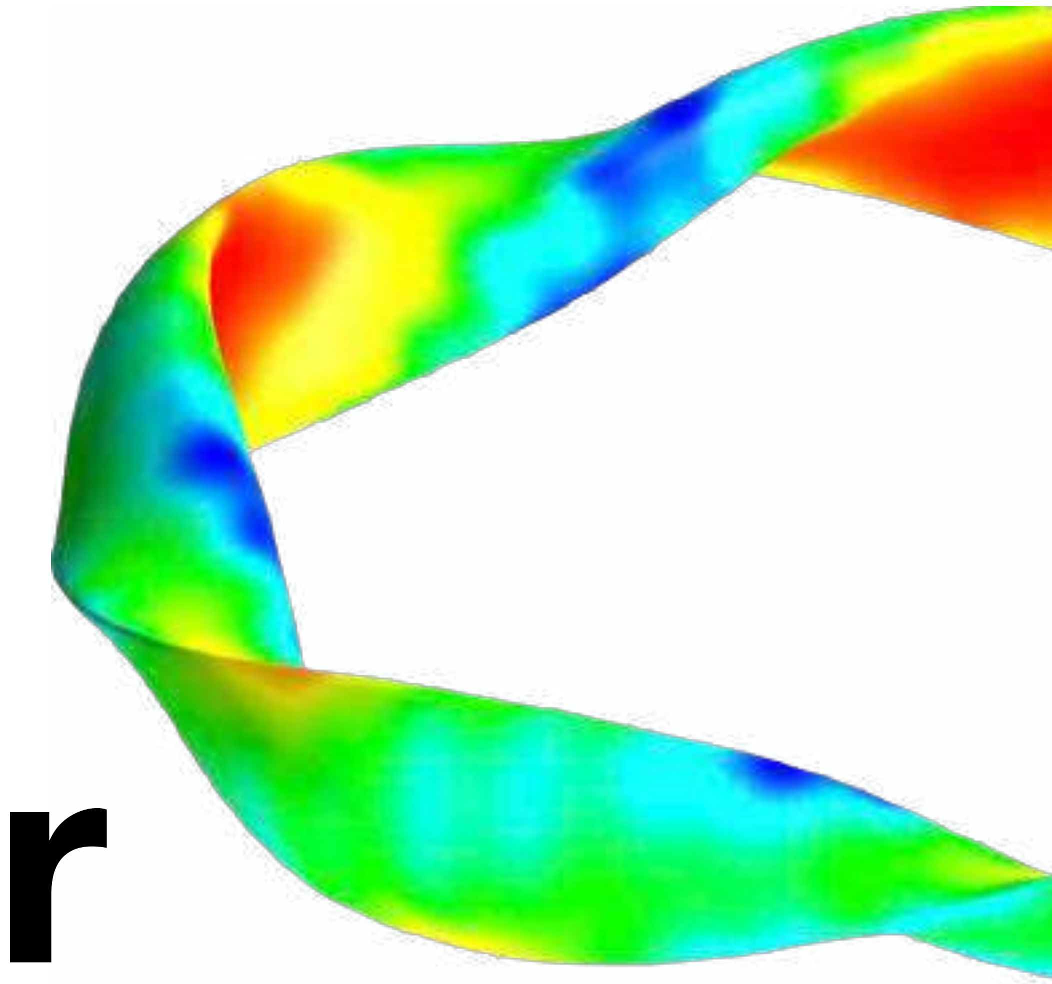

Geometric Considerations for Zonal Flow Activity in Stellarators

Toward Improved Transport Modeling

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[1]Eindhoven University of Technology, Eindhoven, The Netherlands
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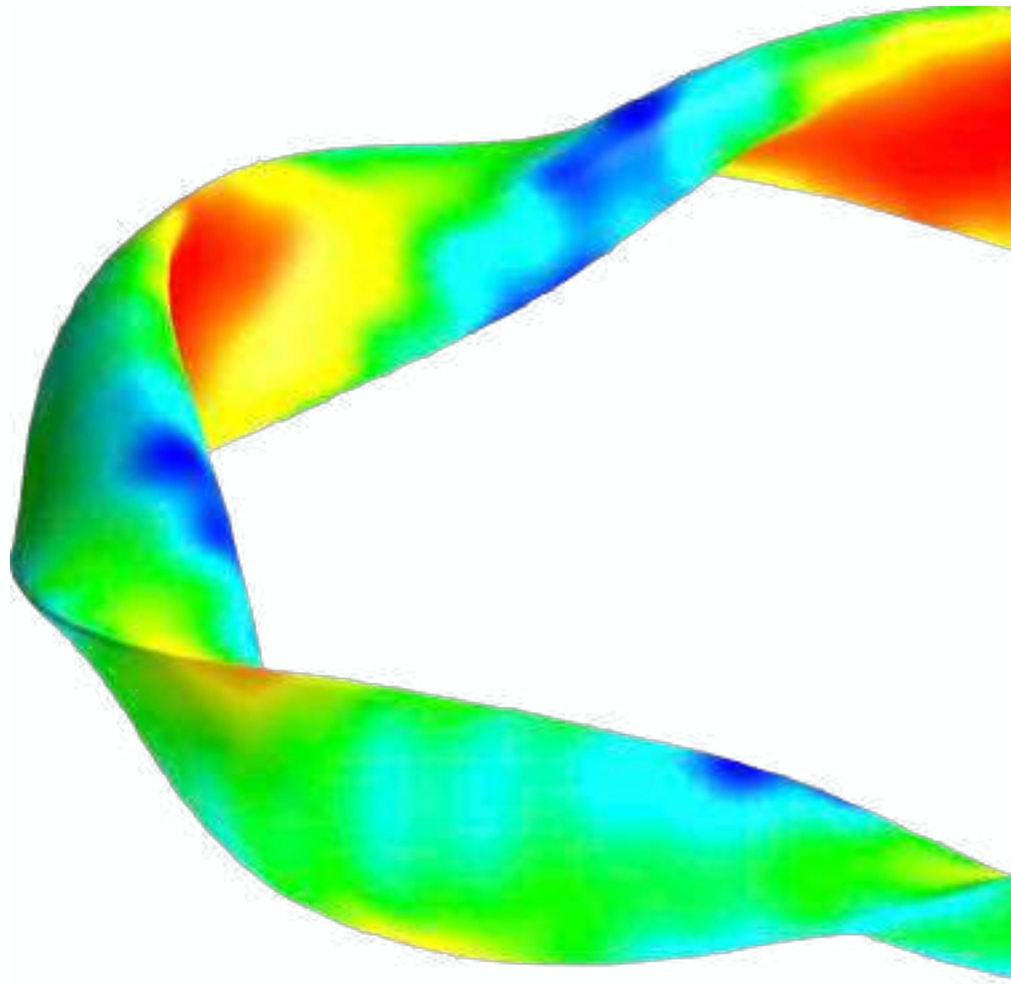
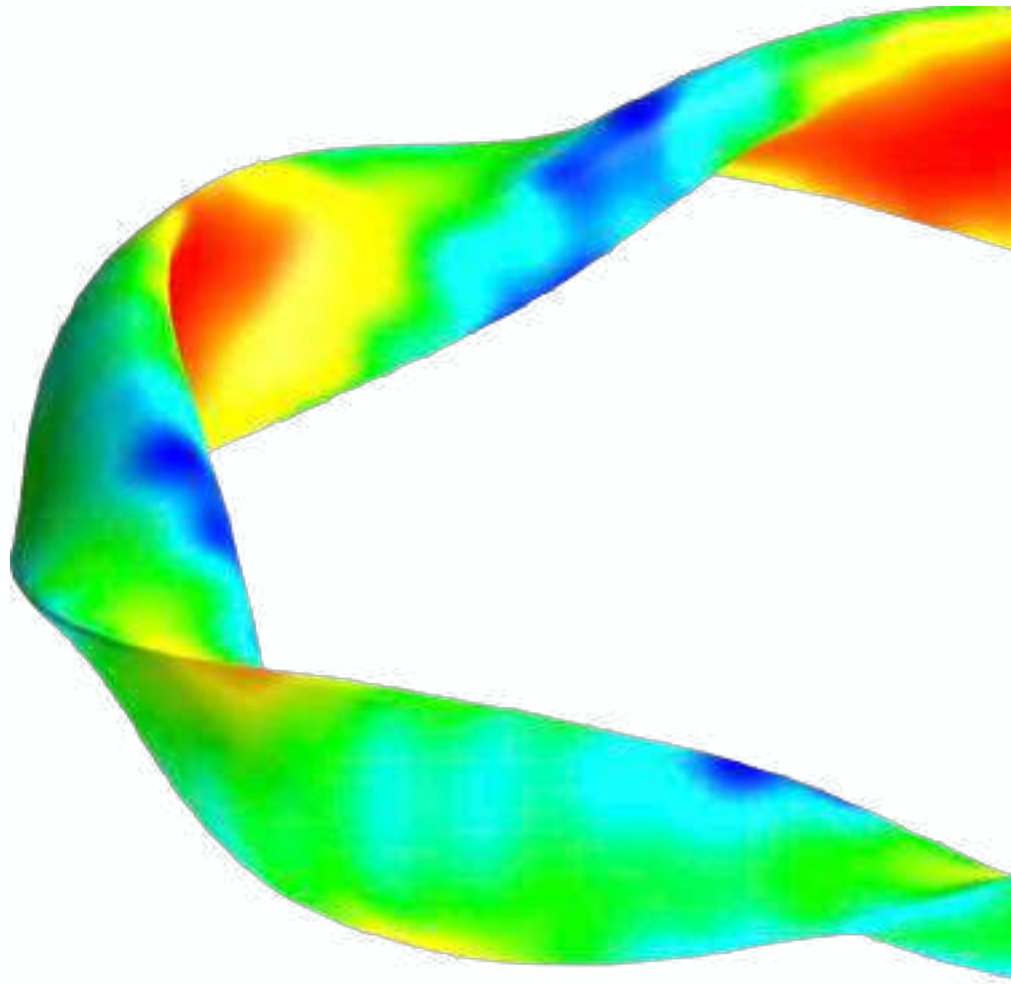
Understanding turbulence dynamics



- Turbulence dominates transport.[1]
- Saturation mechanisms?
- Stellarator geometry –> decisive.
- Simulations: GENE code.[2,3]
  - ITG, adiabatic electron response.
  - Local: Flux tube domain.
- Craft a predictive model:

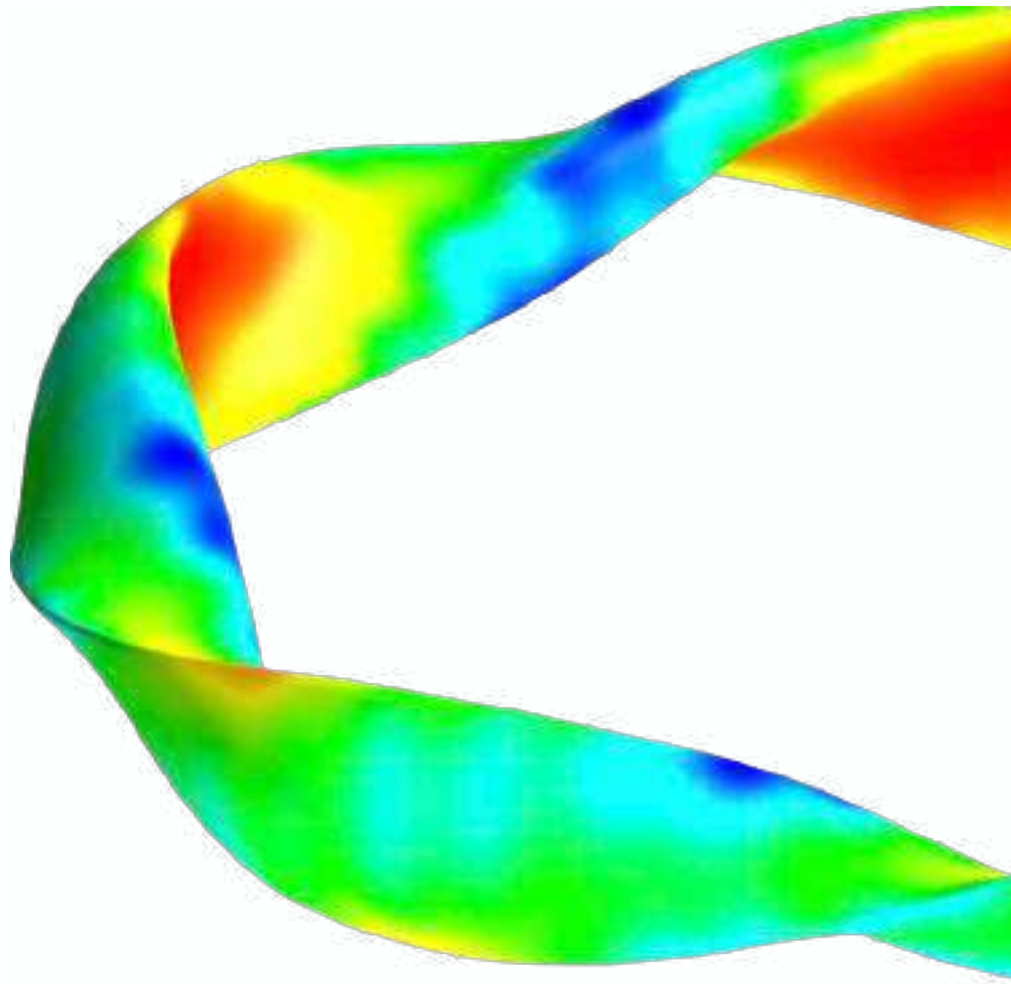
$$\chi_i = f\,(Geometry, Linear\ physics)$$

[1] J.A. Alcusón et al, Proceedings of 45th EPS Conference on Plasma Physics, (Vol. 42A, pp. 841-844). [P2.1088] European Physical Society.
[2] F. Jenko et al, Physics of Plasmas 7, 1904 (2000).
[3] See: http://ww.genecode.org for details



What are the geometric features that influence saturation?

Outline



Geometry in Wendelstein 7-X

Gyrokinetic turbulence modeling

Reduced transport modeling

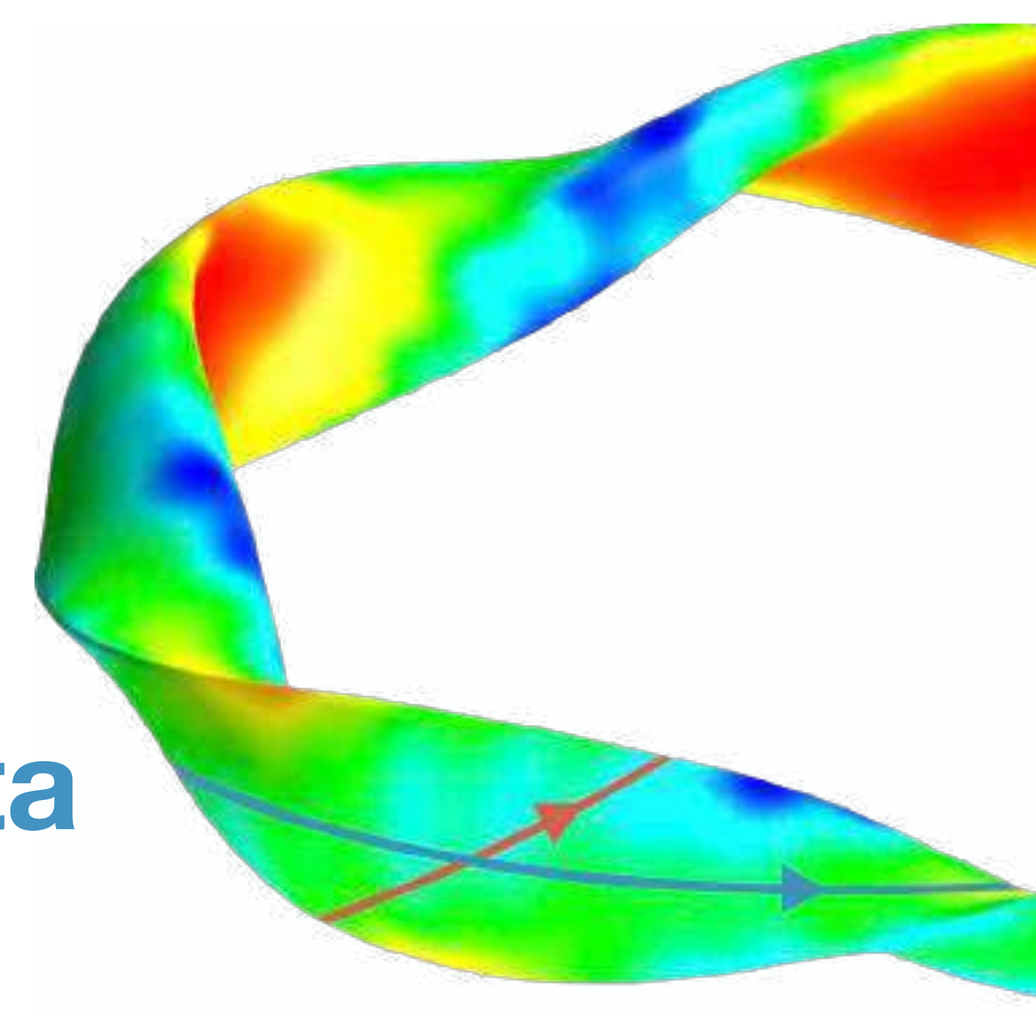
Summary

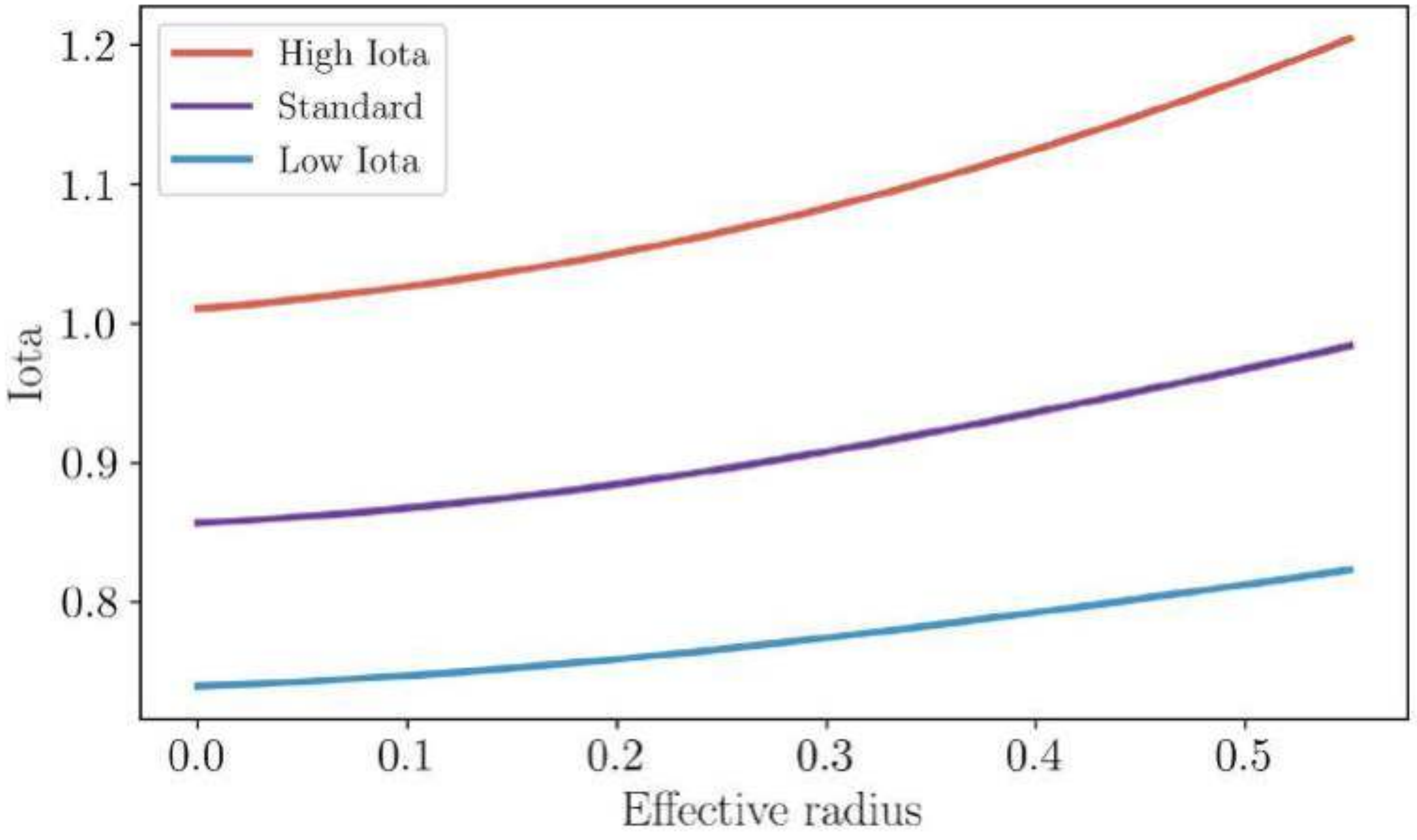
Configurations of Wendelstein 7-X studied

- Experimental flexibility allows:
  - High Iota
  - Standard configuration
  - Low Iota

where: $\frac{\iota}{2\pi} = \frac{poloidal\ turns}{toroidal\ turns} = \frac{1}{q}$

- Impact sample frequency of:
  - Good / bad curvature
  - Periods of geodesic curvature

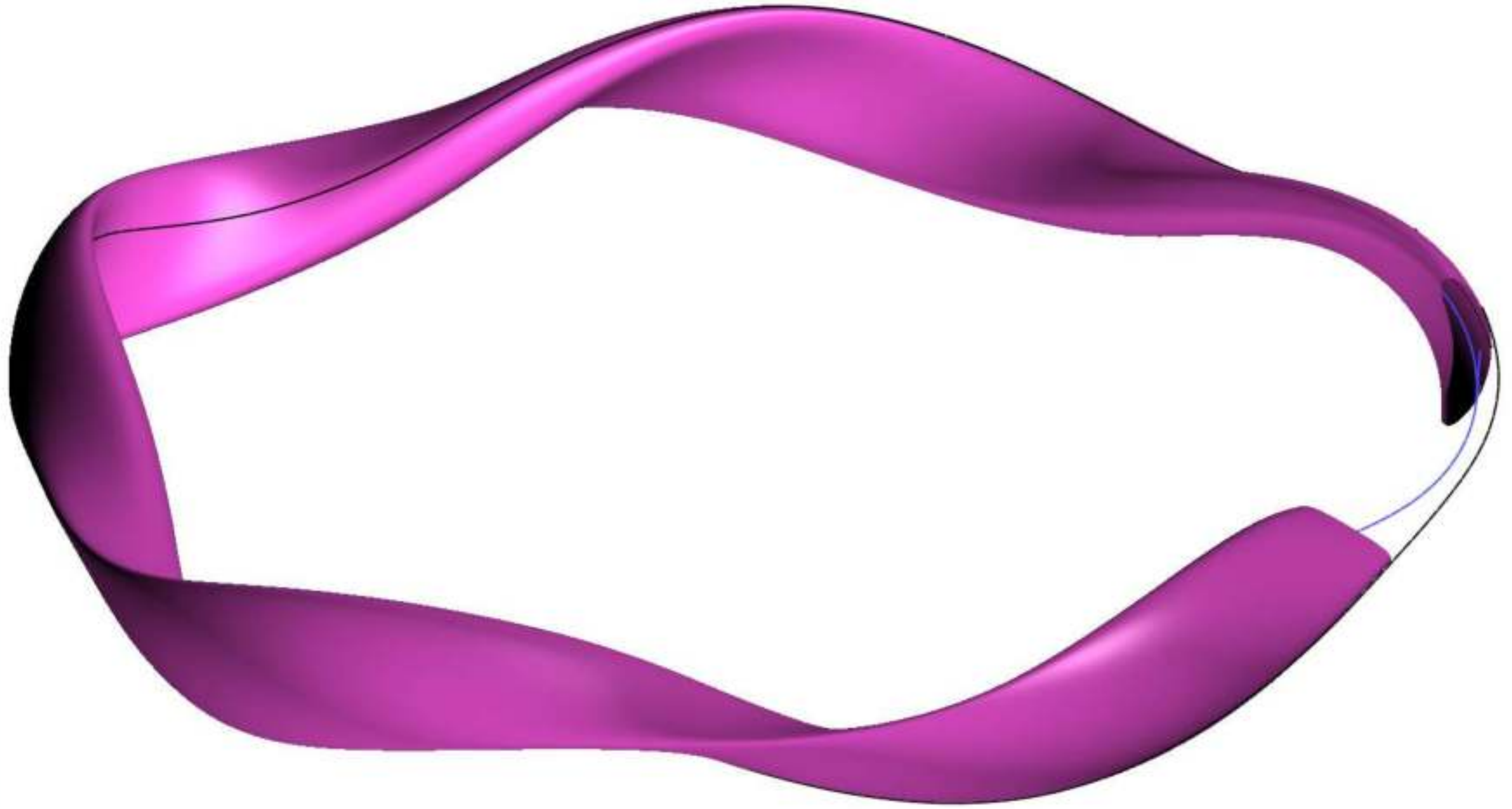




Curvature determines turbulence evolution

Curvature definition:

$$\boldsymbol{\kappa} \equiv \mathbf{b} \cdot \nabla \mathbf{b} = \boldsymbol{\kappa}_N + \boldsymbol{\kappa}_G$$



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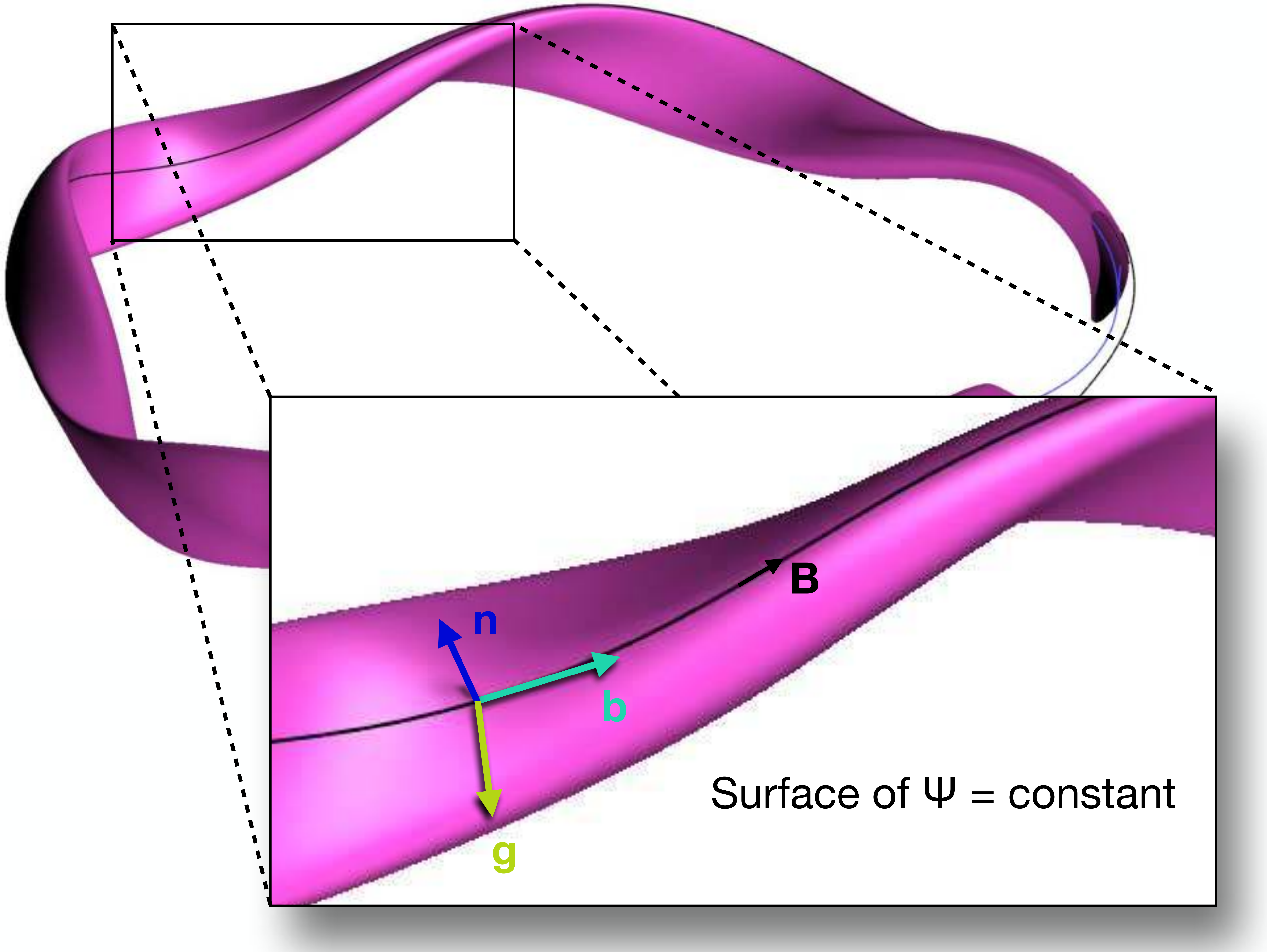

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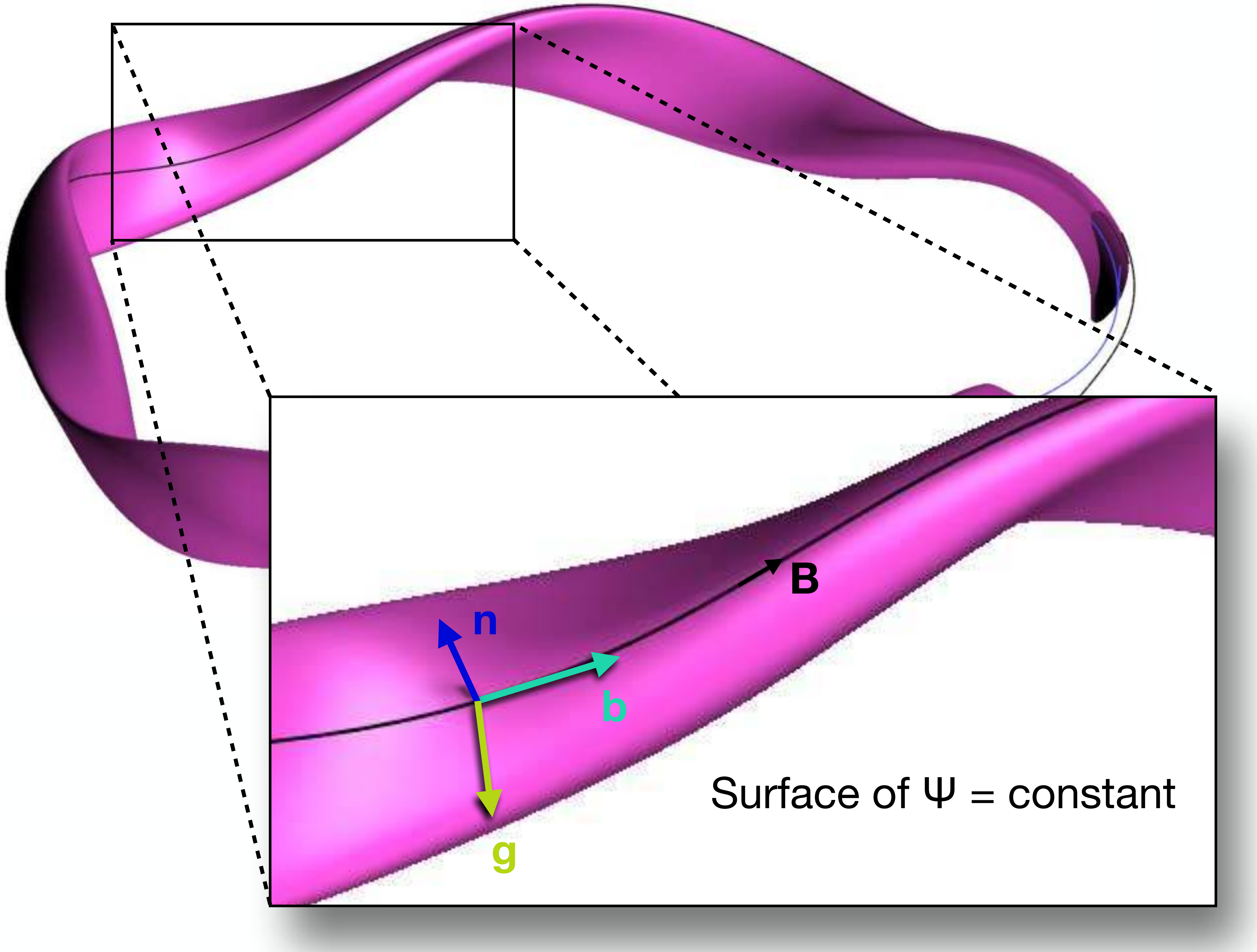
and:

$$\boldsymbol{n} \equiv \nabla \Psi \quad , \quad \boldsymbol{g} \equiv (\mathbf{B} \times \nabla \Psi)$$



Curvature features in Wendelstein 7-X

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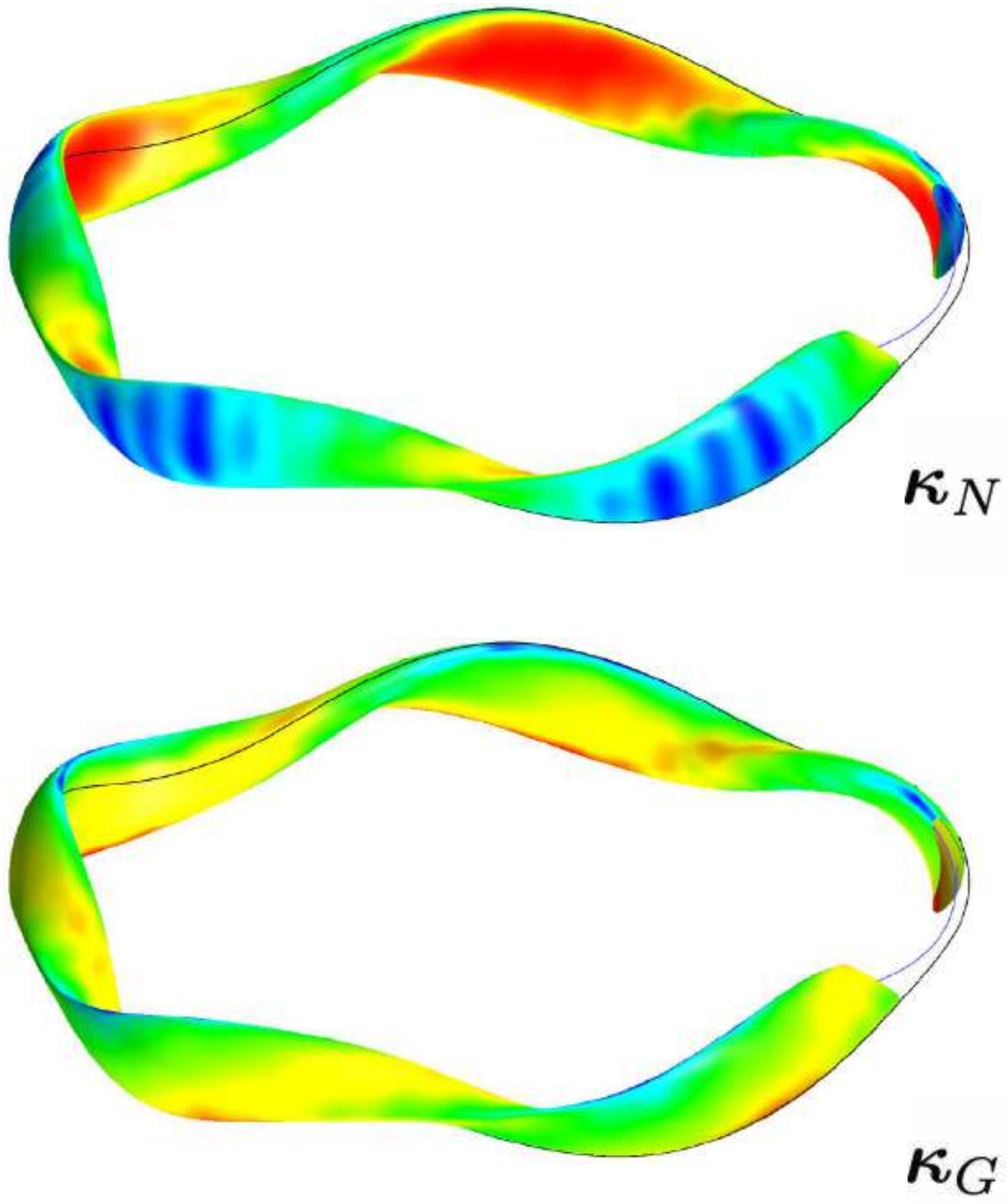

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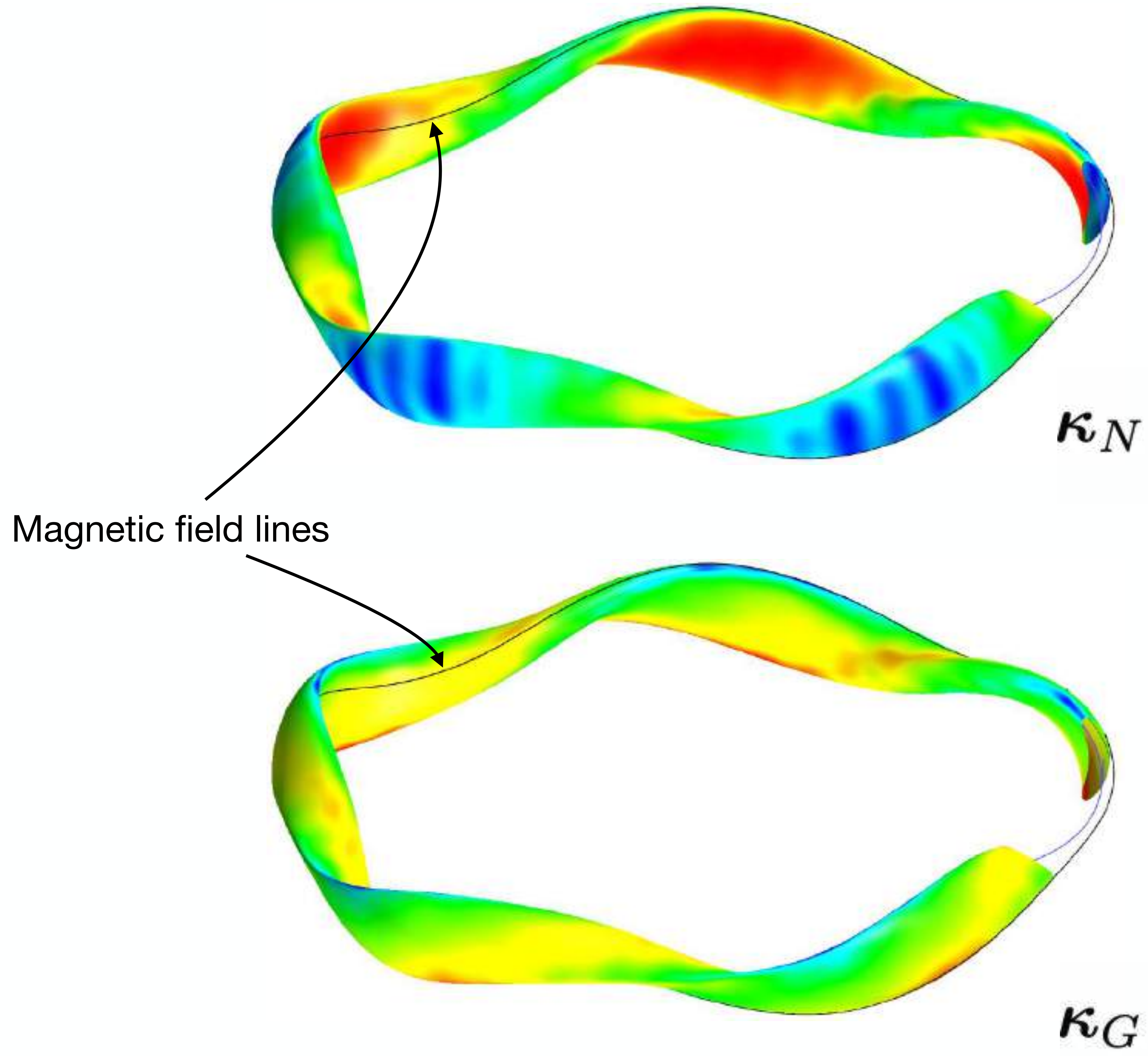

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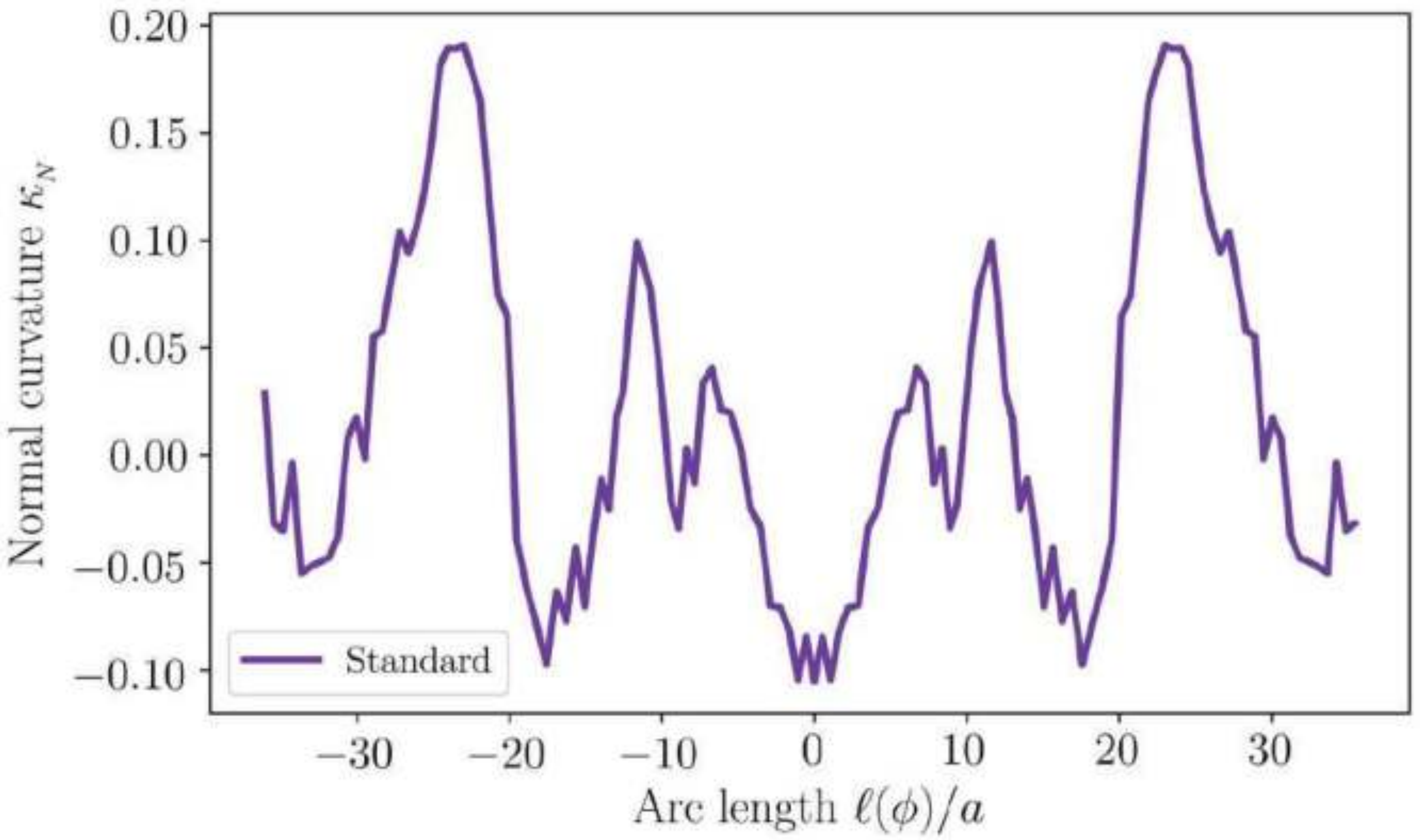
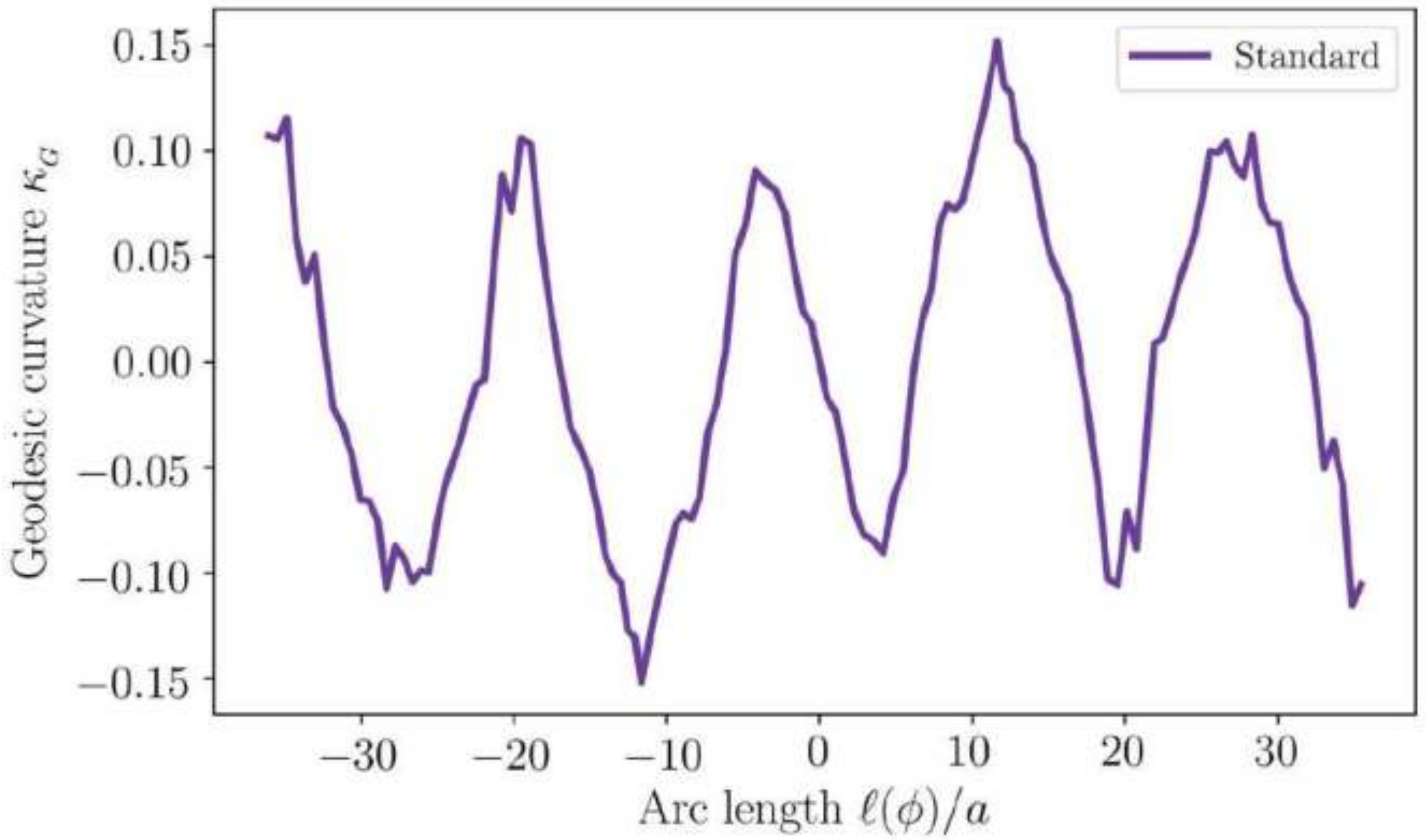
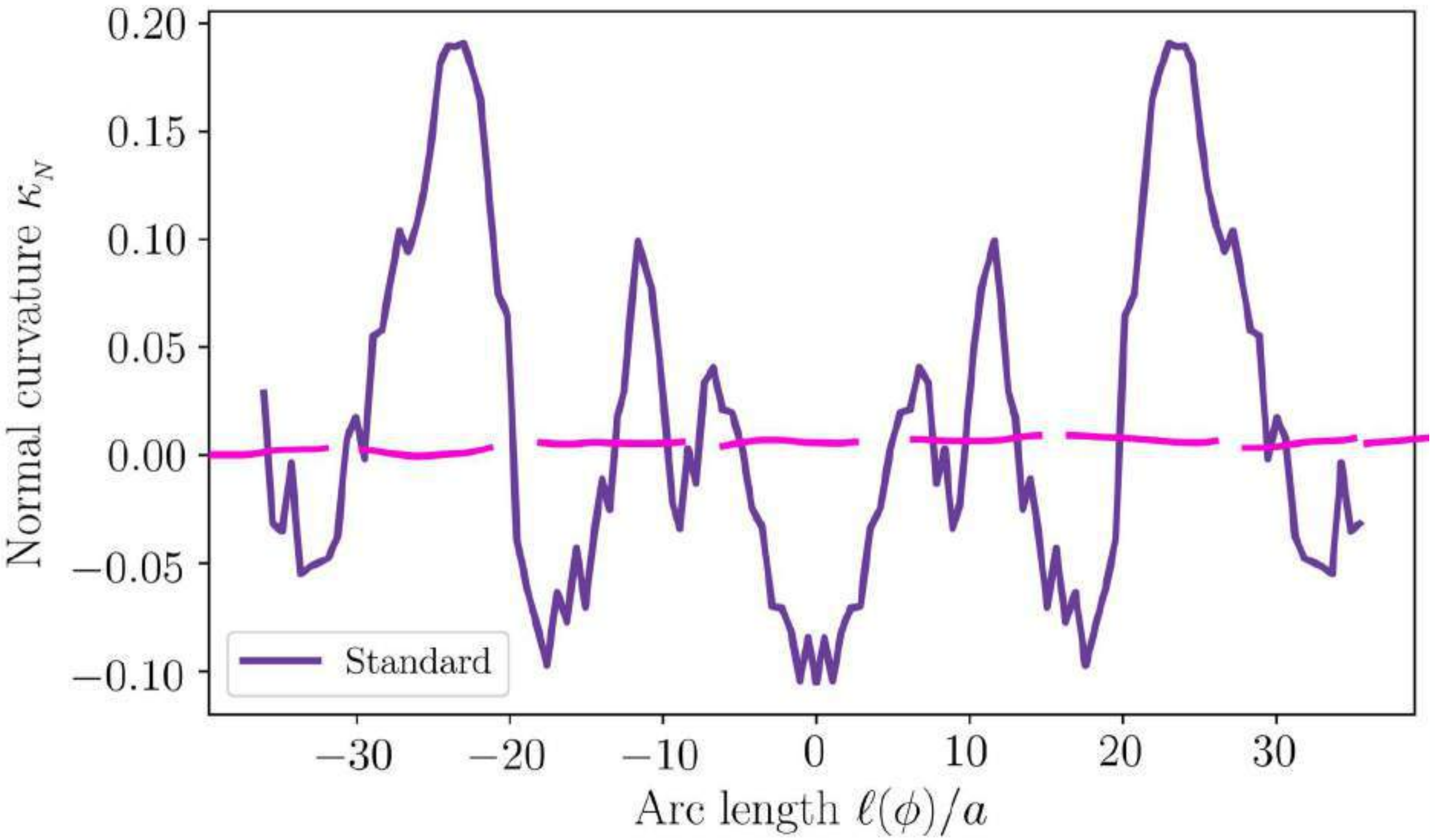
Different iota: ballooning angle –> arc length





Primary modes are localized in “bad” curvature regions

- Negative regions: instability growth.
- High particle drifts



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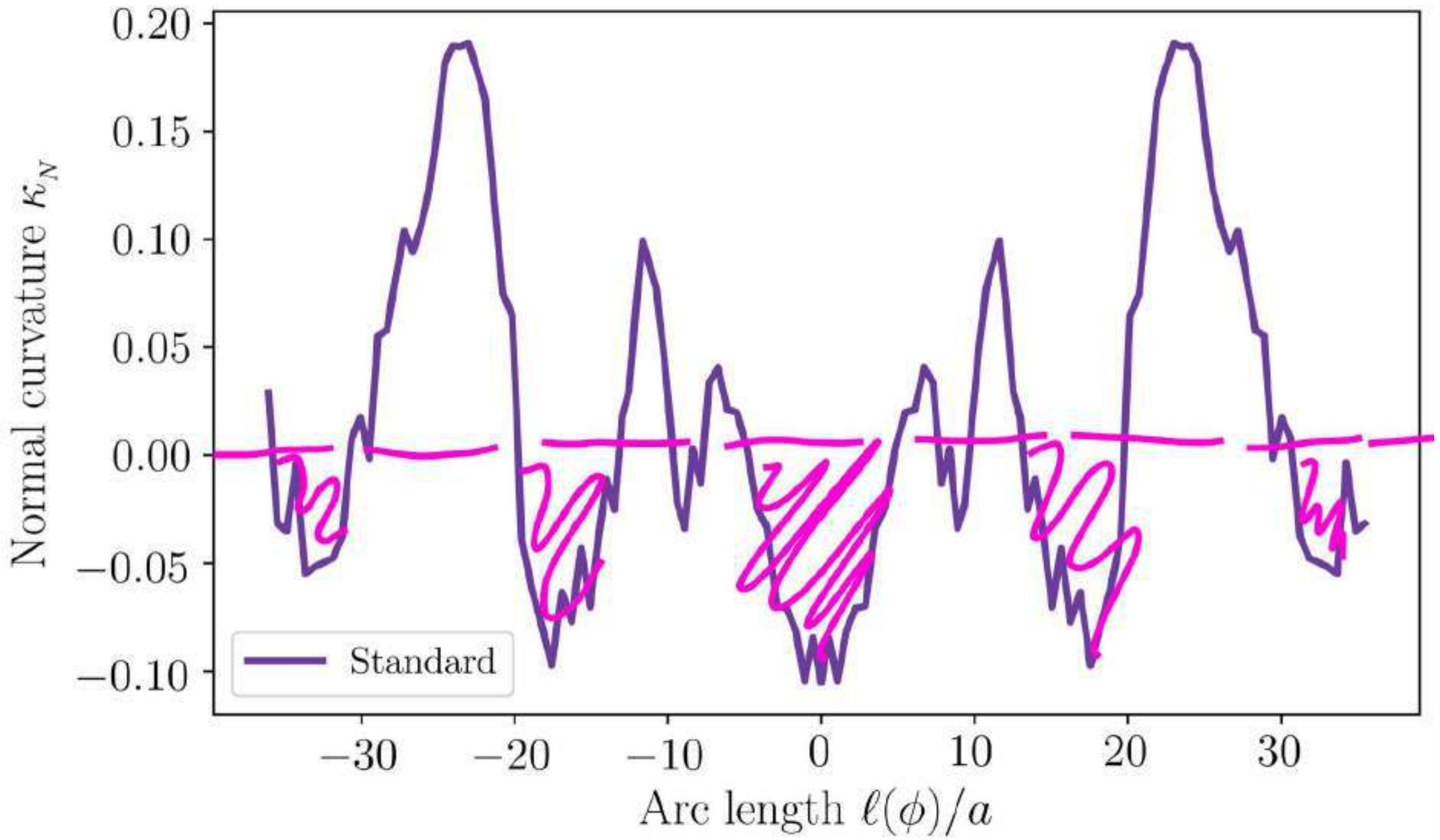
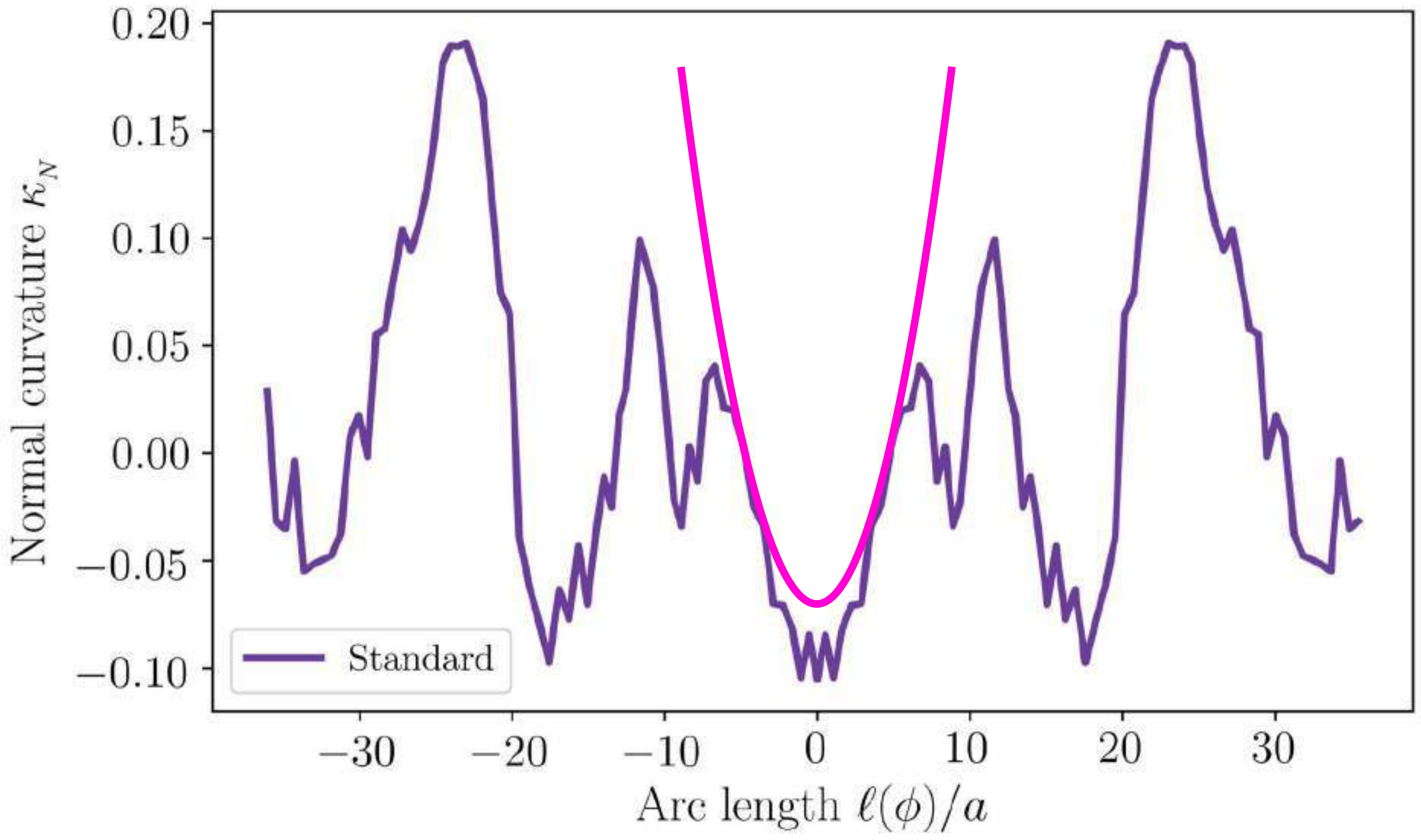


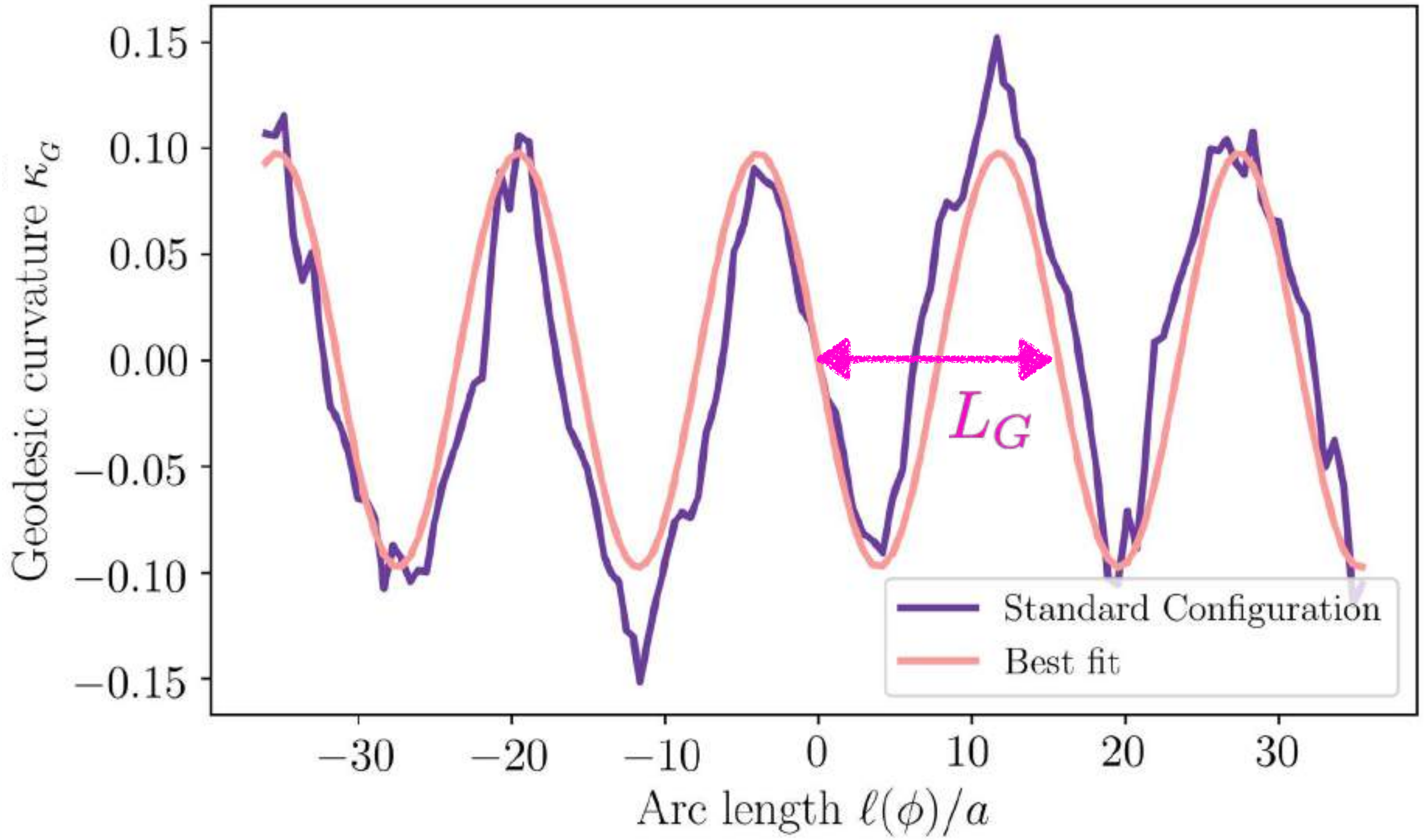
Primary modes are localized in “bad” curvature regions

- Negative regions: instability growth.
- High particle drifts
- Exact eigenfunctions peak at the center.
- Gaussian envelope: *Drift well.*

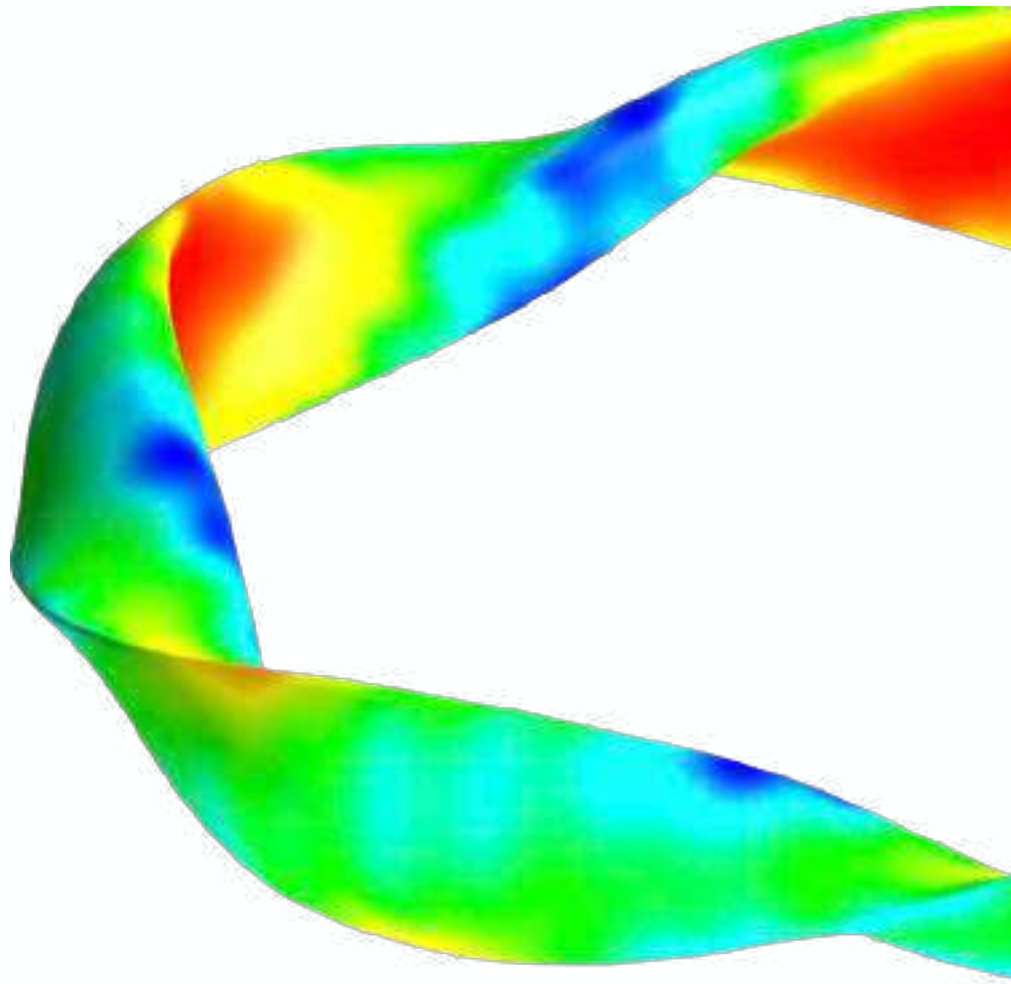


Mode coupling through curvature is characterized by periodicity

- κ_G couples $k_y = 0$ mode to acoustic wave.
- Geodesic scale: $k_{||}$ of the mode.
- Characteristic geodesic scale L_G.



$$\kappa_{G,fit} = |\kappa_G| \sin(2\pi \, \ell / L_G)$$



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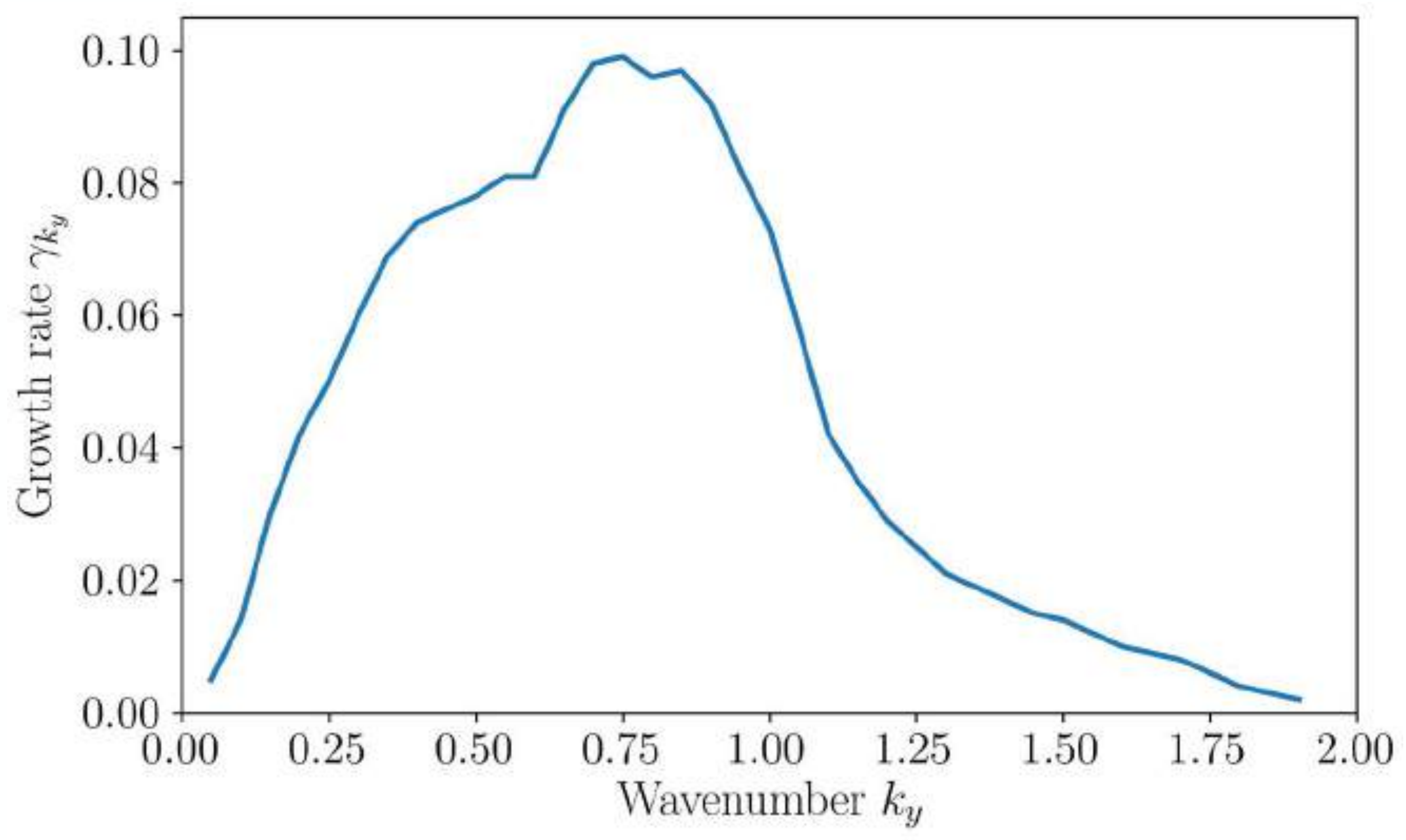
Reduced transport modeling

Summary

Linear estimates of transport ignore saturation

- ITG-driven turbulence.
- Simple quasilinear model:

$$\chi_{QL} = C_1 \sum_{k_y} \frac{\gamma_{k_y}}{k_y^2} \times \Delta k_y$$



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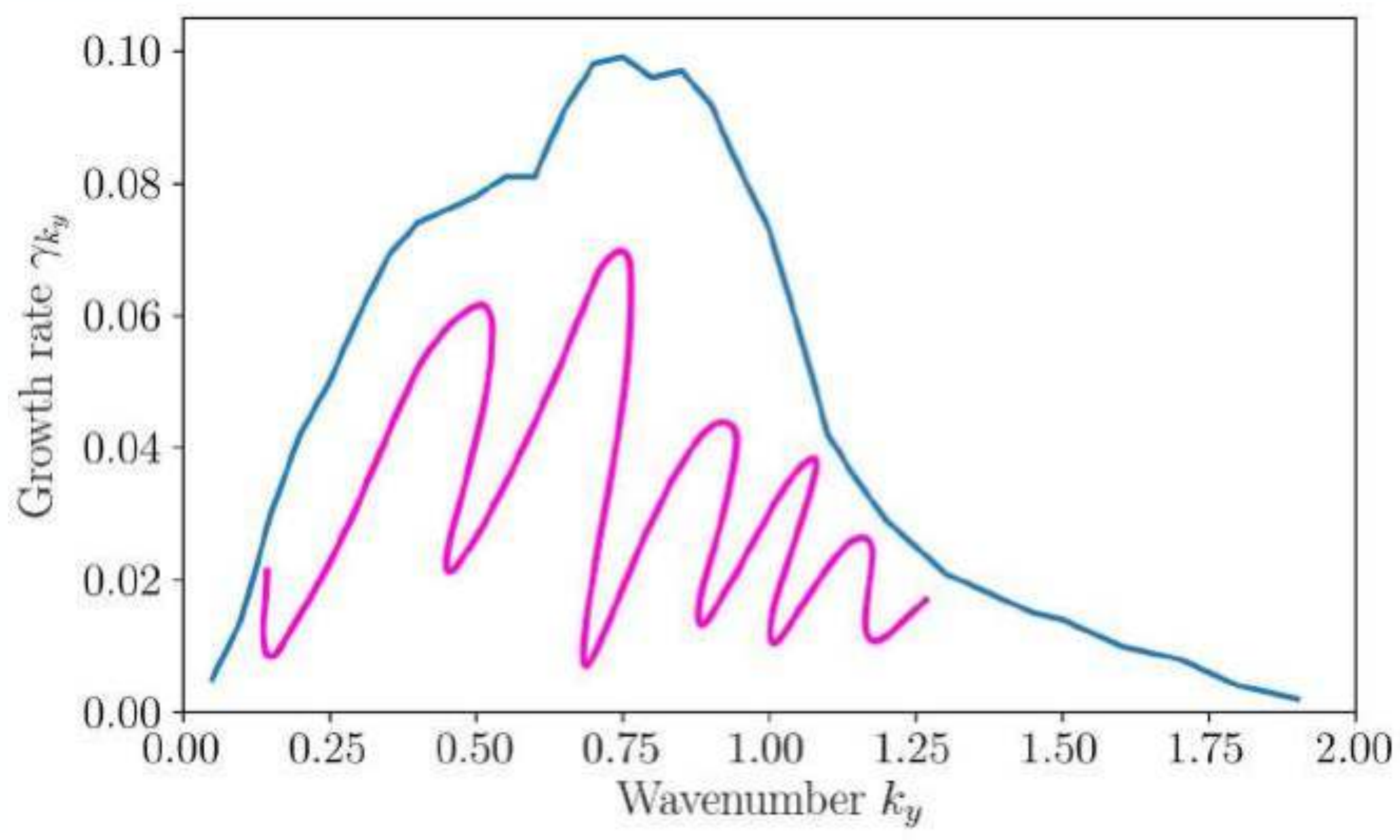
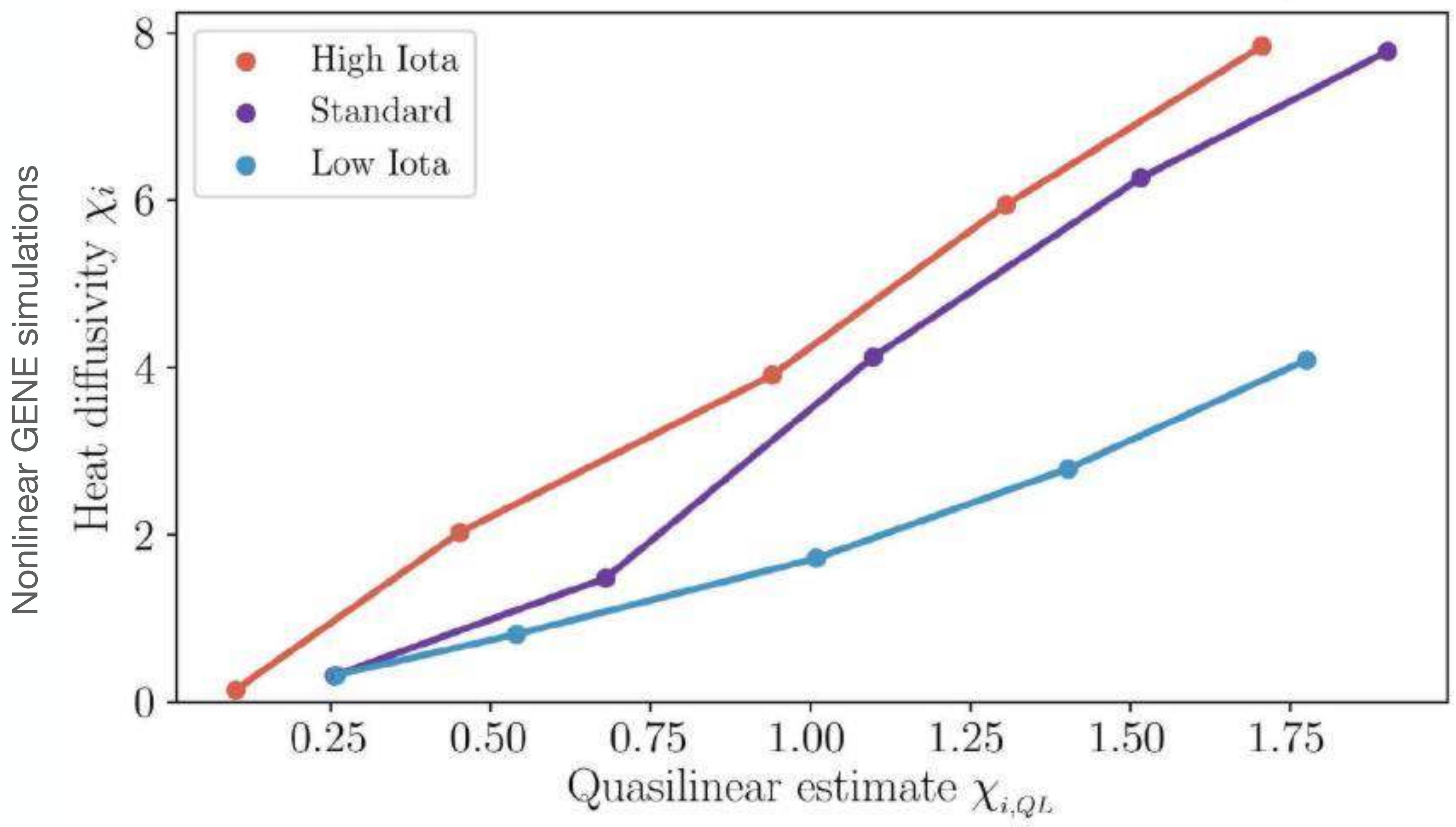


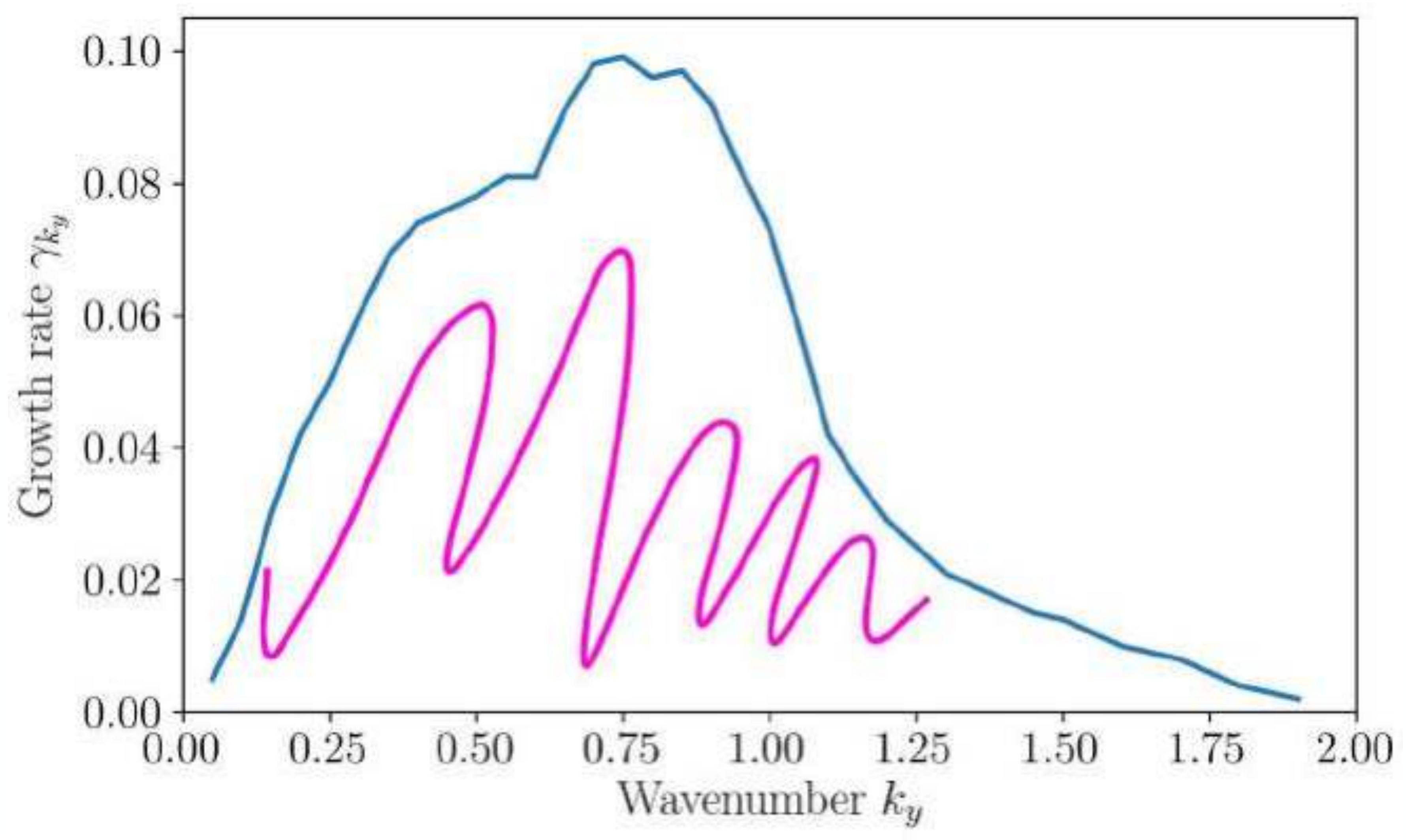


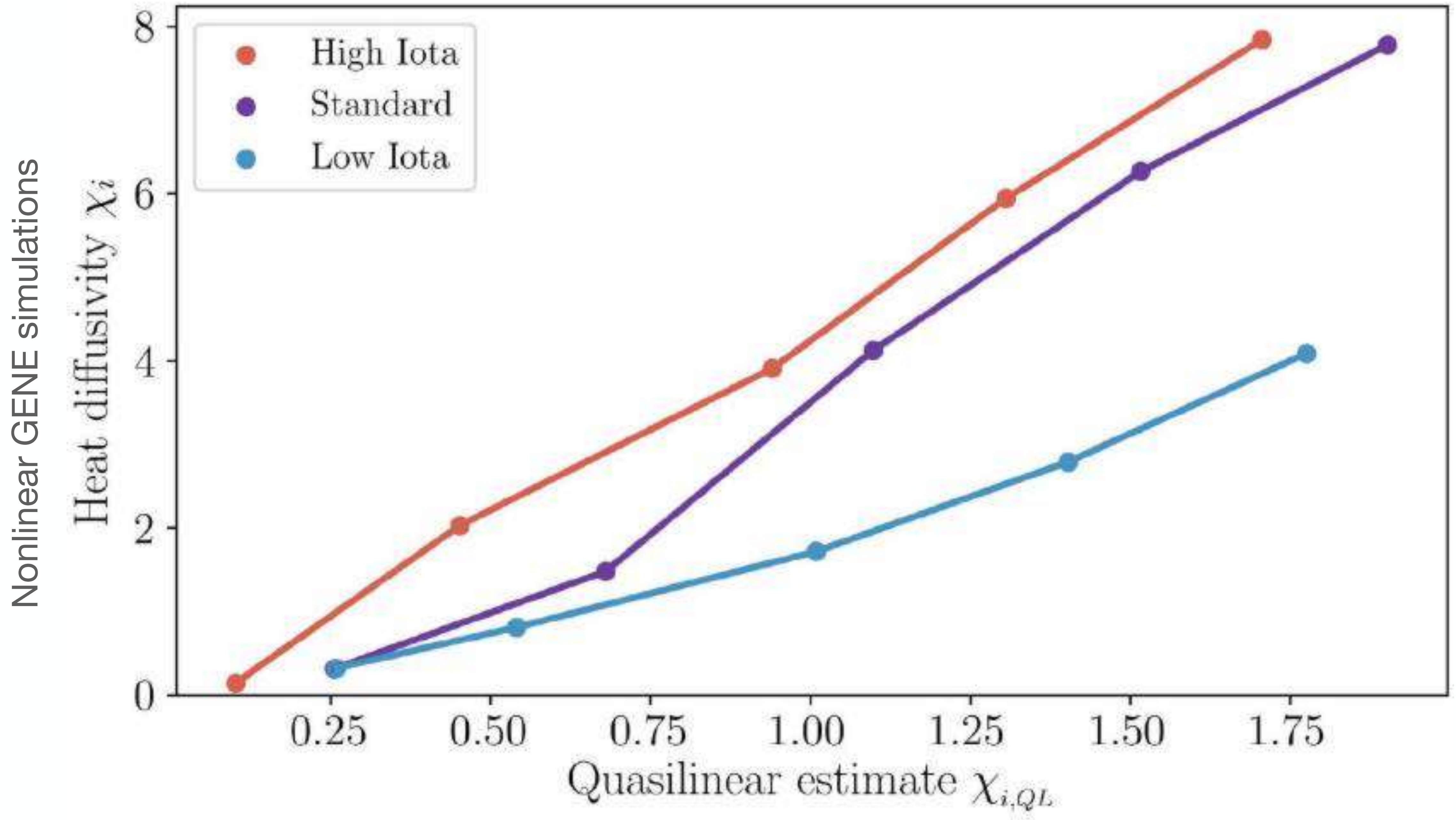
Linear estimates of transport ignore saturation

- ITG-driven turbulence.
- Simple quasilinear model:

$$\chi_{QL} = C_1 \sum_{k_y} \frac{\gamma_{k_y}}{k_y^2} \times \Delta k_y$$

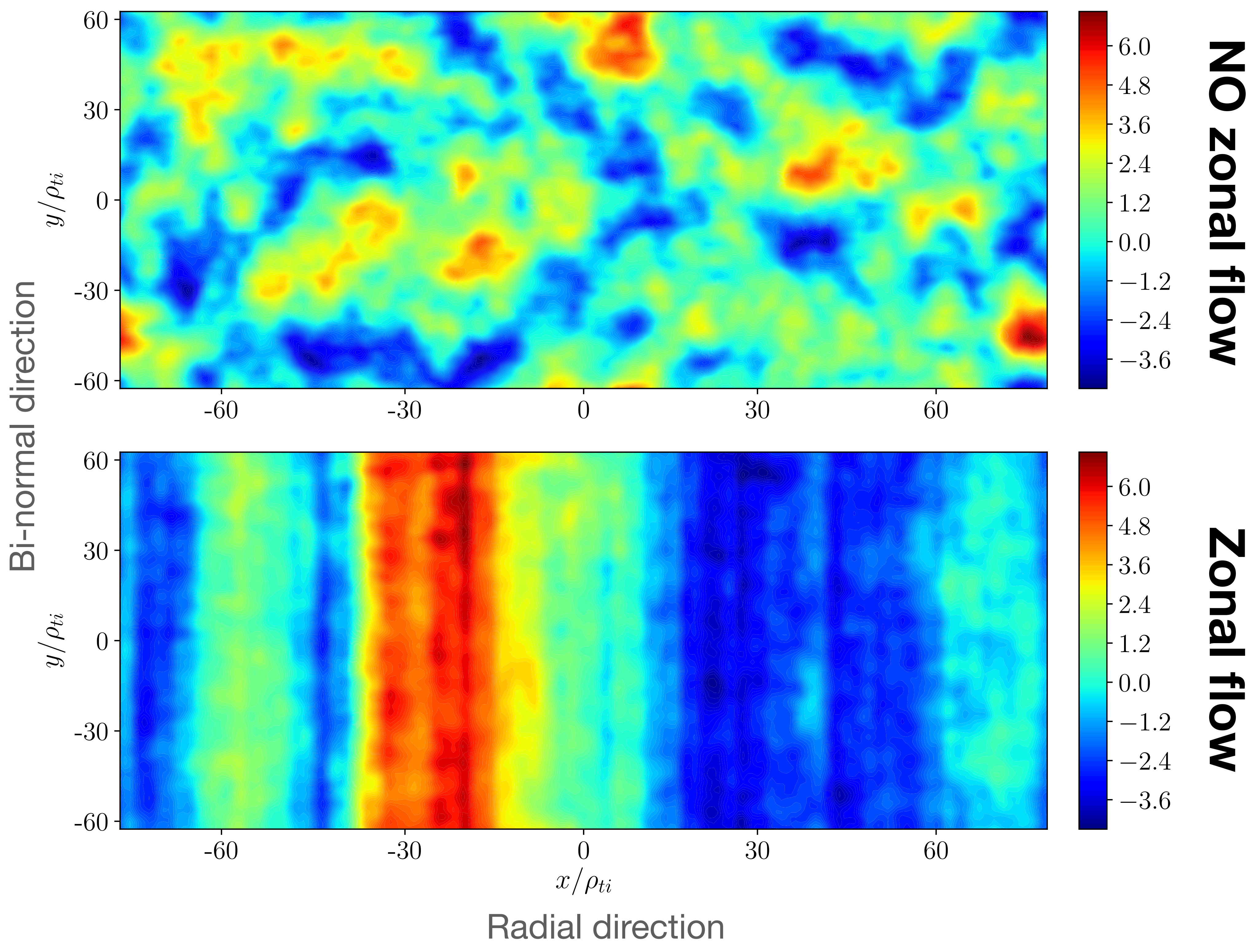
- Pre-factor C_1 clearly depends on geometry.
- Saturation dynamics to be understood.





ITG-driven turbulence induces Zonal Flows

- Primary instability: initial eddies.
- Secondary instability:
  - Poloidal elongated structures.
  - Saturation through shearing.



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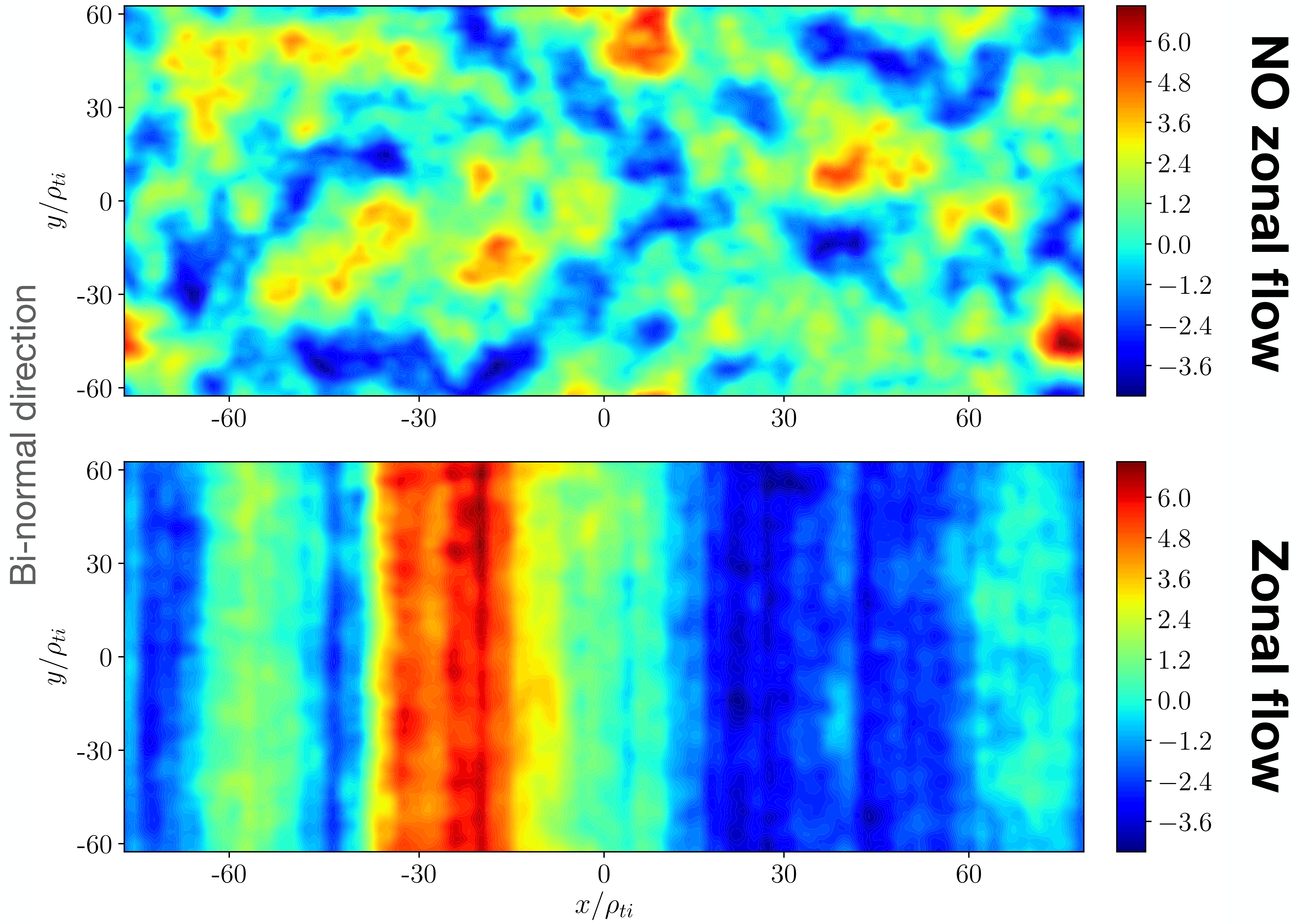
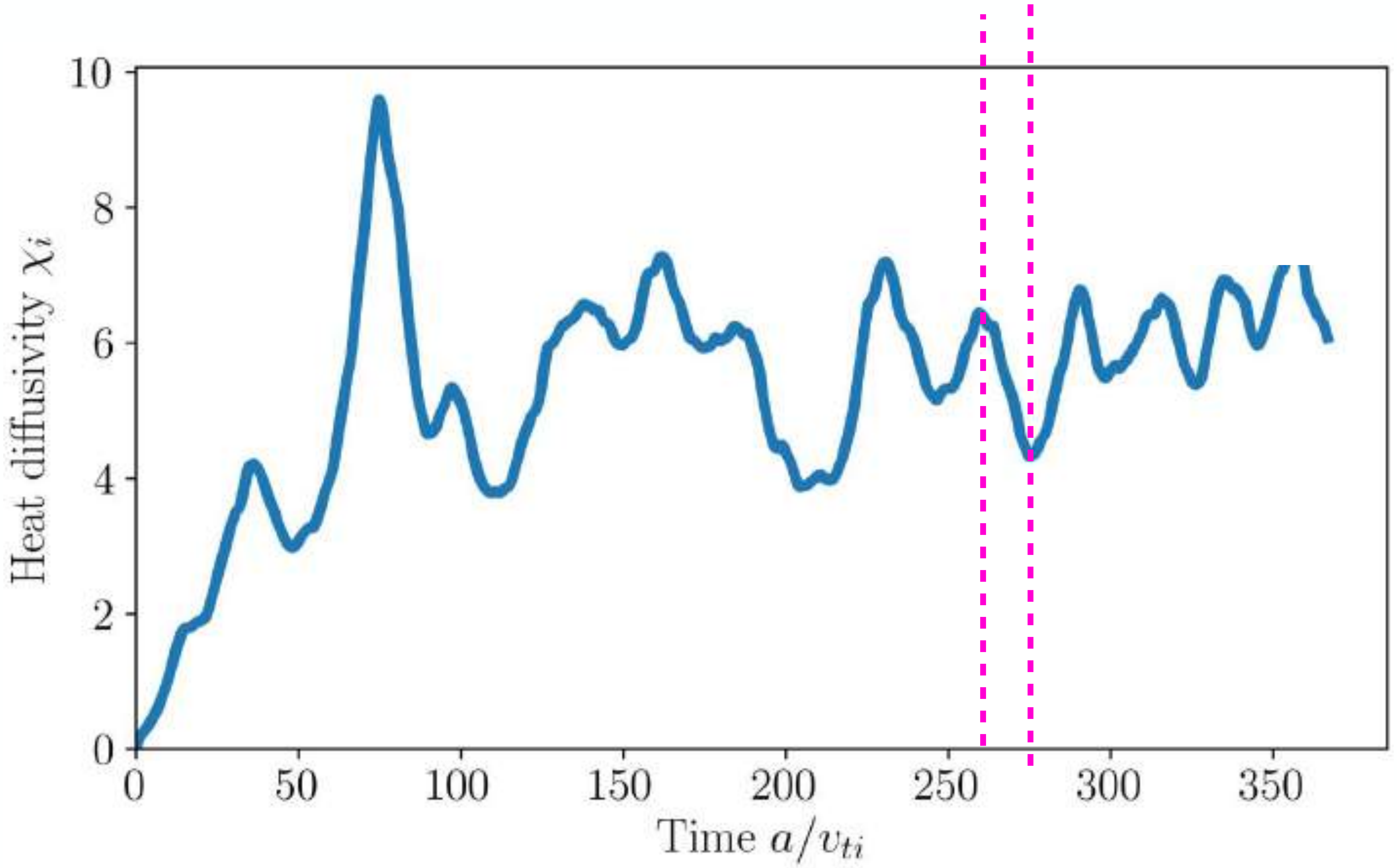


- Curiosity:

Image credit: NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gill

Saturation time scales dictate dynamics of the linear zonal flow response

- Turbulence saturation time.



Saturation time scales dictate dynamics of the linear zonal flow response

- Turbulence saturation time.
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- Characteristics of interest:
  - Residual potential.
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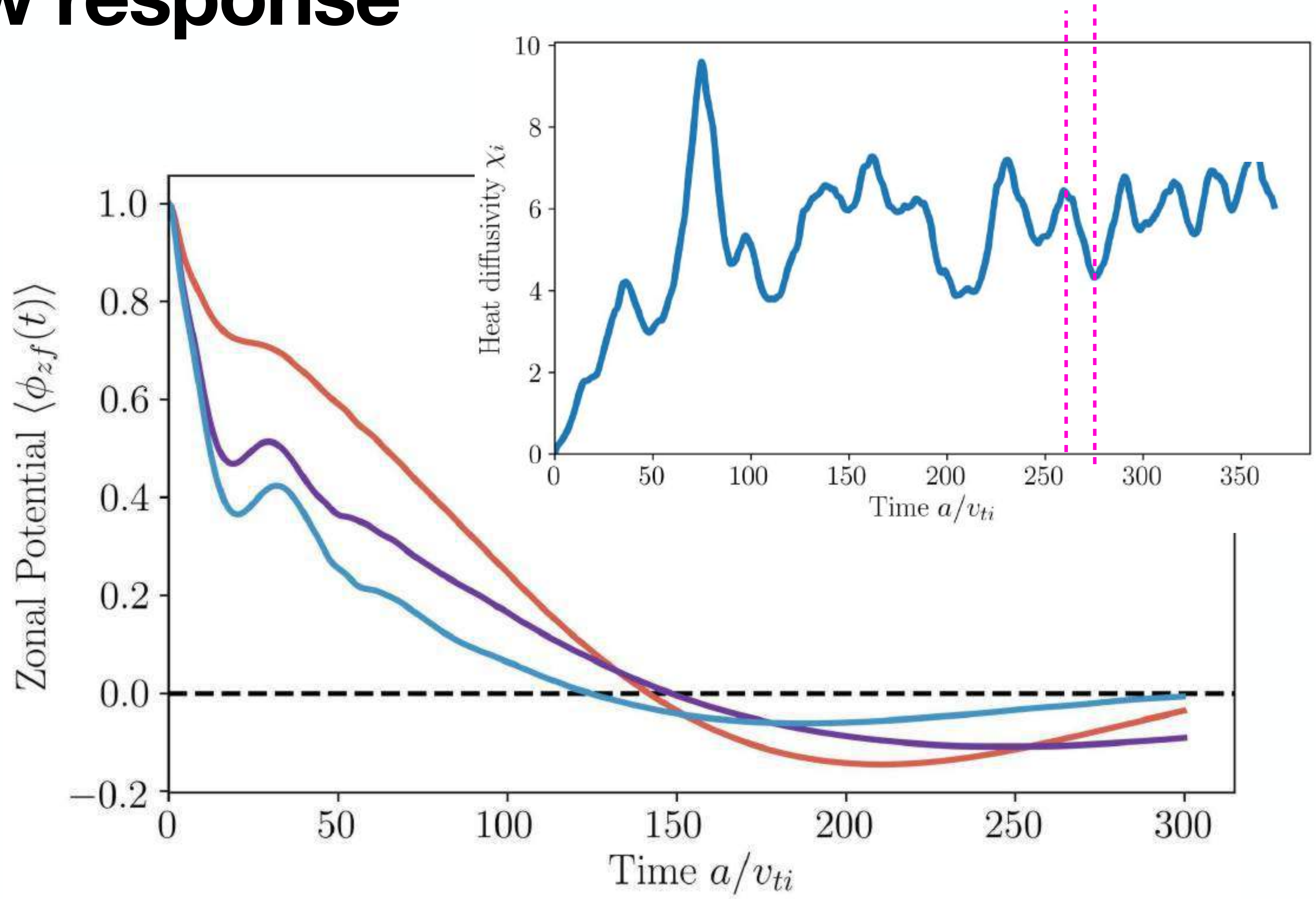

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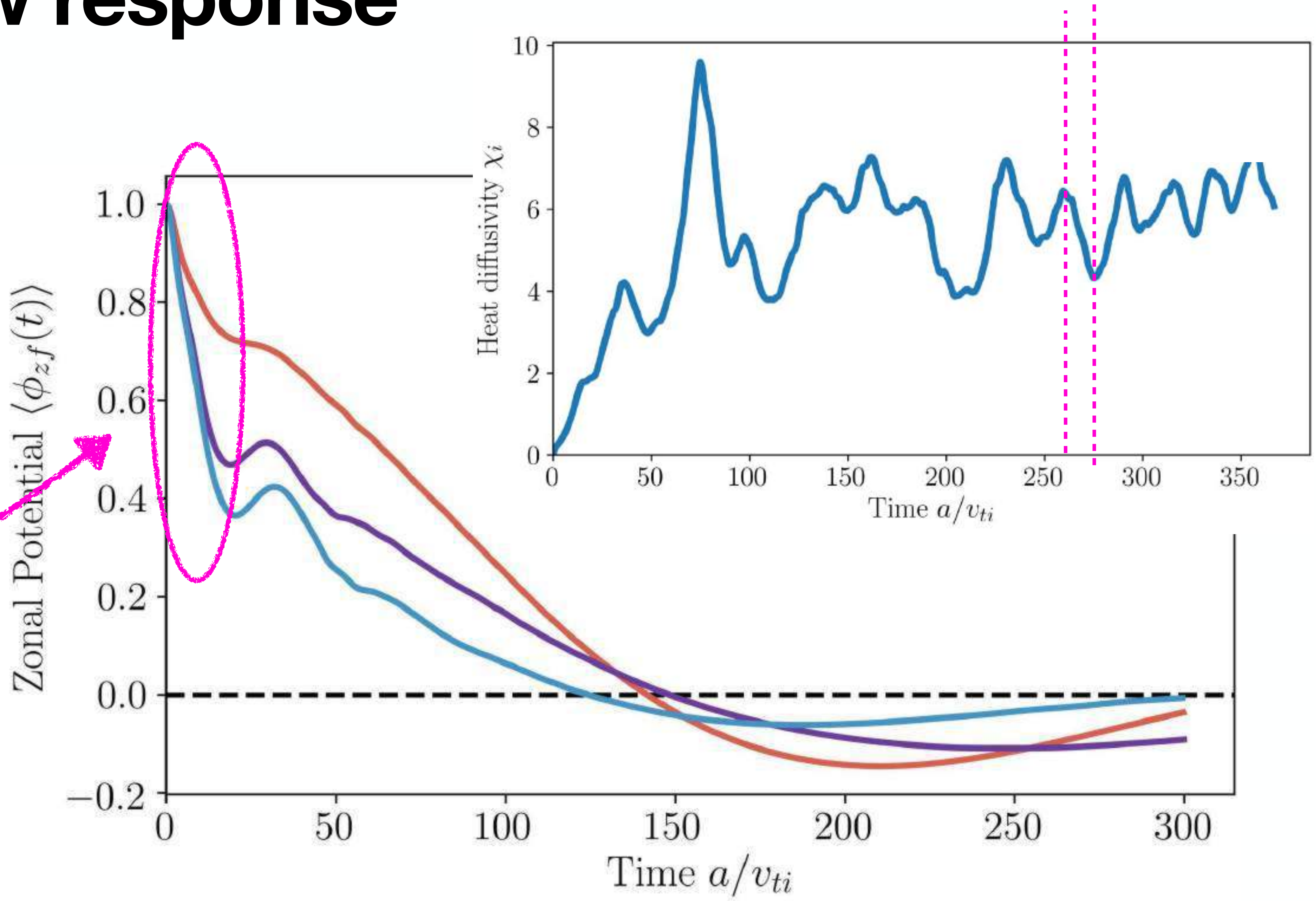

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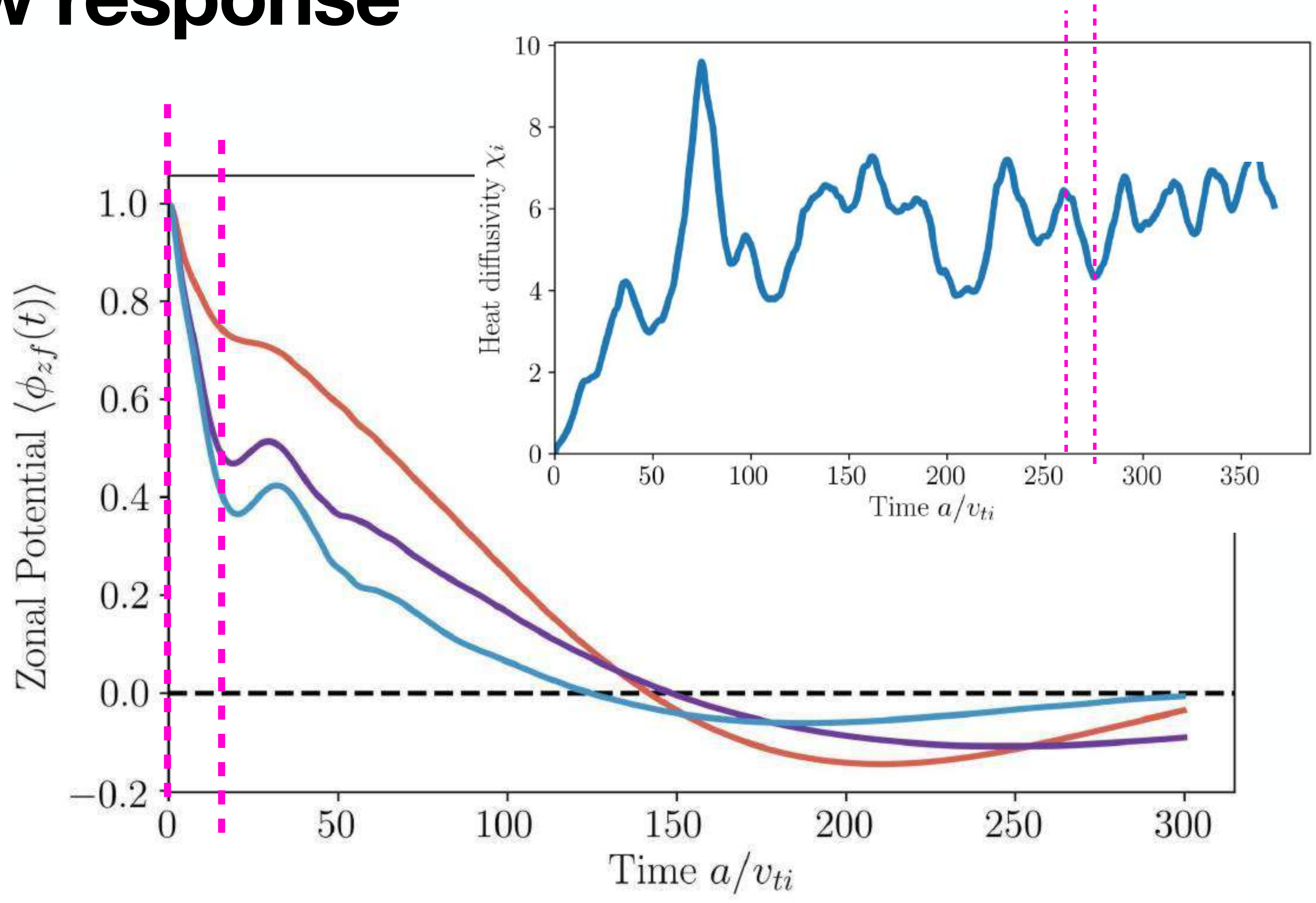

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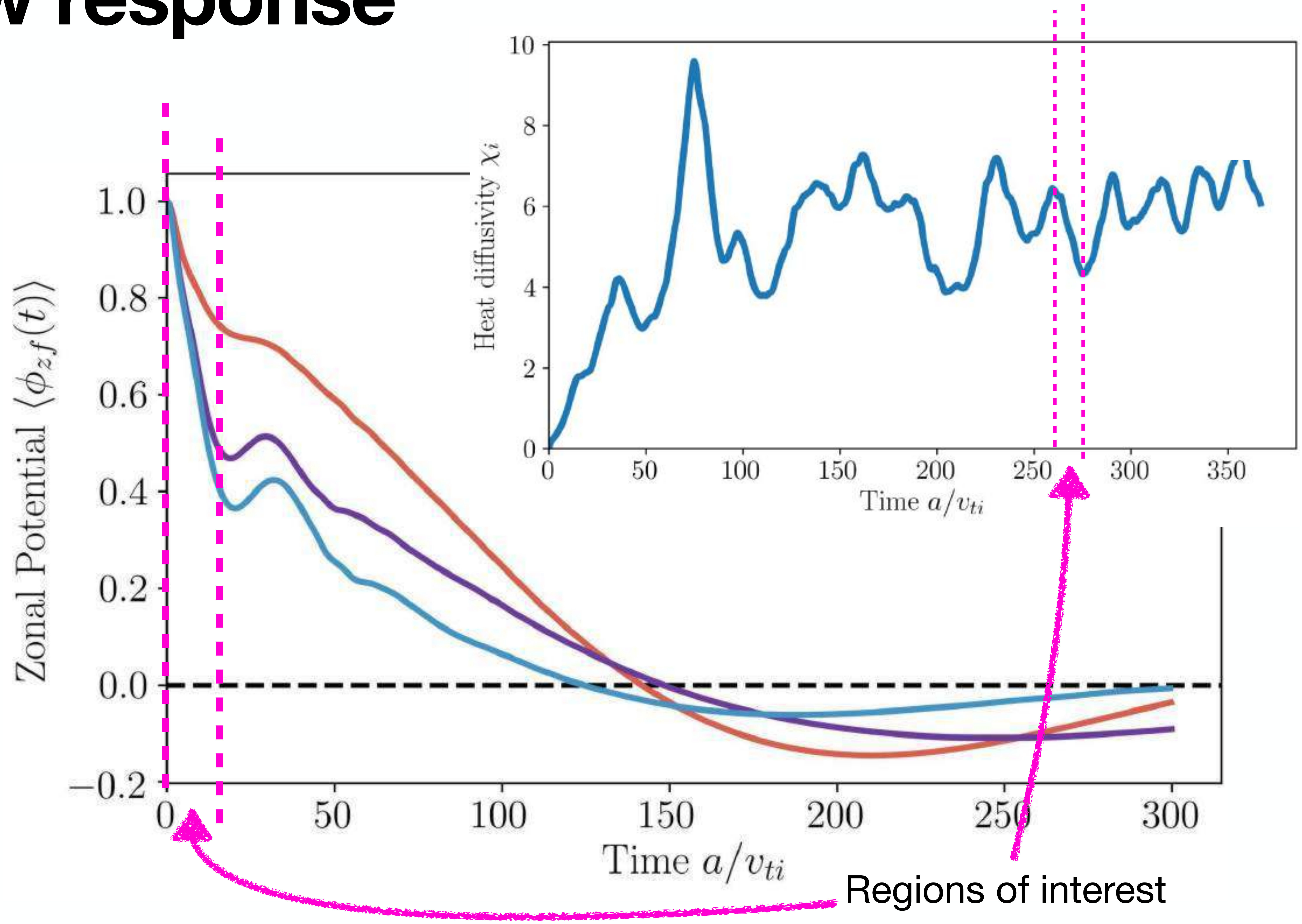
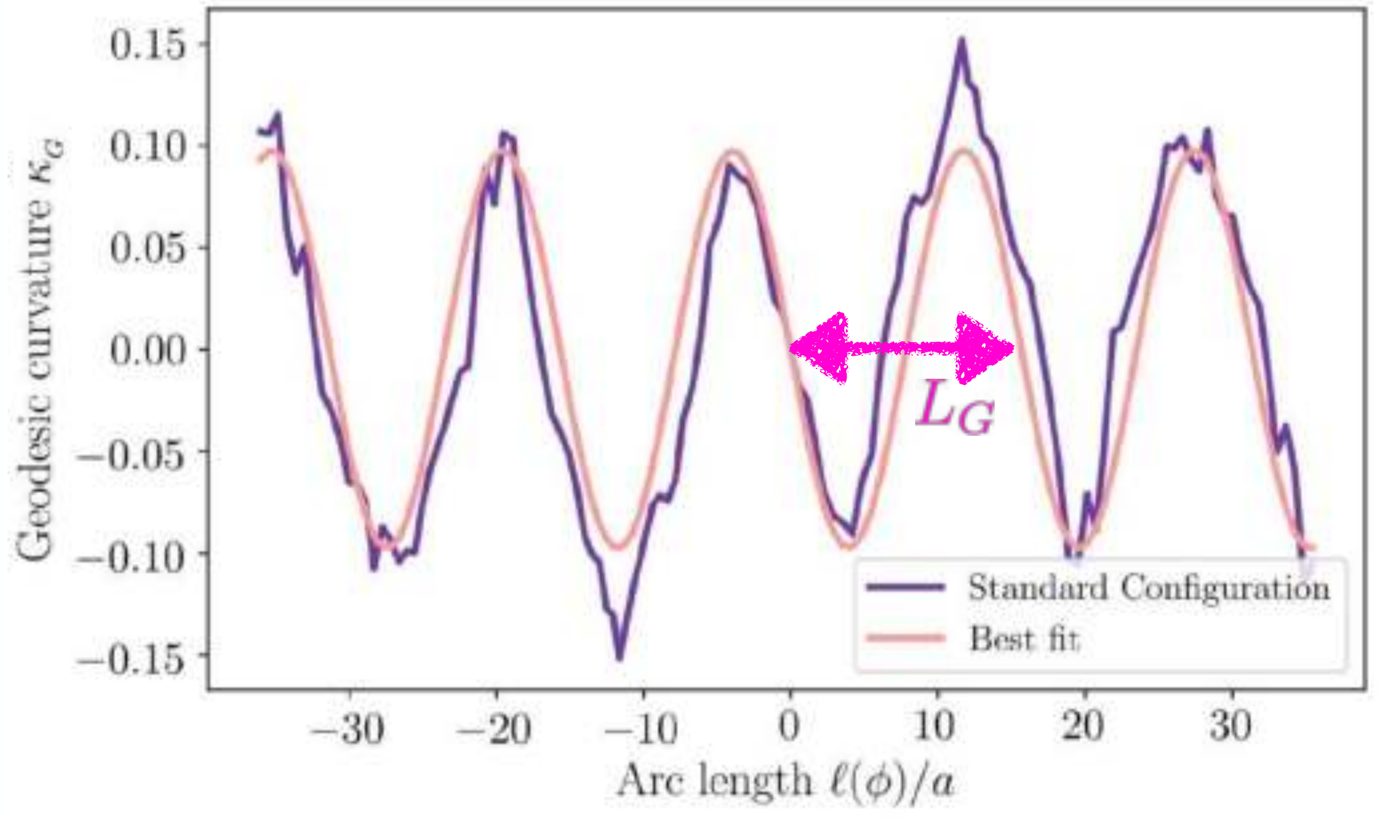
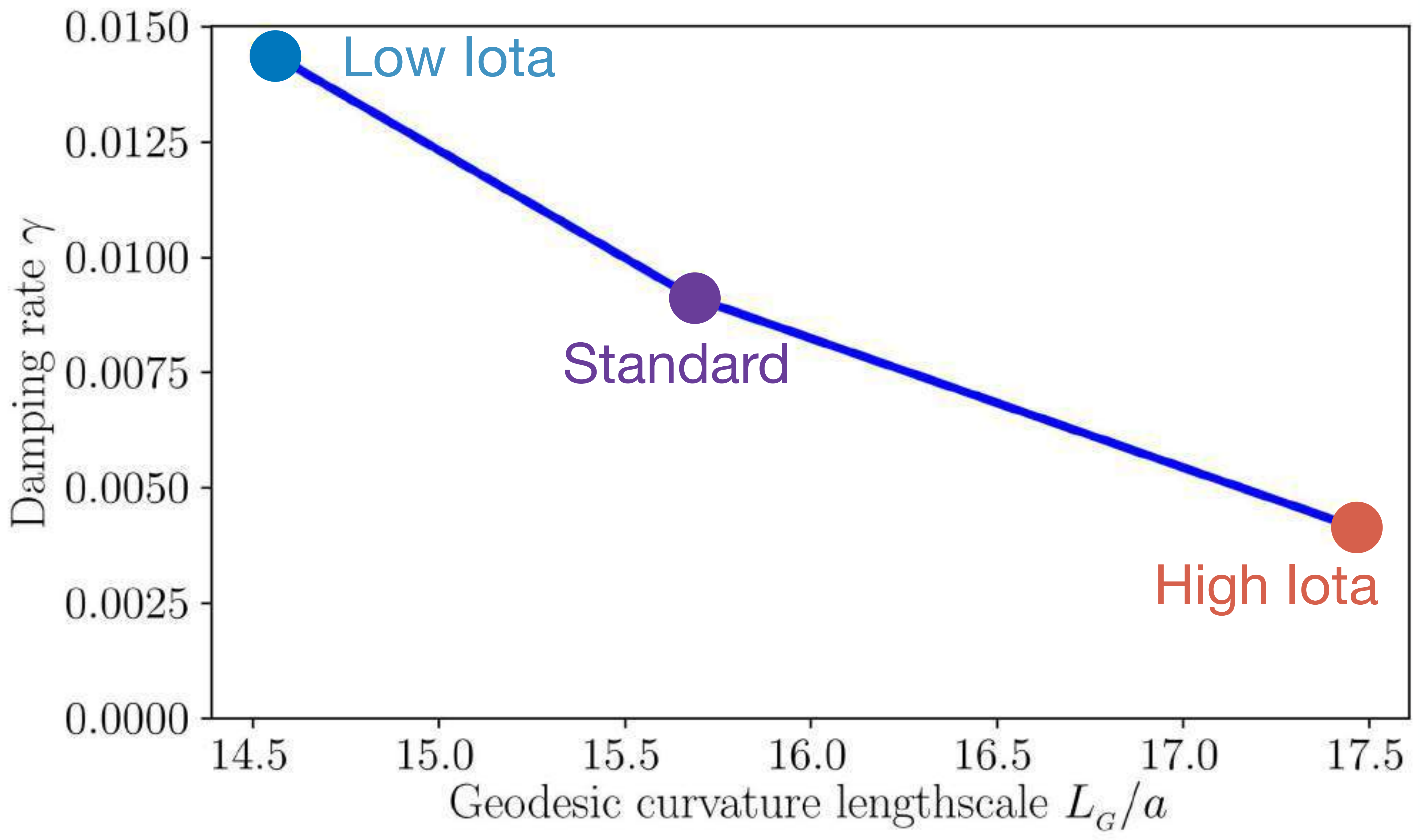


Damping is determined by geodesic curvature

- Weaker damping –> Longer-lived Zonal Flows.

- **Low Iota configuration might see lower zonal flow activity.**





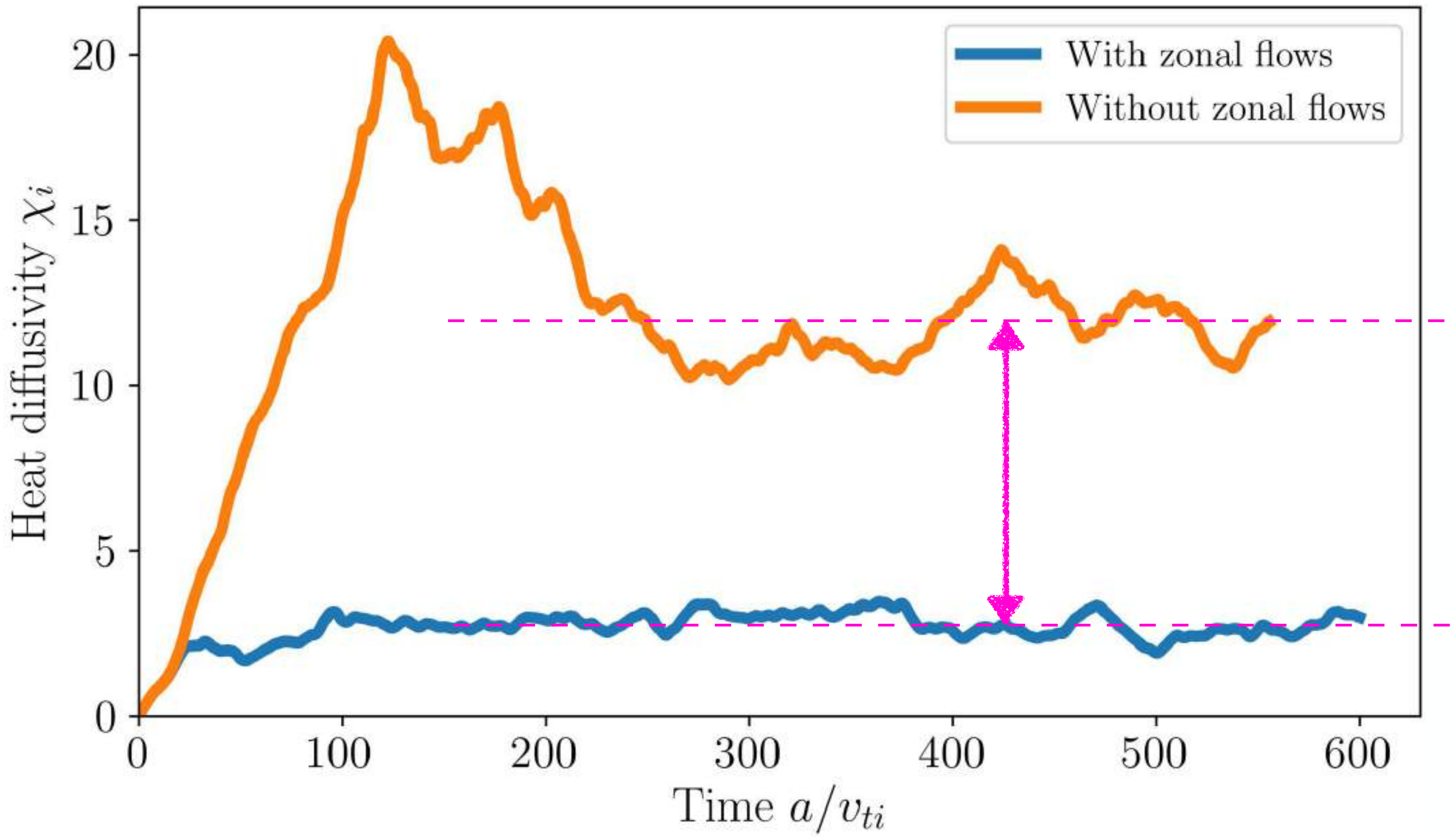
How do zonal flows impact saturation?

A numerical experiment

- Zero zonal flow contrib. at each time step.
- Transport delta:

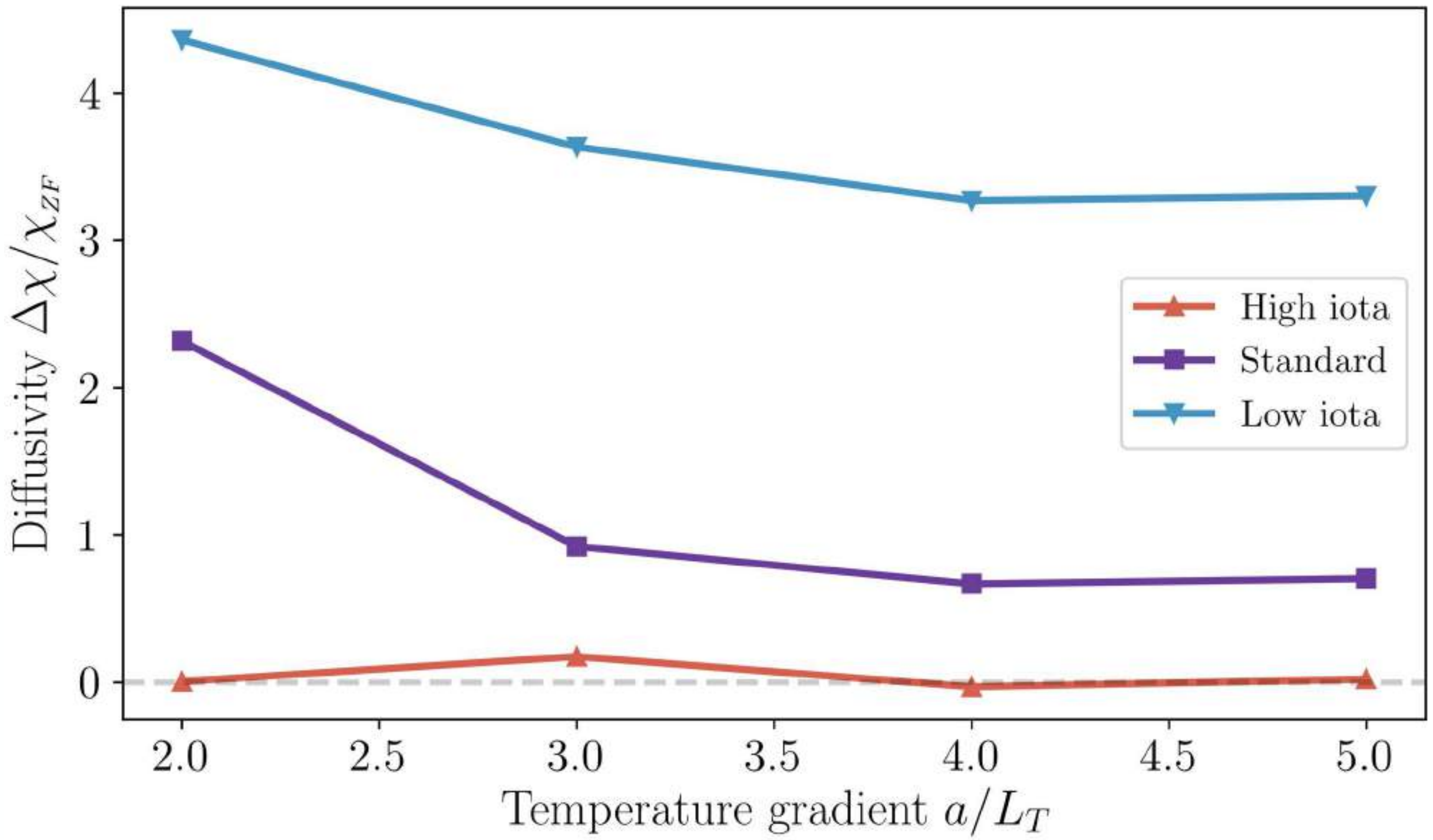
$$\frac{\Delta\chi}{\chi_{ZF}} = \frac{\chi_{no-ZF} - \chi_{ZF}}{\chi_{ZF}}$$

- Configuration impact?



How do zonal flows impact saturation?

- Zero zonal flow contrib. at each time step.
- Low Iota depends on zonal flows to reach saturation.



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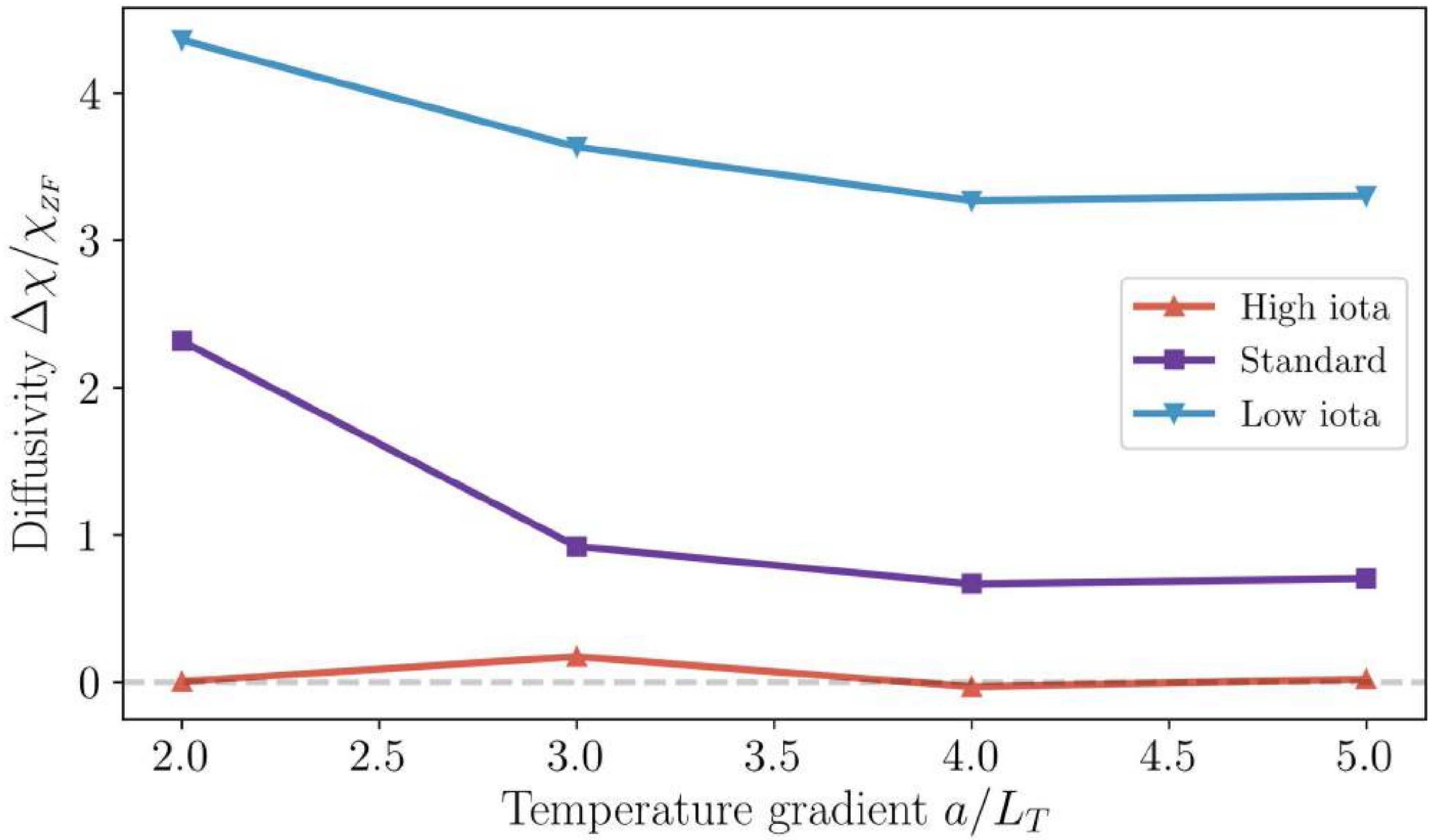
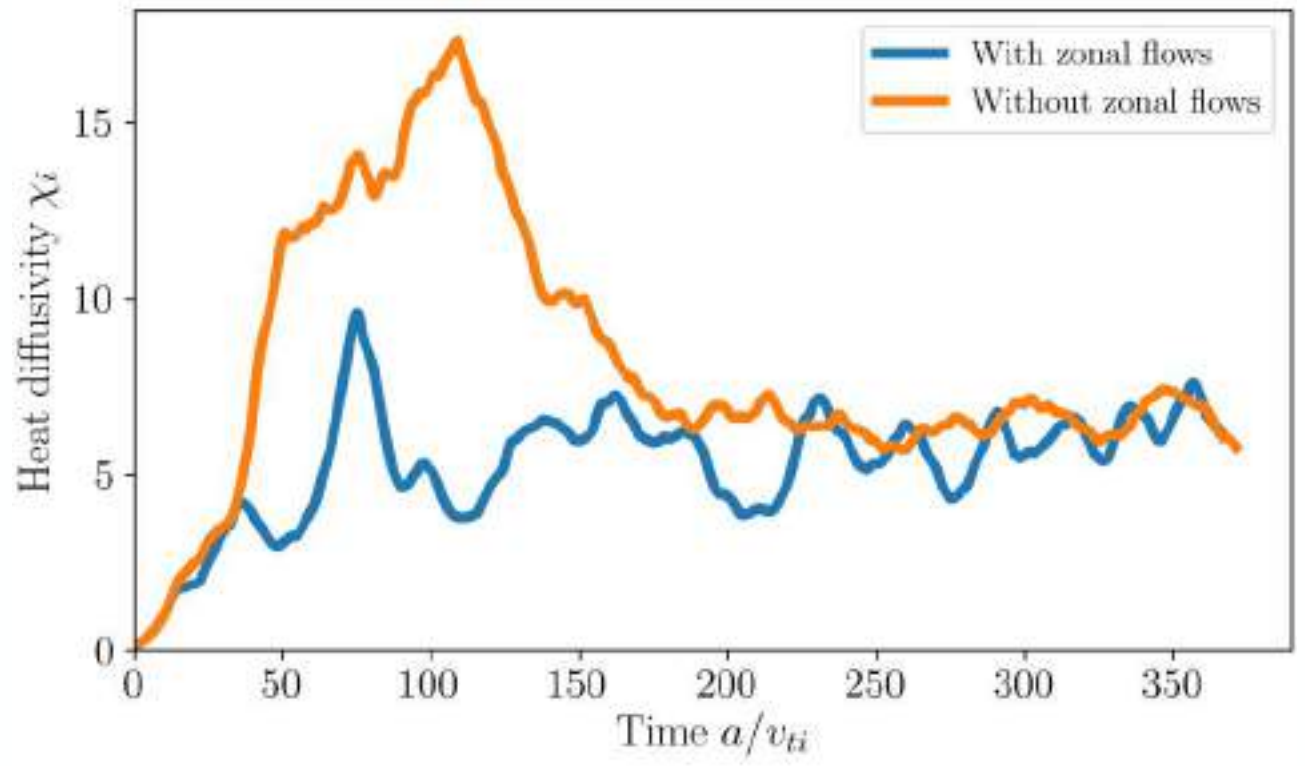
- Zonal Flows make no difference for High Iota.





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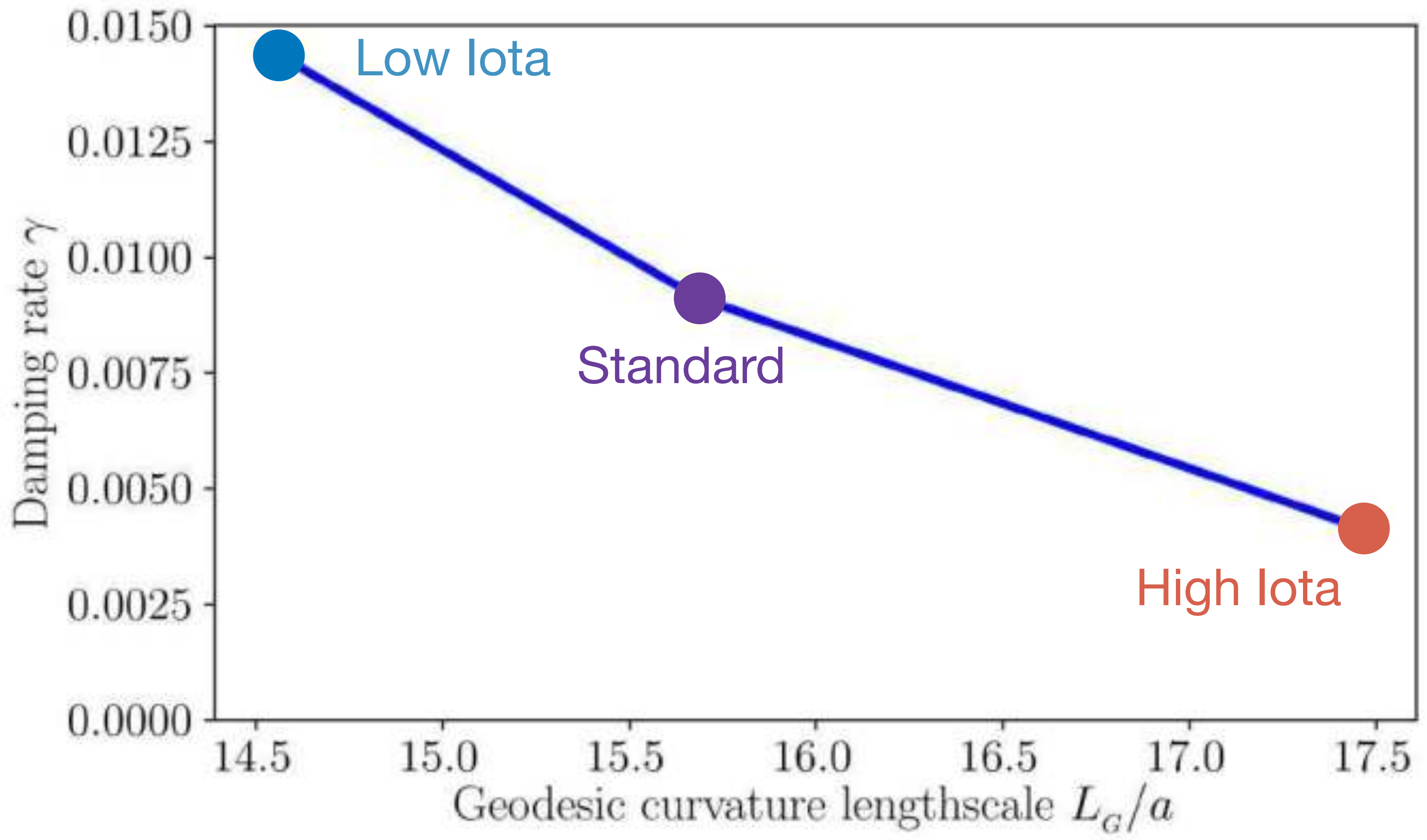

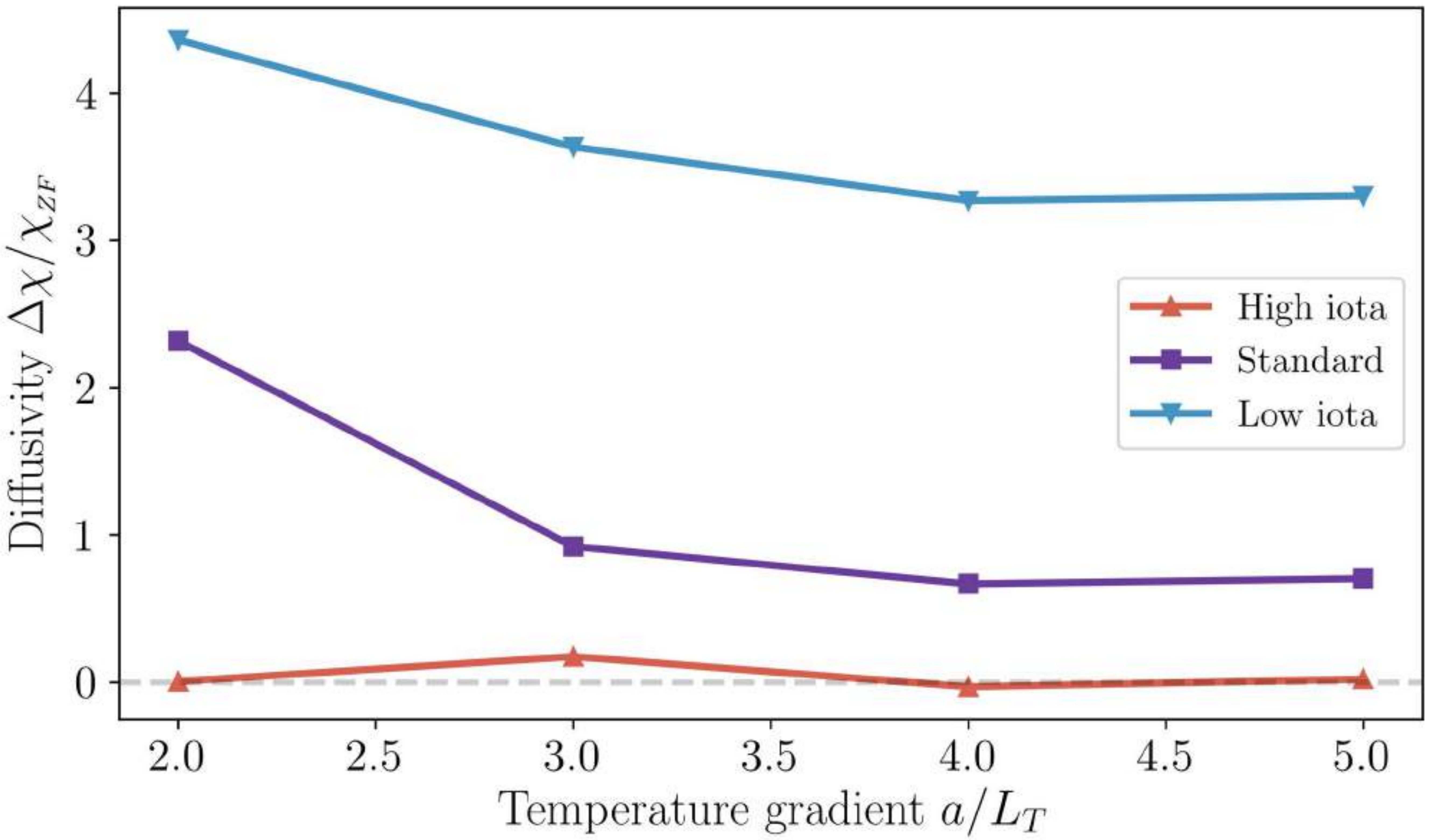

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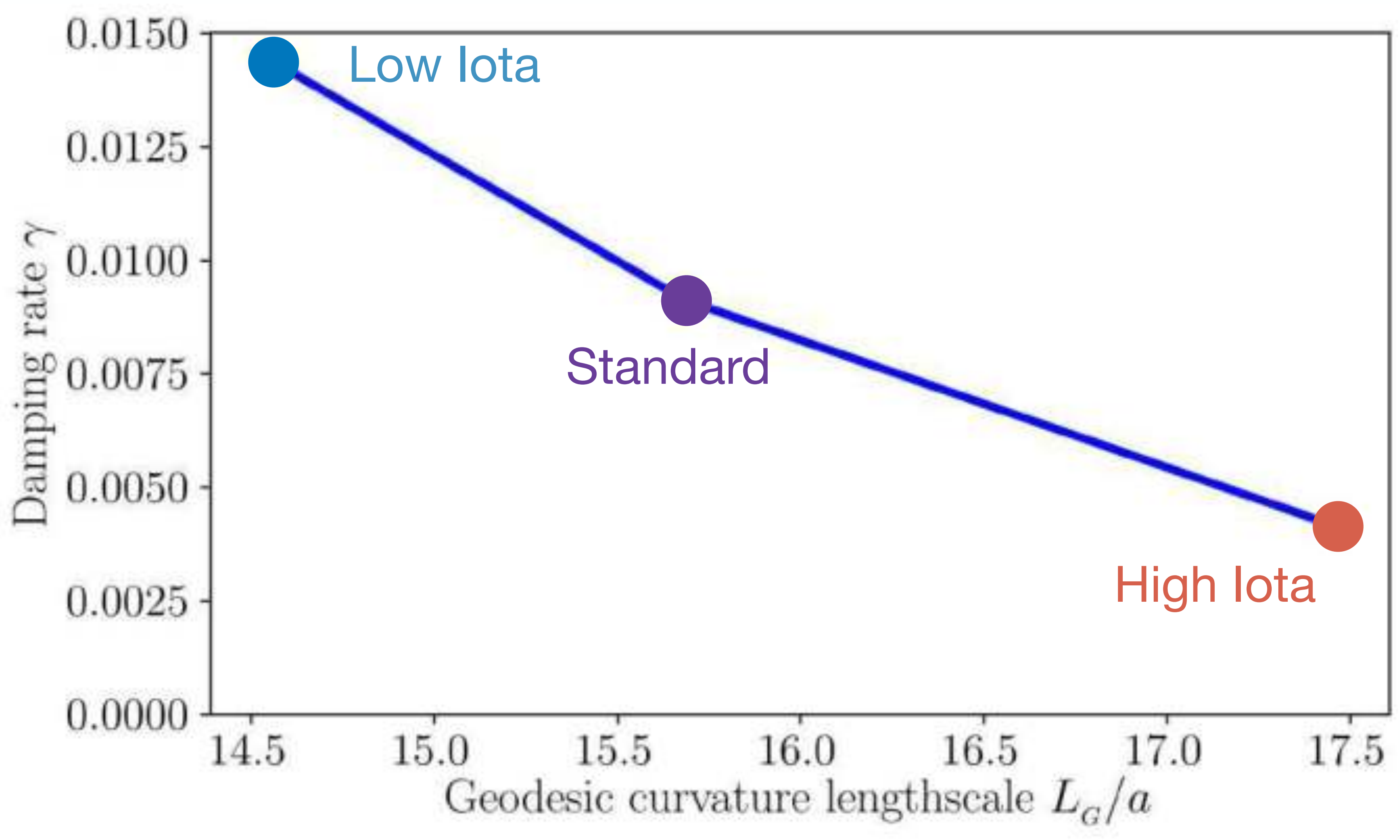
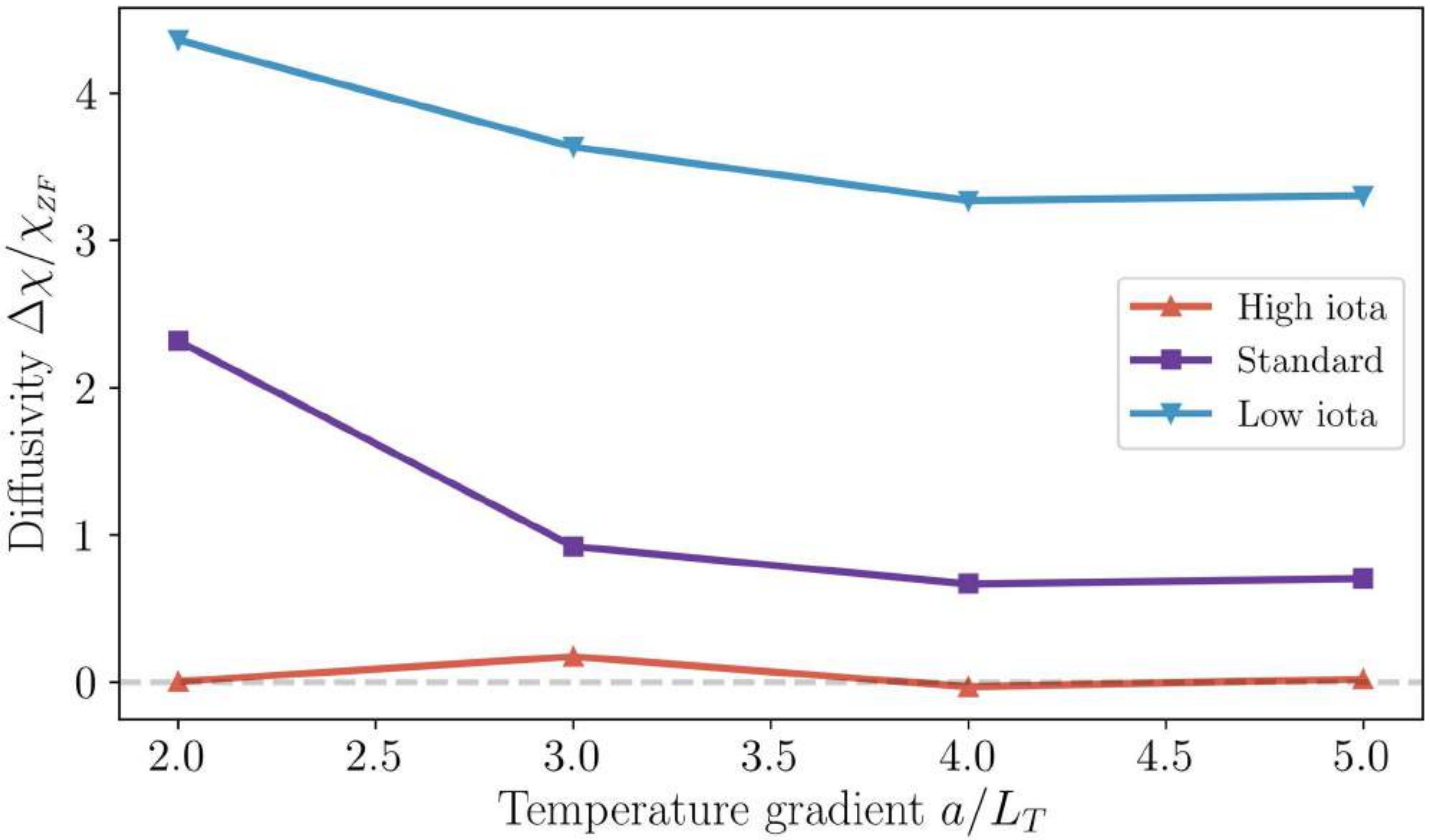
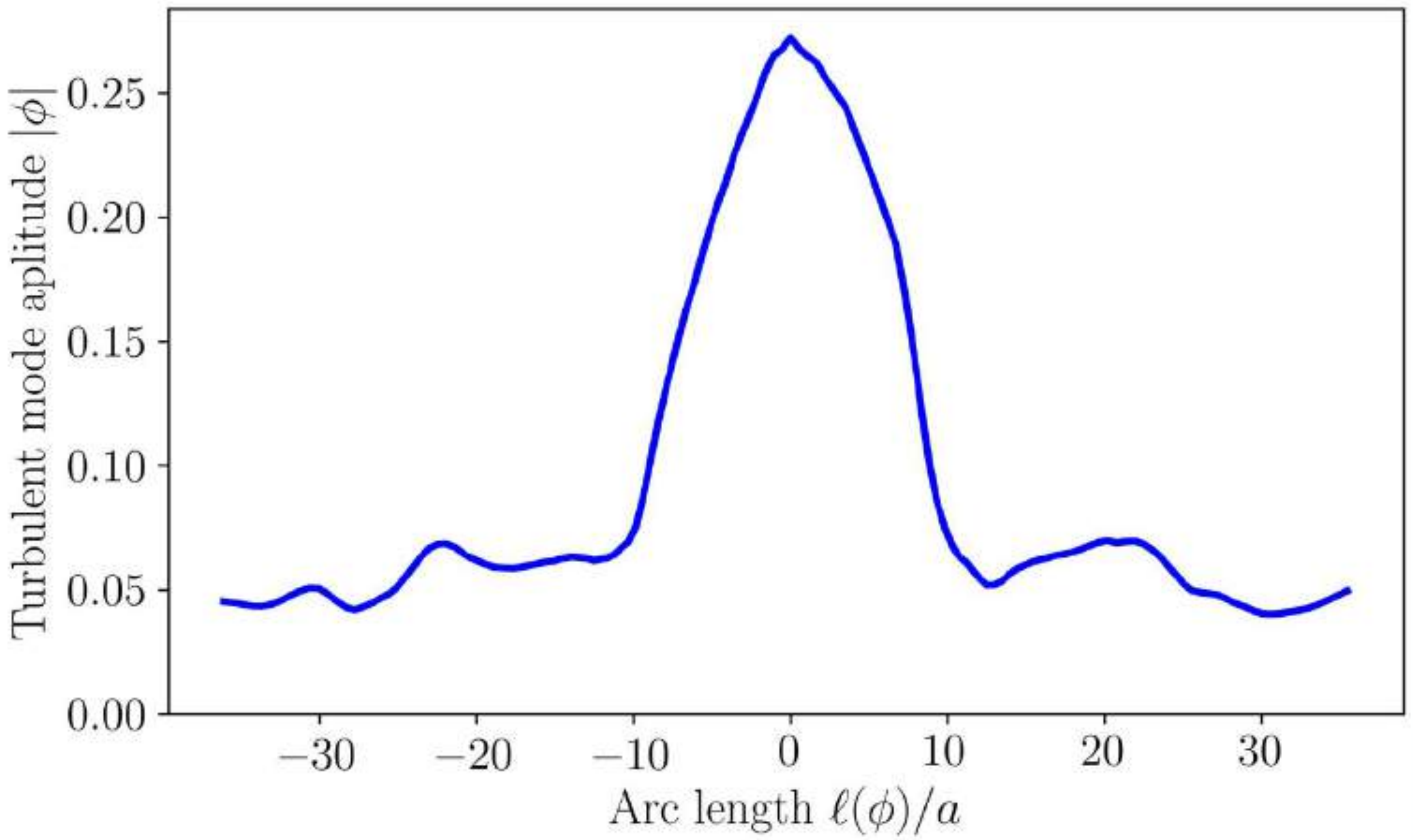




What about zonal flow generation?

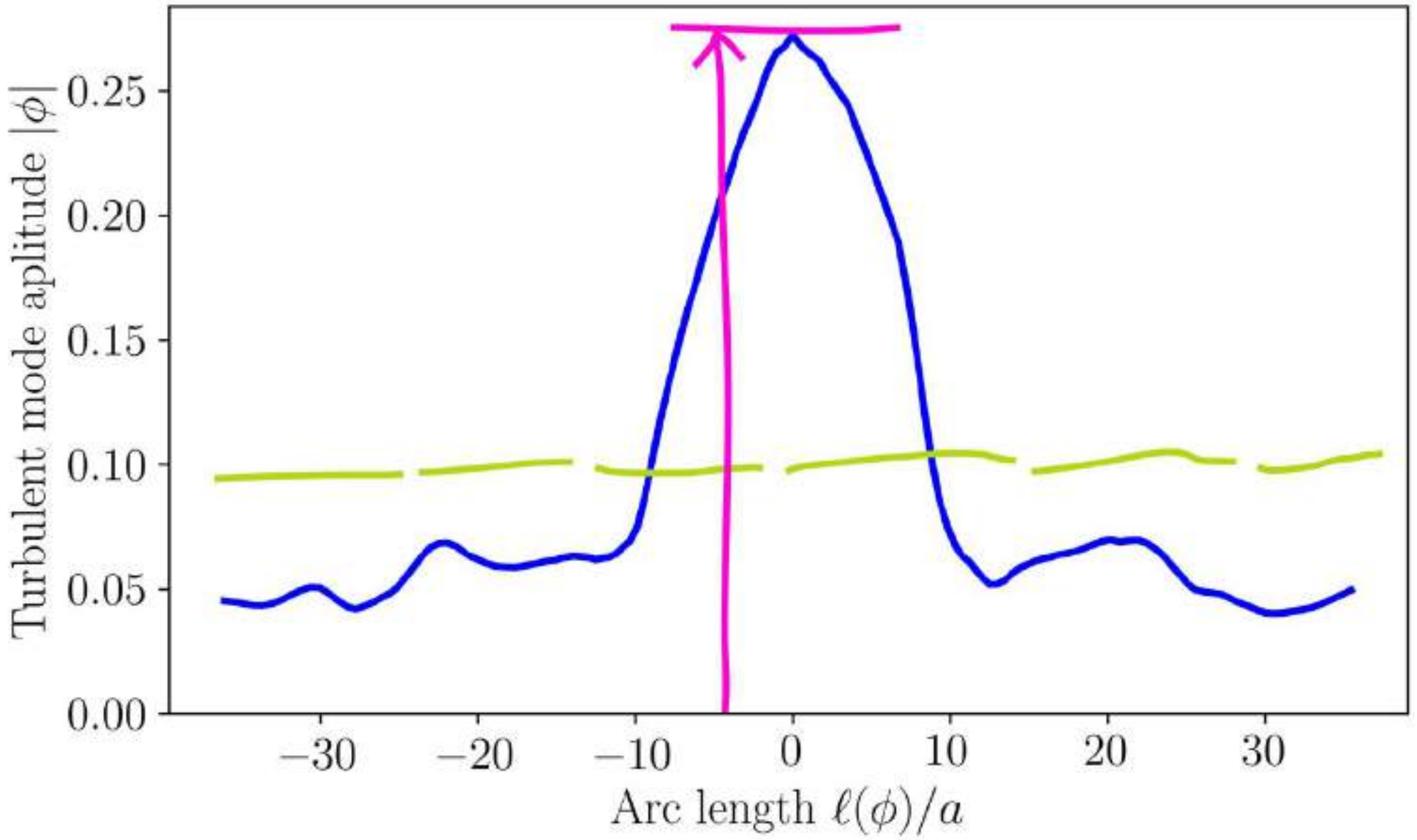
The mode distribution influences zonal flow generation

- Secondary modes depend on primary.
- Strongest mode.



The mode distribution influences zonal flow generation

- Secondary modes depend on primary.
- Strongest mode.
- Space filling factor:[1]
  - Estimates toroidal distribution.
  - Configuration and gradient -dependent.



$$\sigma = \sqrt{\overline{\left|\hat{\phi}_p\right|^2} / \max\left(\left|\hat{\phi}_p\right|\right)}$$

[1] G.G. Plunk et al, Physical Review Letters, 118(10), 105002 (2017).

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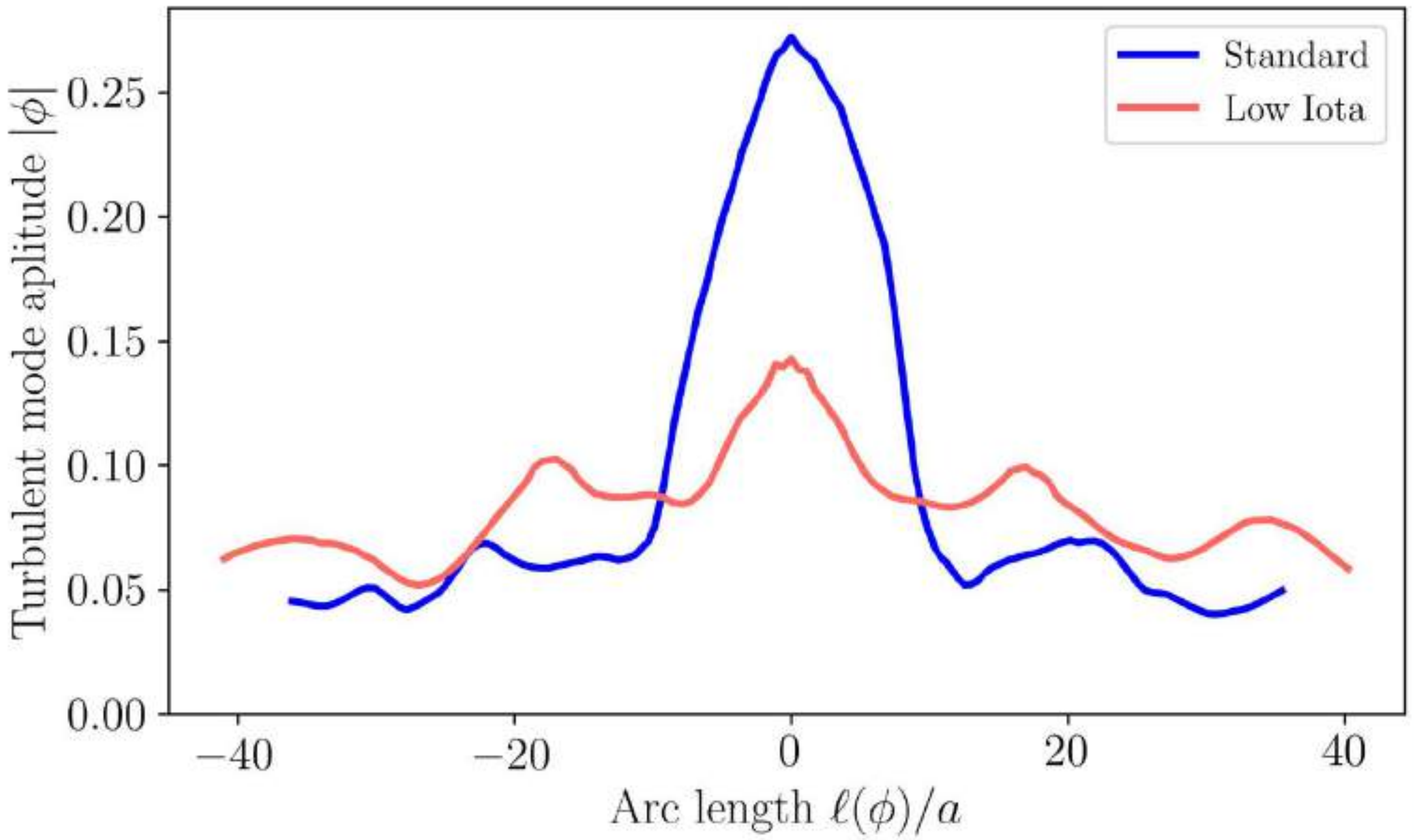

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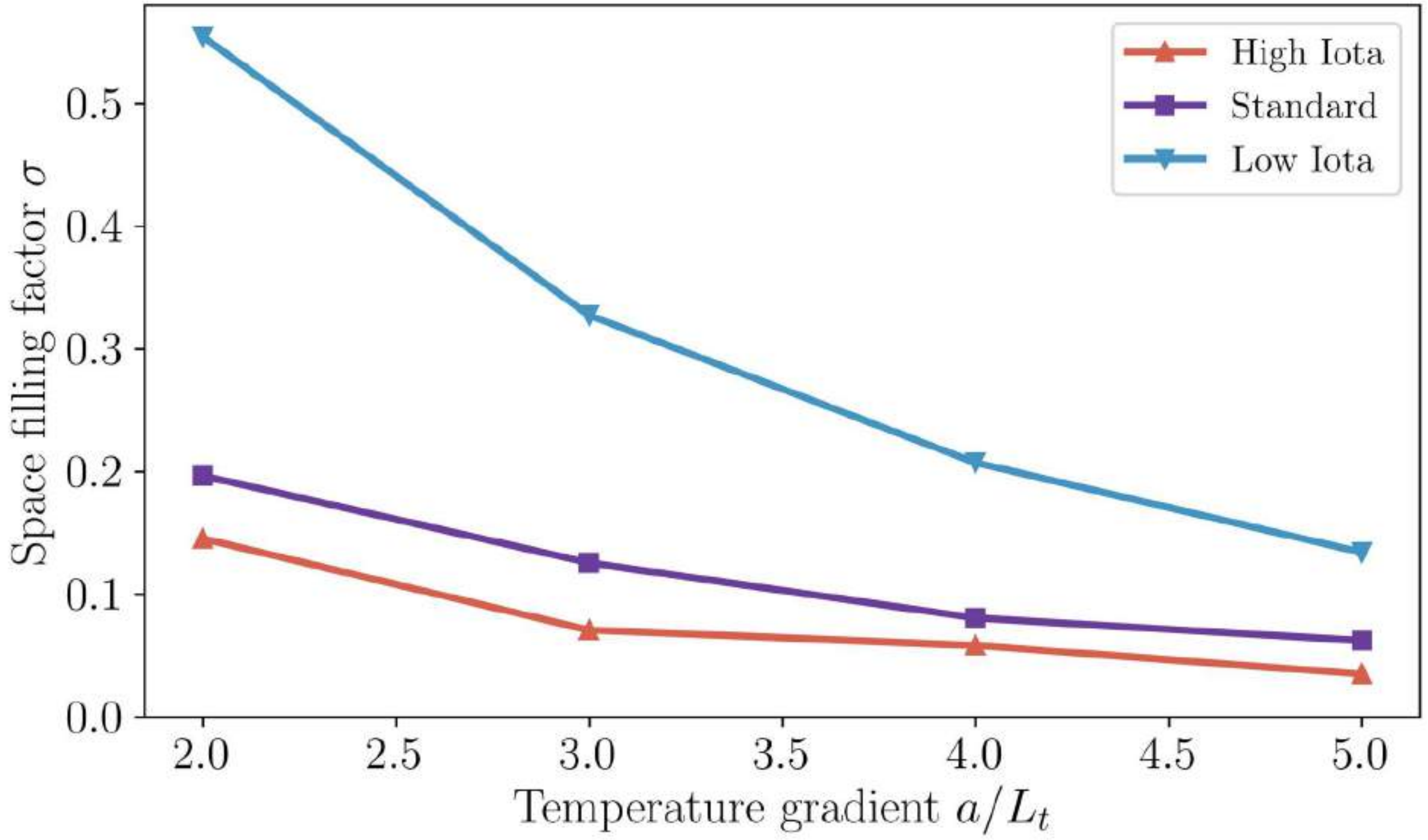
The mode distribution influences zonal flow generation

- Very peaked modes in High iota.
- Mode is spread more evenly in Low Iota.



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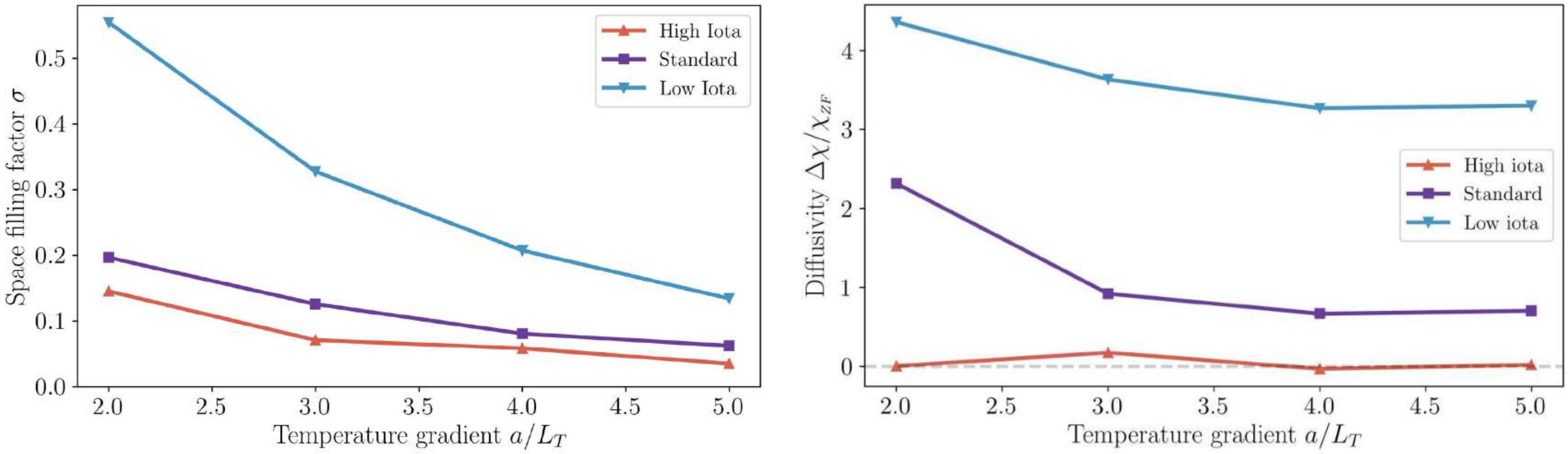
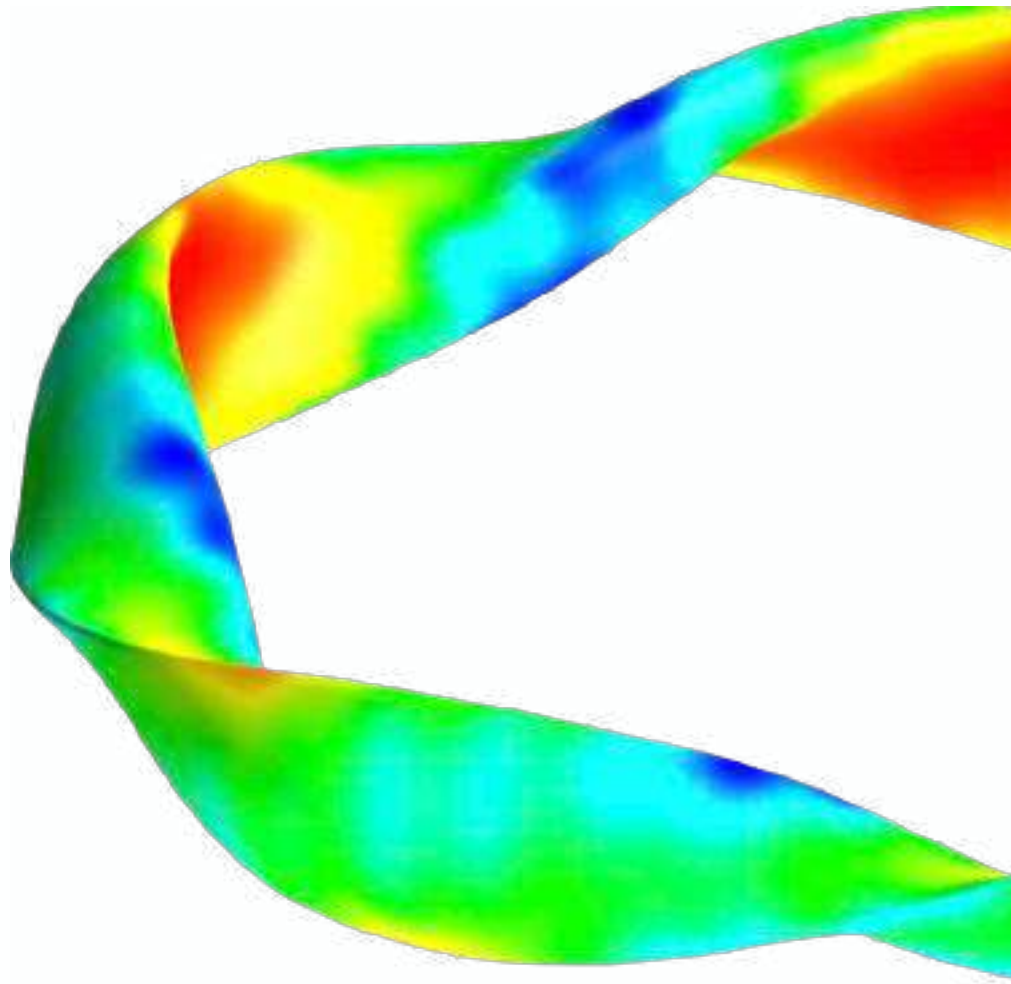
Saturation dynamics within configurations stand apart



- Evenly spread primary modes: efficient generation of zonal flows.
- Low Iota: Stronger dependence on zonal flows for saturation.



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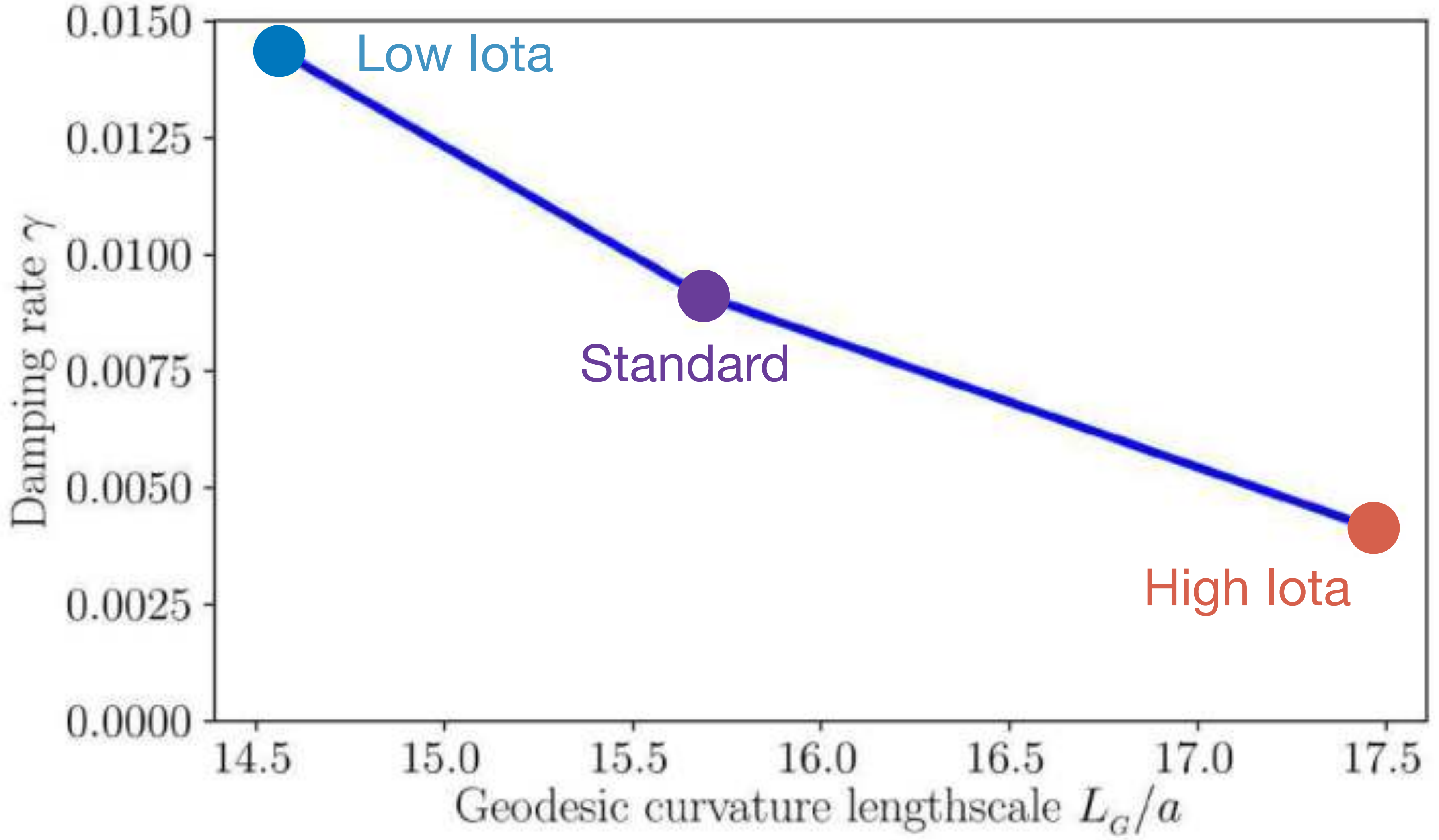
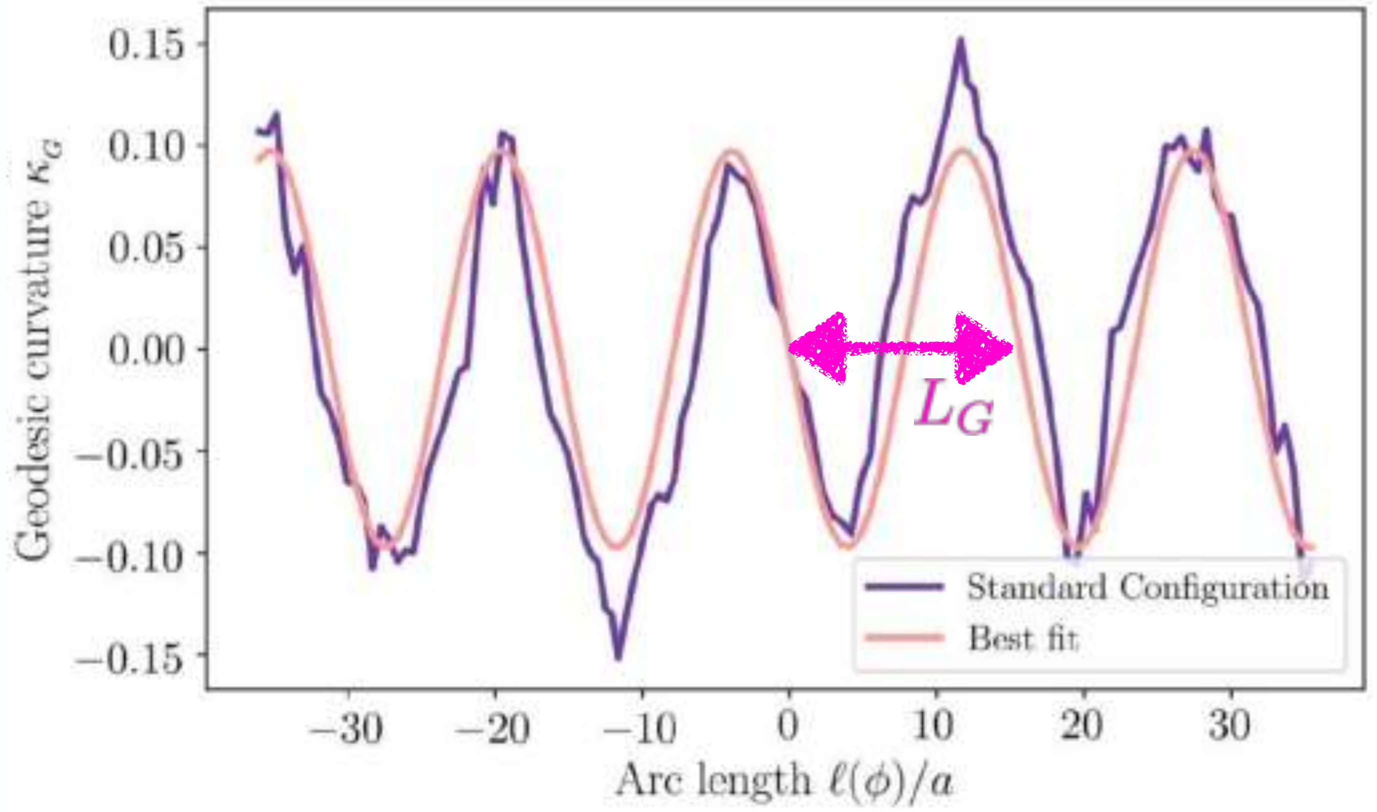
What are the implications?

- Zonal flow damping: inverted predictions.
- L_G: Rapid prediction of damping.
- Improve phenomenological transport models.[1]





[1] M. Nunami et al, Physics of Plasmas, 20(9), 092307 (2013).

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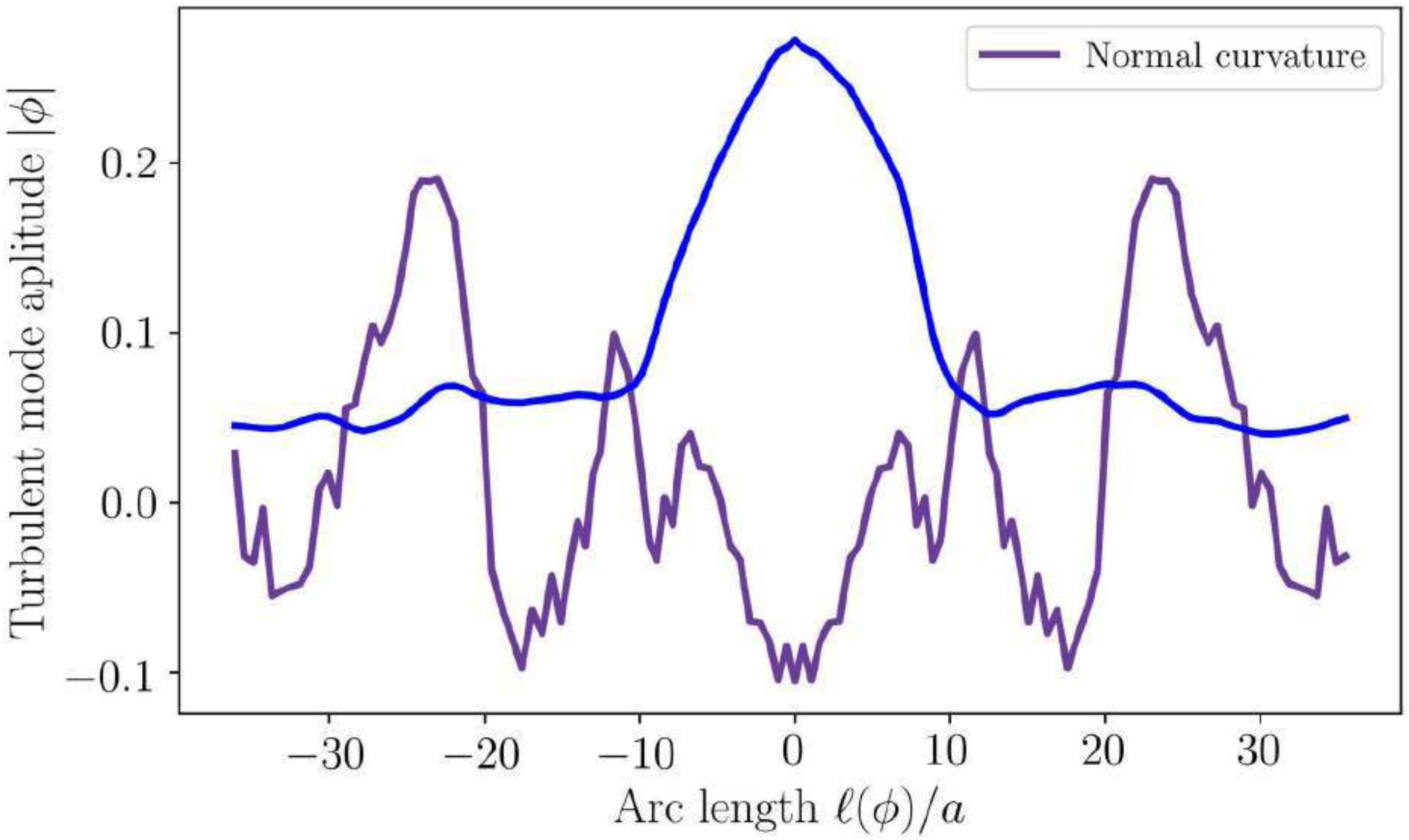
- $\kappa_N \rightarrow \sigma$



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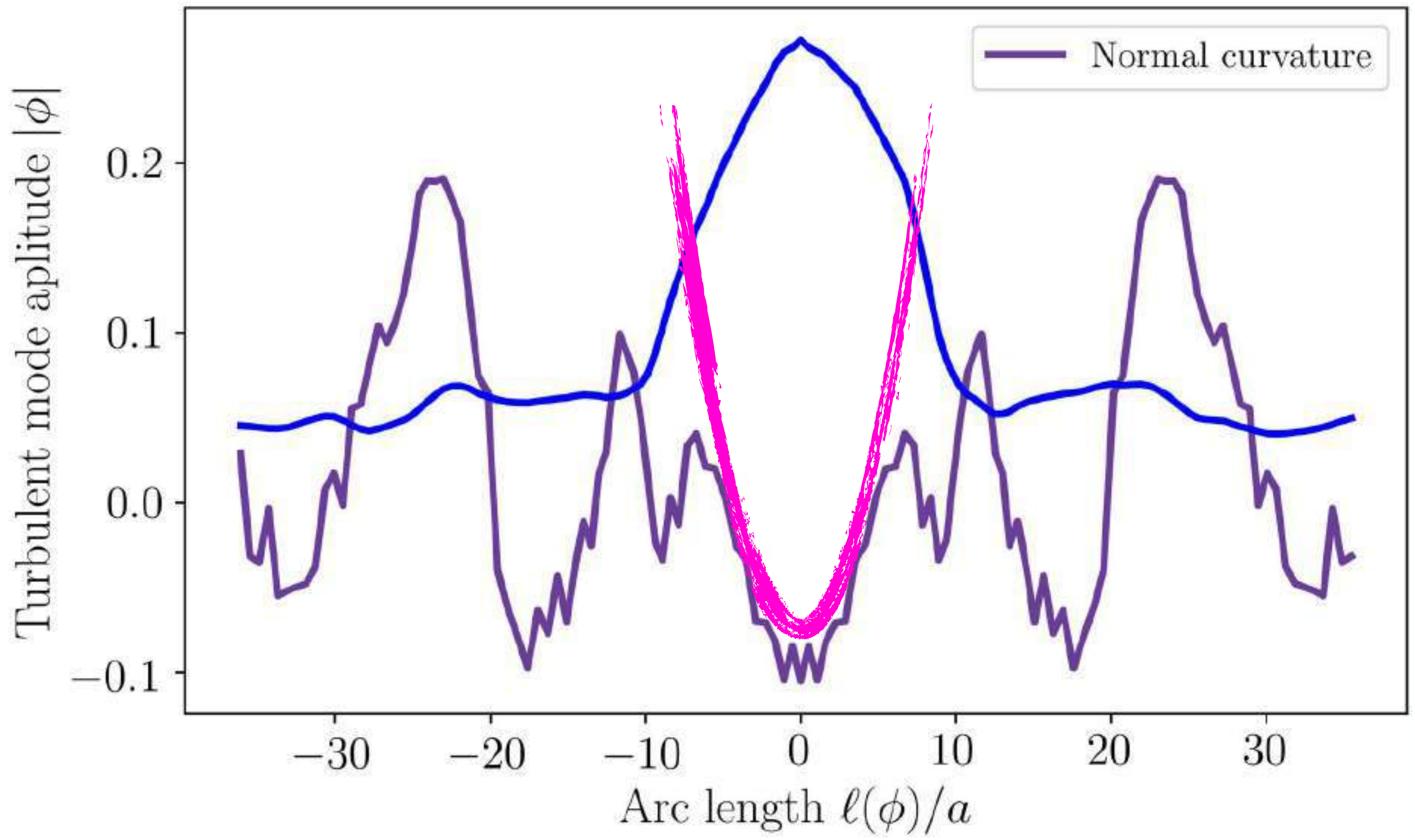
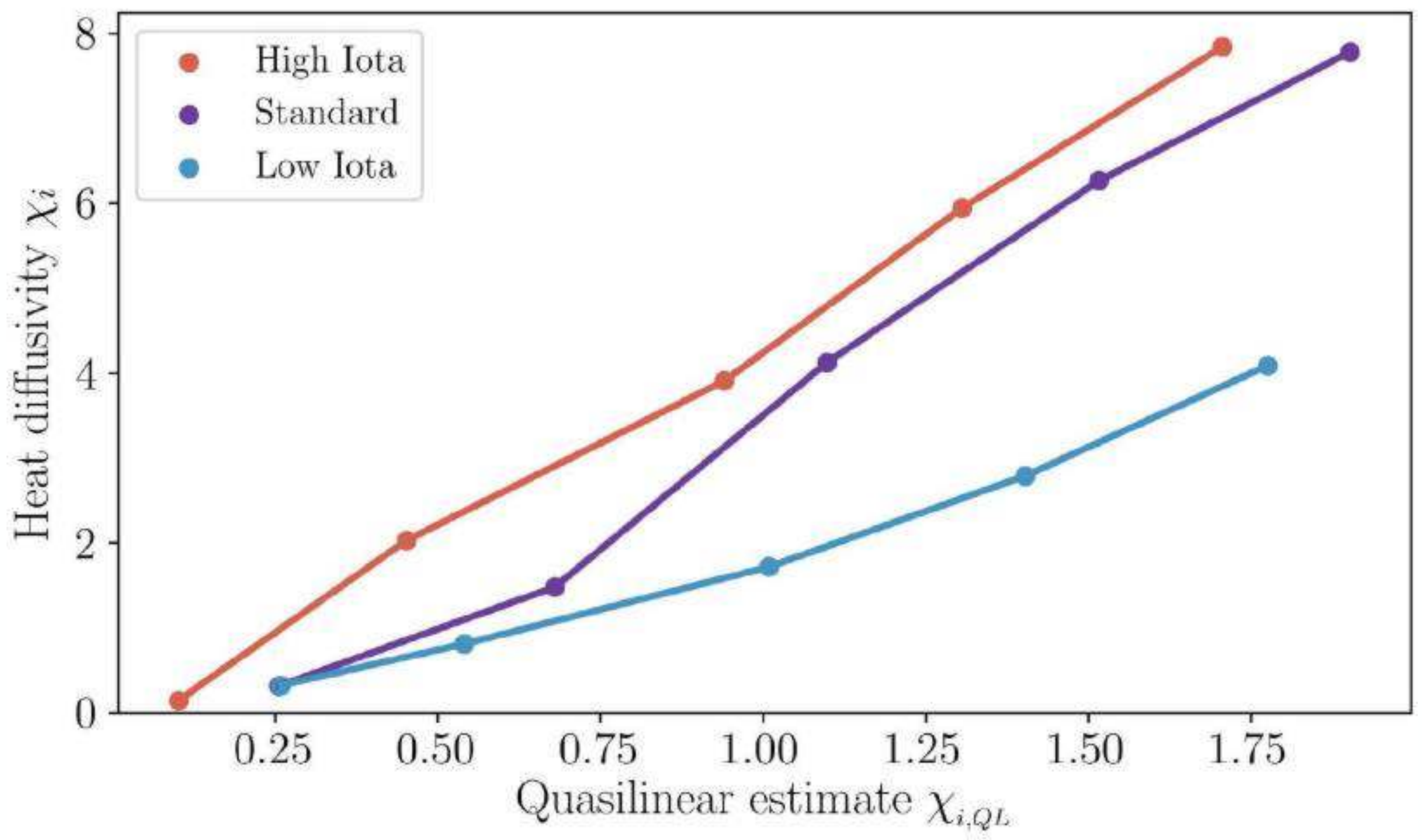
- Improve phenomenological transport models.[1]
- κ_N –> σ
- *Drift well:* proxy for σ.



[1] M. Nunami et al, Physics of Plasmas, 20(9), 092307 (2013).

What are the implications?

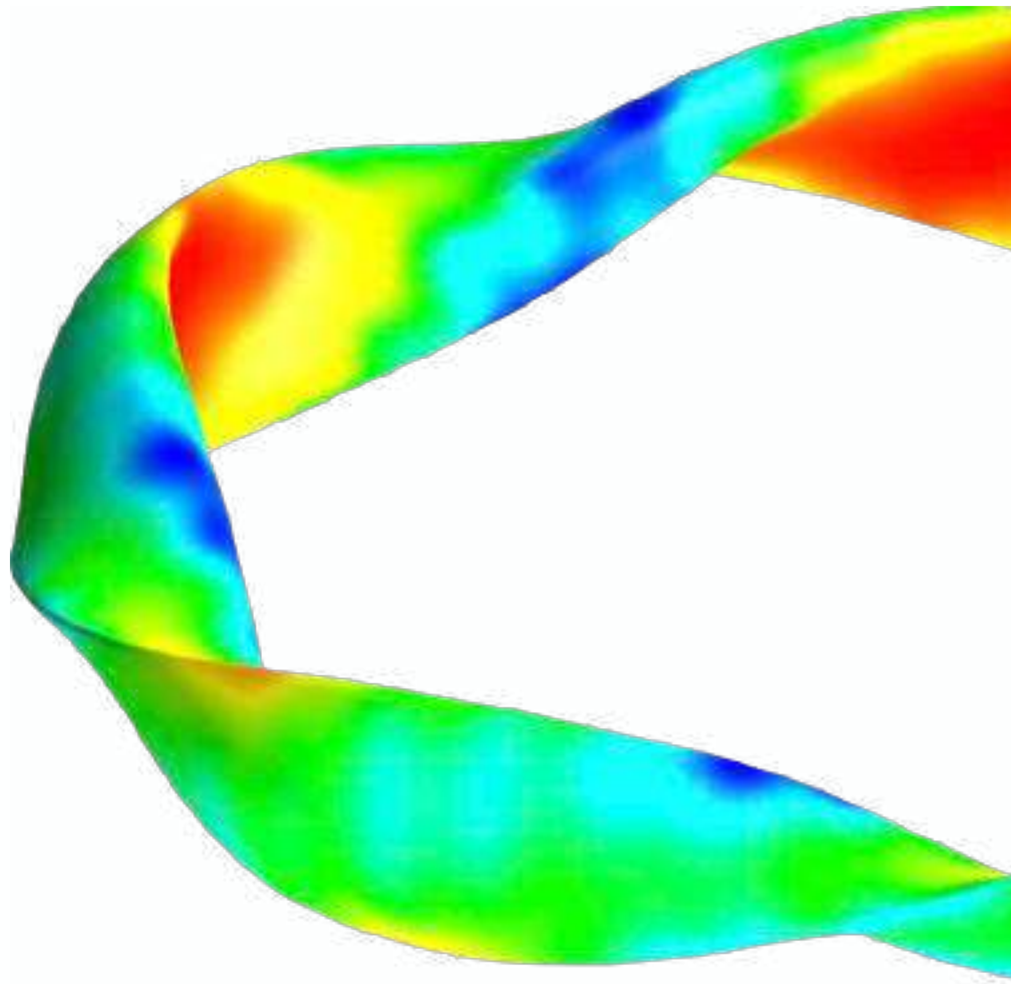
- Zonal flow damping: inverted predictions.
- L_G: Rapid prediction of damping.
- Improve phenomenological transport models.[1]
- κ_G –> σ
- *Drift well:* proxy for σ.
- Next: Extend QL estimate.



$$\chi_i = f\,(Geometry, Linear\ physics)$$

[1] M. Nunami et al, Physics of Plasmas, 20(9), 092307 (2013).

Summary



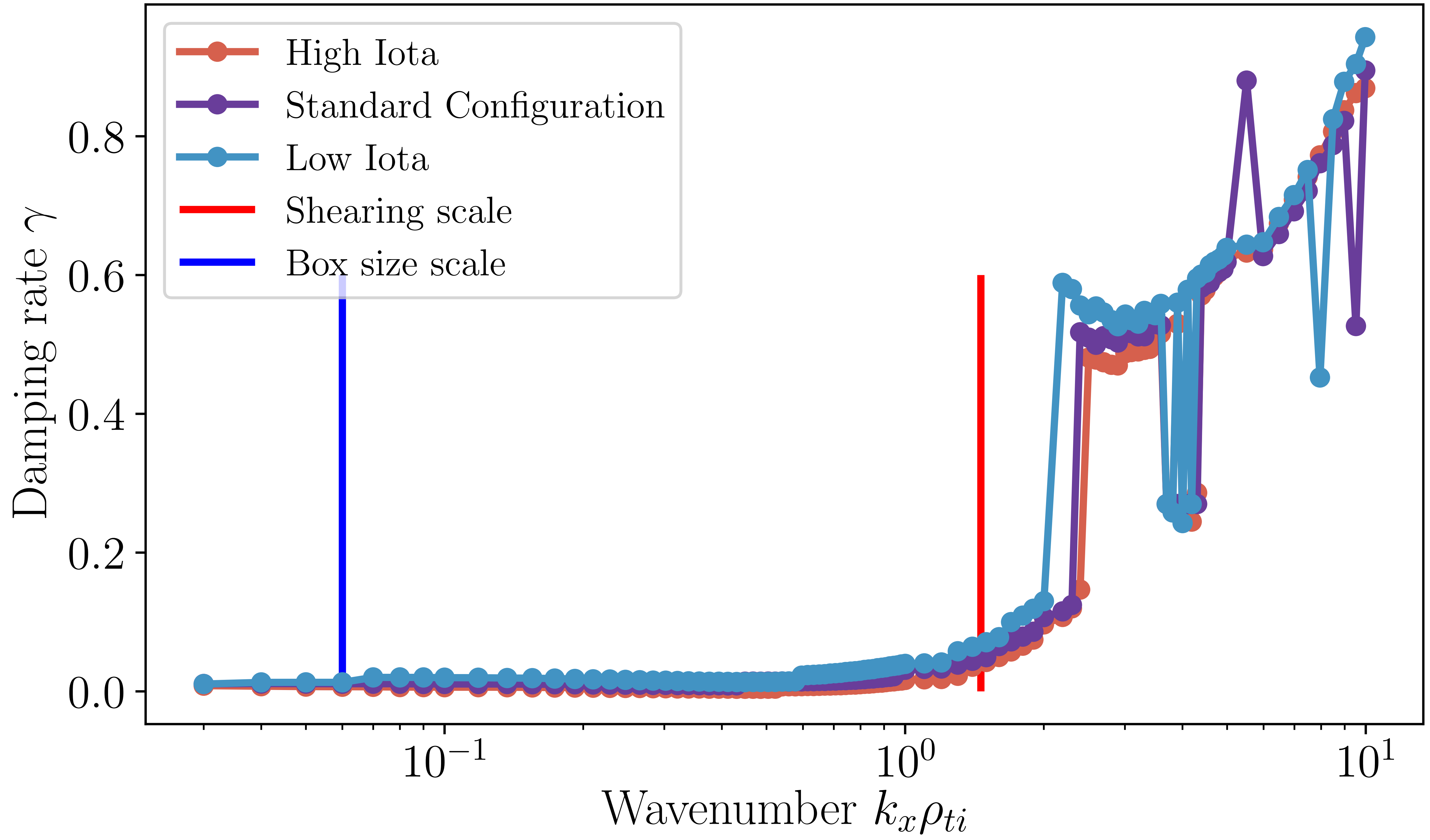
- Basis for improved transport modeling dwells in the field geometry.
- (Linear) Damping predictions are in disagreement with observations.
- Low Iota: Zonal flows have a bigger impact on transport.
- High Iota: Highly localized modes saturate through other mechanisms.
- Space-filling factor σ: Zonal flow generation.
- Outlook: Build a reduced model with geometry features and linear estimates.

Backup slides

Transient damping rate

as a function of the wavenumber

- Zonal flow damping rate depends on the radial length-scale
- Regions of interest: shearing scales and computational “box” size
- No significant variation observed at large scales
- Small scales reflect the same trend



Linear zonal flow response

and the effect of the upper integration limit