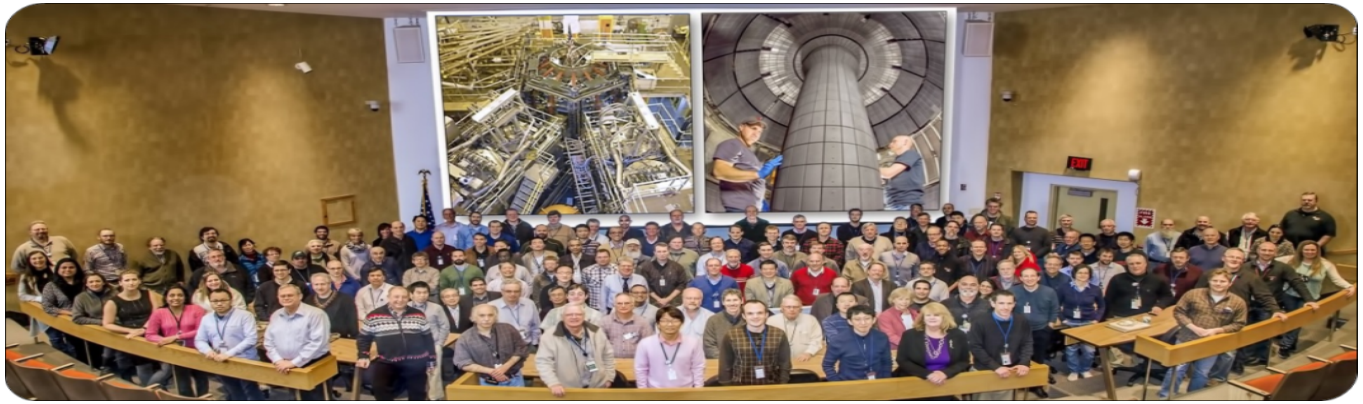
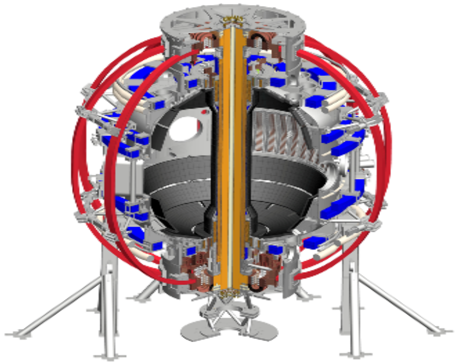
Validation of Ion and Electron Scale Gyrokinetic Simulations in NSTX and Comparisons with a High-k Scattering Synthetic Diagnostic

J. Ruiz Ruiz[1]
W. Guttenfelder[2], A. E. White[1], N. Howard[1], N. F. Loureiro[1], J. Candy[3], Y. Ren[2], D. R. Smith[4], C. Holland[5]
1. MIT 2. PPPL 3. General Atomics 4. U Wisconsin 5. UCSD

60th Annual Meeting of the APS Division of Plasma Physics
Portland, Oregon, Nov 5-9, 2018

PPPL

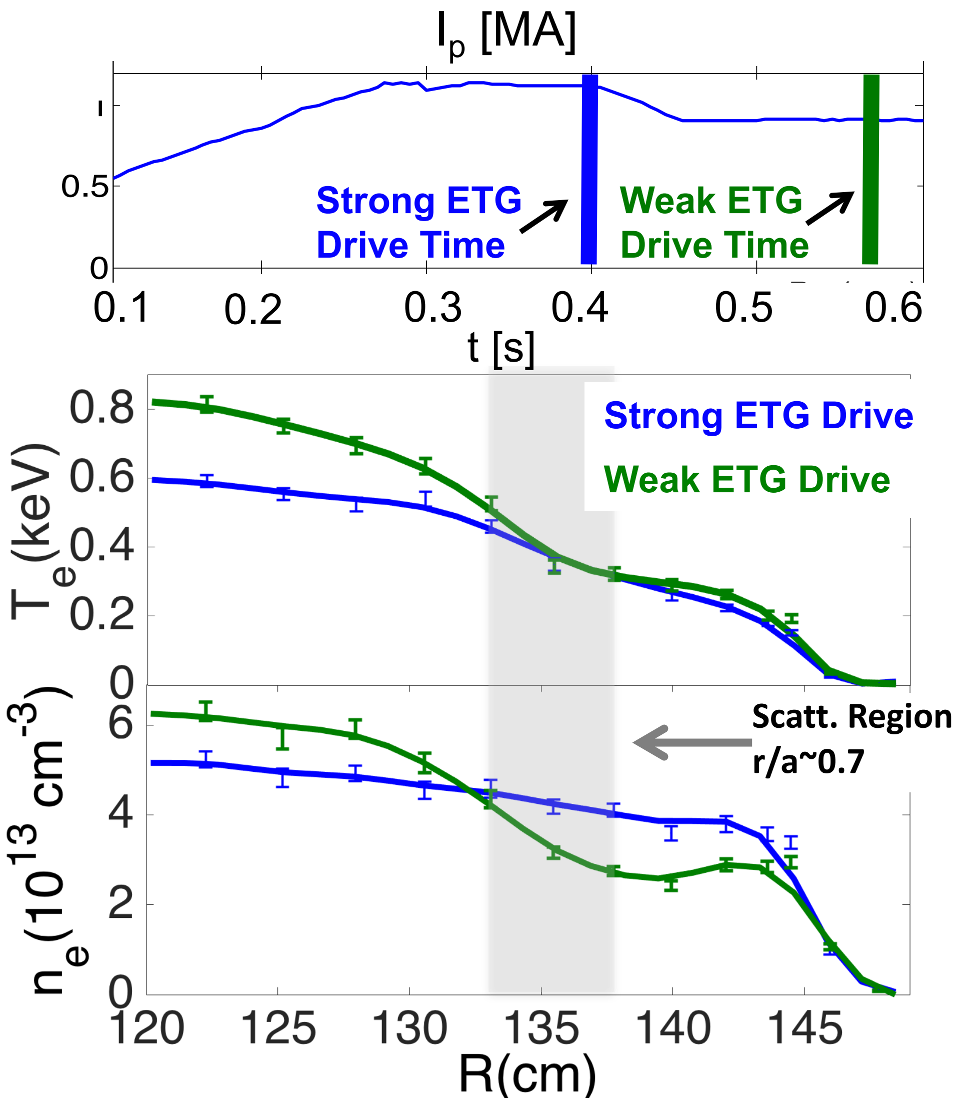




Work supported by DOE contracts DE-AC02-09CH11466 and DE-AC02-05CH11231

Extensive validation effort underway to study electron thermal transport in NSTX H-mode plasma

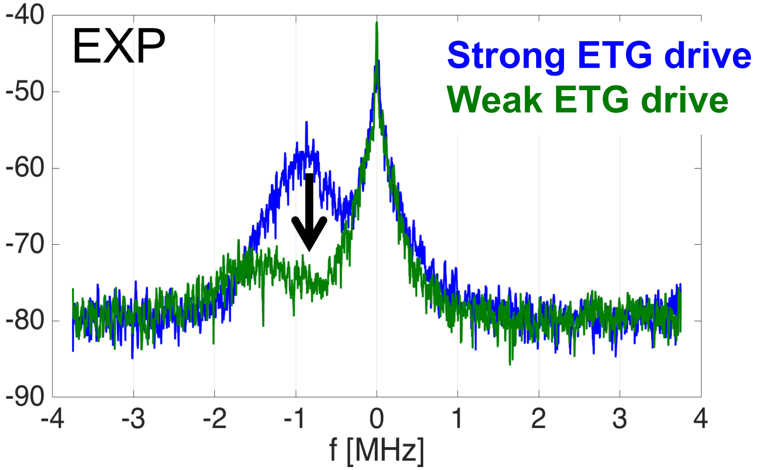
- NBI heated H-mode with controlled current ramp-down; two steady discharge phases, little MHD activity
- Local increase in equilibrium density gradient |∇**n**| modifies ETG drive from strong to weak, consistent with changes in measured high-k turbulence [Ruiz Ruiz PoP 2015]
- **In this work:** Compare experimental heat fluxes and measured high-k turbulence are to validate extensive set of nonlinear ion-scale and electron-scale gyrokinetic simulations



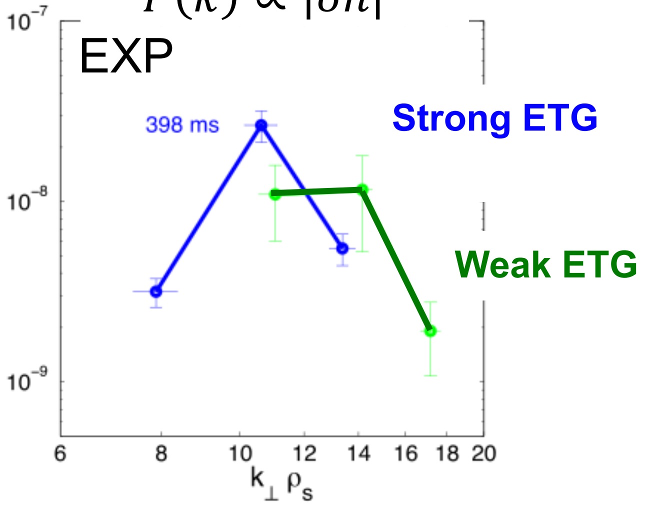
Compare experimental Q_e to all simulations; measured high-k turbulence only to e- scale simulations

- Electron heat flux (Q_e) comparisons with TRANSP are done via sensitivity scans of GYRO simulations within exp. uncertainties
- High-k turbulence comparisons will deploy a new synthetic diagnostic to e- scale simulations that best match to Q_e^{exp}
- ***Can e-scale simulations reproduce the high-k frequency & wavenumber spectra?***

$P(f) \propto |\delta n|^2$

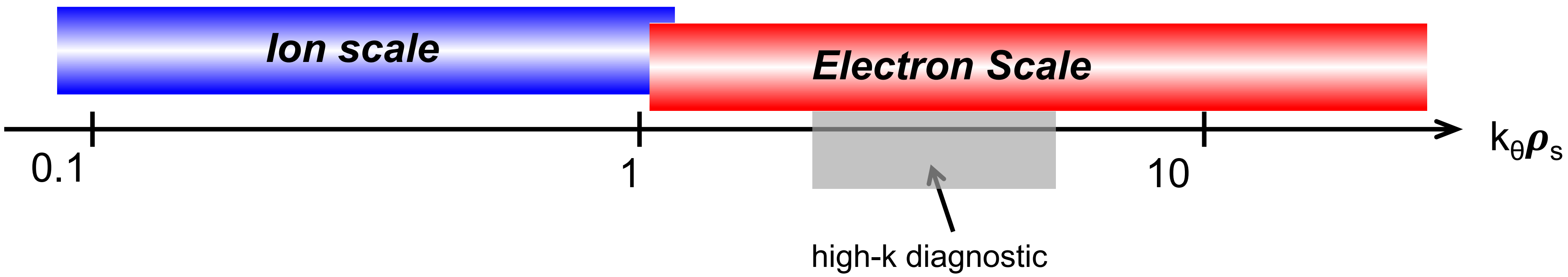


$P(k) \propto |\delta n|^2$



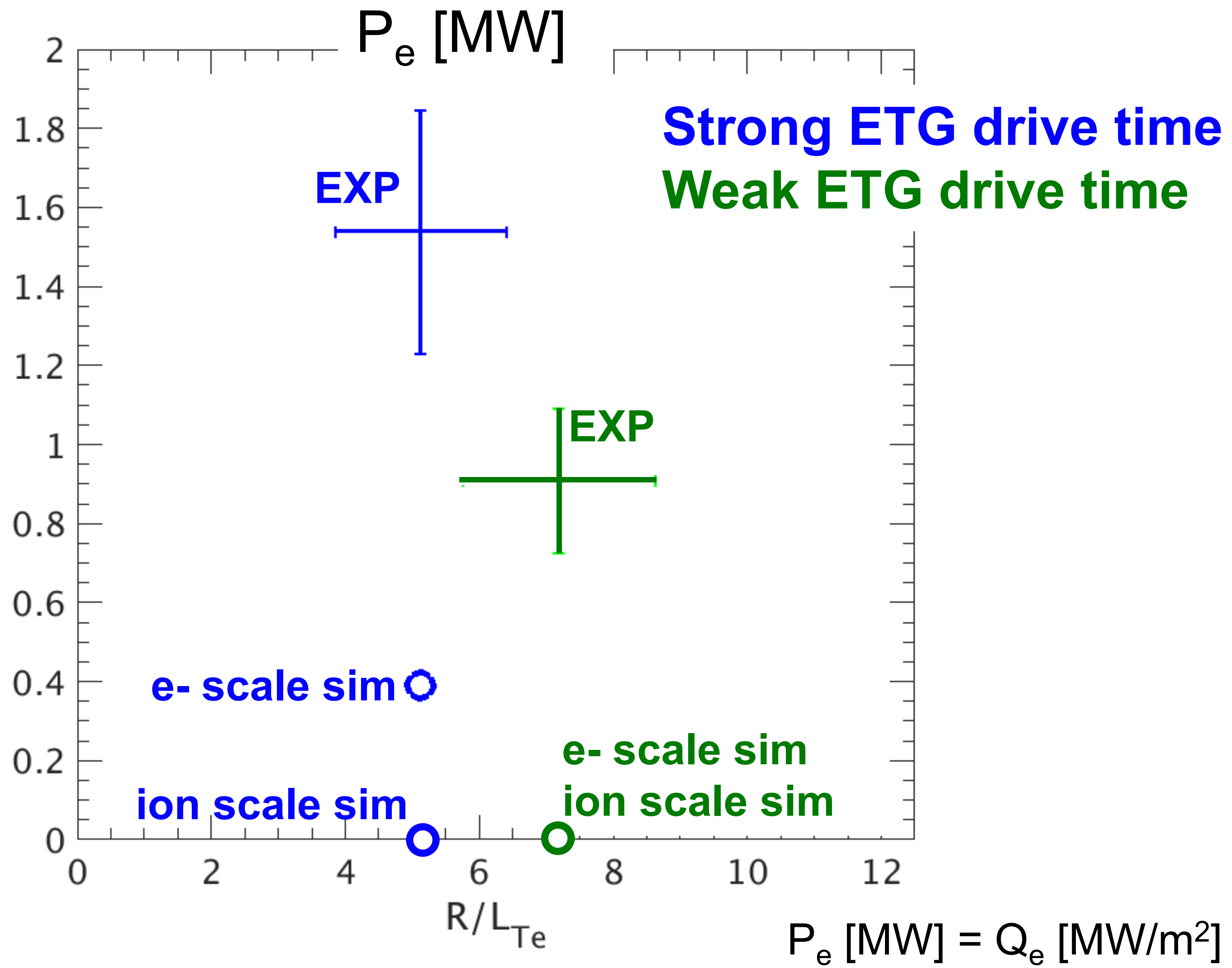
GYRO code is used to perform ion-scale and electron-scale nonlinear gyrokinetic simulations

- **Ion scale** simulation resolves low-k turbulence $k_\theta \rho_s \lesssim 1$
- **Electron scale simulation** resolves ETG-scale turbulence $1 < k_\theta \rho_s \gtrsim 60$



- Experimental profiles used as input
- Local simulations performed at scattering location (r/a~0.7, R~135 cm).
- 3 kinetic species, D, C, e (Z_{eff}~1.85-1.95)
- Electromagnetic: $A_{||}+B_{||}$, β_e~ 0.3 %.
- Collisions (ν_{ei} ~ 1 c_s/a).
- ExB shear (γ_E~0.13-0.16 c_s/a) + parallel flow shear (γ_p ~ 1-1.2 c_s/a)
- Fixed boundary conditions (buffer widths)

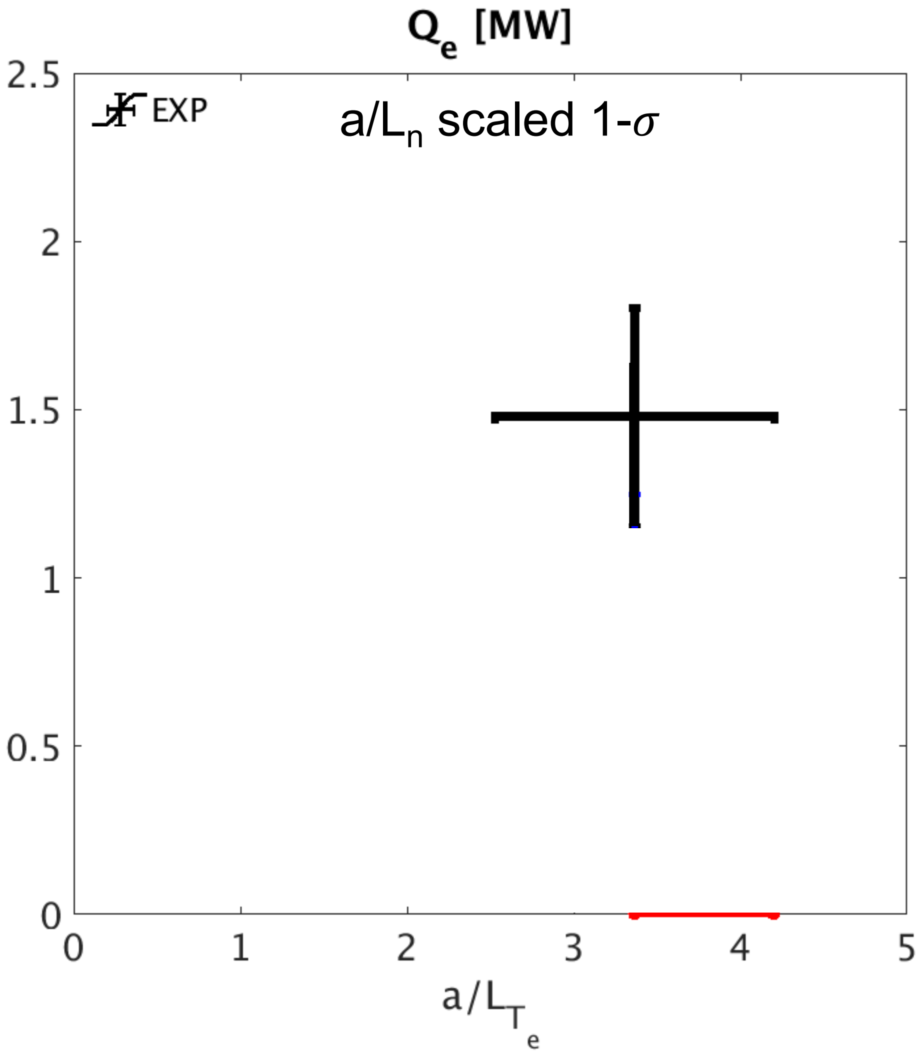
Local ion and electron-scale simulations under-predict experimental Q_e with experimental gradients as input



P_e [MW] = Q_e [MW/m^2] * Area

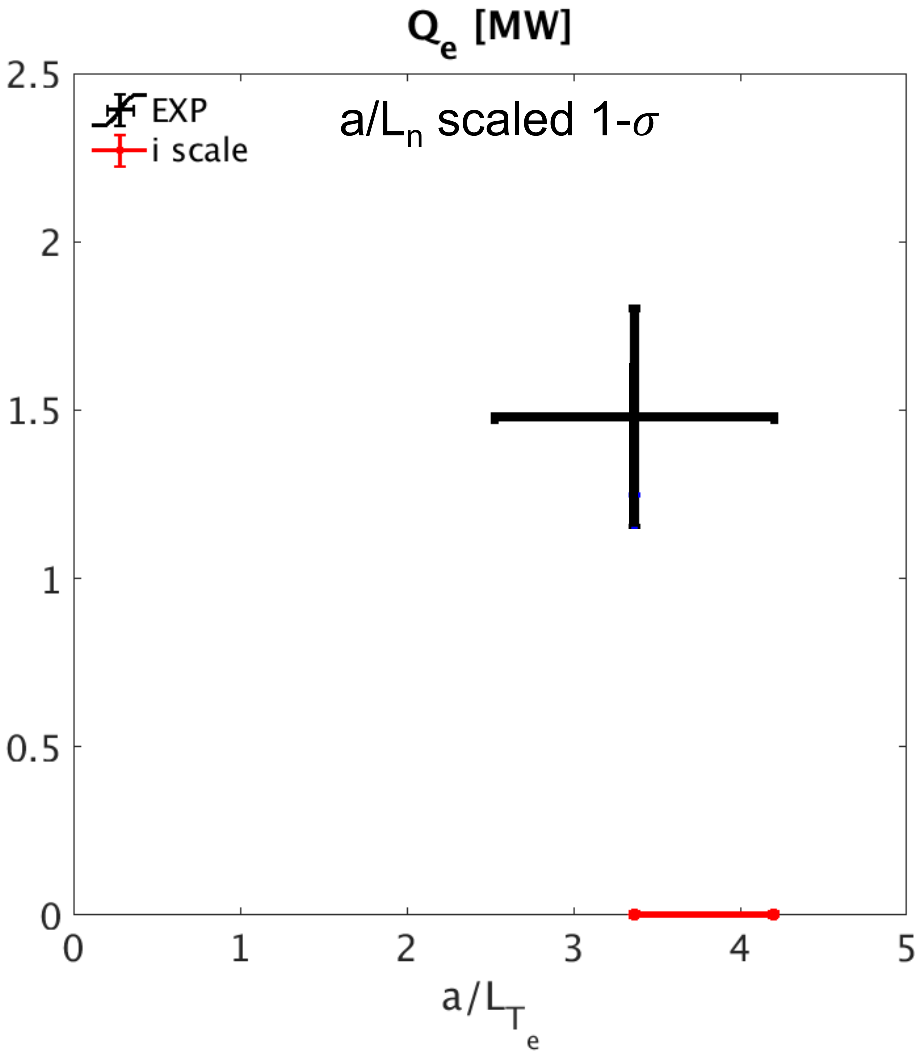
Sensitivity Scans for Heat Flux Comparisons

Strong ETG drive condition: electron scale simulations can match Q_e^{exp} within experimental uncertainty



Sensitivity scans carried out to maximize turbulent drive within error bars

Strong ETG drive condition: electron scale simulations can match Q_e^{exp} within experimental uncertainty

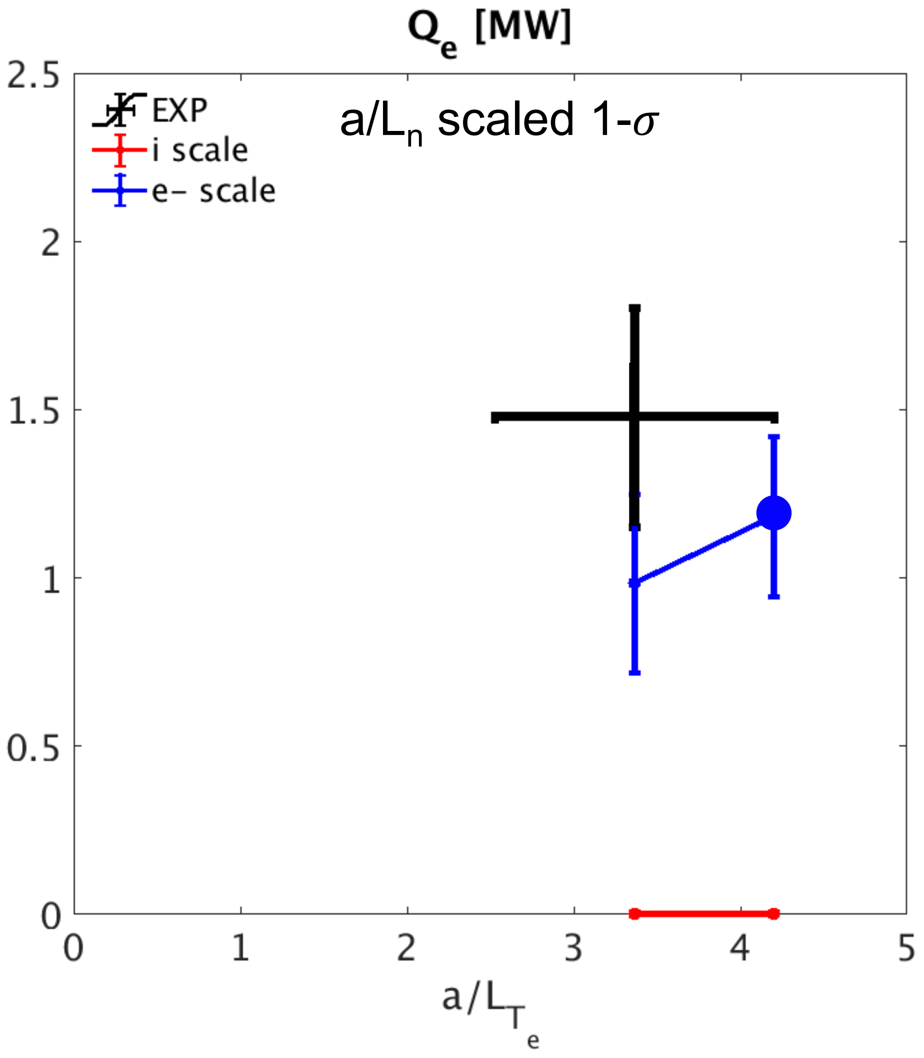


Sensitivity scans carried out to maximize turbulent drive within error bars

Ion scale simulation

- Scans (a/L_T, a/L_n)
- Suppressed by ExB shear (Q_e^{sim} ~ 0)

Strong ETG drive condition: electron scale simulations can match Q_e^{exp} within experimental uncertainty



Sensitivity scans carried out to maximize turbulent drive within error bars

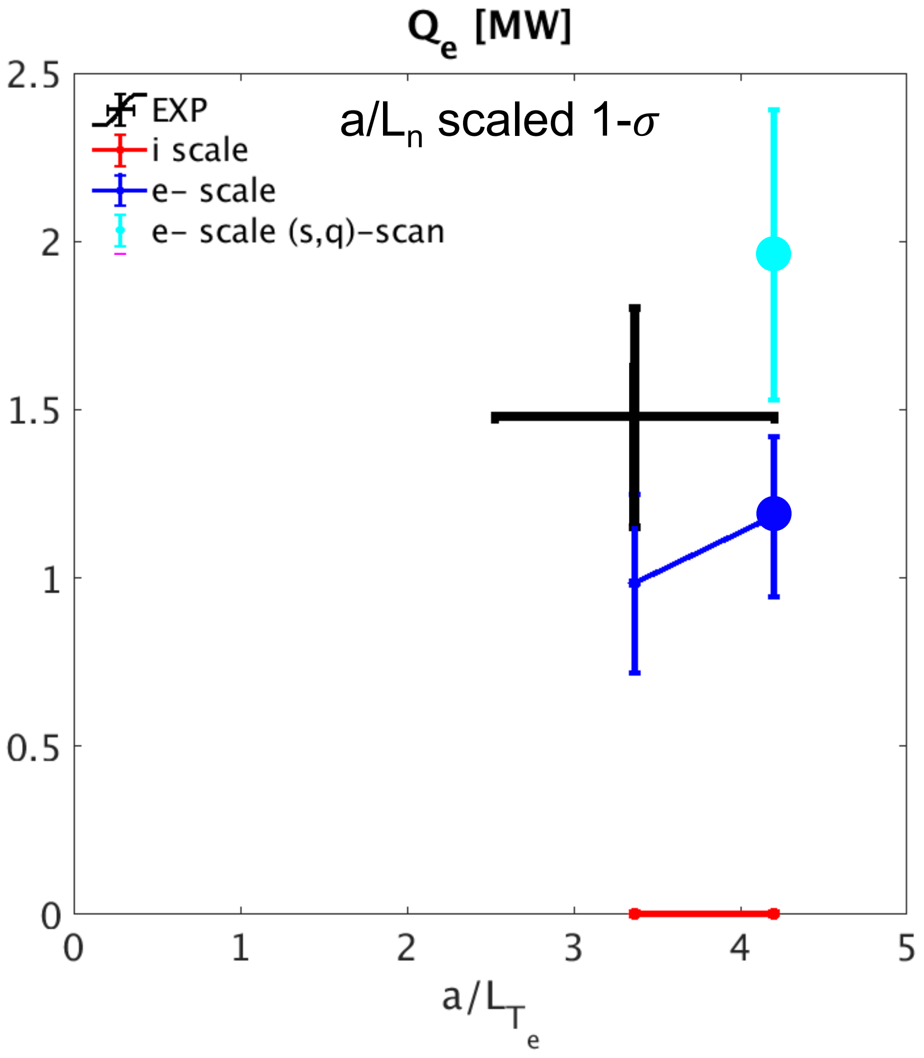
Ion scale simulation

- Scans (a/L_T, a/L_n)
- Suppressed by ExB shear ($Q_e^{sim} \sim 0$)

Electron scale simulation ●

- Scans (a/L_T, a/L_n)
- Can match Q_e^{exp}

Strong ETG drive condition: electron scale simulations can match Q_e^{exp} within experimental uncertainty



Sensitivity scans carried out to maximize turbulent drive within error bars

Ion scale simulation

- Scans (a/L_T, a/L_n)
- Suppressed by ExB shear (Q_e^{sim} ~ 0)

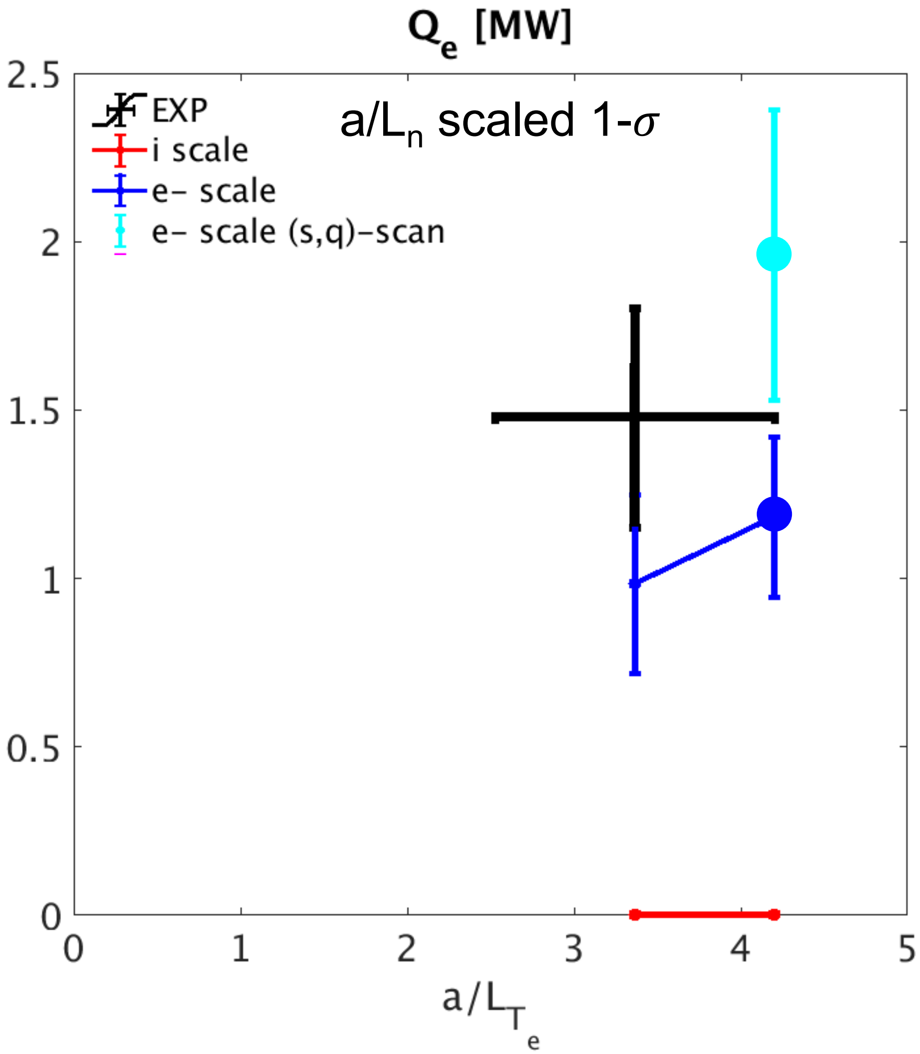
Electron scale simulation ●

- Scans (a/L_T, a/L_n)
- Can match Q_e^{exp}

Electron scale simulation ●

- Scan (a/L_T, a/L_n, q, s)
- Can match Q_e^{exp}

Strong ETG drive condition: electron scale simulations can match Q_e^{exp} within experimental uncertainty



Sensitivity scans carried out to maximize turbulent drive within error bars

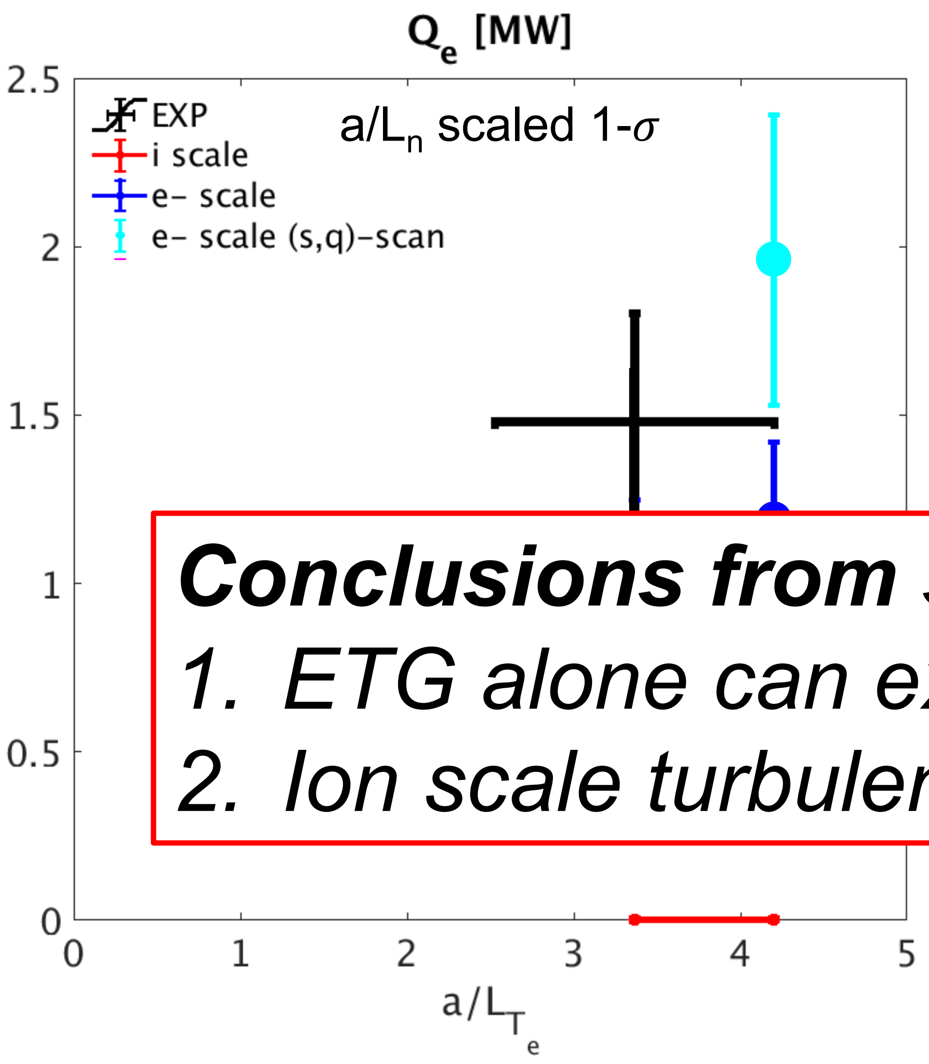
Ion scale simulation
- Scans (a/L_T, a/L_n)
- Suppressed by ExB shear (Q_e^{sim} ~ 0)

Electron scale simulation ●
- Scans (a/L_T, a/L_n)
- Can match Q_e^{exp}

Electron scale simulation ●
- Scan (a/L_T, a/L_n, q, s)
- Can match Q_e^{exp}

Ion heat flux Qi close to neoclassical levels

Strong ETG drive condition: electron scale simulations can match Q_e^{exp} within experimental uncertainty



Sensitivity scans carried out to maximize turbulent drive within error bars

Ion scale simulation

- Scans (a/L_T, a/L_n)
- Suppressed by ExB shear (Q_e^{sim} ~ 0)

Electron scale simulation

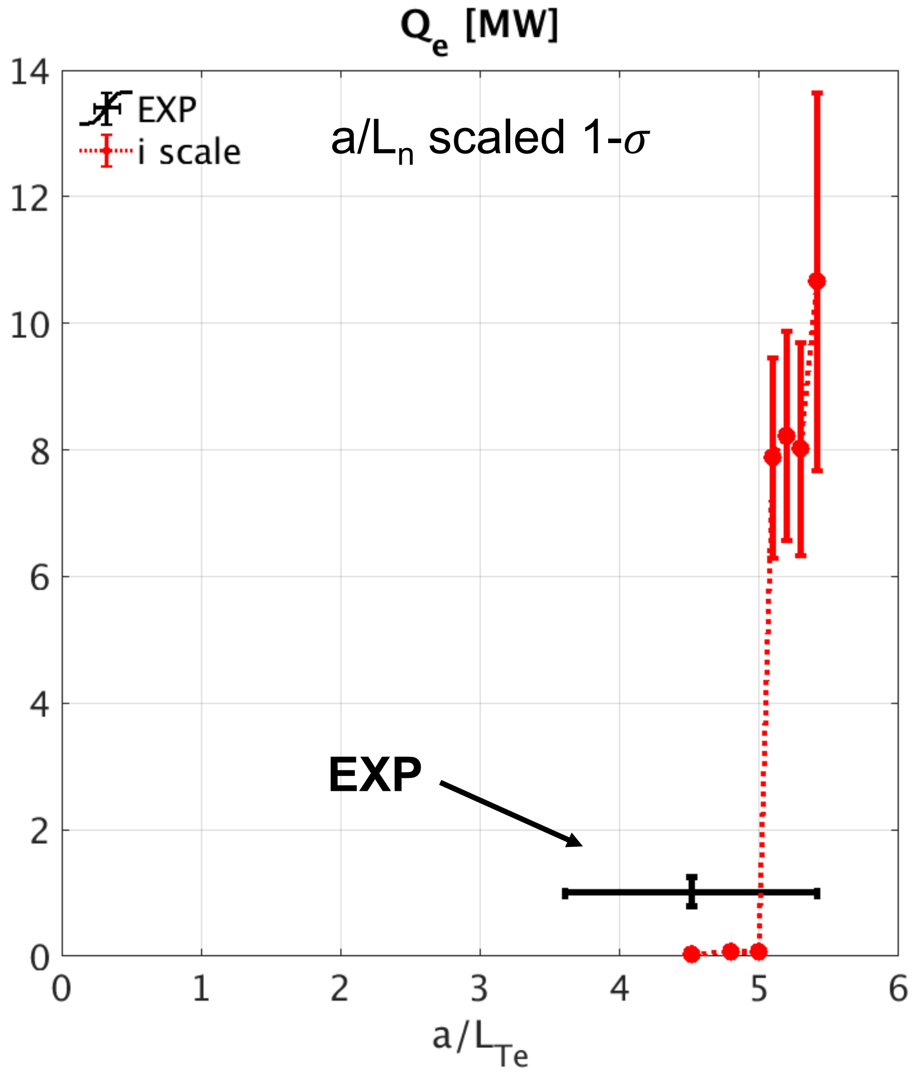
- Scan (a/L_T, a/L_n, q, s)
- Can match Q_e^{exp}

Ion heat flux Qi close to neoclassical levels

Conclusions from strong ETG drive:

1. *ETG alone can explain Q_e^{exp}*
2. *Ion scale turbulence suppressed*

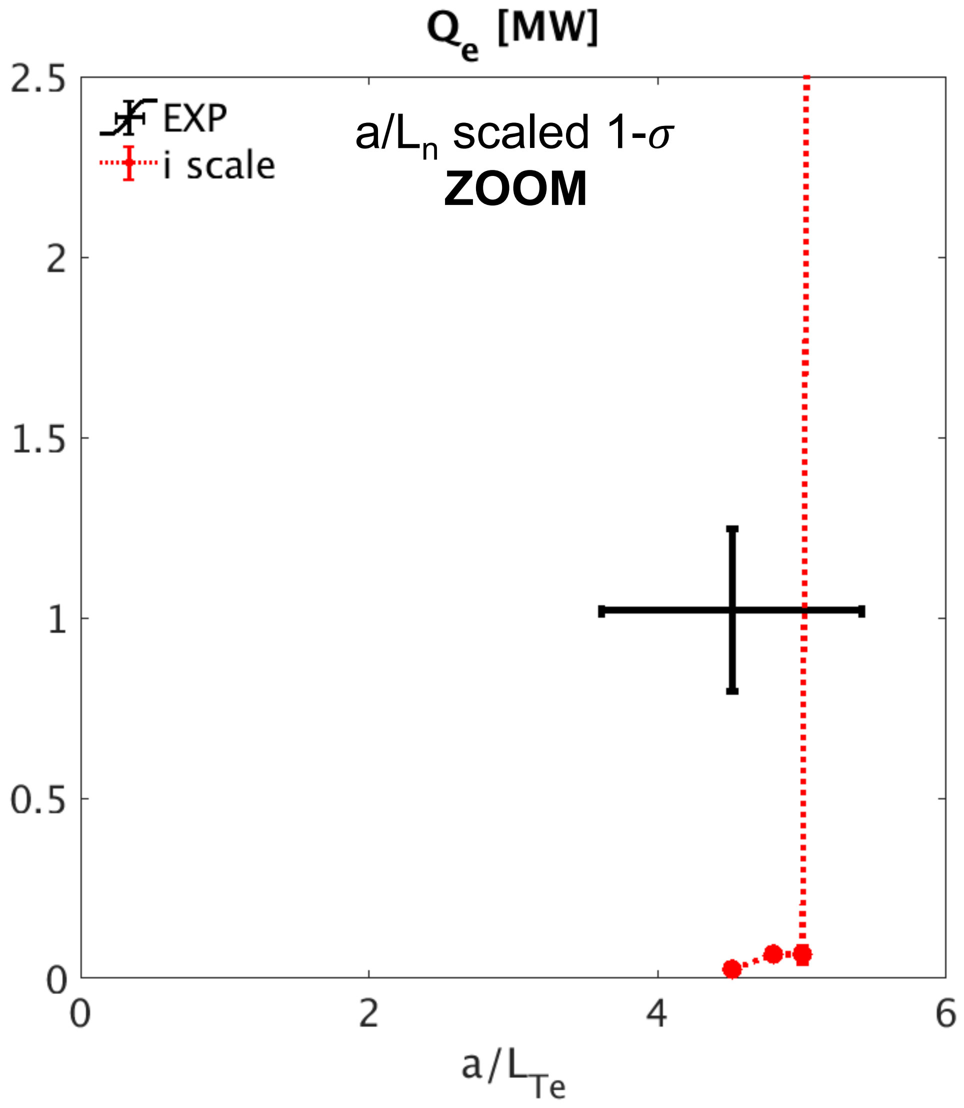
Weak ETG drive condition: sensitivity scans for ion scale simulations bracket Q_e^{exp} within error bars



Ion scale sim (TEM)

- Scans in a/L_T, (a/L_n scaled 1-σ)
- Extremely stiff: $Q_e^{sim} \rightarrow 10 \times Q_e^{exp}$!!

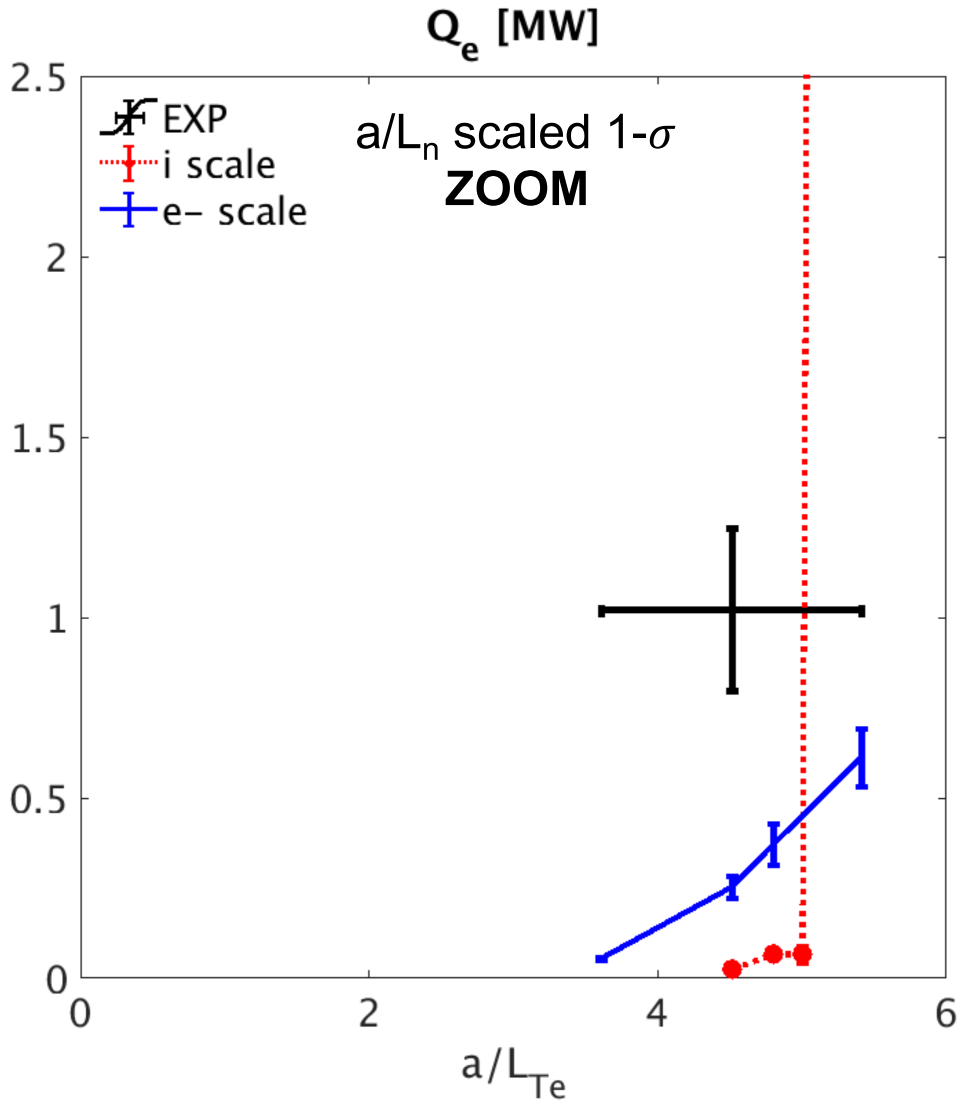
Weak ETG drive condition: sensitivity scans for ion scale simulations bracket Q_e^{exp} within error bars



Ion scale sim (TEM)

- Scans in a/L_T, (a/L_n scaled 1-σ)
- Extremely stiff: Q_e^{sim} → 10 X Q_e^{exp} !!

Weak ETG drive condition: sensitivity scans for ion scale simulations bracket Q_e^{exp} within error bars



Ion scale sim (TEM)

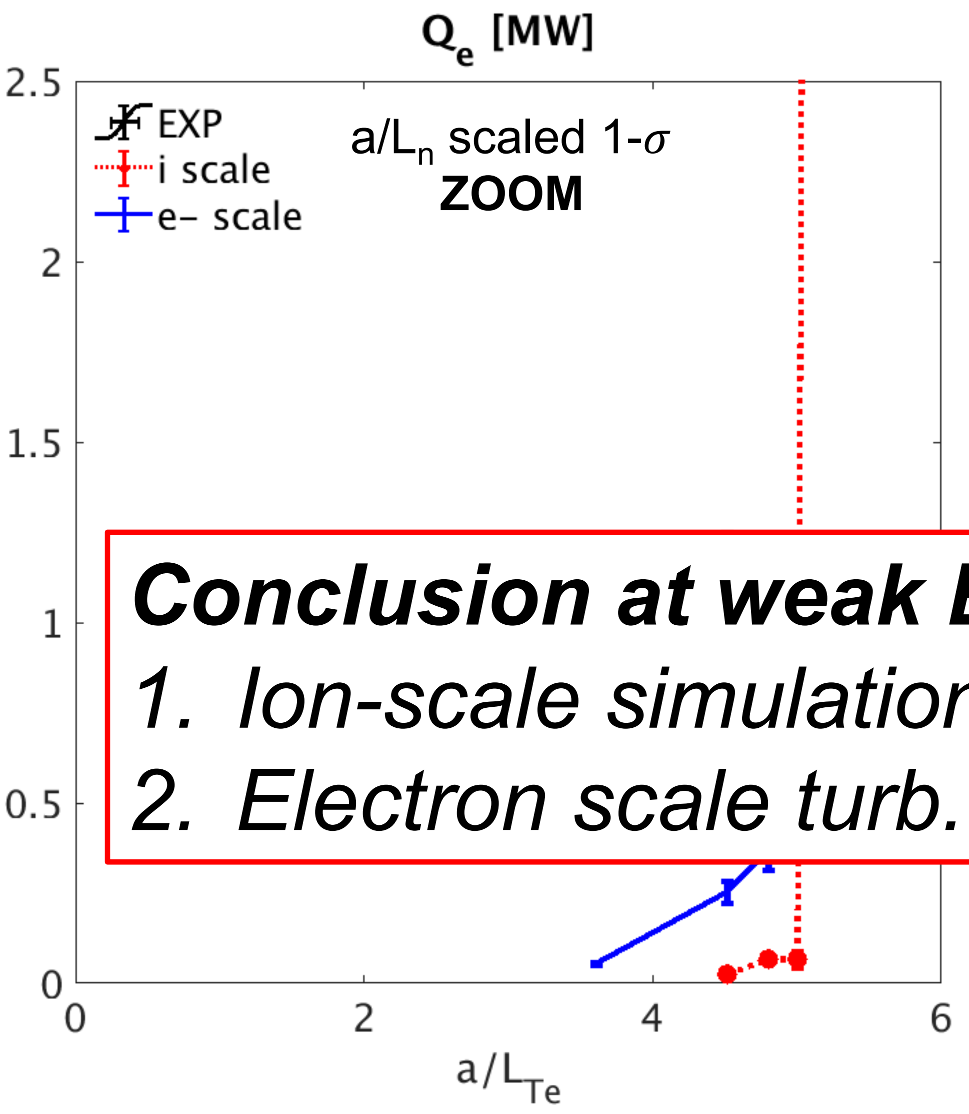
- Scans in a/L_T, (a/L_n scaled 1-σ)
- Extremely stiff: Q_e^{sim} → 10 X Q_e^{exp} !!

Electron scale sim (ETG)

- Scans in a/L_T, (a/L_n scaled 1-σ)
- Less stiff, under-predicts Q_e^{exp}

Ion heat flux *Qi* close to neoclassical levels

Weak ETG drive condition: sensitivity scans for ion scale simulations bracket Q_e^{exp} within error bars



Ion scale sim (TEM)

- Scans in a/L_T, (a/L_n scaled 1-σ)
- Extremely stiff: Q_e^{sim} → 10 X Q_e^{exp} !!

Electron scale sim (ETG)

- Scans in a/L_T, (a/L_n scaled 1-σ)

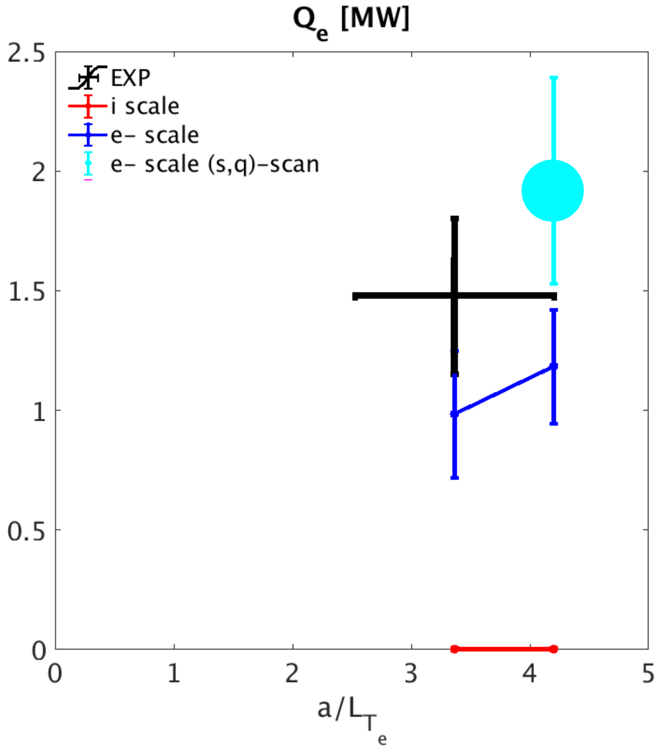
Conclusion at weak ETG Drive:

1. *Ion-scale simulation can bracket Q_e^{exp}*
2. *Electron scale turb. active, cannot match Q_e^{exp}*

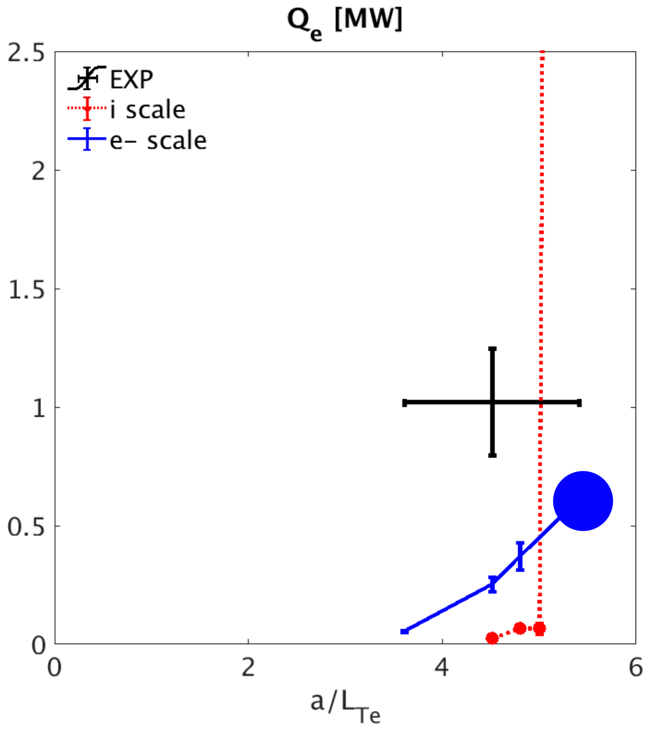
High-k Turbulence Comparisons

Deploy synthetic diagnostic to highest Q_e e- scale simulations

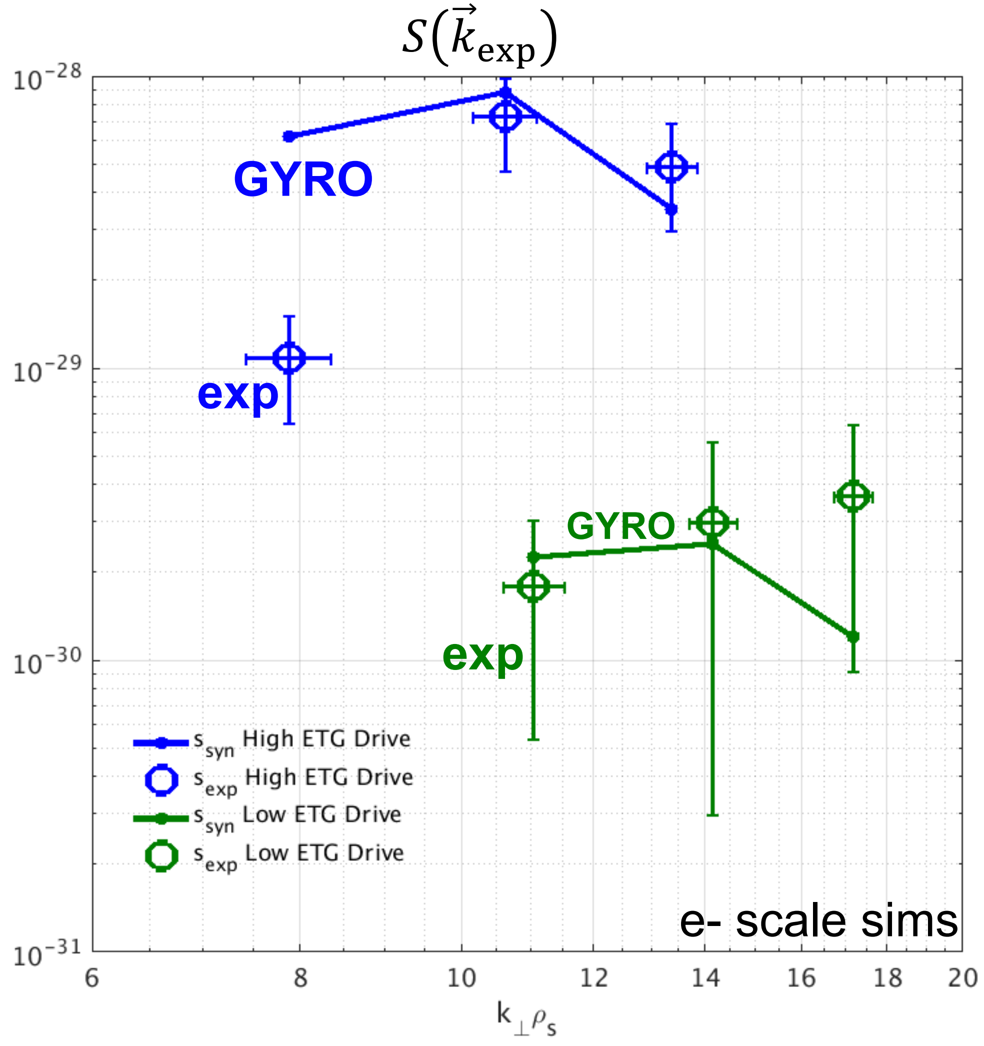
Strong ETG Drive



Weak ETG Drive



Highest Q_e e- scale simulations match k-spectrum shape and fluctuation level ratio



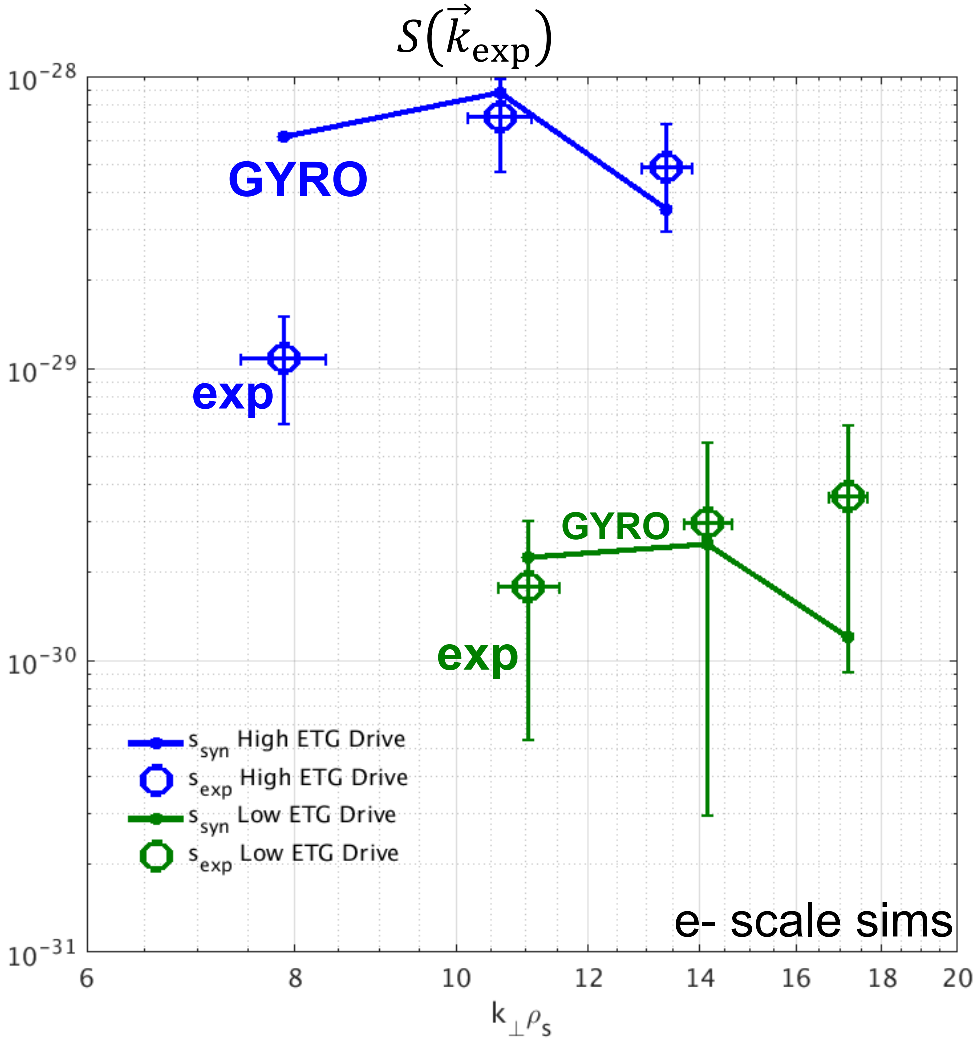
Strong ETG Drive (matched Q_e^{exp})

- Reproduces shape of k-spectrum

Weak ETG Drive (Q_e^{sim}/Q_e^{exp} ~ 65%)

- k-spectra can be matched within error bars

Highest Q_e e- scale simulations match k-spectrum shape and fluctuation level ratio



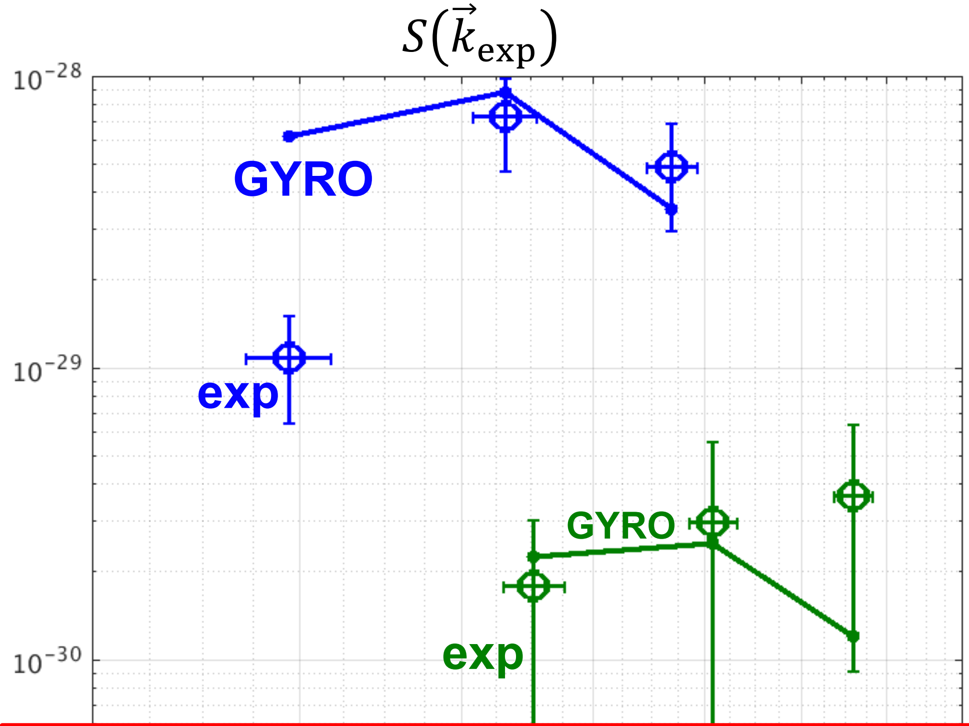
Strong ETG Drive (matched Q_e^{exp})
- Reproduces shape of k-spectrum

Weak ETG Drive (Q_e^{sim}/Q_e^{exp} ~ 65%)
- k-spectra can be matched within error bars

Can match fluctuation level ratio
S(Strong ETG Drive)/S(weak ETG Drive)

***f*-spectra:** k-resolution in e- scale simulation too coarse for quantitative comparisons
➔ need big-box e- scale simulations

Highest Q_e e- scale simulations match k-spectrum shape and fluctuation level ratio



Strong ETG Drive (matched Q_e^{exp})

- Reproduces shape of k-spectrum

Weak ETG Drive (Q_e^{sim}/Q_e^{exp} ~ 65%)

- k-spectra can be matched within error bars

Can match fluctuation level ratio
S(Strong ETG Drive)/S(weak ETG Drive)

***f*-spectra:** k-resolution in e- scale simulation too coarse for quantitative comparisons

Conclusion from synthetic comparisons:
Match shape of k-spectrum and fluctuation level ratio between strong and weak ETG drive, consistent with Q_e agreement

Conclusions and Next Steps

Strong ETG Drive

- Ion-scale turbulence is suppressed
- e- scale can match Q_e^{exp}, consistent with agreement in high-k wavenumber spectrum

e- scale turbulence (ETG) is likely responsible for Q_e^{exp}

Weak ETG Drive

- Ion scale sim can bracket Q_e^{exp} , extremely stiff transport
- Electron scale is active, under-predicts Q_e^{exp}

Ion scale turbulence (TEM) might be responsible for most Q_e^{exp}, cross-scale interactions likely important (ETG active)

Next Steps

- Multi-scale simulation of NSTX H-mode + quant. comparisons with syn. diagnostic
- Deploy synthetic diagnostic for additional NSTX discharges
- Projections of new high-k diagnostic for NSTX-U

Additional Material

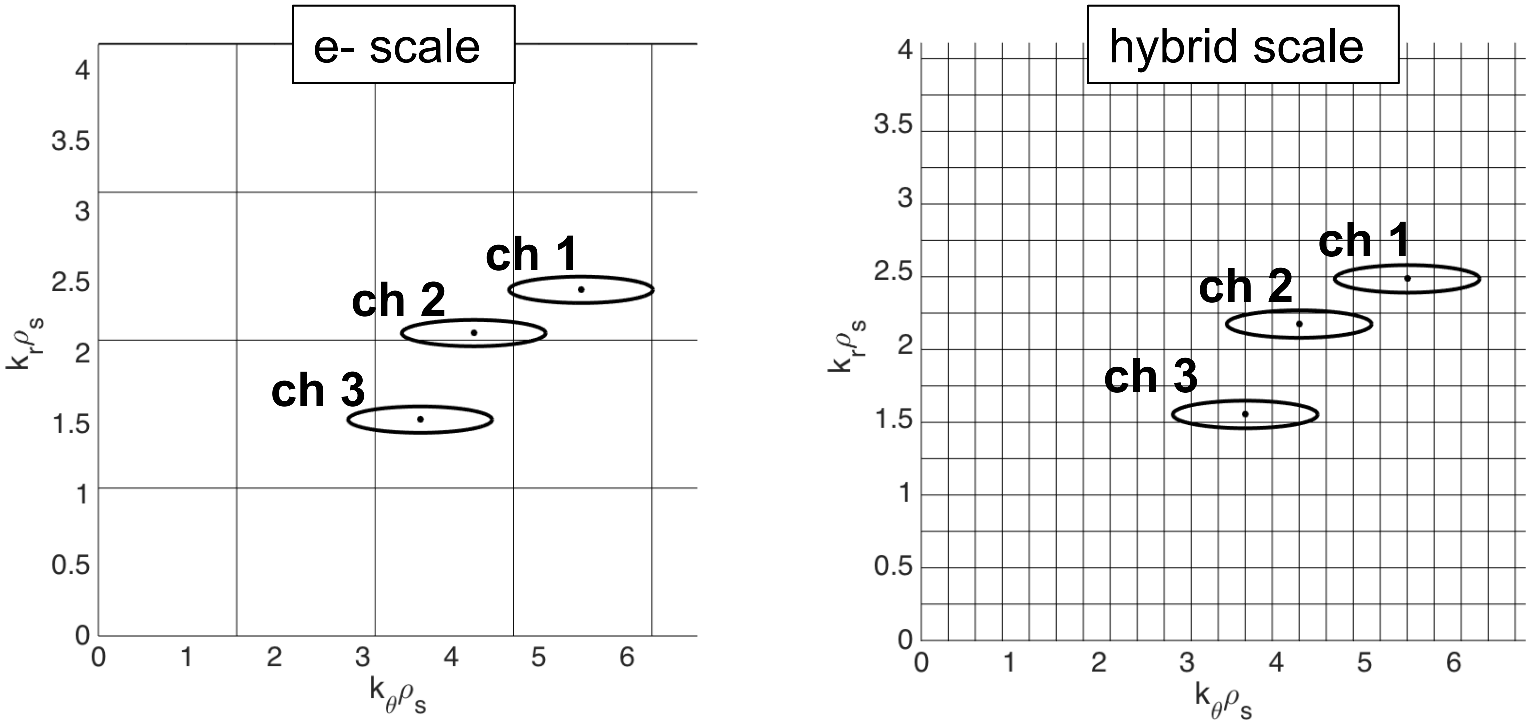
Input Parameters into Nonlinear Gyrokinetic Simulations Presented

	t=398	t = 565
r/a	0.71	0.68
a [m]	0.6012	0.596
n_e [10^19 m-3]	4.27	3.43
T_e[keV]	0.39	0.401
a/L_{ne}	1.005	4.06
a/L_{Te}	3.36	4.51
β_e^{unit}	0.0027	0.003
a/L_{nD}	1.497	4.08
a/L_{Ti}	2.96	3.09
T_i/T_e	1.13	1.39
n_D/n_e	0.785030	0.80371
n_c/n_e	0.035828	0.032715
a/L_{nC}	-0.87	4.08
a/L_{TC}	2.96	3.09
Z_{eff}	1.95	1.84
nu_{ei} (a/c_s)	1.38	1.03
q	3.79	3.07
s	1.8	2.346

	t=398	t = 565
R_0/a	1.52	1.59
SHIFT $=dR_0/dr$	-0.3	-0.355
KAPPA = κ	2.11	1.979
s_k=rdln(κ)/dr	0.15	0.19
DELTA = δ	0.25	0.168
s_δ=rd(δ)/dr	0.32	0.32
M	0.2965	0.407
γ_E	0.126	0.1646
γ_p	1.036	1.1558
ρ_*	0.003	0.0035
λ_D/a	0.000037	0.0000426
c_s/a (10^5 s-1)	4.4	2.35
Qe (gB)	3.82	0.0436
Qi (gB)	0.018	0.0003
Bt_loc [T]	-0.35	-0.35
c_s [m/s]	2.10^5	2.10^5
Ω_i [1/s]	$3.5*10^7$	$3.5*10^7$

Hybrid Scale Simulation Necessary to Correctly Resolve High-k Scattering Wavenumber

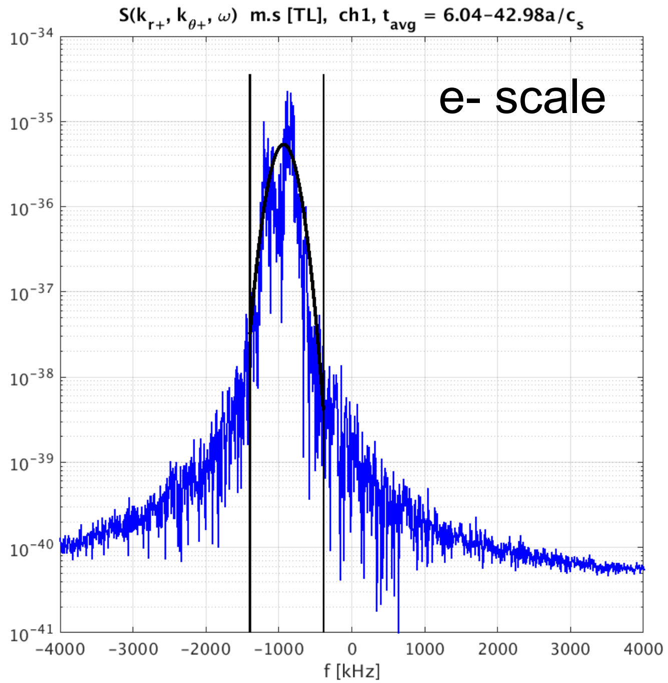
Measurement-k from channels 1-3 of high-k scattering system in NSTX mapped to GYRO wavenumber grid

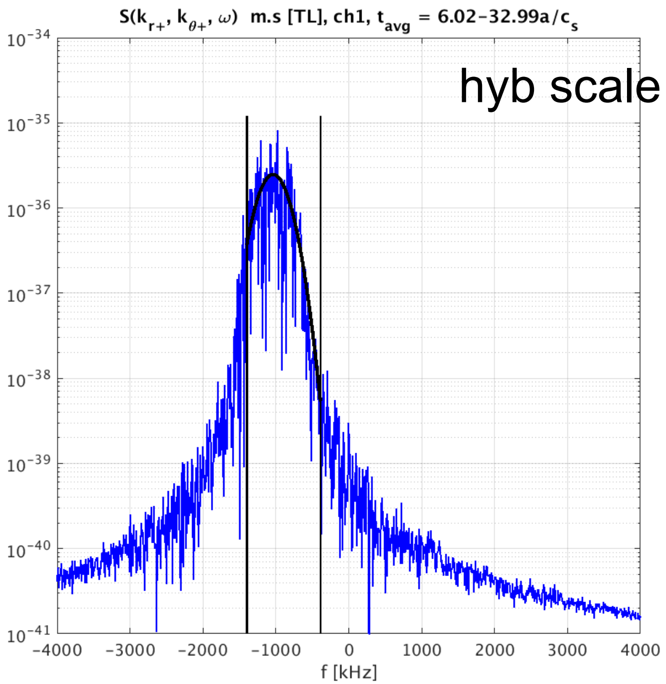


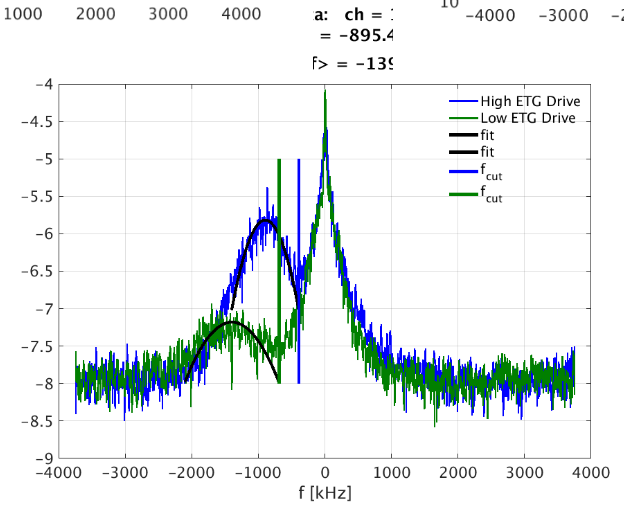
Hybrid scale is NOT multiscale simulation:

- $k_\theta \rho_s{}^{\min} = 0.3$, but does not fully resolve ion scales
- Only run for e- time scales (T^{sim} ~ $30a/c_s$)

Synthetic f-spectrum at High ETG Drive, Ch1







Numerical Resolution Details of GYRO Simulations Needed for Synthetic Diagnostic of High-k Scattering

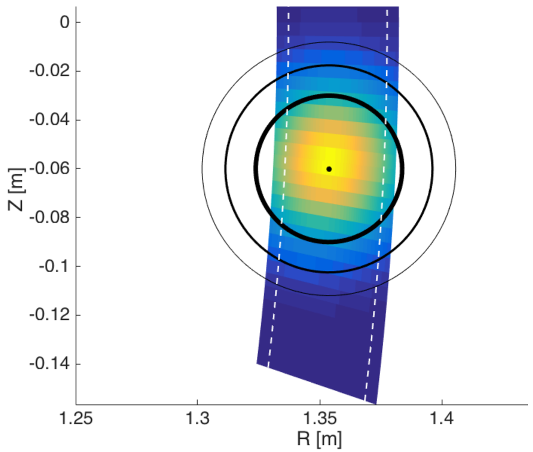
- Extensive Box size scans show **Hybrid Scale Simulation** is trade off:
  - Computational cost ~ **0.5 M CPU h**
  - Correctly resolving experimental k

L_r x L_y = 20-14 x 21-16 ρ_s (L/a~0.08)
n_r x n = 512-450 x 140-220

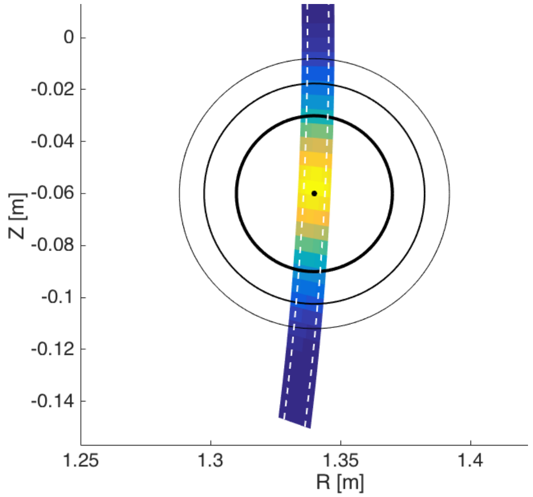
- **Electron Scale Simulation**:
  - Only e- scale turbulence

L_r x L_y = 4 x 6 ρ_s (L/a ~0.02)
n_r x n = 192 x 42

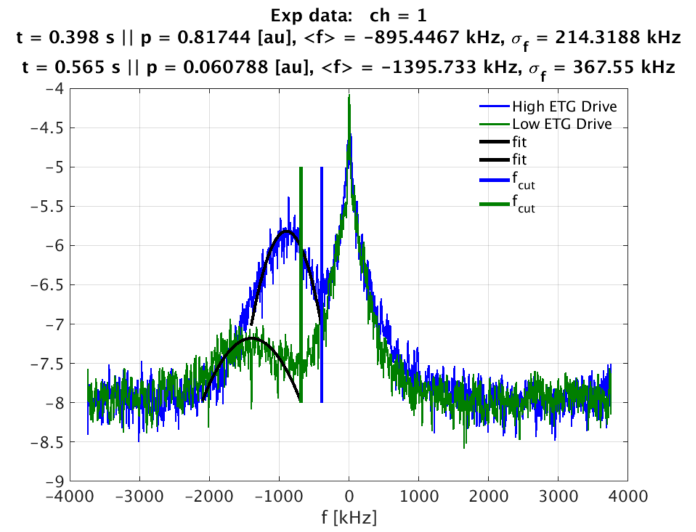
Hybrid Scale

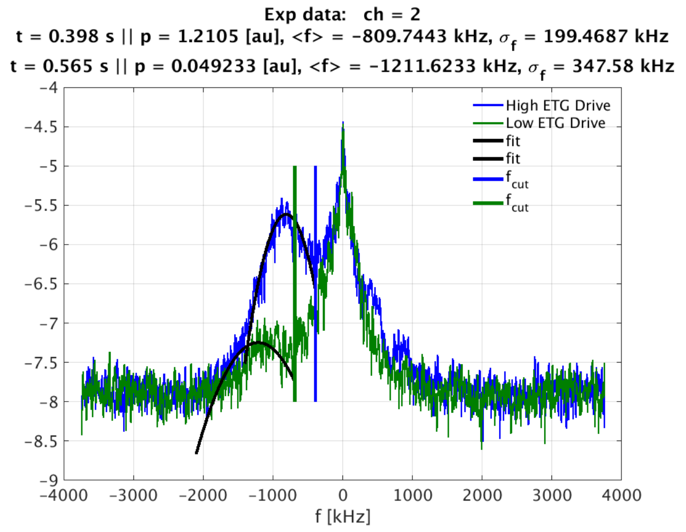


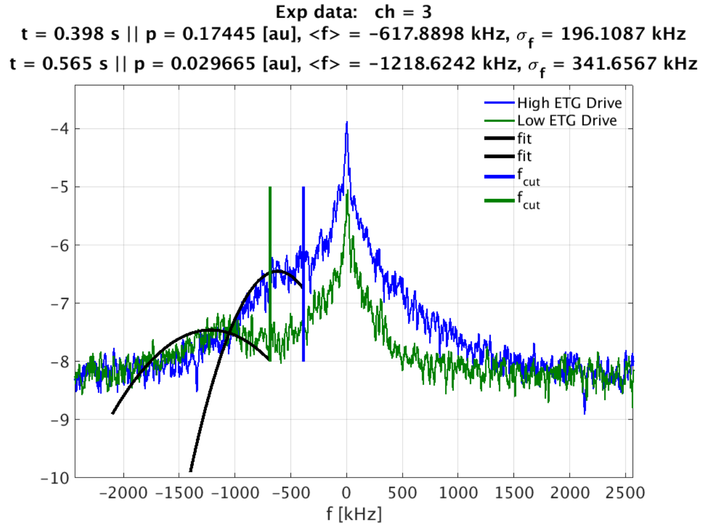
Electron Scale



Experimental f-spectrum for ch1, 2, 3

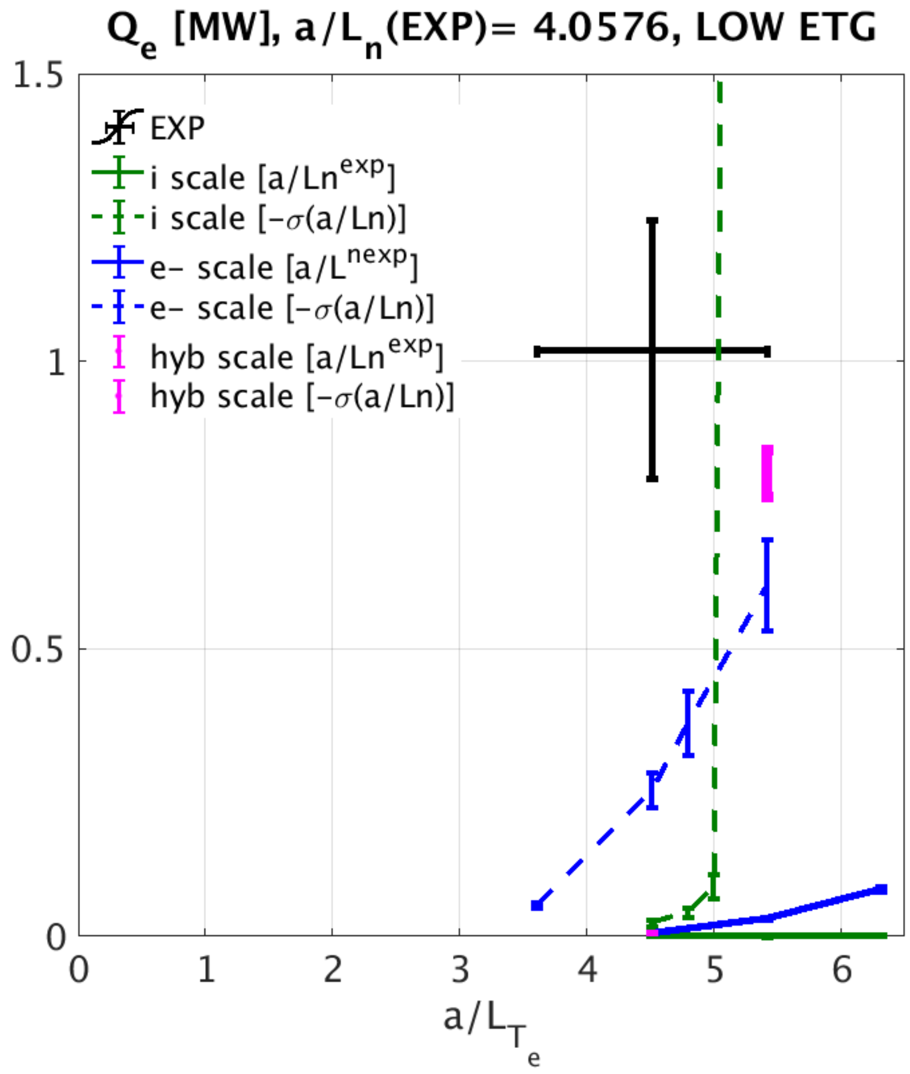






High ETG Drive condition for ch3 has little doppler shift from f=0 (lowest k → low k.v) →contamination of signal by f=0 noise peak

Total Thermal Transport Budget at Low ETG



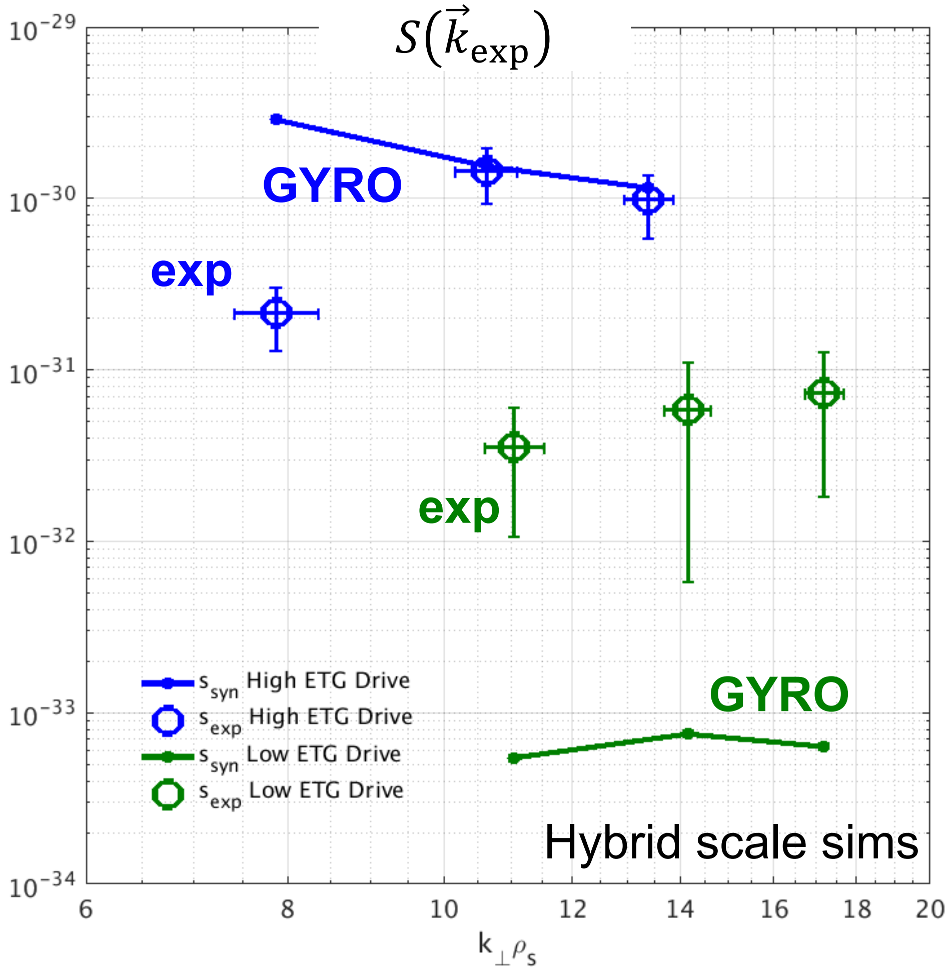
- Q_e^{exp} ~ 1 MW
  - Can be matched by ion scale GK sim within 1σ(+∇T_e,-∇n_e)

- Q_i^{exp} ~ 0.23 MW
  - $Q_i << Q_e$
  - Q_i^{sim}(ion scale) ~ 10X Q_i^{exp} within 1σ(+∇T_e,-∇n_e) (similar to Q_e)
  → Can be matched by ion scale GK sim
  - Neoclassical Q_i still TBD.

Experiment sits near nonlinear threshold of both ion and electron scale turbulence.

Ionscale turbulence displays much higher stiffness than e- scale

GYRO simulations using exp. inputs (∇T, ∇n) under-predict fluctuation power at low ETG drive



Detected fluctuation power is scaled by constant (diagnostic not absolutely calibrated)

High ETG Drive (Q_e^{sim}/Q_e^{exp} ~ 20%):

- GYRO cannot match spectrum at lowest-k (unclean diagnostic signal)

Low ETG Drive (Q_e^{sim} ~ 0)

- Underprediction in fluct. power consistent with under-prediction in Q_e for experimental (∇T, ∇n) inputs in GYRO (hyb. scale shown)

Hybrid-scale sims better match shape of f-spectrum (dominated by Dop shift, not shown)

Mapping $(k_r\rho_s, k_\theta\rho_s)_{GYRO} \rightarrow (k_R, k_Z)^{exp}$

Preamble 3 Wavenumber mapping under simplifying assumptions

$$k_R = (k_r\rho_s)_{GYRO} |\nabla r| / (\rho_s)_{GYRO}$$

$$k_Z = (k_\theta\rho_s)^{loc}_{GYRO} / (\kappa.\rho_s)_{GYRO}$$

- Assumptions
  - $\zeta=0$, $d\zeta/dr=0$ (squareness + radial derivative)
  - $Z_0=0$, $dZ_0/dr=0$ (elevation + radial derivative)
  - UD symmetric (up-down asymmetry of flux surface)
  - theta=0 (outboard mid-plane)

- In the following slides, develop mapping when assumptions are not satisfied, invert

$$(R(r,\theta),Z(r,\theta))=(R_{exp}, Z_{exp}) \rightarrow (r_{exp},\theta_{exp}) .$$