Microtearing turbulence in NSTX

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Overview

- Non-linear simulations
  - Necessary to “resolve” (distinguish) each simulated rational surface
  - Transport is experimentally significant and dominated by magnetic “flutter”
  - Poincare plots indicate globally stochastic

- Scaling of non-linear transport – roughly follows linear scaling
  - Predicted $\chi_{e,sim} \sim \nu_e^{1.1}$ close to experimental trend
  - “Stiff” with ∇T_e but suppressible by experimental levels of $E\times B$ shear
  - Not reproduced by stochastic transport models

- References of interest:
  - W. Guttenfelder et al., Phys. Rev. Lett. 106, 155004 (2011), PoP (2012, in press)
  - E. Wang et al., Phys. Plasmas 18, 056111 (2011)
  - H. Doerk et al., Phys. Rev. Lett. 106, 155003 (2011), PoP (2012, in press)
  - D.J. Applegate, Imperial Thesis (2007)

Nonlinear microtearing simulations in NSTX using GYRO

- Simulations where only microtearing unstable, no ETG (NSTX 120968, r/a=0.6)
  - Electromagnetic (φ, $A_{||}$) and collisional (ν_e)
  - Varying E×B shear (mostly γ_E=0)
  - Deuterium only (but Z_{eff} in collision operator)
  - “Local” → no profile variation in equilibrium quantities

(A) $L_x \times L_y = 80 \times 60 \rho_s$
$n_x \times n_y = 400 \times 8$ ($\Delta x = 0.2\ \rho_s$)
$k_\theta \rho_s$=[0,0.105,0.21,…]
n=[0,5,10,…]

(B) $L_x \times L_y = 80 \times 100 \rho_s$
$n_x \times n_y = 540 \times 16$ ($\Delta x = 0.15\ \rho_s$)
$k_\theta \rho_s$=[0,0.063,0.126,…]
n=[0,3,6,…]

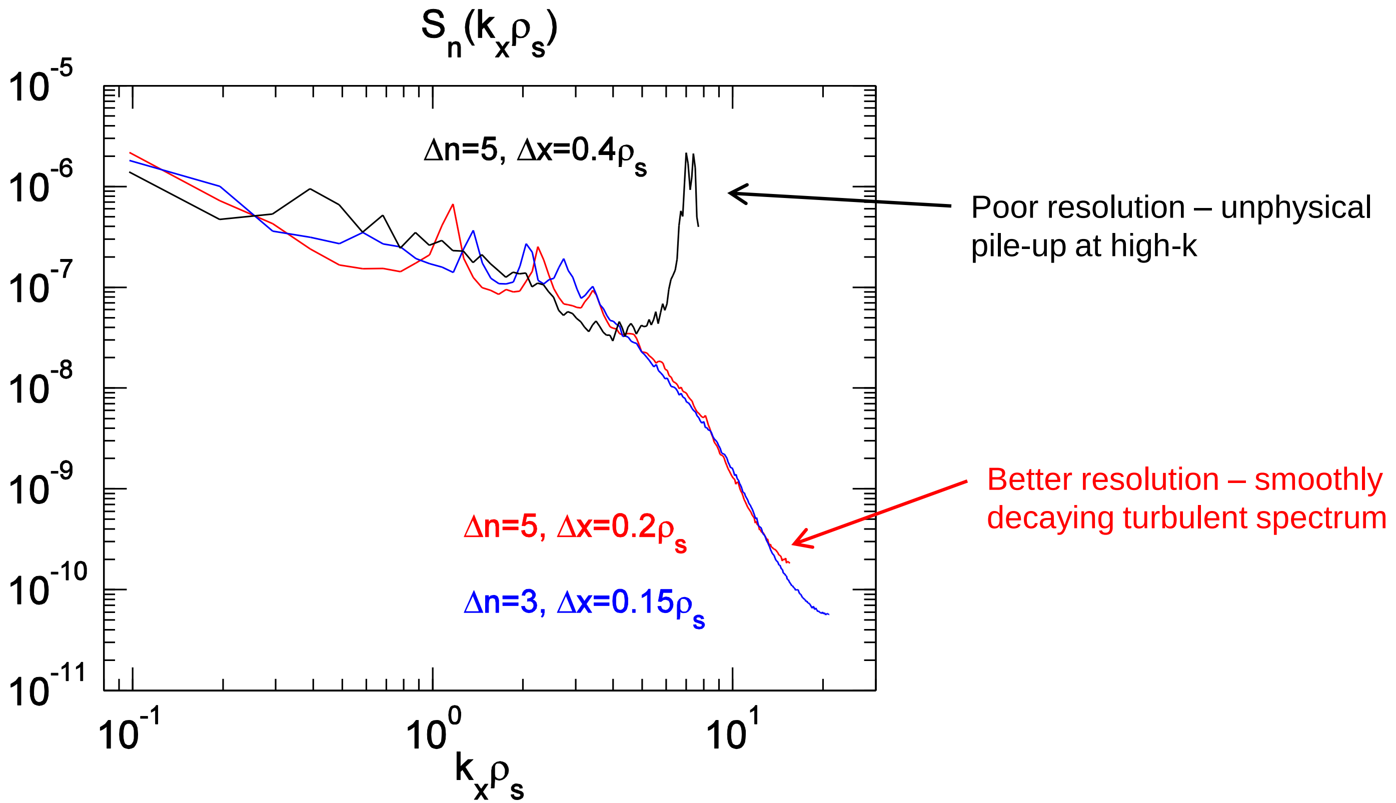
n_θ=14 (parallel mesh points)
n_E=8, n_λ=12 × 2 (velocity space)
dt=0.001-0.002 a/c_s

120968 r/a=0.6 surface

a/L_{Te}=2.73	a/L_n=-0.83
q=1.69	s=1.75
κ=1.7	δ=0.13
T_e/T_i=1.05	Z_{eff}=2.9
β_e=8.8%	ν_{ei}=1.46 c_s/a
($\beta_{e,unit}$=2.5%)	

Fine radial resolution required to obtain decaying nonlinear spectra

- Unphysical pile-up at high-k with insufficient resolution (Δx=0.4 ρ_s)
- Smoothly decaying turbulent spectrum with better resolution (Δx=0.2 ρ_s, Δx=0.15 ρ_s)



- Similar high-k pile-up observed in first careful attempts of GS2 MAST simulations – see Applegate Ph. D. thesis (2007, Imperial College London)

Fine radial resolution required to distinguish *linear* resonant layers of fastest growing mode

- Rough criteria – for finite difference schemes (such as GYRO), four grid points between highest order rational surfaces, min(Δr_{rat})

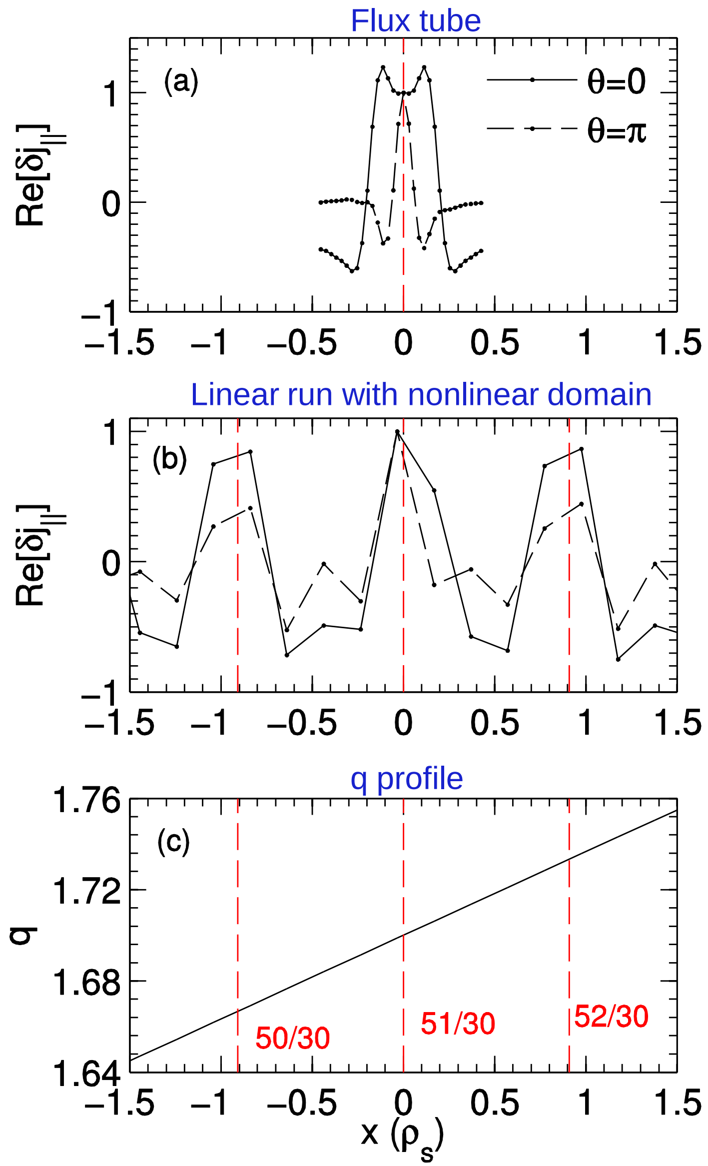
$$(\Delta r)_{rat} = \frac{1}{nq'} = \frac{1}{k_\theta \hat{s}}$$

$$\Delta x/\rho_s \le \frac{\min(\Delta r_{rat}/\rho_s)}{4} = \frac{1}{4 \cdot s \cdot \max(k_\theta \rho_s)}$$

$$\max(k_x \rho_s) \ge 4\pi \cdot s \cdot \max(k_\theta \rho_s)$$

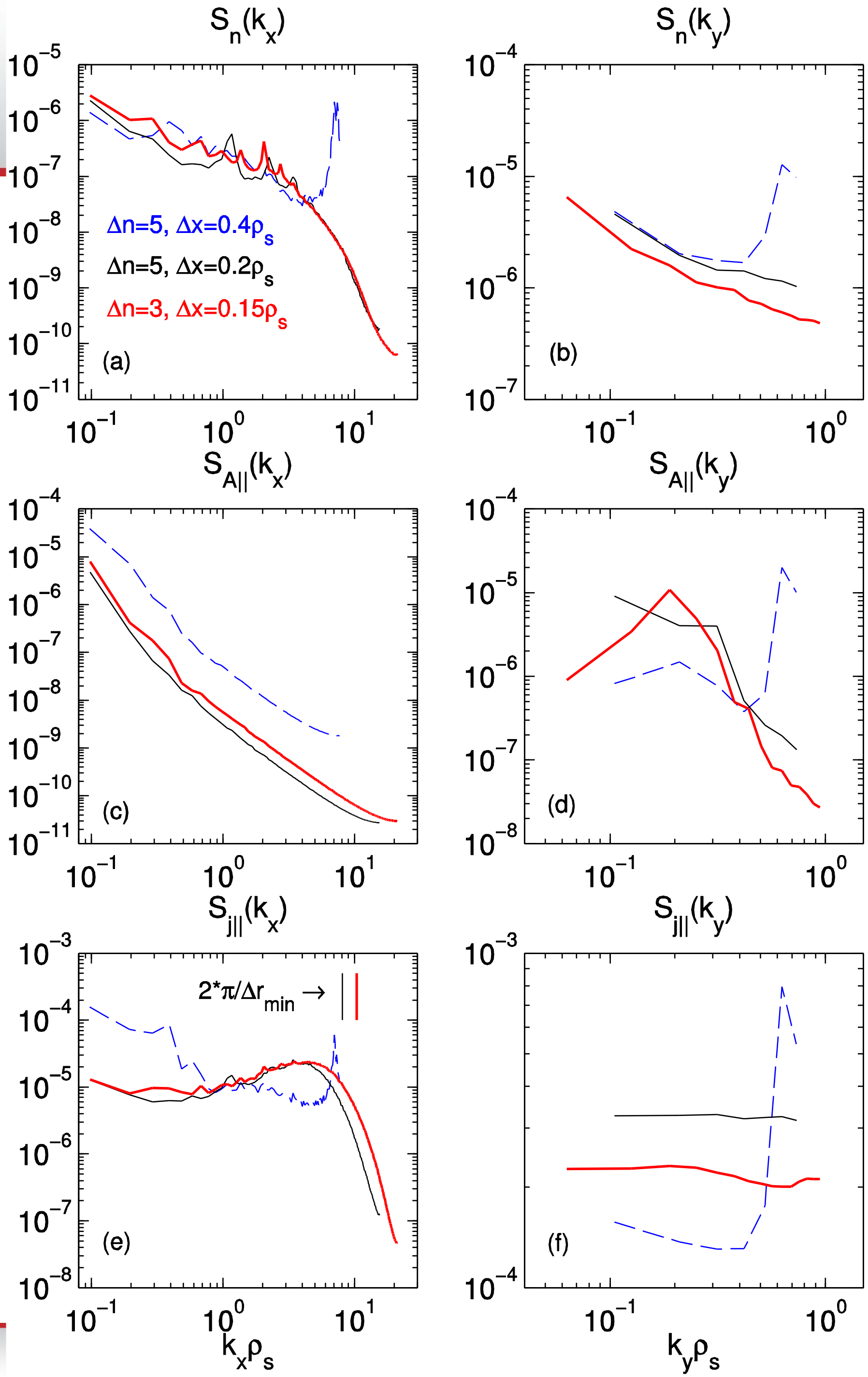
- NSTX (GYRO) min(Δr_{rat})=0.9, Δx=0.15,0.2
- AUG (GENE) min(Δr_{rat})=0.75, Δx=0.39
- MAST (GS2) min(Δr_{rat})=1.2, Δx=0.04

  but L_x=2 ρ_s



For reference, skin depth $\delta_e \approx 0.15\ \rho_s$

$$\frac{\delta_e}{\rho_s} = \left(\frac{2}{\beta_e} \frac{m_e}{m_i} \right)^{1/2}$$



Non-linear spectra and transport downshifted from peak linear growth rate

- Simulated transport (1.2 $\rho_s^2 c_s/a$, 6 m^2/s) comparable to experimental transport (1.0-1.6 $\rho_s^2 c_s/a$, 5-8 m^2/s)
- Negligible particle, momentum, or ion thermal transport

- Well defined peak in transport spectra ($k_\theta\rho_s \approx 0.2$), downshifted from maximum γ_{lin} ($k_\theta\rho_s \approx 0.6$)
- Slowly decaying tail - predicted transport increases ~25% with higher resolution

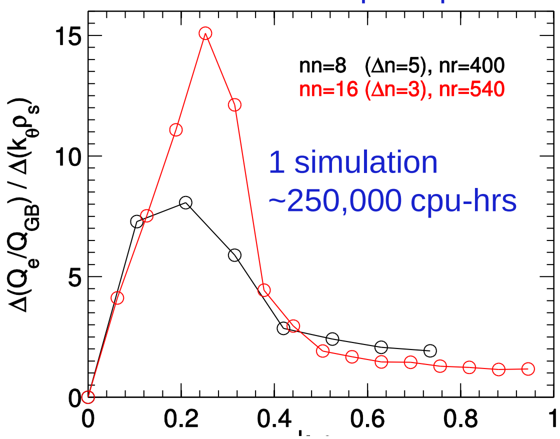
- Analytic nonlinear slab theory* suggests downshift

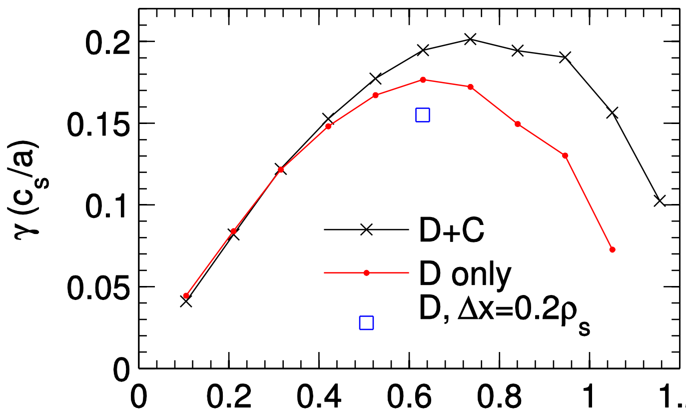
$$\gamma_{k,NL} \sim -\sum_{k'} \left| k \cdot \delta B_{k'} \right|^2 \frac{k_\theta - k'_\theta}{k_\theta + k'_\theta}$$

$$(k_\theta' > k_\theta) \rightarrow \gamma_{k,NL} \sim +|k \cdot \delta B_{k'}|^2$$

but this assumes damped low-k_θ modes

Fractional transport spectra



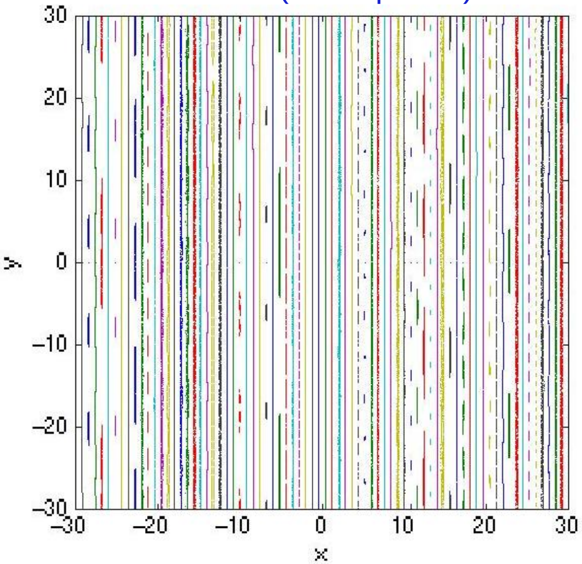


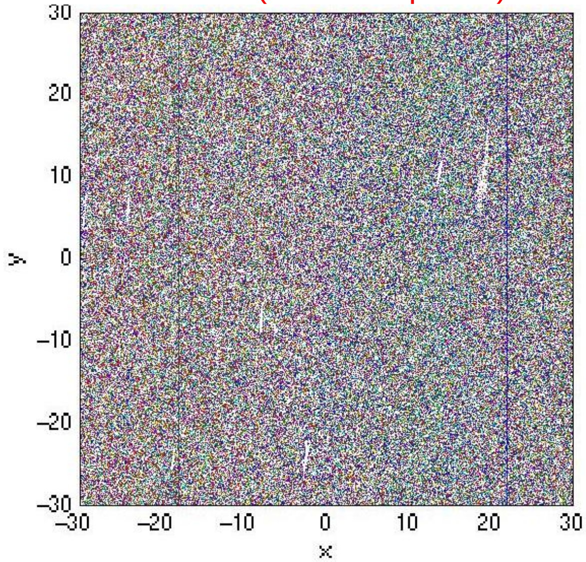
*Drake et al., PRL (1980); Dominguez et al., PoF (1981); Craddock & Terry PoF B (1991)

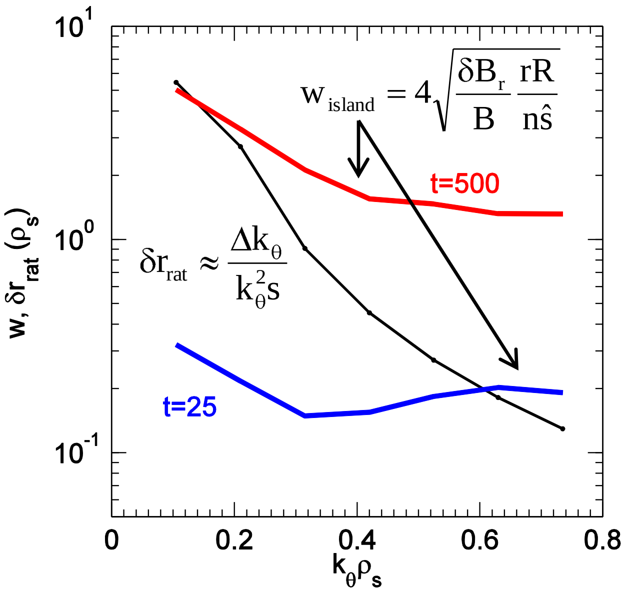
~98% of transport due to magnetic "flutter" contribution

$$Q_{em} = \left\langle \int d^3v \frac{1}{2} m v^2 v_\parallel \delta f \frac{\delta B_r}{B_0} \right\rangle$$

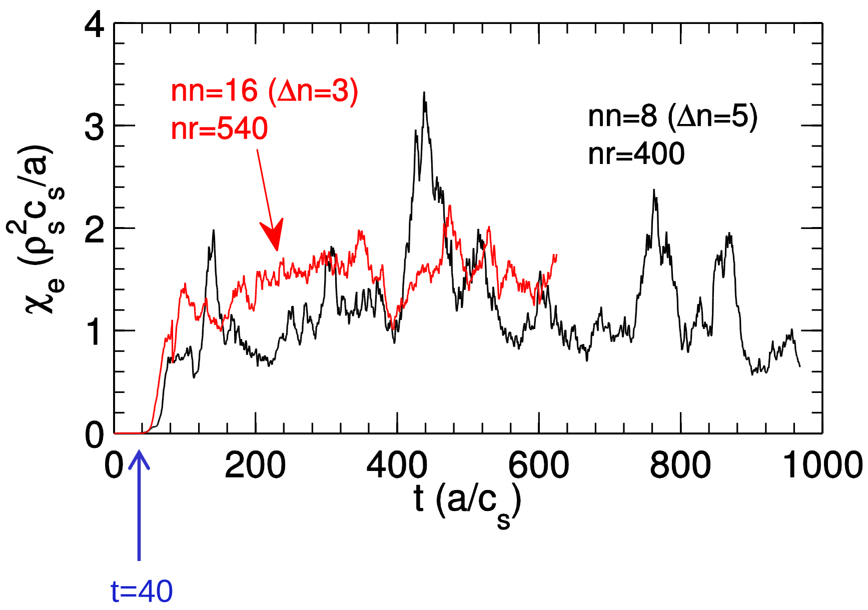
- Flux surfaces become distorted in linear phase (t=25)
- Globally stochastic in saturated phase, complete island overlap $w_{island}(n) > \delta r_{rat}(n)$

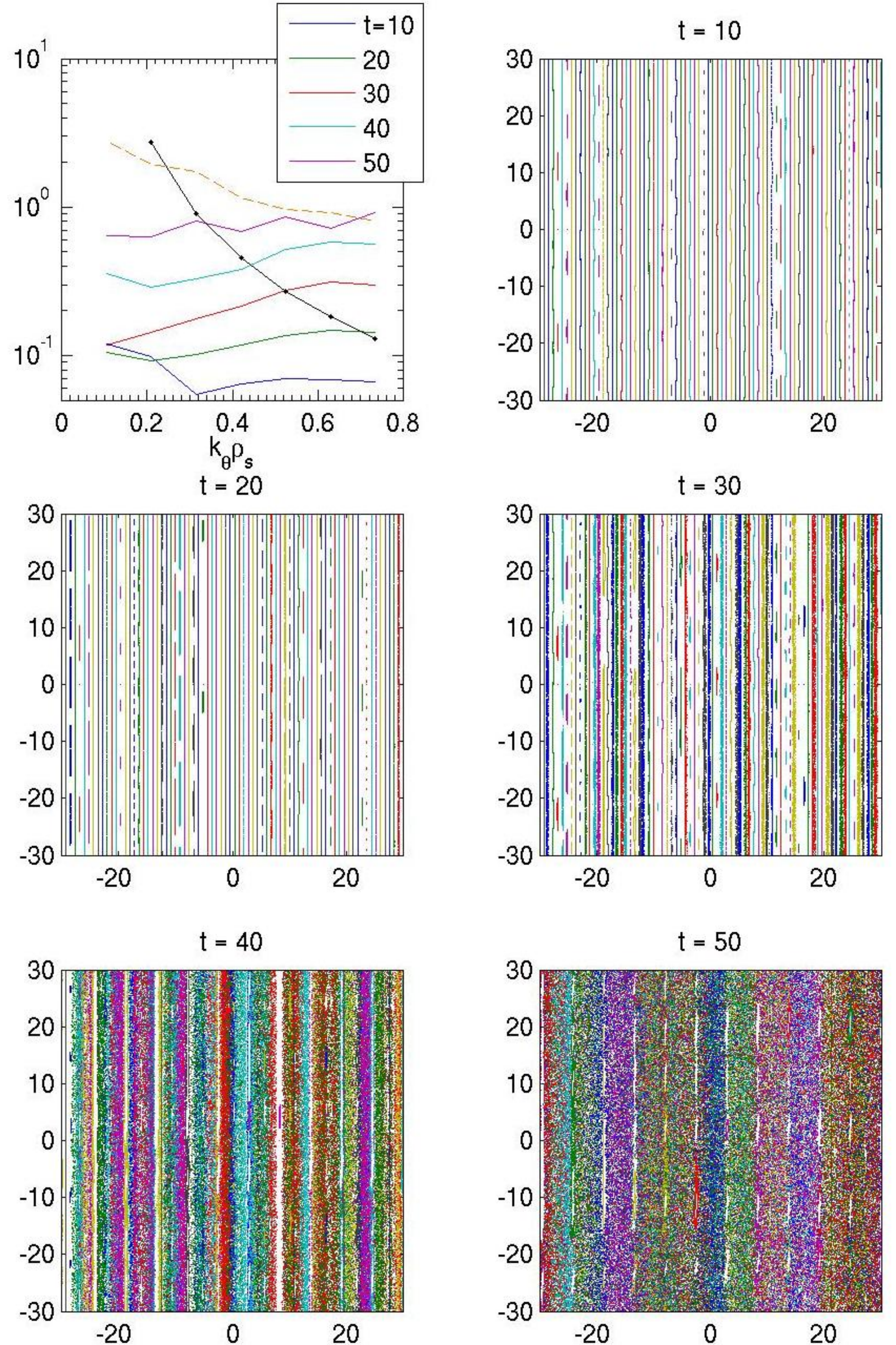






Onset of stochasticity well before maximum transport



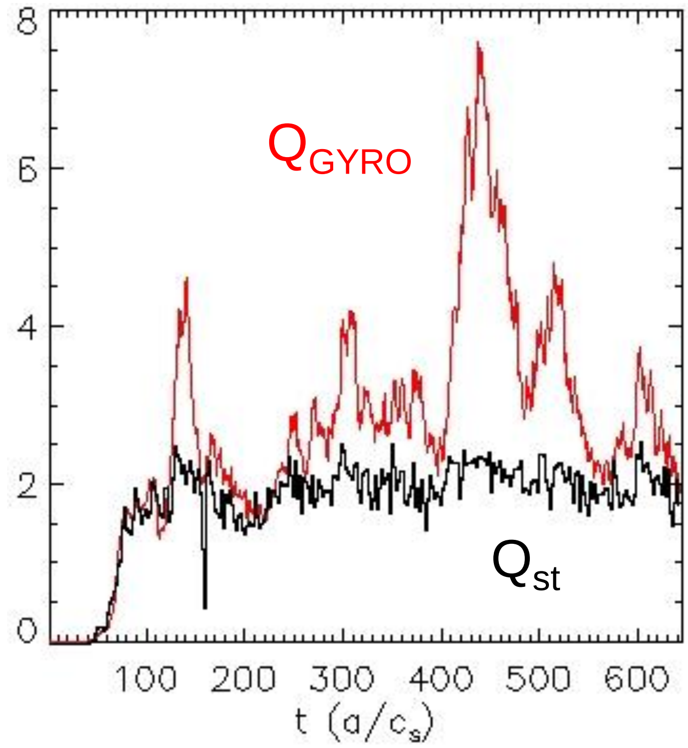


Application of stochastic transport model

$f_p \approx 63\%$ passing particles

$$\chi_{st} \approx 2\left(\frac{2}{\pi}\right)^{1/2} D_{st} v_{te} f_p$$

$$D_{st} = \lim_{s\to\infty} \frac{\left\langle [r_i(s) - r_i(0)]^2 \right\rangle}{2s}$$



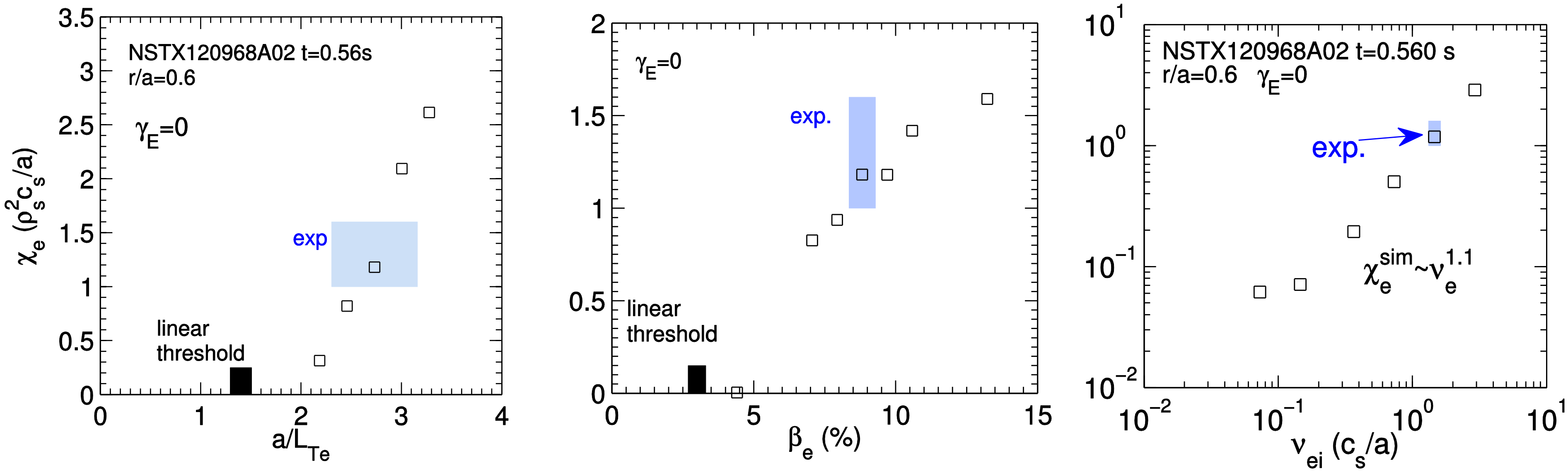
E. Wang et al., Phys. Plasmas **18**, 056111 (2011)

Nevins et al., Phys. Rev. Lett. (2011)

Rechester & Rosenbluth, Phys. Rev. Lett. (1978)

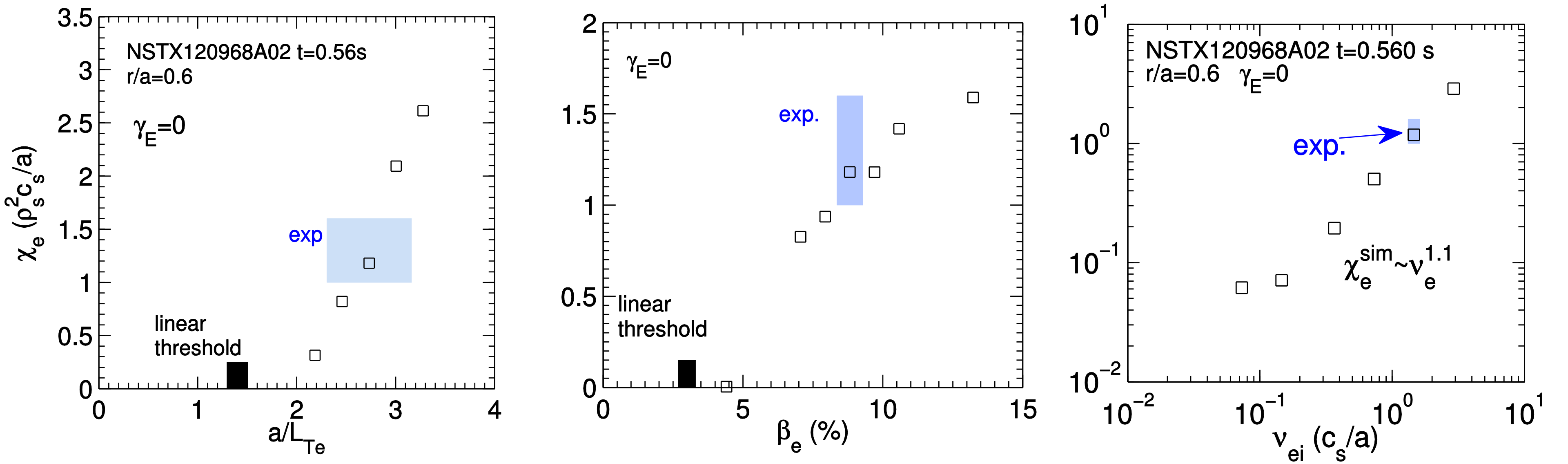
Harvey et al., Phys. Rev. Lett. (1981)

Transport thresholds in a/L_{Te} and β_e, near linear increase with ν_e



- Trends qualitatively follow linear stability scaling

Transport thresholds in a/L_{Te} and β_e, near linear increase with ν_e



- Trends qualitatively follow linear stability scaling
- Rechester-Rosenbluth with quasi-linear saturation[1] $\delta B/B \approx \rho_e/L_{Te}$ does not capture the trends, although it was used with some quantitative success for single test cases[2]

$$\chi_e^{RR} \approx D_m v_{Te} = \left|\frac{\delta B}{B}\right|^2 L_c \cdot v_{Te}$$

$$L_c = \min\begin{bmatrix} qR \\ \lambda_{mfp} \end{bmatrix} \quad \begin{matrix} (\text{collisionless}, \lambda_{mfp} > qR) \\ (\text{collisional}, \lambda_{mfp} < qR) \end{matrix}$$

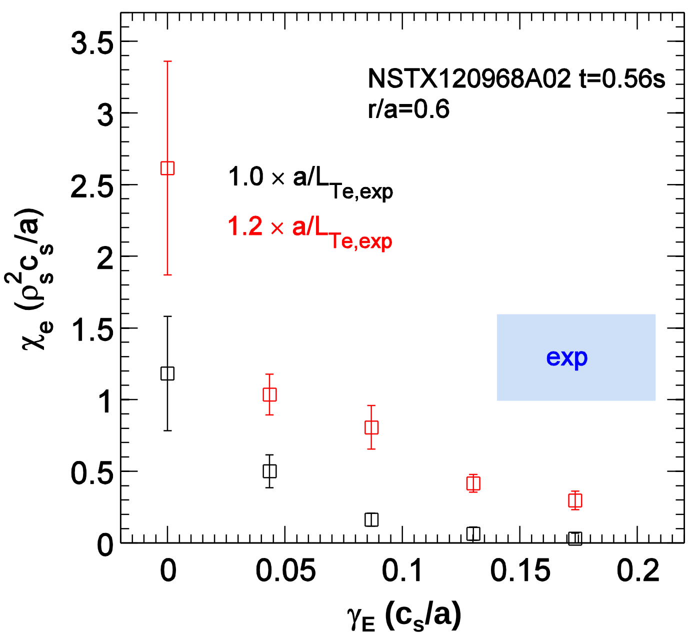
$$\frac{\chi_e^{RR}}{\rho_s^2 c_s / a} = \min\left[1, \frac{1}{\varepsilon^{3/2}\nu_{*e}}\right]\sqrt{\frac{m_e}{m_i}}\frac{qR}{a}\left(\frac{a}{L_{Te}}\right)^2$$

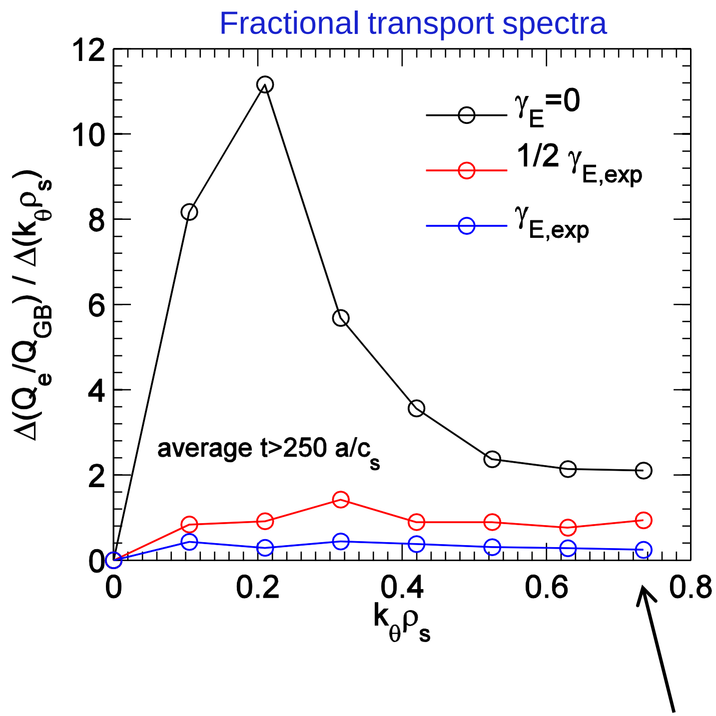
[1]Drake et al., PRL (1980)
Dominguez et al., PoF (1981)
Craddock & Terry PoF B (1991)

[2]K.L. Wong et al., PRL (2007)
I. Predebon et al., PRL (2010)

Nonlinear microtearing transport sensitive to γ_E/γ_{lin}

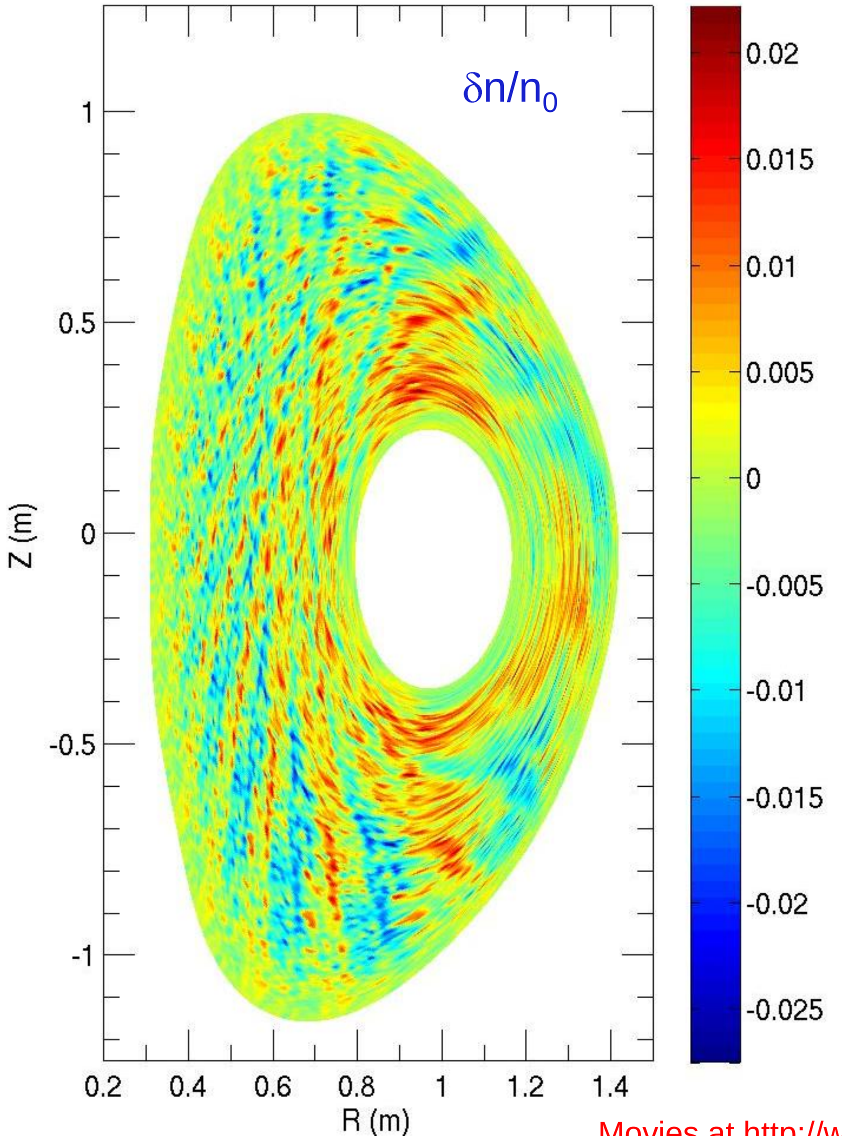
- Transport reduced when increasing γ_E to local experimental value ($\gamma_{E,exp}$~$\gamma_{lin,max}$~0.17 c_s/a)
  → More easily suppressed than ASDEX-UG simulations (at lower $k_\theta\rho_s$~0.1)
- Transport partially recovered with increase in ∇T_e

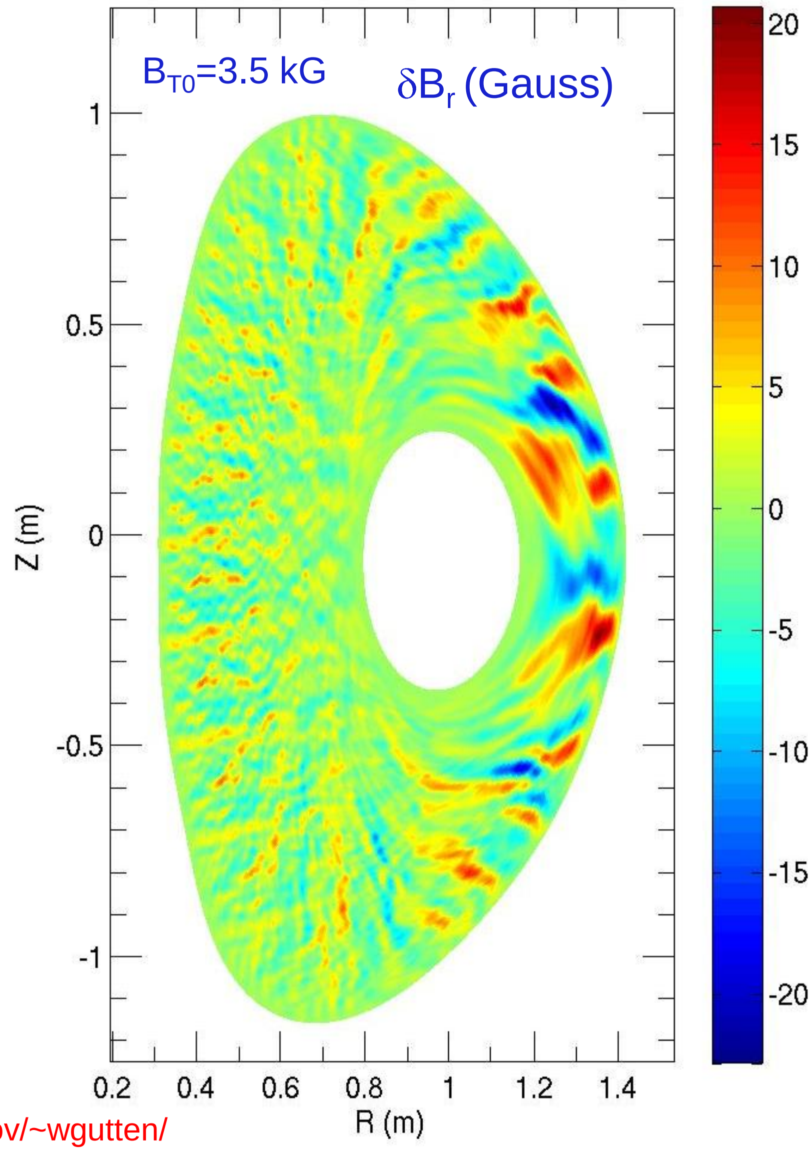




- Higher ionic charge (Z_{eff}>1, through adiabatic response) and improved resolution (binormal and radial) could increase transport
- Profile (non-local) effects could also matter - $\rho_s/a\approx1/100$ & edge more strongly driven

Structure of perturbations in real space distinct from ITG/TEM: narrow δn_e; broad, ballooning δB_r (follows linear structure)





Movies at http://www.pppl.gov/~wgutten/

Summary

- Non-linear microtearing simulations in NSTX
  - Necessary to “resolve” (distinguish) each simulated rational surface
  - Transport is experimentally significant and dominated by magnetic “flutter”
  - Poincare plots indicate globally stochastic

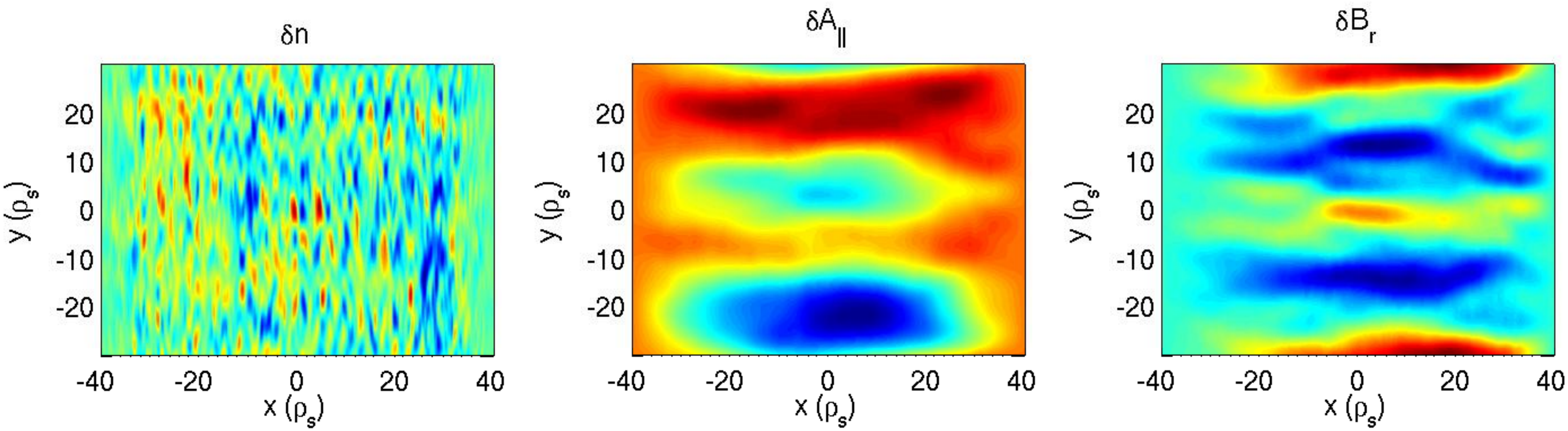
- Scaling of non-linear transport – roughly follows linear scaling
  - Predicted $\chi_{e,sim} \sim \nu_e^{1.1}$ close to experimental trend
  - “Stiff” with ∇T_e but suppressible by experimental levels of $E \times B$ shear
  - Not reproduced by stochastic transport models

- What determines saturation? Is there a useful model for saturation?
- Does the concept of stochasticity help in any way?

Narrow density perturbations remain in nonlinear simulations

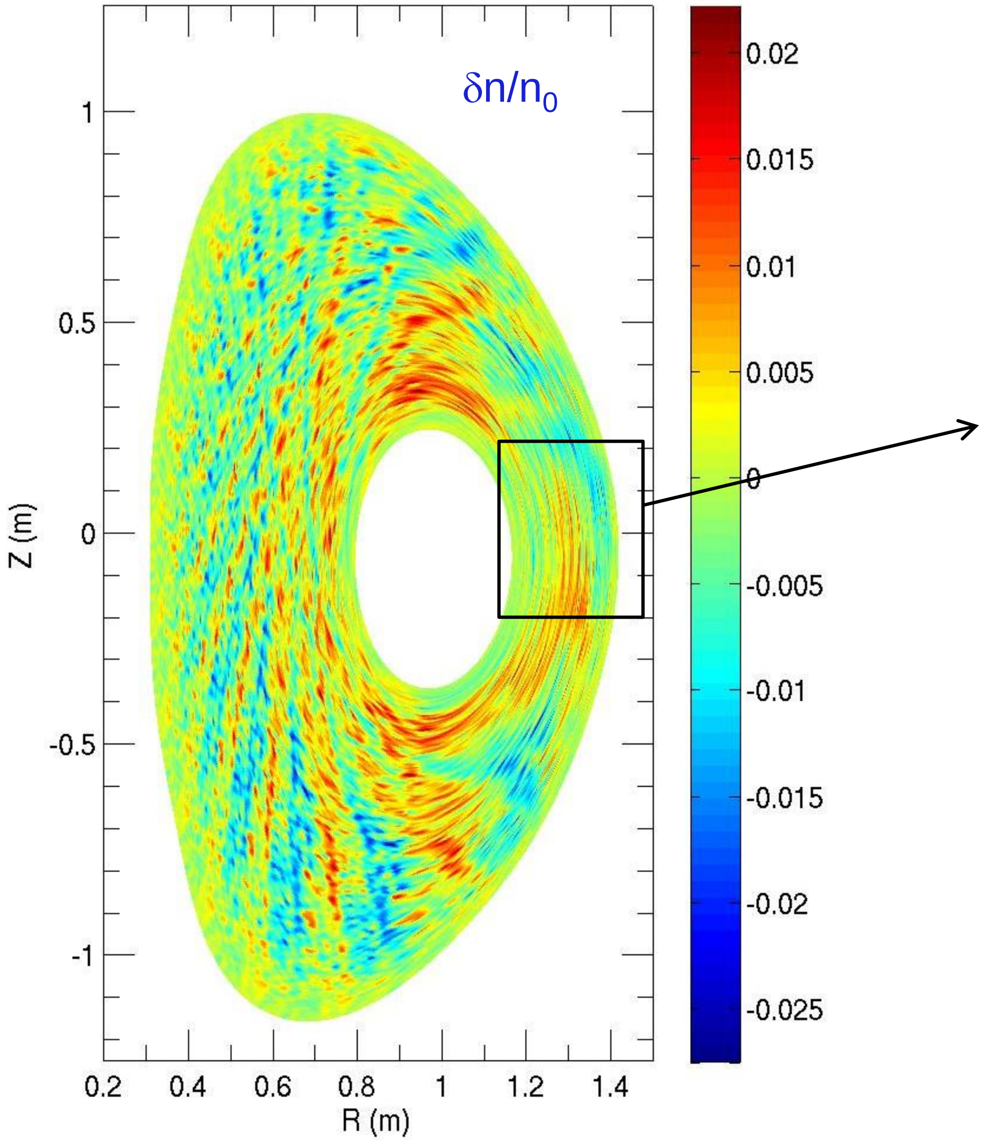
- Narrow radial n, φ, $j_{||}$ structures need to be resolved but $A_{||}$ very broad
- $\delta B_r/B \sim 0.15\% \;\sim\; \rho_e/L_{Te} = 0.065\%$
- $\delta B_r/B \sim \rho_e/L_{Te}$ analytic approximation from Drake et al. PRL 1980; used for NSTX in Wong et al. PRL 2007

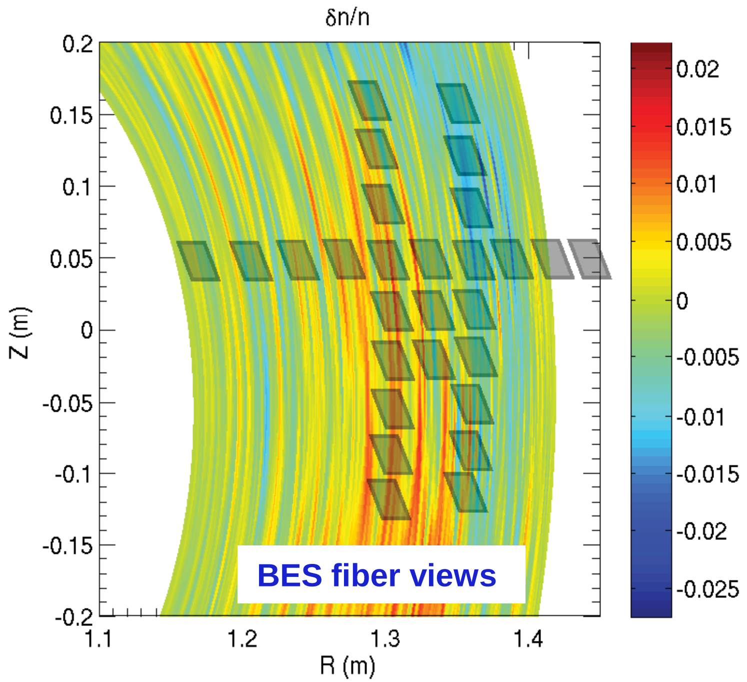
$\delta n/n \approx 0.5\%$ | $\delta A_{||}/\rho_s B \approx 0.8\%$ | $\delta B_r/B \approx 0.15\%$



$\delta T_e/T_e \approx 2\%$
$\delta v_{e,||}/c_s \approx 6\%$

BES for density fluctuations





- BES suitable for long poloidal scale (U-Wisconsin, Smith et al., RSI 2010)
- May average over narrow radial scale – requires synthetic diagnostic and instrument function (D. Smith, BO4.2)

Polarimetry for magnetic field fluctuations

- New UCLA polarimetry system (J. Zhang, PP9.71)
- Simulations suggest $(\delta B/B)_{internal} \leq 0.1\%$ may be detectable (1-2^0 or ~0.3^0 rms mixer phase)