DI31A-2393: Hydromagnetic Waves and Progress in the UMD 3m Experiment

Quick Links:
Scan QR Codes
With Smartphone
Barcode Scanner!
complex.umd.edu

Daniel S. Zimmerman‡, S.A. Triana, and D.P. Lathrop

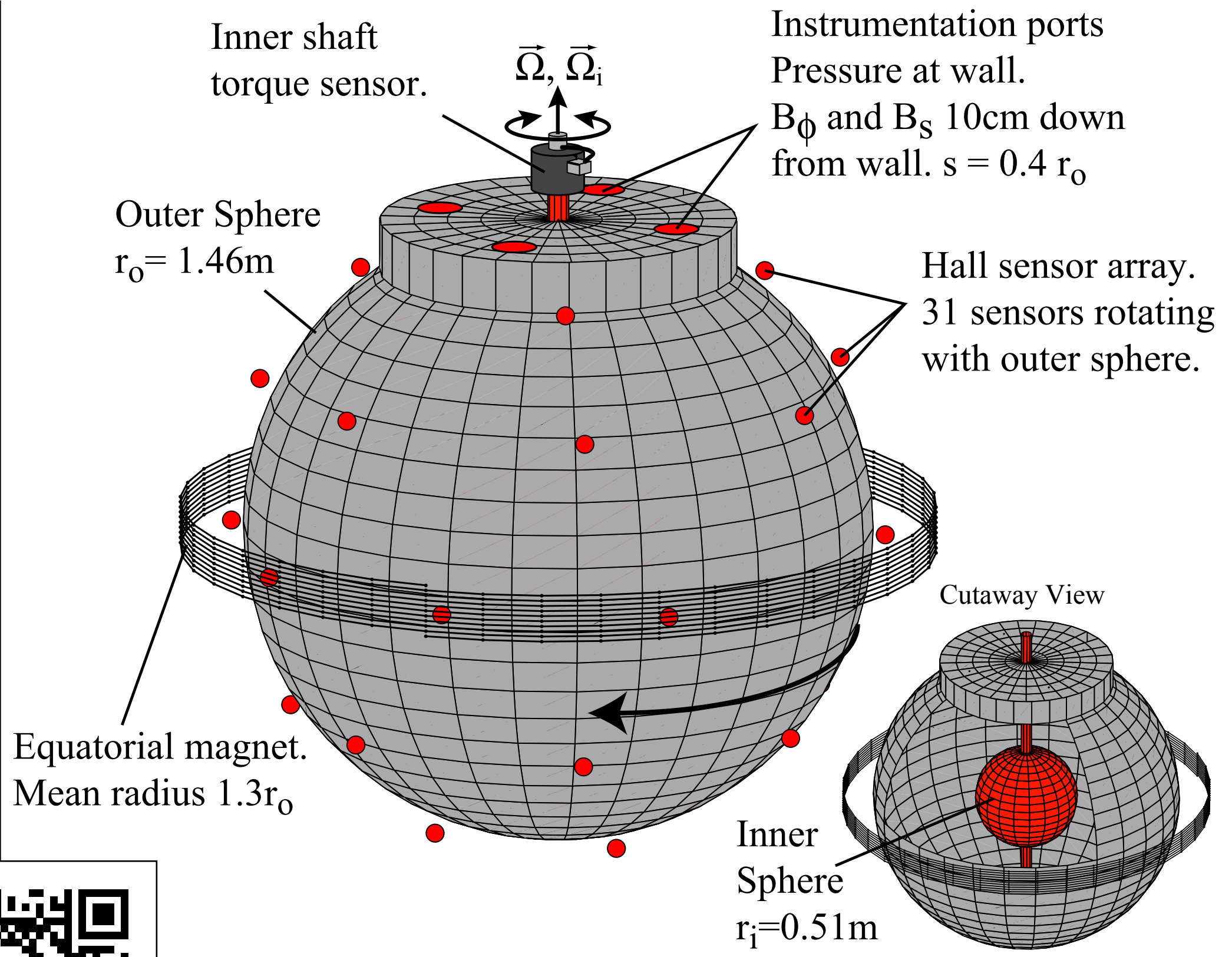
University of Maryland Physics, Geology, IREAP

‡ email: dsz@umd.edu
web: www.danzimmerman.com

Three Meter Experiment & Parameters

This research facility was designed and built hoping to achieve a magnetic dynamo in an experiment as similar as possible to Earth's core. Experiments with liquid sodium have begun; so far no dynamo states have been seen, but measurements in this device can help us better understand the rapidly rotating and strongly magnetized turbulence that prevails in planetary cores. This experiment provides rich data that should be useful to help benchmark and improve predictive models of core dynamics.

Spin: http://youtu.be/NEGoWQ-7THE



YouTube
◀ Spinning
Filling ▶

Relevant Dimensional Quantities:

Ω_i : Inner angular speed, $-15\text{Hz} < \Omega_i/2\pi + < 15\text{Hz}$
Ω: Outer angular speed, $\Omega/2\pi < 4\text{Hz}$
$\Delta\Omega = \Omega_i - \Omega$
L: r_i-r_o, gap width, 0.95m
ρ: Sodium density, 927kg/m^3
μ: Sodium magnetic permeability, $\sim\mu_0$
ν: Sodium kinematic viscosity, 7×10^{-7} m^2/s
η: Sodium magnetic diffusivity, 0.080m^2/s
B_0: Applied field at experiment center, $B_0 < 160$G

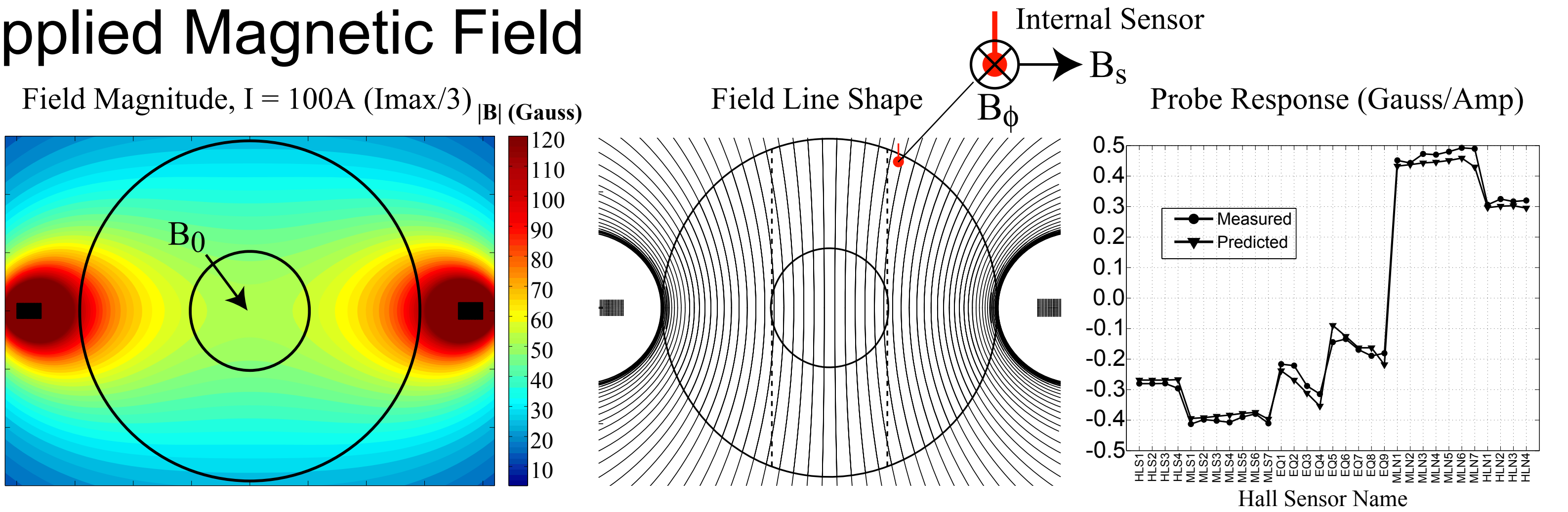
Dimensionless Parameters:

$Ro = \Delta\Omega/\Omega$	$0<\lvert Ro\rvert<100$
$E = \nu/\Omega L^2$	$5\times10^{-8}<E<5\times10^{-6}$
$Re = \Delta\Omega L^2/\nu$	$5\times10^{6}<Re<8\times10^{7}$
$Rm = \Delta\Omega L^2/\eta$	$40<Rm<800$
$\Lambda = B_0^2/\rho\mu\eta\Omega$	$0<\Lambda<0.9$
$S = B_0 L/\eta(\rho\mu)^{1/2}$	$0<S<6$
$Pm = \eta/\nu$	$Pm = 1.1\times10^{-5}$
$\Gamma = r_i/r_o$	$\Gamma = 0.35$
$Ha = B_0\,(L^2/(\rho\mu\eta\nu))^{1/2}$	$0<Ha<1990$

The experiment consists of two coaxial, independently rotating stainless steel shells, effectively electrically insulating boundaries. The ratio of inner to outer boundary radius matches the ratio between the radii of Earth's solid inner and liquid outer core, $\Gamma = 0.35$. The gap between the spheres is filled with almost 12,000kg of sodium metal, liquified and held at 120°C for experiments. So far we have only achieved about half of the listed maximum boundary speeds; the dimensionless parameter list above reflects what we've actually achieved. We can match or exceed the magnetic Reynolds number *Rm* thought to exist in Earth's core, and our low Ekman number *E* is among the lowest achieved in a laboratory experiment, ensuring that the Coriolis force is dominant. By applying a magnetic field, we may approach an Elsasser number Λ near unity, giving Lorentz force comparable to the Coriolis force.

We measure external spherical radial magnetic field B_r with an array of 31 Hall sensors in the rotating frame and internal azimuthal field B_ϕ and cylindrical radial field B_s with a pair of probes intruding into the flow 10cm from the wall and 10cm from the cylinder tangent to the inner sphere. We measure pressure at the wall in three ports depicted above, and a torque sensor on the inner sphere gives a global measure of angular momentum transport.

Applied Magnetic Field



To study hydromagnetic phenomena in the absence of dynamo action, we apply a magnetic field using an electromagnet in the equatorial plane. We choose the field at the center of the experiment as a reference value "B_0" in the dimensionless parameters listed above. However, there is substantial spatial variation as shown here; the field is stronger at the equator ($\sim 2B_0$) and weaker at the poles ($\sim B_0/2$). The rightmost plot shows applied field measured by each sensor compared to the calculated field.

Spherical Harmonic Decomposition: Gauss Coefficients

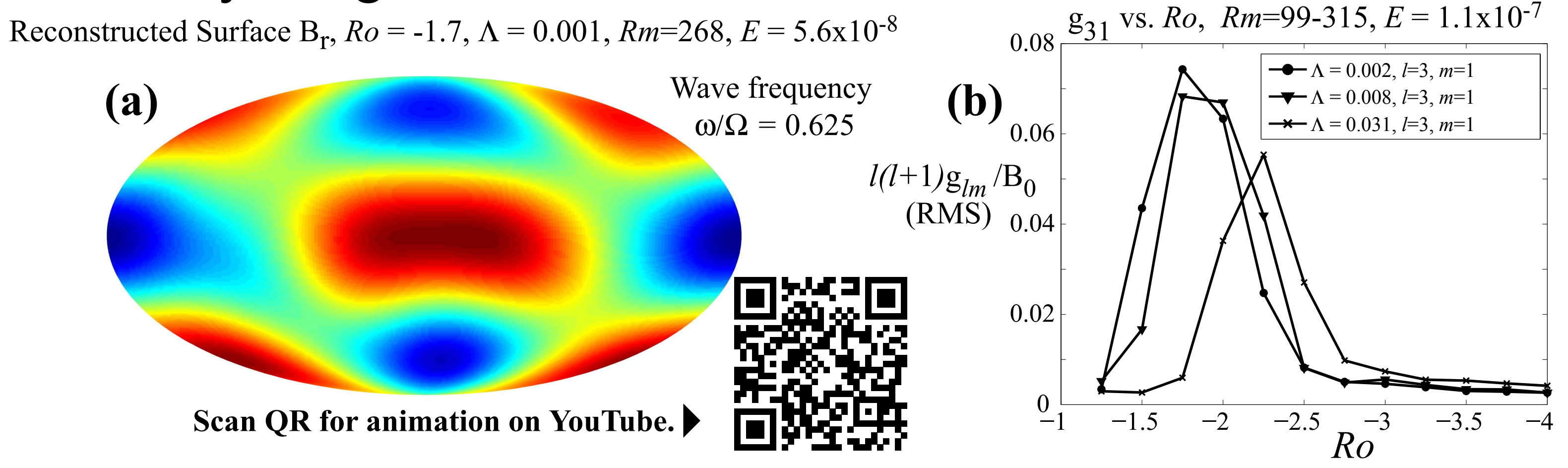
$$B_r(r,\theta,\phi) = \sum_{l=0}^{4}\sum_{m=0}^{l} l(l+1)\left(\frac{a}{r}\right)^{l+2} P_l^m(\cos(\theta))(g_{lm}^c\cos(m\phi) + g_{lm}^s\sin(m\phi))$$

After subtracting the applied field contribution from the 31 sensors of the hall sensor array, we project these measurements of B_r onto vector spherical harmonics, giving the Gauss coefficients $g_{lm}{}^{c,s}$ for the *s*(ine) or *c*(osine) component with order *m* and degree *l* ($l<4$, $m<4$).

Weakly Magnetized Inertial Modes

Reconstructed Surface B_r, $Ro = -1.7$, $\Lambda = 0.001$, $Rm=268$, $E = 5.6\times10^{-8}$

g_{31} vs. Ro, Rm=99-315, $E = 1.1\times10^{-7}$



Scan QR for animation on YouTube. ▶

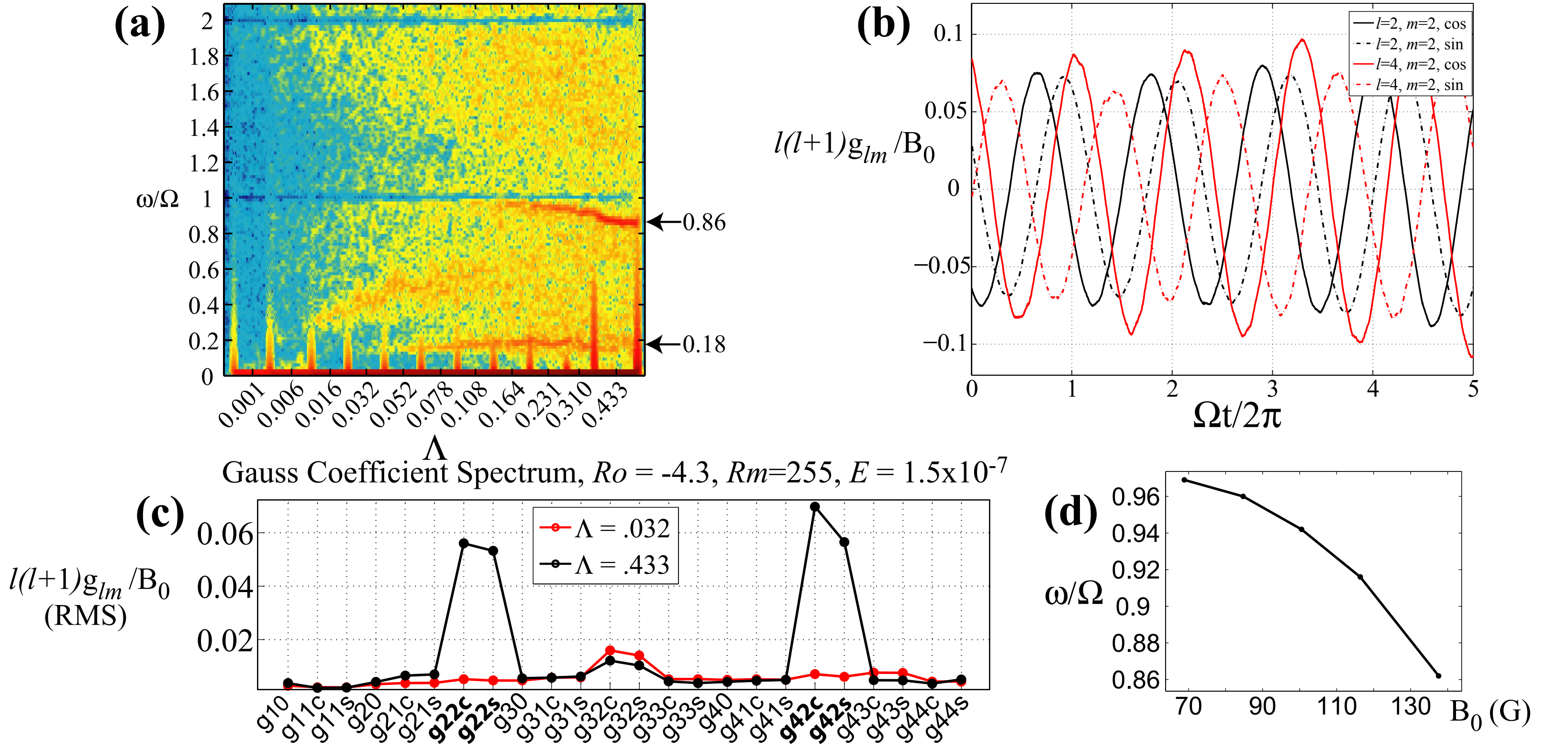
Inertial modes are excited by differential rotation in spherical Couette flow when *E* is low enough(1,2,3). The strongest magnetic induction **(a) is** dominated by l=3, m=1 magnetic field induced by an inertial mode recently confirmed as a mode of a spherical shell(1). With zero magnetic field (water!), this mode peaks at Ro = -1.7. Increasing the Elsasser number Λ shifts the amplitude peak to higher Ro and weakens the induced field relative to the applied field **(b)**, suggesting increased mode damping. Although the applied field here is expected to have weak bulk effects, even $\Lambda \sim O(E^{1/3})$ can modify low Ekman number flows with thin internal layers(4). The Hartmann number *Ha,* which compares the Lorentz and viscous forces, is $Ha = 0.6, 1.3, 2.5$ for the three fields in **(b)** if calculated for a scale $\ell = E^{1/3}L$.

New Waves with Strong Magnetization: MC Modes?

Midlatitude Spectrogram, $Ro = -4.3$, $Rm=255$, $E = 1.5\times10^{-7}$

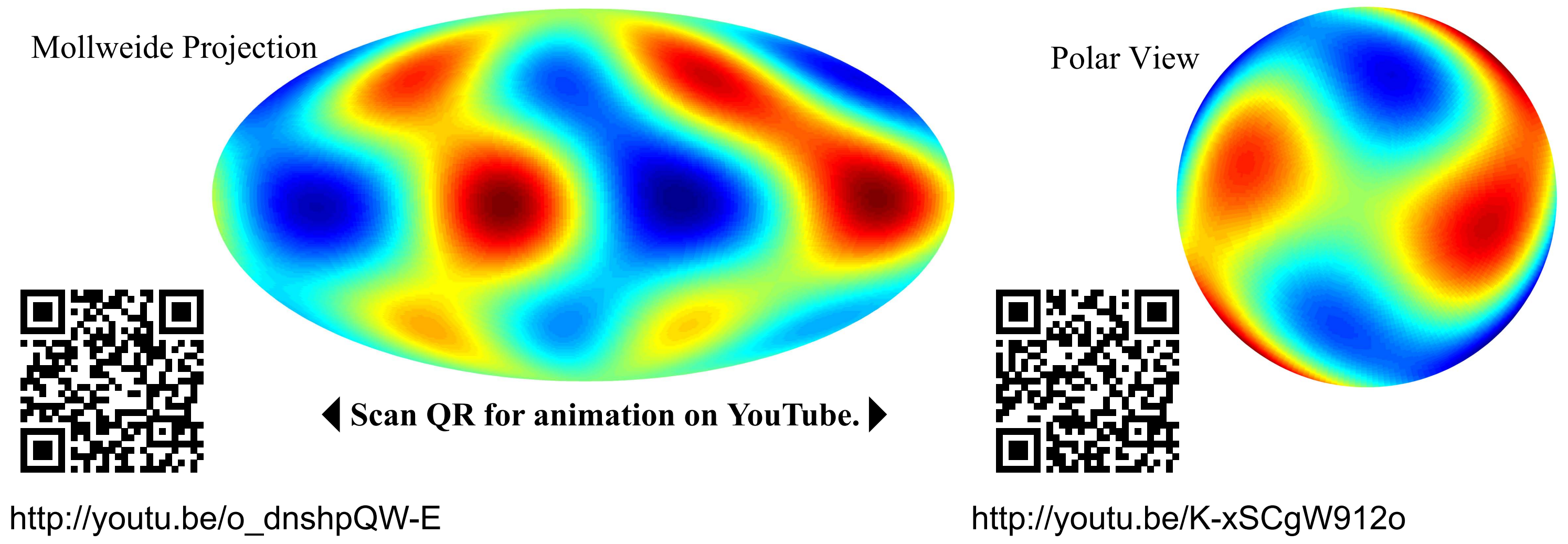
Time Series, $Ro = -4.3$, $\Lambda = 0.433$, $Rm=255$, $E = 1.5\times10^{-7}$

Gauss Coefficient Spectrum, $Ro = -4.3$, $Rm=255$, $E = 1.5\times10^{-7}$



New waves arise at many parameters and we are working to characterize them. We focus here on data with Ro = -4.3. We do this because the unmagnetized basic state shows no noticeable wave peaks above the broadband turbulence. As the magnetic field is increased, the fluctuations in midlatitude magnetic field develop sharp frequency peaks, shown in the spectrogram **(a)** above. At the highest Λ, the magnetic fluctuations are dominated by an oscillation of phase locked $\mathbf{g_{42}}$ and $\mathbf{g_{22}}$ coefficients with $\omega/\Omega = 0.86$, as shown in the time series **(b)** and Gauss coefficient spectrum **(c)** above.

Reconstructed Surface B_r, $Ro = -4.3$, $\Lambda = 0.433$, $Rm=255$, $S = 5.1$, $E = 1.5\times10^{-7}$



◀ **Scan QR for animation on YouTube.** ▶

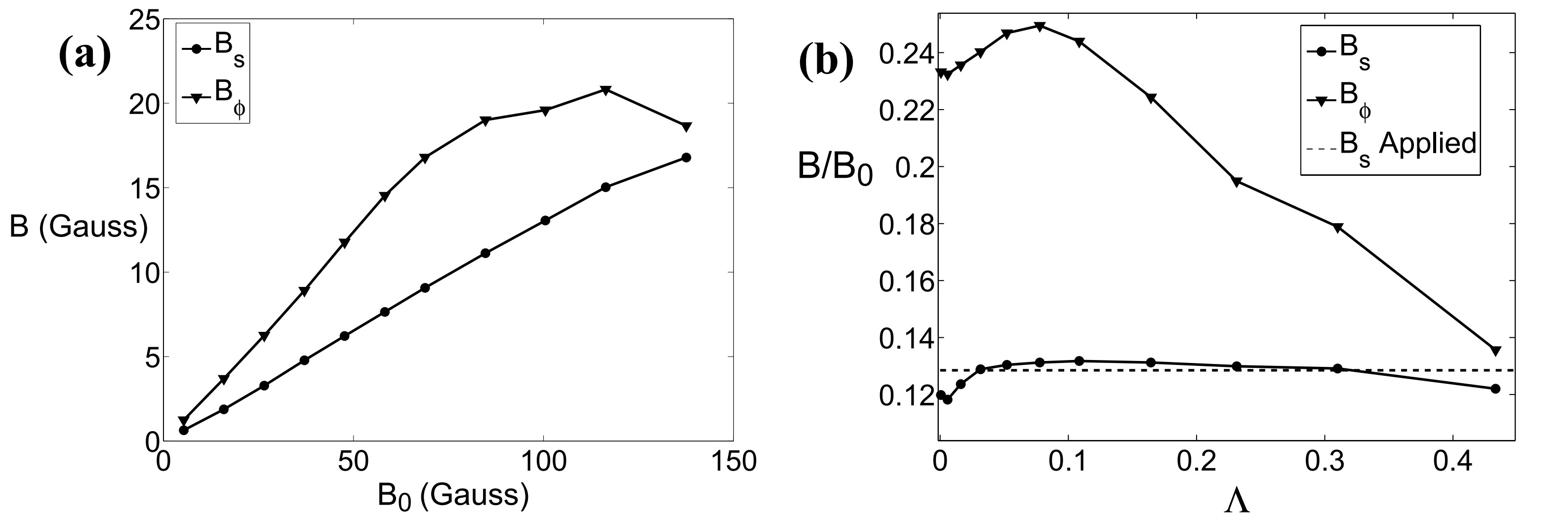
http://youtu.be/o_dnshpQW-E

http://youtu.be/K-xSCgW912o

The two figures above are reconstructions of the radial field at the sphere surface from the Gauss coefficients at one instant. Warm (cool) colors are outwardly (inwardly) directed field. Peak field strength is about 15% of B_0. The spiral structure suggests a mode with different wave speeds at different latitudes, which may result from the stronger field near the equator of the outer sphere. Wave frequency varies with magnetic field, shown in **(d)** above, so this may be a magnetocoriolis mode.

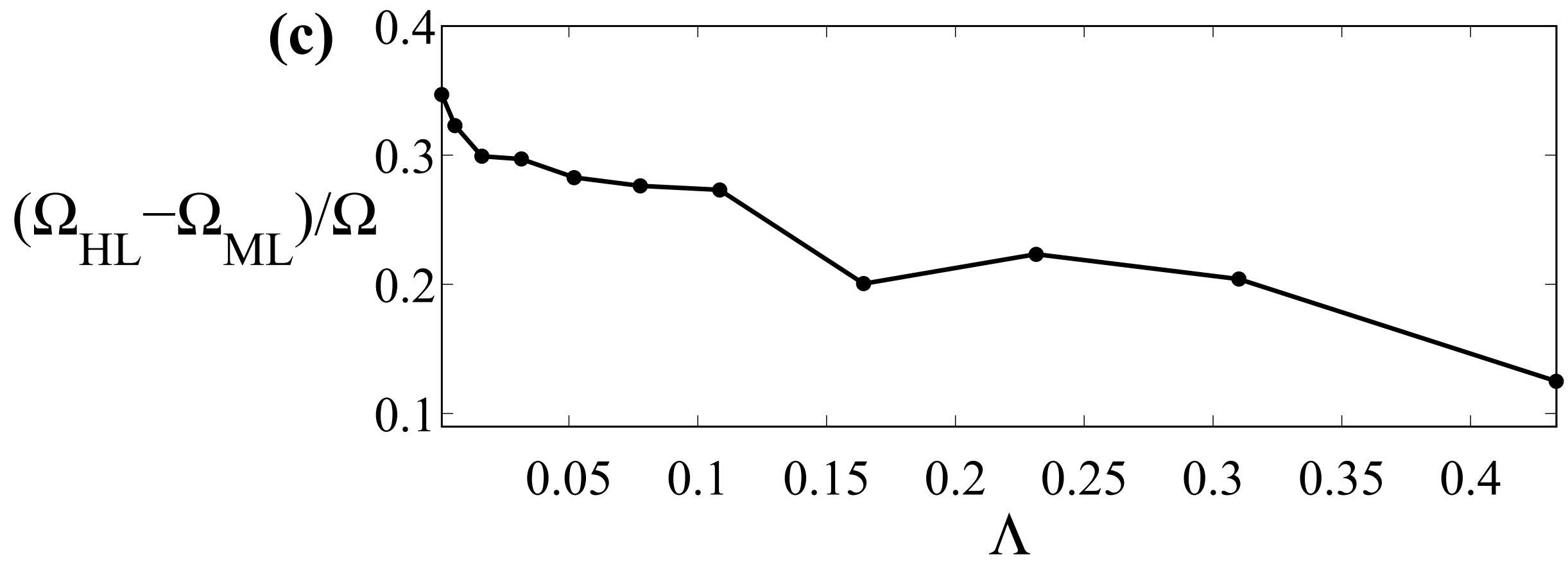
Mean Flow and Field with Strong Magnetization

Mean Internal Fields, $Ro = -4.3$, $Rm=255$, $E = 1.5\times10^{-7}$



We measure azimuthal field inside the sodium at 60cm cylindrical radius, 10cm outside of the tangent cylinder and 10cm from the outer wall. The figures above are taken at constant sphere speeds with increasing magnet current, and show **(a)** the raw field and **(b)** field normalized by B_0. In **(b)**, the dashed line shows the calculated s-component of the applied field at the probe location. The applied field is axisymmetric, so B_ϕ is pure induced field. With weakly conducting walls and a tendency toward geostrophy, we expect that B_ϕ is mainly induced from B_s near the probe location by radial shear. This implies substantial toroidal field gain, a hopeful sign for eventual dynamo states!

At these flow parameters, it seems that the Lorentz force is almost always important. At most flow parameters tested so far, B_ϕ/B_0 decreases with increasing B_0, likely due to reduced velocity shear. The increase seen here in **(b)** for $Ro = -4.3$ up to $\Lambda = 0.1$ is an interesting exception.



$Ro = -4.3$, $Rm=255$, $E = 1.5\times10^{-7}$
Differential fluid angular speed derived from cross-correlating broadband turbulence
Ω_{HL} at 65°S, Ω_{ML} at 33°S

We do not yet have direct measurements of flow velocities in the liquid sodium, but here we use magnetic signals as a surrogate. We cross-correlate higher frequency broadband fluctuations between longitudinally separated probe pairs, assuming that the largest peaks seen in this cross-correlation represent advection of slowly evolving turbulence. Using this assumption, we can calculate the mean fluid angular speed at different latitudes. At **(c)**, the difference in angular speed between the midlatitudes and high mostly generally decreases as Λ is increased. This is consistent with the weaker production of B_ϕ for high Λ but does not explain increased B_ϕ below Λ=0.1.

Summary and Questions

We have performed experiments in a laboratory model of a planetary core at unprecedented parameters, discovering new hydromagnetic internal wave modes and important Lorentz force effects in a variety of turbulent states. We will continue to more fully characterize the rotating and magnetized turbulent flows we find; among other things, we wish to determine whether the observed waves are of a magnetocoriolis type with important Lorentz and Coriolis restoring forces. We will also continue the search for dynamo action in the parameter space we have not yet explored, and we hope to develop and continue collaborations seeking to predictively model the interesting hydromagnetic flows we are studying.

References

Preprint

(1) Rieutord, Triana, Zimmerman, Lathrop, Phys. Rev. E **86**, 026304 (2012) ▶
http://dx.doi.org/10.1103/PhysRevE.86.026304
(2) Matsui, Adams, Kelley, Triana, Zimmerman, Buffett, Lathrop, PEPI Vol. **188**, Iss. 3-4 (2011) ▶
http://dx.doi.org/10.1016/j.pepi.2011.07.012
(3) Kelley, Triana, Zimmerman, Lathrop, Phys. Rev. E **81**, 026311 (2010) ▶
http://dx.doi.org/10.1103/PhysRevE.81.026311
(4) Soward and Hollerbach, JFM, **408**, pp 239-274 (2000)
http://dx.doi.org/10.1017/S0022112099007776

Acknowledgements

We gratefully acknowledge support from NSF Earth Sciences. Design and construction of this major research facility was supported by NSF/MRI EAR-0116129 and continuing scientific work in the 3m experiment is supported by NSF EAR-1114303. This work would not be possible without support of technical supervisor Don Martin and technician Nolan Ballew or the co-pilot skills of Matthew Adams (See Matthew's Poster, NG51C-1783, on Friday A.M.). Special thanks to collaborators Henri-Claude Nataf and Simon Cabanes from ISTerre at UJF Grenoble. Thanks to http://qrcode.littleidiot.be for a nice vector graphics QR generator.