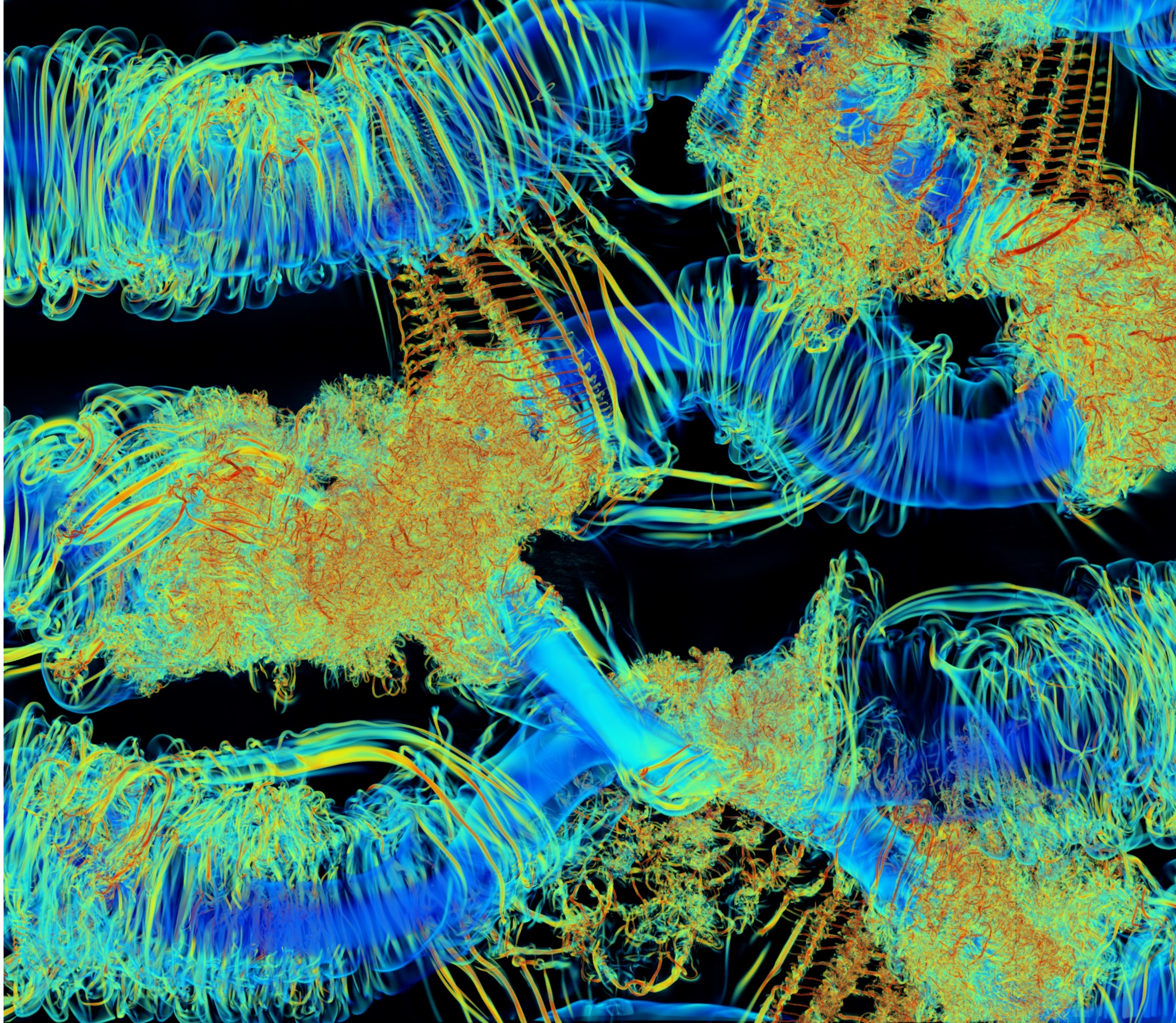
Observations and Modeling of Atmospheric Turbulence Sources

Dave Fritts

and colleagues

**Tom Lund, Ling Wang,
Abhi Doddi, Wenjun Dong,
Tyler Mixa, & Marv Geller**



Outline

- Evidence of nearly continuous turbulence from ~0-100 km
- Evidence of Multi-Scale Gravity Waves (GWs) & Kelvin-Helmholtz Instabilities (KHI) that drive widespread "Sheet & Layer" (S&L) features
- Current Multi-Scale (MS) modeling that approximates GW, instability, and turbulence responses extending from the surface into the thermosphere
  - MS GW breaking that drives S&L structures that induce KHI
  - KHI "tube" & "knot" (T&K) dynamics that drive enhanced turbulence & mixing
- Potential implications for MS GW parameterizations

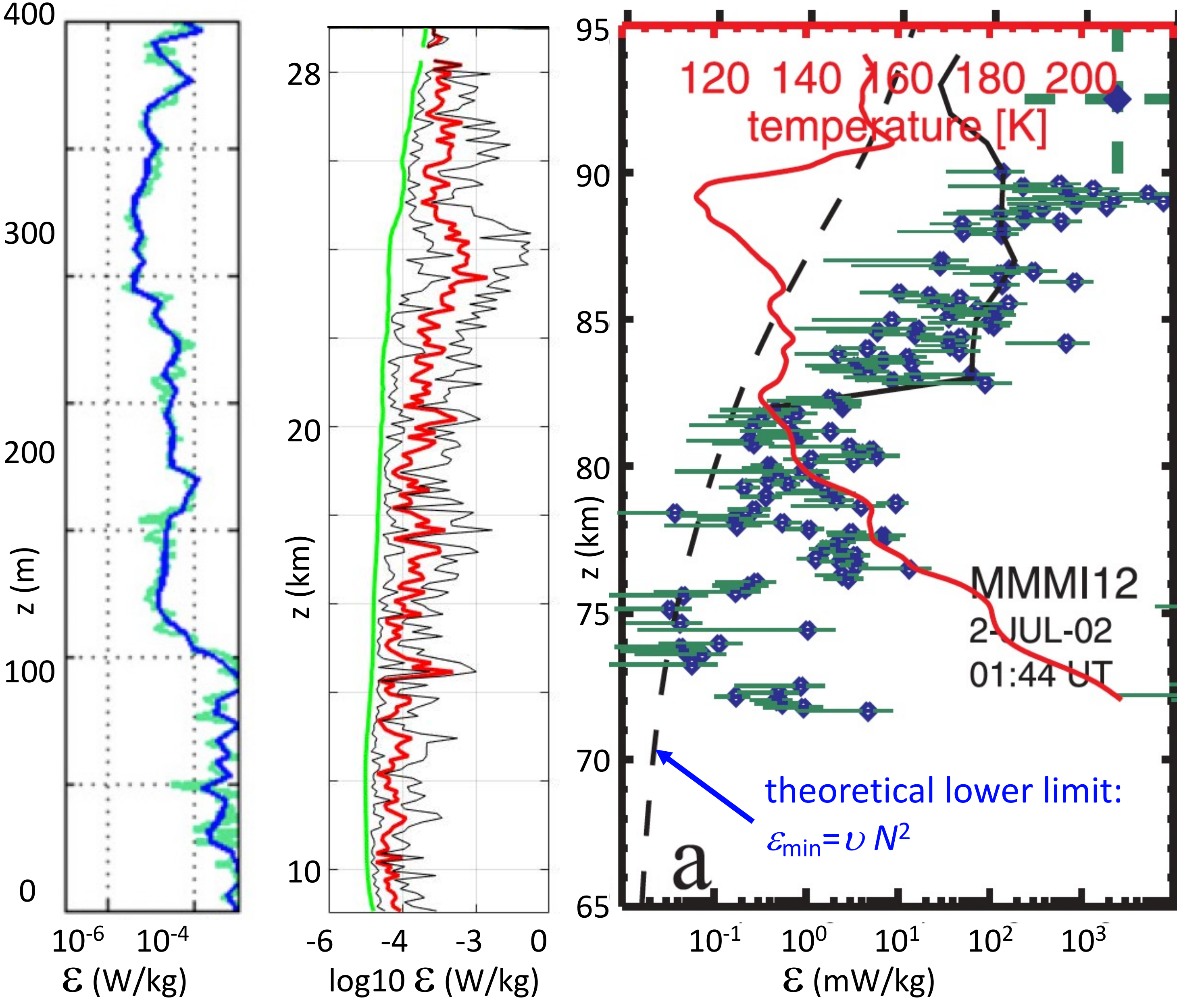
In-Situ Evidence of Turbulence

In-situ measurements reveal turbulence to be nearly continuous in space and time from the surface to >100 km

Left: DataHawk ε profiles (NSF IDEAL)

Center: descending high-res. balloons (AFOSR HYFLITS MURI)

Right: sounding rockets (NASA McWAVE)



Doddi et al. (2021) Doddi & Lawrence (2023) Rapp et al. (2004)

Evidence of ubiquitous MS GW and KHI dynamics

Grand Junction, CO
Jan 2018
U* and *θ

Radiosondes provide evidence of superposed GWs at essentially all altitudes and times

Specific evidence of S&L features are seen in the troposphere and are nearly ubiquitous in the stratosphere

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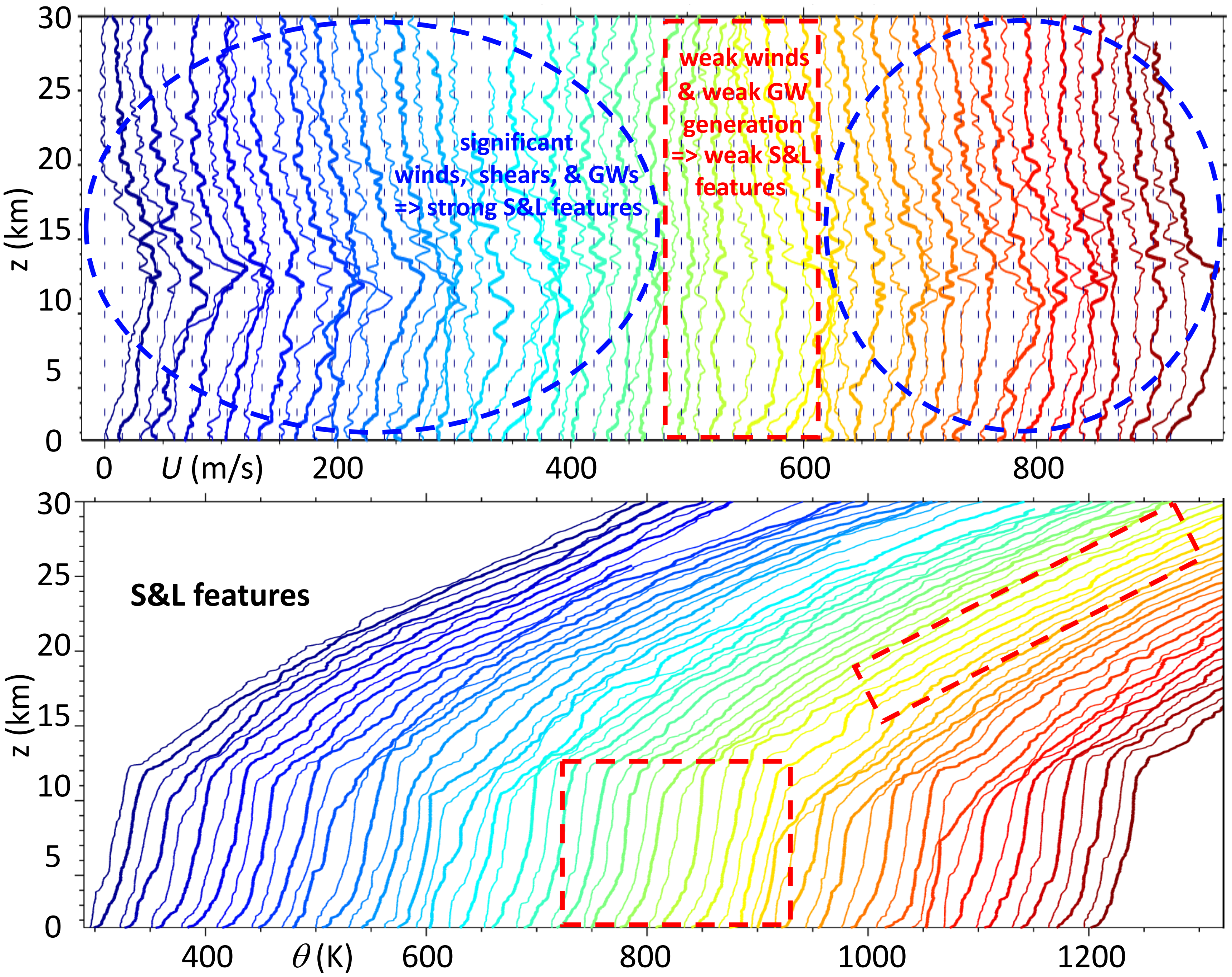
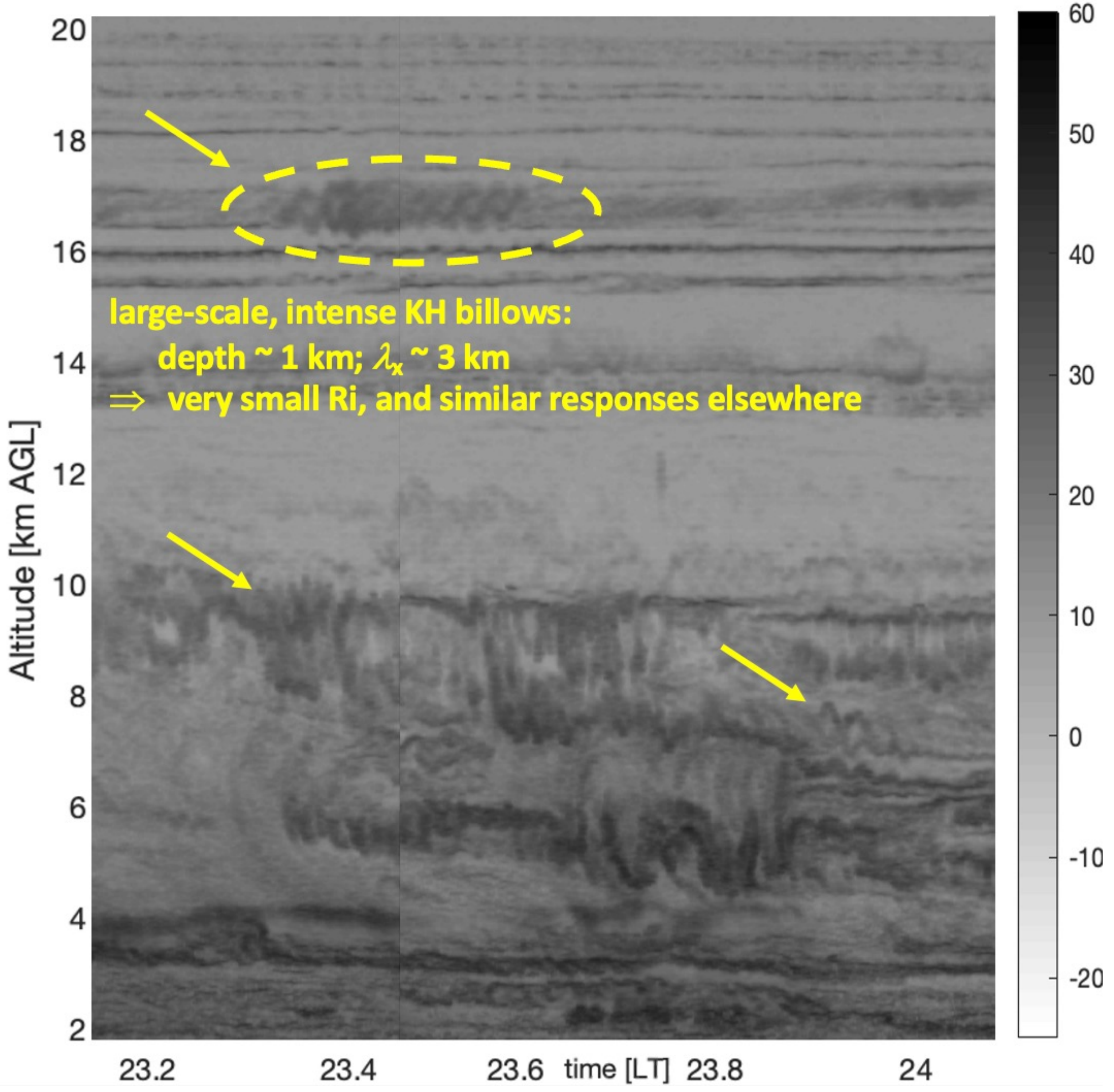
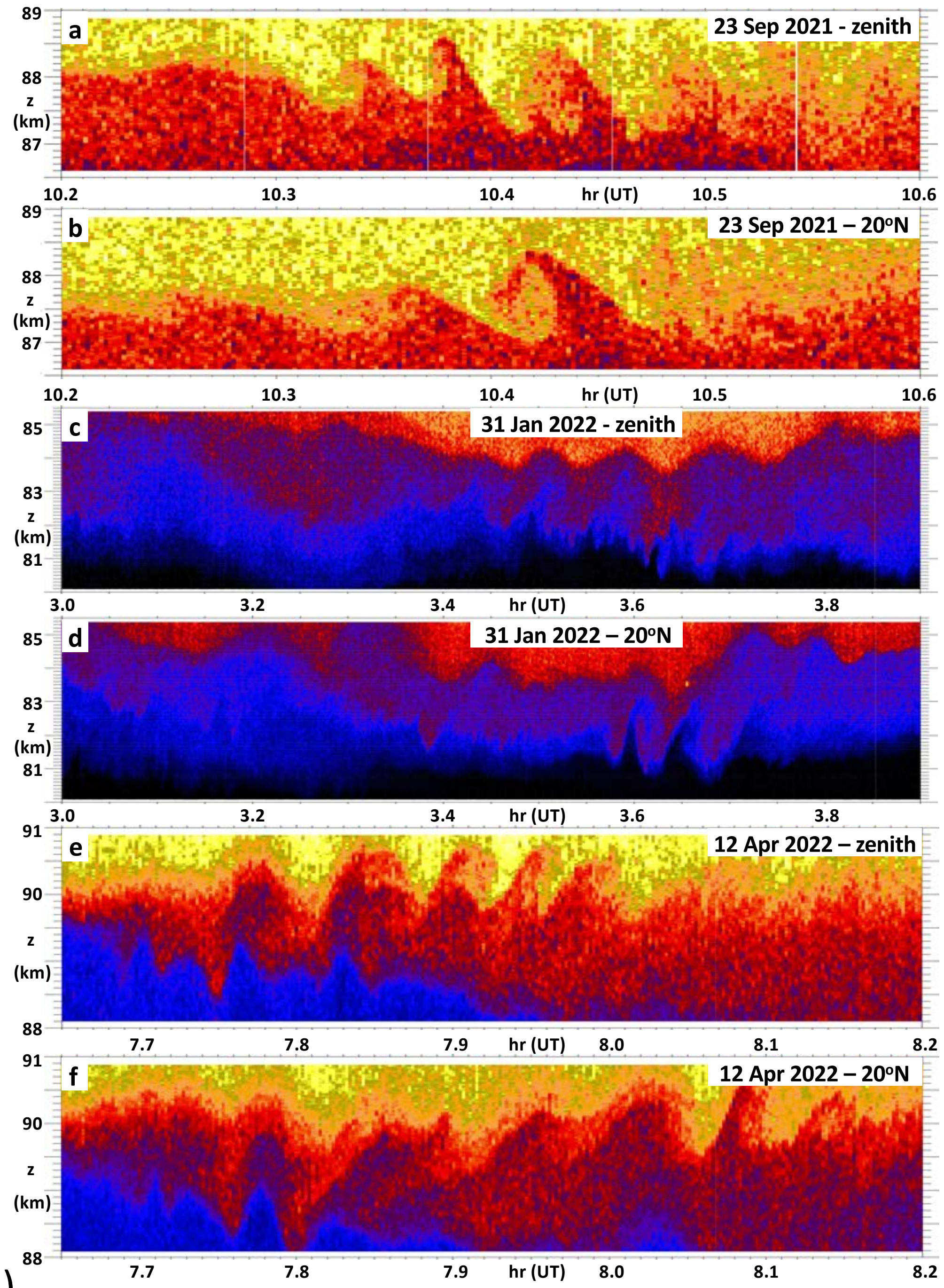
MS GWs apparently account for the S&L features



KHI MS GW environments seen in MU radar and PFRR Na lidar profiling



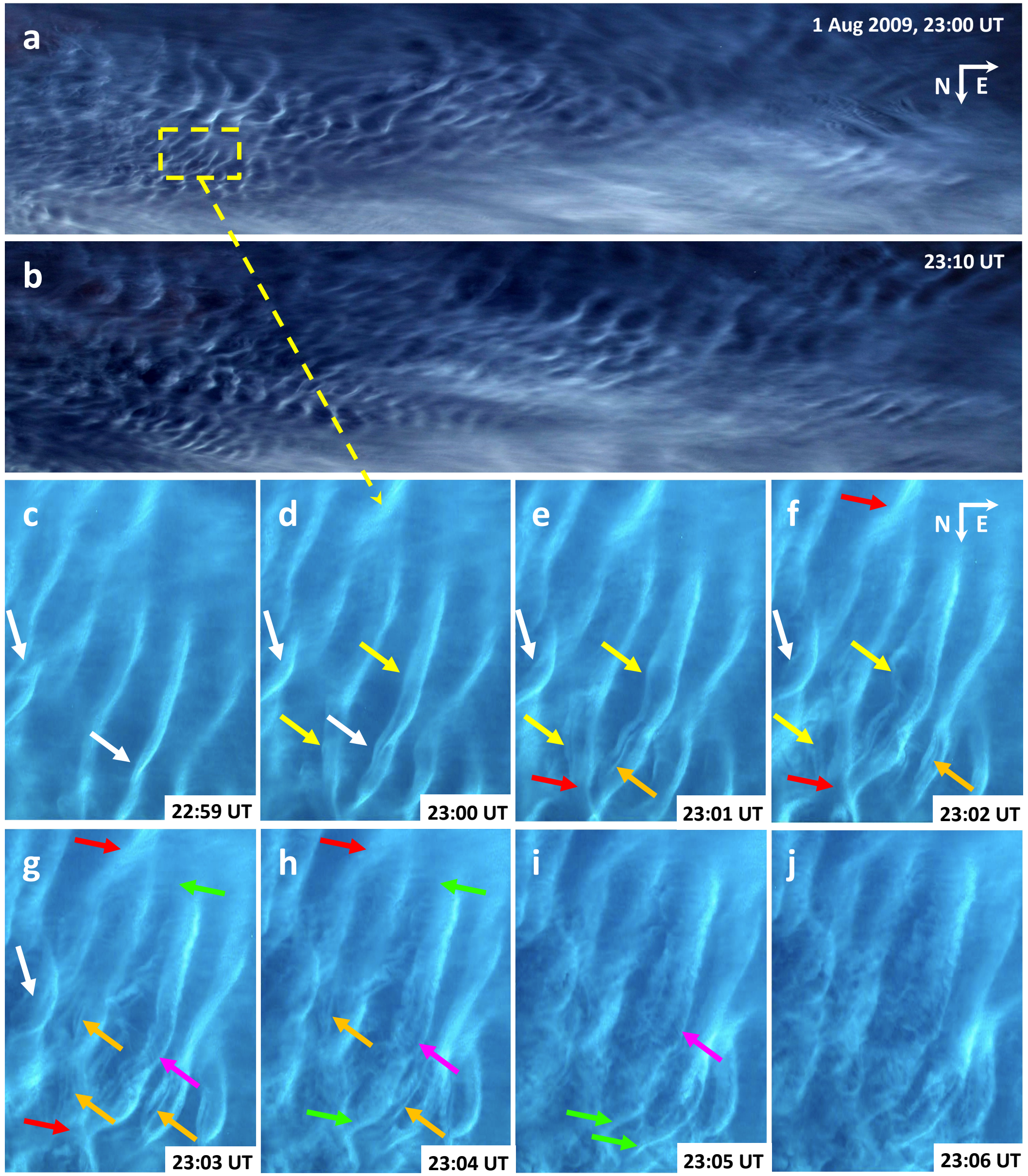
Fukao & Luce (2011)



Fritts et al. (2023a)

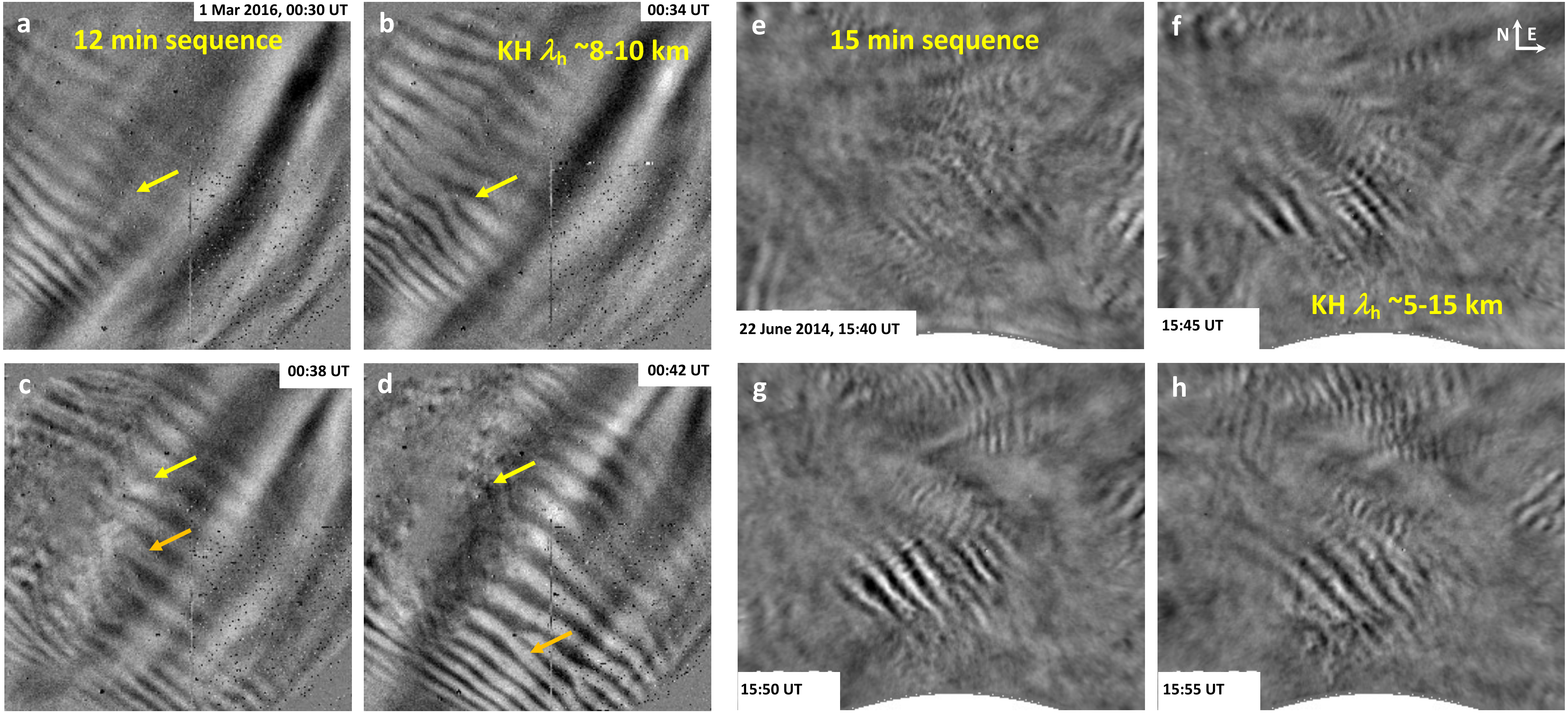
Evidence of ubiquitous MS GW and KHI dynamics - PMC imaging over Scandinavia from Germany (24 June 2009) & Trondheim (01 Aug 2009)

KH λ_h ~3-5 km



G. Baumgarten movies and imaging in Fritts et al. (2023a)

Further evidence of ubiquitous MS GW and KHI dynamics - OH "difference" imaging over the Andes Lidar Observatory (1 March 2016) & Lauder, NZ (22 June 2014)

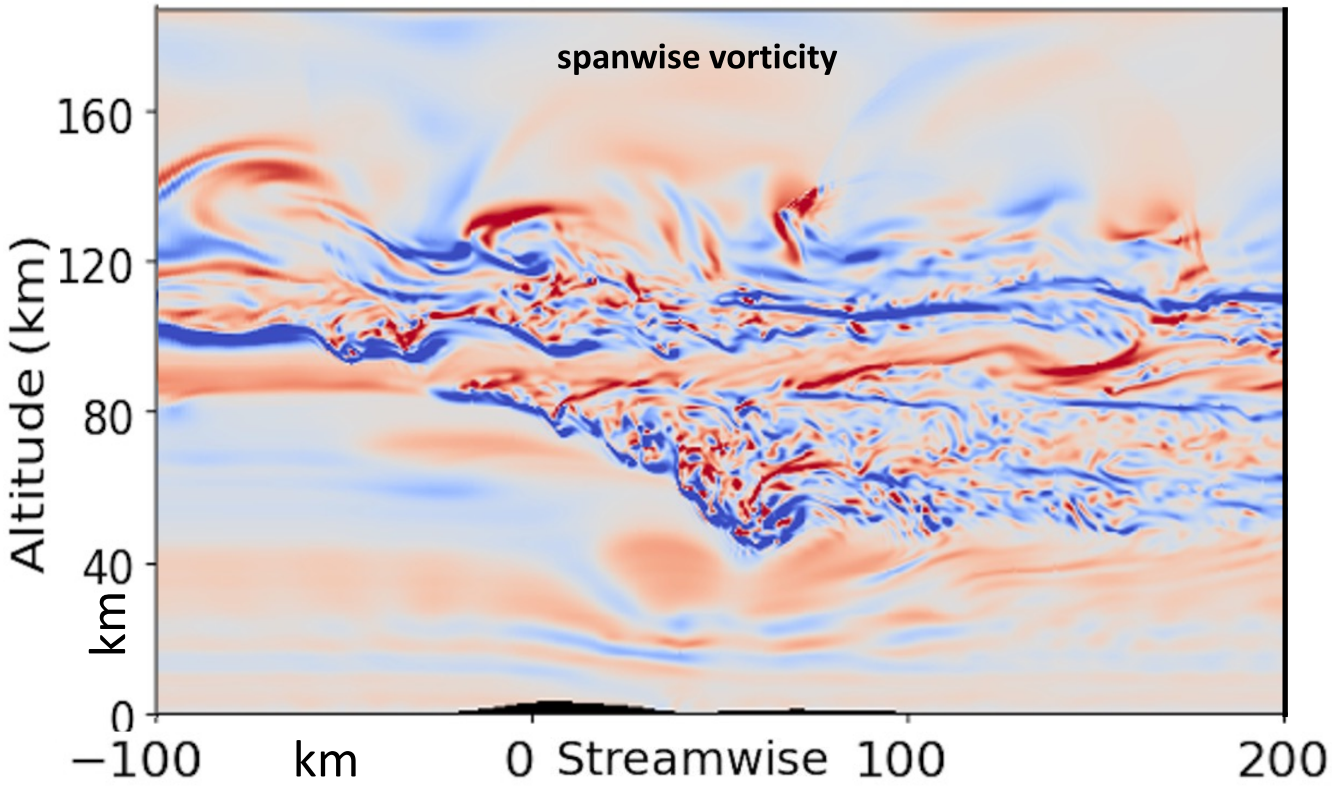


Fritts et al. (2023a)

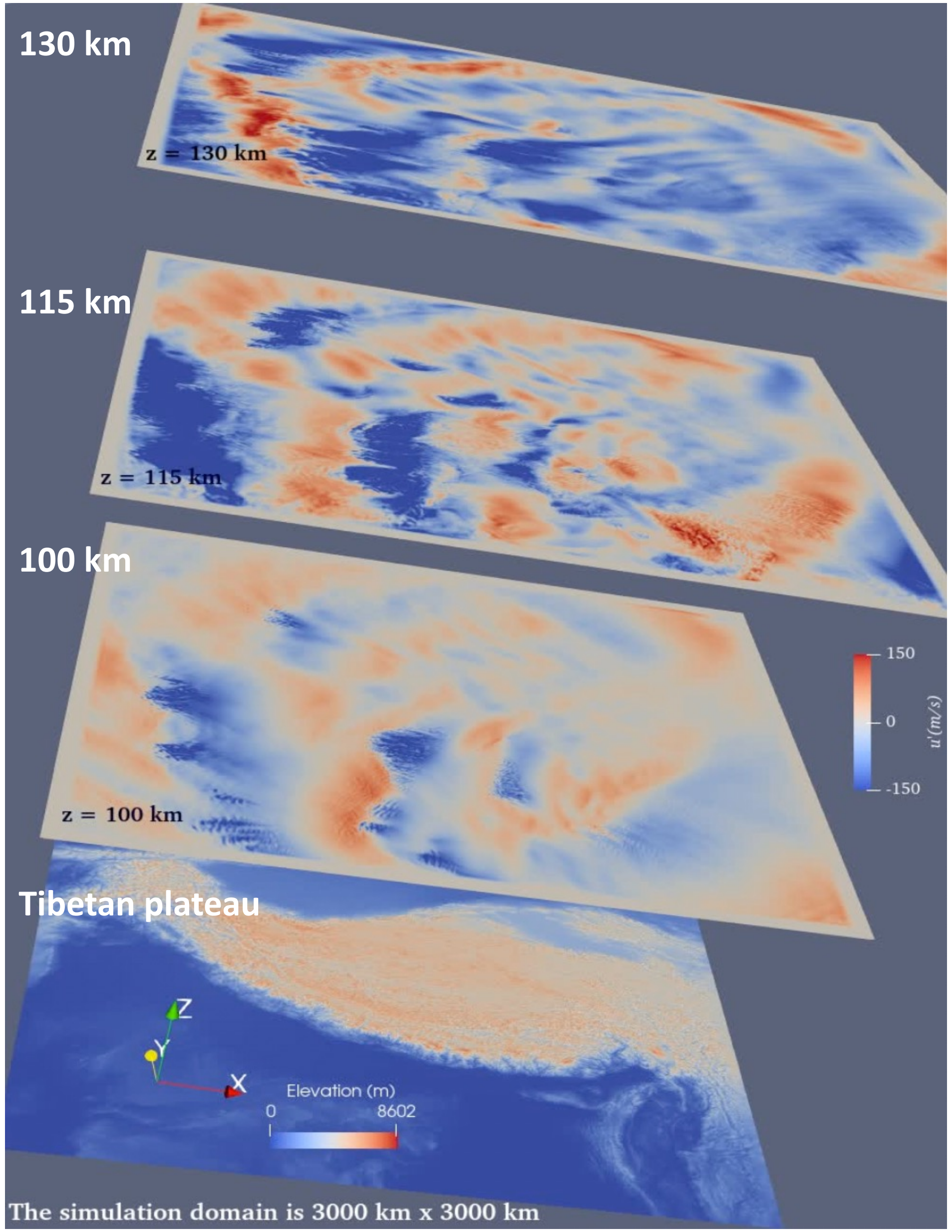
Complex Geometry Compressible Atmosphere Model (CGCAM)

- Mountain wave (MW) modeling indicates turbulence extending to >115 km

- MW breaking drives secondary GWs (SGWs) extending to ~180-400 km in recent applications



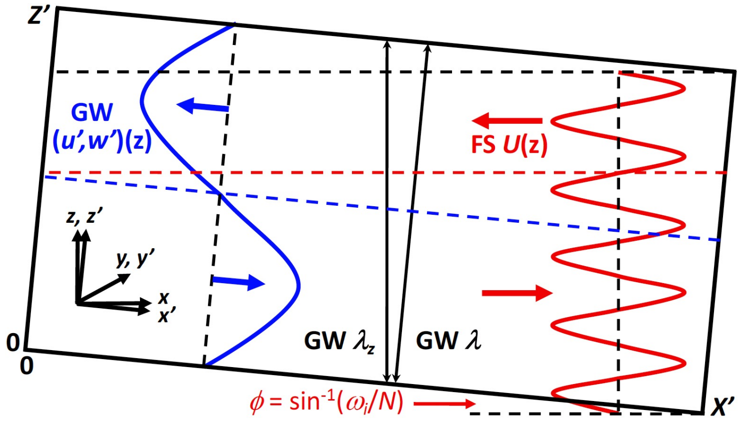
Lund et al. (2020)

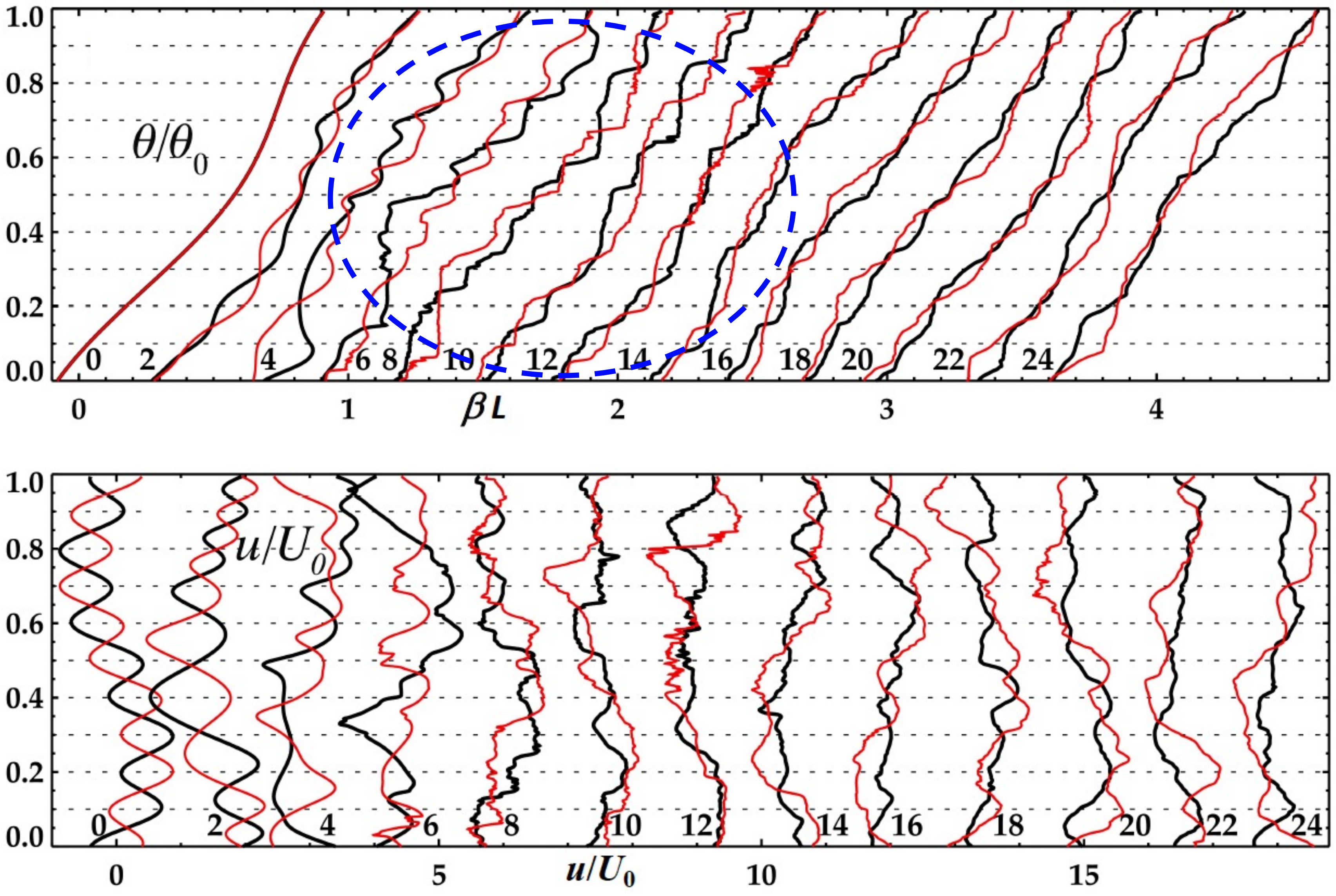


Dong et al. (2023)

Idealized MS GW DNS yield complex GW fields that induce S&L formations

- MS GW breaking
- larger- and smaller-scale induced KHI on highly stratified and sheared sheets
- "sheet and layer" (S&L) structures are strong during active GW breaking



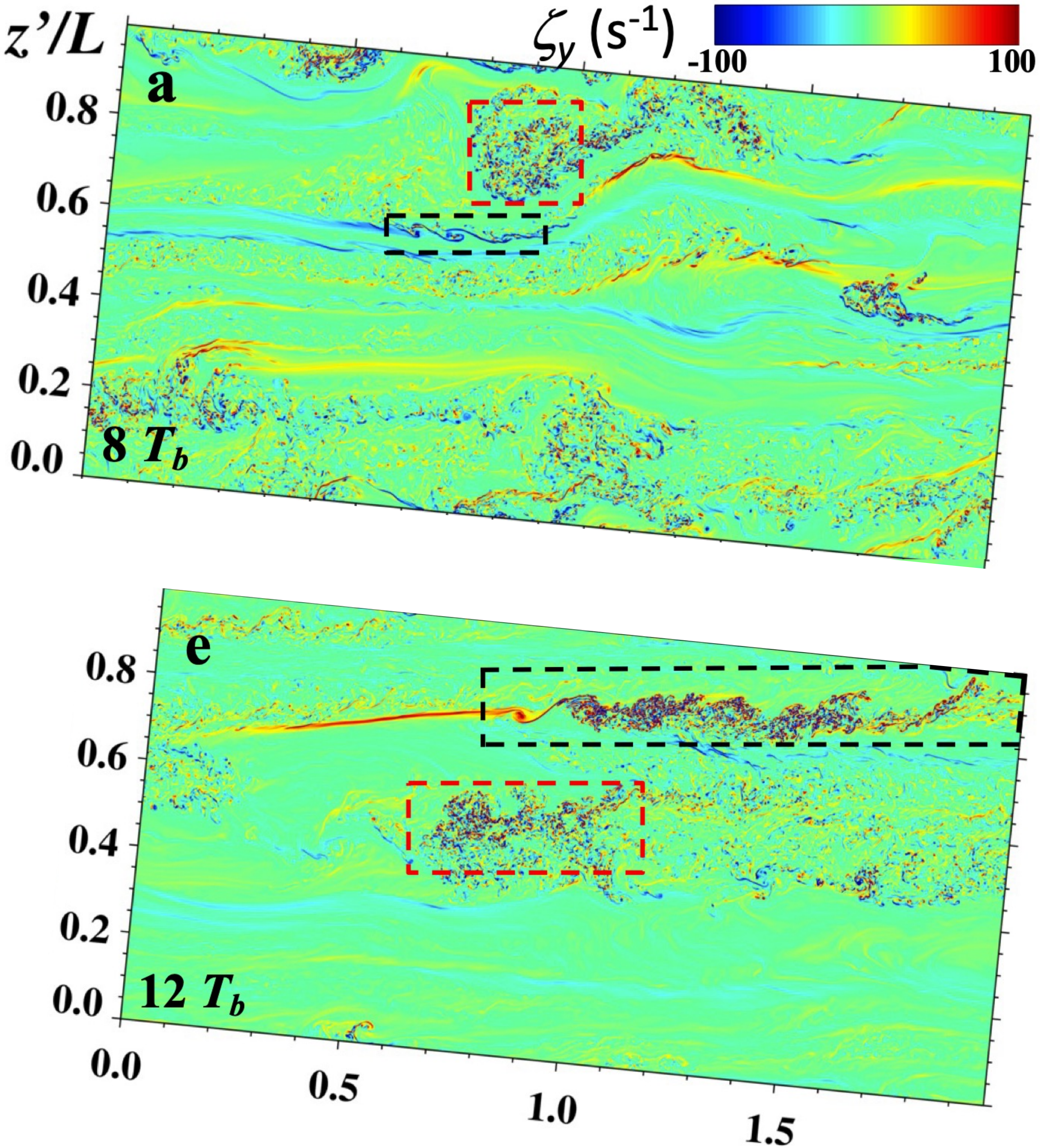


Fritts et al. (2023b, JAS)

This DNS yields complex GW fields shown at a 4 T_b spacing in ζ_y

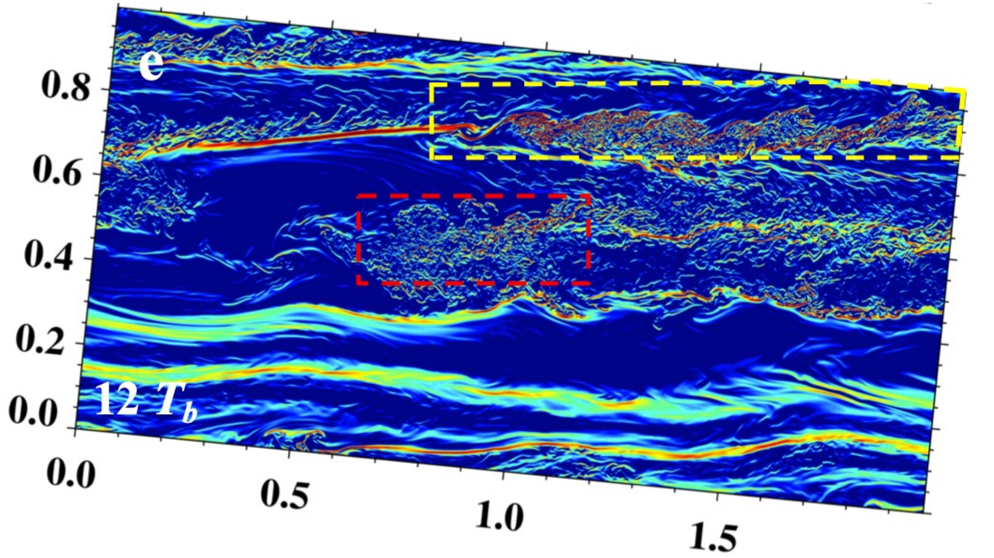
- MS GW breaking (red regions) drives "sheet and layer" (S&L) structures as seen in atmospheric profiling

- large- and small-scale KHI (black regions) arise highly stratified & sheared sheets and can become intense, as seen in atmospheric profiling

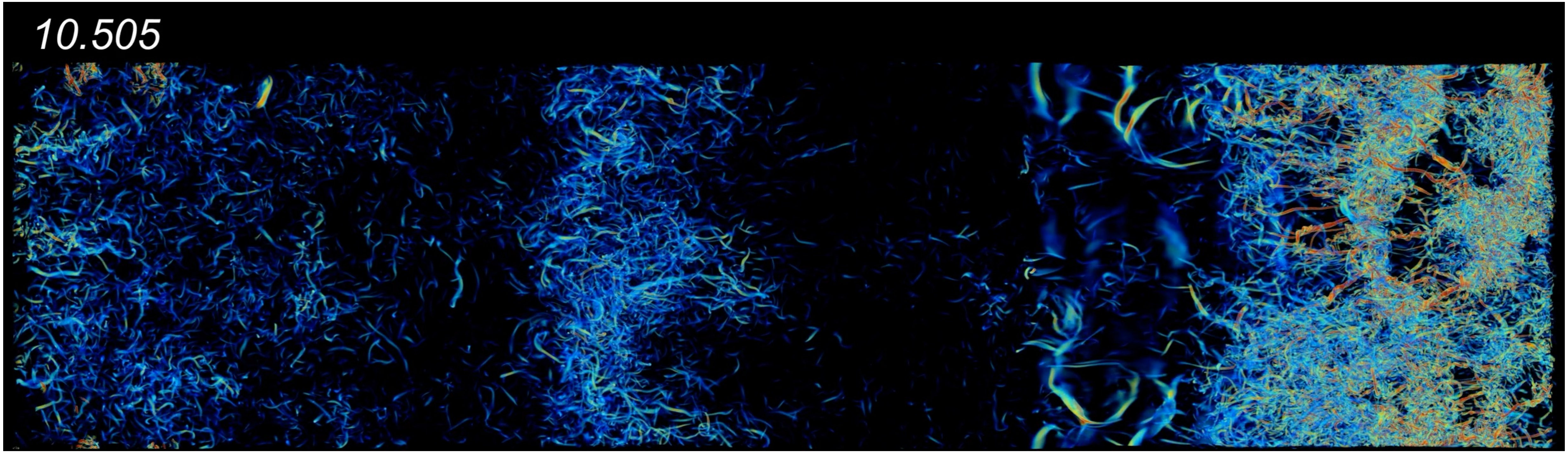


Fritts and Wang (2023, JAS)

MS GW DNS yield intense, large-scale KHI that exhibit "tube" and "knot" (T&K) dynamics

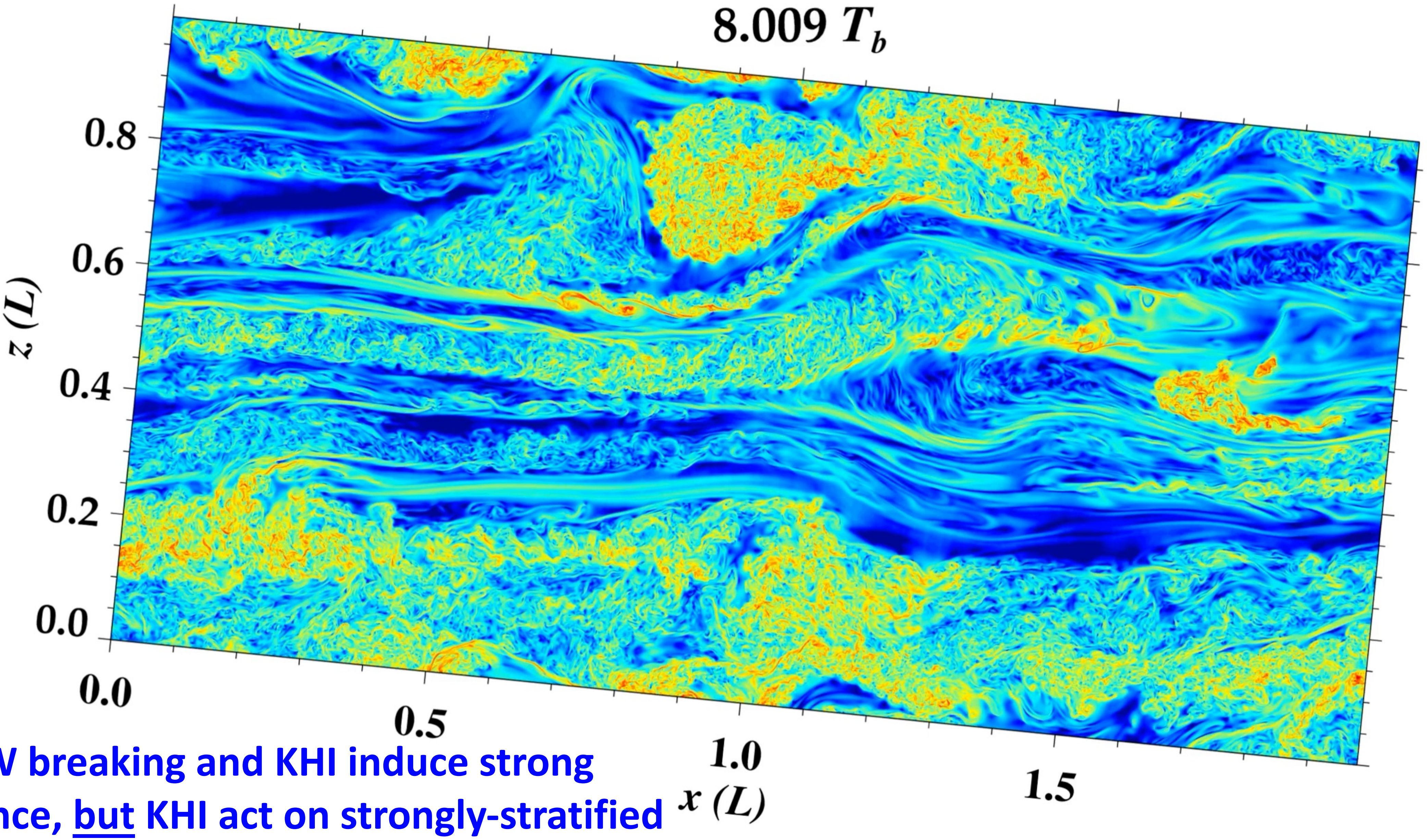


These now appear to be widespread in atmospheric observations, but are not addressed in any current parameterization of GW momentum deposition and mixing



Fritts and Wang (2023, JAS)

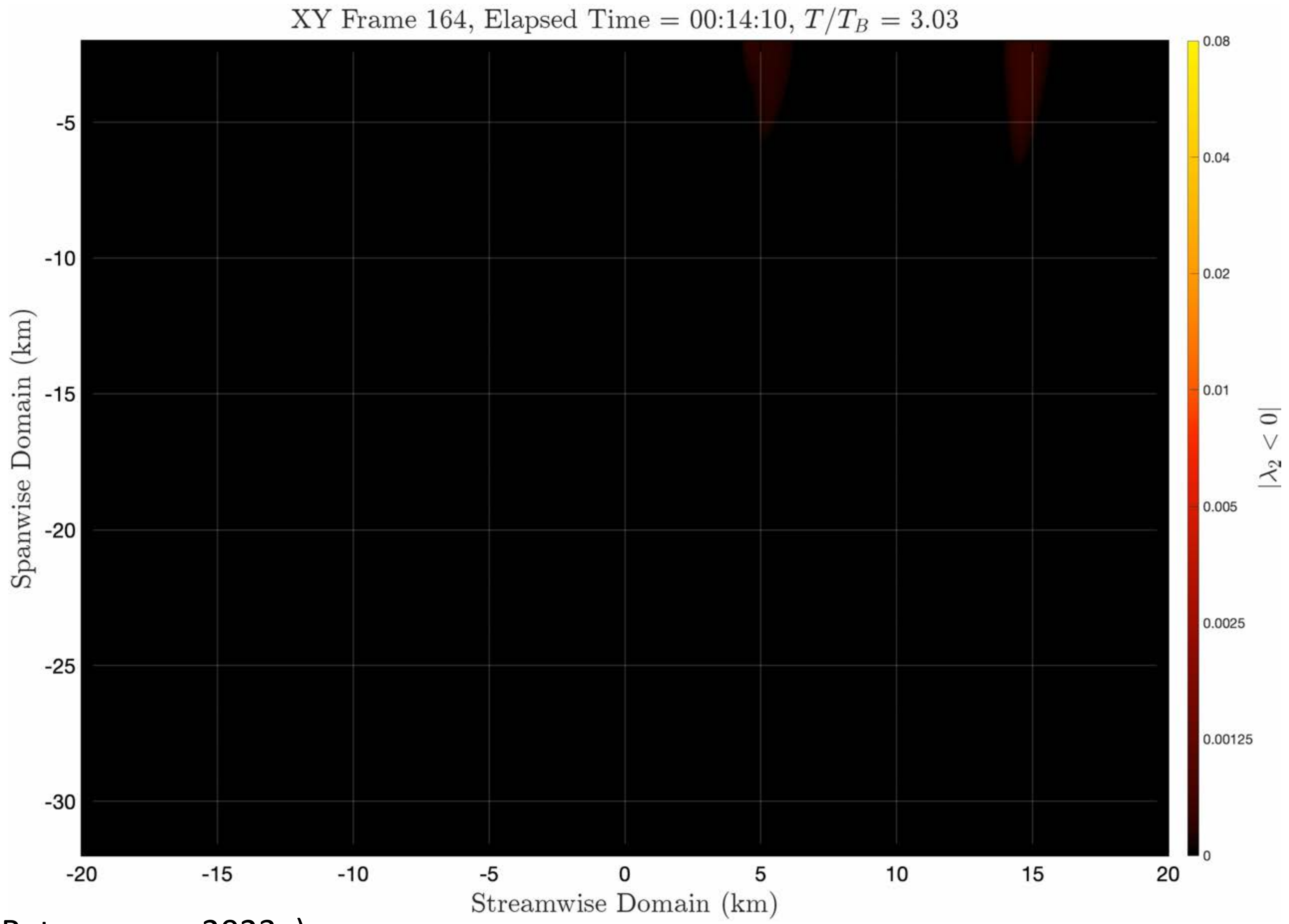
Idealized MS GW DNS yields complex GW fields: $\log_{10}\varepsilon\,(x,z)$ from 8-23 T_b



Both GW breaking and KHI induce strong turbulence, <u>but</u> KHI act on strongly-stratified layers, thus may contribute stronger mixing

CGCAM Modeling Reveals Turbulence Sources to be Active into the Thermosphere

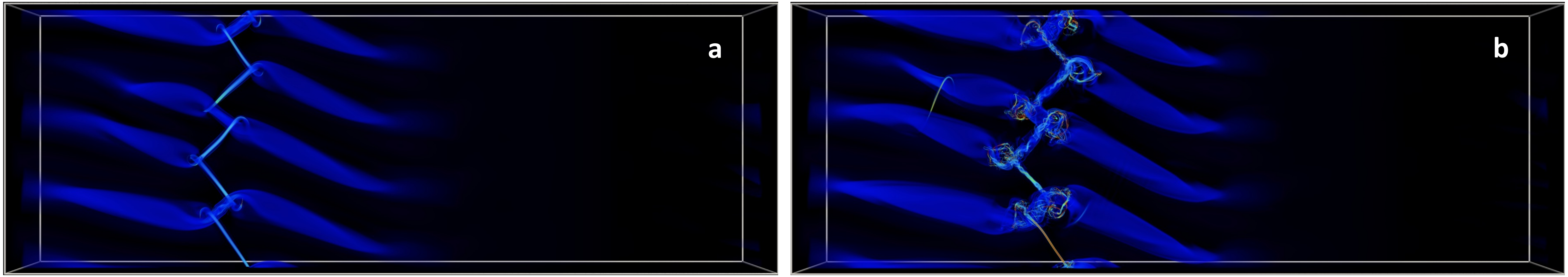
- KHI modeling of an observed event at ~103 km reveals strong turbulence



movie spans 2 T_b

Mixa et al. (JGR, to appear, 2023a)

Spectral Atmosphere Model (SAM) enables GW modulation of a stratified shear layer that reveals KHI T&K feature evolutions that compare well to airglow imaging



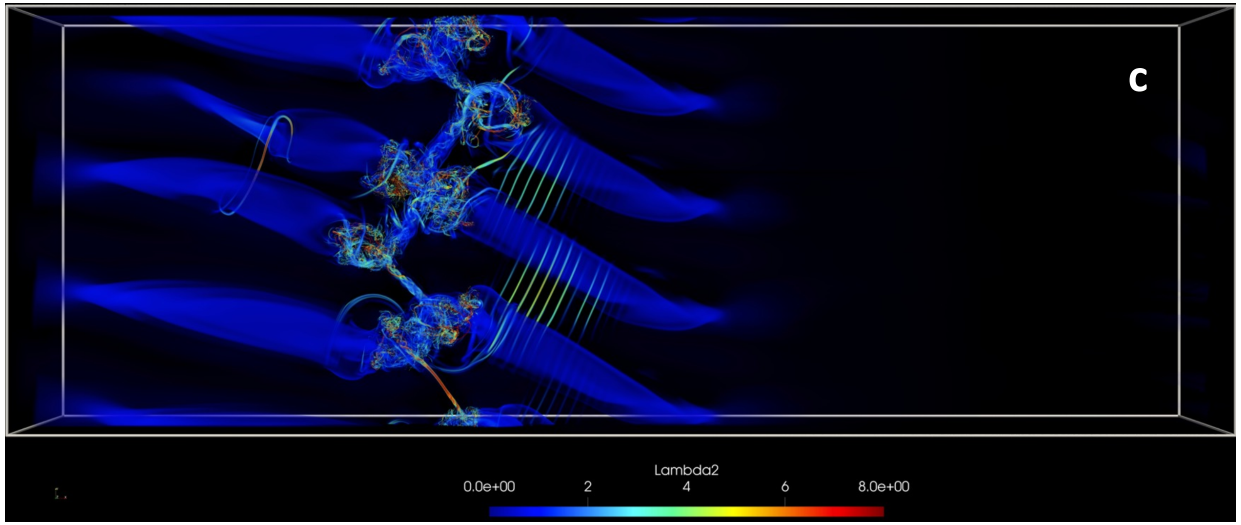
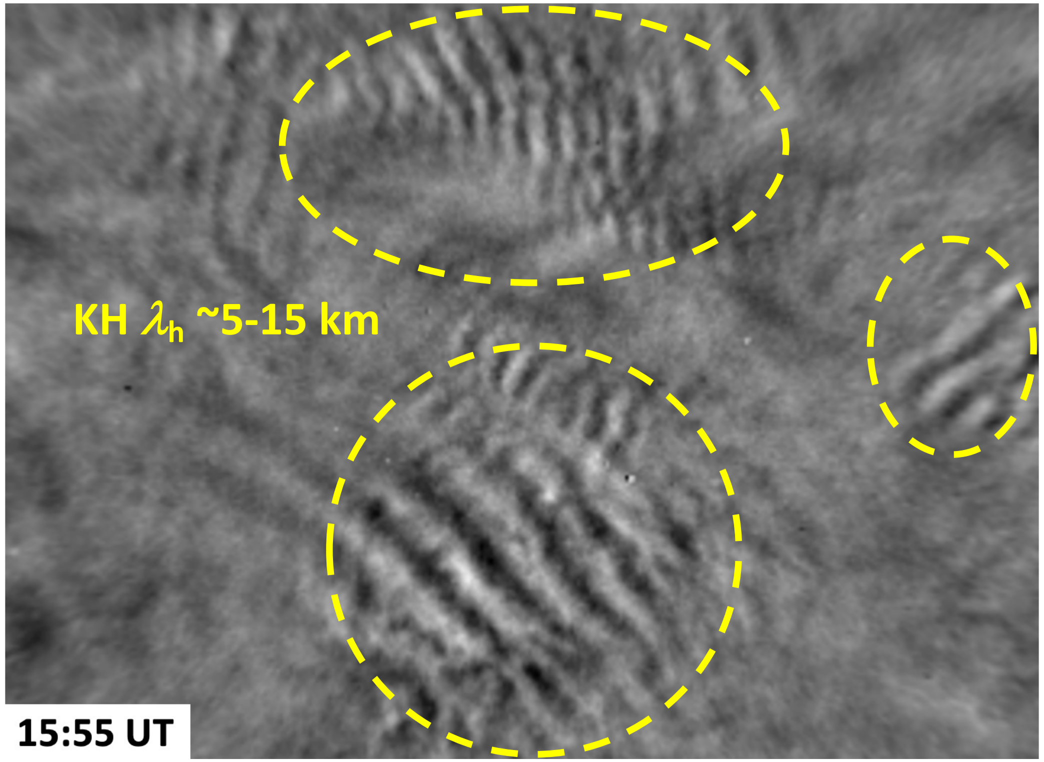


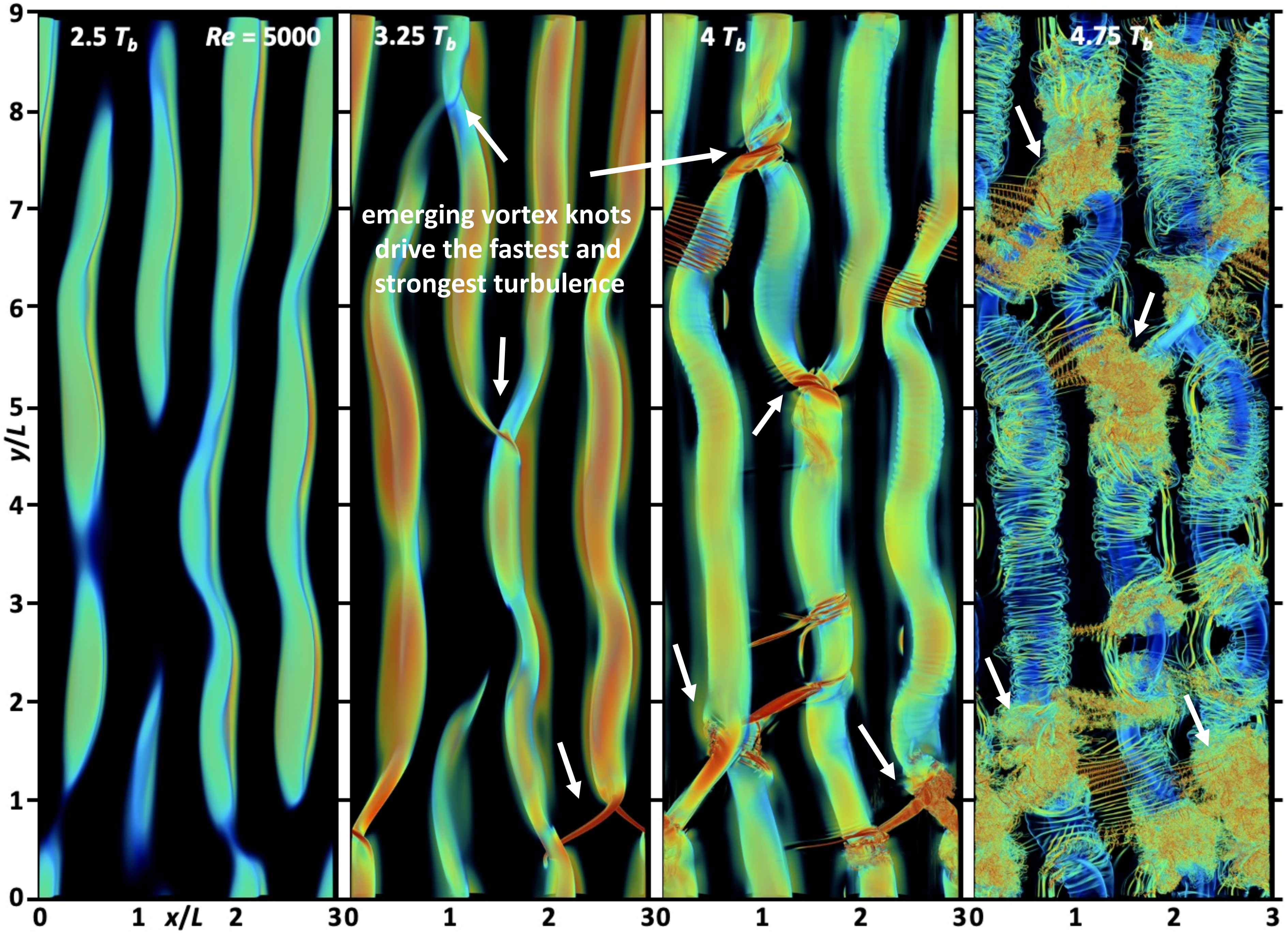
image sequence spans 0.55 T_b, occupies only a portion of the GW phase

Doddi et al. (JFM, to be submitted, 2023)



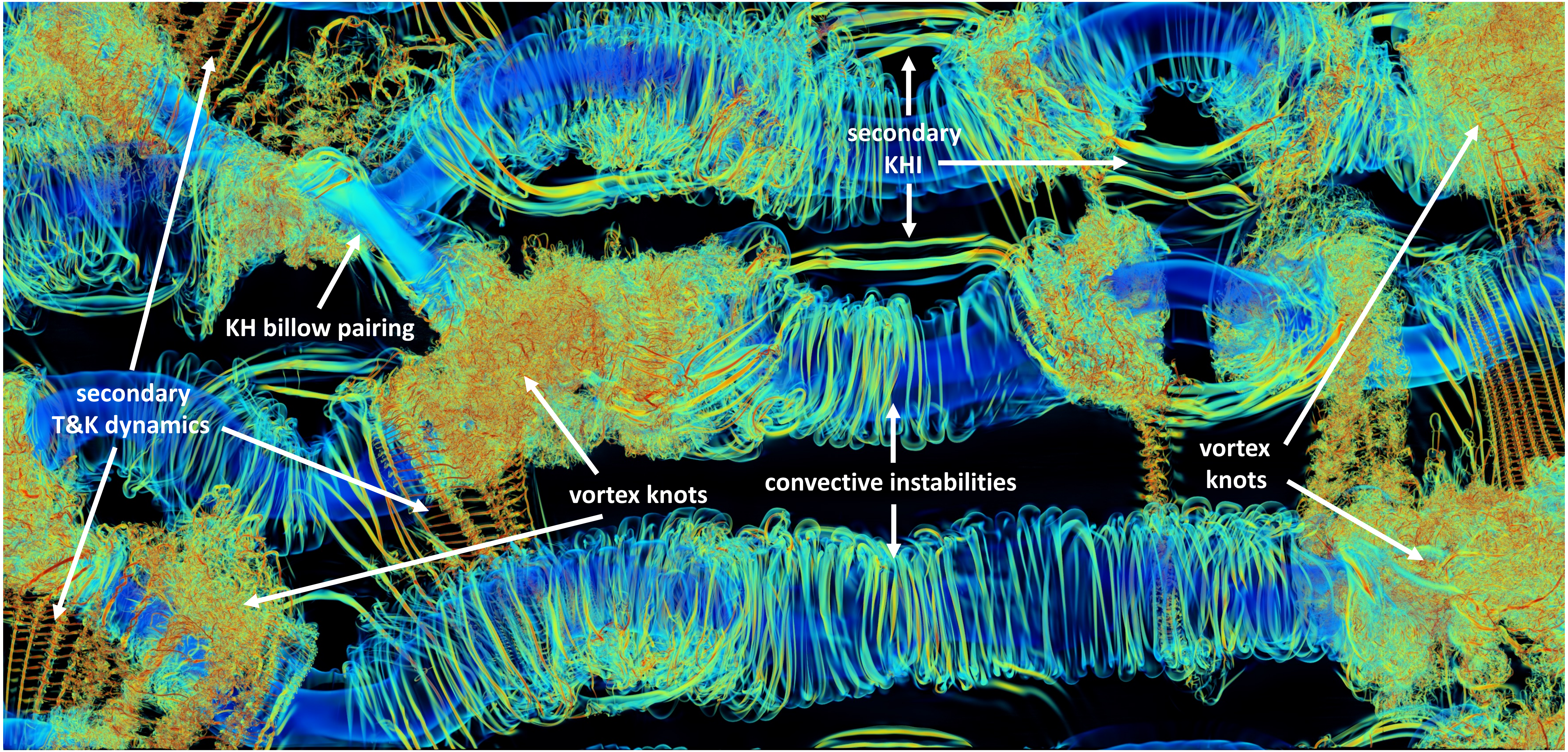
Idealized KHI T&K dynamics

- periodic domain
- 3 or 4 KH billows arise from noise seed
- Re=5000, Ri=0.1 enables strong T&K dynamics
- mis-aligned billows drive strong “knot” turbulence transitions
- other transitions are much weaker

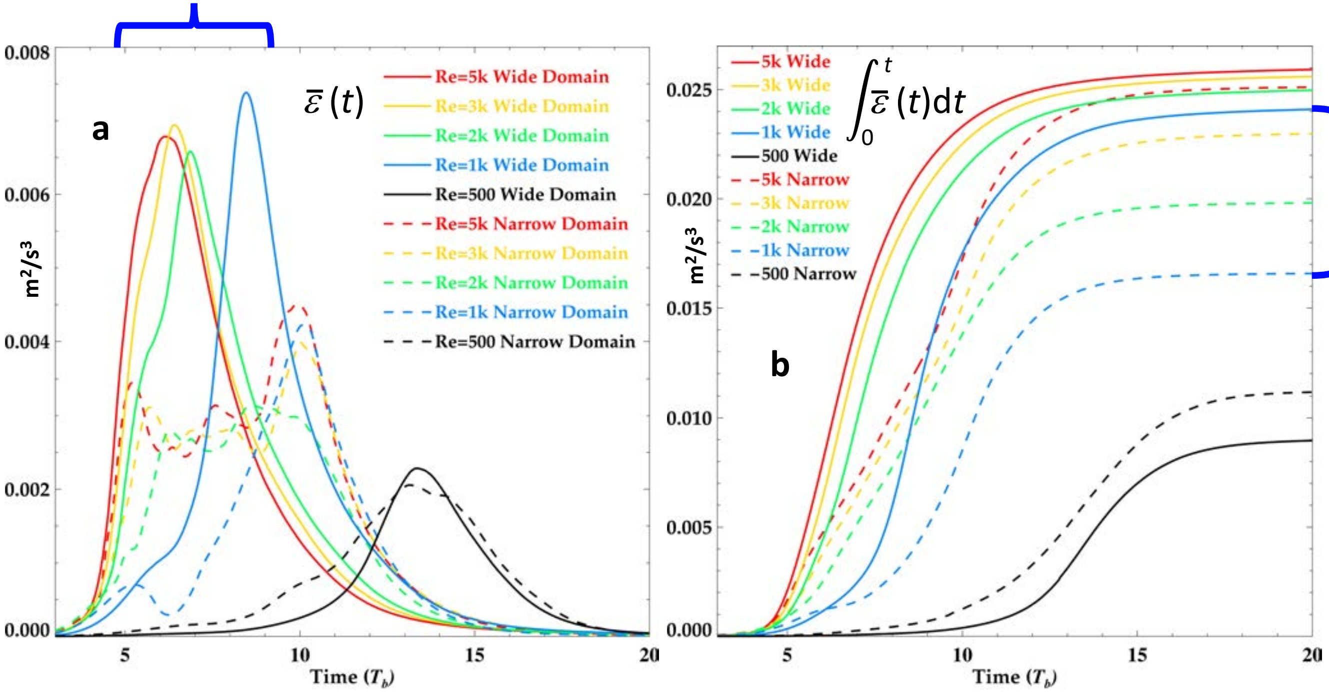


Fritts et al. (2023b)

This DNS captures diverse transitions to turbulence and enables assessments of ε
- vortex "knots" drive the strongest turbulence, yield enhanced ε relative to T&K absence



KHI T&K dynamics yield higher peak and cumulative $\mathcal{E}$



KHI T&K dynamics yield larger cumulative $\mathcal{E}$ than in their absence for intermediate Re

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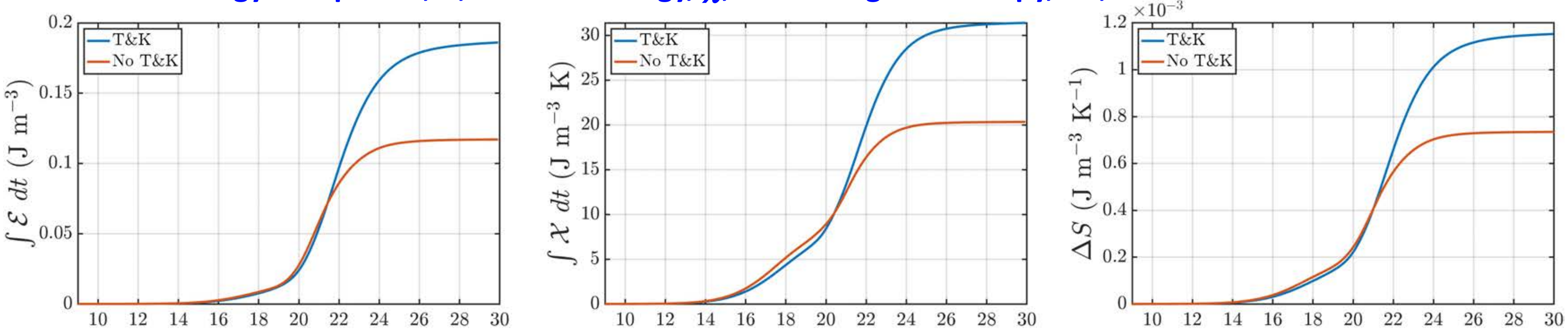
a potential for significantly enhanced mixing by KHI than is now currently parameterized in regional or global models

Cumulative energy dissipation, $\mathcal{E}$, internal energy, χ, and change in entropy, ΔS, in a CGCAM KHI T&K simulation



Fritts et al. (2023b), Mixa et al. (2023b, submitted)

Summary

- Evidence of nearly continuous turbulence from ~0-100+ km
  - Evidence of a broad spectrum of Gravity Waves (GWs) & Kelvin-Helmholtz Instabilities (KHI) yielding widespread "Sheet & Layer" (S&L) features
  - Current Multi-Scale (MS) modeling can approximate GW, instability, and turbulence responses to various GW sources from ~0-400 km
    - GW breaking driving S&L structures
    - KHI on strongly stratified and sheared vortex sheets
    - KHI breakdown to turbulence largely due to "tube" and "knot" (T&K) dynamics
  - Improved "GW" parameterizations will likely need to account for
    - GW superpositions and intermittency of GW breaking
    - enhanced dissipation and mixing due to ubiquitous KHI T&K dynamics
    - generation of SGWs that play increasing roles at altitudes above ~80 km