Understanding Turbulence using Active and Passive Multipoint Measurements in Laboratory Magnetospheres

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Acknowledging many contributions from Darren Garnier, Jay Kesner, and the
Students and scientists conducting research in support of the CTX and LDX Laboratory Magnetospheres

Mini-Conference on Bridging the Divide Between Space and Laboratory Plasma Physics II
Thursday, October 26, 2017
APS DPP • Milwaukee, WI

Multipoint Measurements are a “bridge” between Laboratory and Space Plasma Physics

“Looking to the future, I believe that ***progress requires bunches of satellites***, though these are as yet in no published program. One is continually conscious of this need for reasons which have a direct analogue on the ground... Since satellites are being launched singly, the scientific returns are less than they could be.”

Jim Dungey, Inaugural lecture as Professor of Physics at Imperial College, 1966.

“Magnetospheric Constellation: Past, Present and Future”
Vassilis Angelopoulos and Harlan Spence
Geophysical Monograph 109, pp. 247-262 (AGU, 1999)

Kilo-Satellites & Constellations

"a constellation composed of ***several hundred satellites*** appears to be within the scope of a Solar-Terrestrial Probe line mission costs"

“The **Kilo-Satellite** Constellation Concept,” Harry Petschek, *et al.*, pp. 51-57, (Berkeley, 1998).

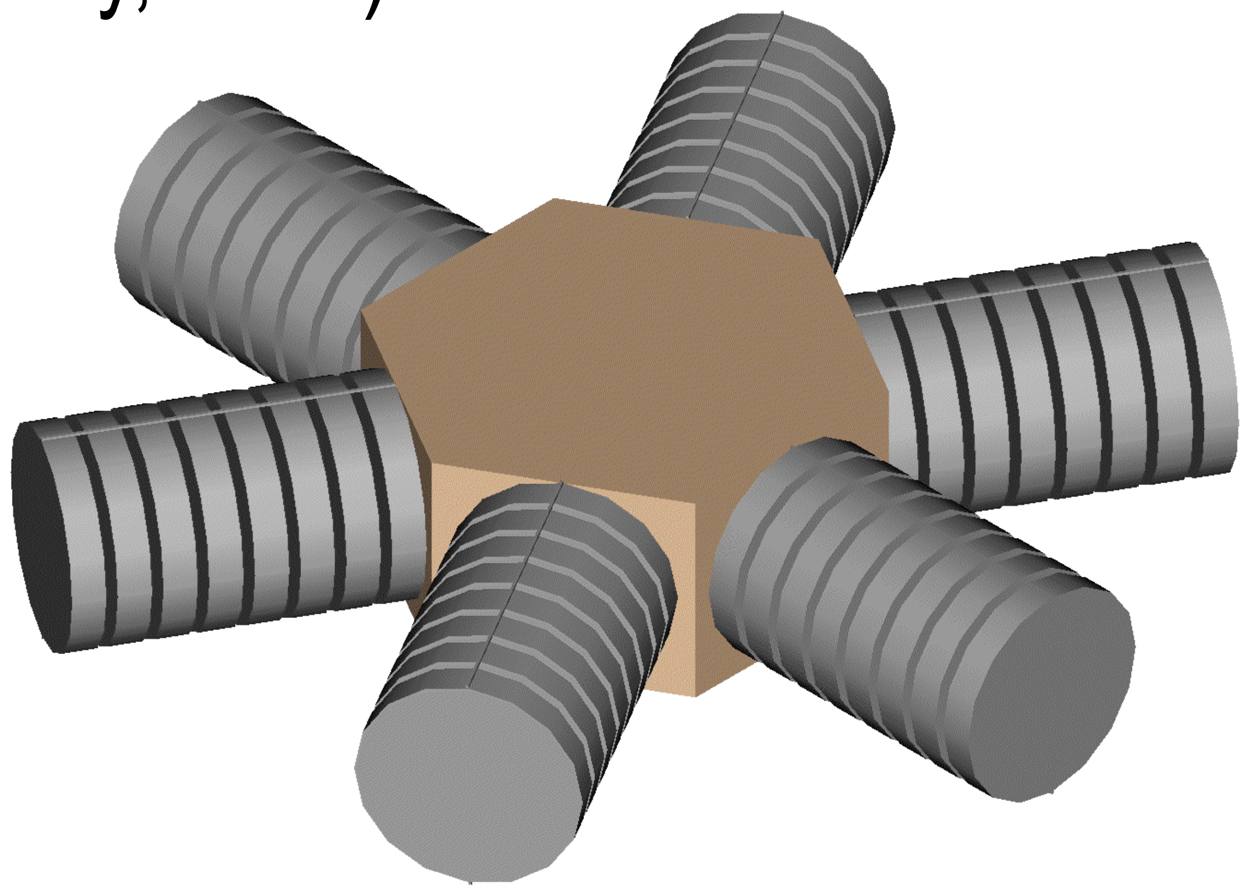


Figure 5. Satellite packaging arramgement in Pegasus XL payload compartment. Satellites will be moved mechanically to the outside position prior to release.

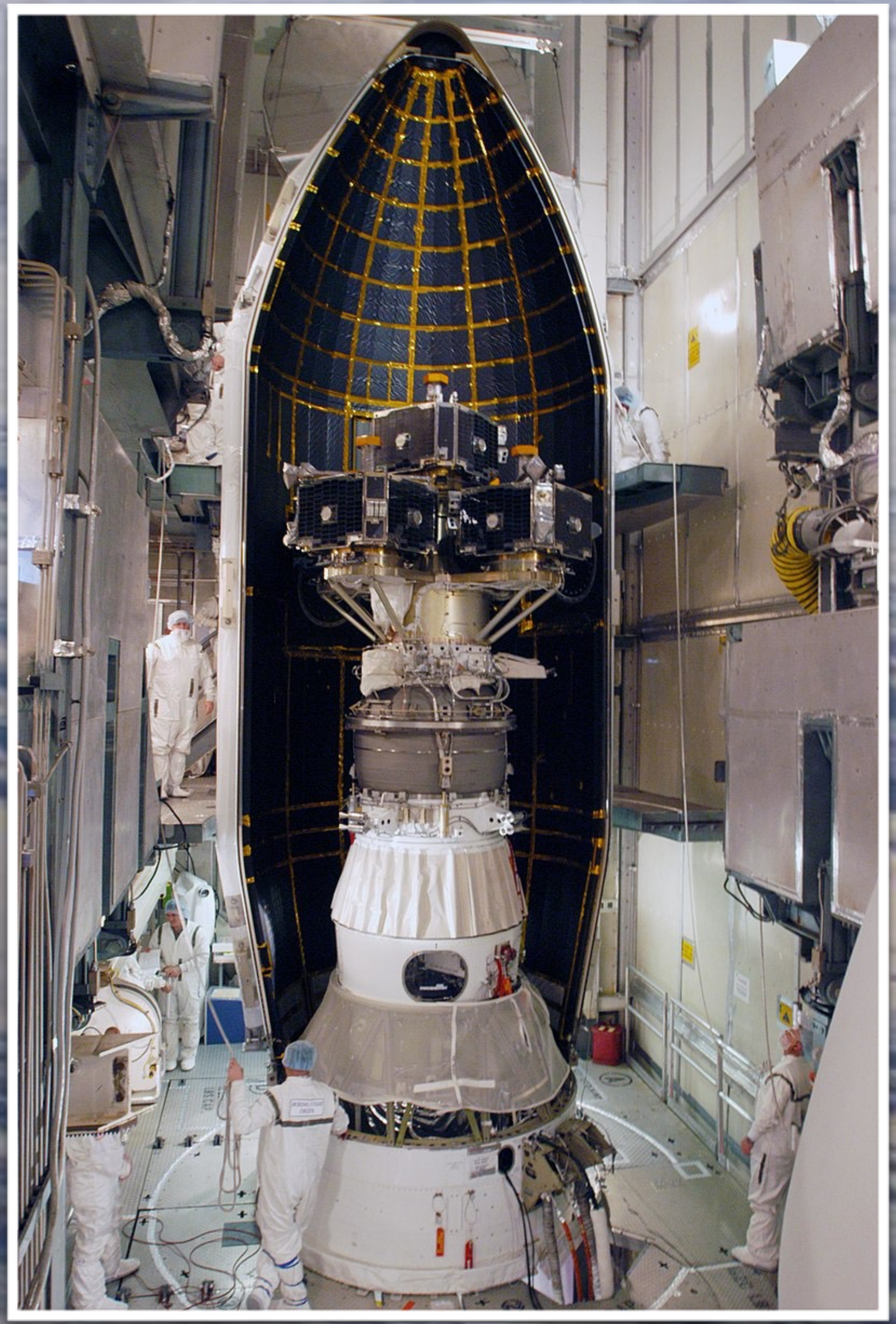
“Deployment of ***~80 autonomous micro-satellites*** to monitor the Earth's magnetosphere and measure the plasma and magnetic field in the near-equatorial magnetosphere is a necessary and sufficient condition for answering long standing, high priority questions … [and] mission concept is technically feasible and fiscally modest”

“On the Necessity and Feasibility of an Equatorial Magnetospheric **Constellation**,” Vassilis Angelopoulos, *et al.*, pp. 14-21, (Berkeley, 1998).

Science Closure and Enabling Technologies for Constellation Class Missions, edited V. Angelopoulos and P. V. Panetta (Berkeley, 1998)

Room yet to expand multi-point measurements from "**clusters**" to "**bunches**" to "**constellations**"

MMS (4)



THEMIS (3+2)

Two Approaches to Multipoint Measurements in the Lab

- Movable sensors in reproducible and/or coherent plasmas (*only in the lab*)

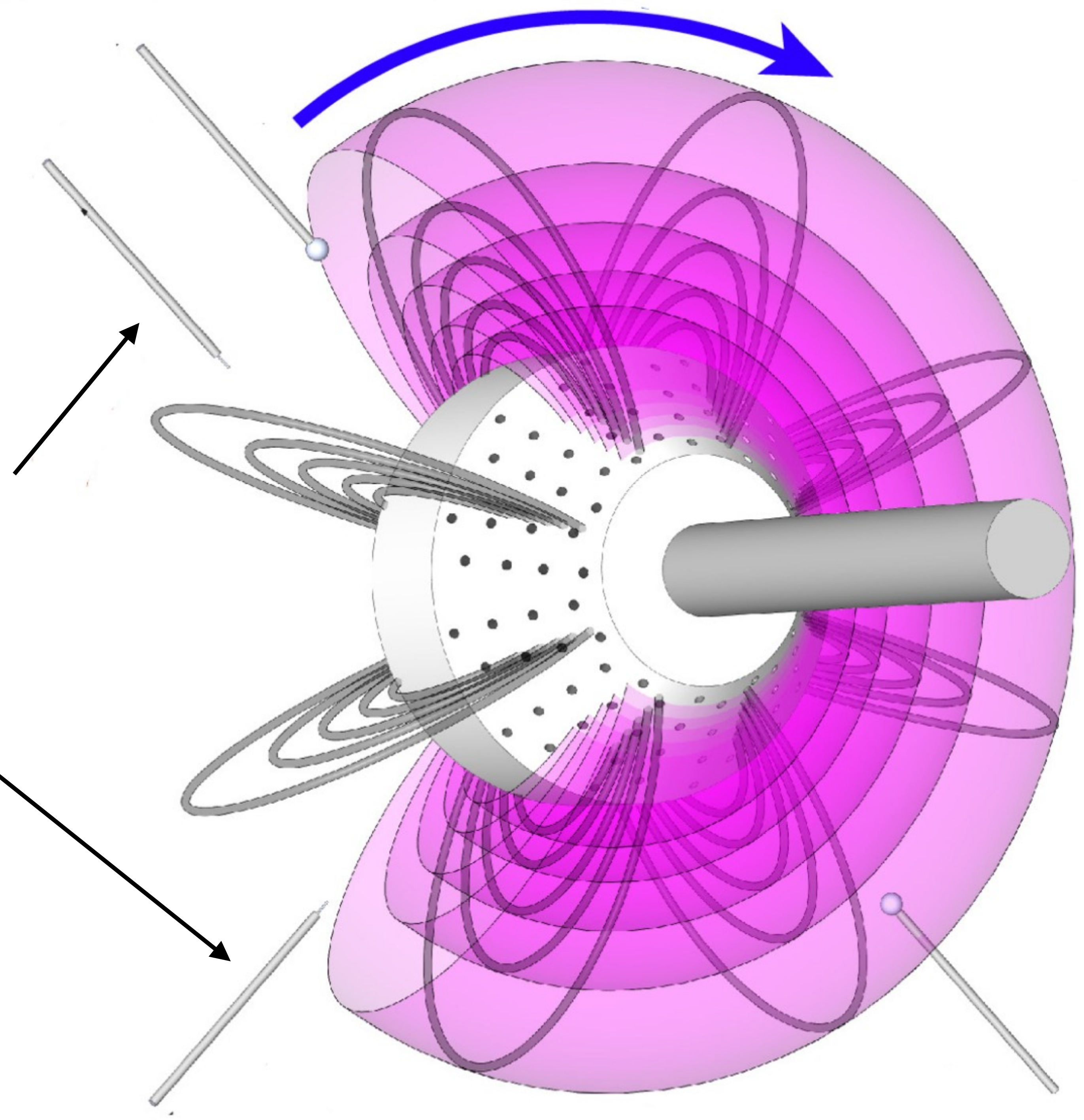
➡ Simultaneous multipoint sensors in transient, turbulent, or chaotic plasmas (*also in space constellations*)

Movable Probes in “Reproducible” Lab Plasmas

Example: Saturated, Coherent Centrifugal Interchange Mode

Phys. Plasmas **12**, 055703 (2005)

Supersonic Rotation (Mach > 1)



Rotating Laboratory Magnetosphere

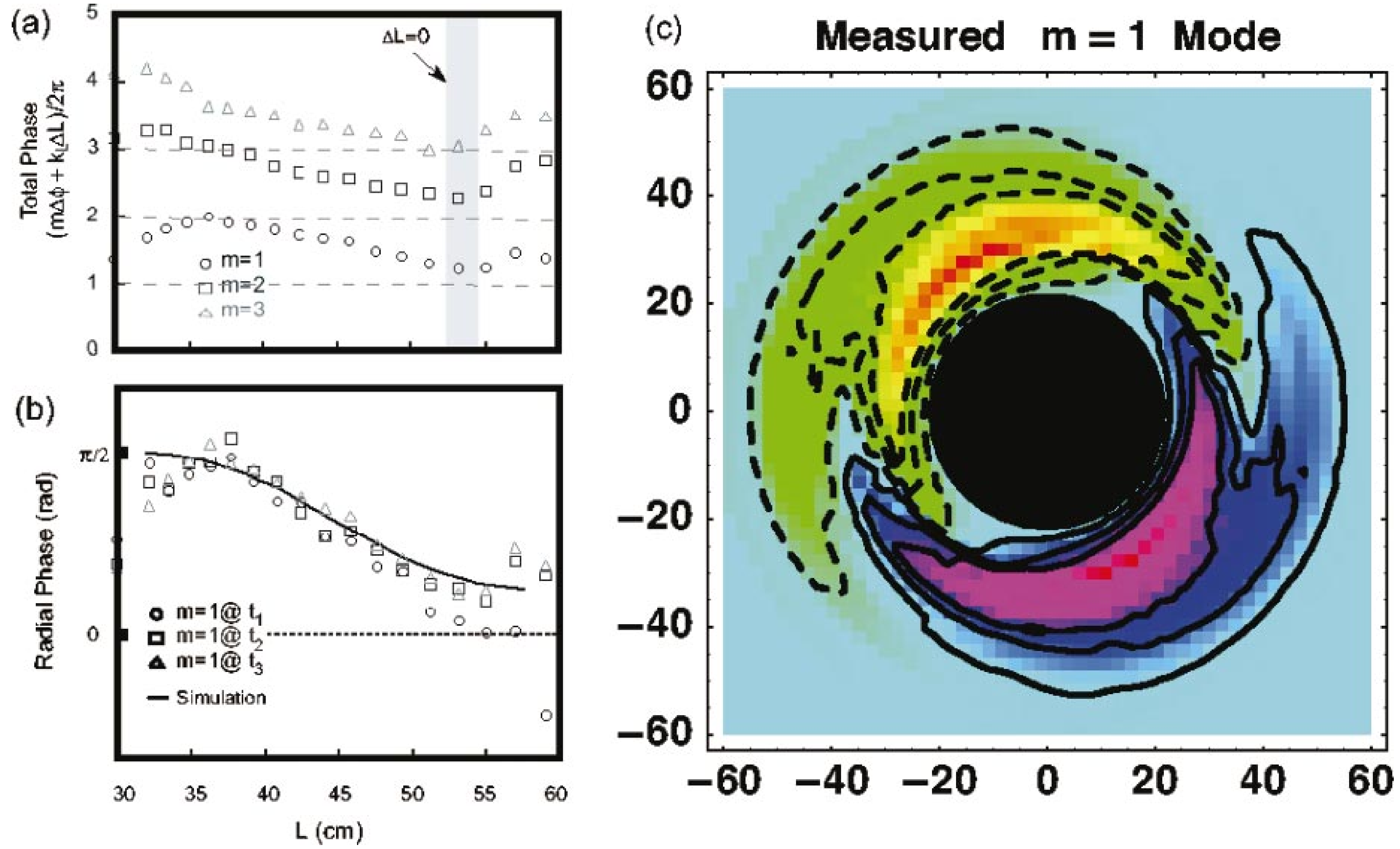
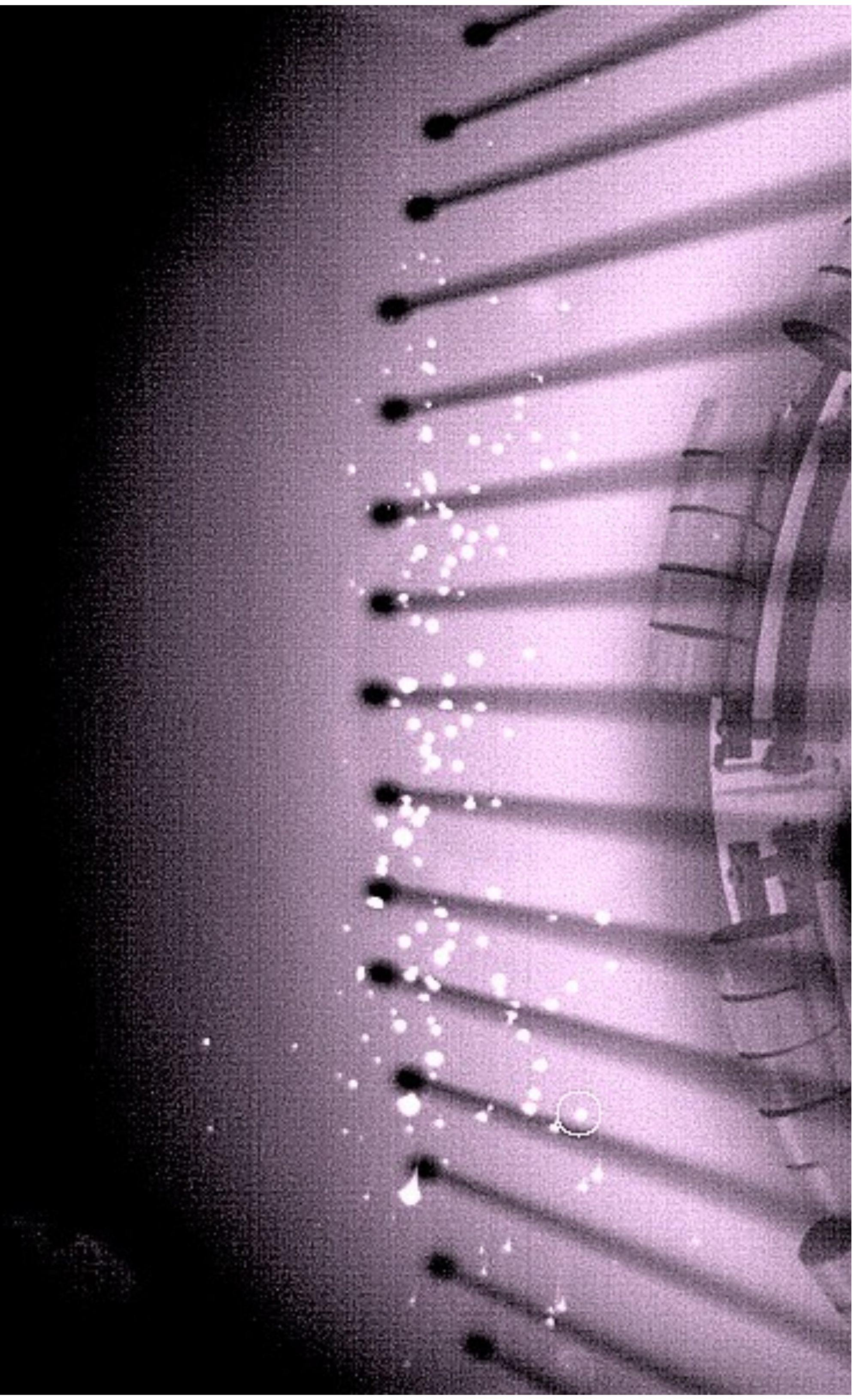
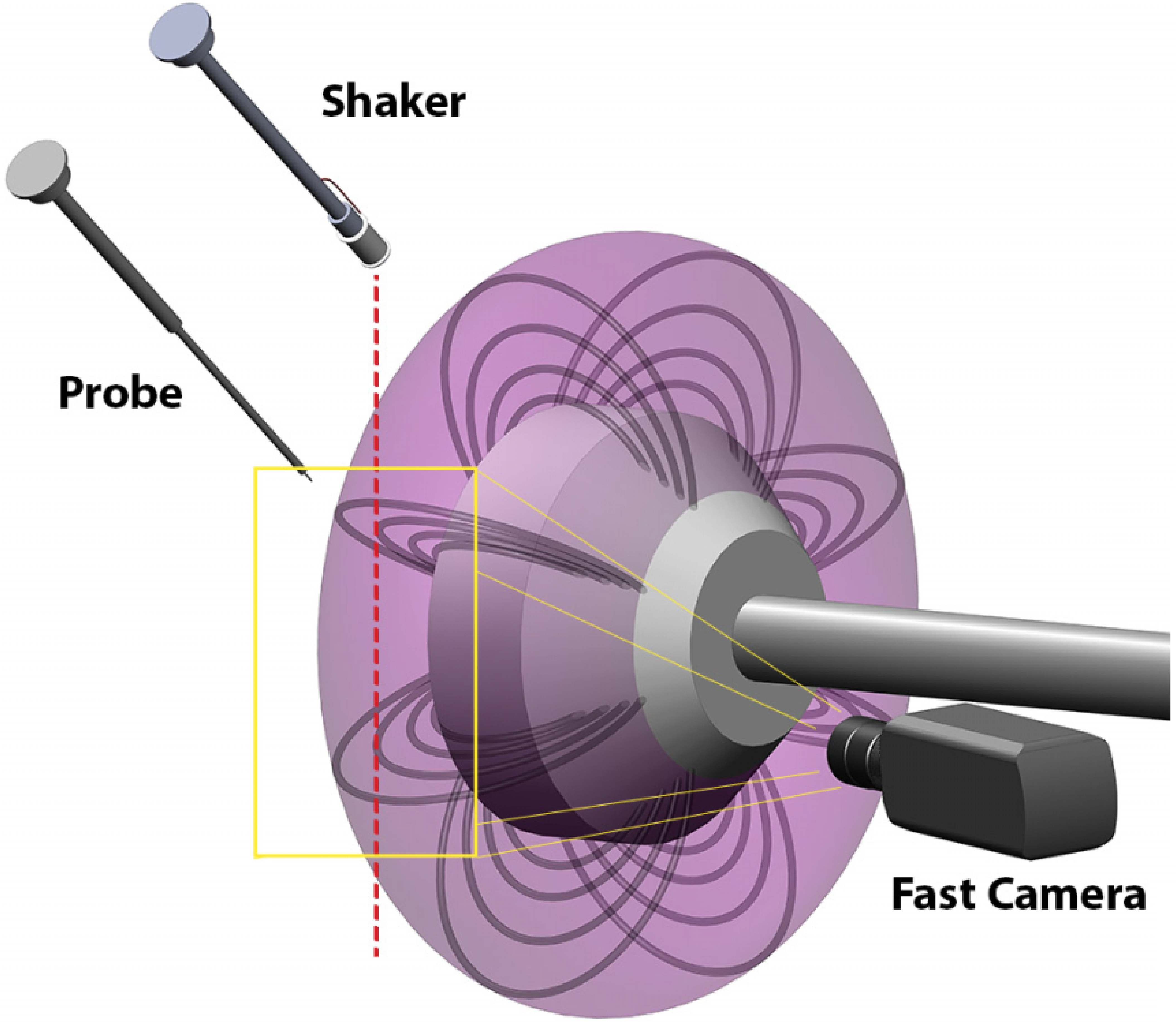
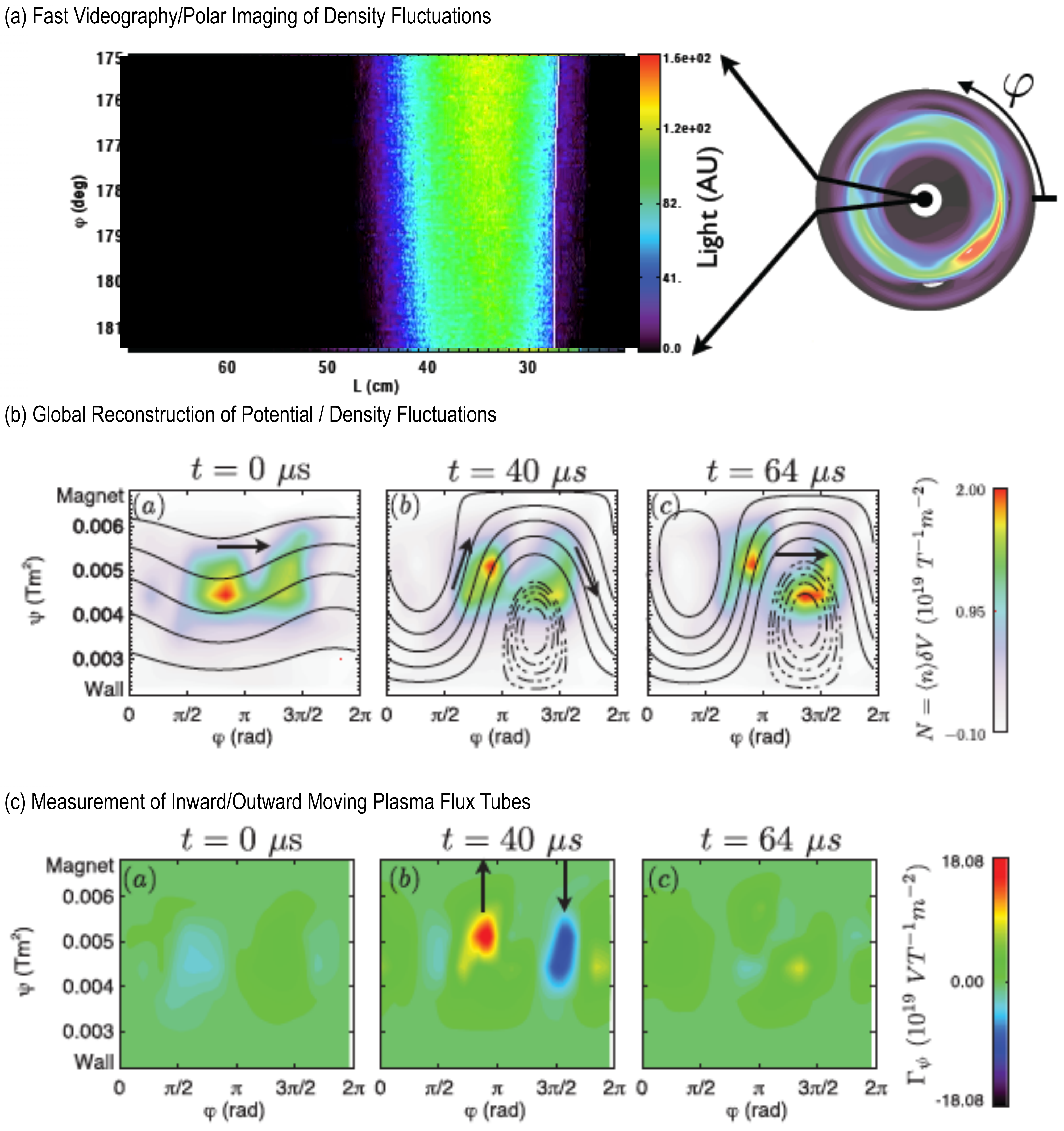


FIG. 7. (Color). (a) Total phase of the correlation function between two probes as a function of the radial position of one probe for the three lowest harmonics. (b) The radial phase for the $m=1$ mode at three different times during a discharge. Solid line is the result of numerical simulation. (c) Reconstructed $m=1$ component of the interchange mode.

High-Resolution Measurements of Plasma Turbulence Requires a Different Approach… **Simultaneous Multi-Points (like satellite constellations)**

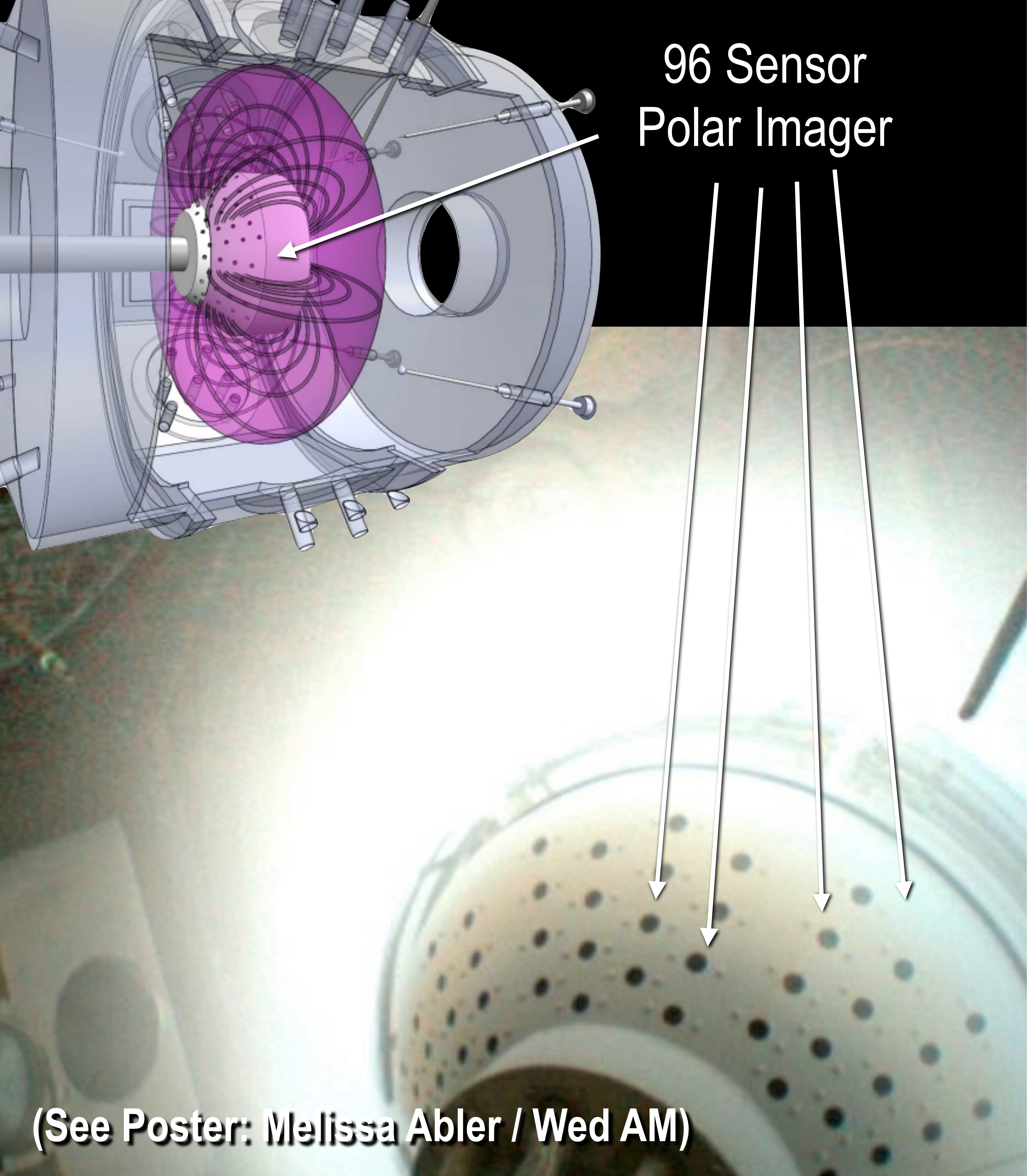


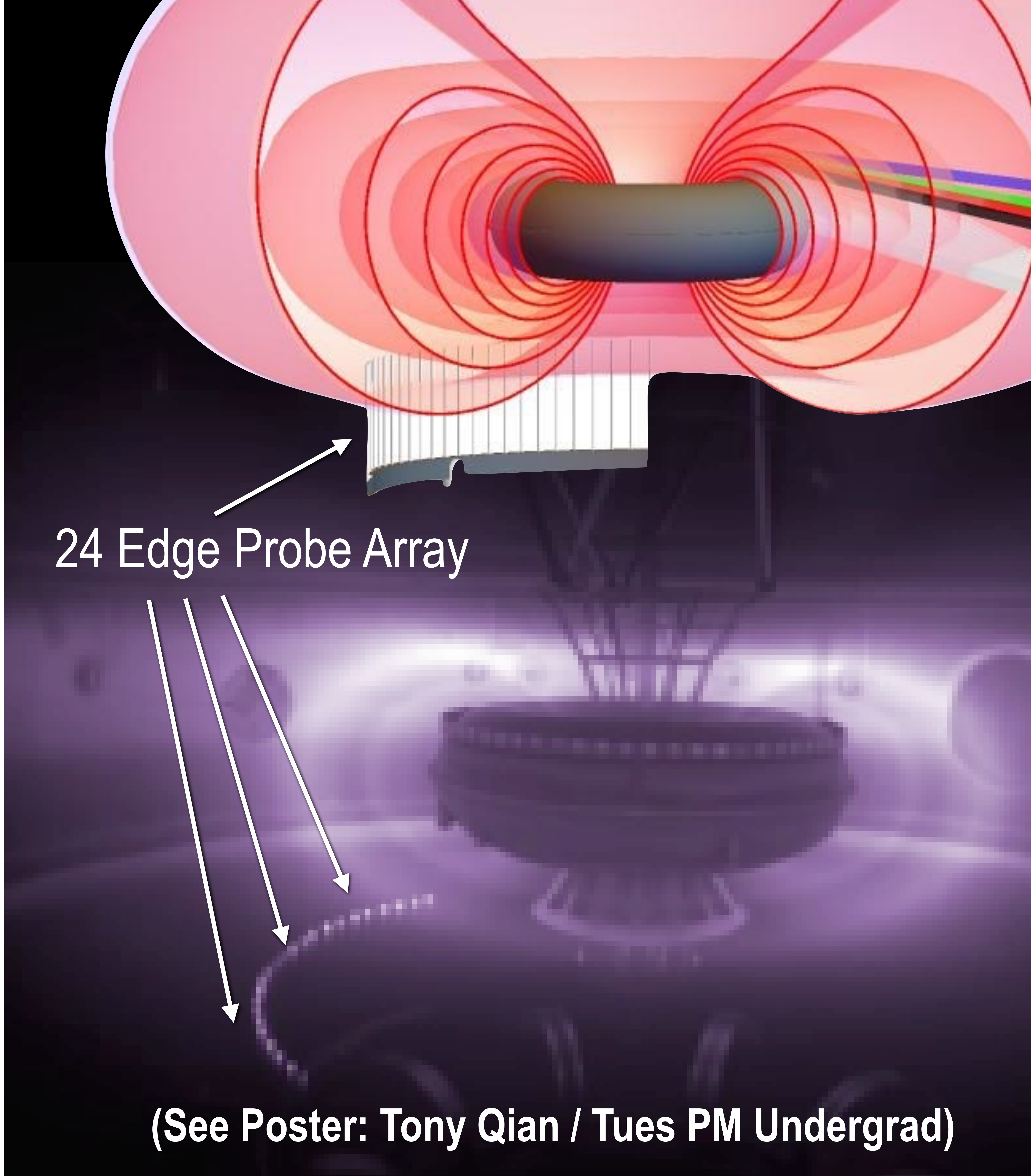




Example: Tracking free-falling dust "constellations"

Roberts, et al. *Rev Sci Instrum* **86**, 083510 (2015).


96 Sensor
Polar Imager
(See Poster: Melissa Abler / Wed AM)


24 Edge Probe Array
(See Poster: Tony Qian / Tues PM Undergrad)

Jack Capon’s Maximum-Likelihood Method for High-Resolution Detection of Power Spectrum (1969)

“High-Resolution Frequency-Wavenumber Spectrum Analysis,” *Proc. IEEE* **57**, 1408 (1969).

21 × 25 = 525 sensors (!!)

Large Aperture Seismic Array (LASA)

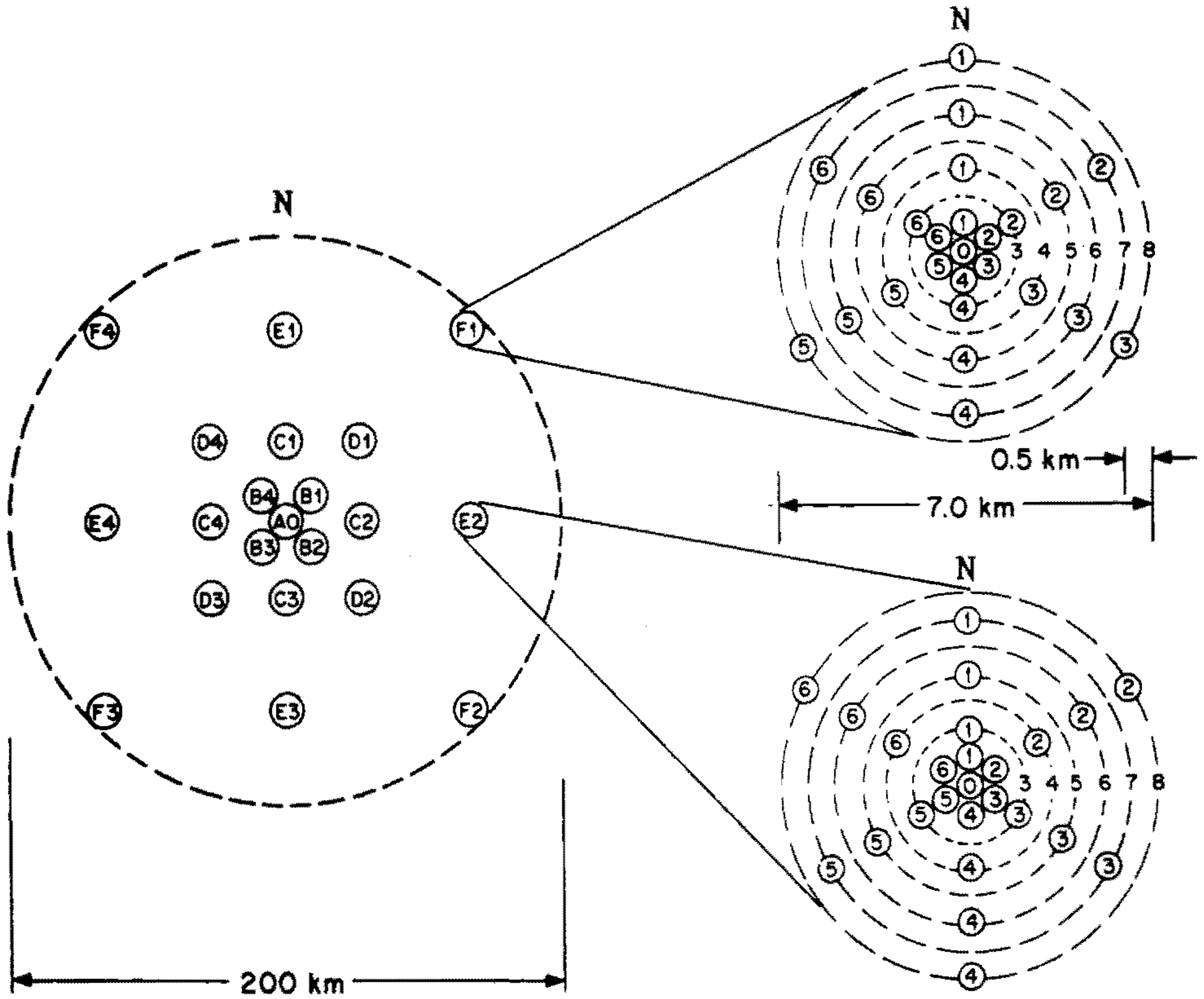


Fig. 1. General arrangement of the large aperture seismic array.

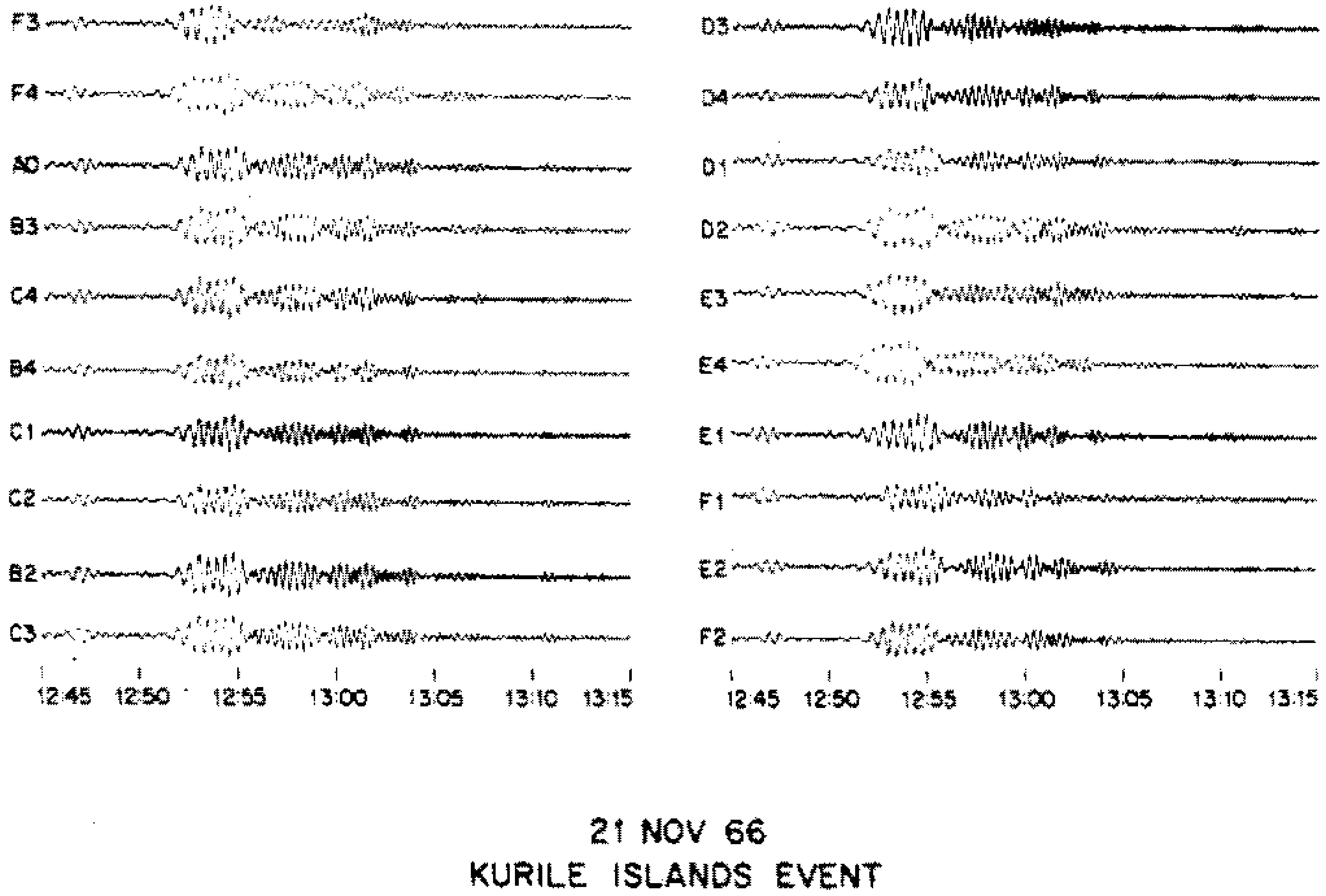


Fig. 6. The long-period waveforms for 21 November 1966 Kurile Islands event.

Belmont, Sahraoui, and Rezeau, "Measuring and understanding space turbulence," *Adv in Space Res.* **37**, 1503 (2006).

(Special thanks to Dr. Yasuhito Narita (yasuhito.narita@oeaw.ac.at) for suggesting this method)

Jack Capon's Maximum-Likelihood Method for High-Resolution Detection of Power Spectrum (1969)

"High-Resolution Frequency-Wavenumber Spectrum Analysis," *Proc. IEEE* **57**, 1408 (1969).

Nonlinear Filters Depend upon Full Cross-Correlation Matrix, $\mathbf{C}_{ij}^{-1}$

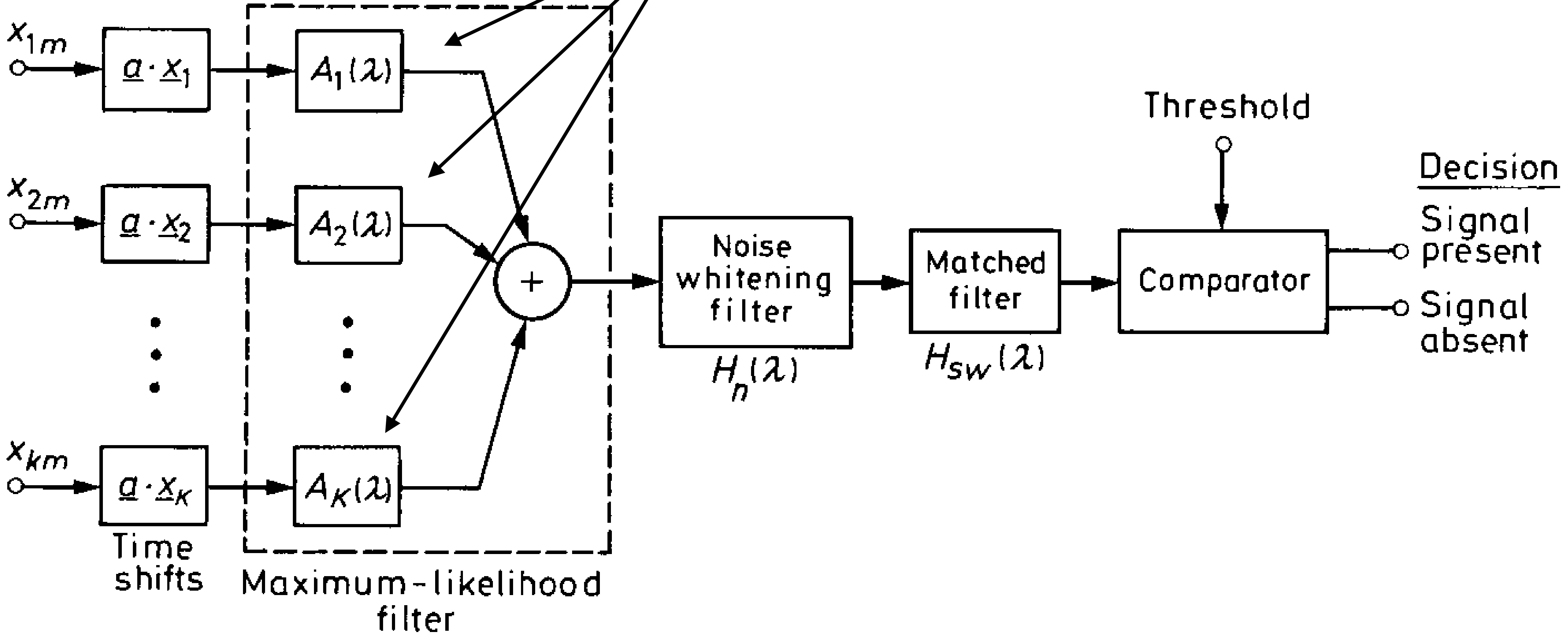
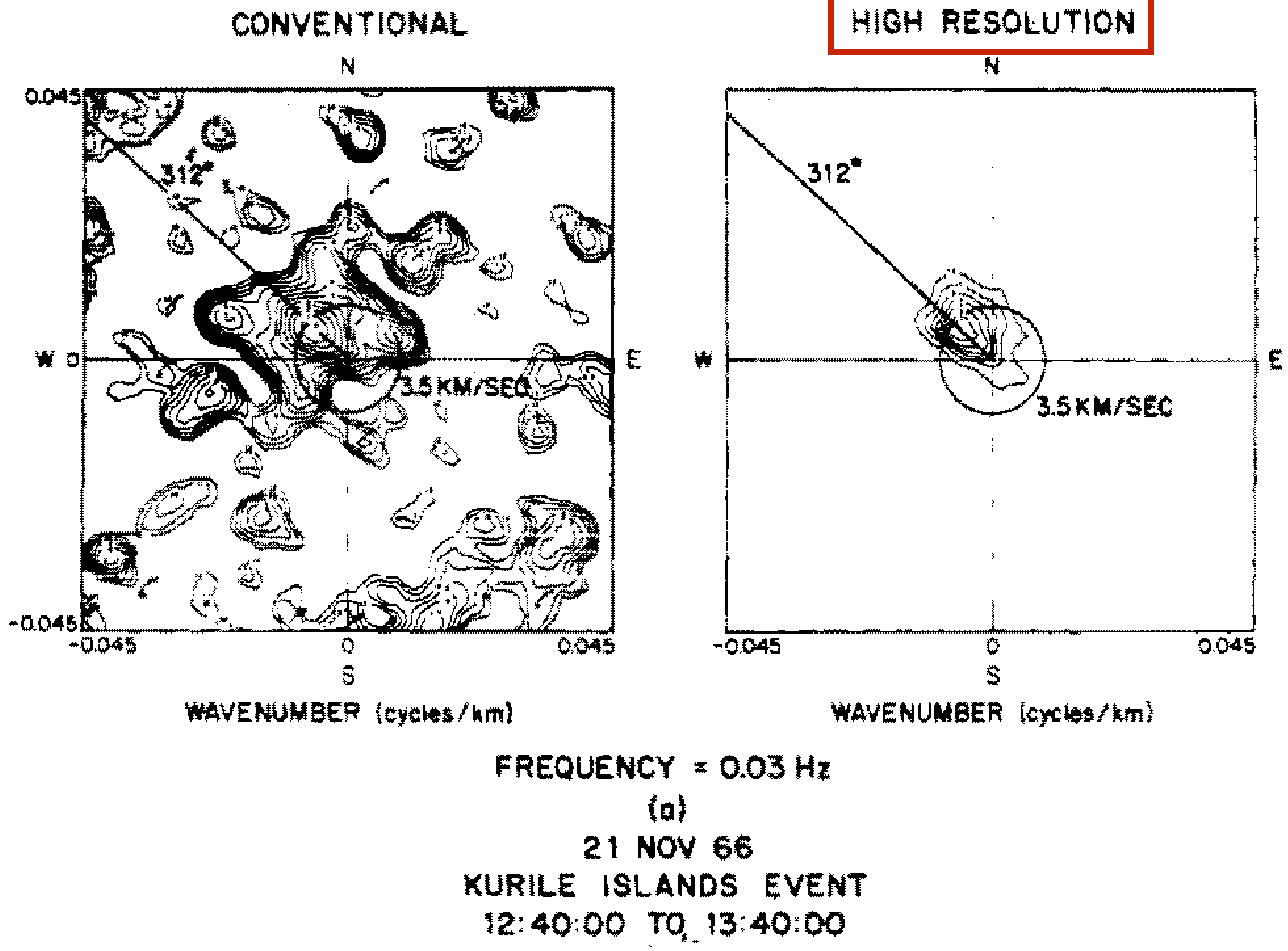


Fig. 5.1. Optimum detector for a known signal in additive Gaussian noise when the observation interval is large

21 × 25 = 525 sensors (!!)



Large Aperture Seismic Array (LASA)

Multiprobe Measurements to Understand Turbulence in Magnetospheric Geometry

- **Imaging global chaotic structures**
  [Brian Grierson, et al., *Phys Plasmas* **16**, 055902 (2009)]
- **Regulating turbulence with phase-controlled current injection**
  [Thomas Roberts, et al., *Phys Plasmas* **22**, 055702 (2015)]
- **Plasma compressibility and turbulence in magnetospheric geometry**
  [Darren Garnier, et al., *Phys Plasmas* **24**, 012506 (2017)]

➡ Tony Qian [Tues PM Undergrad Poster] **High-resolution measurement of turbulent (ω, k) power spectrum in a turbulent laboratory magnetosphere**

➡ Melissa Abler [Wed AM Poster] **Exciting the cascade in a turbulent laboratory magnetosphere**

High-Resolution Power Spectrum from ***Ensemble Cross-Correlation Matrix***

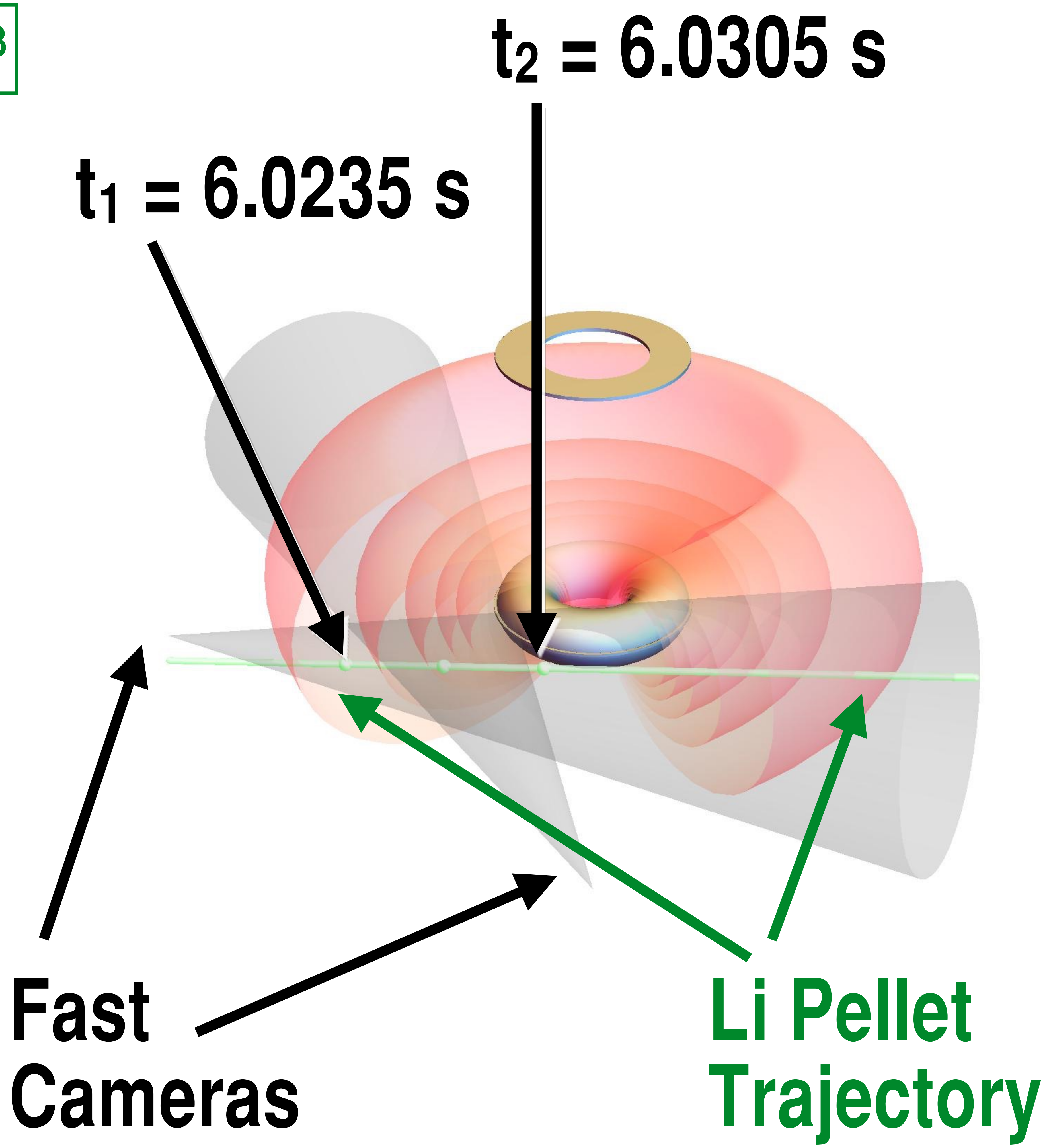
$$P(\omega,\, m) = \frac{1}{\sum_{i,j} \langle C_{i,j} \rangle^{-1} \exp[im(\theta_j - \theta_i)]}$$

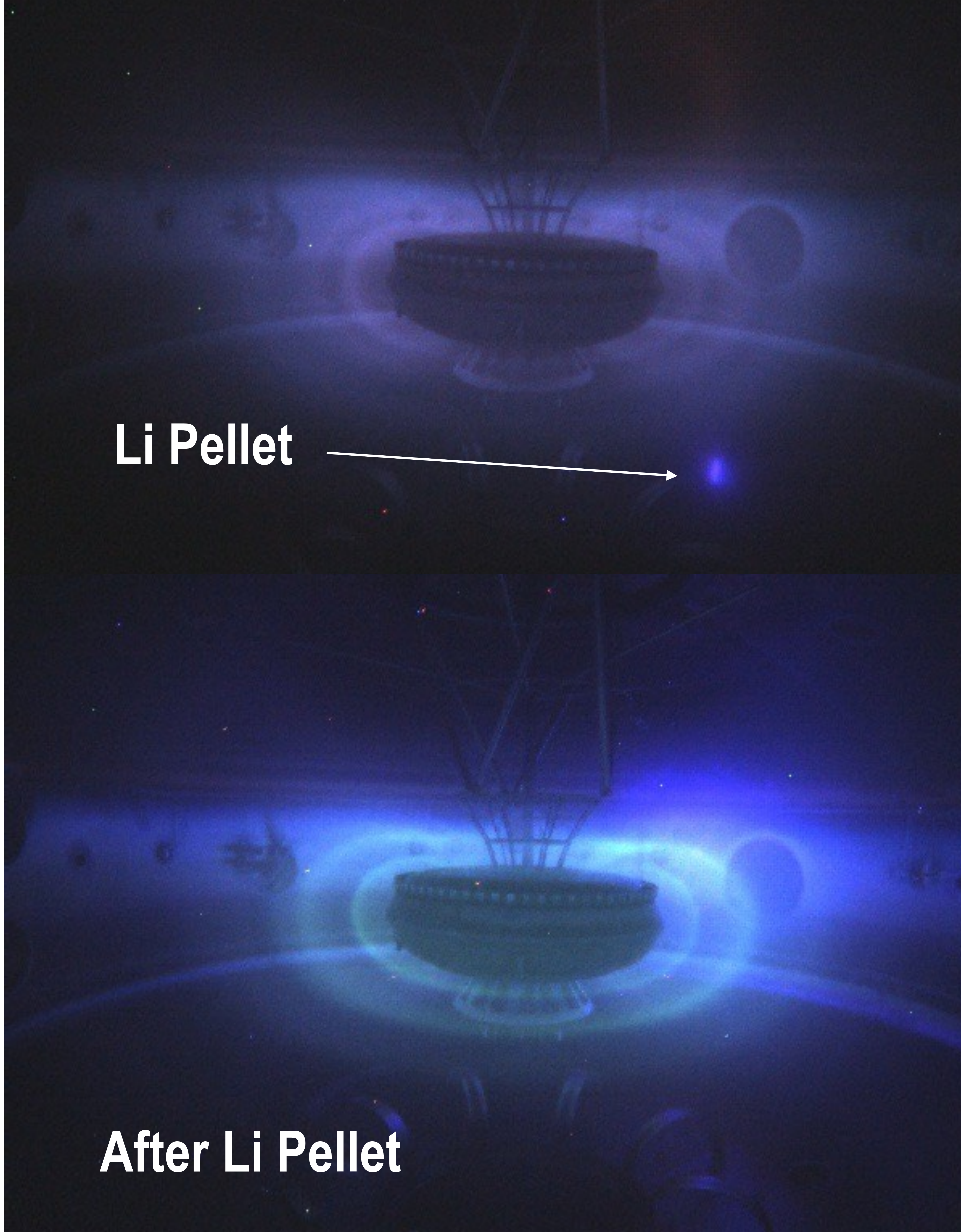
Enceladus: The Source of Saturn's E-Ring

Cassini-Huygens (1997-2017)

Li Pellet Injection Provides *Internal* Particle Source and Cools Plasma Core

1 mm³



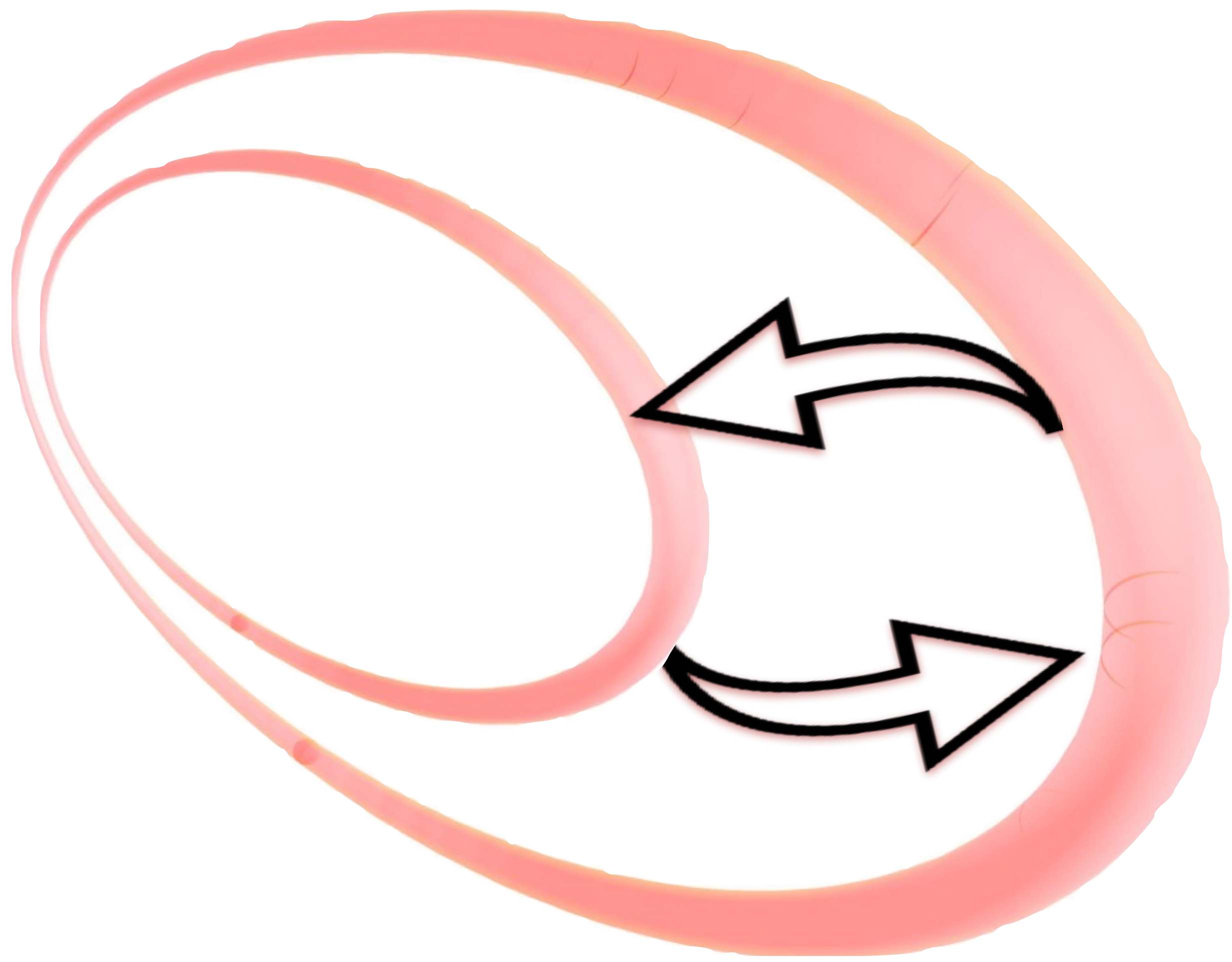


×5 Peak Density
×3 Electrons
÷3 Energy

15 ms
Pellet travels @ 175 m/s

Entropy Mode Physics

Rosenbluth, "Low-Frequency Limit of Interchange Instability," *Phys Fluids* **11**, 869 (1968).



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

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

Unique and Important profile parameters:

$\omega_n^* \sim \omega_d$ and $\omega_p^* \sim \gamma\, \omega_d$ *and* $\boldsymbol{\eta \sim 2/3}$

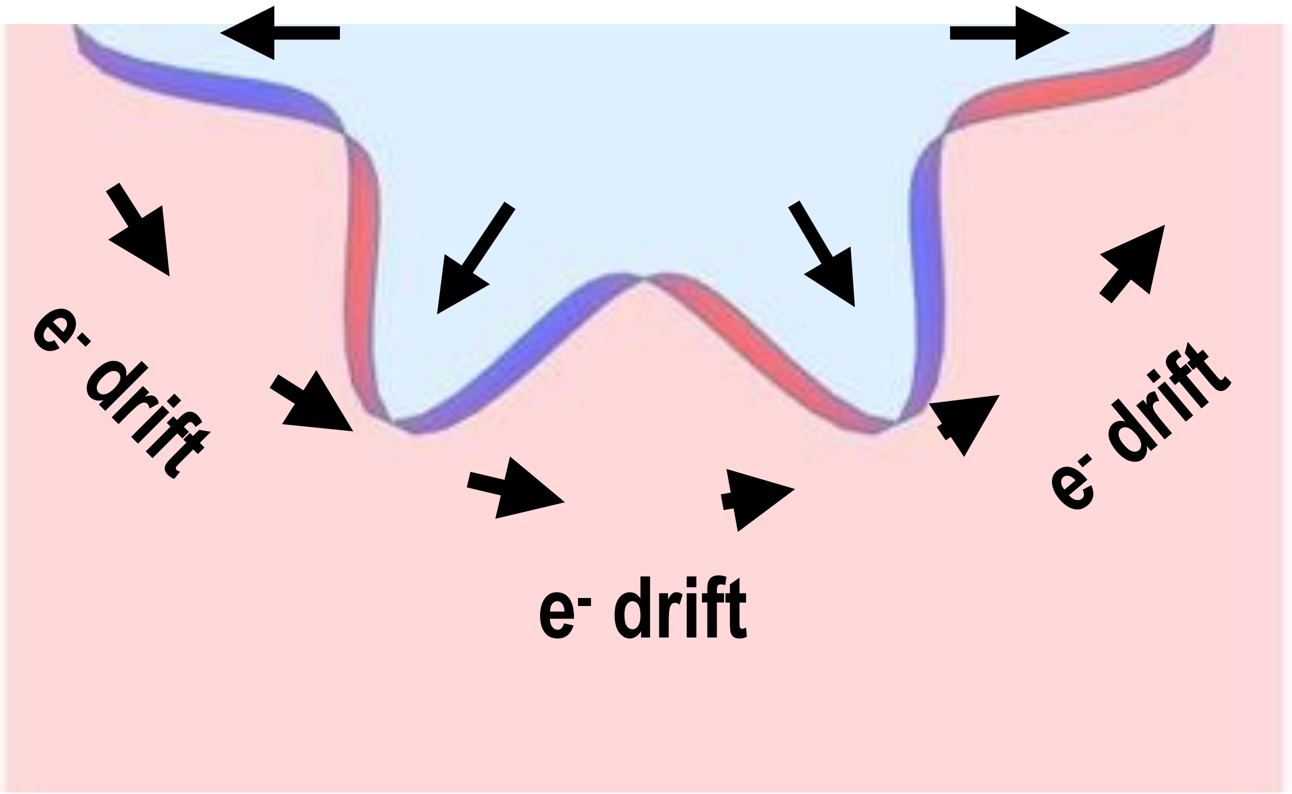
$$\Delta(nV) \sim \begin{cases} > 0, & \eta < 2/3 \\ = 0, & \eta = 2/3 \\ < 0, & \eta > 2/3 \end{cases}$$

Kesner, *Phys Plasmas*, **7**, 3887 (2000) (Linear drift-kinetics)
Ricci, Rogers, Dorland, and Barnes, *Phys Plasmas*, **13**, 062102 (2006) (Linear gyro-fluid)

Entropy Mode ***Reverses*** Direction with η

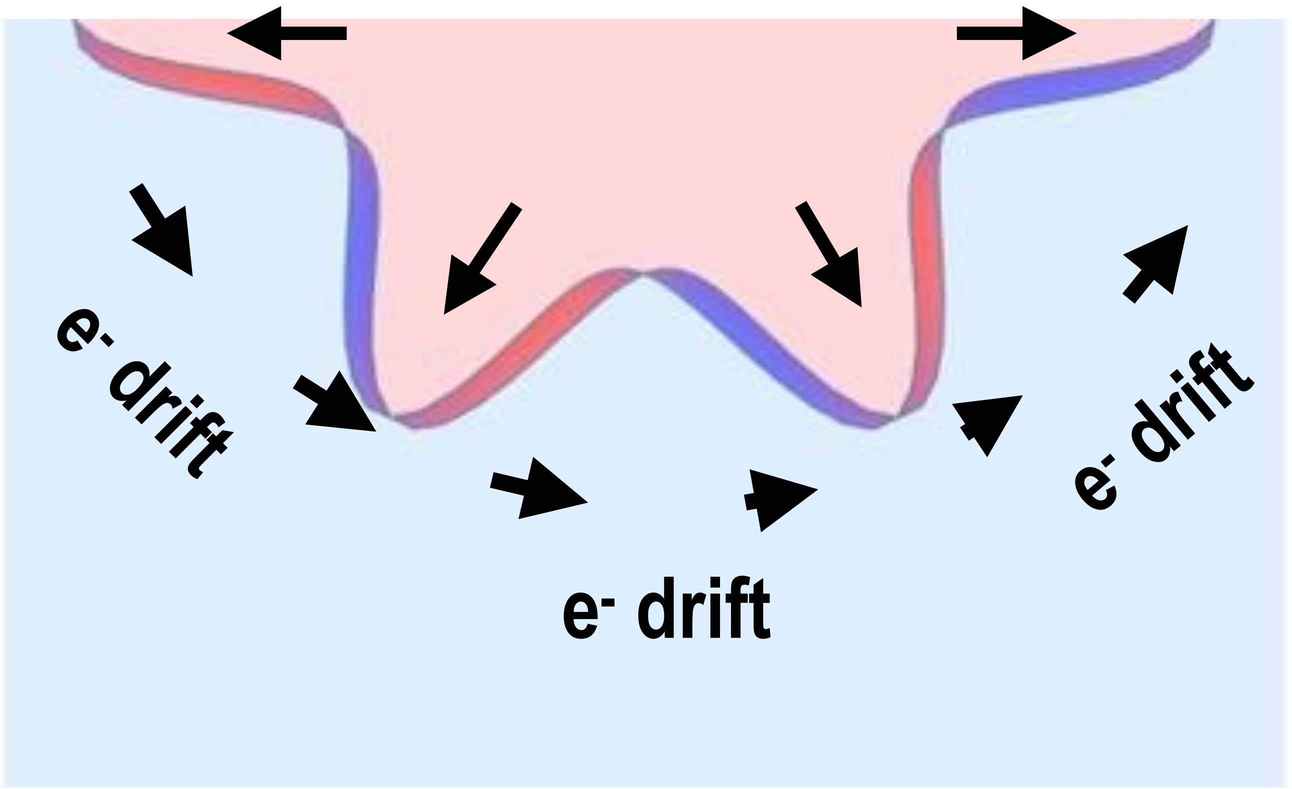
$\eta < 2/3$

"Cool Core"

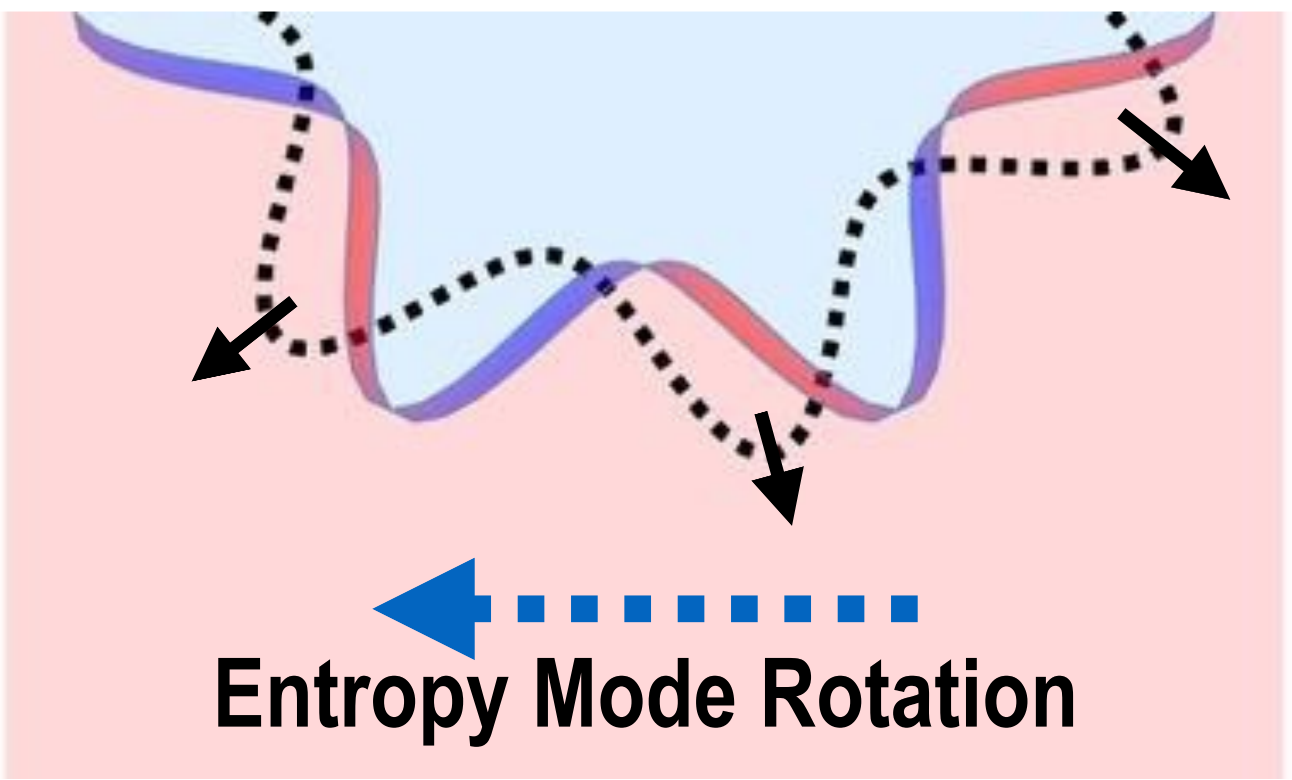


$\eta > 2/3$

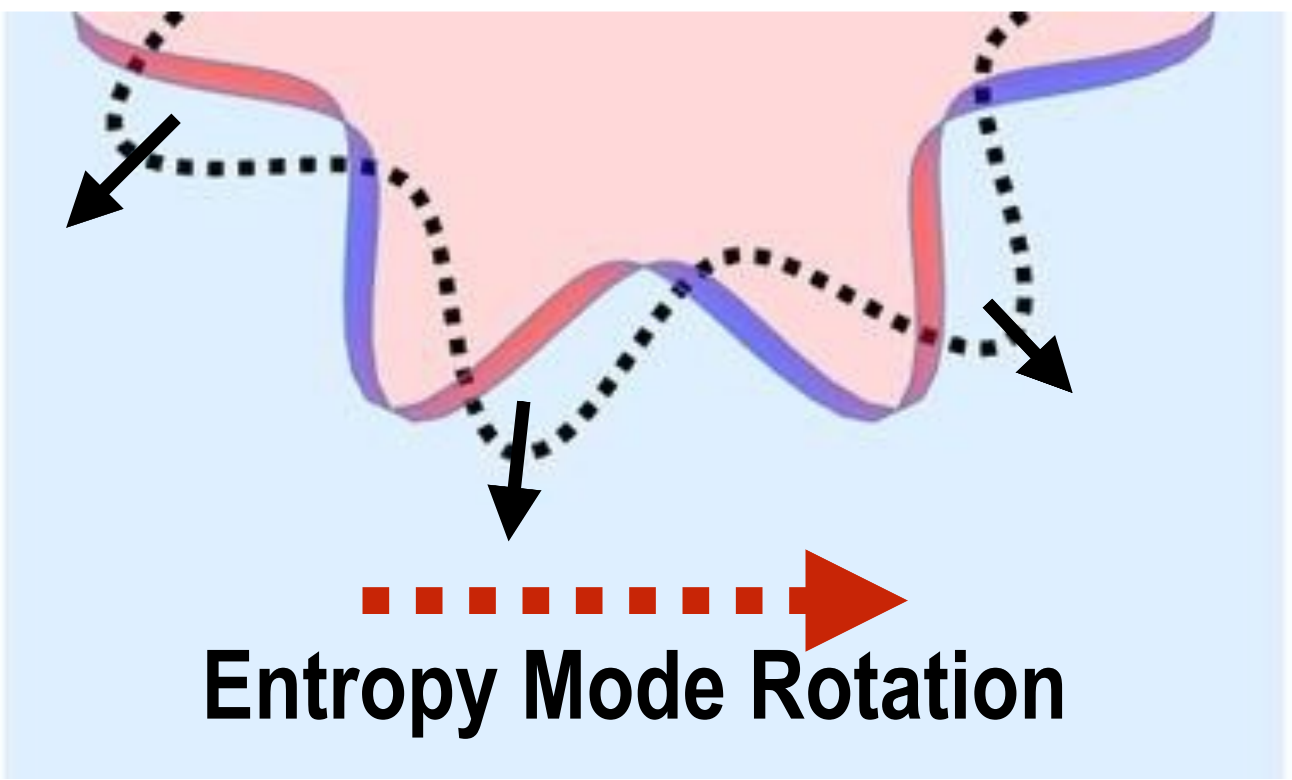
"Warm Core"



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



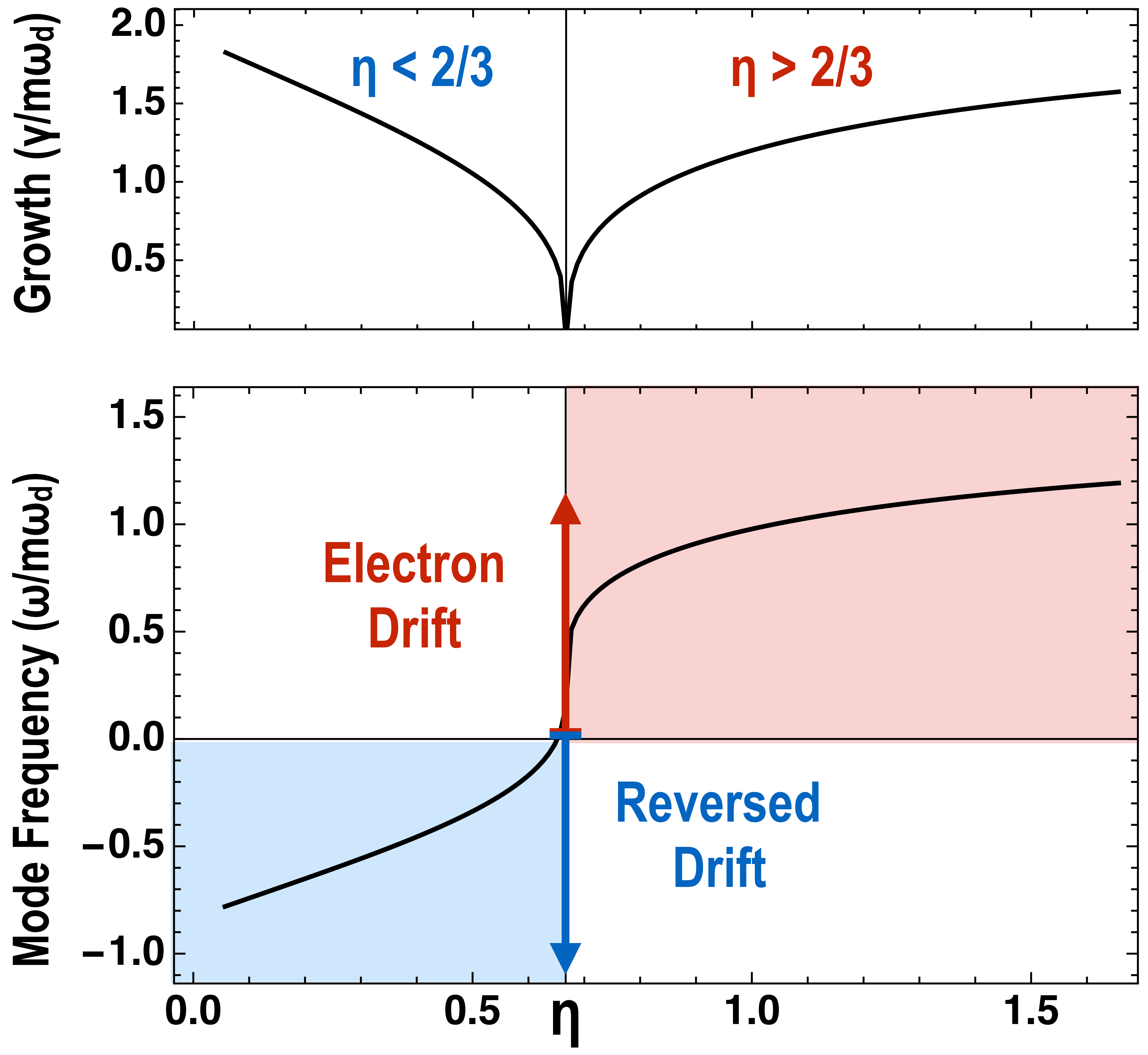
Inward Temperature Flux
Outward Particle Flux



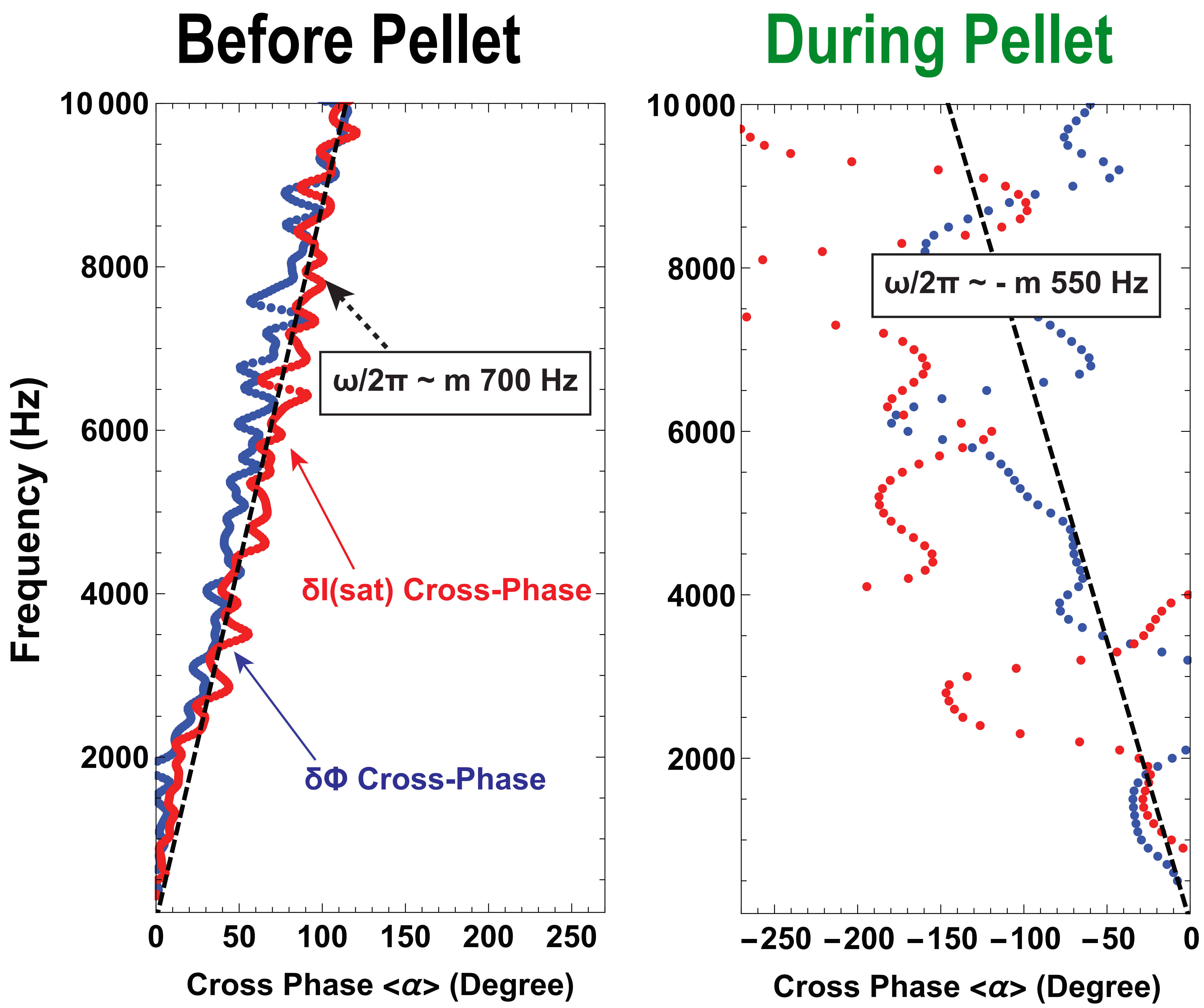
Outward Temperature Flux
Inward Particle Flux

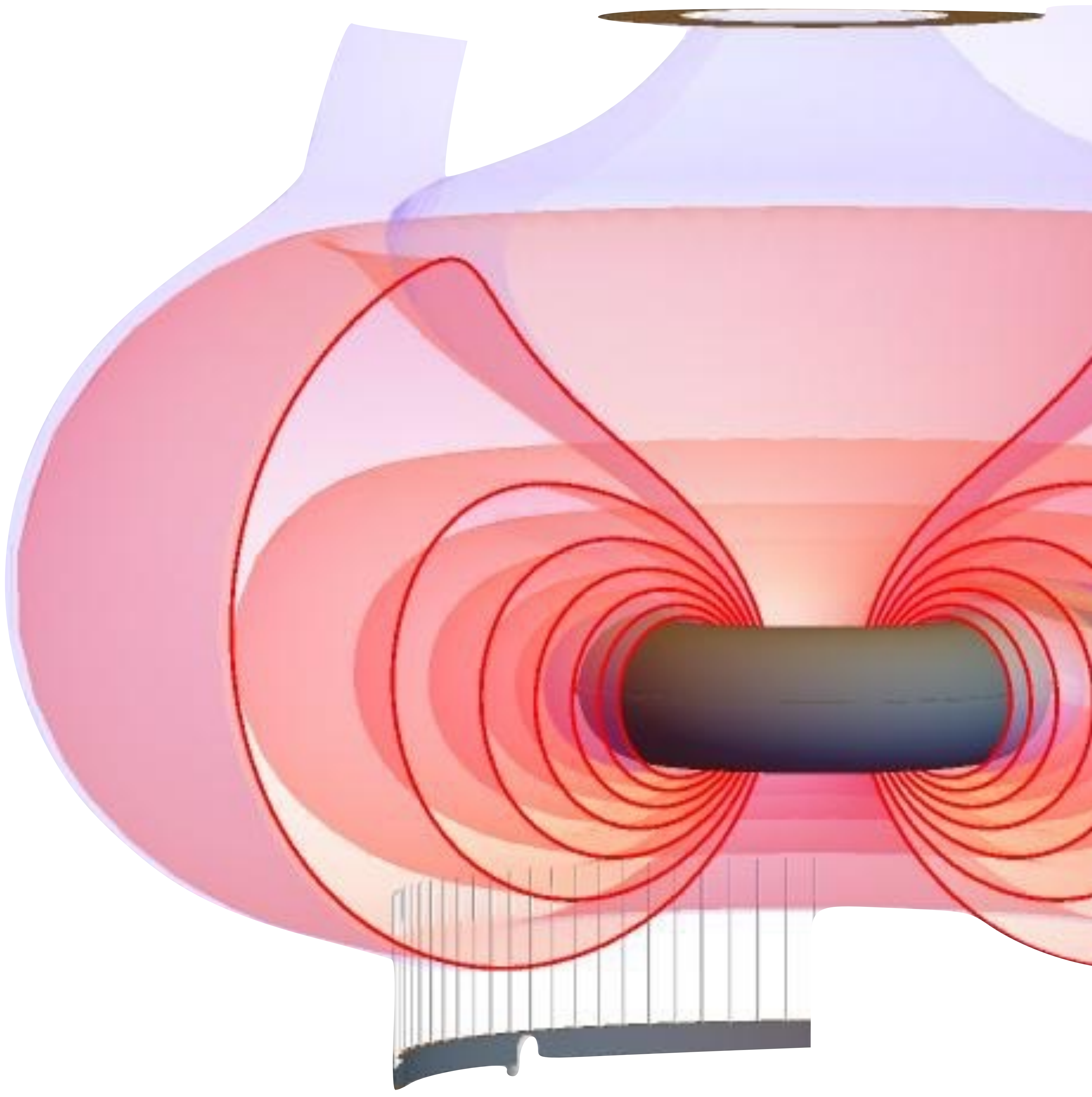
$\Delta W_p \sim \Delta(PV^{5/3}) \sim 0$

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



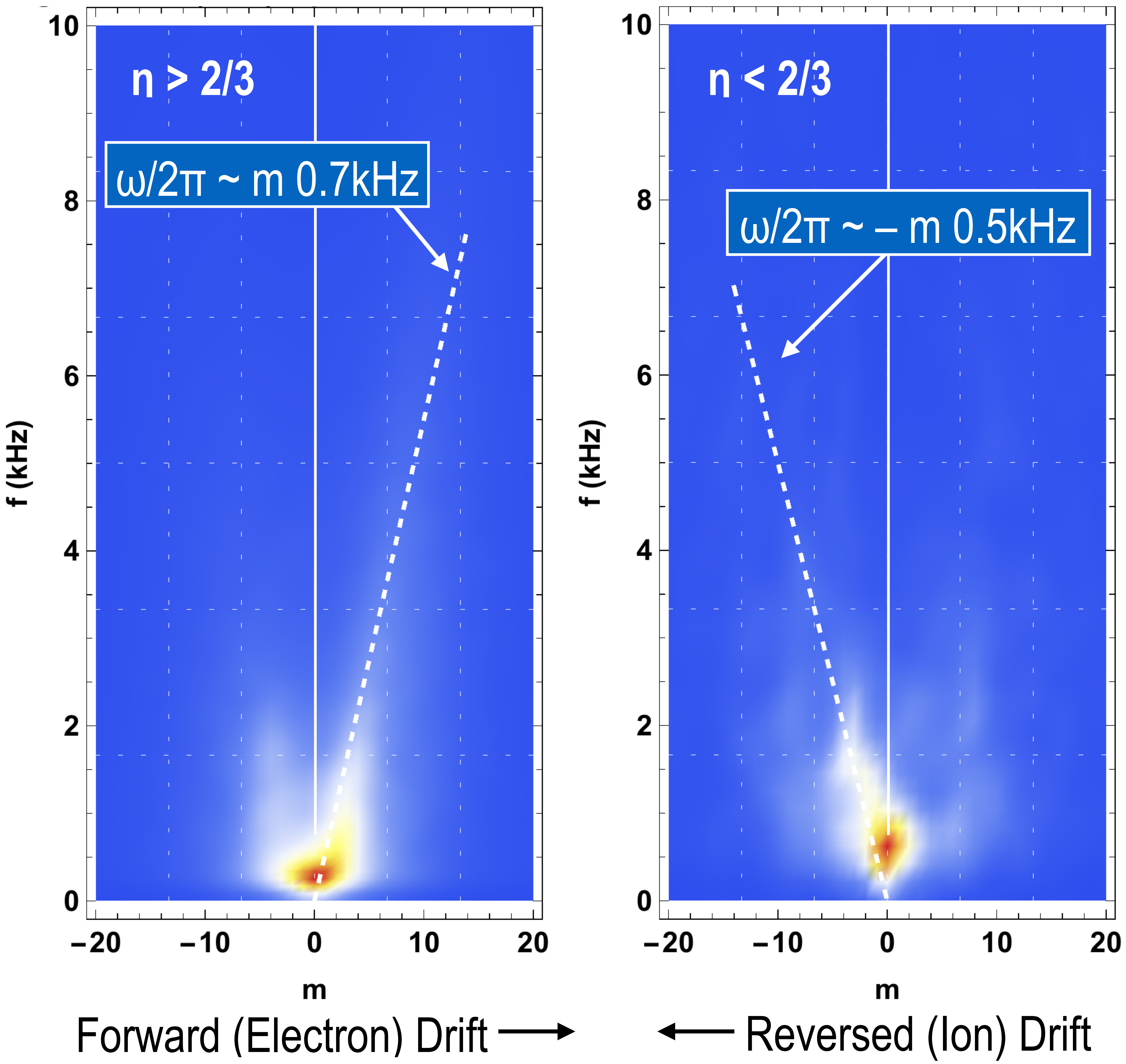
Ensemble Cross-Phase: *Two* Probes



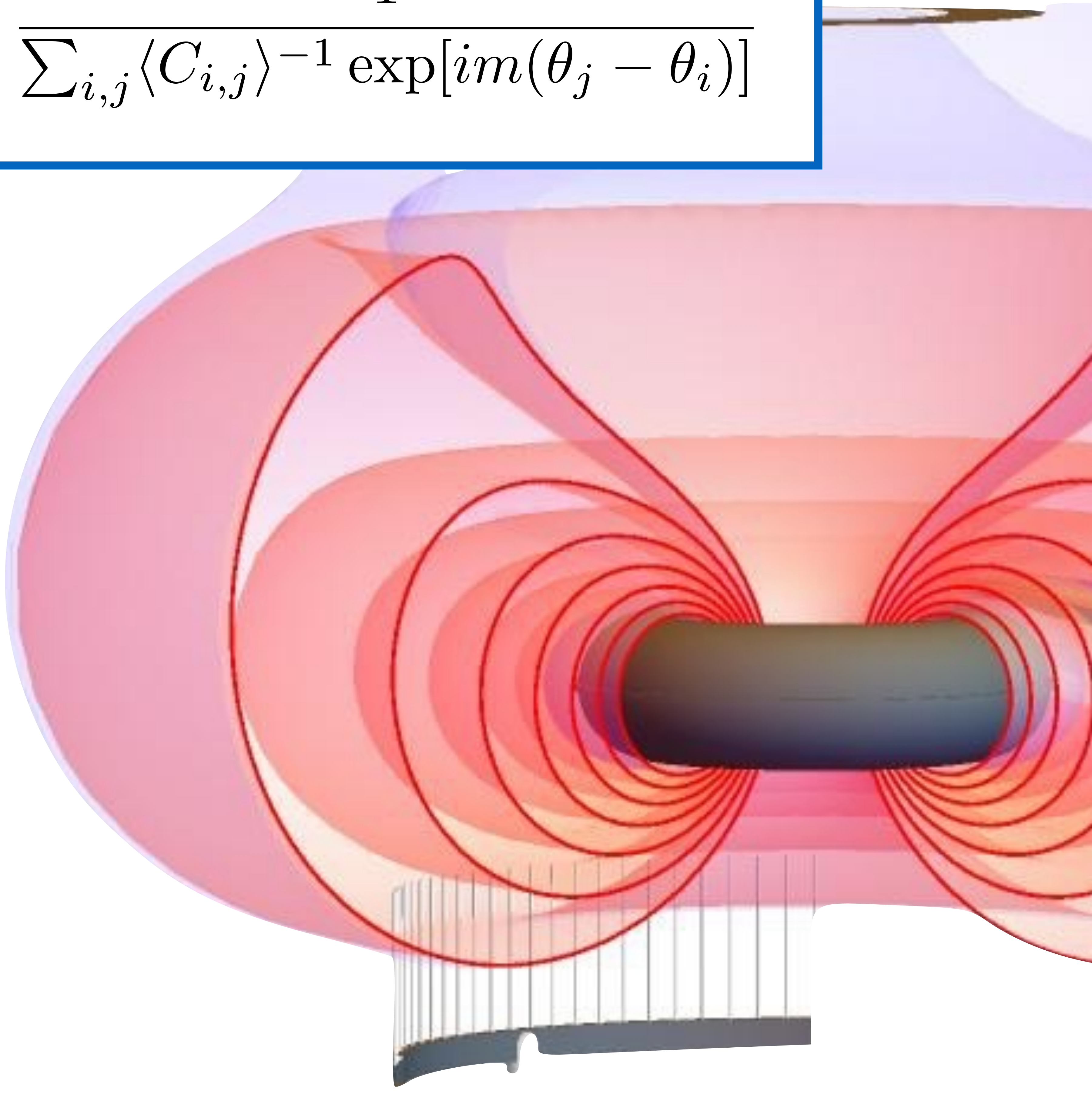


High-Res Power Spectra: ***Sixteen*** Probes

Power Spectrum $|\delta\Phi(\omega,m)|^2$

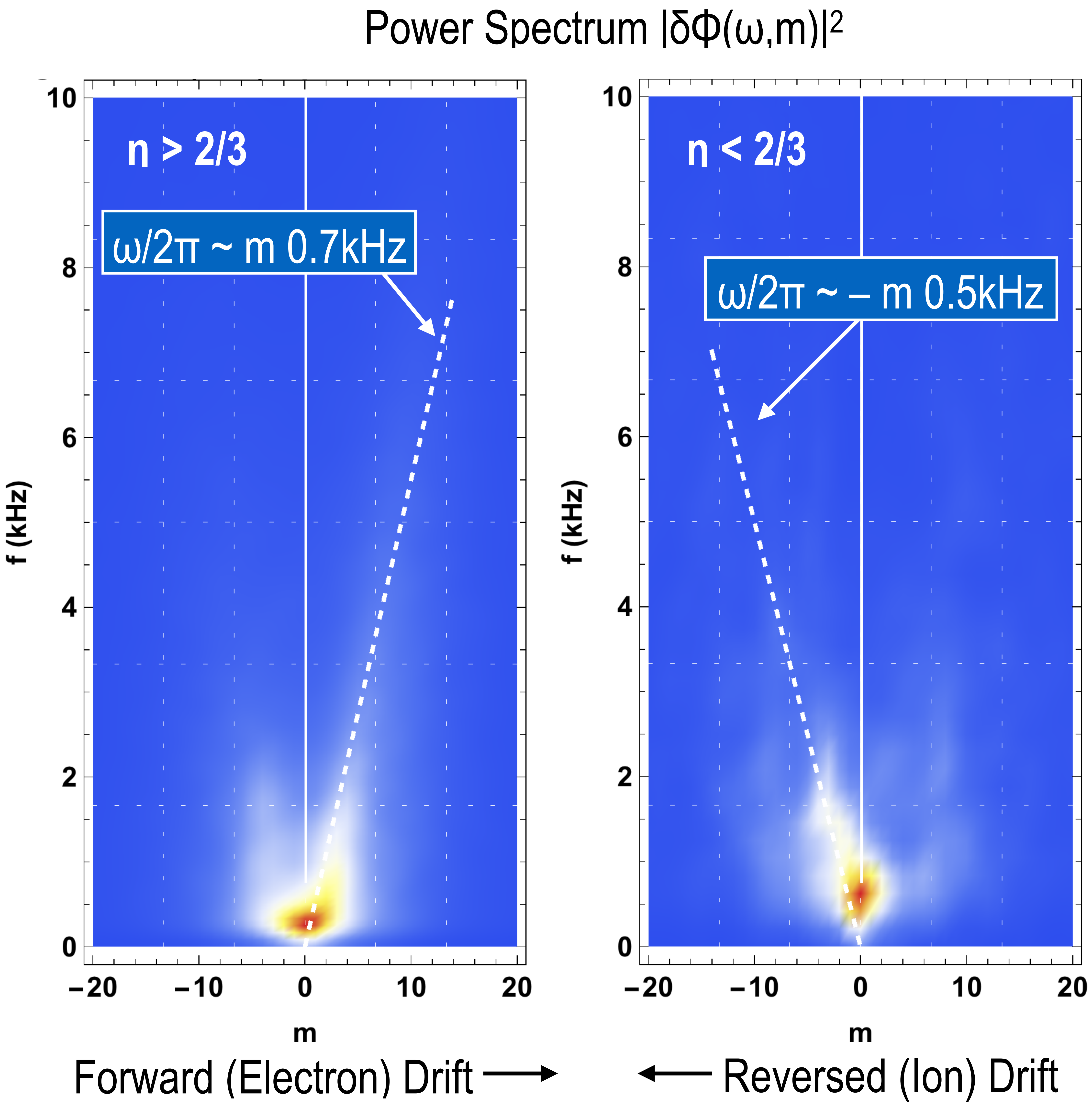


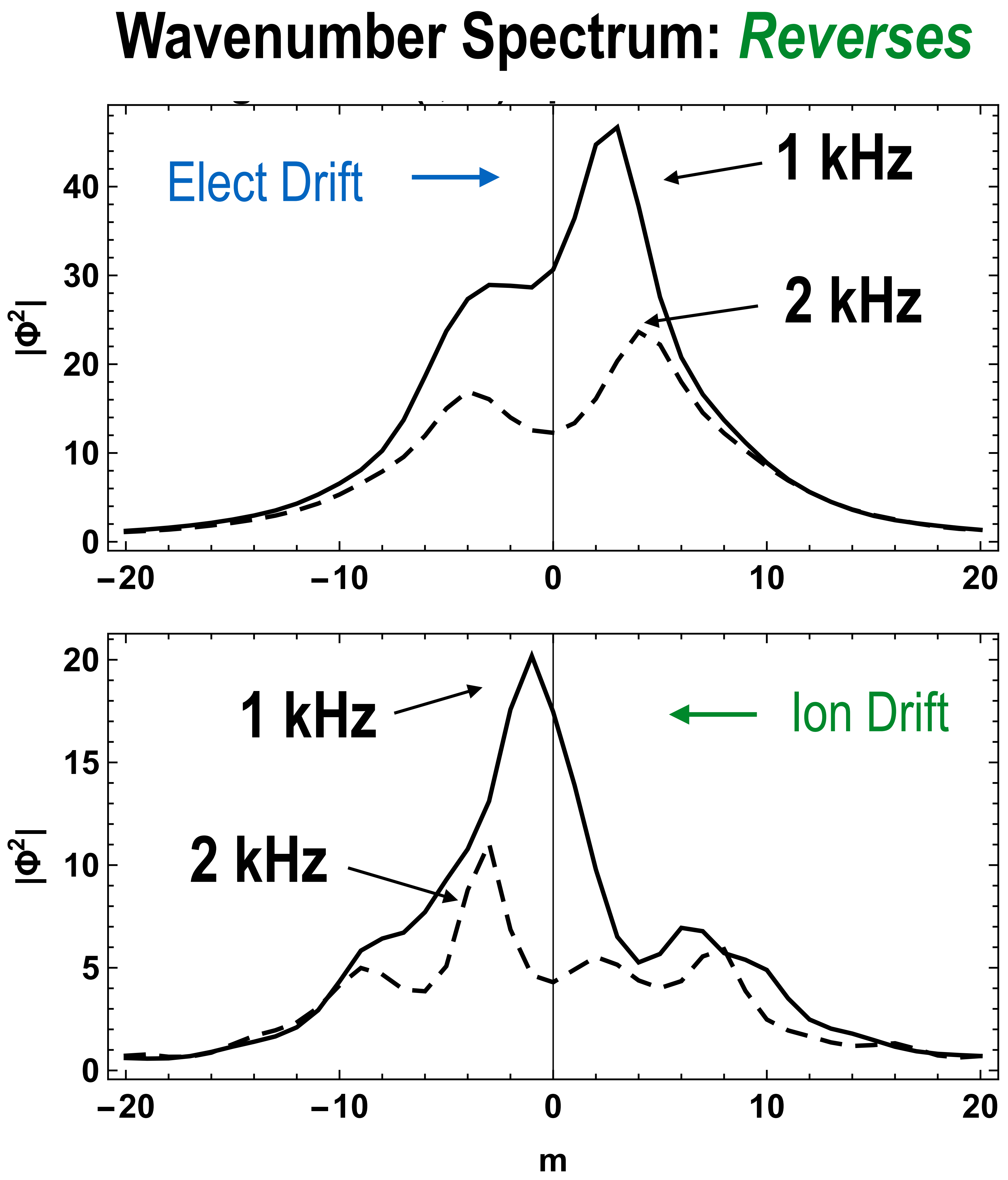
$$P(\omega,\, m) = \frac{1}{\sum_{i,j} \langle C_{i,j} \rangle^{-1} \exp[im(\theta_j - \theta_i)]}$$



(See Poster: Tony Qian / Tues PM Undergrad)

High-Res Power Spectra: ***Sixteen*** Probes



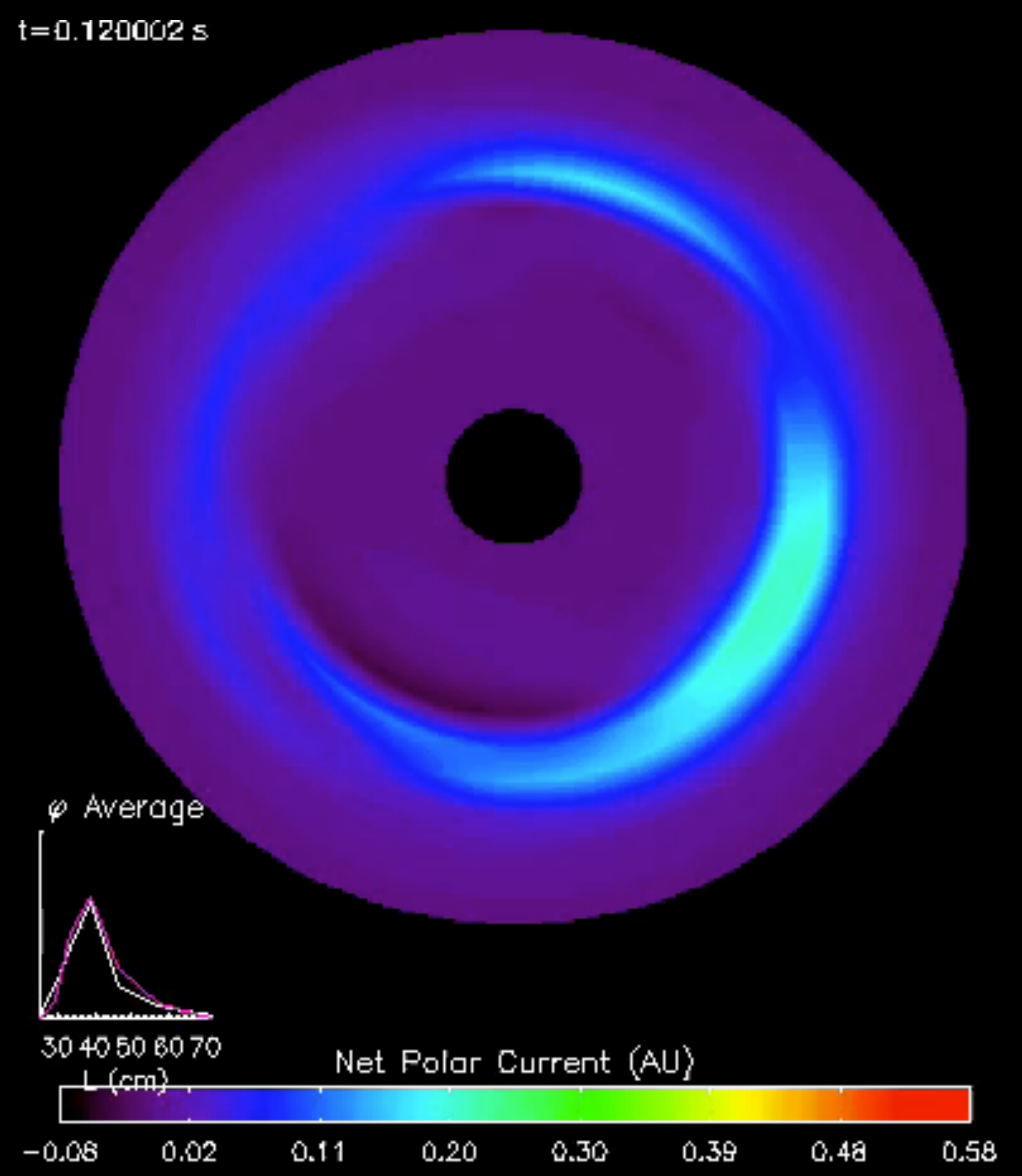


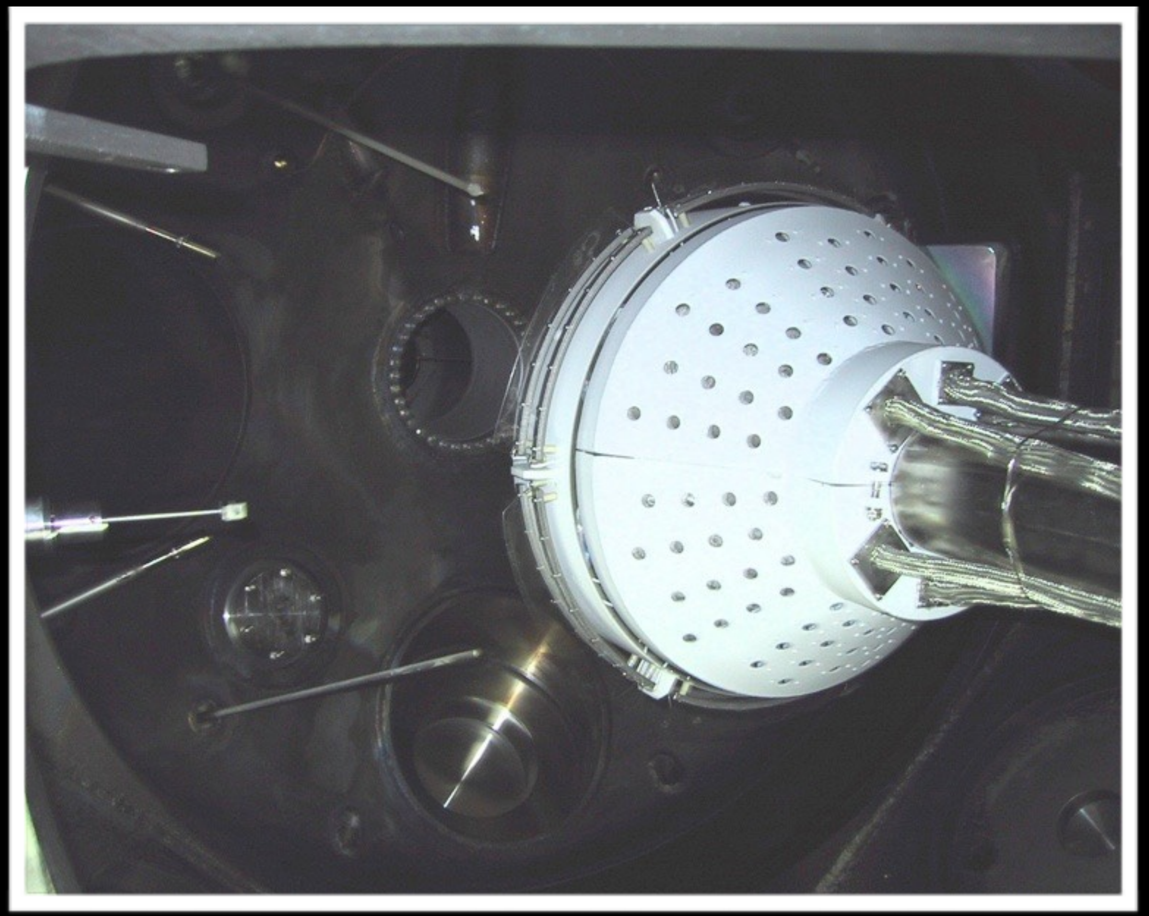
(See Poster: Tony Qian / Tues PM Undergrad)

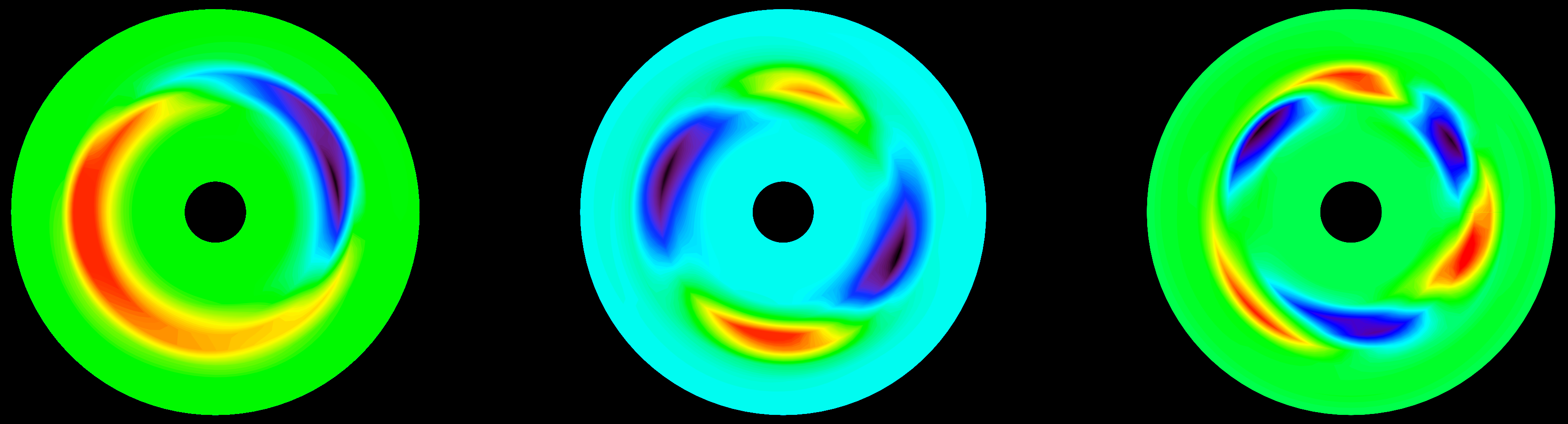
Whole Plasma Imaging of Entropy Mode Structure

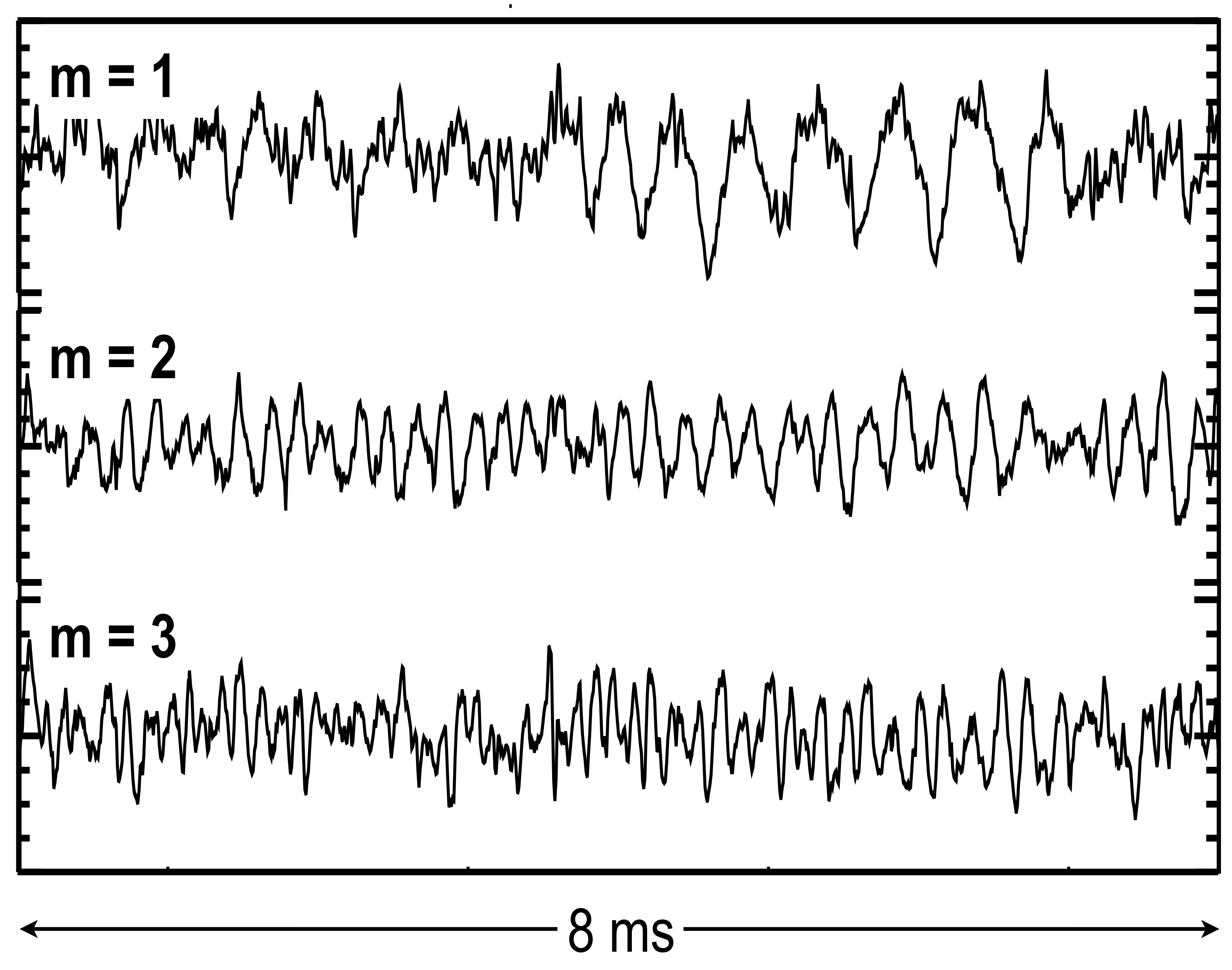
Rotating Global Modes, Chaotic Amplitudes and Phases, Inverse Cascade

Proton "Aurora" in the Lab



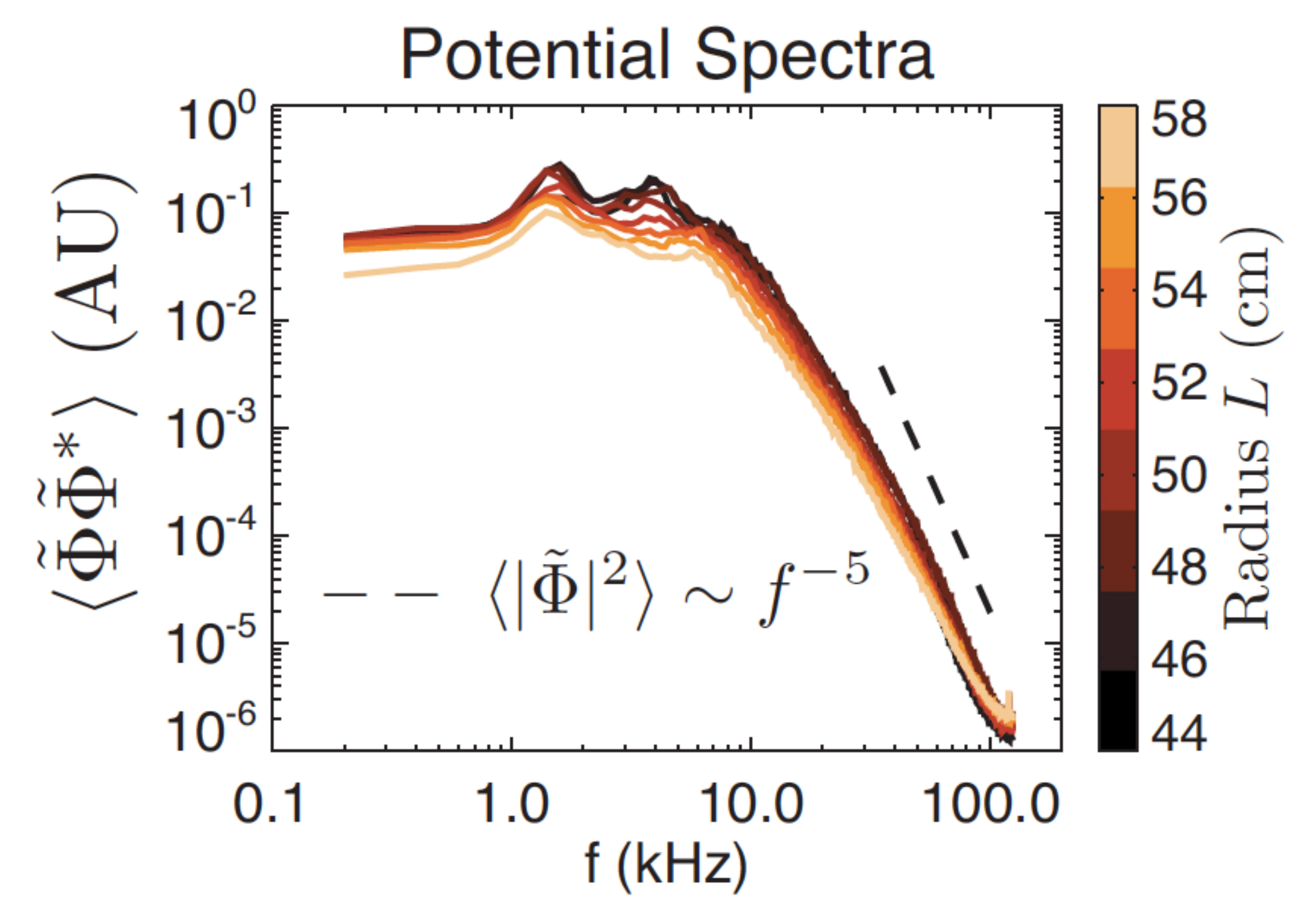


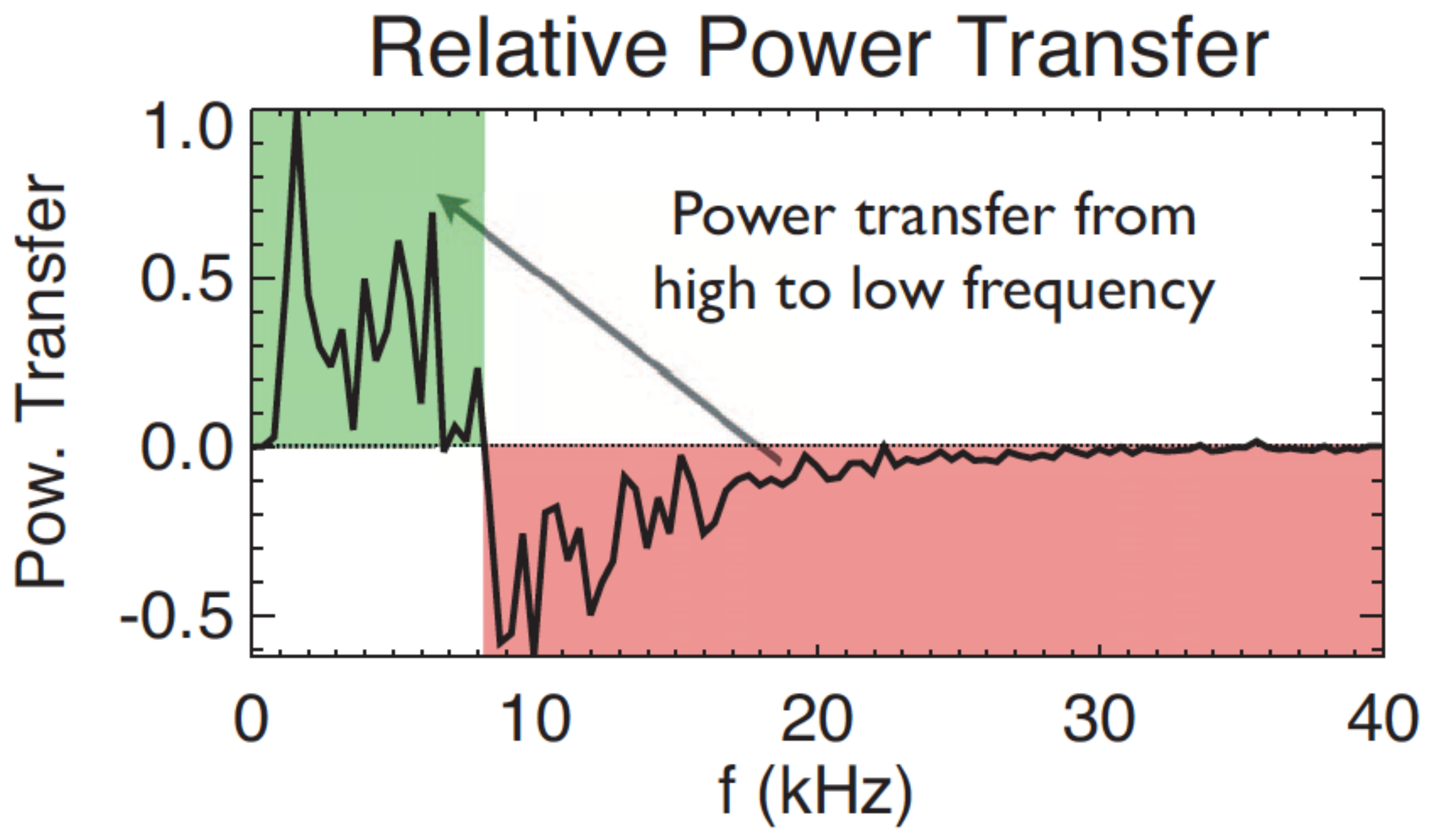




Global Structures are Chaotic

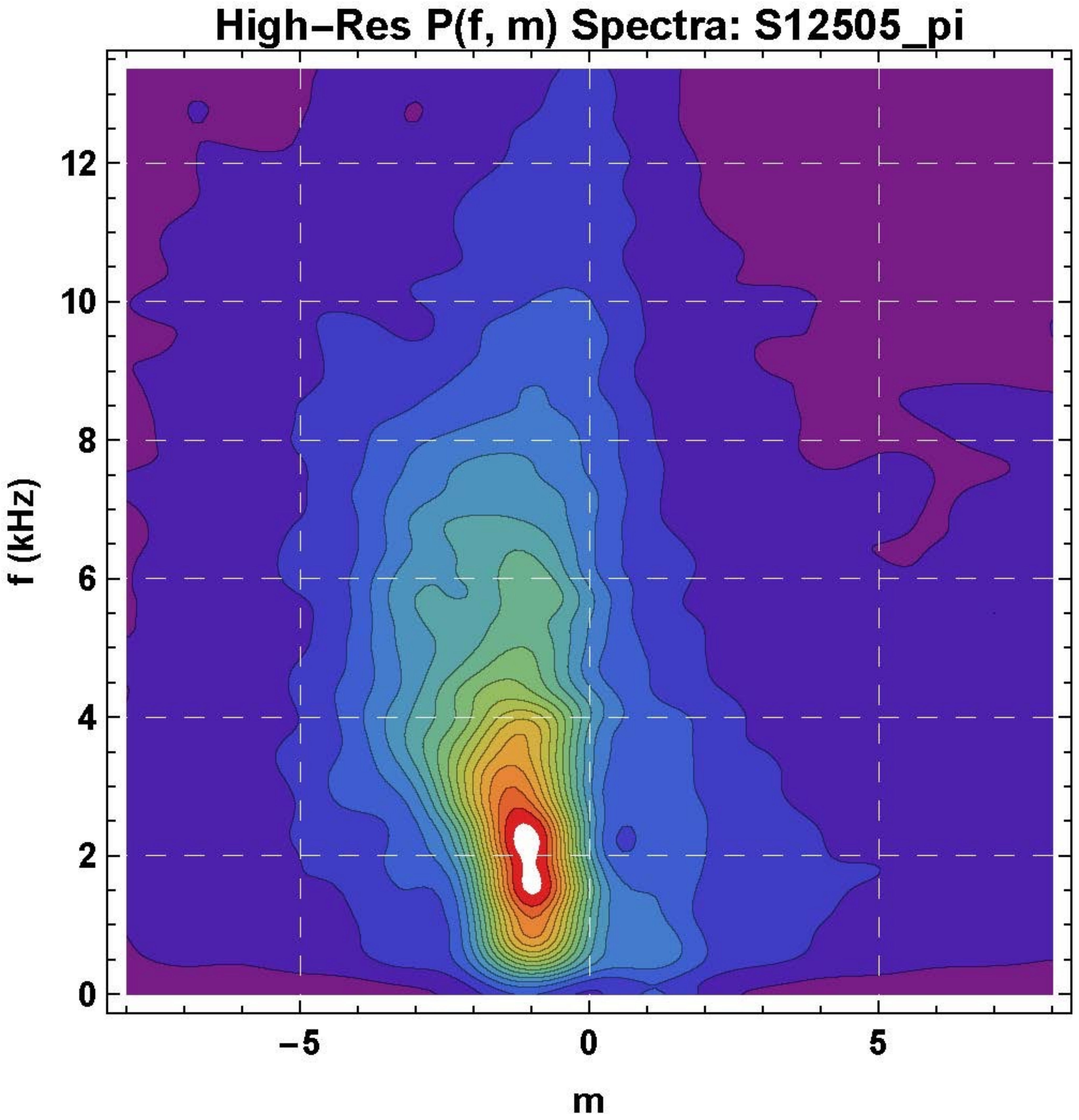
One Probe





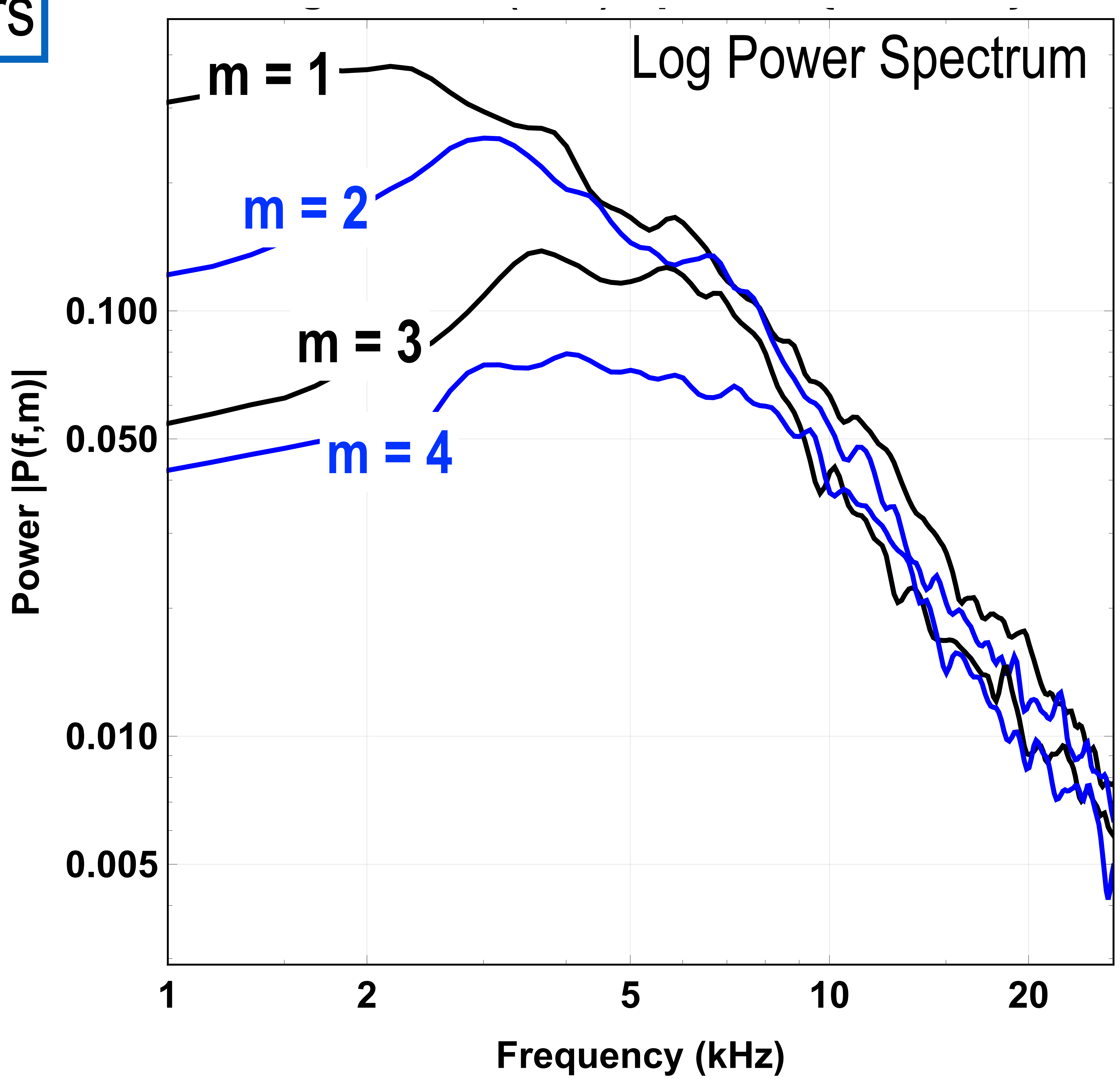
Grierson, M. Worstell, and M. Mauel, *Phys Plasmas* **16**, 055902 (2009).

High-Resolution Power Spectrum



← Forward (Electron) Drift

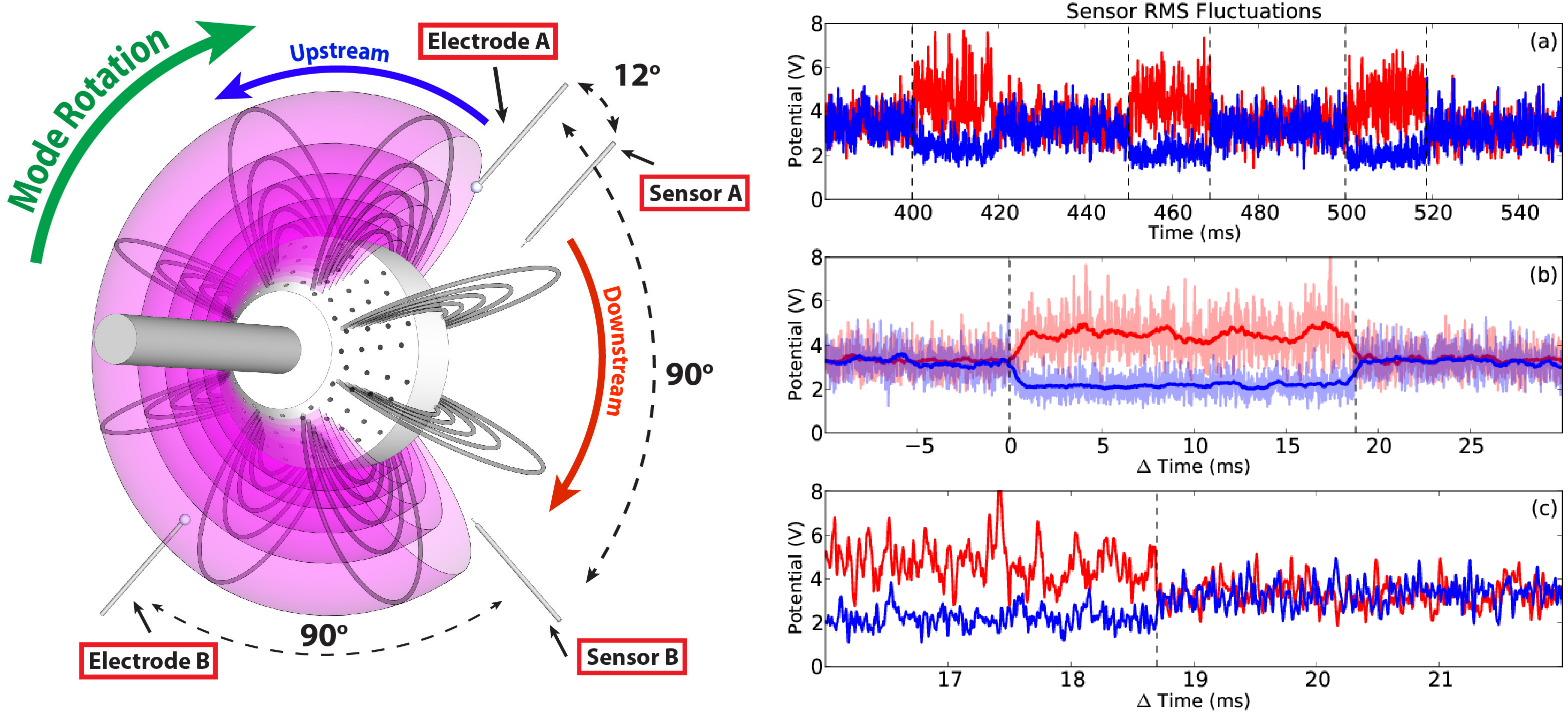
21 Sensors



(See Poster: Melissa Abler / Wed AM)

Regulating Turbulent Convection with an “Artificial Ionosphere”

(Current Injection Feedback)



Ionospheric Resistance:
$\Sigma < 0$ or $\Sigma > 0$

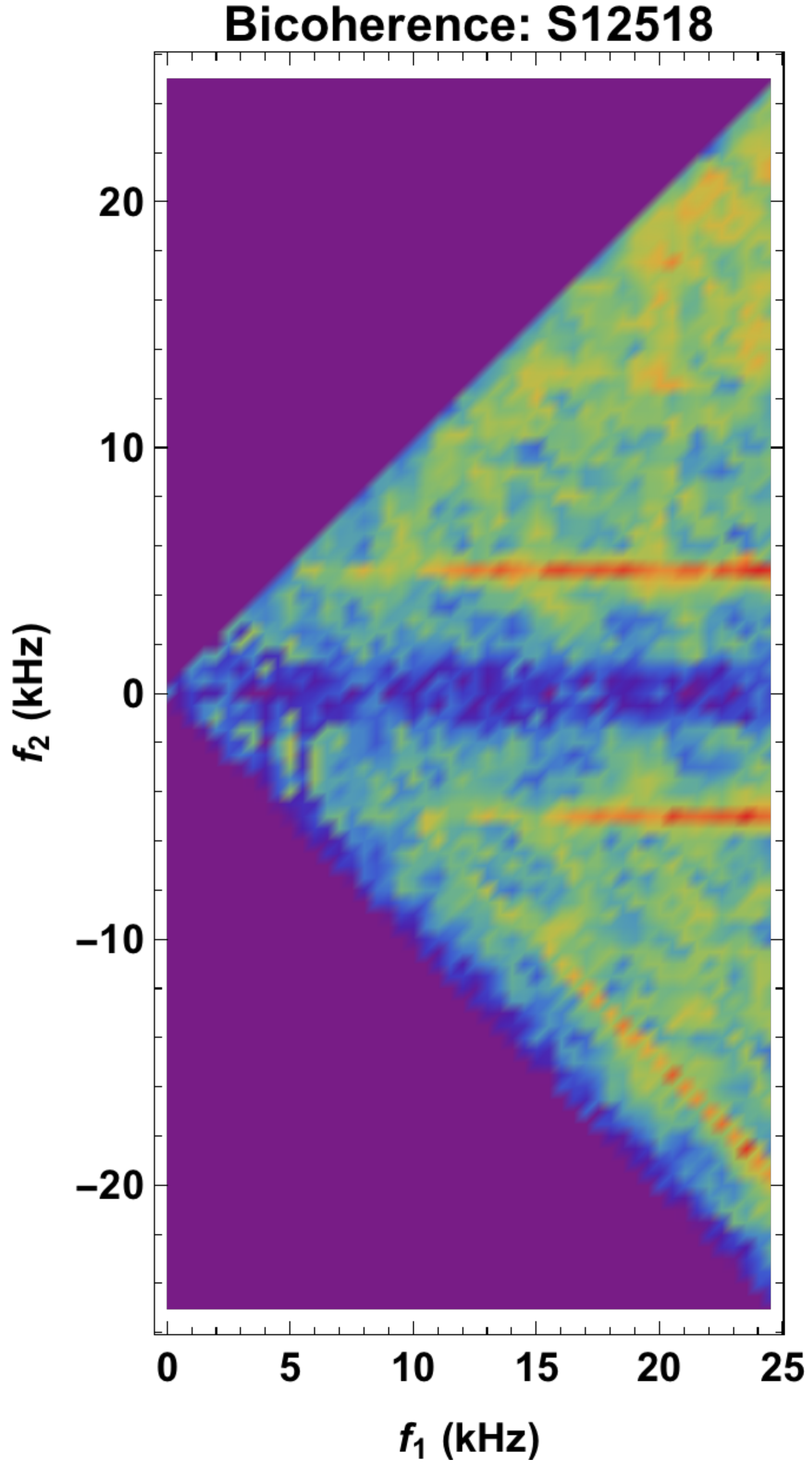
T.M. Roberts, Mauel, and Worstell, "Local regulation of interchange turbulence in a dipole-confined plasma torus using current-collection feedback," Phys Plasmas 22, 055702 (2015).

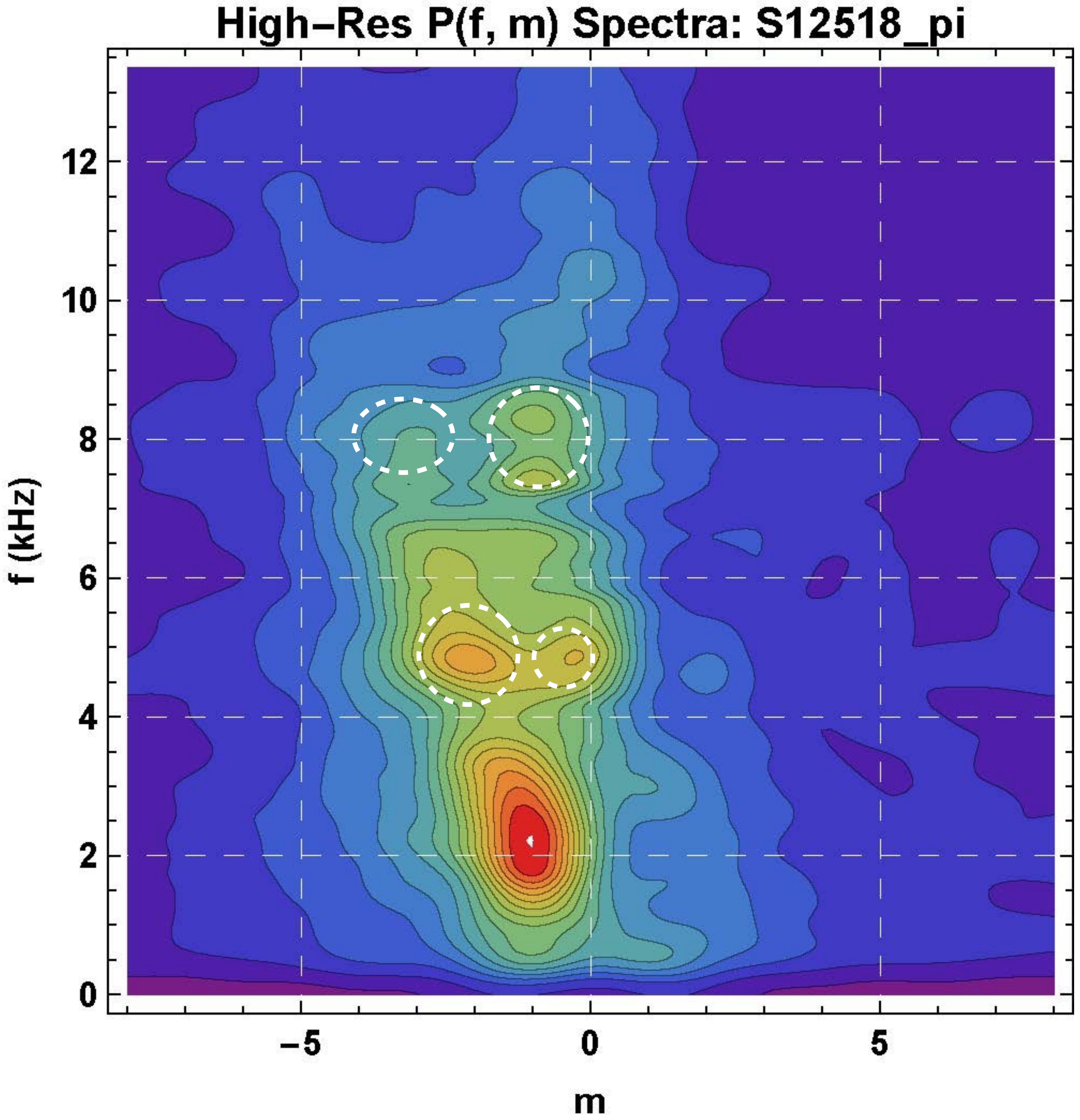
(See Poster: Melissa Abler / Wed AM)

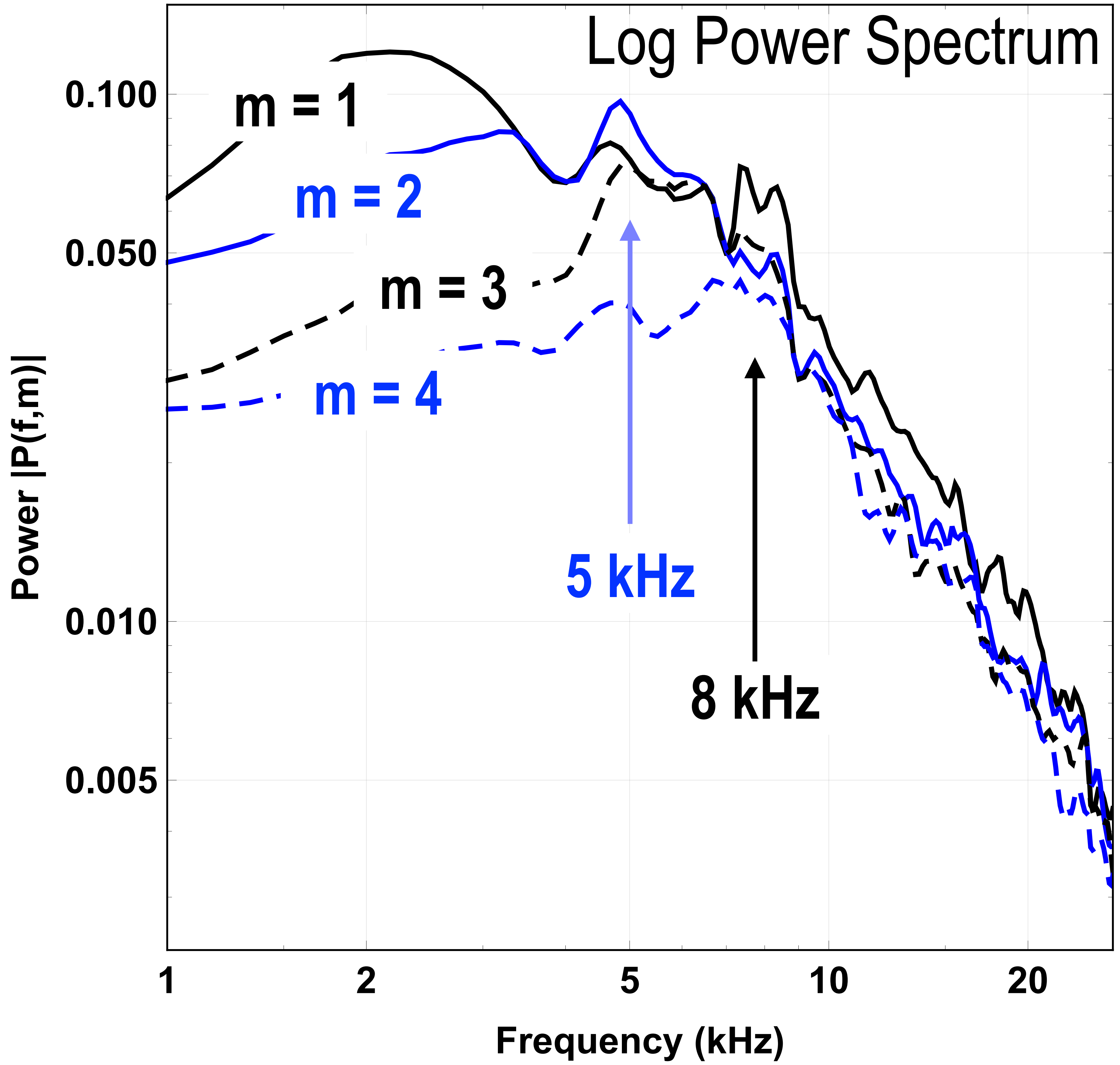
High-Resolution Power Spectrum

Local Current Injection @ 5 kHz & 8 kHz

21 Sensors







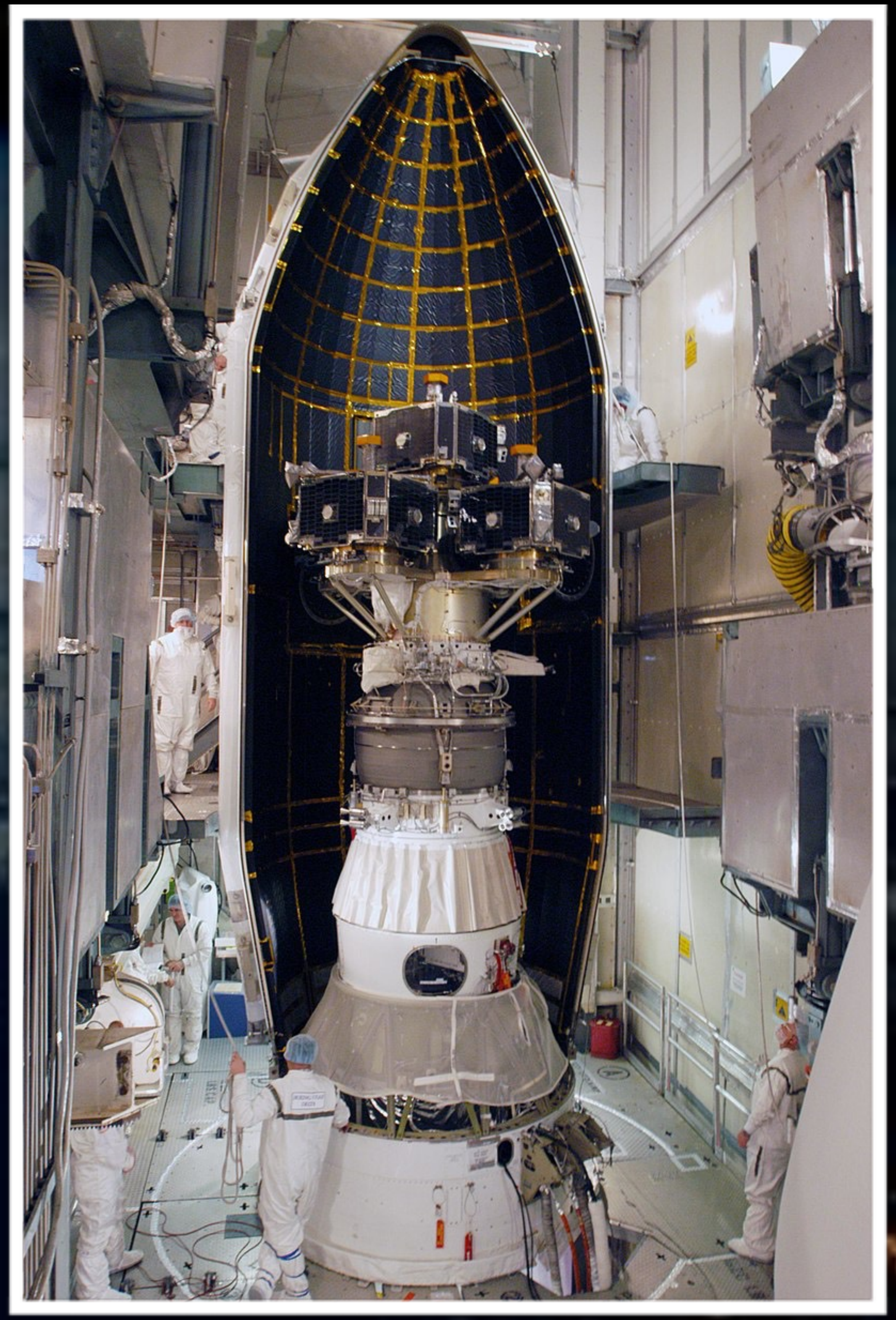
Towards direct measurement on nonlinear wave energy transfer in turbulent plasma

(See Poster: Melissa Abler / Wed AM)

Summary

- "Progress requires bunches of satellites"
  - Jim Dungey (1966)
- Laboratory instruments demonstrate and validate *methods for multi-point measurements* of plasma dynamics, turbulence, and transport.
- Capon's maximum likelihood method for multipoint measurements show *high-resolution* details of the nonlinear cascade and turbulent spectra in laboratory magnetosphere.

MMS



THEMIS

(See Posters: Melissa Abler and Tony Qian)