Nonlinear Dynamics of Deep Gravity Waves in the Thermosphere

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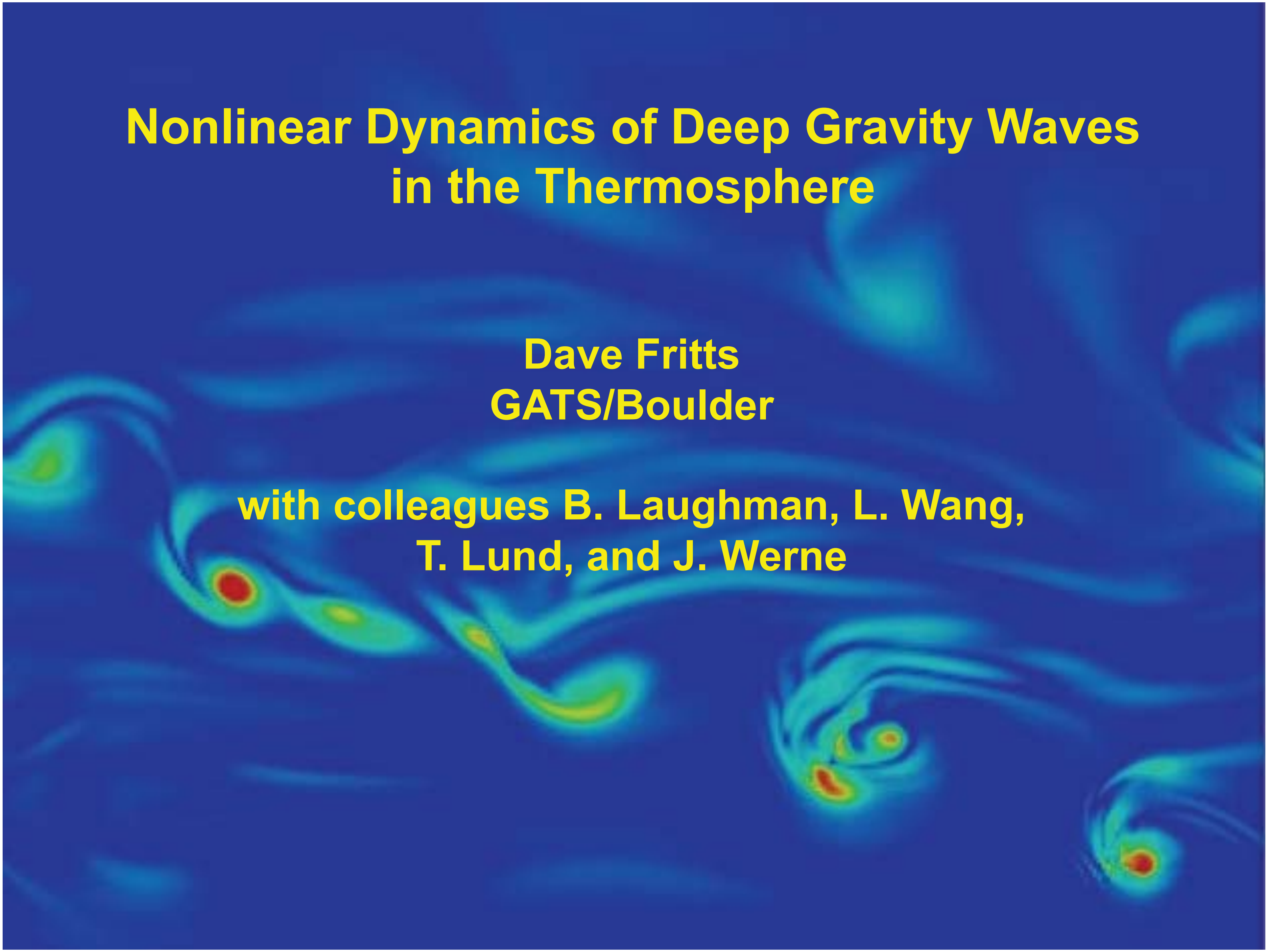


Numerical Models Employed for GW Studies

1. **Pseudo-spectral model solving Boussinesq Navier-Stokes eqns.**

   Capabilities:

   - very high resolution (and high Reynolds numbers, $Re = \lambda_z^2/T_b\nu$)
   - accurate descriptions of instabilities & turbulence
   - valid for $\lambda_z^2 << (4\pi H)^2$ or λ_z ~ 10 km or less

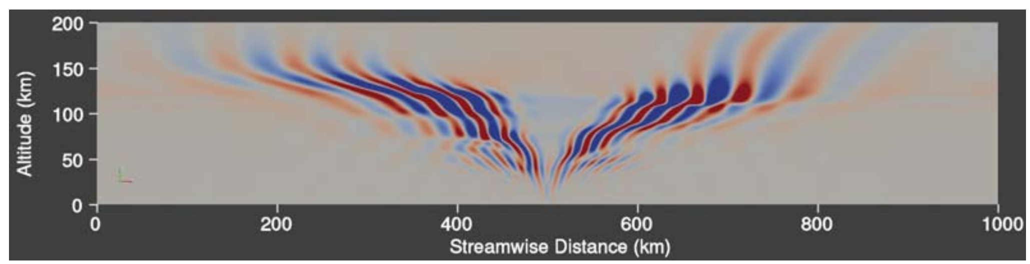
   (KH instability for Ri = 0.05)

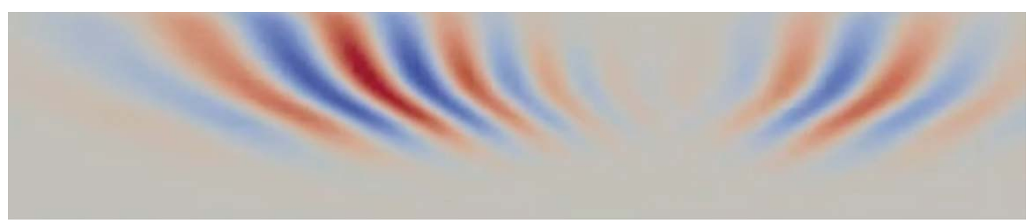
2. **Finite-volume model solving Compressible or Anelastic Navier-Stokes eqns.**

   Capabilities:

   - high resolution (and *Re*)
   - NL dynamics spanning ~15 to 20 *H* (~0-400 km)

   (GW responses to convective plume and tsunami)





transient response, portion of 3200 x 250 km domain

Why are Gravity Waves Nonlinear at High Altitudes?

Large-scale and large-amplitude GWs yield

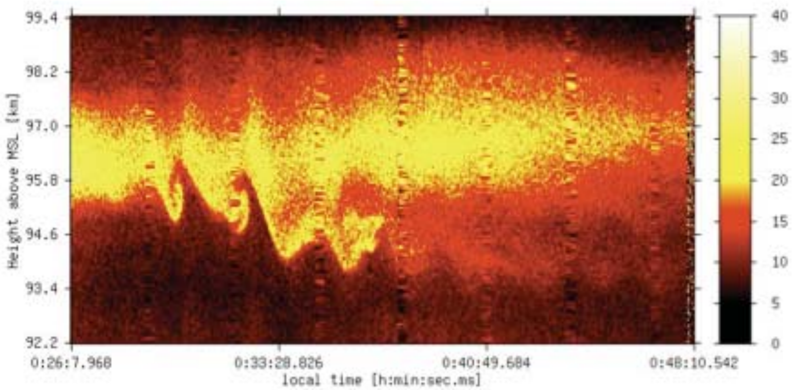
- large Reynolds numbers, $Re = \lambda_z^2/T_b\nu$,   => flow instabilities
- large momentum transport and effects

z ~80 - 100 km =>
high *Re* (10^4 - 10^6)
dynamics
(strong instabs.)

z ~120 - 160 km =>
low *Re* (10^2 - 10^3)
dynamics
(weaker instabs.)

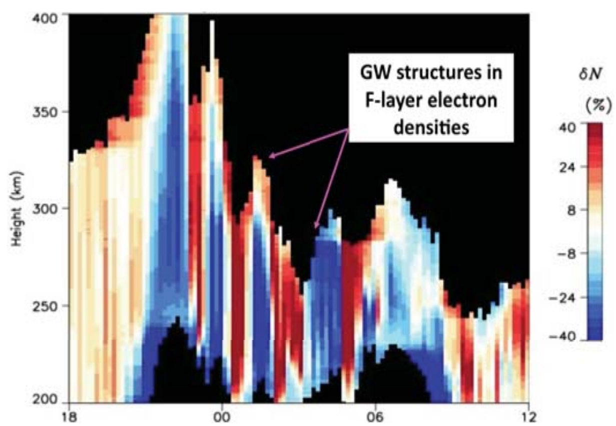
z >200 km =>
V Low *Re* (1 - 10^2)
dynamics
(large amplitudes,
but no neutral
instabilities)

KH instabilities, λ_h ~ 5-10 km

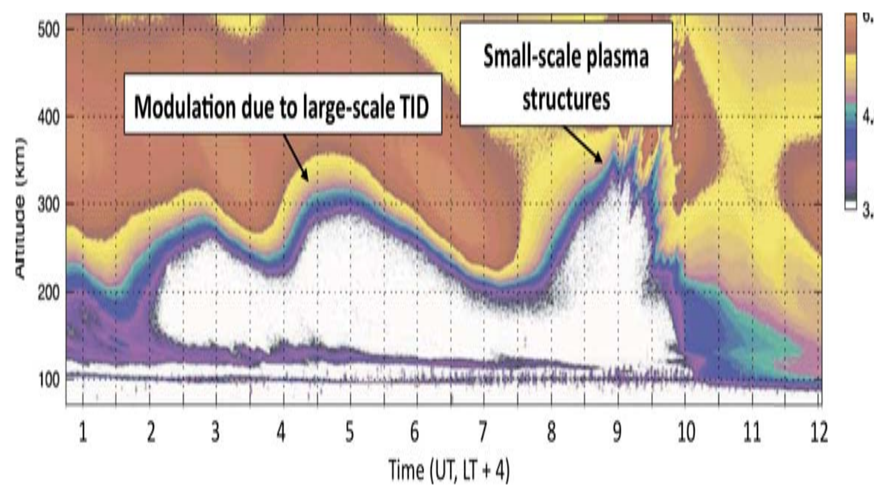


GW breaking in NLC, λ_h ~ 30 km

conv. GWs in N_e densities



auroral GWs in the Arecibo ISR N_e densities



3 highlights

- <u>**Multi-scale GW dynamics**</u> **(high *Re*) ~90 km**

- <u>**GW self acceleration and effects**</u> **(large GW amps.) ~100 – 140 km**

- <u>**GW instability in the LT**</u> **(large GW amps., lower *Re*) ~120 – 160 km**

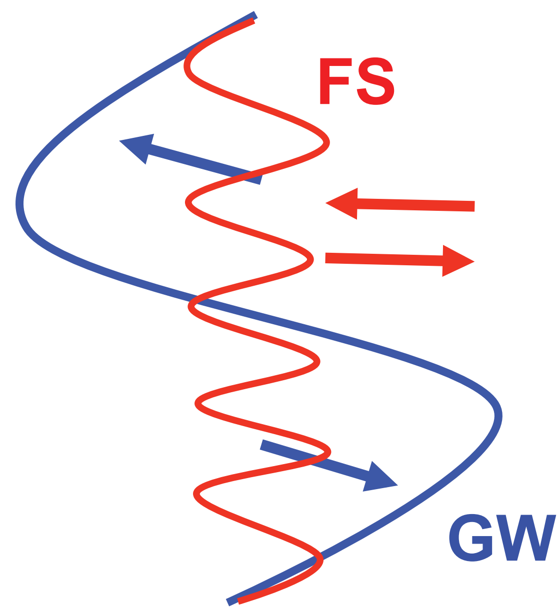
1. Multi-Scale GW Dynamics ~80 – 100 km

Superpositions of larger- and smaller-scale waves are ubiquitous
- these superpositions are largely unexplored at present

Consider a superposition of

- **a "stable" GW** (a = ½, $Ri_{min} >> 1$),
  with $\lambda_{zGW} = 10$ km

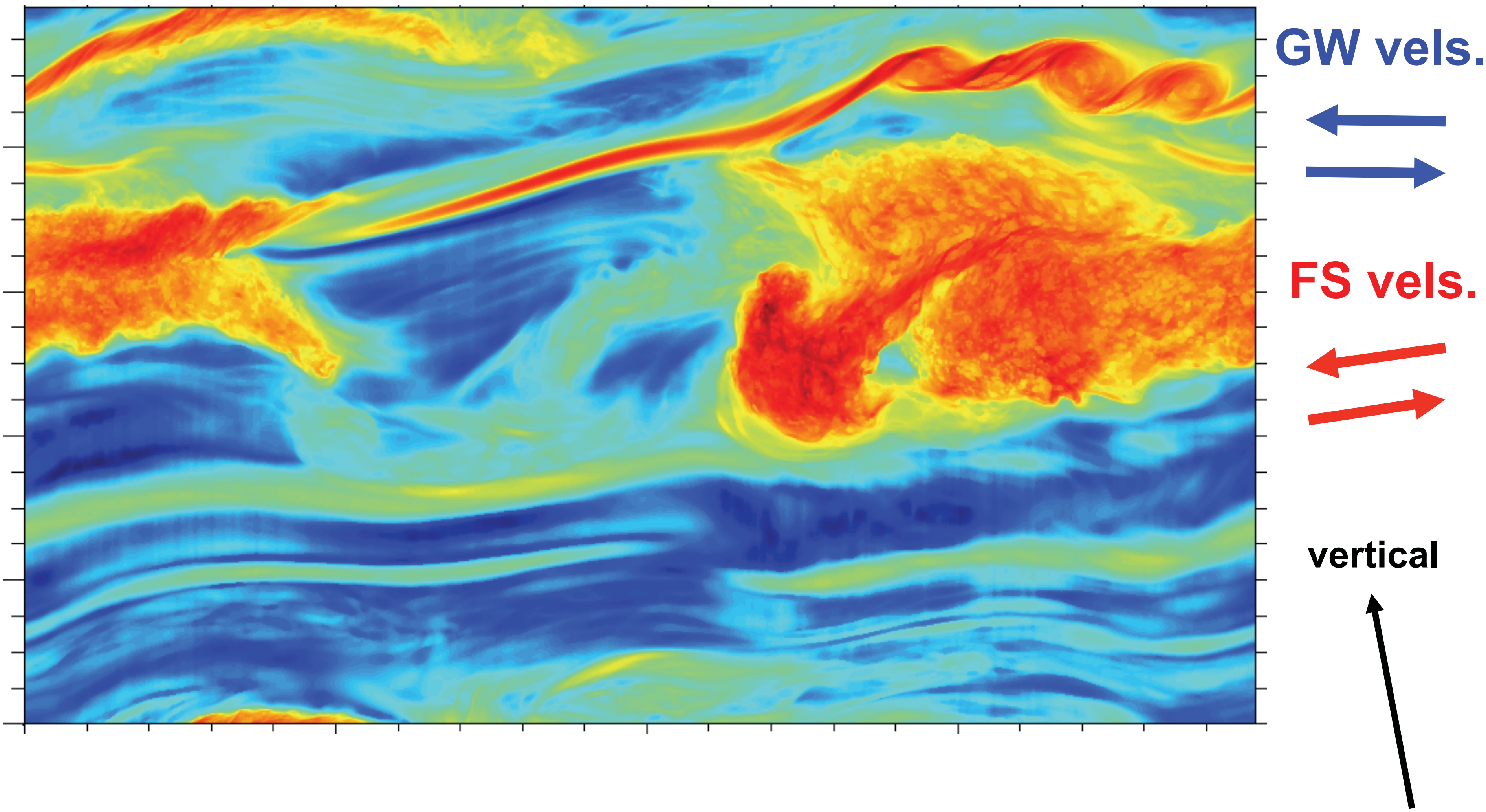
- **a marginally stable fine structure** (FS) with
  $u'_{FS} \sim 2N \sin(m_{FS} z)$,
  $\lambda_{zFS} = 2$ km
  ($Ri_{min} = ¼$)



GW – fine structure superposition (aligned shears)

both GW and fine structure are individually stable

(red is high vorticity)

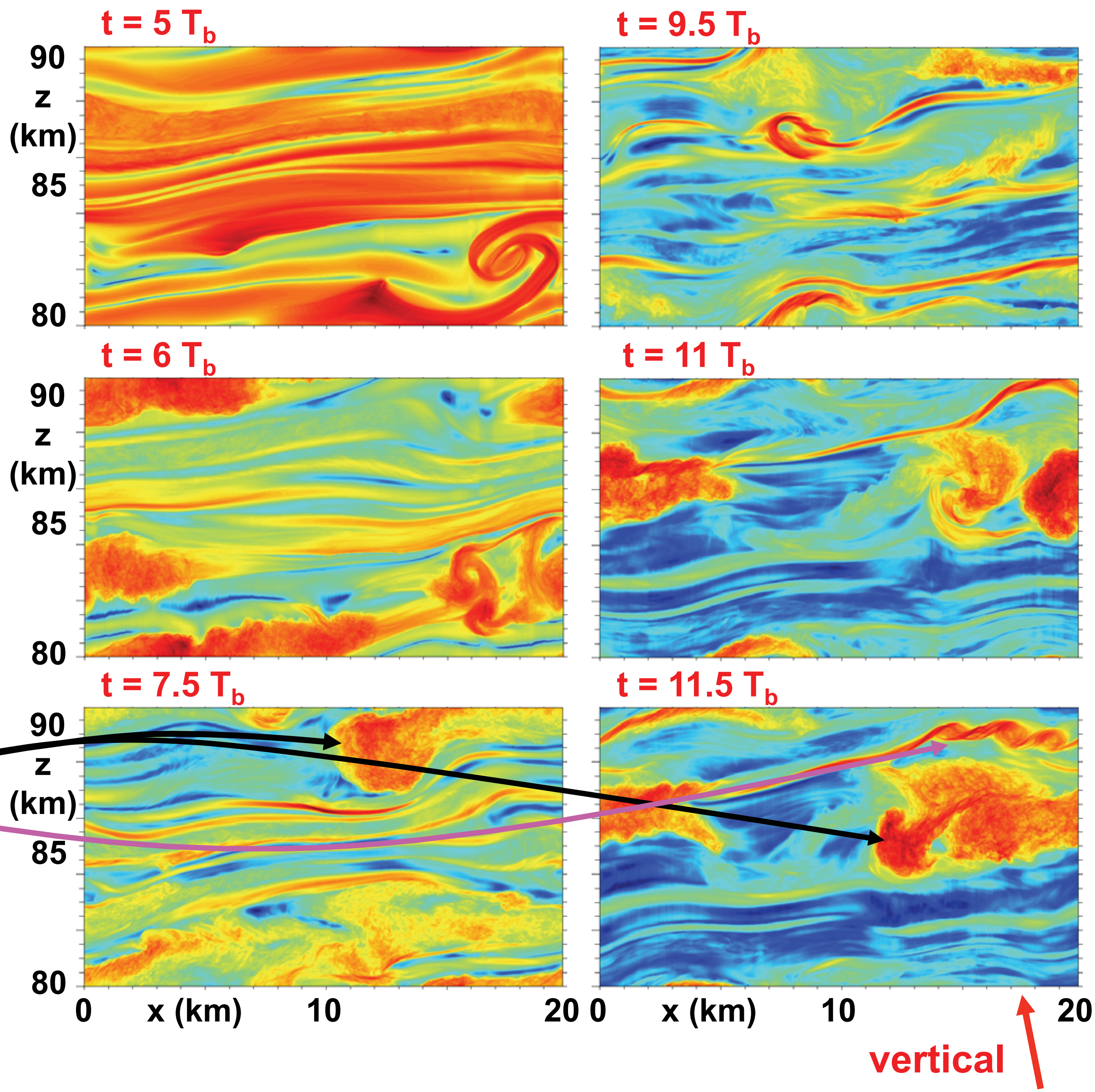


GW – fine-structure interactions at z ~90 km (*Re* ~ 50,000)

energy dissipation rate (ε) in x-z cross sections (along the GW and FS motions)

GW-FS interactions lead to

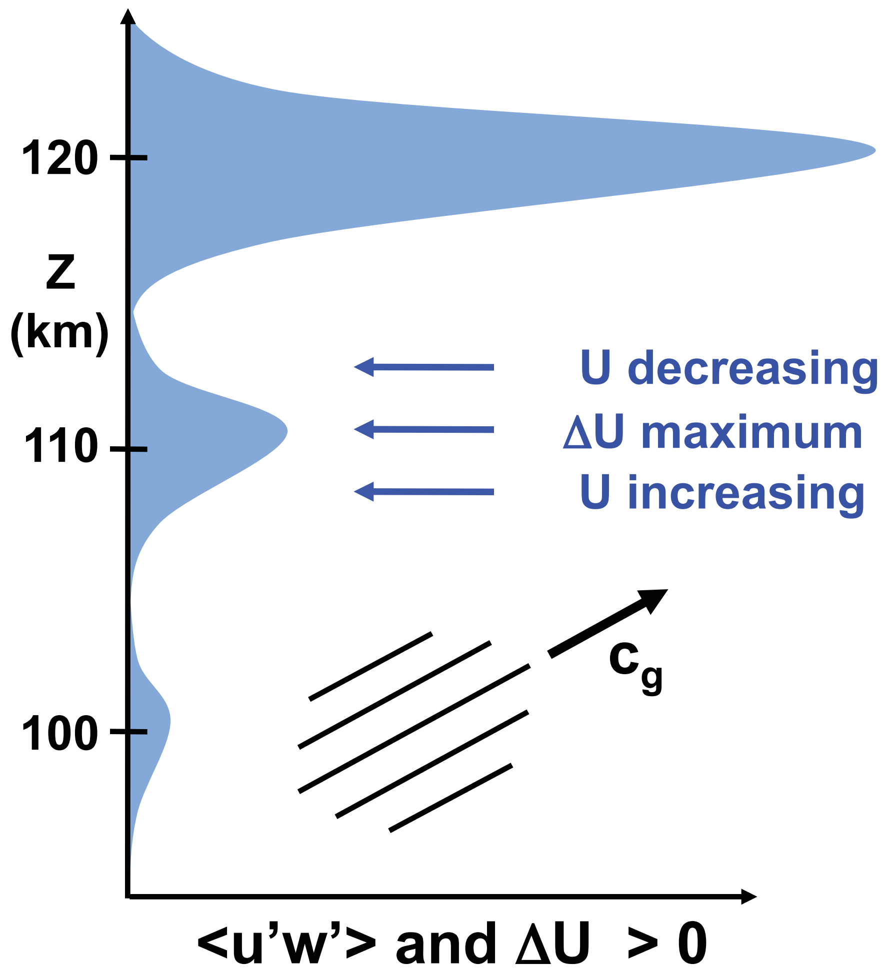
1. strong wave-wave interactions
2. strong, intermittent, GW breaking, KH instability
3. layering of winds, temperatures, and turbulence



2. GW Self Acceleration and Effects

Decreasing mean density

=> - GW amplitudes increase as $a \sim 1/\rho^{1/2}(z)$
- $\Delta U \sim 1/\rho(z)$
- large flow accelerations, altered GW phase structures



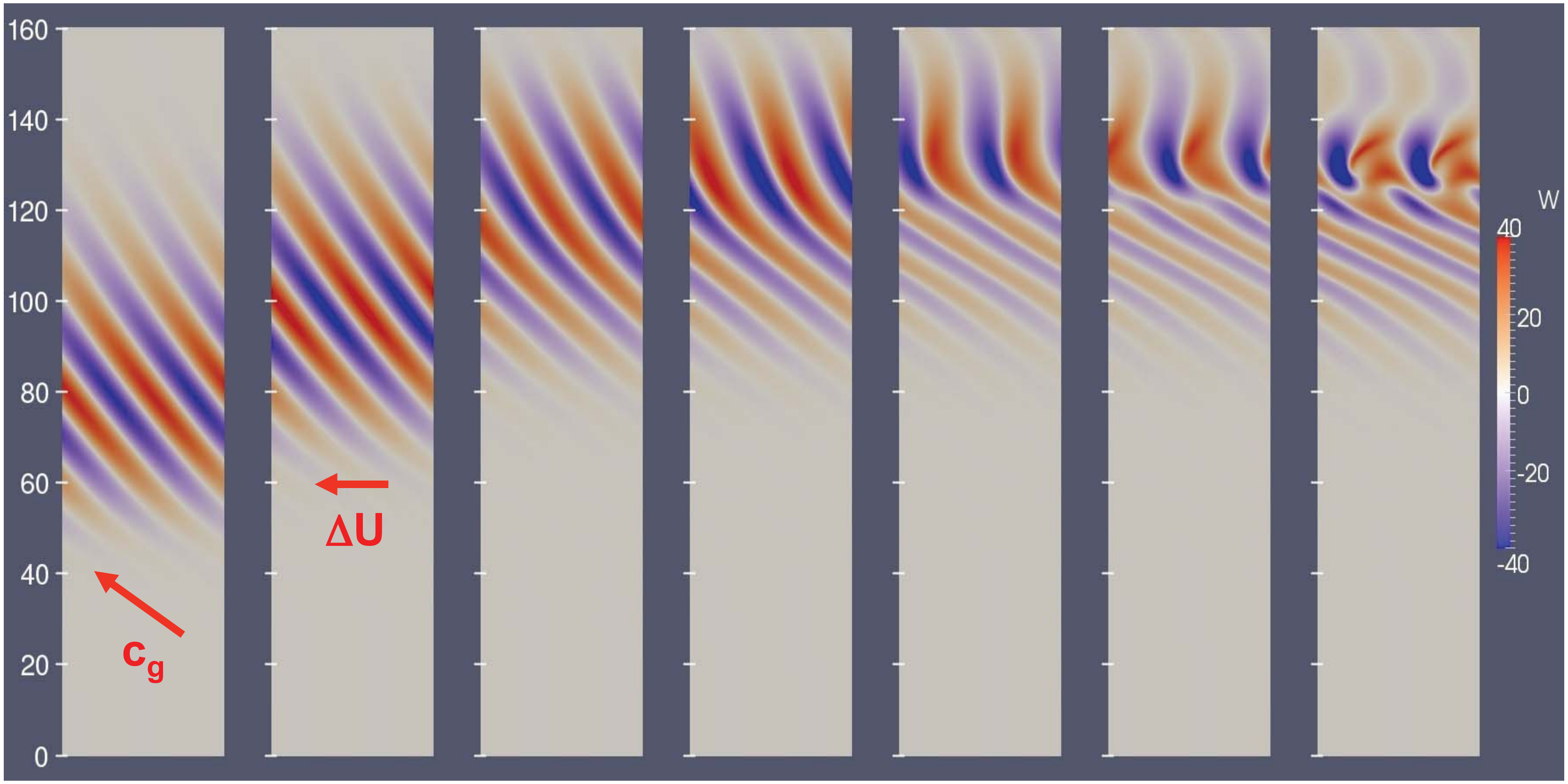
=> self-acceleration & phase distortion

=> leading edge of GW packet accelerates

trailing edge decelerates

"Self-acceleration" of a localized GW packet

=> - steepening phase structures at leading edge
- altered GW group velocities and GW instability



Δt ~ 5 GW periods

GW with initial $\lambda_x = \lambda_z = 20$ km, $N = 0.02\ s^{-1}$, $\omega = N/1.4$

3. GW instability in the TI

large-scale GWs

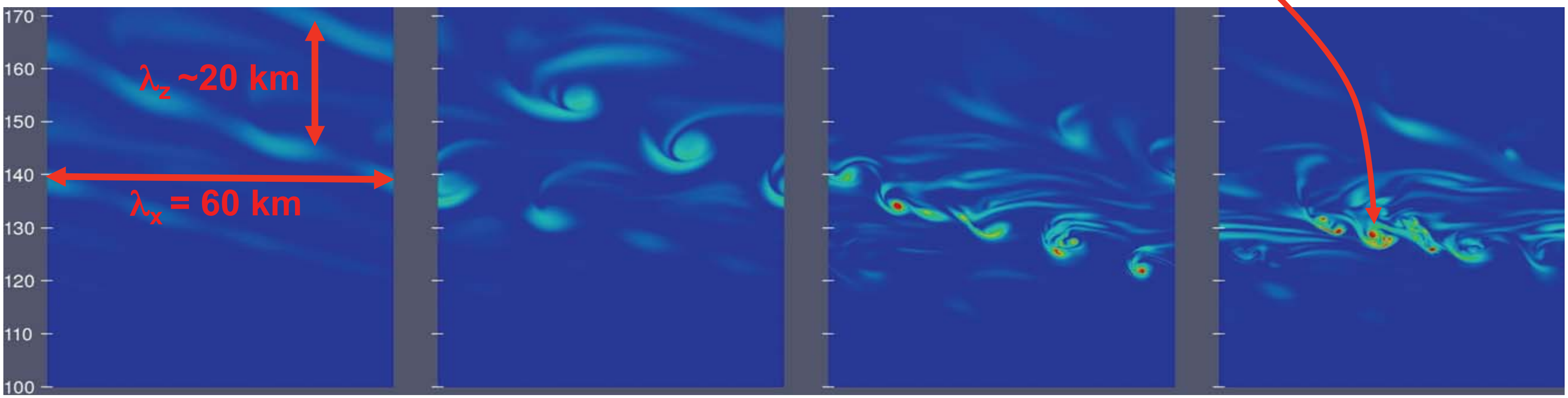
- penetrate to high altitudes
- achieve large amplitudes
- maintain moderate Reynolds numbers

$\Rightarrow$ Momentum transport and instabilities
<u>both</u> play large roles

GW breaking @ z ~ 100-160 km assuming constant U(z)

u' ~ c-U ~ 50 m/s, ω ~ N/3, Re ~10^3 at z ~160 km

minimum scales of turbulence ~1 km (130 km)



=> - turbulence should be expected intermittently well above ~100 km when GW amplitudes and wavelengths are sufficiently large

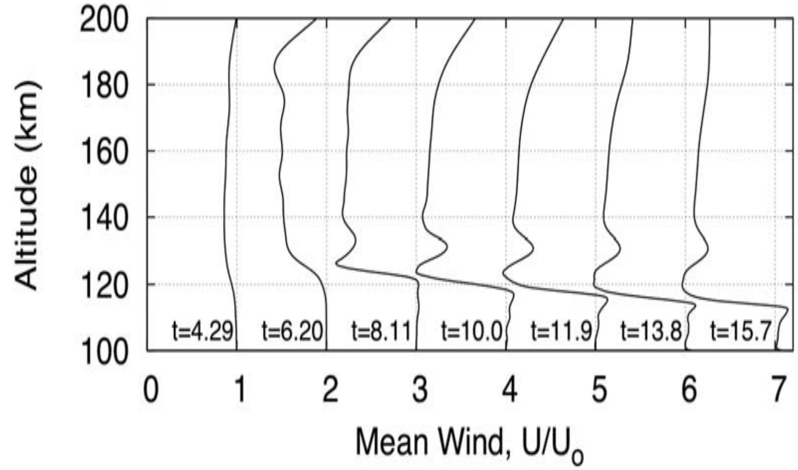
- turbulence scales are much larger than we see in the MLT due to the larger viscosity and thermal diffusivity and lower *Re*

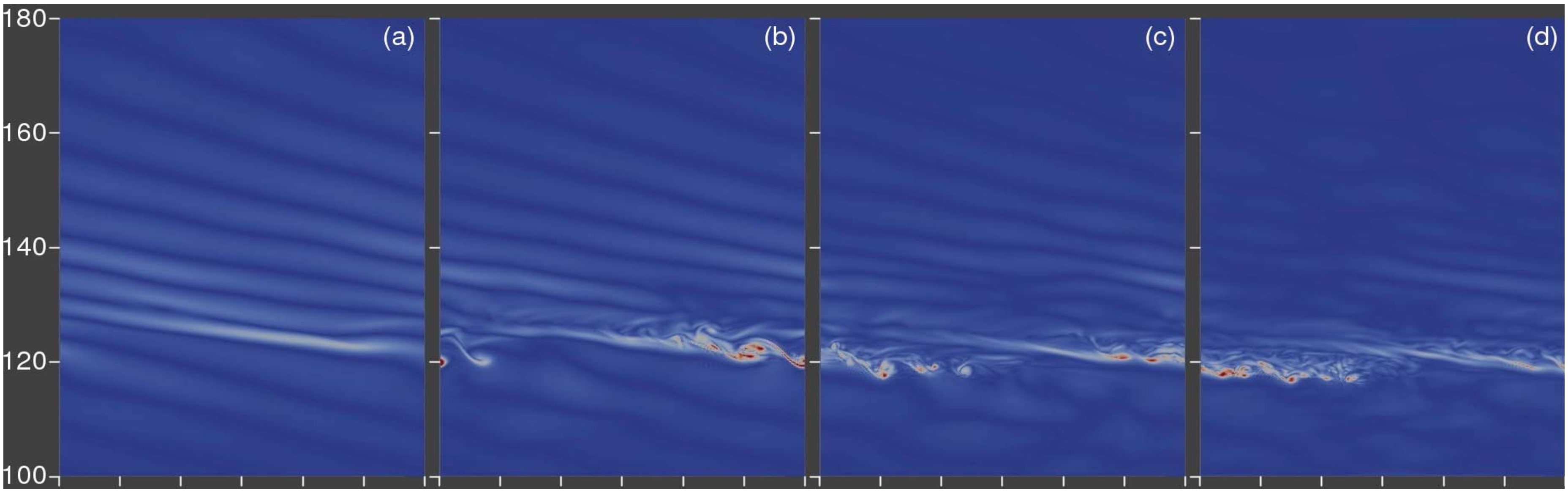
Same GW evolution, but now allowing mean flow changes

this case exhibits large induced mean winds

=> confinement of shears and instabilities to lower altitudes

evolving U(z,t) => accelerations towards GW phase speed





- instability character is now much different, due to GW critical level approach
- turbulence scales are smaller due to lower altitude, higher *Re*

Summary

Current models are now able to address nonlinear dynamics
in the MLT and TI at realistic scales and Reynolds numbers

GW momentum transport, transience, and instabilities all play
major roles in the thermosphere

Multi-scale simulations reveal complex interactions and impacts
on the motion field at large and small scales

Momentum transport by large-amplitude GWs induce strong GW
self acceleration effects at high altitudes

Large-scale GWs can induce instabilities extending well into the
lower thermosphere for sufficient GW scales and amplitudes