Comparisons of GYRO and GS2 Including E×B Flow Shear

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Background

- Most gyrokinetic microstability codes include passing and trapped electrons, accurate plasma shaping, multiple kinetic species, collisions, magnetic fluctuations, and equilibrium $\mathbf{E}\times\mathbf{B}$ flow shear.
- Linear mode frequencies are used routinely for interpreting turbulence measurements in experiments (TEM unstable?).
- Nonlinear predictions of transport and/or turbulence characteristics are used extensively to interpret and predict transport in experiments.
- ★ **However, the codes have not been “verified” (shown to correctly solve the underlying equations) for present-day experiments spanning a range of discharge conditions.**

Verification

- No analytical verification in such regimes ⇒
  - "**benchmarking**": Code is "correct" if it agrees with others (unlikely all would produce exact same erroneous results).
- "Apples-to-apples" comparisons between codes:*
  - same plasma, including shaping (EFIT or Miller parameterization with elongation, triangularity and gradients, R/a, q, shear, etc.)
  - same physics (electromagnetic, collisions, trapped electrons, $\mathbf{E}\times\mathbf{B}$ shear, etc.)
  - periodic (flux-tube) radial domain (dictated by GS2), or $\rho^* = \rho_s/a << 1$.
  - sufficient temporal, spatial, velocity-space resolutions

* Eulerian (continuum, fixed grid) GYRO and GS2 in what follows. Plan to add Langrangian (moving grid) particle-in-cell (PIC) code GEM.

Validation NOT Shortcut to Verification

- Validation: Comparisons of fluxes, turbulence parameters between code and experiment.
- Codes rarely agree with experiment using default plasma profiles.
- Plasma profiles must be independently adjusted in all combinations within experimental uncertainties to seek agreement.

★ **No way to distinguish code errors from experimental uncertainties**

Outline

DIII-D shot 129813, t = 1.5 s

- Linear
  - full physics
- Nonlinear
  - no **E×B** flow shear
    - full physics
    - collisionless*
  - **with E×B flow shear**
    - **full physics**
    - **collisionless***

C-Mod shot 1101014009, t = 1.0 s

- **Linear**
  - **full physics**
  - **collisionless***
  - **collisionless, no impurity***
- **Nonlinear**
  - **no E×B flow shear**
    - **electrostatic**

*treated because of code disagreements with full physics

Physics Features

- $\delta B_\perp$ ($\delta B_\|$ neglected)
- passing and trapped electrons
- Miller shaping parameters
- electron collisions (Lorentz model)
- one impurity (C^{6+} in DIII-D, B^{5+} in C-Mod)
- local (flux-tube) radial domain ($\rho^* = \rho_s/a << 1$)
- finite Debye length

★ All the above referred to as “full physics.”

- $\mathbf{E}\times\mathbf{B}$ flow shear

DIII-D

DIII-D Parameters ($\rho = 0.5$)

- DIII-D shot 128913: 1 NB, L-mode, 2.1 T, 1.0 MA

Parameter	Value
r (m)	0.33
a (m)	0.60
n_e (10^{19} m^{-3})	2.1
T_e (keV)	1.0
n_i/n_e	0.94
n_{imp}/n_e	0.011
$T_i/T_e = T_{inp}/T_e$	0.83
$a/L_{ne} = a\, \mathrm{dln}(n_e)/\mathrm{d}r$	1.1
$a/L_{ni} = a\, \mathrm{dln}(n_i)/\mathrm{d}r$	1.1
$a/L_{Te} = a\, \mathrm{dln}(T_e)/\mathrm{d}r$	2.6
$a/L_{Ti} = a\, \mathrm{dln}(T_i)/\mathrm{d}r$	1.8
$a/L_{Timp} = a\, \mathrm{dln}(T_{imp})/\mathrm{d}r$	1.8

Parameter	Value
$R_0(r)/a$	2.8
$\Delta = \mathrm{d}R_0(r)/\mathrm{d}r$	-0.086
q	1.8
$s = r\, \mathrm{dln}(q)/\mathrm{d}r$	0.58
κ	1.3
$s_\kappa = r\, \mathrm{dln}(\kappa)/\mathrm{d}r$	0.046
δ	0.15
$s_\delta = r\, \mathrm{d}\delta/\mathrm{d}r$	0.17
β	0.0035
ρ^*	0.0037
Z_{eff}	1.3
$\nu_{ei}\, a/c_s$	0.11

$c_s = (T_e/m_i)^{1/2}$

r = half-width of flux surface at elevation of centroid

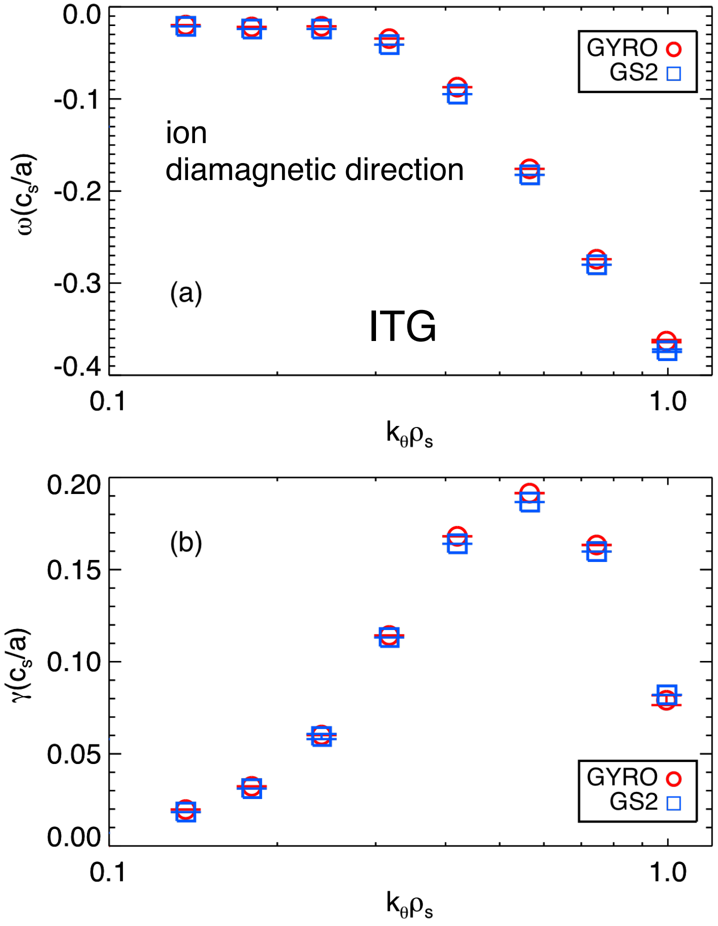
Linear Results

$k_r = 0$ for GS2

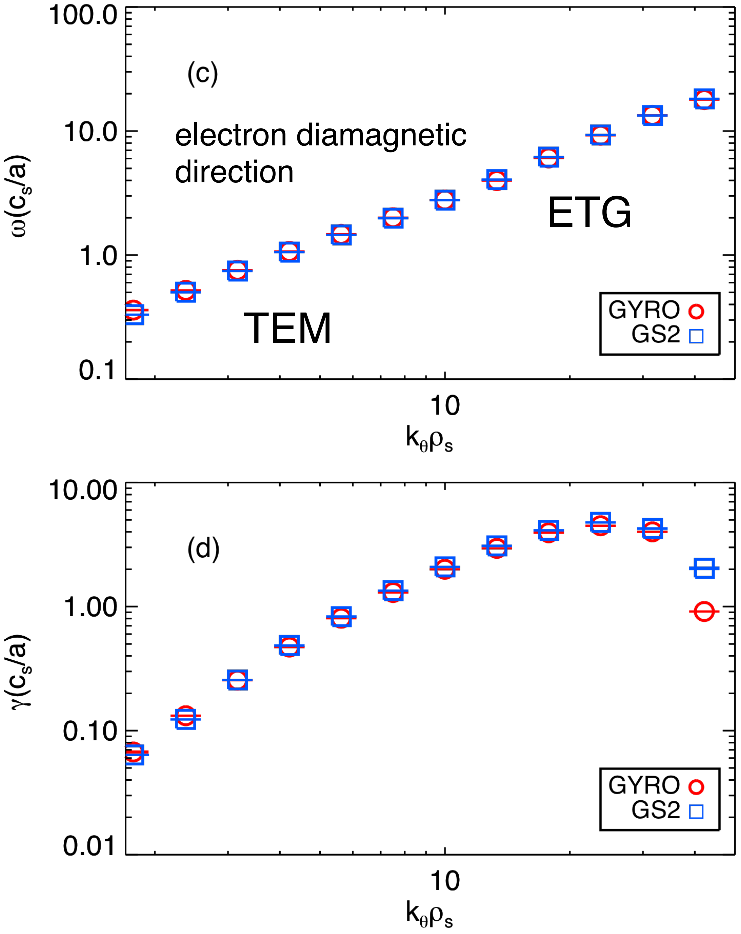
GYRO solves in real space

Linear Frequencies, Full Physics

low $k_\theta \rho_s$



high $k_\theta \rho_s$



- Excellent agreement

Nonlinear Results

No E×B Flow Shear

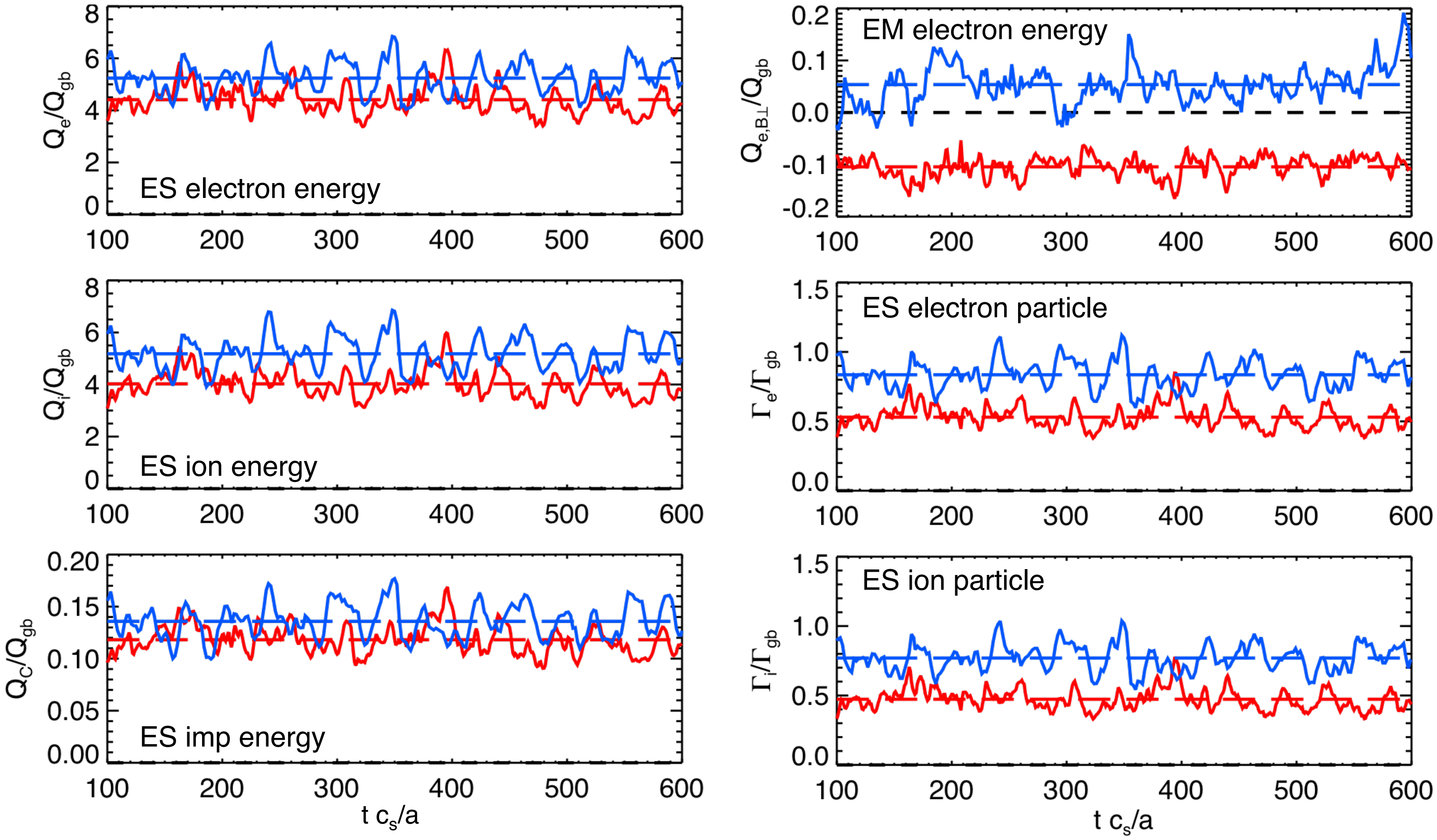
Nonlinear Simulations, no E×B

- 16 poloidal modes
- $0 < k_\theta \rho_s \lesssim 1$
- $L_\theta \sim 100\rho_s$ (wavelength of lowest nonzero k_θ)
- $L_r \sim 150\rho_s$
  - $n_r = 144$ (GS2) $\Rightarrow \Delta r \sim \rho_s$
  - $n_r = 192$ (GYRO) $\Rightarrow \Delta r \sim 0.8\rho_s$
- Velocity-space grid points:
  128 (GYRO), 592 (GS2)

Comparisons between GS2, GYRO
No E×B

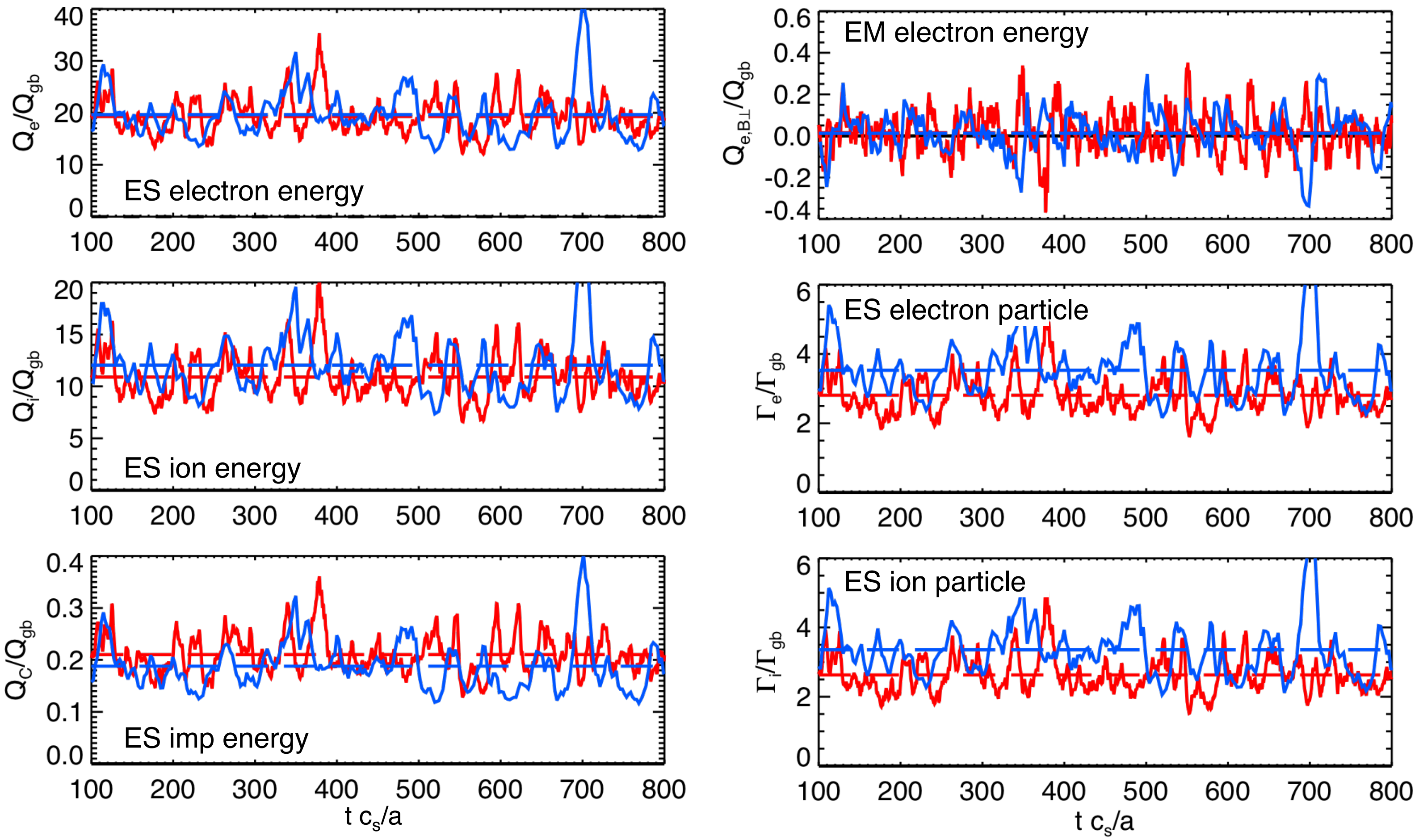
Full Physics, no E×B

GYRO red, GS2 blue $\quad Q_{gb} \equiv n_e T_e c_s (\rho^*)^2 \quad \Gamma_{gb} \equiv Q_{gb}/T_e$



- ◆ Differences, especially in particle fluxes.
- ◆ GS2 fluxes always larger (or more positive).

Collisionless, no E×B

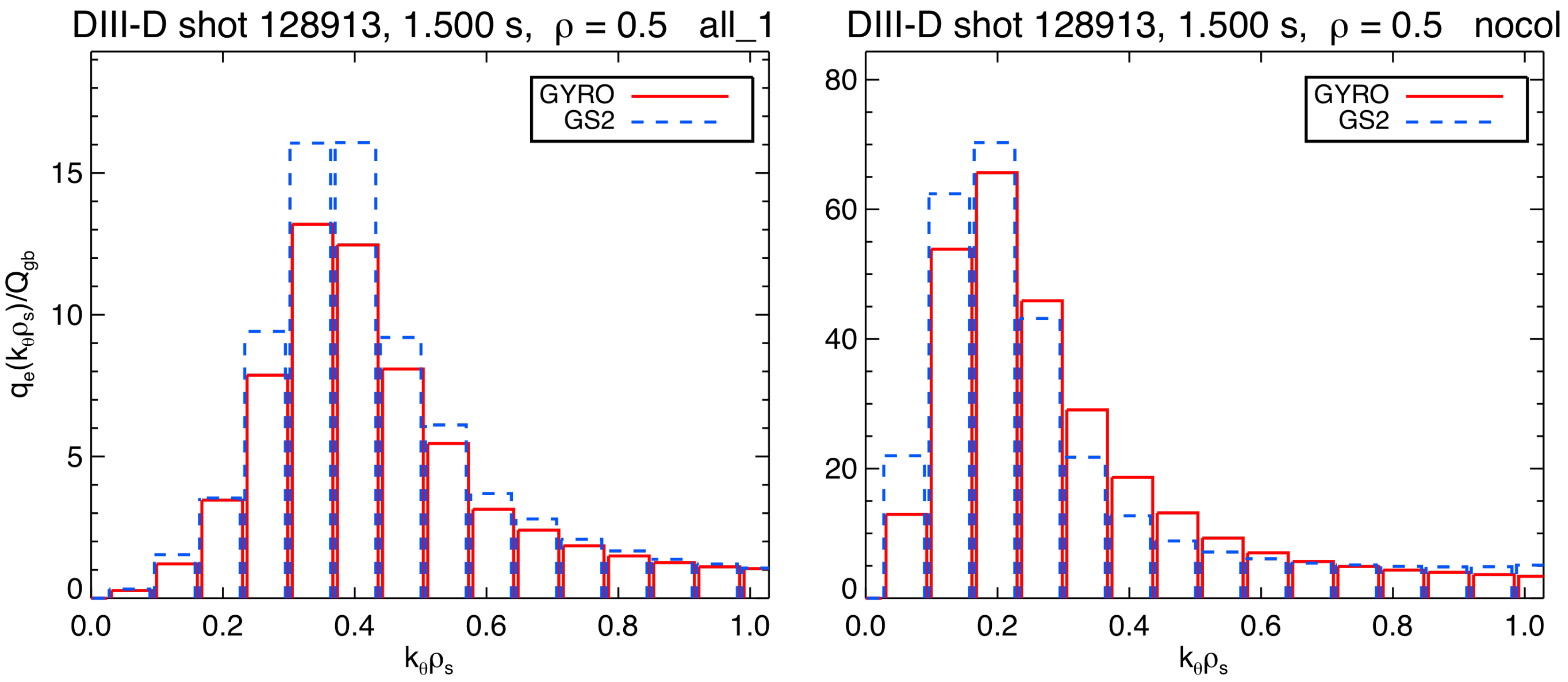


◆ Much better agreement

Electron Energy Flux Spectra, no E×B

Full Physics

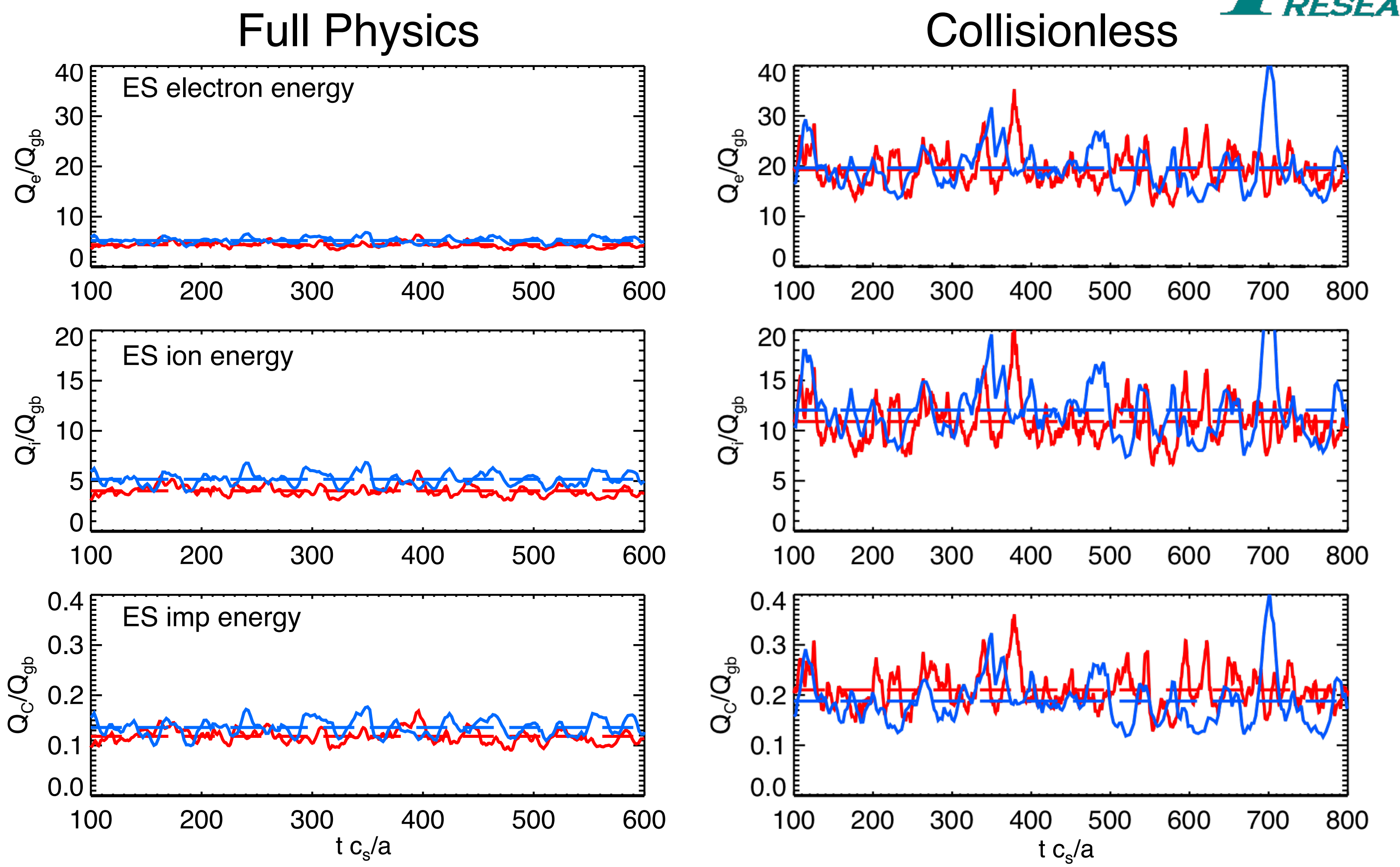
Collisionless



- Peaks are in ITG range.
- Shapes agree well.
- Peaks downshifted by factor ~2.
- GS2 slightly downshifted from GYRO.

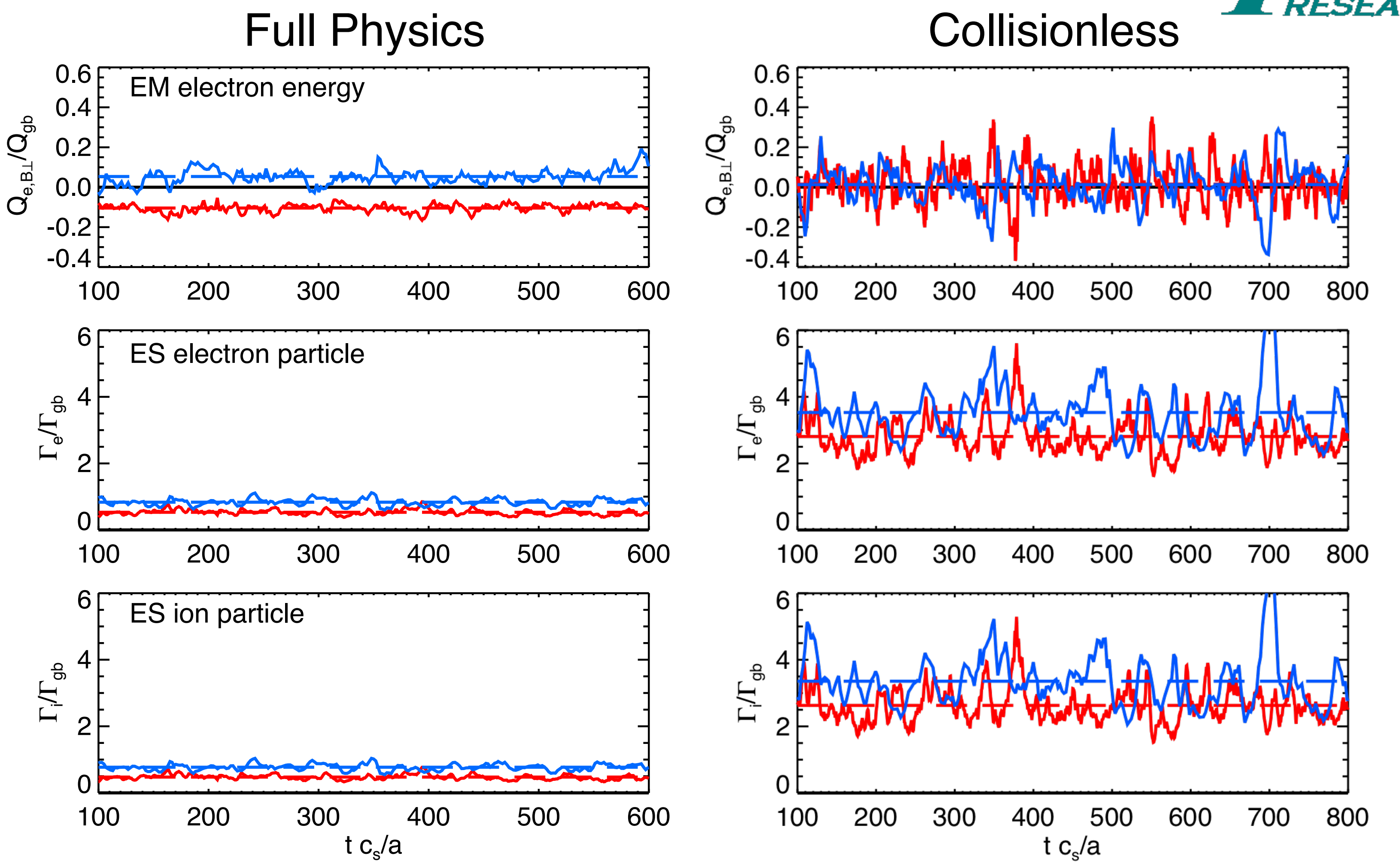
Effects of Collisions
No E×B

Collisional Effects, no E×B



- ◆ Electron, ion fluxes greatly increase without collisions.
- ★ **Absolute** differences between fluxes about the same.

Collisional Effects, no E×B (cont.)



- ◆ Electron, ion particle fluxes much larger without collisions.
- ★ Absolute differences between particle fluxes *smaller* with collisions.

Nonlinear Results

With E×B Flow Shear

$$\gamma_{\mathbf{E\times B}}\, a/c_s = 0.064$$

$$\gamma_{\mathbf{E\times B}}/\gamma_{\max} \approx 0.3$$

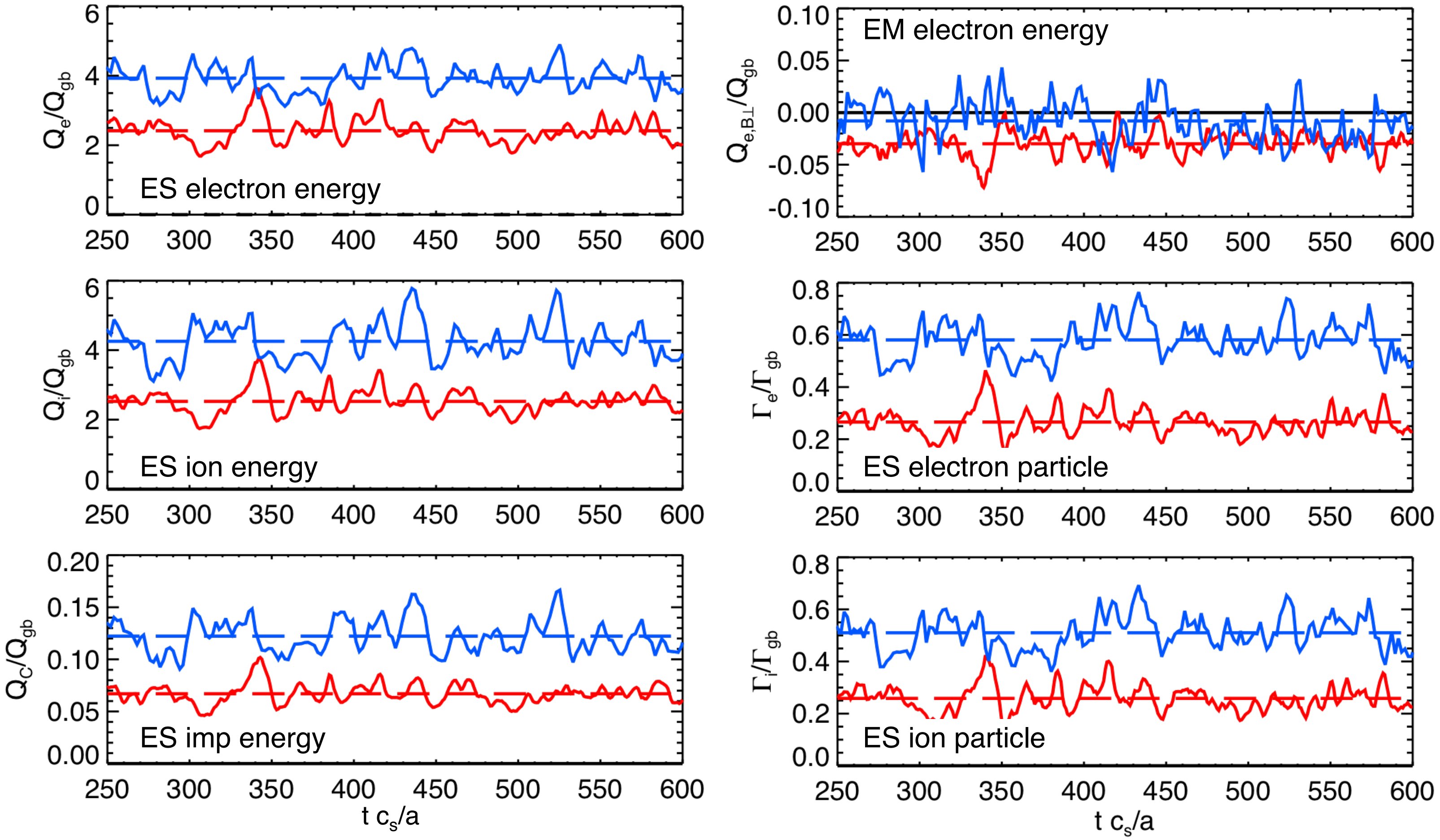
$$\gamma_{\mathbf{E\times B}}/\nu_{ei} \approx 0.6$$

Nonlinear Simulations, with E×B

- 16 poloidal modes
- $0 < k_\theta \rho_s \lesssim 1$
- $L_\theta \sim 100\rho_s$ (wavelength of lowest nonzero k_θ)
- $L_r \sim 100\rho_s$
  - $n_r = 144$ (GS2) $\Rightarrow \Delta r \sim 0.7\rho_s$
  - $n_r = 192$ (GYRO) $\Rightarrow \Delta r \sim 0.5\rho_s$
- Velocity-space grid points:
  240 (GYRO), 592 (GS2)

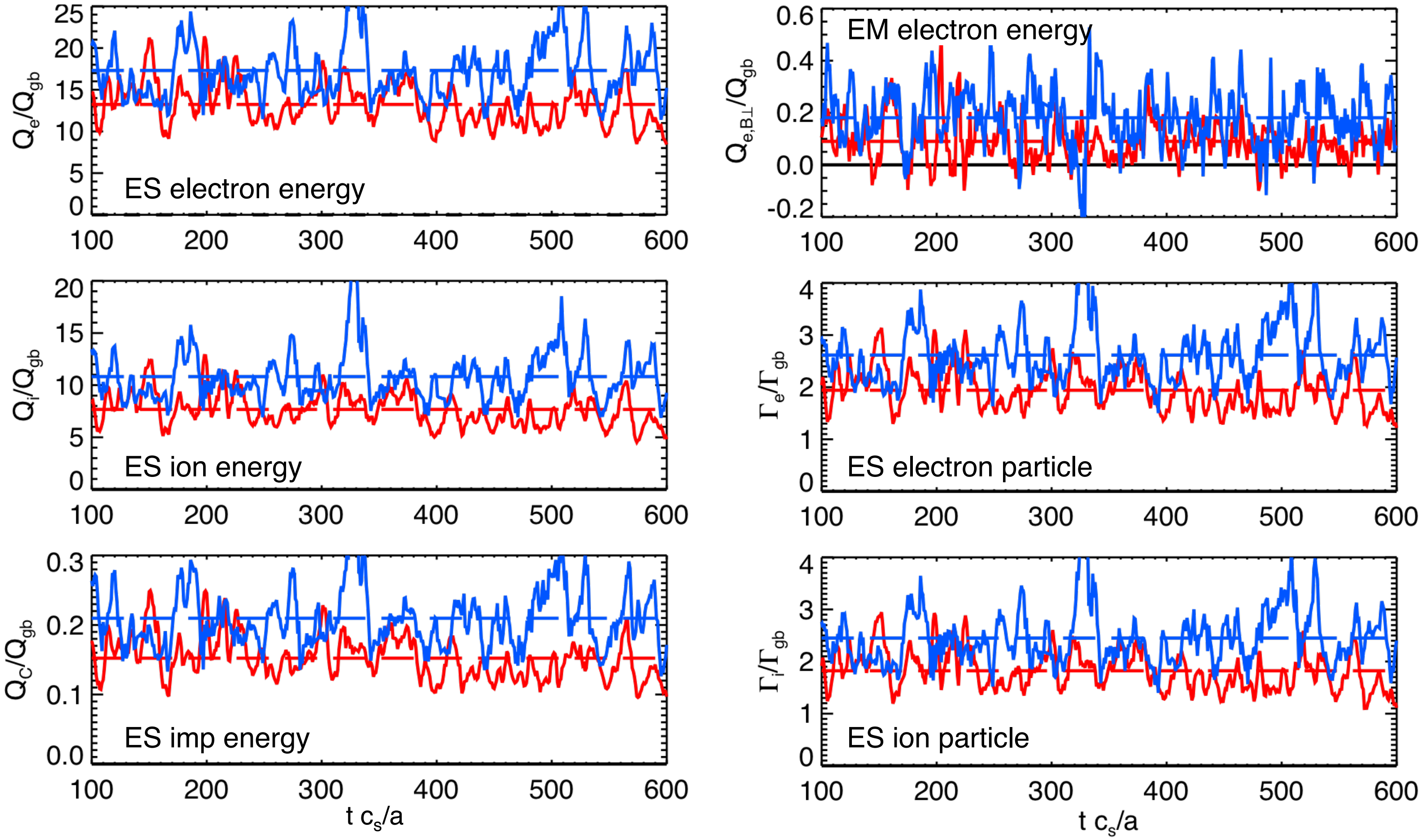
Comparisons between GS2, GYRO with E×B

Full Physics, with E×B



- ◆ Factor ~ 2 disagreement in electrostatic fluxes
- ◆ Again, GS2 fluxes always larger (or more positive).

Collisionless, with E×B

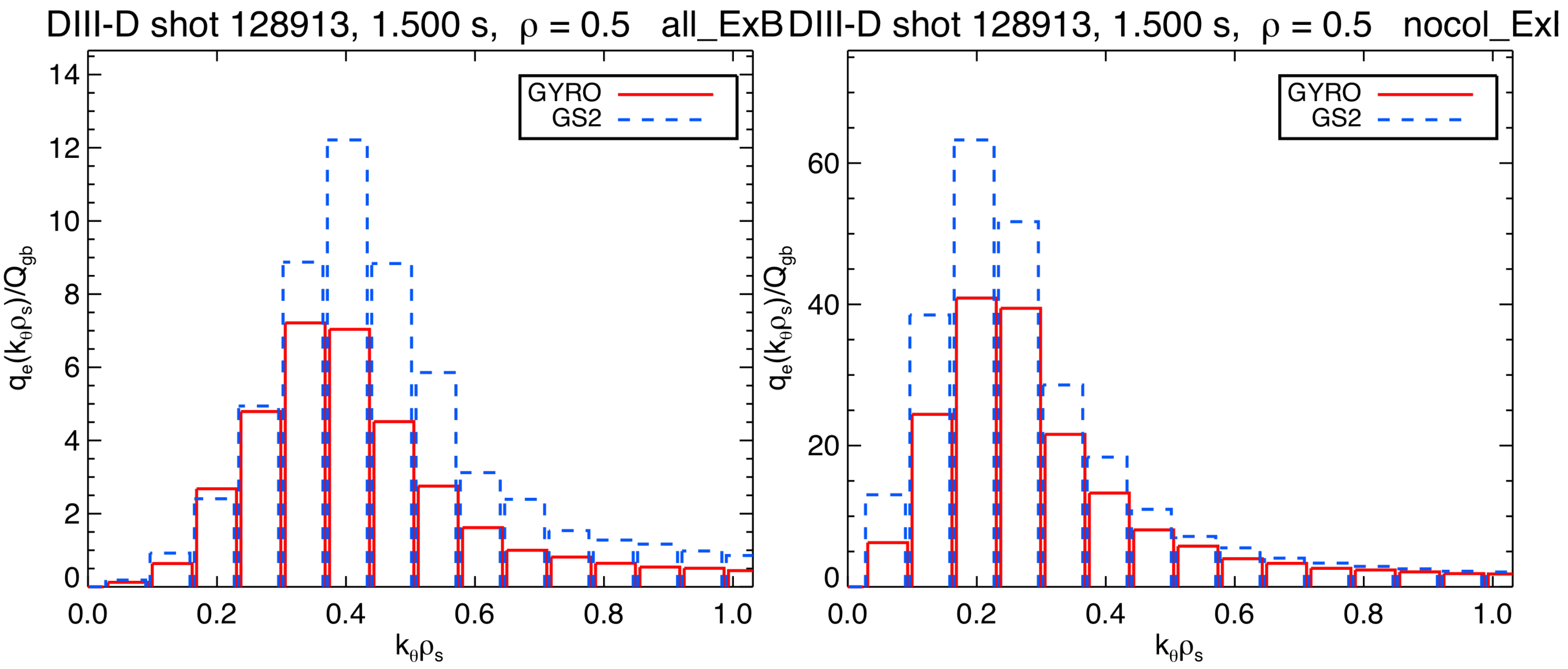


- Factor ~ √2 disagreement in ES fluxes, GS2 larger
- Absolute differences about same as with full physics.

Electron Energy Flux Spectra, with E×B

Full Physics

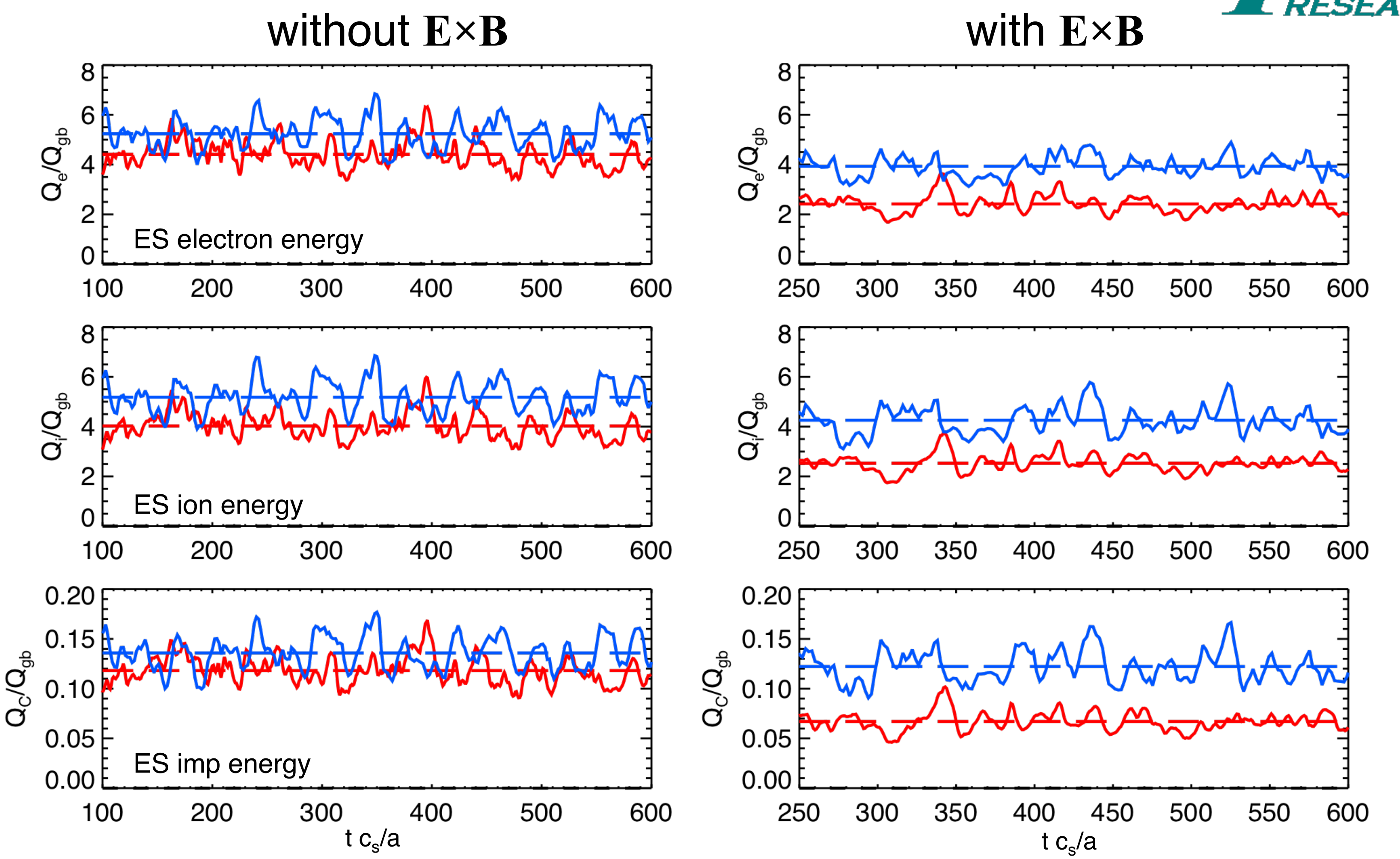
Collisionless



- ◆ Peaks are in ITG range.
- ◆ GYRO slightly downshifted, smaller than GS2
- ◆ Peaks downshifted by same factor ~2 as without **E**×**B**.
- ◆ GYRO smaller than GS2

Effects of E×B Flow Shear

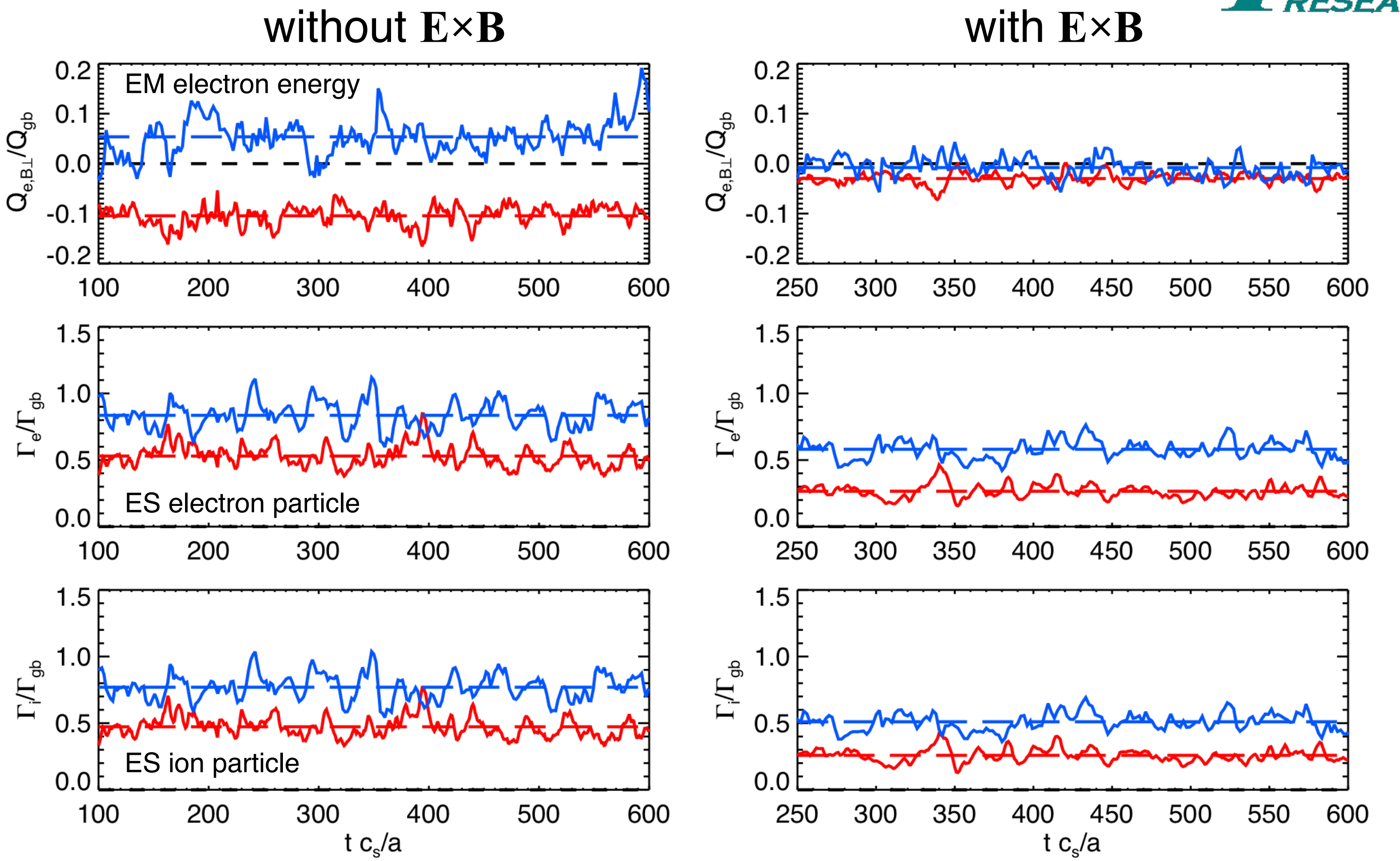
E×B Effects, Full Physics



◆ GS2 electron, ion fluxes decrease ~ 20% with E×B.

◆ GYRO fluxes decrease ~ 40%.

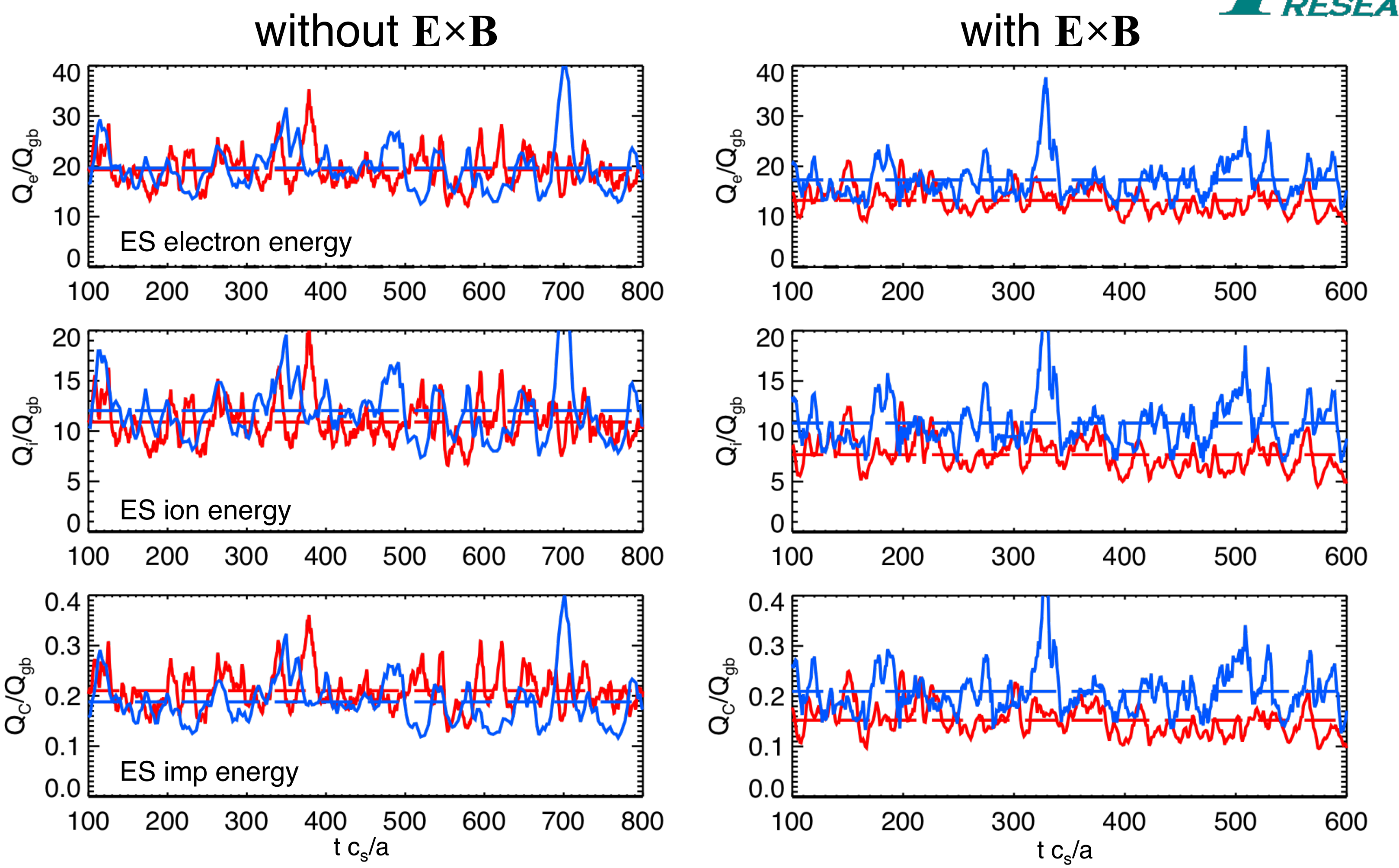
E×B Effects, Full Physics (cont.)



◆ GS2 particle fluxes decrease ~ 25% with **E×B**.

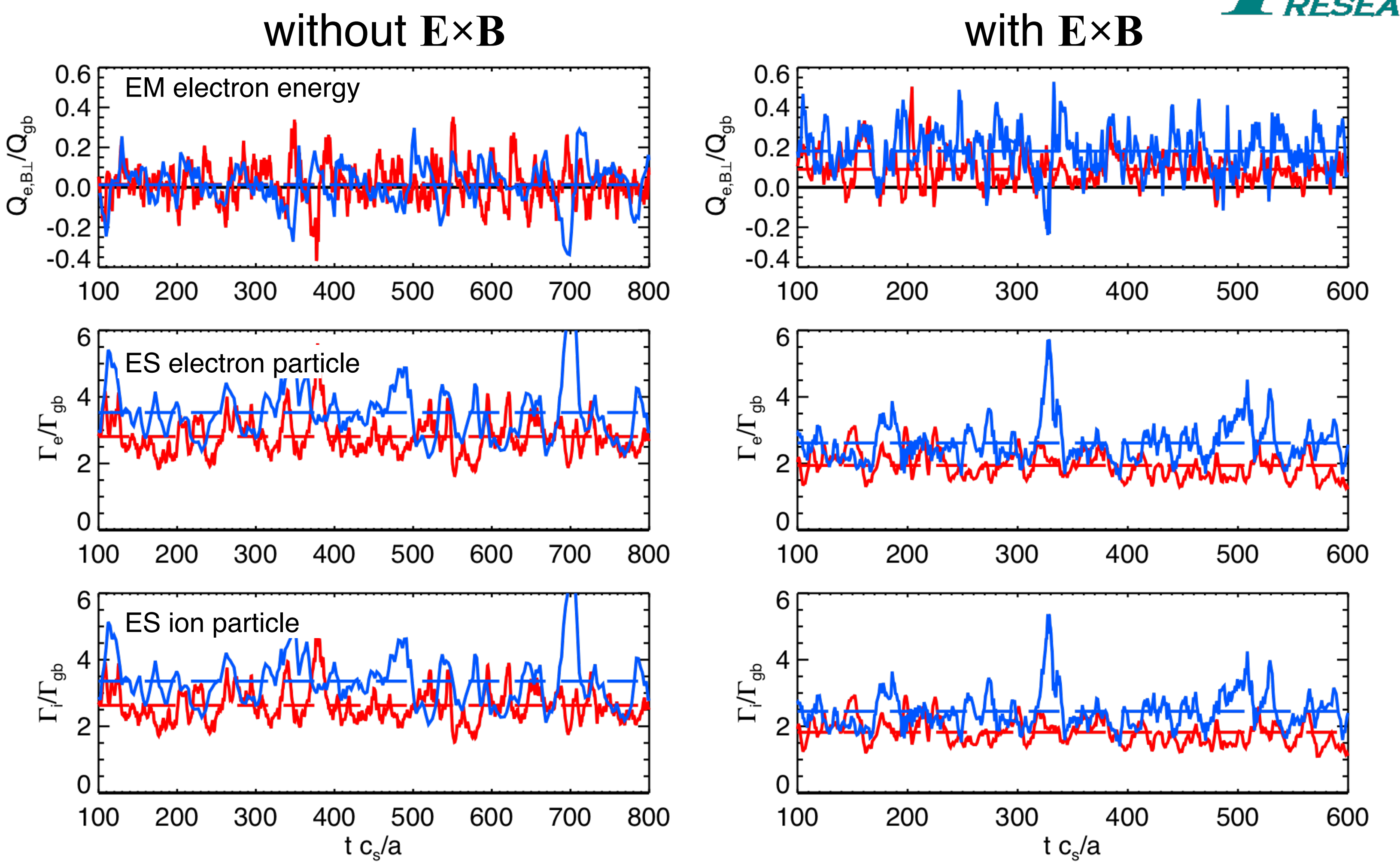
◆ GYRO particle fluxes decrease ~ 45%.

E×B Effects, Collisionless



- GYRO fluxes decrease ~ 30% with E×B.
- GS2 fluxes decrease only slightly.

E×B Effects, Collisionless (cont.)



- ◆ GYRO particle fluxes decrease ~ 30% with **E×B**.
- ◆ Except for EM energy, GS2 fluxes decrease ~ 25%.

DIII-D Summary

- Without E×B
  - Full physics: Frequencies agree but fluxes less so. (However, none exhibit large *absolute* differences between codes.)
  - Collisionless: GYRO and GS2 fluxes (and frequencies) agree.
- With E×B
  - GS2 and GYRO fluxes disagree by factor ~ √2 (collisionless) to 2 (full physics). GYRO fluxes are reduced by flow shear more than those from GS2.

	linear	nonlinear	
		no ExB	ExB
collisional	✓	✗	✗
collisionless	✓	✓	✗

Especially bad: Actual discharges have collisions and rotational shear.

★ In essentially all cases, GS2 fluxes greater (or more positive) than GYRO fluxes (or vice-versa).

C-Mod

First Results

C-Mod vs DIII-D Parameters ($\rho = 0.5$)

- DIII-D shot 128913: 1 neutral beam, L-mode, 2.1 T, 1.0 MA
- C-Mod shot 1101014009: 1 MW ICRH, L-mode, 5.3 T, 1.2 MA

Parameter	DIII-D	C-Mod
r (m)	0.33	0.12
a (m)	0.60	0.22
n_e (10^{19} m^{-3})	2.1	14.6
T_e (keV)	1.0	1.6
n_i/n_e	0.94	0.87
n_{imp}/n_e	0.011	0.026
$T_i/T_e = T_{inp}/T_e$	0.83	0.71
$a/L_{ne} = a\ \mathrm{dln}(n_e)/\mathrm{d}r$	1.1	0.36
$a/L_{ni} = a\ \mathrm{dln}(n_i)/\mathrm{d}r$	1.1	0.36
$a/L_{Te} = a\ \mathrm{dln}(T_e)/\mathrm{d}r$	2.6	2.4
$a/L_{Ti} = a\ \mathrm{dln}(T_i)/\mathrm{d}r$	1.8	1.9
$a/L_{Timp} = a\ \mathrm{dln}(T_{imp})/\mathrm{d}r$	1.8	1.9

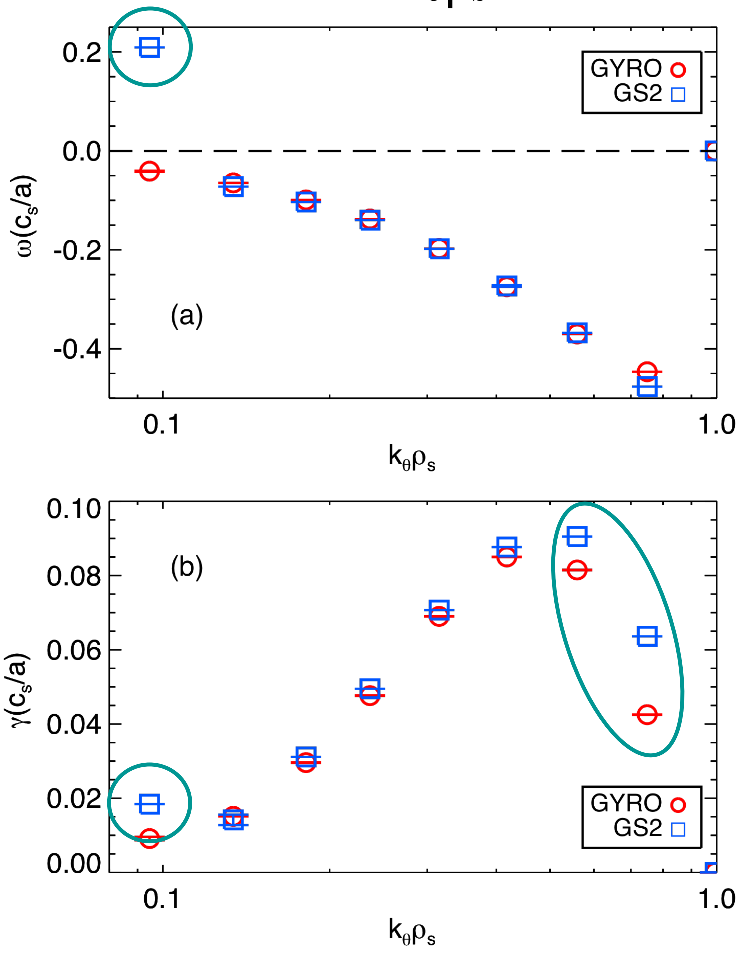
Parameter	DIII-D	C-Mod
$R_0(r)/a$	2.8	3.1
$\Delta = \mathrm{d}R_0(r)/\mathrm{d}r$	-0.086	-0.034
q	1.8	1.2
$s = r\ \mathrm{dln}(q)/\mathrm{d}r$	0.58	0.86
κ	1.3	1.3
$s_\kappa = r\ \mathrm{dln}(\kappa)/\mathrm{d}r$	0.046	0.068
δ	0.15	0.15
$s_\delta = r\ \mathrm{d}\delta/\mathrm{d}r$	0.17	0.17
β	0.0035	0.0058
ρ^*	0.0037	0.0052
Z_{eff}	1.3	2.3
$\nu_{ei}\ a/c_s$	0.11	0.10

r = half-width of flux surface at the elevation of the centroid

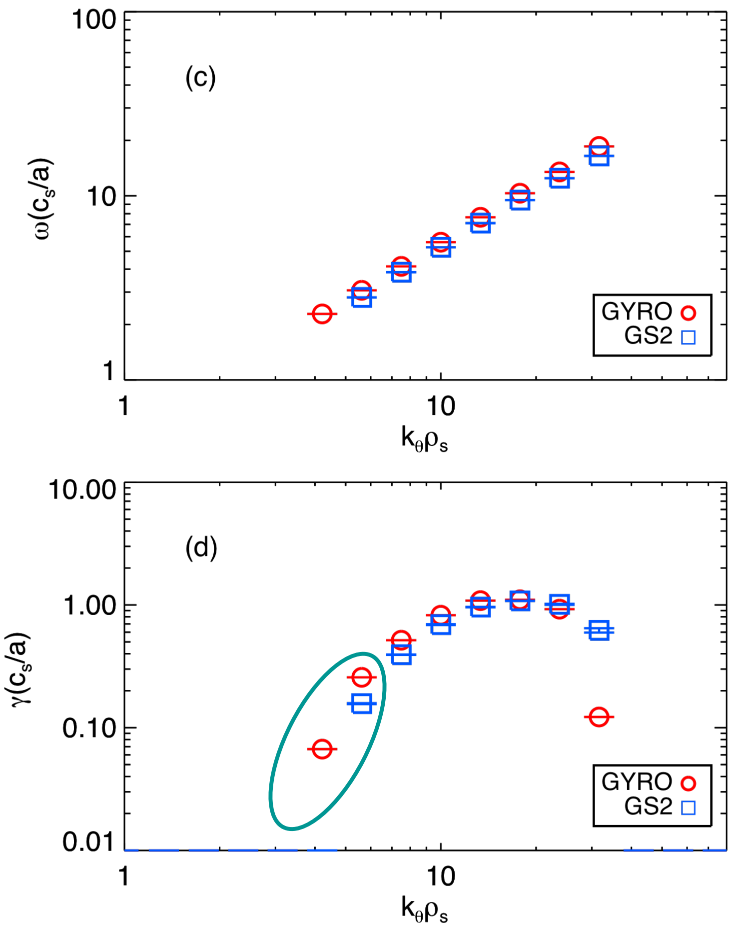
Linear

Linear Frequencies: Full Physics

low $k_\theta\rho_s$



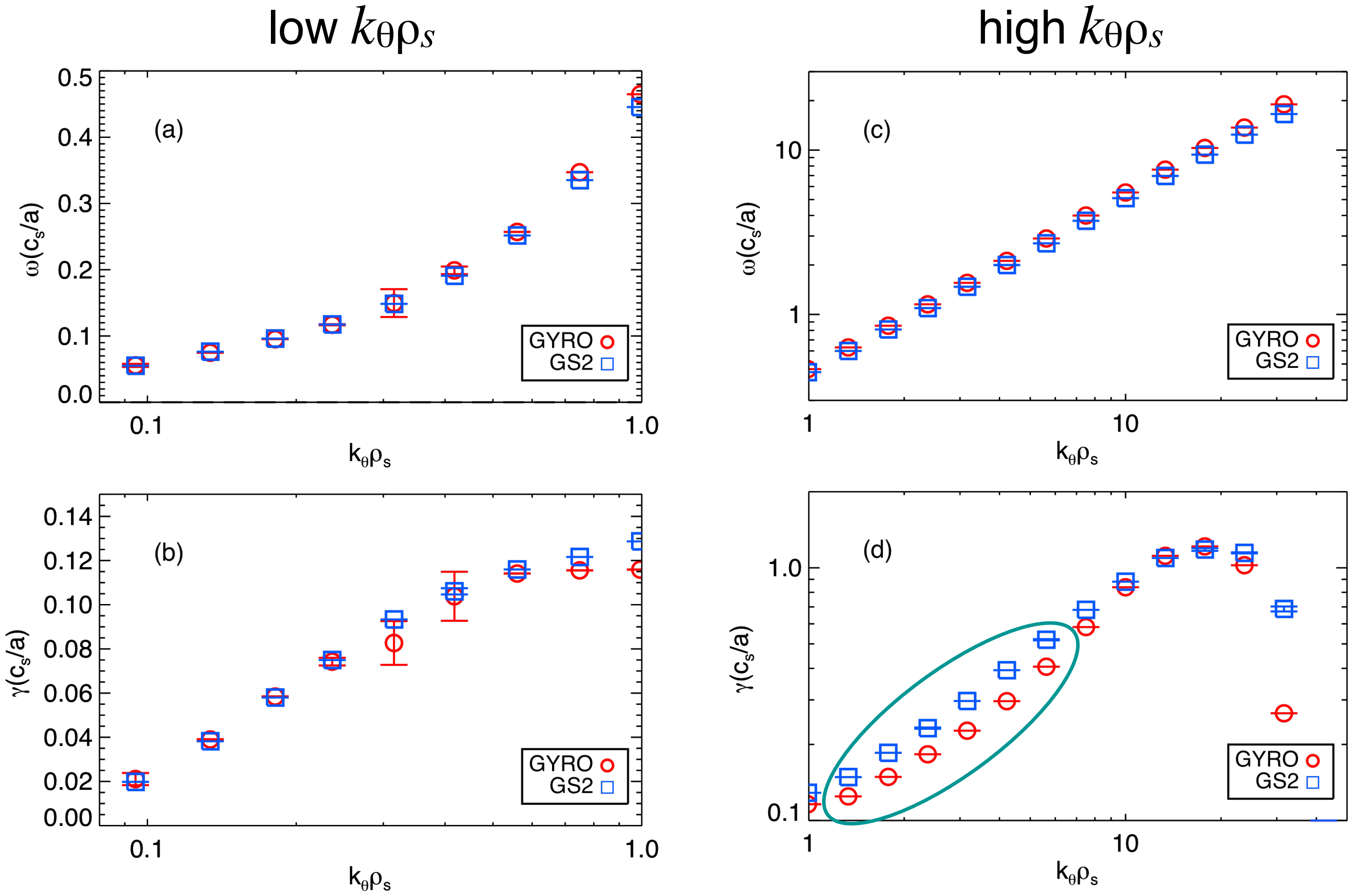
high $k_\theta\rho_s$



- Tearing mode from GS2 at lowest $k_\theta\rho_s$
    - Otherwise ITG
- **Stable** in TEM region
    - Otherwise ETG

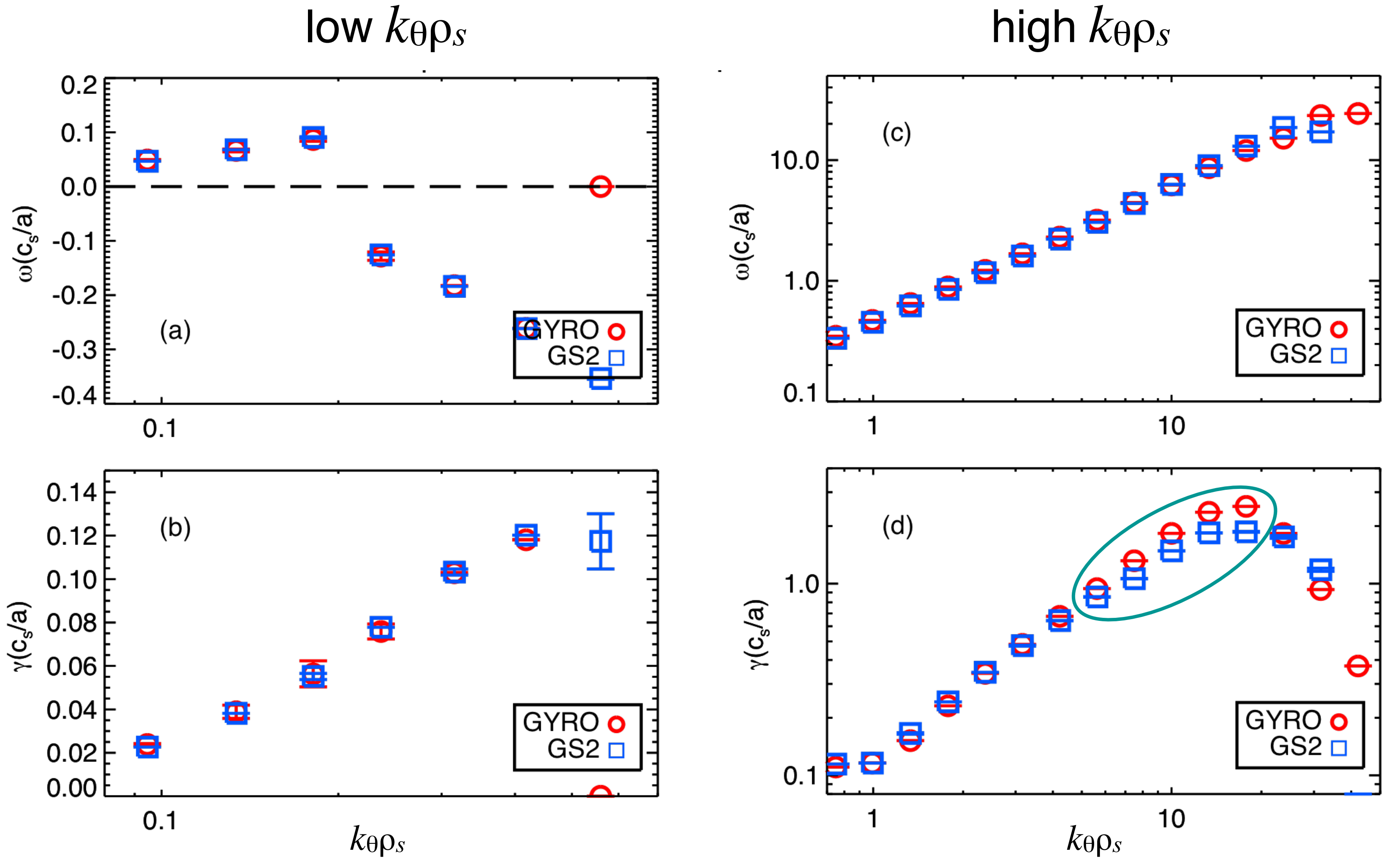
Linear Frequencies: Collisionless

4th-State RESEARCH



- ◆ Good agreement
- ◆ Propagation in e$^-$ direction
- ◆ Poor agreement between growth rates in TEM region

Linear Frequencies: Collisionless, no Impurity



- Good agreement
- Good agreement except at highest $k_\theta \rho_s$
- Similar to DIII-D collisionless result

C-Mod Summary - Linear

- Full physics:
  - Tearing mode at lowest $k_\theta\rho_s$ from GS2, electrostatic mode from GYRO.
  - Frequencies agree except growth rates next to *stable* TEM region.
- Without collisions:
  - Frequencies agree except in *unstable* TEM region where GYRO growth rates are lower than those from GS2.
- Without either collisions *or* impurity:
  - Frequencies agree except at highest $k_\theta\rho_s$.
- Without impurity alone (not shown):
  - virtually same as full physics.

	collisions	no collisions
impurity	✗	✗
no impurity	✗	✓

- Electrostatic (not shown):
  - virtually same as full physics, except GS2 tearing mode → ITG.

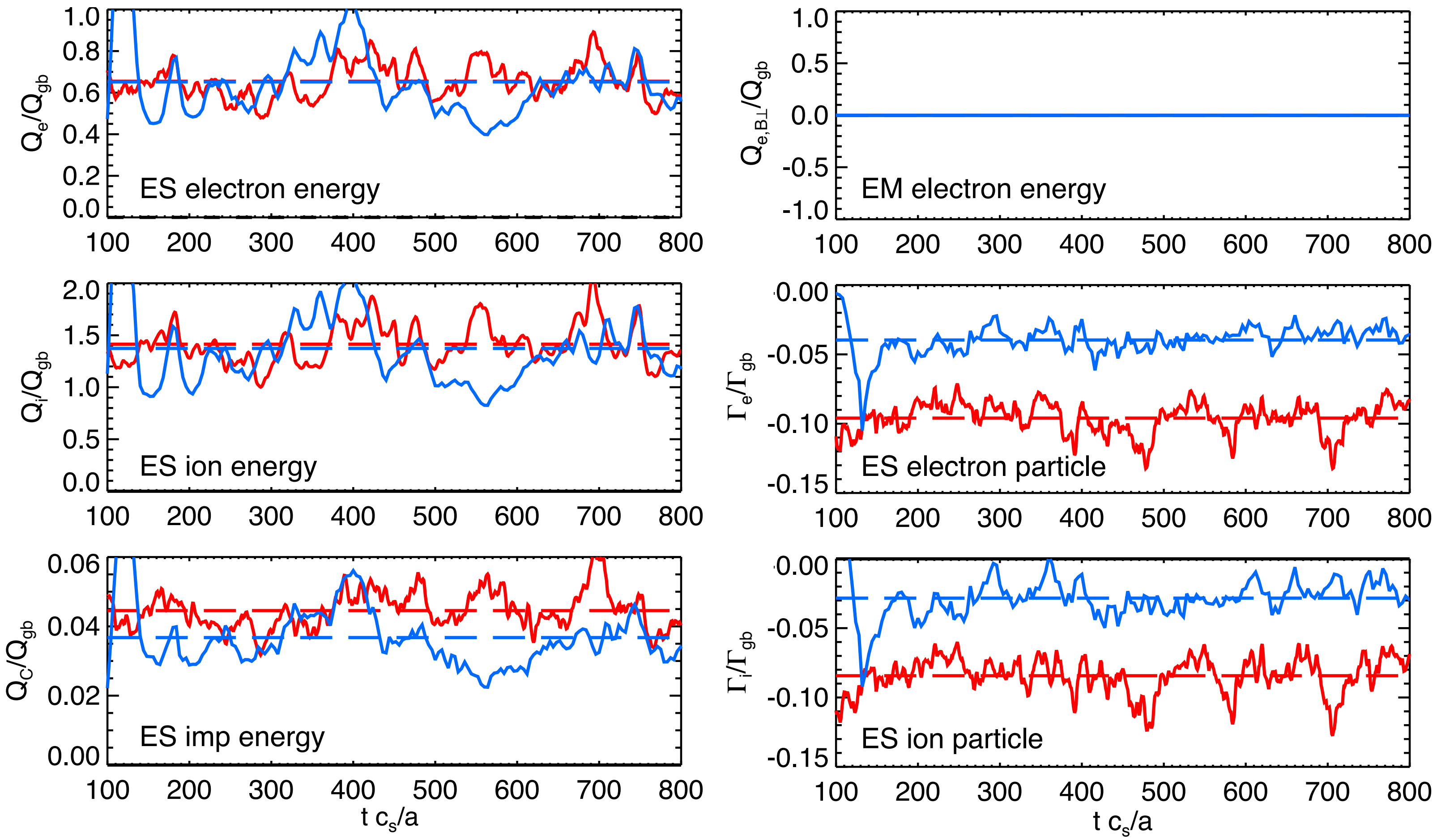
Nonlinear Results

Electrostatic, no E×B Flow Shear

$$\gamma_{\mathbf{E\times B}}\, a/c_s = 0.0015$$

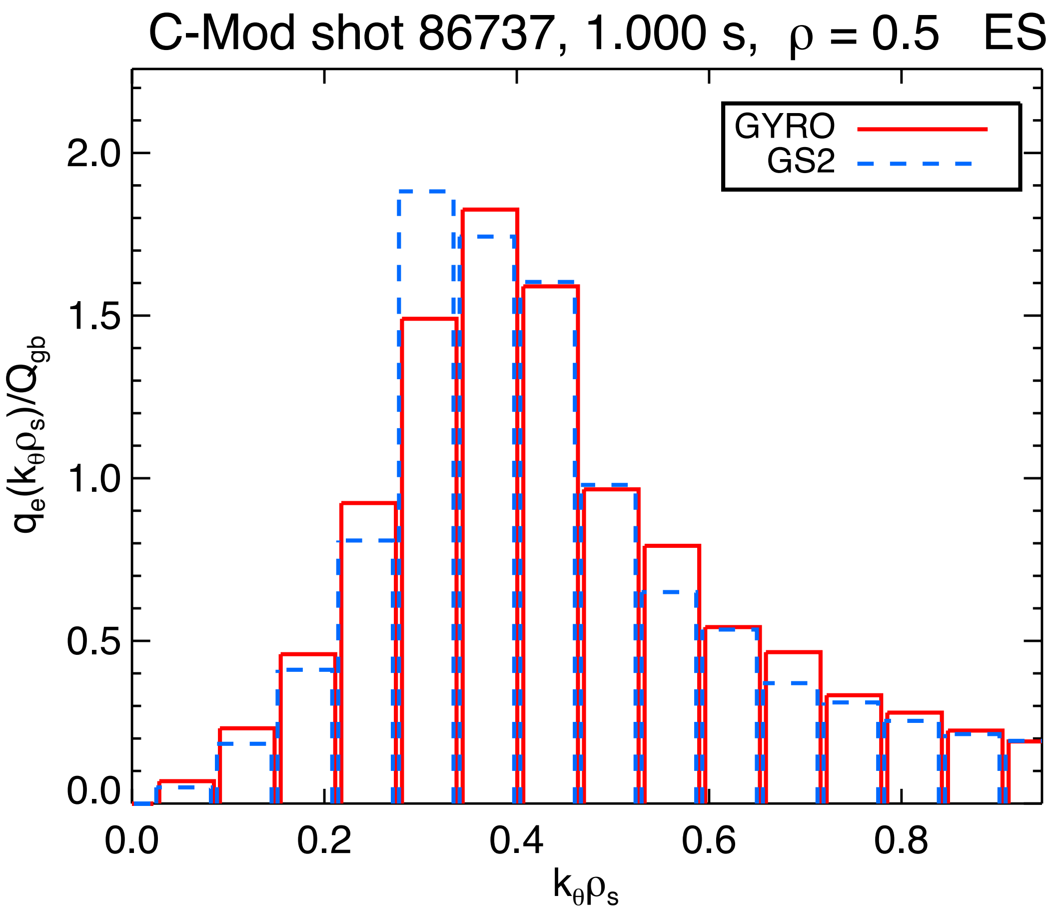
$$\gamma_{\mathbf{E\times B}}/\gamma_{\max} < 0.02 \ll 1$$

Electrostatic, no E×B



- Good agreement (?) except for (inward) particle fluxes. However, they and impurity energy fluxes small.

Electron Energy Flux Spectra, no ExB



- Peaks about the same but *broader* than DIII-D

C-Mod Summary - Nonlinear

- Without **E×B**
  - Good agreement between GS2, GYRO except for (inward) particle fluxes. However, normalized C-Mod particle fluxes very small.
  - Slow oscillations in time: require longer runs for definitive conclusions.
- C-Mod absolute flux densities much greater than those of DIII-D.

Future Work

- DIII-D discharge
  - Understand and resolve (?) code differences with **E**×**B**.
- C-Mod discharge
  - Understand and resolve (?) differences in linear results. Investigate effects of density and q profile, impurity concentration.
  - Run nonlinear simulations longer.
  - Perform simulations with and without collisions, impurity, **E**×**B**.
- Discharges which community already desires simulations of.
- Learn to run GEM and add to benchmarking/verification.
  - ★Three codes would greatly enhance credibility of verification exercises, especially when additional code is PIC.
  - Perform simulations for discharges presented here.
  - Understand and resolve (?) differences, if any, with GYRO and/or GS2.
- Investigate other radii, e.g., closer to edge.

★ In all cases, check simulation convergence w.r.t.
radial resolution & box size, # poloidal modes, time step.

Future Work (cont.)

Longer term (next calendar year):

- Investigate other discharges:
  - ITER scenario (need license to access data)
  - DIII-D high rotation, β, etc.
  - C-Mod I-mode, ITB, etc.
- Develop quantitative metric for agreement between codes.
- Compare fundamental fluctuation characteristics among codes, e.g.,
  - magnitudes of fluctuations in density, temperature, etc.,
  - cross phase between density and temperature fluctuations.