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Exploring gyrokinetic turbulence with a moment-based approach

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EUROfusion

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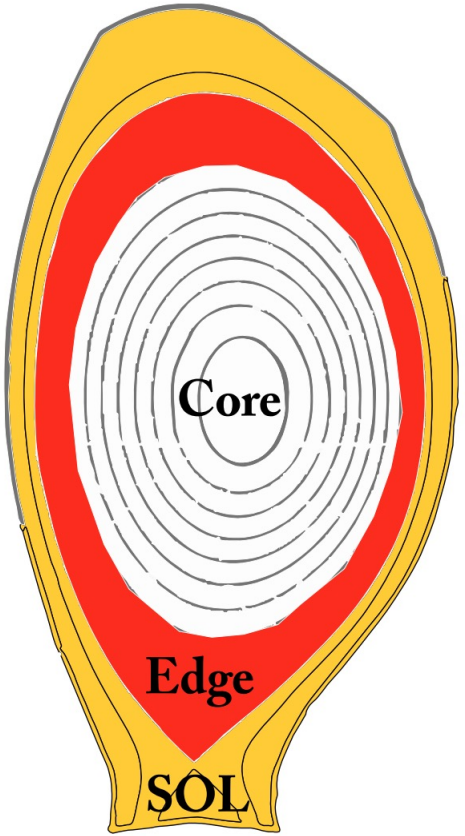
The tokamak edge: a challenging region

- Large range of collisionalities
- Large fluctuations
- Complex geometry
- Two modelling approaches
  - Fluid models (SOL)
  - GK models (core)

  Not ideal for the edge
- Can we do better with GK?



[Jorge 2019]

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Gyrokinetics

- The gyrokinetic (GK) theory **considers**

$$\omega_{turb} \ll \Omega_{ci}$$

$$\lambda_{turb} \gtrsim \rho_i$$

- **Collisional** GK Boltzmann equation [1]

$$\frac{\mathrm{d}}{\mathrm{d}t} F_a(\boldsymbol{x}, v_{\parallel}, v_{\perp}, t) = \sum_b C(F_a, F_b)$$

+ Maxwell's equations

[1] Catto, P. J. 1978. Plasma Physics 20 (7), 719–722.

A new approach to the tokamak boundary turbulence

- **New GK model** valid at **arbitrary collisionality** based on a **Hermite-Laguerre** decomposition in the v-space [2,3,4,5]

$$F_a = \sum_{p,j=0}^{\infty} M_a^{pj}(\boldsymbol{x},t) H_p(v_\parallel) L_j(v_\perp^2)$$

Gyro-moments (GMs)

[2] Frei, B. J., Jorge, R. & Ricci, P. 2020. Journal of Plasma Physics 86 (2).
[3] Frei, B.J., Ball, J., Hoffmann, A.C.D., Jorge, R., Ricci, P. & Stenger, L. 2021,. Journal of Plasma Physics 87 (5).
[4] Mandell, N. R., Dorland, W. & Landreman, M. 2018. Journal of Plasma Physics 84 (1), 905840108.
[5] Mandell, N. R., Dorland, W., Abel, I., Gaur, R., Kim, P., Martin, M. & Qian, T. 2022 (arXiv:2209.06731v3) .

First nonlinear numerical results

- Based on a code I developed to **evolve nonlinearly GM** in δf limit

$$F_a = F_{a0}(\boldsymbol{x}, v_\parallel, v_\perp) + g_a(\boldsymbol{x}, v_\parallel, v_\perp, t) \qquad g_a/F_0 \ll 1$$

We discuss

- **Validation** against GK continuum code GENE [6]
- Convergence properties and **efficiency**
- Comparison between different **collision models**
- **Bridge** between **high-fidelity GK and reduced fluid** modelling
- **Multi-scale** and **multi-fidelity** simulations of triangularity

[6] Jenko, F., Dorland, W. & Kotschenreuther, M. 2000 Physics of Plasmas 7 (5), 1904–1910.

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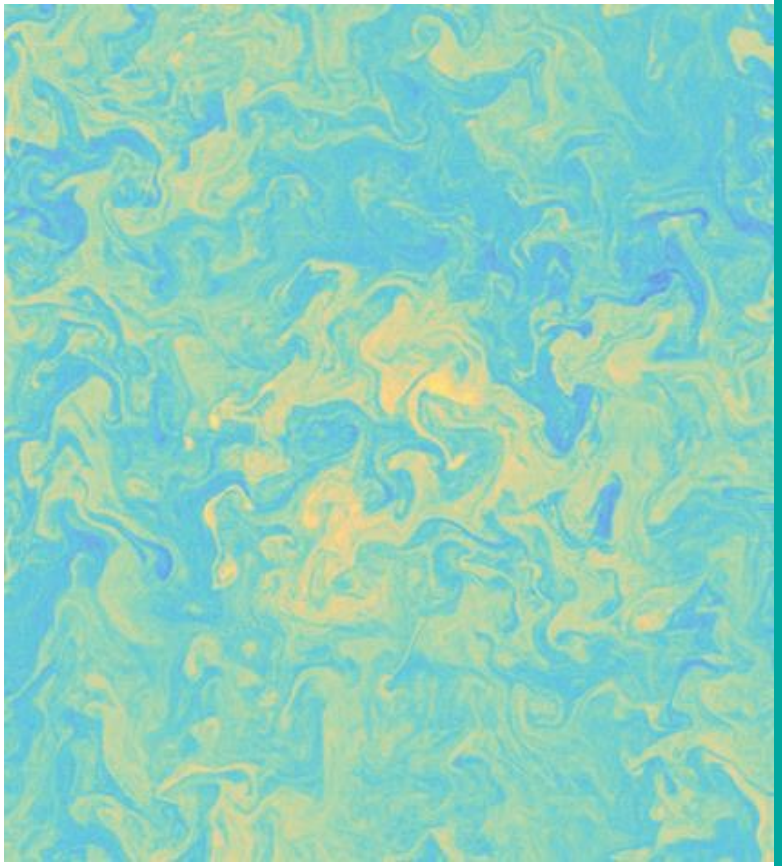

Outline

A.C.D. Hoffmann

A. The δf gyro-moment approach
   I. Hermite-Laguerre projection of GK Boltzmann eq.
B. 2D Z-pinch turbulence
C. Cyclone base case
D. Application to tokamak shaping
   I. Short review
   II. GM as a multi-fidelity framework
   III. Turbulent GK transport and shaping
E. Conclusion and Outlook

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The δf gyrokinetic model

- Main assumption: $\bar{F}_a = F_{a0}(\boldsymbol{x}, v_\parallel, v_\perp) + g_a(\boldsymbol{x}, v_\parallel, v_\perp, t)$
- Electrostatic GK equation in field aligned coordinates for the perturbed distribution function g_a [7]

$$\partial_t g_a + i\omega_{Ba} g_a + \{g_a + F_{aM}, J_0\phi\} = C(a,b)$$

- Magnetic drifts
- Nonlinear $E\times B$ drift
- Equilibrium background profiles (diamagnetic drifts)
- Collisions

[7] Brizard, A. J. & Hahm, T. S. Reviews of Modern Physics 79 (2), 421–468

Projecting GK Boltzmann on a Hermite-Laguerre basis

- Decompose the perturbed distribution function on the Hermite-Laguerre basis [8,9]

$$\boxed{g_a(\boldsymbol{x}, v_\parallel, v_\perp, t)} = \sum_{p,j=0}^{\infty} \boxed{N_a^{pj}(\boldsymbol{x}, t)} \boxed{H_p(v_\parallel) L_j(v_\perp^2)}$$

with

$$\boxed{N_a^{pj}(\boldsymbol{x}, t)} := \int dv_\parallel dv_\perp \boxed{g_a(\boldsymbol{x}, v_\parallel, v_\perp, t)} \boxed{H_p(v_\parallel) L_j(v_\perp)}$$

→ **GOAL: solve GK Boltzmann by evolving its perturbed gyro-moments (GMs)**

[8] Mandell, N. R., Dorland, W. & Landreman, M. 2018. Journal of Plasma Physics 84 (1), 905840108.
[9] Frei, B. J., Hoffmann, A.C.D. & Ricci, P. 2022. Journal of Plasma Physics 88 (3), 905880304

A.C.D. Hoffmann

GK modelling expressed as a set of fluid-like equations

1 eq. (5D + time)

$$\int dv_{\parallel} dv_{\perp} \left(\partial_t g_a + i\omega_{Ba} g_a + \{F_{aM} + g_a \, , J_0 \phi\} = C(a,b) \right) \mathrm{H}_p L_j$$

$$\partial_t N_a^{pj} + \mathcal{M}_a^{pj} + \mathcal{D}_a^{pj} + \mathcal{S}_a^{pj} = \mathcal{C}_a^{pj}$$

Inf. #eqs. (3D + time)

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δf flux-tube GM hierarchy

$$\partial_t N_a^{pj} + \mathcal{M}_a^{pj} + \mathcal{D}_a^{pj} + \mathcal{S}_a^{pj} = \mathcal{C}_a^{pj}$$

Perpendicular and parallel magnetic drifts

$$\mathcal{M}_a^{pj} = \frac{\tau_a}{z_a}\mathcal{C}_{xy}\left[\sqrt{(p+1)(p+2)}N_a^{p+2,j} + \ldots\right.$$

$$+\frac{\tau_a}{z_a}\mathcal{C}_{xy}\left[2(j+1)N_a^{pj} - (j+1)N_a^{p,j+1} + \ldots\right.$$

δf flux-tube GM hierarchy

$$\partial_t N_a^{pj} + \mathcal{M}_a^{pj} + \mathcal{D}_a^{pj} + \mathcal{S}_a^{pj} = \mathcal{C}_a^{pj}$$

Collisions

- **Linear GK collisions operators** are projected onto the Hermite-Laguerre basis [10,11]

Complexity ↓

Landau	(linearized Fokker-Planck)
Sugama	(multi-species, ad-hoc field term)
Pitch-angle	(like-species operator, small mass ratio limit)
Dougherty	(diffusion in v-space + conservation)

❖ Matrix-vector multiplication on the GMs

[10] Frei, B. J., Hoffmann, A.C.D. & Ricci, P. 2022. Journal of Plasma Physics 88 (3), 905880304
[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

Closure of the GM hierarchy

- The GM Poisson equation (quasi-neutrality)

$$\left[\sum_a \frac{z_a^2}{\tau_a}\left(1-\sum_{n=0}^{\infty}\mathcal{K}_n^2\right)\right]\phi = \sum_a z_a \sum_{n=0}^{\infty}\mathcal{K}_n N_a^{0n}$$

- In the code, we consider a finite number of moments
  > *Closure by truncation*

$$N^{pj} = 0 \text{ for } p > P \text{ or } j > J$$

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The GYrokinetic Advanced COllision MOment solver

The code I developed during my thesis

- Fortran, FFTW, MPI
- Pseudo-spectral in perpendicular and fourth order finite difference in the parallel direction
- Miller geometry, electromagnetic effects, kinetic and adiabatic electron models, GK collision operators

Fully open-source, GIT repository + wiki

Can run on Windows, macOS and HPC plateforms

gitlab.epfl.ch/ahoffman/gyacomo

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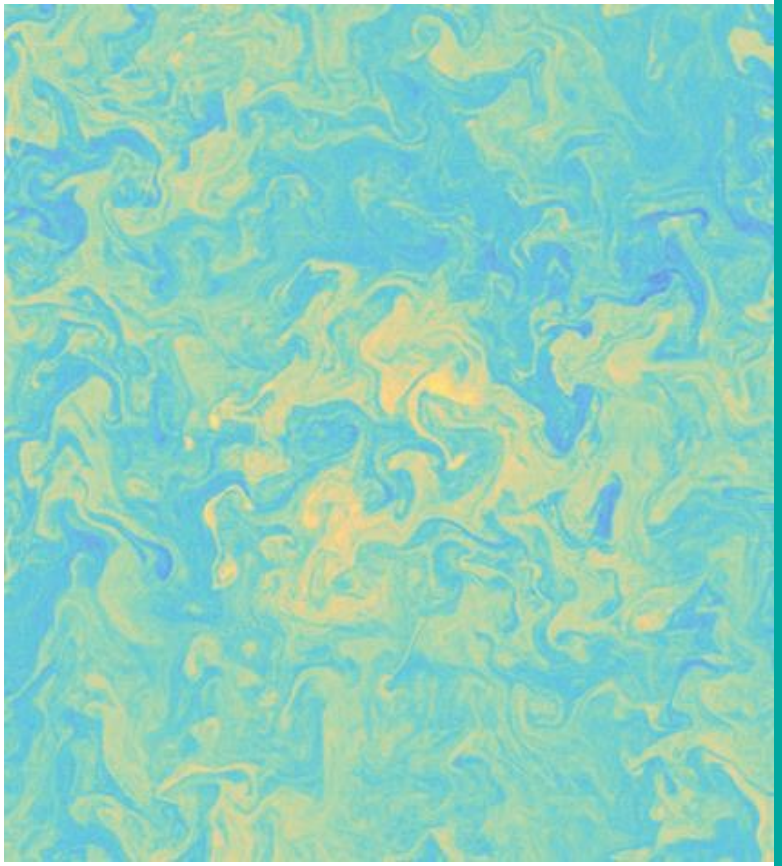

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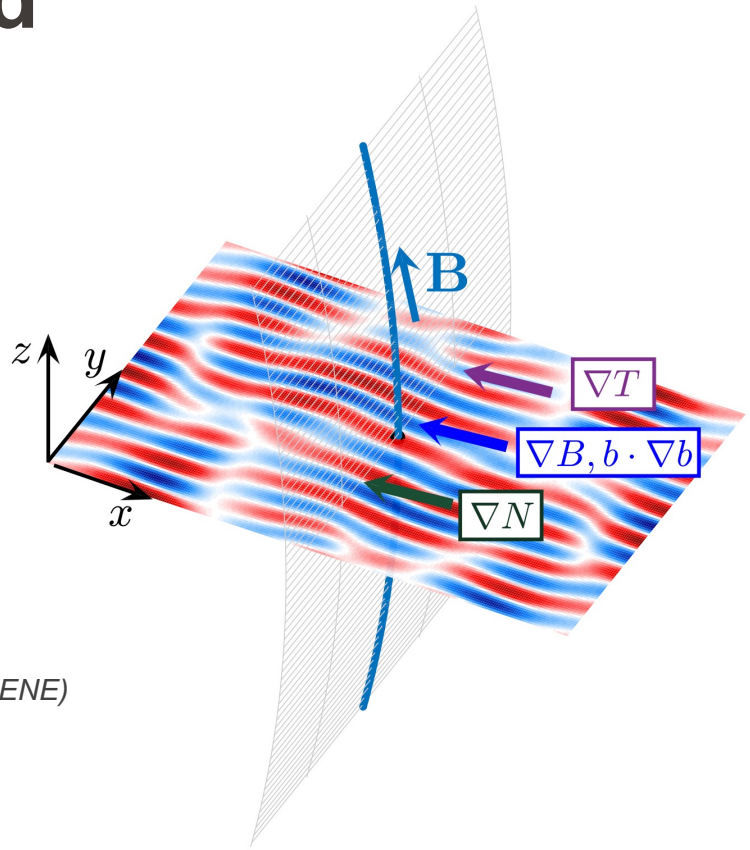
Z-pinch: ideal test bed

- Constant curvature
- $k_{\parallel} \sim 0$, consider a 2D system (x,y)
- Kinetic ions and electrons
- Well studied test case

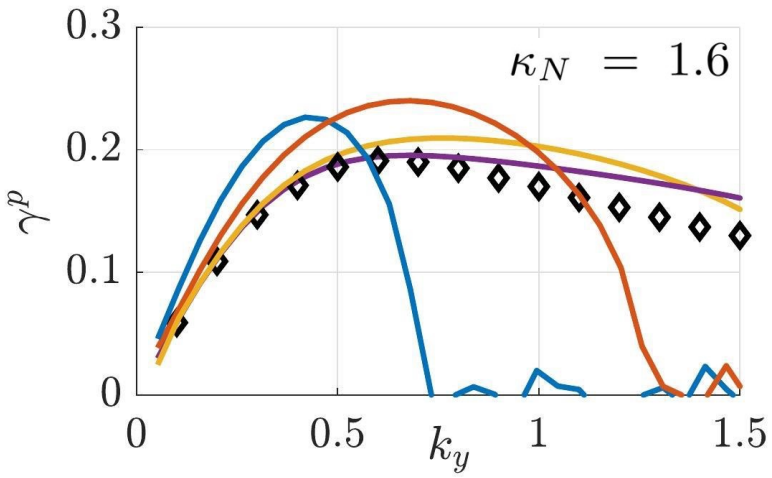
Ricci 2006 (GS2), Kobayashi 2012-2015 (GS2),
Ivanov 2020-2022 (RFM), Hallenbert 2020-2022 (RFM and GENE)



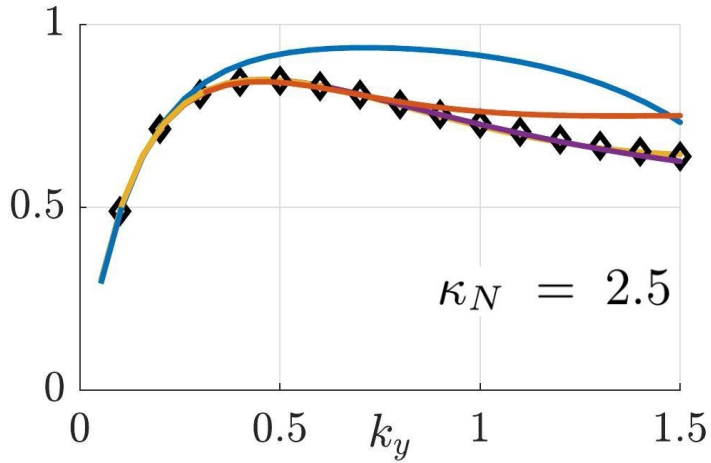
[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

Linear instability: entropy mode

Low drive



High drive



GENE (32x16)	$(P,J) = (4,2)$	$(P,J) = (8,4)$	$(P,J) = (10,5)$	$(P,J) = (20,10)$

Hermite (P) Laguerre (J) maximal polynomial degree used

[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

Z-pinch and zonal flows dynamics

1. Unstable linear **entropy mode**

2. **Kelvin-Helmholtz** secondary instability

3. Emergence of **zonal flows**

[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

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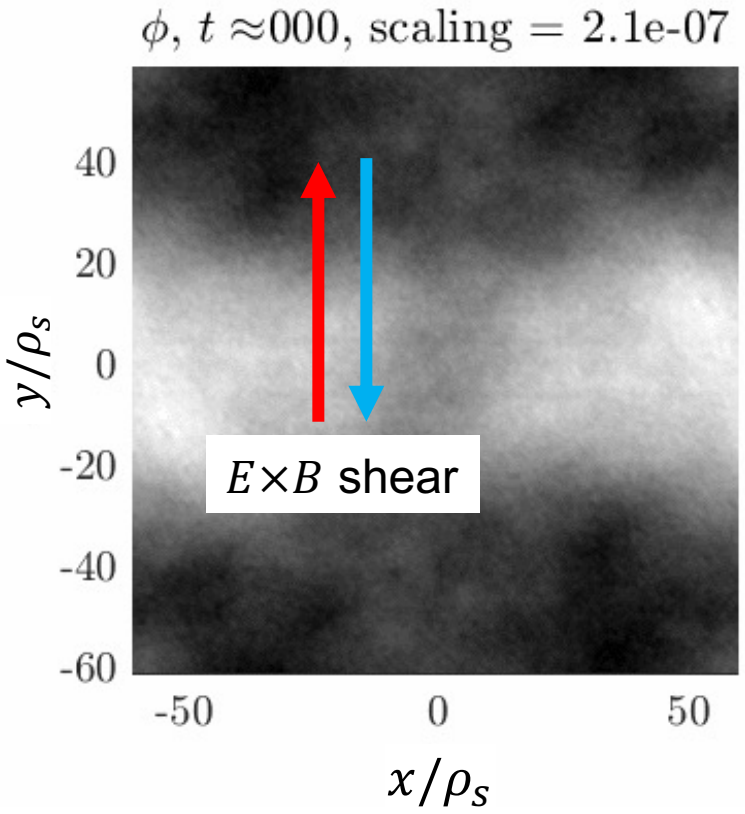

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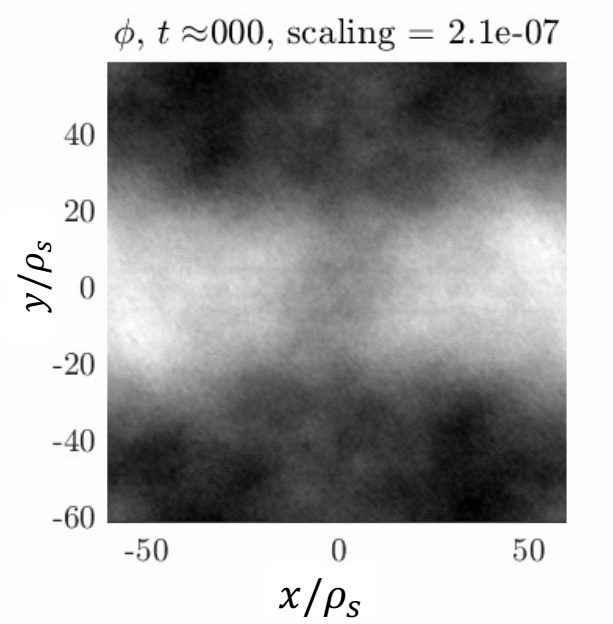
ZFs dominate at low gradient

ZF dominated



Developed turbulence

Density gradient

[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

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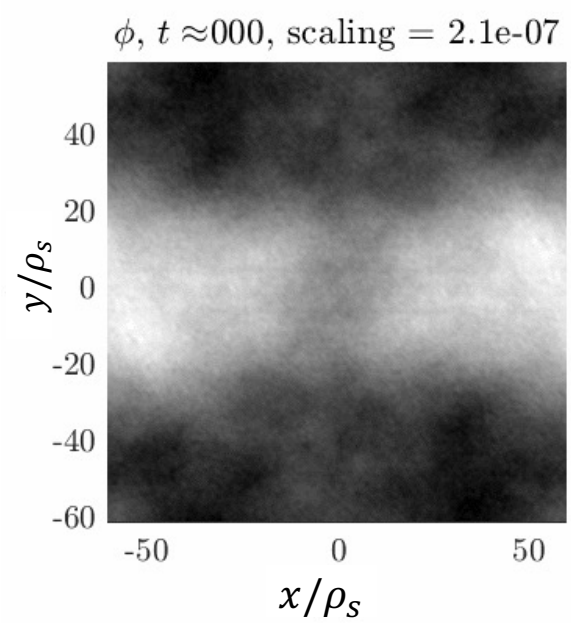

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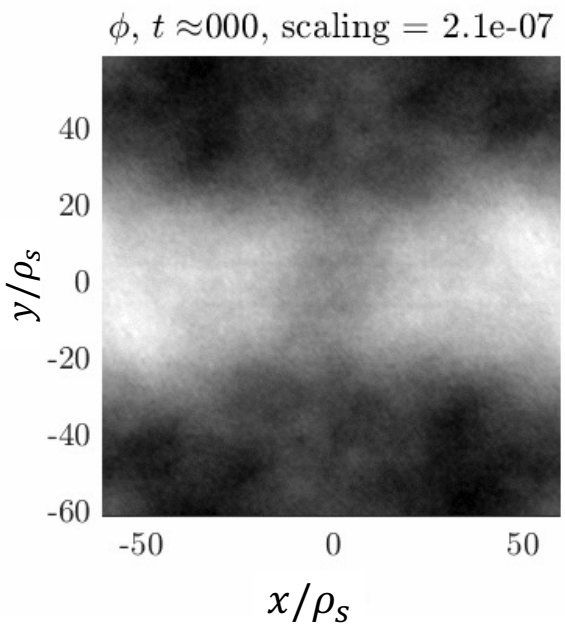

Density gradient

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[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

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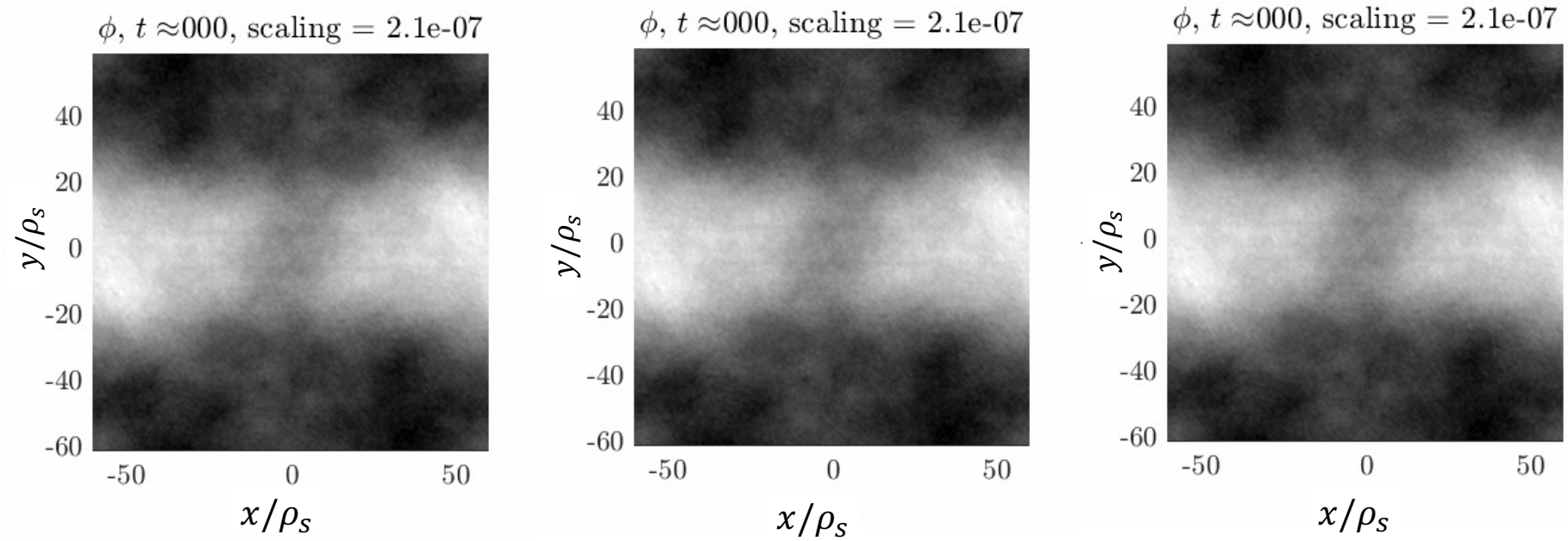

Density gradient

Swiss Plasma Center

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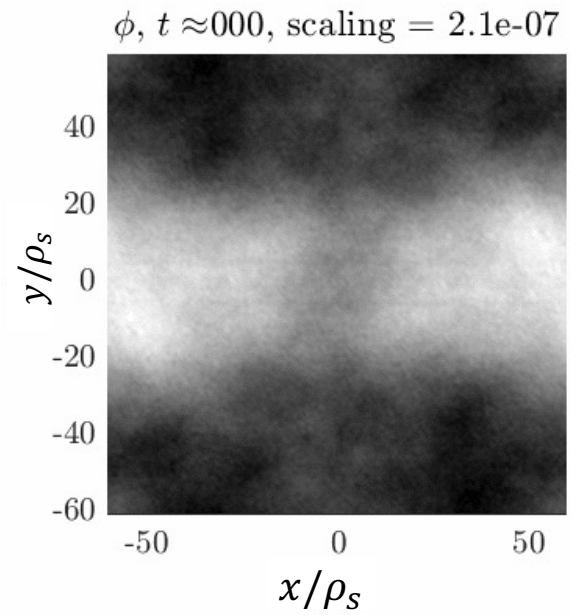
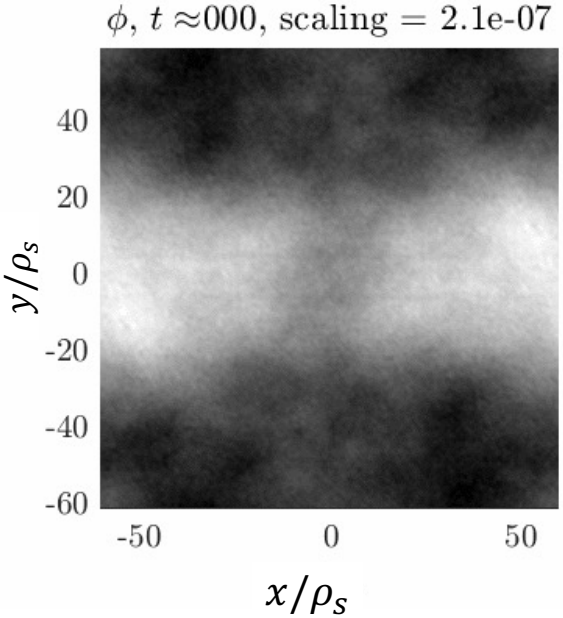
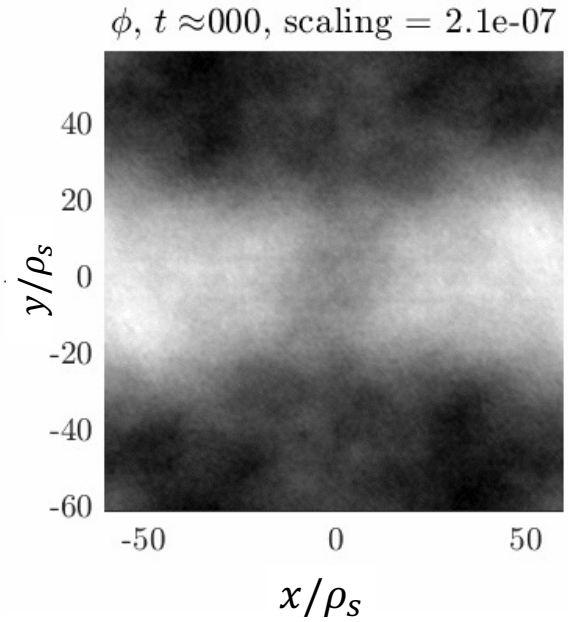




Developed turbulence



Density gradient

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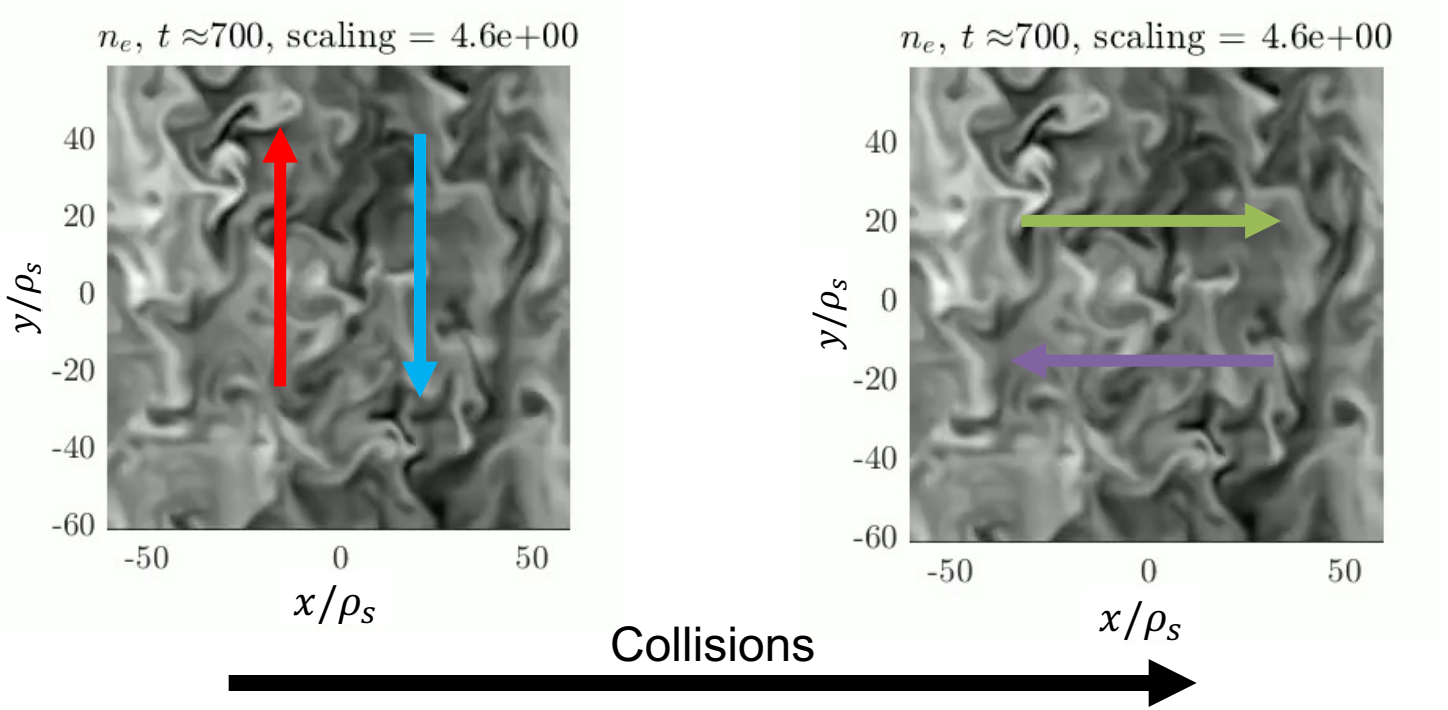
Plasma
Center

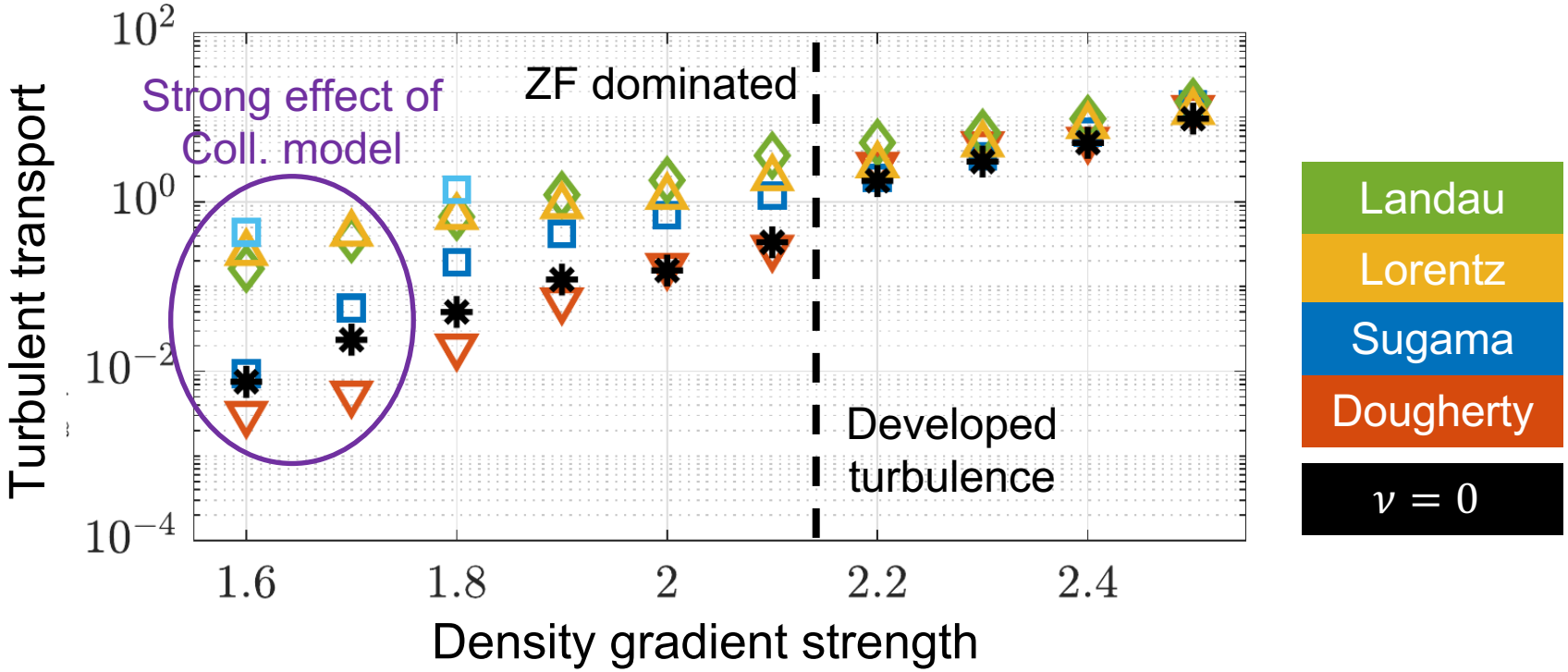
[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

ZFs weakened by collisions



[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

Strong sensitivity to collision model



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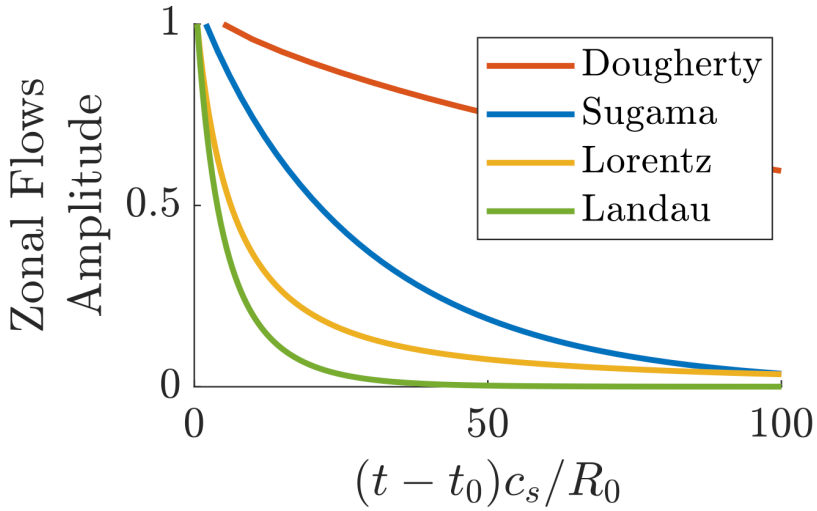
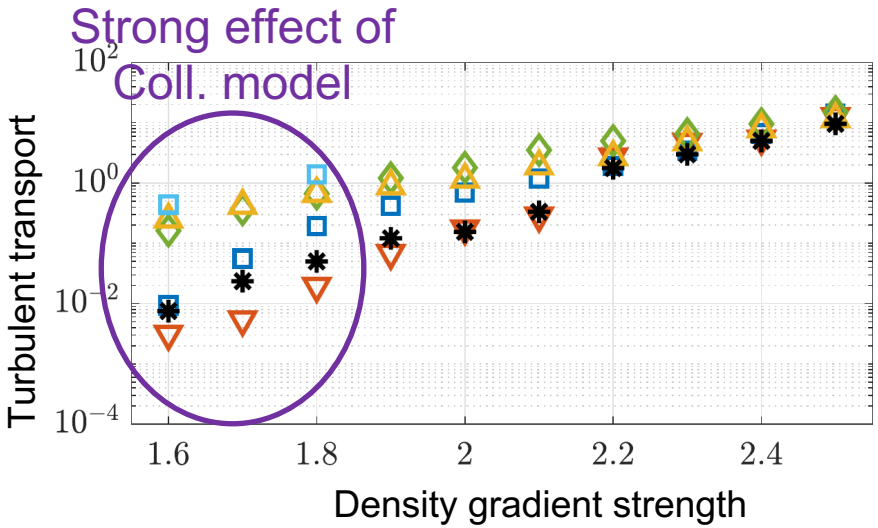
Investigating collision model impact





- **Linear growth rate does not explain transport**
- High transport is related to **ZF damping**

[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

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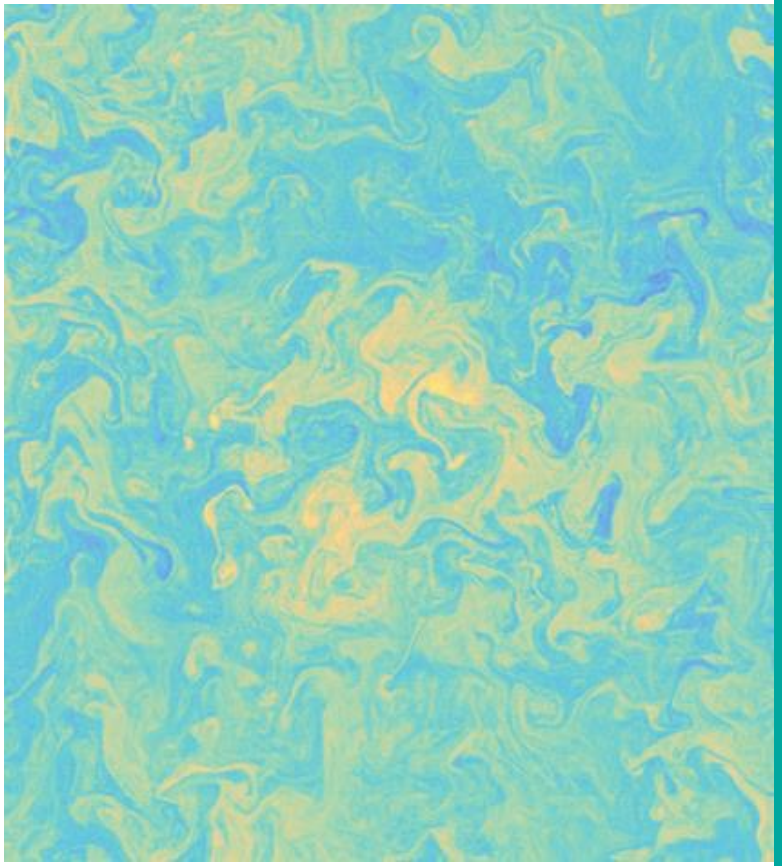

Outline

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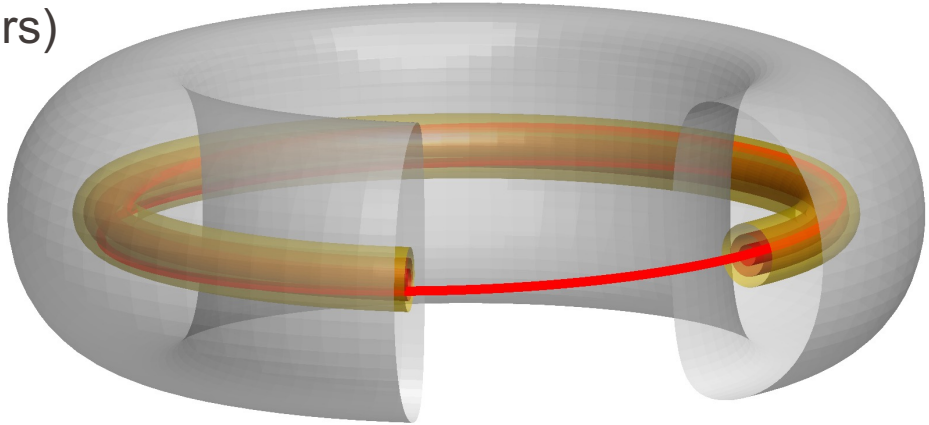
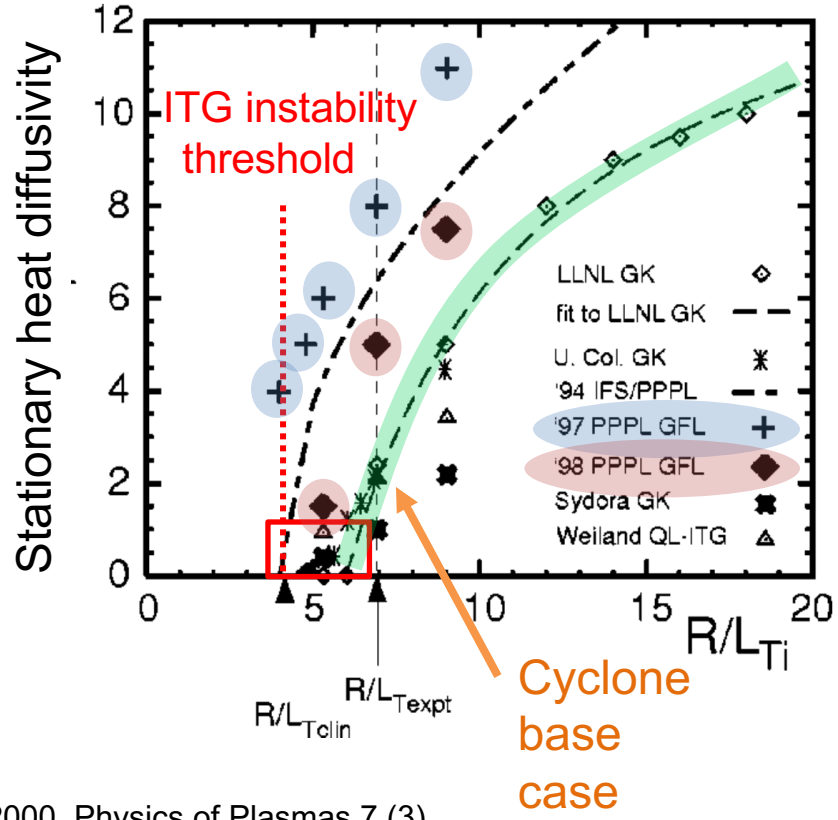
Cyclone base case: Standard test bed in tokamak geometry

- Standard test case for GK code validation [12,13] (based on DIII-D core parameters)
- 3D system
- Toroidal flux-tube s-α geometry
- Adiabatic electrons
- Dimits et al. 2000 point out spurious result of the gyrofluid models **What about the GMs?**



[12] Lin, Z., Hahm, T. S., Lee, W. W., Tang, W. M. & Diamond, P. H. 1999. Physical Review Letters 83 (18)
[13] Dimits et al. 2000. Physics of Plasmas 7 (3)

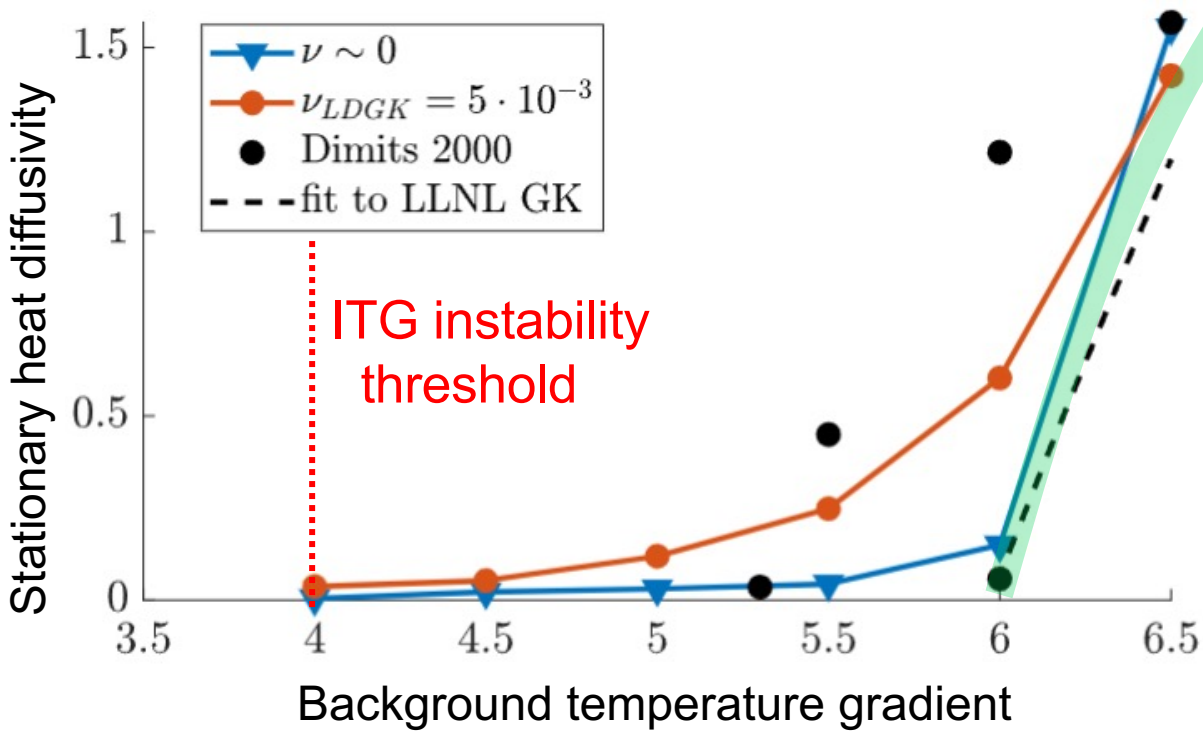
Dimits shift and gyrofluids



Cyclone base case

[13] Dimits et al. 2000. Physics of Plasmas 7 (3)

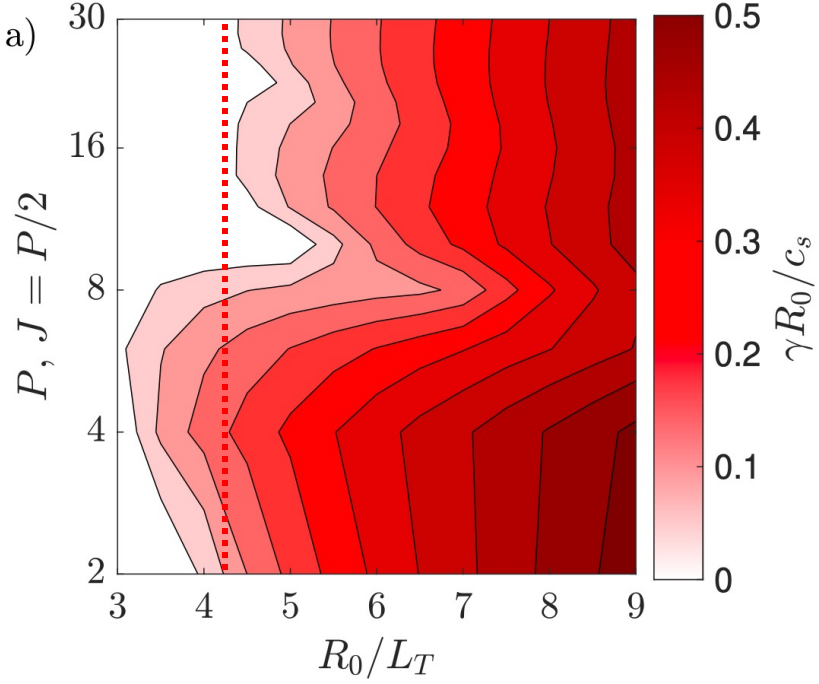
GM resolves the Dimits shift



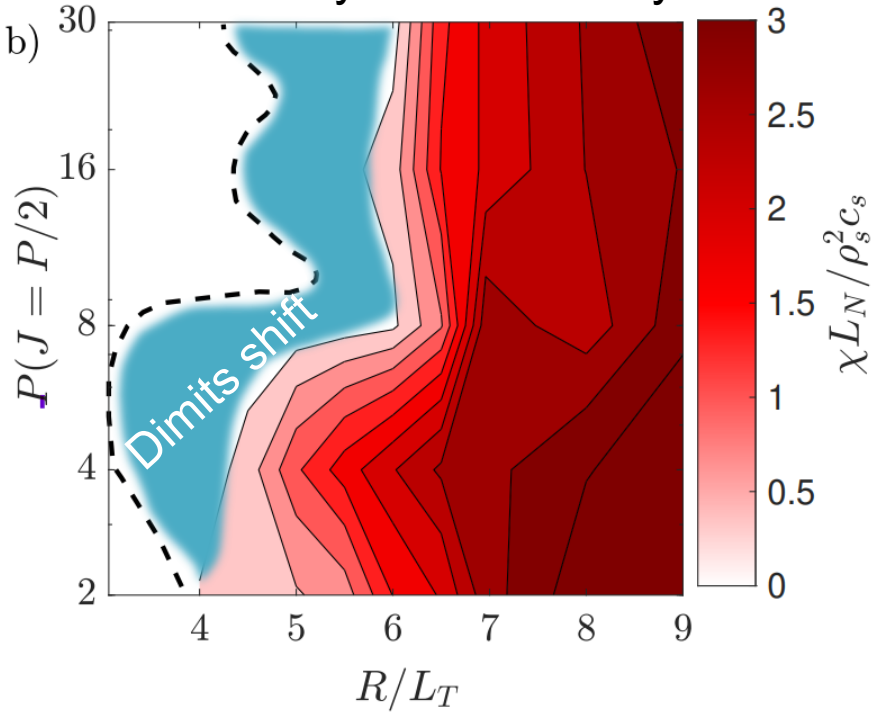
[14] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023, 89 (6), 905890611.

GM resolves the Dimits shift before linear convergence

Peak ITG growth rate



Stationary heat diffusivity



Cyclone base case

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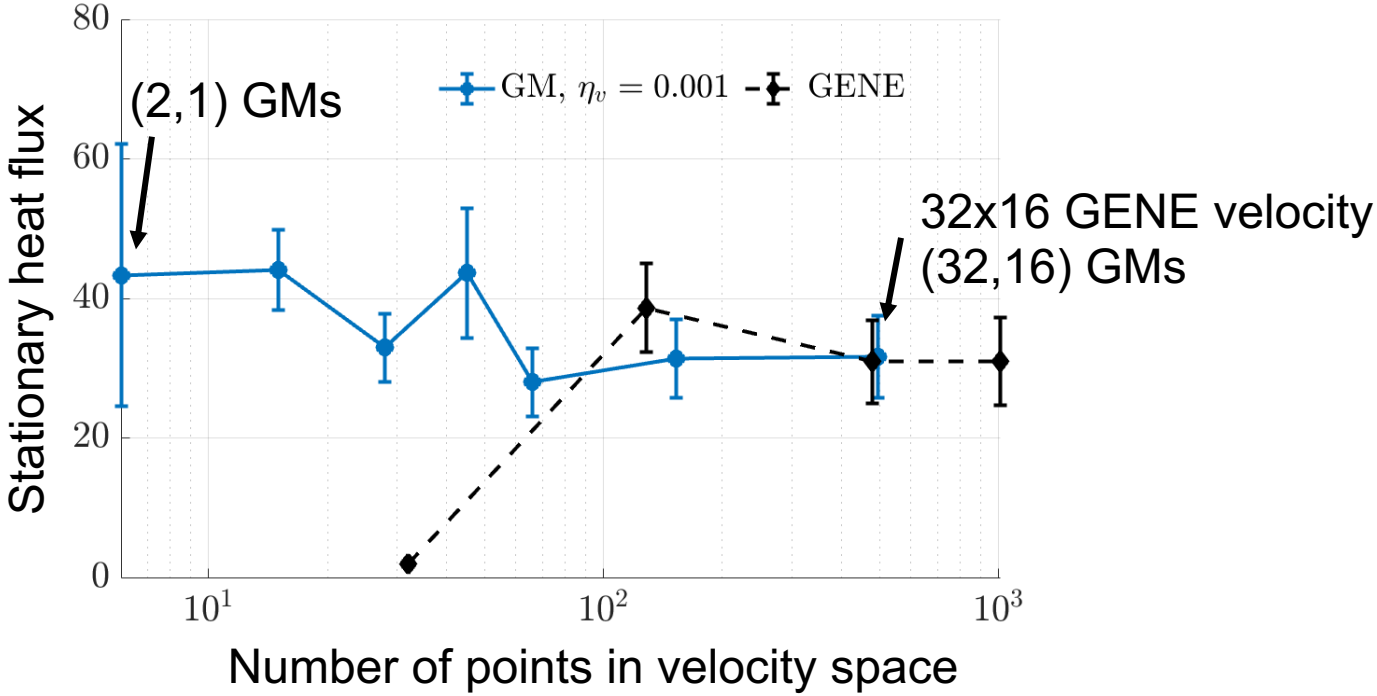
GM is efficient and improves with collisions



[14] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023, 89 (6), 905890611.

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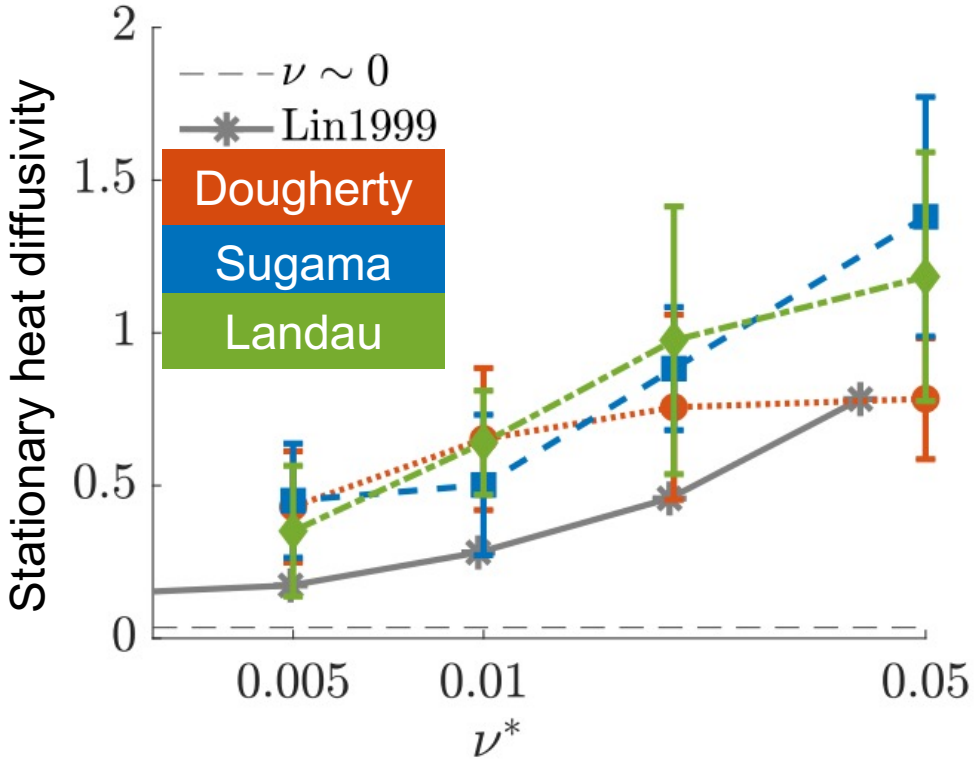
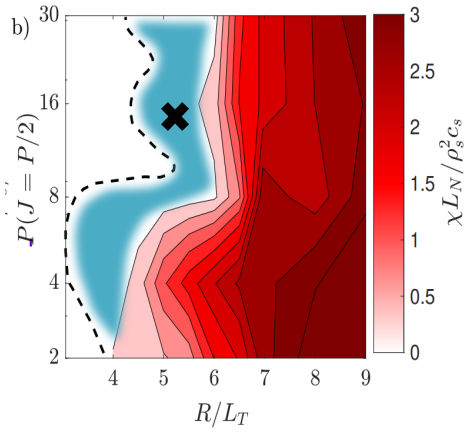
Weak role of the collision model

Cyclone base case





Hypothesis:
- Low collisionality
- Adiabatic electron model
- ITG

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[14] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023, 89 (6), 905890611.

First GM nonlinear simulations: *what did we learn?*

- **Proof of concept**

  GM approach retrieves continuum GK results in a wide range of conditions (entropy mode, ITG, toroidal effects, Dimits shift)

- **Linear convergence vs. Nonlinear convergence**

  Nonlinear transport converges faster than the linear growth rate

- **Importance of collision model**

  Z-pinch : Dougherty and Sugama fail to predict transport
  CBC : No strong impact of collision model (adiabatic electrons)

- GM is **extremely efficient at strong collisions and gradients**

  ~20x-100x less expensive than GENE

[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023, 89 (2), 905890214.
[14] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023, 89 (6), 905890611.

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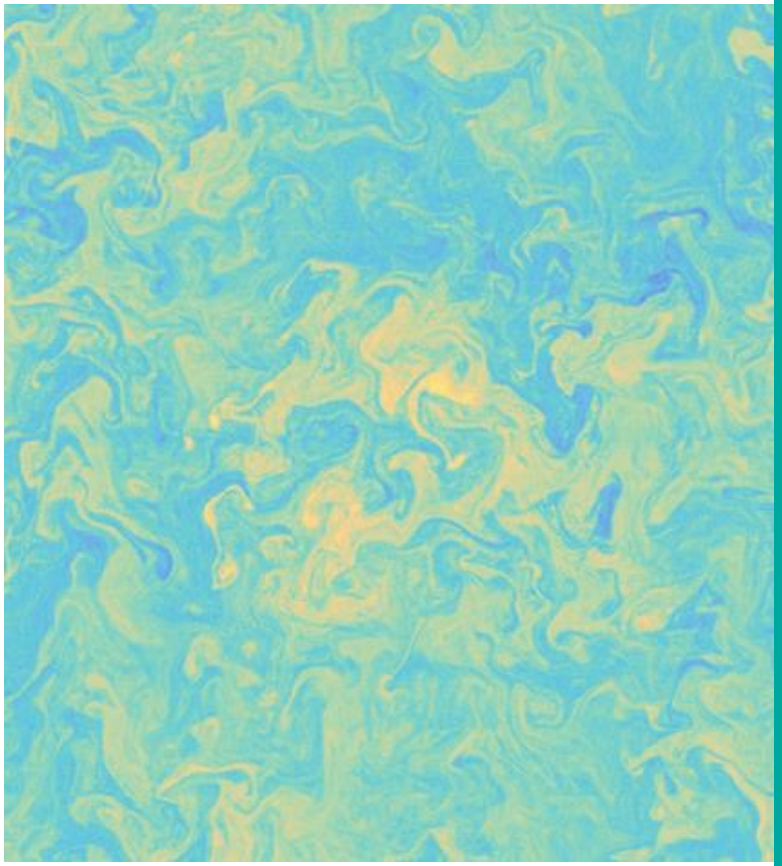

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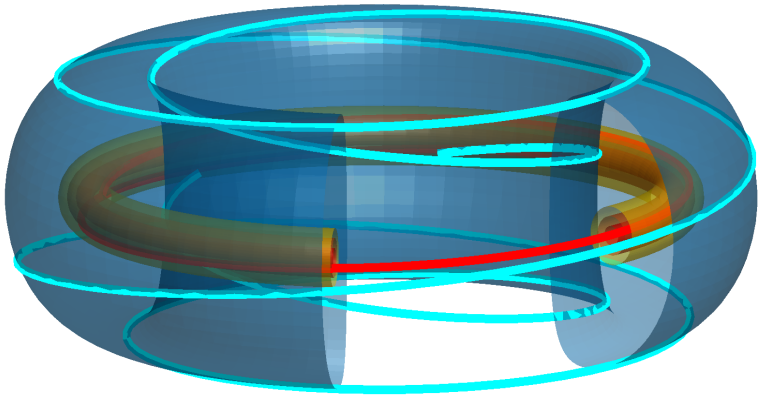
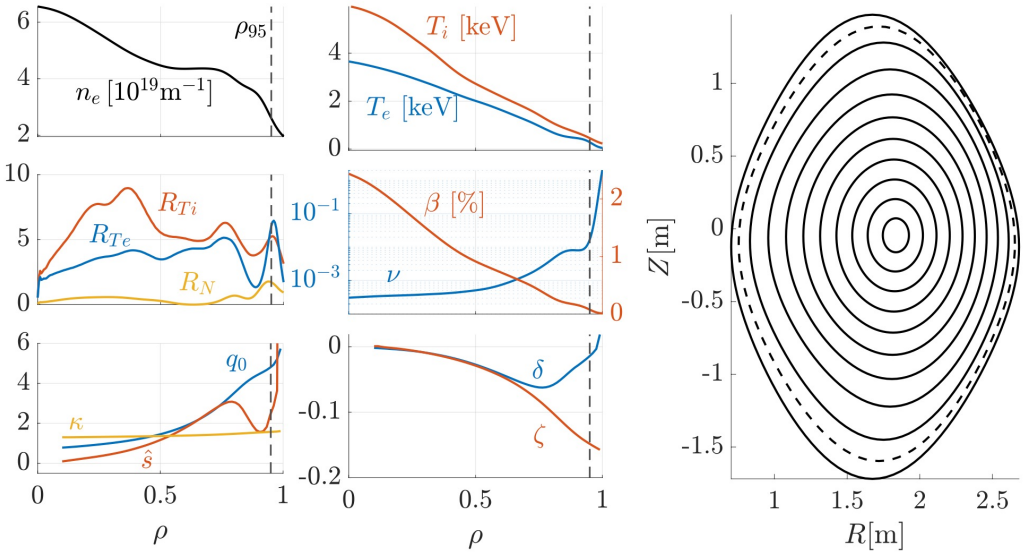
Tokamak shaping and transport

- Negative triangularity can improve confinement (TCV, DIII-D, AUG)
- **Open questions:** role of collisions, zonal flows, type of instability, globa vs local?
- Extensive computational scans required
- Tradeoff between **model fidelity** and **computational cost**



Realistic DIII-D parameters (#186473)

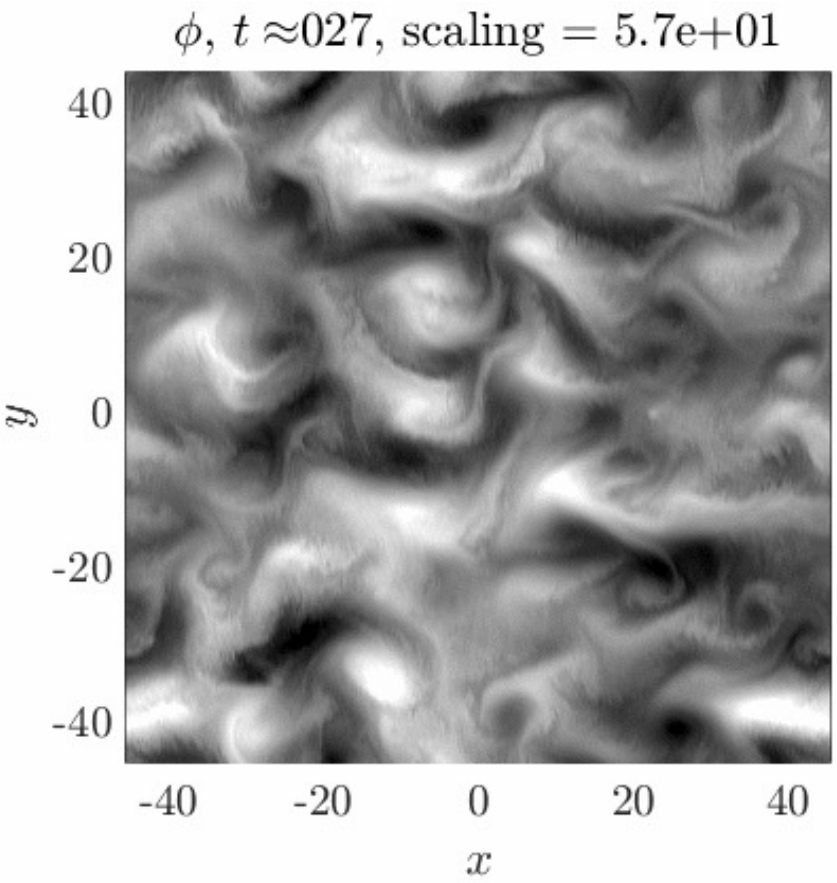


Safety factor	q_0	$= 4.8$	Density gradient	R_N	$= 1.7$
Magn. shear	$\hat{s}$	$= 2.5$	Electr. temp. gradient	R_{T_e}	$= 6.0$
Inverse aspect ratio	ϵ	$= 0.3$	Ion temp. gradient	R_{T_i}	$= 5.2$
Elongation	κ	$= 1.6$	Temperature ratio	T_i/T_e	$= 1\,(1.6)$
Elongation shear	s_κ	$= 0.5$	Mass ratio	m_i/m_e	$= 10^3\,(3.7\times10^3)$
Triangularity	δ	$= 0.0$	Collision parameter	ν	$= 1.7\times10^{-2}$
Squareness	ζ	$= 0\,(-0.15)$	Magn. pressure ratio	β	$= 7.6\times10^{-4}$

First multi-scale GM simulation

- Realistic DIII-D L-mode parameters at $\rho = 0.95$
- 10 GMs
- 768x384x24 xyz resolution
- 400 CPUh per time unit

- **ETG-ITG** coupling is observed
- Comparison between NT and PT



[15] Hoffmann and Ricci, soon available on arXiv

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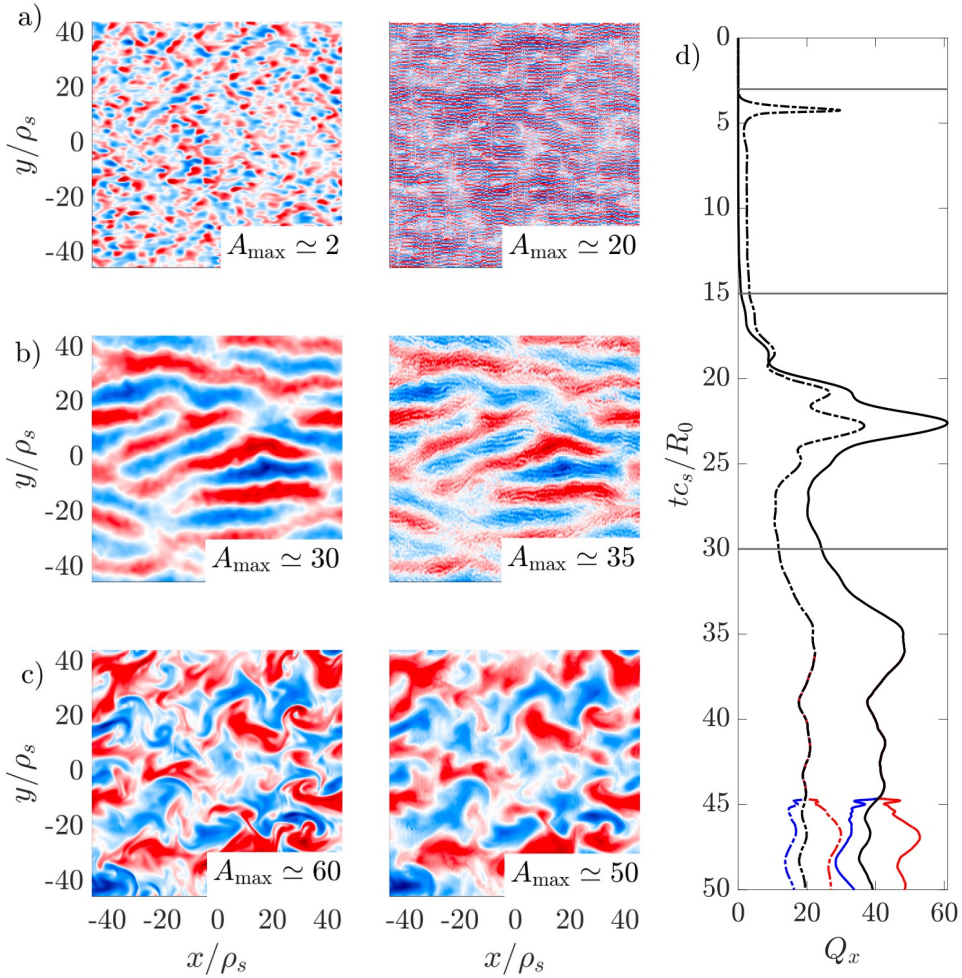


[15] Hoffmann and Ricci, soon available on arXiv

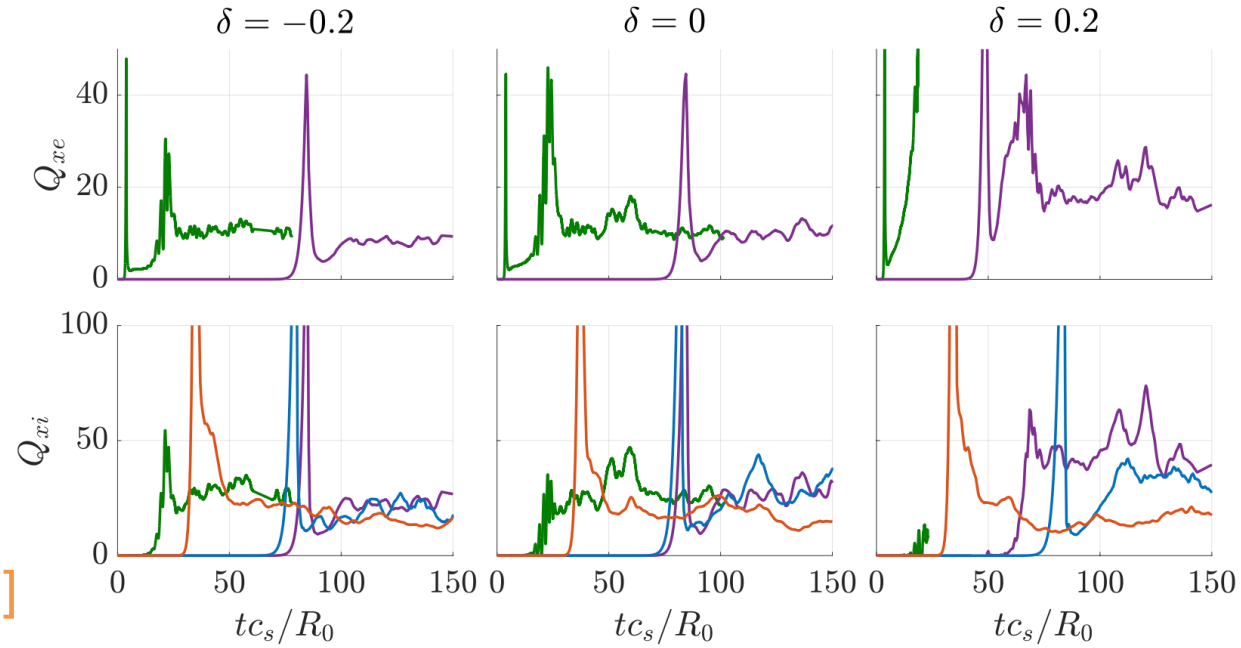
Multi-fidelity reveals triangularity mechanisms

Multi-scale

Ion-scale

Adiabatic elect.

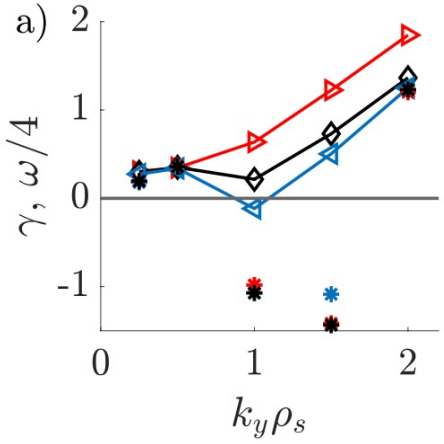
Hot elect. [16,17]

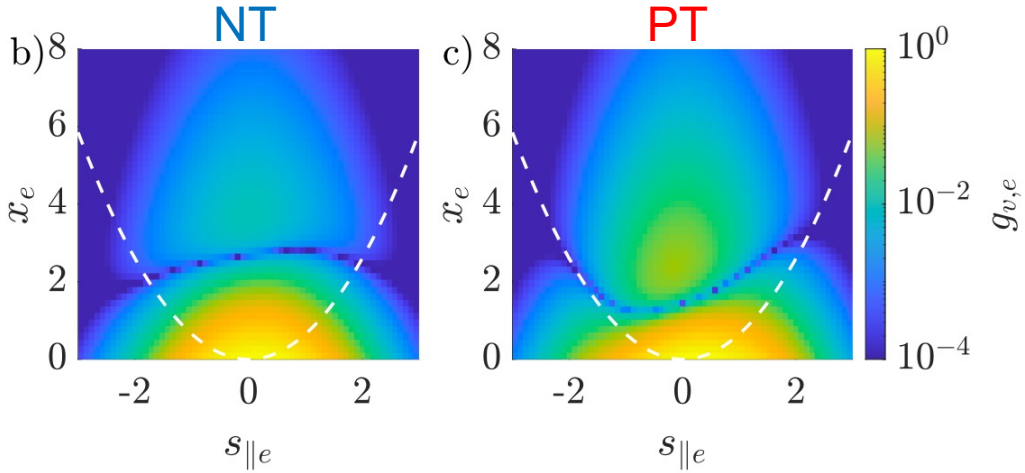


[15] Hoffmann and Ricci, soon available on arXiv
[16] Ivanov, P., Schekochihin, A., & Dorland, W. (2022). Journal of Plasma Physics, 88(5), 905880506.
[17] Hoffmann, Giroud-Garampond and Ricci, soon available on arXiv

10 GMs can evolve TEM-driven turbulence

- The **PT transport increase** is partly due to TEMs
- Comparison between PT and NT distribution function shows **TEM-like feature.**
- TEM-driven turbulence is **accessible with only 10 GMs.**

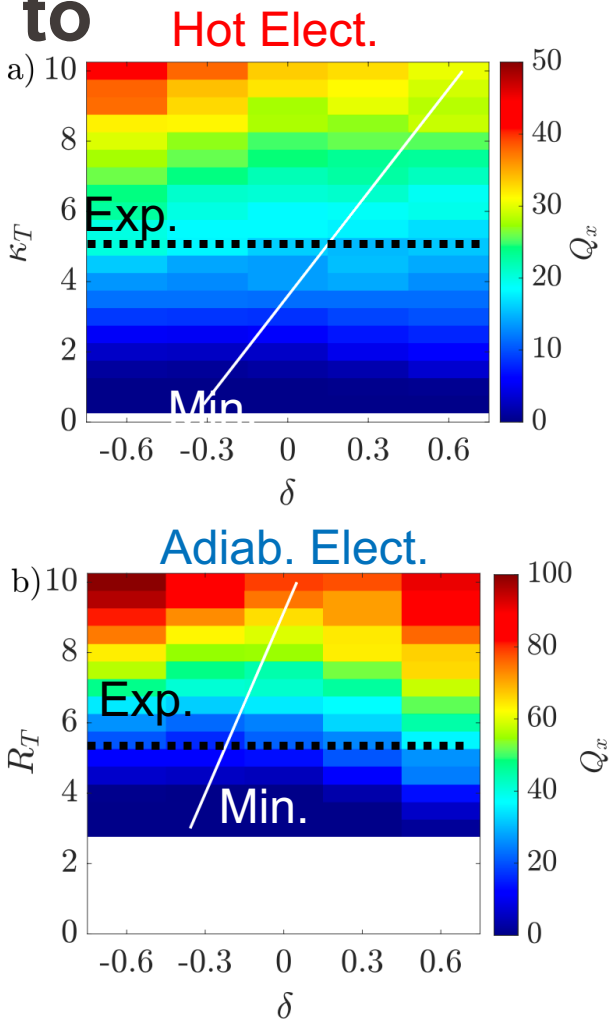




[15] Hoffmann and Ricci, soon available on arXiv

The fluid model is sensitive to shaping

- **Computationally light scans** in temperature gradient and triangularity
- Identification of **adequate regions for fluid modelling** [16,17]
- **Confinement degradation** when larger gradient (confirmed in literature)



[15] Hoffmann and Ricci, soon available on arXiv
[16] Ivanov, P., Schekochihin, A., & Dorland, W. (2022). Journal of Plasma Physics, 88(5), 905880506.
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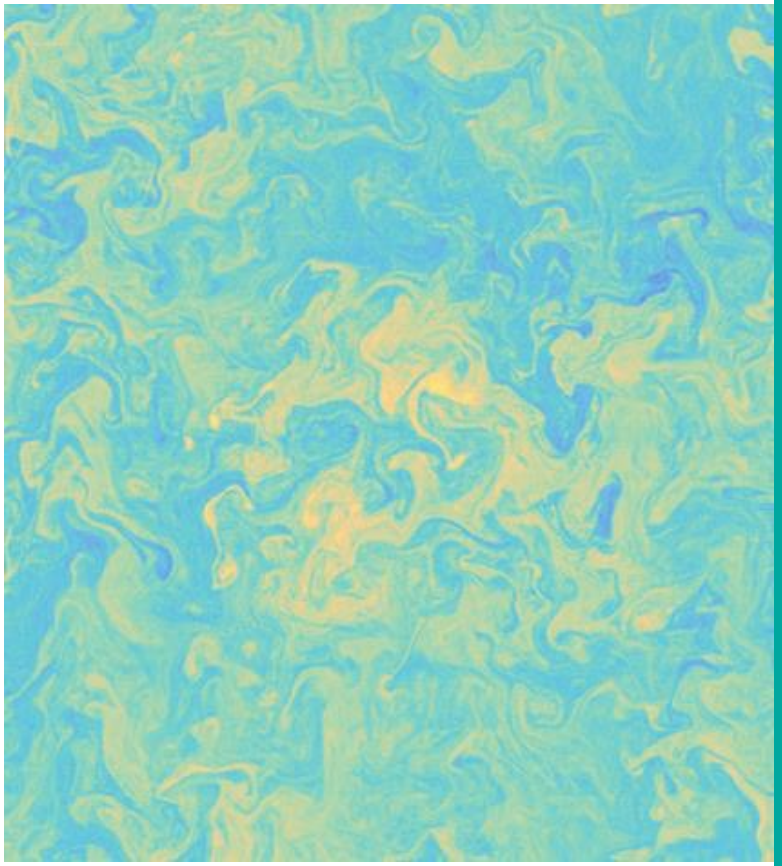
EPFL



Outline

A.C.D. Hoffmann

Swiss Plasma Center

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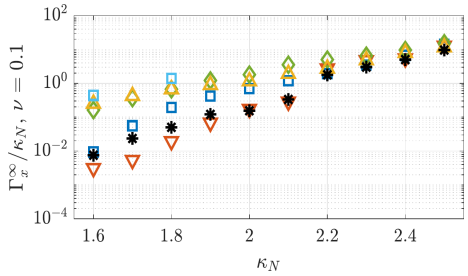
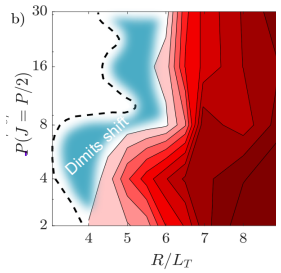
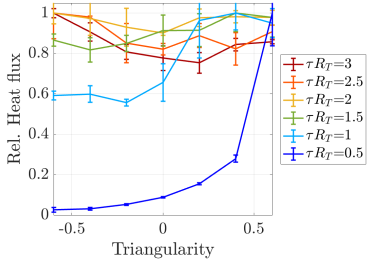
Conclusion & Outlook

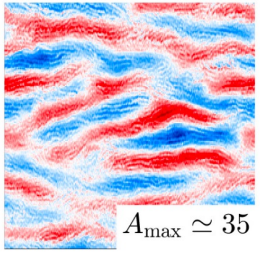
GM δf approach proved its abilities to

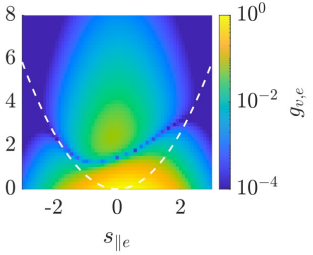
- ✓ simulate entropy mode 2D Z-pinch turb.
- ✓ **compare collision operators**
- ✓ solve the cyclone base case & Dimits shift
- ✓ **efficient in strong gradient-collisions**
- ✓ **Multiscale GK** simulations with ultra high spatial resolution are at reach (ETG-ITG, EM)
- ✓ scan turb. transport in tokamak edge relevant conditions **very fast** (multi-fidelity)









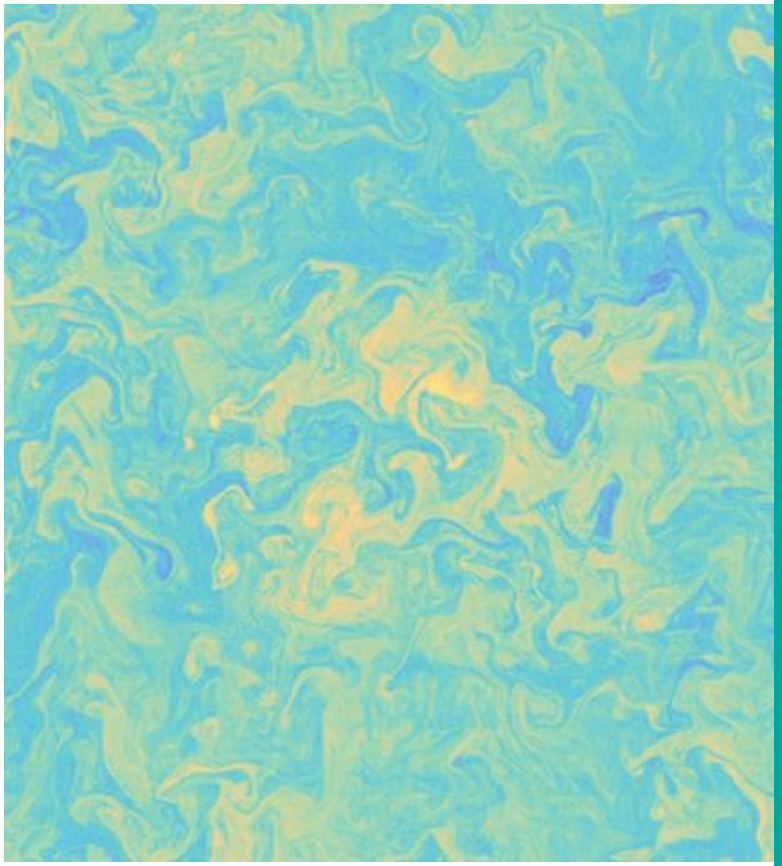


Outlooks

- ❑ Fully electromagnetic + impurities
- ❑ **Full-F** model implementation (J. Mencke) and **nonlinear collisions** (S. Ernst)

gitlab.epfl.ch/ahoffman/gyacomo

EPFL



Thank you for your attention

A.C.D. Hoffmann

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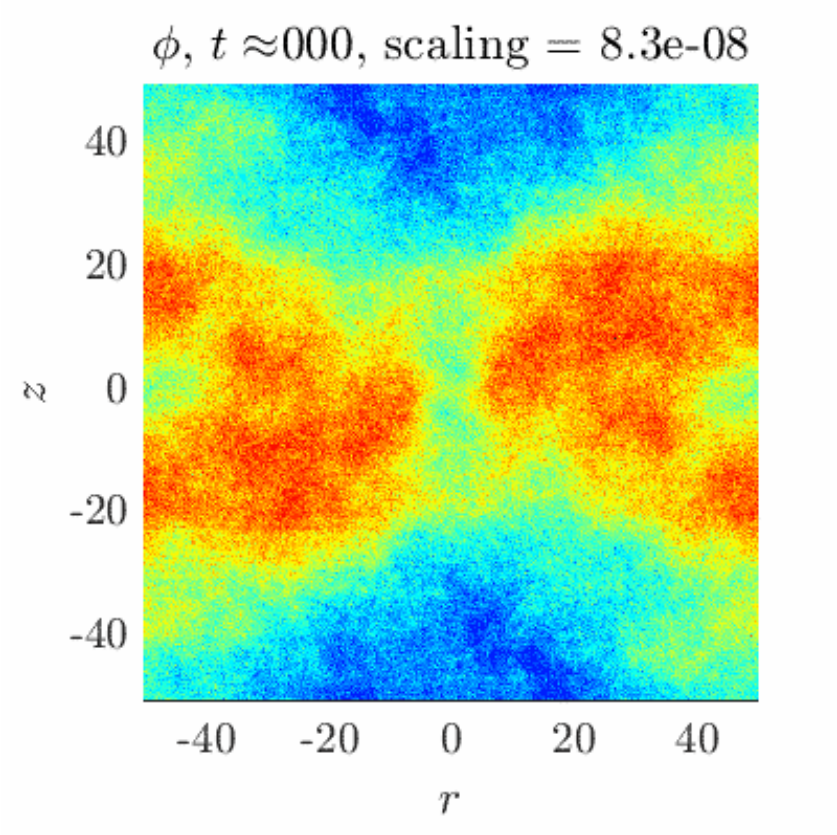

Backup slides

δf flux-tube GM hierarchy

$$\partial_t N^{pj} + \mathcal{S}^{pj} + \mathcal{M}_\perp^{pj} + \mathcal{M}_\parallel^{pj} + \mathcal{D}_N^{pj} + \mathcal{D}_T^{pj} = \mathcal{C}^{pj}$$

Nonlinear $E \times B$ term

$$\mathcal{S}^{pj} = \sum_{n=0}^{\infty} \left\{ \sum_{s=0}^{n+j} d_{njs} N^{ps}, \mathcal{K}_n \phi \right\}_{xy}$$

Gyroaveraging operator :

$$J_0(ck_\perp^2 v_\perp^2) = \sum_{j=0}^{\infty} \mathcal{K}_j(ck_\perp^2) L_j(v_\perp^2)$$

$$\mathcal{K}_j(y) = y^j e^{-y}/j!$$

$$c = \frac{1}{2}\frac{m_e T_i}{m_i T_e}$$

Projecting the ExB term and avoiding aliasing

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Bessel-Laguerre relation

$$J_0(k_\perp v_\perp) = \sum_{n=0}^{\infty} \mathcal{K}_n(k_\perp) L_n(v_\perp^2)$$

$$S_a = (ik_x J_0 \phi) * (ik_y g_a) - (ik_y J_0 \phi) * (ik_x g_a)$$

$$\mathcal{S}_a^{pj} = \int ds_{\parallel a} dx_a \left[(ik_x \overbrace{\sum_{n=0}^{\infty} \mathcal{K}_n L_n}^{J_0} \phi) * (ik_y g_a H_p L_j) - \ldots \right]$$

$$\int dv_\parallel dv_\perp \; H_p L_j$$

Commutation

$$= \sum_{n=0}^{\infty} (ik_x \mathcal{K}_n \phi) * (ik_y \int ds_{\parallel a} dx_a \, [g_a H_p L_n L_j]) - \ldots$$

Projecting the ExB term and avoiding aliasing

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A.C.D. Hoffmann

$$= \sum_{n=0}^{\infty} (ik_x \mathcal{K}_n \phi) * (ik_y \int ds_{\|a} dx_a \, [g_a H_p L_n L_j]) - \ldots$$

$$= \sum_{n=0}^{\infty} (ik_x \mathcal{K}_n \phi) * (ik_y \int ds_{\|a} dx_a \left[g_a H_p \sum_{s=0}^{n+j} d_{njs} L_s \right]) - \ldots$$

Laguerre multiplication

$$= \sum_{n=0}^{\infty} (ik_x \mathcal{K}_n \phi) * \left(ik_y \sum_{s=0}^{n+j} d_{njs} N_a^{ps} \right) - \sum_{n=0}^{\infty} (ik_y \mathcal{K}_n \phi) * \left(ik_x \sum_{s=0}^{n+j} d_{njs} N_a^{ps} \right)$$

/!\ Polynomial aliasing in sum truncation

δf flux-tube GM hierarchy

$$\partial_t N^{pj} + \mathcal{S}^{pj} + \mathcal{M}_{\perp}^{pj} + \mathcal{M}_{\parallel}^{pj} + \mathcal{D}_N^{pj} + \mathcal{D}_T^{pj} = \mathcal{C}^{pj}$$

Diamagnetic drifts

$$\mathcal{D}_N^{pj} = ik_y \kappa_N \mathcal{K}_j \phi \delta_{p0},$$

$$\mathcal{D}_T^{pj} = ik_y \phi \kappa_T \left\{ \mathcal{K}_j \left[\frac{1}{\sqrt{2}} \delta_{p2} - \delta_{p0} \right] + \left[(2j+1)\mathcal{K}_j - (j+1)\mathcal{K}_{j+1} - j\mathcal{K}_{j-1} \right] \delta_{p0} \right\}$$

δf flux-tube GM hierarchy

$$\partial_t N^{pj} + \mathcal{S}^{pj} + \mathcal{M}_{\perp}^{pj} + \mathcal{M}_{\parallel}^{pj} + \mathcal{D}_N^{pj} + \mathcal{D}_T^{pj} = \mathcal{C}^{pj}$$

Perpendicular and parallel magnetic drifts

$$\mathcal{M}_{\perp}^{pj} = \frac{\tau}{q}\mathcal{C}_{k_x k_y}\left[\sqrt{(p+1)(p+2)}n^{p+2,j} + \cdots\right.$$

$$+ \frac{\tau}{q}\mathcal{C}_{k_x k_y}\left[(2j+1)n^{pj} - (j+1)n^{p,j+1} + \cdots\right.$$

$$\mathcal{M}_{\parallel}^{pj} = \frac{\hat{B}^{-1}}{J_{xyz}}\frac{\sqrt{\tau}}{\sigma}\left\{\partial_z \aleph^{p\pm1,j} - \partial_z \ln B\left[(j+1)\aleph^{p\pm1} + \cdots\right.\right.$$

Treatment of the Bessel function and kernels

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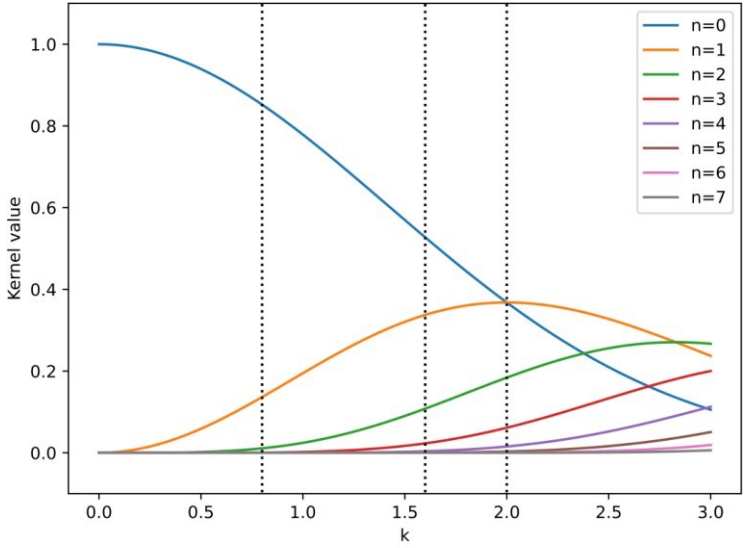


Figure 4: The first eight kernel functions

$$J_0(kv_\perp) = \sum_{n=0}^{\infty} K_n(k) L_n(v_\perp^2) \quad \text{with} \quad K_n(k) \underset{y=k^2/4}{=} \frac{y^n}{n!} e^{-y}$$

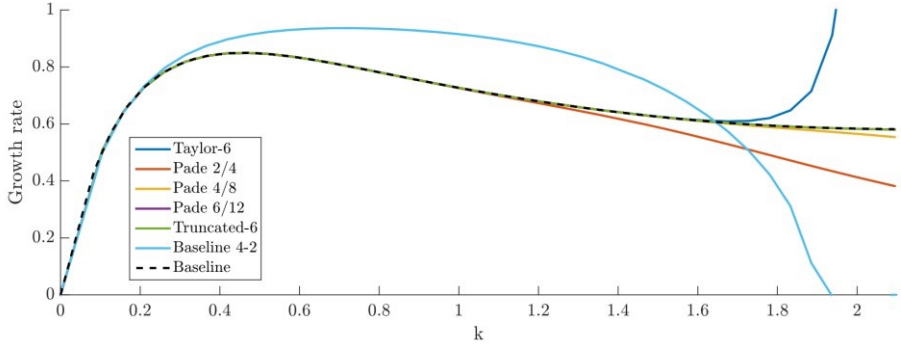
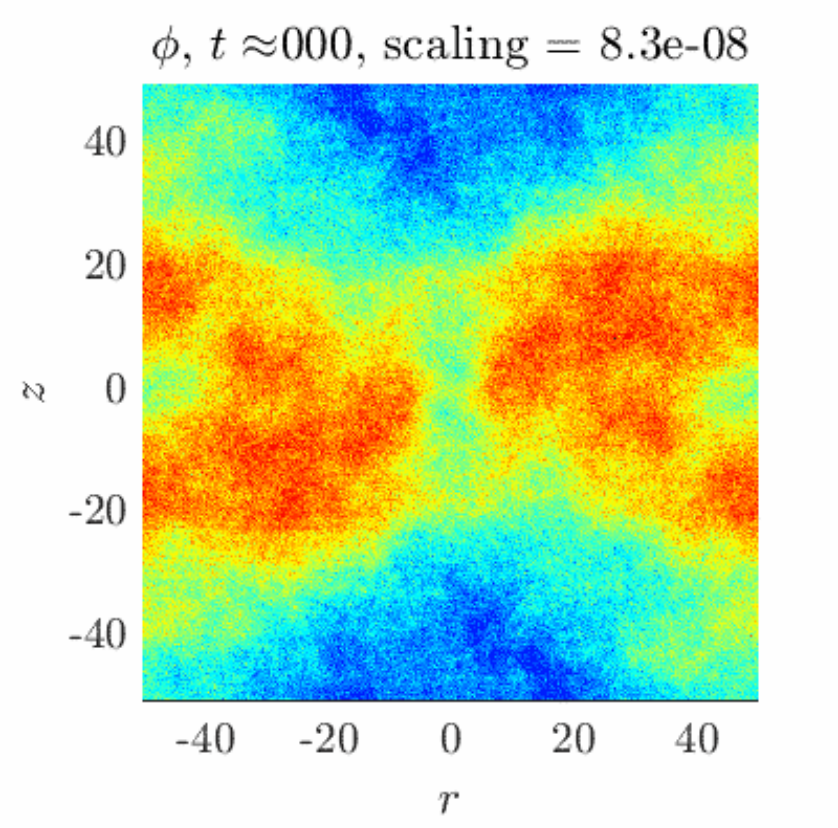


Figure 6: Growth rate found using the linear solver for different kernel approximation methods with $P_{max} = 30$, $J_{max} = 15$ for all methods except *Baseline 4-2*

Semester Project, L. Driever 2022

Movies of Z-pinch turbulence



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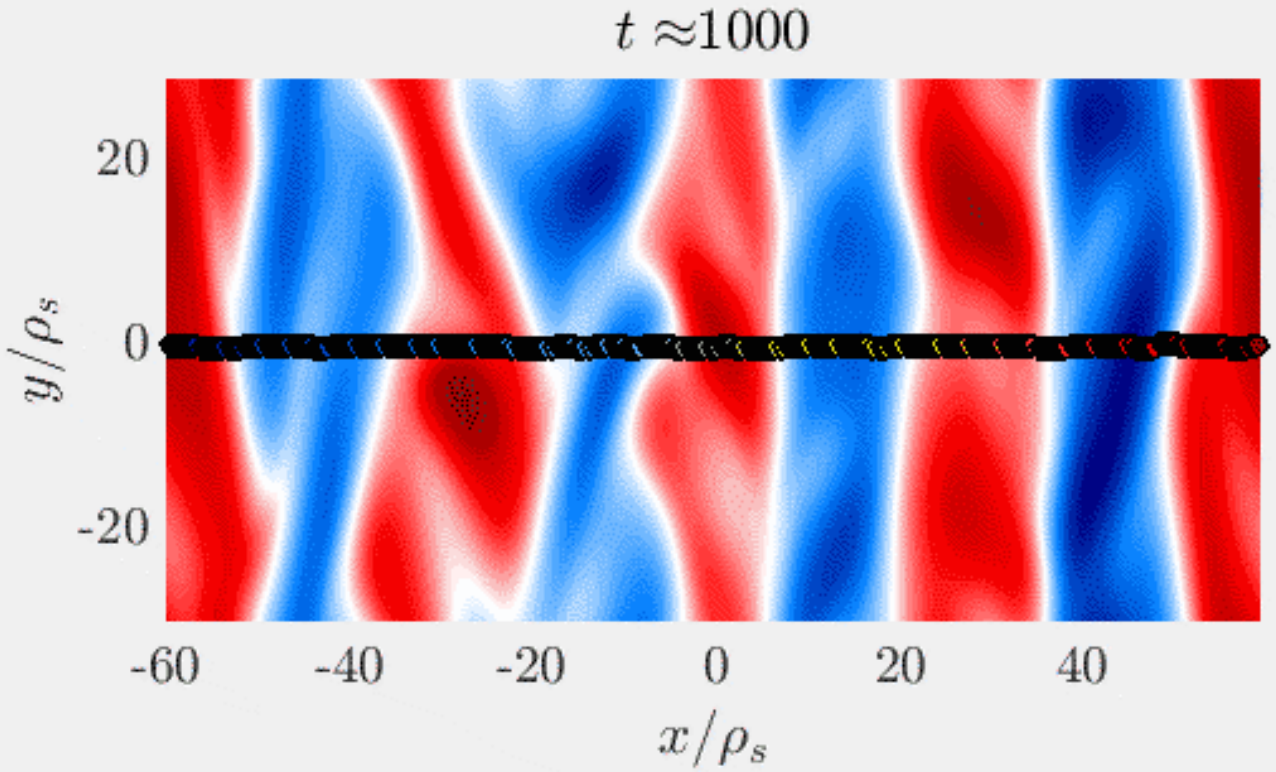
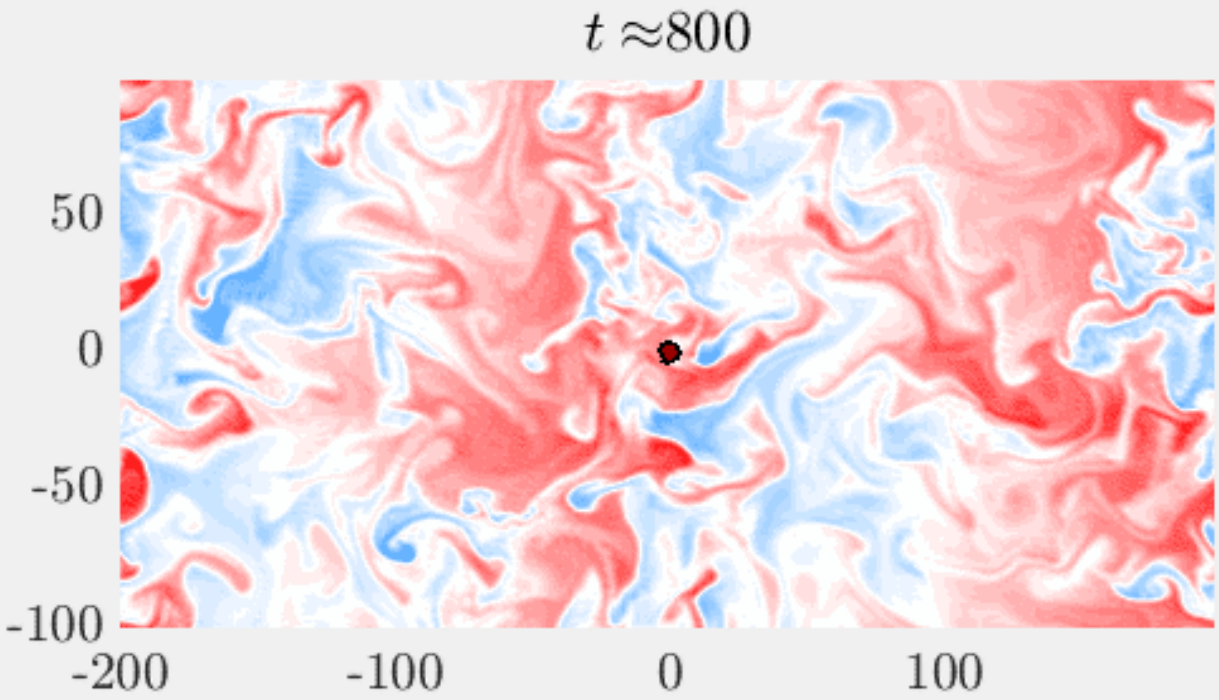
The particle point of view



[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

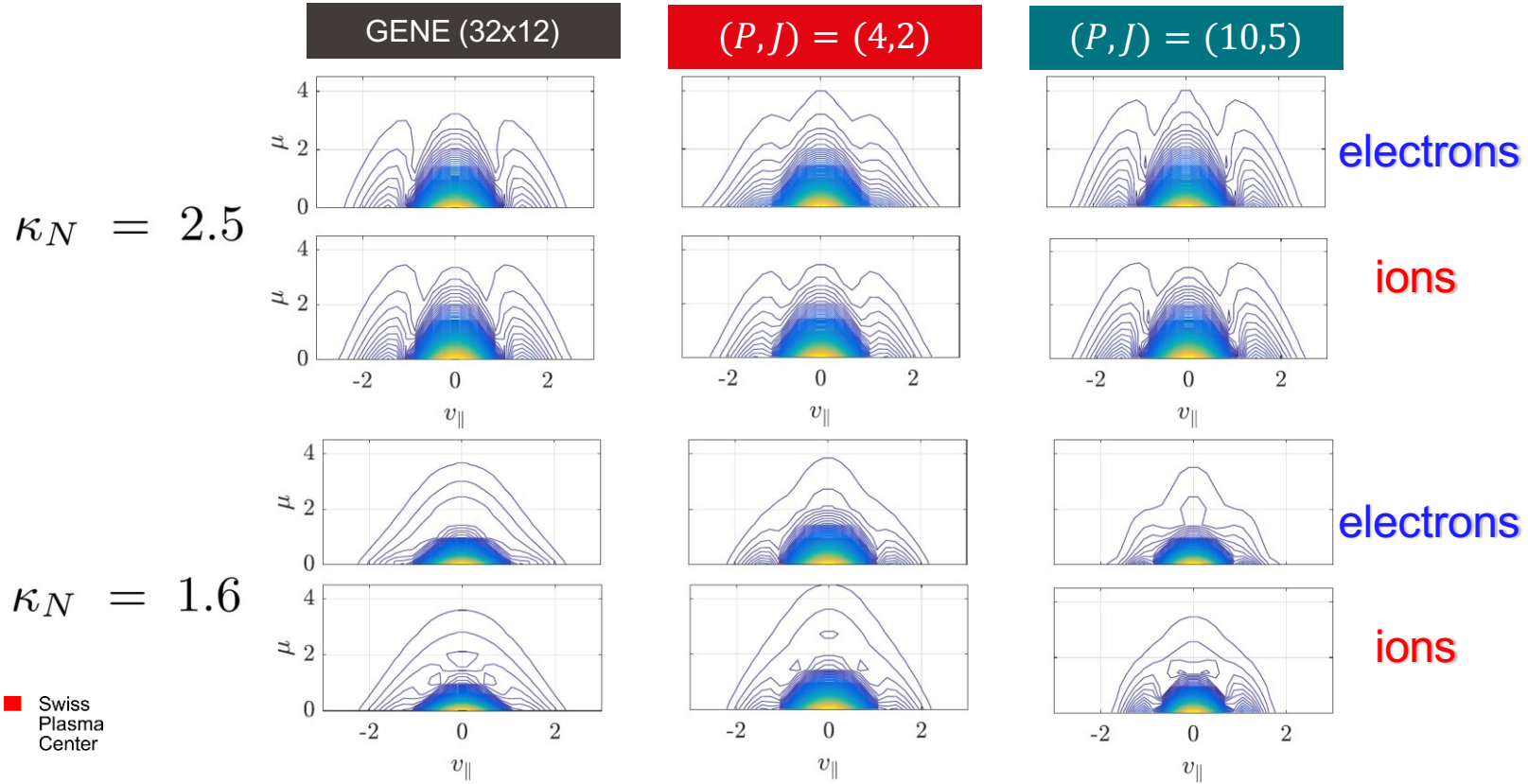
The particle point of view



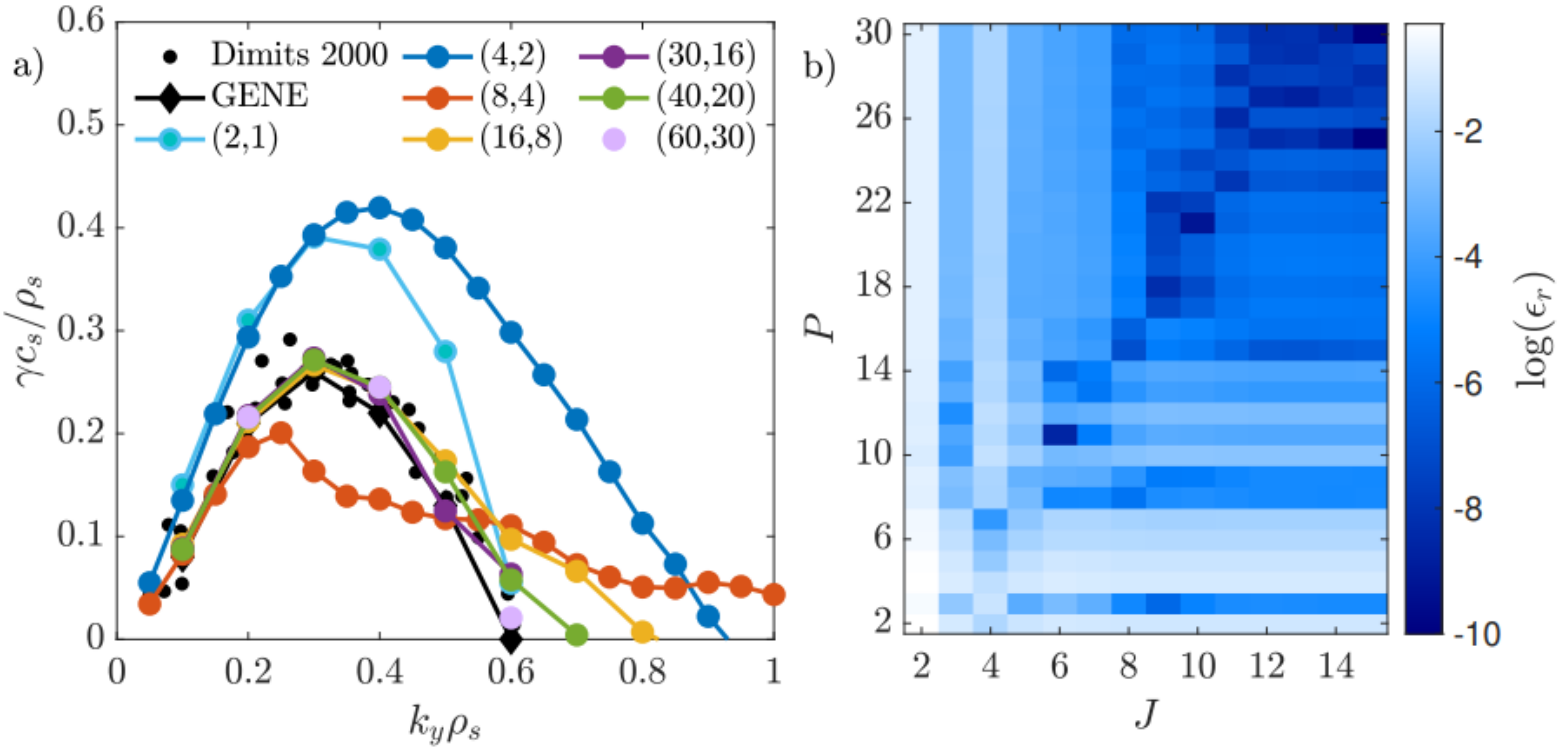
[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023 (2), 905890214.

A.C.D. Hoffmann

Z-pinch: velocity distribution function

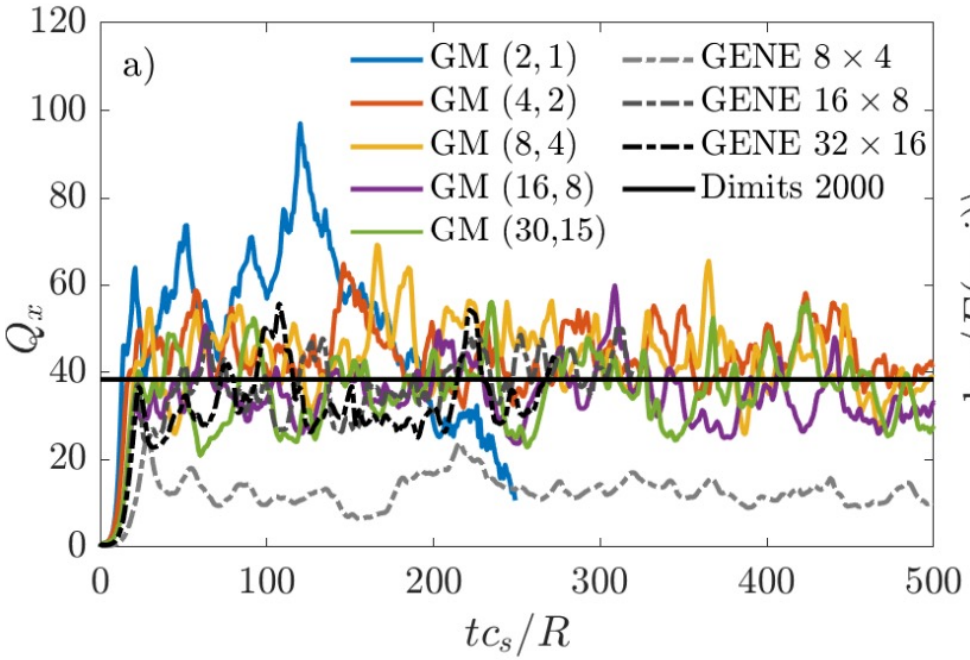


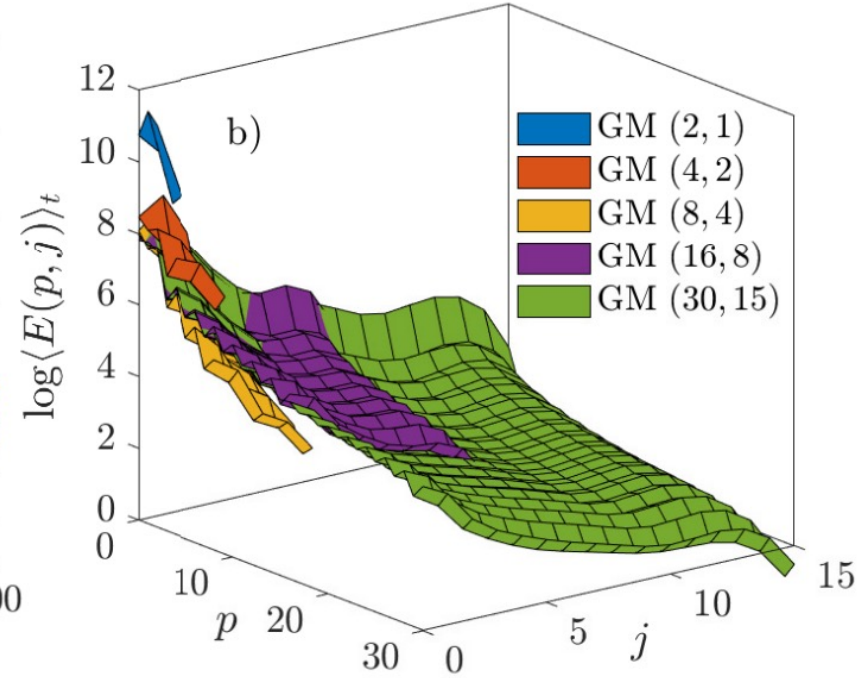
Cyclone base case [1] :
linear ITG convergence analysis



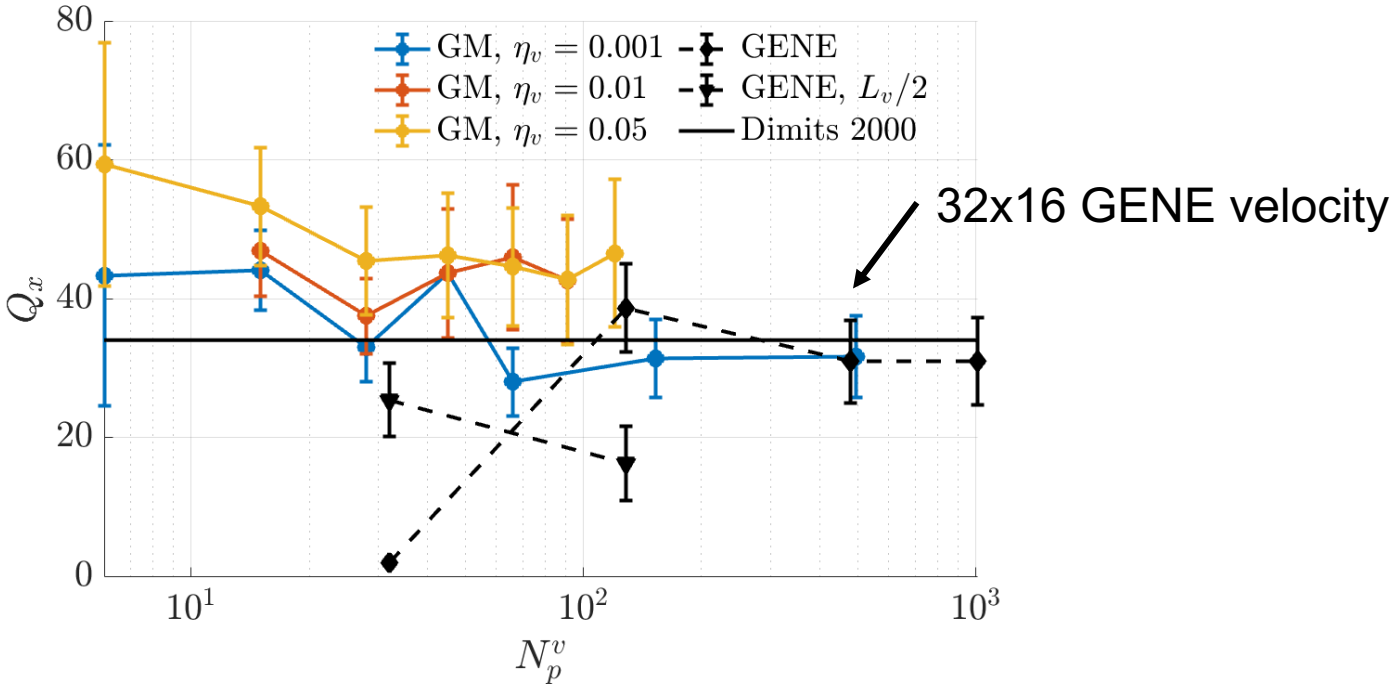
[1] Dimits et al. 2000 Phys. Of Plasma 7

CBC Nonlinear results



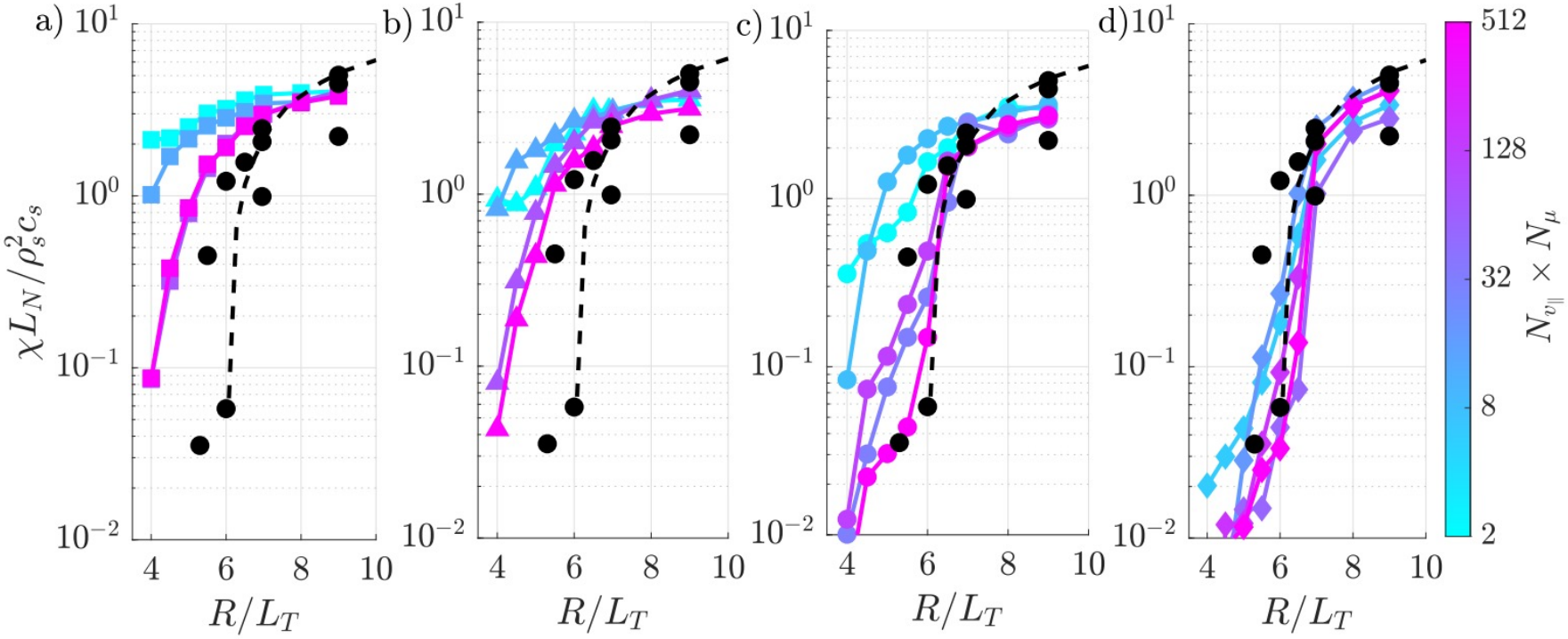


GM is efficient and improves with collisions



[11] Hoffmann, A.C.D., Frei, B.J. & Ricci, P. 2023, submitted to JPP, available on arXiv

Detailed convergence study



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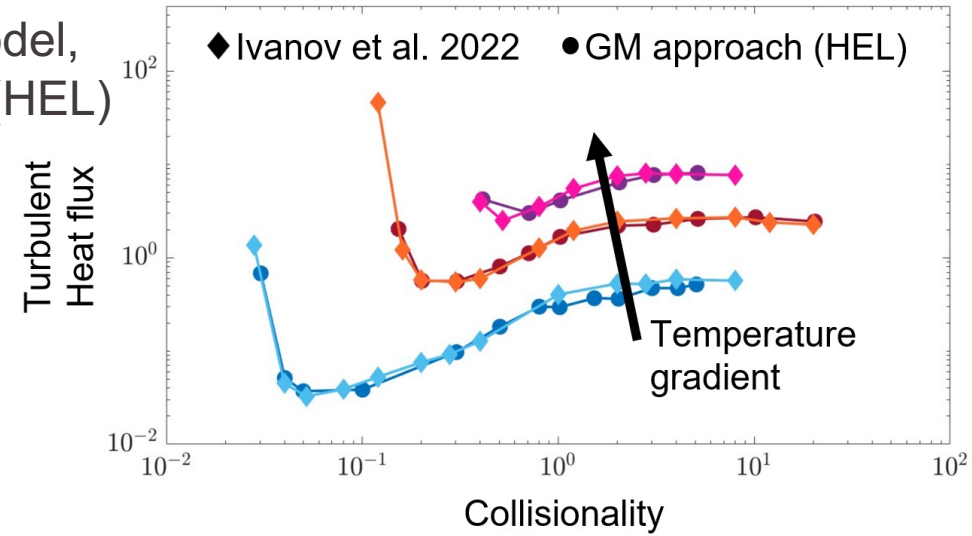
GM multi-fidelity

GMs can be used to bridge towards reduced models

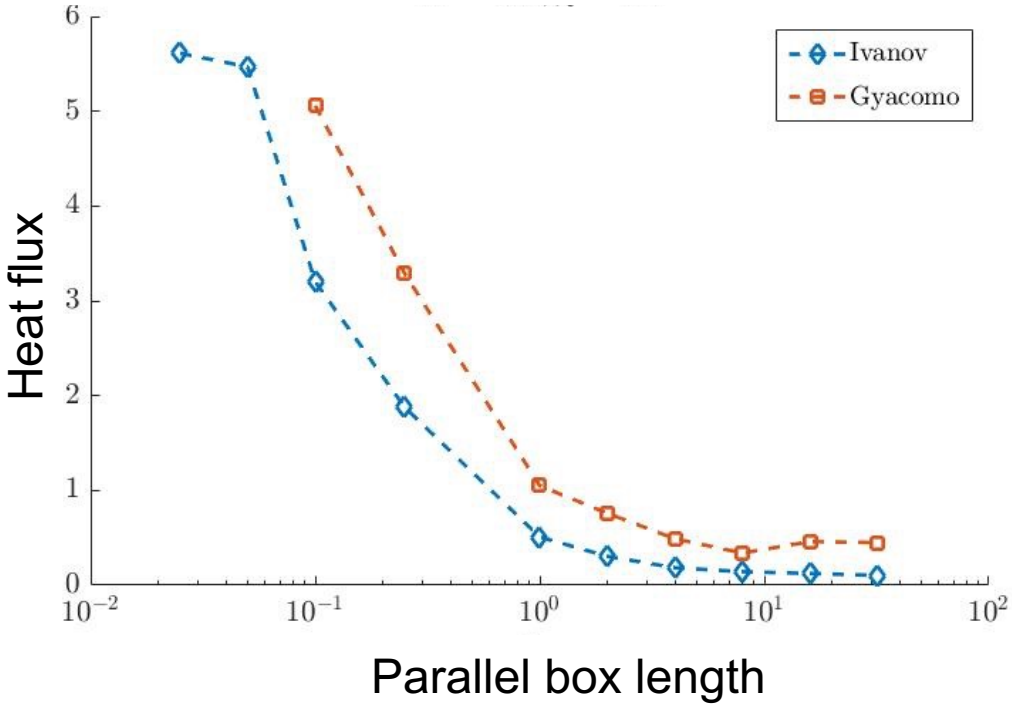
- **Ivanov et al. 2022 [13]:**
  Reduced three moments GK model, for $T_i/T_e \ll 1$ hot electrons limit (HEL) in a 3D Z-pinch geometry.
- In the HEL, **the GM model is analytically equivalent** [14]
- Numerical validation setting $T_i/T_e = 10^{-3}$ (we evolve $\mathrm{N}^{00}, \mathrm{N}^{10}, \mathrm{N}^{20}, \mathrm{N}^{01}$)



[13] Ivanov, P., Schekochihin, A., & Dorland, W. (2022). Journal of Plasma Physics, 88(5), 905880506.
[14] Hoffmann, Giroud-Garampond and Ricci, soon available on arXiv

Reduced model equivalency

3D Z-pinch, heat flux vs. parallel box length



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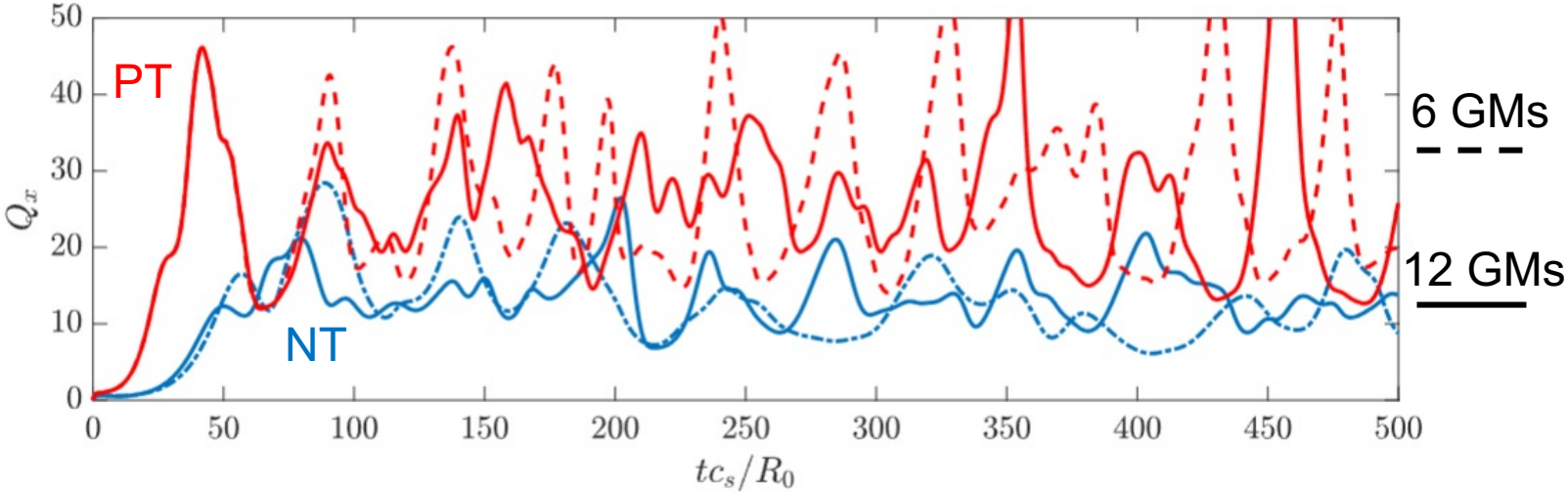
GM retrieves negative triangularity effects

- NT impact is observed at coarse velocity resolution



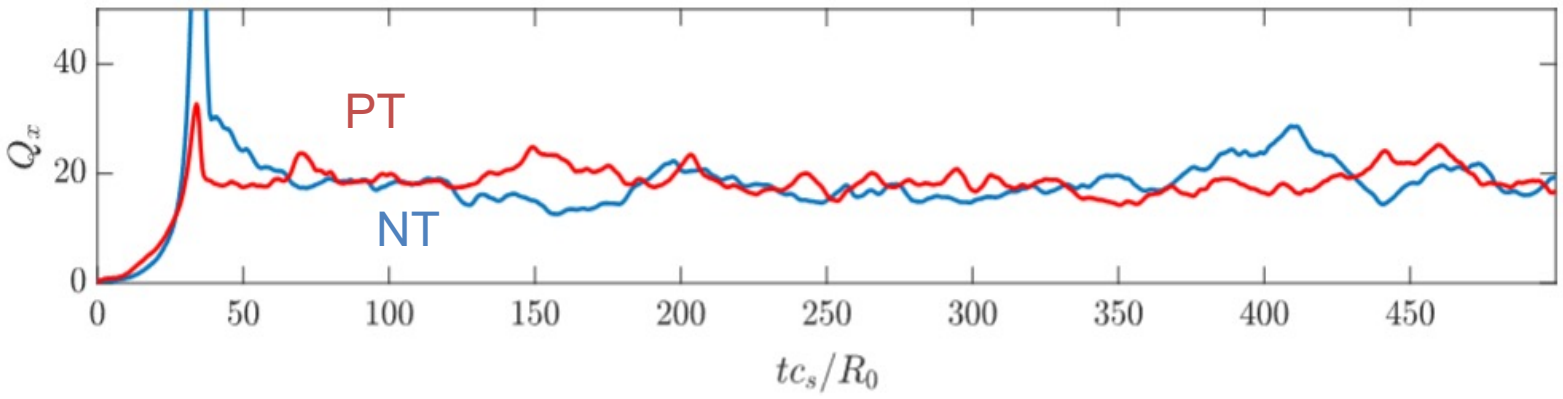
How much can we reduce the model?

[15] W. Boyes et al 2023 Nucl. Fusion 63 086007

Simplification of the model

Hot electrons limit

- Setting $\tau = 0.001$ in the GM code and scaling the gradients τR_T

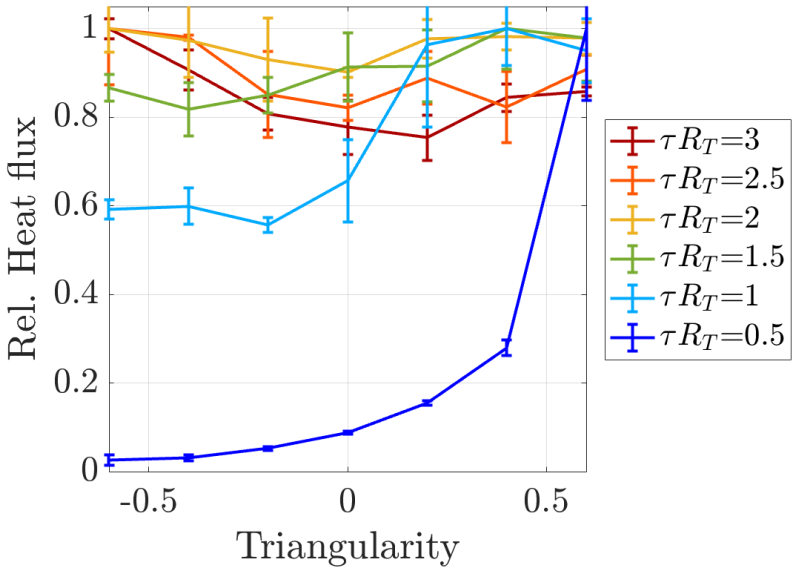


NT impact is lost. Why?

[16] Ivanov, P., Schekochihin, A., & Dorland, W. (2022). Journal of Plasma Physics, 88(5), 905880506.
[17] Hoffmann, Giroud-Garampond and Ricci, soon available on arXiv

Hot electrons limit and edge shaping

- **HEL allows to run inexpensive nonlinear scans**
- Triang. is detrimental (also observed in Merlo et al. 2023)



❖ Triang. Effect is observed **at lower gradients**

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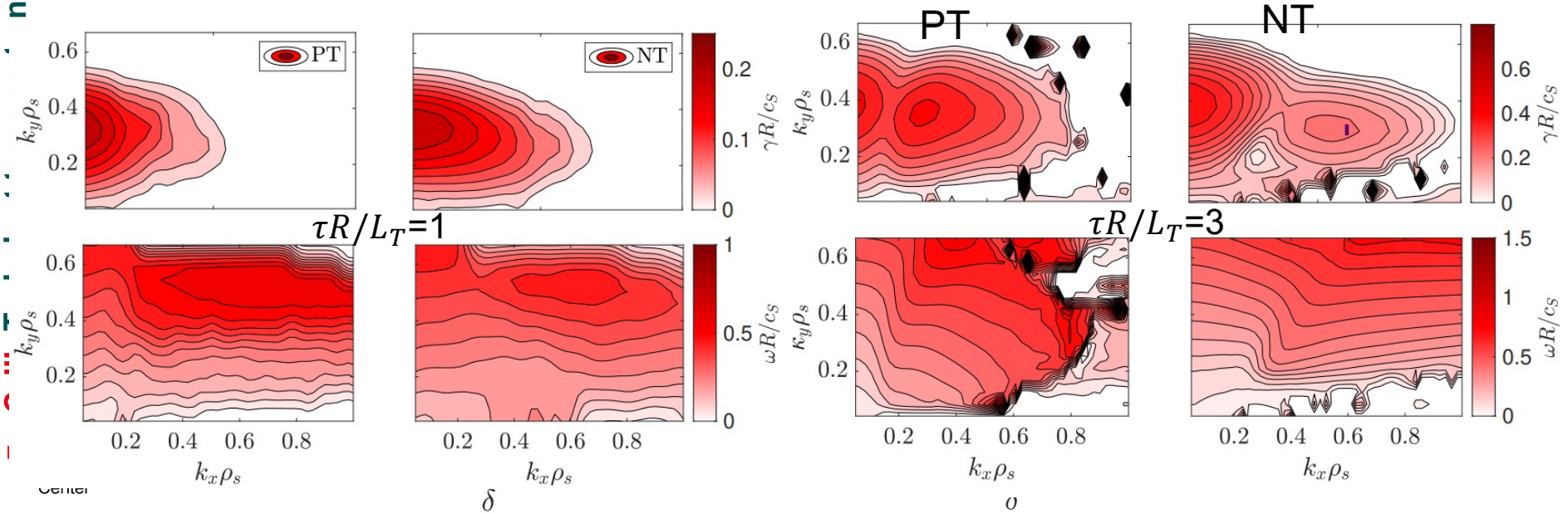
GM multi-fidelity

Application to tokamak edge shaping

- Hot electron limit **extensive scan**
- NT improvements vanish for large gradients and triang. becomes detrimental (also observed in Merlo et al. 2023)

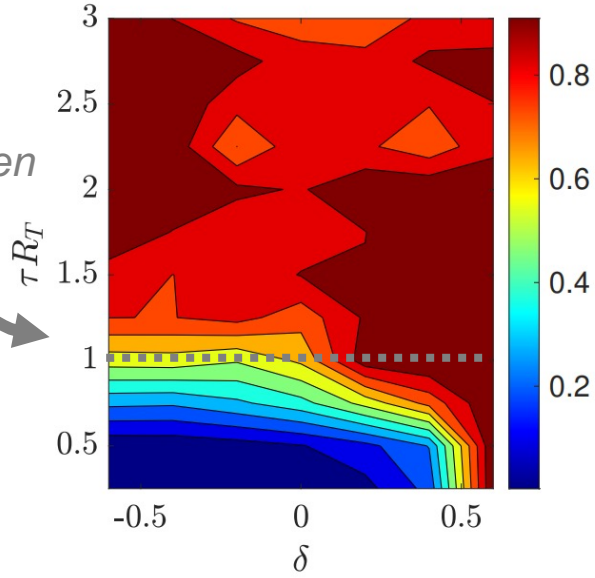


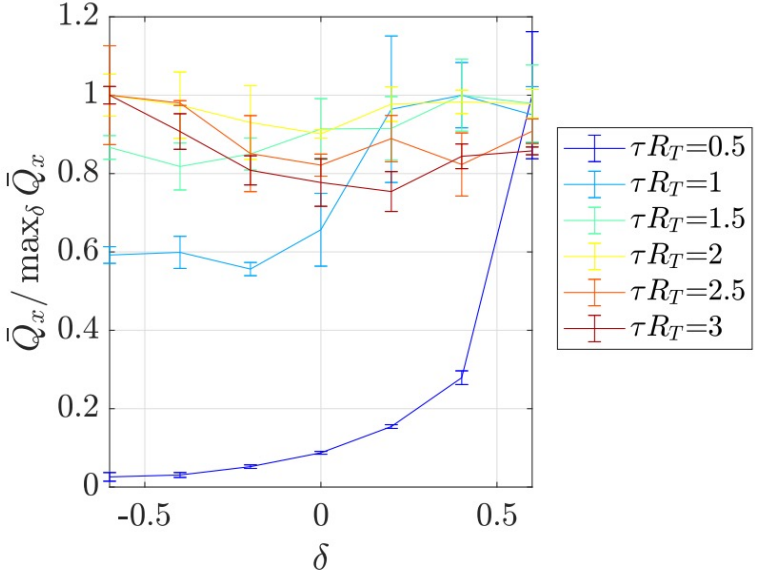
GM multi-fidelity

Application to tokamak edge shaping

- Hot electron limit **extensive scan**
- NT improvements vanish for large gradients and triang. becomes detrimental (also observed in Merlo et al. 2023)

Something must happen here





GM multi-fidelity
Application on tokamak edge shaping

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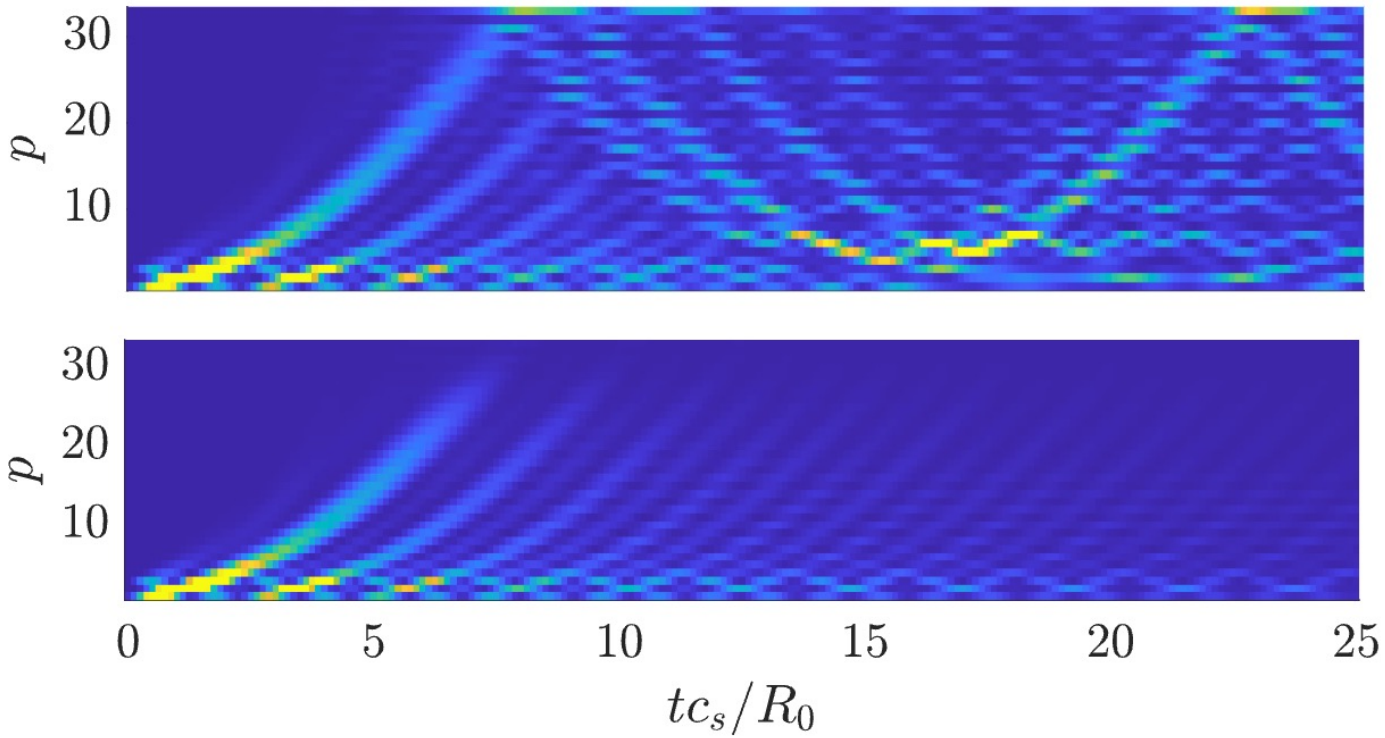
- The hot electron limit reduces the GM equations to

$$\partial_t n + \{n, \phi\} + \tau \left\{ T_\perp, \frac{k_\perp^2}{2}\phi \right\} = -\frac{\tau}{q}\mathcal{C}_{k_x k_y}\left(\sqrt{2}T_\parallel - T_\perp\right) - \left(2\mathcal{C}_{k_x k_y} + R_N i k_y\right)\phi$$

$$\partial_t T_\perp + \{T_\perp, \phi\} = R_T i k_y \phi, \qquad \partial_t T_\parallel + \{T_\parallel, \phi\} = -\frac{\sqrt{2}}{2} R_T i k_y \phi$$

Rosenbluth-Hinton test and echoes



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Collision matrices and eigen values