Validation of gyrokinetic simulations in NSTX including comparisons with a synthetic diagnostic for high-k scattering

J. Ruiz Ruiz[1,2]

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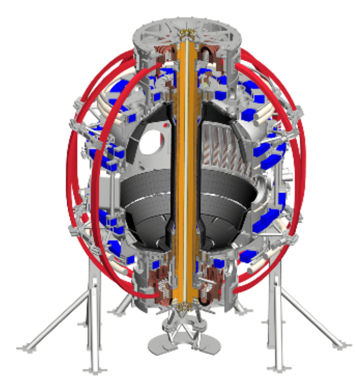
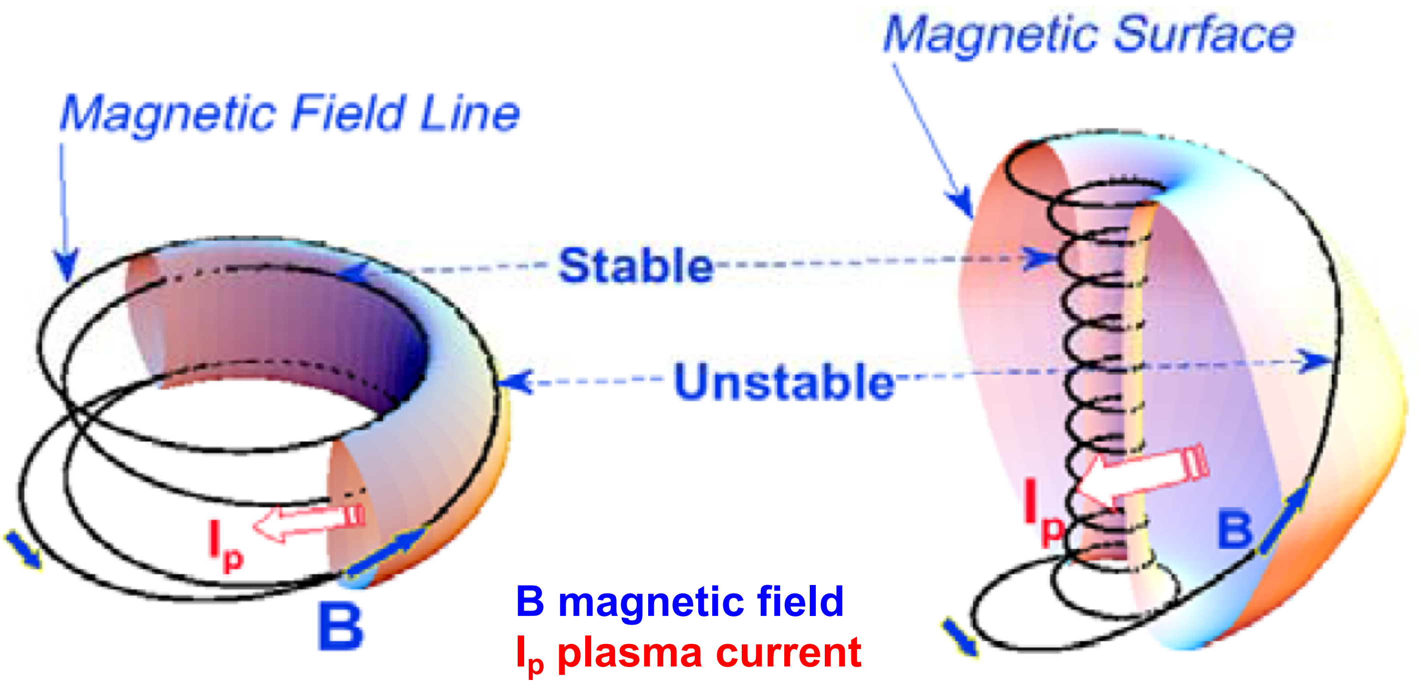
1. MIT **2**. Oxford **3**. PPPL **4**. NFRI **5**. UC Davis **6**. U Wisconsin **7**. Nova Photonics, Inc. **8**. General Atomics

20th International Spherical Tokamak Workshop
ENEA, Frascati, Oct 28-31, 2019



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

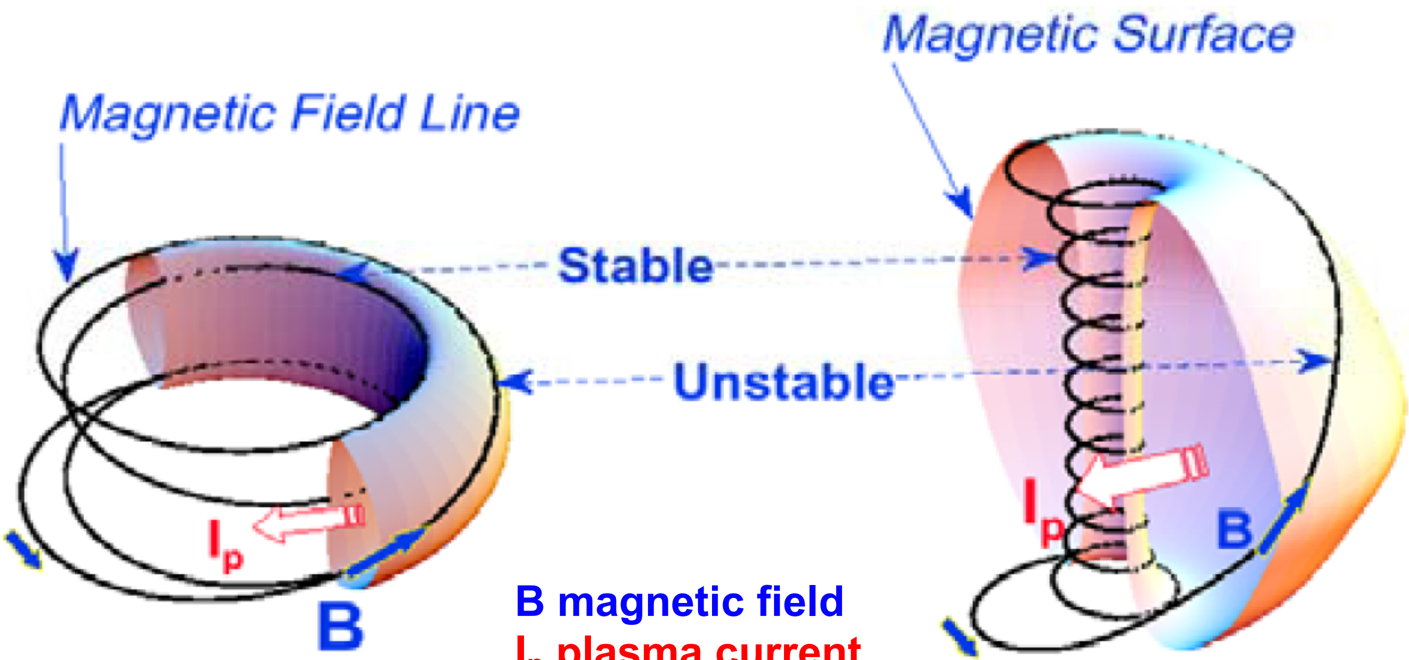
Spherical tokamaks (STs) minimize time-spent by plasma particles in the 'unstable', bad-curvature side



Standard tokamak:
e.g: JET, Alcator C-Mod, DIII-D, AUG, etc.

Spherical tokamak:
e.g: NSTX (PPPL), MAST (CCFE)

This talk will focus on the Spherical Torus (ST) NSTX



B magnetic field
I_p plasma current

Spherical tokamaks:

- Small aspect ratio A
- High-beta β
- High shaping of magnetic surfaces
- High toroidal rotation (if neutral beam driven)

Can improve macro & micro stability [*]

[*] Rewoldt PoP 1996, Kim PhysFlu 1993, Kaye NF 2007

ST H-modes have reported neoclassical levels of ion thermal transport, transport dominated by electron channel

- 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, beta, strong plasma shaping*** [*Rewoldt PoP 1996, Kaye NF 2007*].

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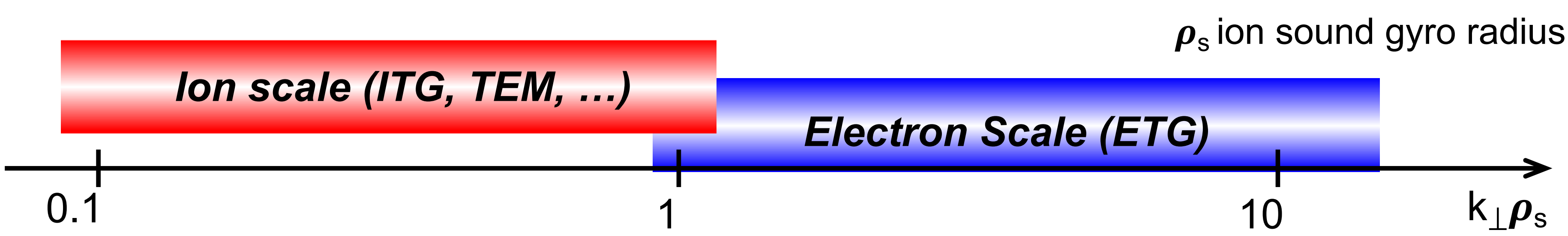
- This work will compare predictions of **electron-scale turbulence** and transport to experimental measurements at NSTX:
  - Electron thermal power **P_e [MW]** : ➔ using gyrokinetic simulation (GYRO).
  - Turbulence fluctuations : ➔ using gyrokinetic sim. & synthetic diagnostic.



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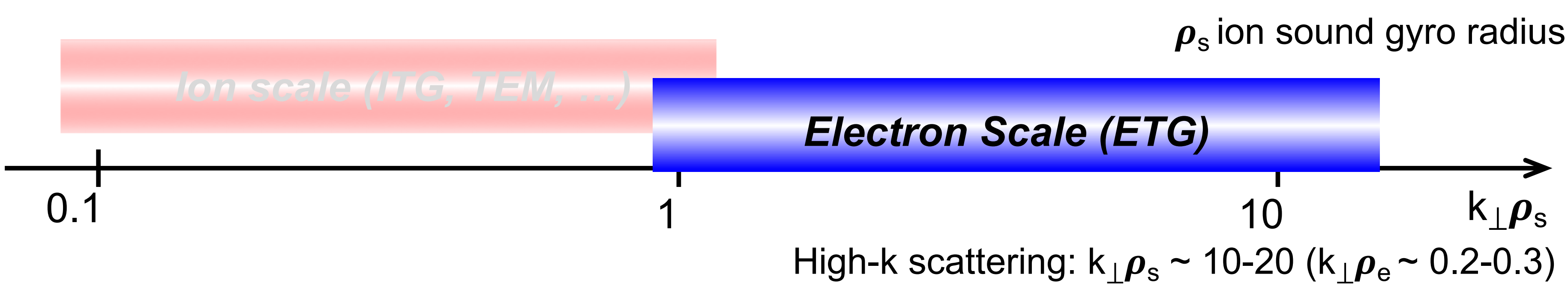

Outline

- Turbulence fluctuation measurement (high-k scattering).
- GYRO simulation details.
- NSTX H-mode discharge under study.
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  - f-spectra comparisons
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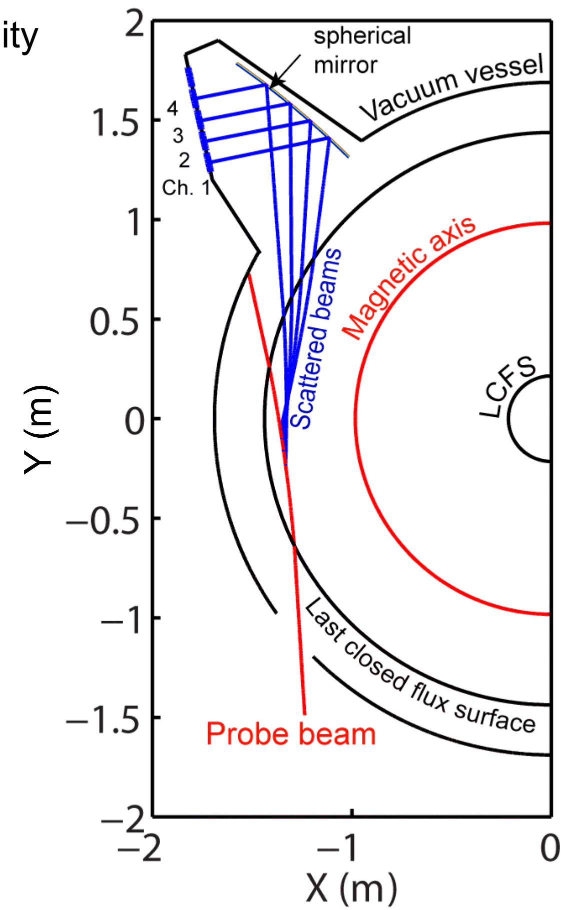
Use a high-k scattering diagnostic to probe electron-scale turbulence on NSTX

- Scattered power density $P_s \propto \left|\frac{\delta n_e}{n_e}\right|^2$, δn_e electron density



View from top of NSTX

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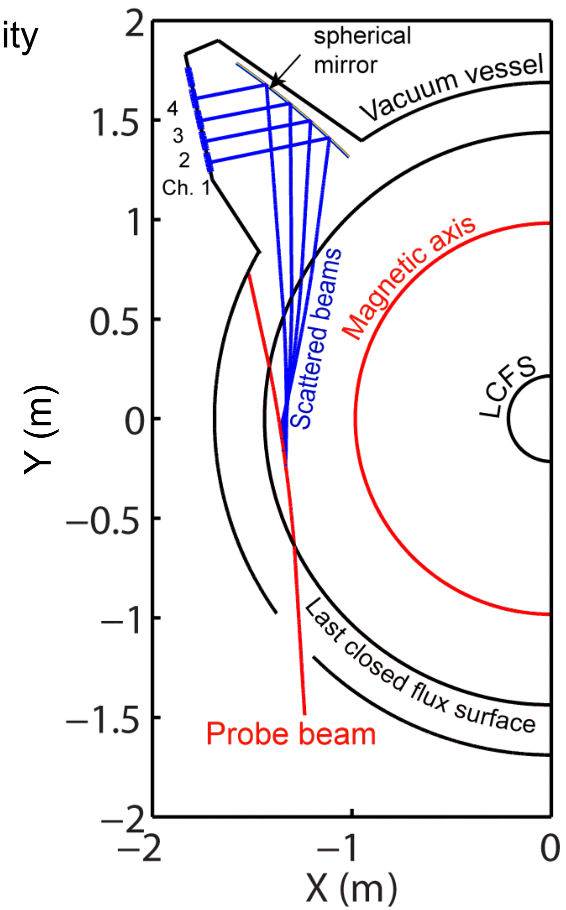
- Scattered power density $P_s \propto \left|\frac{\delta n_e}{n_e}\right|^2$, δn_e electron density
- Gaussian microwave probe beam
  - f = 280 GHz (>> f_{pe}, f_{ce})
- Ray tracing to determine $\vec{k}_{turb}$

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



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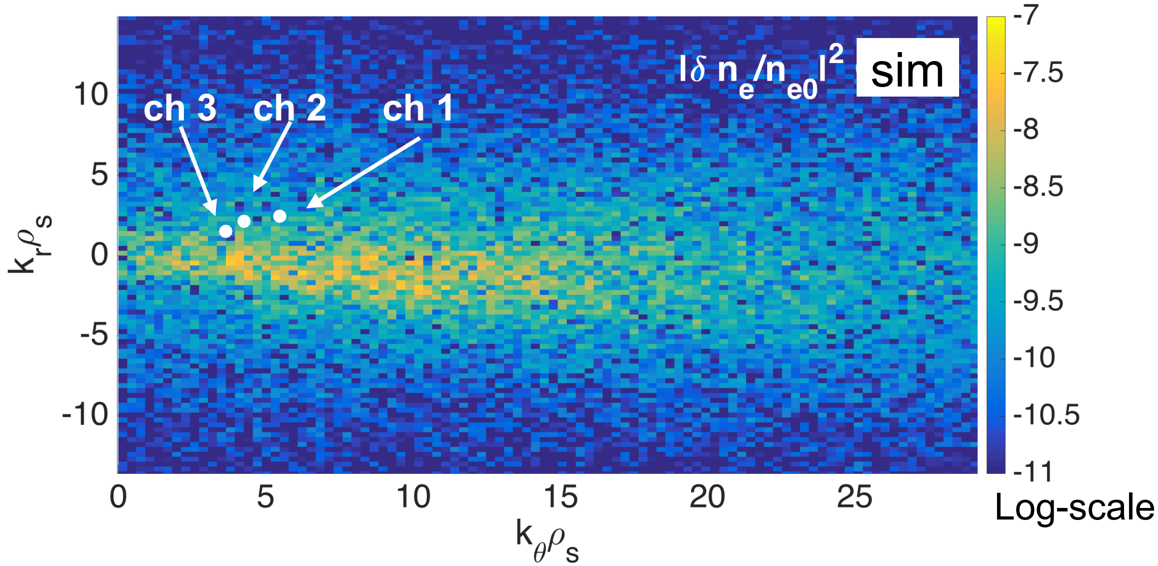

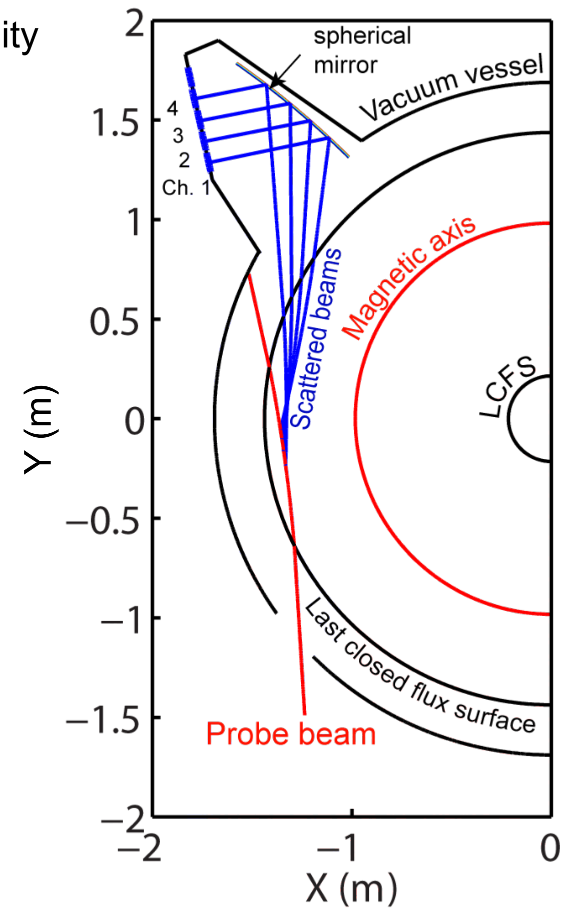

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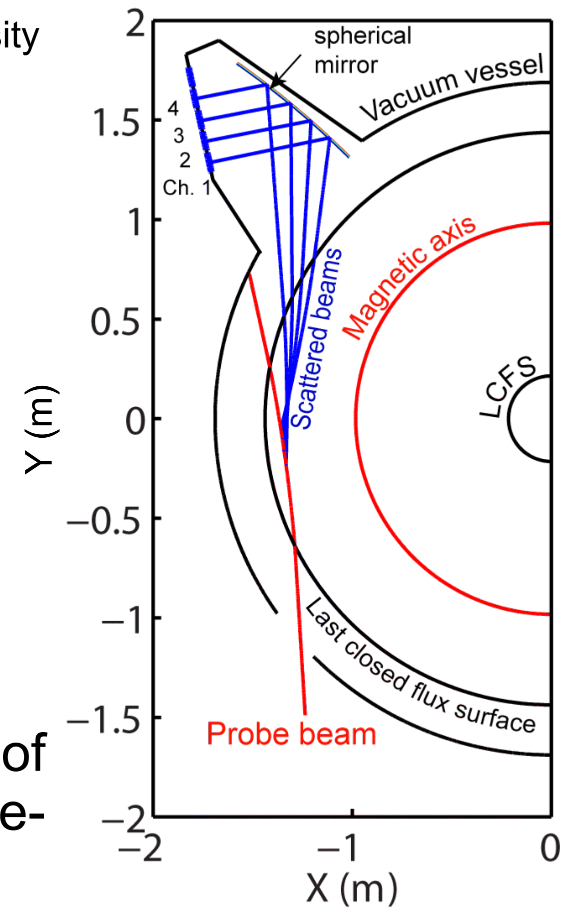
- Scattering system is ***toroidally*** localized [*]

➔ We model a 2D synthetic diagnostic

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



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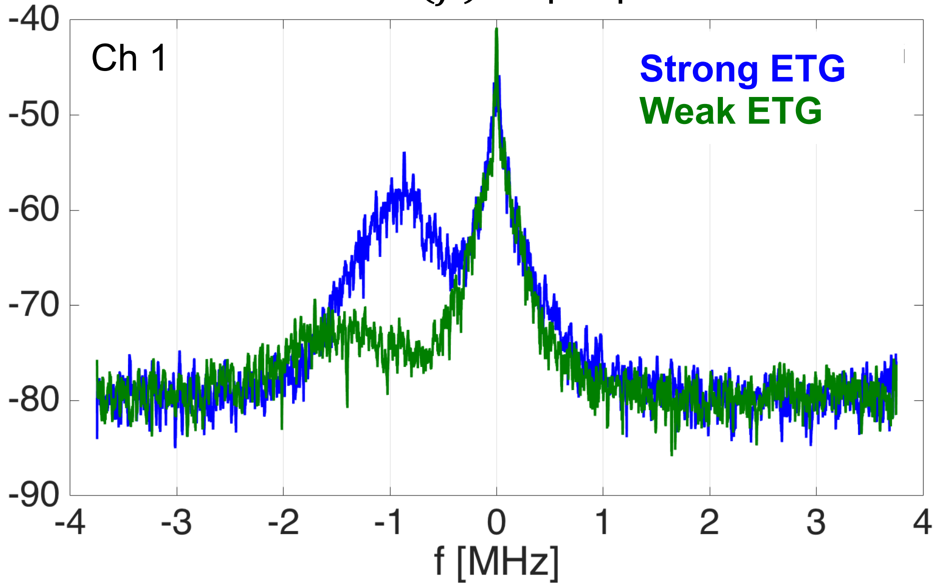
[*] Mazzucato PoP 2003, PPCF 2006

High-k scattering provides measurements of frequency and wavenumber spectra of electron-scale turbulence

Frequency spectra:
$S(f) \propto |\delta n|^2$



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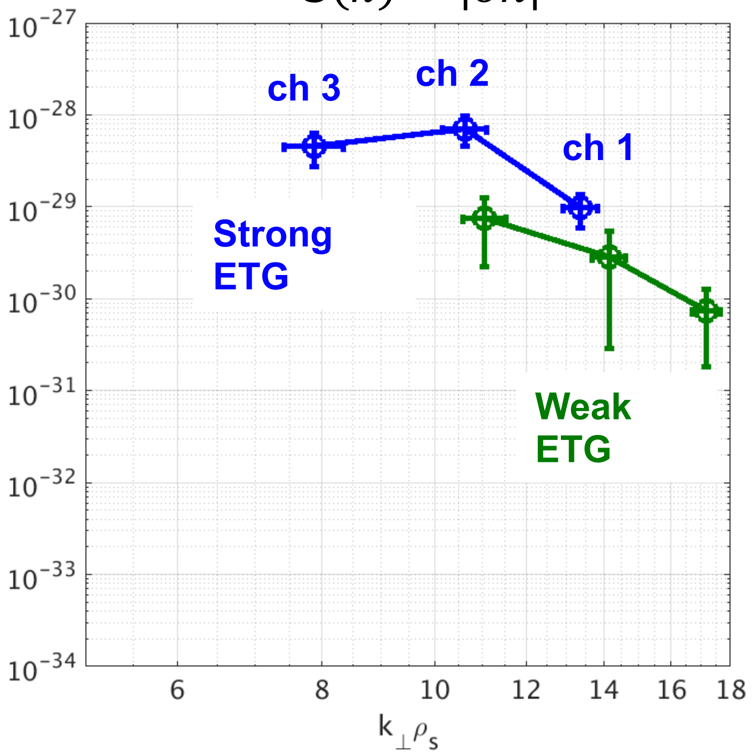

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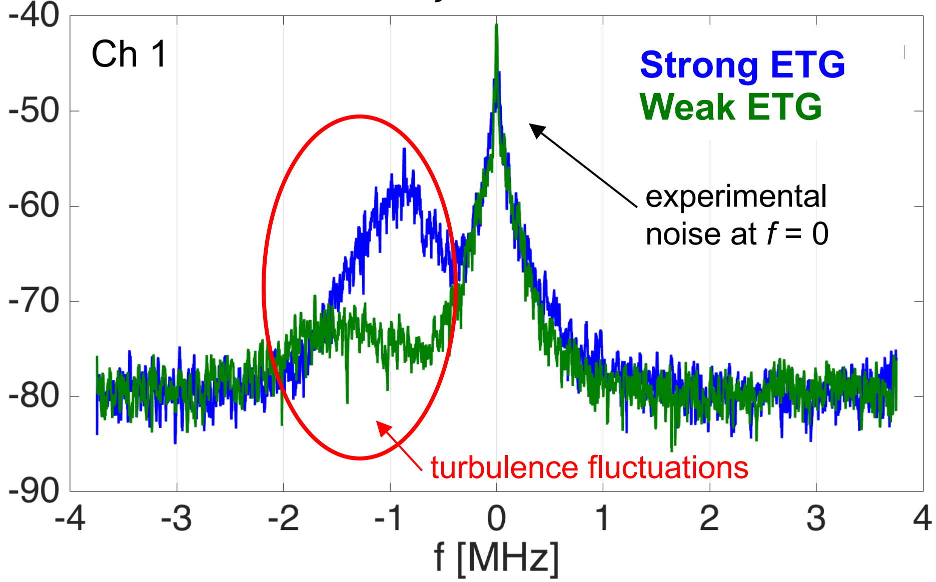

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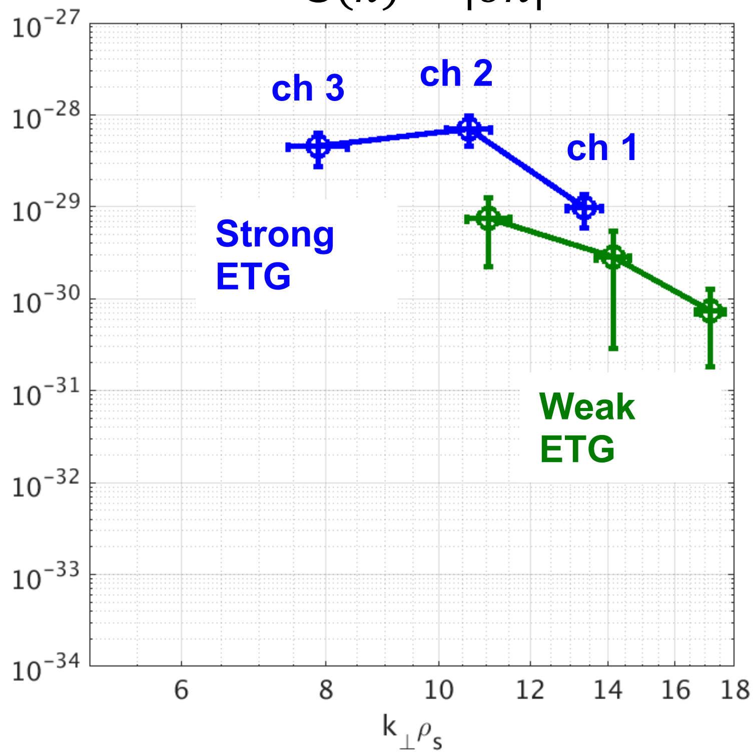

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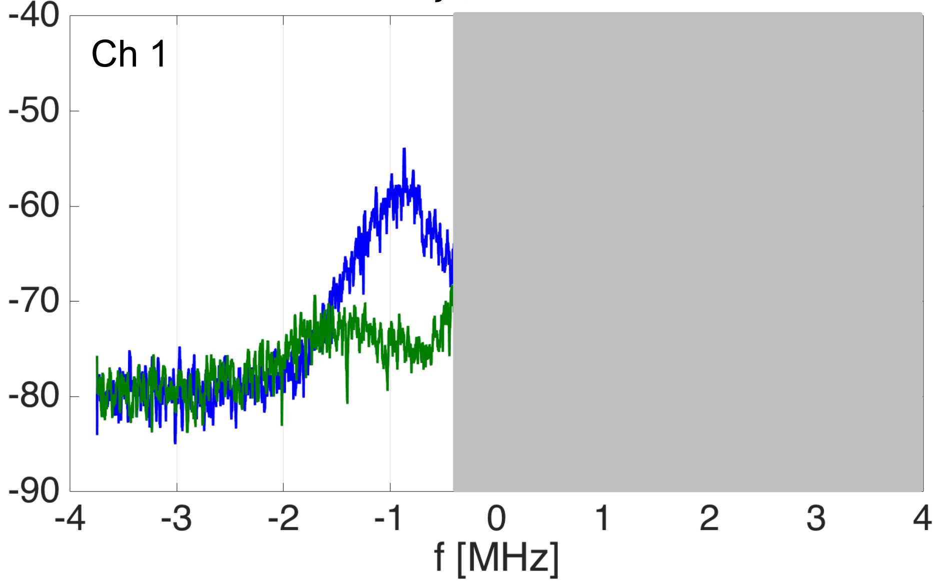

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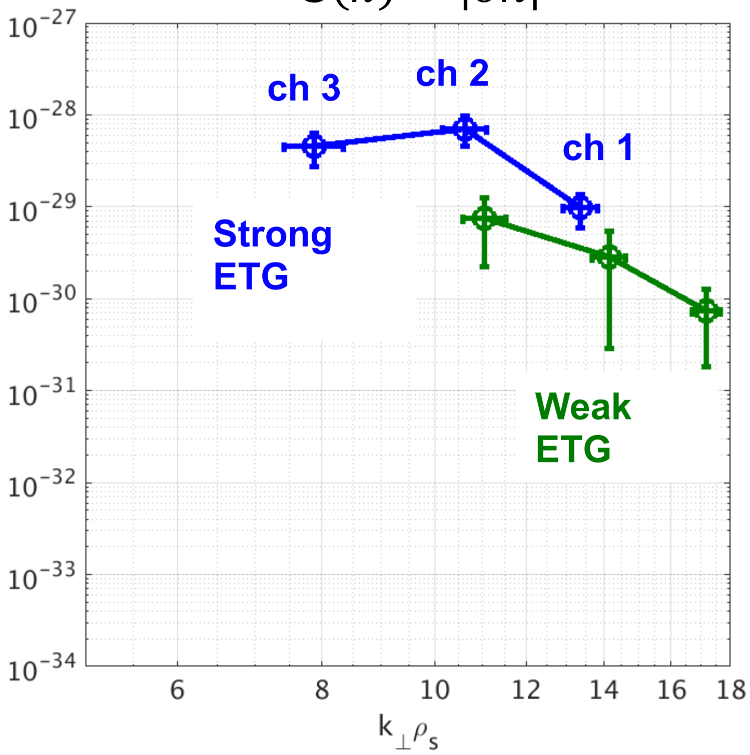

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Accurate high-k turbulence comparisons require 'big-box' electron-scale simulation

- **Ion-scale** turbulence simulation $(\boldsymbol{k_\theta \rho_s \leq 1})$.
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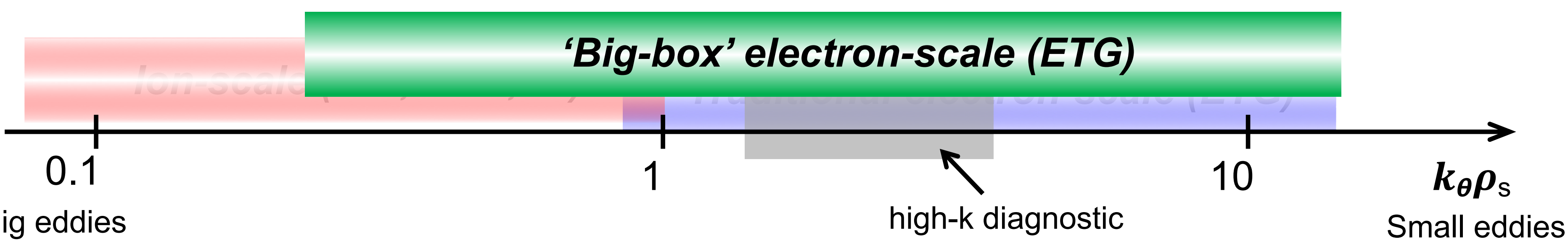

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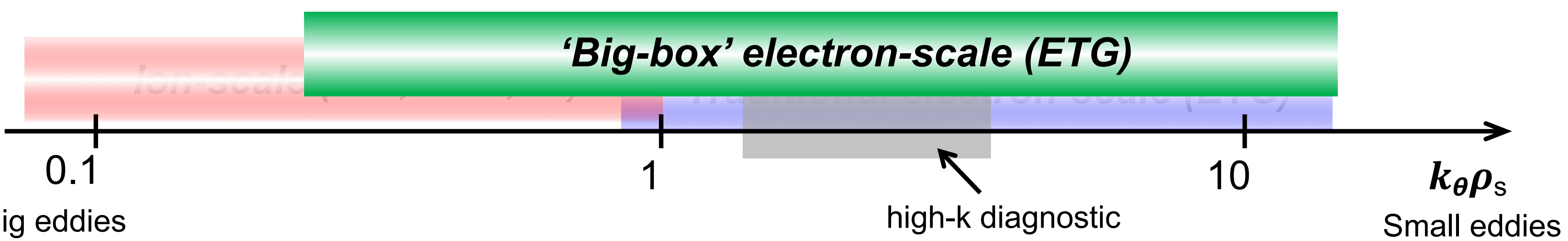
- Experimental profiles used as input to GYRO
  - Local simulations performed at scattering location (r/a ~ 0.7, R~135 cm).
  - 3 kinetic species, D, C, e- (Z_{eff}~1.85-1.95)
  - Electromagnetic: $A_{||}+B_{||}$ (**β_e~ 0.3%**).
  - Collisions (**ν_{ei} ~ 1 c_s/a**).
  - ExB shear (γ_E~0.13-0.16 c_s/a)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



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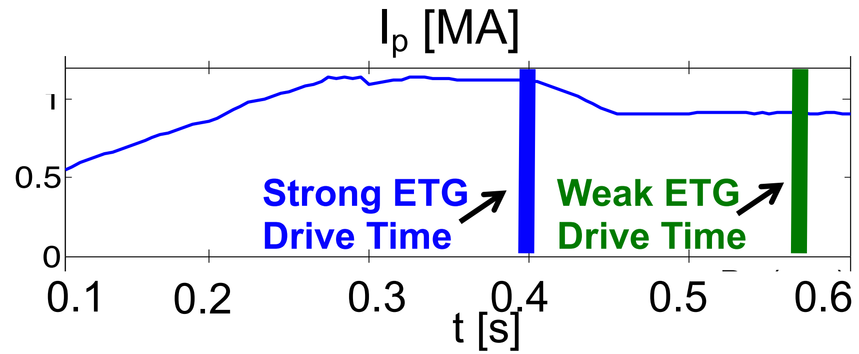
- NBI heated H-mode with controlled current ramp-down; two steady discharge phases, little MHD activity.



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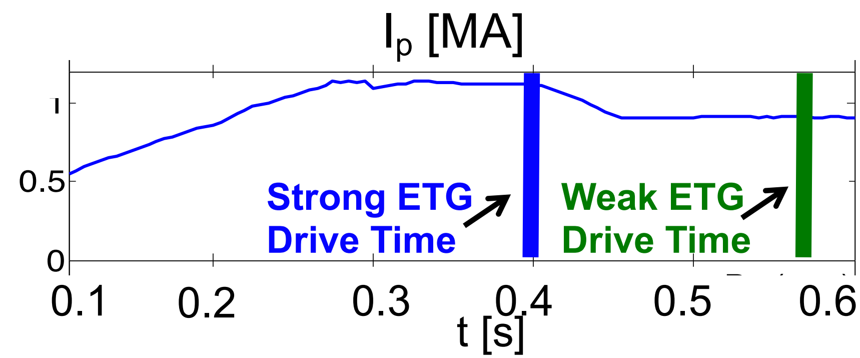

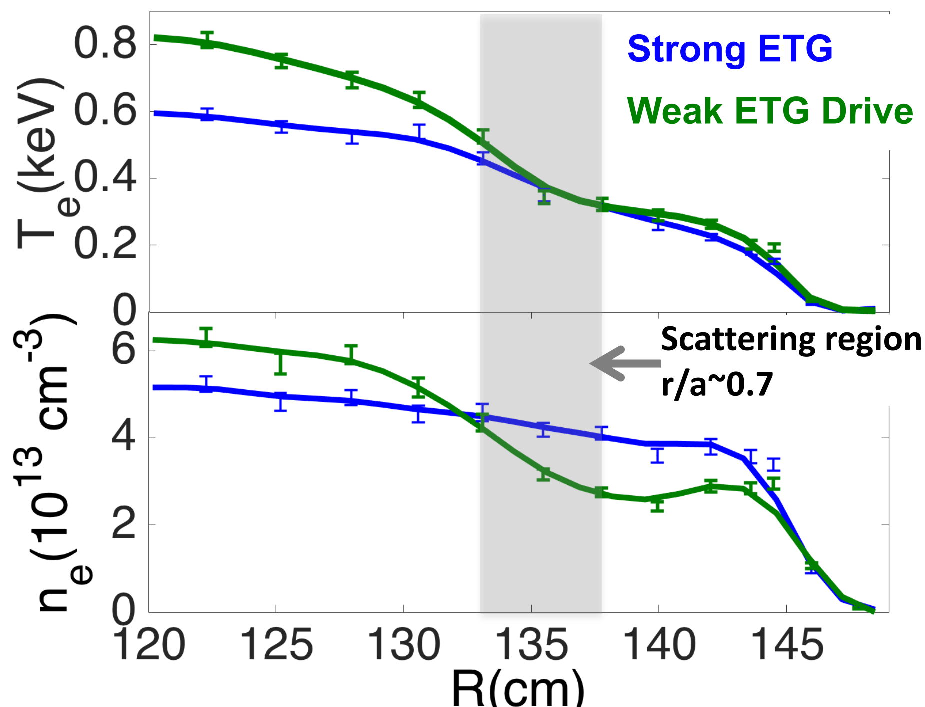

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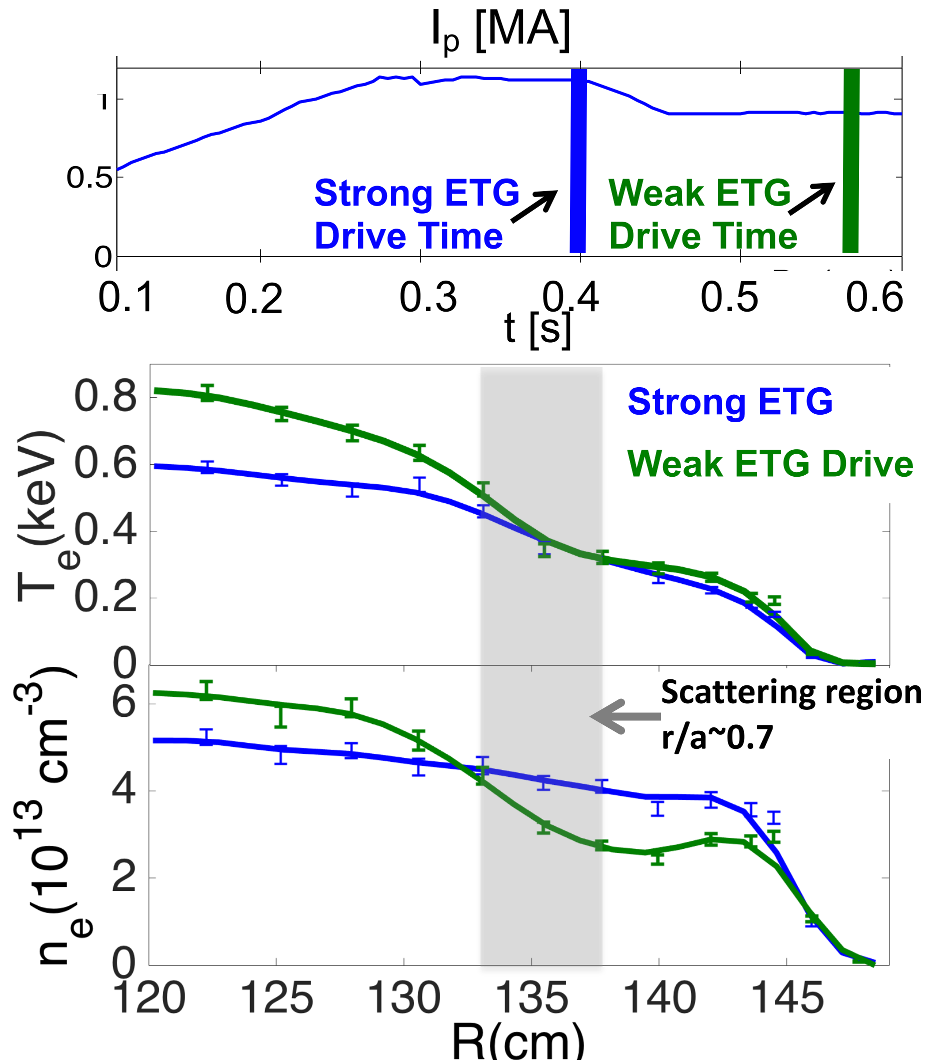
- In this work, perform sensitivity scans in $\{\nabla T_e, \nabla n_e, q, \hat{s}\}$ to compare:
  - **Electron thermal power P_e** (TRANSP) via sensitivity scans of GYRO sims.
  - **High-k turbulence freq. and k-spectra** via synthetic diagnostic for GYRO.
- Details in Ruiz Ruiz PPCF 2019.



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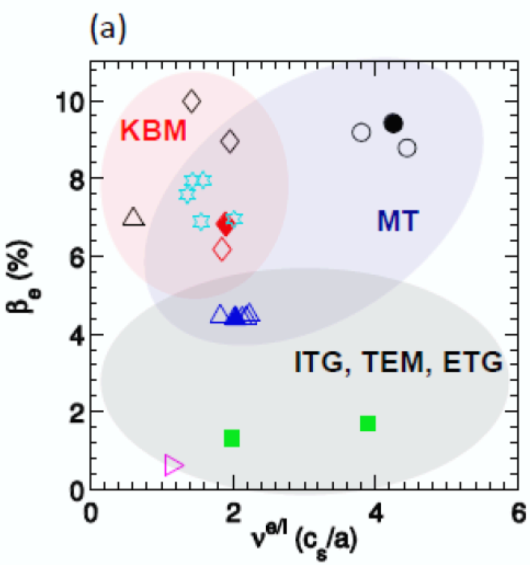

Dominant linear instability:

(a) Low β_e: Electrostatic ITG/TEM/ETG.
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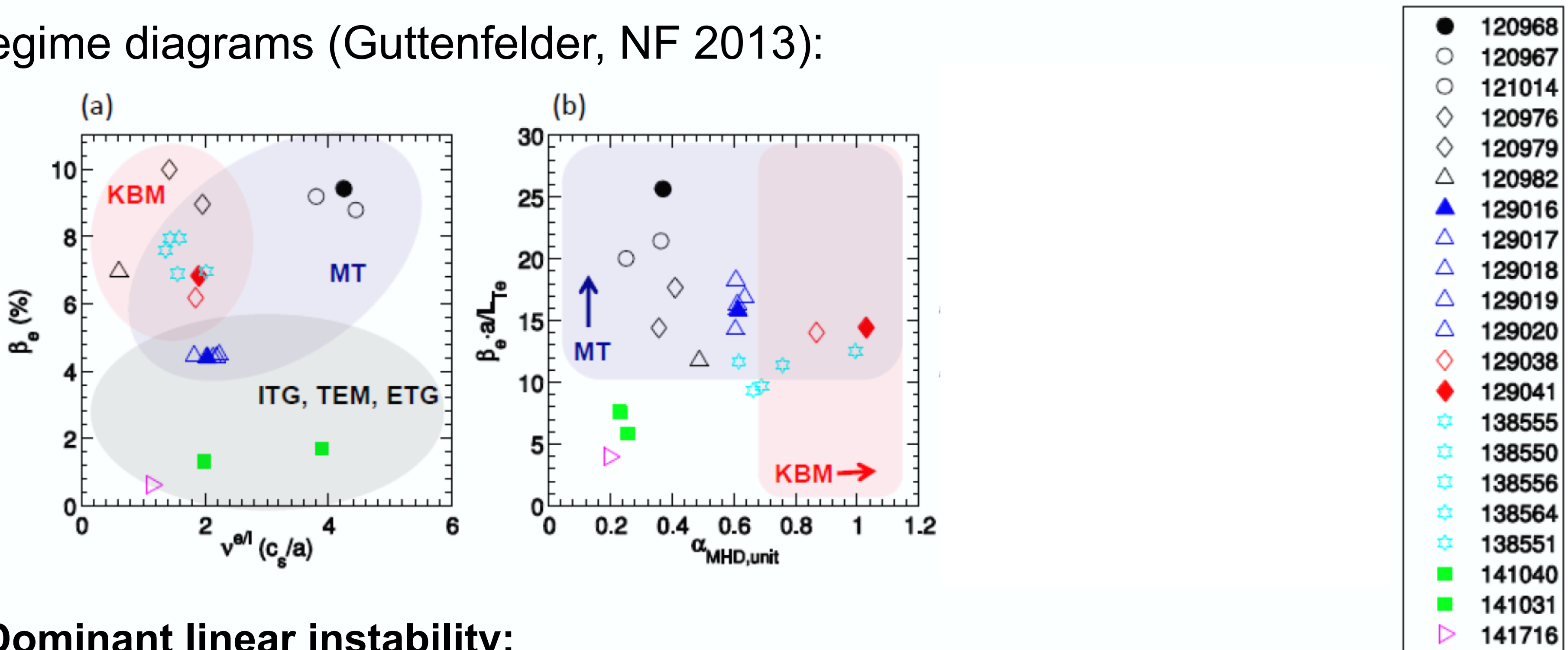

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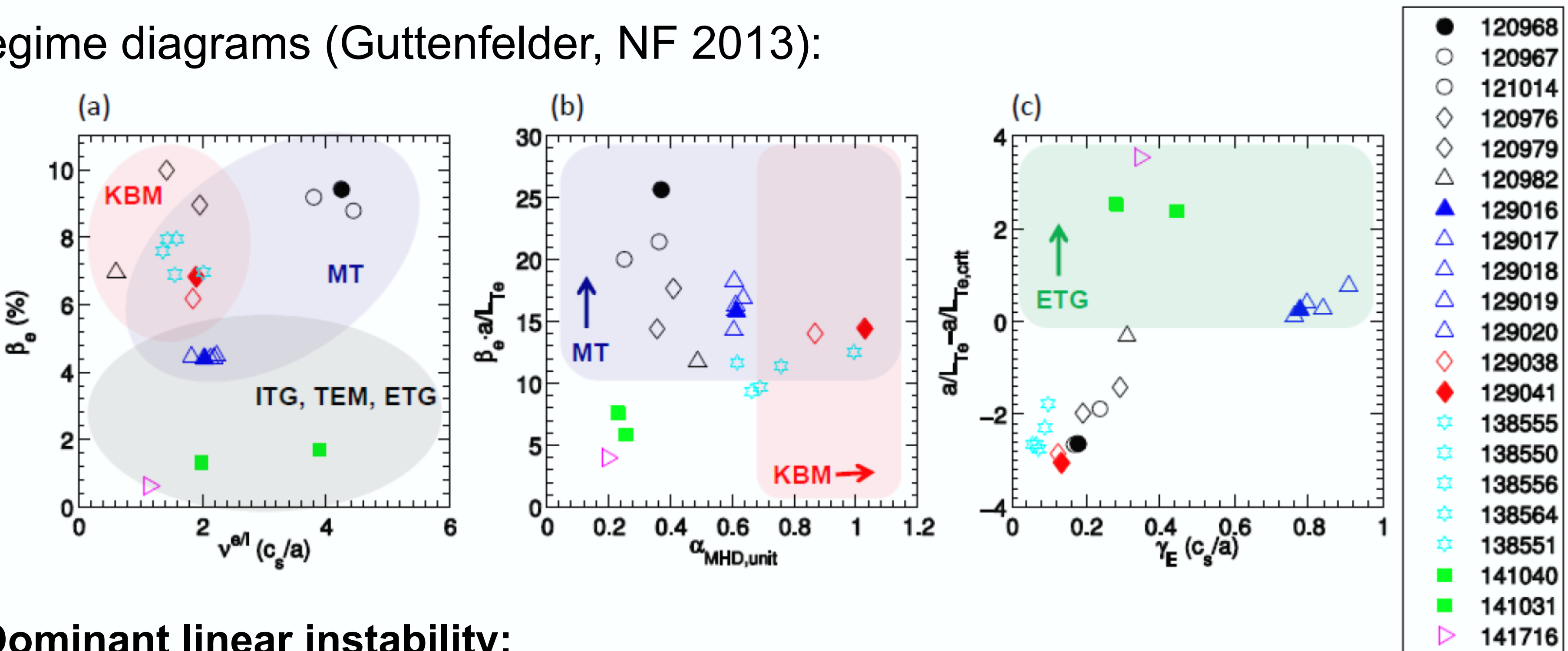

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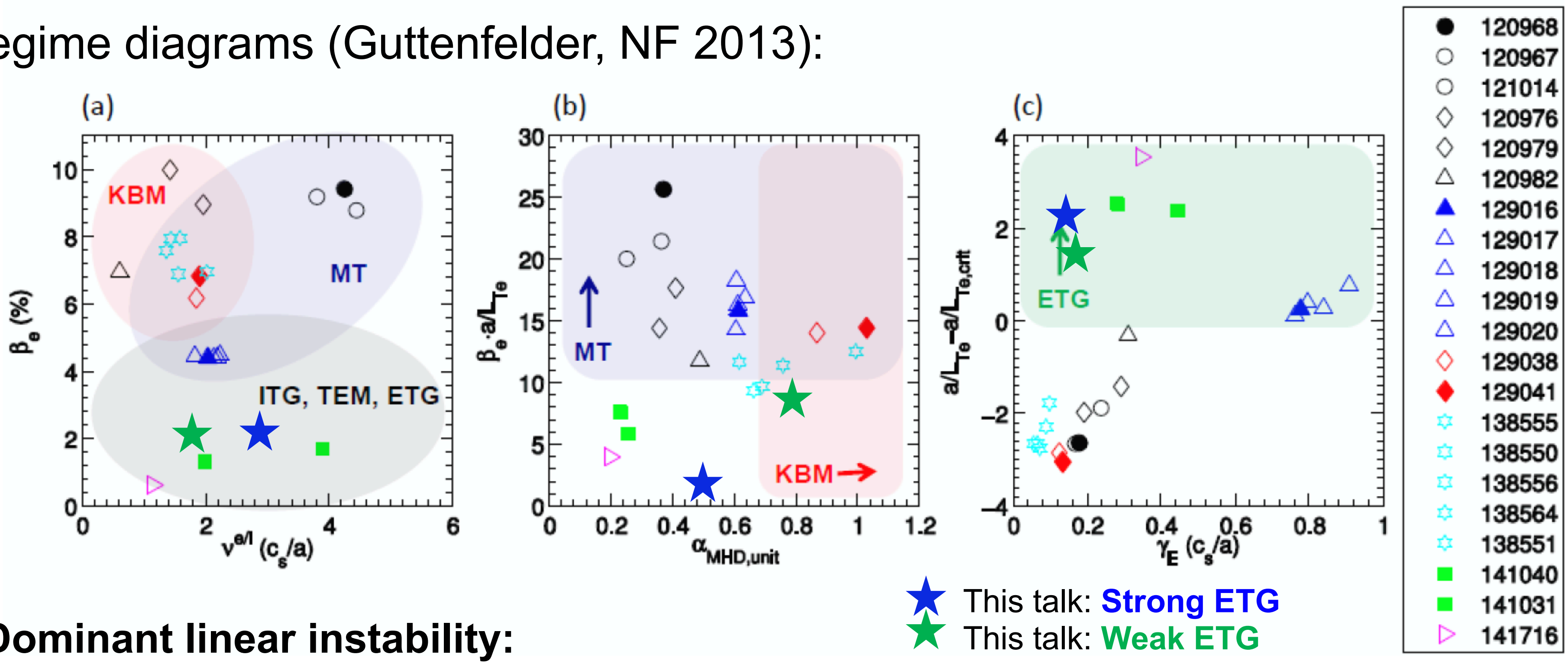

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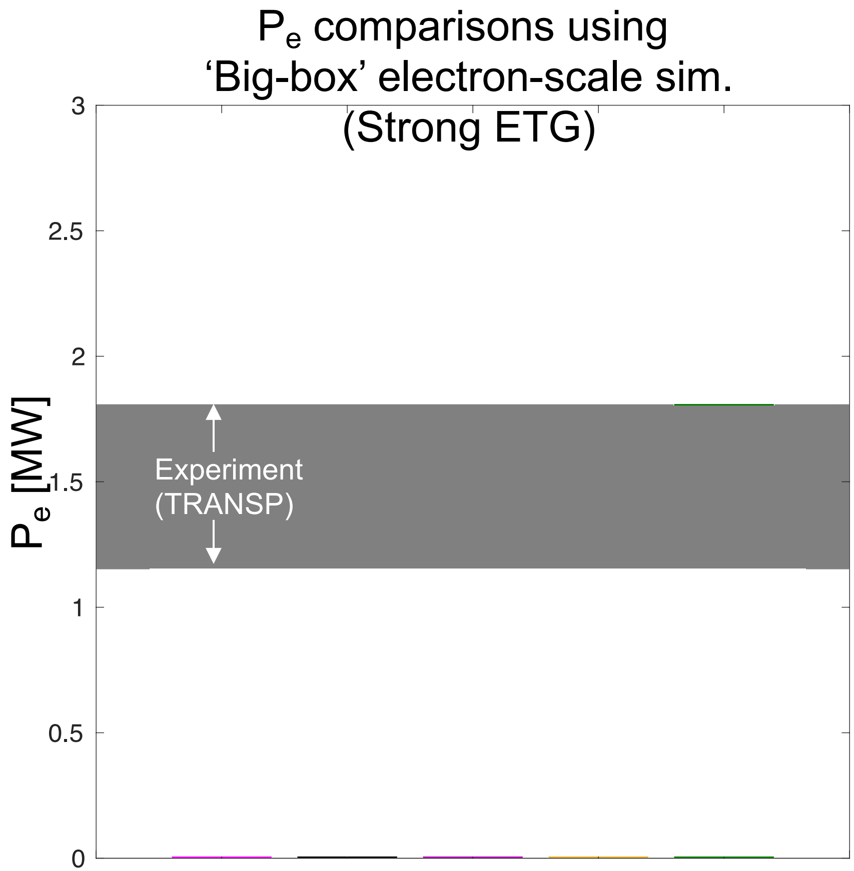
Ion-scale turbulence contributions can be neglected in the strong and weak ETG conditions

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



Simulation:

Perform sensitivity scans maximizing turbulence drive in 5 'big-box' e- scale sims.

- 1-σ(∇T,∇n) max. uncertainty.
- 10% q, 20% $\hat{s}$

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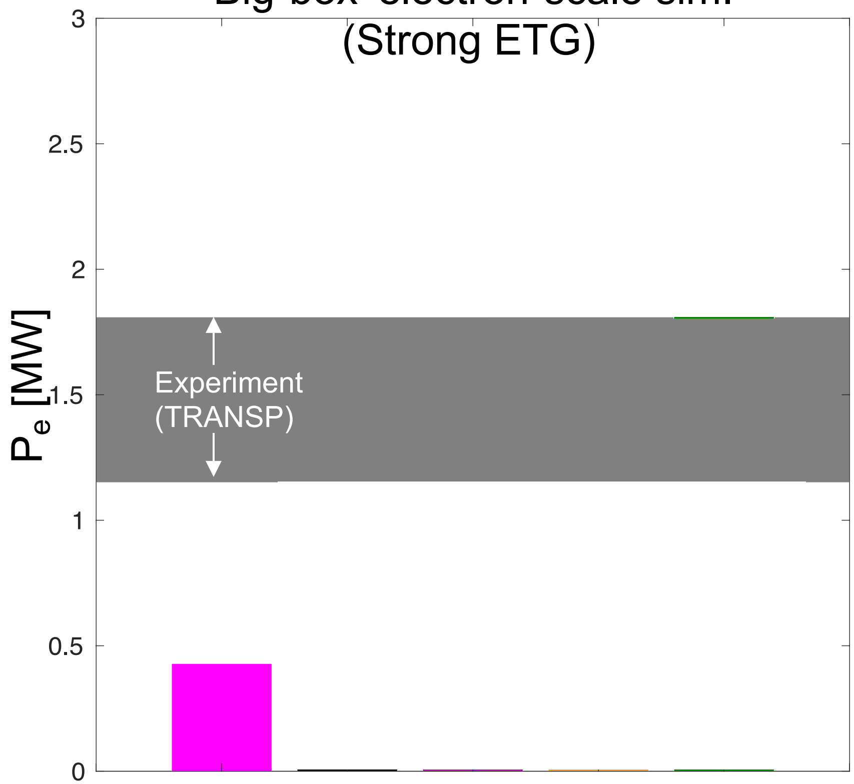
P_e comparisons using
'Big-box' electron-scale sim.
(Strong ETG)



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'Big-box' electron-scale sim

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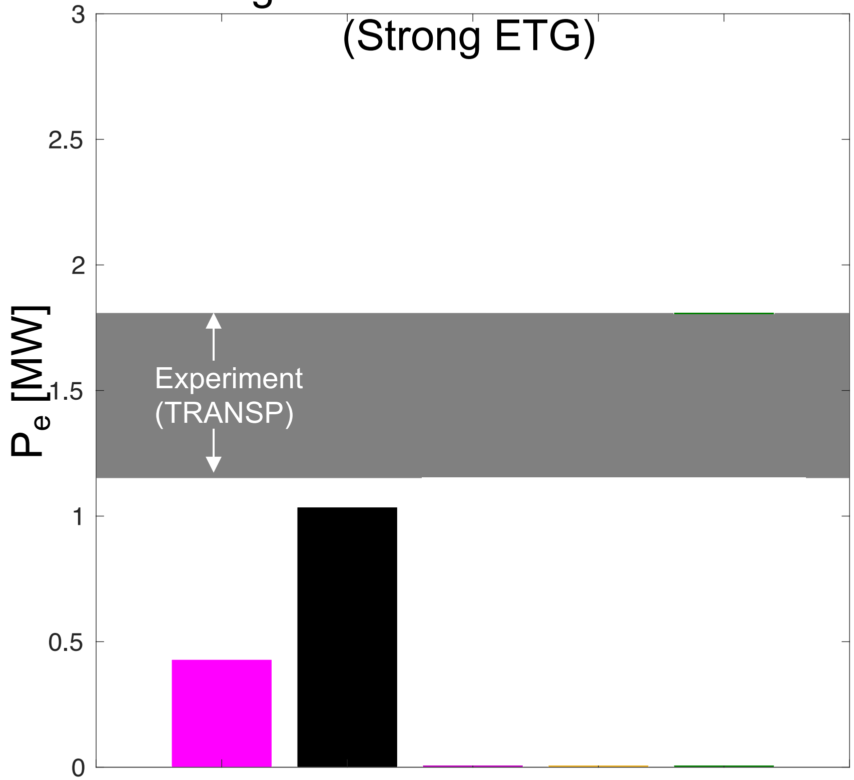

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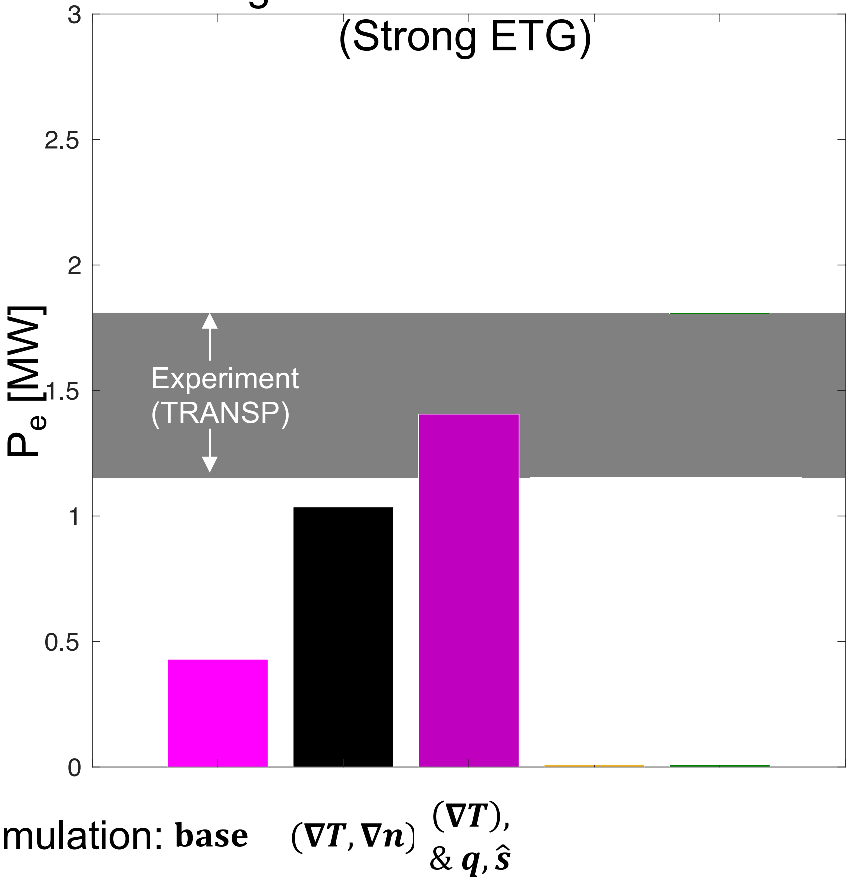

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'Big-box' electron-scale sim

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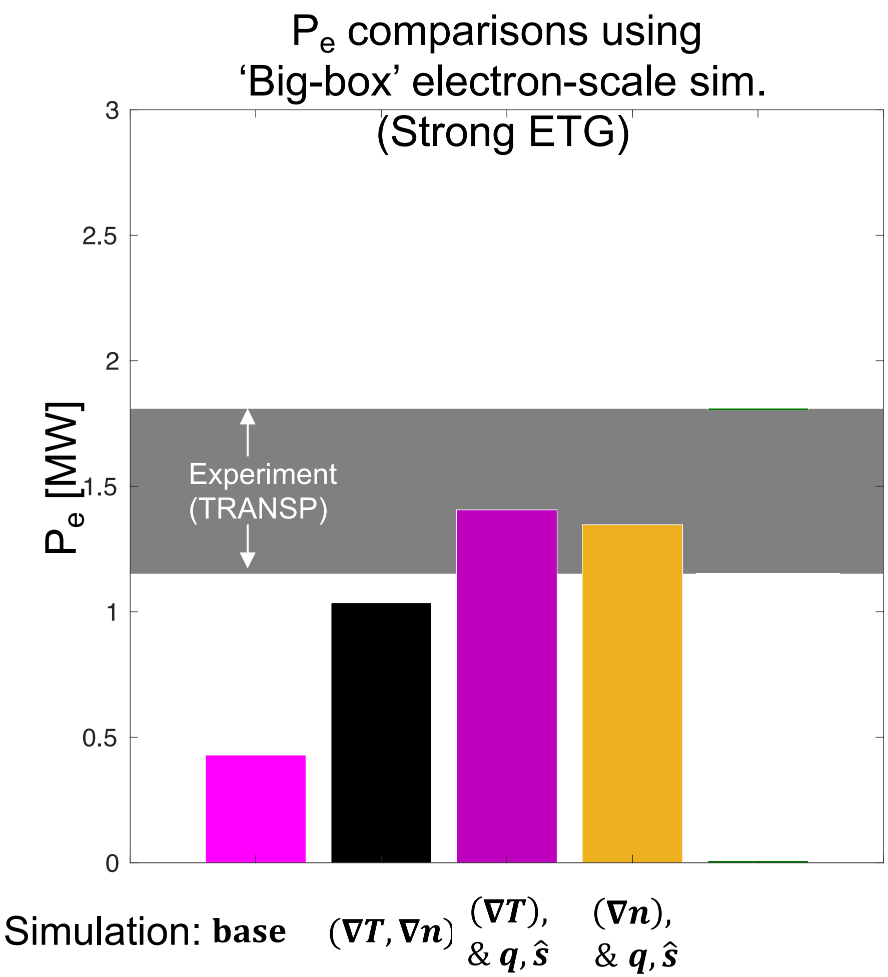

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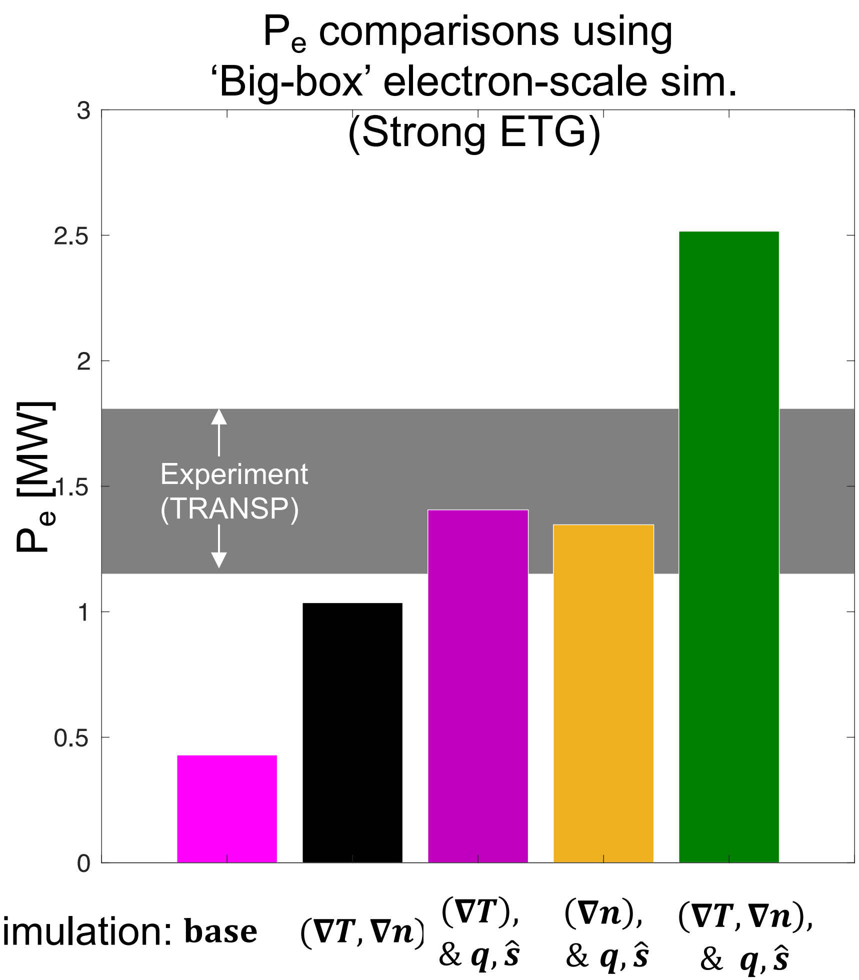

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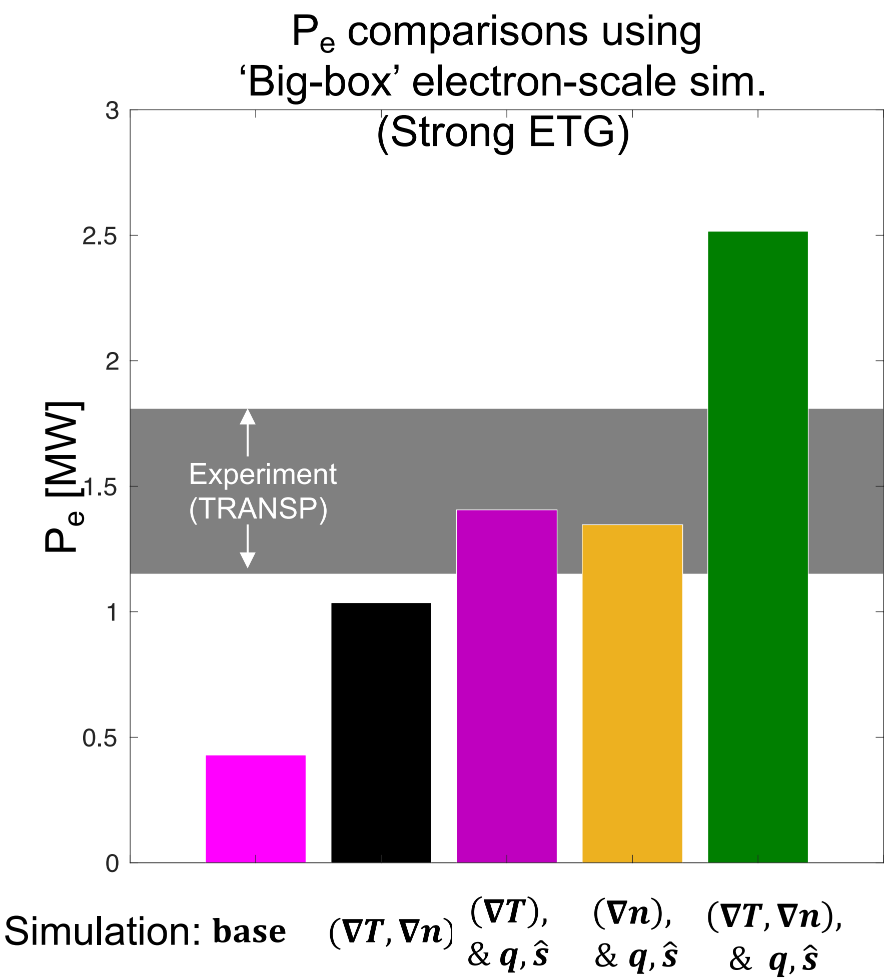
- $\sigma(\nabla n)$, q, $\hat{s}$: match P_e
- $\sigma(\nabla T, \nabla n)$, q, $\hat{s}$: overpredict P_e

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



[*] Ricci PoP 2011

Perform sensitivity scans maximizing turbulence drive in 5 'big-box' e- scale sims.

- 1-σ(∇T, ∇n) max. uncertainty.
- 10% q, 20% $\hat{s}$

'Big-box' electron-scale sim

- Base (exp parameters): underpredict P_e
- $\sigma(\nabla T, \nabla n)$: underpredict P_e
- $\sigma(\nabla T)$, q, $\hat{s}$: match P_e
- $\sigma(\nabla n)$, q, $\hat{s}$: match P_e
- $\sigma(\nabla T, \nabla n)$, q, $\hat{s}$: overpredict P_e

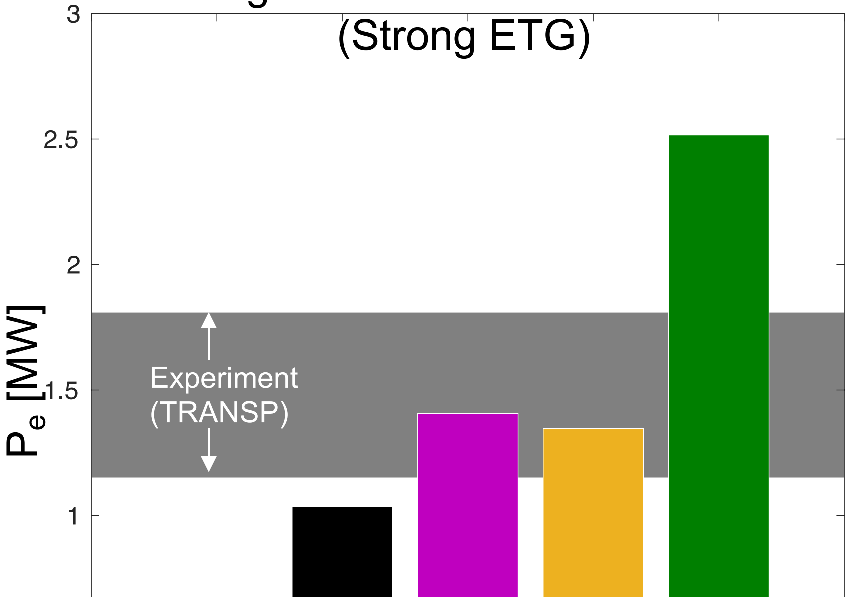
Validation metric $\mathbf{R_{Pe}}$ [*]

	$\mathbf{R_{Pe}}$
Base	1
$\sigma(\nabla T, \nabla n)$	0.29
$\sigma(\nabla T)$, q, $\hat{s}$	0.006
$\sigma(\nabla n)$, q, $\hat{s}$	0.01
$\sigma(\nabla T, \nabla n)$, q, $\hat{s}$	1

1 = bad
0 = good

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

P_e comparisons using
'Big-box' electron-scale sim.
(Strong ETG)



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'Big-box' electron-scale sim

- Base (exp parameters): underpredict P_e
- $\sigma(\nabla T, \nabla n)$: underpredict P_e
- $\sigma(\nabla T)$, q, $\hat{s}$: match P_e
- $\sigma(\nabla n)$, q, $\hat{s}$: match P_e
- $\sigma(\nabla T, \nabla n)$, q, $\hat{s}$: overpredict P_e

Strong ETG condition

- *Electron-scale turbulence can explain P_e.*
- *Scanning q and $\hat{s}$ is needed for matching P_e.*

Outline

- Turbulence fluctuation measurement (High-k scattering).
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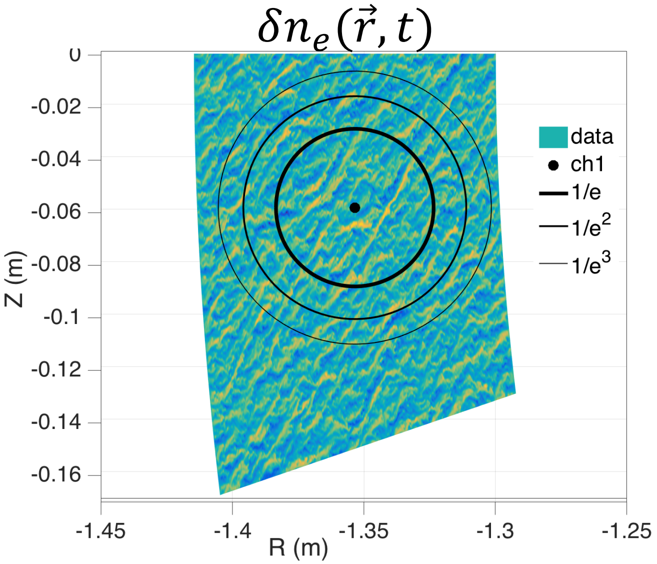
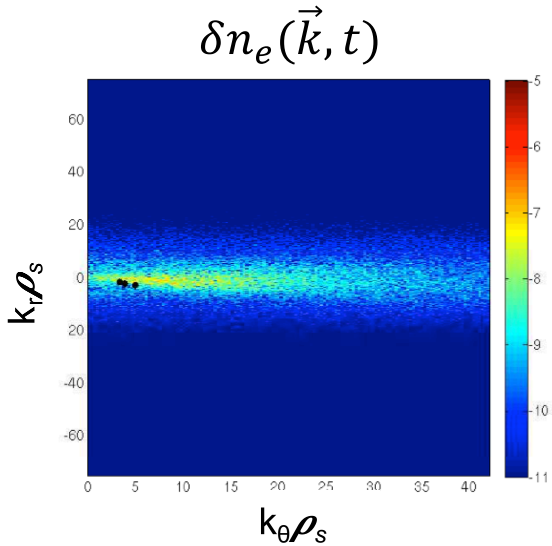
- Electron-scale turbulence comparisons:
  - Synthetic diagnostic description
  - f-spectra comparisons
  - k-spectra comparisons

Two synthetic diagnostics are implemented for quantitative comparisons of e- scale turbulence [*]

Real space formulation: $\psi_R(\vec{r})$



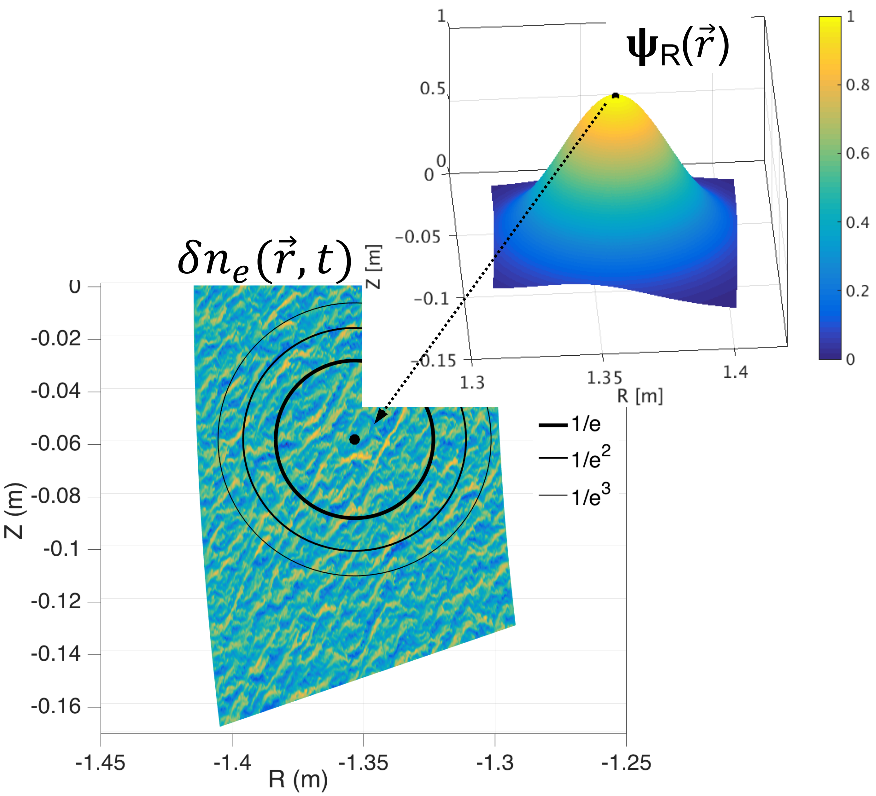
k –space formulation: $\psi_K(\vec{k}-\vec{k}_0)$



[*] Ruiz-Ruiz to be submitted

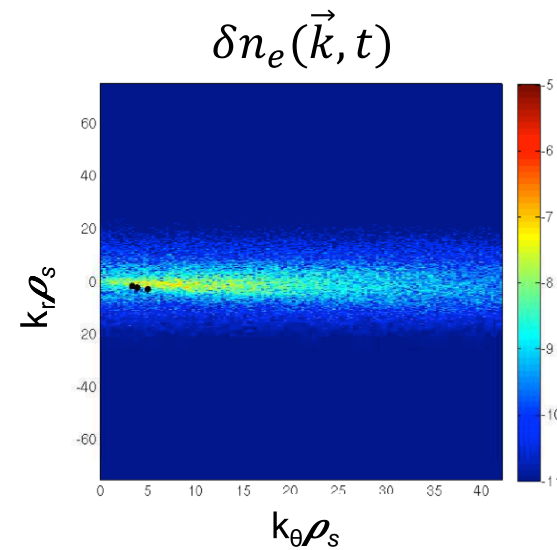
Two synthetic diagnostics are implemented for quantitative comparisons of e- scale turbulence [*]

Real space formulation: $\boldsymbol{\psi}_{\mathrm{R}}(\vec{\boldsymbol{r}})$



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

$\boldsymbol{k}$ –space formulation: $\boldsymbol{\psi}_{\mathrm{K}}(\vec{\boldsymbol{k}} - \vec{\boldsymbol{k}}_0)$



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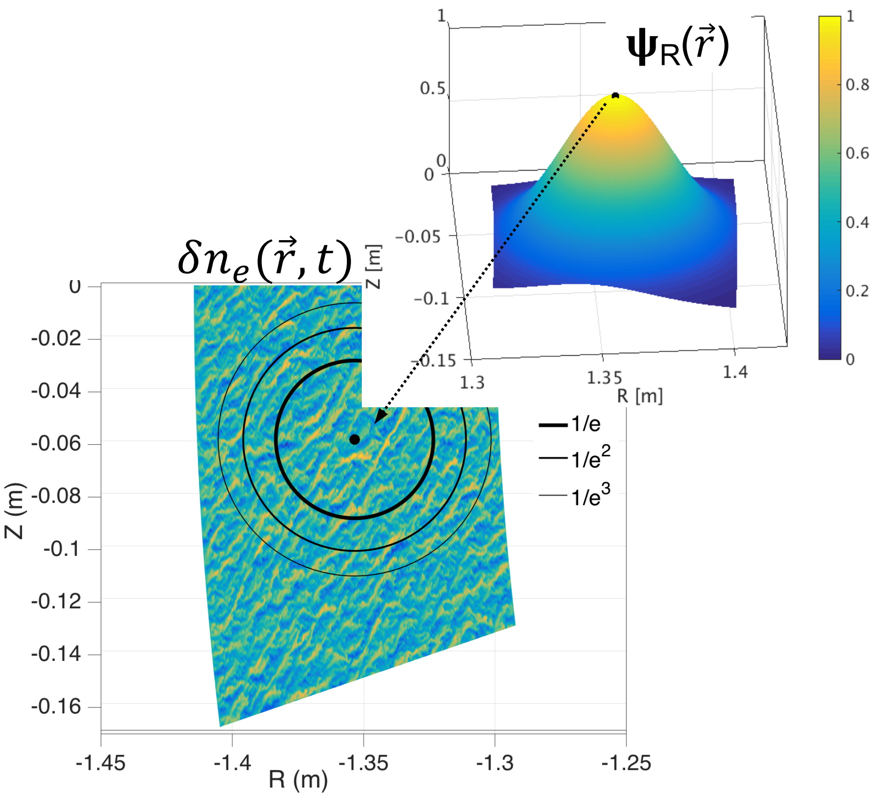
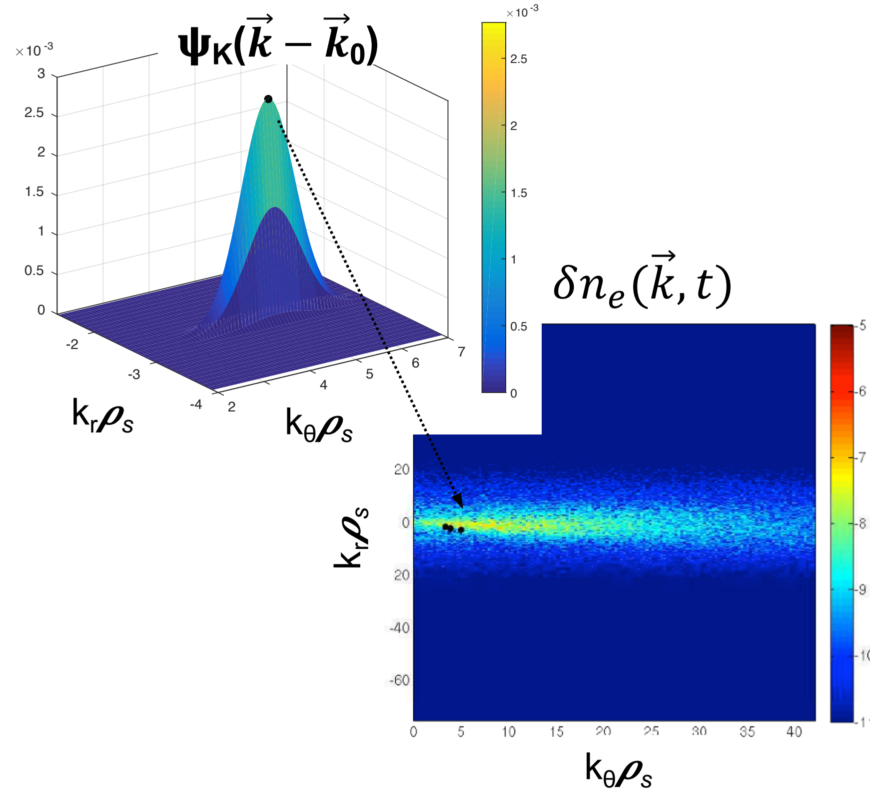


$$\delta\hat{n}_e^{syn}(t) = \int \delta n_e(\vec{r},t)\,\boldsymbol{\psi}_R(\vec{r})\,e^{-i\vec{k}_0\cdot\vec{r}}\,d^3\vec{\mathbf{r}}$$

k –space formulation: $\boldsymbol{\psi}_K(\vec{k}-\vec{k}_0)$

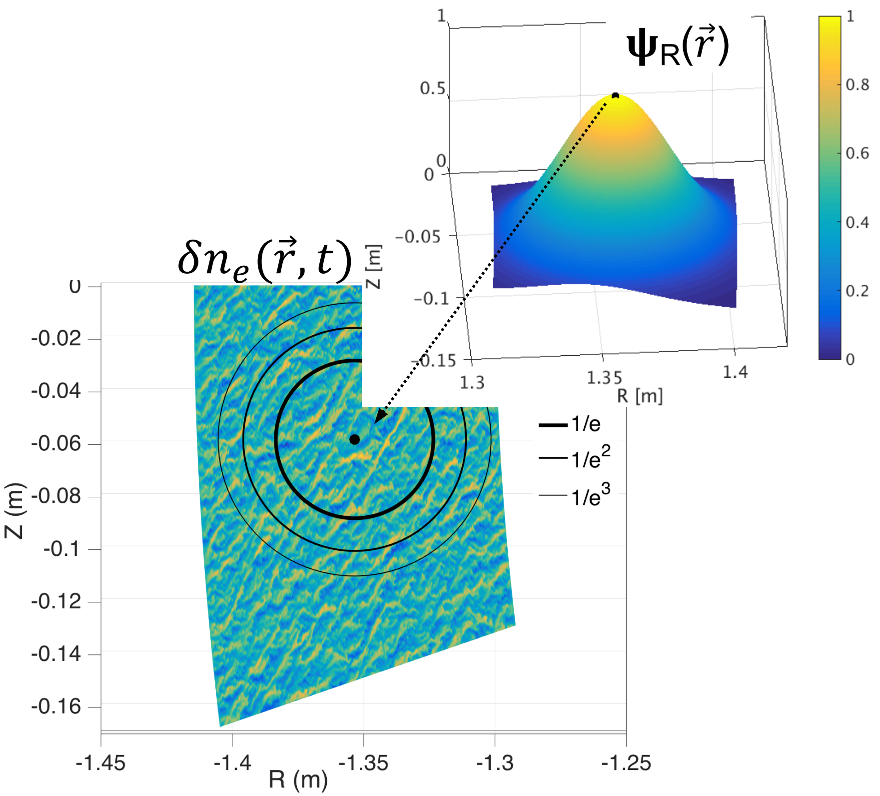


$$\delta\hat{n}_e^{syn}(t) = \frac{1}{(2\pi)^3}\int \delta n_e(\vec{k},t)\,\boldsymbol{\psi}_K(\vec{k}-\vec{k}_0)\,d^3\vec{\mathbf{k}}$$

[*] Ruiz-Ruiz to be submitted

Two synthetic diagnostics are implemented for quantitative comparisons of e- scale turbulence [*]

Real space formulation: $\boldsymbol{\psi}_{\mathrm{R}}(\vec{r})$



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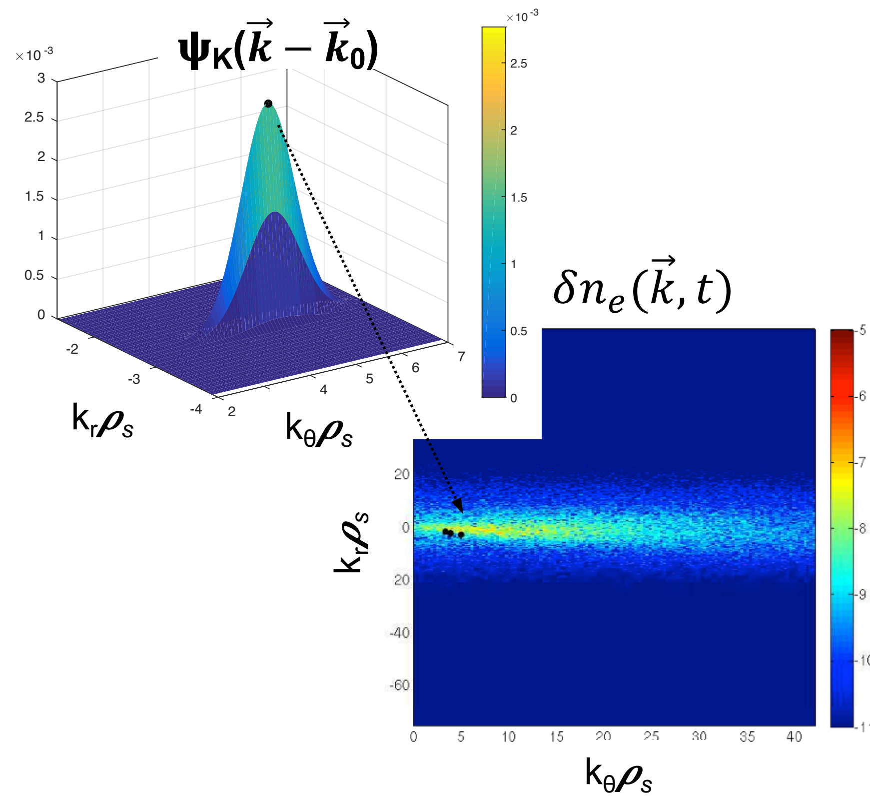

$$\delta\hat{n}_e^{syn}(t) = \int \delta n_e(\vec{r},t)\boldsymbol{\psi}_{\mathrm{R}}(\vec{r})e^{-i\vec{k}_0\cdot\vec{r}}\,d^3\vec{\boldsymbol{r}}$$

$$\delta\hat{n}_e^{syn}(t) = \frac{1}{(2\pi)^3}\int \delta n_e(\vec{k},t)\boldsymbol{\psi}_{\mathrm{K}}(\vec{k}\text{-}\vec{k}_0)\,d^3\vec{\boldsymbol{k}}$$

Obtain a time series of turbulent density fluctuations $\boldsymbol{\delta\hat{n}_e{}^{syn}(t)}$

[*] Ruiz-Ruiz to be submitted

Outline

- Turbulence fluctuation measurement (High-k scattering).
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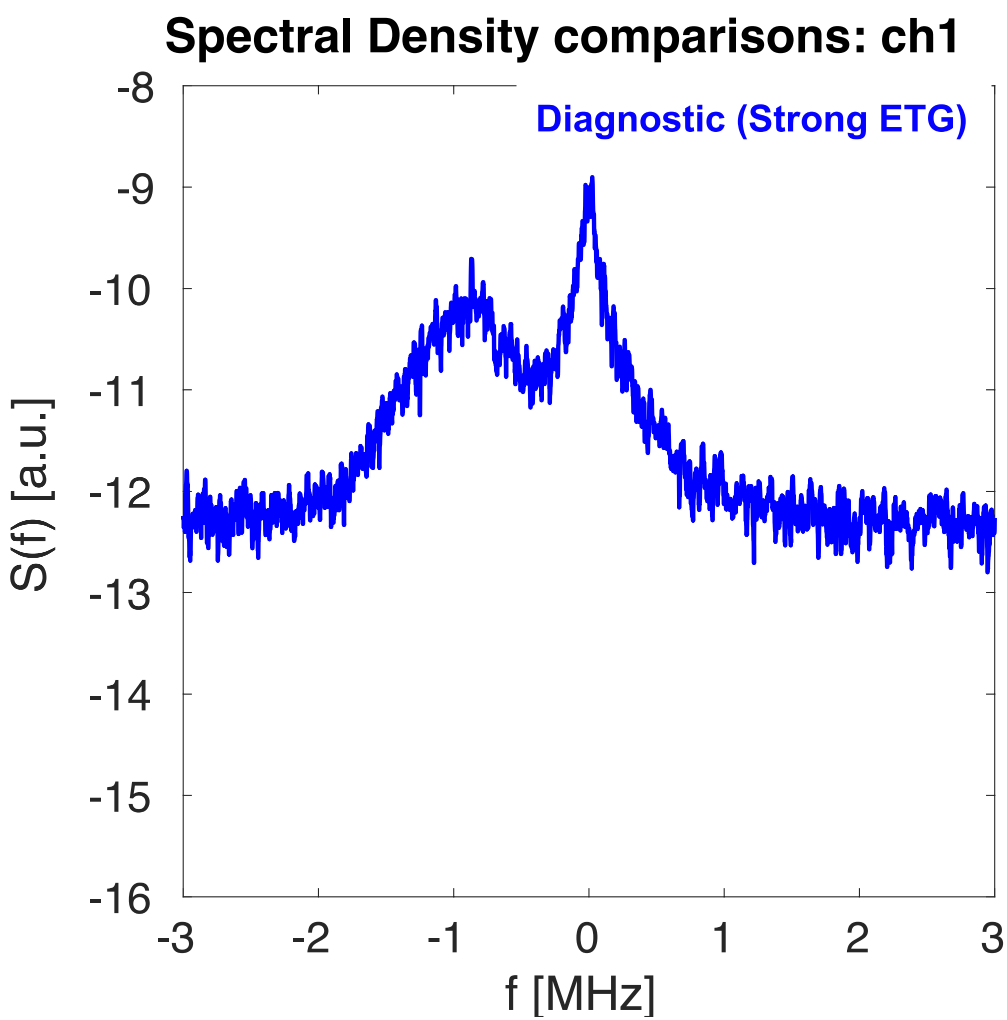
  - k-spectra comparisons

Synthetic f-spectrum reproduces spectral peak and spectral width W_f



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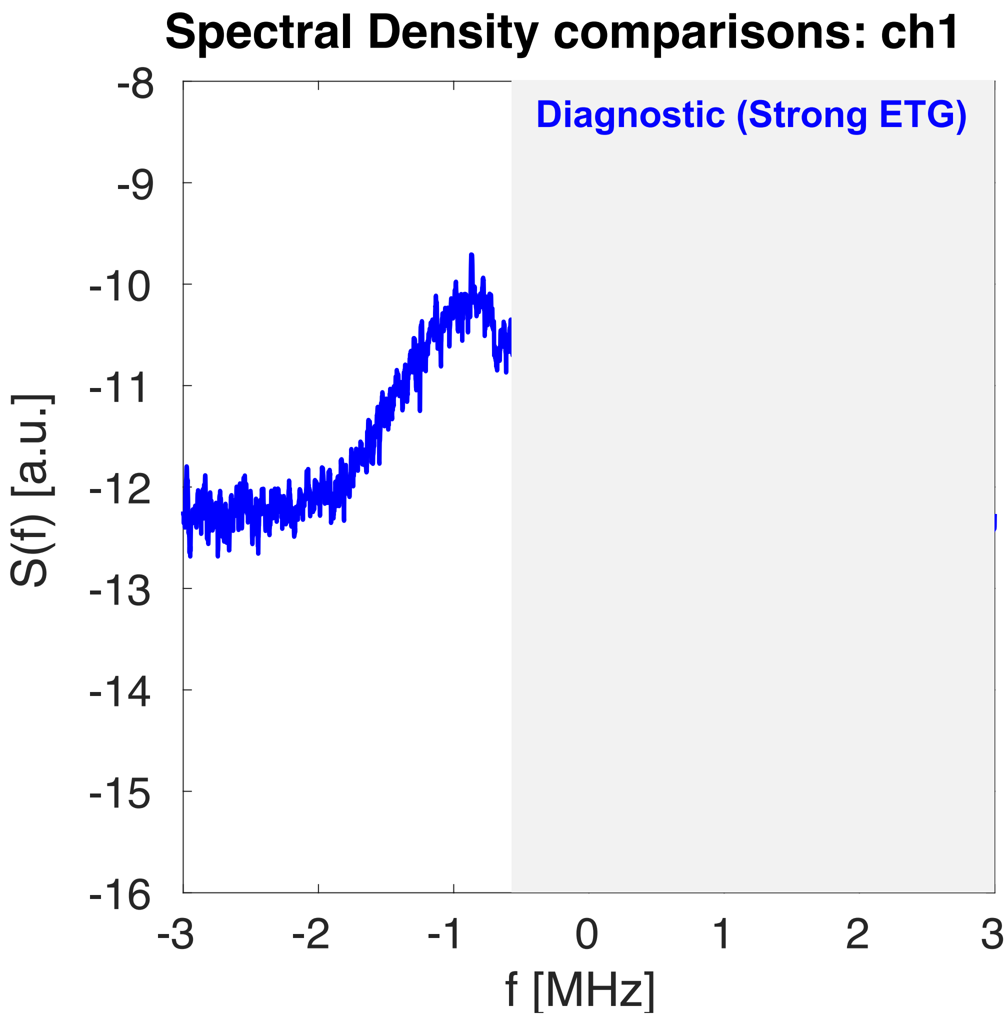

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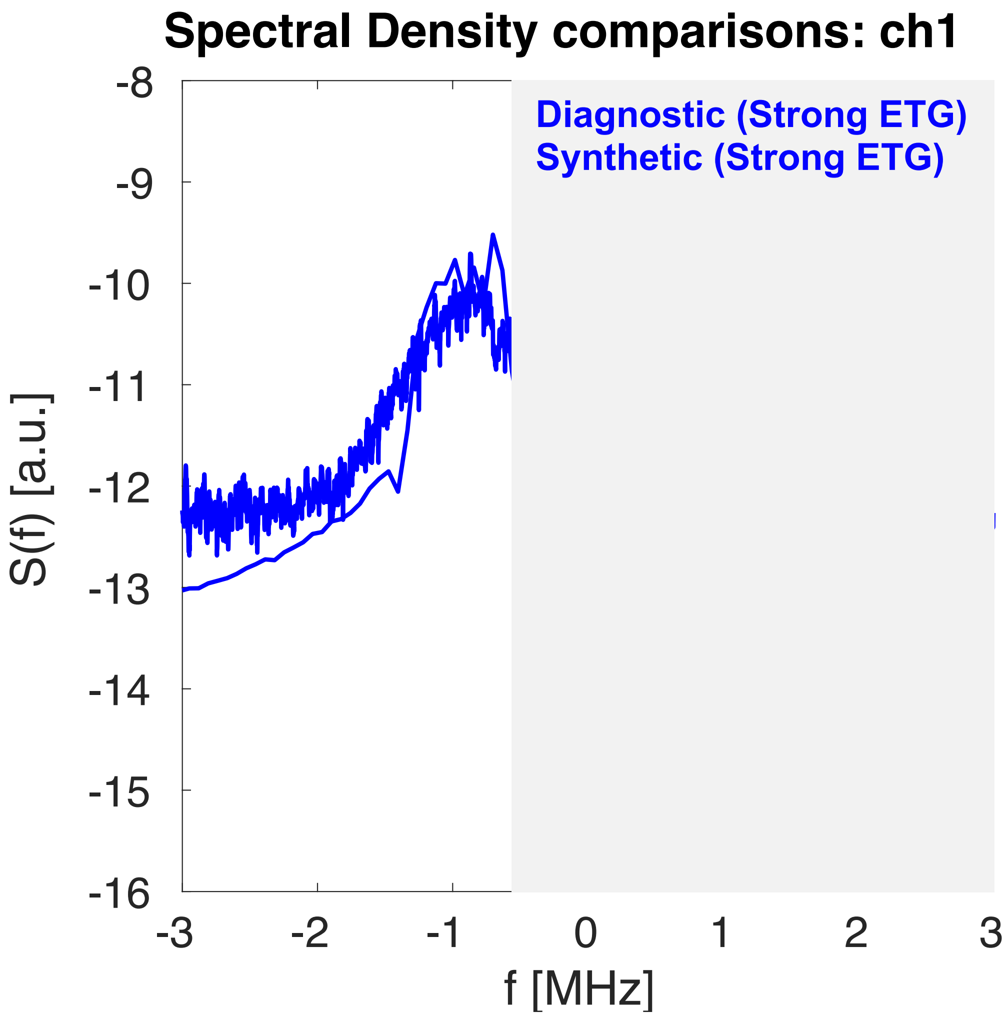

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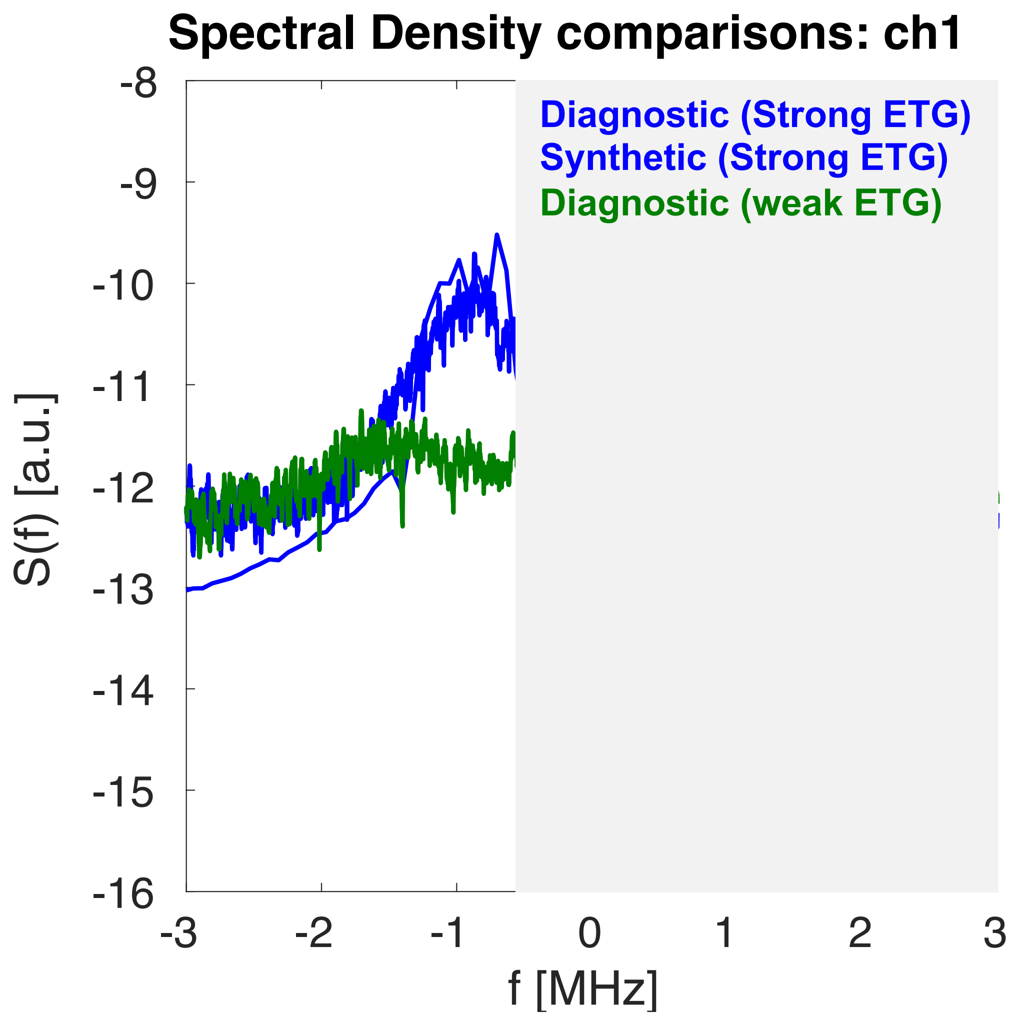

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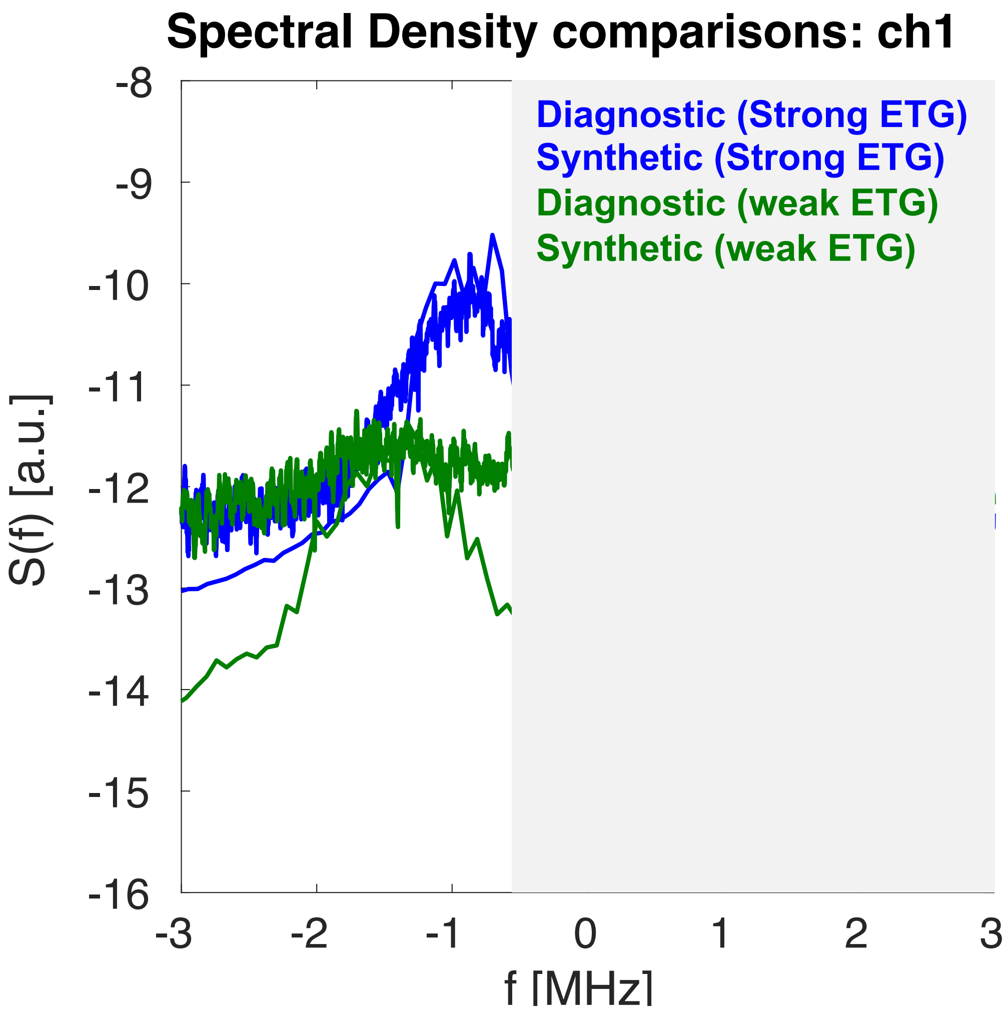

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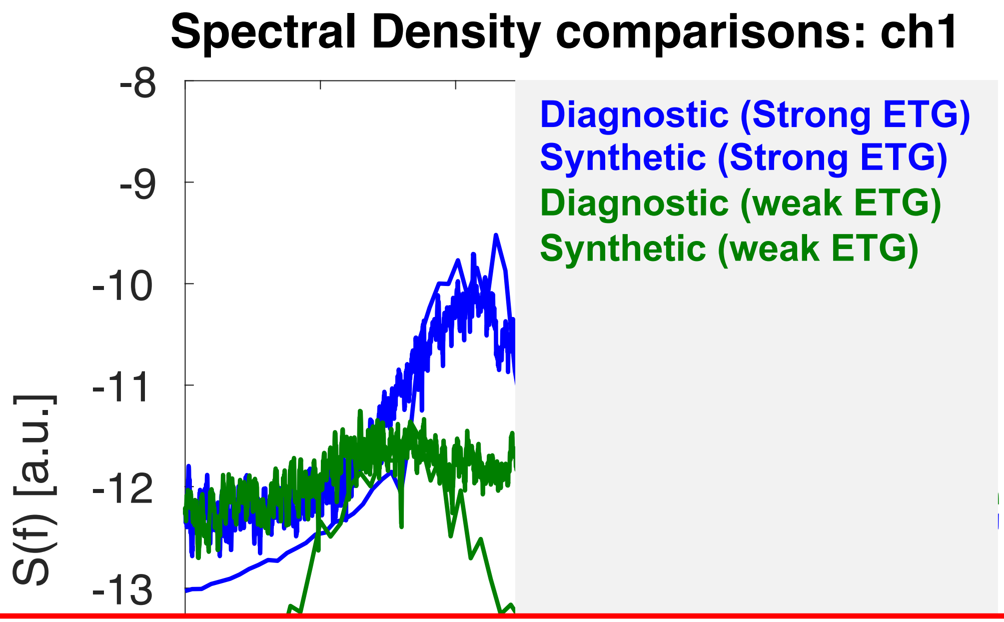

Frequency spectra comparisons

- *Good agreement is achieved in the frequency spectra.*
- *Synthetic frequency spectrum should match experiment as a test of simulation and synthetic diagnostic.*
- *Cannot be used to differentiate between simulations.*

Outline

- Turbulence fluctuation measurement (High-k scattering).
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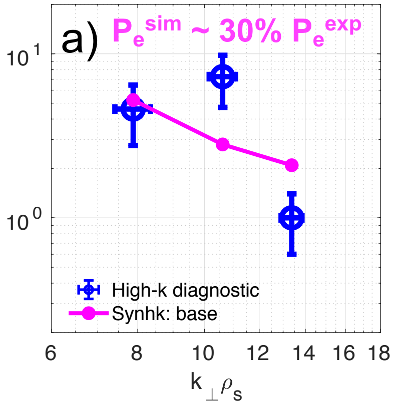
  - f-spectra comparisons
  - k-spectra comparisons
    - 5 ‘big-box’ e- scale sims for the strong ETG case
    - 1 ‘big-box’ e- scale sim for the weak ETG case

k-spectra comparisons isolate the importance of q and $\hat{s}$ in determining the *shape* of the k-spectrum

k-spectra shape comparisons for the strong ETG condition
5 'big-box' e- scale sims.



- Synthetic spectra are scaled to compare the *shape* of the k-spectrum $S(k)$.

[∗] Ricci PoP 2011, Holland PoP 2016

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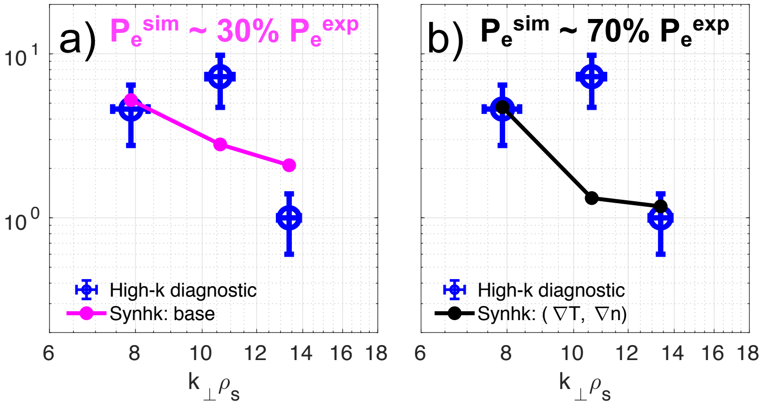

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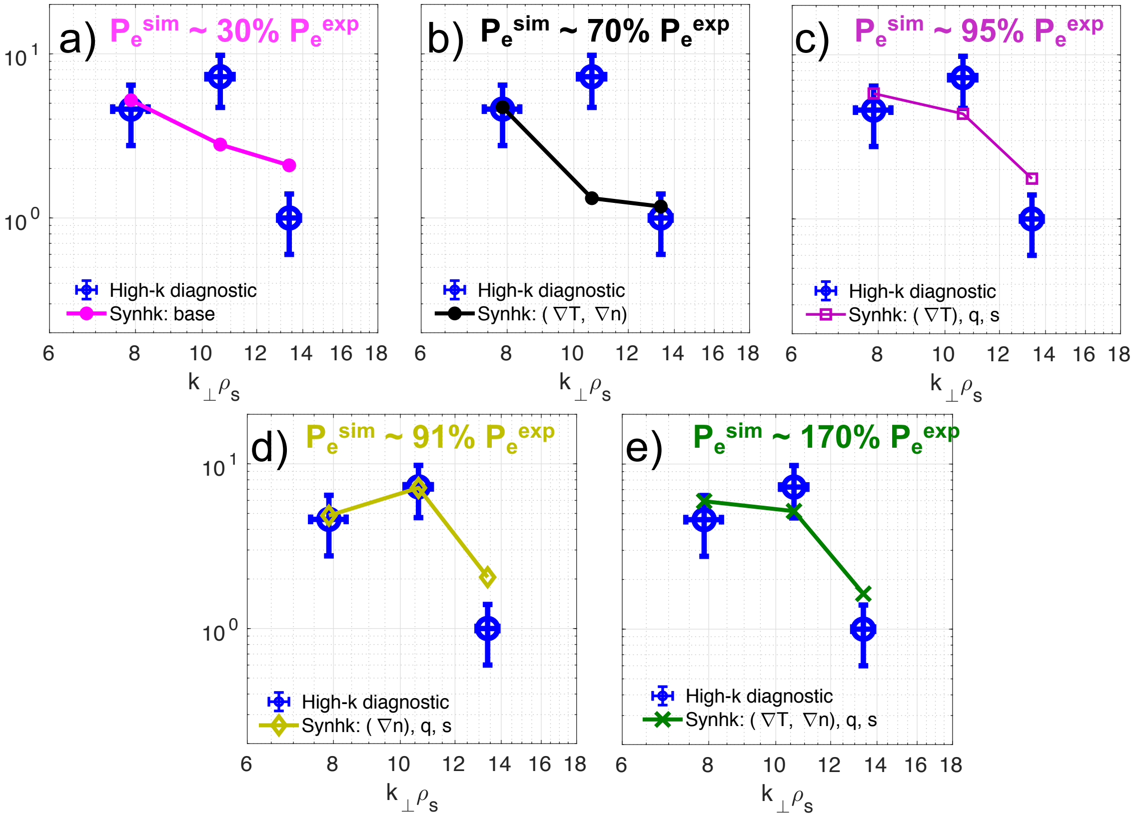

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- Simulations run with scaled-$q, \hat{s}$ (c, d, e) best match the shape of the k-spectrum.

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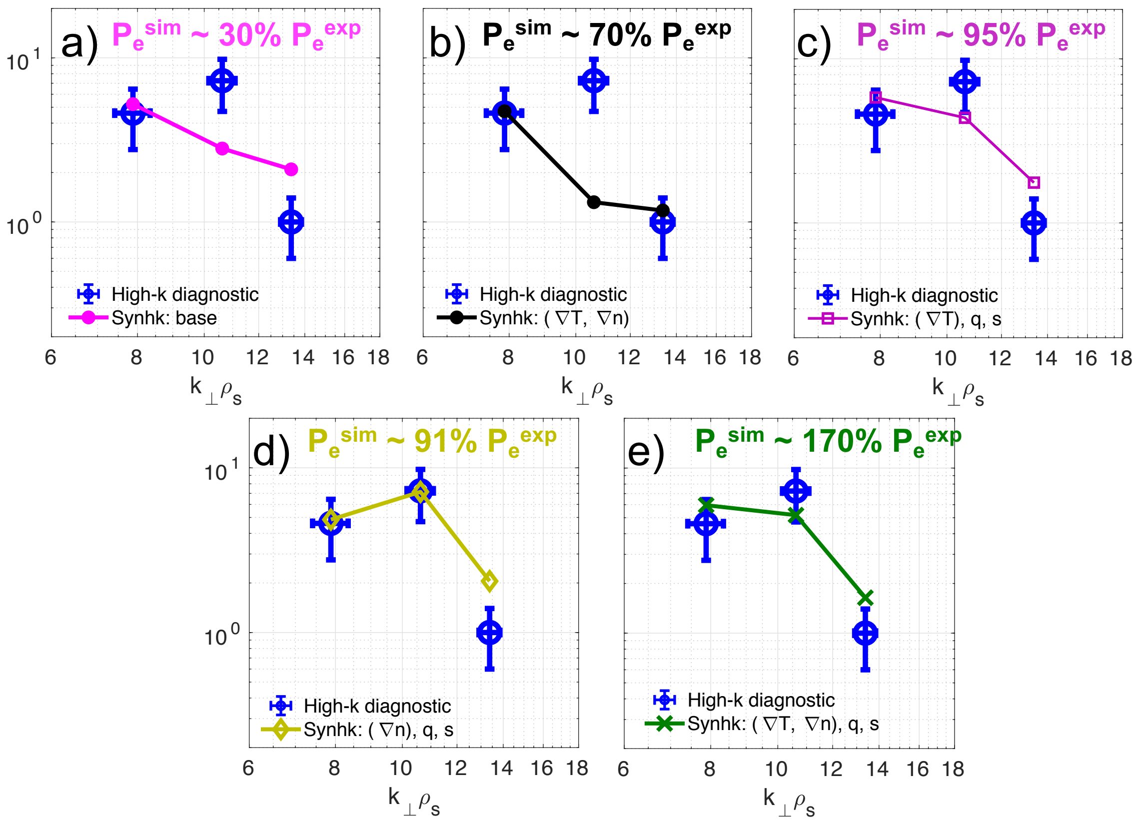

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- Simulations run with scaled-$q, \hat{s}$ (c, d, e) best match the shape of the k-spectrum.
- Validation metric R_{shape} $\epsilon[0,1]^{[*]}$

	R_{shape}
Base	1
$\sigma(\nabla T, \nabla n)$	0.99
$\sigma(\nabla T)$, q, $\hat{s}$	0.98
$\sigma(\nabla n)$, q, $\hat{s}$	0.53
$\sigma(\nabla T, \nabla n)$, q, $\hat{s}$	0.76

1 = bad
0 = good

[∗] Ricci PoP 2011, Holland PoP 2016

k-spectra comparisons isolate the importance of q and $\hat{s}$ in determining the *shape* of the k-spectrum

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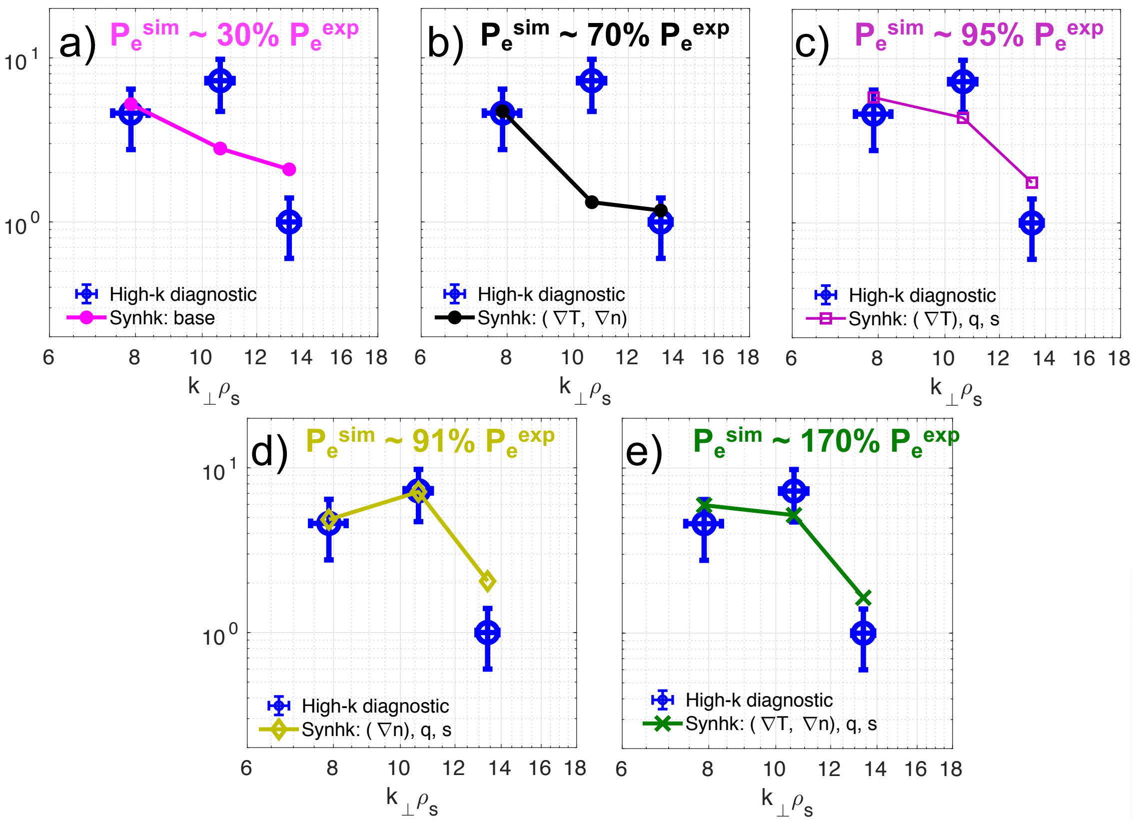

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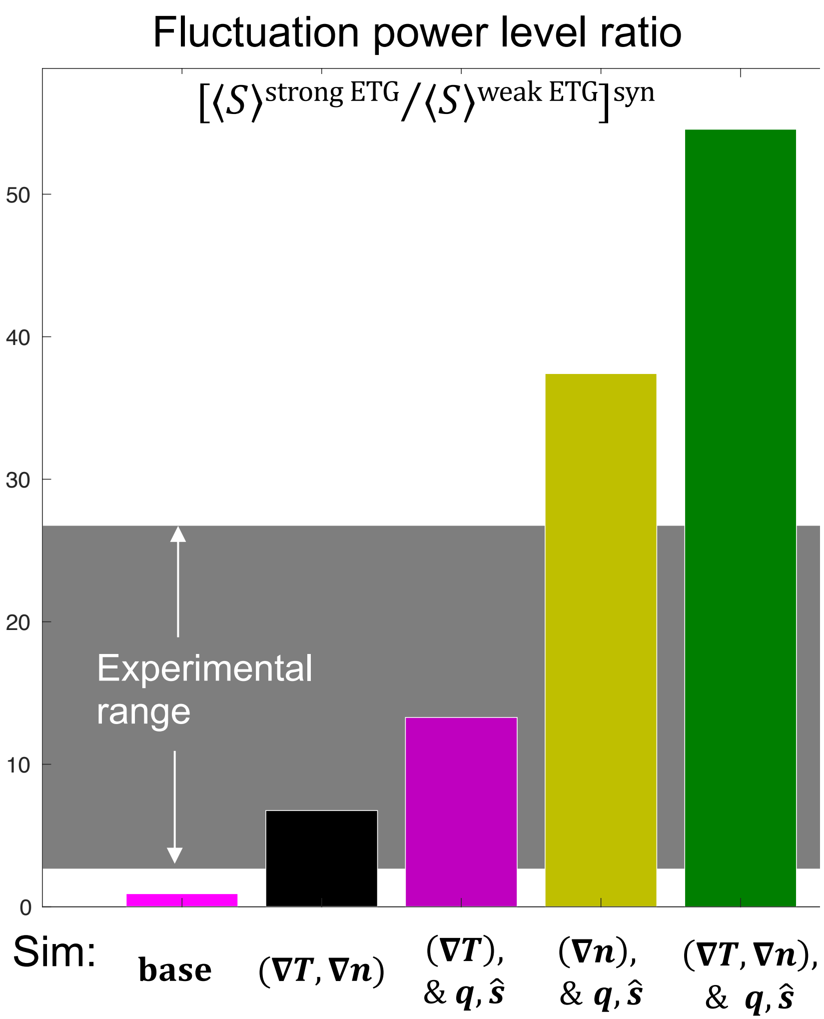
- Validation metric R_{shape} $\epsilon[0,1]$[*]

	R_{Pe}	R_{shape}
Base	1	1
$\sigma(\nabla T, \nabla n)$	0.29	0.99
$\sigma(\nabla T)$, q, $\hat{s}$	0.006	0.98
$\sigma(\nabla n)$, q, $\hat{s}$	0.01	0.53
$\sigma(\nabla T, \nabla n)$, q, $\hat{s}$	1	0.76

1 = bad
0 = good

[*] Ricci PoP 2011, Holland PoP 2016

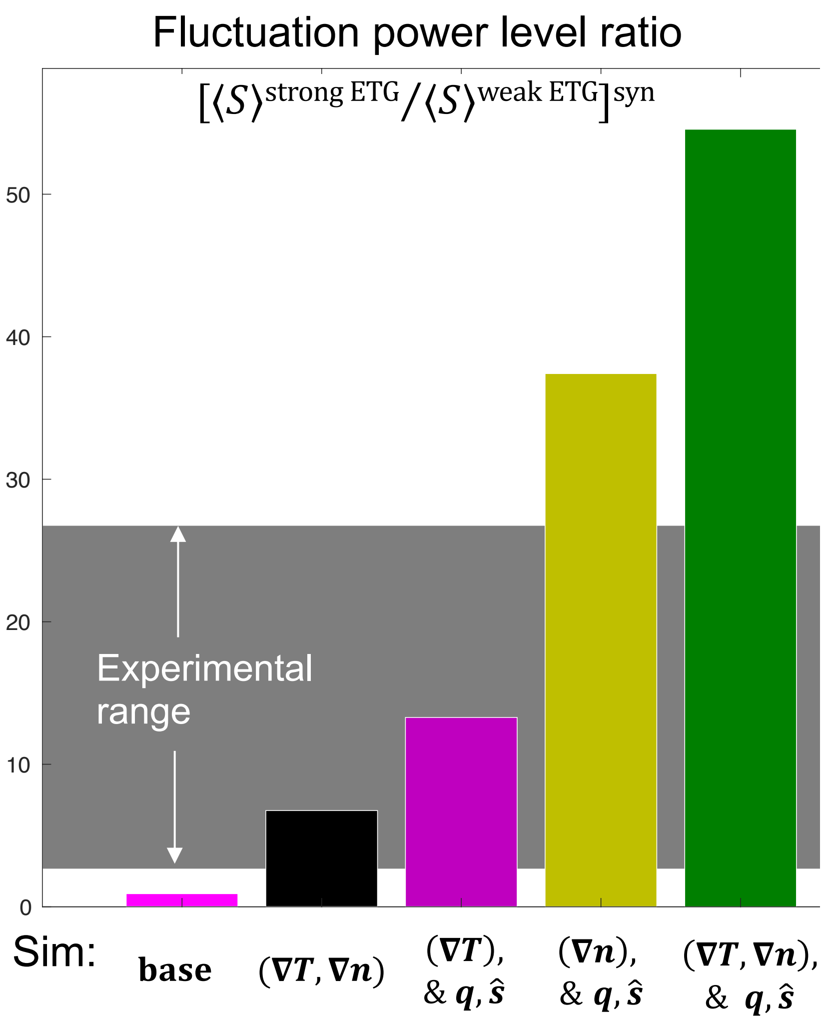
Fluctuation level ratio between strong and weak ETG conditions can be quantitatively compared to experiment



- GYRO sim. for the *weak ETG* condition matched P_e.

1 = bad
0 = good

Fluctuation level ratio between strong and weak ETG conditions can be quantitatively compared to experiment

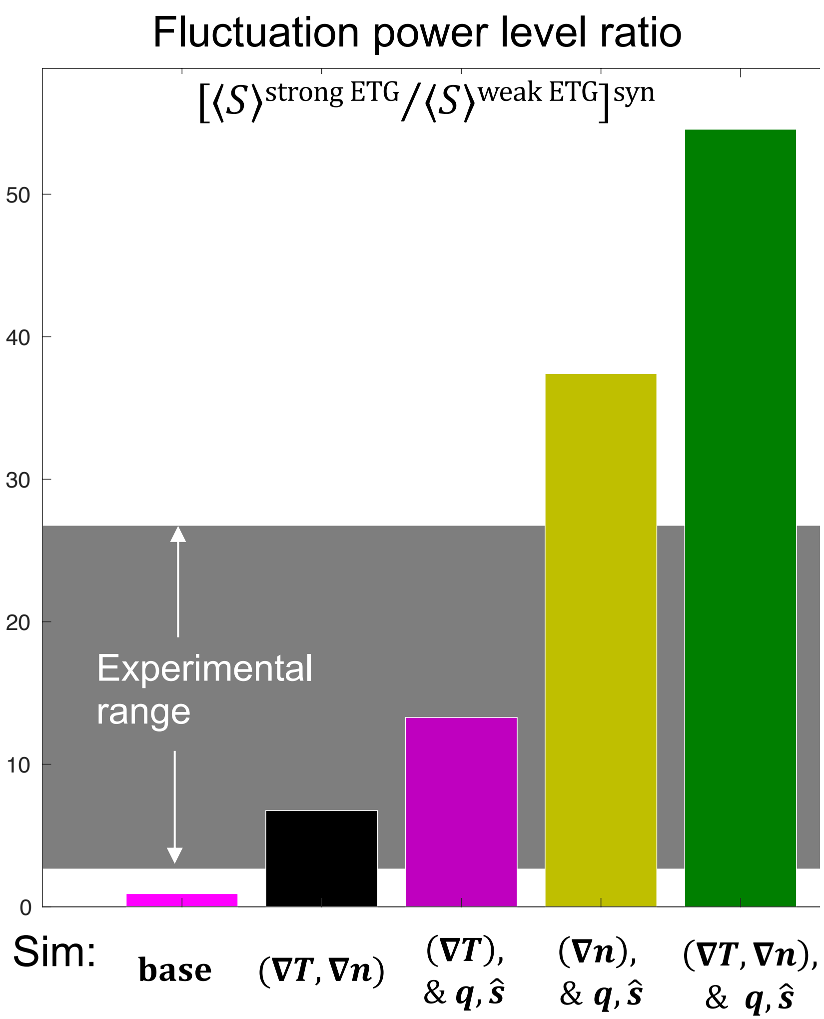


- GYRO sim. for the *weak ETG* condition matched P_e.
- Validation metric $R_{ratio} \epsilon [0, 1]$

	R_{ratio}
Base	0.18
$\sigma(\nabla T, \nabla n)$	0.05
$\sigma(\nabla T)$, q, $\hat{s}$	0.01
$\sigma(\nabla n)$, q, $\hat{s}$	0.47
$\sigma(\nabla T, \nabla n)$, q, $\hat{s}$	0.72

1 = bad
0 = good

Fluctuation level ratio between strong and weak ETG conditions can be quantitatively compared to experiment



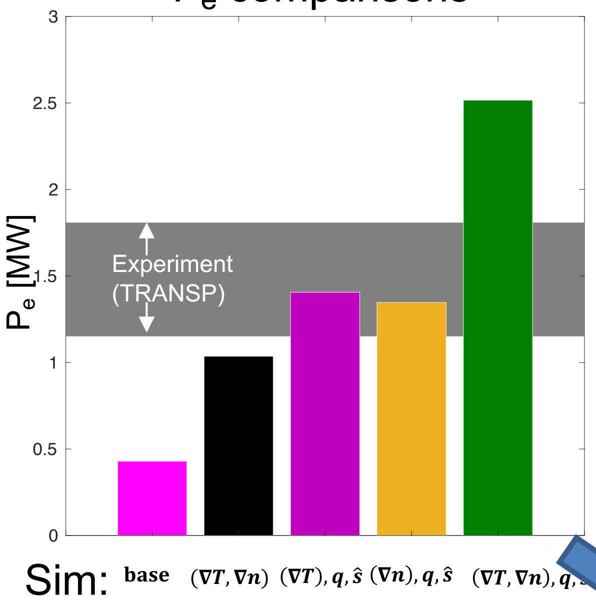
- GYRO sim. for the *weak ETG* condition matched P_e.
- Validation metric $R_{ratio} \epsilon [0, 1]$

	R_{Pe}	R_{shape}	R_{ratio}
Base	1	1	0.18
$\sigma(\nabla T, \nabla n)$	0.29	0.99	0.05
$\sigma(\nabla T)$, q, $\hat{s}$	0.006	0.98	0.01
$\sigma(\nabla n)$, q, $\hat{s}$	0.01	0.53	0.47
$\sigma(\nabla T, \nabla n)$, q, $\hat{s}$	1	0.76	0.72

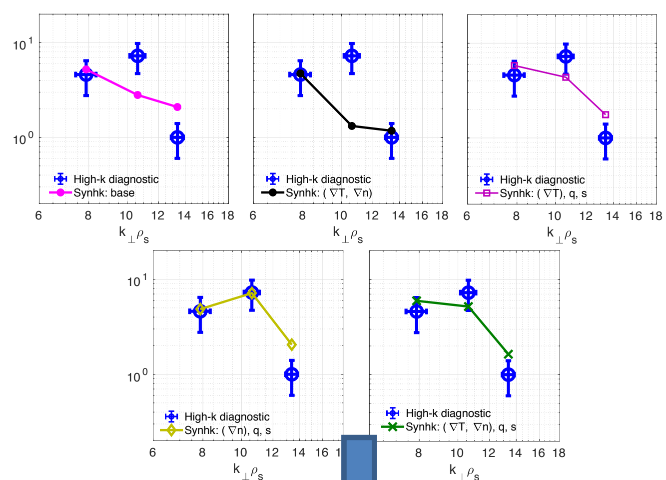
1 = bad
0 = good

All comparisons are condensed via a composite metric for discrimination between simulations

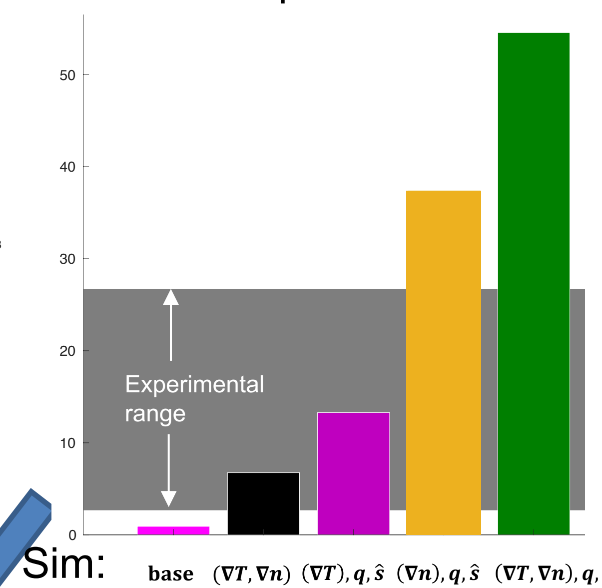
P_e comparisons



k-spectra shape comparisons



Fluctuation level ratio comparisons



- Composite metric M [*] ϵ $[0,1]$:

$$M = \frac{\sum_i h_i R_i}{\sum h_i}$$

	M
Base	0.67
$\sigma(\nabla T, \nabla n)$	0.47
$\sigma(\nabla T)$, q, $\hat{s}$	**0.40**
$\sigma(\nabla n)$, q, $\hat{s}$	**0.40**
$\sigma(\nabla T, \nabla n)$, q, $\hat{s}$	0.76

Reference for M

0 ➔ perfect agreement
0.04 ➔ error ~ 1σ
0.5 ➔ error ~ 2σ
0.9 ➔ error ~ 3σ

[∗] Holland PoP 2016

Main outcome: Validated e- scale GK simulations in the NSTX core using high-k turbulence measurements for the 1st time.

[*] ST-FNSF, Brown FST 2017
[**] Sorbom FED 2015

Main outcome: Validated e- scale GK simulations in the NSTX core using high-k turbulence measurements for the 1st time.

Summary

- **1st simultaneous agreement between exp. & sim. of P_e, fluct. level ratio and k-spectra shape of e- scale turbulence in a tokamak ➔ ETG-driven turbulence can dominate in core-gradient region of modest beta NSTX H-modes.**

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- Implemented two equivalent synthetic high-k diagnostics → novel 'big-box' e- scale is required for quantitative e- scale turb. comparisons.
- High-k f-spectrum not a critical constraint to discriminate between simulations.
- Importance of $(q, \hat{s})$ in matching P_e and determining shape of k-spectrum.

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Main outcome: Validated e- scale GK simulations in the NSTX core using high-k turbulence measurements for the 1^{st} time

Summary

- **1^{st} simultaneous agreement between exp. & sim. of P_e, fluct. level ratio and $\boldsymbol{k}$-spectra shape of e- scale turbulence in a tokamak ➔ ETG-driven turbulence can dominate in core-gradient region of modest beta NSTX H-modes.**
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- Importance of $(q, \hat{s})$ in matching P_e and determining shape of k-spectrum.

Broader Impact:

- A new framework applicable to additional coherent scattering turbulence measurements, like Doppler Backscattering, reflectometry, etc.
- Improved confidence in turbulent-transport models for prediction and optimization of future fusion reactors (ITER, ST-FNSF [*], ARC[**]).
- This work motivates further work in higher $\boldsymbol{\beta}$ and lower collisionality conditions in NSTX-U and MAST-U.
- This work has demonstrated a multi-level validation methodology to enable future validation efforts of turbulent transport models.

[*] ST-FNSF, Brown FST 2017
[**] Sorbom FED 2015

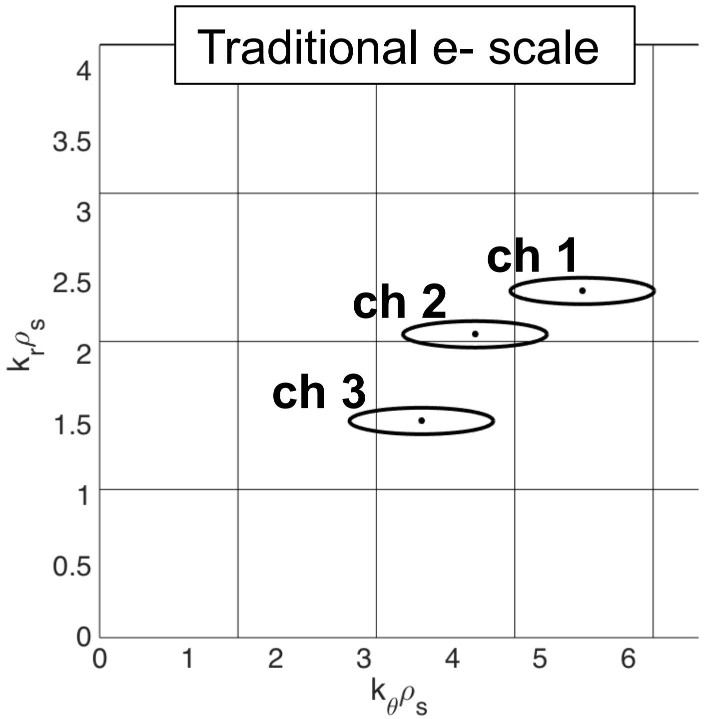
Thank you

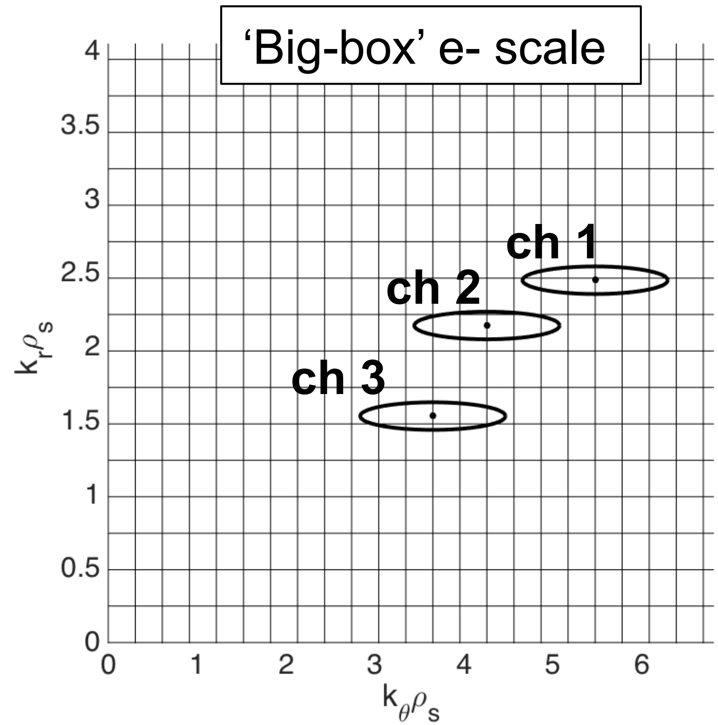
MIT PhD Thesis Committee
Prof. Anne White
Dr. Nathan Howard
Prof. Nuno Loureiro

Princeton Plasma Physics Lab (PPPL)
Dr. Walter Guttenfelder
Dr. Yang Ren

Backup

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





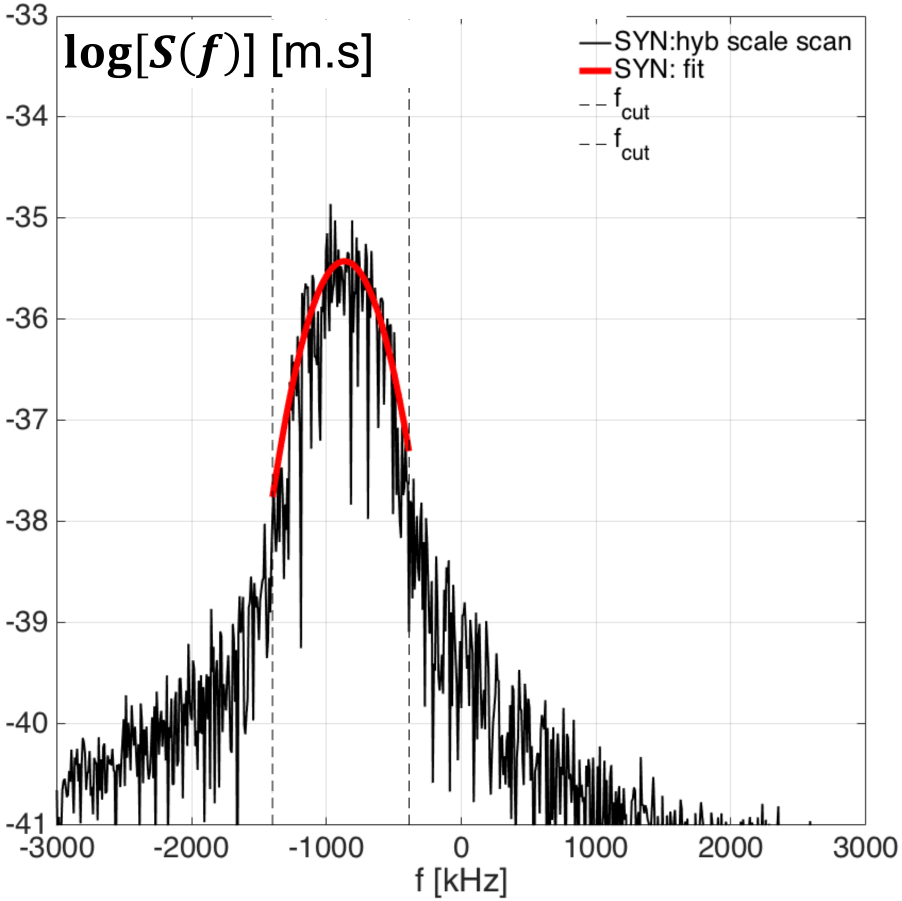
	$k_\theta\rho_s$ [min, max]	$k_r\rho_s$ [min, max]
e- scale	[1.5, 65 or 86]*	[1, 47 or 32]*
'Big-box' e- scale	[0.3, 65 or 88]*	[0.3, 32]

Computationally intensive
~ 1-2 M CPU h/sim

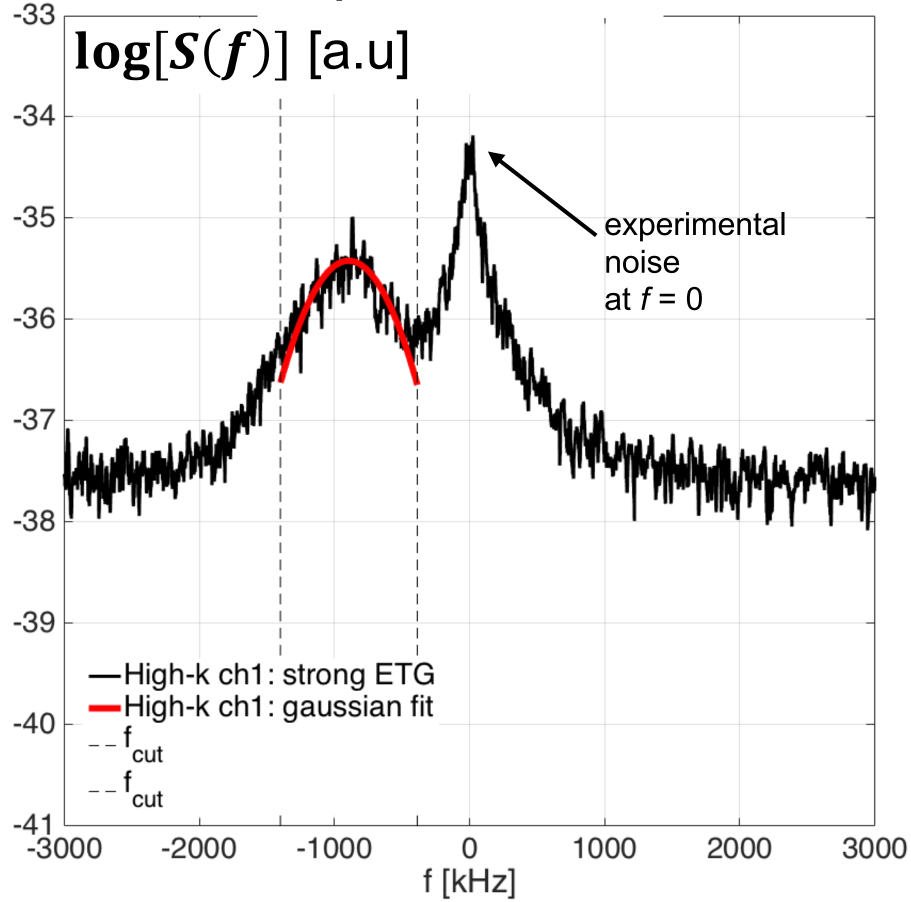
* max $\mathbf{k_\theta\rho_s}$ different in two exp. conditions

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

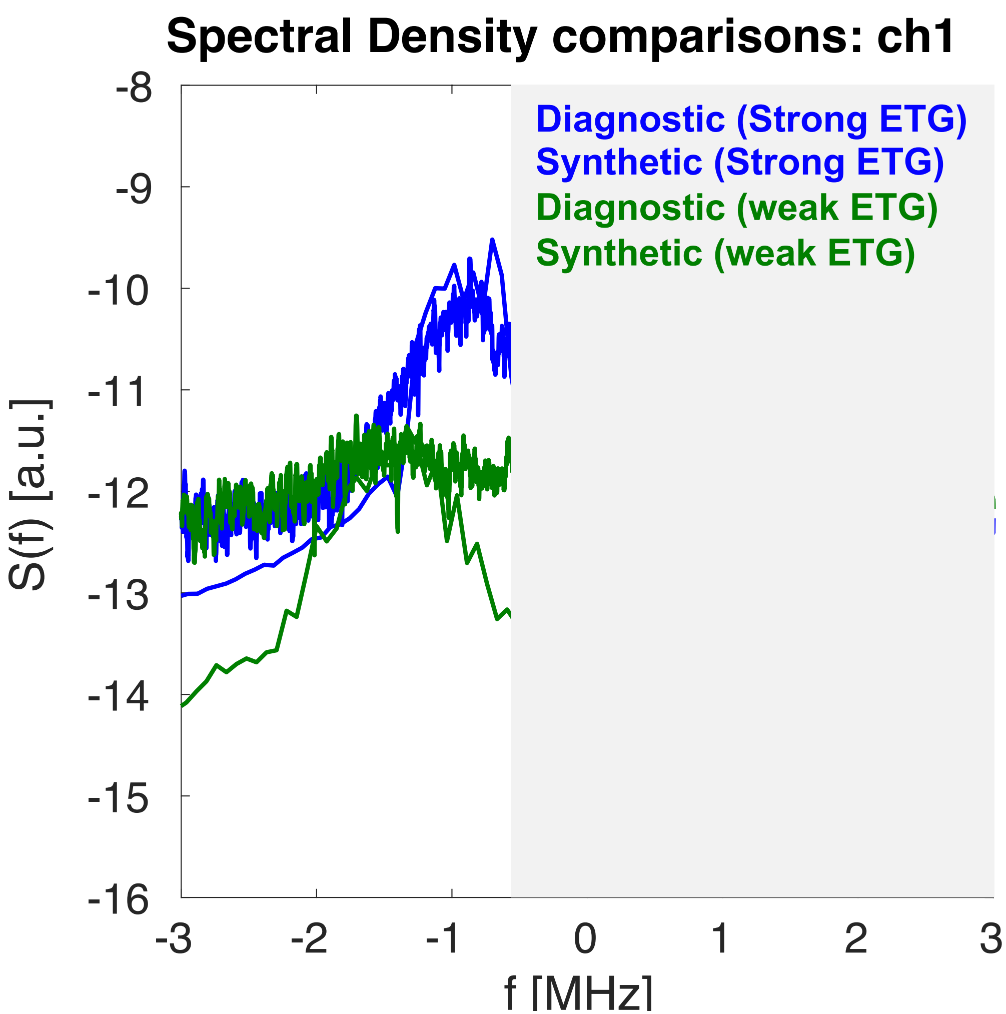
Simulation



Experiment



Synthetic f-spectrum reproduces spectral peak $< f >$, close to match spectral width W_f



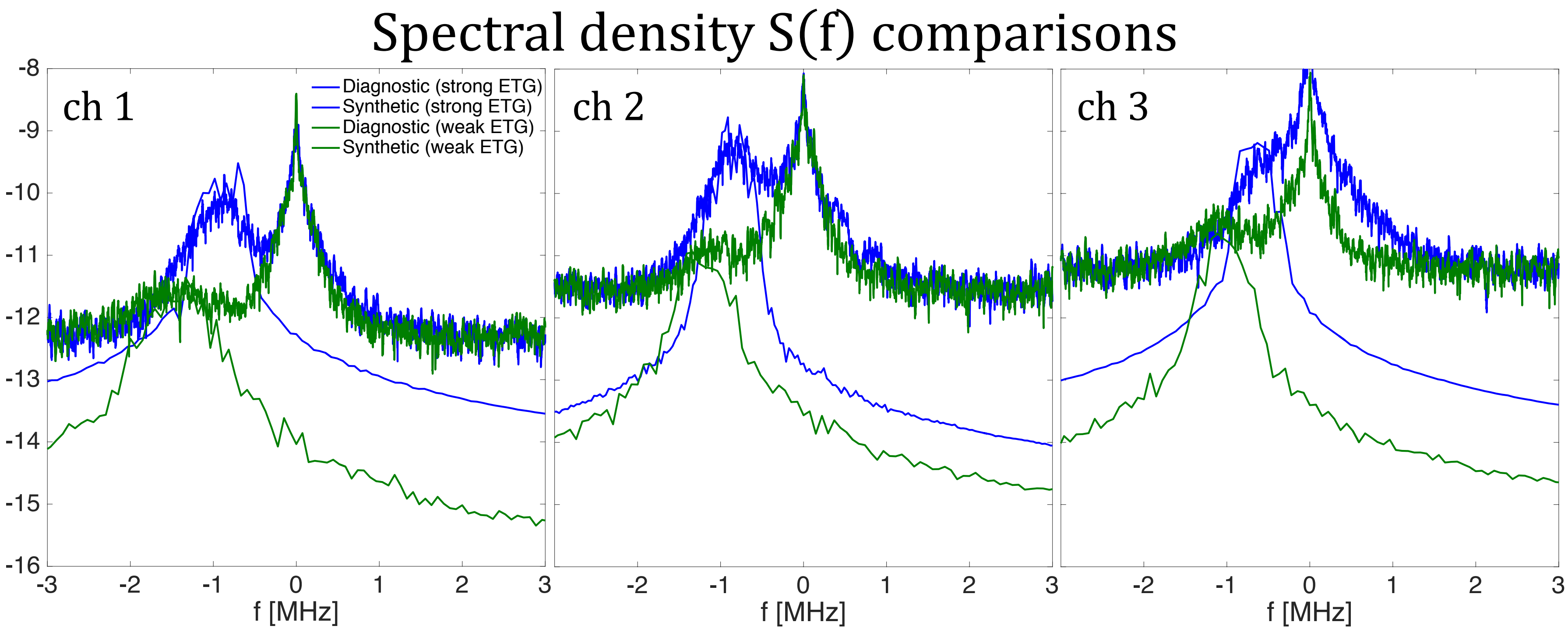
STRONG ETG ch1

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

WEAK ETG ch1

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

f-spectrum agreement is achieved for all channels



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

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

- **Spectral peak $< f >$** 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 constraint on simulation model

- **Spectral width W_f** determined by combination of:
  - **Turbulence spectrum in plasma frame**
  - k-resolution of the high-k diagnostic
  - k-grid resolution of the simulation
  - Doppler shift

- f-spectrum does not provide critical constraints to discriminate between models.

- We find the wavenumber spectrum more useful for selection of simulations.

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

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

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  - **Turbulence spectrum in plasma frame**
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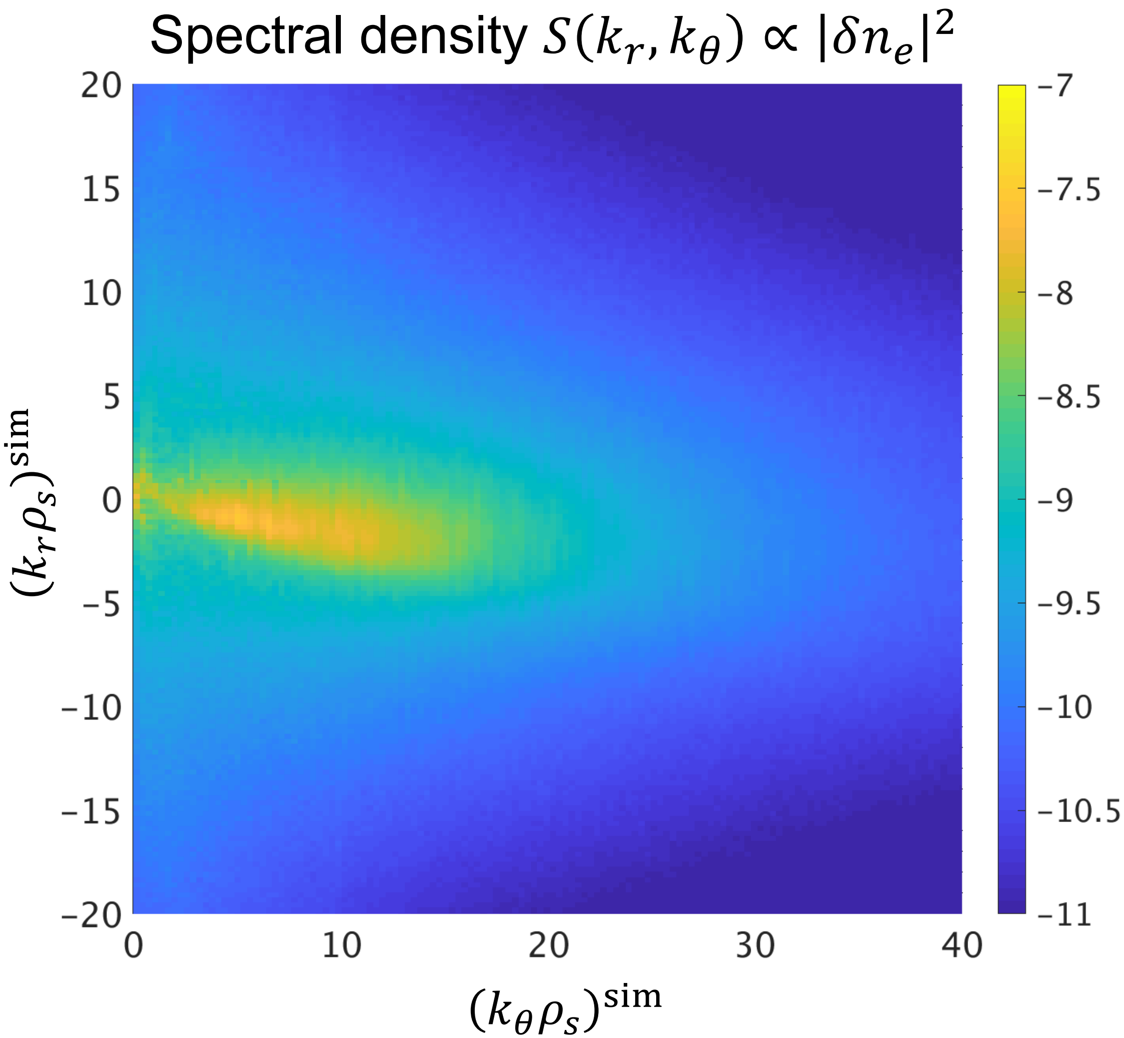
Frequency spectra comparisons

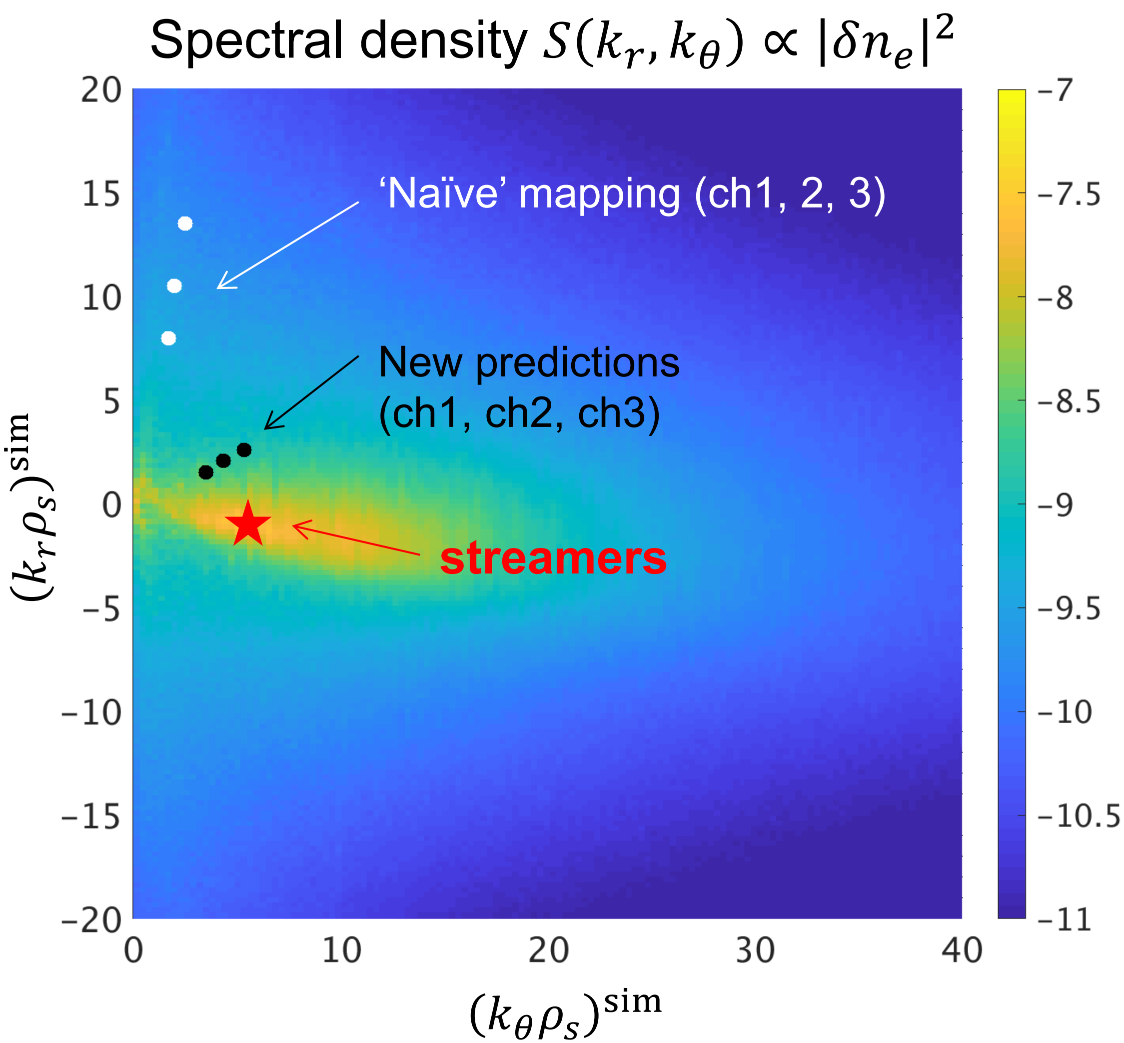
- *Good agreement is achieved in the frequency spectra.*
- *Synthetic frequency spectrum should match experiment as a test of simulation and synthetic diagnostic.*
- *Cannot be used to differentiate between simulations.*

• ons.

Synthetic diagnostic revealed high-k measurement is closer to 'streamer' peak than 'naïve' mapping suggests



Synthetic diagnostic revealed high-k measurement is closer to ‘streamer’ peak than ‘naïve’ mapping suggests



‘Naïve’ mapping does not take into account field-aligned geometry.

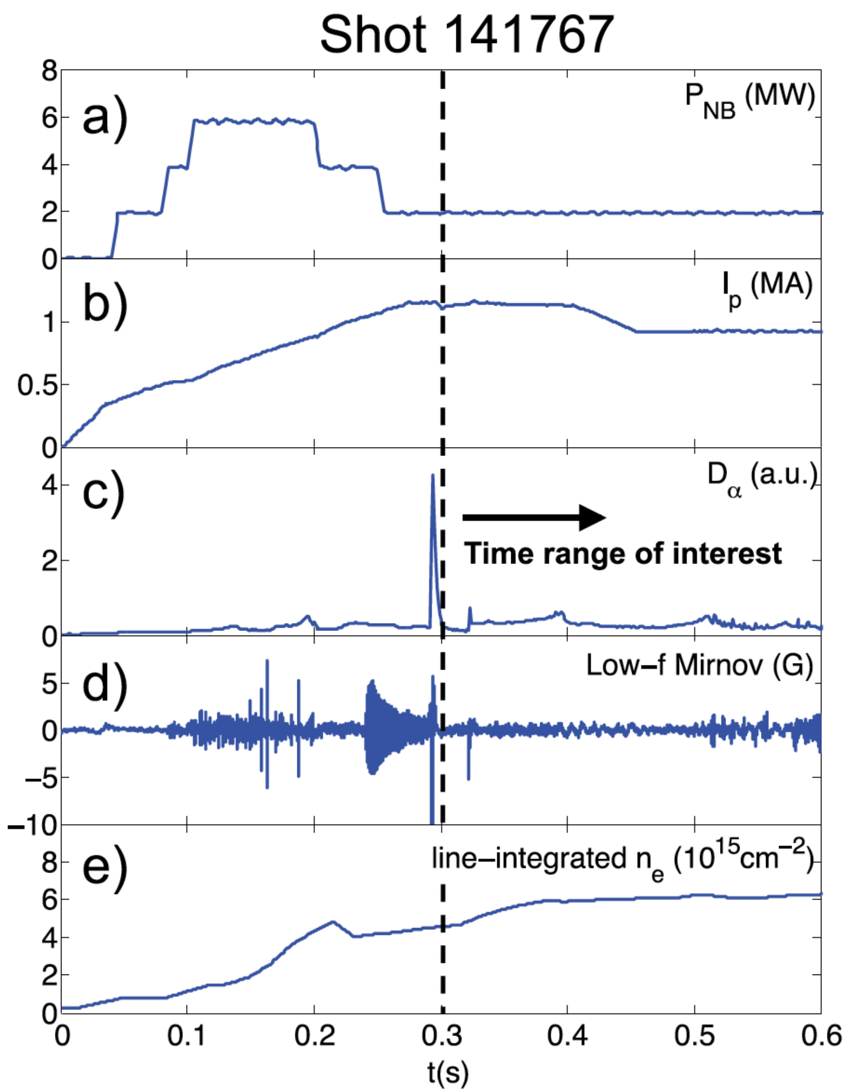
Geometric effects ($\mathrm{B_{ref}},\ \kappa, |\nabla r|, ..$) bring the measured k close to peak in fluctuation spectrum.

Streamers (★) : predicted to dominate ETG transport in *low-beta* ST parameters [*].

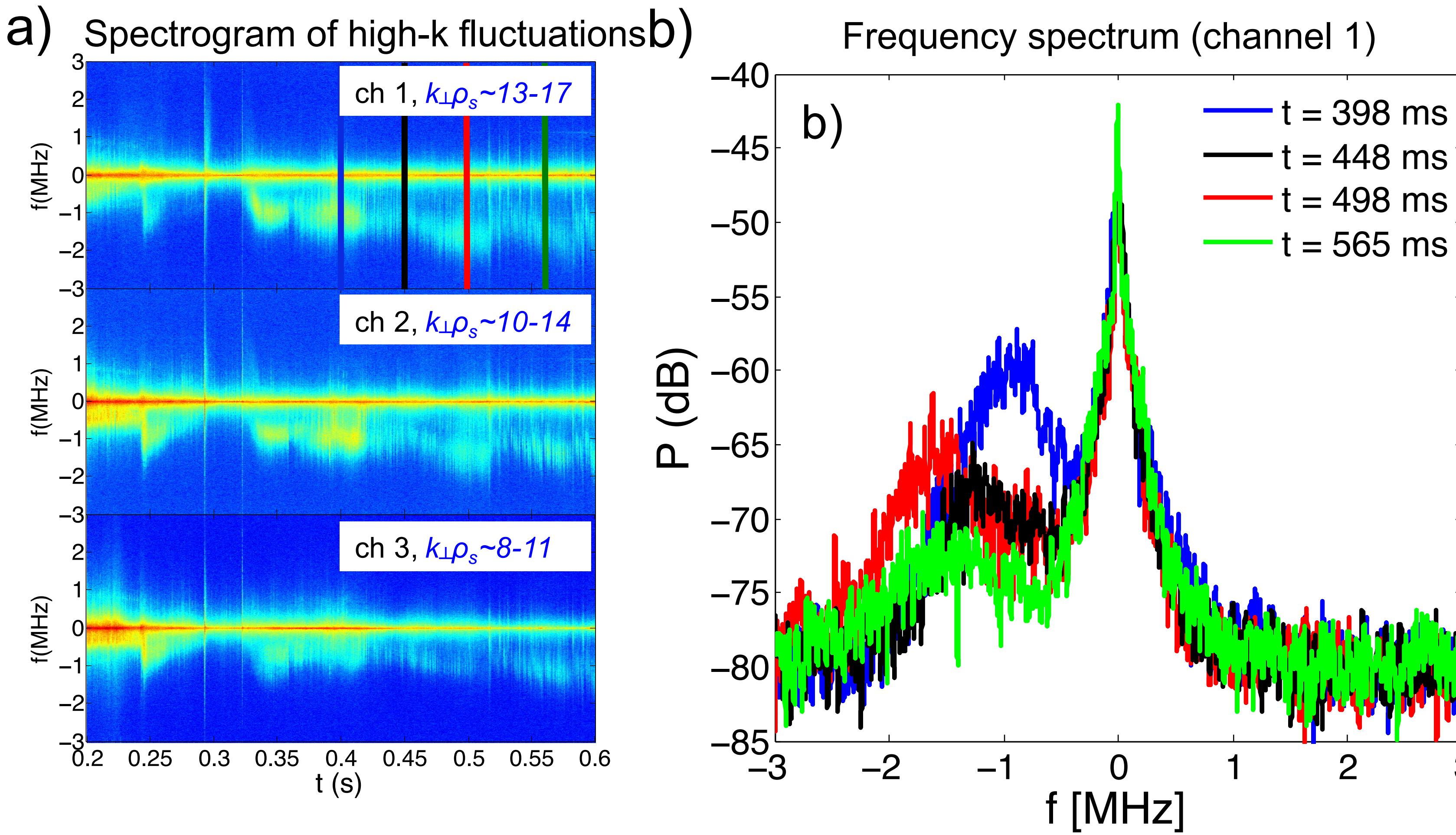
➔ *Suggests high-k measurement is more relevant to ETG transport than previously thought.*

[*] Roach PPCF 2005, 2009, Joiner PPCF 2006, Guttenfelder PoP 2011, NF 2013

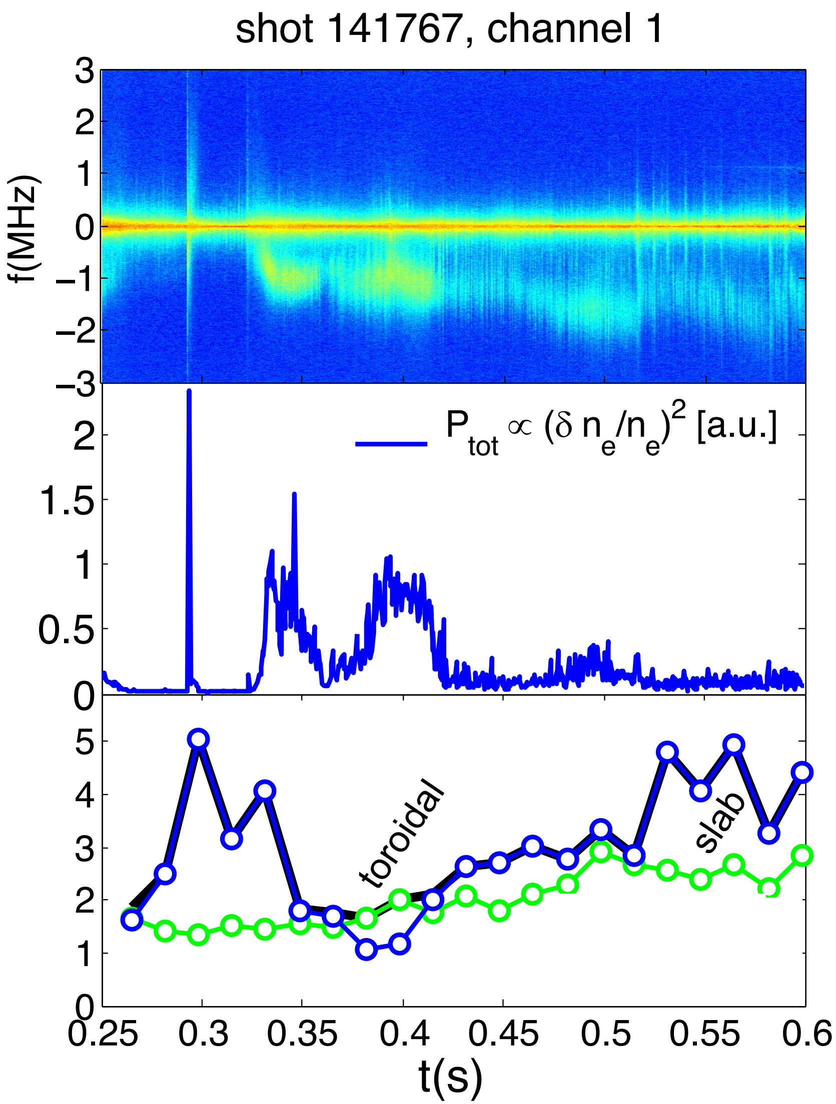
Discharge conditions



Spectrogram of high-k density fluctuations



High-k Density Fluctuations are Linearly Stabilized by Density Gradient through the Critical Gradient



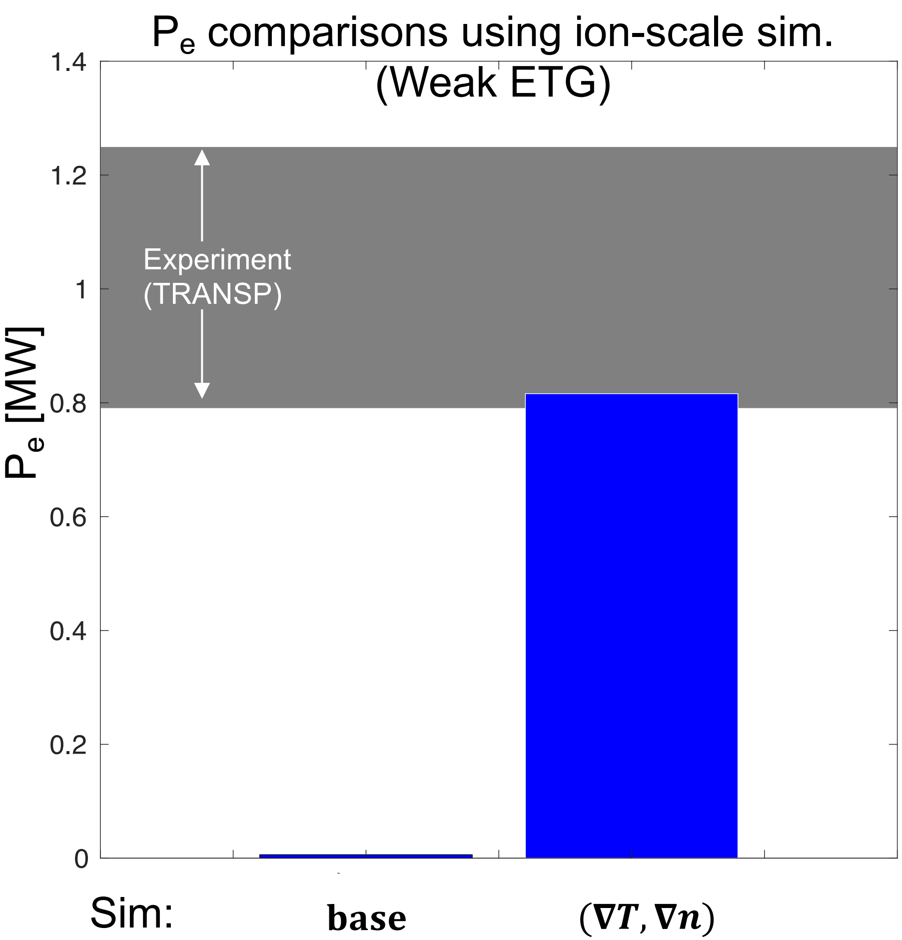
- ***R/L_{ne}*** is a *linear* ***stabilizing*** mechanism when it dominates the Jenko critical gradient (Jenko PoP 2001).

$$(R/L_{Te})_{crit} = \max \begin{cases} 0.8R/L_{ne} \\ f(\tau, \hat{s}/q, \varepsilon, \varepsilon\, d\kappa/d\varepsilon) \end{cases}$$

- ***R/L_{ne}*** increases and fluctuations decrease.
- ***R/L_{ne}*** increases at constant **(R/L_{Te}^{exp}) - $(R/L_{Te})_{crit}$** suggests ***R/L_{ne}*** further ***nonlinearly*** stabilizes turbulence.

$(R/L_{Te})_{crit}$ Jenko		
$f(\tau, \hat{s}/q, \varepsilon, \varepsilon\, d\kappa/d\varepsilon)$	toroidal
$0.8R/L_{ne}$	slab

Weak ETG Condition: electron-scale turbulence simulation can match P_e

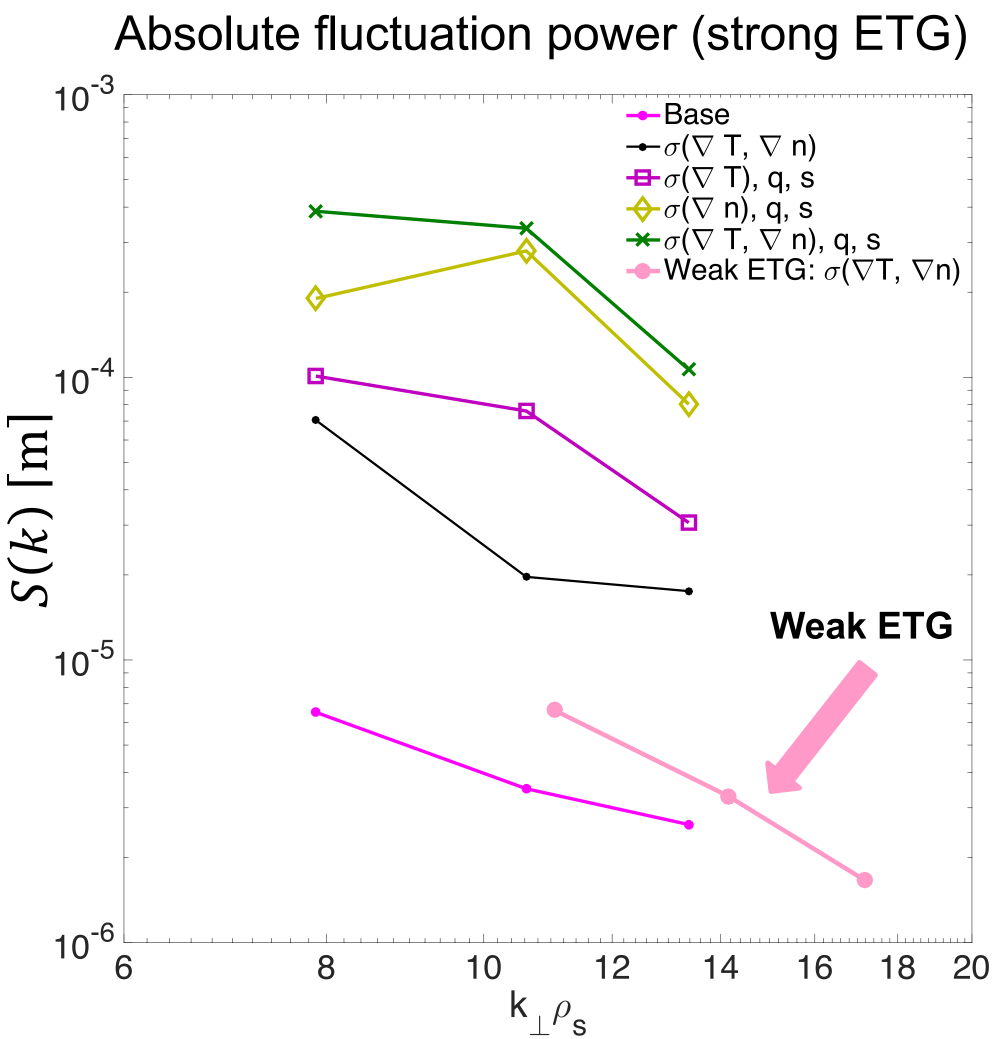


Perform 2 'big-box' e- scale sims.

'Big-box' electron-scale sim

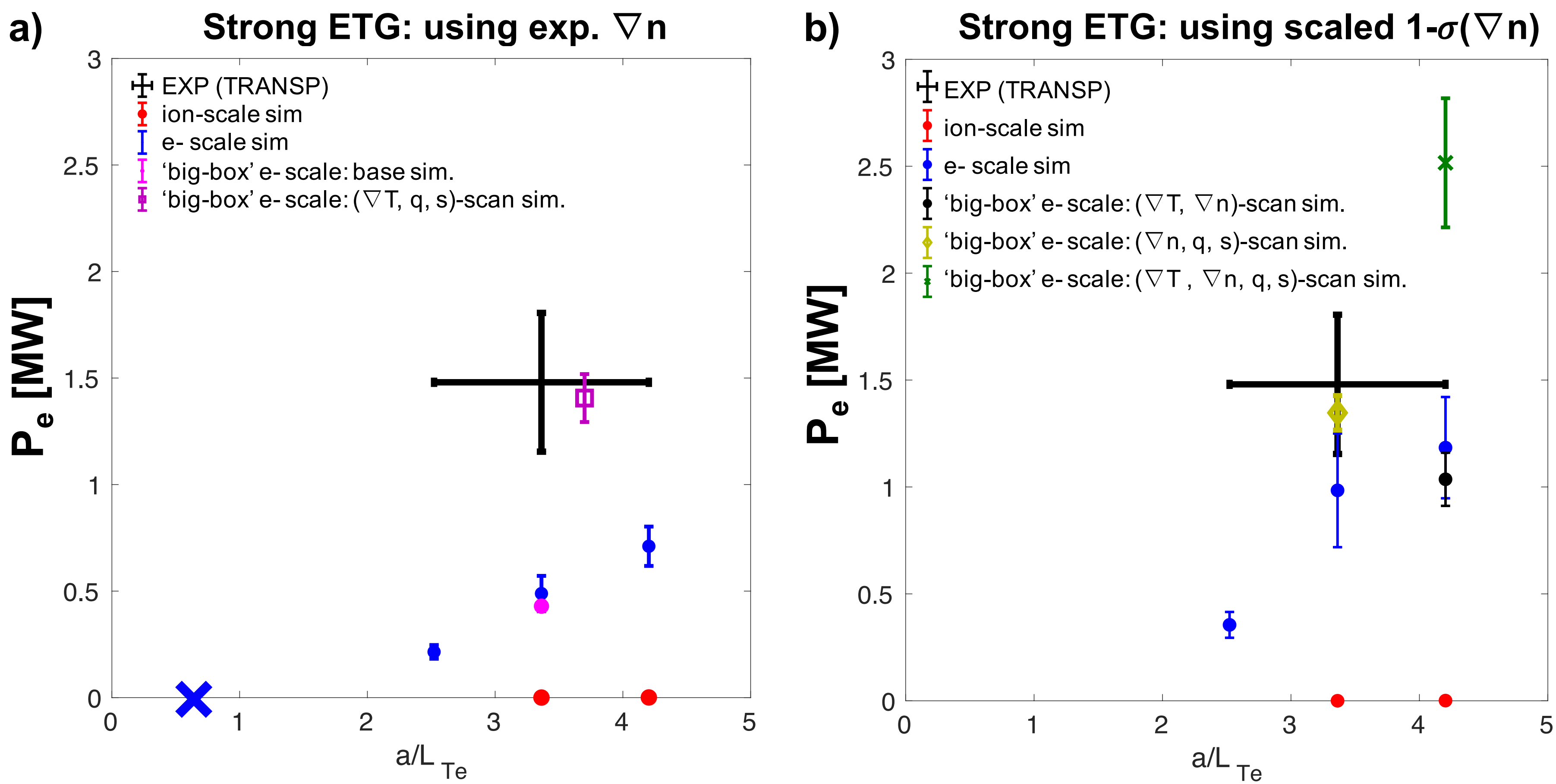
- Base (exp parameters): $P_e^{sim} \sim 0$
- $\sigma(\nabla T, \nabla n)$ scan: Match P_e
- e- scale turbulence close to marginal

Compare fluctuation level ratio between 5 ‘big-box’ sims. for the strong ETG to the weak ETG condition



- Experiment since not absolutely calibrated.
- Synthetic spectra have absolute units.

Total thermal transport budget Strong ETG

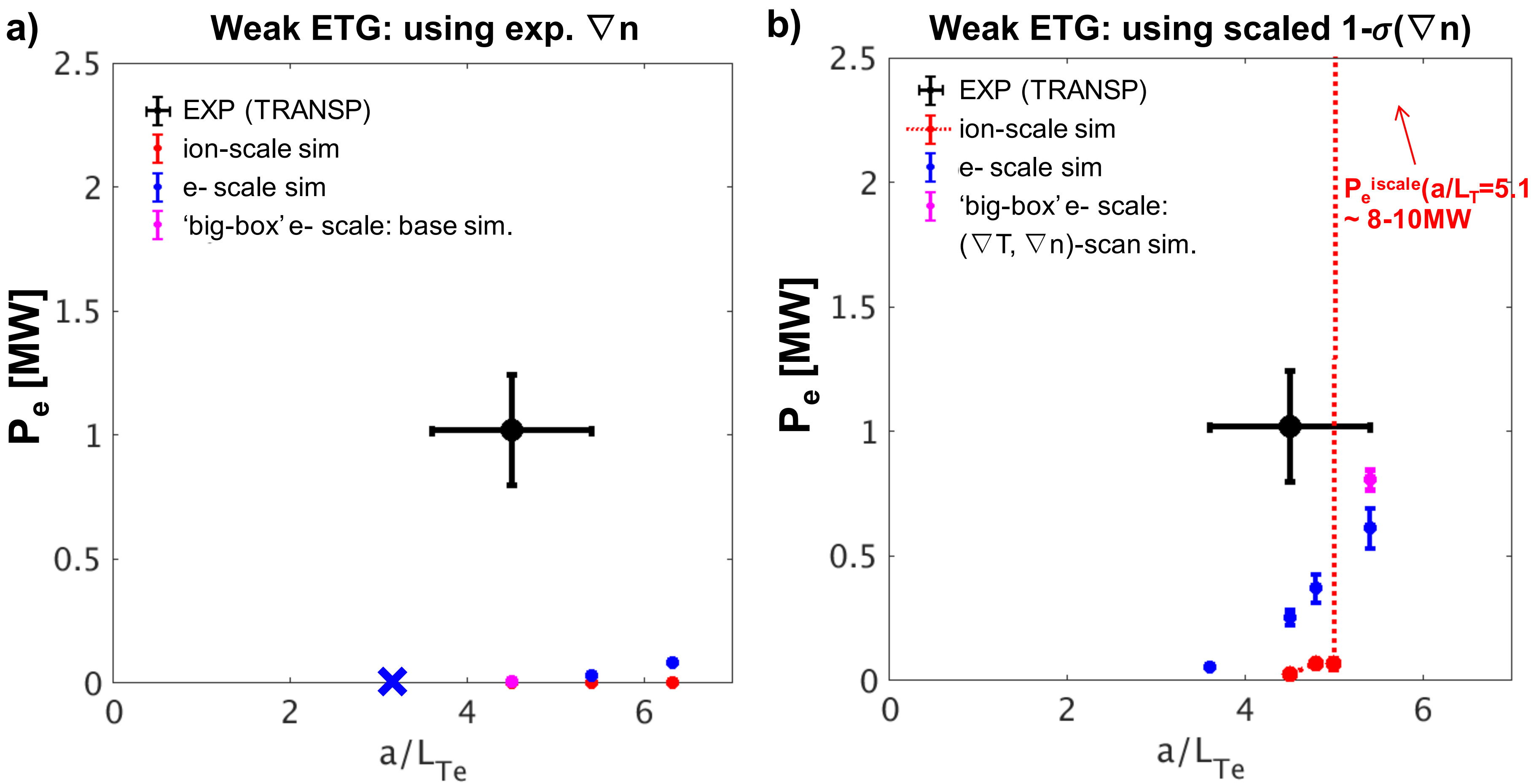


$a/L_{te}^{crit,ETG} \sim 0.66$

$\sigma(a/L_{Te}) \sim 25\%$, $\sigma(a/L_{ne}) \sim 50\%$

$a/L_{te} = 3.36$, $a/Ln_e = 1.0048$, $q = 3.79$, $s = 1.8$ (toroidal)

Total thermal transport budget Weak ETG



$a/L_{te}^{crit,ETG} \sim 3$

$\sigma(a/L_{Te}) \sim 30\%$, $\sigma(a/L_{ne}) \sim 30\%$,

$a/L_{Te} = 4.5$, $a/L_{n_e} = 4.06$, $q = 3.07$, $s = 2.35$ (slab)