Transport in presence of microturbulence and tearing modes

BOUT++ in the integrated modeling tool OMFIT

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Mini-workshop on BOUT++ in OMFIT

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UC San Diego

OUTLINE

Physical motivations (slides, 15min)

Interactions between microturbulence and tearing modes

Capabilities of the BOUT++ module in OMFIT (15min)

Results on the effects of a magnetic island on the turbulent transport

Tutorial 1: (45min)

Understanding the BOUT++interface module

Running a script on NERSC/hopper or other systems

Tutorial 2: (45min)

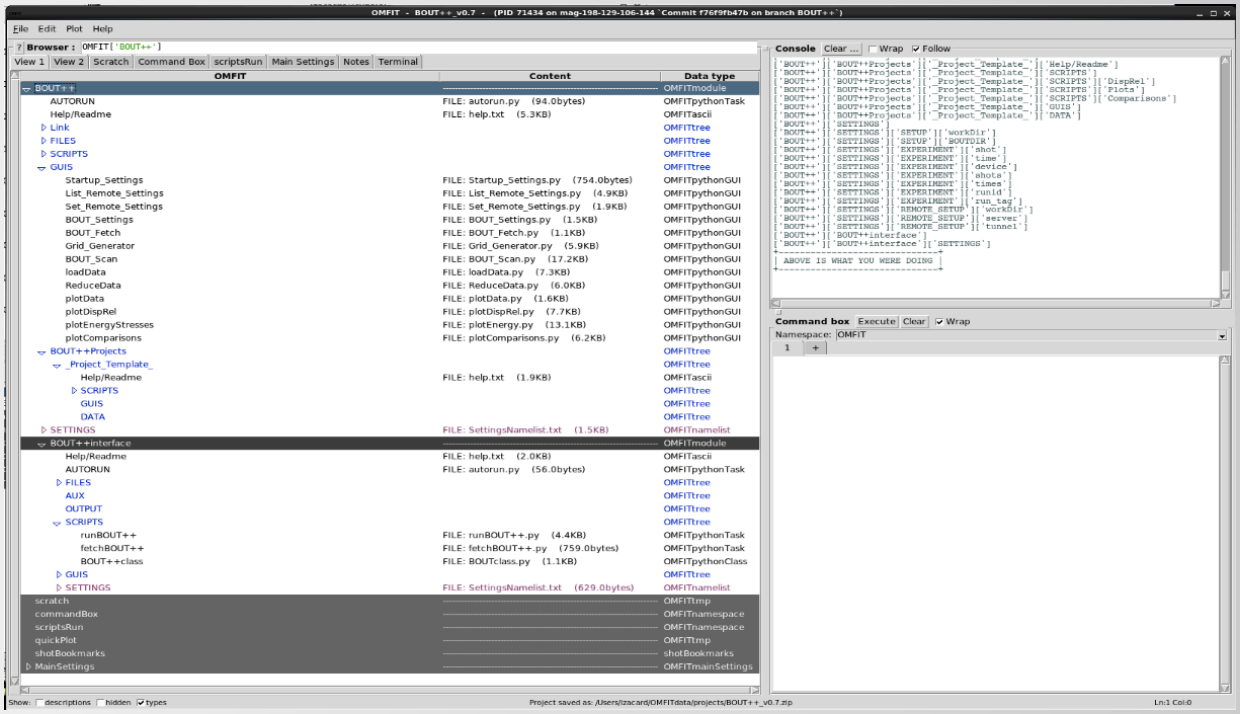
How to create your BOUT++Projects in the BOUT++ module

Creation of your own scripts/GUIs

One Modeling Framework for Integrated Tasks

- Graphical User Interface (GUI)
- Daily assistance/review (GitHub), incremental work
- After 2 years:

  >40 users; >30 modules; ***ATOM*** (M$ 3.7 for 3 years,>15 people): GA, UCSD, LLNL, ORNL…; >10^3 executions of OMFIT in 4 months
- MDS+ library
- remote connections
- BOUT++ available with BOUT++class
- Fast to build a code interface
- NetCDF, PBS, IDL, Matlab, g-file…
- Integrated studies



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OUR STEPS

- 2D/3D tearing modes
  - Model verification and validation of the dispersion relation
- 2D/3D ITG
  - Model verification and validation of the dispersion relation
- **2D microturbulence w/o or with magnetic island**
  - Model verification and accuracy with energy evolution
  - Effects of the island
- 3D microturbulence w/o or with magnetic island:
  - Verification. Effects of the island.
- Perspectives for the following 6 months:
  - Self-consistent evolution of the magnetic field
  - Modification of the Rutherford equation due to effective microturbulence

Motivation

- **MHD** and **microturbulence** (i.e. on ion gyroradius scales or smaller) both important determinants of plasma confinement and device performance
- Historically, MHD and microturbulence considered separately
  - No tractable rigorous theory capable of handling both, especially for relevant reactor geometry and parameters
- However, clear that MHD and microturbulence coexist in many experiments, so potential couplings need to be investigated
- In order to make progress on this challenging problem, start by investigating nonlinear couplings between tearing mode and ITG turbulence in a minimal fluid model
- **GOALS:**
  - Modification of the Rutherford equation with an effective turbulence
  - Long spatial range effects of a magnetic island on the turbulence

Use curvature-driven "four-field" ITG model to examine nonlinear interactions with imposed island

- Set $d\psi/dt = 0$, <u>turbulent</u> flutter nonlinearities to zero ($\beta \to 0$)
- Allow separate n, ϕ fluctuations to allow self-consistent zonal flow response and quantify Ohm's law nonlinearity in presence of small but finite η

$$d_t\tilde{n} = \frac{a}{L_B}\frac{\partial}{\partial y}\left(\tilde{\phi} - \tilde{n}\right) + \nabla_\parallel\left(\tilde{J}_\parallel - \tilde{V}_\parallel\right) + \tilde{B}\cdot\vec{\nabla}J_I + D\nabla_\perp^2\tilde{n}$$

$$d_t\tilde{\Omega} = -\frac{a}{L_B}\frac{\partial}{\partial y}\left((1+\tau)\tilde{n} + \tau\tilde{T}_i\right) + \nabla_\parallel\tilde{J}_\parallel + \tilde{B}\cdot\vec{\nabla}J_I + \tau\frac{a}{L_{Ti}}\frac{\partial\tilde{\Omega}}{\partial y} + D\nabla_\perp^2\tilde{\Omega}$$

$$d_t\tilde{V}_\parallel = -\nabla_\parallel\left(\left(1+\tau\right)\tilde{n} + \tau\tilde{T}_i\right) + D\nabla_\perp^2\tilde{V}_\parallel$$

$$d_t\tilde{T}_i = -\tau\frac{a}{L_{Ti}}\frac{\partial\tilde{\phi}}{\partial y} - \left(\Gamma - 1\right)\left(\tau\nabla_\parallel\tilde{V}_\parallel - \lambda\frac{a}{L_B}\frac{\partial}{\partial y}\left(\tilde{\phi} + \tau\tilde{n} + \tau\tilde{T}_i\right)\right) + \tau D\nabla_\perp^2\tilde{T}_i$$

$$\eta\tilde{J}_\parallel = -\nabla_\parallel\left(\tilde{\phi} - \tilde{n}\right), \quad \tilde{J}_\parallel = -\nabla_\perp^2\tilde{\psi}, \quad d_t = \partial_t + \frac{1}{\rho^*}\left\{\tilde{\phi},\ .\ \right\}, \quad \nabla_\parallel f = \frac{\partial f}{\partial z} + B_{y0}\left(x\right)\frac{\partial f}{\partial y} + \vec{B}_I\cdot\vec{\nabla}f$$

“Four-field” ITG linear dispersion

- The linear dispersion relation is $D(\omega) = A_4\omega^4 + A_3\omega^3 + A_2\omega^2 + A_1\omega + A_0$

$$A_4 = \tau k_\perp^2$$

$$A_3 = \tau\left(C_{Ti} + k_\perp^2(C_{B0} + C_{B1})\right)$$

$$A_2 = \tau C_{B1}\left(C_{Ti} + C_{B2}\right) + \tau C_{B0}\left(C_{Ti} + k_\perp^2 C_{B1}\right) + k_\perp^2\left(\Gamma - 1\right)\left(\tau i k_z\right)^2 - \tau\Omega_B^* C_{BTi} - \tau\left(1+\tau\right)k_\perp^2$$

$$A_1 = C_{B0}C_{B1}C_{Ti} + \tau^2\left(\Gamma - 1\right)\left(k_z^2 C_{Ti} + k_\perp^2 C_{B1} - \lambda\Omega_B^{*2} C_{B1}\right) - \tau\Omega_B^* C_{B1}C_{BTi} + \tau C_{B0}C_{B1}C_{B2}$$
$$+\tau\left(1+\tau\right)k_\perp^2\left(C_{Ti} + k_z^2 C_{B0}\right) + \lambda\tau^2\left(\Gamma - 1\right)k_\perp^2 k_z^2\Omega_B^*$$

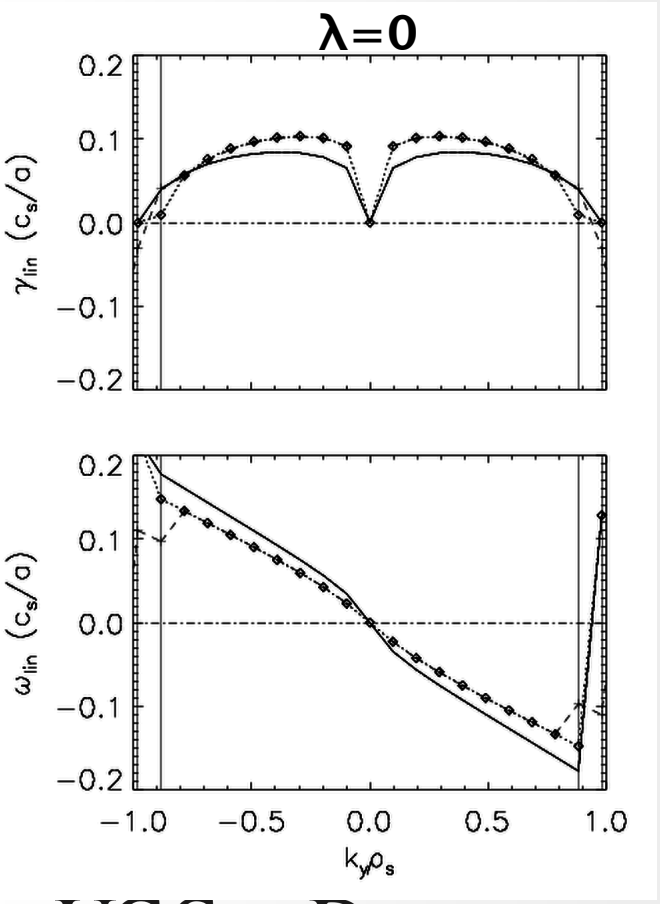
$$A_0 = \tau^2\left(\Gamma - 1\right)k_z^2 C_{B1}\left(C_{Ti} + C_{B2} - \left(1+\tau\right)\Omega_B^*\right) + \tau k_z^2\left(C_{B2}C_{BTi} + \lambda\left(1+\tau\right)\left(\Gamma - 1\right)\Omega_B^* C_{Ti}\right)$$
$$+\lambda\tau^2\left(\Gamma - 1\right)k_z^2\Omega_B^* C_{Ti} - \tau\left(1+\tau\right)k_z^2\Omega_B^* C_{BTi}$$

$$C_{Ti} = -\frac{k_z^2}{\eta} + \tau k_\perp^2\Omega_{Ti}^*, \quad C_{B0} = \lambda\left(\Gamma - 1\right)\Omega_B^*, \quad C_{B1} = -\frac{k_z^2}{\eta} - \Omega_B^*$$

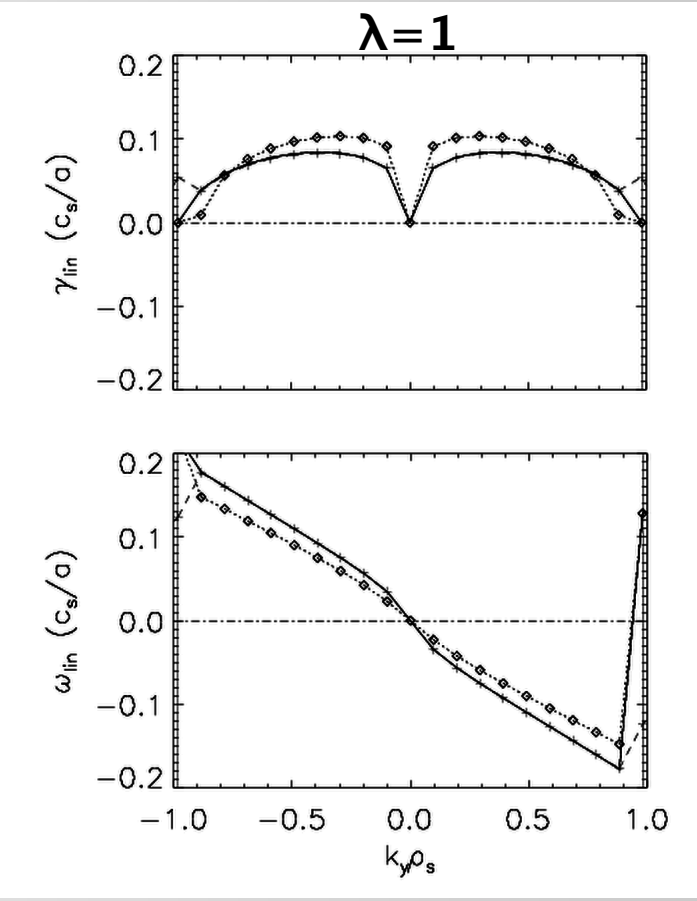
$$C_{B2} = \left(1+\tau\right)\Omega_B^* + \frac{k_z^2}{\eta}, \quad C_{BTi} = C_{B0} - \tau\Omega_{Ti}^*, \quad \Omega_f^* = i k_y \frac{a}{L_f}$$

“Four-field” ITG linear dispersion

- For the 2D-limit w/o island: the dispersion relation is well validated
- Consider limiting case: $n_0(x) = 1$, $a/L_B = 0.1$, $a/L_{Ti} = 0.3$, $\eta = 0$



theory λ=0
theory λ=1
+ + simulation

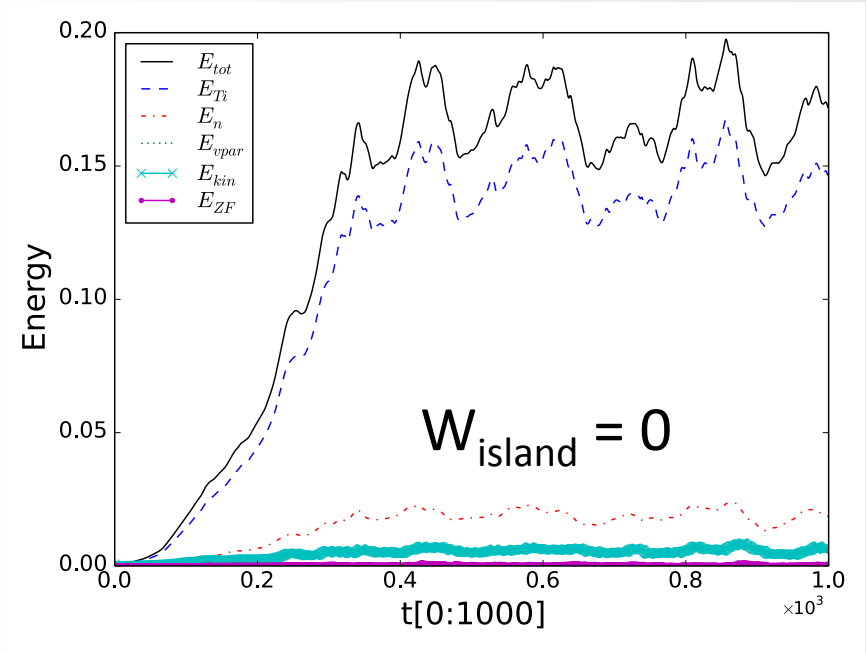


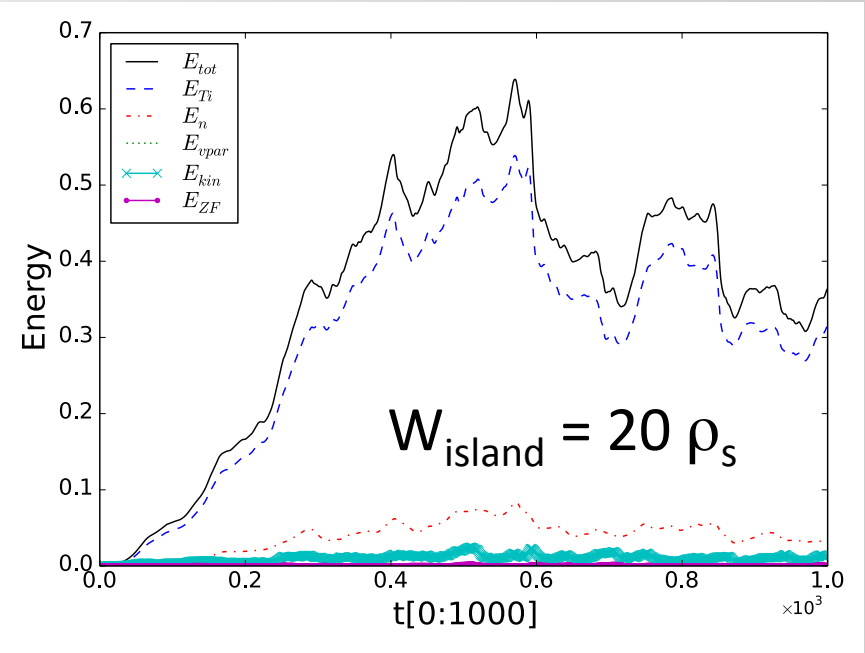
Solve 2D system using BOUT++ framework

- 64 x 64 ρ_s box (a = 32, b=64), NX=151, NY=129
- ψ_{eq}= -$x^2/(2L_s)$ + $\psi_{island}\cos(2\pi y/b)$
- Base parameters:
  a/L_B=0.1, a/L_{Ti}=0.3, η=1e-4, D=1e-2, ν=0.05
- All cases force $\langle \tilde{n} \rangle_{yz} = \langle \tilde{V}_{\parallel} \rangle_{yz} = \langle \tilde{T}_i \rangle_{yz} = 0$ to prevent quasilinear relaxation (will relax this assumption in future work)

Cases without island show significant "burstiness" and long-timescale dynamics

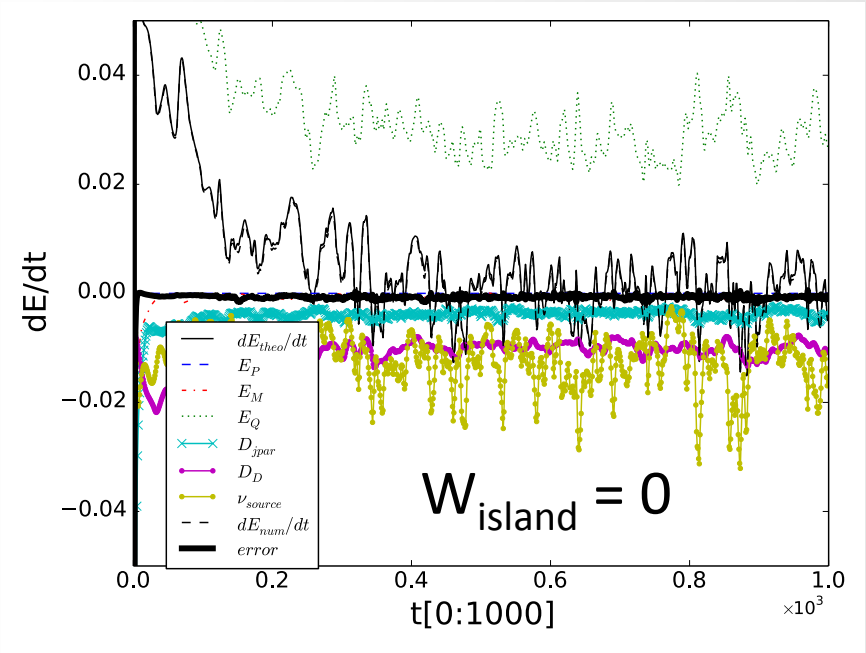
- Saturation of the turbulence observed. Burst-like of the energy appears when $W_{island} = 20\ \rho_s$

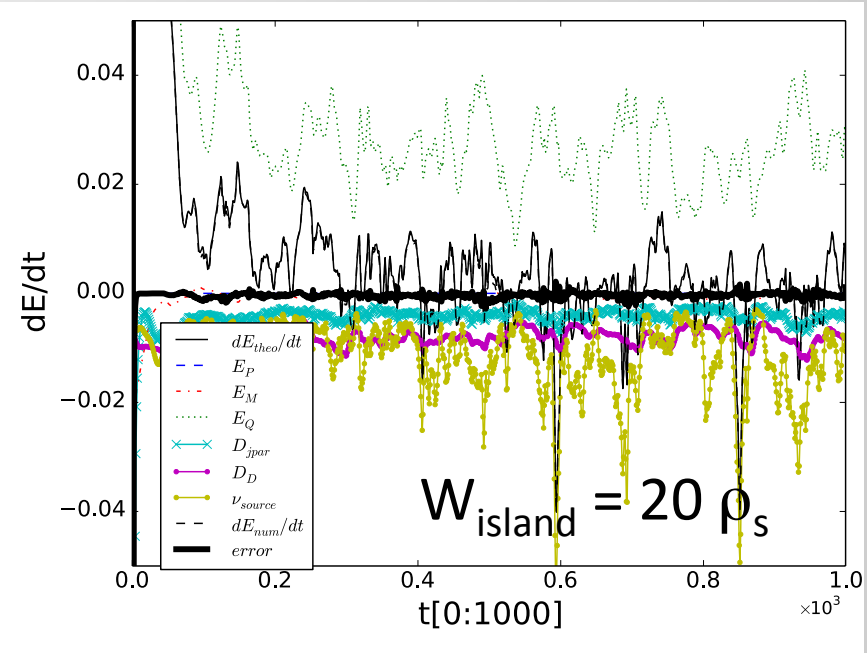




Energy balance: numerical accuracy

- Saturation of the turbulence confirmed. Burst-like of the energy better understood.



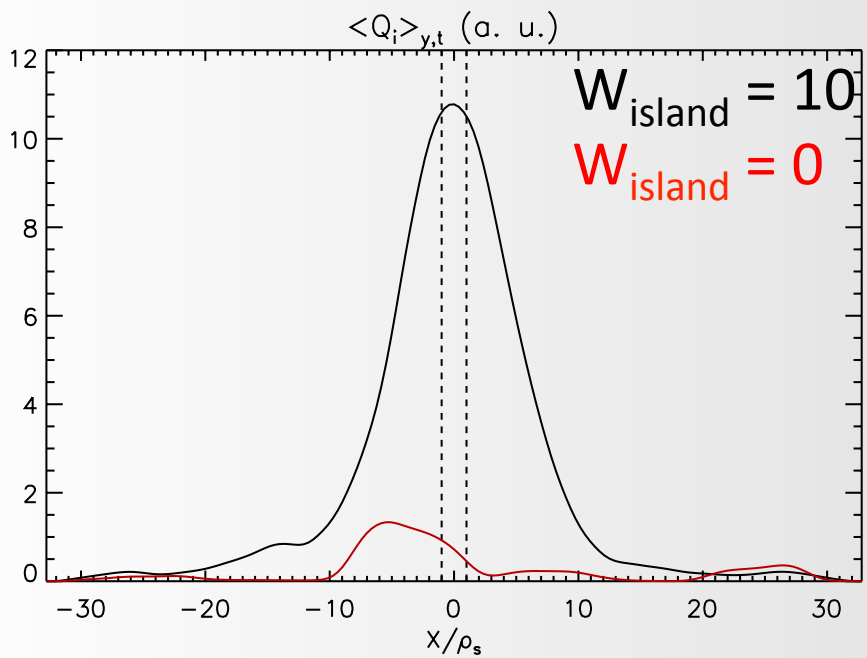


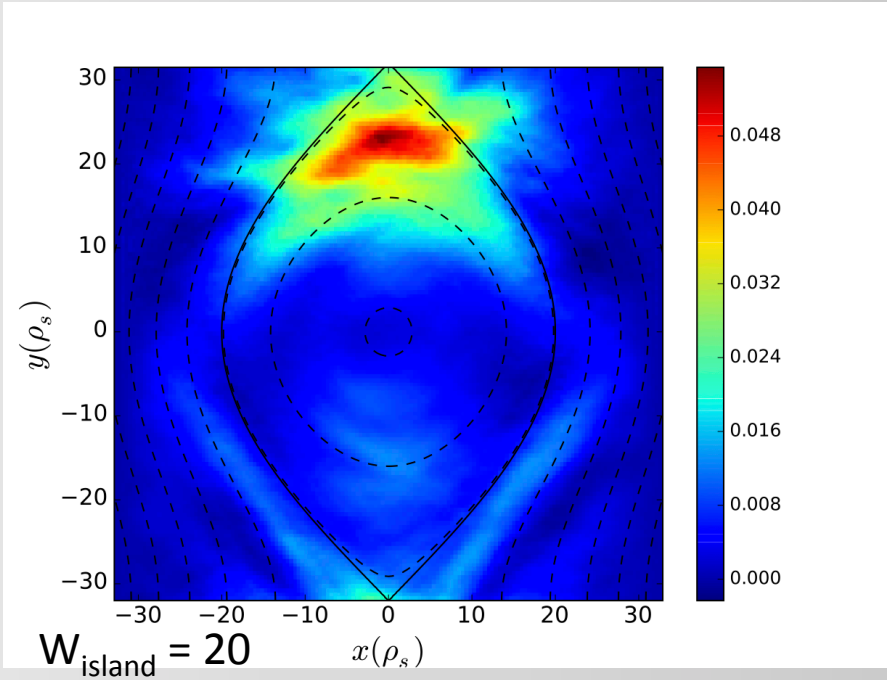
In these simulations, island increases heat flux, concentrates flux near X-point

Robustness of results and parameter sensitivities still need to be assessed

Question: Is it a physical shift with respect to the X-point?

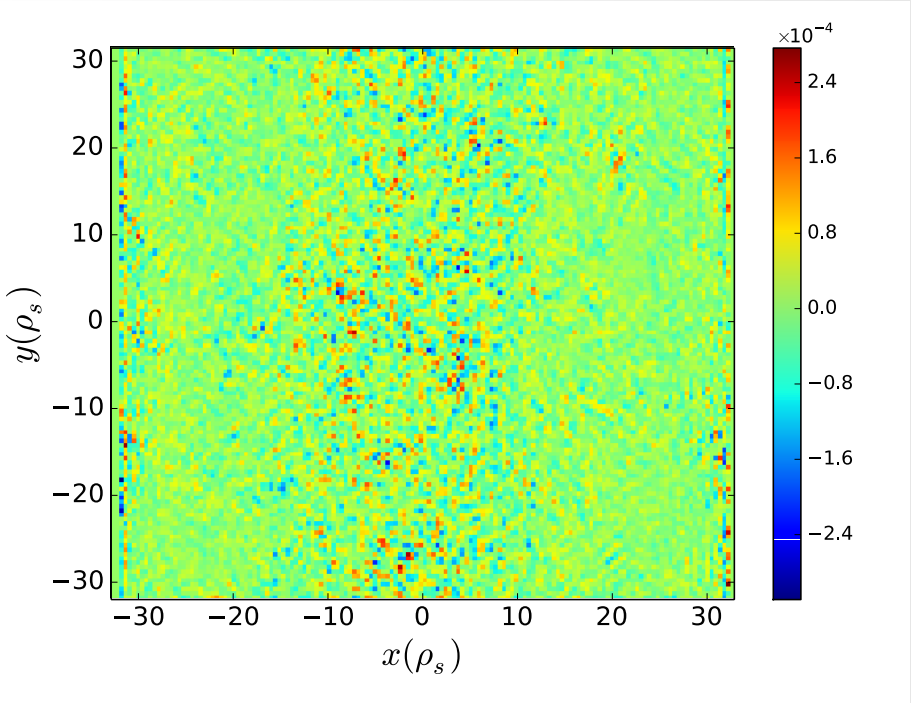
$$\left\langle Q_i(x,y)\right\rangle_t = \left\langle \tilde{V}_{ExB,x}\tilde{T}_i\right\rangle_t$$



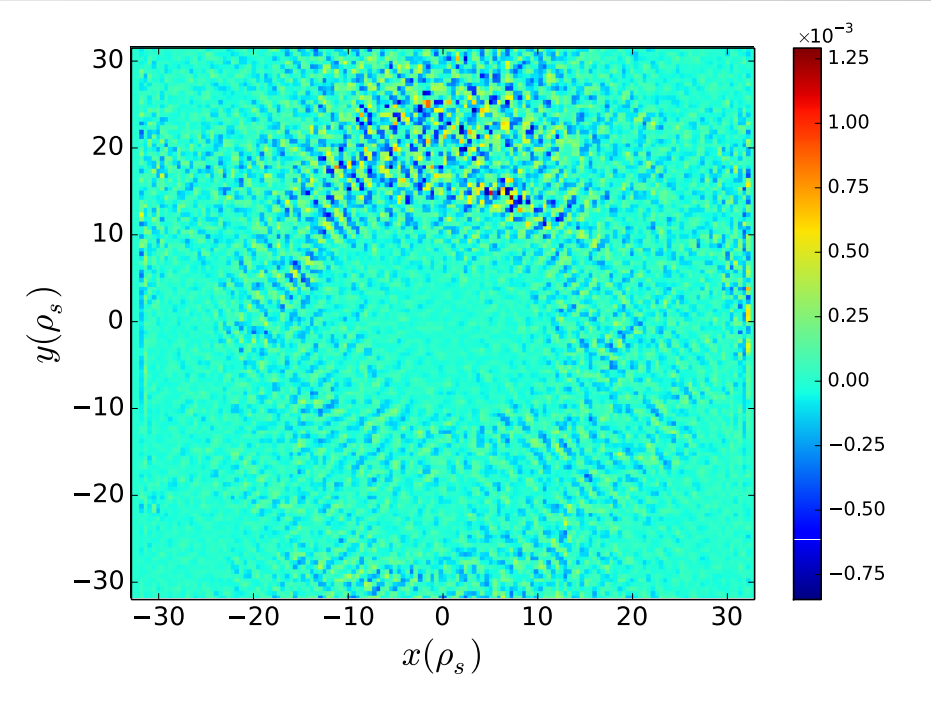


Influence of Island on Reynolds Stress $\left\langle \left\{ \tilde{\phi}, \nabla_\perp^2 \tilde{\phi} \right\} \right\rangle_{z,t}$

- Note finite island case has RS order magnitude larger than no-island case



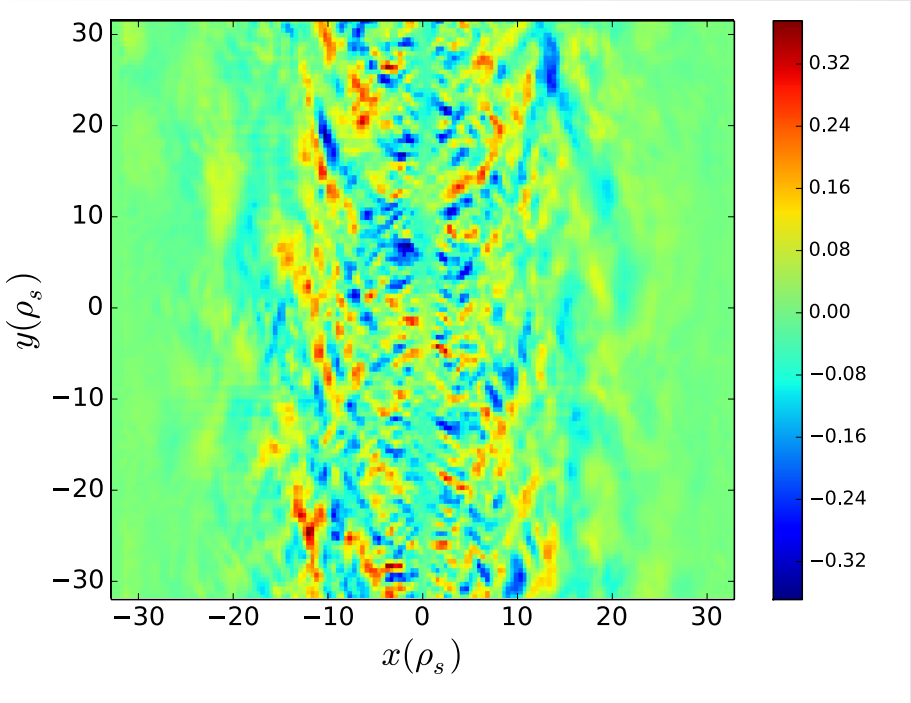
W_{island} = 20

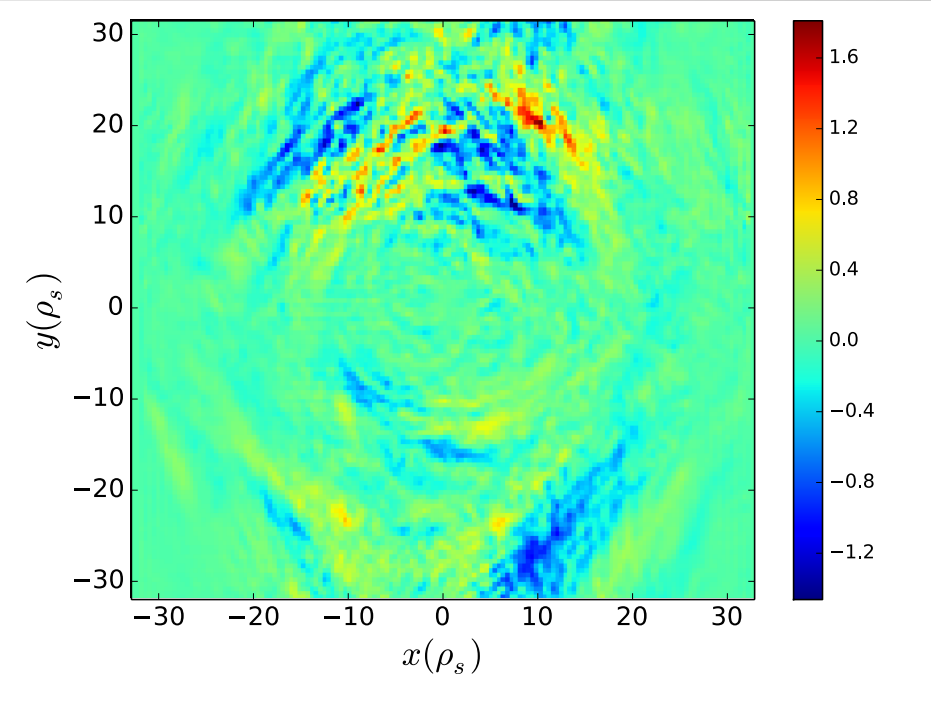


Influence of Island on Maxwell Stress $\left\langle \left\{ \tilde{\psi}, \nabla_\perp^2 \tilde{\psi} \right\} \right\rangle_{z,t}$

- Note β = 0, calculate by inverting $\nabla_\perp^2 \tilde{\psi} = \frac{1}{\eta} \nabla_\parallel^0 \left(\tilde{\phi} - \tilde{n} \right)$

$W_{island} = 20$

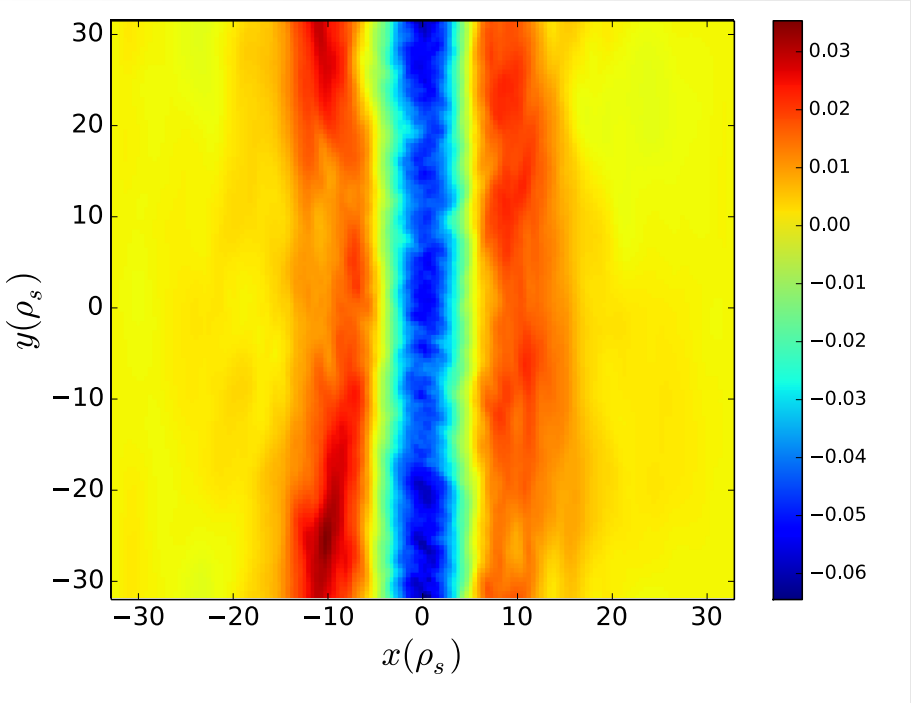


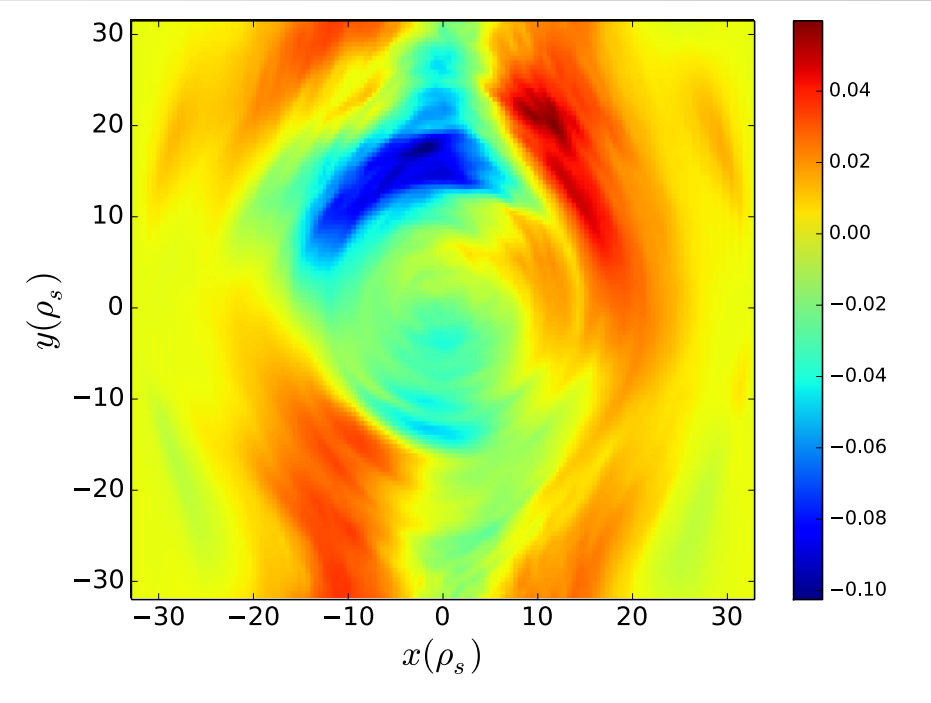


Influence of Island on Ohm's Law Nonlinearity

$$\left\langle \left\{ \tilde{\psi}, \tilde{\phi} - \tilde{n} \right\} \right\rangle_{z,t}$$

$W_{island} = 20$





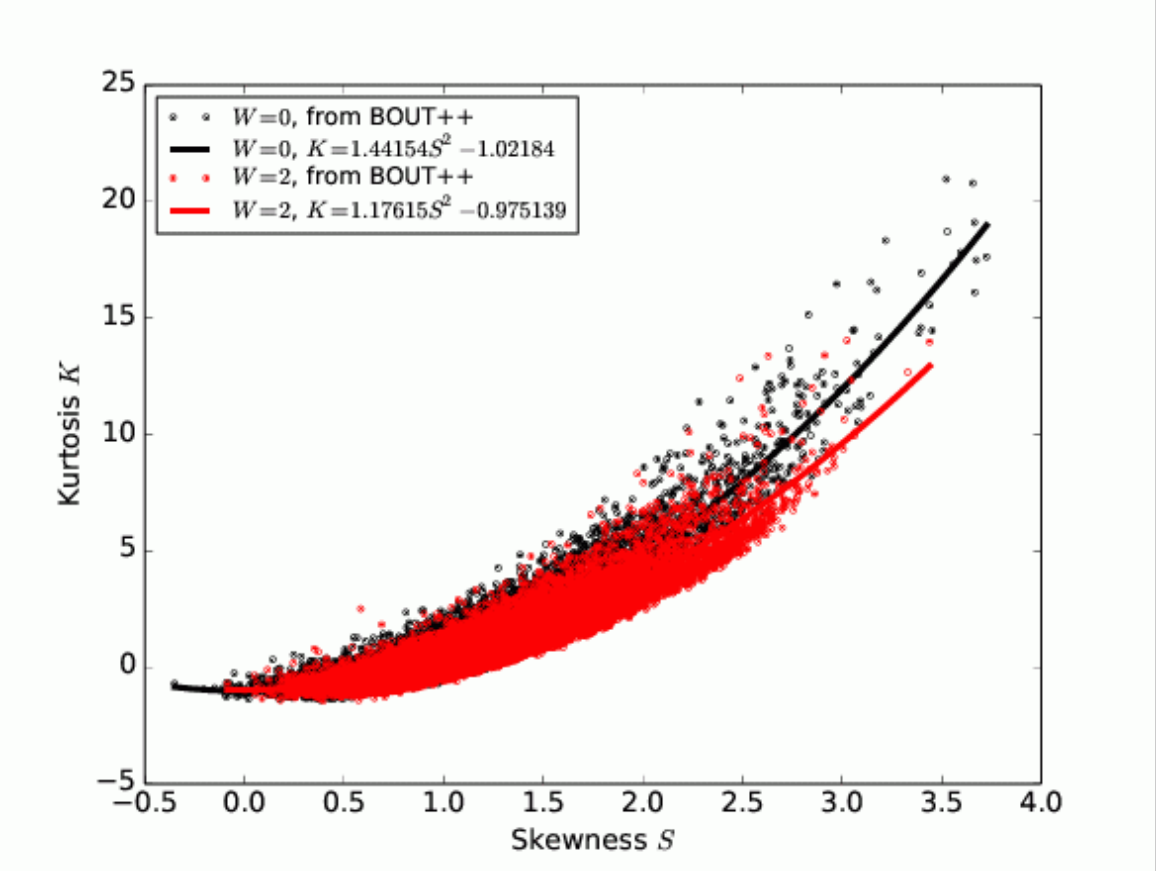
Statistics: Probability Density Function

<u>Effect of island on turbulence statistics:</u>

- Kurtosis decreases for higher Skewness

- Skewness range of values decreases

What is the conclusion?

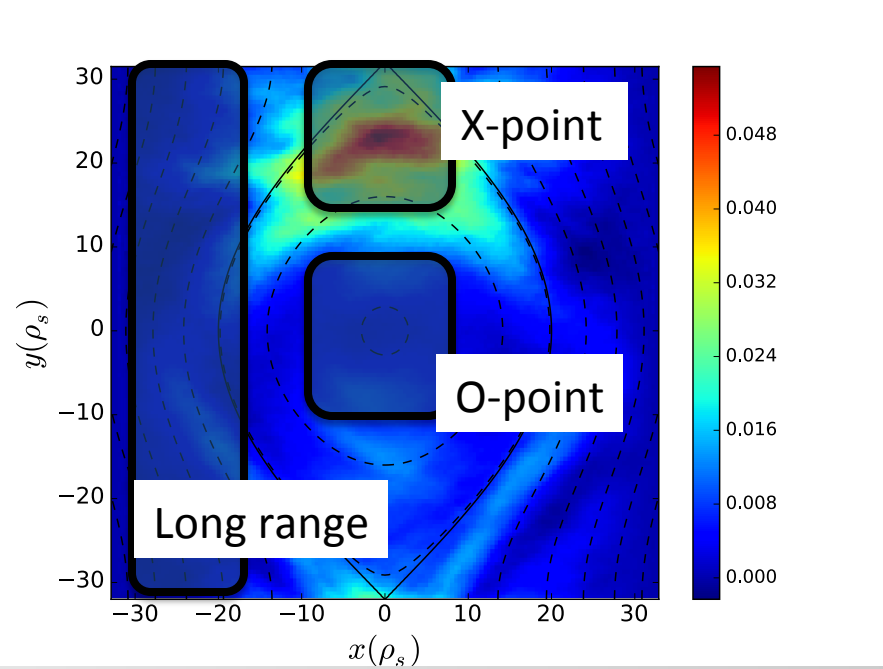


Statistics: Probability Density Function

Effect of island on turbulence statistics:

Skewness $$S = E\left[\left(\frac{X - E[X]}{\mathrm{var}[X]}\right)^3\right]$$

Kurtosis $$S = E\left[\left(\frac{X - E[X]}{\mathrm{var}[X]}\right)^4\right]$$



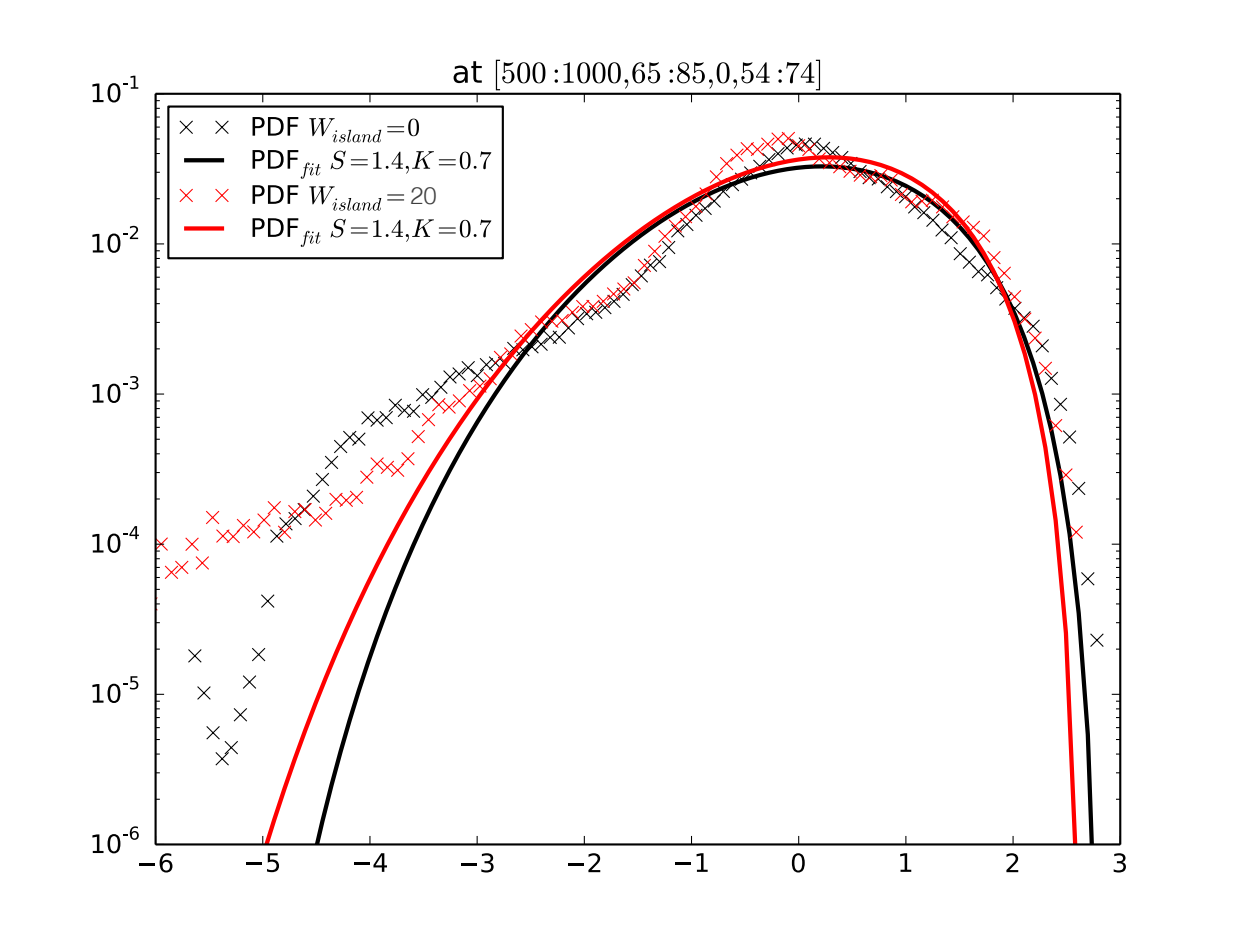
Focus on 3 zones:

- close to the O-point
- close to the X-point
- long range effect

Statistics: Probability Density Function

Effect of island on turbulence statistics:

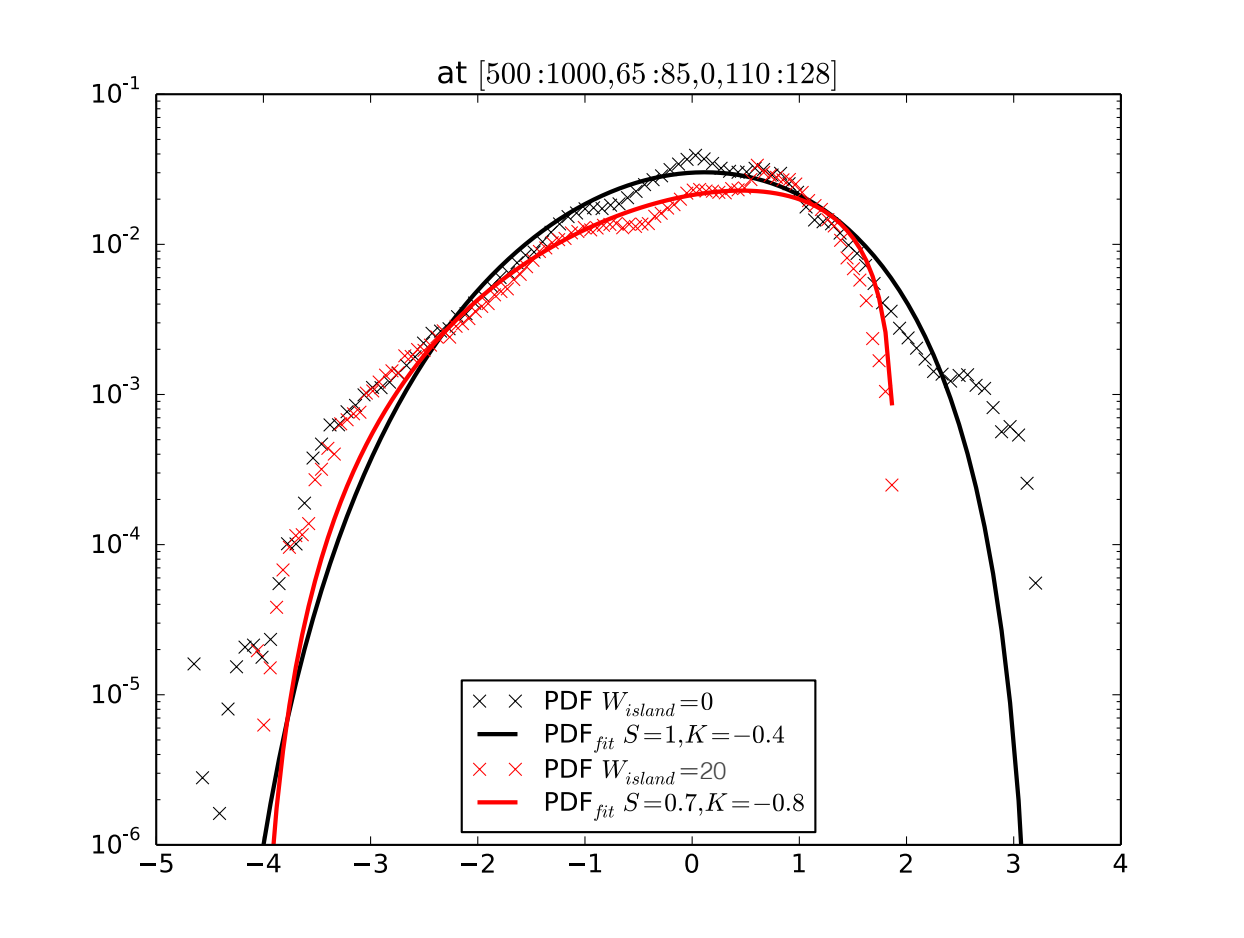
O-point



Statistics: Probability Density Function

Effect of island on turbulence statistics:

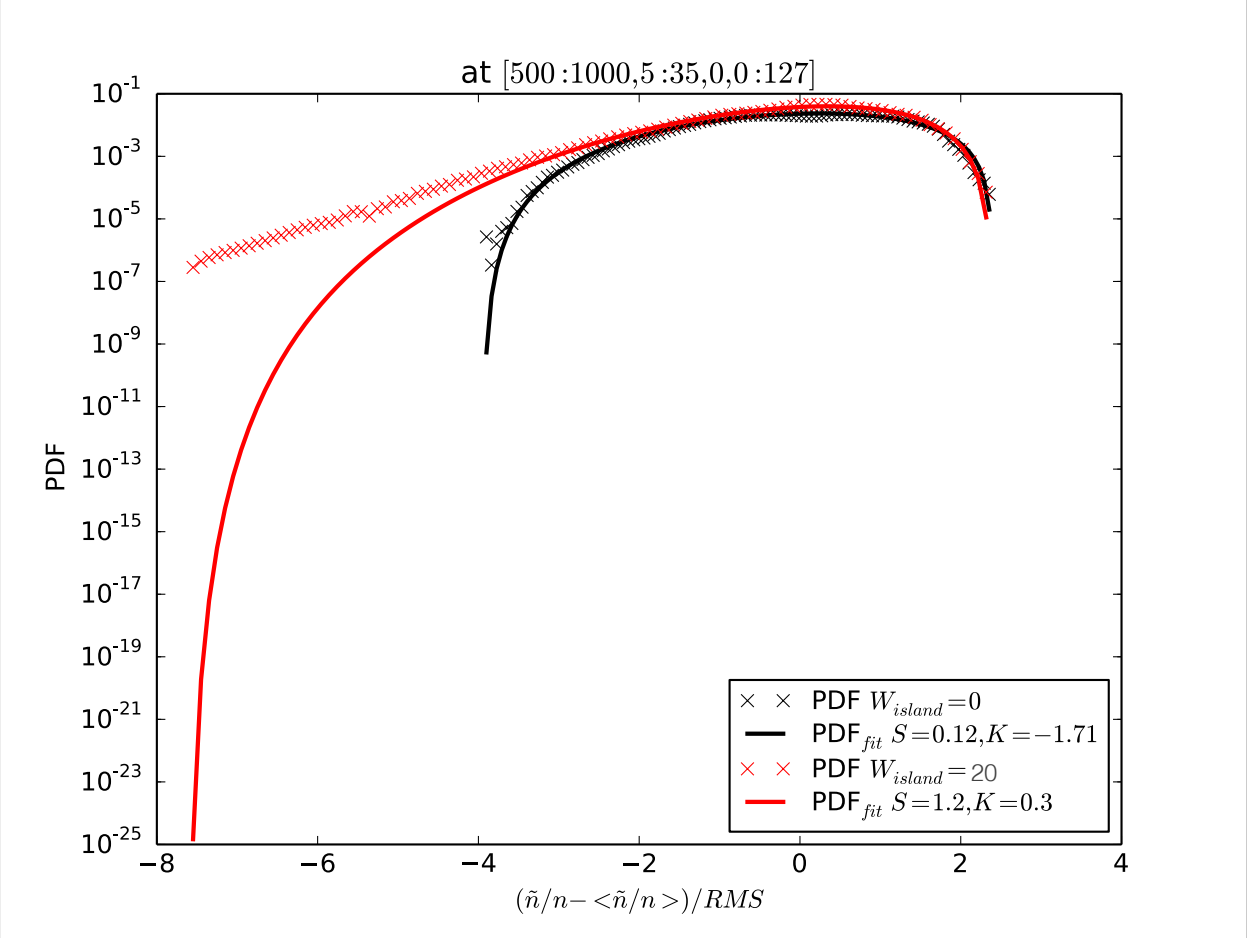
X-point



Statistics: Probability Density Function

Effect of island on turbulence statistics:

Long range



Conclusion:

- Increase of the long range turbulence
- Decrease of the turbulence close to the X-point

Future directions

- Work presented here represents (our) first steps into nonlinear modeling of problem, many future directions to pursue

- **Goals for future work:**
  - Understanding why island response is so strong/spatially large
  - Transition to 3D, source driven system
  - Move to self-consistent evolving island (likely needs to use BOUT preconditioners)
  - More nonlinear simulations to map out couplings of ITG and tearing mode as function of drives dT_{i0}/dx and dJ_{z0}/dx. **What is net direction of energy transfer (when summed over all couplings)?**
  - Additional physics: density gradient, curvature, improved gyrofluid closures

- **Endgoals:**
  1. incorporation of turbulence effects into Rutherford equation
  2. quantifying "zone of influence" of tearing mode on turbulence- how far from rational surface/island separatrix does turbulence feel impact of island