Submesoscale stirring by balanced and unbalanced flows

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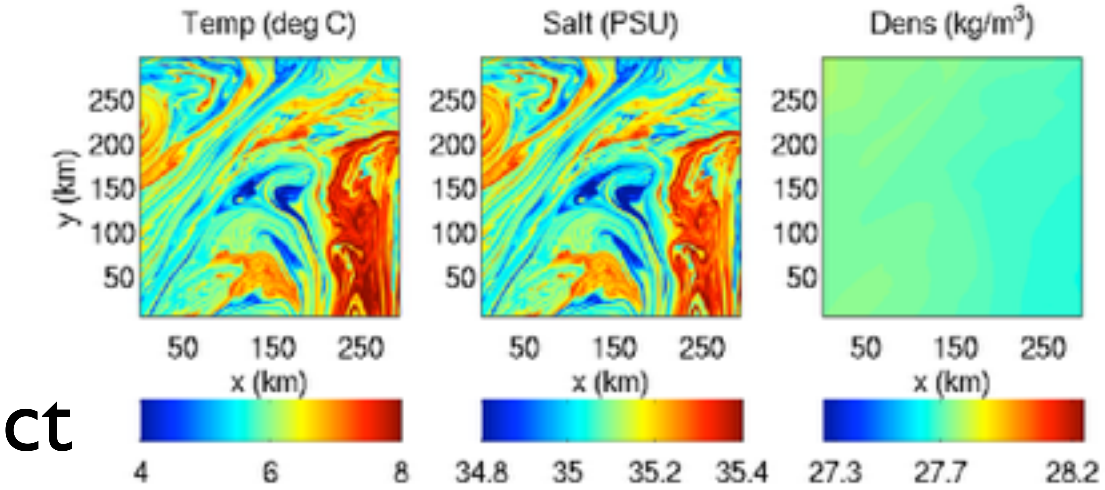
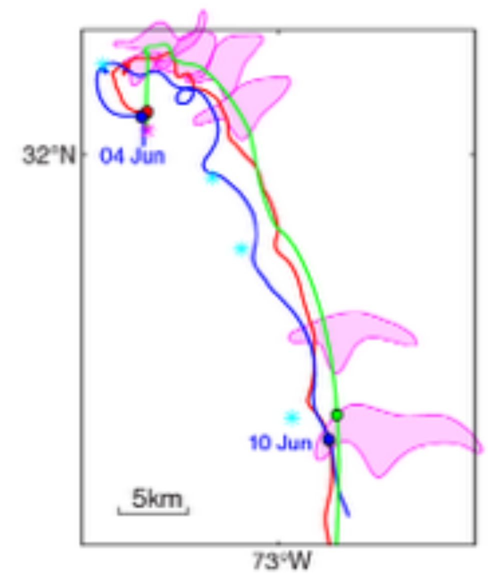
IFREMER

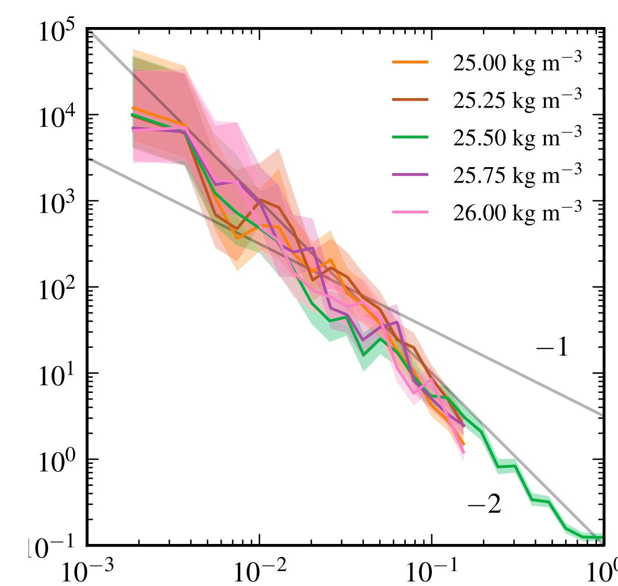
Mysteries of submesoscale stirring

Observed everywhere:

- T/S exhibit high 3D submesoscale variance, but compensate in their effect on density
- Dye spreading experiments imply submesoscale isopycnal diffusivity κ ~ O(1) m^2/s
- [Tracers show wavenumber power spectra with power law $k^{-1 \text{ to } -2}$, at all depths]
- What stirring mechanisms are at work?







Outline

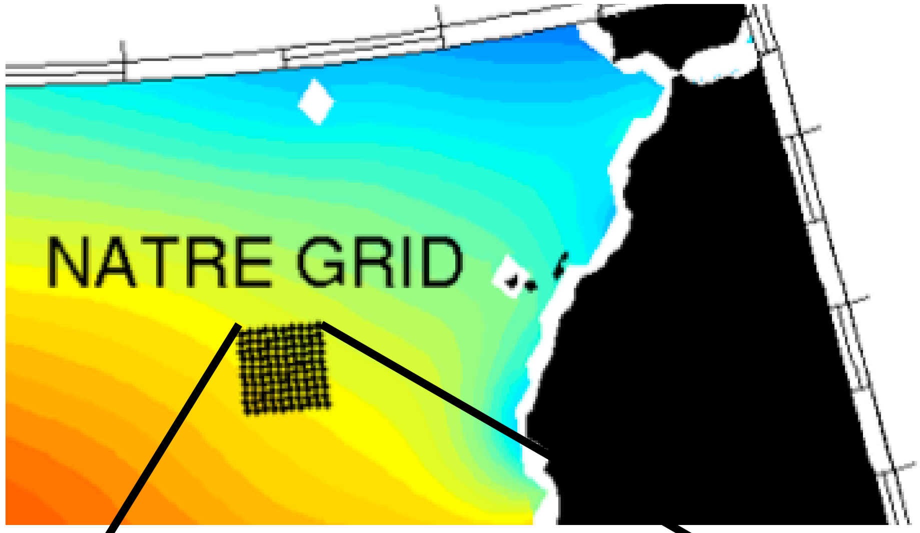
1. Generation of compensated submesoscale T-S variance by mesoscale stirring as predicted by Klein, Treguier & Hua '98 [w/ R. Ferrari & J. Taylor]

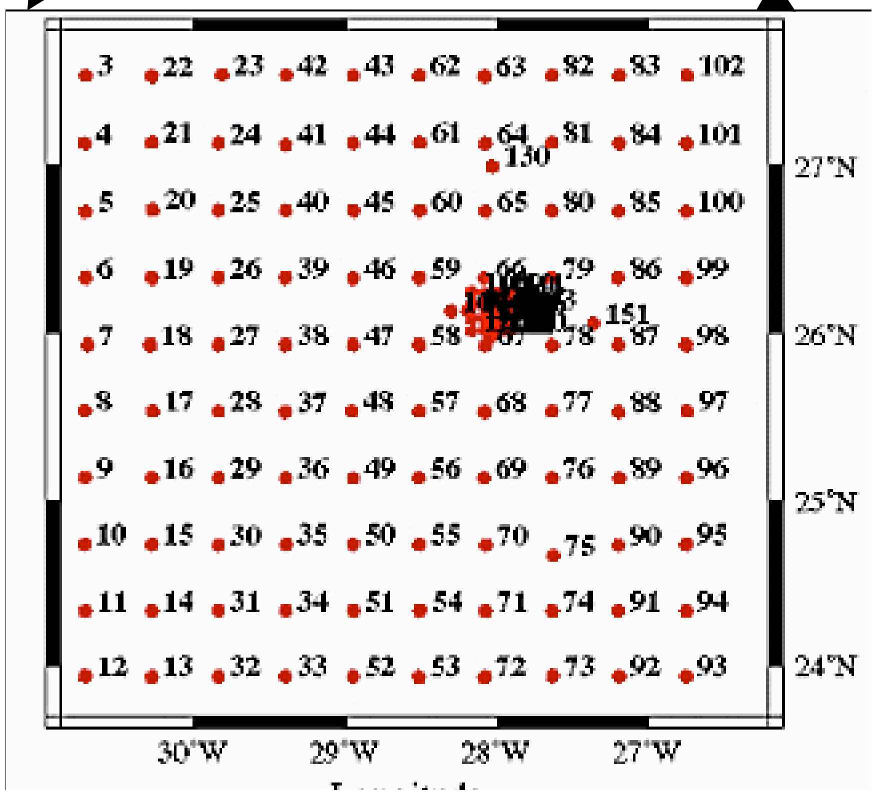
2. Internal waves themselves can disperse tracers (!) [w/ J. Early]

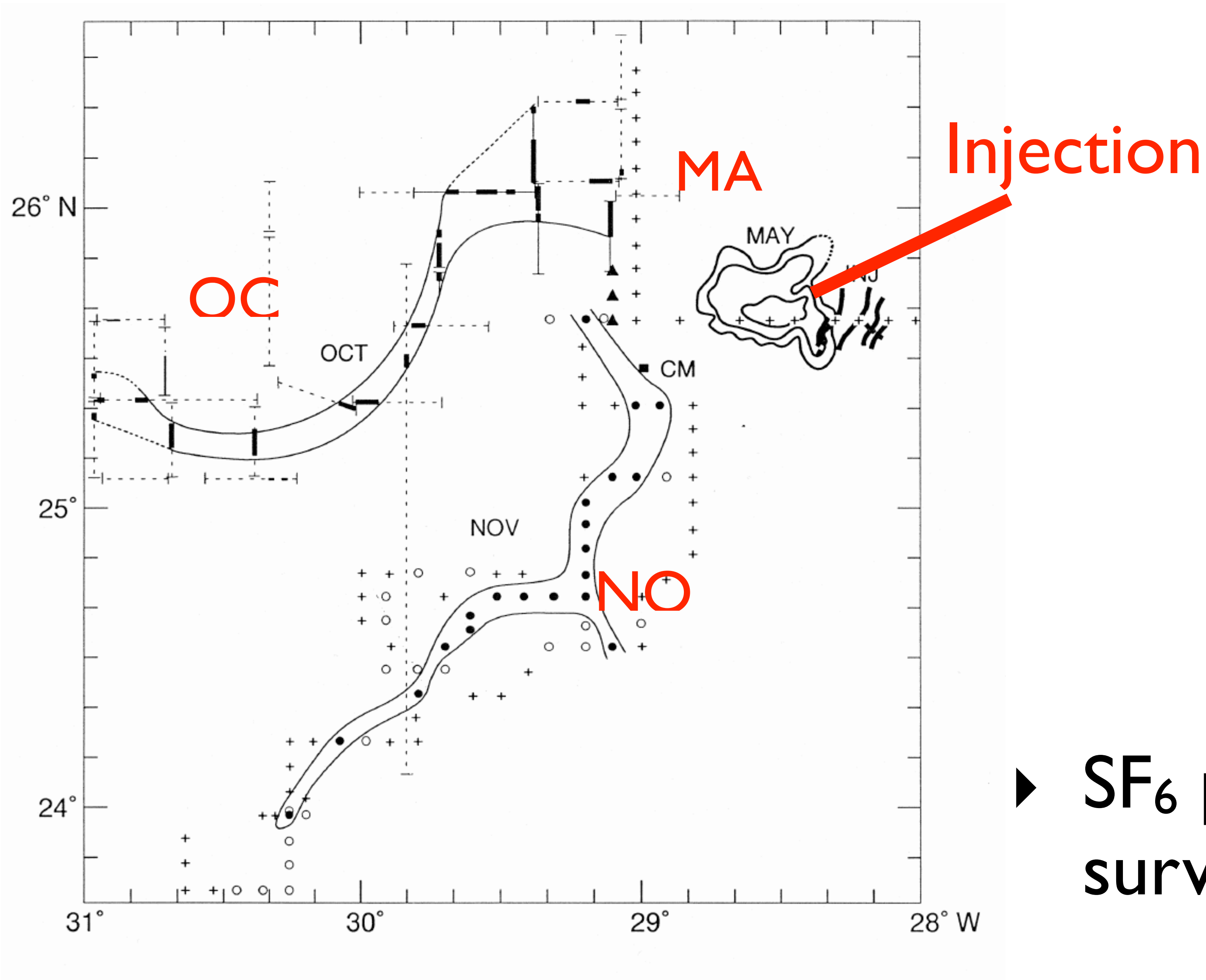
North Atlantic Tracer Release Experiment

- HRP survey on 400 km^2 grid:
  127 T/S/shear profiles (0-4000m)

- Moored current array: (200-3500m)

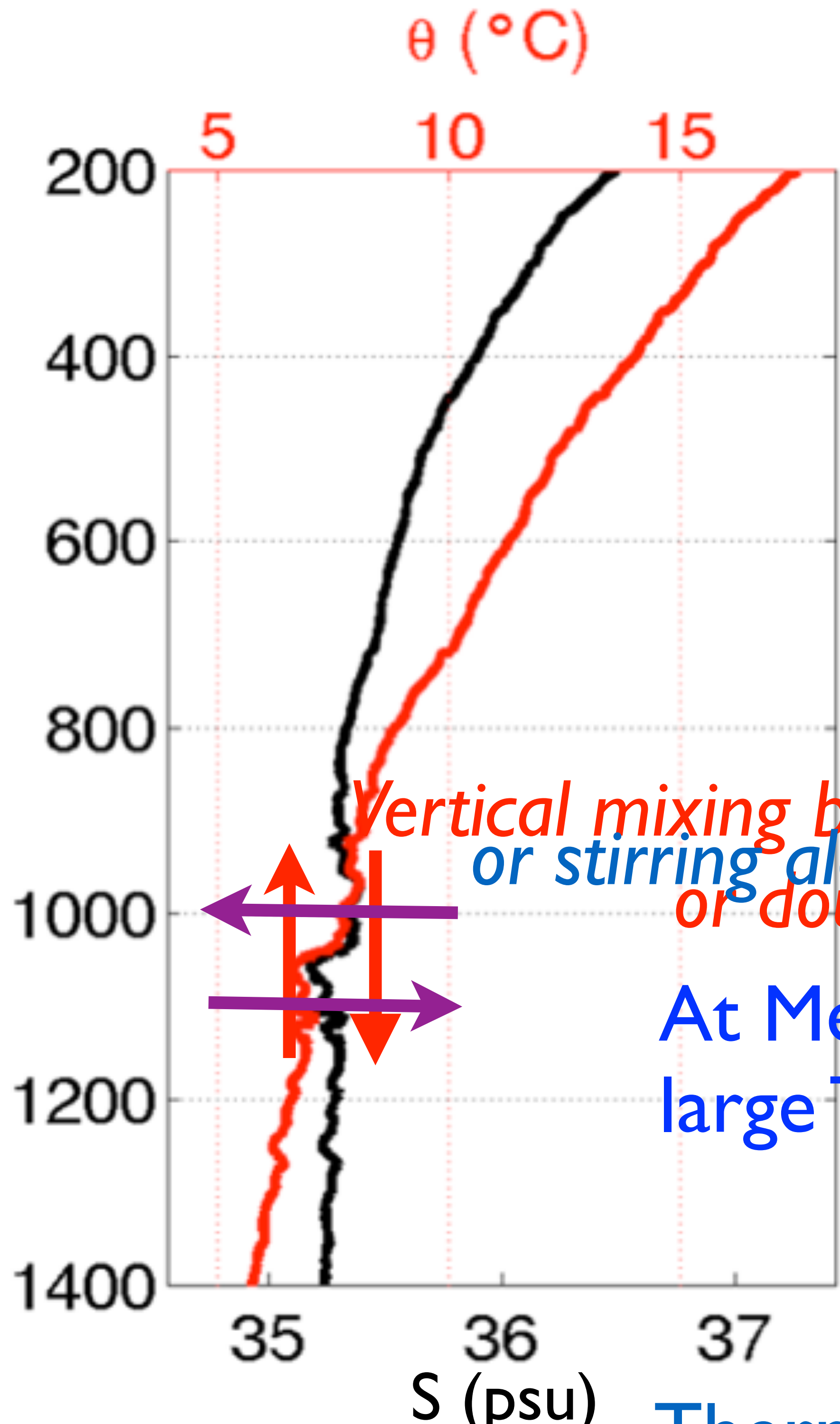






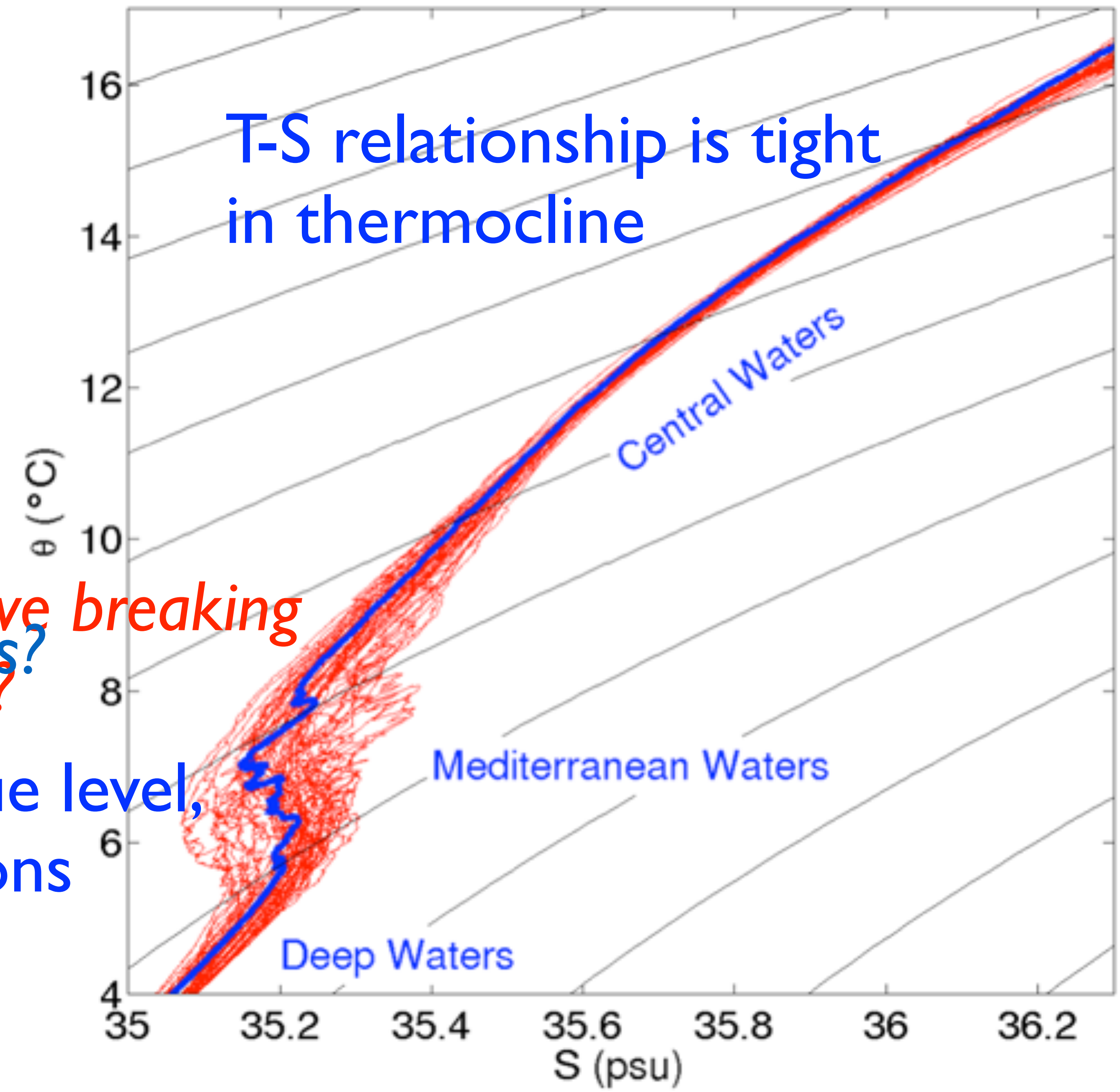
- SF_6 patch released at 300m, surveyed over next 30 months

T-S Profiles in NATRE



Vertical mixing by internal wave breaking
or stirring along isopycnals?
or double diffusion?

At Med Salt Tongue level,
large T-S fluctuations



T-S relationship is tight
in thermocline

Thermohaline fluctations have little signature on density:
compensated fronts of 1-5km in horizontal, 10-100m in vertical.

=> Stirring along isopycnals will effectively stir tracers inclined to isopycnals, not density (Klein, Treguier and Hua 1998)

Journal of Marine Research, 56, 589–612, 1998

Three-dimensional stirring of thermohaline fronts

by Patrice Klein[1], Anne-Marie Treguier[1] and Bach Lien Hua[1]

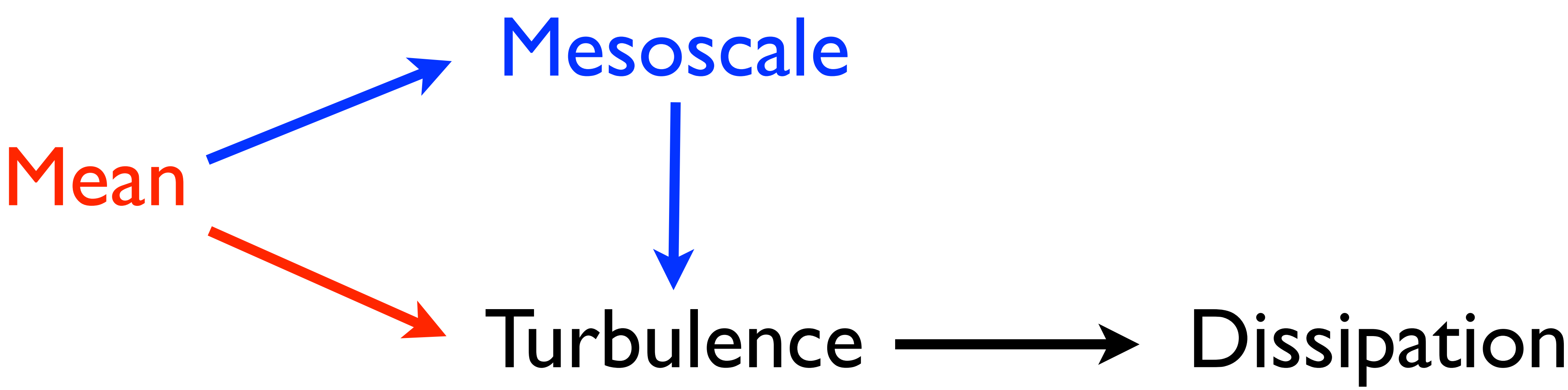
ABSTRACT

This study investigates the stirring of the thermohaline anomalies in a fully turbulent quasi-geostrophic stratified flow. Temperature and salinity fields are permanently forced at large scales and are related to density by a linear equation of state. We show, using some inherent properties of quasi-geostrophic turbulence, that the 3-D ageostrophic circulation is the key dynamical characteristic that governs the strength and the spatial distribution of small-scale thermohaline fronts that are strongly density compensated. The numerical simulations well illustrate the formation by the mesoscale eddy field of sharp thermohaline fronts that are mainly located in the saddle regions and around the eddy cores and have a weak signature on the density field. One important aspect revealed by the numerical results is that the thermohaline anomalies experience not only a direct horizontal cascade but also a significant vertical cascade. One consequence of this 3-D cascade is that the ultimate mixing of the thermohaline anomalies will not be necessarily maximum at the depth where the large-scale temperature and salinity anomalies are maximum. Some analytical arguments allow us to identify some of the mechanisms that drive this 3-D cascade.

Temperature variance budget in NATRE

Where large scale lateral gradients are present, mesoscale stirring generates variance.

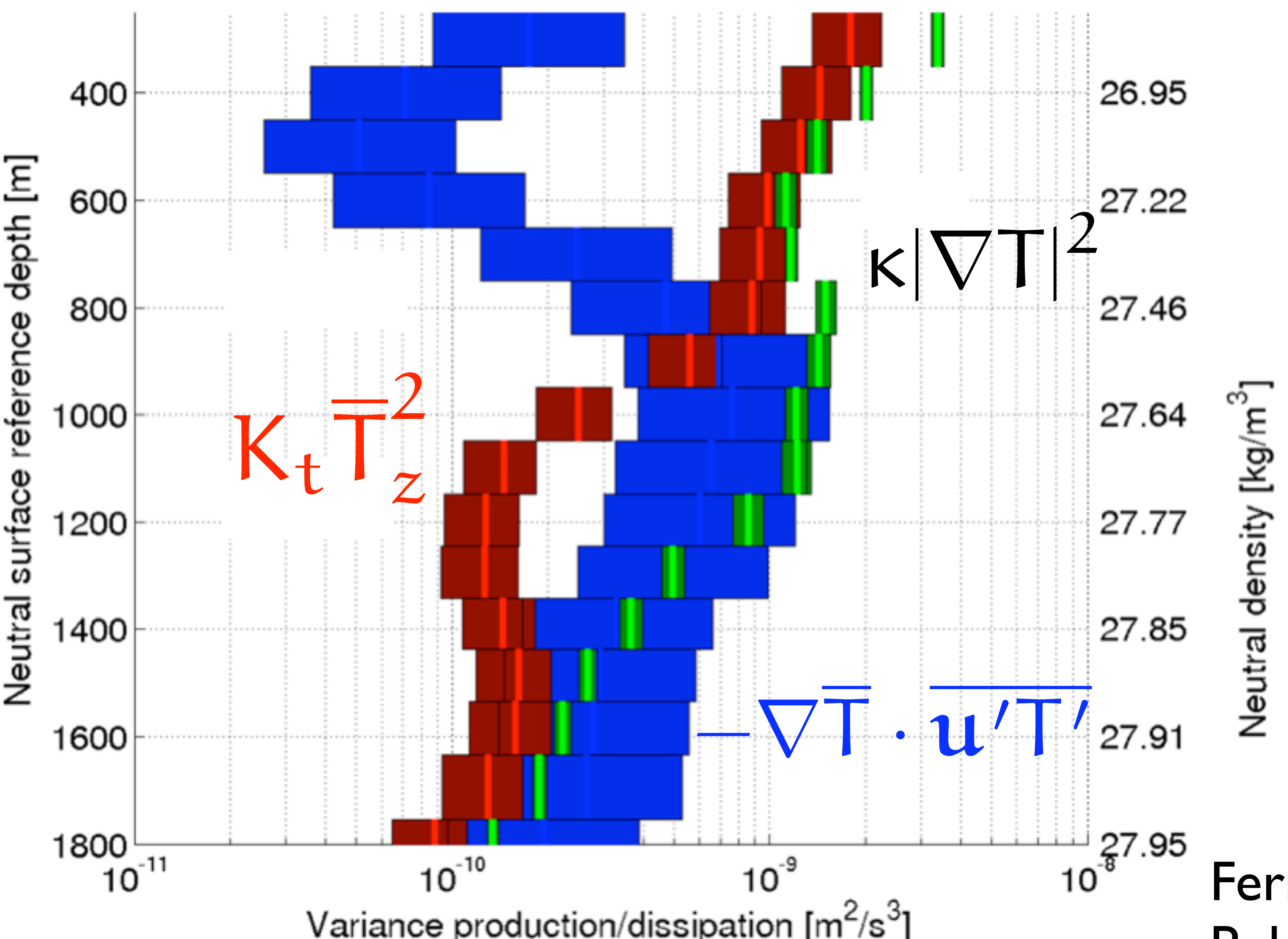
Med Salt level (lateral gradients present)



Central waters (weak lateral gradients)

$$-\nabla\overline{T}\cdot\overline{\mathbf{u}'T'} + K_t\overline{T}_z^2 = \kappa|\nabla T|^2$$

Temperature variance budget in NATRE

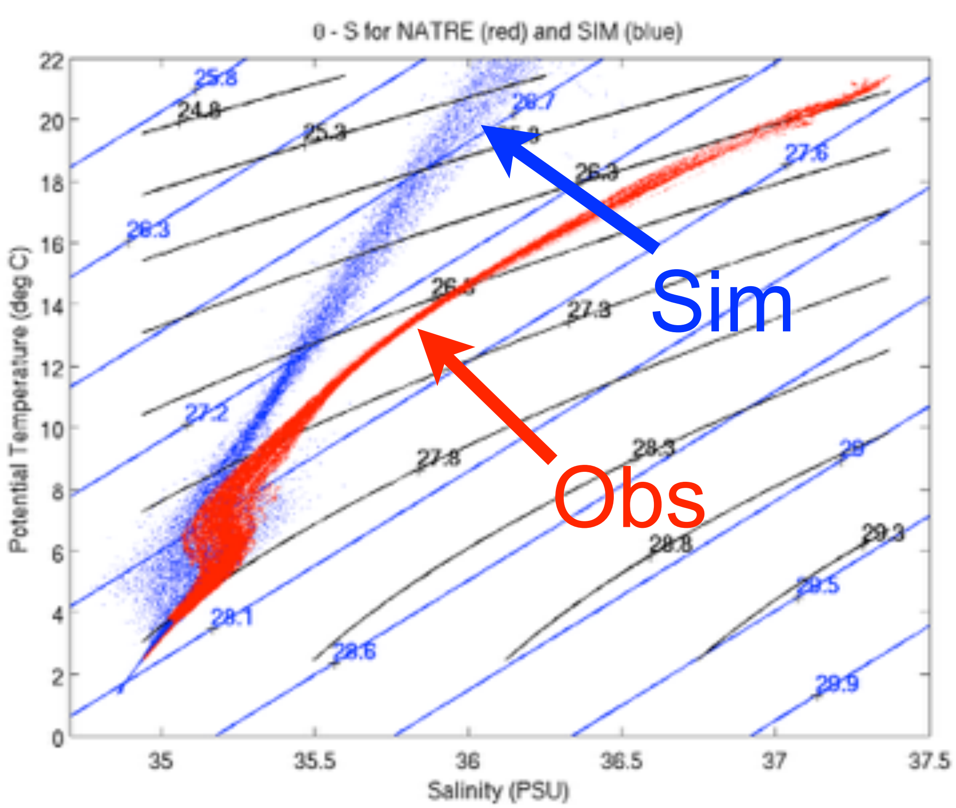


Ferrari and Polzin (2005)

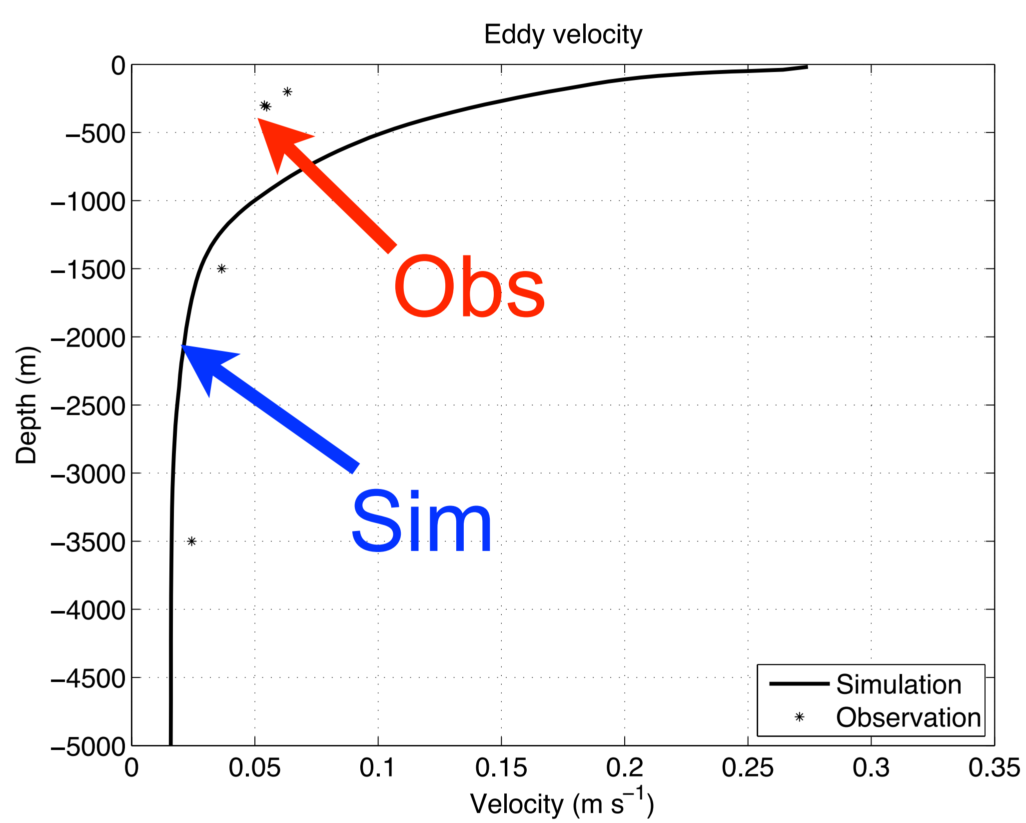
QG modeling

- QG simulation on 1000^2 km domain, 1 km resolution, with 80 vertical levels of 35-120m
- Mean T/S from HRP; density from nonlinear EOS; spice from linear EOS applied at Med Salt Tongue level; mean velocity from moored array

T-S distribution

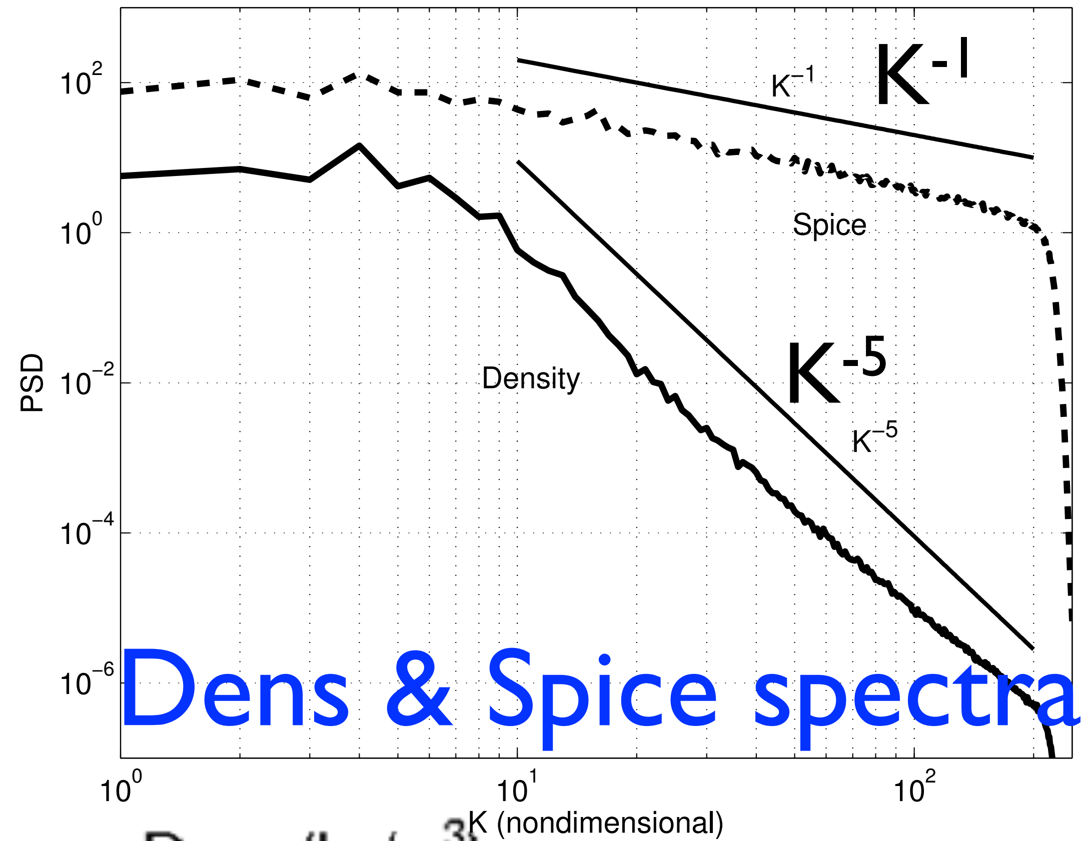


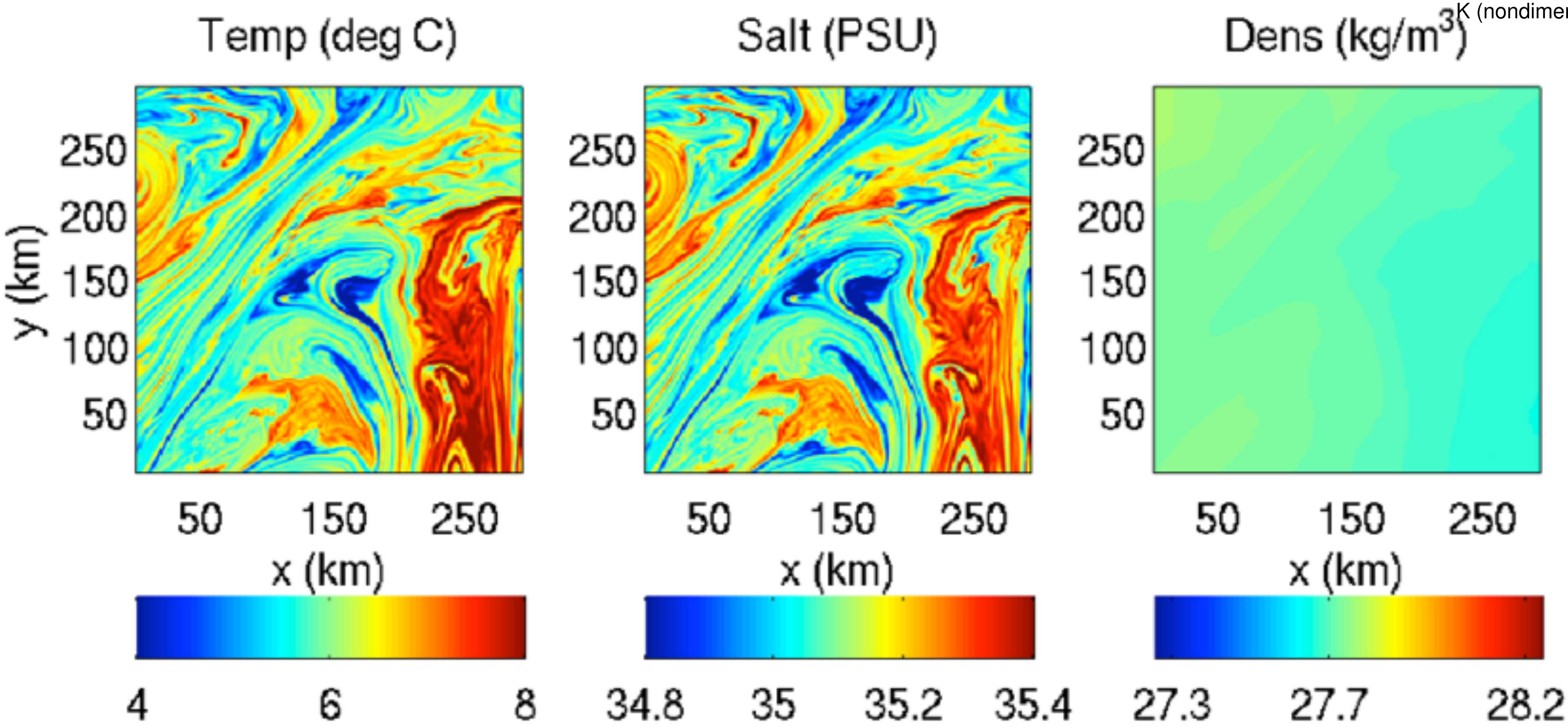
Eddy velocity



Lateral structure

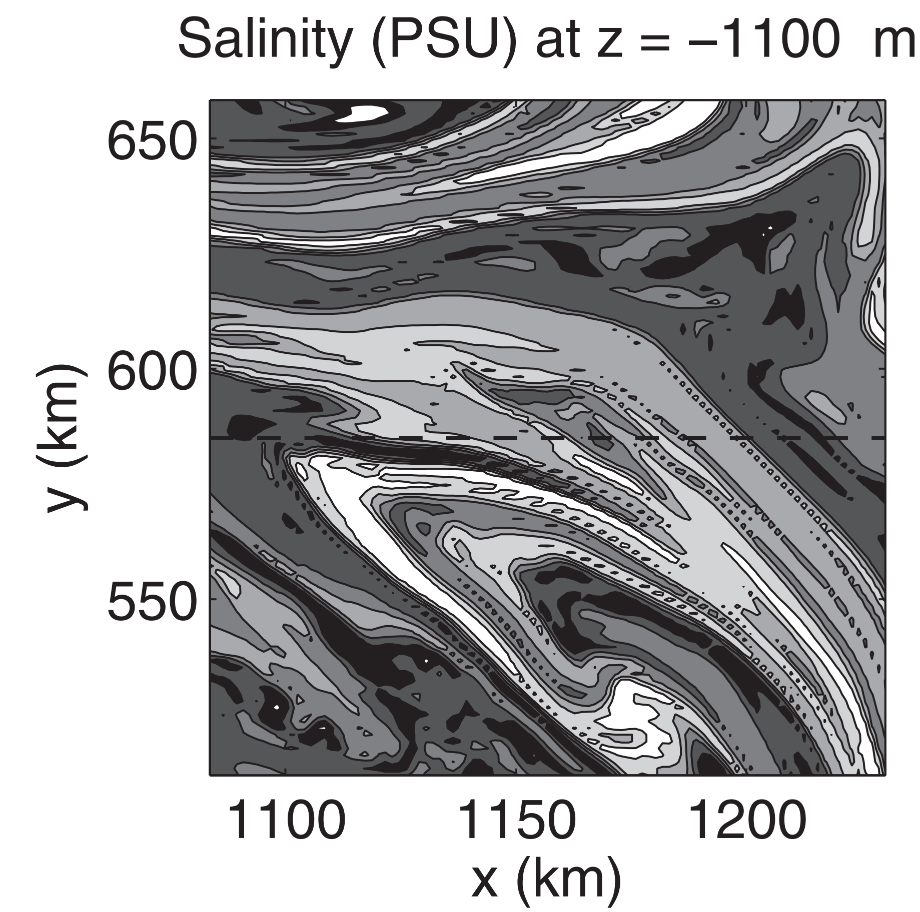
- Spectra: Tracer ~ K^{-1}, density ~ K^{-5}
- T, S passive tracers => filamentation compensated in effect on density
- Interior: little density gradient, ample tracer variance along isopycnals

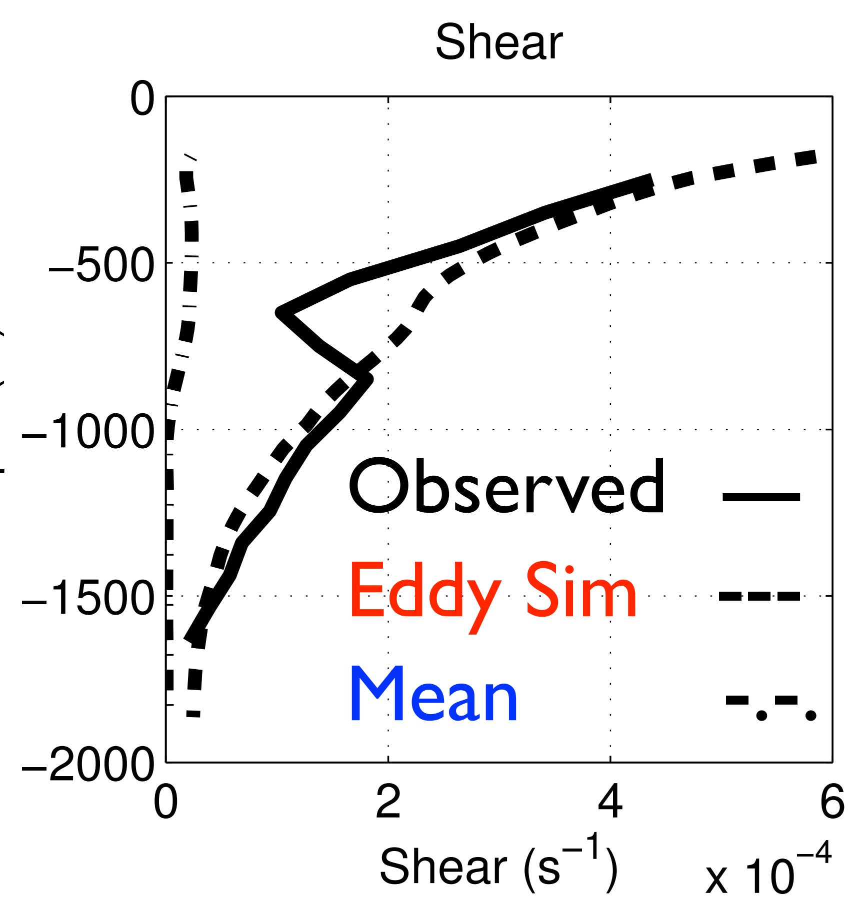


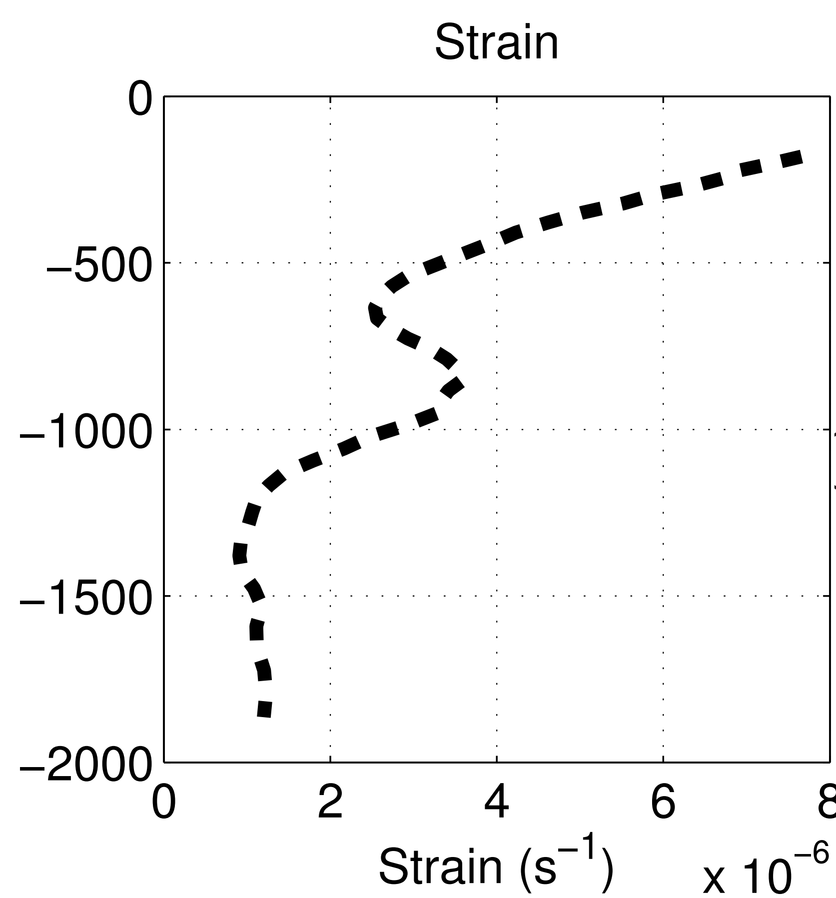


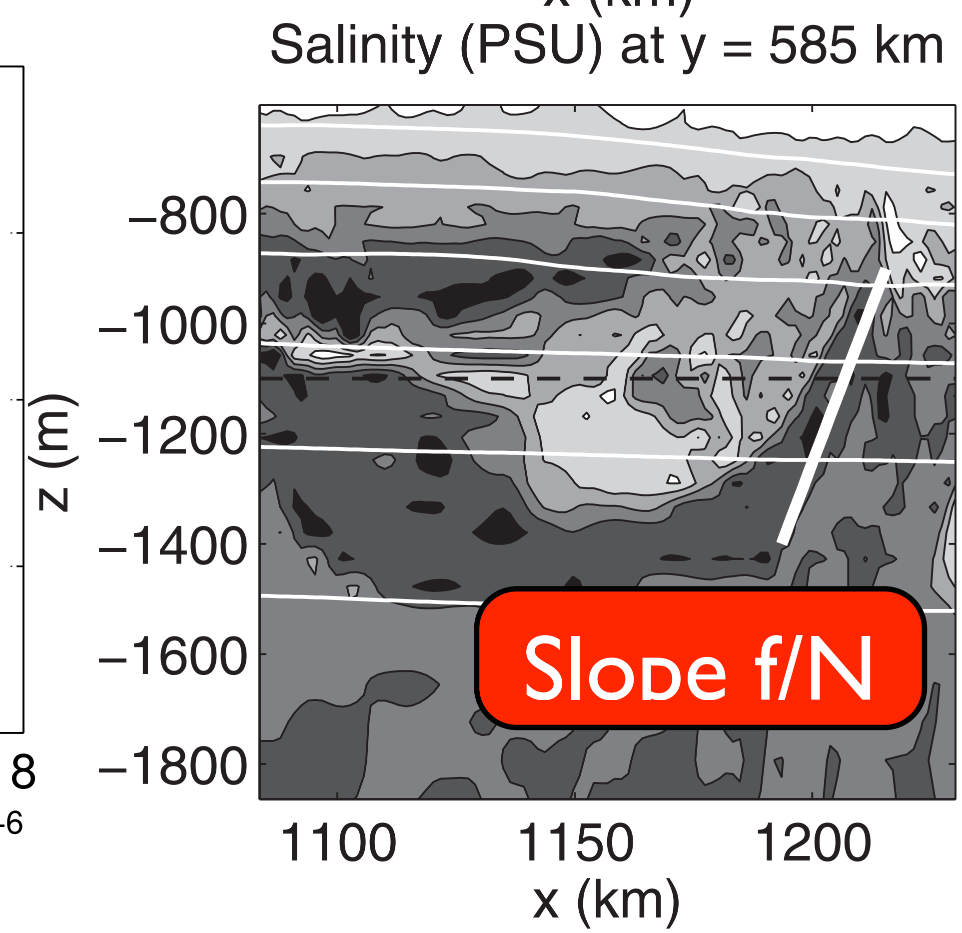
Vertical structure

- 3D cascade => ample strain and shear at submesoscales
- Shear/Strain ~ N/f (independent of scale)
- Tracer (T & S) filaments are 3D, with aspect ratios following shear/strain ~N/f



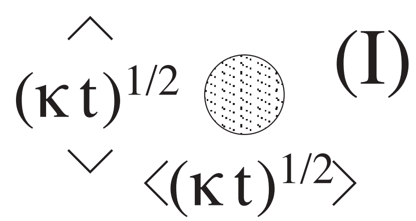




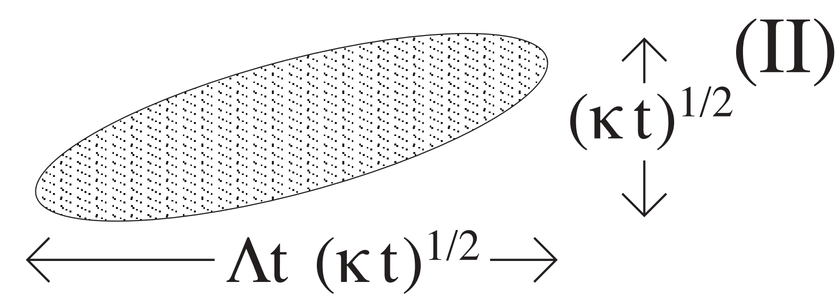


Kinematic argument for tracer slope

Tracer blob evolves with diffusion and velocity:



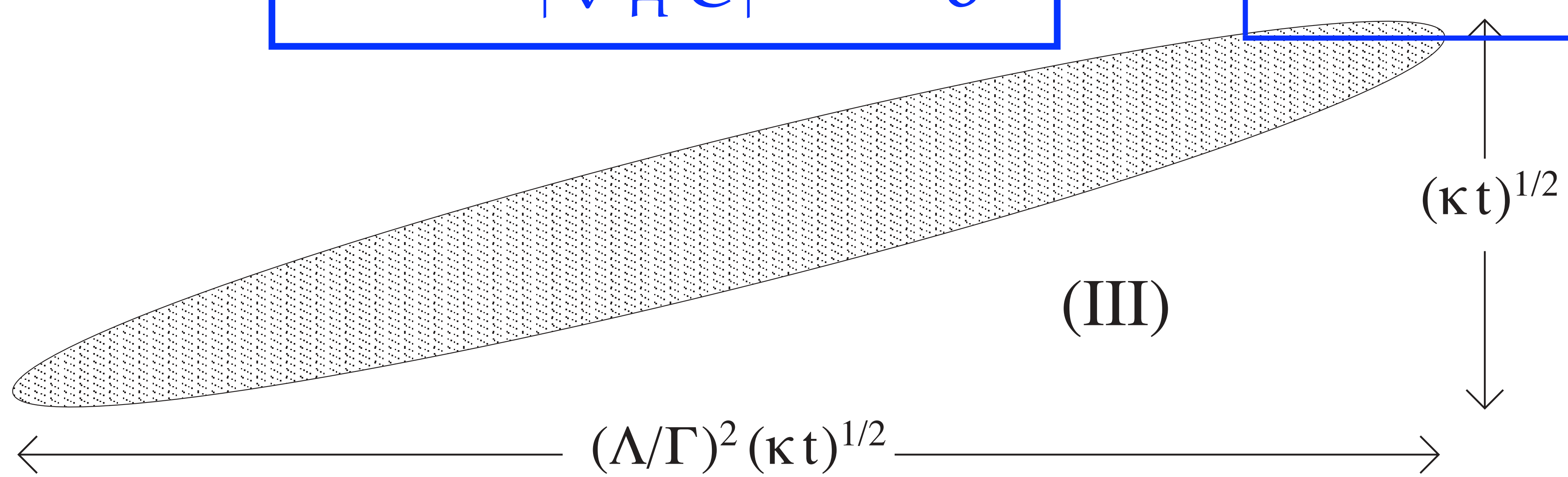
$$\mathbf{u} = (\sigma x, -\sigma y + \Lambda z, 0)$$



Haynes (2001)

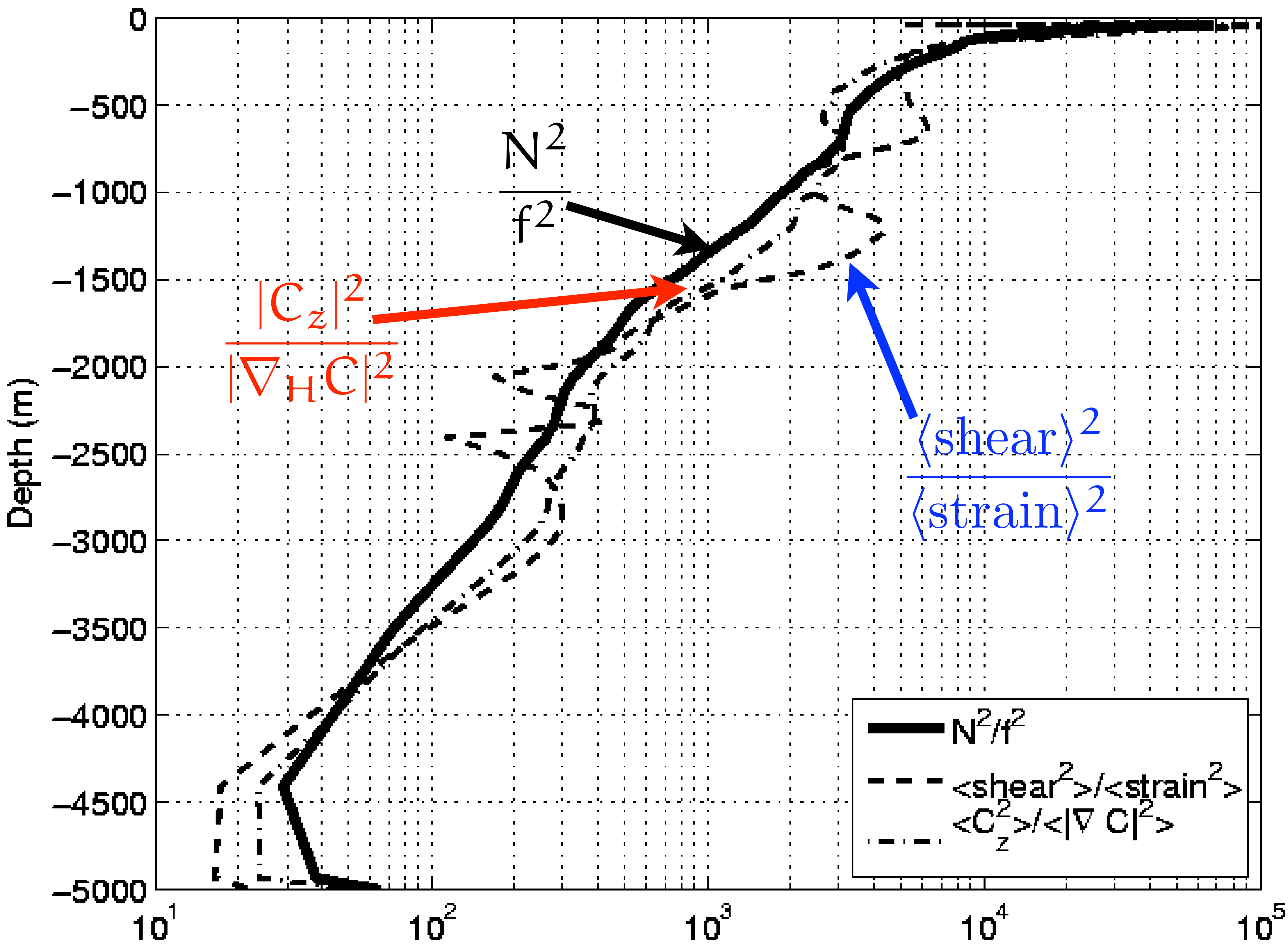
At long times: $\alpha^2 \equiv \frac{|C_z|^2}{|\nabla_H C|^2} \sim \frac{\Lambda^2}{\sigma^2}$

$$\kappa_H \sim \alpha^2 \kappa$$

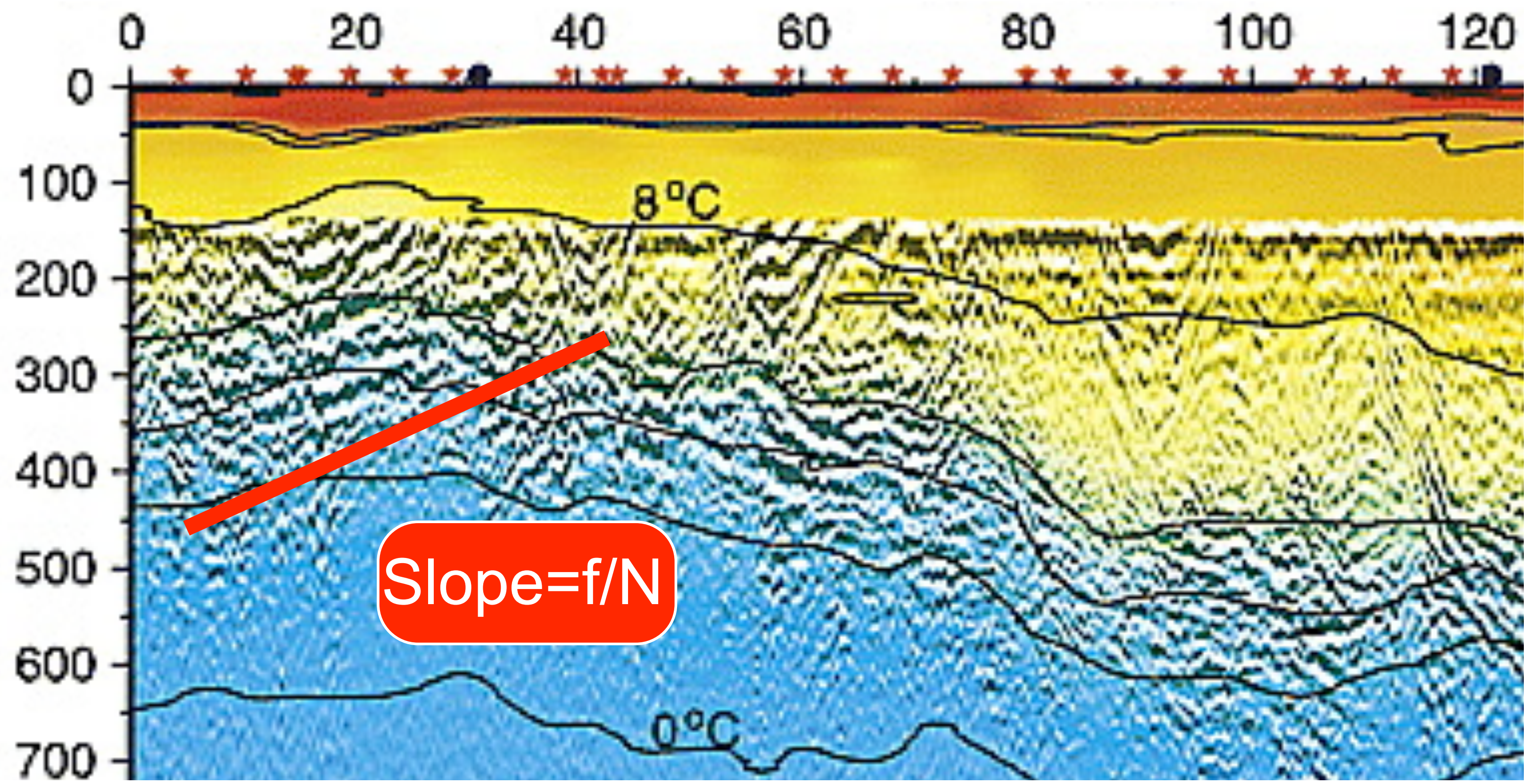


Geostrophic stirring field has $\frac{\Lambda^2}{\sigma^2} \sim \frac{N^2}{f^2}$

Tracer and Velocity Aspect Ratios

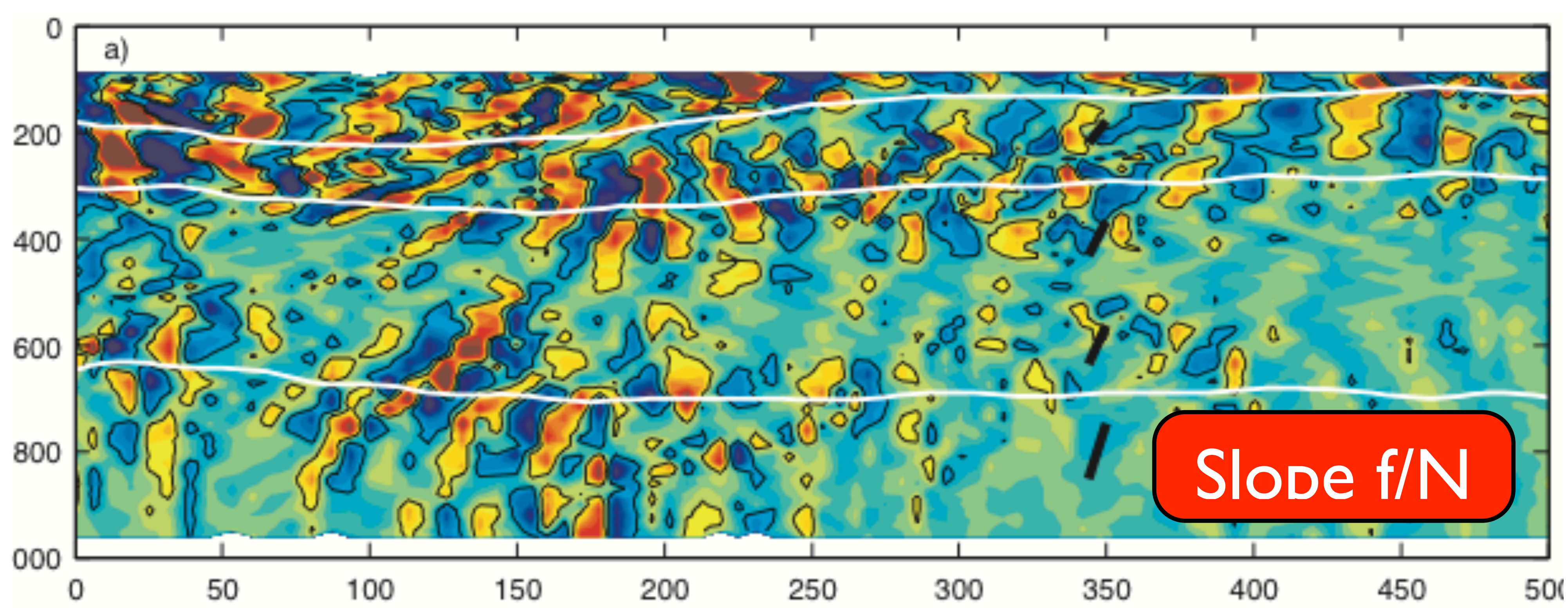


Observational support



Seismic observations of temperature (Nandi et al 04)

2.5 years glider data along central Pacific track (Cole & Rudnick 12)



Conclusions - Part I

- Mesoscale stirring produces T-S intrusions consistent with those found in NATRE
- Variance production by mesoscale stirring sufficient to explain measured turbulent dissipation at MST level
- Vertical diffusion can set observed tracer filament widths: Eddy stirring linked to small-scale turbulence
- W/ J. Taylor: identical 3D periodic QG and Boussinesq simulations show mesoscale controls stirring, even at high Ro, when Bous model forms $k^{-5/3}$ submesoscale energy spectrum

Balanced initial BC unstable states

Start with flow in geostrophic balance:

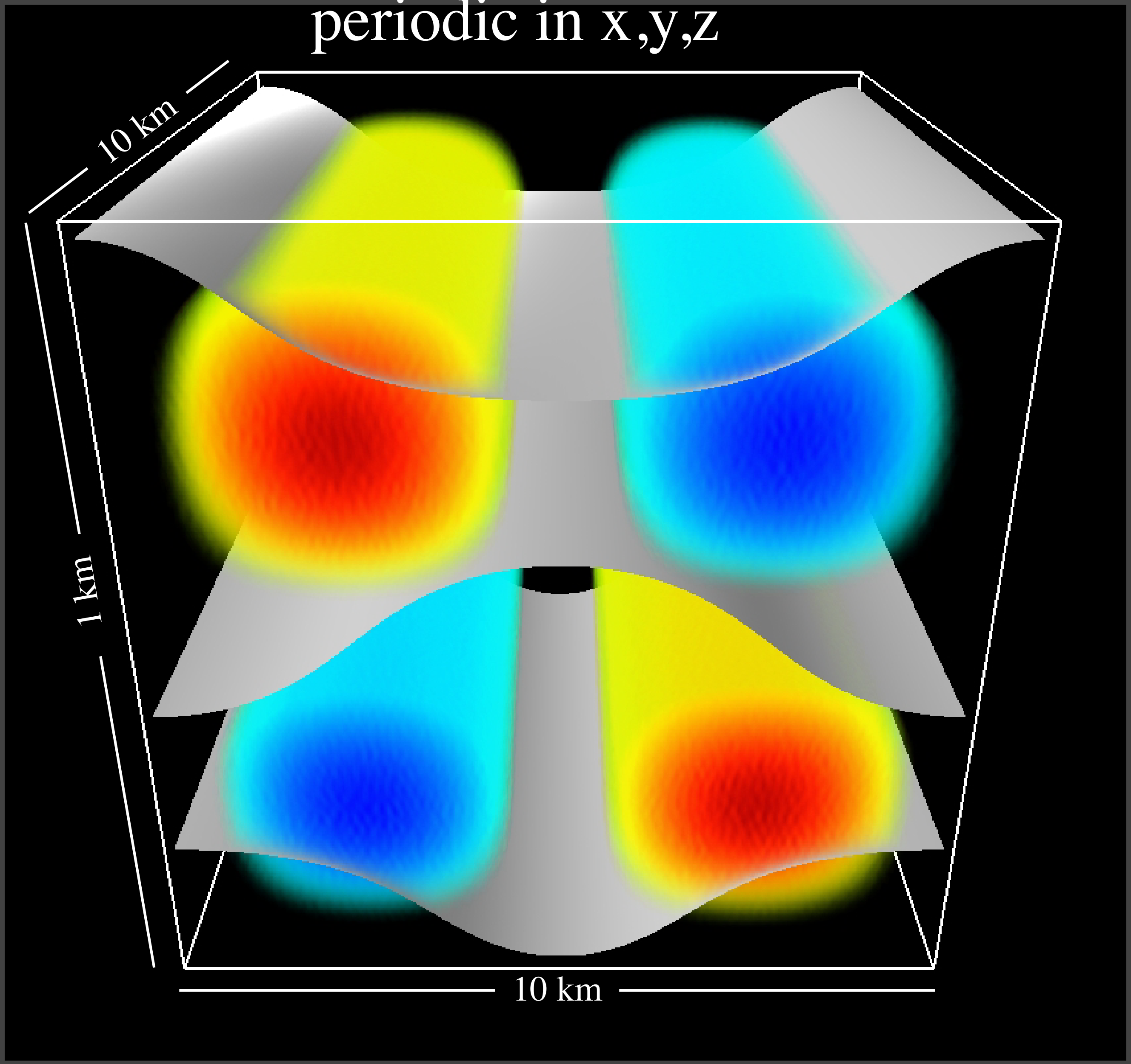
$$\begin{cases} u = \dfrac{M^2}{f m_0} sin(l_0 y) sin(m_0 z) \\ b = \dfrac{M^2}{l_0} cos(l_0 y) cos(m_0 z) + N^2 z \end{cases}$$

Simulation 1

$$Ro = M^2/Nf = 0.125$$
$$Ri = N^2 f^2/M^4 = 64$$
$$N/f = 2$$
$$(N_x, N_y, N_z) = (512, 512, 128)$$

Simulation 2

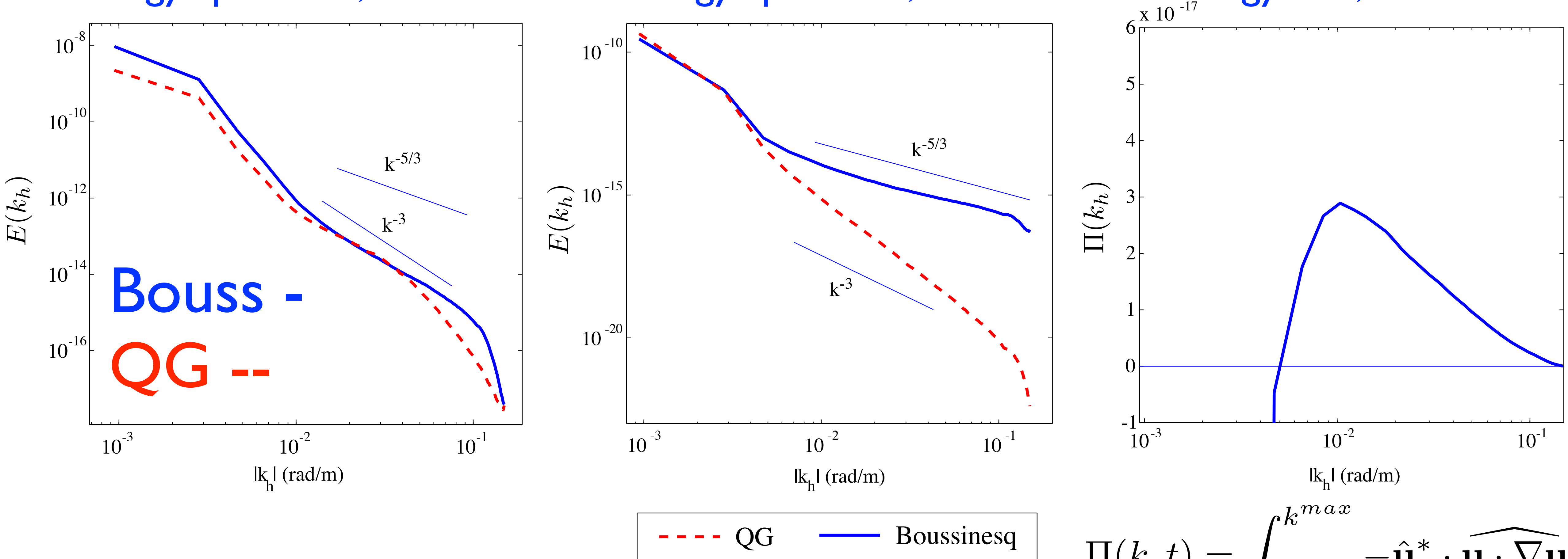
$$Ro = M^2/Nf = 0.418$$
$$Ri = N^2 f^2/M^4 = 5.76$$
$$N/f = 5$$
$$(N_x, N_y, N_z) = (512, 512, 256)$$



Energy spectra and fluxes

- Small scales more energetic in high Ro Boussinesq sim
- A forward energy cascade occurs for L < 1km

Energy spectrum, Ro=0.125 | Energy spectrum, Ro=0.418 | Energy flux, Ro=0.418

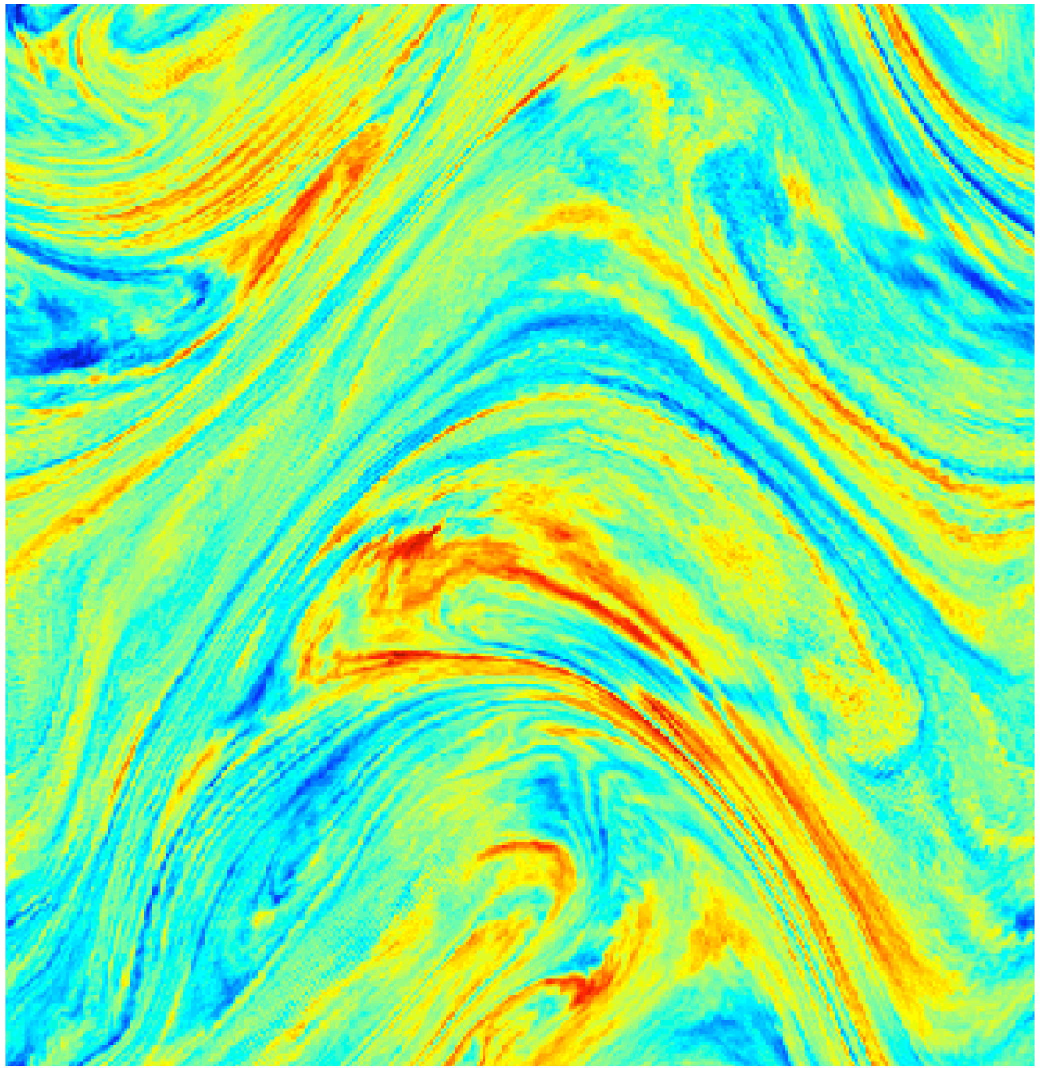


$$\Pi(k,t) = \int_k^{k^{max}} -\hat{\mathbf{u}}^* \cdot \widehat{\mathbf{u} \cdot \nabla \mathbf{u}} dk'$$

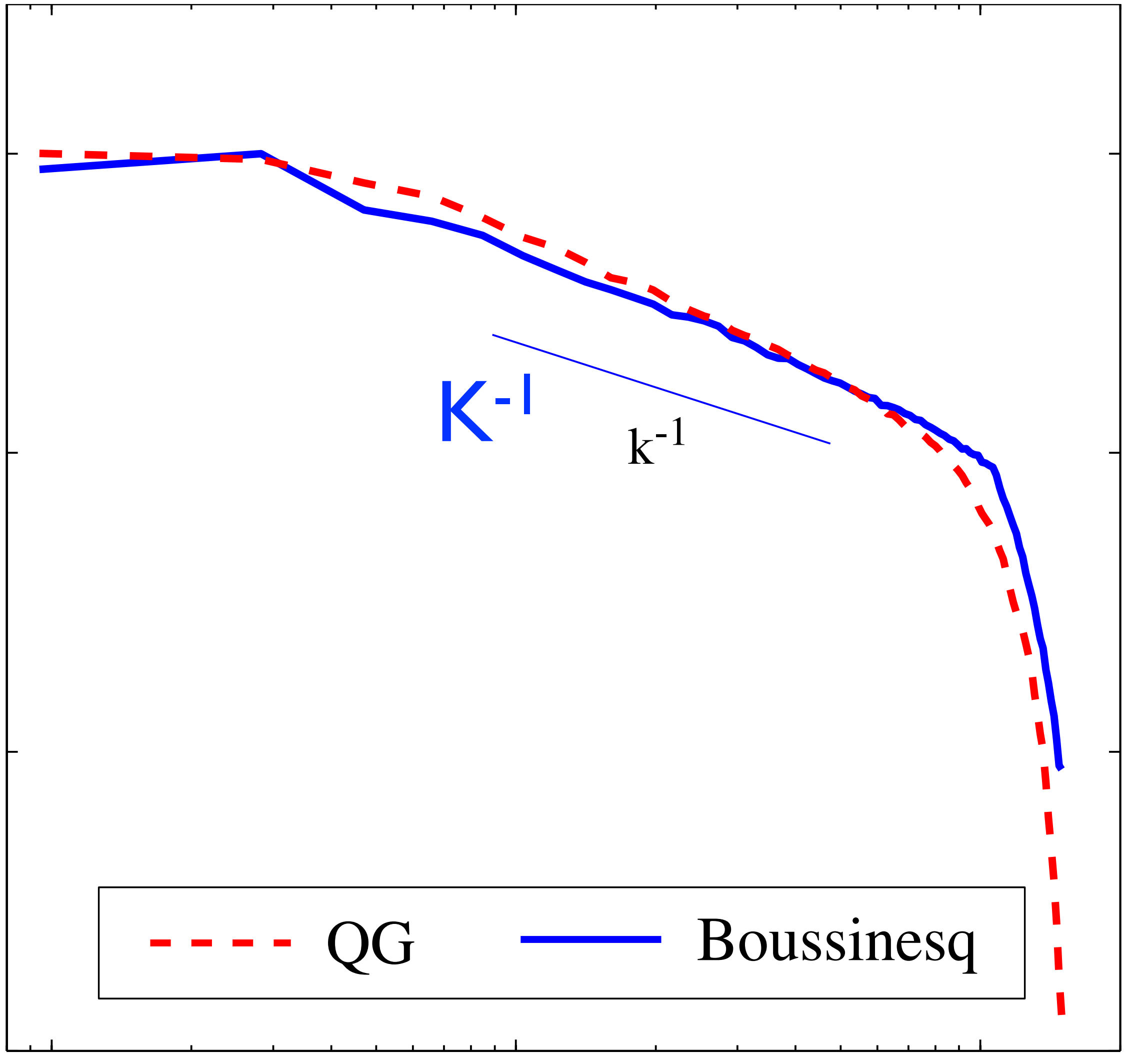
QG model does not capture small-scale energy or forward flux

But tracer spectrum has -1 slope in both cases!

Lateral tracer slice



Variance spectra



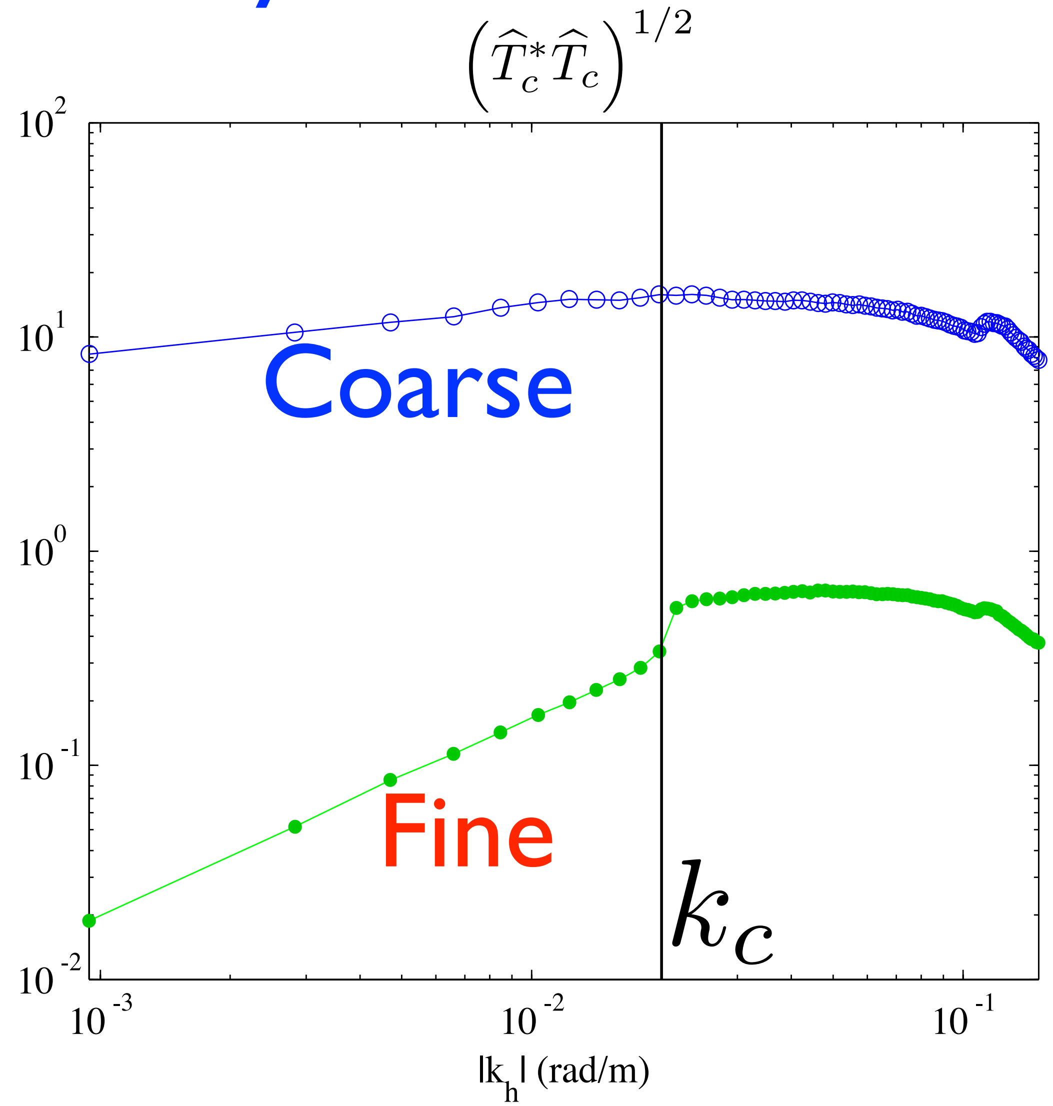
Tracer stirring by mean gradient

Spectral variance budget

$$\frac{\partial}{\partial t}\left(\frac{\widehat{c}^*\widehat{c}}{2}\right) = -\widehat{c}^*\widehat{\mathbf{u}\cdot\nabla c} - \widehat{c}^*\widehat{v}\frac{dC}{dy} + \widehat{c}^* D_c$$

$$\widehat{\mathbf{u}\cdot\nabla c} = \widehat{T}_c(k)$$

Split velocity into coarse and fine parts: $\mathbf{u} = \mathbf{u}^f + \mathbf{u}^c$



Tracer stirring dominated by scales above spectral break in KE…

The “Scalable Lateral Mixing and Coherent Turbulence” Directed Research Initiative (ONR)

Observation (mostly)

Eric D'Asaro (APL/Seattle), Lou Goodman (UMass), Jody Klymak (UVic), Eric Kunze (APL), Jim Ledwell (WHOI), Craig Lee (APL), Murray Levine (OSU), Jonathan Nash (OSU), Tom Sanford (APL), Kipp Shearman (OSU), Miles Sundermeyer (UMass), Brian Concannon (NAVAir)

Modeling/Theory (mostly)

Raffaele Ferrari (MIT), Ramsey Harcourt (APL), Pascale Lelong (NRWA), Amala Mahadevan (WHOI), Jim McWilliams (UCLA), Jeroen Molemaker (UCLA), Tamay Ozgokmen (RSMAS), Roger Samelson (OSU), Eric Skyllingstad (OSU), Shafer Smith (Courant/NYU), Amit Tandon (UMass), Leif Thomas (Stanford)

Evolution of the DRI

Timeline

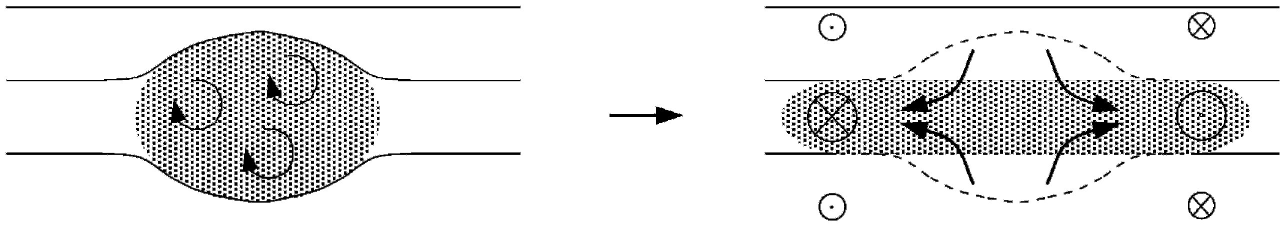
May 2008: Initial planning meeting
Jan 2009: ONR funding began
June 2010: Virtual experiment
Aug 2010: Test cruise (Cape Hatteras)
June 2011: Summer experiment (Cape Hatteras)
Mar 2012: Winter experiment

DRI Objective: Develop a combined modeling and observational program to investigate the mechanism that control transport and mixing at lateral scales of 100m-10km.

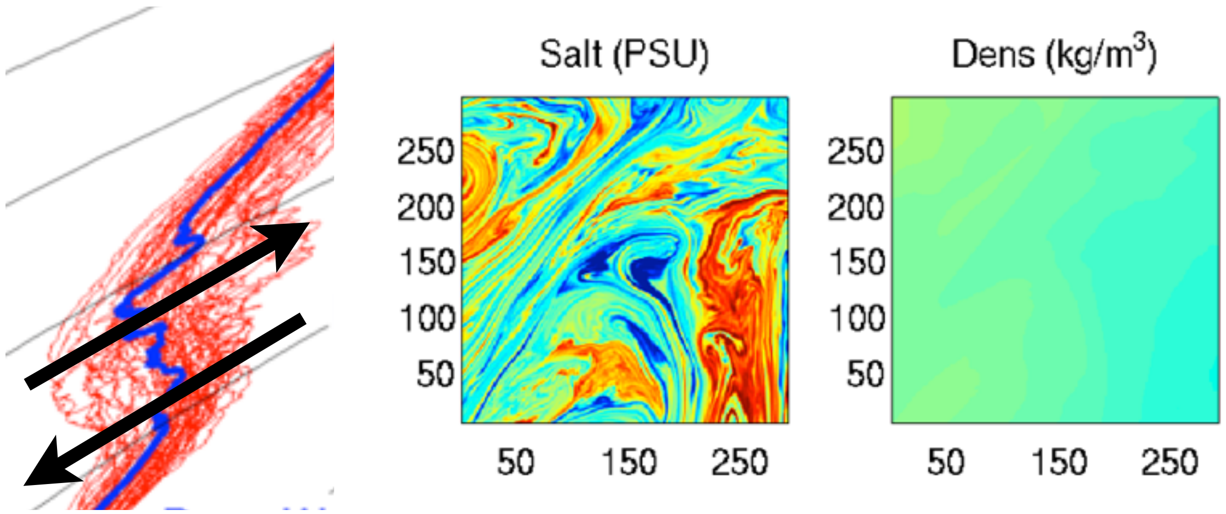
Hypothesis-driven plan

ONR insisted that the group develop a set of competing **hypotheses** that would serve as a basis for all future planning. Initial meetings led to:

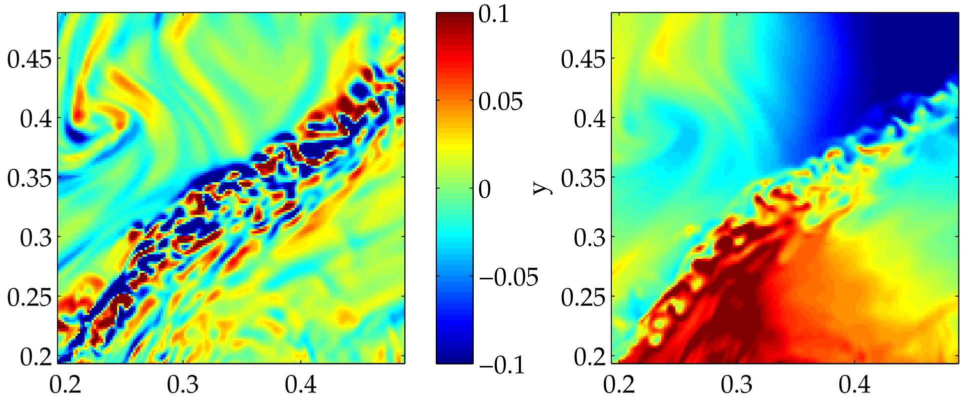
1. Inhomogeneous IW mixing creates PV anomalies that are responsible for significant isopycnal mixing.



2. Mesoscale straining leads to a cascade of tracer and PV variance, and submesoscale isopycnal mixing.



3. Unbalanced submesoscale instabilities feed a forward cascade of energy, scalar and PV variance, leading to isopycnal and diapycnal mixing.



I. "Open Ocean" (shallow ML, moderate EKE)

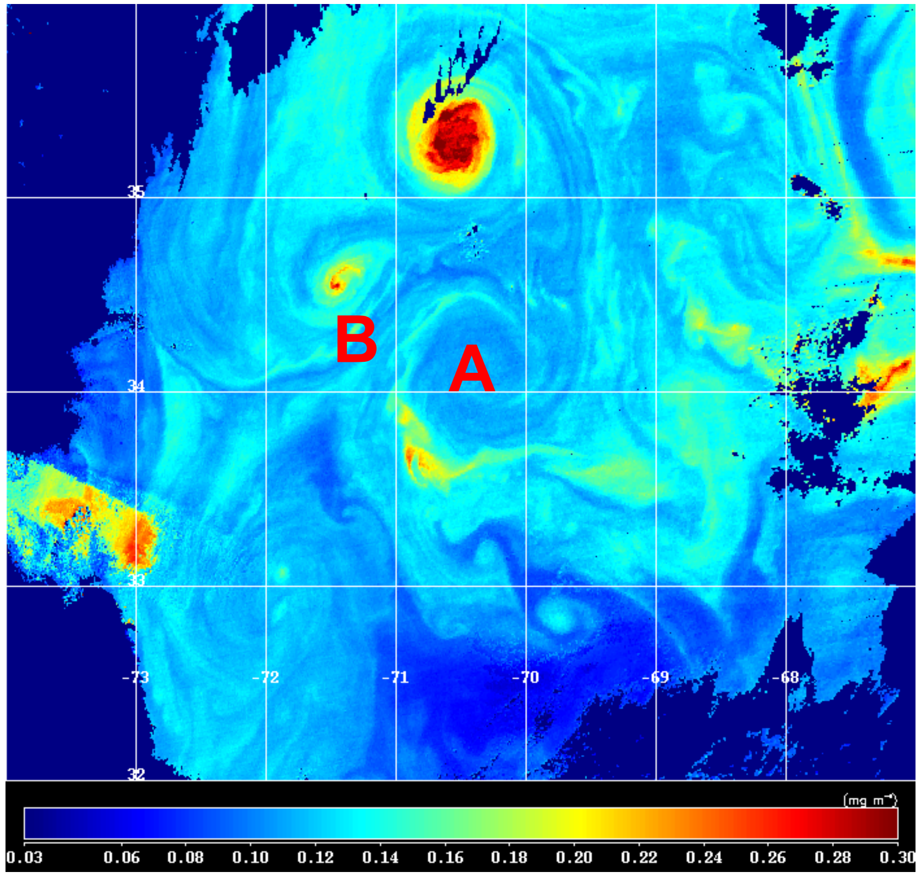


Figure 1: Sea surface chlorophyll distribution derived from sea surface color in the western Sargasso Sea on May 27, 2007 showing generic open ocean conditions that could be used to test hypotheses 1-3.

II. "Frontal" (deep ML, strong front)

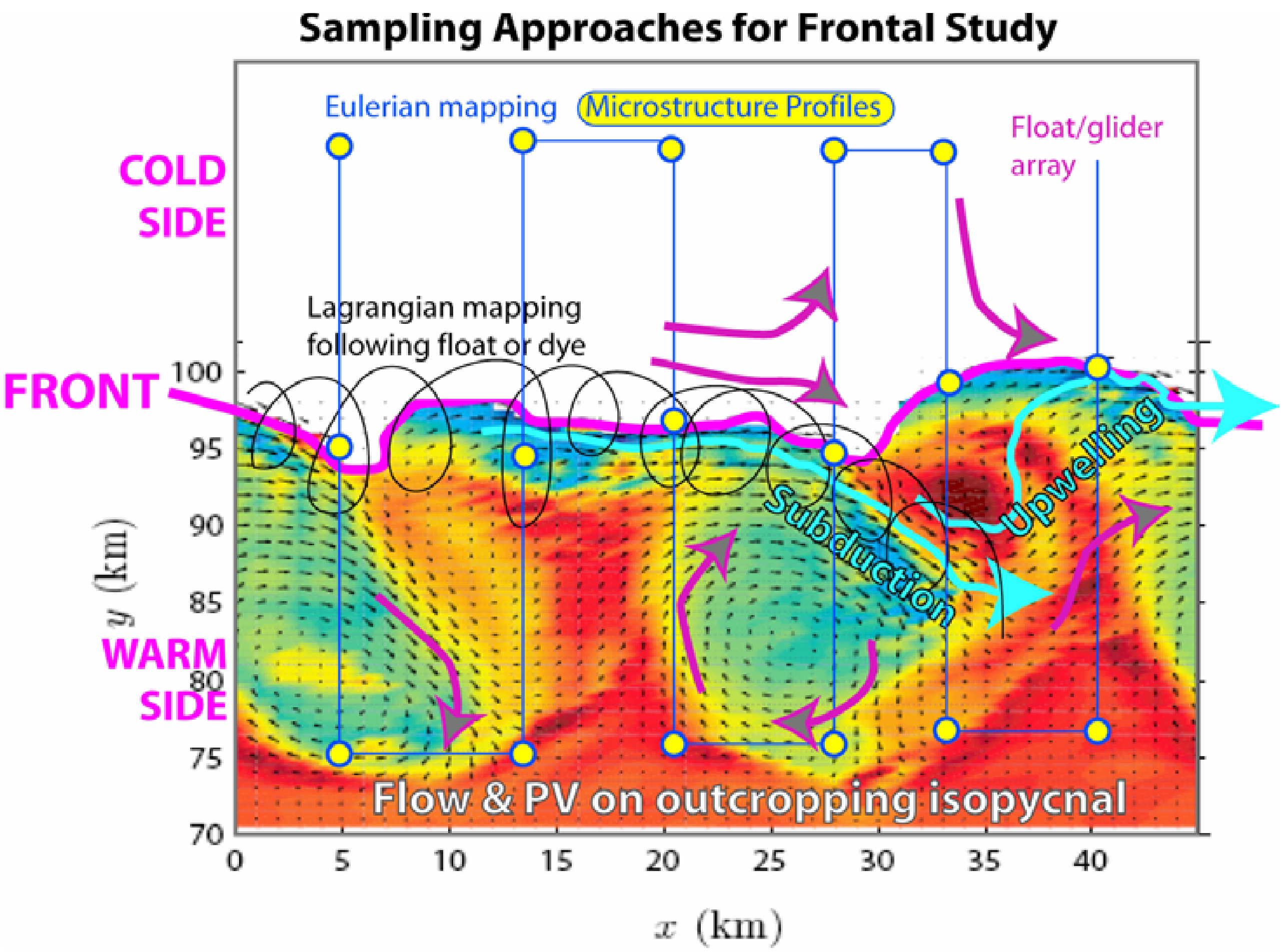


Figure 2: Schematic of possible sampling strategies for field site 2 superimposed on a simulation of a submesoscale frontal instability (from Thomas, 2007). Potential experimental elements are described in the text.

June 2011 campaign

Near field sampling

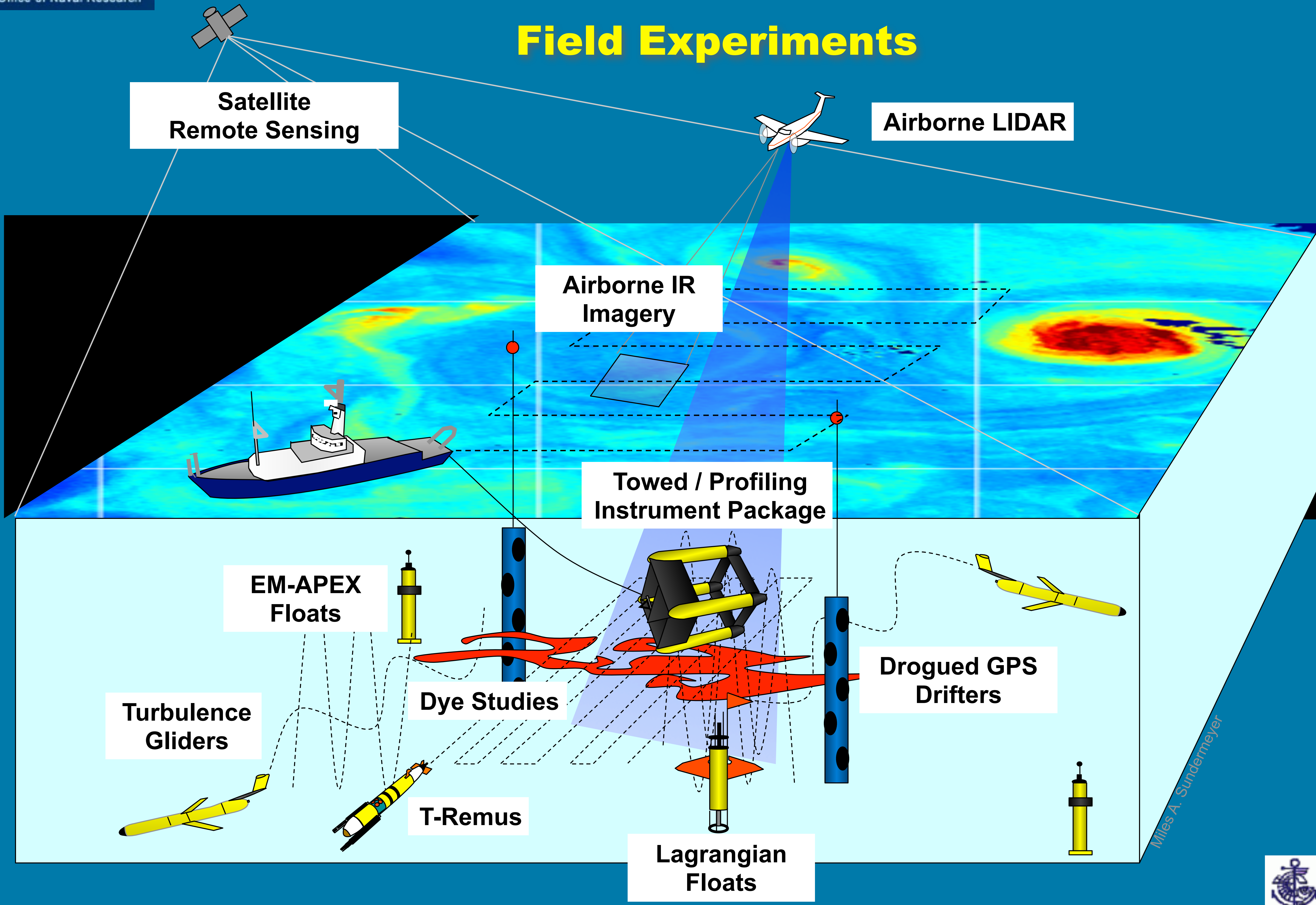
Medium scale sampling

Large scale sampling

Platform	Instrument, Sensors, and/or Activity	Responsible Investigators
C. Hatteras	Dye Release	Ledwell
	Lagrangian Floats, CTD, Fluorometer	D'Asaro
	Drogued Drifters and T-strings	Sundermeyer, Lelong
	OSU Moving Vessel Profiler, CTD, Fluorometer	Levine
	UMass Towed Acrobat, CTD, Fluorometer	Sundermeyer, Birch
	Hull-mounted ADCP	Pierce
Endeavor	EM-APEX Constellation, CTD, u, v	Sanford, Lien, Dunlap
	U.Vic. Moving Vessel Profiler, CTD, Fluorometer	Klymak
	OSU Gliders	Shearman
Oceanus	Triaxus Towed CTD, Fluorometer, ADCP	Lee
	T-REMUS, CTD, ADCP, Microstructure	Goodman
	Gateway Buoy, T-string	Goodman
	Hammerhead towed CTD/Microstructure	Kunze
All 3 ships	Ship ADCP	Pierce
All 3 ships	Ship ADCP/Towed CTD synthesis	Shcherbina
	SVP Drifters	Lelong, Ozgokmen
P3-*Orion*	LIDAR	Concannon, Terray
APL-UW	INFLO data system	Harcourt
	Shipboard data systems	Sellers, Stolp

ONR LatMix

Field Experiments

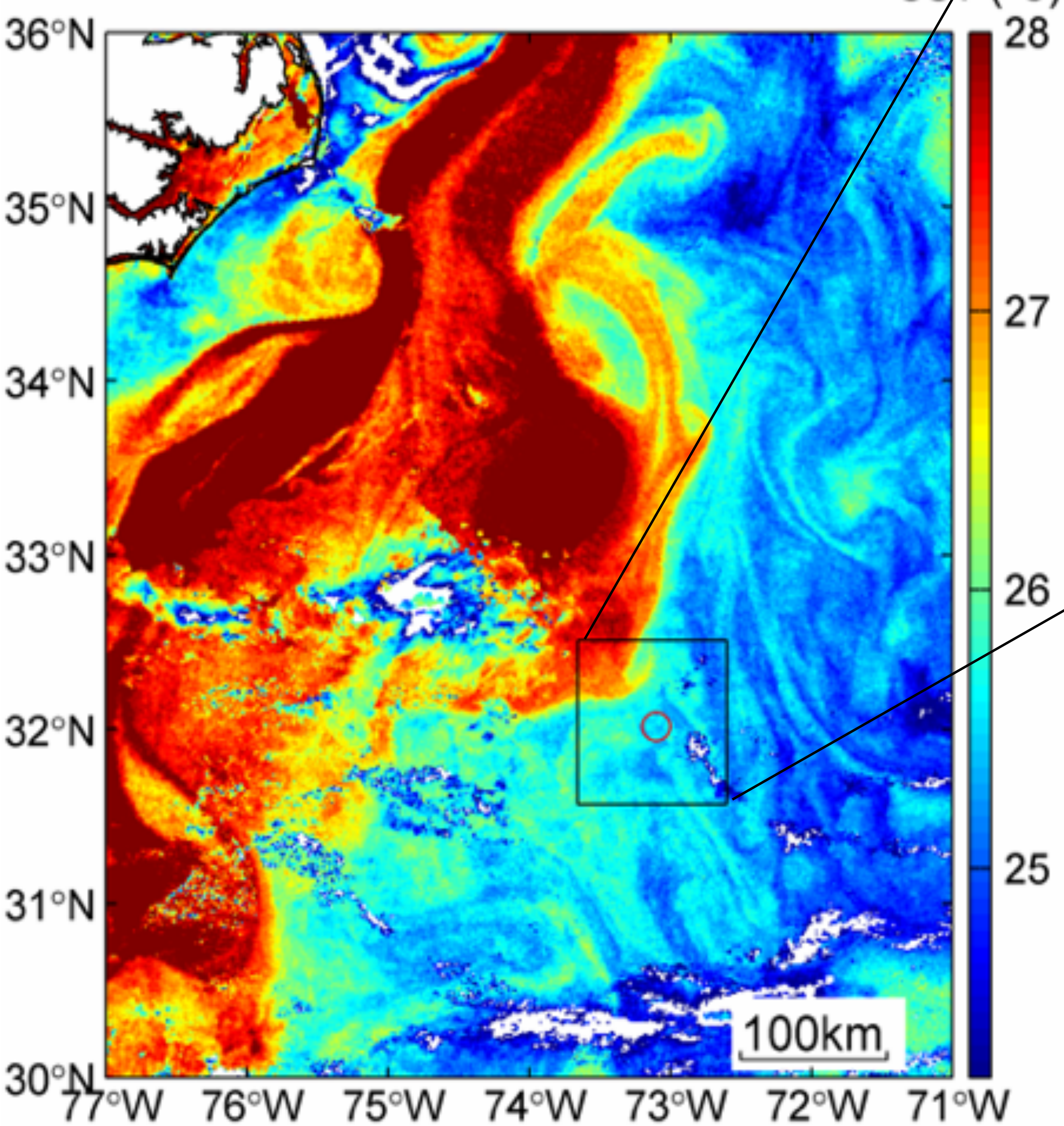


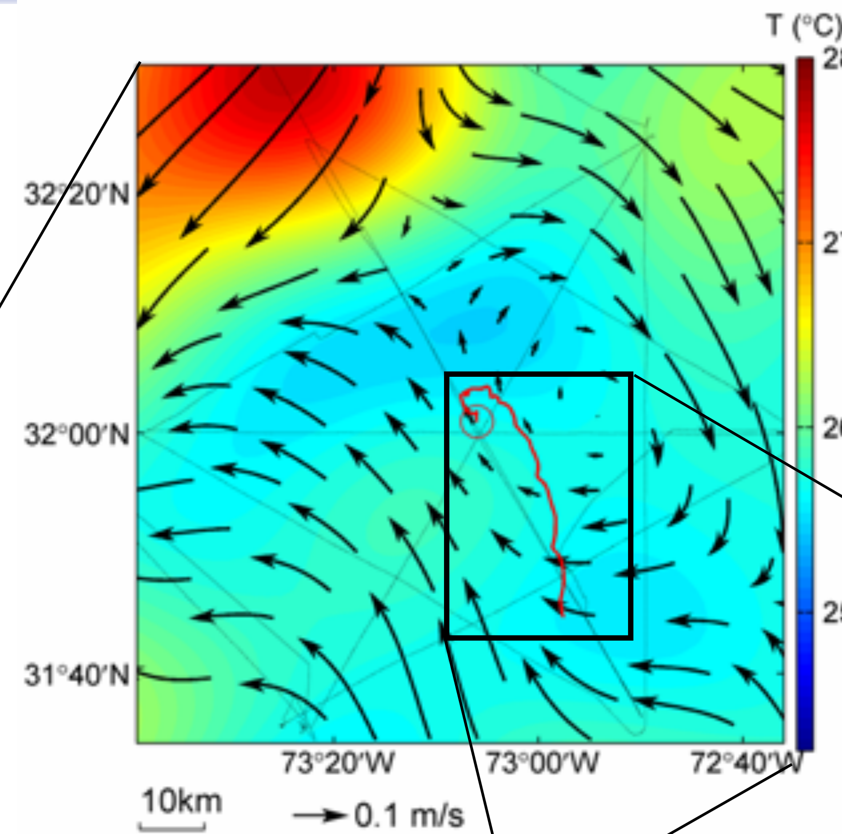
Office of Naval Research

Sundermeyer

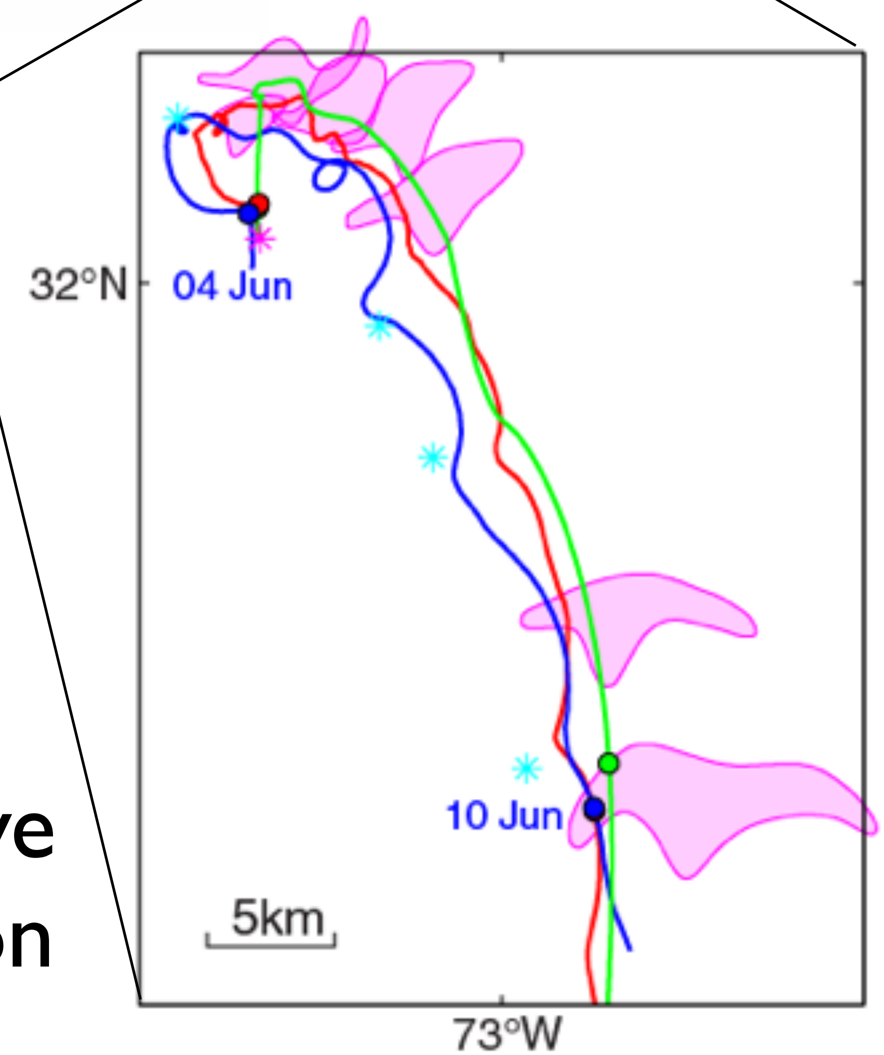
Weak strain area - rhodamine dye release

AVHRR SST 4 June 11





COM path



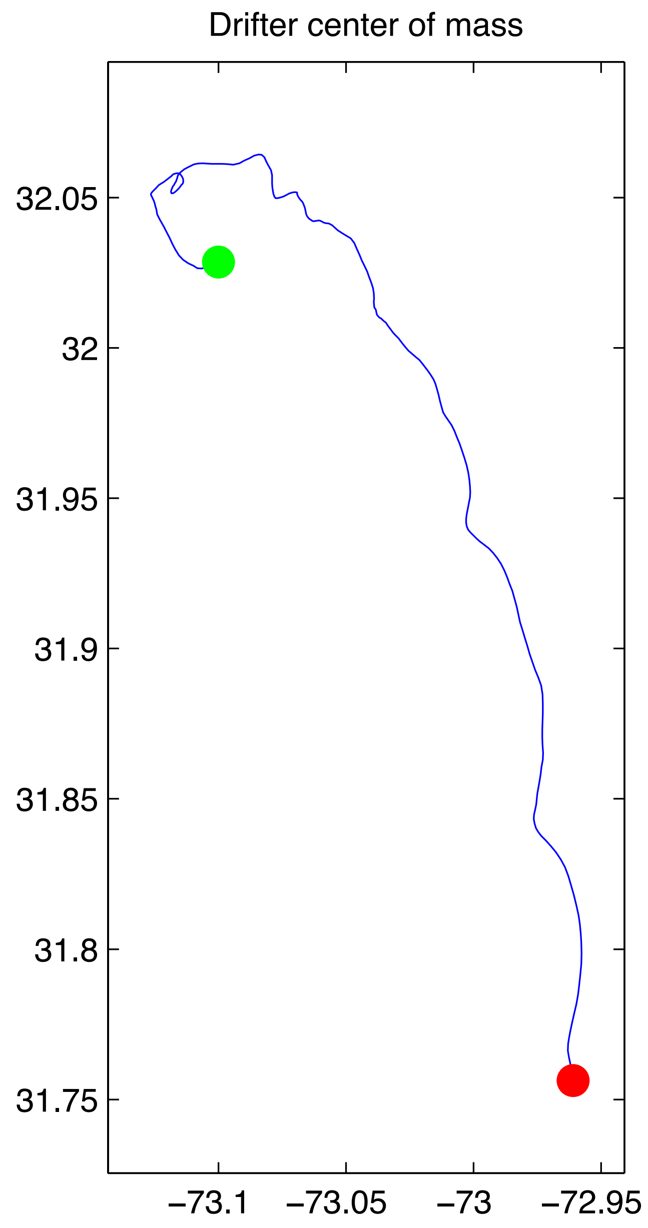
Rhodamine dye patch evolution

Dye vs Drifter Diffusivity

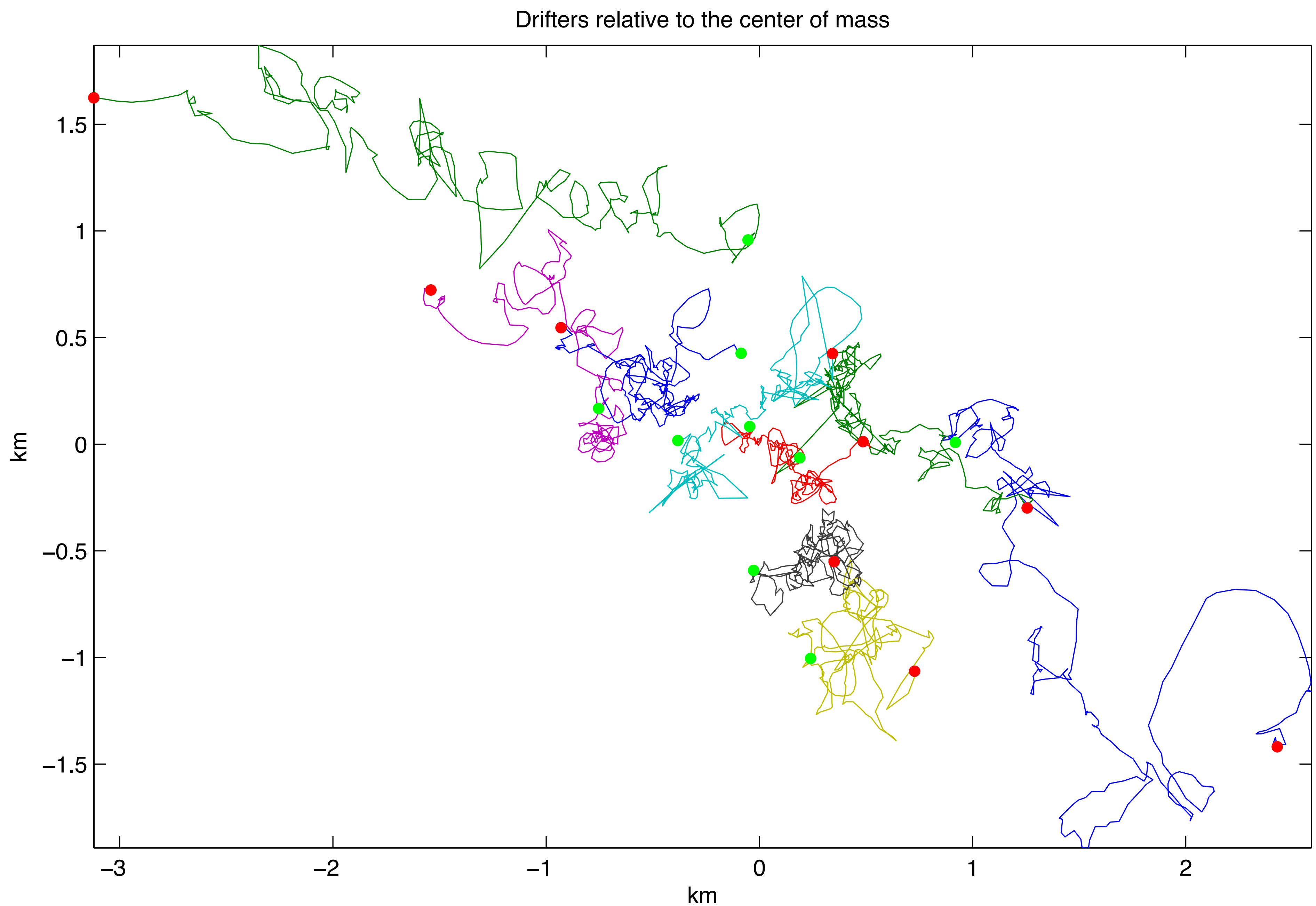
- Analysis of dye spreading by D. Birch and M. Sundermeyer implies lateral diffusivity of $O(1)\ \mathrm{m}^2/\mathrm{s}$
- J. Early: Drifters released with dye provide an alternate means to compute lateral diffusivity; find $O(.1)\ \mathrm{m}^2/\mathrm{s}$
- What is causing the observed diffusivity?
- Why are the dye and drifters so different?

Drogued drifters to track dye

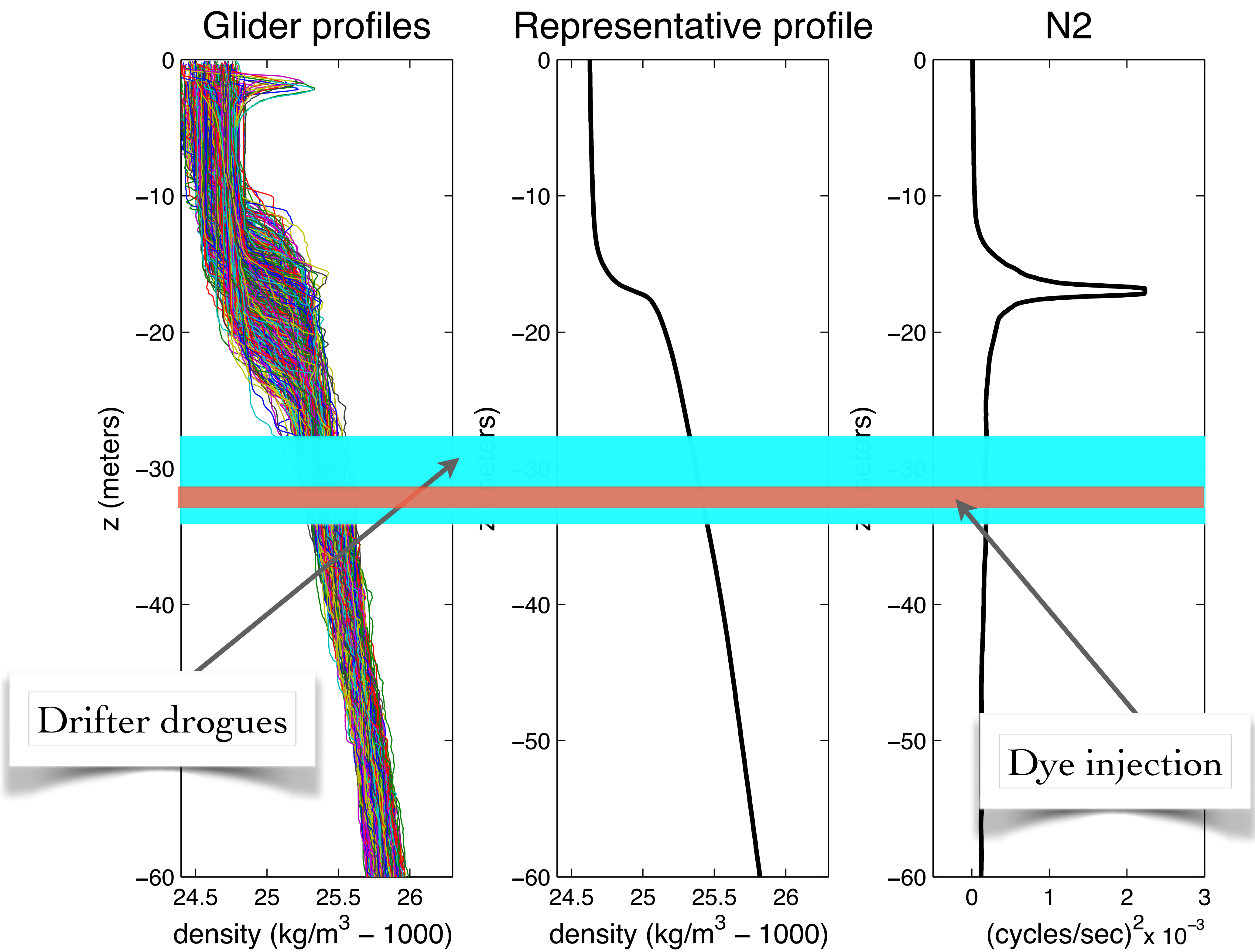
COM



Drifters relative to COM

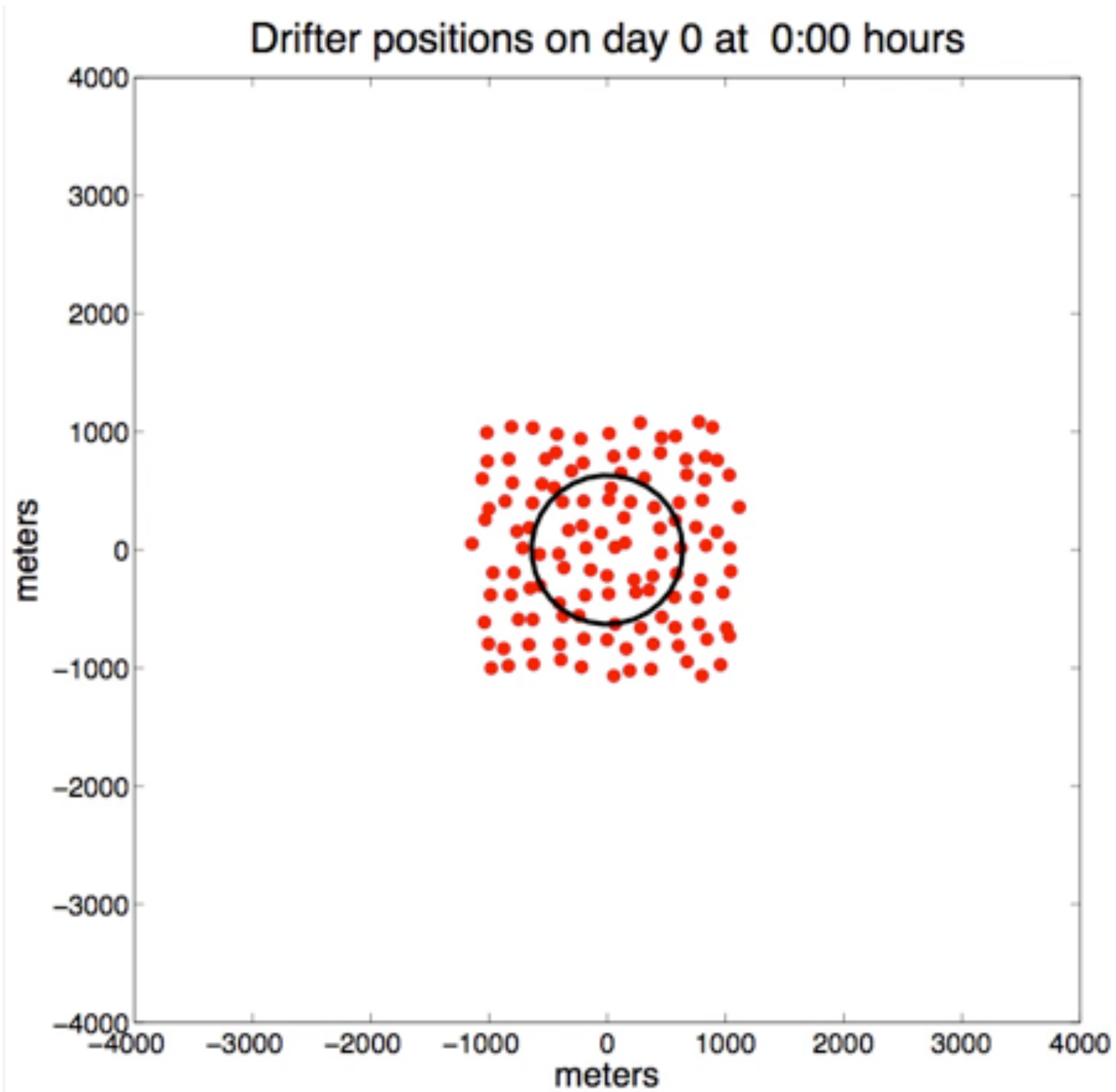


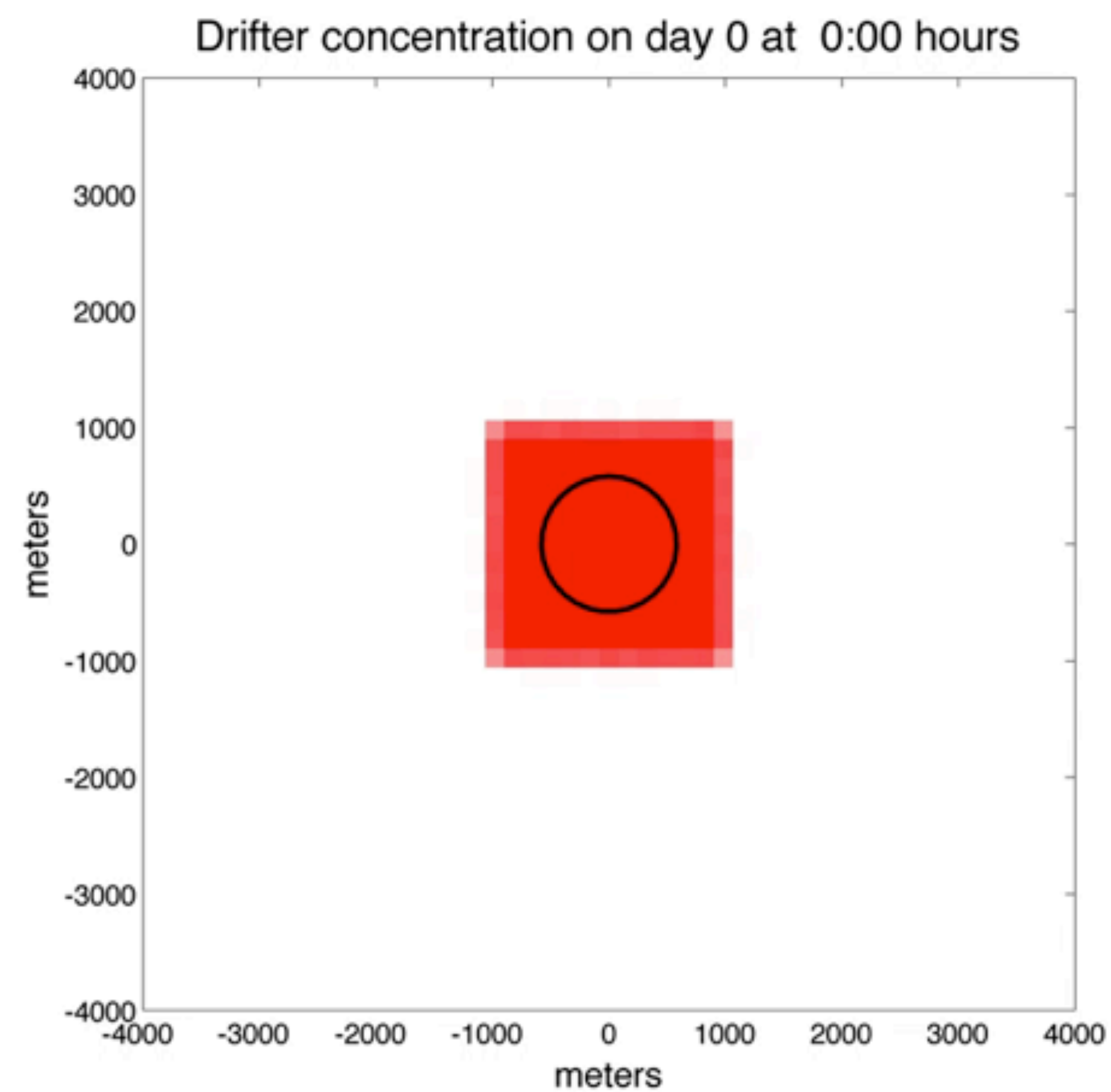
Density from gliders



Particles on random walk with constant diffusivity

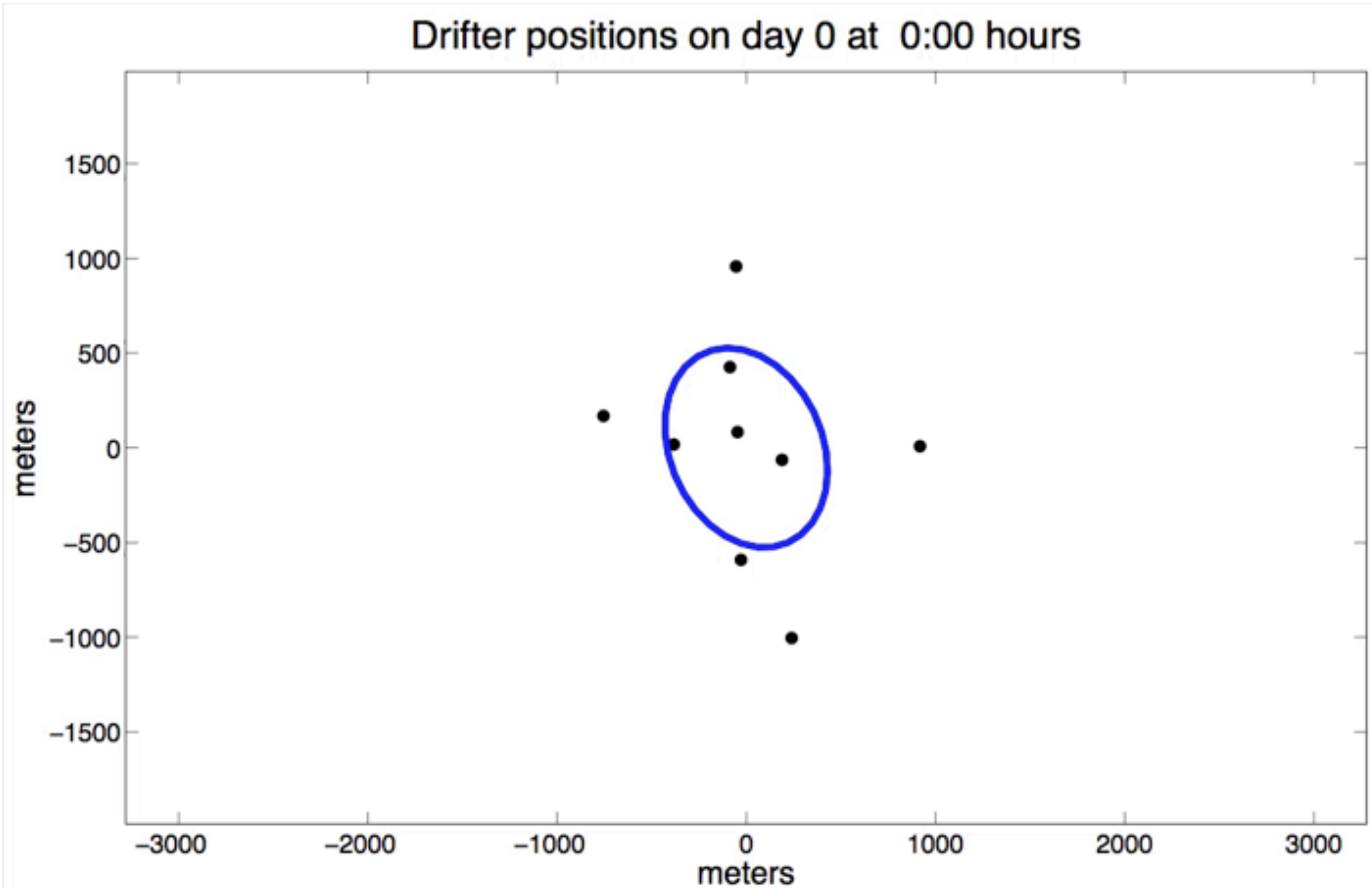
$$\partial_t \begin{bmatrix} x_i(t) \\ y_i(t) \end{bmatrix} = \sqrt{2\kappa}\,\mathbf{dW}_i. \quad \text{Large N =>} \quad \phi_t = \kappa \nabla^2 \phi$$





2^{nd} moment

Drifter trajectories in COM coordinates



Observed 2nd moment

Isotropic model, $\kappa = 0.57 \pm 0.13 \text{ m}^2/\text{s}$

Strain-Diffusivi

- Isotropic diffusivity is *not* a good model.
- The drifters are clearly being stretched by a strain field.
- Need a model to account for strain and diffusivity.

Strain-Diffusivity Model

- Model for tracer $\phi(x, y, t)$,

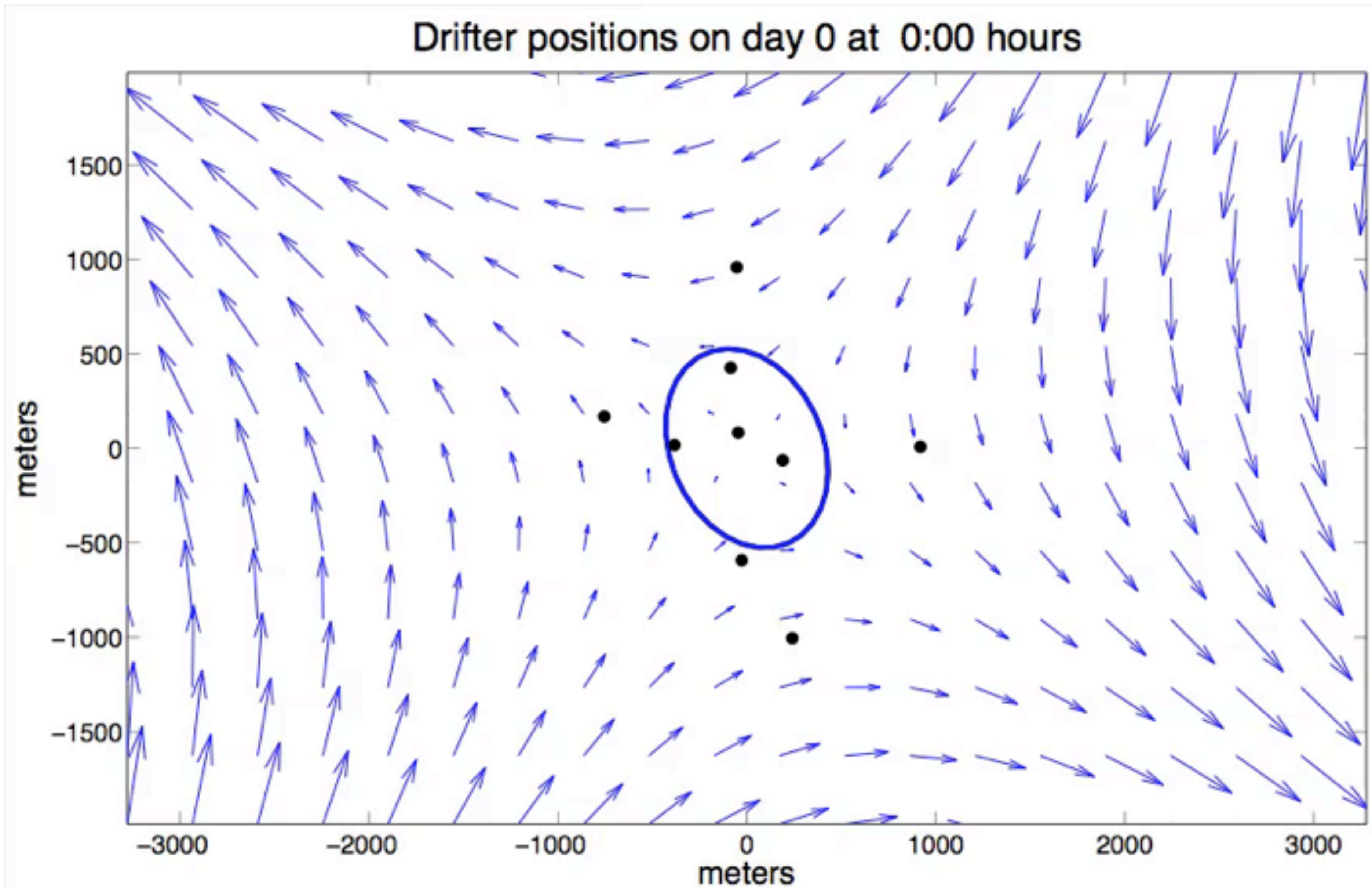
$$\phi_t + \frac{\sigma}{2}\left(x\cos 2\theta - y\sin 2\theta\right)\phi_x - \frac{\sigma}{2}\left(x\sin 2\theta + y\cos 2\theta\right)\phi_y = \kappa\nabla^2\phi.$$

- Model for particle $(x_i(t), y_i(t))$, **[Birch & Sundermeyer]**

$$\partial_t \begin{bmatrix} x_i(t) \\ y_i(t) \end{bmatrix} = \frac{\sigma}{2}\begin{bmatrix} \cos 2\theta & -\sin 2\theta \\ -\sin 2\theta & -\cos 2\theta \end{bmatrix}\begin{bmatrix} x_i(t) \\ y_i(t) \end{bmatrix} + \sqrt{2\kappa}\,\mathbf{dW}_i.$$

- Strain σ, angle θ, diffusivity κ, are parameters to find by minimizing an error function.

Drifter trajectories in COM coordinates

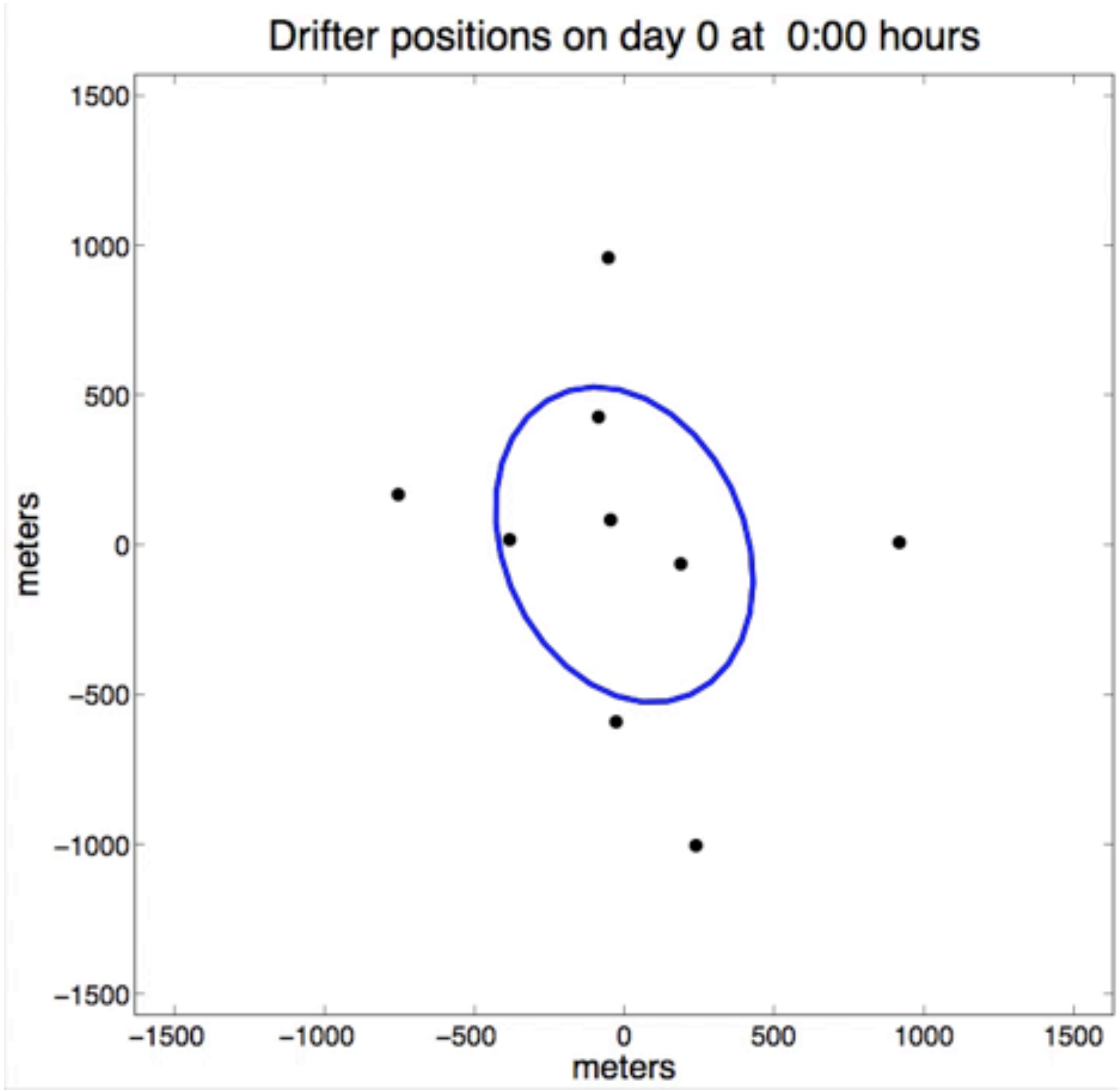


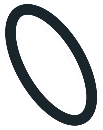
Observed 2nd moment

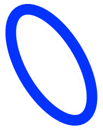
Strain-diffusivity model,

$\kappa = 0.20 \pm 0.04 \text{ m}^2/\text{s}, \sigma = 3.4 \cdot 10^{-6} \text{ s}^{-1}, \theta = -32^\circ$

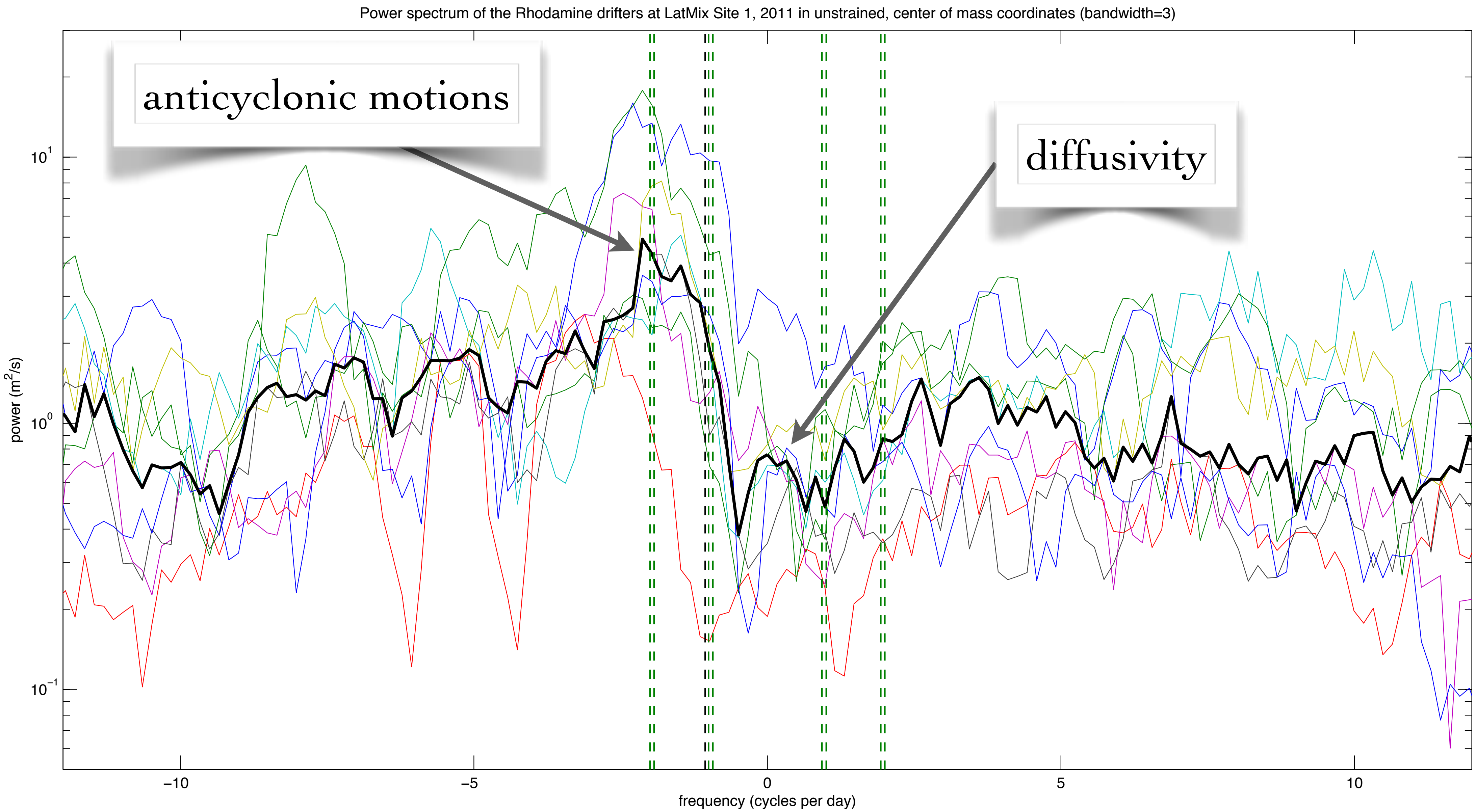
Drifter trajectories with strain removed



 Observed 2nd moment

 Isotropic model, $\kappa = 0.23 \pm 0.06 \text{ m}^2/\text{s}$

Velocity spectra from unstrained, COM drifter tracks



Velocity spectrum looks like internal waves.
Single particle diffusivity estimates also give $\kappa = 0.2\ \mathrm{m}^2/\mathrm{s}$

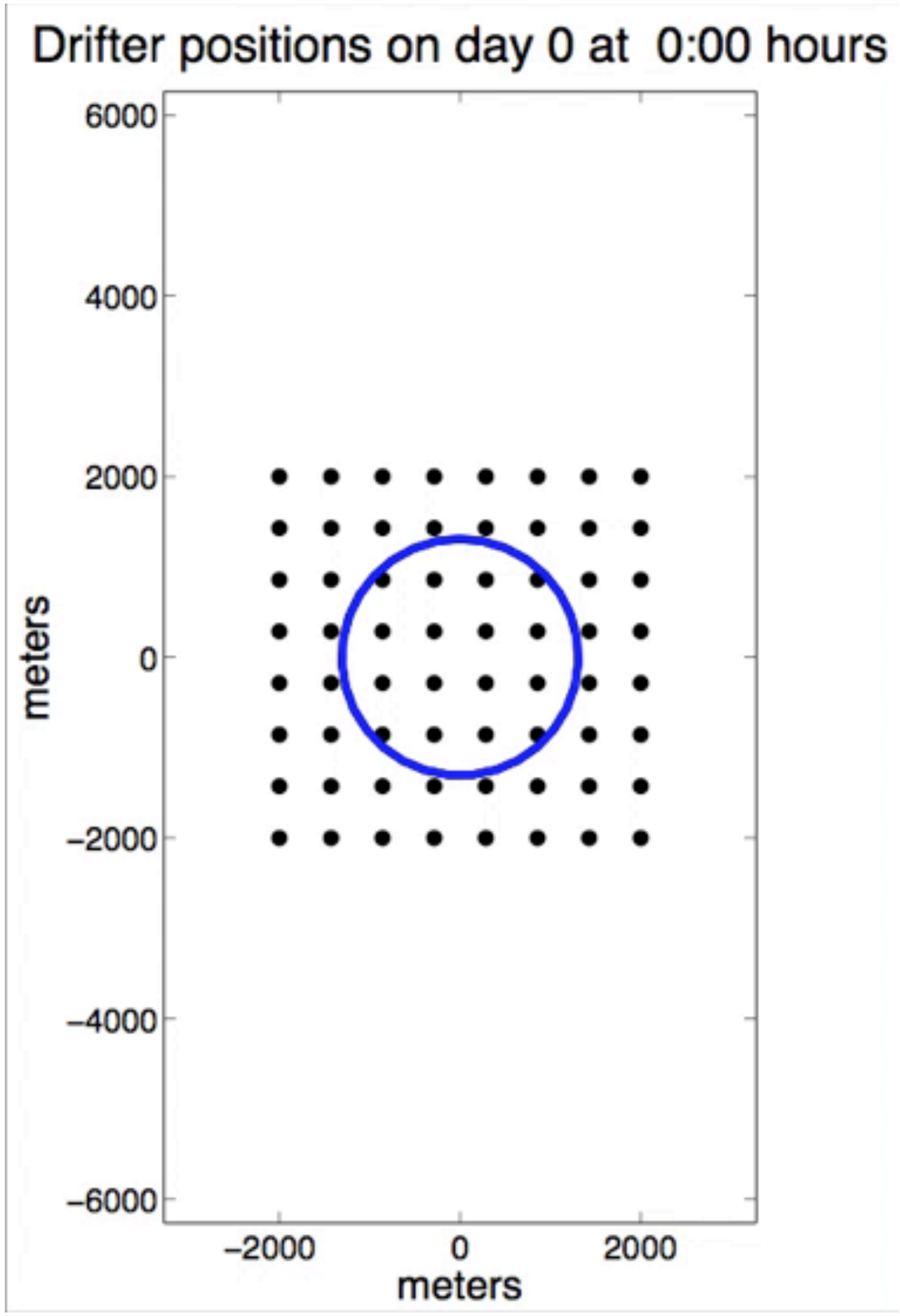
Null hypothesis test

- Below scale of eddy, IWs are only motion observed
- Dye spreads on isopycnal, drifters spread at constant depth, with average velocity over 6m length of drogue
- Advect particles with GM spectrum of waves, with energy matched to observations:
  - **Dye-like particles:** isopycnal following and diffusive, subject to shear dispersion.
  - **Dye-like non-diffusive particles**: isopycnal following, but not subject to shear dispersion.
  - **Drifter-like particles**: fixed z, averaged over depth.

Drifter-Like Particles

GM linear wave model set to match observed energy levels of dye release region.

More particles than were released in experiment.

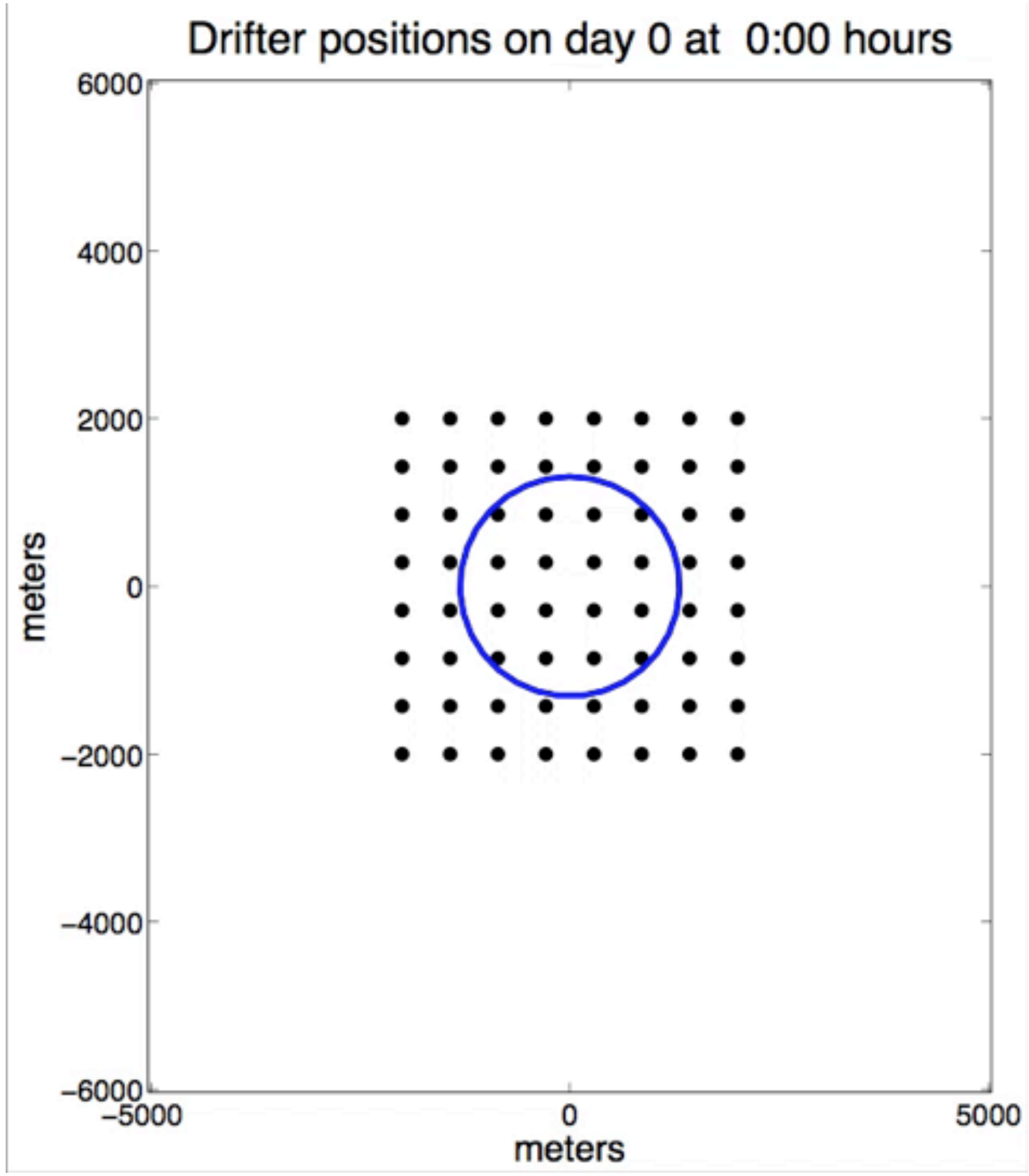


Observed 2nd moment

Isotropic model, $\kappa = 0.26 \pm 0.08\ \mathrm{m}^2/\mathrm{s}$

Dye-Like Particles

- Much higher diffusivity than for drifter-like particles (Dewar 1980 predicted similar result!)
- Diffusive & non-diffusive (not shown) cases indistinguishable => shear dispersion negligible (Birch & Sundermeyer, too)



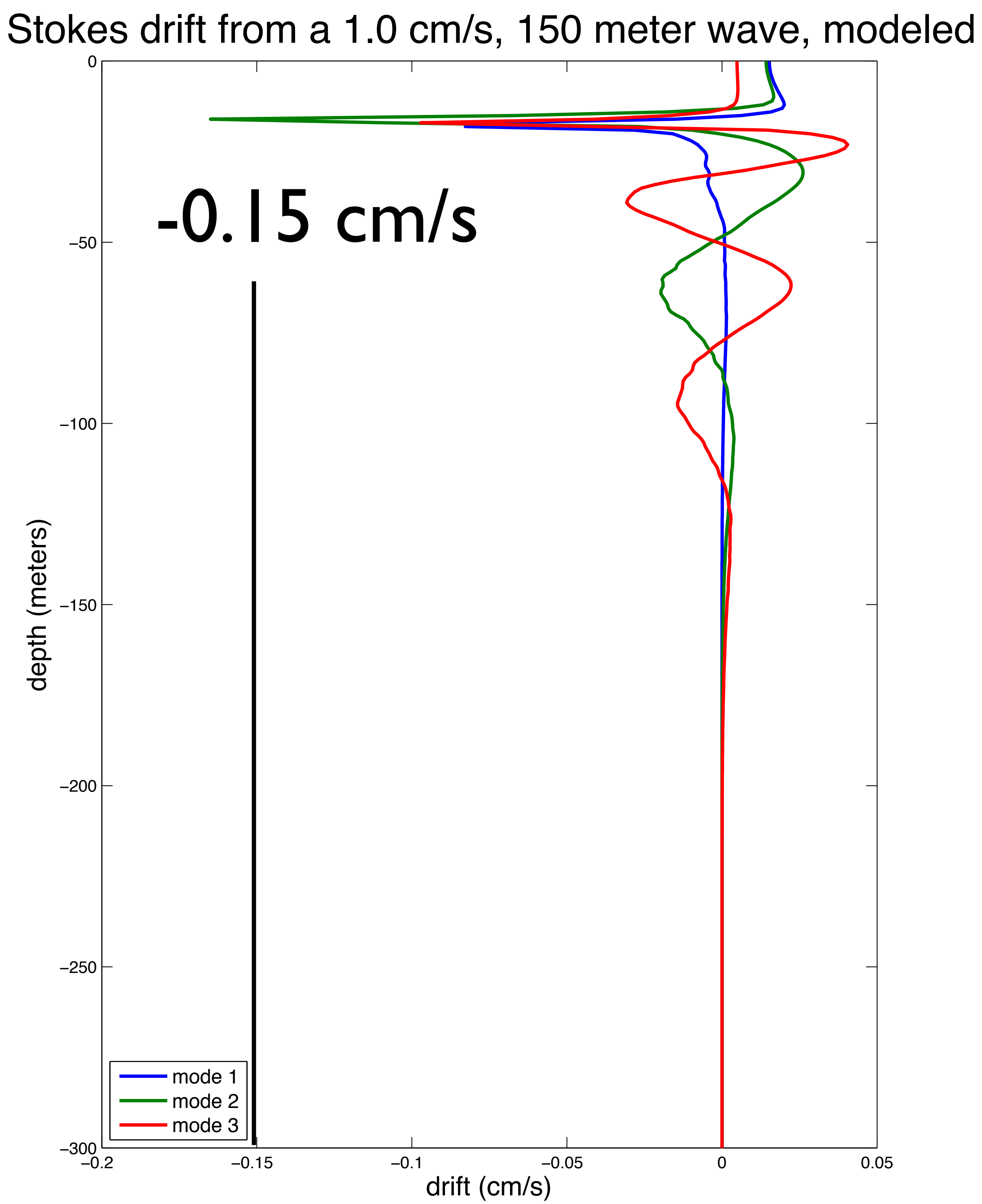
Observed 2nd moment

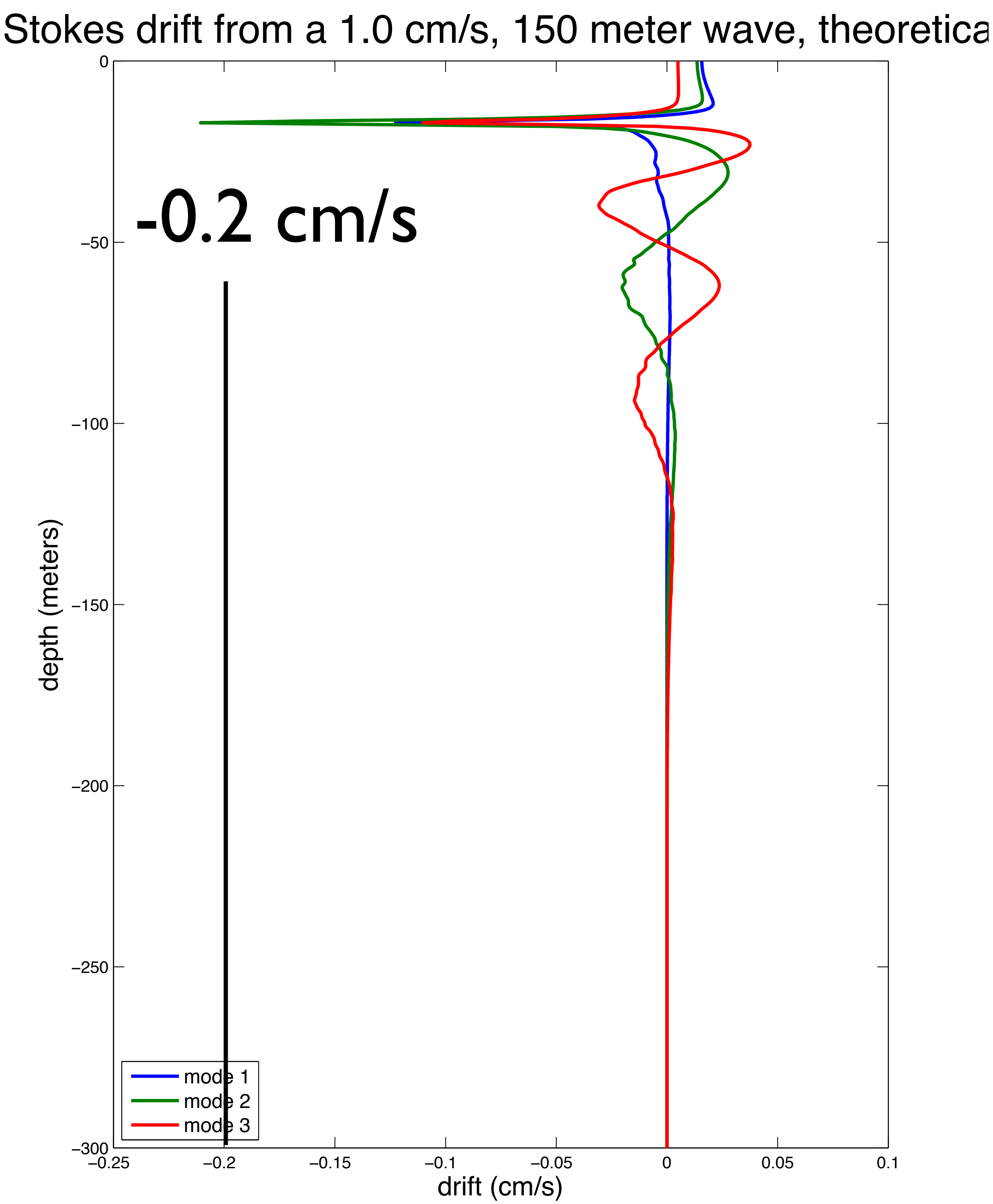
Isotropic model, $\kappa = 1.8 \pm 0.2 \text{ m}^2/\text{s}$

Stokes drift from internal waves?

- Stokes drift $\boldsymbol{u}^S = \overline{(\boldsymbol{\xi} \cdot \nabla)\boldsymbol{u}}$ $\partial_t \boldsymbol{\xi} = \boldsymbol{u}$
- For 3D transverse plane wave, $\boldsymbol{u} \propto \boldsymbol{k}^{\perp} \Rightarrow \boldsymbol{u}^S = 0$
- But with modal solutions, $u = U\cos(kx + ly - \omega t)F_j(z)$ consistent with boundary and polarization conditions, Stokes drift does not vanish…
- Effect greatly exaggerated by non-constant N^2!
- [and even 3D plane waves yield drift for drifters on constant-z surfaces (Dewar 1980)]

Stokes drift for observed stratification





THE EFFECT OF INTERNAL WAVES ON NEUTRALLY BUOYANT FLOATS
AND OTHER NEAR-LAGRANGIAN TRACERS

by

WILLIAM KURT DEWAR

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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GEM! Thanks to B. Young for pointing this out

Conclusions - Part 2

- Drifters consistently show a much lower diffusivity than the dye release.
- The difference may be explained by their different transport mechanisms.
- Shear dispersion does not appear to be significant.
- Stokes drift may account for the observed diffusivity.