U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Validation of Gyrokinetic Simulations in NSTX via Comparisons of Simulated Turbulence with a New High-k Scattering Synthetic Diagnostic

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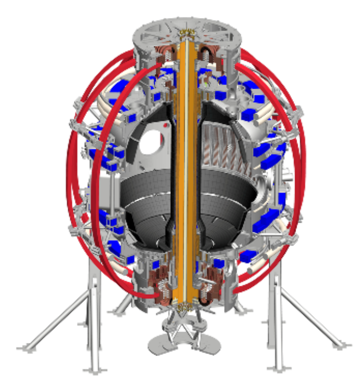
Interview for postdoctoral position, PPPL, Princeton NJ
January 31, 2019

Alcator C-Mod

PPPL



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

Outline

- Motivation
- NSTX H-mode discharge under study
- High-k Scattering at NSTX
- Numerical GYRO simulations needed
- Electron heat flux comparisons
- Synthetic comparisons
  - Synthetic diagnostic description
  - Validation workflow
  - k-spectra and f-spectra comparisons

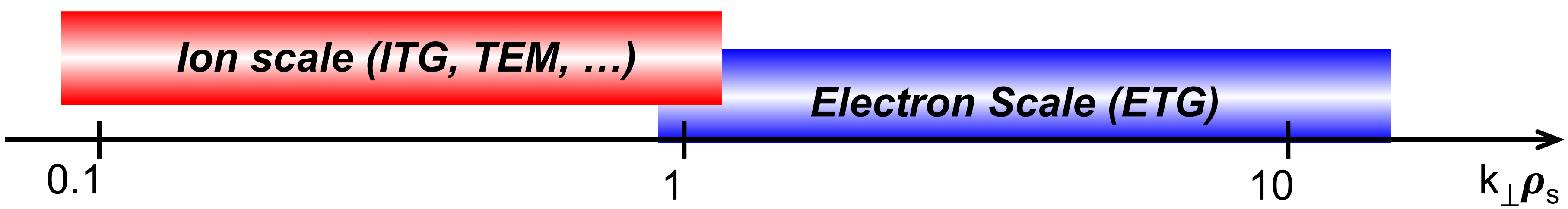
Electron Thermal Transport P_e is Dominant Heat Loss Mechanism is Spherical Tokamak NBI-heated H-modes

- Ion thermal transport ($\mathbf{P_i}$) observed close to neoclassical levels in NSTX NBI heated H-modes, due to ***suppression of ion scale turbulence by ExB shear and strong plasma shaping*** [*cf. Kaye NF 2007*].

- **Electron thermal transport is always anomalous**

- **This work will focus on electron thermal transport $\mathbf{P_e}$:** Compare experimental heat fluxes and measured high-k turbulence spectra to validate extensive set of nonlinear gyrokinetic simulations (GYRO):
  - **Ion scale: $k_\theta \rho_s < 1$**
  - **Electron scale: $k_\theta \rho_s > 1$**

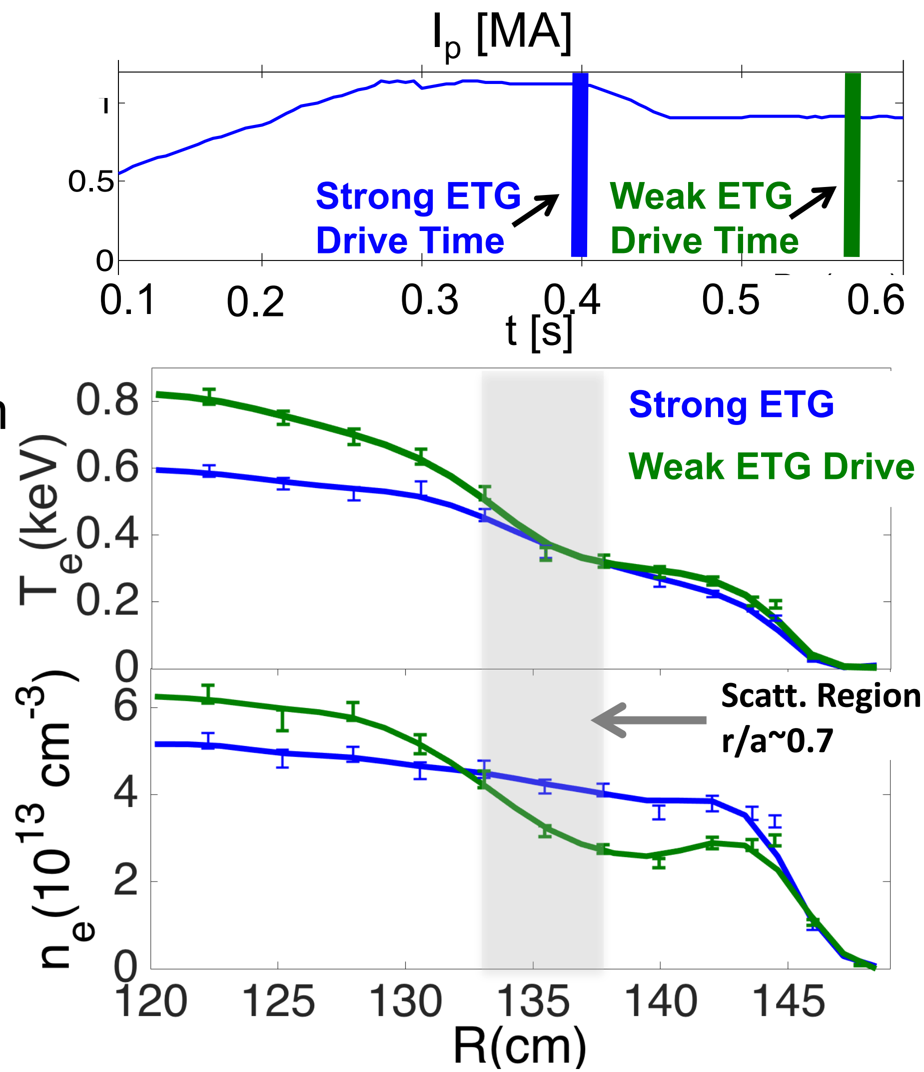
$\boldsymbol{\rho}_s$ ion sound gyro radius



High-k scattering: $k_\perp \rho_s \sim 10\text{-}20$ ($k_\perp \rho_e \sim 0.2\text{-}0.3$)

Validate NL GYRO simulation in an NSTX NBI-heated H-mode featuring strong and weak ETG conditions

- Controlled I_p ramp-down separates two steady discharge phases; little MHD activity.
- Local increase in equilibrium density gradient $|\nabla \mathbf{n}|$ modifies ETG drive from strong to weak, consistent with changes in measured high-k turbulence [*]
- P_e [MW] and turbulence levels very sensitive to ∇T_e , ∇n_e [*]
  - $\nabla \mathbf{T_e}$: ETG drive
  - $\nabla \mathbf{n_e}$: ETG stabilizing mechanism



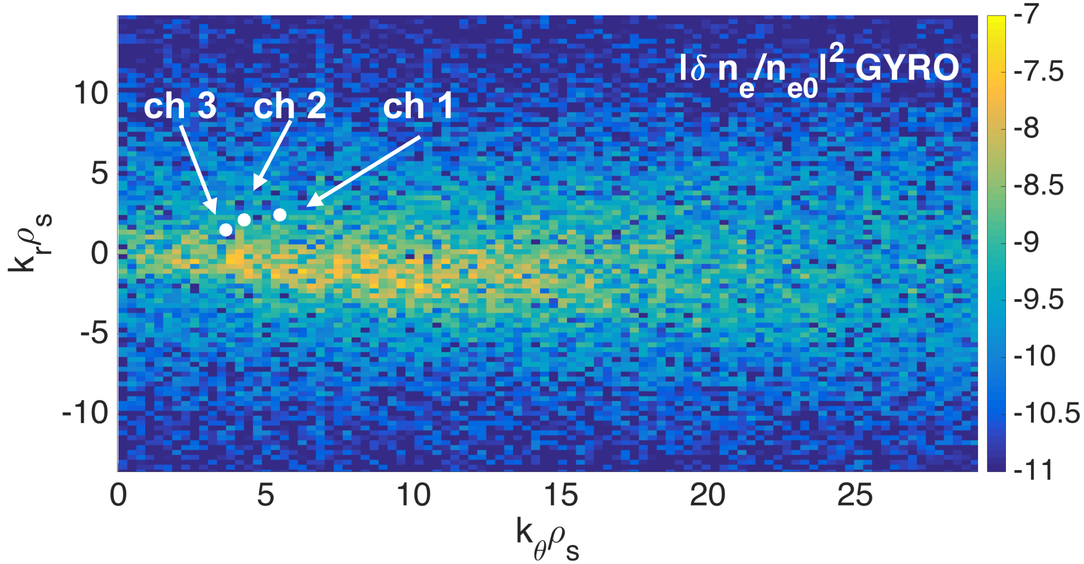
[*] Ruiz Ruiz PoP 2015

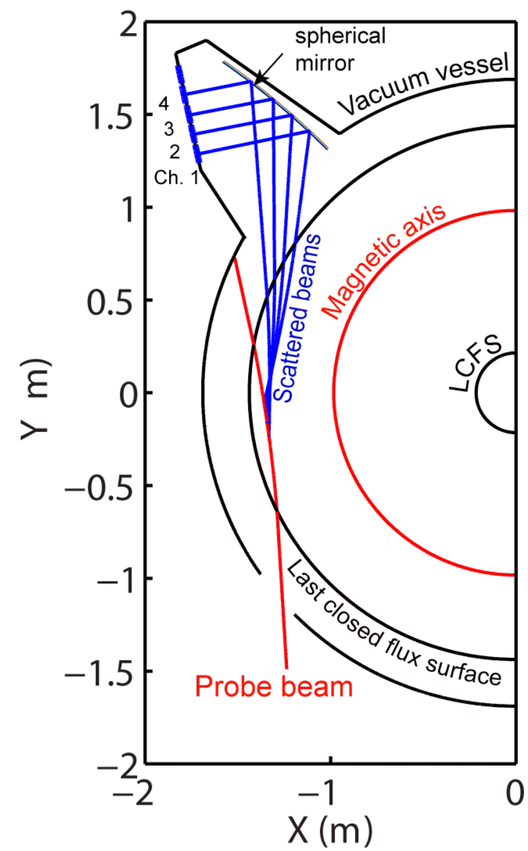
Use a high-k scattering diagnostic to probe electron scale turbulence on NSTX

- Scattered power density $P_s \propto \left(\frac{\delta n}{n}\right)^2$
- Gaussian microwave probe beam
  - f = 280 GHz (>> f_{pe}, f_{ce})
- **Ray tracing to determines $\vec{k}_{turb}$**

$$\begin{cases} \vec{k}_s = \vec{k}_{turb} + \vec{k}_i \\ \omega_s = \omega_{turb} + \omega_i \end{cases}$$

- Experimental $\vec{k}_{turb}$ mapped to GYRO $(k_r, k_\varphi, k_\theta)$





View from top of NSTX

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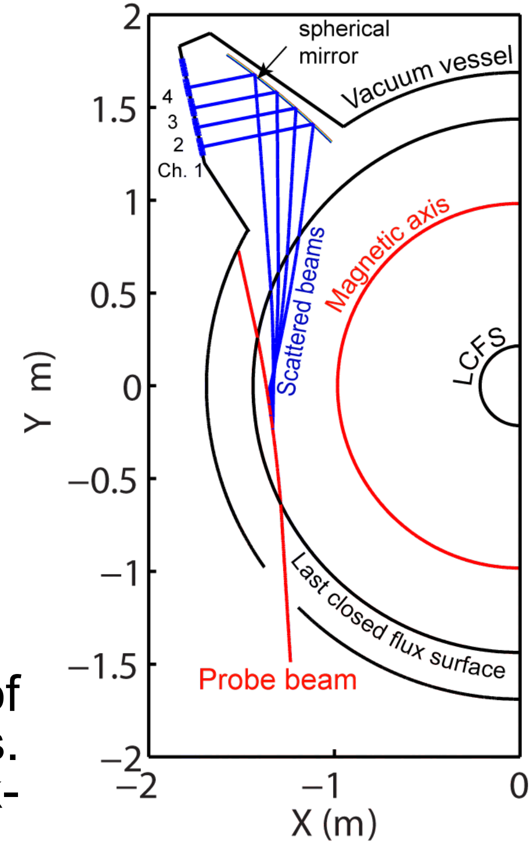
- Scattering system is ***toroidally*** localized [*]

➔ We model a 2D synthetic diagnostic

- **Preview**: Synthetic high-k diagnostic will require use of **hybrid scale** simulations (~ big-box e- scale simulations. Traditional e- scale simulations lack numerical k-resolution)



View from top of NSTX

[*] Mazzucato PoP 2003, Mazzucato NF 2006

Compare electron thermal power P_e to all simulations; high-k turbulence only to hybrid simulation

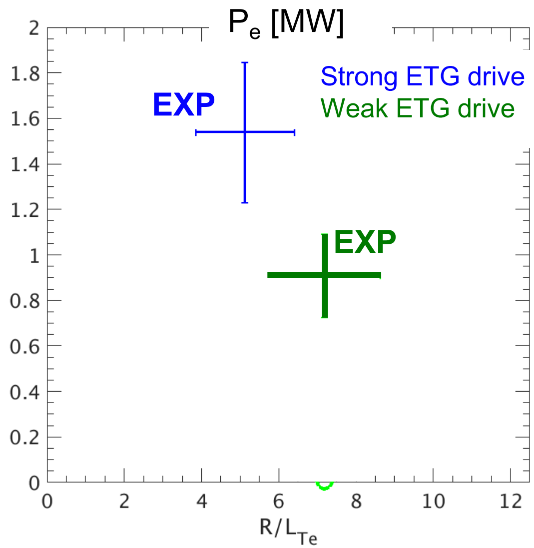
GYRO simulation comparisons

- **Electron thermal power P_e** (TRANSP) comparisons via sensitivity scans of GYRO simulations within uncertainties → ion scale, hybrid scale

- **High-k turbulence spectra** comparisons via synthetic diagnostic → hybrid scale
  - $\boldsymbol{f}$-spectrum (spectral peak $< \boldsymbol{f} >$, width $\boldsymbol{\sigma_f}$)
  - $\boldsymbol{k}$-spectrum shape
  - Relative fluctuation level

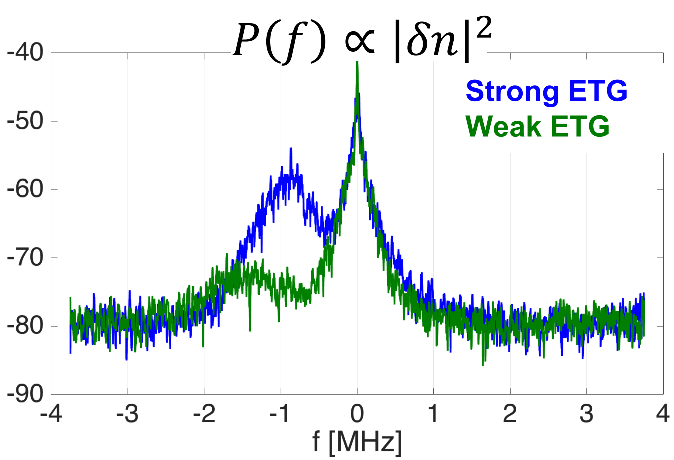
- Will NOT compare
  Absolute fluctuation level (diagnostic not absolutely calibrated)

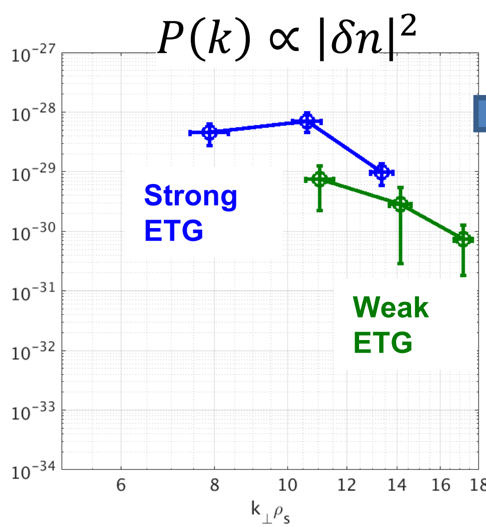
Compare electron thermal power P_e to all simulations; high-k turbulence only to hybrid simulation



GYRO simulation comparisons

ion scale
hybrid scale





hybrid scale

Main questions we aim to answer with this validation effort

Can we explain electron thermal transport P_e?

Can we explain the measured high-k fluctuation spectra?

Are measured fluctuations responsible for any thermal transport P_e?

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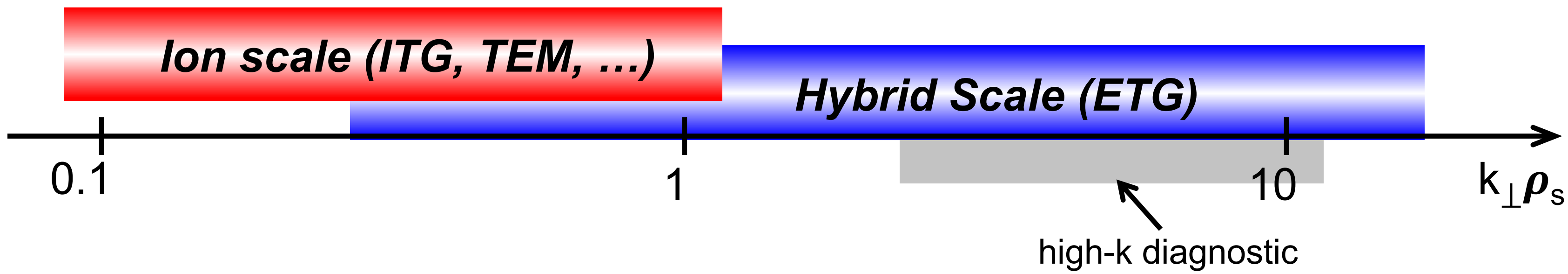
→ Use gyrokinetic simulation and a synthetic diagnostic to constrain turbulence model

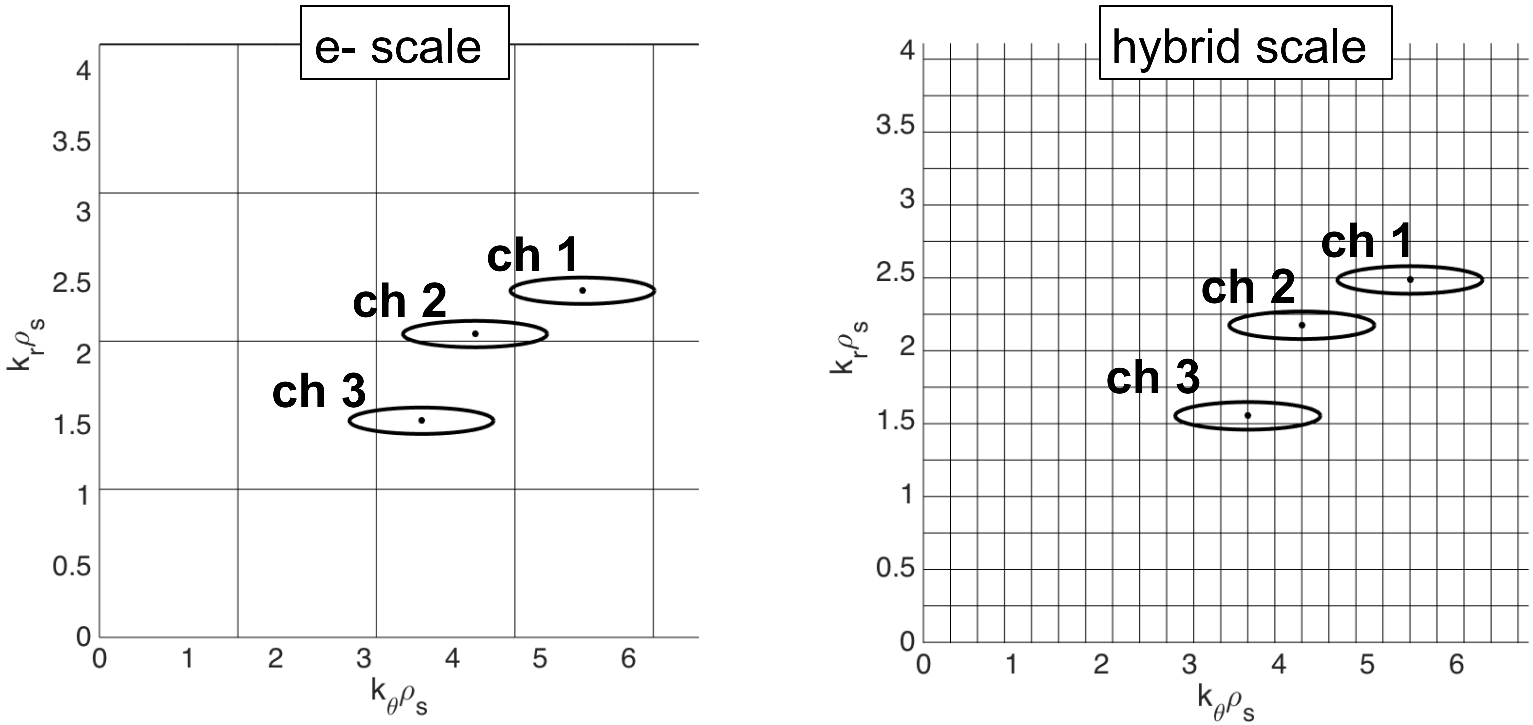
Numerical resolution details of GYRO ion scale and hybrid scale simulations

- **Ion scale** simulation only simulates ion scale turbulence $(k_\theta \rho_s \leq 1)$
- **Hybrid scale** simulation contain same physics as standard e- scale simulation (ETG), but different wavenumber resolution for synthetic diagnostic deployment

- 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 (radial buffer region).



Wavenumber grid from standard e- scale simulation is too coarse to resolve measurement k



	$k_\theta\rho_s$ [min, max]	$k_r\rho_s$ [min, max]
e- scale	[1.5, 65 or 86]*	[1, 47 or 32]*
Hybrid scale	[0.3, 65 or 88]*	[0.3, 32]

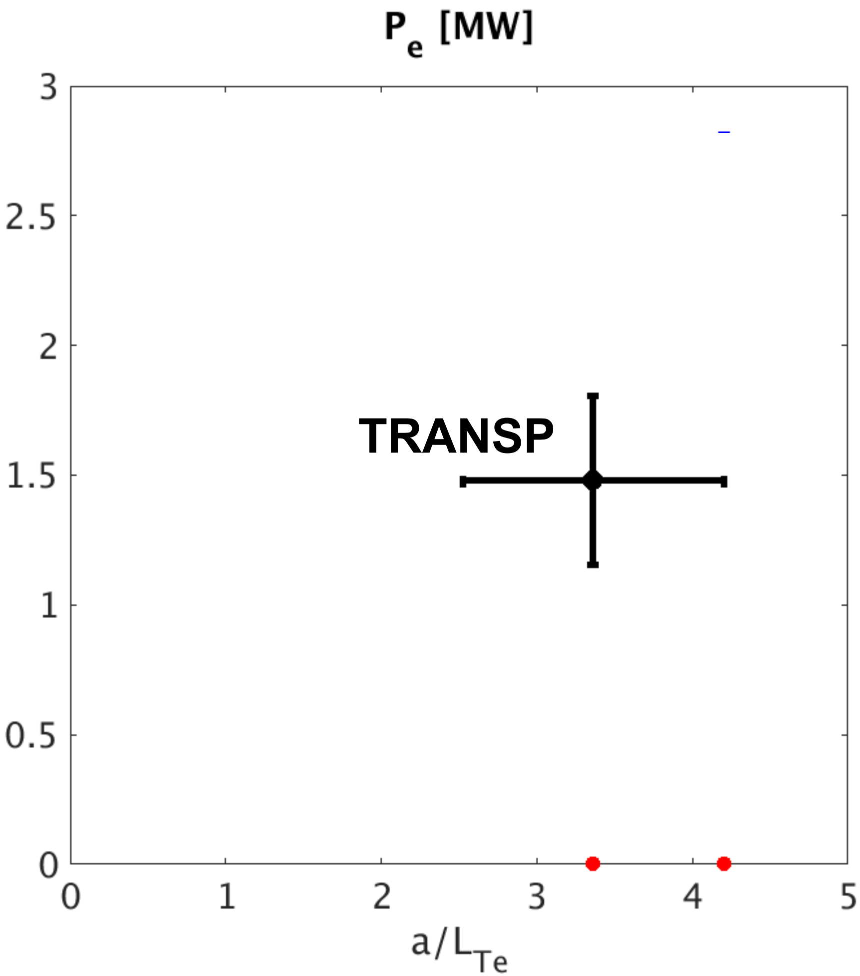
Computationally intensive

~ 1M CPU h/sim

* max $\mathbf{k_\theta\rho_s}$ is different for high and low ETG cases

Flux comparisons via sensitivity scans maximizing thermal transport P_e

Strong ETG condition: electron scale turbulence can match P_e within experimental uncertainty



Perform scans to maximize turbulence drive

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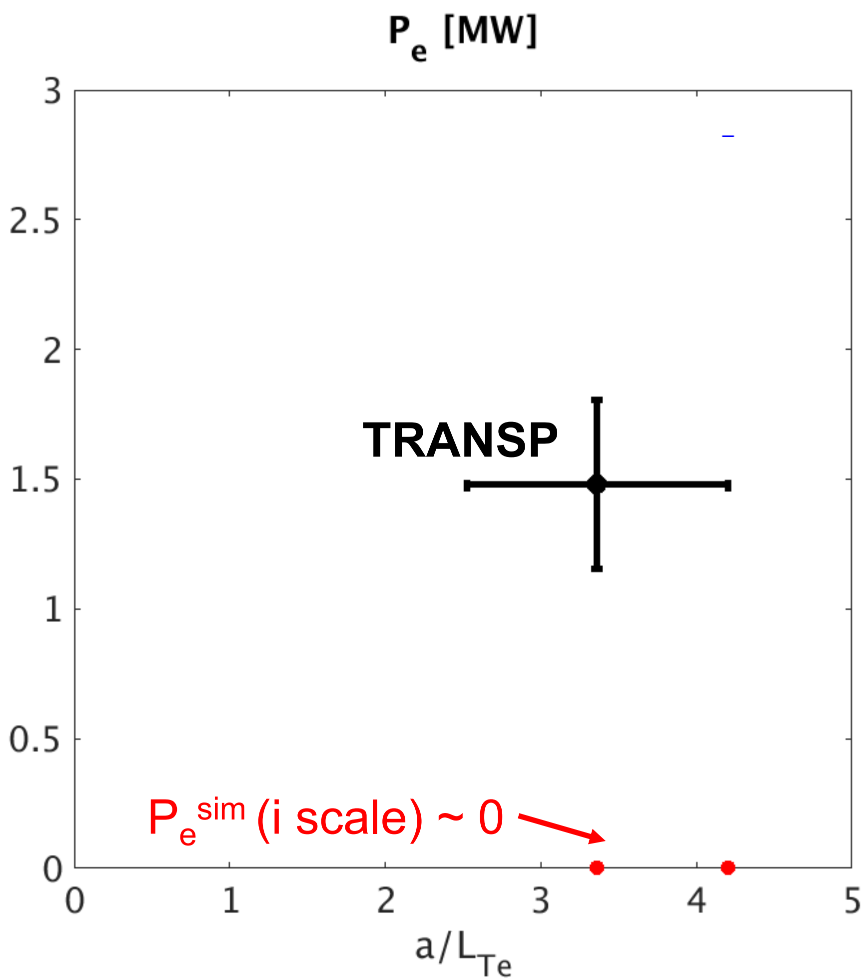
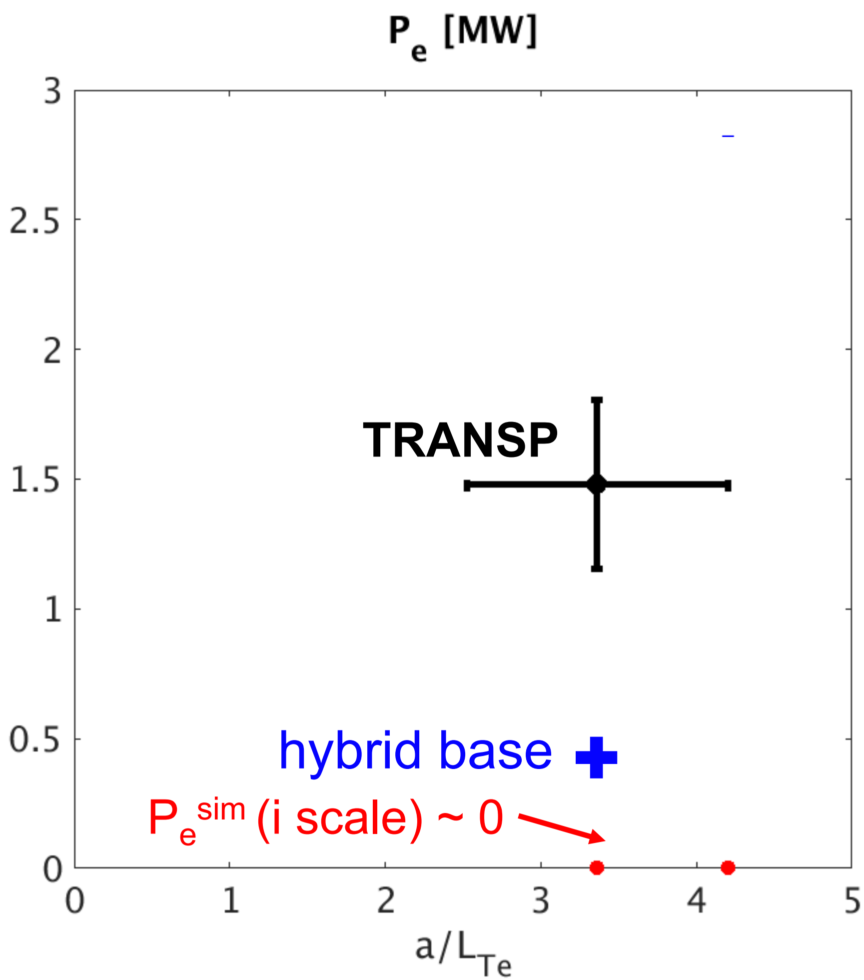


Perform scans to maximize turbulence drive

Ion scale sim ●

- Scans in $\sigma\{\nabla T, \nabla n\}$ → P_e^{sim} (i scale) ~ 0
- Suppressed by ExB shear

Strong ETG condition: electron scale turbulence can match P_e within experimental uncertainty



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Hybrid scale sim

- Base (exp parameters): ✚ underpredict P_e

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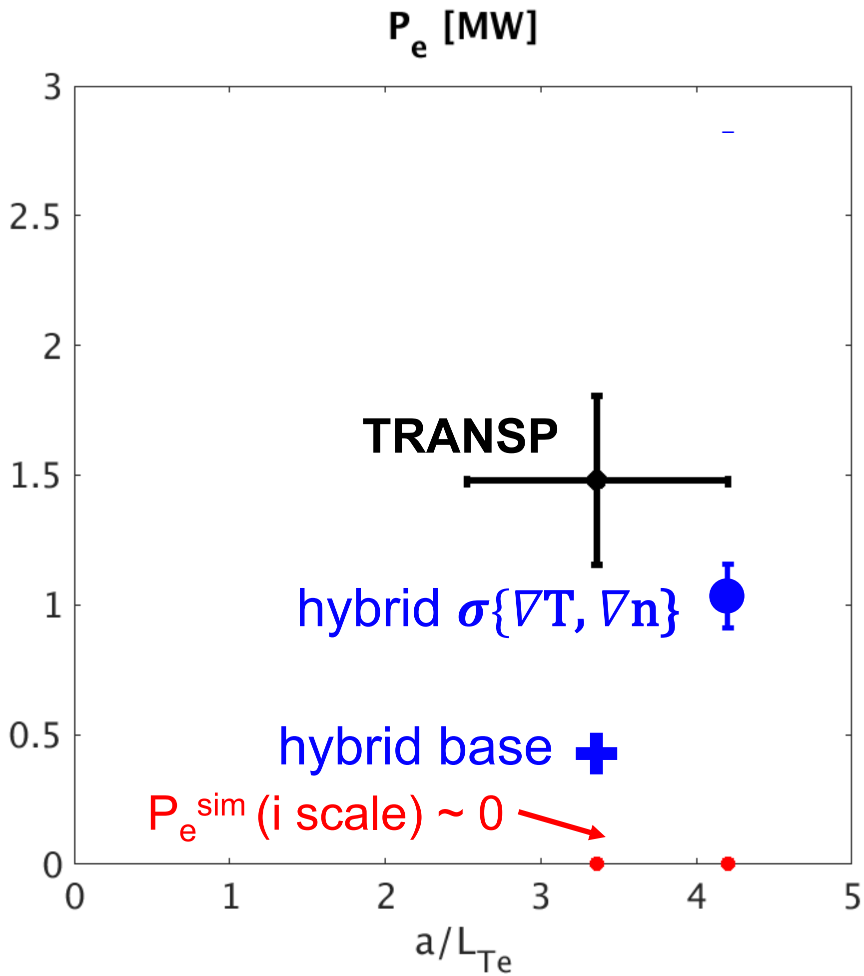

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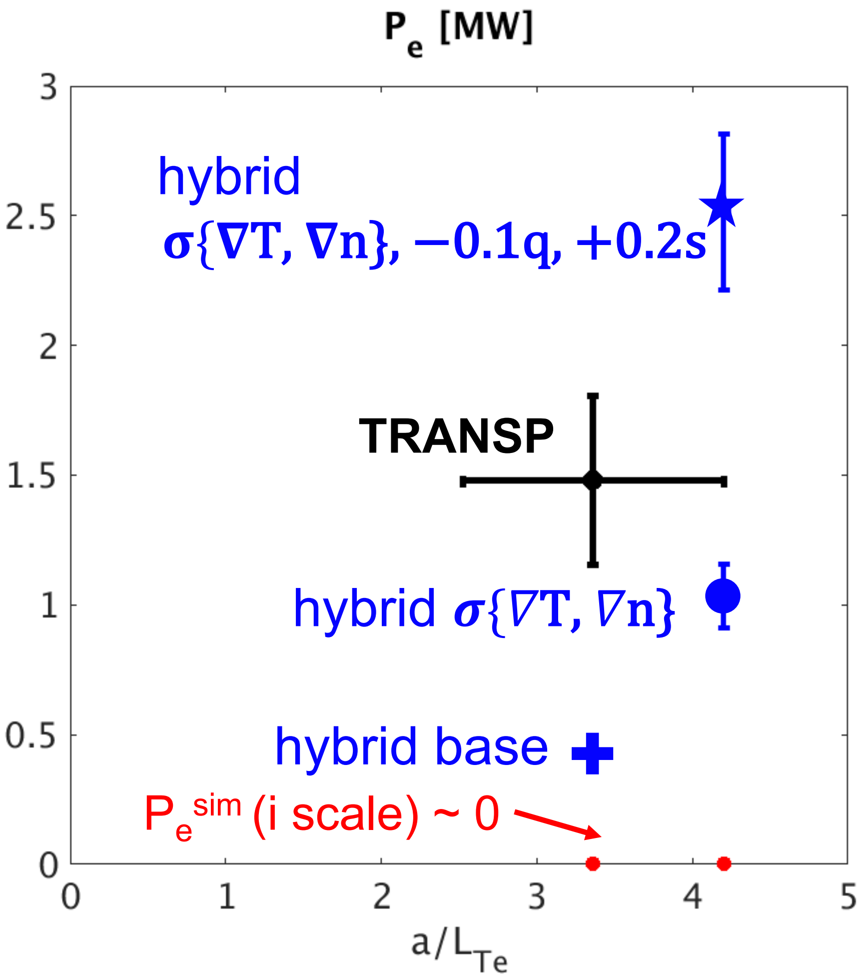

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- $\sigma\{\nabla T, \nabla n\}$, $-0.1q$, $+0.2s$: ★ overpredict P_e

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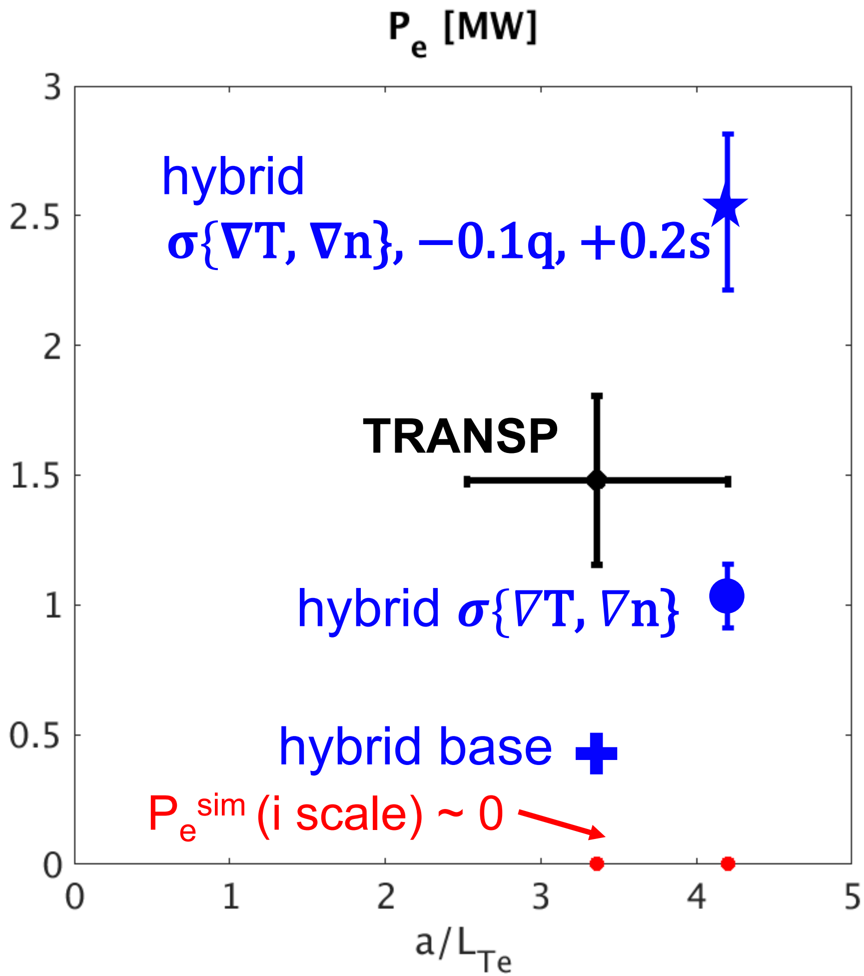

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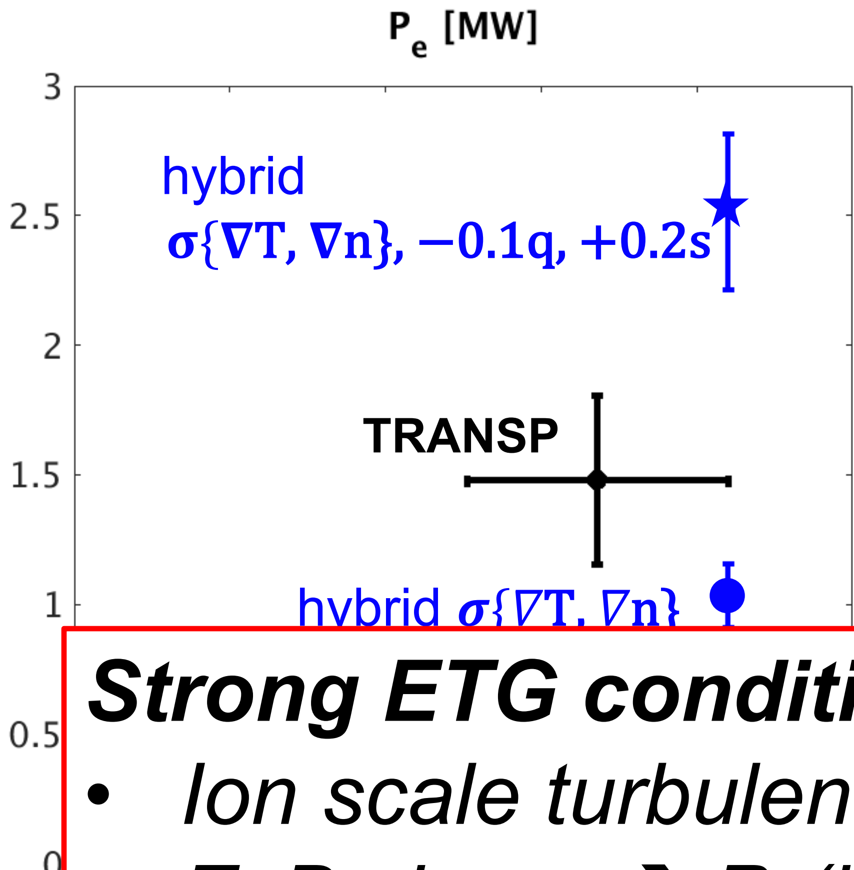
Ion thermal transport $\mathbf{P_i}$ close to neoclassical levels (NEO)

Strong ETG condition: electron scale turbulence can match P_e within experimental uncertainty



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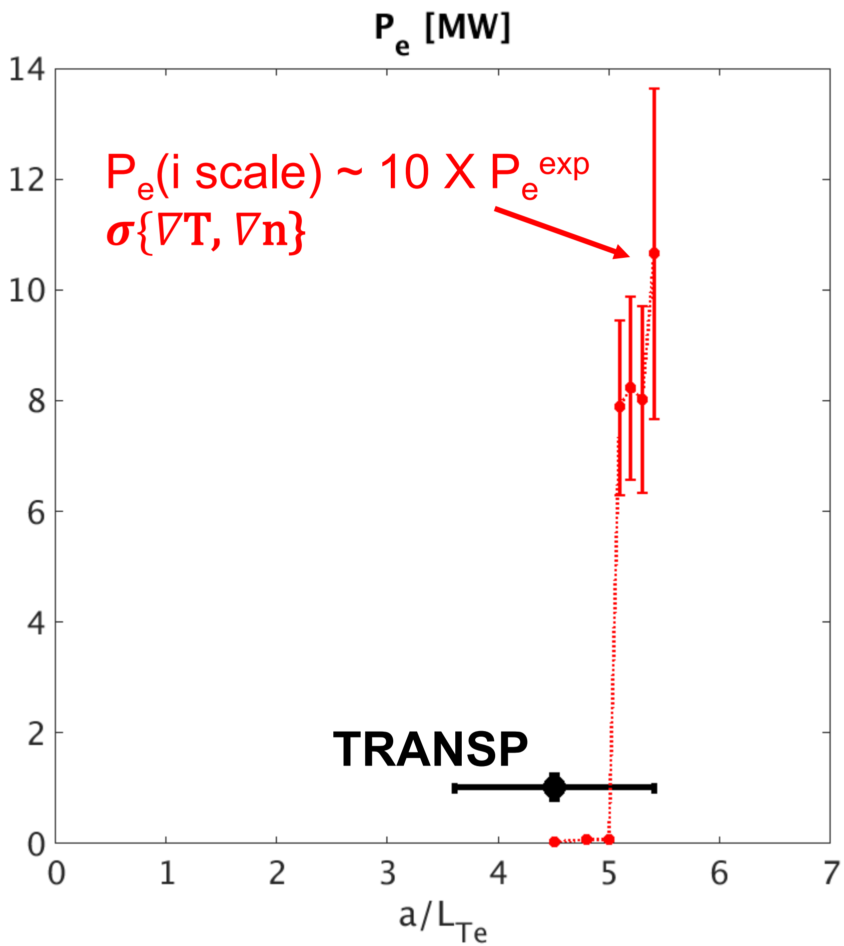
Strong ETG condition

- *Ion scale turbulence stabilized by strong ExB shear → P_e(i scale ~ 0)*
- *Electron scale turbulence can explain P_e*

Weak ETG condition: ion scale simulation can bracket P_e within error bars, hybrid scale can match P_e



Ion scale sim

- Scans performed for scaled -$\sigma(\nabla n)$
- $\nabla T-$scans show extremely stiff P_e (TEM), close to marginal (Dimits shift regime)

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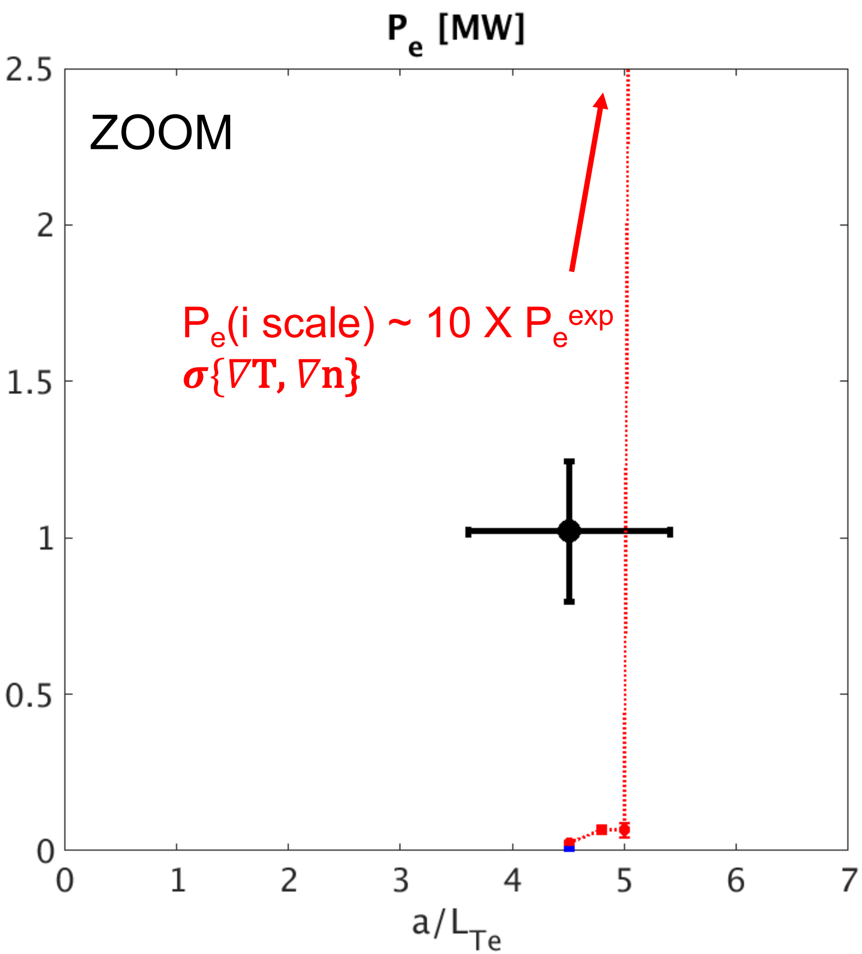

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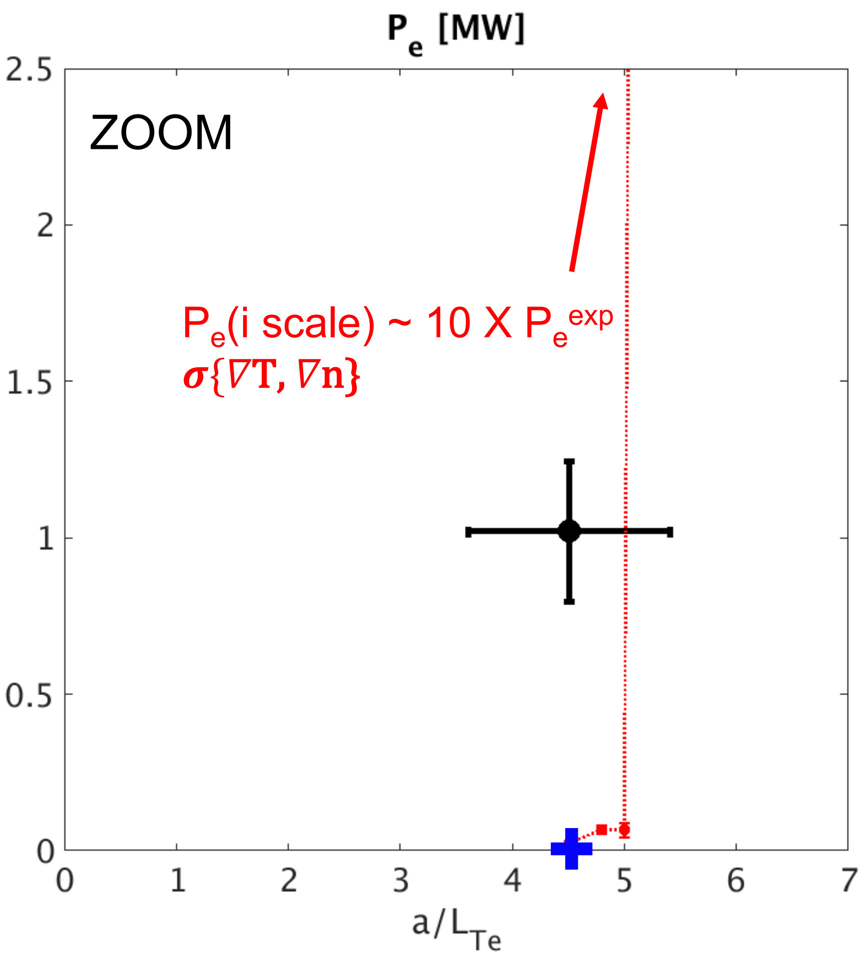

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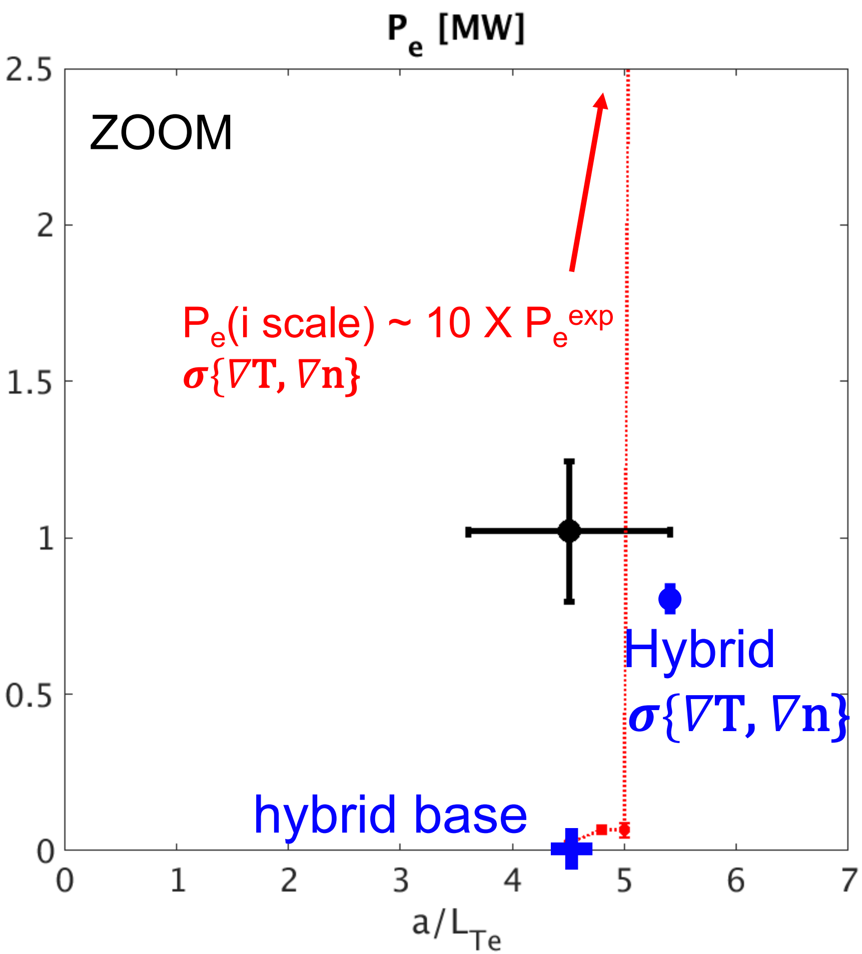

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- e- scale turbulence also close to marginal

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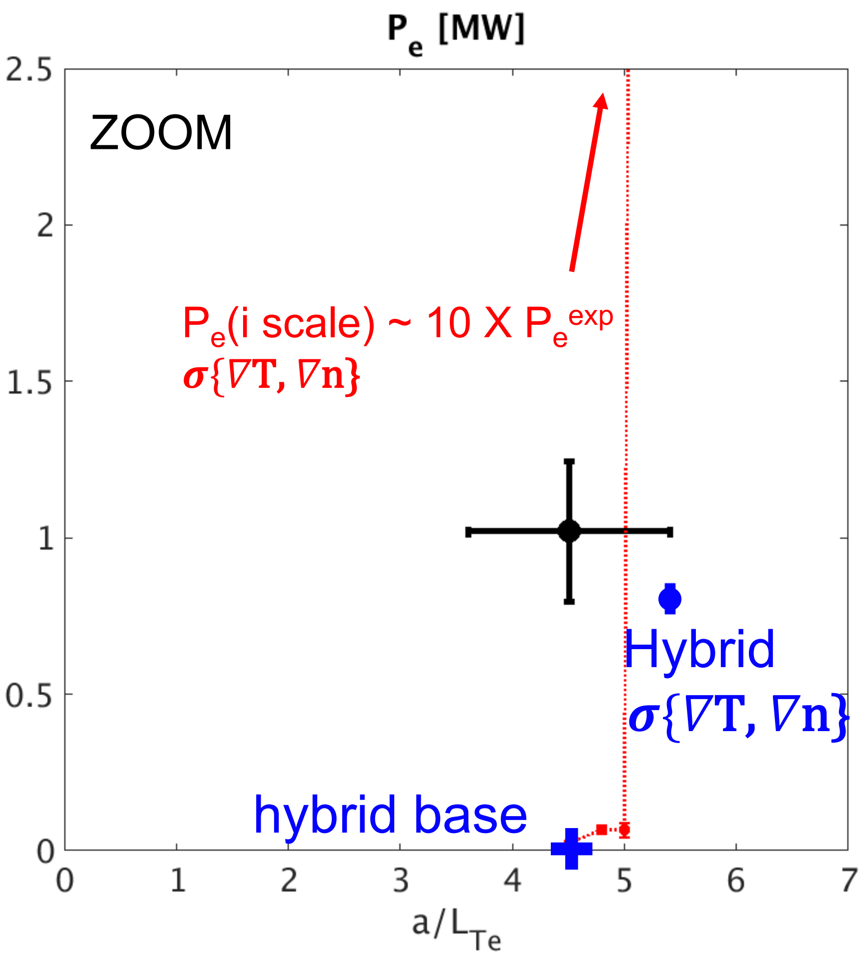

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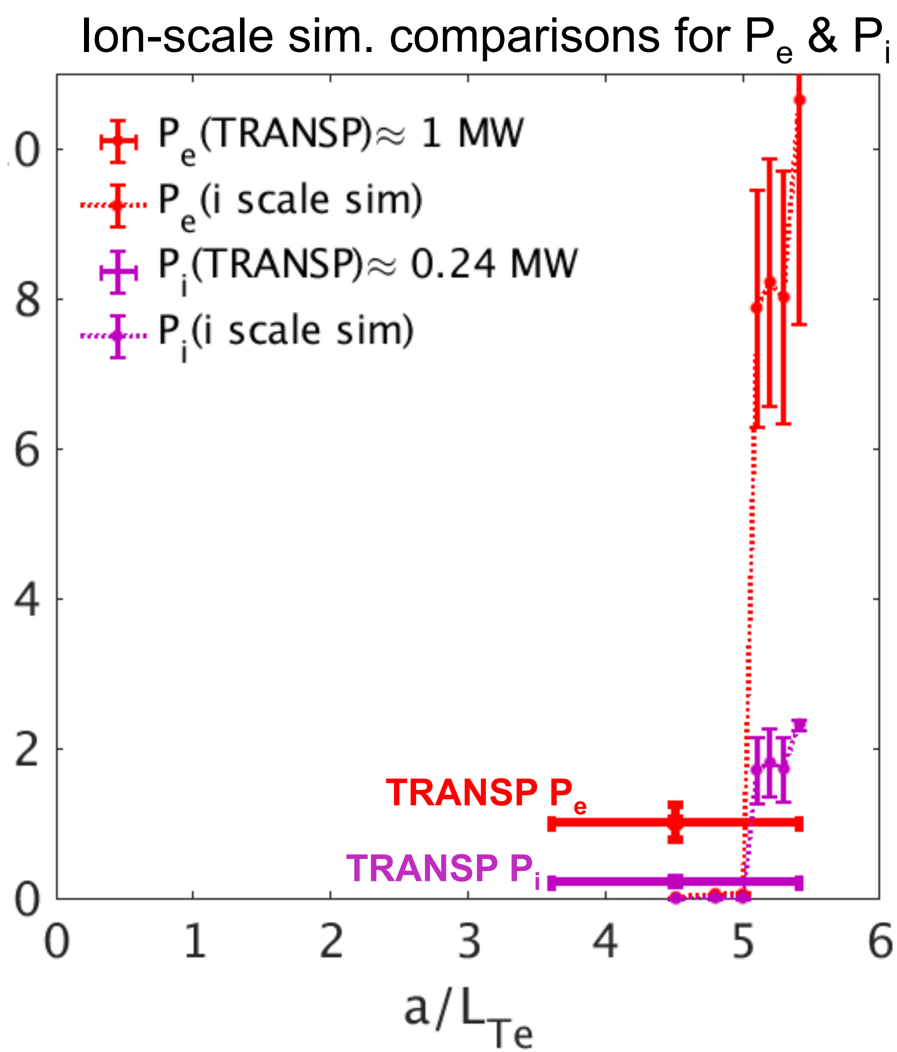
Is ion or electron scale turbulence responsible for P_e?

Weak ETG ion thermal transport: ion scale simulation brackets experimental P_i



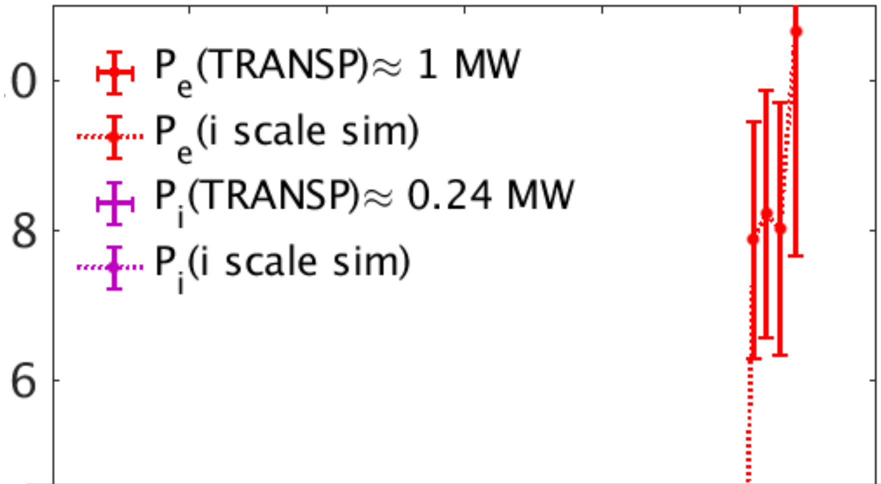
- Electron thermal transport P_e
  P_e(i scale) ~ 10 X P_e^{exp} for $a/L_{Te} > 5$
- Ion thermal transport P_i
  P_i(i scale) ~ 10 X P_i^{exp} for $a/L_{Te} > 5$
- P_i overprediction conflicts with neoclassical transport levels ~ 0.3 MW

➔ *Suggest at most a small ion-scale turbulence level*

- Negligible ion thermal transport from e-scales

Weak ETG ion thermal transport: ion scale simulation brackets experimental P_i

Ion-scale sim. comparisons for P_e & P_i



- Electron thermal transport P_e
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- Ion thermal transport P_i
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- P_i overprediction conflicts with neoclassical transport levels ~ 0.3 MW

➔ *Suggest at most a small ion-scale*

Weak ETG condition

- *Ion scale turbulence displays stiff TEM transport:*
  P_e , P_i (i scale) → 10 X P_e^{exp}, P_i^{exp}
- *GYRO overprediction conflicts with neoclassical P_i*
- *Electron scale turbulence can match P_e*

Open questions remaining from thermal power comparisons

What is the responsible transport mechanism for the weak ETG condition?

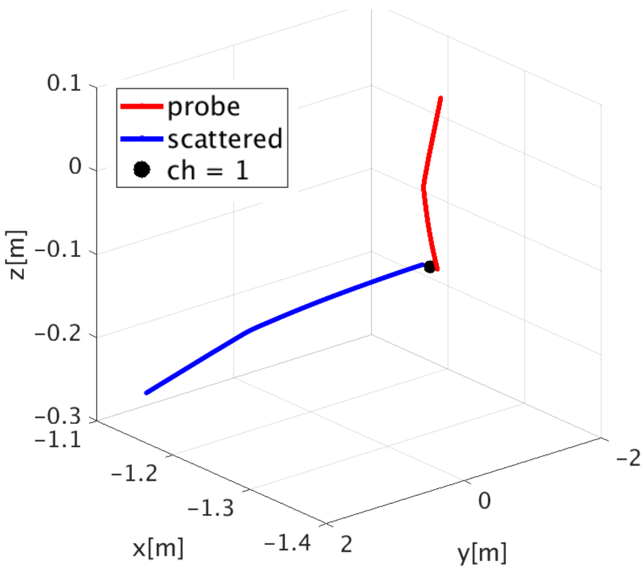
Are we matching simulations for the good reasons?

Which simulation is most experimentally meaningful?

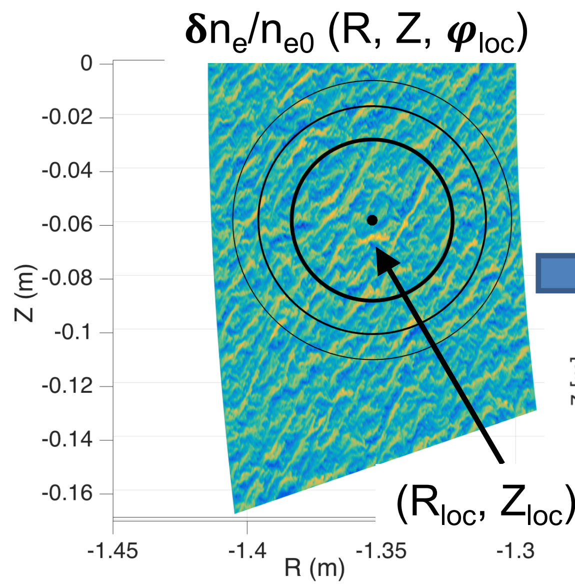
➔ Constrain models using a synthetic diagnostic for high-k scattering

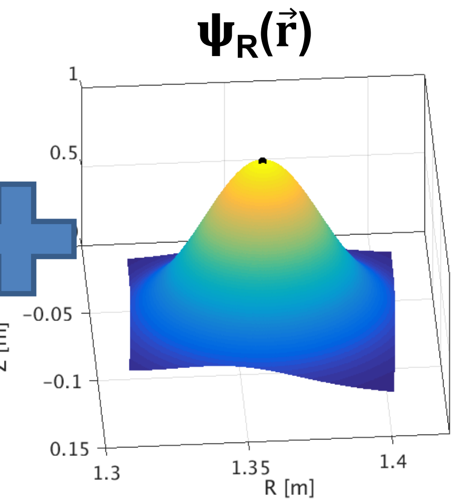
Synthetic diagnostic is applied to hybrid simulation for direct comparison with measured high-k fluctuations

Ray tracing in 3D



Filter turbulence in 2D



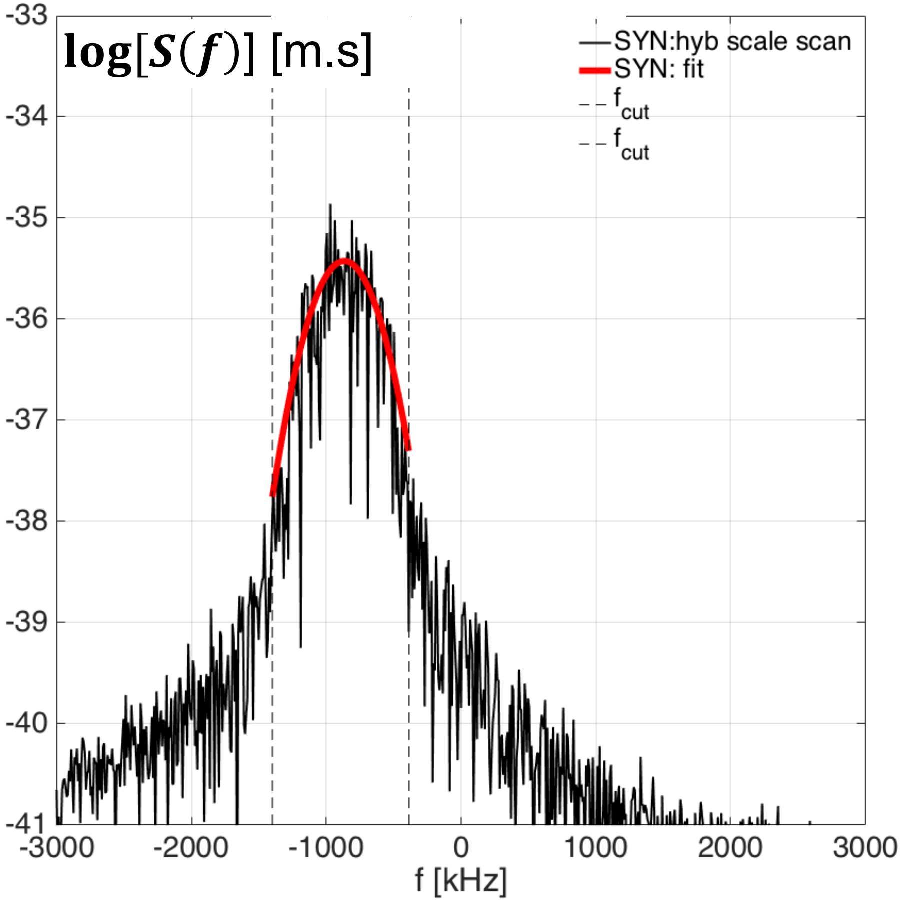


$$\delta\hat{n}_e^{syn}(t) = \int \delta n_e(\vec{r},t)\psi_R(\vec{r})e^{-i\vec{k}_0\cdot\vec{r}}d^3\vec{r}$$

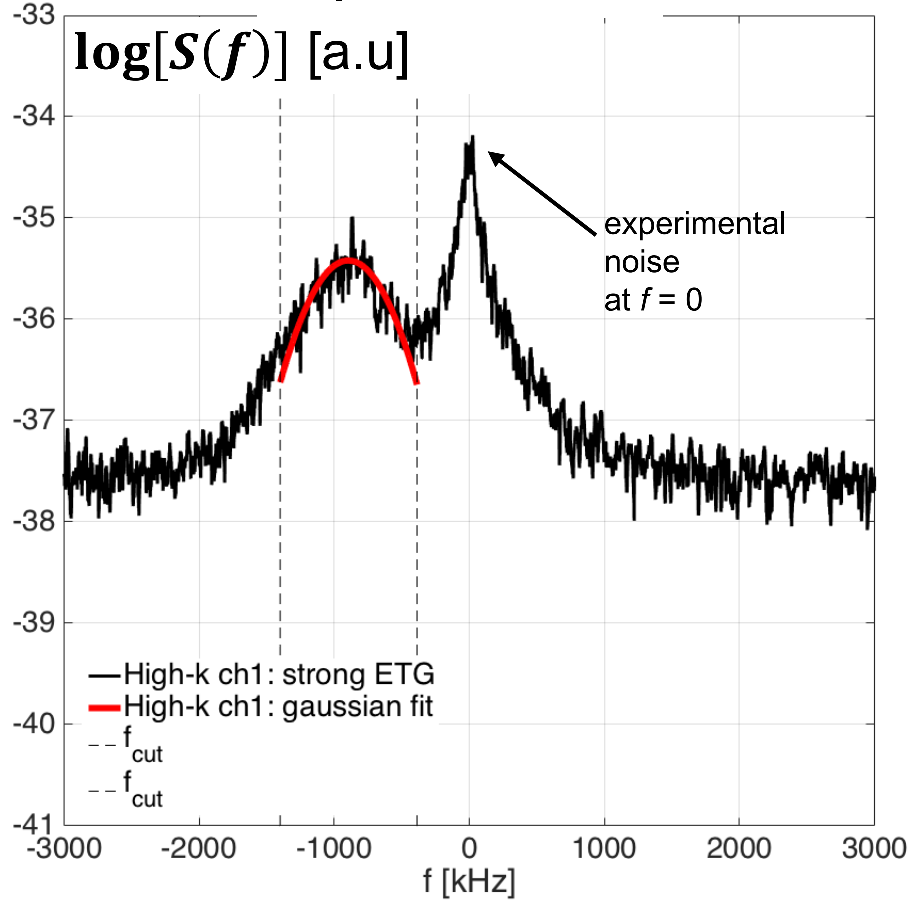
- Gaussian filter in space is applied to raw GYRO density fluct. amplitude
- Obtain a filtered time series of density fluctuations $\delta\hat{n}_e^{syn}(t)$ (analyzed the same way as experiment)
- New implementation in real space differs from past work (Poli PoP 2010)

Compare total power P_{tot}, spectral peak $< f >$ and spectral width σ_f in a prescribed frequency band

Simulation



Experiment



f-spectrum is determined by turbulence characteristics, k-resolution and Doppler shift

- **<u>Spectral peak $< f >$</u>** is dominated by Doppler Shift

$$f_{\text{turb}} \ll f_{\text{Dop}}$$

$$f_{\text{Dop}} = \vec{k} \cdot \vec{v} \sim 1\text{MHz}$$
$$f_{\text{turb}} \sim 50 - 100\ \text{kHz}$$

  - Not a critical constrain on simulation model

- **<u>Spectral width σ_f</u>** determined by combination of:
  - Turbulence spectrum in plasma frame
  - k-resolution of the high-k diagnostic
  - k-grid resolution of the simulation
  - Doppler shift

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Difficult to discriminate between models using the frequency spectrum

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Difficult to discriminate between models using the frequency spectrum

- **<u>Total power P_{tot}</u>** from each channel → k-spectrum

Synthetic comparisons presented for hybrid simulations

1. k-spectrum
    - Shape
    - Relative fluctuation level

2. $\boldsymbol{f}$-spectrum (spectral peak $< \boldsymbol{f} >$, width $\boldsymbol{\sigma_f}$)

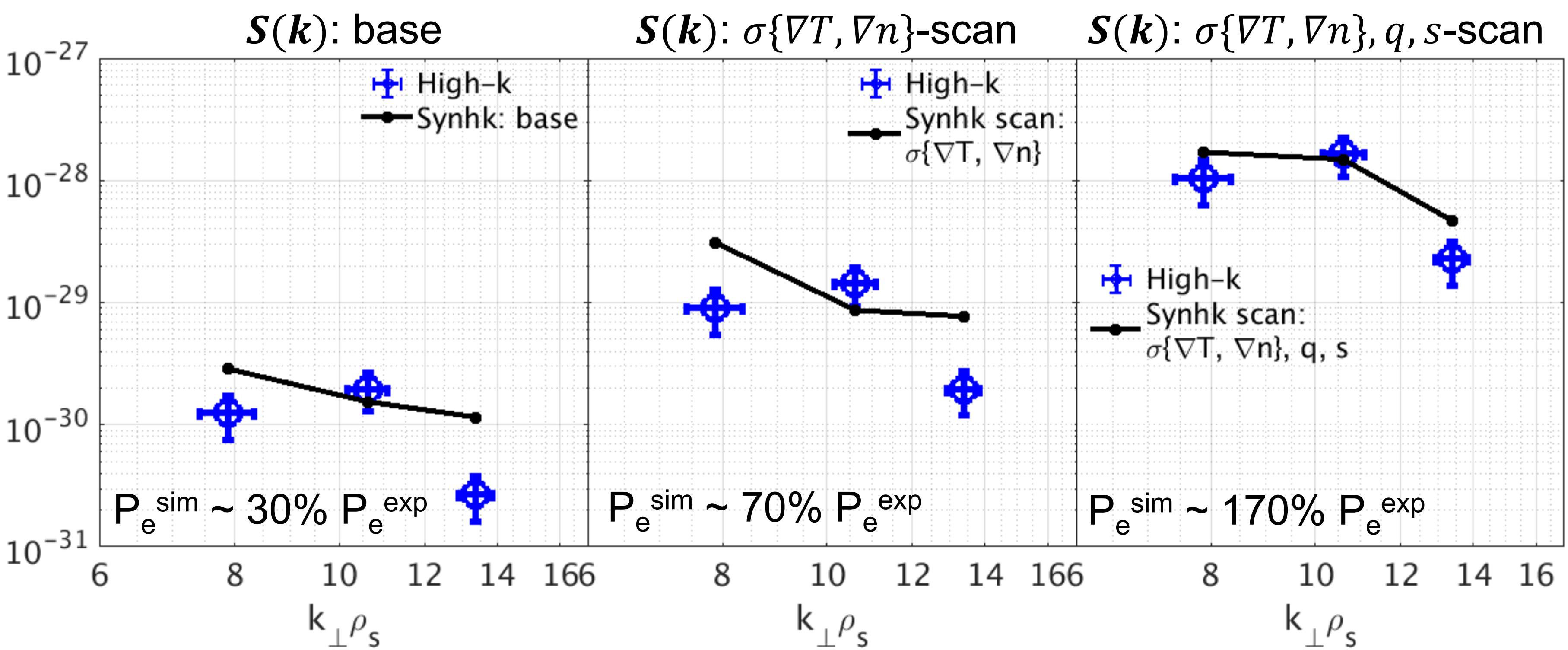
Note

- We use f-spectrum to compute k-spectrum
- k-spectrum allows for better discrimination between models

→ will discuss k-spectrum first

k-spectra comparisons for strong ETG case: $\sigma\{\nabla T, \nabla n\}, q, s$-scan best matches $\boldsymbol{k}$-spectrum shape

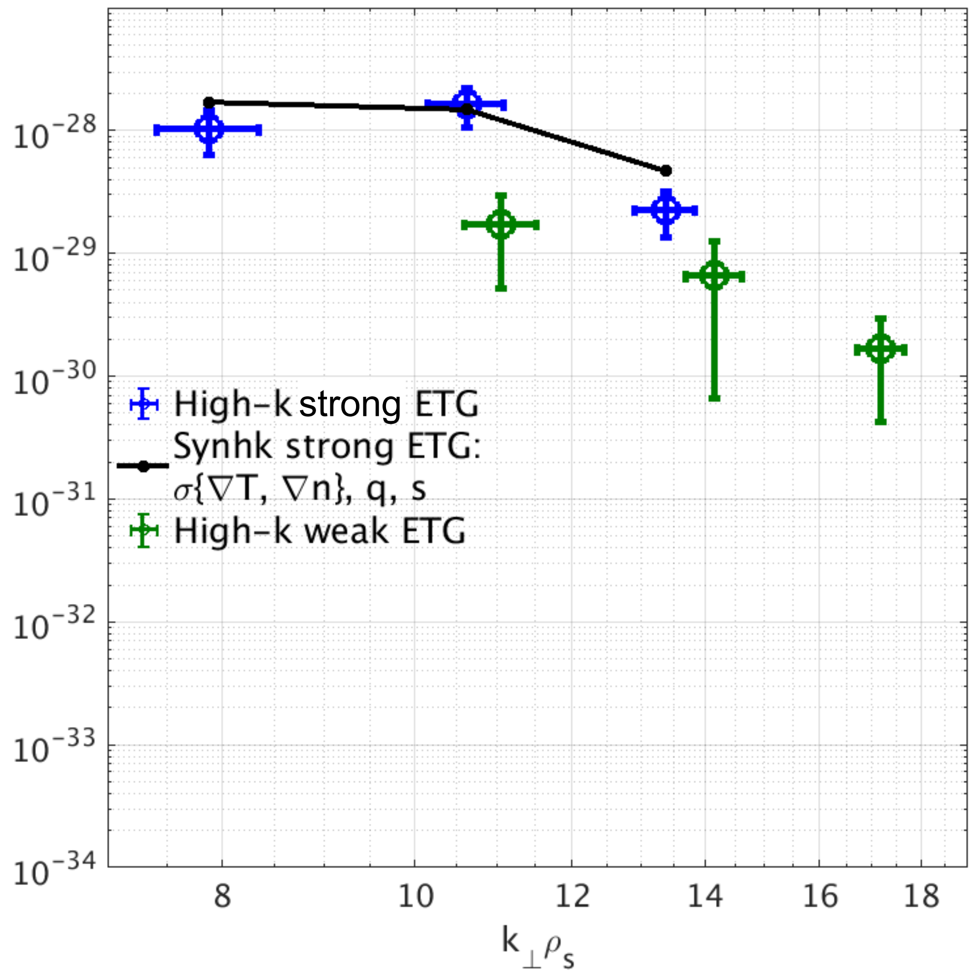
Experiment is not calibrated: rescale $\boldsymbol{S}(\boldsymbol{k})^{\mathrm{exp}}$ ✛ to minimize k-spectrum 'distance'



- Best match in $\boldsymbol{k}$-spectrum shape found for $\sigma\{\nabla T, \nabla n\}, q, s$-scan (via validation metric)
- Combination of (q, s)-scan results in improved $\boldsymbol{k}$-spectrum agreement

Compare relative fluctuation level between best k-spectrum match for strong ETG case and weak ETG

$\boldsymbol{S}(\boldsymbol{k})$ for strong ETG: $\sigma\{\nabla T, \nabla n\}, q, s$-scan



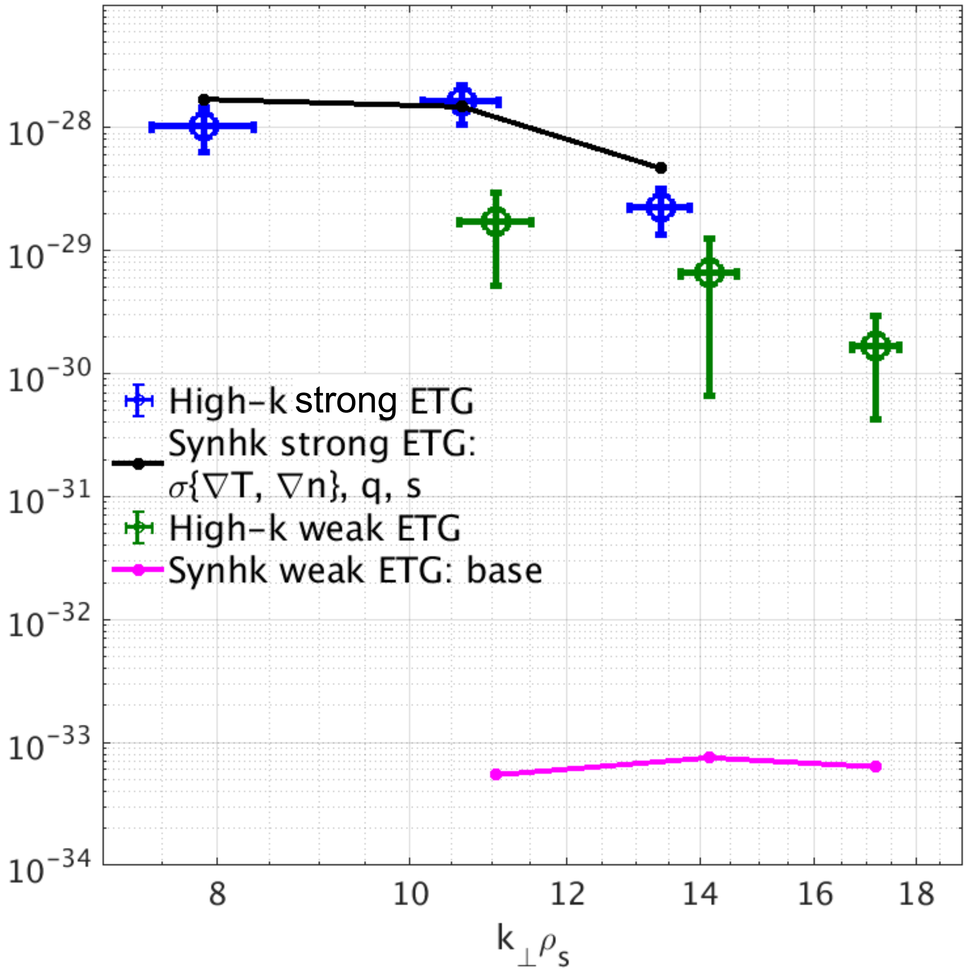
Strong ETG: P_e^{sim} ~ 170% P_e^{exp}

Weak ETG:

- Experimental k-spectrum scaled by same constant as strong ETG (preserve fluctuation level ratio)

Compare relative fluctuation level between best k-spectrum match for strong ETG case and weak ETG

$\boldsymbol{S}(\boldsymbol{k})$ for strong ETG: $\sigma\{\nabla T, \nabla n\}, q, s$-scan



Strong ETG: P_e^{sim} ~ 170% P_e^{exp}

Weak ETG:

- Experimental k-spectrum scaled by same constant as strong ETG (preserve fluctuation level ratio)

- **Base sim** (exp parameters): P_e ~ 0 underpredicts weak ETG fluct level

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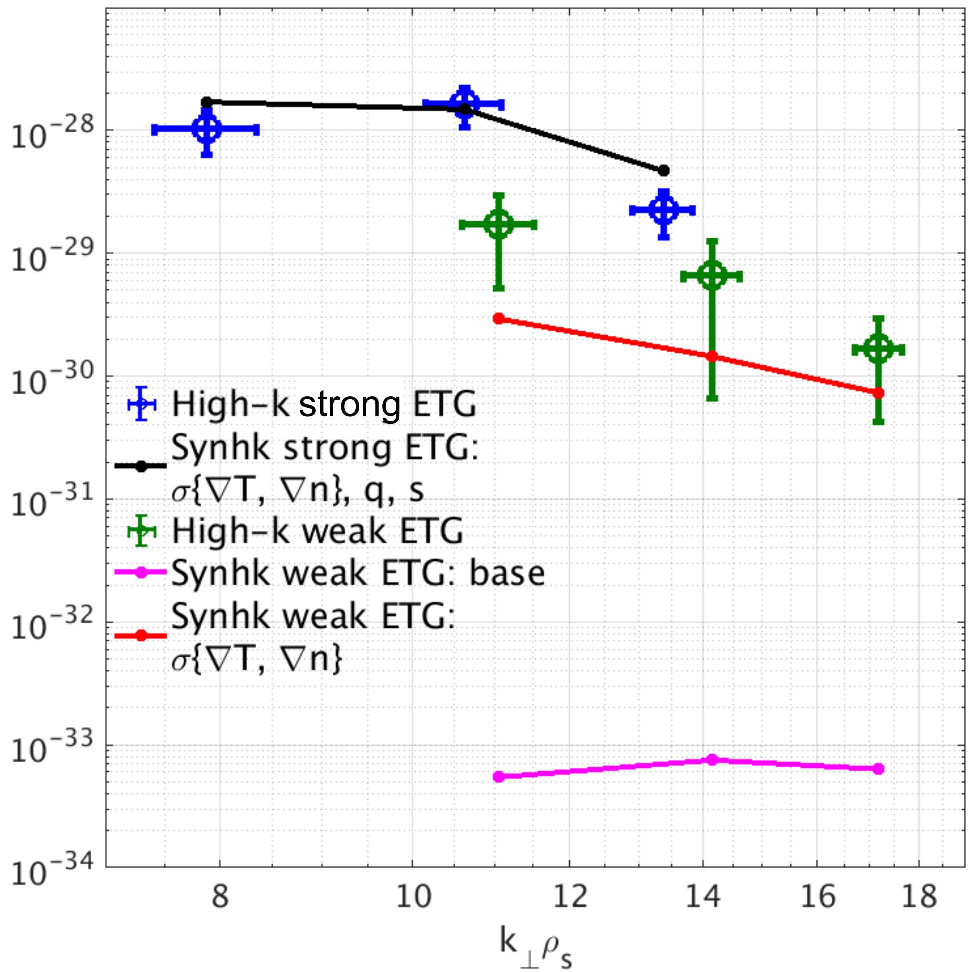

Strong ETG: $P_e^{sim} \sim 170\% \; P_e^{exp}$

Weak ETG:

- Experimental k-spectrum scaled by same constant as strong ETG (preserve fluctuation level ratio)
- **Base sim** (exp parameters): $P_e \sim 0$ underpredicts weak ETG fluct level
- $\boldsymbol{\sigma\{\nabla T, \nabla n\}}$**-scan:** $P_e \sim 80\% \; P_e^{exp}$
  - Matches k-spectrum shape
  - Close to match fluct. level ratio

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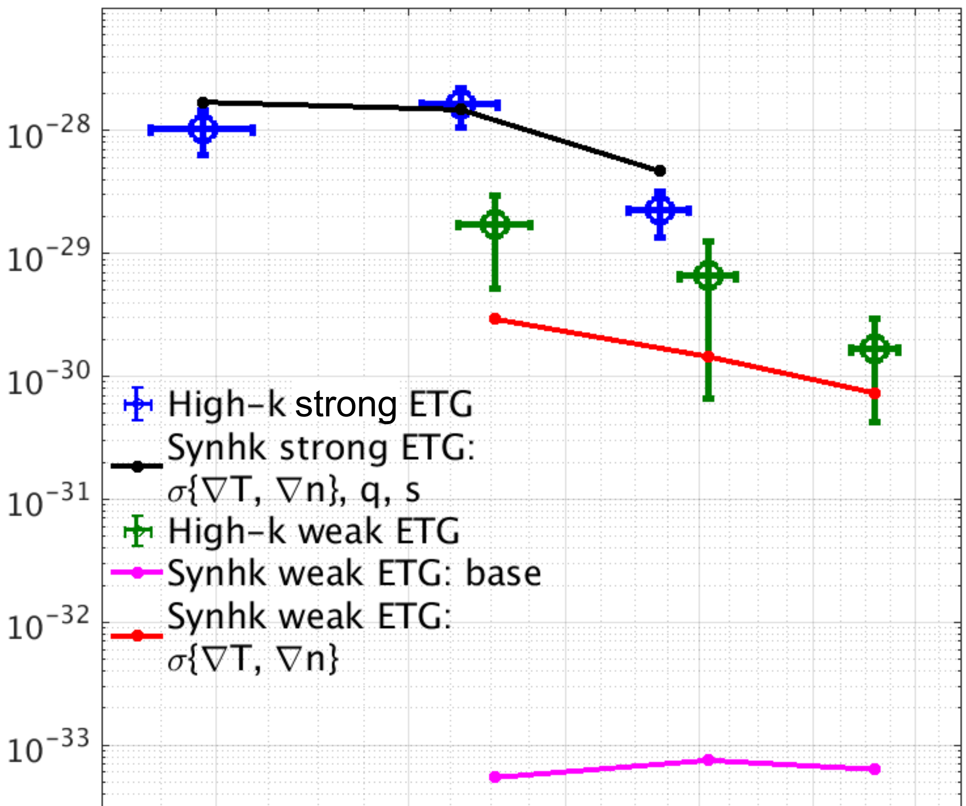

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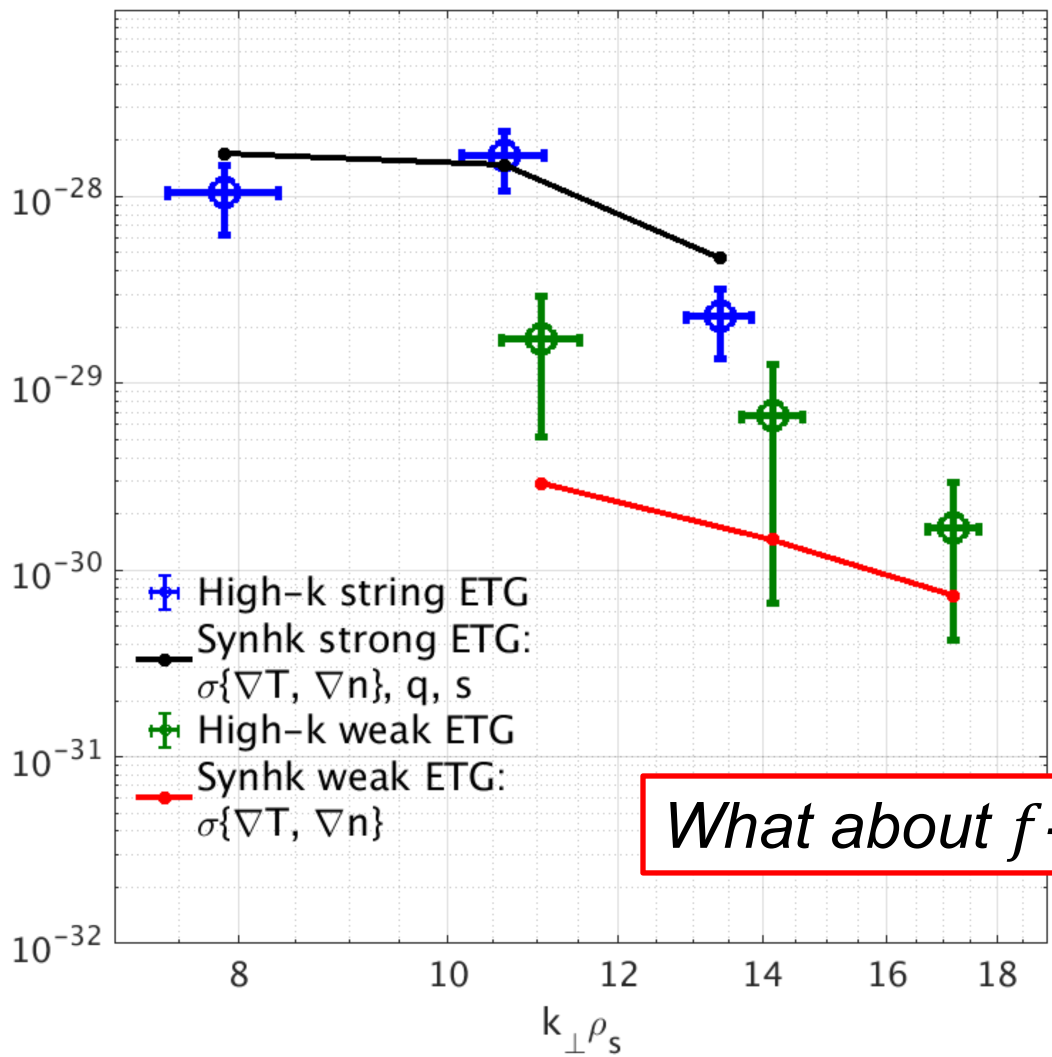
  - Close to match fluct. level ratio

1

➔ *Finite level of ETG, producing experimentally relevant P_e is needed to match* k-spectra constrains

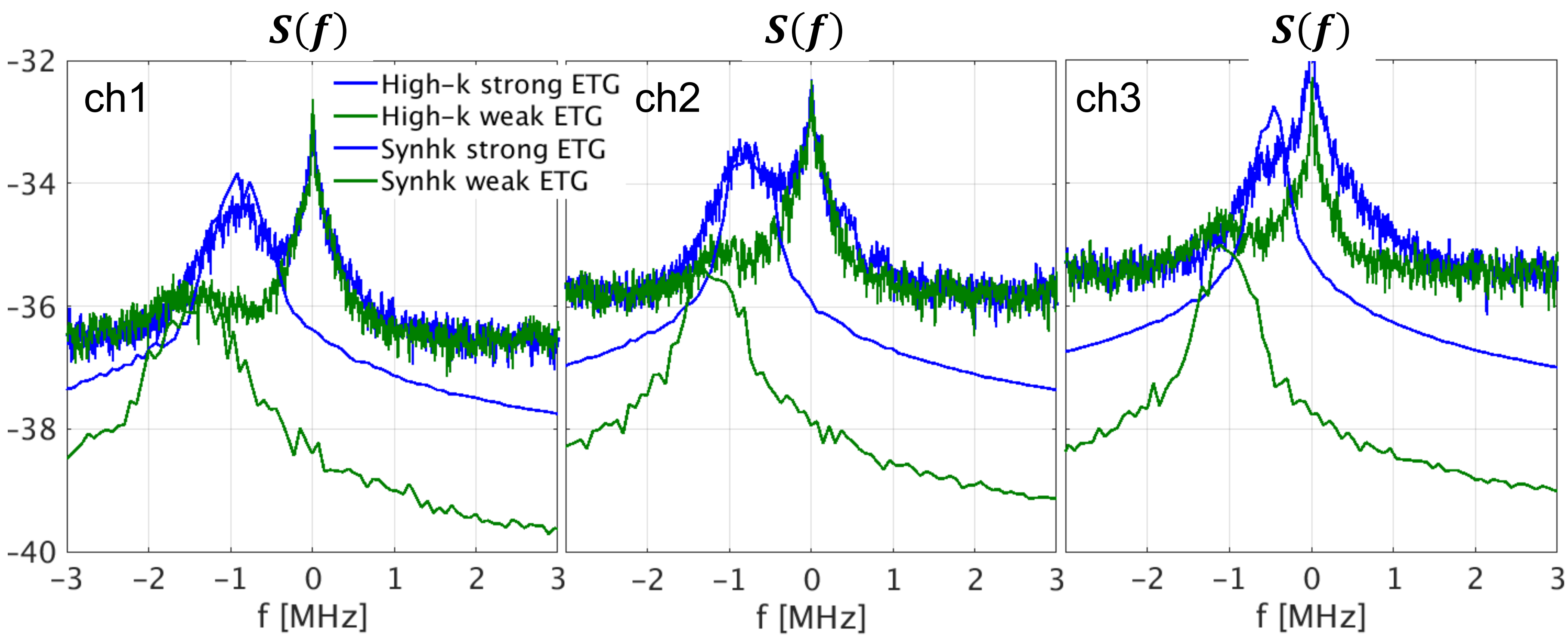
Found simulation conditions for strong & weak ETG case that agree with k-spectra constrains

$\boldsymbol{S(k)}$ for strong ETG: $\sigma\{\nabla T, \nabla n\}, q, s$-scan



What about f-spectrum?

Synthetic f-spectrum reproduces spectral peak $< f >$, close to match spectral width σ_f for all channels



STRONG ETG ch1

	Exp	Sim
$< f >$ [MHz]	-0.91	-0.89 [0.1]
σ_f [MHz]	0.21	0.17 [0.1]

WEAK ETG ch1

	Exp	Sim
$< f >$ [MHz]	-1.39	-1.40 [0.1]
σ_f [MHz]	0.36	0.26 [0.1]

Recall motivation of this work

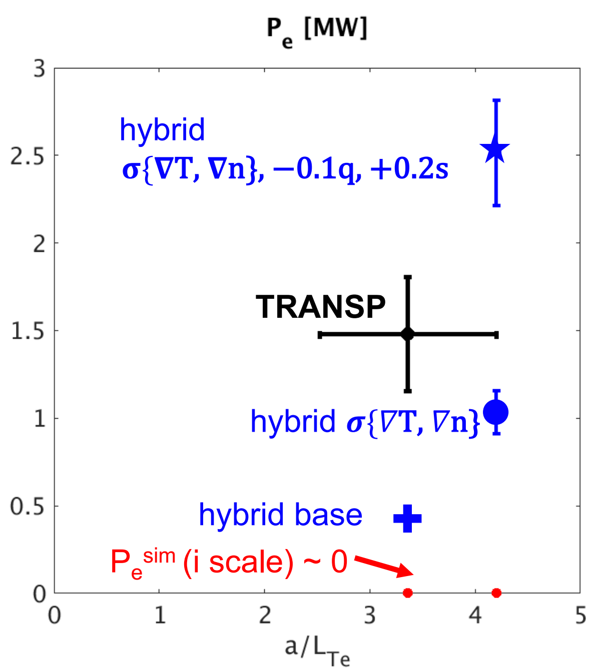
Can we explain electron thermal transport P_e?

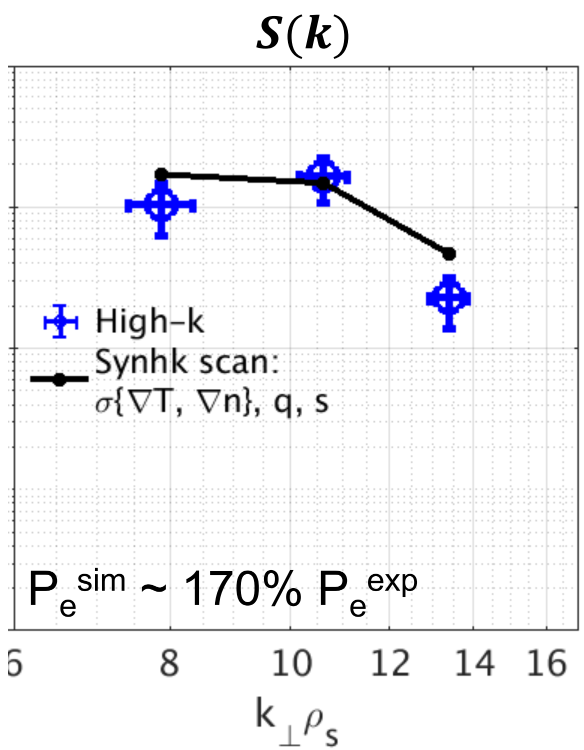
Can we explain the measured high-k fluctuation spectra?

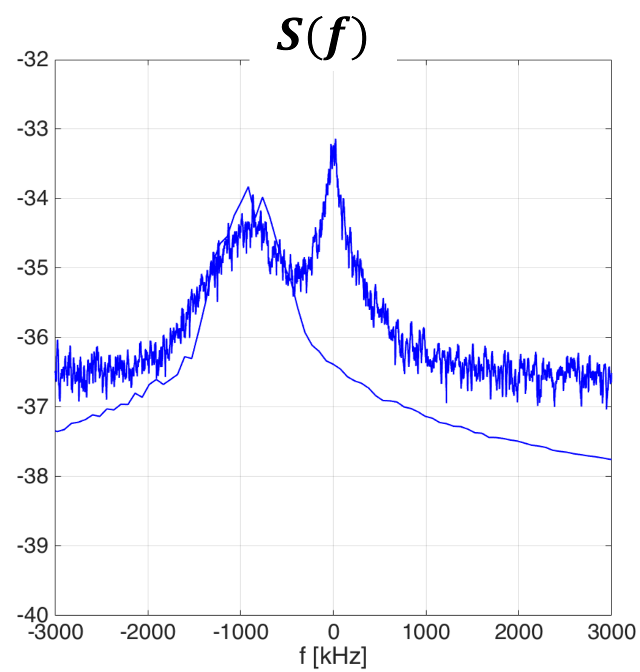
Are measured fluctuations responsible for any thermal transport P_e?

Discussion at Strong ETG

- Ion-scale turbulence is suppressed by ExB shear
- e- scale can explain P_e^{exp}, consistent with agreement in high-k f & k-spectra







Discussion at Strong ETG

- <u>Ion-scale</u> turbulence is suppressed by ExB shear
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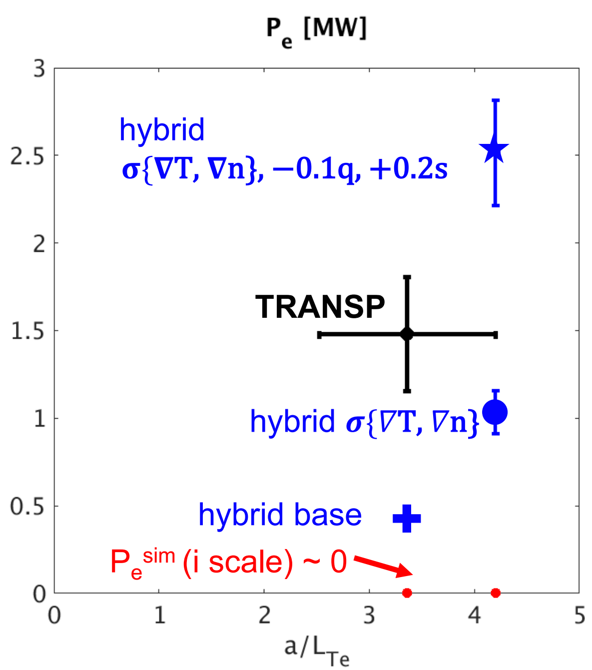
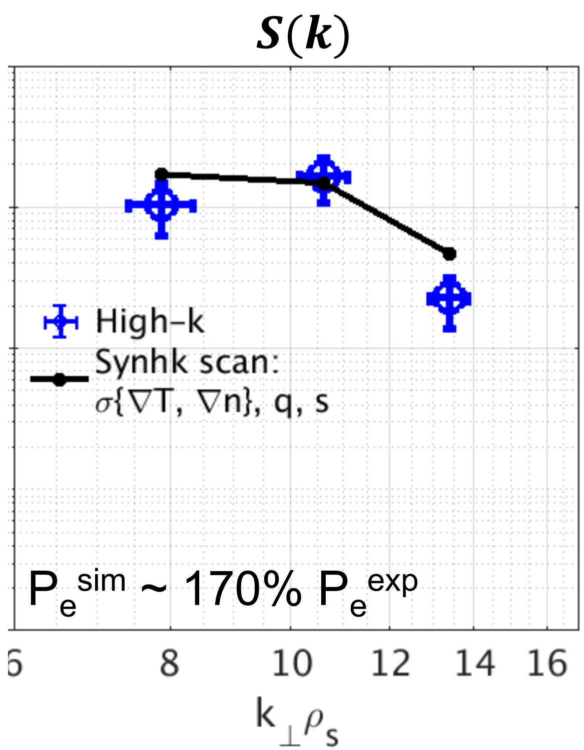
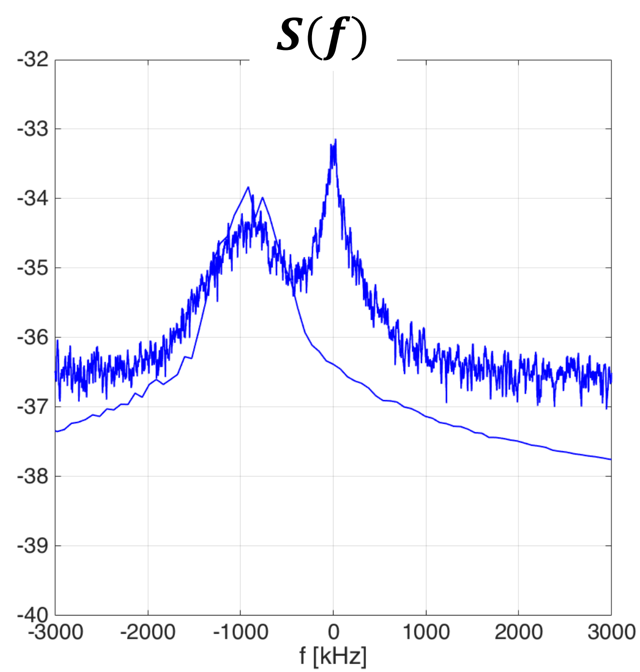


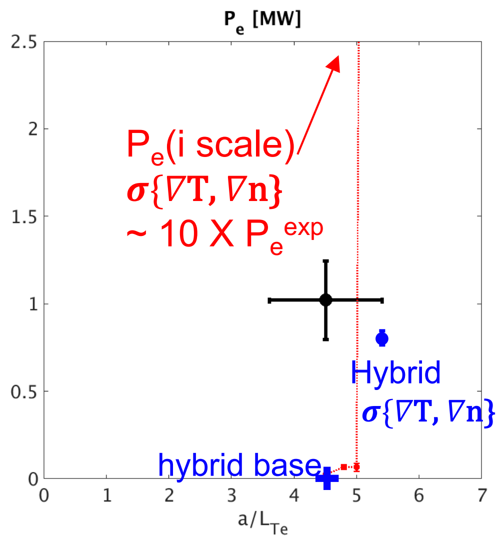


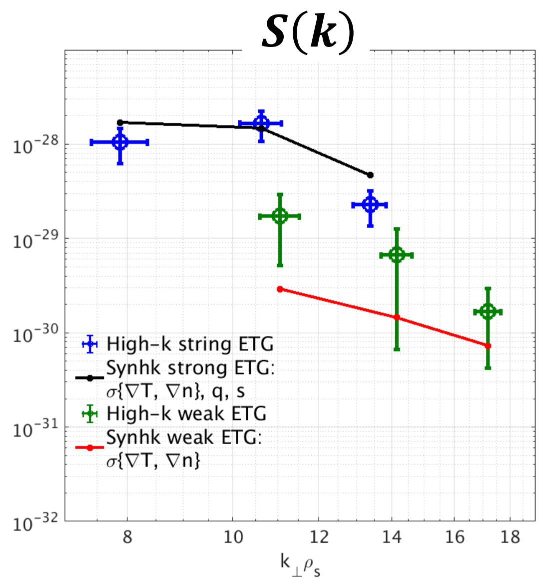


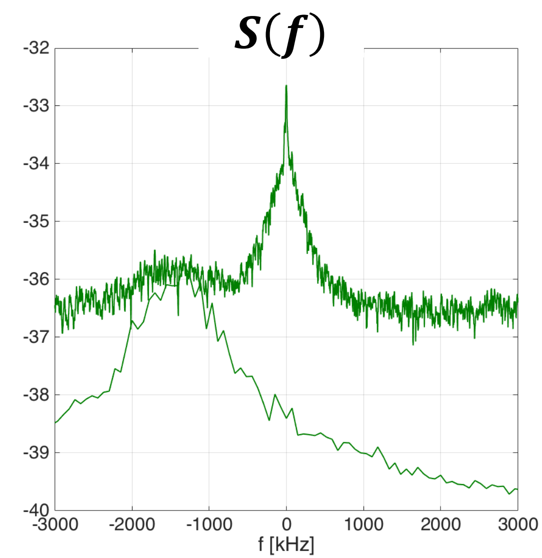
➔ *e- scale turbulence (ETG) is likely responsible for P_e^{exp}*

Discussion at Weak ETG

- <u>Ion scale</u> sim can bracket P_e^{exp} , extremely stiff transport
- <u>Electron scale</u> is active, can match P_e^{exp}





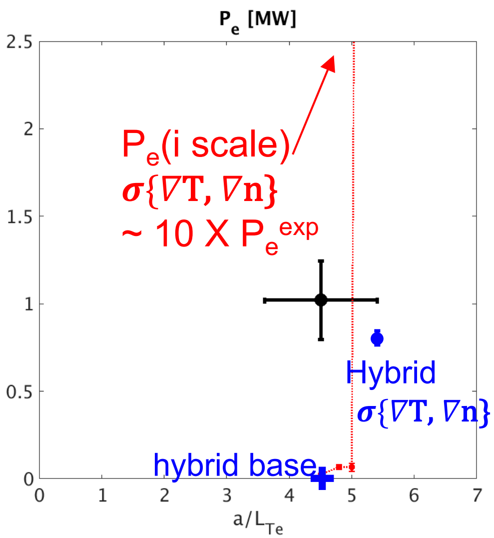


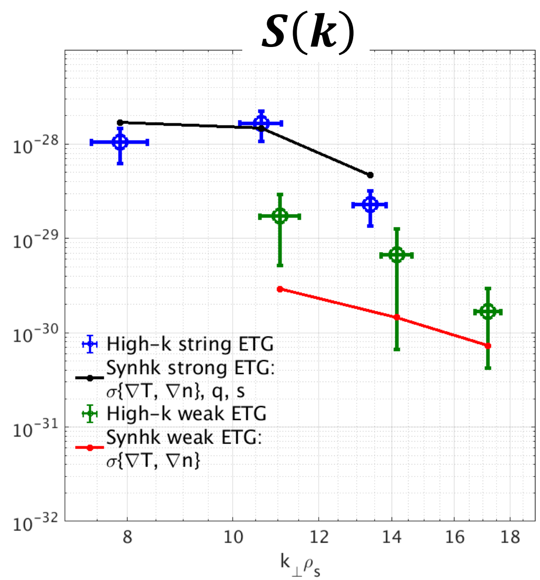
Is ion or e- scale turbulence responsible for P_e?

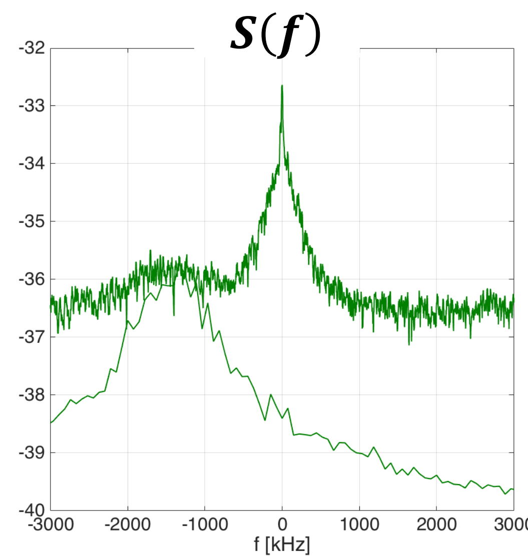
- *__k-spectra__ ➔ finite level of ETG is needed to match fluct. level ratio*
- *Ion thermal transport ~ neoclassical ➔ suggests small ion scale turbulence level*
- *But e- scale alone cannot explain P_e!! ➔ missing P_e could come from ion scales*
- *Both ion & e- scales ~ marginal ➔ cross-scale coupling? affecting P_e, not P_i?*

Discussion at Weak ETG

- <u>Ion scale</u> sim can bracket P_e^{exp} , extremely stiff transport
- <u>Electron scale</u> is active, can match P_e^{exp}







Is ion or e- scale turbulence responsible for P_e?

➔ Probably a combination of ion scale (TEM) and e-scale turbulence (ETG) is responsible for P_e^{exp}

➔ cross-scale interactions likely important

Conclusions and next steps

What we have done

- Implemented a synthetic high-k diagnostic, and used it to discriminate between gyrokinetic turbulence models and plasma conditions.
- Validated local NL gyrokinetic simulations against experimental power balance and high-k turbulence measurements in the core-gradient region of an NSTX NBI-heated H-mode.
  - **Strong ETG**: ETG is mechanism responsible for P_e.
  - **Weak ETG**: Combination of ETG/TEM responsible for P_e (+ cross-scale coupling?).

Next Steps

- Multiscale simulation of NSTX H-mode? + synthetic diagnostic?
- Apply reduced transport models (TGLF).
- Quantitative predictions for new high-k, 3D/toroidal effects.

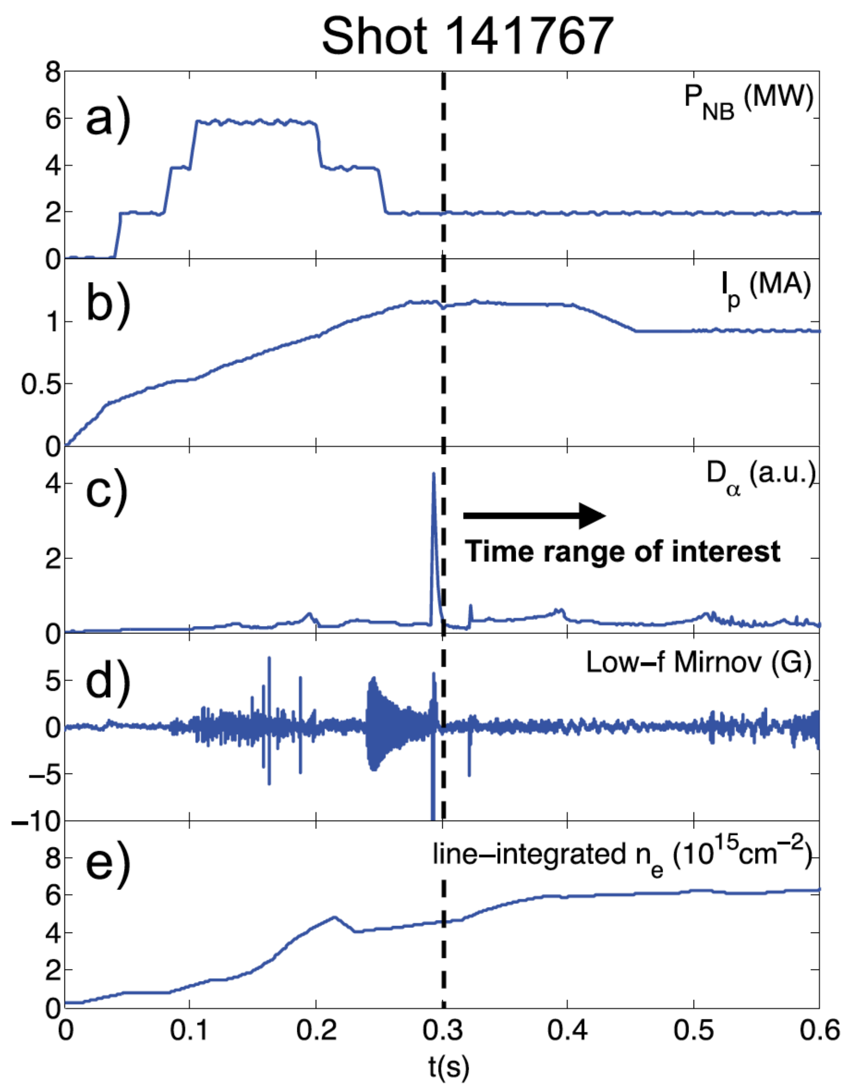
Questions

Input Parameters into Nonlinear Gyrokinetic Simulations Presented

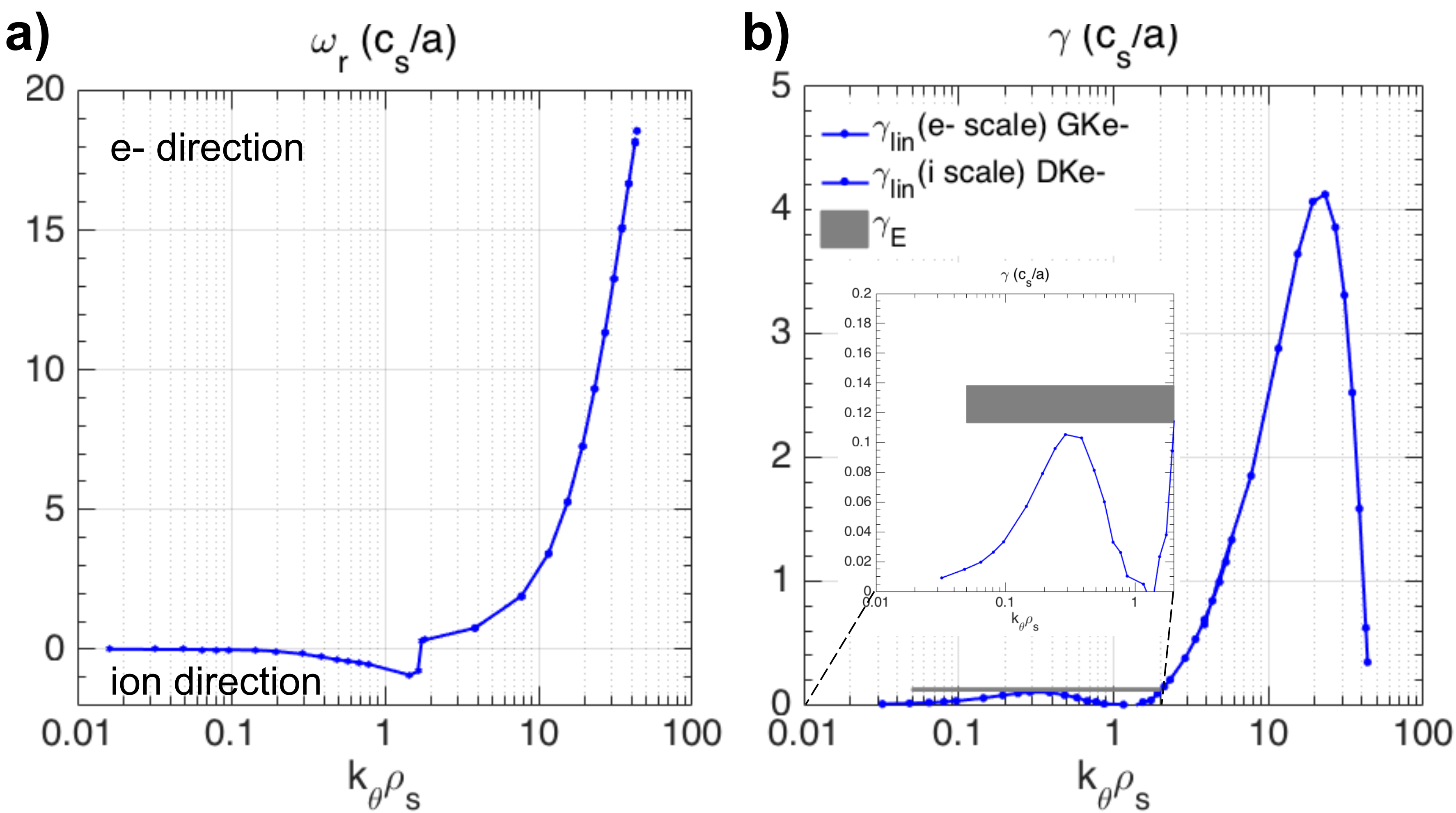
	t=398	t = 565
r/a	0.71	0.68
a [m]	0.6012	0.596
n_e [10^19 m-3]	4.27	3.43
T_e[keV]	0.39	0.401
a/L_{ne}	1.005	4.06
a/L_{Te}	3.36	4.51
β_e^{unit}	0.0027	0.003
a/L_{nD}	1.497	4.08
a/L_{Ti}	2.96	3.09
T_i/T_e	1.13	1.39
n_D/n_e	0.785030	0.80371
n_c/n_e	0.035828	0.032715
a/L_{nC}	-0.87	4.08
a/L_{TC}	2.96	3.09
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

R_0/a	1.52	1.59
SHIFT $=dR_0/dr$	-0.3	-0.355
KAPPA = κ	2.11	1.979
$s_k=r d\ln(\kappa)/dr$	0.15	0.19
DELTA = δ	0.25	0.168
$s_\delta=rd(\delta)/dr$	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]	$3.5*10^7$	$3.5*10^7$

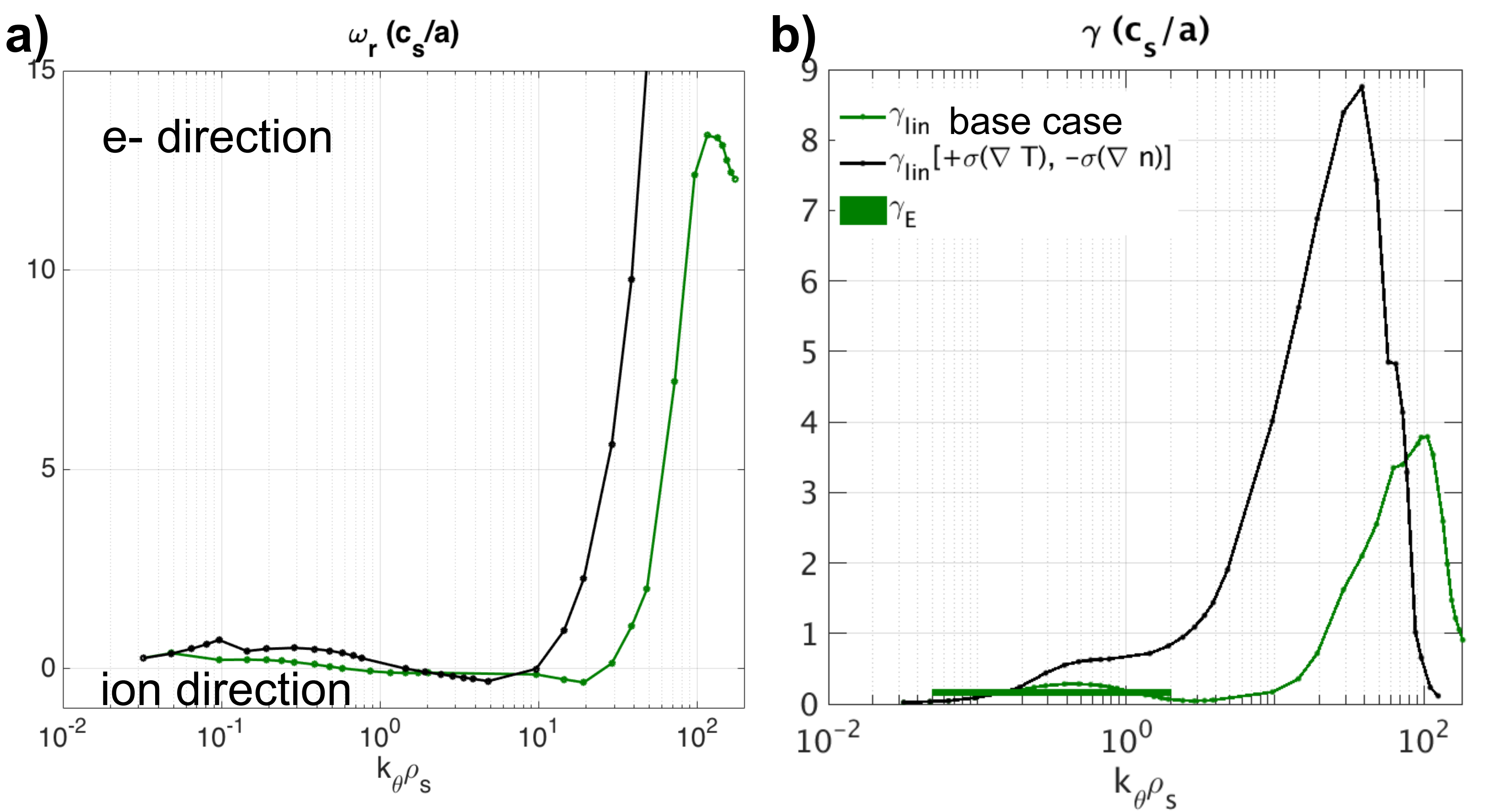
Discharge conditions



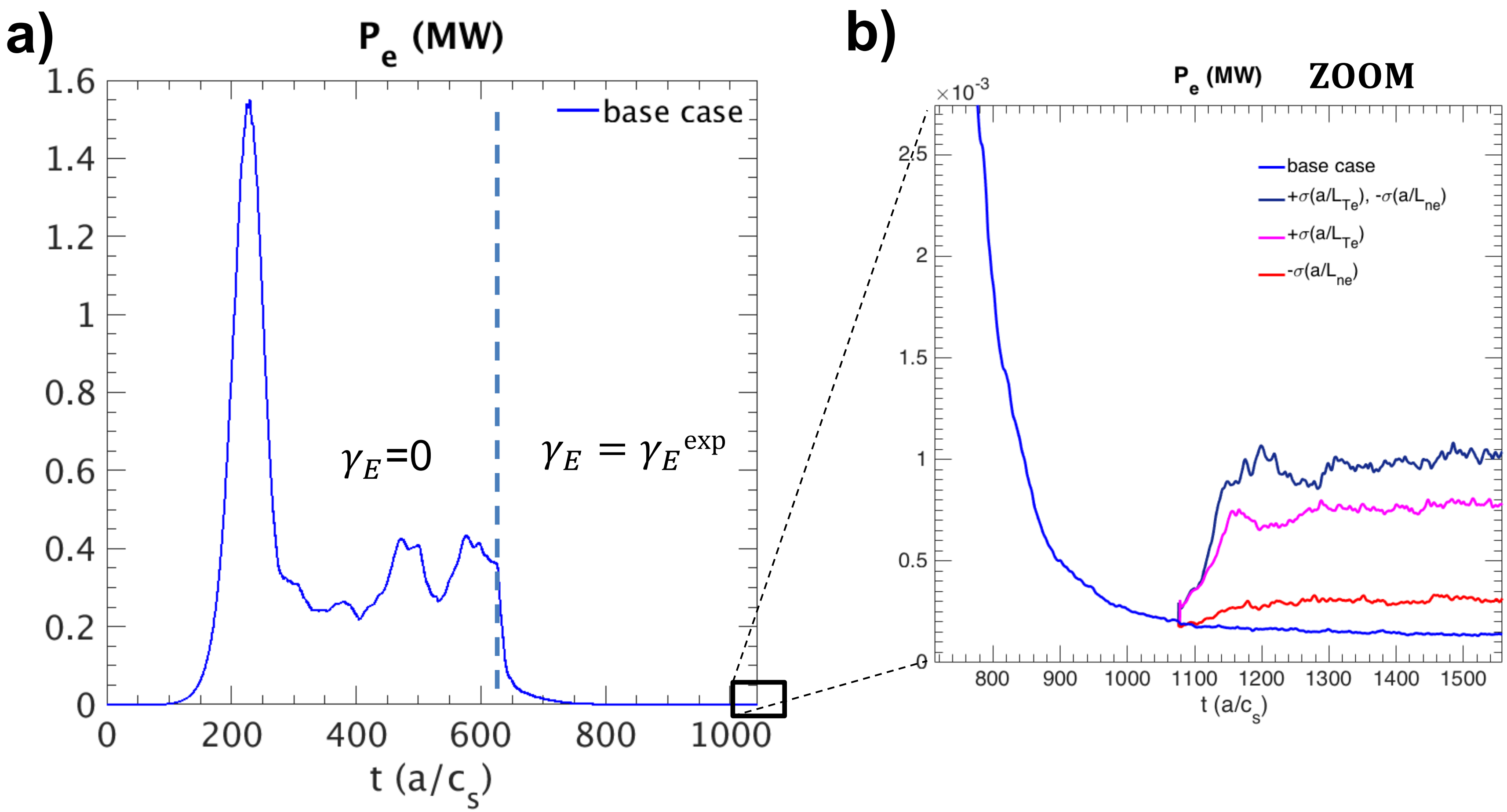
Linear Stability Strong ETG



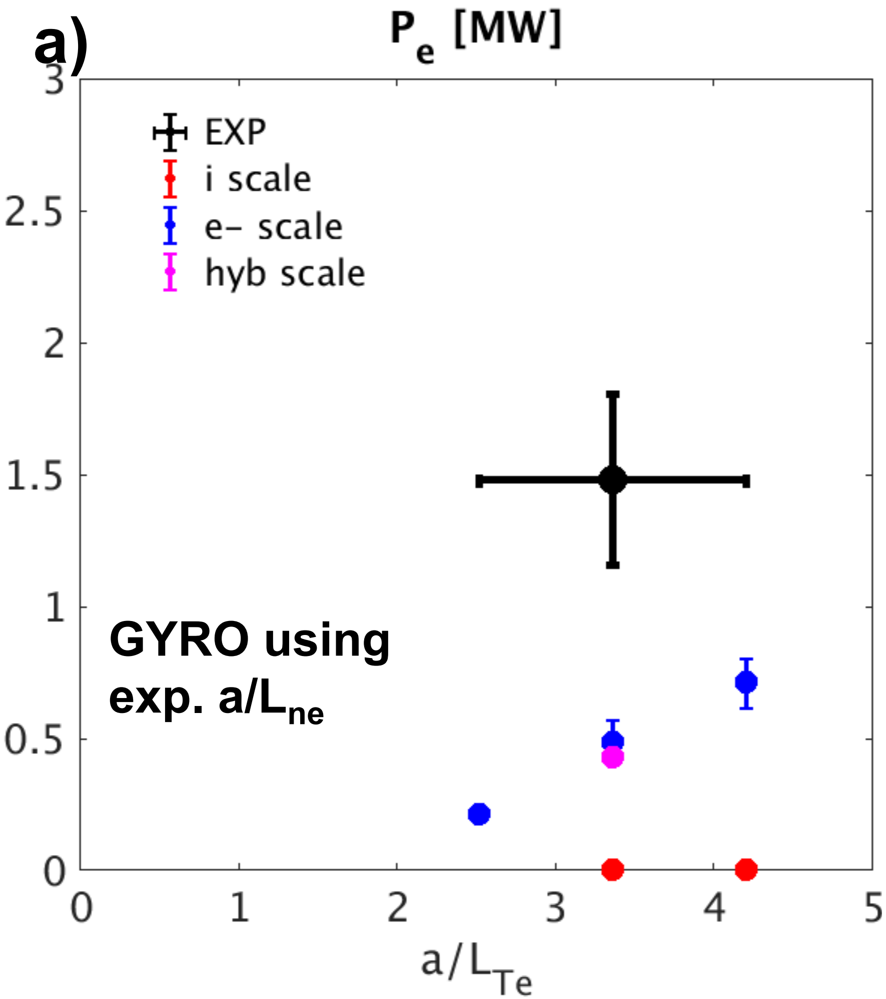
Linear Stability Weak ETG

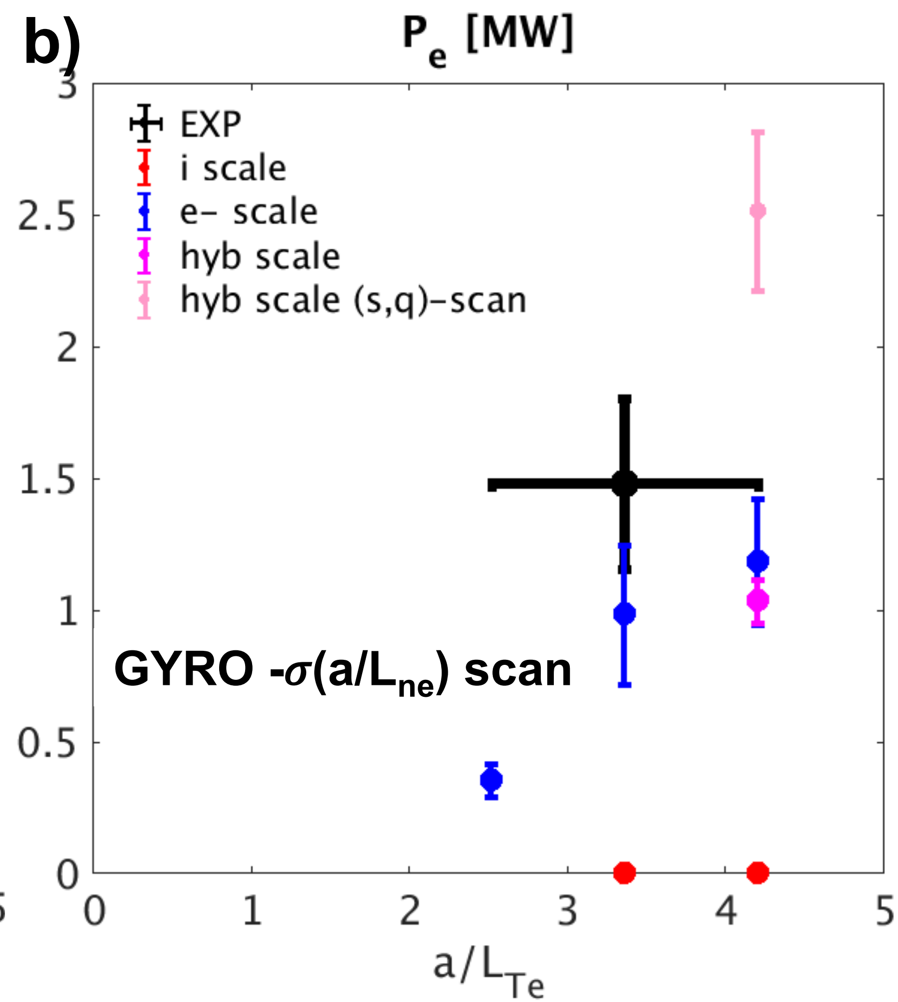


Ion scale NL simulation Strong ETG

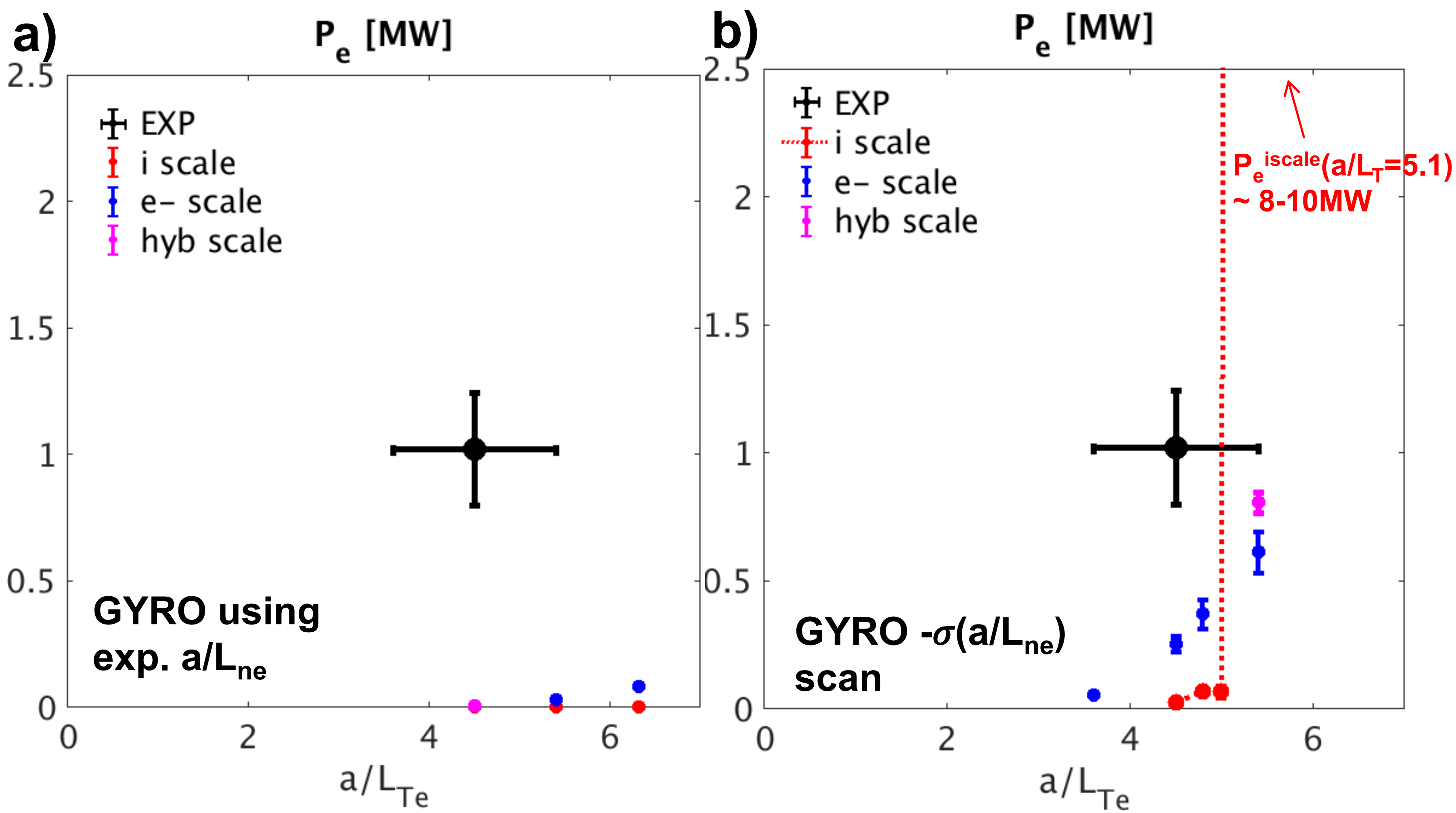


Total electron thermal transport budget strong ETG

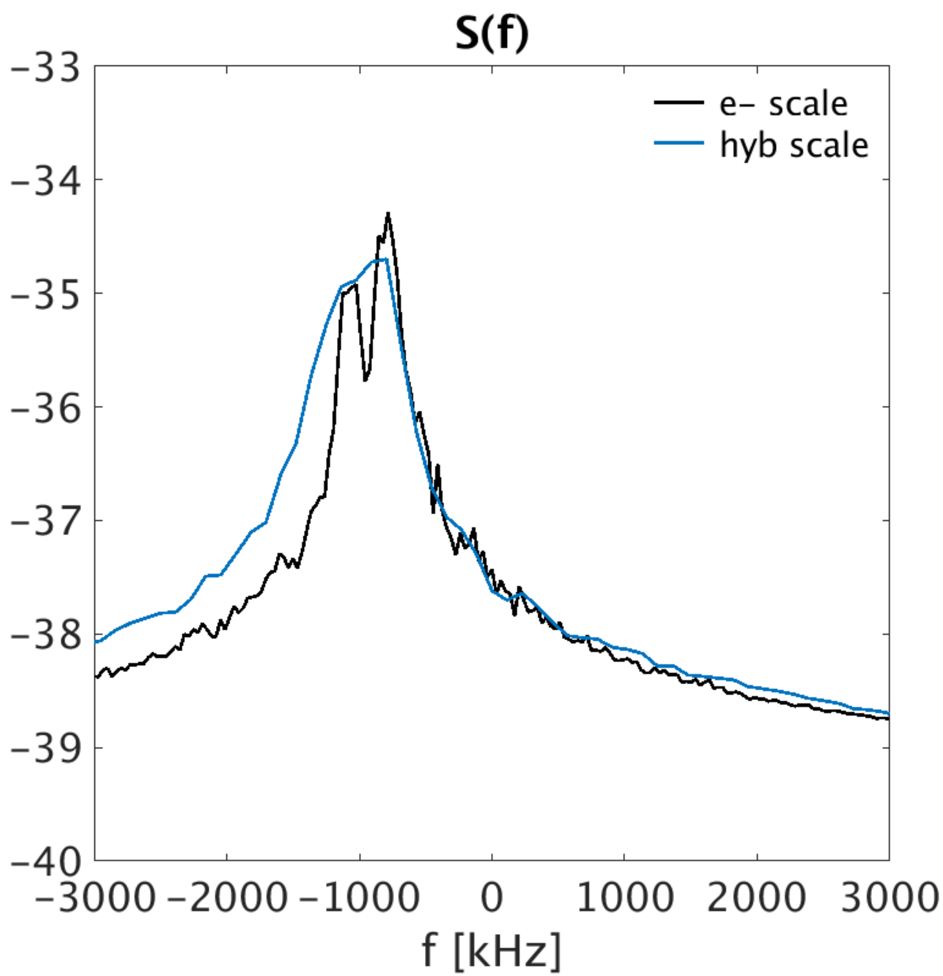




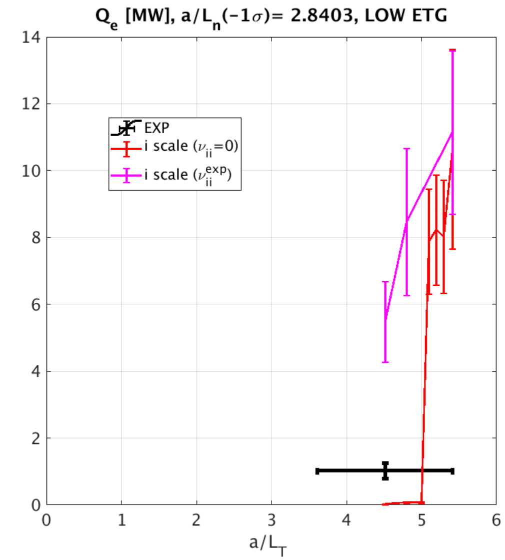
Total electron thermal transport budget weak ETG

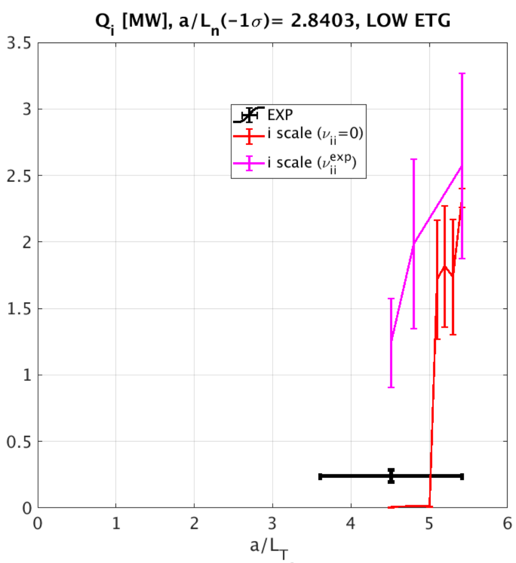


Electron scale and hybrid simulation synthetic f-spectra



Comparisons between Q_e & Q_i for $\boldsymbol{\nu}_{ii} = 0$ and $\boldsymbol{\nu}_{ii} = \boldsymbol{\nu}_{ii}^{exp}$





- GYRO simulations of NSTX H mode plasma
- Compare ion scale simulation output when ion-ion collisions are present and when they are not
  - Add collisional damping on ZF
  - Expected to be important close to marginality – even more in high $\boldsymbol{\nu}_{ee}$ (GYRO NU_EI ($\boldsymbol{\nu}_{ee}$) ~ 1)
- a/Ln is scaled down 1 sigma from experimental value. Performed scan in a/L_{Te}
- GYRO predicts 10 X Q_e^{exp} & Q_i^{exp} for a/L_{Te} (+ 1σ), a/L_{ne} (-1σ)

Input turbulence drives
a/LTe^{exp}=4.5128
$\sigma_{\nabla Te}$ = 20%
a/Lne^{exp}=4.0576
$\sigma_{\nabla ne}$= 30%

Title here

- Column 1

- Column 2

Intro

- First level
  - Second level
    - Third level
      - You really shouldn't use this level – the font is probably too small

Here are the official NSTX-U icons / logos

NSTX Upgrade

NSTX Upgrade

NSTX-U

NSTX-U

National Spherical Torus
eXperiment Upgrade

National Spherical Torus eXperiment Upgrade

Instructions for editing bottom text banner

- Go to View, Slide Master, then select top-most slide
  - Edit the text box (meeting, title, author, date) at the bottom of the page
    - Then close Master View