# GK microturbulence investigations in stellarators towards anomalous optimization

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FACT Present main optimization lines (QI,QA,QH) have **not** addressed turbulent (anomalous) transport (AT)

REASON **3D** GK turbulence simulations are **very recent**, e.g.

T.-H.Watanabe, H.Sugama, S.Ferrando-Margalet, PRL 100 (2008)

P.Xanthopoulos, F.Merz, T.Görler, F.Jenko, PRL 99 (2007)

## Key questions

1. Is AT important in optimized stellarators, and if **yes**...
2. Do 3D features affect AT level/structure, and if **yes**...
3. Are there realistic methods for reducing AT, and if **yes**...
4. Do these comply with or contradict present optimizations?

# Introduction (2/2)

This presentation investigates the impact of 3D geometry on the ZF response ($k_y = k_\parallel = 0$) for collisionless electrostatic ITG-ae turbulent transport by analyzing:

1. The effect of drift optimization in **W7X** comparing realistic standard vs. low mirror configurations
2. The effect of local shear and geodesic curvature in **NCSX** via a numerical modification

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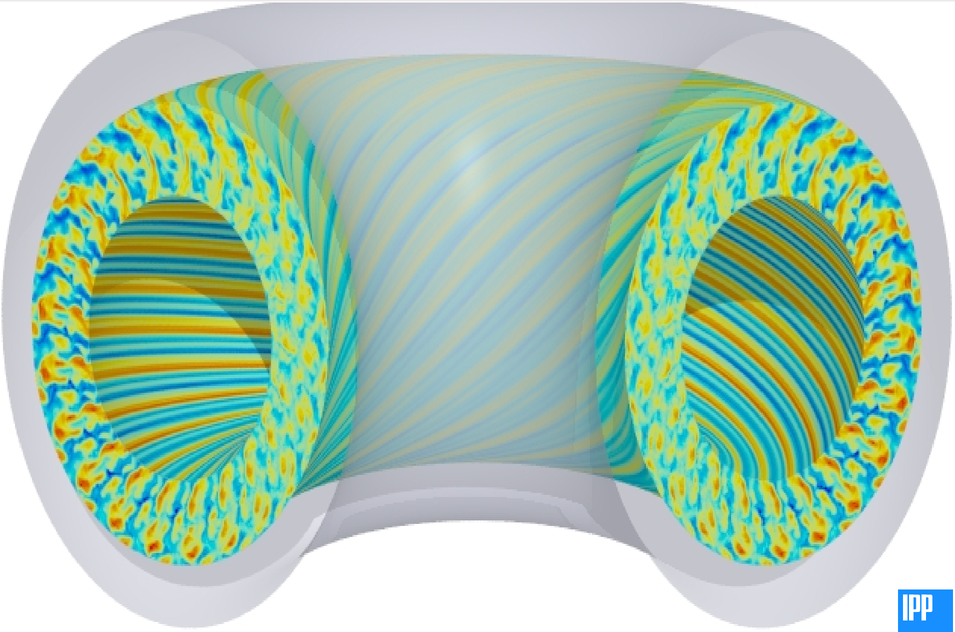
# The nonlinear GK code GENE

Developers: F.Jenko, T.Dannert, T.Görler, F.Merz, M.Püschel, D.Told ...

- Eulerian solver of the gyrokinetic Vlasov-Maxwell equations on $(x, y, z, v_{\|}, \mu)$ grid (initial value or eigenvalue mode)
- Includes multispecies (fully gyrokinetic), collision operators, electromagnetic effects
- Excellent scaling up to at least 32K processors on BlueGene/L
- Flux-tube domain in 3D, global for circular tokamak

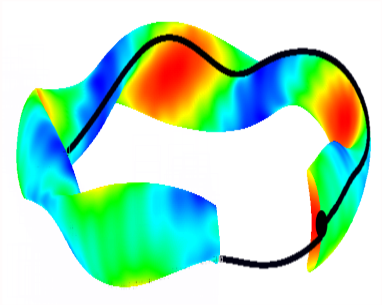
For more info please visit: **www.ipp.mpg.de/∼fsj/gene**

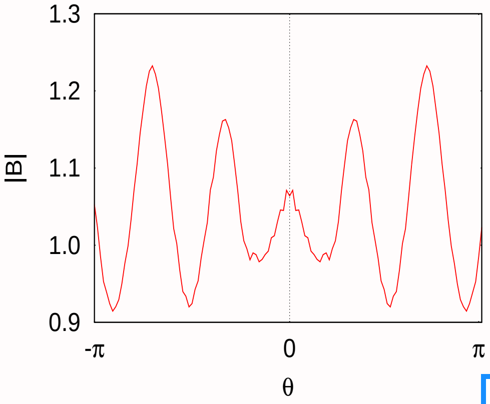


# GIST : Geometry Interface for Stellarators and Tokamaks

with: W.Cooper, Yu.Turkin, A.Runov, J.Geiger **PoP 16 082303 (2009)**

- 3D/2D geometry for GK codes using VMEC/EFIT equilibria
- Extensively tested and thoroughly documented





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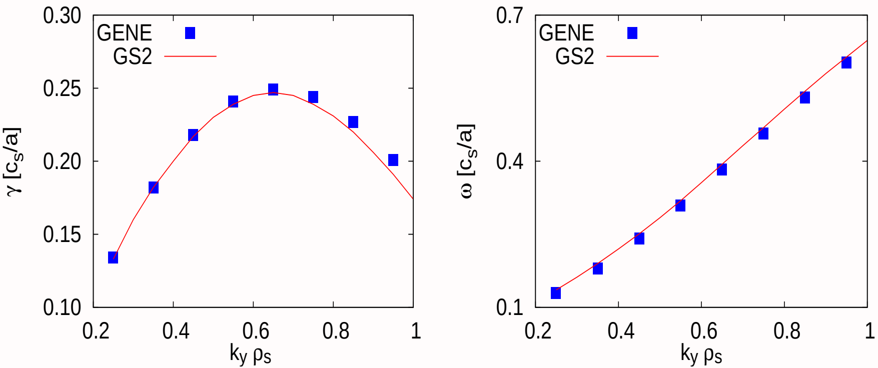
# GENE vs. GS2 for DIII-D/VMEC

with: D.Mikkelsen, W.Dorland **PoP 15 122108 (2008)**




Invariance under coordinate transformations implies

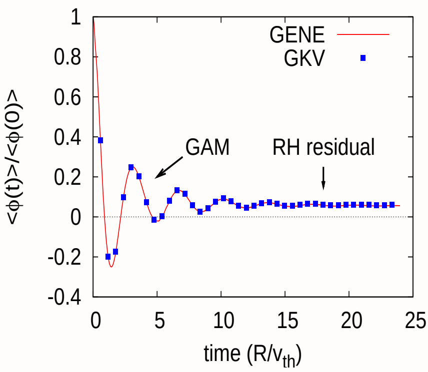
$$(d\ln T_i/d\rho)^{GENE} = \frac{\alpha}{\rho_0}(d\ln T_i/d\rho)^{GS2} \quad \& \quad k_y^{GENE} = \frac{\rho_0}{\alpha}k_y^{GS2}$$

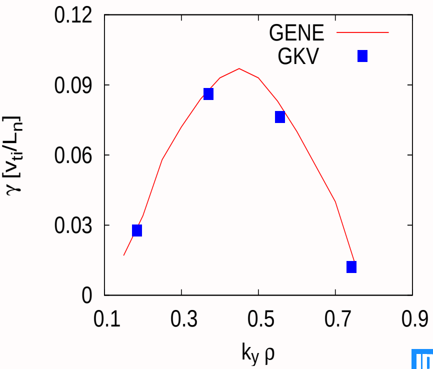
# GENE vs. GKV for LHD standard configuration

with: H.Sugama, T.-H.Watanabe (private communication)

Initial zonal perturbation $\phi_{k_x}(0)$ evolves as a superposition of

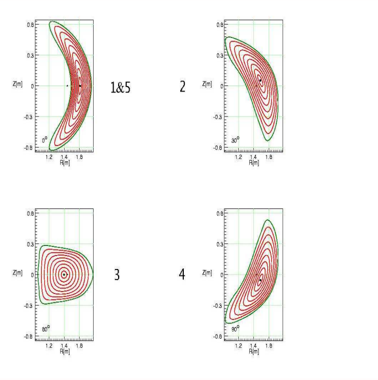
1. A damped oscillating **Geodesic Acoustic Mode (GAM)**
2. A zero-frequency undamped **(Rosenbluth-Hinton) residual**

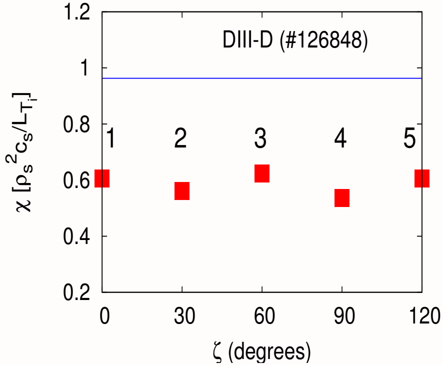


# Cross-machine comparison: **NCSX vs. DIII-D** $(\rho/a = 0.8)$

ITG-**ae** turbulence comparable among stellarators & tokamaks



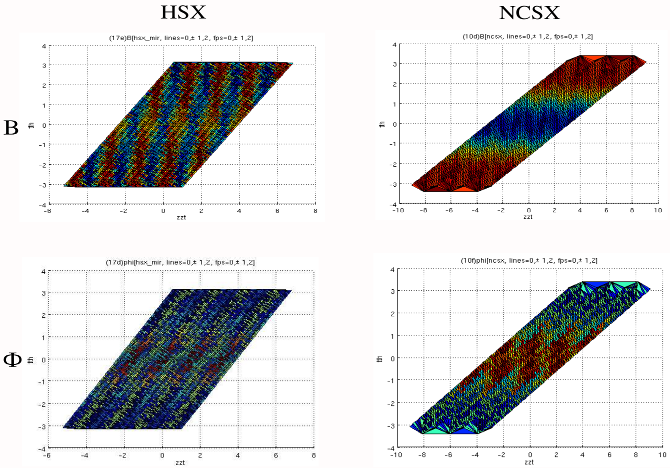




Small $\chi_i$ variation for NCSX is **non**trivial; metrics **do** change

# Geometry dependence of ITG turbulence (GENE/GIST@PPPL)

with: H.Mynick, A.Boozer **PoP Letters, to appear**

ITG-**ae** turbulence **balloons** outboard even for QH configuration



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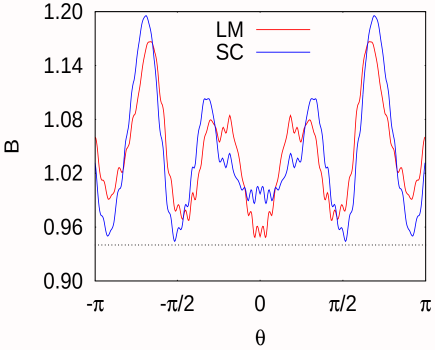
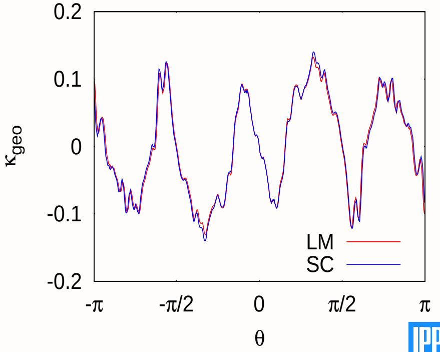
## Geometry

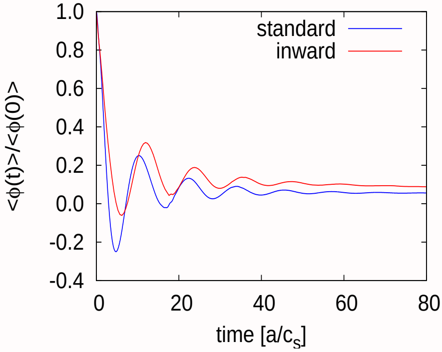
- We compare W7X/SC vs. W7X/LM (reduced $b_{0,1}$, **same q**) following LHD paradigm [H.Sugama et al., PFR 3 (2008)]
- For **SC** smaller effective ripple is predicted than for **LM** [C.Beidler, H.Maassberg, PPCF 43 (2001)]

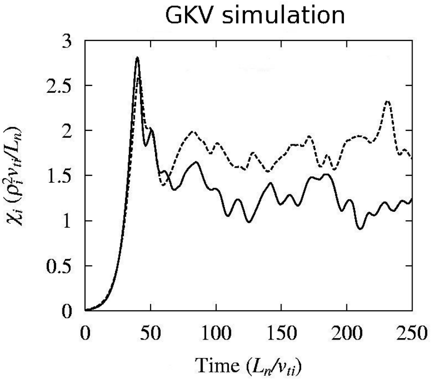


# The LHD paradigm

A drift-optimized LHD configuration **(Inward Shifted)** demonstrates lower ITG transport levels in view of **slower GAM damping + larger RH residual**



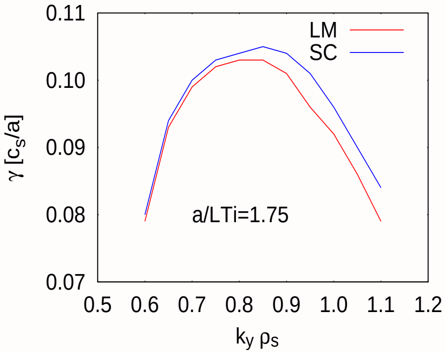

**Dashed: STANDARD**

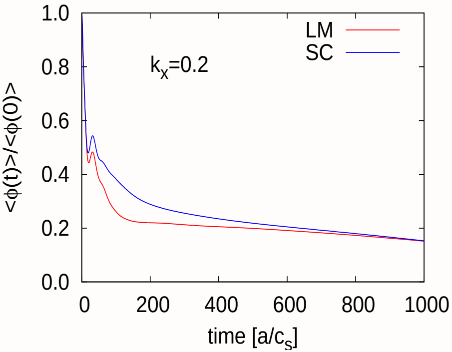
**Solid: INWARD-SHIFTED**

# Effect of drift optimization in W7X (2/4)

## Linear physics

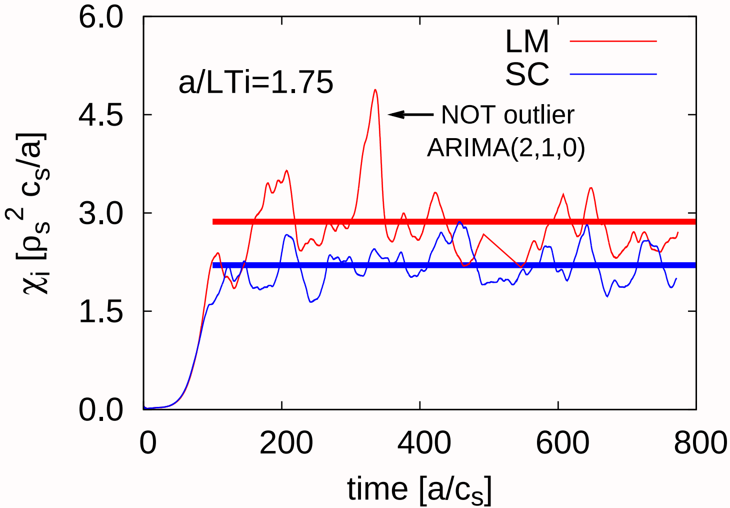
**SC** manifests larger growth rates <u>but</u> slower GAM damping



**NL simulation: $96 \times 128 \times 512 \times 128 \times 32$**

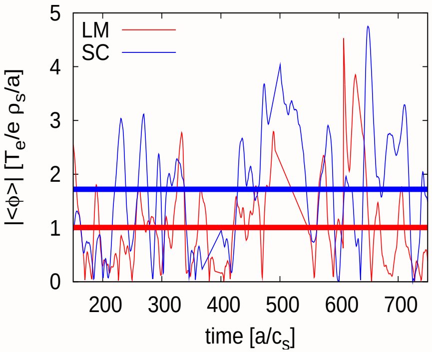
**SC** demonstrates smaller $\chi_i$ ($\approx$ 25%) than **LM**

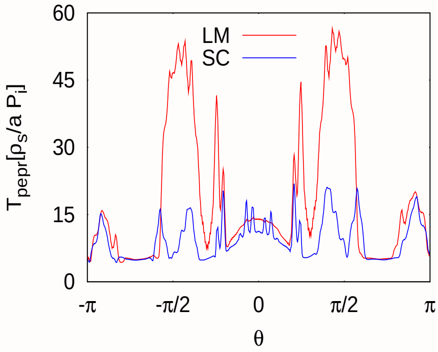


# Effect of drift optimization in W7X (4/4)

## NL simulation – Diagnostics

**SC** shows low trapped particle activity and increased ZF level



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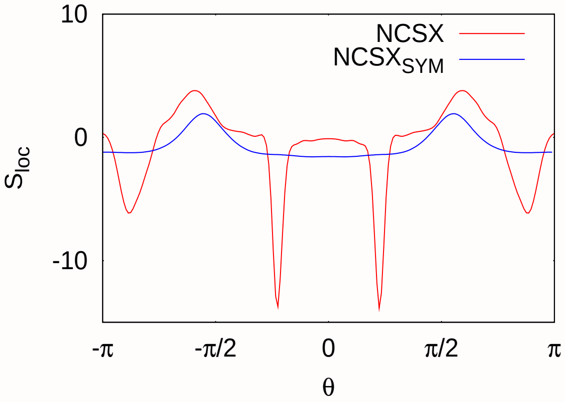
# Effect of local shear in NCSX

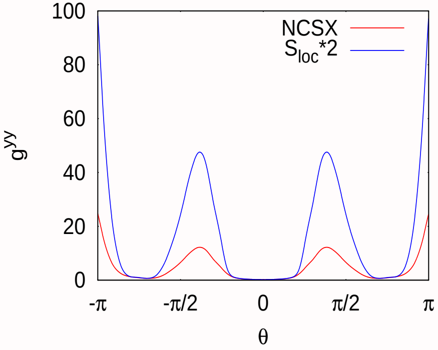
Local shear $\frac{d}{d\theta}\left(\frac{g^{xy}}{g^{xx}}\right)$ important for stellarators

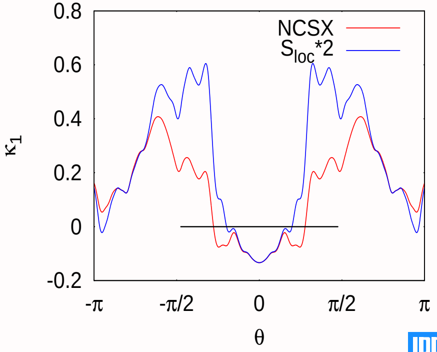


## Geometry

We uniformly double local shear (via $g^{xy}$) for NCSX/S3 and

- Adjust $g^{yy} = \frac{B_N^2+(g^{xy})^2}{g^{xx}}$ (field alignment constraint)
- Adjust $\kappa_1 = \frac{1}{\sqrt{g^{xx}}}\left(\kappa_{nor} + \frac{g^{xy}}{B_N}\kappa_{geo}\right)$

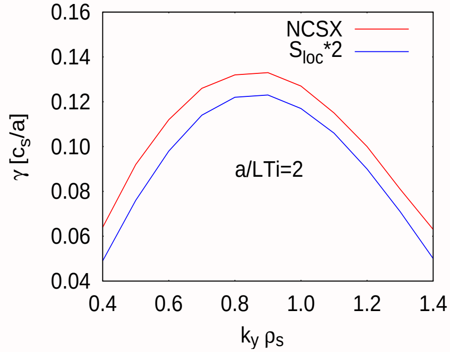


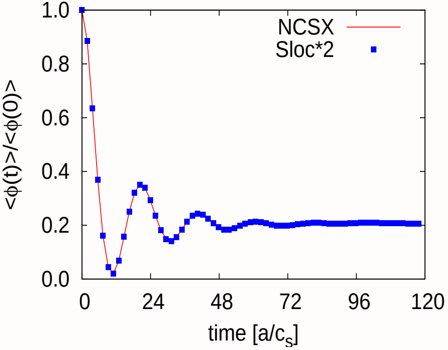



# Effect of local shear in NCSX (2/4)

## Linear physics

- Isomorphic $k_y$ reduction of growth rates
  $k_\perp^2 = g^{xx} k_x^2 + 2g^{xy} k_x k_y + g^{yy} k_y^2$ **"FLR stabilization"**
- Zonal flows are linearly identical

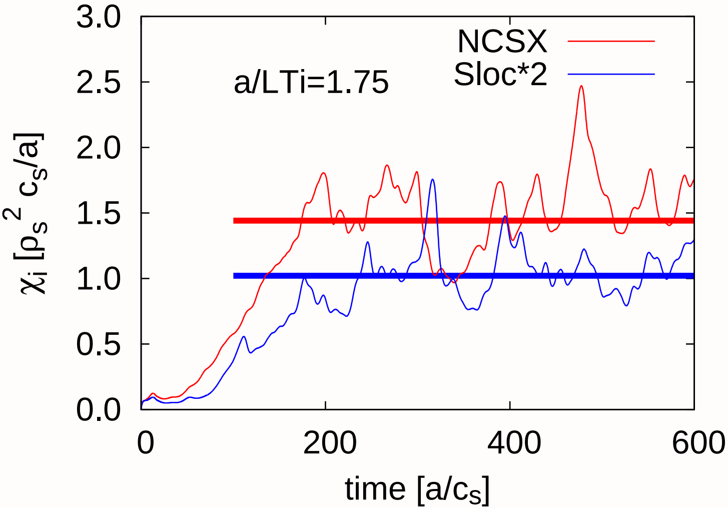



**Minor increase** from $a/L_{Ti,0} = 1.30$ to $a/L_{Ti,0} = 1.37$

**NL simulation**

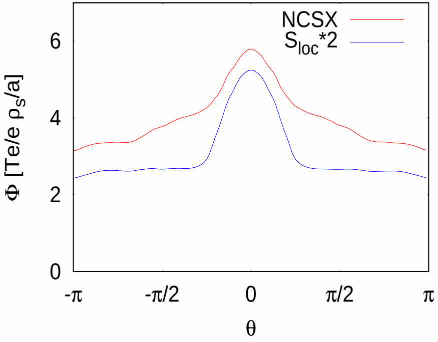
Enhanced local shear induces smaller $\chi_i$ ($\approx$ 32%)

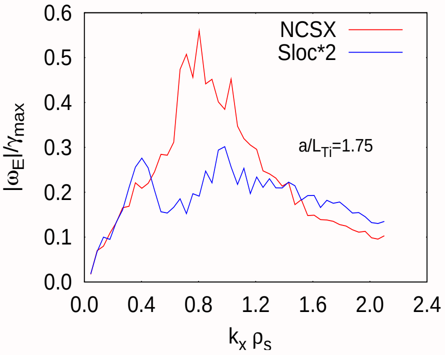


# Effect of local shear in NCSX (4/4)

## NL simulation – Diagnostics

- **Localization** modifies nonlinear ZF behavior **unfavorably**
- Positive linear effect (smaller growth rates) is preserved

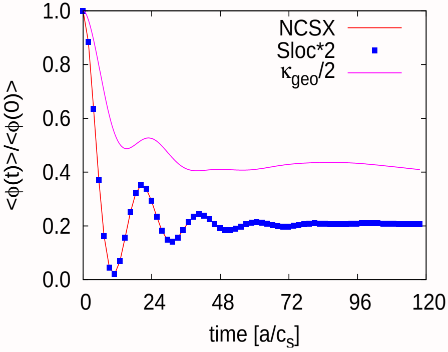


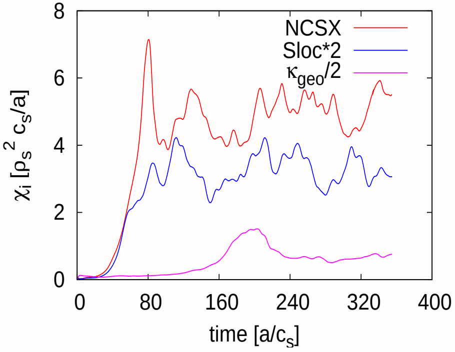



# Effect of geodesic curvature in NCSX

## Improving ZF levels

Uniformly reducing $\kappa_{\mathbf{geo}} \sim \nabla_{||}(\mathbf{j}_{||}/\mathbf{B})$ (here by factor 2) increases ZF **residual** and effectively mitigates turbulence



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# Summary (1/2)

- The GENE/GIST package is a **trustworthy** and **flexible** tool for investigations of 3D microturbulence, in **agreement** with GKV & GS2 (further "thankless work" maybe required)
- ITG-ae turbulence is expected to be **comparable** among present-day optimized stellarators and tokamaks wrt both **level & mode structure** (kinetic electrons are important)
- Several 3D features are **regulators of AT** which **conform to** MHD&NC optimization (optimizers should include GK analysis)

# Summary (2/2)

## 3D features regulating ITG-ae turbulence (this talk)

1. Drift optimization (alignment of B-minima)
   - **Reduces AT** via slowing down GAM damping (for W7X)
   - **Compatible with** NC optimization
2. $\kappa_{geo}$ minimization (PS & bootstrap currents)
   - **Reduces AT** by increasing RH residual
   - **Compatible with** MHD optimization
3. Local shear enhancement (shaping)
   - **Reduces AT** via reduction of growth rates
   - **Compatible with** MHD optimization

"In God we trust.
All others must have data."

– W. Edwards Deming –

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# Gyrokinetic Vlasov equation

## Collisionless electrostatic version

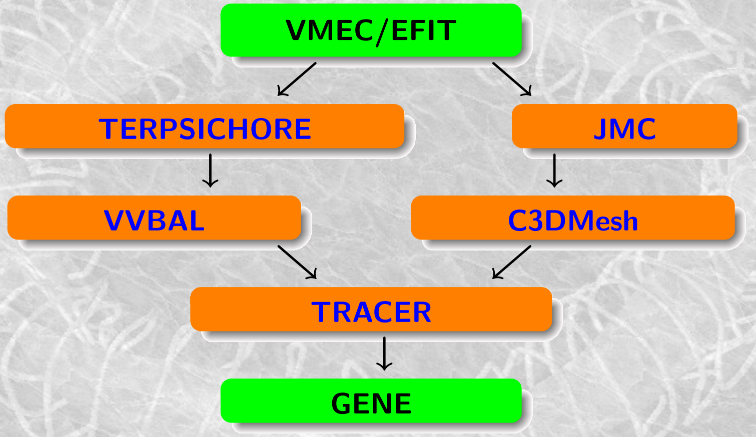
$$\frac{\partial(\delta f_j)}{\partial t} + \left(\frac{\partial \Phi_j}{\partial \rho}\frac{\partial G_j}{\partial \nu} - \frac{\partial \Phi_j}{\partial \nu}\frac{\partial G_j}{\partial \rho}\right) \quad \textbf{[nonlinearity]}$$

$$\textbf{[linear advection]} + F_{j0}\left(\omega_{n_j} + \omega_{T_j}(v_\parallel^2 + \mu B - \frac{3}{2})\right)\frac{\partial \Phi_j}{\partial \nu}$$

$$\textbf{[curvature drift]} + \frac{1}{2\sigma_j}\left(\mu B + 2v_\parallel^2\right)\left(\mathcal{K}_1\frac{\partial G_j}{\partial \rho} + \mathcal{K}_2\frac{\partial G_j}{\partial \nu}\right)$$

$$\textbf{[parallel dynamics]} + \alpha_j v_\parallel \nabla_\parallel G_j - \frac{\alpha_j}{2}\mu \nabla_\parallel B\frac{\partial(\delta f_j)}{\partial v_\parallel} = 0$$

# GIST workflow – **MHD** (left) & **FLT** (right) branches



# Calculation of "bad curvature" = negative part of $\boldsymbol{\kappa} \cdot \mathbf{e_1}$

## via **MHD** (pressure balance + Ampere's law)

$$
\begin{aligned}
\kappa_1 &= -\frac{a^2\sqrt{s}}{qB_N}\left\{\frac{q'B}{2P'}\mathbf{B}\cdot\boldsymbol{\nabla}\left(\frac{\mathbf{j}\cdot\mathbf{B}}{B^2}\right)(\theta-\theta_k)\right.\\
&- \frac{B}{2\sqrt{g}\Psi'}\left[\sqrt{g}\mathbf{B}\cdot\boldsymbol{\nabla}\left(B_s/B^2\right)+\frac{\sqrt{g}P'}{B^2}\right.\\
&+ \left.\left.\frac{1}{B^2}(J\Psi''-I\Phi'')-\partial_s\sqrt{g}\right]\right\}
\end{aligned}
$$

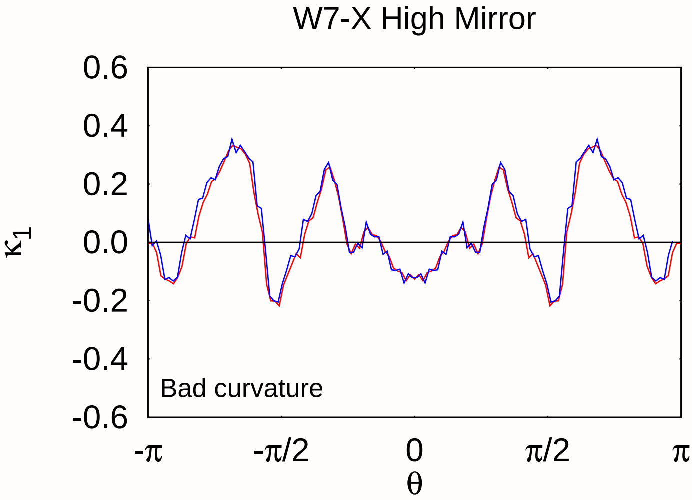
## via **FLT** (r,z = cylindrical coordinates)

$$
\begin{aligned}
\kappa_1 &= \frac{\sqrt{g}}{r(r^2+\dot{r}^2+\dot{z}^2)^2}\times\\
&\left\{C_2^2[(r^2+\dot{z}^2)\ddot{r}-2r\dot{r}^2-r^3-r\dot{z}^2-r\dot{z}\ddot{z}]\right.\\
&- \left.C_2^1[(\dot{r}^2+r^2)\ddot{z}-\dot{r}\ddot{r}\dot{z}-r\dot{r}\dot{z}]\right\}
\end{aligned}
$$

IPP

# Evaluation of “bad curvature”

Necessary and sufficient condition for **consistency** in geometry



# Effect of local shear on AT in NCSX (3/4)

**NL simulation**

Local shear overall reduces AT levels and modifies scaling