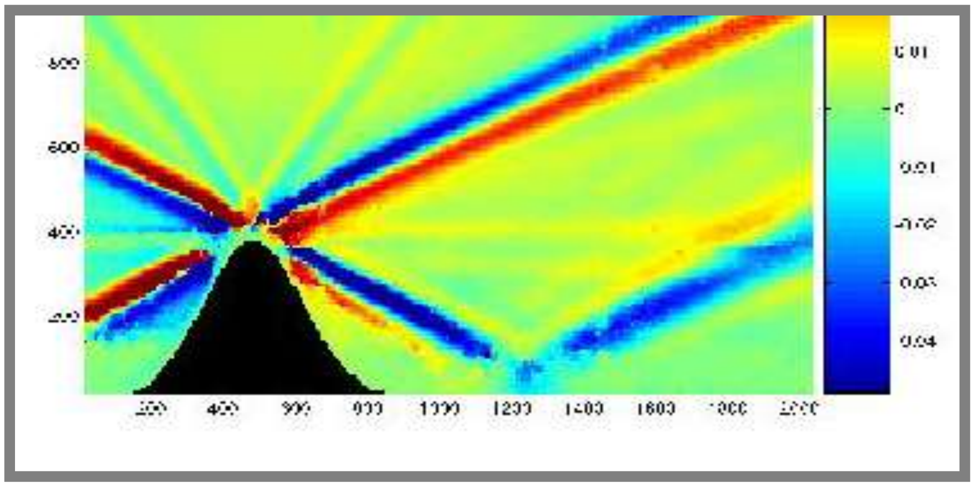
Internal Tide Energetics:
Generation, Propagation & Breaking



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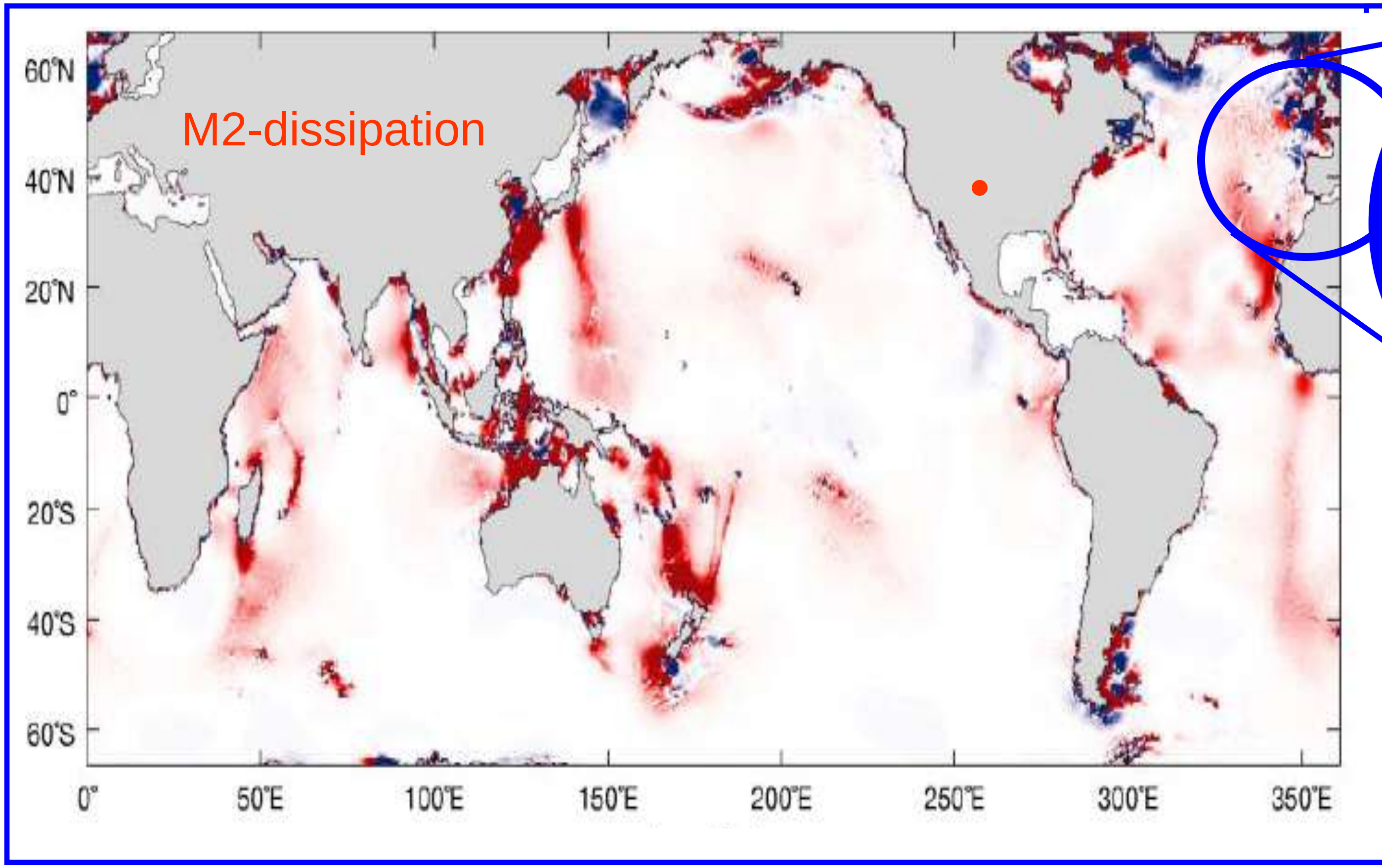
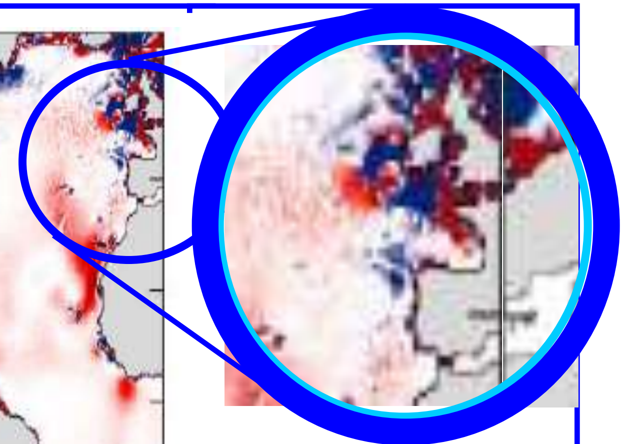
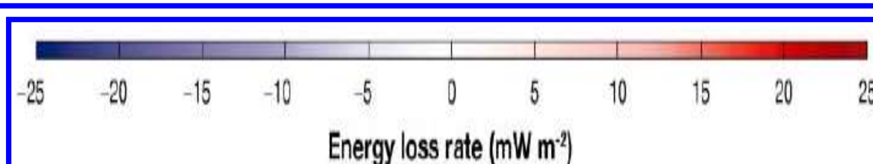
Tidal Energy Budget



Bay of Biscay





Tide Dissipation:

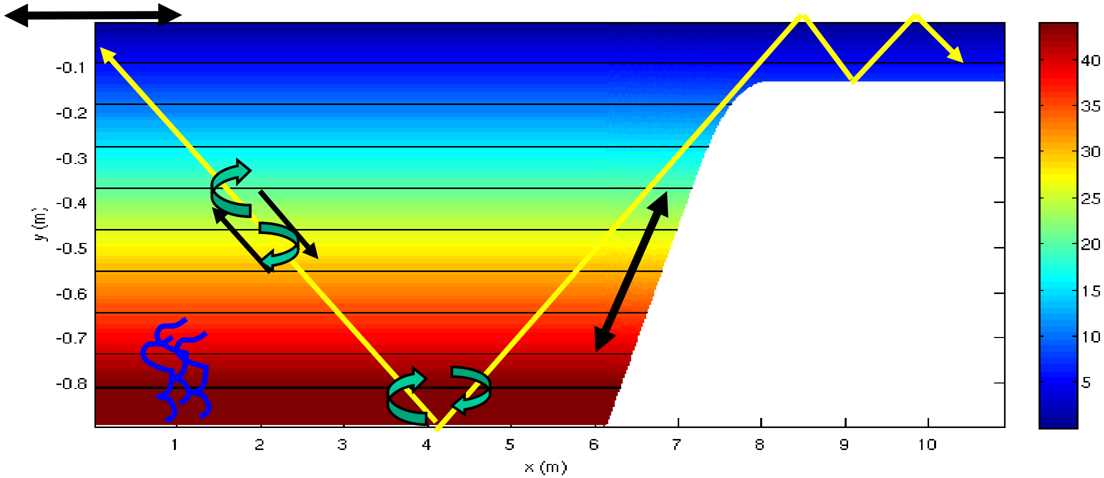
M2: 2.5 TW (3.5)

<u>IT: 1.1 TW</u>

Gulf Stream: 1 PW

Garrett & Kunze, 2007;
Egbert & Ray, 2001

Internal Tide Energetics

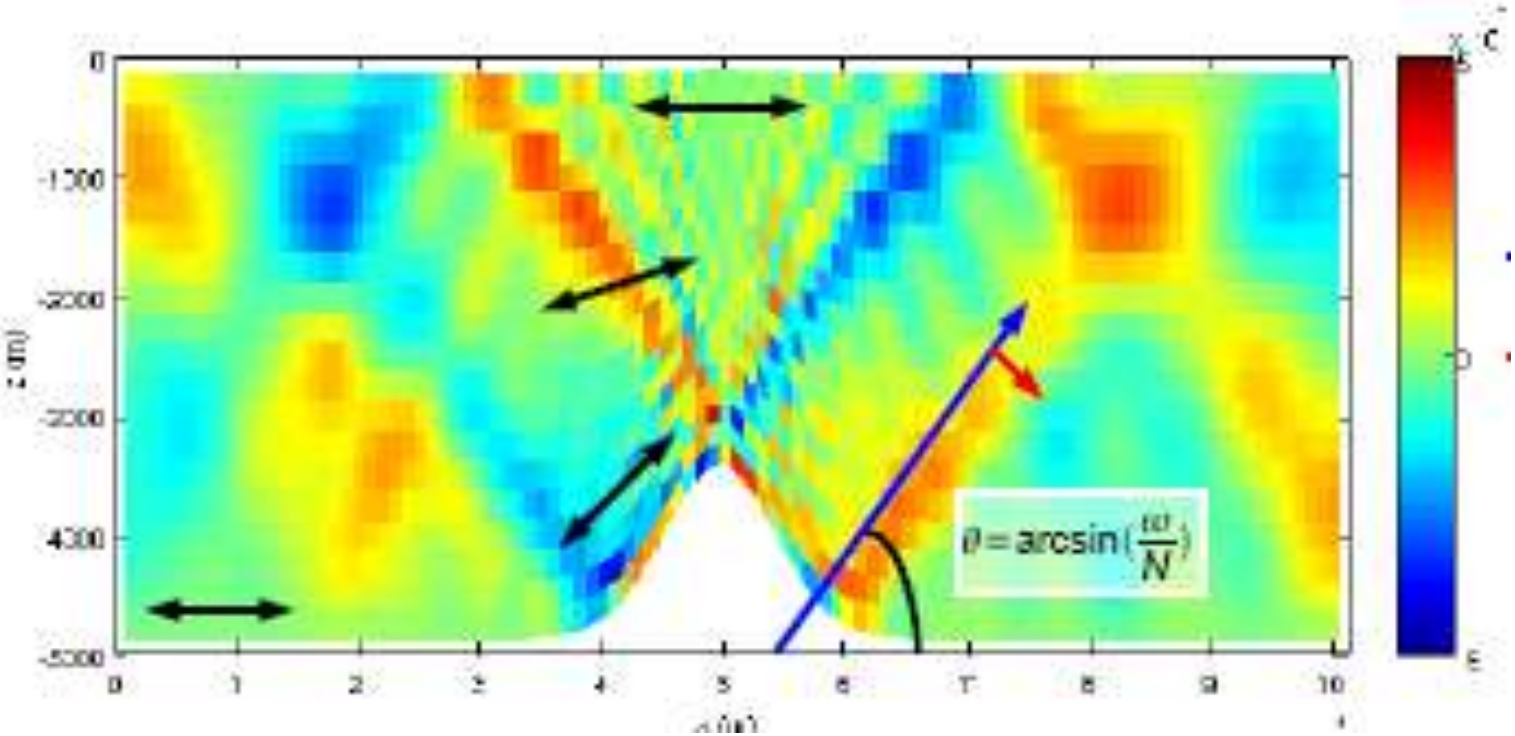


Wide range of scales:

Global Tide		Internal Tides		Turbulent Mixing
1000 km	↔	100 – 1 km	↔	10 km – 0.01 mm
day		day – hour		day – ms

Thermo–Haline Circulation

Density anomaly after $3T_0$:



barotropic tide

IW energy flux

IW phase prop.

$T = 12.4\,h$ → $\theta \approx 8^{\circ}$

$N = 10^{-3}\,s^{-1}$

$\Delta x = 1\,km$

$250 \leq \Delta z \leq 175\,m$

Coastal Ocean Model: Symphonie(NH)

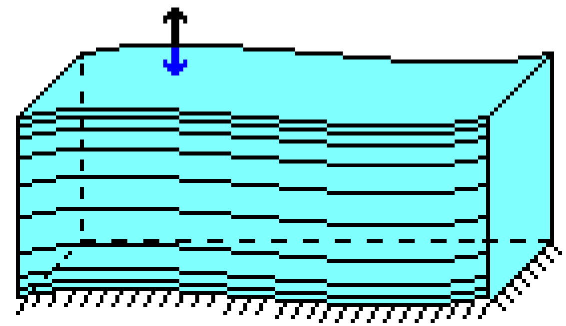
Characteristics:

- Time-splitting
- C-grid
- Generalised σ-coordinates
- Turbulence Closure:
  Gaspar et al. (1990)

Tools:

- Wavelets / Windowed FT
- (W)eof analysis
- Energy Flux Analysis
- Ensemble modelling

Energy Conserving



$$\vec{\nabla} \cdot \vec{v} = 0 \qquad \rho = \rho(p, S, T)$$

Applications:

-NW-Mediterranean Sea:
- forecasting (Estournel et al., 2007)
- biogeochemistry (Ulses et al., 2008)
- climate studies (Herrmann et al., 2007)

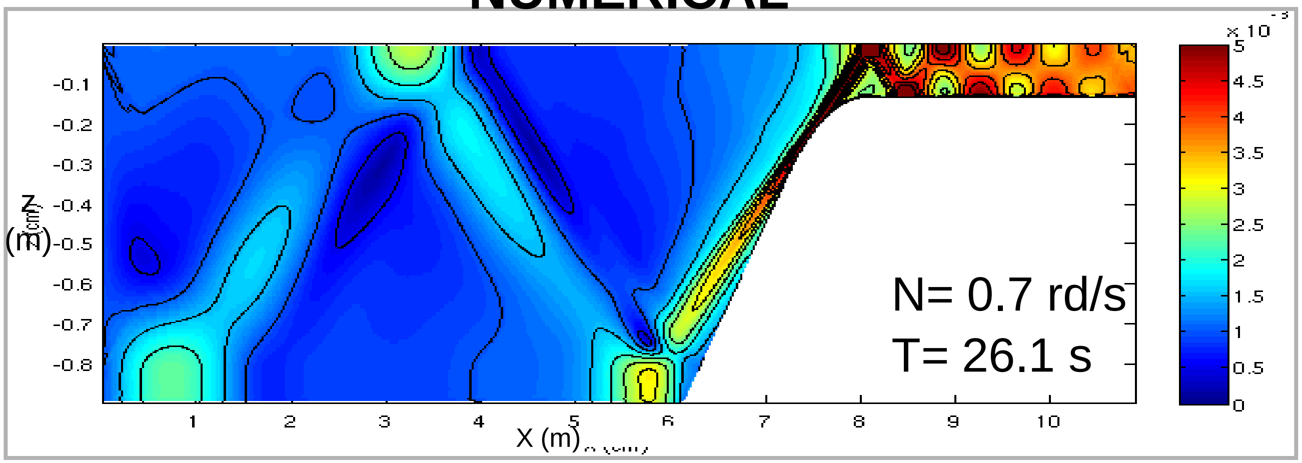
- Bay of Biscay + Academic + Small
- internal tide modelling (Pairaud, 2005)

(Marsaleix et al., 2008, doi:10.1016/j.ocemod.2007.07.005 **)**

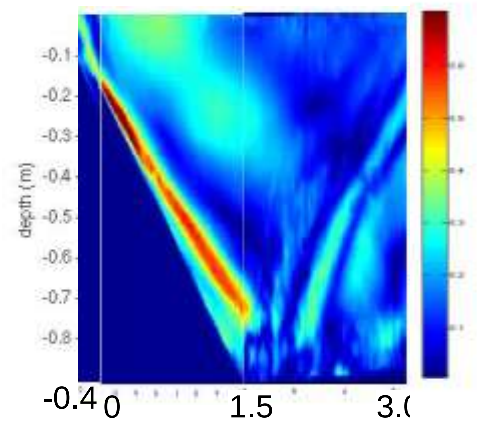
Symphonie Validation

- Numerically Consistent Energetics (Marsaleix et al., 2008)
- Bay of Biscay IT observations (hydrostatic) (Pairaud, 2005)
- Coriolis-platform (C. Staquet, LEGI, Grenoble)

NUMERICAL



LAB



Laboratory Study

- Oscillating Gaussian Ridge (with A. Paci at **SPEA/CNRM-GAME**)
  - validation & parameter studies

Channel: 4x0.5x0.4 m

Synthetic Schlieren: Density

(Gostiaux et al., ‘05; Sutherland et al., ‘98)

Gaussian ‘Seamount’

$h(x)= h0 \exp(-x^2/a^2)$

h0= 11 cm

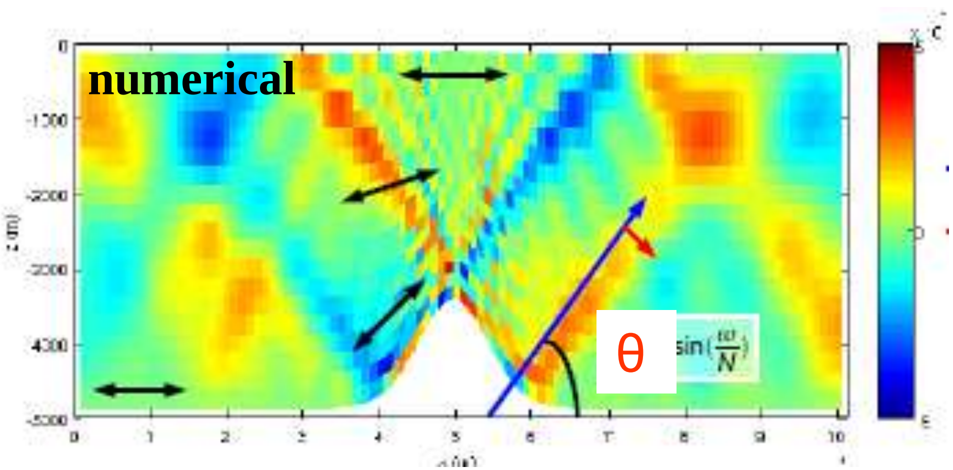
a= 5.7 cm

Evolution of the anomaly of density gradient during the establishment of the internal tide.

Linear Stratification: N ~ 1.1 rad/s

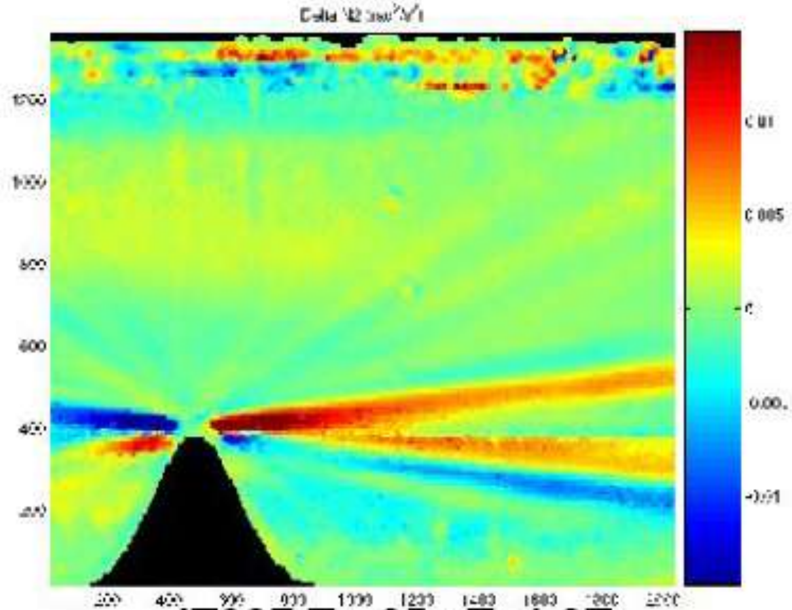
Forcing Frequency: 0.1 ○ ω ○ 1.1 rad/s

Internal wave slope: 5 ○ θ ○ 83 (measured)

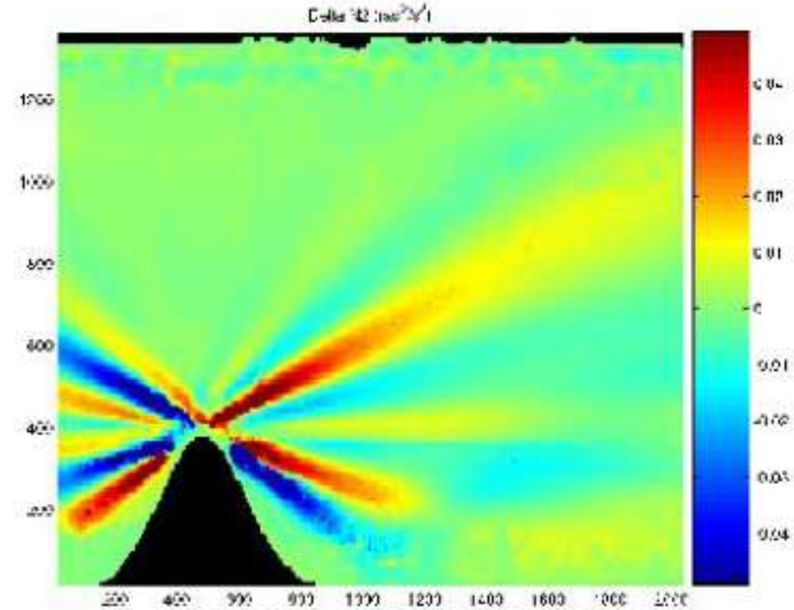


Note 1. $\omega^2 = N^2 \sin^2 \theta$

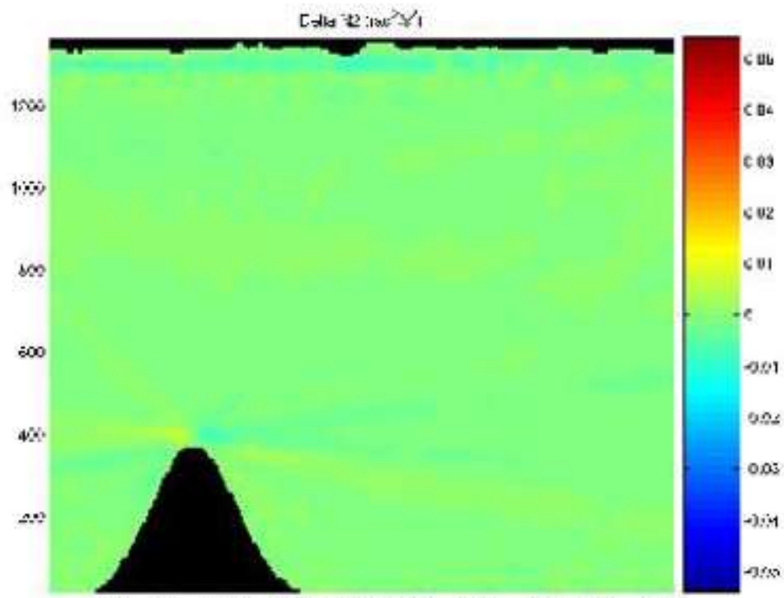
Note 2. Ridge Oscillates!



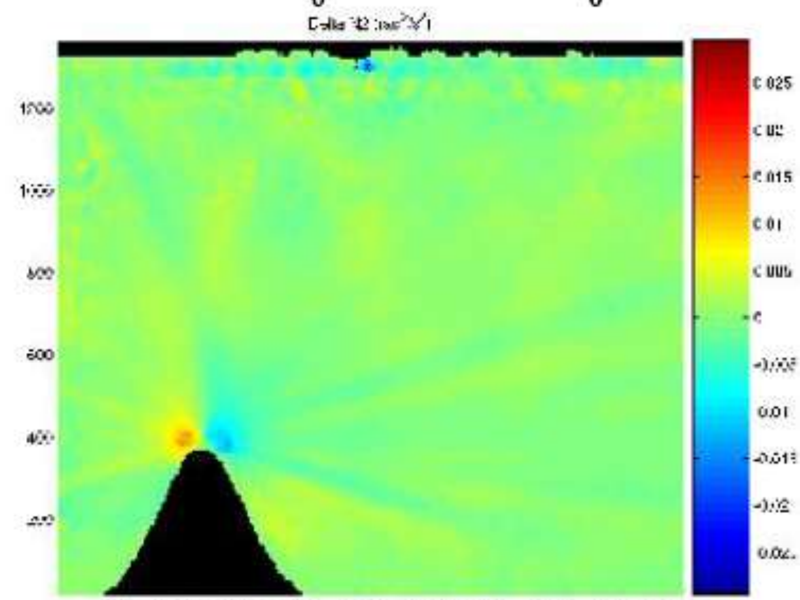
IT037 T_0=65s T~1.9T_0



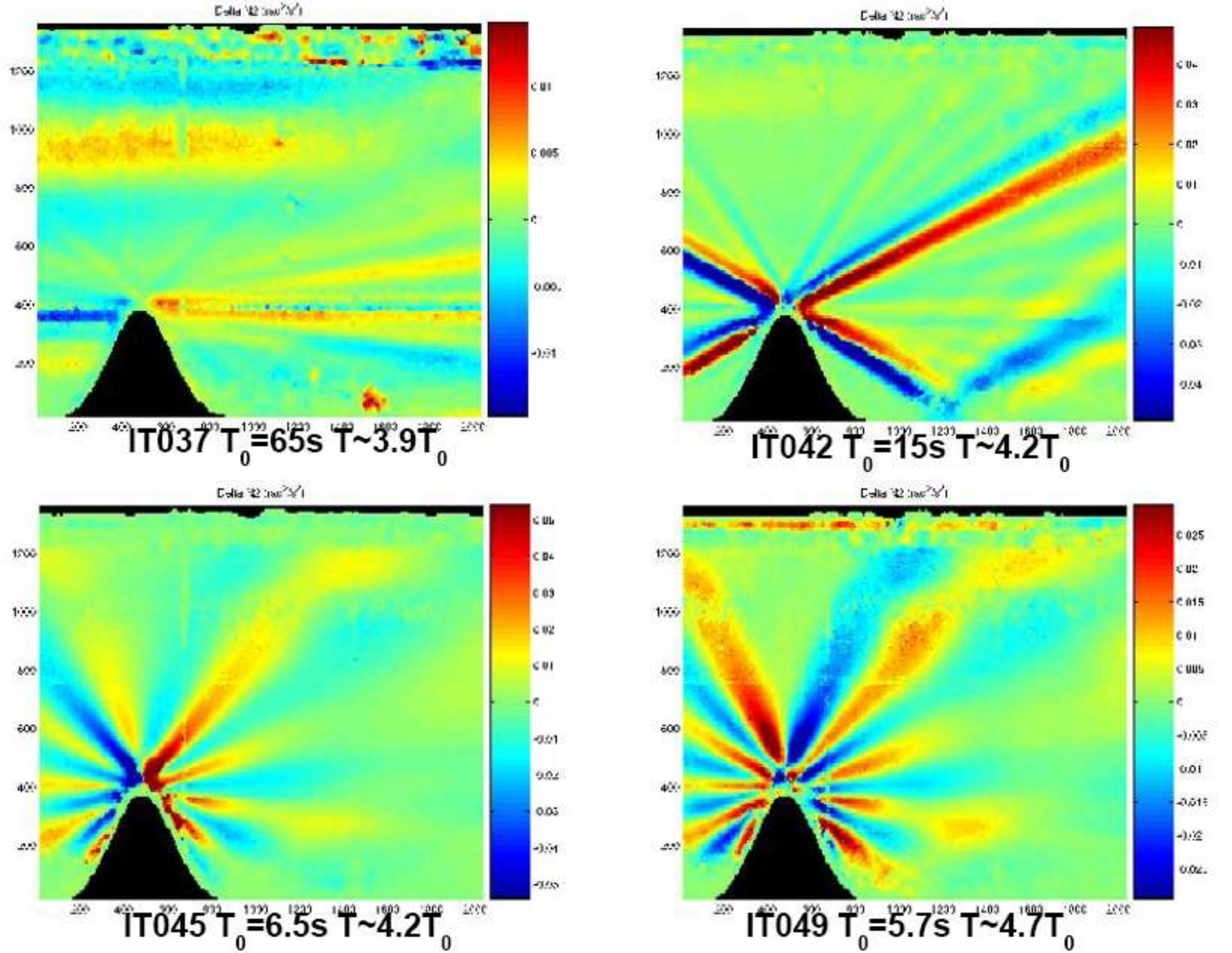
IT042 T_0=15s T~2.1T_0



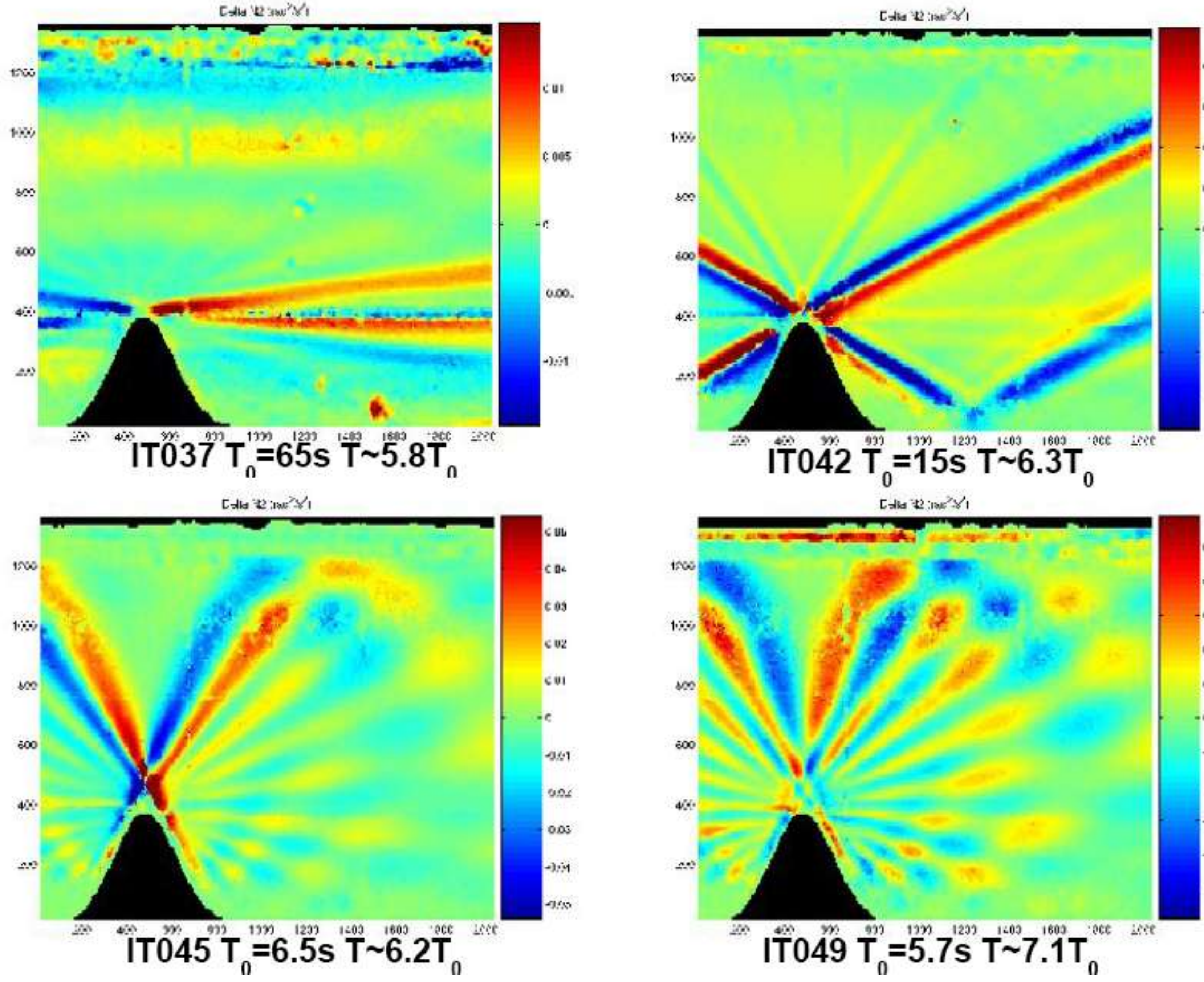
IT045 T_0=6.5s T~2.1T_0

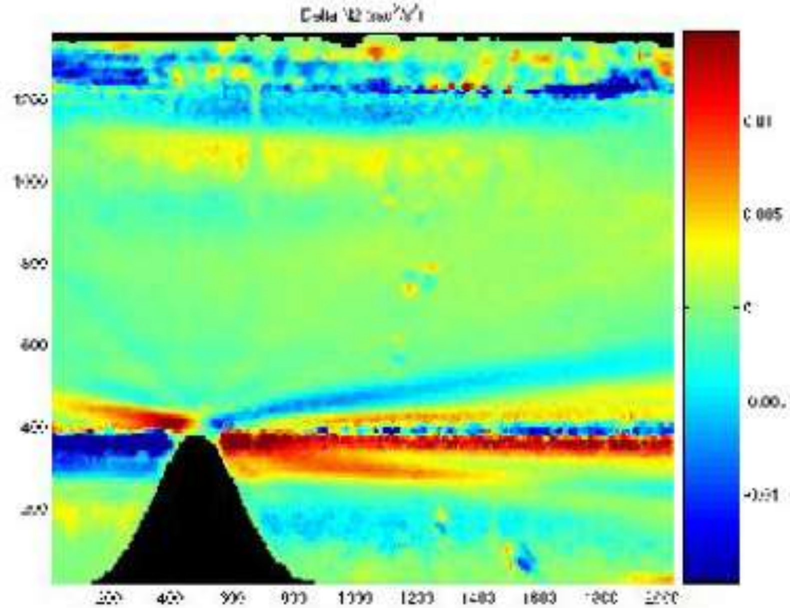


IT049 T_0=5.7s T~2.4T_0

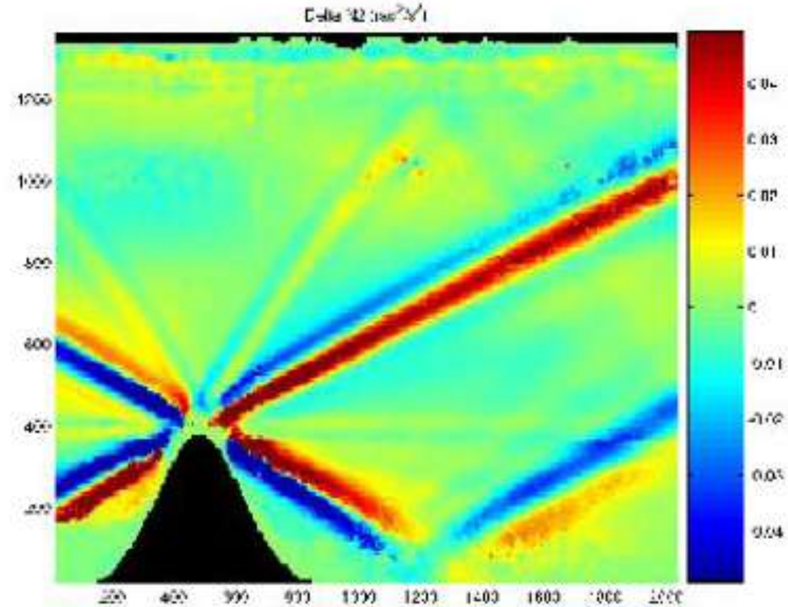


IT037 T_0=65s T~3.9T_0
IT042 T_0=15s T~4.2T_0
IT045 T_0=6.5s T~4.2T_0
IT049 T_0=5.7s T~4.7T_0

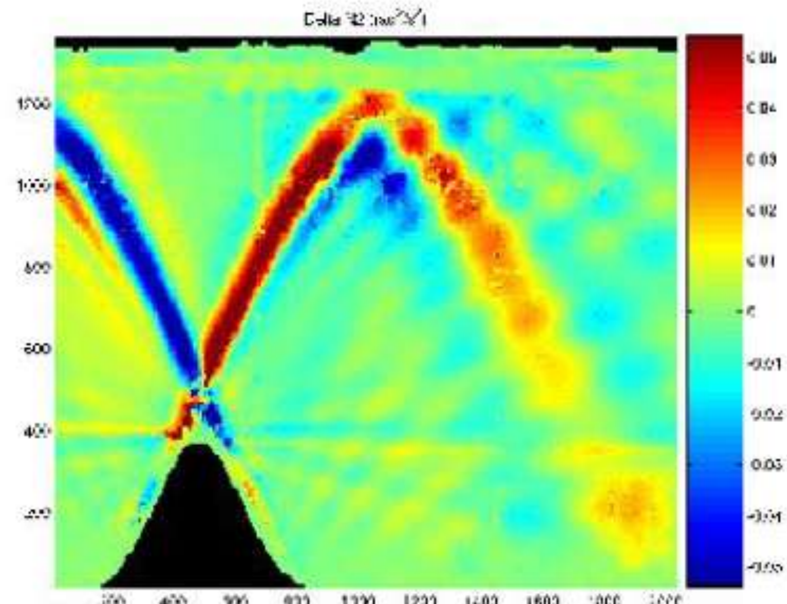

IT037 T0=65s T~5.8T0
IT042 T0=15s T~6.3T0
IT045 T0=6.5s T~6.2T0
IT049 T0=5.7s T~7.1T0



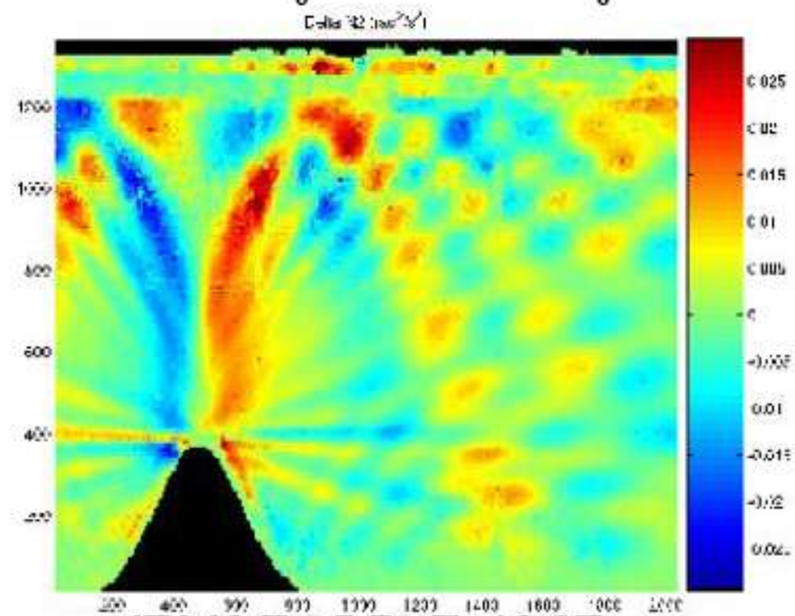
IT037 T_0=65s T~10.1T_0



IT042 T_0=15s T~10.9T_0



IT045 T_0=6.5s T~10.8T_0



IT049 T_0=5.7s T~12.3T_0

Preliminary Conclusions

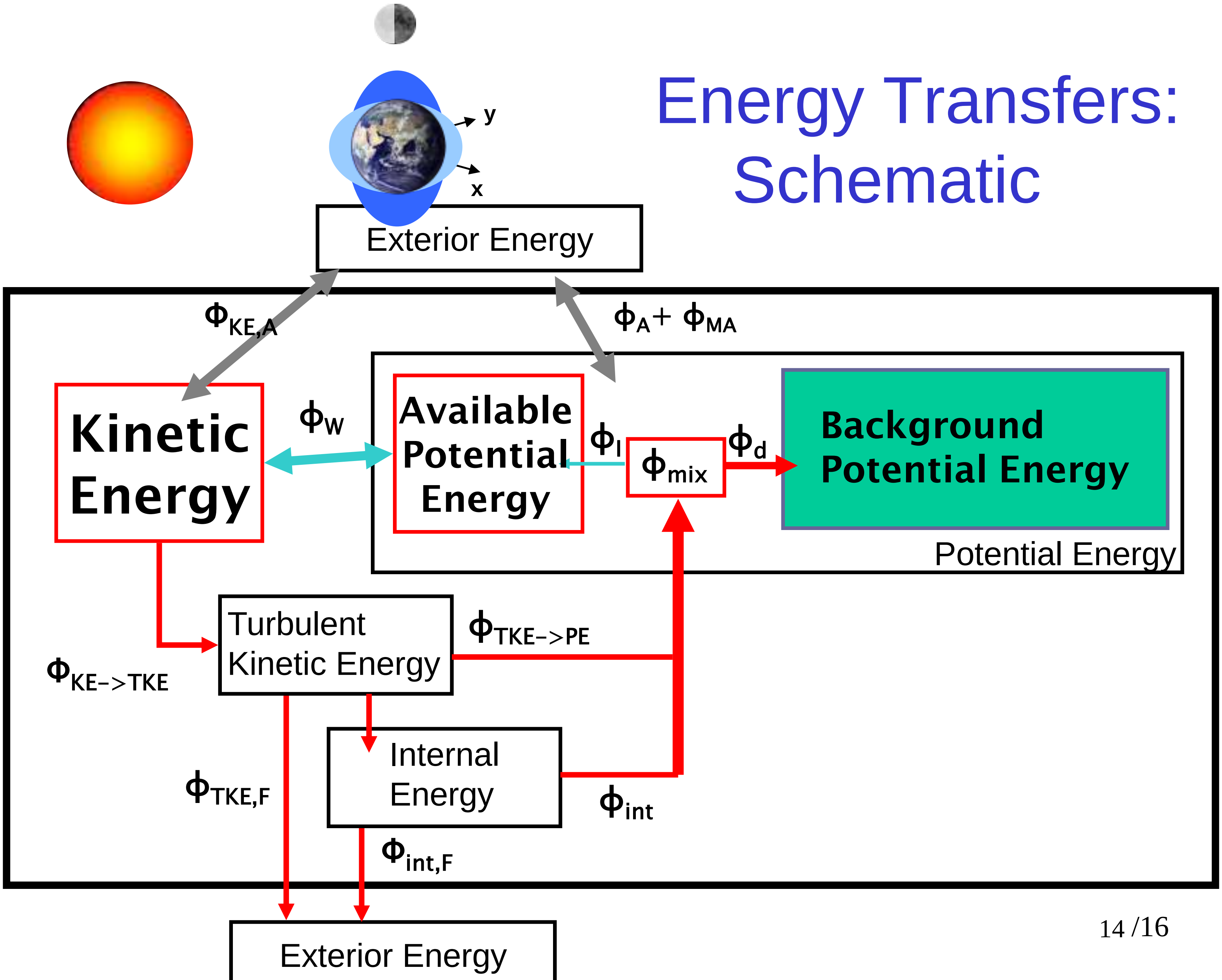
- Internal tide establishes more rapidly for small ω, θ
- Many rays (subharmonics?) generated for ω ✹ N
- ΔN^2_{max} augments then diminishes with θ:

0.01 rad²/s² for θ= 5º

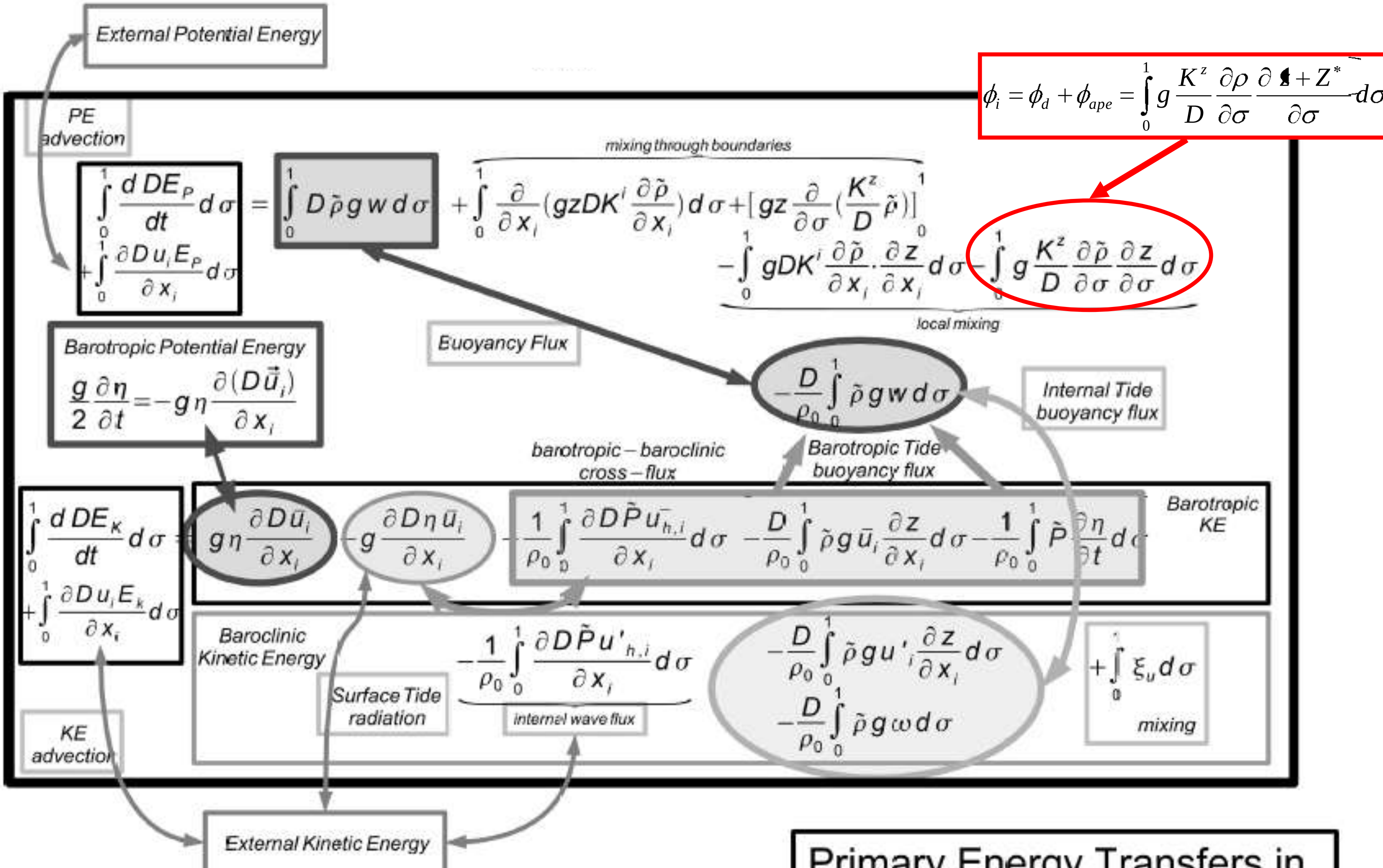
MAX for θ= 45º ✹ 0.05 rad²/s²

0.03 rad²/s² for θ= 83º

Energy Transfers: Schematic



Energy Equations



Primary Energy Transfers in Internal Wave Generation

Summary & Perspectives

- Internal tides estimated 30% of available tidal energy:

  Where does the energy go?

- Symphonie is suitable for IT-modelling at and across different scales
- When ω ✹ N : strong non-linearity & subharmonics form.

- Experimental:
  - Particle Imaging Velocimetry ✹ u, w; E_K (August 2008)
  - link model & observations ✹ *numerical moving 'ridge'*

    (Gerkema & Zimmerman, 1995)
- Modelling:
  - explore f 🕓 0, 3D effects
  - quantification of E_K ✶✹ APE, diapycnal mixing, APE_0 (Shepherd, 1993)
  - 3D NH embedded modelling of tidal ray reflection and soliton generation in the Bay of Biscay (with Dauxois, Gostiaux and others)
- Theory:
  - multi-scale analysis ($\lambda_0 >> \lambda_{IGW}$, $T_0 = T_{IGW}$, N, L_B, h_0, H)
  - explanation ω ✹ N – dynamics

Questions:

- Non-Boussinesq effects: work by compression
- Non-traditional dynamics (horizontal components of Coriolis)
- GGG, PPG (f non-zero)
- What about PPPP?
- Qualitative explanation for ω ✹ N observations by Taylor & Sarkar, jfm, 2007?