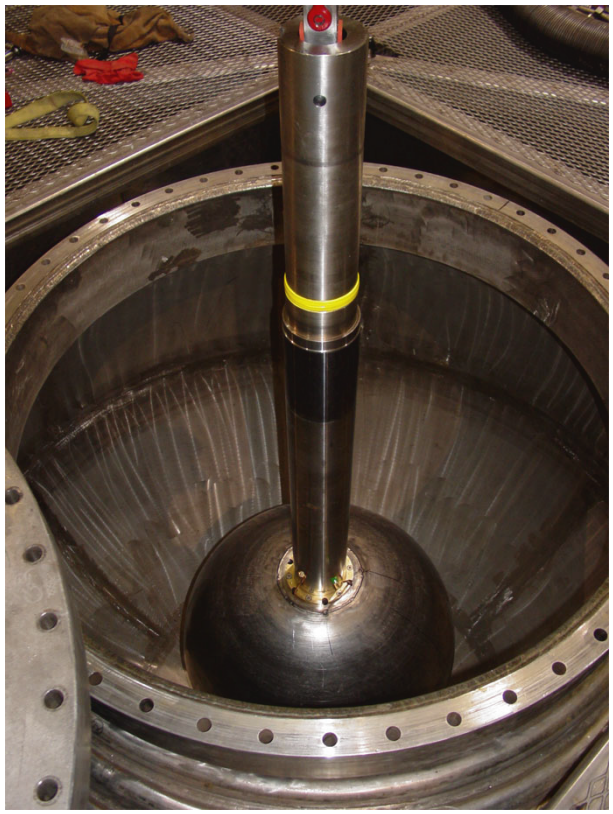
UNIVERSITY OF MARYLAND

Bi-Stable Turbulent Spherical Couette

Daniel S. Zimmerman
Santiago Andrés Triana
Daniel P. Lathrop
Physics/IREAP



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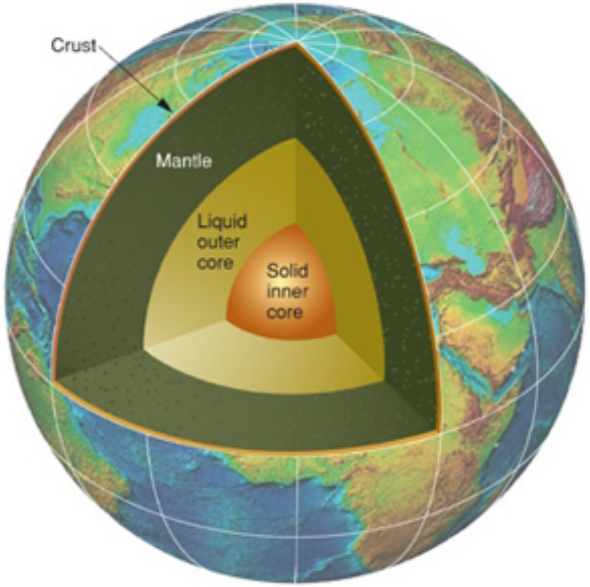
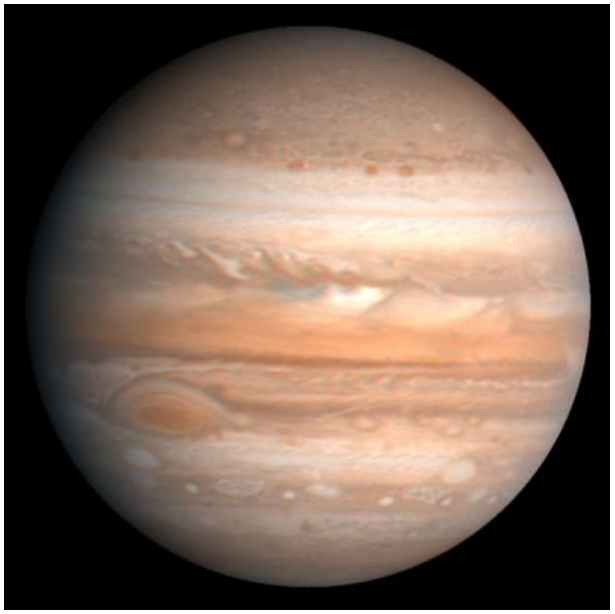
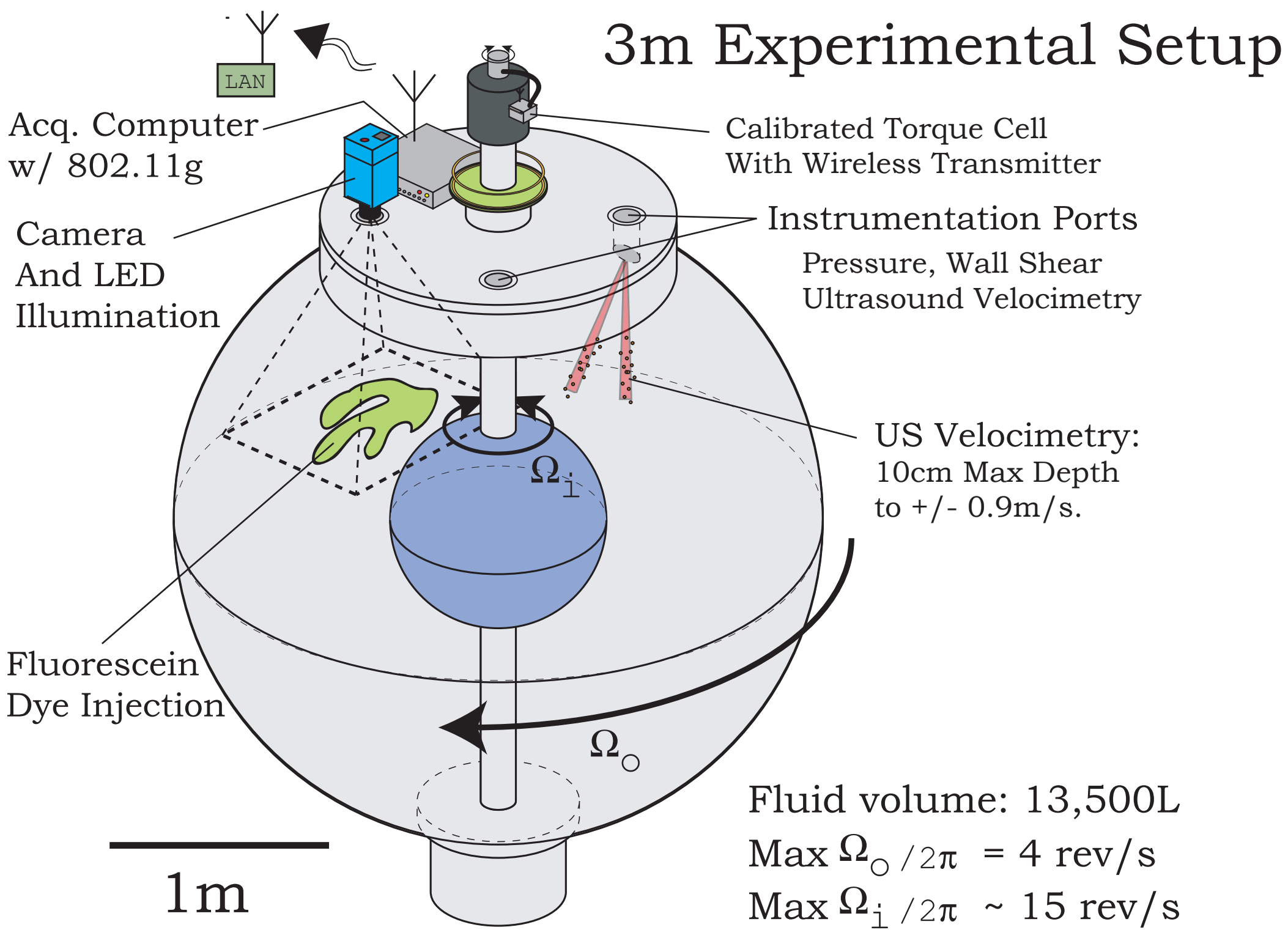
Rotation and Turbulence





Close to home and afar...
Coriolis acceleration is important...
Not just homogeneous, isotropic, 3D...
Atmospheres, oceans, planetary dynamo...

3m Experimental Setup



Fluid volume: 13,500L

Max $\Omega_o / 2\pi$ = 4 rev/s

Max $\Omega_i / 2\pi$ ~ 15 rev/s

Max Power Input: 320kW

Rotating Turbulence

$$\frac{\partial \vec{U}}{\partial t} + Ro\vec{U} \cdot \nabla \vec{U} + 2\hat{z} \times \vec{U} = -\nabla p + E\nabla^2 \vec{U}$$

$$Ro = \frac{U}{\Omega L} \qquad E = \frac{\nu}{\Omega L^2}$$

System - Scale, typical Spherical Couette convention:

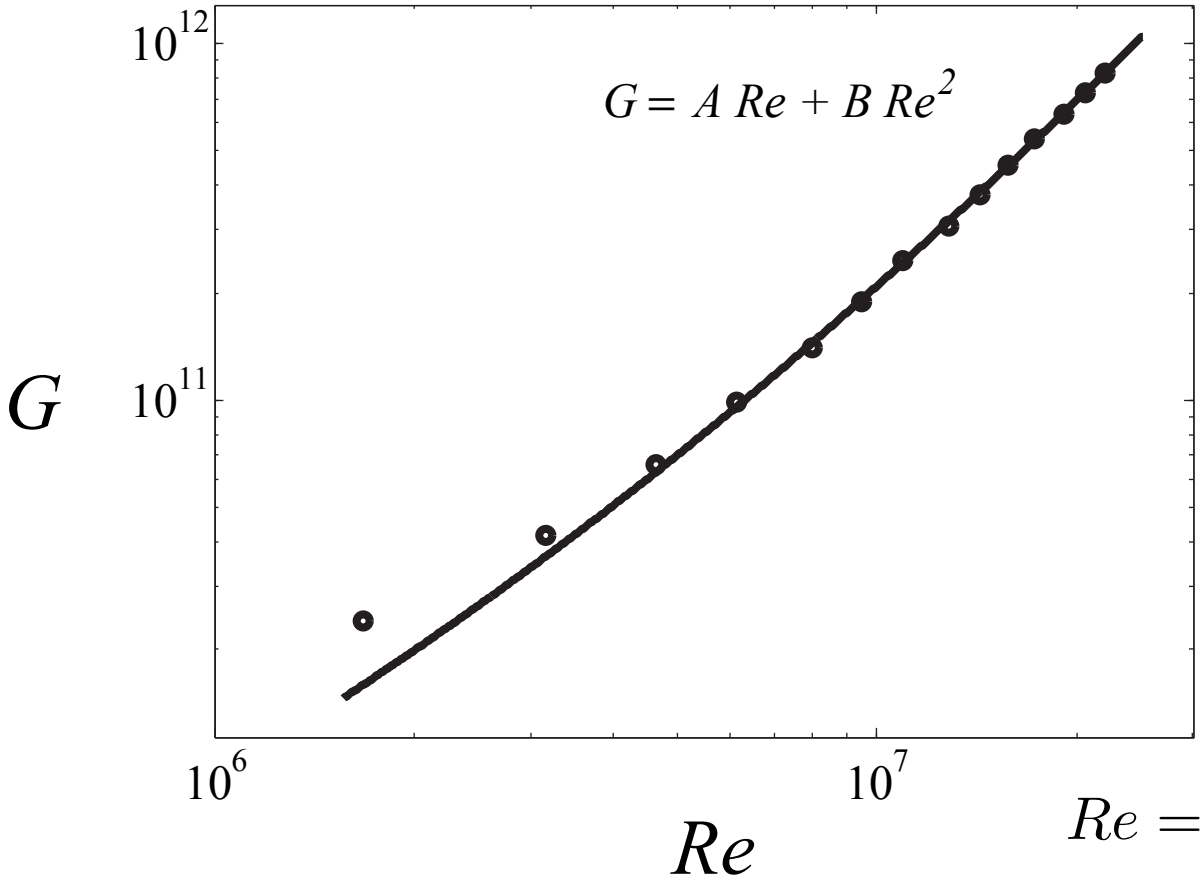
$$E = \frac{\nu}{\Omega_{outer}(r_o - r_i)^2} \sim 10^{-7} \qquad Re = \frac{\Omega_i r_i L}{\nu} \sim 10^7$$

$$Ro = \frac{\Omega_o - \Omega_i}{\Omega_o} \sim \text{0.05 - 3.5}$$

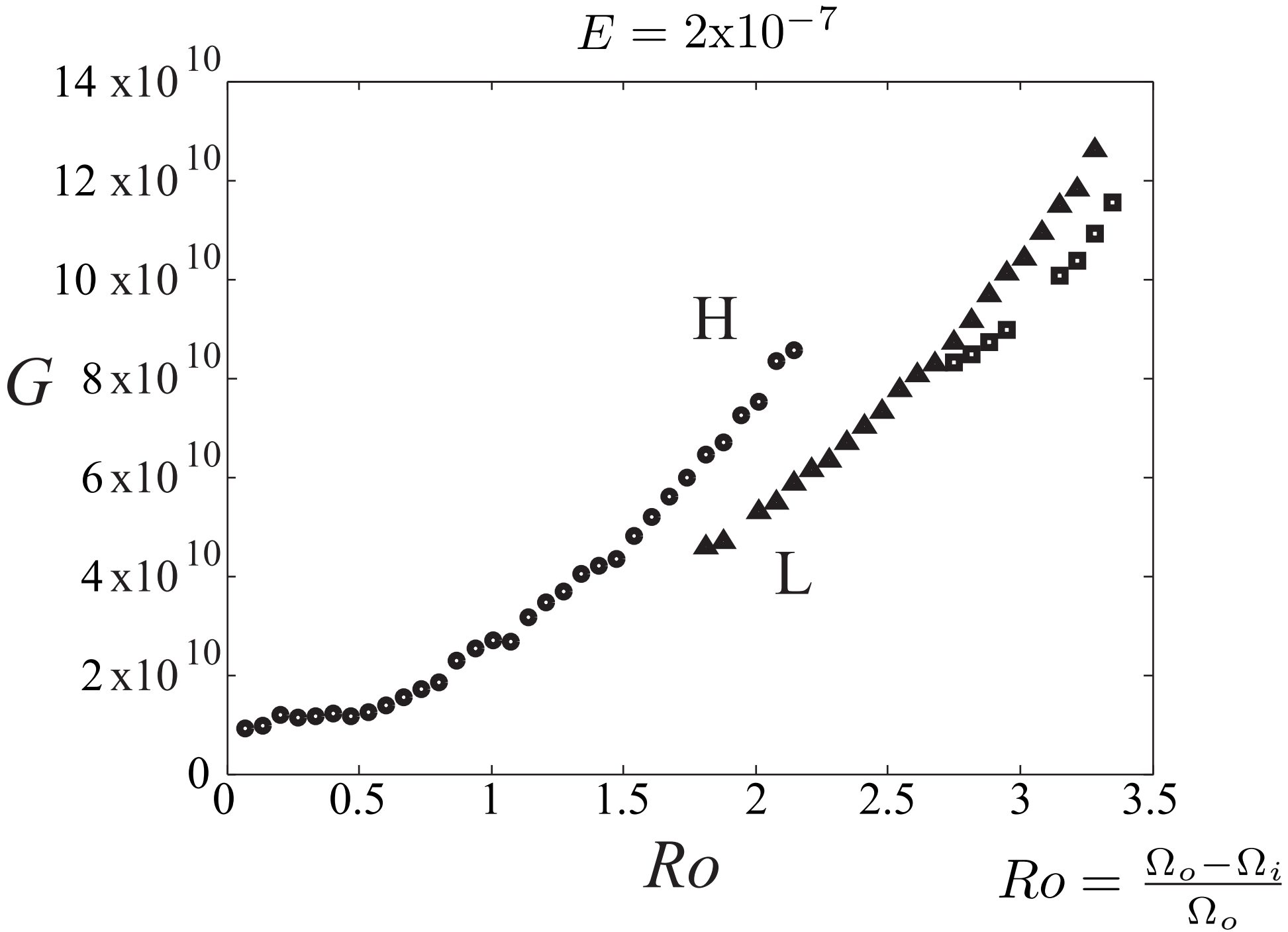
Dimensionless Torque

$$G = \frac{\text{Torque}}{\rho \nu^2 r_i}$$

Dimensionless Torque, Outer Stationary



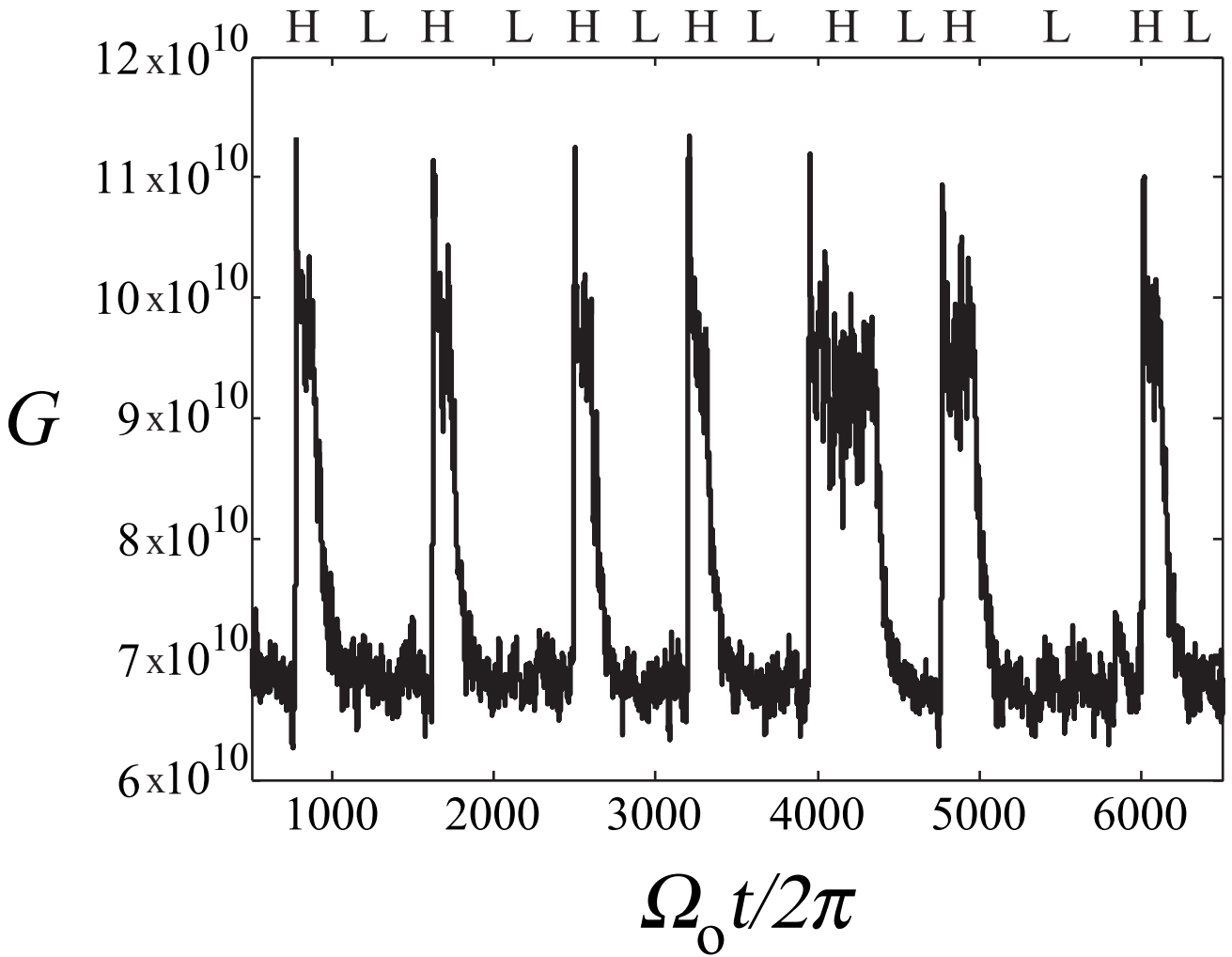
Dimensionless Torque, Outer Rotating



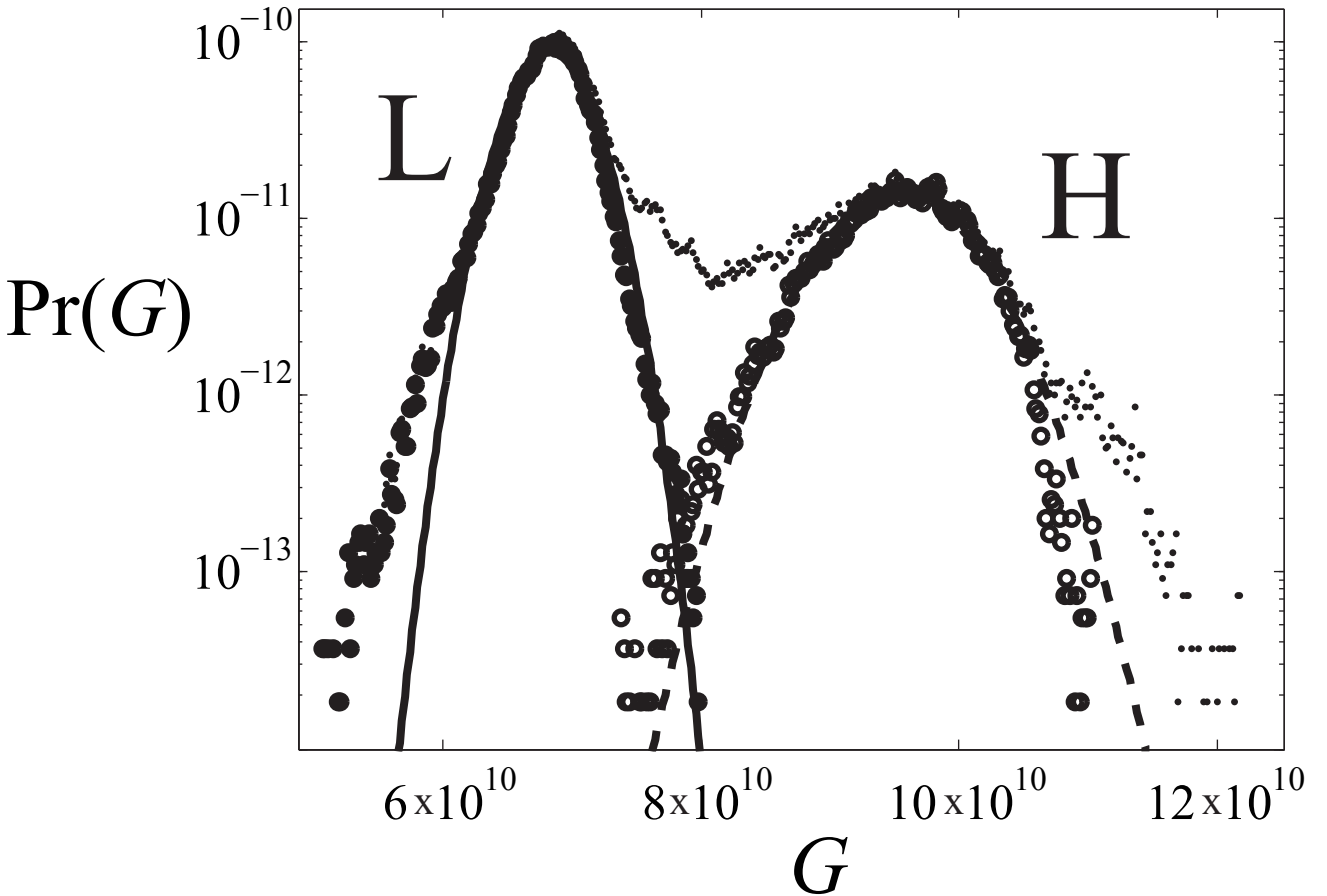
Torque Time Series

$Ro = 2.13$

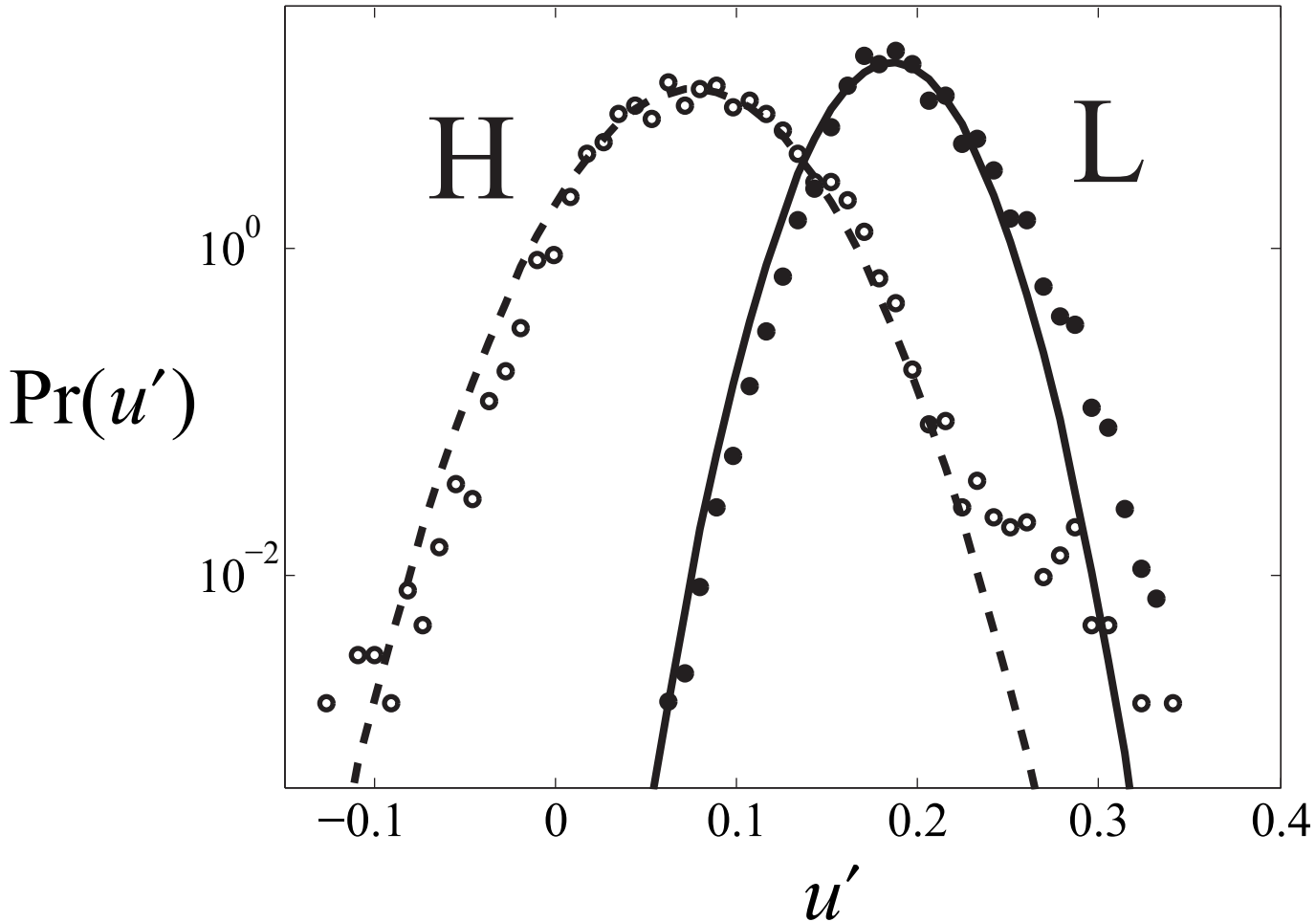
$E = 2\ \text{x}10^{-7}$



Torque Probability Distribution

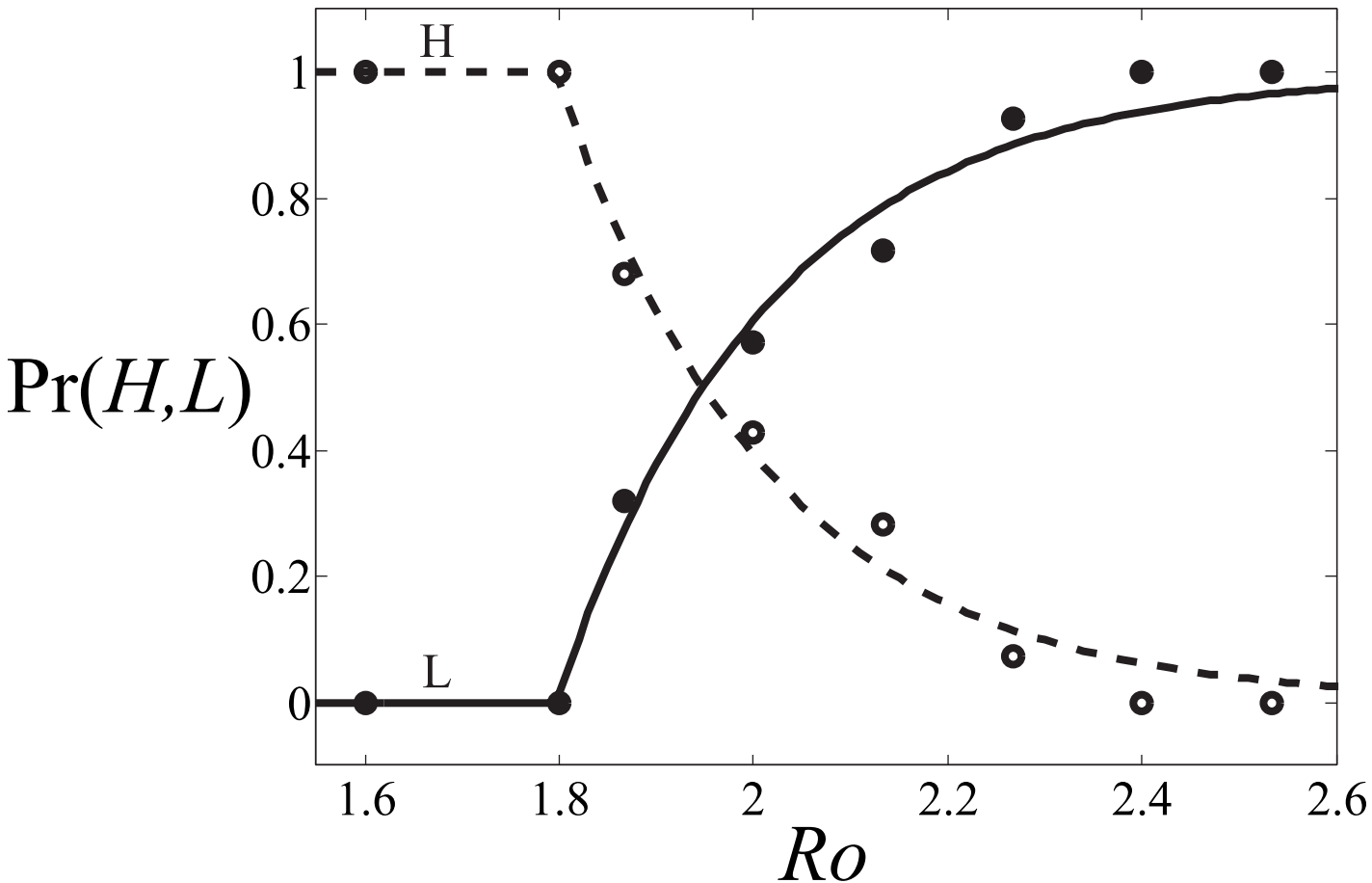


Azimuthal Velocity (Local Ro)



State Probability vs. Ro

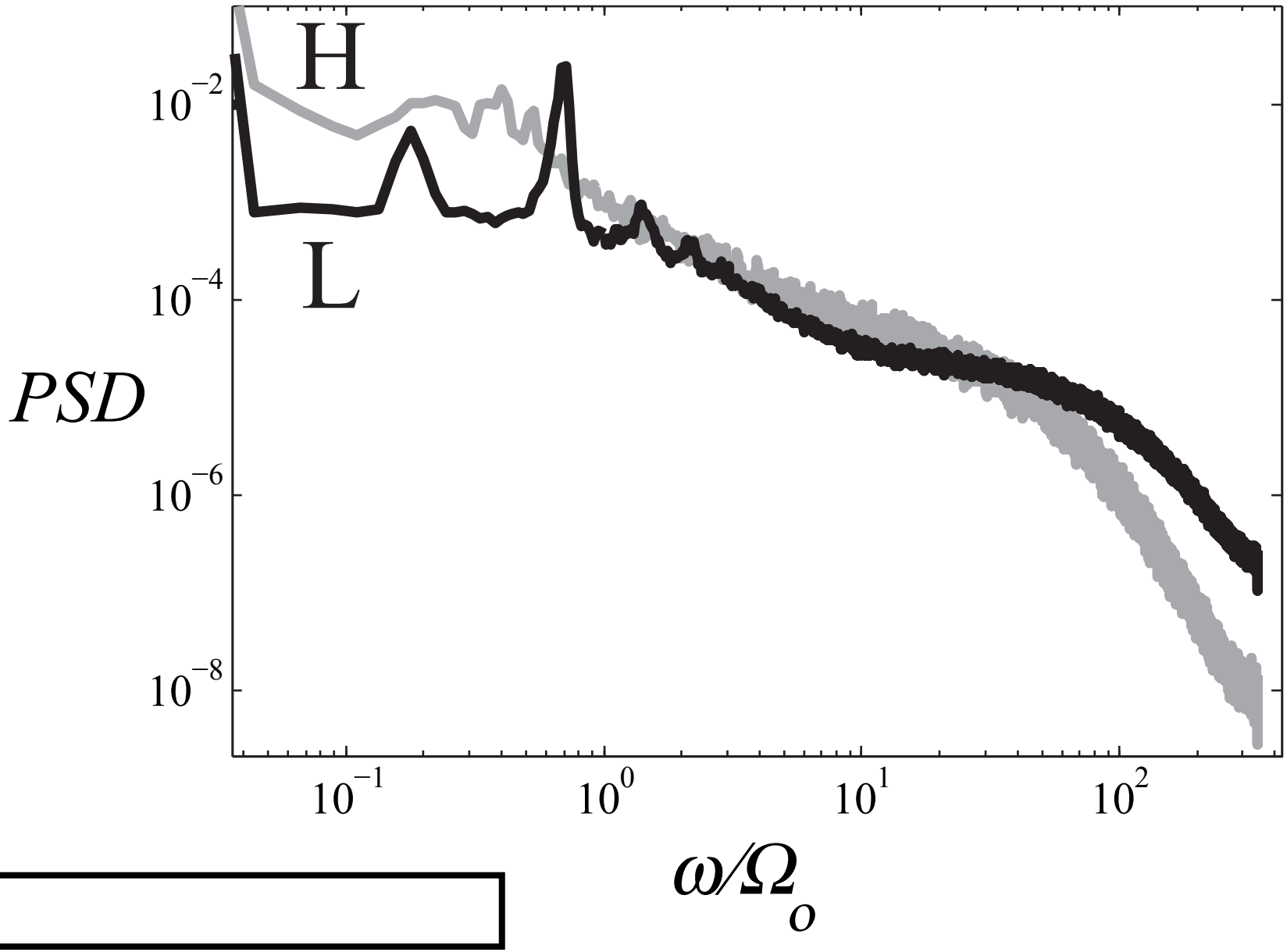
$E = 2\ \text{x}10^{-7}$



Two States & Connections

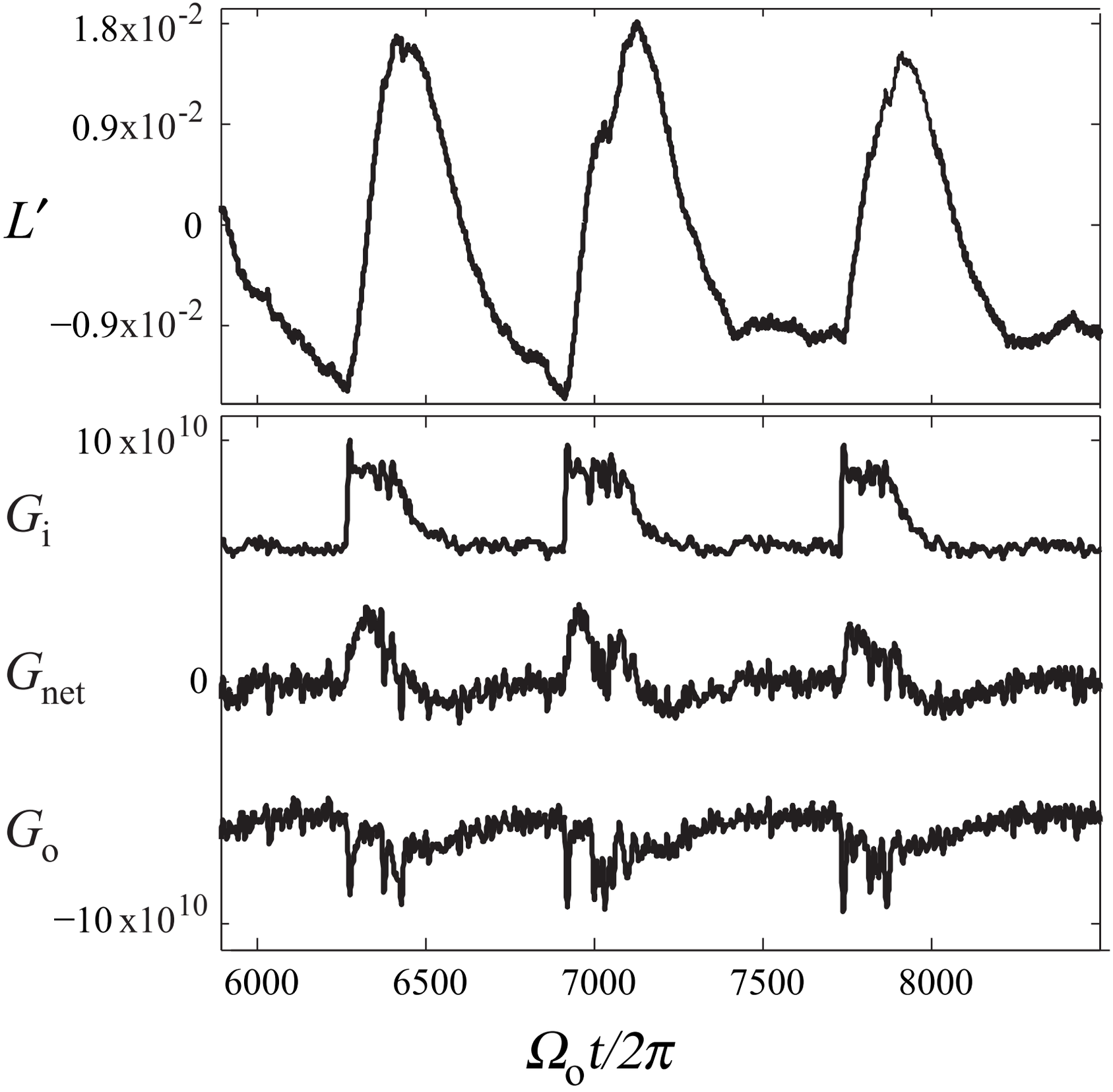
$E = 2\ \mathrm{x}10^{-7}$

Wall Shear Power Spectra

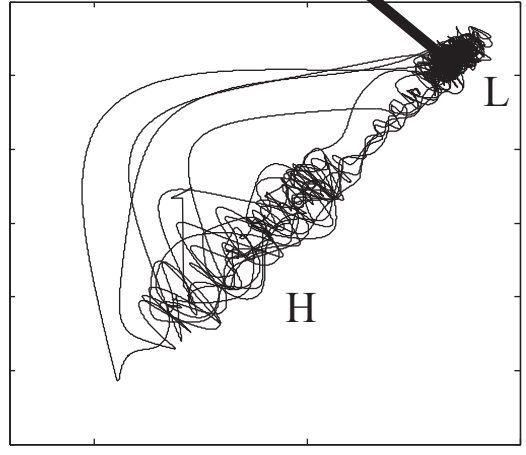


Wall Pressure Sound File - Sped Up 900x

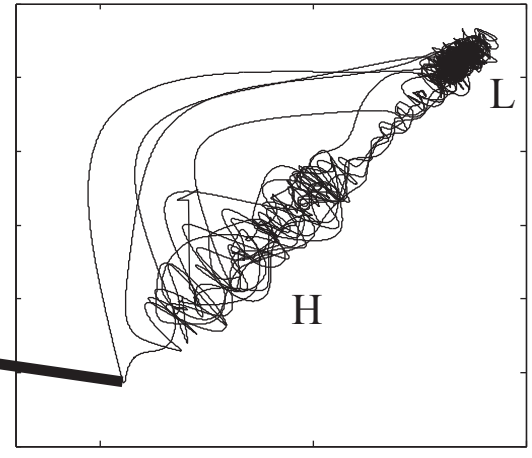
Net Angular Momentum



Movie - Low Torque State



Movie - High Torque Onset

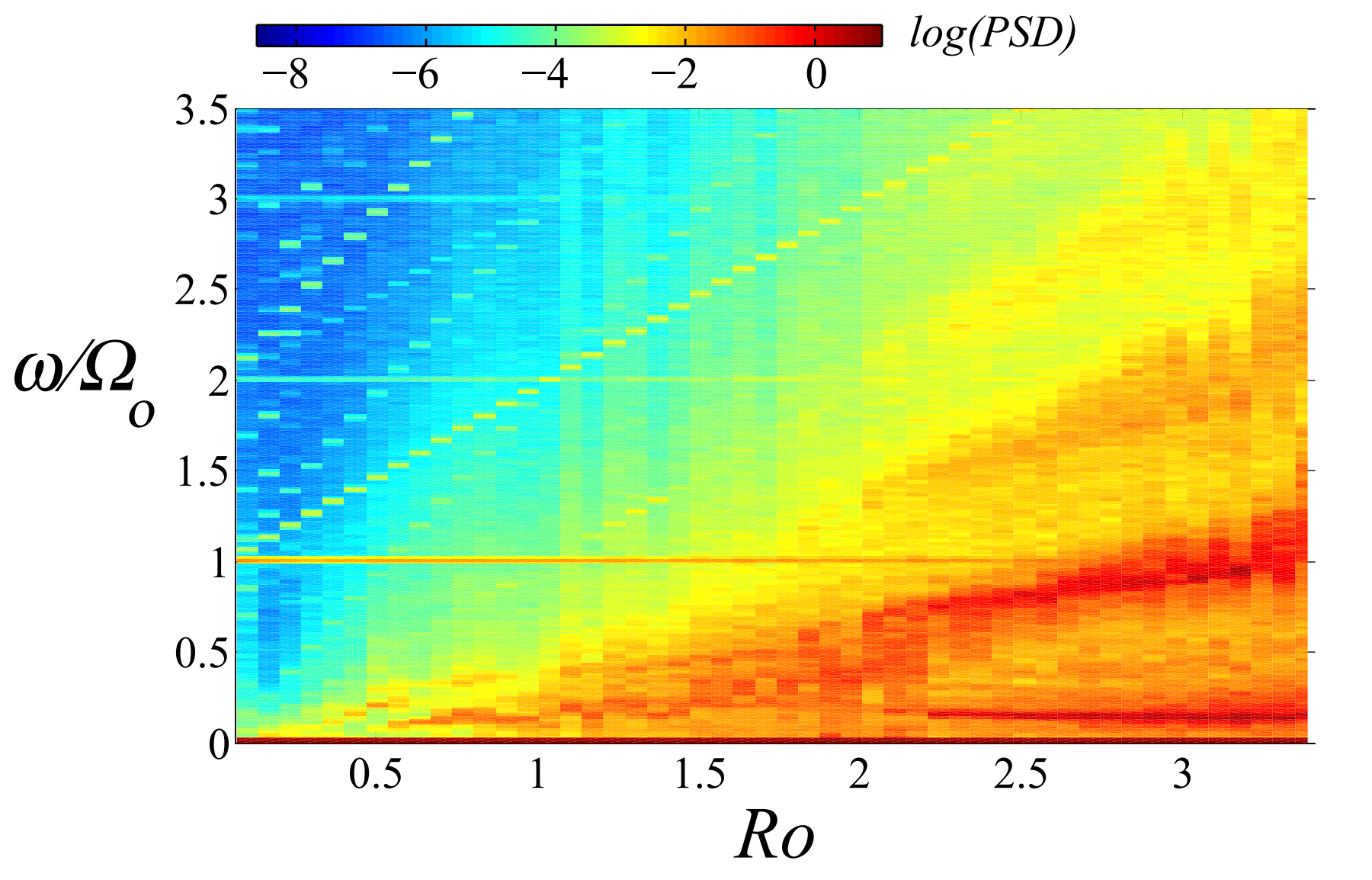


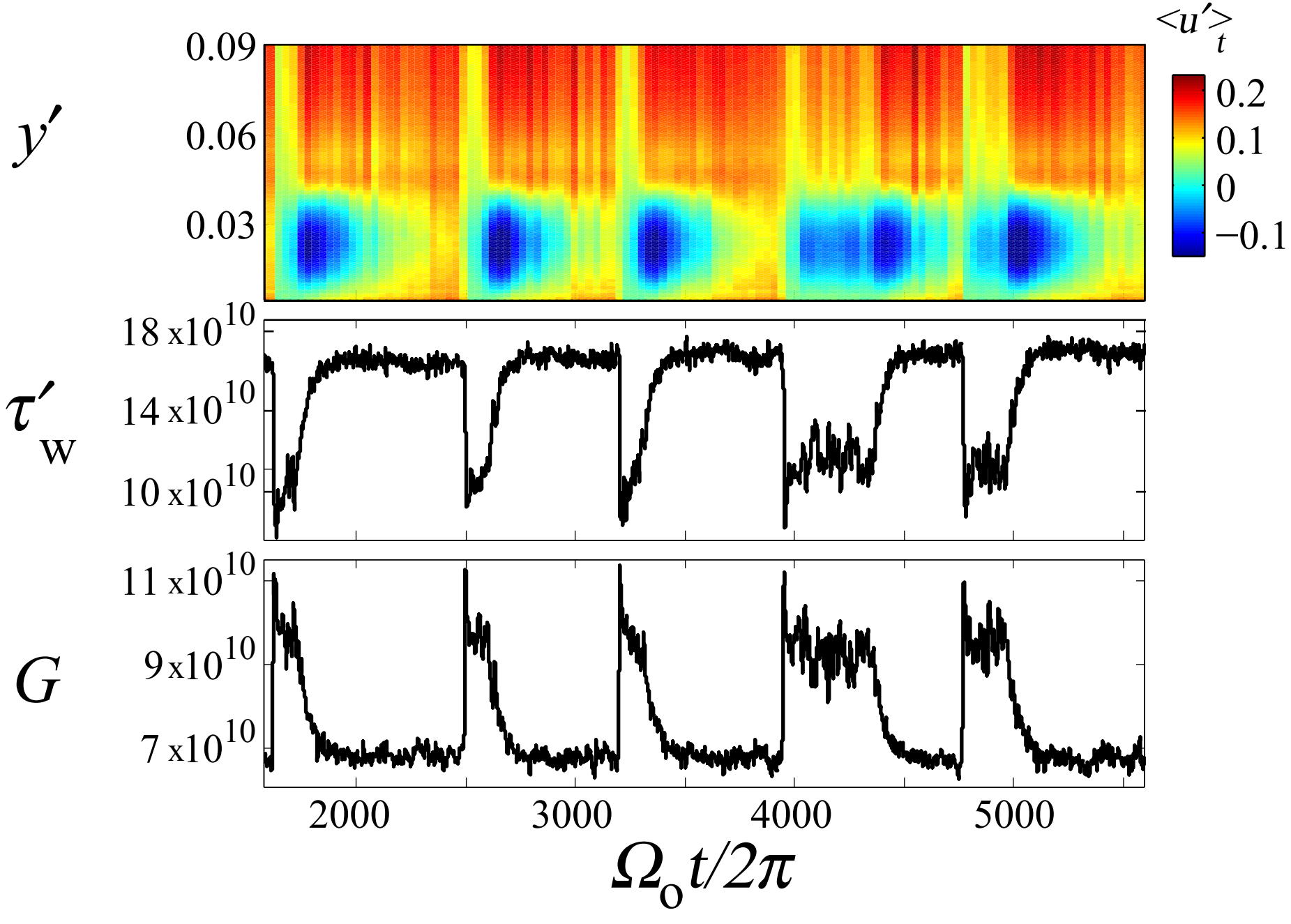
Conclusions:

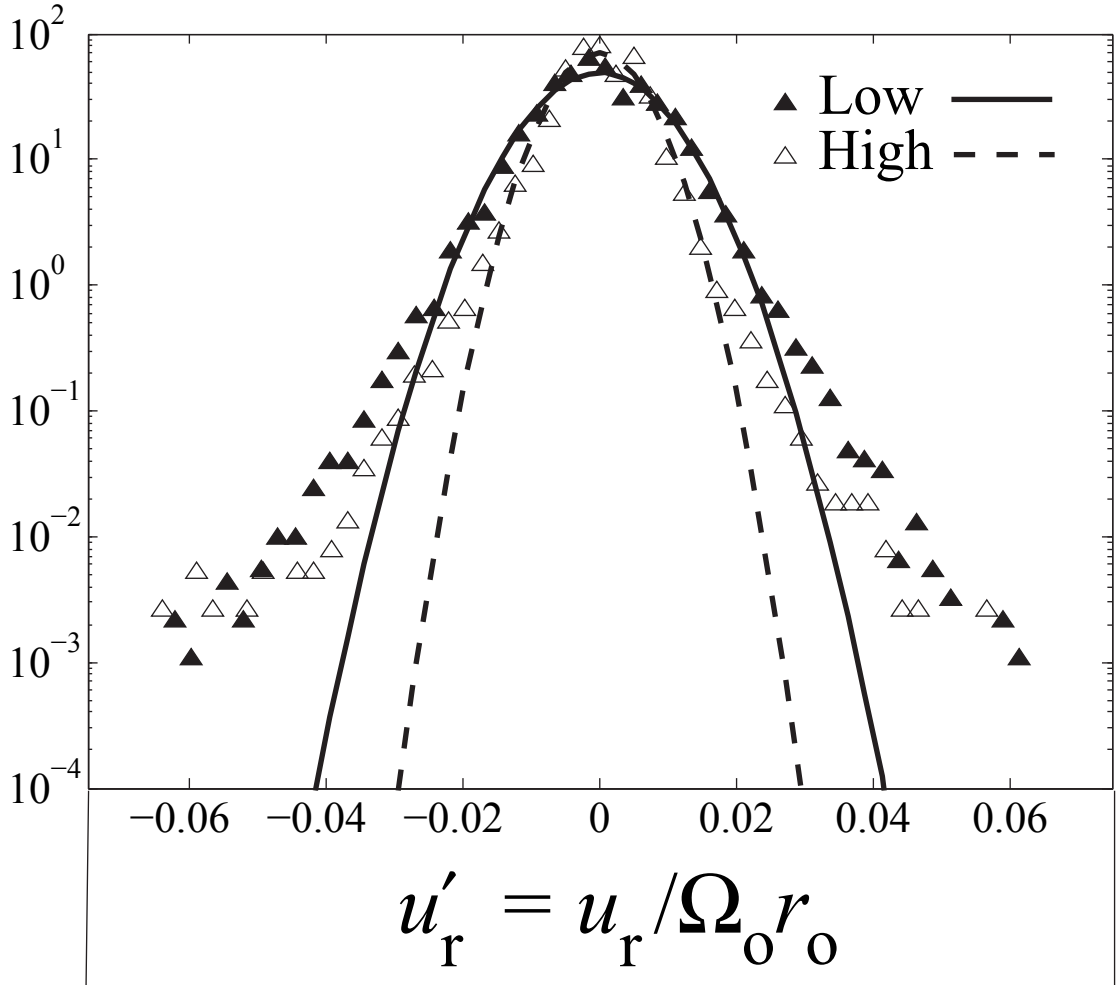
- Turbulent rapidly rotating spherical Couette flow exhibits bistablity.
- Intermittent connections between different turbulent states.

Outstanding Questions:

- What separates states in phase space?
- Where does this live in Ro, E parameter plane?
- Second (and further?) turbulent bistable states?


log(PSD)
−8
−6
−4
−2
0
3.5
3
2.5
2
1.5
1
0.5
0
ω/Ω_o
0.5
1
1.5
2
2.5
3
Ro

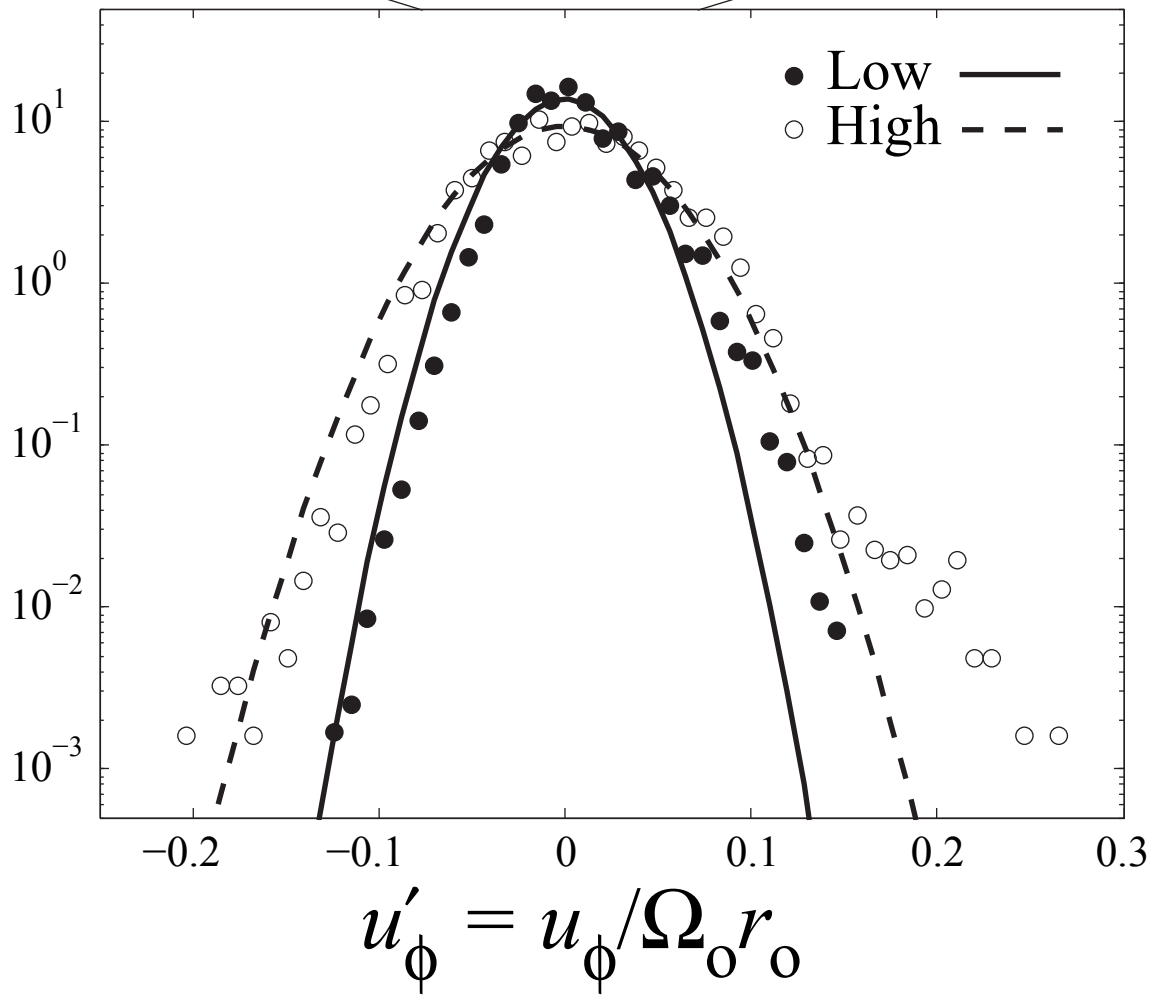

$\langle u' \rangle_t$
0.2
0.1
0
−0.1
y'
0.09
0.06
0.03
τ'_w
18 x10^10
14 x10^10
10 x10^10
G
11 x10^10
9x10^10
7 x10^10
2000
3000
4000
5000
$\Omega_o t/2\pi$



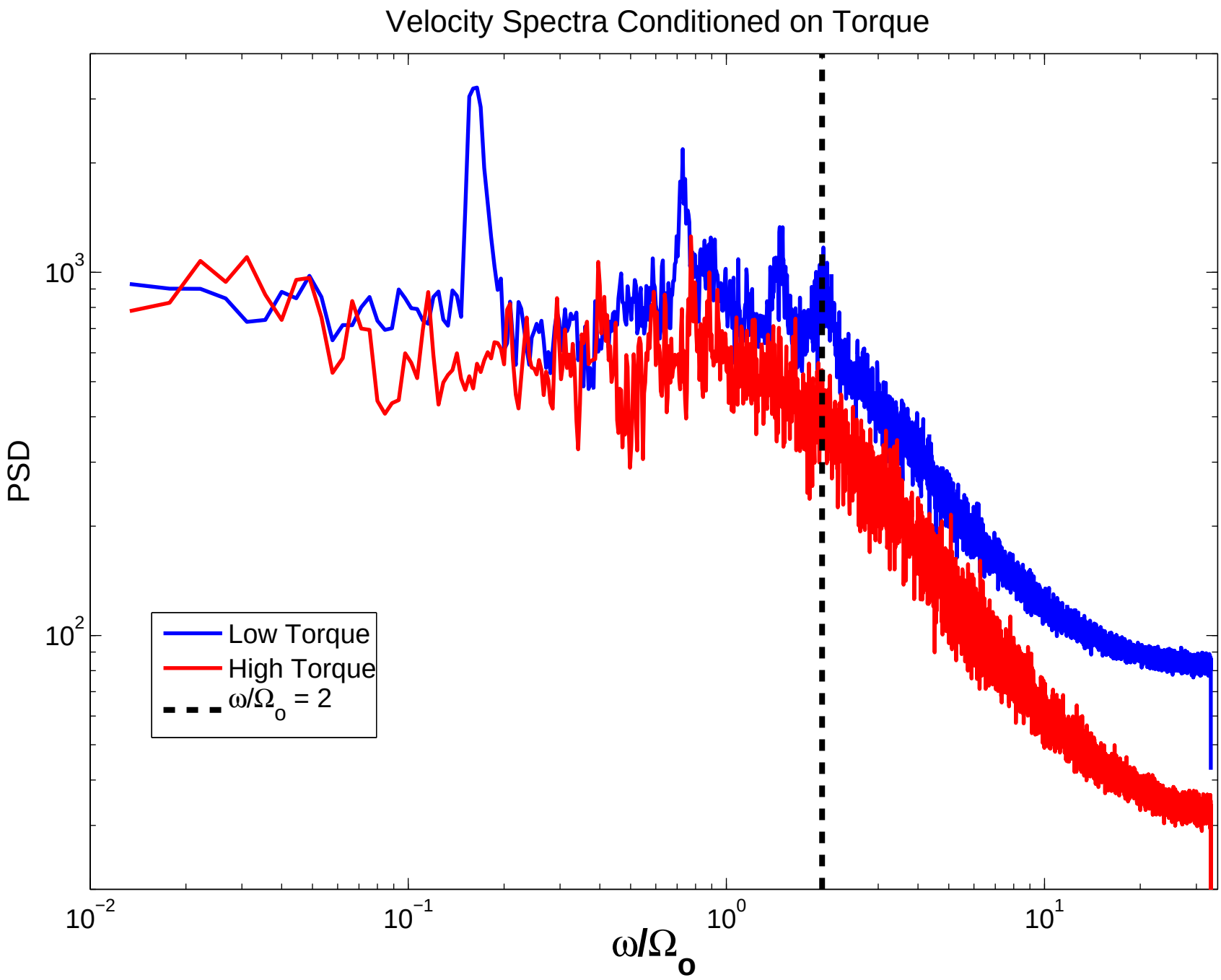
$\Pr(u'_{\mathrm{r}})$

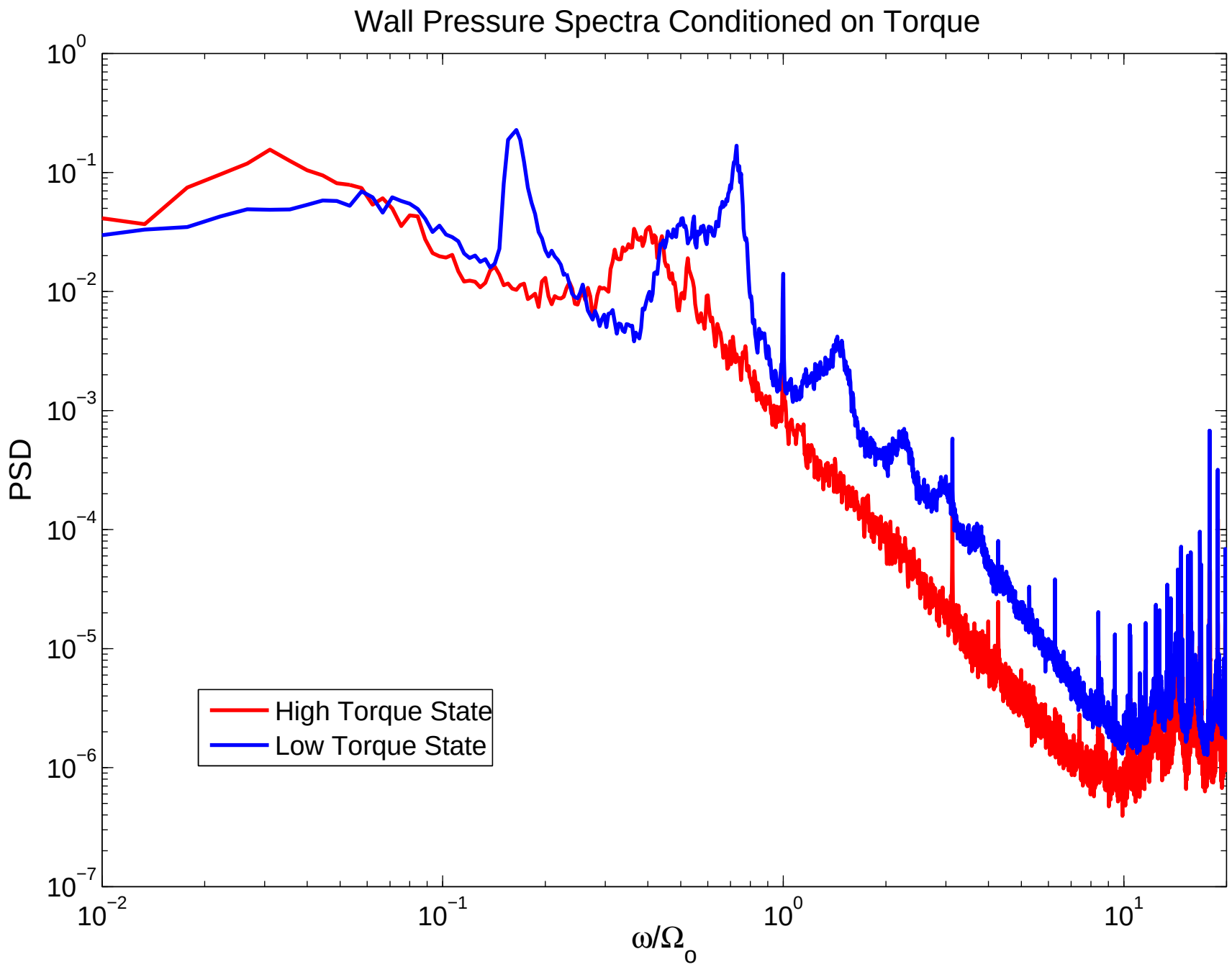
$\sigma_{u'_{\mathrm{r}}} / \sigma_{u'_{\phi}}$

H	0.13
L	0.28

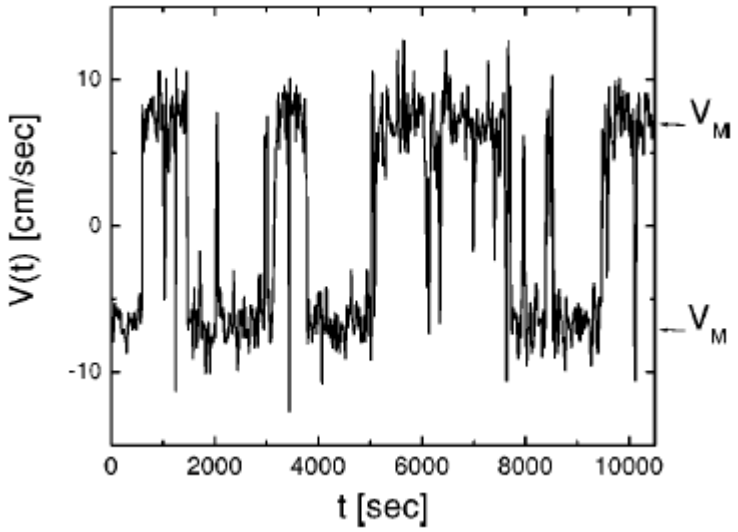


$\Pr(u'_{\phi})$

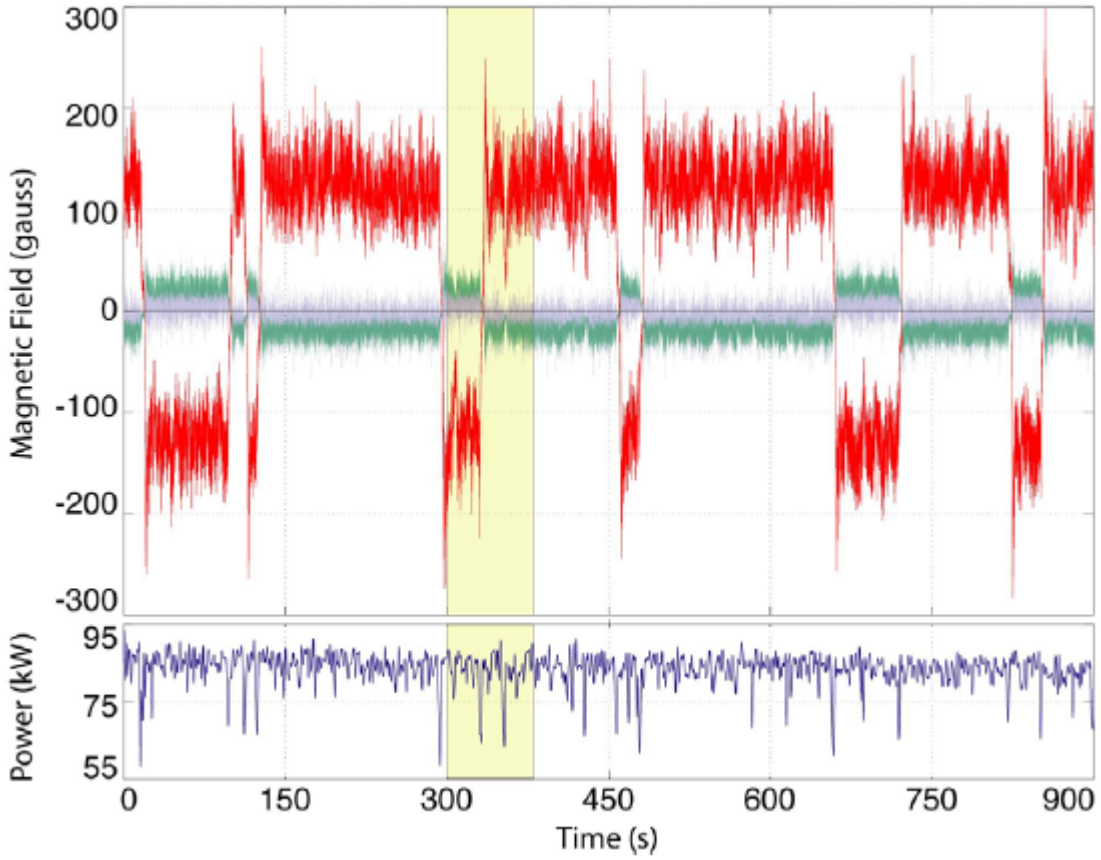

Velocity Spectra Conditioned on Torque
PSD
10^3
10^2
10^{-2}
10^{-1}
10^0
10^1
ω/Ω_o
Low Torque
High Torque
$\omega/\Omega_o = 2$


Wall Pressure Spectra Conditioned on Torque
PSD
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-1}
10^{0}
10^{1}
ω/Ω_o
High Torque State
Low Torque State

Bi-Stability in Turbulent Flows

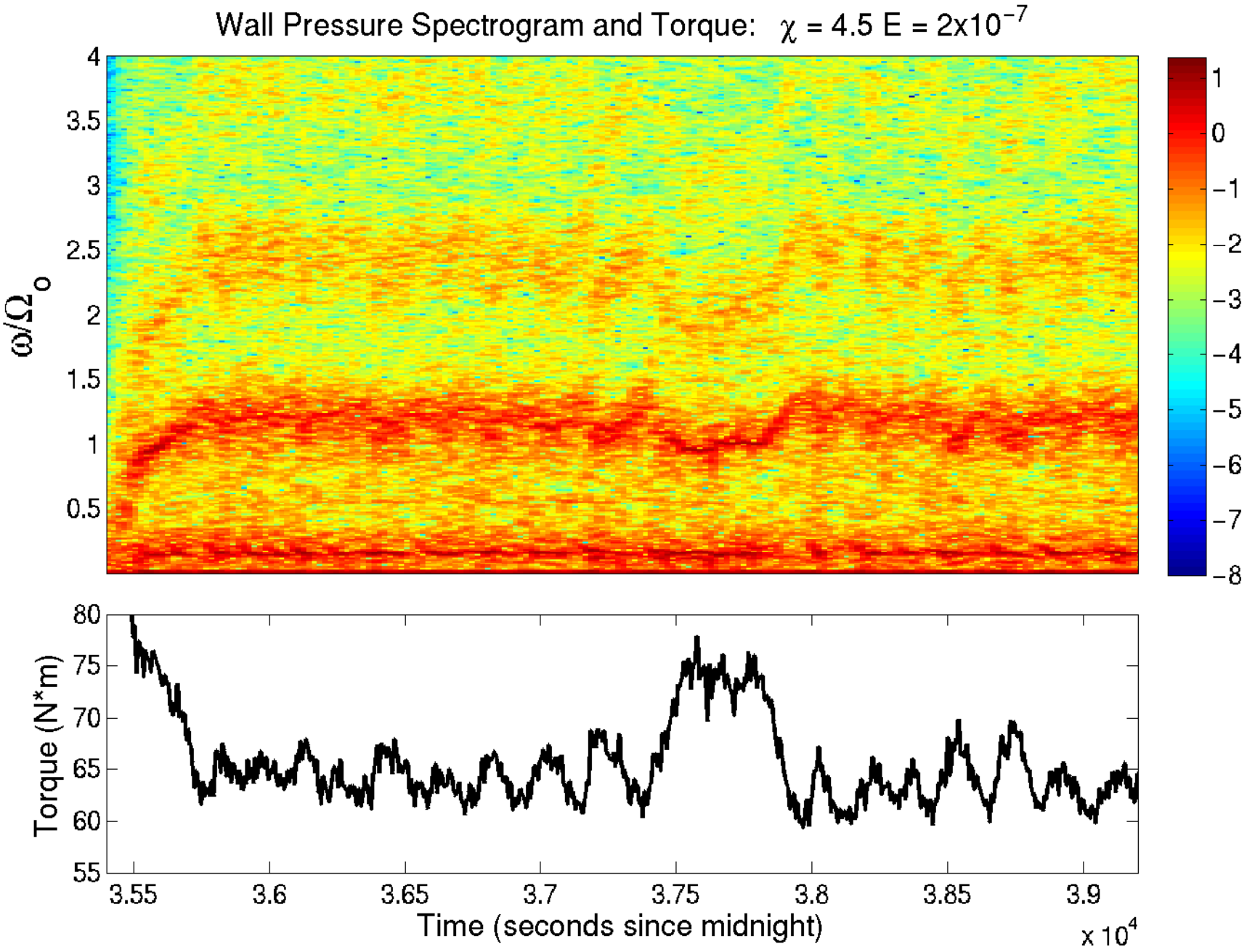


Sreenivasan et. al (2002)
PHYSICAL REVIEW E, VOLUME 65, 056306



EPL, 77 (2007) 59001

Mean circulation in turbulent convection...
Laboratory dynamo high Re, VKS 2...
Earth's magnetic field...
Solutions allowed by symmetries...


Wall Pressure Spectrogram and Torque: χ = 4.5 E = 2x10^-7
ω/Ω_o
4
3.5
3
2.5
2
1.5
1
0.5
1
0
−1
−2
−3
−4
−5
−6
−7
−8
Torque (N*m)
80
75
70
65
60
55
3.55
3.6
3.65
3.7
3.75
3.8
3.85
3.9
Time (seconds since midnight)
x 10^4