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EGU

Outstanding Student & PhD candidate Presentation contest

A laboratory study of turbulent magnetoconvection:

Could thermoelectricity induce asymmetry in geomagnetic secular variation?

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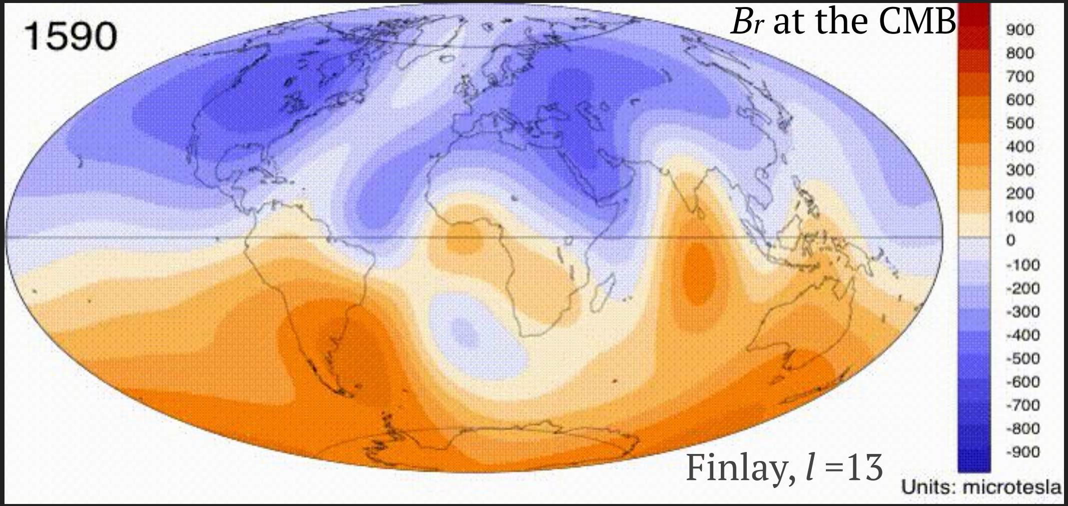
The Geodynamo



- ❖ Time-dependent secular variation
- ❖ Inclination anomaly from paleomagnetic data
  - ➢ Asymmetry during field reversals
  - ➢ Hemispheric asymmetry
  - ➢ Debates
- ❖ **Source of asymmetry**
  - ➢ **Deeper core flows? Or near-CMB dynamics?**
  - ➢ **Thermoelectricity**

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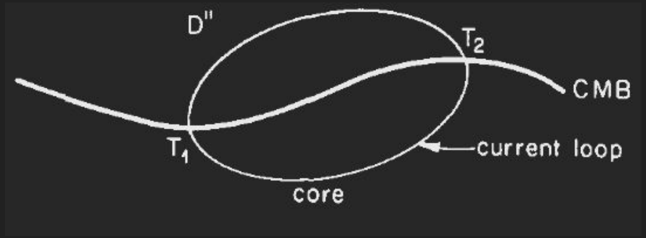
Conundrum of Thermoelectricity at CMB

$$\Phi_{TE} \sim \widetilde{S} \Delta T_p$$

- All focused on **toroidal field generation**. Too small to explain polarity asymmetry.
  - Elsasser (1939): Thermoelectricity (TE) → geomagnetism
  - Runcorn (1954), Merrill et al. (1979) (1990): TE from CMB
  - TE generates Mercury's dynamo? (Stevenson 1987, *EPSL*; Giampieri & Balogh 2002, *P&SS*)
- To characterize the system: laboratory experiment!



Merrill et al. 1990

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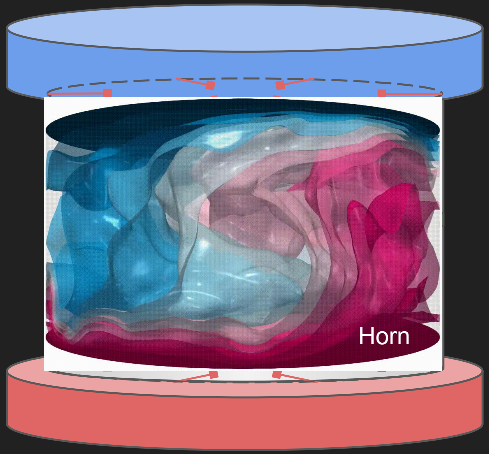
Experiment Setup



Working fluid: liquid gallium (Pr = 0.027, Rm < 0.015)

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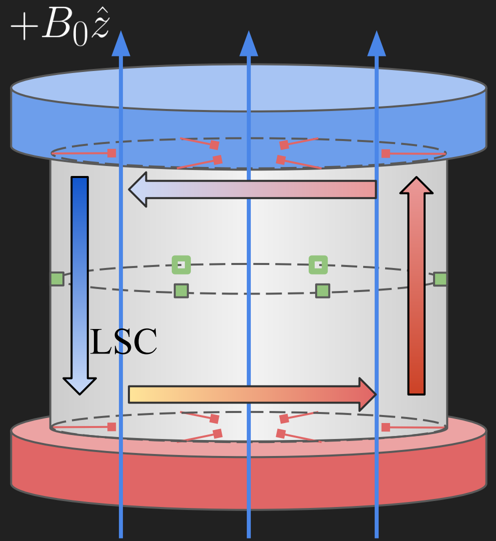
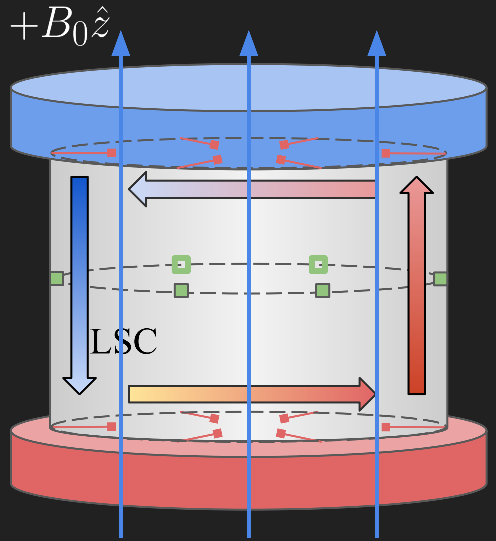
Experiment Setup



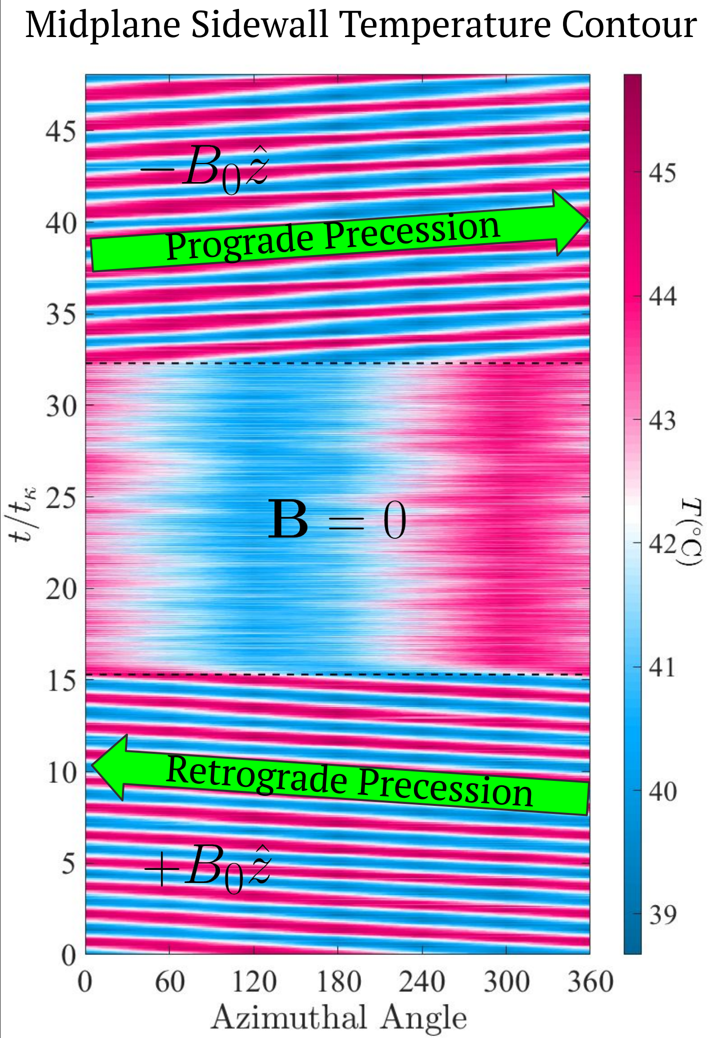
Working fluid: liquid gallium (Pr = 0.027, Rm < 0.015)

- Thermal signals → fluid motions in liquid metal.
- Classical turbulent Rayleigh-Bénard convection setup with a vertical B field
- Large Scale Circulation (LSC) → self-sustaining ∇T at the top/bottom boundaries.
- B field should inhibits convective fluid motions (low Rm).

Experiment Results



Thermal Diffusion Times



Xu *et al.* 2022, *JFM*

- ❖ Slow **magneto-precession (MP) mode**
- ❖ Sensitive to the polarity of the magnetic field
- ❖ No significant change in heat transfer

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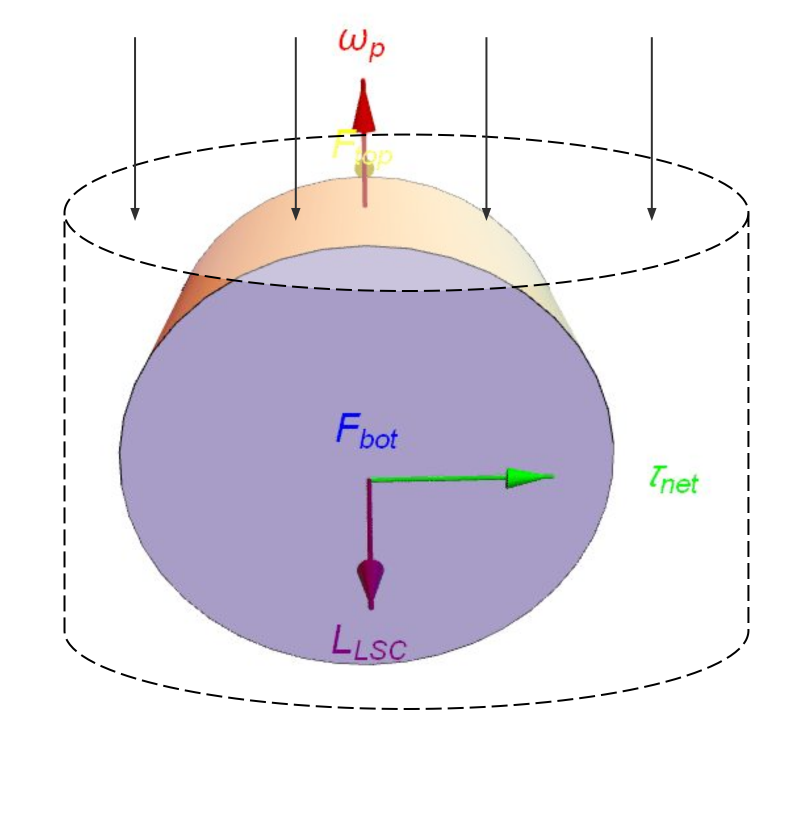
Analytical Model for TEMC



- Thermoelectric precession angular frequency:

$$\boldsymbol{\omega}_{MP} = \frac{\tau_{net}}{L_{LSC}}(-\hat{e}_b)$$

$$\omega_{MP} = \frac{\pi^{1/2}}{\Gamma^{3/2}} \frac{\sigma_0 X_0 B \mathcal{T}}{2\rho U_{ff} H}(-\hat{e}_b)$$

- Precession reverses its direction if B is flipped
- Agree with experimental data <16%

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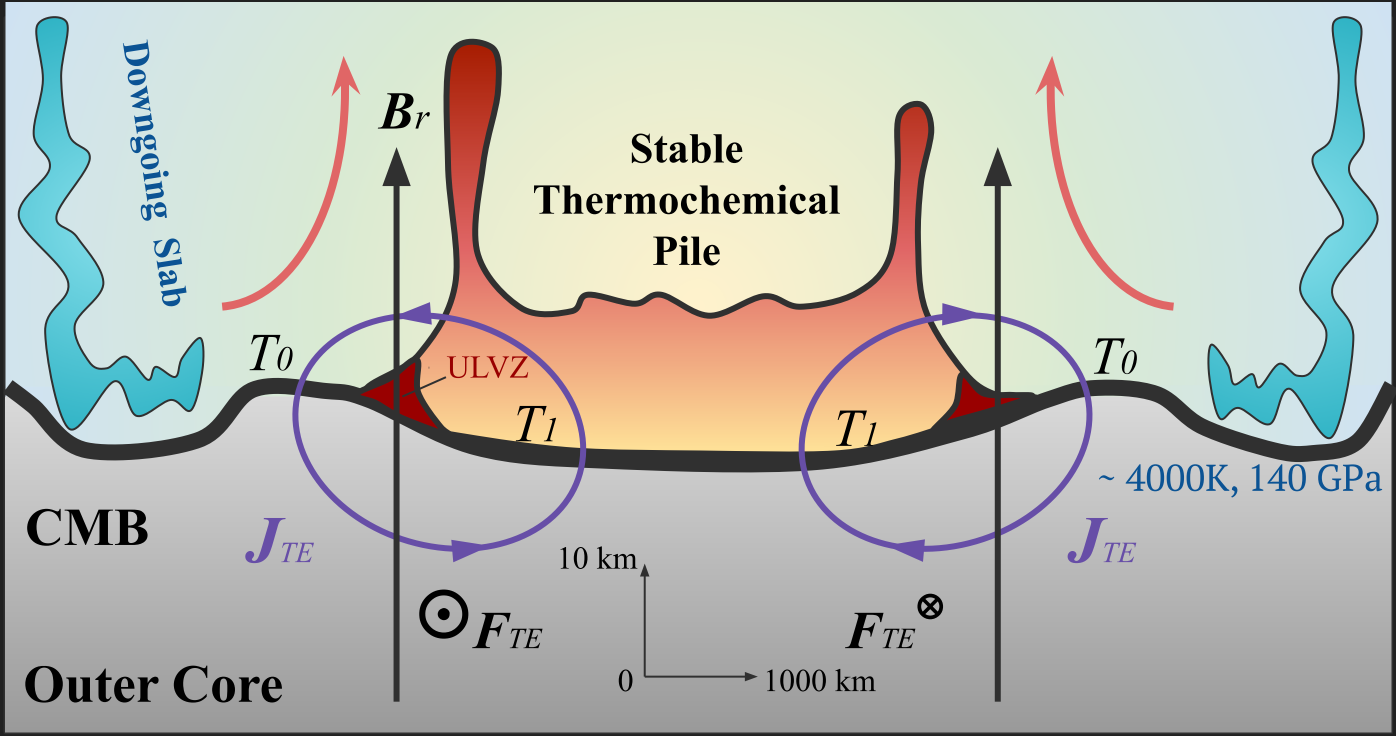
Thermoelectricity at CMB?



- TE currents with B field can exert torques on core fluid near CMB mega-ULVZs
- Potential new dynamic mechanism for core-mantle coupling.
- Induction equation: changes in velocity field that can cause polarity asymmetry in geomagnetic fields.
- Current uncertainty: CMB properties

Xu et al. 2022, *JFM. Adapted from Garnero, McNamara & Shim (2016) and Deschamps, Rogister & Tackley (2018)*

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Looking for Geophysical Evidence and Collaborations

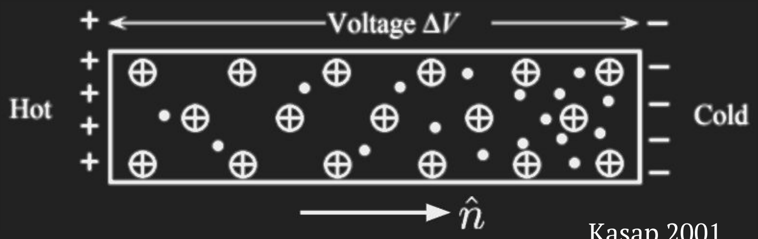
- **Mantle dynamicists:**
  - Thermal gradient along CMB?
- **Mineral Physicists:**
  - Seebeck coefficients of CMB materials? Possibly can be studied by first-principle simulations.
- **Theorists/experimentalists:**
  - Controlled ∇T TEMC experiments including effects of rotation & stratification.
- **Geophysicists:**
  - Observations of polarity asymmetry in paleomagnetic secular variations near mega-ULVZs.

Xu *et al.* 2022, *JFM*

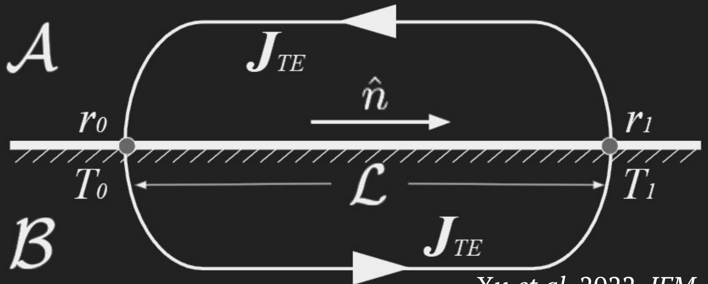
Backup

Thermoelectric Effects

- The Seebeck Effect : Temperature gradient ⟶ Electric potential $\Phi_{TE} \sim \widetilde{S}\Delta T_p$



Kasap 2001



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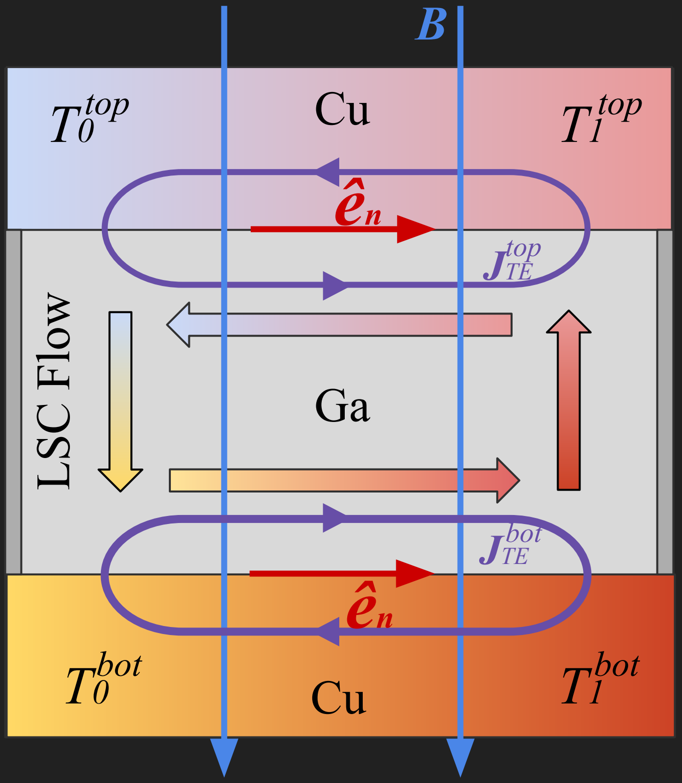
- TE currents generated from an imposed temperature gradient with a perpendicular B field → Lorentz forces $\boldsymbol{F}_L$ on liquid metal (Shercliff 1979).

Analytical Model for TEMC



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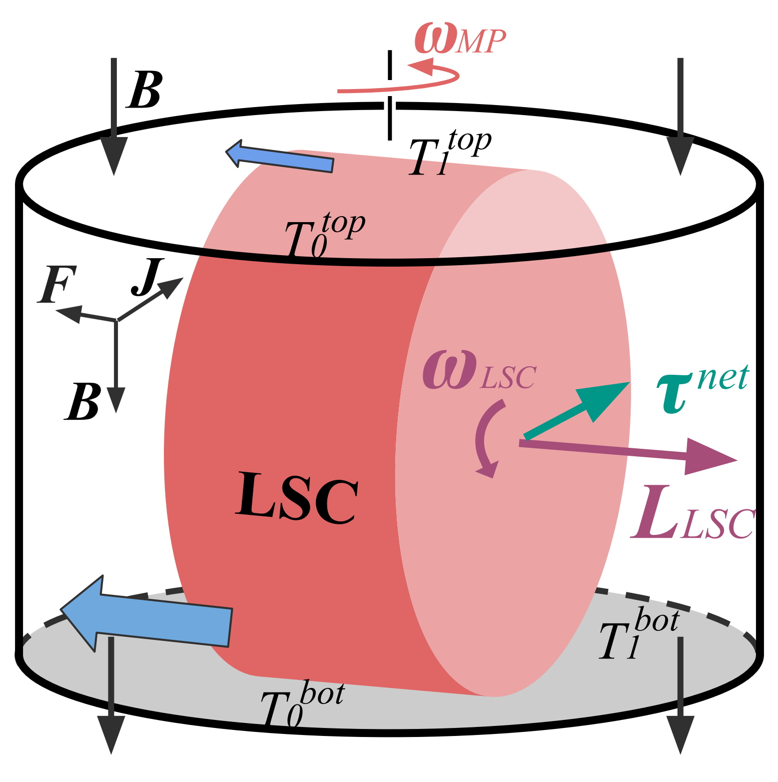
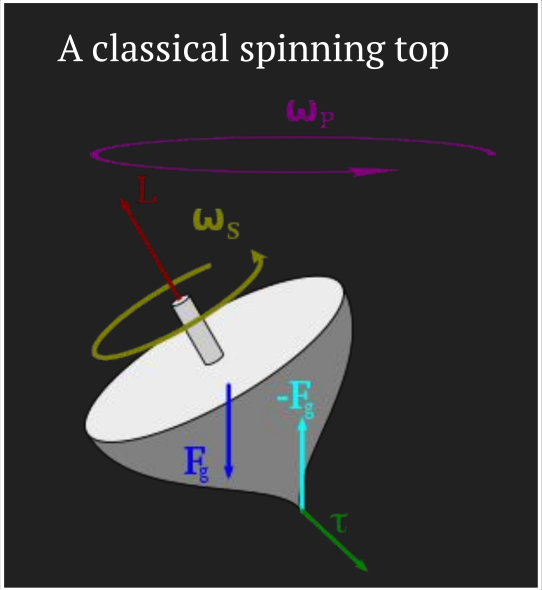
- LSC creates $\delta T_\perp$ at top and bottom boundaries
- $\delta T_\perp$ generates TE currents J_{TE} at the interfaces
- TE currents J_{TE} and the vertical B field generate Lorentz Forces $\boldsymbol{F}_L = \boldsymbol{J}_{TE} \times \boldsymbol{B}$
- The net $\boldsymbol{F}_L$ generates torques perpendicular to the moment of inertia of the LSC.
- TE magneto-precessional mode!

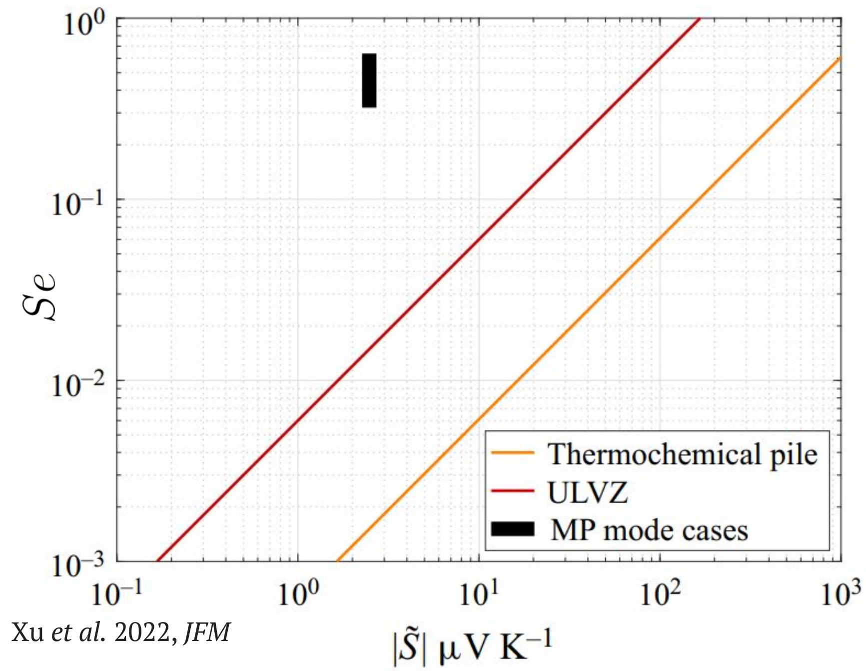
Analytical Model for TEMC



Xu *et al.* 2022, *JFM*



Seebeck Number Estimates



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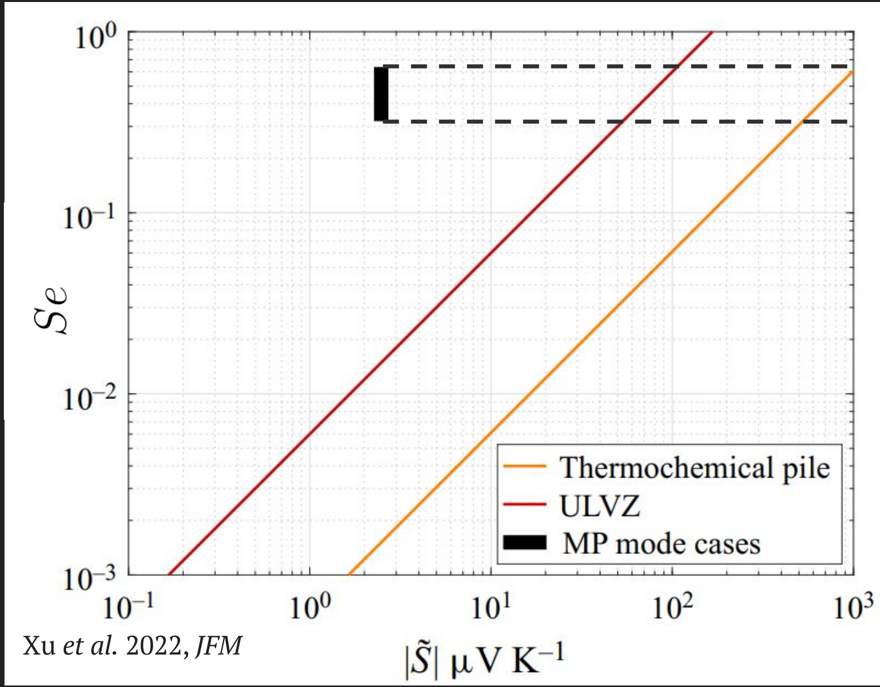
Net Seebeck Coefficient, $\widetilde{S}$

Seebeck Number, *Se,* measures significance of the TE dynamics:

$$Se = \frac{|\widetilde{S}|\Delta T_p}{U_C B_r L} = \frac{\text{TE Potential}}{\text{Motion Induced Potential}}$$

- ❖ ΔT_p: lateral temperature difference ~ 300K
- ❖ U_c: Outer core flow speed near CMB ~ 0.1mm/s
- ❖ B_r: Radial geomagnetic field ~1mT
- ❖ Length of thermochemical pile ~ 5000km
- ❖ Length of ULVZs ~ 500km

Seebeck Number Estimates



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Net Seebeck Coefficient, $\widetilde{S}$

- TEMC flows are at $Se \gtrsim \mathcal{O}(10^{-1})$
- Thermochemical pile or ULVZ: $|\widetilde{S}| \gtrsim \mathcal{O}(10^2) - \mathcal{O}(10^3)$
- **Mantle dynamicists:**
  - Thermal gradient along CMB?
- **Mineral Physicists:**
  - Seebeck coefficients of CMB materials? Possibly can be studied by first-principle simulations.
- **Theorists/experimentalists:**
  - Controlled ∇T TEMC experiments including effects of rotation & stratification.


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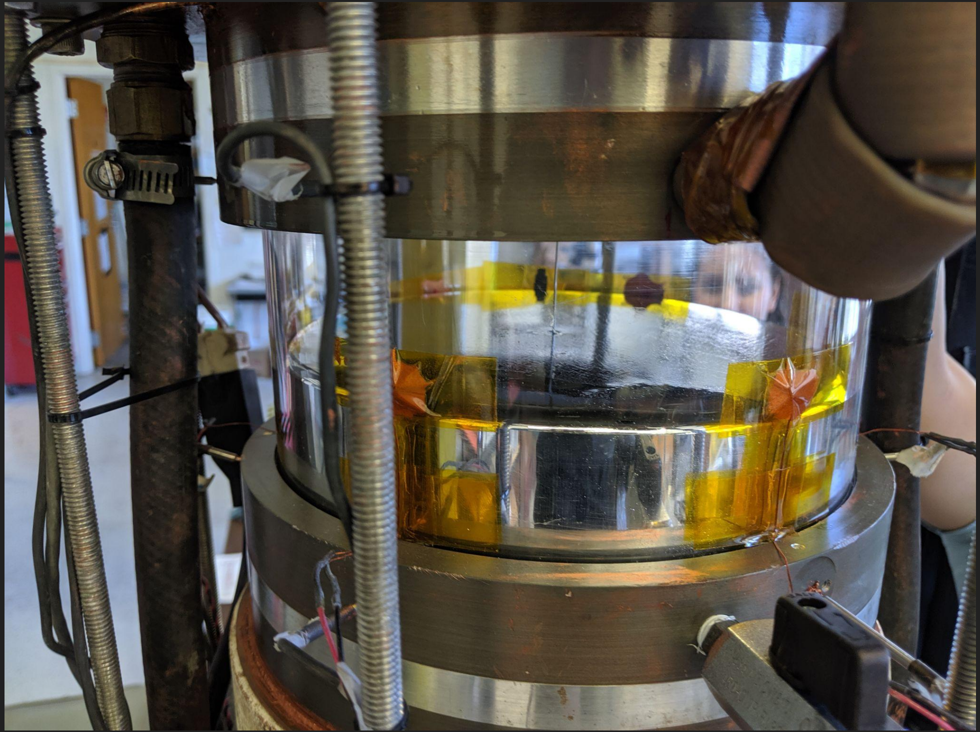
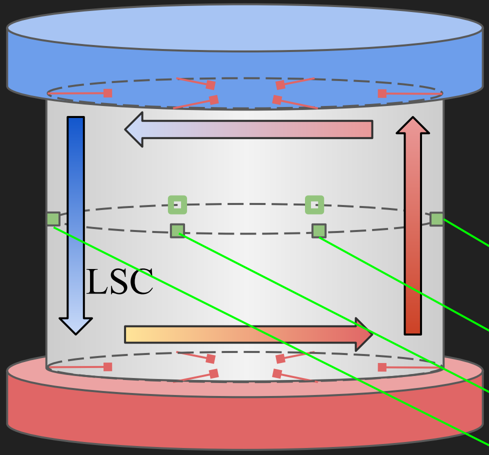
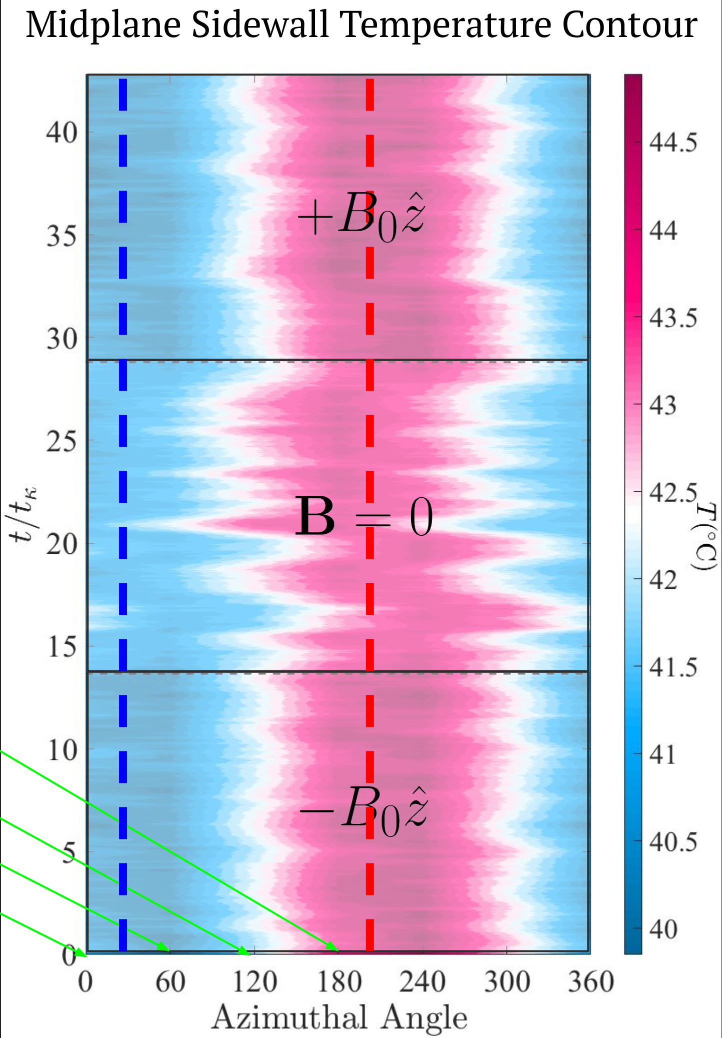


- Study 1: Electrically-**insulated** Boundary: Teflon-coated Aluminum

$\mathbf{B} = 0$



Thermal Diffusion Times

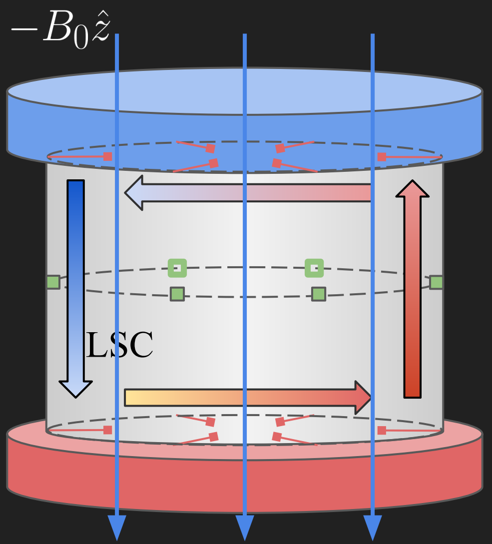


Xu *et al.* 2022, *JFM*

$$Ra = \frac{\text{Buoyancy}}{\text{Diffusion}} = 1.62 \times 10^6$$

$$N = \frac{\text{Lorentz}}{\text{Inertia}} = 0$$

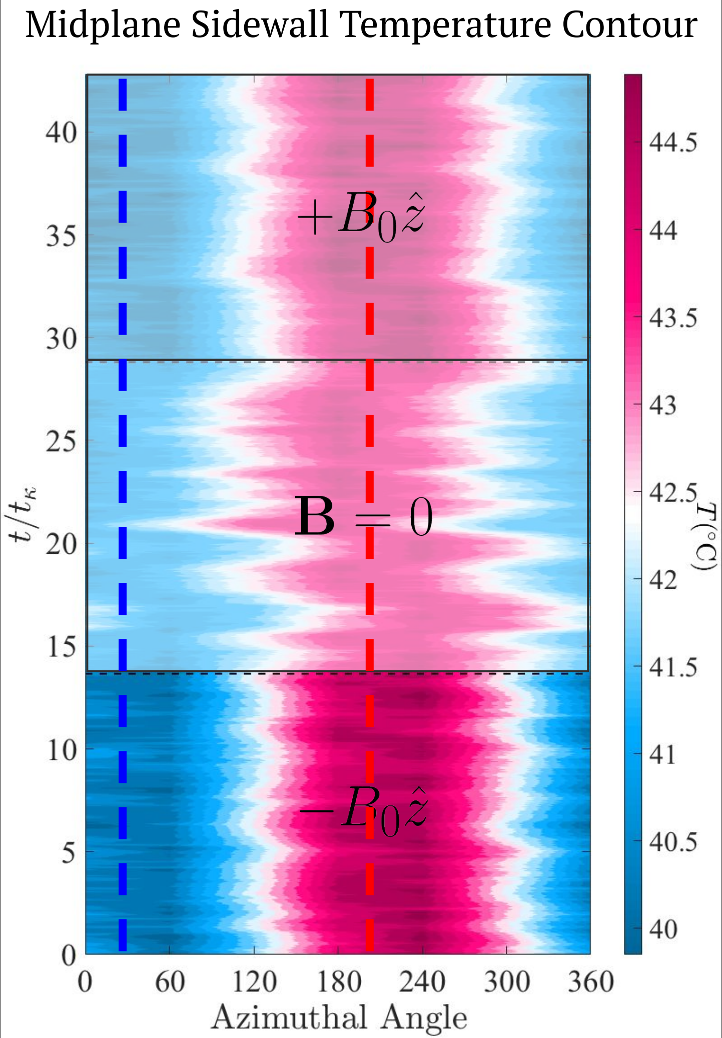
- Study 1: Electrically-**insulated** Boundary: Teflon-coated Aluminum



$$Ra = \frac{\text{Buoyancy}}{\text{Diffusion}} = 1.62 \times 10^6$$

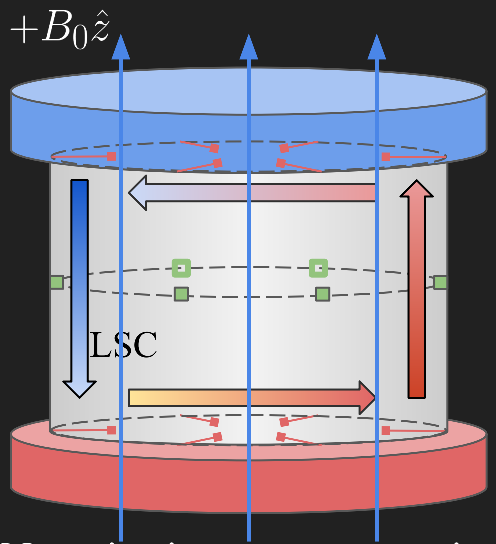
$$N = \frac{\text{Lorentz}}{\text{Inertia}} = 0.29$$

Thermal Diffusion Times

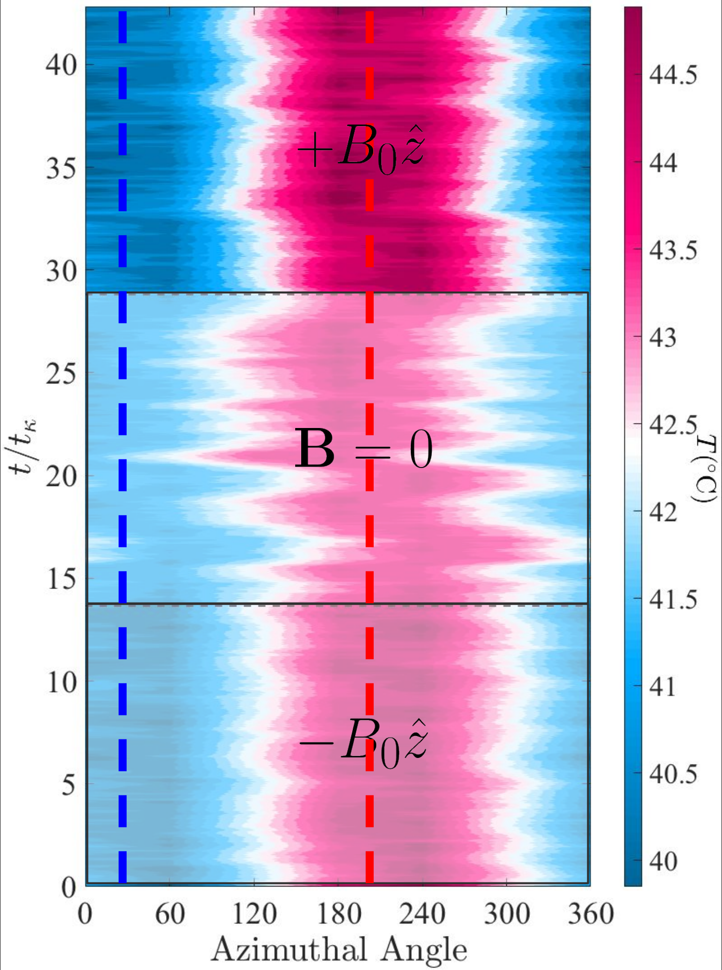


Xu *et al.* 2022, *JFM*

- Study 1: Electrically-**insulated** Boundary: Teflon-coated Aluminum



Thermal Diffusion Times

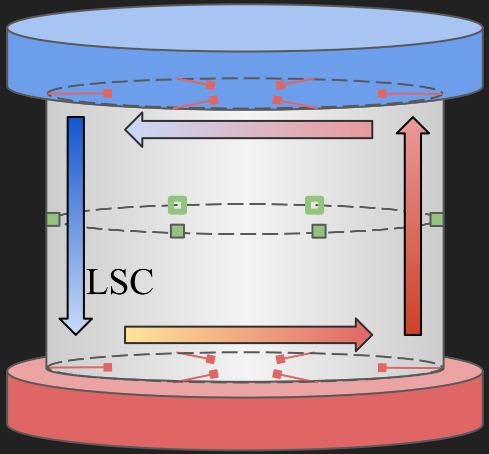


Xu *et al.* 2022, *JFM*

- ❖ LSC persists in magnetoconvection
- ❖ Agree with our expectation from the standard Low-*Rm* approximation (Cioni, 2000; Zürner *et. al*, 2020)
- ❖ MC's characteristic frequency agrees with prediction (Vogt *et. al*, 2018)

- Study 2: Electrically-**conducting** Boundary: Copper

$\mathbf{B} = 0$

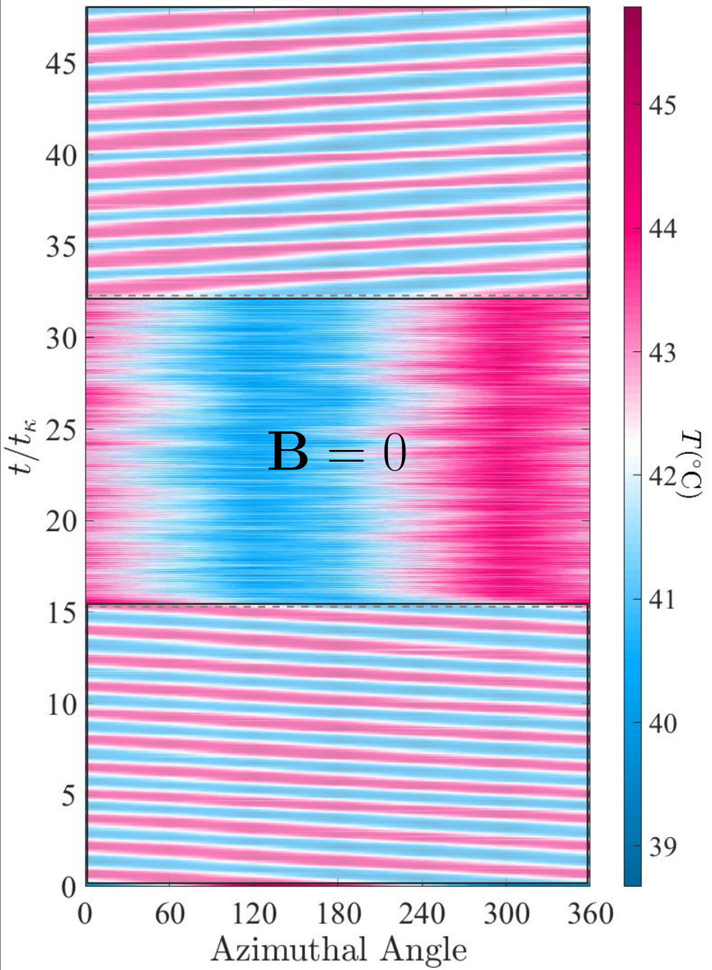


$$Ra = \frac{\text{Buoyancy}}{\text{Diffusion}} = 1.80 \times 10^6$$

$$N = \frac{\text{Lorentz}}{\text{Inertia}} = 0$$

Thermal Diffusion Times

Midplane Sidewall Temperature Contour



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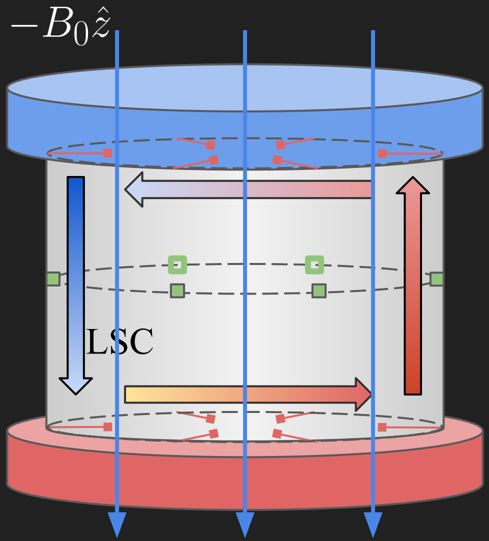
- Study 2: Electrically-**conducting** Boundary: Copper

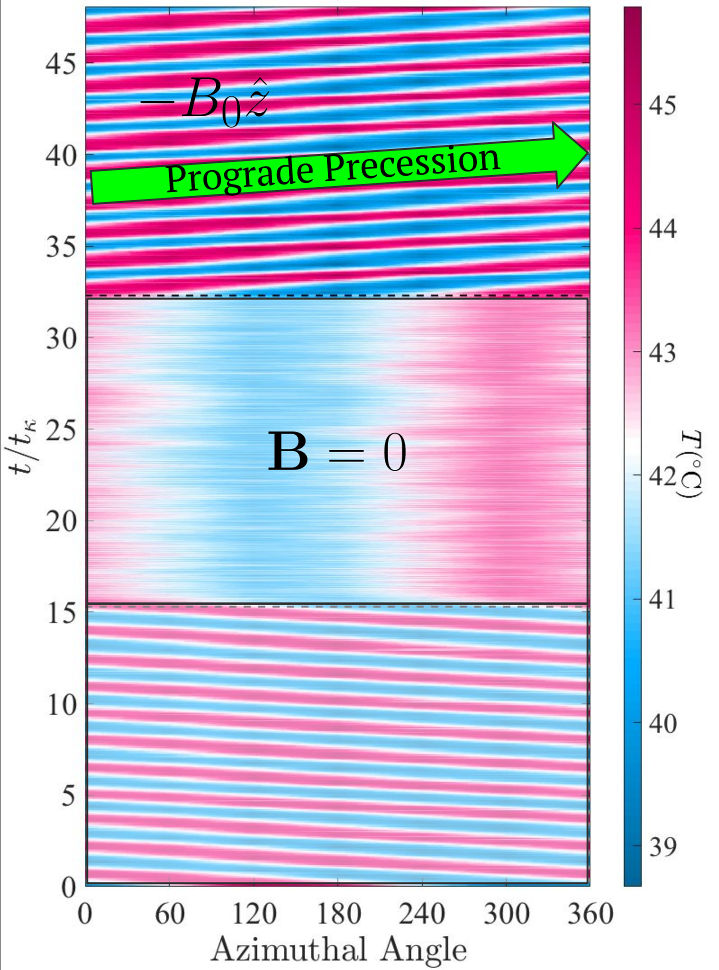


$$Ra = \frac{\text{Buoyancy}}{\text{Diffusion}} = 1.83 \times 10^6$$

$$N = \frac{\text{Lorentz}}{\text{Inertia}} = 0.31$$

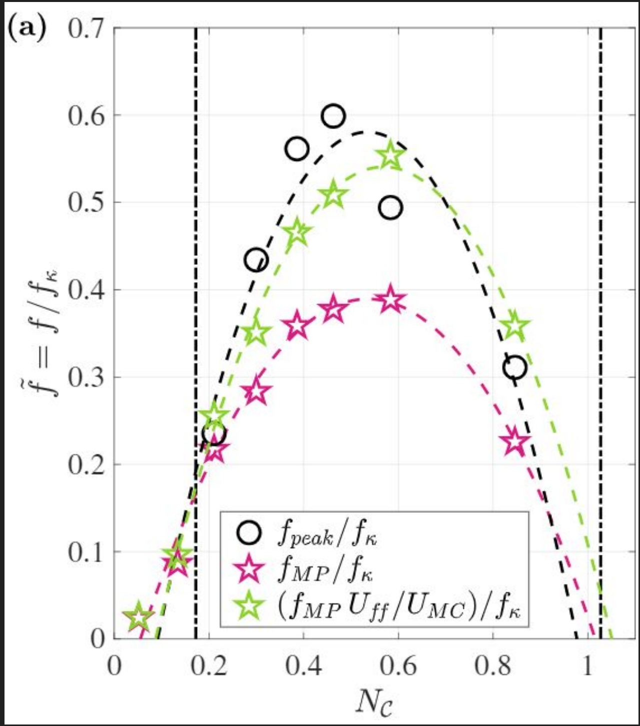
Thermal Diffusion Times

Midplane Sidewall Temperature Contour



Xu *et al.* 2022, *JFM*

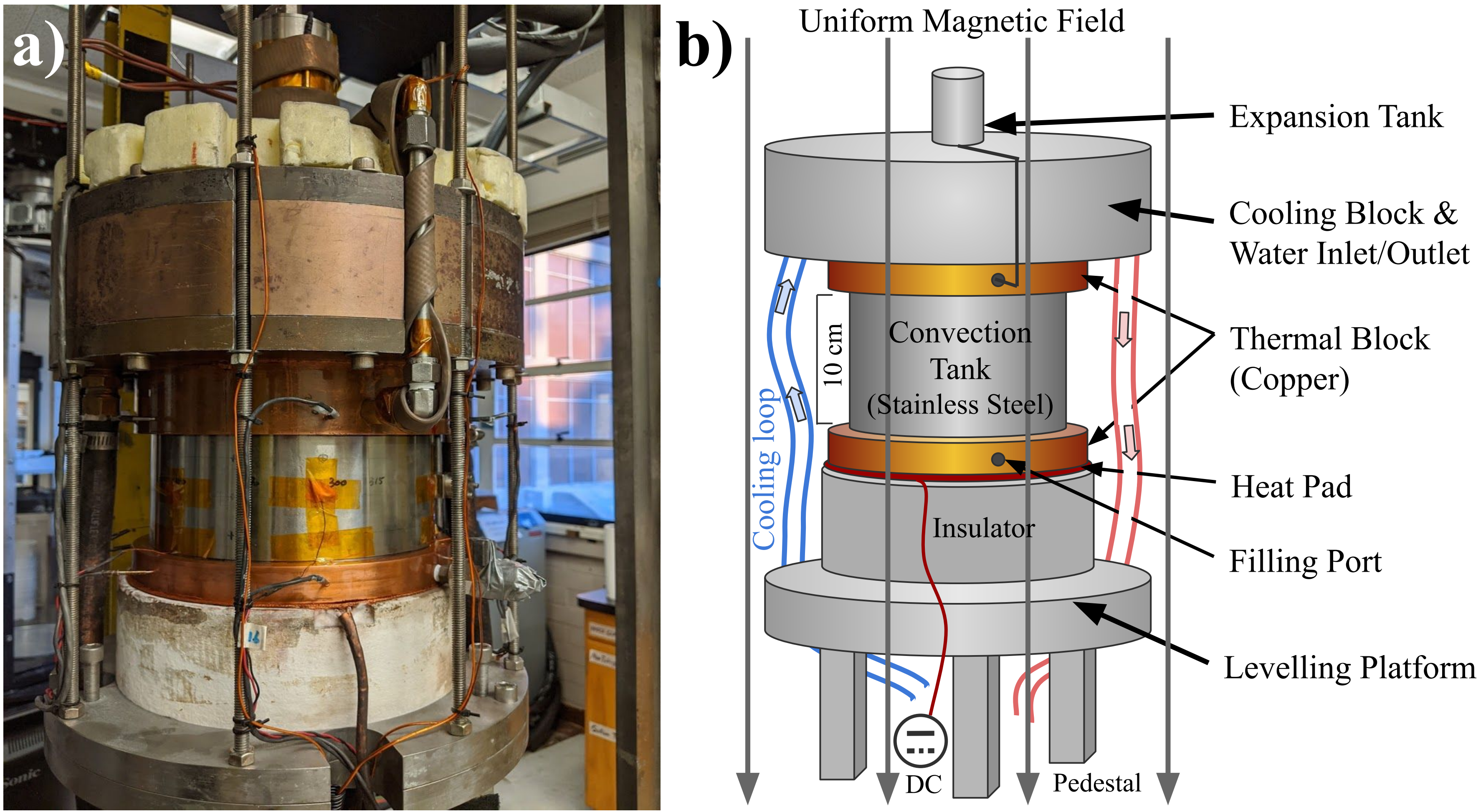
Analytical Model vs. Experimental Data



Lorentz/Inertia

Xu *et al.* 2022, *JFM*

- Fixed *Ra* (Buoyancy/ Diffusion), varying N_C (Lorentz/Inertia).
- <16% difference between the model using U_{MC} (Zürner *et. al*, 2020) and the experiments.
- When Lorentz force becomes comparable with the inertia ($N_C \gtrsim 1$) → multi-cellular flow.

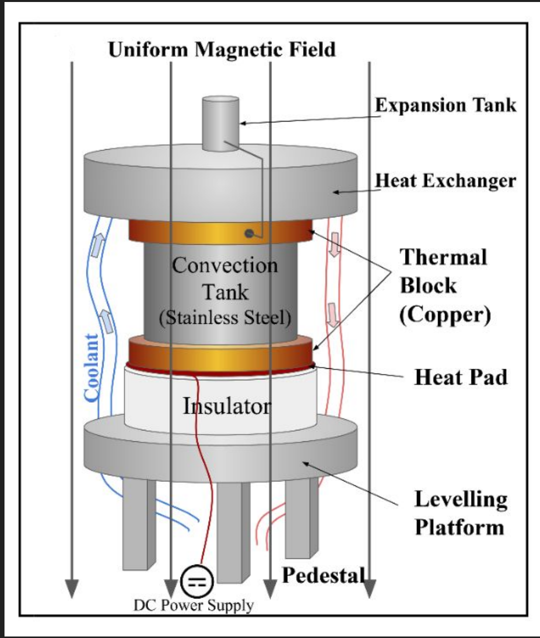

a)
b)
Uniform Magnetic Field
Expansion Tank
Cooling Block &
Water Inlet/Outlet
Thermal Block
(Copper)
Convection
Tank
(Stainless Steel)
10 cm
Cooling loop
Heat Pad
Insulator
Filling Port
Levelling Platform
DC
Pedestal

Low-Rm (Quasistatic) Approximation

Working fluid: liquid gallium $Rm \lesssim 0.015$

- In this limit, the induced magnetic field by fluid motion is negligible. The resulting Lorentz force is:

$$\boxed{\mathbf{F} = \mathbf{J} \times \mathbf{B}_0 \sim -\sigma \mathbf{u}_\perp B_0^2}$$

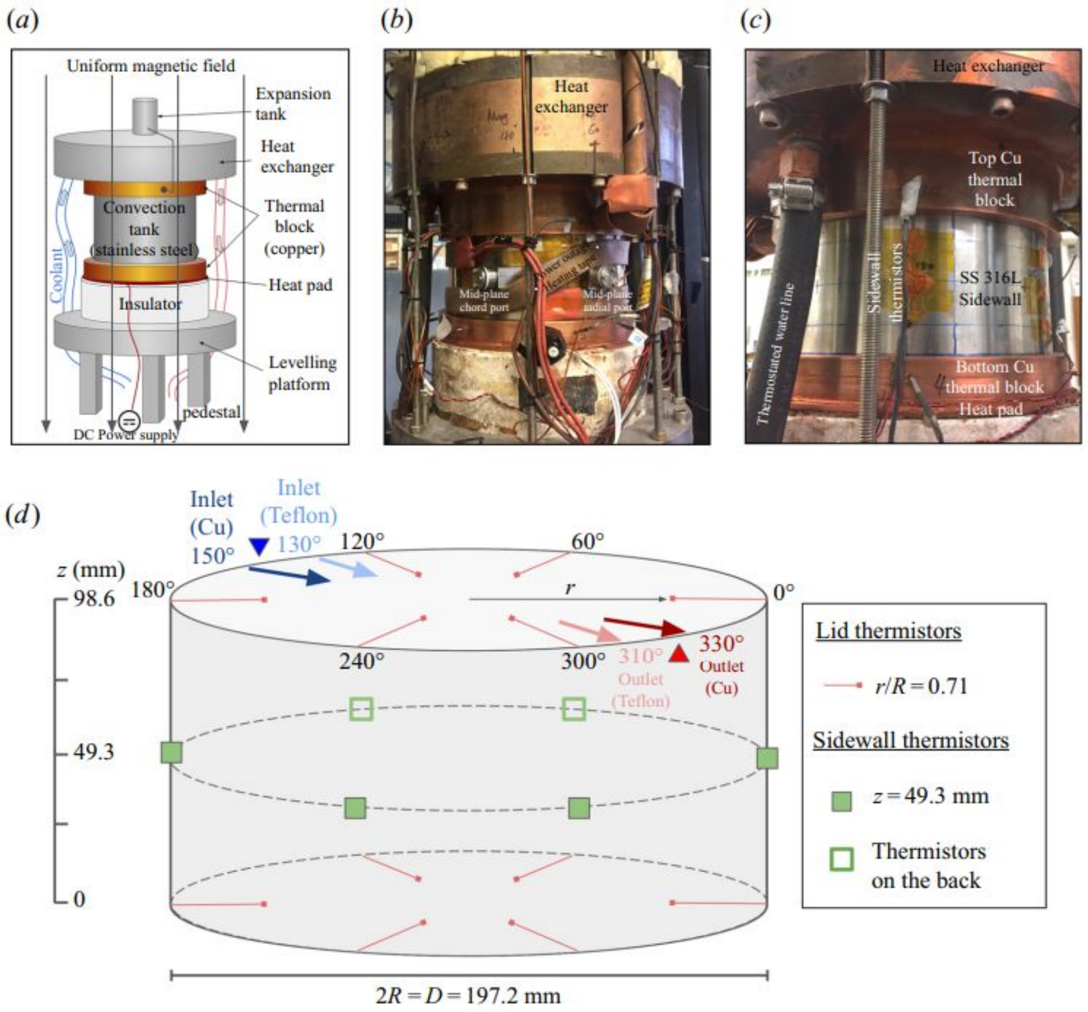


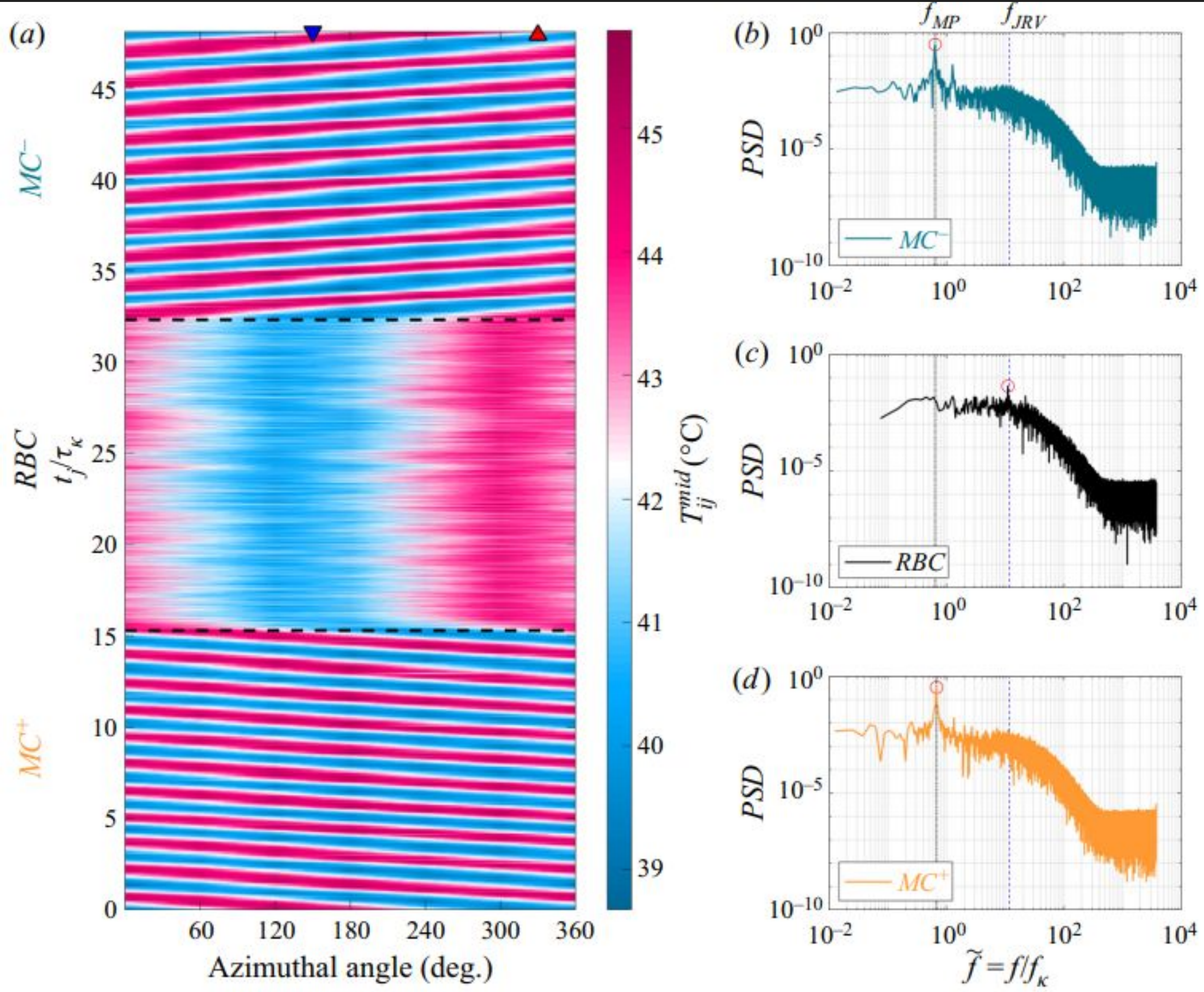
RoMag, UCLA

Expectation:

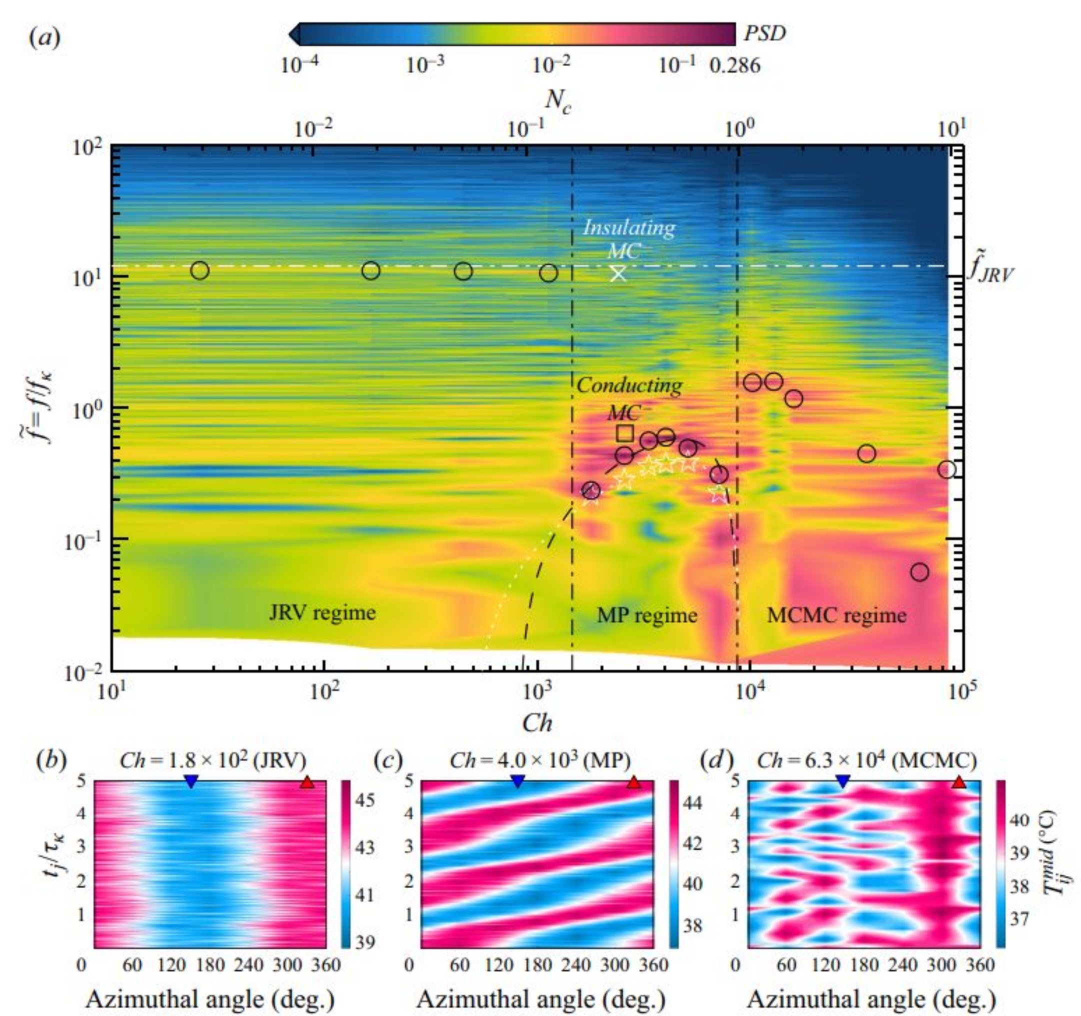
- The Lorentz forces act as the magnetic drag.
- No traveling/oscillatory mode.
- Vectical polarity of the applied field should not matter.

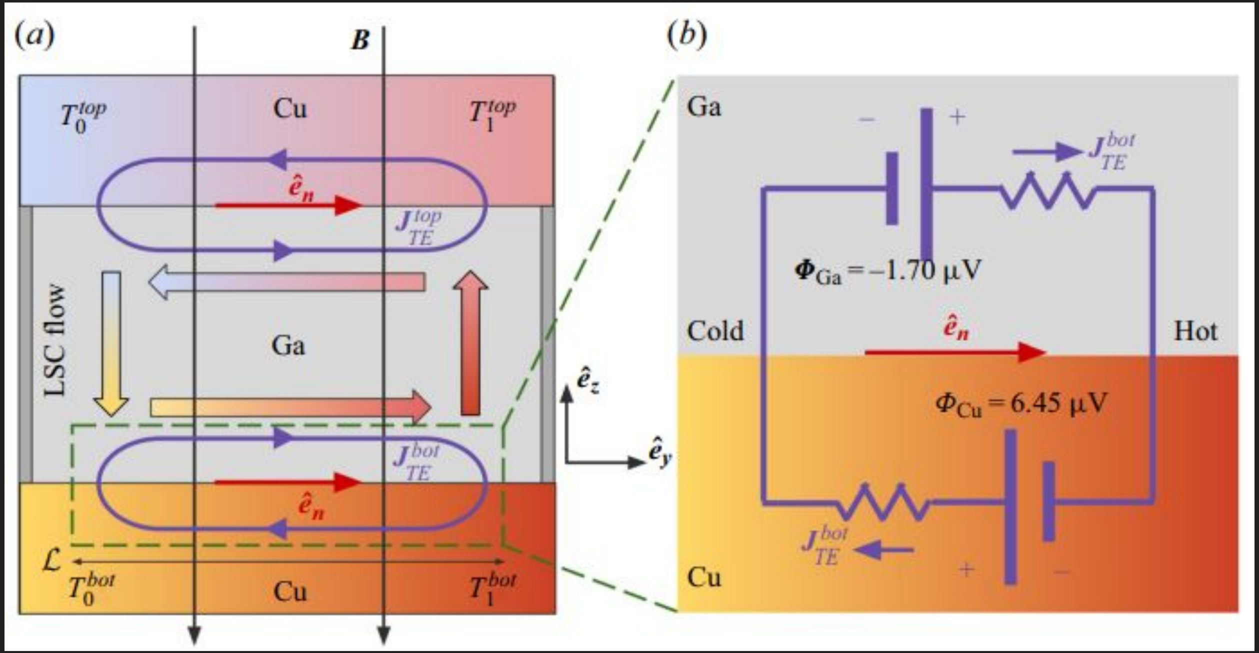
Number names	Symbol	Definition	Equivalence	Current study
Magnetic Reynolds	Rm	$\frac{U_{ff}H}{\eta}$	$RePm$	$\lesssim 10^{-2}$
Magnetic Prandtl	Pm	$\frac{\nu}{\eta}$	—	1.7×10^{-6}
Prandtl	Pr	$\frac{\nu}{\kappa}$	—	2.7×10^{-2}
Rayleigh	Ra	$\frac{\alpha g \Delta T H^3}{\nu\kappa}$	—	$\sim 2 \times 10^6$
Chandrasekhar	Ch	$\frac{\sigma B^2 H^2}{\rho\nu}$	—	$[0, 8.4 \times 10^4]$
Seebeck	Se	$\frac{\lvert\tilde{S}\rvert \Delta T/H}{U_{ff}B}$	—	$\sim [10^{-2}, 1]$
Aspect ratio	Γ	$\frac{D}{H}$	—	2.0
Reynolds	Re	$\frac{U_{ff}H}{\nu}$	$\sqrt{\frac{Ra}{Pr}}$	$\lesssim 8.7 \times 10^3$
Péclet	Pe	$\frac{U_{ff}H}{\kappa}$	$\sqrt{RaPr}$	$\lesssim 2.2 \times 10^2$
Convective interaction	N_C	$\frac{\sigma B^2 H}{\rho U_{ff}}$	$\sqrt{\frac{Ch^2 Pr}{Ra}} = \frac{Ch}{Re}$	$\lesssim 10$
Thermoelectric interaction	N_{TE}	$\frac{\sigma B \lvert\tilde{S}\rvert \Delta T}{\rho U_{ff}^2}$	SeN_C	$\lesssim 10$

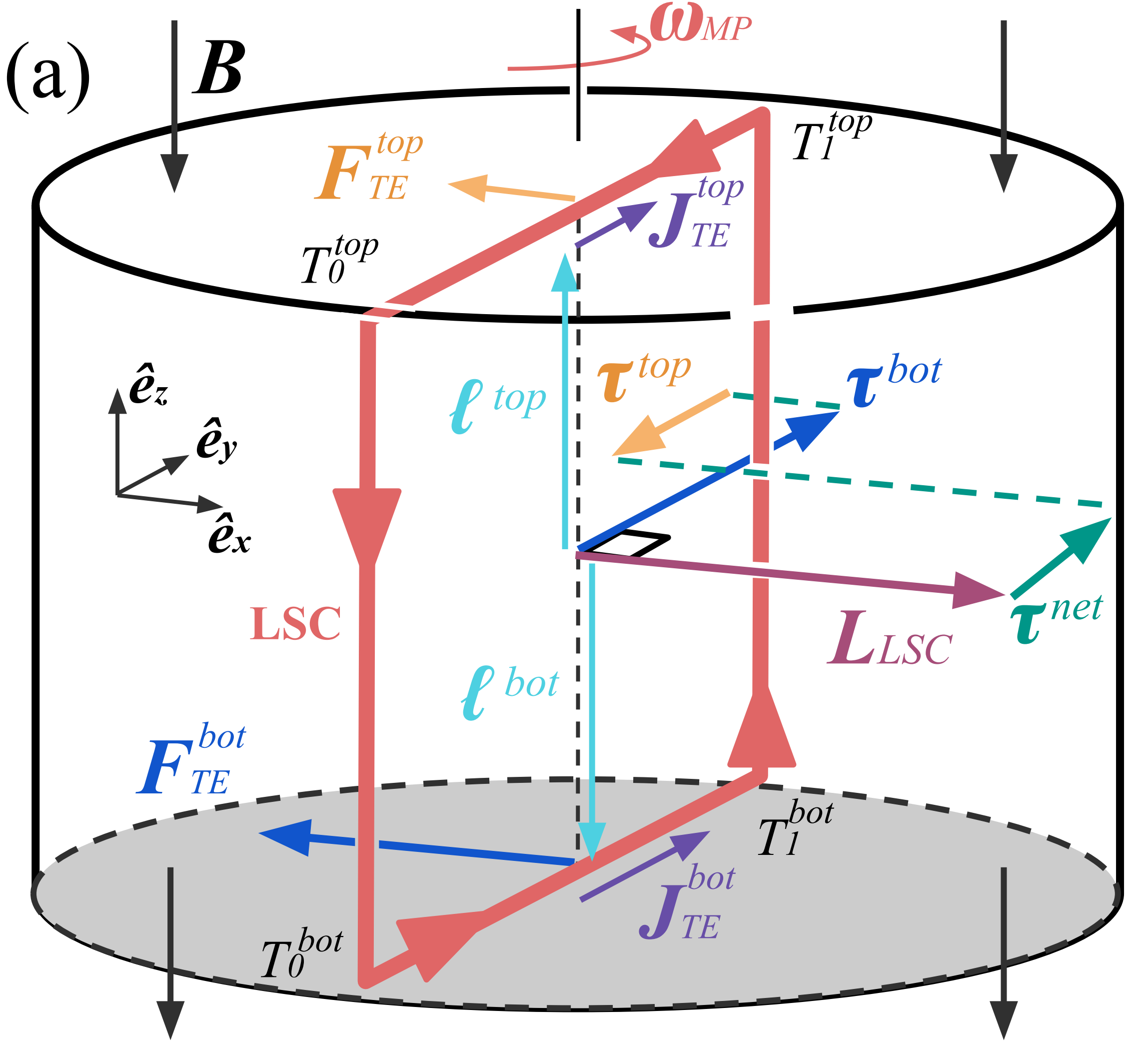

(a)
Uniform magnetic field
Expansion tank
Heat exchanger
Convection tank (stainless steel)
Thermal block (copper)
Coolant
Heat pad
Insulator
Levelling platform
pedestal
DC Power supply
(b)
Heat exchanger
Mid-plane chord port
Mid-plane radial port
(c)
Heat exchanger
Top Cu thermal block
SS 316L Sidewall
Sidewall thermistors
Thermostated water line
Bottom Cu thermal block
Heat pad
(d)
Inlet (Cu) 150°
Inlet (Teflon) 130°
120°
60°
180°
0°
r
z (mm)
98.6
49.3
0
240°
300°
310° Outlet (Teflon)
330° Outlet (Cu)
Lid thermistors
r/R = 0.71
Sidewall thermistors
z = 49.3 mm
Thermistors on the back
2R = D = 197.2 mm



(a)
MC⁻
RBC
MC⁺
t_j/τ_κ
Azimuthal angle (deg.)
T_{ij}^{mid} (°C)
(b)
(c)
(d)
f_{MP}
f_{JRV}
PSD
MC⁻
RBC
MC⁺
$\tilde{f} = f/f_\kappa$


(a)
PSD
10−4 10−3 10−2 10−1 0.286
Nc
Insulating MC
Conducting MC
f̃JRV
f̃ = f/fκ
JRV regime
MP regime
MCMC regime
Ch
(b) Ch = 1.8 × 10² (JRV)
(c) Ch = 4.0 × 10³ (MP)
(d) Ch = 6.3 × 10⁴ (MCMC)
tj/τκ
Tij mid (°C)
Azimuthal angle (deg.)
Azimuthal angle (deg.)
Azimuthal angle (deg.)


(a)
B
Cu
T_0^{top}
T_1^{top}
$\hat{e}_n$
J_{TE}^{top}
LSC flow
Ga
J_{TE}^{bot}
$\hat{e}_n$
$\mathcal{L}$
T_0^{bot}
Cu
T_1^{bot}
$\hat{e}_z$
$\hat{e}_y$
(b)
Ga
J_{TE}^{bot}
$\Phi_{Ga} = -1.70\ \mu V$
Cold
$\hat{e}_n$
Hot
$\Phi_{Cu} = 6.45\ \mu V$
J_{TE}^{bot}
Cu



(a)
B
ωMP
F top TE
T1 top
J top TE
T0 top
τ top
τ bot
ℓ top
ê z
ê y
ê x
LSC
L LSC
τ net
ℓ bot
F bot TE
T1 bot
J bot TE
T0 bot

Symbols	Description	Value
σ_0	Cu–Ga effective electric conductivity, (2.5)	3.63×10^6 S m^{-1}
B	magnetic field intensity	120 gauss
$\mathcal{L}$	Horizontal length scale of thermoelectric current loops, $\approx \Gamma H$	197.2 mm
X_0	Cu–Ga Seebeck prefactor, (6.6)	-7.89×10^{-9} V K^{-2}
ρ	Liquid gallium density	6.08×10^3 kg m^{-3}
R^*	Effective radius of the LSC, (6.1)	0.08 m
U_{ff}	Free-fall velocity, (2.10)	0.03 m s^{-1}
$\overline{T}$	Mean fluid temperature, (3.5)	42.50 °C
ΔT	Vertical temperature difference across the fluid, (3.3)	7.03 K
T^{bot}	Bottom interface mean temperature	319.23 K
δT^{bot}	Bottom interface mean temperature difference, (5.2)	3.44 K
T^{top}	Top interface mean temperature	312.07 K
δT^{top}	Top interface mean temperature difference, (5.2)	2.24 K
$\mathcal{T}$	$(T^{bot}\delta T^{bot} - \delta T^{top}\delta T^{top})$	399.11 K^2

- Euler's equation:

$$\boldsymbol{\tau}^{net} = \frac{\mathrm{d}\boldsymbol{L}_{LSC}}{\mathrm{d}t} = I\frac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}t} + \boldsymbol{\omega} \times \boldsymbol{L}_{LSC}$$

$$\boldsymbol{\omega} = \omega_{LSC}\hat{e}_x + \boldsymbol{\omega}_{MP}$$

- Thermoelectric net torque:

$$\boldsymbol{\tau}^{net} = \frac{\sigma_0 V_{LSC} X_0 B \underbrace{\left(T^{bot}\delta T^{bot} - T^{top}\delta T^{top}\right)}_{\mathcal{T}}}{4\Gamma}(\hat{e}_x \times \hat{e}_b)$$

- Thermoelectric precession angular frequency:

$$\boldsymbol{\omega}_{MP} = \frac{\tau_{net}}{L_{LSC}}(-\hat{e}_b)$$

$$\boldsymbol{\omega}_{MP} = \frac{\sigma_0 X_0 B}{2\rho U_{ff}\Gamma R^*}\left(T^{bot}\delta T^{bot} - T^{top}\delta T^{top}\right)(-\hat{e}_b) = \frac{\pi^{1/2}}{\Gamma^{3/2}}\frac{\sigma_0 X_0 B\mathcal{T}}{2\rho U_{ff} H}(-\hat{e}_b)$$

Conclusion

- Thermoelectric effects in turbulent liquid metal magnetoconvection experiments
- Novel thermoelectric precession mode
- TE currents with B field can exert torques on core fluid near CMB → New potential mechanism for core-mantle coupling

Xu *et al.* 2022, *JFM*