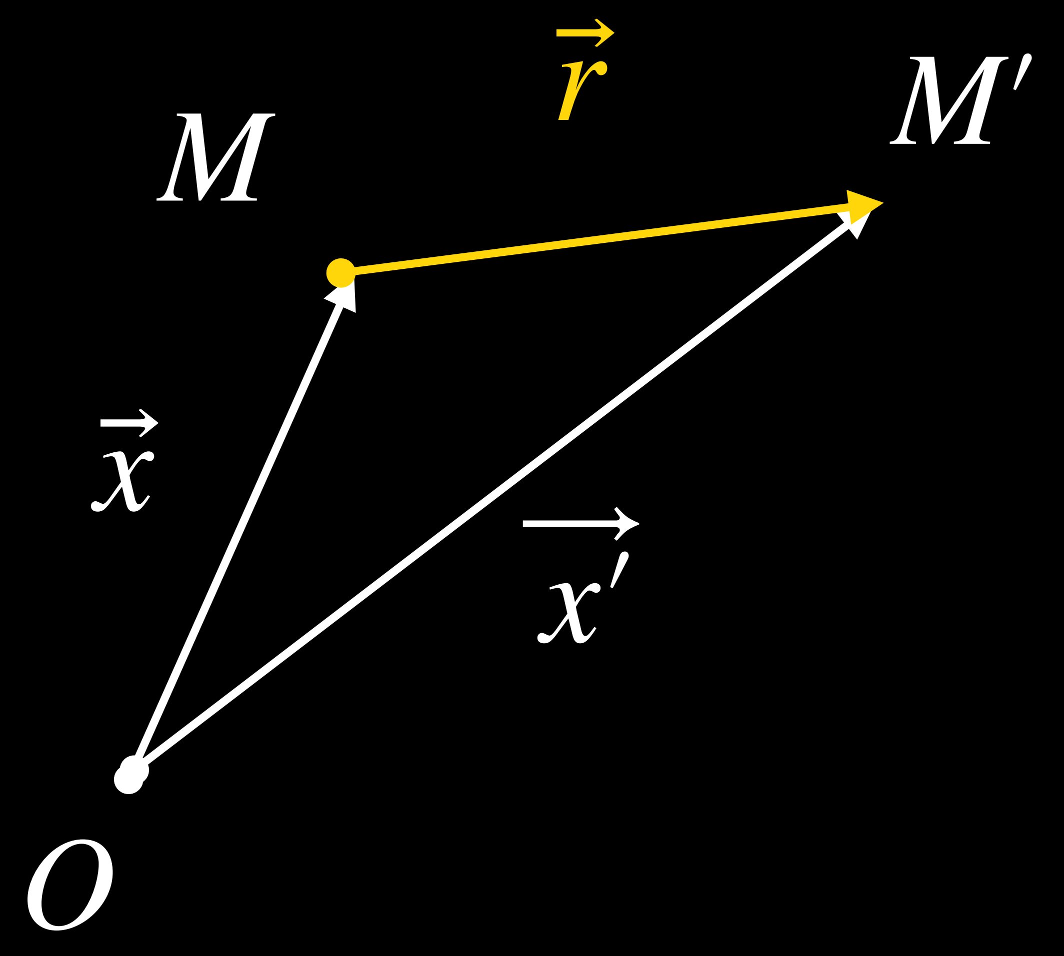
Recipe:

- Compute the magnetic field increments $\delta\vec{b}$.
- Raise its absolute value to a power $p \geq 1$.
- Compute its ensemble average $\left\langle \left|\delta b\right|^p \right\rangle$.
- Repeat the operation for many values of $\vec{r}$ and p.

$$\delta\vec{b} \equiv \vec{b}(\vec{x'}) - \vec{b}(\vec{x})$$



3D direct numerical simulation

pseudo-spectral code: `AsteriX` [R. Meyrand et al., 2018, PRX]

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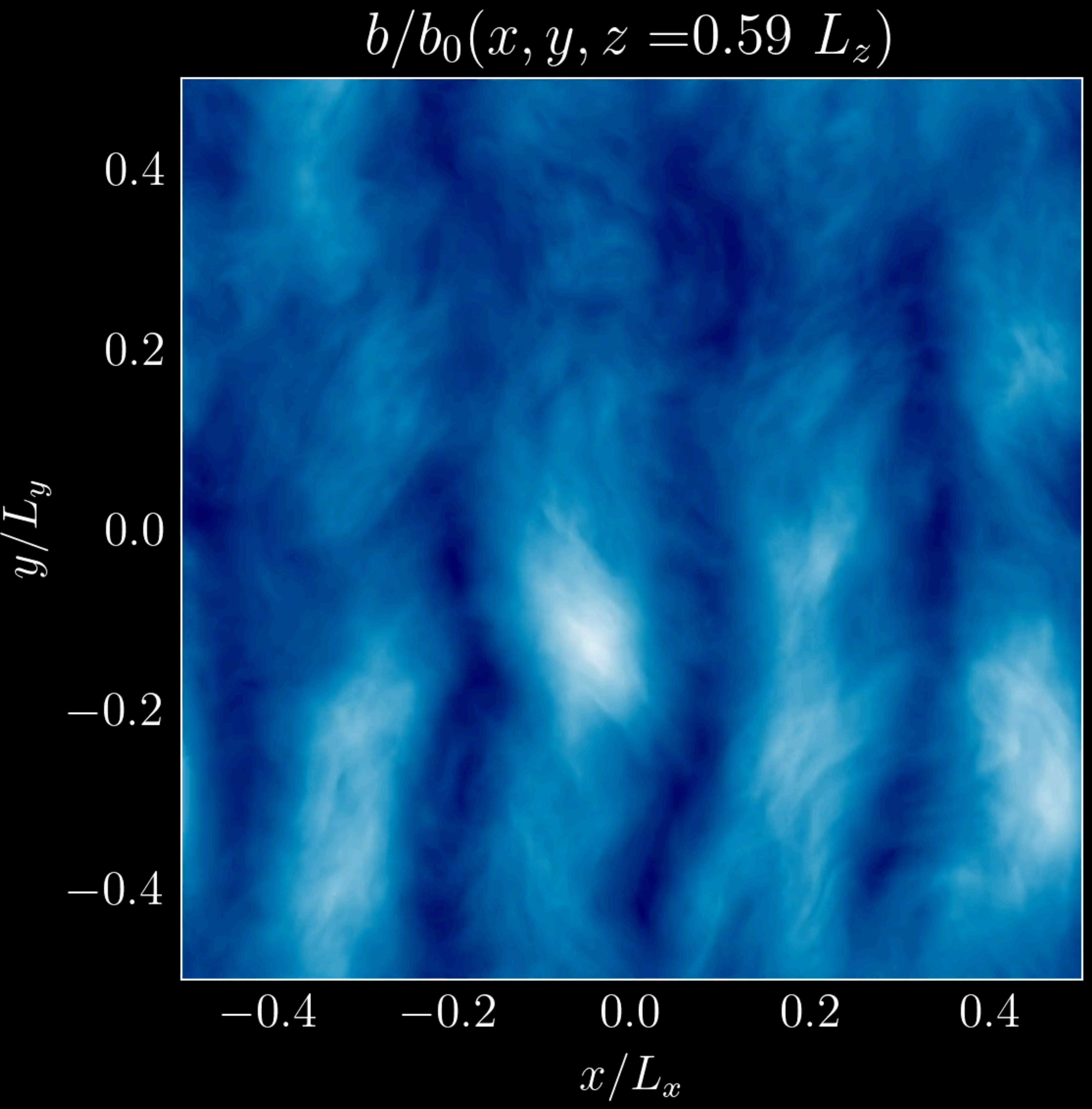

Weak turbulence

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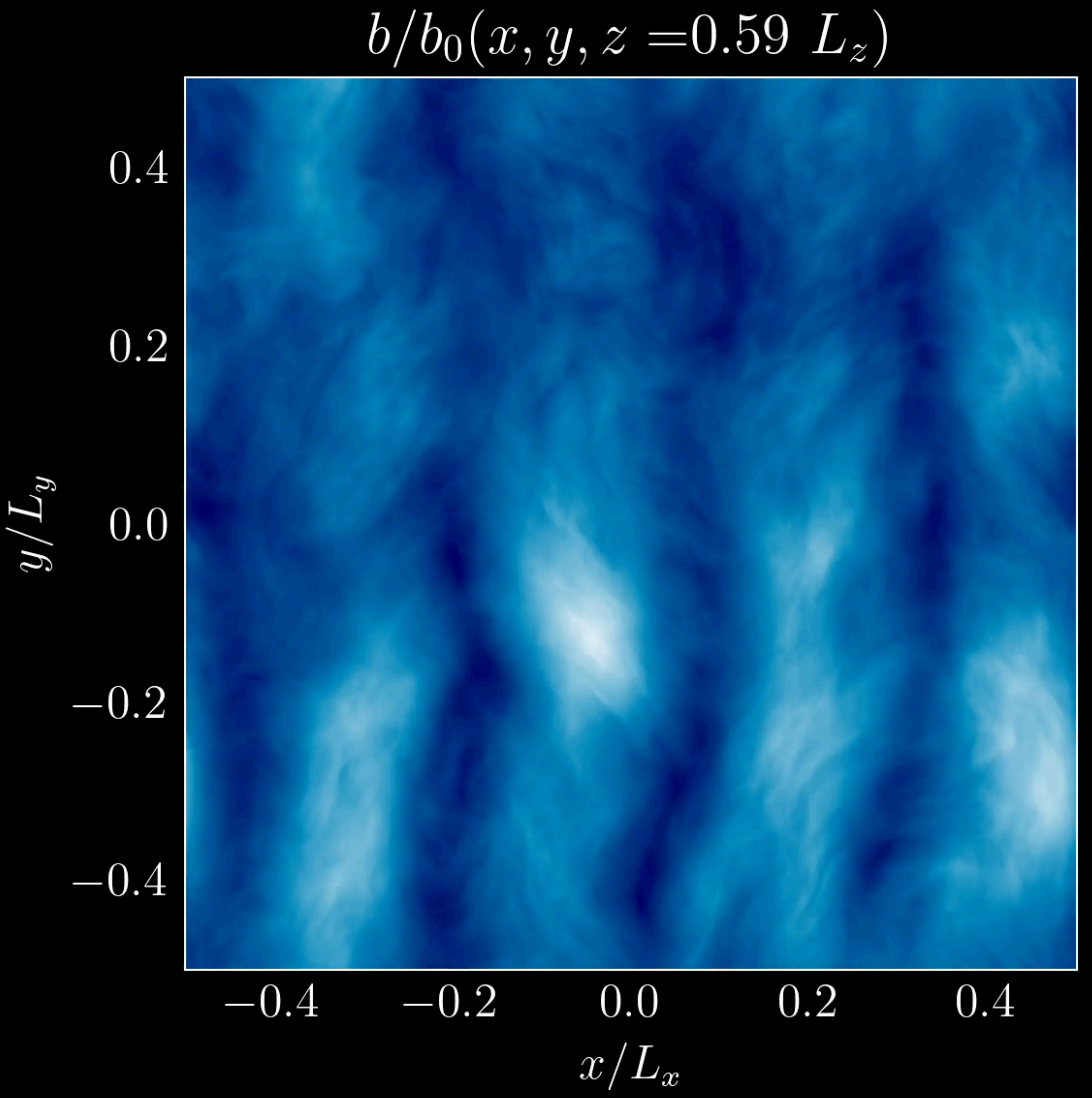

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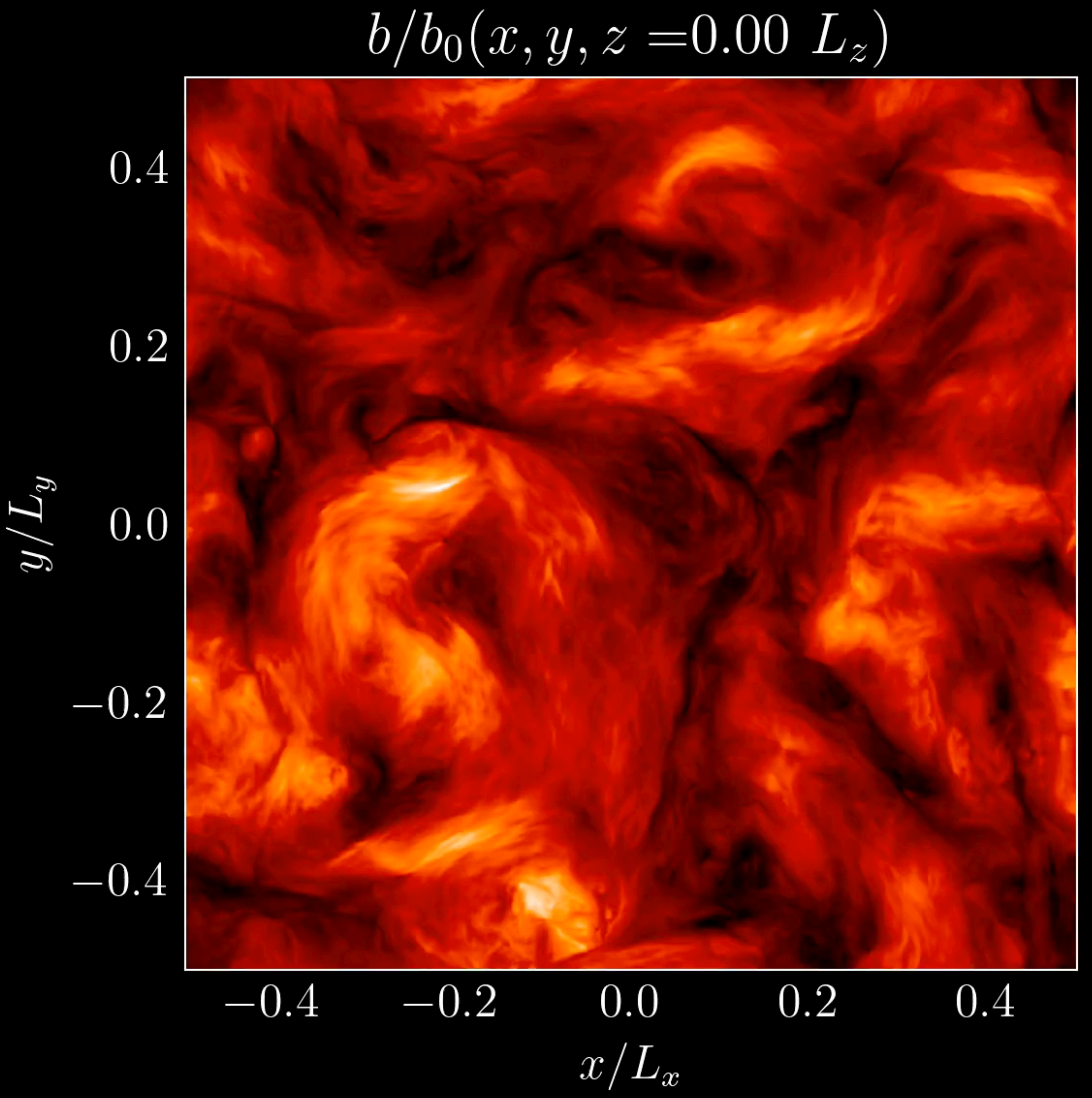

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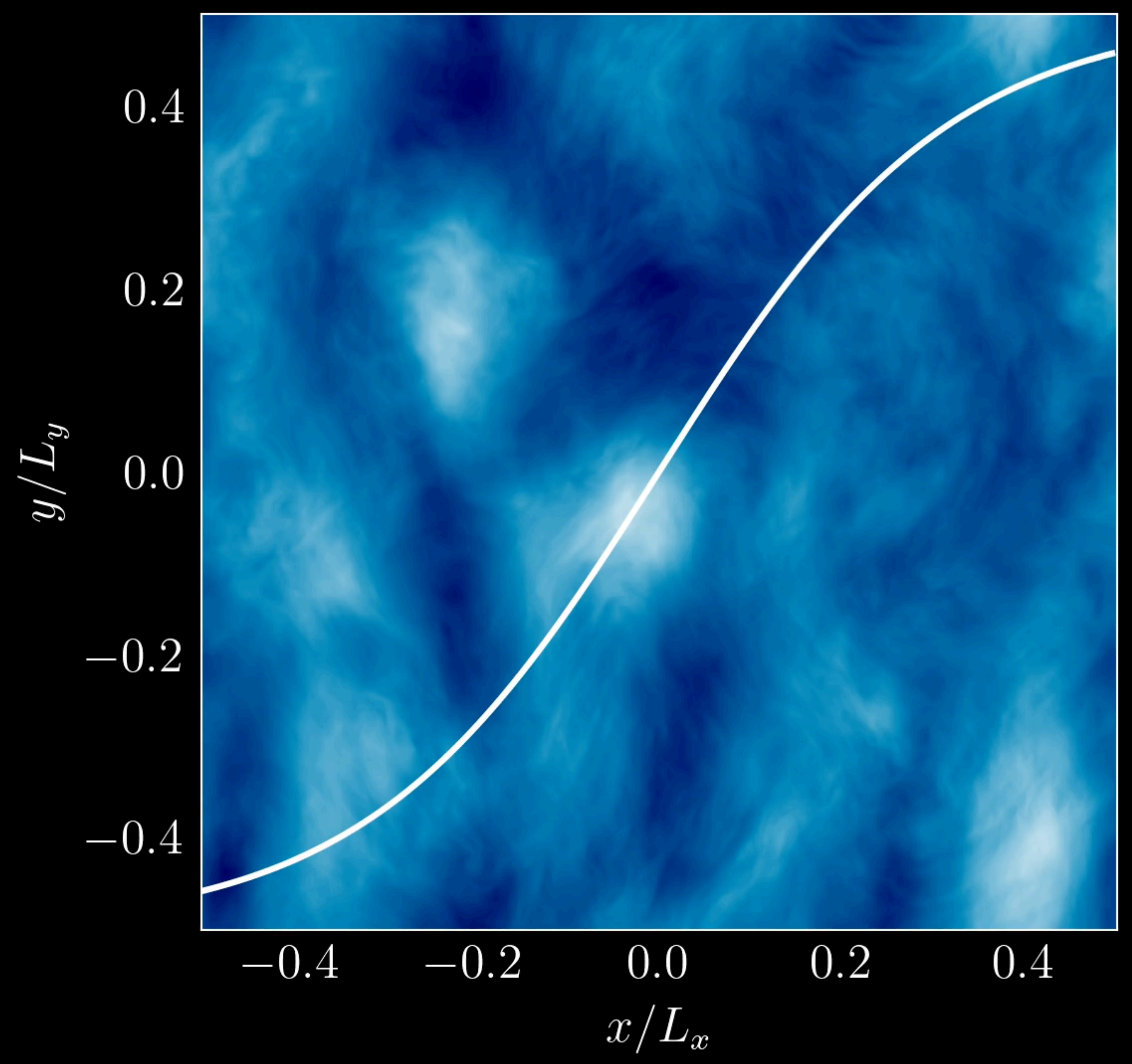
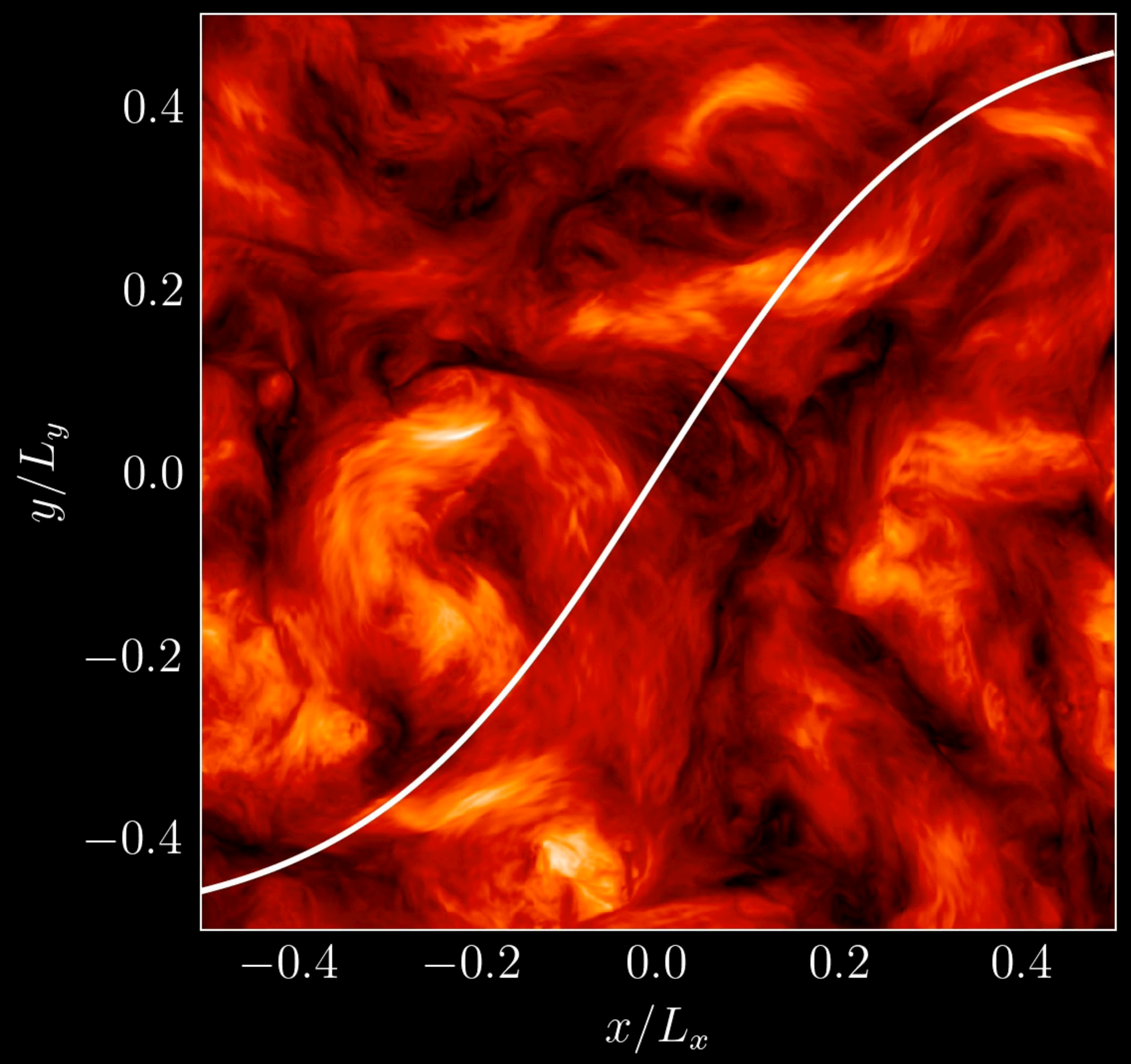
Virtual spacecraft measurements





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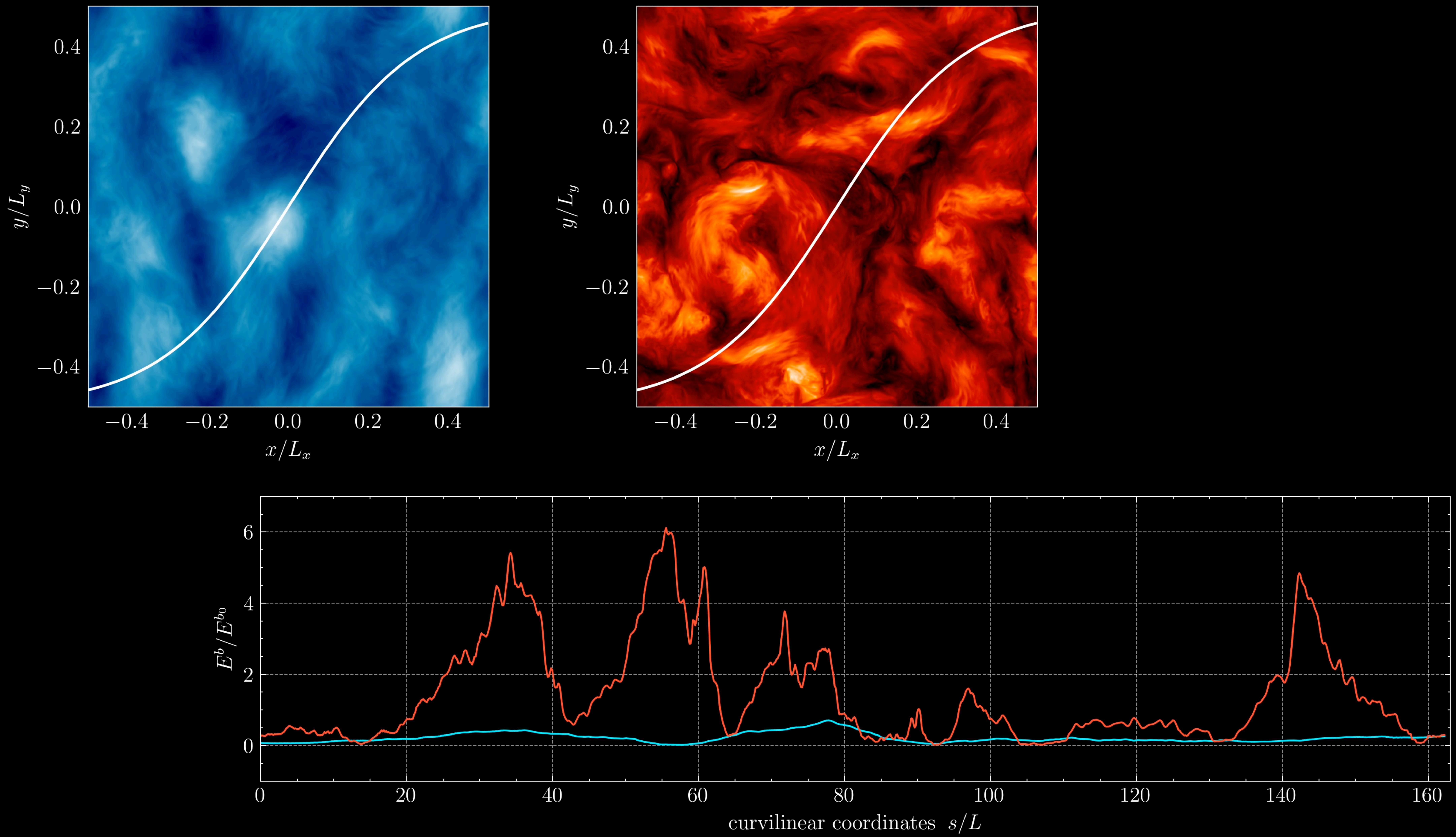

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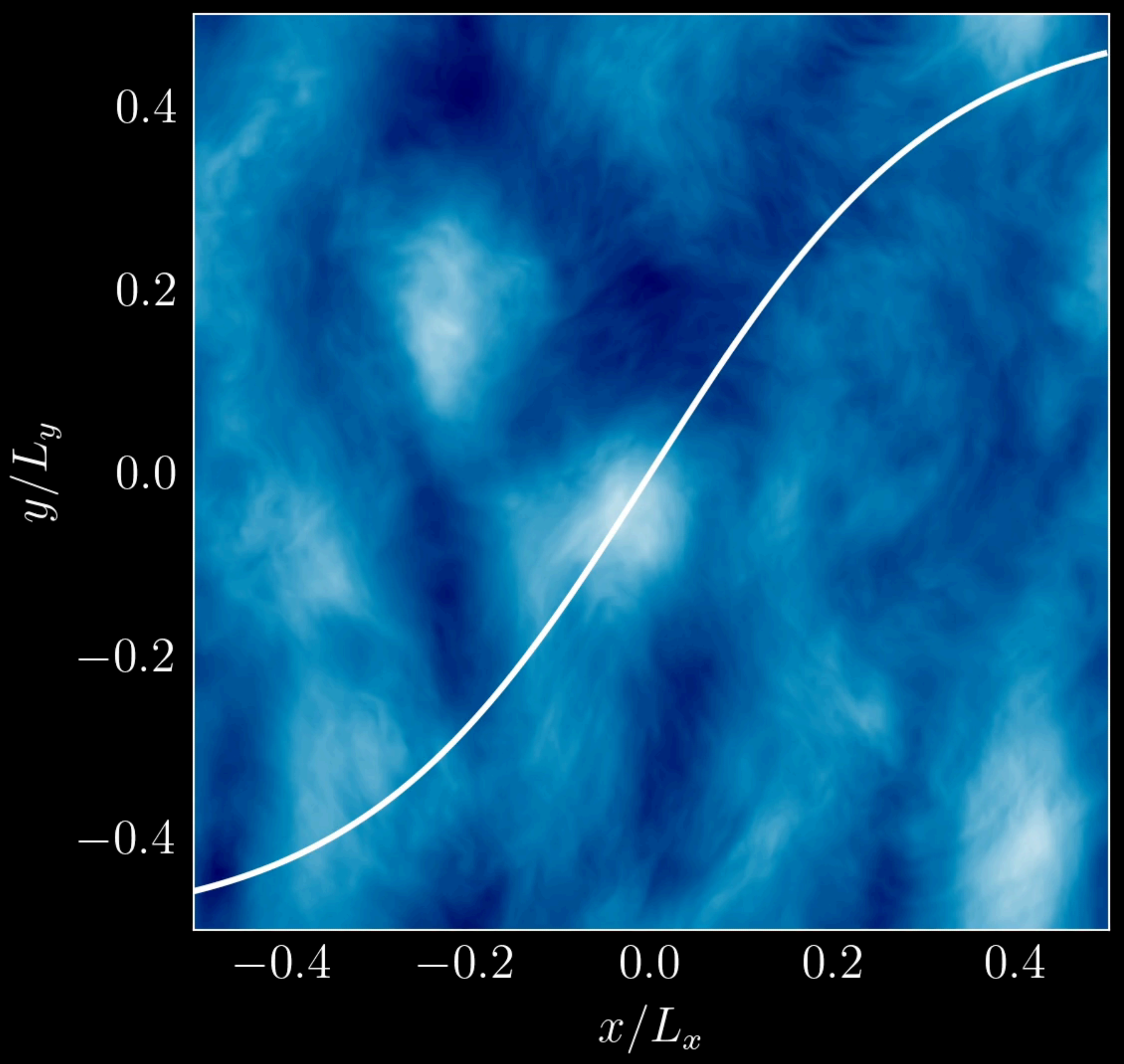
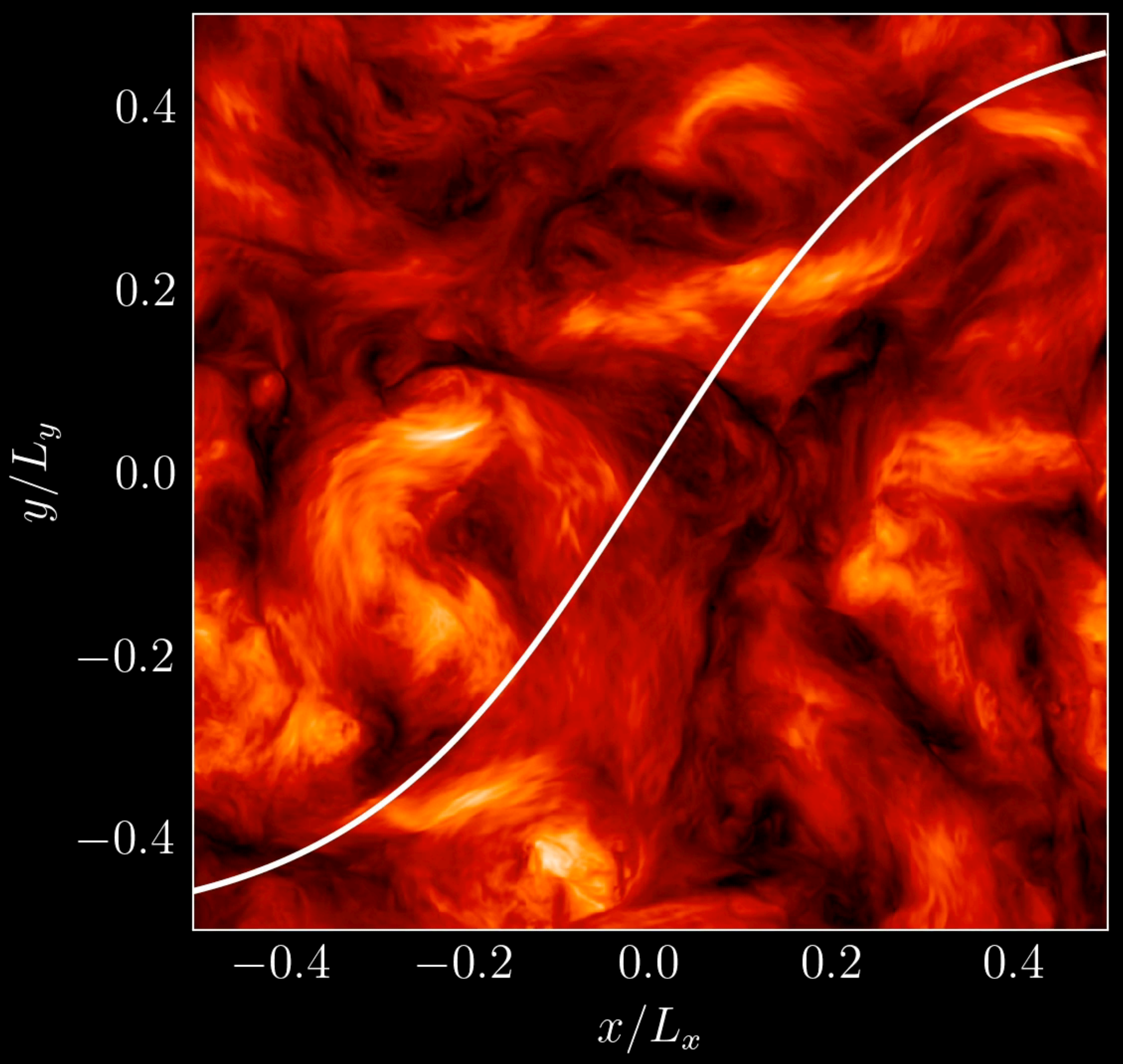
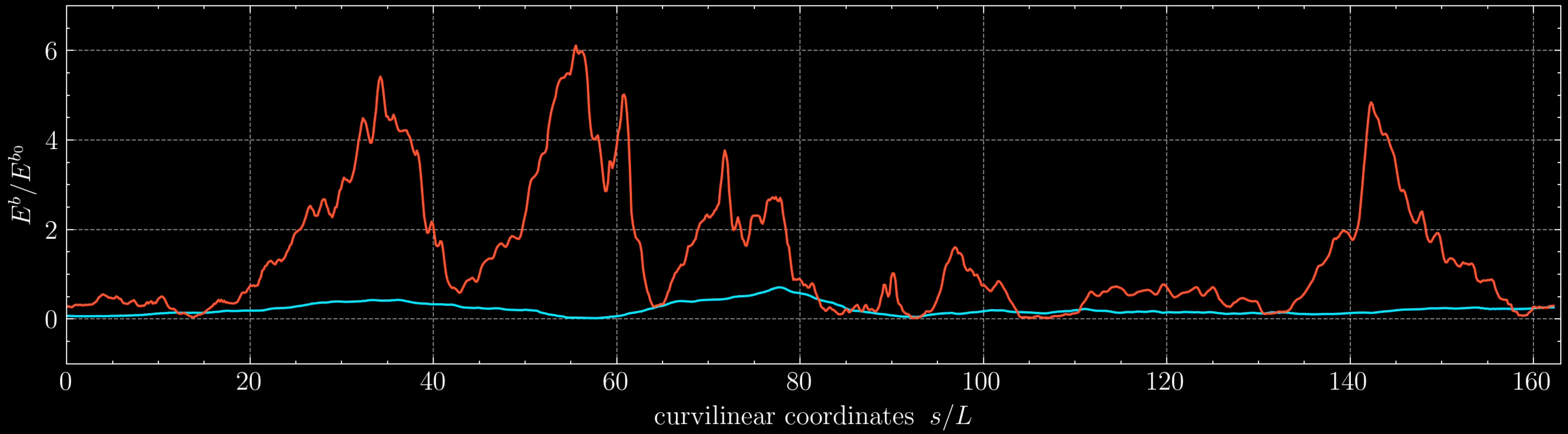




⇒ Strong regime seems to be more intermittent



Identification of the regimes

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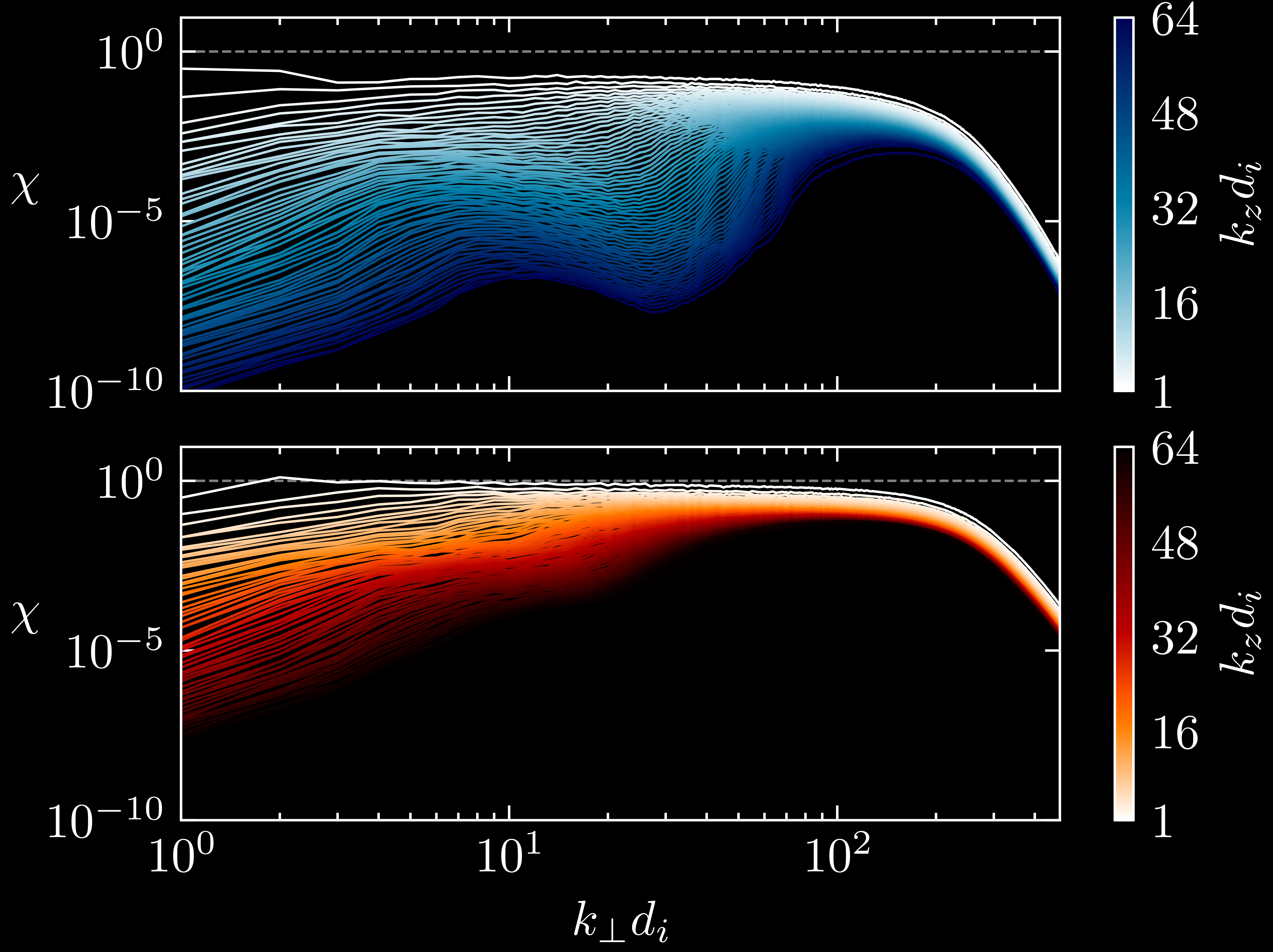

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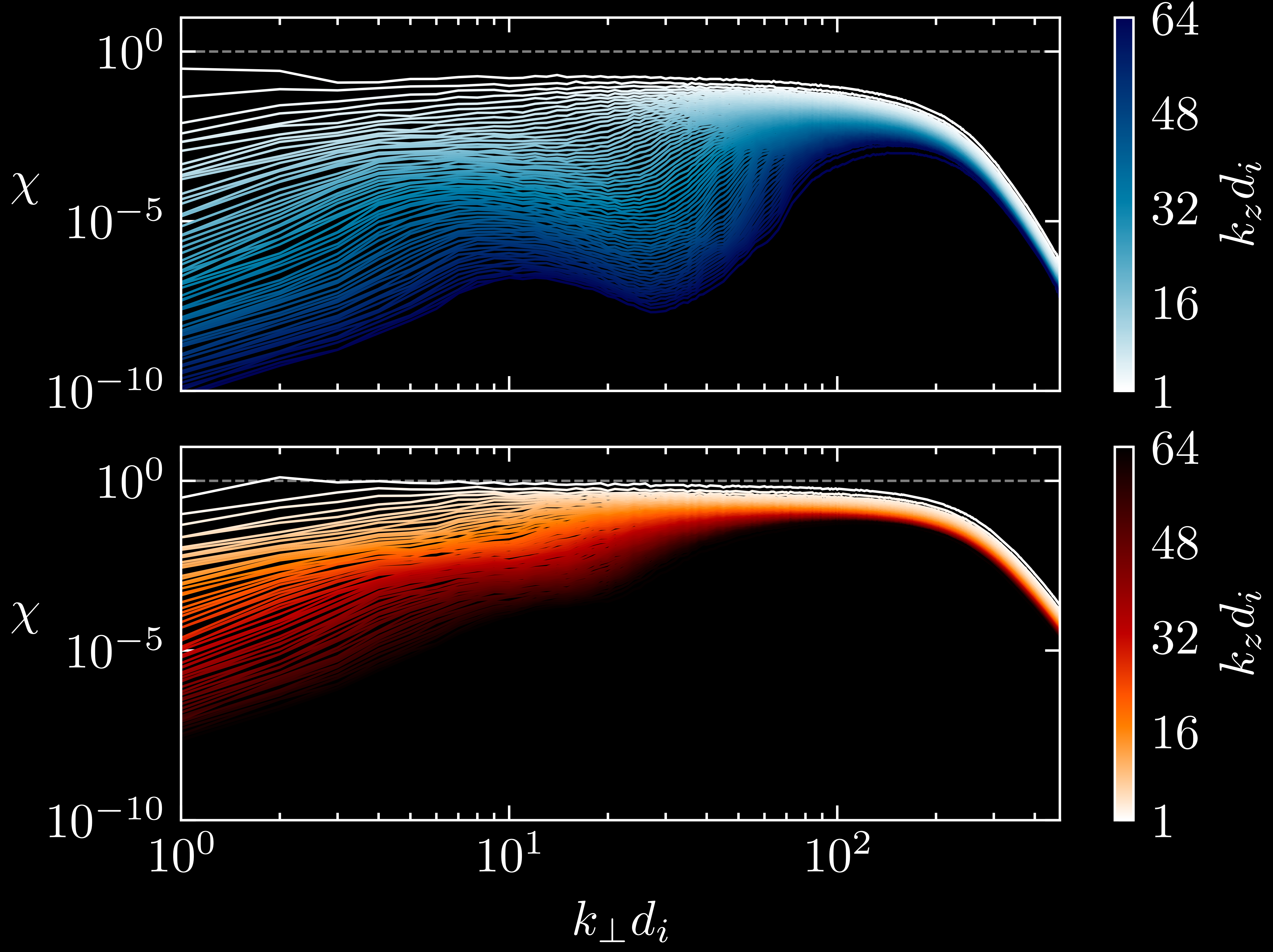

It seems to be the two regimes of interest.

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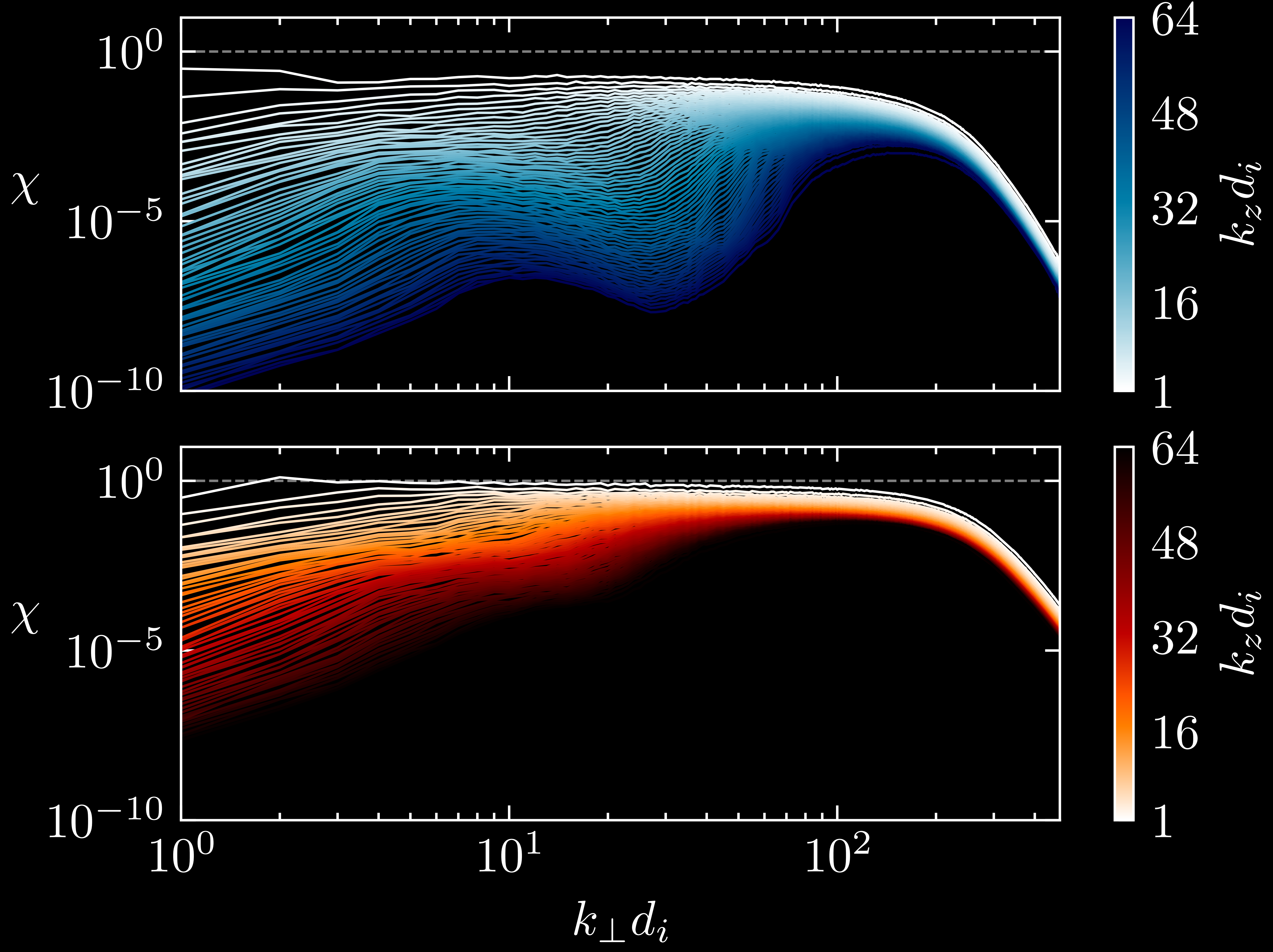

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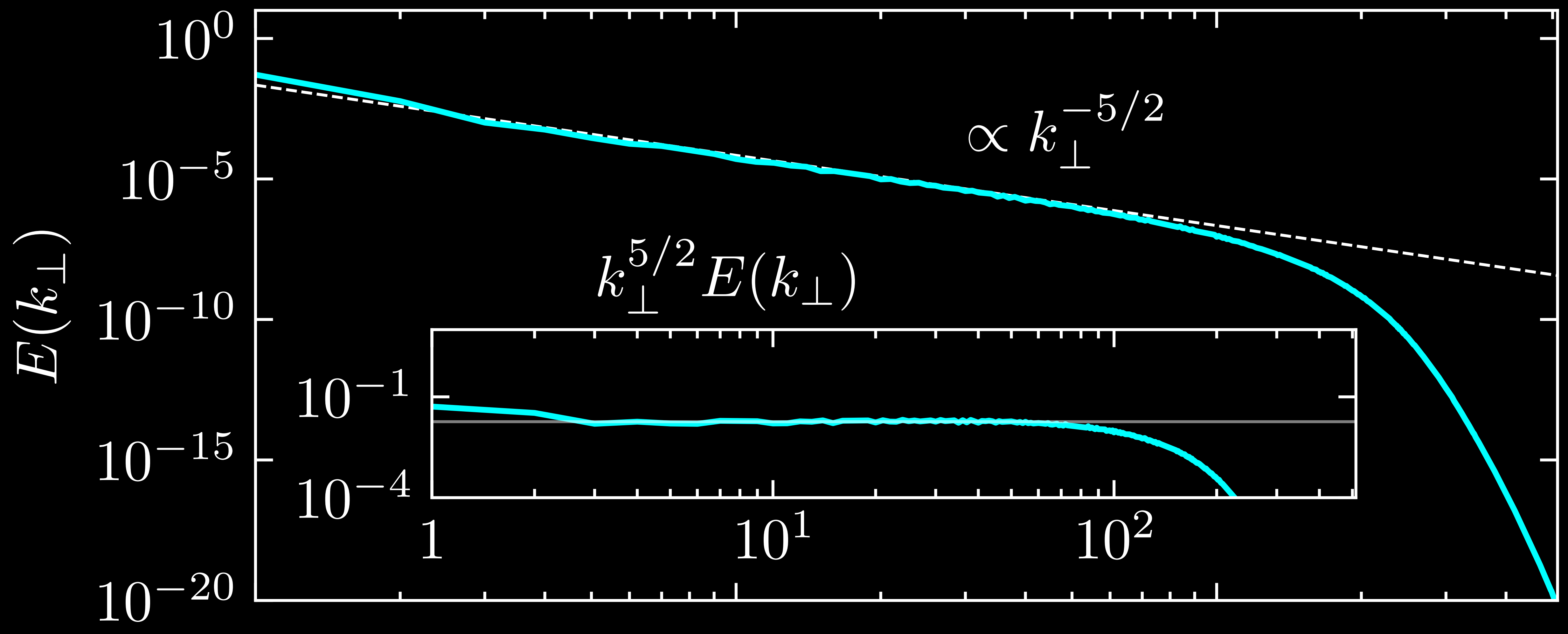
What about spectra?

Identification of the regimes



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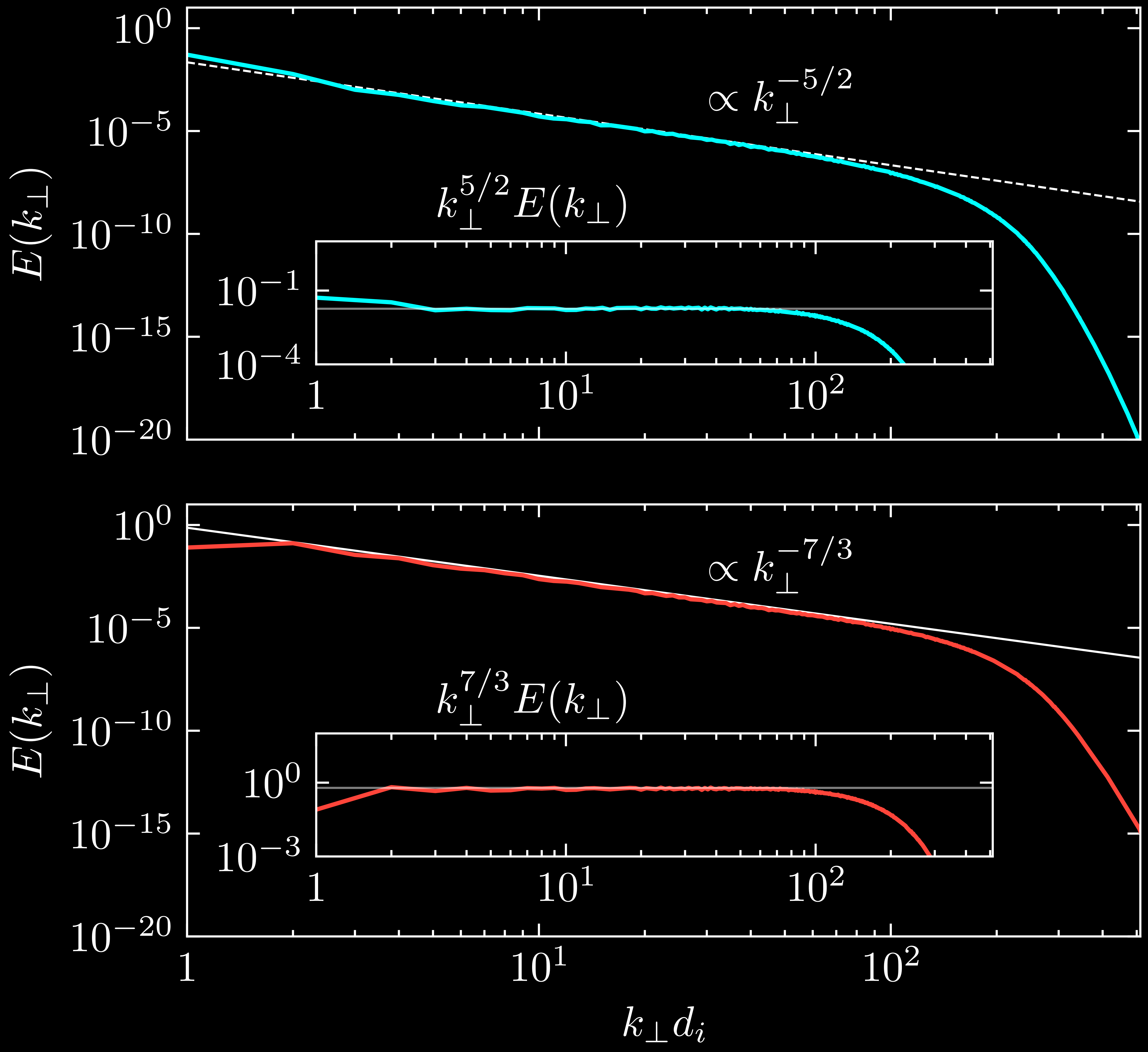

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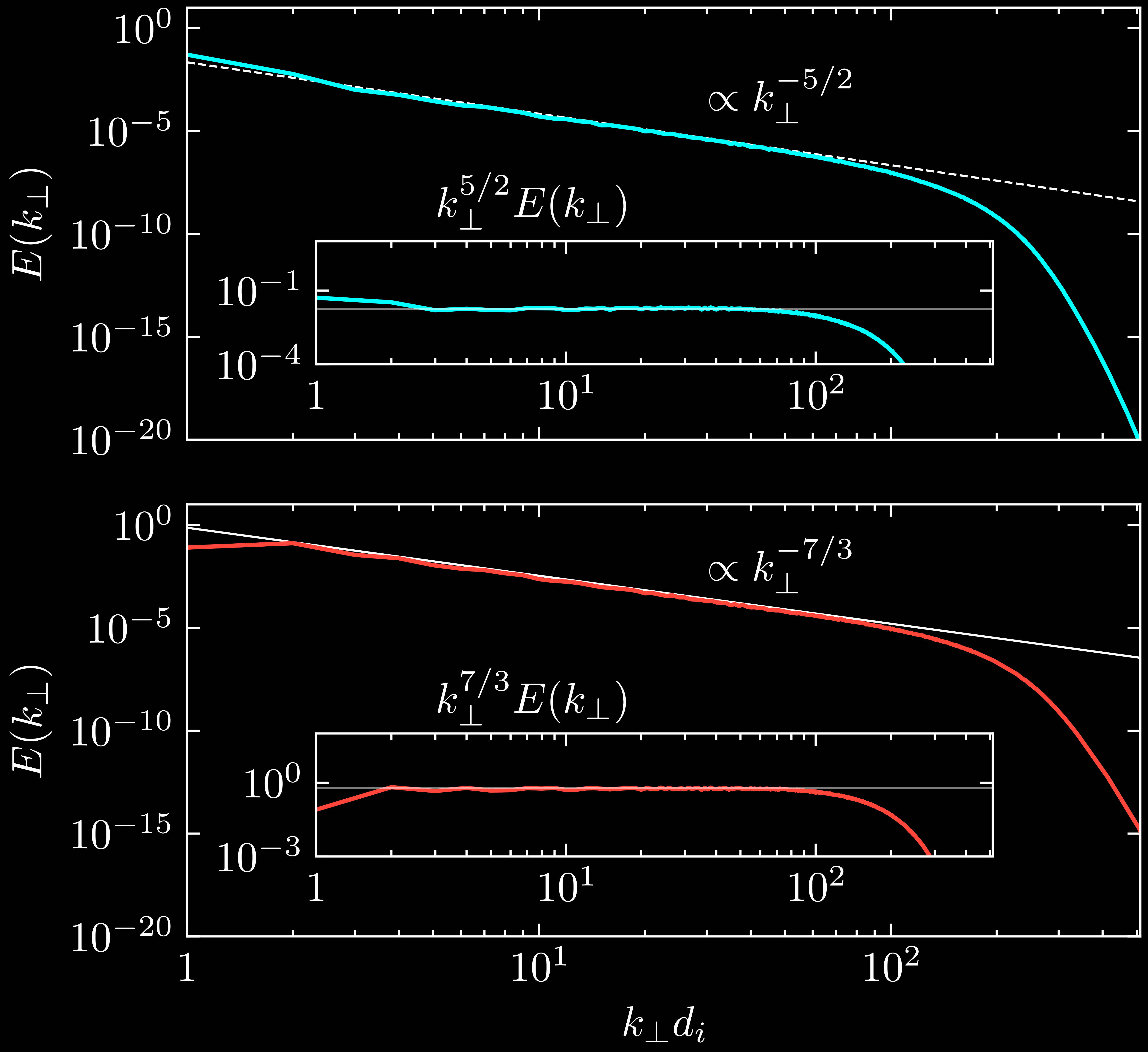

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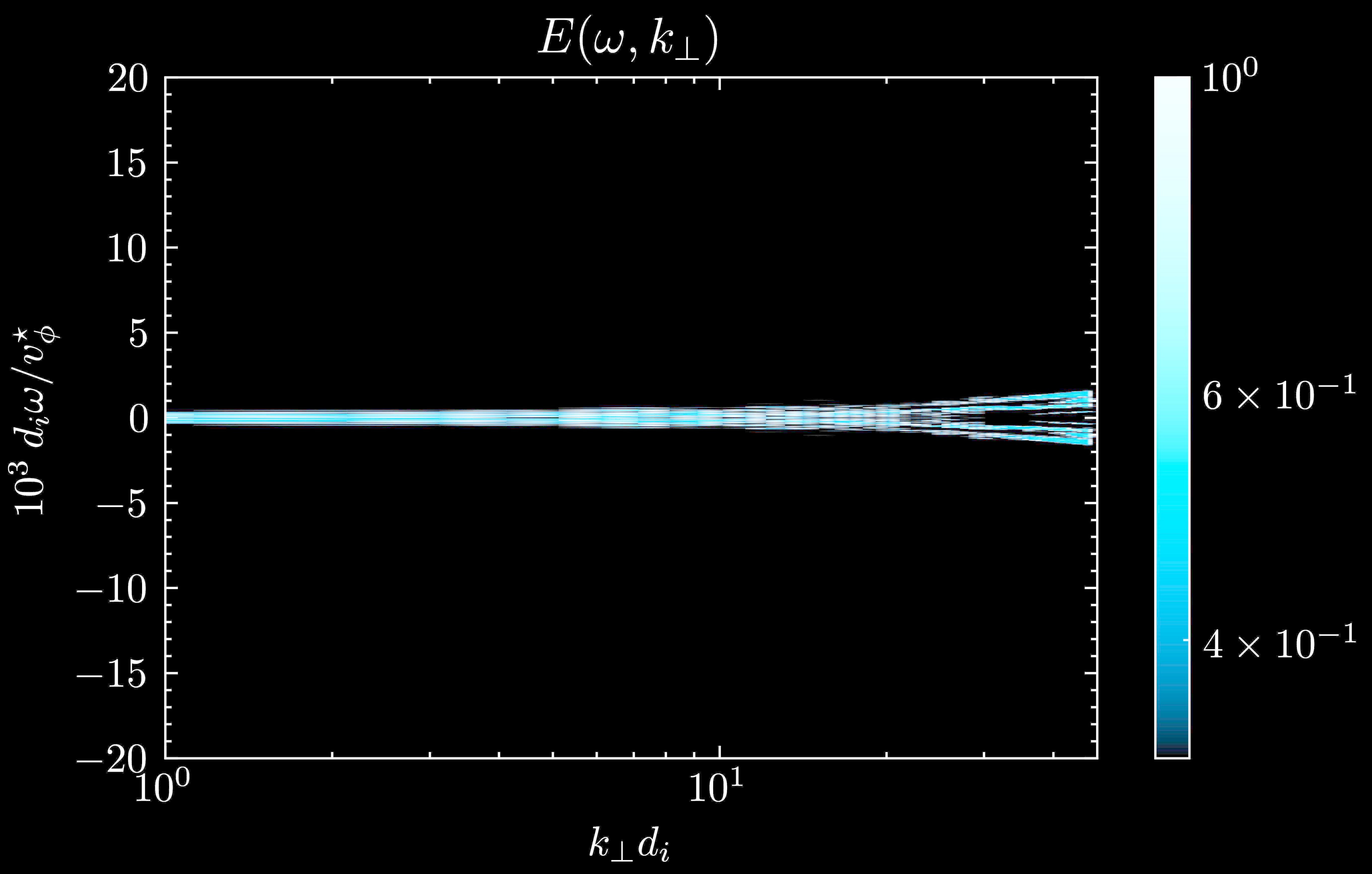

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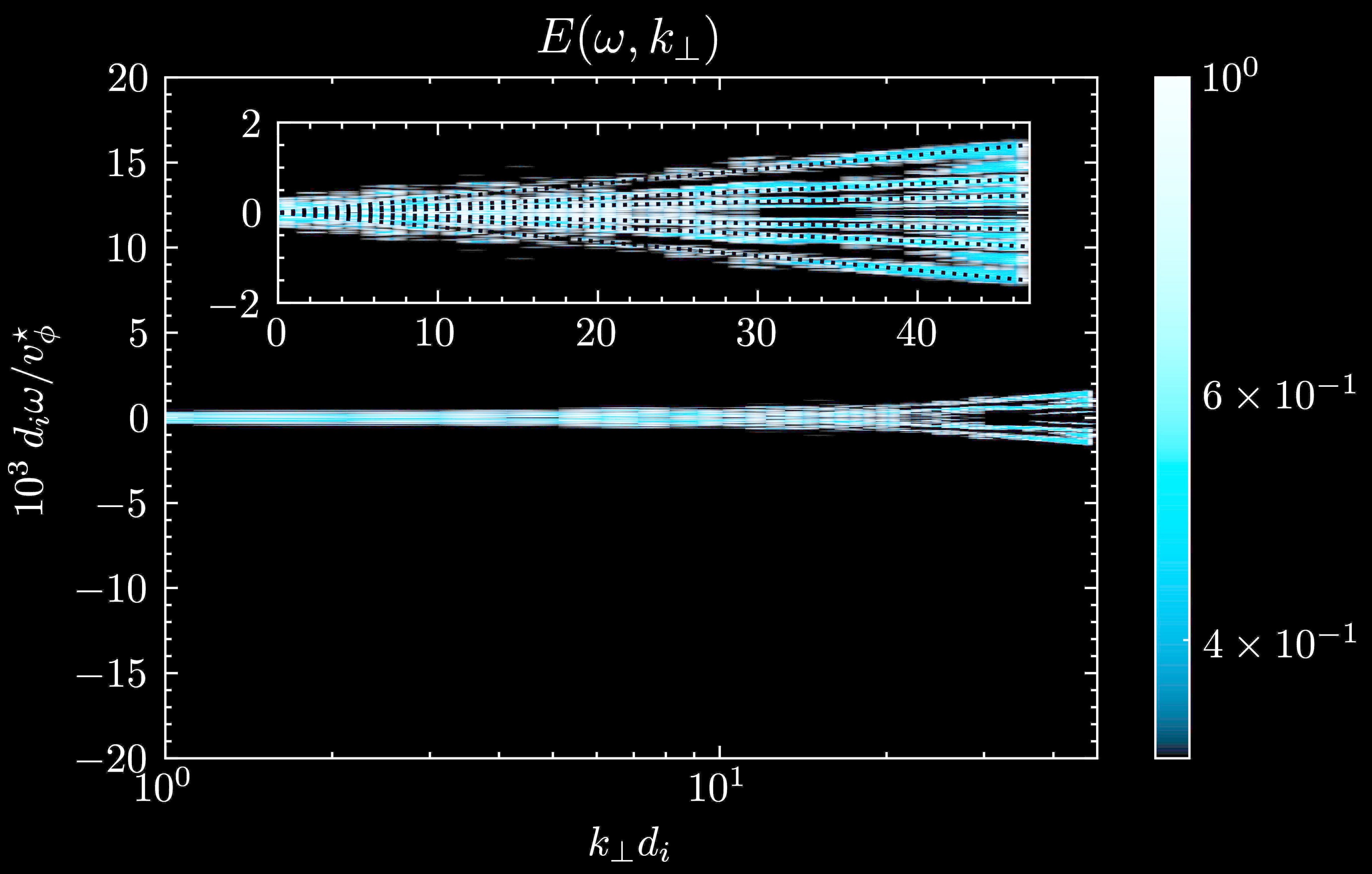

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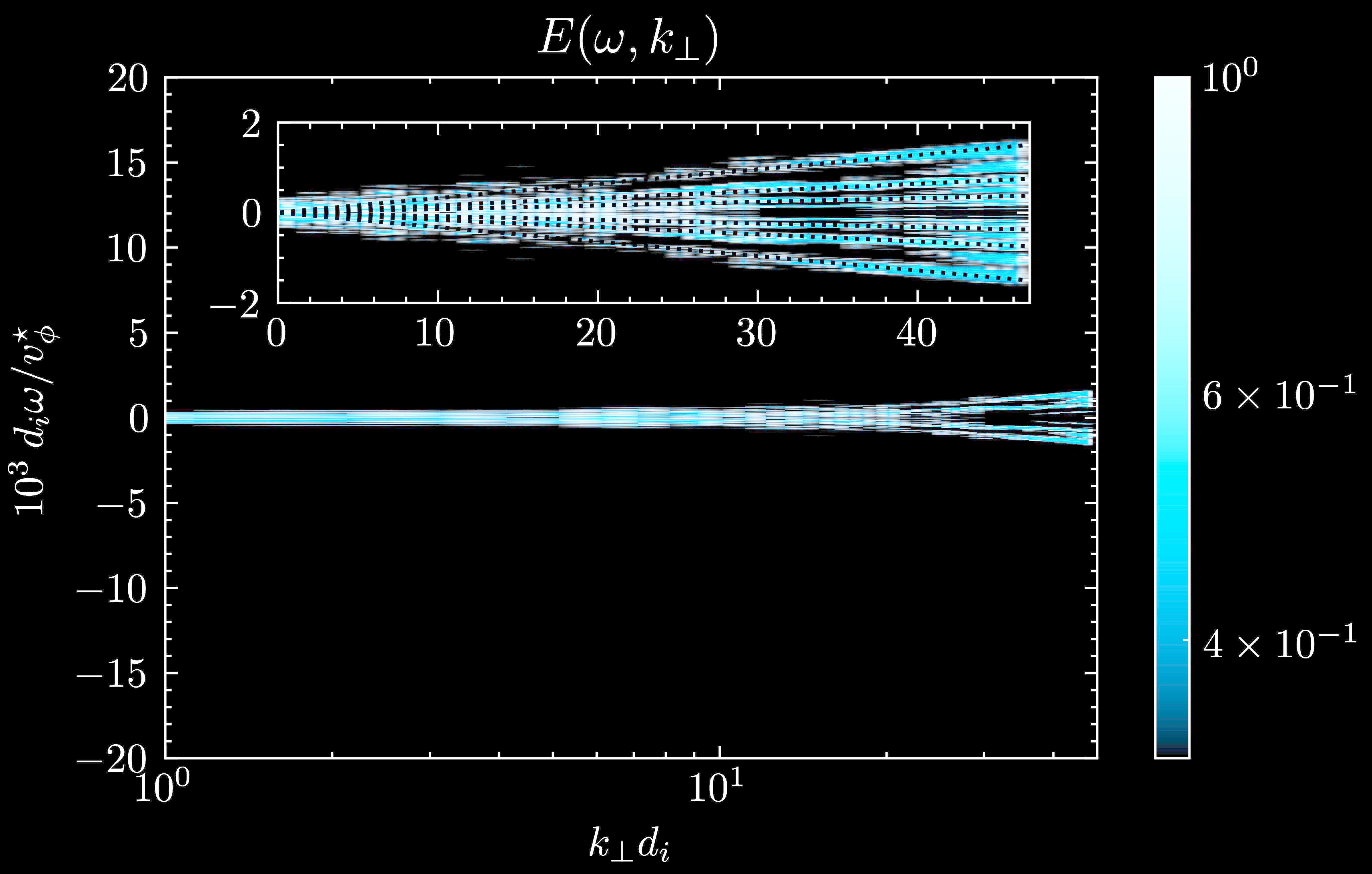

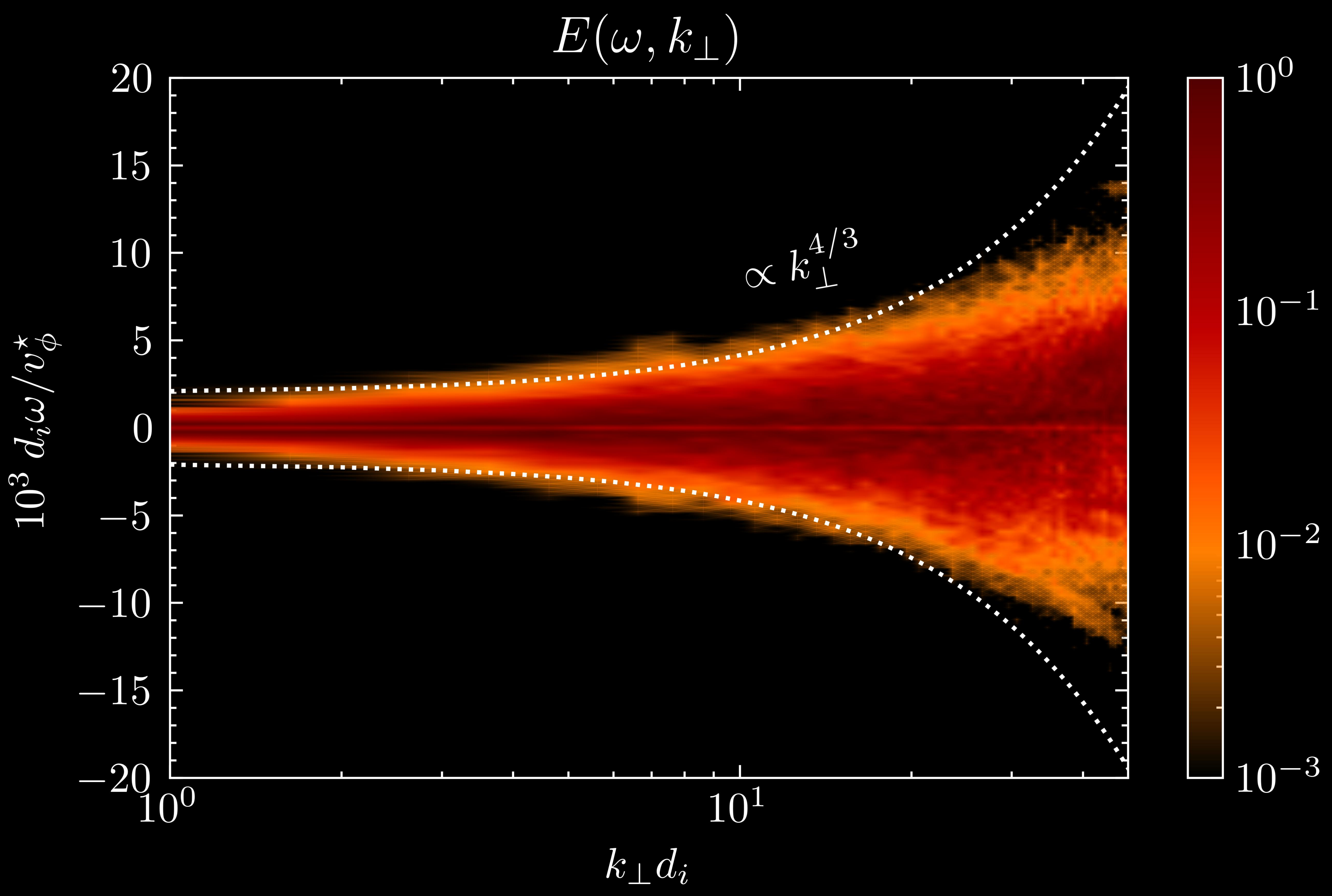

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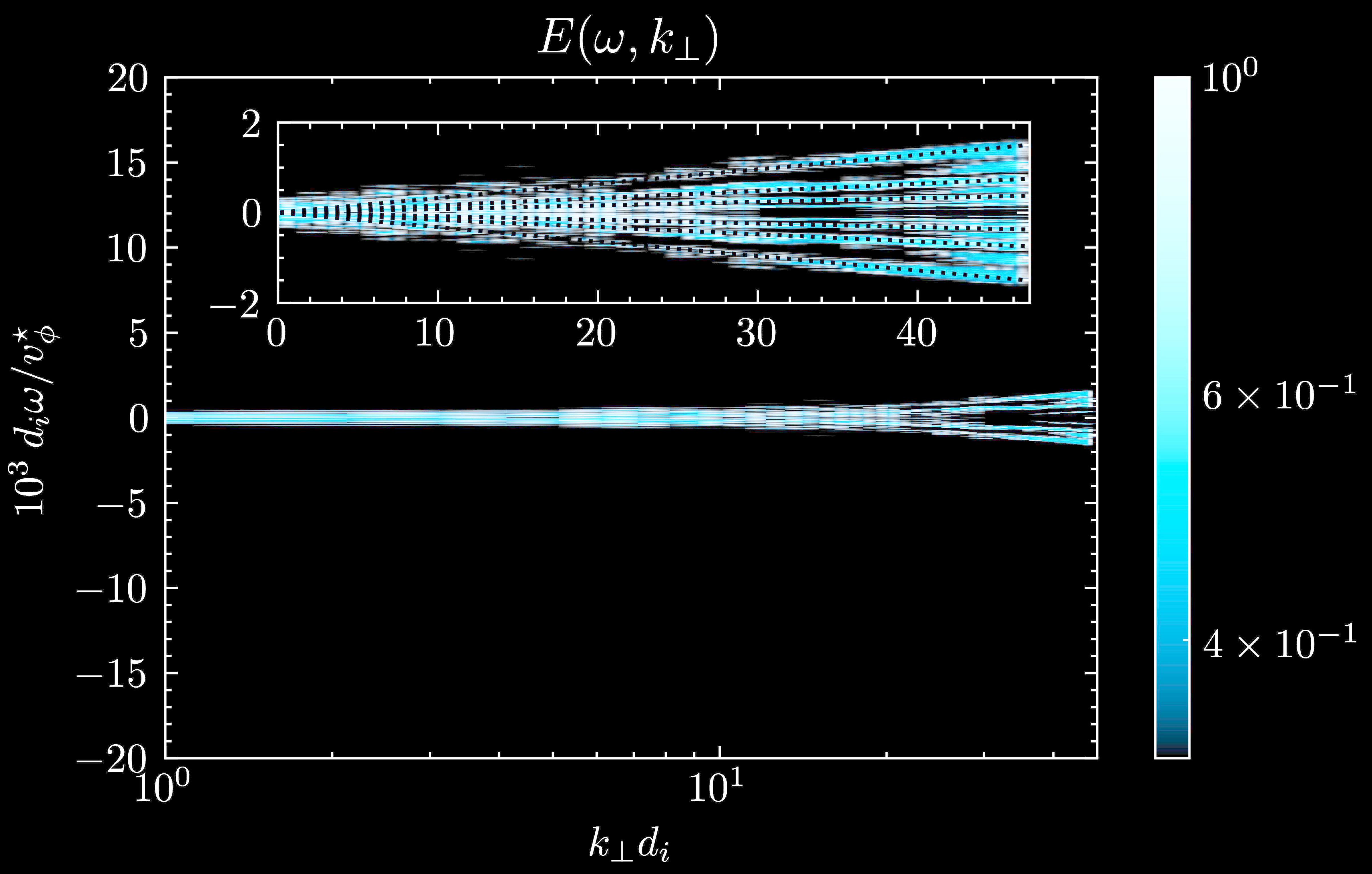
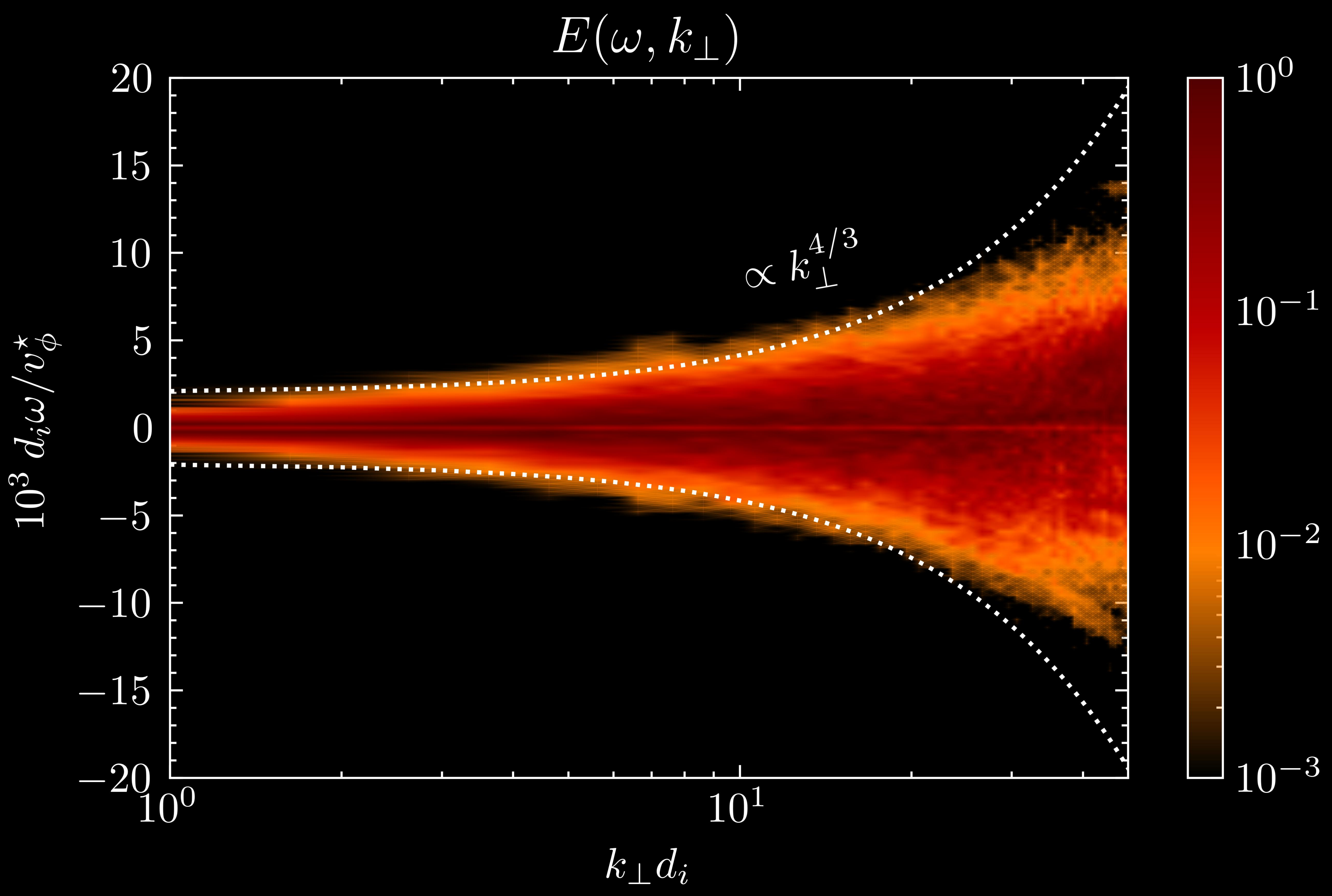
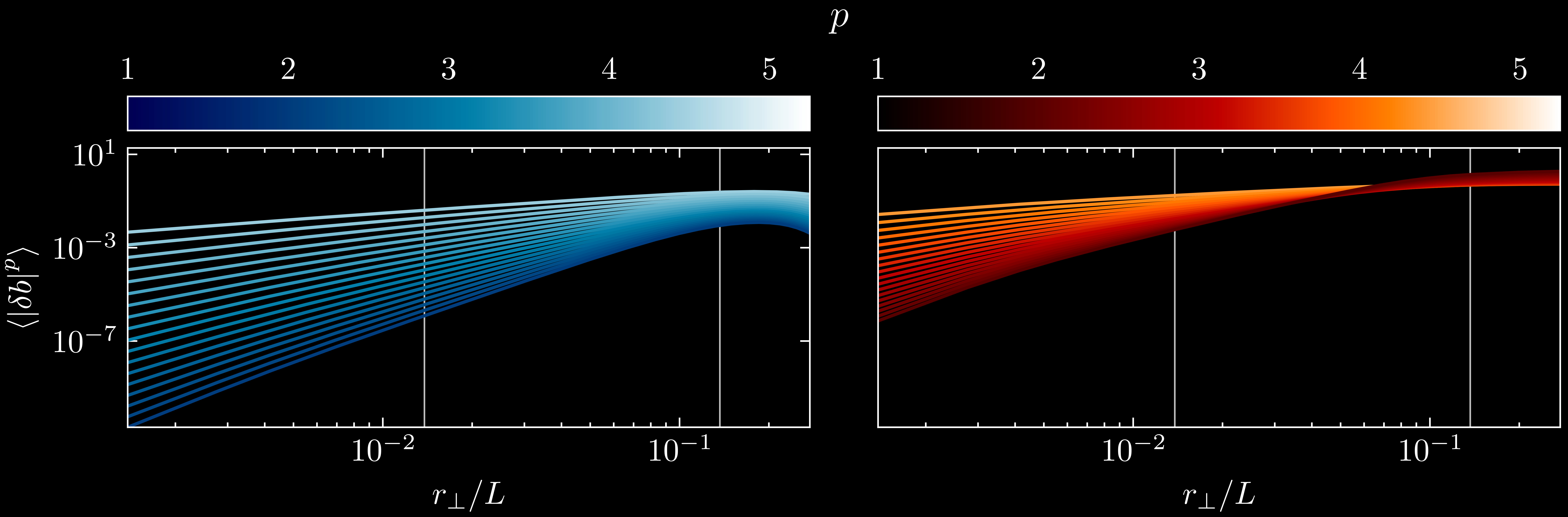




We have the two regimes of interest.

Intermittency



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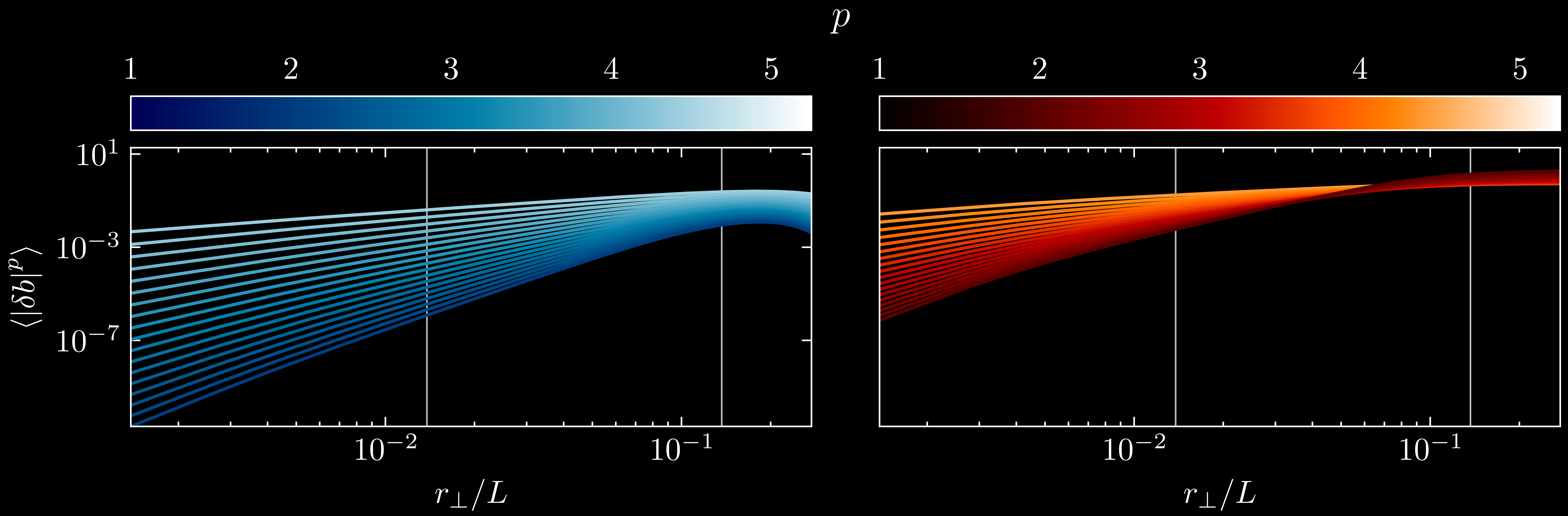
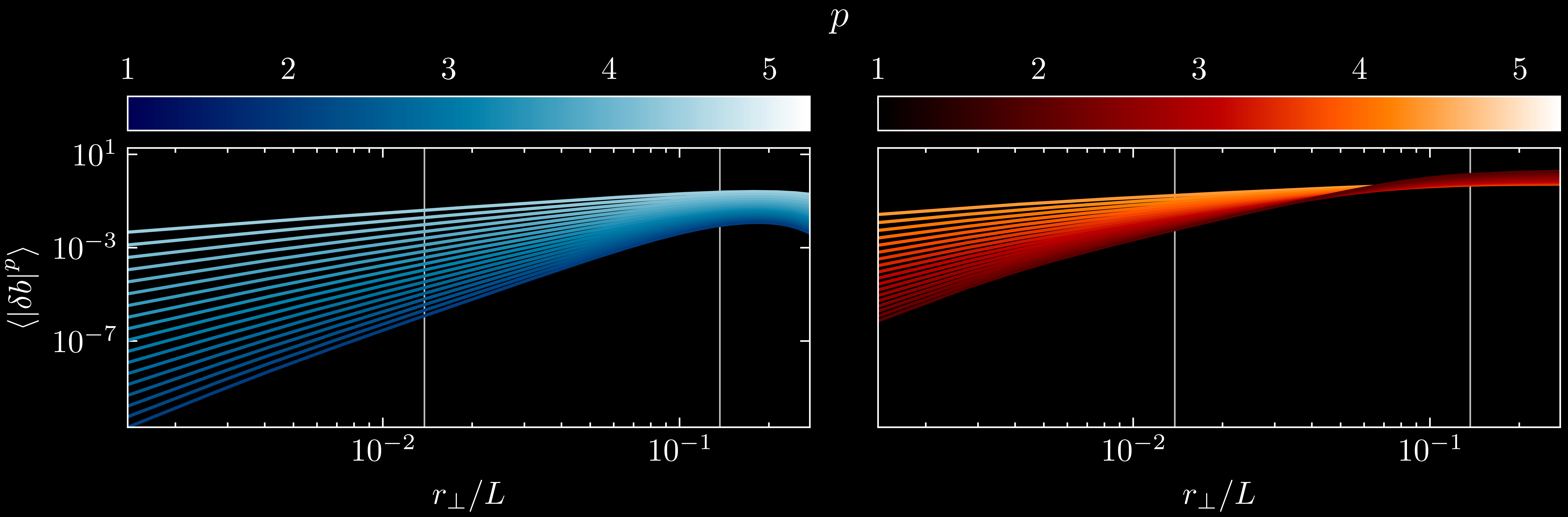


The slopes have → Linear dependance on p. ⇒ monofractal

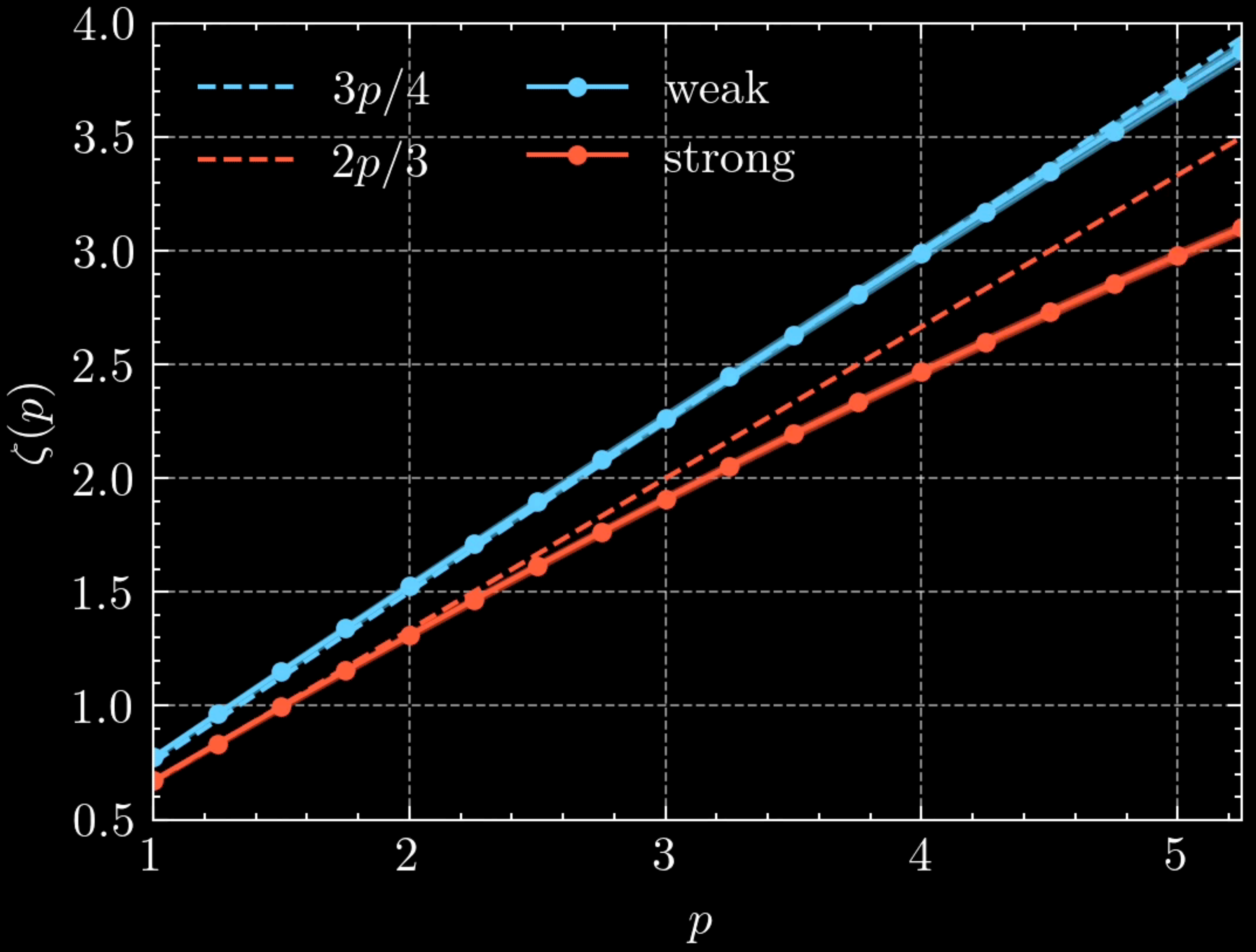
Intermittency



The slopes have

- Linear dependance on p. $\Rightarrow$ monofractal
- Nonlinear dependence on p. $\Rightarrow$ multifractal

Intermittency



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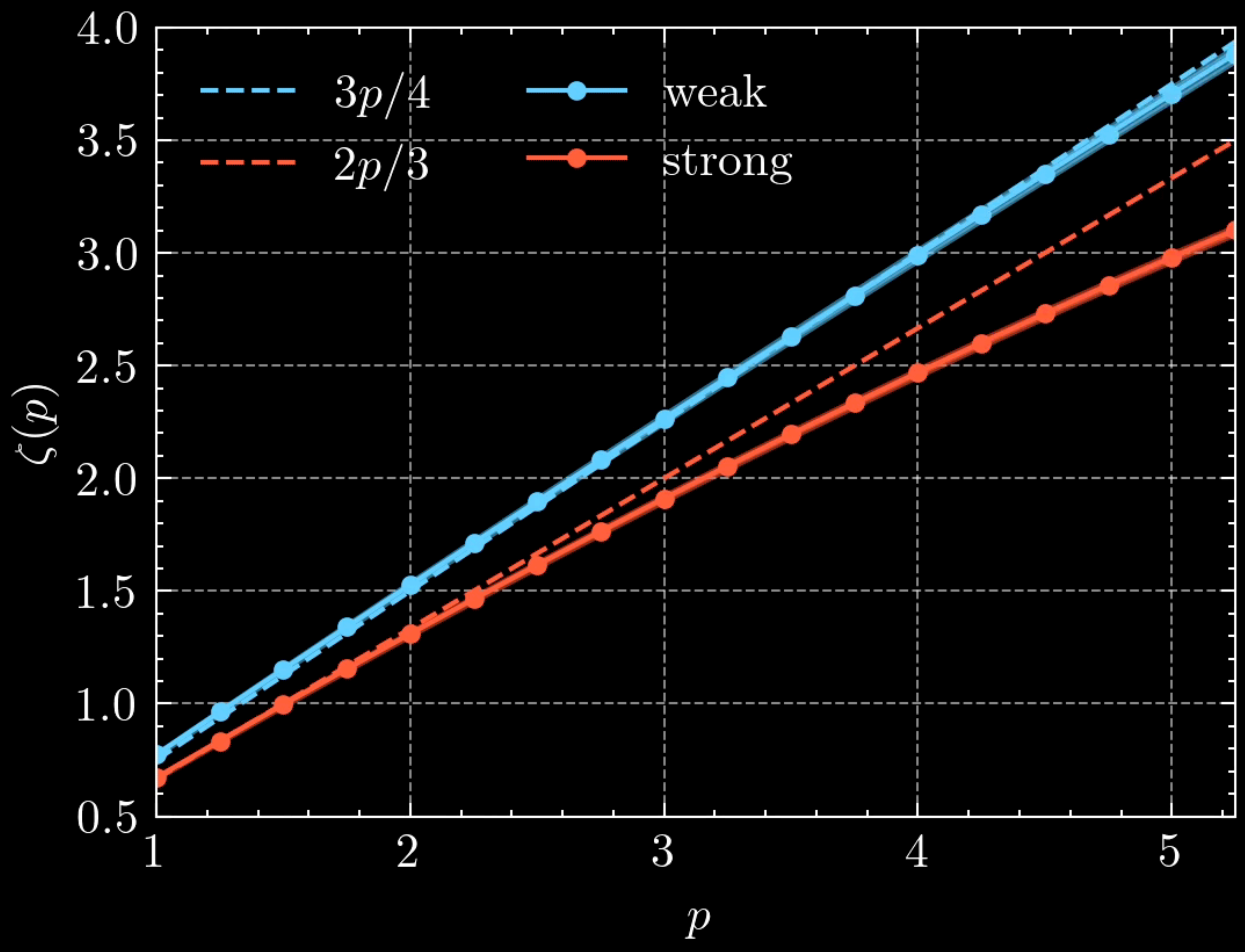
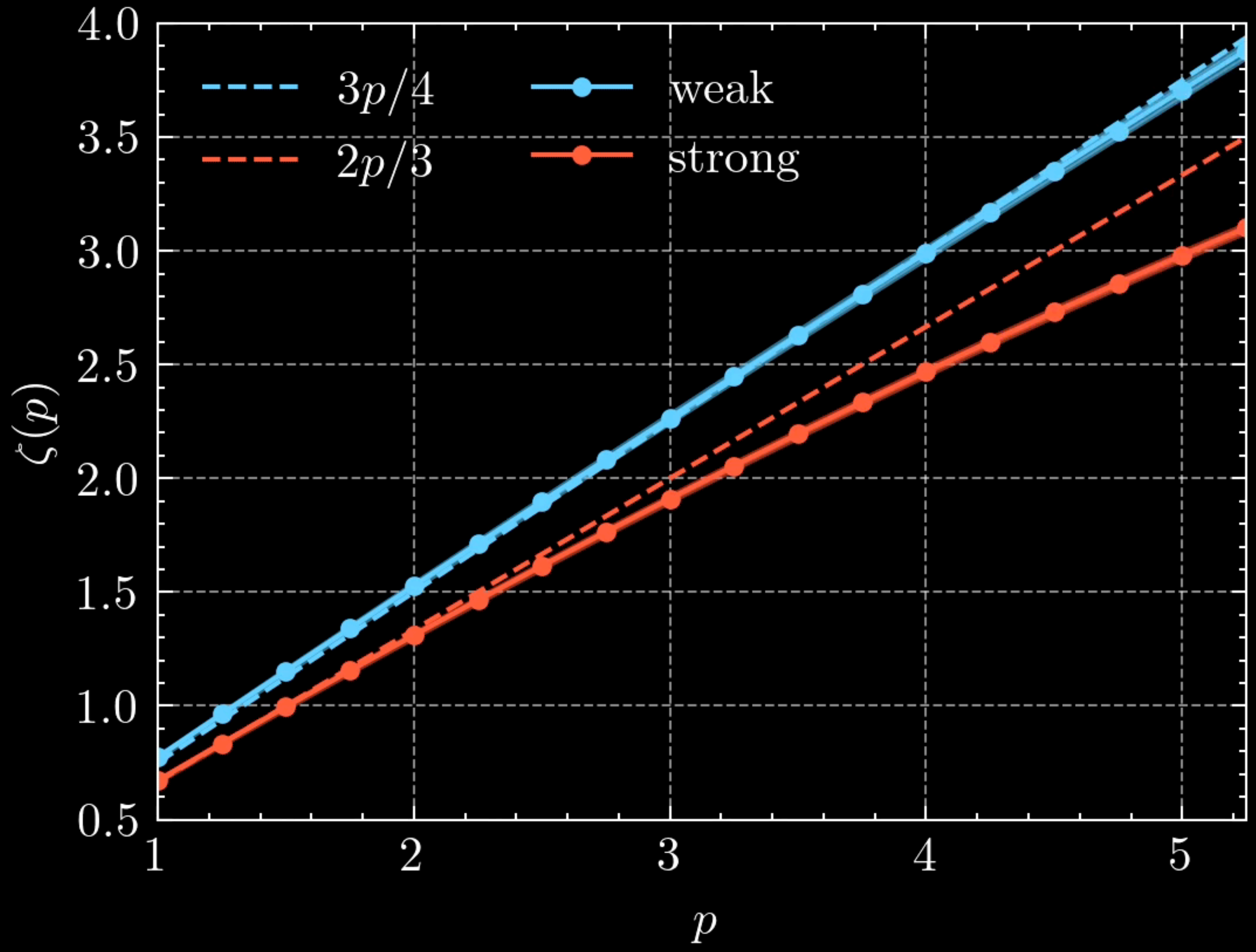


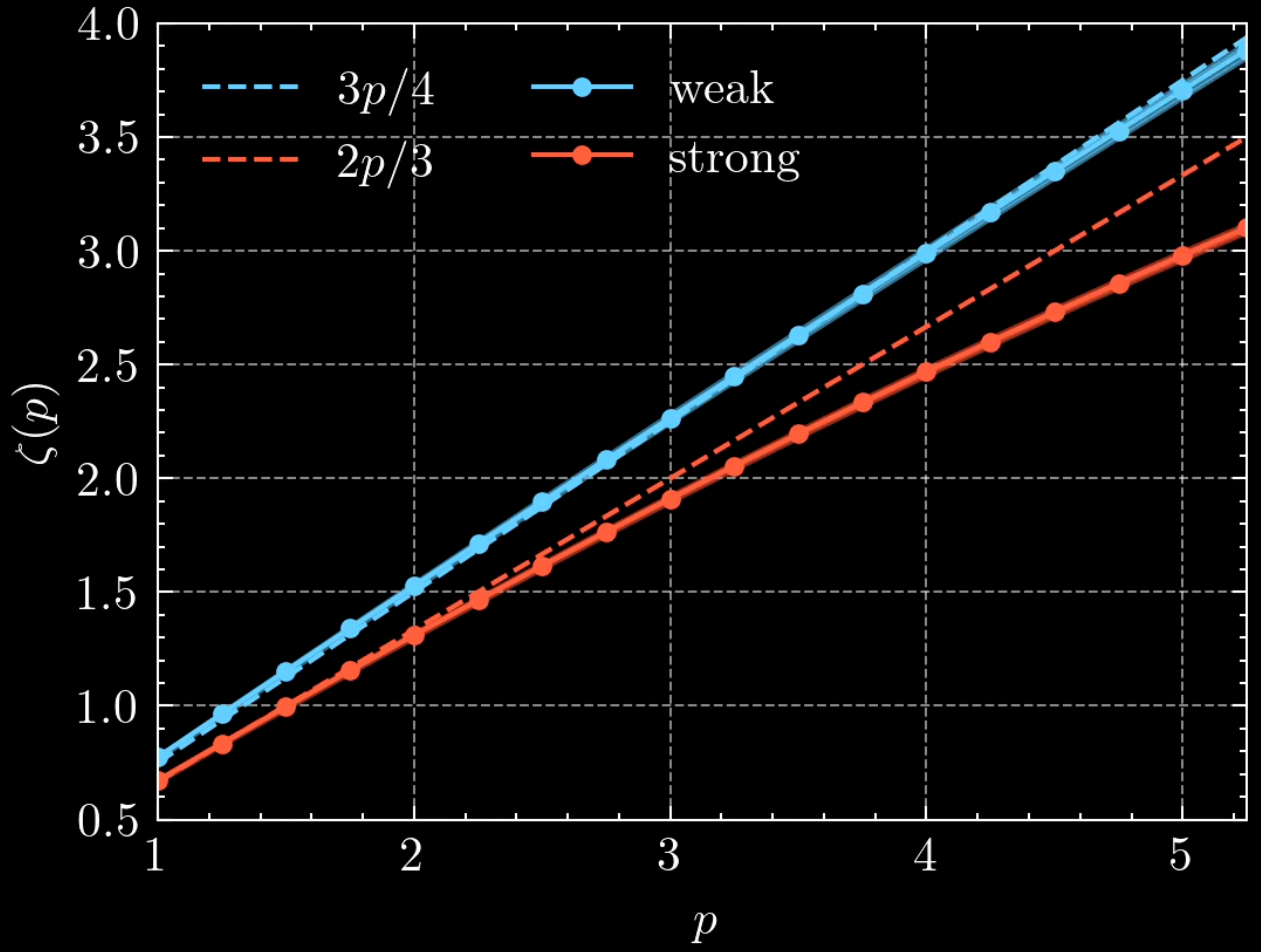
- Weak regime is monofractal.

Intermittency



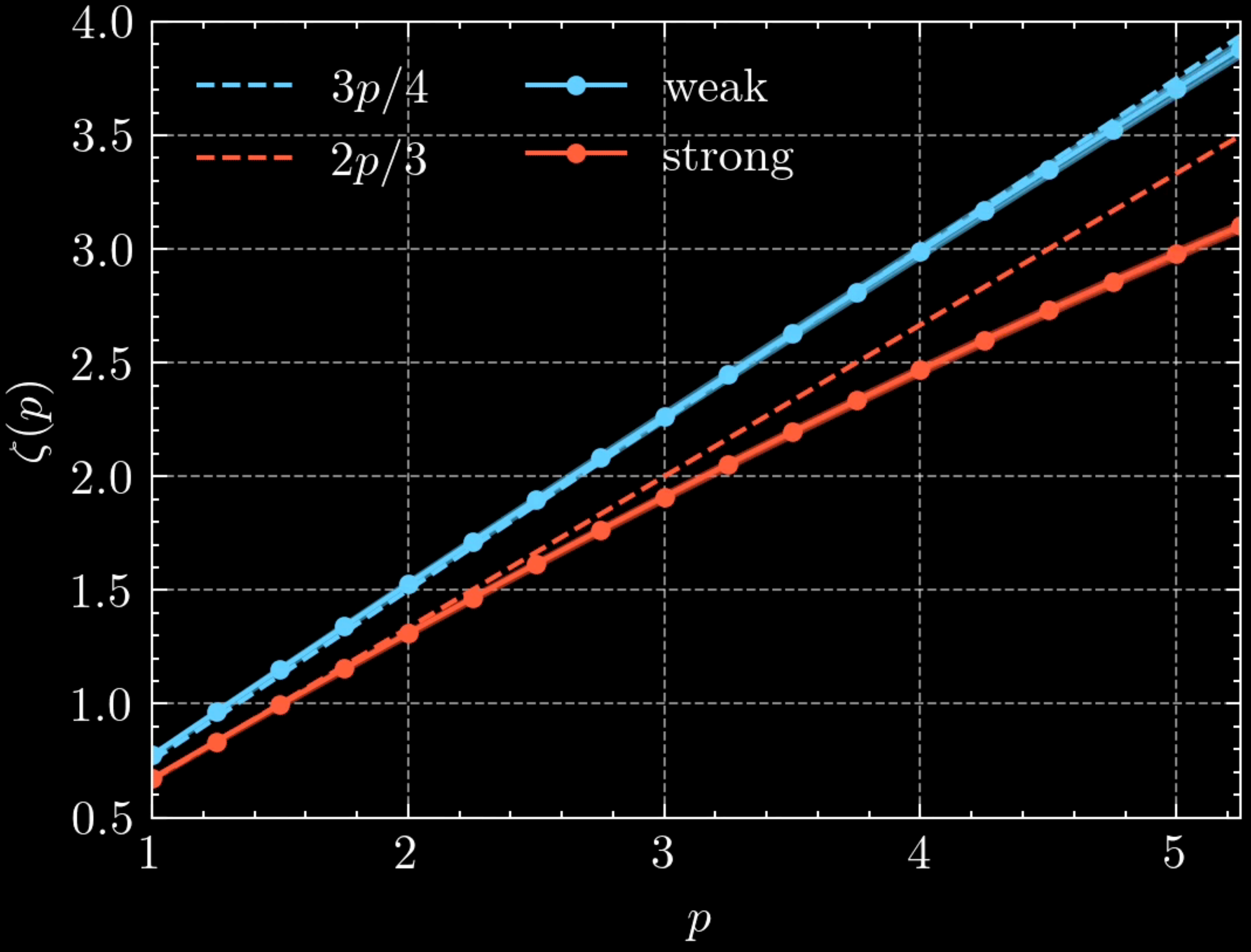
- Weak regime is monofractal.
- Strong regime is multifractal.

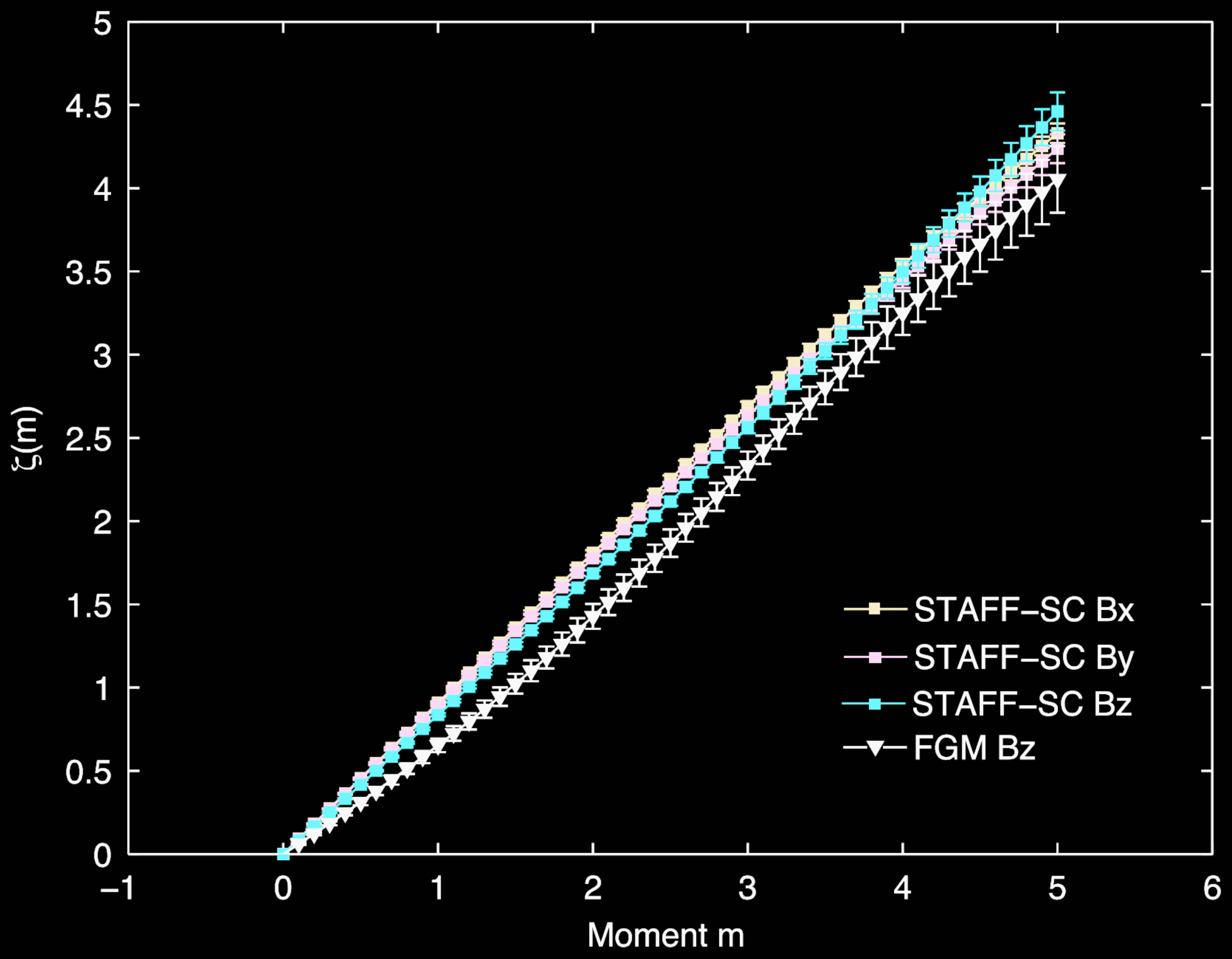
Intermittency



- Weak regime is monofractal.
- Strong regime is multifractal.
- Intermittency distinguishes the two.

What are the data?





[K. H. Kiyani et al., 2009, PRL]

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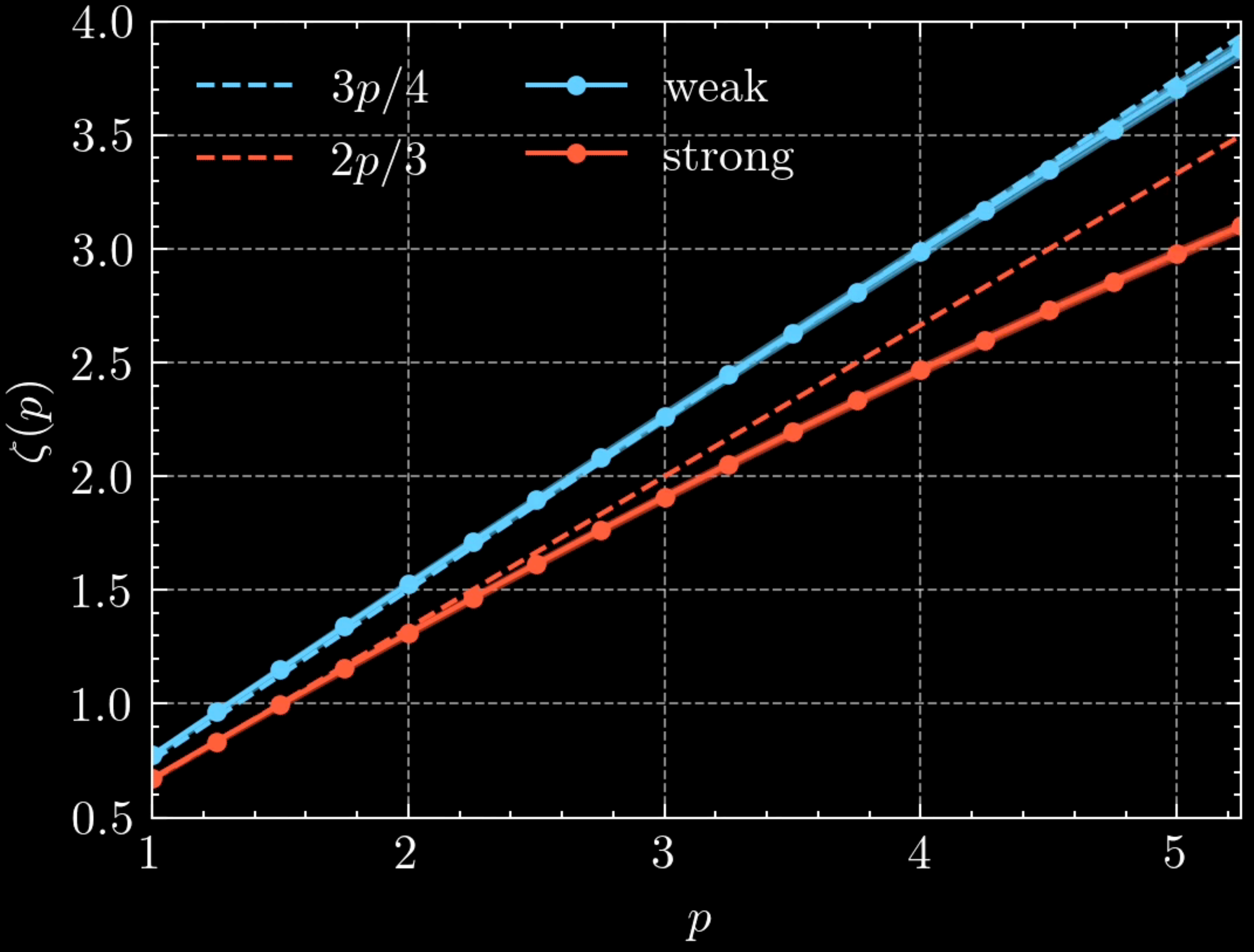

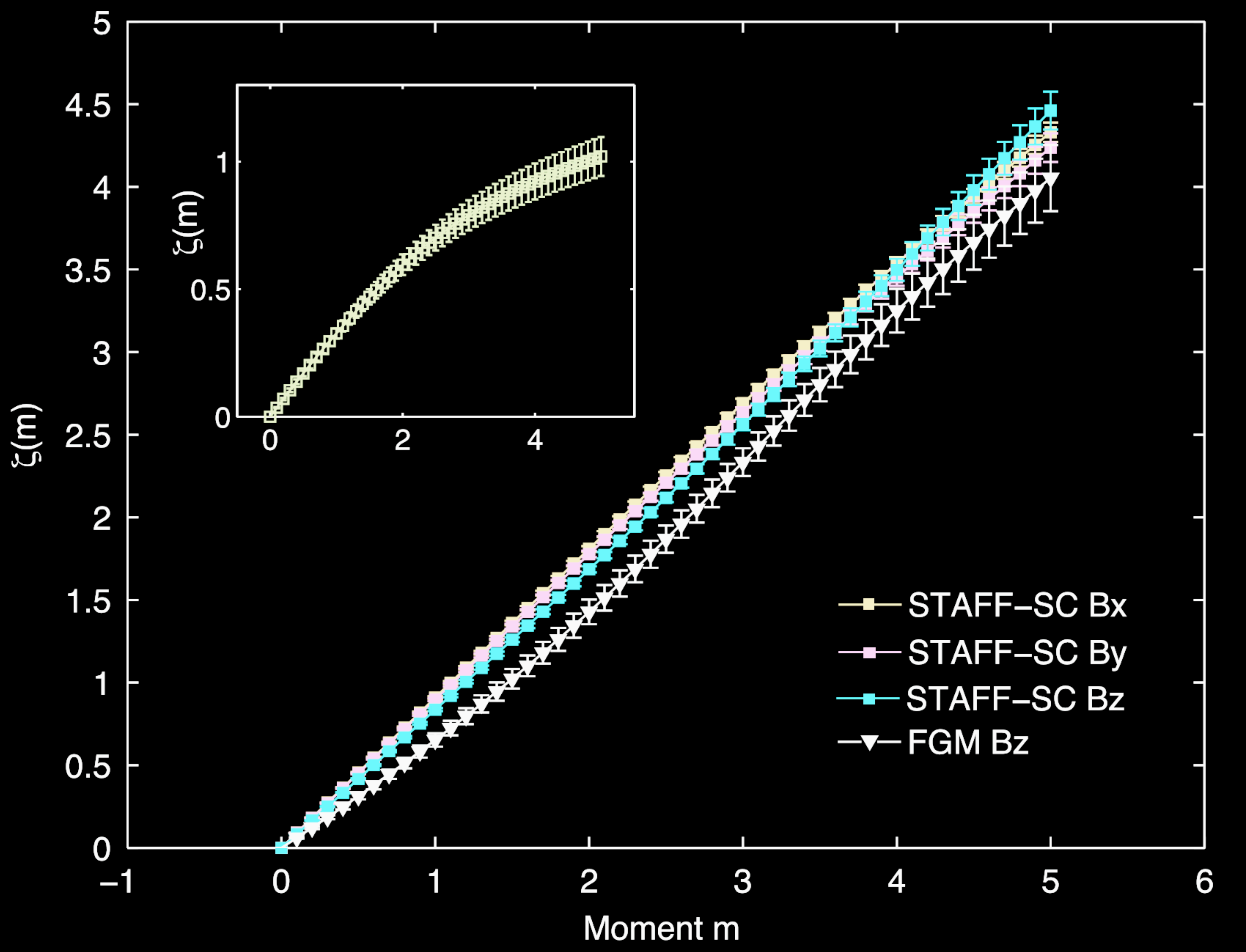

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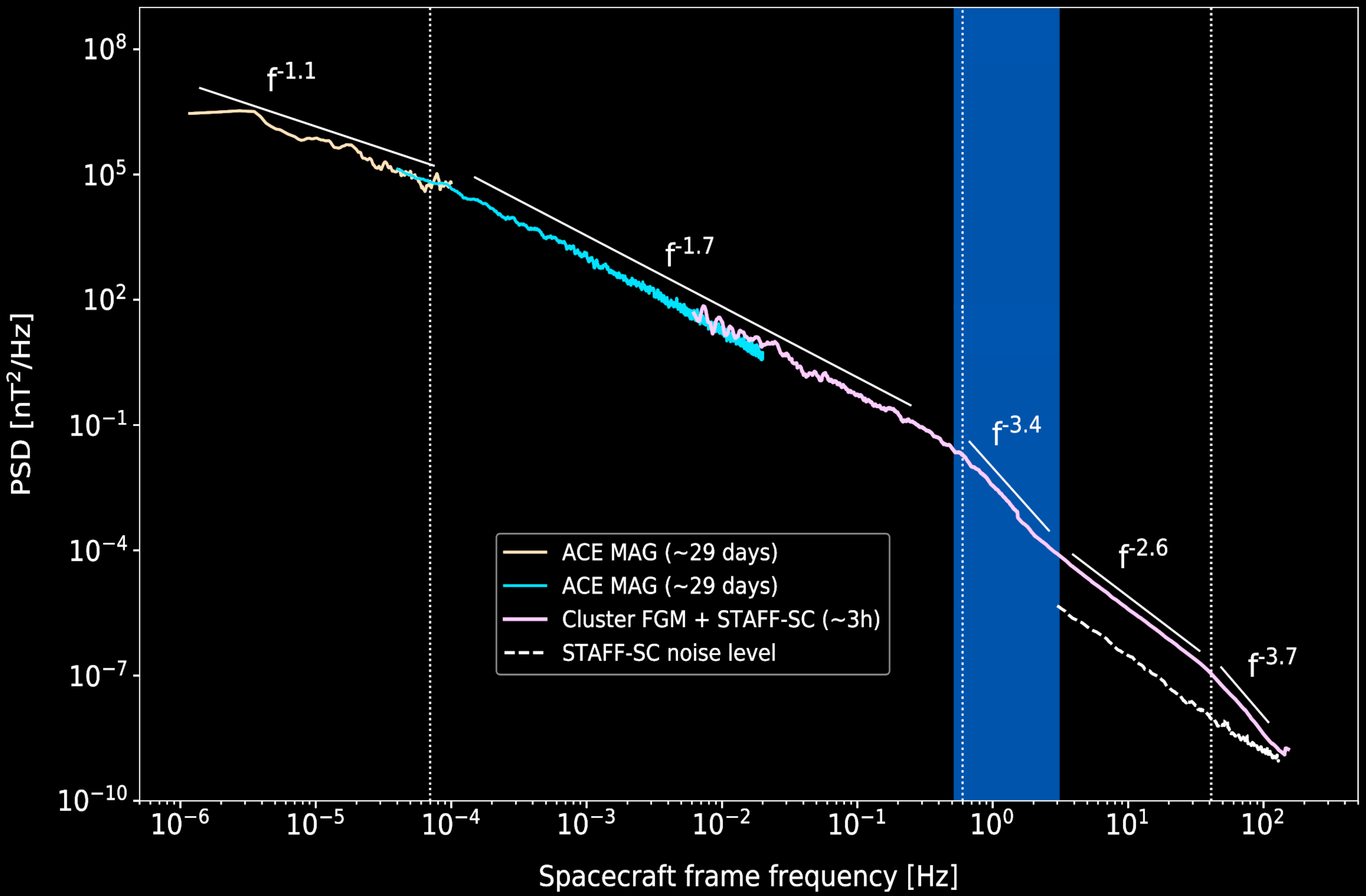

[F. Sahraoui, 2020, PRL]

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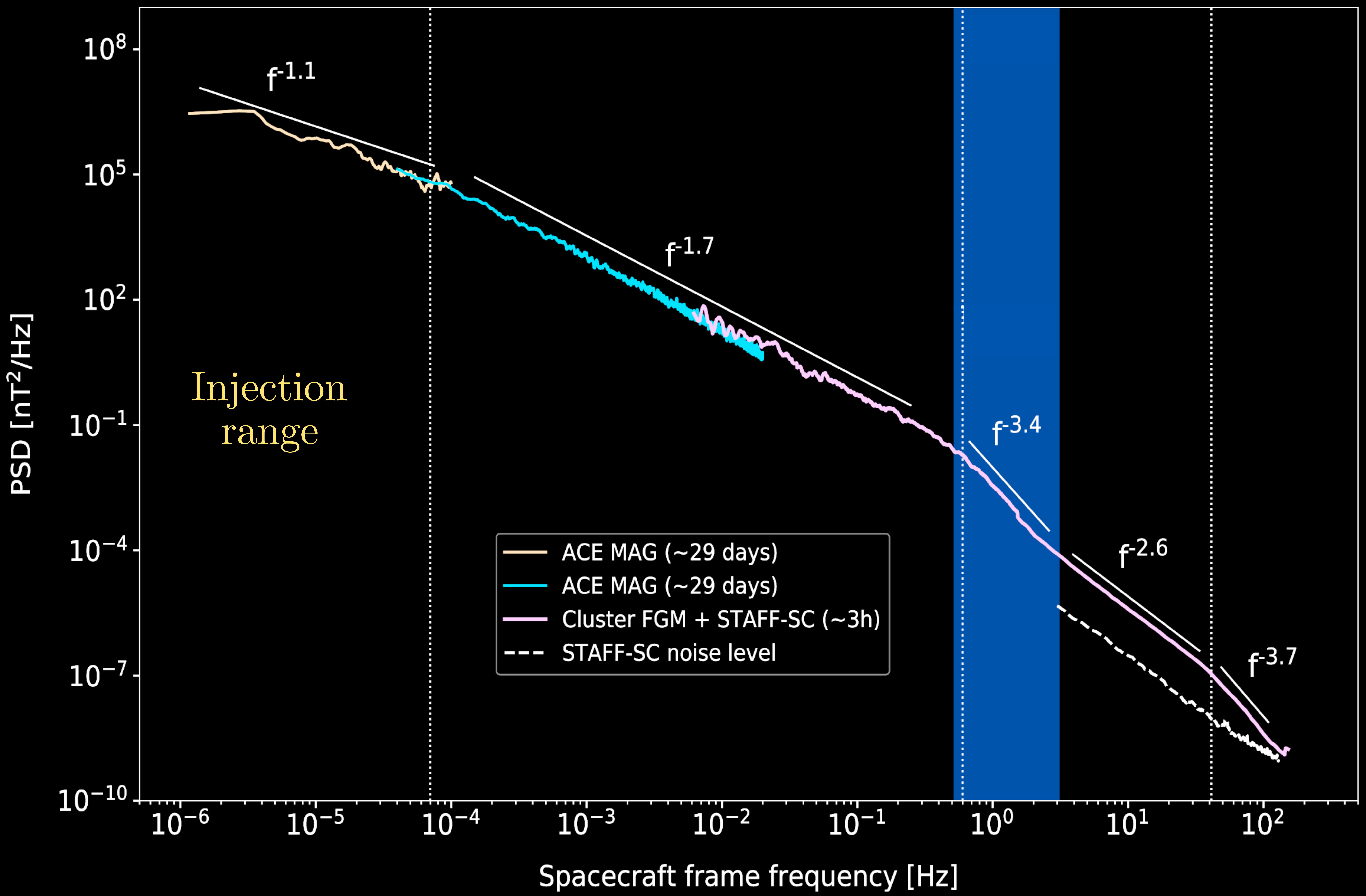
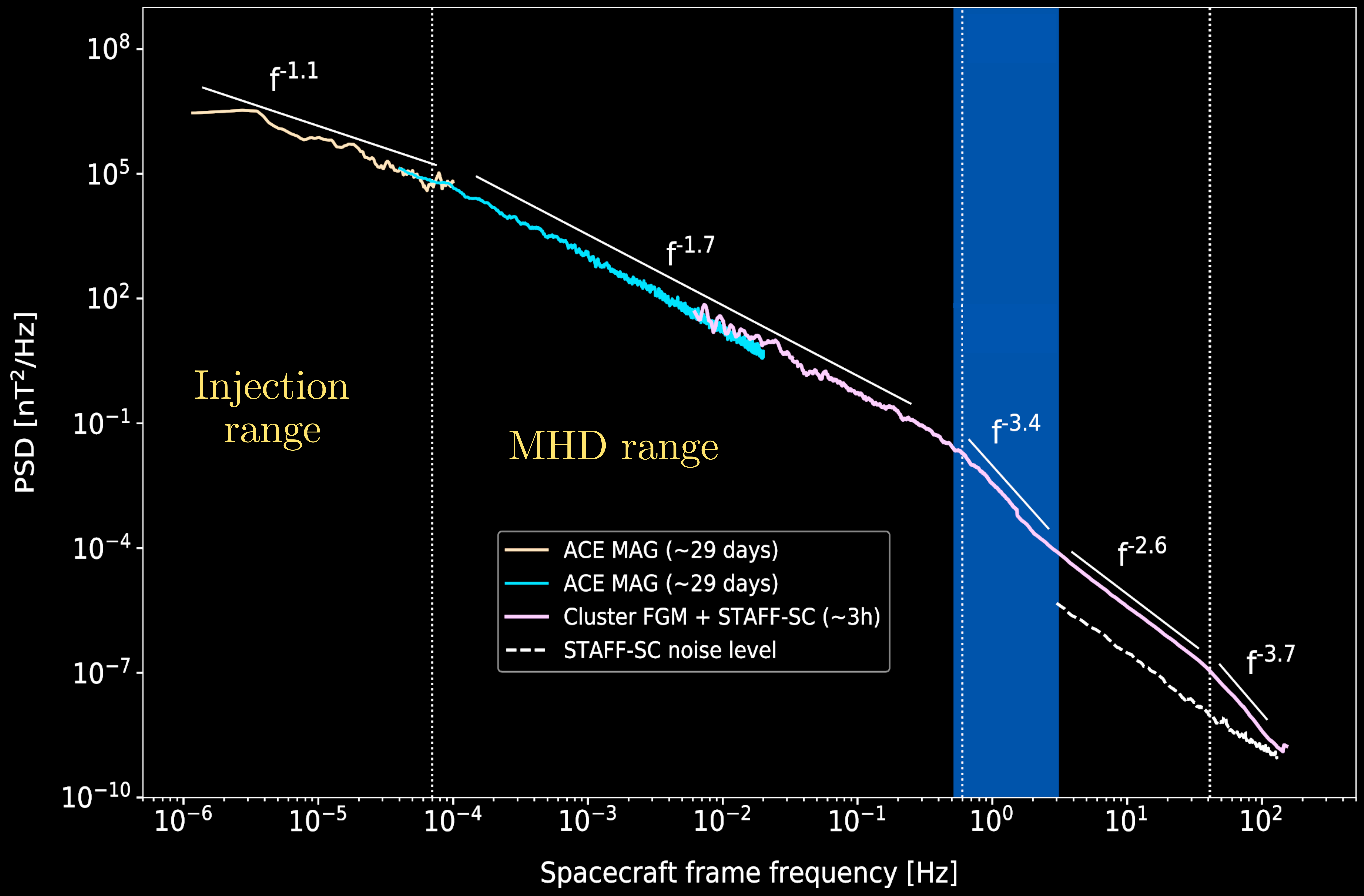


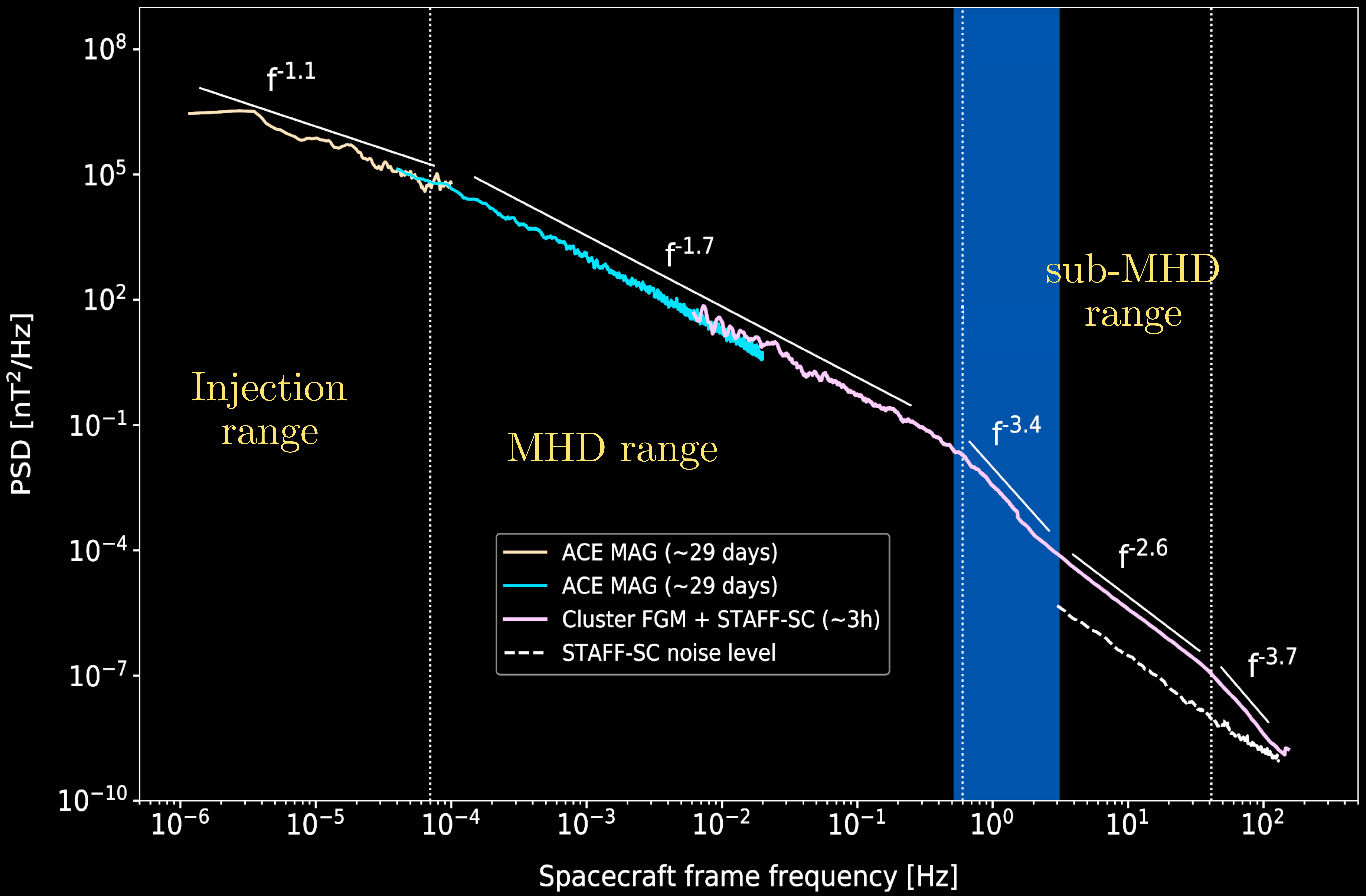
[F. Sahraoui, 2020, PRL]

What are the data?



[F. Sahraoui, 2020, PRL]

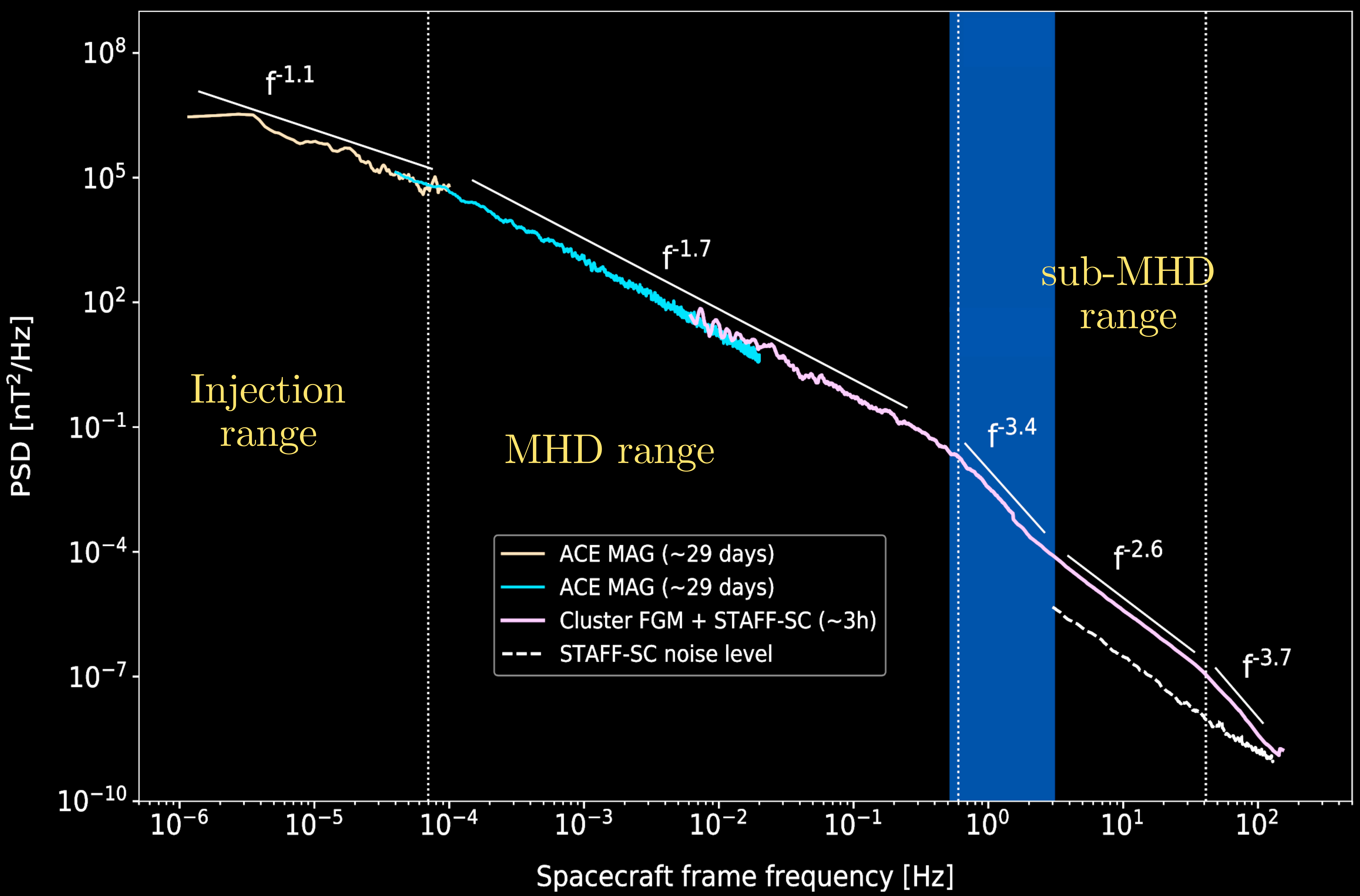
What are the data?



[F. Sahraoui, 2020, PRL]

What are the data?

Transition range



[F. Sahraoui, 2020, PRL]

The reset

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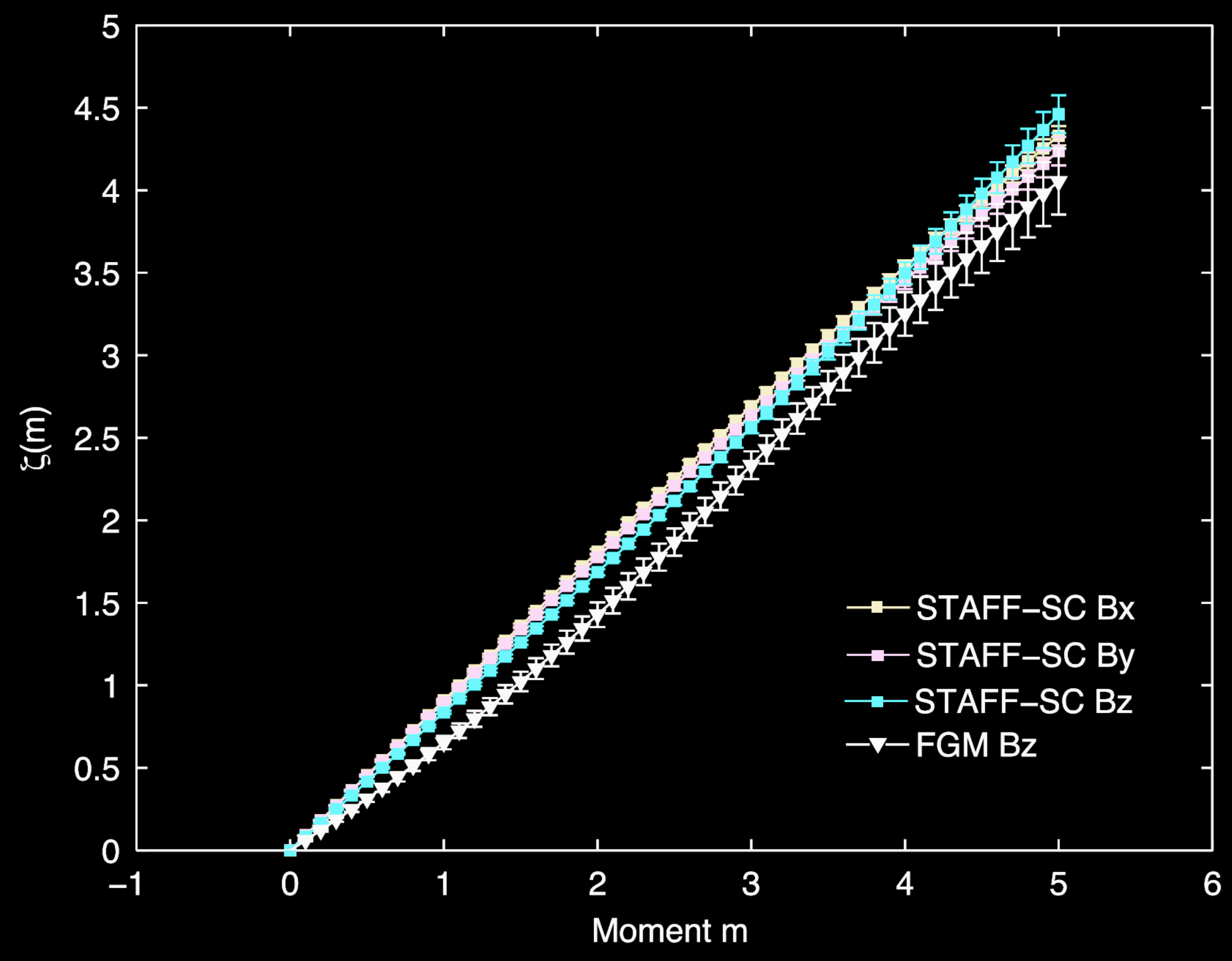
This reset makes it impossible to explain these data using strong turbulence alone.



[T. A. Bowen, 2023, *to be published*] [R. Meyrand et al., 2021, *JPP*] [J. Squire et al., 2022, *NatAs*]

Take home message

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- Spectra are not enough to distinguish the two regimes.
- Only the weak regime has a monofractal intermittency.
- Caveat: viscous dissipation is used despite the solar wind being collisionless.

vincent.david@unh.edu

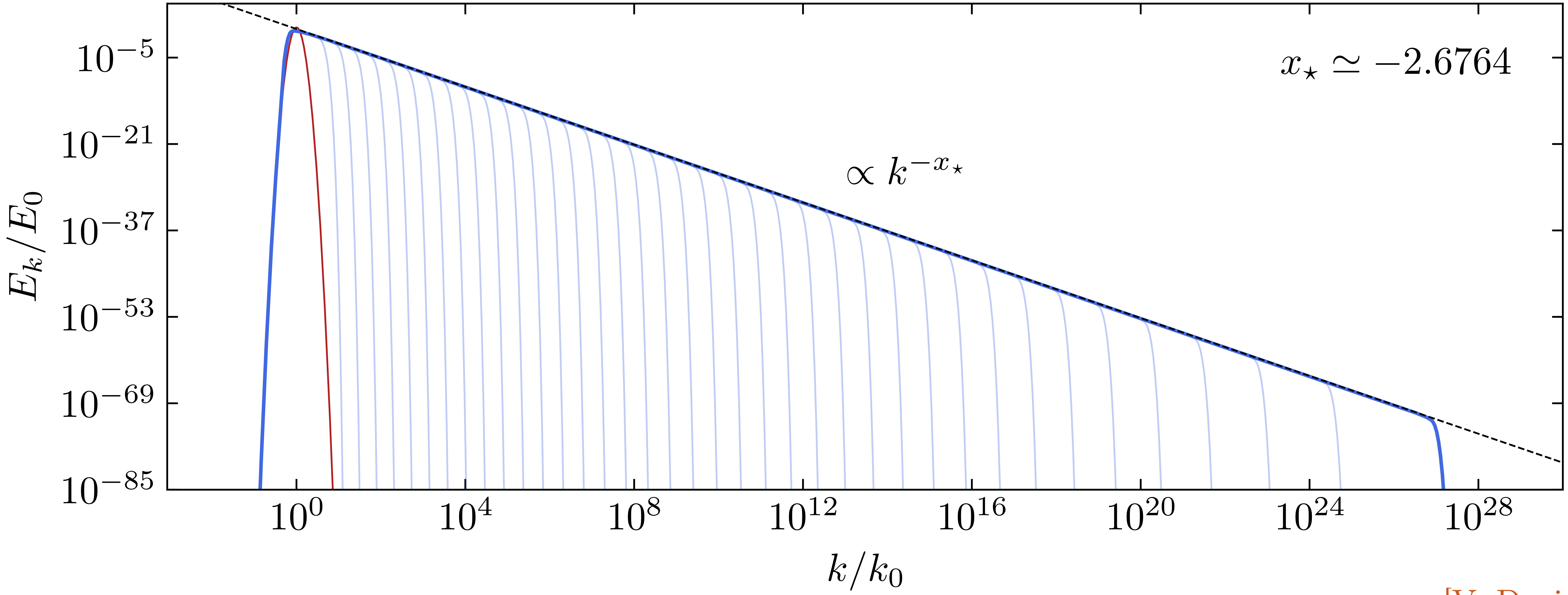
Additional slide

Depends on the type of wave.

The order of the resonant wave interaction -2.

The dimension of the system.

$$\frac{\partial E_k}{\partial t} = \frac{\partial}{\partial k}\left[k^m E_k^n \frac{\partial}{\partial k}\left(\frac{E_k}{k^{d-1}}\right)\right], \quad (m, n, d) = (7,1,2)$$



[V. David, PhD manuscript]