# Comparing Turbulence Measurements with Simulations

## *Experimental, Multi-Machine Tutorial on Validation of Nonlinear Gyrokinetic Transport Models*

A. E. White (MIT) with thanks to
T. Goerler (MP-IPP), M. Greenwald (MIT)
W. Guttenfelder (PPPL), C. Holland (UCSD), N. T. Howard (MIT)

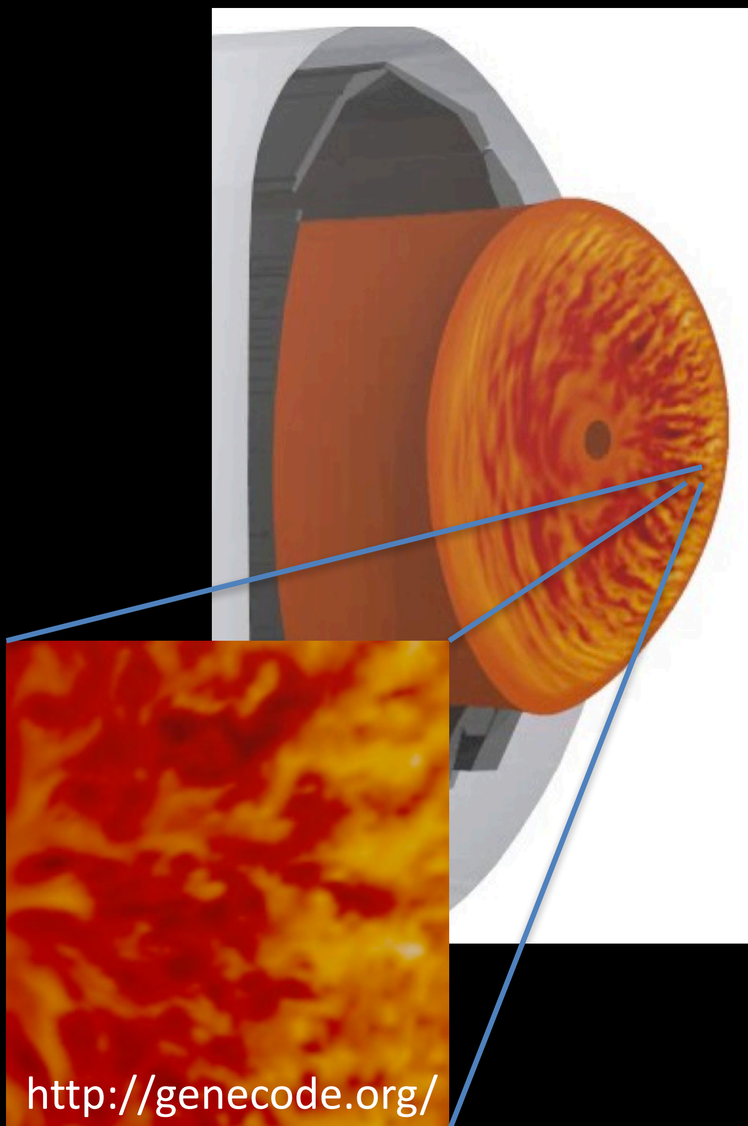
17th European Fusion Theory Conference
9 - 12 October 2017, Athens - Greece

NSE
Nuclear Science
and Engineering
science : systems : society

# Validation in Science and Engineering

- **Science**
  - Extends scientific method into areas where understanding theory requires extensive numerical simulation
  - Seeking explanations, deeper understanding of physics
- **Engineering**
  - No claim that the model in question is correct or complete, only that it is useful
  - Seeking the "best approximate model”

# In Core of Fusion Plasmas Turbulence Plays Important Role in Transport




- **Eddies are on scales of electron gyro-radius and ion gyro-radius**
  **$\rho_e \approx$ 0.06mm**
  **$\rho_i \approx$ 3.6mm**
  **at 10keV and 5.4 T**
- **Size of plasma a ≈ 1m**
- **Frequencies 10kHz to over 1 MHz**
- **Fluctuation amplitudes, $\tilde{n}/n \leq$ 0.1-10%**
- **Broad spatiotemporal range presents challenge for experiments and simulations**

# Core Turbulence In Fusion Plasmas Is Described By Nonlinear Gyrokinetics

- **Gyrokinetics describes turbulence in stellarators and tokamaks**
  (J. Alonso and F. Parra – Thurs. Talks)

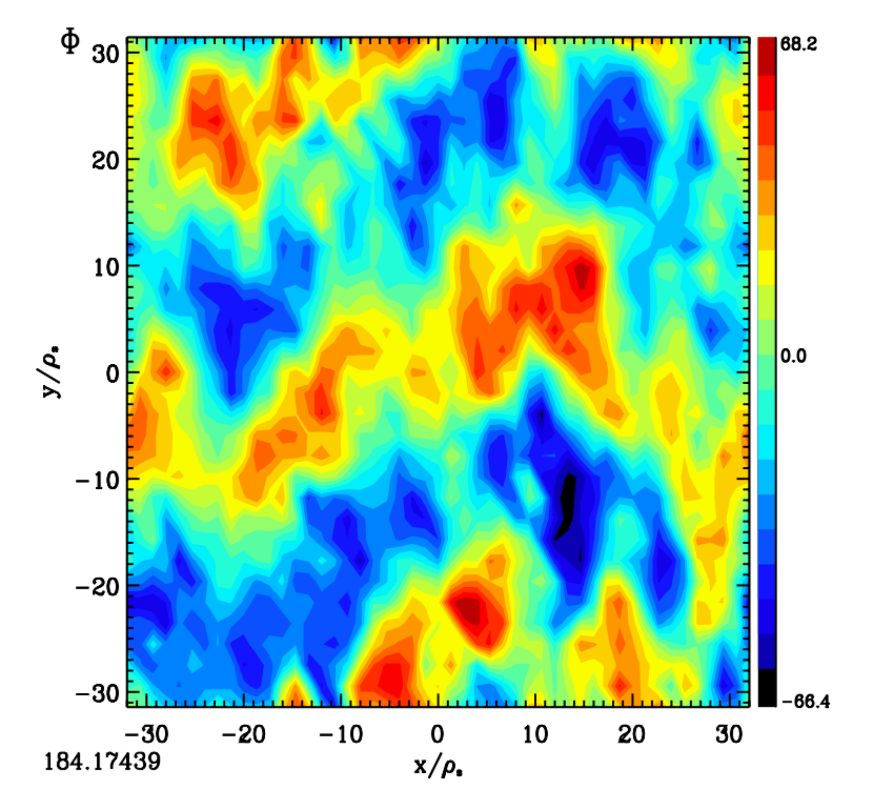
- **Theory actively being developed**

  - **Details of fast ion – turbulence interactions**
    (G. Wilkie – afternoon talk)

  - **Effects of a non-axisymmetric 3-D equilibrium magnetic field**
    (A. Zocco Tues. Talk)

- **Numerical approaches are also evolving; e.g. electromagnetic gyrokinetic simulations**
  (A. Mishchenko - next)

**ITG turbulence in W7X, study with GENE, showing high-resolution simulation output**




Xanthopoulos PRL 2007

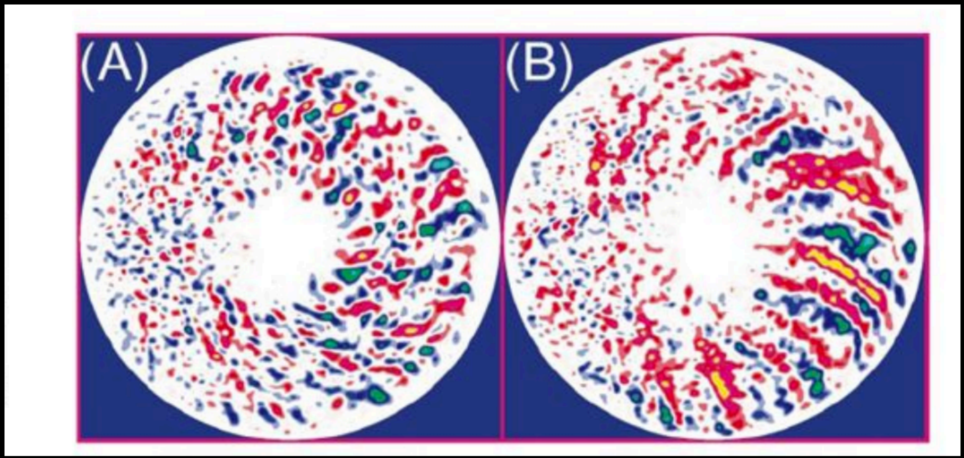
# A (Very) Brief History of Comparing Gyrokinetic Codes with Experiment

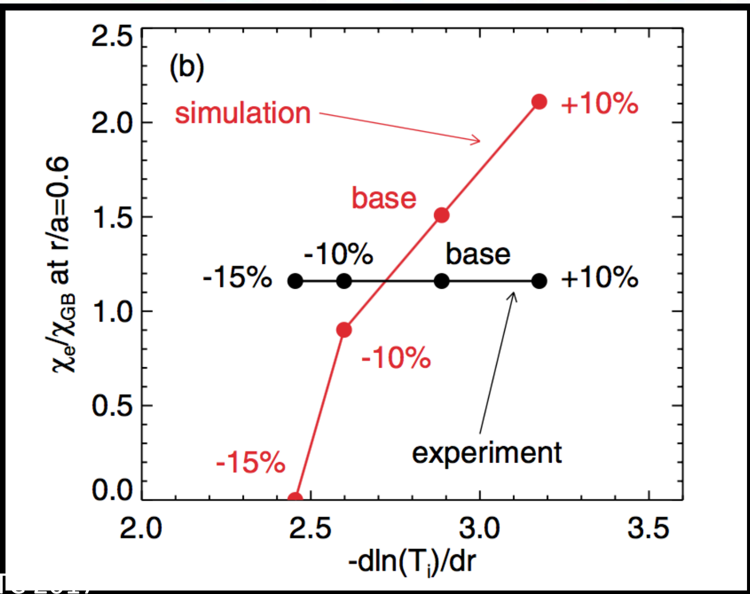
- **1980s-1990s, rough models available and discrepancies with experiments were orders of magnitude**

- **1990s-2000s, higher physics fidelity led to breakthroughs**

  – **Demonstration of Zonal Flow – turbulence interactions** [Lin Science 1998]

  – **Ability to match ion and electron thermal diffusivities within experimental error** [Candy PRL 2003]



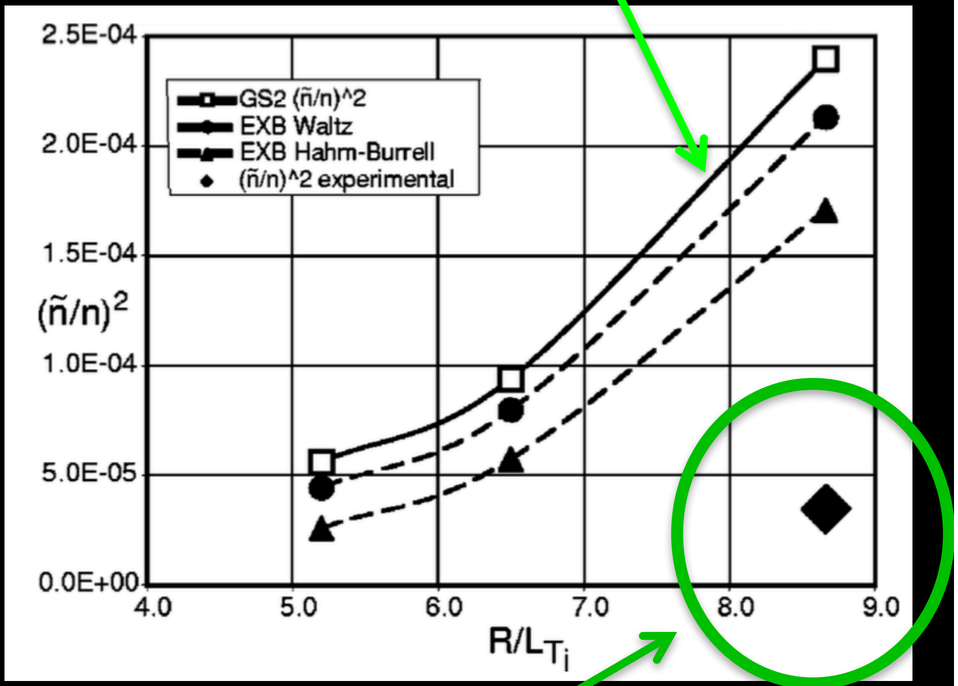
# Turbulence Measurements Were Key Element of the First "Validation" Paper

- **Nonlinear gyrokinetic simulations of DIII-D L-mode** [Ross PoP 2002]
  - Electron & ion heat fluxes
  - Long-wavelength density fluctuations measured with Beam Emission Spectroscopy (BES)

- **Different models run with GS2 – with and without ExB shear**

- **Understanding discrepancies would be addressed with further experiment and simulation**

Simulation results (three different models) for density fluctuation level




Experimental low-k ($k_\theta \rho_s < 0.5$) density fluctuation level

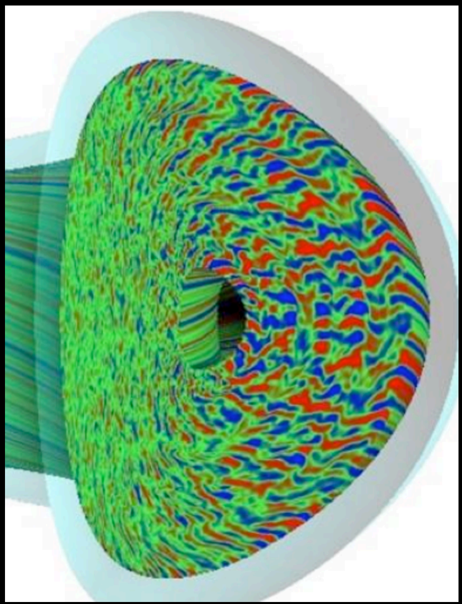
# Validation Work Has Most Often Been Done Using "δf" Gyrokinetic Codes

- **Conventional "δf" formulation, GK equations are derived using expansion in small $\rho^* = \rho_i/a$, starting from the Fokker–Planck equation**

- **At first order, fluctuations and fluxes are calculated as code outputs**

- **A single code can be used to run many different models**

- **Validation has revealed importance of**
  - ✓ Realistic geometry
  - ✓ Kinetic electrons
  - ✓ Collisions
  - ✓ Effects of ExB shear and Zonal Flows
  - ✓ Electromagnetic effects (sometimes)
  - ✓ Multi-scale effects (ITG-TEM-ETG) (sometimes)

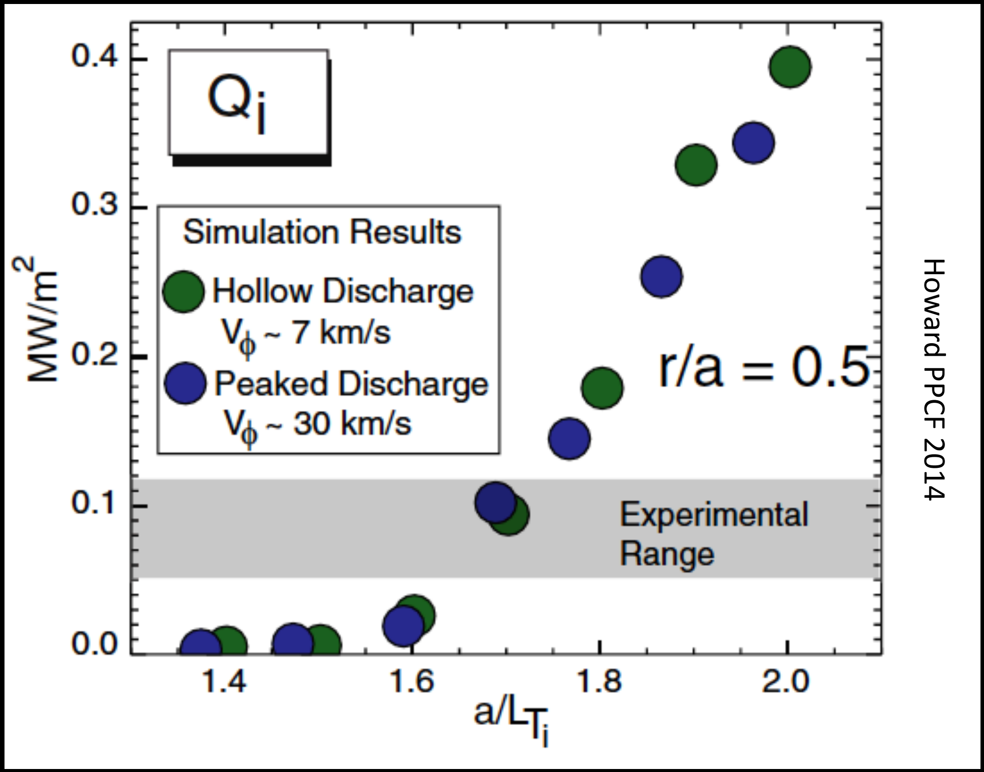


https://fusion.gat.com/theory

# Validation Efforts Have Revealed Many Challenges to Quantitative Comparison

- **Experimental Gradients Usually Close to Critical Gradient**
- **Very stiff: ~10% change in $a/L_{Ti}$ gives 10x increase in heat flux**
- **Within experimental range of $a/L_{Ti}$, move from stable to unstable**
- **Parameter scans (multiple code runs) must be used to address model sensitivity**

**GYRO simulations of C-Mod L-mode plasmas**

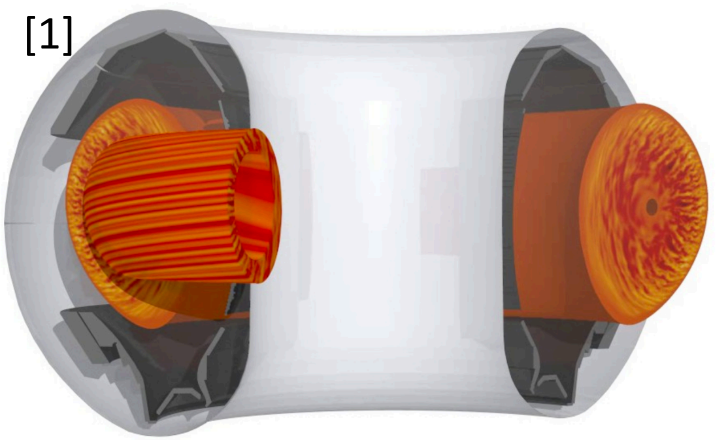



Howard PPCF 2014

# Validation Requires Dedicated Experiments to Optimize Comparisons

- **Nonlinear gyrokinetic codes take experimental data as input**
- **Experimental goals:**
- **reduce error and uncertainty on the inputs to the code**
- **reduce error on measured turbulence and inferred fluxes that are compared to code outputs**

[1]



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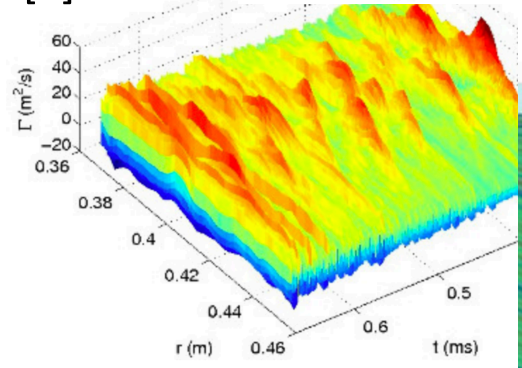


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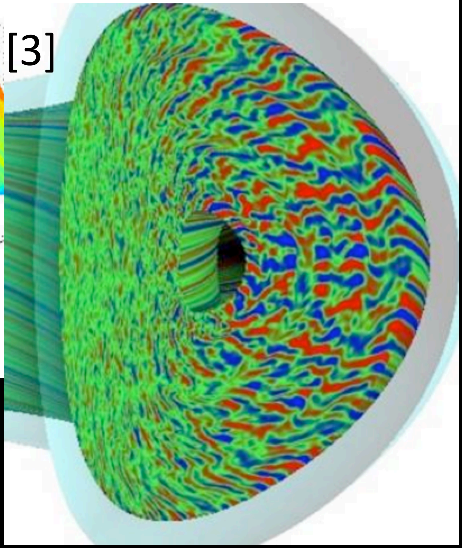
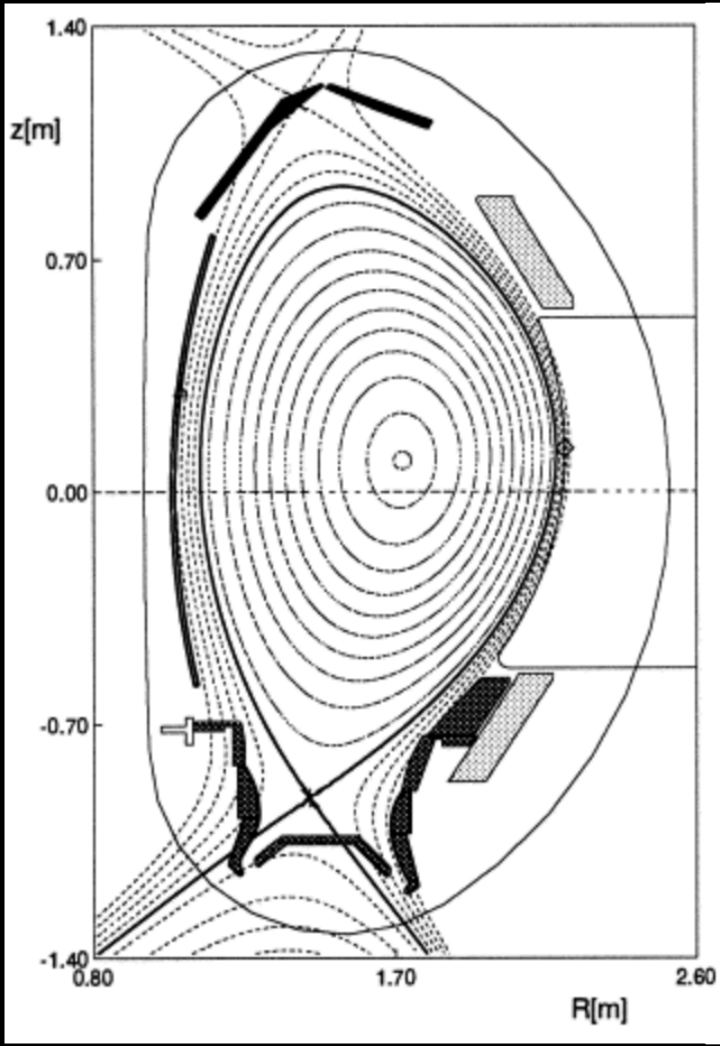


[1] http://genecode.org/ [2] http://physics.aalto.fi/en/groups/fusion/research/elmfire/ [3] https://fusion.gat.com/theory

# Magnetic Equilibrium Reconstruction Cannot be Taken For Granted

- **Variety of codes in the experimental community**
  - EFIT widely used in the US
  - CLISTE used at AUG
- **Iterating with magnetic and kinetic data or MSE/Polarimeter helps constrain results, reduce mapping errors that affect pressure profiles**
- **Error in equilibrium reconstruction, q, s-hat, can be reduced < 5-10%**



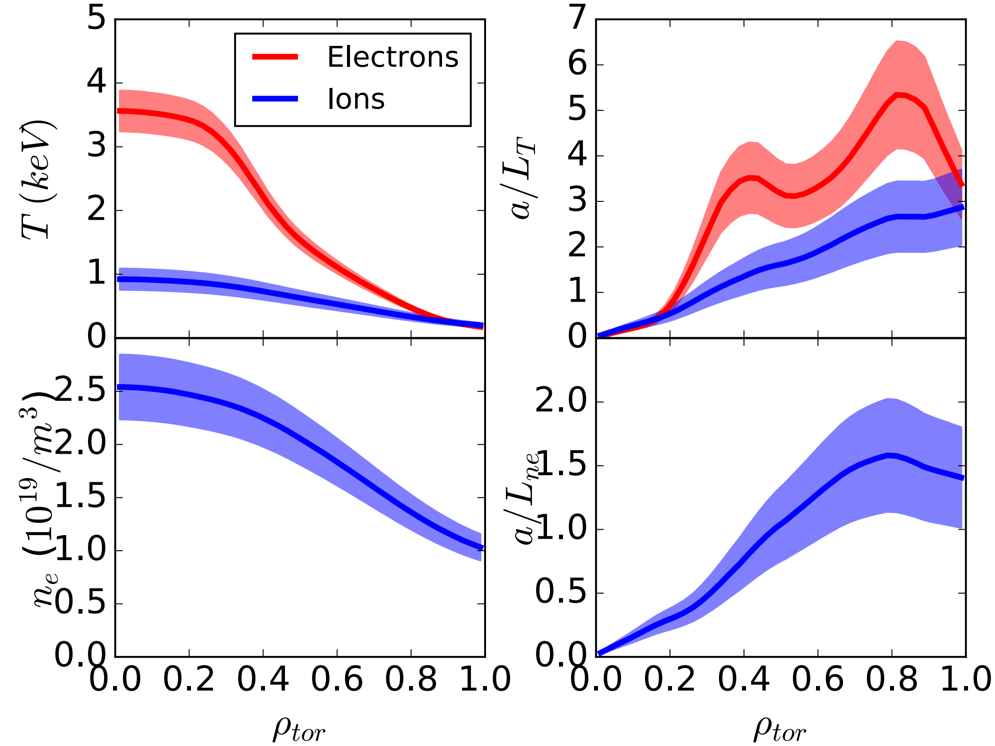

Schneider FED 2000

# Even High Quality Radial Profile Measurements Can Have Large Errors

- **Electron temperature and density profiles are measured reliably with high temporal and spatial resolution**
  **$a/L_{Te}$, $a/Ln$ ~ 10-20 %**

- **Ion temperature and rotation profiles more challenging and not available in all conditions**
  **$a/L_{Ti}$ ~ 15-30%**

- **Redundancy is important, time averaging, repeat shots**



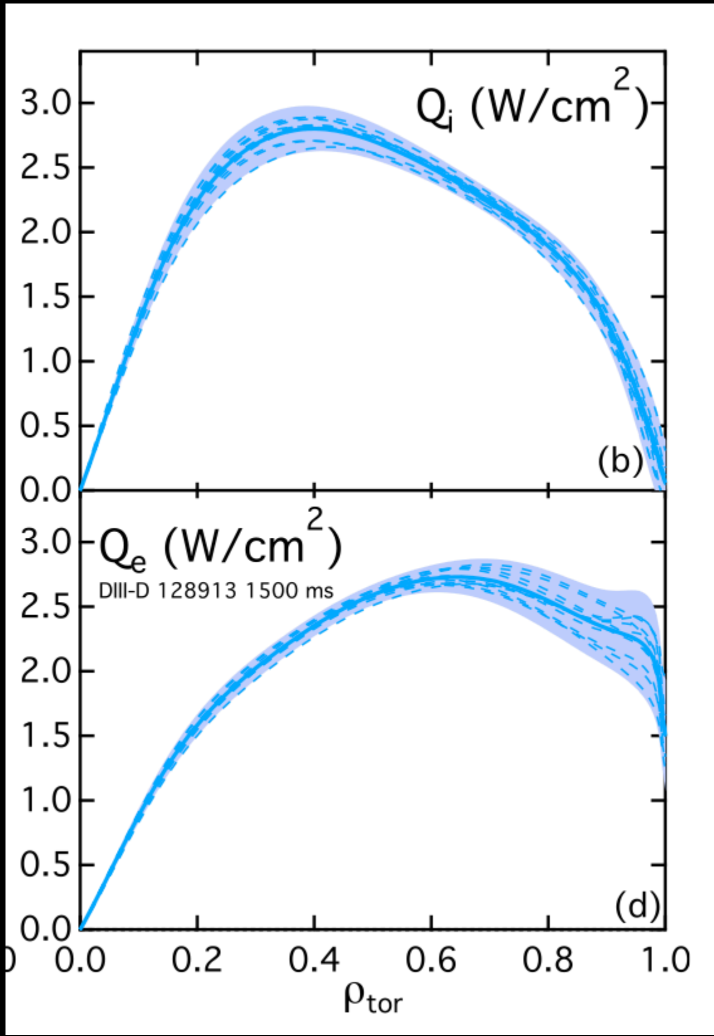

AUG example, courtesy S. Freethy APS 2017

# Power Balance Calculations Are First Point of Comparison With Gyrokinetic Codes

- **Codes like TRANSP, ASTRA, etc. used to calculate experimental transport levels**
  - Radiated power measurements
  - Zeff, measurements of impurities
  - Fast ion pressure
  - Etc.

- **Several internal consistency checks are possible to reveal systematic errors**

- **Error analysis of power balance is non-trivial, error ~ 10-30%**
  [Petty NF 1998, White PoP 2010, Holland PoP 2016, Paezi FST 2017]




**Holland PoP 2016**

# Large Uncertainties and Model Sensitivity Motivate Comparisons with Turbulence

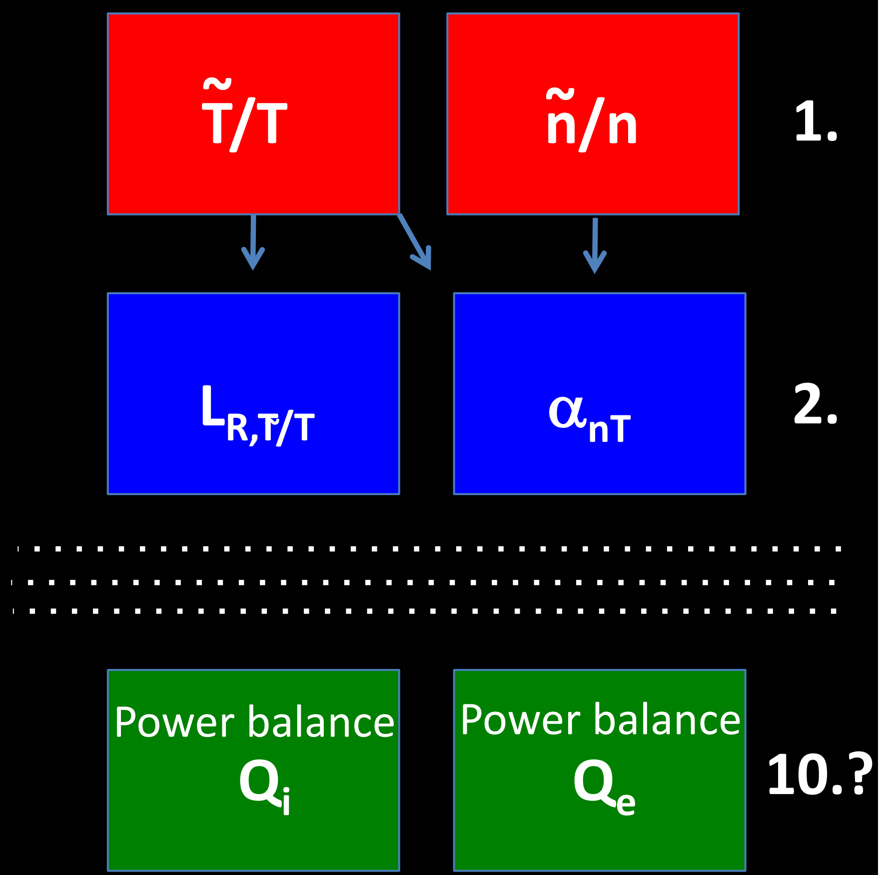
- **Challenges addressed:**
  Fortuitous agreement/disagreement
  Discriminating between models

- **Fluctuation levels tend to be measured most directly, are at highest level**

- **Correlation lengths, cross-phase angles are at second level**

- **Inferred heat fluxes from power balance at lowest level, because not measured directly**

**Primacy Hierarchy**




Terry PoP 2008, Greenwald PoP 2010

# Many Diagnostics Used To Measure Plasma Turbulence And Compare With Simulations

## *Density Fluctuations, $\tilde{n}/n$*

**Beam Emission Spectroscopy (BES)**
**Low k, ITG/TEM**
$k_\perp \rho_s < 0.5$

**Doppler reflectometer (DR)**
**Intermediate k, ITG/TEM/ETG**
$0.5 < k_\perp \rho_s < 5$

**High-k Coherent scattering**
**High k, ETG**
$k_\perp \rho_s > 5$

## *Electron Temperature Fluctuations, $\tilde{T}/T$*

**Correlation Electron Cyclotron Emission (CECE)**
**Low k, ITG/TEM**
$k_\perp \rho_s < 0.5$

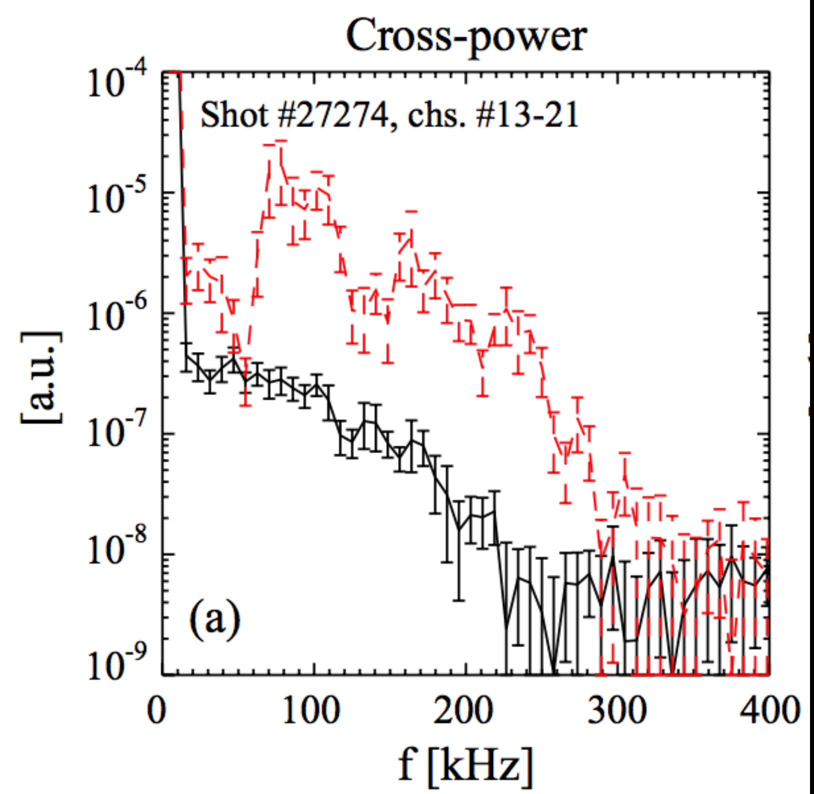
## *And more…*

- UF-CHERS Ti, n fluctuations
- HIBP $\phi$, n fluctuations
- PCI line integrated $\tilde{n}/n$
- etc.

# Beam Emission Spectroscopy (BES) Used To Measure Low-k Density Fluctuations

- **BES sample volume determined by optics + atomic physics of beam-plasma interaction**
- **Measurement of absolute fluctuation level data is possible - intensity of light fluctuations**
- **Good spatiotemporal resolution**
- **Neutral beam injection required, perturbative in some plasmas**
- **Can measure**
  - **Power spectrum**
  - **Fluctuation level**
  - **Radial and poloidal correlation lengths**
  - **Eddy motion, Eddy tilt**

**MAST BES data**




Field PPCF 2014

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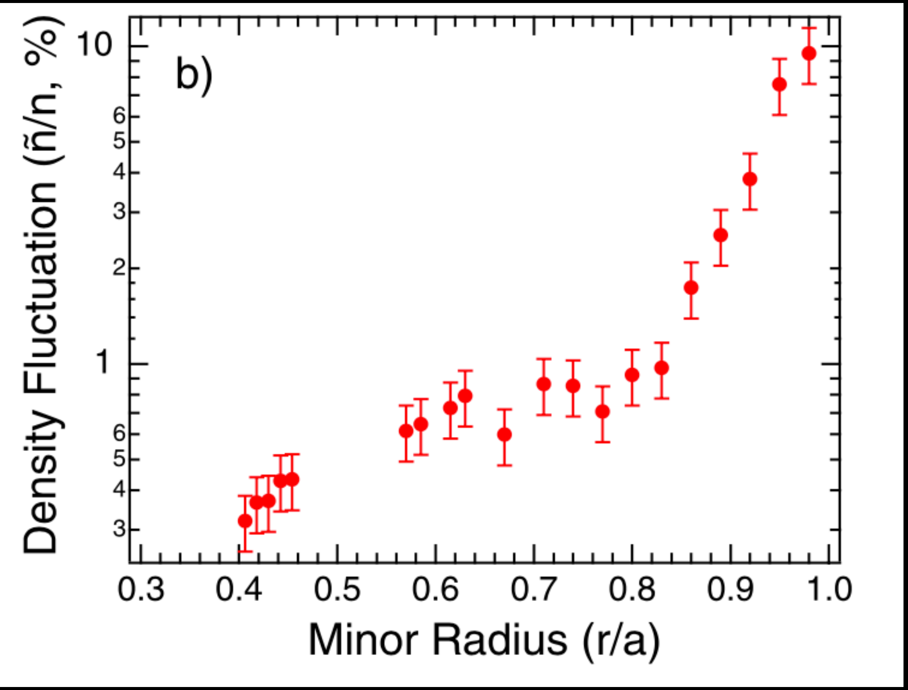
**DIII-D BES data**




McKee 2007

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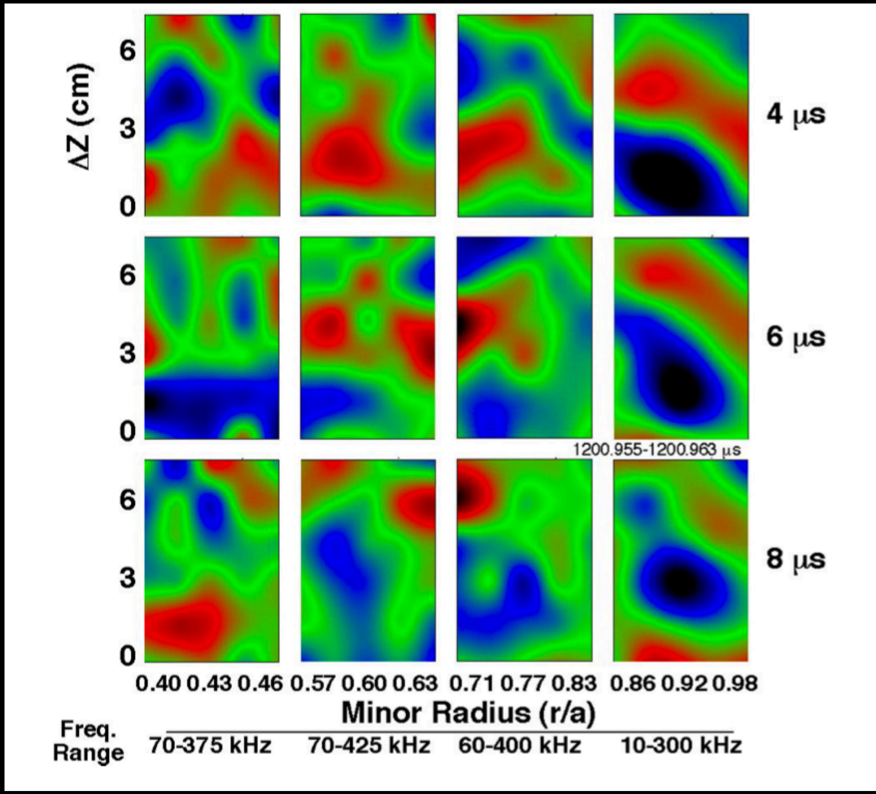
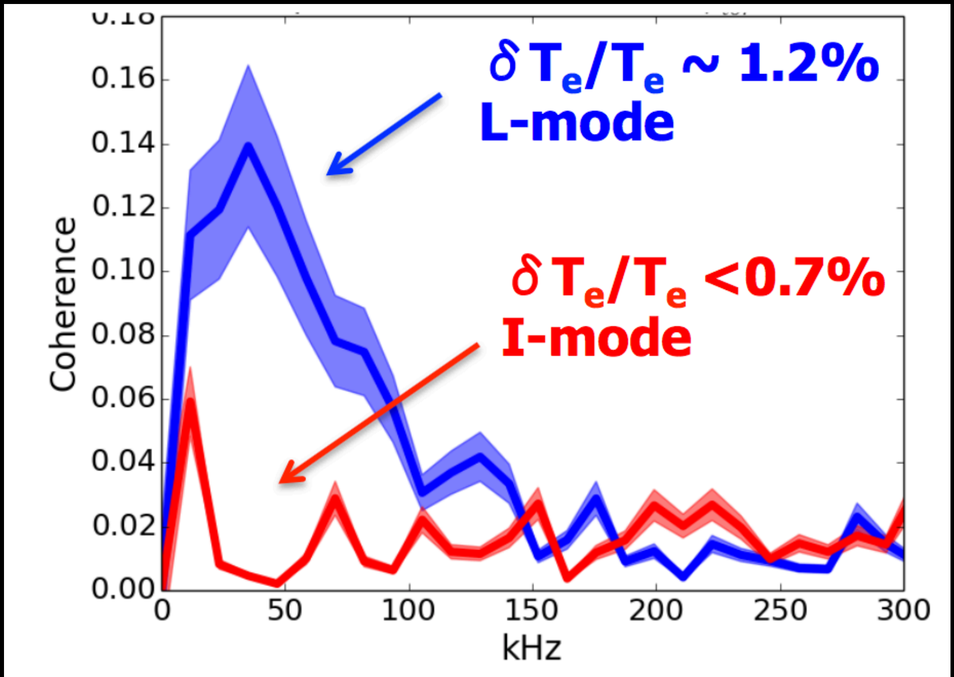



McKee 2007

# Low-k Electron Temperature Fluctuations from Correlation ECE (CECE) Radiometers

- **CECE sample volume is determined by optics + physics of EC emission**
- **Correlate two electron cyclotron emission signals to extract turbulence from noise**
- **Good spatial resolution, non-perturbative, passive, but time averaging required to reduce noise**
- **Cam measure**
  - **Power spectrum**
  - **Fluctuation level**
  - **Radial correlation lengths**

**First at W7-AS and TEXT** [Sattler PRL 1994, Cima PoP 1995], **now widespread AUG, C-Mod, DIII-D, TCV, W7X, EAST**




**C-Mod Data**

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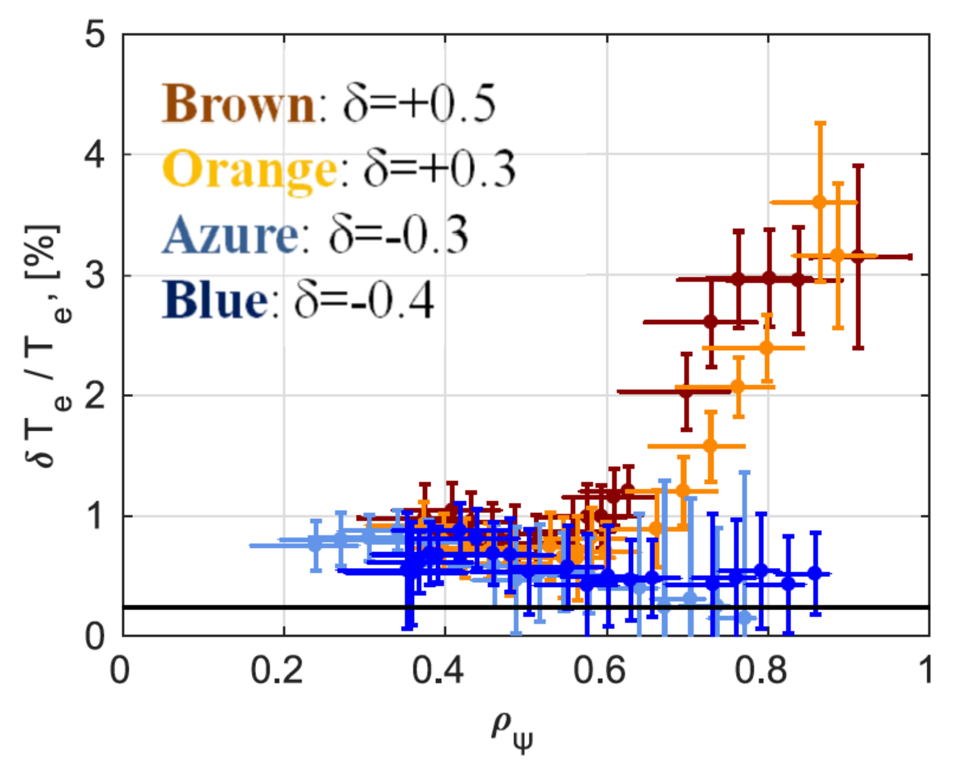



**TCV Data**

# Phase Angle Between Low –k $\tilde{n}_e$ and $\tilde{T}_e$ Measured With Coupled Reflectometer and Radiometer

- **nT-phase angle measurements first done at W7AS** [Haese RSI 1999]
- **Reflectometer cut-off at one frequency at same position as ECE resonance at different frequency**
- **n-T phase diagnostics now operating at AUG and DIII-D and is proposed for EAST and W7-X** [White PoP 2010, Freethy RSI 2016, Cao RSI 2016]

**AUG Data**

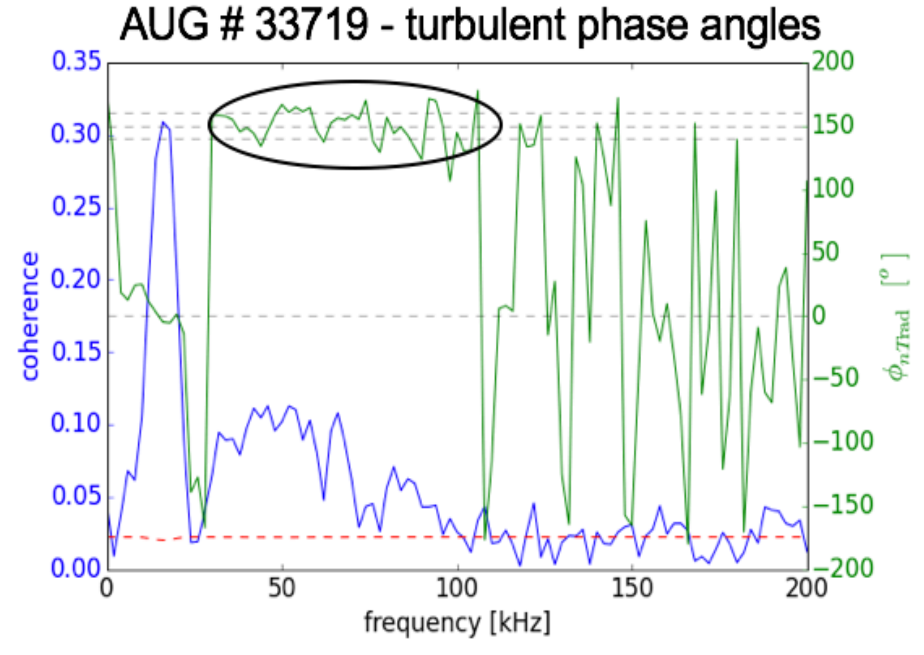
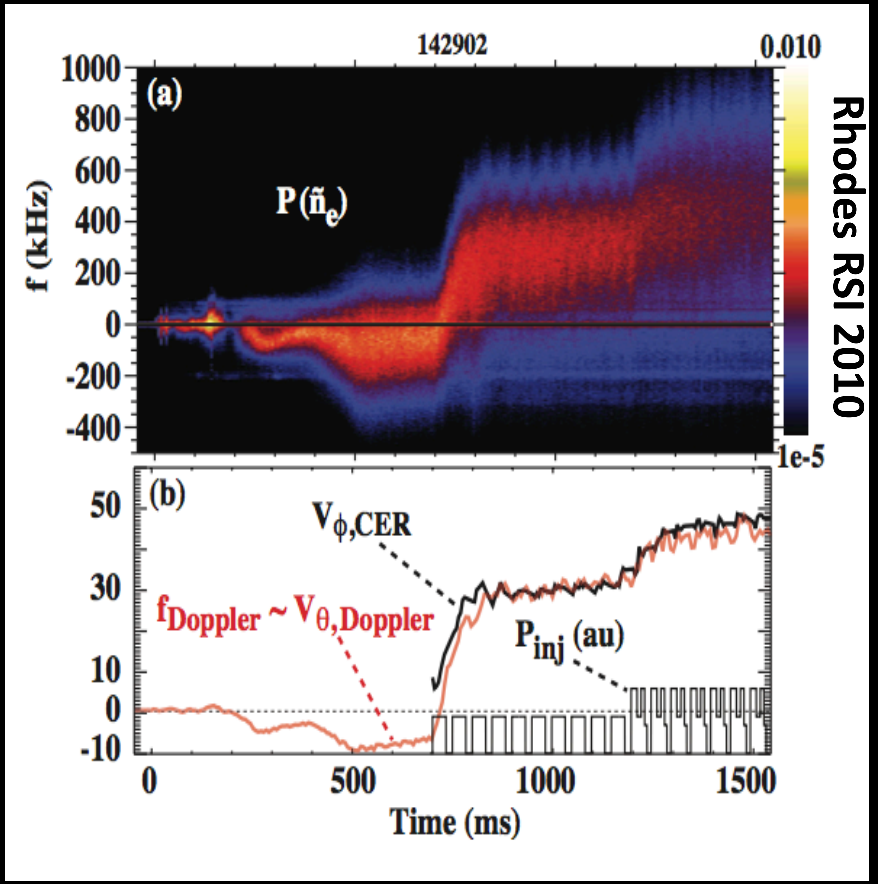



**Figure from S. J. Freethy, US/EU TTF, Williamsburg, VA, April 25-28 2017**

# Doppler Reflectometer Measures Intermediate k-range Density Fluctuations

- **Doppler reflectometer exploits spatial resolution of reflectometery with wavenumber sensitivity of scattering measurements**
- **Bragg condition (scattering) to isolate density fluctuations at particular wavenumber**
- **Frequency spectrum shows peak shifted by plasma rotation (used to measure rotation)**
- **Can measure partial wavenumber spectrum of density fluctuations**

**DIII-D Tokamak Data**



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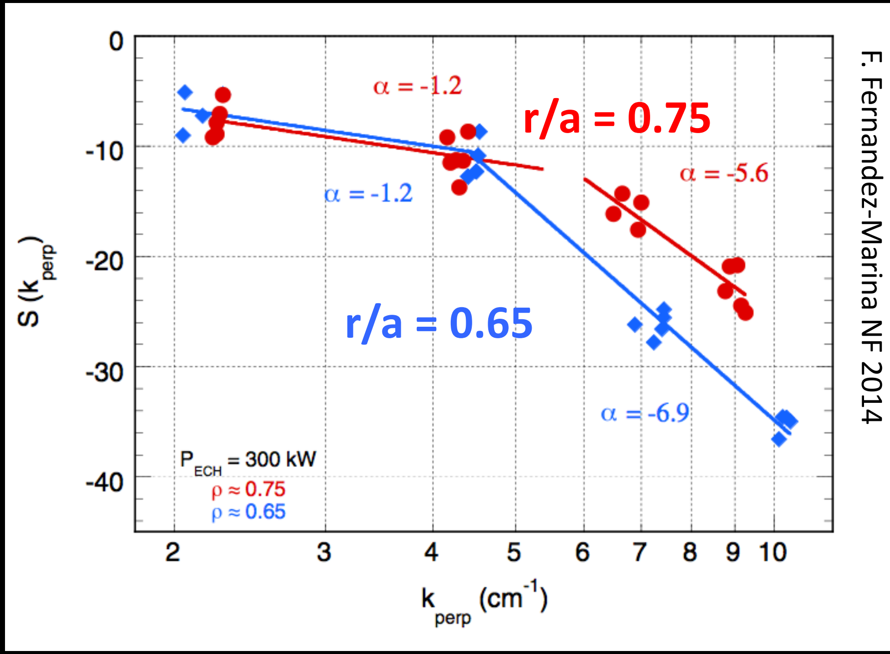
Stellarator TJ-K Data

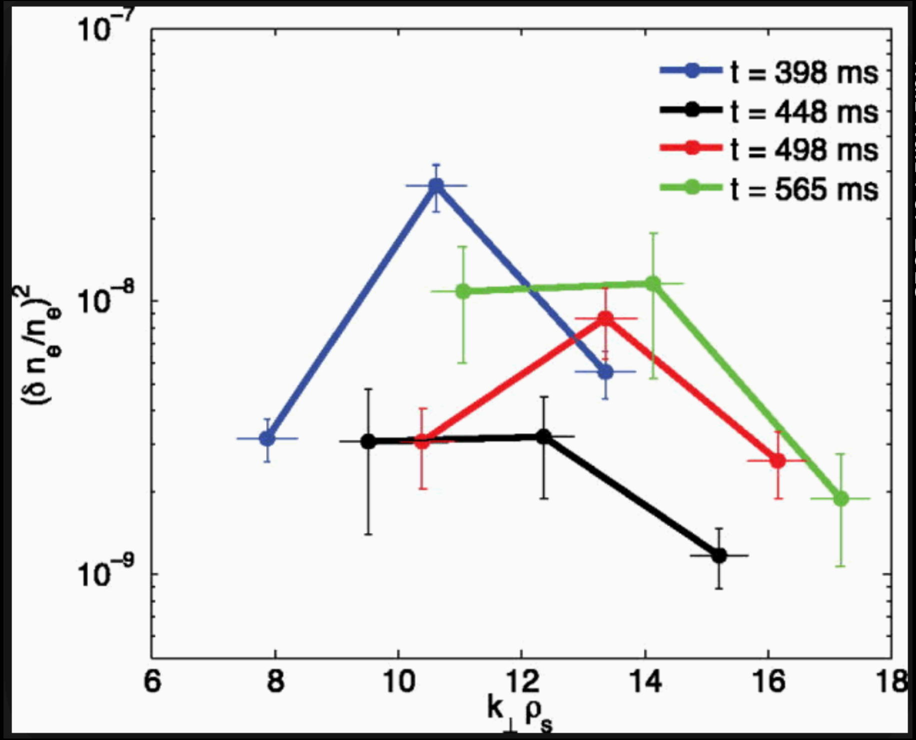



F. Fernandez-Marina NF 2014

# High-k ETG Scale Density Fluctuation Measurements from Coherent Scattering

- **Coherent scattering measures density fluctuations at high wavenumbers**
- **Scattering volume sets spatial resolution, optics/geometry sets the wavenumber detected**
- **Recent advances in coherent scattering diagnostics allow spatially resolved high-k measurements** DIII-D [Rhodes PoP 2007] and NSTX [Smith PRL 2008] and KSTAR [Lee RSI 2016]

NSTX high k scattering data




Ruiz Ruiz PoP 2015

# Fluctuation Diagnostics Cannot Measure the Turbulence Perfectly

- **Each fluctuation diagnostic samples limited range of wavenumbers**
  - **BES, CECE, nT-phase: Low-k,** $k_\perp \rho_s < 0.5$
  - **Doppler Reflectometer: Intermediate-k,** $0.5 < k_\perp \rho_s < 5$
  - **Coherent scattering: High-k,** $5 < k_\perp \rho_s$
- **Measurements are made in the lab frame – plasma is rotating**
- **Gyrokinetic codes output fluctuation spectra as function of wavenumber over broad range, in the plasma frame**
- **Synthetic diagnostics are needed to convert simulation outputs into measurable quantities in lab-frame: frequency and wavenumber spectra, fluctuation levels, correlation lengths, etc.**
- **Sensitivity scans (multiple code runs) used to probe uncertainties**

# Simplest Synthetic Diagnostics Take Spatial Averaging and/or k Sensitivity Into Account

- **Spot-size or sample volume of diagnostic comes into play for measurements like BES, CECE, nT-phase etc.**
- **Wavenumber matching, scattering physics and spot-size effects relevant for Doppler reflectometer, coherent scattering**

Spot size < wavelength,
Wave is detected

Spot size > wavelength,
Wave is NOT detected

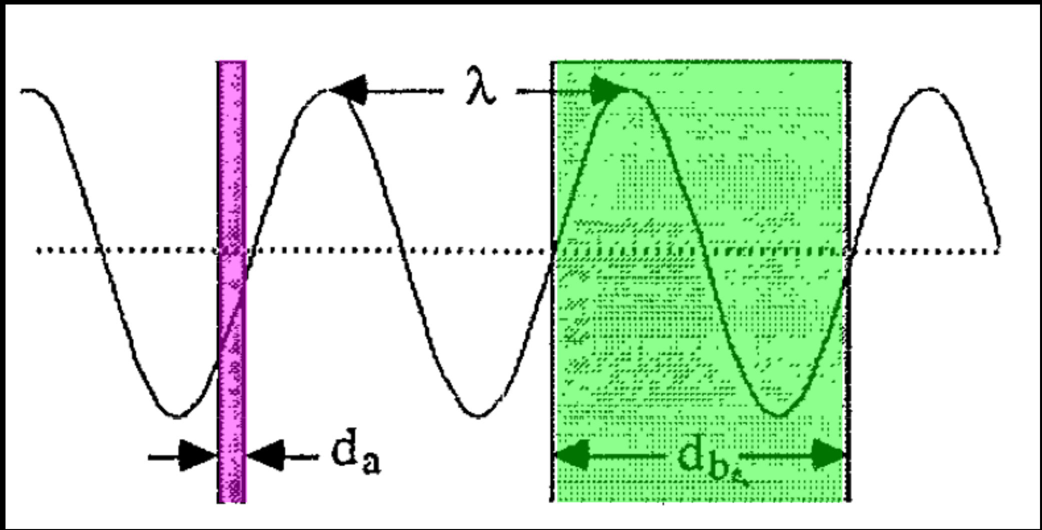
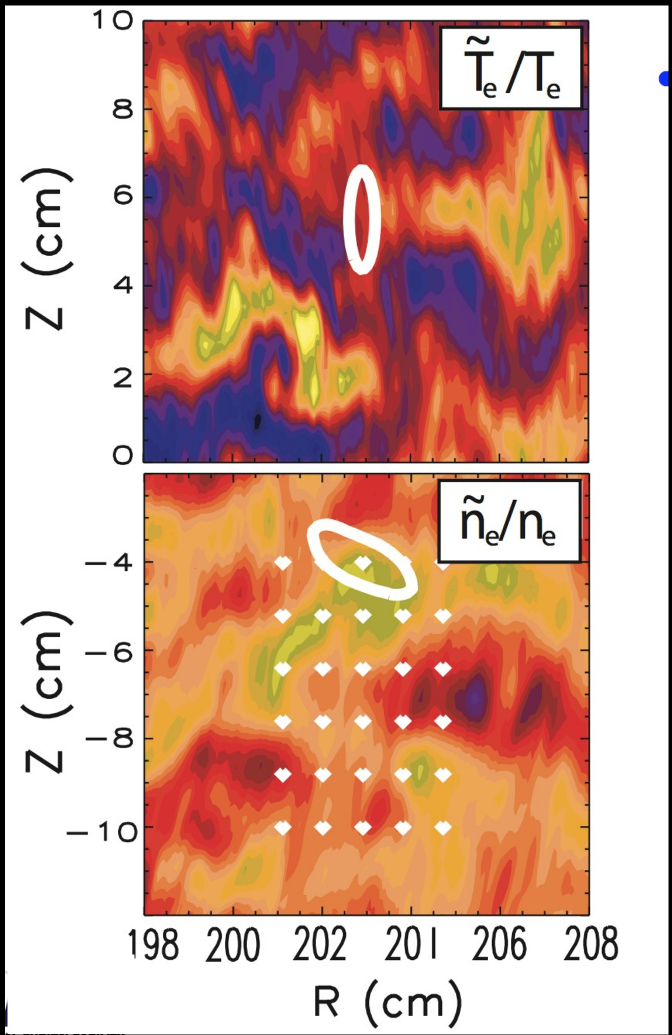
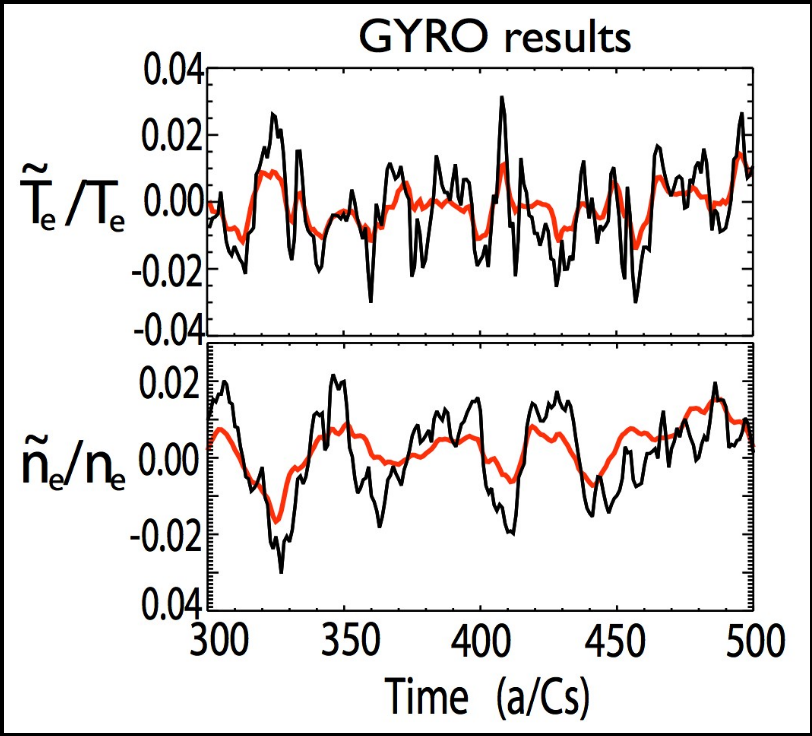



Figure from Bravenec Rev. Sci. Instrum. 88 (l), January 1995

# Applying Synthetic Diagnostic Models Is Like Applying Filters to Raw Simulation Data



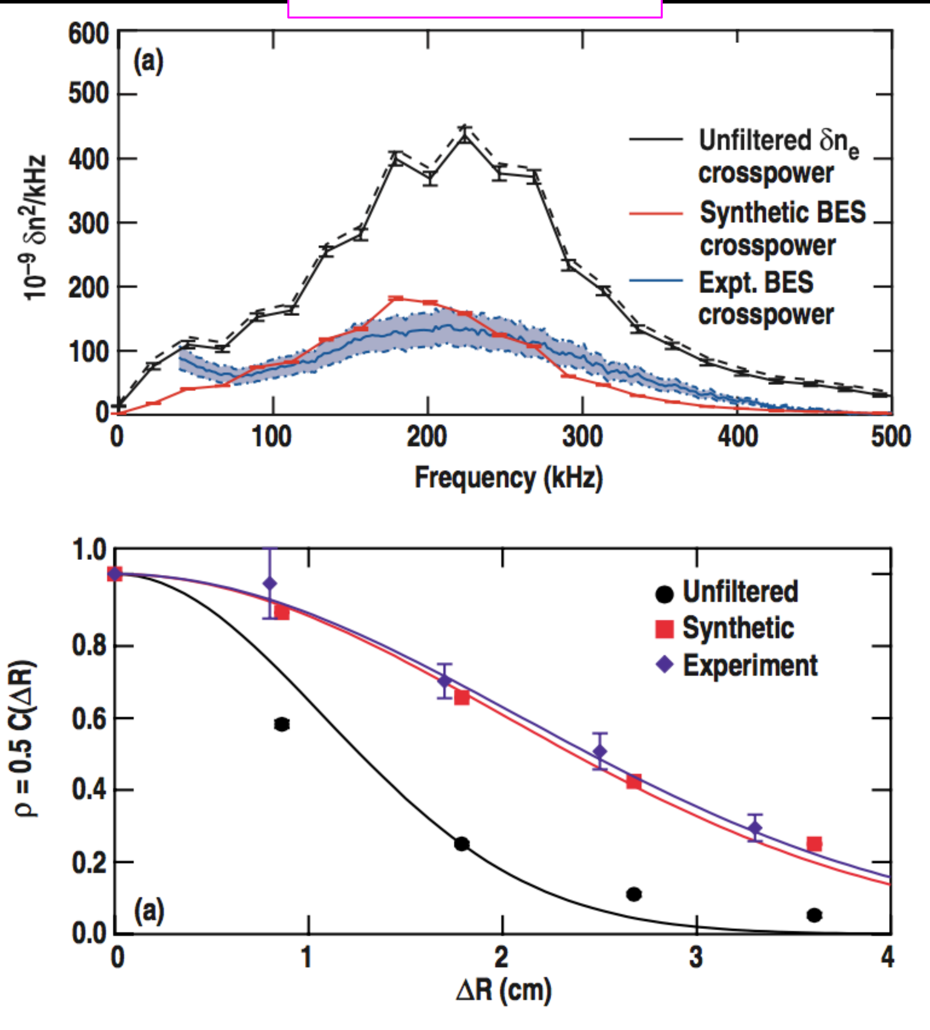




Figures from White APS 2007,
Numerical details in Holland PoP 2009

# Synthetic Diagnostic for BES Gives Example of Several General Results

- **Low-pass filter in k-space leads to reduced fluctuation level and increased correlation length**
- **Without the synthetic diagnostic, simulation results cannot match experiment within error bars**
- **BES synthetic diagnostics have been implemented in several codes**
  - **GYRO** [Holland PoP 2009]
  - **NEMORB** [Field PPCF 2014]
  - **GS2** [Bravenec RSI 2006]

Tokamak DIII-D

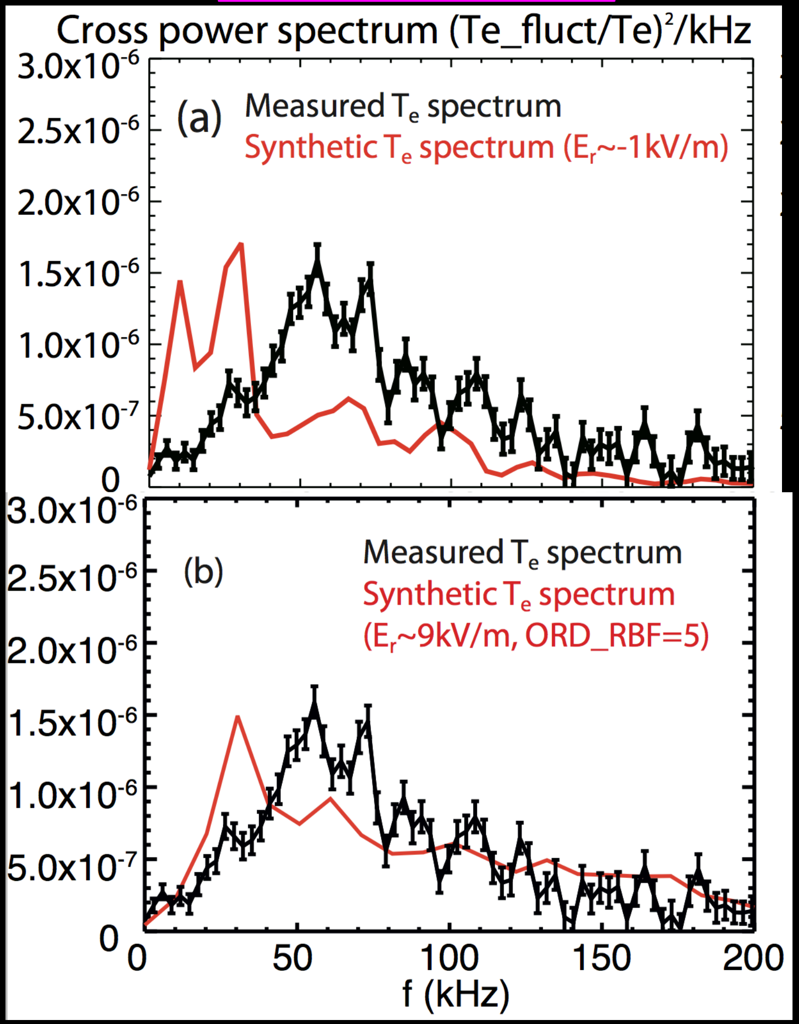



Holland PoP 2009

# Synthetic Diagnostic for CECE Gives An Example of Importance of Doppler Shift

- CECE synthetic diagnostic is a low-pass filter in k-space, similar to  BES in that respect
- Synthetic diagnostic must include effects of background plasma rotation to get frequency spectrum
- Doppler shifts leads to shift in peak of spectrum, and broadening
- CECE synthetic diagnostic implemented in several codes
  - GYRO [Holland PoP 2009]
  - GENE [Goerler PoP 2014]

**Tokamak C-Mod**

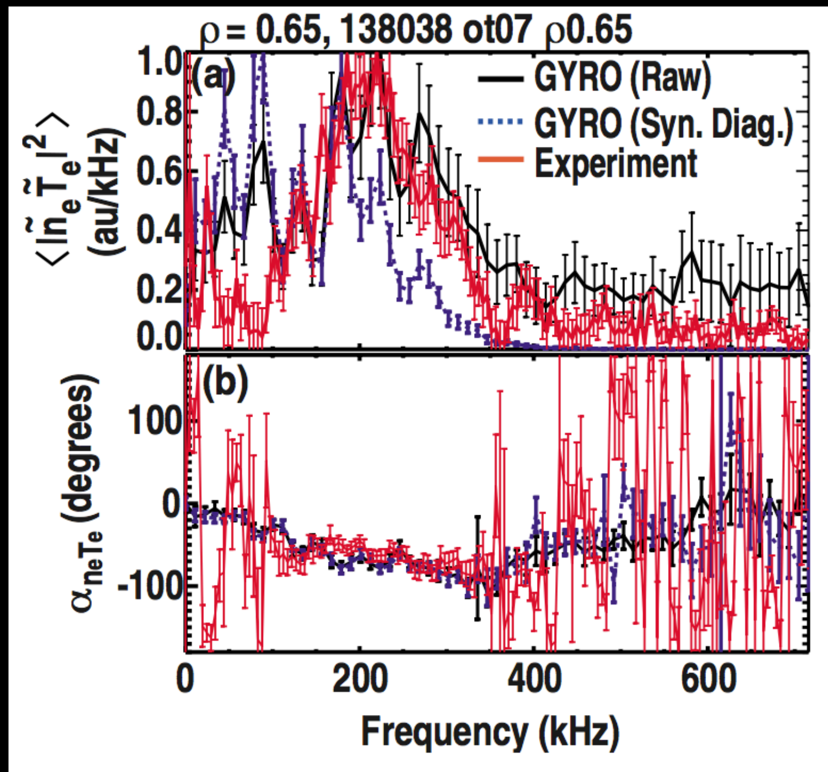



Sung PoP 2016

# nT-Phase Synthetic Diagnostics Have Also Employed Simple Low-pass k Filters

- **nT-phase has been compared to gyrokinetic simulations on DIII-D with GYRO and GENE** [White PoP 2010, Goerler PoP 2014]
- **Interesting measurement, because linear phases are often in good agreement with nonlinear phases over a broad parameter range**
- **nT-phase may be insensitive to many small changes in inputs, but tracks large changes (e.g. ITG vs TEM dominance)**

Tokamak DIII-D




White PoP 2010

# Doppler Reflectometer Synthetic Diagnostic Work Shows Importance of Intermediate-k Turbulence

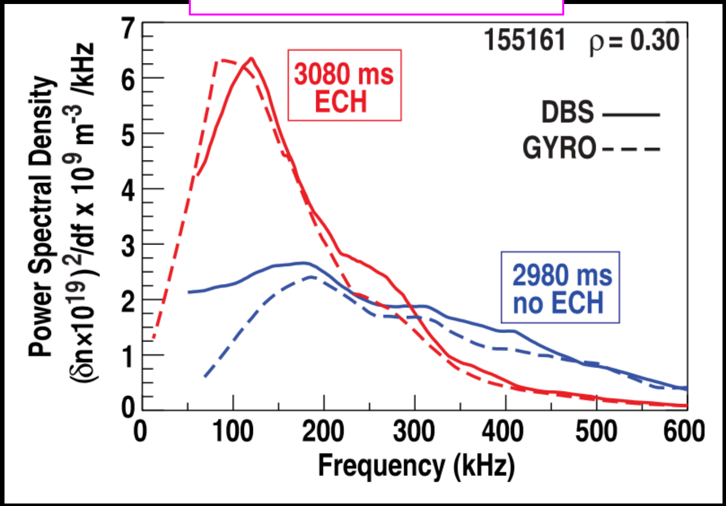
- **Synthetic diagnostic takes into account the finite sample volume, and wavenumber sensitivity of measurement**

- **In DIII-D experiment, in one case, TEM turbulence could be isolated using synthetic diagnostics**

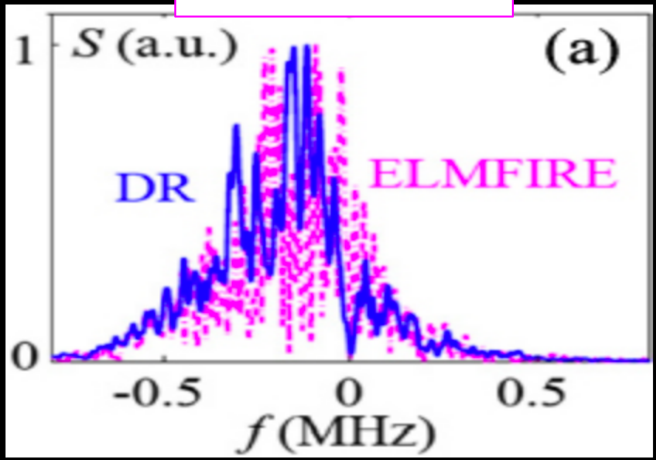
- **Synthetic diagnostics have been implemented in several codes**

- **GYRO** [Ernst PoP 2016]
- **ELMFIRE** [Leerink PRL 2012, Gusakov PPCF 2013]
- **GENE** [Happel PPCF 2017]

Tokamak DIII-D



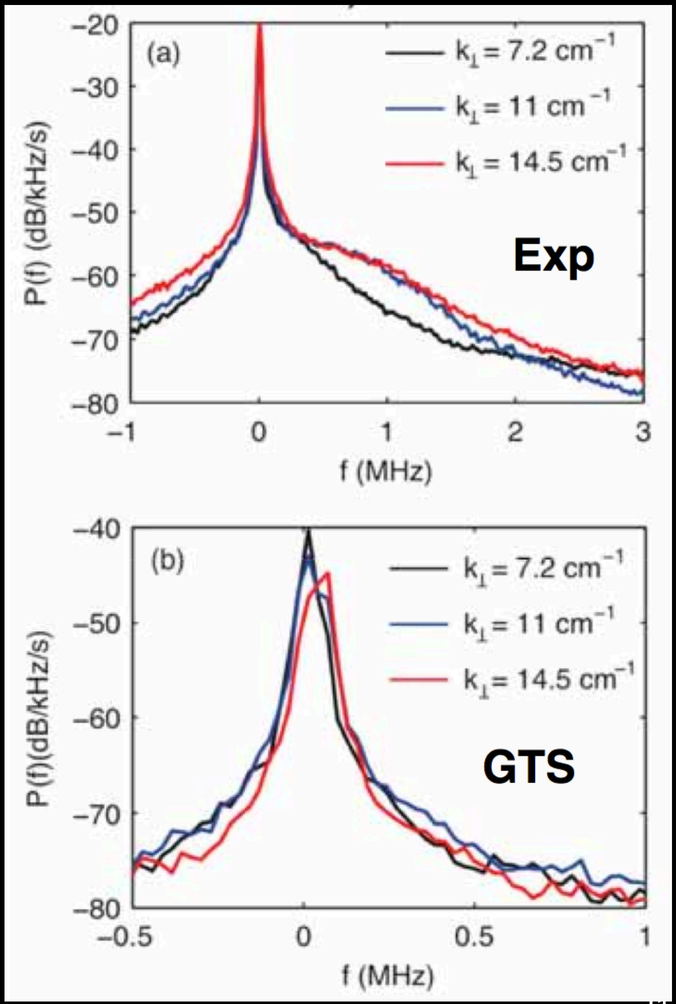

Tokamak FT-2



# High-k Scattering Synthetic Diagnostics Still Under Development

- **Coherent scattering synthetic diagnostic must take into account**
  - **Spatial sample volume**
  - **Scattering geometry**
  - **Wavenumber sensitivity in 3-D ($k_R$, $k_{pol}$, $k_{tor}$)**
- **Mapping to gyrokinetic code geometry is nontrivial , and is area of active research** [Poli APS 2010, Ruiz Ruiz APS 2016, TTF 2017]

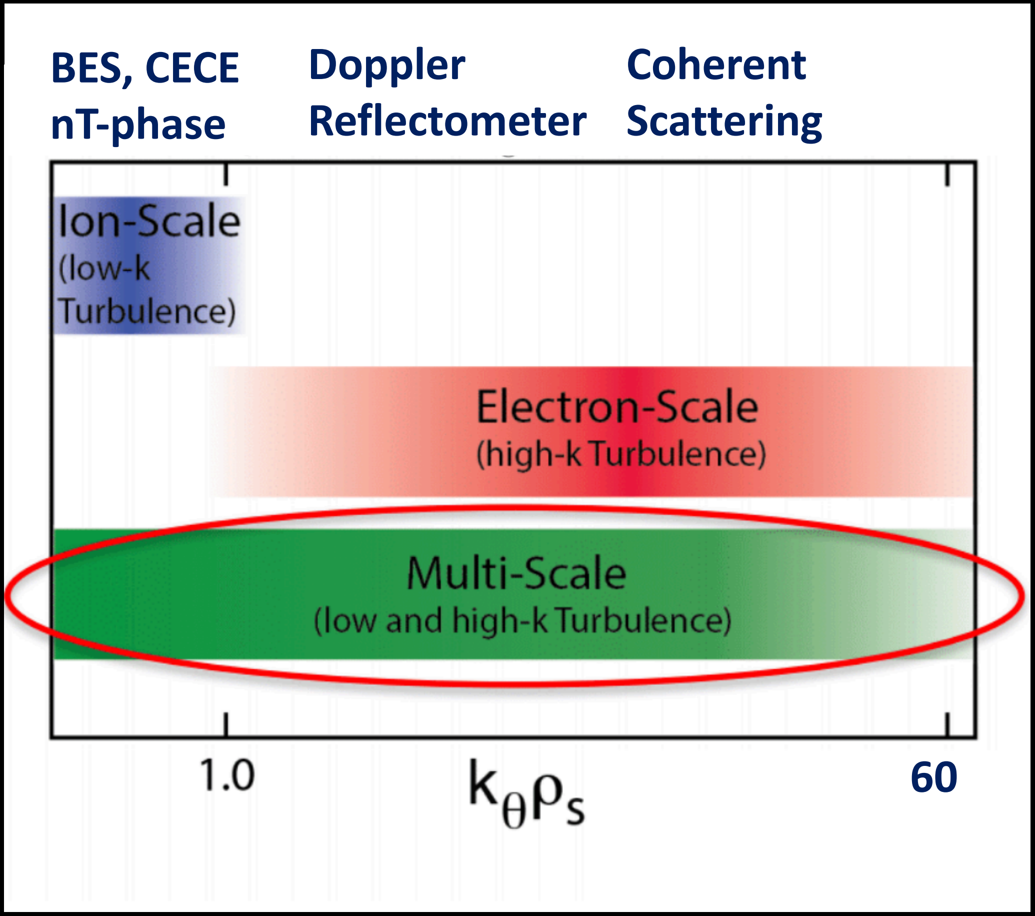
Tokamak NSTX




Poli APS 2010

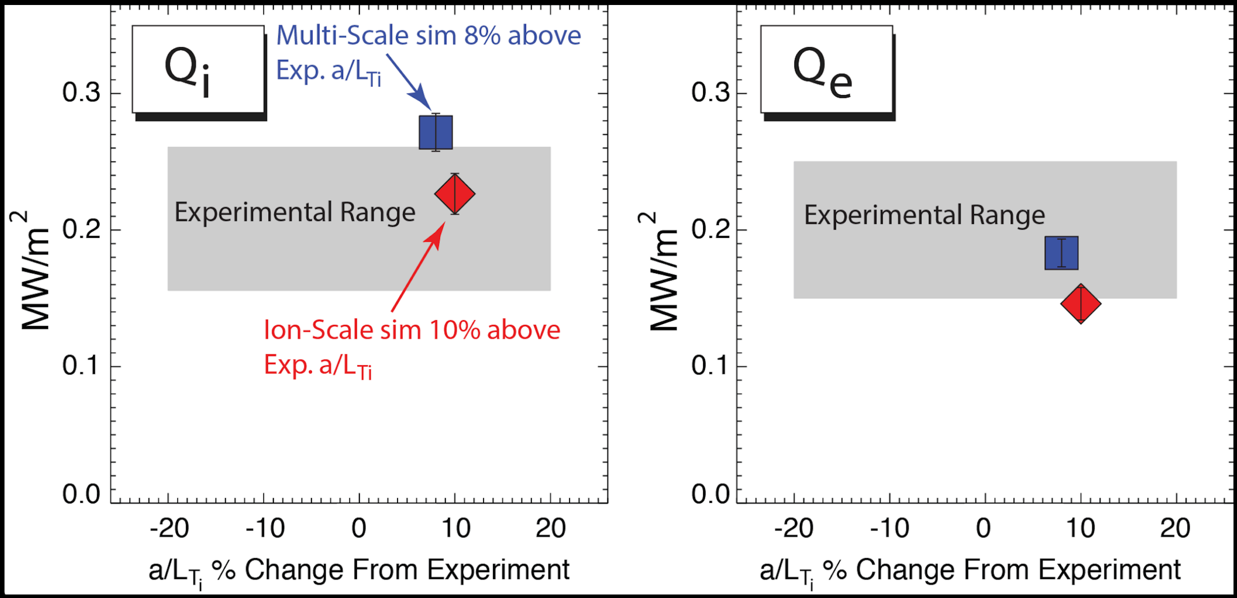
# Similar to Turbulence Diagnostics, Simulations Often Cover Limited k-range

- **Turbulence diagnostics are ”single-scale”, one measurement does not probe all unstable k**
- **Most validation work has been done with single- scale simulations**
- **Multi-scale simulations are possible, but are very computationally expensive**



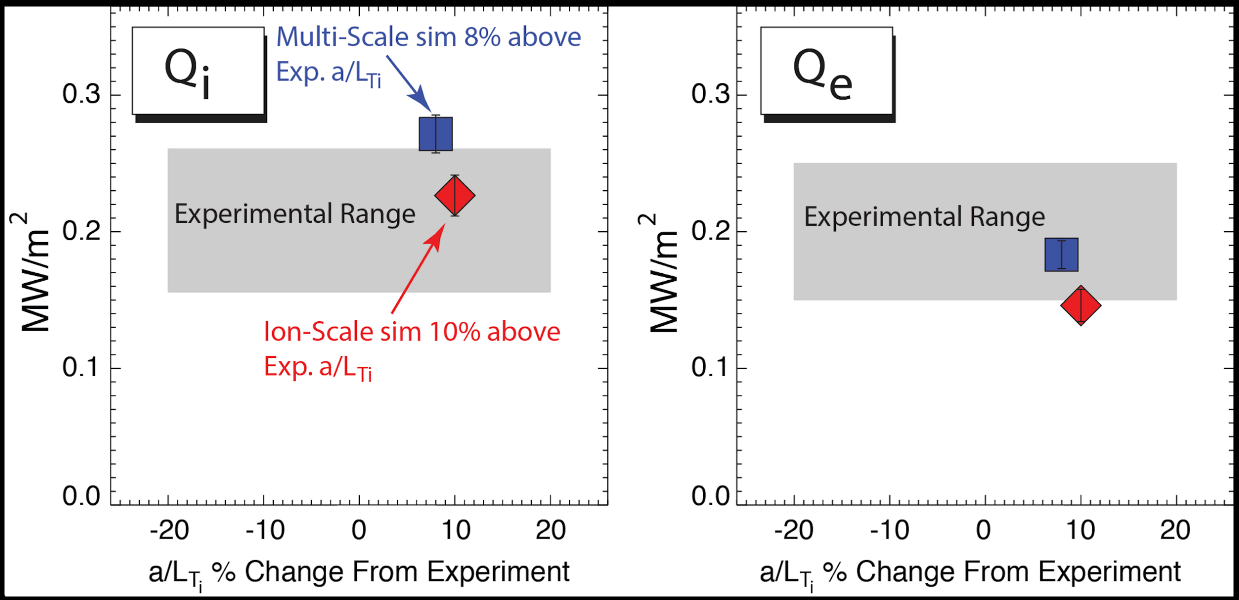
# Recent Multi-Scale Gyrokinetic Simulations Raise New Questions

- **Realistic mass ($m_i/m_e$ = 3600) multi-scale simulations of C-Mod plasmas** [Howard PoP 2014]
- **Multi-scale simulations show increases in electron heat flux - expected**
- **Increase in ion heat flux due to cross-scale interactions – not expected** [Howard PoP 2014, PPCF 2015, Maeyama PRL 2015, Howard NF 2016, NF 2017]



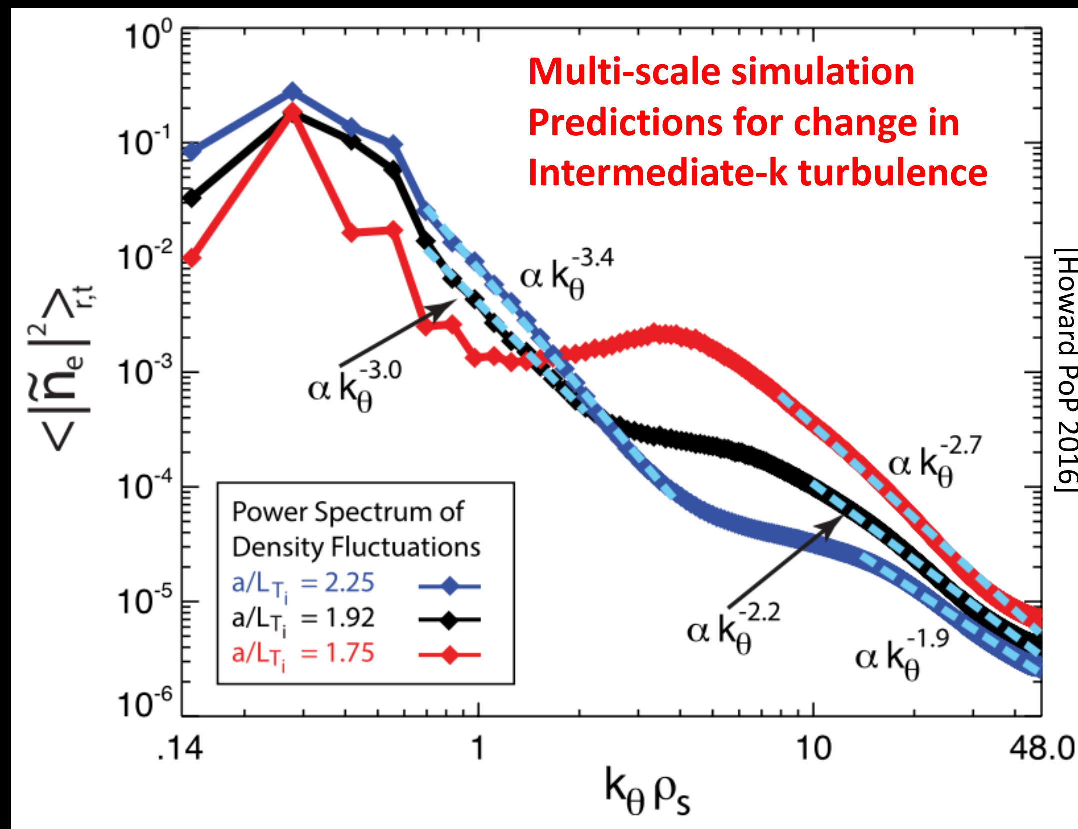
# Engineering Perspective: When is Ion-Scale Model Good Enough?

**H-mode case from C-Mod shows that BOTH ion-scale simulation (red) and multi-scale simulation (blue) can match experiment within error bars**



# "Predict First": Multi-Scale Predictions for Turbulence Can Be Compared with Experiment

- **Changes in turbulence predicted by multi-scale simulations cannot be modeled in single-scale simulations**
- **Test prediction, further constrain model**
- **DIII-D experiments conducted using Doppler Reflectometer** [Howard, Weds Poster]
- **Predict first initiative – important frontier in gyrokinetic validation**

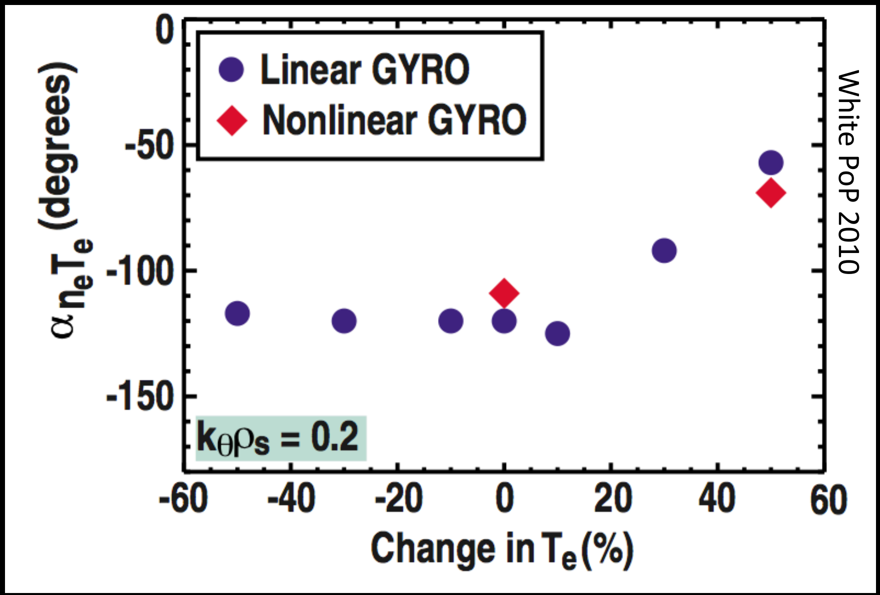



[Howard PoP 2016]

# Documenting Code Predictions In Advance Is Important Aspect of Validation

- **Run nonlinear gyrokinetic simulations *before* an experiment, "Predict first initiative"** [Mantica NF 2017, EU-TTF Summary]
- **Predictive experimental design can leverage existing simulations from past validation studies**
- **In example here, nonlinear GYRO runs were used to predict a change in phase angle with increased Te/Ti, later tested experimentally**

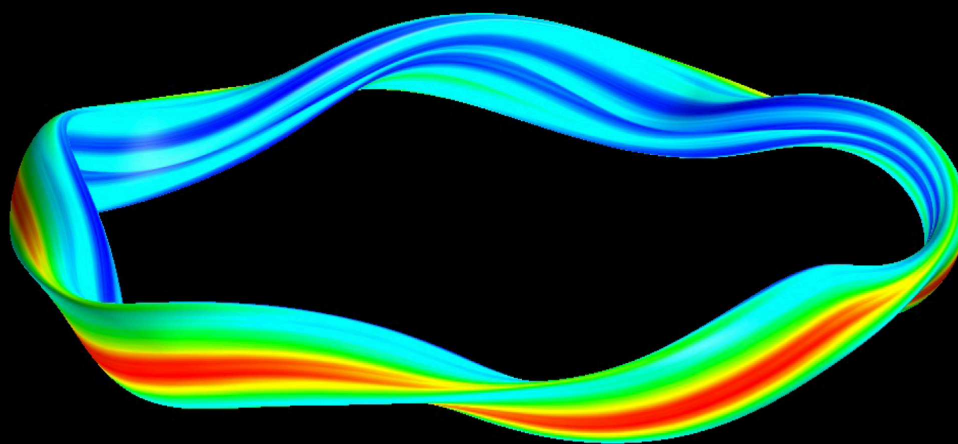
DIII-D nT-phase "predict first" example




White PoP 2010

# "Predict First" with Nonlinear Gyrokinetics for New Fusion Device – W7-X

- **Nonlinear GENE simulations have been used to predict turbulence characteristics in W7-X**
- **Stellarators: prospects for optimizing turbulent-transport [Xanthopoulos ISHW 2009, 2013]**
- **W7-X will have several turbulence diagnostics for experimental campaigns (PCI, CECE )**



https://www.pavlosipp.com/

# Validation Can Be Used to Inform Reduced Model Development

- **Development of reduced, quasi-linear transport models e.g. QuaLiKiz** [Bourdelle PoP 2026]
- **Build on physics knowledge gained from validation of nonlinear gyrokinetic simulation** [Staebler PoP 2016, TGLF SAT1]
- **Brings us back to our other goal of validation, engineering perspective**

**Transport model predictions for ITER temperature profile**

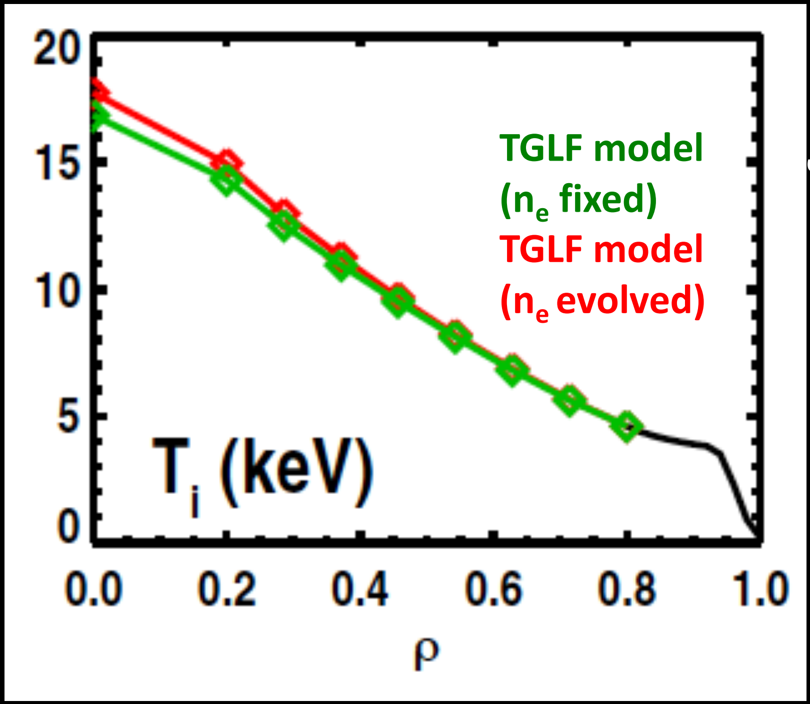
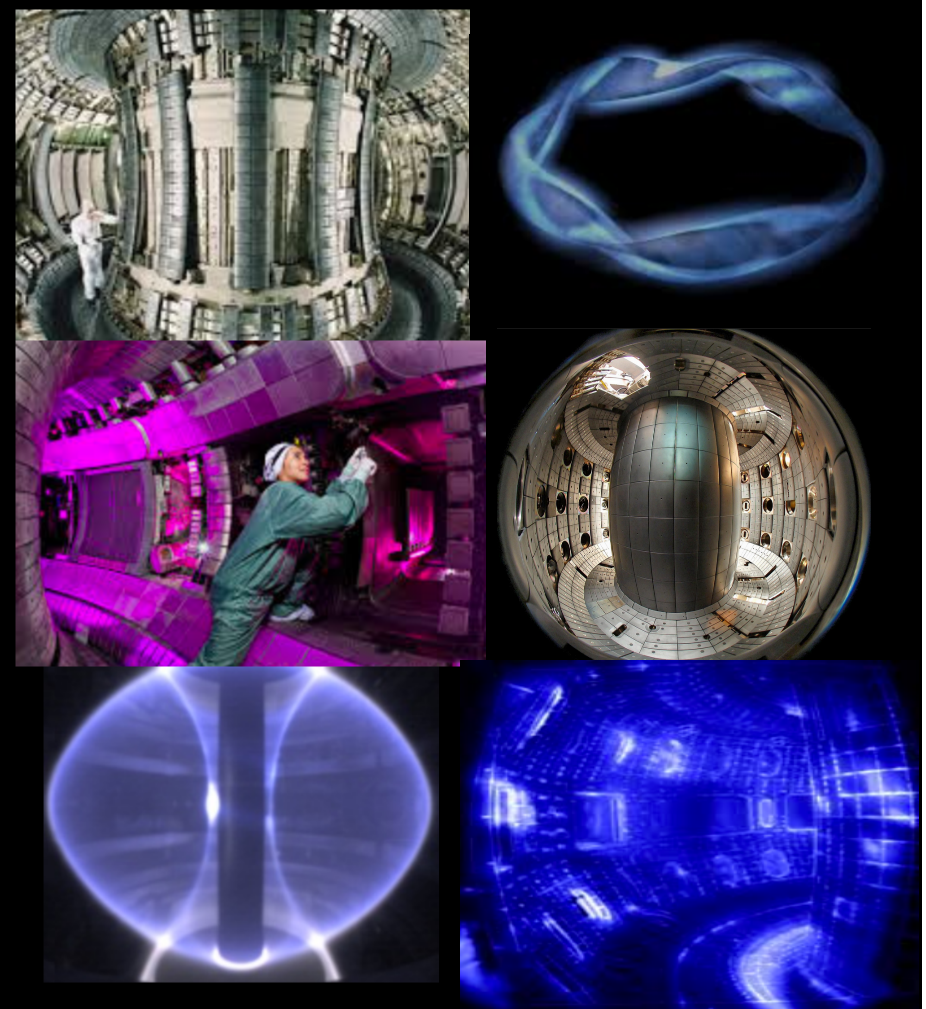



Figure from Grierson TTF 2016

# Current Devices are Excellent Platforms for Validation, Should Expand our Efforts

- **Experiment and simulation have driven each other forward**
- **Turbulence measurements provide critical constraints on gyrokinetic codes**
- **Validation has been essential to study of physics of turbulent transport**
- **This informs reduced model development, predictions for ITER performance**



# Current Devices are Excellent Platforms for Validation, Should Expand our Efforts

**Thank you very much!**