

DISENTANGLING MESOSCALE STRAIN AND INTERNAL WAVES USING SURFACE DRIFTERS

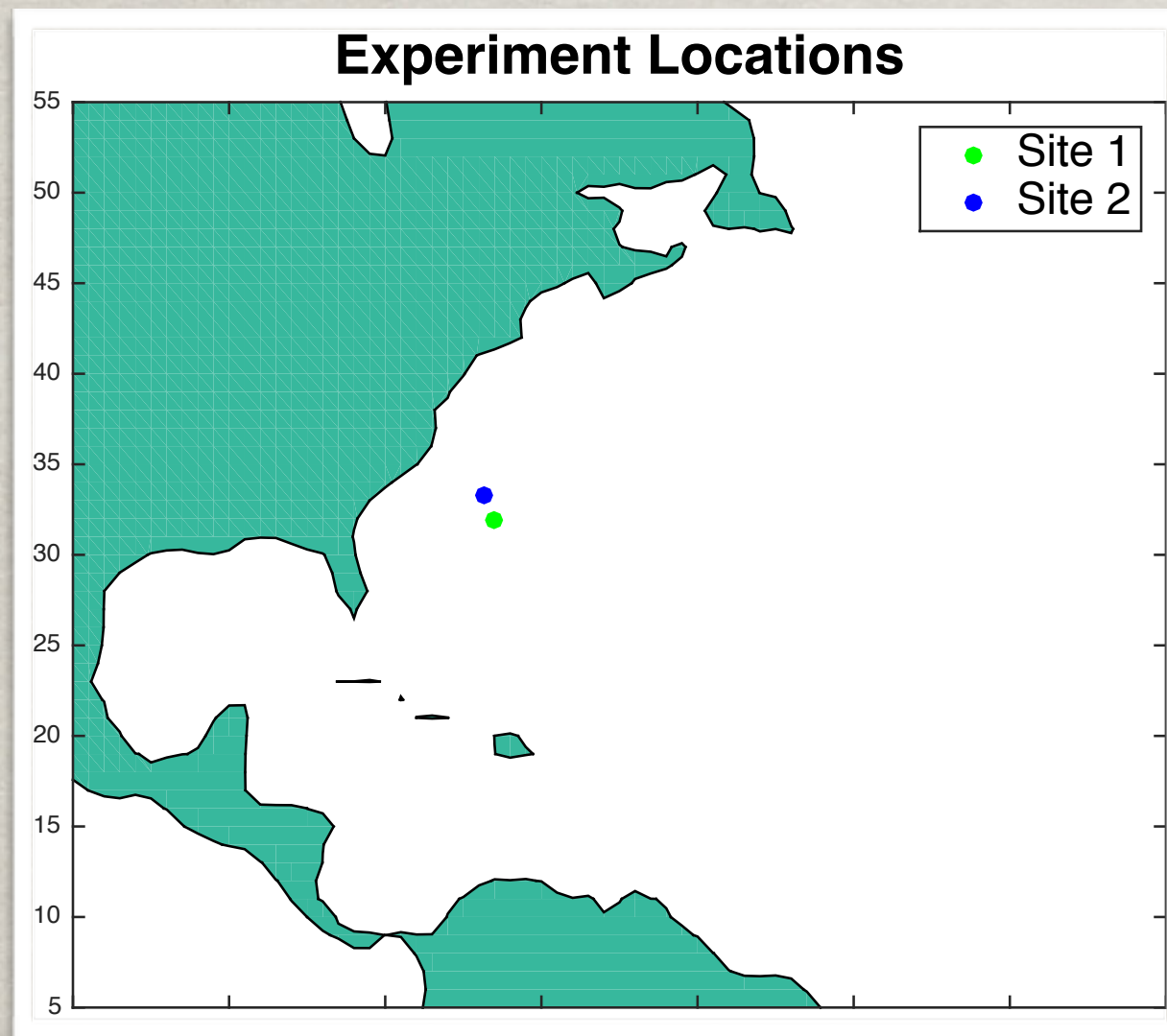
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LATMIX GROUP

LATMIX SUMMER 2011

☼ What causes the $O(1)$ m²/s lateral diffusivity at scales 0.1 to 10 km?



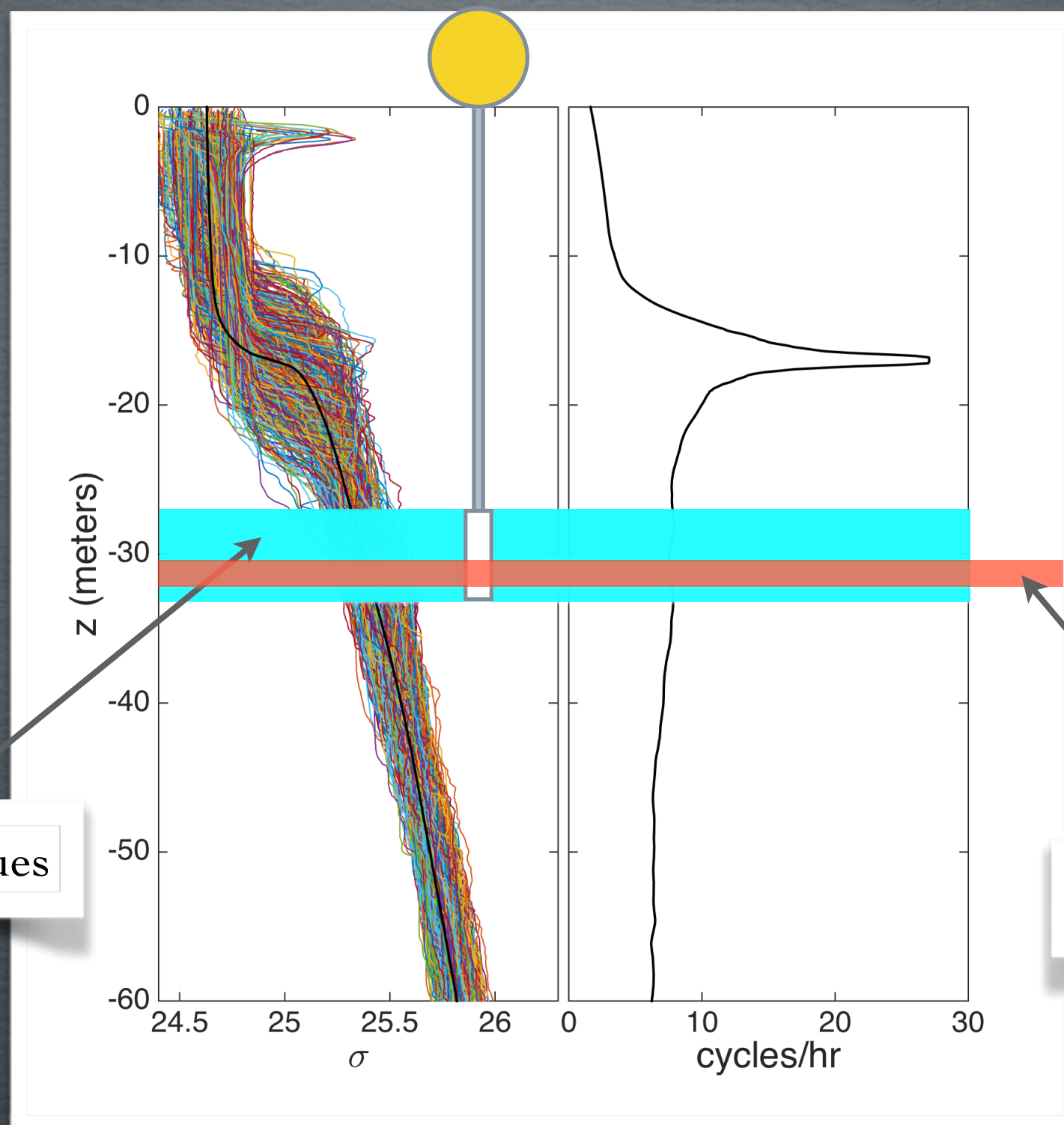
Measurements from

- dye release
- gliders
- drifters
- many others...

Two experiments, each over 6 days

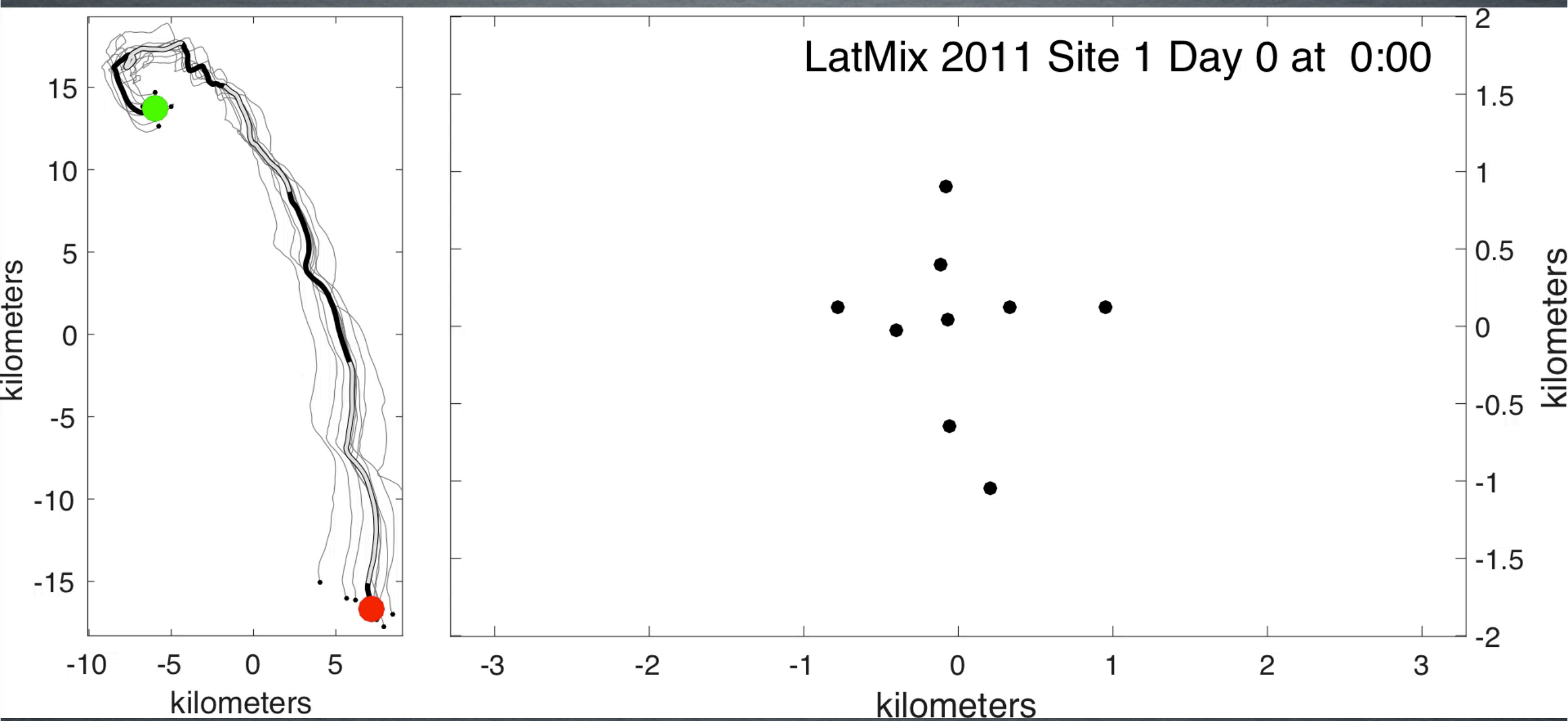
DENSITY FROM GLIDER PROFILES

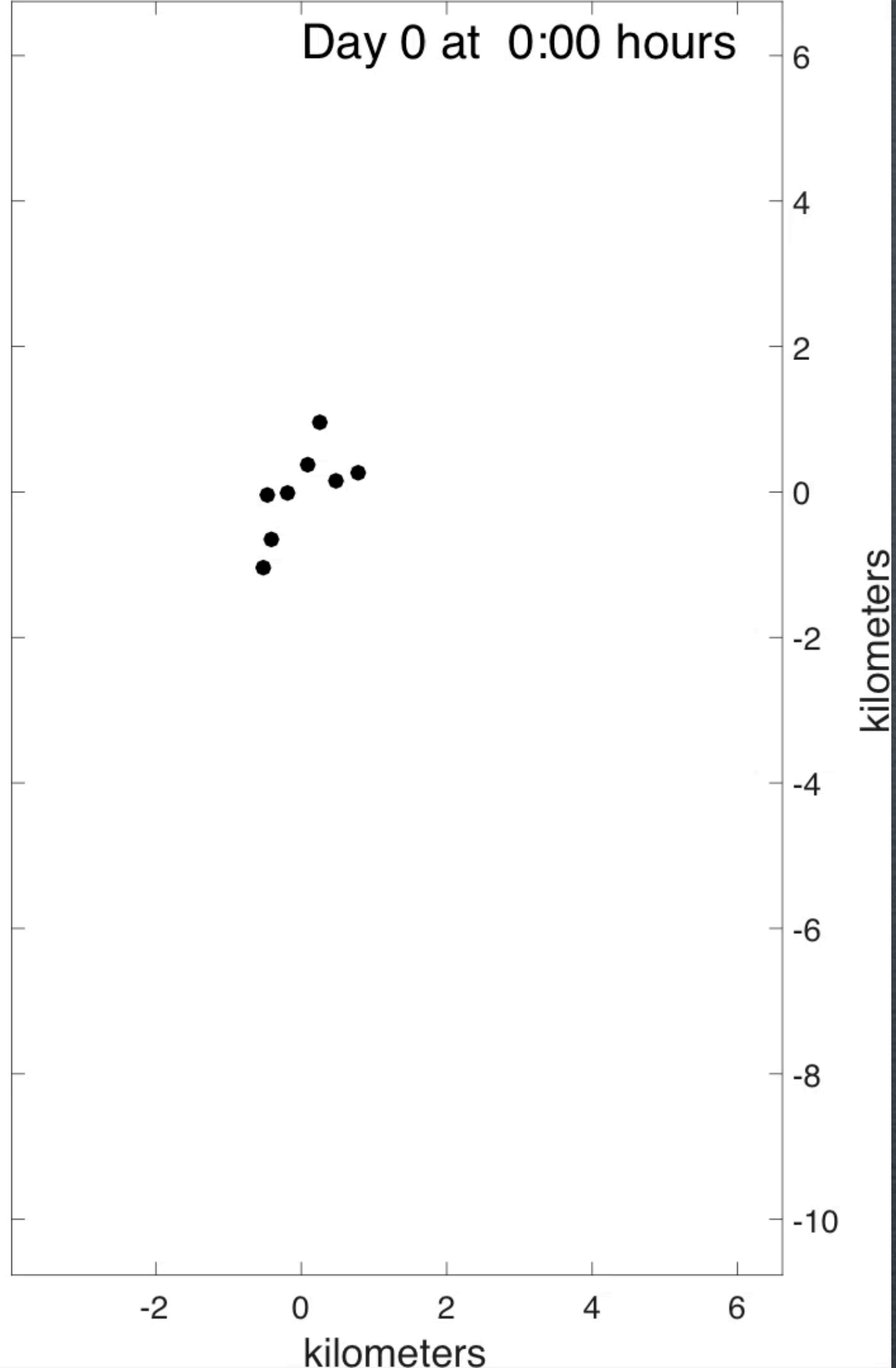
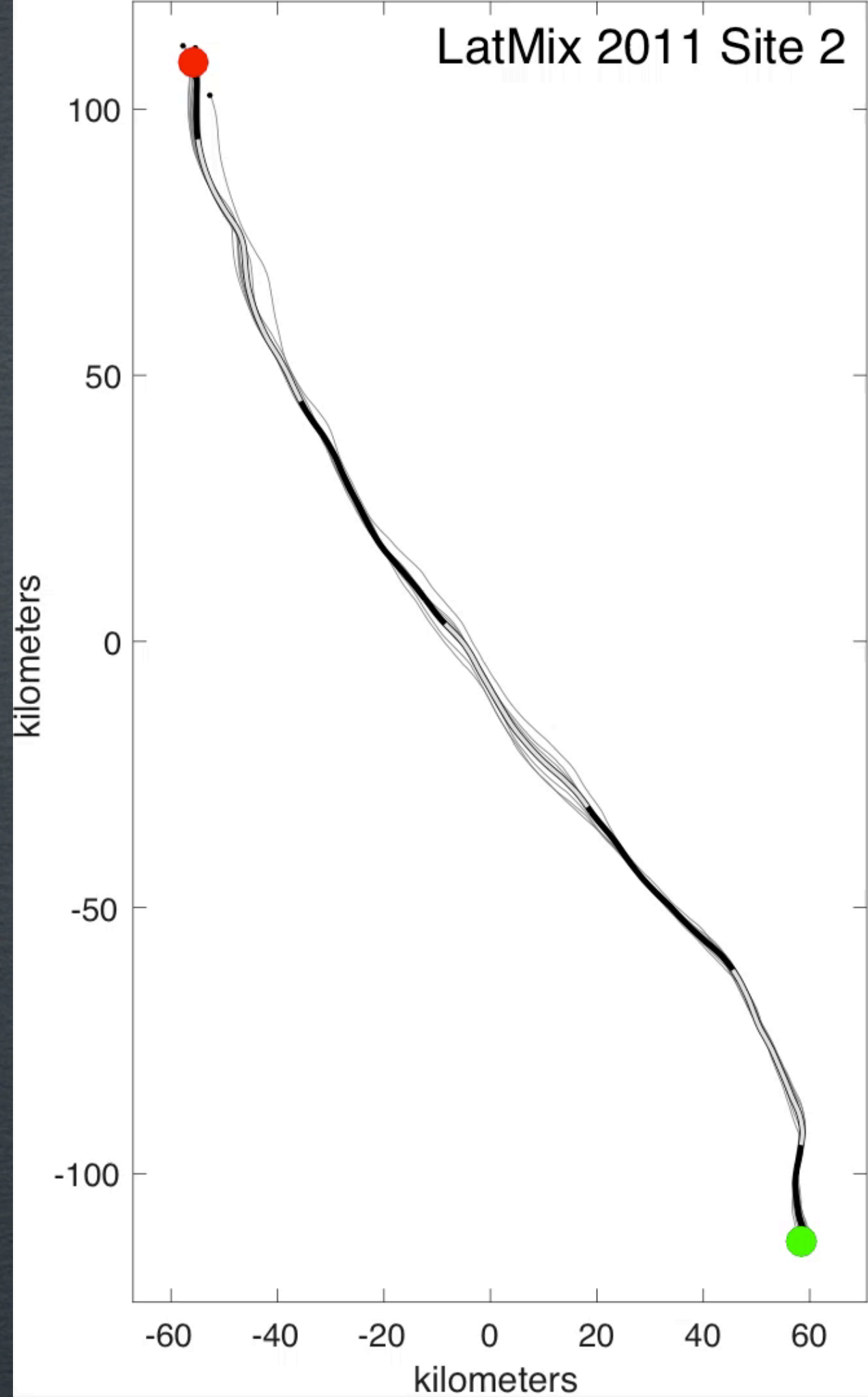
KIPP SHEARMAN



Drifter drogues

Dye injection





DECOMPOSING THE FLOW

$$u = u(t)_{\text{background}} + u(t)_{\text{mesoscale}} + u(t)_{\text{submesoscale}}$$

VORTICITY-STRAIN-DIFFUSIVITY MODEL

✻ Model for particle $(x_i(t), y_i(t))$,

$$\begin{aligned} \partial_t \begin{bmatrix} x_i(t) \\ y_i(t) \end{bmatrix} = & \\ & + \begin{bmatrix} u_0(t) \\ v_0(t) \end{bmatrix} \\ & + \frac{1}{2} \begin{bmatrix} \sigma_n & \sigma_s - \zeta \\ \sigma_s + \zeta & -\sigma_n \end{bmatrix} \begin{bmatrix} x_i(t) + x_0 \\ y_i(t) + y_0 \end{bmatrix} \\ & + \sqrt{2\kappa} d\mathbf{W}_t. \end{aligned}$$

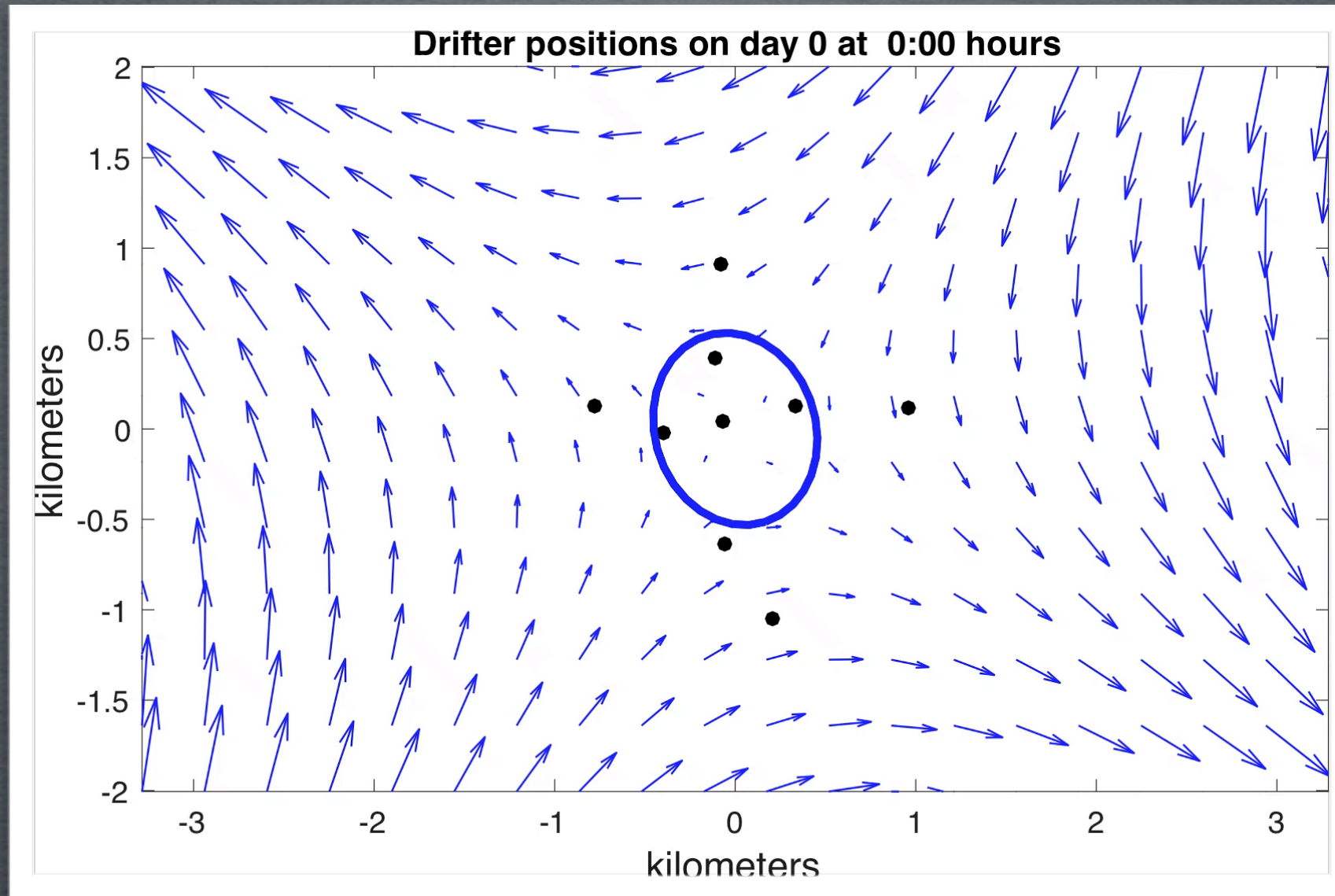
Background

Mesoscale

Submesoscale

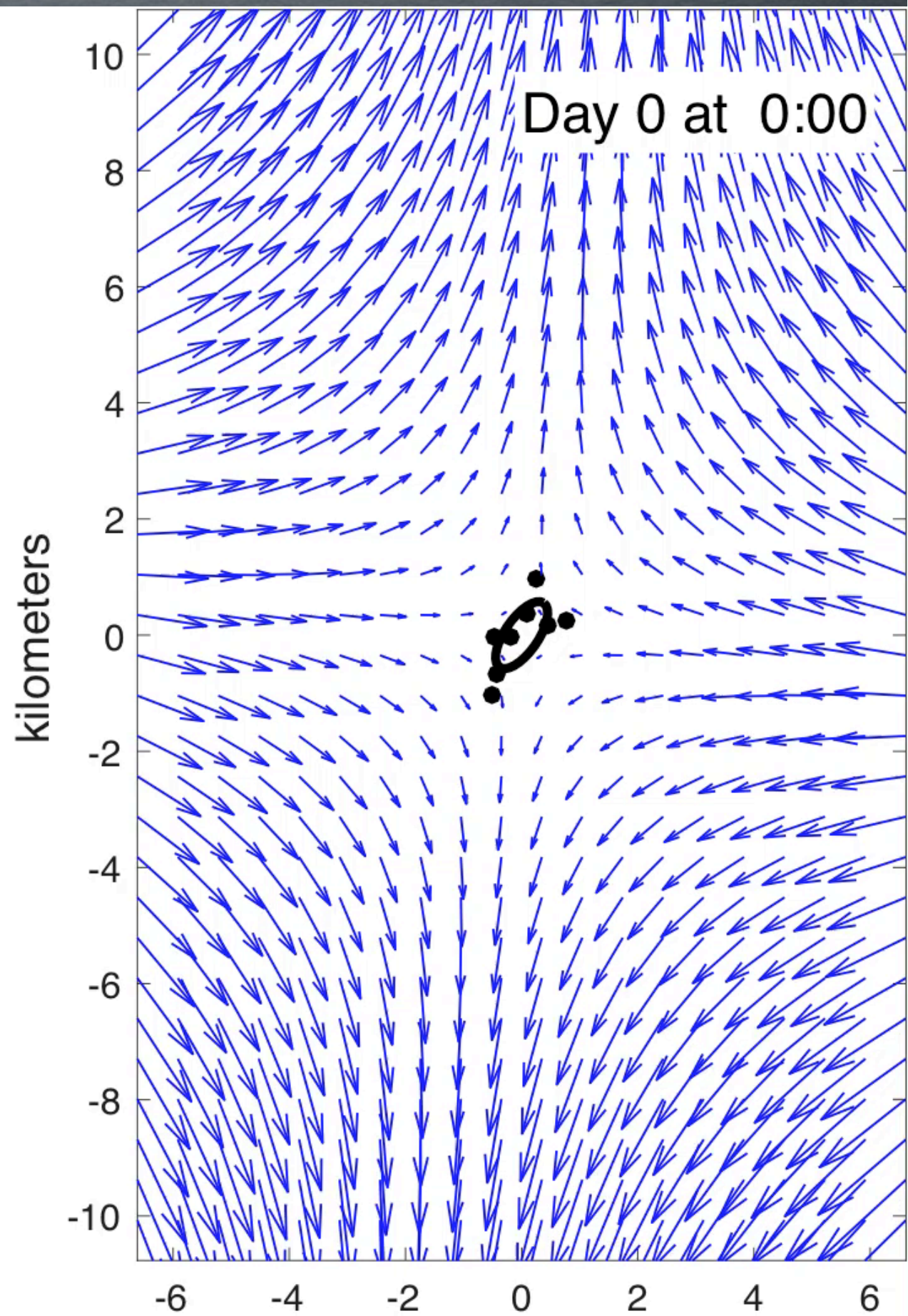
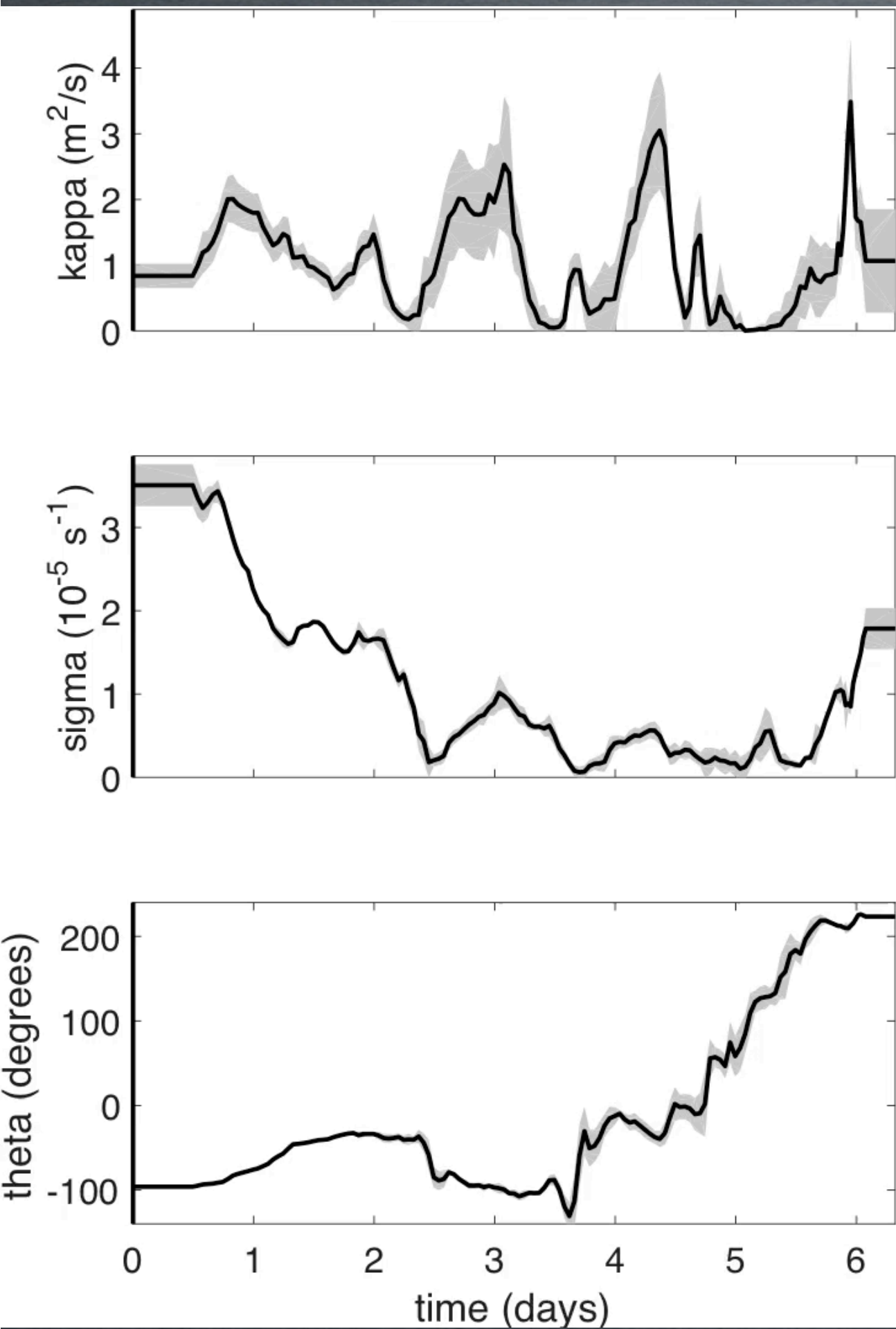
✻ Vorticity ζ , strain σ , angle θ , diffusivity κ , are parameters to find by minimizing an error function.

DRIFTER TRAJECTORIES IN CENTER-OF-MASS COORDINATES.



 Observed 2nd moment

 Strain-diffusivity model,
 $\kappa = 0.18 \text{ m}^2/\text{s}, \sigma = 3.52 \cdot 10^{-6} \text{ s}^{-1}, \theta = -33^\circ$



DIFFUSIVITY RESULTS

(AFTER REMOVING MESOSCALE STRAIN)

Site 1 (weak strain):

✱ Dye diffusivity: $O(1) \text{ m}^2/\text{s}$

✱ Drifters diffusivity: $O(.1) \text{ m}^2/\text{s}$

Site 2 (moderate strain):

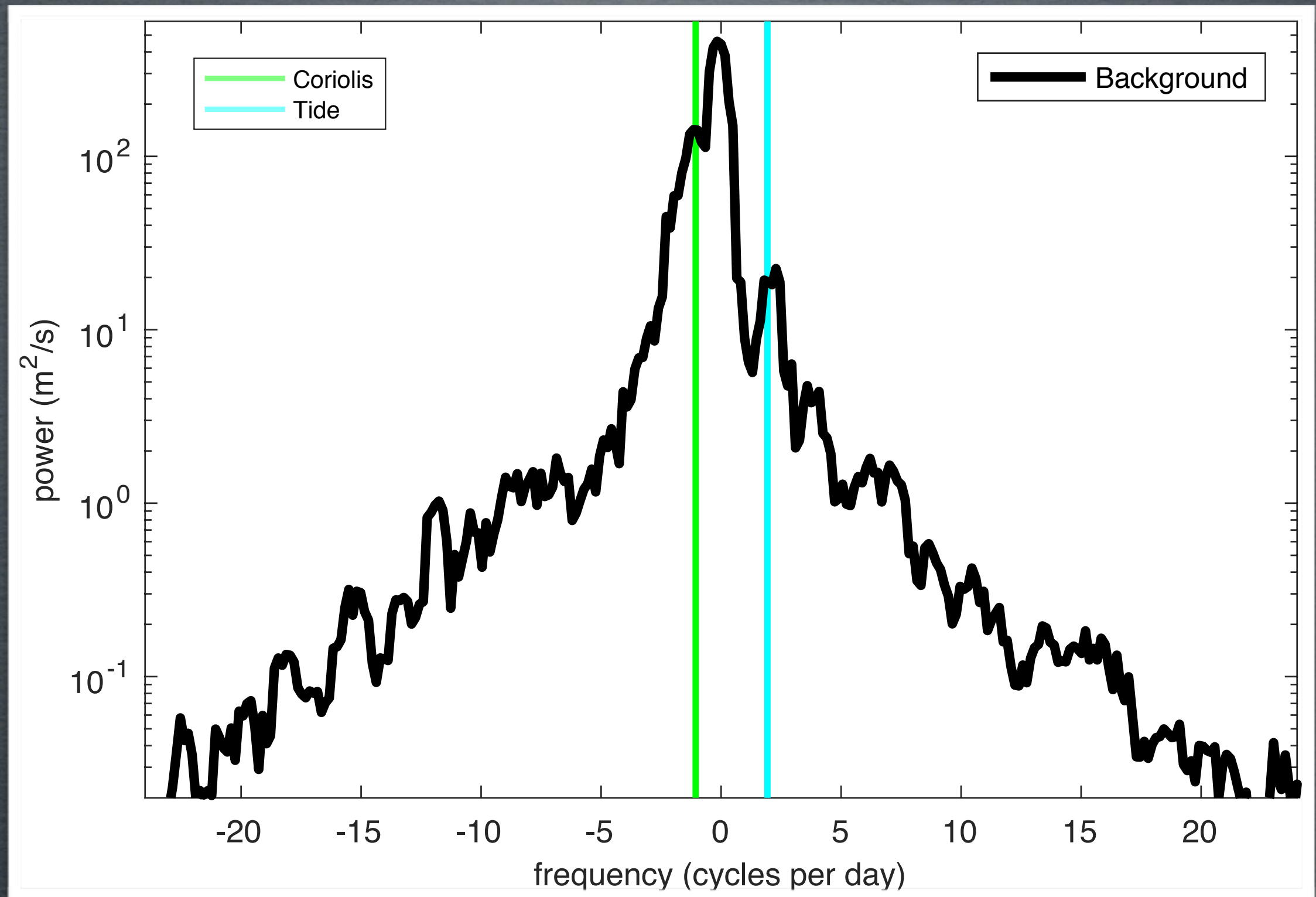
✱ Dye diffusivity: $O(1) \text{ m}^2/\text{s}$

✱ Drifters diffusivity: $O(1) \text{ m}^2/\text{s}$

Can we explain why these are different?

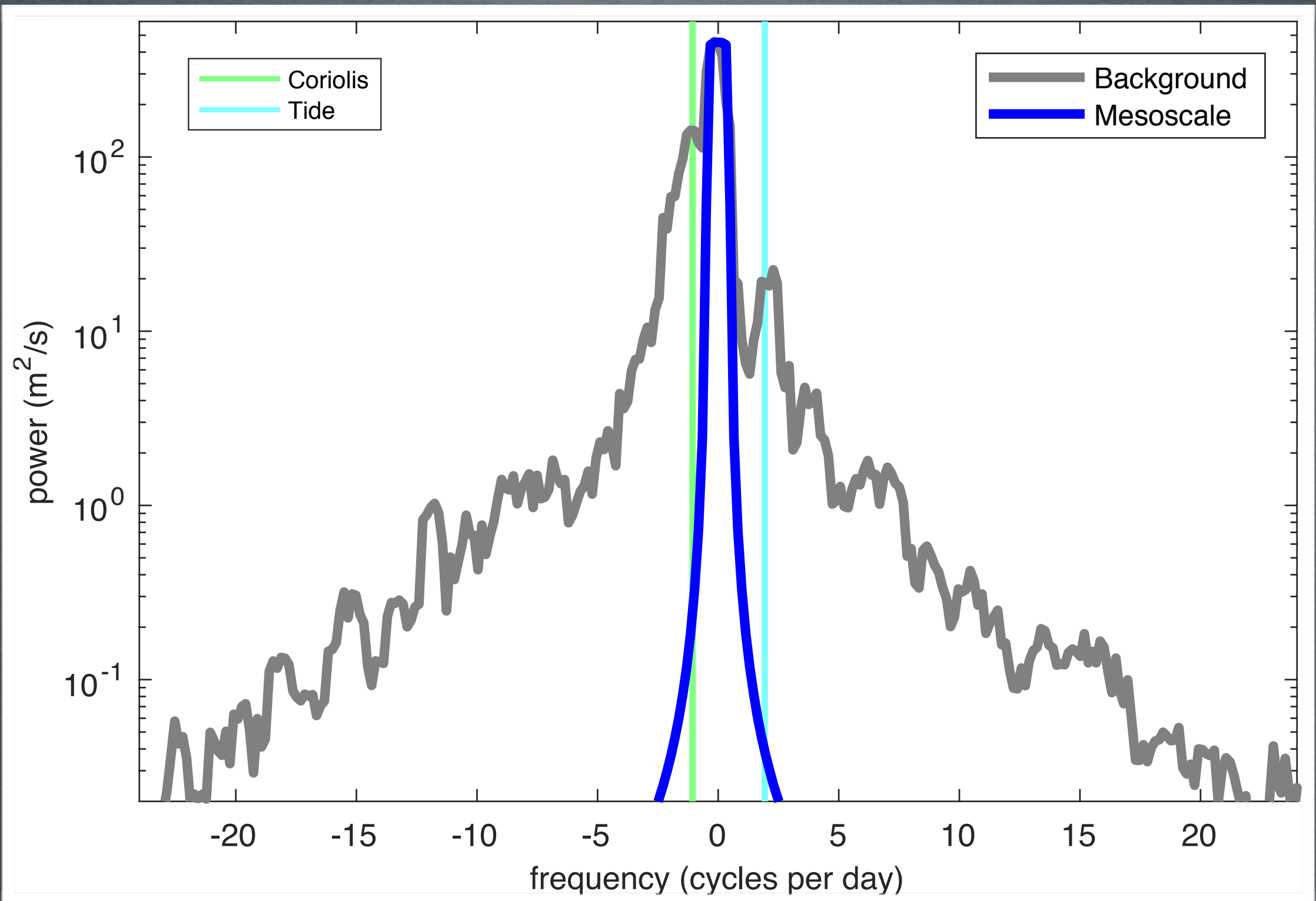
VELOCITY SPECTRA

SITE 1 (WEAK STRAIN)



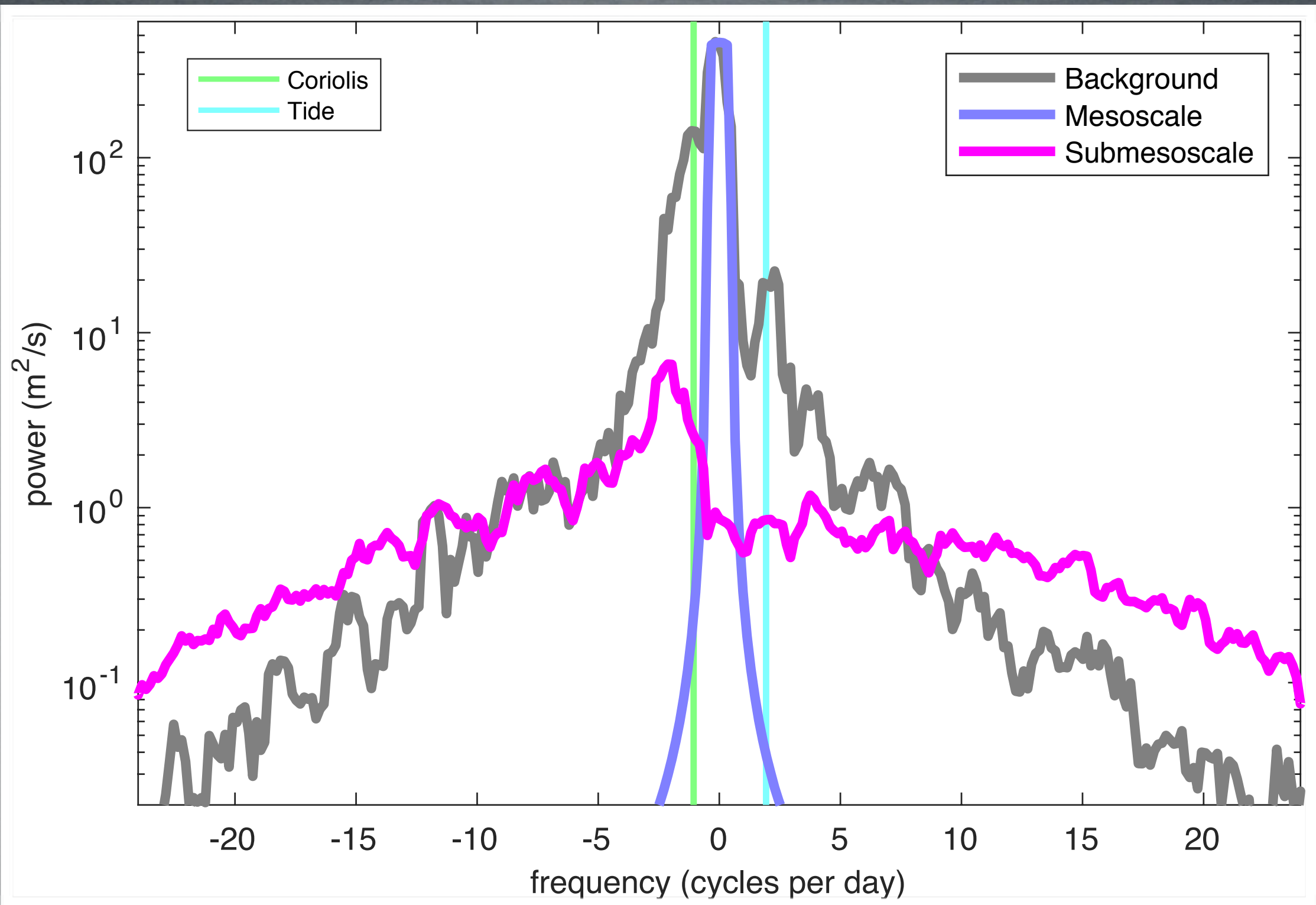
VELOCITY SPECTRA

SITE 1 (WEAK STRAIN)

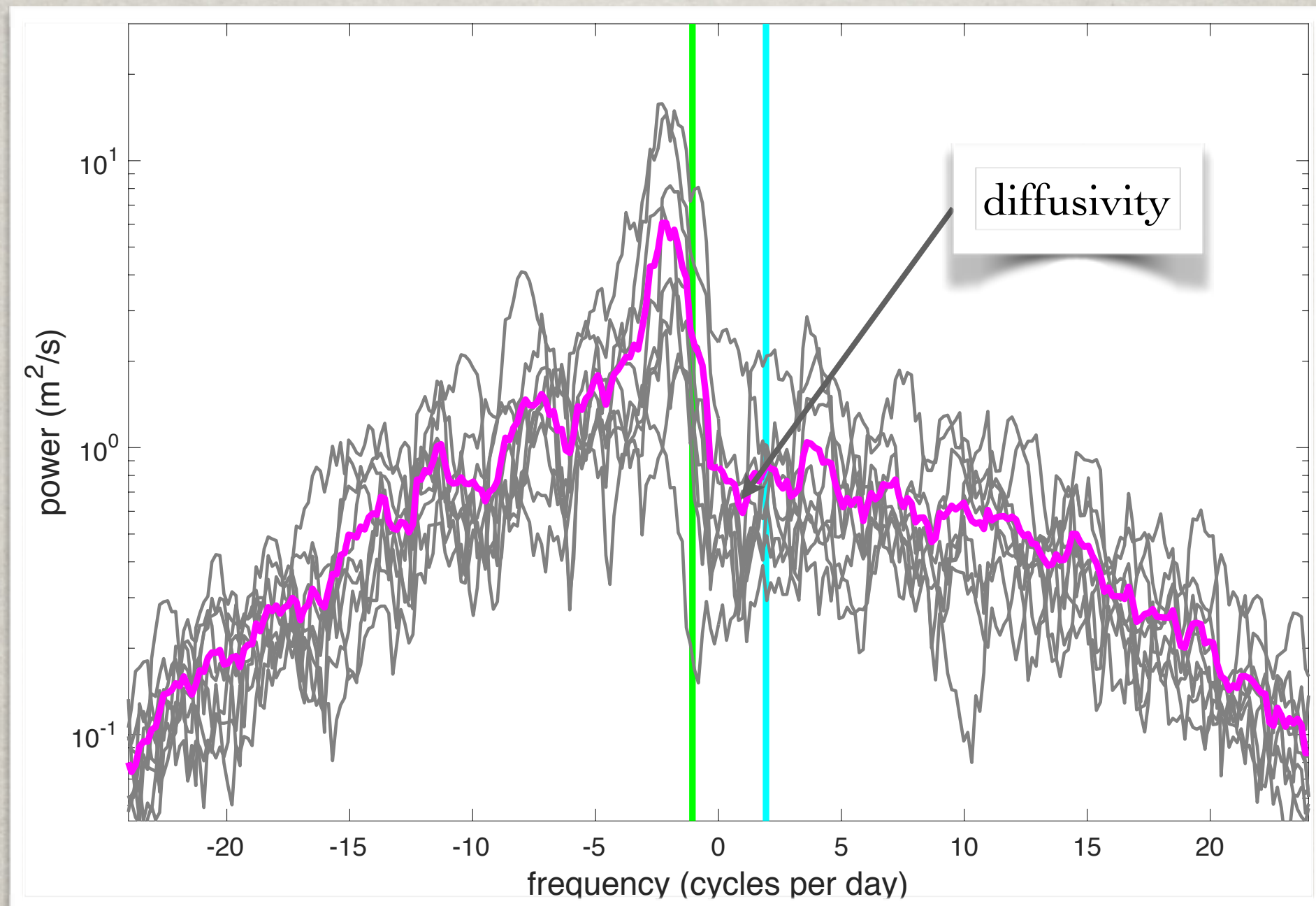


VELOCITY SPECTRA

SITE 1 (WEAK STRAIN)



VELOCITY SPECTRA

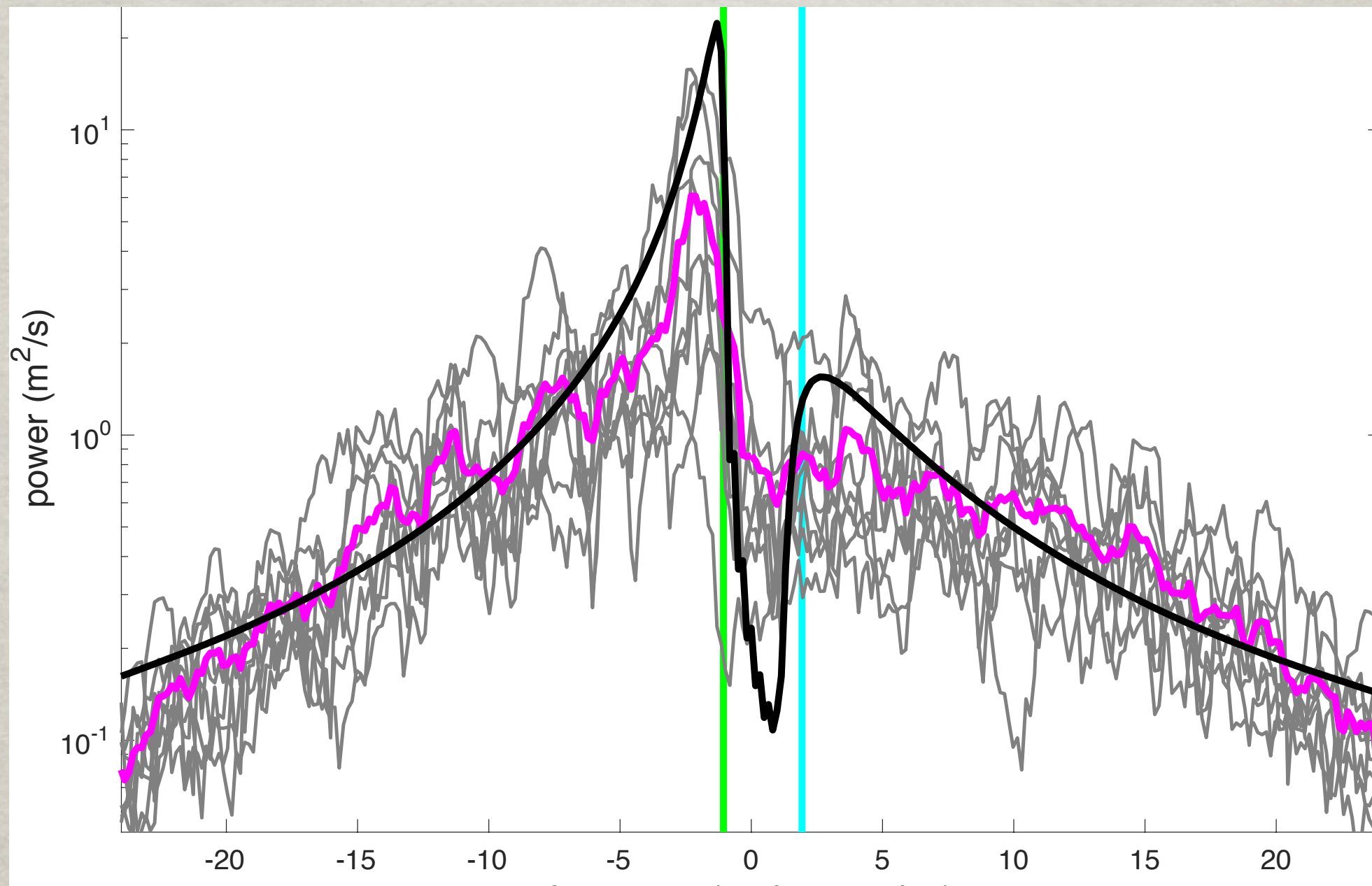


- Velocity spectrum looks like internal waves.
- Single particle diffusivity estimates also give $\kappa = 0.2 \text{ m}^2/\text{s}$

INTERNAL WAVE VELOCITY SPECTRUM

- ✱ Garrett-Munk spectrum is a model for the internal wave spectrum.
- ✱ Need a 'Lagrangian' version — same as Eulerian version to lowest order.
- ✱ Need to center-of-mass frame attenuation filter.

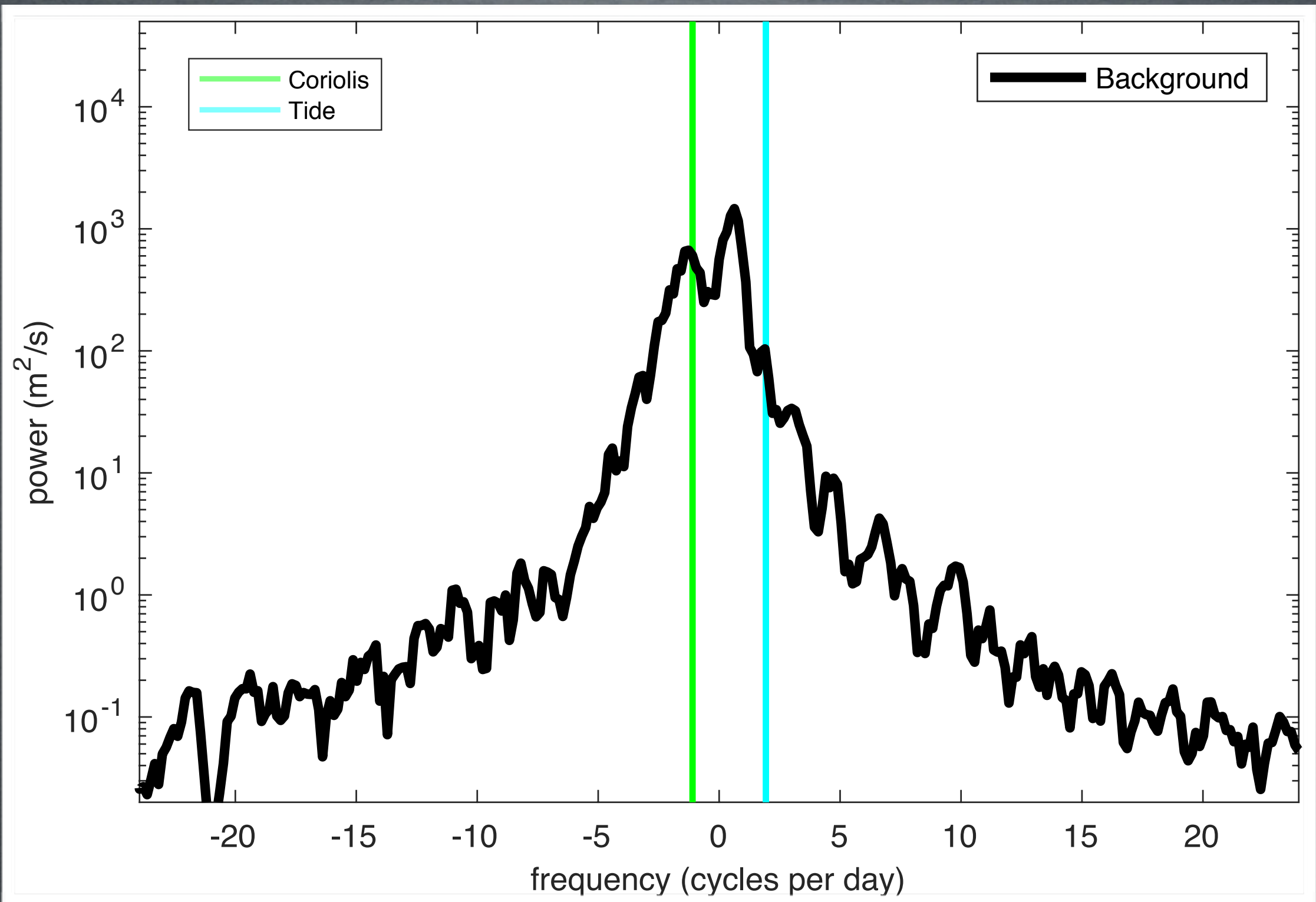
SITE 1 SPECTRA



- ☼ Theoretical GM spectrum for center-of-mass internal waves at 0.5 GM reference level (magenta).

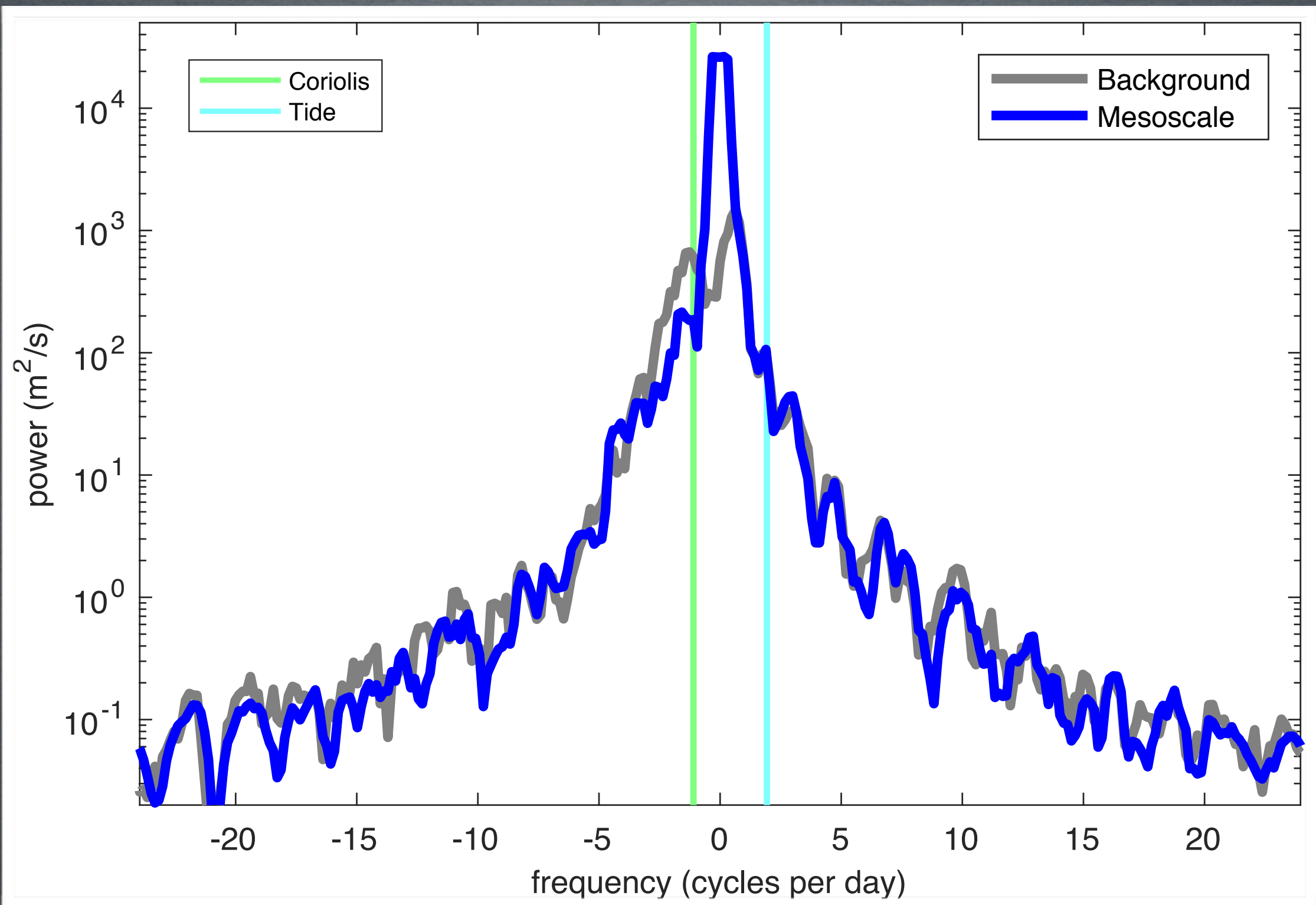
VELOCITY SPECTRA

SITE 2 (MODERATE STRAIN)



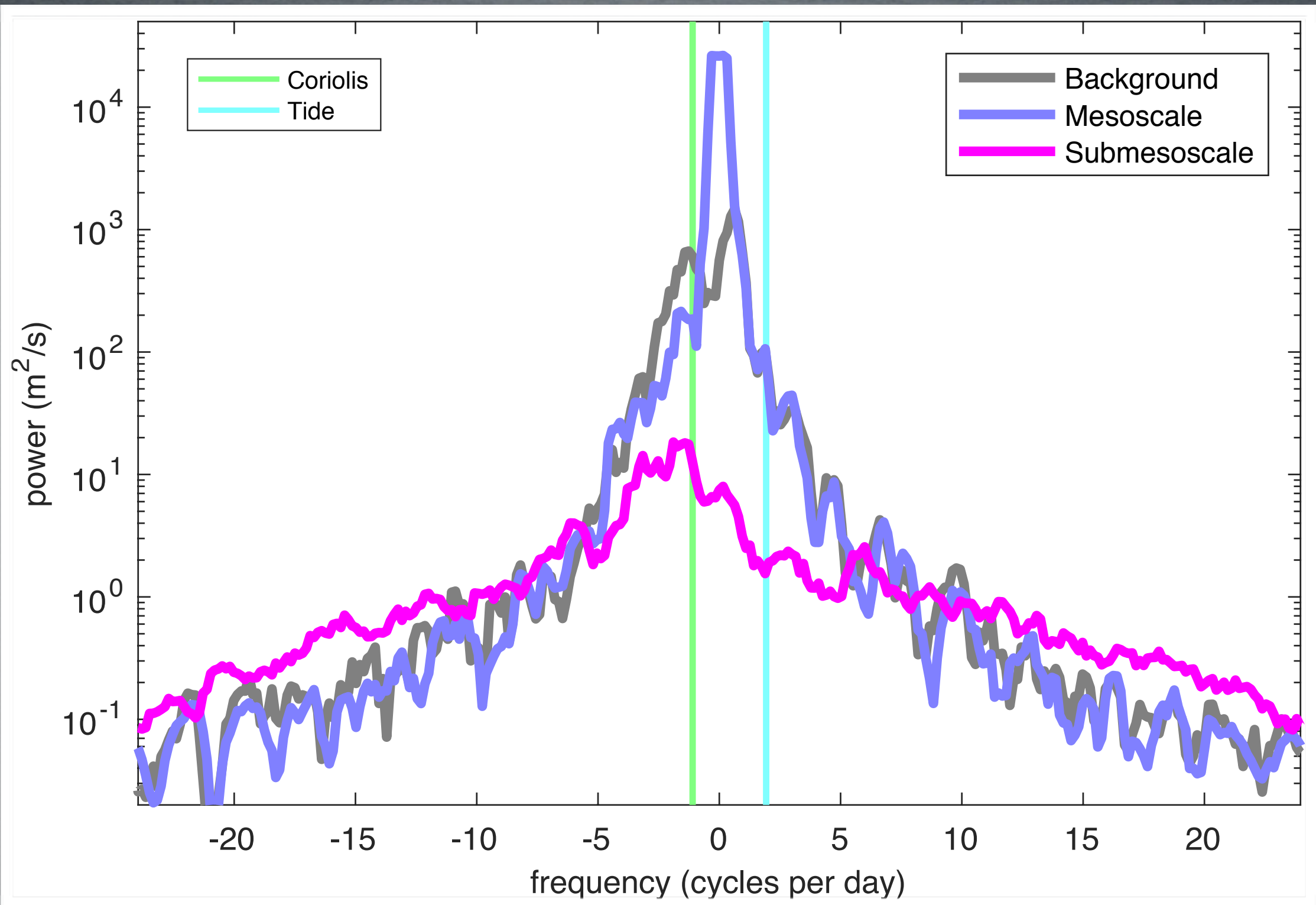
VELOCITY SPECTRA

SITE 2 (MODERATE STRAIN)

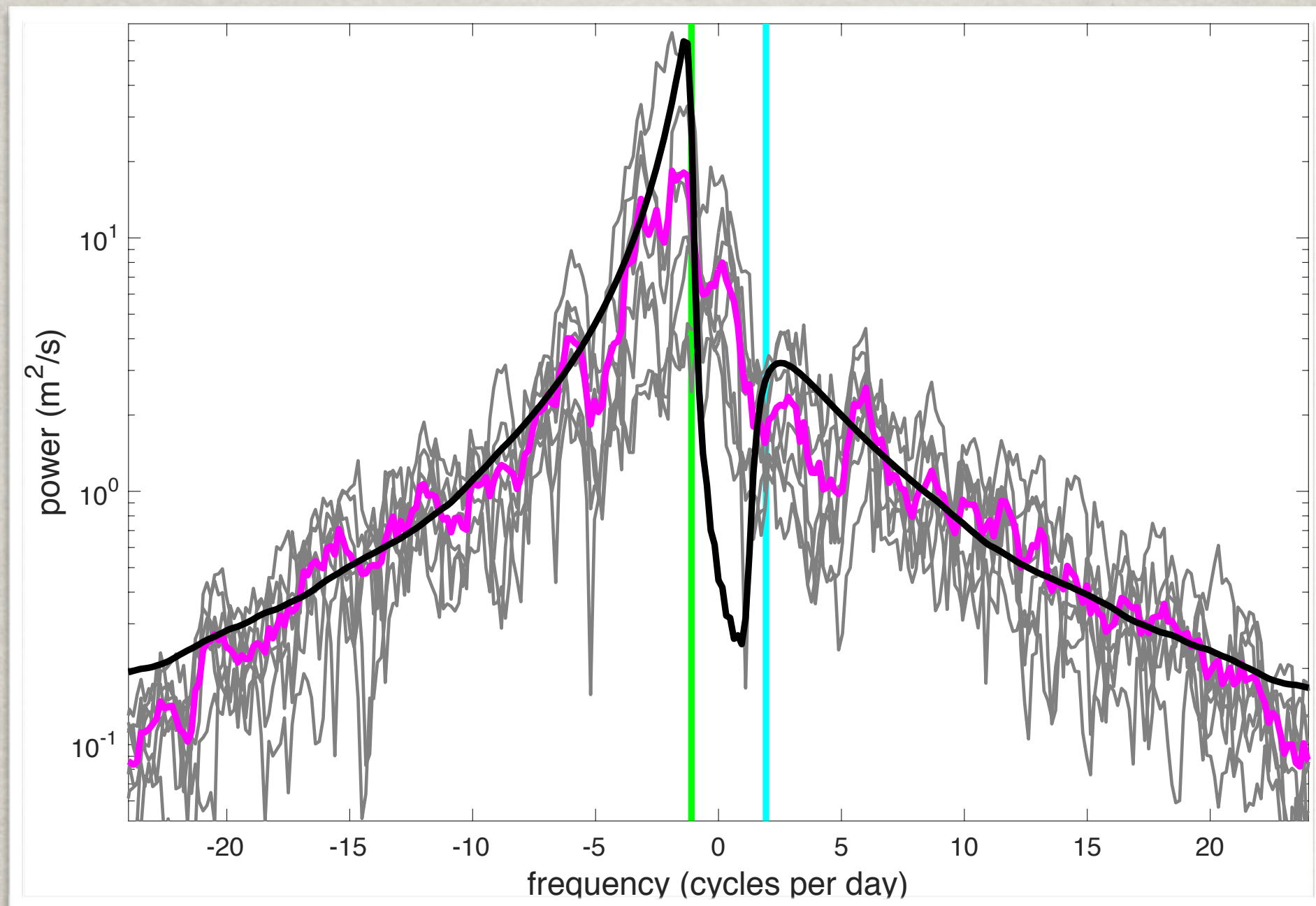


VELOCITY SPECTRA

SITE 2 (MODERATE STRAIN)



VELOCITY SPECTRA



- Velocity spectrum looks like internal waves.
- Single particle diffusivity estimates also give $\bar{\kappa} = 1.1 \text{ m}^2/\text{s}$

LINEAR INTERNAL WAVES

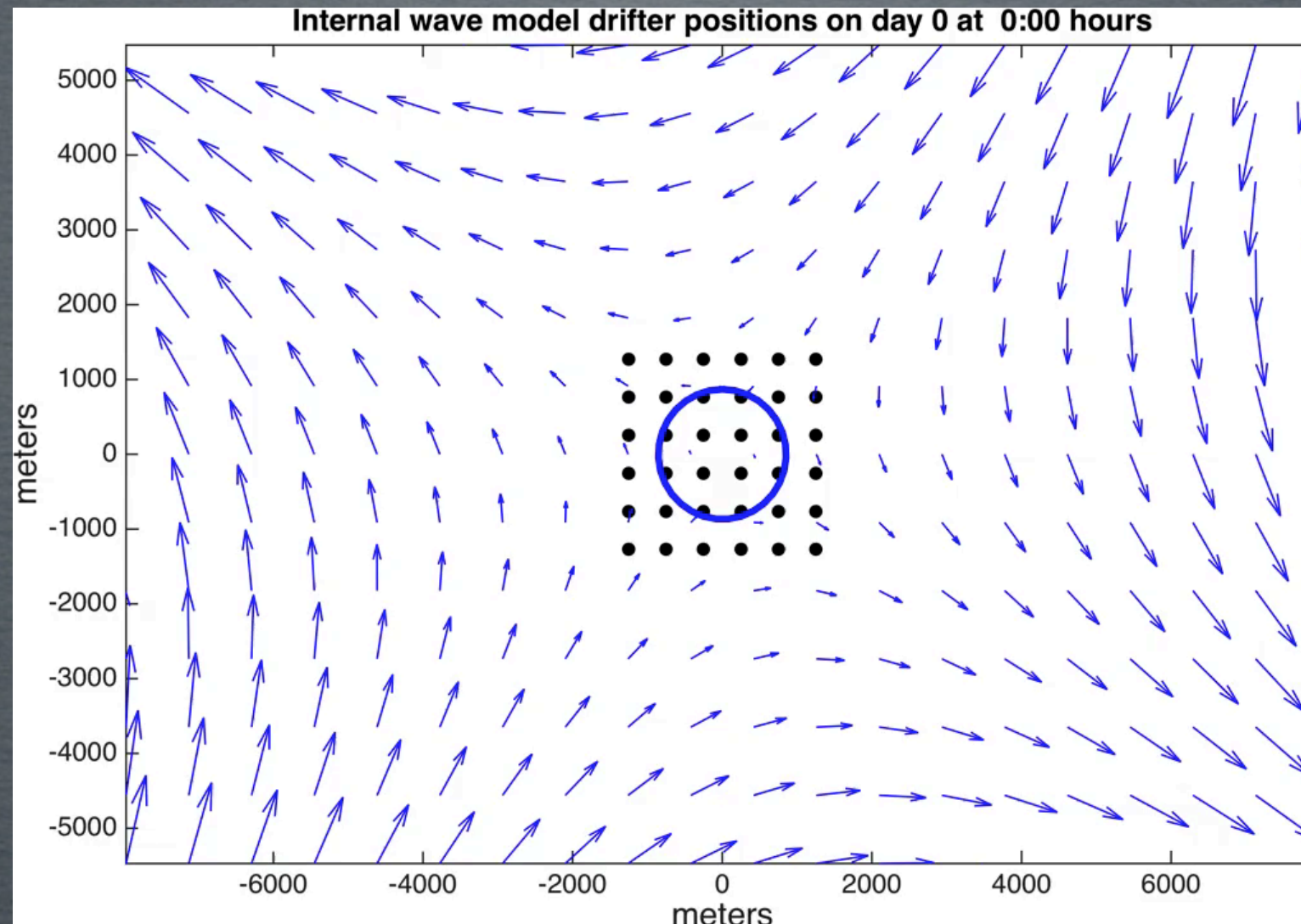
Can the observed spectra and diffusivity be explained by linear internal waves?

INTERNAL WAVE MODEL

- ✱ Uses realistic stratification.
- ✱ Matches energy level at 50 meters with observations.
- ✱ Model uses *analytical* solution to advect particles.
- ✱ Vertical resolution of 1 meter, horizontal resolution of 60 meters.

DRIFTER-LIKE PARTICLES

FROM AN INTERNAL WAVE MODEL WITH STRAIN

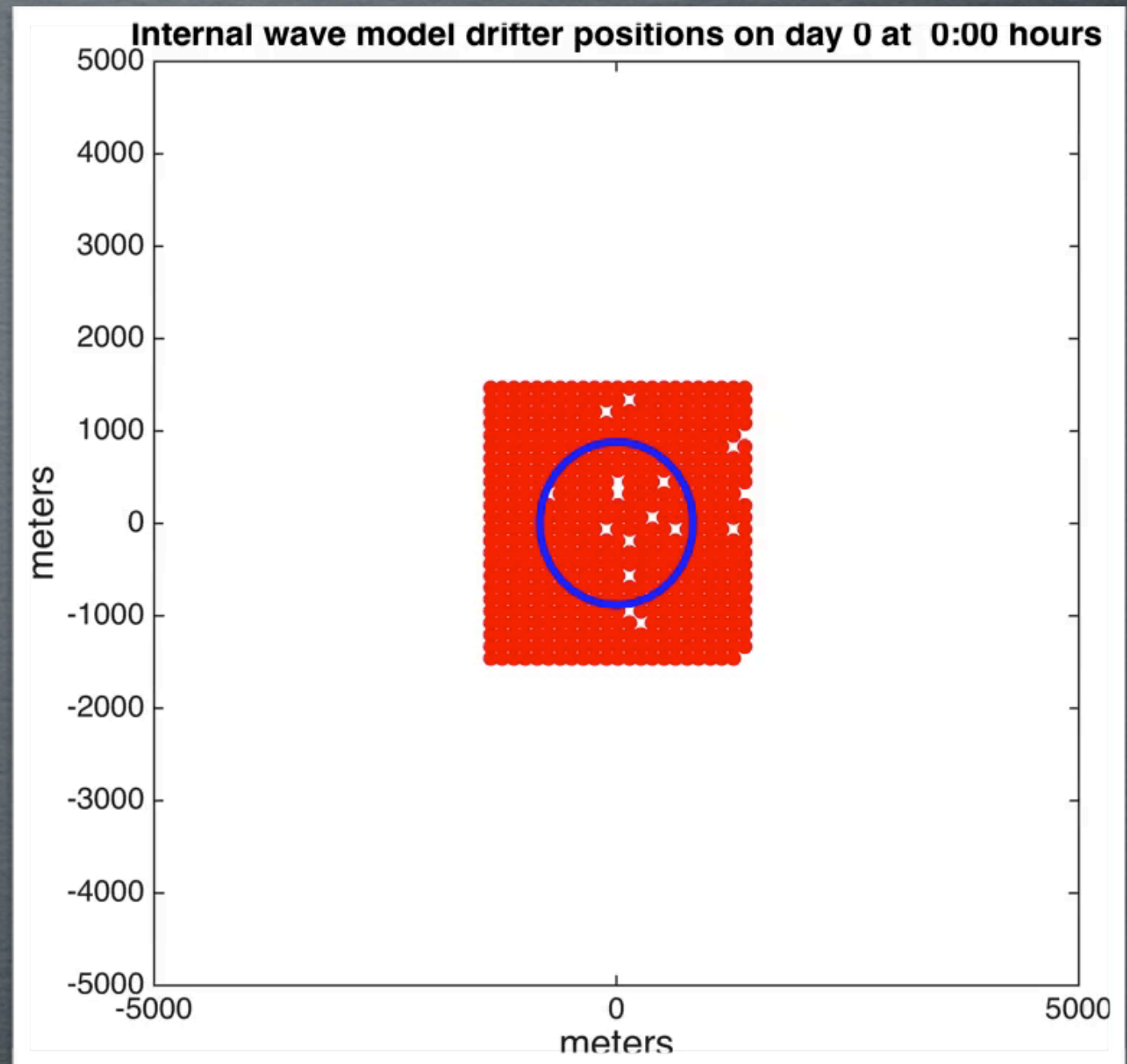


○ Observed 2nd moment

○ Strain-diffusivity model,
 $\kappa = 0.18 \text{ m}^2/\text{s}, \sigma = 3.52 \cdot 10^{-6} \text{ s}^{-1}, \theta = -33^\circ$

DYE-LIKE PARTICLES

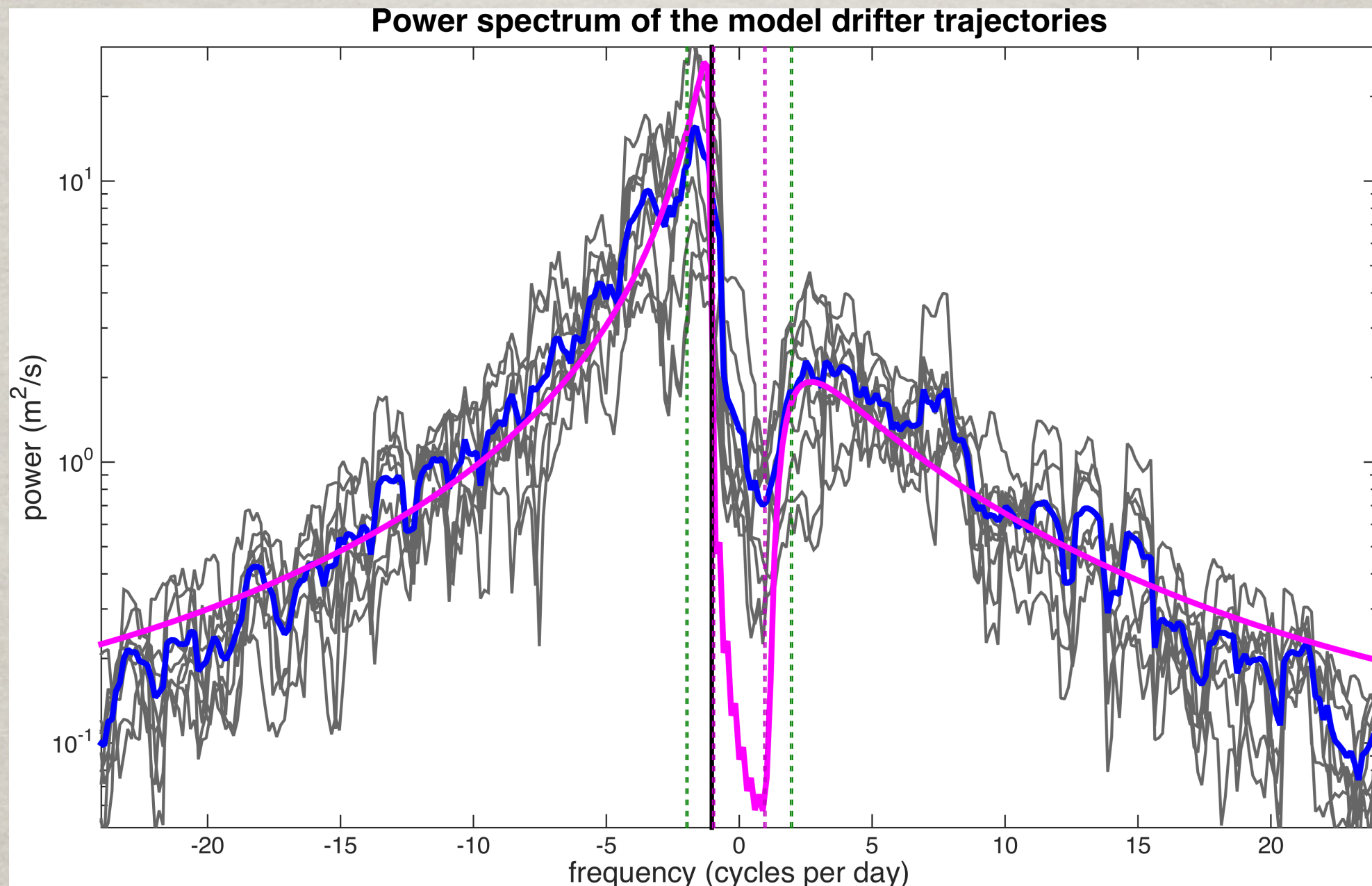
- Much higher diffusivity than the drifter-like particles
- Diffusive and non-diffusive particles are nearly indistinguishable, which means shear-dispersion is a negligible effect.



○ Observed 2nd moment

○ Isotropic model, $\kappa = 1.0 \text{ m}^2/\text{s}$

VELOCITY SPECTRA



- ✻ Theoretical GM spectrum for center-of-mass internal waves at 0.5 GM reference level (magenta).

CONCLUSIONS

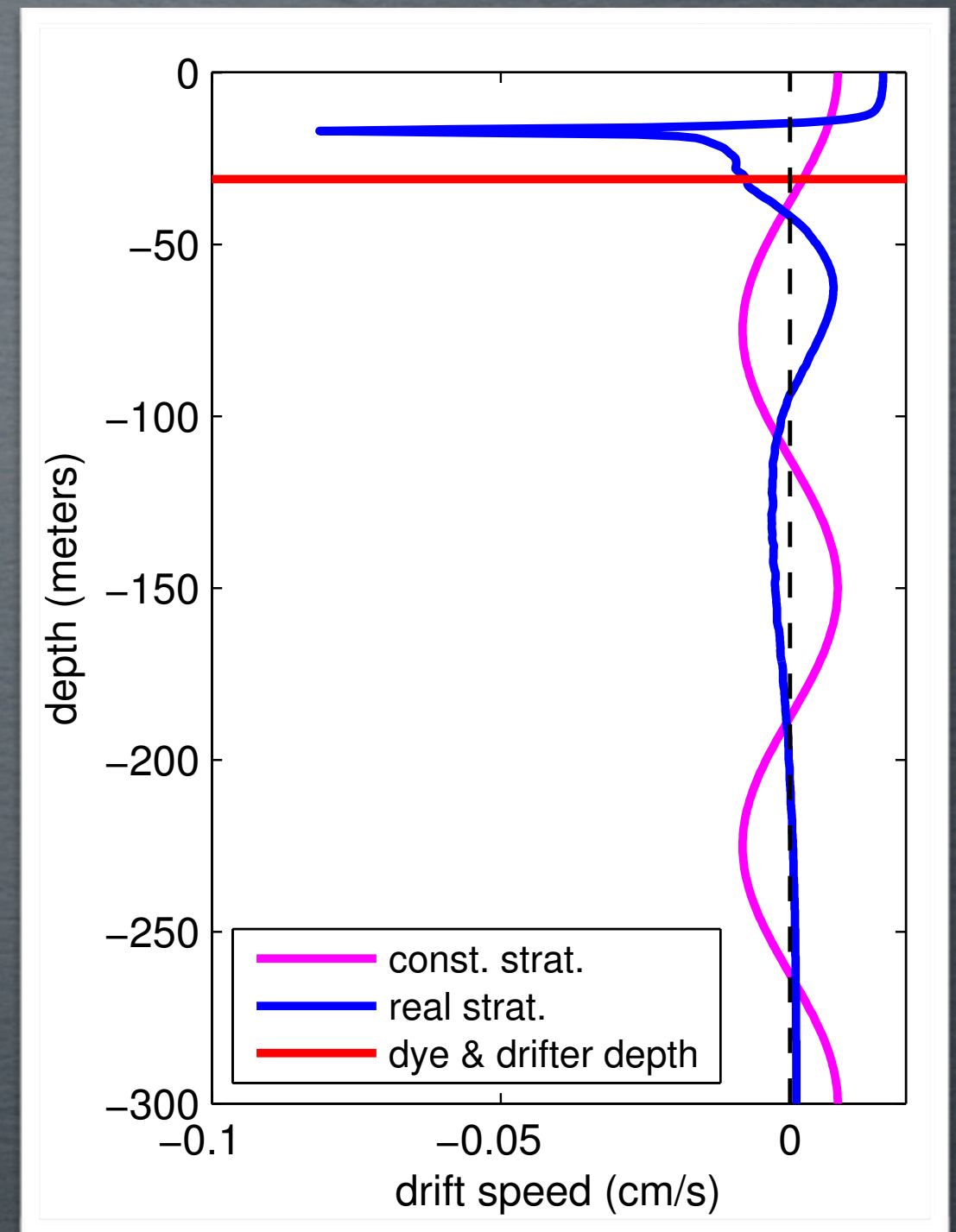
- ✱ Drifters consistently show a much lower diffusivity than the dye release.
- ✱ The difference may be explained by their different transport mechanisms in realistic stratification.
- ✱ Shear dispersion does not appear to be significant.
- ✱ Observed diffusivity is consistent with the hypothesis that the dynamics are controlled by linear internal waves.
- ✱ Stokes drift may account for the observed diffusivity.

STOKES DRIFT

- ✱ Linear internal wave model leaves exactly one mechanism for dispersion: **Stokes drift**.
- ✱ Previous estimates of Stokes drift by internal waves suggest a diffusivity much too small.
- ✱ So what's different?

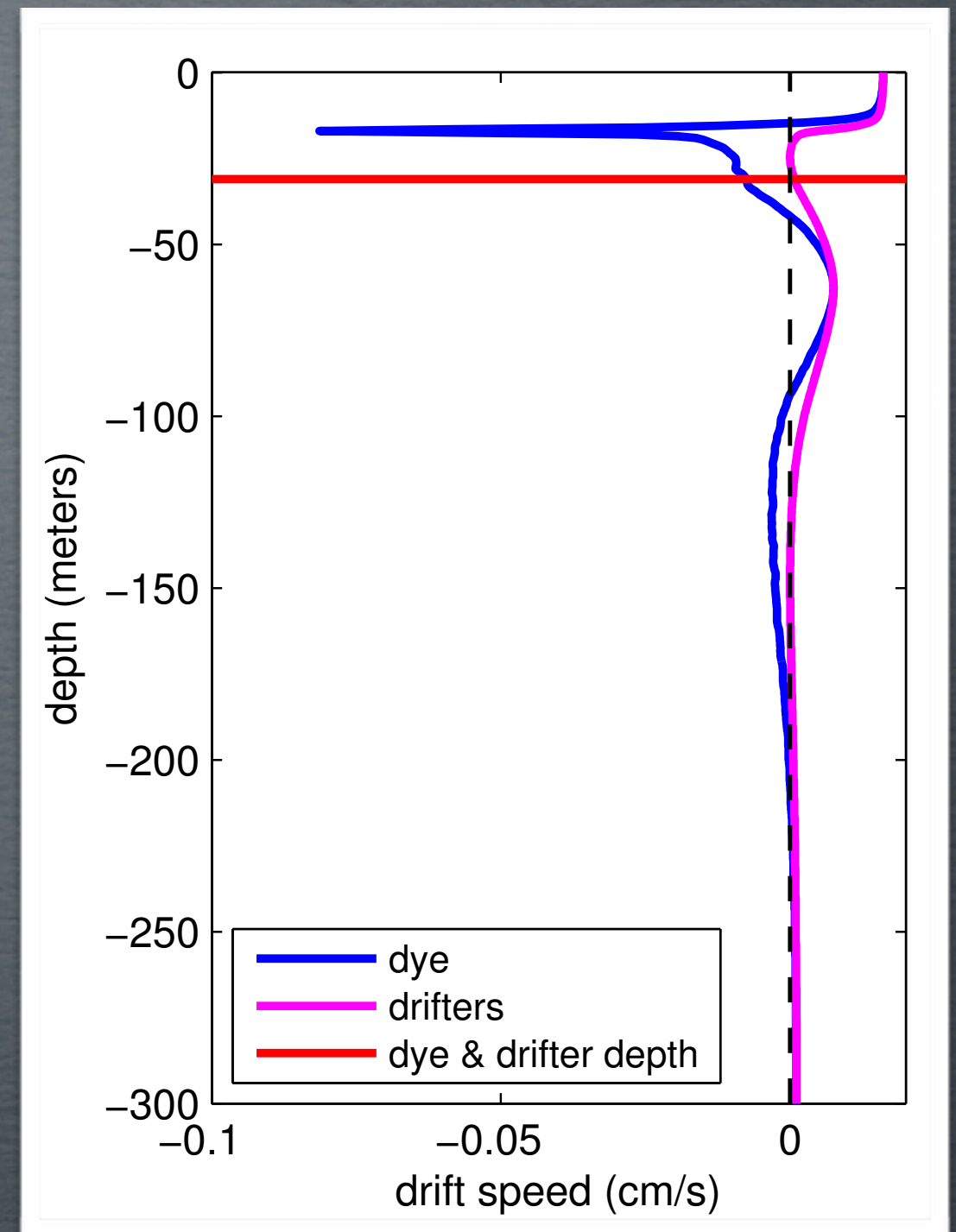
STOKES DRIFT AS A FUNCTION OF DEPTH

- Vertical mode-2, 1 cm/s, 1.5 km wavelength wave.
- Pycnocline significantly enhances Stokes drift, just like the ocean surface.



STOKES DRIFT AS A FUNCTION OF DEPTH

- Comparison of drifter versus dye drift.
- Dye or drifters may dominant, depending on depth.



LINEAR INTERNAL WAVES

✻ Single internal wave,

$$u(x, y, z, t) = U \cos(kx + \omega t) F_j(z)$$

$$v(x, y, z, t) = -U \frac{f}{\omega} \sin(kx + \omega t) F_j(z)$$

$$w(x, y, z, t) = U h_j k \sin(kx + \omega t) G_j(z)$$

$$\eta(x, y, z, t) = -U h_j \frac{k}{\omega} \cos(kx + \omega t) G_j(z)$$

✻ Vertical structure determined from eigenvalue problem,

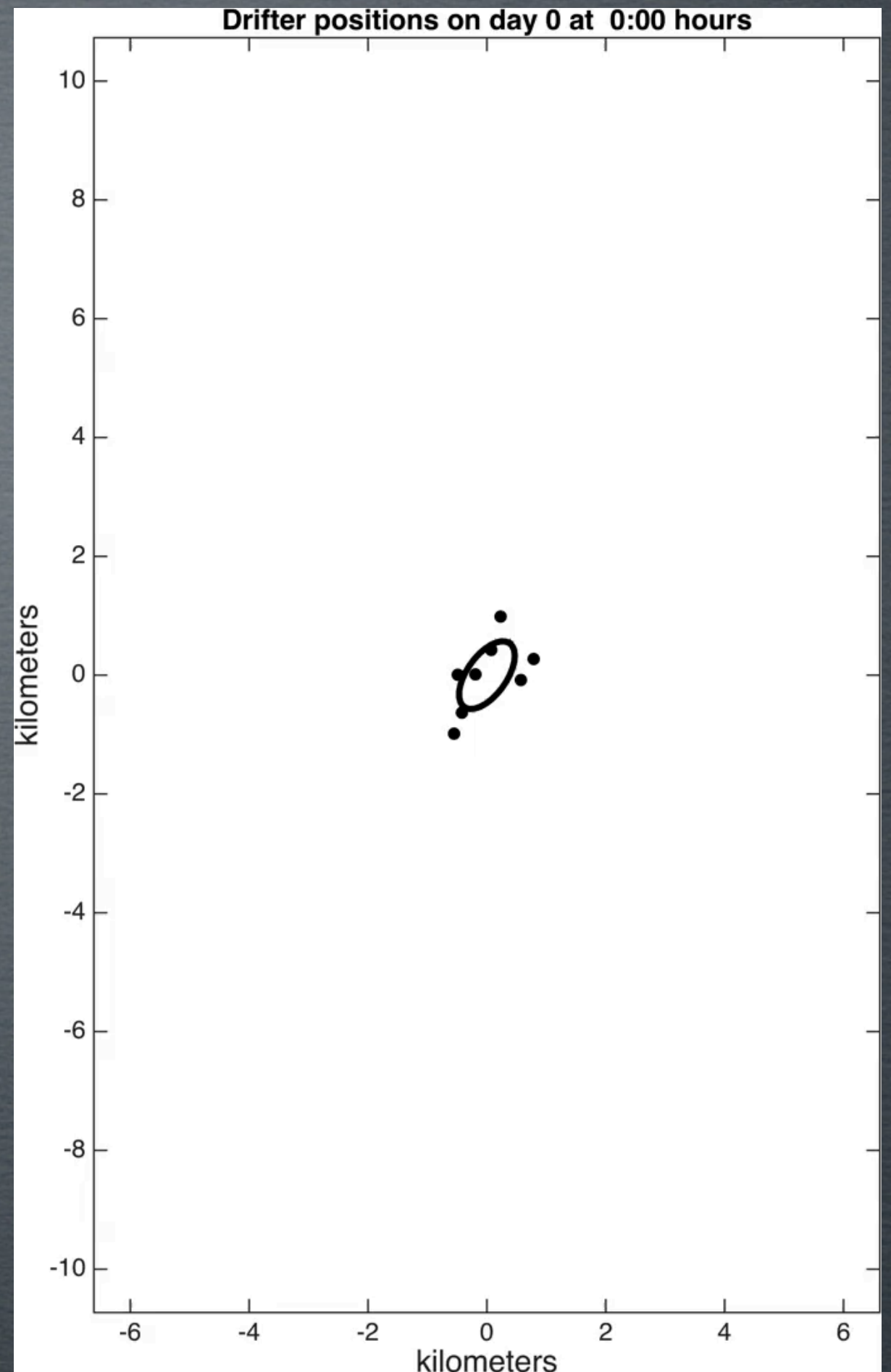
$$G_{zz}^{(j)}(z) - k^2 G^{(j)}(z) = \frac{f_0^2 - N^2(z)}{g h_j} G^{(j)}(z)$$

$$F(z) = h G_z(z)$$

✻ Now sum up a full Garrett-Munk like spectrum

SITE 2 DRIFTER TRAJECTORIES

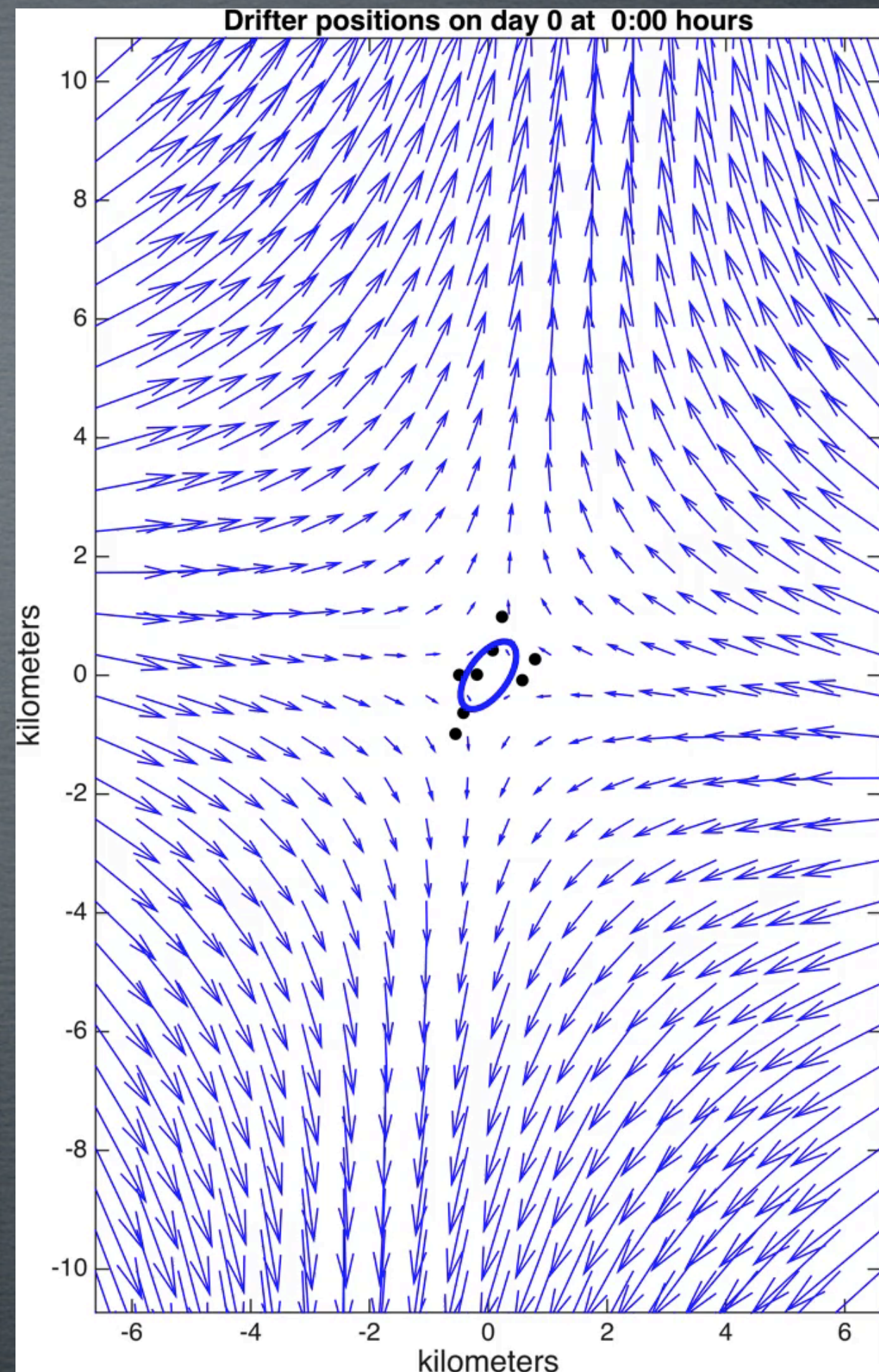
Moderate time varying
strain field.



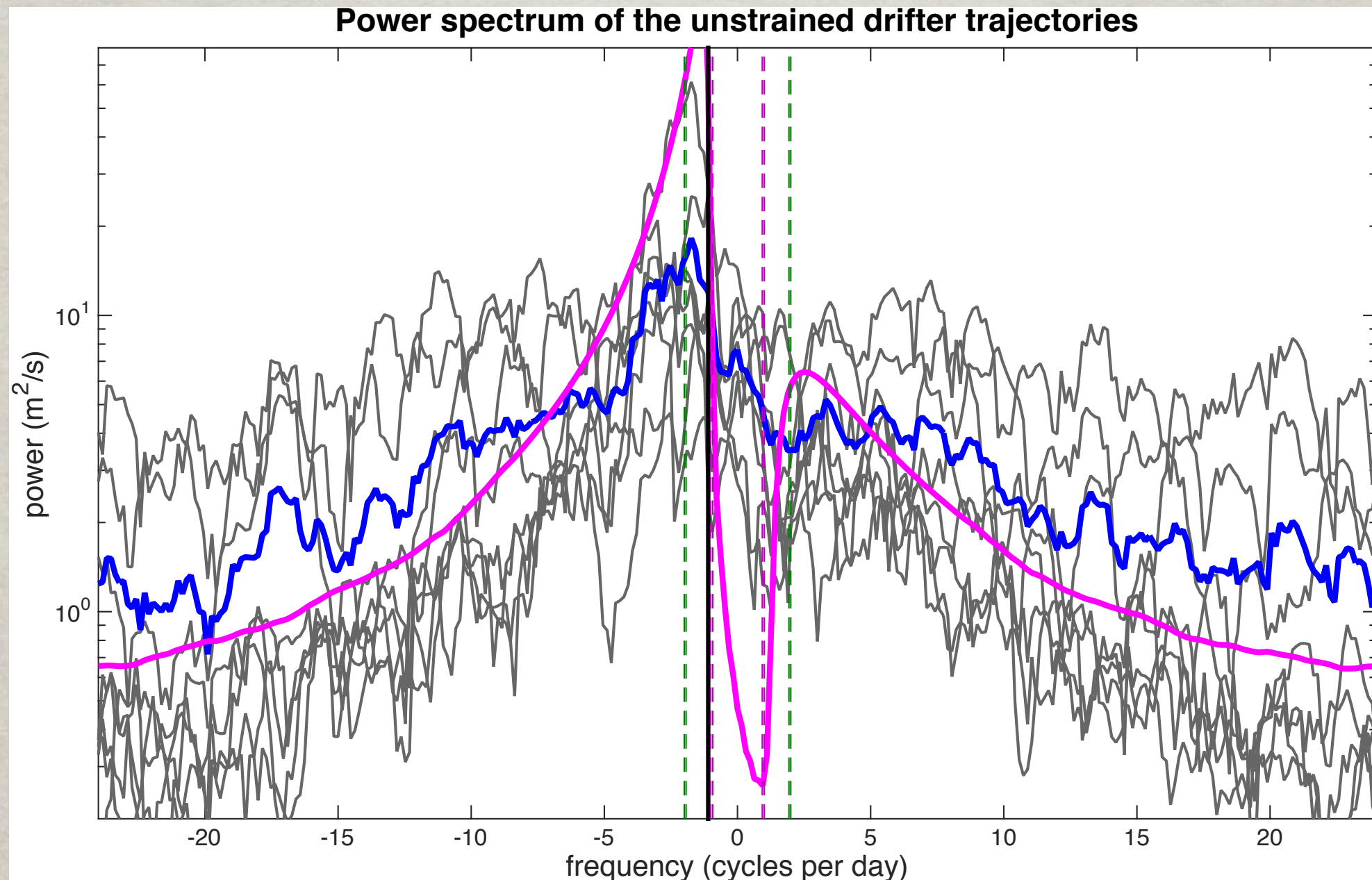
SITE 2 TRAJECTORIES WITH SOLUTION

 Observed 2nd moment

 Strain-diffusivity model
 $\bar{\kappa} = 1.1 \text{ m}^2/\text{s}$



SITE 2 SPECTRA



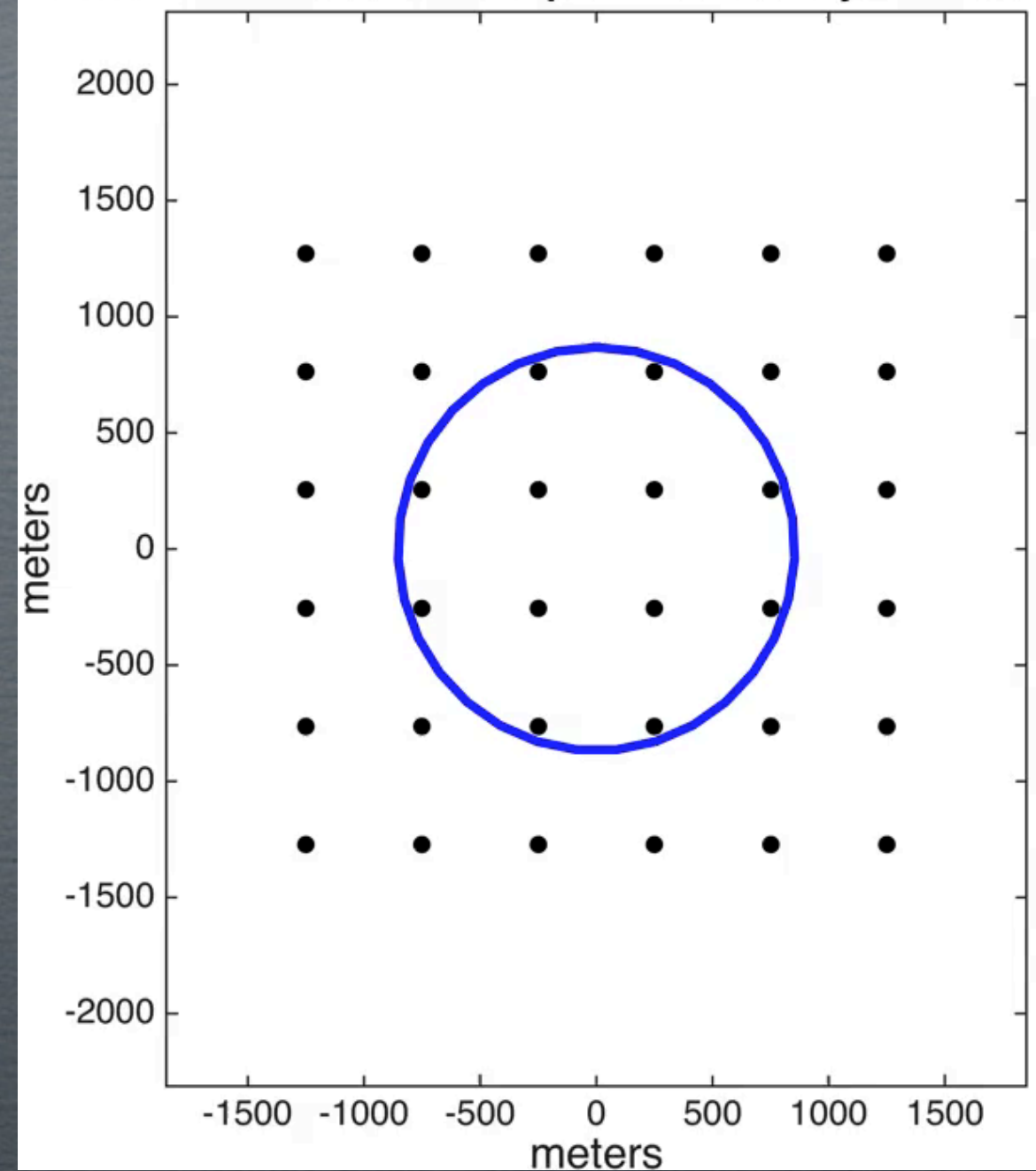
- ☼ Theoretical GM spectrum for center-of-mass internal waves at 1.0 GM reference level (magenta).

DRIFTER-LIKE PARTICLES

FROM A LINEAR INTERNAL WAVE MODEL

- More particles than the real experiment, but similar scales.

Internal wave model drifter positions on day 0 at 0:00 hours



 Observed 2nd moment

 Isotropic model, $\kappa = 0.05 \text{ m}^2/\text{s}$