Exploring Plasma Dynamics with Laboratory Magnetospheres

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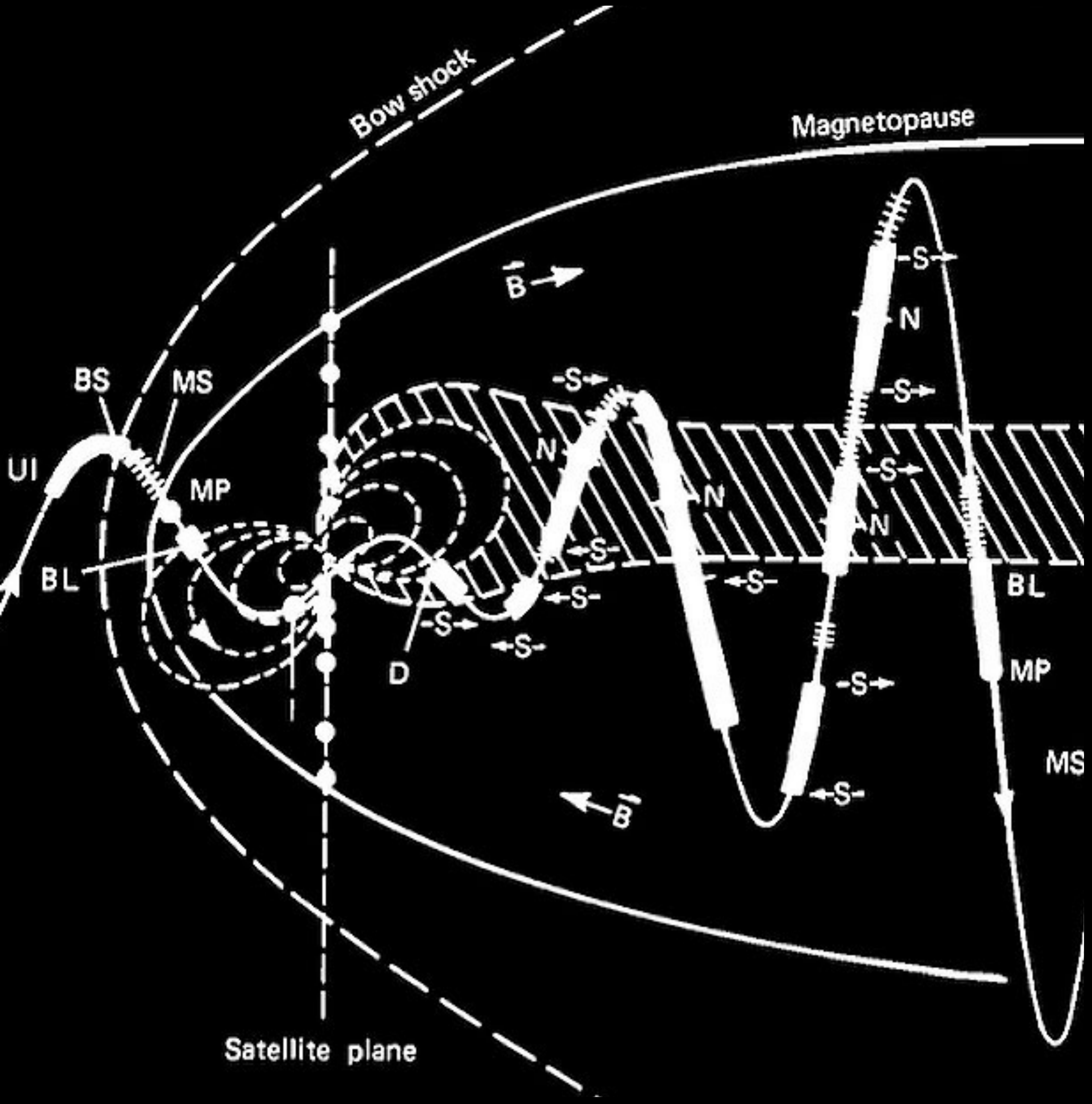
Columbia University

with help 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

Naval Research Laboratory
May 11, 2016 • Washington, DC

Akira Hasegawa invited to Voyager 2’s encounter with Uranus

January 24, 1986

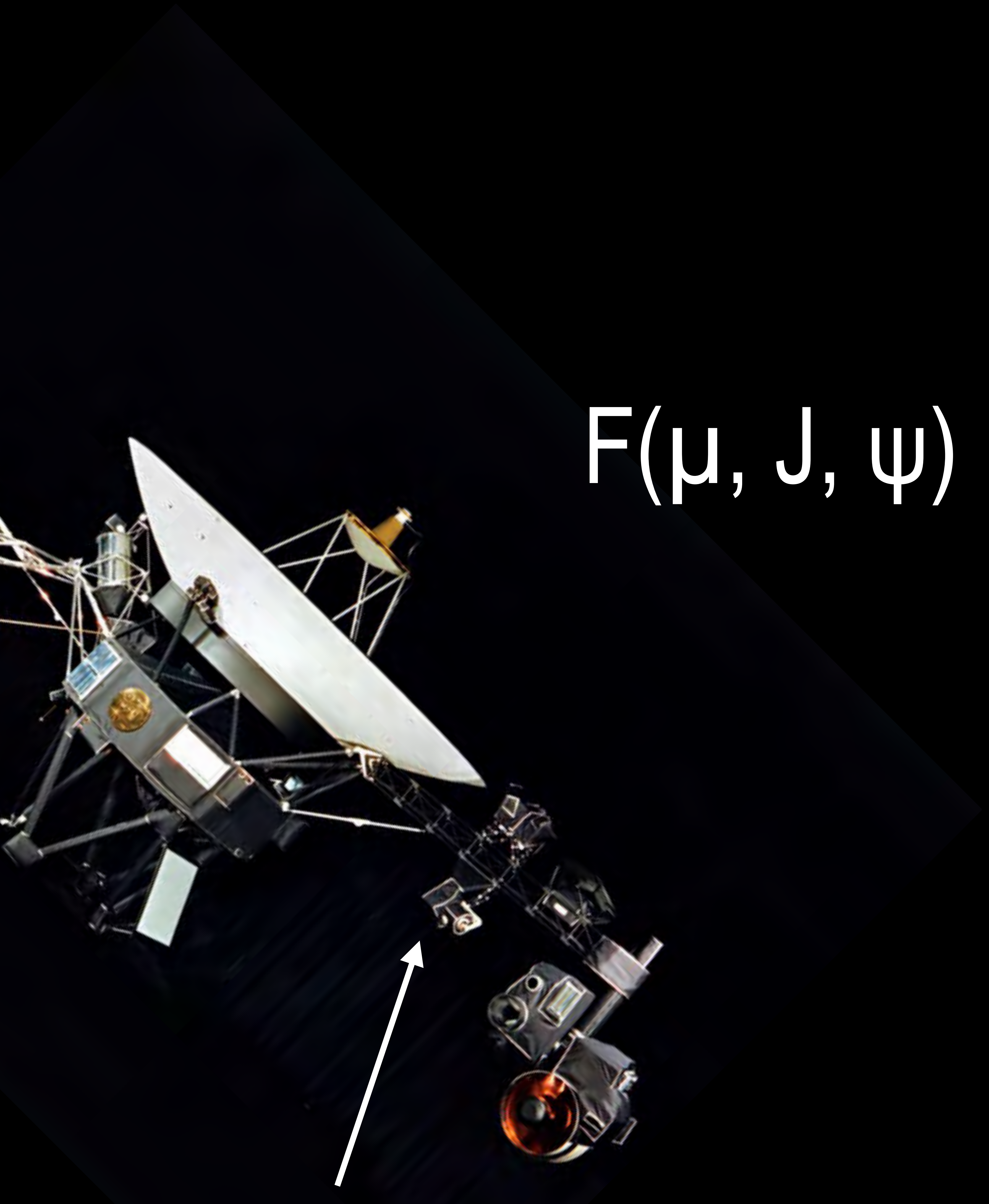


12 Hour Flyby

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

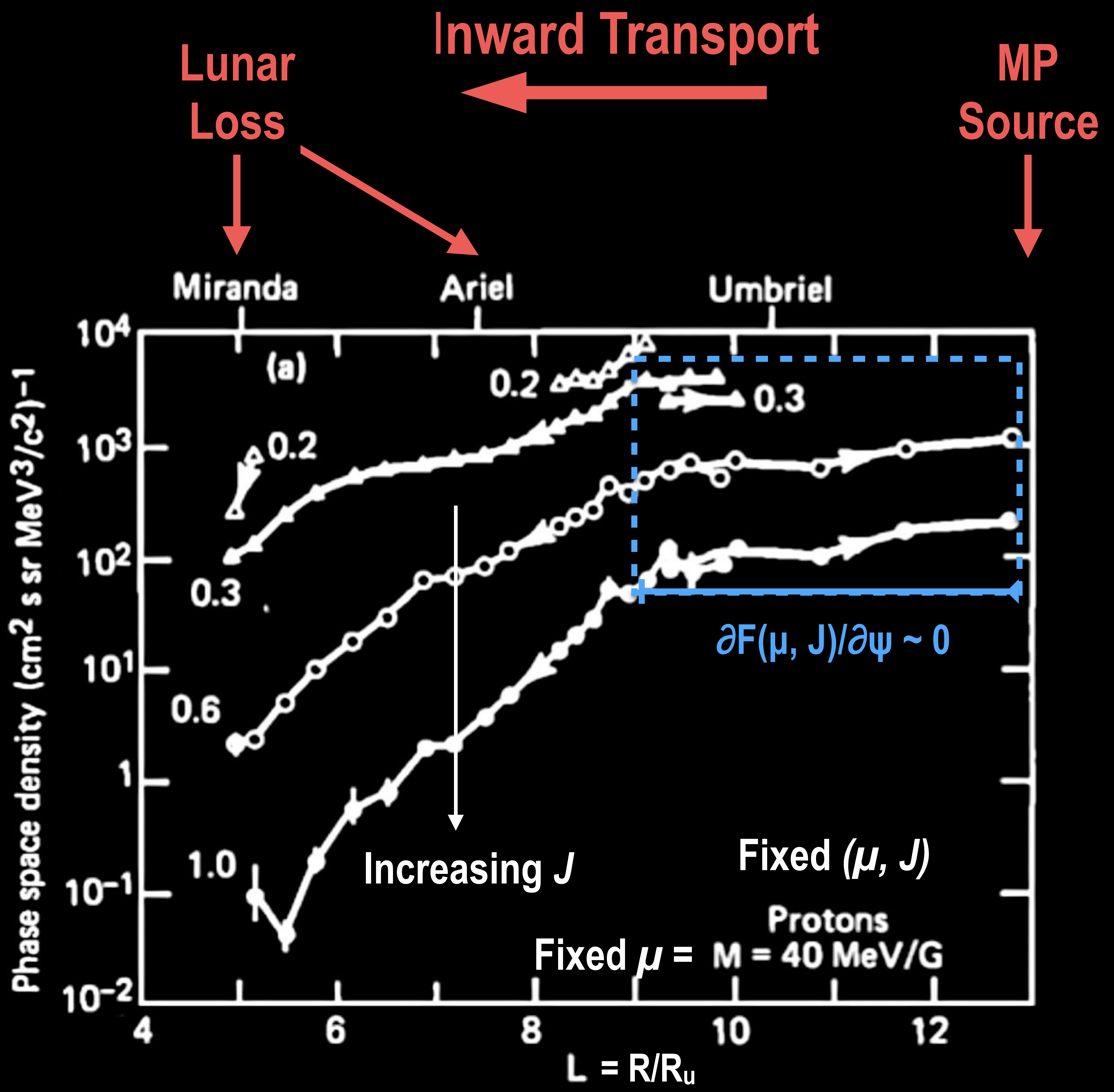
Ed Stone, *JGR* **92**, 14,873 (1987)

Inward Transport of Energetic Particles



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

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



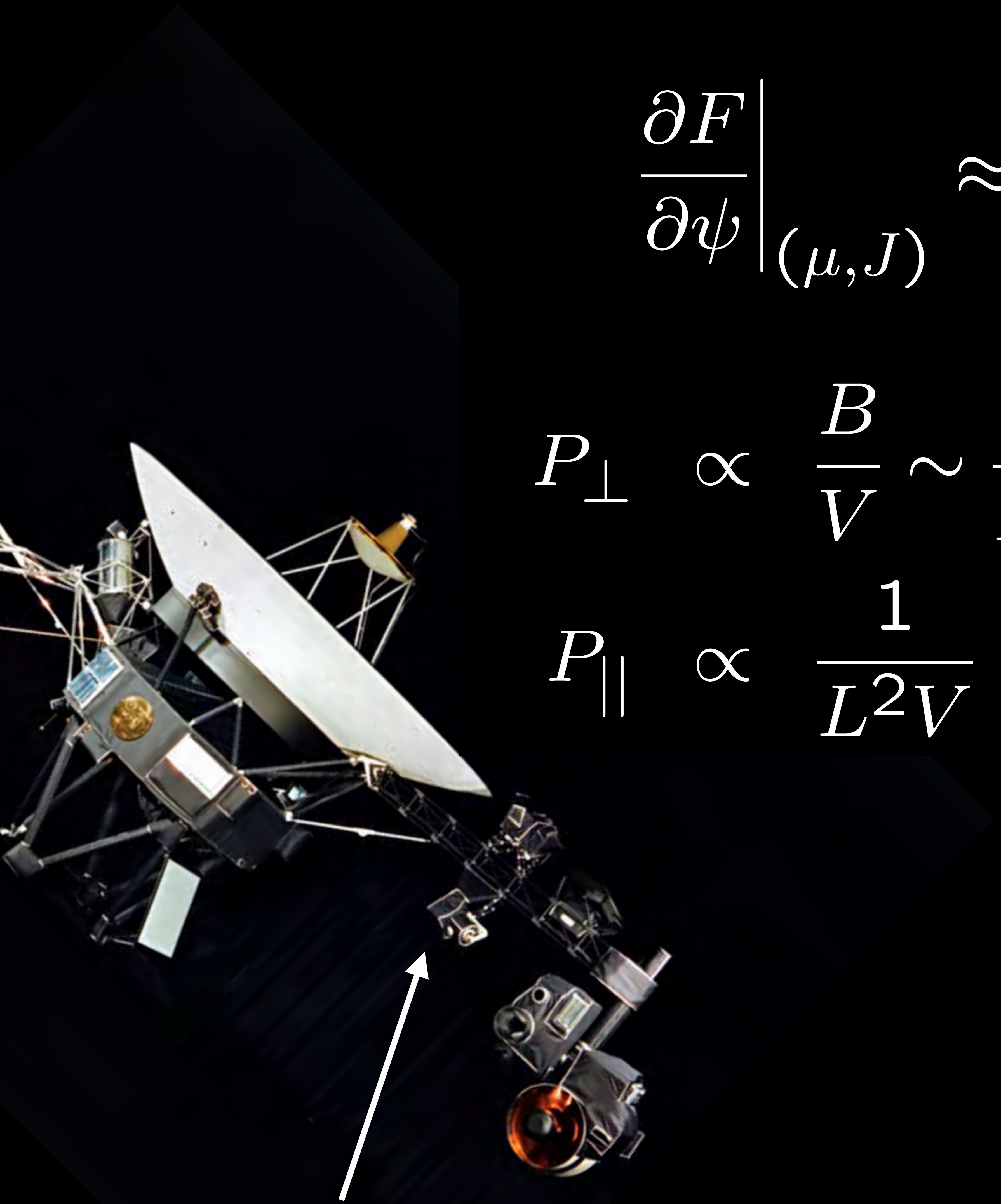
Chen, *et al.*, *JGR* **92**, 15,315 (1987)

Inward Transport Creates Centrally-Peaked Pressure

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

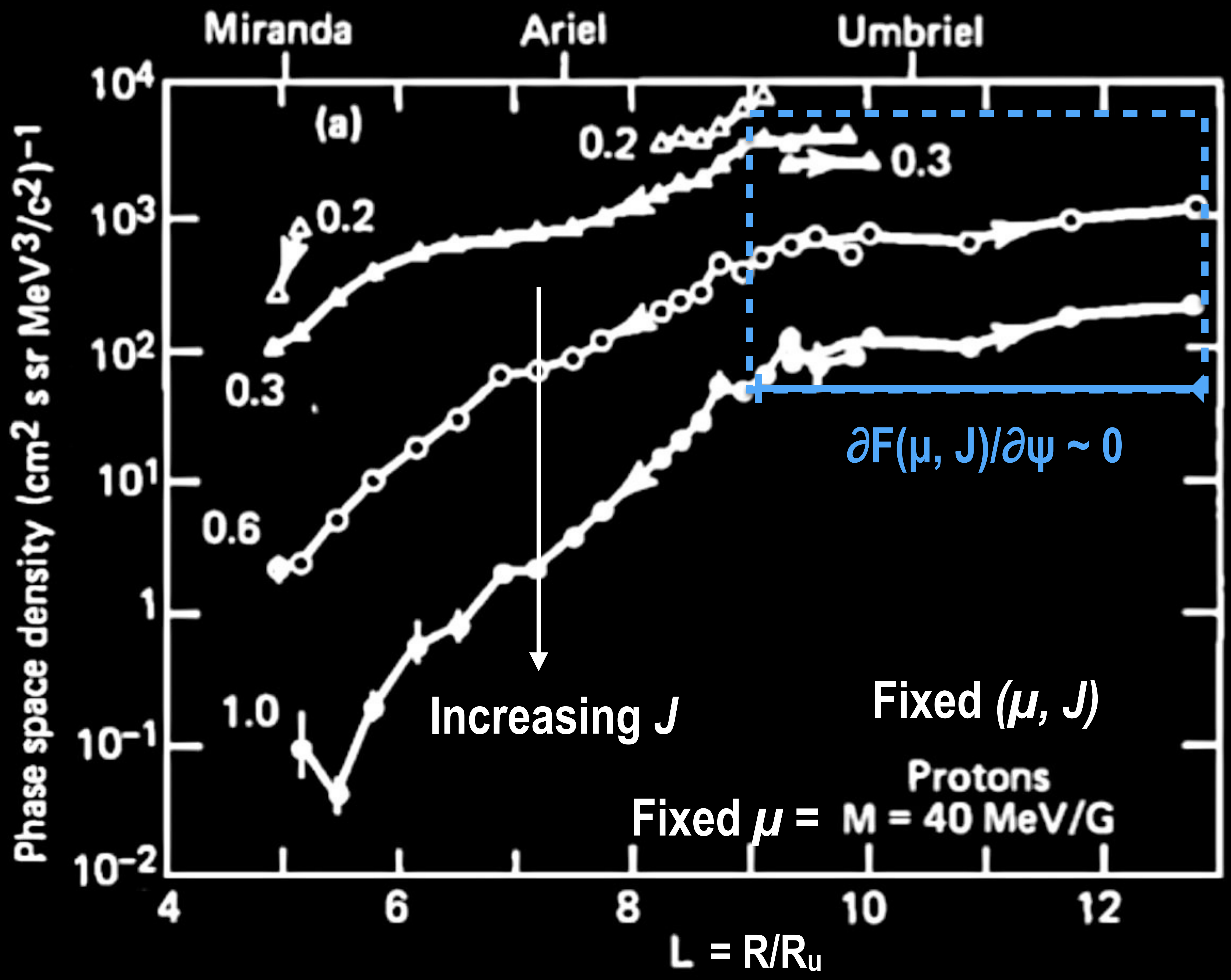
$$P_\perp \propto \frac{B}{V} \sim \frac{1}{L^7}$$

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



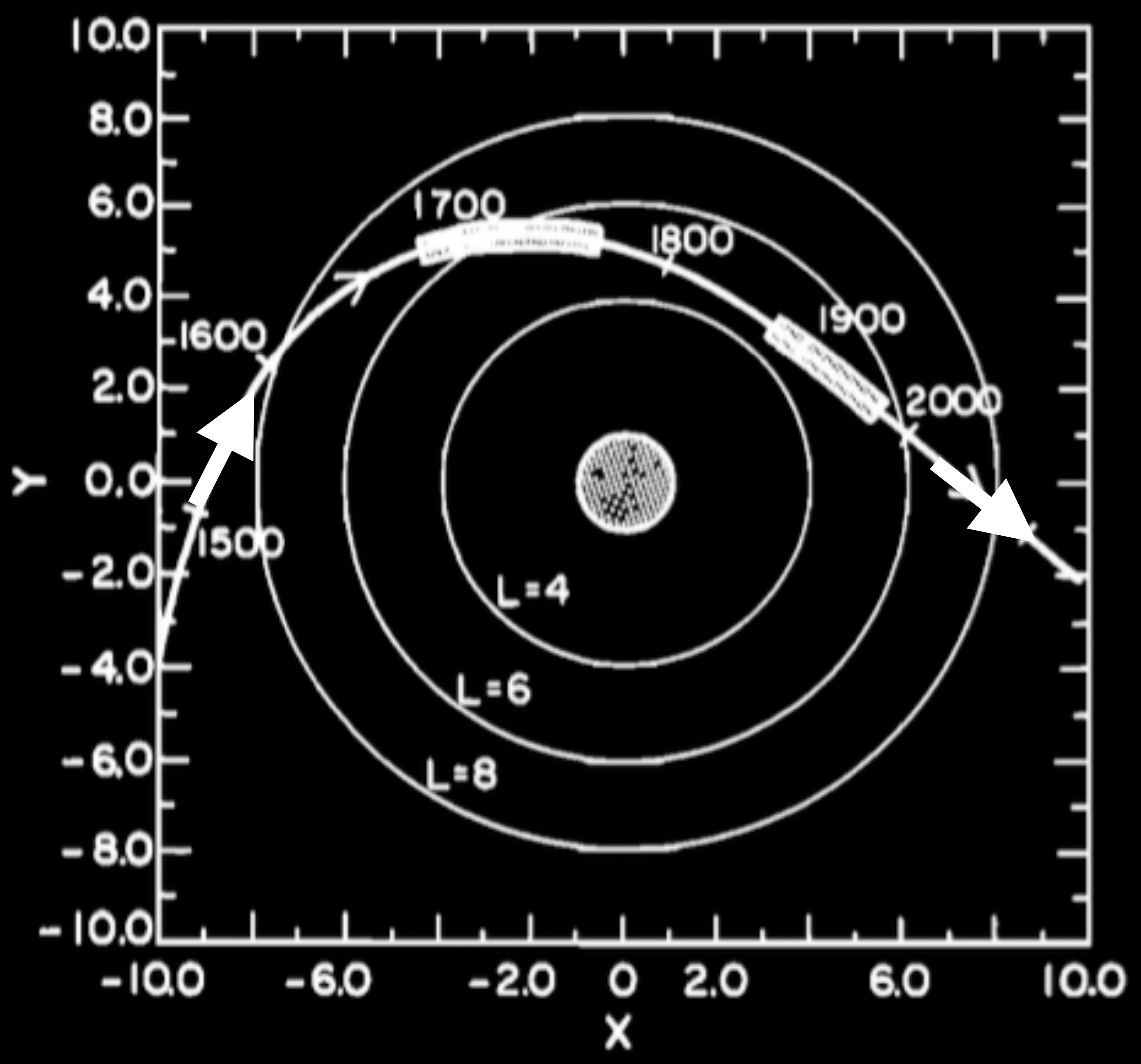
Low-Energy-Charged Particles (LECP)
Protons: 10 keV – 150 MeV

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

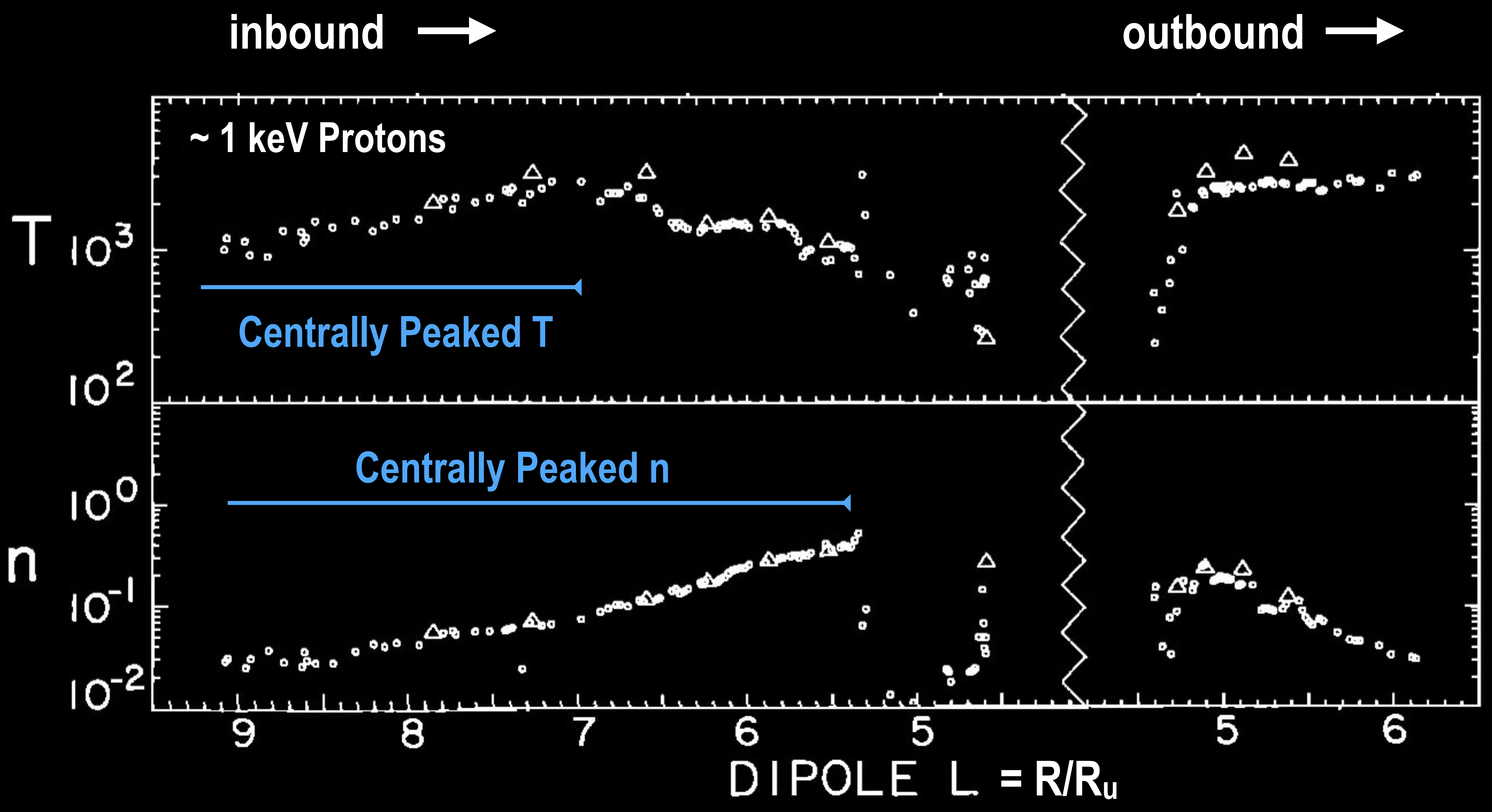


Chen, *et al.*, *JGR* **92**, 15,315 (1987)

Lower Energy (thermal) Plasma has Centrally-Peaked Temperature and Density



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



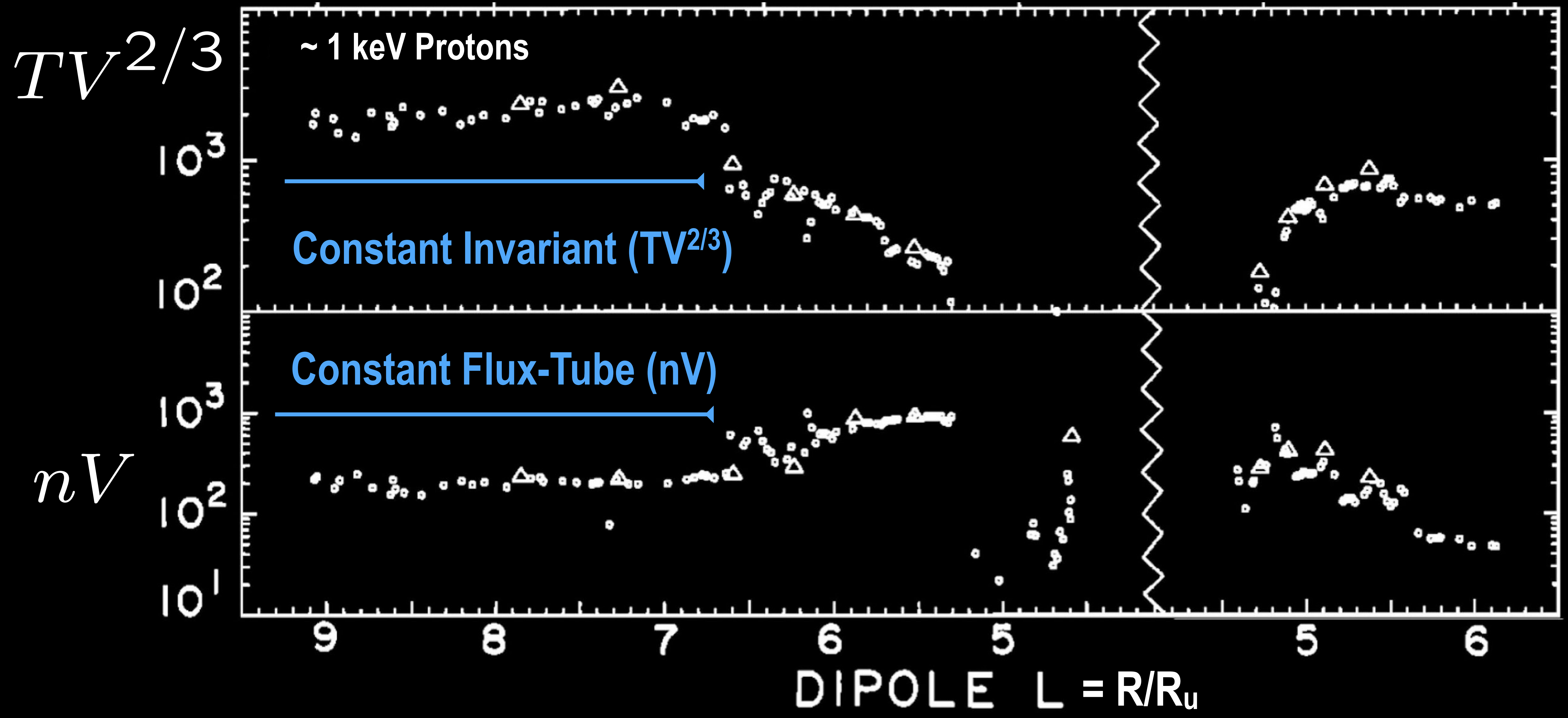
Selesnick and McNutt, *JGR* **92**, 15,249 (1987)

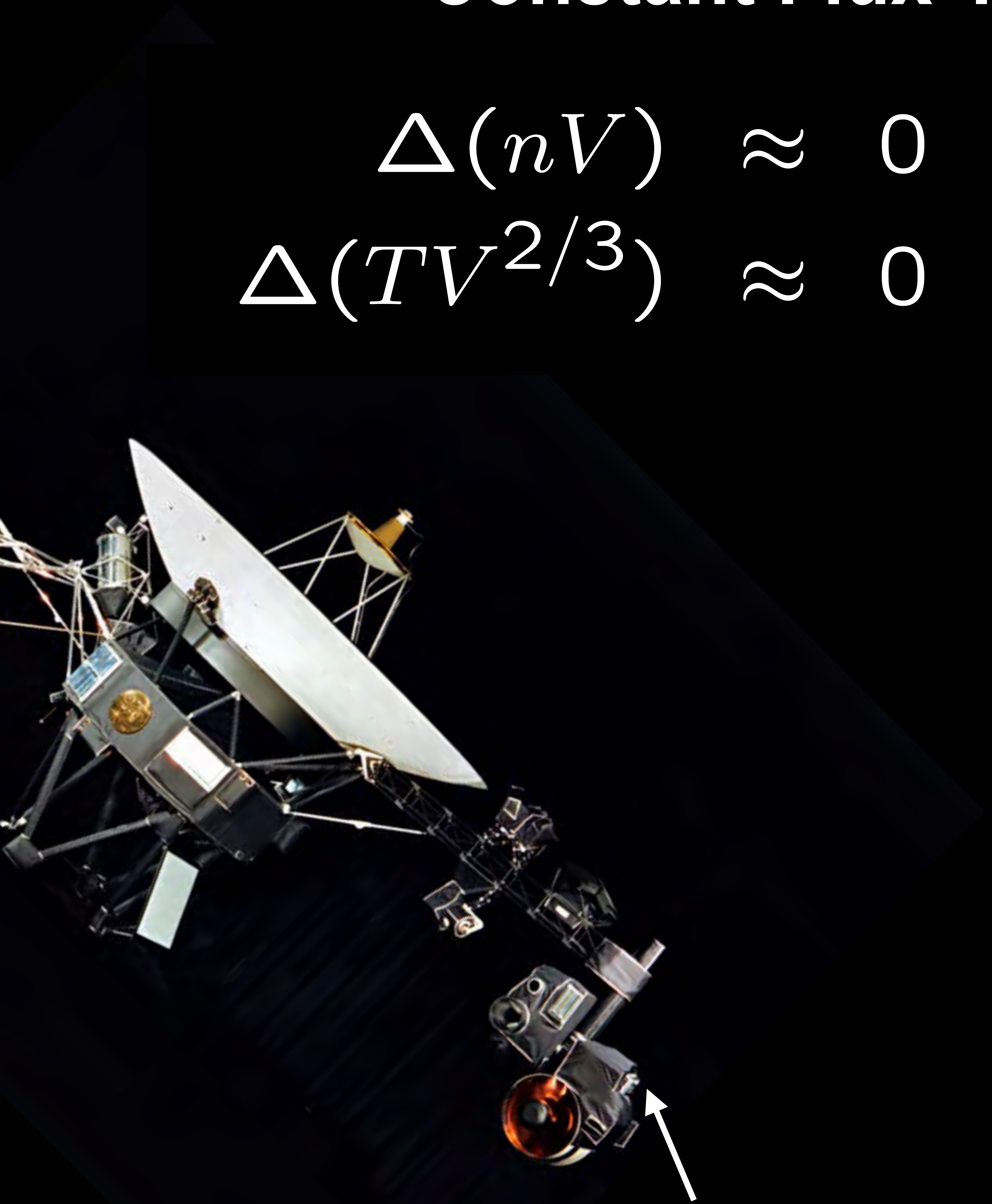
Interchange Motion of Thermal Plasma Creates Regions with Constant Flux-Tube Content and Invariant Temperature

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

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

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***

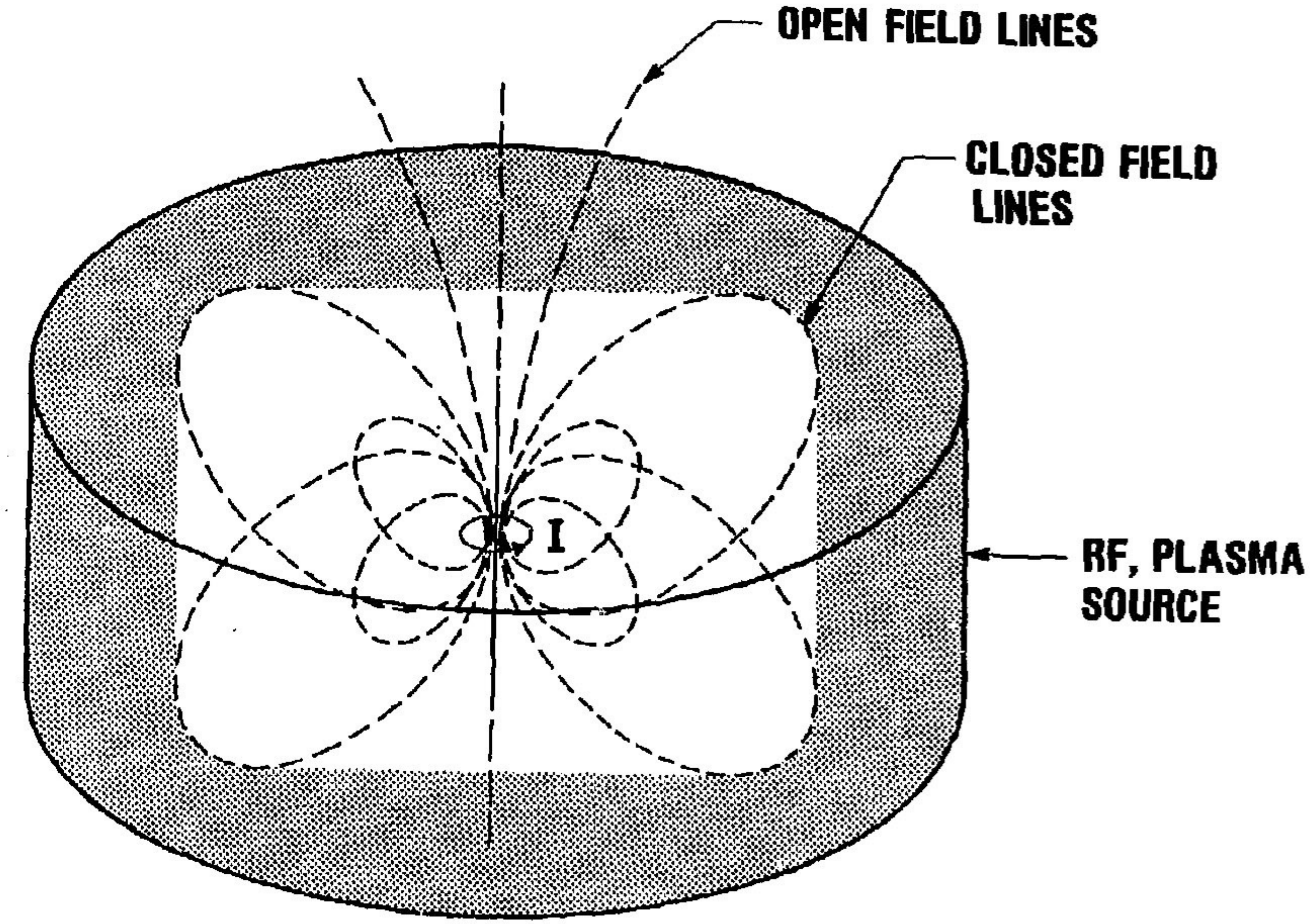
➡ Marginally stable profiles $\Delta(\mathbf{P\ V^{5/3}}) \sim 0$ ***at high beta***, $\beta \geq 1$

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)

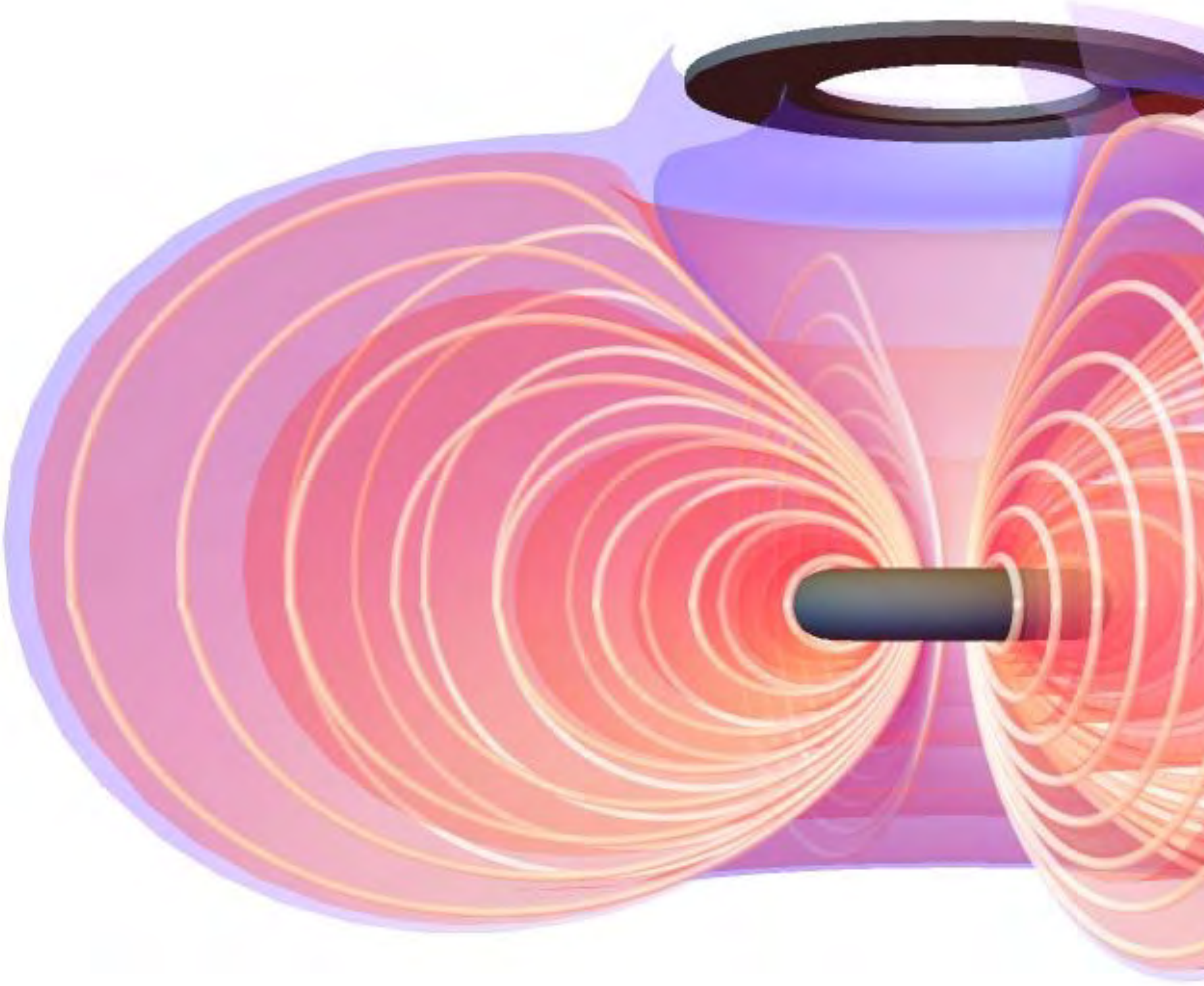
Does magnetospheric physics apply to magnetic confinement in the laboratory?

- ***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)

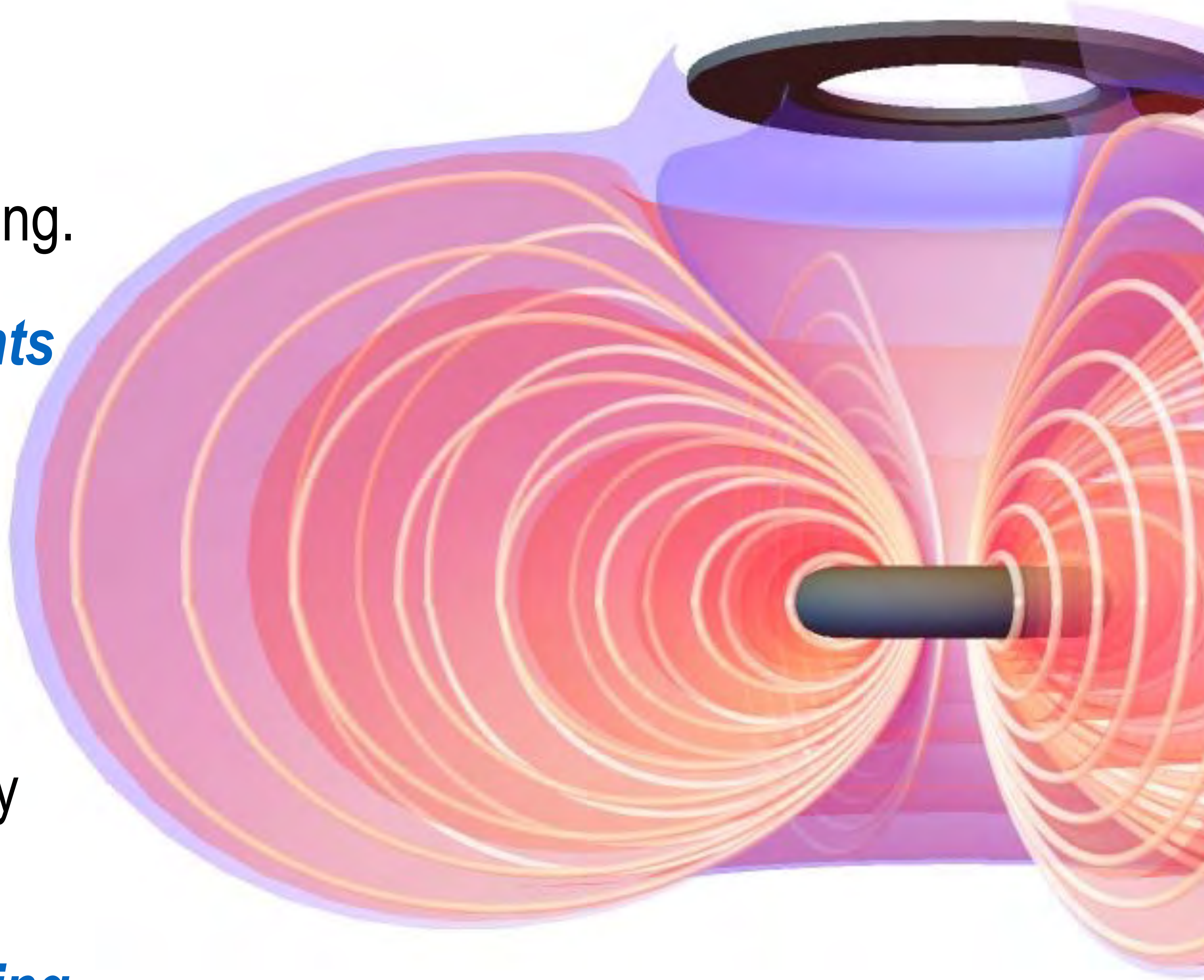
During the past decade, LDX and RT-1 have shown the physics of magnetospheric radial transport and stability ***does apply to the laboratory***



- ***Levitation creates a large confinement volume with plasma regulated by turbulent radial transport.***
- ***Density profiles are always centrally peaked***, and particle transport can be either ***inward*** or ***outward*** depending upon the location of the particle source.
- ***Interchange and entropy instabilities cause low-frequency fluctuations***, and

  Turbulent "self-organization" creates regions of ***nearly uniform*** flux-tube content (**$n\ V$**) and entropy density (**$P\ V^{5/3}$**).
- ***High local beta, β ~ 1, in steady state, can be achieved*** provided drift-resonant fast particle instabilities are stabilized.

LDX and RT-1 have also shown the laboratory magnetosphere is a simple and versatile configuration for ***fundamental study of toroidal magnetic confinement***



- ***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.

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

- ***Nonlinear gyrokinetics is a good model for understanding*** radial transport driven by interchange and entropy mode turbulence.

19 PhD Dissertations

Thomas Roberts, "Local Regulation of Interchange Turbulence in a Dipole-Confined Plasma Torus using Current Injection Feedback", Ph.D. Columbia University, (2015).

Matthew Worstell, "Symmetry Breaking and the Inverse Energy Cascade in a Plasma", Ph.D. Columbia University (2013).

Matt Davis, "Pressure profiles of plasmas confined in the field of a dipole magnet", Ph.D. Columbia (2013).

Sumire Kobayashi, "Gyrokinetic Simulations of Closed Field Line Systems", Ph.D. Dartmouth (2010).

Antoin Cerfon, "Analytic calculations of MHD equilibria and of MHD stability boundaries in fusion plasmas", Ph.D. MIT (2010).

Yoshihisa Yano, “Experimental analysis of he magnetic field structure on the high-beta plasmas in the magnetospheric plasma device,” 2010, PhD, U. Tokyo

Jennifer Ellsworth, "Characterization of Low-frequency Density Fluctuations in Dipole-confined Laboratory Plasmas", Ph.D., MIT, (2010).

Brian Grierson, "Interchange Turbulence in a Dipole-Confined Plasma," Ph.D. Columbia (2009).

Alex Boxer, "Interchange Stationary Profiles in the Levitated Dipole Experiment (LDX)", Ph.D., MIT, (2008).

Alexie Kouznetsov, "Theoretical prediction of тau_E and β in a large aspect ratio LDX", Ph.D., MIT (2007).

Eugenio Ortiz, "Observation of Hot Electron Interchange Instability in a High Beta Dipole Confined Plasma", Ph.D. Columbia (2007).

Ishtak Karim, "Equilibrium and Stability Studies of Plasmas in a Dipole Magnetic Fields Using Magnetic Measurements", Ph.D., MIT, (2007).

Natalia Krasheninnikova, "Effects of hot electrons on the stability of a closed field line plasma," Ph.D. MIT (2006).

Haruhiko Saitoh, "Experimental Study on the Confinement of Electron Plasma and Formation of Flow of Neutral Plasma in an Internal Conductor System", Ph.D., Univ. Tokyo (2005).

Ben Levitt, "Global Mode Analysis of Centrifugal and Curvature Driven Interchange Instabilities," Ph.D. Columbia (2004).

Dmitry Maslovsky, "Suppression of Nonlinear Frequency Sweeping of Resonant Interchange Modes in a Magnetic Dipole with Applied Radio Frequency Fields," Ph.D. Columbia (2003).

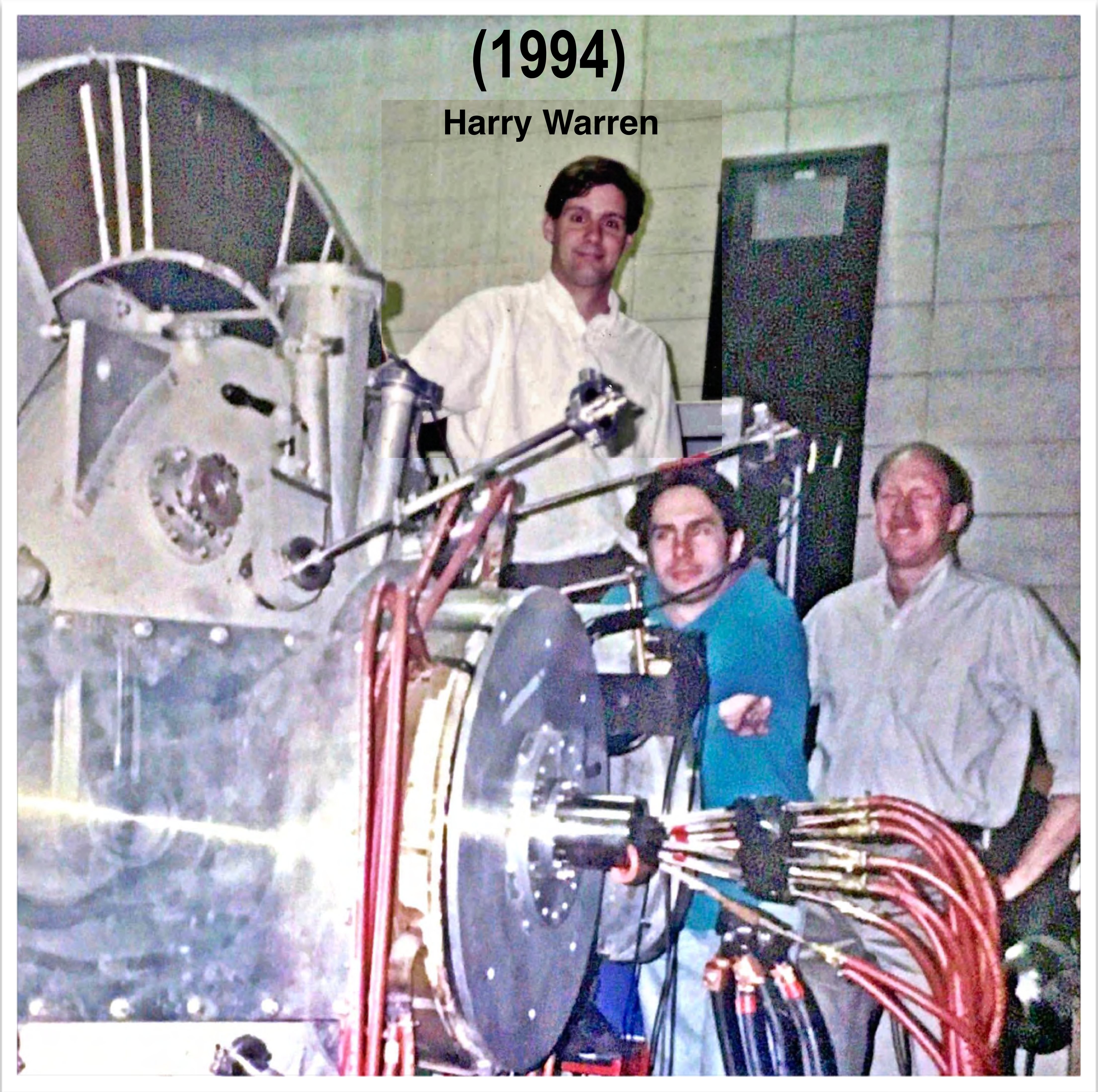
John Tonge, "Particle Simulations of Instabilities in Space and Astrophysical Plasmas", Ph.D. UCLA (2002).

Andrei Simakov, "Plasma stability in a dipole magnetic field", Ph.D. MIT (2001).

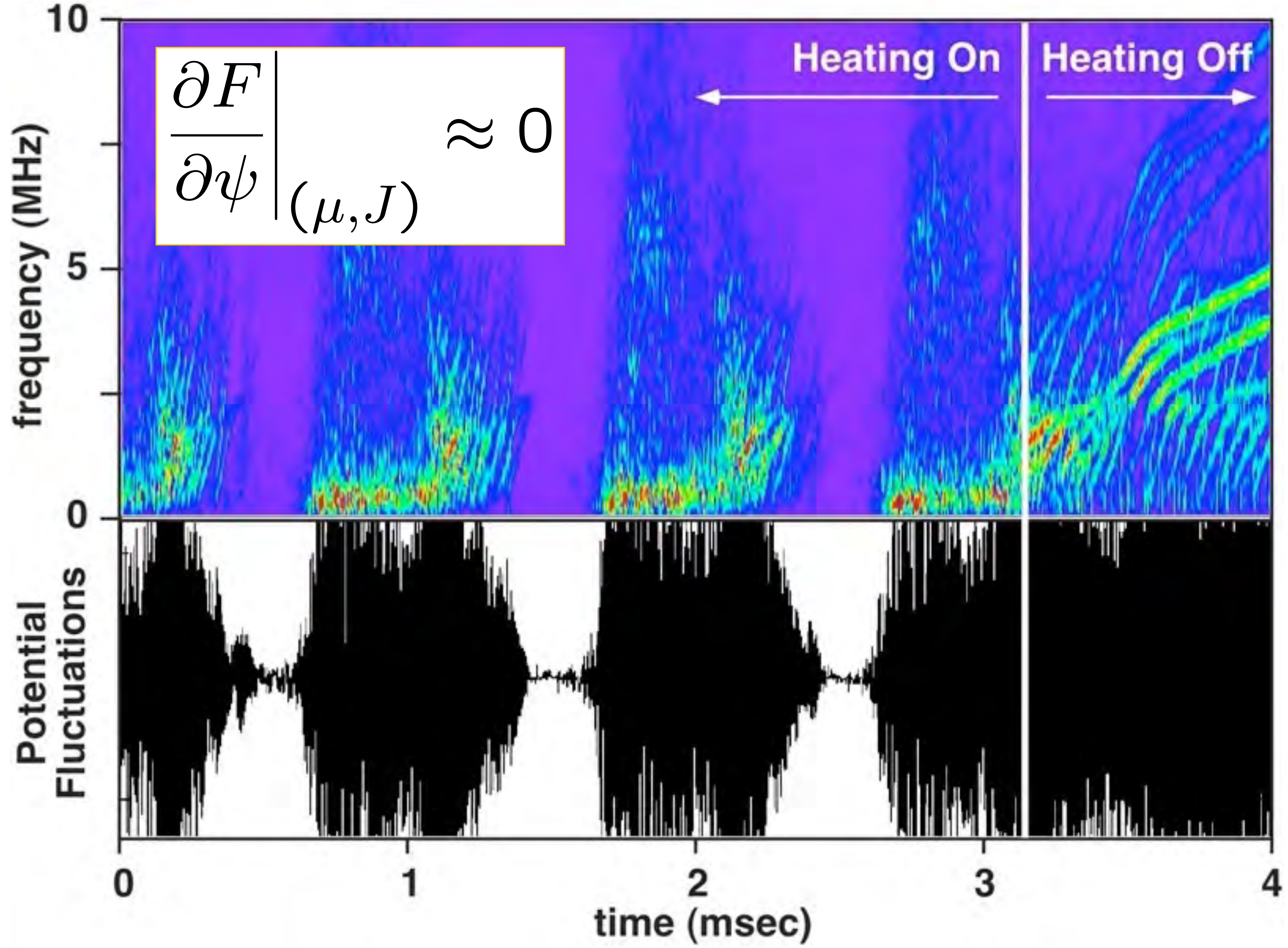
Harry Warren, "Observation of Chaotic Particle Transport Driven by Drift-Resonant Fluctuations in the Collisionless Terrella Experiment," Ph.D. Columbia (1994).

and **10 M.S. Dissertations**

19 PhD Dissertations



Drift-Resonant Radial Transport



Harry Warren, "Observation of Chaotic Particle Transport Driven by Drift-Resonant Fluctuations in the Collisionless Terrella Experiment," Ph.D. Columbia (1994).

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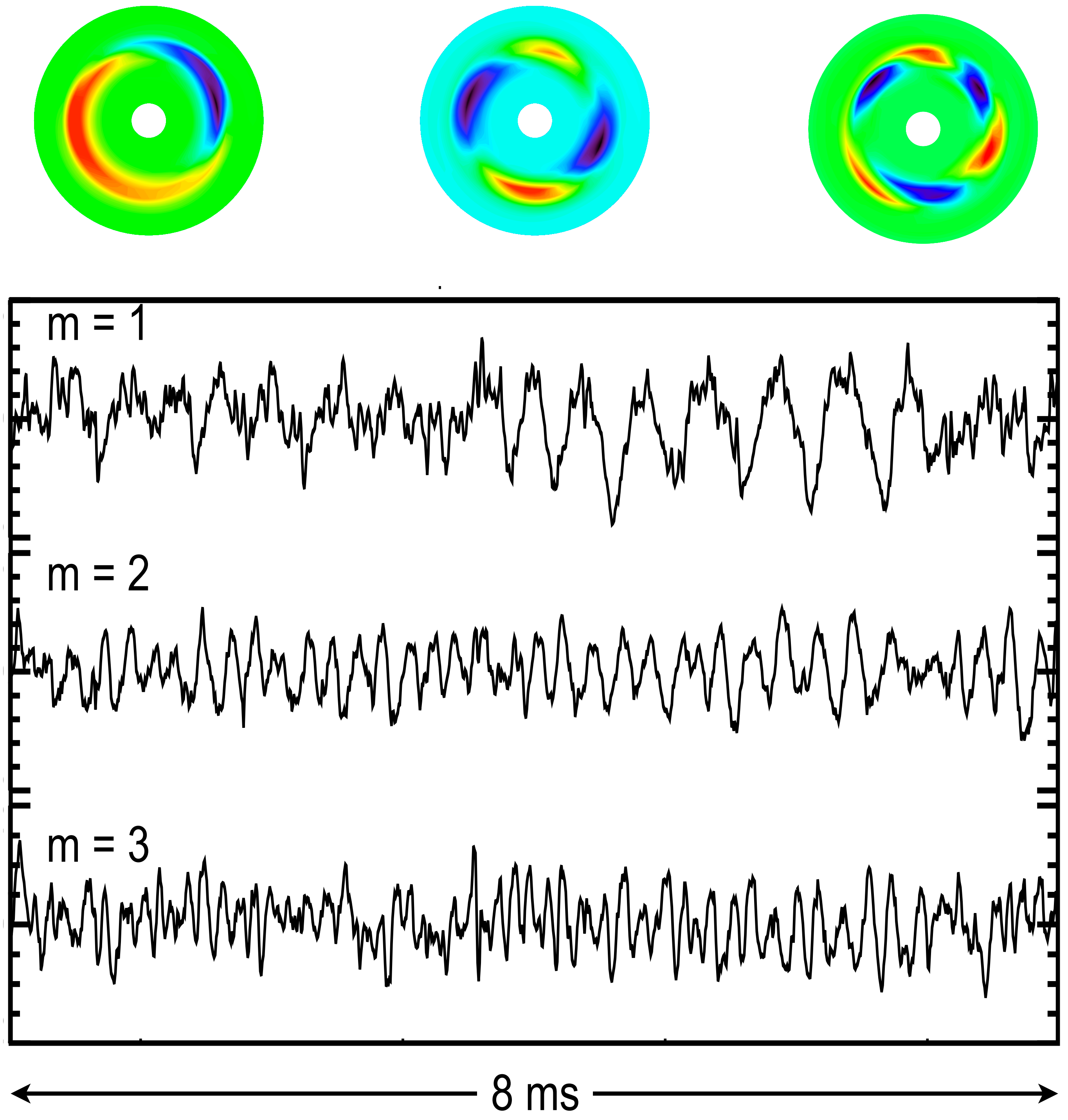
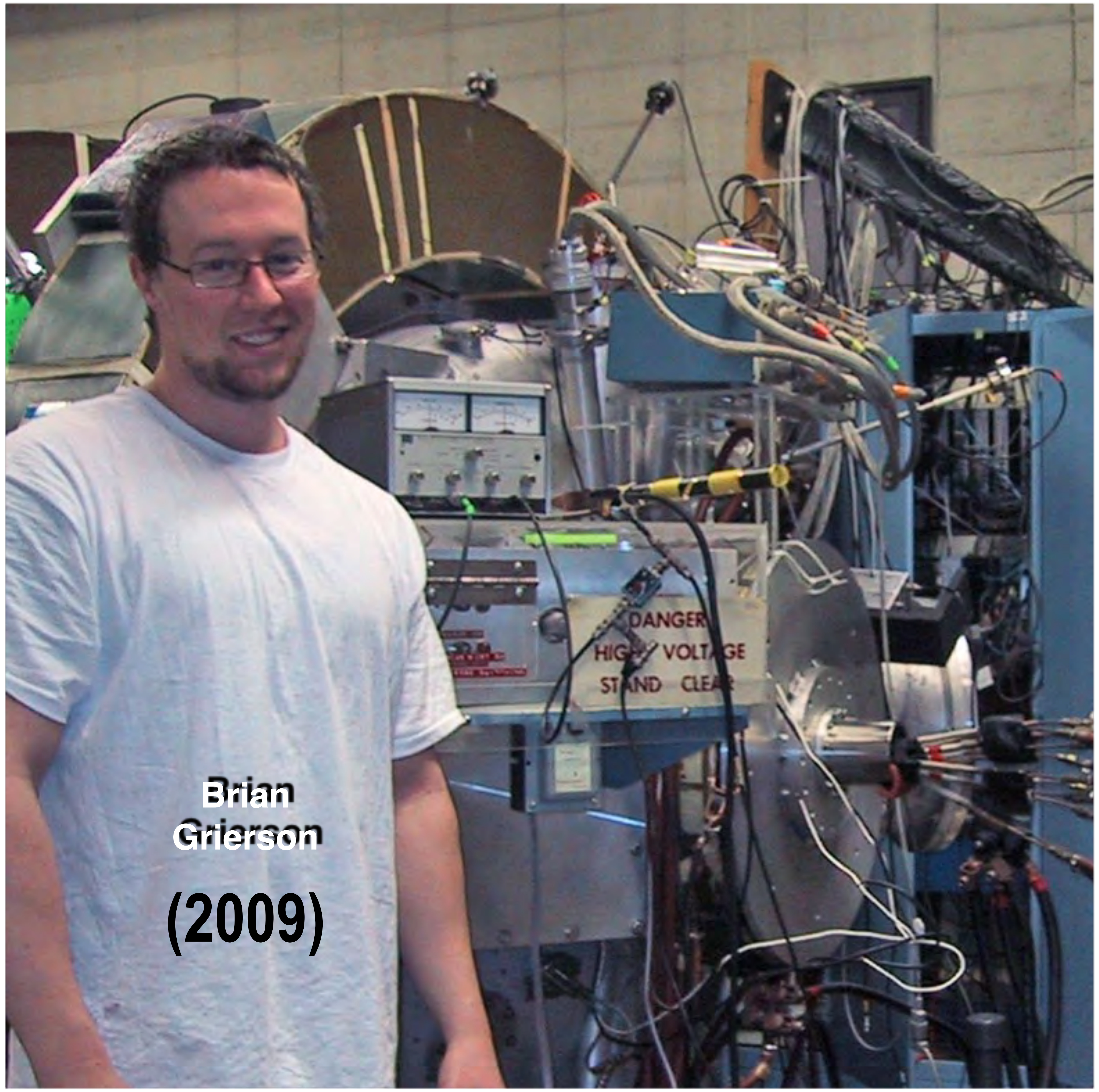


Convective Structures Dynamics

Brian Grierson, "Interchange Turbulence in a Dipole-Confined Plasma," Ph.D. Columbia (2009).



Turbulent Interchange Transport

Outline

- ***Two laboratory magnetospheres***: LDX and RT-1, having large flux-tube expansion
- ***Particle transport and turbulent relaxation*** to centrally-peaked profiles (***LDX***)
    - Matt Davis (PhD *Columbia*) and Alex Boxer (PhD *MIT*)
- ***Understanding entropy mode turbulence*** near marginal stability (***GS2***)
    - Sumire Kobayashi (PhD *Dartmouth/Rogers*)
- ***Achieving record high local β*** by stabilizing fast electron interchange instability (***RT-1***)
    - Yoshihisa Yano (PhD *Univ Tokyo/Yoshida*)
- ***Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement***

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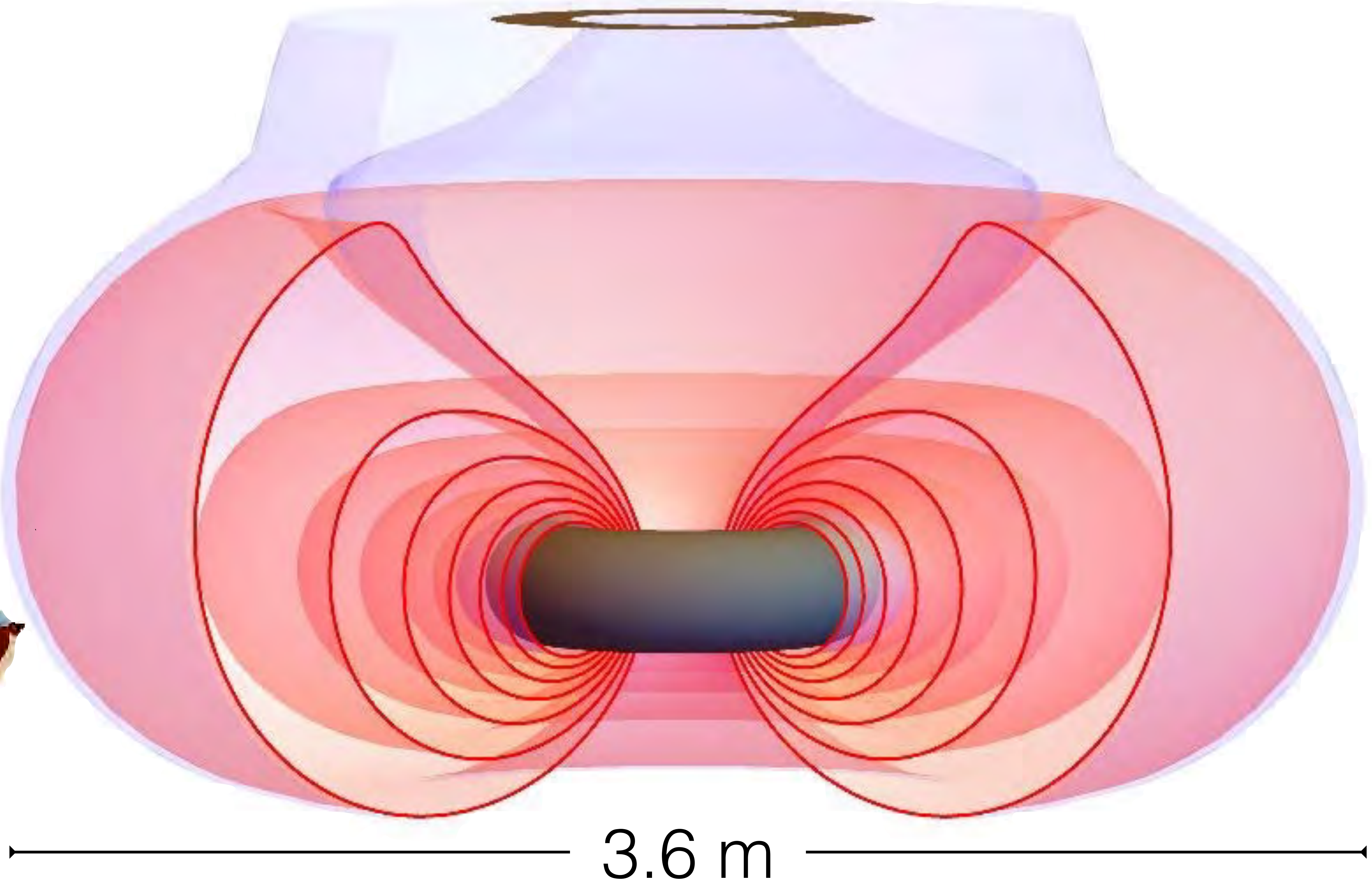
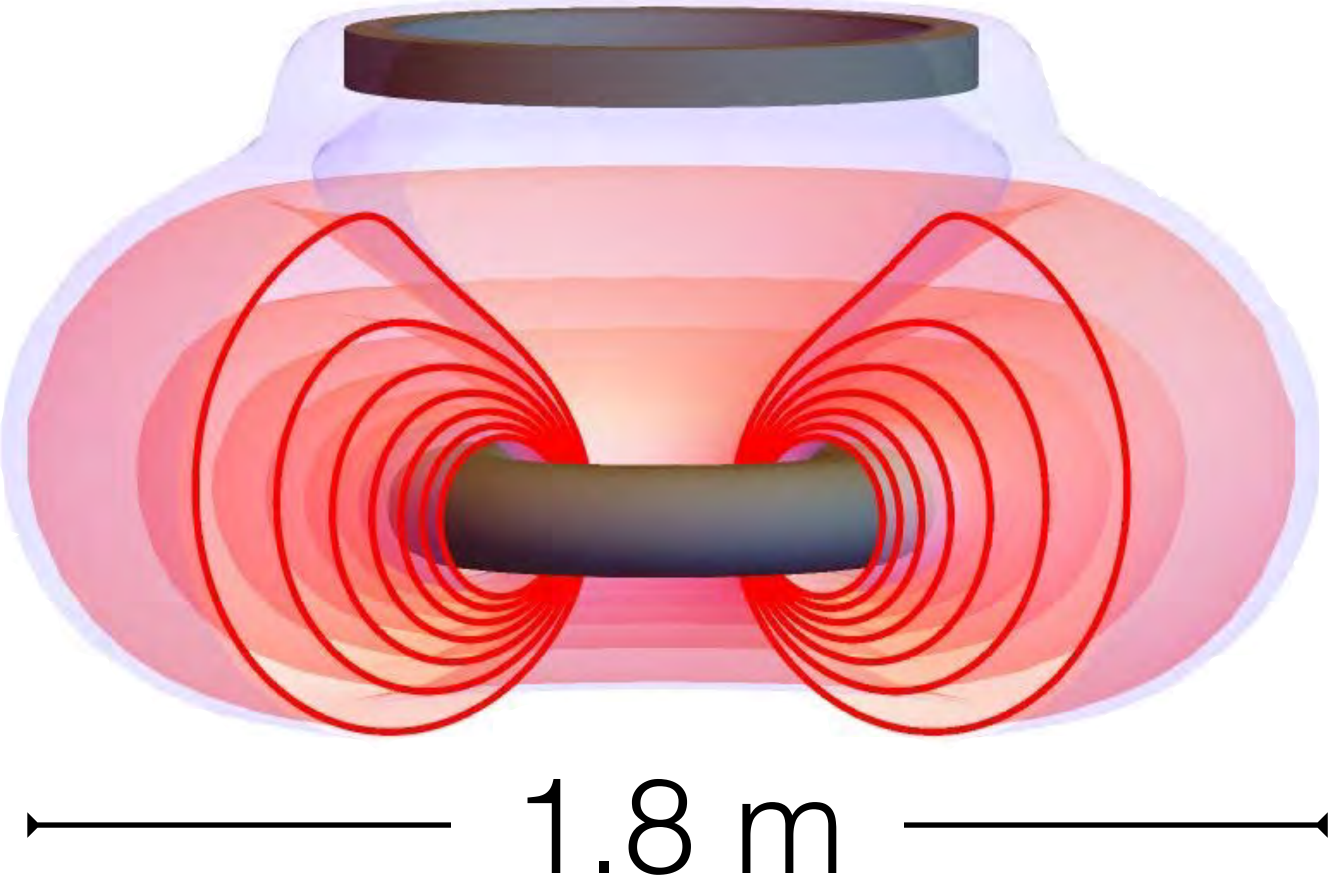
Two Laboratory Magnetospheres



Levitated Dipole Experiment (LDX)

(1.2 MA · 0.41 MA m^2 · 550 kJ · 565 kg)
Nb_3Sn · 3 Hours Float Time
24 kW ECRH

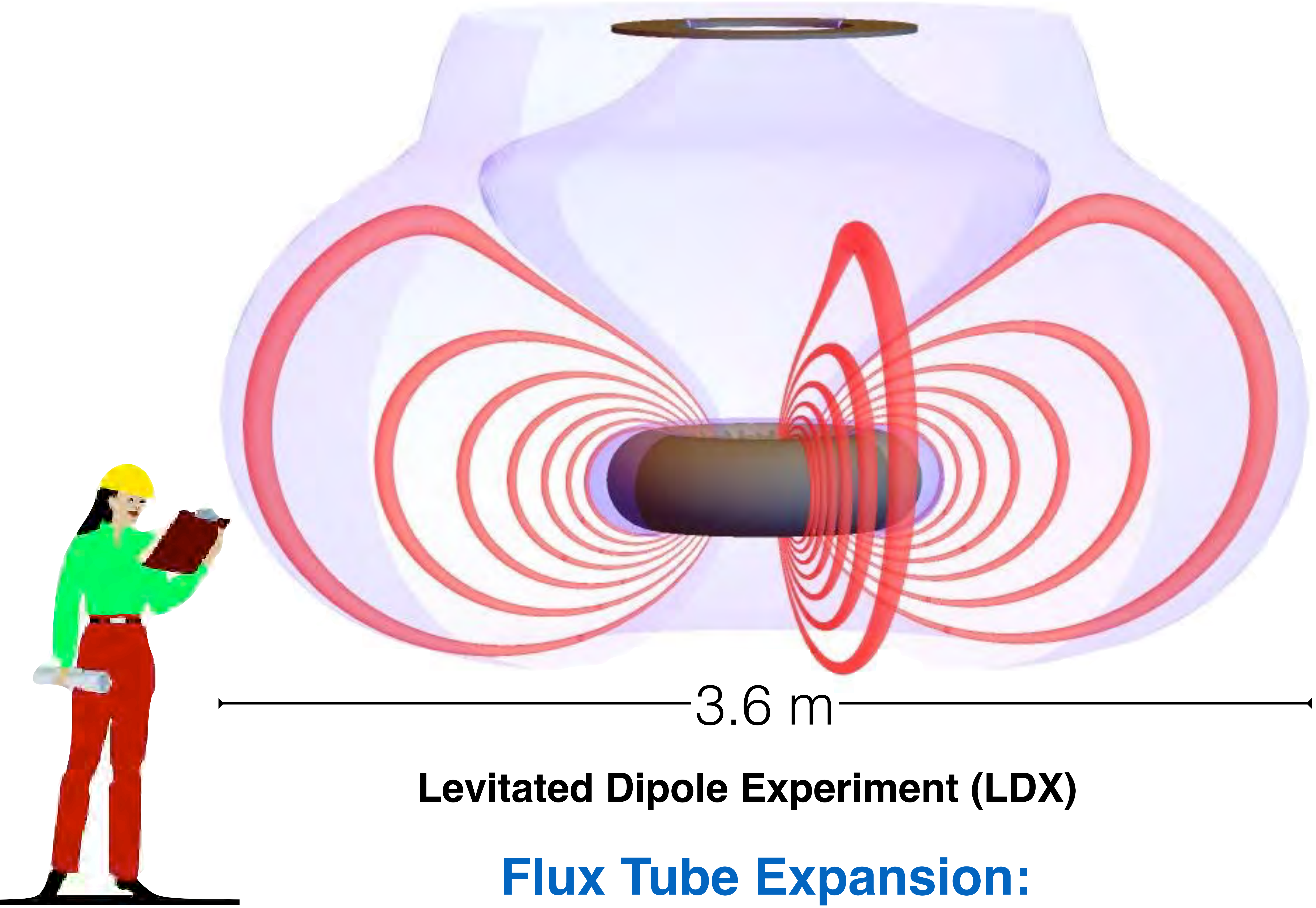


Ring Trap 1 (RT-1)

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

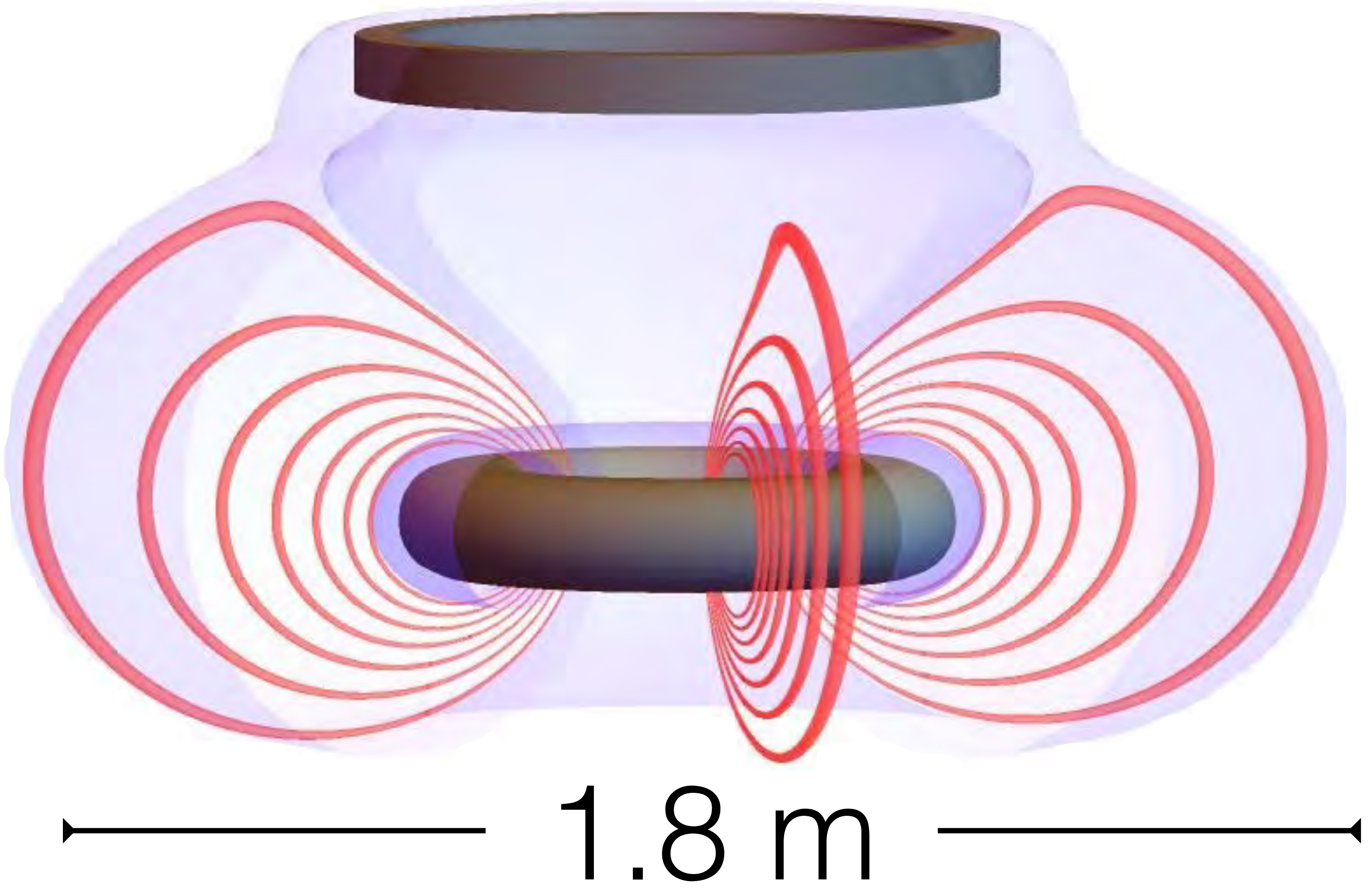
Laboratory Magnetospheres: Designed for Maximum Flux Tube Expansion

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



Levitated Dipole Experiment (LDX)

Flux Tube Expansion:
δV(out)/δV(in) = 100



Ring Trap 1 (RT-1)

Flux Tube Expansion:
δV(out)/δV(in) = 40

Large Flux Tube Expansion Maximizes Plasma's Stable Pressure Gradient

Ideal MHD interchange instability limits plasma pressure gradient relative to the rate of **flux-tube expansion…**

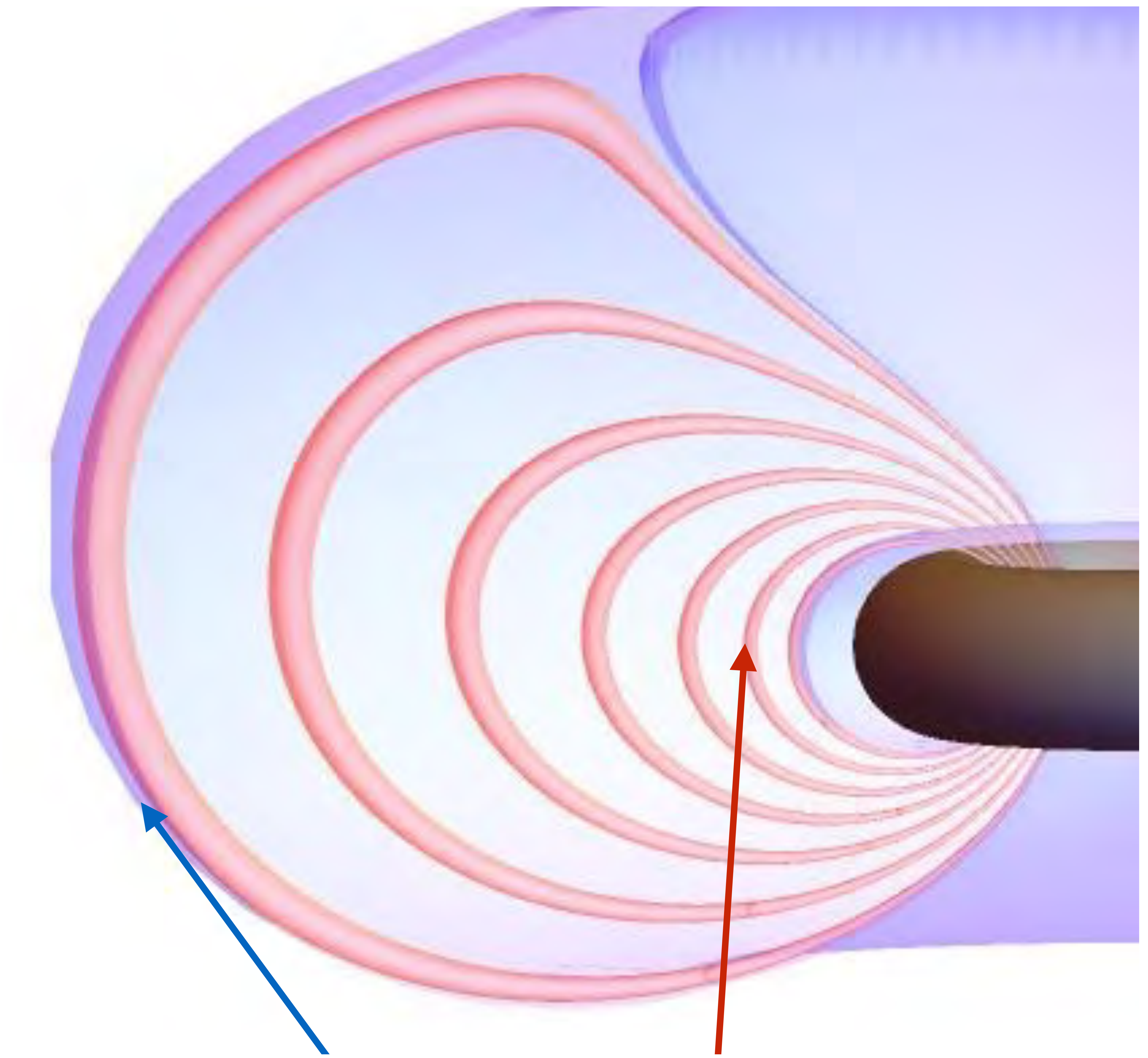
$$\Delta W_p = \Delta\left(PV^{5/3}\right)\frac{\Delta V}{V^{5/3}} > 0$$

and steep pressure gradients are MHD stable, ***even as β >> 1***.

MHD stability ***requires*** finite plasma pressure at edge.

$$\Delta W_p = \underbrace{\Delta P \Delta V}_{\text{Bad Curvature}} + \underbrace{\frac{5}{3}\frac{P}{V}(\Delta V)^2}_{\text{Compressibility}} > 0$$

Magnetosphere: Magnetopause plasma sustained by solar wind
Laboratory: Scrape-off-layer (SOL) maintained by escaping plasma

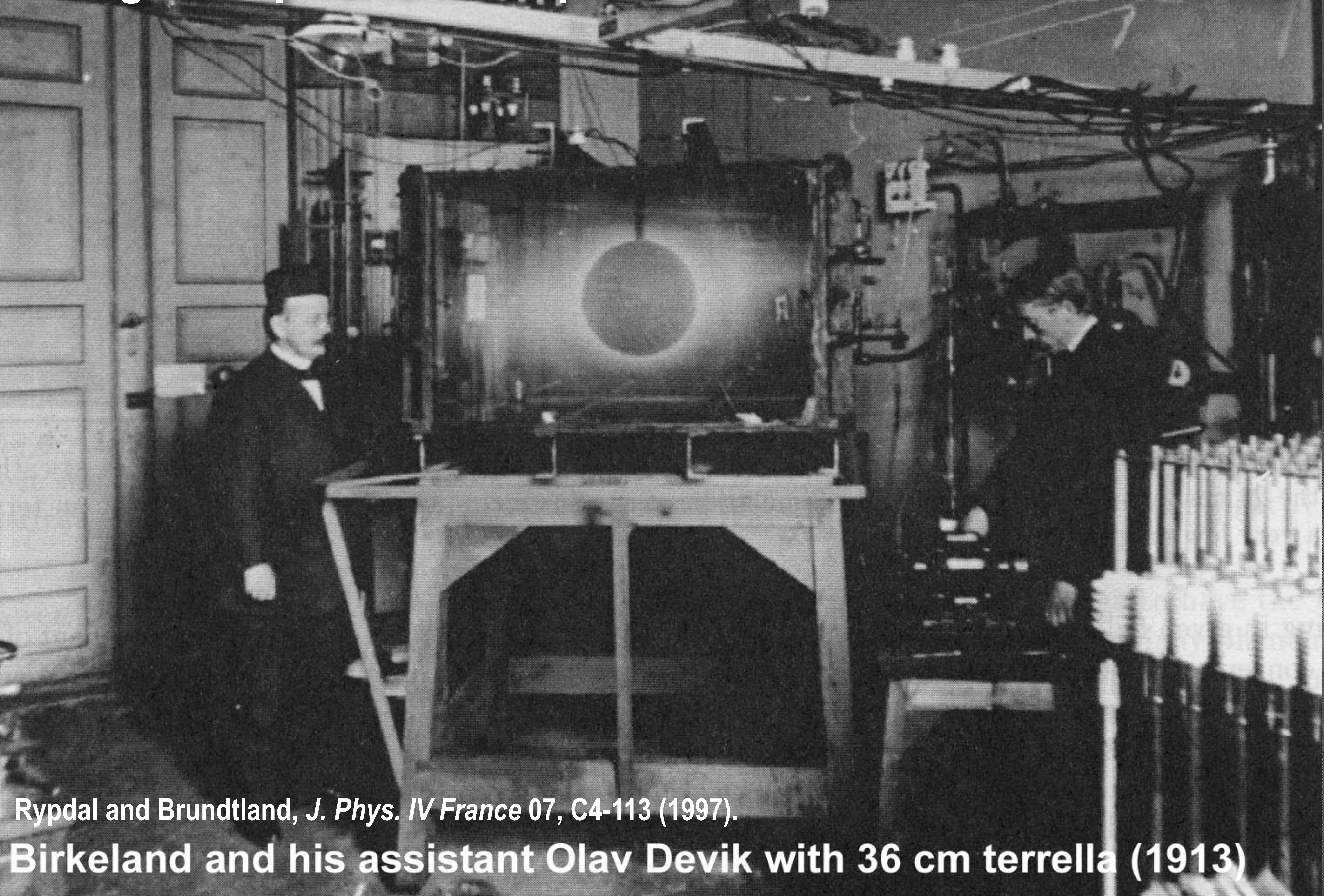


Edge pressure* must rise in proportion to *core pressure

$$\frac{P(core)}{P(edge)} \le \left(\underbrace{\frac{V(edge)}{V(core)}}_{\text{Flux-Tube Expansion}}\right)^{5/3} \sim 2000$$

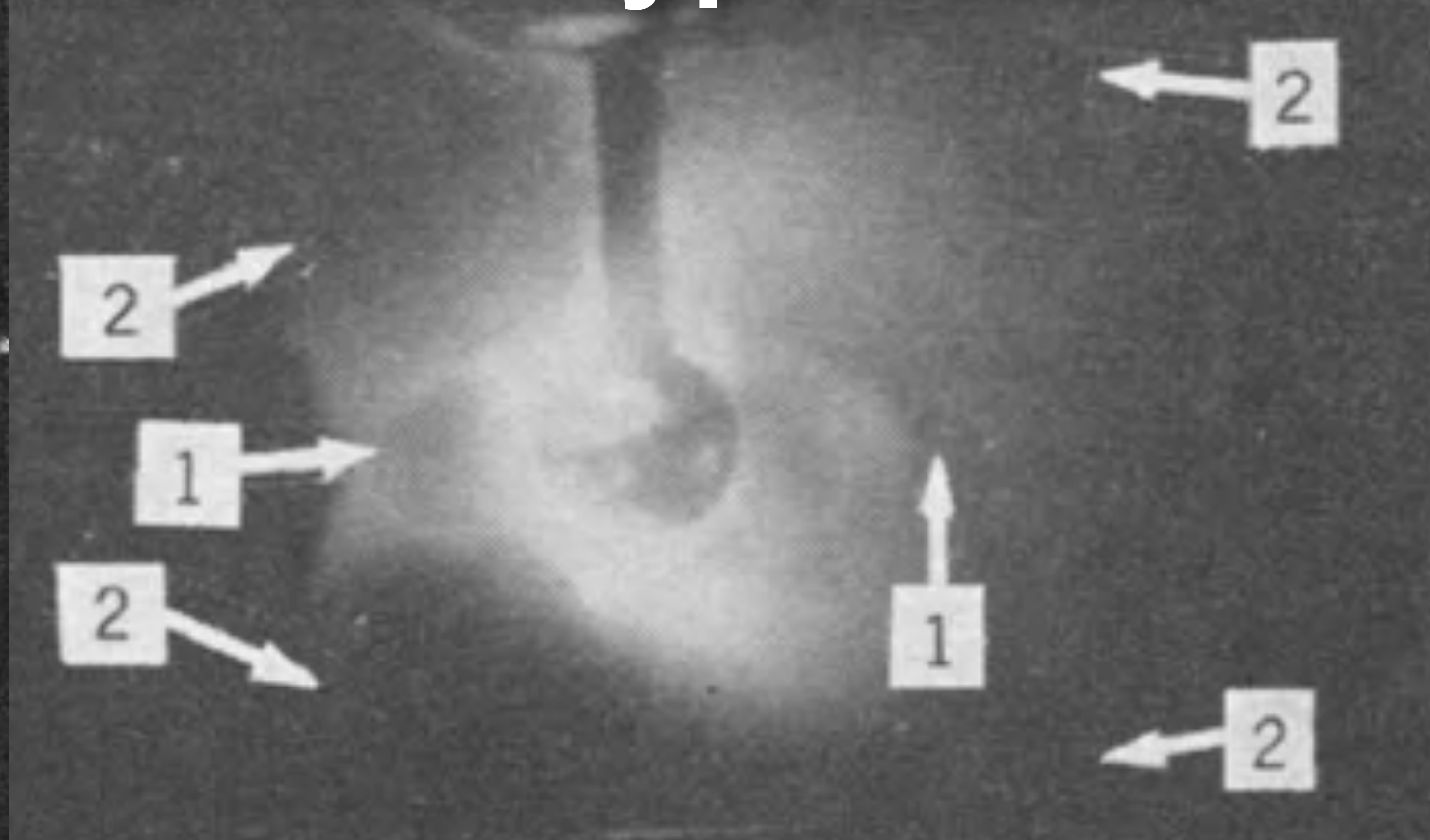
Rosenbluth and Longmire, "Stability of plasmas confined by magnetic fields," *Ann Phys*, **1**, 120 (1957)
Gold, "Motions in the magnetosphere of the Earth," *JGR*, **64** 1219 (1959)
Garnier, *et al.*, "Magnetohydrodynamic stability in a levitated dipole," *PoP*, **6**, 3431 (1999).
Krasheninnikov, *et al.*, "Magnetic dipole equilibrium solution at finite plasma pressure," *PRL*, **82**, 2689 (1999)

The Early Great Terrella Experiments Explored the Magnetospheric/Ionospheric Current Structure and the “Auroral Hypothesis”

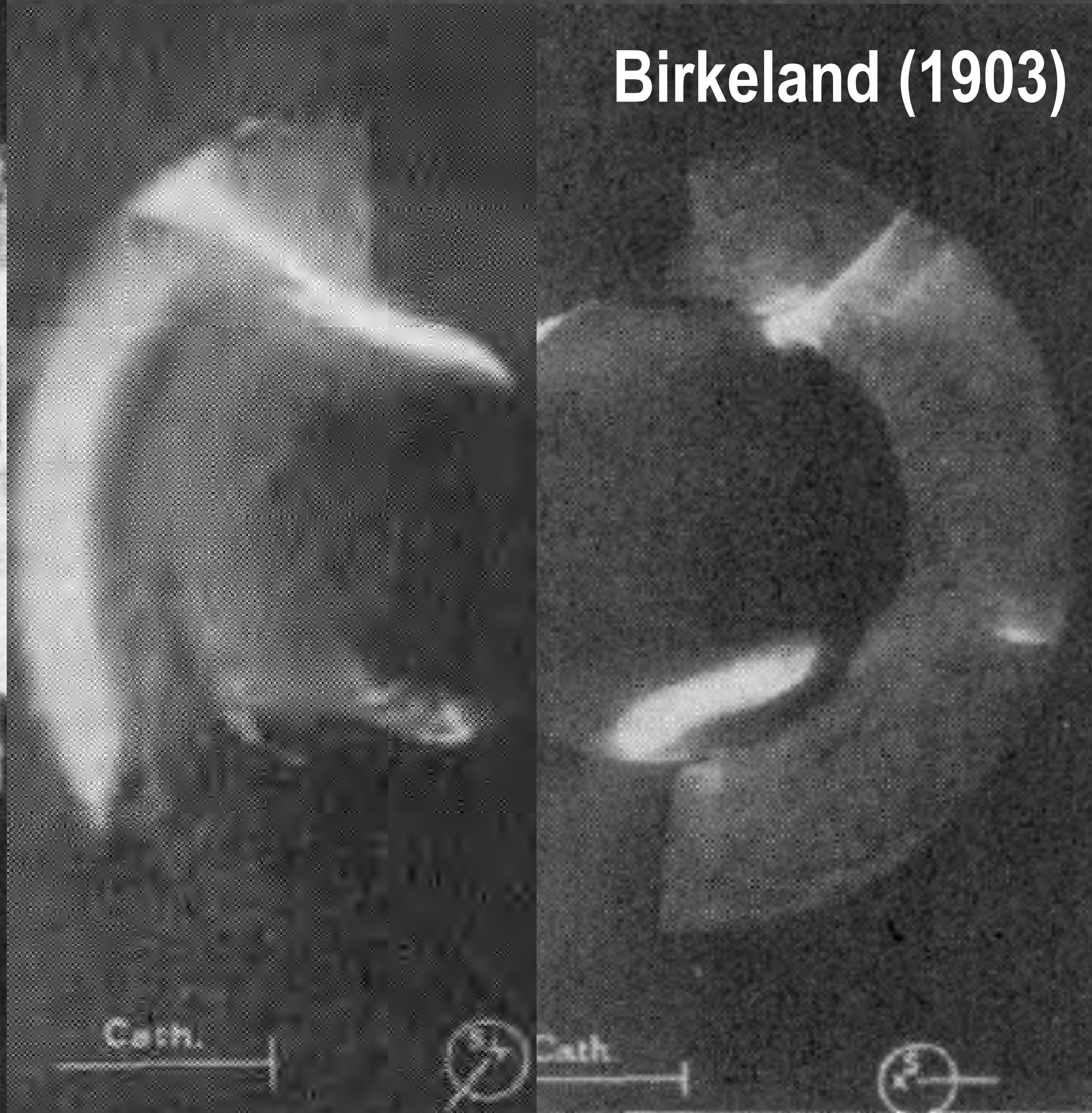


Rypdal and Brundtland, *J. Phys. IV France* 07, C4-113 (1997).

Birkeland and his assistant Olav Devik with 36 cm terrella (1913)

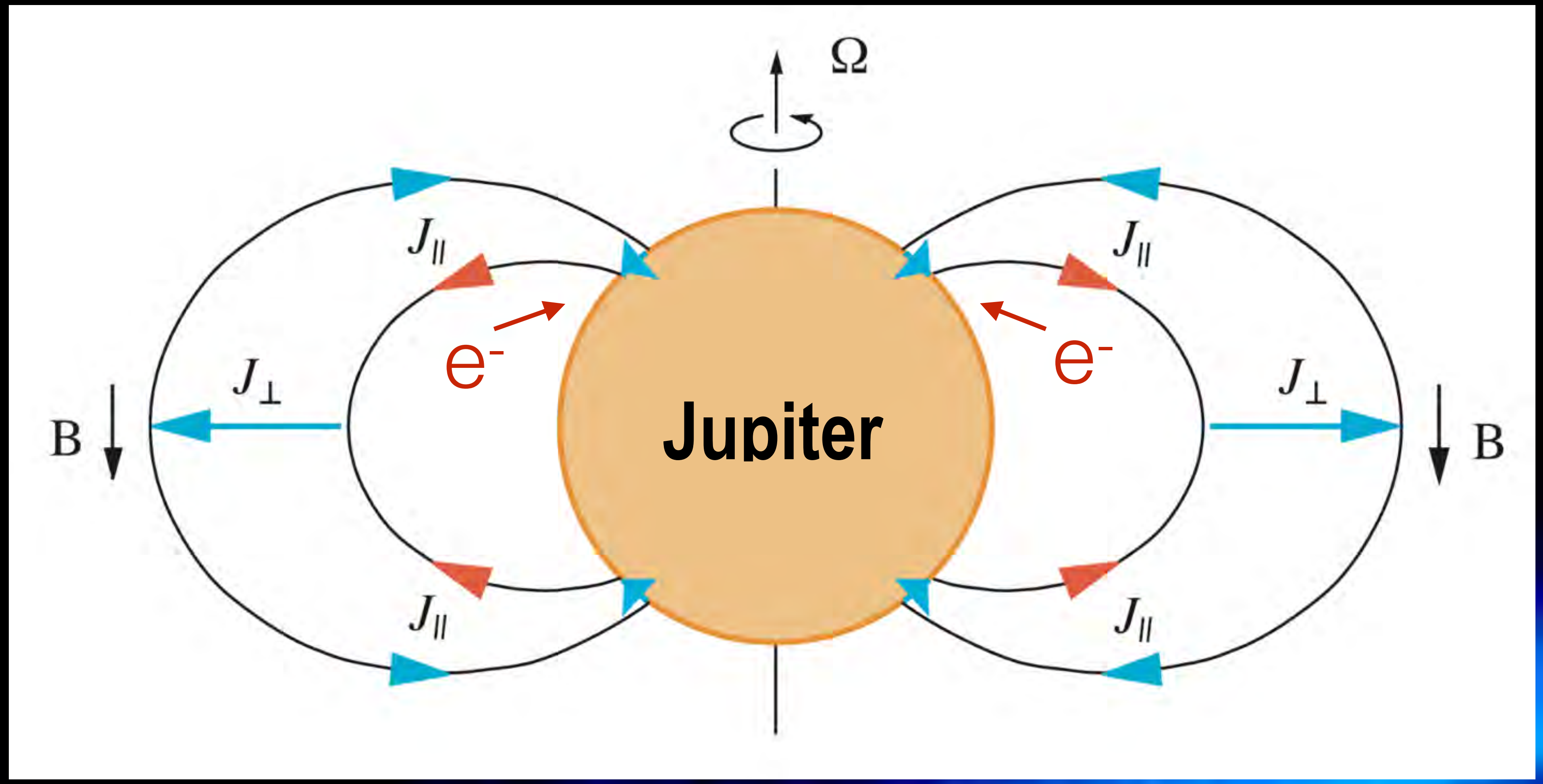


Danielsson and Lindberg (1964)



Birkeland (1903)

The Laboratory Magnetosphere Explores Stability and Transport *Without* Field-Aligned Currents and *Without* the Magnetospheric Dynamo



Magnetospheric Dynamo:
100 TW Auroral Power
Regulates Interchange Motion

Hill and Vasyliūnas, "Jovian auroral signature of Io's corotational wake," JGR, 107, 1464 (2002).

Hubble (Dec 9, 2000)

Comparing Laboratory and Planetary Magnetospheres

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

Internally driven interchange instabilities

Externally driven by solar wind

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

Externally driven by applied µwave power

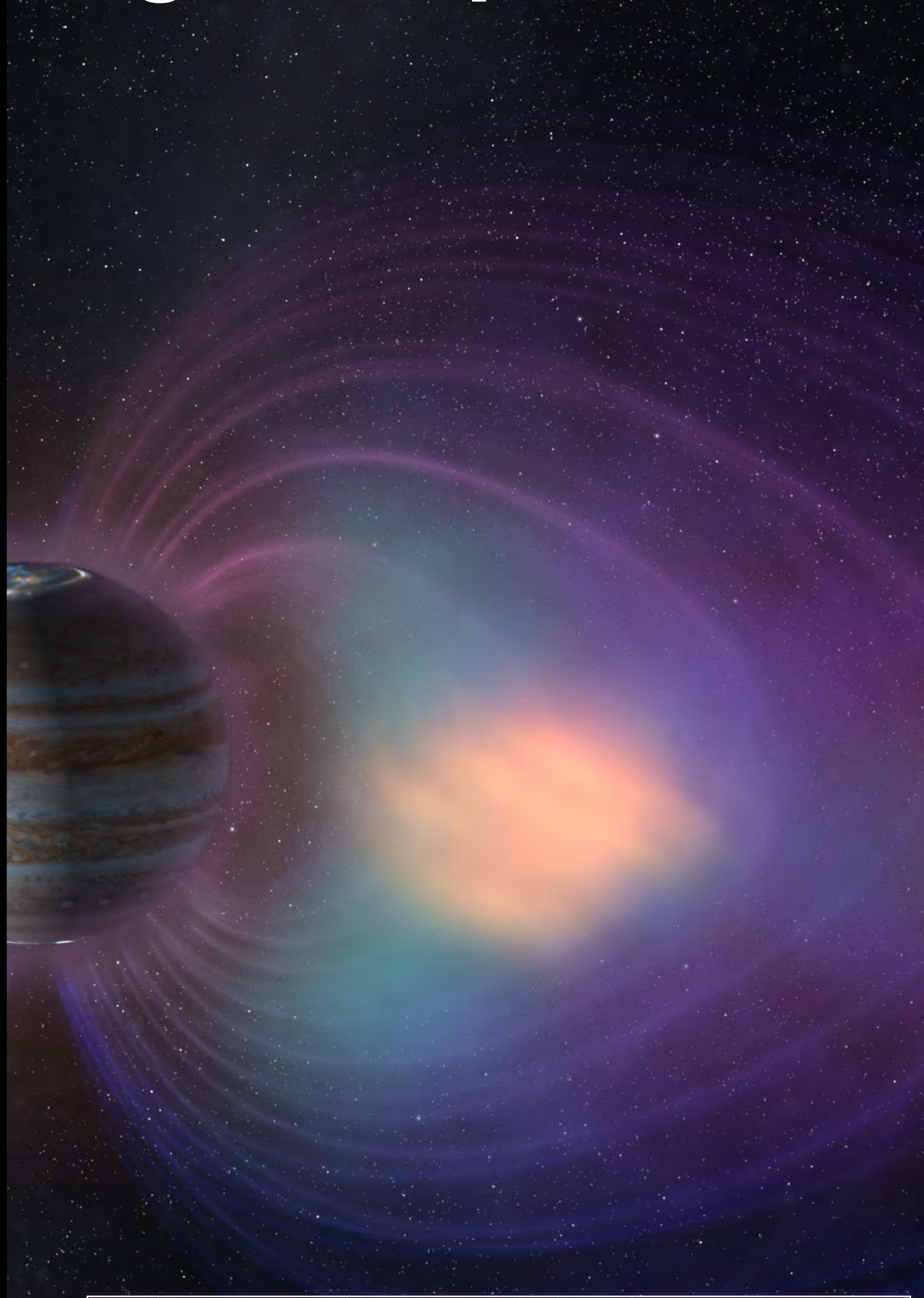
Internally driven by plasma chorus

Ionosphere?

No*

Yes

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

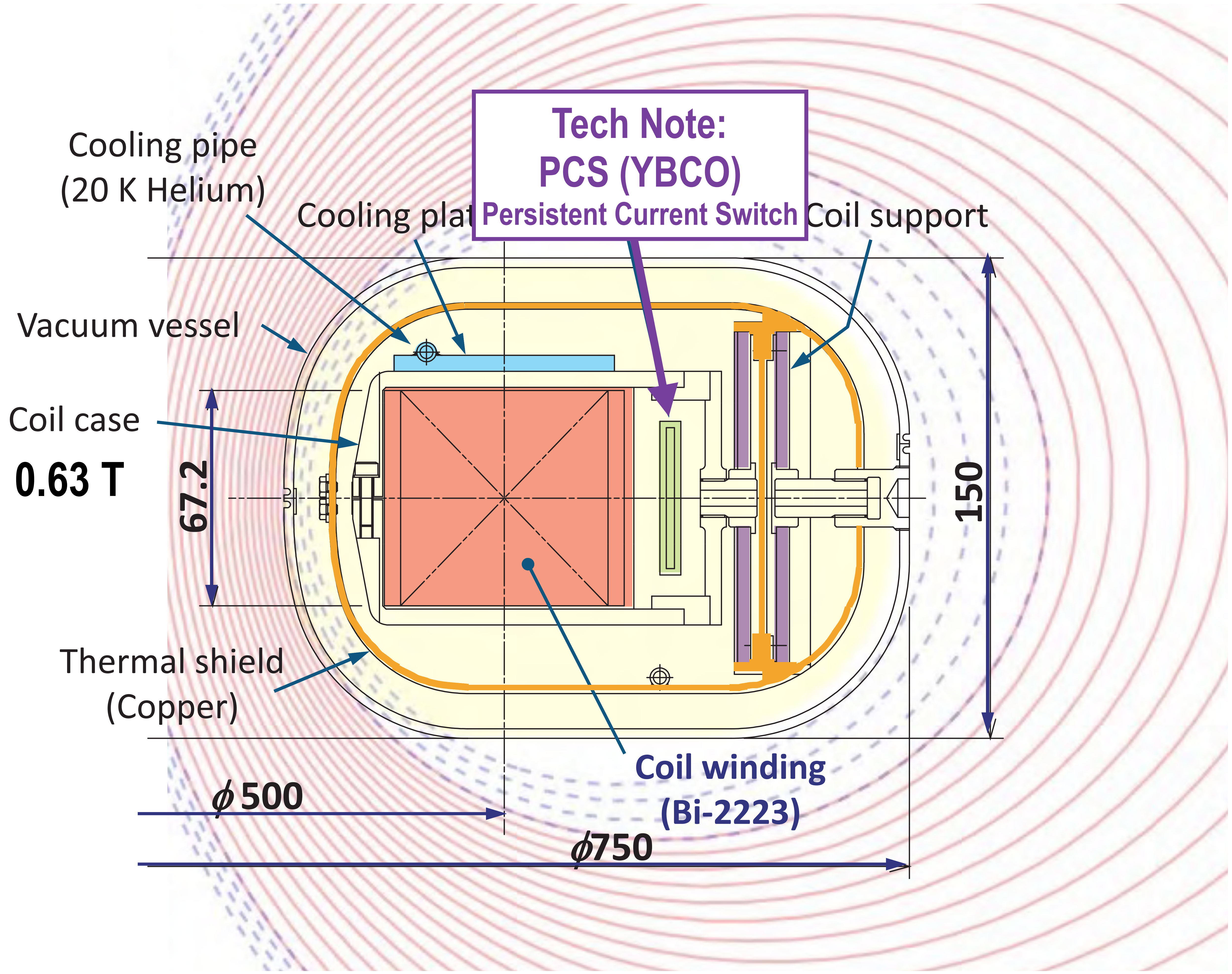


(Very very ***gigantic*** magnetized plasma!)

LDX (MIT/Columbia)

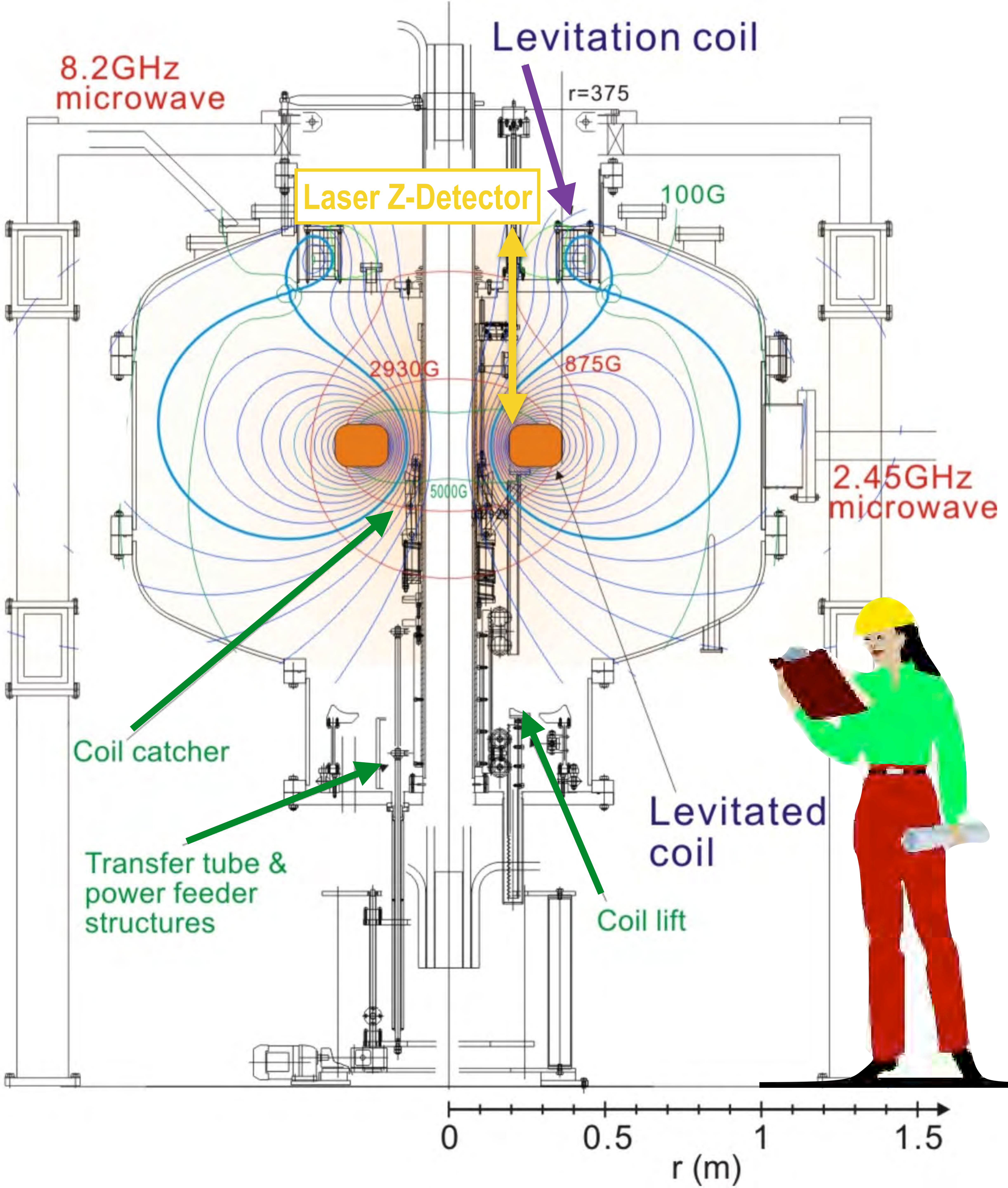
RT-1 (U Tokyo)

Ring Trap 1 (RT-1)

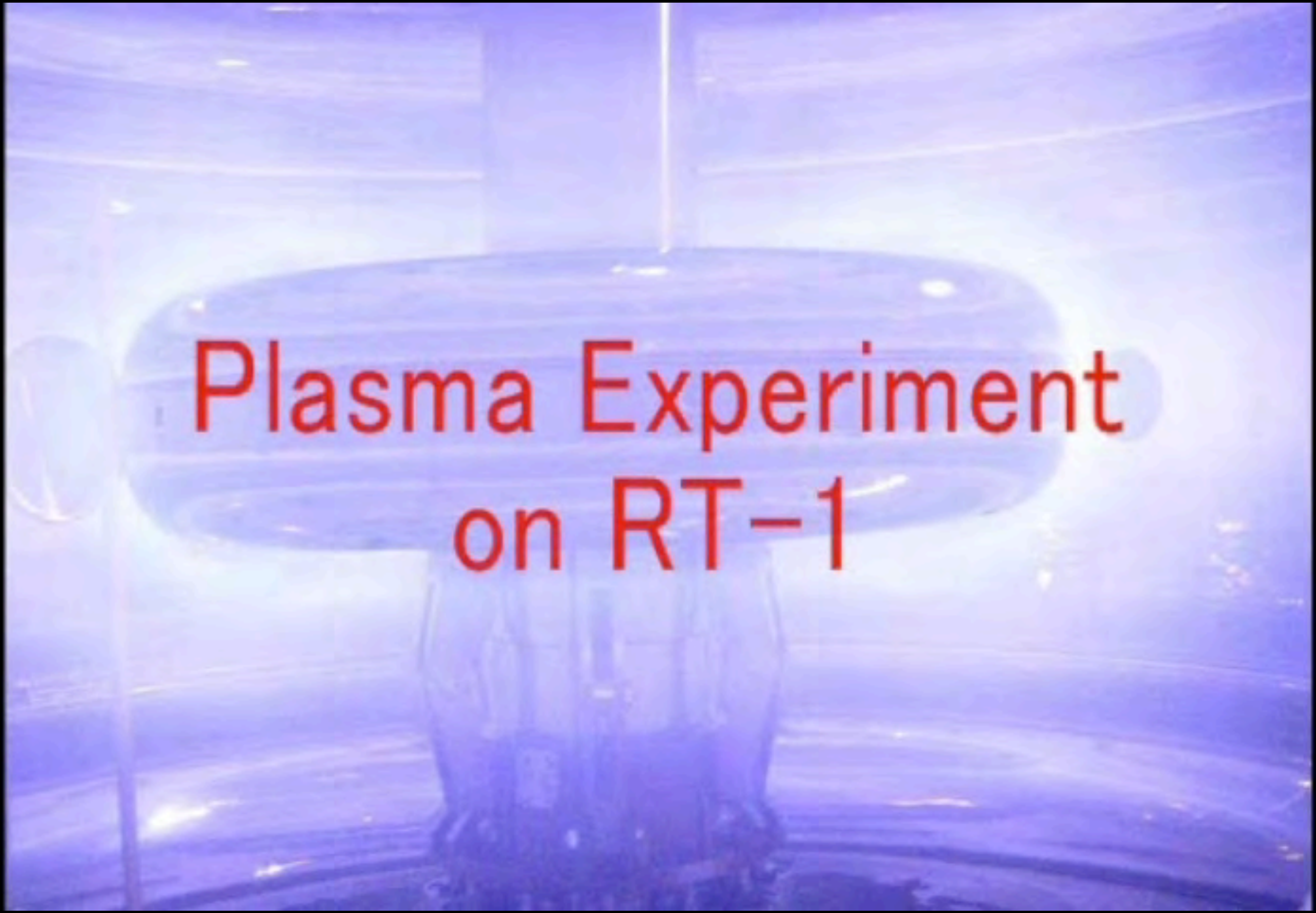


(0.25 MA · 0.17 MA m^2 · 22 kJ · 112 kg)

Bi-2223 · 6 Hours Float Time

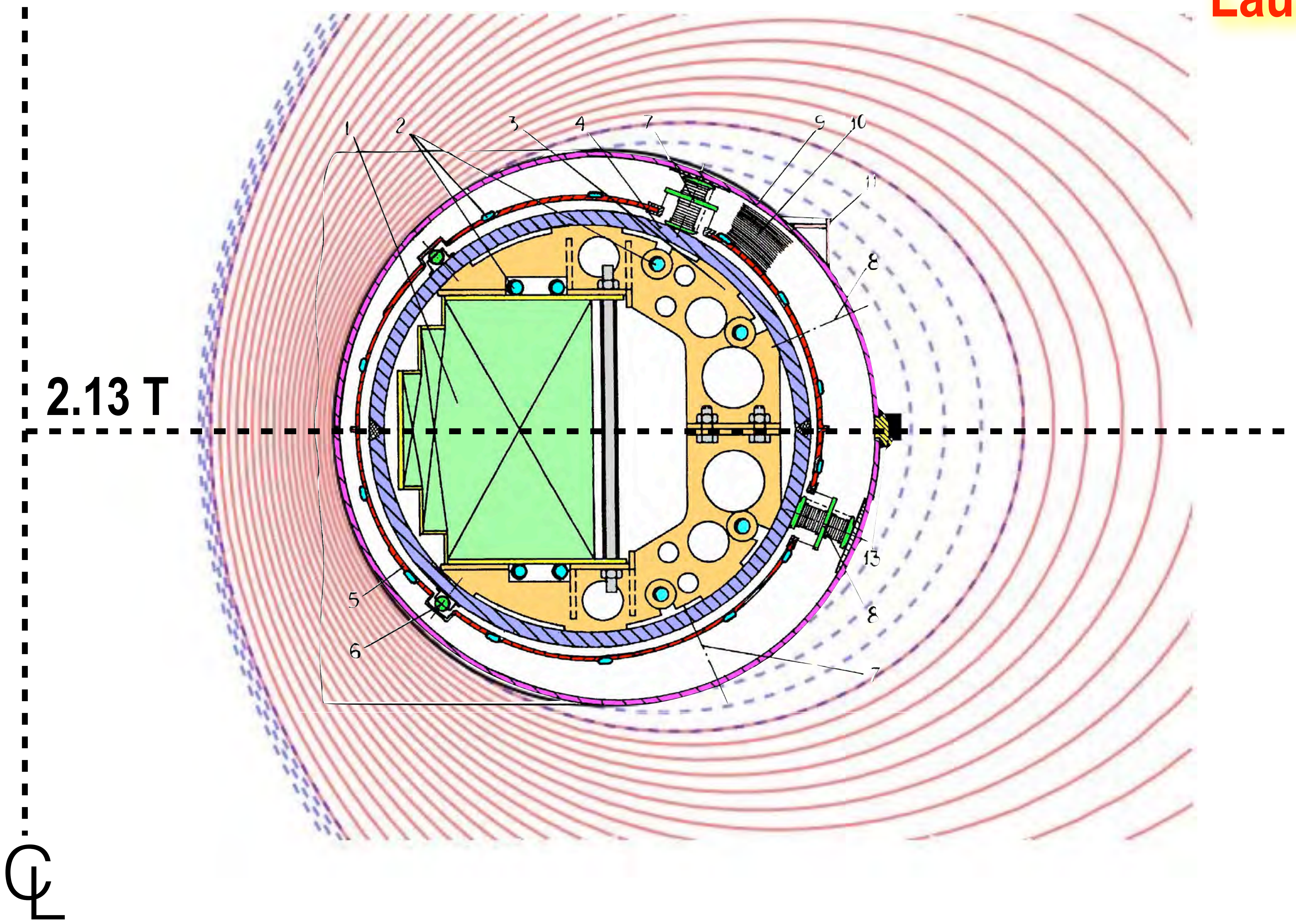


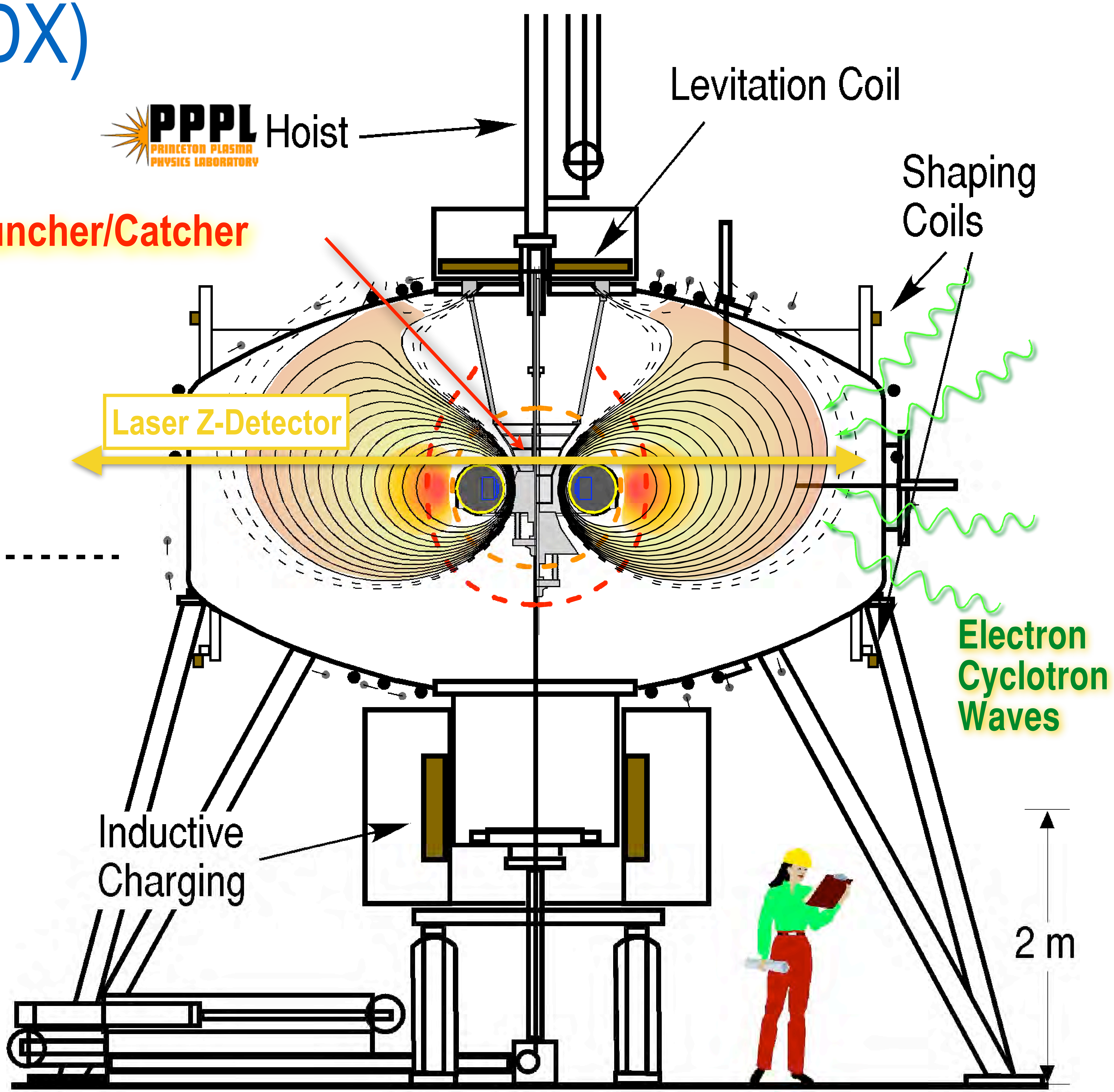
Launching/Catching Superconducting Ring



Levitated Dipole Experiment (LDX)

×20 Larger Magnet Energy
×20 Larger Plasma Volume

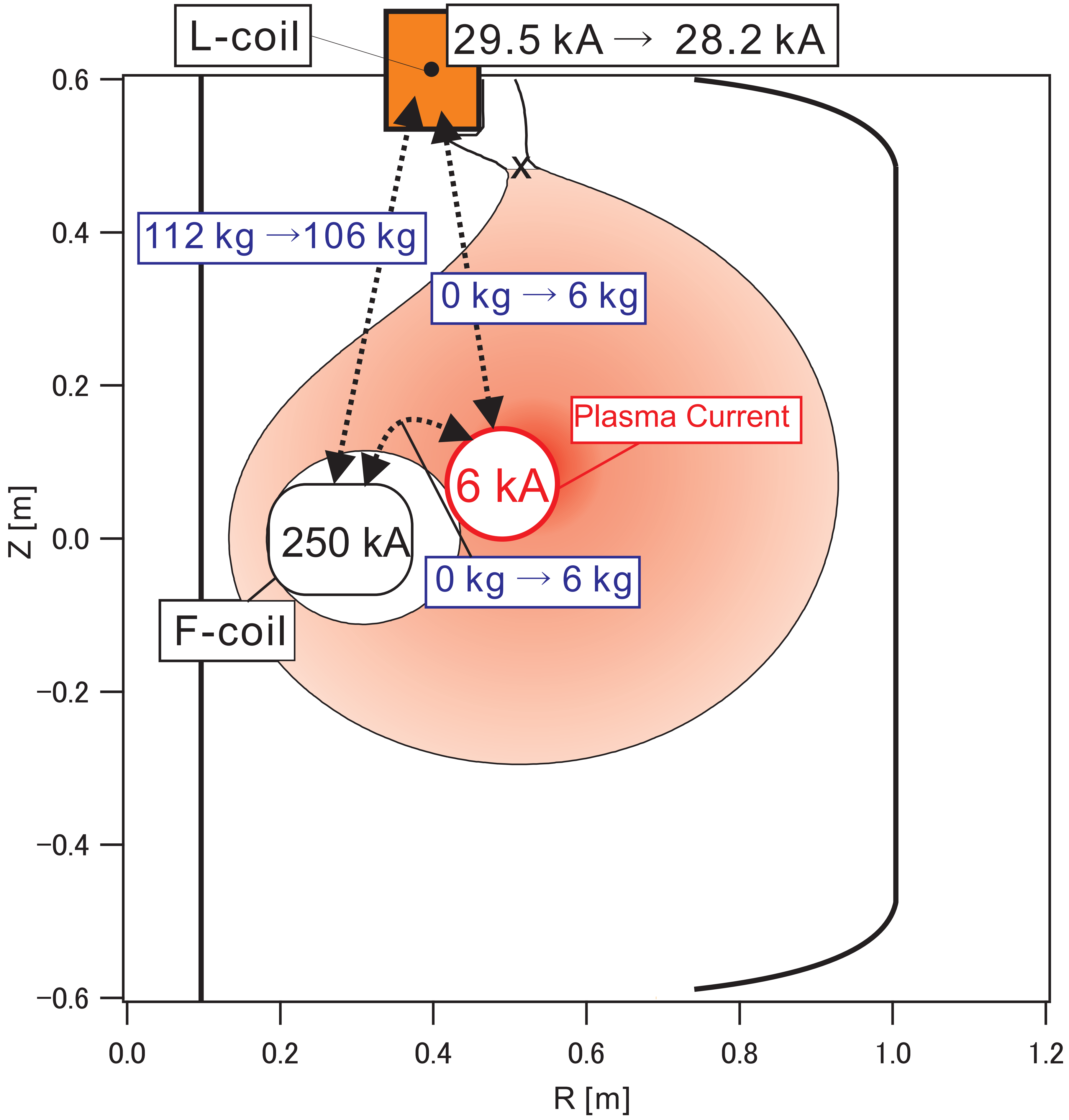


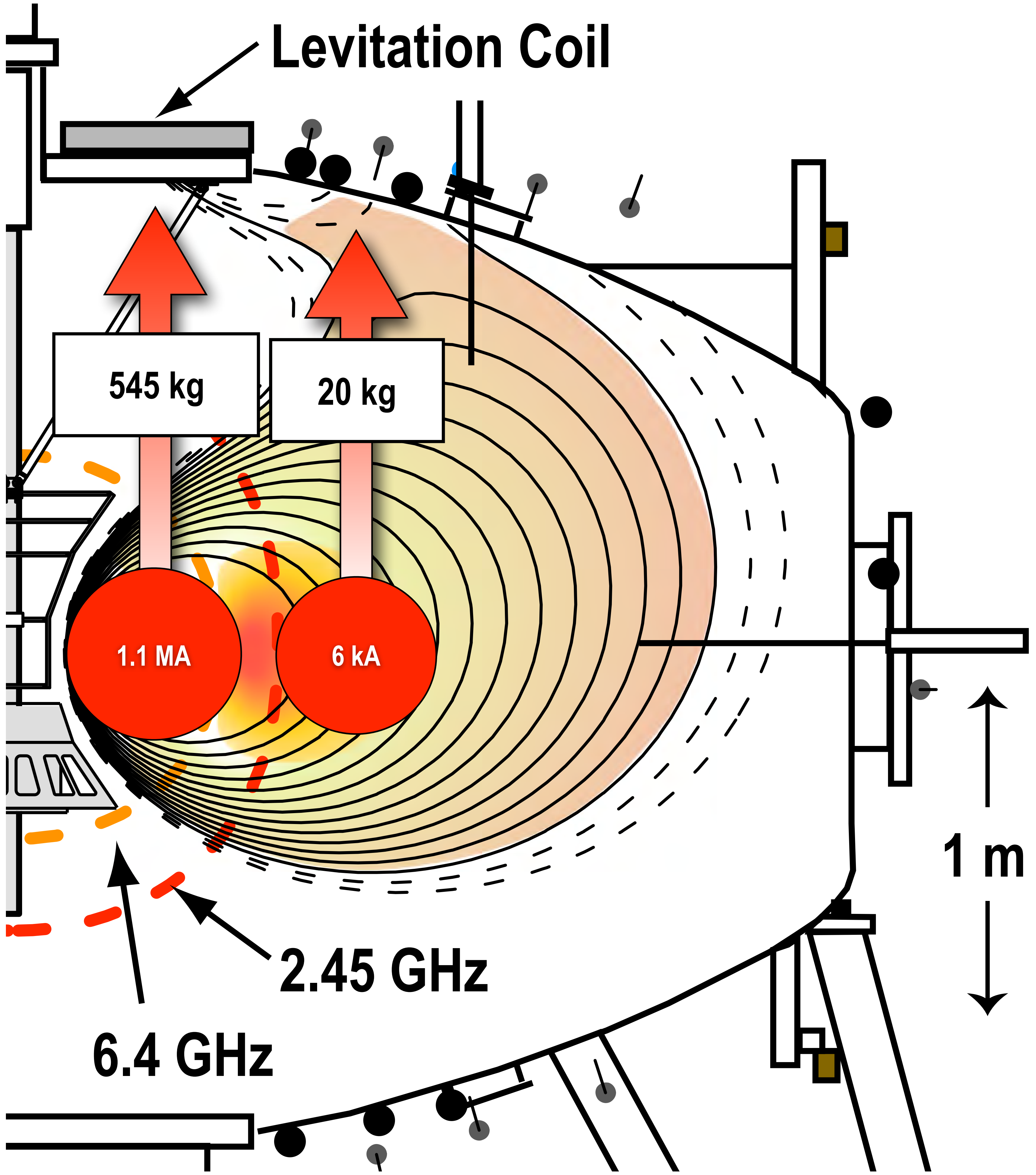


(1.2 MA · 0.41 MA m² · 550 kJ · 565 kg)

Nb_3Sn · 3 Hours Float Time

Tech Note:
Routine and Reliable Levitation with Upper “Attractive” Levitation Coil
Excellent Control (± 4mm) even with High β Plasma Ring Current





Levitation coil current *decreases* under feedback control for high β plasma.

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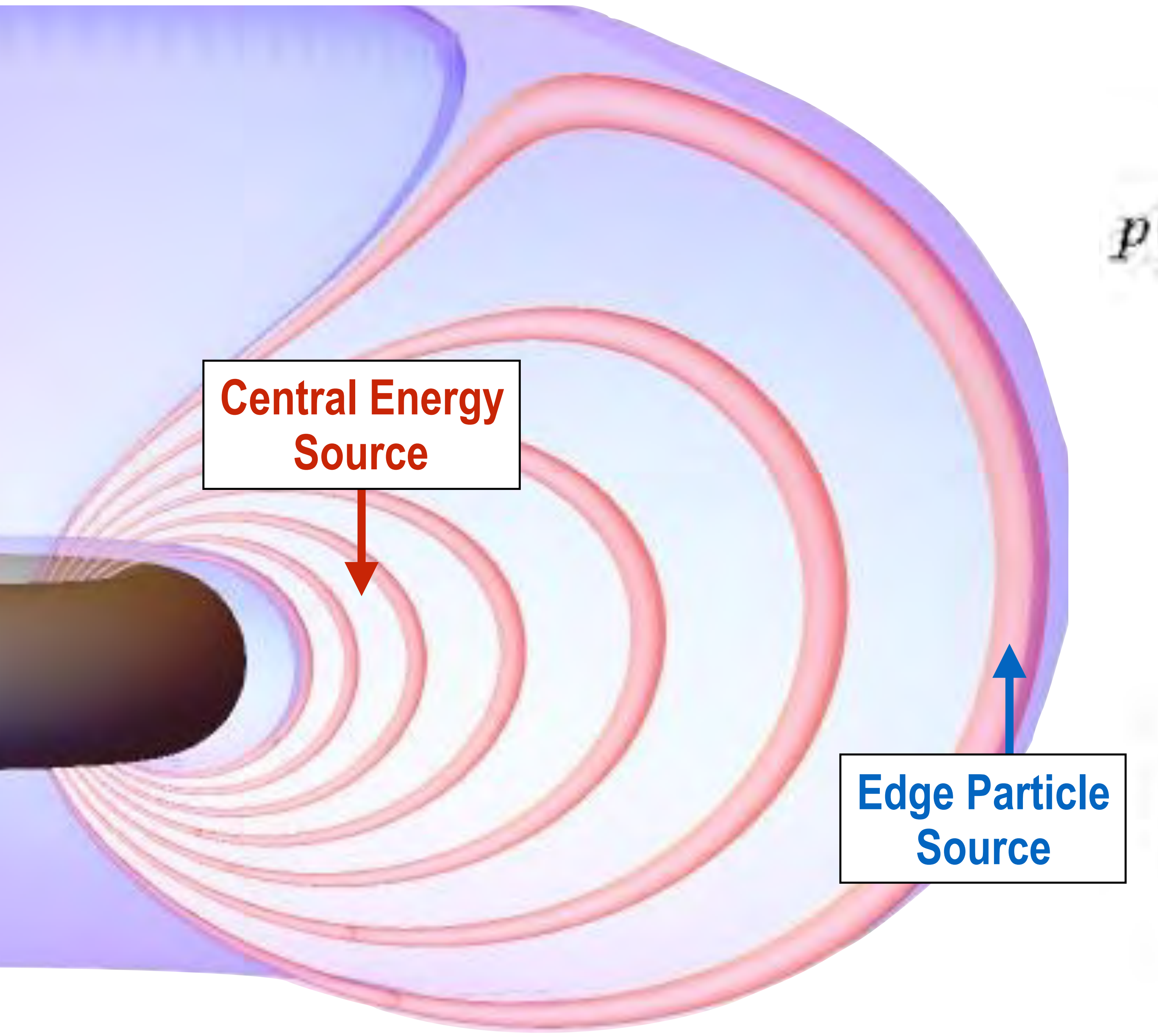
Solar wind drives radial diffusion in planetary magnetospheres.

In the laboratory, Central heating excites instability, and Centrally-Peaked Pressure and Density are the Final State of Turbulent Self-Organization



Central Energy Source

Edge Particle Source

Central Energy Source

Outward

Edge Particle Source

Inward

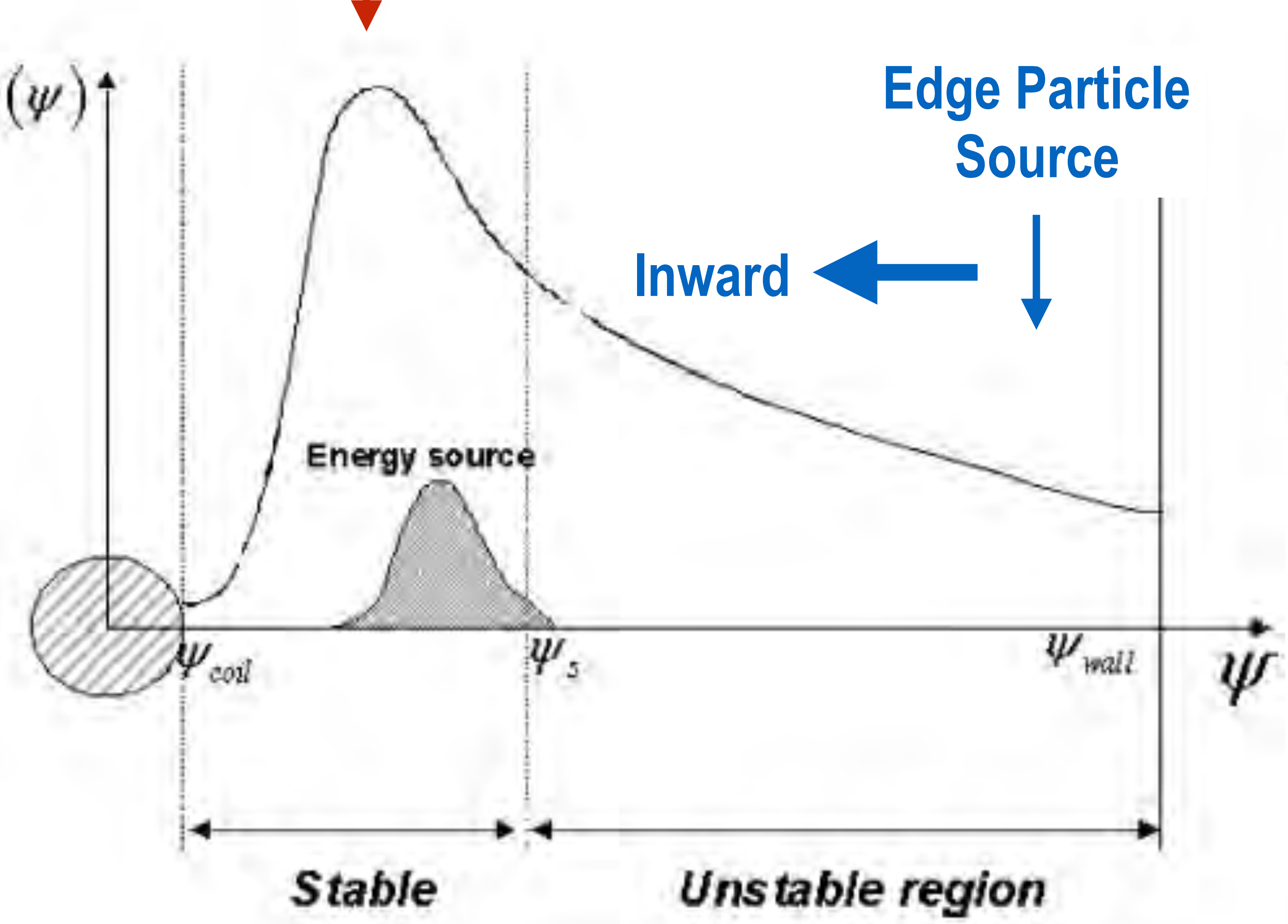


FIG. 1. The LDX schematic profile.

Quasilinear MHD Interchange Turbulence

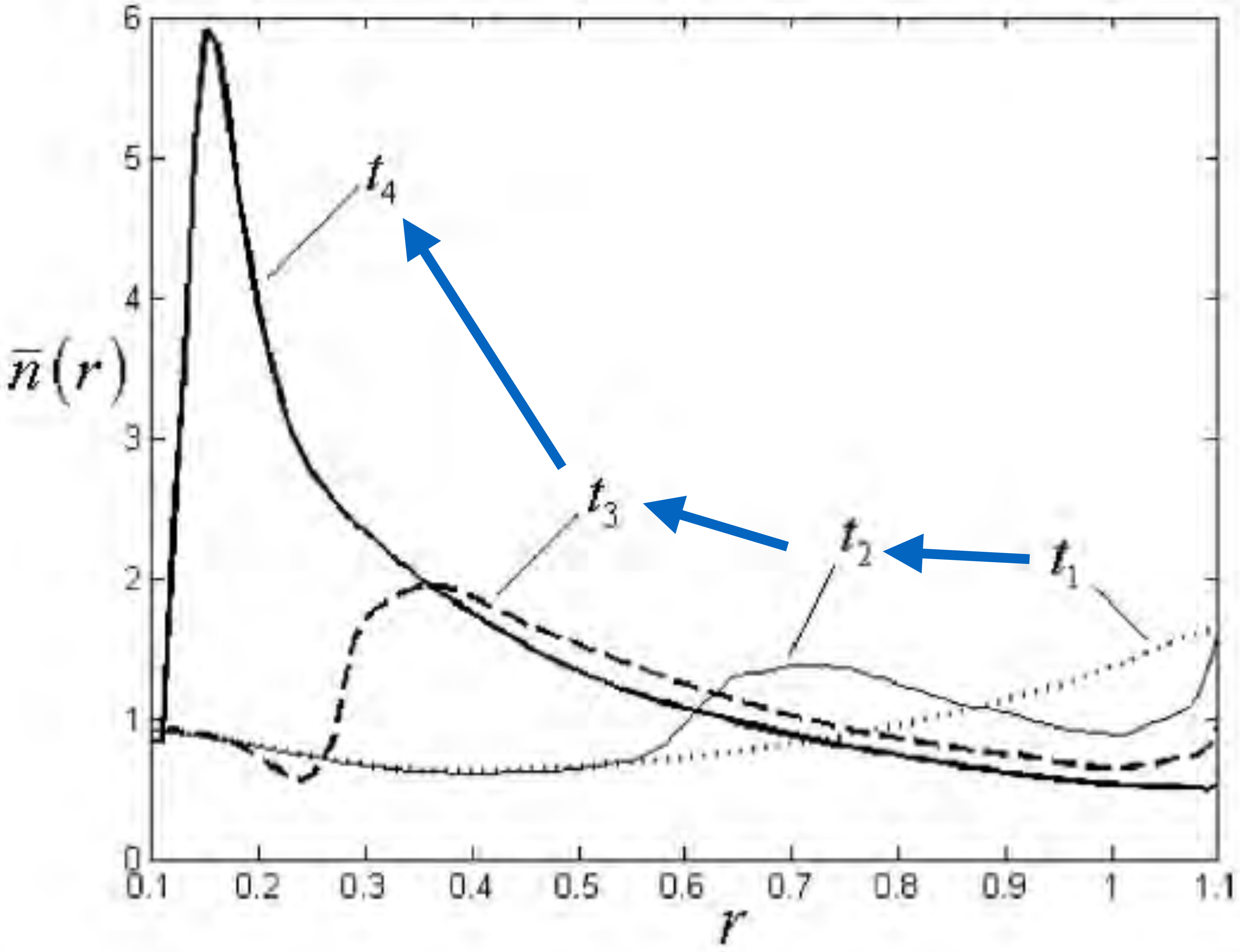


FIG. 5. The snapshots of the "self-organizations" process. Time t_1: before an instability is excited; t_2–t_4: different stages of self-organization.

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).

Entropy Modes have changed the way we think about Turbulent Self-Organization

The MHD interchange mode limits *pressure* gradients, but entropy modes drive turbulent "self-organization" even when MHD interchange is stable.

Entropy Modes regulate *density* and *temperature* gradients, driving $\eta \rightarrow 2/3$.

$$\Delta\left(nV\right) \sim 0 \quad \text{and} \quad \Delta\left(TV^{2/3}\right) \sim 0 \quad \text{and} \quad \eta = \frac{\Delta \ln T}{\Delta \ln n} = \frac{2}{3}$$

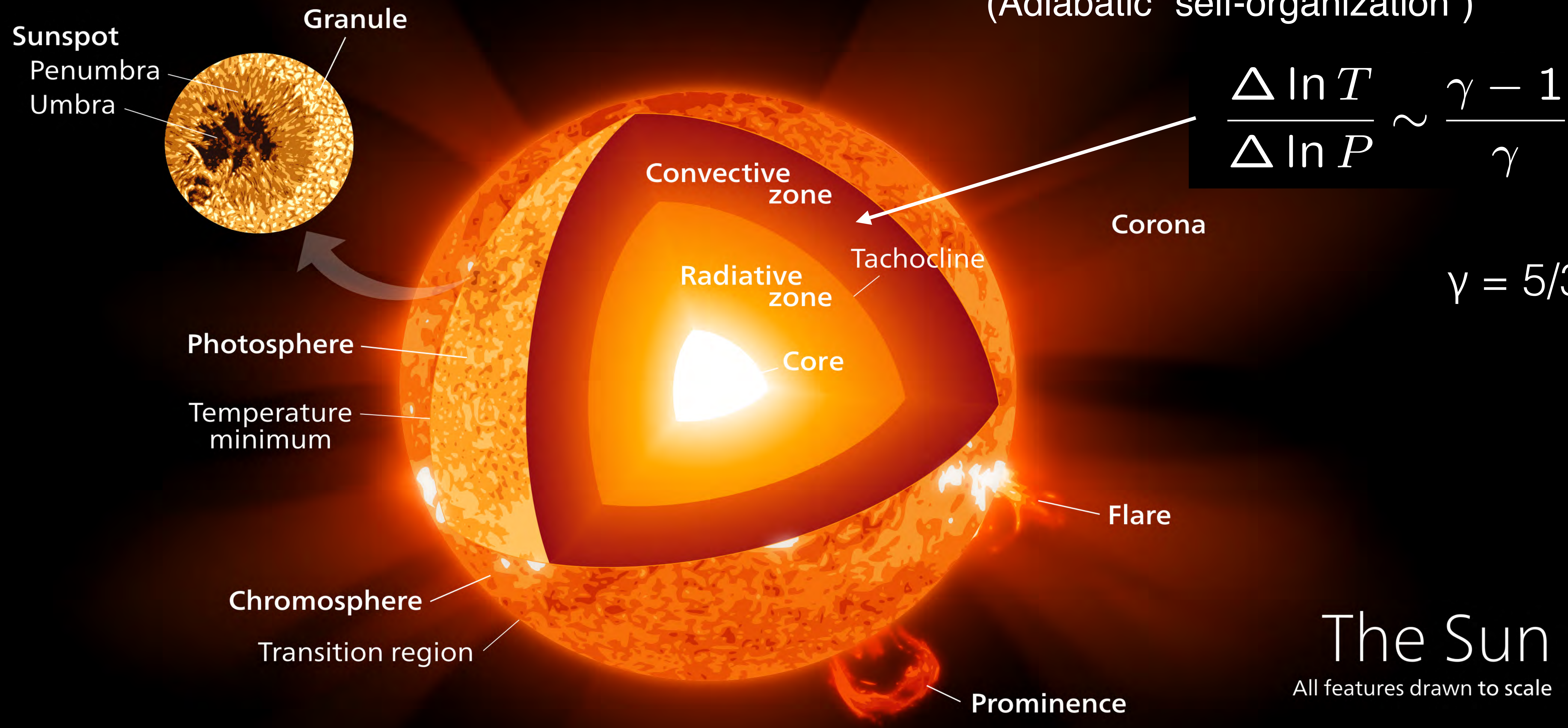
Entropy mode transport depends upon the relative gradients of density and temperature profiles, and **η determines the direction of particles flux…**

- When η > 2/3 (a "**warm core**"), particles pinch **inward** & temperature **outward**.
- When η < 2/3 (a "**cool core**"), particles **outward** & temperature pinches **inward**.

Sumire Kobayashi, Rogers, and Dorland, "Particle Pinch in Gyrokinetic Simulations of Closed Field-Line Systems," *PRL*, **105**, 235004 (2010).
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)

Plasma Turbulent Heat Convection

(Adiabatic “self-organization”)



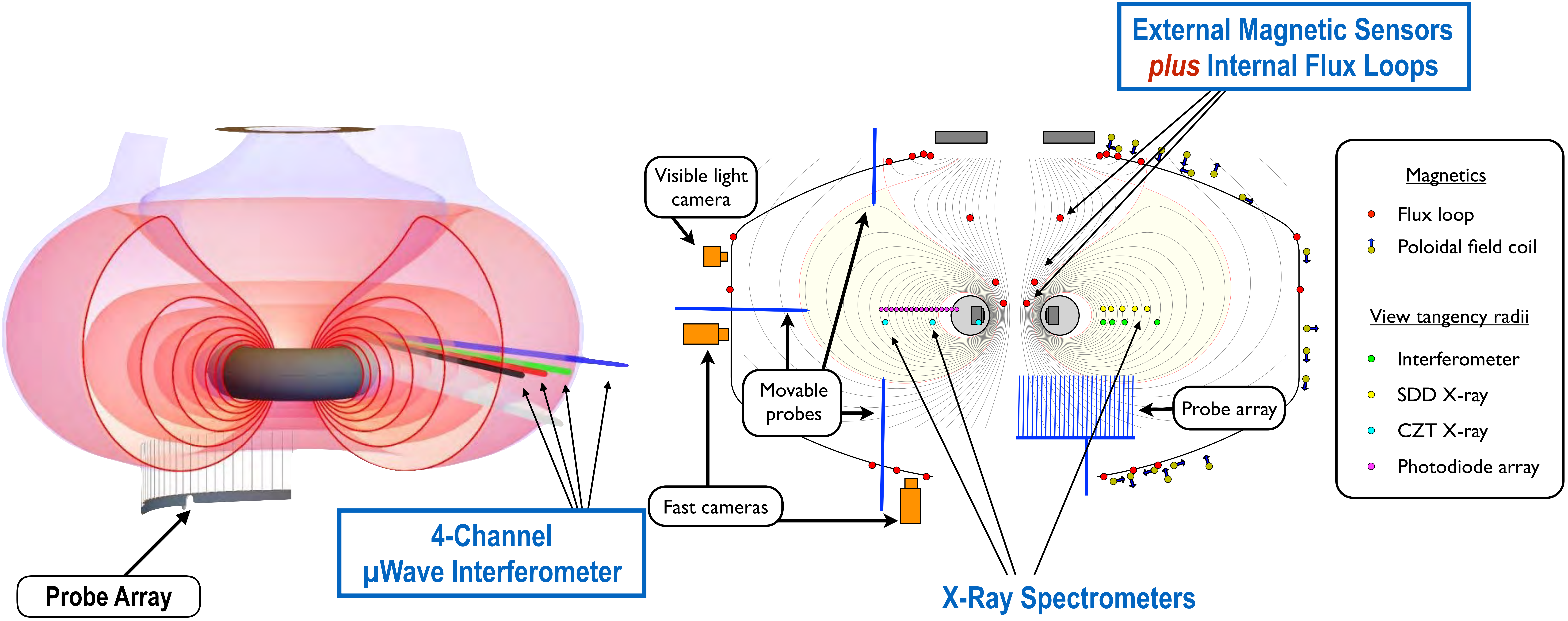
$$\frac{\Delta \ln T}{\Delta \ln P} \sim \frac{\gamma - 1}{\gamma}$$

$\gamma = 5/3$

Image Credit: Kelvinsong Wikimedia Commons

Measurement of Pressure and Density Turbulent Self-Organization in LDX

Matt Davis (PhD Columbia) and Alex Boxer (PhD MIT)



External Magnetic Sensors
***plus* Internal Flux Loops**

Visible light camera

Movable probes

Fast cameras

Probe array

Probe Array

4-Channel µWave Interferometer

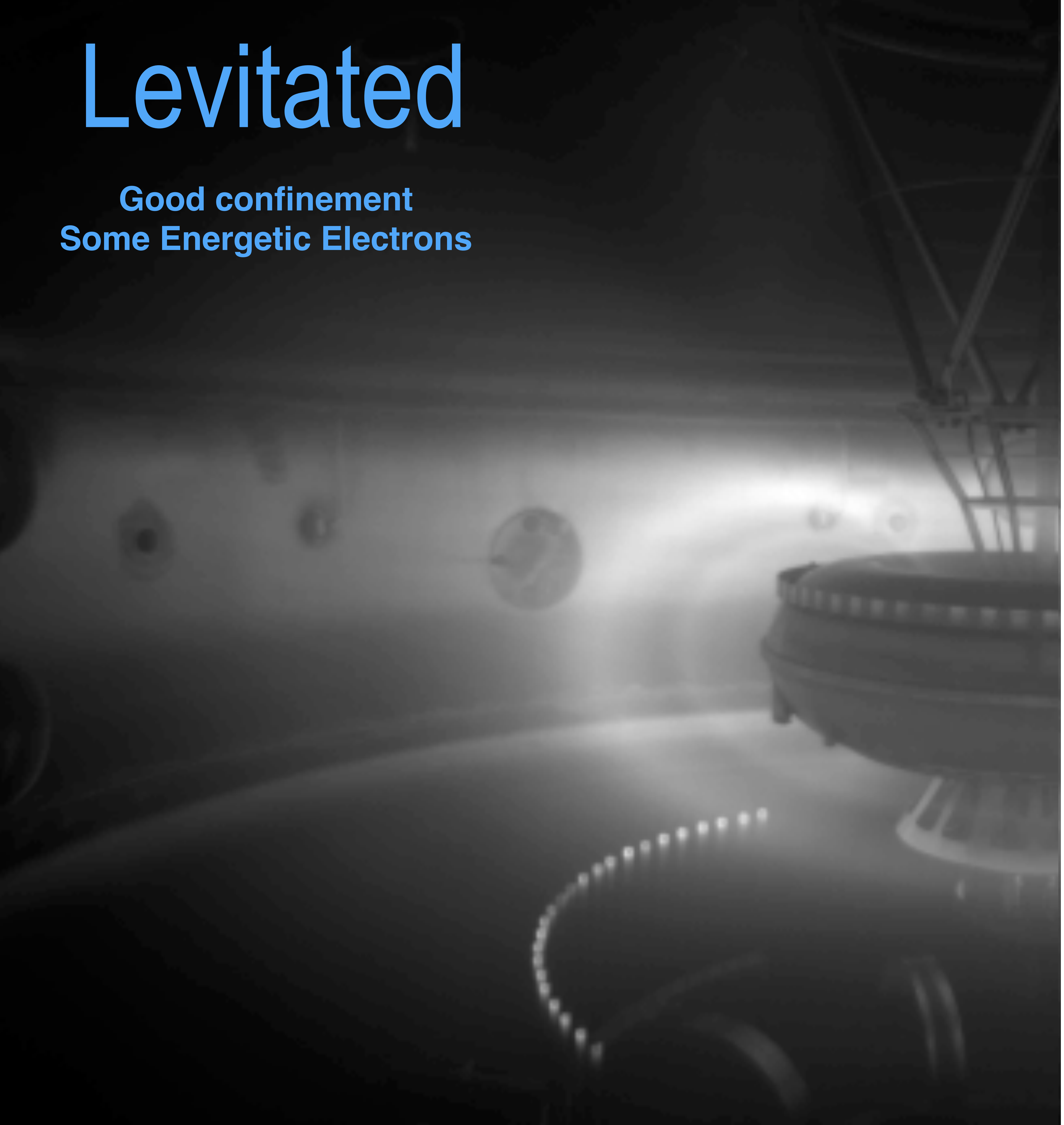
X-Ray Spectrometers

<u>Magnetics</u>

- ● Flux loop
- ↕ Poloidal field coil

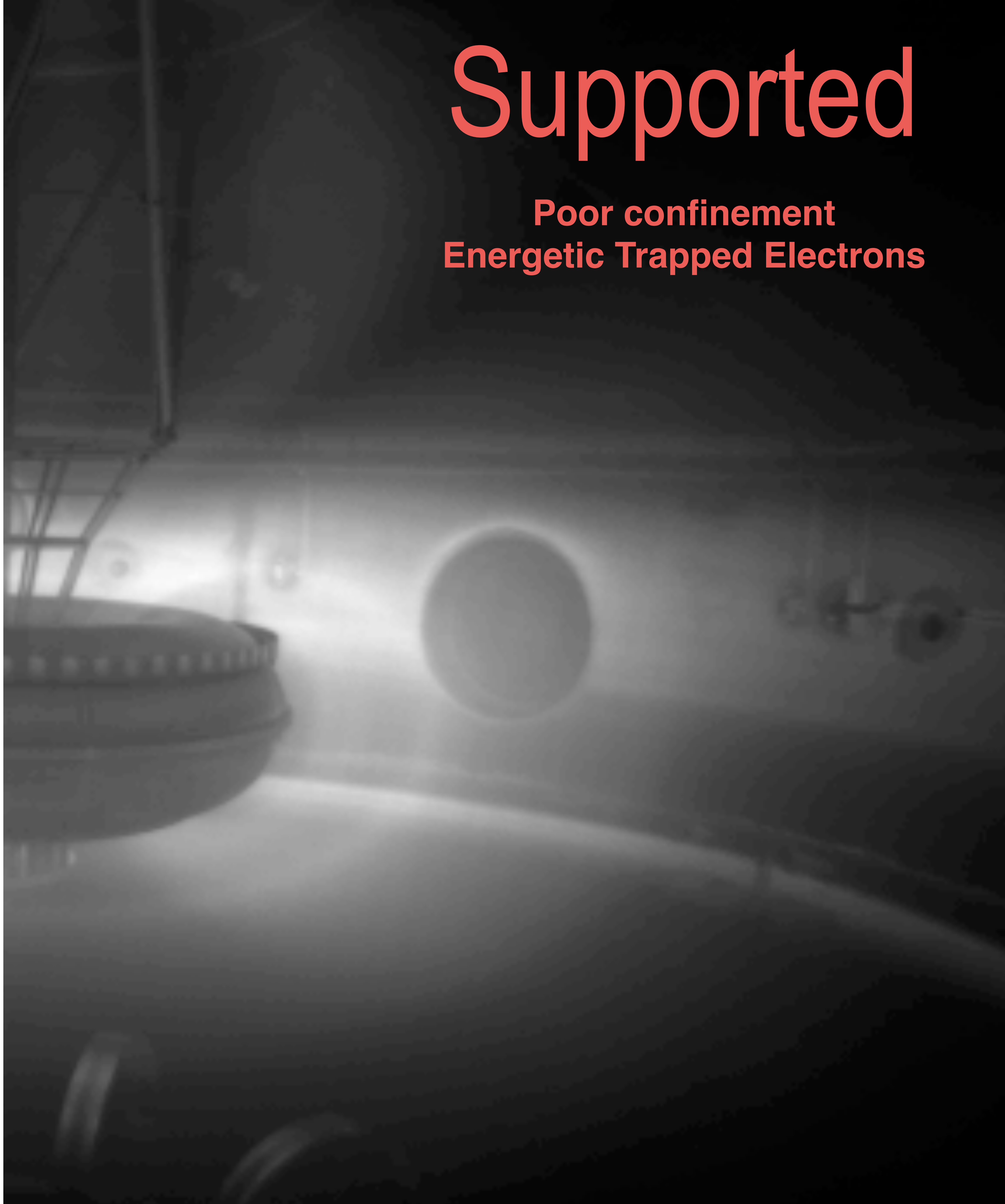
<u>View tangency radii</u>

- ● Interferometer
- ● SDD X-ray
- ● CZT X-ray
- ● Photodiode array



Levitated

Good confinement
Some Energetic Electrons



Supported

Poor confinement
Energetic Trapped Electrons

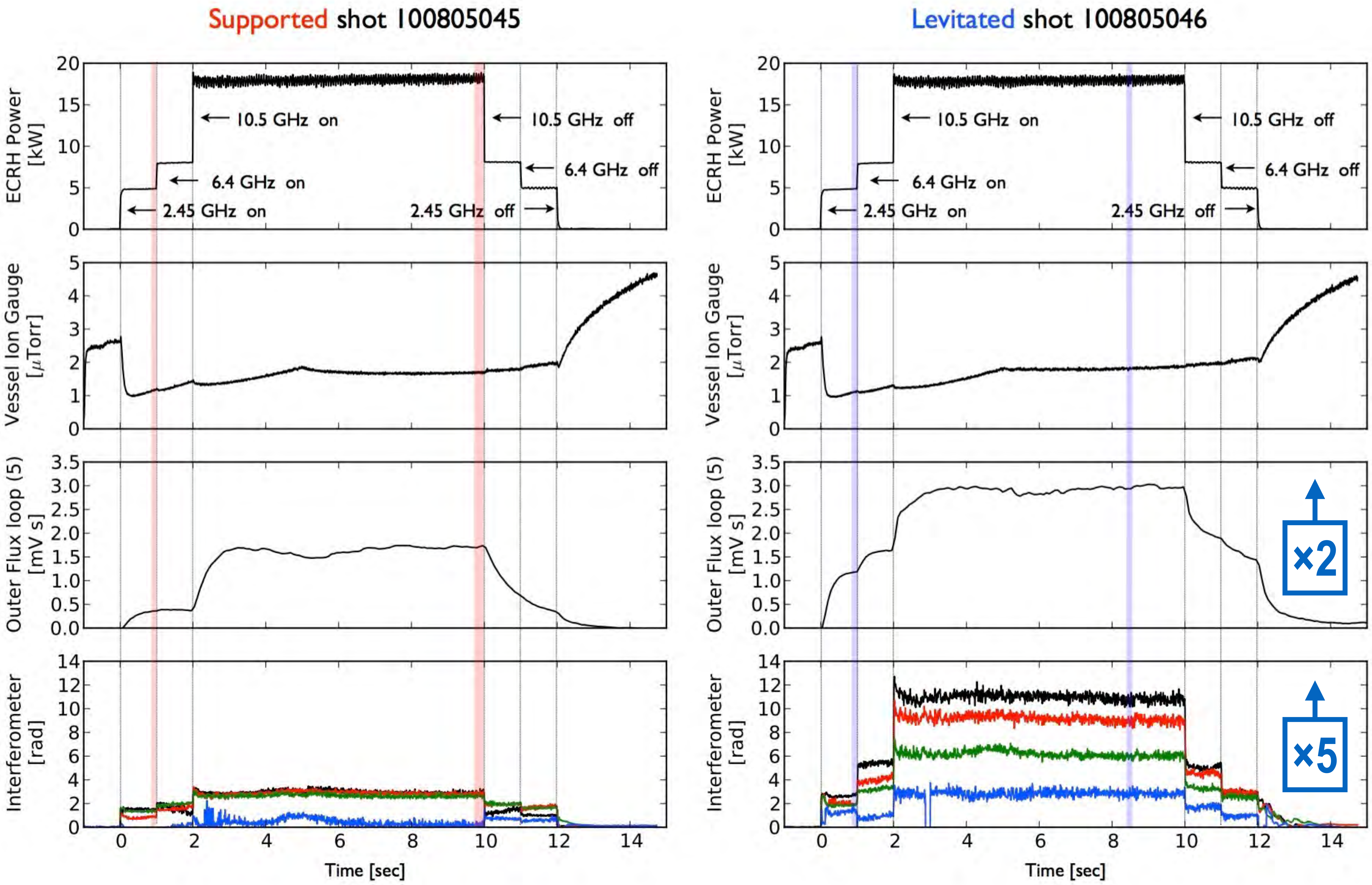
Example Plasma Discharges: **Supported** vs. **Levitated** Coil

18 kW ECRH

***Actively* Controlled Neutral Pressure**

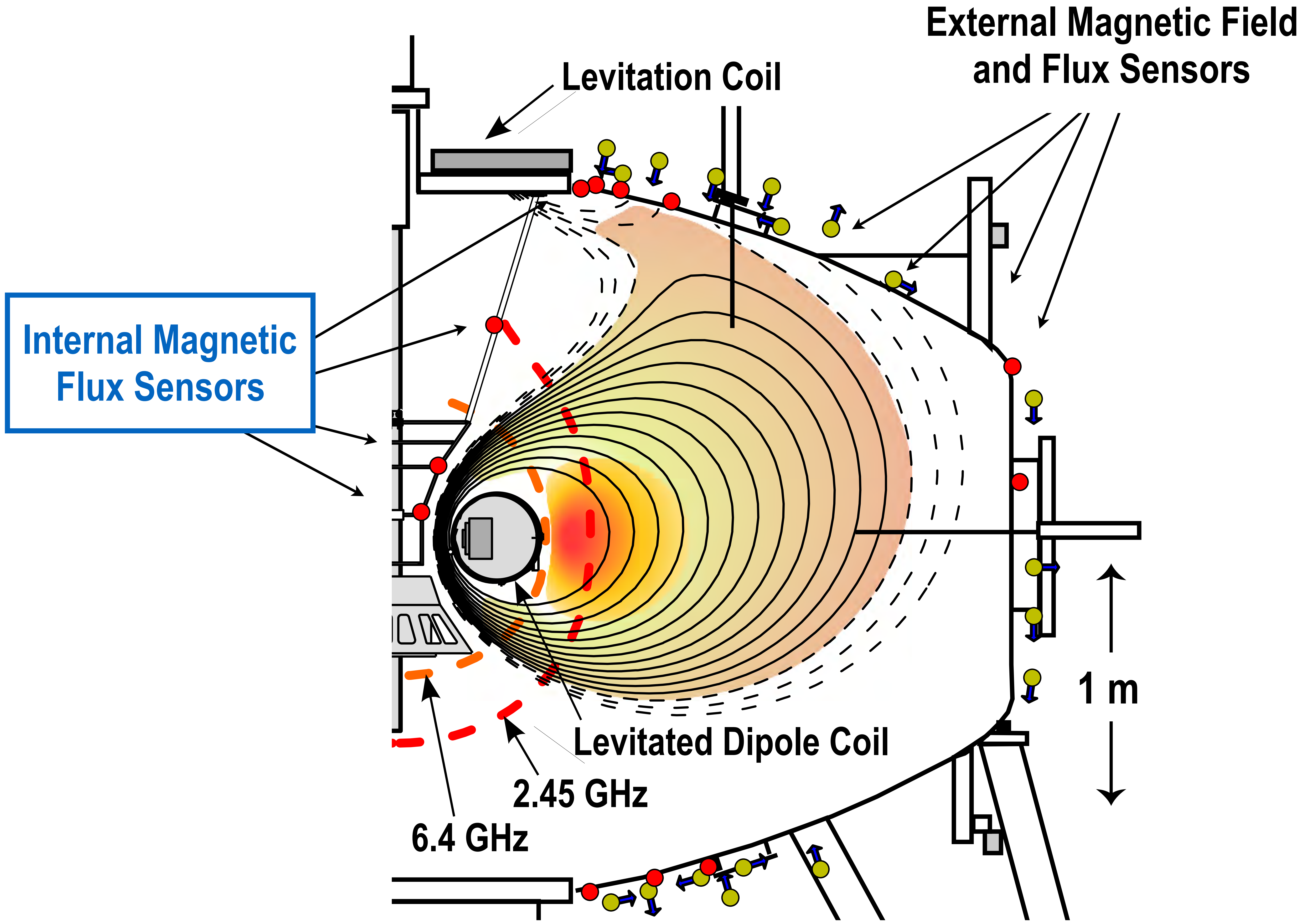
Flux from Plasma Ring Current

Plasma Line Density



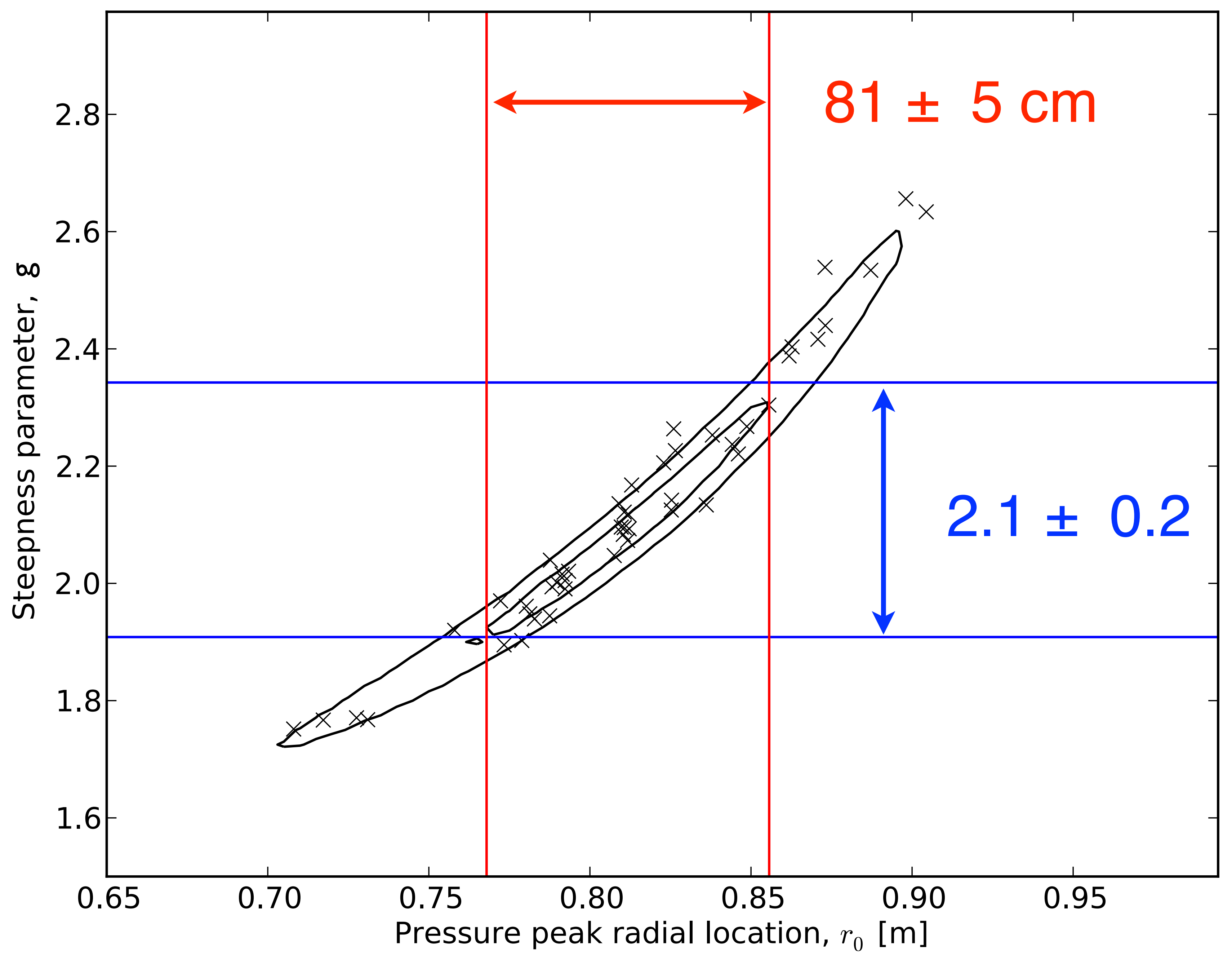
Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

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



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

Reconstruction Results in Very Good Accuracy of Pressure Profile



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

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

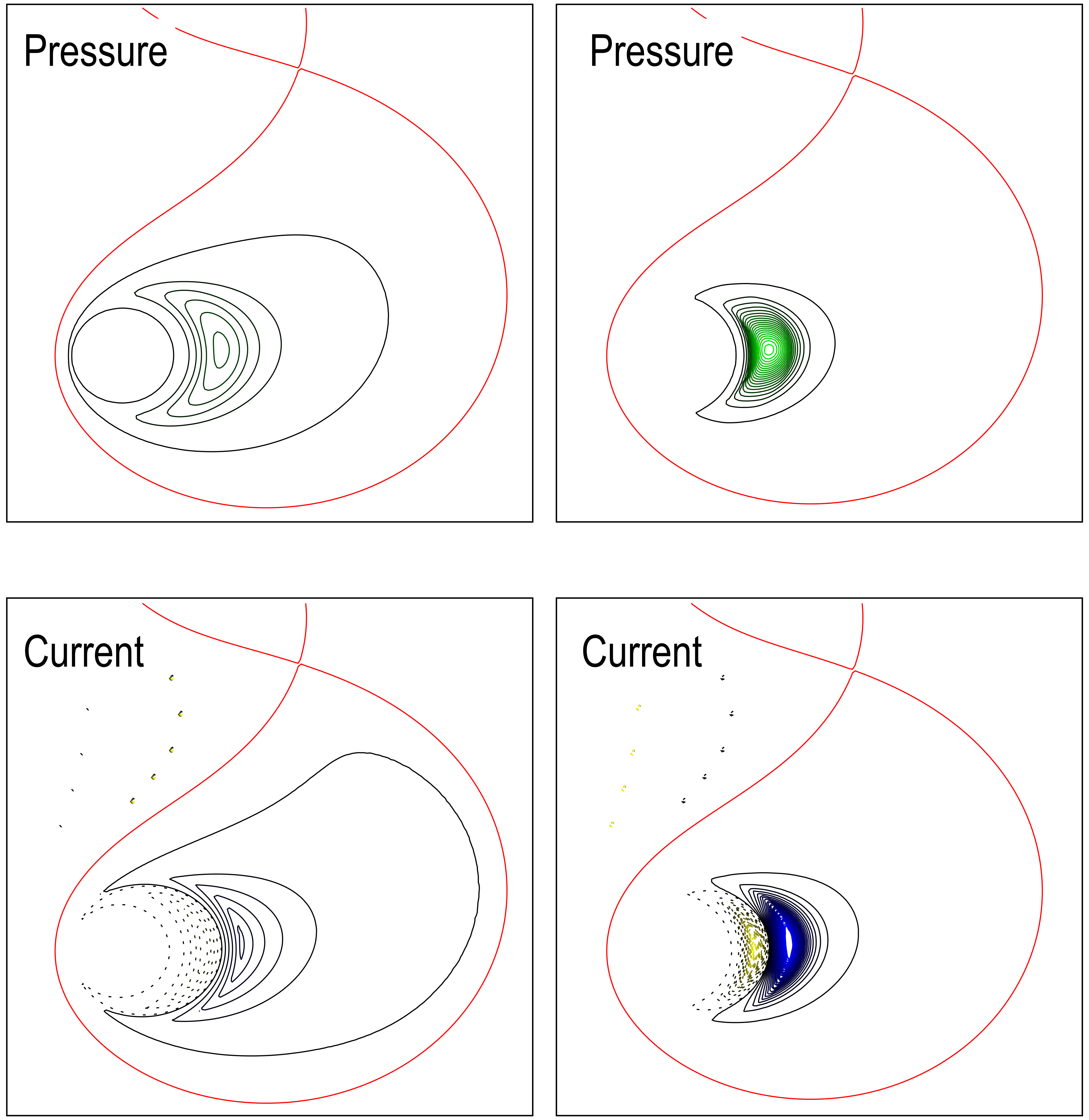
Levitated Coil: Broad Isotropic Pressure Profile
Supported Coil: Narrow Anisotropic Pressure Profile

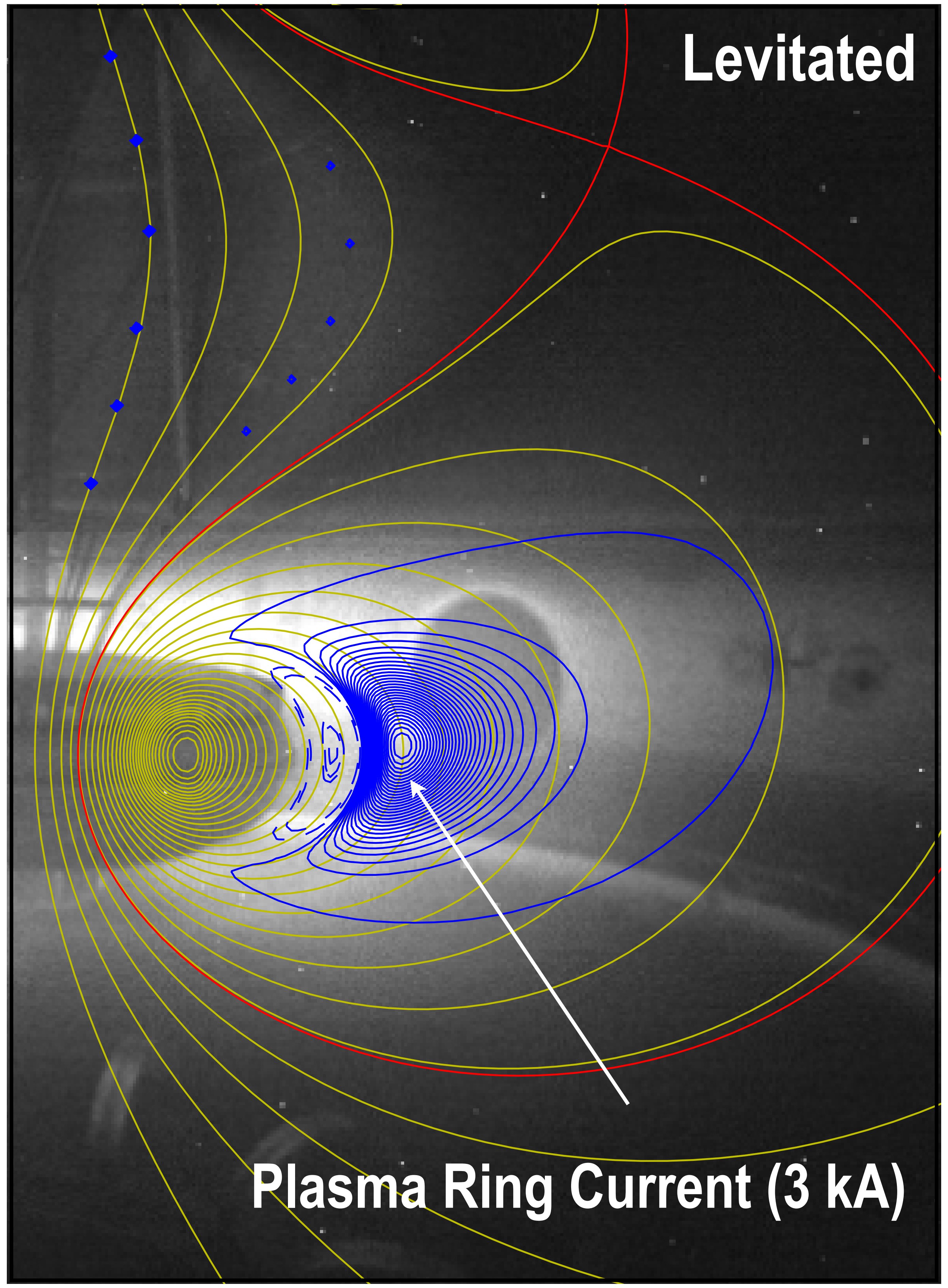
$P_\perp \sim P_\parallel$

Levitated

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

Supported



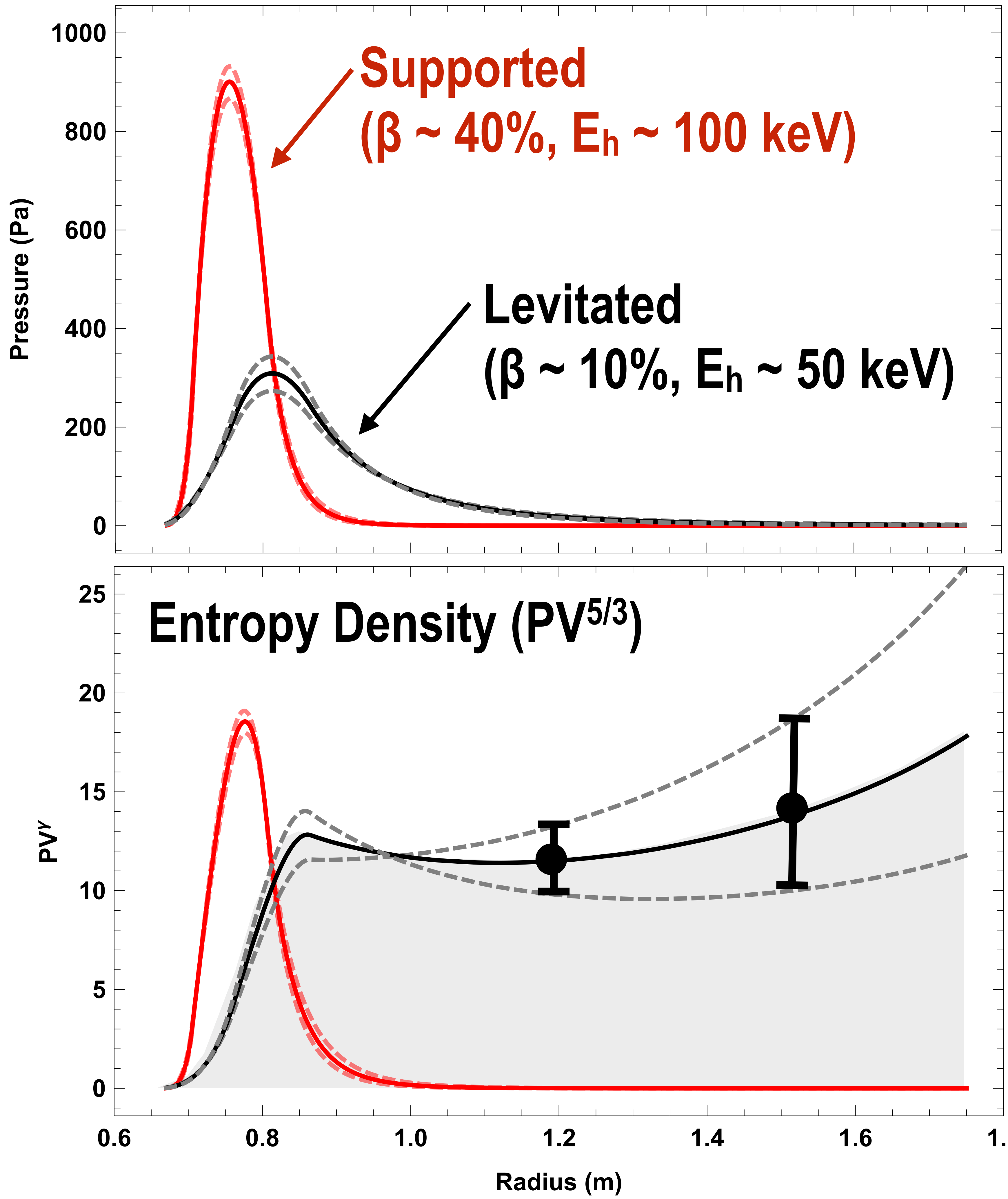


Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

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

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

Supported: No Thermal Confinement
(only energetic trapped electrons)

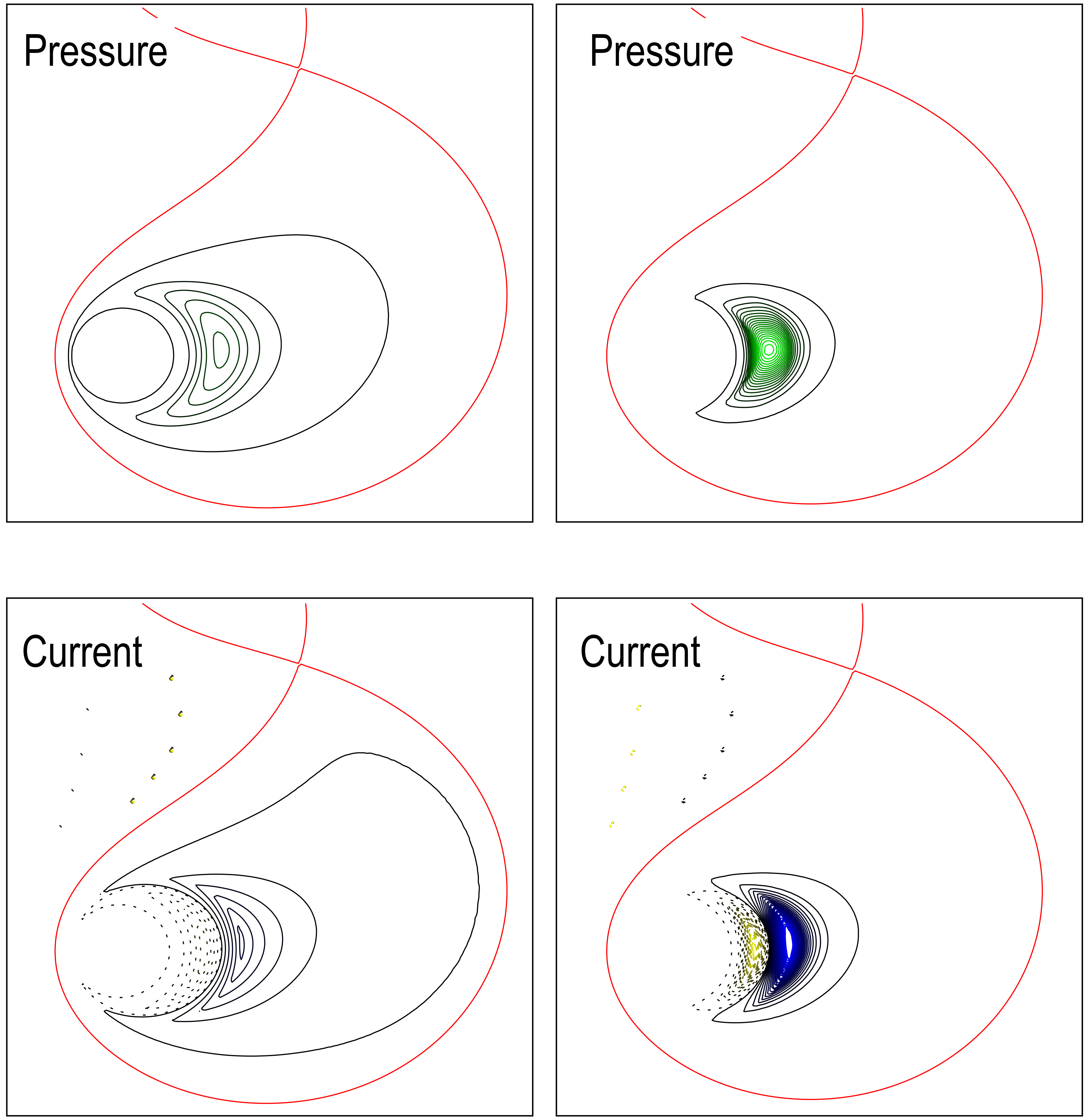


$P_{\perp}$ ~ $P_{||}$

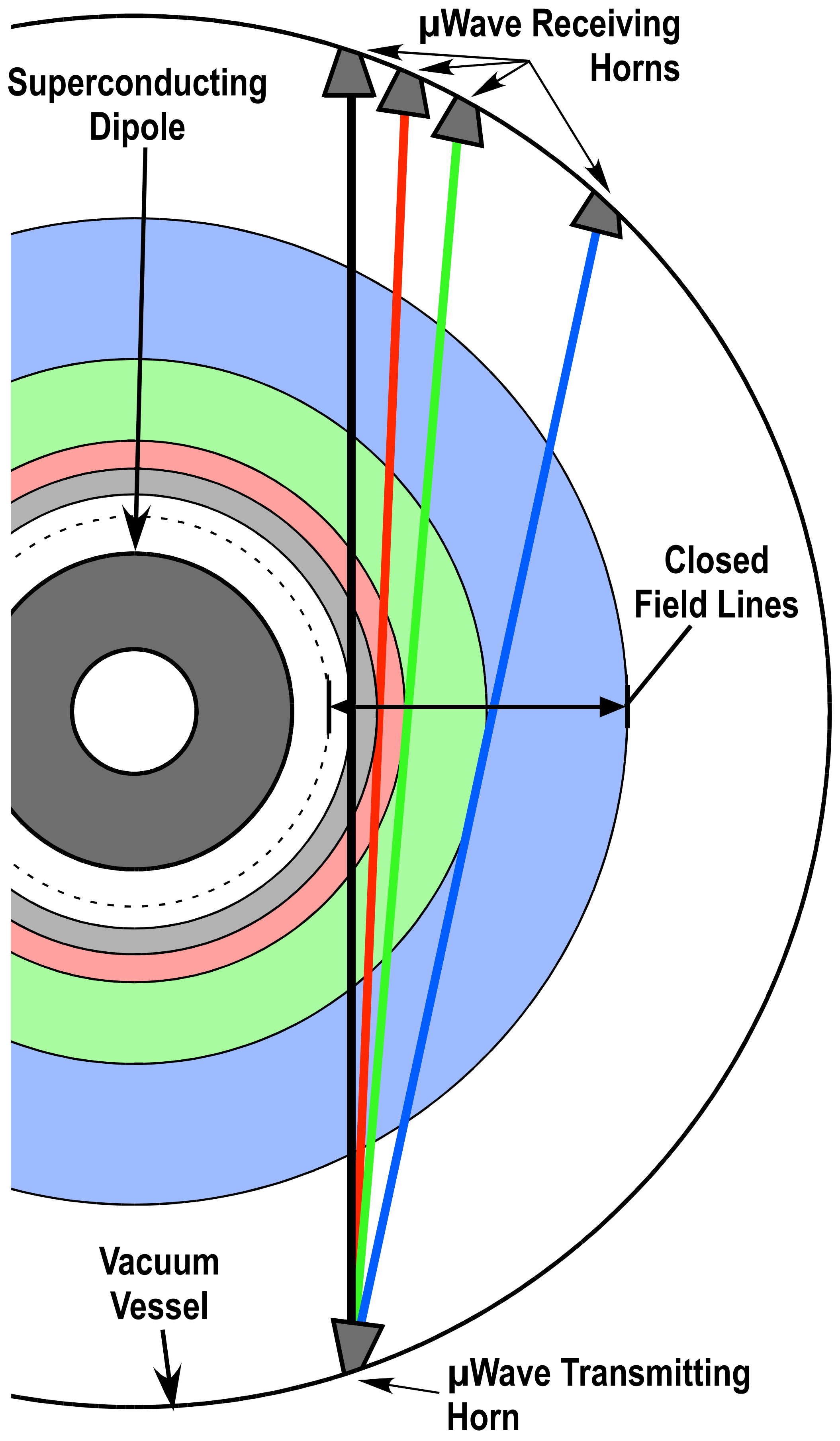
Levitated

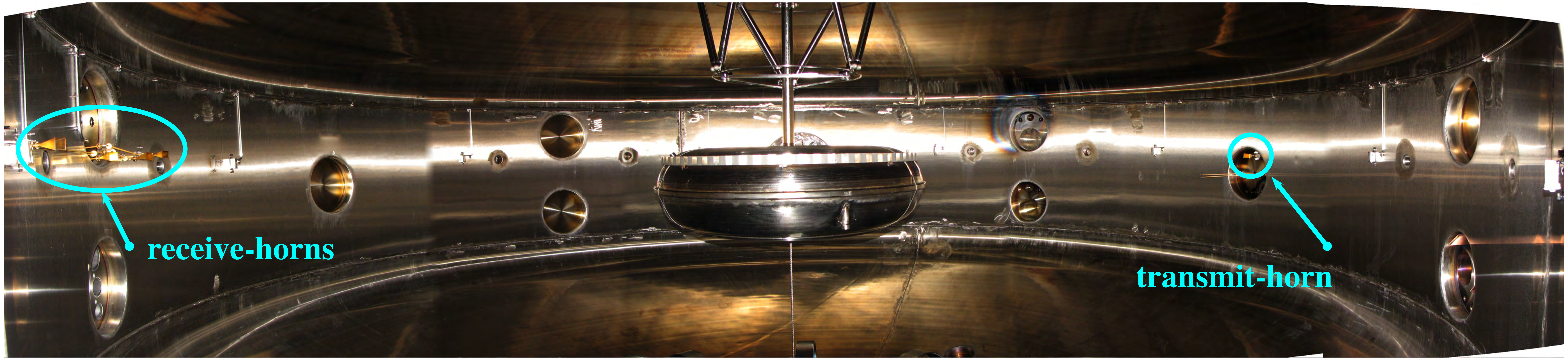
$P_{\perp}$ ~ 5 $P_{||}$

Supported



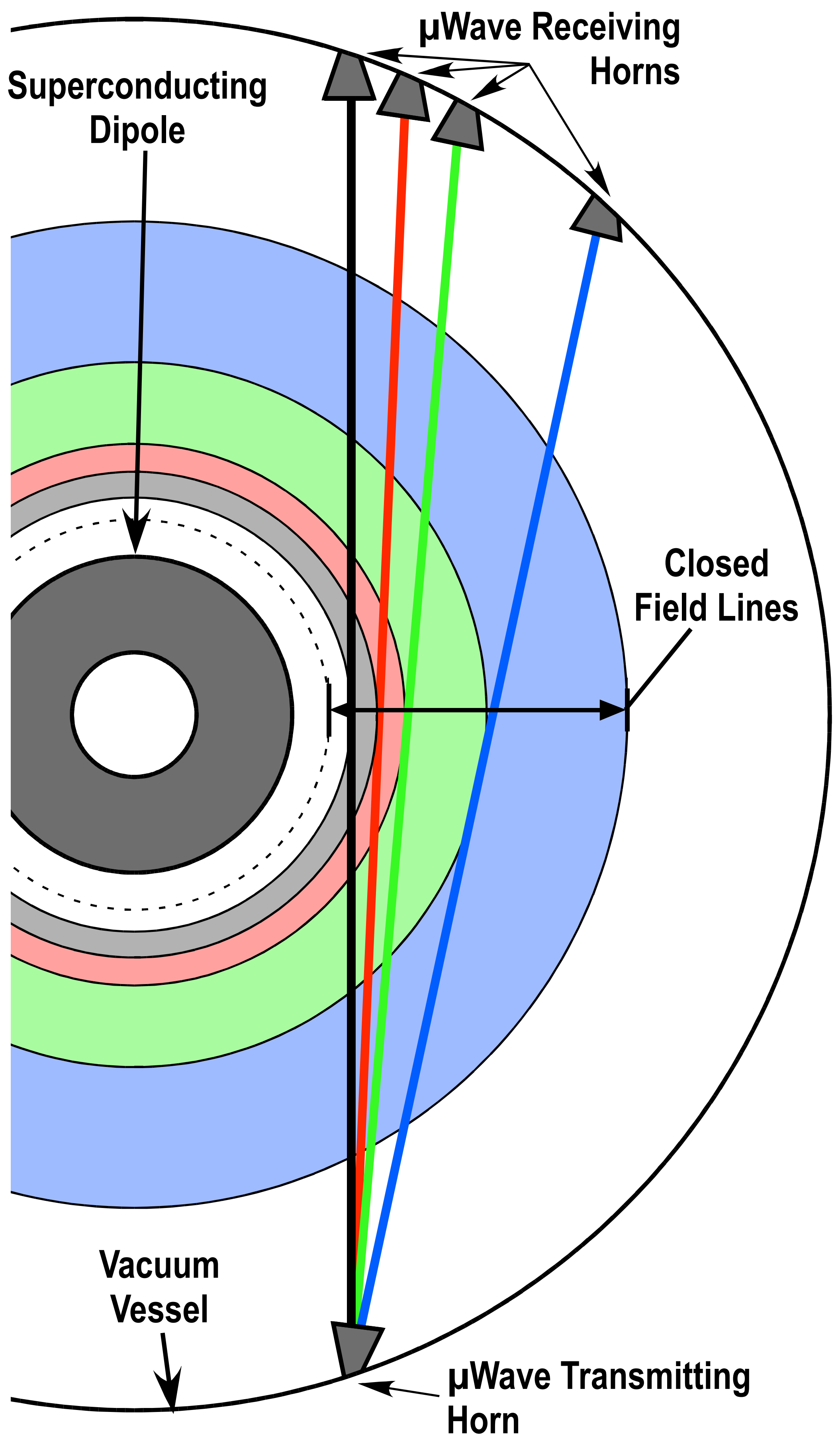
Multichannel Microwave Interferometer

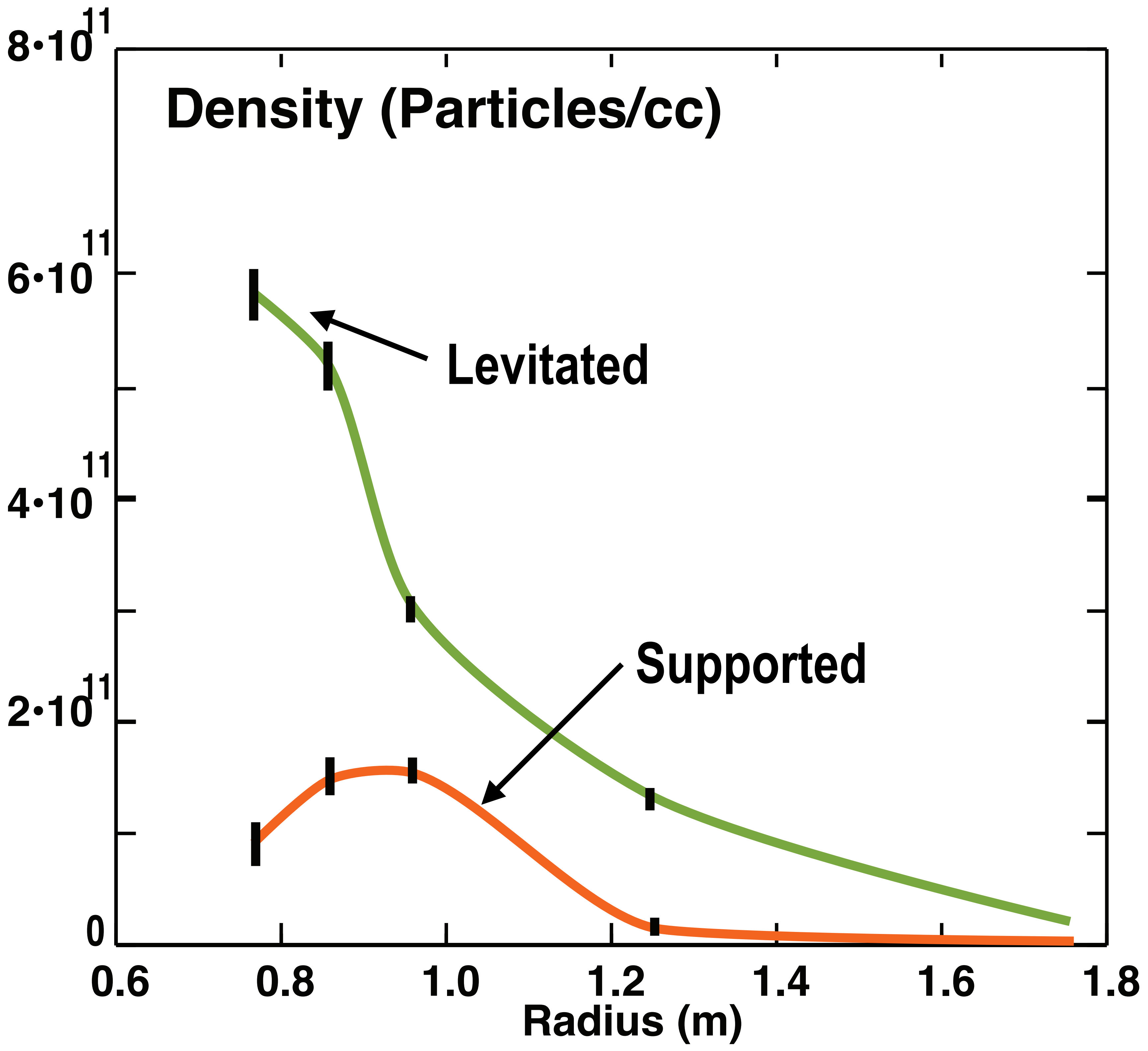


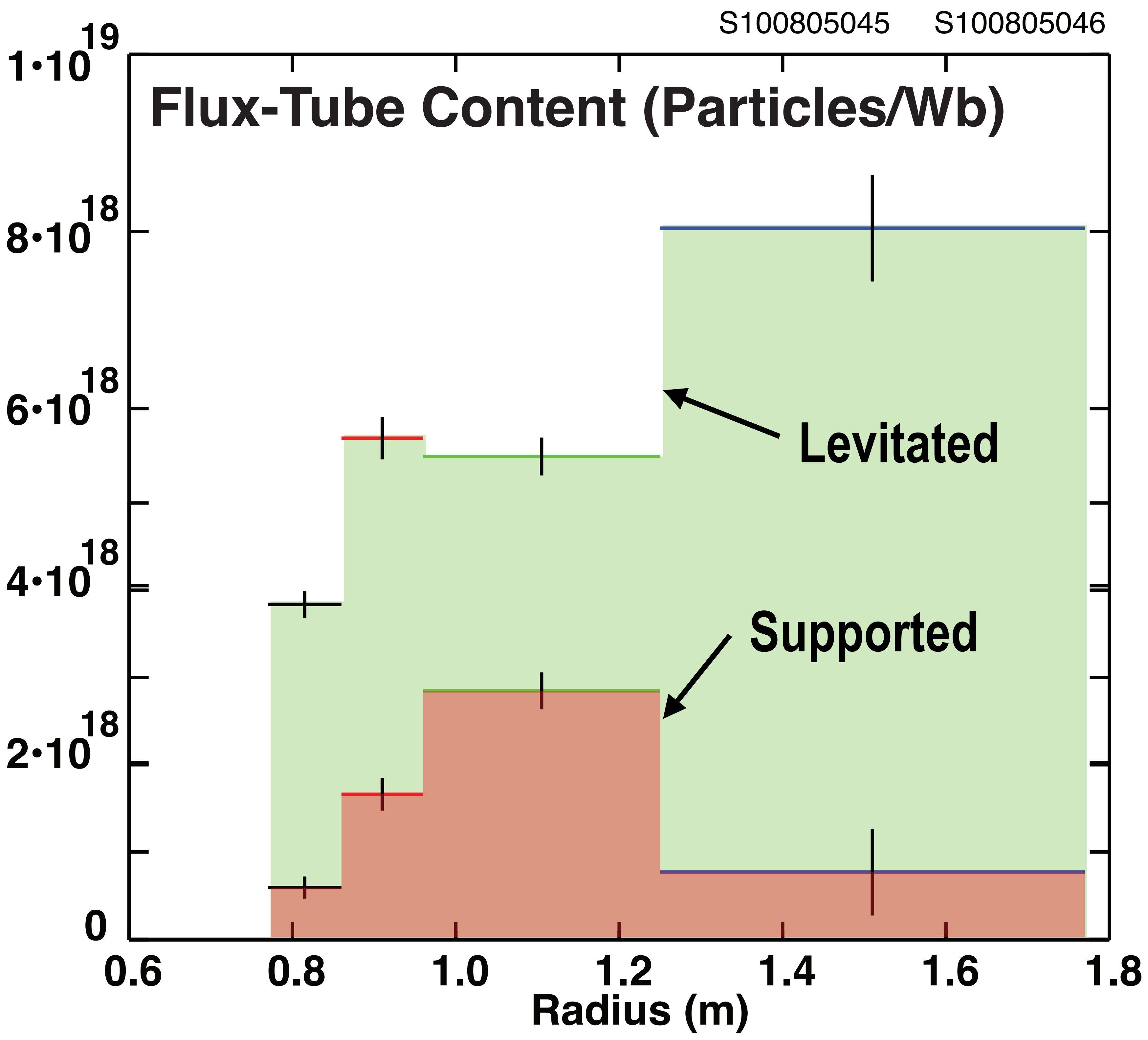


Boxer, *et al.*, "Multichannel microwave interferometer for the levitated dipole experiment," *Rev Sci Instrum* **80**, 043502 (2009).

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

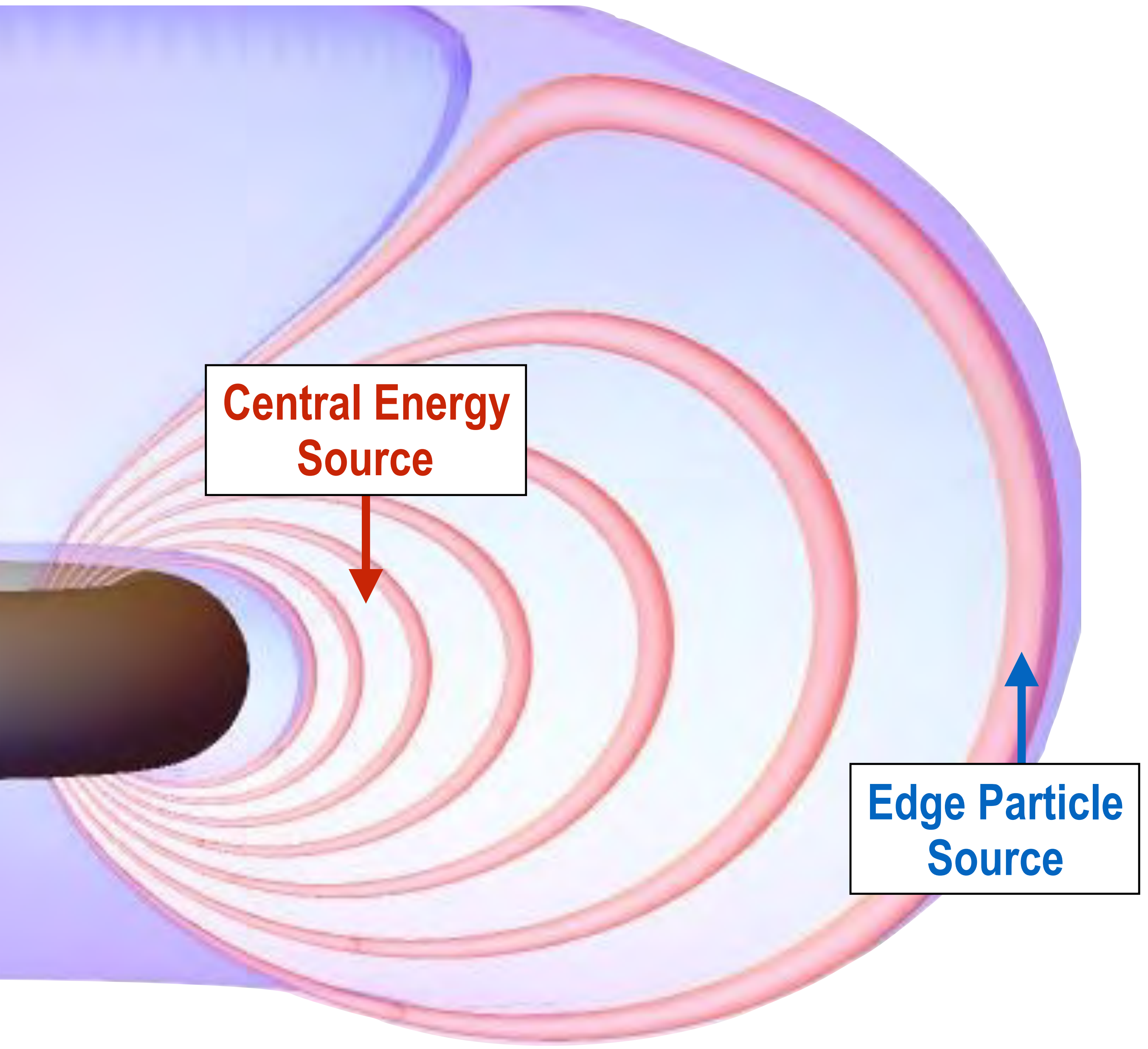


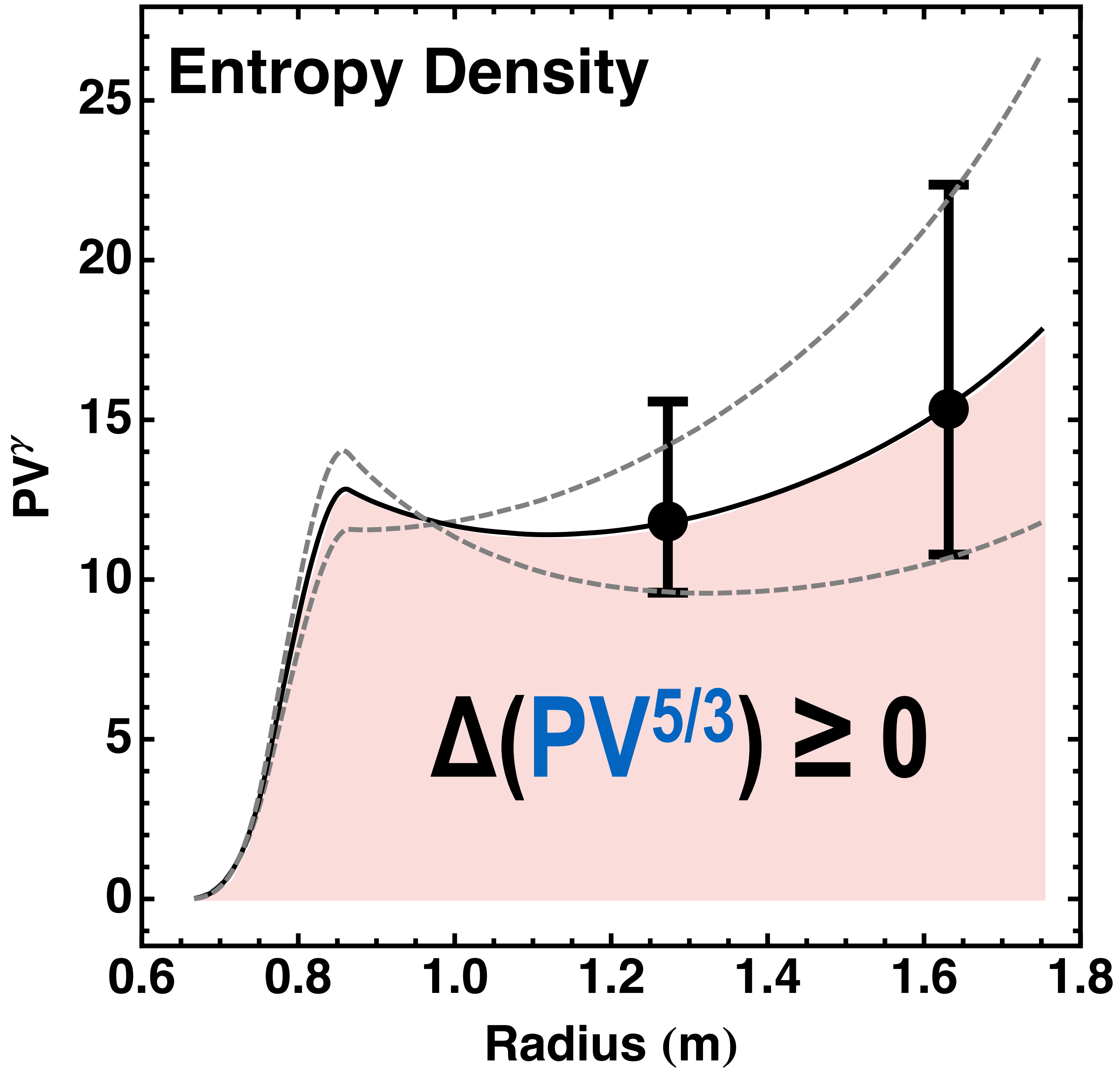


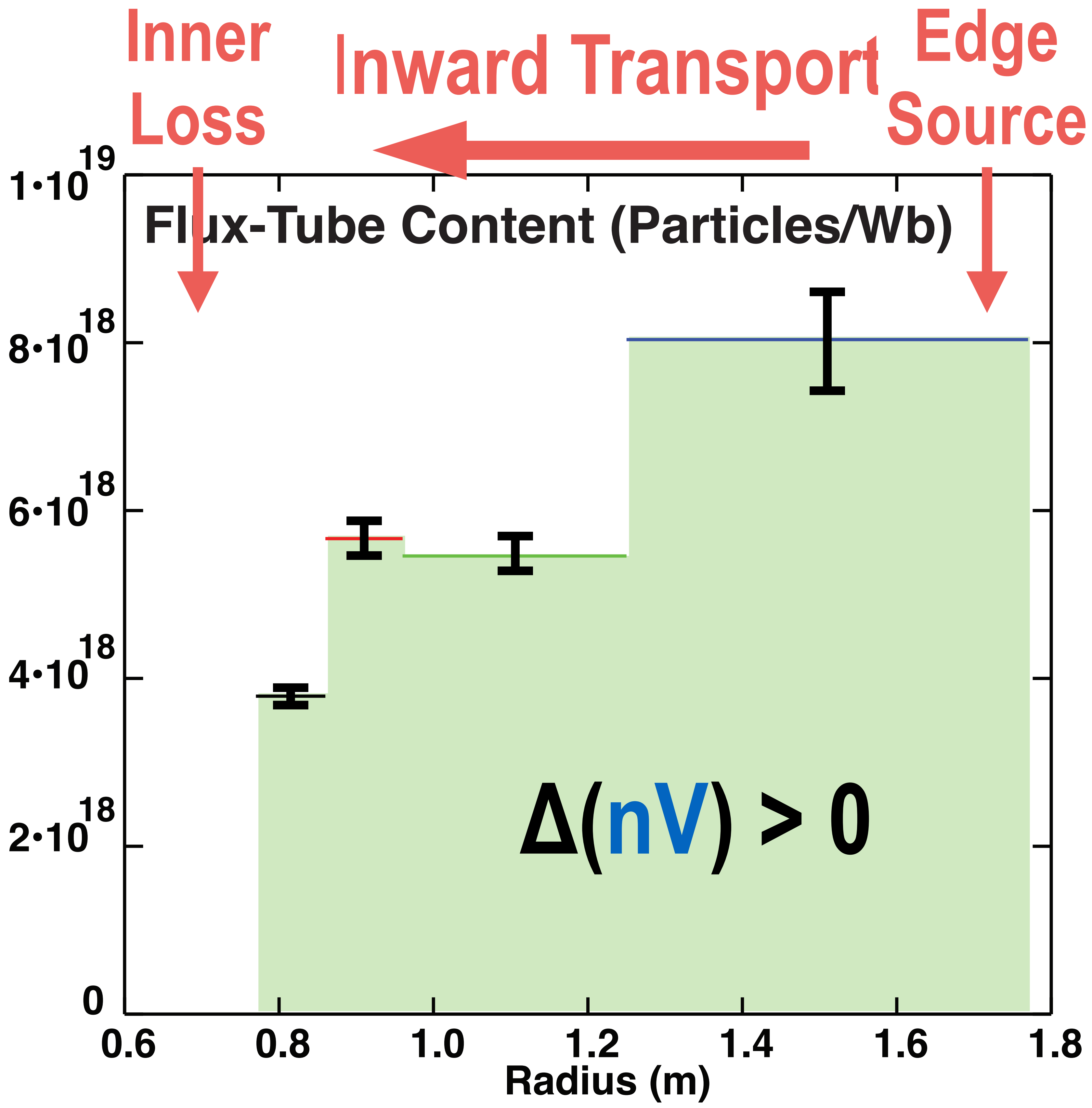


Boxer, *et al.*, "Multichannel microwave interferometer for the levitated dipole experiment," *Rev Sci Instrum* **80**, 043502 (2009).

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







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

$\eta > 2/3$

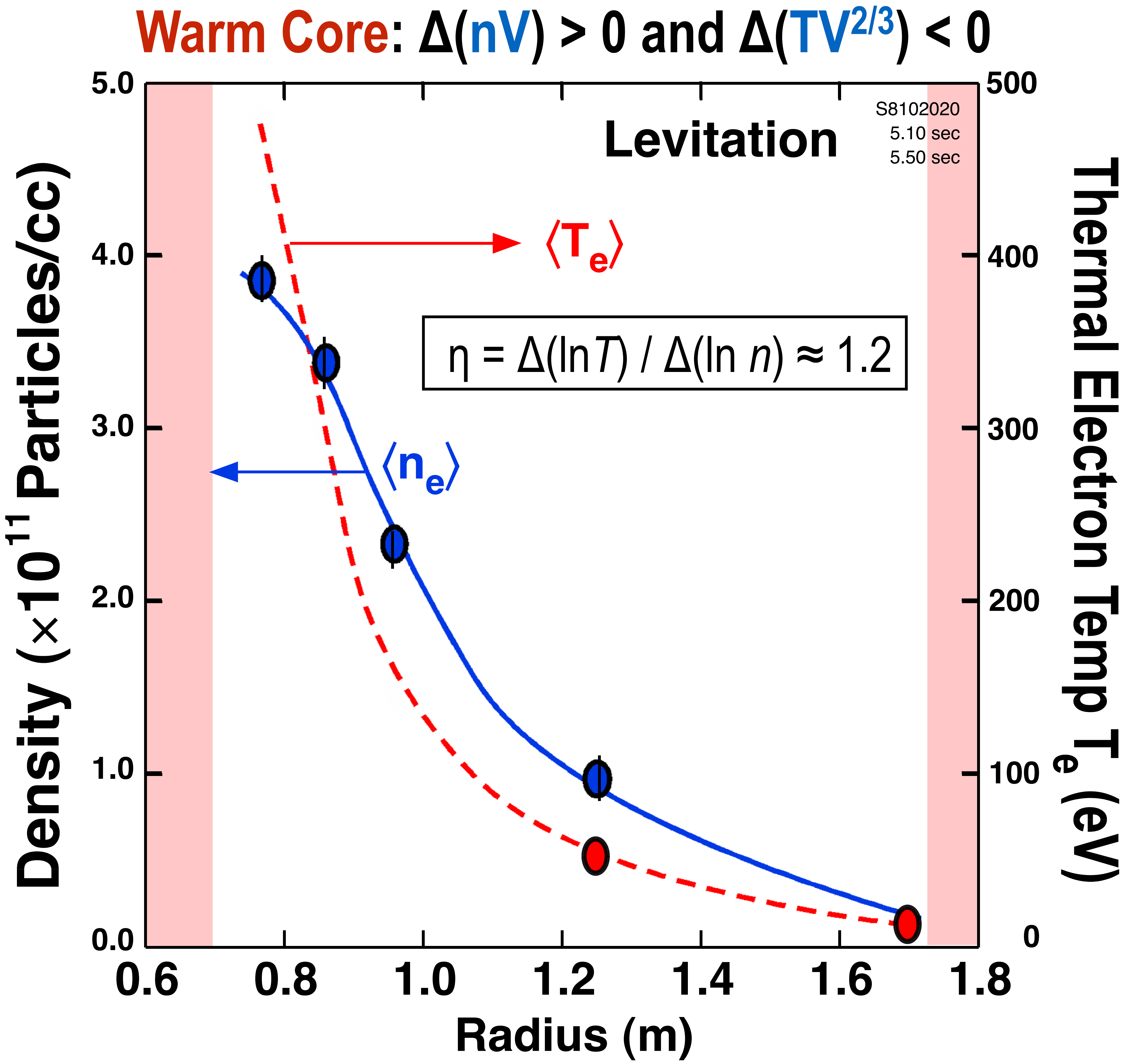
$$\eta = \frac{\Delta \ln T}{\Delta \ln n}$$

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).

Edge fueling and central ECRH creates a "warm core" with $\eta > 2/3$

Example thermal profile: Short-pulse heating before appearance of energetic electrons…

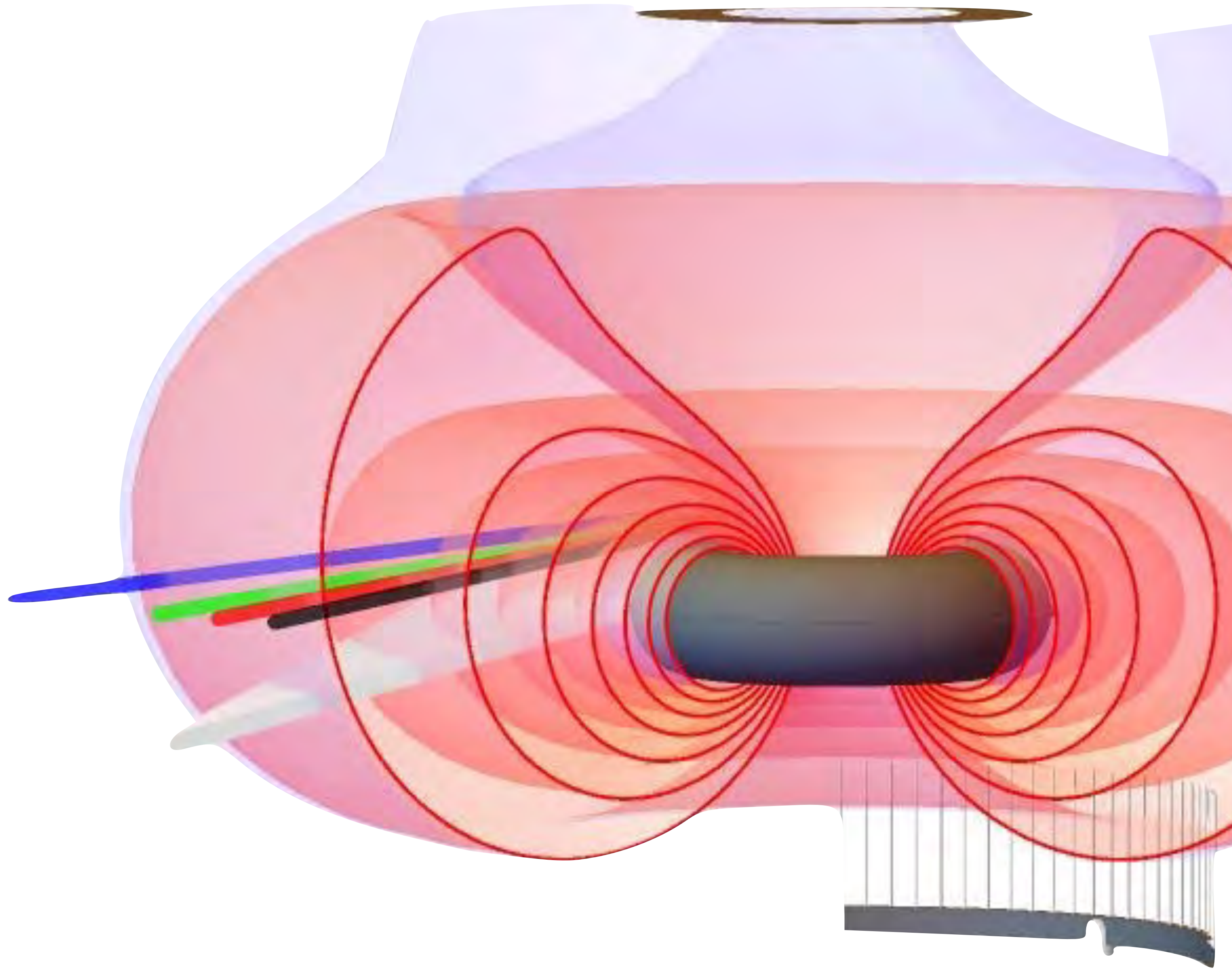
- 11 kW ECRH creates thermal plasma energy: $W_{th} \approx 100$ J.
- Measured *edge* $T_e \approx 15$ eV, density profile, and stored energy, imply ***central* T_e ~ 500 eV**
- "**Warm core**" with $\eta > 2/3 \sim 1.2$
- $\rho^* \sim 0.02$, $\omega_d/2\pi \approx 0.8$ kHz
- Semi-collisional thermal electrons: $2\pi\, \nu_e/\omega_b \sim 0.006$
  (Thermal electrons bounce > 100 times in a collision time.)



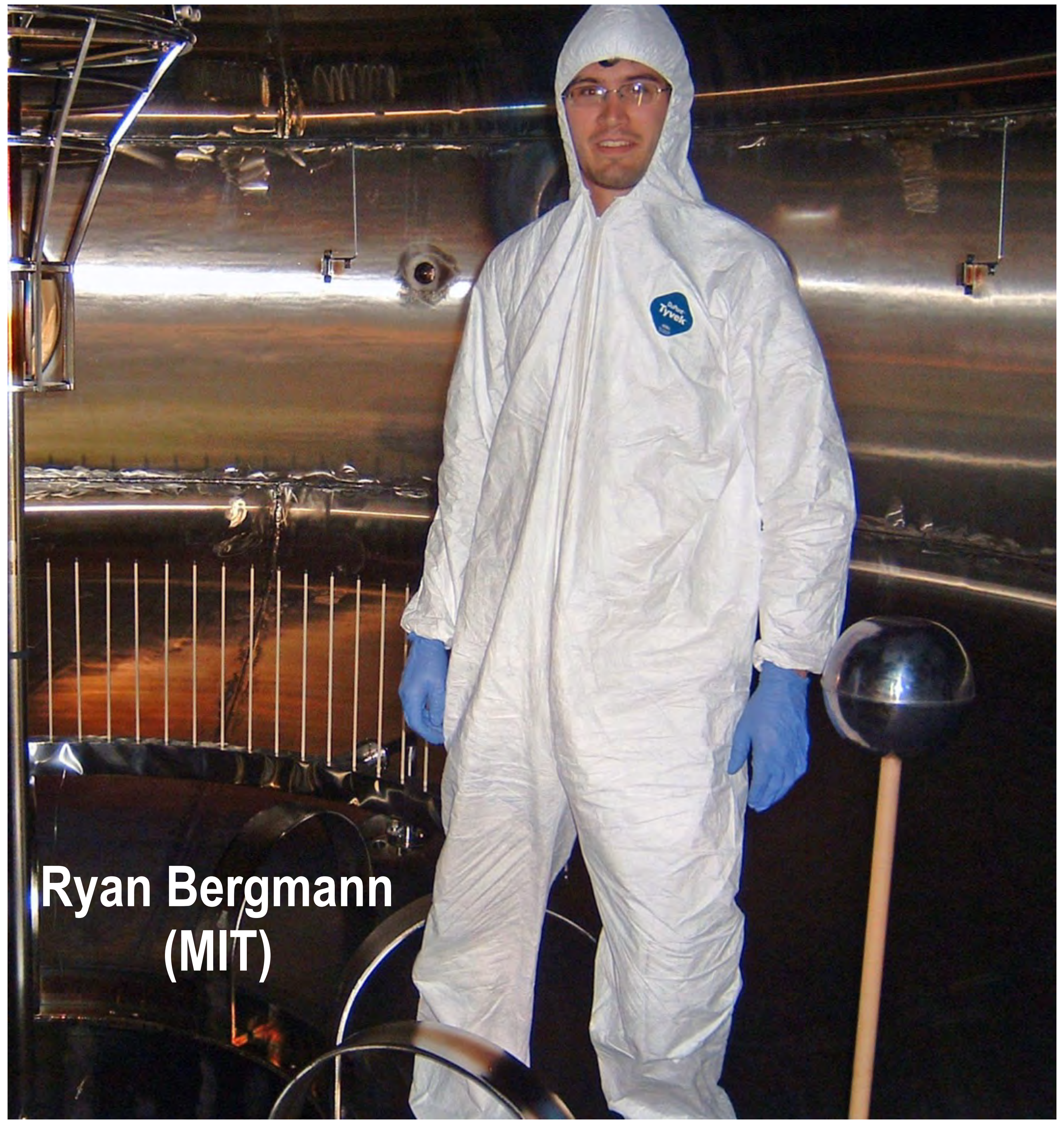
Warm Core: $\Delta(nV) > 0$ and $\Delta(TV^{2/3}) < 0$

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



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

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

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

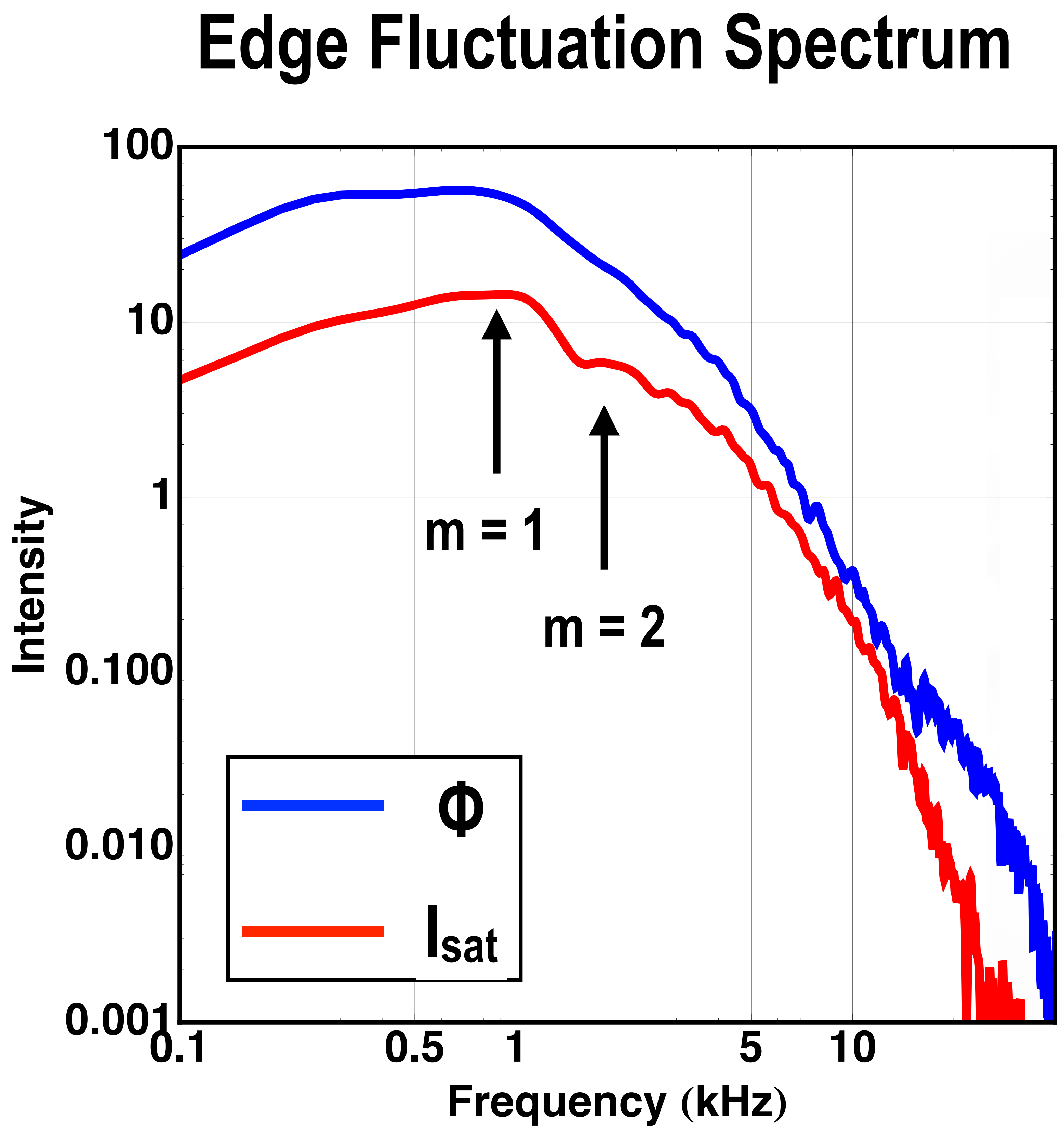
$$\boxed{\frac{\partial}{\partial t}(nV)=\underbrace{\langle S\rangle}_{\text{Source}}+\frac{\partial}{\partial\psi}D_{\psi}\frac{\partial}{\partial\psi}(nV)}$$

Radial Diffusion due to Interchange/Entropy Turbulence

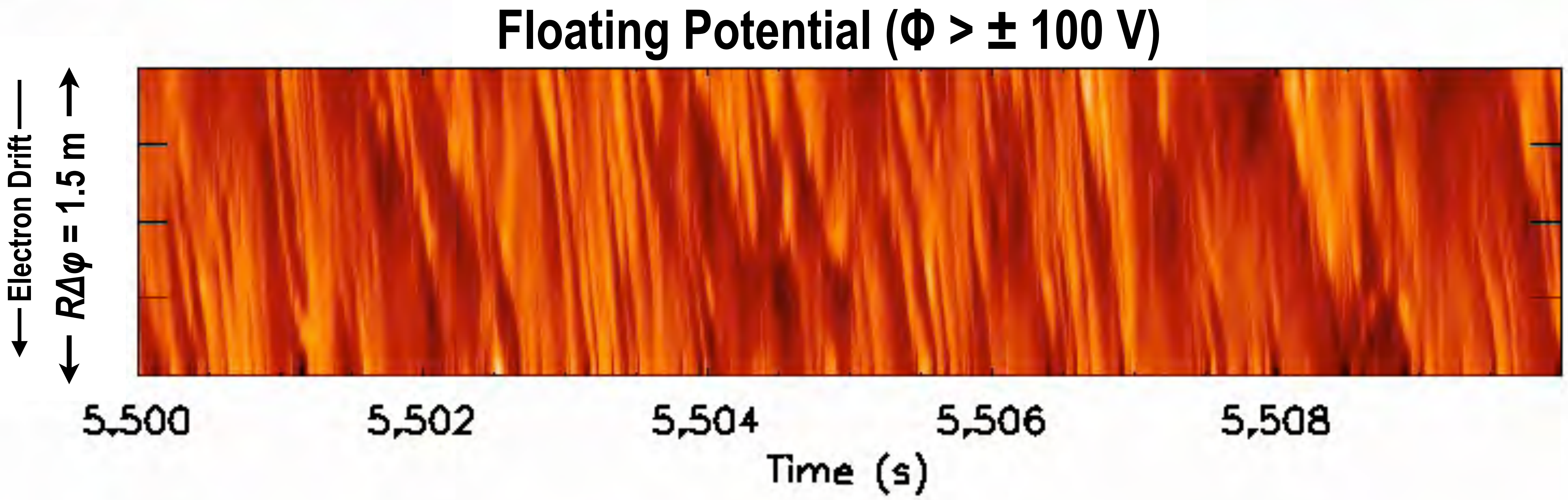
Alex Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet,” *Nat Phys* **6**, 207 (2010).

Turbulent Fluctuations Propagate in Electron Drift Direction

(during edge gas fueling)



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



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

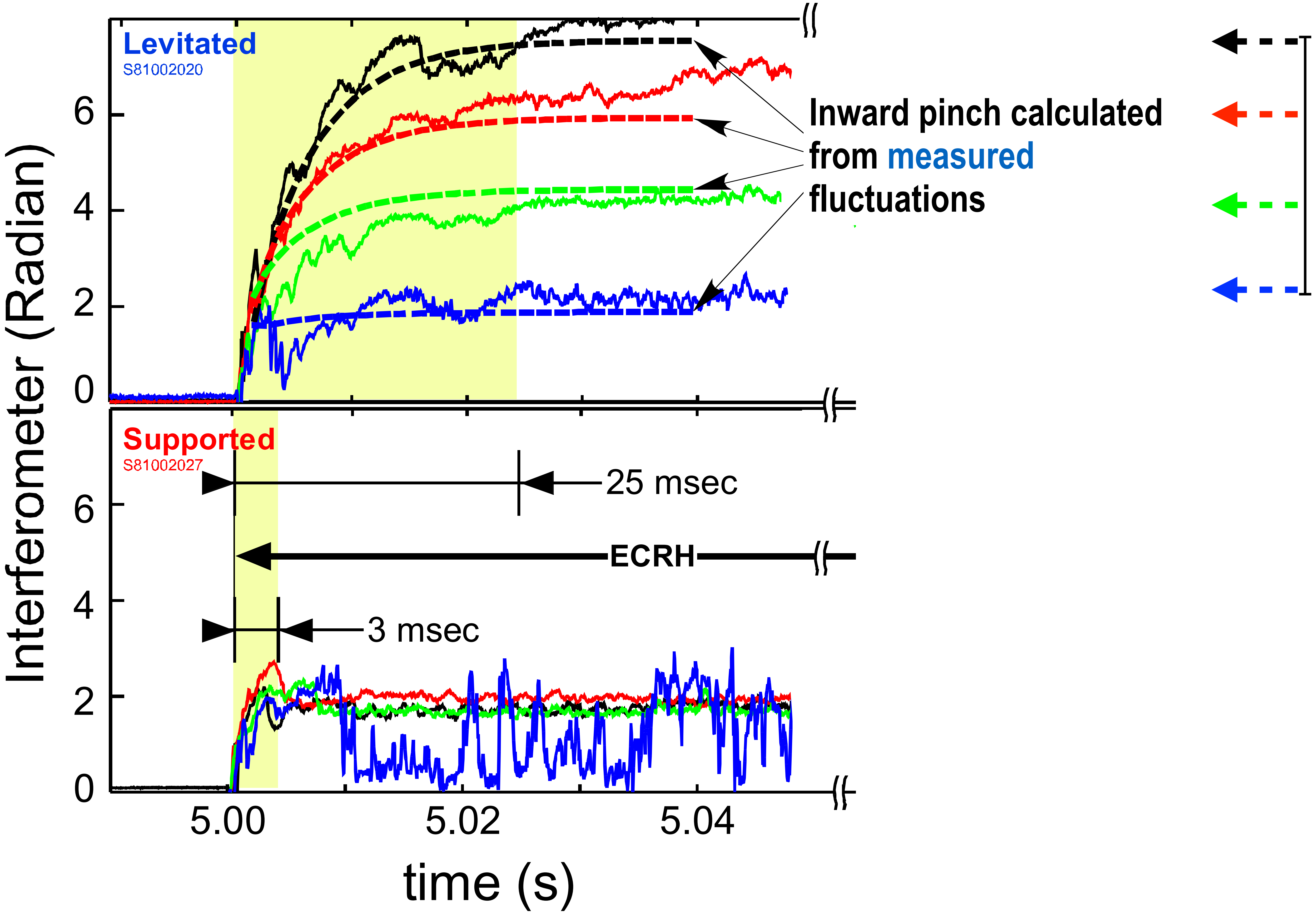
m = 1, 2, 3, 4, 5, 6, …

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).

Rate of Inward Diffusion Agrees using Measured Interchange Diffusion Coefficient

With levitated dipole, inward turbulent transport sets profile evolution



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

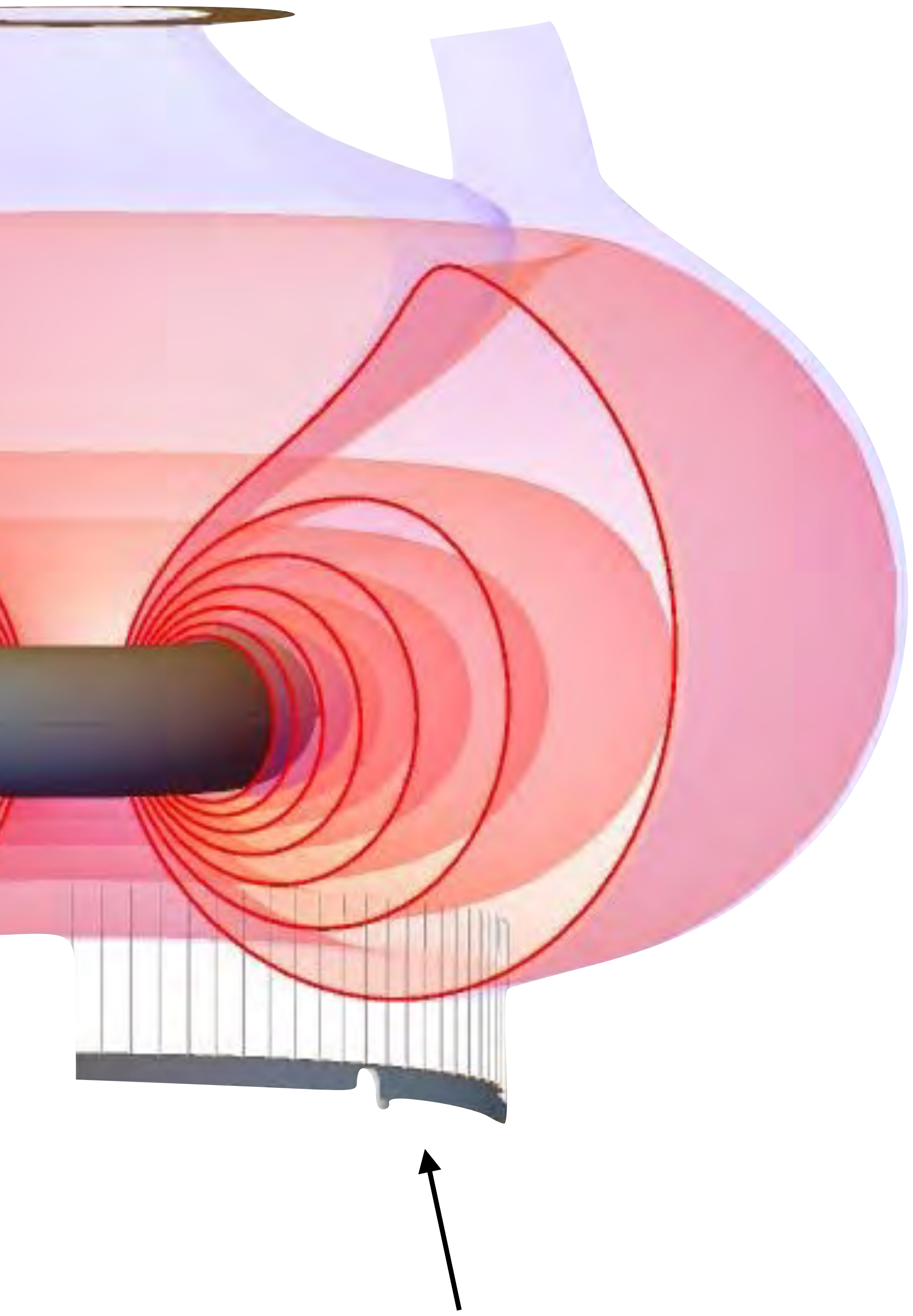
$$\boxed{D_\psi \sim 0.047\ (\mathrm{Wb}^2/\mathrm{s})}$$

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

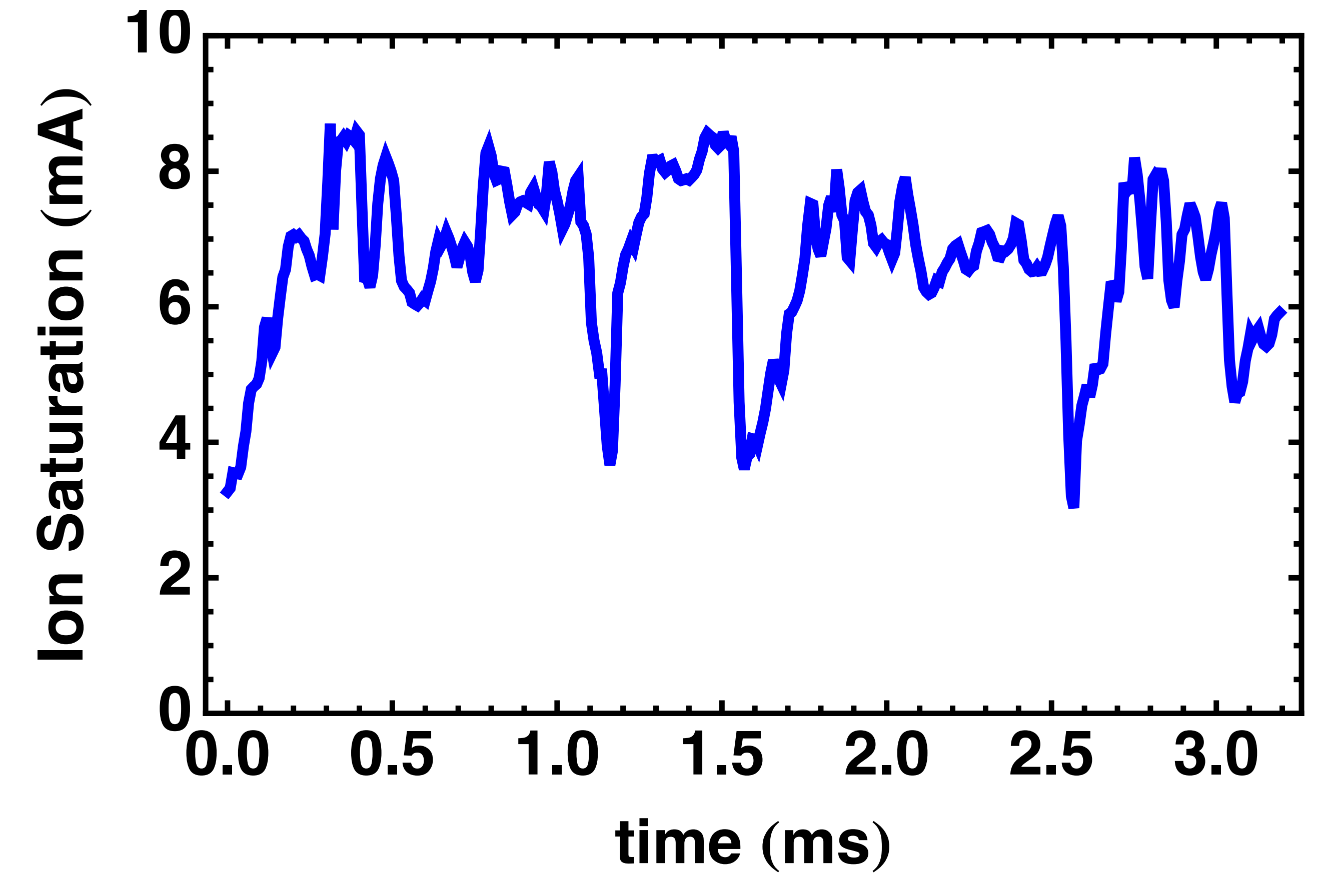
$$D_\psi = R^2 \langle E_\varphi^2 \rangle \tau_c$$

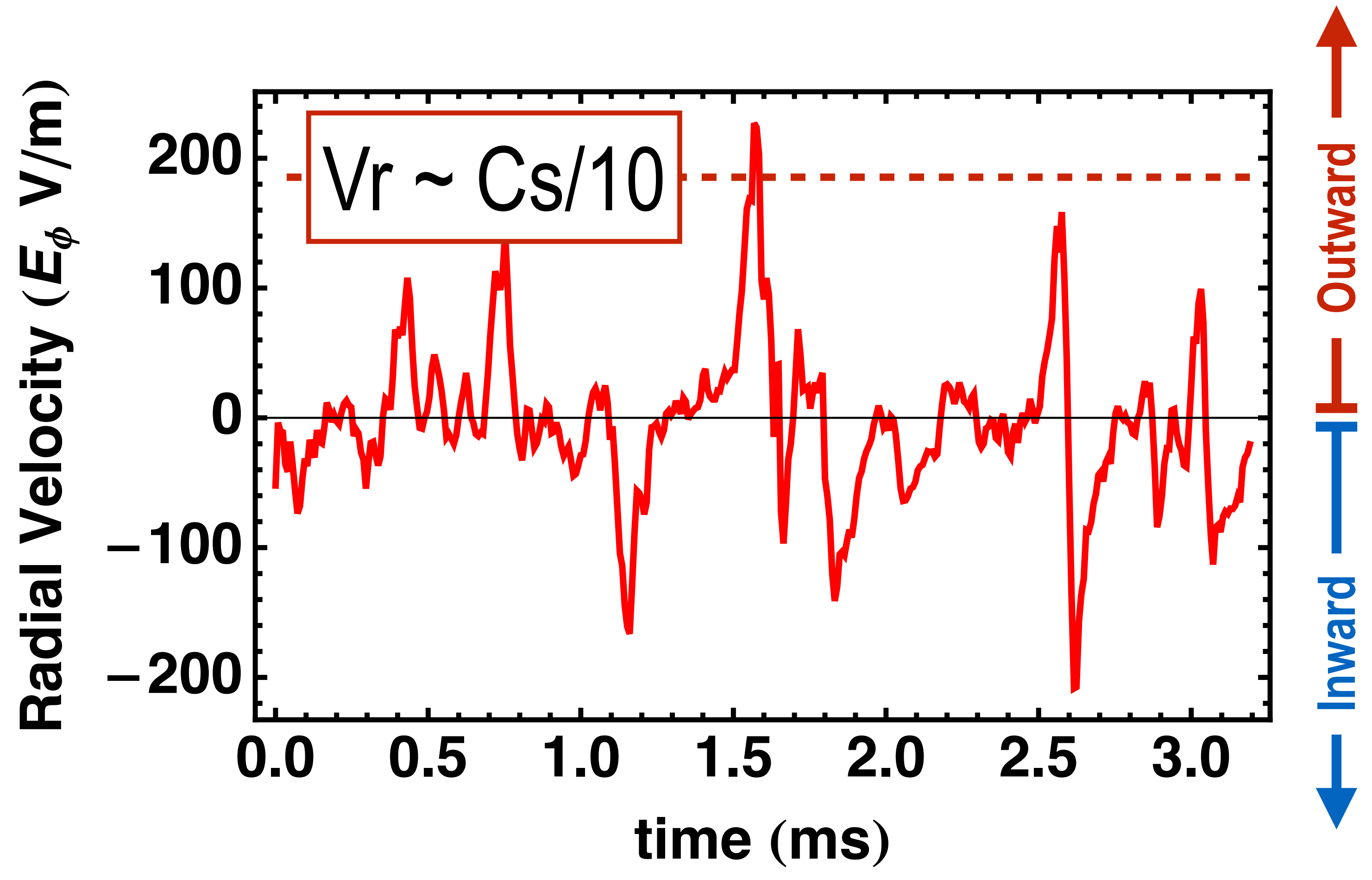
Thomas Birmingham, “Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation,” *JGR*, **74**, (1969).
Alex Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nature Phys* **6**, (2010).

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



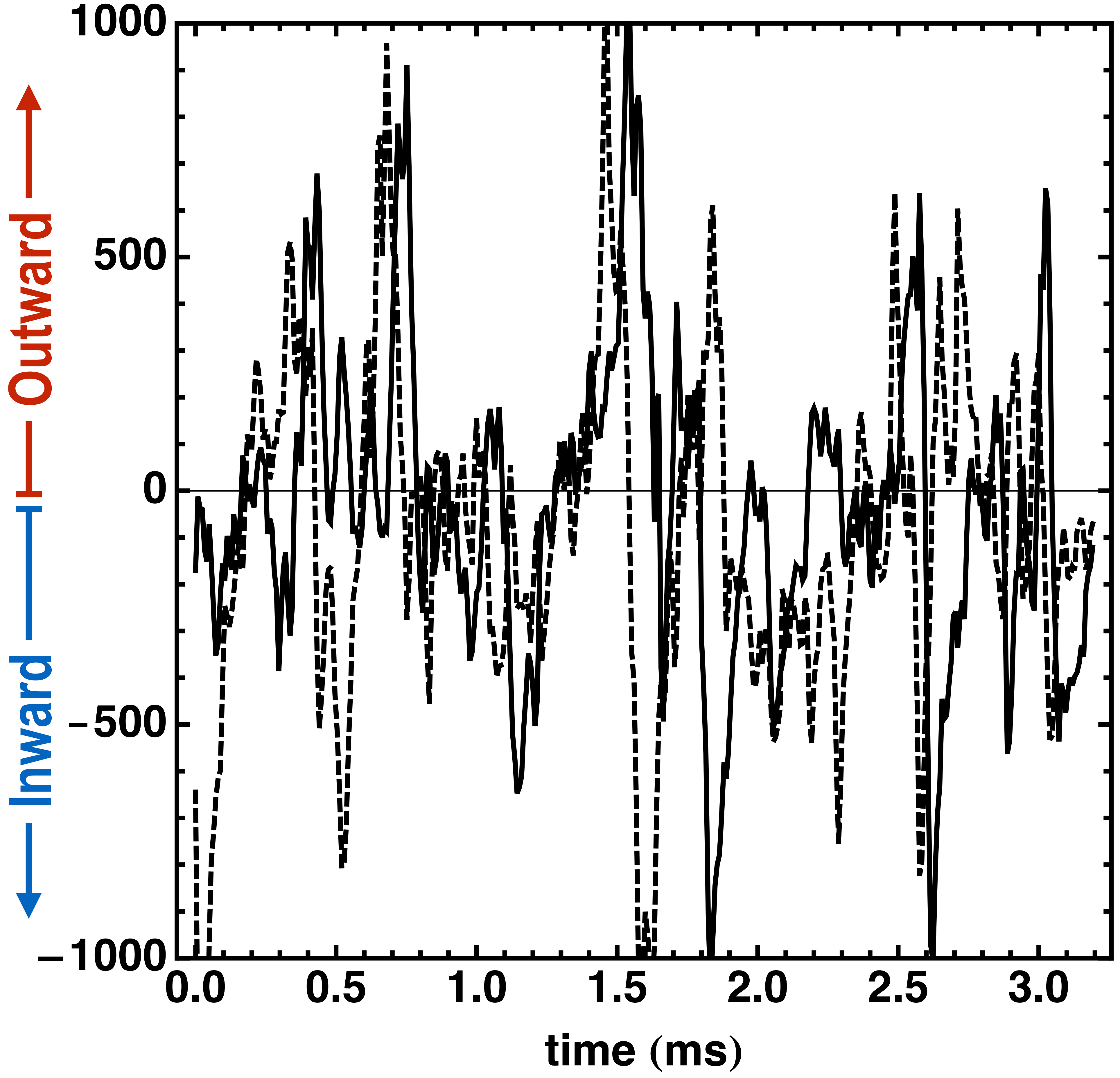
Probe Array:
Floating Potential, E_φ
Ion Saturation Current
Radial **E**×**B** Flux





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

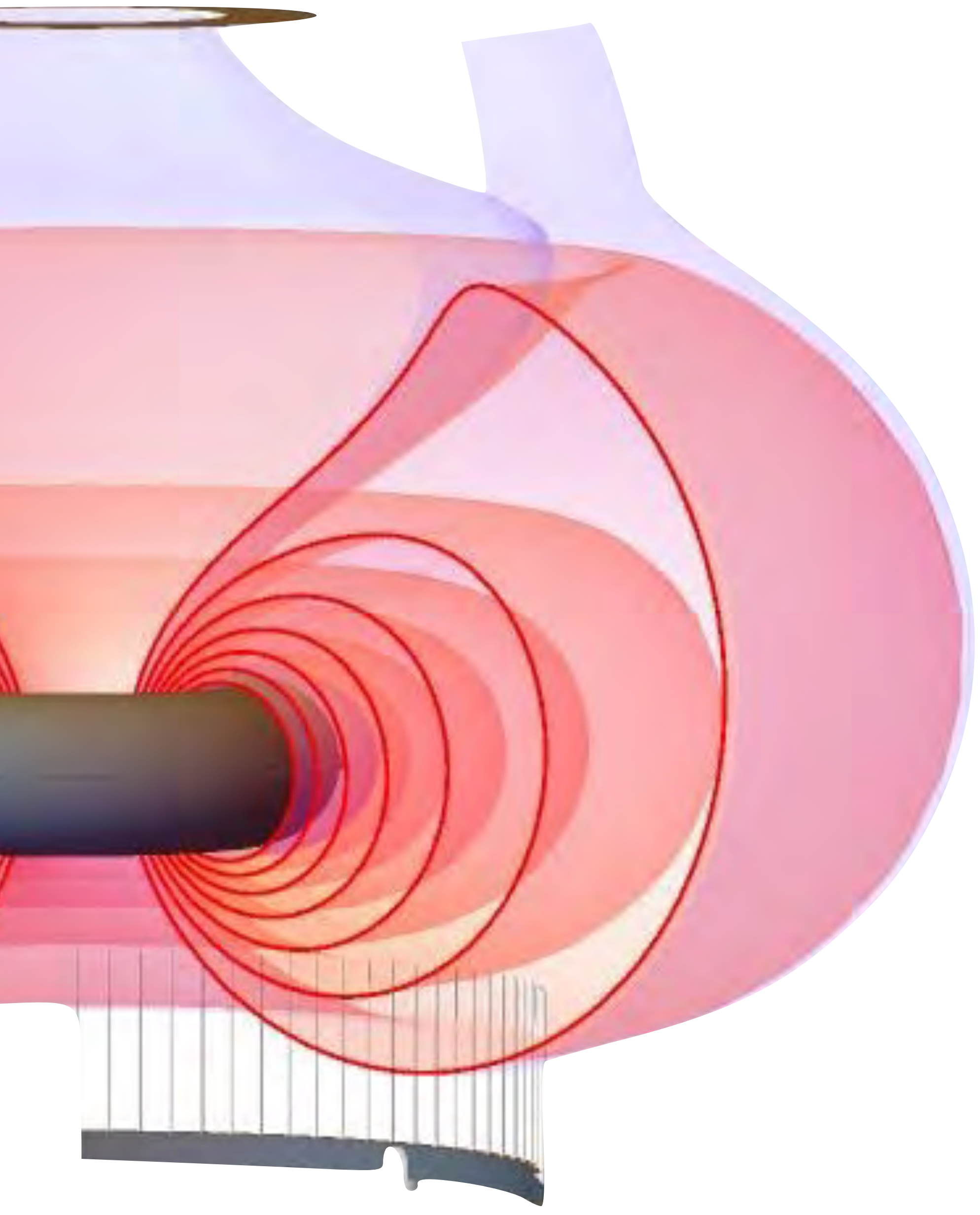
“Bursty” Inward/Outward Filaments



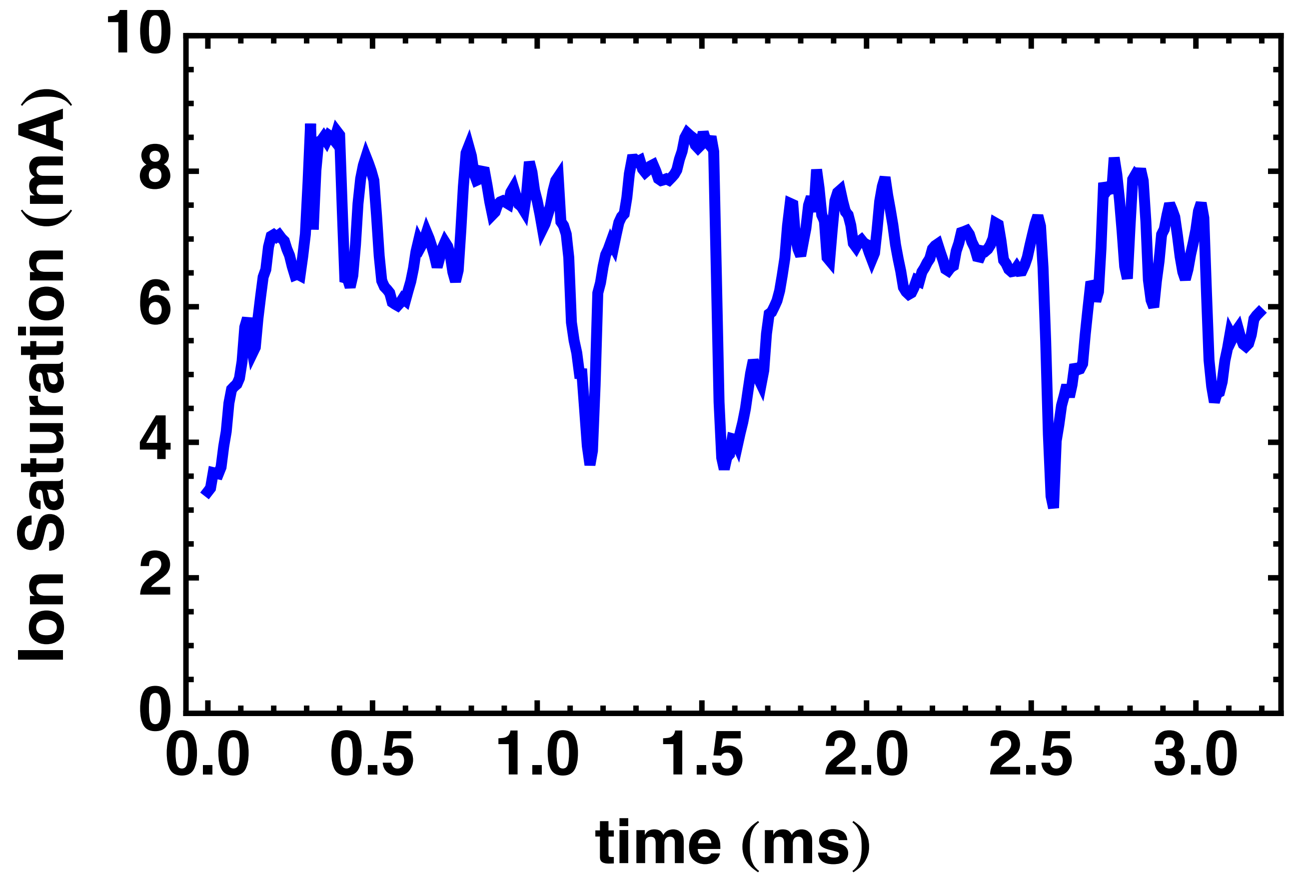
Radial Flux ~ $(E_\varphi/B) \times I_{sat}$

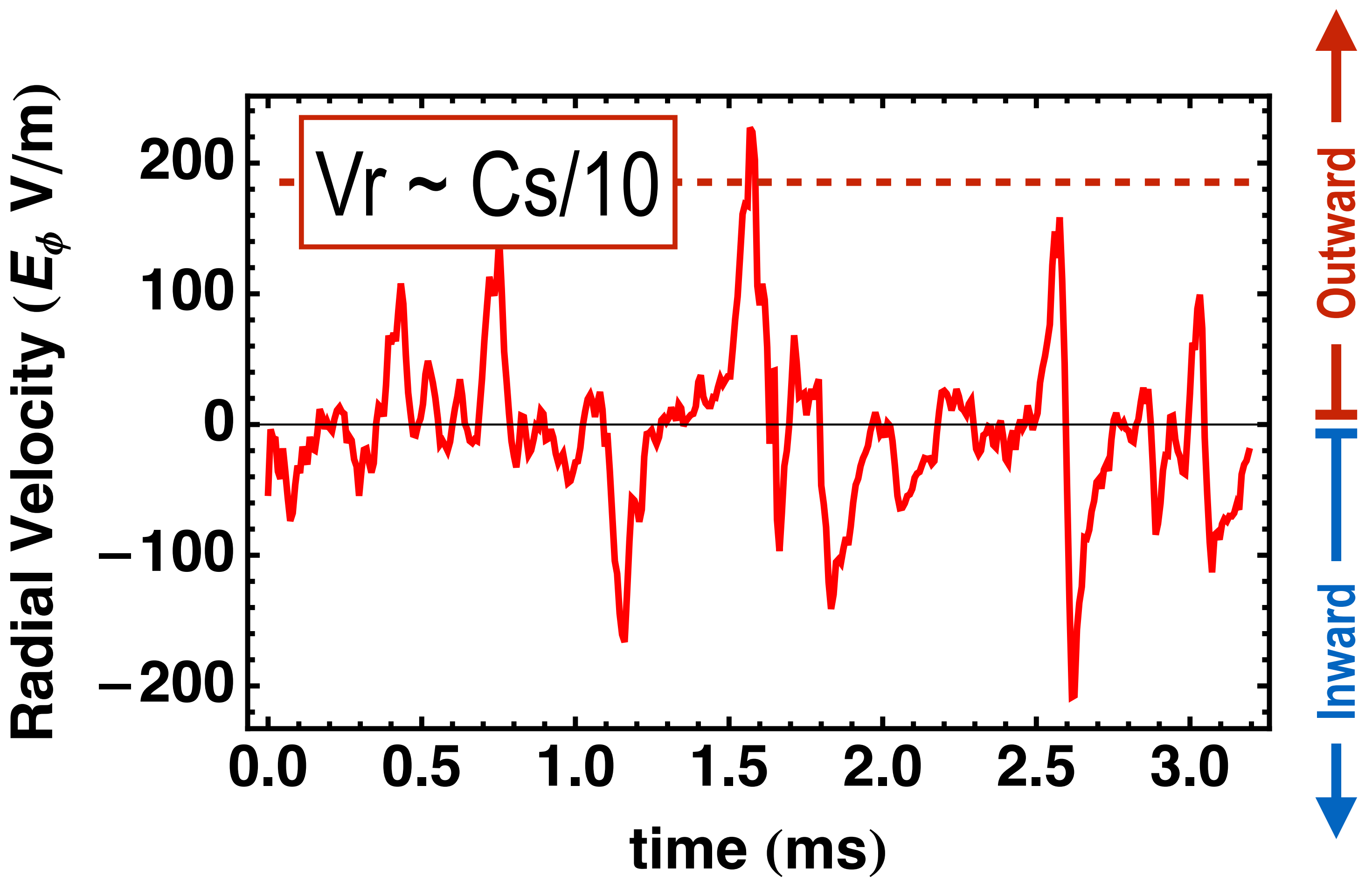
Jen Ellsworth, *Characterization of Low-Frequency Density Fluctuations in Dipole-Confined Laboratory Plasmas*, PhD MIT (2010).
Grierson, *et al.*, "Transport Induced by Large Scale Convective Structures in a Dipole-Confined Plasma," *PRL* **105**, 205004 (2010).

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

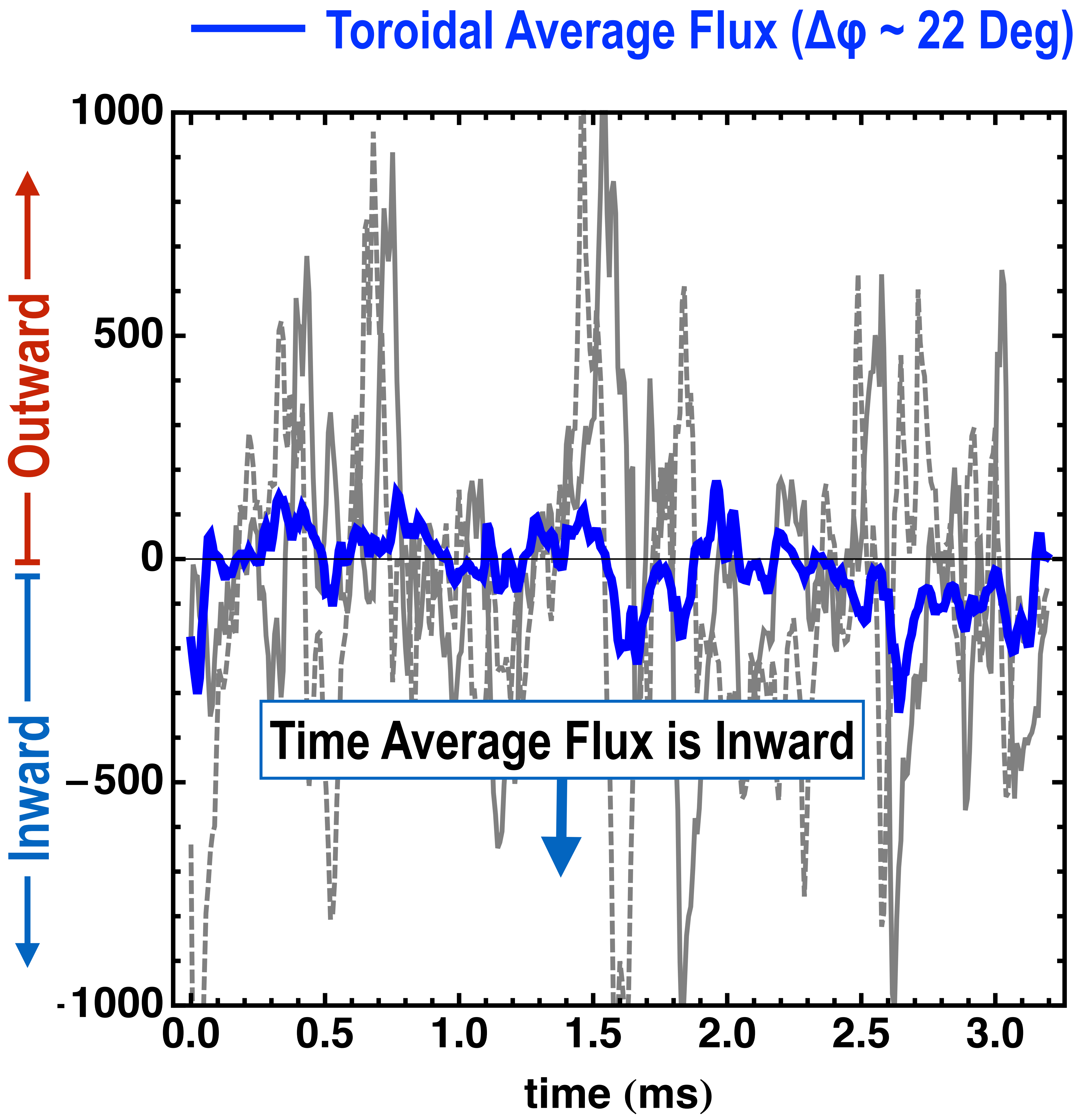


Probe Array:
Floating Potential, E_φ
Ion Saturation Current
Radial **E**×**B** Flux





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



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

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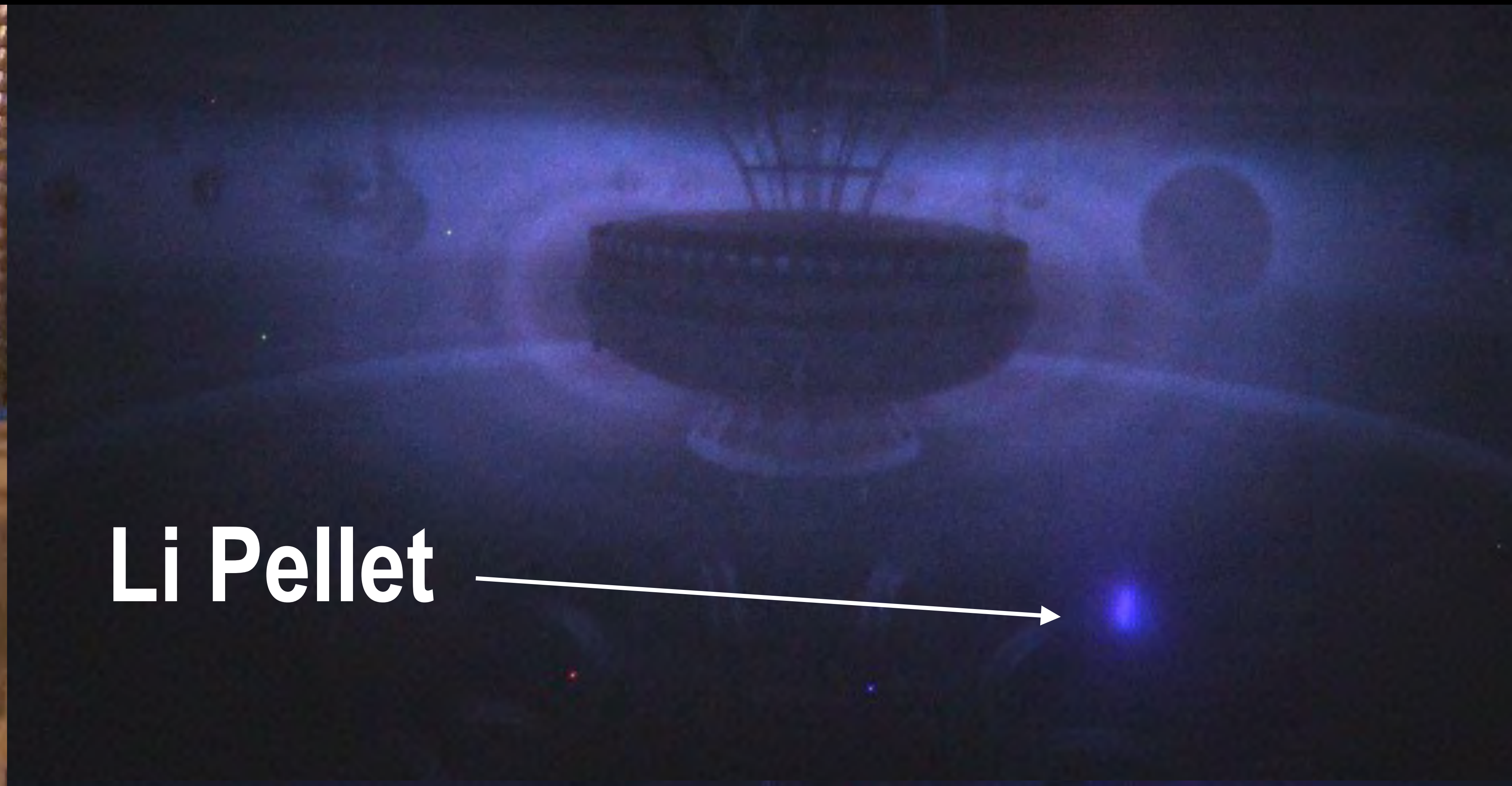
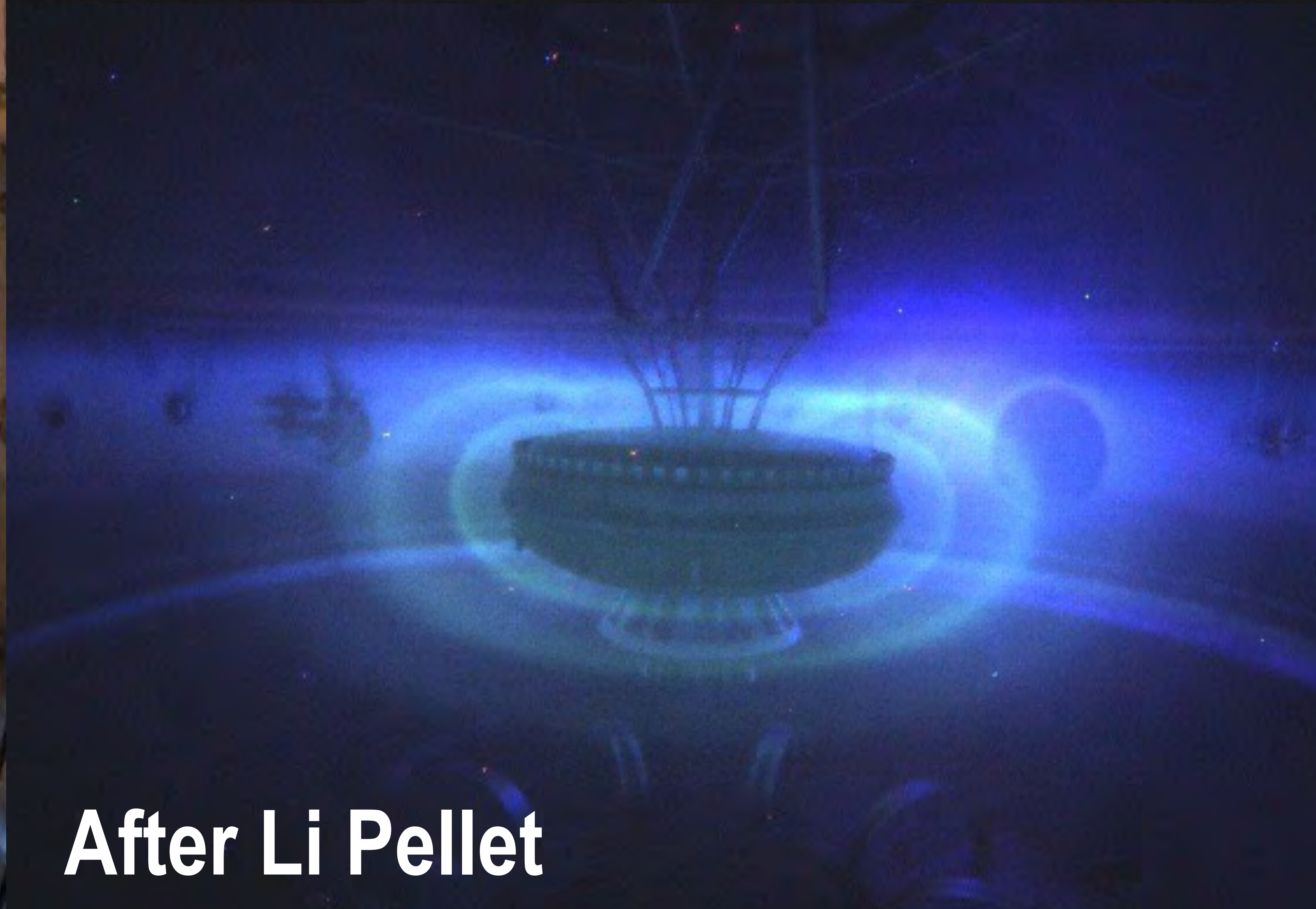
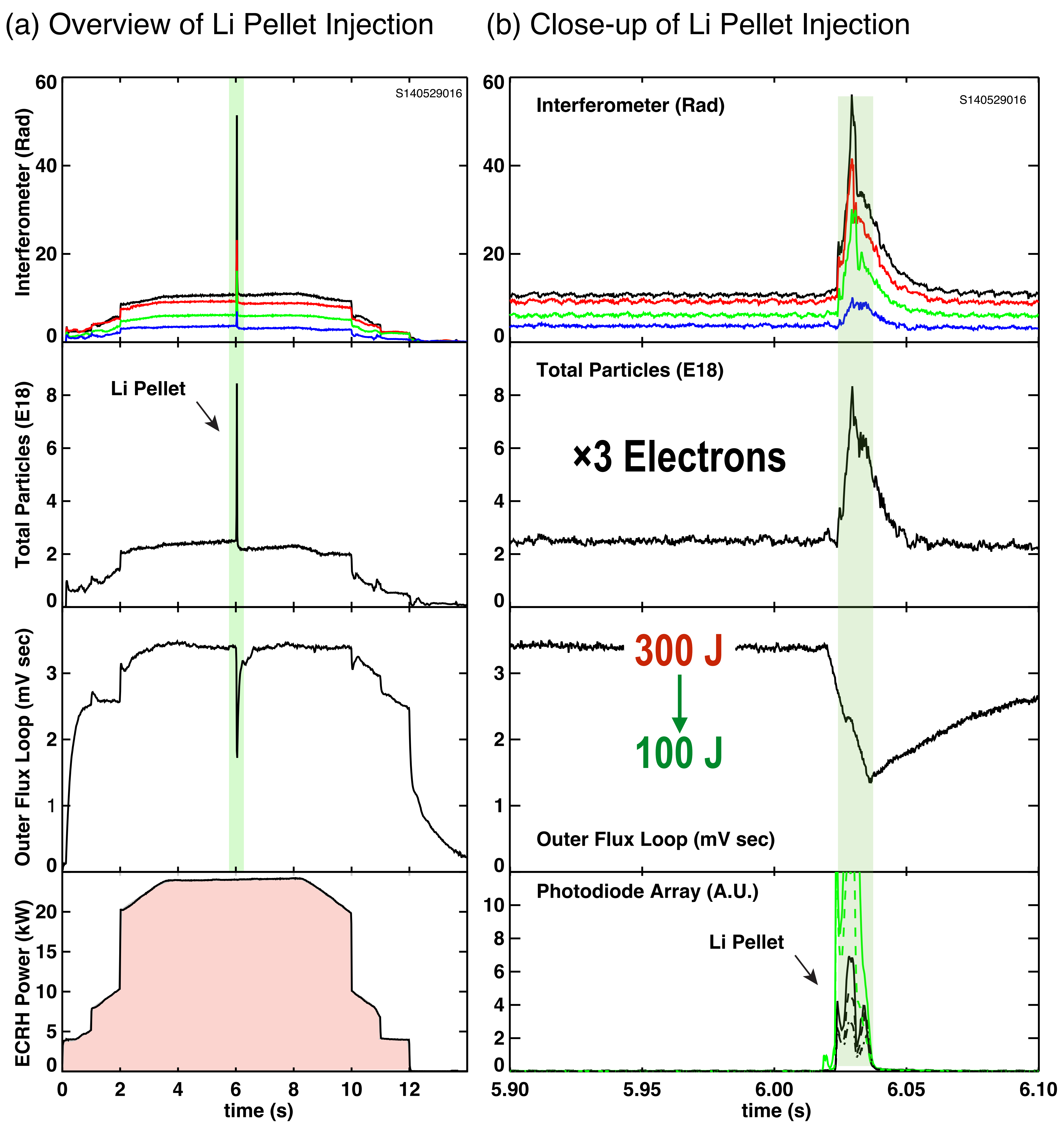
Grierson, *et al.*, "Transport Induced by Large Scale Convective Structures in a Dipole-Confined Plasma," *PRL* **105**, 205004 (2010).

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

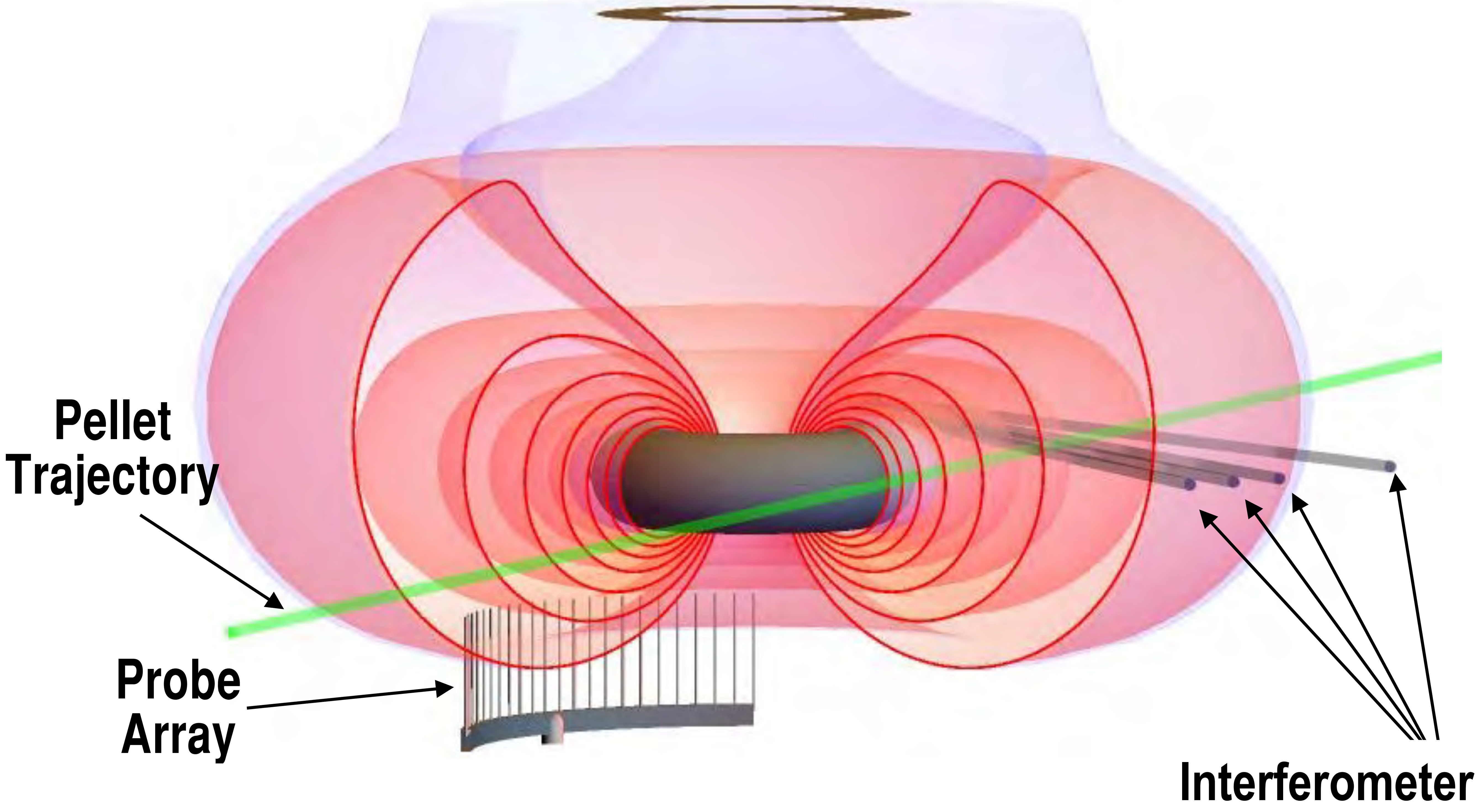




Li Pellet Injection Provides Internal Particle Source and Cools Plasma Core

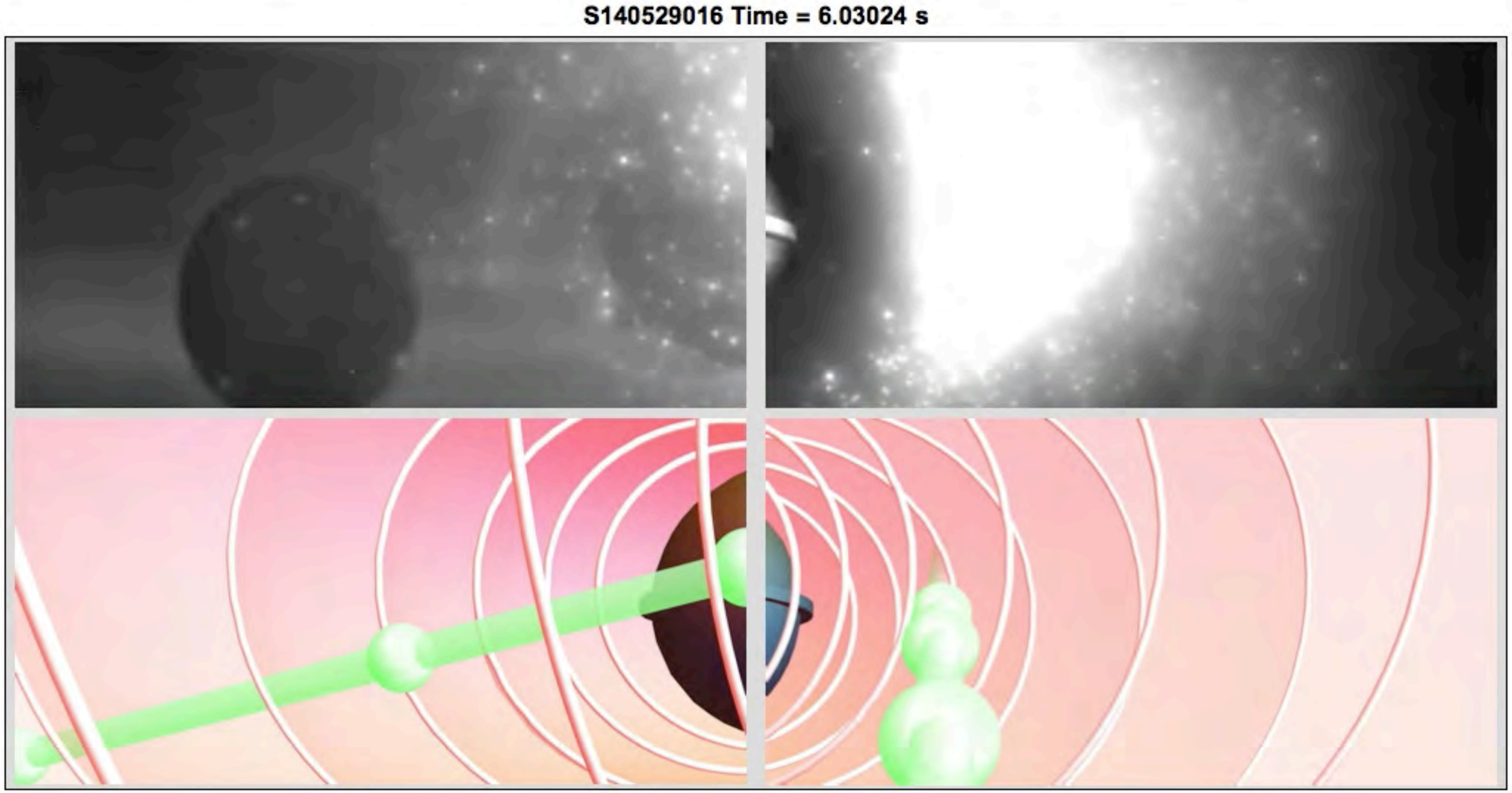

(a) Overview of Li Pellet Injection

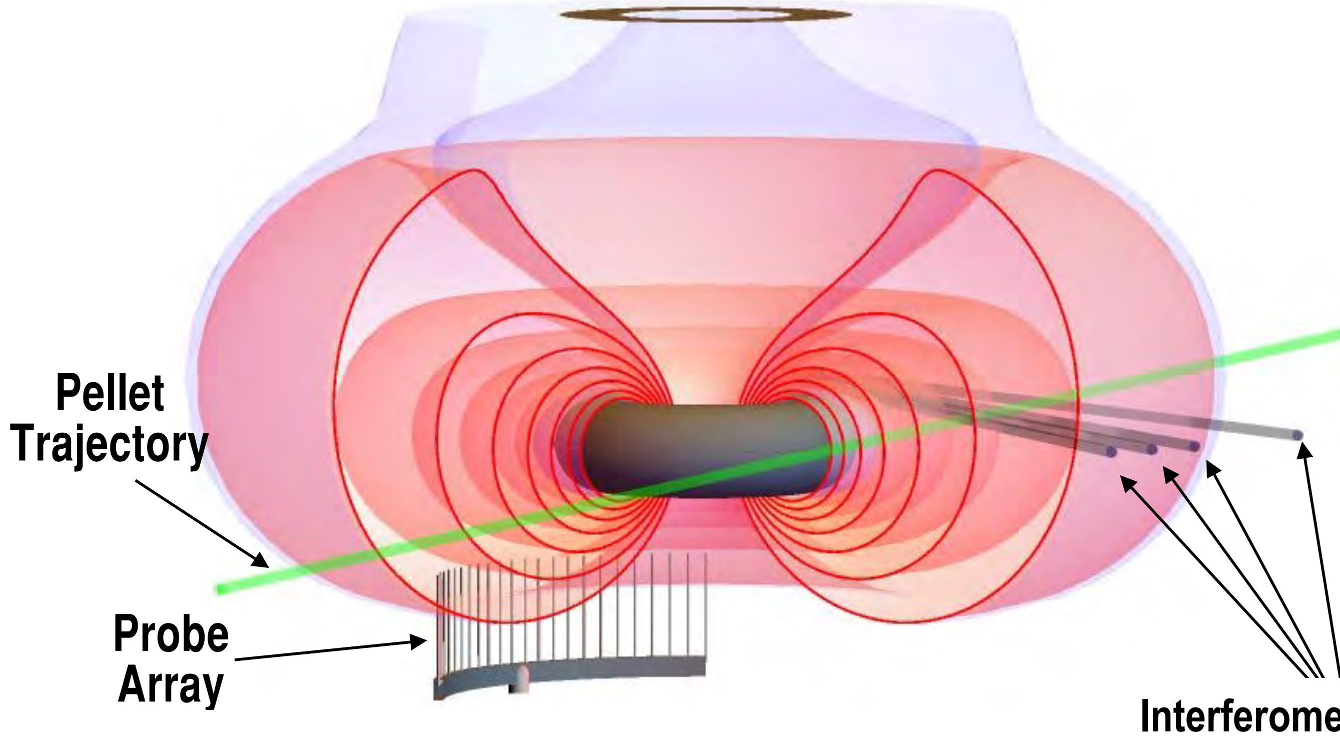
(b) Close-up of Li Pellet Injection



×5 Peak Density
×3 Electrons
÷3 Energy

Li Pellet Injection Provides Internal Particle Source and Cools Plasma Core





×5 Peak Density
×3 Electrons
÷3 Energy

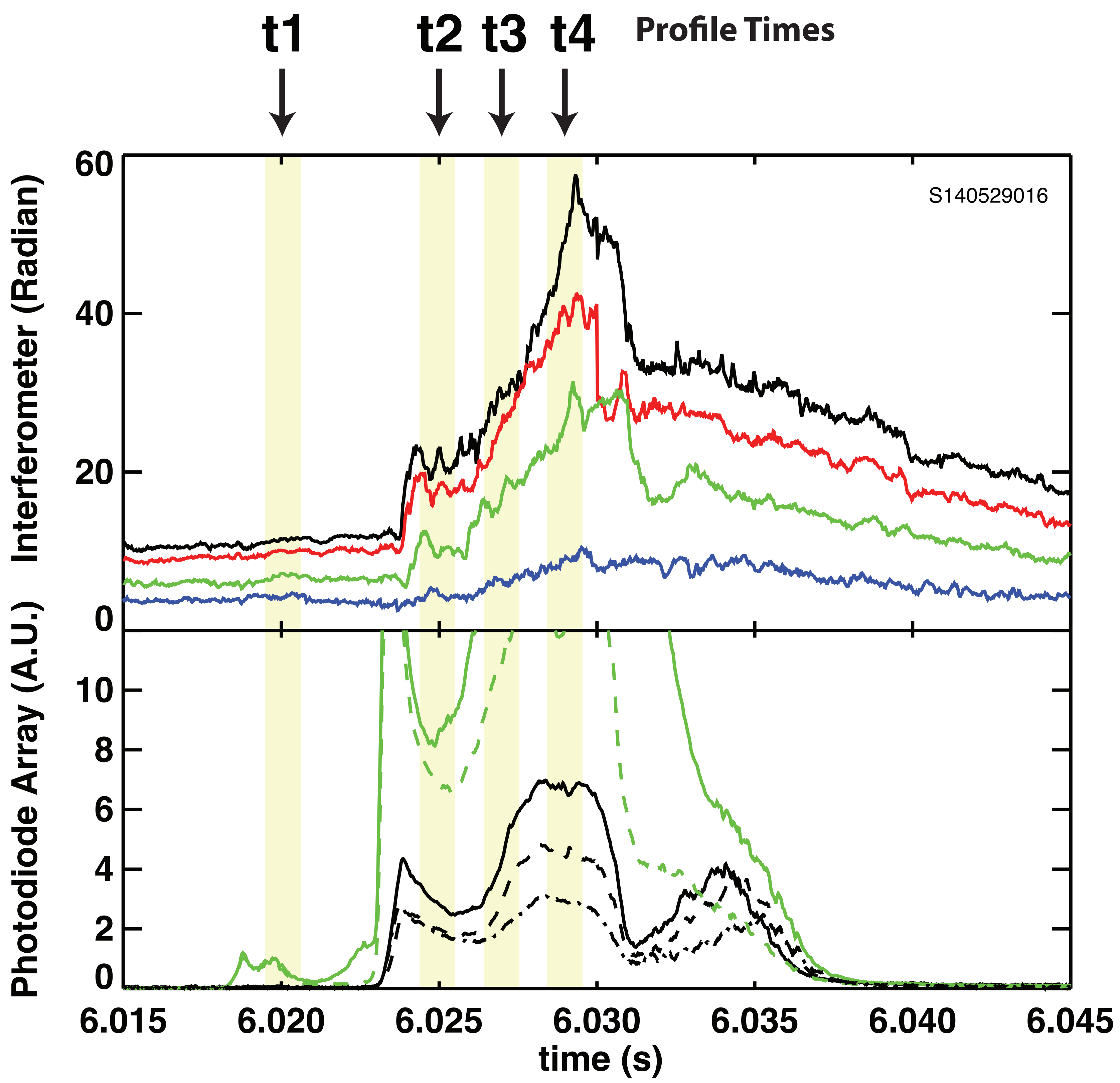
17 ms traveling at 225 m/s

Li-Pellet Injection Increases Central Density (×5), **Cools Core Temperature**, and Decreases η < 2/3

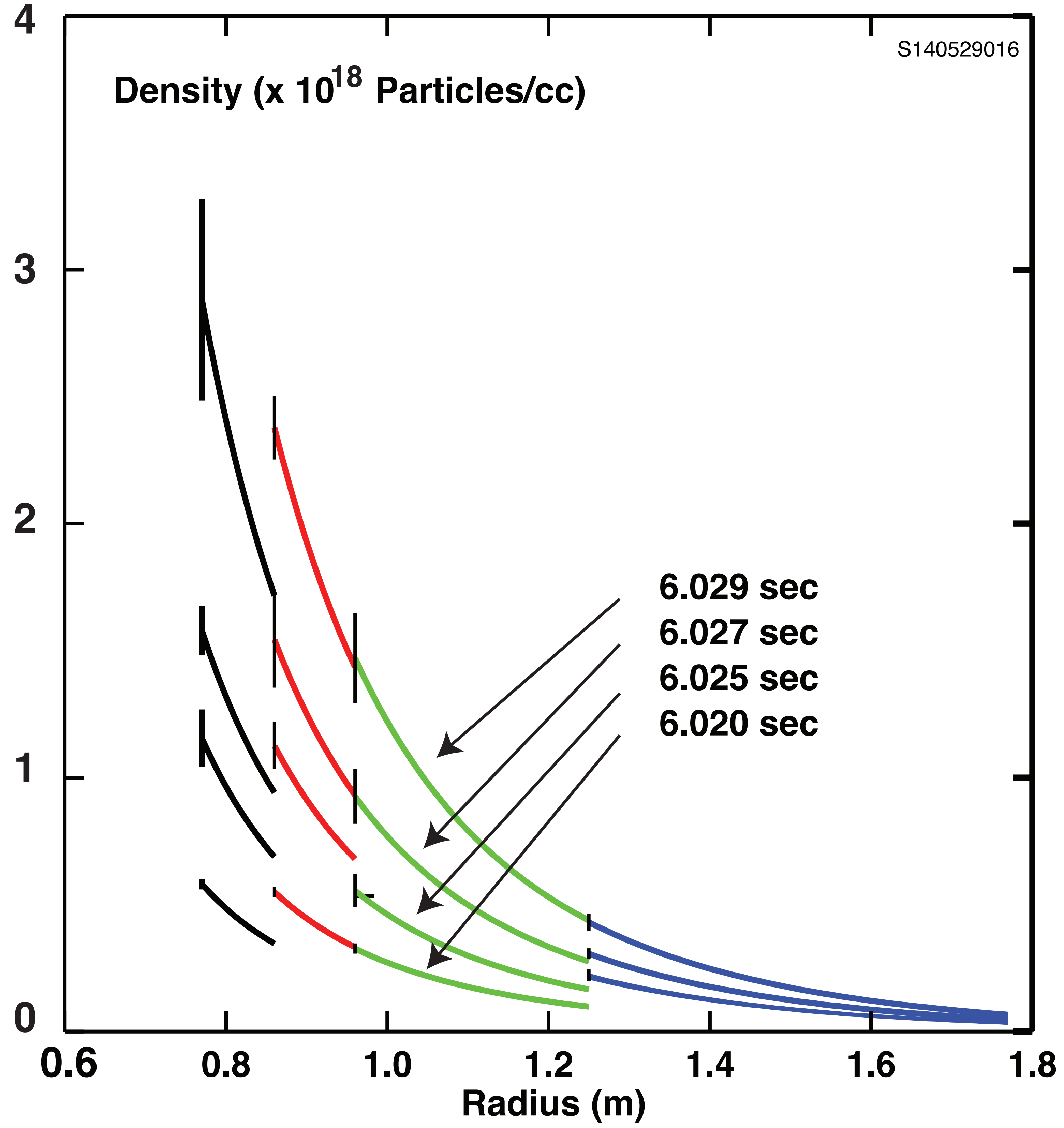
η > 2/3 (“**warm core**”/edge fueling) becomes η < 2/3 (“**cool core**”/pellet fueling)

Δ(nV) ~ 0

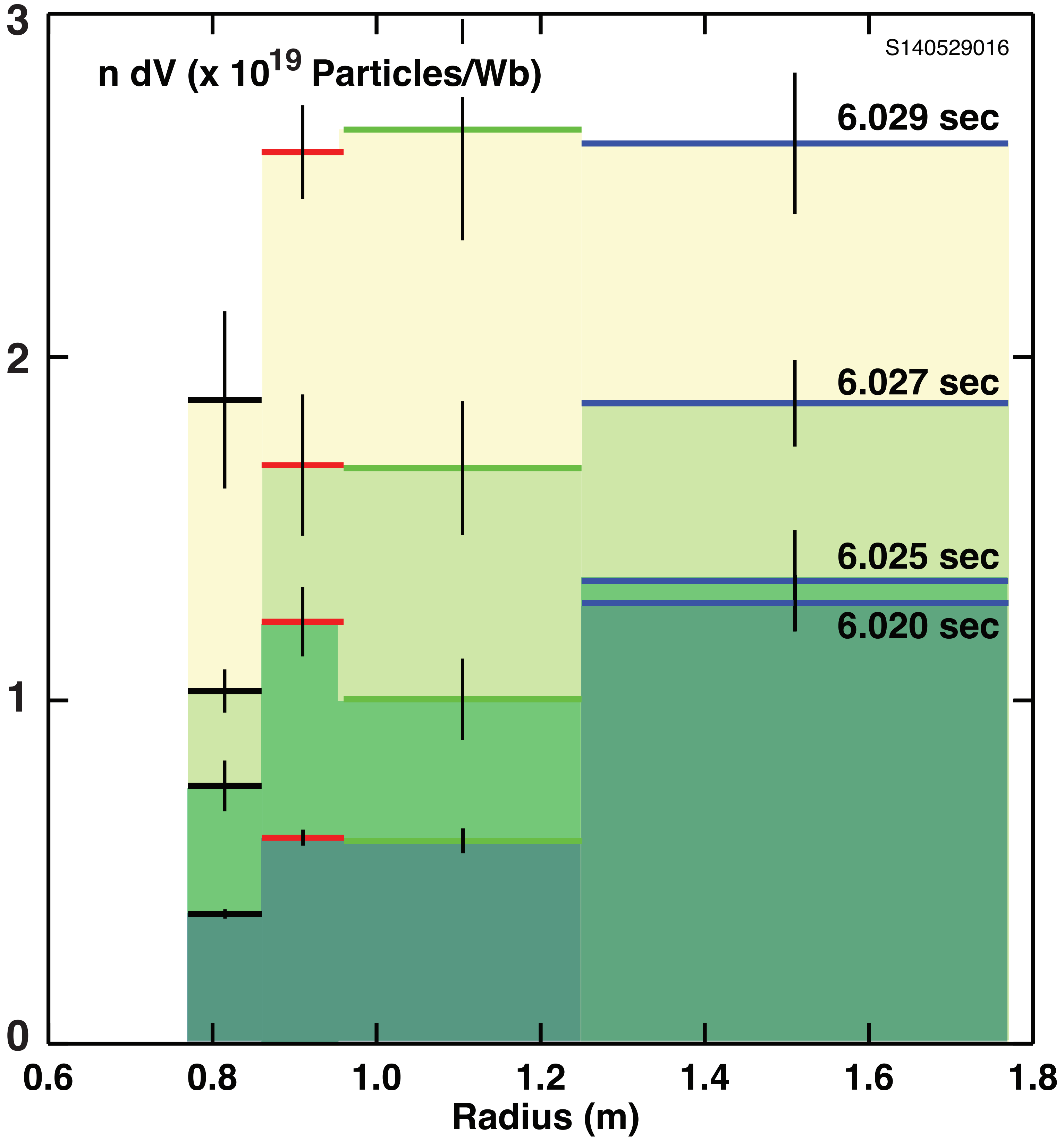
(a) Line Density and Photodiode Array



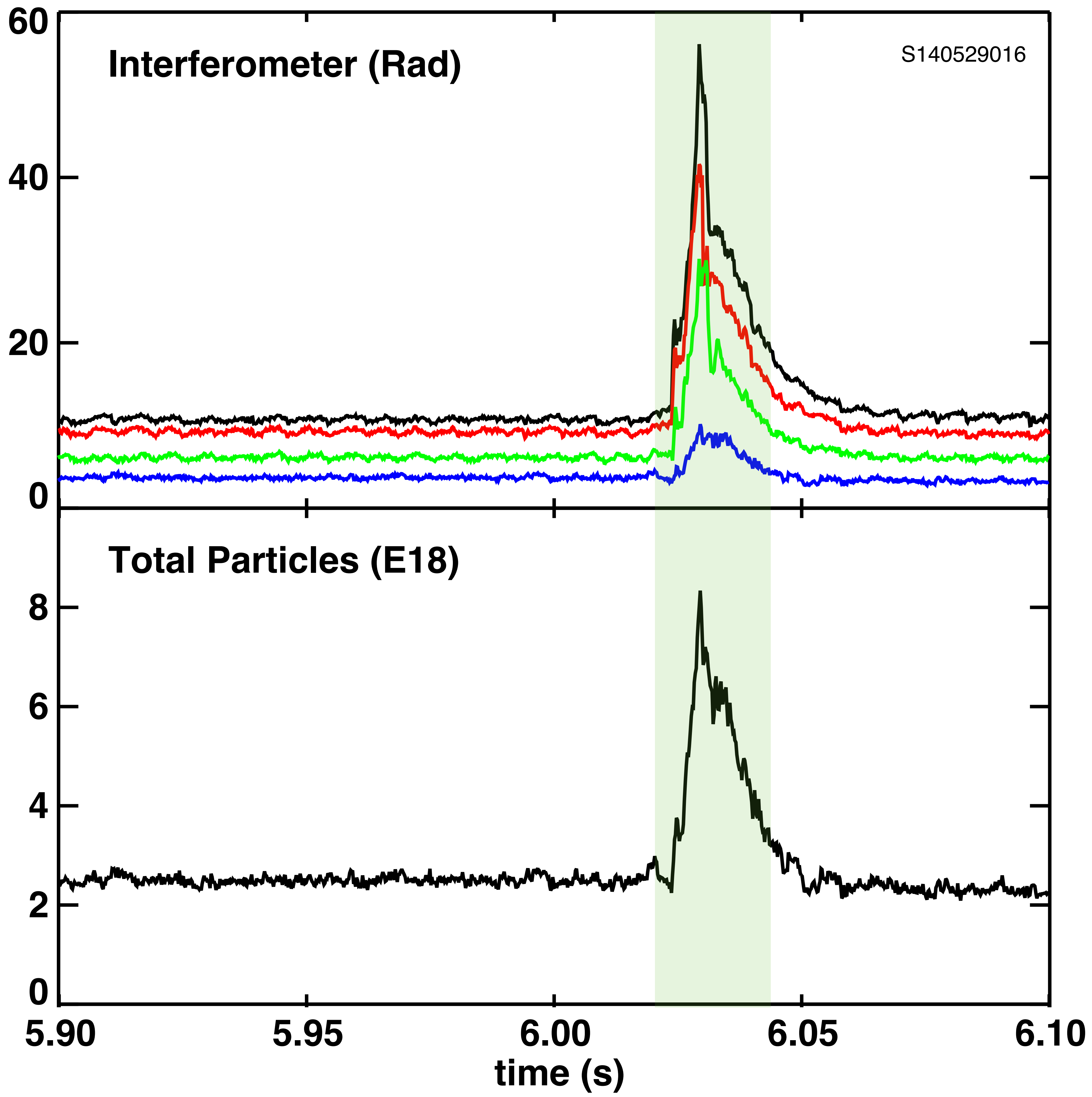
(b) Electron Density Profile Evolution



(c) Particle Number per Weber Evolution

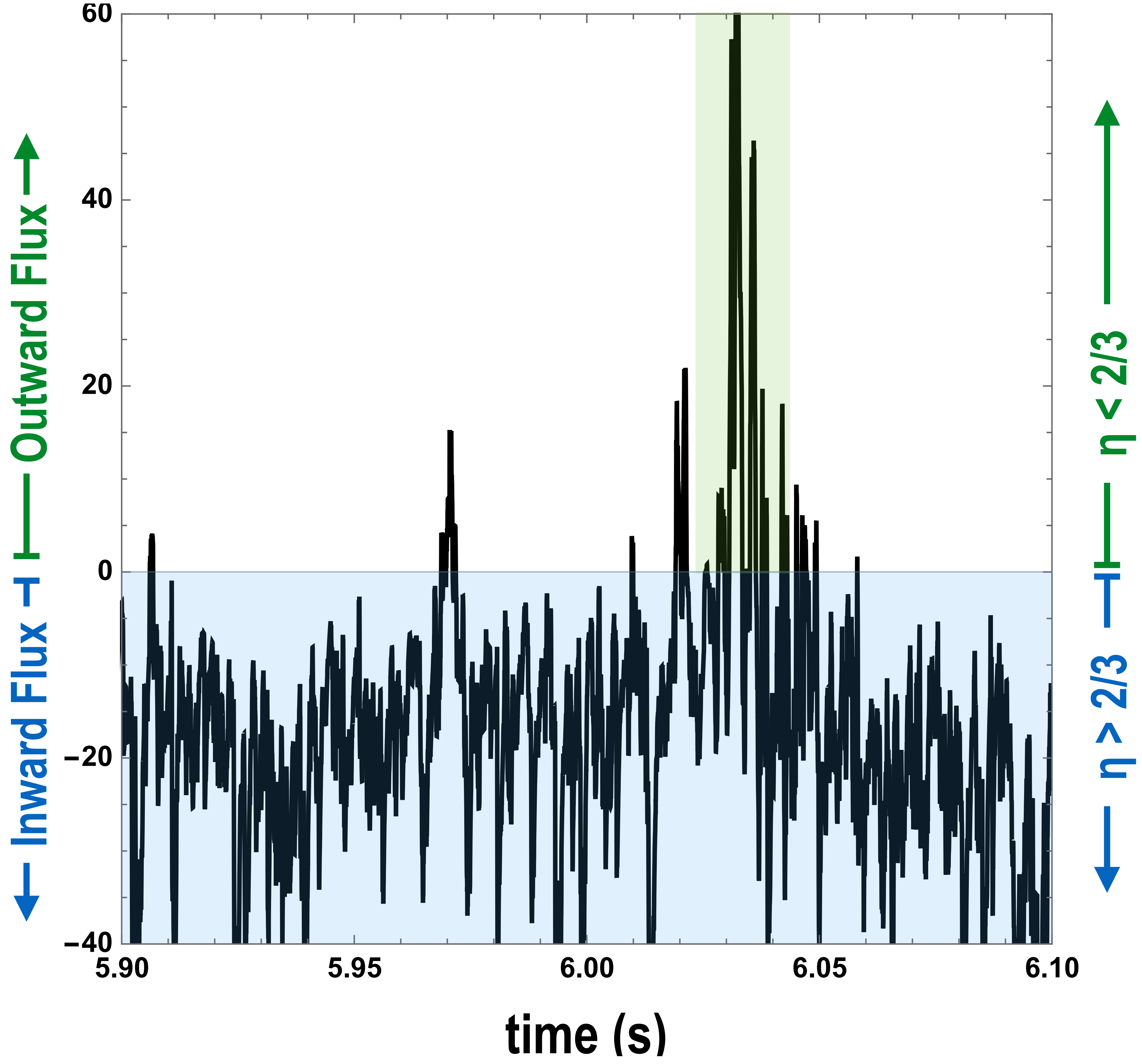


“**Cool Core**”/Li Pellet Fueling ***Reverses*** Direction of Particle Flux



Average Radial Particle Flux from Edge Probe Array

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

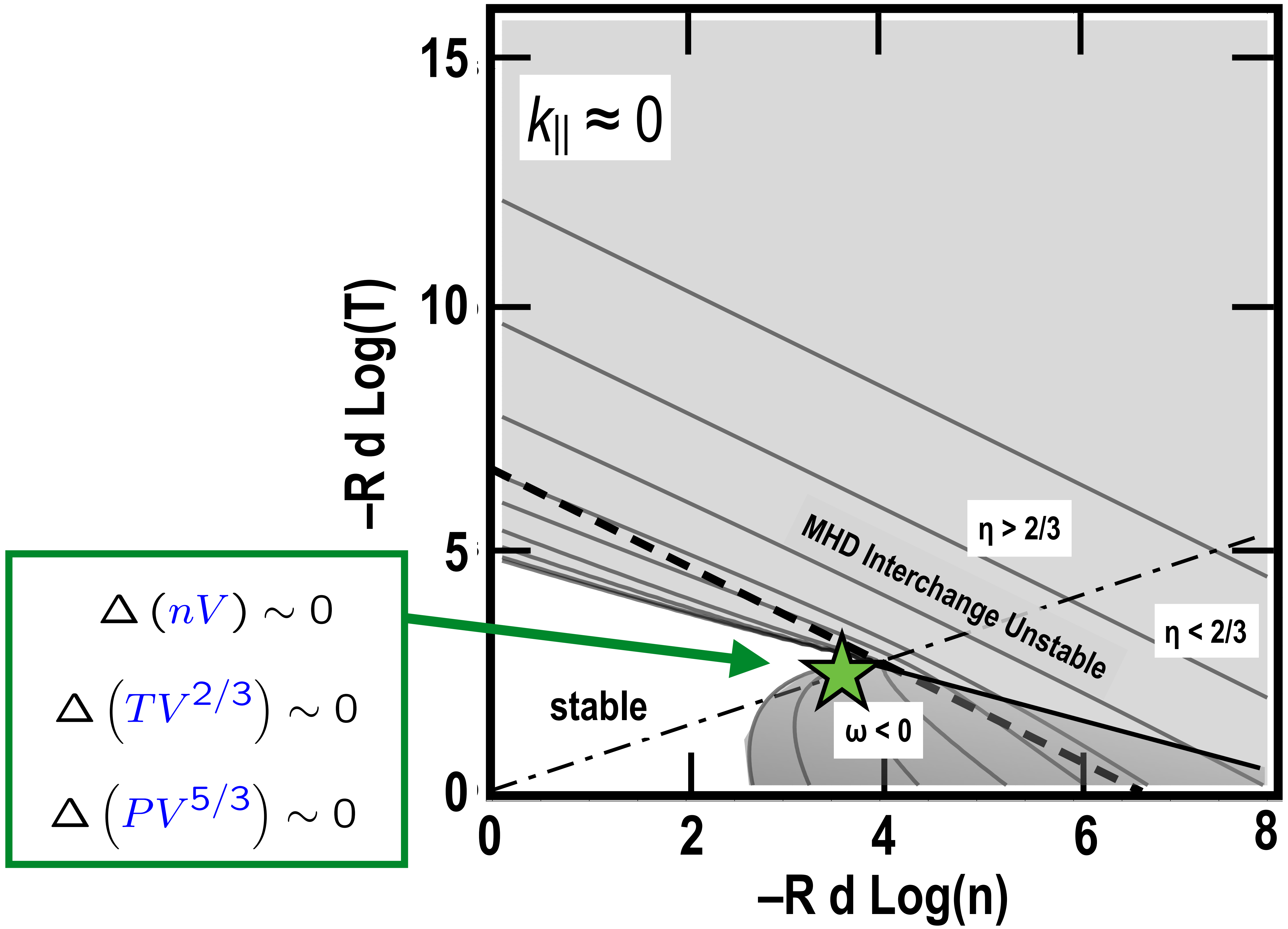


Outline

- *Two laboratory magnetospheres*: LDX and RT-1, having large flux-tube expansion
- *Particle transport and turbulent relaxation* to centrally-peaked profiles (***LDX***)
  - Matt Davis (PhD *Columbia*) and Alex Boxer (PhD *MIT*)
- ***Understanding entropy mode turbulence*** near marginal stability (***GS2***)
  - Sumire Kobayashi (PhD *Dartmouth/Rogers*)
- *Achieving record high local* β by stabilizing fast electron interchange instability (***RT-1***)
  - Yoshihisa Yano (PhD *Univ Tokyo/Yoshida*)
- *Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement*

Physics Tools Used to Understand Magnetic Confinement in Tokamaks can be Applied to the Laboratory Magnetosphere

(a) Dipole Interchange-Entropy Modes



$\triangle(nV) \sim 0$

$\triangle\left(TV^{2/3}\right) \sim 0$

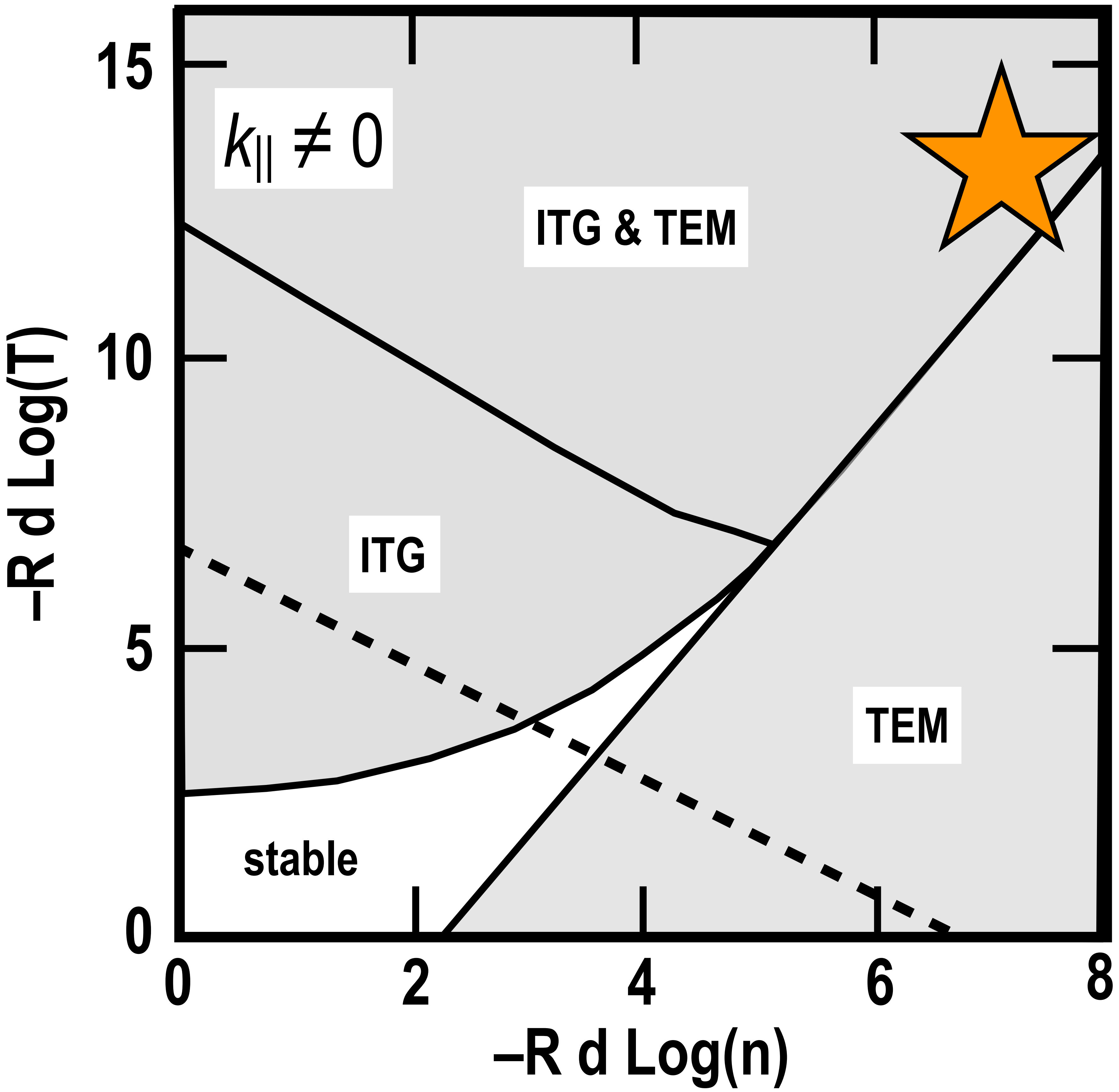
$\triangle\left(PV^{5/3}\right) \sim 0$

Weak gradients: $\omega_p^* \sim \omega_d$

Stable by compressibility and field line tension

From Ricci, et al., *Phys Plasma*, **13**, 062102 (2006)

(b) Tokamak ITG-TEM Modes



Steep gradients: $\omega_p^* >> \omega_d$

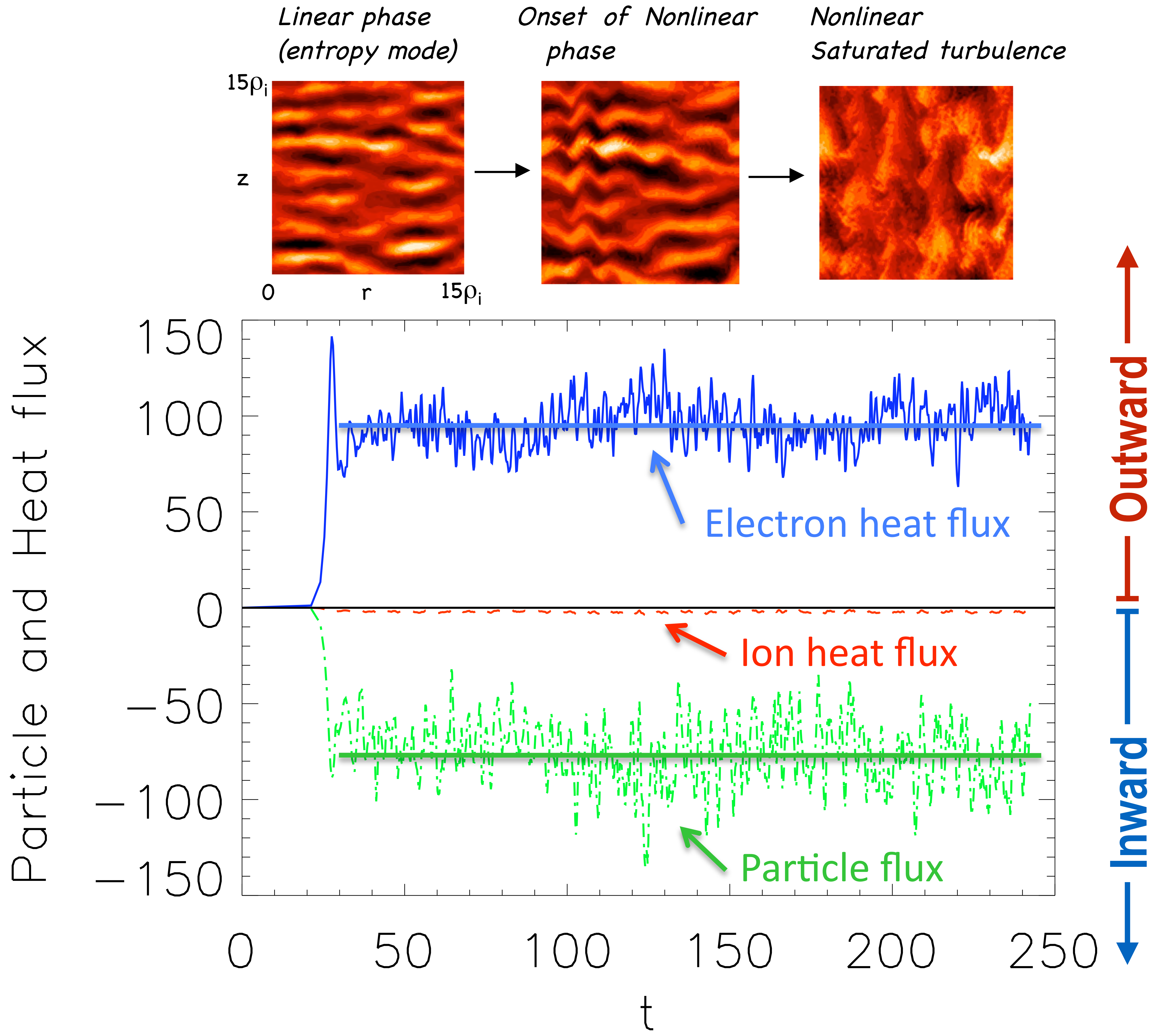
Stable by average good curvature and magnetic shear

X. Garbet, *Comptes Rendus Physique* **7**, 573 (2006)

Gyrokinetic Simulations of Closed Field Line Systems

Sumire Kobayashi (PhD Dartmouth)

- 5D Gyrokinetic (GS2) simulations and quasilinear theory of entropy mode turbulence consistent with observations.
- "***Warm Core***", η > 2/3, creates inward particle pinch and outward heat transport.
- "***Cool Core***", η < 2/3, creates outward particle pinch and inward heat flux.
- ***Furthermore***: Nonlinear simulations show zonal flows, with significant transport reduction, appear at low collisionality.



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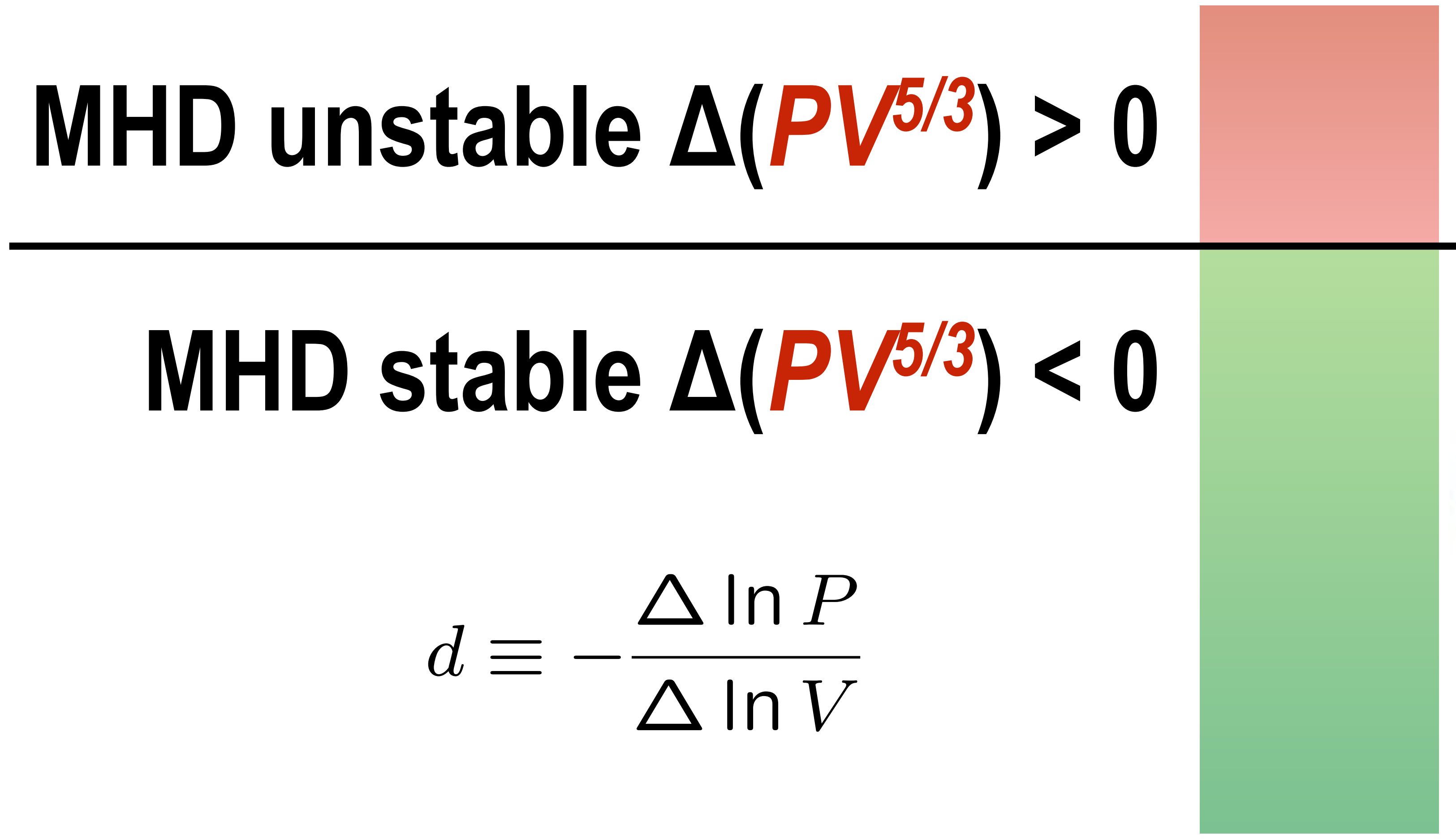
Sumire Kobayashi, Rogers, and Dorland, "Gyrokinetic Simulations of Turbulent Transport in a Ring Dipole Plasma," PRL 103, 055003 (2009).

GS2 show Entropy Modes Drive Turbulent "Self-Organization" *even* when MHD Interchange is Stable

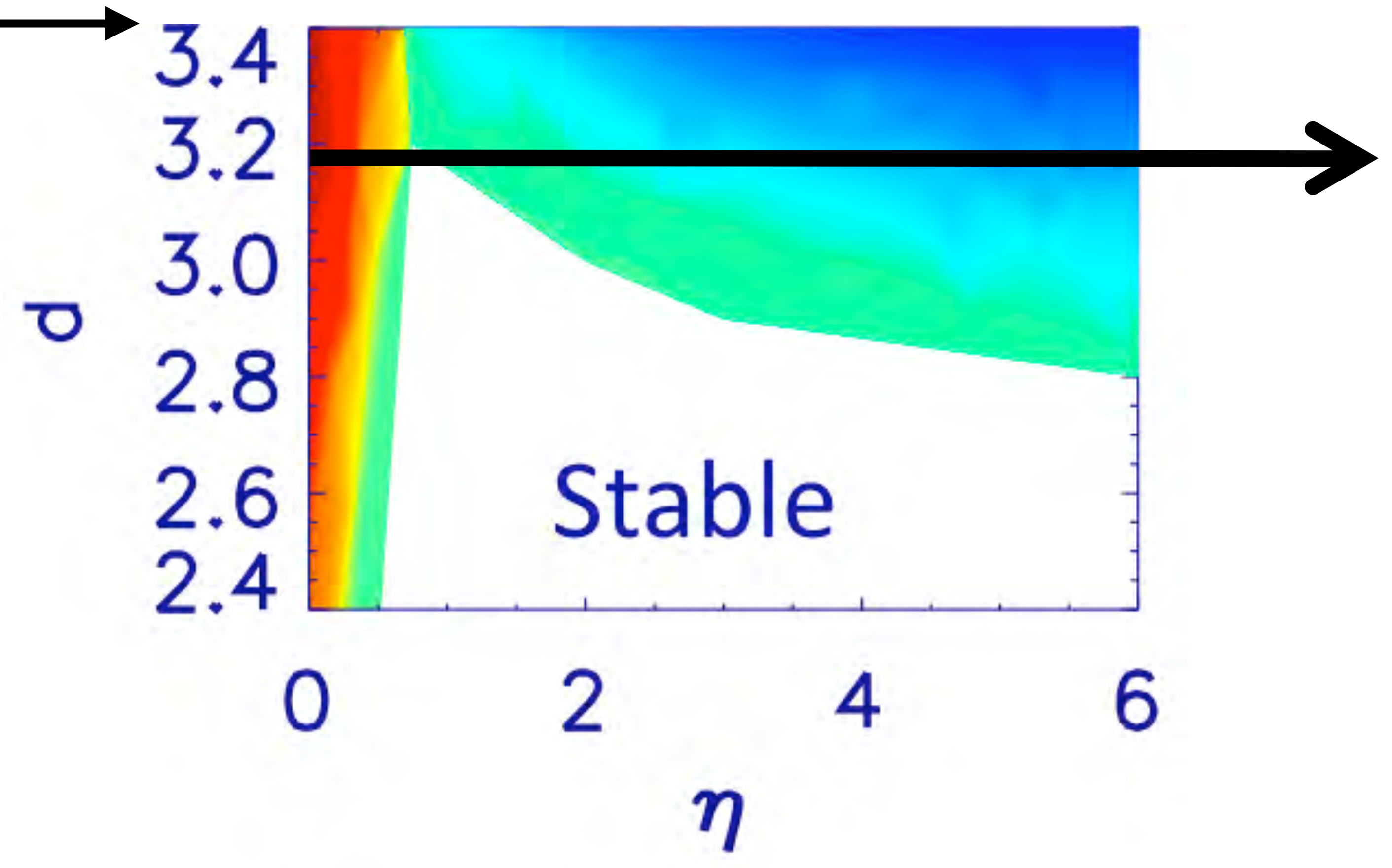


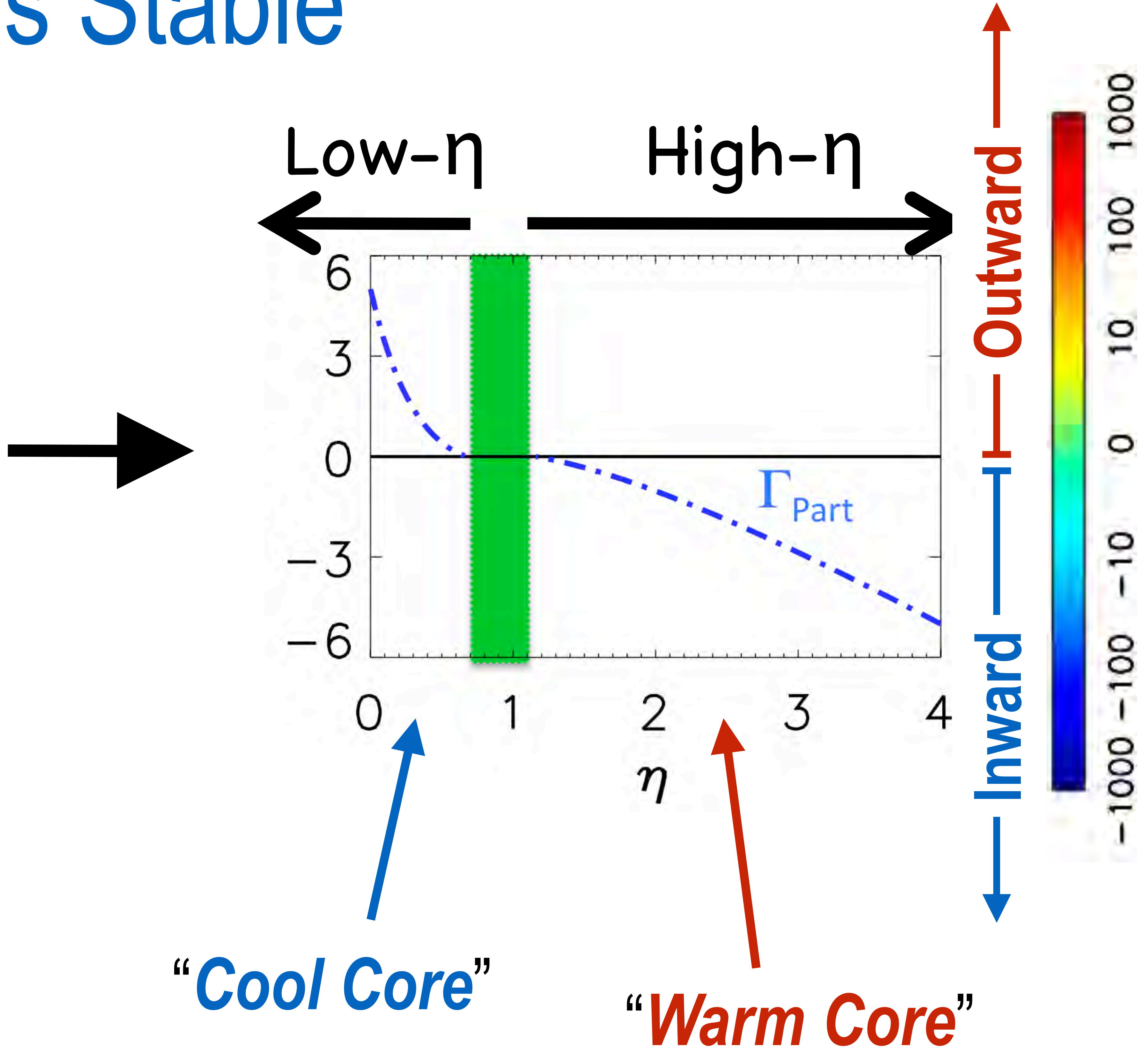
MHD unstable $\Delta(PV^{5/3}) > 0$

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

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

Particle Flux



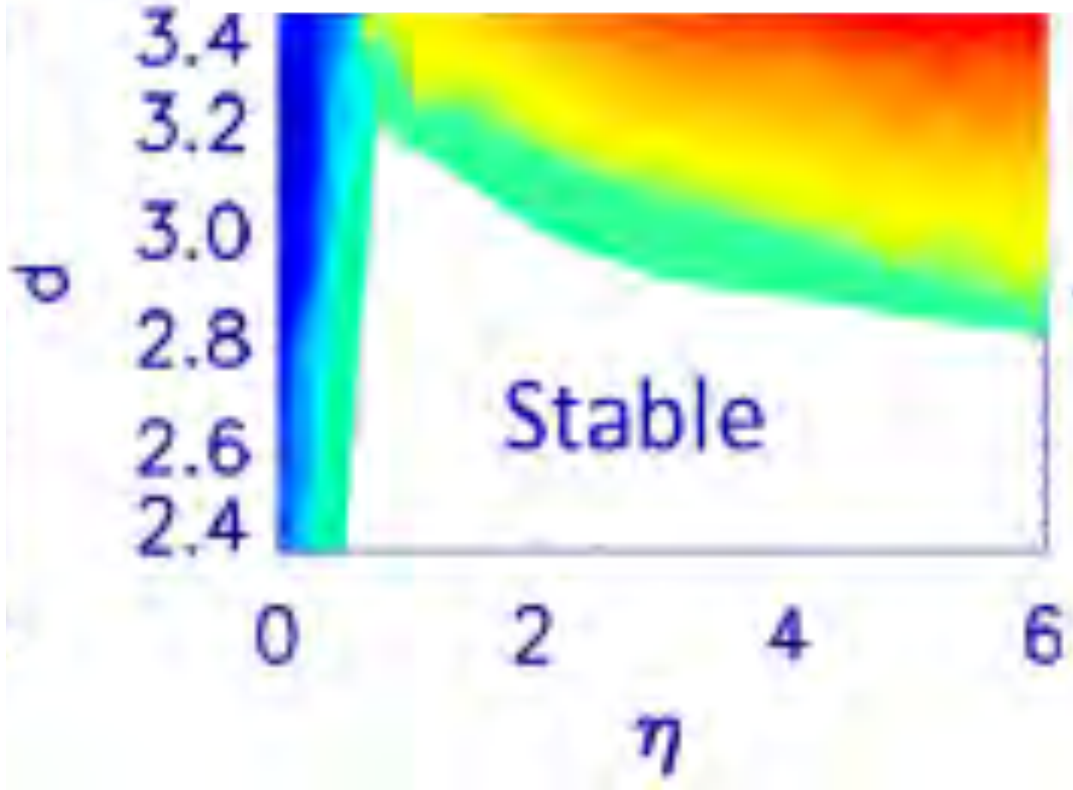


"*Cool Core*"

"*Warm Core*"

- "***Warm Core***", η > 2/3, creates inward particle pinch and outward heat transport.
- "***Cool Core***", η < 2/3, creates outward particle pinch and inward heat flux.

Temperature Flux



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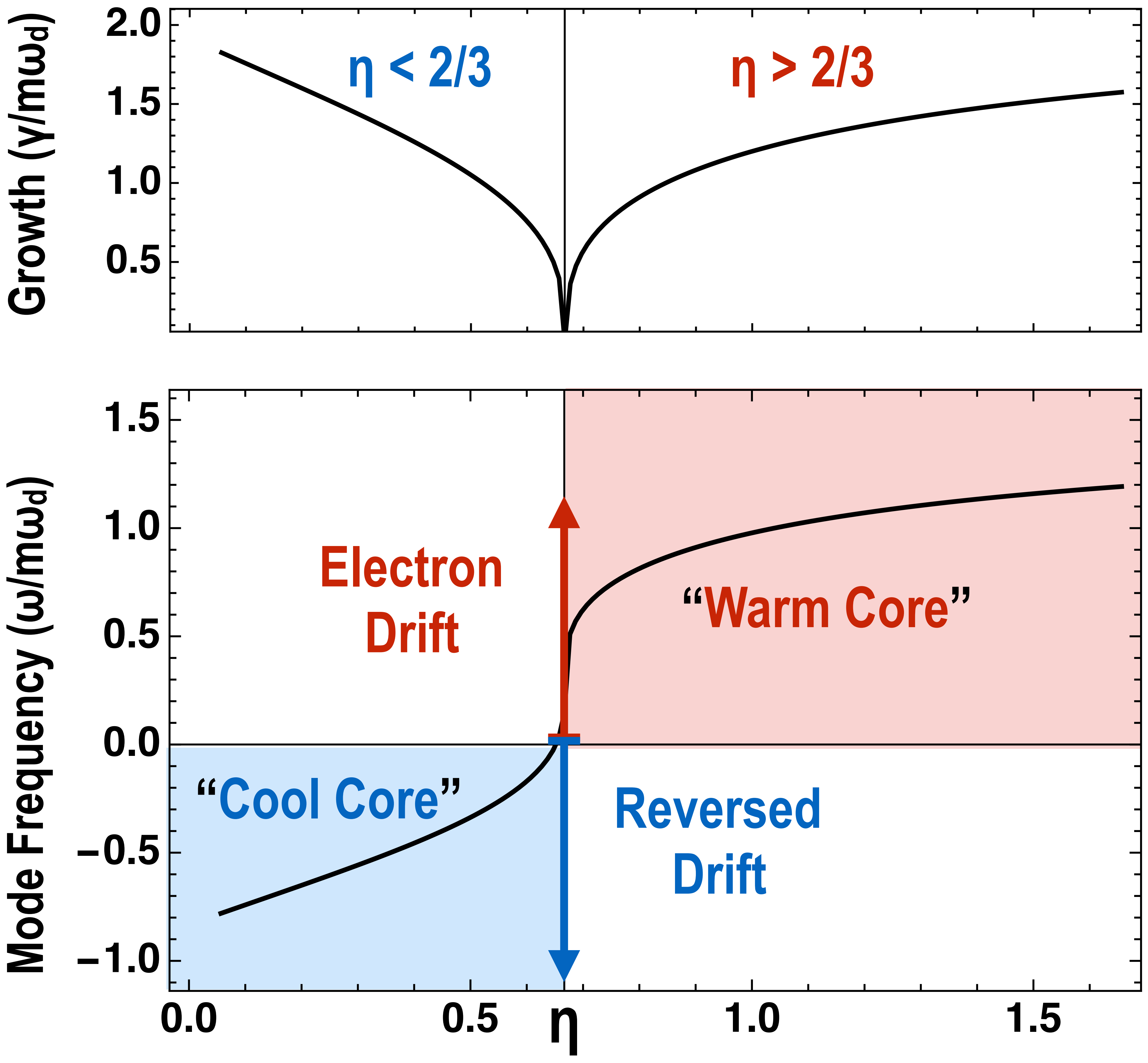
When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η

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

η < 2/3
Outward Particle Flux

η > 2/3
Inward Particle Flux



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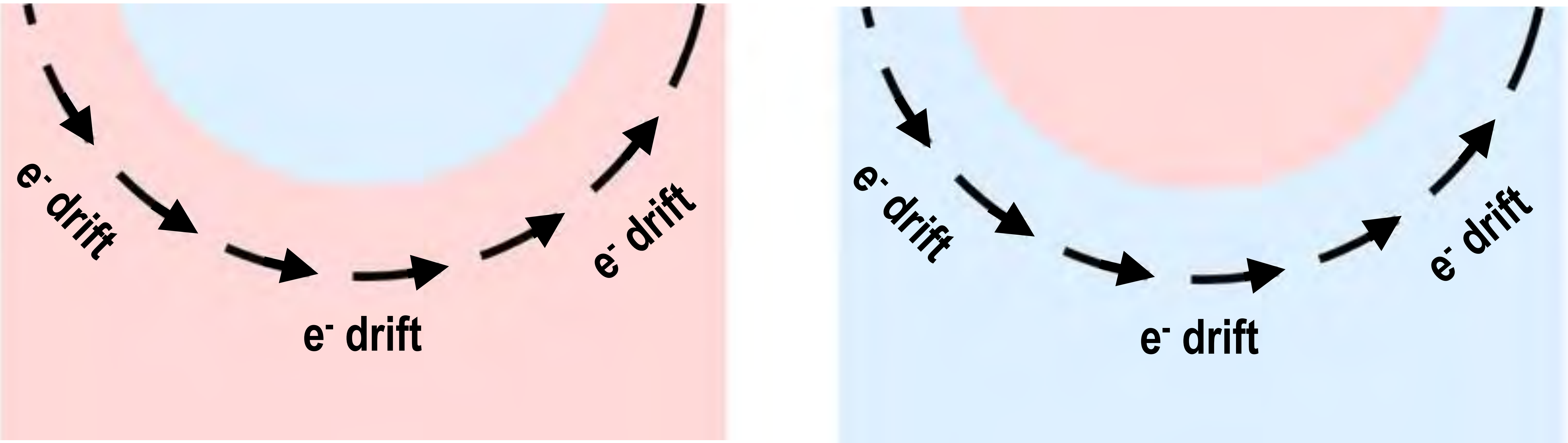
When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η

$\eta < 2/3$

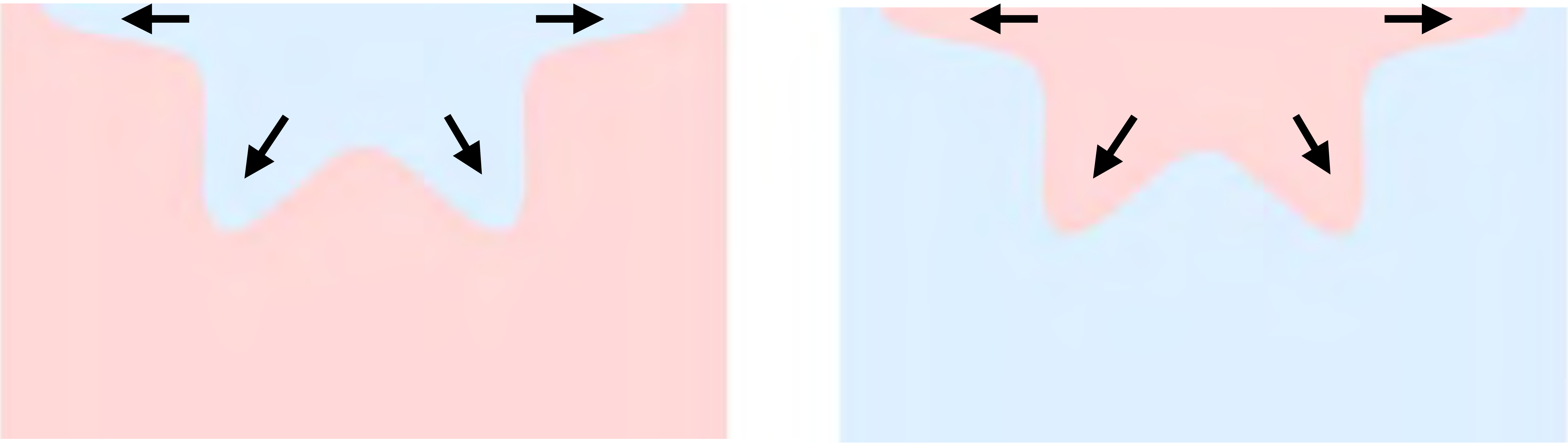
"Cool Core"

$\eta > 2/3$

"Warm Core"



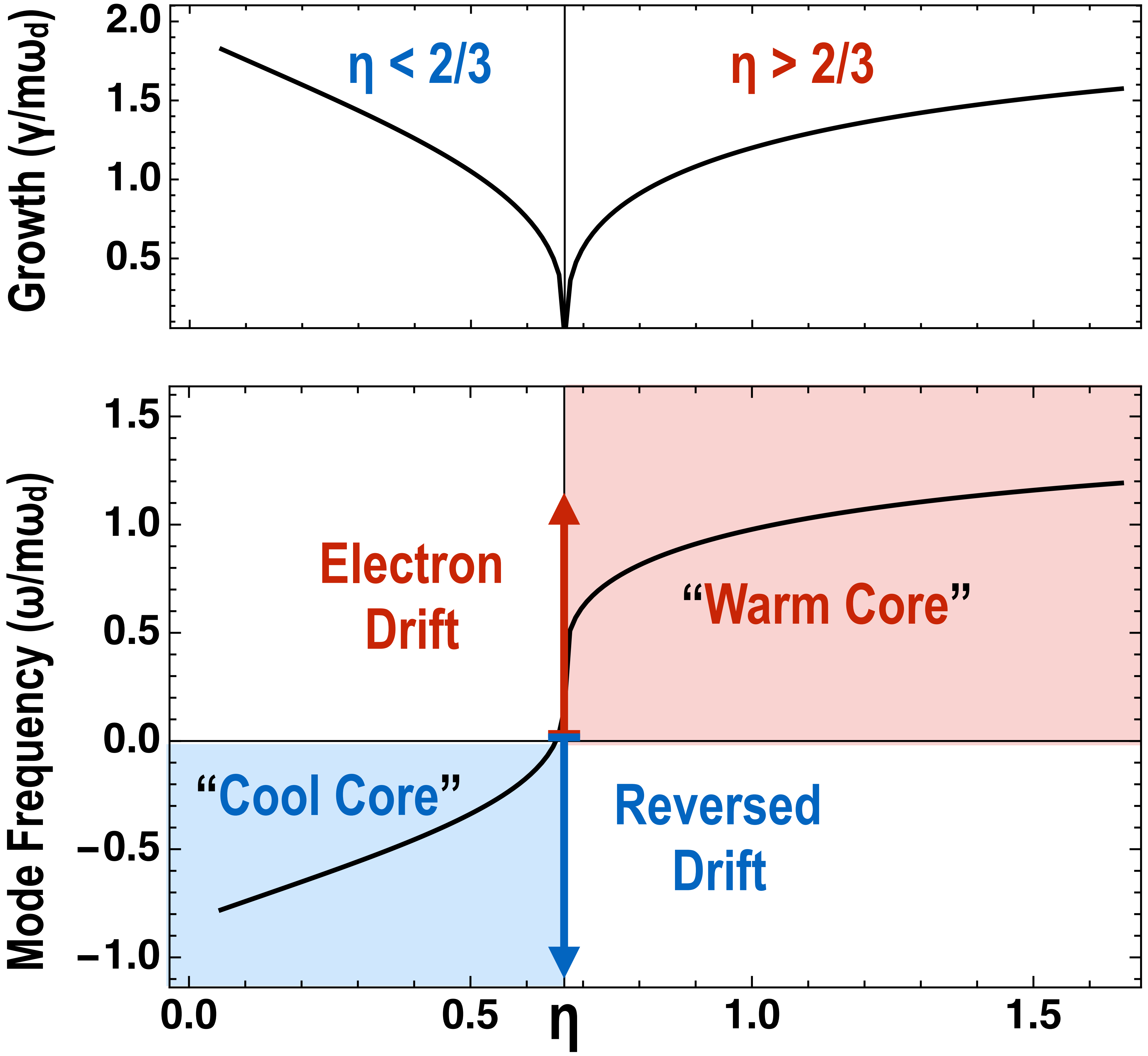
$\Delta W_p \sim \Delta(PV^{5/3}) \sim 0$ Energy & Pressure *Unchanged* for Adiabatic Mixing



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

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

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



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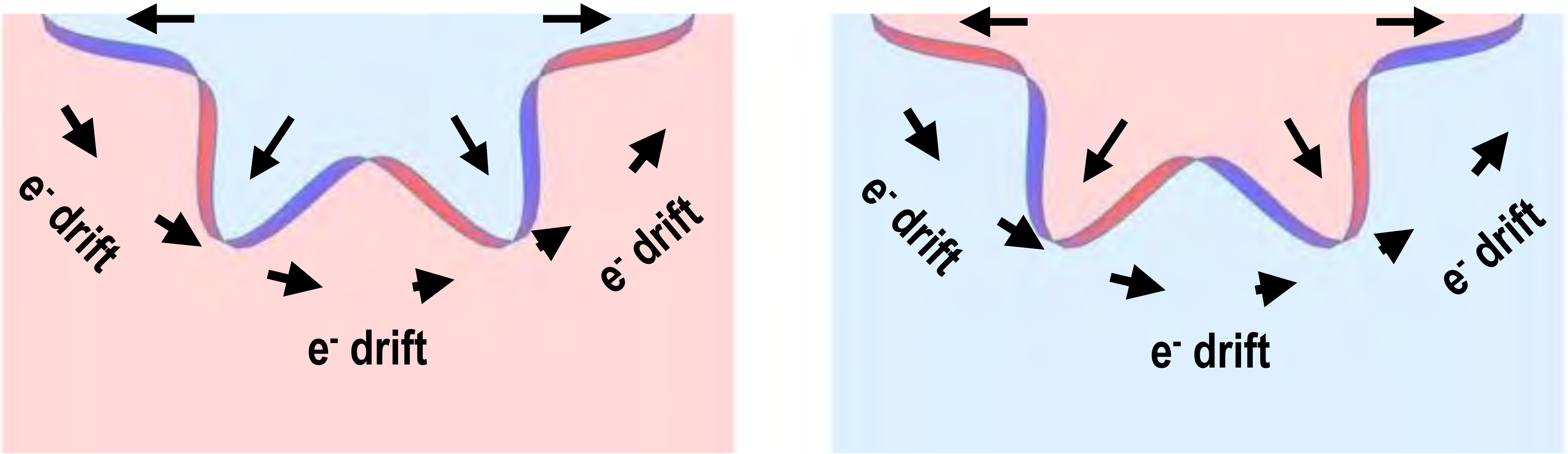
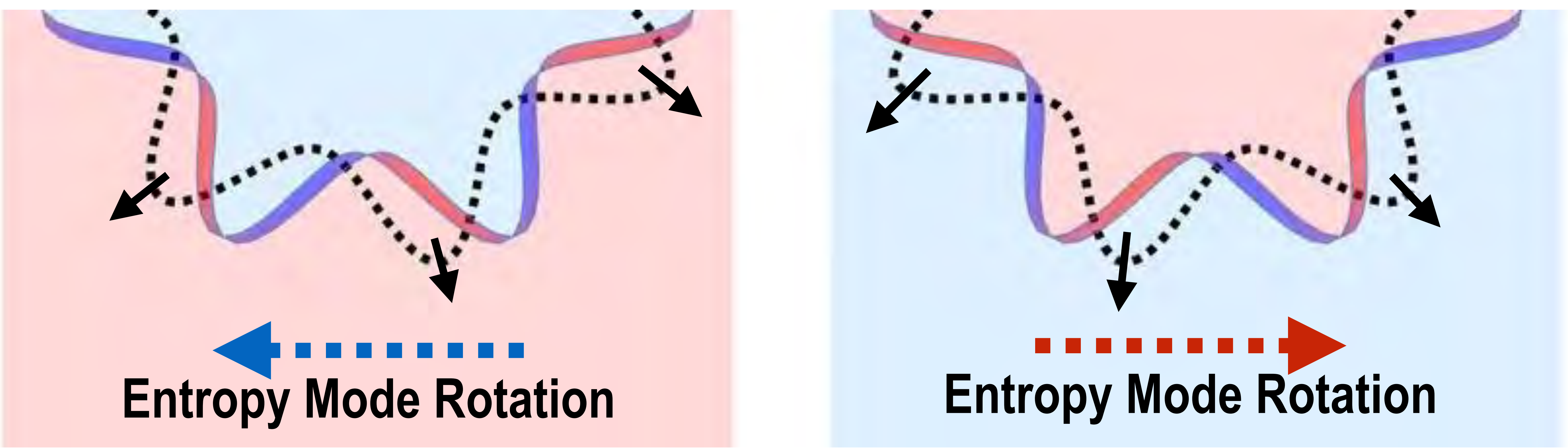
When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η

η < 2/3 **η > 2/3**

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



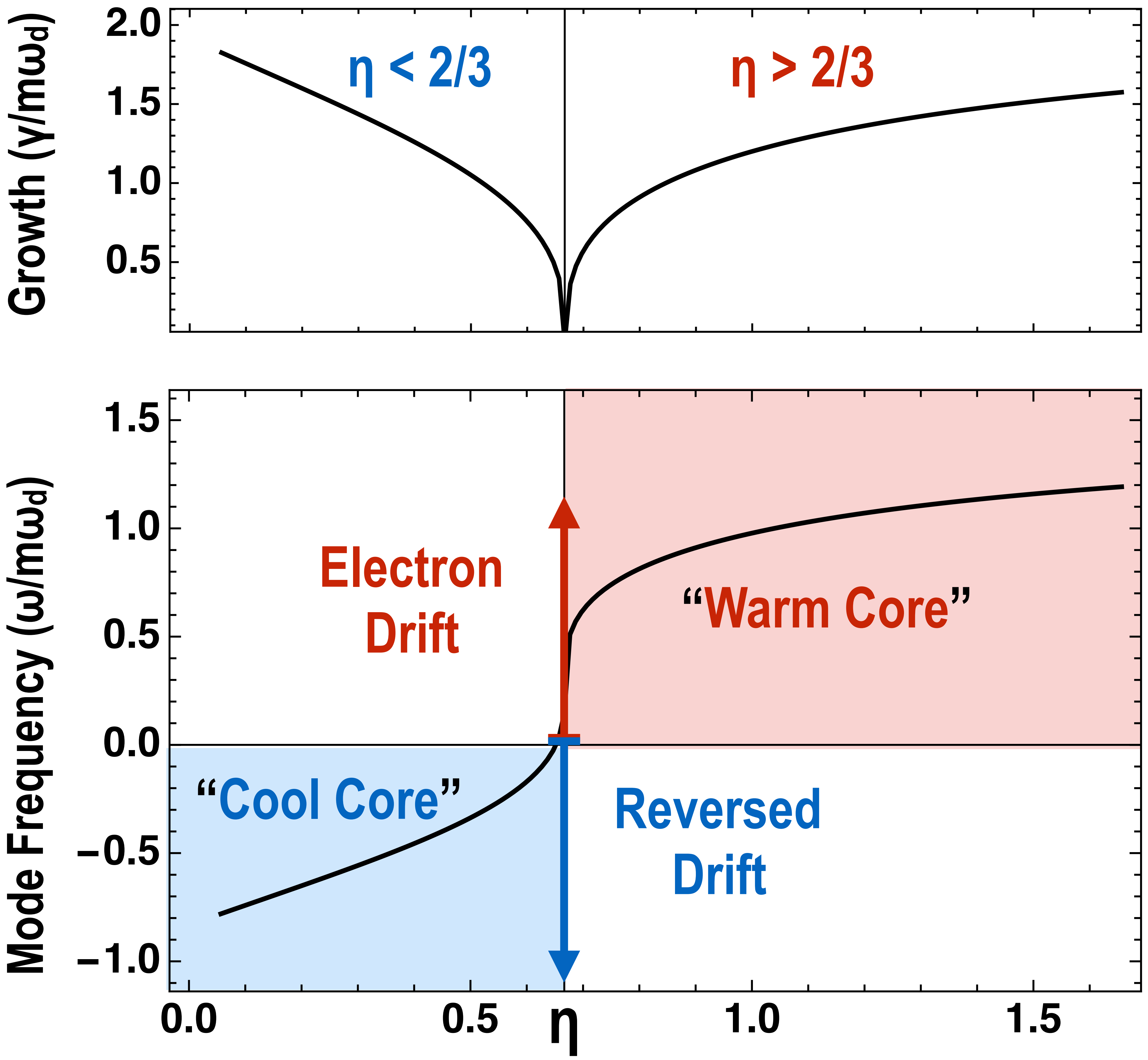
Drift-Kinetic *Heat* moves toroidally from Warm to Cool Flux-Tubes



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

η < 2/3
***Outward* Particle Flux**

η > 2/3
***Inward* Particle Flux**



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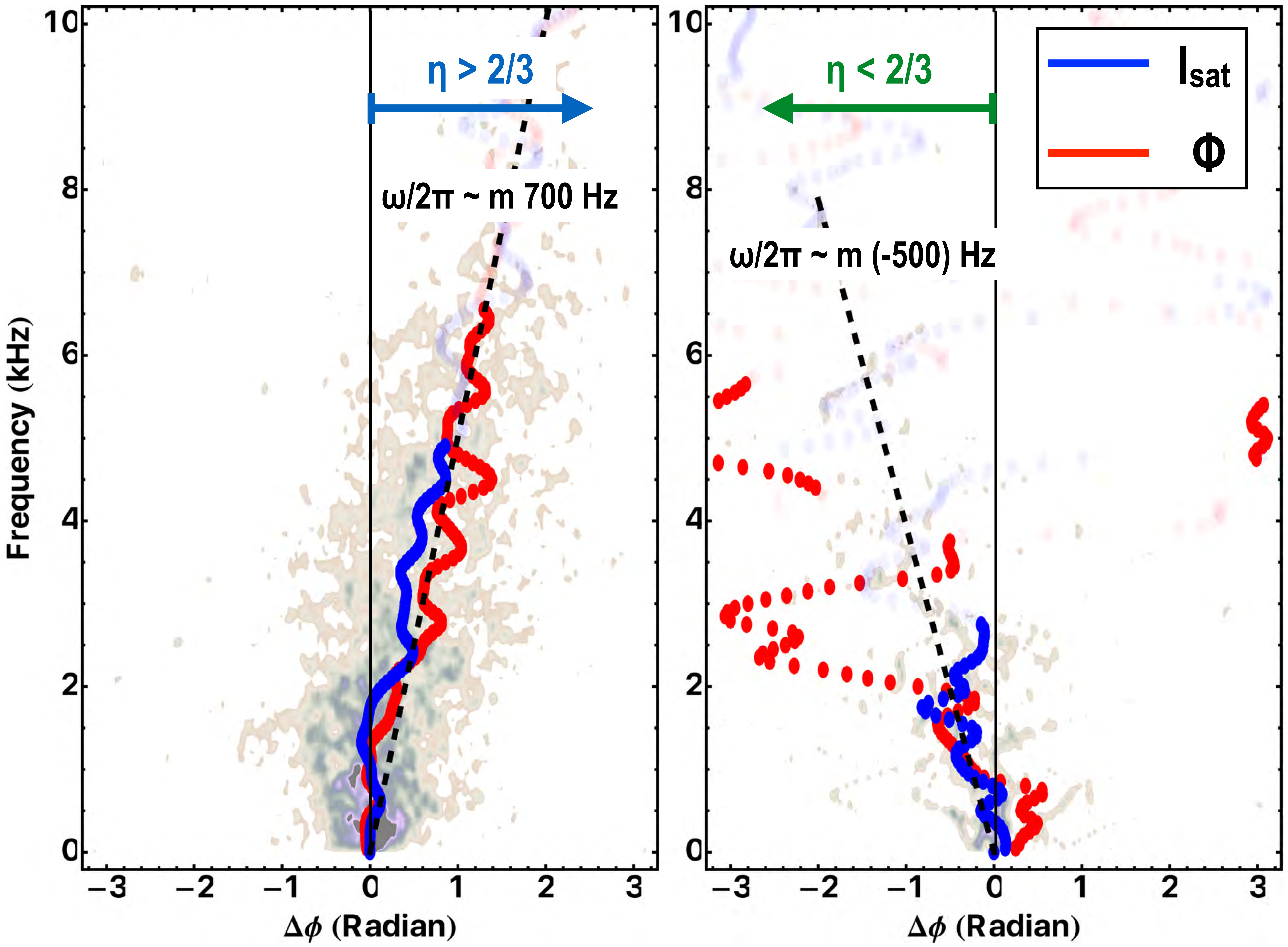
Dispersion Measurements during Pellet Injection agree with Linear Theory
Entropy Modes ***Reverse*** Direction with ***Reversal*** of Particle Flux

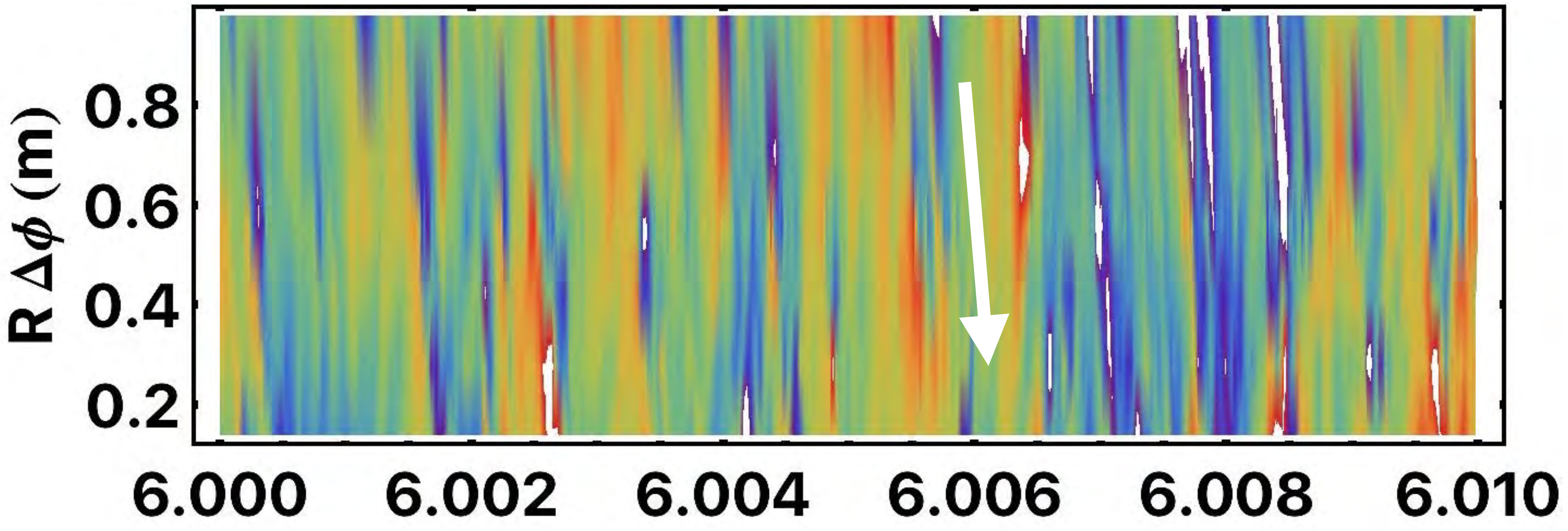
Ensemble-Averaged Entropy Mode Dispersion

Before Pellet Injection **During Pellet Injection**

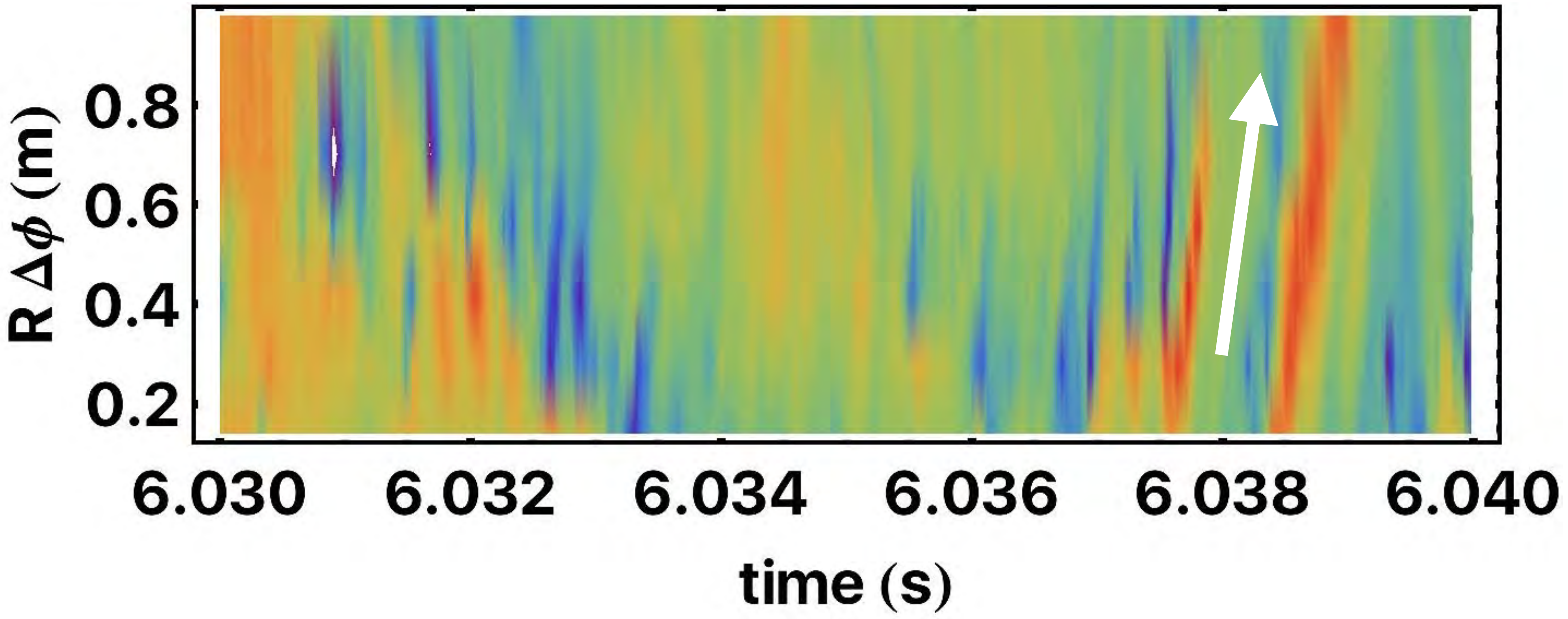


Potential Fluctuations Reverse Direction

Before Pellet Injection



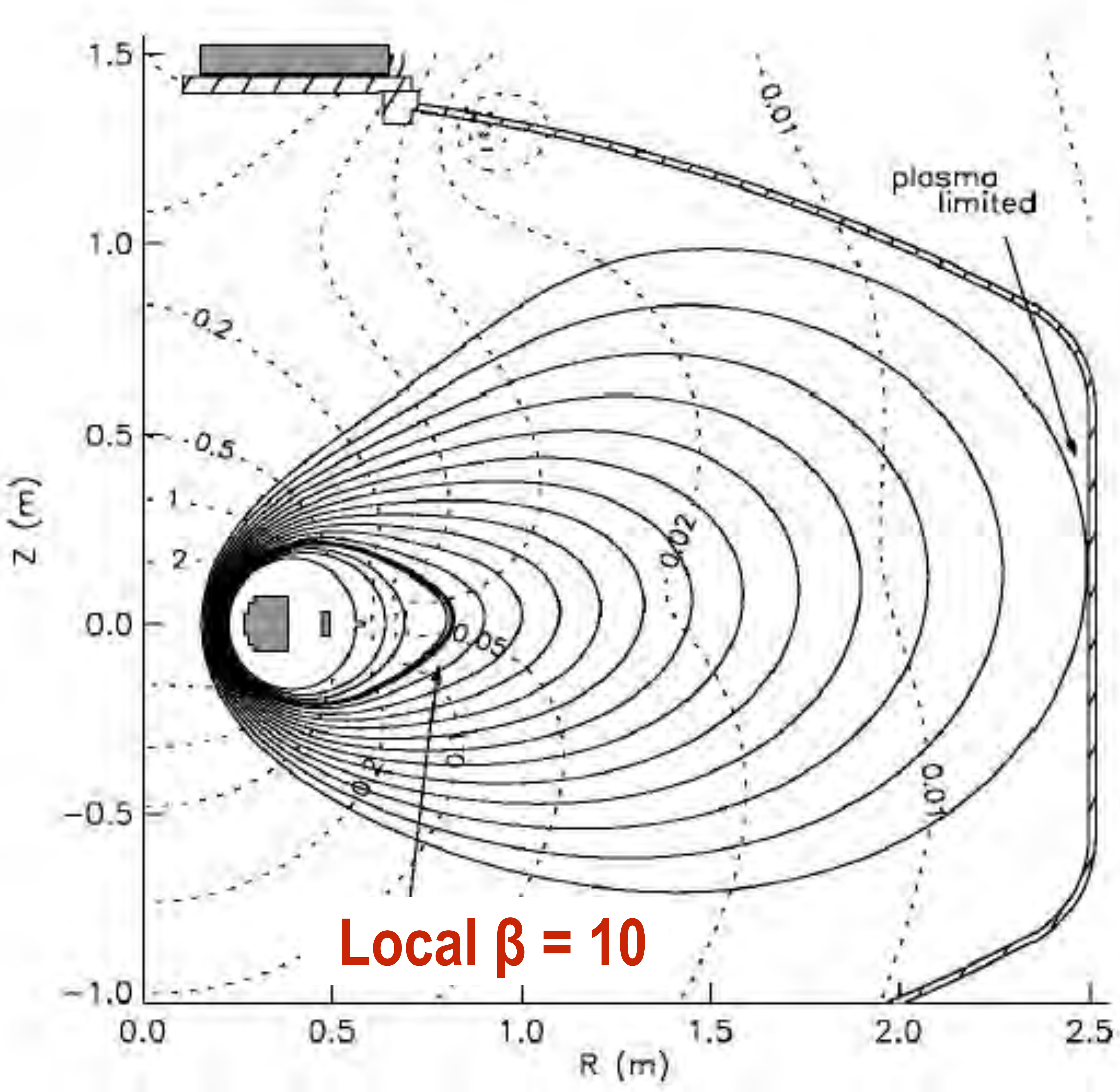
During Pellet Injection



Outline

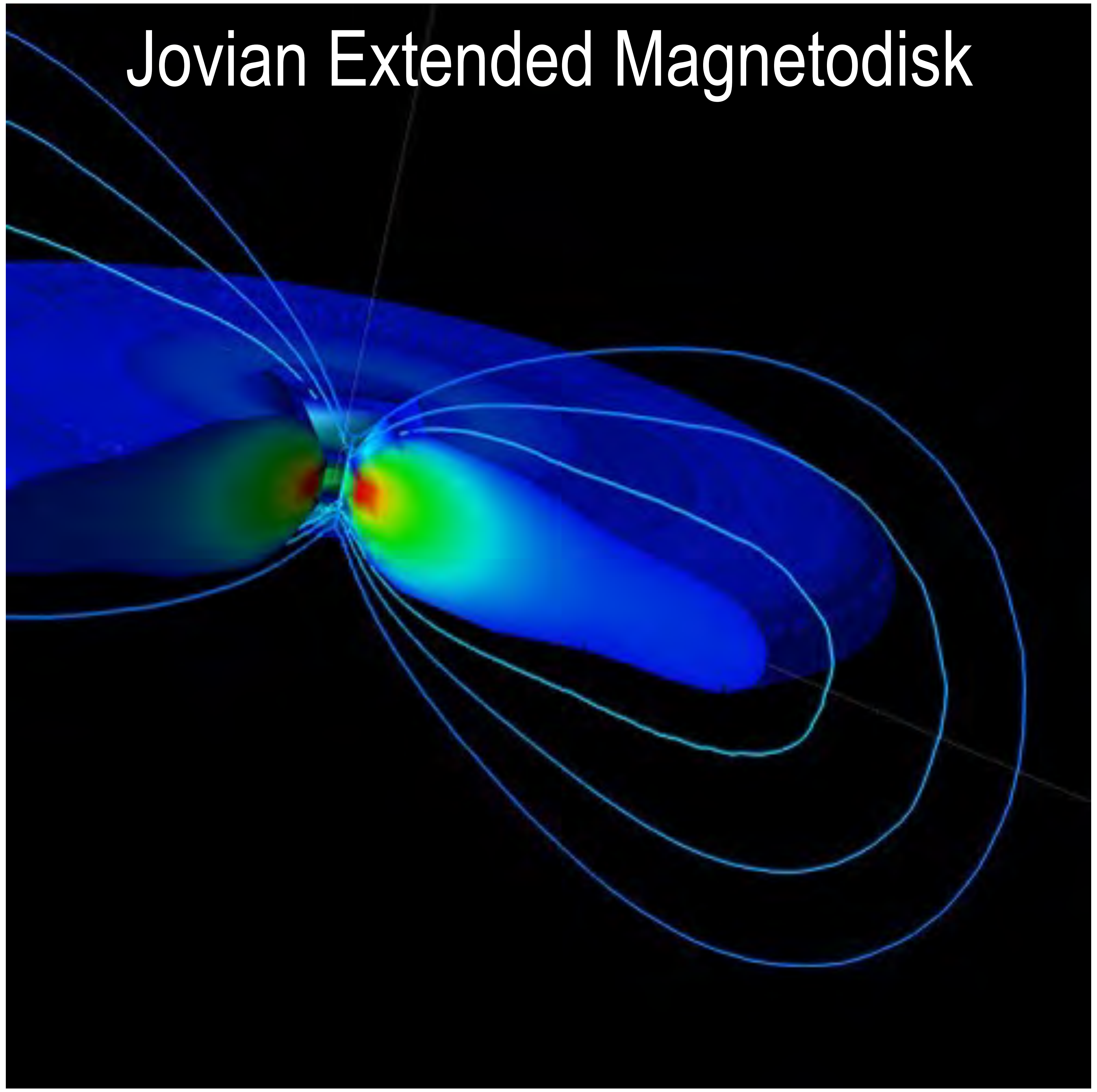
- ***Two laboratory magnetospheres***: LDX and RT-1, having large flux-tube expansion
- ***Particle transport and turbulent relaxation*** to centrally-peaked profiles (***LDX***)
  - Matt Davis (PhD *Columbia*) and Alex Boxer (PhD *MIT*)
- ***Understanding entropy mode turbulence*** near marginal stability (***GS2***)
  - Sumire Kobayashi (PhD *Dartmouth/Rogers*)
- ***Achieving record high local β*** by stabilizing fast electron interchange instability (***RT-1***)
  - Yoshihisa Yano (PhD *Univ Tokyo/Yoshida*)
- ***Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement***

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



Local β = 10

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



Jovian Extended Magnetodisk

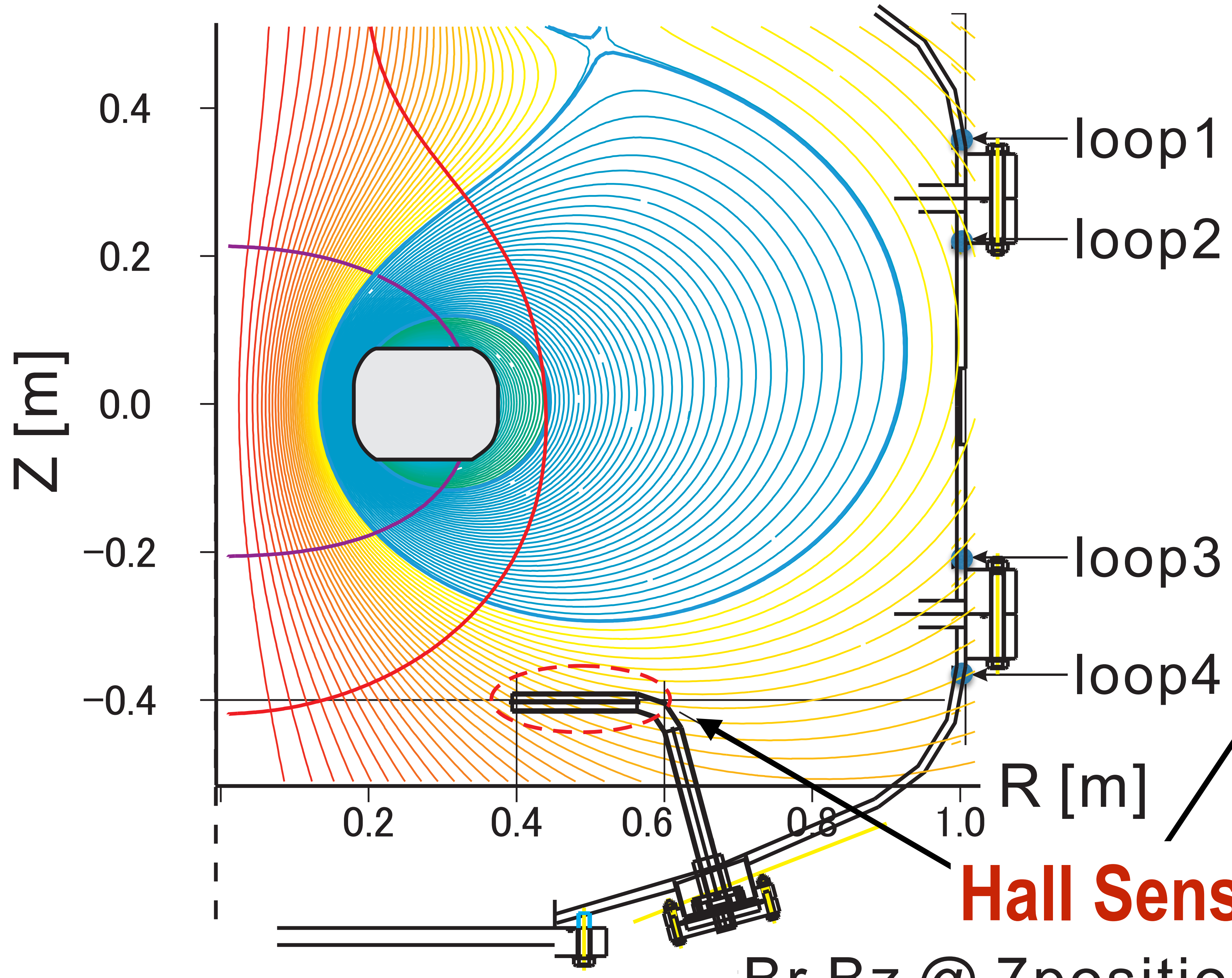
Garnier, Kesner, and Mauel, “Magnetohydrodynamic stability in a levitated dipole,” *Phys Plasmas* **6**, 3431 (1999).
Shiraishi, Ohsaki, and Yoshida, “Relaxation of a quasisymmetric rotating plasma: A model of Jupiter’s magnetosphere,” *Phys Plasmas* **12**, 092901 (2005)

Measuring Record Peak β ~ 1 with Internal Hall Probe in RT-1

(Yoshihisa Yano, PhD Univ Tokyo)

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

Equilibrium Profile Reconstruction



Hall Sensors

Br,Bz @ 7positions

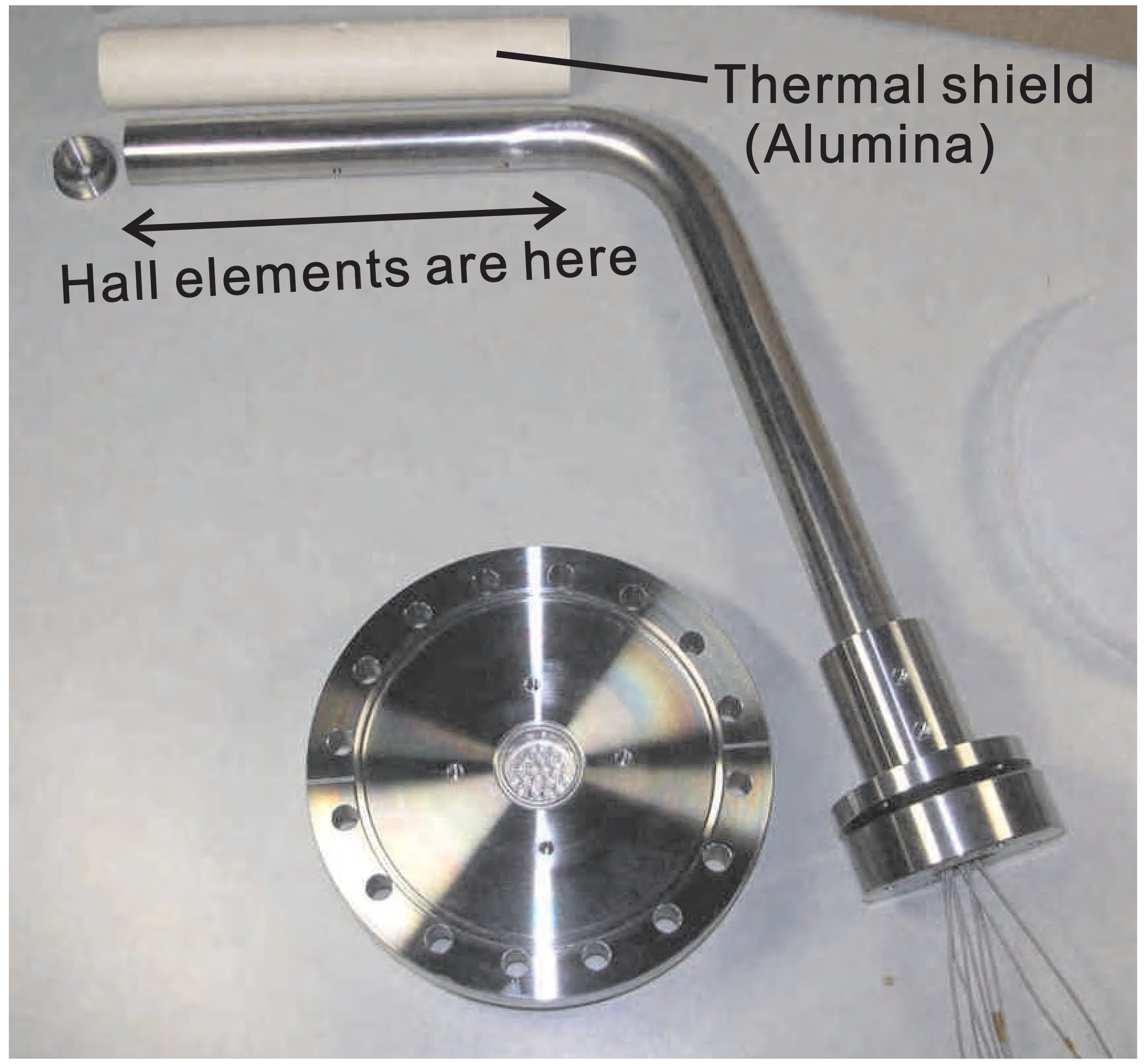
Dessler-Parker-Sckopke Relationship:

Earth's Magnetosphere Energy = 0.54 GJ/A × I_{RC}

LDX's Plasma Energy = 0.12 J/A × I_{RC}

Plasma Ring Current ~ Energy ~ Peak Beta

Internal **Hall Probe** for Accurate Ring Current Profile Reconstruction

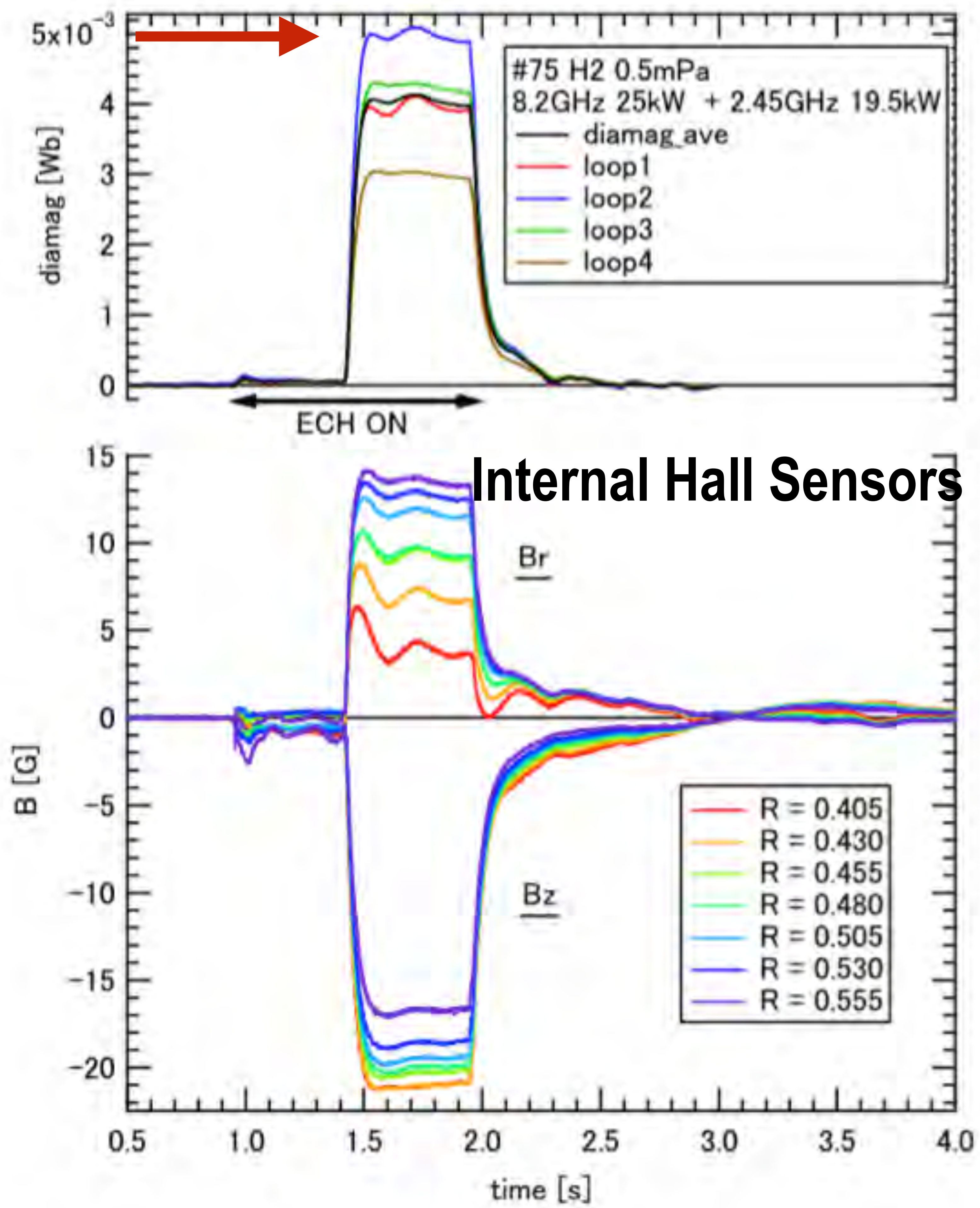


Measuring Record Peak β ~ 1 with Internal Hall Probe in RT-1

(Yoshihisa Yano, PhD Univ Tokyo)

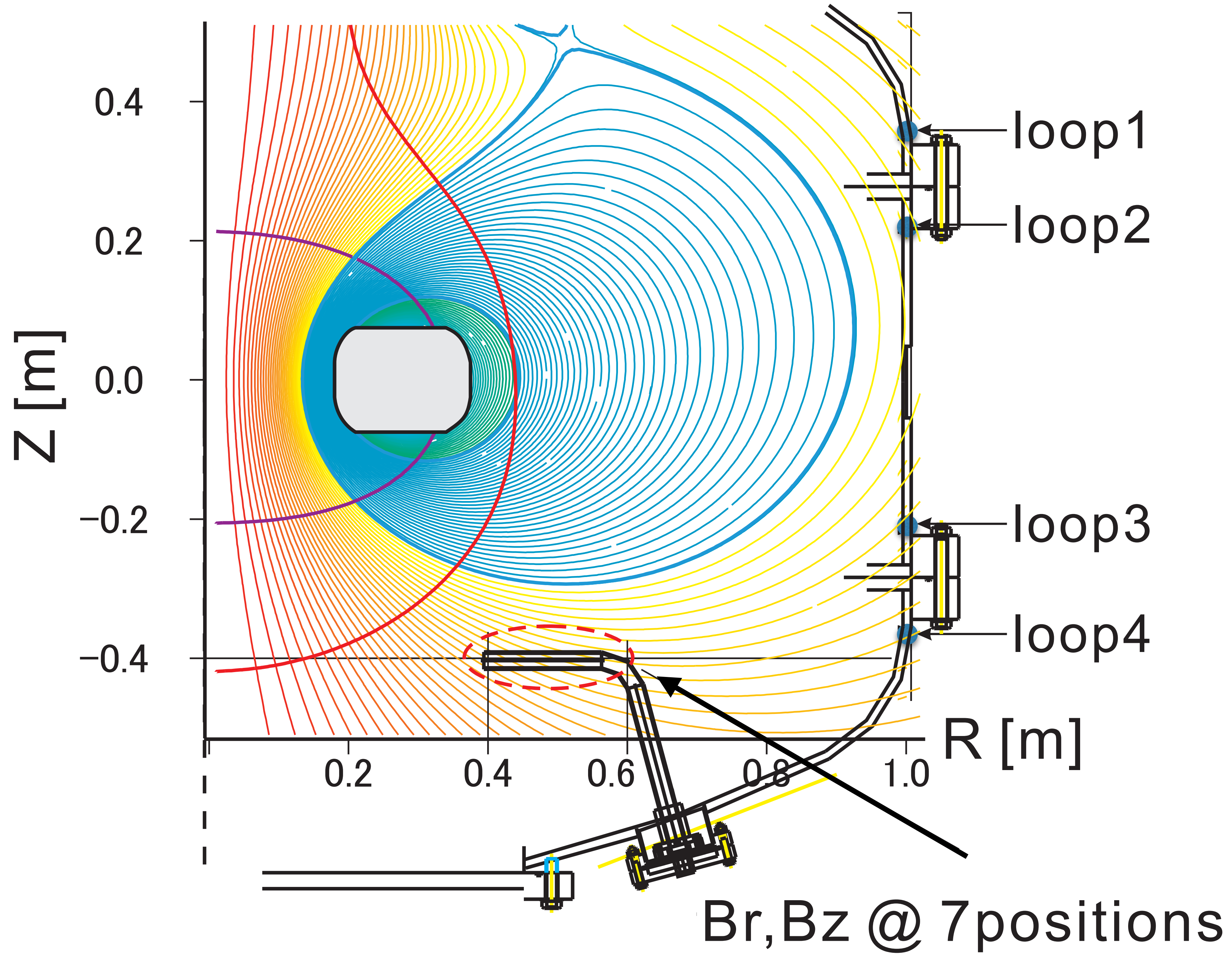
80% Peak β
5 mWb

25 kW 8.2 GHz
19 kW 2.45 GHz



$$\beta \approx 0.18\Delta\Psi \ (\mathrm{mWb}^{-1}, \text{ Peak-local})$$

Equilibrium Profile Reconstruction



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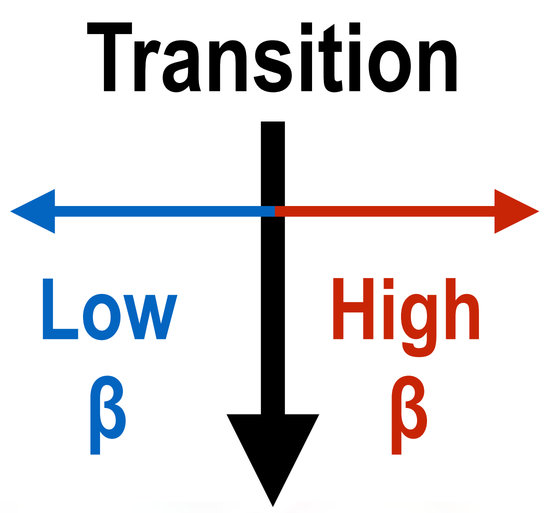
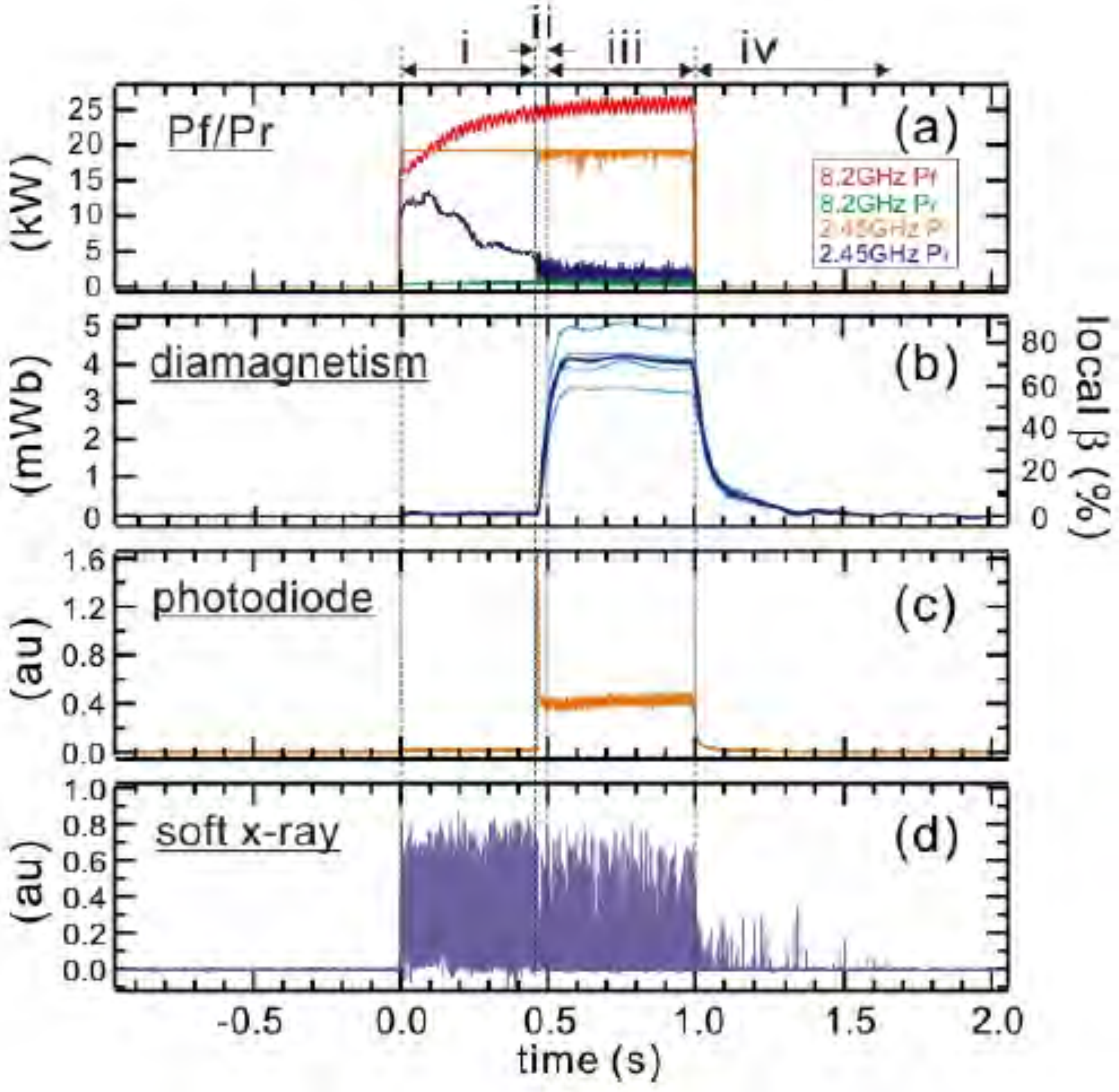
Saitoh, et al., "Observation of a new high-β and high-density state of a magnetospheric plasma in RT-1," Phys Plasmas 21, 082511 (2014).
Saitoh, et al., "High-β plasma formation and observation of peaked density profile in RT-," Nuc Fus 51, 063034 (2011).

Hot Electron Interchange (HEI) Instability Must be Stabilized to Achieve High β

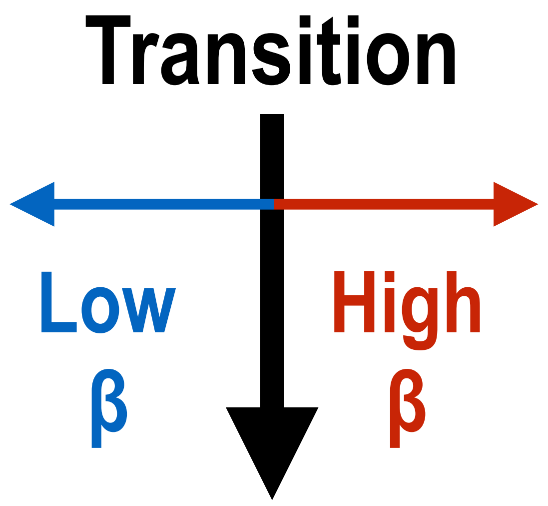

Transition

Low β

High β



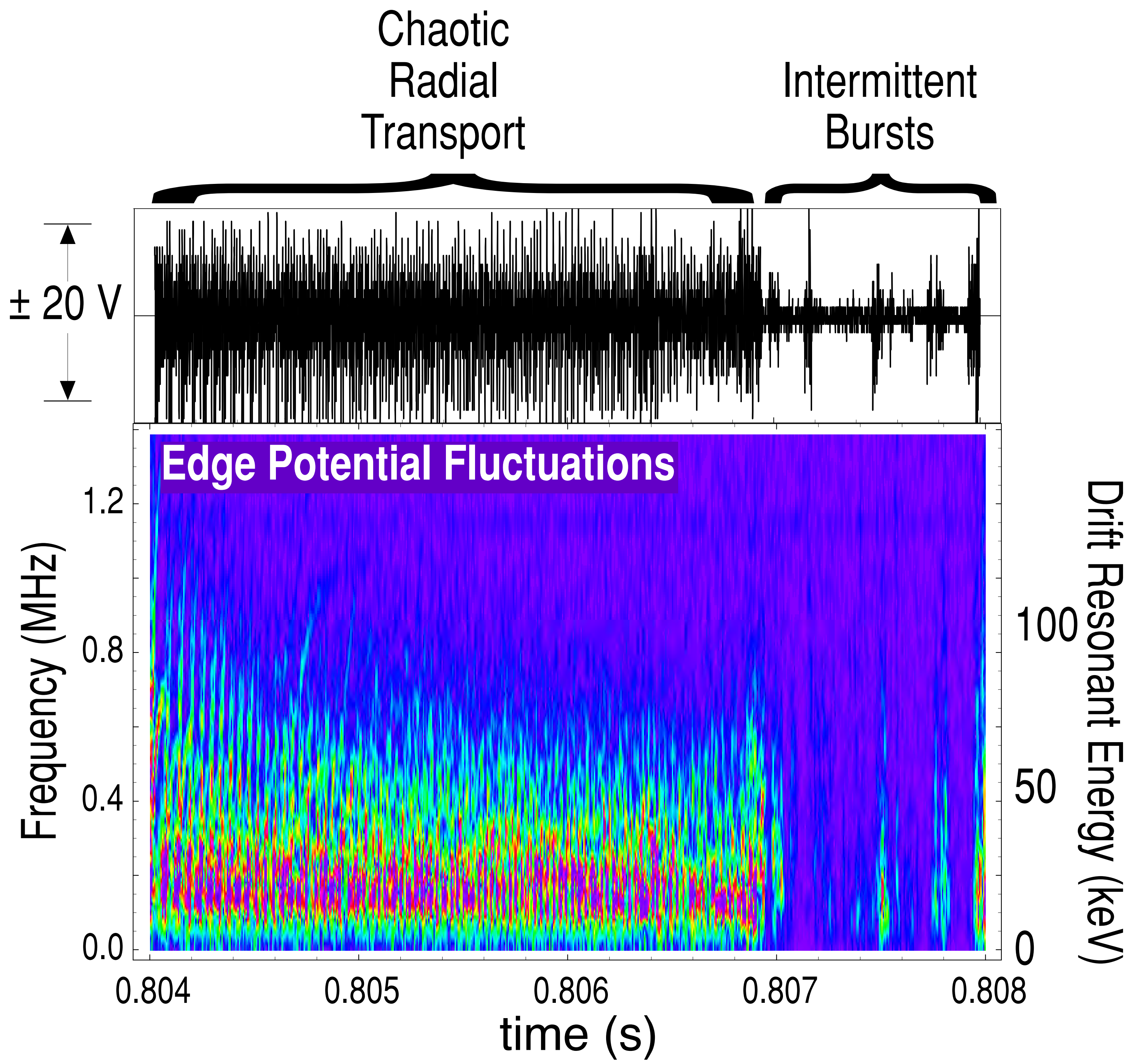
RT-1


Transition

Low β

High β

Fast Electron Instability Prevents High β build-up ...

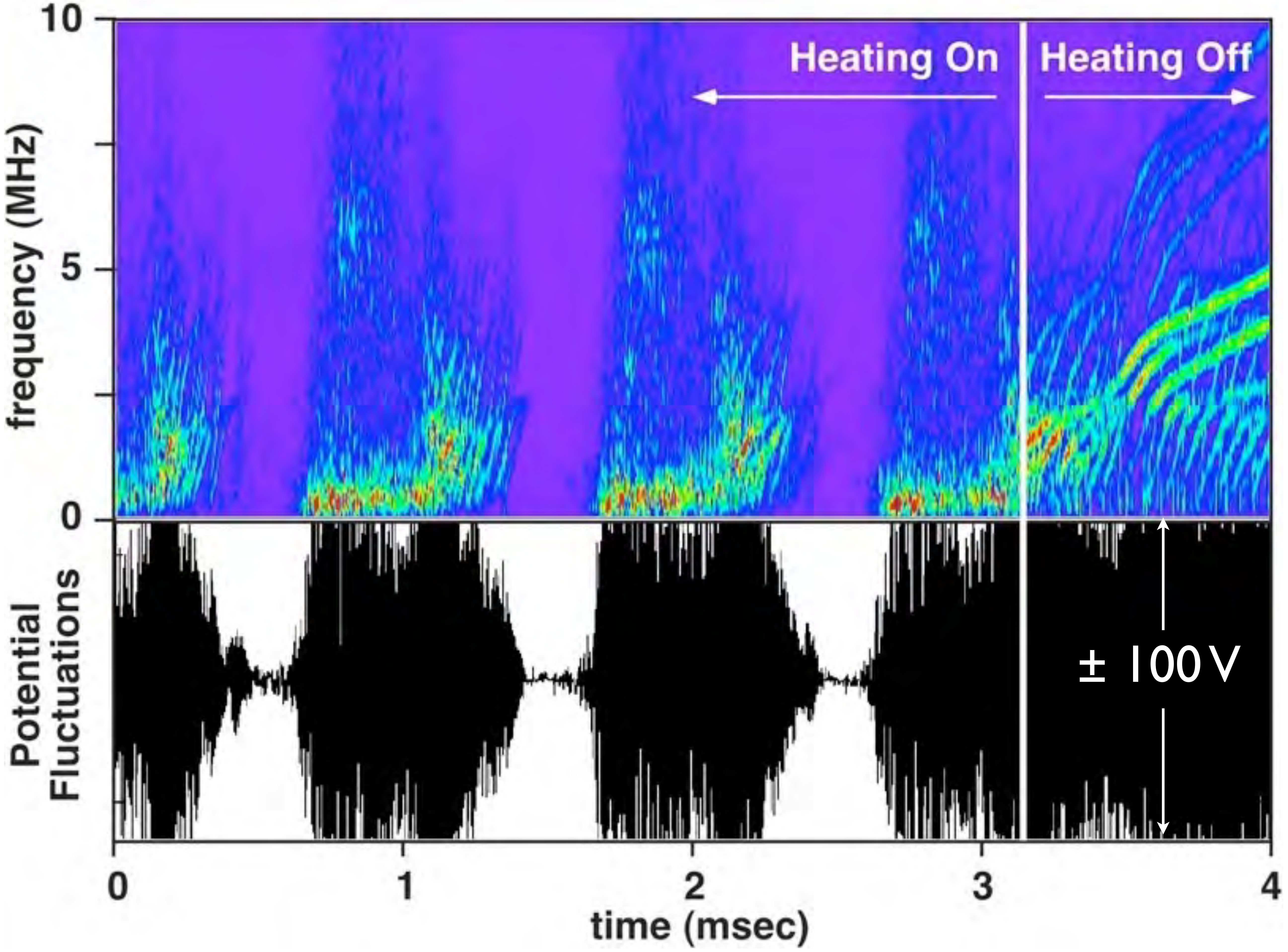


LDX

Achieving High β with ECRH Requires Stabilization of Hot Electron Interchange Mode and Creates a stable ***"Artificial Radiation Belt"***

- ECRH *always* generates energetic electrons
- Hot Electron Interchange (HEI) modes appear with both supported and levitated magnets whenever the plasma density is too low.
- HEI instabilities are drift-resonant ($\omega \sim m\omega_{dh} \sim 1$ MHz), have global structures, with nonlinear frequency chirping.
- Transport preserves phase-space density F(μ, J).
- Can be stabilize with dense, colder plasma:

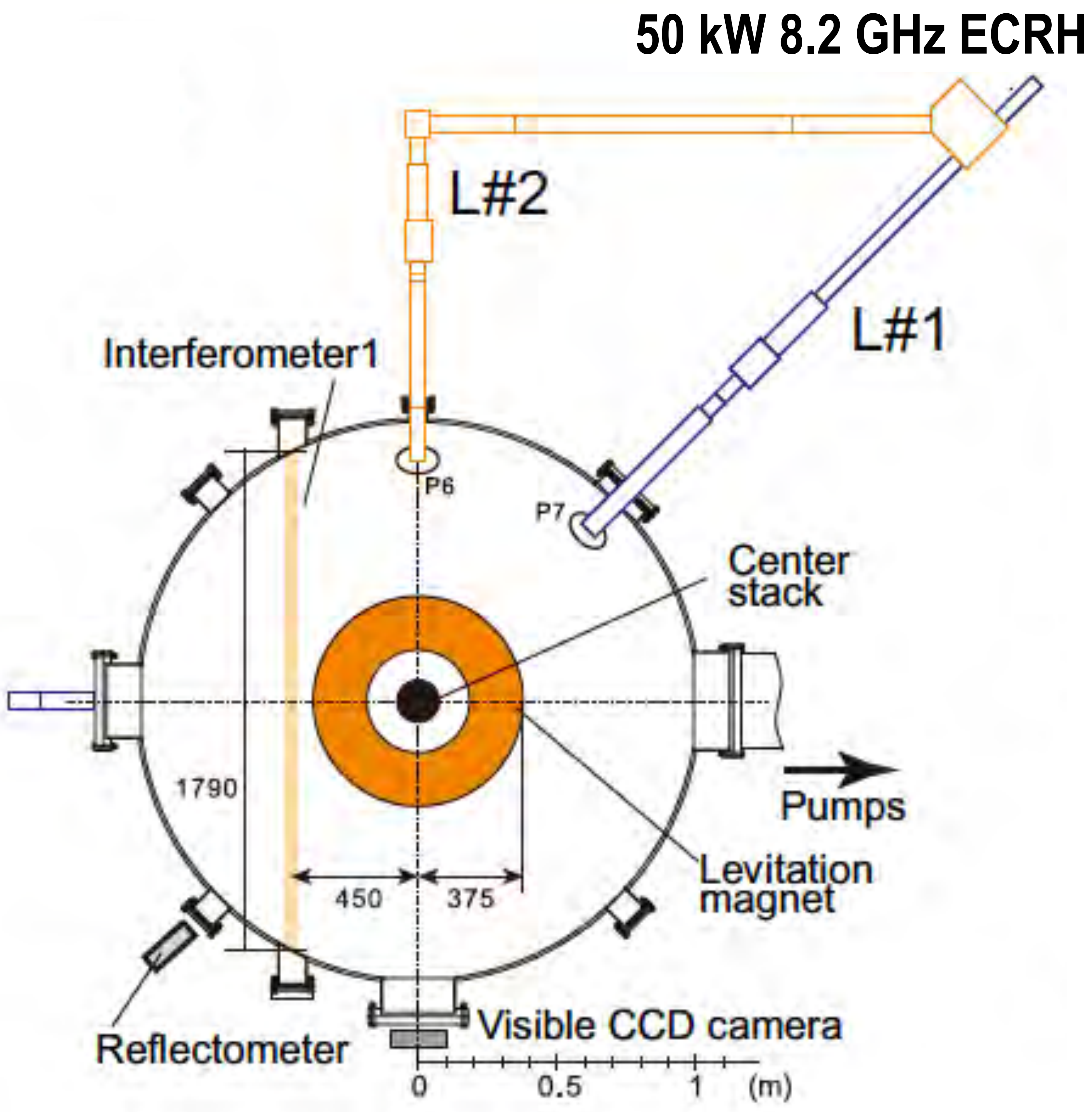
$$-\frac{d\ln n_{hot}}{d\ln V} > 1 + \underbrace{\frac{m_\perp^2}{24}\frac{\omega_{dh}}{\omega_{ci}}\frac{n_{ion}}{n_{hot}}}_{\text{Cold Density Stabilization}}$$



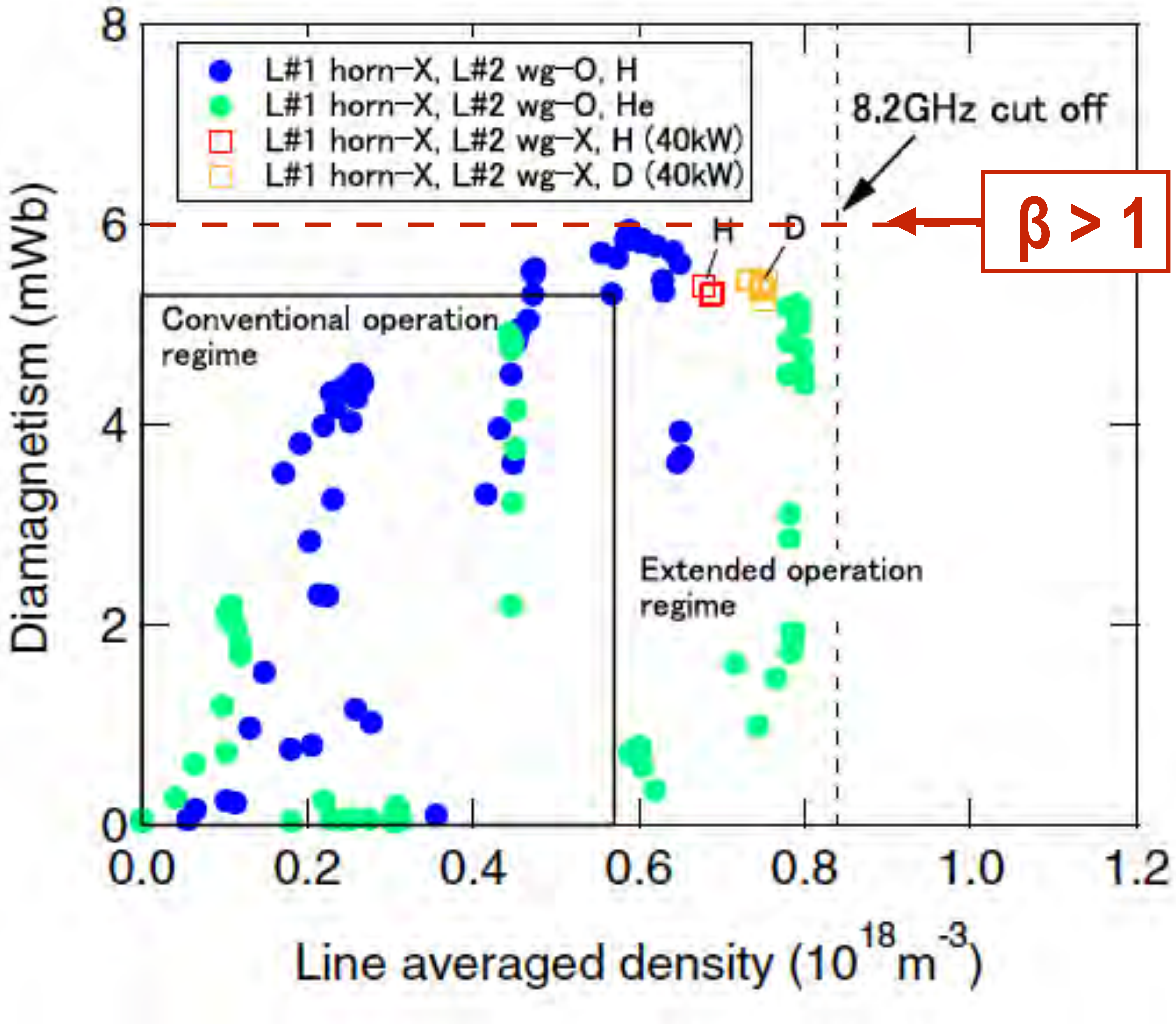
(Six PhD Dissertations: **Harry Warren**, Maslovsky, Levitt, Krasheninnikova, Grierson, Ortiz)

RT-1 Achieved Record Peak β > 1 with 50 kW ECRH 8.2 GHz Heating

Higher μWave frequency makes higher density accessible.
Higher μWave power creates higher peak local β.

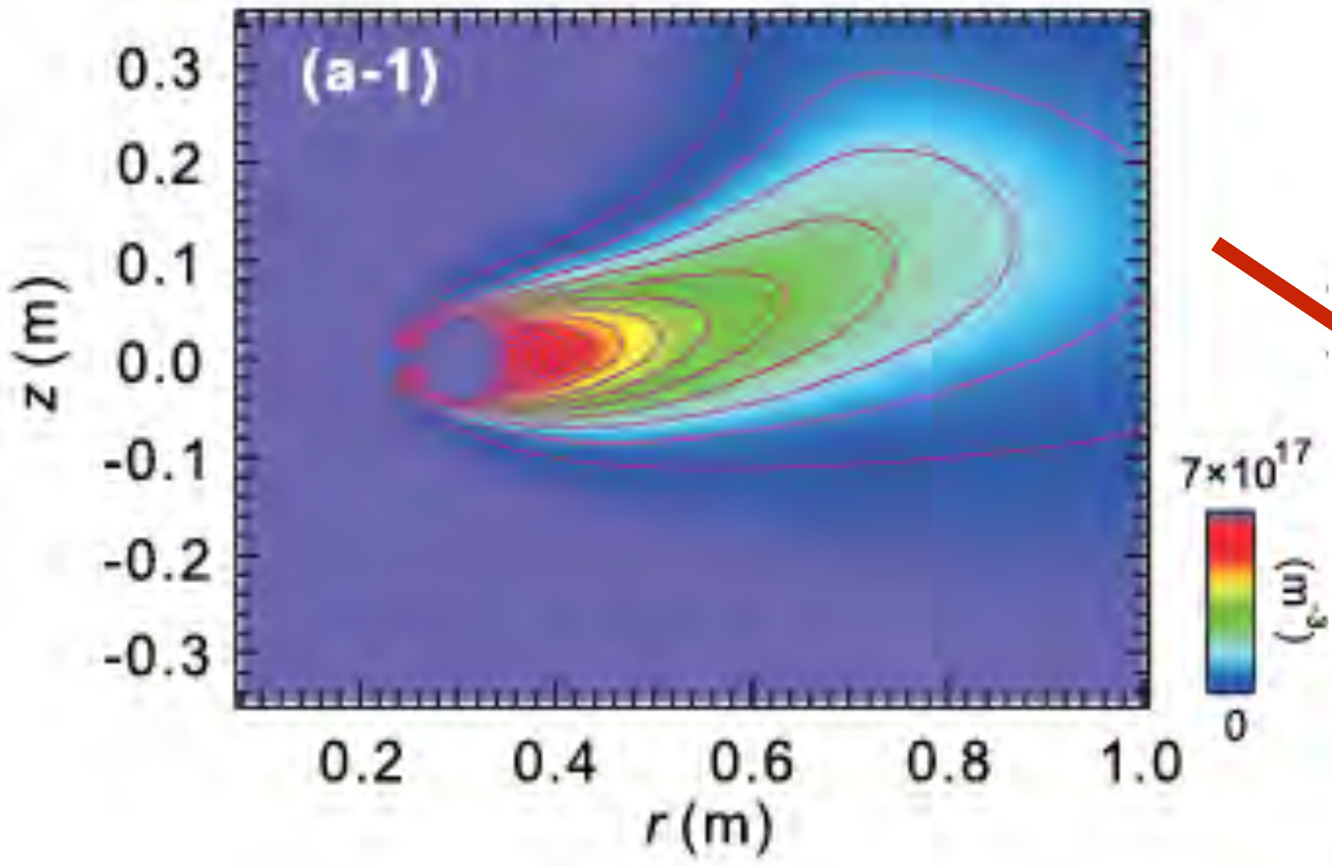


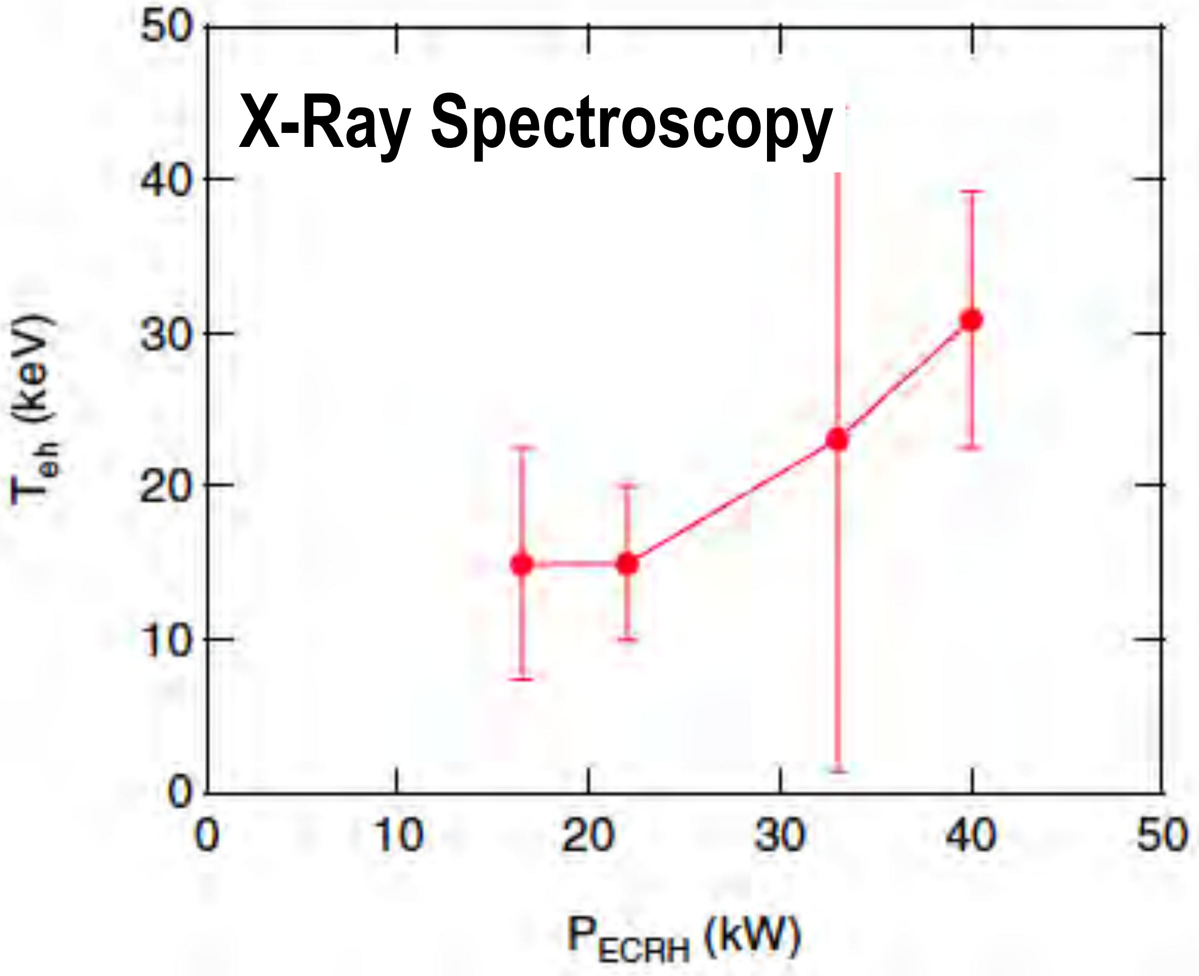
Higher Power and Higher Density

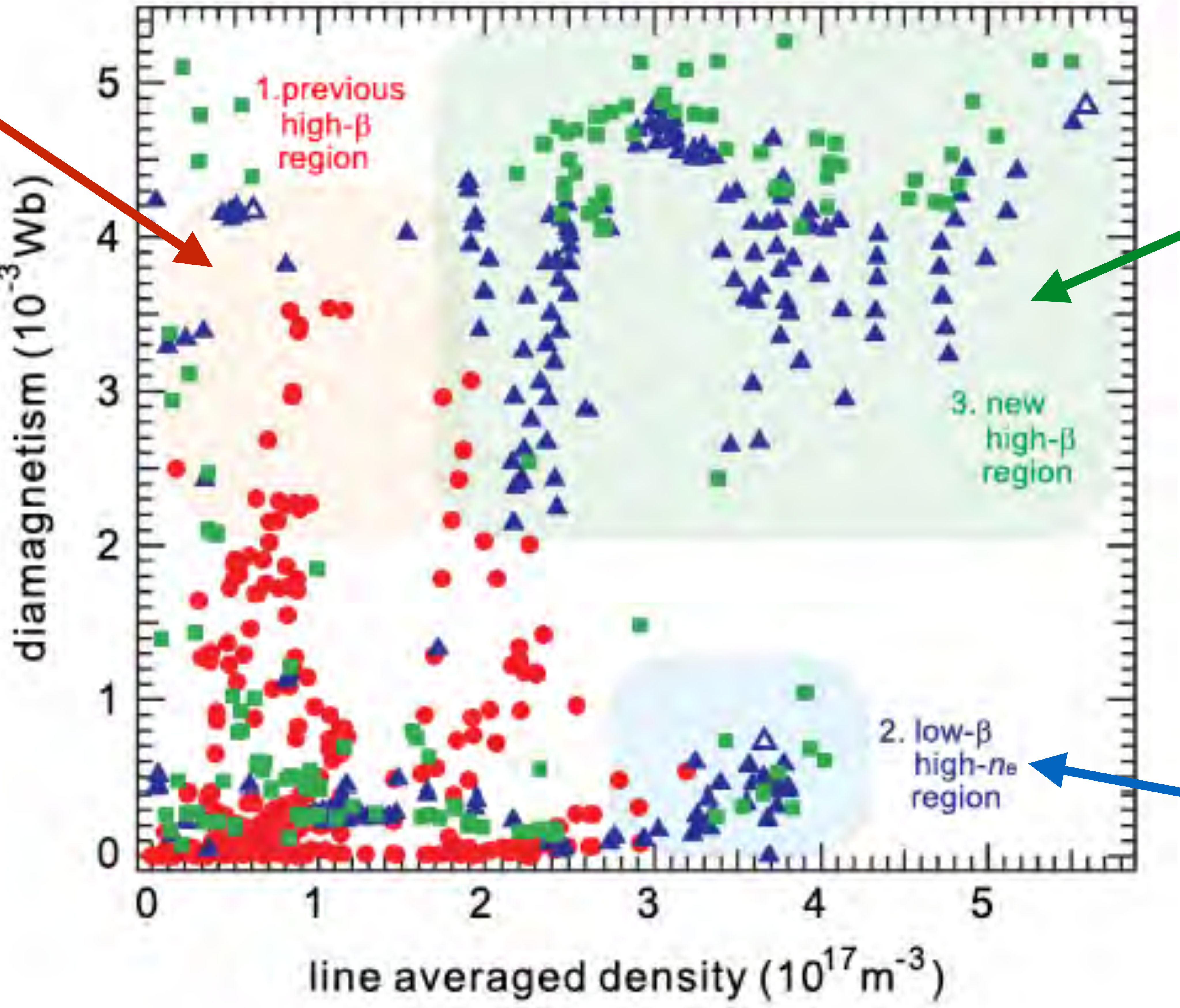


RT-1 has ***Three Regimes*** of High-β Operation depending upon Background Neutral Density and ECRH Power

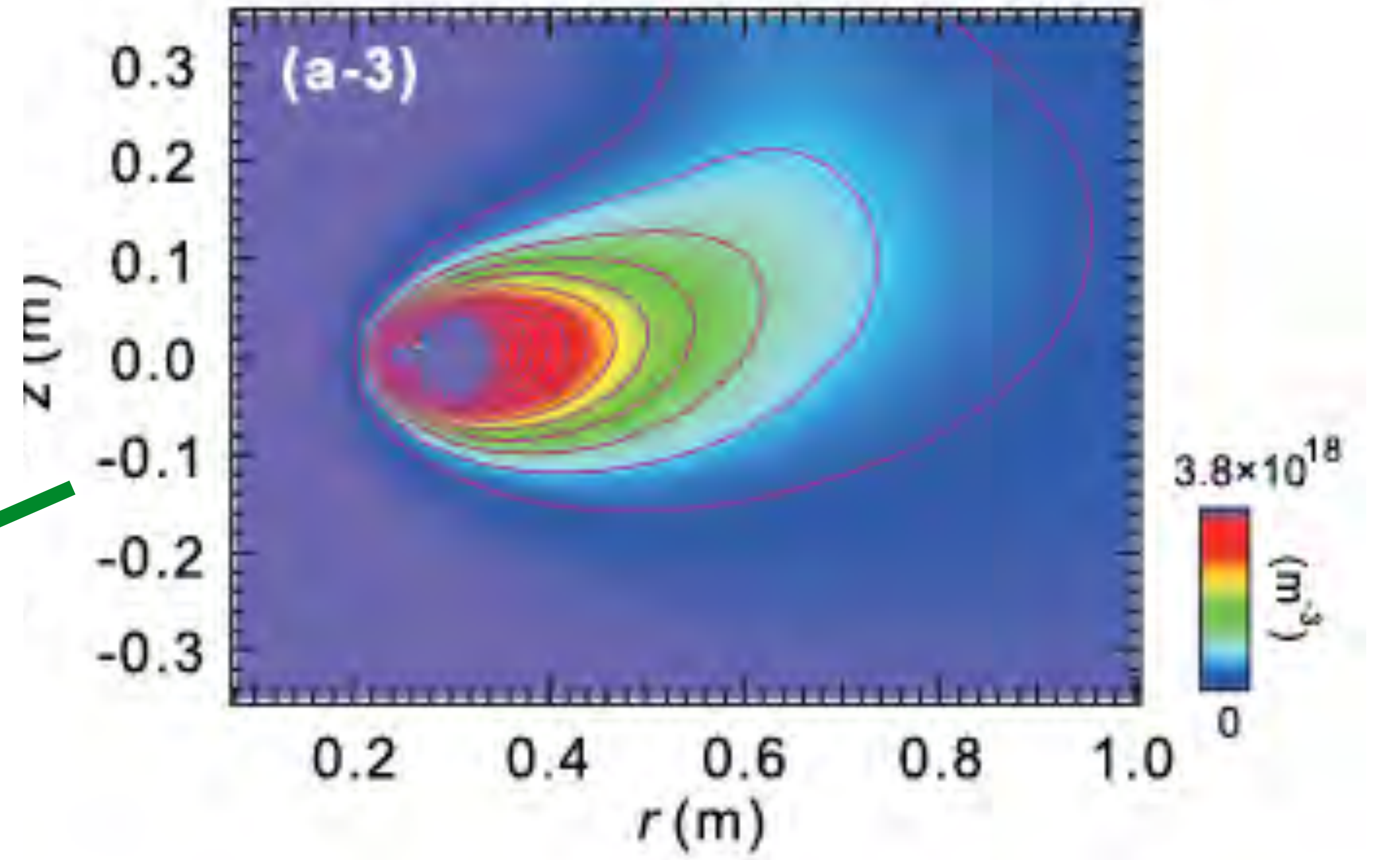
$P_\perp >> P_\parallel$



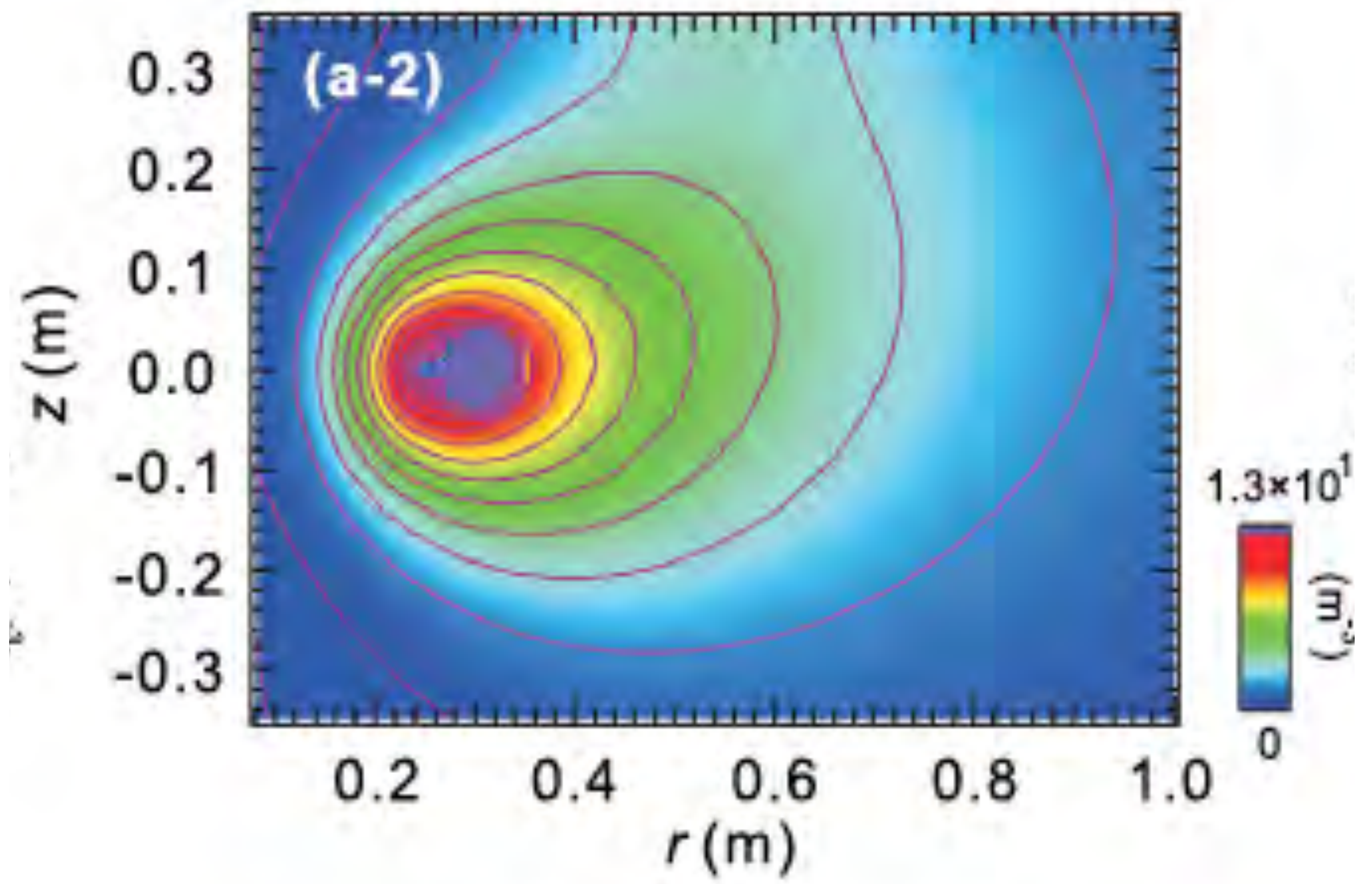




$P_\perp \gtrsim P_\parallel$



$P_\perp \sim P_\parallel$



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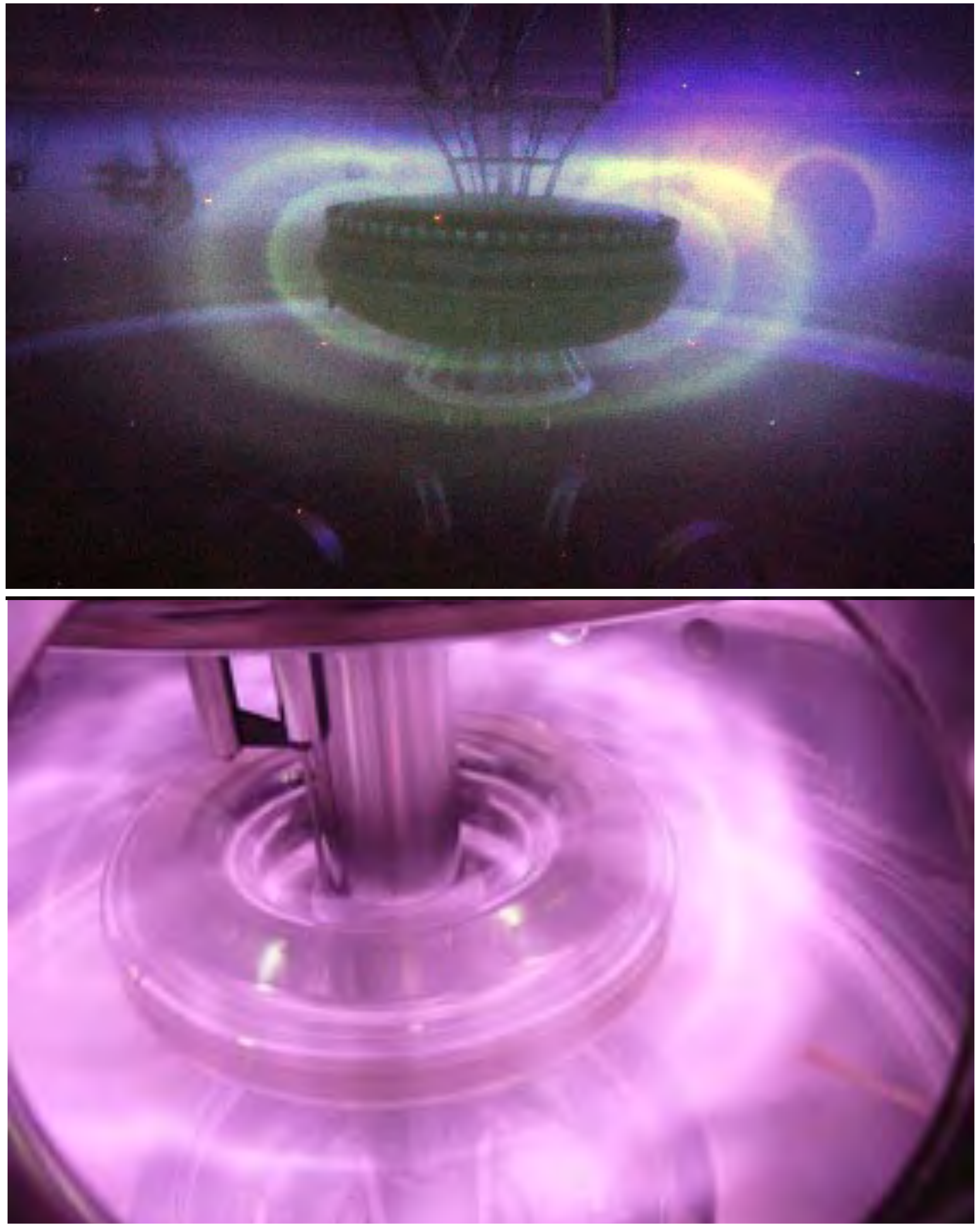
The Axisymmetric Plasma Torus is a *New Paradigm* for the Laboratory Study of Steady-State and High-Beta Plasma Transport

- ***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.

- ***Fascinating radial transport processes*** relevant to space and to many toroidal confinement devices: *up-gradient pinch, zonal flows, bursty interchange filaments, avalanches* …

Nonlinear gyrokinetics provides a good model for predicting radial transport driven by interchange and entropy instabilities



Answering Hasegawa’s 1987 question:
Magnetospheric physics ***does apply*** to magnetic confinement in the laboratory

✓ LDX, RT-1, theory and simulation show no limits scaling to stable high-β equilibria to larger size.

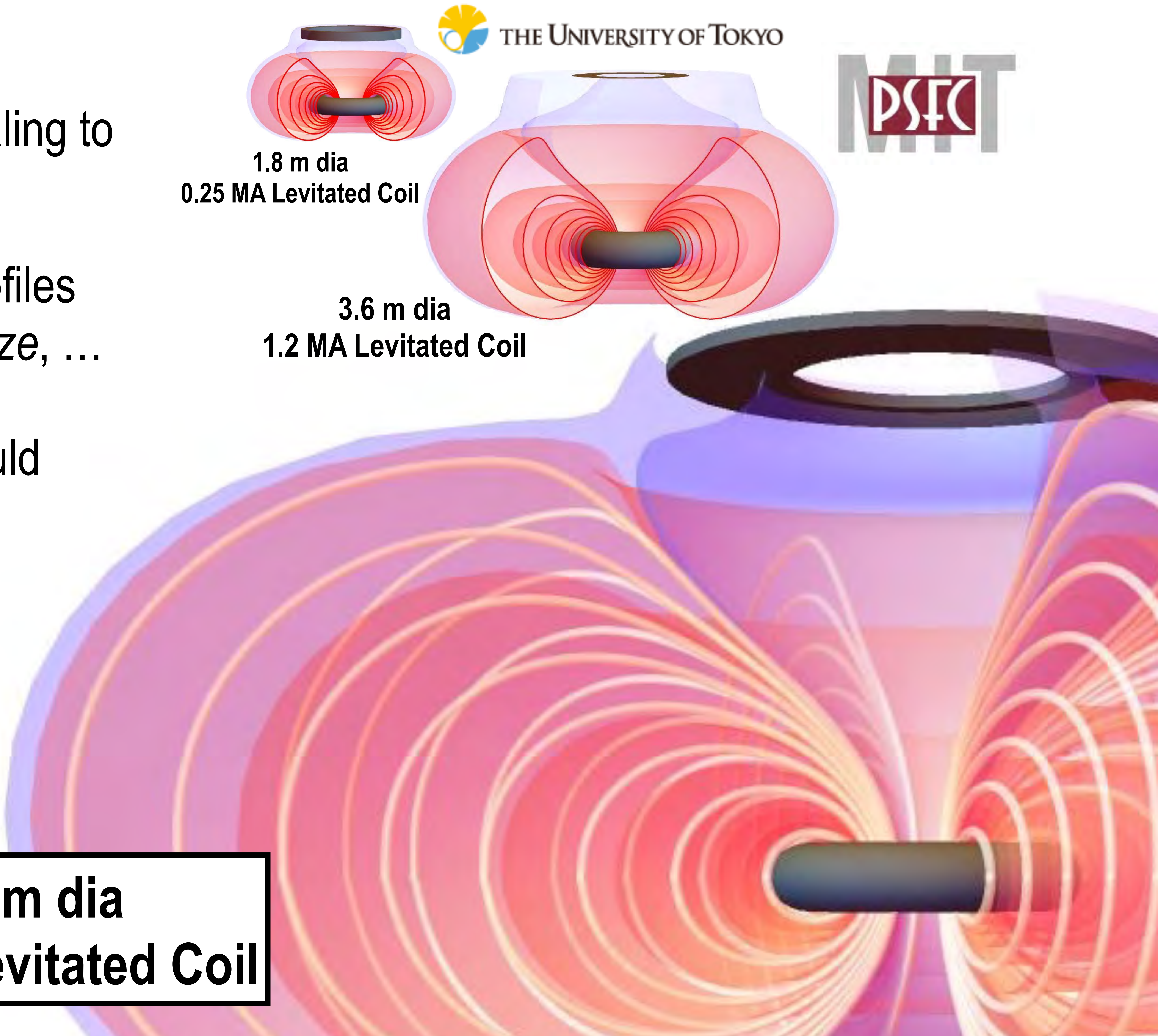
➡ Turbulent self-organization and centrally-peaked profiles appear to be robust and (should?) persist *to large size*, …

With only a small superconducting magnetic, we could create and study very large confined plasma for …

➡ **Fundamental plasma physics**

➡ **Space science and technology**

➡ **Magnetic plasma confinement science**



THE UNIVERSITY OF TOKYO

PSFC MIT

1.8 m dia
0.25 MA Levitated Coil

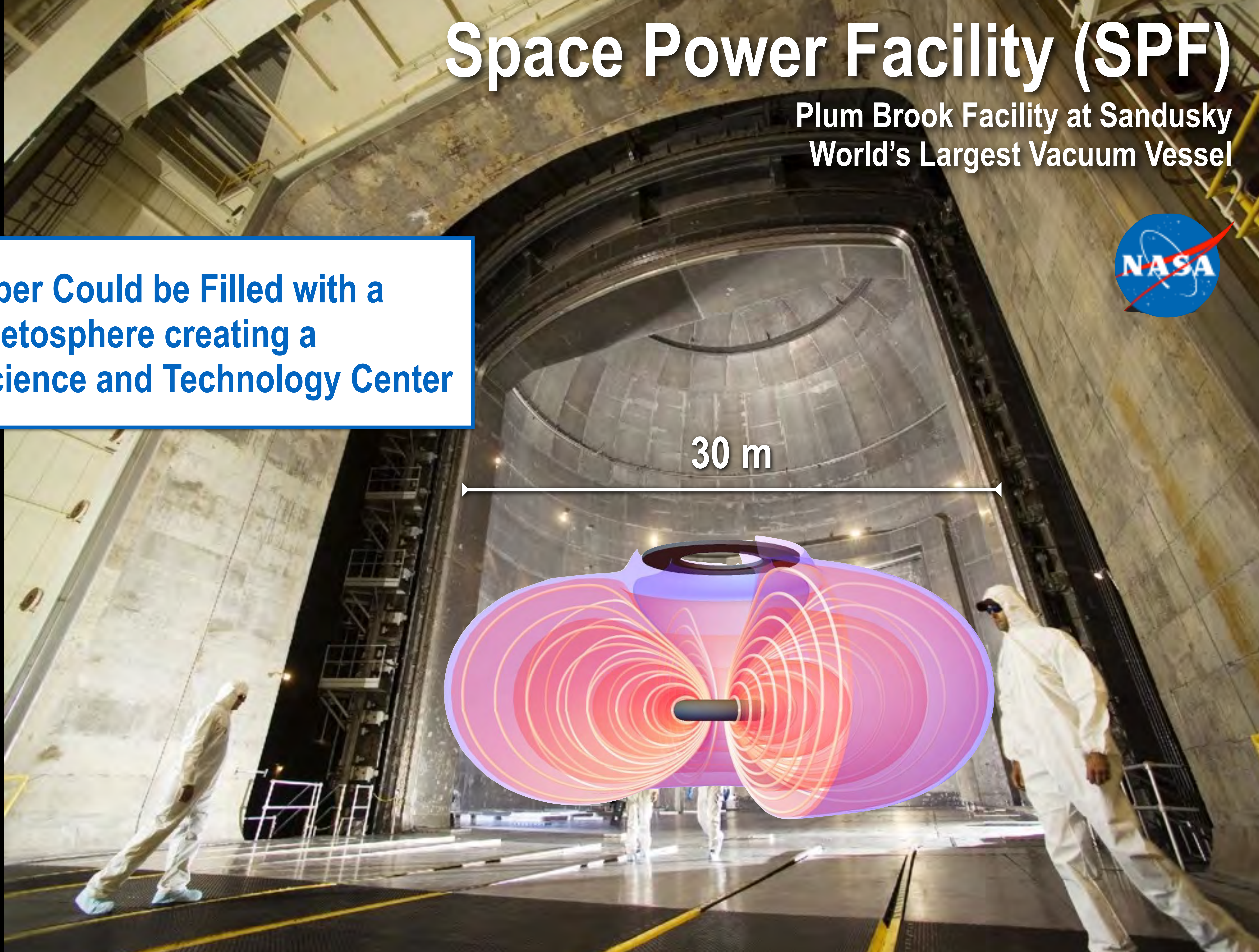
3.6 m dia
1.2 MA Levitated Coil

15 m dia
15 MA Levitated Coil

Space Power Facility (SPF)

Plum Brook Facility at Sandusky
World's Largest Vacuum Vessel

A Large Space Chamber Could be Filled with a Laboratory Magnetosphere creating a National Space Plasma Science and Technology Center




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