Working Towards MRI Detection in the Laboratory

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Accretion Disks

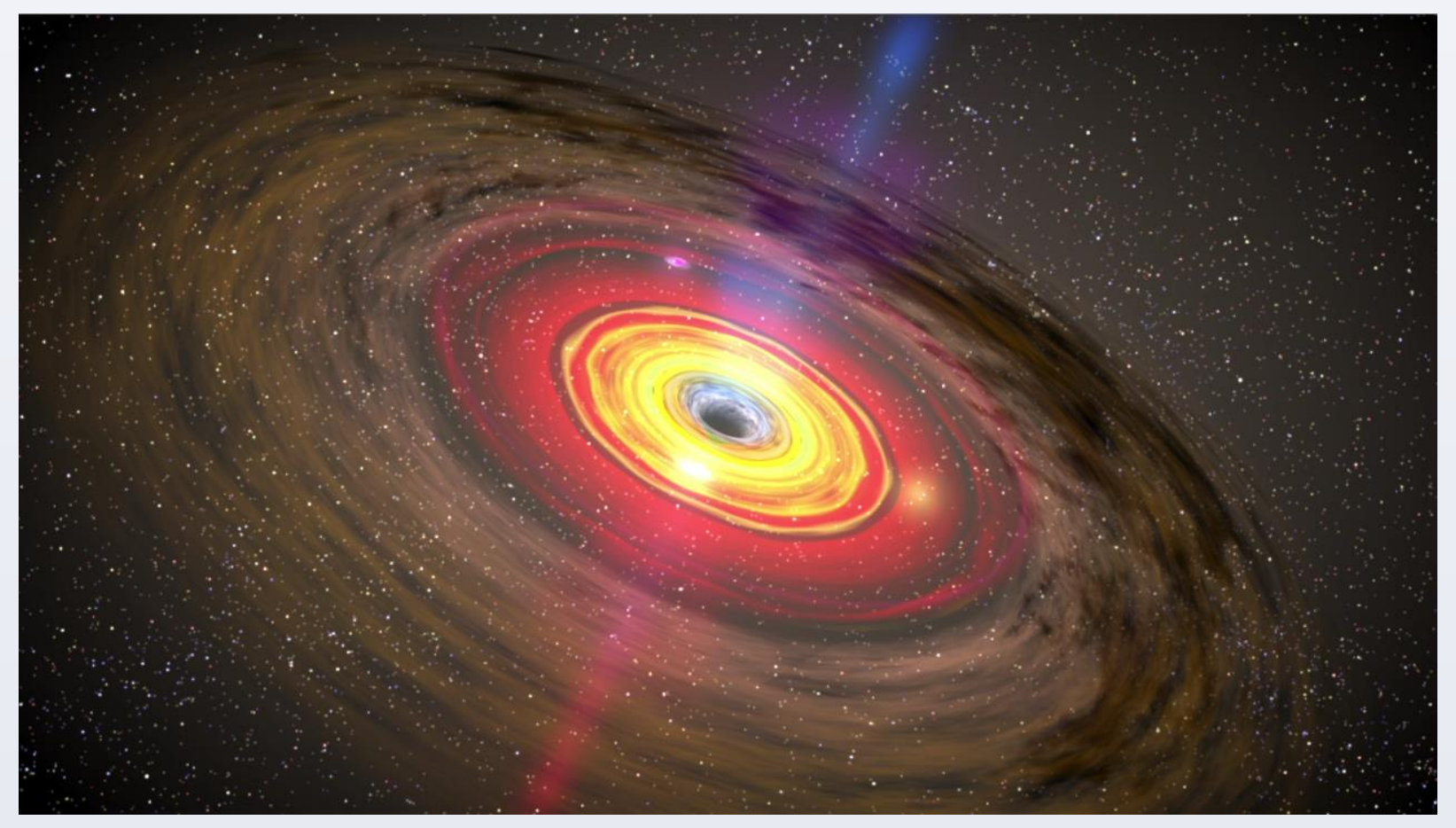


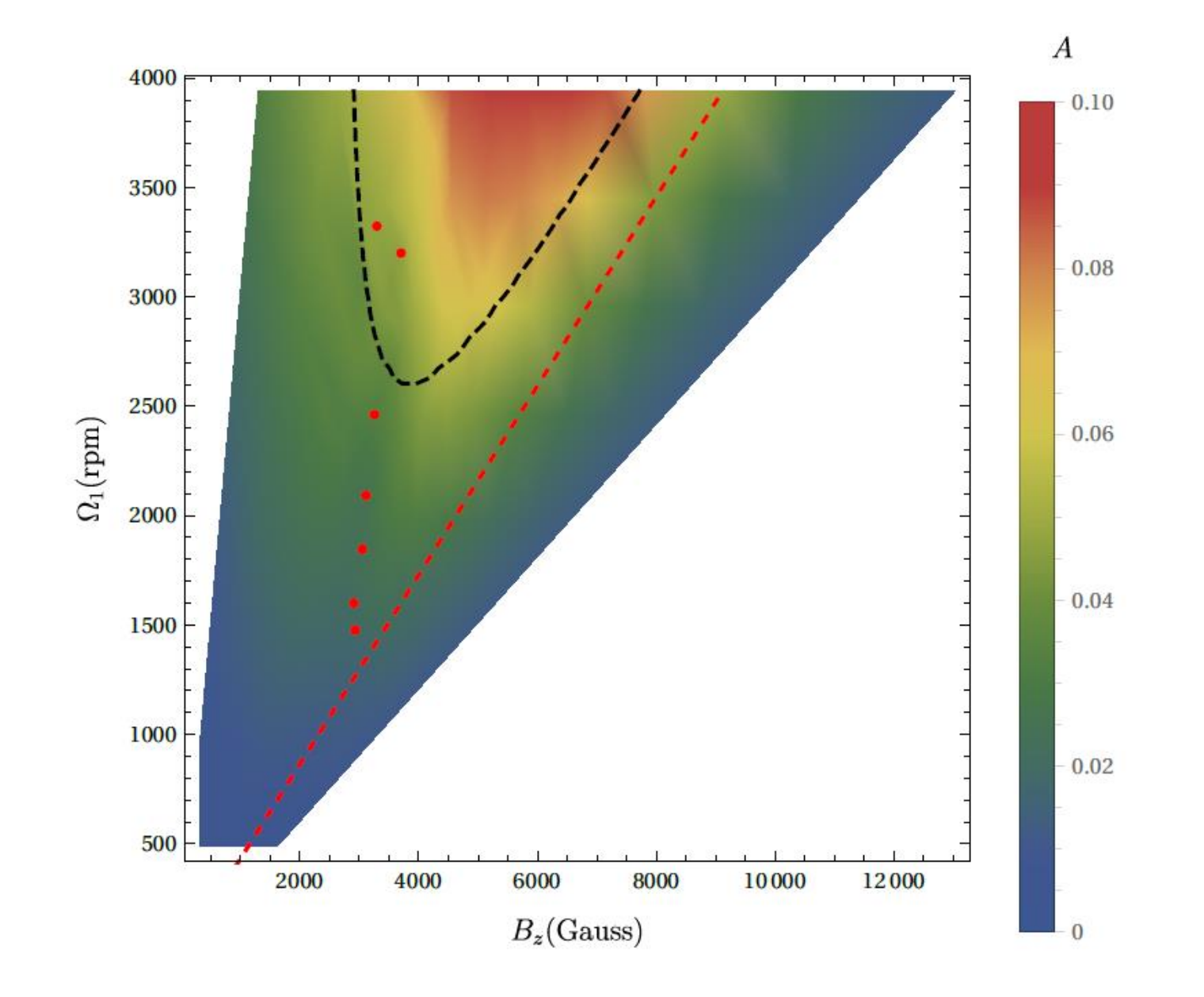
Image Credit: NASA/Goddard Space Flight Center

- **Accretion disks are a ubiquitous feature throughout the universe, formed as gas, dust, and plasma spiral in towards a gravitational source such as a black hole or neutron star.**
- **Problem: For particles to fall into an accretion disk, they must lose angular momentum. Conservation of angular momentum means particles moving outward must gain angular momentum.**
- **Magnetorotational Instability (MRI) is a predicted mechanism that allows angular momentum to be transported out of an accretion disk [1].**
- **MRI has yet to be observed in the laboratory.**

Theory of MRI

- The basic idea behind MRI is the frozen flux property of the conducting plasmas in accretion disks
- If two parcels of plasma start vertically on top of each other, and one of them begins to fall inward, the magnetic field will stretch to follow it.
- The magnetic field behaves as a spring pulling on the two parcels. But because of the rotation in the disk, this causes the inner parcel to fall farther in.

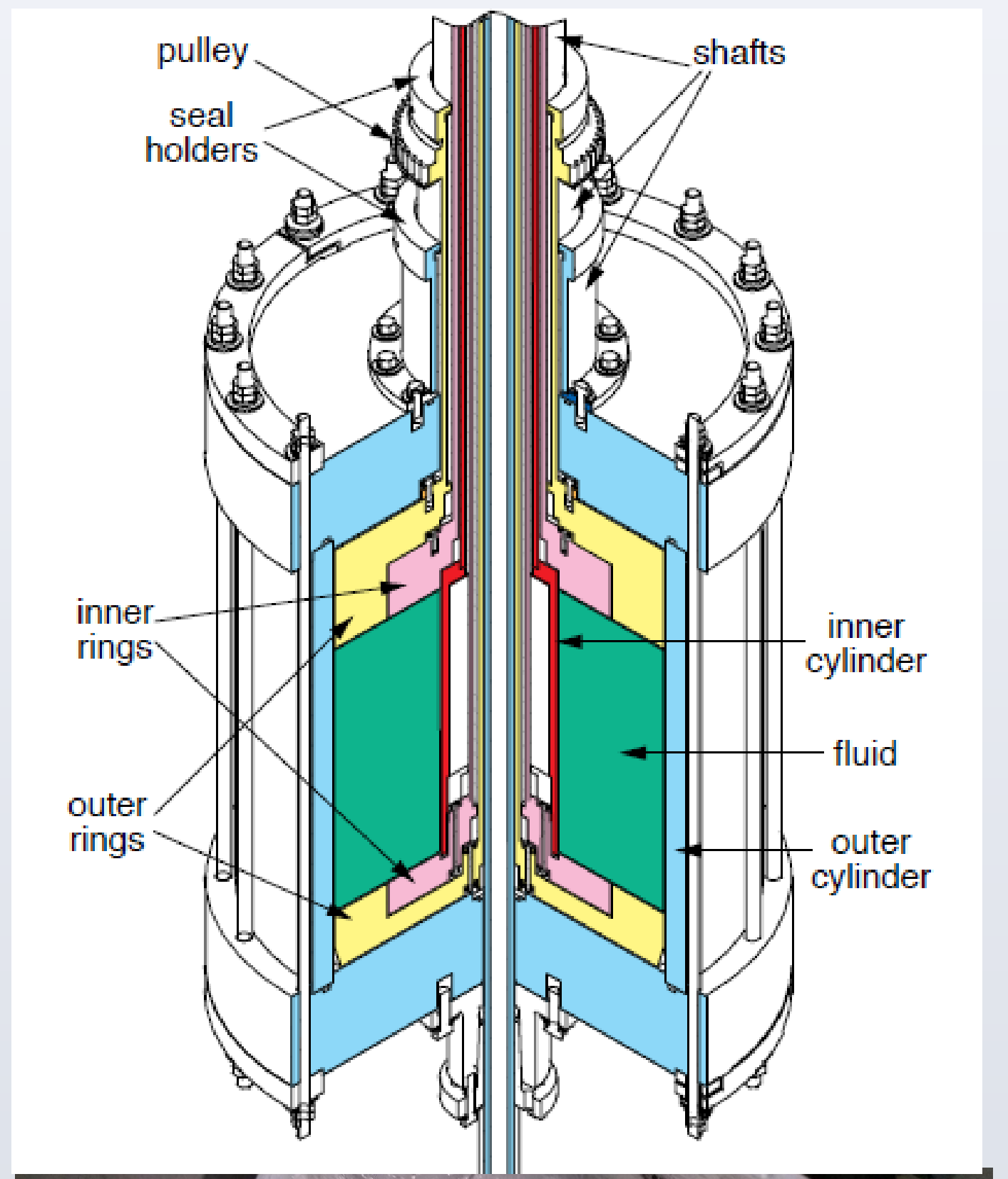
MRI is only predicted for intermediate magnetic field strengths relative to the rotation speed. If it is too weak, the viscosity of the fluid will damp the instability. If it is too strong, the magnetic field prevents the fluid from separating radially.



Numerical simulation results by Himawan Winarto [2]. Black dotted line indicates MRI unstable region predicted by simple linear model. Red dots indicate non-linear magnetic field signal in simulations indicating MRI instability.

The MRI Apparatus

We cannot generate an accretion disk in the lab, so we capture as many salient features as possible in the MRI apparatus. It creates a Taylor-Couette flow profile ($\Omega = a + b/r^2$) in the fluid using differentially rotating rings and cylinders [3].



Properties

- Height(h) = 28 cm
- Inner Cylinder Radius(R_1) = 7.06 cm
- Inner Ring Radius(R_3) = 13.25 cm
- Outer Cylinder Radius(R_2) = 20.3 cm
- Ratio Ω_1: Ω_3: Ω_2 = 1: 0.55: 0.1325

Six magnetic coils (bottom three shown in image) provide a vertical B field up to 6000 Gauss

Filled with a gallium, tin, and indium eutectic alloy (galinstan) that is liquid at room temperature.

Properties

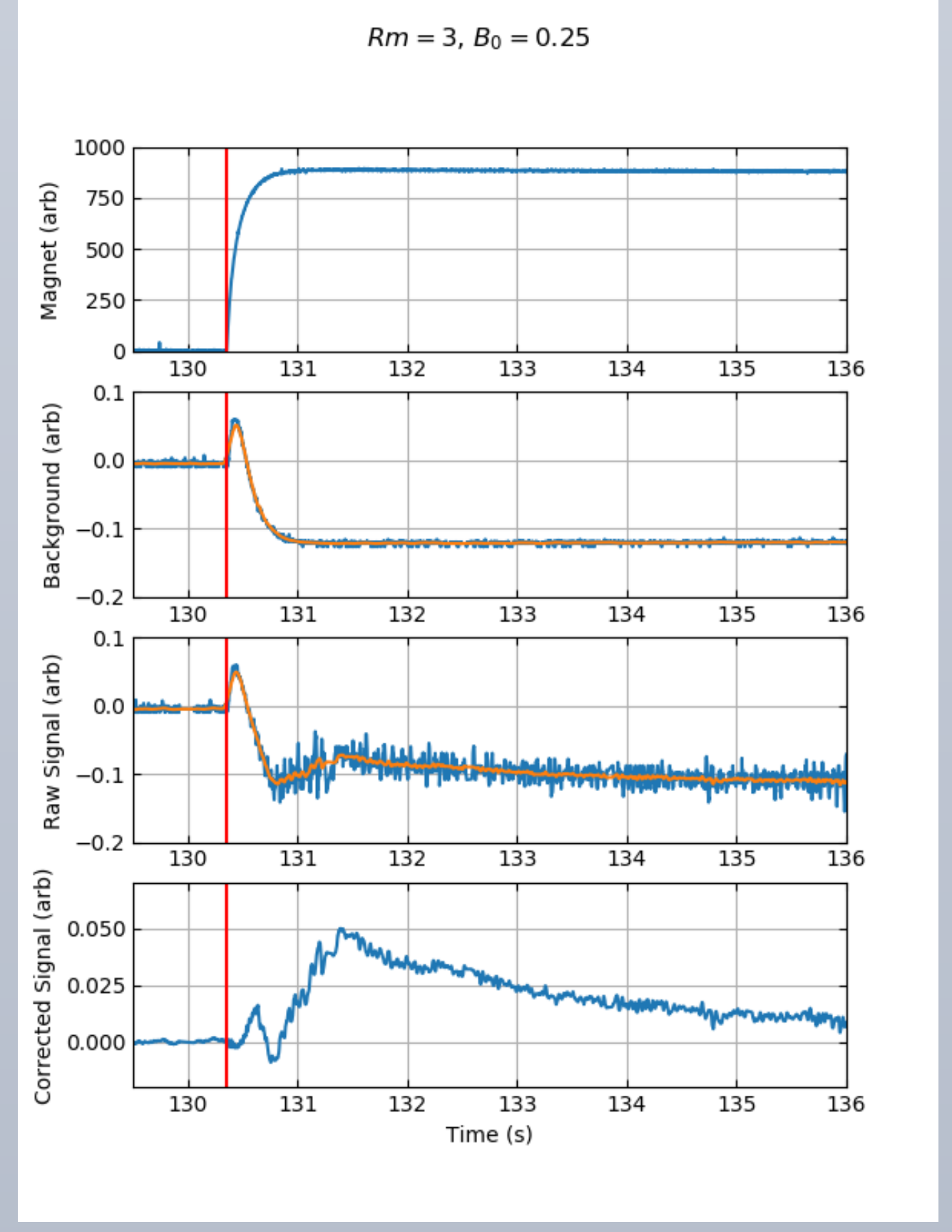
- Density(ρ) = 6.34 g/cm^3
- Viscosity(ν) = 0.0030 cm^2/s
- Magnetic Diffusivity(η) = 2570 cm^2/s

Measurement of MRI

- The MRI instability induces radial flows in the Galinstan, which will produce radial magnetic fields.
- Hall sensors installed on the top, middle, and bottom of the machine detect the magnetic field in the radial direction.
- Ultrasonic Doppler Velocimetry (UDV) sensors measure the azimuthal velocity of the galinstan.
- To isolate the MRI signal from other signal caused by non-ideal solenoids and induced fields, we take data with the magnets on without spinning the machine and subtract the background signal.

MRI Results

This data was taken in May 2018



Bottom Hall sensor
Ω_1 = 1477, B_z = 2440 G

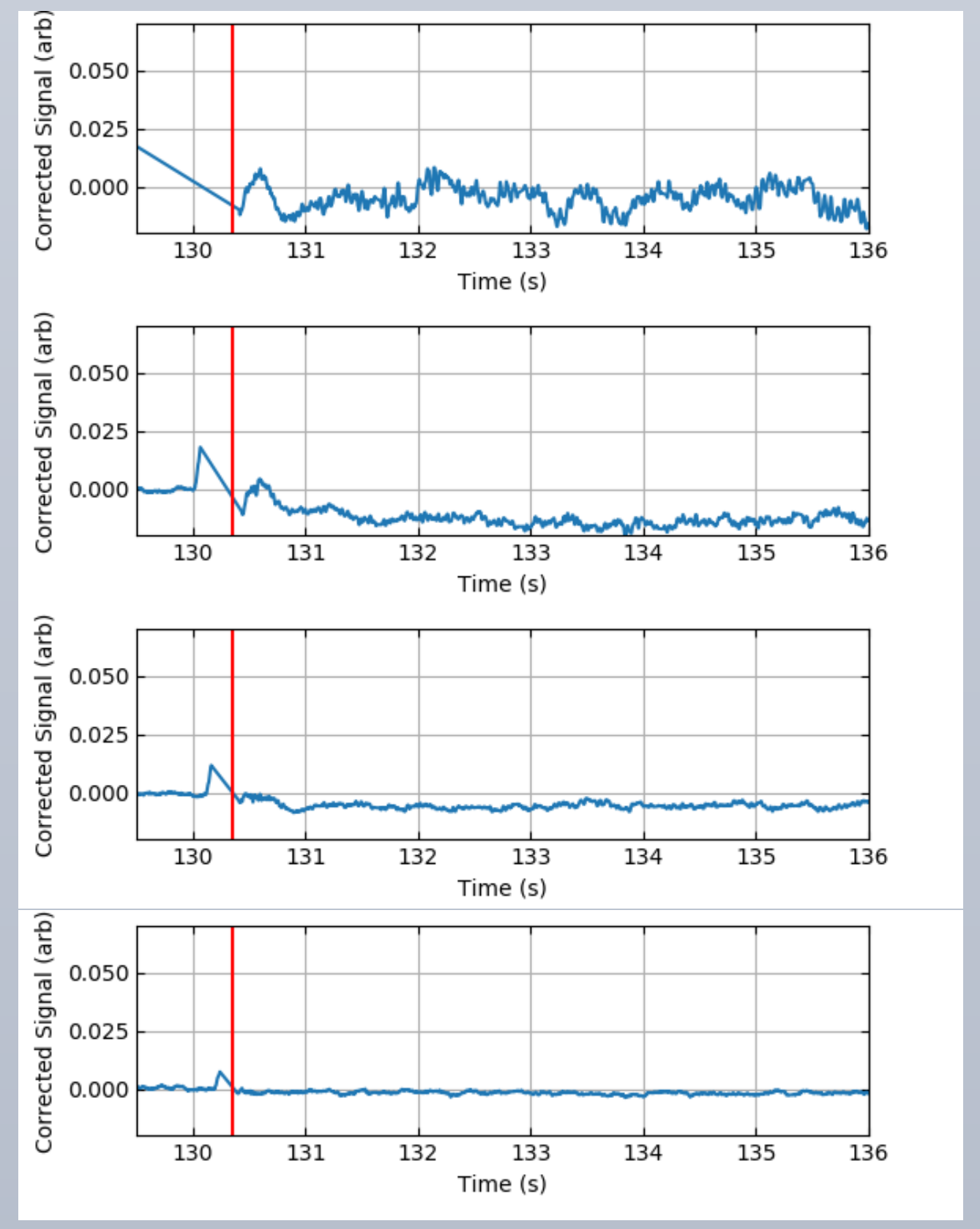
The magnetic Reynolds number is given for our system by

$$R_m = \frac{\Omega_1 R_1^2}{\eta}$$

The dimensionless magnetic field B_0 is the fraction of the characteristic field

$$B_0 = \frac{B_z}{\Omega_1 R_1 \sqrt{\rho\mu_0}} = \frac{B_z R_1}{R_m \eta \sqrt{\rho\mu_0}}$$

The B_r values obtained after subtracting off background have peak value of around 50 Gauss, indicating potential observation of MRI.

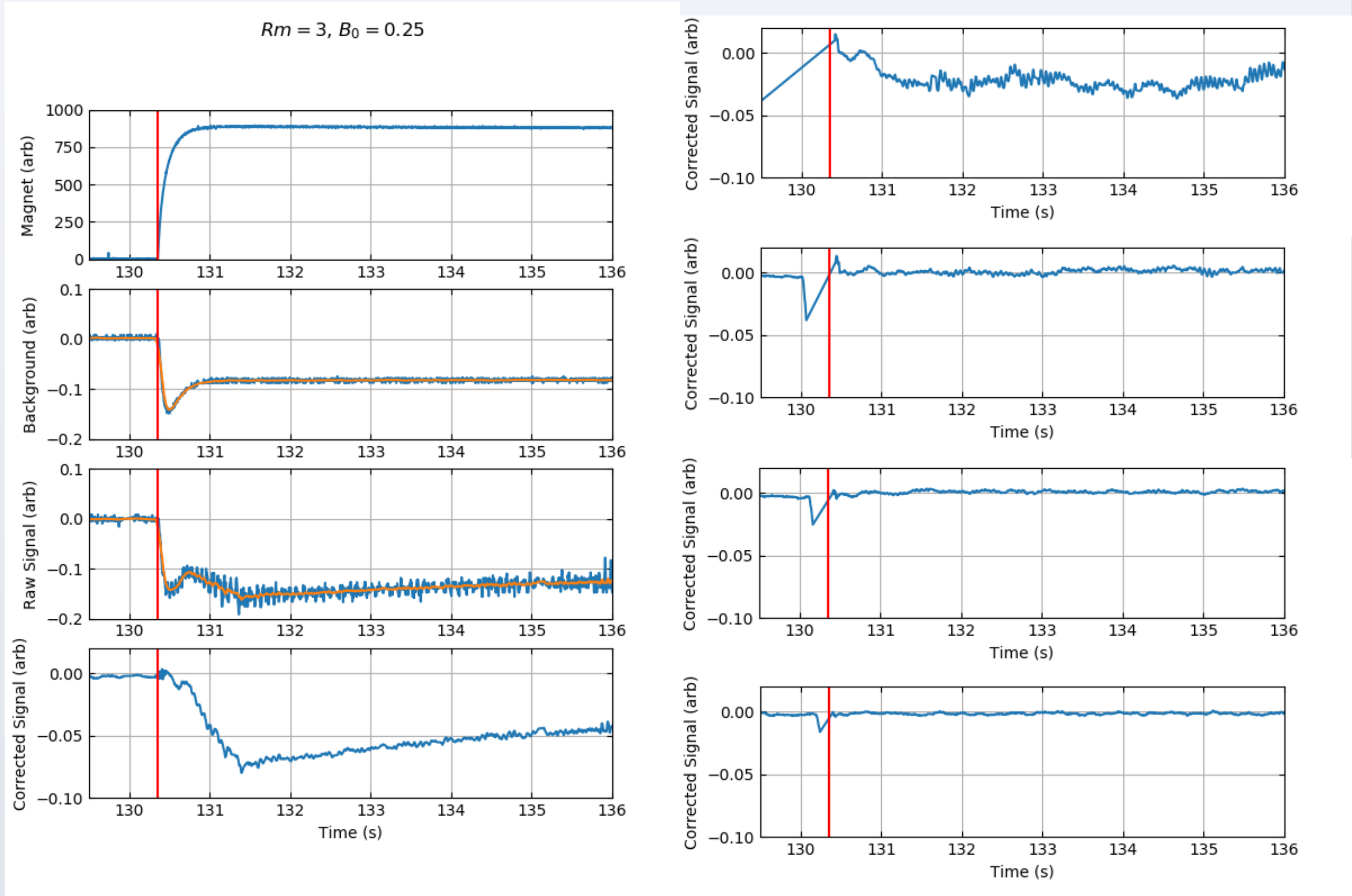


Bottom Hall sensor
Ω_1 = 1477, B_z = 1950, 1460, 976, 488 G from top to bottom

For smaller values of B_0, the signal is approximately zero, indicating that MRI is probably not occurring under these conditions.

The fact that the signal disappears at smaller magnetic field is consistent with the threshold behavior we expect to see from MRI.

Further Results



This data was collected from the top Hall sensor under the same conditions as the bottom Hall probes. They display the similar MRI signals as the bottom Hall probes.

Compared to simulations of the MRI unstable region, this is close to the minimum speed and magnetic field predicted for MRI to appear, based off of simulations (bottom left of poster).

To gather evidence that the signal is in fact MRI, future work involves mapping more of the rotational speed/magnetic field strength region.

- At R_m = 3, measurements at higher magnetic field will establish whether MRI shuts off when the field is too strong, as predicted.
- At higher R_m, measurements will establish whether the MRI unstable region covers larger ranges of magnetic field strength at higher rotational speeds, as predicted.
- At lower R_m, we expect to see no MRI signal for any field.

My Work

- Assisted with disassembly and reassembly of the MRI apparatus and repair efforts.
- The MRI apparatus has not been able to run this summer due to binding between the inner cylinder and inner ring.
- Attempts to resolve this issue revolved around lightening the load on the bearings or better lubricating them.
- Graphite powder, Drislide, and Moly-Dee were tested in bearings but failed under full load in the machine, perhaps indicating a deeper unresolved problem.
- In the longer term, the outer ring and/or lid could be enlarged to sit on the outer cylinder to redistribute the load, but this is a large adjustment that requires significant commitment of time and effort.

References

Accretion Disk image from https://svs.gsfc.nasa.gov/10545

Papers:

[1] J. Balbus, S. Hawley. A powerful local shear instability in weakly magnetized disks. i - linear analysis. ii - nonlinear evolution. Astrophysical Journal, 376:214–233, July 1991. doi: 10.1086/170270.

[2] Himawan Winarto. Laboratory Study of Magnetorotational Instability. Princeton University, Senior Thesis, May 2, 2018.

[3] E. Schartman, H. Ji and M. Burin, "*Development of a Couette-Taylor flow device with active minimization of secondary circulation* ", Rev. Sci. Instrum. **80**, 024501 (2009).