Understanding Plasmas Turbulence and Transport using the Laboratory Magnetosphere

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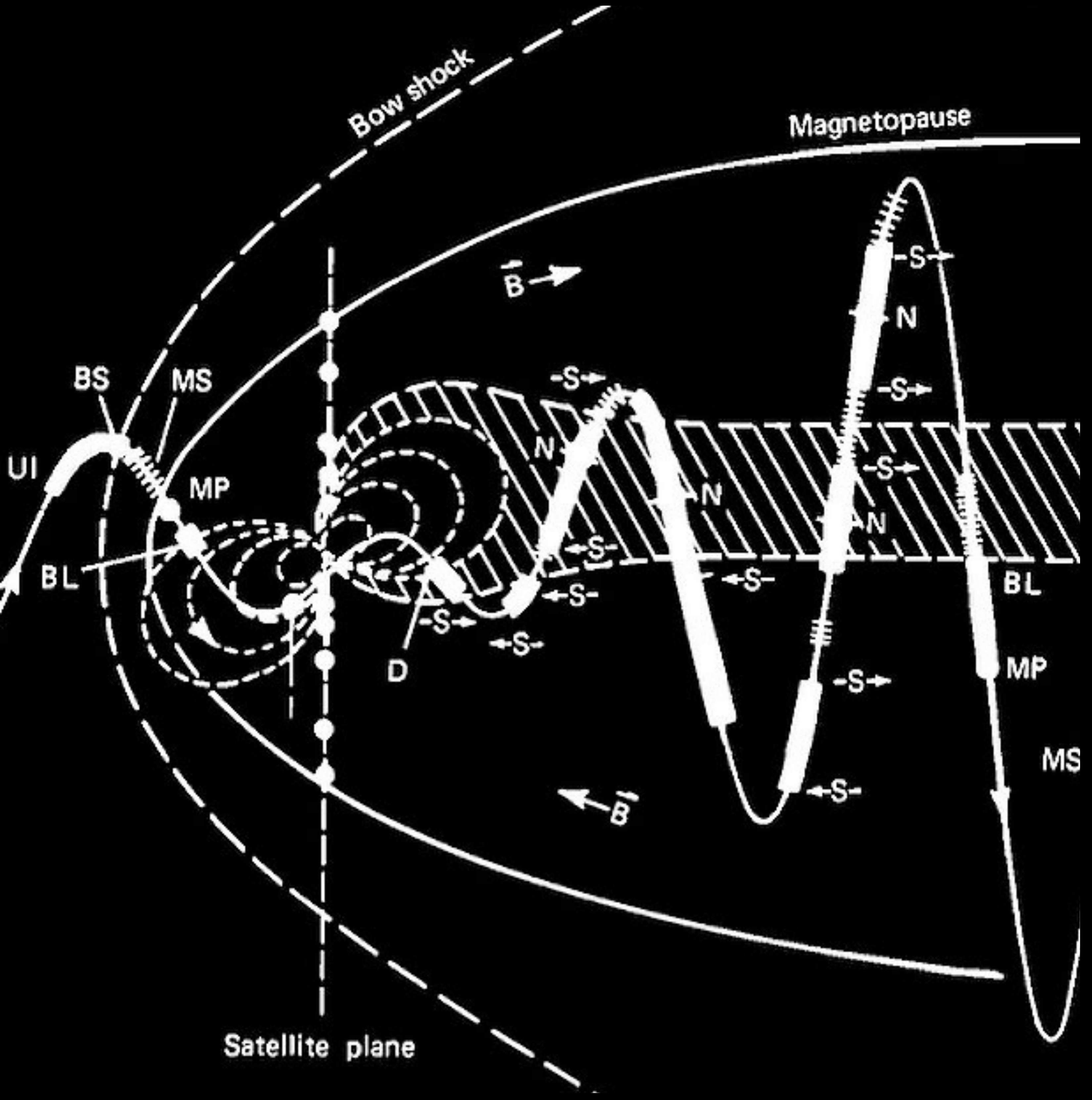
Columbia University

representing results from Darren Garnier, Jay Kesner, Masaki Nishiura, Barrett Rogers, Zensho Yoshida, and the students and scientists conducting research in support of the CTX, LDX, and RT-1 Laboratory Magnetospheres

10th International Nonlinear Wave and Chaos Workshop – NWCW17
March 20-24, 2017 • La Jolla, CA

Akira Hasegawa invited to Voyager 2’s encounter with Uranus

January 24, 1986



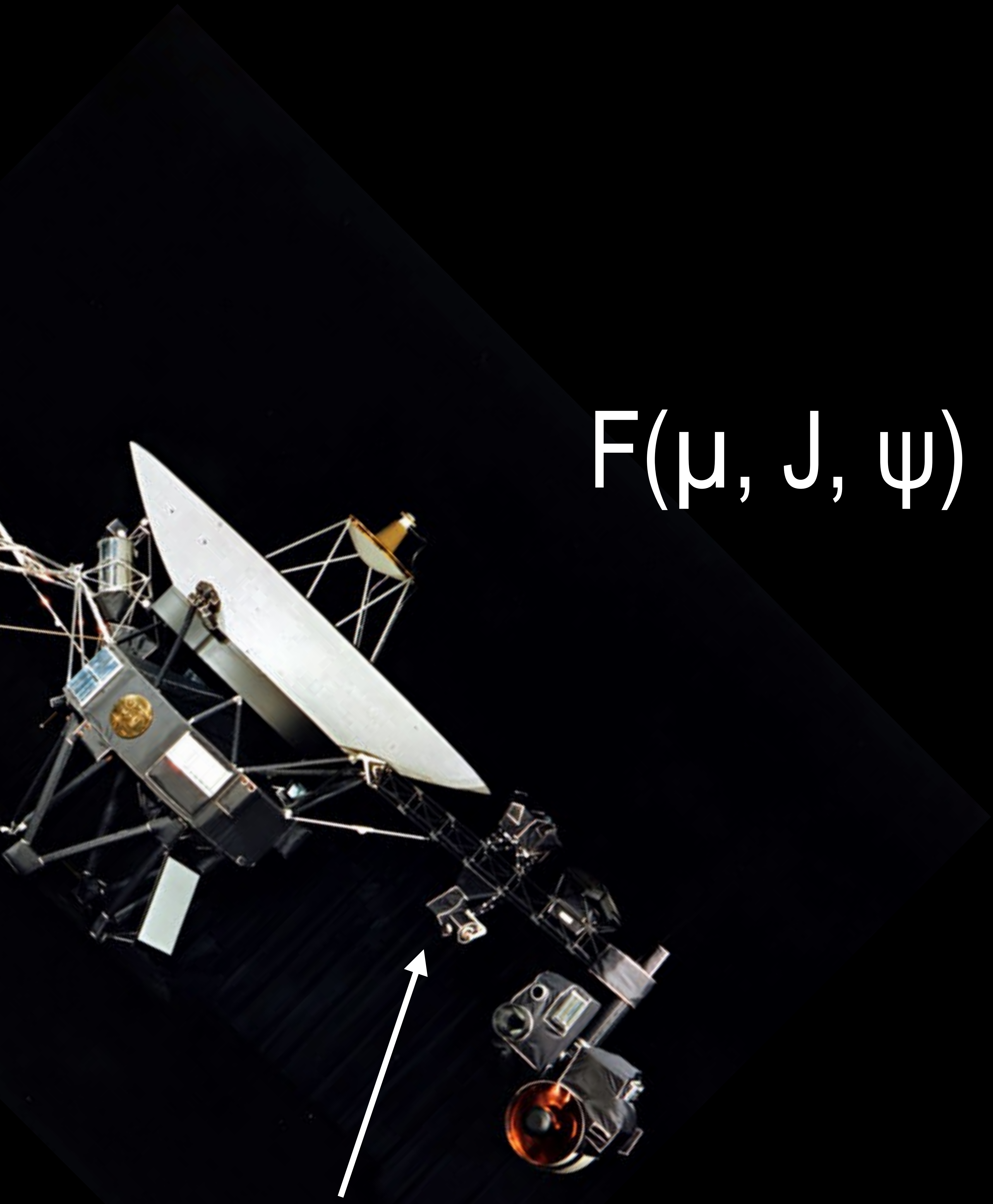
12 Hour Flyby

10 Newly Discovered Moons
Large, Tilted Magnetosphere
Long, Twisted Magnetotail
Substorm Injection
Inward diffusion and convection
Energetic Particles
Centrally-peaked Profiles
Plasma - Moon Interactions
…

Ed Stone, *JGR* **92**, 14,873 (1987)

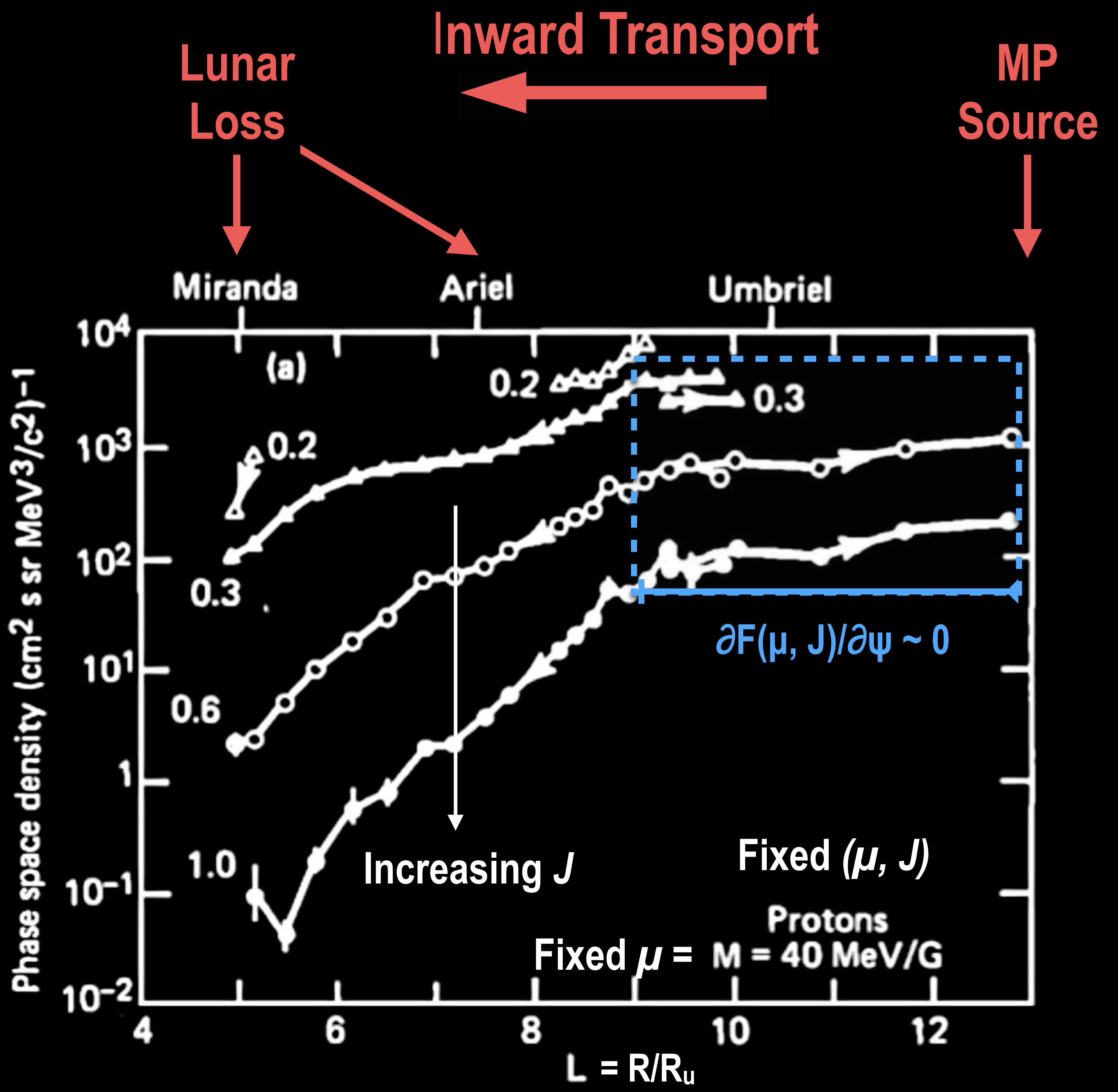
Akira Hasegawa (Alfvén Prize 2011)

Inward Transport of Energetic Particles



$F(\mu, J, \psi)$

Low-Energy-Charged Particles (LECP)
Protons: 10 keV – 150 MeV



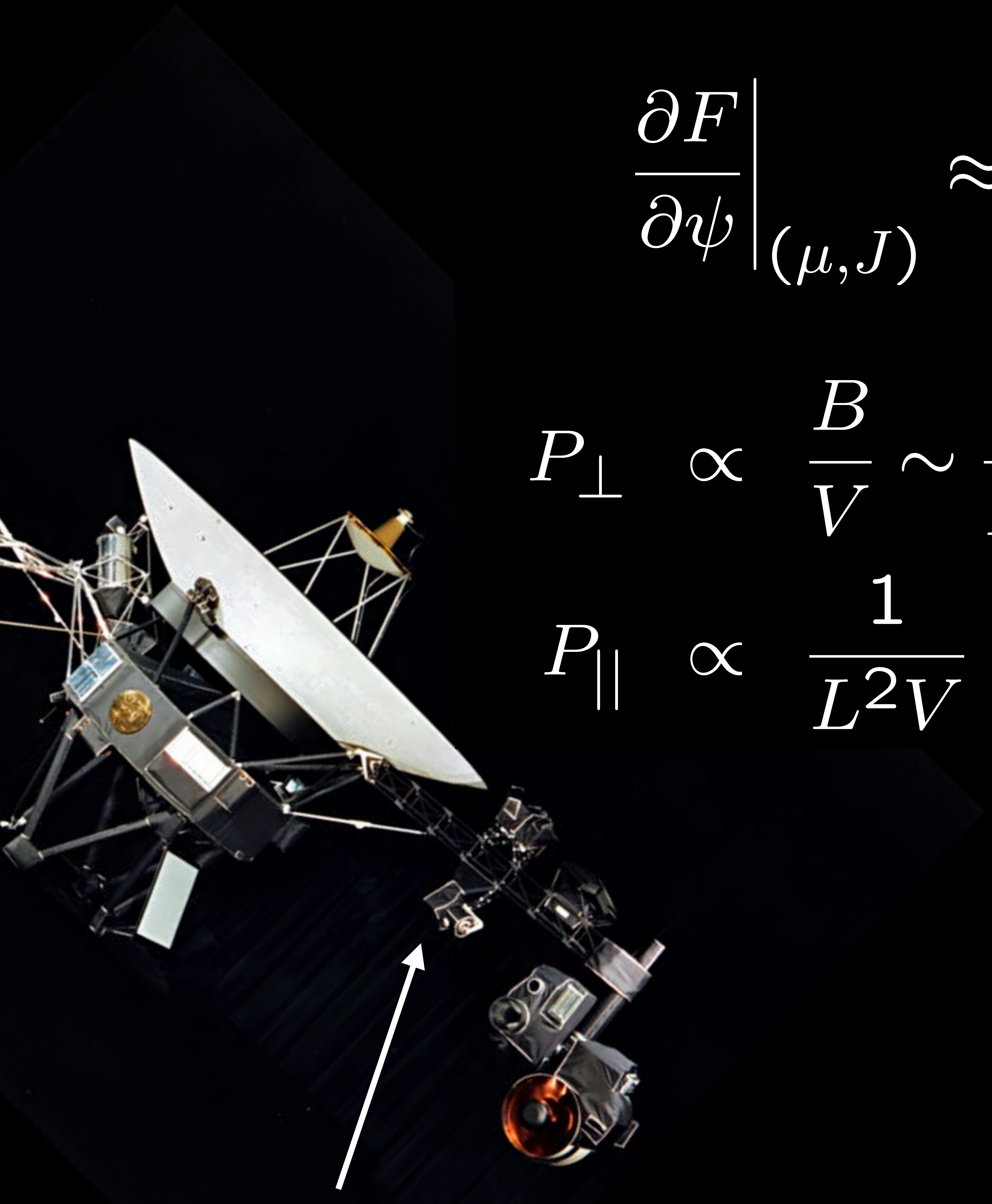
Chen, *et al.*, *JGR* **92**, 15,315 (1987)

Inward Transport Creates Centrally-Peaked Pressure

$$\left.\frac{\partial F}{\partial \psi}\right|_{(\mu,J)} \approx 0$$

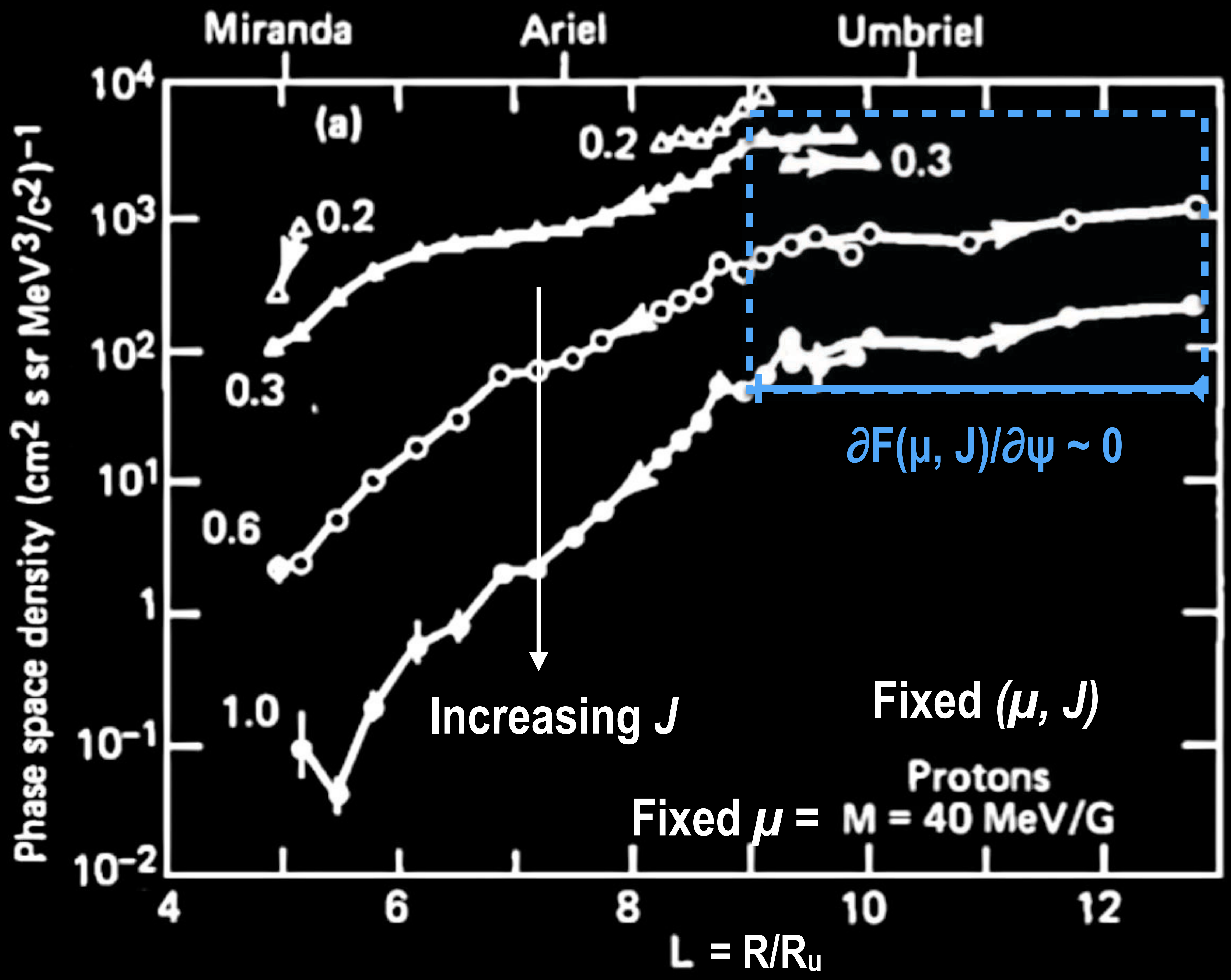
$$P_\perp \propto \frac{B}{V} \sim \frac{1}{L^7}$$

$$P_{||} \propto \frac{1}{L^2 V} \sim \frac{1}{L^6}$$



Low-Energy-Charged Particles (LECP)
Protons: 10 keV – 150 MeV

Inward transport of magnetospheric plasma *compresses* and *heats*…



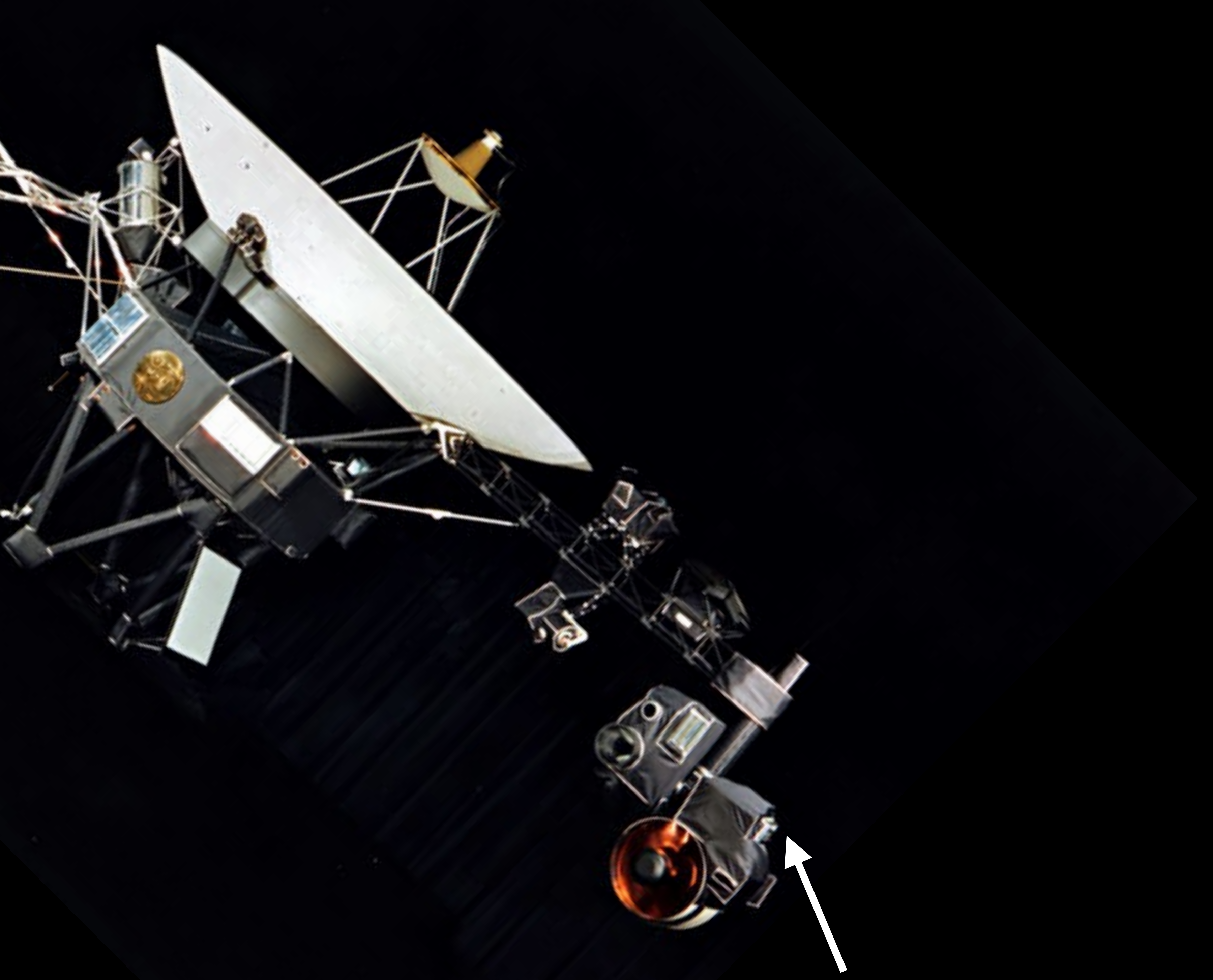
Chen, *et al.*, *JGR* **92**, 15,315 (1987)

Convection of Thermal Plasma Creates Regions with Constant Flux-Tube Content and Invariant Temperature

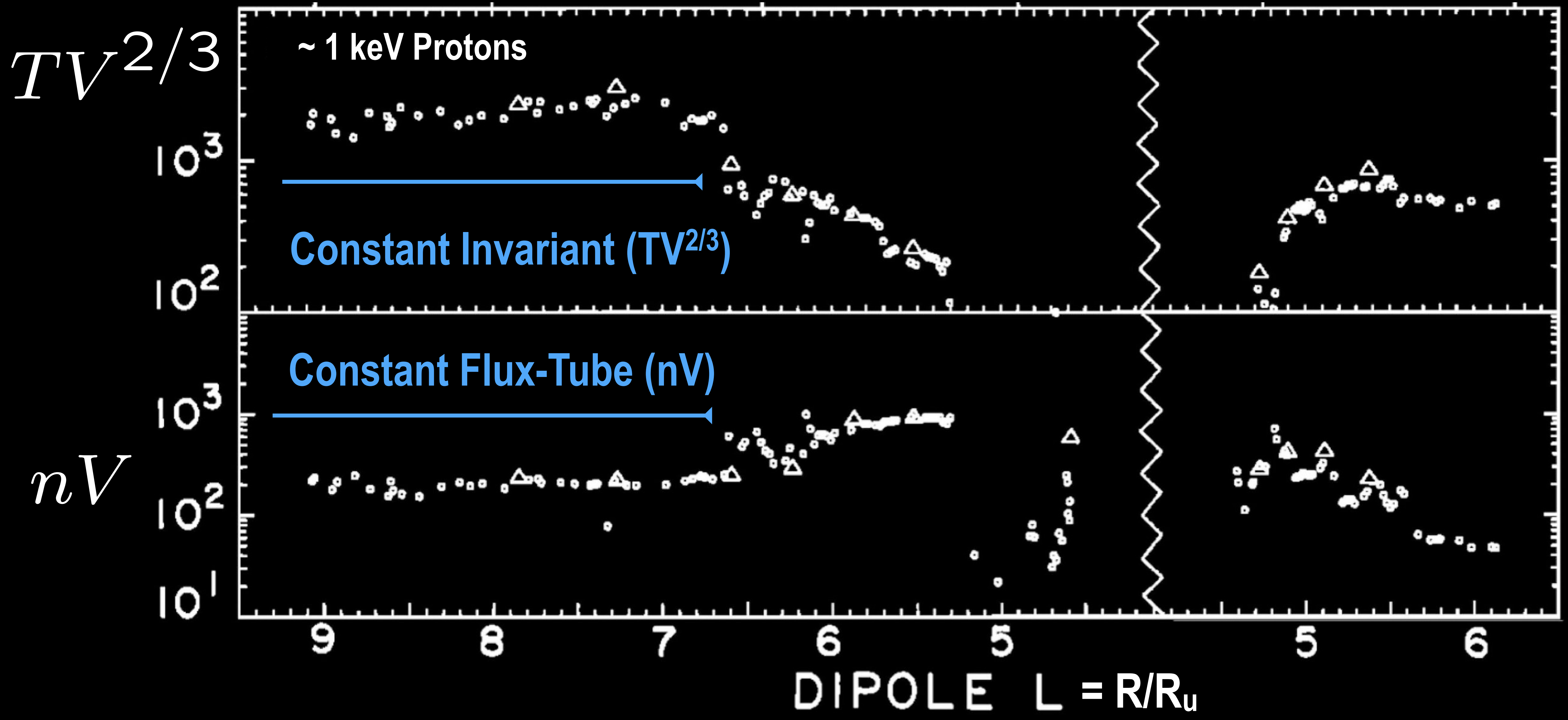
$$\Delta(nV) \approx 0$$

$$\Delta(TV^{2/3}) \approx 0$$

Flux-tube Volume = $V = \int \frac{dl}{B} \propto L^4$



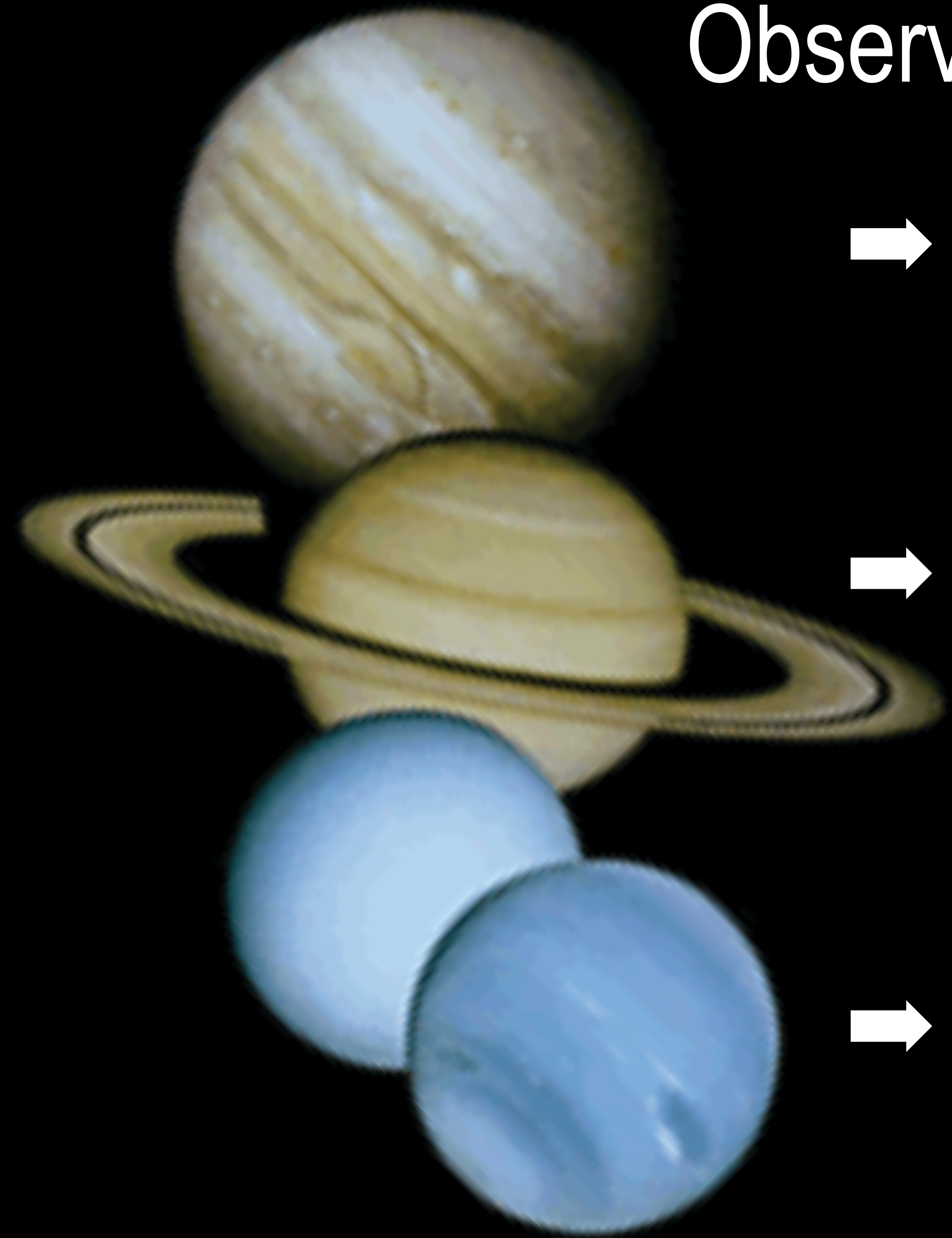
Plasma Science Experiment (PLS)
Ions and Electrons: 10 eV – 5.9 keV



Selesnick and McNutt, *JGR* **92**, 15,249 (1987)

Magnetospheres are Nature's Laboratories for Magnetic Confinement Physics

Voyager 2 Encounters: Jupiter (1979), Saturn (1981), Uranus (1986), Neptune (1989)



Observations of magnetospheric radial transport and stability…

➡ Inward transport of energetic particles preserve (μ, J) creating ***centrally-peaked pressure***

➡ Interchange motion of thermal plasma preserves flux-tube content (**$n V$**) and invariant temperature (**$T V^{2/3}$**) creating ***centrally peaked profiles***

➡ Marginally stable profiles $\Delta(P V^{5/3}) \sim 0$ ***at high beta***, $\beta \geq 1$

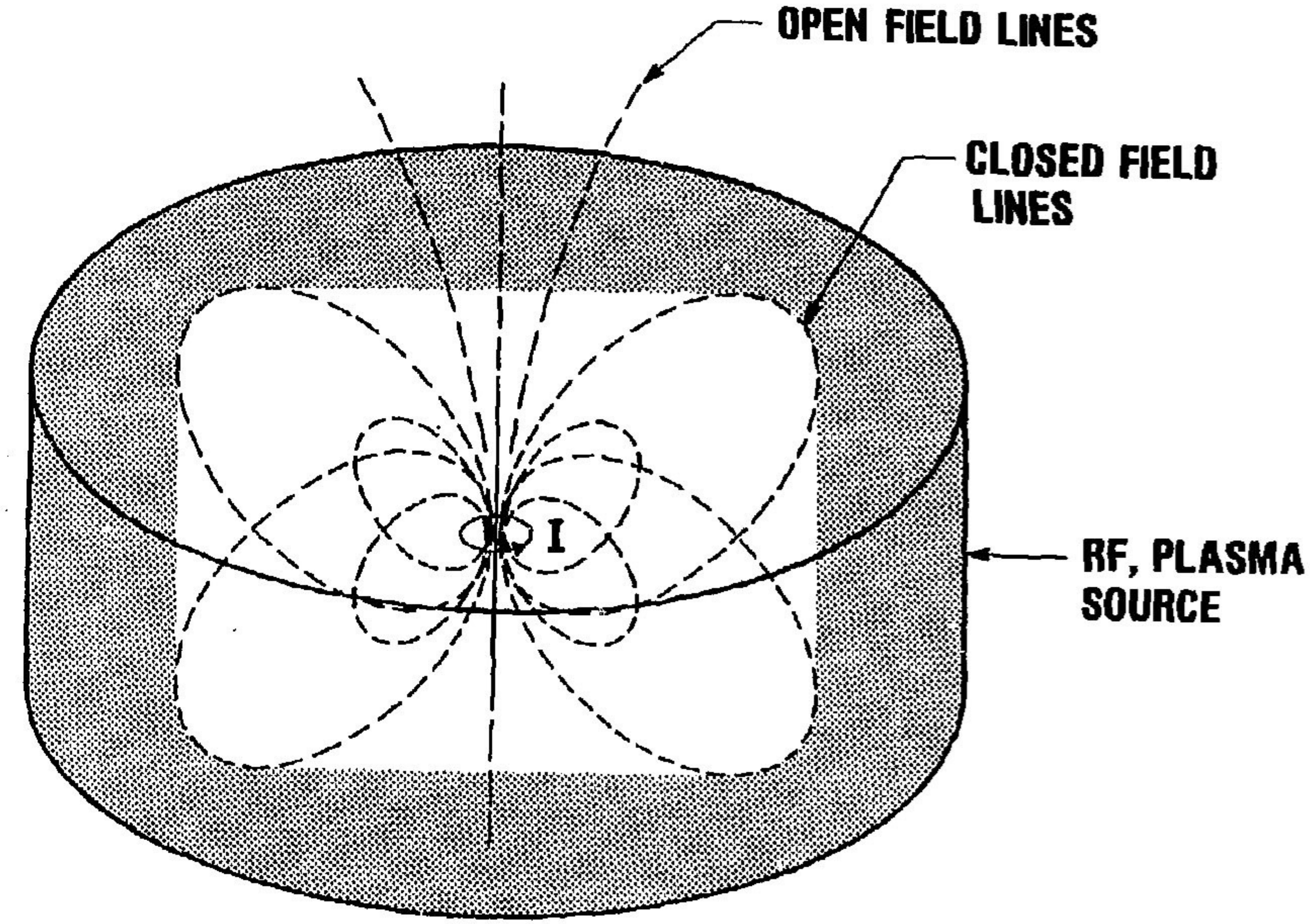
Stone and Lane, *Science*, **206**, 925 (1979)
Stone, *JGR* **88**, 8639 (1983)

Stone, *JGR* **92**, 14,873 (1987)
Stone and Miner, *Science*, **246**, 1417 (1989)

Akira Hasegawa (Alfvén Prize 2011)

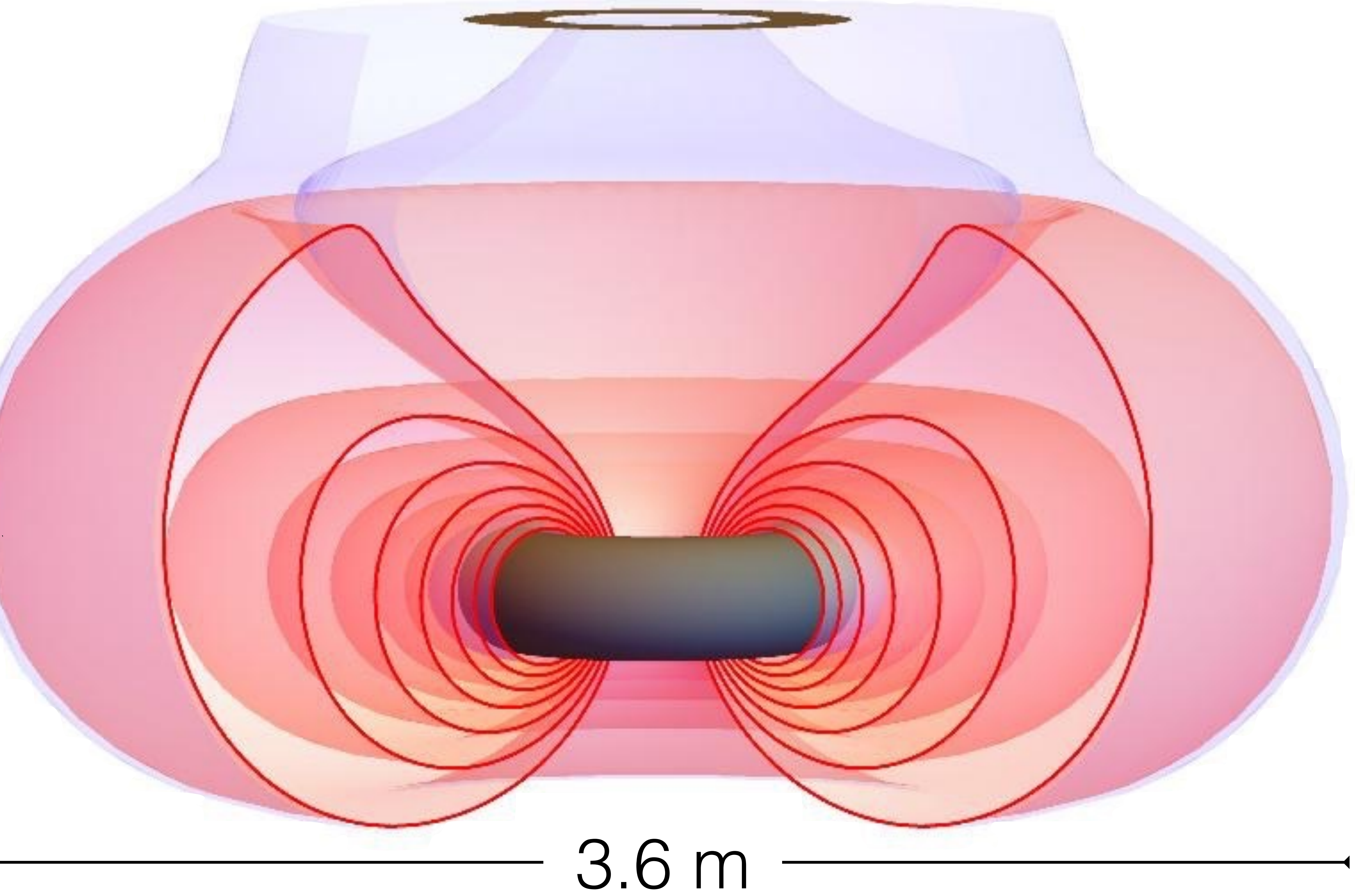
Does magnetospheric physics apply to magnetic confinement in the laboratory?

- ***Levitate*** a small, high-current superconducting current ring within a very large vacuum vessel
- ***Inject*** heating power and a source of plasma particles at outer edge (SOL)
- ***Somehow drive*** low-frequency fluctuations that create radial transport, preserve (μ, J), and sustain "centrally-peaked" profiles at marginal stability
- ***Achieve*** high beta, $\beta \geq 1$, steady-state, and link space and fusion studies



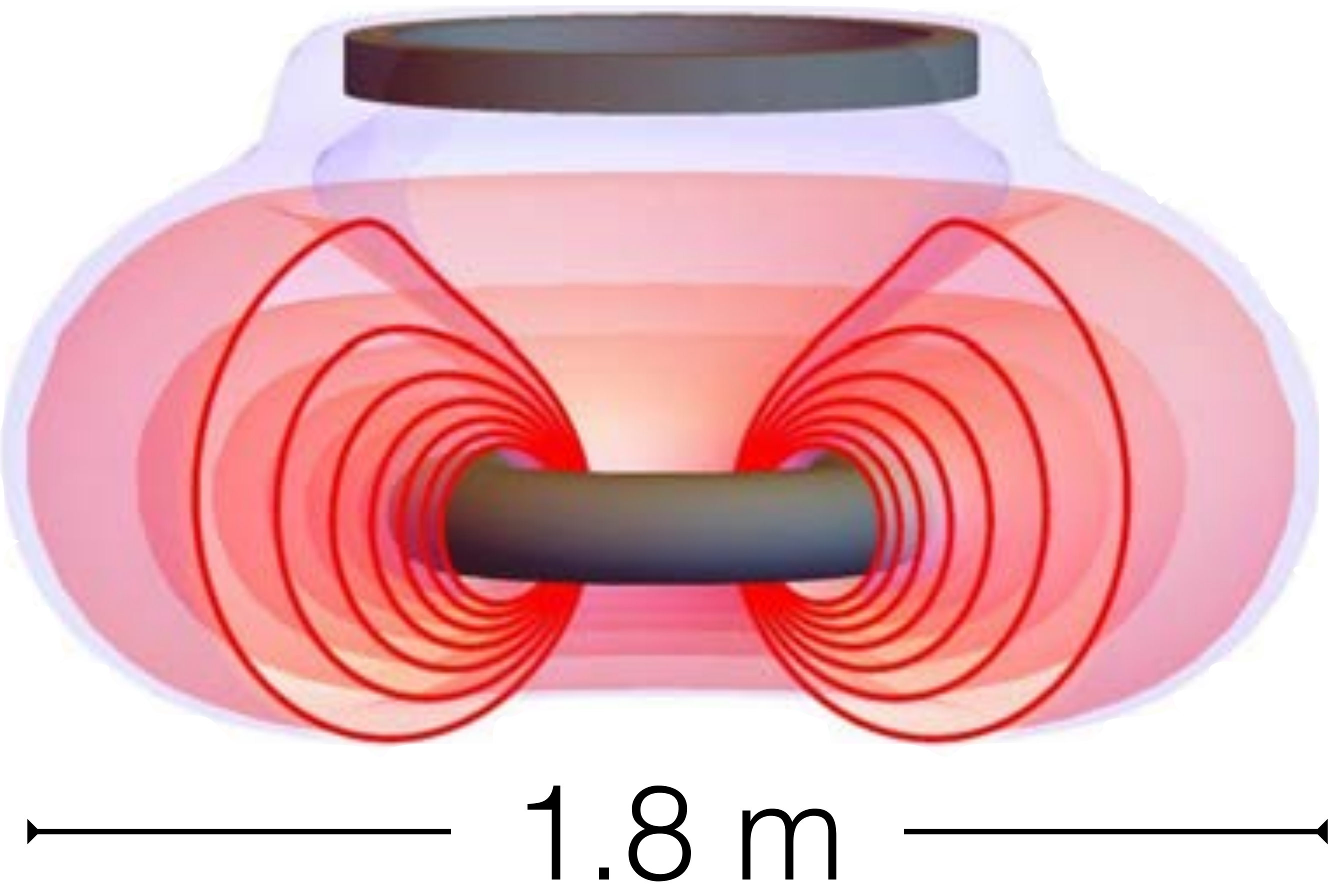
Akira Hasegawa, *Comments on Plasma Physics and Controlled Fusion* **11**, 147 (1987)

Laboratory Magnetospheres



Levitated Dipole Experiment (LDX)

(1.2 MA · 0.41 MA m^2 · 550 kJ · 565 kg)
Nb$_3$Sn · 3 Hours Float Time
24 kW ECRH



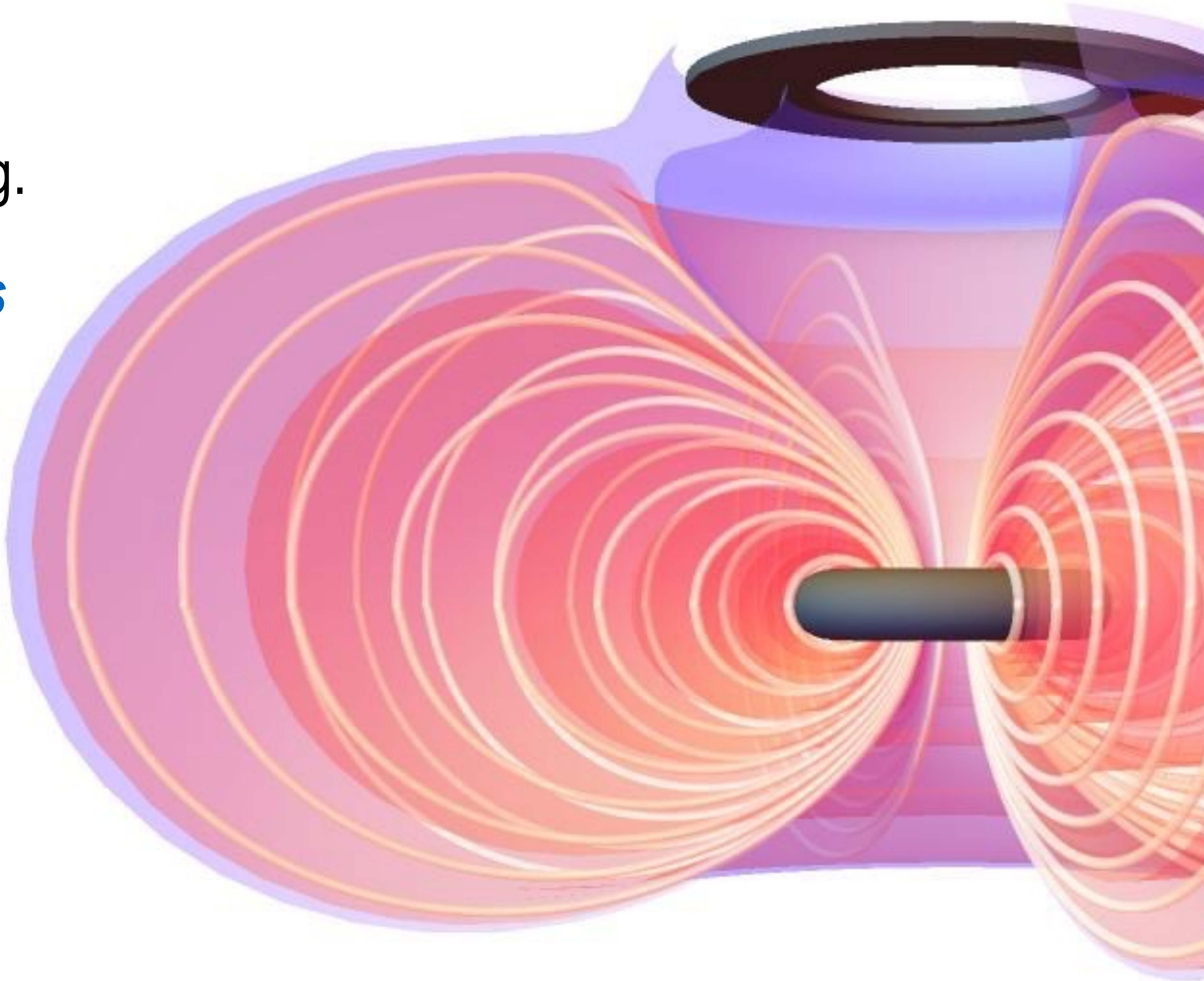
Ring Trap 1 (RT-1)

(0.25 MA · 0.17 MA m^2 · 22 kJ · 112 kg)
Bi-2223 · 6 Hours Float Time
50 kW ECRH

LDX (MIT/Columbia)

RT-1 (U Tokyo)

During the past decade, LDX and RT-1 have shown the physics of magnetospheric radial transport and stability ***does apply to the laboratory***



- ***Levitation is robust and reliable***

  Very good ***access*** for diagnostics, plasma heating and fueling.

- ***Simple, axisymmetric torus with no field-aligned currents***

  Classical particle orbits with comparable passing and trapped dynamics .

  Good confinement of heat, density, energetic particles.

  Very high local plasma pressure, $\beta > 1$

- ***Radial transport processes*** relevant to space and to many toroidal confinement devices.

- ***Quasilinear drift-kinetics & nonlinear gyro-kinetics are good models for understanding*** turbulent radial transport in the laboratory magnetosphere.

Comparing Laboratory and Planetary Magnetospheres

Very large and
Unlike any other ***laboratory*** plasma; with $\omega_d \sim \omega^*$

Low-frequency ($\omega \sim m\omega_d$)

Internally driven interchange/entropy instabilities
←

Externally driven by solar wind
→

High-frequency ($\omega \sim n\omega_c$)

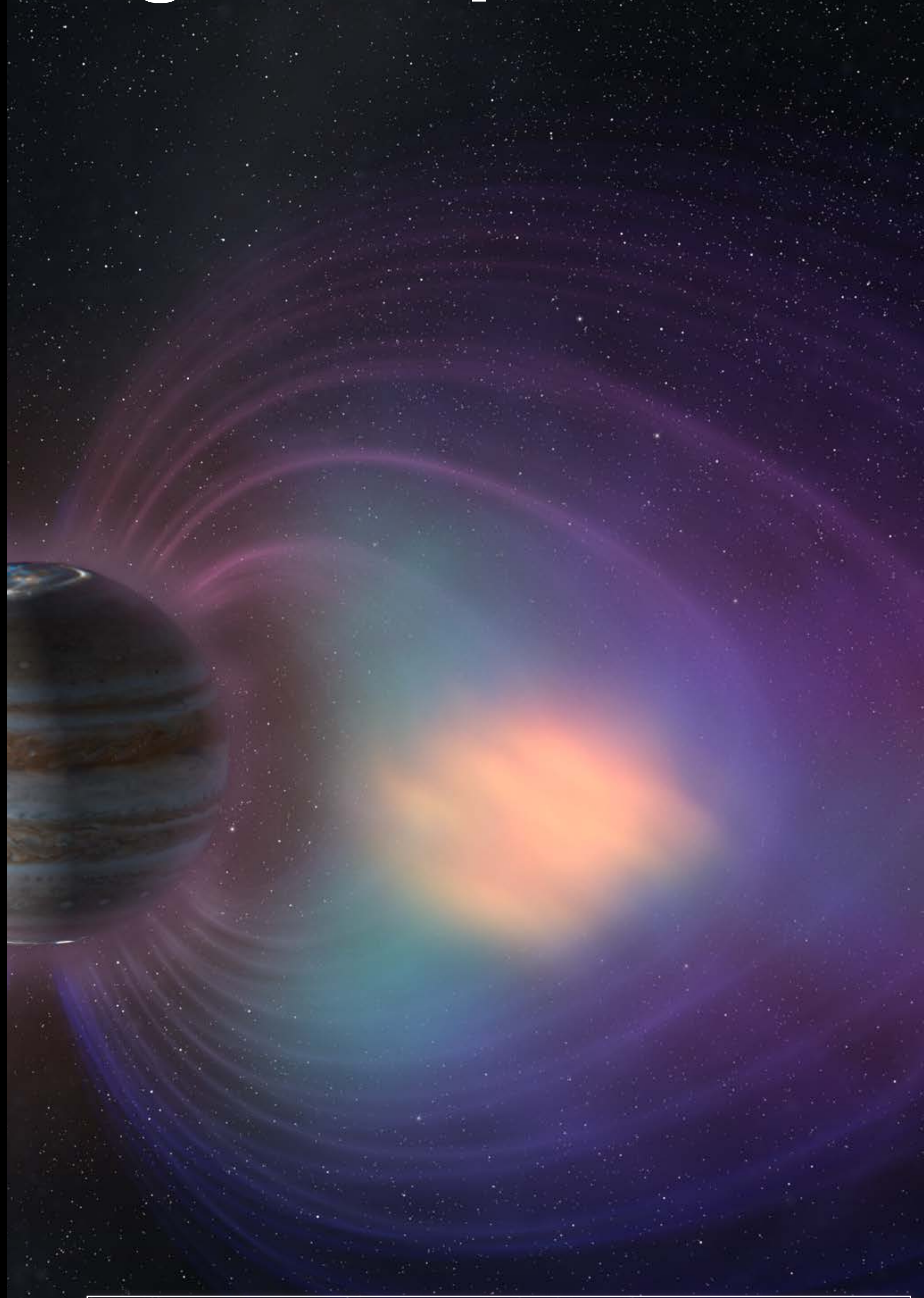
Externally driven by applied µwave power
←

Internally driven by plasma chorus
→

Ionosphere?

*No**
←

Yes
→



(Very very ***gigantic*** magnetized plasma!)

Nonlinear Wave Physics

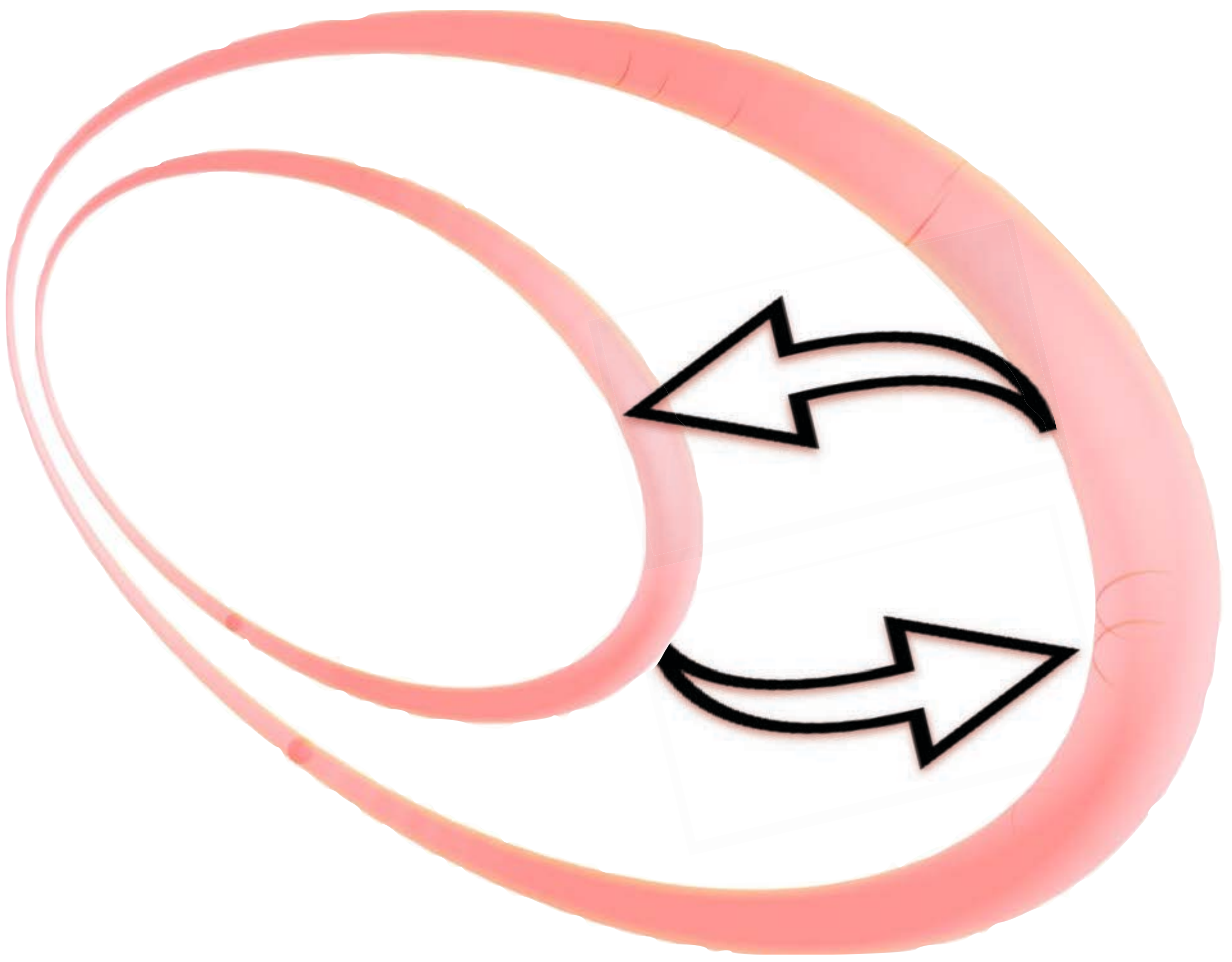
- ➡ **Turbulent inward pinch:** low-frequency interchange/entropy mode turbulence, electrostatic particle transport in semi-collisional plasma $P_\perp \sim P_{||}$, turbulent relaxation to “stationary” centrally-peaked profiles, inverse cascade, chaotic global mode dynamics, …
- **Record high local β > 1 with “artificial radiation belt” (energetic electrons)** and exploring electromagnetic turbulence, collisionless transport, anisotropic pressure $P_\perp > P_{||}$, …
- **Ongoing/Unsolved problems** linking space/laboratory magnetospheric physics: regulation of turbulence with “artificial ionosphere”, spectrum control and mode-mode coupling, Alfvén wave dynamics in a turbulent magnetosphere, finite ion temperature, $T_i \sim T_e$, FLR, APEX/PAX, *large high-density high-beta magnetized plasma*, …

Low-Frequency Electrostatic Turbulent Pinch

(Turbulent “Self-Organization” creates the highly peaked profiles envisioned by Hasegawa.)

$\omega \sim \omega_d \ll \omega_b$

$E_{\|} \sim 0$



$$V = \int \frac{dl}{B} \propto L^4$$

$$2\langle\kappa_\psi\rangle = -\frac{\partial}{\partial\psi}\log V$$

(Curvature Pinch)

$$\Rightarrow \Delta\,(nV) \sim 0$$

$$\text{Particle Flux} = n\,\underbrace{2D\langle\kappa_\psi\rangle}_{\text{inward pinch}} - \underbrace{D\,\frac{\partial n}{\partial\psi}}_{\text{diffusion}}$$

Turbulent E×B radial motion

$$D_\psi = R^2\langle E_\varphi^2\rangle\tau_c$$

$$\Rightarrow \Delta\left(PV^{5/3}\right) \sim 0$$

$$\text{Temperature Flux} \approx \frac{2}{3}T\,\underbrace{2D\langle\kappa_\psi\rangle}_{\text{inward pinch}} - \underbrace{D\,\frac{\partial T}{\partial\psi}}_{\text{diffusion}}$$

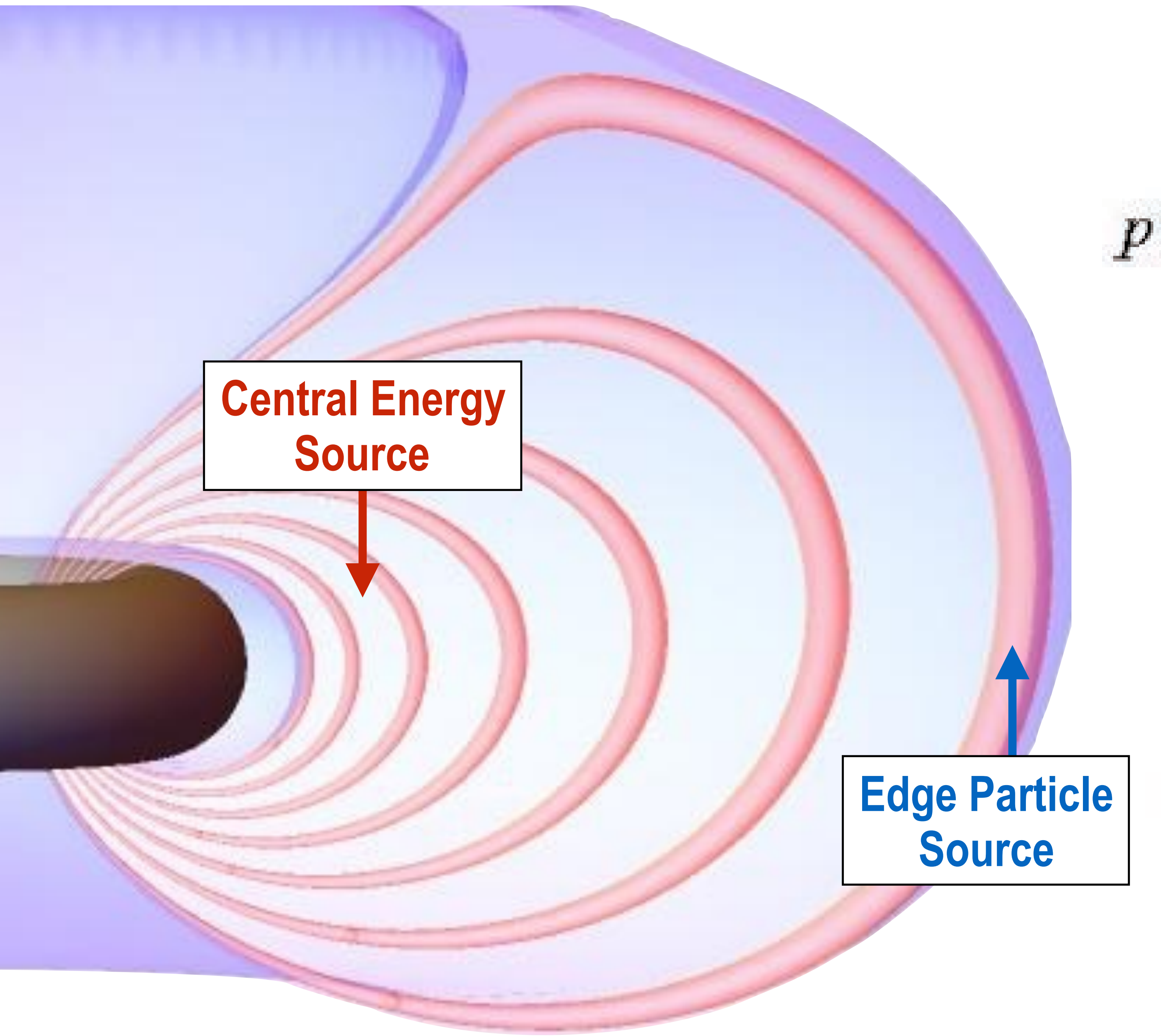
$$\boxed{\eta = \frac{\Delta \ln T}{\Delta \ln n} \Rightarrow 2/3}$$

Thomas Birmingham, “Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation,” *JGR*, **74**, (1969).
Kesner, Garnier, and Mauel, "Fluctuation driven transport and stationary profiles," *Phys Plasmas*, **18**, 050703 (2011).
Garbet, *et al.*, “Turbulent fluxes and entropy production rate,” *Phys Plasmas*, **12**, 082511 (2006).

Self-Organized Mixing: Dye Stirred in Glass

Solar wind drives radial diffusion in planetary magnetospheres, *but in the lab*…

Central heating excites instability that drives Centrally-Peaked Pressure and Density as the Final State of Turbulent Self-Organization



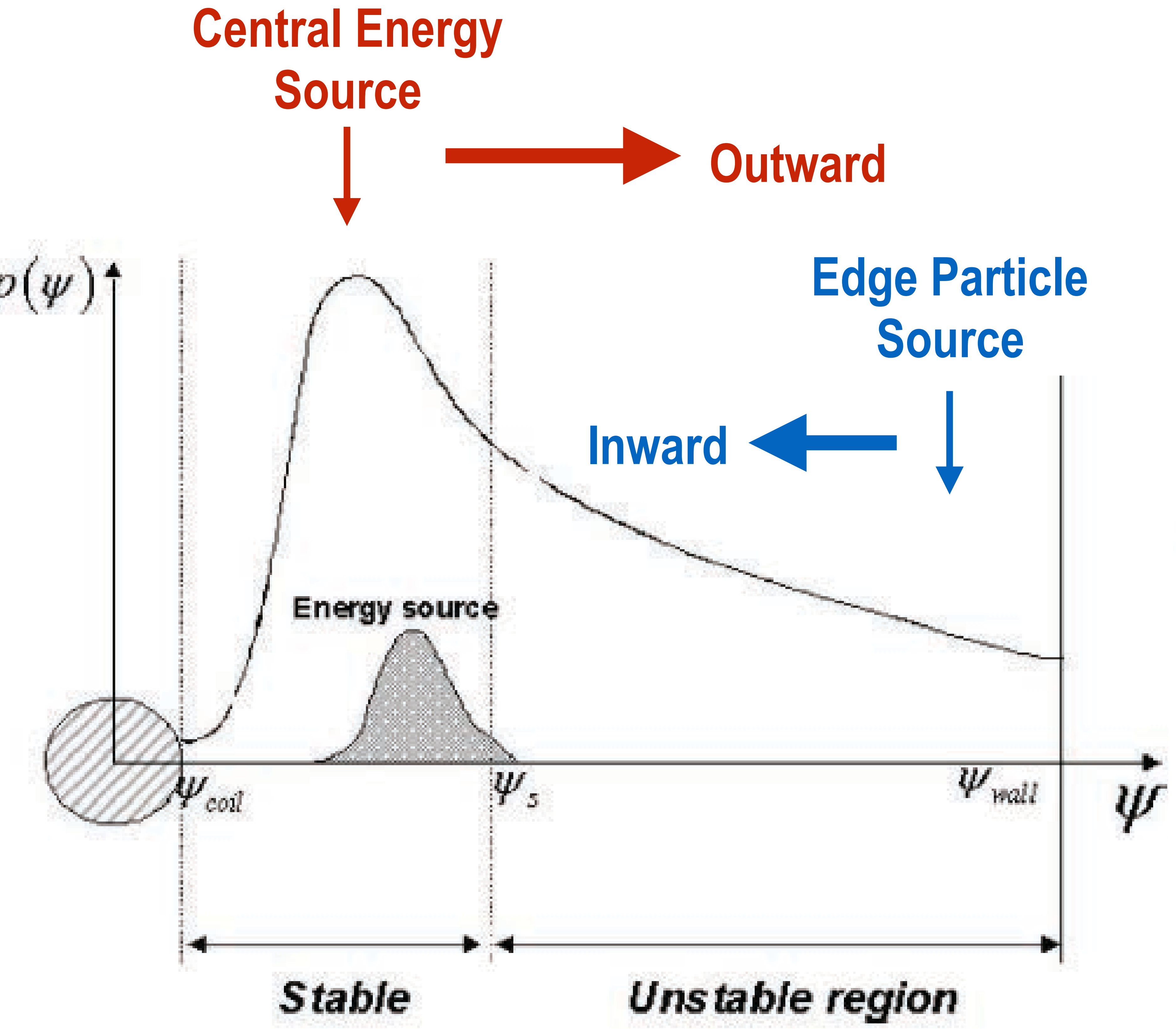


FIG. 1. The LDX schematic profile.

Quasilinear MHD Interchange Turbulence

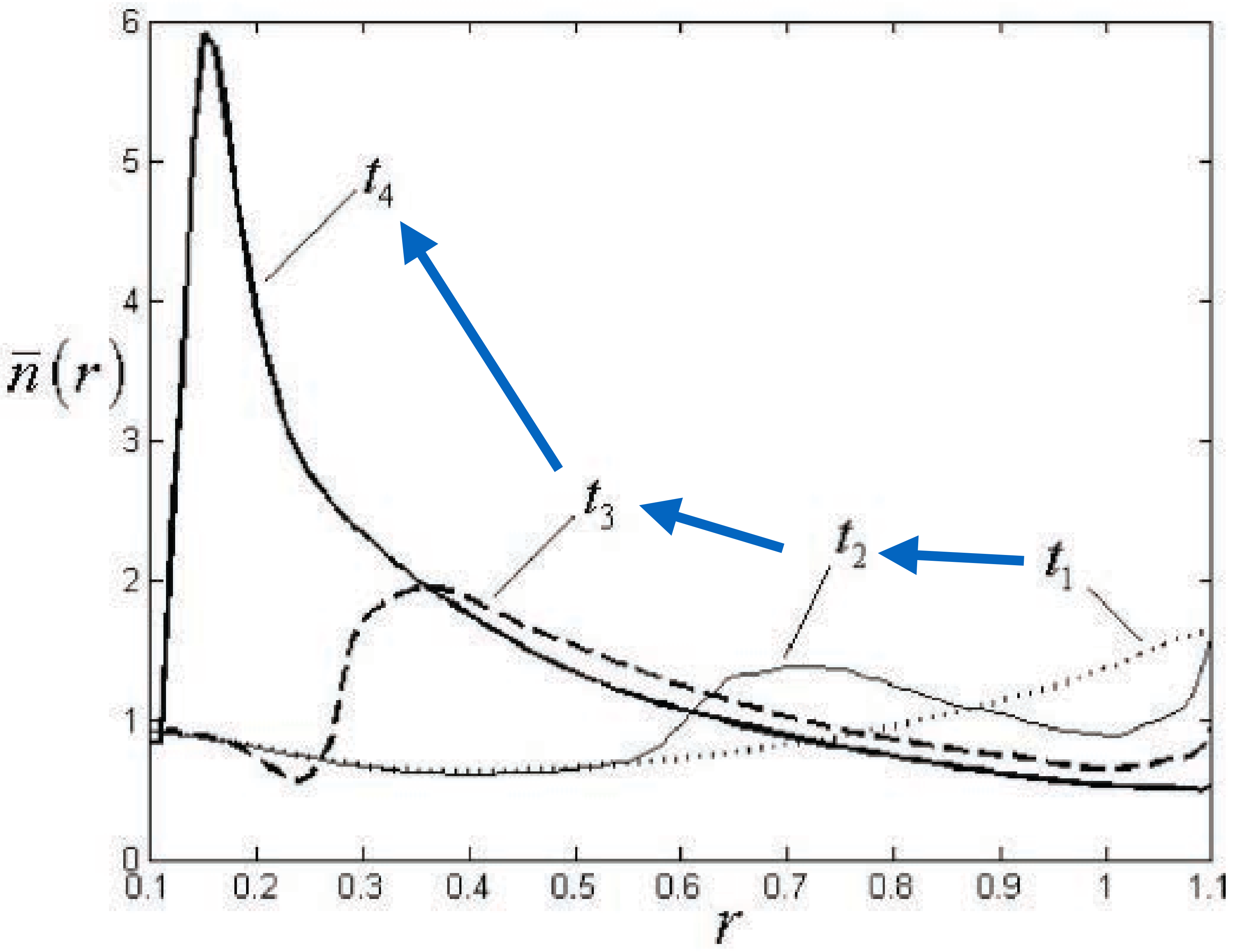
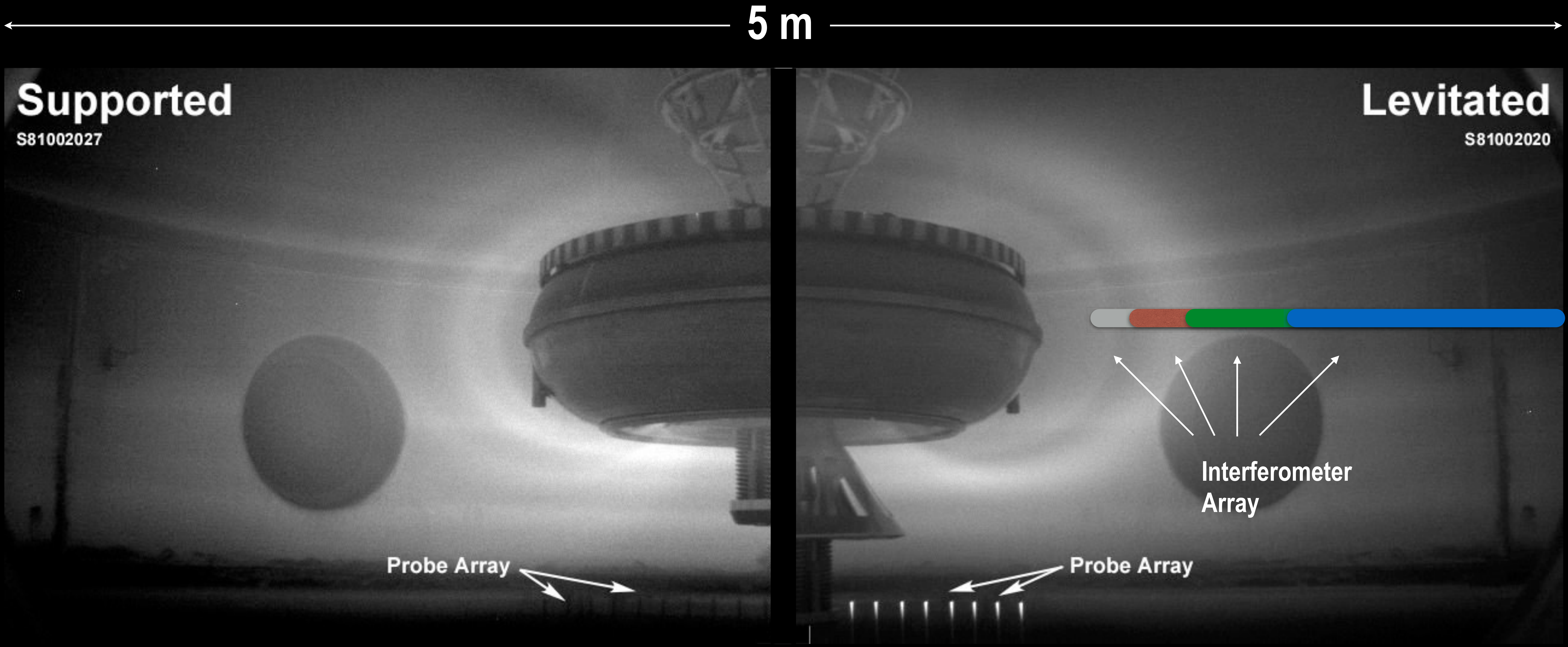


FIG. 5. The snapshots of the "self-organizations" process. Time t_1: before an instability is excited; $t_2 - t_4$: different stages of self-organization.

Alexie Kouznetsov (PhD MIT/Freidberg), *et al*, "Quasilinear theory of interchange modes in a closed field line configuration," *Phys Plasmas*, **14**, 102501 (2007)
John Tonge (PhD UCLA/Dawson), *et al.*, "Kinetic simulations of the stability of a plasma confined by the magnetic field of a current rod," *Phys Plasmas* **10**, 3475 (2003).

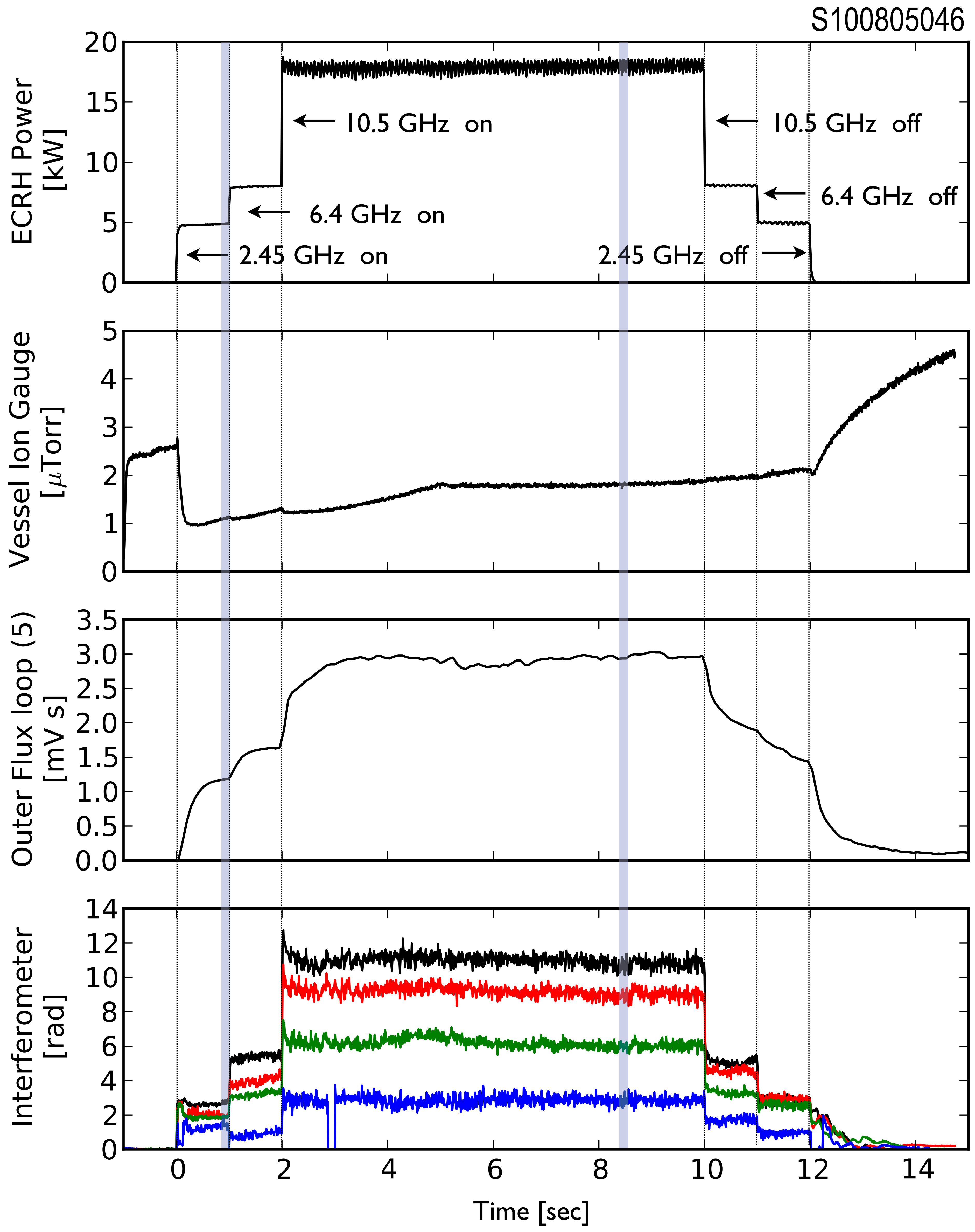
Measurements:

Density Profile *with* Interferometry
Fluctuations *with* Probes and Cameras
Pressure/Ring Current *with* Magnetics



Example Plasma Experiment

- 18 kW injected electron cyclotron waves
- Plasma energy 250 J (3 kA ring current)
- Peak β ~ 10% (>100% achieved in RT-1)
- Hydrogen gas density 4×10^{10} cm^{-3}
- Peak plasma density 10^{12} cm^{-3}
- Peak $\langle T_e \rangle > 0.5$ keV (thermal; $T_e \gg T_i$)
- Energetic electrons $\langle E \rangle \sim 50$ keV
- Density proportional to injected power
- Sustained, dynamic, "steady state"



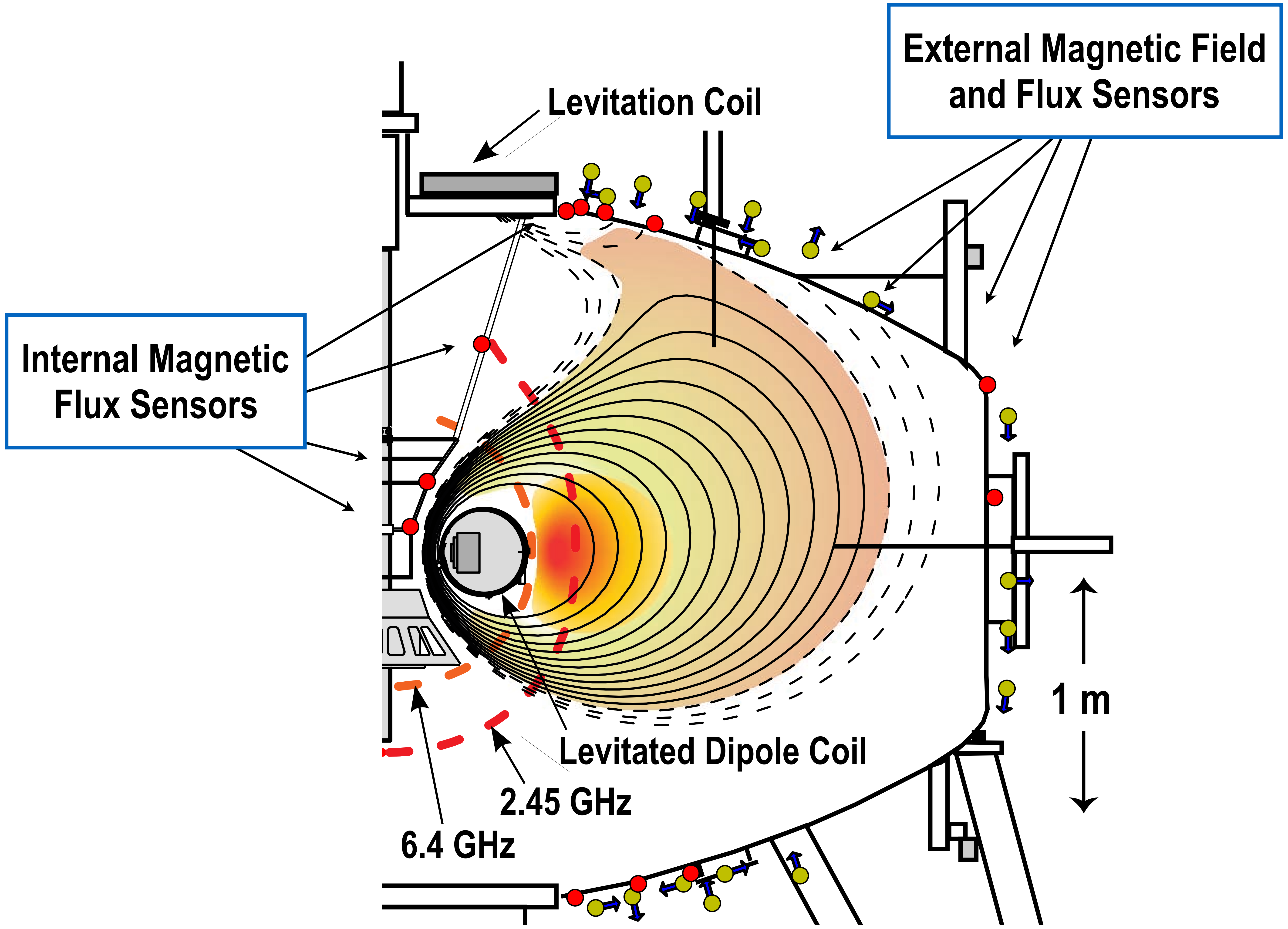
18 kW ECRH

***Actively* Controlled Neutral Pressure**

Flux from Plasma Ring Current

Plasma Line Density

Accurate Reconstruction of the Plasma Pressure from the Plasma Ring Current Requires Internal Magnetic Sensors


Internal Magnetic Flux Sensors

Levitation Coil

External Magnetic Field and Flux Sensors

Levitated Dipole Coil

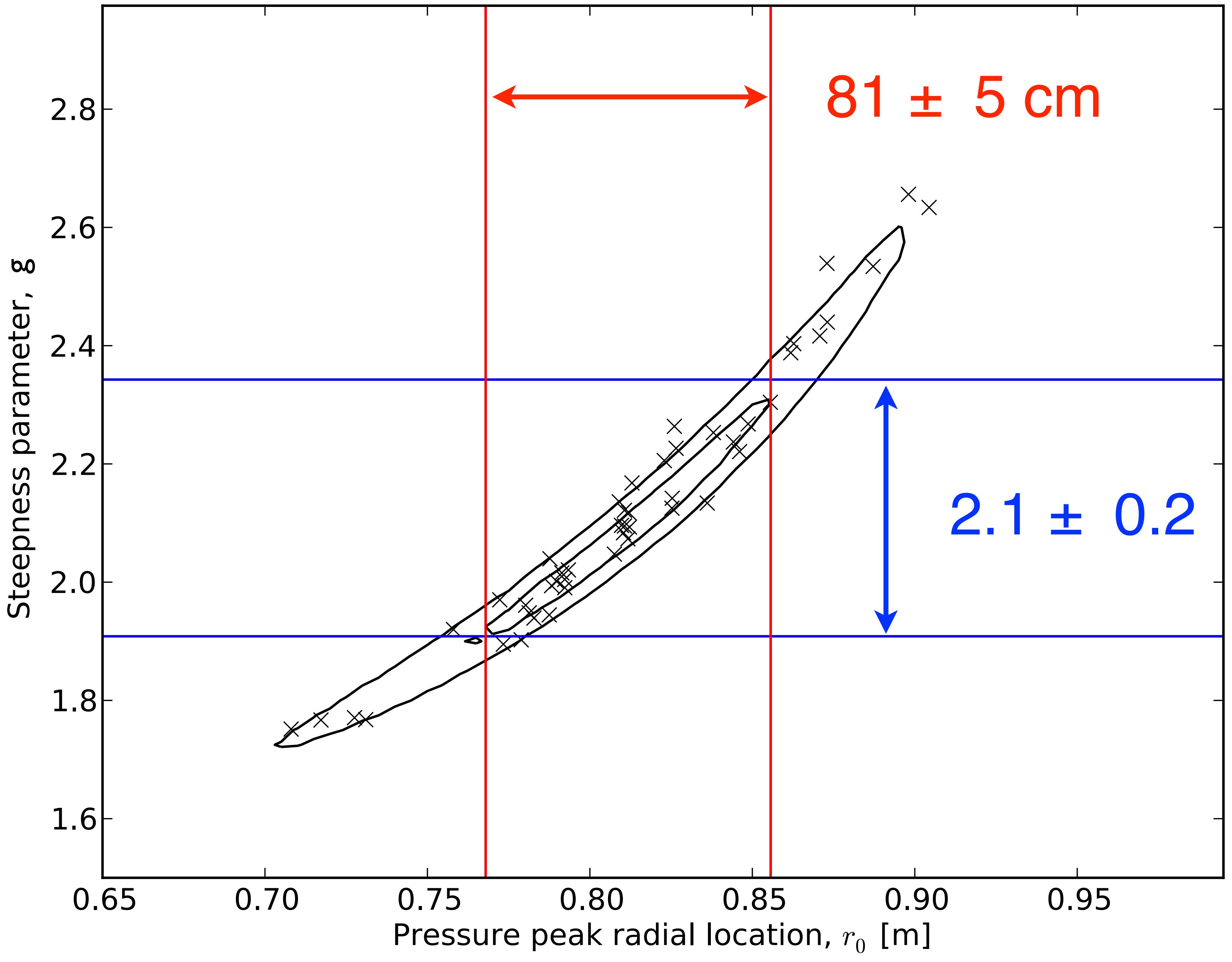
2.45 GHz

6.4 GHz

1 m

$$\mathbf{J}_\perp = \frac{\mathbf{B}\times\nabla P_\perp}{B^2} + \frac{\mathbf{B}\times\kappa}{B^2}(P \;\; - P_\perp)$$

Reconstruction Results in Very Good Accuracy of Pressure Profile



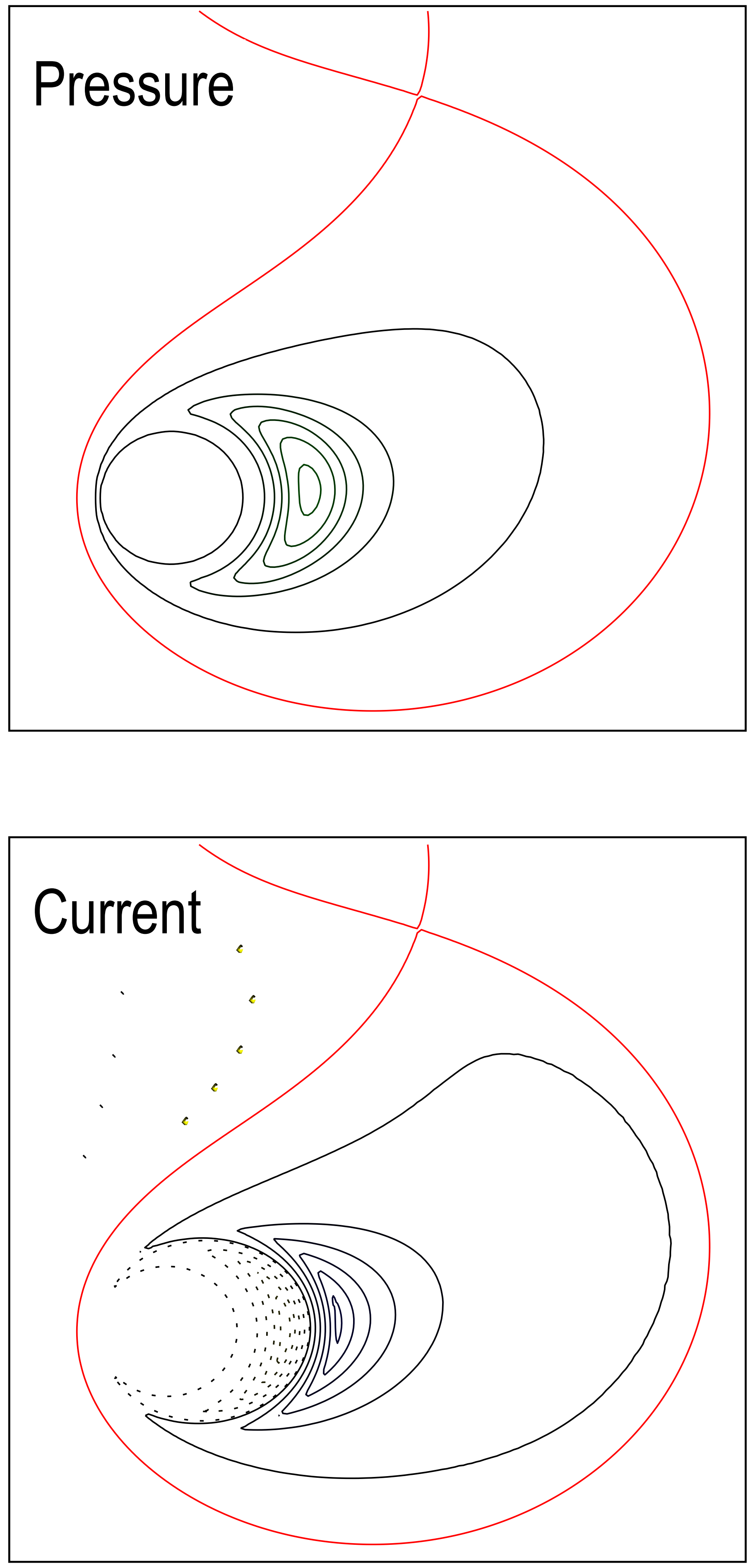
$$P_\perp \sim P_\parallel$$

Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

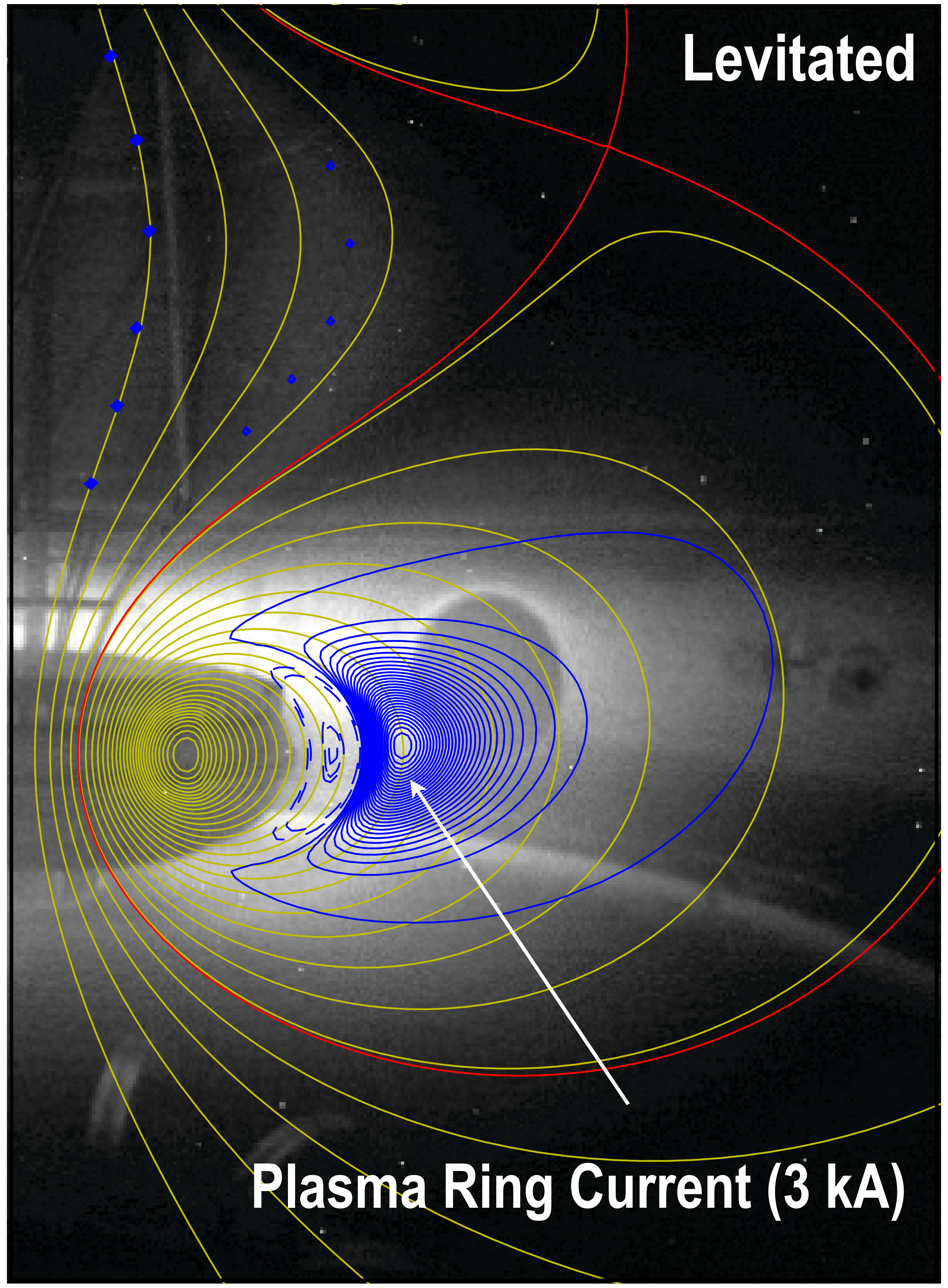
Levitated Coil: Broad Isotropic Pressure Profile

$P_{\perp} \sim P_{||}$

Levitated



Plasma Energy (270J)



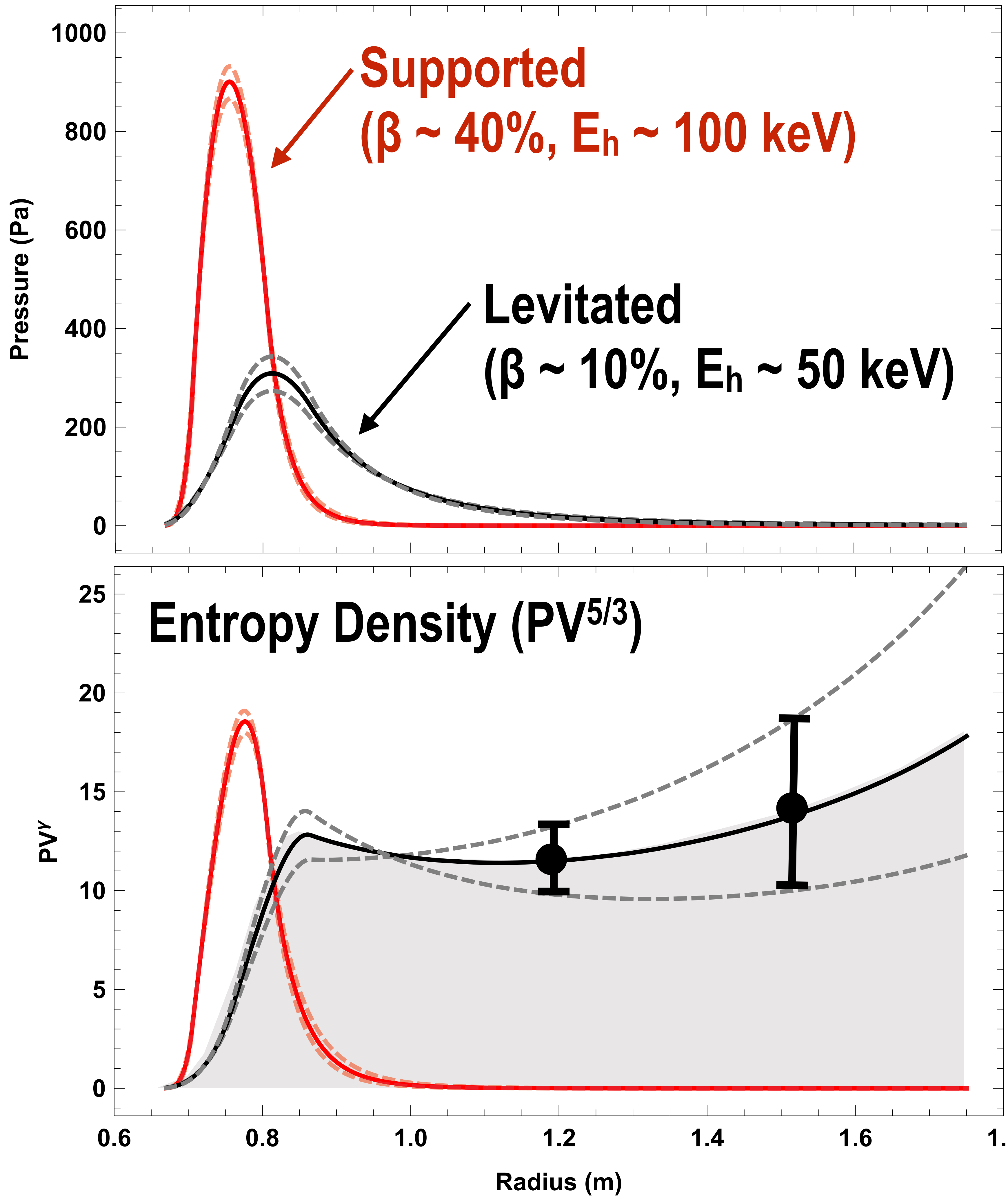
Levitated Coil: Broad Isotropic Pressure Profile
Supported Coil: Narrow Anisotropic Pressure Profile

- **Supported**:
  - High peak beta, $\beta \sim 40\%$
  - ➡ *No thermal confinement*
  - Ideal MHD ***unstable***
- **Levitated**:
  - Peak beta, $\beta \sim 10\%$
  - Broad profile and very good thermal confinement
  - Marginally ***stable*** $\Delta(PV^{5/3}) \geq 0$

!!

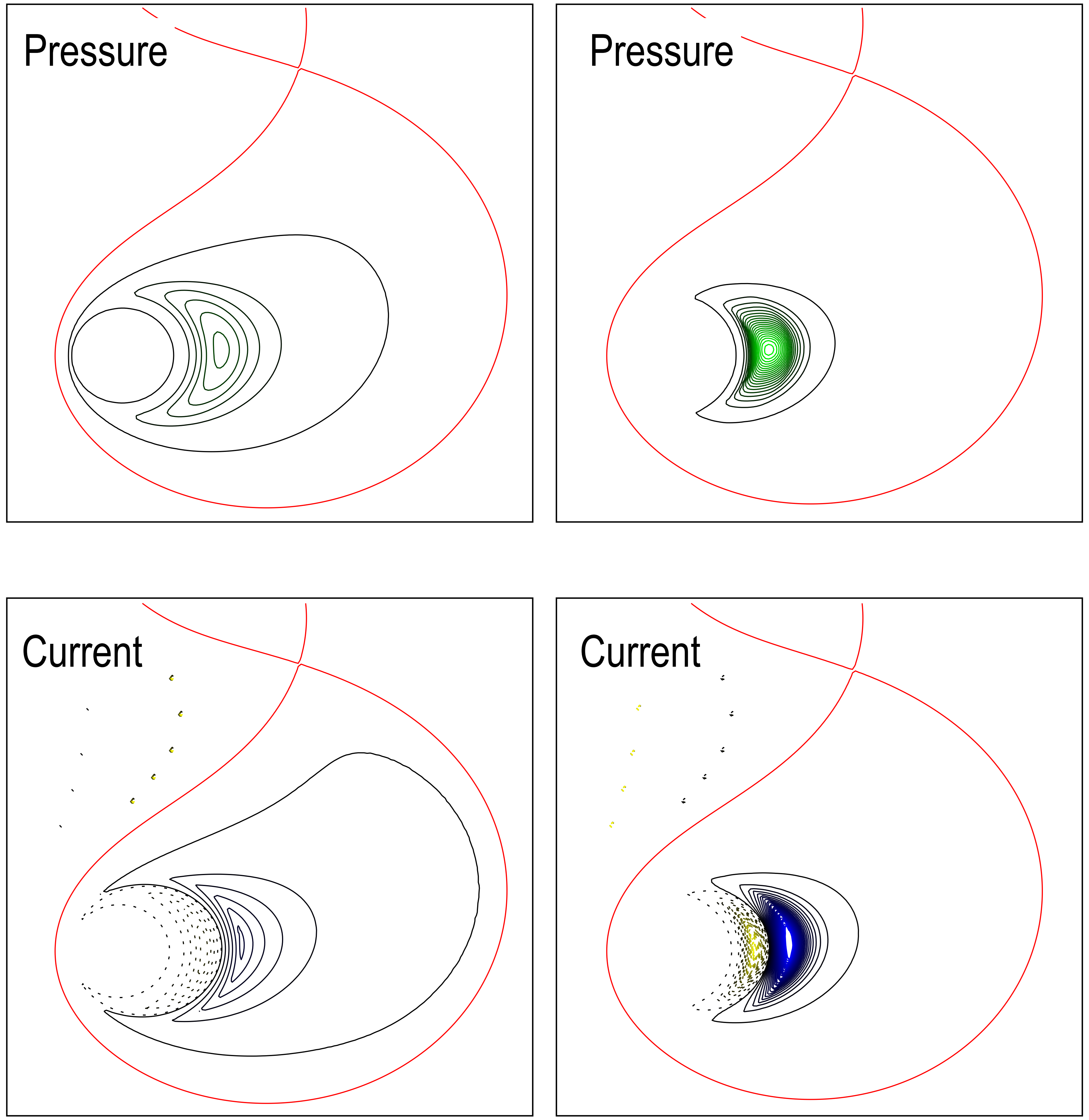
RT-1: $\beta > 100\%$

Supported: No Thermal Confinement
(only energetic trapped electrons)



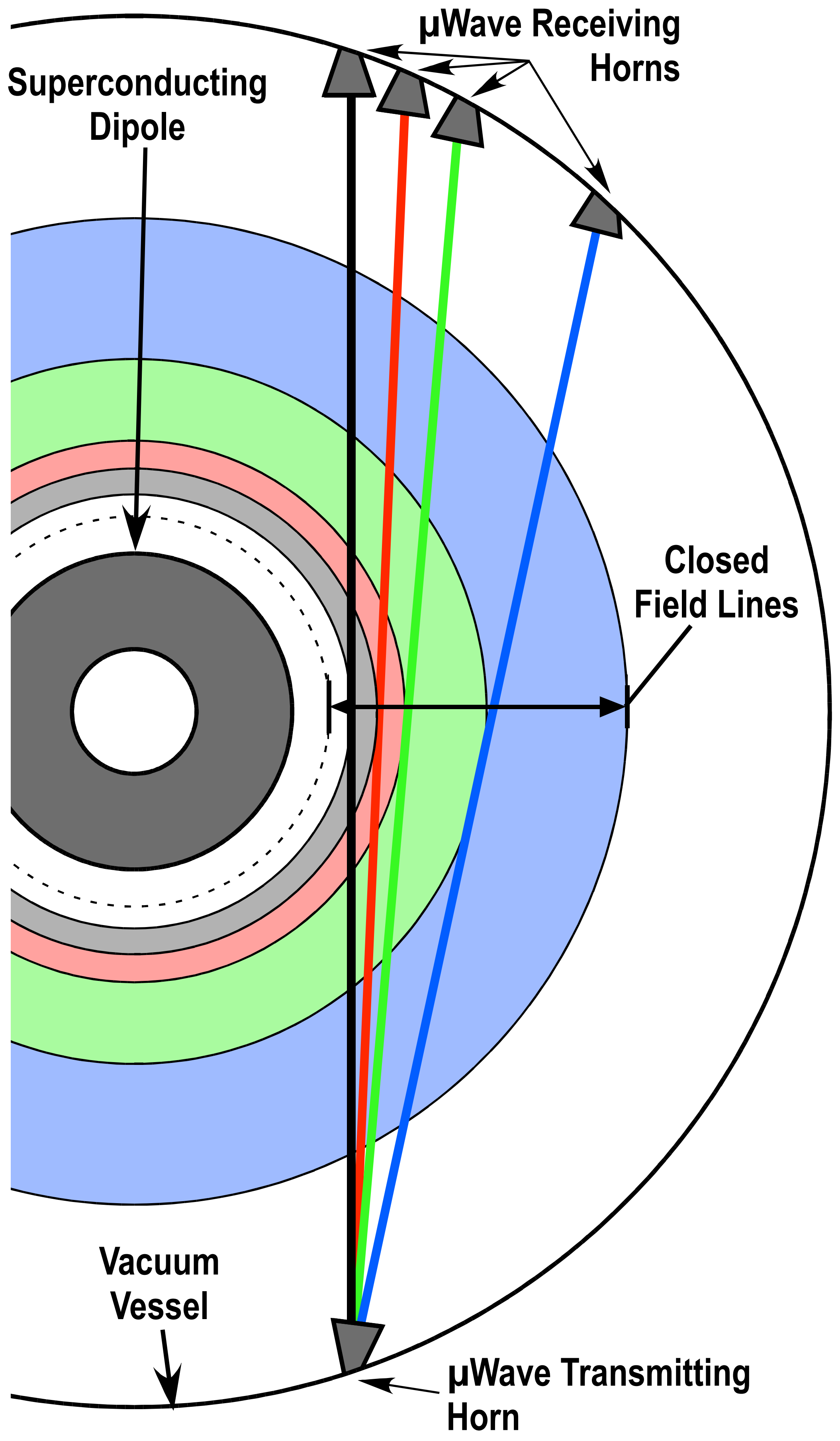
$P_\perp \sim P_\parallel$
Levitated

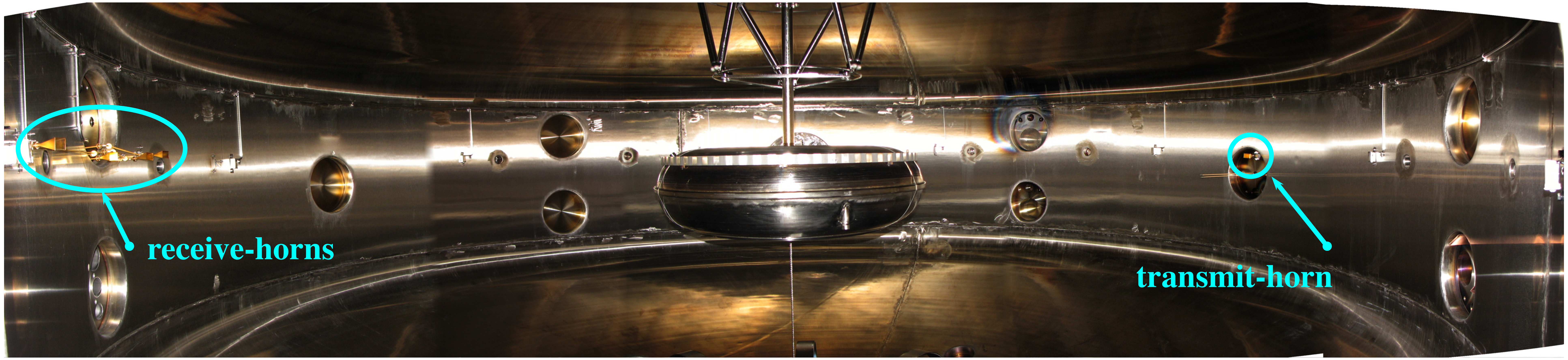
$P_\perp \sim 5\,P_\parallel$
Supported



(Equal Plasma Energy ~ 270J and Ring Current ~ 3kA)

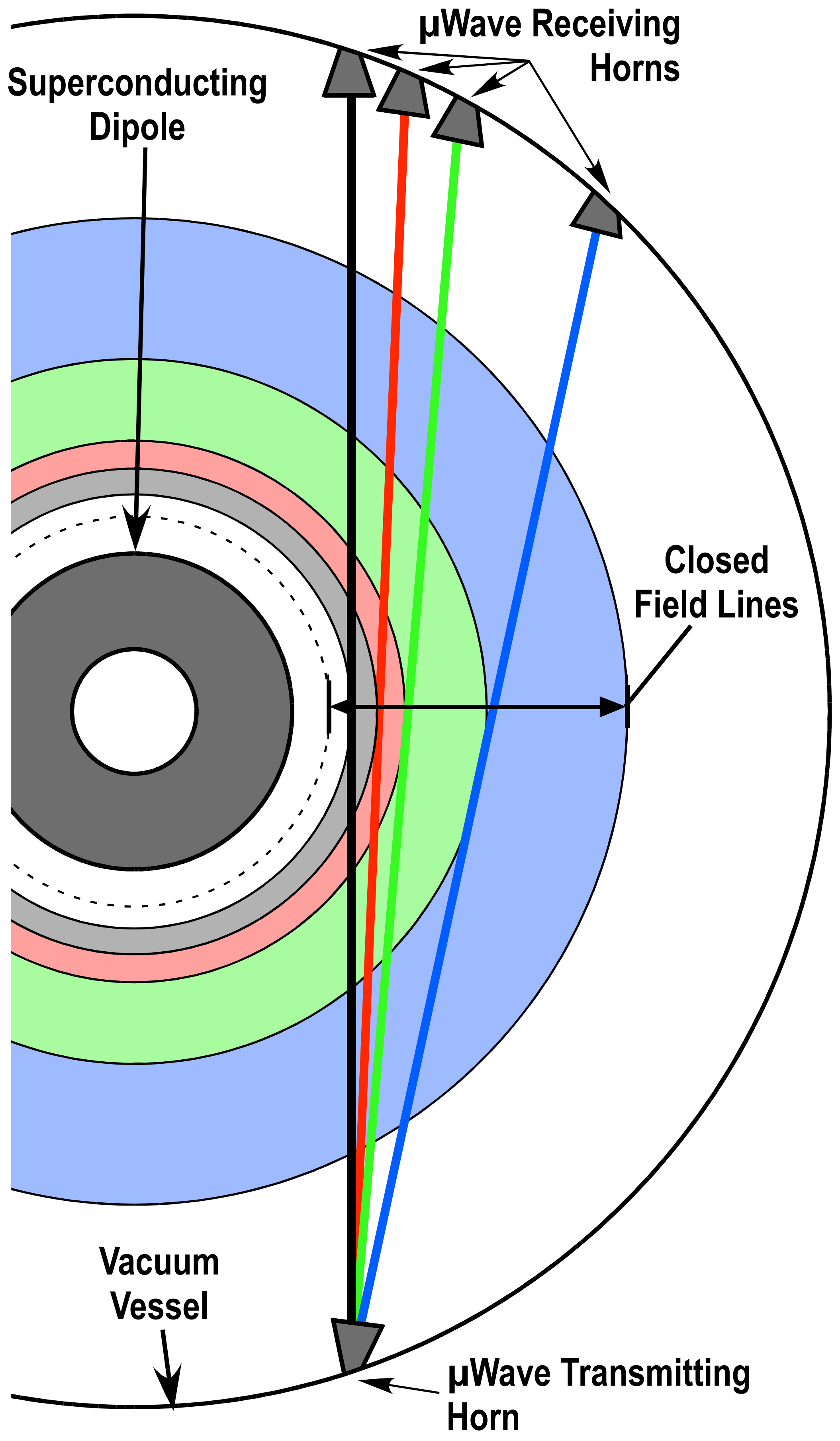
Multichannel Microwave Interferometer



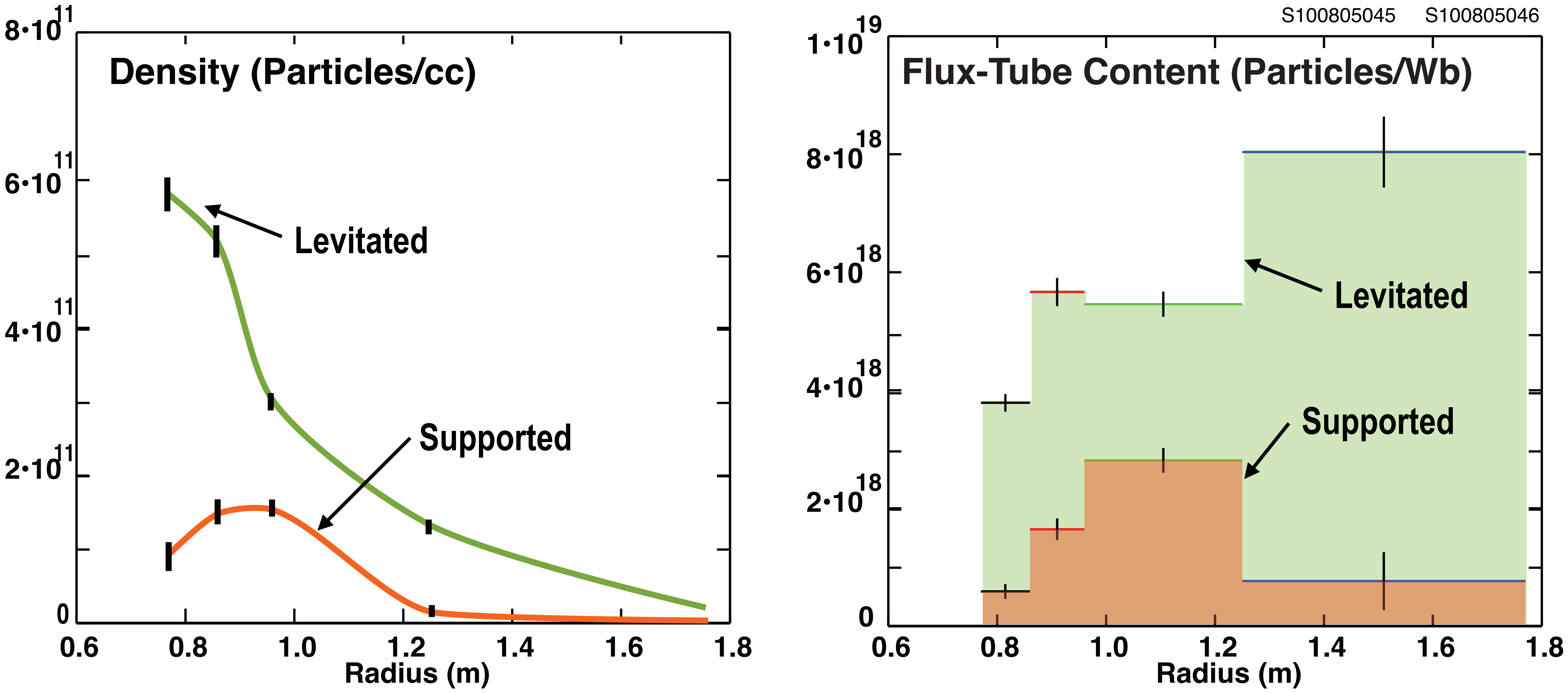


Boxer, *et al.*, "Multichannel microwave interferometer for the levitated dipole experiment," *Rev Sci Instrum* **80**, 043502 (2009).

Levitated Coil creates Centrally-Peaked Density Profile
Supported Coil shows Poor Particle Confinement

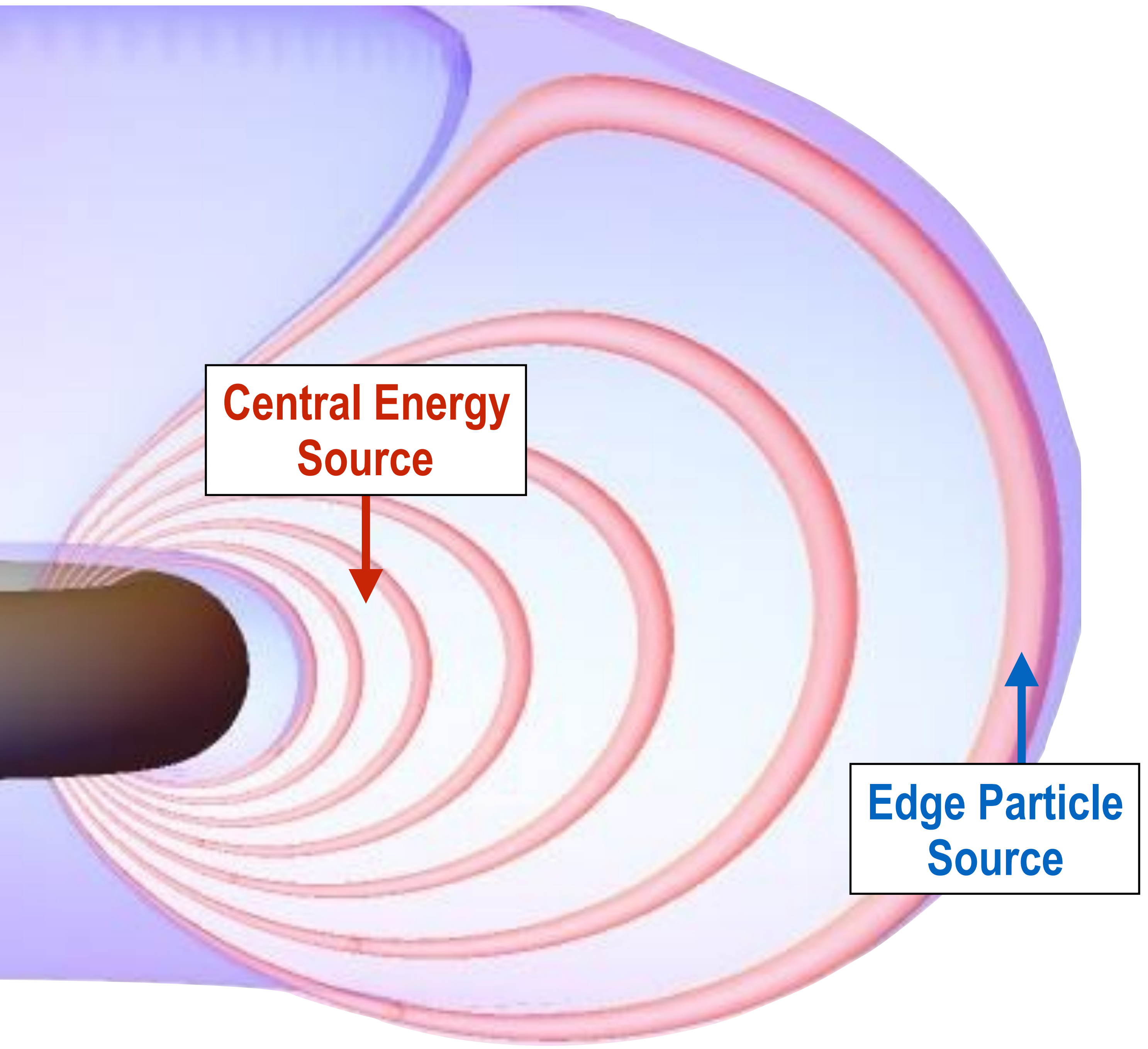


Time Averaged n and (nδV) Profiles

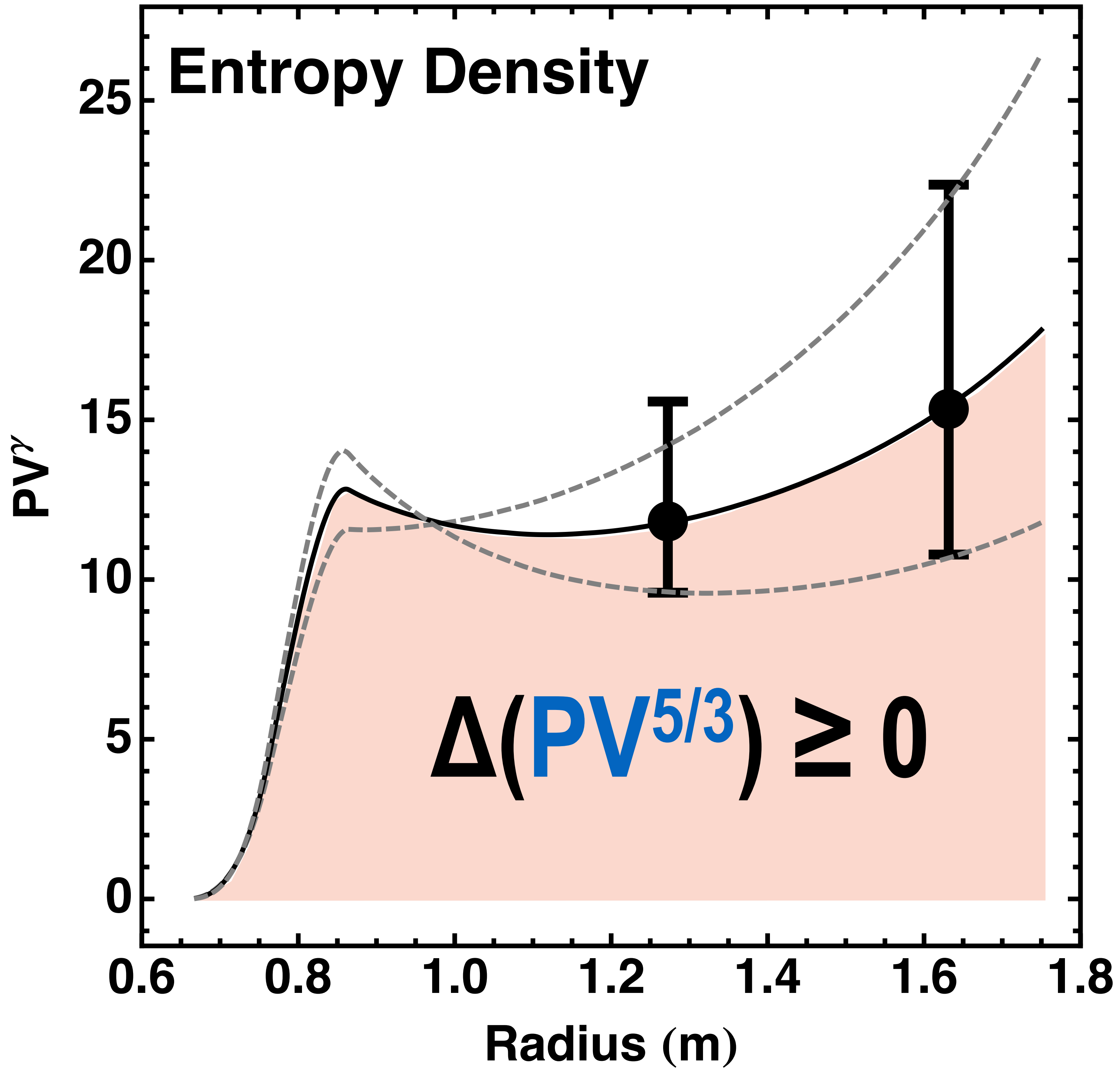


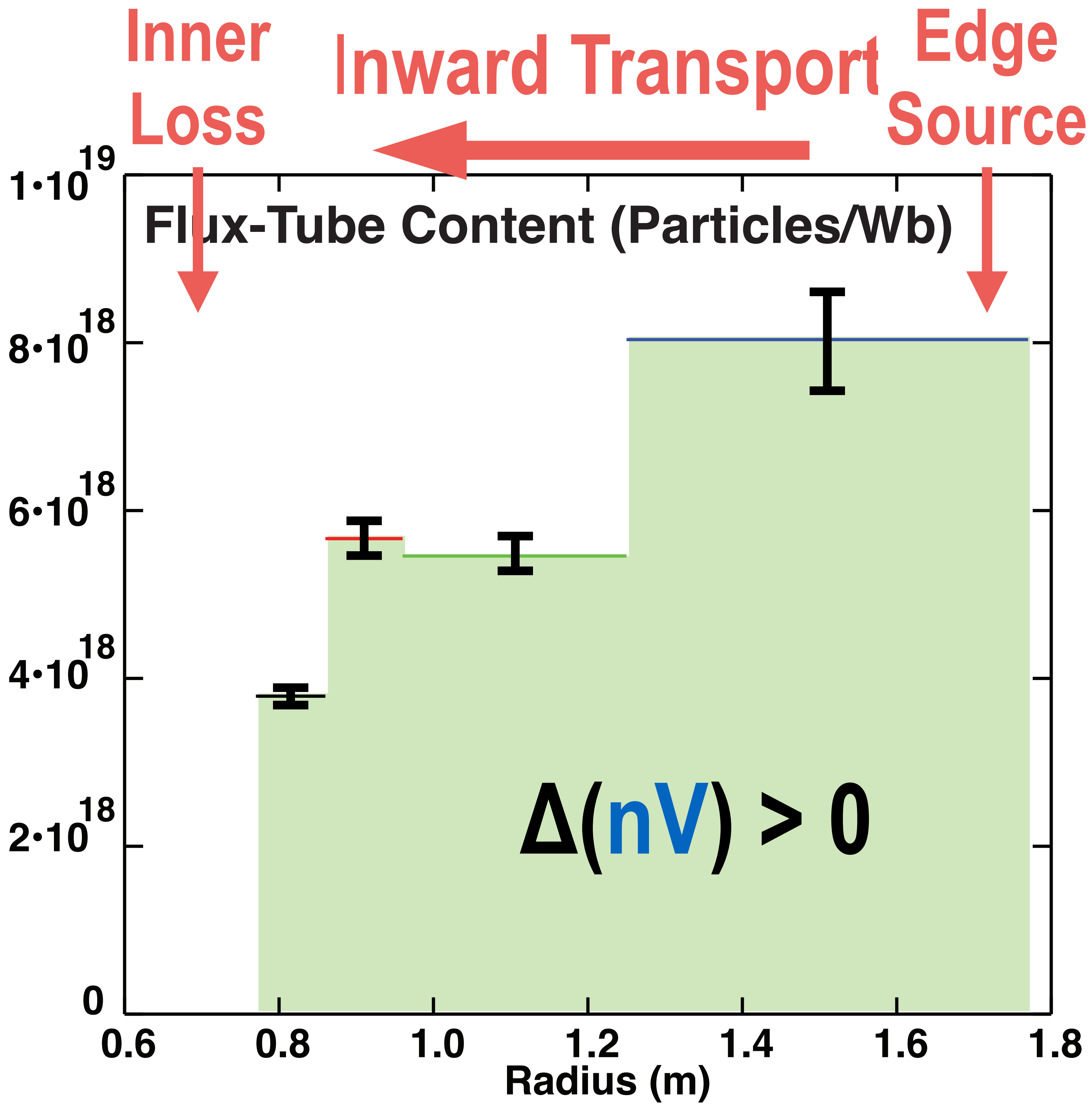
Boxer, *et al.,* "Multichannel microwave interferometer for the levitated dipole experiment," *Rev Sci Instrum* **80**, 043502 (2009).

Pressure and Density Profiles ***During Levitation*** Indicate ***Marginally Stable Pressure*** ($PV^{5/3}$) and Flux-Tube Content (nV) ***Decreasing Inward***



“warm core”
η > 2/3





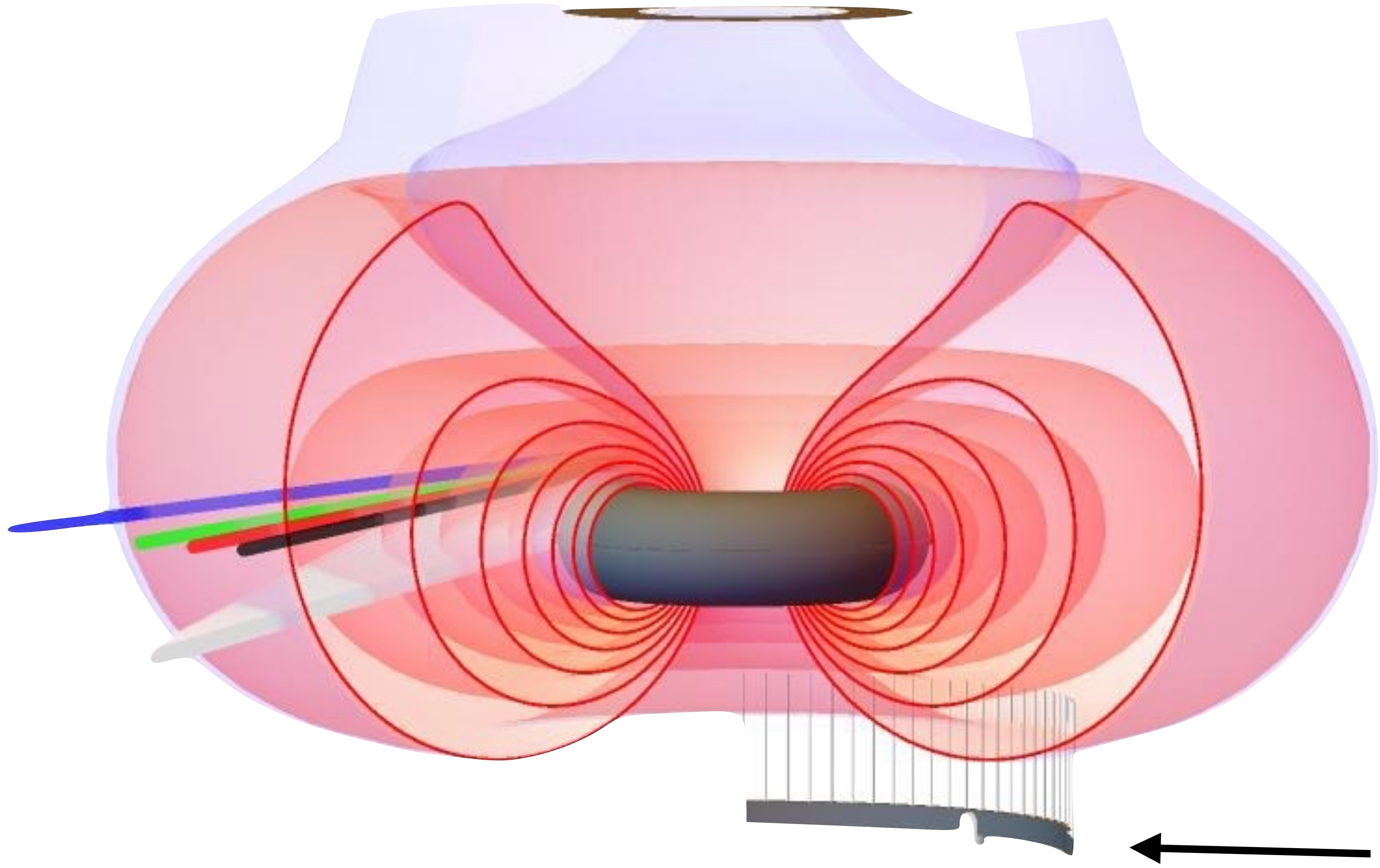
Warm Core: $\Delta(nV) > 0$ and $\Delta(TV^{2/3}) < 0$

$\eta > 2/3$

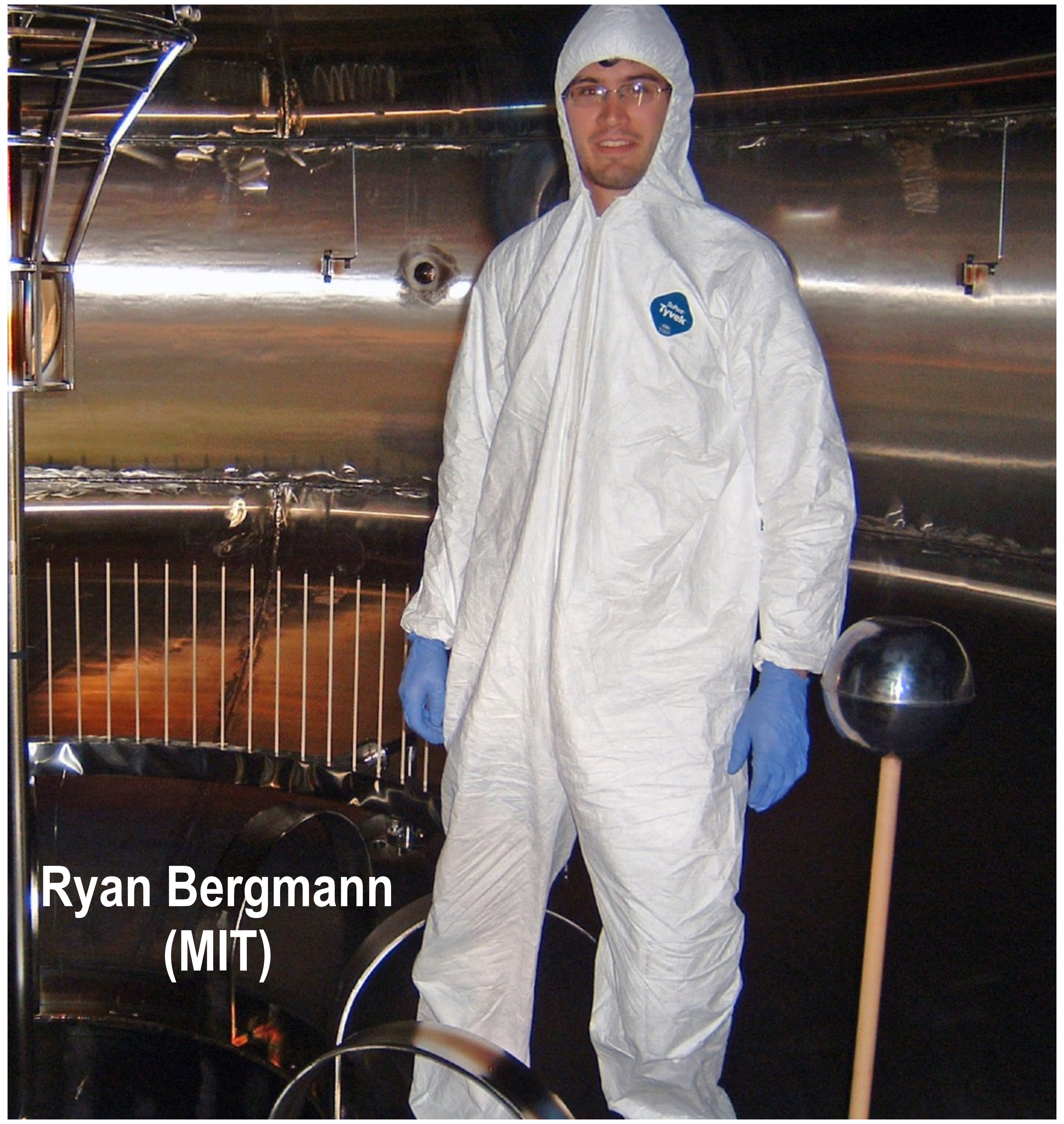
$$\eta = \frac{\Delta \ln T}{\Delta \ln n}$$

Alex Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet,” *Nat Phys* **6**, 207 (2010).
Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

The Radial Diffusion Coefficient is Measured by Ensemble Correlation of the Measured Radial E×B Velocity



Edge Probe Array
Measures Radial
E×B Velocity



$$\mathbf{E} \cdot \mathbf{B} = 0$$

$$\dot{\psi}(t) = R E_{\varphi}(t) = \nabla\psi \cdot \mathbf{E} \times \mathbf{B}$$

$$D_{\psi} = \lim_{t \to \infty} \int_0^t dt' \langle \dot{\psi}(t') \dot{\psi}(0) \rangle \equiv R^2 \langle E_{\varphi}^2 \rangle \tau_c$$

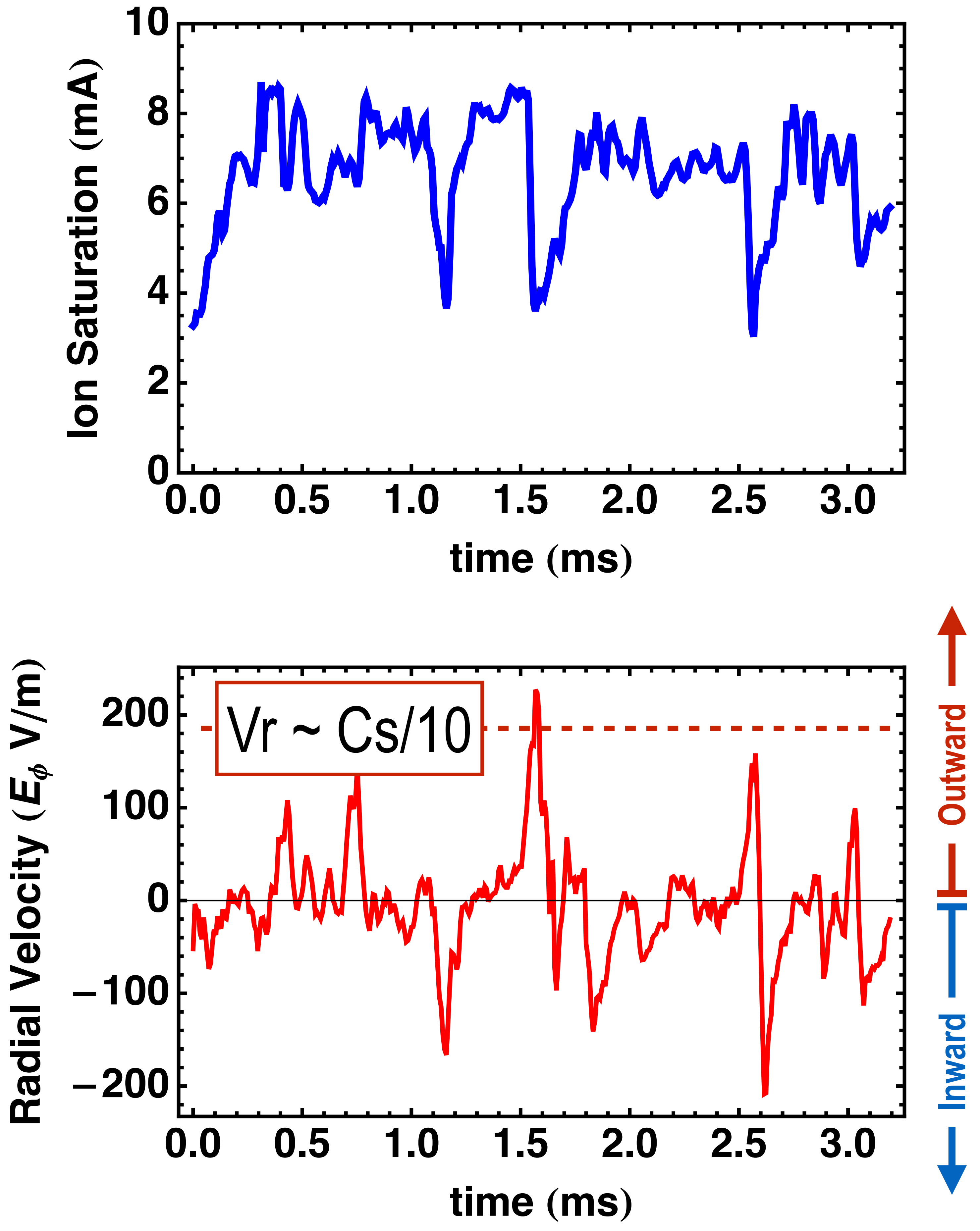
$$\boxed{\frac{\partial}{\partial t}(nV) = \underbrace{\langle S \rangle}_{\text{Source}} + \frac{\partial}{\partial \psi} D_{\psi} \frac{\partial}{\partial \psi}(nV)}$$

Radial Diffusion due to Interchange/Entropy Turbulence

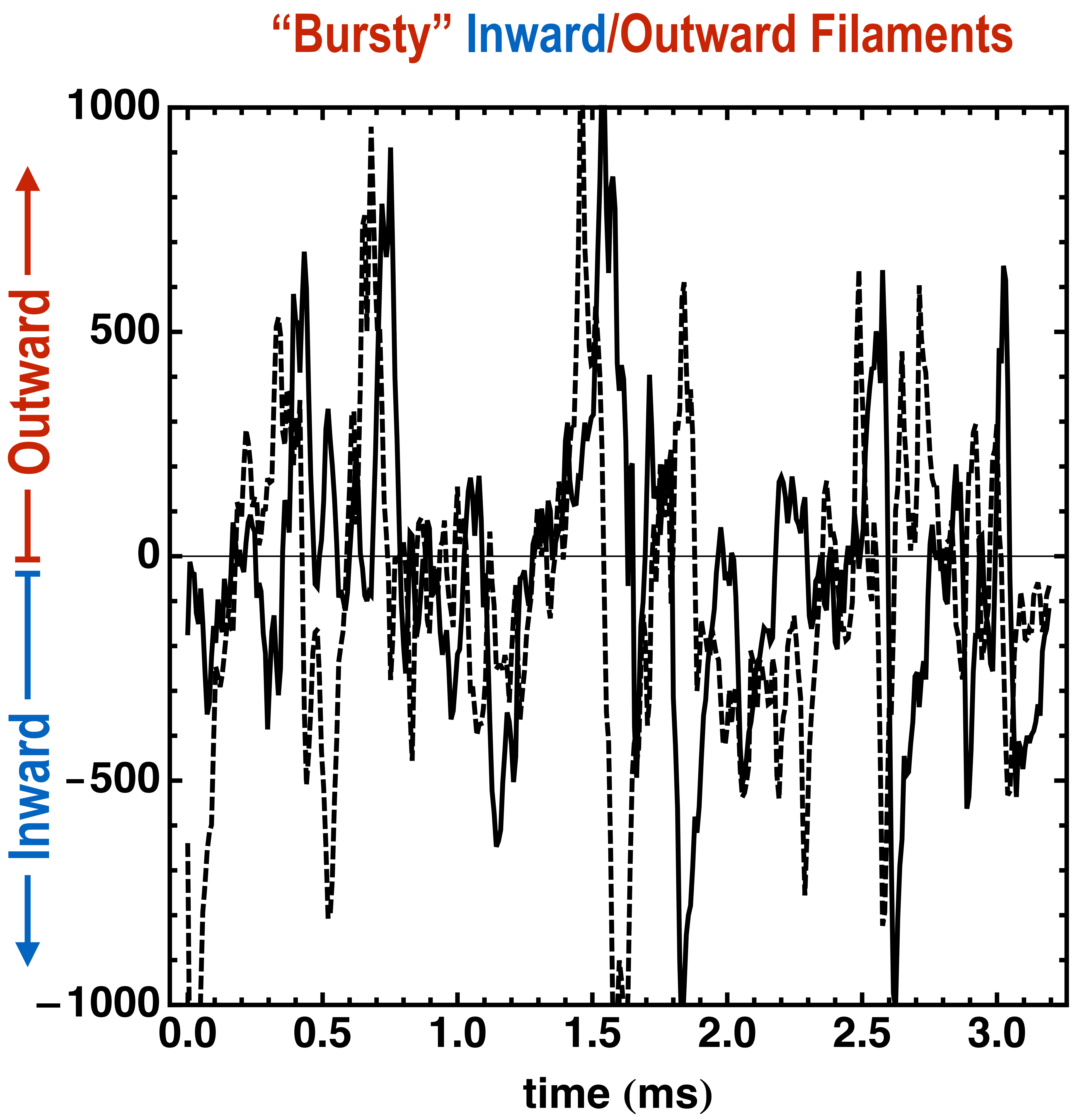
Alex Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet,” *Nat Phys* **6**, 207 (2010).

Edge Transport is “Bursty”: Outward Warm Filaments and Inward Cool Filaments

Probe Array:
Floating Potential, E_φ
Ion Saturation Current
Radial **E**×**B** Flux



$RE_\varphi \sim \Delta\Phi/\Delta\varphi$



Radial Flux ~ $(E_\varphi/B) \times I_{sat}$

Jen Ellsworth, *Characterization of Low-Frequency Density Fluctuations in Dipole-Confined Laboratory Plasmas*, PhD MIT (2010).
Grierson, *et al.*, "Transport Induced by Large Scale Convective Structures in a Dipole-Confined Plasma," *PRL* **105**, 205004 (2010).

Edge Transport is “Bursty”: Outward Warm Filaments and Inward Cool Filaments

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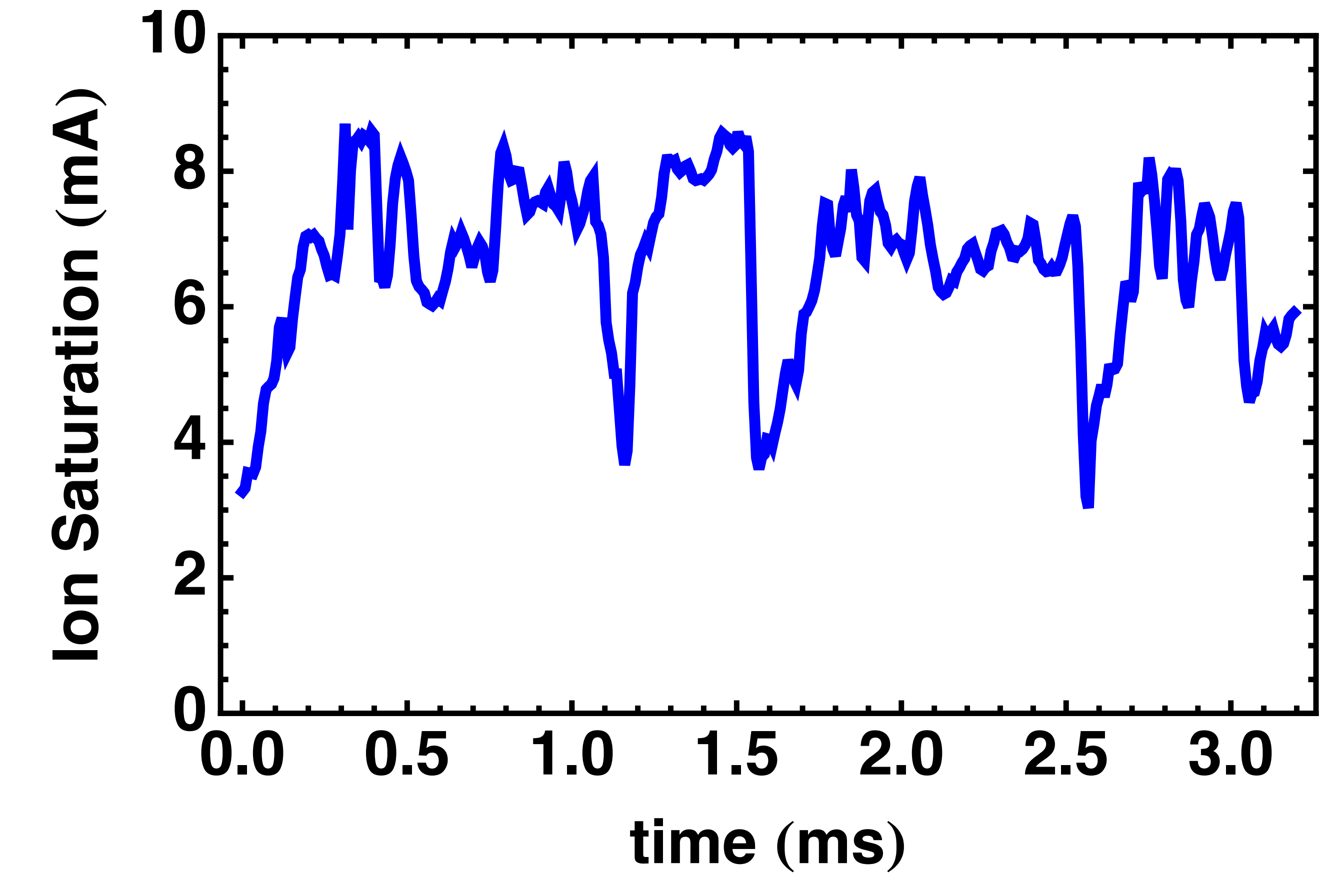

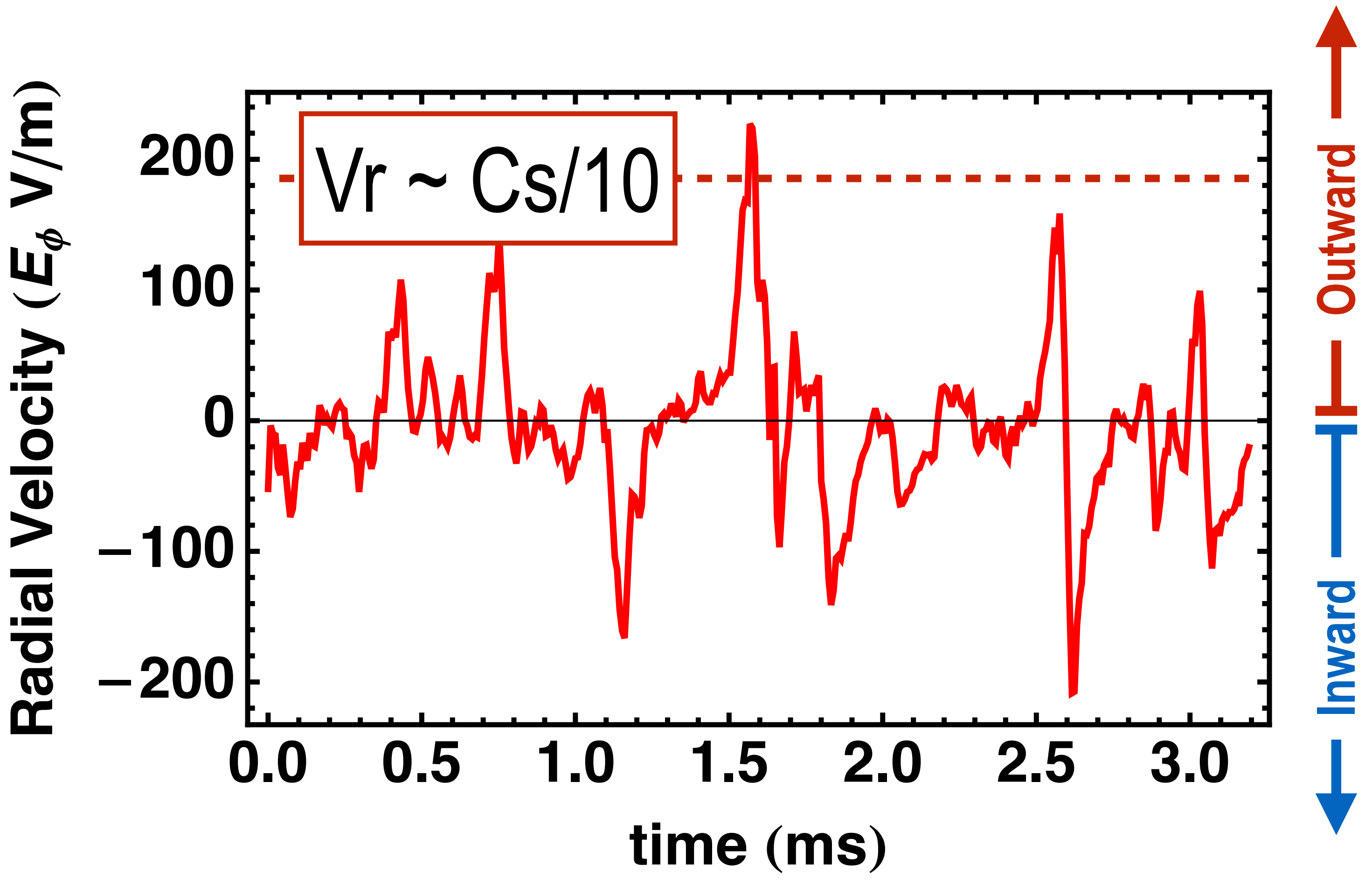

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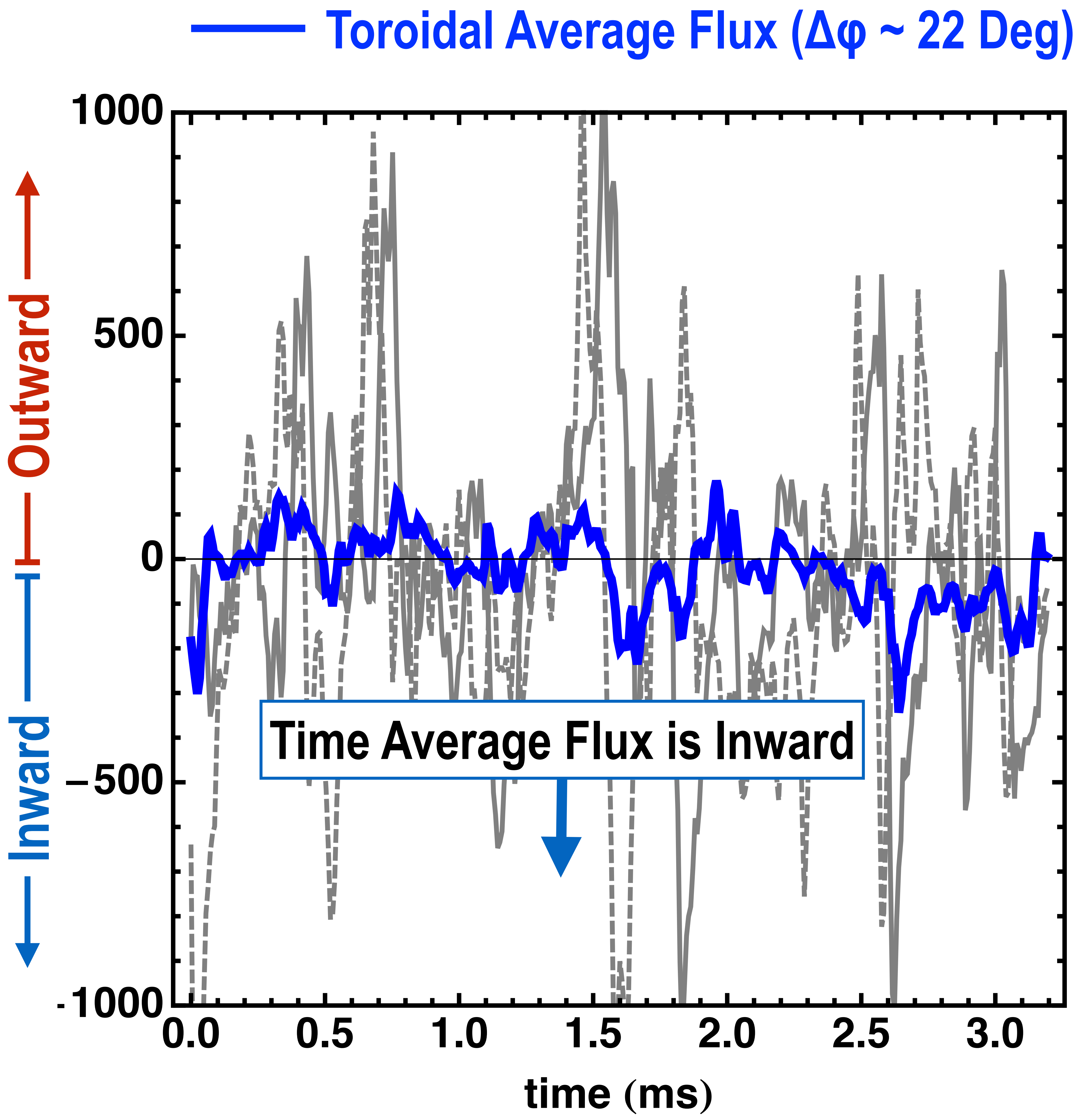

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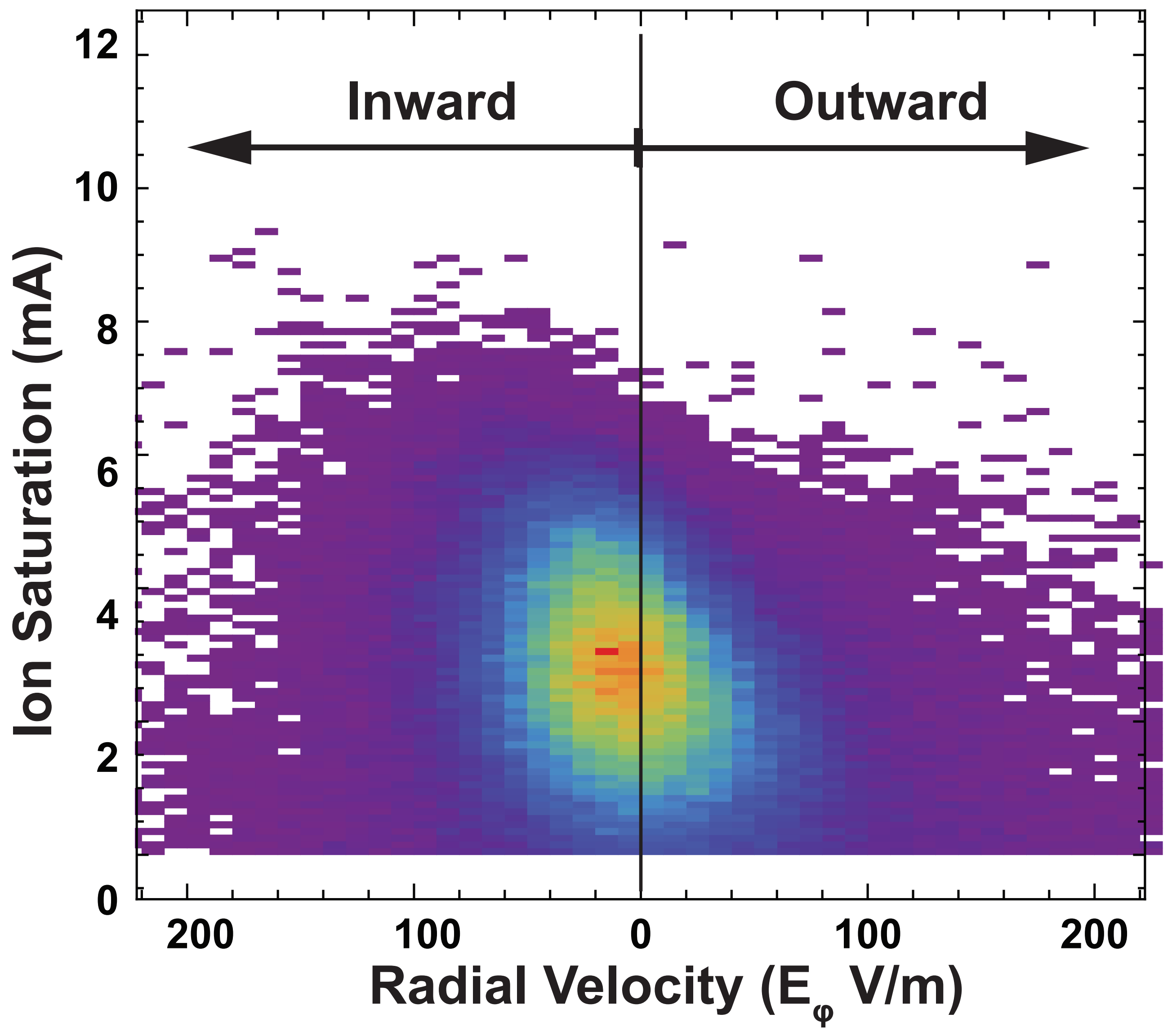
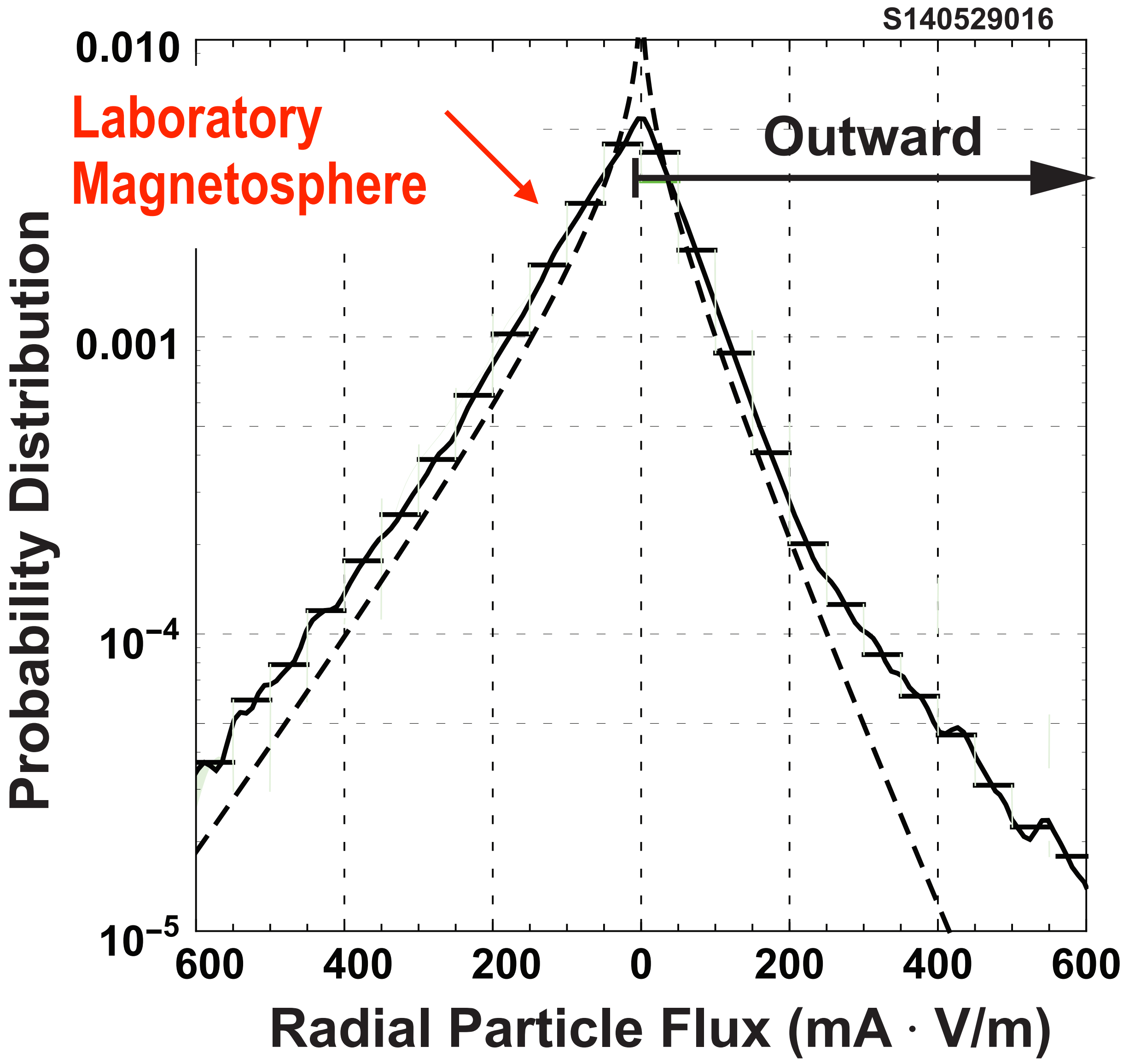
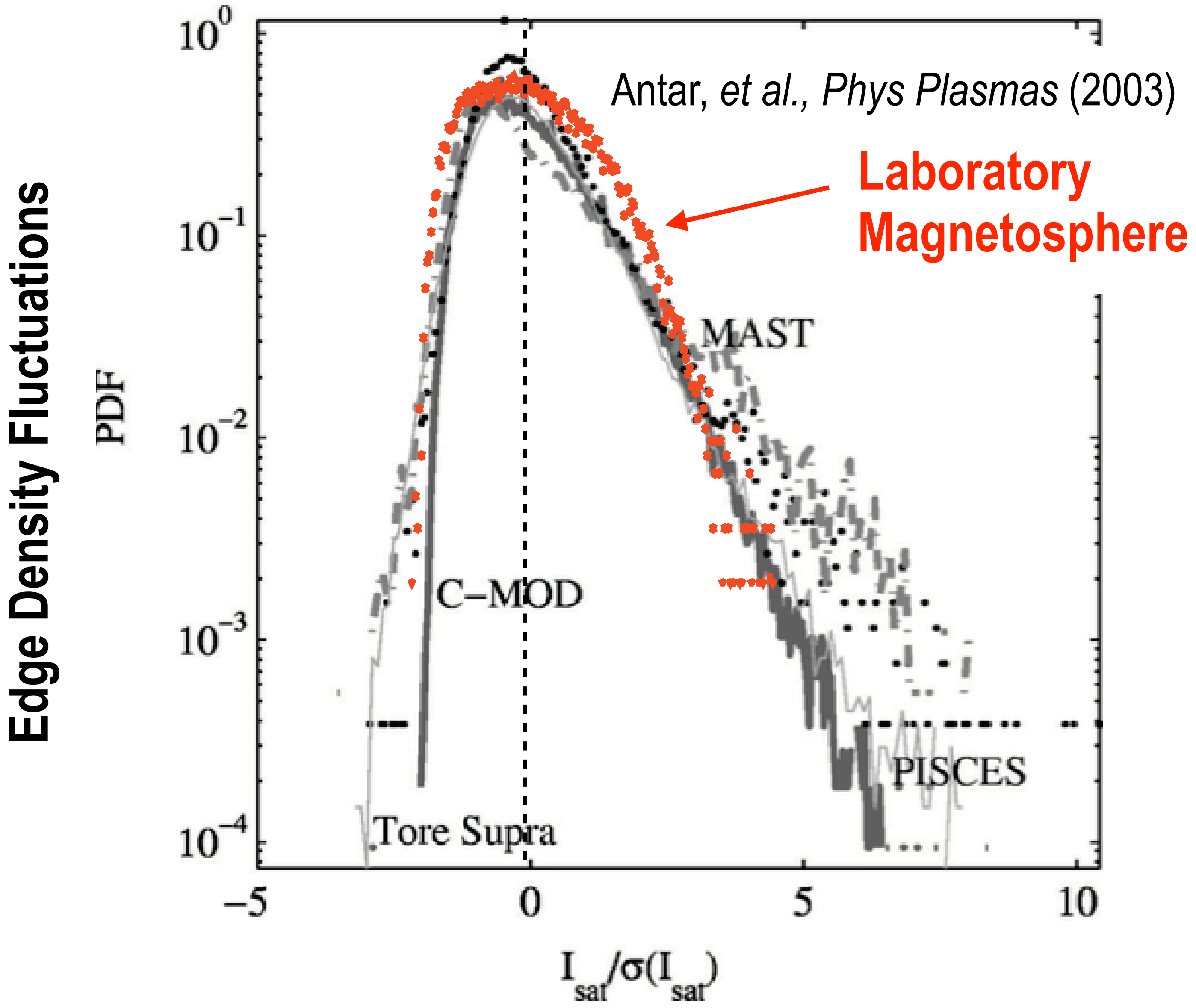
Surprising “Universal” Turbulence Statistics of the Plasma Torus

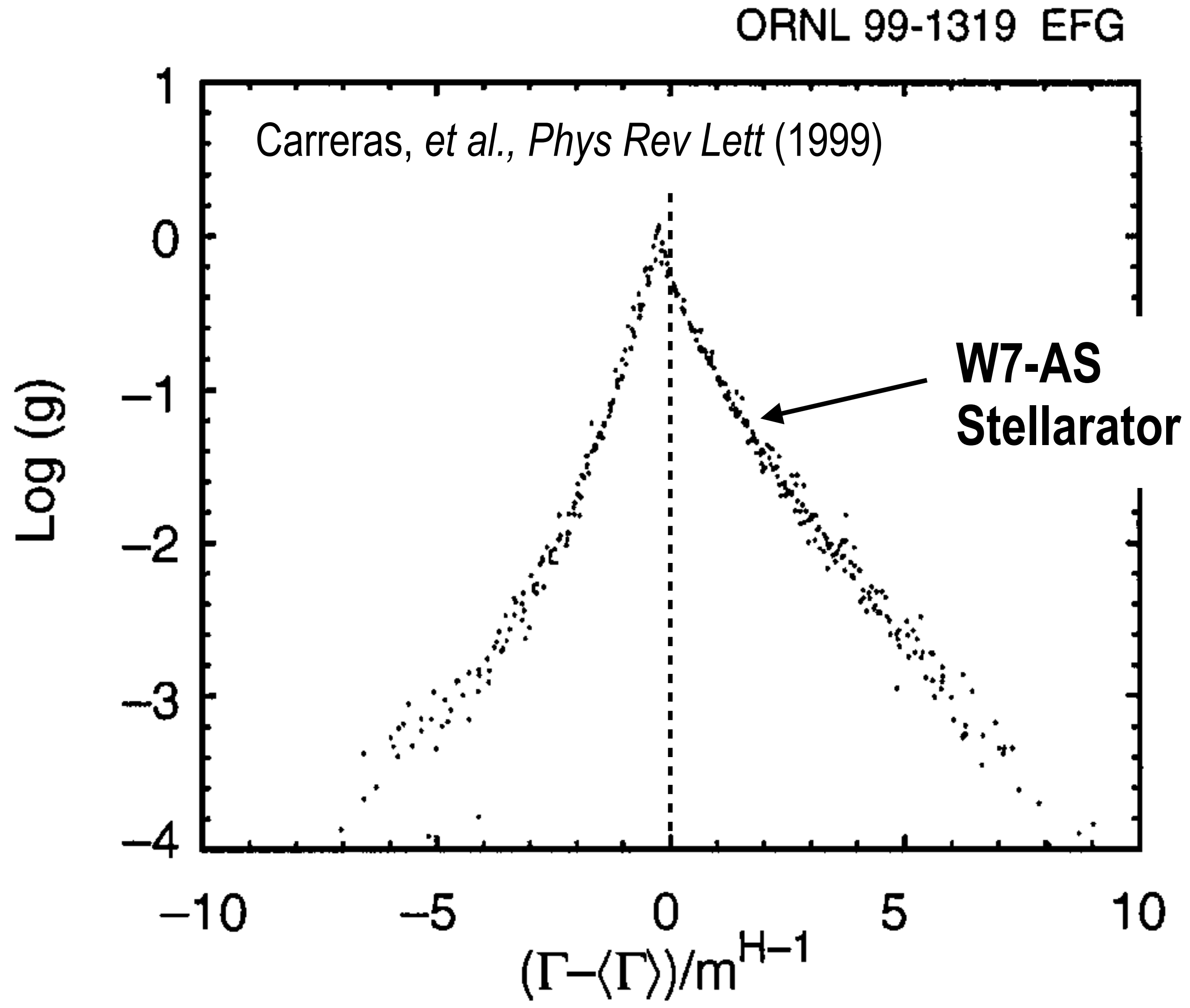
(a) Probe Array Histogram



(b) Local Radial Flux



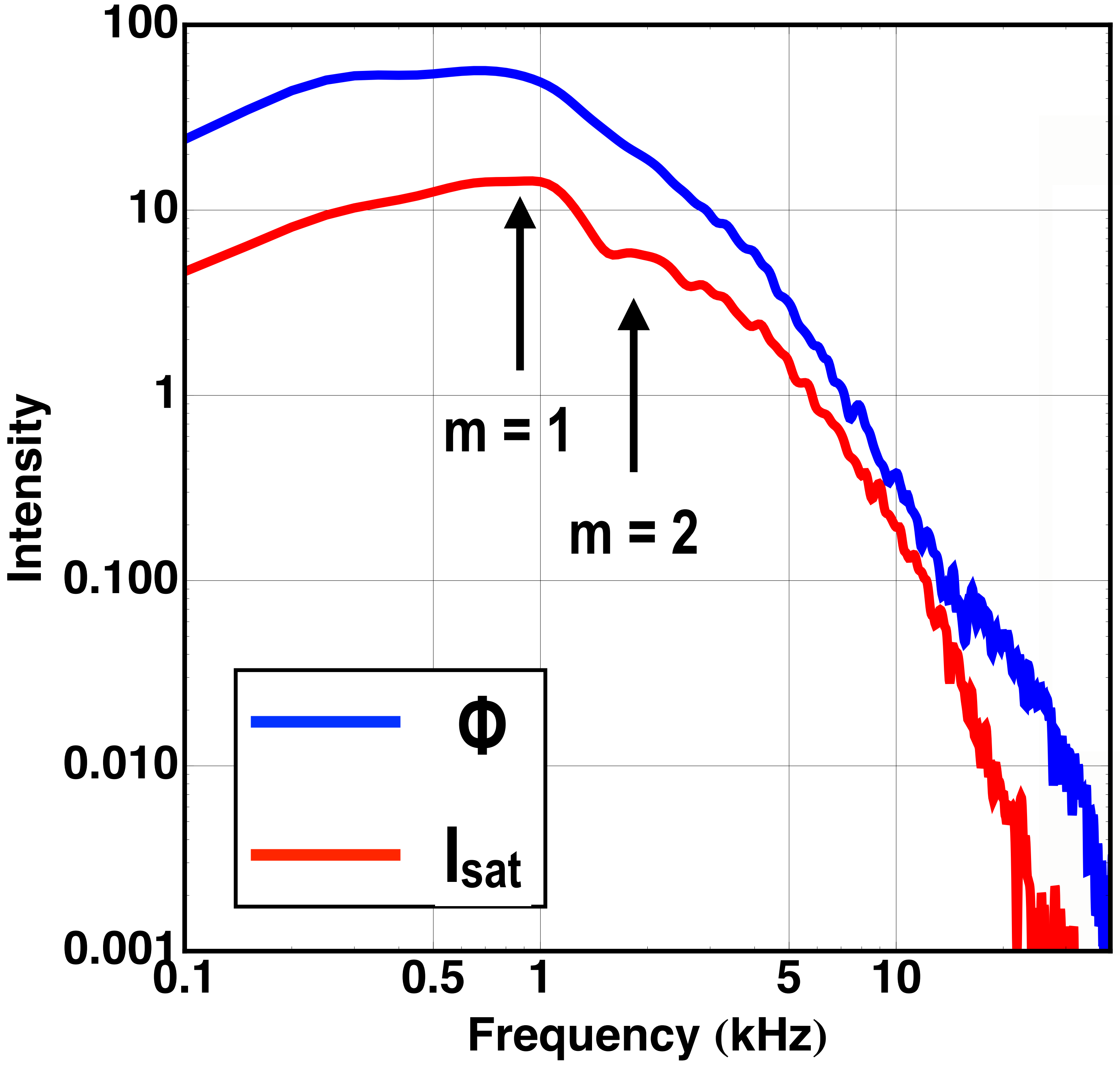

Antar, *et al.*, *Phys Plasmas* (2003)


Carreras, *et al.*, *Phys Rev Lett* (1999)

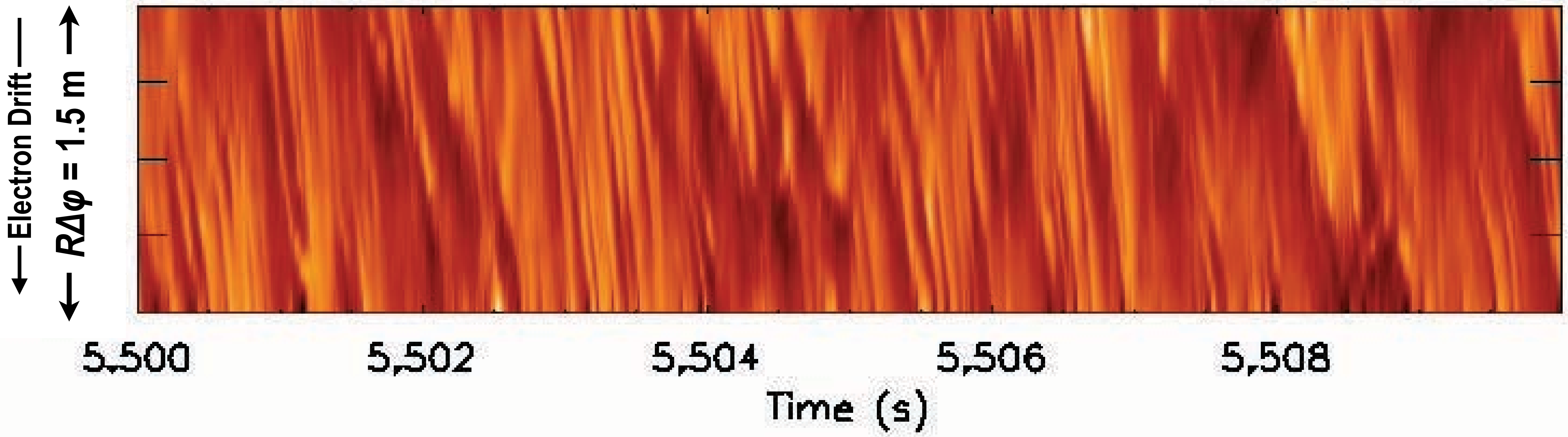
Intermittent plasma flux:
Carreras, et al., *Phys Plasmas*, (1996)

Turbulent Fluctuations Propagate in Electron Drift Direction

(during edge gas fueling)


Edge Fluctuation Spectrum

$|E_\varphi| \sim 55$ V/m (RMS) $\tau_C \sim 16$ μsec


Floating Potential (Φ > ± 100 V)

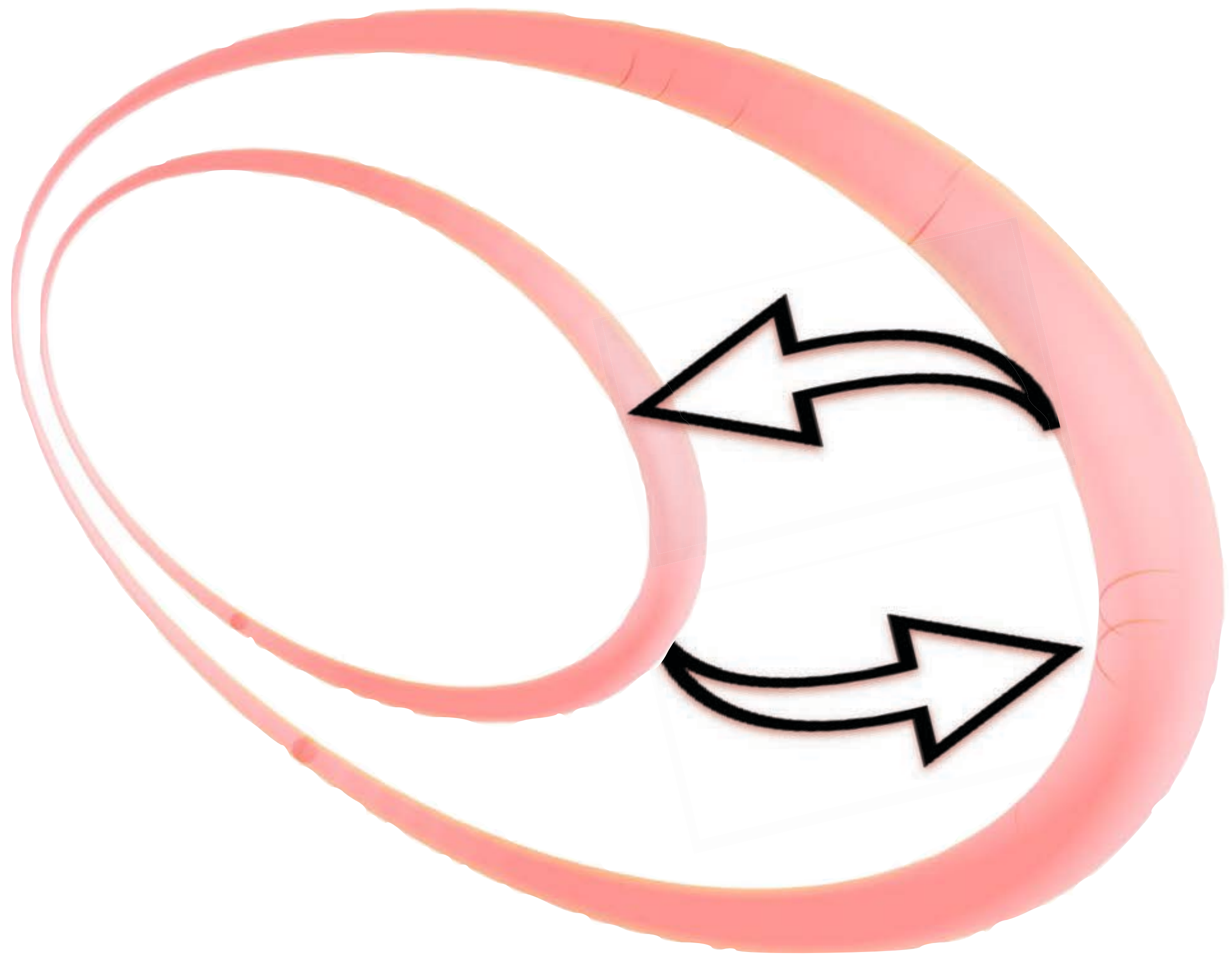
$\omega \approx m\,\omega_d \sim 2\,\pi\,m\,700$ Hz

$m = 1, 2, 3, 4, 5, 6, \ldots$

Inverse mode structure cascade, chaotic mode dynamics, …

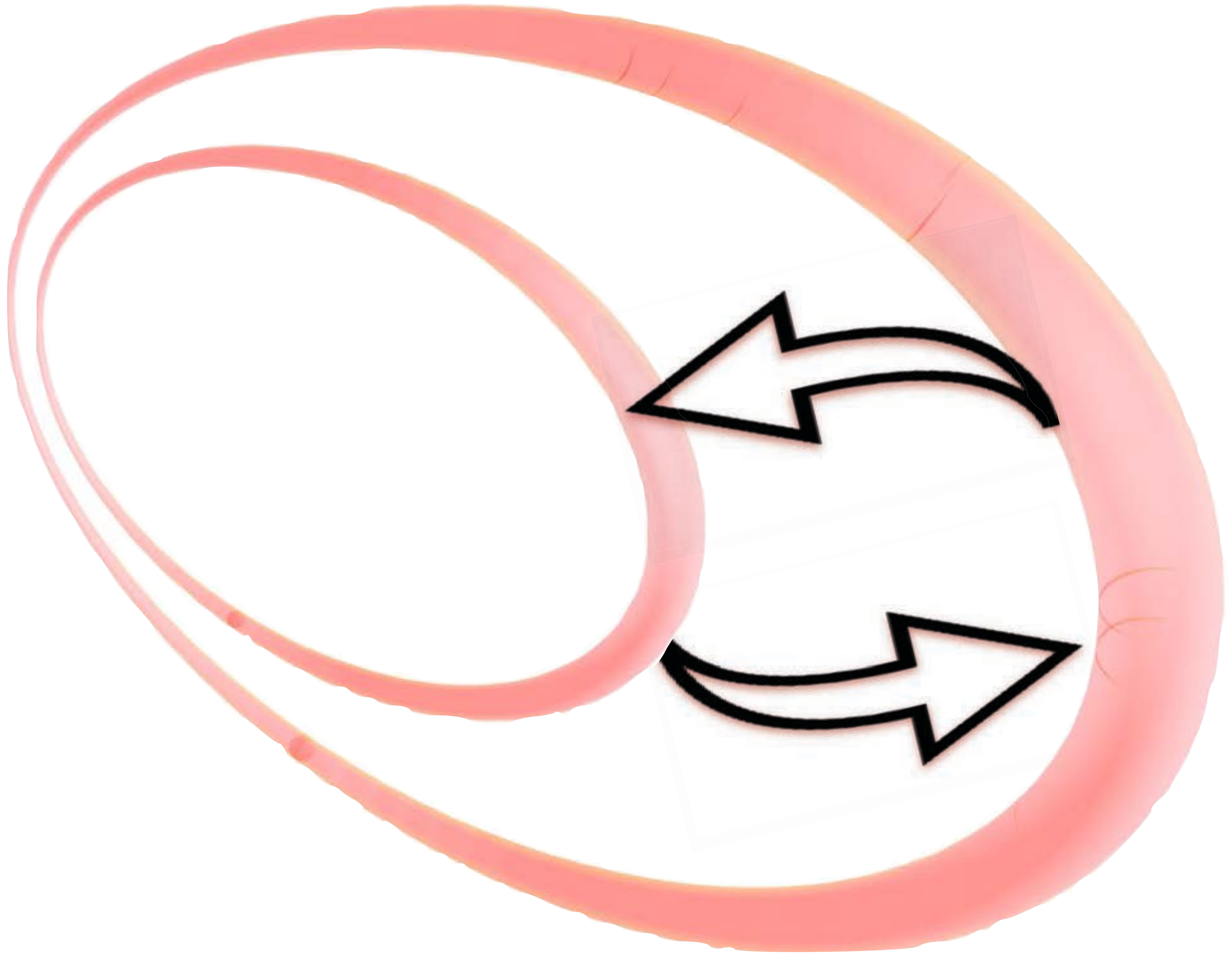
Jen Ellsworth, *Characterization of Low-Frequency Density Fluctuations in Dipole-Confined Laboratory Plasmas*, PhD MIT (2010).
Grierson, Worstell, and Mauel, "Global and local characterization of turbulent and chaotic structures in a dipole-confined plasma," *Phys Plasmas* **16**, 055902 (2009).

Interchange/Entropy Mode Turbulence Questions



- What are the spatial structures, $\Phi(\varphi,\psi)$, of the eigenmodes?
- Growth rates and toroidal rotation frequencies?
- What determines the turbulent spectrum and fluctuation cascade?
- What is the magnitude & *direction* (i.e. “pinch”) of plasma transport?
- How does everything above change with plasma profiles?

Interchange/Entropy Mode Physics

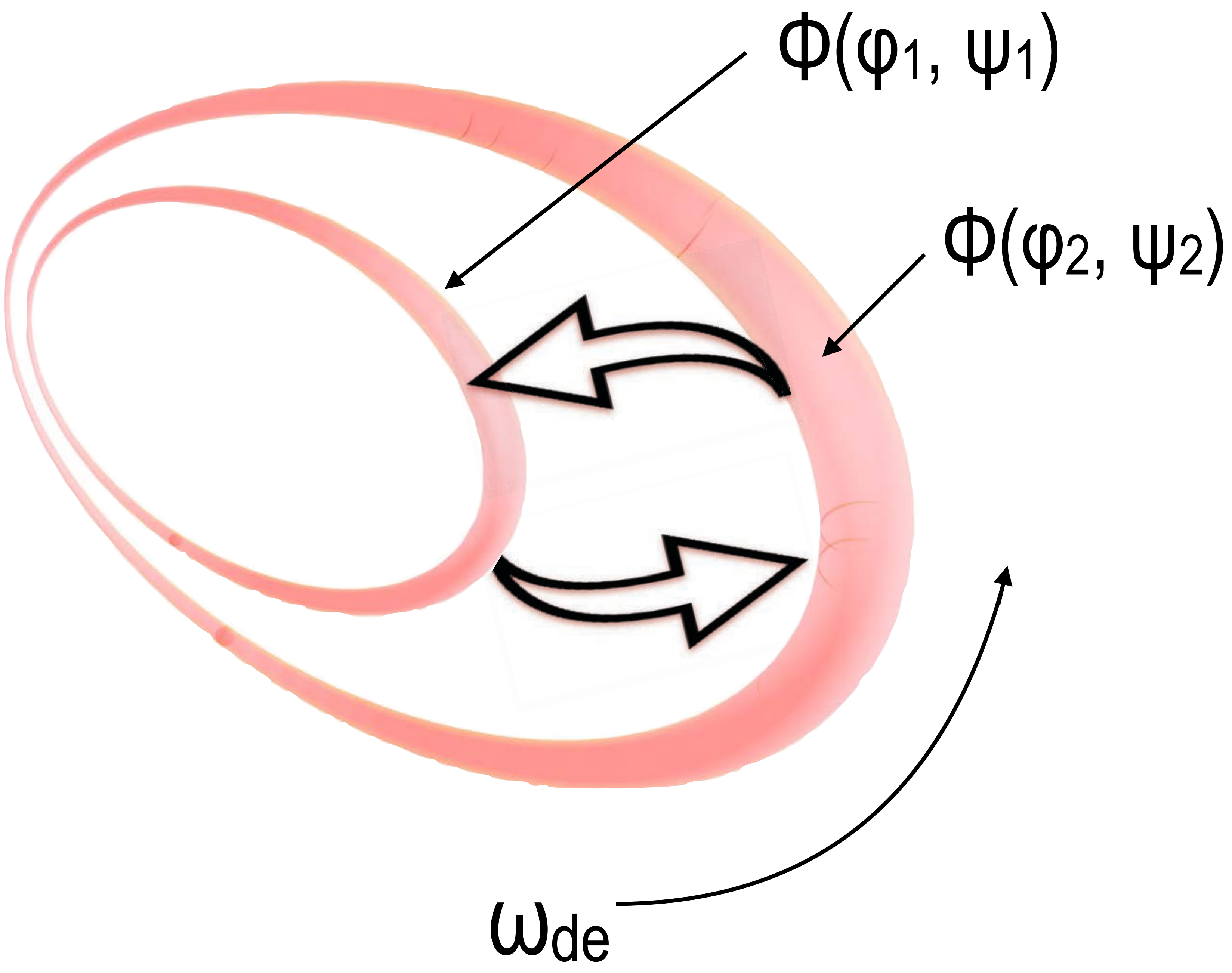


- Kesner, *Phys Plasmas*, **7**, 3887 (2000) (*Linear drift-kinetics*)
- Ricci, Rogers, Dorland, and Barnes, *Phys Plasmas,* **13**, 062102 (2006) (*Linear gyro-fluid*)
- Kobayashi, Rogers, and Dorland, *Phys Rev Lett*, **105**, 235004 (2010) (*Nonlinear gyro-kinetics*)

➡ **Bounce-averaged equations with drift-resonant closure:**

  - Rosenbluth, "Low-Frequency Limit of Interchange Instability," *Phys Fluids* **11**, 869 (1968).
  - Beer and Hammett, "Bounce averaged trapped electron fluid equations for plasma turbulence," *Phys Plasmas*, **3**, 4018 (1996).

Interchange/Entropy Mode Physics



$$V = \int \frac{dl}{B} \propto L^4$$

$$2\langle \kappa_\psi \rangle = -\frac{\partial}{\partial \psi} \log V$$

- $\nabla \cdot J_\perp = 0$. (without FAC)
  Ion (inertial) polarization current balances perturbed diamagnetic current; only one key dimensionless parameter: $\rho^* \equiv \rho_s/L \ll 1$

- $\omega \sim \omega_d \ll \omega_b$.
  Bounce-averaged kinetics; transport mediated by drift-resonance

- $2\gamma \langle \kappa_\psi \rangle \, \partial(PT/e)/\partial\varphi$.
  Magnetic drift causes collisionless "curvature heat flux"; imparting real toroidal phase velocity to entropy mode

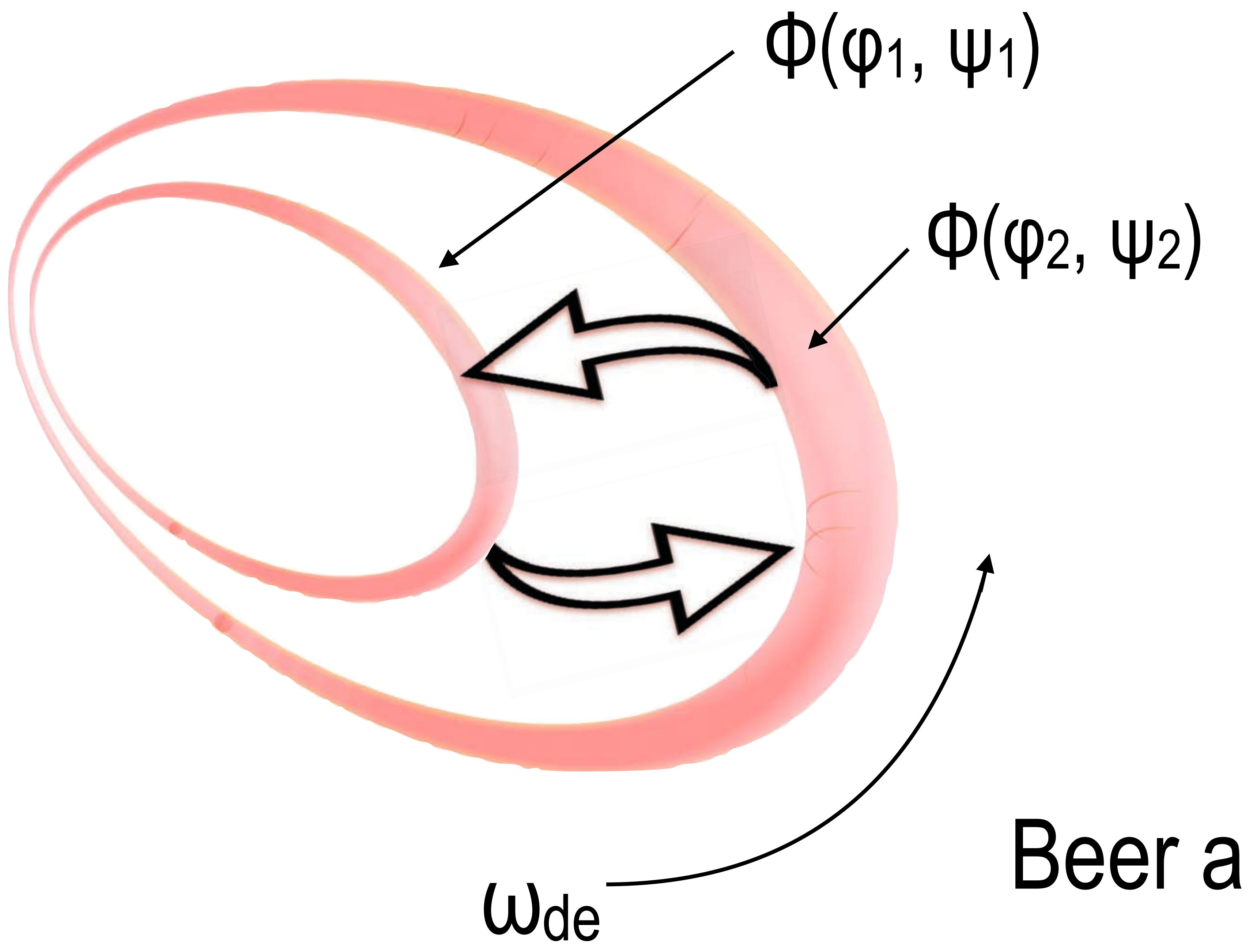
- Drift profile parameters (*unique*):
  $\Delta(n\delta V) \sim \omega_n^*/\omega_d - 1$ and $\Delta(P\delta V^\gamma) \sim \omega_p^*/\omega_d - \gamma$ and $\eta = \omega_p^*/\omega_n - 1$

- ***Beer-Hammett*** bounce-integrated drift-resonant closure should allow (relatively simple?) reduced dimensional ***whole plasma nonlinear modeling.***

Interchange/Entropy Mode Physics

Rosenbluth (1968)

$$\frac{\partial \tilde{F}}{\partial t} + \omega_d(\mu, J, \psi)\,\frac{\partial \tilde{F}}{\partial \varphi} + \frac{\partial \tilde{\Phi}}{\partial \varphi}\,\frac{\partial F_0}{\partial \psi}\bigg|_{\mu,\,J} \approx 0$$



$$\begin{aligned}
\tilde{n}\delta V &= \oint \frac{dl}{B} \iiint d^3v\ \tilde{F}(\psi) \\
\tilde{P}\delta V &= \frac{2}{3} \oint \frac{dl}{B} \iiint d^3v\ E\,\tilde{F}(\psi) \\
\tilde{R}\delta V &= \frac{4}{15} \oint \frac{dl}{B} \iiint d^3v\ E^2\,\tilde{F}(\psi) \\
\tilde{S}\delta V &= \frac{8}{105} \oint \frac{dl}{B} \iiint d^3v\ E^3\,\tilde{F}(\psi) \\
\vdots &= \vdots
\end{aligned}$$

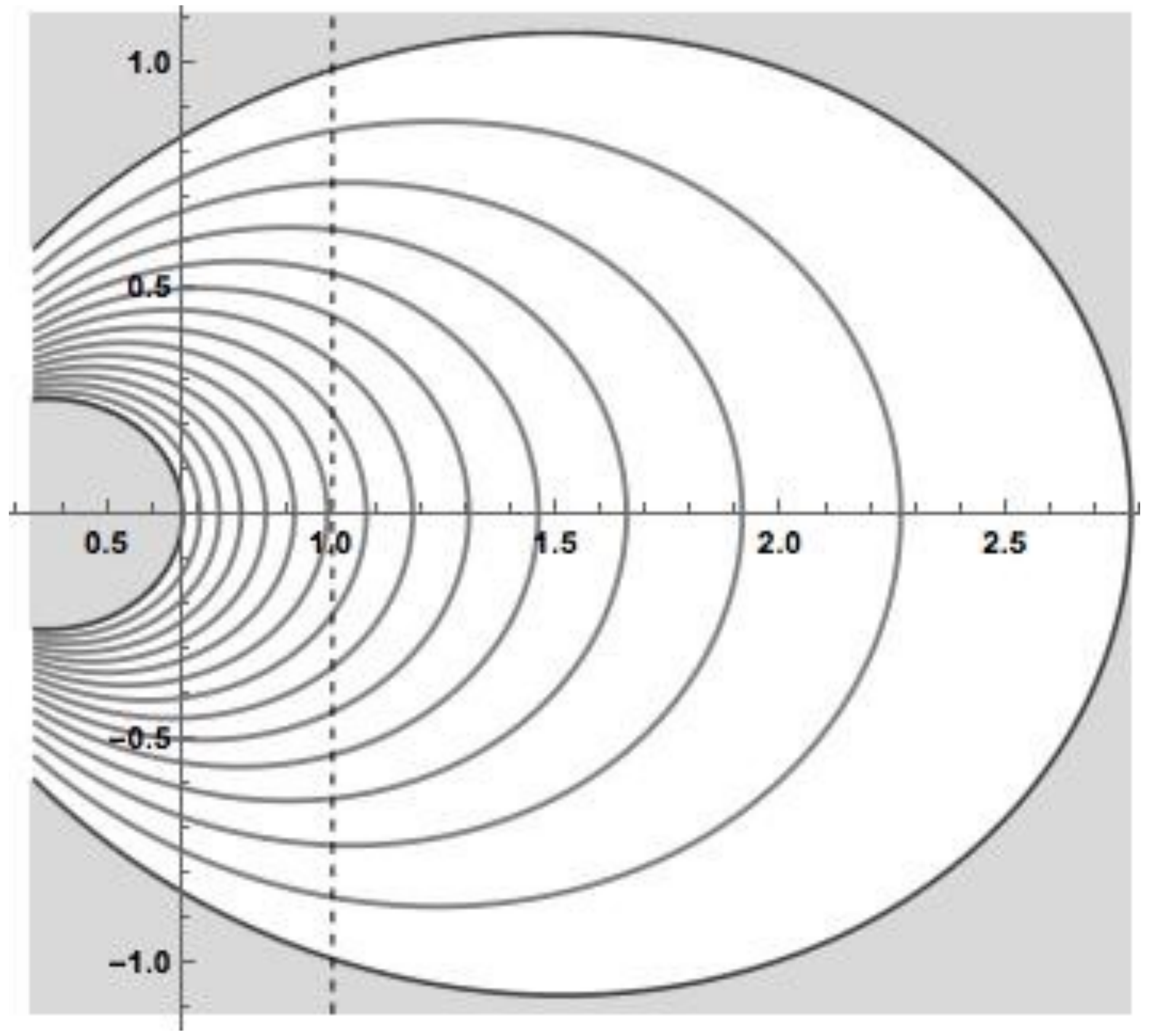
Drfit-Resonant Closure

$$\tilde{S} \approx -i\left(\nu_n \tilde{N} + \nu_p \tilde{P} + \nu_r \tilde{R}\right)$$

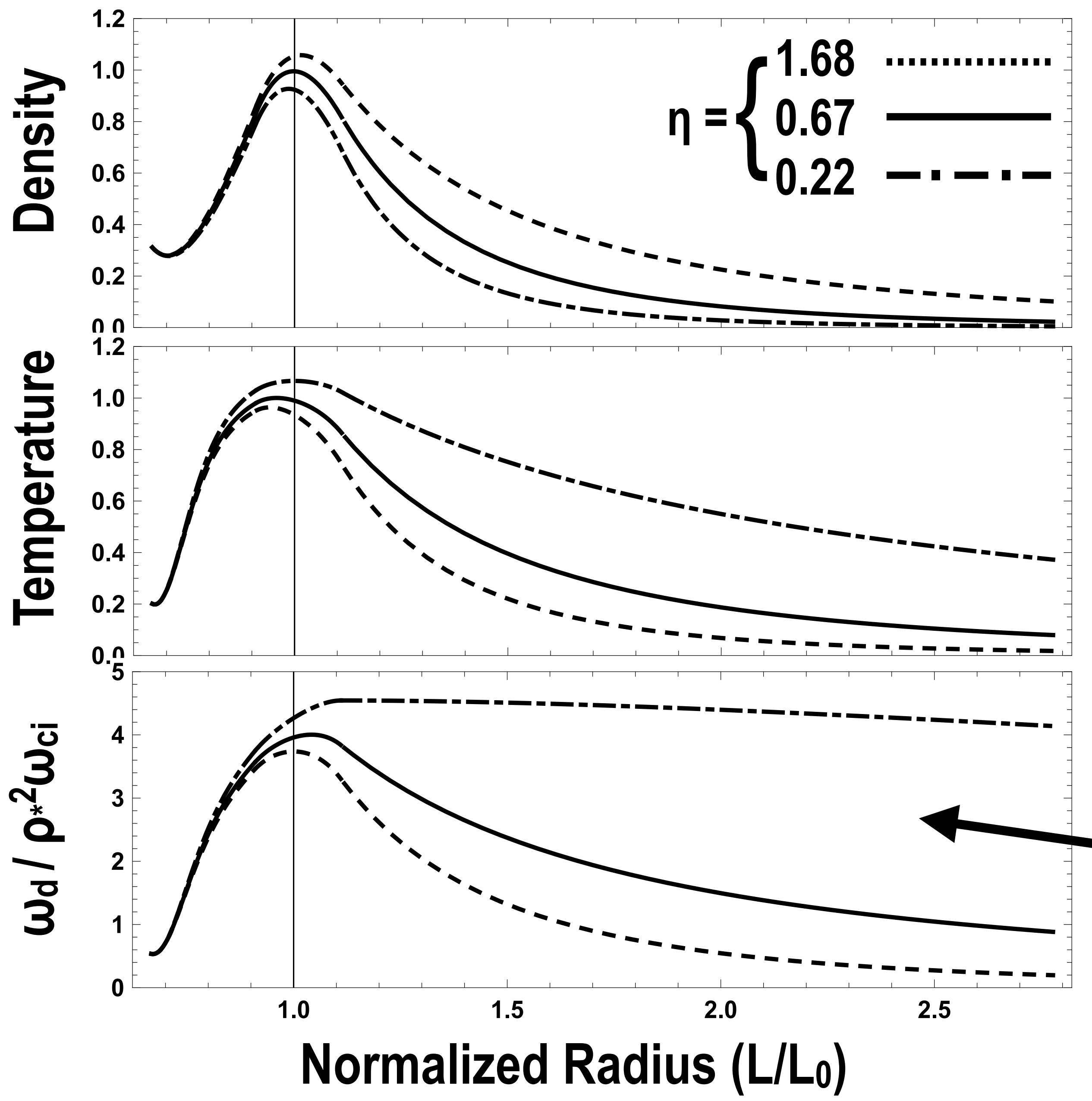
Beer and Hammett (1996)

$$\begin{pmatrix}
\omega & -m\bar{\omega}_d & 0 & 0 & \cdots \\
0 & \omega & -\gamma m\bar{\omega}_d & 0 & \cdots \\
0 & 0 & \omega & -(2\gamma-1)m\bar{\omega}_d & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{pmatrix} \cdot \begin{pmatrix} \tilde{n}\delta V \\ \tilde{P} \\ \tilde{R} \\ \tilde{S} \\ \vdots \end{pmatrix} = m\tilde{\Phi} \begin{pmatrix} \partial(n_0\delta V)/\partial\psi \\ \partial(P_0\delta V^{5/3})/\partial\psi \\ \partial(R_0\delta V^{7/3})/\partial\psi \\ \vdots \end{pmatrix}$$

Global Entropy Mode Structure Depends on Drift Parameter η



$$\boxed{\eta = \frac{\Delta \ln T}{\Delta \ln n} \Rightarrow 2/3}$$



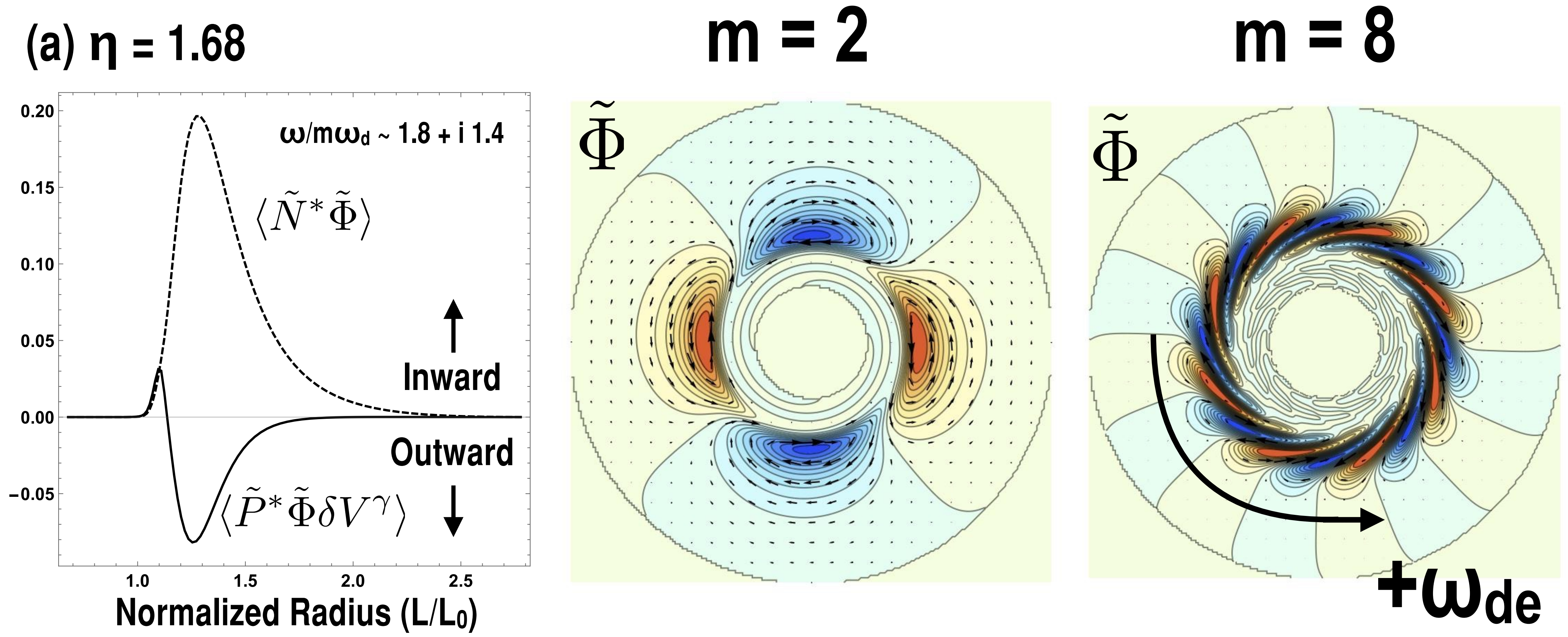
Warm Core (Peaked T)

η = γ - 1 = 2/3

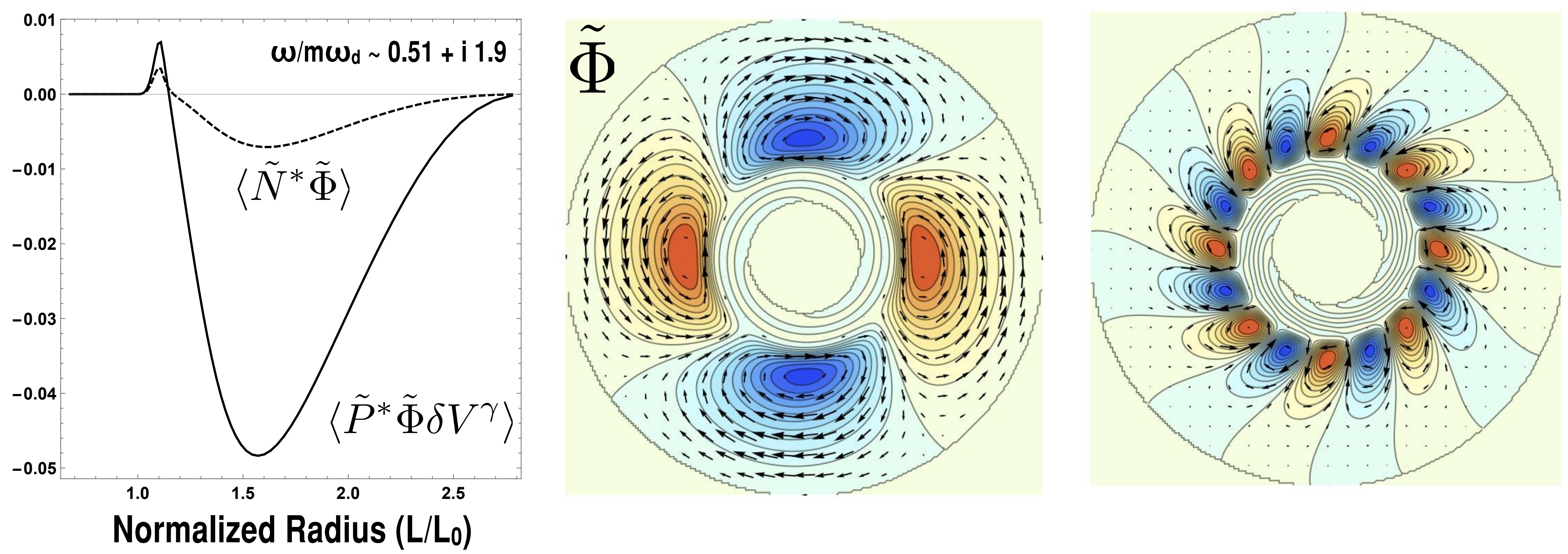
Cool Core (Peaked n)

Strong or Weak Radial variation of Drift Resonance

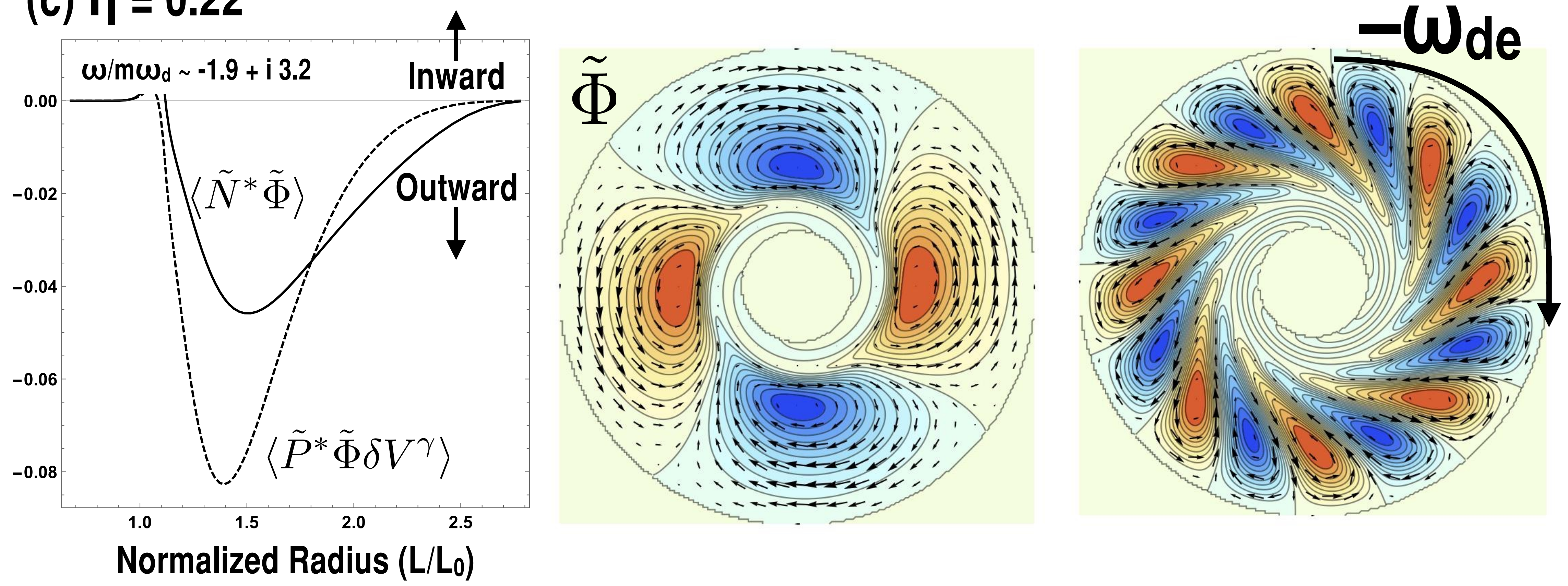
(a) η = 1.68



(b) η = 0.67

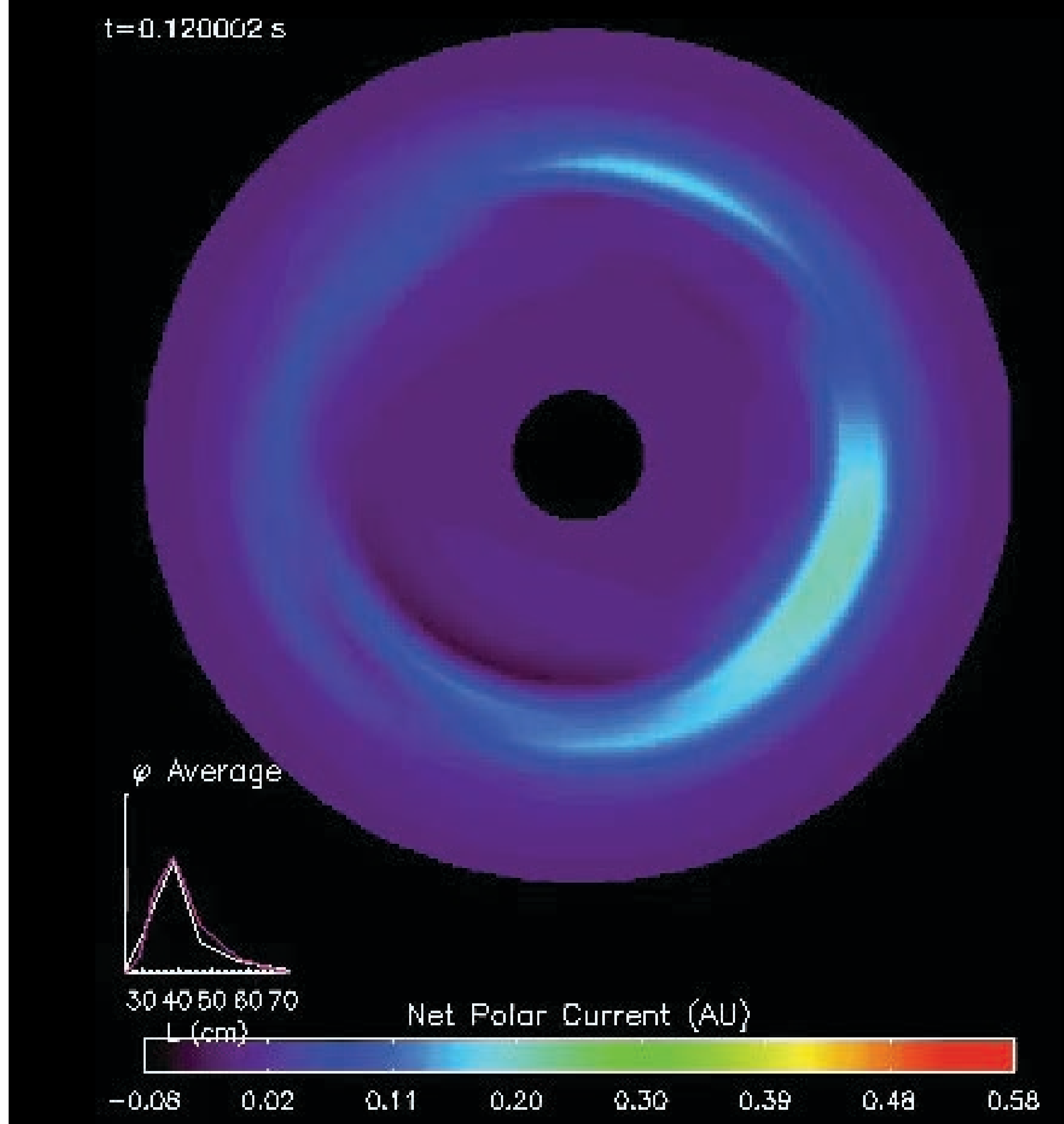


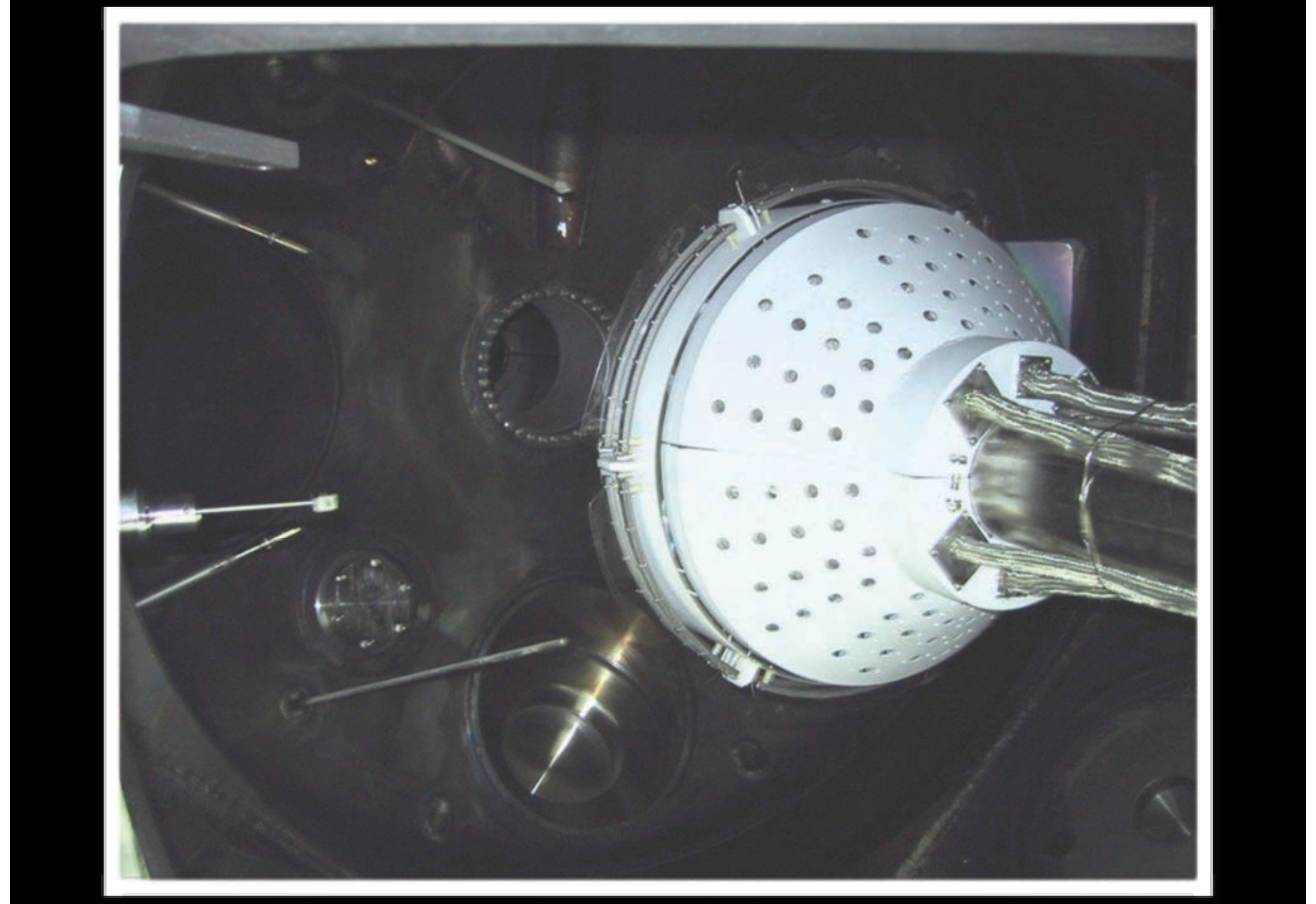
(c) η = 0.22

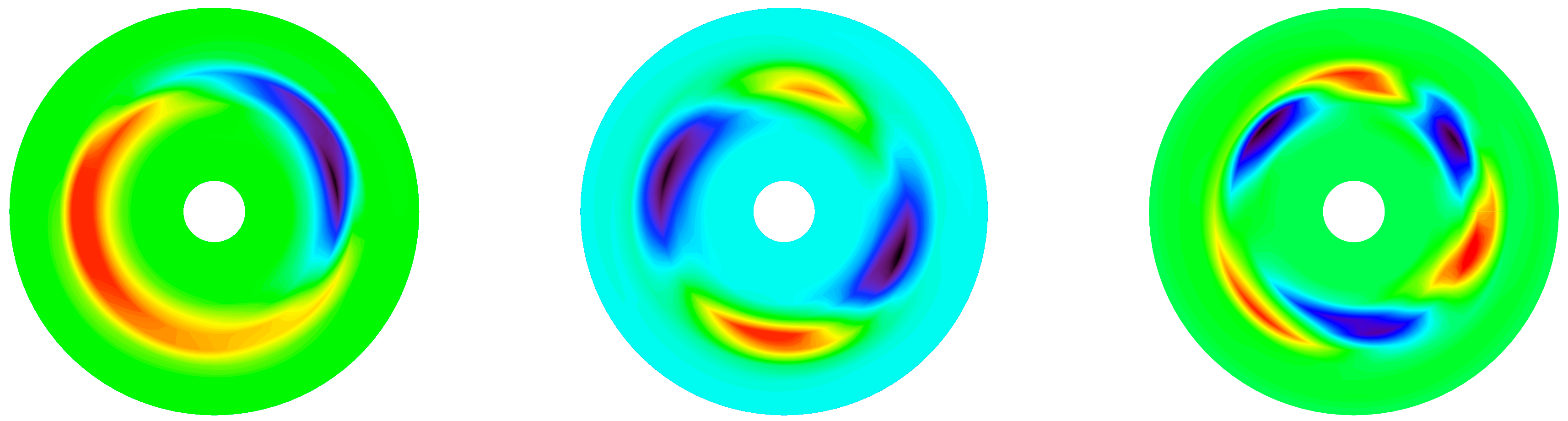


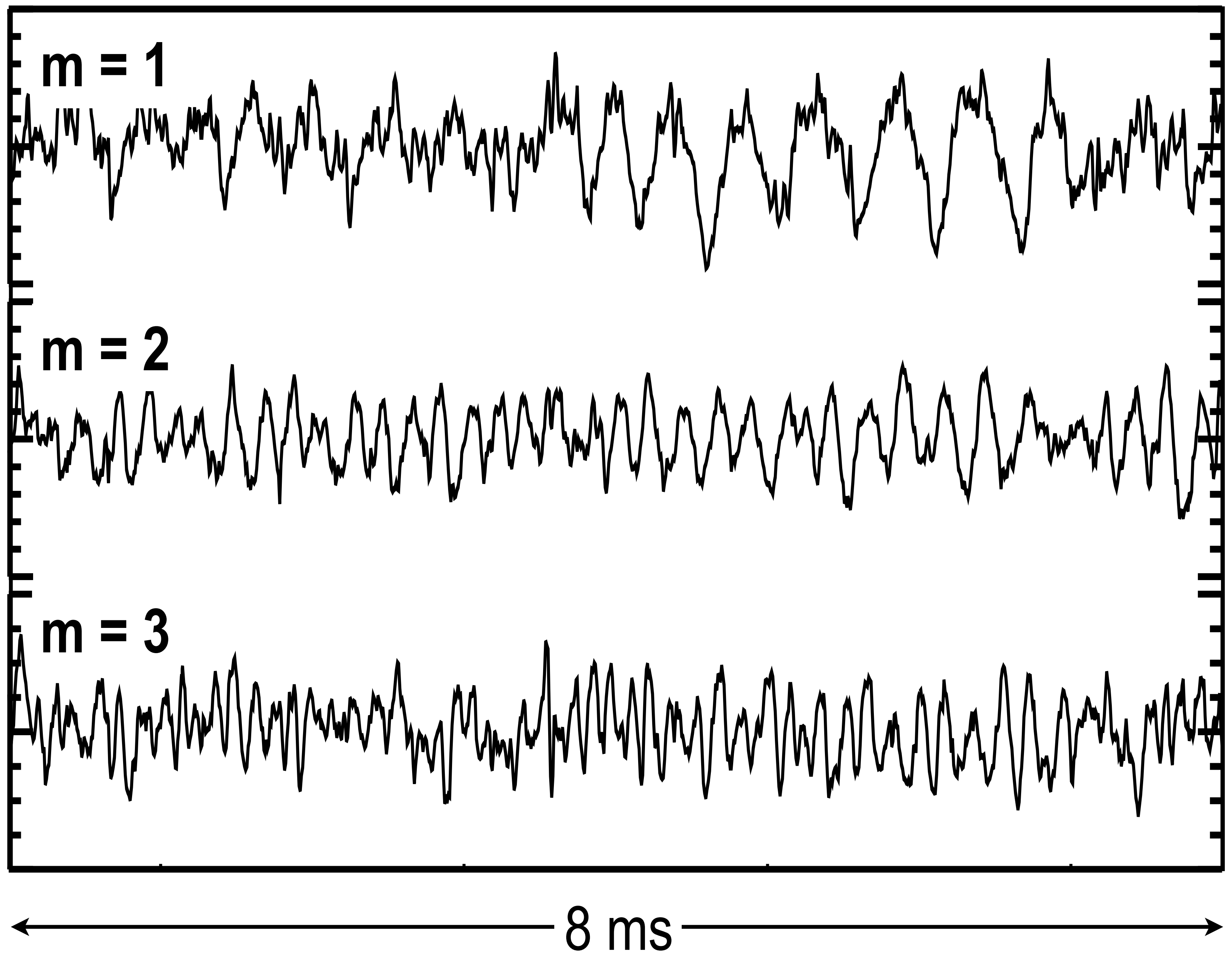
Whole Plasma Imaging of Interchange/Entropy Mode Structure
Rotating Global Modes, Chaotic Amplitudes and Phases, Inverse Cascade

Proton Aurora in the Lab

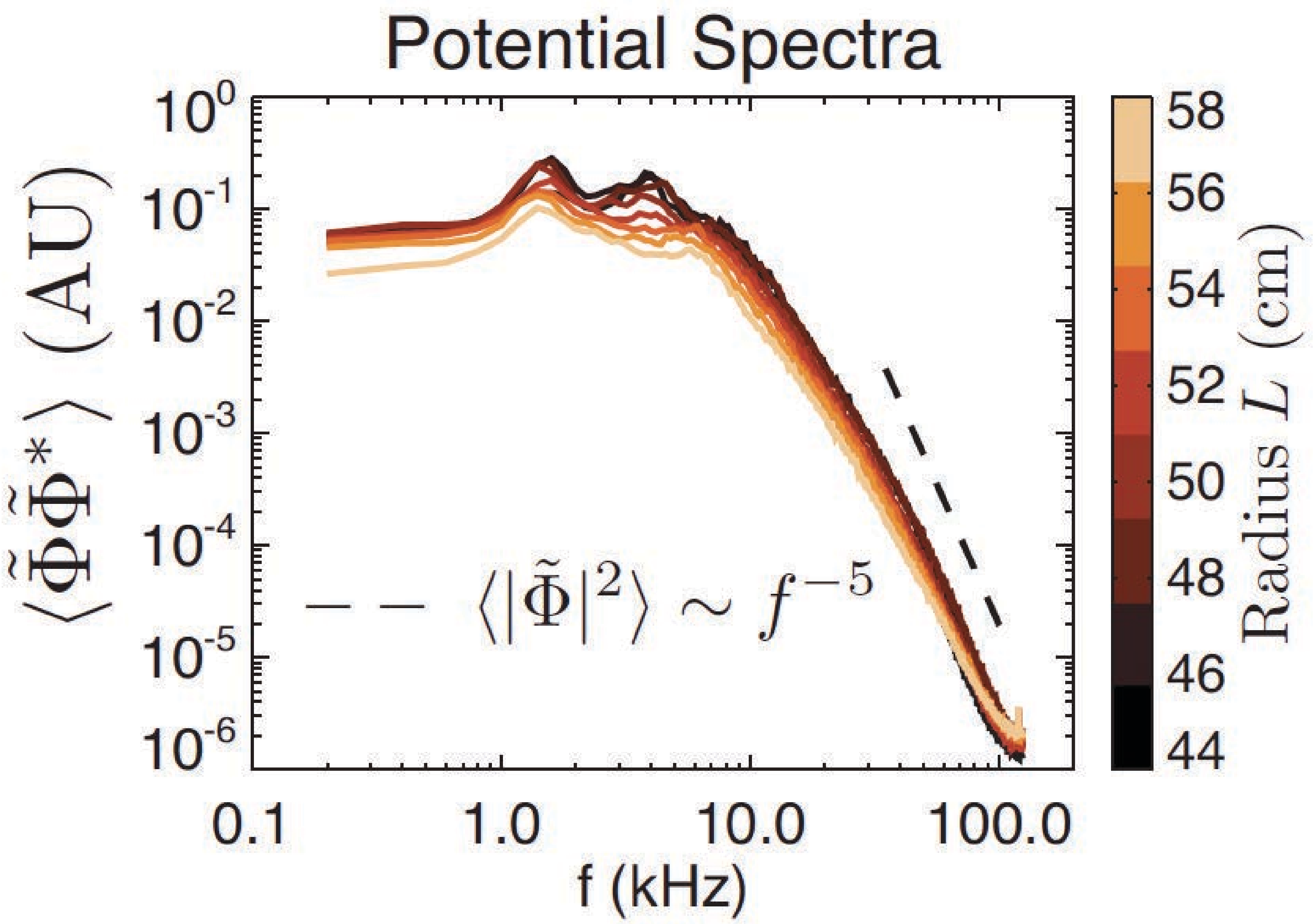


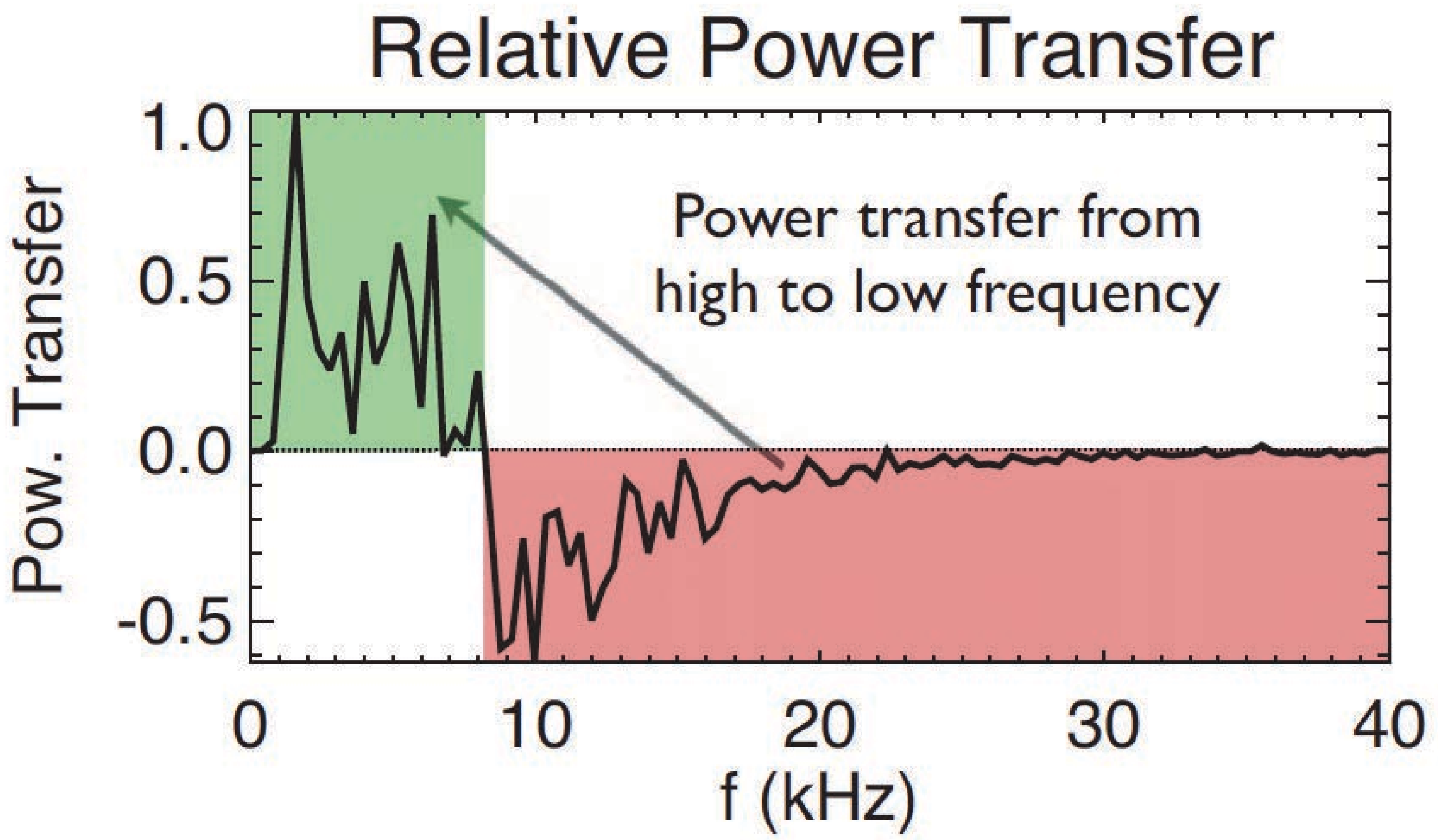






Global Structures are Chaotic





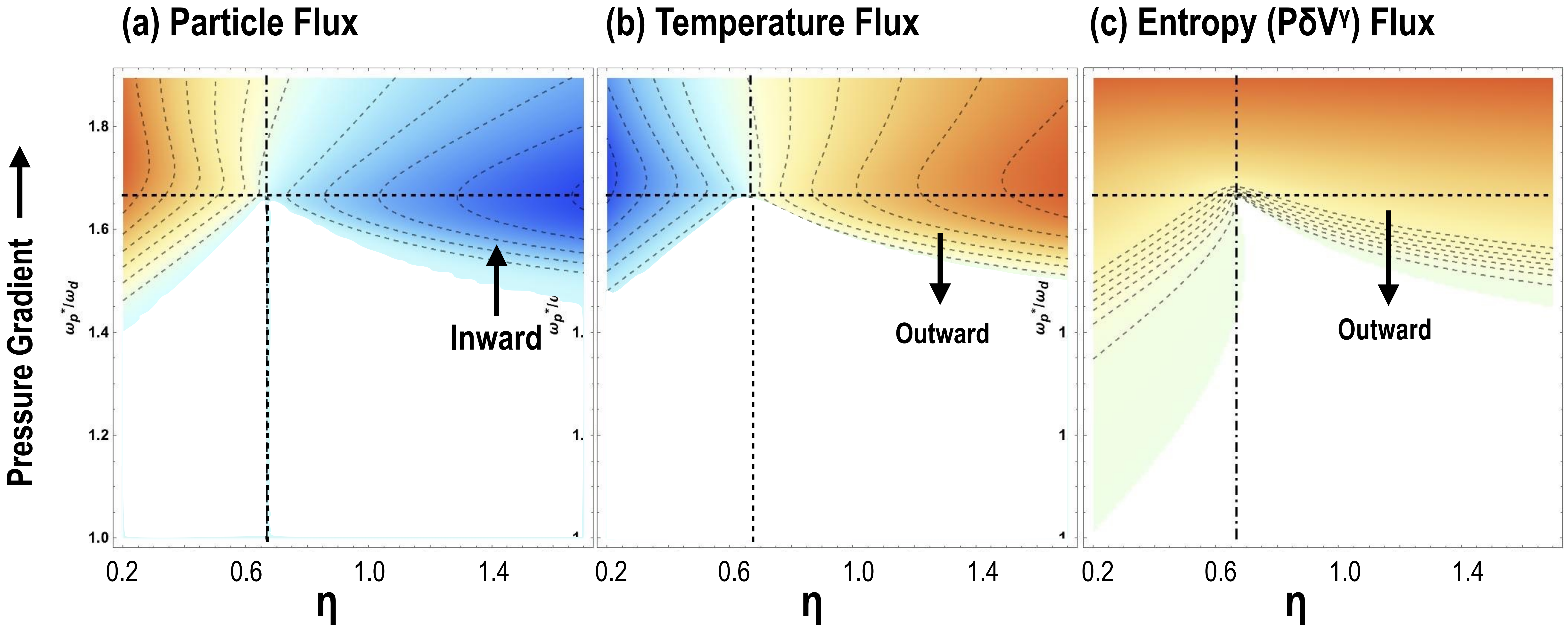
Grierson, M. Worstell, and M. Mauel, *Phys Plasmas* **16**, 055902 (2009).

Global Quasilinear Flux with Drift-Kinetic Closure reproduces GS2 Gyro-Kinetics

Quasilinear Flux

$$\Gamma_n = \sum_m \Re\{im\tilde{\Phi}_m\tilde{N}_m^*\}$$

$$\Gamma_p = \sum_m \Re\{im\tilde{\Phi}_m\tilde{P}_m^*\}$$


(a) Particle Flux

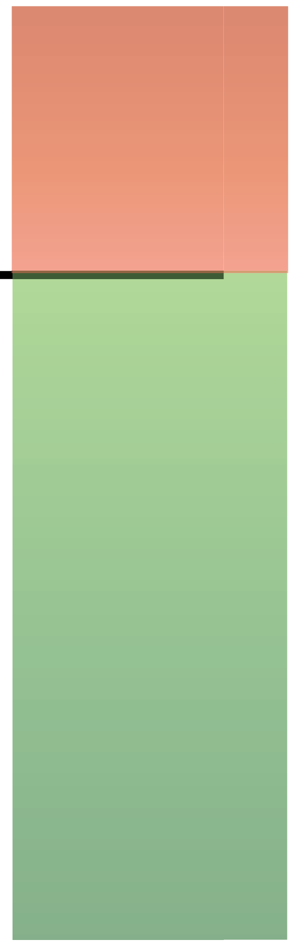
(b) Temperature Flux

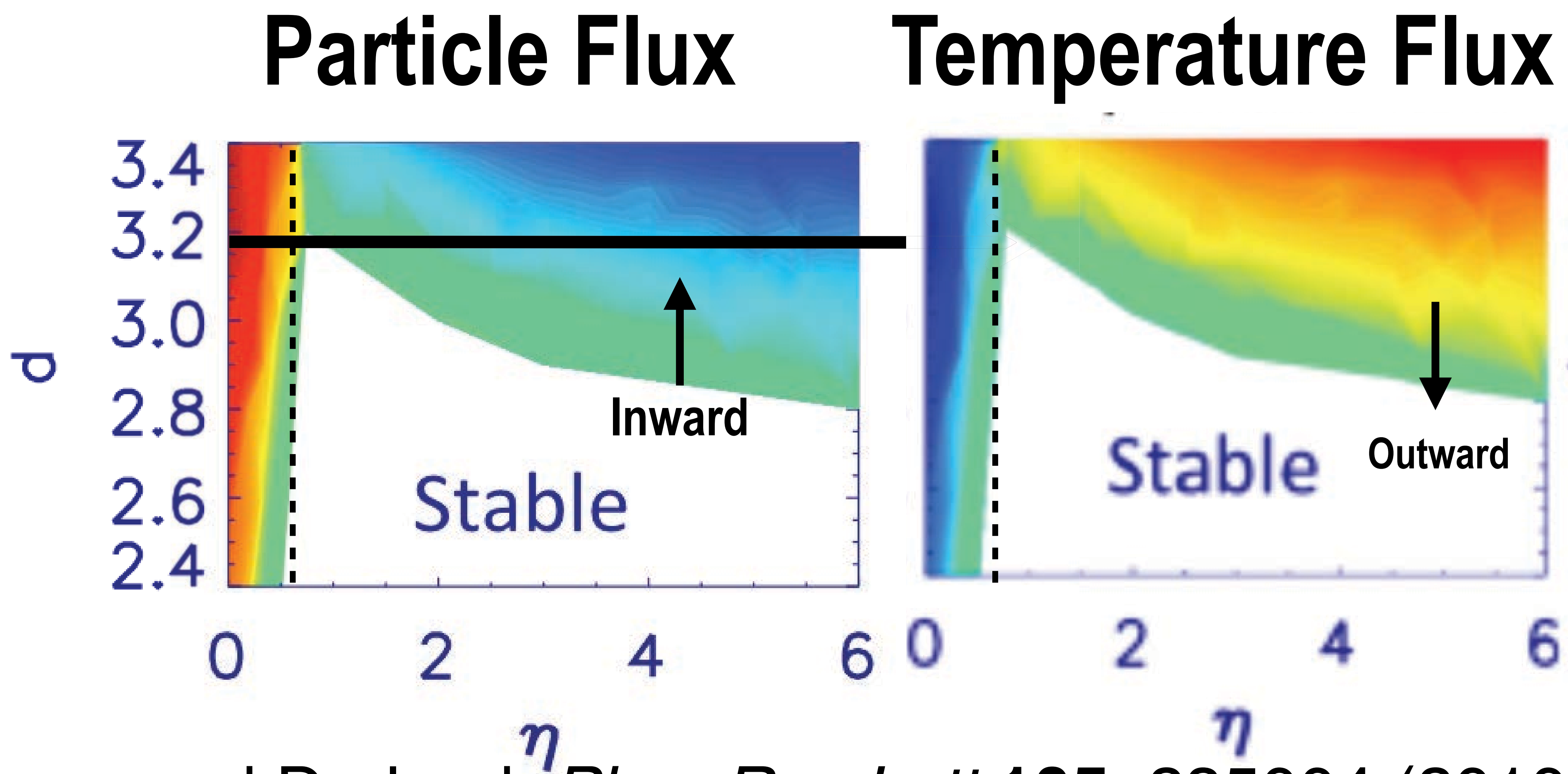
(c) Entropy ($P\delta V^\gamma$) Flux

MHD unstable $\Delta(PV^{5/3}) > 0$

MHD stable $\Delta(PV^{5/3}) < 0$

$$d \equiv -\frac{\Delta \ln P}{\Delta \ln V}$$




Particle Flux

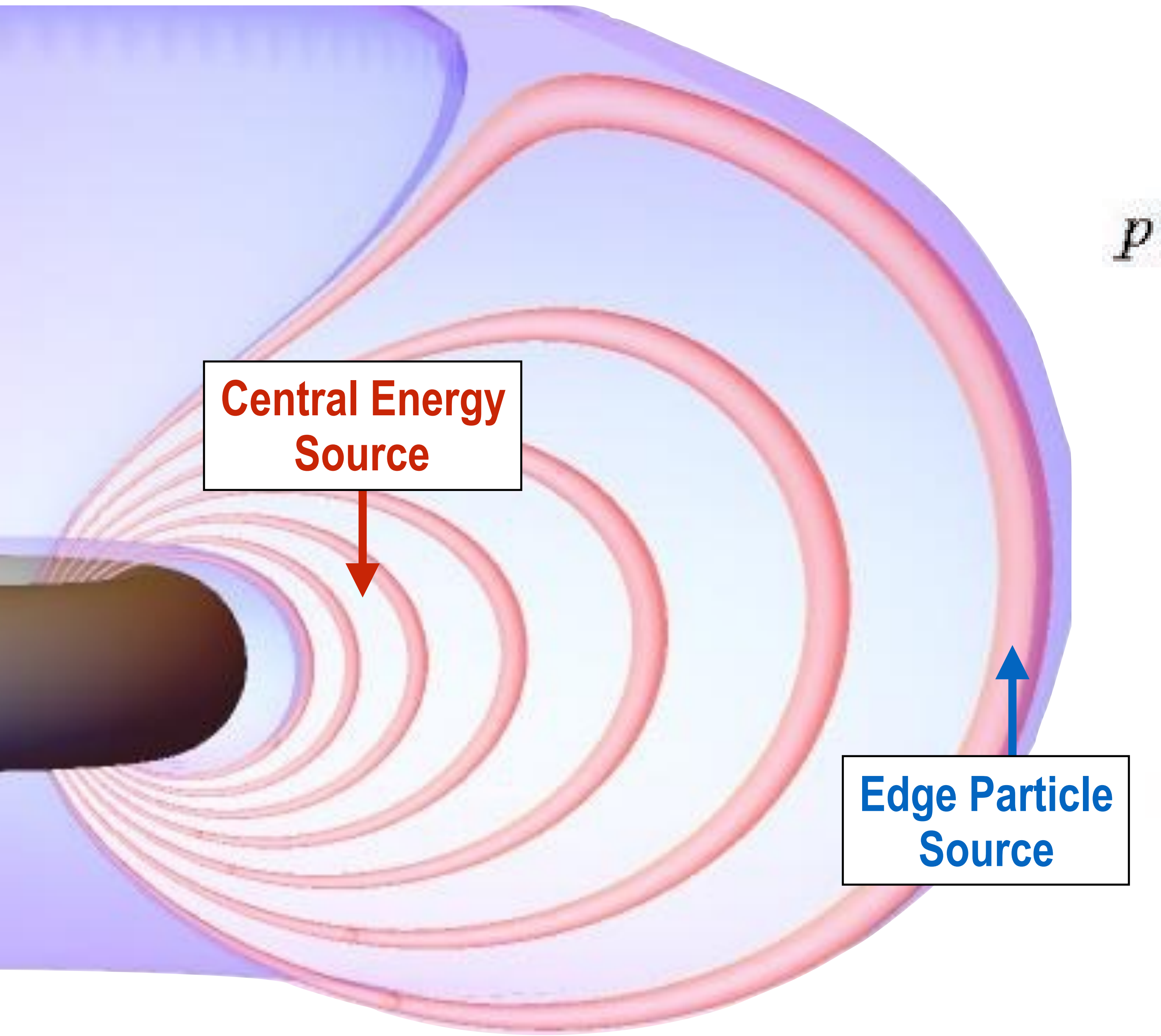
Temperature Flux

Nonlinear Gyrokinetic Flux (GS2)

Kobayashi, Rogers, and Dorland, *Phys Rev Lett* **105**, 235004 (2010)

Solar wind drives radial diffusion in planetary magnetospheres, *but in the lab*…

Central heating excites instability that drives Centrally-Peaked Pressure and Density as the Final State of Turbulent Self-Organization



“warm core”
η > 2/3

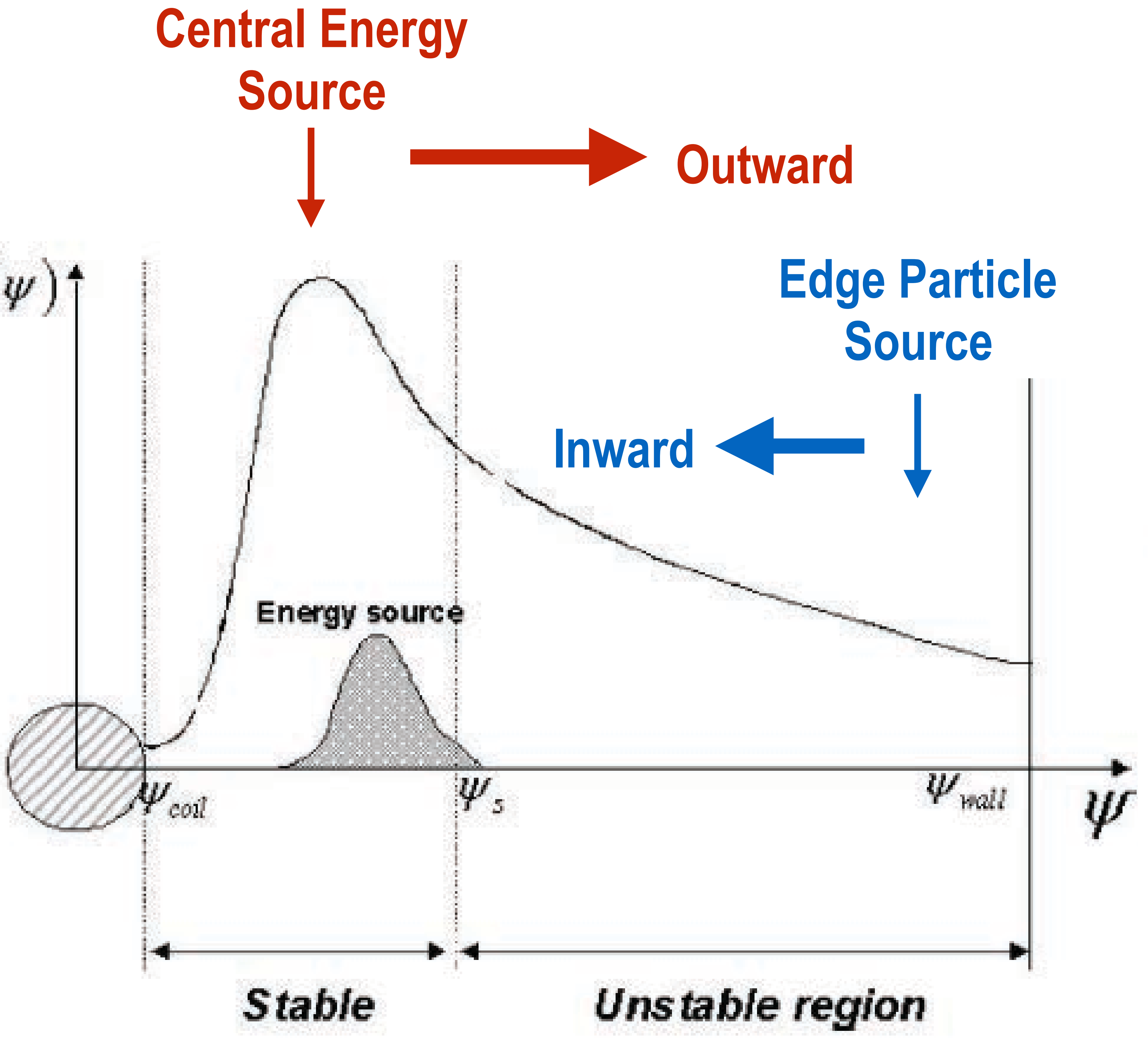


FIG. 1. The LDX schematic profile.

Quasilinear MHD Interchange Turbulence

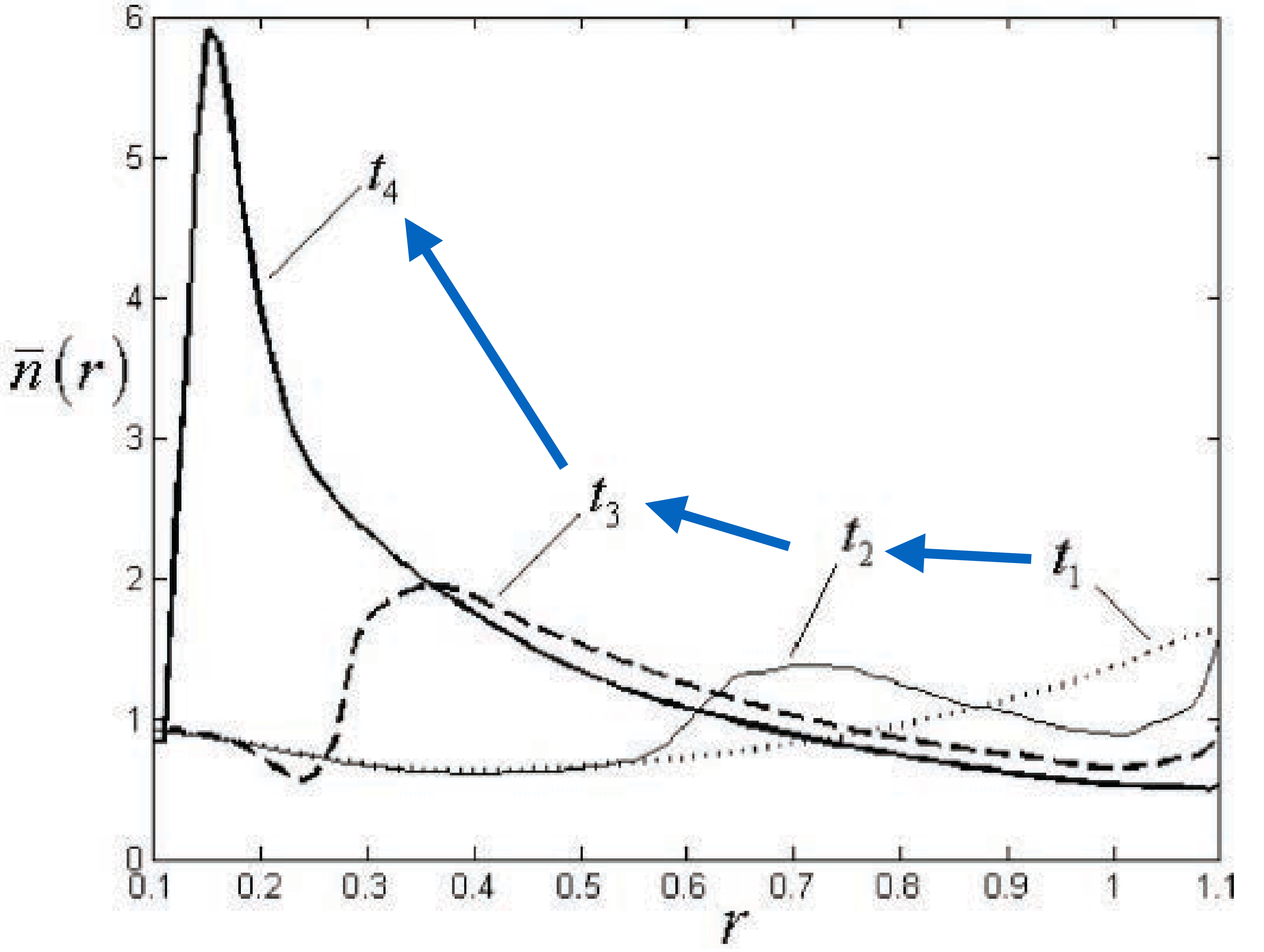


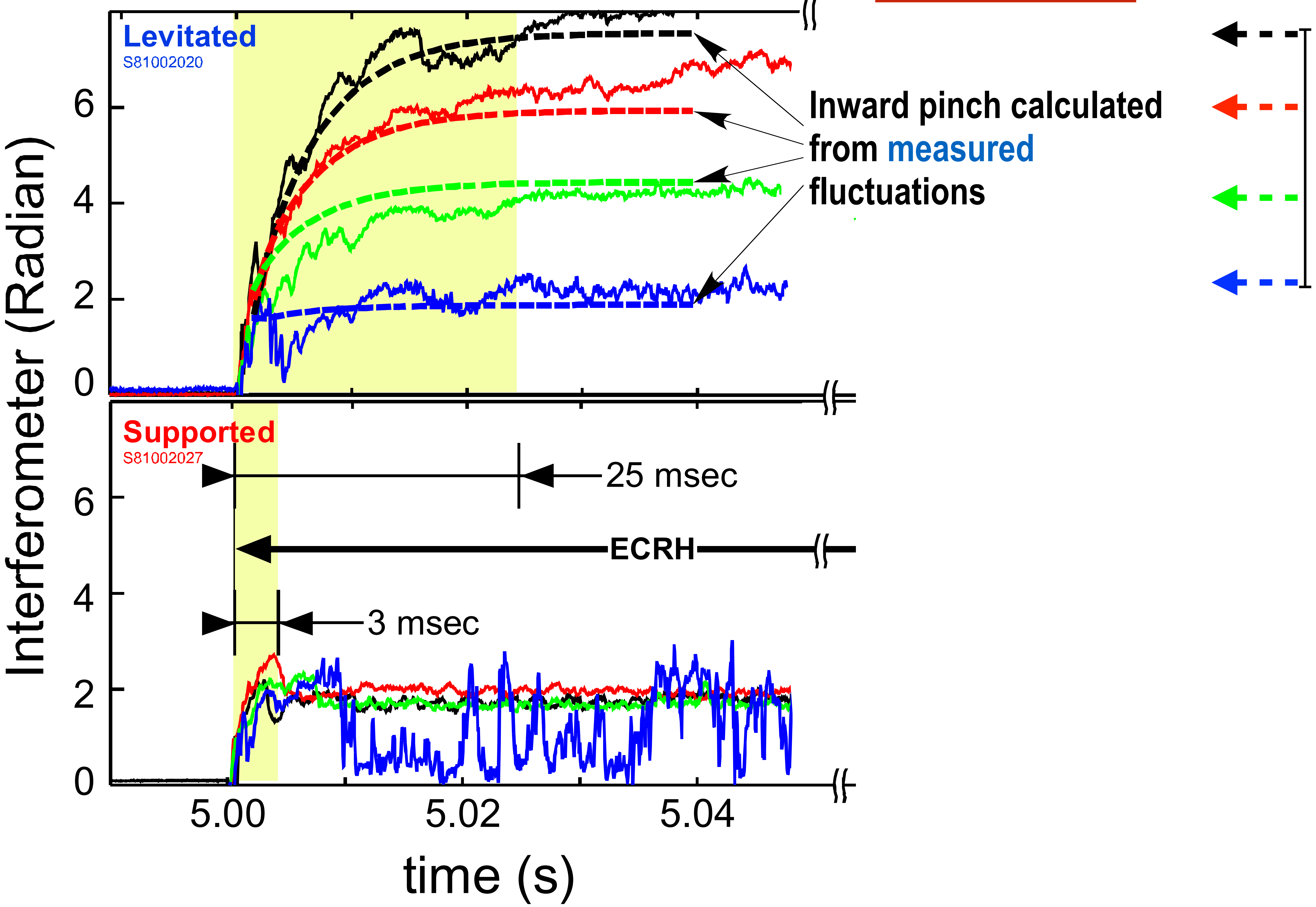
FIG. 5. The snapshots of the “self-organizations” process. Time t_1: before an instability is excited; t_2–t_4: different stages of self-organization.

Alexie Kouznetsov (PhD MIT/Freidberg), *et al*, “Quasilinear theory of interchange modes in a closed field line configuration,” *Phys Plasmas*, **14**, 102501 (2007)
John Tonge (PhD UCLA/Dawson), *et al.*, “Kinetic simulations of the stability of a plasma confined by the magnetic field of a current rod,” *Phys Plasmas* **10**, 3475 (2003).

Rate of Inward Turbulent Pinch Agrees with Measured Diffusion Coefficient

With levitated dipole, inward turbulent transport sets profile evolution

“warm core”
$\eta > 2/3$



Inward pinch calculated from **measured** fluctuations

$$D_\psi \sim 0.047\ (\mathrm{Wb}^2/\mathrm{s})$$

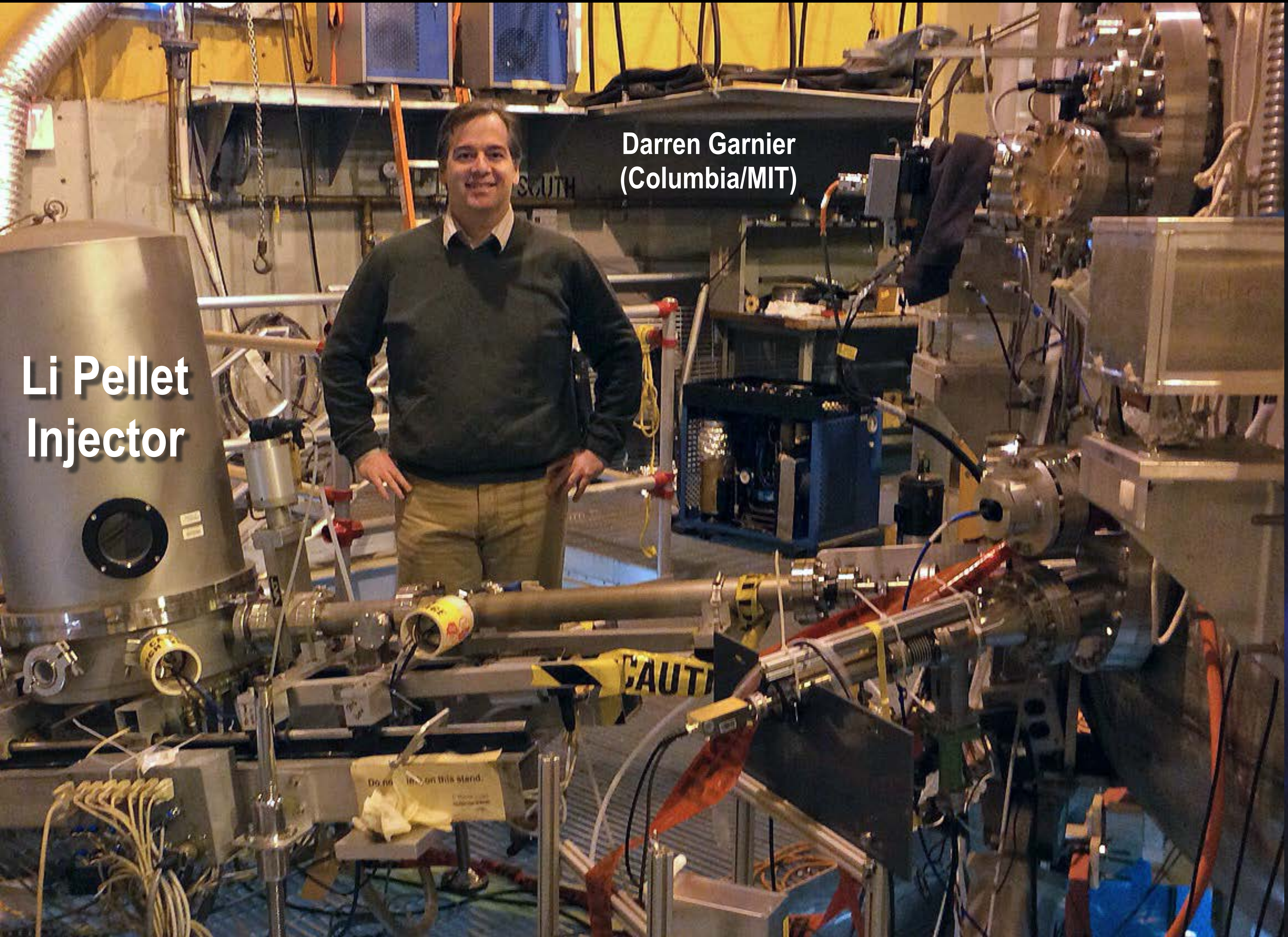
$$\frac{\partial}{\partial t}(nV) = \underbrace{\langle S\rangle}_{\text{Edge Source}} + \frac{\partial}{\partial \psi} D_\psi \frac{\partial}{\partial \psi}(nV)$$

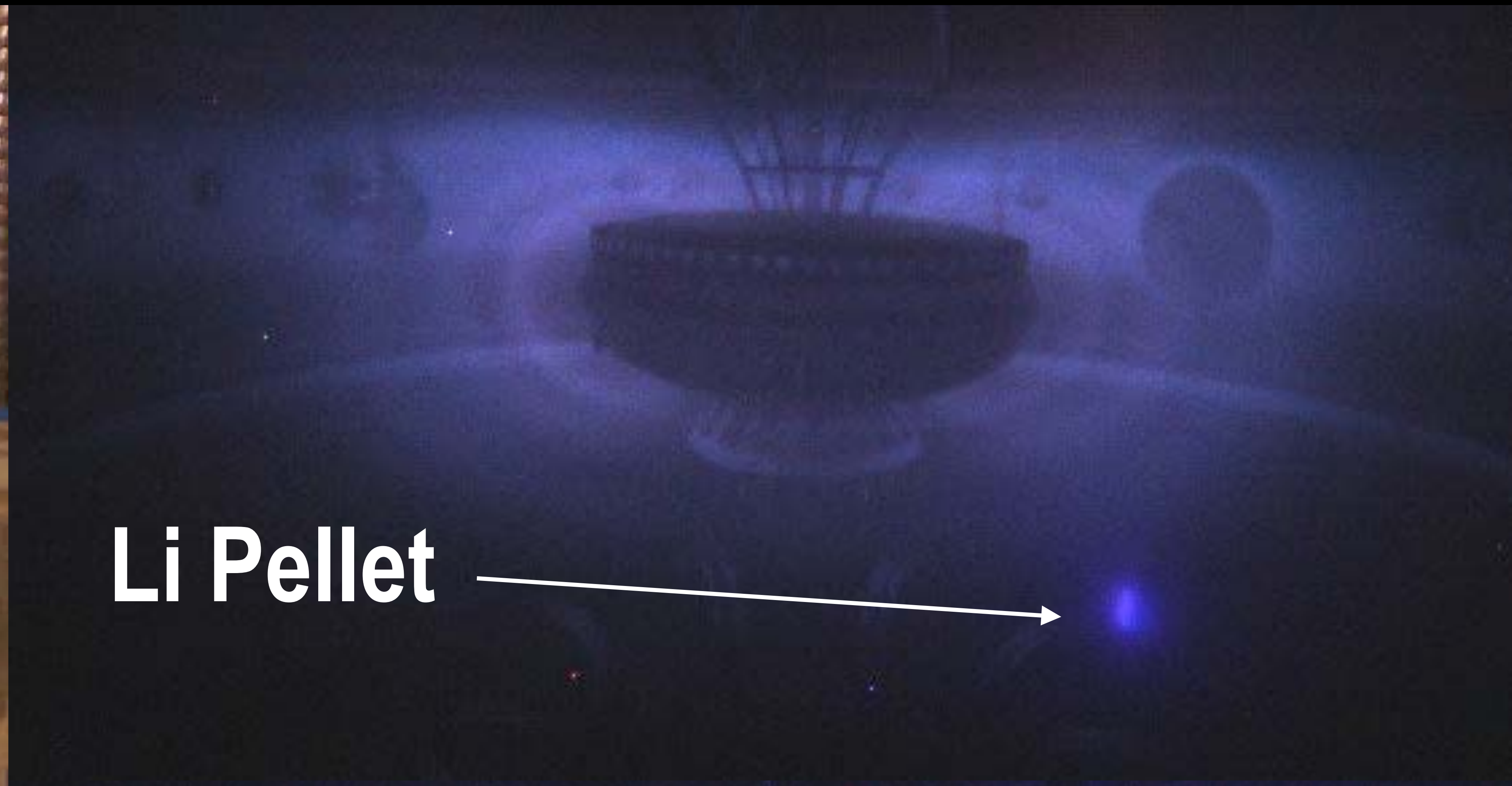
$$D_\psi = R^2 \langle E_\varphi^2 \rangle \tau_c$$

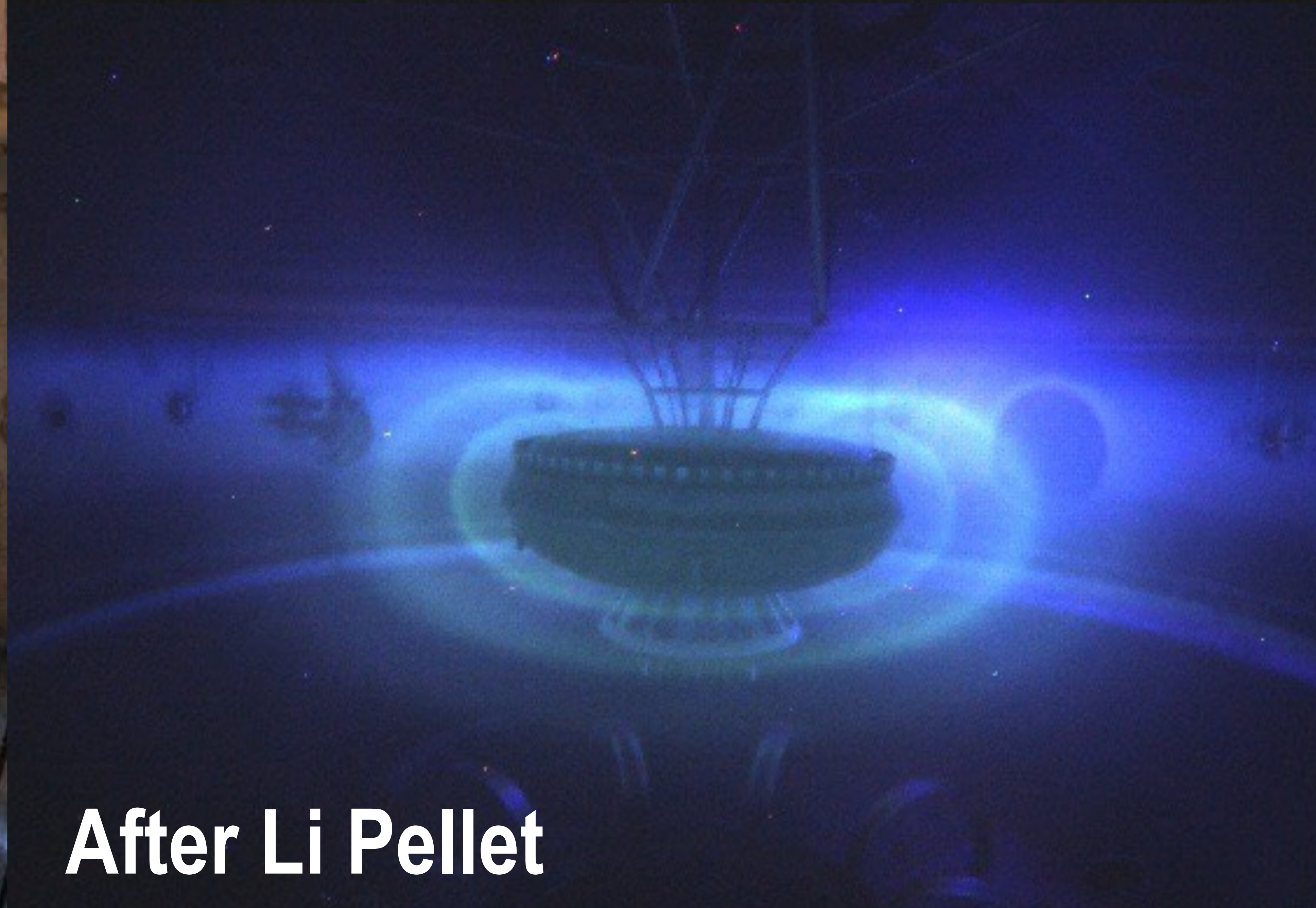
$|E_\varphi| \sim 55$ V/m (RMS) $\tau_c \sim 16$ μsec

Thomas Birmingham, “Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation,” *JGR*, **74**, (1969).
Alex Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nature Phys* **6**, (2010).

High Speed Pellet Injection Cools Core & Creates Internal Fueling and *Reverses* the Direction of Particle Diffusion

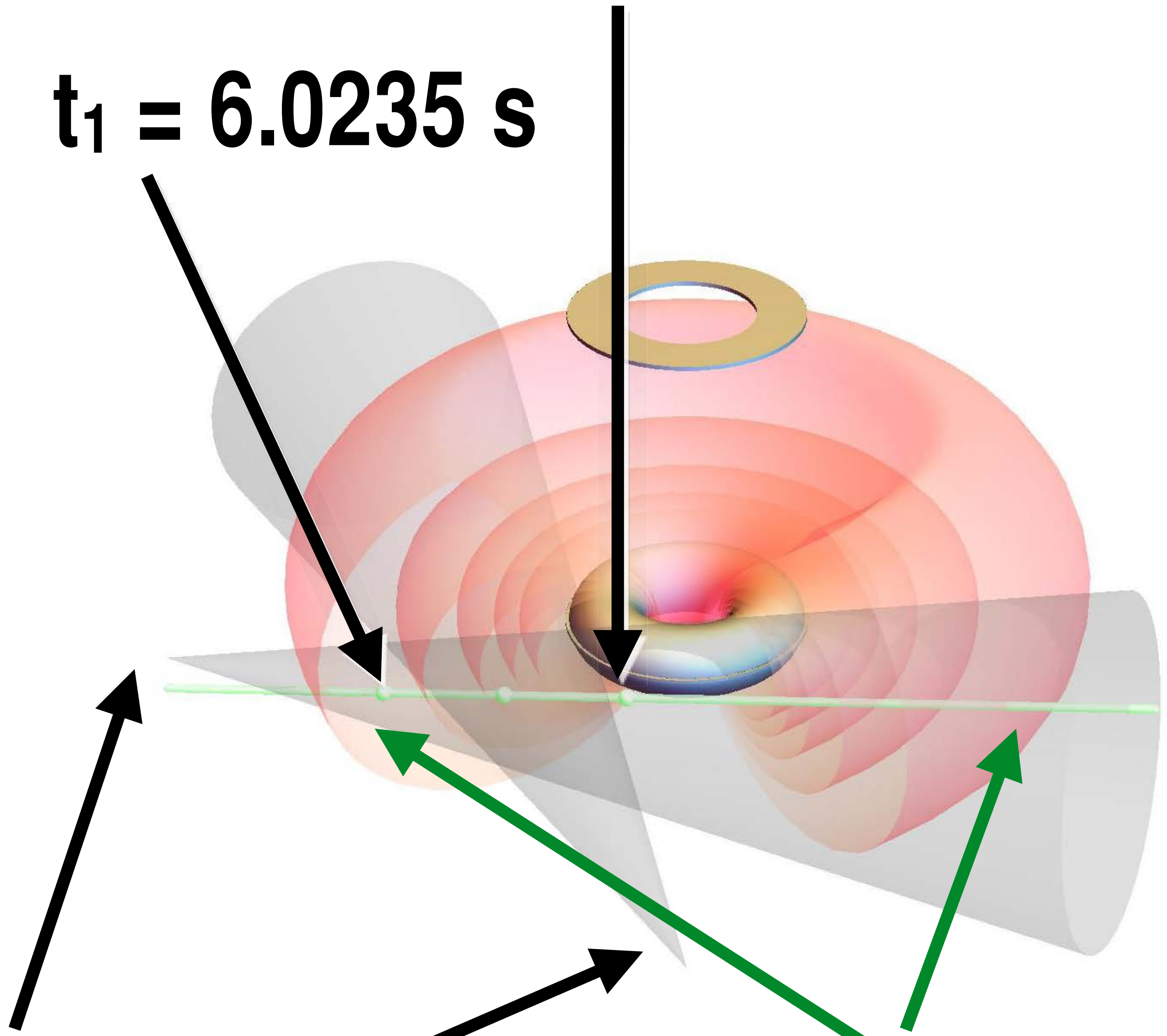






Li Pellet Injection Provides Internal Particle Source and Cools Plasma Core

1 mm^3



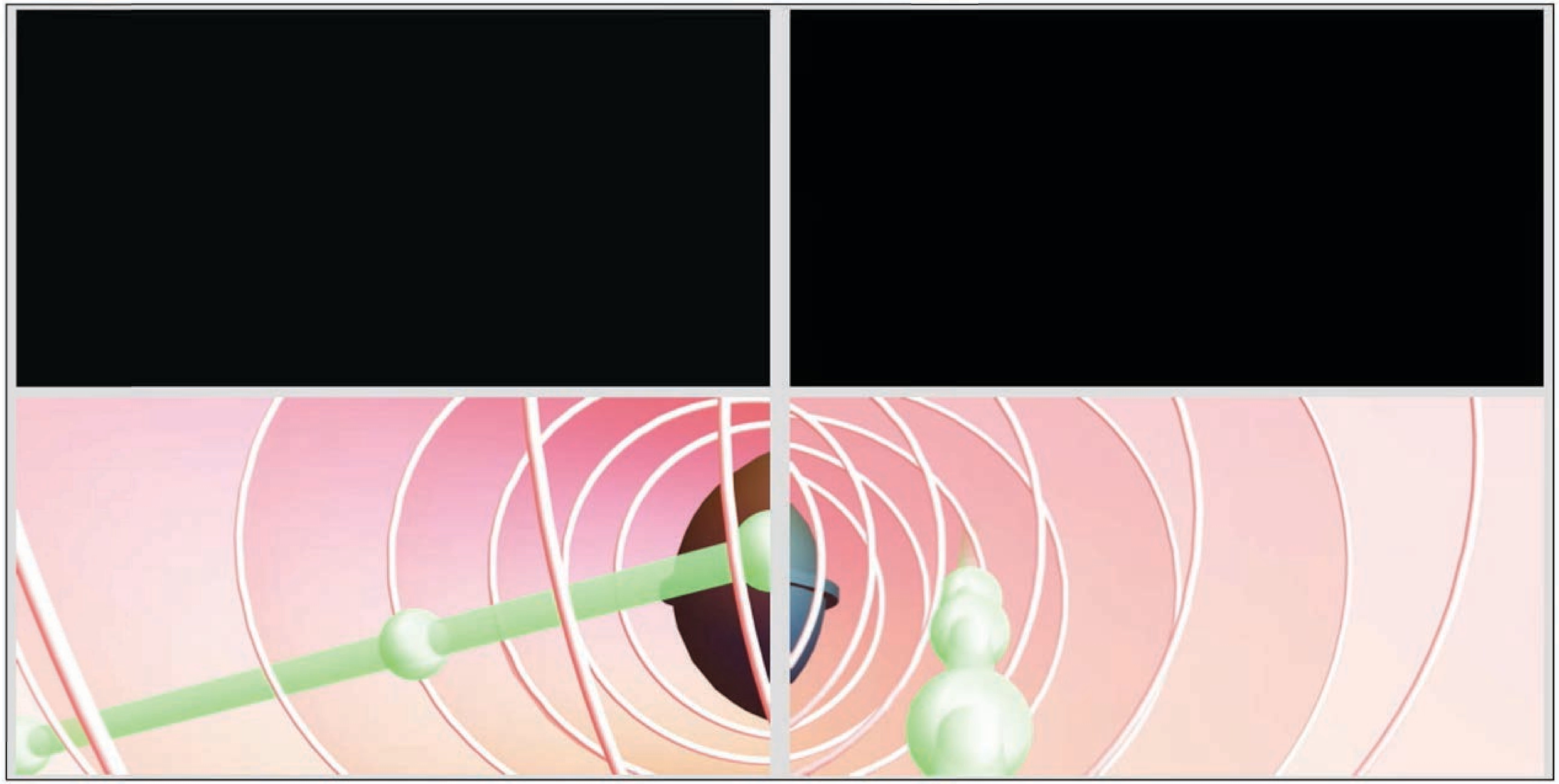
t_2 = 6.0305 s

t_1 = 6.0235 s

Fast Cameras

Li Pellet Trajectory

S140529016 Time = 6.01550 s

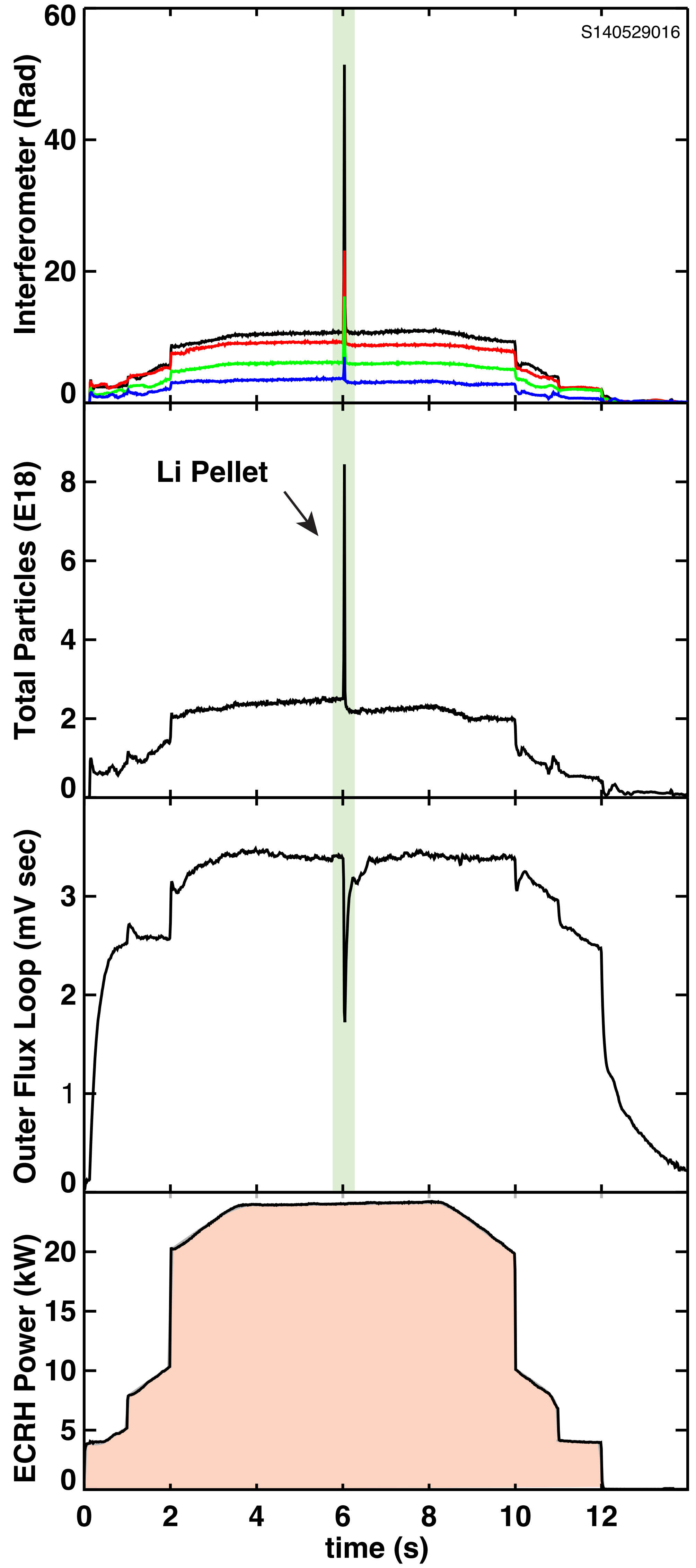


×5 Peak Density
×3 Electrons
÷3 Energy

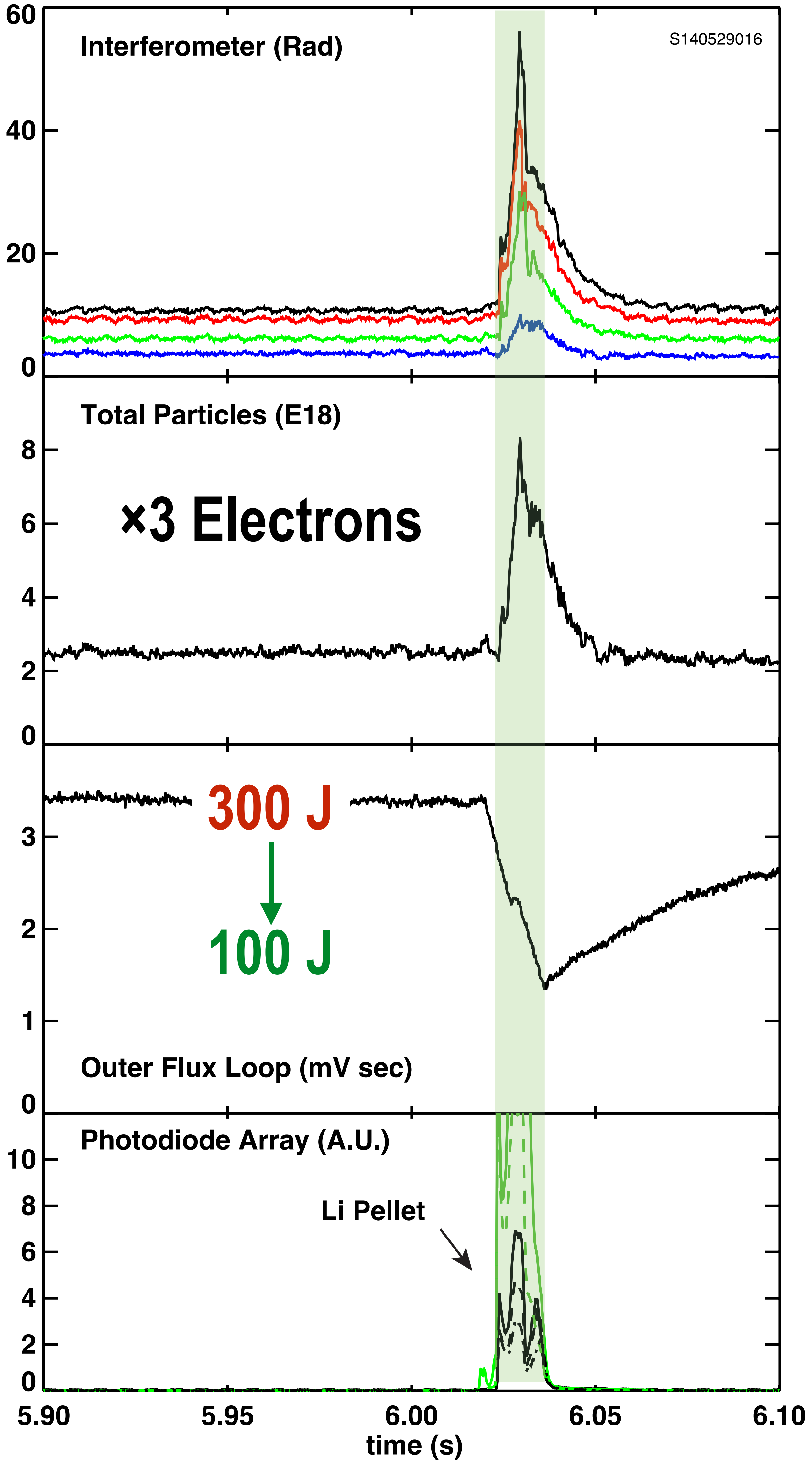
19 ms records pellet traveling at 175 m/s

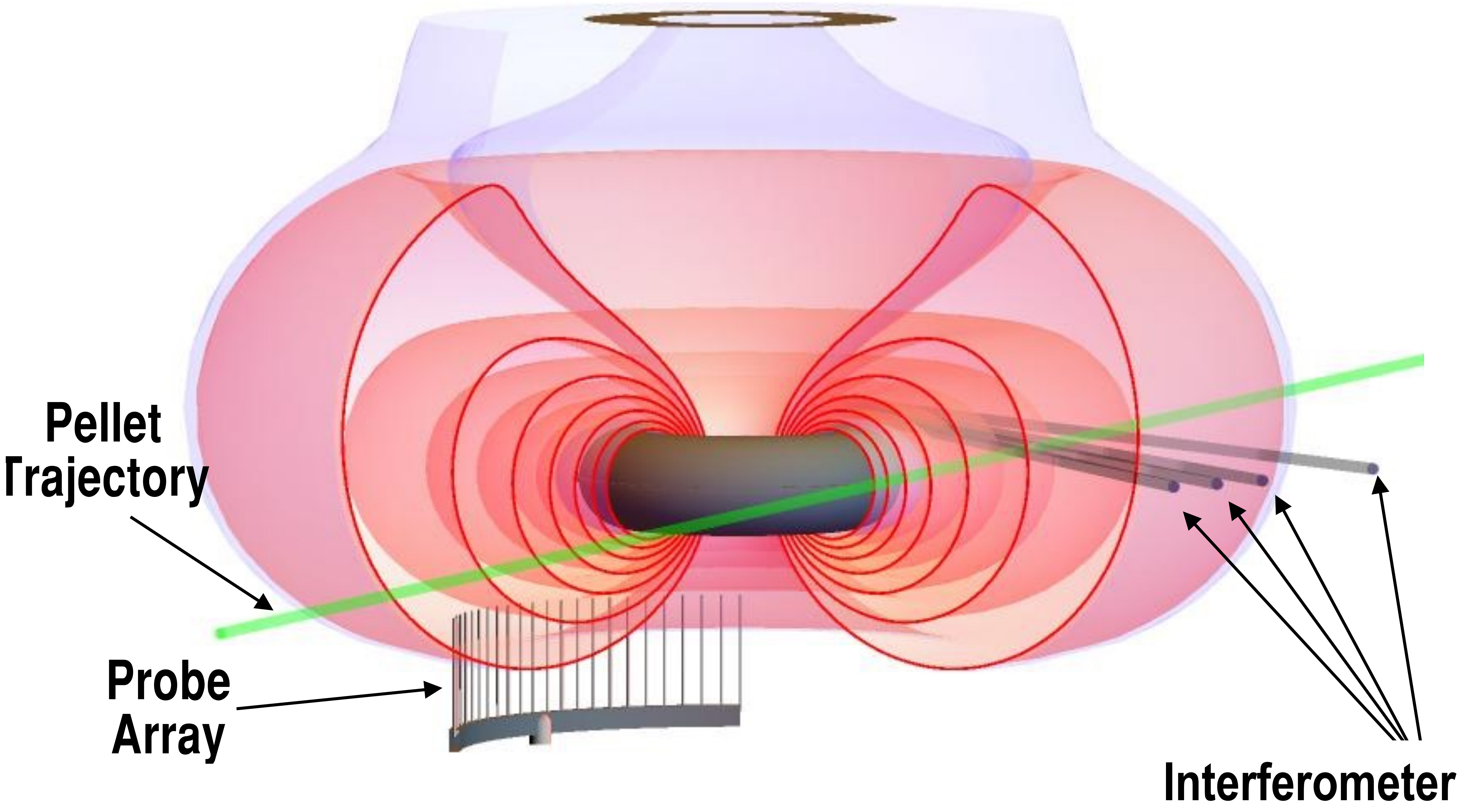
Li Pellet Injection Provides Internal Particle Source and Cools Plasma Core

(a) Overview of Li Pellet Injection



(b) Close-up of Li Pellet Injection

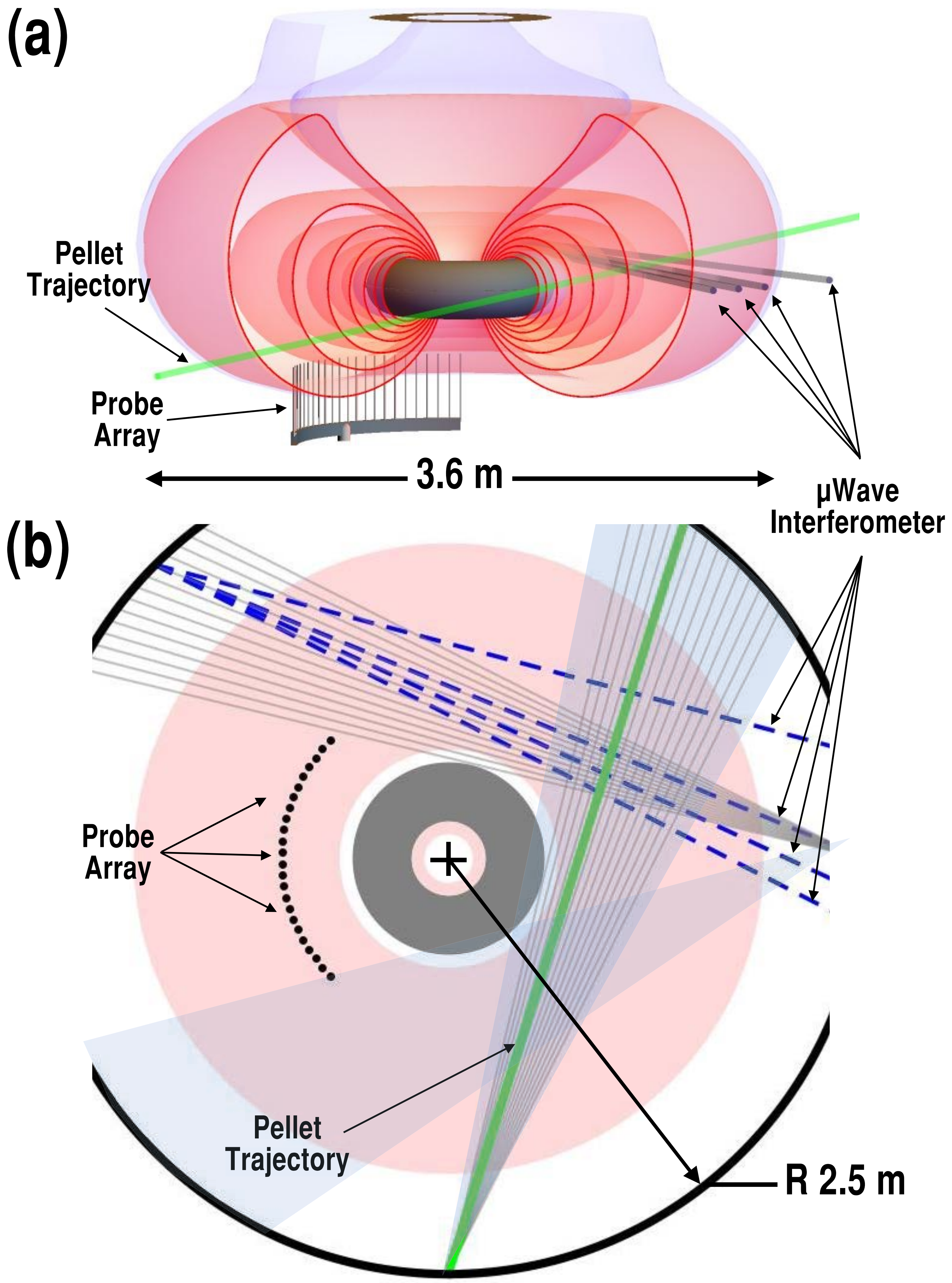




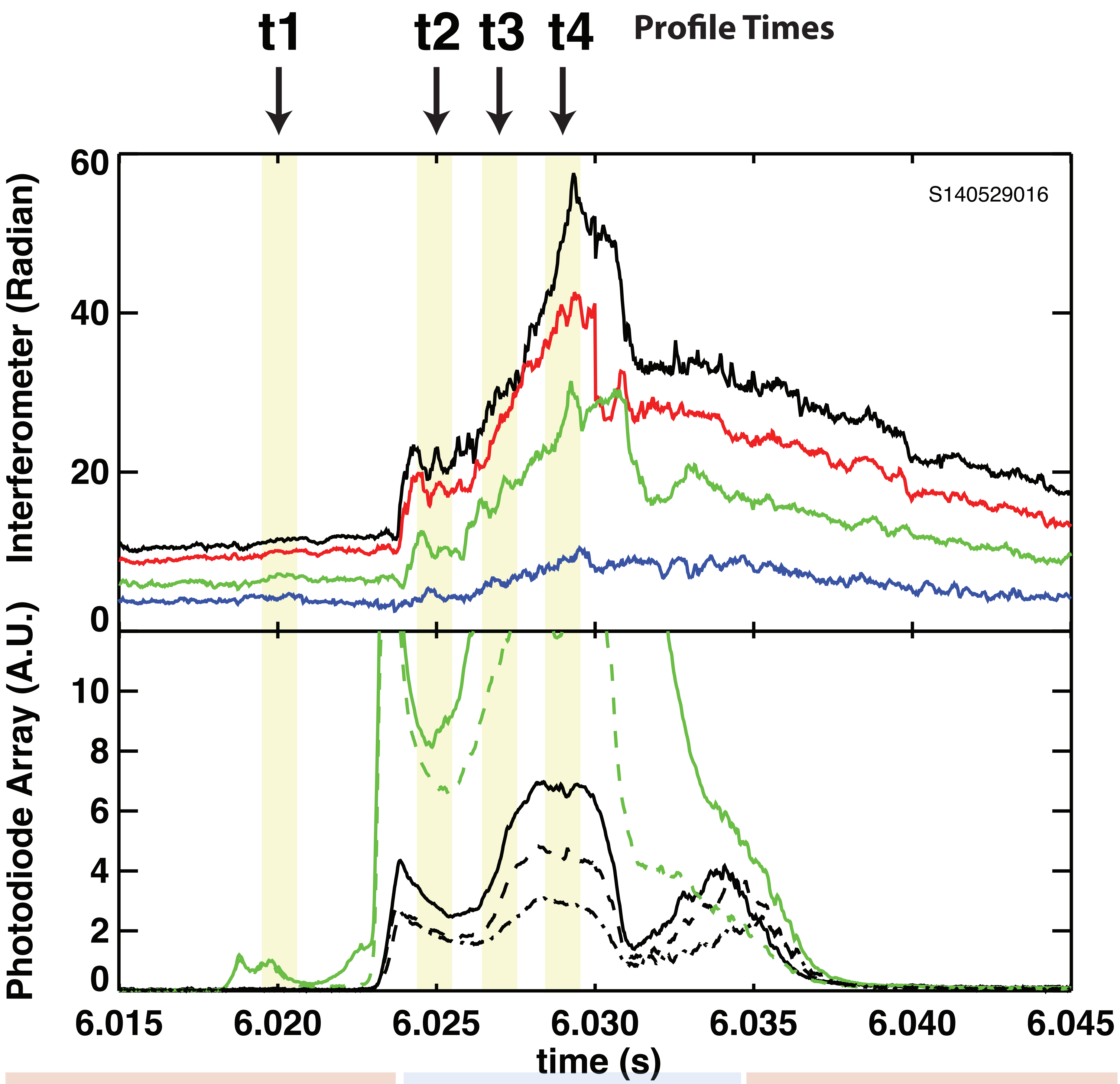
×3 Electrons
÷3 Energy

Drift Parameter η < 2/3 “Reverses” with Pellet Injection

Δ(nV) ~ 0

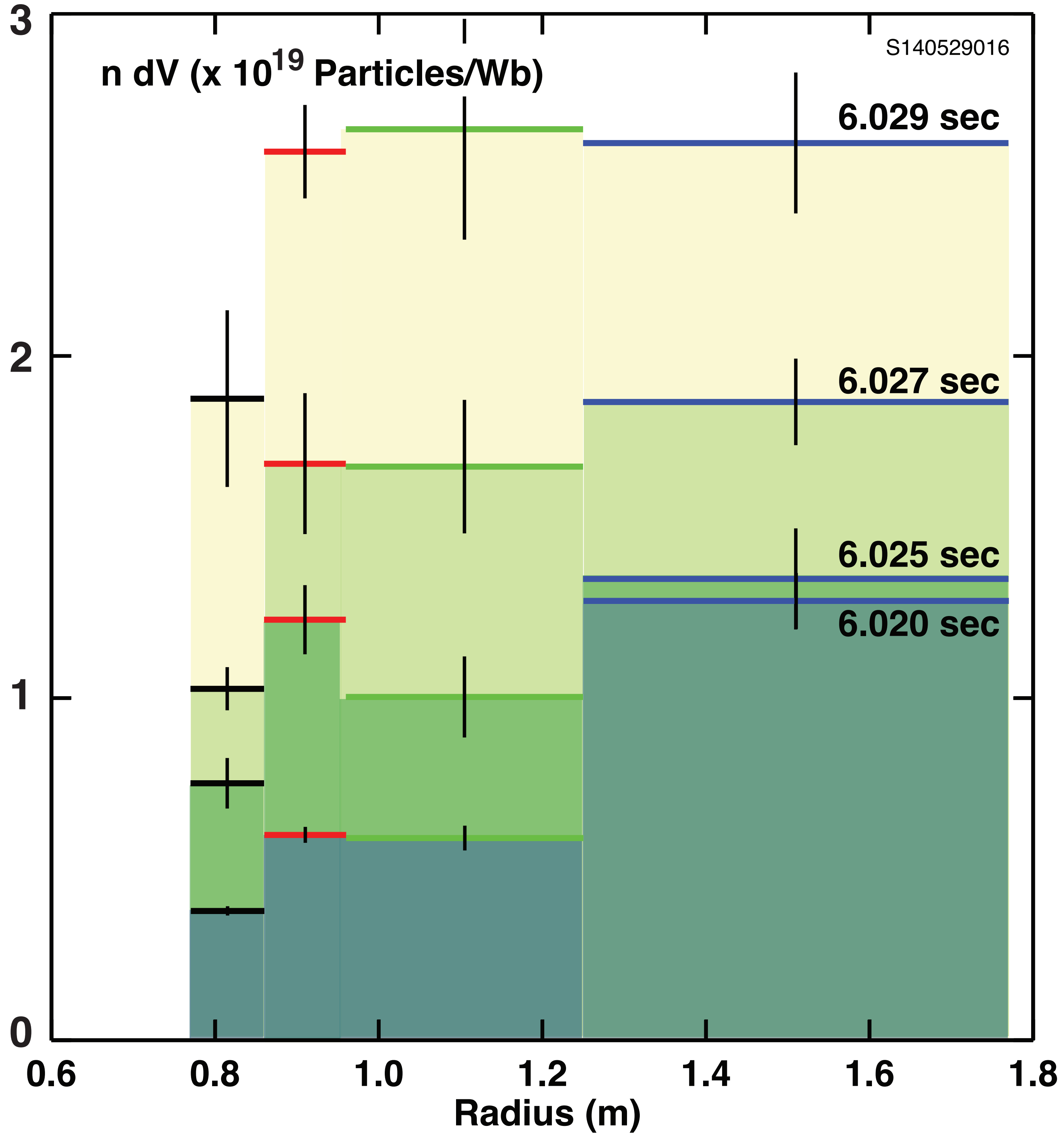


(a) Line Density and Photodiode Array

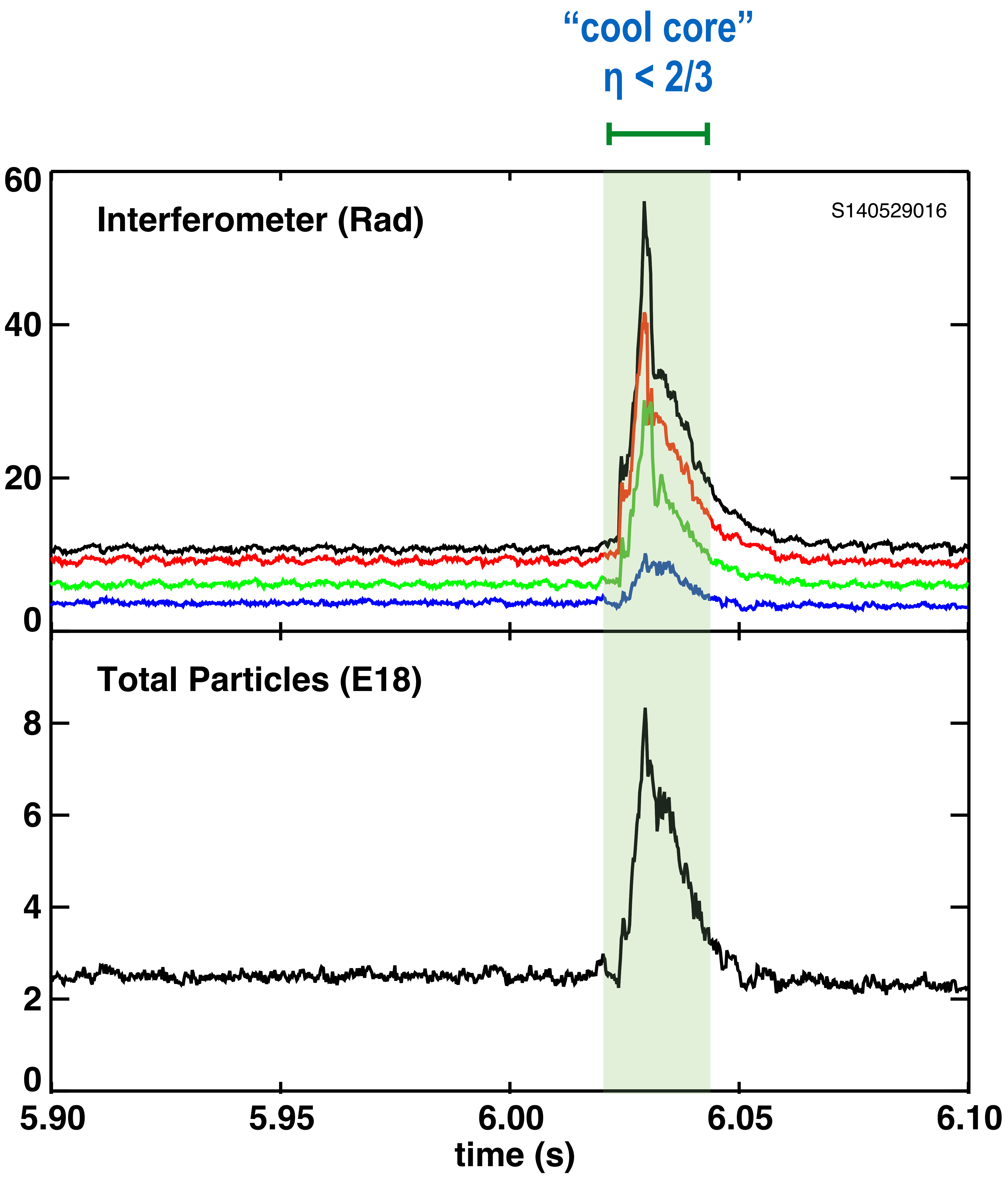


η > 2/3 | η < 2/3 | η > 2/3

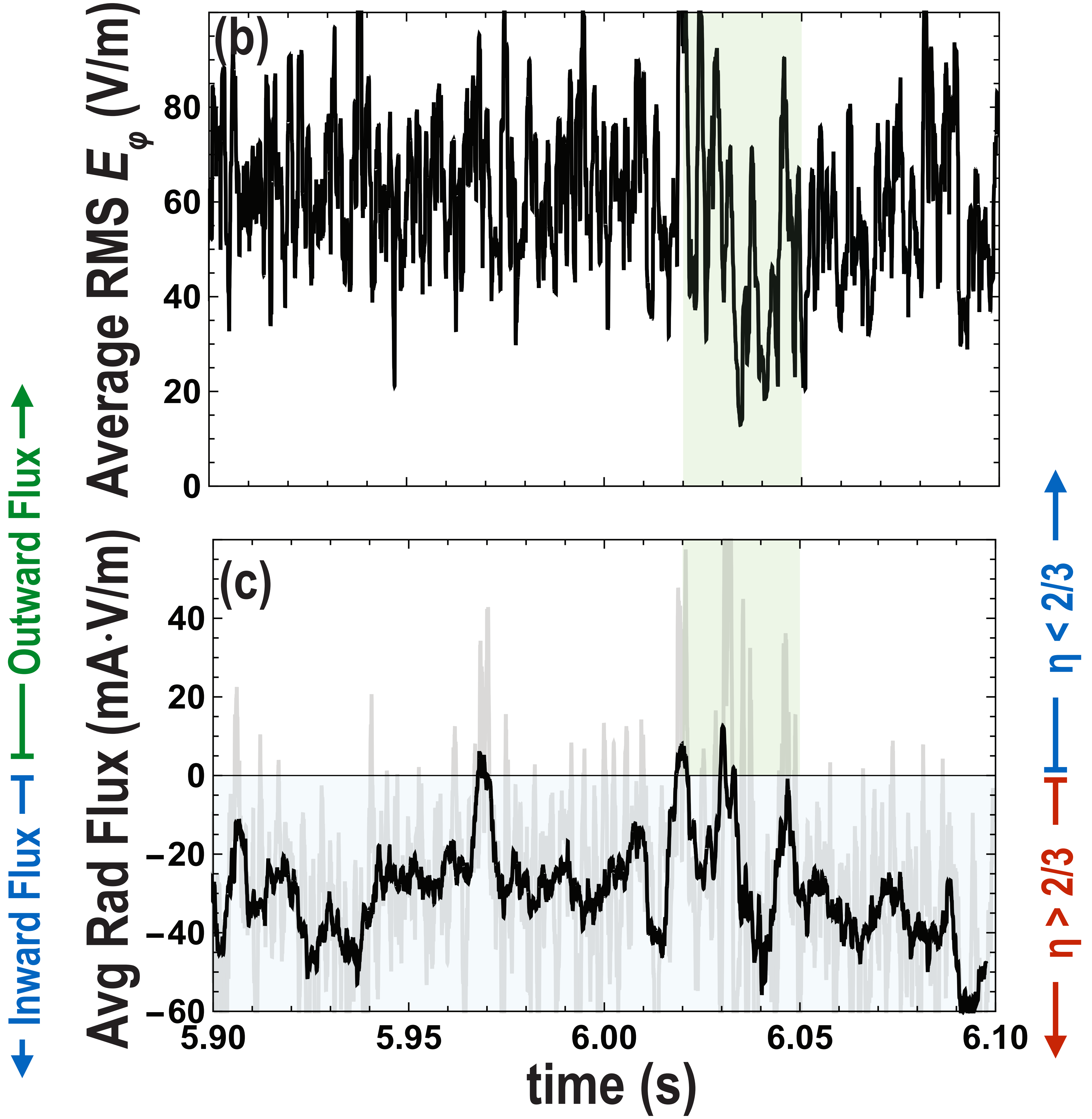
(c) Particle Number per Weber Evolution



“Cool Core”/Li Pellet Fueling ***Reverses*** Direction of Particle Flux



$$\langle \Gamma_\psi \rangle = \langle\langle R E_\phi I_{sat} \rangle\rangle_{(\Delta\phi,\Delta t)}$$

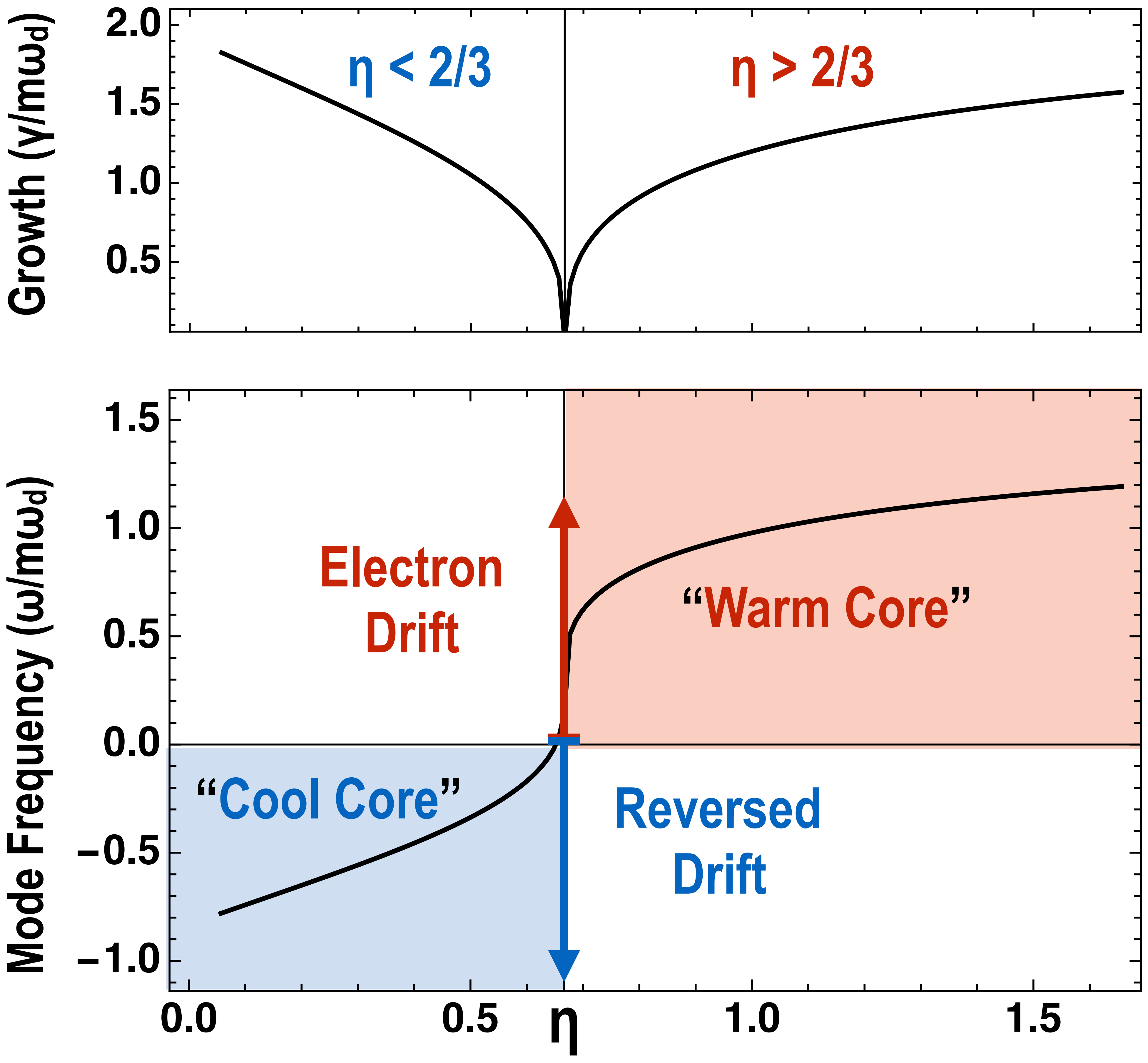


When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η

$$\Delta W_p \sim \Delta(PV^{5/3}) \sim 0$$

η < 2/3
Outward Particle Flux

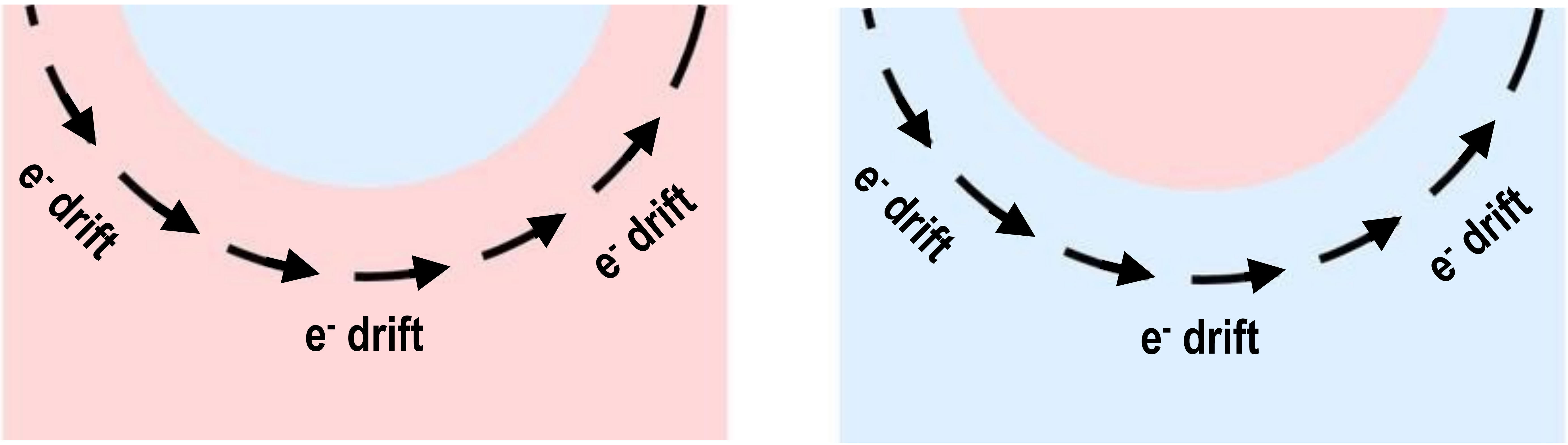
η > 2/3
Inward Particle Flux



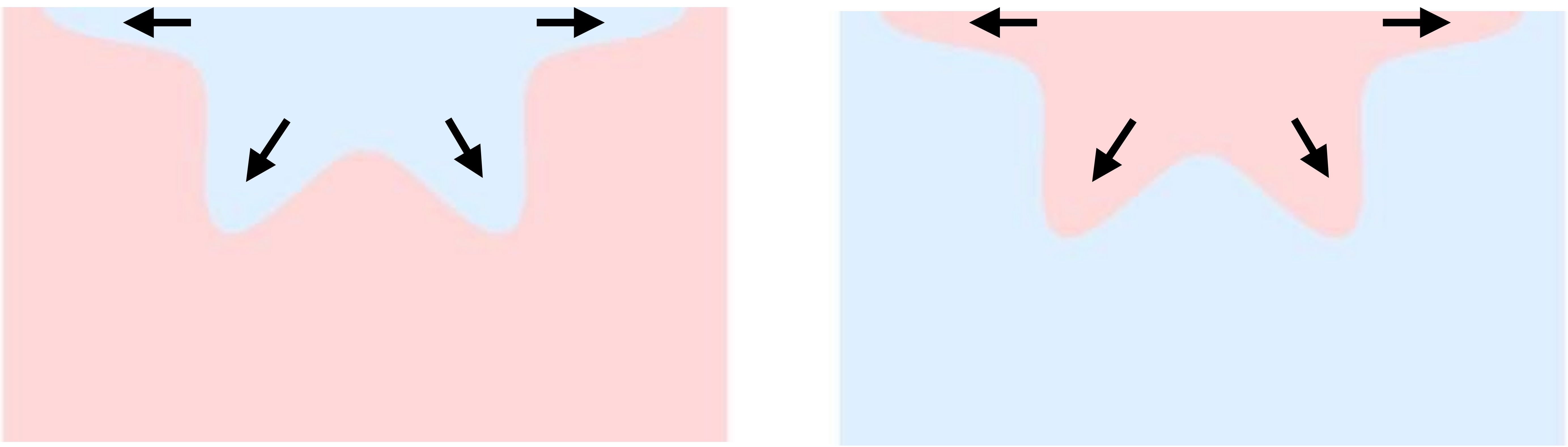
When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η

$\eta < 2/3$ **$\eta > 2/3$**

"Cool Core" **"Warm Core"**



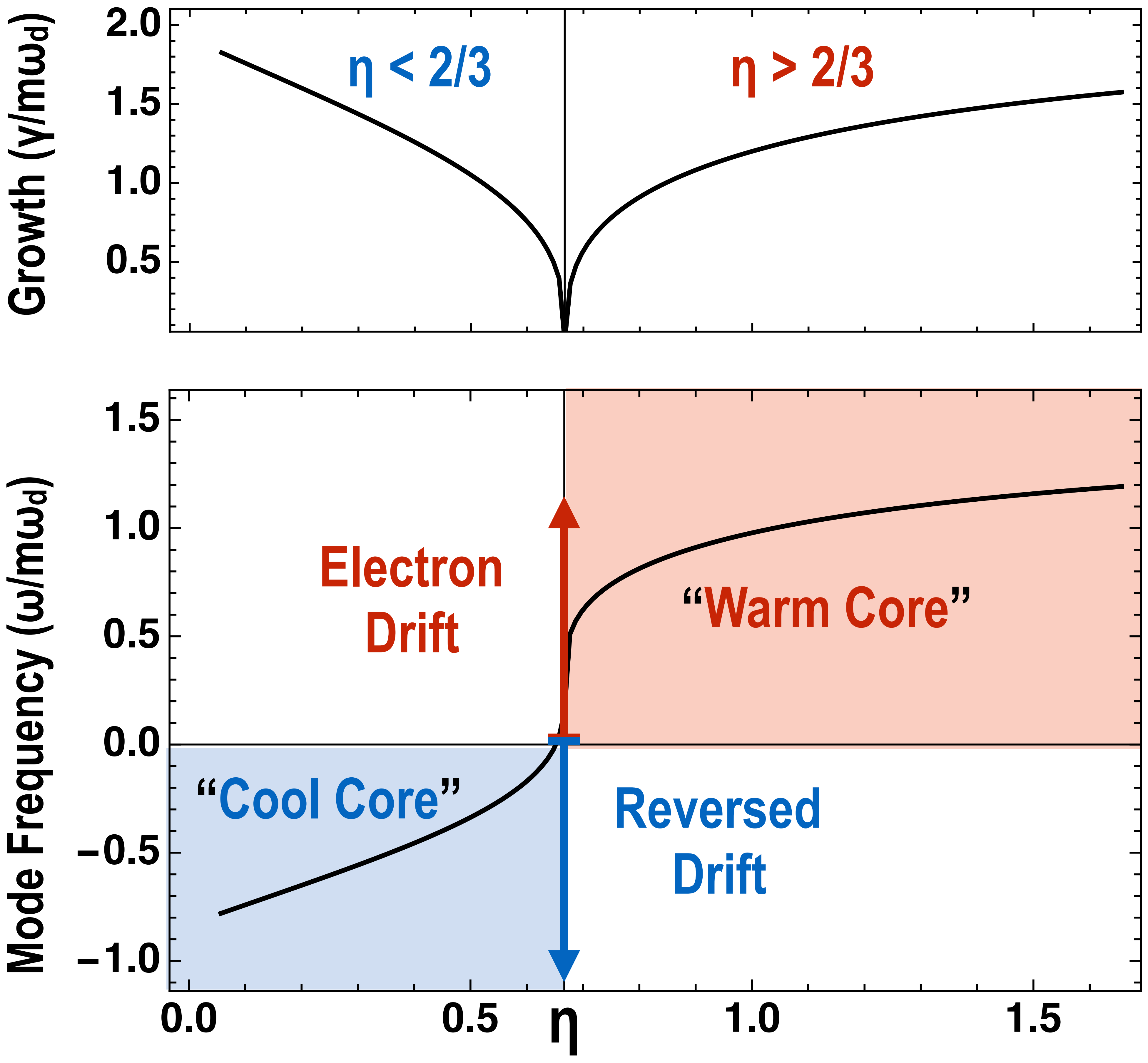
$\Delta W_p \sim \Delta(PV^{5/3}) \sim 0$ Energy & Pressure *Unchanged* for Adiabatic Mixing



$\Delta W_p \sim \Delta(PV^{5/3}) \sim 0$

$\eta < 2/3$
***Outward* Particle Flux**

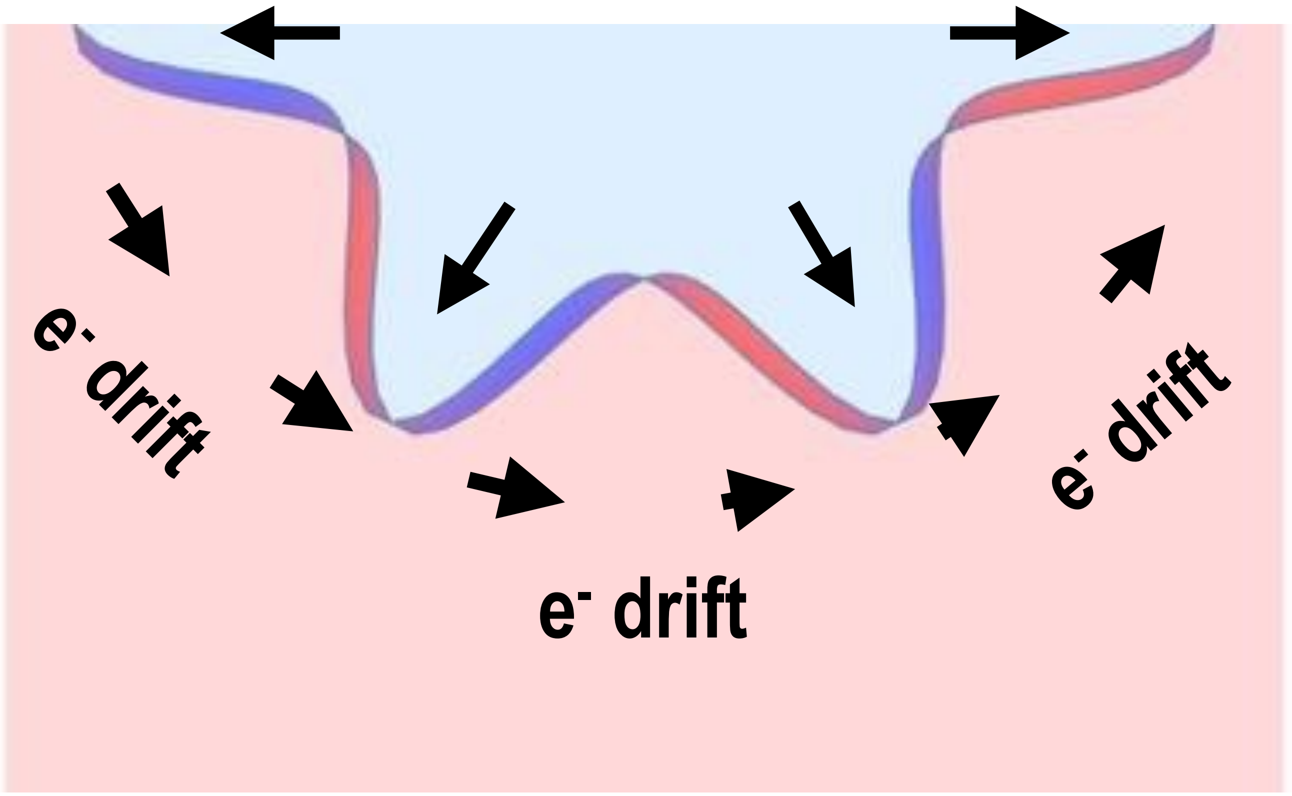
$\eta > 2/3$
***Inward* Particle Flux**



When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η

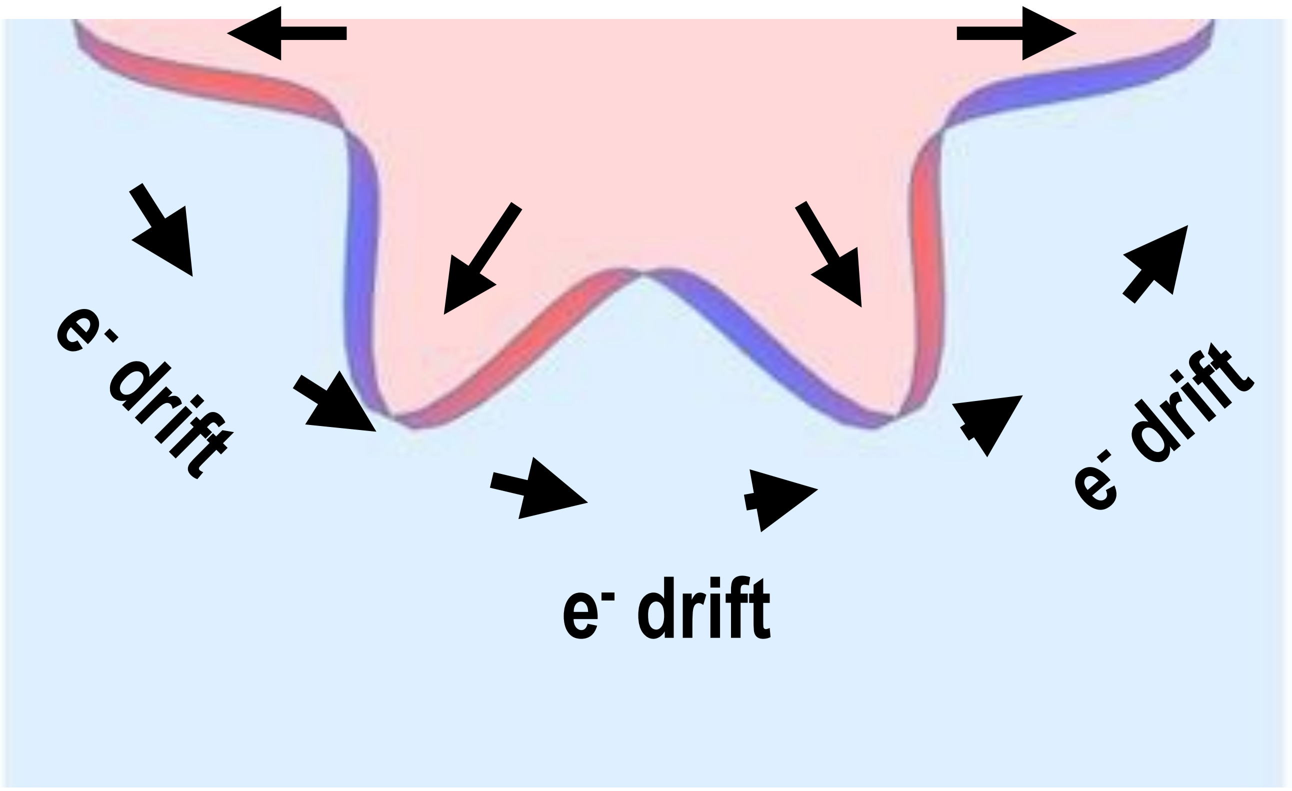
$\eta < 2/3$

"Cool Core"

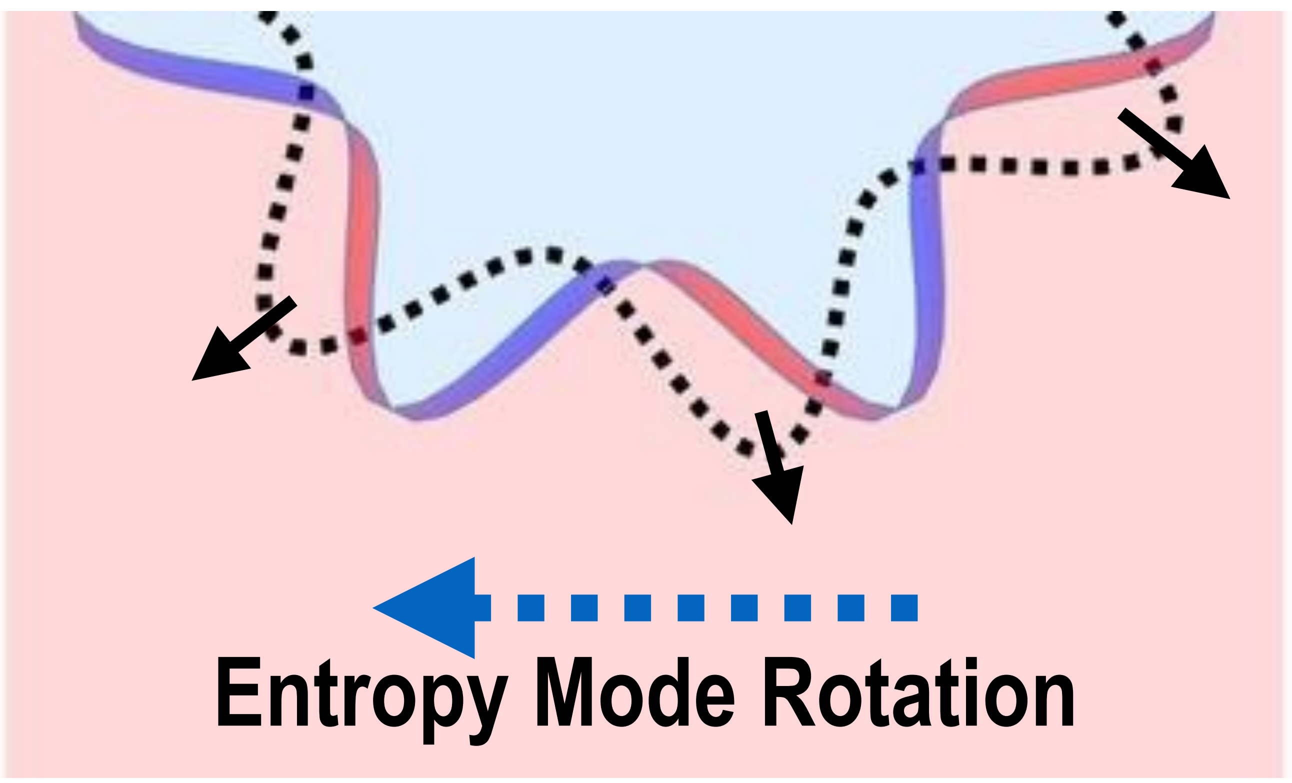


$\eta > 2/3$

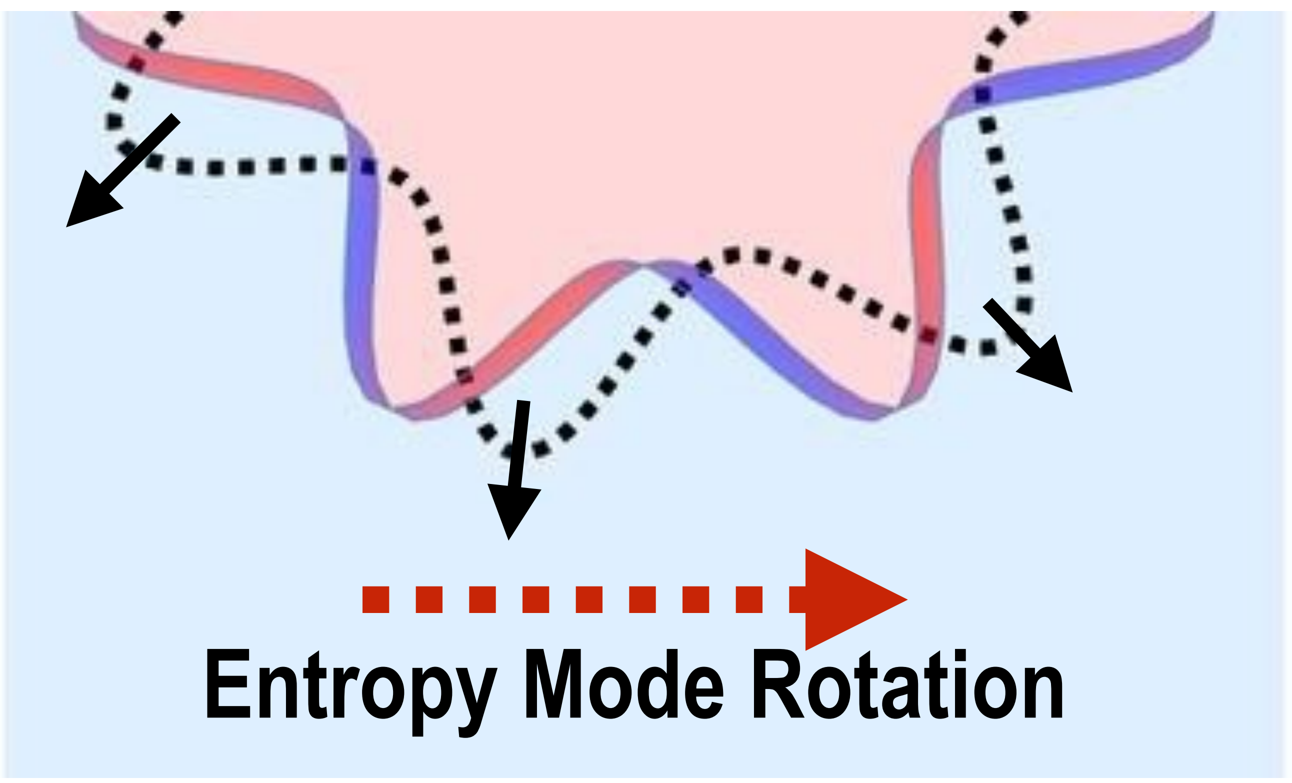
"Warm Core"



Drift-Kinetic *Heat* moves toroidally from Warm to Cool Flux-Tubes



***Inward* Temperature Flux**
***Outward* Particle Flux**

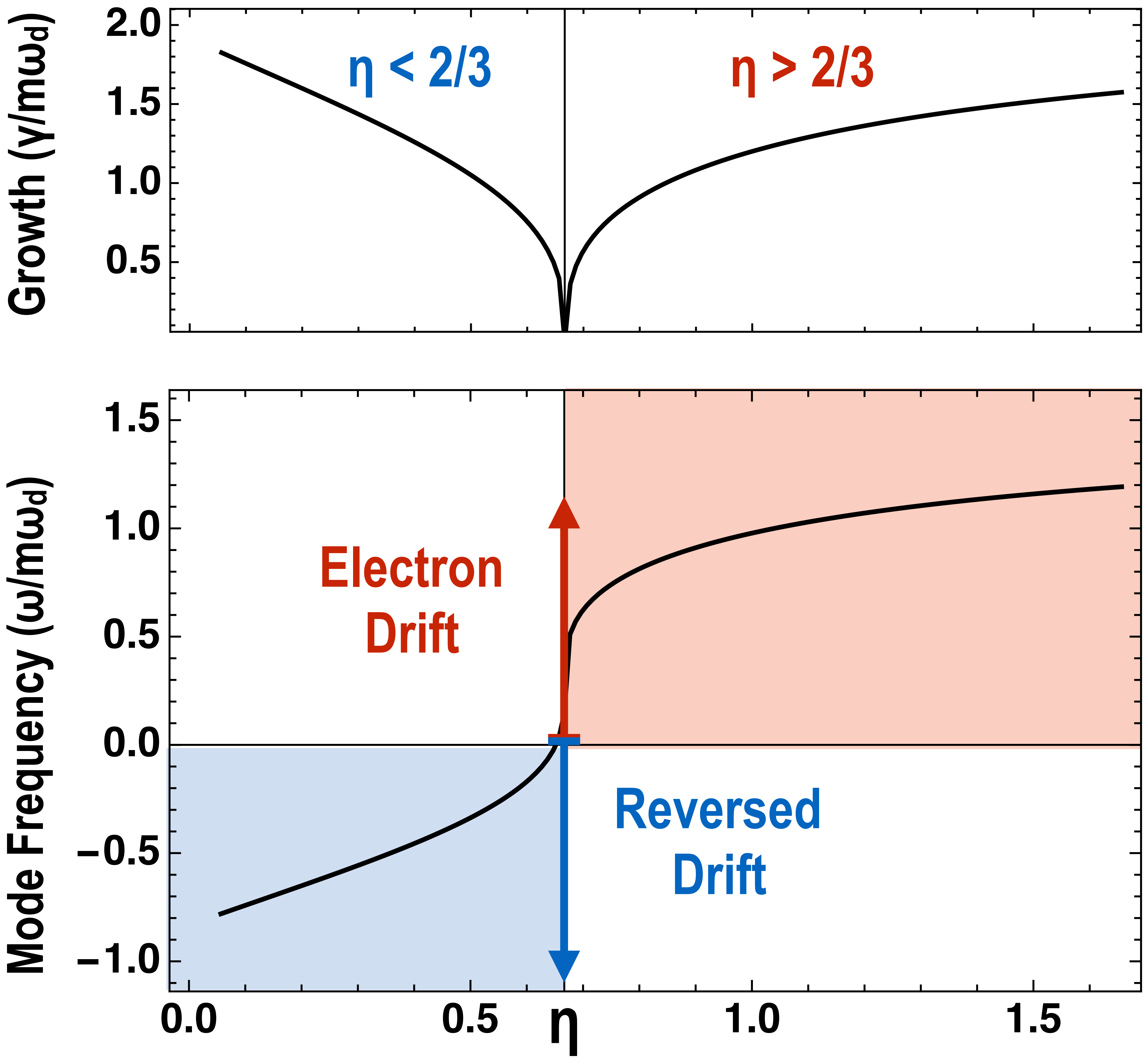


***Outward* Temperature Flux**
***Inward* Particle Flux**

$\Delta W_p \sim \Delta(PV^{5/3}) \sim 0$

$\eta < 2/3$
***Outward* Particle Flux**

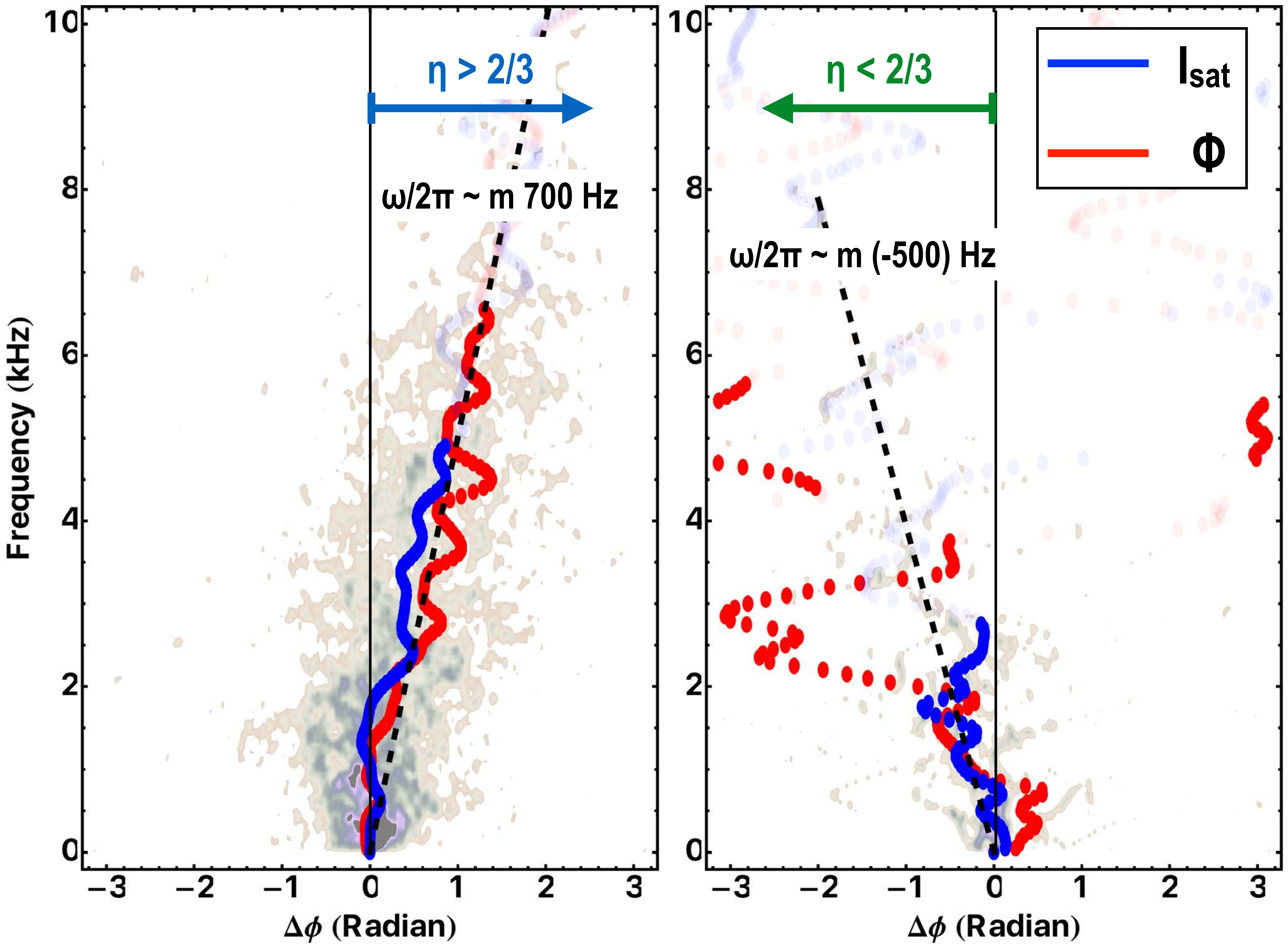
$\eta > 2/3$
***Inward* Particle Flux**



Dispersion Measurements during Pellet Injection agree with Linear Theory
Entropy Modes ***Reverse*** Direction with ***Reversal*** of Particle Flux

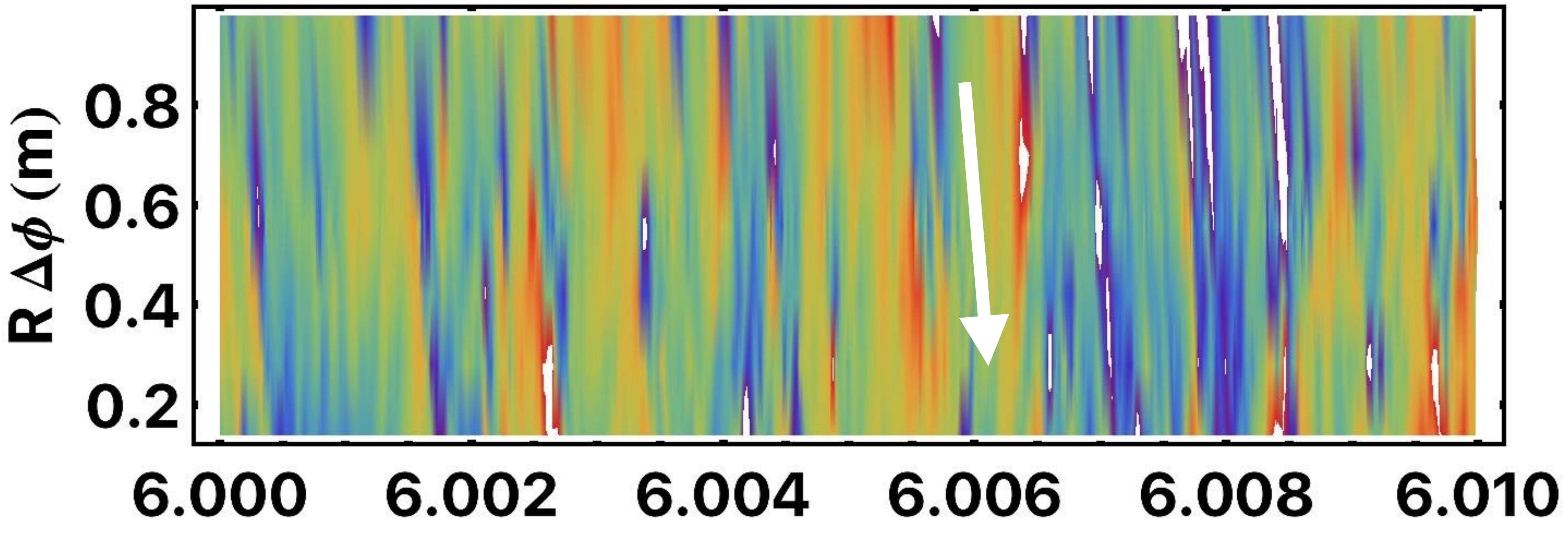
Ensemble-Averaged Entropy Mode Dispersion

Before Pellet Injection **During Pellet Injection**

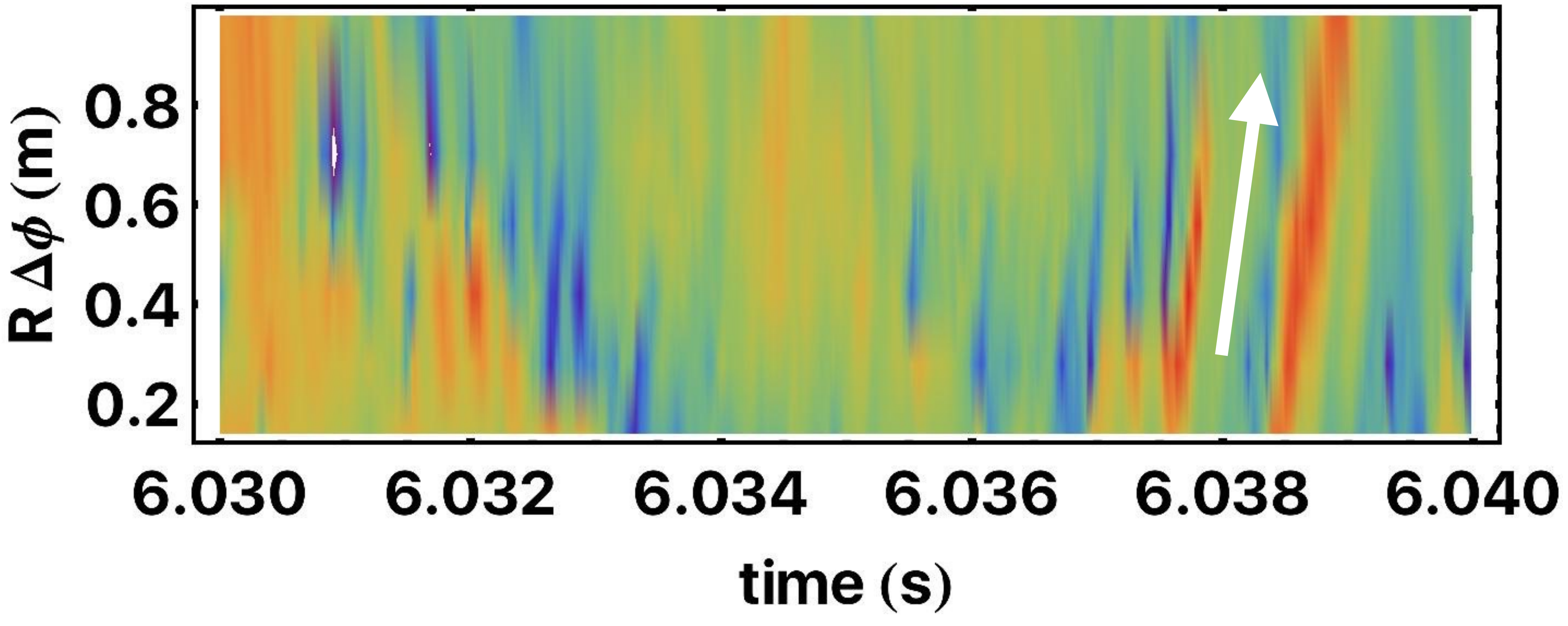


Potential Fluctuations Reverse Direction

Before Pellet Injection



During Pellet Injection



Physics

- ✓ **Turbulent inward pinch:** low-frequency electrostatic interchange/entropy mode turbulence, **causes particle and/or temperature “pinch”** and turbulent relaxation to centrally-peaked profiles. (*Also*: inverse cascade, chaotic global mode dynamics, bursty flows, …)

- ➡ **Record high local β > 1 with “artificial radiation belt” (energetic electrons)** and exploring electromagnetic turbulence, collisionless transport, anisotropic pressure $P_\perp > P_\|$, …

- **Ongoing/Unsolved problems** and opportunities linking space/laboratory magnetospheric physics: regulation of turbulence with “artificial ionosphere”, spectrum control and mode-mode coupling, Alfvén wave dynamics in a turbulent magnetosphere, *large high-density high-beta magnetized plasma*, finite ion temperature, $T_i \sim T_e$, FLR, APEX/PAX, …

Stable Toroidal Plasmas at Very High Local β are Characteristics of the Giant Magnetospheres and Predicted for the Laboratory Magnetosphere

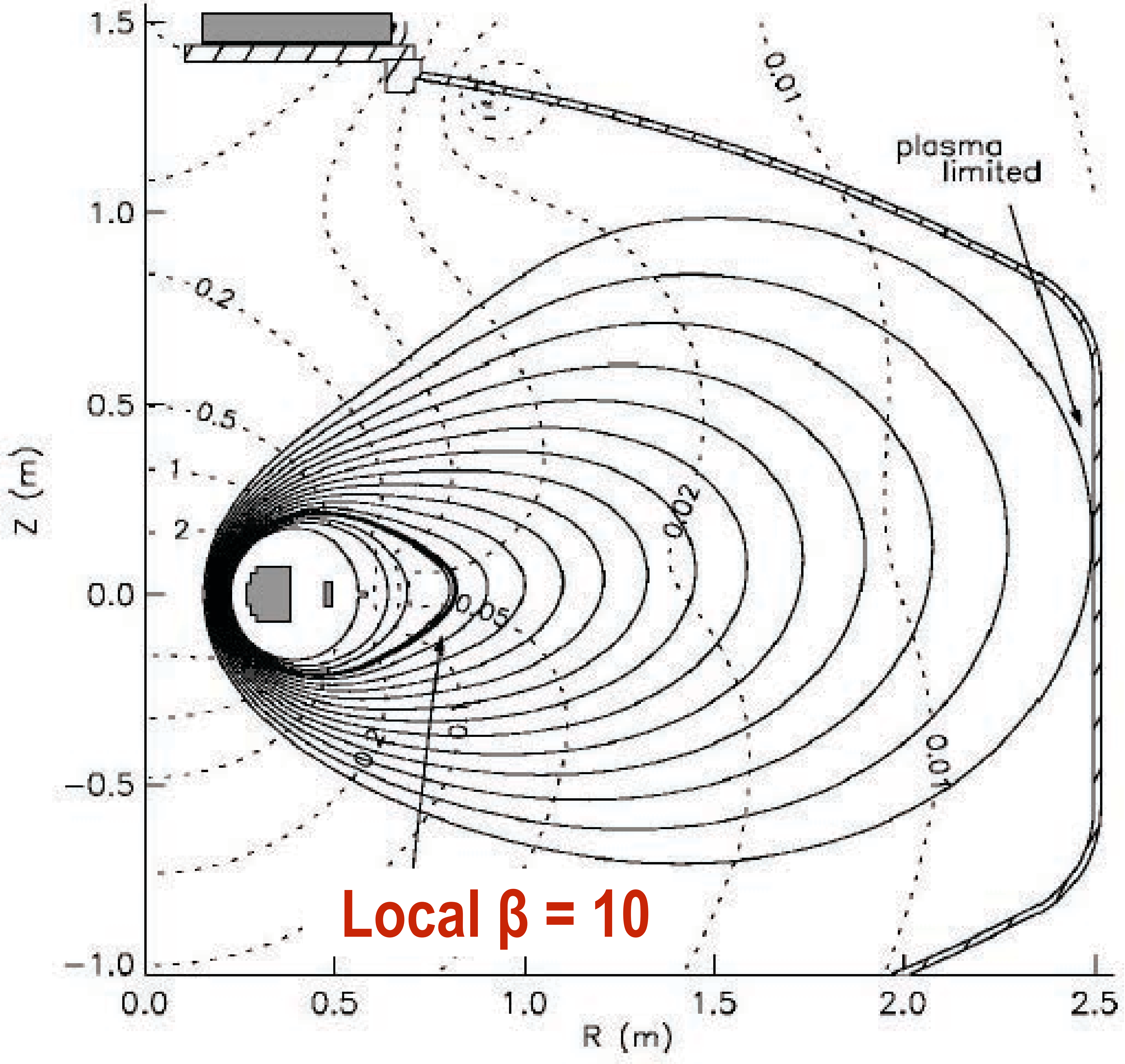
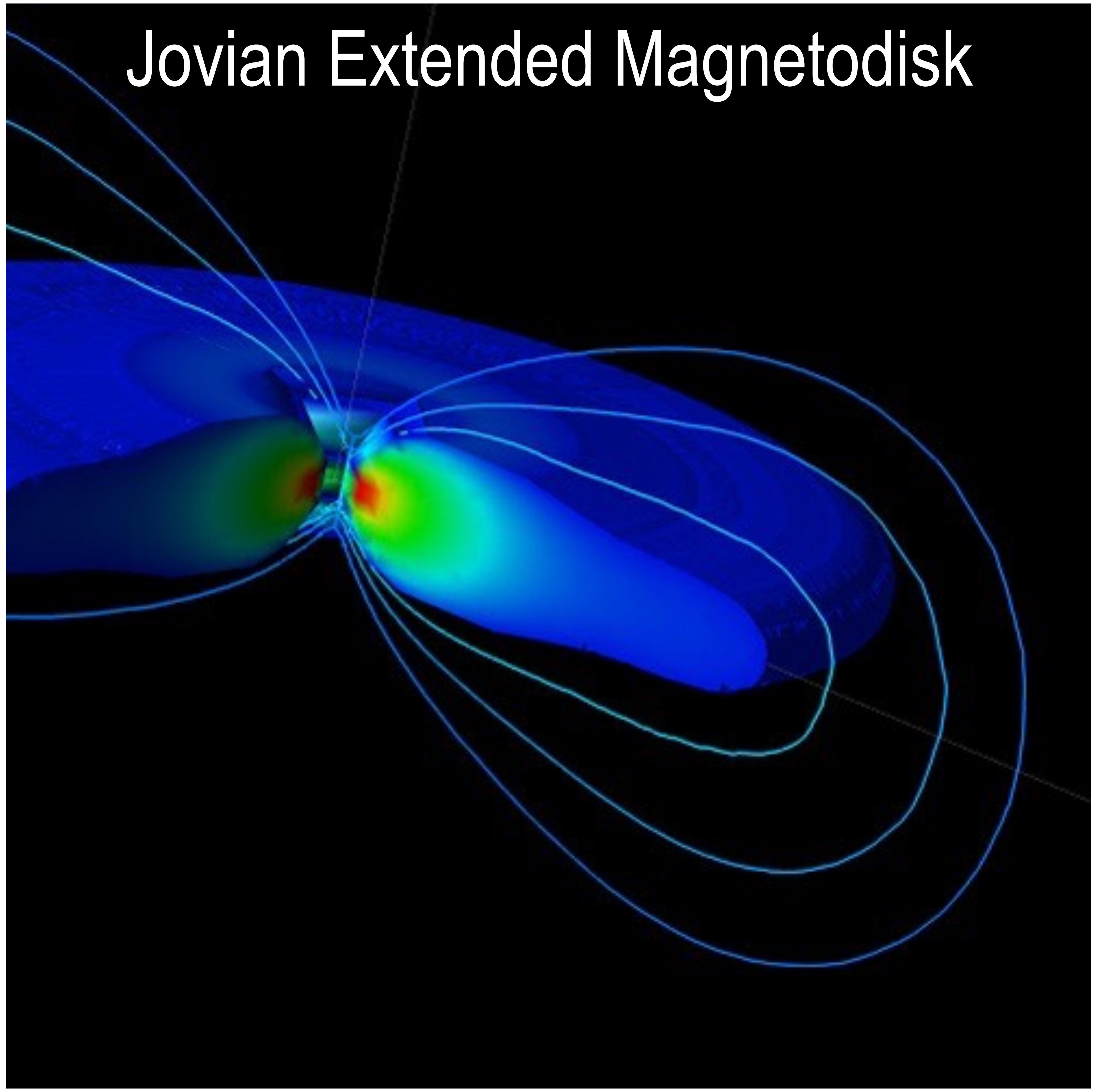


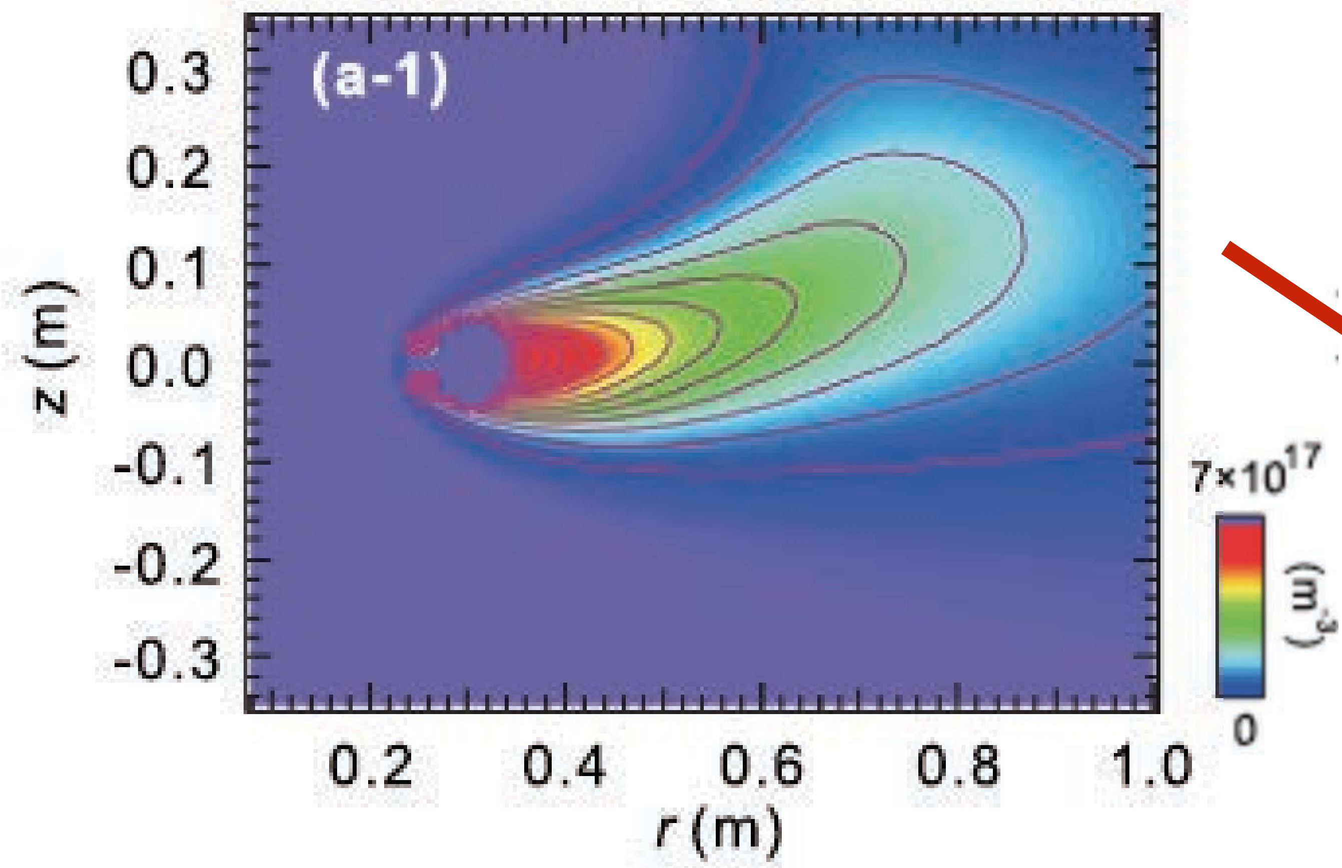
FIG. 2. High β equilibrium ($\beta_{max} = 10$) solution in the LDX geometry.

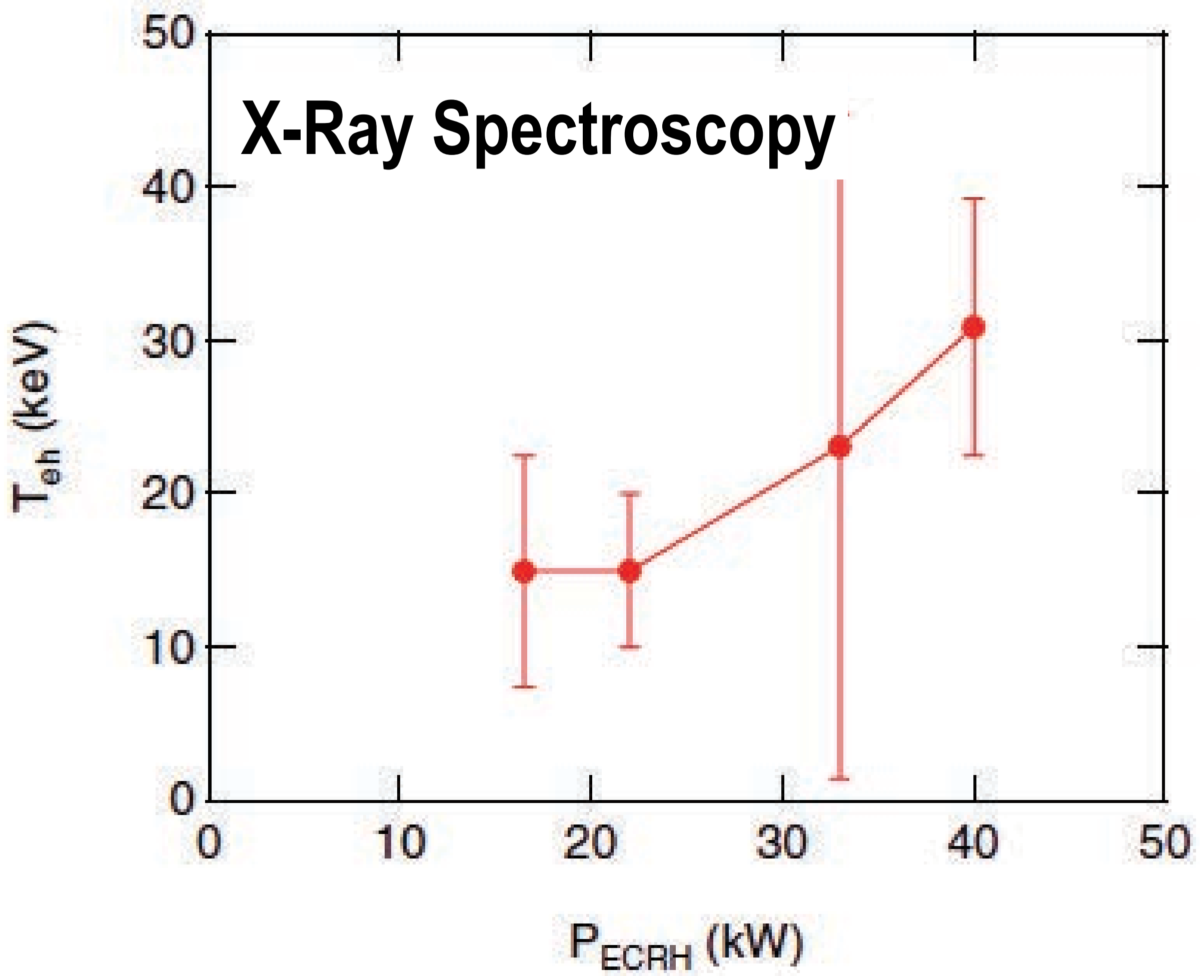


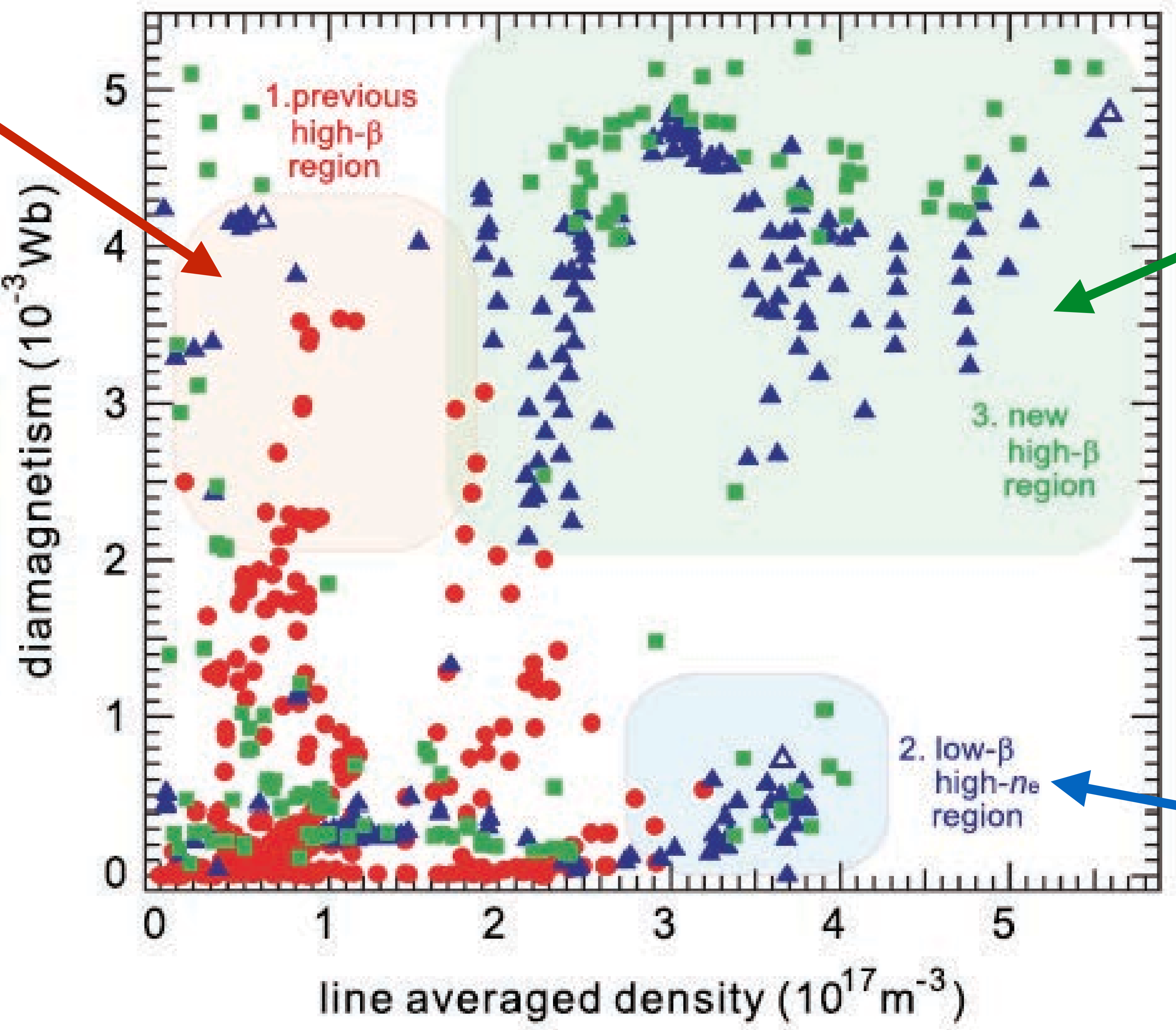
Garnier, Kesner, and Mauel, “Magnetohydrodynamic stability in a levitated dipole,” *Phys Plasmas* **6**, 3431 (1999).
Shiraishi, Ohsaki, and Yoshida, “Relaxation of a quasisymmetric rotating plasma: A model of Jupiter’s magnetosphere,” *Phys Plasmas* **12**, 092901 (2005)

RT-1 has ***Three Regimes*** of High-β Operation depending upon Background Neutral Density and ECRH Power

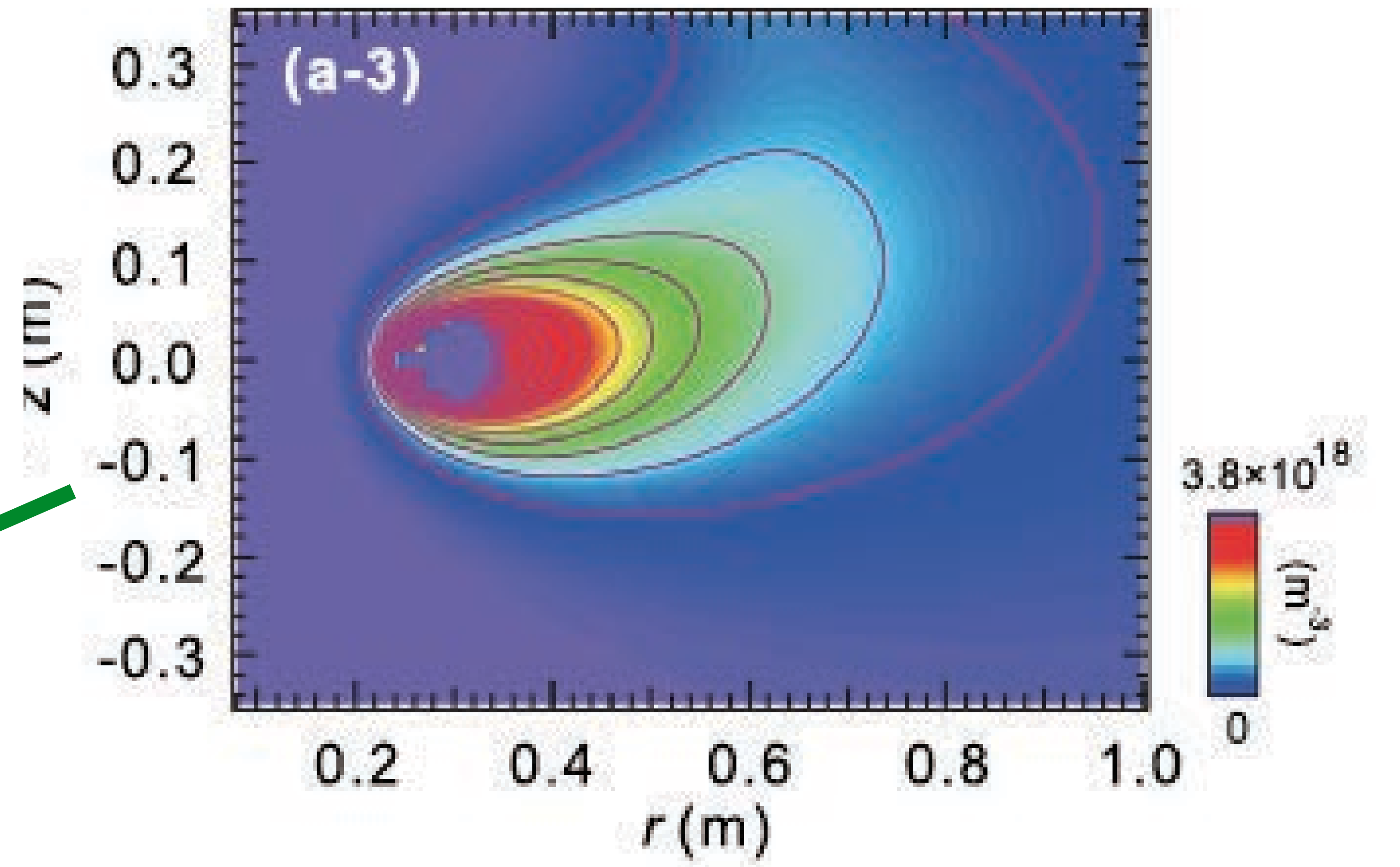
$P_\perp >> P_\parallel$



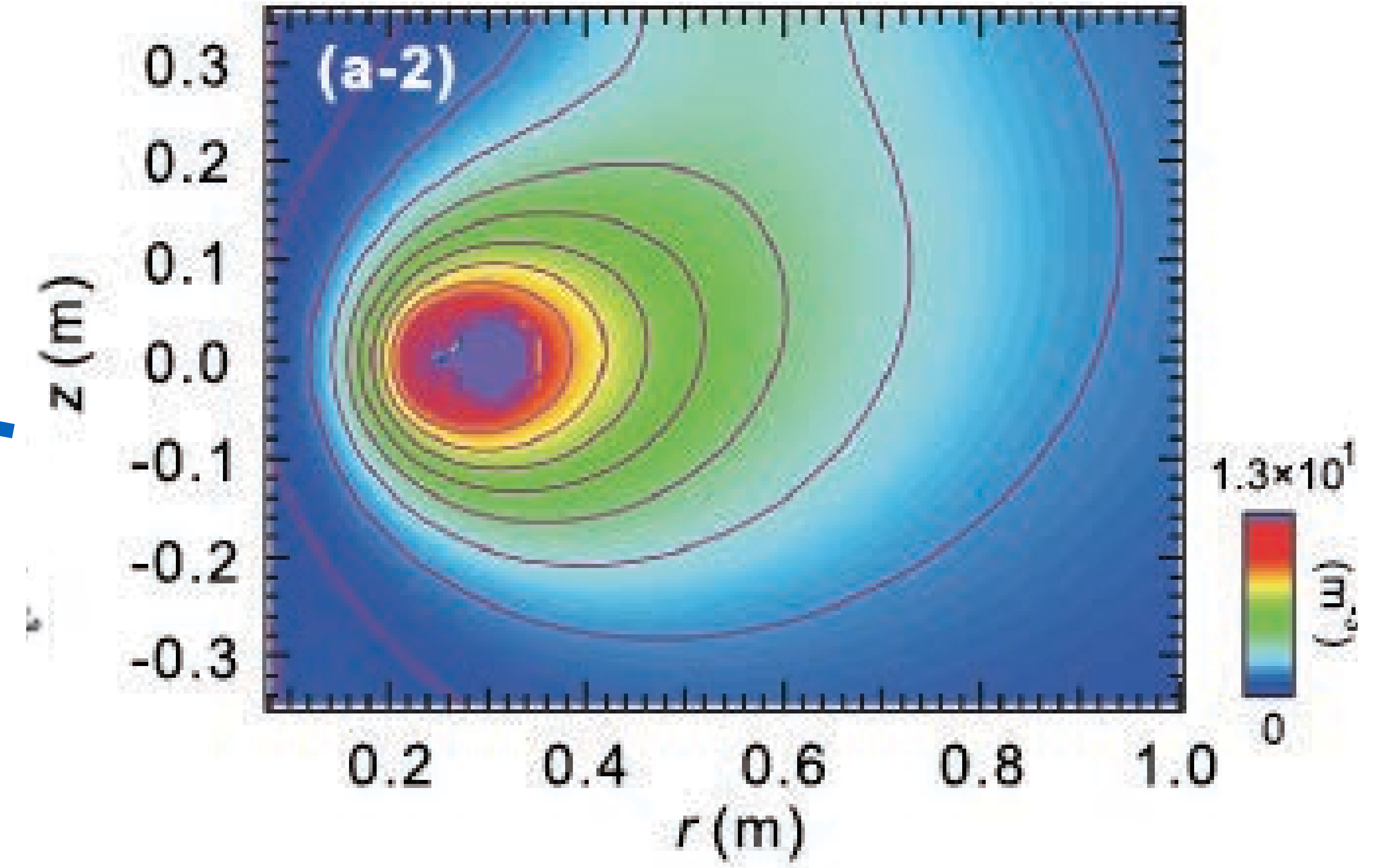




$P_\perp \gtrsim P_\parallel$



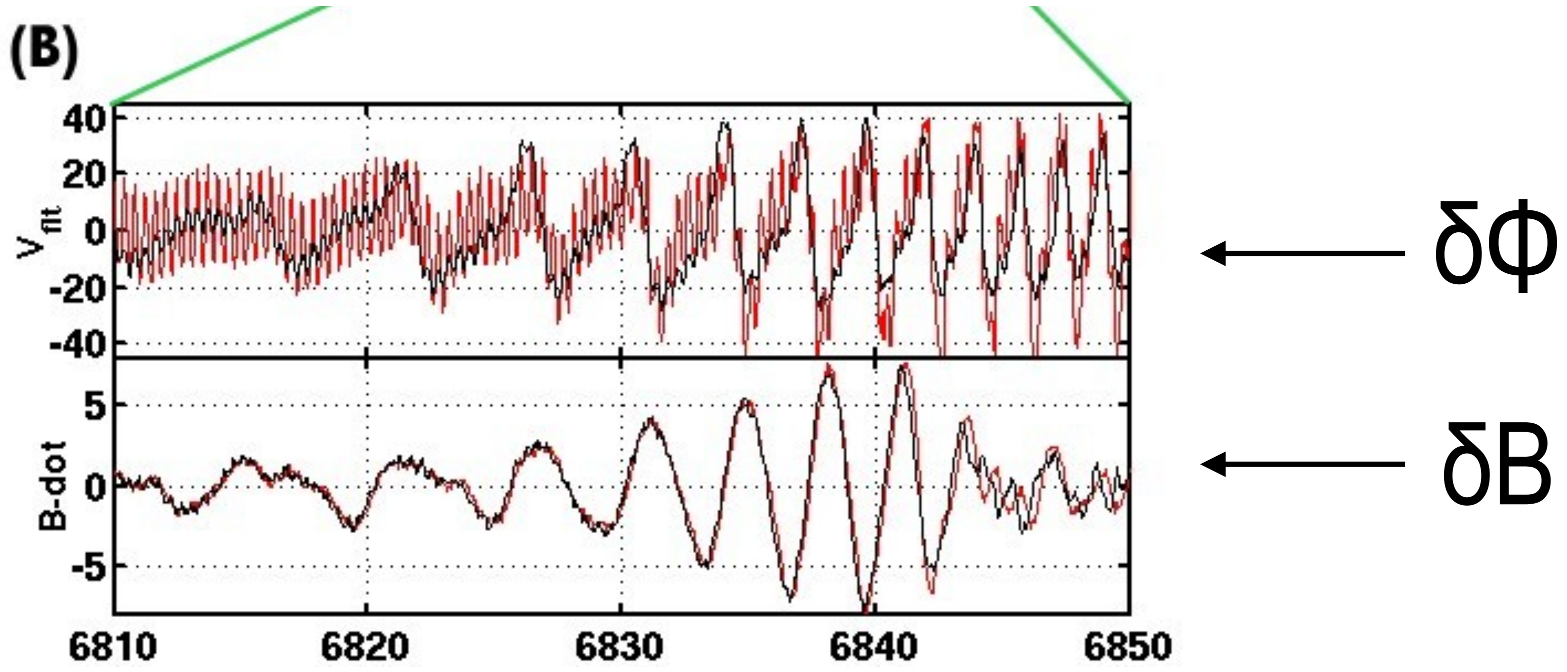
$P_\perp \sim P_\parallel$

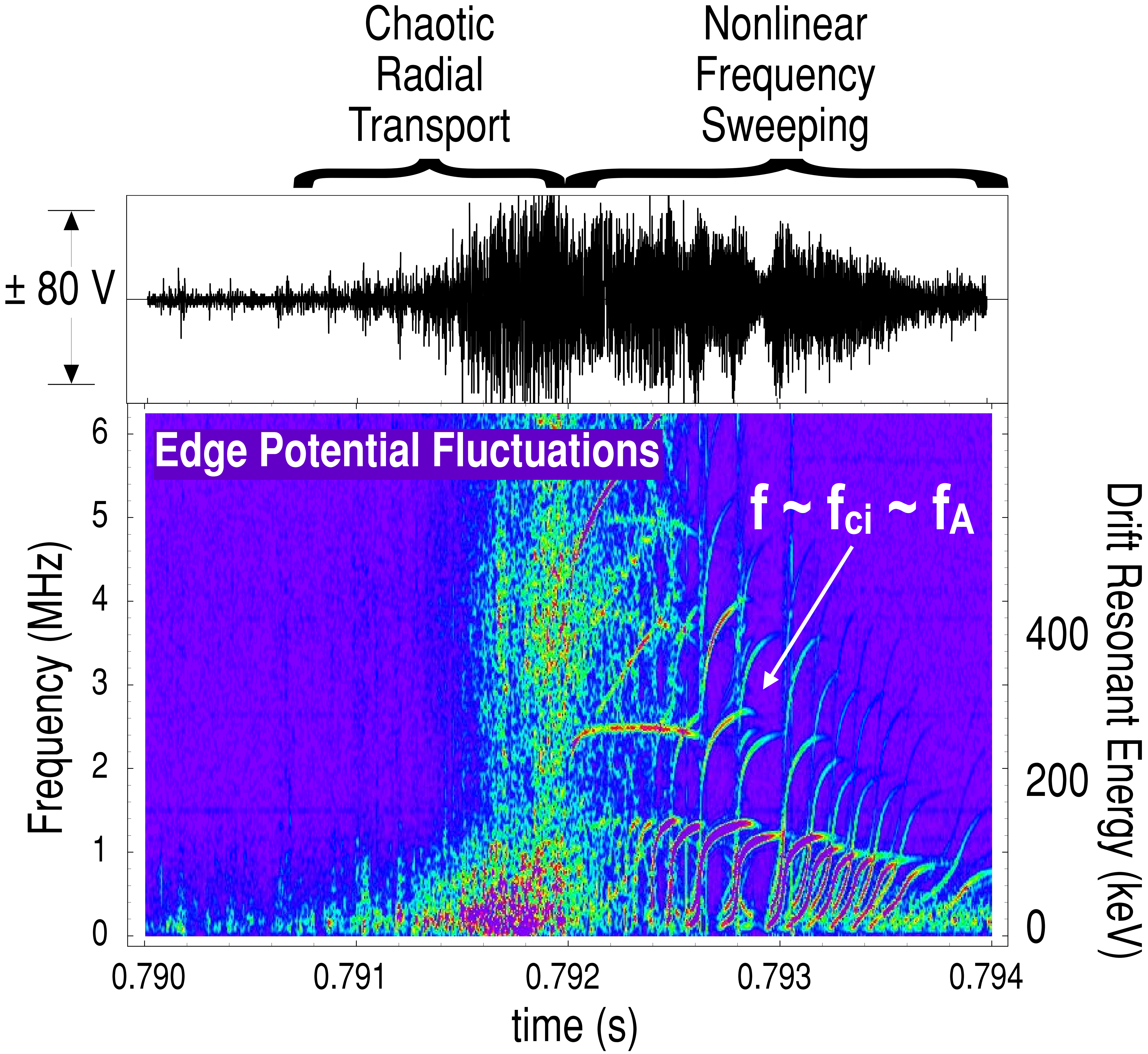


Nishiura, et al., "Improved beta (local beta >1) and density in electron cyclotron resonance heating on the RT-1 magnetosphere plasma," Nuc Fus 55, 053019 (2015).
Saitoh, et al., "Observation of a new high-β and high-density state of a magnetospheric plasma in RT-1," Phys Plasmas 21, 082511 (2014).

With electron heating (ECRH) high β creates an ***“Artificial Radiation Belt”*** and Electromagnetic Turbulence

- HEI instabilities are drift-resonant ($\omega \sim m\omega_{dh} \sim 1$ MHz) with have global mode structures (at low plasma density)
- Transport preserves phase-space density $F(\mu, J)$
- Nonlinear frequency chirping due to “buoyant” phase-space holes
- At high β, **very strong magnetic fluctuations** reaching Alfvén and ion cyclotron frequencies
- Transport, echoes, variability, secondary instabilities, resemble magnetospheric radiation belt dynamics.

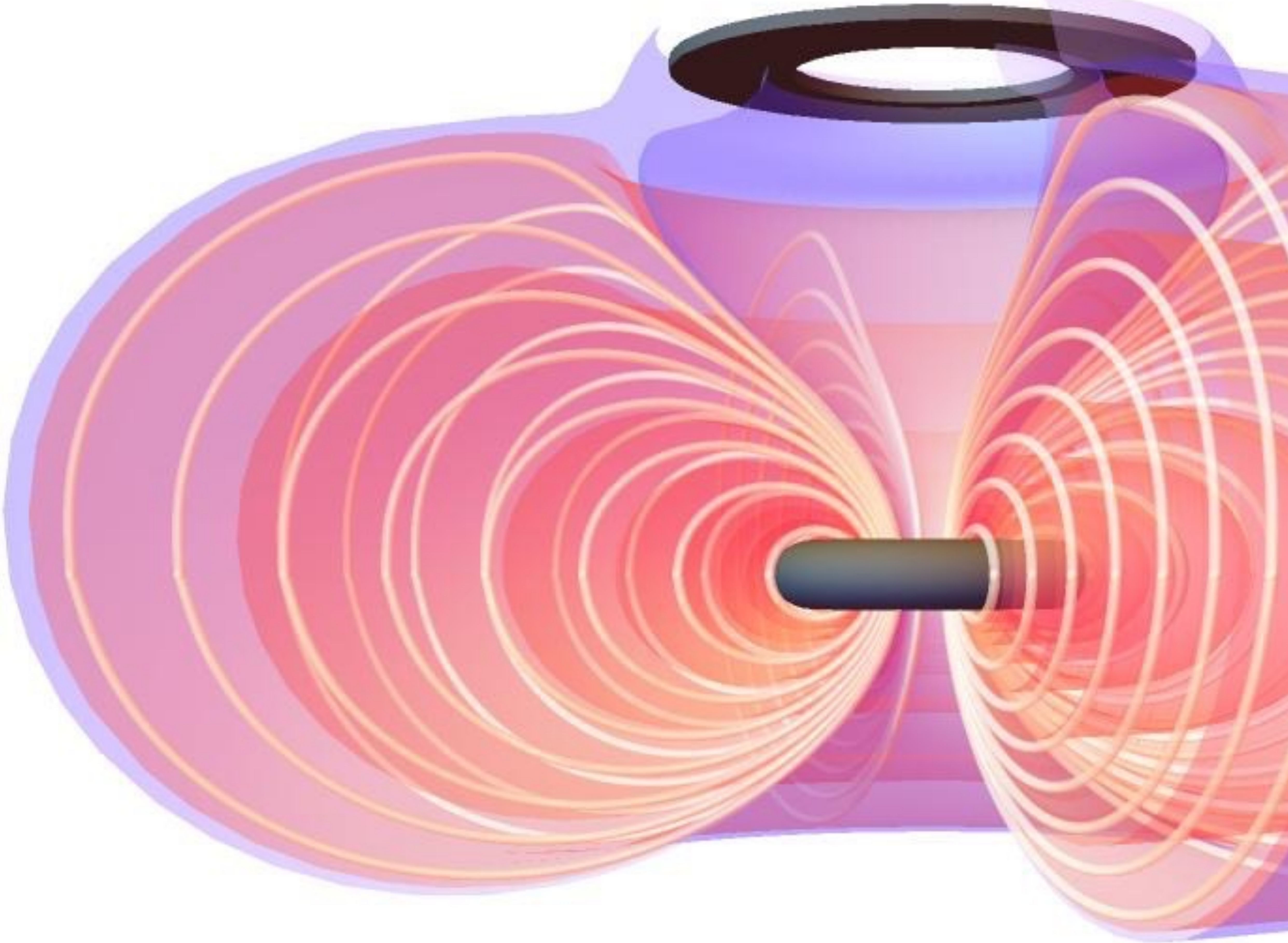




The Axisymmetric Plasma Torus is a *New Paradigm* for the Laboratory Study of Steady-State and High-Beta Plasma

- ***Levitation is robust and reliable*** with very good access for diagnostics, plasma heating and fueling.
- ***Simple, axisymmetric torus with no field-aligned currents*** with classical particle orbits and good confinement of heat, density, and energetic particles, APEX/PAX, …
- ***Unique radial transport processes*** relevant to space and to many toroidal confinement devices: *up-gradient pinch, inverse cascade, bursty interchange filaments, minimum entropy production …*

  Nonlinear drift/gyrokinetics appears to provide a good model for predicting radial transport driven by interchange/entropy instabilities



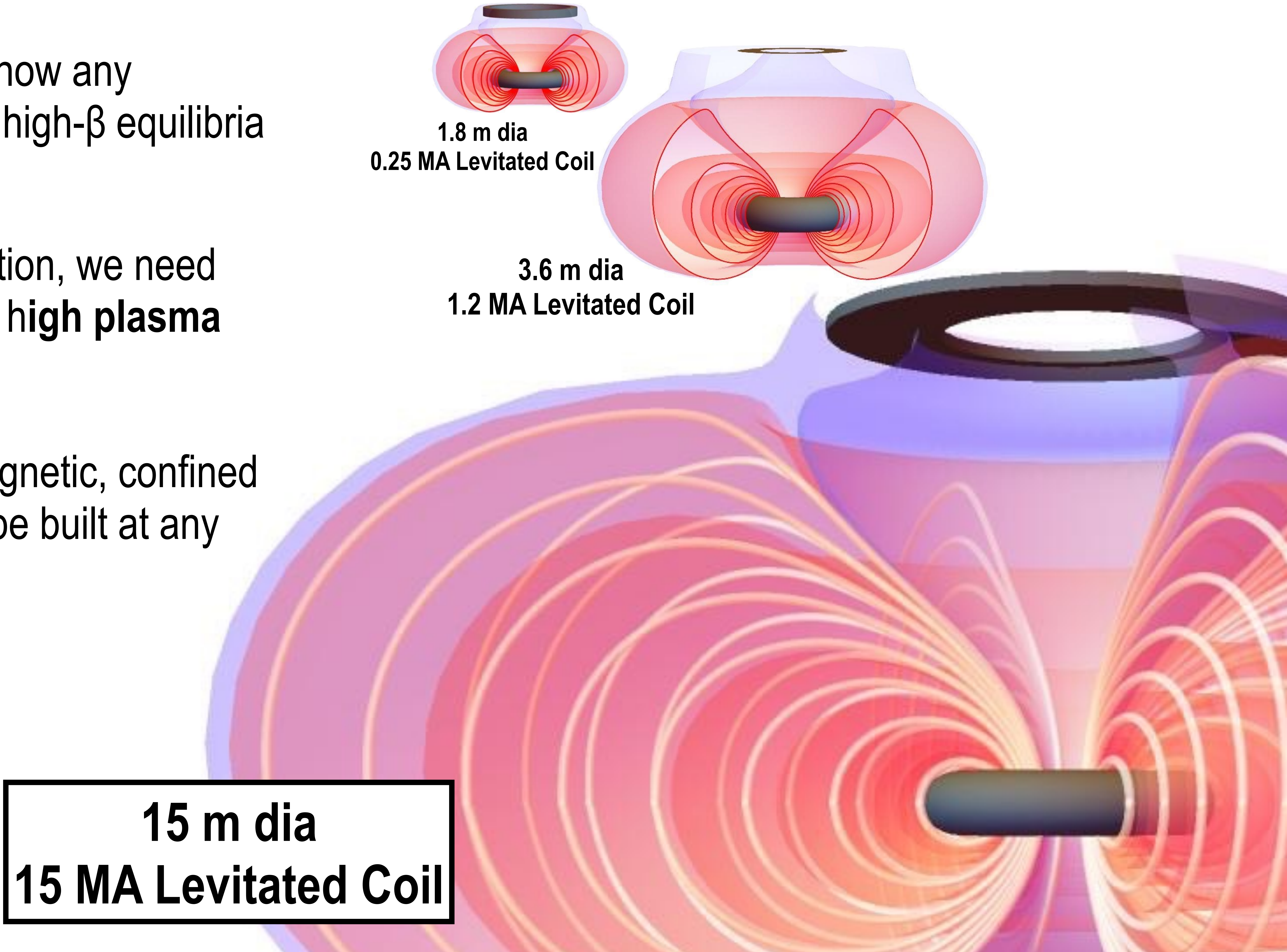
Hasegawa’s 1987 Question: Does magnetospheric physics apply to fusion magnetic confinement in the laboratory?

- ✓ LDX, RT-1, theory and simulation do not show any limitations preventing the scaling of stable high-β equilibria to larger size.
- ➡ However, the answer to Hasegawa’s question, we need laboratory tests with **high power heating**, **high plasma density**, and **larger size**.

  But, with only a small superconducting magnetic, confined and collisionless magnetized plasma can be built at any size …

$$\rho/L = \rho^* \ll 1$$

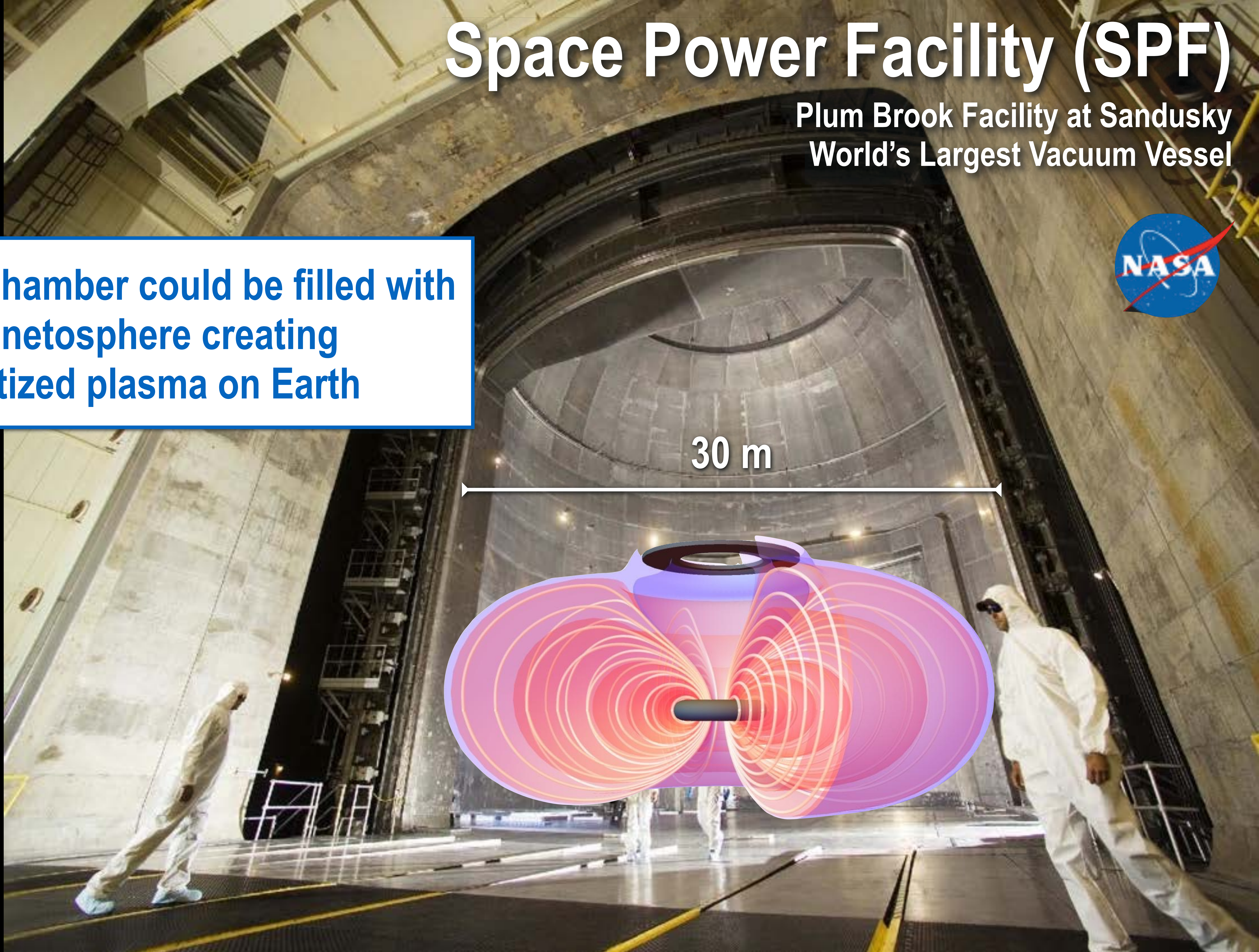
$$c/L\omega_{pi} = \lambda^* \ll 1$$



Space Power Facility (SPF)

Plum Brook Facility at Sandusky
World’s Largest Vacuum Vessel

Example: Large space chamber could be filled with a laboratory magnetosphere creating the largest magnetized plasma on Earth




ACQUIRE CURRENCY
FLAMMABLE GASES
LABORATORY
NO SMOKING
WEST
DANGER
HIGH VOLTAGE
STAND CLEAR
WEST