# Taming turbulence in magnetized plasmas: from fusion energy to black hole accretion disks

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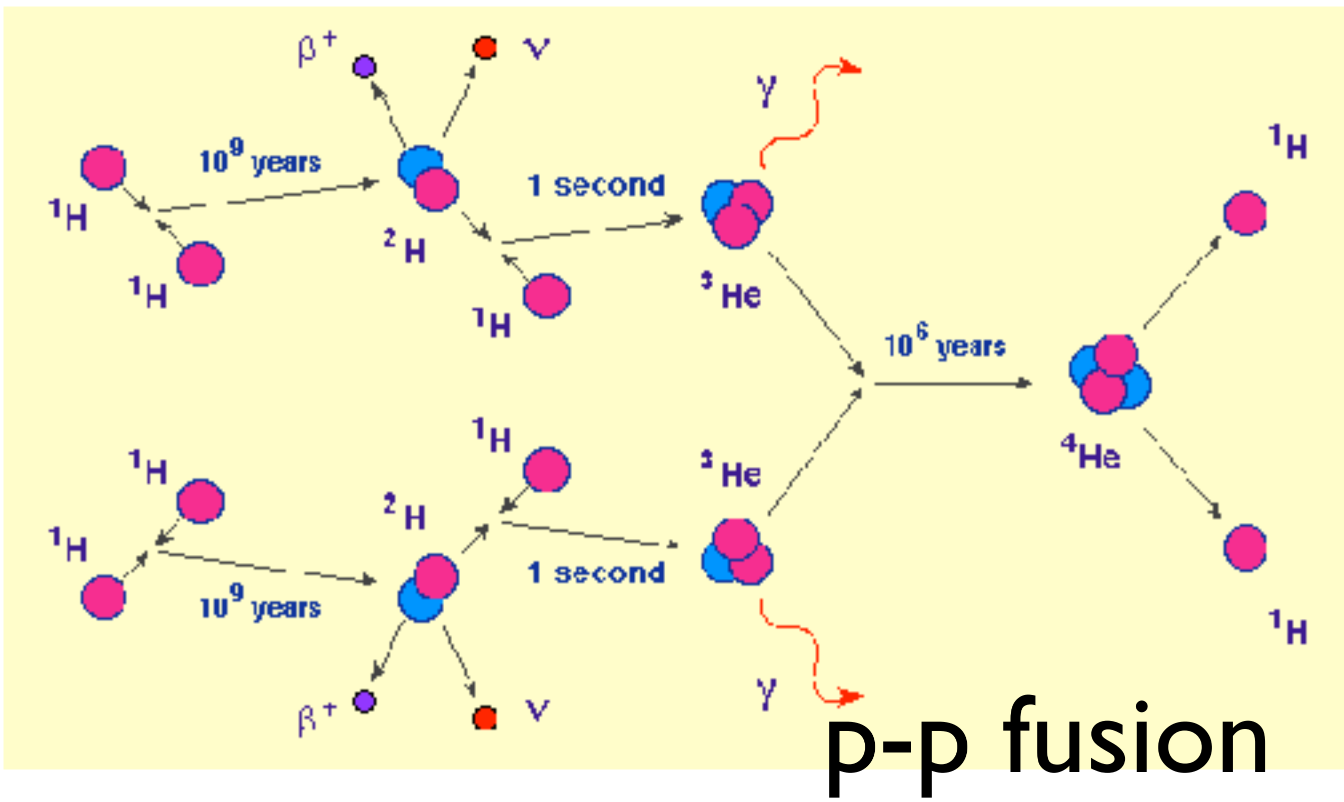
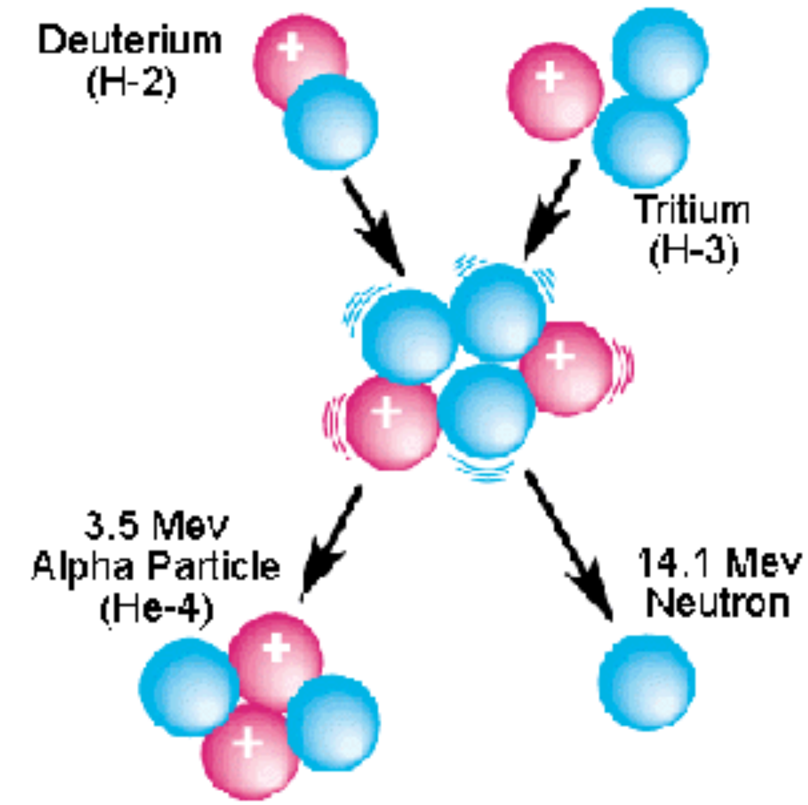
# Summary

- **How to keep a magnetic bottle from leaking?**: In fusion plasmas turbulent leakage of heat and particles is a key issue. Sheared flow can reduce this leak.
- **How do you feed a black hole?**: Collisional accretion ineffective in hot plasmas; Alfvénic turbulence can explain transport and heating in disks. Laboratory experiments investigate the energy cascade in Alfvénic turbulence.

# Fusion Basics

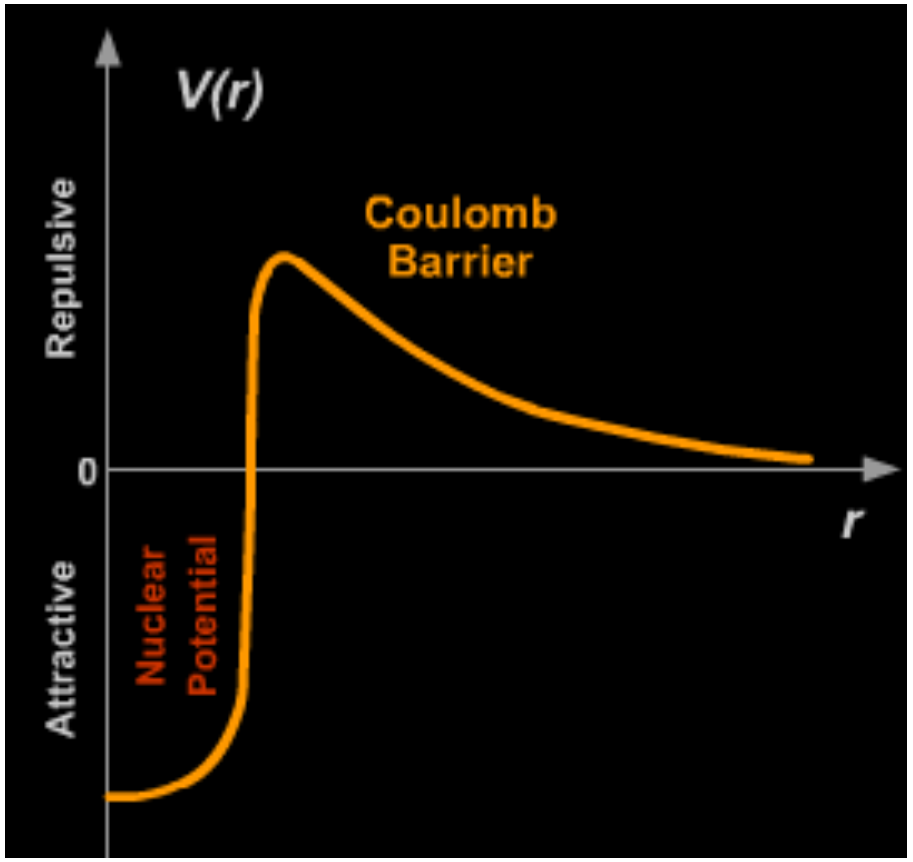



Deuterium-Tritium Fusion Reaction

- Stars are powered by fusion reactions, initially p-p fusion
- D-T reaction is the most accessible in the laboratory (highest cross-section)
- Need moderate energy to overcome Coulomb barrier (~100 keV)

# Fusion in the lab: need confined plasma

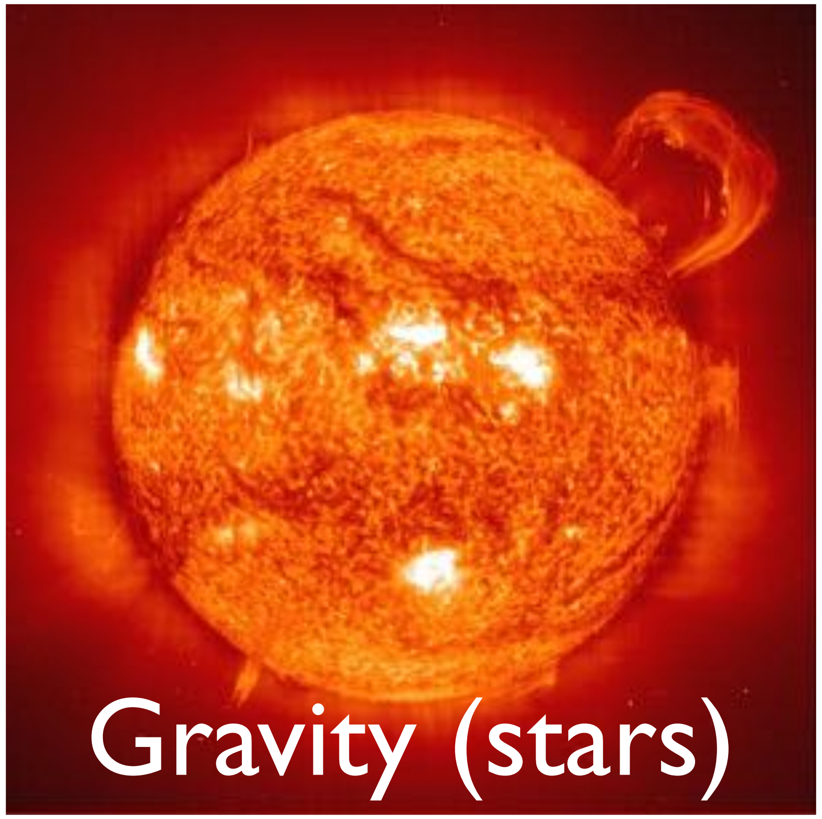




- Scattering cross-section >> fusion cross-section: Need confinement to allow multiple collisions before fusion occurs (fusion of particle beams will not work…)

➡ Thermonuclear fusion in a confined plasma (T~10 keV)

# Plasma confinement schemes



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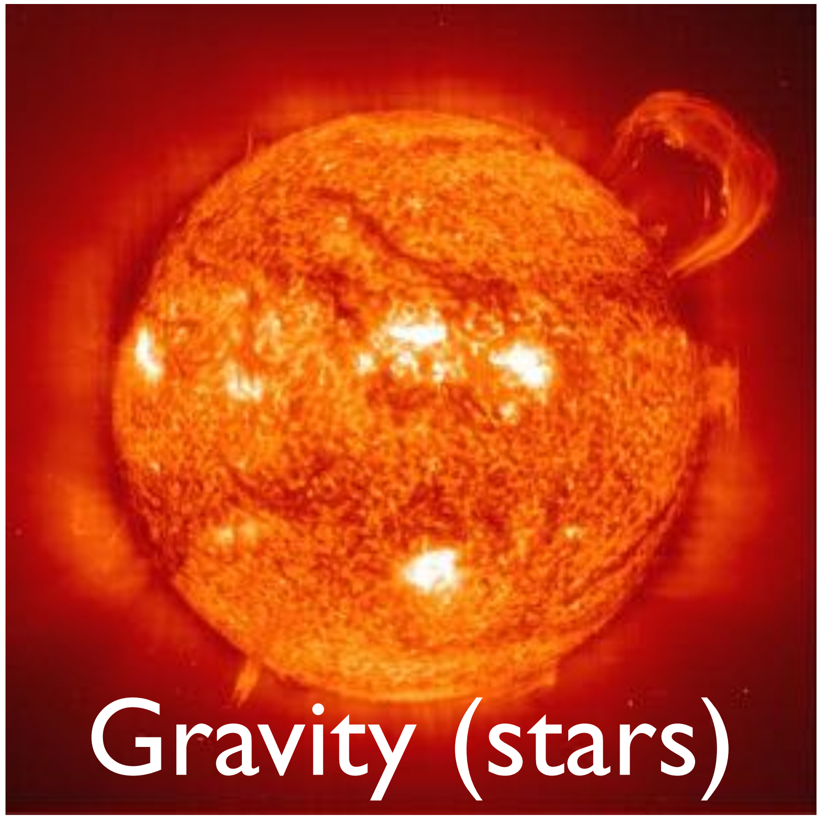


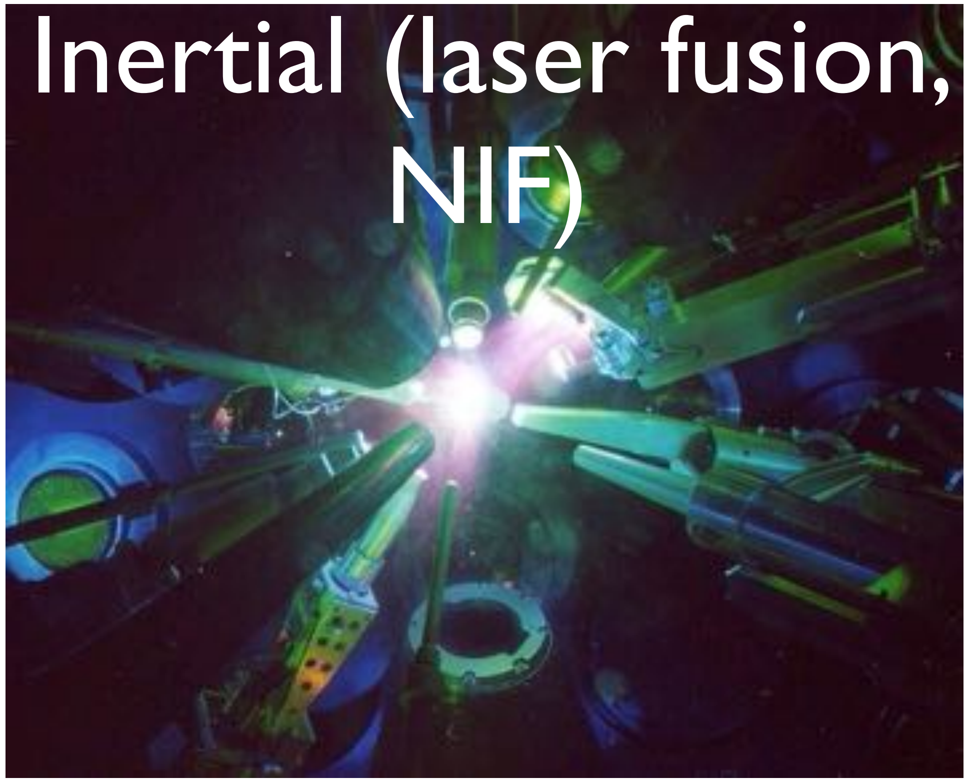

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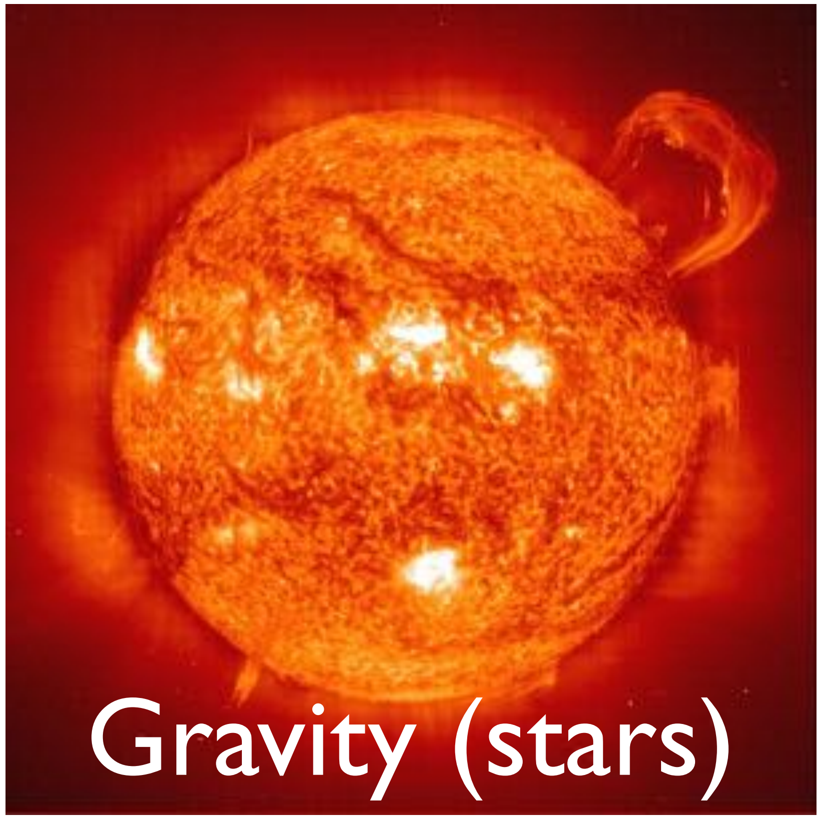
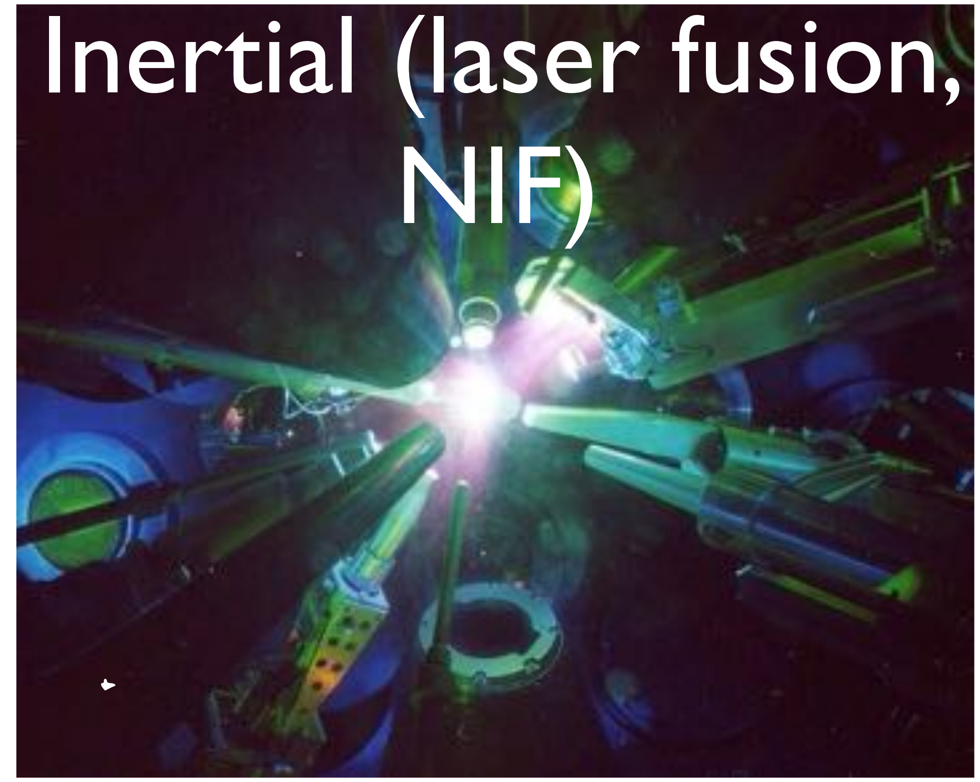
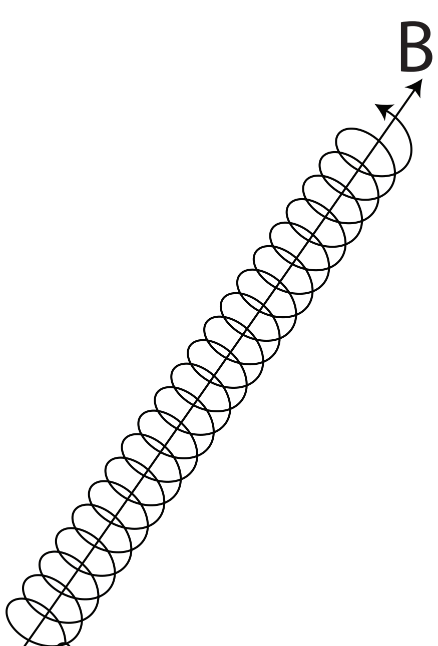
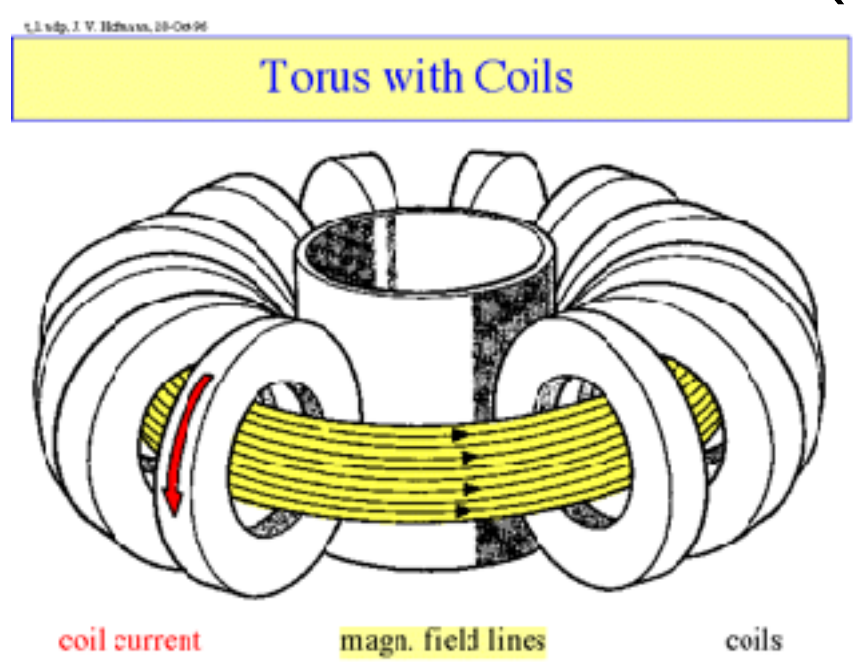



## Magnetic Confinement (tokamak)



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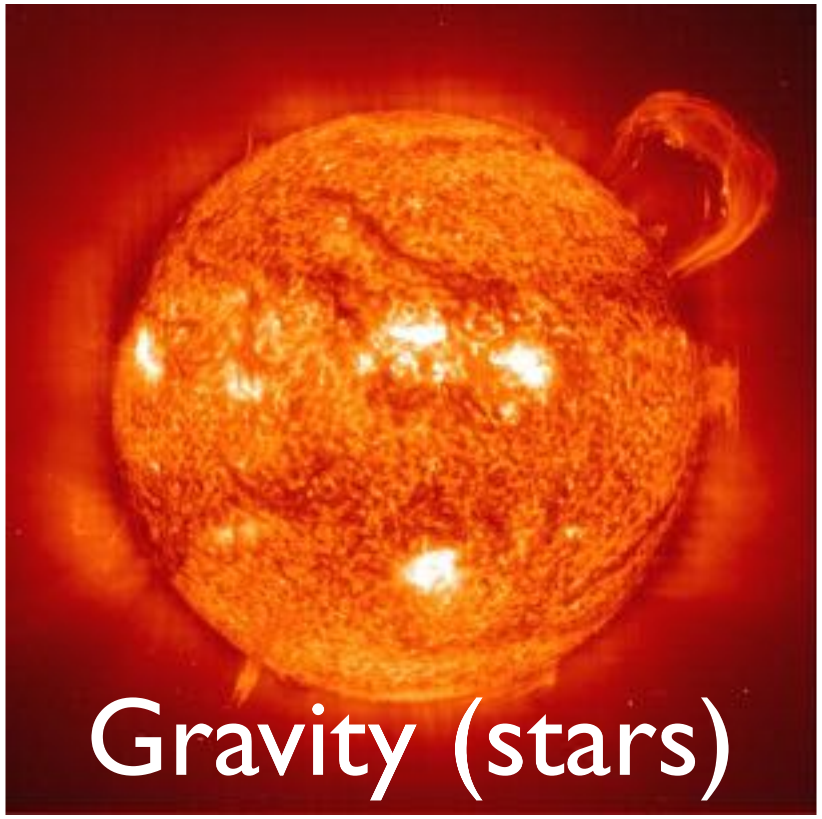


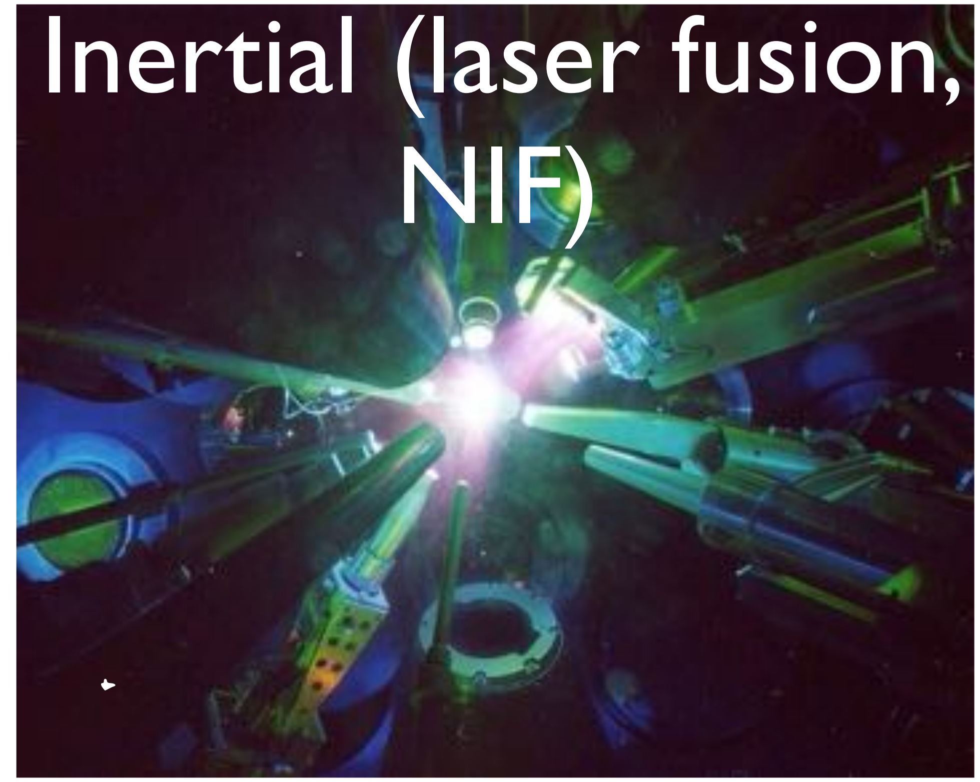


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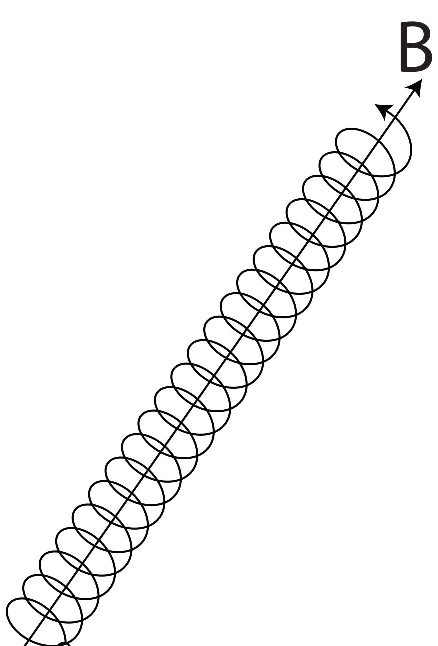
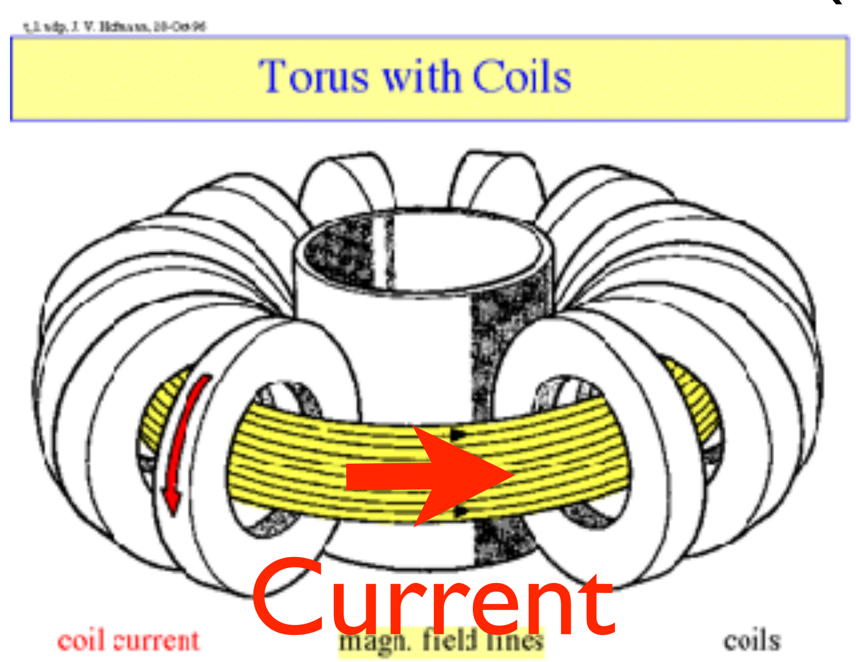
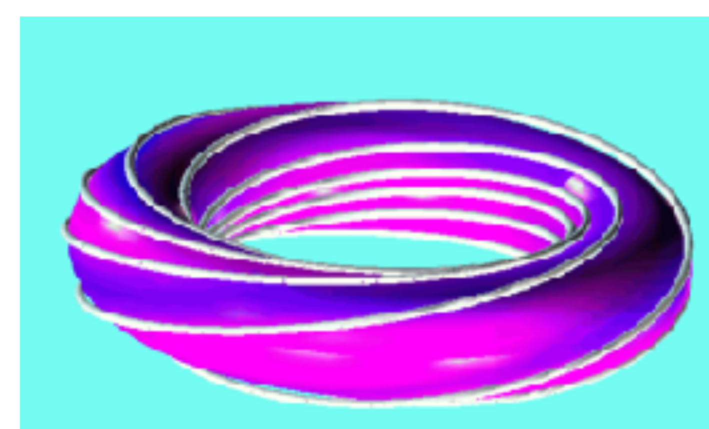
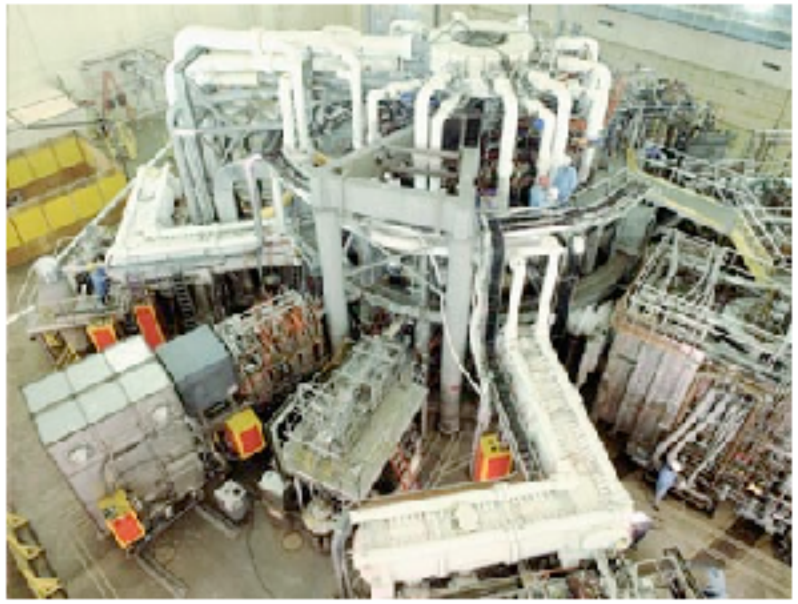
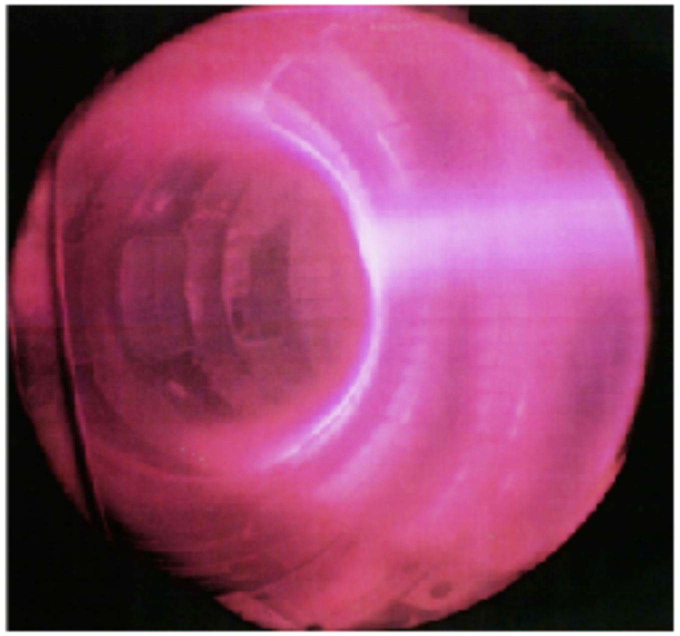


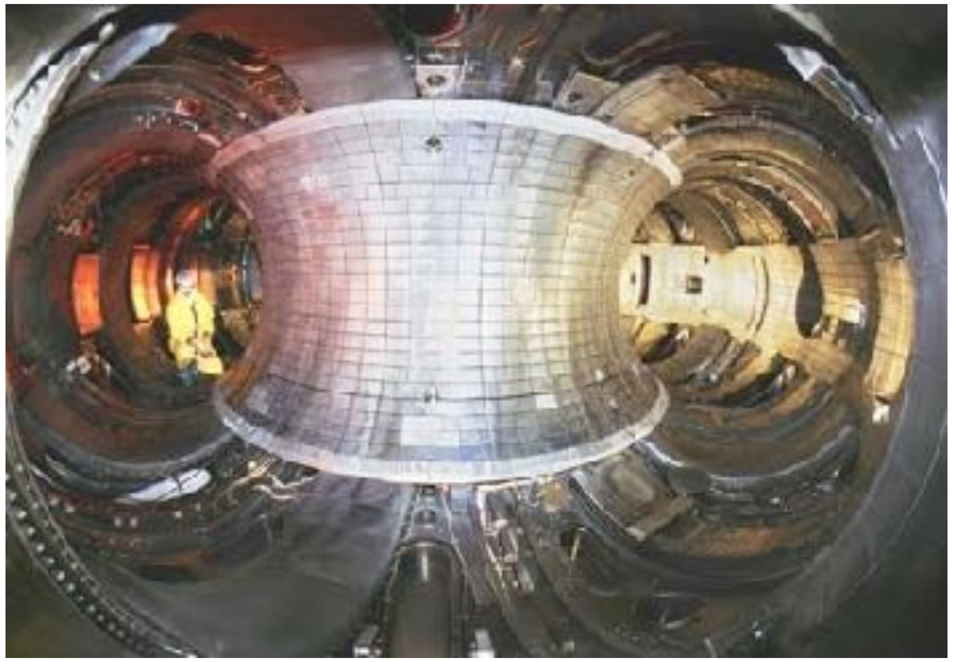



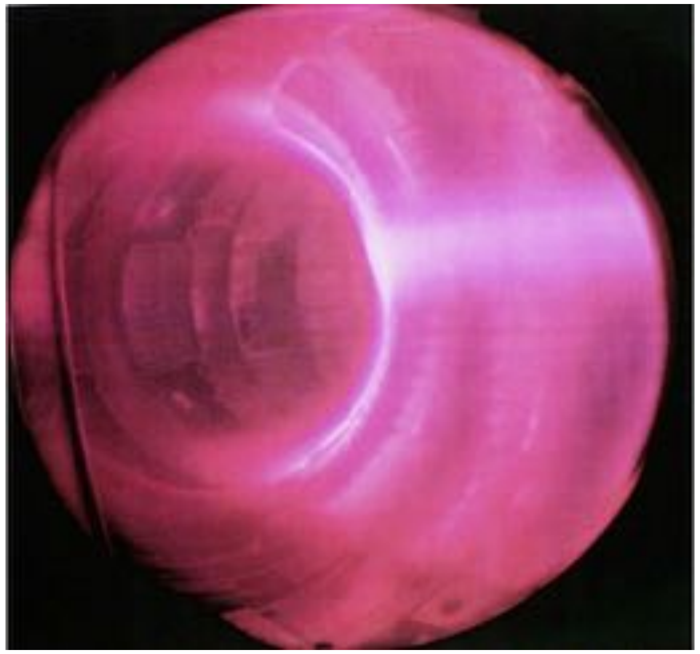
# Heating a magnetically confined plasma

- Initial heating is Ohmic: run current through the gas (can get you to ~1keV (10 million degrees))
- To get to fusion temperatures (100 million degrees+), use neutral beam injection (directly inject energetic particles) or RF heating (cyclotron resonance)
- TFTR, Princeton Plasma Physics Lab (above) used NBI to reach 50 keV (500 million degrees): hottest spot in solar system (maybe the galaxy except for AGN)

# Great success in confining hot plasmas and generating fusion power in Tokamaks





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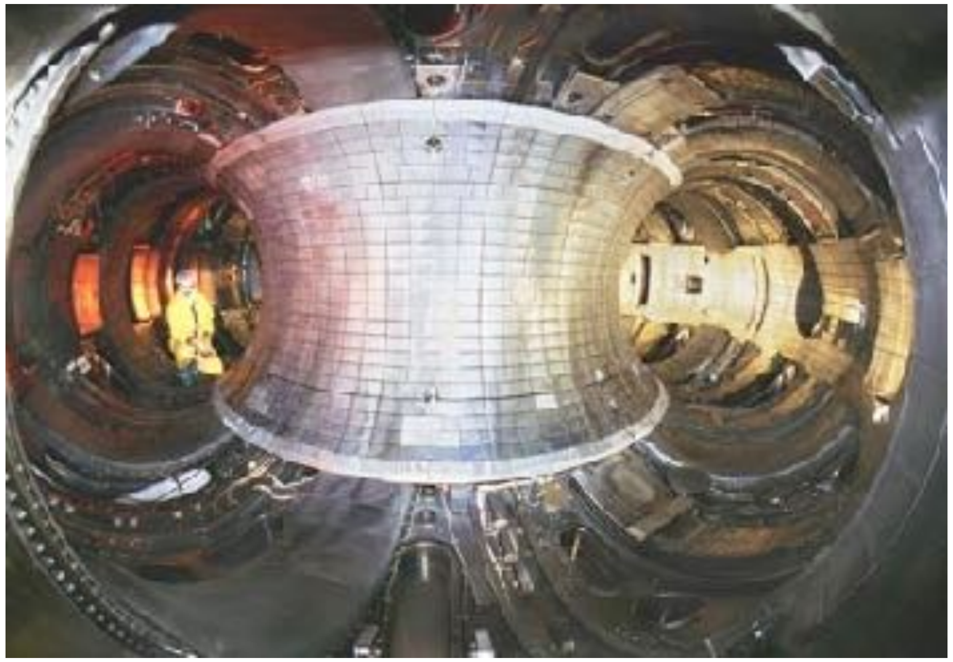

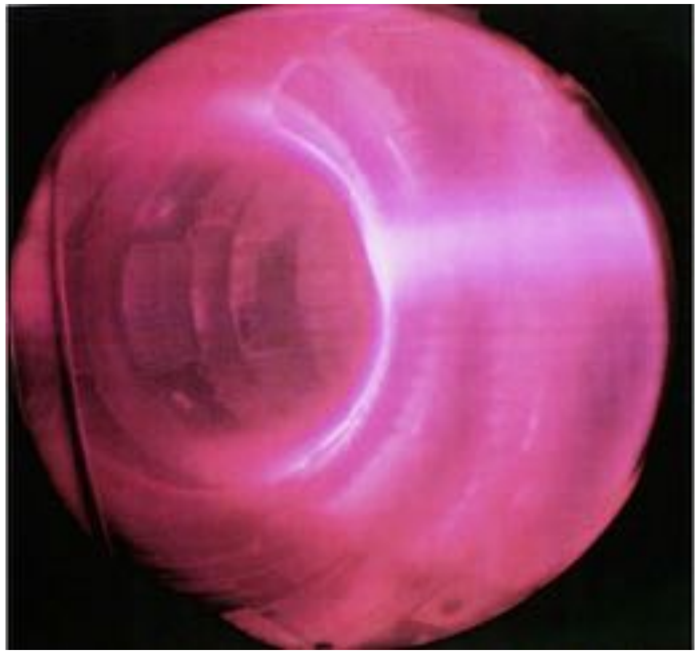

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- Exceeded required temperatures and densities for fusion
    - Record ion temperature of 50 keV on TFTR (Neutral Beam heating)
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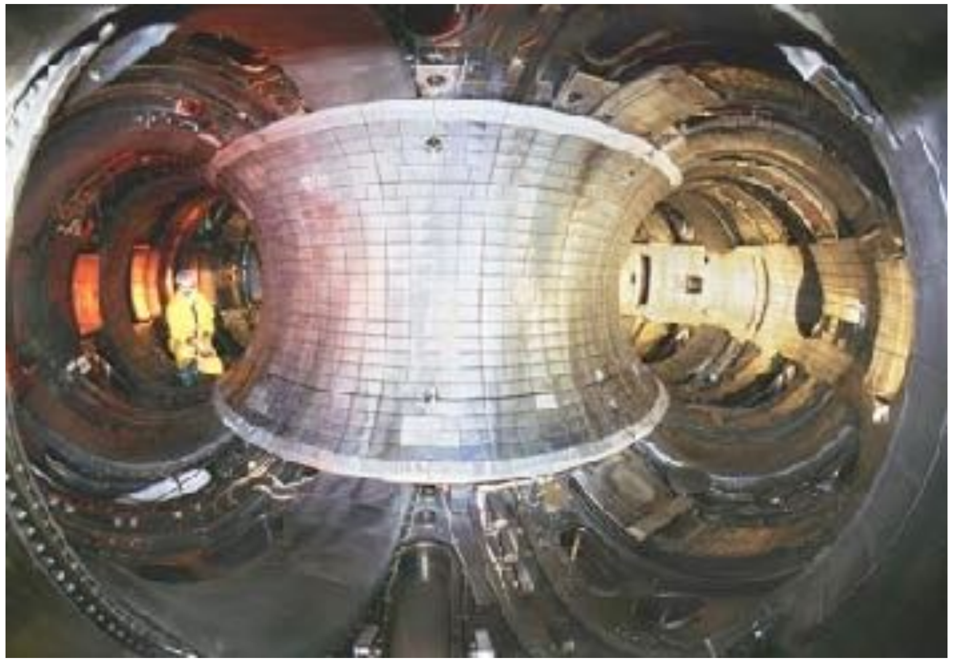

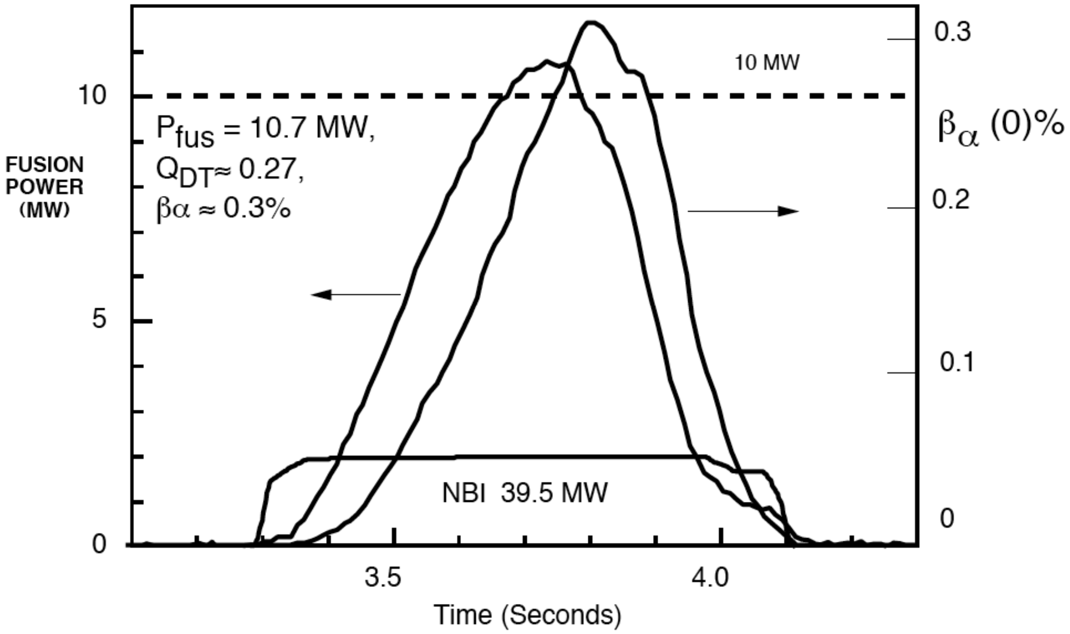


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- Exceeded required temperatures and densities for fusion
    - Record ion temperature of 50 keV on TFTR (Neutral Beam heating)
    - 6 atm central pressure (central density $1x10^{20}$ $m^{-3}$)
- TFTR produced >10MW of D-T fusion power in the early 90's (bested by JET (UK) later on with 16MW) (but only for ~1s in both cases)

# So what's the hold-up?


We can confine hot plasmas and produce significant fusion power, so why aren't fusion reactors in use today?

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- Problem: in current devices the required heating power to reach and maintain fusion temperatures exceeds the fusion power output
- Why? Confinement is not perfect, our magnetic bottle can leak heat at a significant rate
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➡ Turbulent cross-field transport is the primary cause of the "leak"

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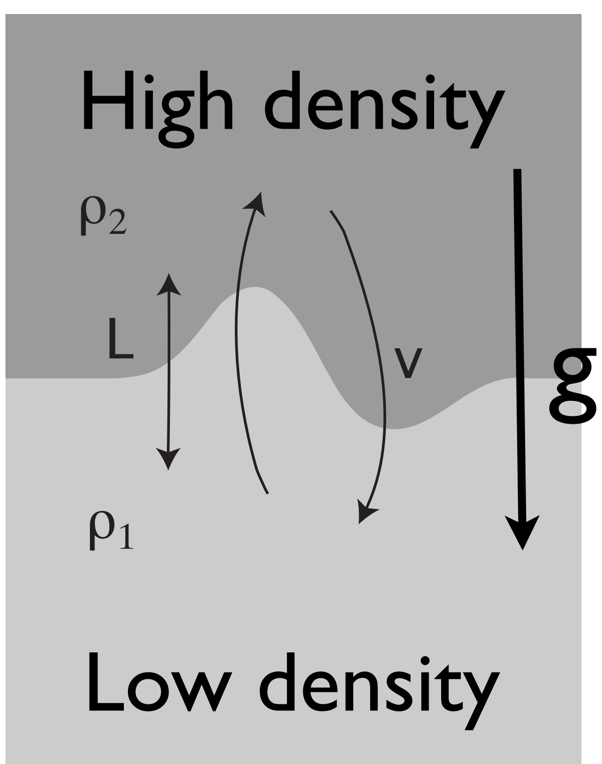

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- Interchange drive is important (analogous to Rayleigh-Taylor). In tokamak, effective gravity provided by magnetic field gradient/curvature

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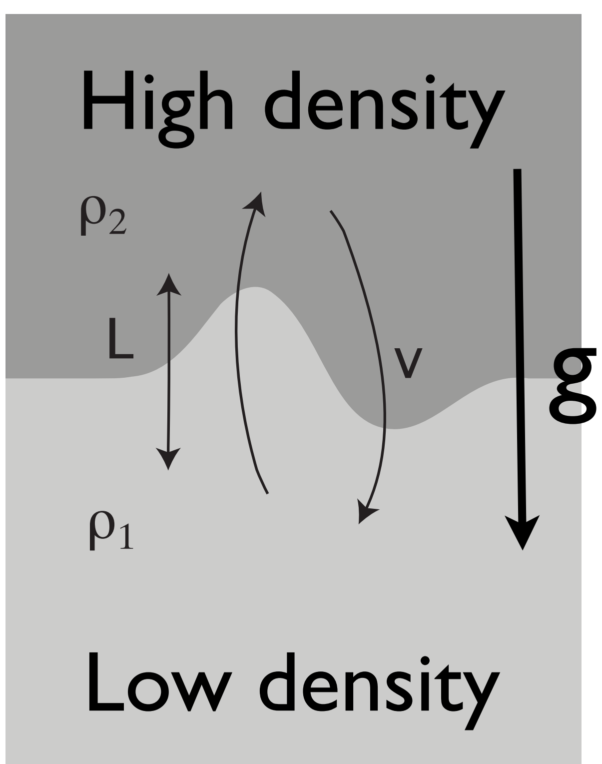
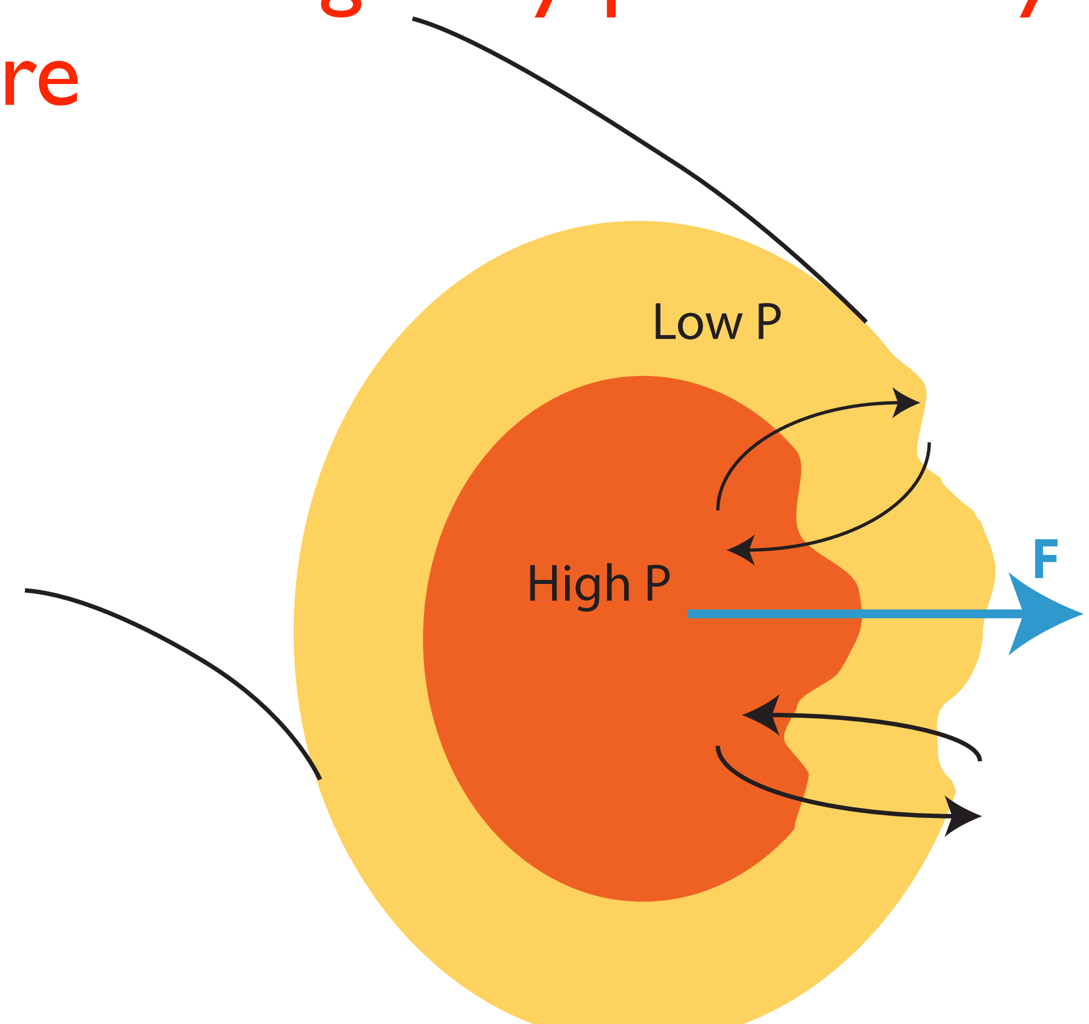


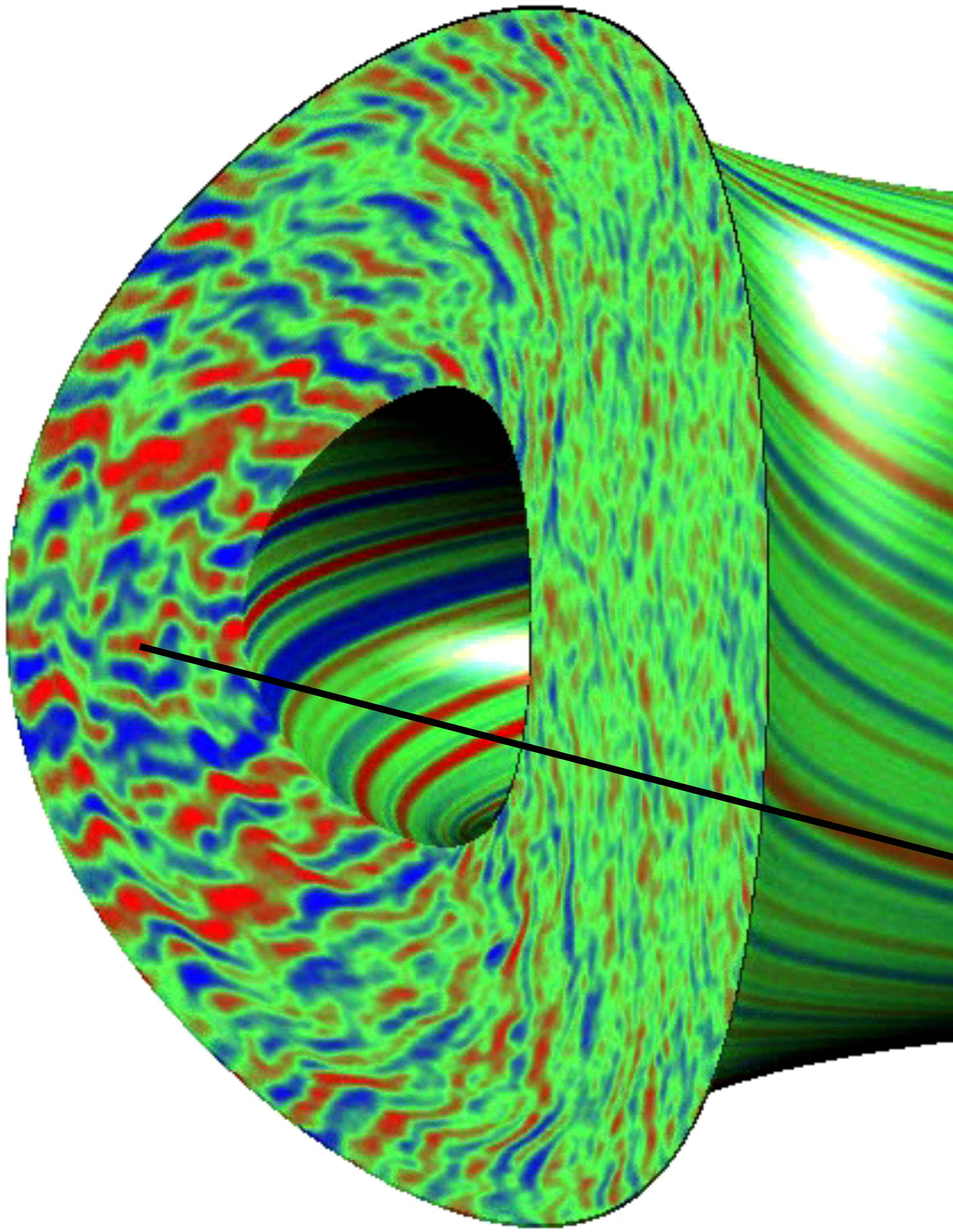



# Simulation of turbulence in a tokamak

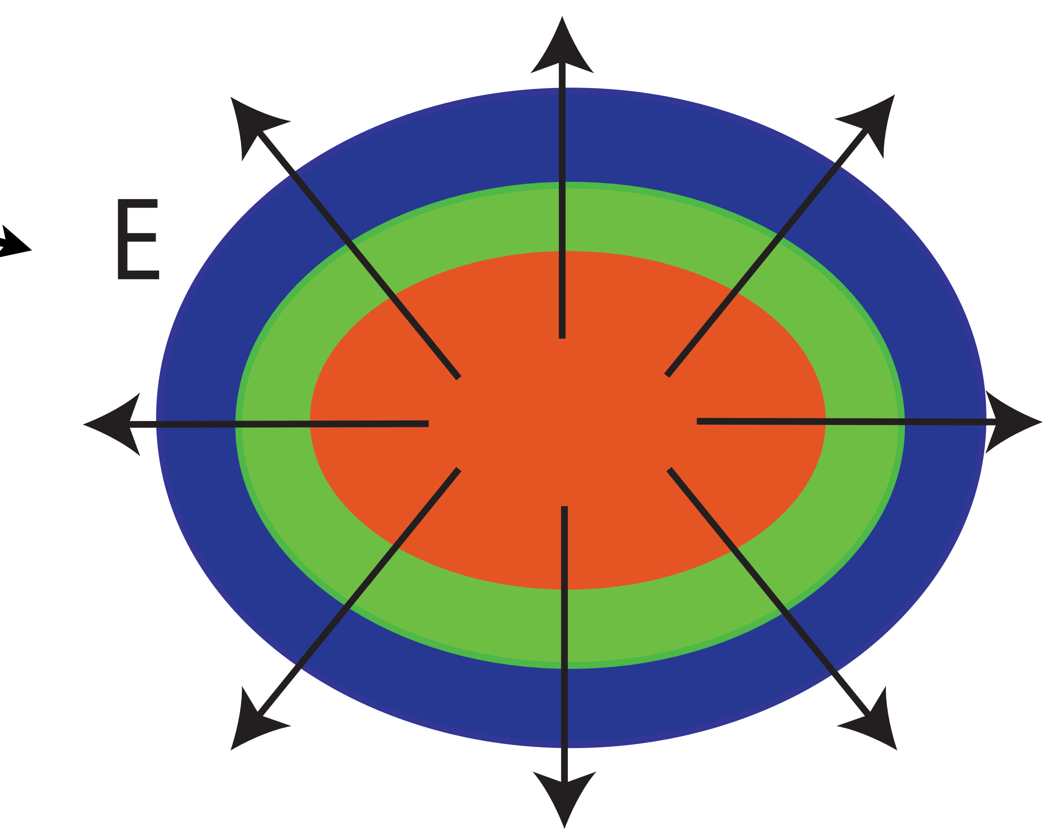
Code: **GYRO**

**Authors:** Jeff Candy and Ron Waltz

# Turbulent Transport by “Eddies”



- Movie shows electrostatic potential
- Contours of potential are contours of ExB flow




Gyrokinetic simulation by Jeff Candy, Ron Waltz (GA)

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$$v_{\text{drift}} = \frac{\vec{E} \times \vec{B}}{B^2}$$

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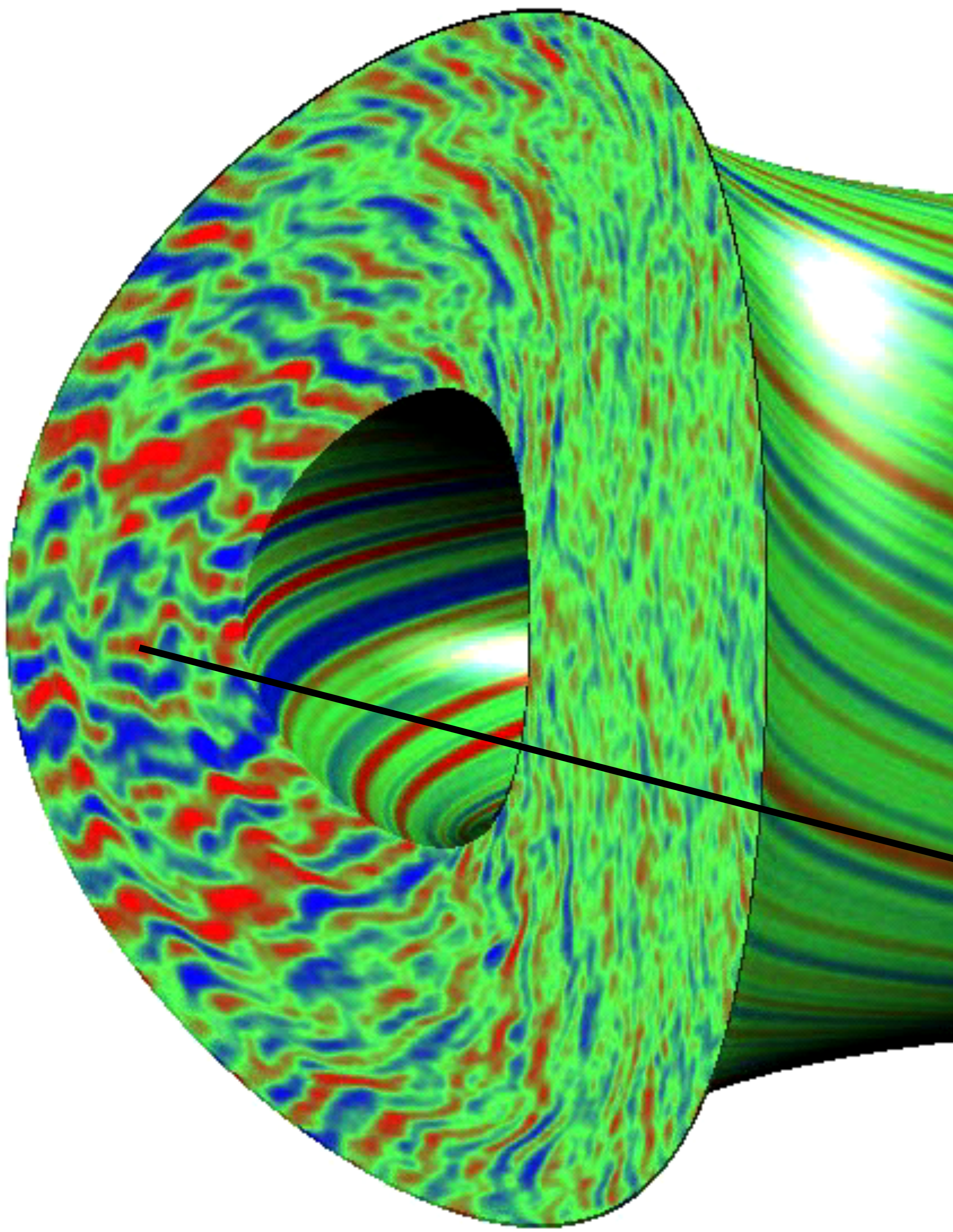

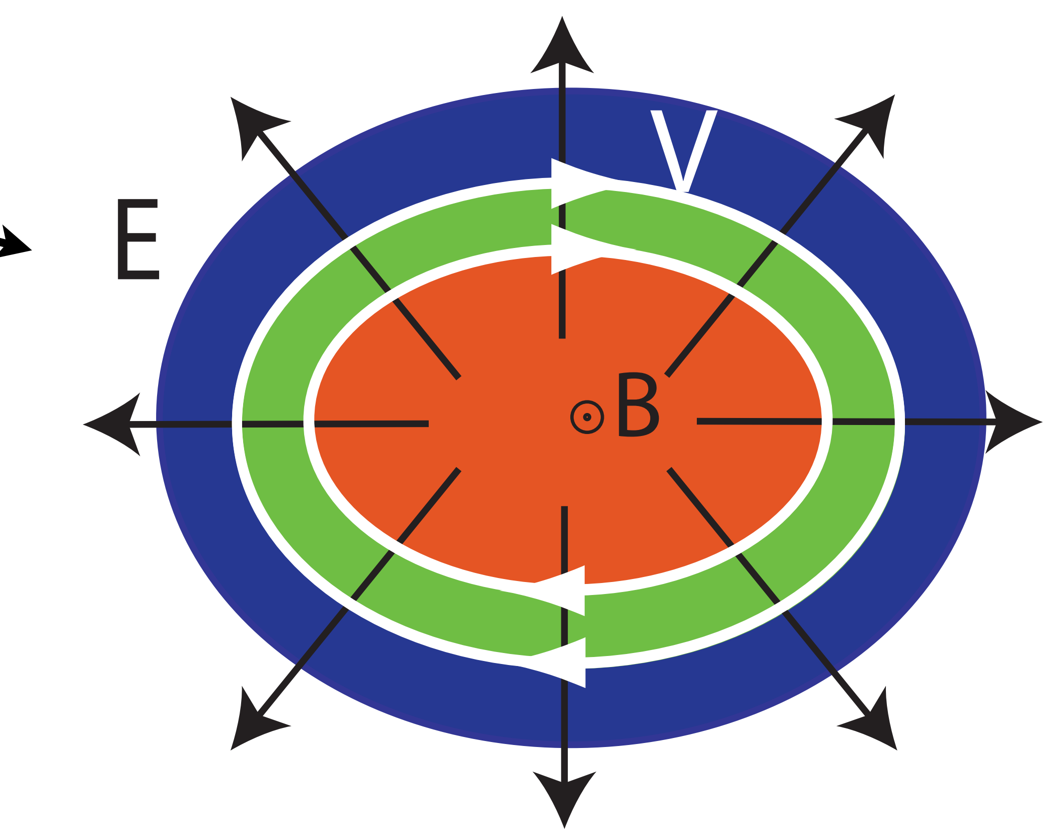


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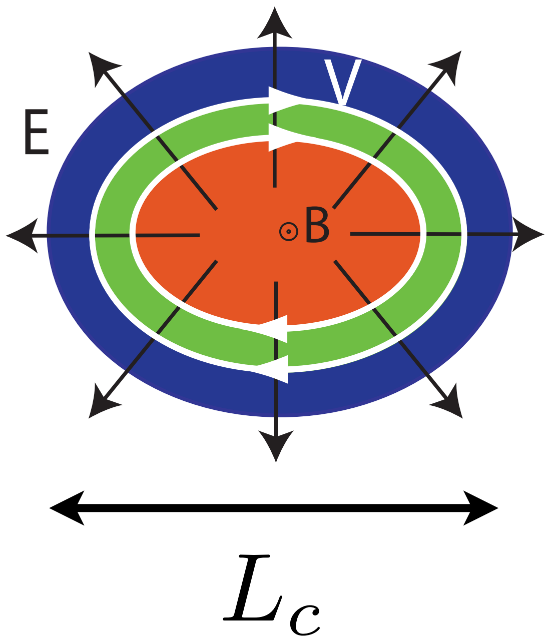
# Turbulent Transport by "Eddies"

- Turbulent diffusion: random walk by eddy decorrelation




$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c}$$

Eddy size ($L_c^2$)

Eddy "turnover" time ($\tau_c$)

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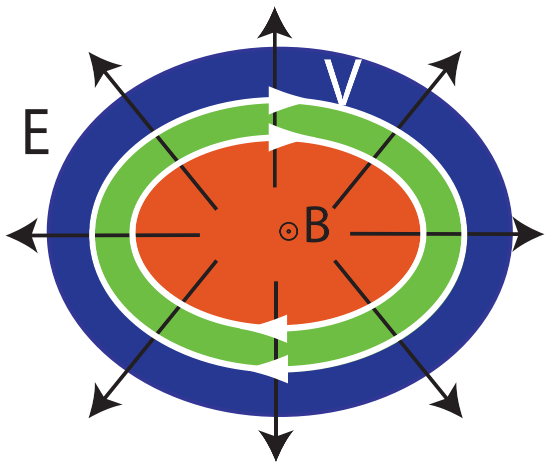


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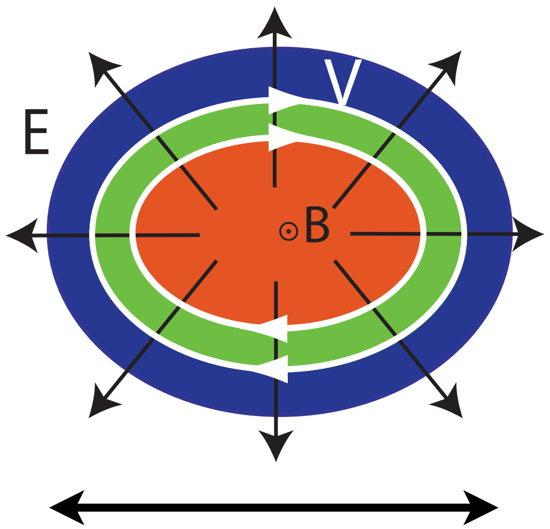


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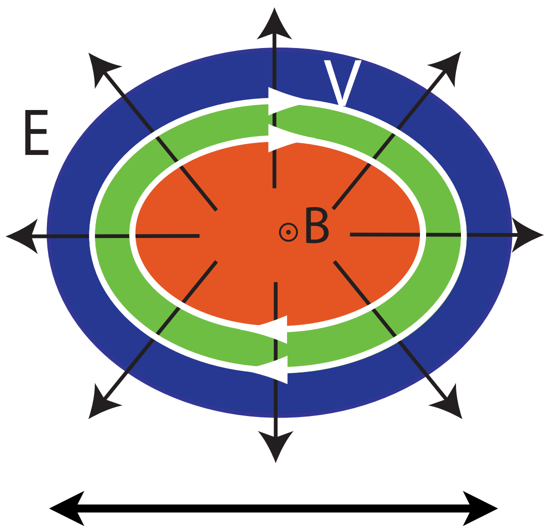


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Classical diffusion: $D_{\text{class}} \sim \rho^2 \nu \sim T^{-1/2} \quad (\nu \sim T^{-3/2})$

Collisional diffusion weaker as plasma gets hotter
(hot plasmas are “collisionless”)

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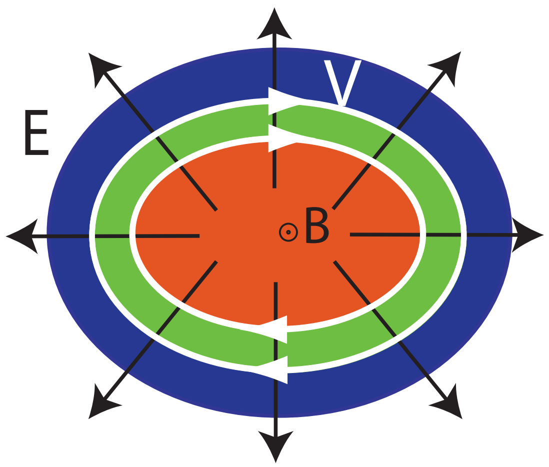


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**Classical diffusion:** $D_{\text{class}} \sim \rho^2\nu \sim T^{-1/2} \quad (\nu \sim T^{-3/2})$

- Turbulent diffusion coefficient orders of magnitude larger than classical (not shown here)
- More importantly: scaling with T is opposite. As T goes up (more heating power is added) confinement degrades. Consistent with so-called "low-confinement" mode or L-mode in experiments.

# Unexpected confinement breakthrough: H-mode

Wagner, Phys. Rev. Lett. 49, 1408 (1982)

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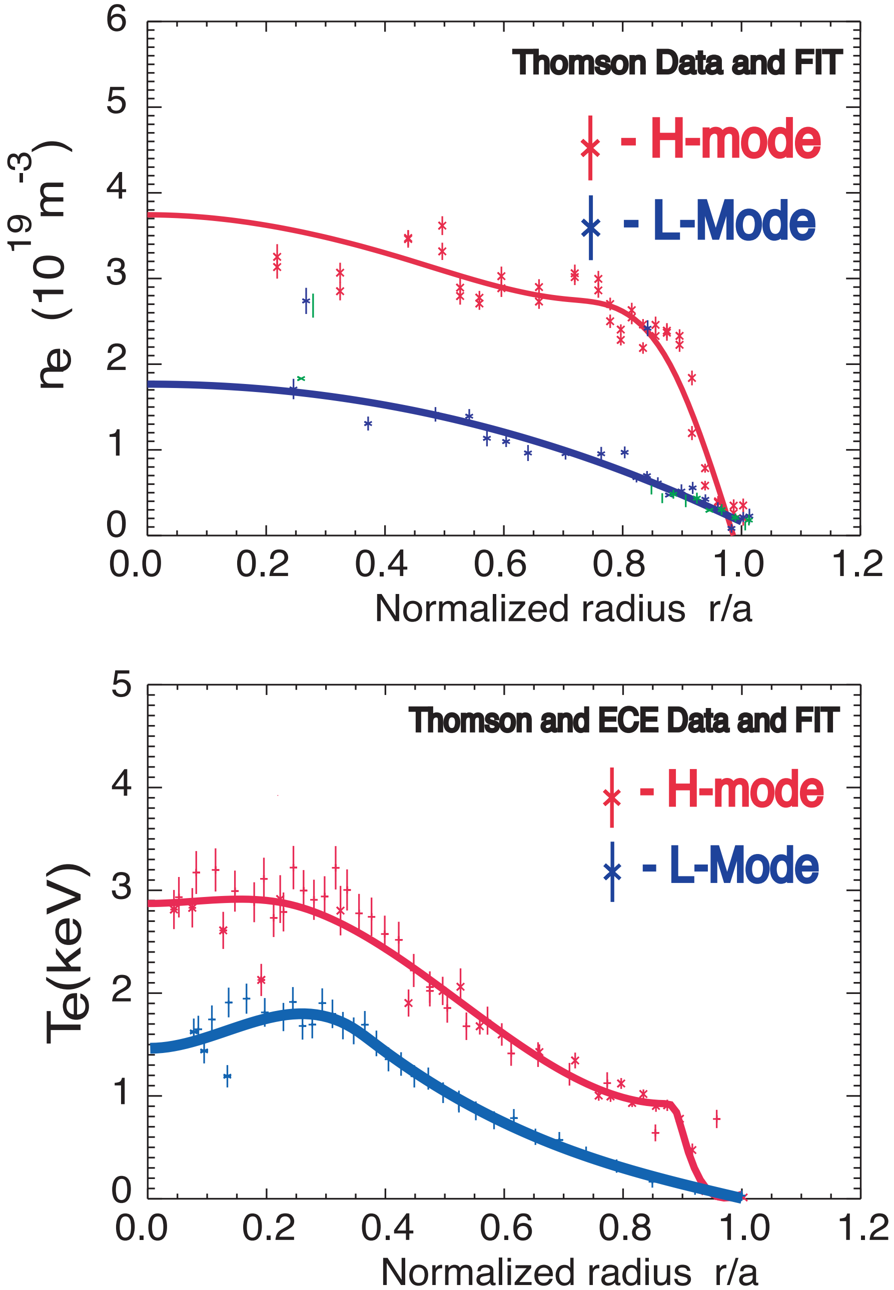


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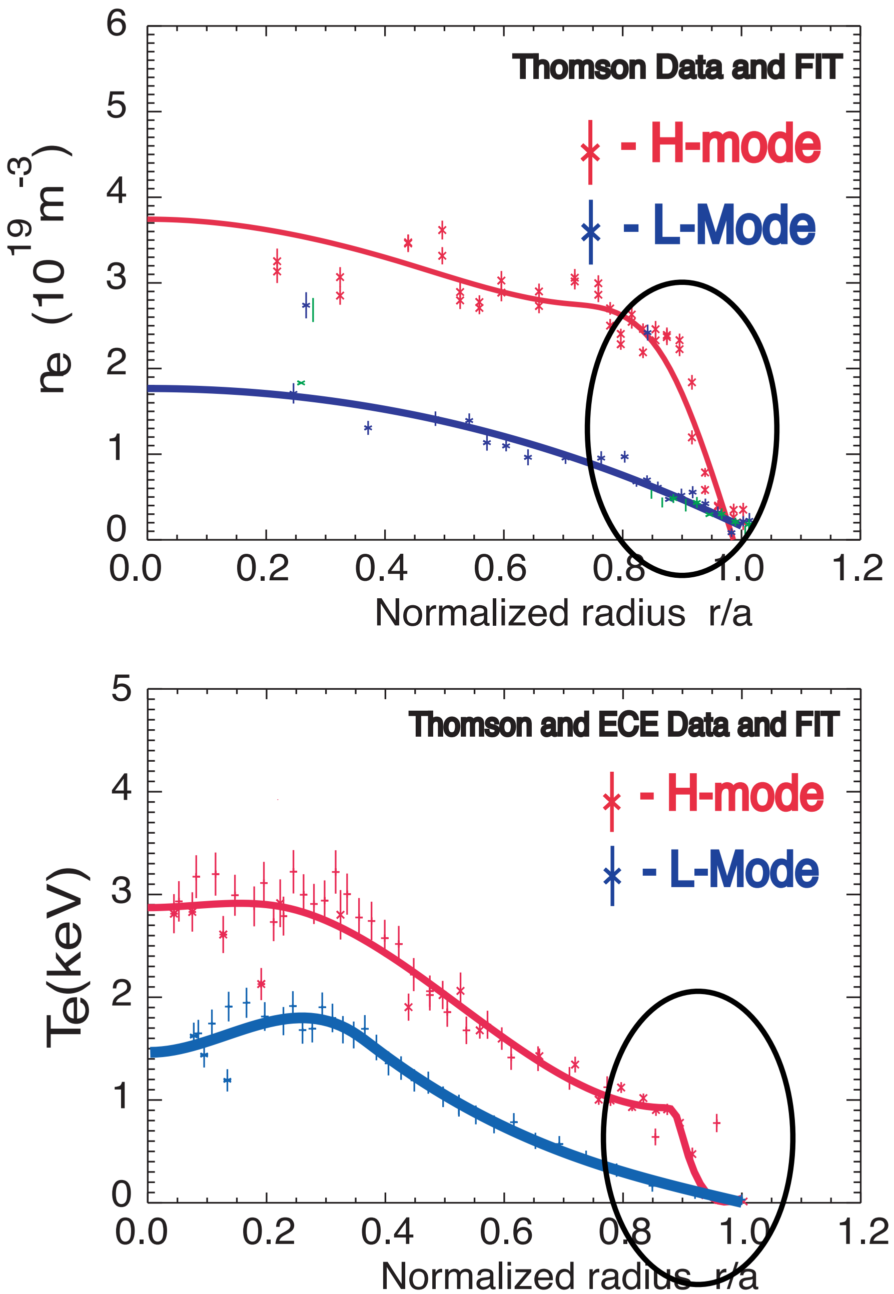


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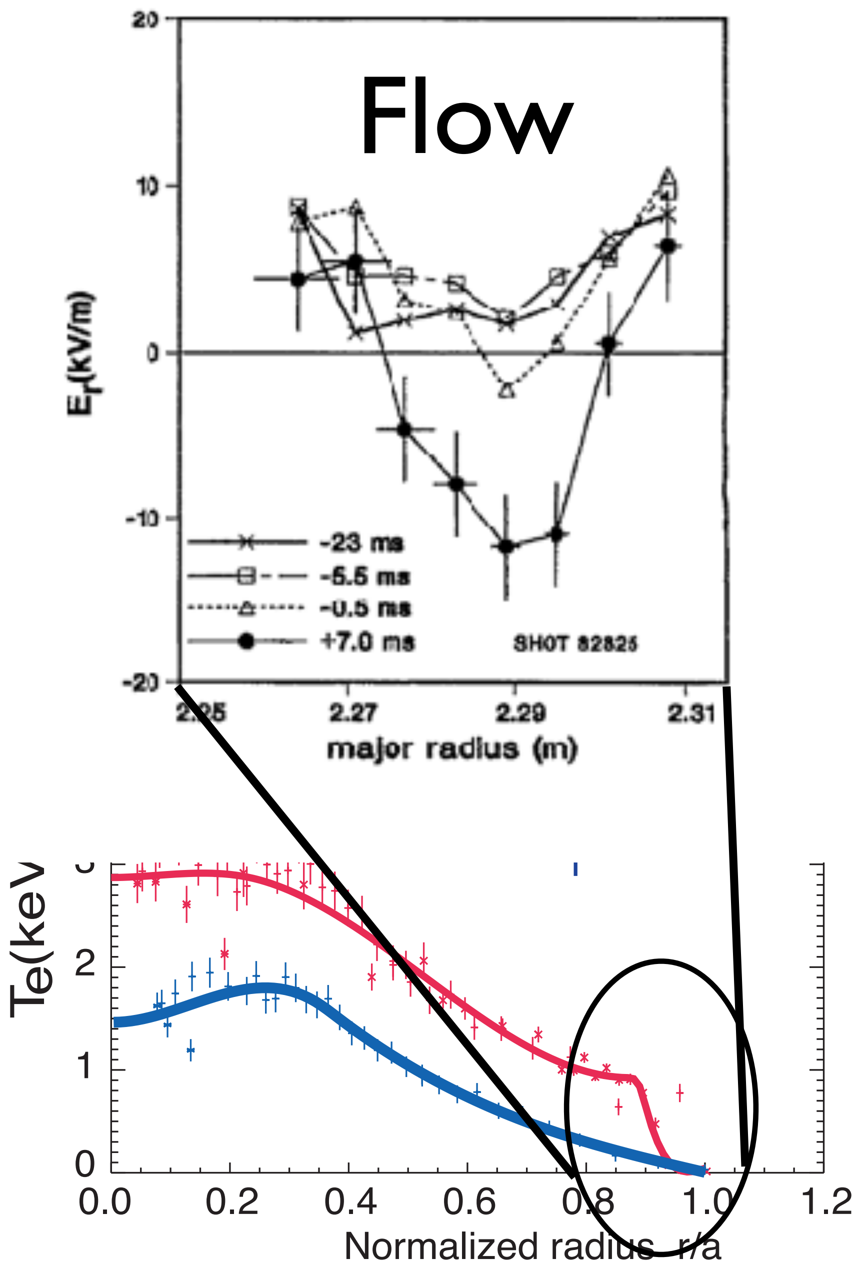


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- Edge transport barrier forms, with steepened gradients ("pedestal")
- Can maintain much hotter and denser plasma for the same input power (increase in "confinement time")
- During H-mode, strong, localized, cross-field flow (rotation) observed in the barrier region

Burrell, Phys. Plasmas 4, 1499 (1997)

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- JET's record 16MW D-T result was in H-mode: came close to break-even, $Q=P_{fus}/P_{heat}$~0.66

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- Important advances in understanding changes in turbulence and turbulent transport in H-mode (more on this later), but a lot of work remains
    - e.g. don't know mechanism for H-mode trigger, what determines height of "pedestal", what sets residual transport in H-mode....

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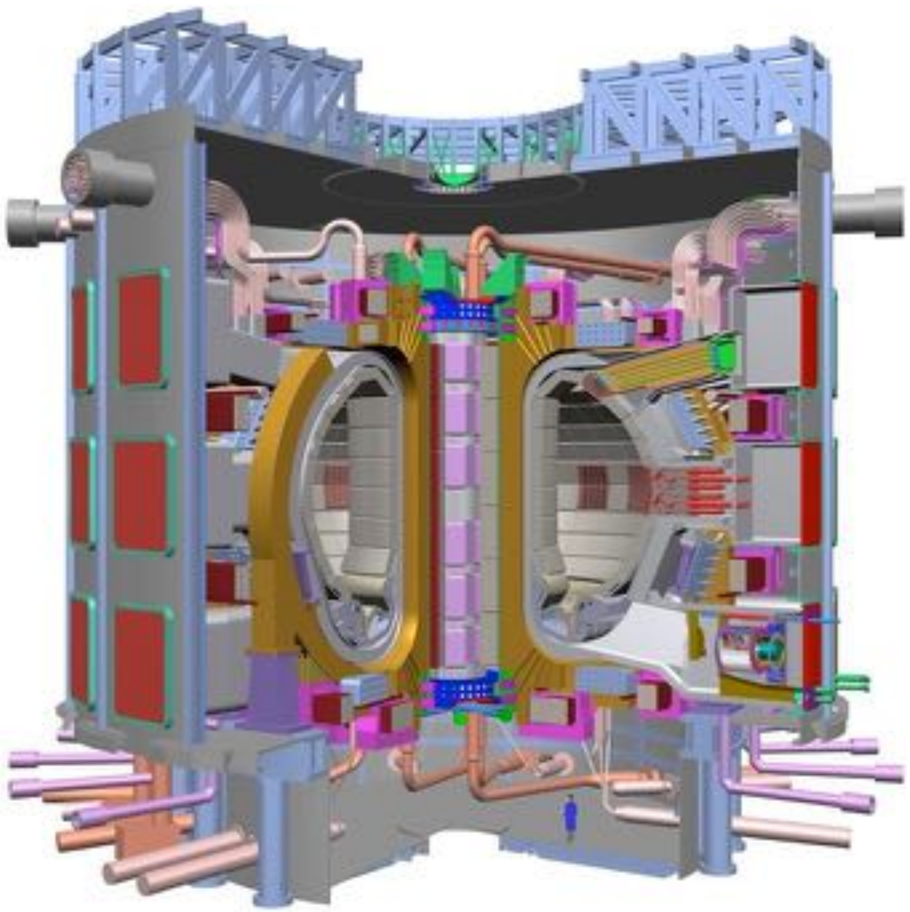
➡ To move beyond JET and design the next step experiment, must rely on projections using empirical transport scaling laws

# ITER: into the era of burning plasmas

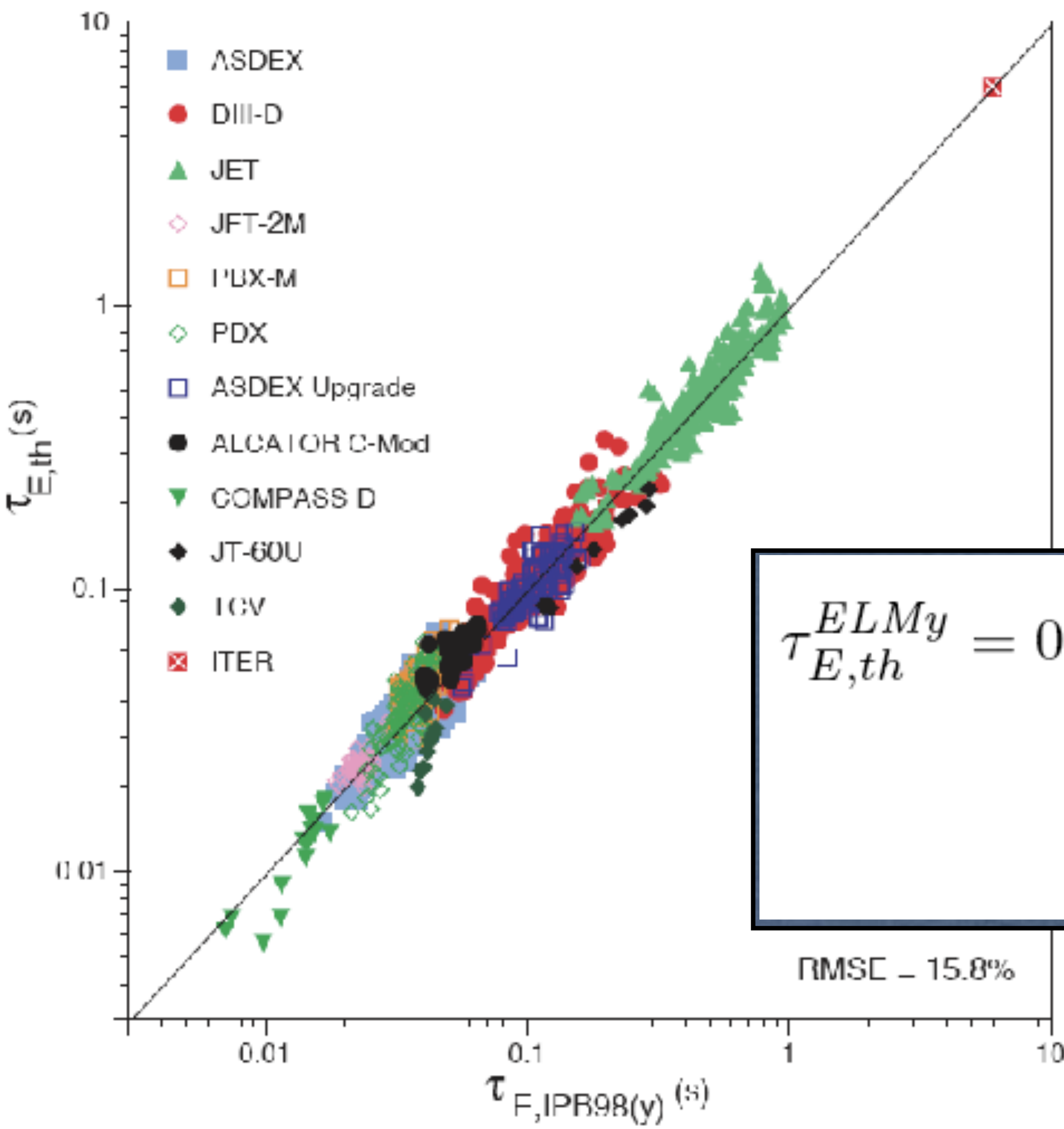


- Huge device, R~6.2m, a~2m
- Superconducting coils, 400s pulse
- 500MW fusion power, Q=5-10
- Under construction (Cadarache, France)

- First fusion plasma in which alpha particle heating will dominate external heating (burning plasma)
- Not a demonstration reactor, but a physics experiment to understand and control burning plasmas

# Transport in ITER

- ITER baseline operation uses H-mode for improved confinement, transport predictions are largely based on empirical scaling laws:




$$\tau_{E,th}^{ELMy} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} \times M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78} \quad (20)$$

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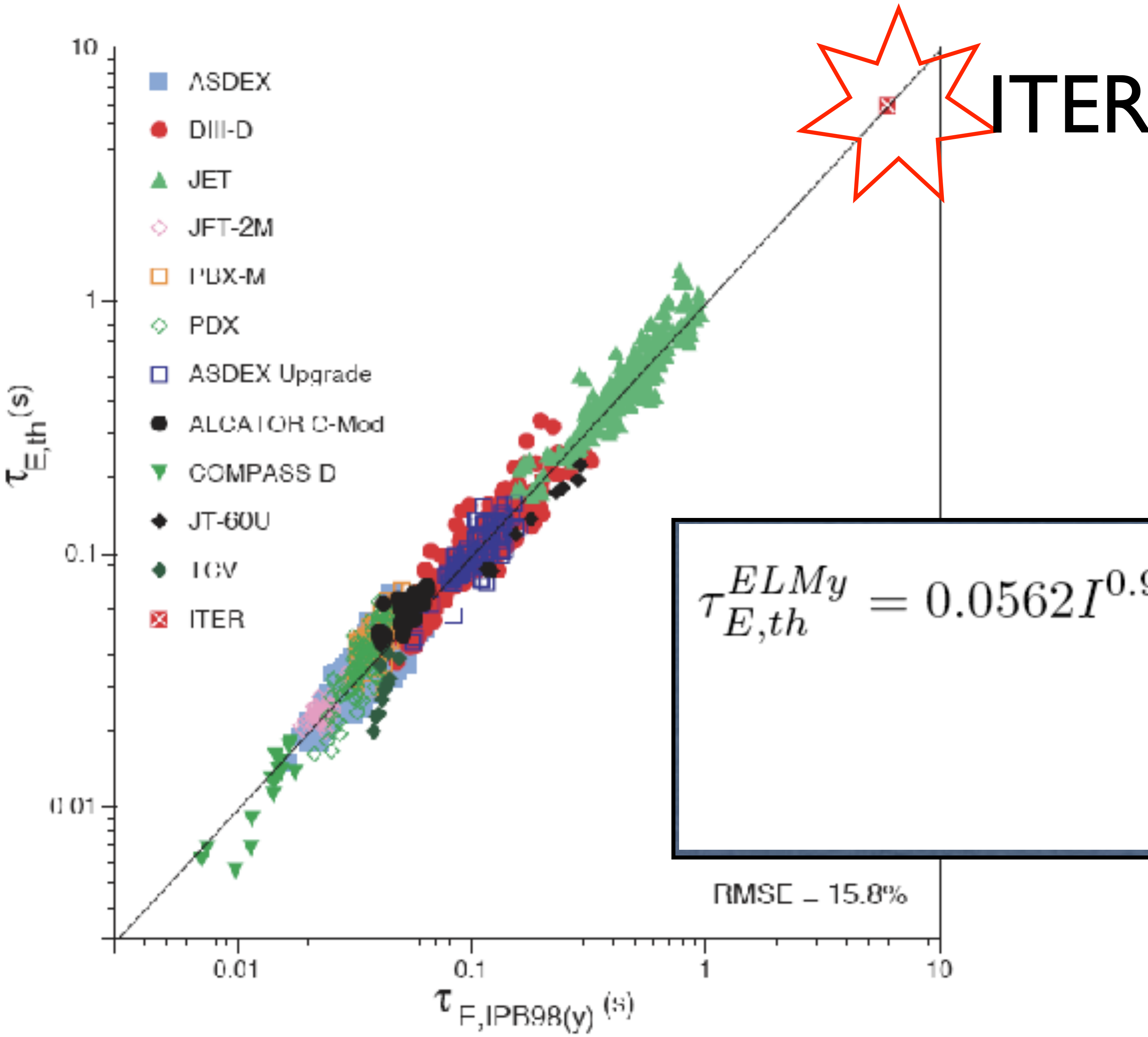


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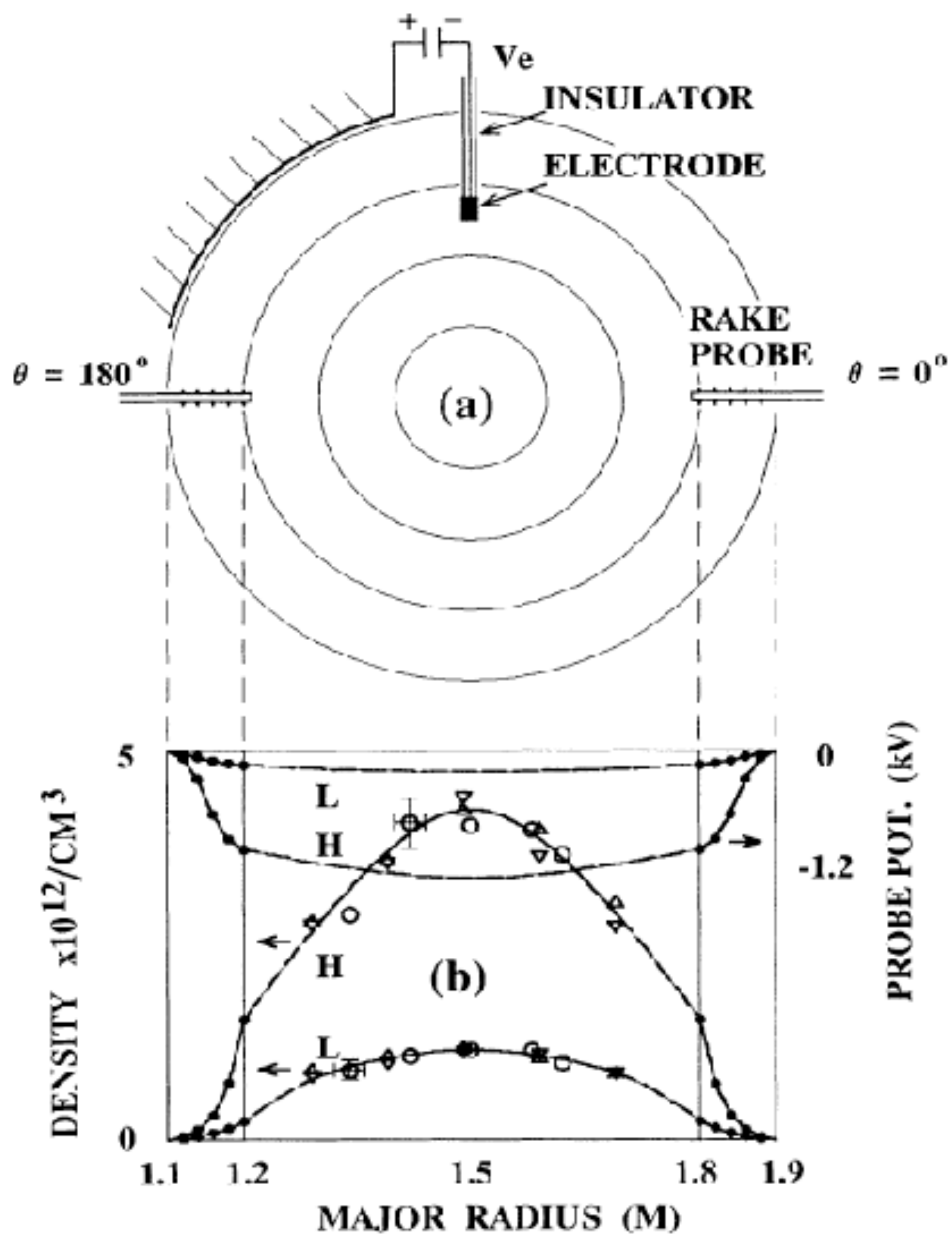
➡ Motivation for detailed studies of basic physics of turbulence and transport in magnetized plasmas

# UCLA tokamak biasing experiments linked H-mode confinement transition to edge flow

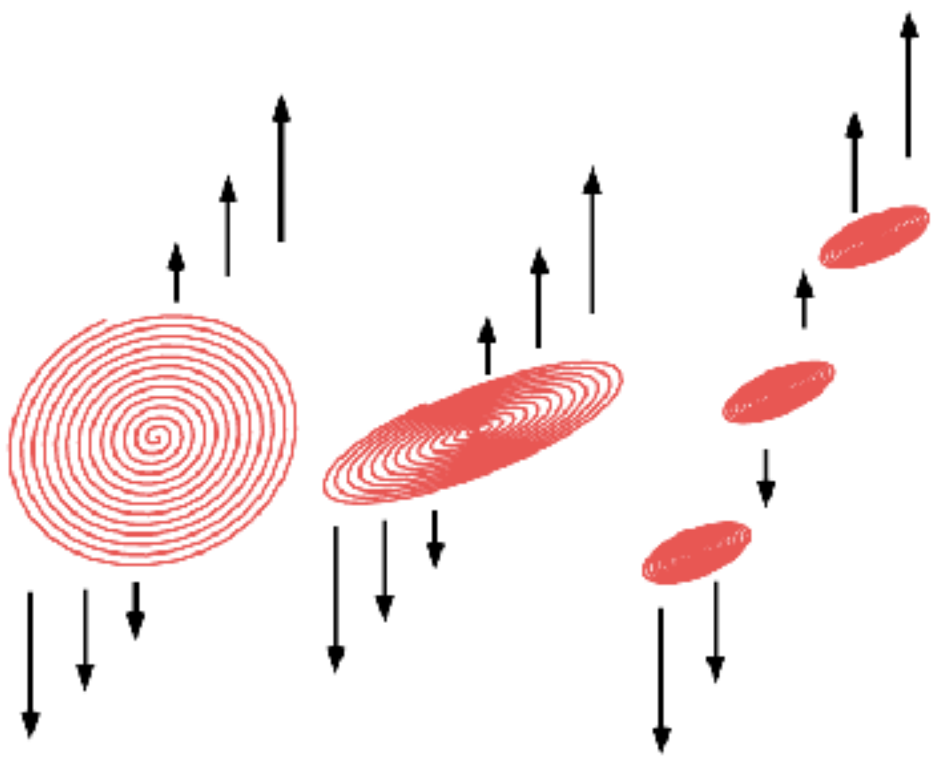



- Research by UCLA tokamak group (Bob Taylor) in the late 80's
- Triggered H-mode not with increased power, but by directly driving edge flow
- Established that edge flow is cause, not effect, of H-mode transition

Taylor, et al., Phys. Rev. Lett. 63, 2365 (1989)

# Progress in explaining H-mode: shear suppression of turbulent transport

- Transport barrier due to presence of significant shear in edge flow
- Heuristic argument: Sheared flow "breaks up" turbulent eddies, smaller eddies means smaller transport [Biglari, Diamond, Terry]



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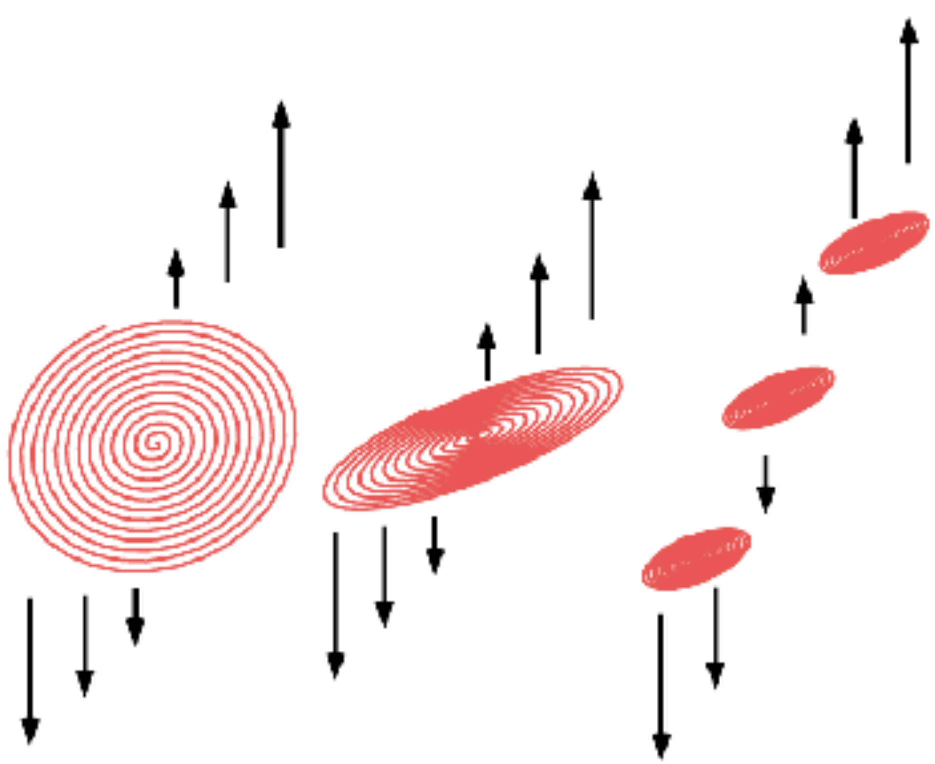


- Expect the shear to impact turbulence when shearing timescale is comparable to eddy turnover time (often taken as comparable to linear growth rate)

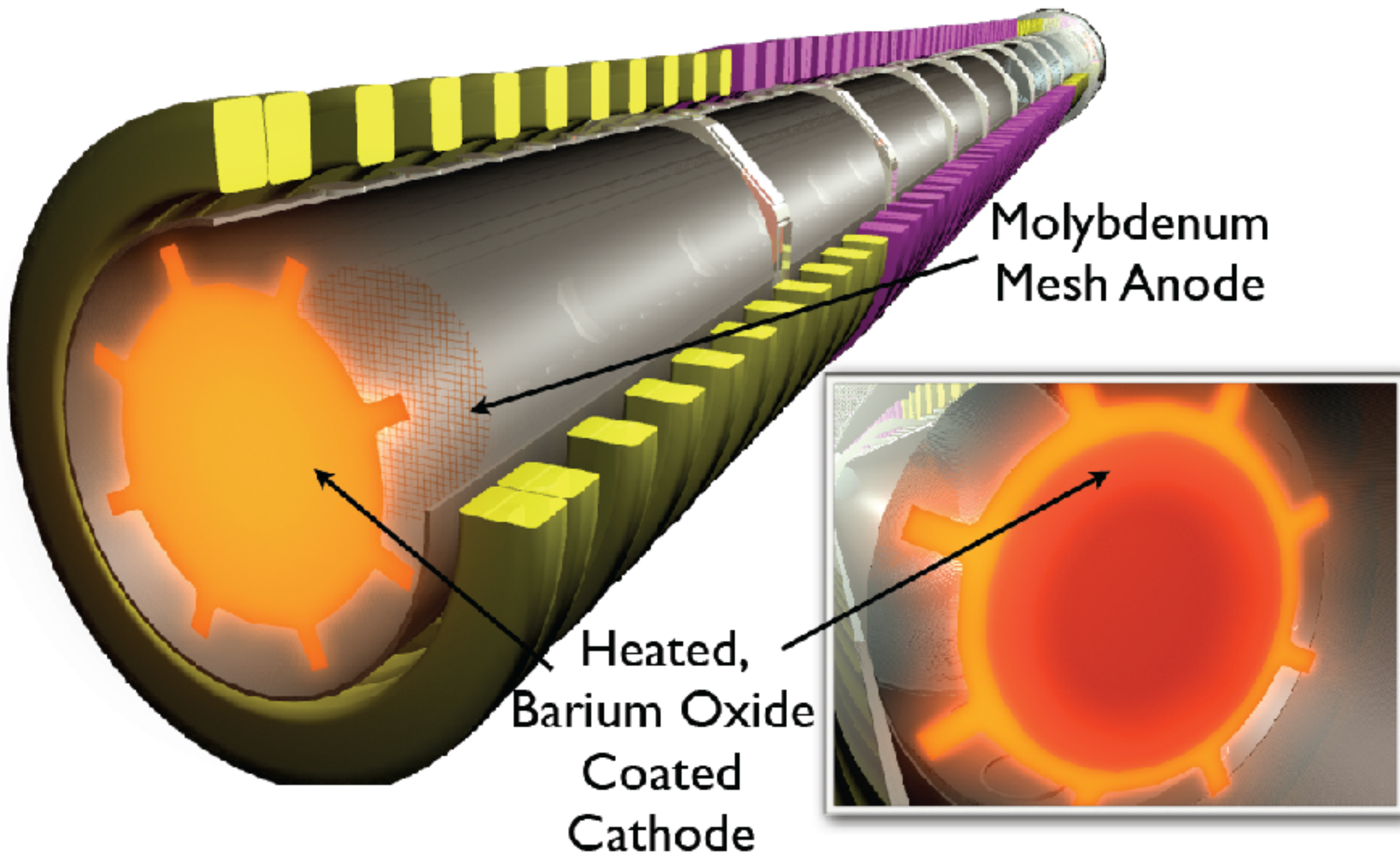
$$\gamma_s = \frac{\partial v}{\partial r}$$

Review: P. W. Terry, Rev. Mod. Phys. 72, 109 (2000)

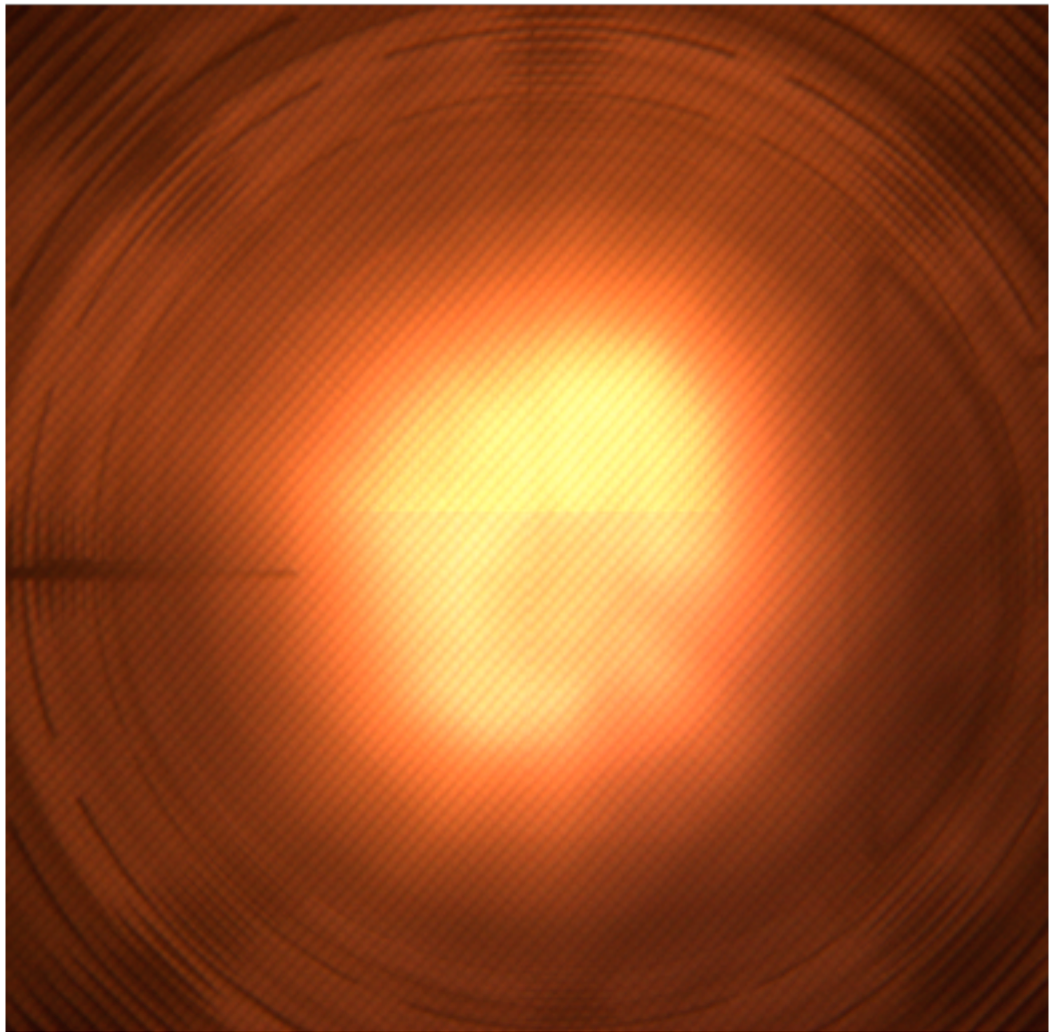
# The LArge Plasma Device (LAPD) at UCLA

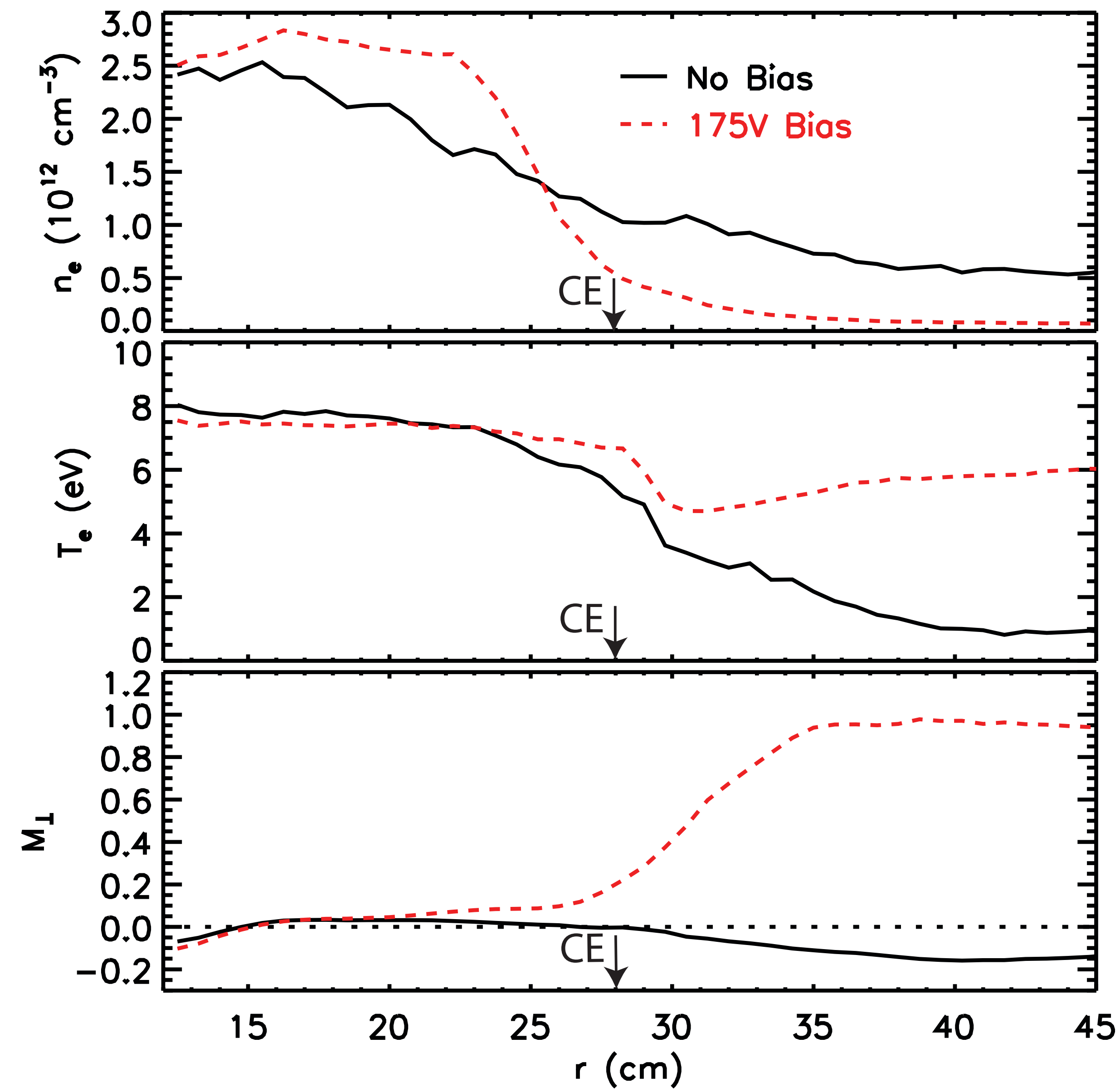
- Solenoidal magnetic field, cathode discharge plasma (BaO and $LaB_6$)
- BaO Cathode: n ~ $10^{12}$ $cm^{-3}$, $T_e$ ~ 5-10 eV, $T_i \lesssim$ 1 eV
- $LaB_6$ Cathode: n ~ $5 \times 10^{13}$ $cm^{-3}$, $T_e$ ~ 10-15 eV, $T_i$ ~ 6-10 eV
- B up to 2.5kG (with control of axial field profile)
- Large plasma size, 17m long, D~60cm (1kG: ~300 $\rho_i$, ~100 $\rho_s$)
- High repetition rate: 1 Hz

# LAPD Plasma source



# Example Plasma Profiles

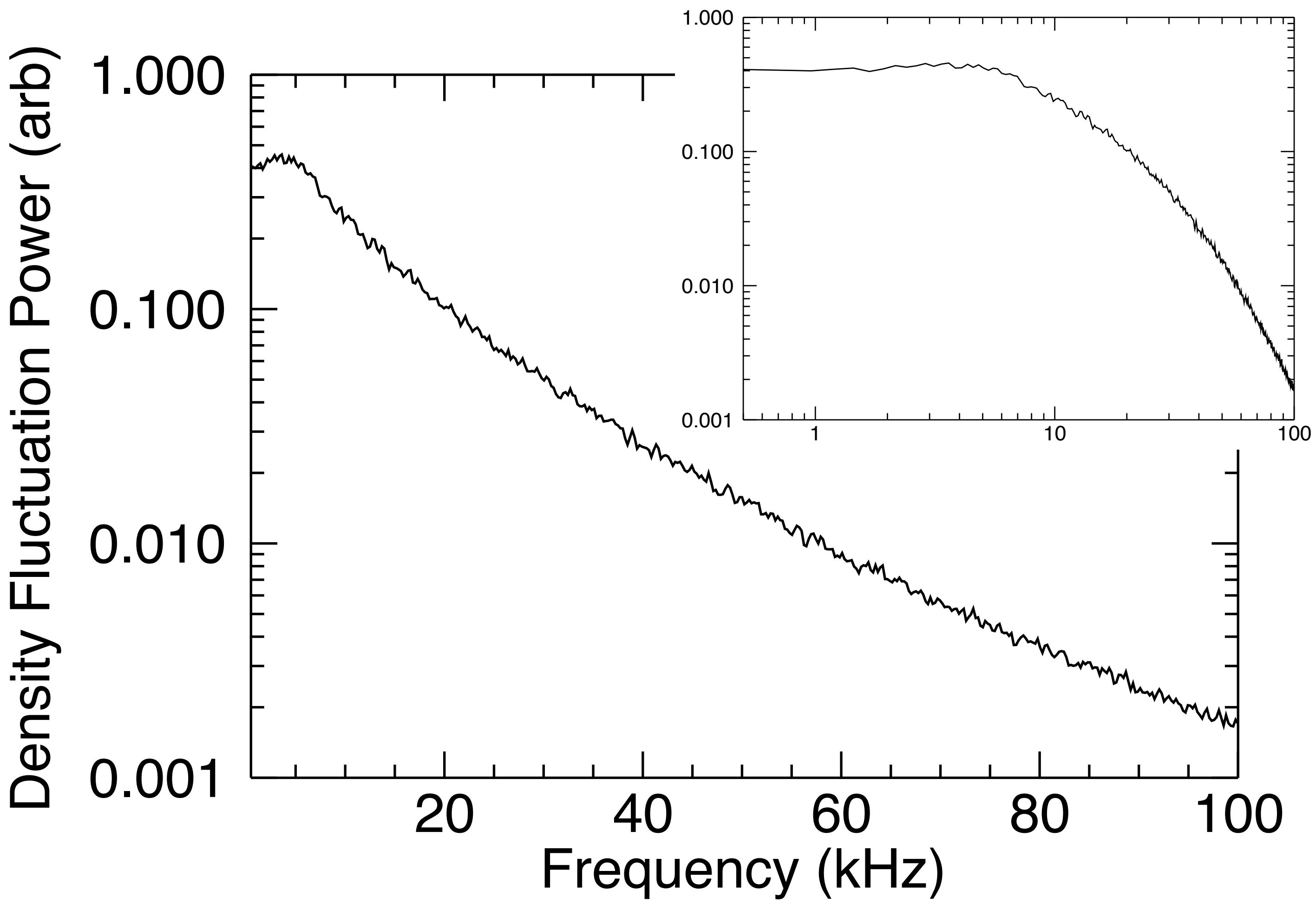


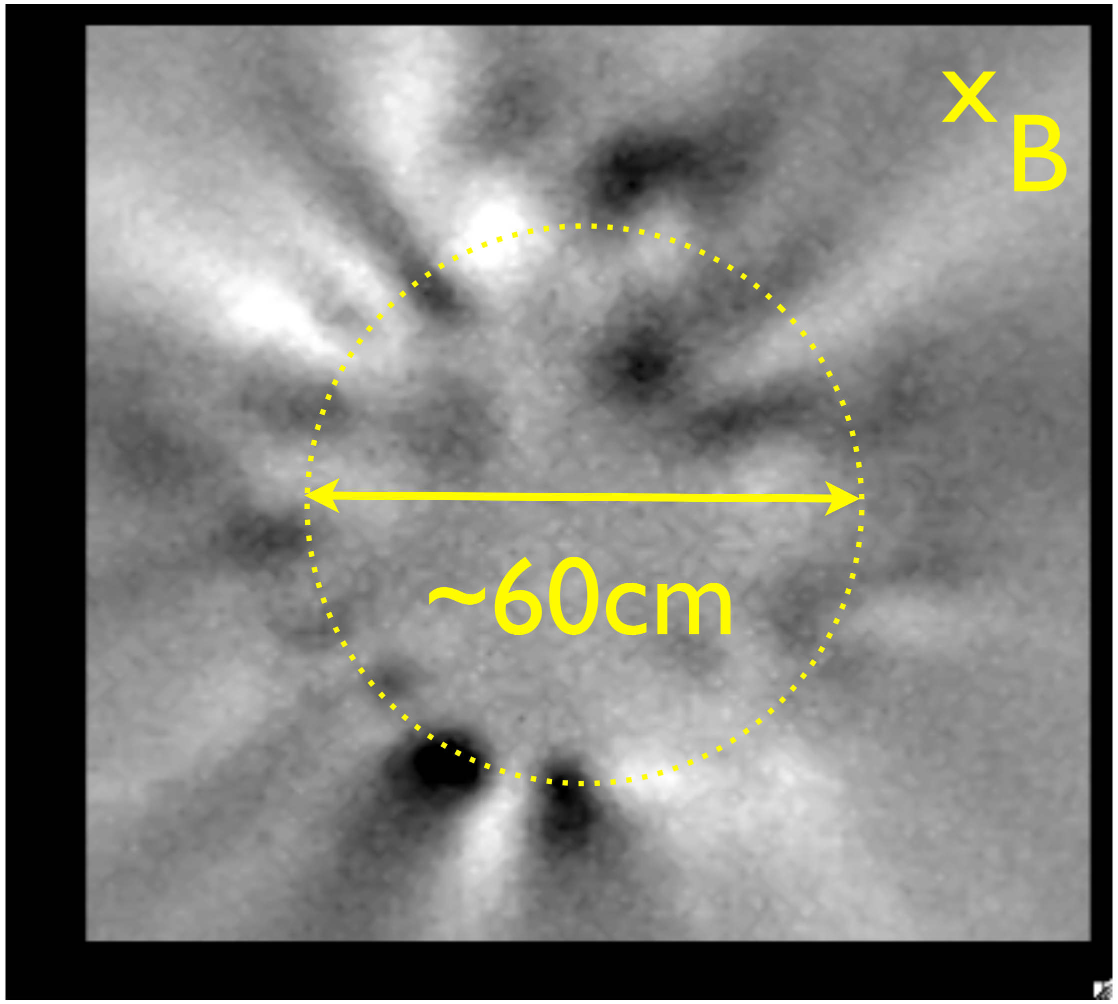



- Low field case (400G) (also shown: with particle transport barrier via biasing*); generally get flat core region with D=30-50cm
- Broadband turbulence generally observed in the edge region

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

# Turbulence and transport in LAPD

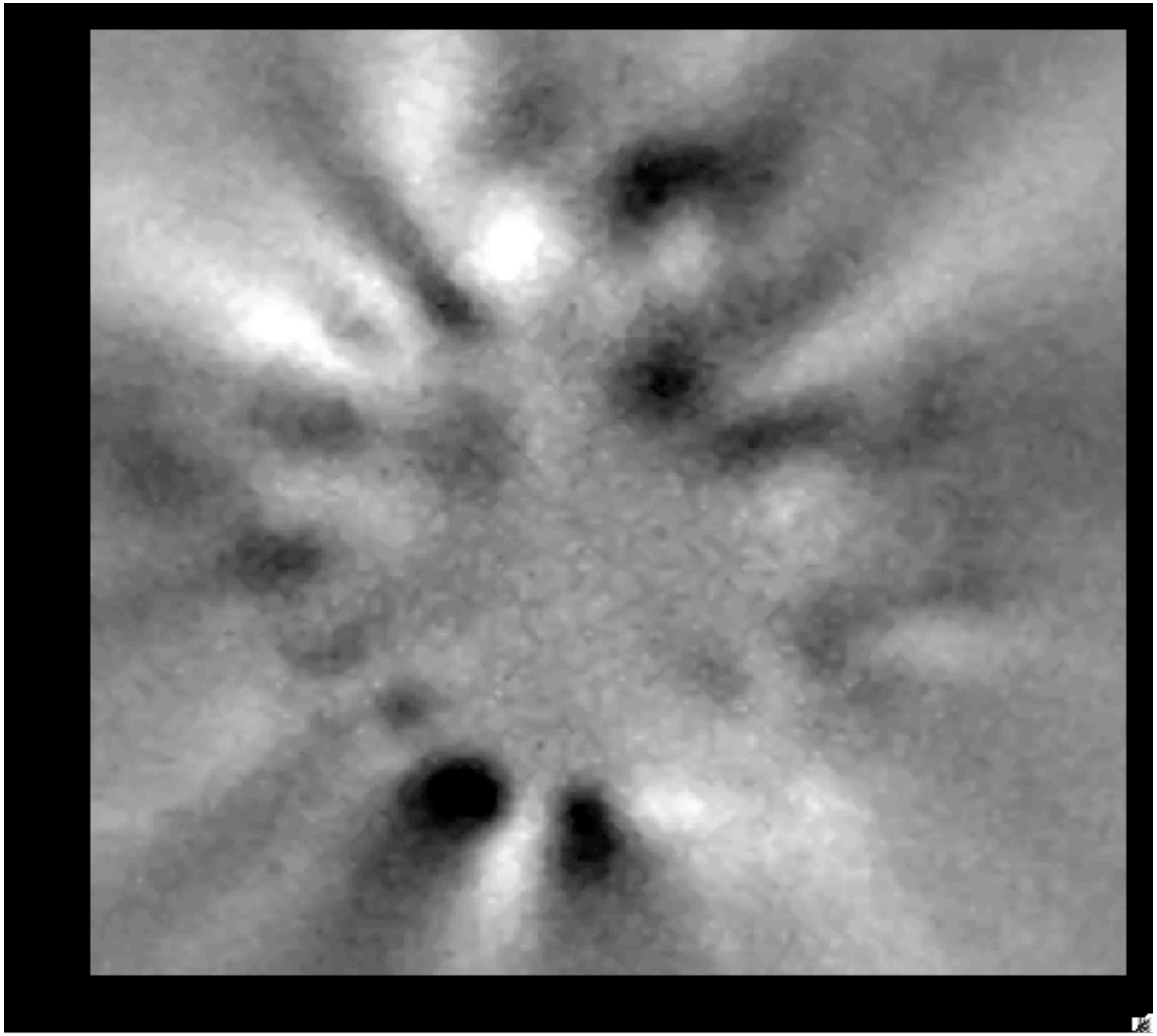



- Broadband turbulence observed in edge (free energy from pressure gradient (drift waves) and driven flow (e.g. KH)). Exponential spectrum observed [Pace 2008]

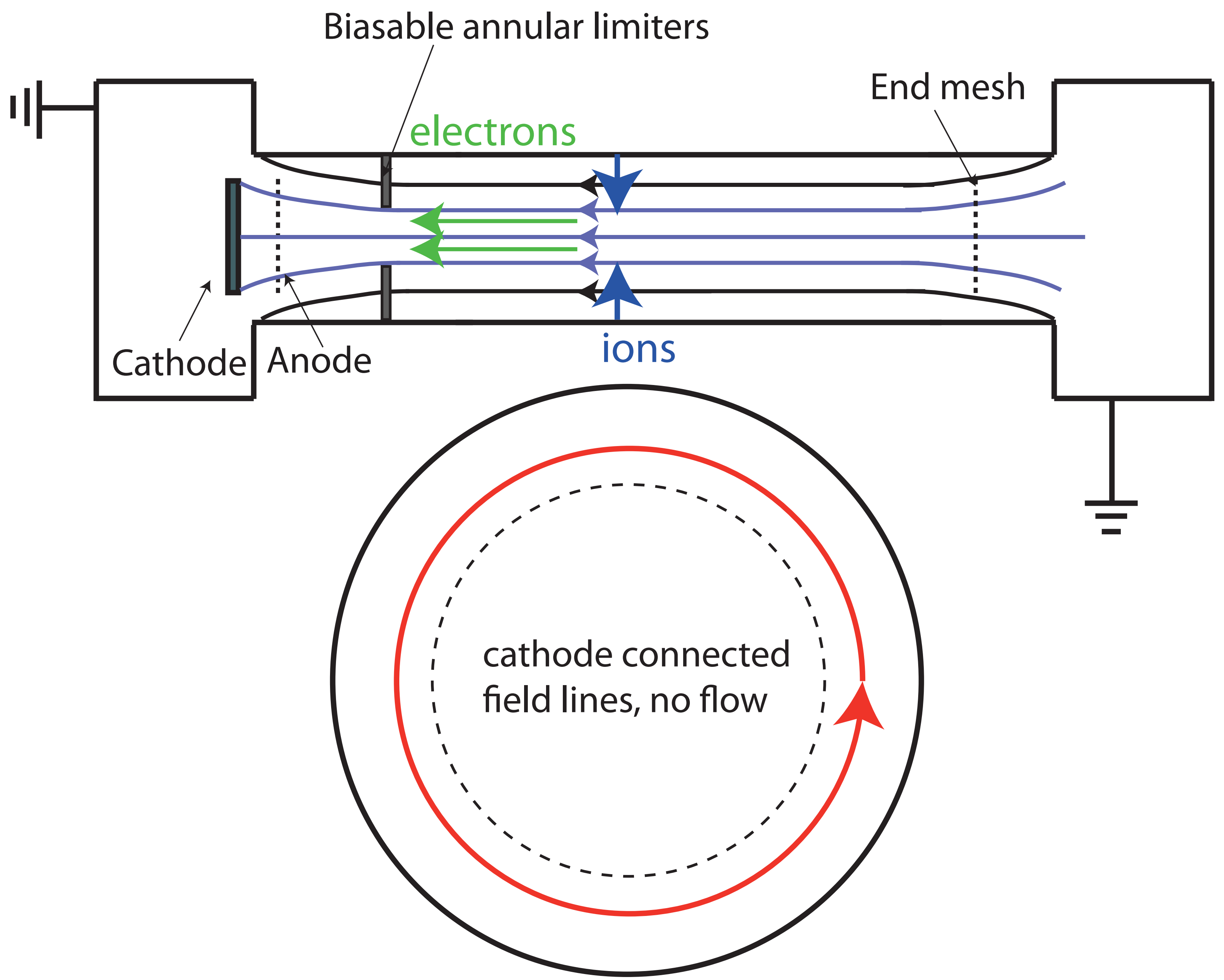
- Large plasma size allows perp. turbulent transport to compete with parallel losses; profile set by perp transport; confinement modification apparent in profile changes

# Visible light imaging of LAPD turbulence



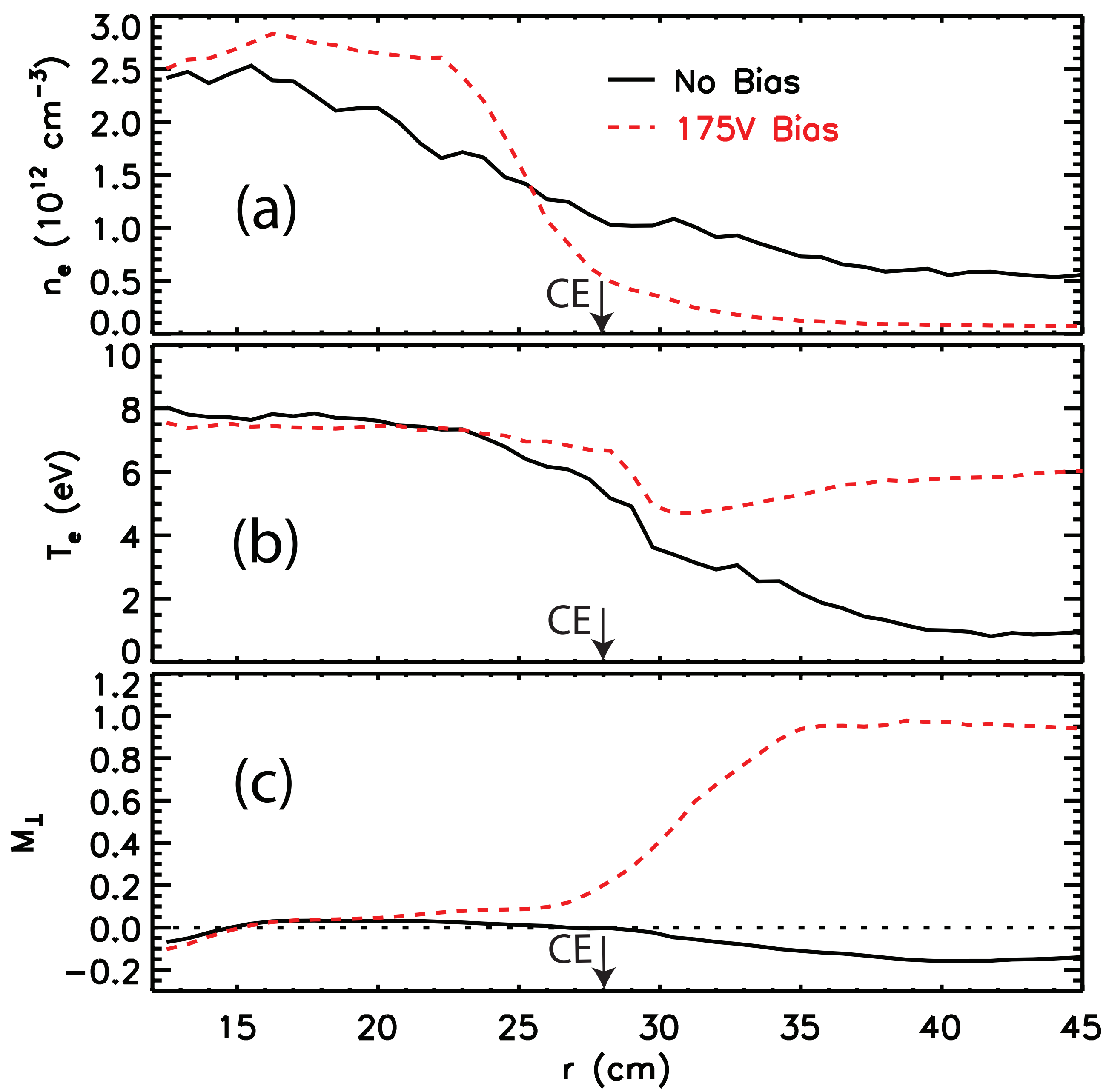
Fast framing camera (~50k frames per second, ~10ms total time), visible light (neutral He), viewed along B

# Bias-driven flow in LAPD




- Bias structure in contact with edge plasma, drive radial currents, results in torque, plasma edge rotates
- Even without direct biasing, plasma self-biases, spontaneously rotates

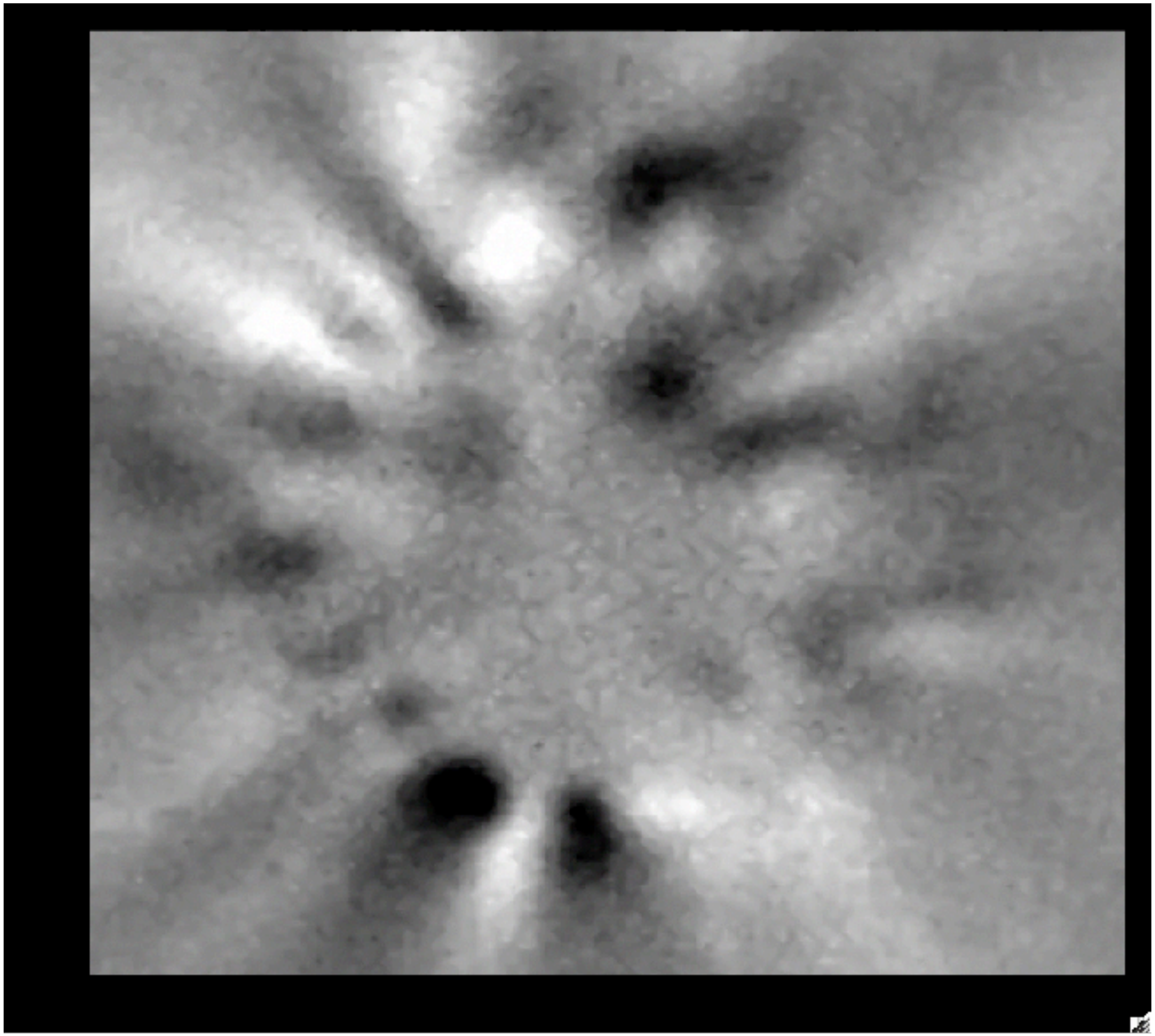
# “H-mode” observed in LAPD with driven flow



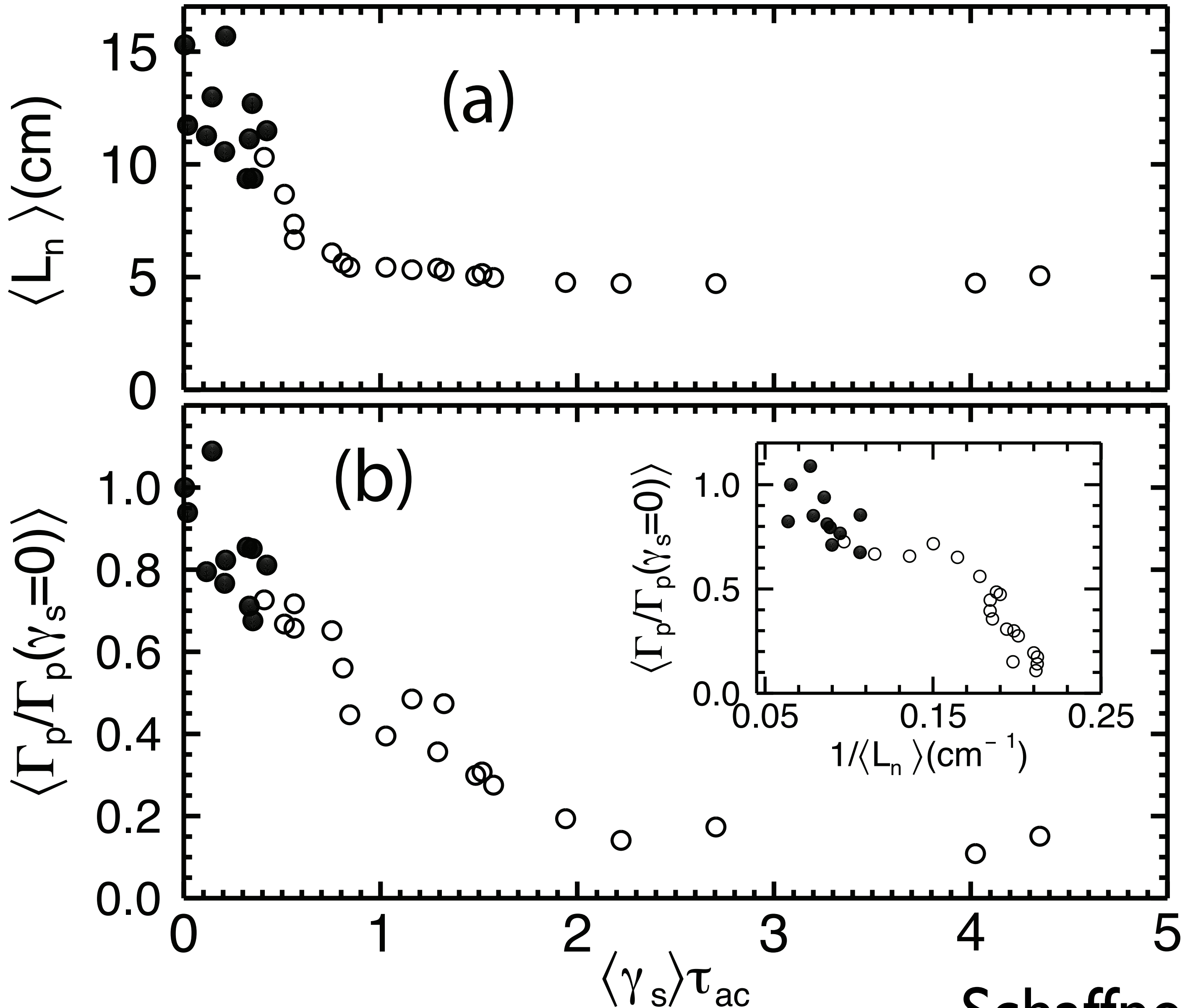

- With sufficiently large driven flow, see profile steepening (“H-mode” in LAPD)
- Detailed transport modeling shows that transport is reduced to classical levels during biasing (consistent with Bohm prior to rotation)
- Turbulence in edge (localized on pressure gradient) is modified, turbulent transport eliminated

Carter & Maggs, Phys. Plasmas 16, 012304 (2009)

# So what happens to turbulence? Fast framing camera movie (40k frames/s)



# Details: documenting the response of turbulence to shear

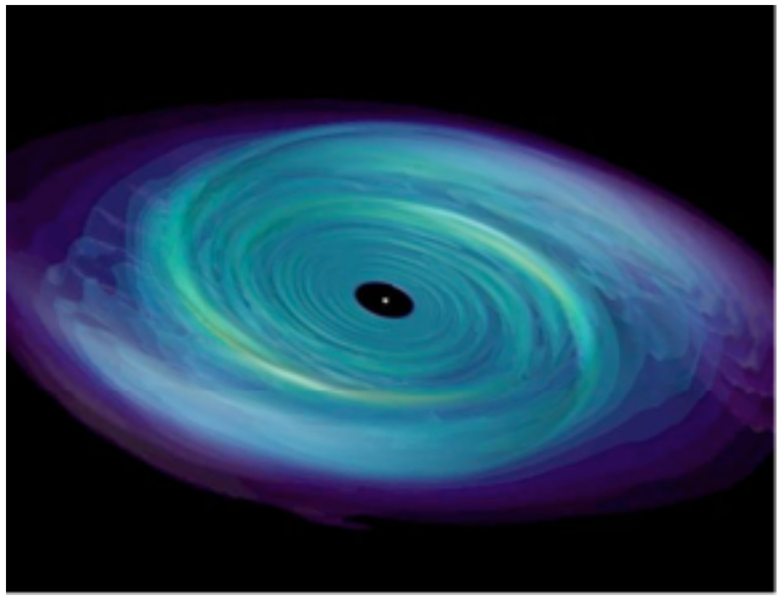


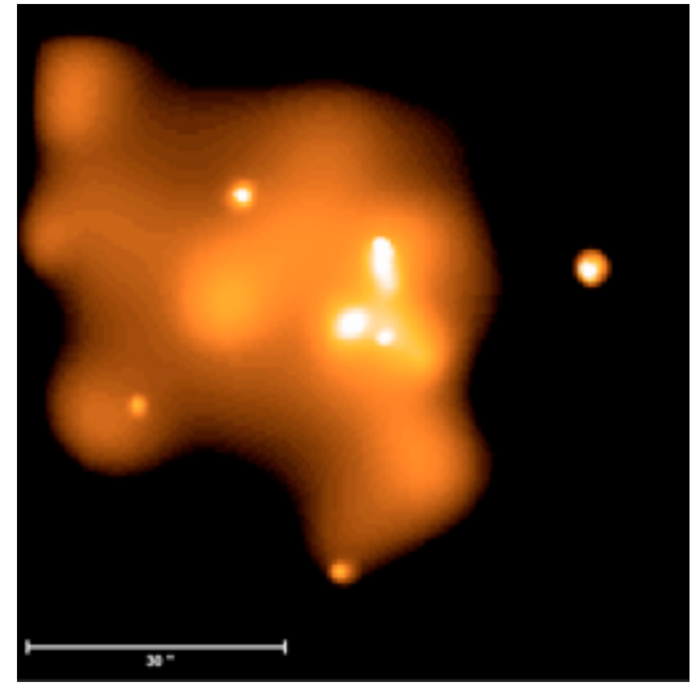

Schaffner et al., PRL 109, 135002 (2012)

Schaffner et al., PoP 20, 055907 (2013)

Data challenges existing models; will be used to test existing and new simulation capability targeted at predicting transport in devices like ITER

# Accretion disks: feeders for forming/growing stars, planets, black holes

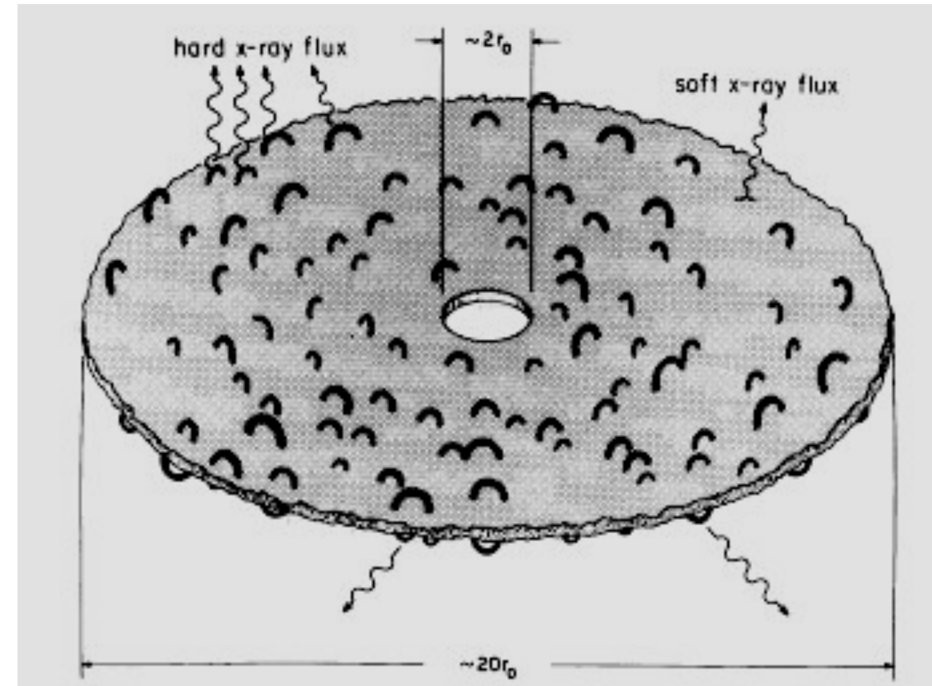




- Matter will orbit the central object, will not fall in unless there is friction/drag (conservation of angular momentum)
- By falling into object, tremendous amounts of energy can be released (of order 10x $mc^2$ for black hole disk) (can lead to large luminosity, e.g. AGNs)
- Classical disks: collisions between protons and electrons causes friction; electrons are heated leading to strong radiation that keeps disk cool (relevant to protostar, planetary, some BH disks)

# "Classical" accretion: drag provided by collisions among the plasma particles in the disk

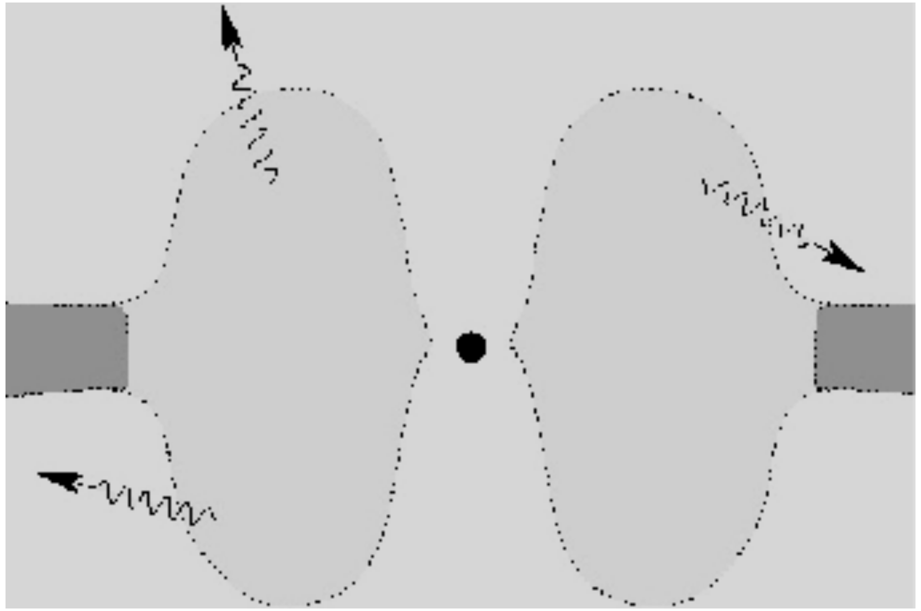
- Only happens in "cool" disks (remember plasmas become "collisionless" as they get hot)
- In classical disk, energy gets transferred to light particles via collisions: electrons are heated




- Electrons radiate this energy away very effectively (x-rays due to synchrotron radiation); keeps disk cool, results in "thin"disk (relevant to protostar, planetary disks, some BH)

# Problem with “hot” disks: collisions too infrequent to explain observed accretion rates

- Radiatively inefficient disks are often observed: not enough radiation to cool disk as matter accretes, energy gets stored in thermal energy, get puffed-up, thick disk



# Problem with “hot” disks: collisions too infrequent to explain observed accretion rates

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- Because plasma is very hot, collisions are too infrequent to explain observed rates of accretion!
- Turbulence to the rescue? Problem: disks are hydrodynamically stable (no “linear” instability in Keplerian flow of neutral gas)

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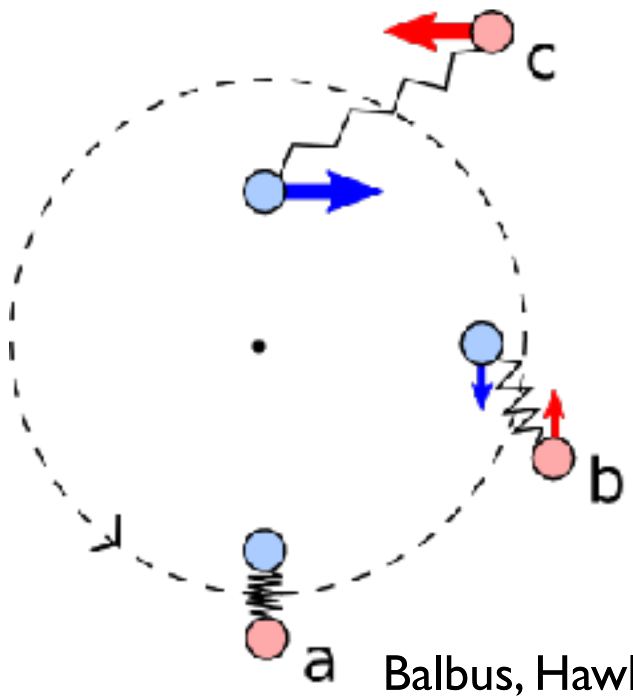
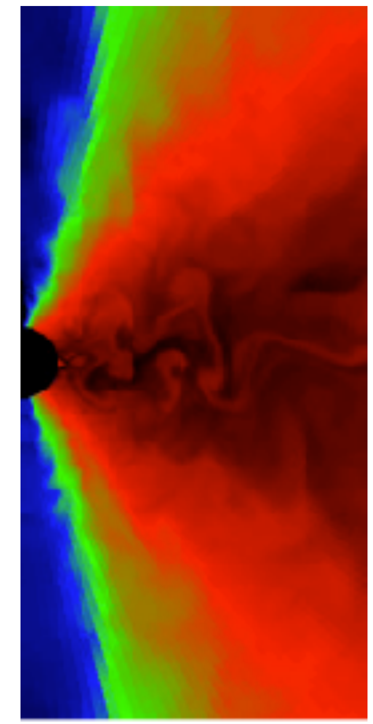
➡ However, if you acknowledge this "gas" is a plasma, and that magnetic fields can be present, there is an instability: Magnetorotational Instability (MRI) [Velikhov, Chandrasekhar, Balbus, Hawley]

# Magnetorotational instability (MRI): transports momentum, but where does energy go?



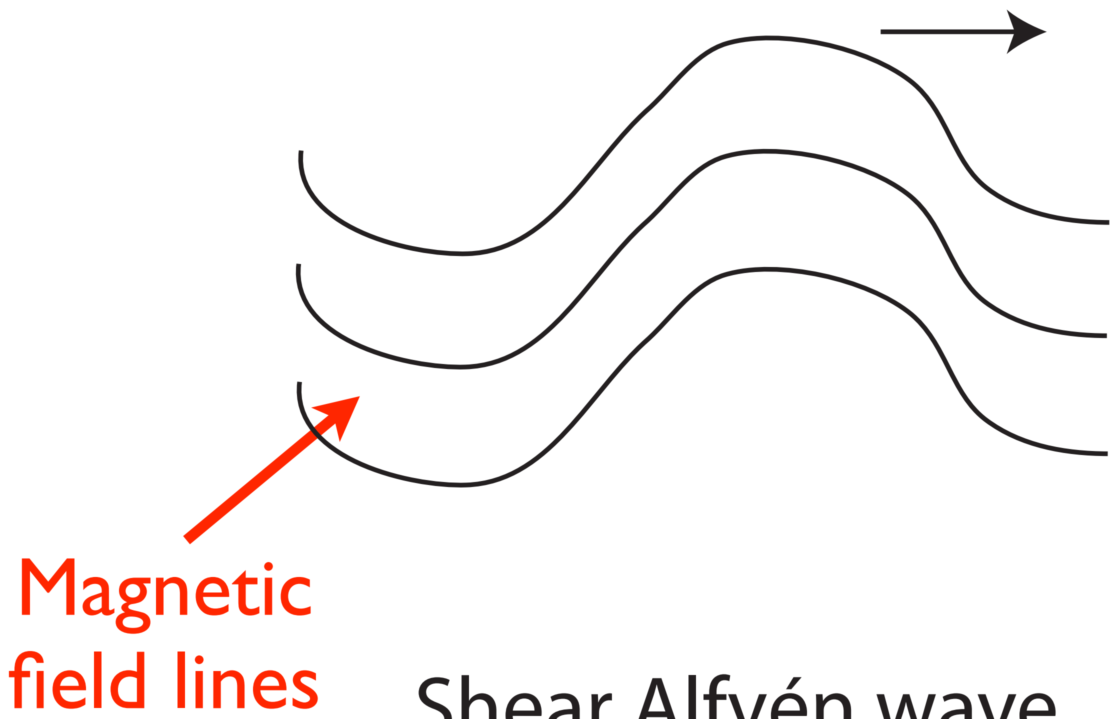

Balbus, Hawley, Rev. Mod. Phys. 70, 1–53 (1998)



MRI simulation (Stone)

- Presence of weak magnetic field allows instability: angular momentum transported outward, matter inward
- Instability provides "anomalous" viscosity, accretion can occur
- Energy released in accretion gets taken up by turbulent magnetic fields which grow as part of the instability: where does this energy go and why isn't it radiated away?

# Energy in MRI can drive turbulent cascade of Alfvén waves




Shear Alfvén wave

- Shear Alfvén wave: analogous to wave on string, tension provided by field line, mass by plasma

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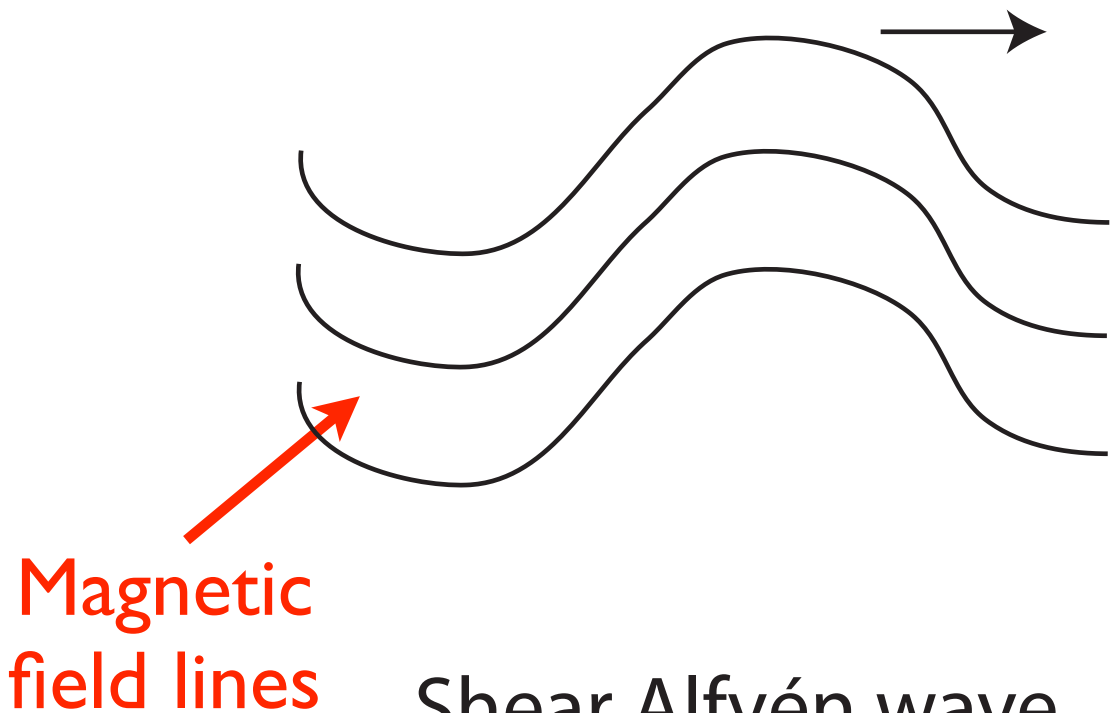
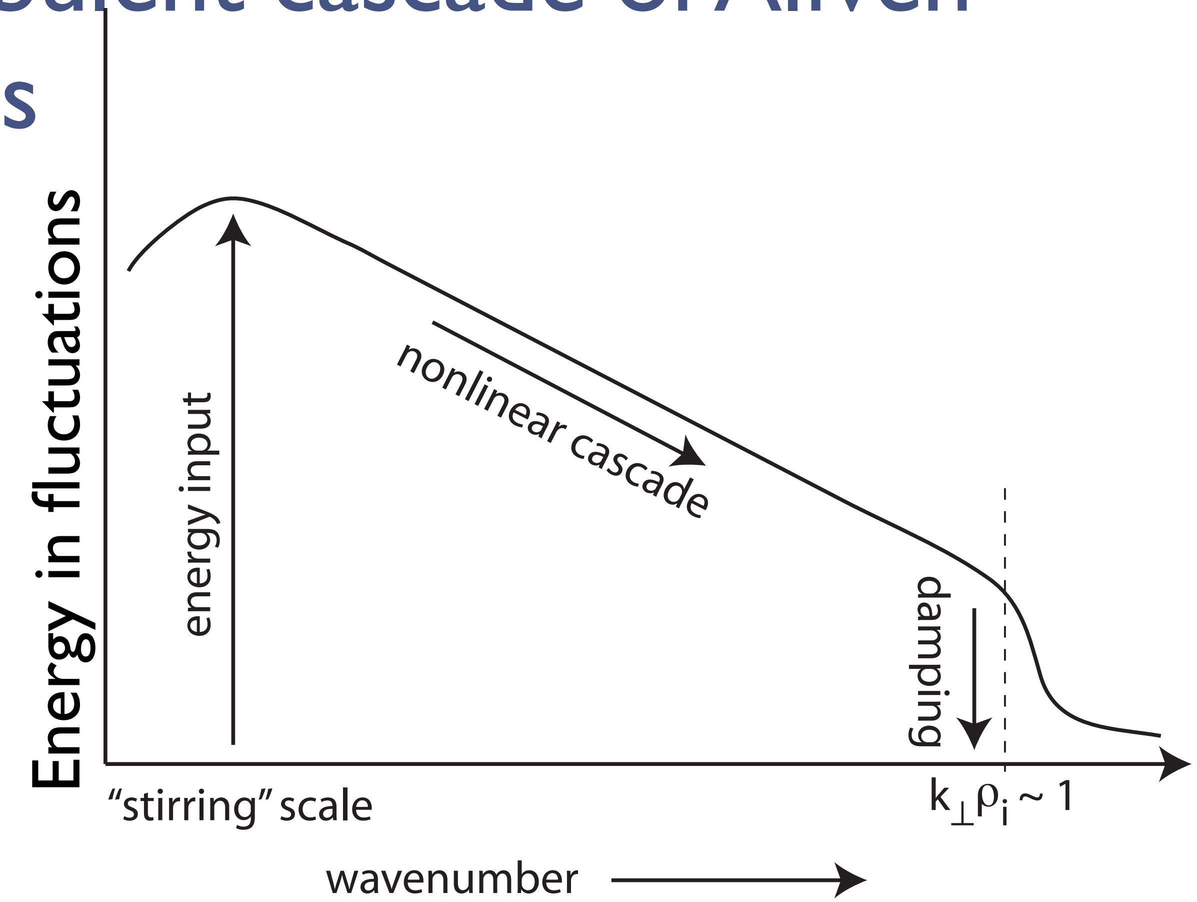



Shear Alfvén wave

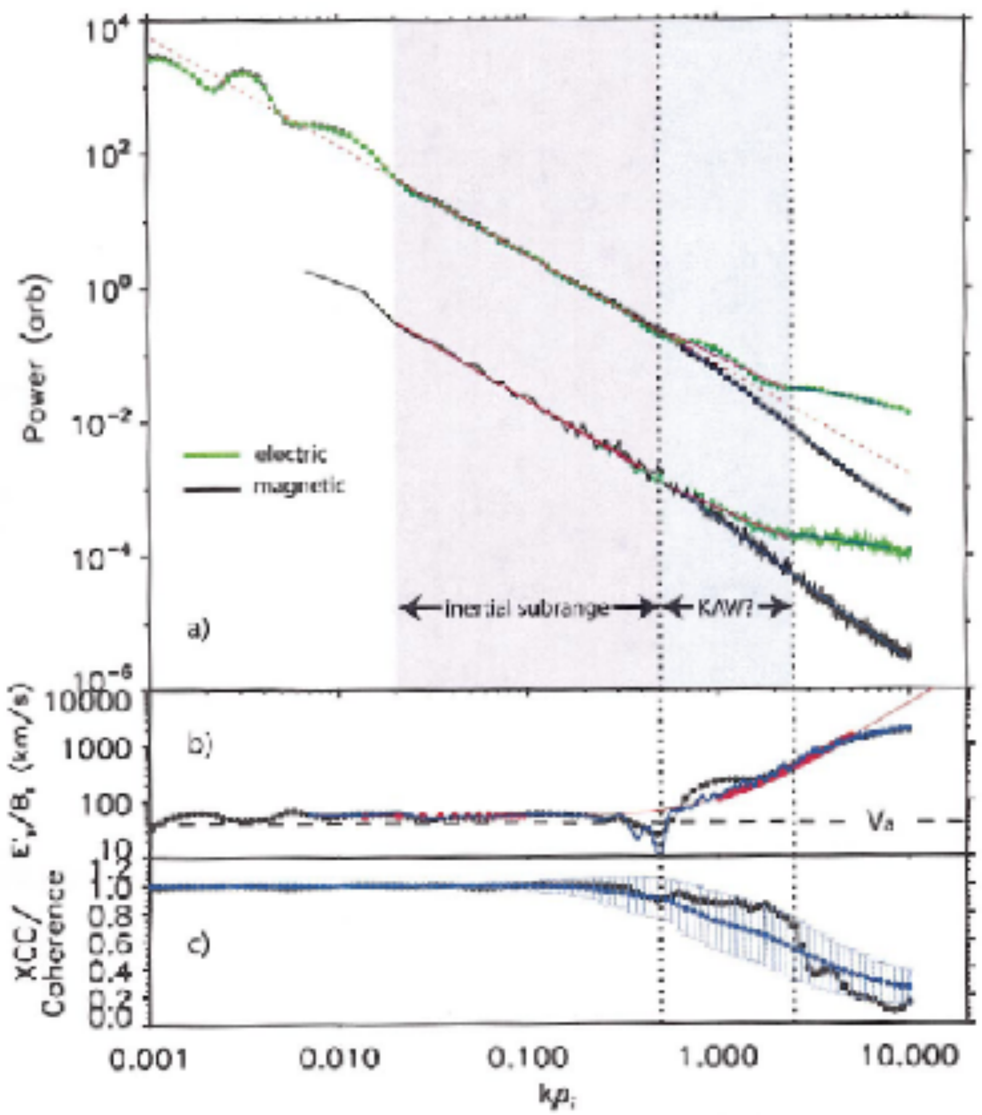



- Shear Alfvén wave: analogous to wave on string, tension provided by field line, mass by plasma
- MRI acts as large scale "stirring"; instability perturbations are like large-scale Alfvén waves
- Nonlinear interaction among waves generates daughter waves at smaller spatial scales; cascade down to dissipation scales where energy dissipated into plasma thermal energy

Quataert *ApJ* **500** 978 (1998)

- Direct ion heating possible at dissipation scale: could explain observations

# Turbulent Alfvénic cascade observed in the solar wind

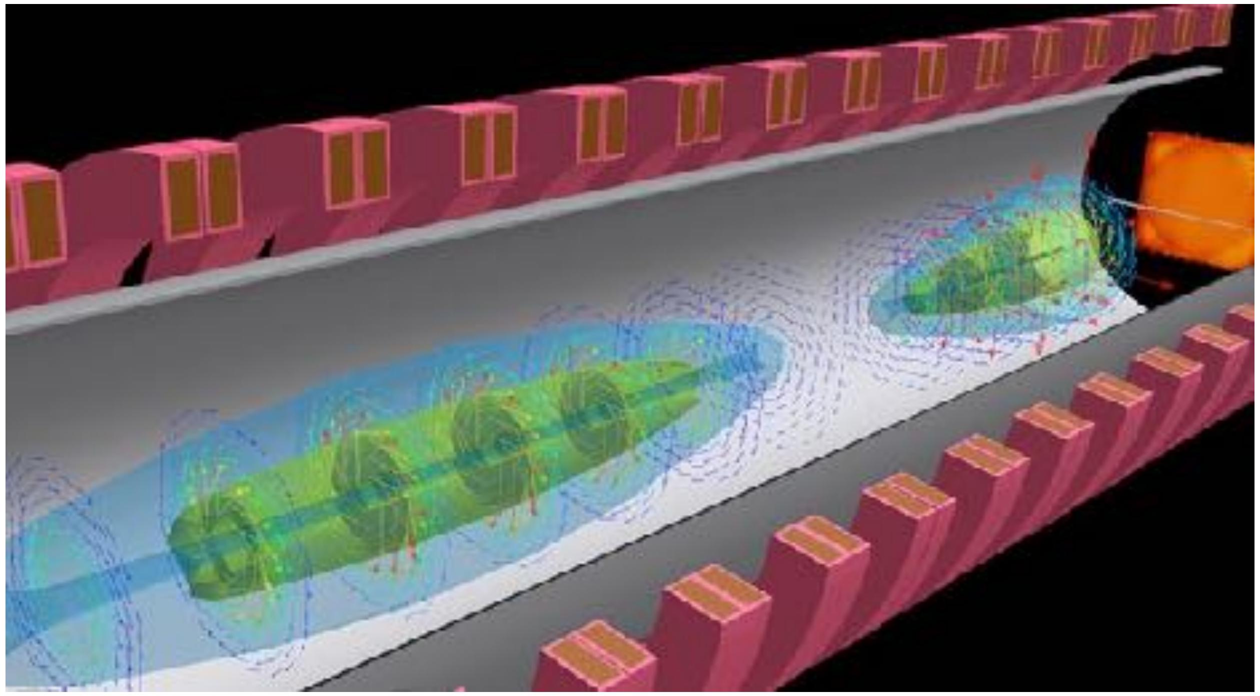



Bale, et al. PRL 94, 215002 (2005)

- "Stirring" comes from strong flows, AWs that originate at the sun
- Satellite measurements of electric and magnetic field fluctuations reveals turbulent spectrum

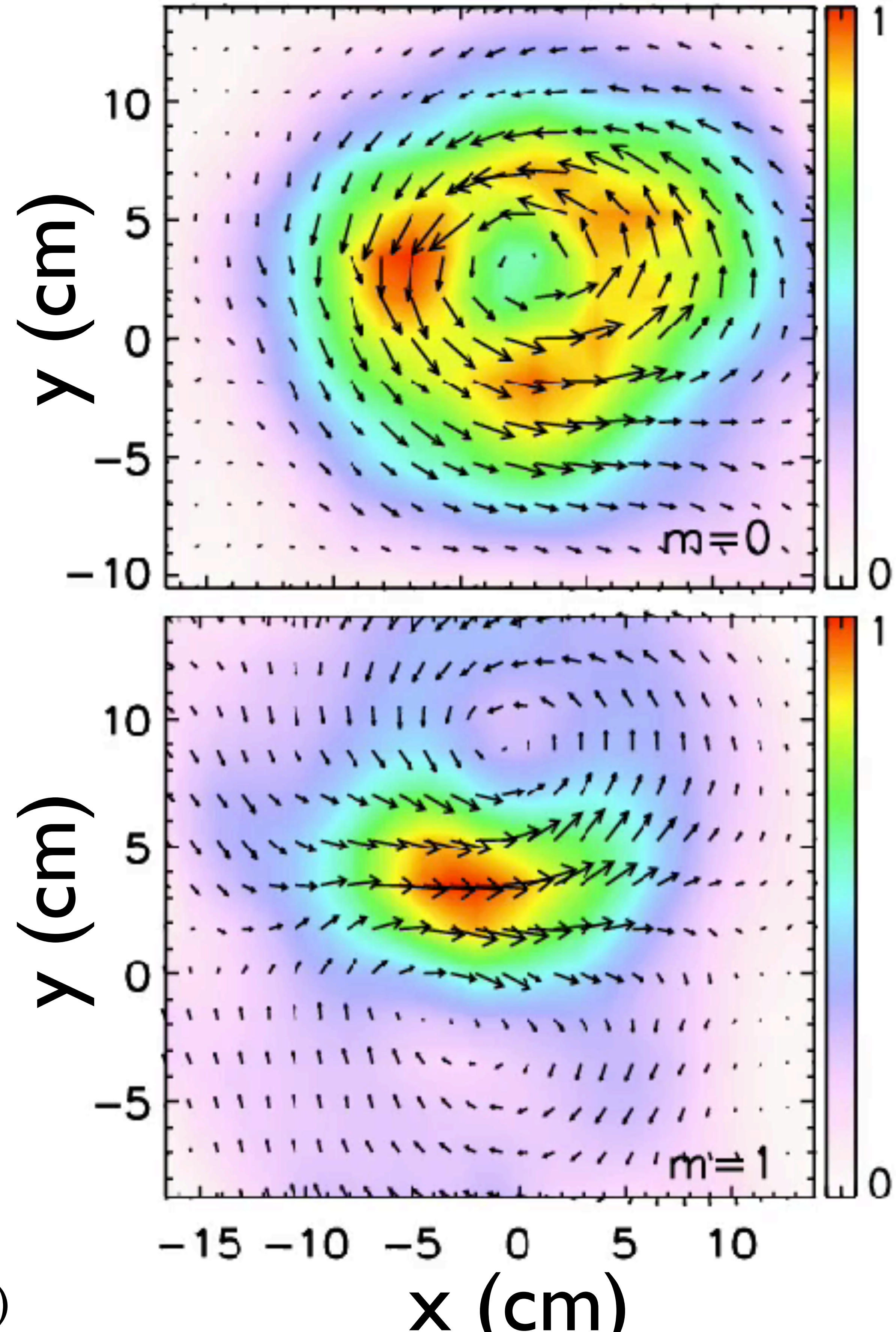
- Questions raised: what sets shape of spectrum (power law observed, close to Komolgorov); how is energy dissipated
- Motivates laboratory study of wave-wave interactions among Alfvén waves

# Alfvén waves in LAPD



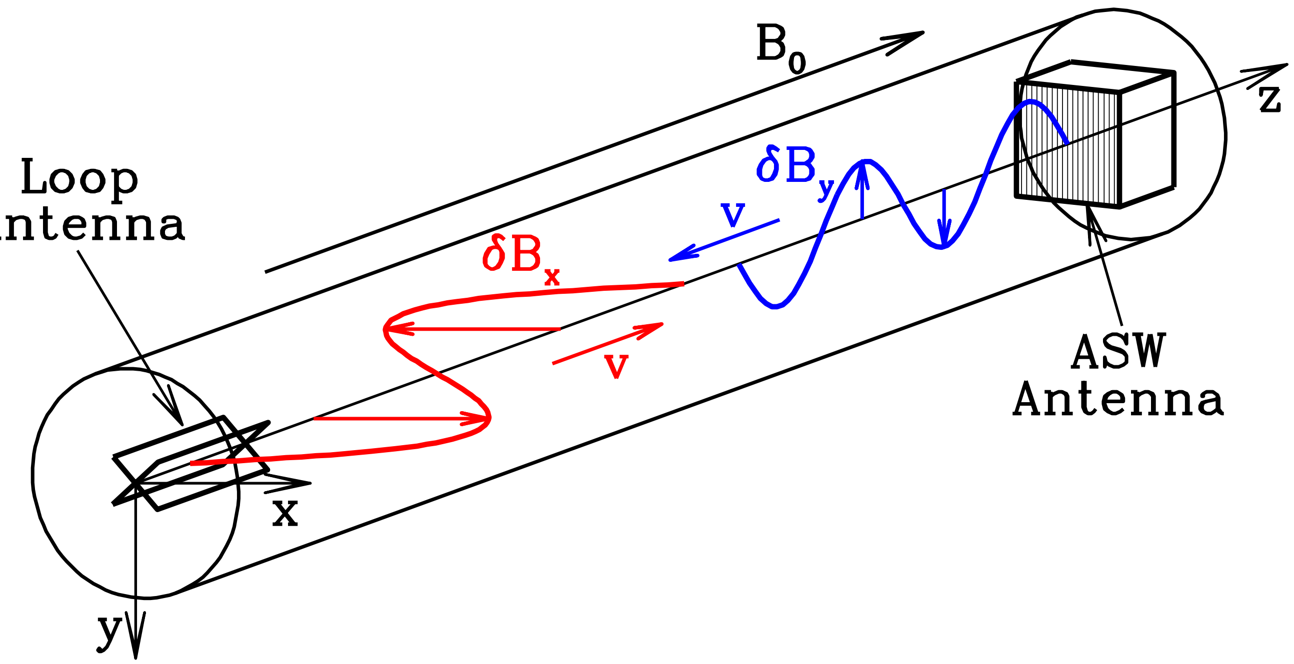
above: Alfvén wave pattern excited by “disk” antenna

right: m=0 and m=1 cylindrical Alfvén eigenmodes



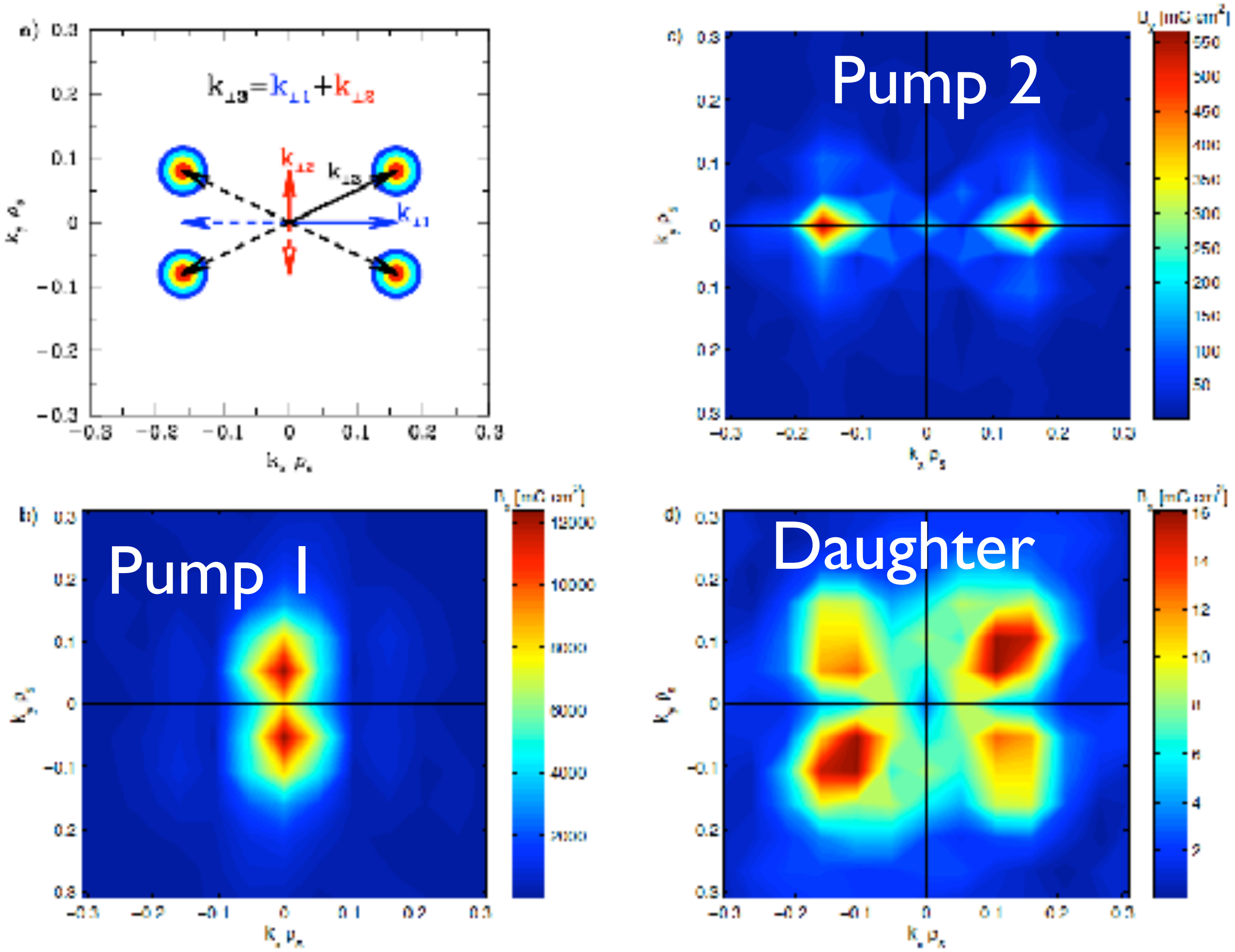

Review: Gekelman et al., Phys. Plasmas, 18, 055501 (2011)

# LAPD experiments: collision of counter-propagating Alfvén waves




- Collision of counter-propagating expected to produce cascade (Ideal MHD prediction, e.g. Goldreich-Sridhar)
  - Co-propagating waves can also interact (beat-wave drive of quasimodes [Carter 2006], sound waves [Dorfman 2012, 2013])
- Relevant to "weak" turbulence theories (daughter wave small compared to pump waves, need many collisions to cascade)

# First laboratory observation of daughter AW production: consistent with weak turbulence theory




Howes et al., PRL 109, 255001 (2012)

Drake et al., PoP 20, 072901 (2013)

- Wavenumber, magnitude consistent with theoretical predictions (can be used to validate weak turbulence predictions of power law exponent)
- Future work: variation of NL interaction with scale, dissipation, strong turbulence/production of cascade?

# Summary

- **How to keep a magnetic bottle from leaking?**: In fusion plasmas turbulent leakage of heat and particles is a key issue. Sheared flow can reduce this leak.
- **How do you feed a black hole?**: Collisional accretion ineffective in hot plasmas; Alfvénic turbulence can explain transport and heating in disks. Laboratory experiments investigate the energy cascade in Alfvénic turbulence.