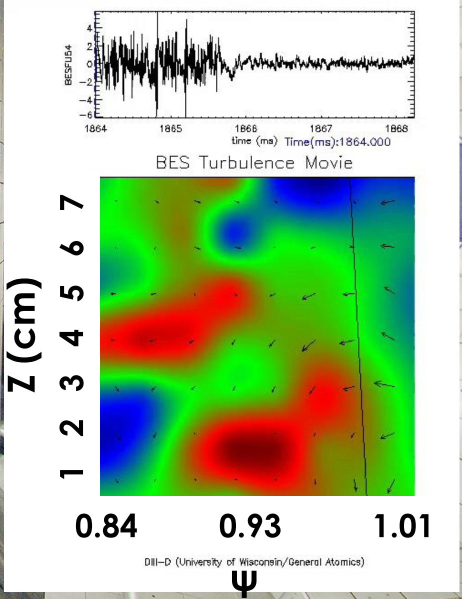
Turbulence and Sheared Flow Structures Behind the Isotopic Dependence of the L-H Power Threshold

**Z. Yan[1], P. Gohil[2], G.R.McKee[1],
L. Schmitz[3], B. Grierson[4], D. Eldon[2],
X.Q. Xu[5], Y.M. Wang[5,6], T. Rhodes[3],
C.C. Petty[2], and DIII-D Team**

[1]University of Wisconsin-Madison, Madison, Wisconsin, US
[2]General Atomics, San Diego, California, USA
[3]University of California Los Angeles, Los Angeles, California, USA
[4]Princeton Plasmas Physics Laboratory, Princeton, New Jersey, USA
[5]Lawrence Livermore National Laboratory, Livermore, California, USA
[6]Institute of Plasma Physics, Chinese Academy of Sciences, Heifei, China



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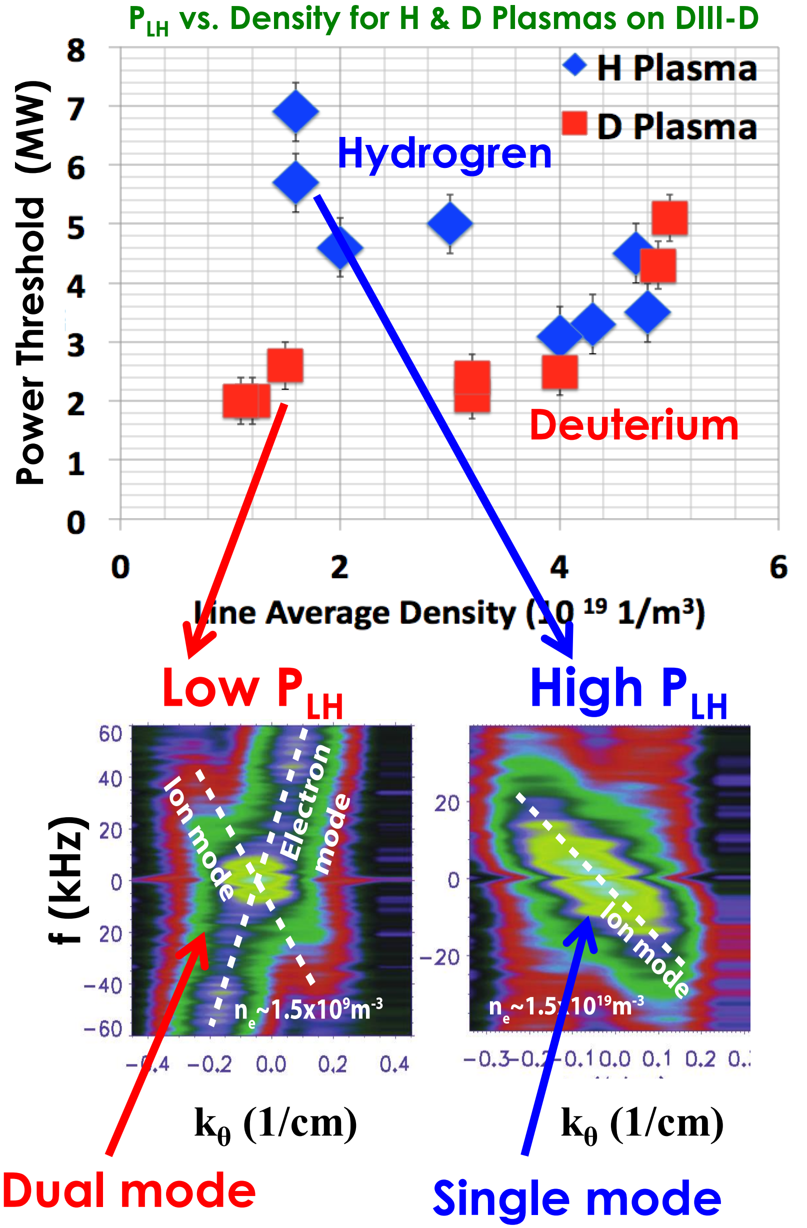
Understanding the Isotopic Dependence of the L-H Transition Power Threshold is Critical to ITER Operation

- **Hydrogen observed to exhibit a higher L-H transition power threshold (P_{LH}) than Deuterium on multiple experiments (DIII-D, JET, AUG, JT-60U)**
  - Underlying mechanisms unclear:
    - *Ion mass, velocity, neutral penetration, turbulence?*
    - *Strong density dependence to P_{LH}*
- **Edge turbulence properties may explain the L-H transition process and power threshold difference for H and D:**
  - Turbulence amplitude
  - Multimode turbulence
  - Decorrelation rates



Turbulence Driven Shear Flows Trigger the L-H Transition

Turbulence Properties

Increased Turbulence amplitude

Multiple edge instabilities
Different mode interactions

Increased turbulent Reynolds stress driving m=0,n=0 flow V_{pol}

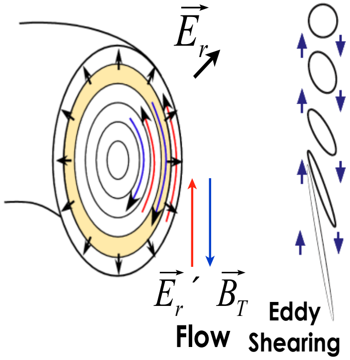
Increased kinetic energy transfer to V_{pol}

Lower Decorrelation rate (Eddy torn apart rate)

Turbulence suppressed

Trigger transition at Lower Power Input

L. Schmitz, EX/P3-11



- Evolution of full turbulence characteristics needs to be included in L-H transition model

Z. Yan, et al., PRL, 112, 125002, (2014)
G. Tynan *et al.*, Nucl. Fusion (2013)
I. Cziegler *et al.*, PPCF, (2014)

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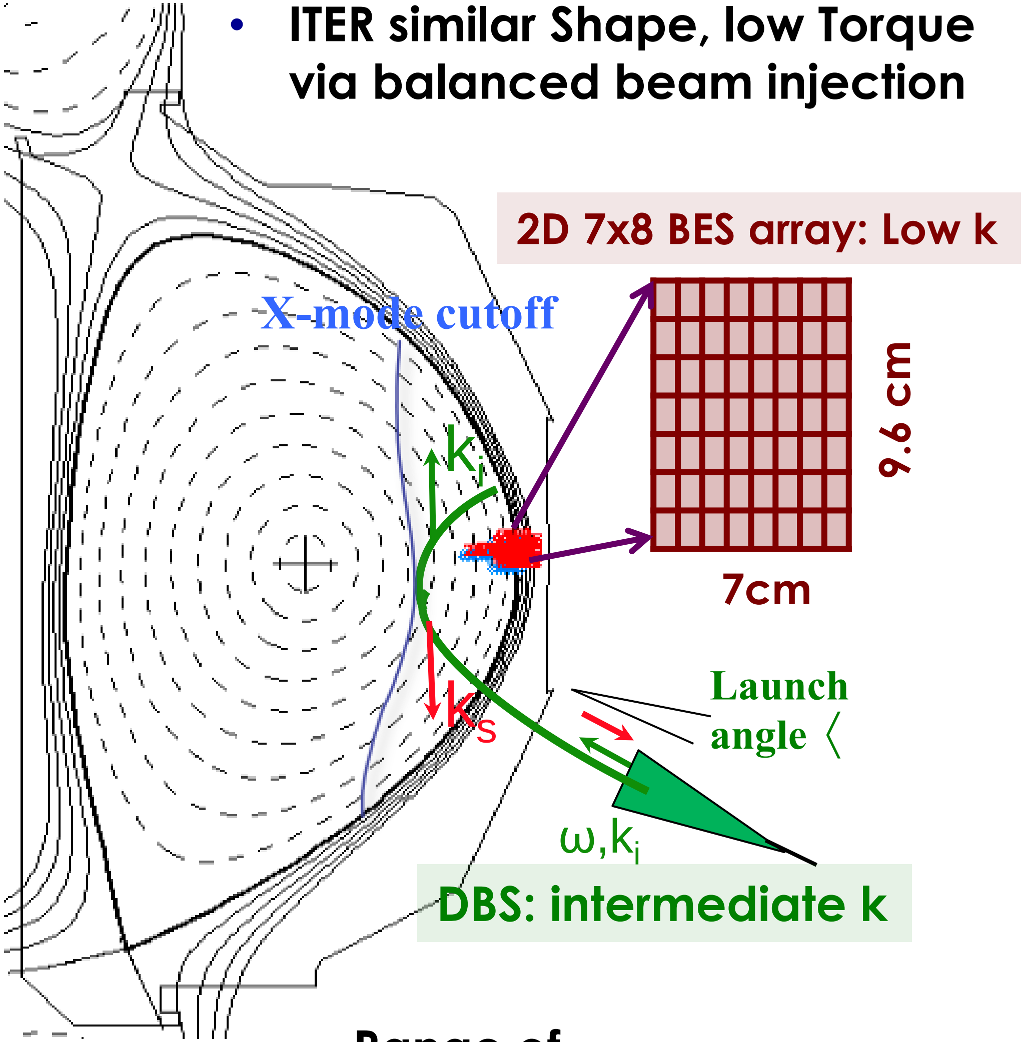
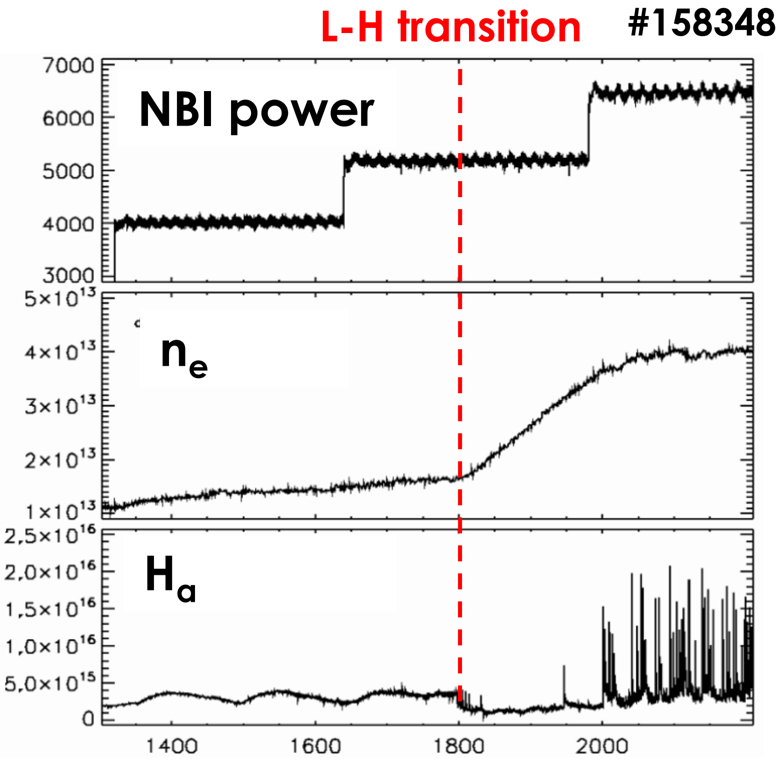
L-H Power Threshold Measured vs Isotope (H & D) and Density in ITER Similar Shape Plasmas

- ITER similar Shape, low Torque via balanced beam injection



- Range of measurements overlaps

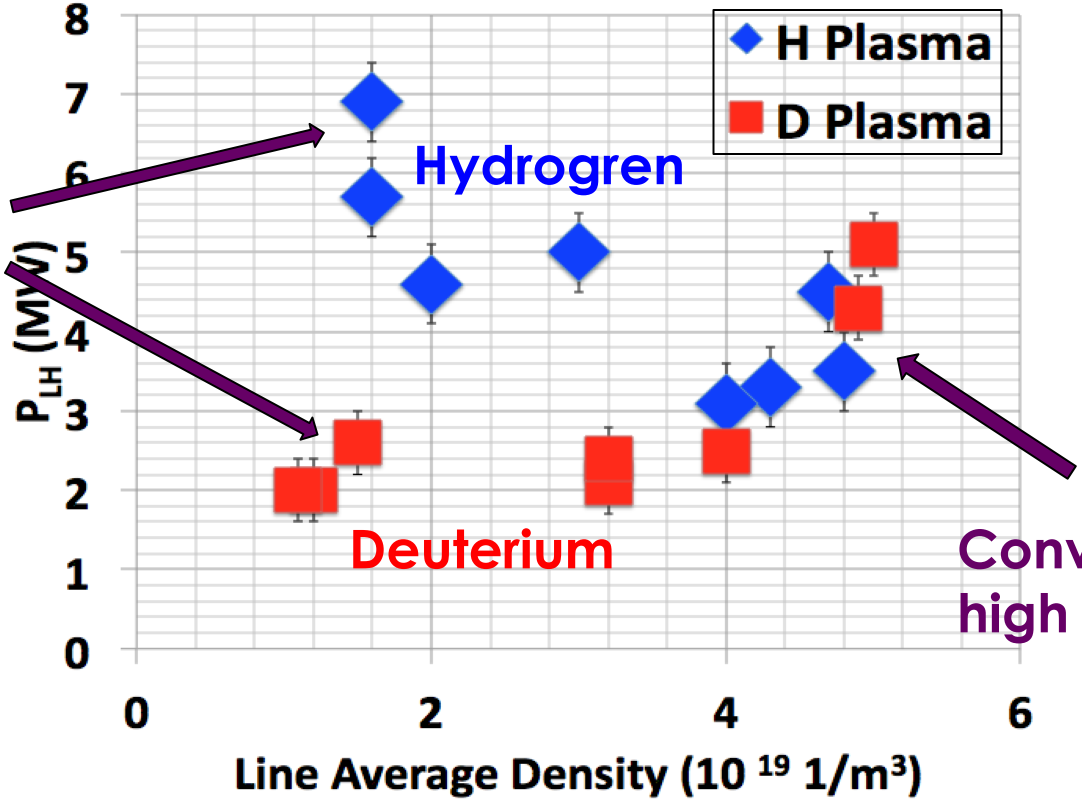
- Density varied for both D and H Plasmas



- Measure L-mode Turbulence right before transition

H & D Power Thresholds Differ Significantly at Low Density but Converge at Higher Densities

- Overall, P_{LH} in H is higher in D plasmas
- Below n_e~4e19 m^{-3} P_{LH} diverges with P_{LH} increasing significantly in H plasmas
- Suggest possible access to H-mode for ITER at higher density for Hydrogen

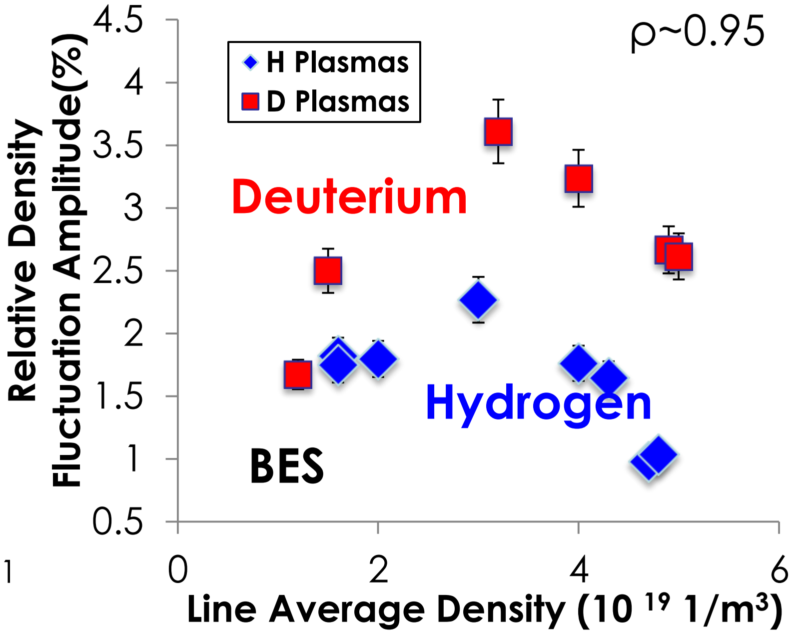


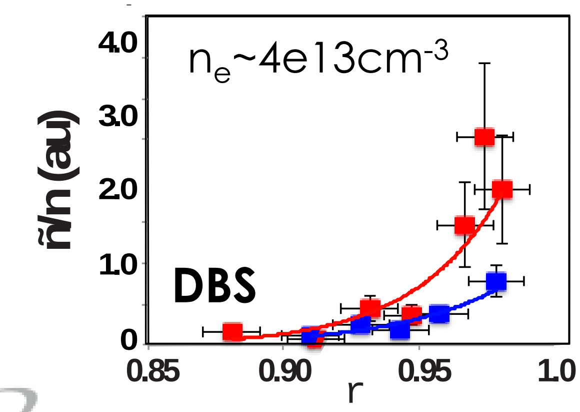
Big difference at low density

Converge at high density

Turbulence Provides Stronger Drive of Shear Flow via Reynolds stress [1] in D Plasmas

- **Higher edge turbulence amplitude in D plasmas**
  - Low-k density fluctuations $K_\theta < 3\ cm^{-1}$
  - L-mode phase, at the time right before L-H transition
- **Similar behavior observed at intermediate wave number** $K_\theta \sim 4\text{-}6\ cm^{-1}$





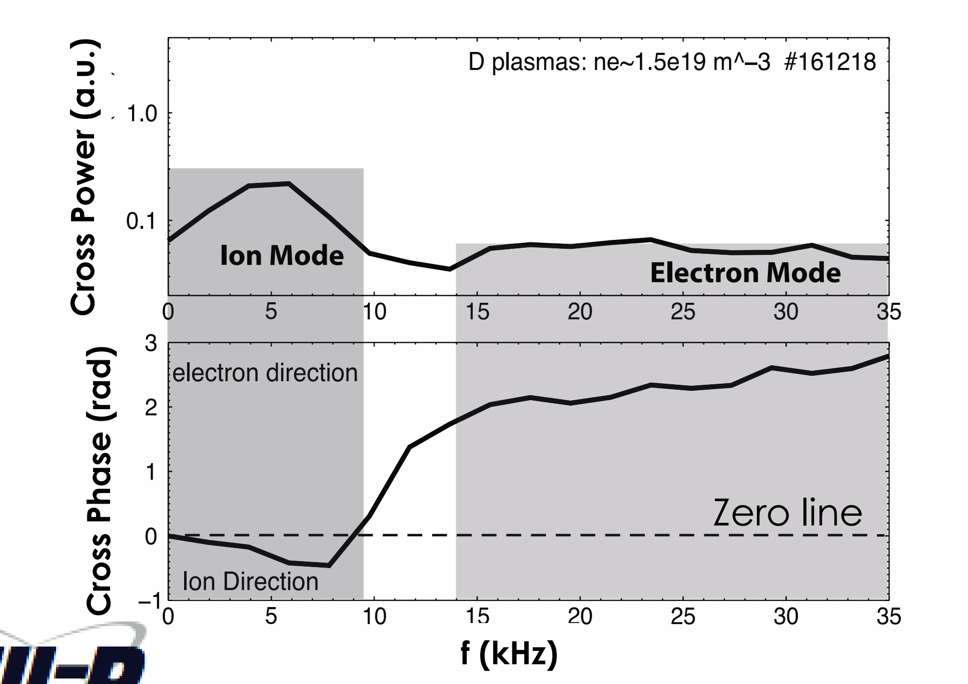
L. Schmitz, EX/P3-11

L-mode turbulence right before transition

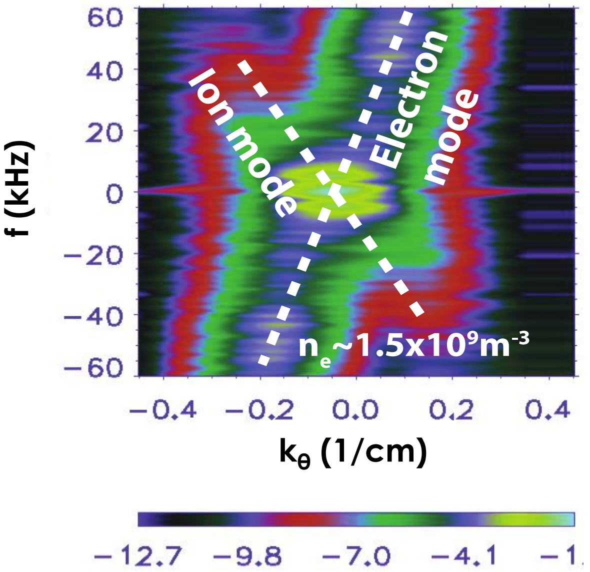
[1] Z. Yan, et al., PRL, 112, 125002, 2014

Dual Modes are Observed in both D and H plasmas when Power Threshold is Minimal

- **Dual modes are only observed at edge, ρ~0.95**
- **Propagate in opposite direction in the lab frame**
  - Mode <10kHz: ion diamagnetic direction – negative cross phase
  - Mode >10kHz : electron diamagnetic direction – positive cross phase
- **Suggesting different instabilities, ITG, TEM, RBM**
  - need edge simulation to find the nature of the dual modes



S(f,k) of edge turbulence



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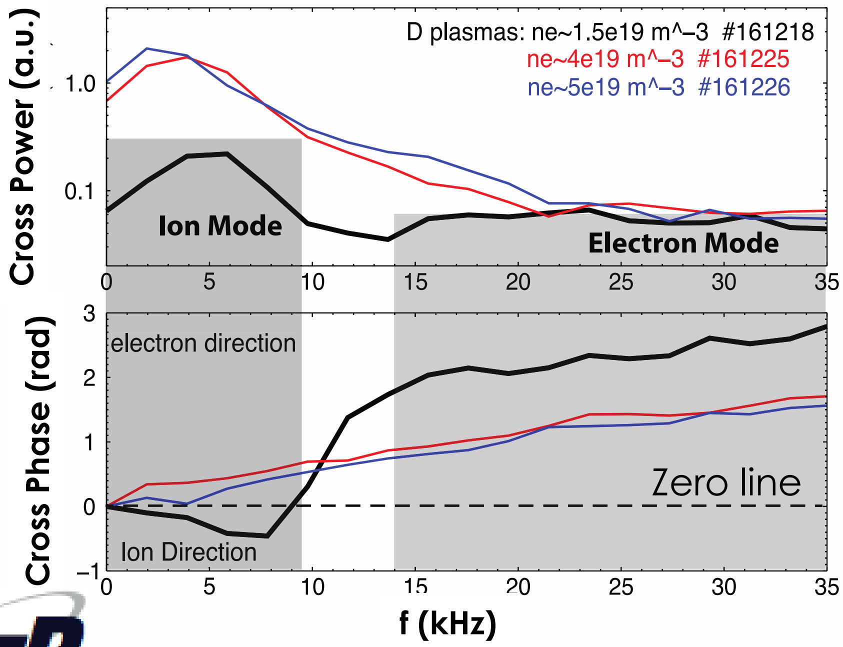

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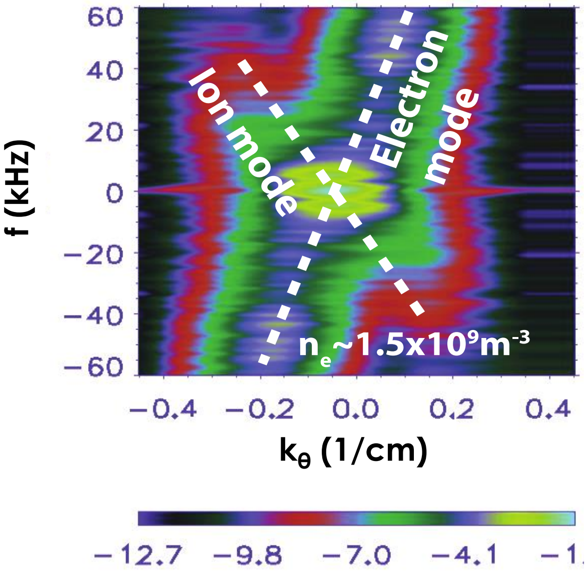
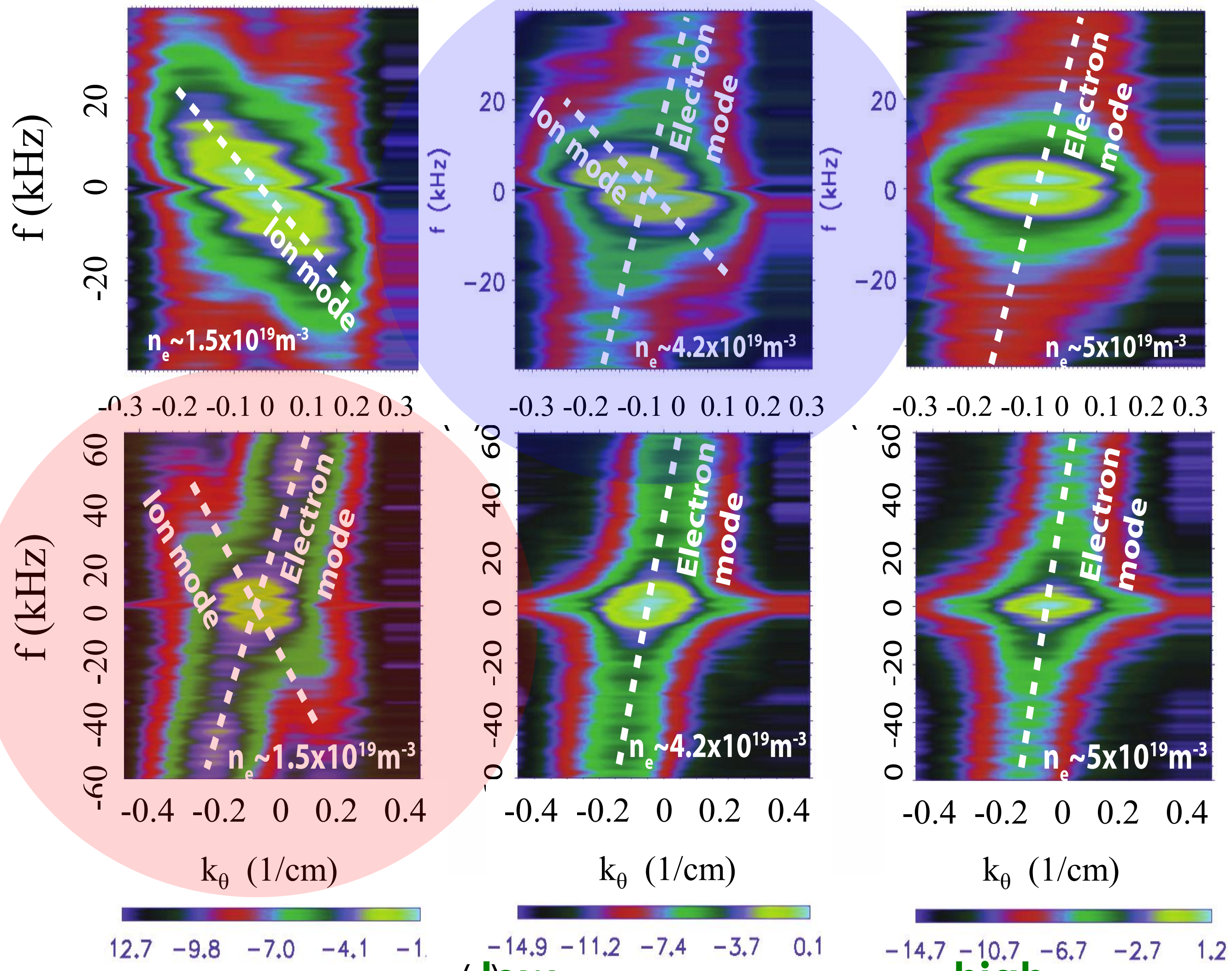


Hydrogen and Deuterium each exhibit Co-existing Ion and Electron Mode at Minimum in P_{LH}

Density low → high

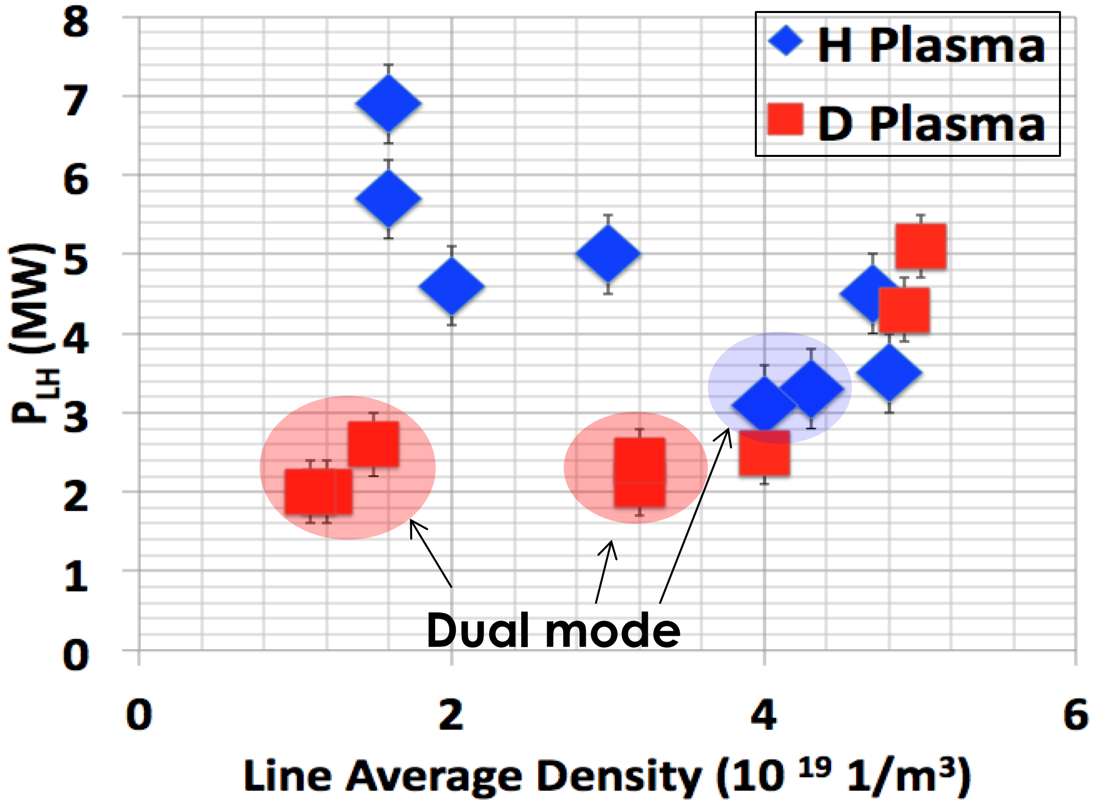
Hydrogen

Deuterium



low → high **Density**

Dual Modes Observed at the P_{LH} Minimum for both D and H Plasmas

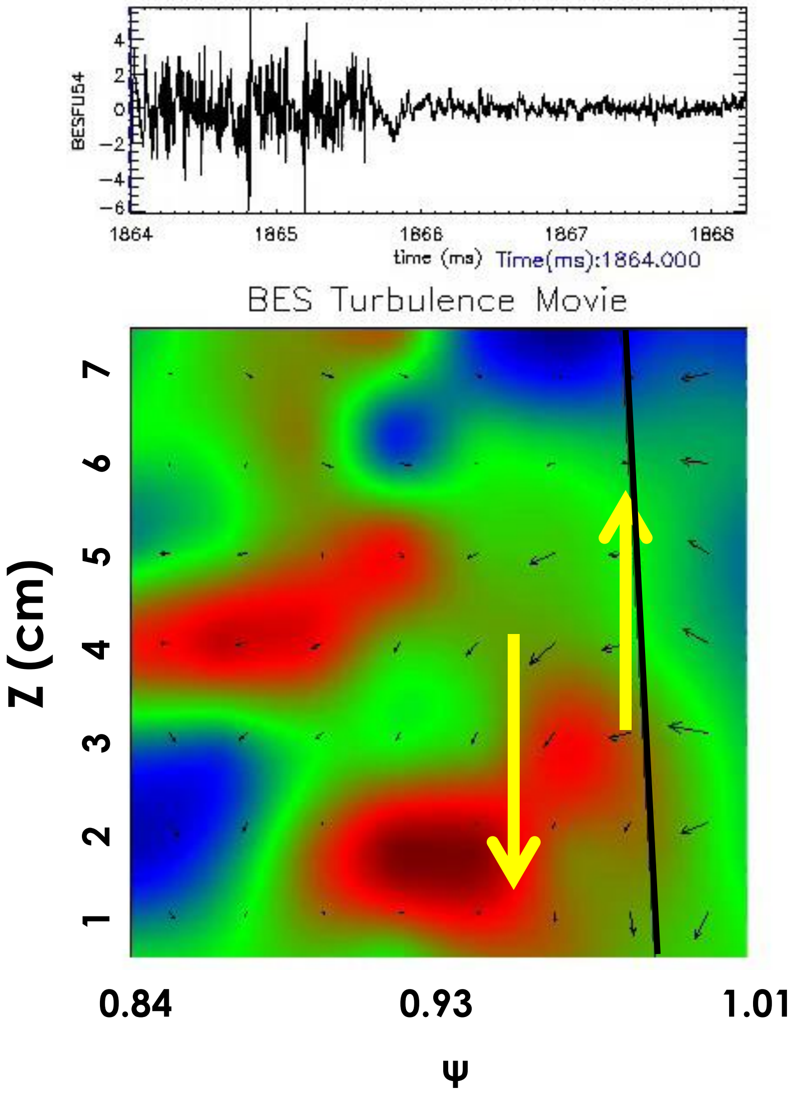


- **Such dual modes are also observed in favorable magnetic geometry, but not in unfavorable magnetic geometry**
  - Ion grad-B drift towards dominant X-point

Turbulence Dynamics Visualized from 2D Imaging

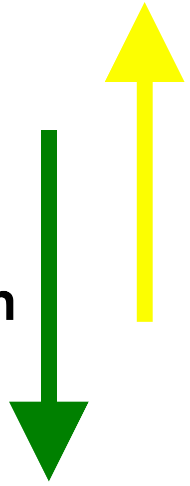
- **L-mode density fluctuation from 2D BES measurements**
  - Red: positive density perturbation
  - Blue: negative density perturbation

D plasma, n_e~1.5e19 m^{-3}



Counter-propagating Modes Observed near Plasmas Edge from Fast Imaging

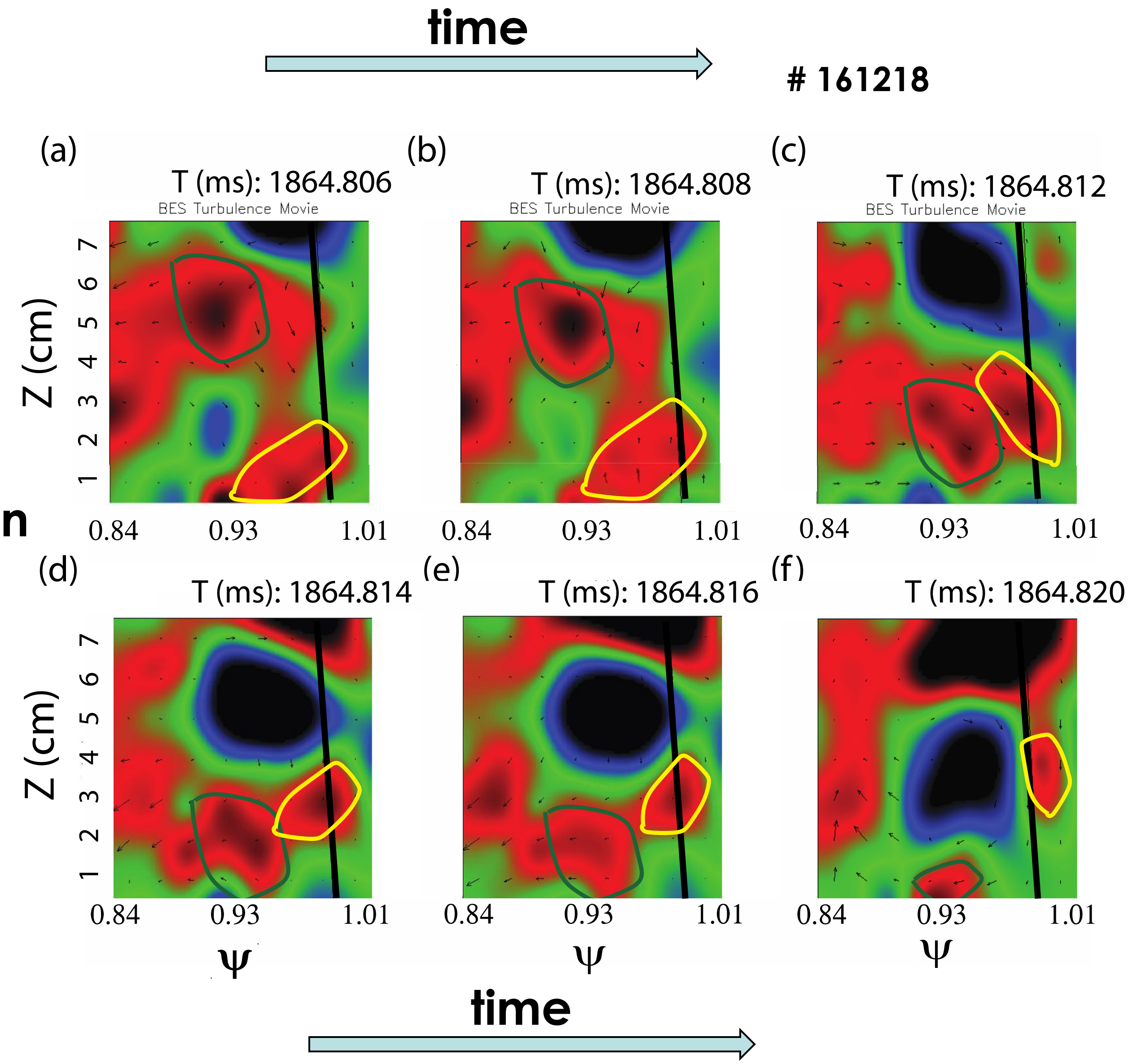
- **Opposite Poloidal Propagation**
  – increasing shear



Ion direction

Electron direction

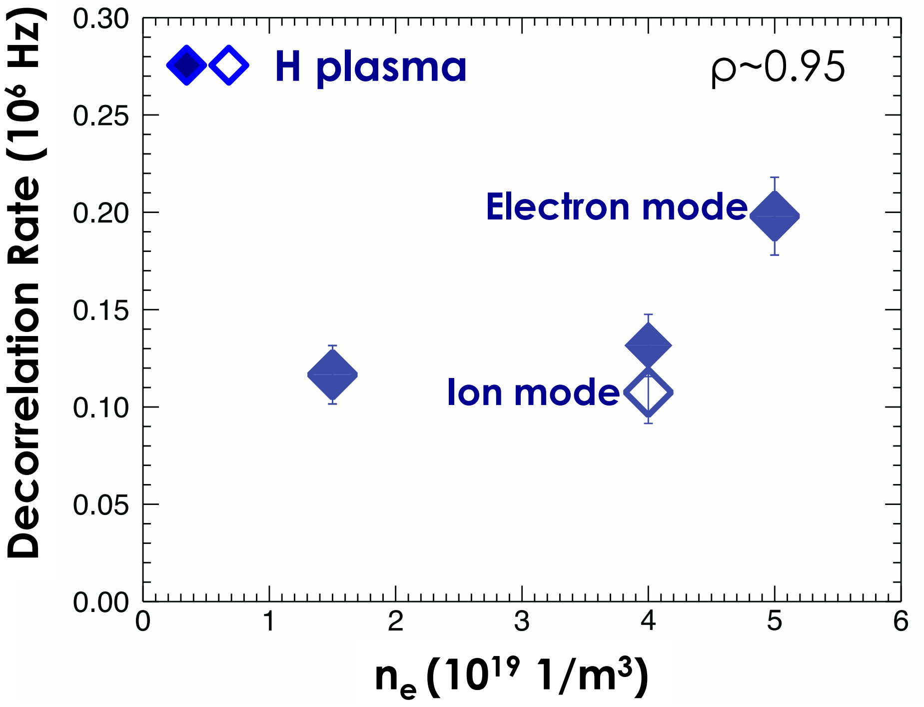
L-mode turbulence



Higher Turbulence Decorrelation Rate in H Plasmas than in D Plasmas at all Densities

- **Suggesting stronger shear will be needed to suppress turbulence in H plasmas**

- **Modes propagating in the ion diamagnetic direction has lower decorrelation rate**



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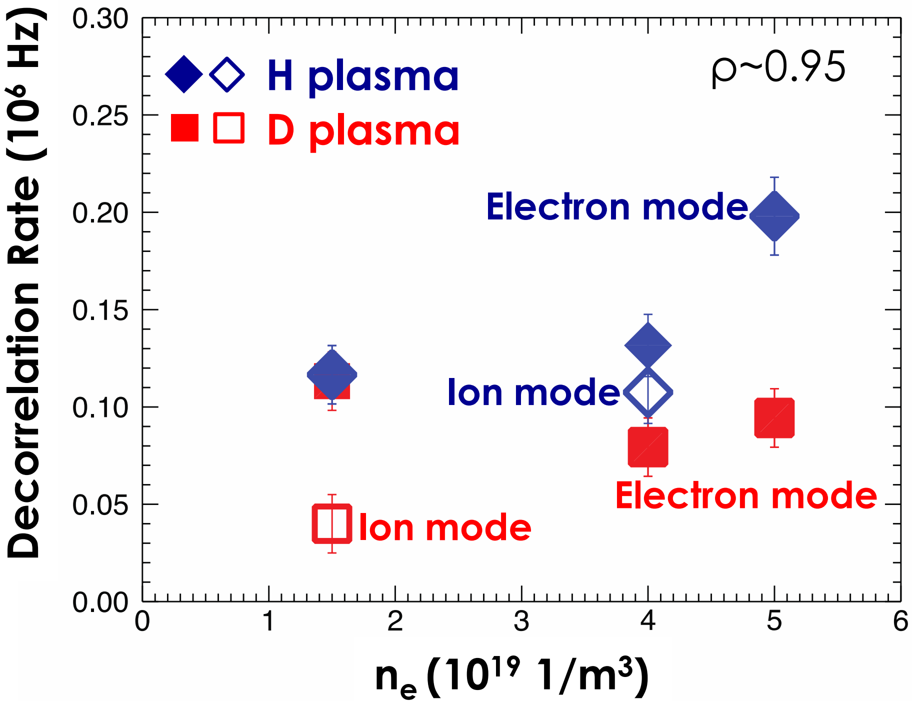
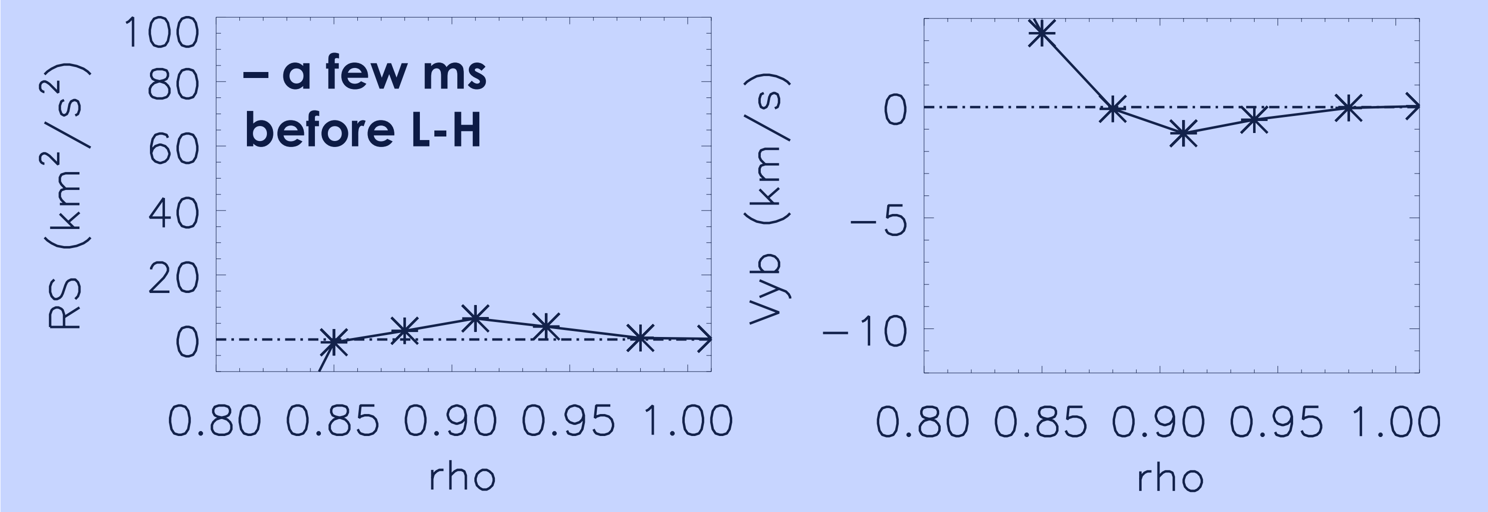


Higher Drive for Turbulence Velocity Approaching Transition in D Plasmas when Dual Modes Present

Reynolds stress **Turbulence poloidal velocity**

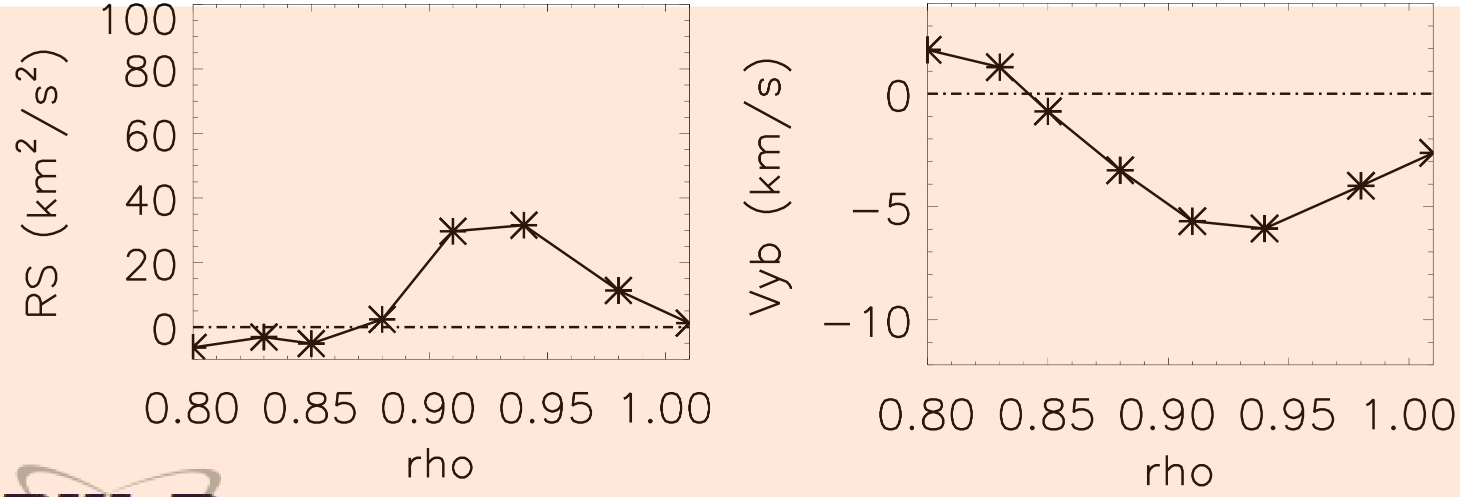
n_e~1.5e19m^{-3}



– a few ms before L-H

H plasma
P_{LH}=High

Single mode



D plasma
P_{LH}=Low

Dual mode

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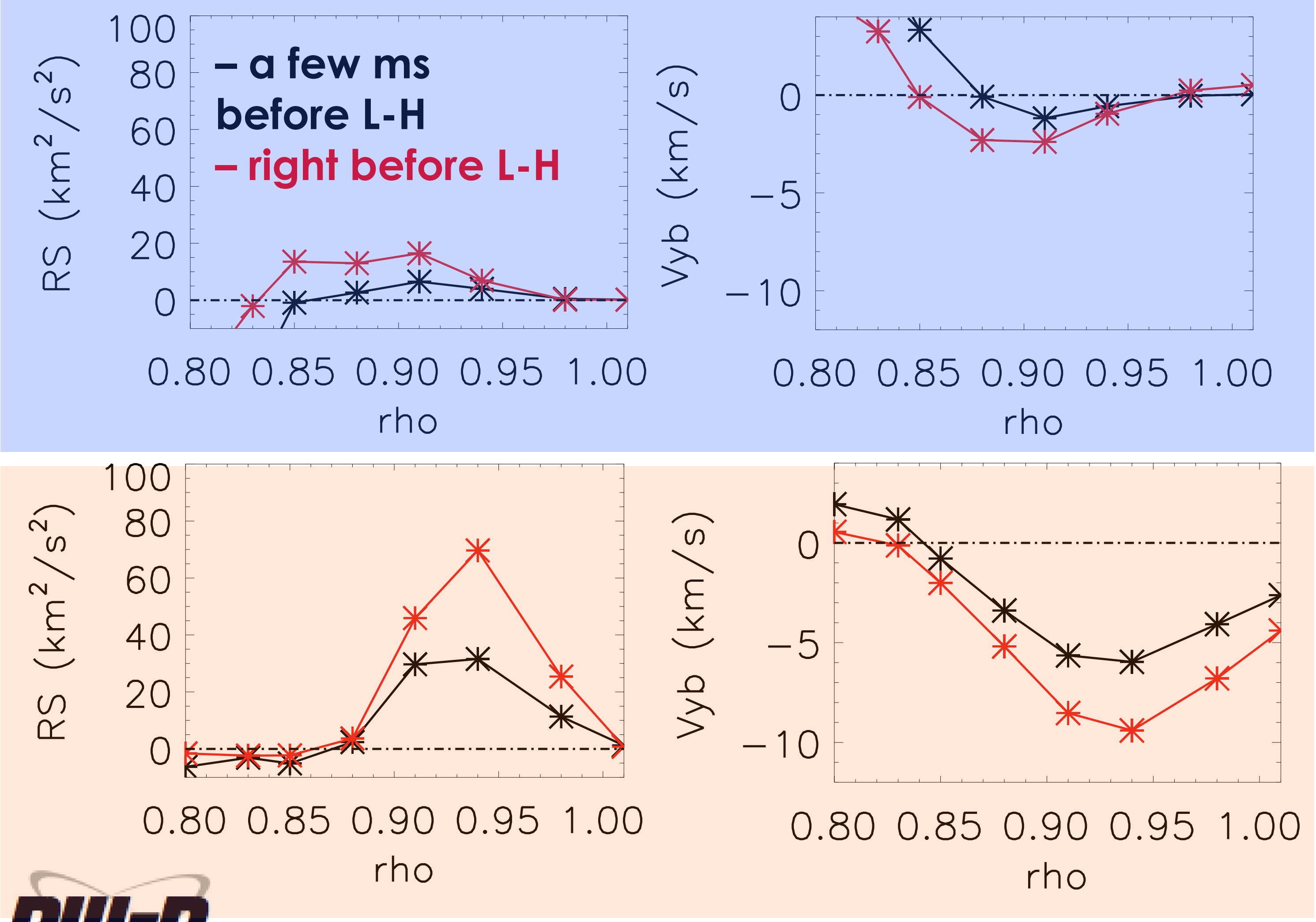
Higher Drive for Turbulence Velocity Approaching Transition in D Plasmas when Dual Modes Present

Reynolds stress **Turbulence poloidal velocity**



n_e~1.5e19m^{-3}

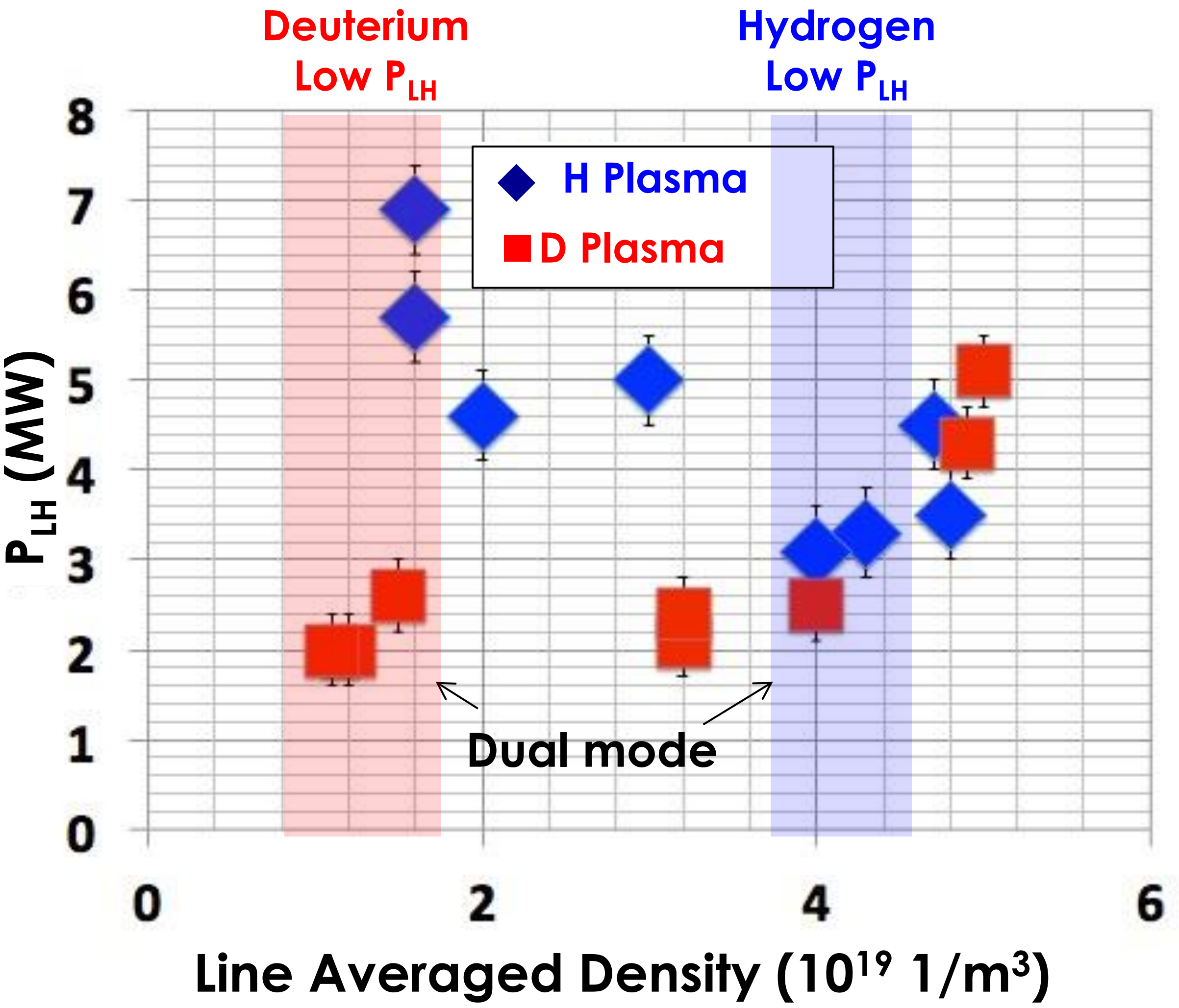
H plasma
P_{LH}=High

Single mode

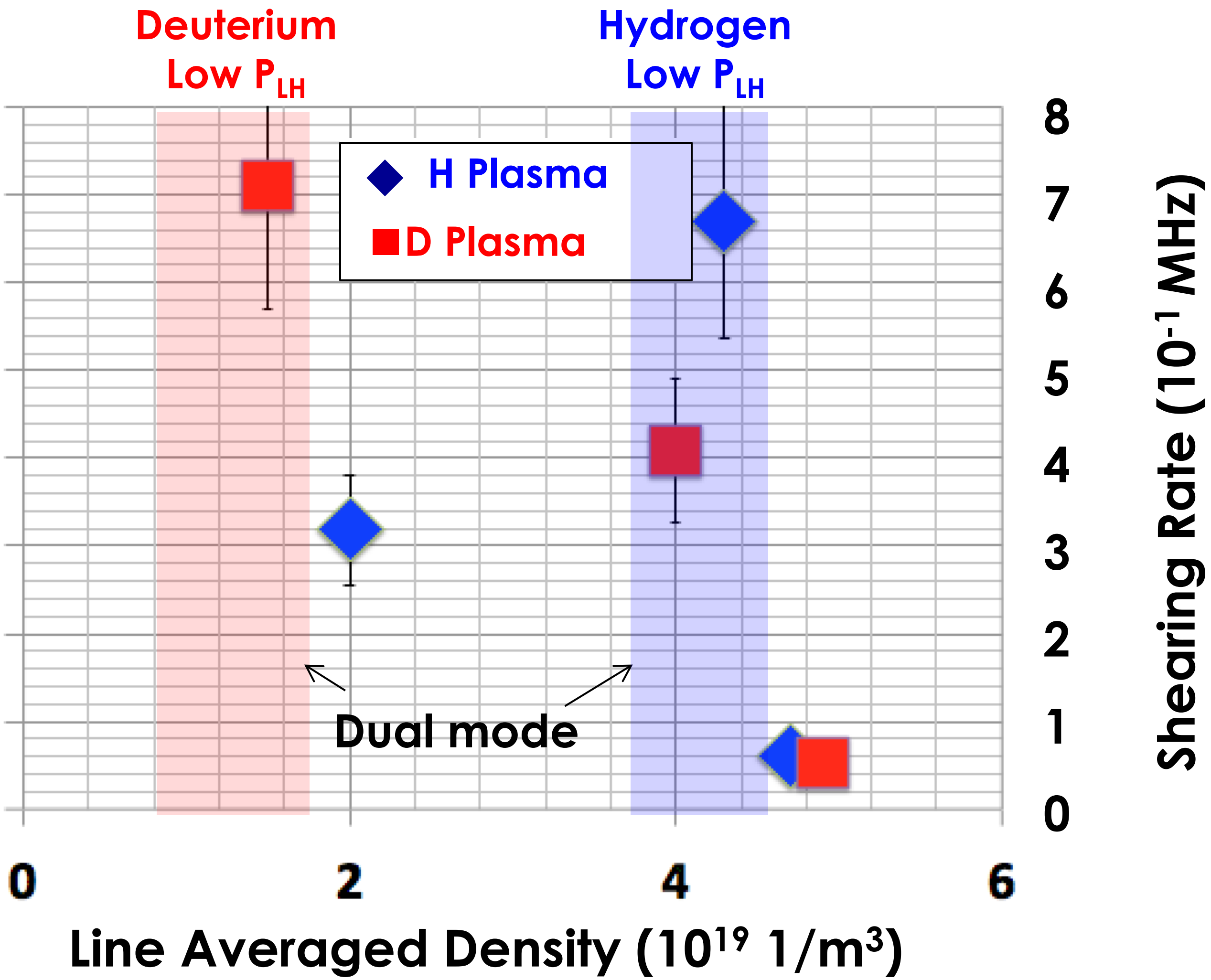
D plasma
P_{LH}=Low

Dual mode

Highest Shear Correlates with Presence of Dual Modes and Corresponding Lower Power Threshold



Highest Shear Correlates with Presence of Dual Modes and Corresponding Lower Power Threshold



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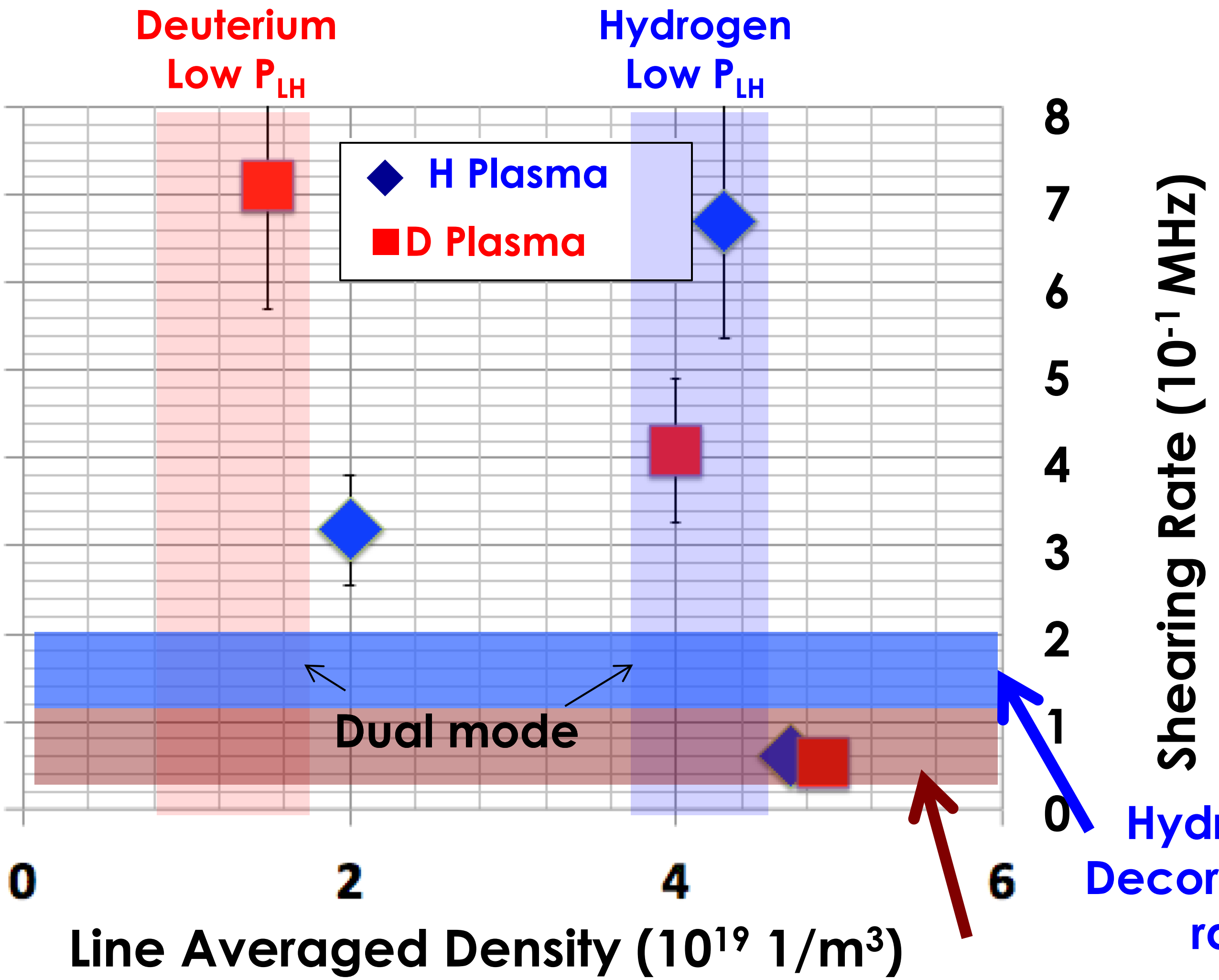

Hydrogen Decorrelation rate

Deuterium Decorrelation rate

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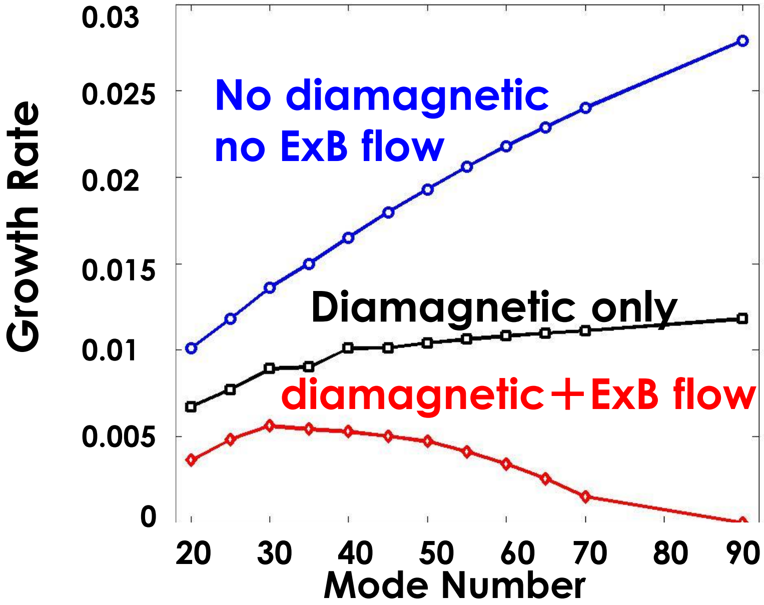
Preliminary BOUT++ Calculations Show Dual Mode Structure Consistent with Experimental Observation

- **BOUT++ 6-field model is applied to experimental profiles**
  - net linear growth rates are self-consistently reduced by diamagnetic and ExB flow
- **Linear growth rate comparable to decorrelation rate**
- **Localized just inside the separatrix**
- **Most unstable modes n=20-70 peaking at n=35**

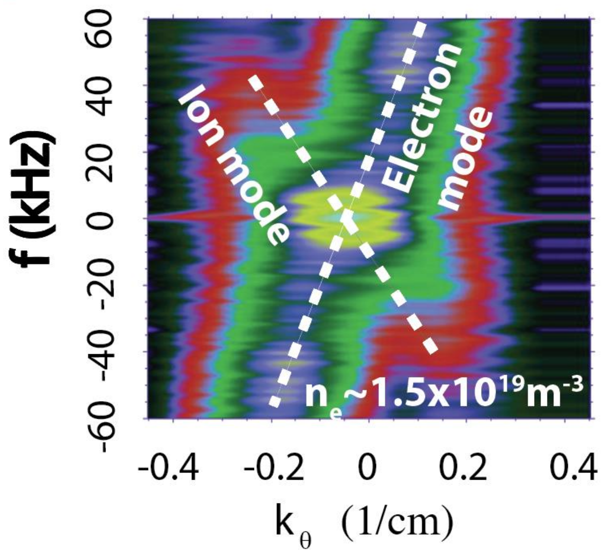


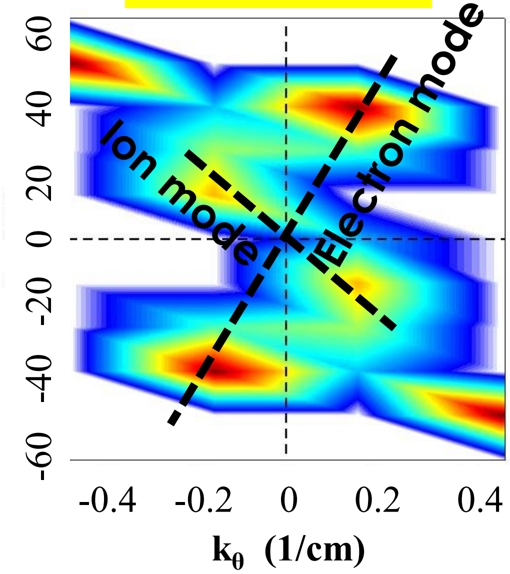
Preliminary BOUT++ Calculations Show Dual Mode Structure Consistent with Experimental Observations

Experiment

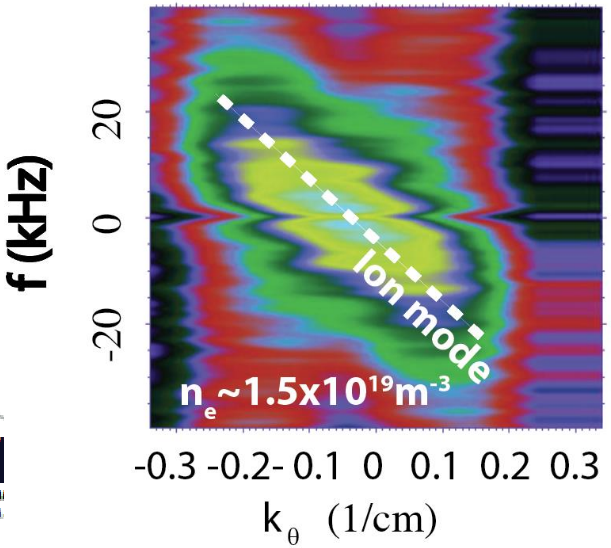
Simulation

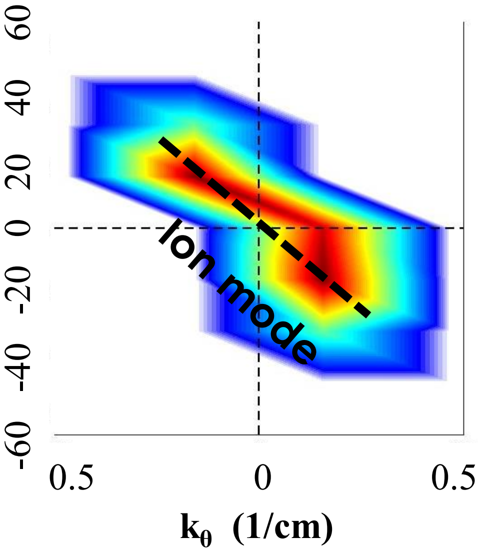
n_e~1.5e19m^{-3}





Deuterium
Dual mode





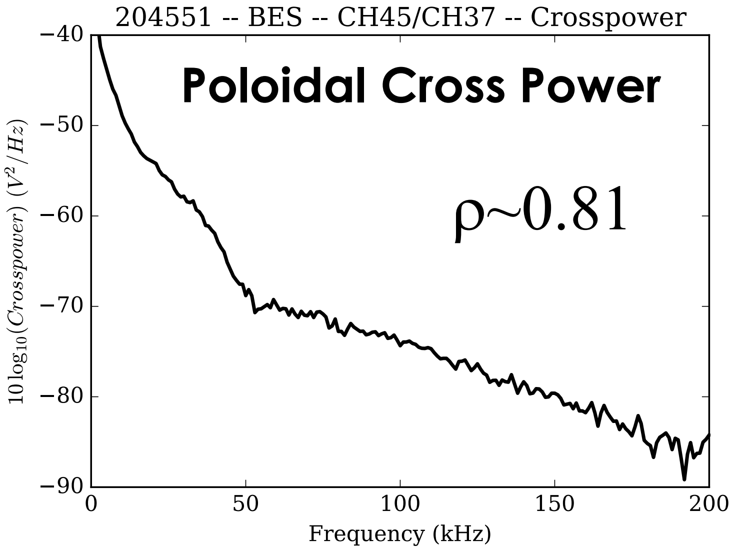
Hydrogen
Single mode

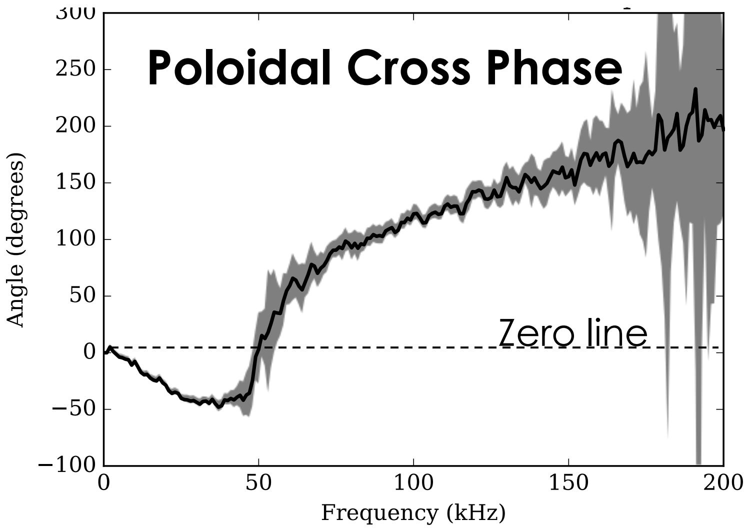
Dual Modes Observed Recently with BES in the Edge of the NSTX-U Plasmas

- **Similar to the dual mode turbulence observed on DIII-D**
  - Counter propagating
  - Localized inside the separatrix
  - Observed in L-mode plasmas

- **Suggests a universality to the dual-mode nature of tokamak edge turbulence**

M. Kriete, D. Smith, U Wisconsin (APS-2016)





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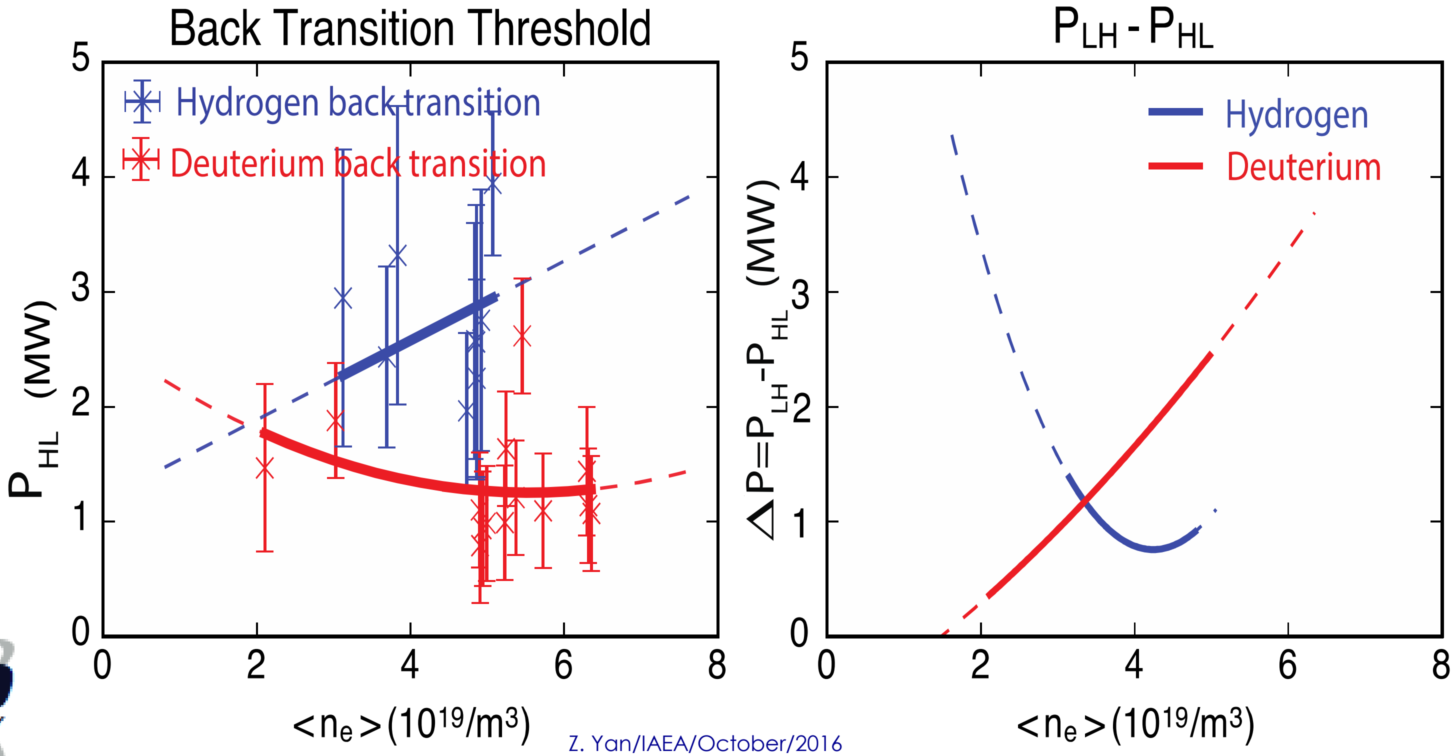
NSTX

Brief Note on
H-L Back Transition

– More details presented in poster

Stronger Hysteresis in Deuterium Plasmas at Higher Density

- **Back transition power threshold has a small dependence on electron density for both D and H plasmas**
- **Power difference between forward and backward transition increases with electron density**
  - stronger hysteresis in D plasma as n_e>4e19 m^{-3}



Summary: Turbulence Dynamics Help Explain Difference in Isotopic Dependence of L-H Transition

- **P_{LH} in H >> P_{LH} in D at low density, but converge at higher density**
  – Easier access to H-mode in H plasmas at higher density

- **Higher fluctuations measured in D**
  – Provides enhanced Reynolds Stress drive for shear flow and triggers L-H transition

- **Lower decorrelation rate in D**
  – Requires lower shear to suppress turbulence

- **Low L-H power threshold associated with Dual counter propagating modes**
  – Hypothesized that mode interaction may favor shear flow generation

- **Modes characteristics consistent with preliminary BOUT++ simulations**

- **The measurements suggest a complex behavior that can inform a more complete model of the L-H transition power threshold for ITER and beyond**

Back Up

Turbulence Energy Transfers over Broad Range of Spatial Scales

Simplified equation[1,2] of

Turbulence kinetic energy:

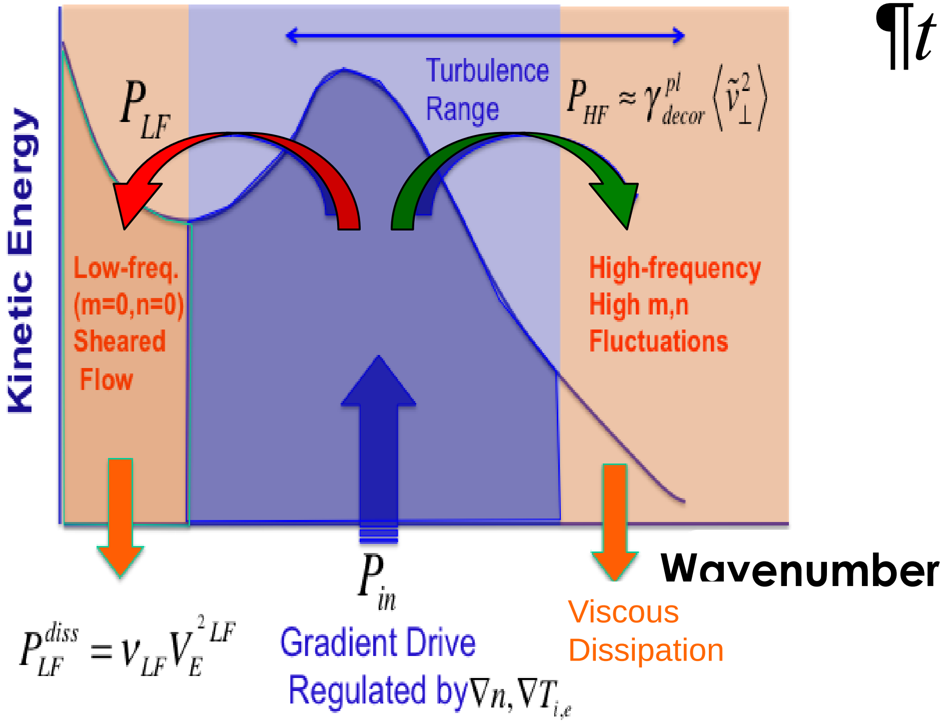
$$\frac{\P\tilde{V}_{\wedge}^2}{\P t} = (\overset{P_{in}}{\boxed{g_{eff}}} - \overset{P_{HF}}{\boxed{g_{decorr}}})\tilde{V}_{\wedge}^2 - \overset{P_{LF}}{\boxed{\left\langle \tilde{V}_r \tilde{V}_q \right\rangle \frac{\P V_{ZF}}{\P r}}}$$

Zonal flow kinetic energy:

$$\frac{\P V_{ZF}^2}{\P t} = \boxed{\left\langle \tilde{V}_r \tilde{V}_q \right\rangle \frac{\P V_{ZF}}{\P r}} - uV_{ZF}^2$$

sink

source

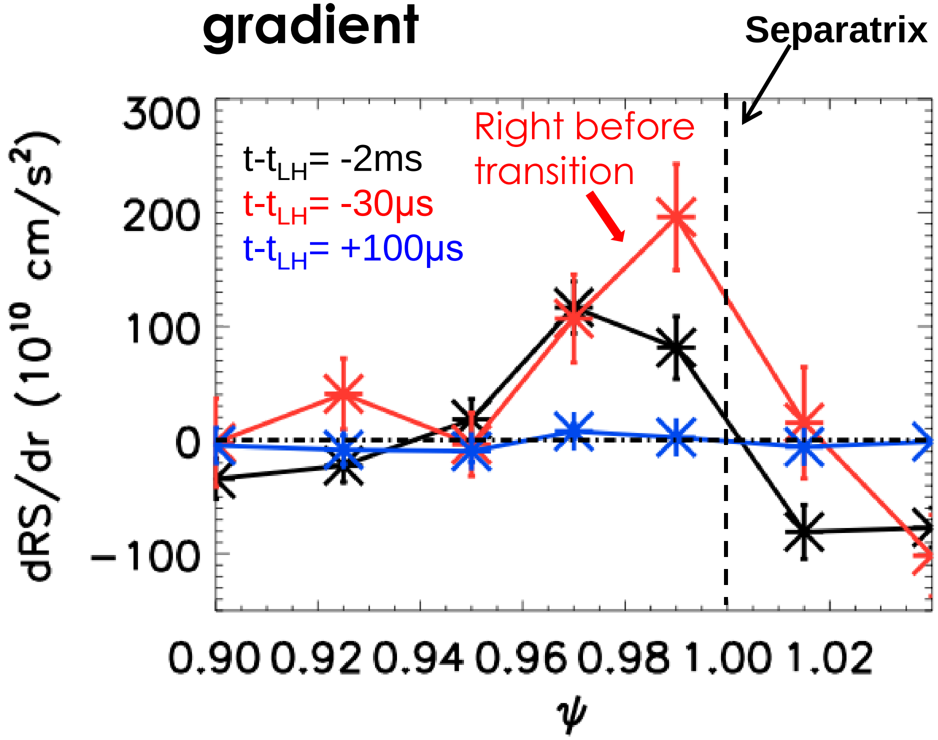


[1] P. Manz, et al., PoP, 19, 012309, 2012

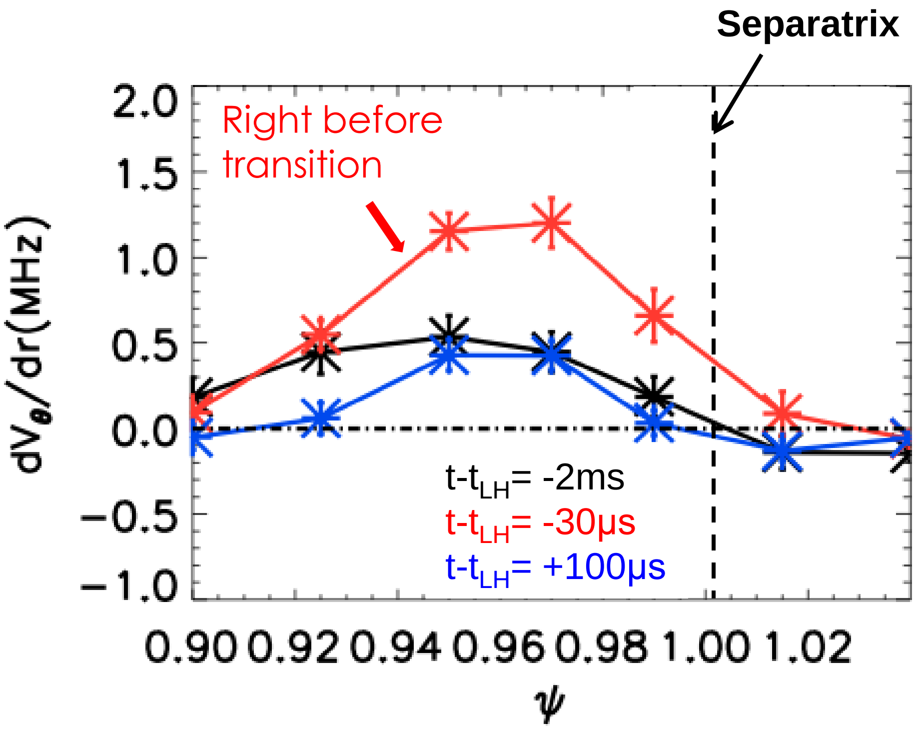
[2] G. Tynan, et al, NF, 53, 073053 2013

Turbulence Velocity Shear Driven by Reynolds Stress Increases approaching the L-H Transition

Radial profile of Reynolds stress gradient

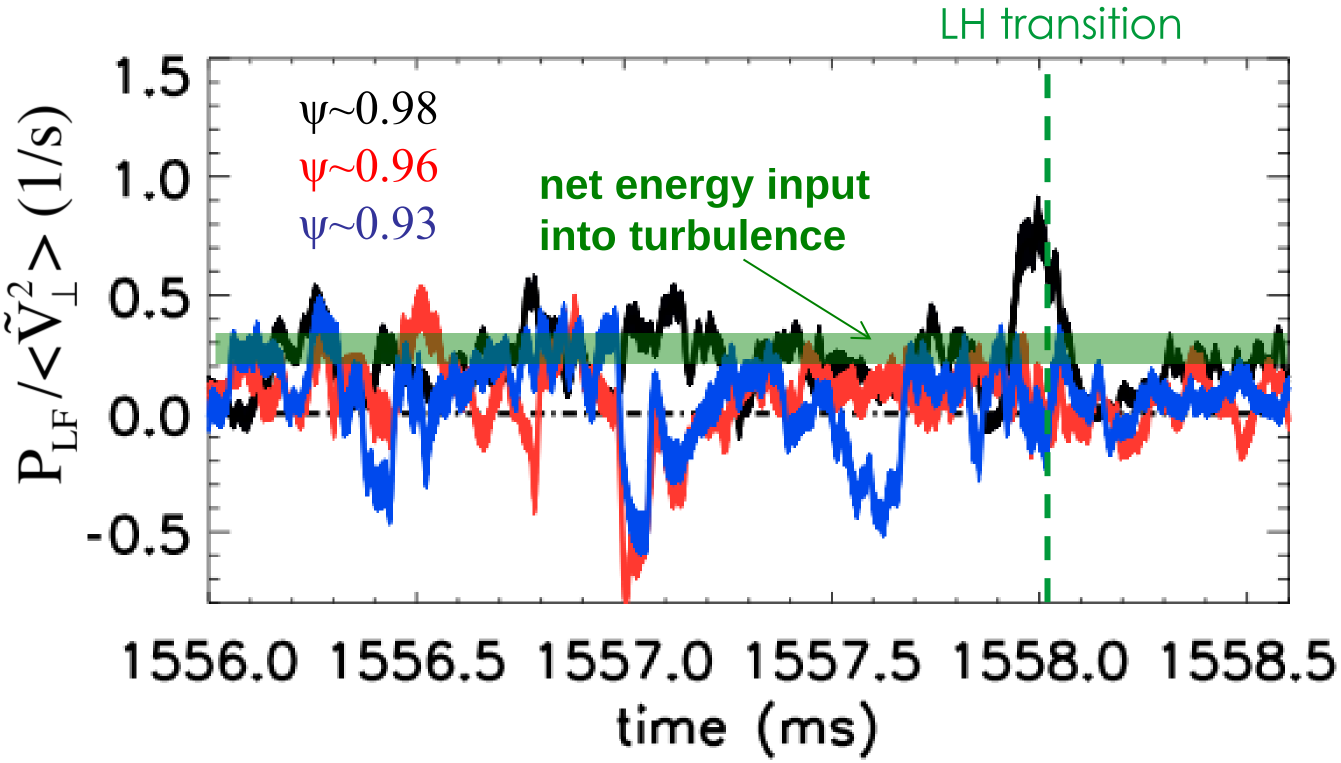


Radial profile of velocity shear



Energy Transfer from Turbulence to the Flow Plays Key Role in the L-H Transition

energy transfer rate into flow $$P_{LF}/\langle\tilde{V}_{\perp}^{2}\rangle = \langle\tilde{V}_r\tilde{V}_\theta\rangle\frac{\partial V_{ZF}}{\partial r}/\langle\tilde{V}_{\perp}^{2}\rangle > \gamma_{eff} - \gamma_{decorr}$$ **net energy input rate into turbulence**



- **The rapid change in energy transfer is localized to the plasma edge region**

Z. Yan, et al., PRL, 112, 125002, (2014)