Flow, turbulence and transport in laboratory plasmas (at least in LAPD and DIII-D)

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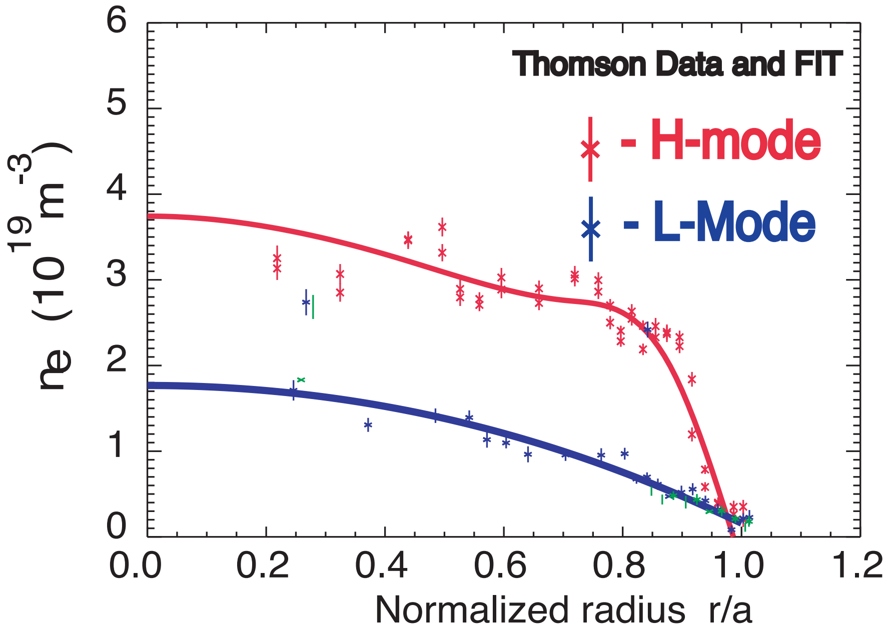
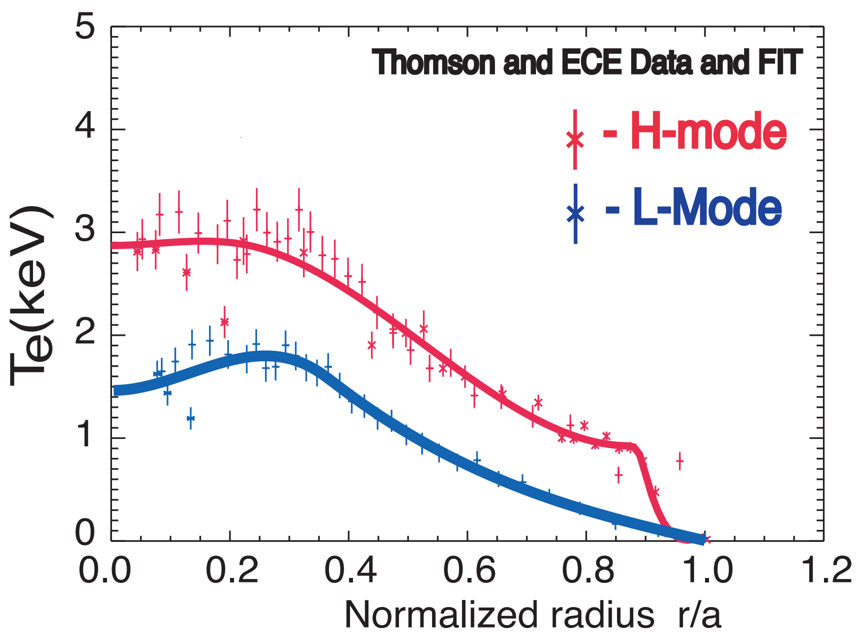
Summary/Outline

- Suppression of turbulent particle transport in LAPD by flow shear [Schaffner, et al., PRL 109, 135002 (2012)]
  - External control of cross-field flow in the presence of pressure-gradient driven turbulence [might be nonlinear instability: Friedman, et al., PoP 19, 102307 (2012)]
  - Transport decreases with shearing, enhanced at low shear; reduction due to turbulent amplitude reduction
- Critical gradient response in electron temperature fluctuations in DIII-D [Hillesheim, et al., PRL 110, 045003 (2013)]
  - Electron temperature gradient varied at constant heating power using ECH in DIII-D [DeBoo]
  - Electron temperature fluctuations increase beyond threshold value in L_{Te}, same critical gradient for Q_e increase from global power balance; consistent with turn-on of TEM

Turbulent transport reduction by sheared flow

- "H-mode" in tokamaks: edge transport barrier associated with edge flow layer (E_r "well")





Data from DIII-D

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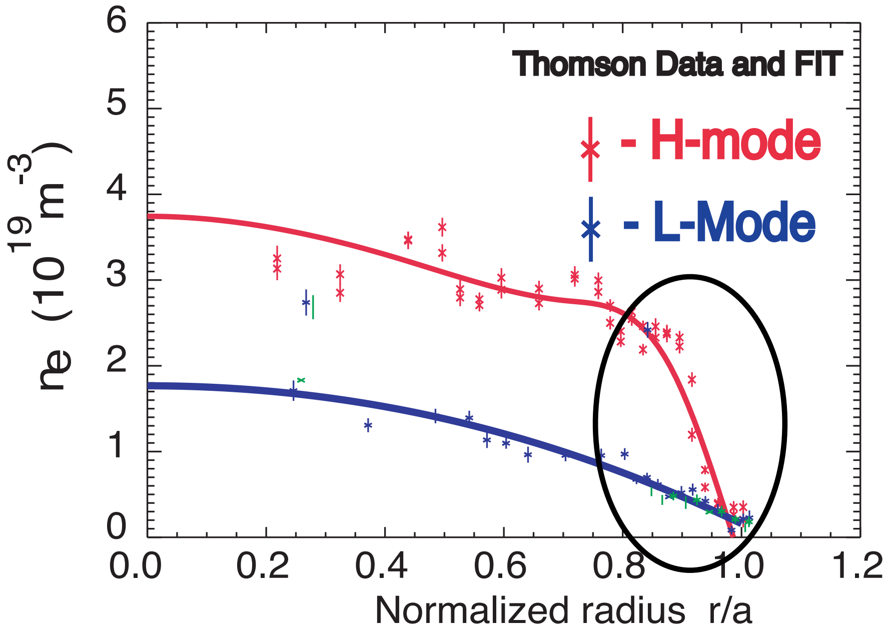

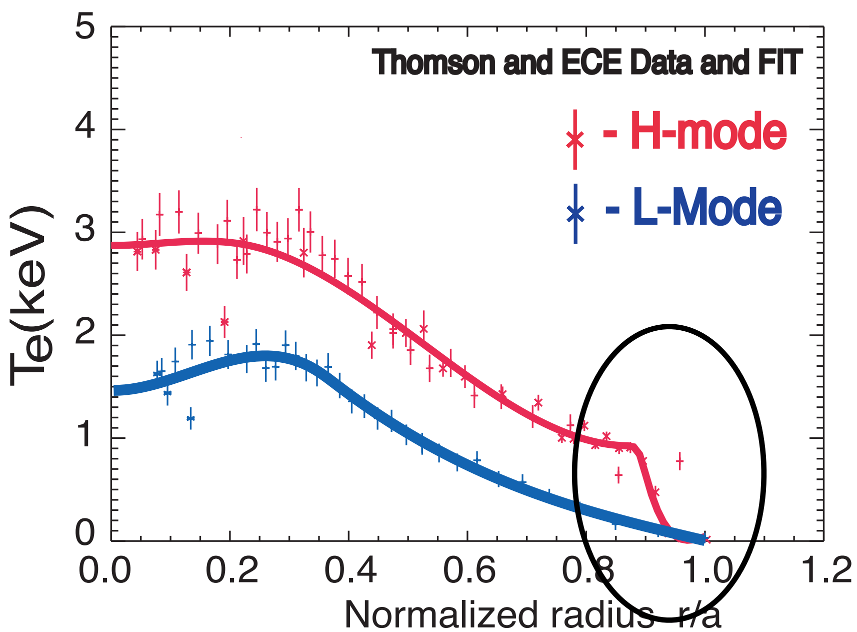

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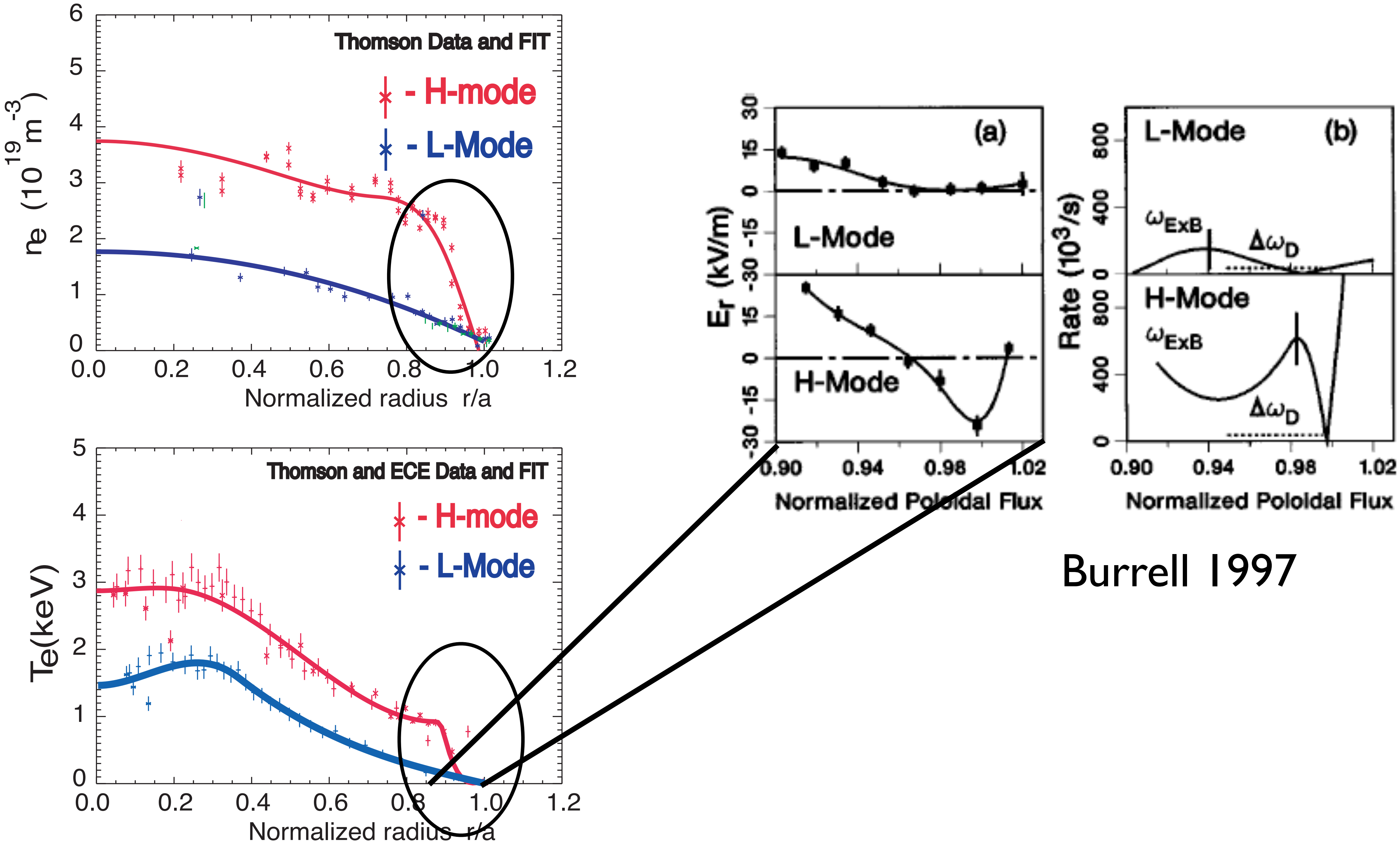

Data from DIII-D

Burrell 1997

Turbulent transport reduction by sheared flow

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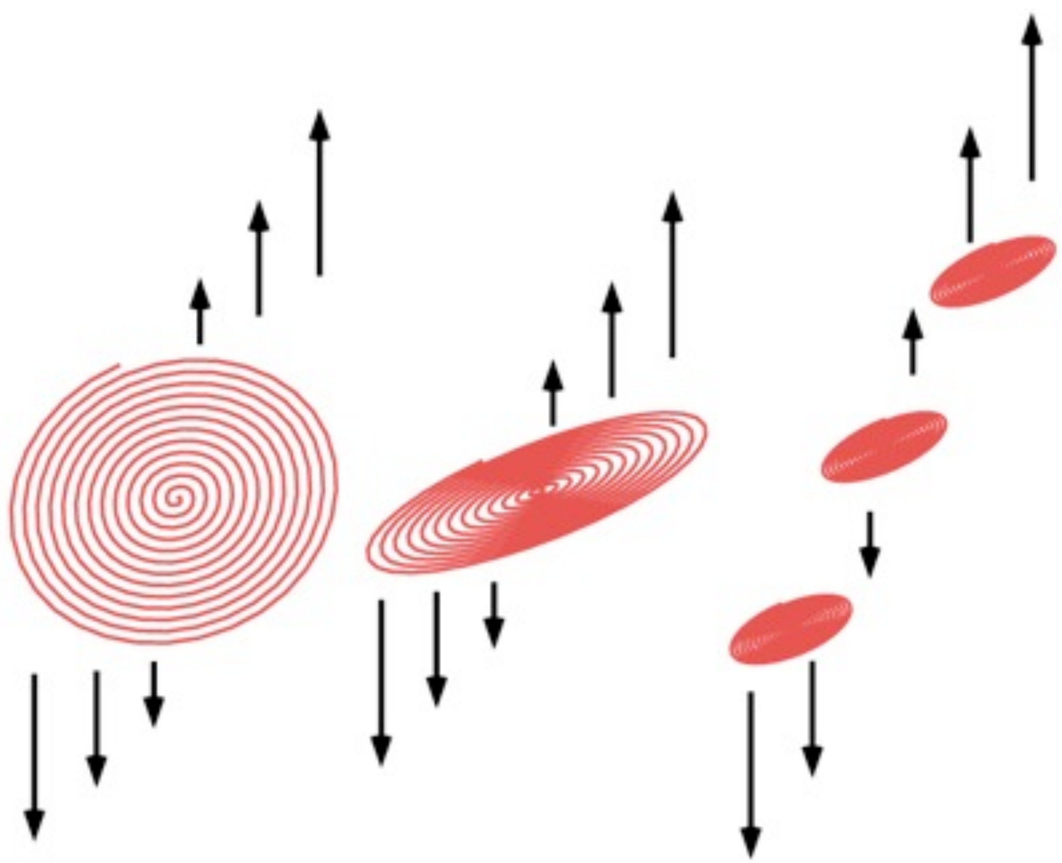


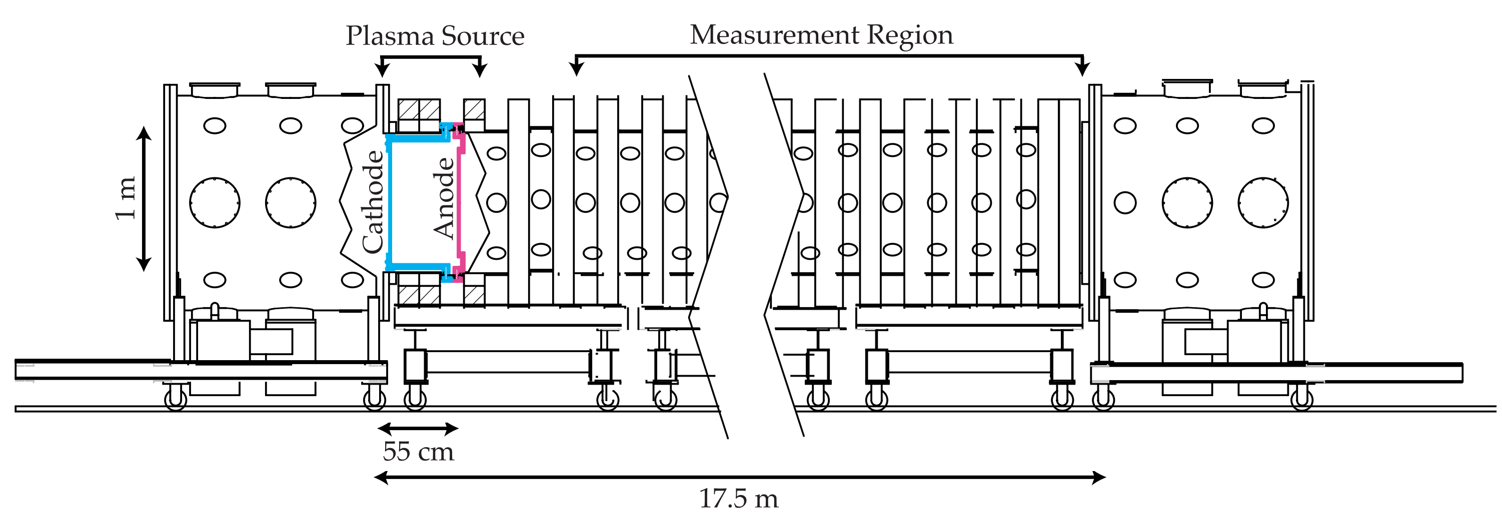
- Biglari, Diamond, Terry (BDT 90): transport modified by radial decorrelation or "shearing apart" of eddies
- Flow shear dynamically important if shearing rate comparable to eddy turnover time

Motivation for basic experiment investigating shear suppression of transport

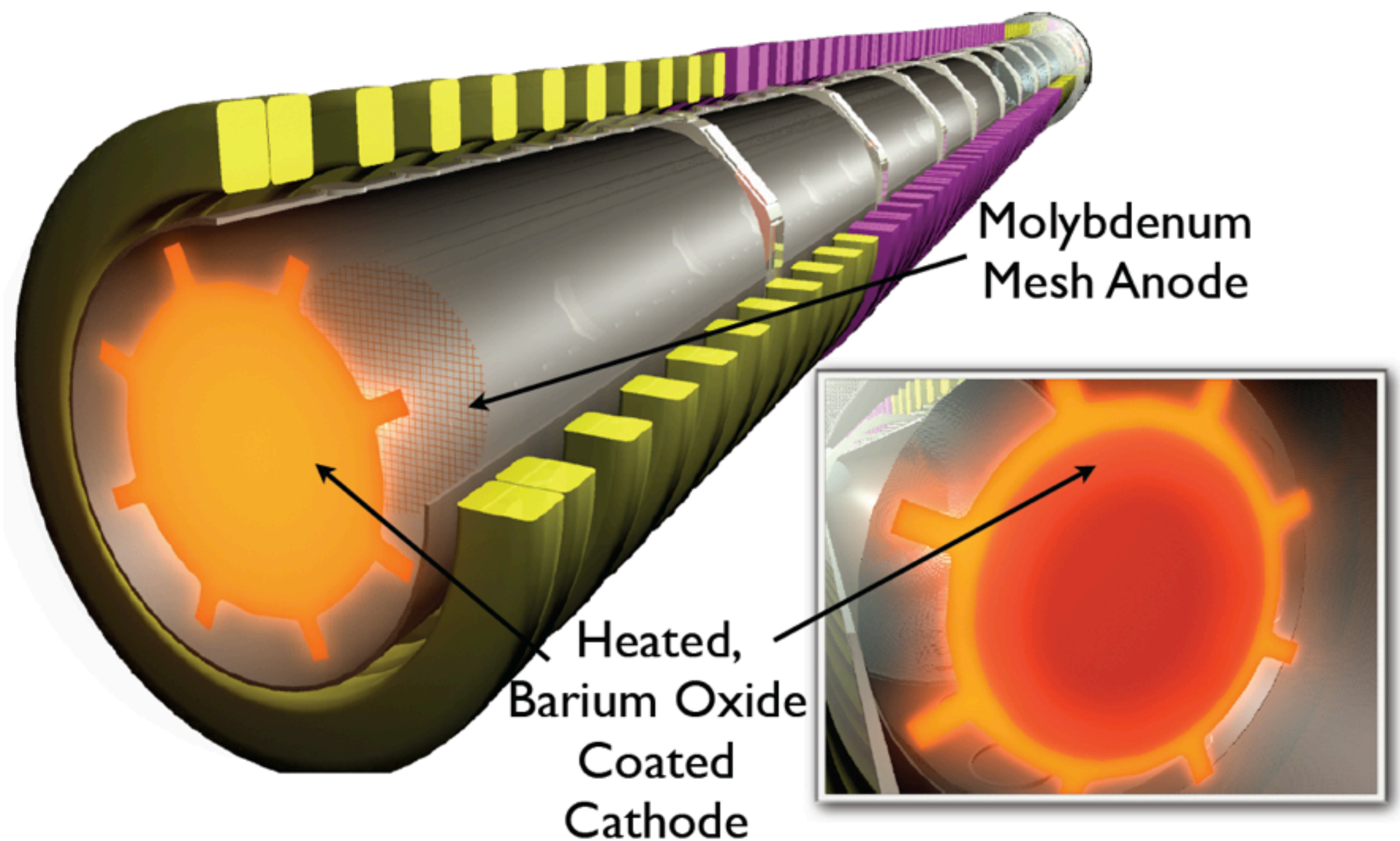
- Large body of work demonstrating shear suppression of turbulent transport in experiment and simulation [see, e.g., Burrell 97, Tynan 09, Terry 00...]
- However, fundamental questions remain about mechanism for transport reduction: decorrelation models (e.g. BDT) underpredict suppression (by ~ an order of magnitude). New ideas: enhanced coupling to damped eigenmodes by shear flow [Terry], nonlinear spectral shift [Staebler], etc.
- Role of shear-driven instabilities?: parallel velocity gradient instability in tokamaks [Barnes, Highcock, et al.]; Kelvin-Helmholtz, Rotational interchange in linear devices
- Predicting transport in current and future devices (ITER) requires validation of models against experiment: predicting shear suppression accurately is absolutely critical

The LArge Plasma Device (LAPD) at UCLA

- US DOE/NSF sponsored user facility (http://plasma.physics.ucla.edu)
- Solenoidal magnetic field, cathode discharge plasma
- $0.5 < B < 2\,\mathrm{kG}, n_e \sim 10^{12}\,\mathrm{cm}^{-3}, T_e \sim 5\,\mathrm{eV}, T_i \sim 1\,\mathrm{eV}$
- Large plasma size, 17m long, D~60cm (1kG: ~300 ρ_i, ~100 ρ_s)
- High repetition rate: 1 Hz



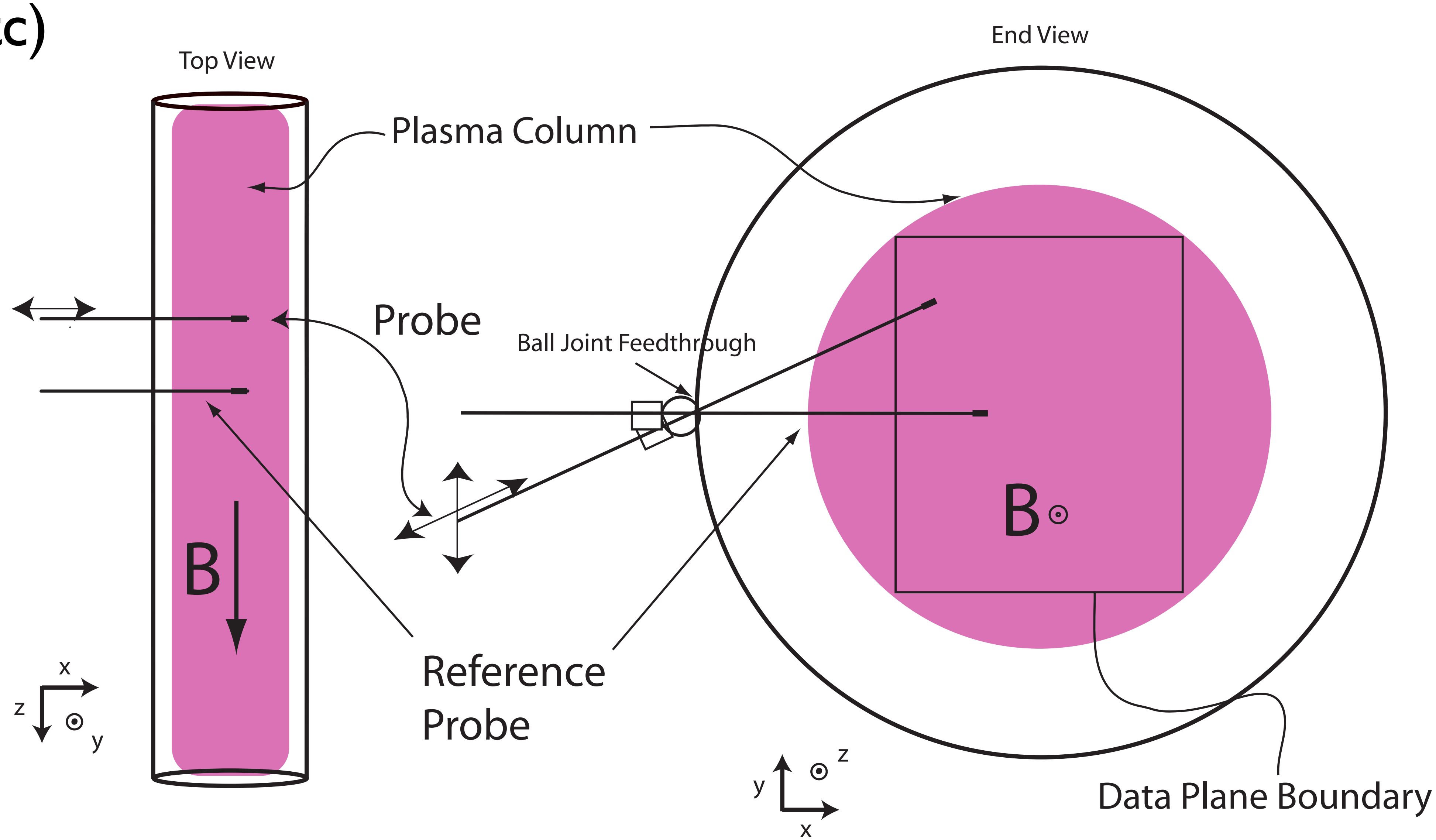
LAPD Plasma source



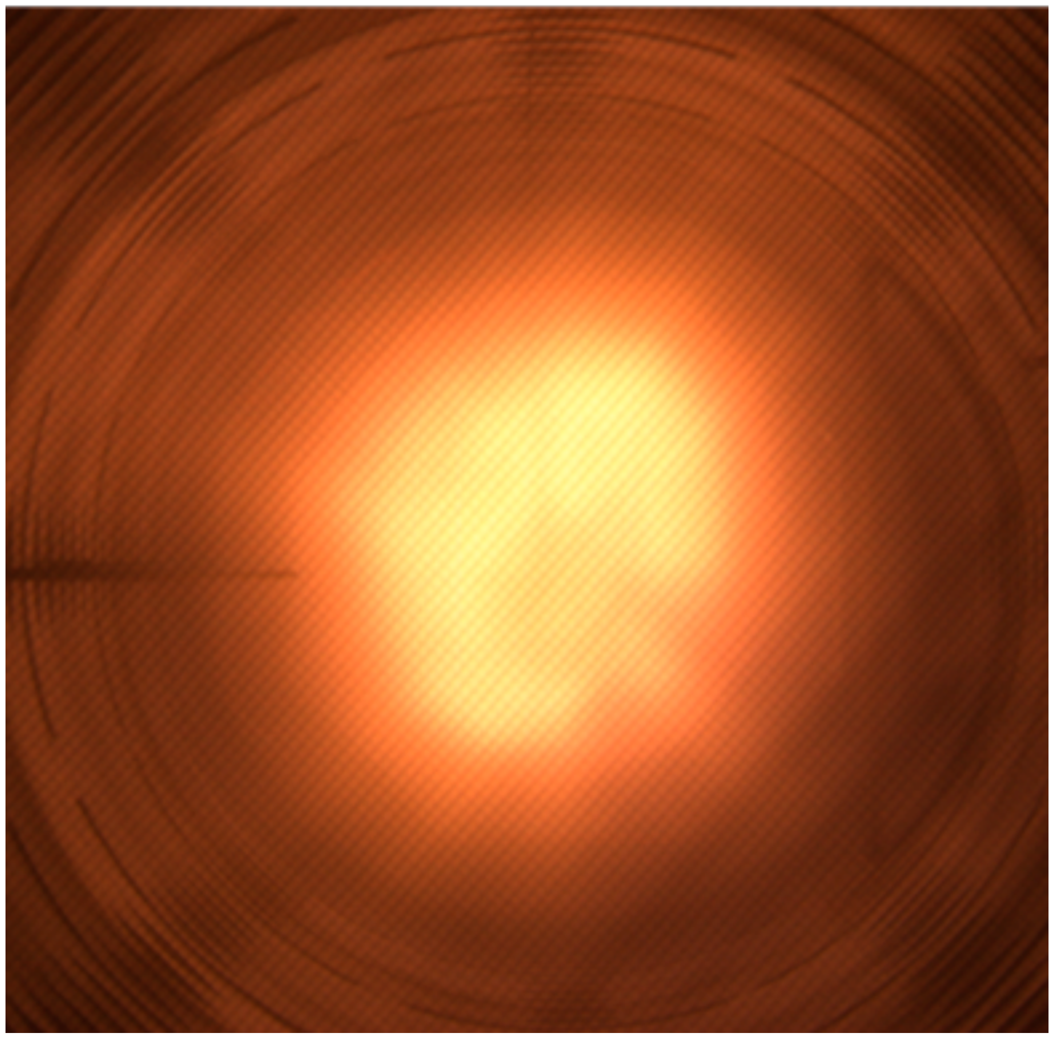
Measurement methodology in LAPD

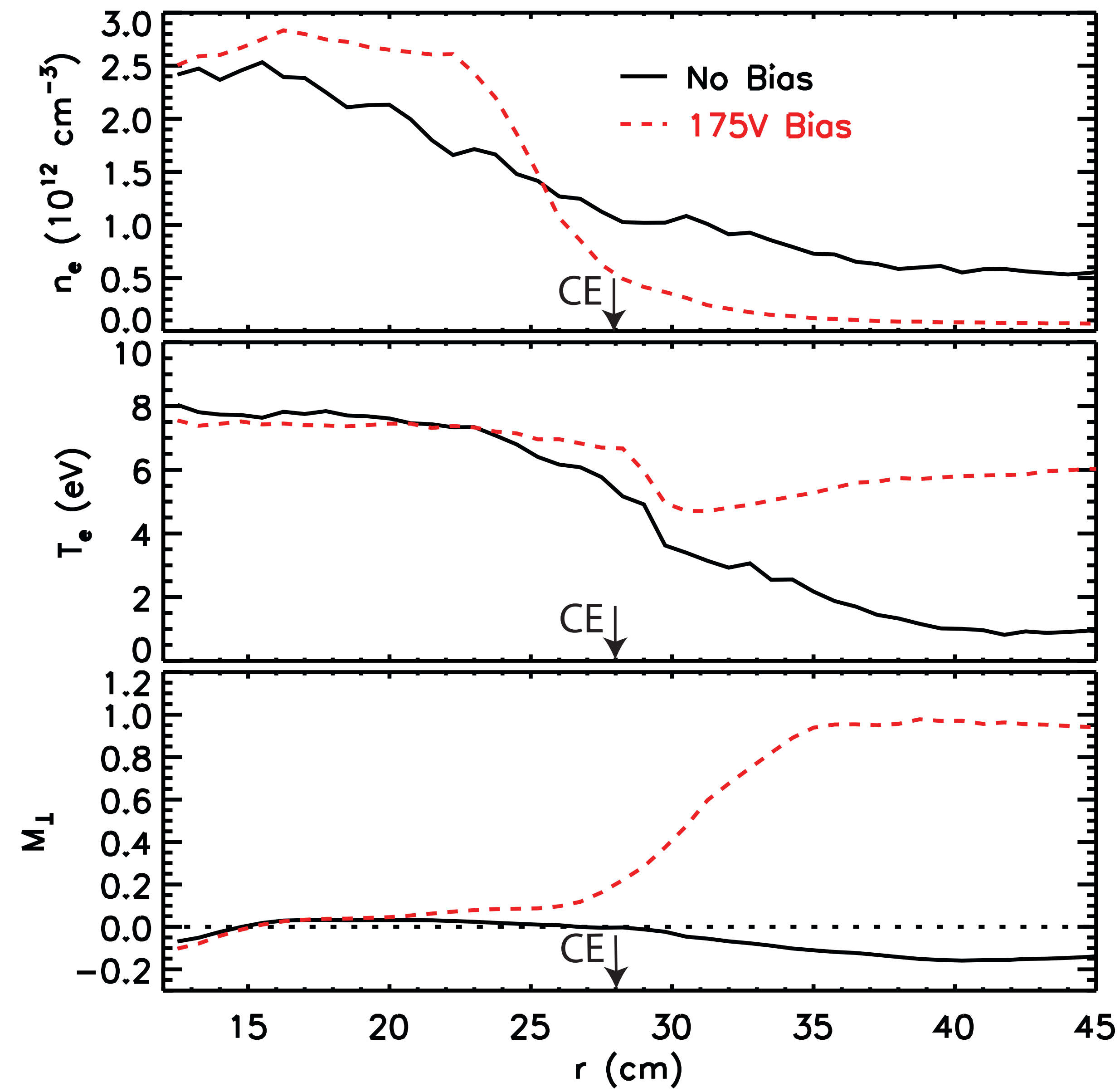
- Use single probes to measure local density, temperature, potential, magnetic field, flow: move single probe shot-to-shot to construct average profiles

- Add a second (reference) probe to use correlation techniques to make detailed statistical measurements of turbulence (structure, etc)



LAPD Plasma Profiles

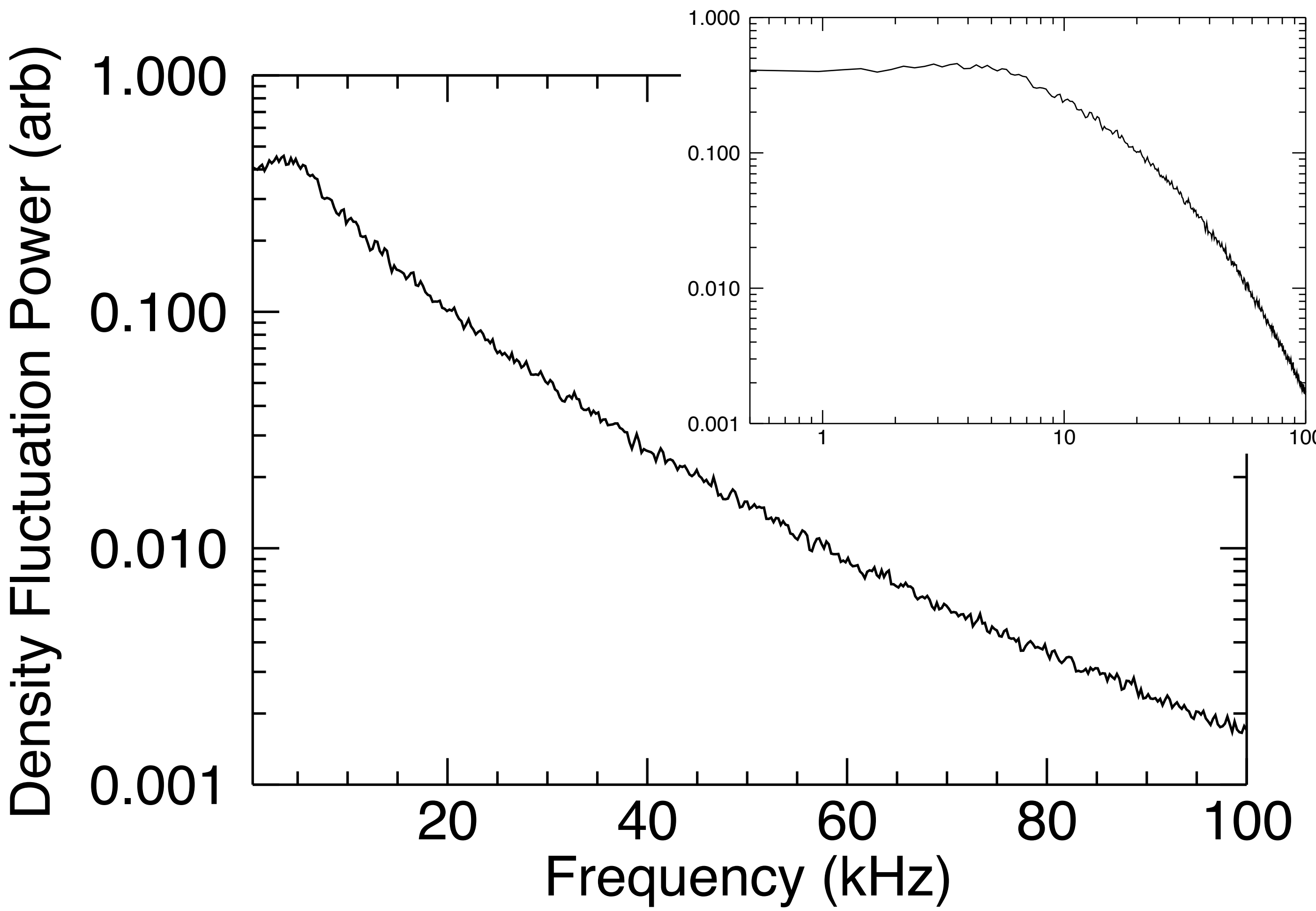


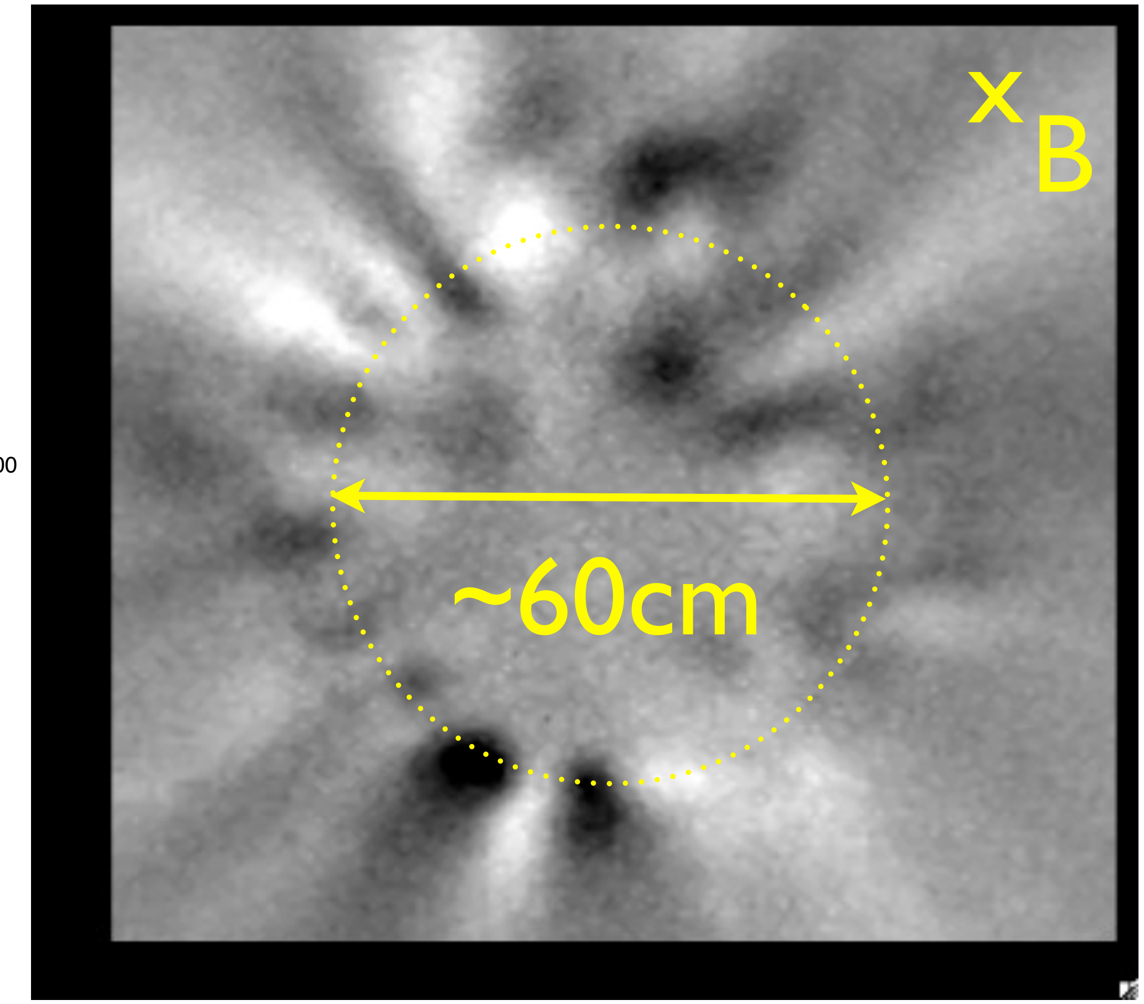


- Low field case (400G) (also shown: with particle transport barrier via biasing*); generally get flat core region with D=30-50cm
- Broadband turbulence generally observed in the edge region (localized to pressure gradient)

* Carter, et al, PoP 16, 012304 (2009)

Turbulence and transport in LAPD





- Broadband turbulence observed in edge (free energy from pressure gradient (drift waves) and driven flow (e.g. KH)). Exponential spectrum often observed [Pace, Shi, Maggs, Morales]

- Large plasma size allows perp. transport to compete with parallel losses; profile set by perp transport; confinement modification apparent in profile changes

Visible light imaging of LAPD turbulence

Fast framing camera (~50k frames per second, ~10ms total time), visible light (neutral He), viewed along B

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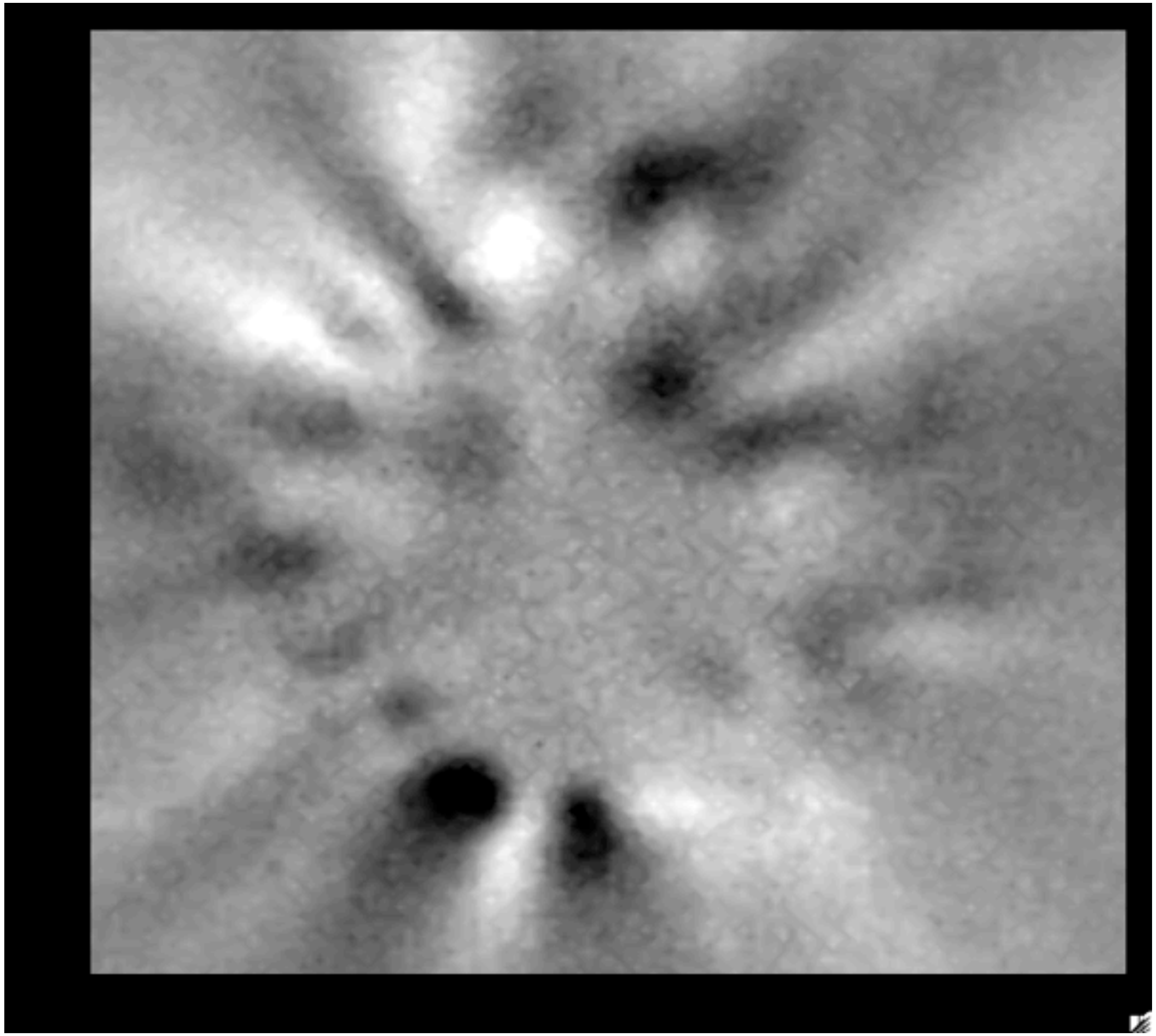

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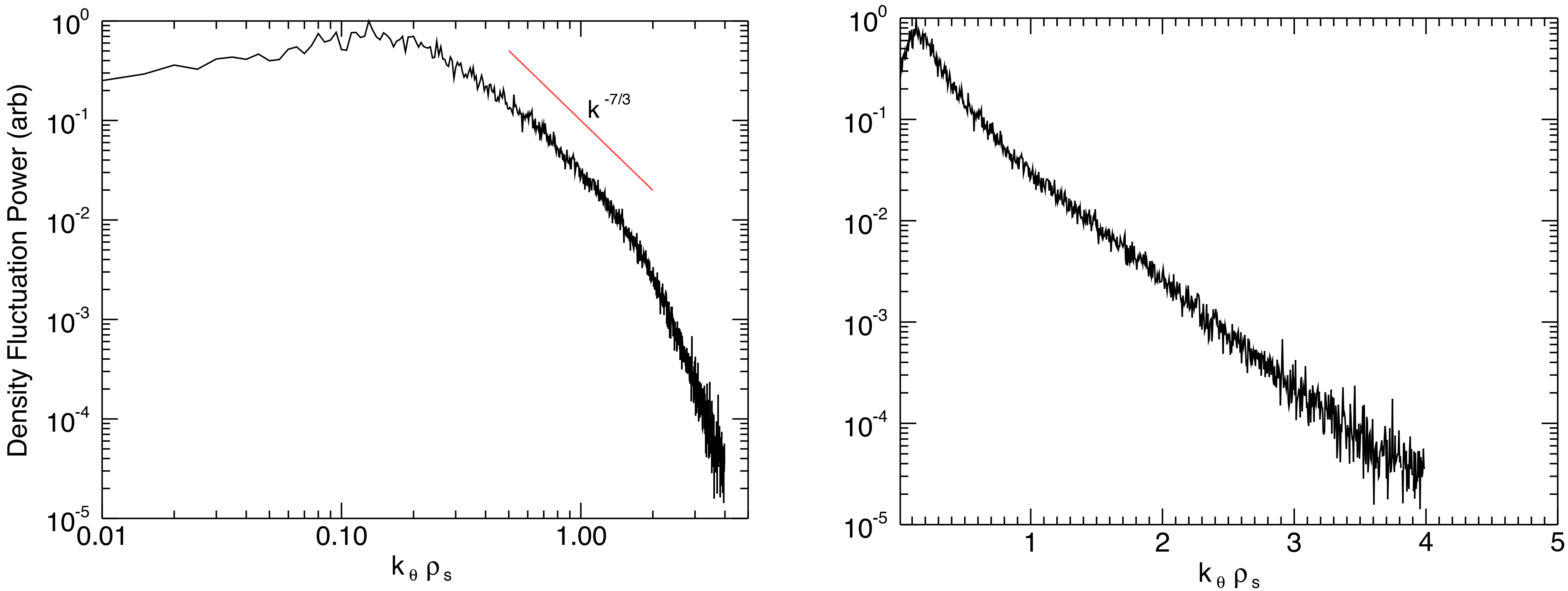
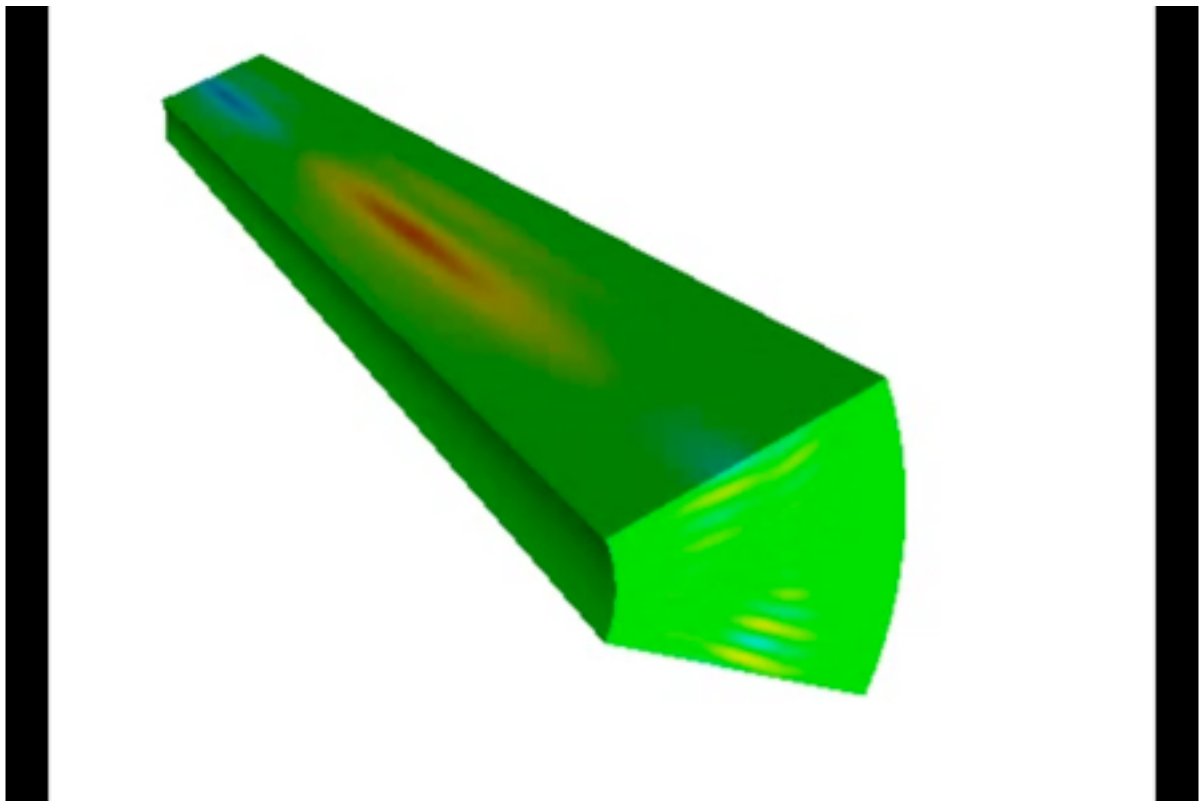
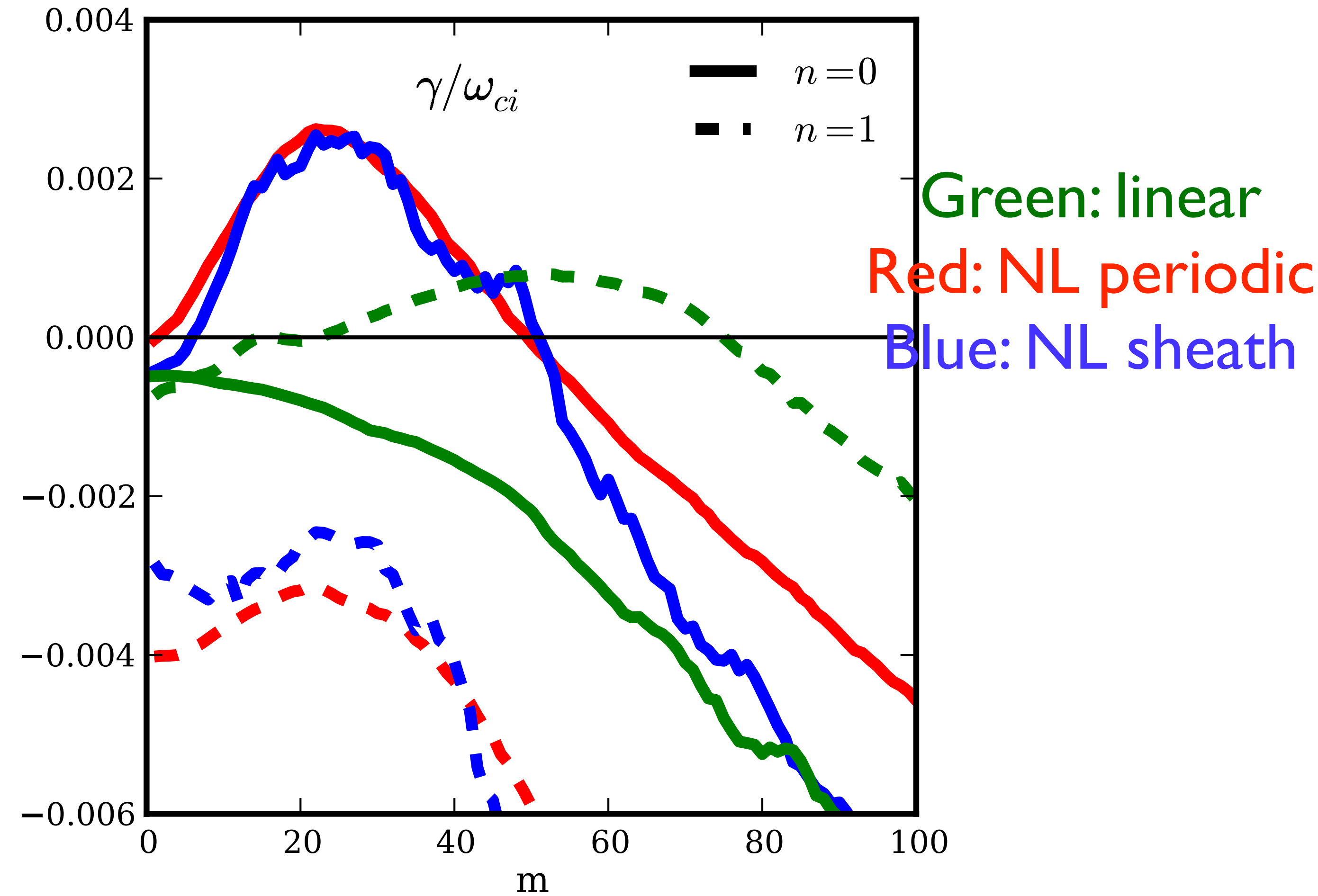
Wavenumber spectra



- Wavenumber spectra from pairs of probes (above), correlation planes, camera images
- Fastest growing linear instability: $k_\theta\ \rho_s \sim 1$ (resistive drift wave)
- Power law? Exponential?

Even though linearly unstable, nonlinear instability may explain saturated state





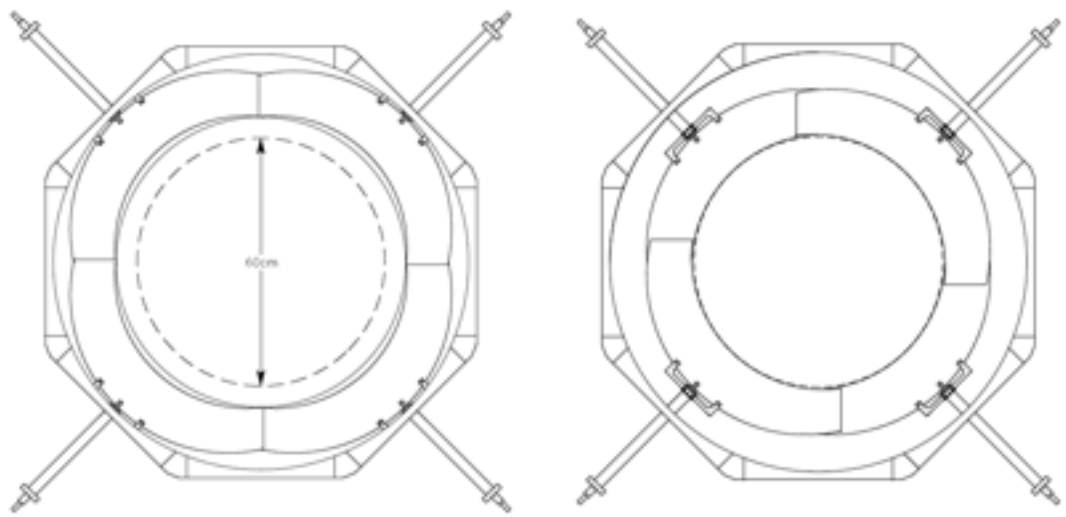
- Two-fluid simulations of LAPD turbulence (BOUT++)
- Resistive drift wave linearly unstable; however flute-like fluctuations dominate saturated state
- Nonlinear instability drives n=0 perturbations [Friedman, et al. PoP 19, 102307 (2012)]; robust to changes in axial boundary condition [Friedman et al., PoP in press]

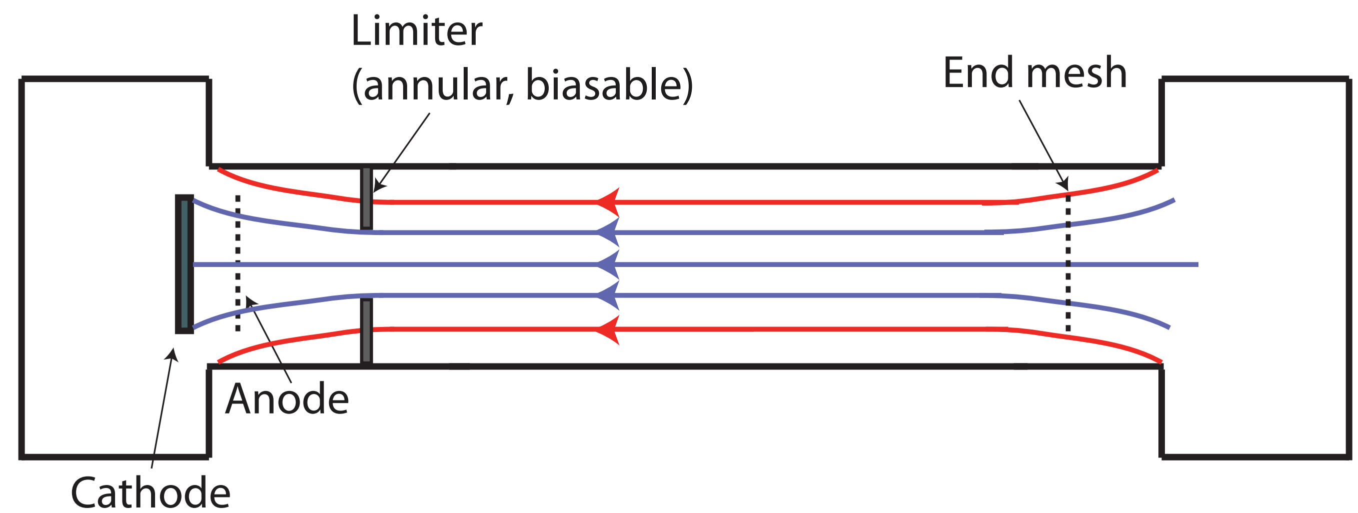
(Prior art: Drake, Biskamp, Zeiler, Scott…)

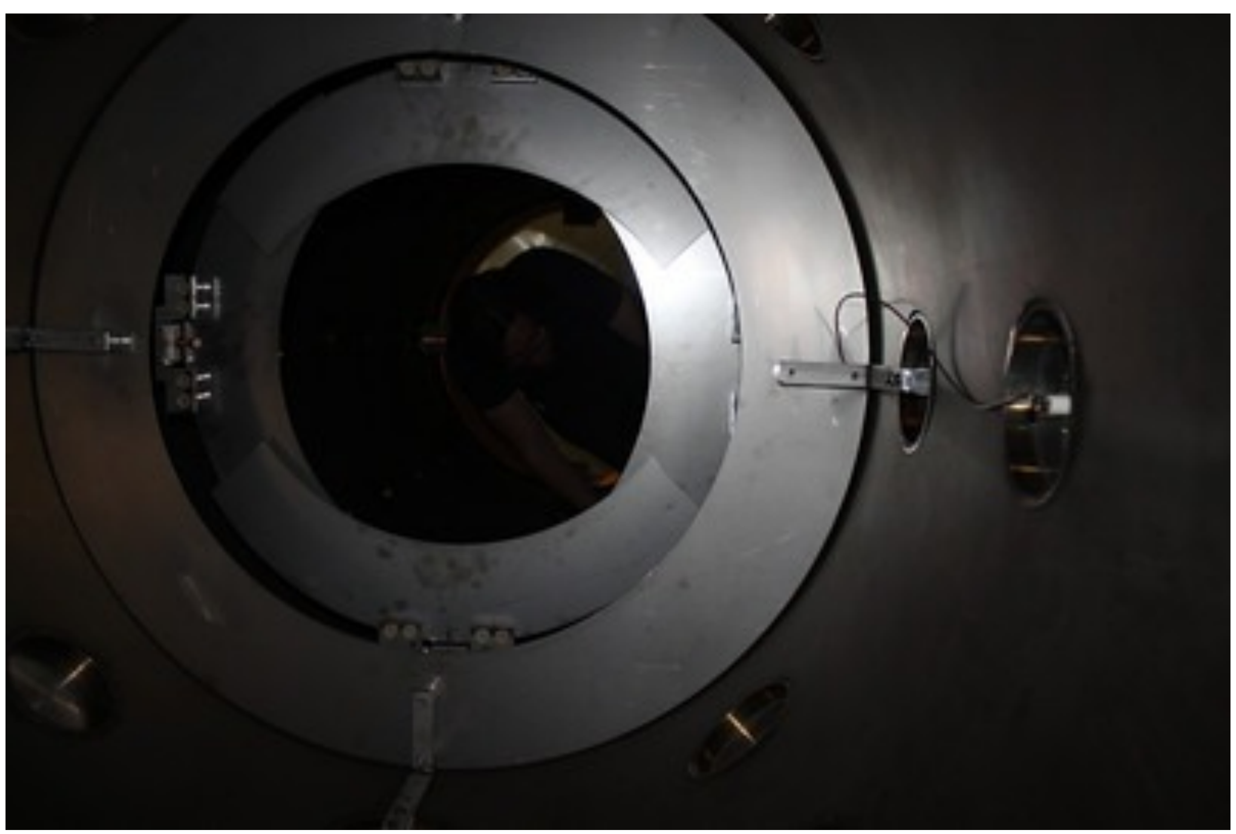
Using biasing to drive cross-field flow

- Electrode immersed in plasma, biased relative to chamber wall (tokamak) or plasma source (LAPD)
- Cross-field current driven (e.g. via Pedersen conductivity), provides torque to spin up plasma
- Following CCT [Taylor 89], technique used widely to drive flow and generate transport barriers: tokamaks , stellarators, RFPs, mirror machines ... [Weynants 92, Sakai 93, Boedo 02, Silva 06, …]
- LAPD biasing experiments provide combination of precise flow control and extensive measurements to provide detailed response of turbulence to shearing required to validate theoretical models and simulations

Variable-aperture limiter biased to drive azimuthal flow

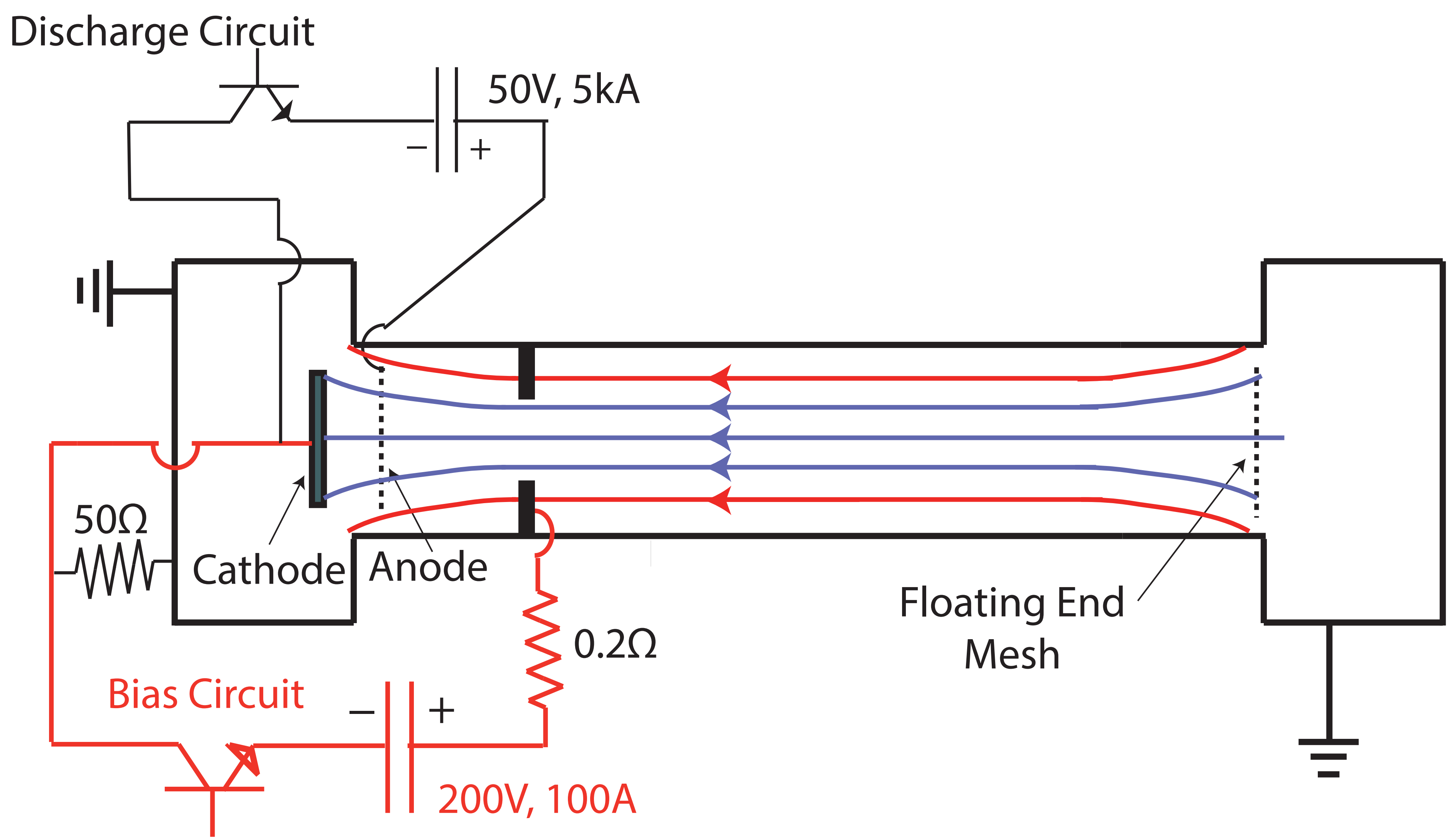






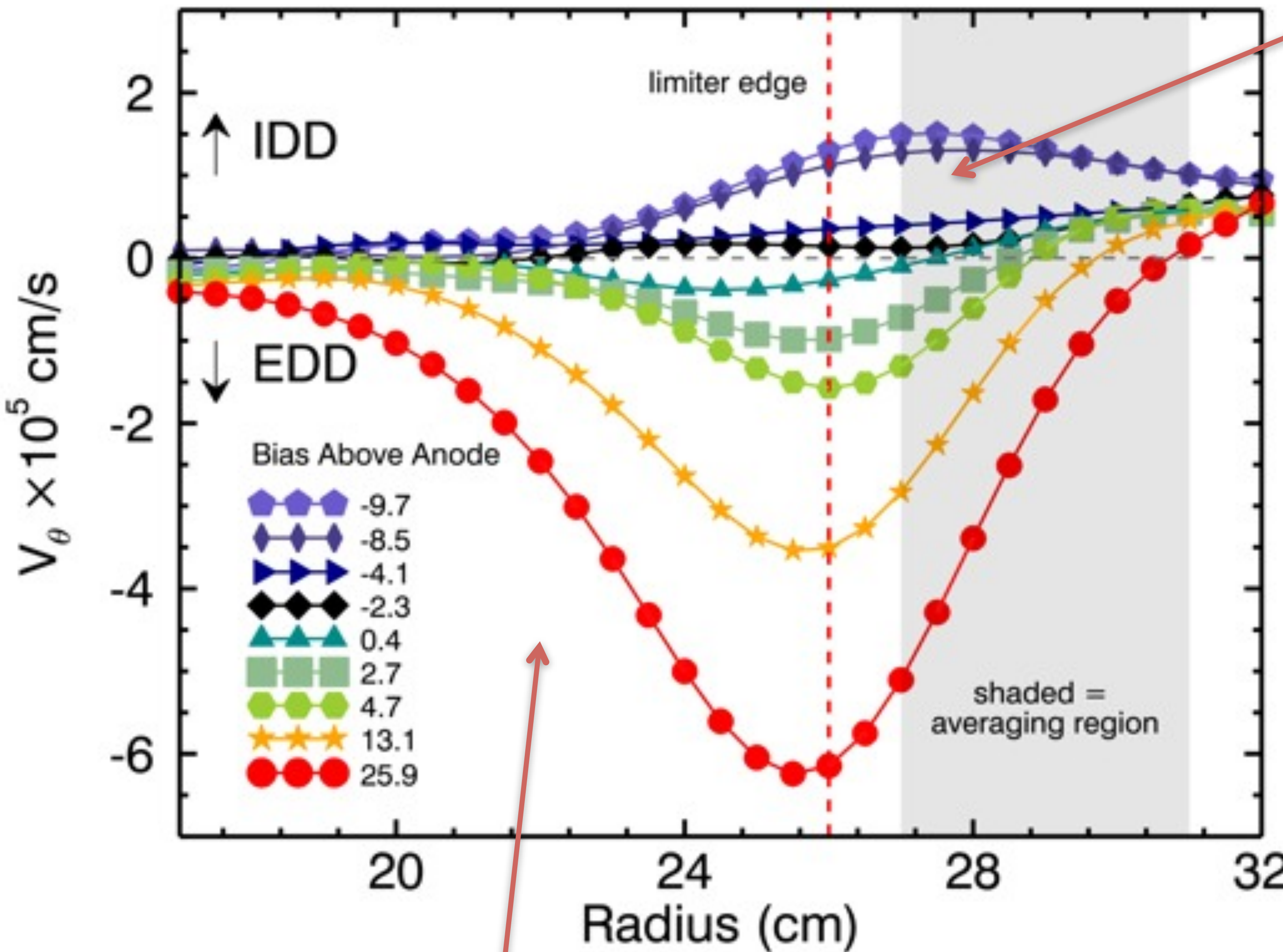
- Variable aperture, for these studies set to 52cm diameter
- Biased relative to the plasma source cathode

Variable aperture limiter biased to drive azimuthal flow



- Limiters collect electrons, current closes via cross-field ion current (Pedersen conductivity) and parallel electron current on cathode-connected field lines
- Flows driven in edge (“core” plasma line-tied to cathode)

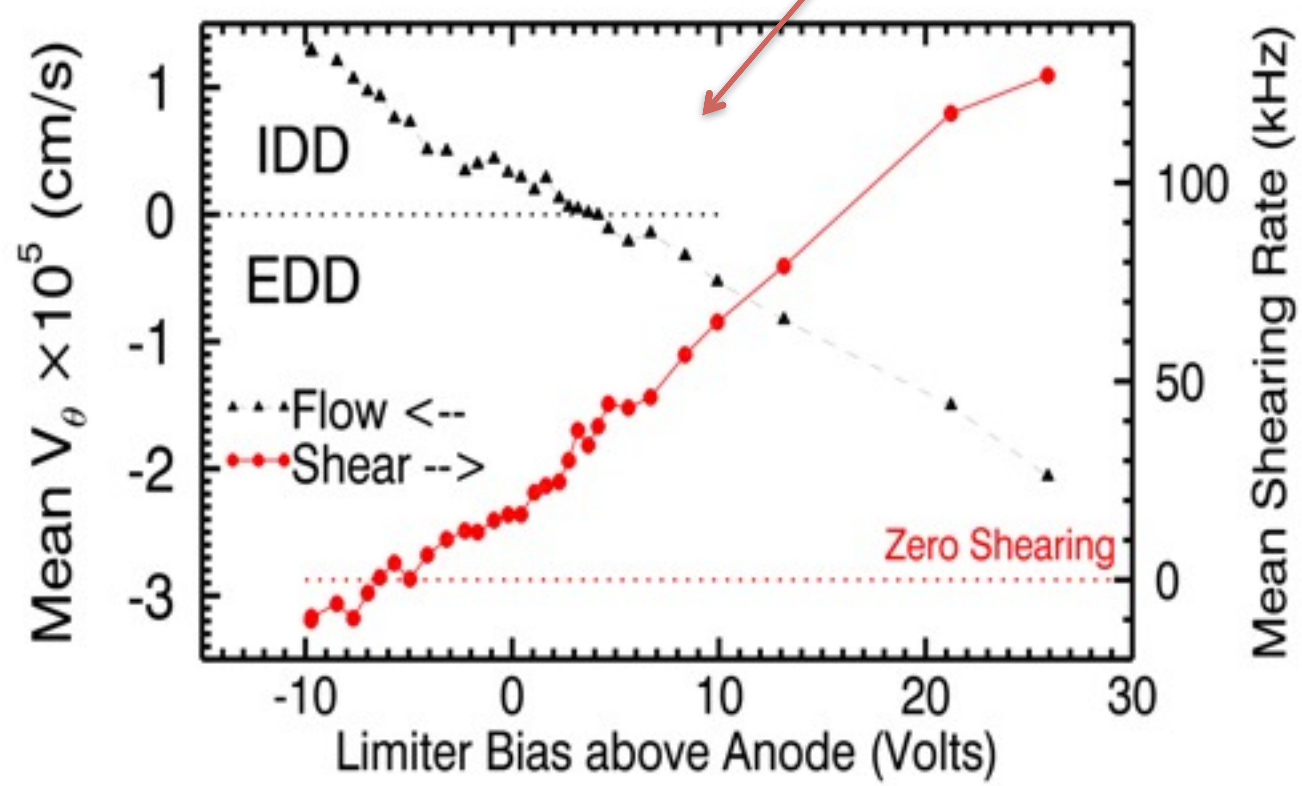
Continuous control on edge flow/shear is achieved, including flow reversal and zero shear state



Spontaneous (unbiased) flow in IDD

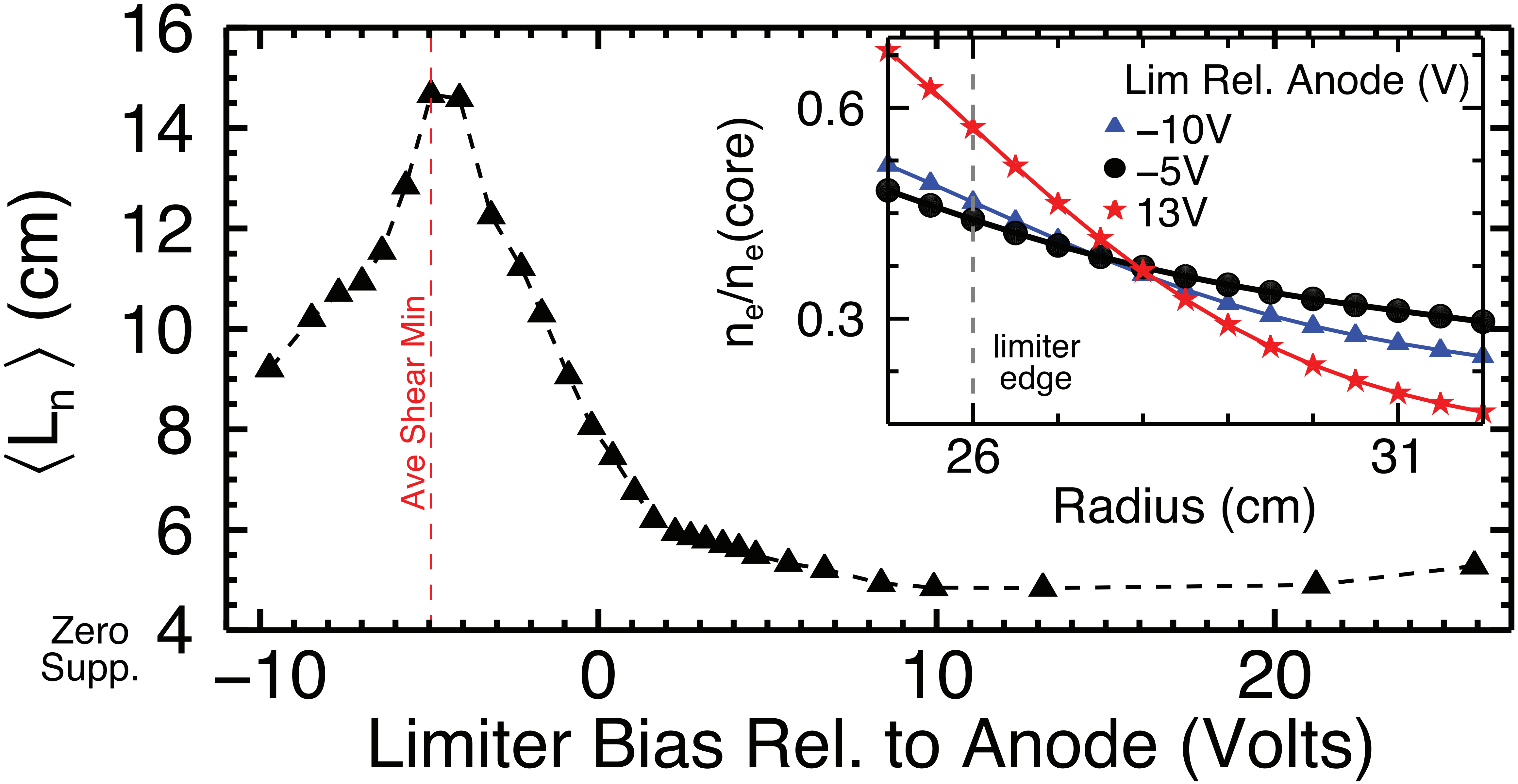
Biasing drives flow in EDD, opposing spontaneously induced flow

Average edge flow velocity and shearing rate scale linearly with limiter bias

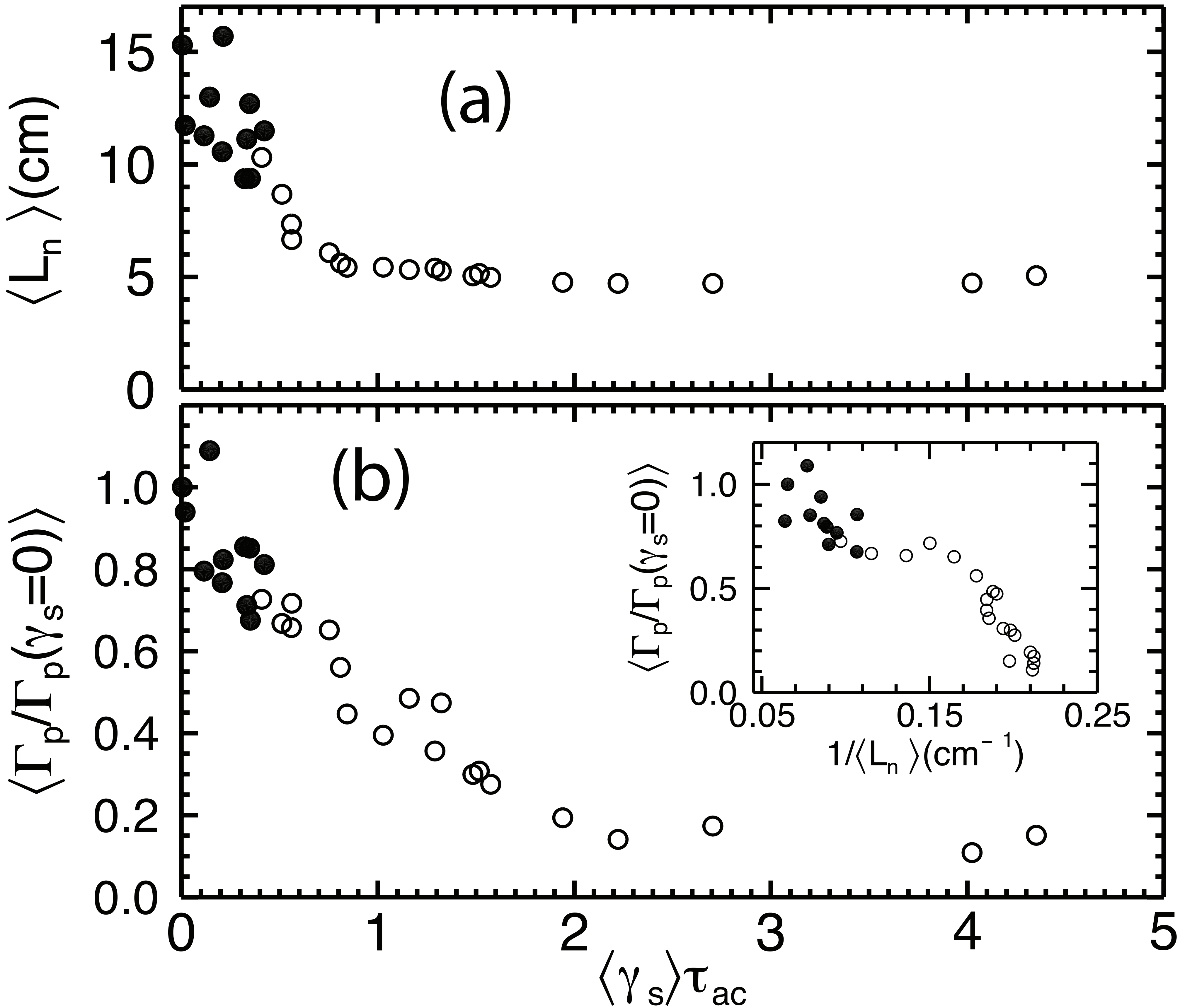


Confinement enhanced in both flow directions; degraded at low shear

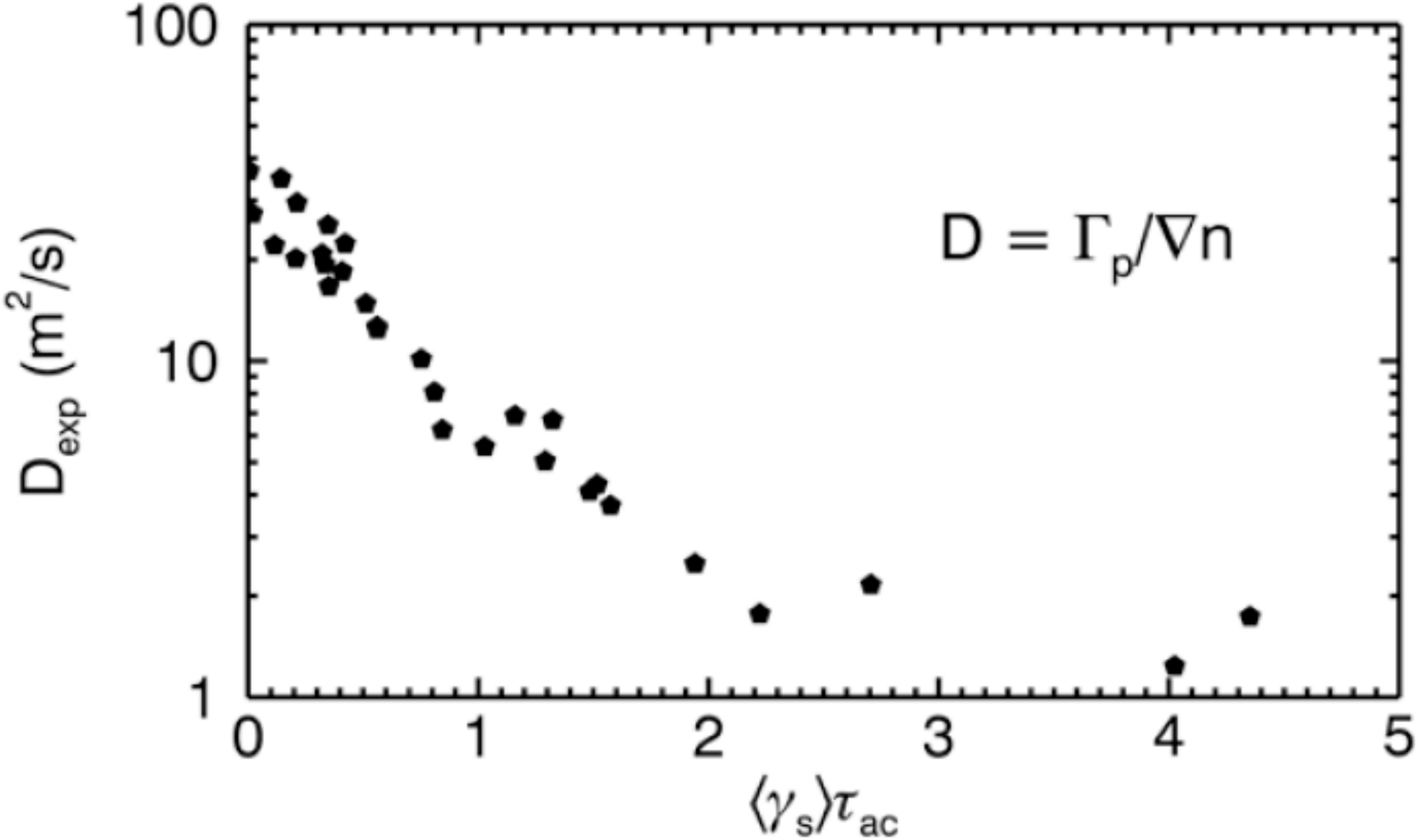
$$L_n = |\ln \frac{dn}{dr}|^{-1}$$



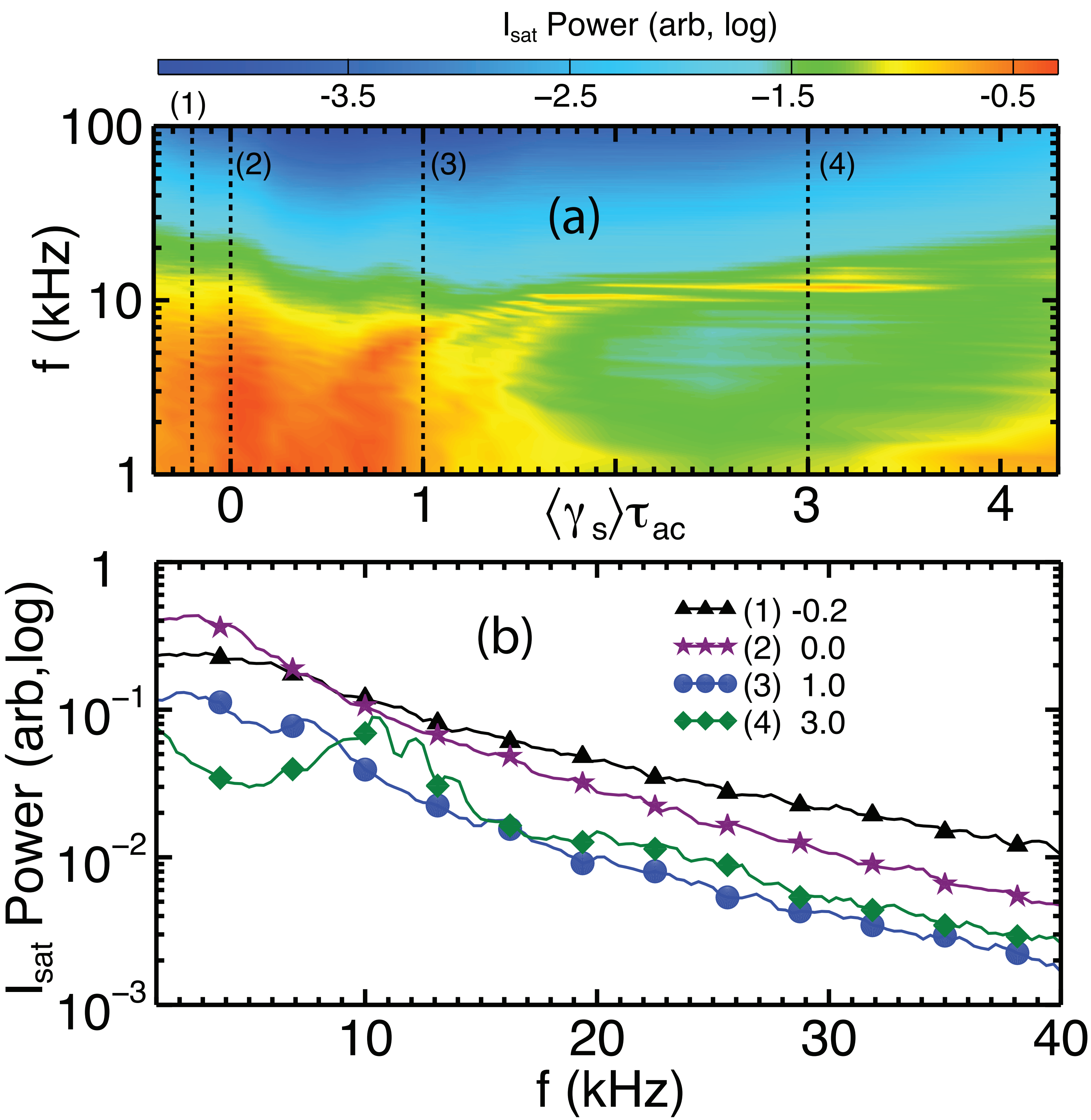
Profile steepens, flux decreases with shearing rate



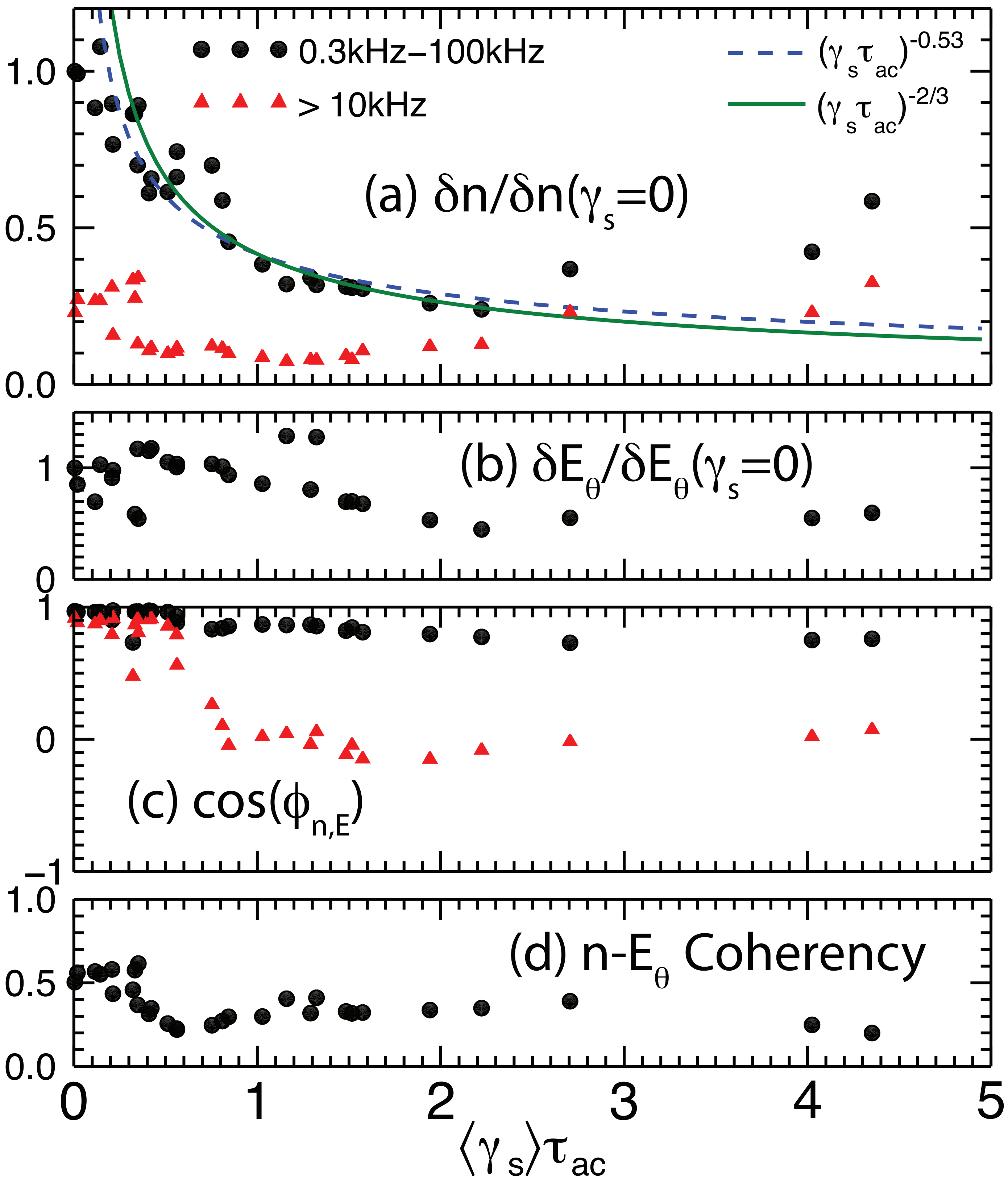
Inferred diffusivity drops by a factor of ~40



Fluctuation power is reduced with increased shearing and enhanced at low shear



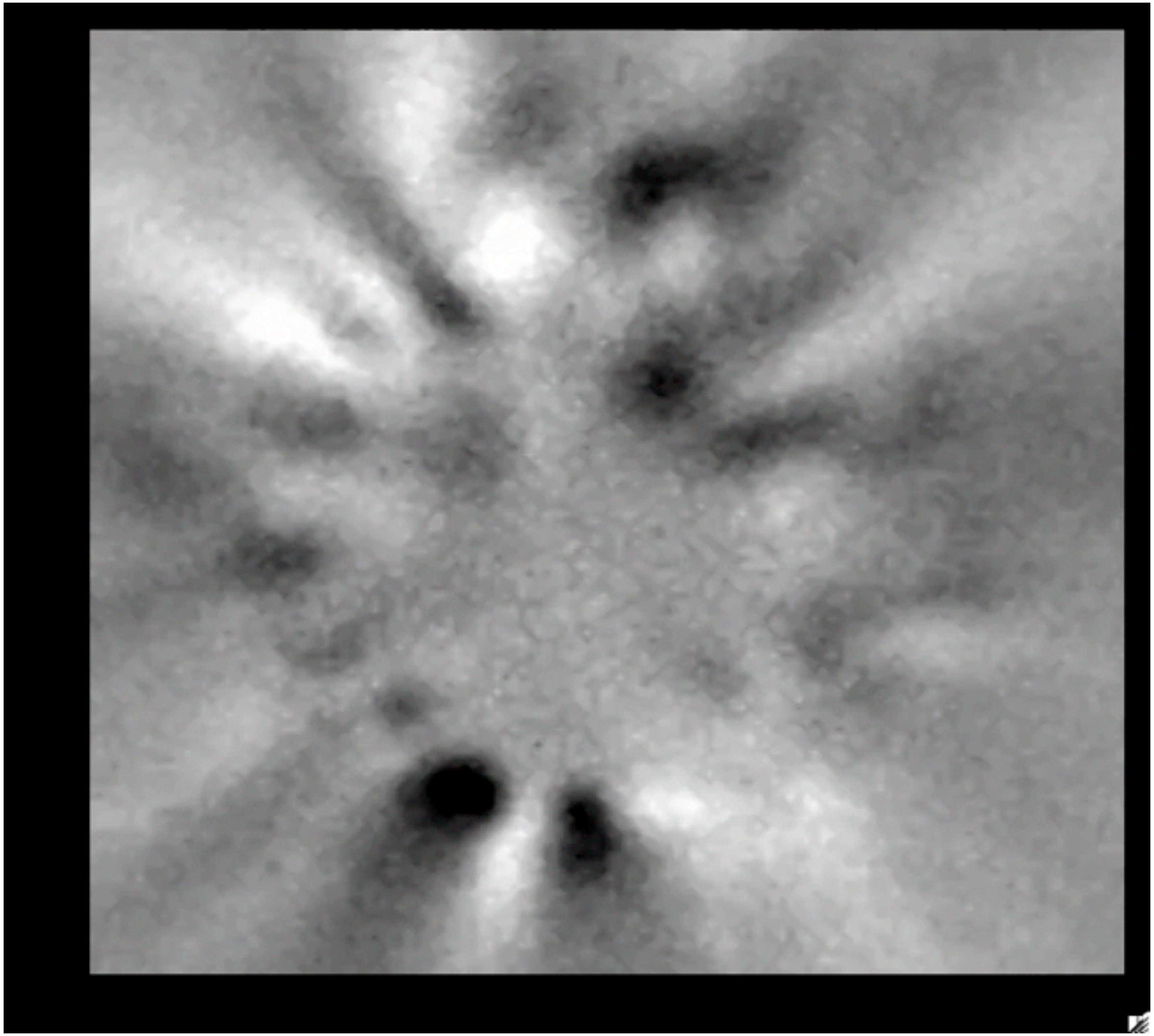
Turbulent amplitude reduction dominates transport suppression



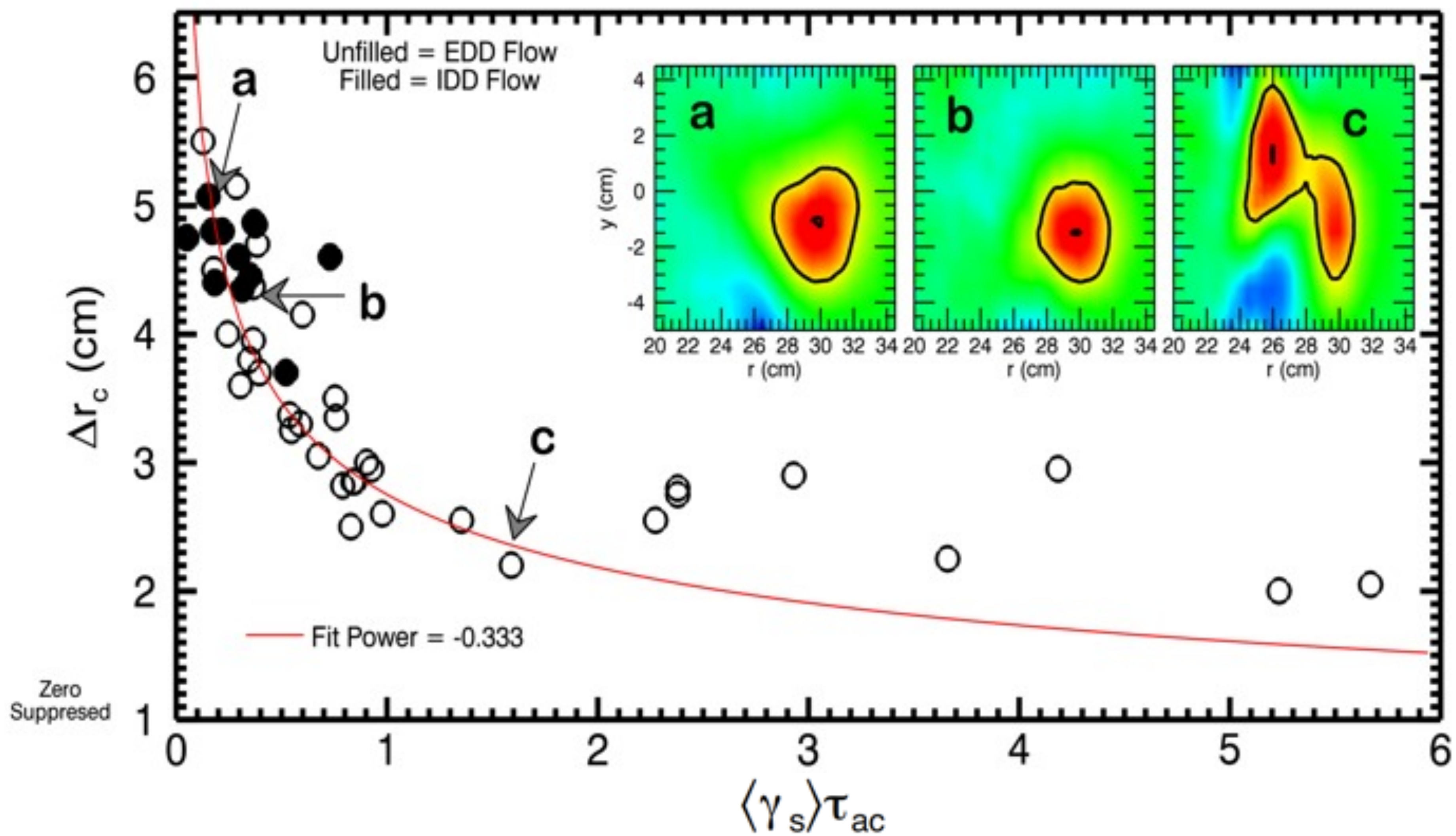
- Density fluctuations drop substantially, electric field reduction weaker
- Crossphase largely unchanged (distinct from previous results: due to lower shear?)
- Coherent mode emerges, but causes no net transport
- Compares well with BDT, but shouldn't apply!

Effect of driven rotation on turbulence: visible imaging

Effect of driven rotation on turbulence: visible imaging



Radial correlation length decreases with shear



- Again, fits BDT theory surprisingly well; however, trend in gradient scale length is similar
- Coherent mode dominates at higher shearing

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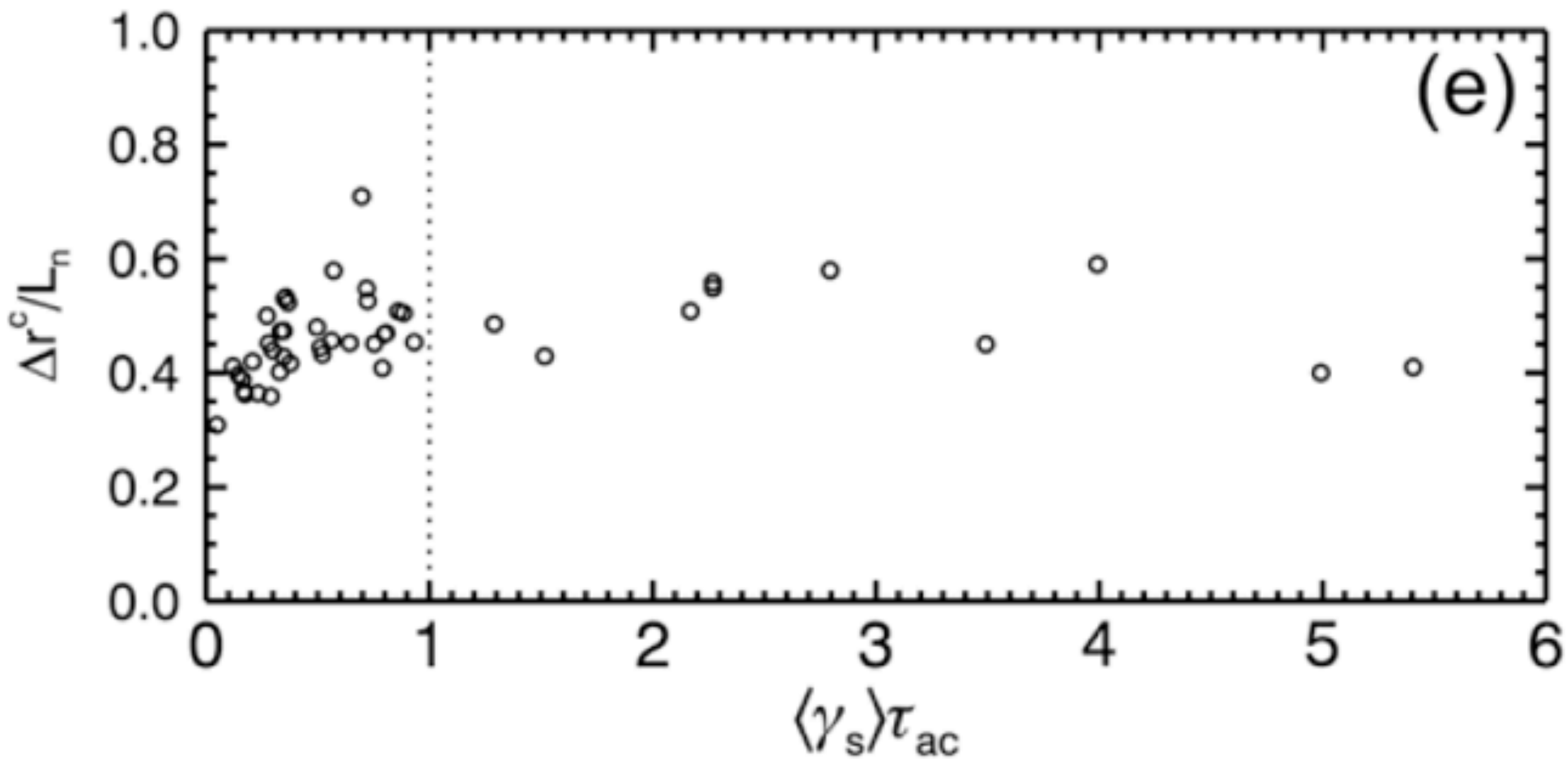

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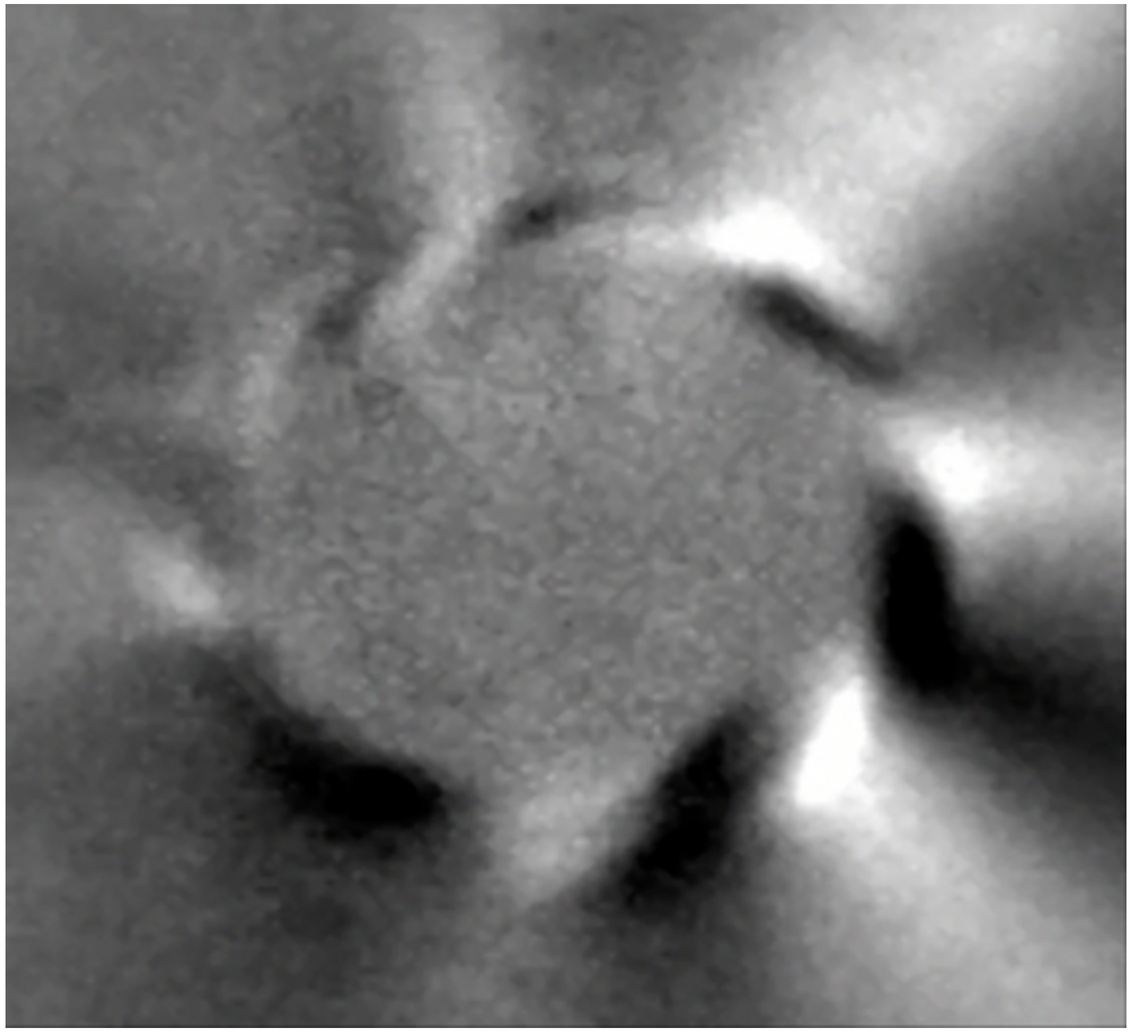
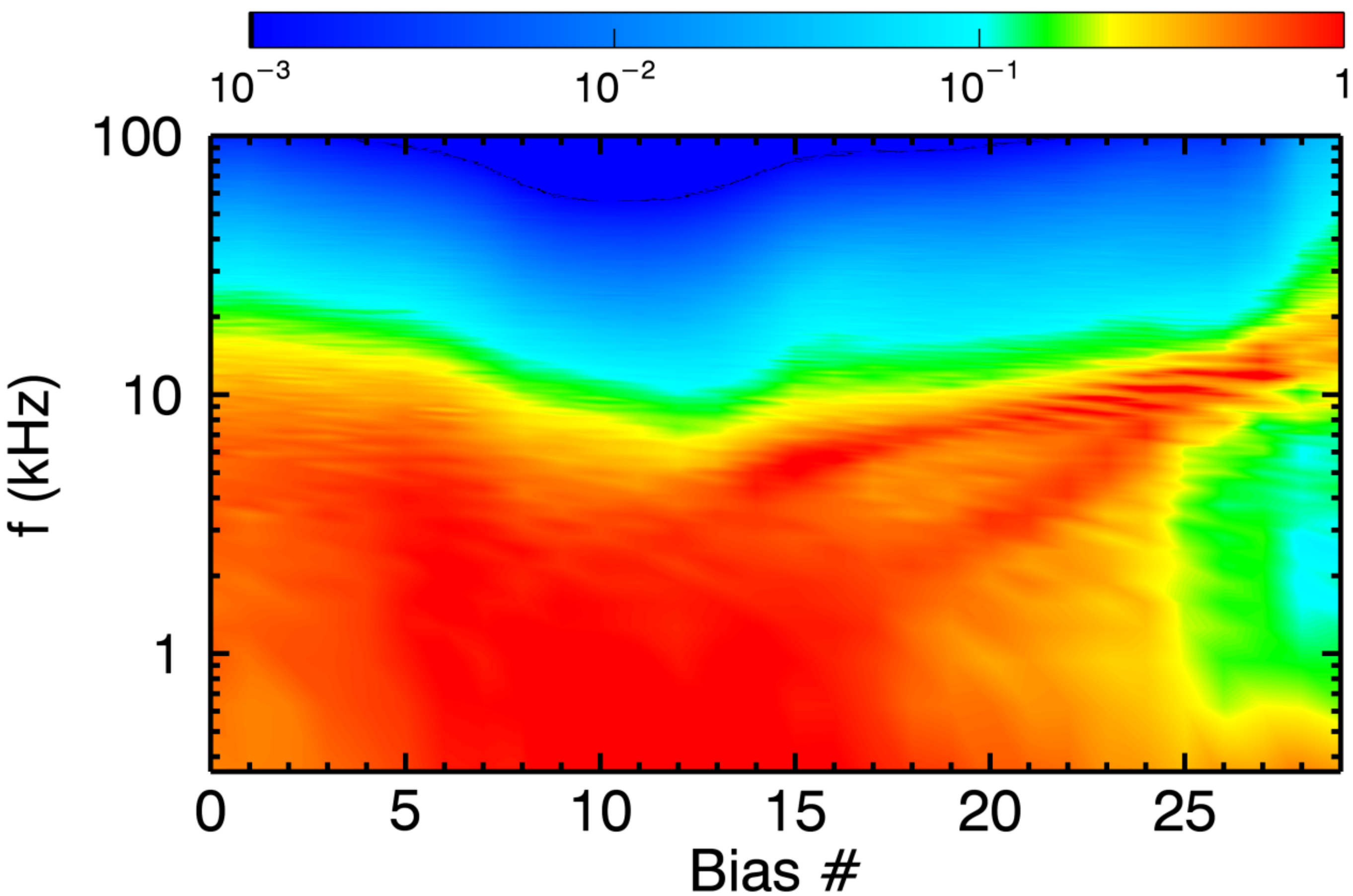
Coherent modes observed at high flow/shear

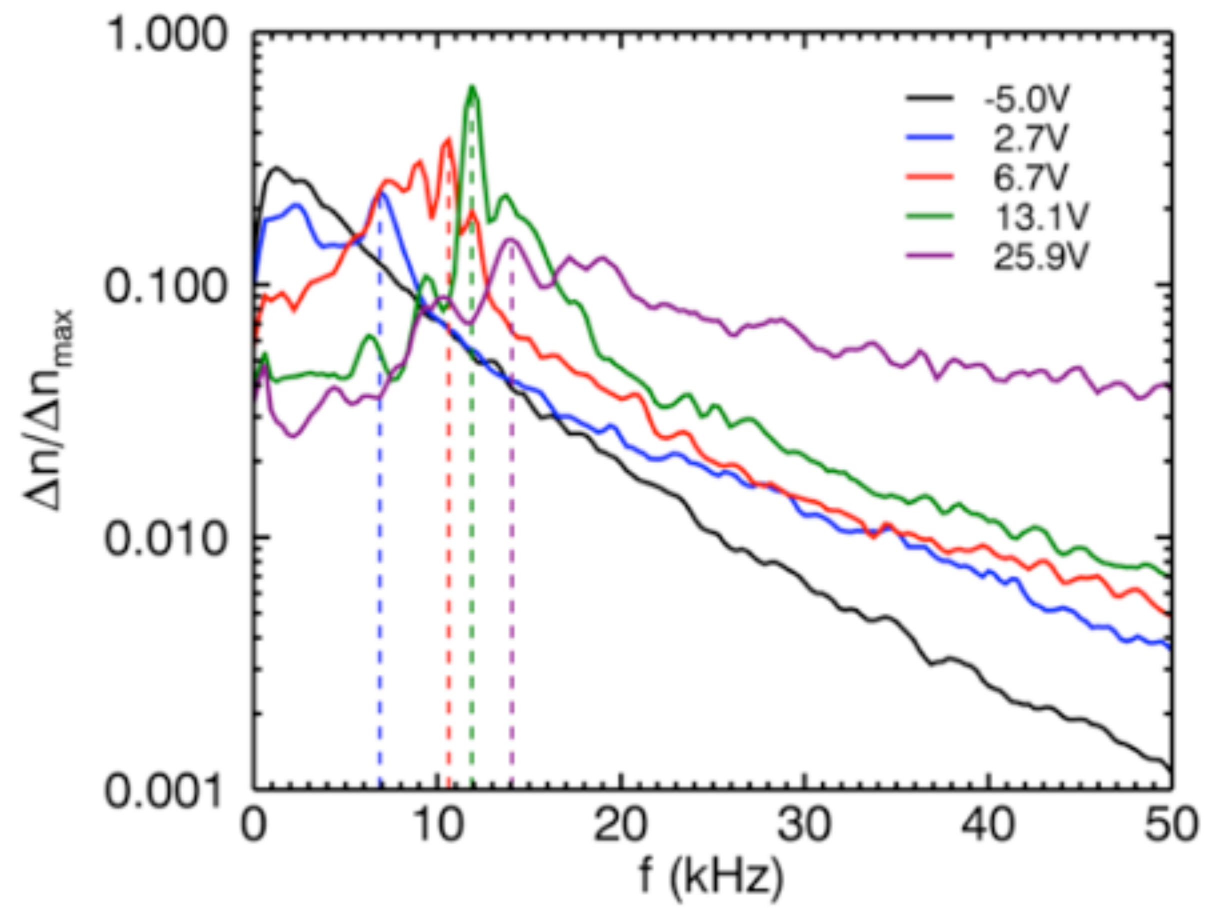


- Spatially and temporally coherent mode excited with strong rotation

- Localized to limiter edge (peak of flow)

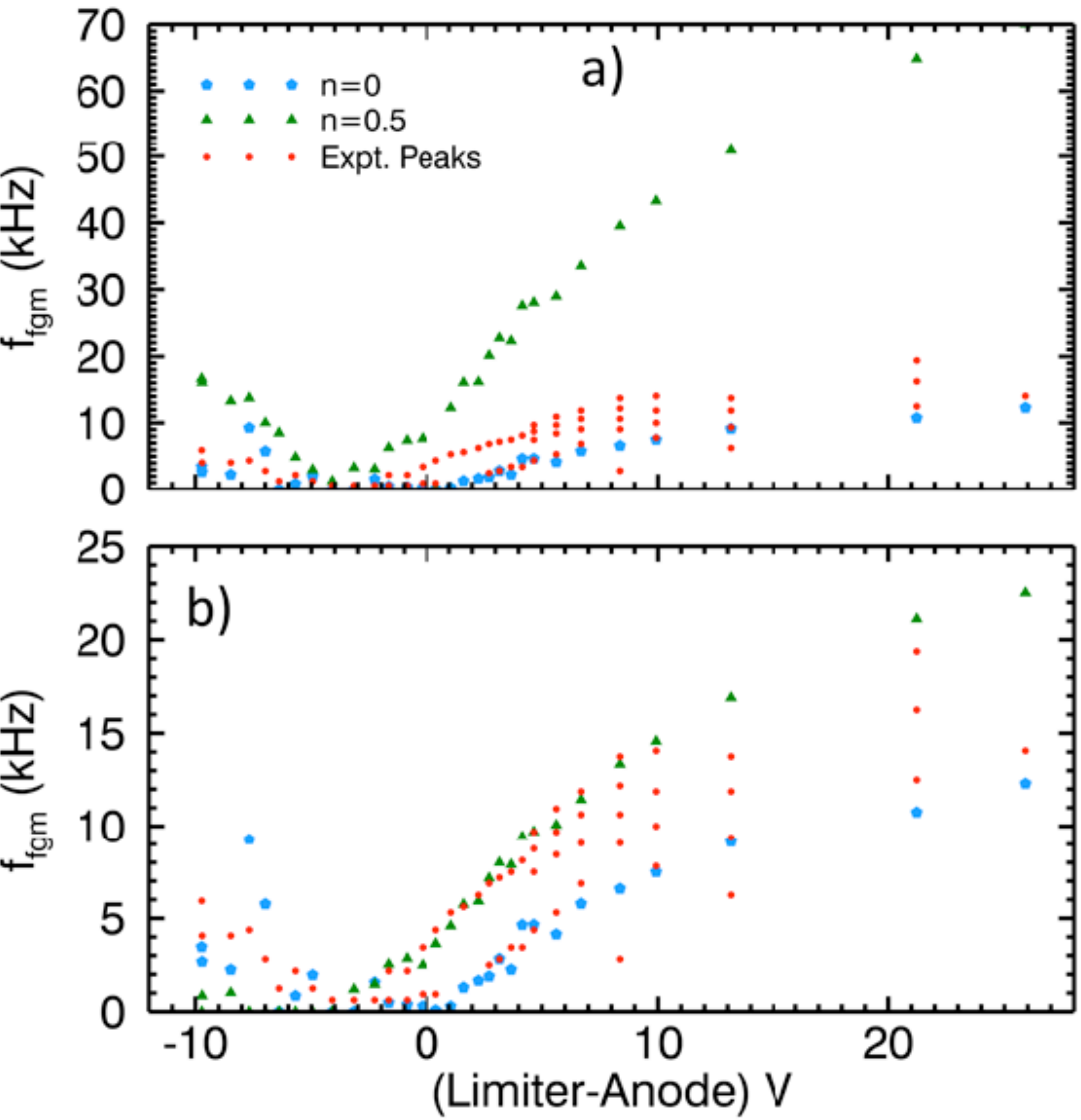
Coherent modes observed at high flow/shear





- Two primary coherent peaks observed, both scale with bias/ flow
- Interaction/sidebands observed as modes cross

Coherent modes: consistent with low-m rotational interchange instability



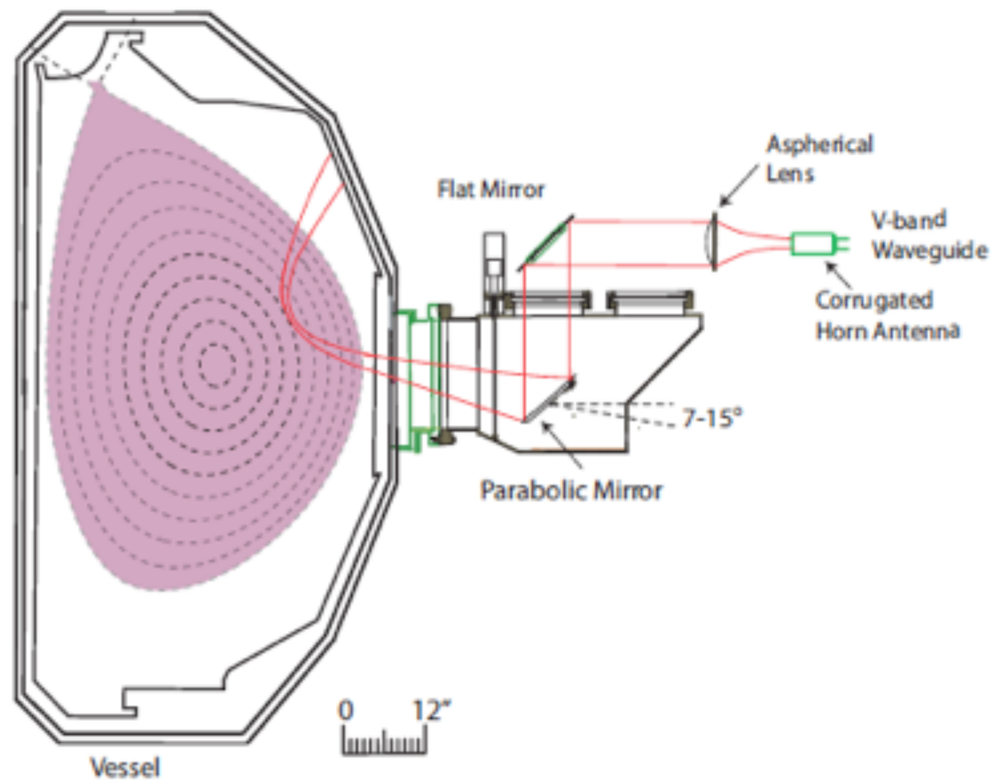
Braginskii two-fluid linear eigenmode solver; using experimental profiles

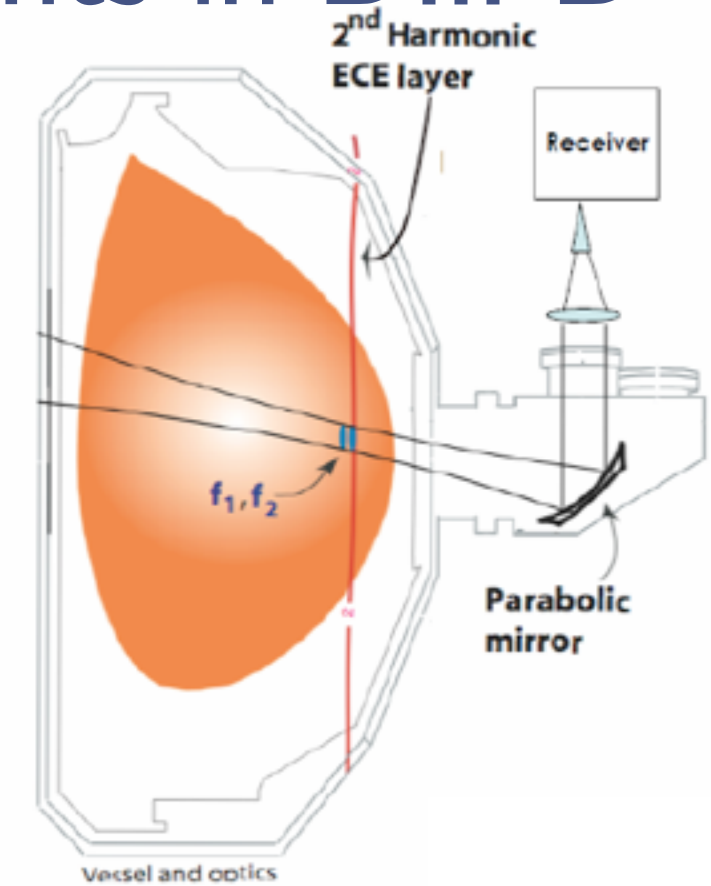
Rotational interchange (n=0) and drift-interchange (n=0.5) modes unstable

Real frequency tracks observation well with increasing bias

No net transport caused by these modes

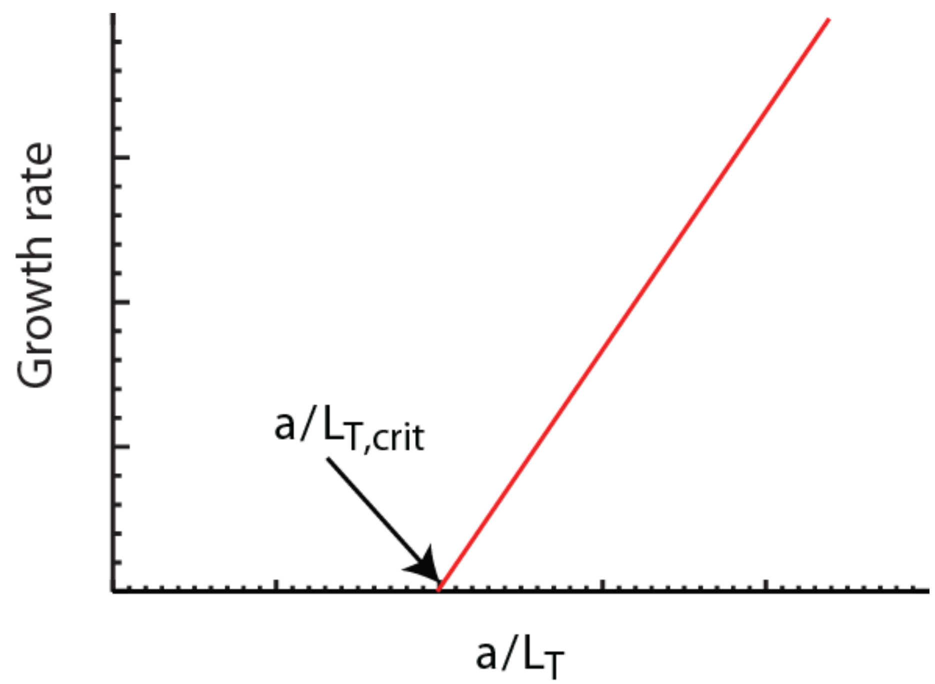
Turbulence measurements in DIII-D

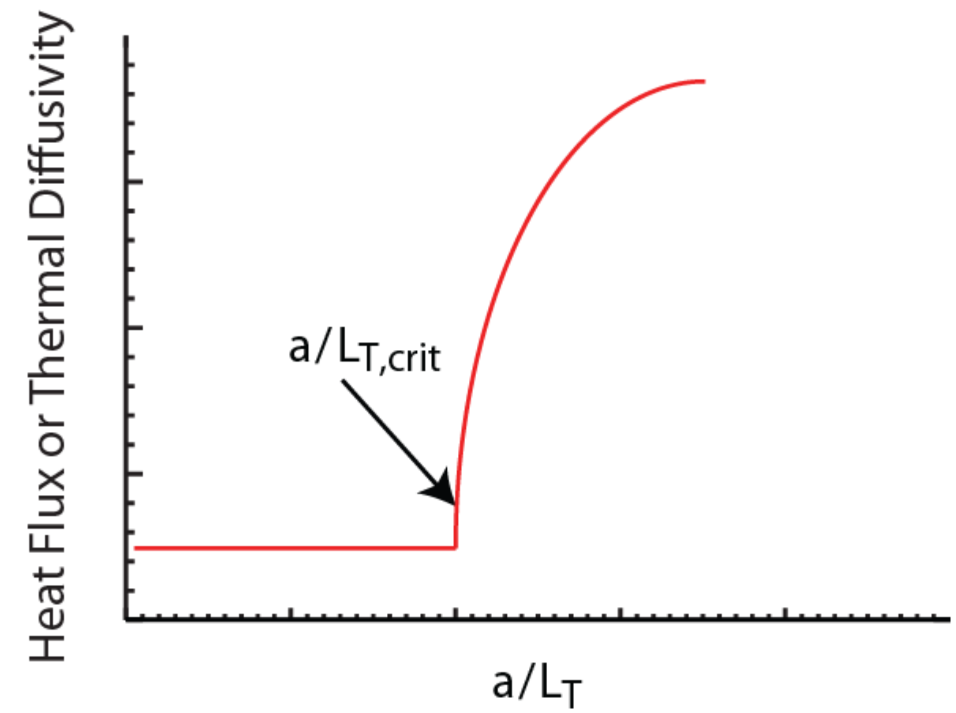




- UCLA group (Peebles) experts in microwave-based diagnostics
- Reflectometry, Doppler Backscattering: microwaves launched into tokamak, reflect off of cutoff; look at reflected or backscattered wave, measure local density fluctuations and flows, low-k for reflectometry, higher k ("intermediate") for DBS [Hillesheim, et al., RSI 80, 083507 (2009)]
- Correlation electron cyclotron emission diagnostic: plasma optically thick at 2nd harmonic EC emission, temperature, temperature fluctuations from received power [White, et al., RSI 79, 103505 (2008)]

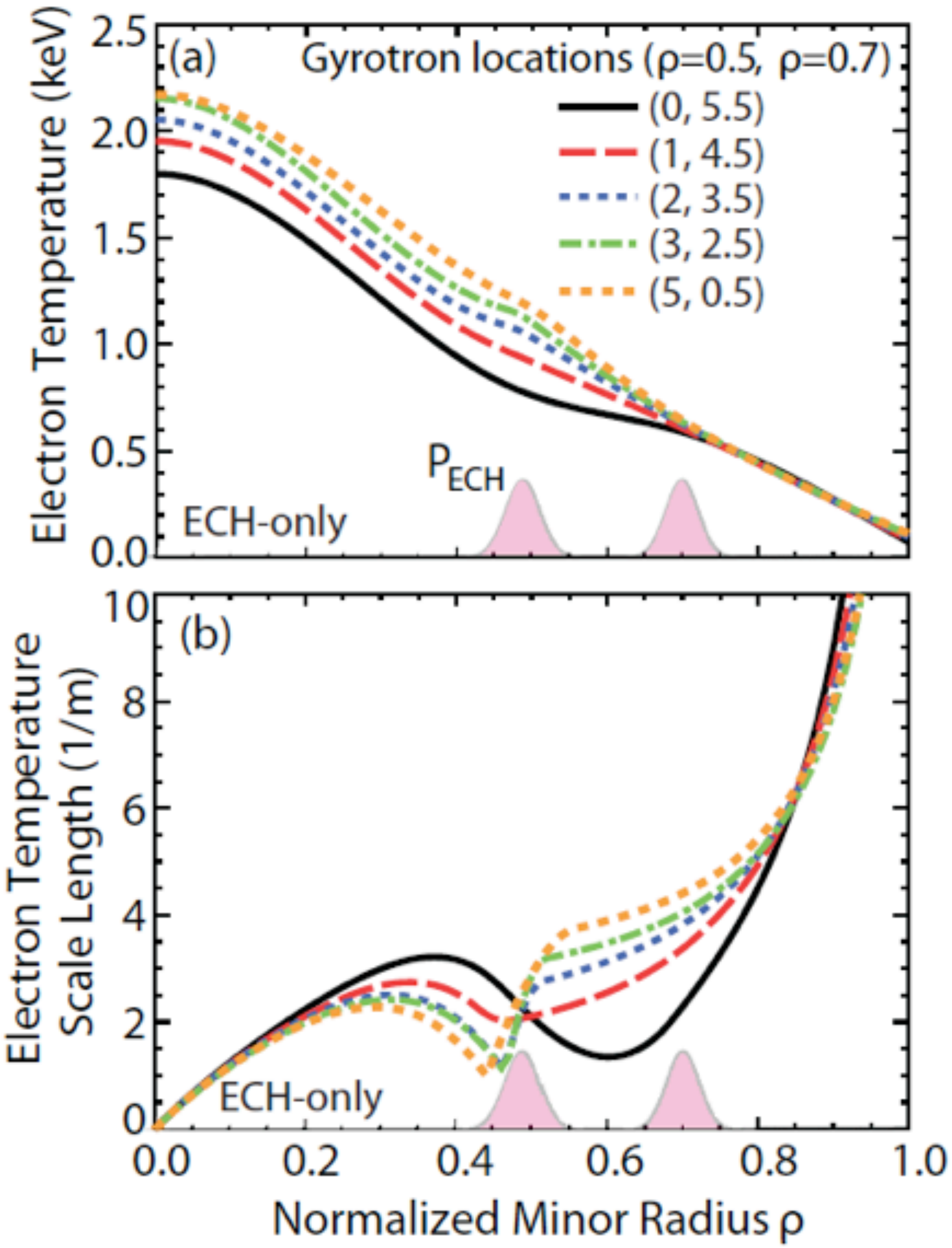
Critical gradients/"stiff" profiles in tokamaks





- Beyond temperature-gradient instability threshold, heat flux increases rapidly
- As you pour in more power, little change in profiles needed to exhaust heat via turbulent transport: profiles are "stiff"
- Similar to solar wind: observed anisotropy does not exceed instability thresholds (at least not much): if mirror/firehose is excited, drives isotropization very effectively

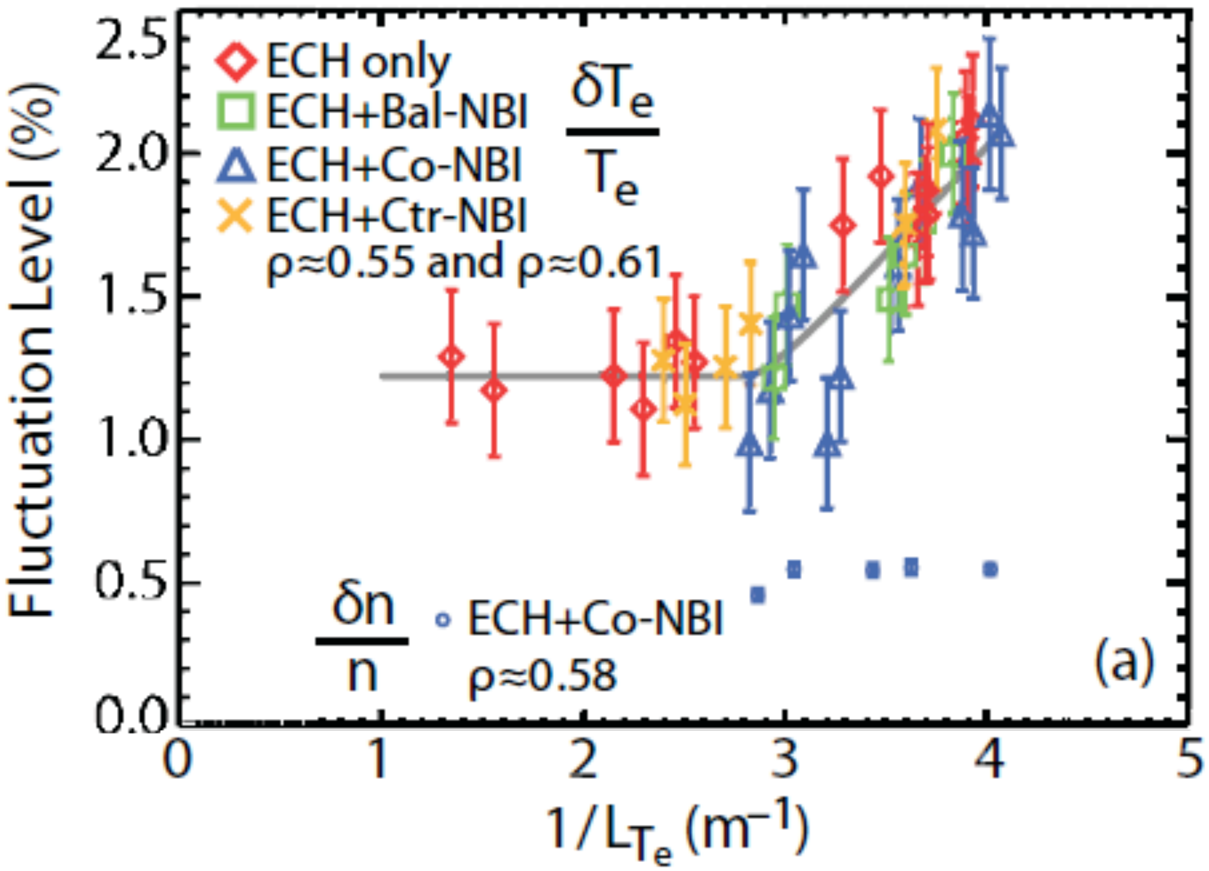
Varying L_T using ECH in DIII-D



- Electron cyclotron resonant heating (2nd harmonic) with steerable antenna (to vary deposition location)
- Keep total injected power constant, change localization to create a range of profiles with varying L
- Other parameters (density profile, flow profiles, etc) kept roughly constant

J.C. DeBoo *et al Nucl. Fusion* **45** 494 (2005)

The result: T_e fluctuations increase beyond critical gradient



- Experiment: long-wavelength ($k_\perp \rho_s < 0.3$) electron temperature fluctuations increase steadily beyond a threshold L_T
- Density fluctuations (Low-k, BES) do not show increase

Hillesheim, et al., PRL 110, 045003 (2013)

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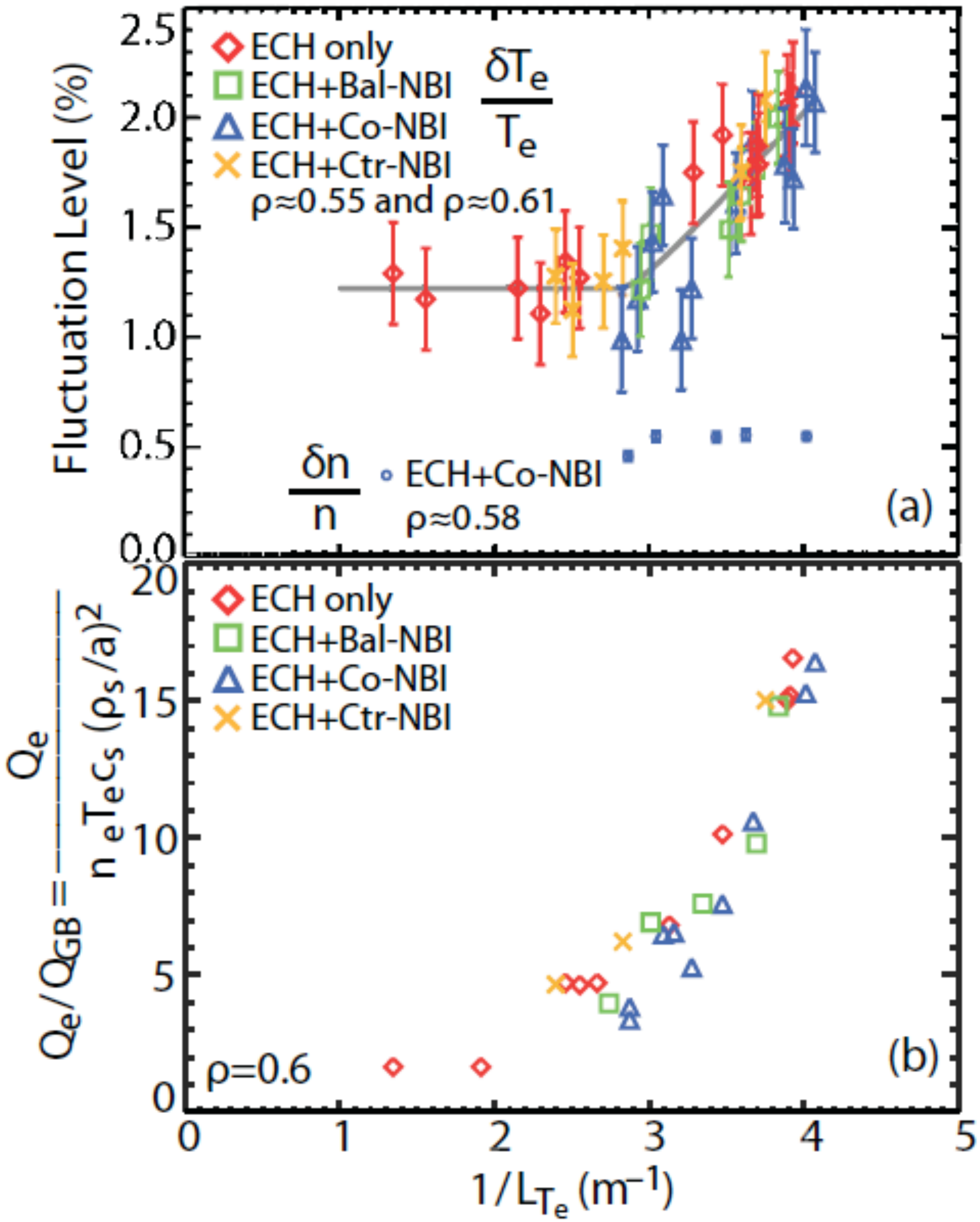
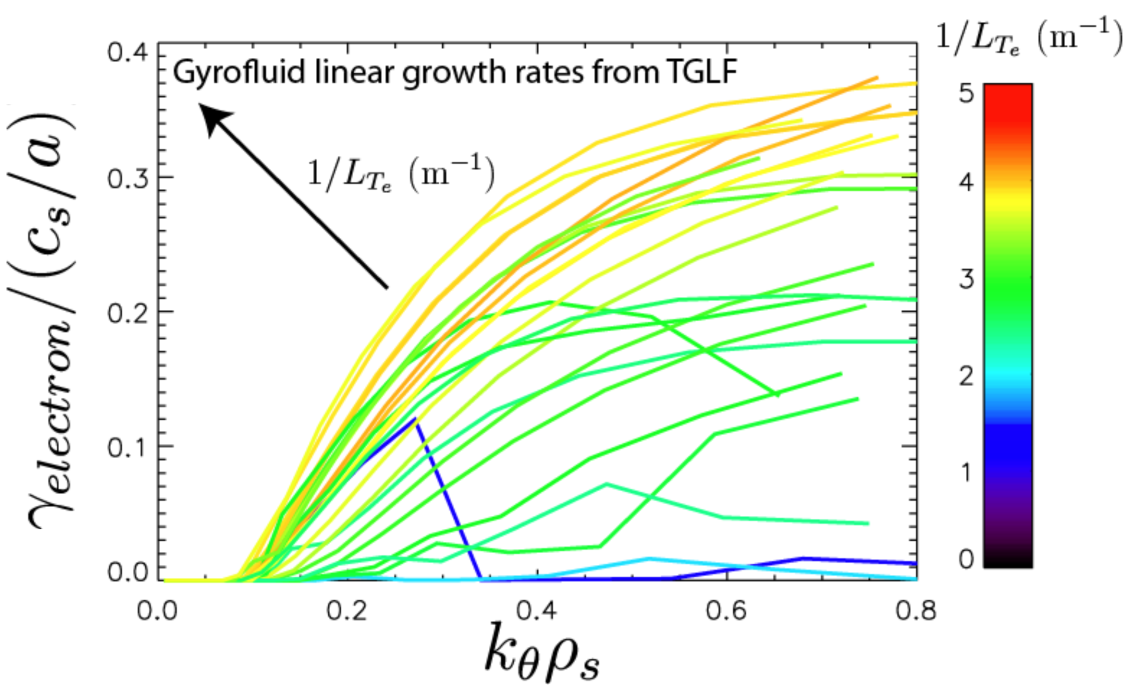
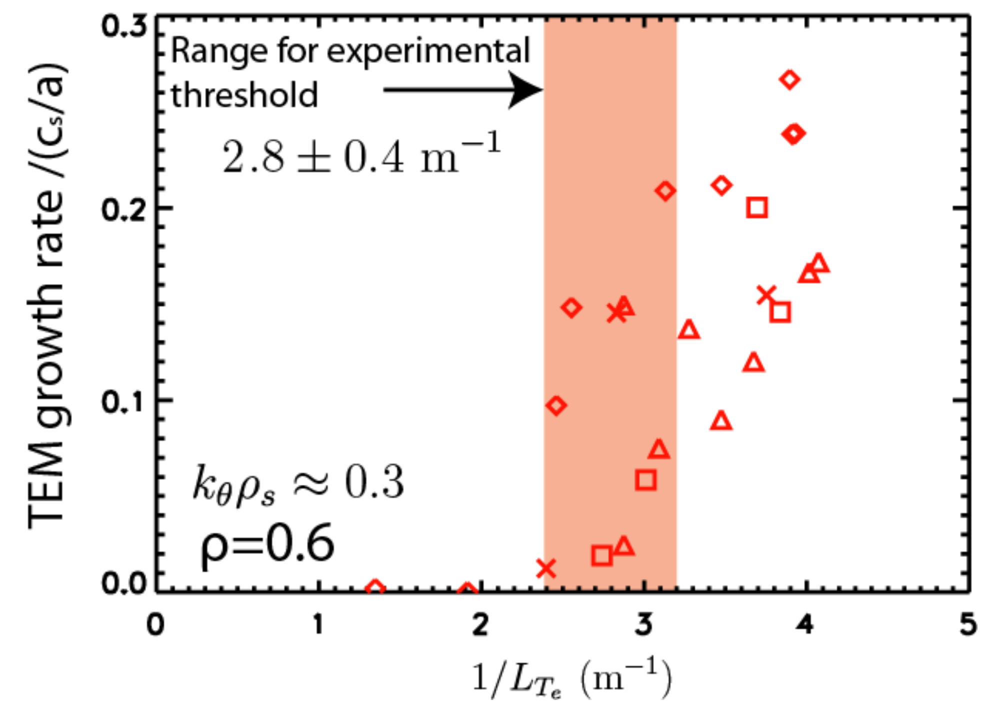


- Experiment: long-wavelength ($k_\perp \rho_s < 0.3$) electron temperature fluctuations increase steadily beyond a threshold L_T
- Density fluctuations (Low-k, BES) do not show increase
- Threshold consistent with critical gradient as determined from electron heat flux (power balance)

Hillesheim, et al., PRL 110, 045003 (2013)

Consistent with threshold for Trapped Electron Mode





- Linear growth rate calculations (TGLF) using expt profiles
- Crit. gradient consistent with linear threshold for TEM (temp. gradient driven)
- Mode characteristics (temperature density cross-phase, propagation direction) consistent
- Below threshold: density gradient driven TEM?

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    - Transport decreases with shearing, enhanced at low shear; reduction due to turbulent amplitude reduction
- Critical gradient response in electron temperature fluctuations in DIII-D [Hillesheim, et al., PRL 110, 045003 (2013)]
    - Electron temperature gradient varied at constant heating power using ECH in DIII-D [DeBoo]
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