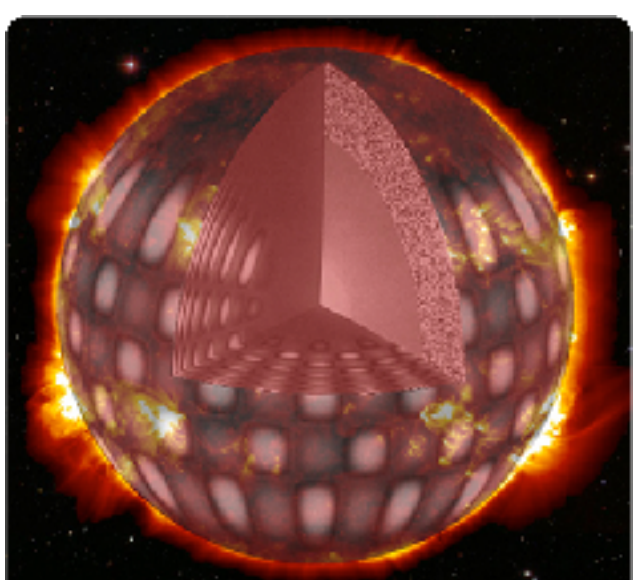
Excitation of internal waves and QBO-like flows from turbulent sources

Michael LE BARS
with P. Léard, L. Couston, D. Lecoanet, B. Favier & P. Le Gal

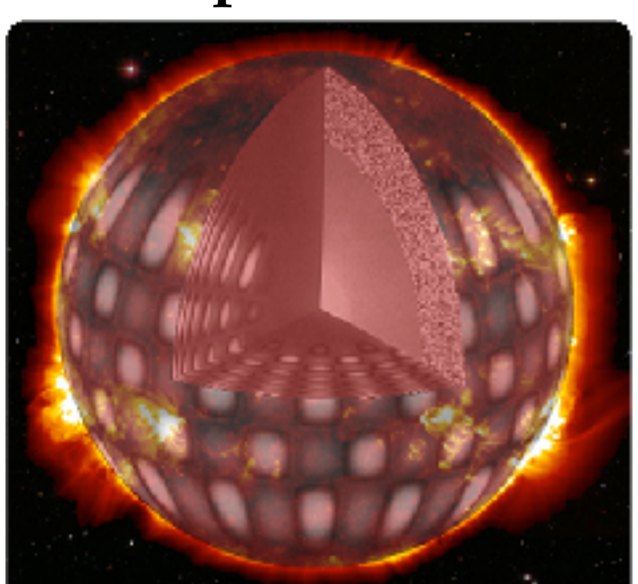


a generic problem

- numerous natural and industrial problems = turbulent fluid layer adjacent to a stably stratified one
- stratified layer, **<u>not motionless!</u>** waves = energy and momentum transport
- time- and length-scale separation: difficult to model…

self-organising 2-layer system, including all time and length scales, the turbulent excitation and the two-way couplings…

spectrum?

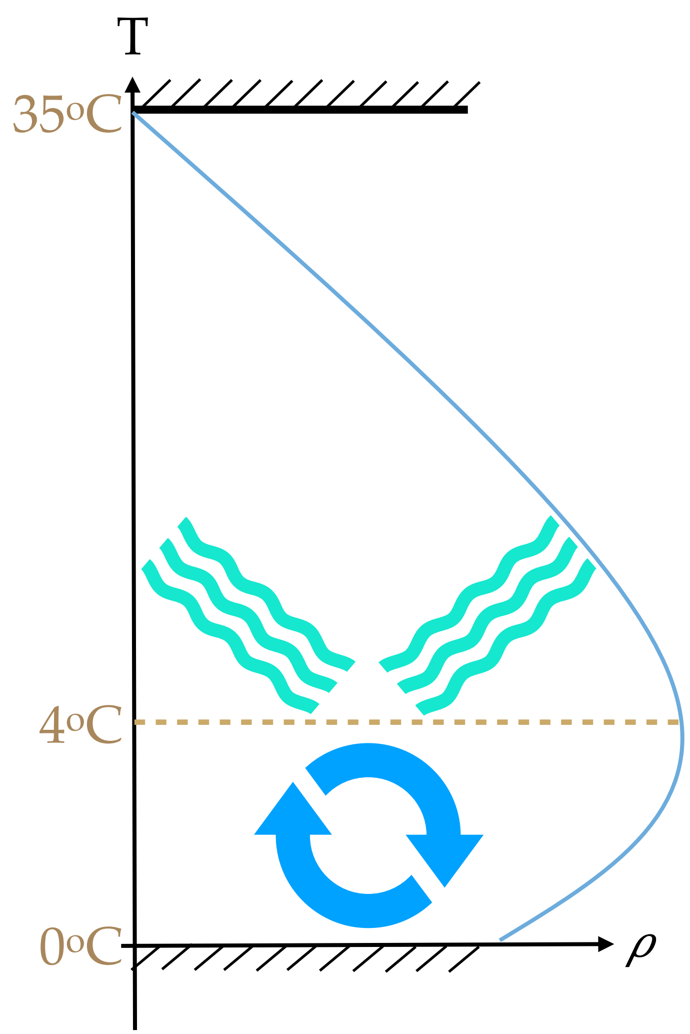


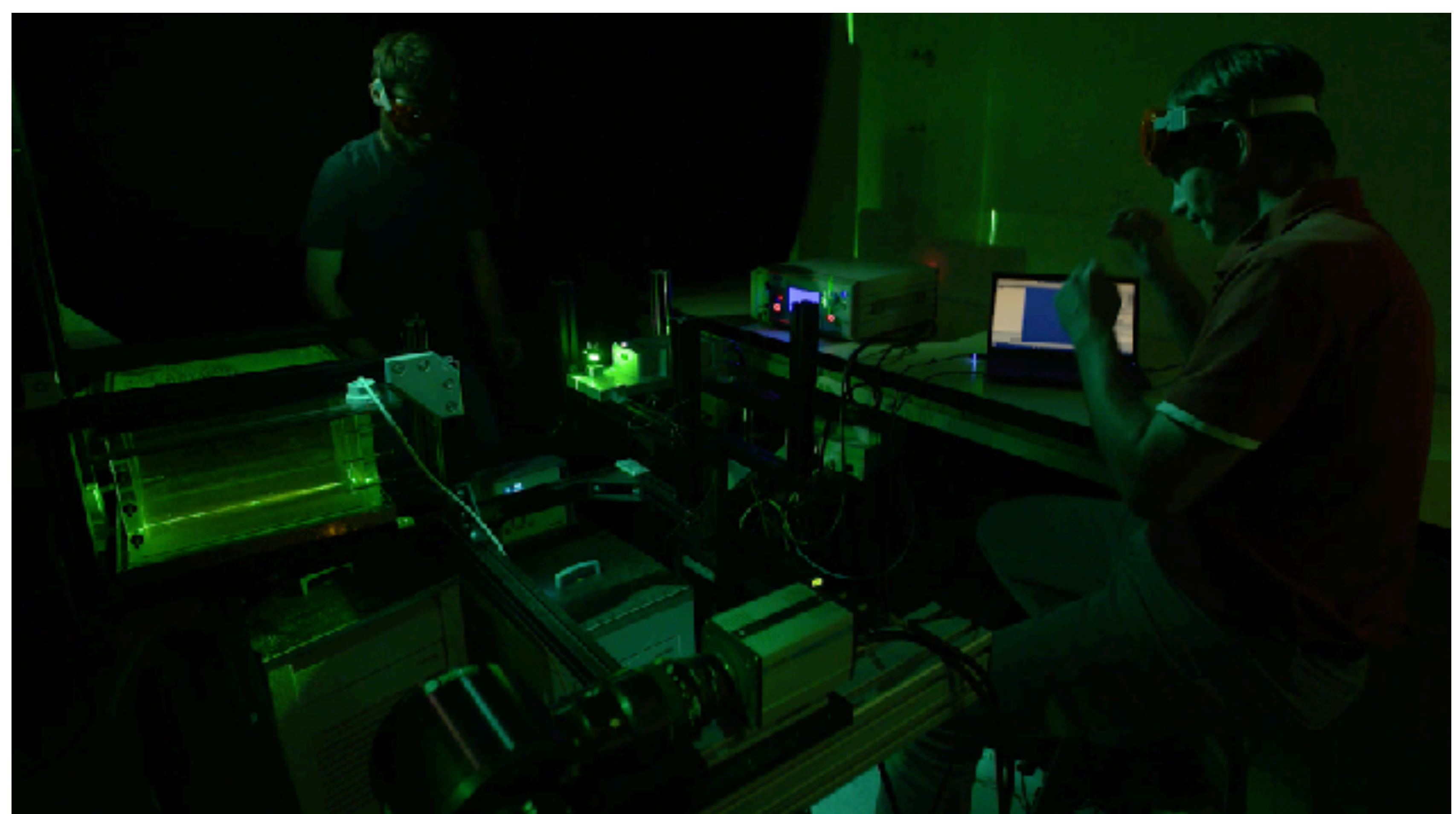
mixing efficiency?

momentum transfer?

a simple lab model

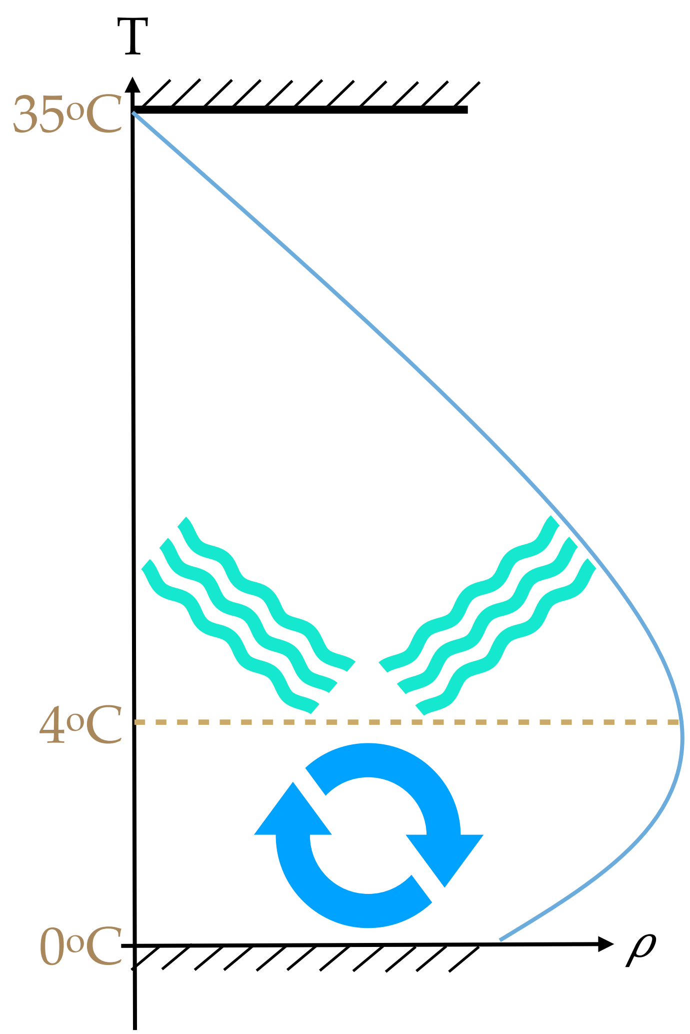
Water = max density at 4°C (Townsend 1964)





Le Bars et al. 2015
Leard et al. 2019

a simple lab model



Ra = 7x10^6
N = 0.13 Hz.

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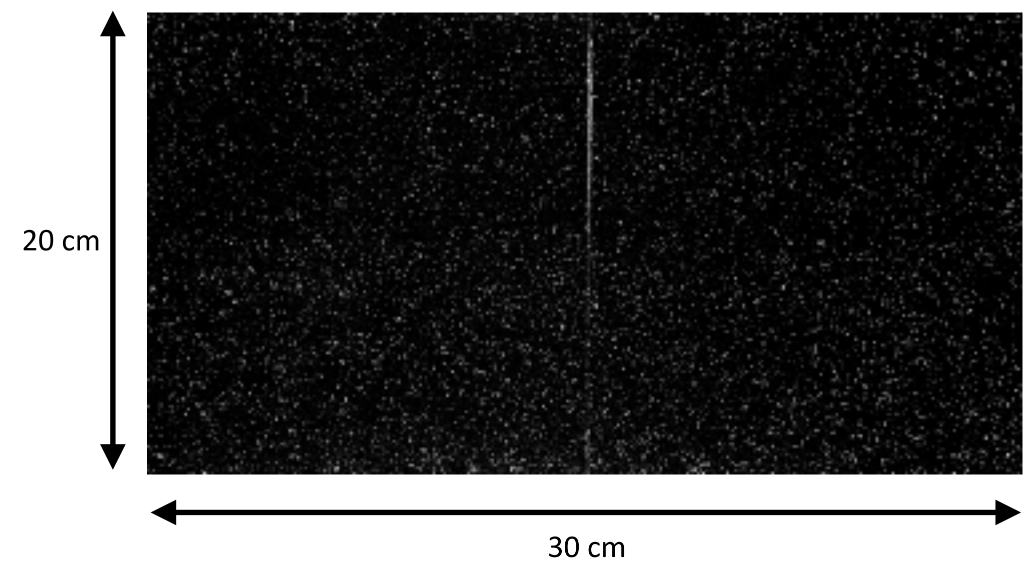

Accelerated 30 times

Le Bars et al. 2015
Leard et al. 2019

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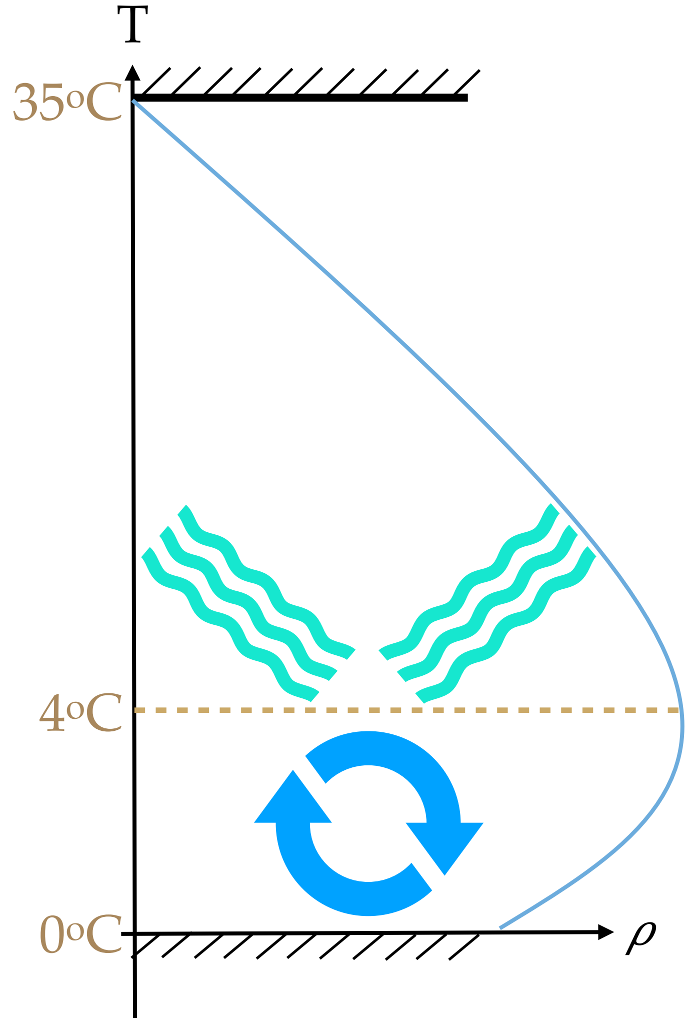

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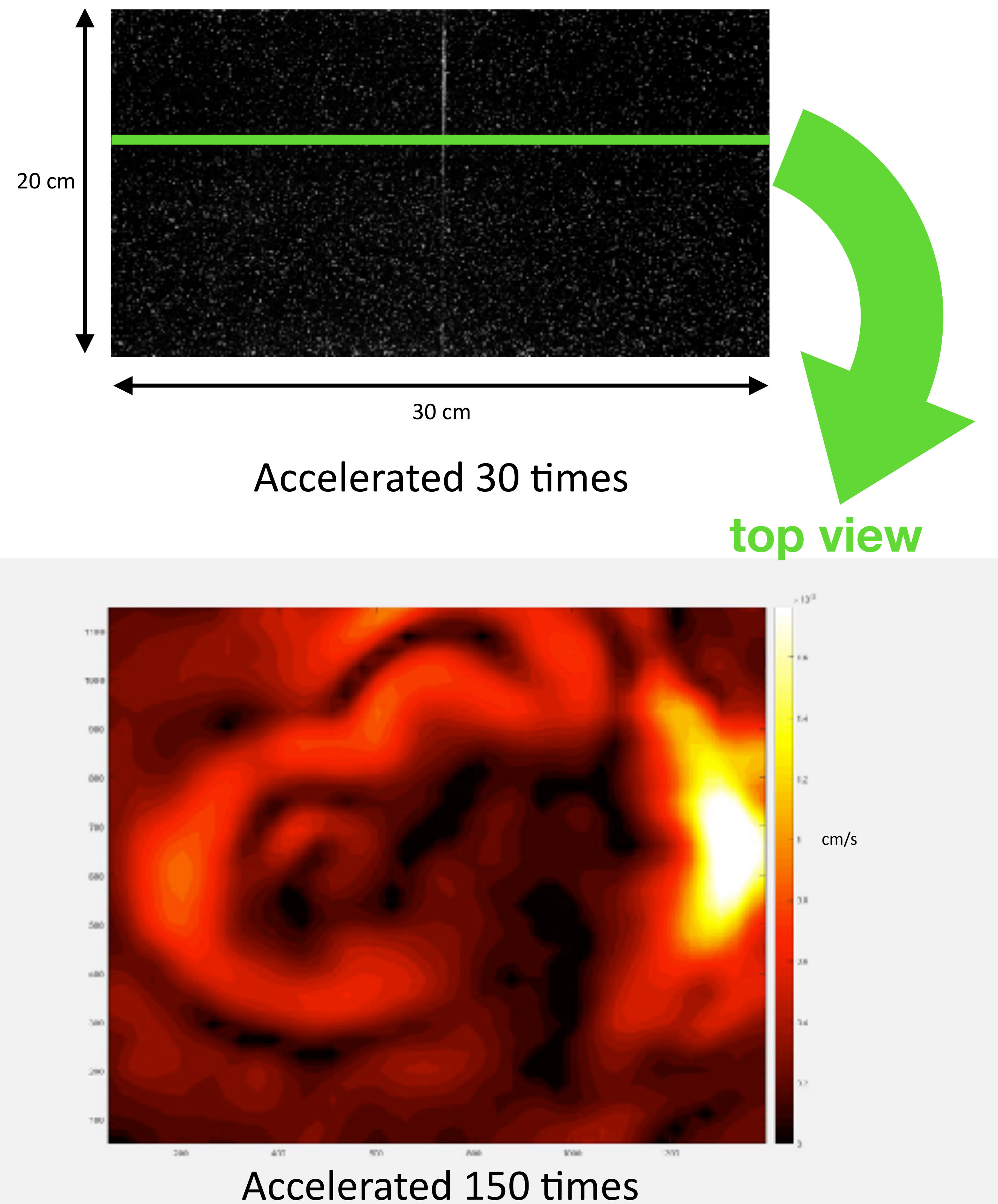

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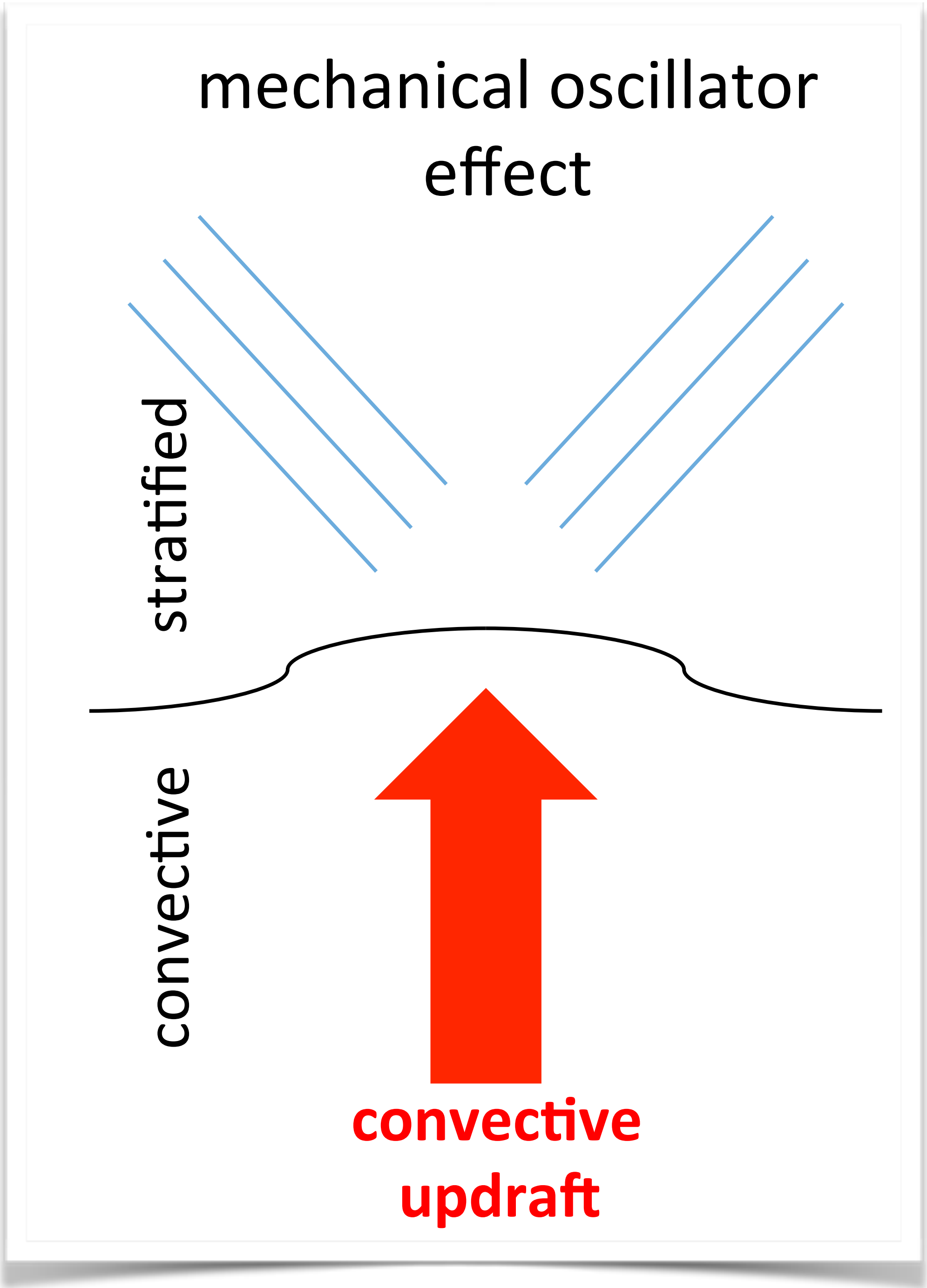
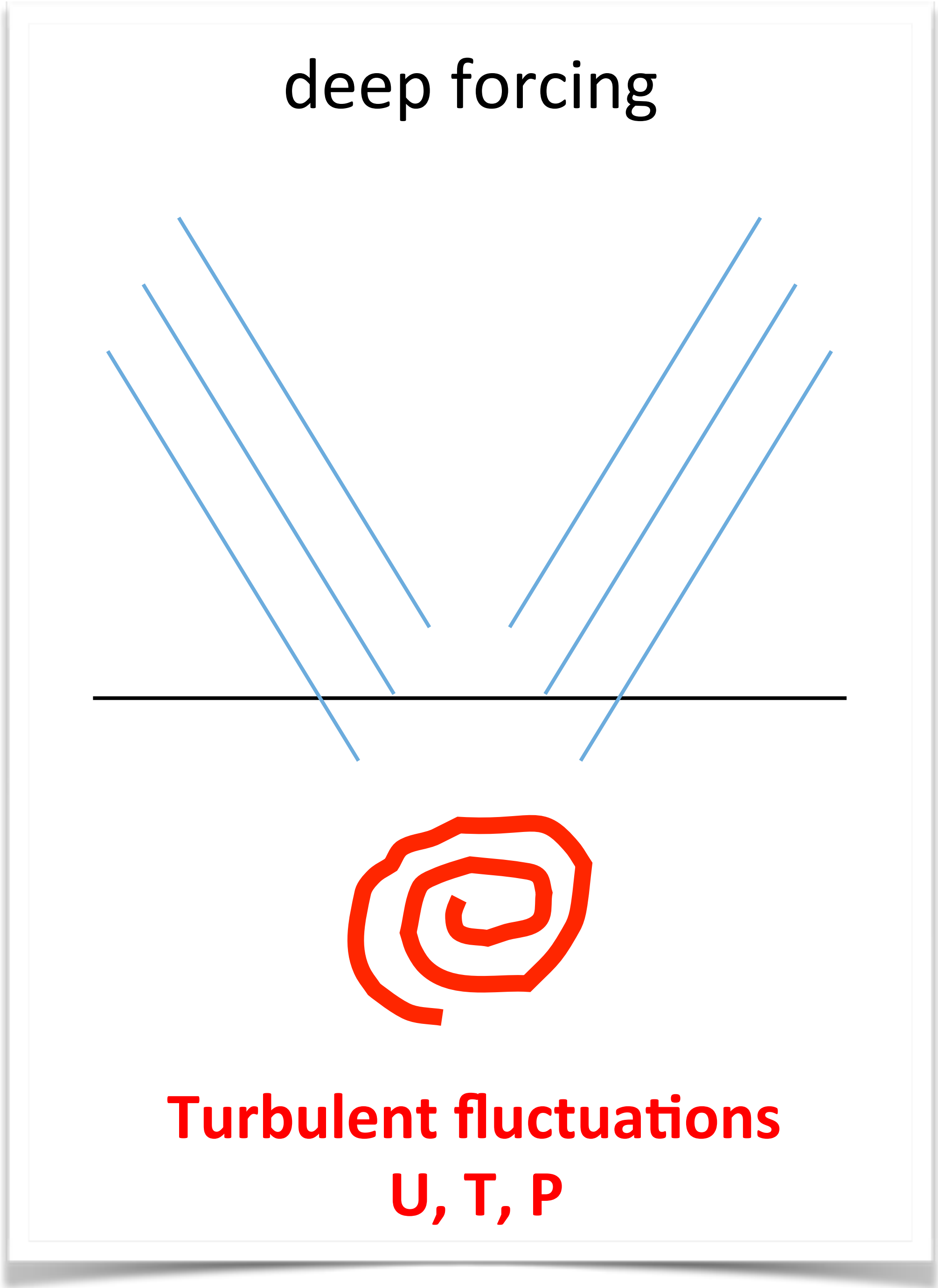
source of the waves?

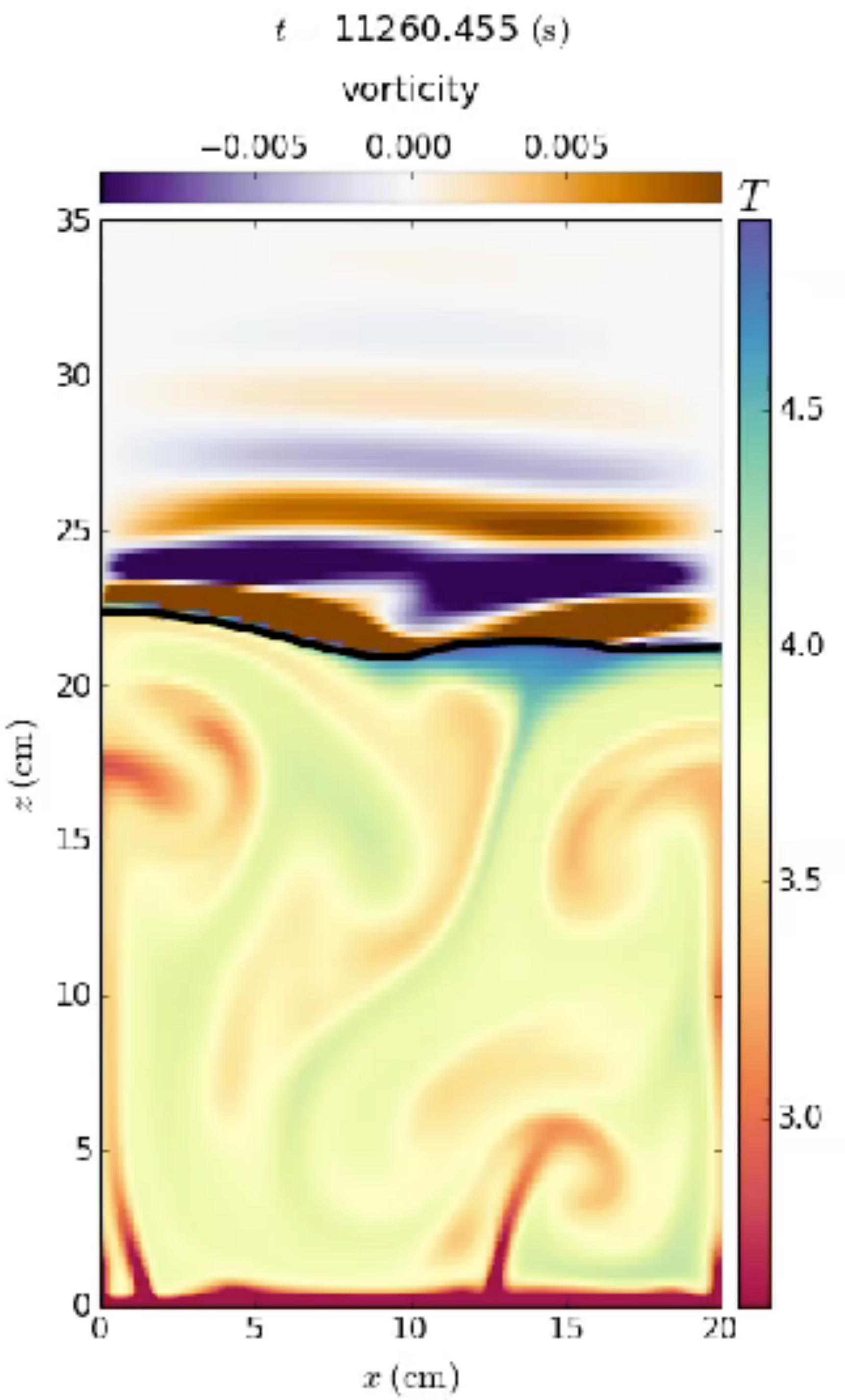




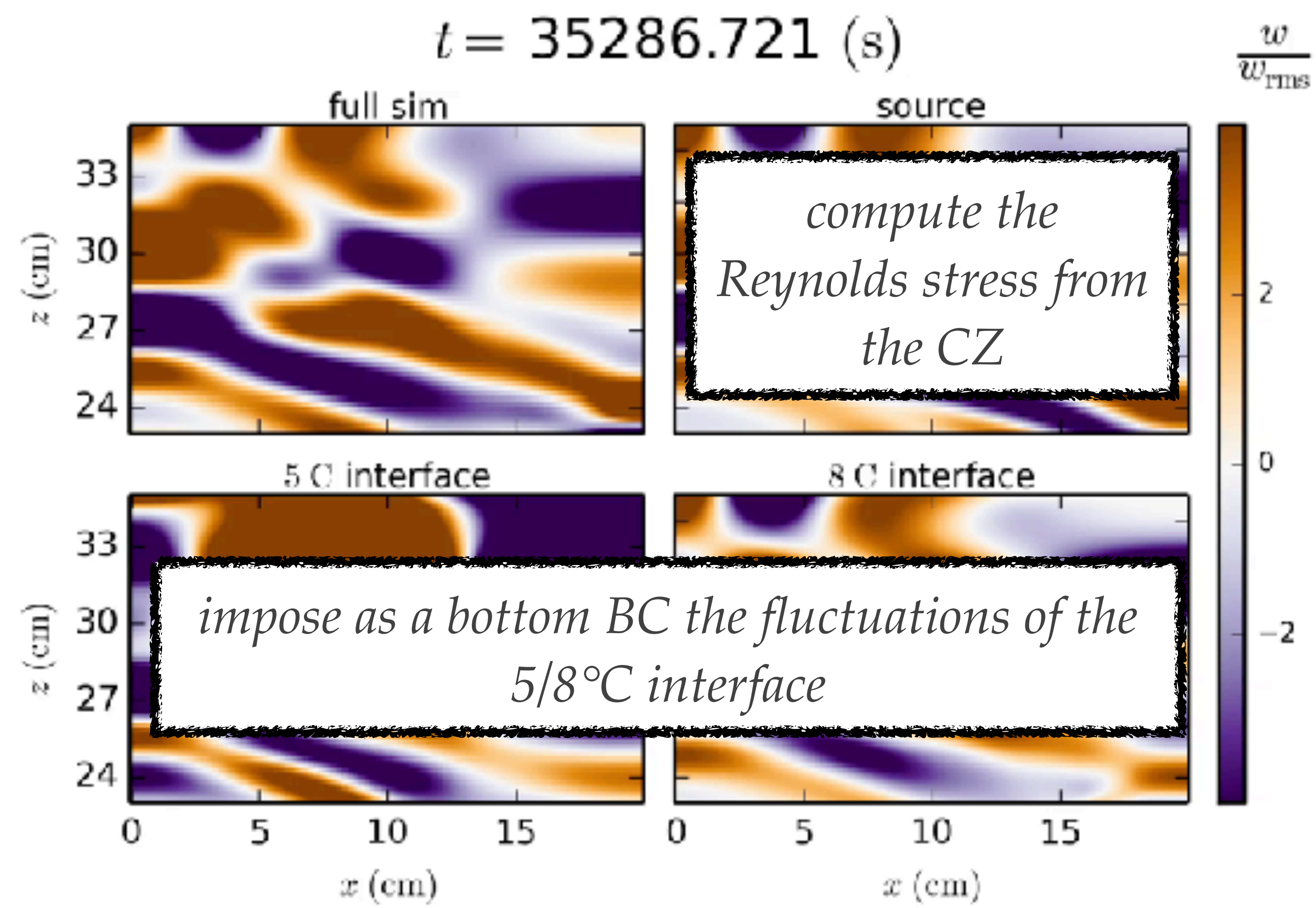
(e.g. Ansong & Sutherland 2010)

source of the waves?

DNS using the open-source solver Dedalus - here, 2D…



simulations of the simulation using the open-source solver Dedalus



solve the linear wave equation with an imposed background density profile and a source term

Lecoanet et al. 2015

source of the waves?

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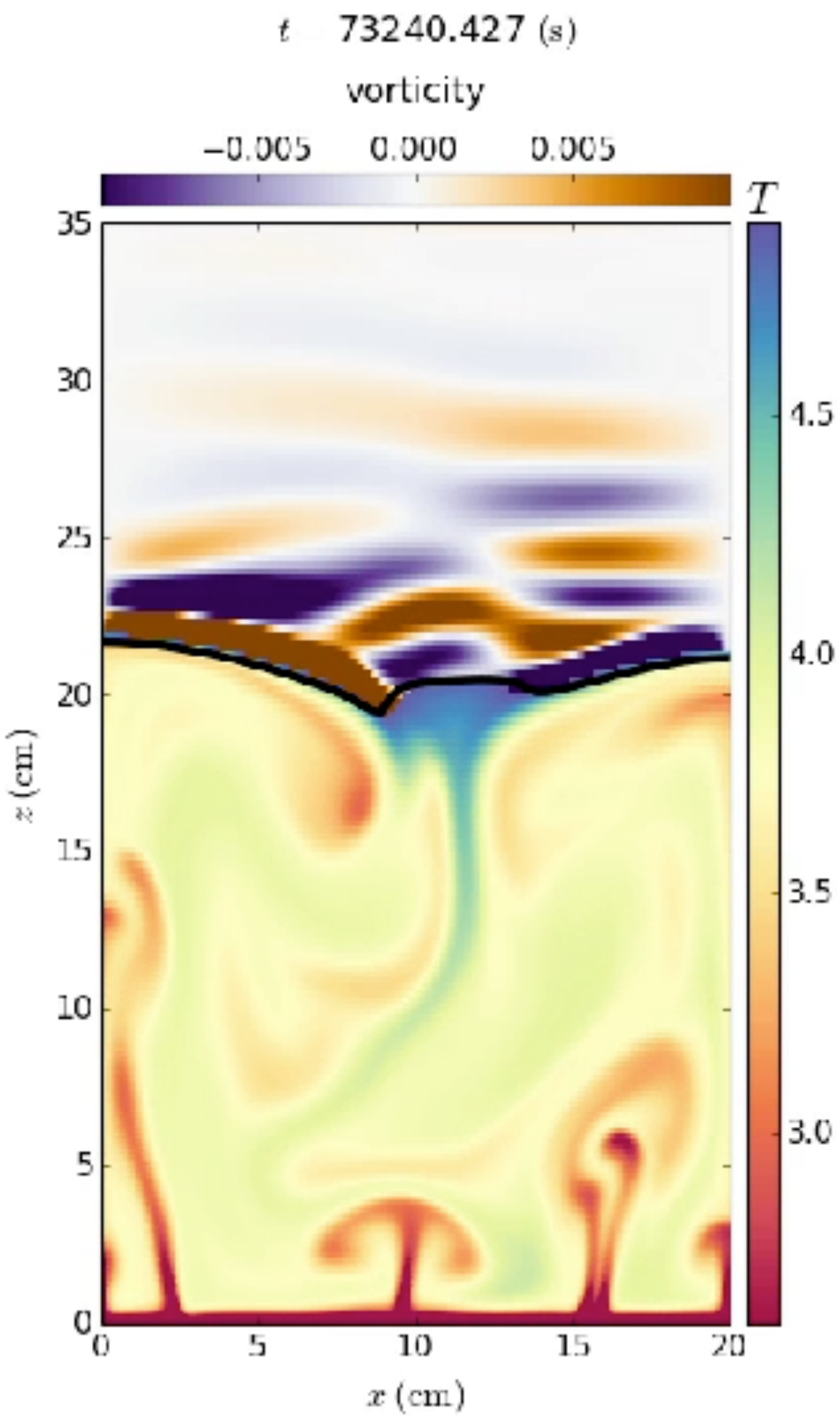

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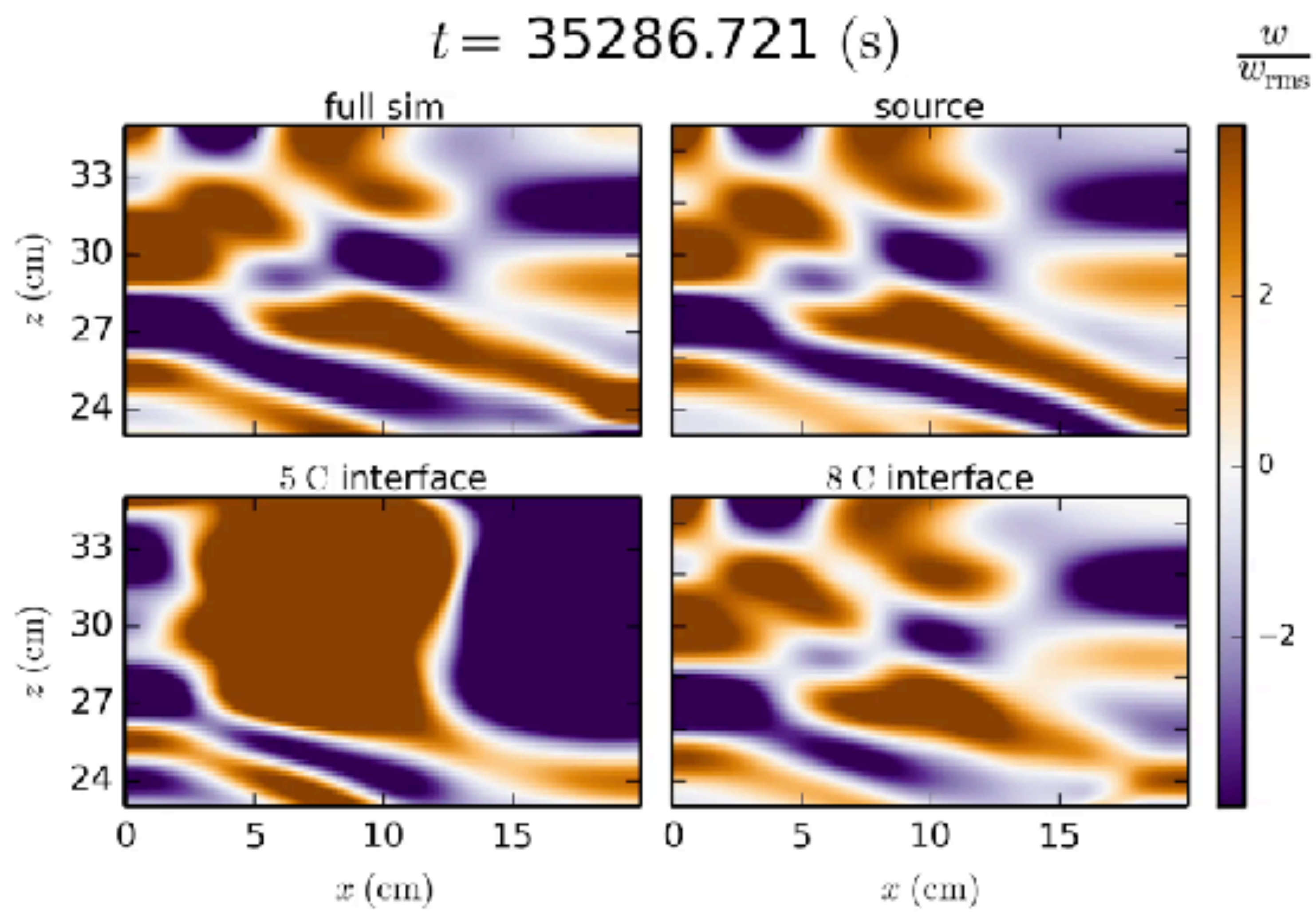

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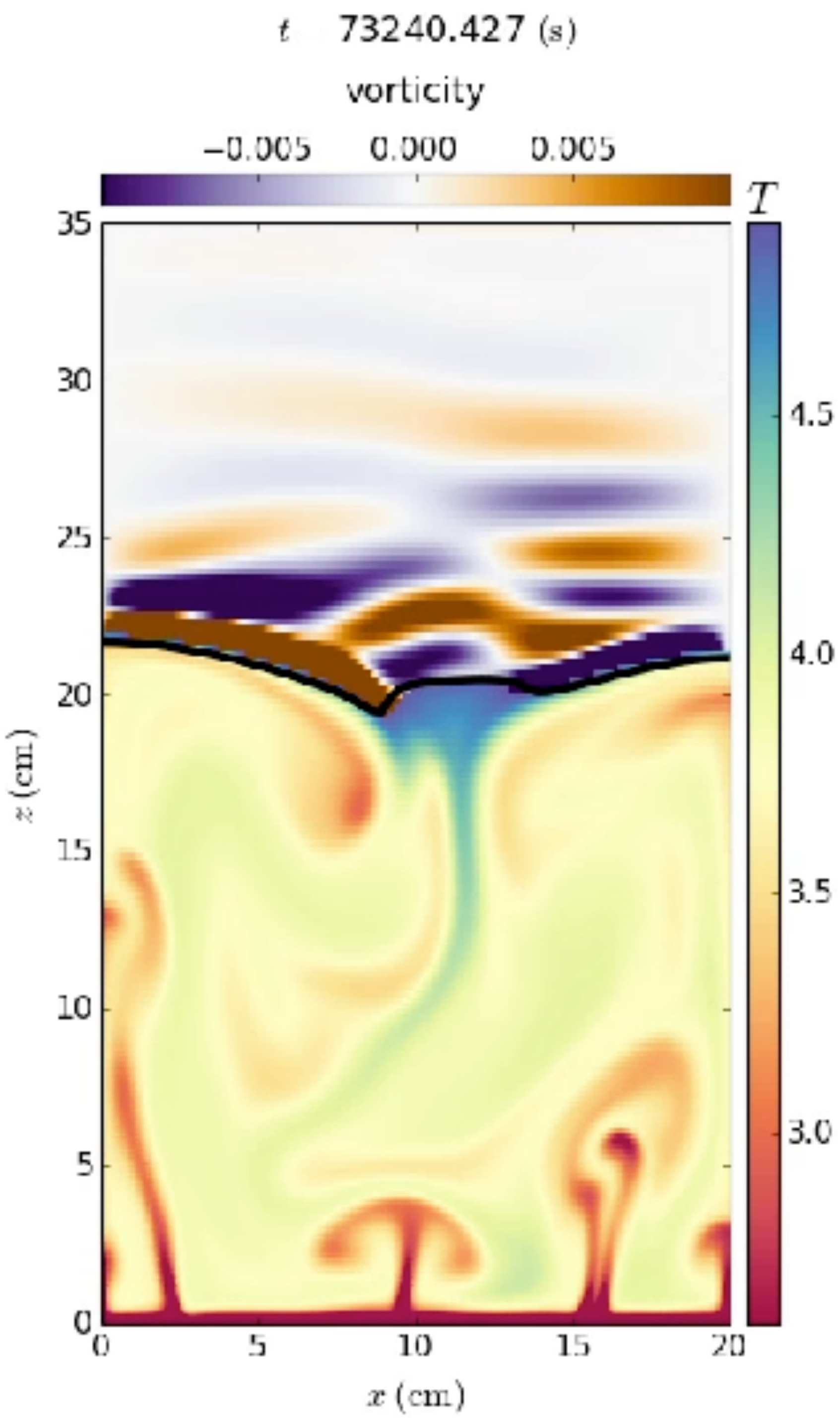

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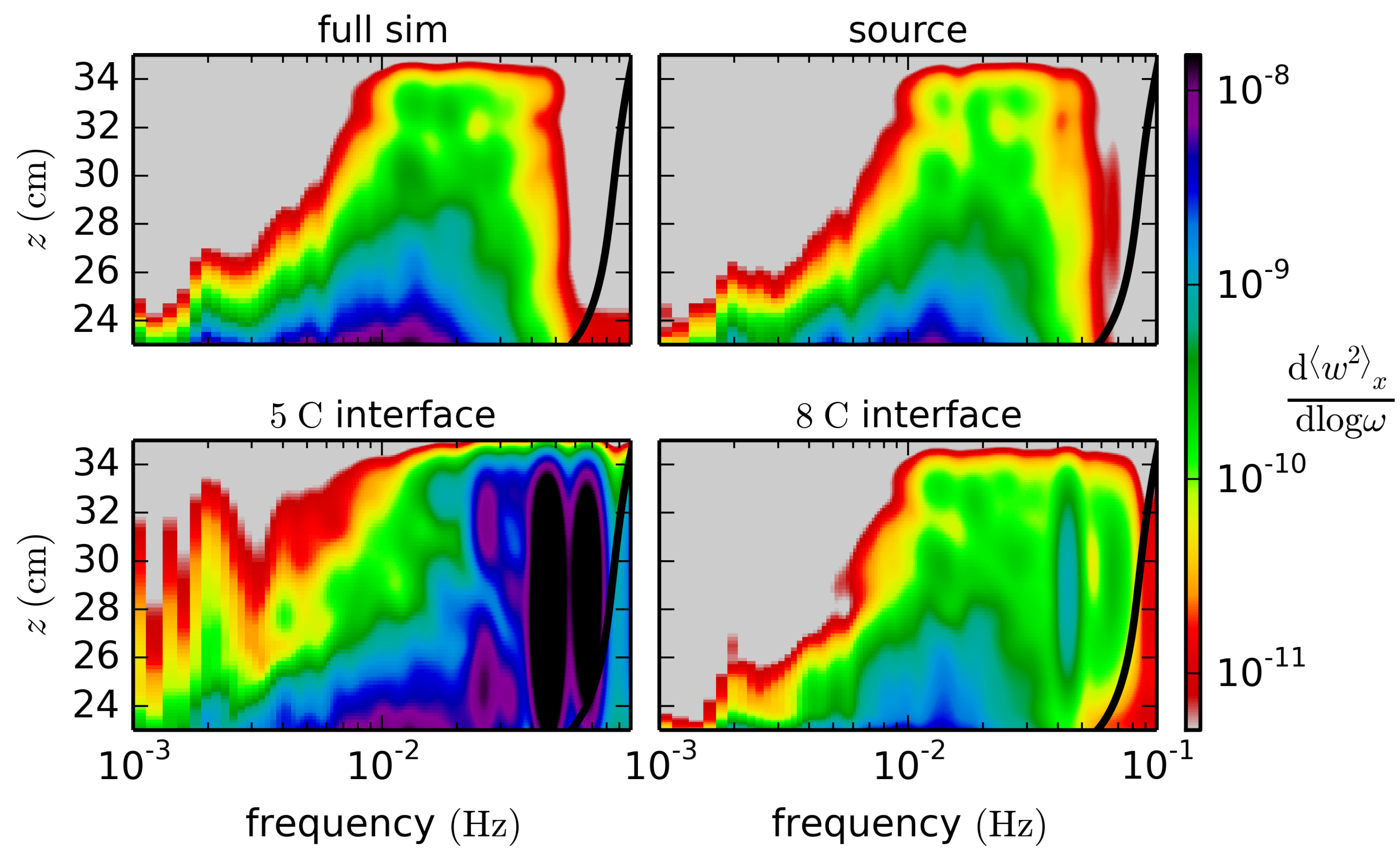
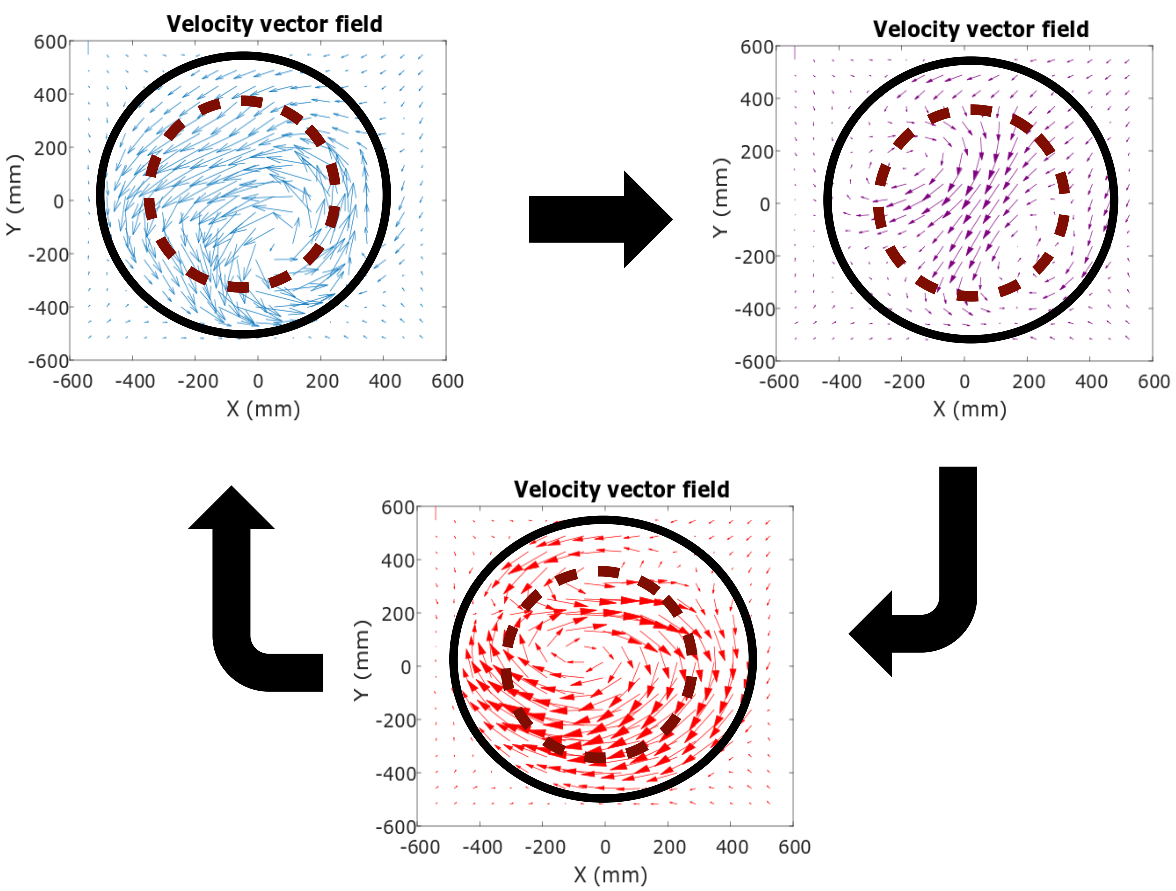


- waves excited by deep forcing rather than mechanical oscillator
- wave field correctly predicted by the linear propagation from the interface including the full dissipation

Lecoanet et al. 2015

QBO in the 4ºC set-up?

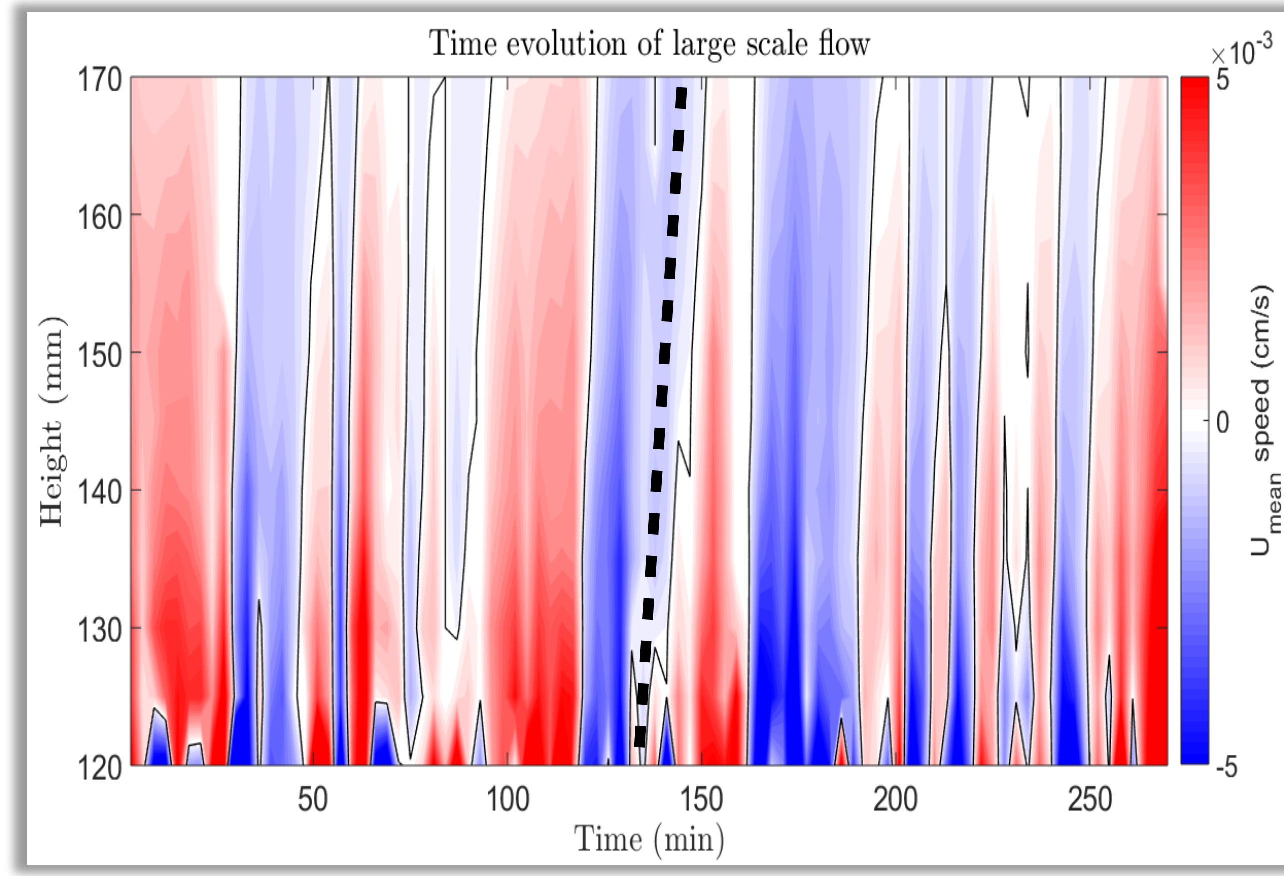
average over a ring…

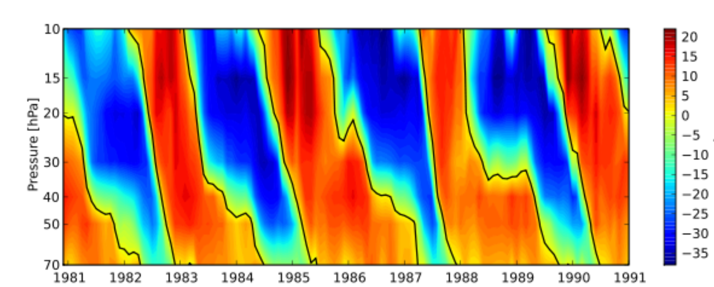


Full cycle ≈ 1 hour

horizontal mean-field at a given depth

… scan at different height through time





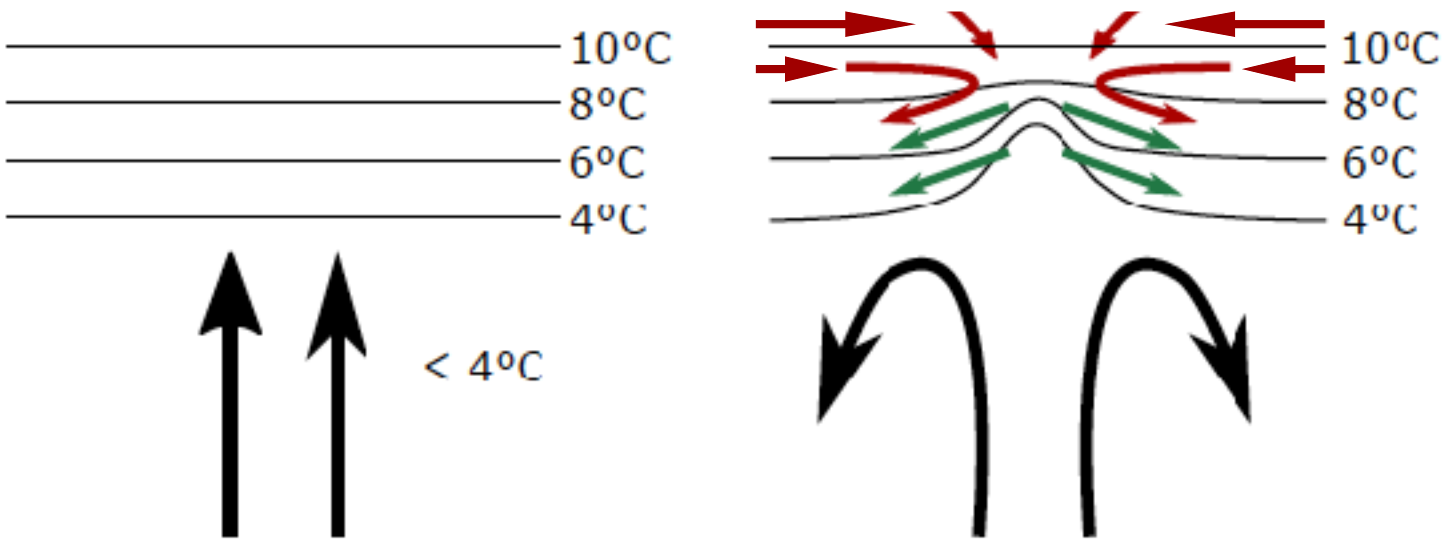
monthly-mean zonal-mean equatorial zonal wind in m/s between about 20 and 35 km

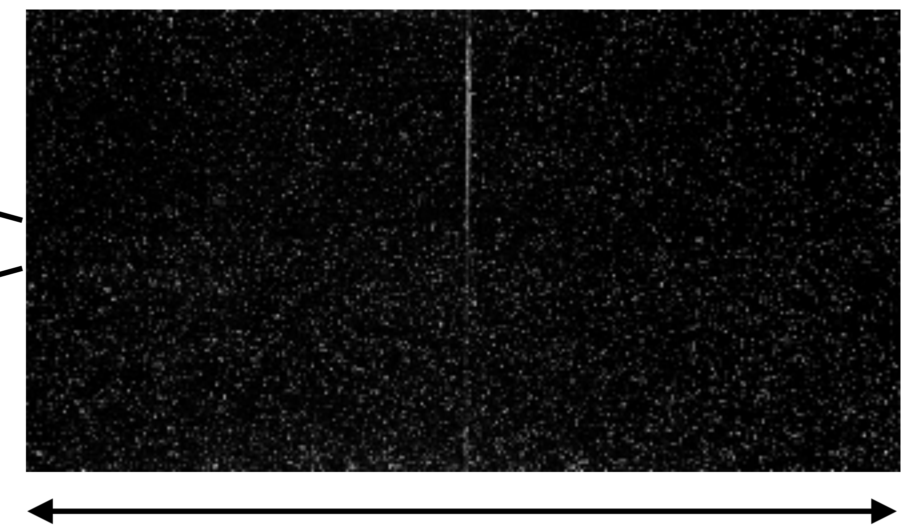
reversals, but phase speed: wrong direction and ~ viscous diffusion

Leard et al. 2019

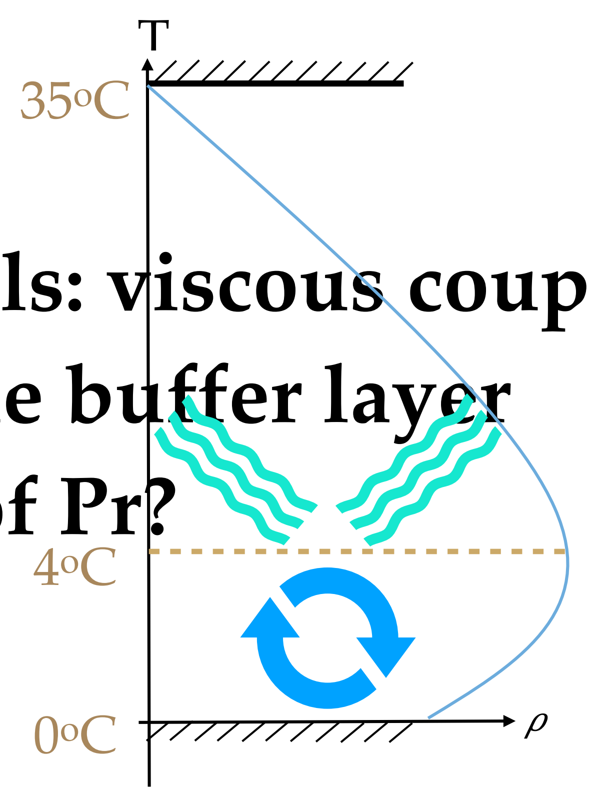
QBO in the 4°C set-up?

buffer layer: specific thermal coupling

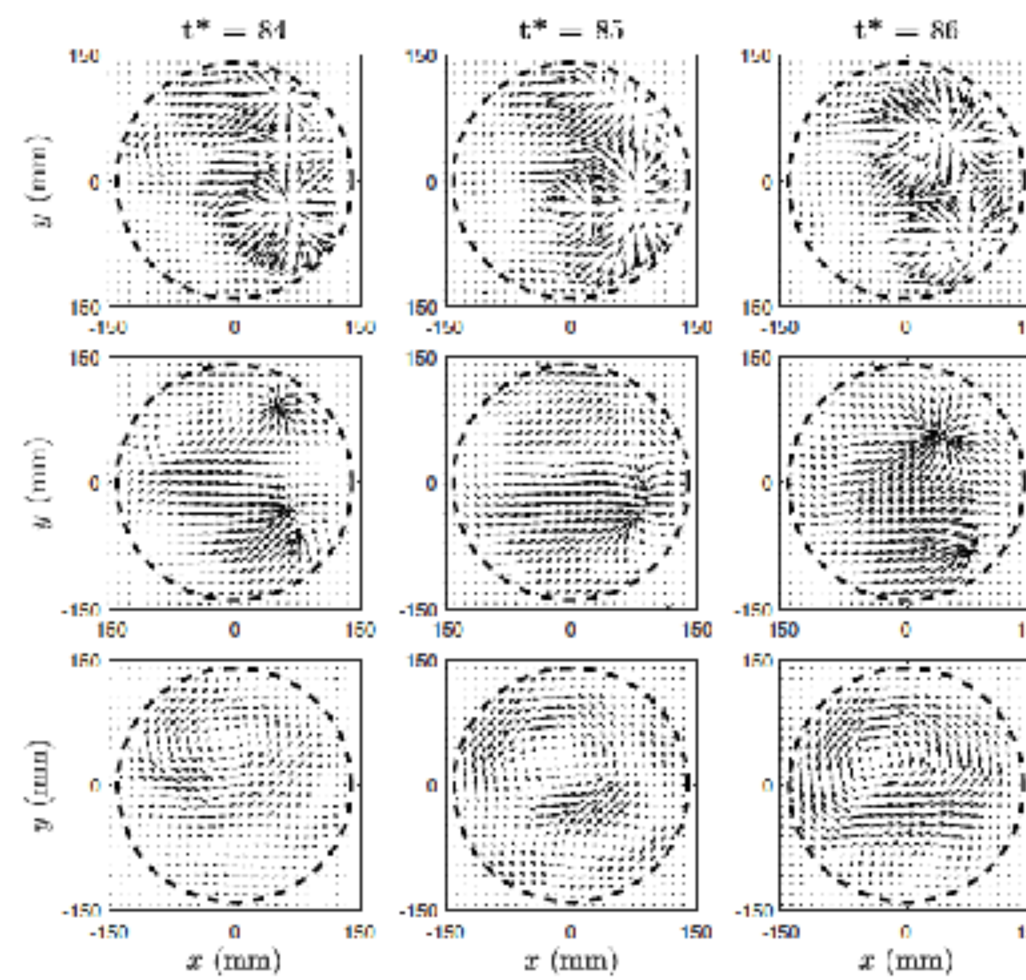




Accelerated 30 times



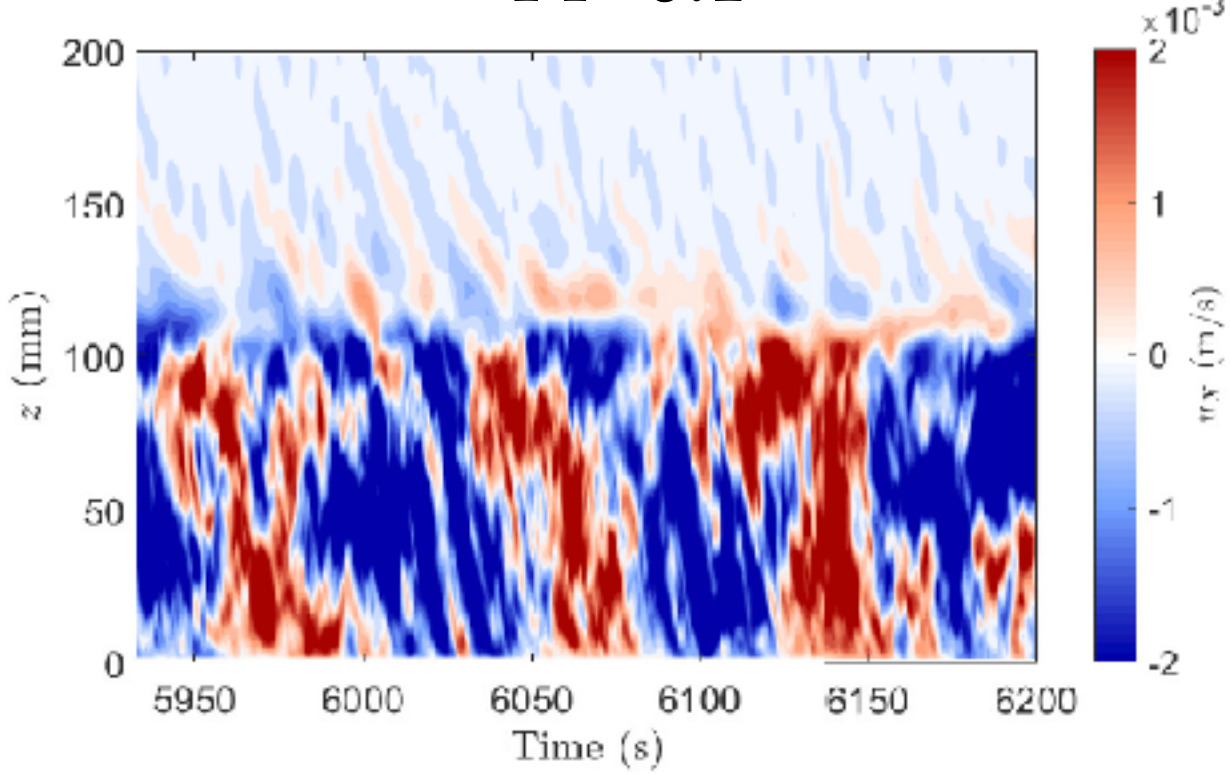
- **reversals: viscous coupling with the buffer layer**
- **effect of Pr?**



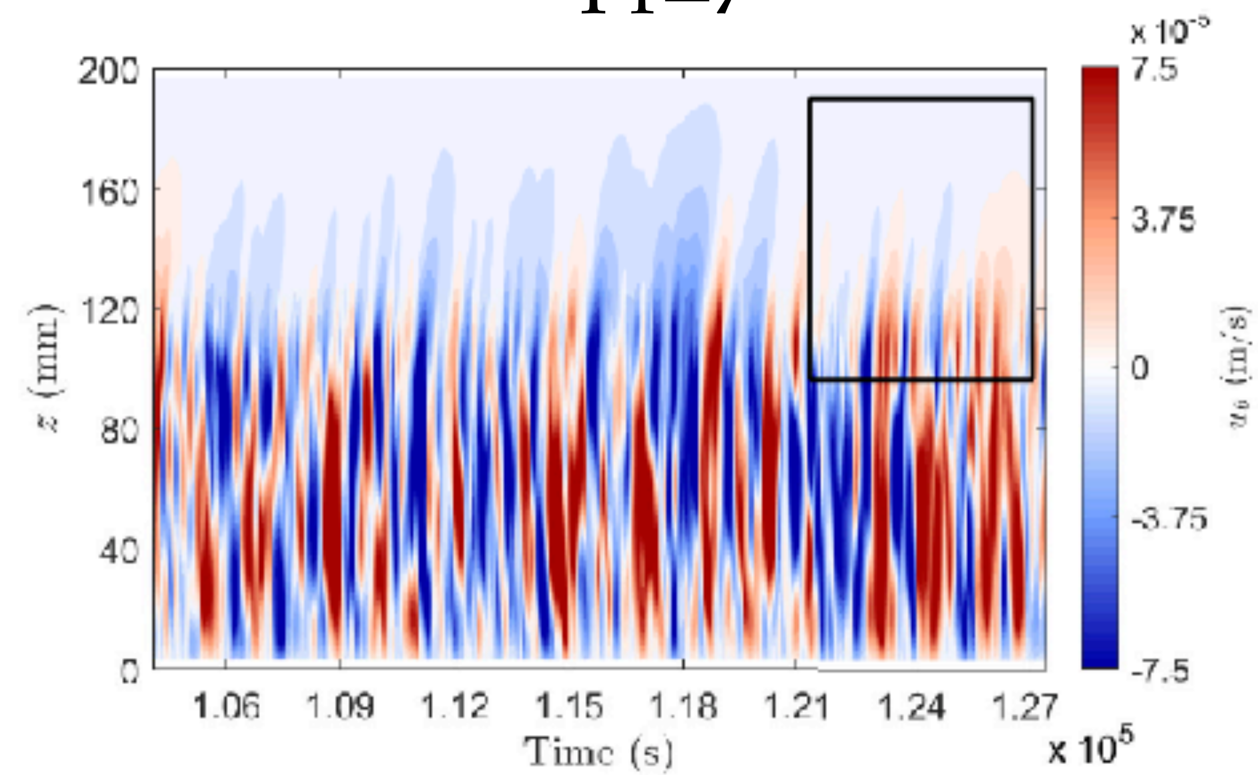
Leard et al. 2019

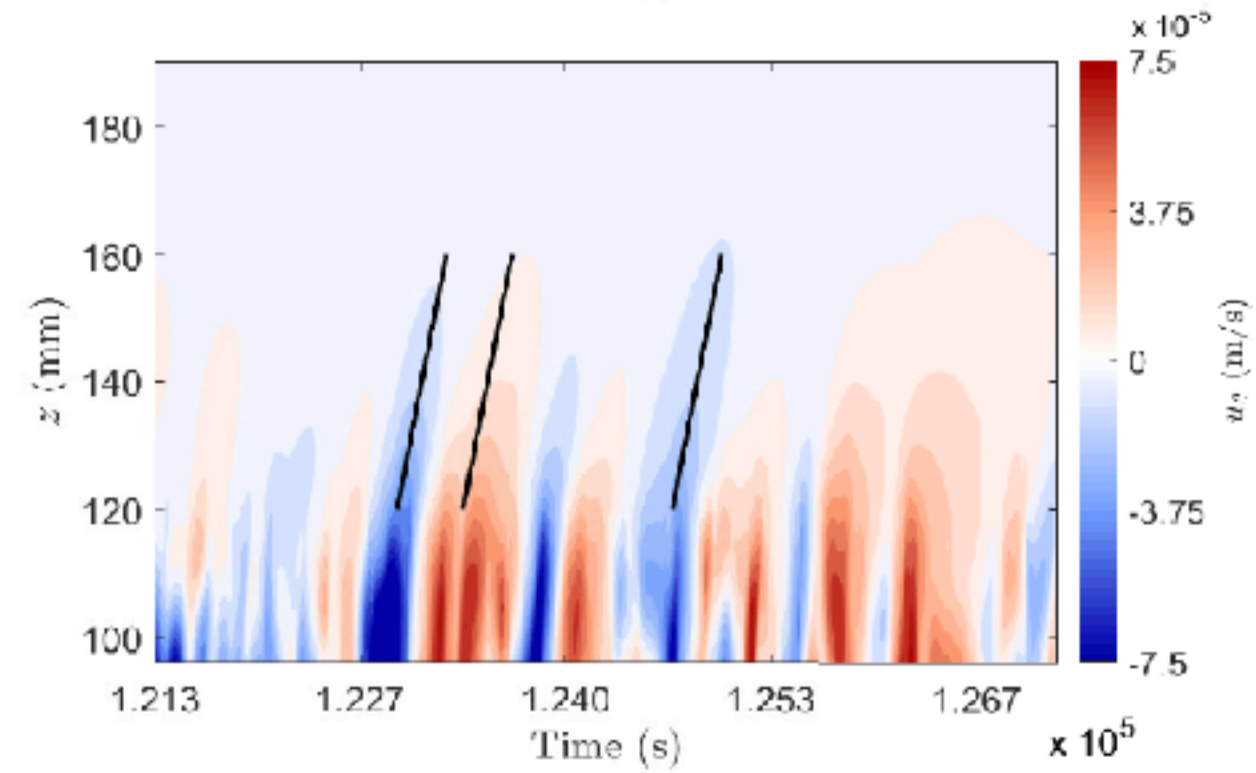
QBO in the 4°C set-up?

Pr=0.1



Pr=7





- **reversals: viscous coupling with the buffer layer**
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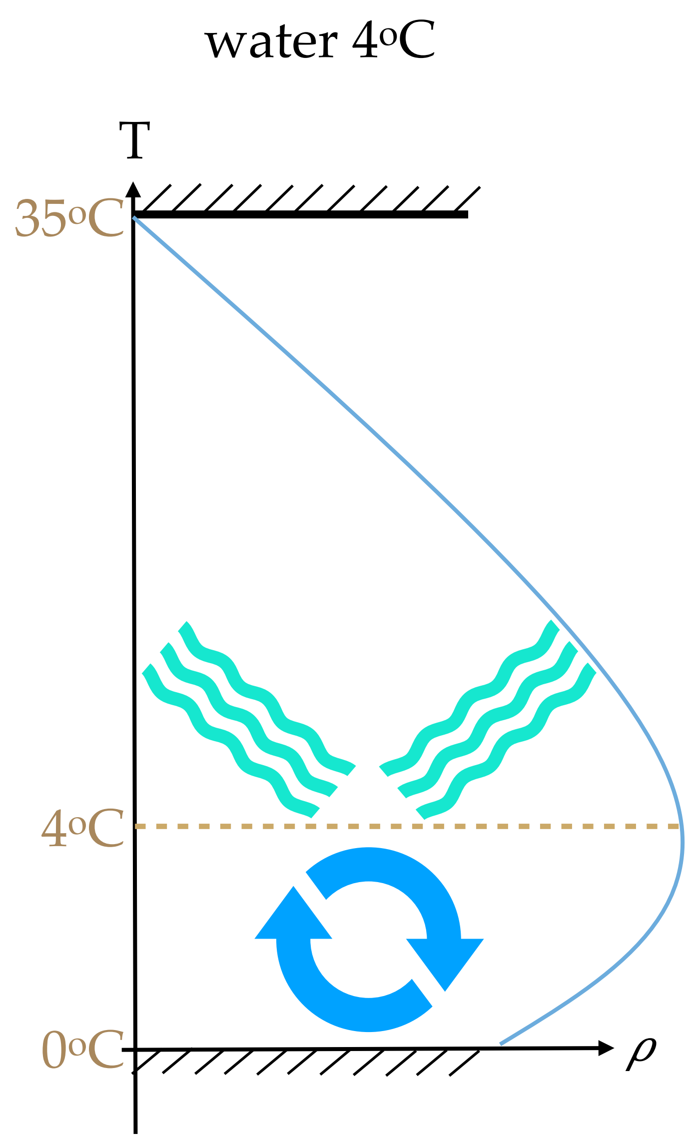
3D-numerical simulation with Nek5000

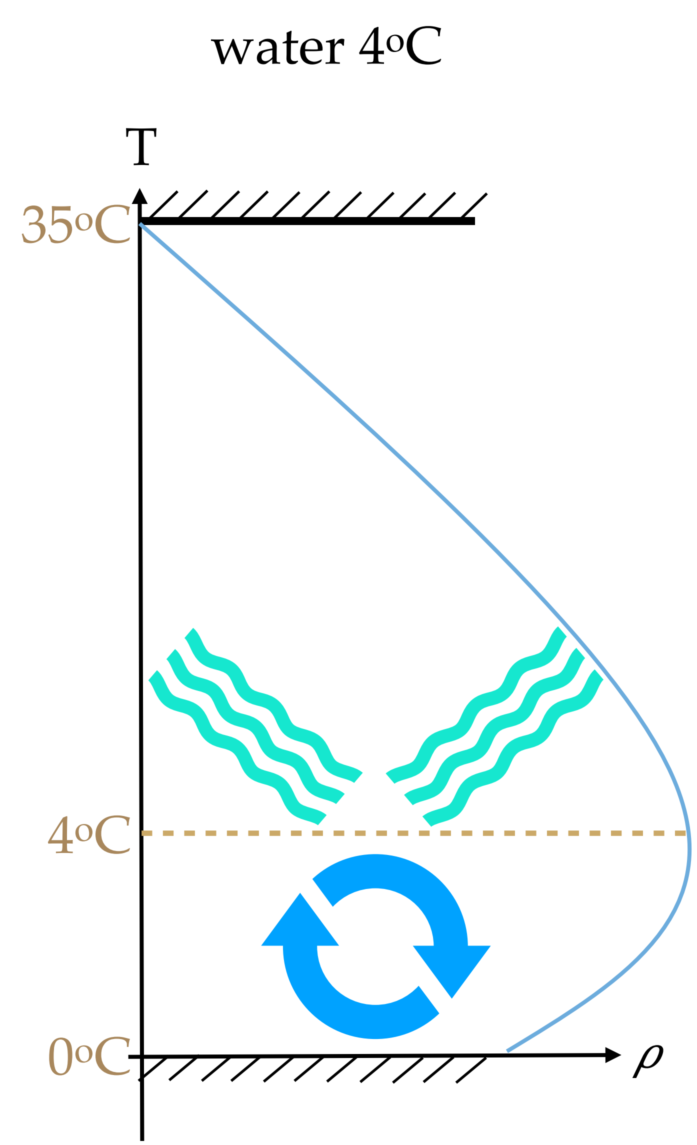
Leard et al. 2019

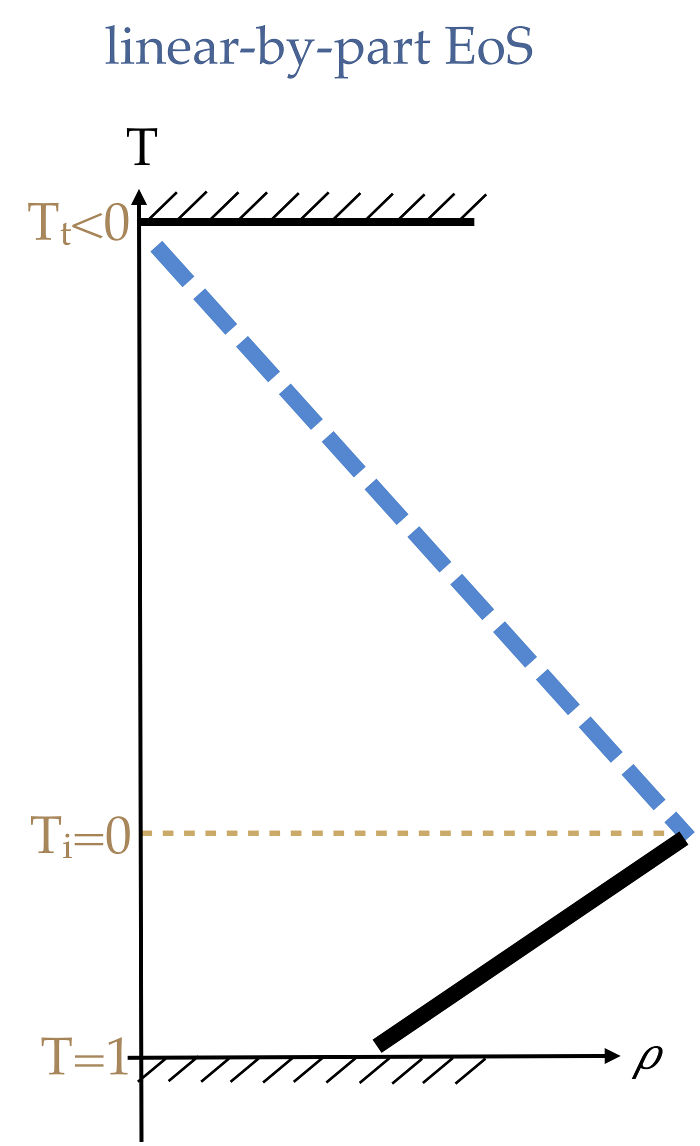
a simple numerical model



no independent control of the intensity of the convection and of the stratification…

a simple numerical model





$$\partial_t \boldsymbol{u} + \boldsymbol{u}\cdot\nabla\boldsymbol{u} = -\nabla p + \mathrm{Pr}\nabla^2\boldsymbol{u} - \mathrm{Pr}\,\mathrm{Ra}\rho\hat{z},$$

$$\partial_t T + \boldsymbol{u}\cdot\nabla T = \nabla^2 T,$$

$$\nabla\cdot\boldsymbol{u} = 0.$$

$$\rho = -\alpha(T)T = \begin{cases} -T, & T \geqslant 0 \\ \mathcal{S}T, & T < 0, \end{cases}$$

stiffness S

(independent control of convection vs. stratification intensity)

Couston et al. 2017

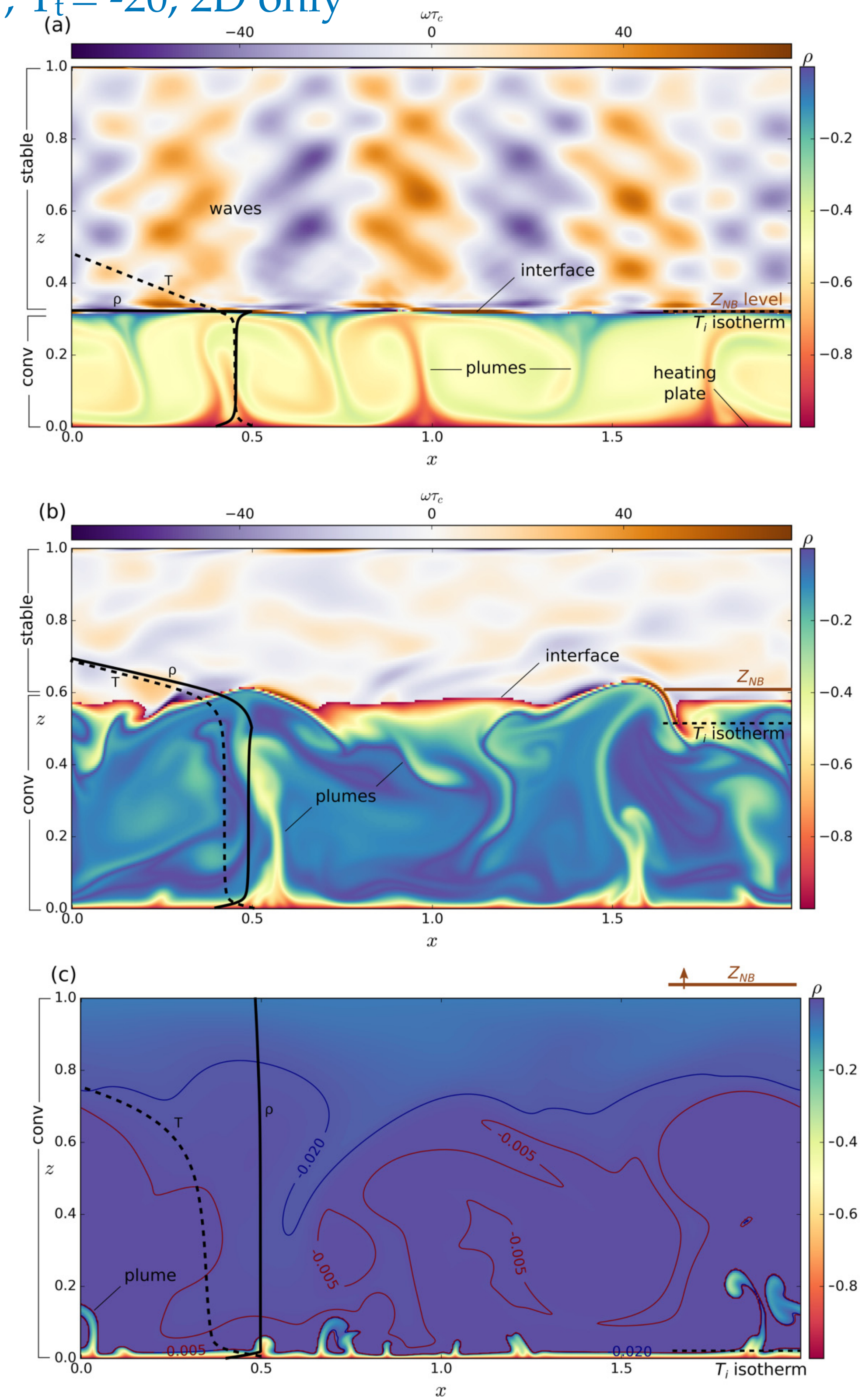
regimes as a function of S

Ra = 8x10^7 , T_t = -20, 2D only

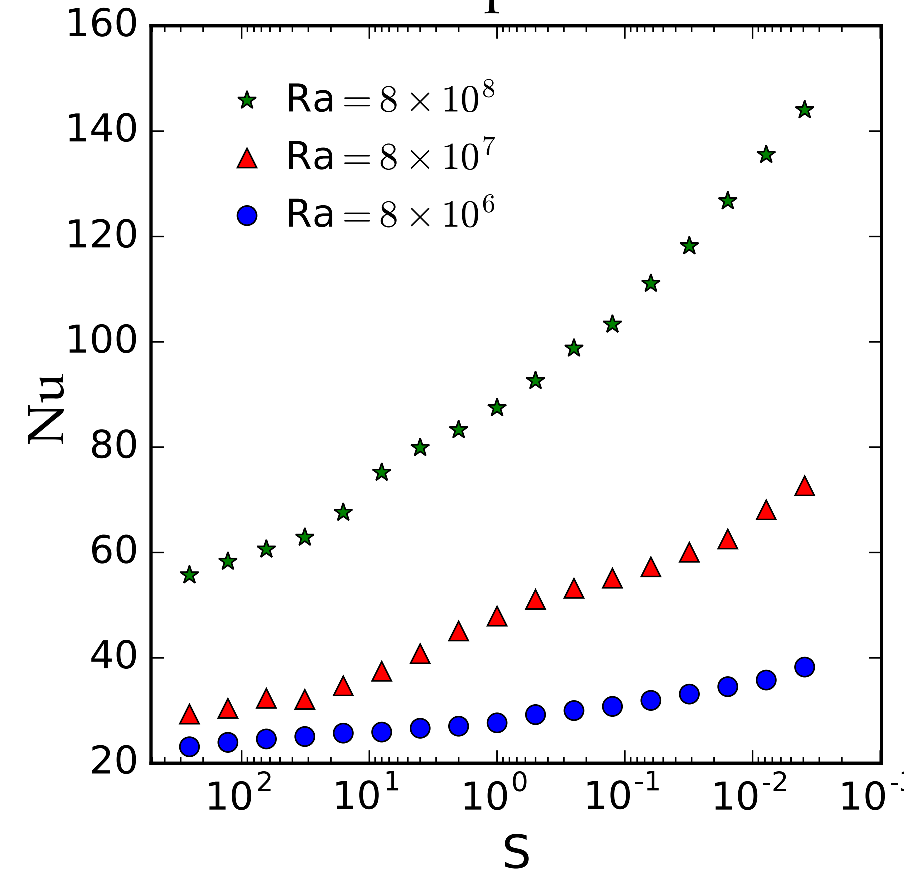
S = 2^8

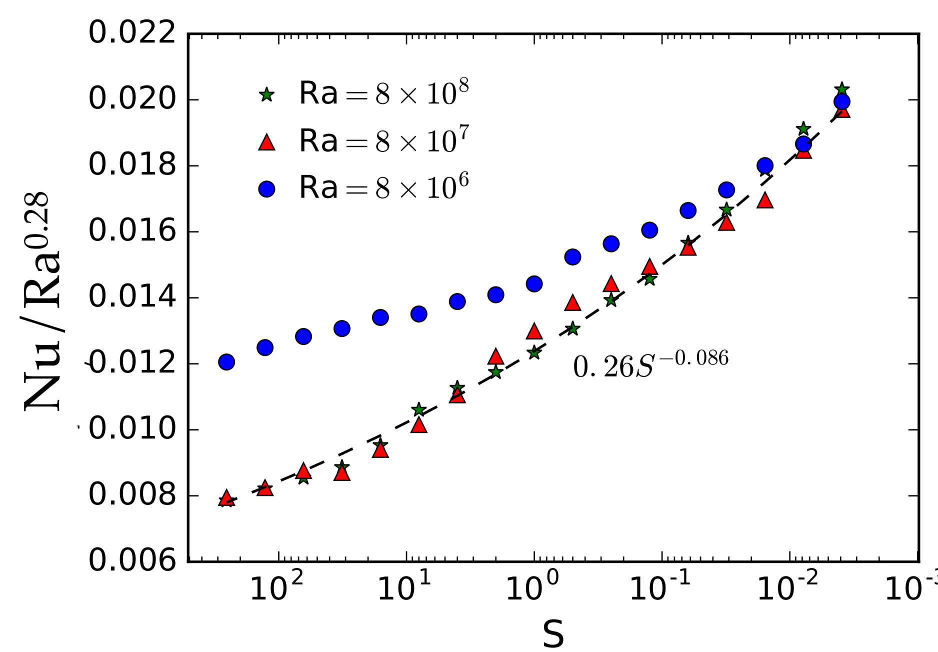
S = 1

S = 2^{-8}



heat flux dependence on S

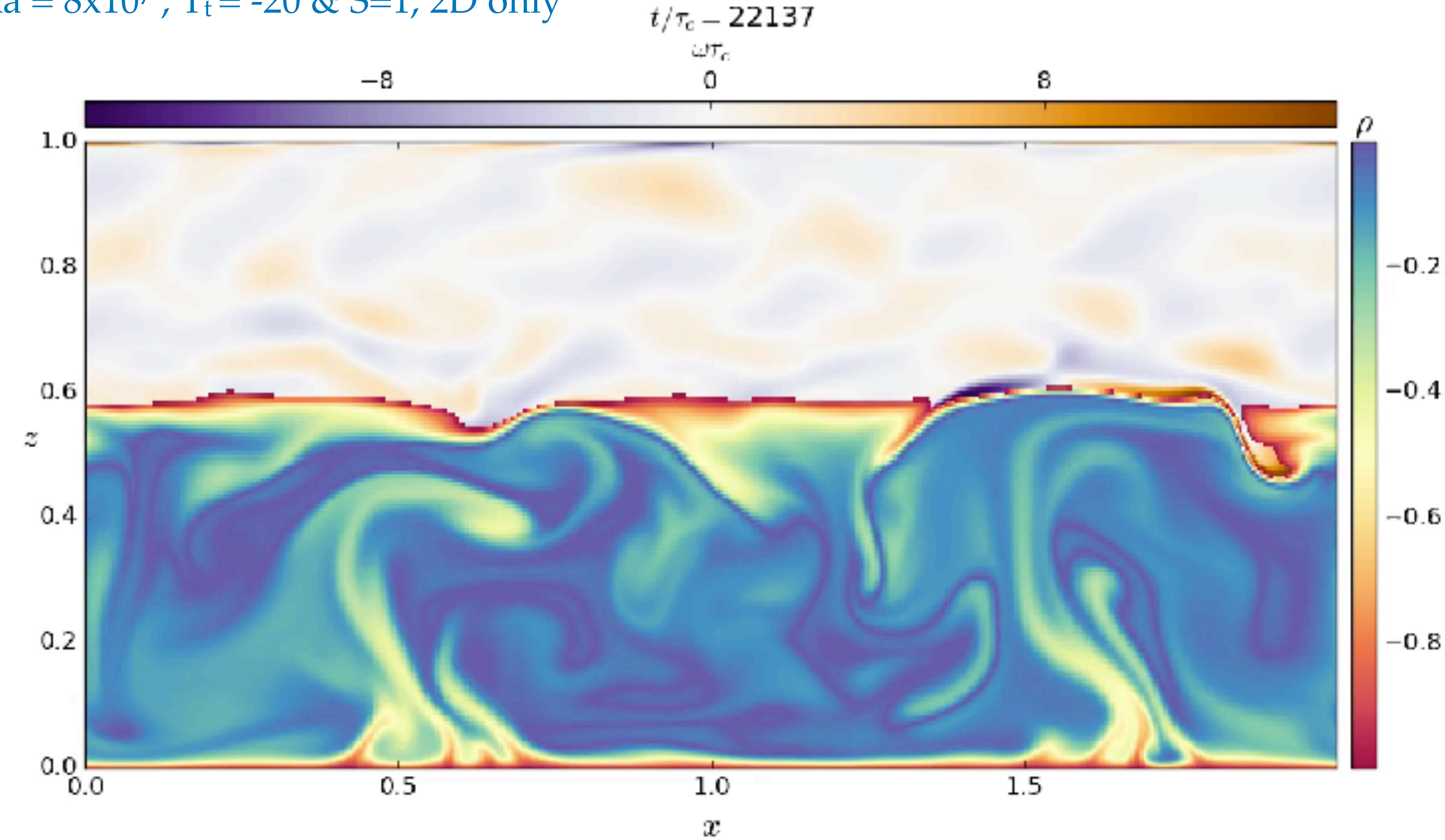




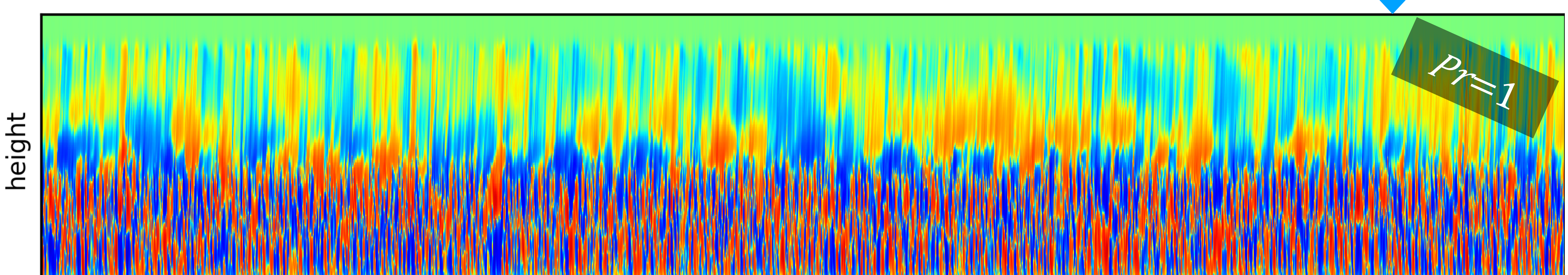
Couston et al. 2017

systematic study of the QBO

Ra = 8x10^7 , T_t = -20 & S=1, 2D only



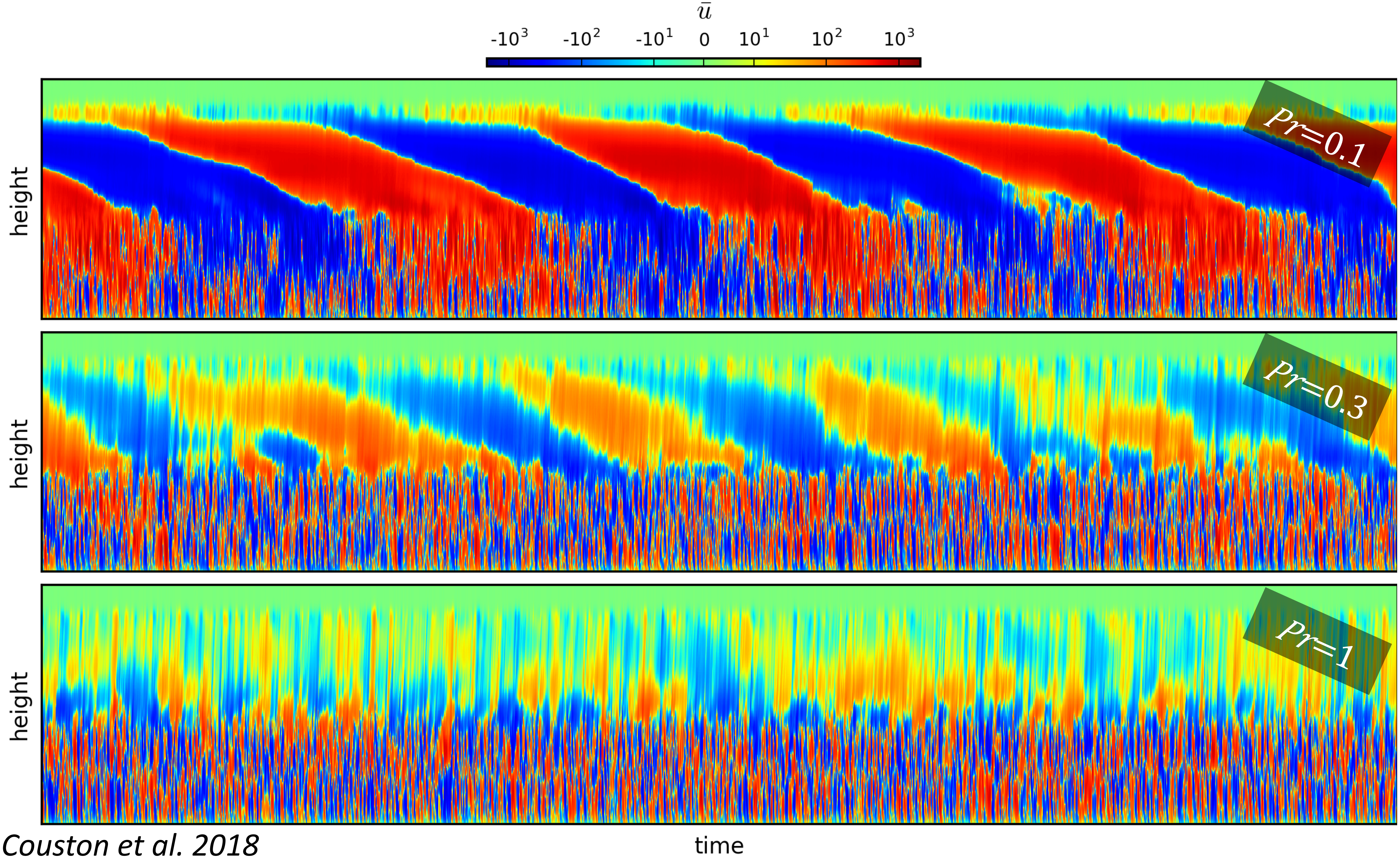
horizontal-averaging of the horizontal velocity as a function of time & depth



Couston et al. 2018

QBO: generic at low Pr?

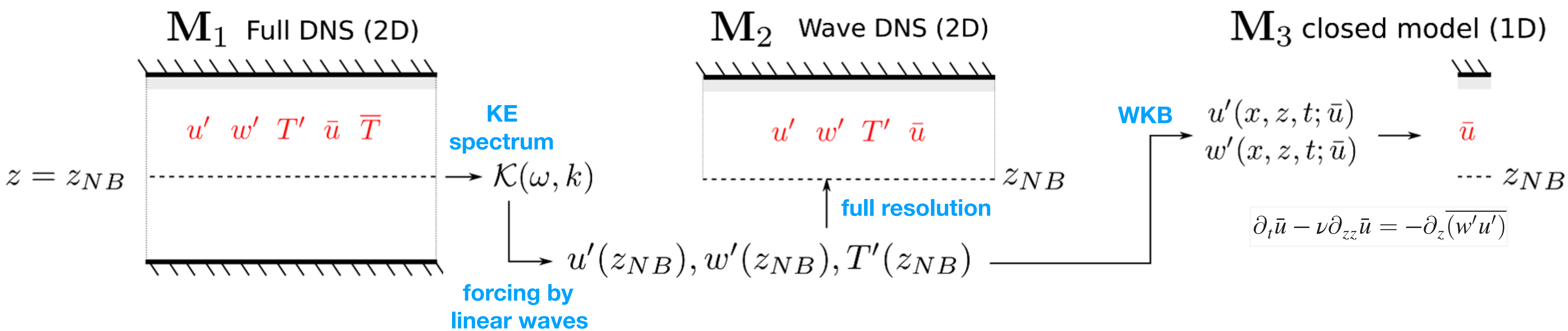
Ra = 8x10^7 , T_t = -20 & S=1, 2D only

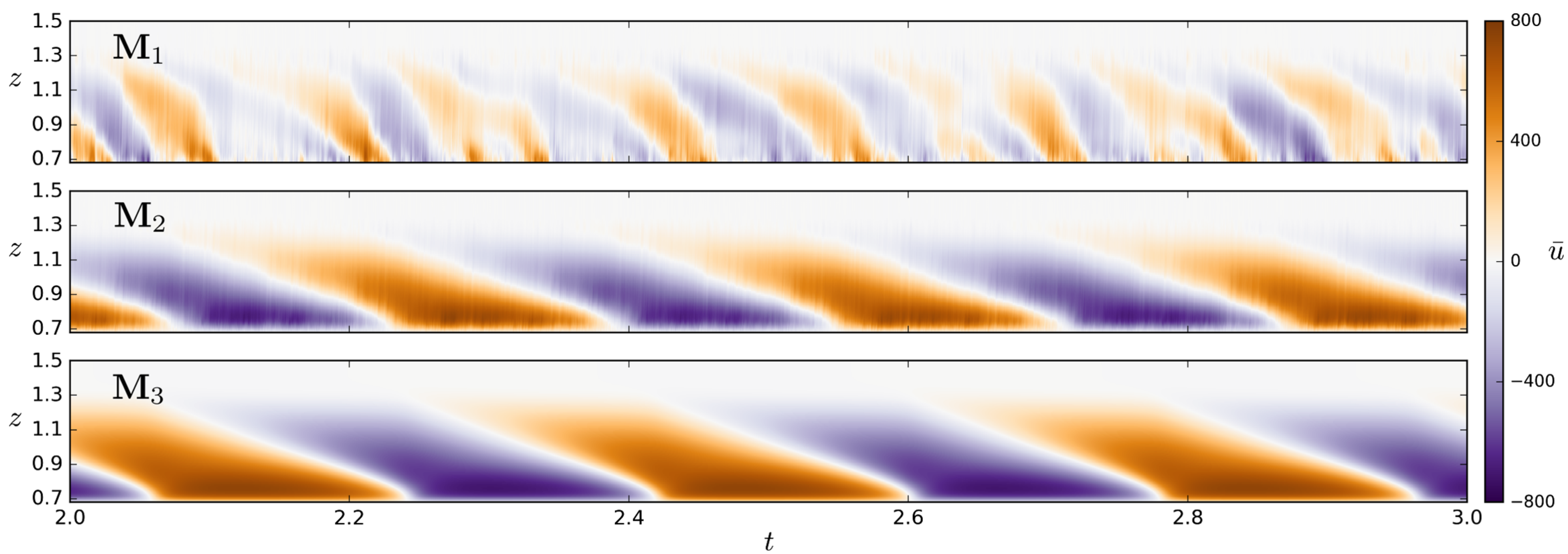


Couston et al. 2018

parameterization for the QBO

- how to correctly parameterise waves in GCM to get a predictive model of QBO?
- available data = local (in space and time) values of the fluctuations



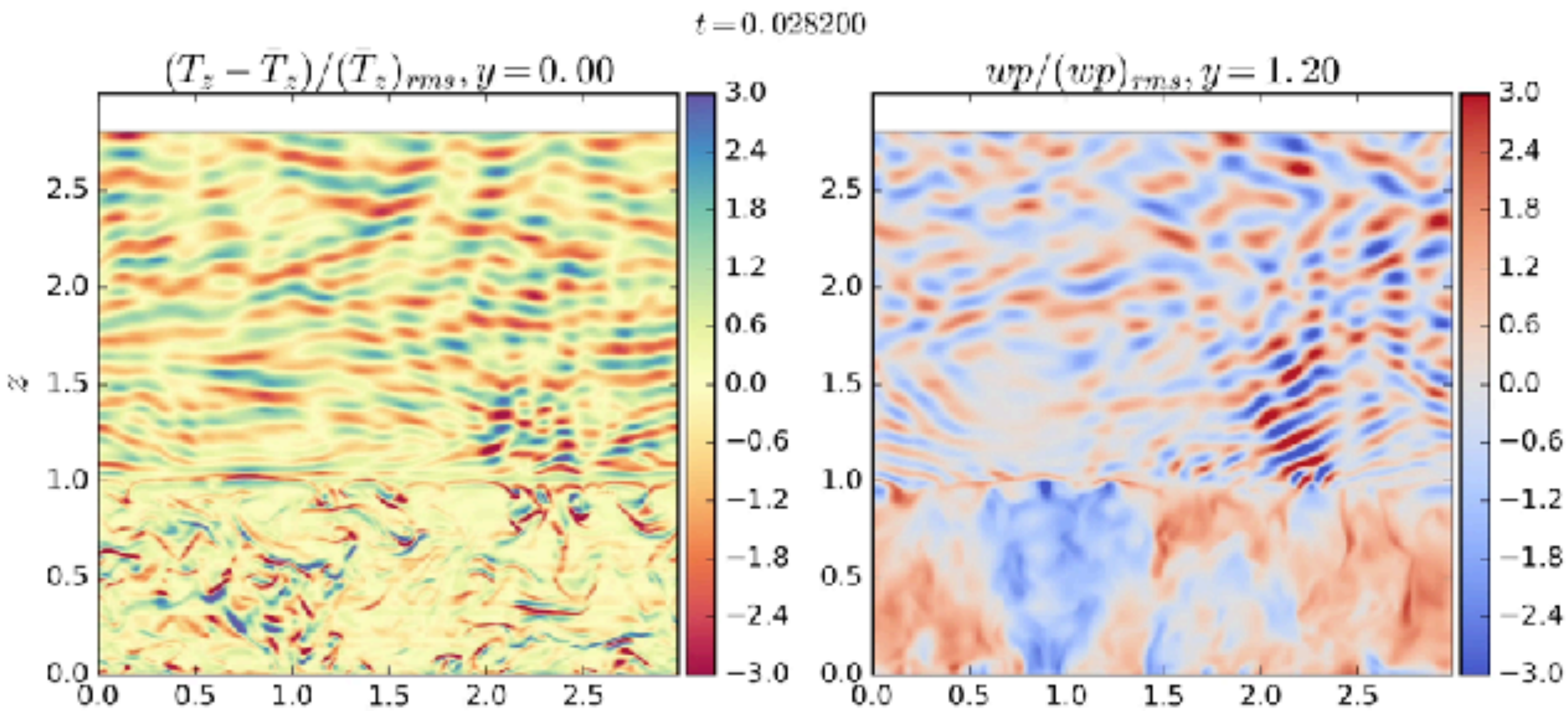


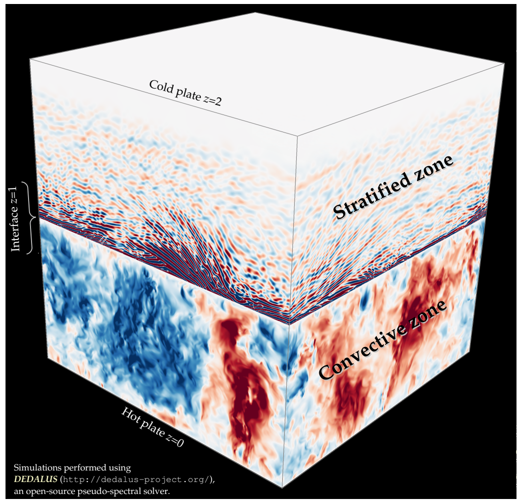
higher order statistics from data & more evolved stochastic excitation processes (e.g. Lott & Guez 2013) are necessary

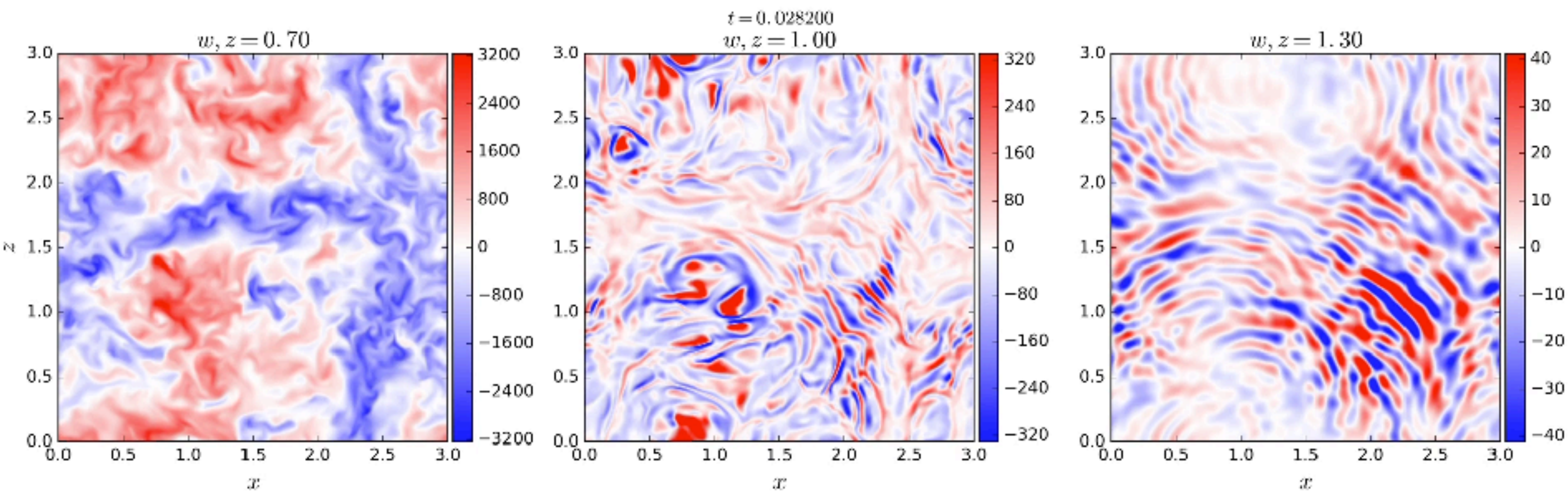
other points to discuss this week...

- massive 3D simulations

Ra = 4×10^7 & S=10







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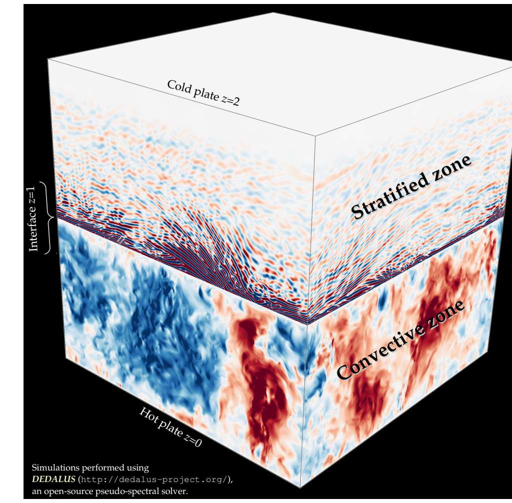
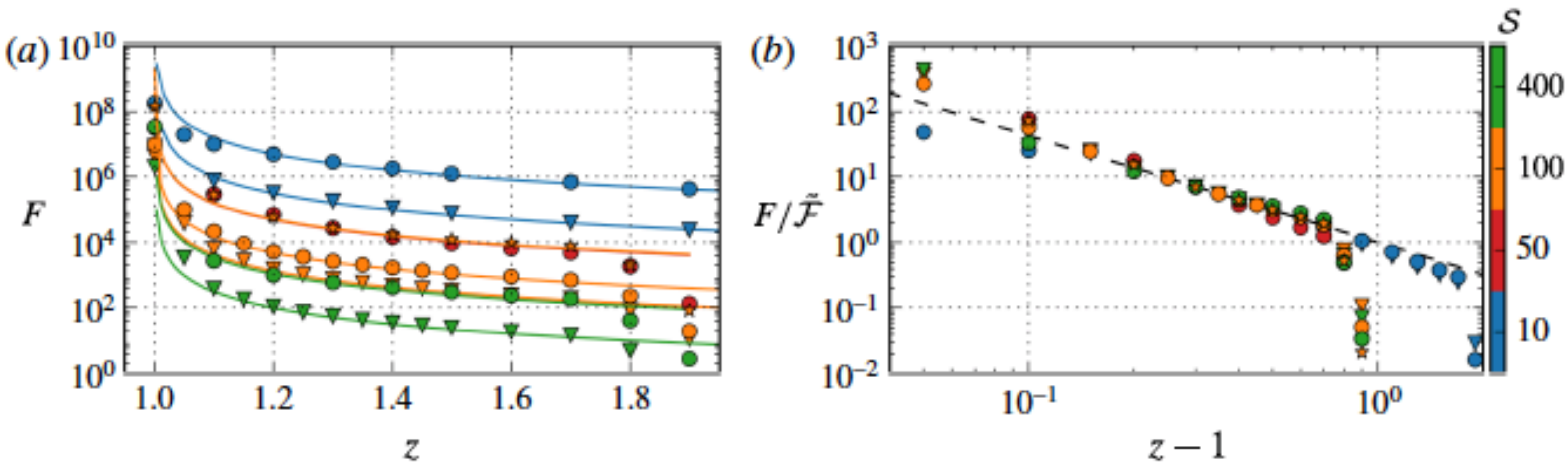


∇ Ra = 4x10^7
O Ra = 2x10^8
☆ Ra = 1x10^9



in agreement with Lecoanet & Quataert (2013), where excitation by Reynolds stresses due to eddies in the turbulent region, large Ra and large stratification:

- wave energy flux spectrum scales like $k^4 f^{-13/2}$
- total wave energy flux decays like $z^{-13/8}$

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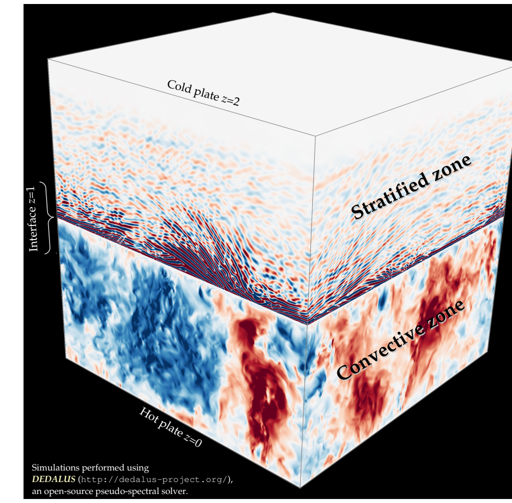
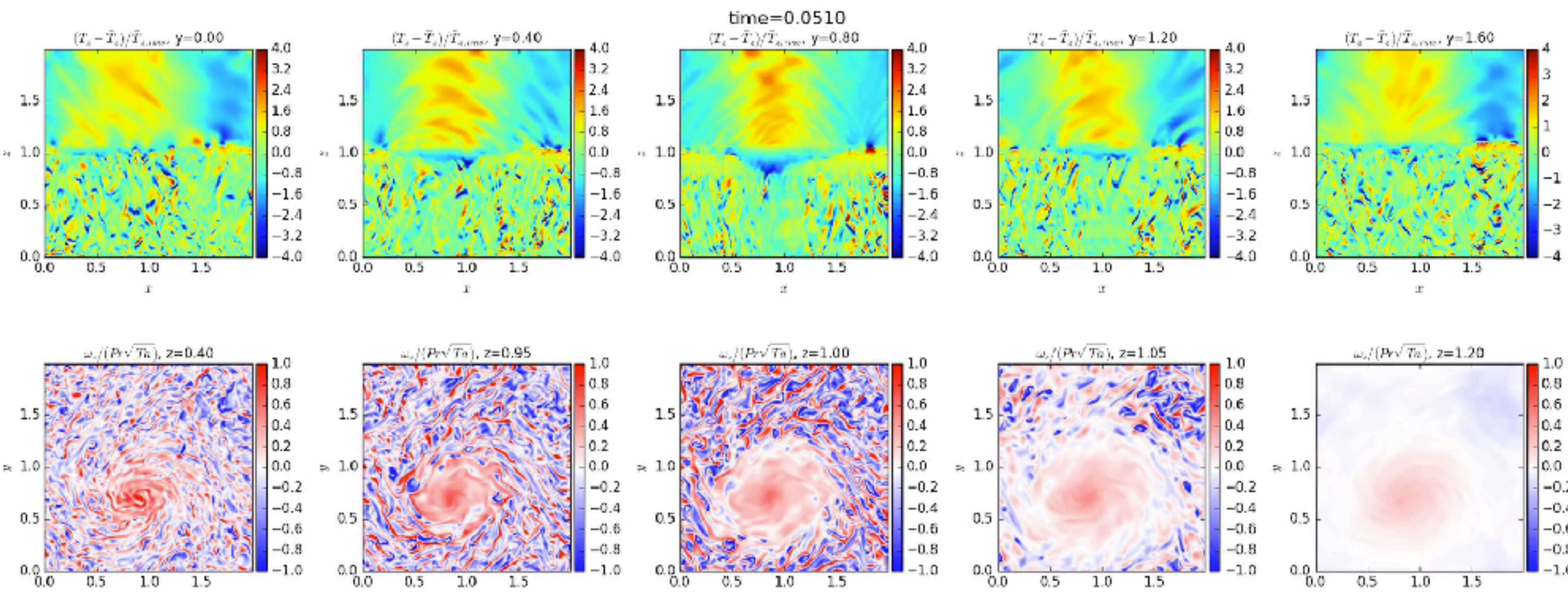
  - ✓ effect of rotation: saturation of inverse cascade and generic shape and size (Couston et al. 2019)





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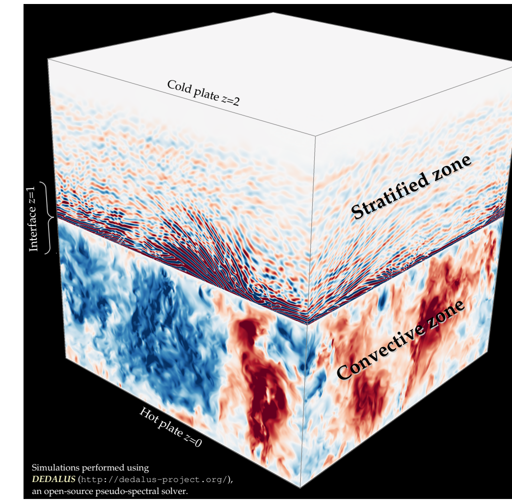
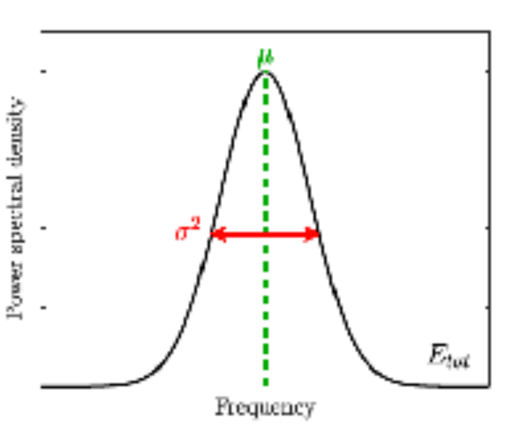


- extension of classical Plumb's QBO model to multi-wave forcing: see poster by P. Leard



gaussian excitation

… a wider spectrum favours QBO…