Magnetic effects on helioseismic modes in simulations of convection

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Magnetic effects on modes

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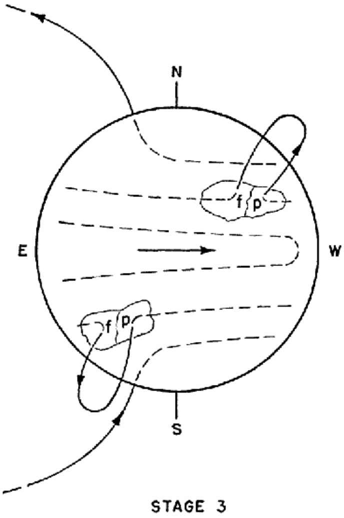

Flux tubes rising from the bottom of the convection zone

(Babcock 1961)

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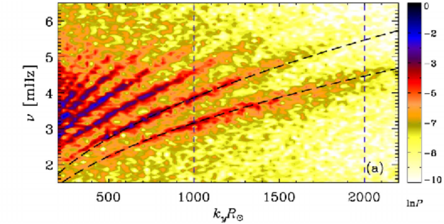
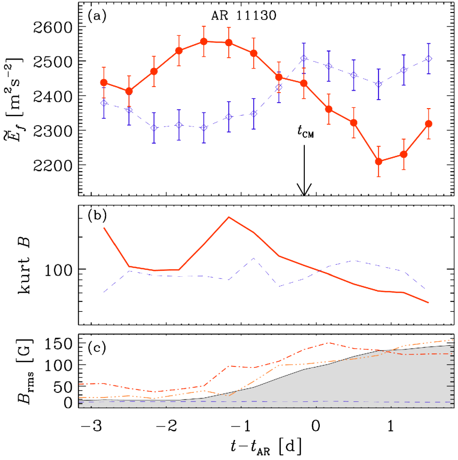
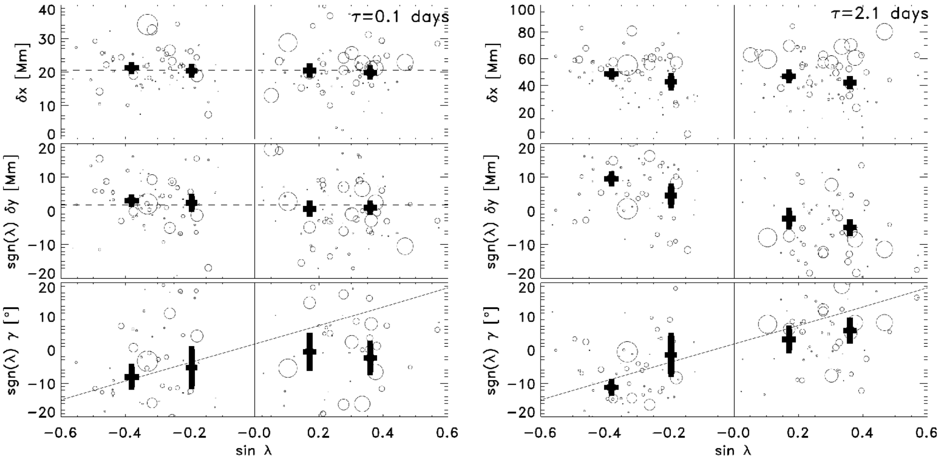




- Rising flux tubes cross the top 10 Mm of the CZ in a few hours (Cheung et al. 2010)
- f mode strengthens 48 hours before emergence (Singh, Raichur, and Brandenburg 2016; Waidele et al. 2023)

Figures from Singh, Raichur, and Brandenburg (2016)



(Kosovichev and Stenflo 2008; Schunker et al. 2020)

Figure from Schunker et al. (2020)

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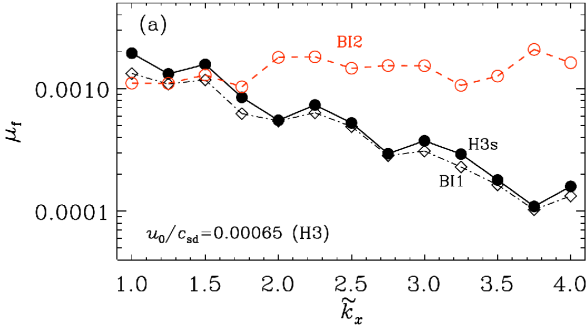
Analytical work (Miles, Allen, and Roberts 1992; Rui and Fuller 2023; Tripathi and Mitra 2022, 2024)

Simplified **2D forced-turbulence simulations** (Singh, Brandenburg, and Rheinhardt 2014; Singh et al. 2015, 2020)



(Singh et al. 2020)

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$$\frac{\mathrm{D} \ln \rho}{\mathrm{d}t} = -\nabla \cdot \boldsymbol{u}$$

$$\rho \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{d}t} = -\nabla p - \rho g \hat{\boldsymbol{z}} + \boldsymbol{J} \times \boldsymbol{B} + \nabla \cdot \left(2\rho\nu \overleftrightarrow{S} \right)$$

$$\rho T \frac{\mathrm{D}s}{\mathrm{d}t} = q - \nabla \cdot (\boldsymbol{F}_{\mathrm{rad}} + \boldsymbol{F}_{\mathrm{SGS}}) + 2\rho\nu S_{ij} S_{ij}$$

$$\boldsymbol{F}_{\mathrm{rad}} = -K_0 \, \rho^{-2} \, T^{13/2} \, \nabla T$$

$$\boldsymbol{F}_{\mathrm{SGS}} \equiv -\rho T \chi_{\mathrm{SGS}} \nabla s' \,, \quad s' \equiv s - \langle s \rangle_{xy}$$

$$q = -\frac{\rho \left(c_s^2 - c_{\mathrm{cool}}^2 \right)}{\tau_{\mathrm{cool}}} \Theta\left(\frac{z - z_{\mathrm{cool}}}{w_{\mathrm{cool}}} \right)$$

Prescribed magnetic field

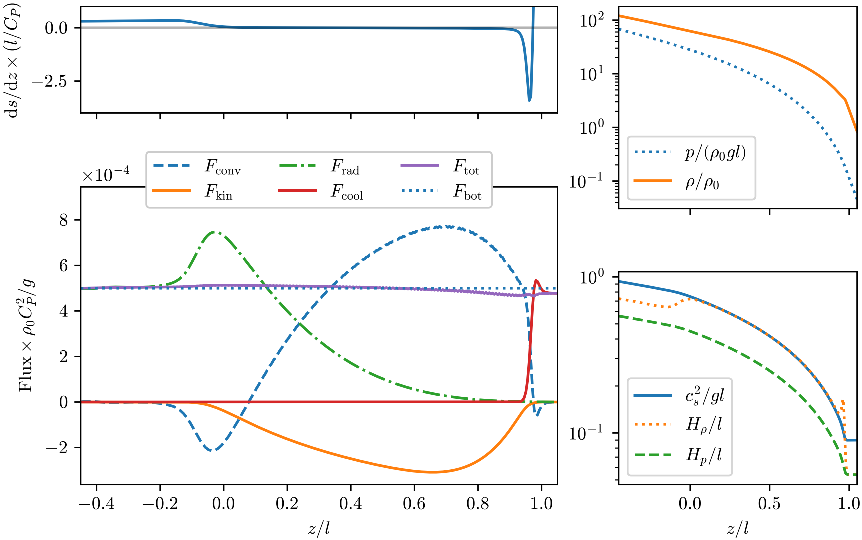
$$L_x = L_y = 16 L_z$$

$$N_x \times N_y \times N_z = 1152^2 \times 288$$

Pencil code

`https://pencil-code.nordita.org`

The non-magnetic case



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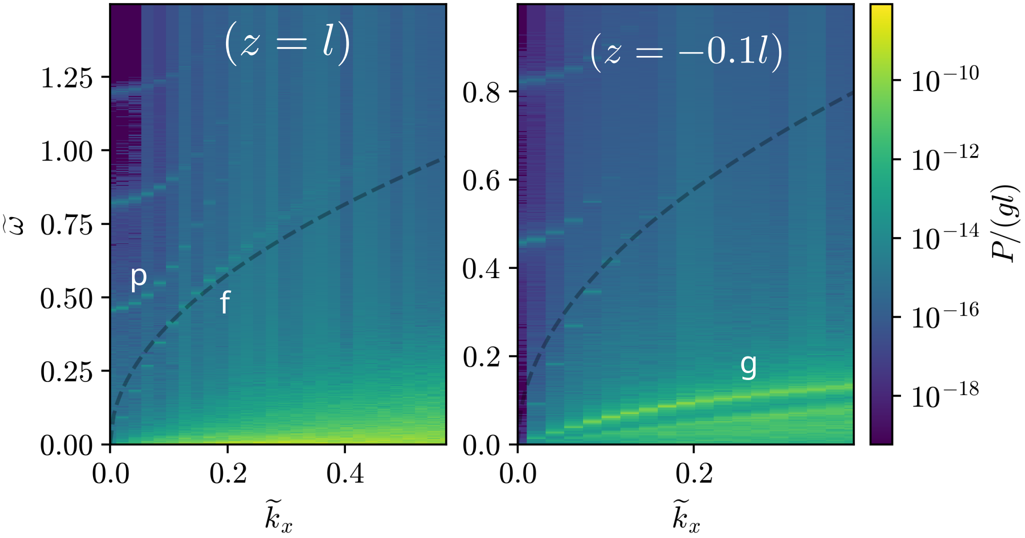

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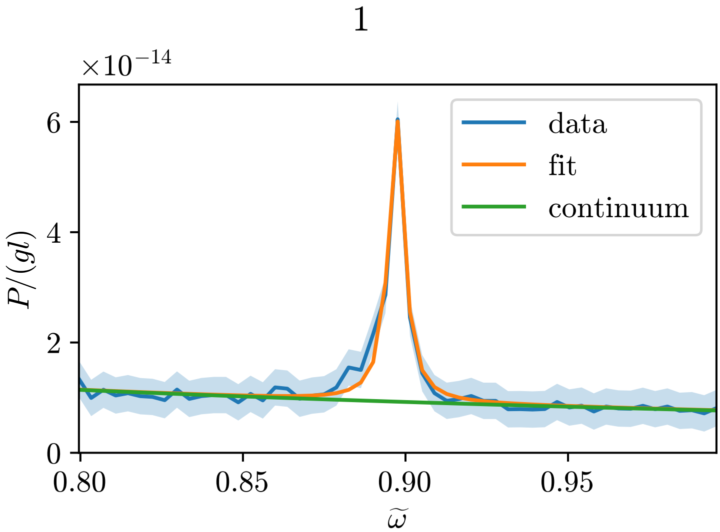
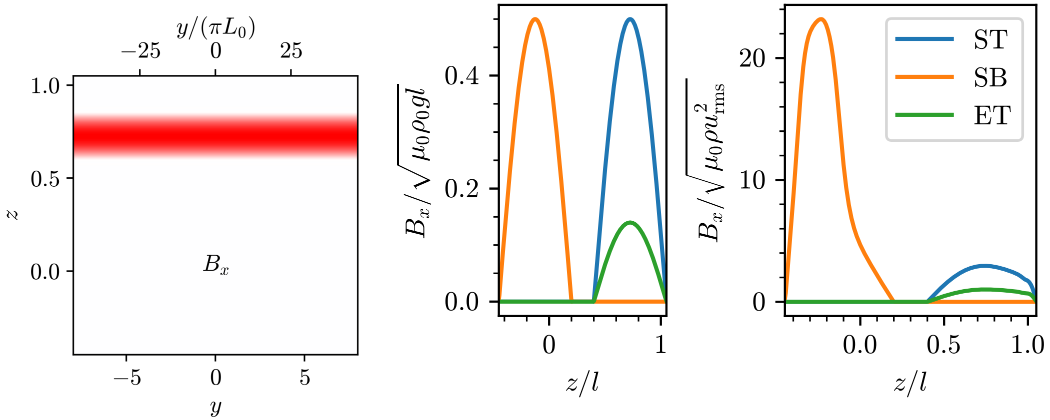


Area under fit

↓

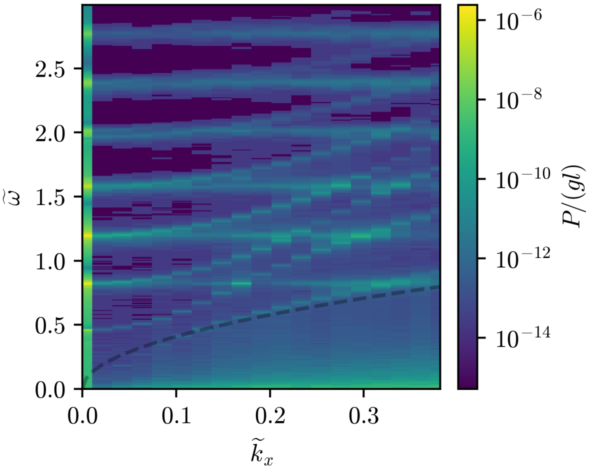
'Mode mass'

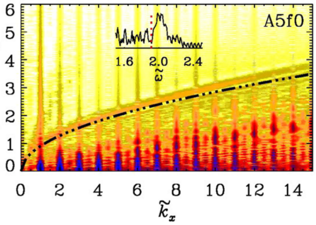
Magnetic field configuration



$B_y = B_z = 0$

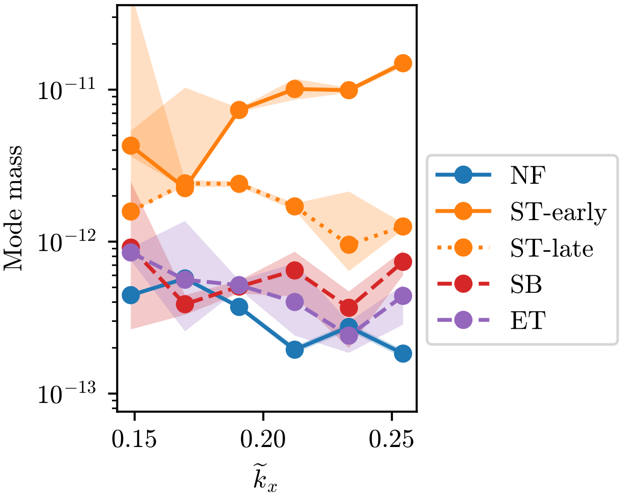
k-ω diagram in a magnetic case





$k = 0$ strengthening similar to 'Bloch modes' (Singh, Brandenburg, and Rheinhardt 2014)?

Magnetic effects on the f mode



- Strong ***B*** at top boosts mode by an order of magnitude
- Effect is transient

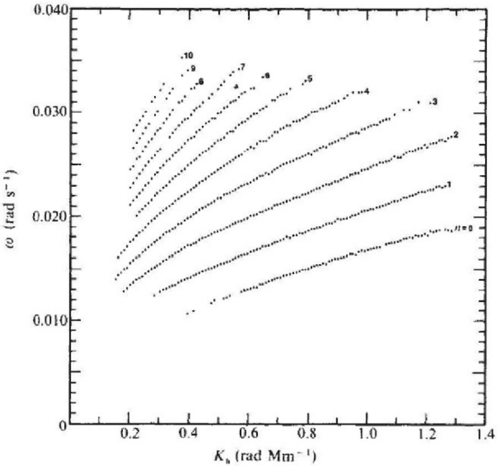
Summary

- First convection simulations which show magnetic strengthening of f modes
- Magnetic strengthening of the f mode is transient

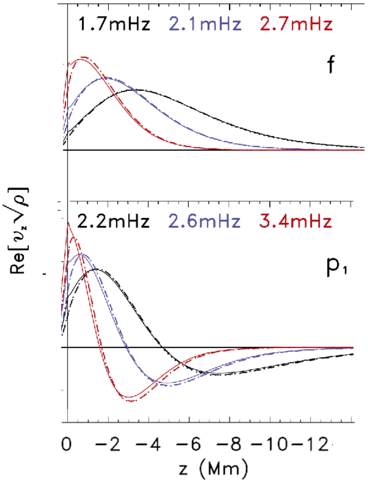
Future

- More realistic, time-dependent magnetic field configurations
- Helioseismic inversions for subsurface magnetic fields
- Magnetic effects on inertial modes

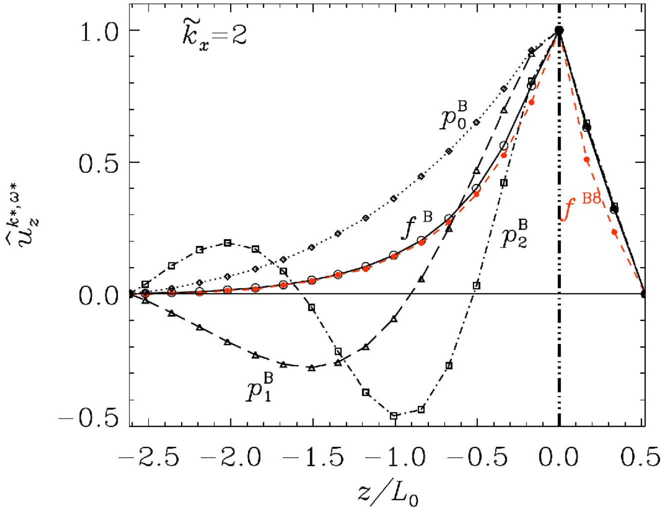
Radial nodes of the p mode



(Duvall 1982)



(Schunker et al. 2011)



"p_0" mode?

(Singh et al. 2015)

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(Birch, Kosovichev, and Duvall 2004; Schunker et al. 2011)

$$\frac{\mathrm{d}y_1}{\mathrm{d}z} = \left(-\frac{1}{2}\frac{\mathrm{d}\ln\rho_0}{\mathrm{d}z} - \frac{1}{2}\frac{\mathrm{d}\ln c}{\mathrm{d}z} + \frac{g}{c^2}\right) y_1 + \left(\frac{N^2}{\omega c} - \frac{\omega}{c}\right) y_2$$

$$\frac{\mathrm{d}y_2}{\mathrm{d}z} = \left(\frac{\omega}{c} - \frac{ck^2}{\omega}\right) y_1 + \left(-\frac{1}{2}\frac{\mathrm{d}\ln\rho_0}{\mathrm{d}z} + \frac{1}{2}\frac{\mathrm{d}\ln c}{\mathrm{d}z} + \frac{N^2}{g}\right) y_2$$

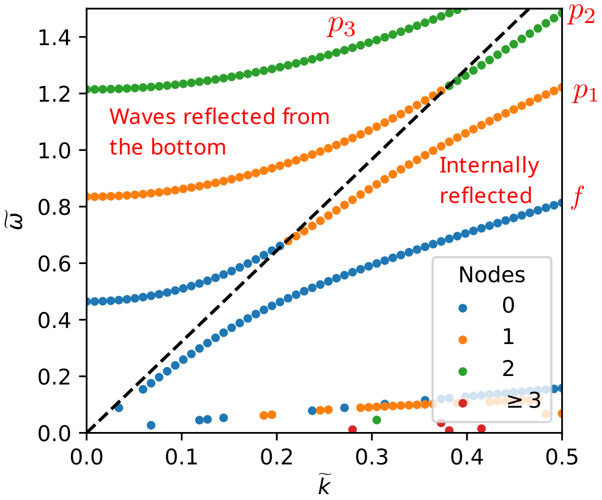
$$y_1 \equiv \frac{i\widetilde{p}}{\sqrt{\rho_0 c}}$$

$$y_2 \equiv \widetilde{u}\sqrt{\rho_0 c}$$

Boundary conditions:

- Bottom: impenetrable
- Top: zero Lagrangian pressure pert.

Change of node number along a ridge!

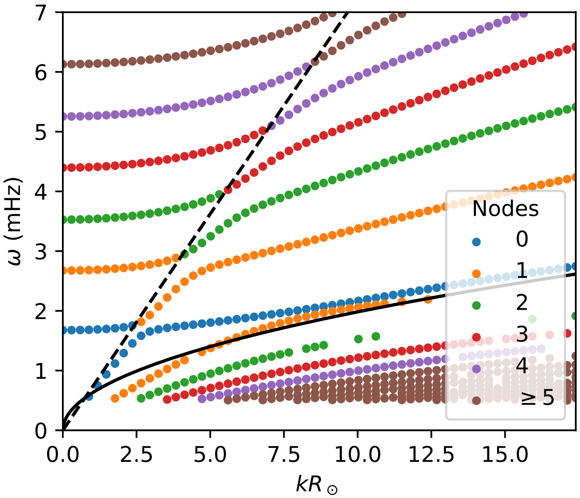


Background from the convection simulation I described earlier (effect of magnetic fields on f modes)

Black dashed line:

$\omega = c_{\text{bot}} k.$

But does it matter for the Sun?



Background state from Solar Model S

(Christensen-Dalsgaard et al. 1996)

Lower boundary at $-690\,\mathrm{Mm}$

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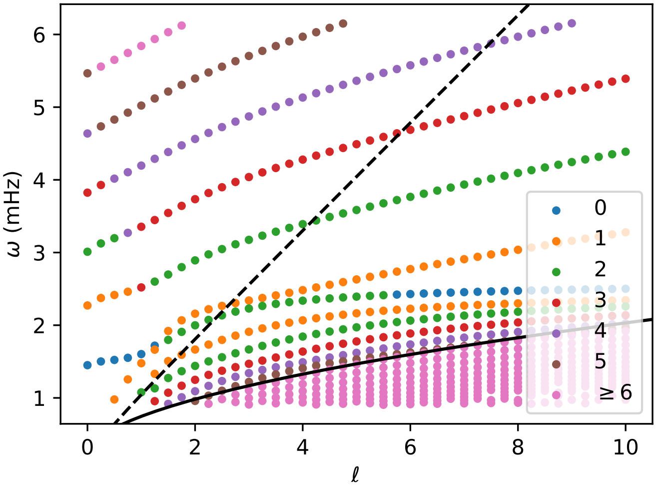

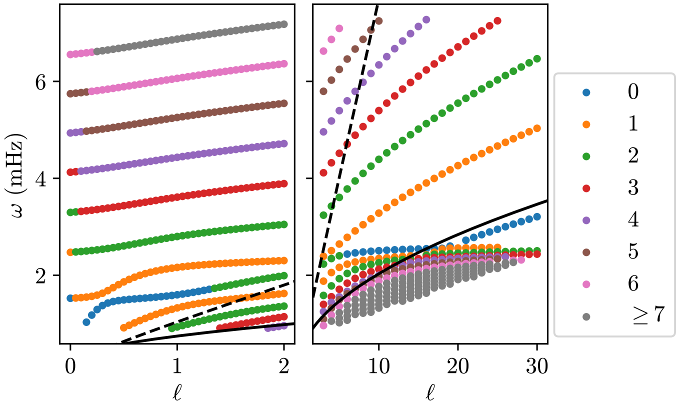

Inner 5% of radius removed

Summary of today's talk

Nodes of p modes

The number of radial nodes of a p mode ridge is wavenumber-dependent

Spherical effects are messy

Magnetic effects on the f mode

Large-scale magnetic fields strengthen the f mode (transiently) only if near the surface

THE END

You should've stopped at the previous slide

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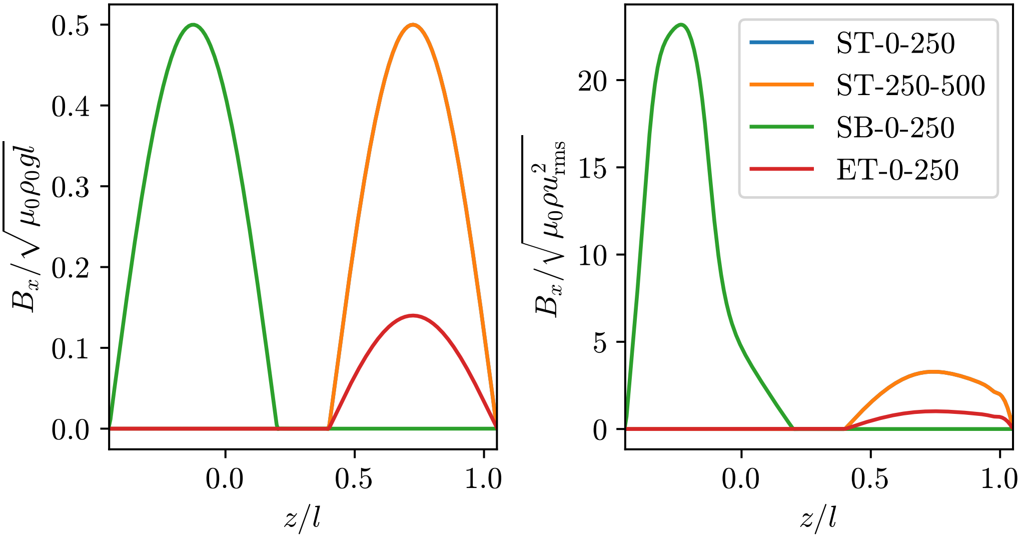
Backup slides


0.5
0.4
0.3
0.2
0.1
0.0
$B_x/\sqrt{\mu_0\rho_0 g l}$
0.0
0.5
1.0
z/l
20
15
10
5
0
$B_x/\sqrt{\mu_0\rho u_{\rm rms}^2}$
ST-0-250
ST-250-500
SB-0-250
ET-0-250

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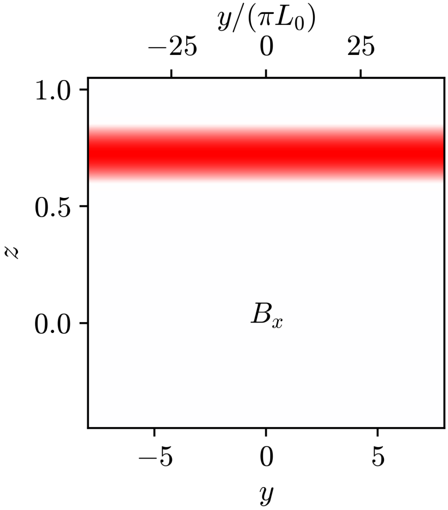

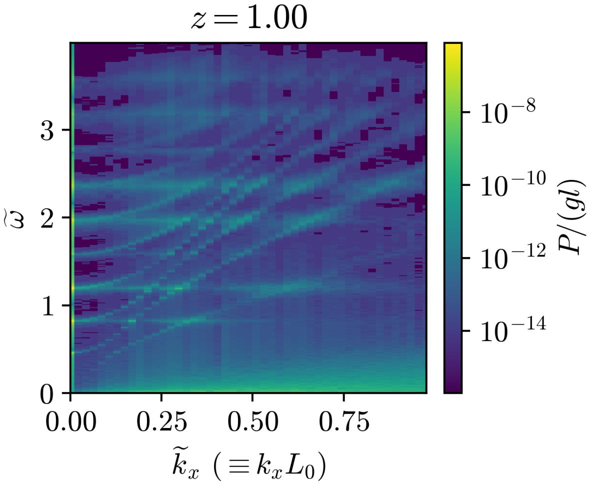

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Impenetrable:

$$y_2(z_b) = 0$$

Zero Lagrangian pressure perturbation:

$$\delta p \equiv \partial p + \boldsymbol{\xi} \cdot \nabla p$$

Corresponding BC is

$$\omega y_1 - \frac{y_2}{\rho_0 c} \frac{\mathrm{d} p_0}{\mathrm{d} z} = 0$$

Some eigenfunctions