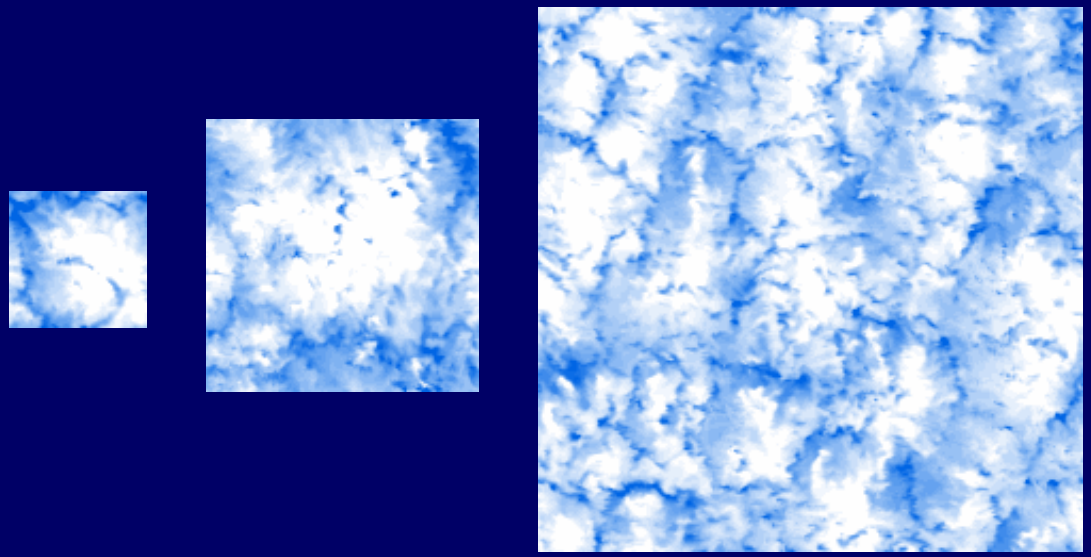
Spectral transfer of TKE and scalar variance in the meso- and micro-scale range:

direction of the average flow and the significance of backscatter



Harm Jonker, Peter Duynkerke, Stephan de Roode, Jordi Vila

Department of Multi-Scale Physics
Faculty of Applied Sciences

TU Delft

The spectral gap ...

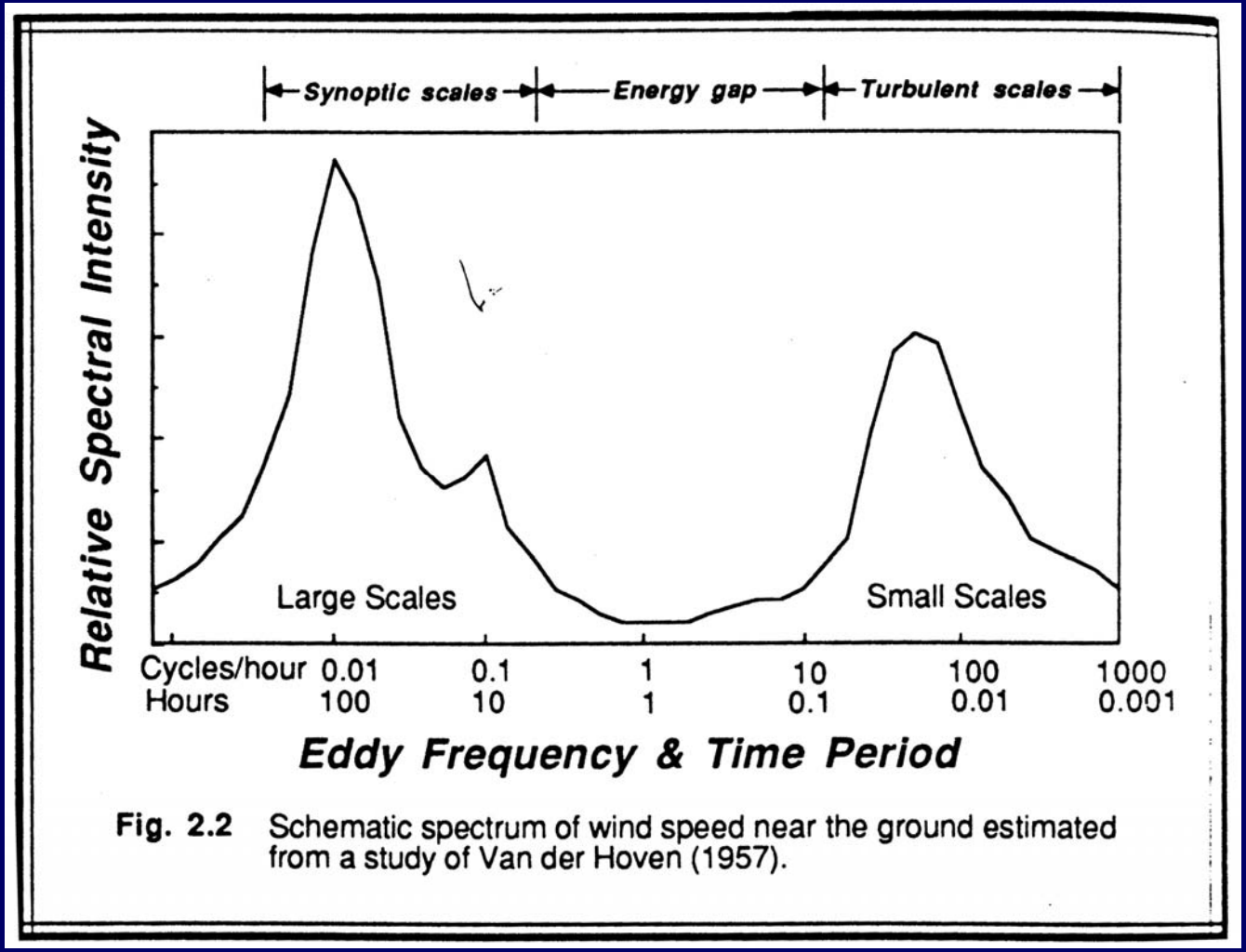


Fig. 2.2 Schematic spectrum of wind speed near the ground estimated from a study of Van der Hoven (1957).

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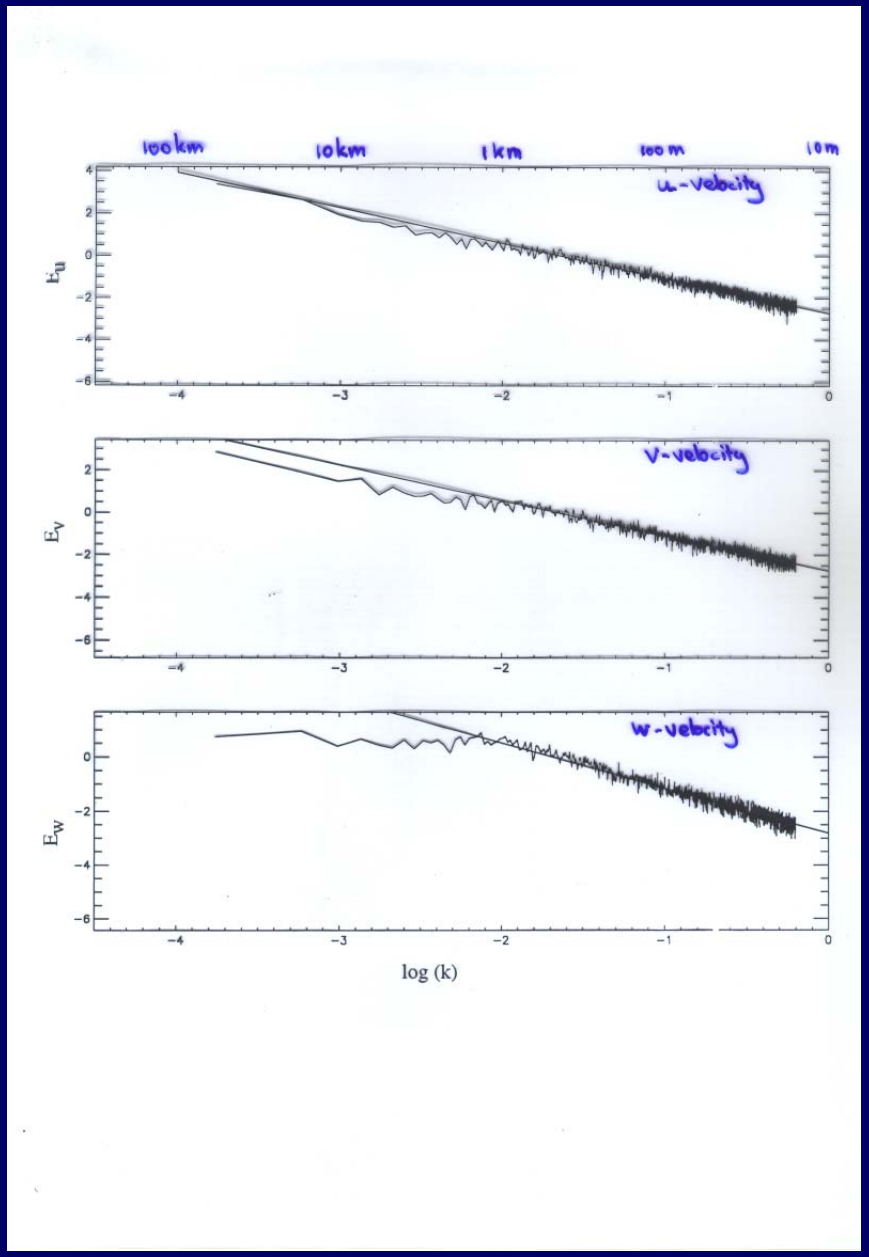
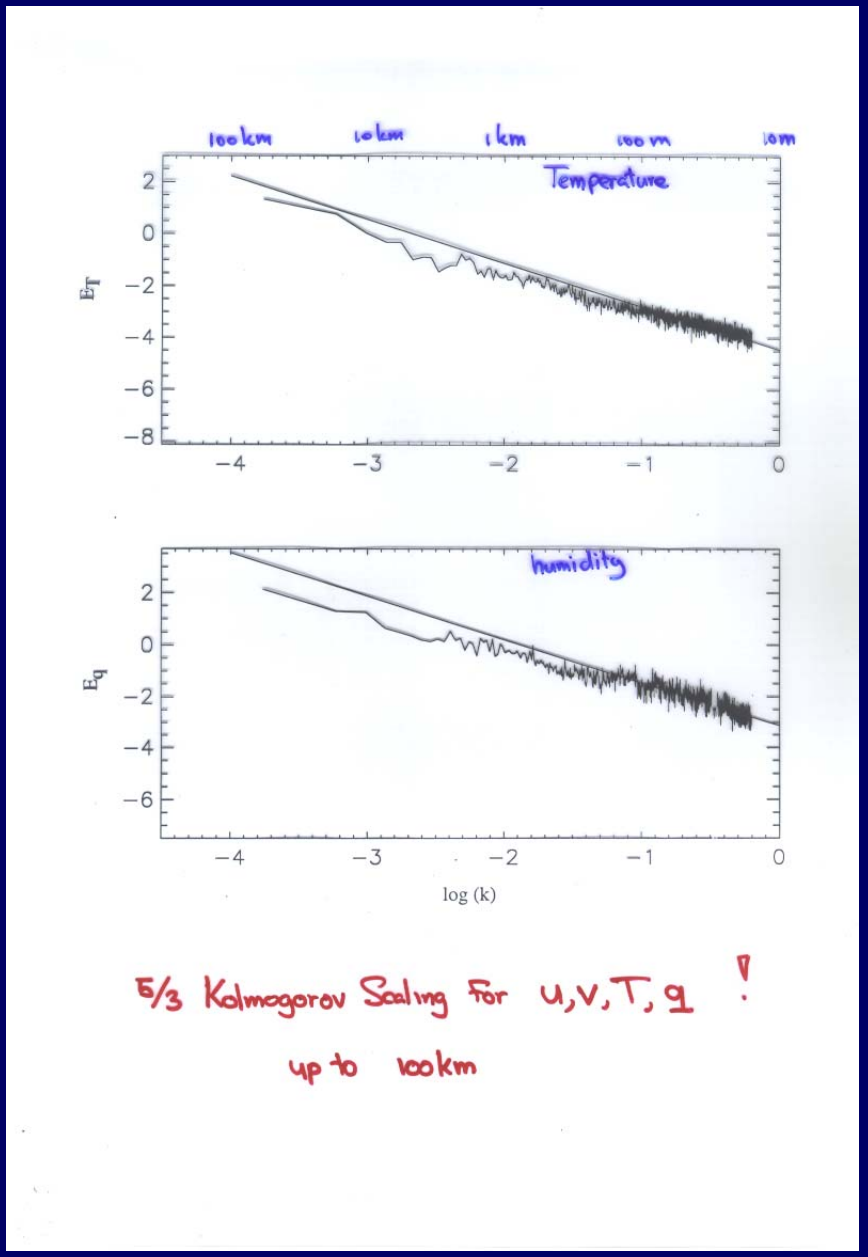
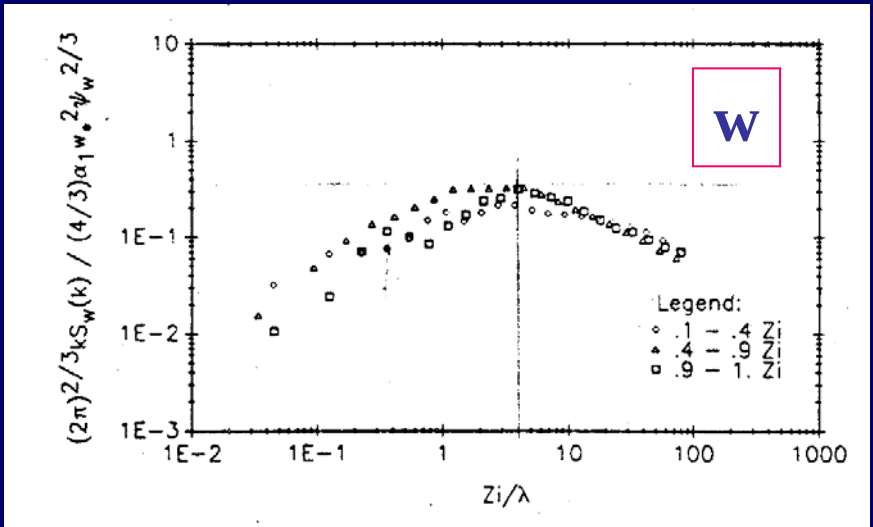
ASTEX aircraft observations

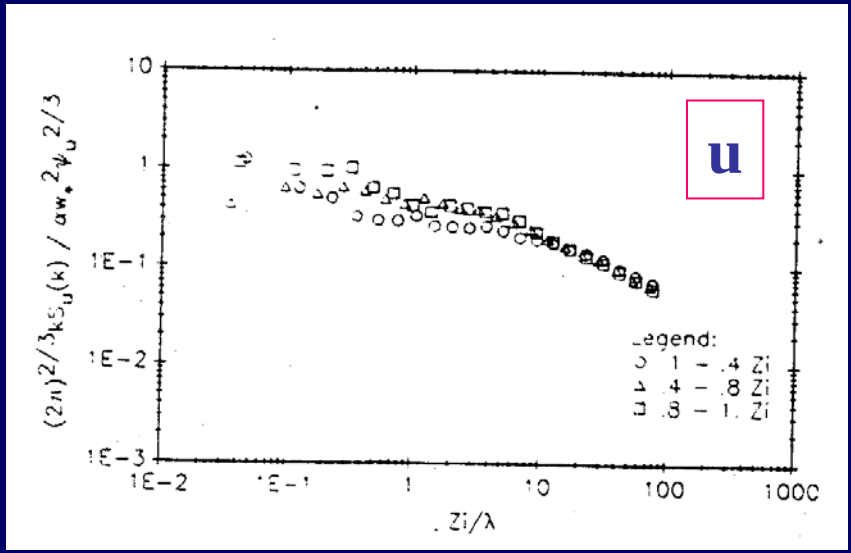


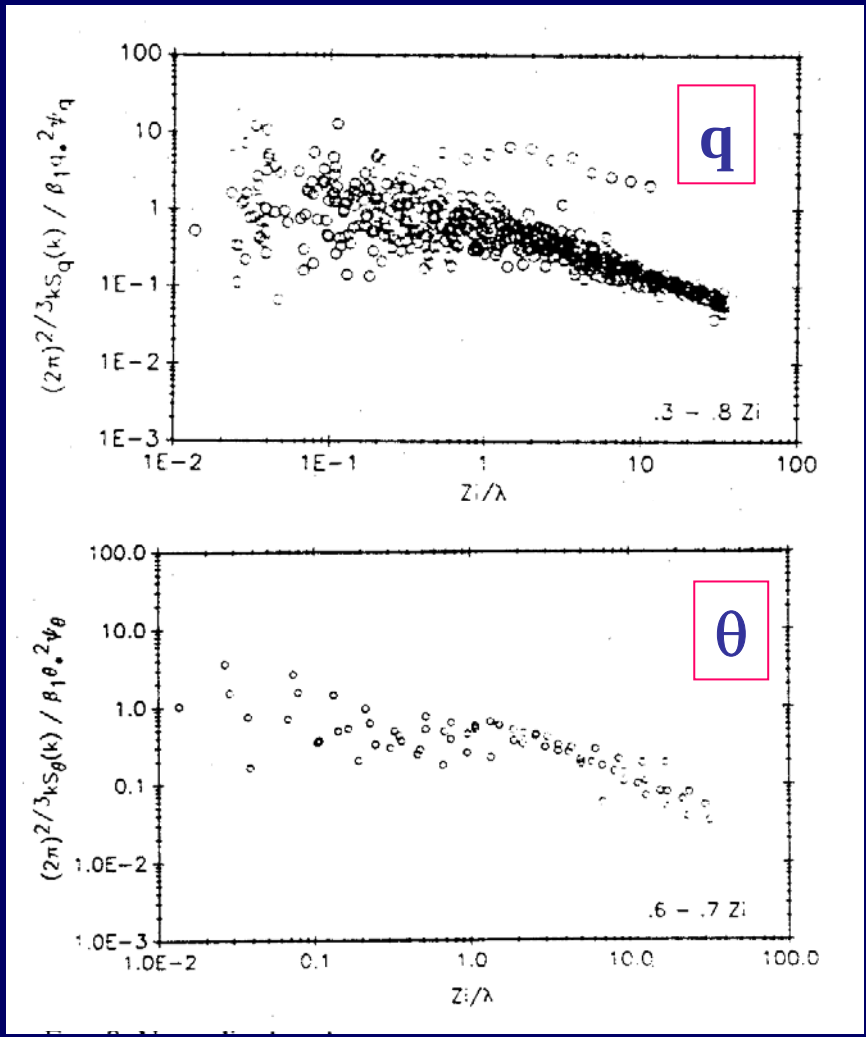


Atmospheric Observations: Sc

Nucciarone & Young 1991

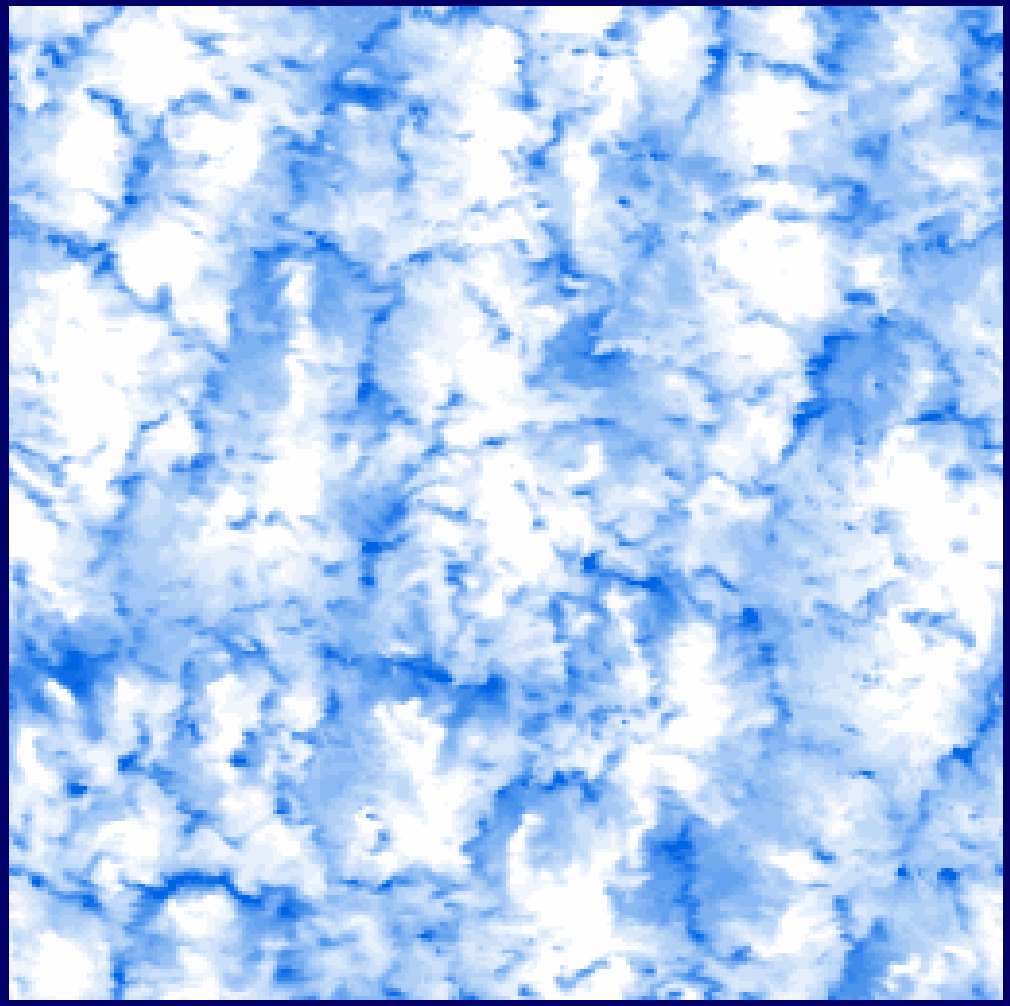




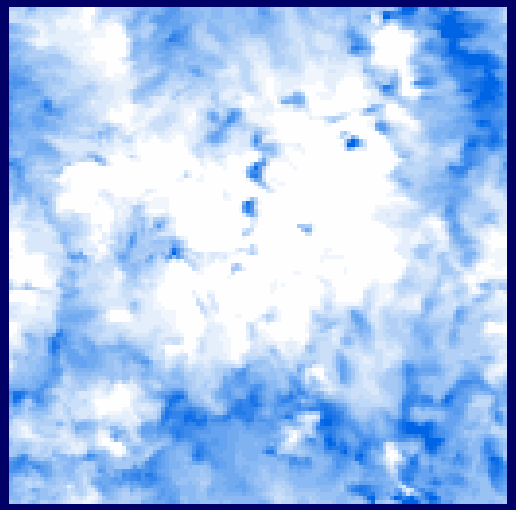


LES of Sc (ASTEX) Horizontal slice, t = 12hr, liquid water q_l

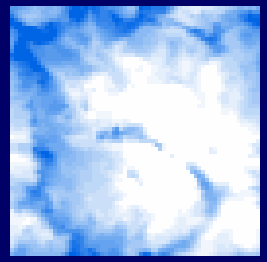
L = 25.6km



L = 12.8km



L = 6.4km

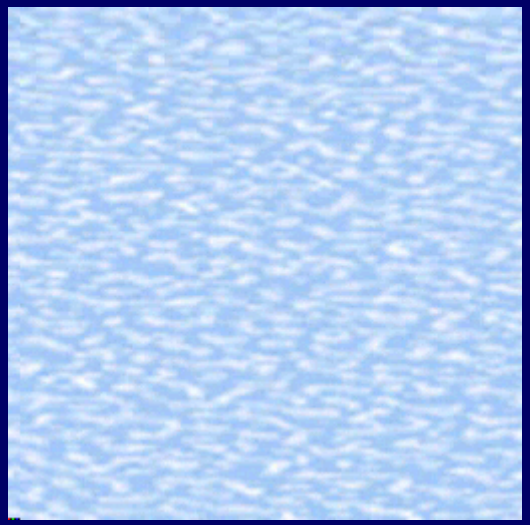


$\Delta x = \Delta y = 100m$

LES of Sc (ASTEX)

Horizontal slice, t = 1...12hr, liquid water q_l

L = 12.8km $\Delta x = \Delta y$ = 100m



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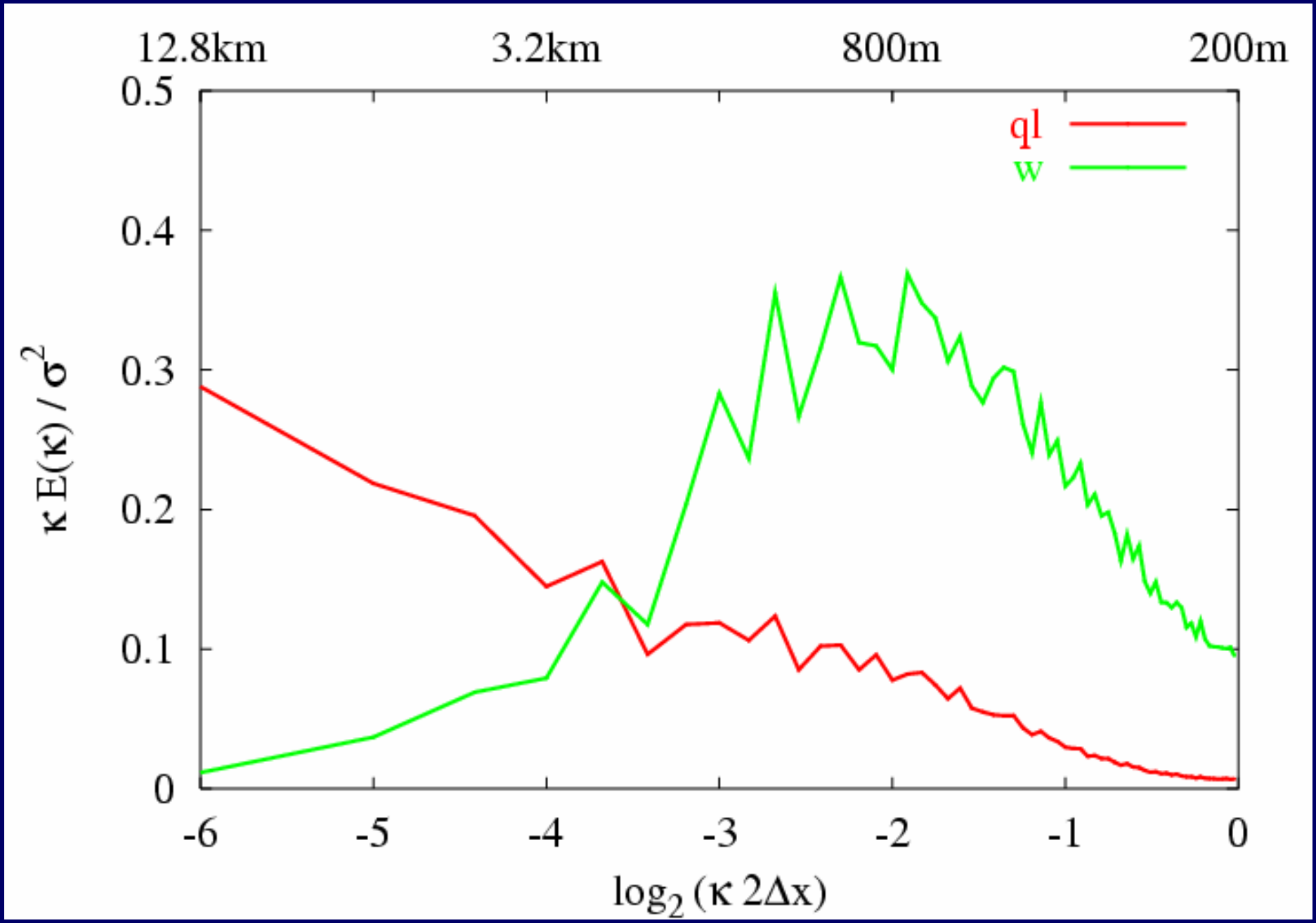

12.8km
3.2km
800m
200m
0.5
0.4
0.3
0.2
0.1
0
κ E(κ) / σ2
ql
w
-6
-5
-4
-3
-2
-1
0
log2 (κ 2Δx)

Intermediate Conclusions

1) the formation of **dominating** mesoscale fluctuations is an integral part of PBL dynamics!

- no mesoscale forcings

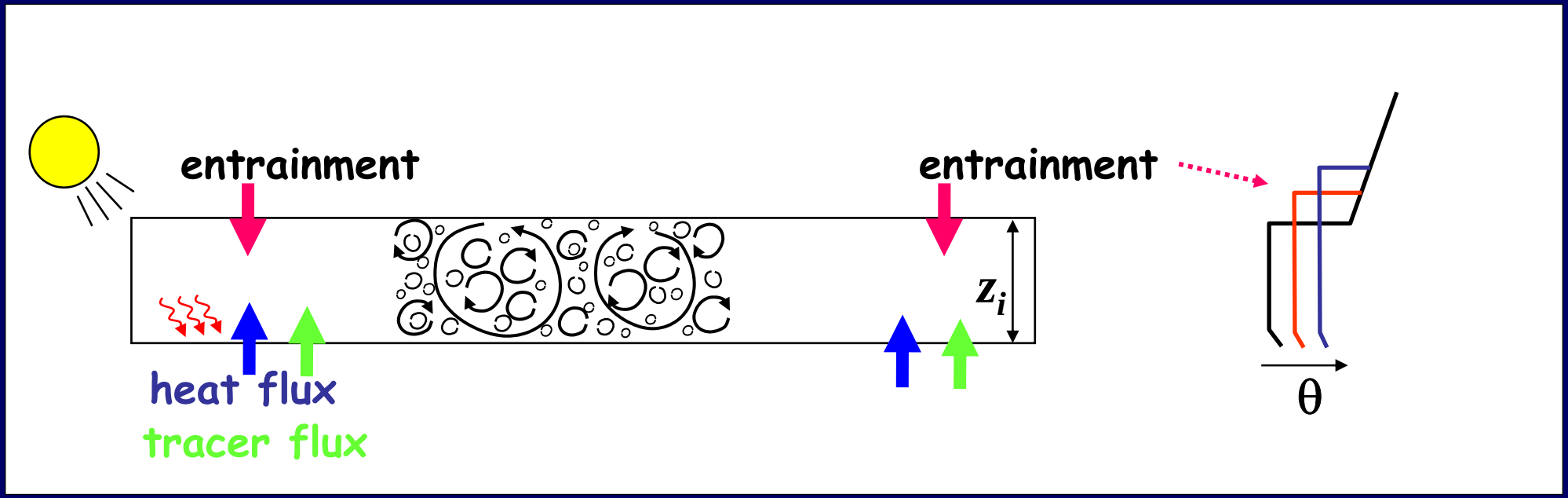
- what is the origin (mechanism) ?

  - latent heat release
  - radiative cooling
  - entrainment
  - inverse cascade

Atkinson and Zhang
Fiedler, van Delden,
Muller and Chlond,
Randall and Shao,
Dornbrack, ...

Convective Atmospheric Boundary Layer

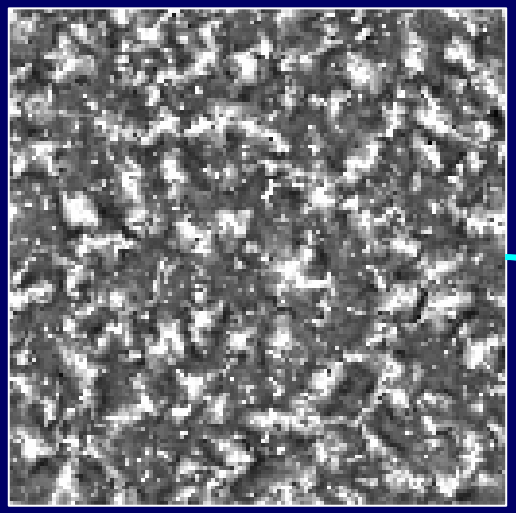
penetrative convection

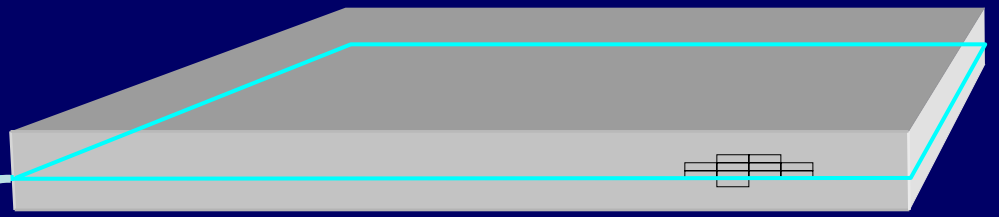


TU Delft

LES

w

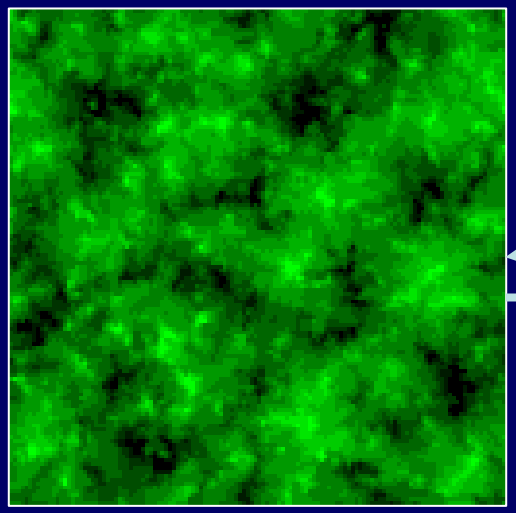




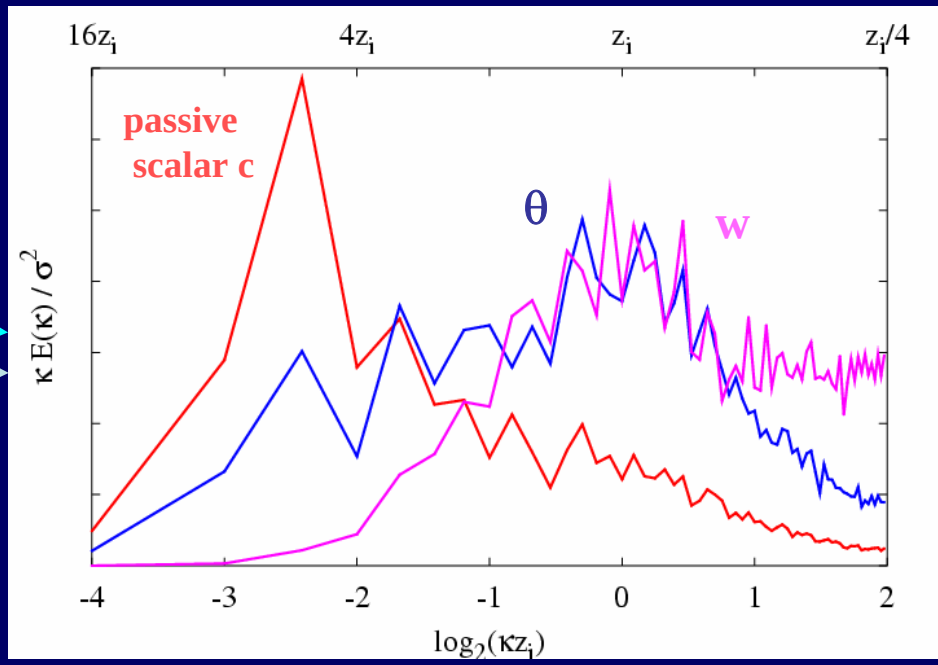
variance spectra

$$\sigma^2 = \int \left(c(\vec{x}) - \bar{c}\right)^2 d\,\vec{x} \quad = \int_0^\infty E_c(k)\,dk$$

c



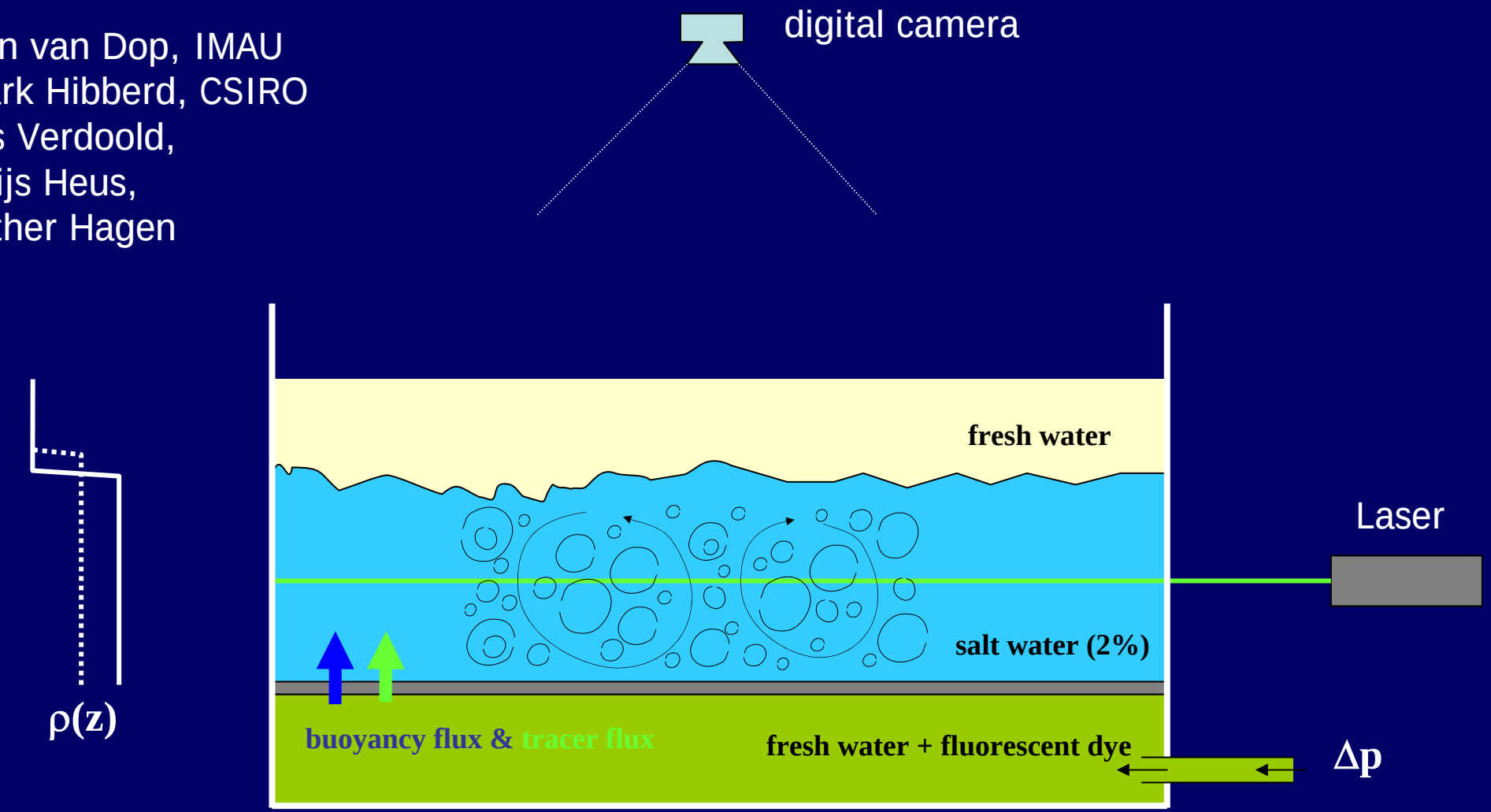
FFT (2D)



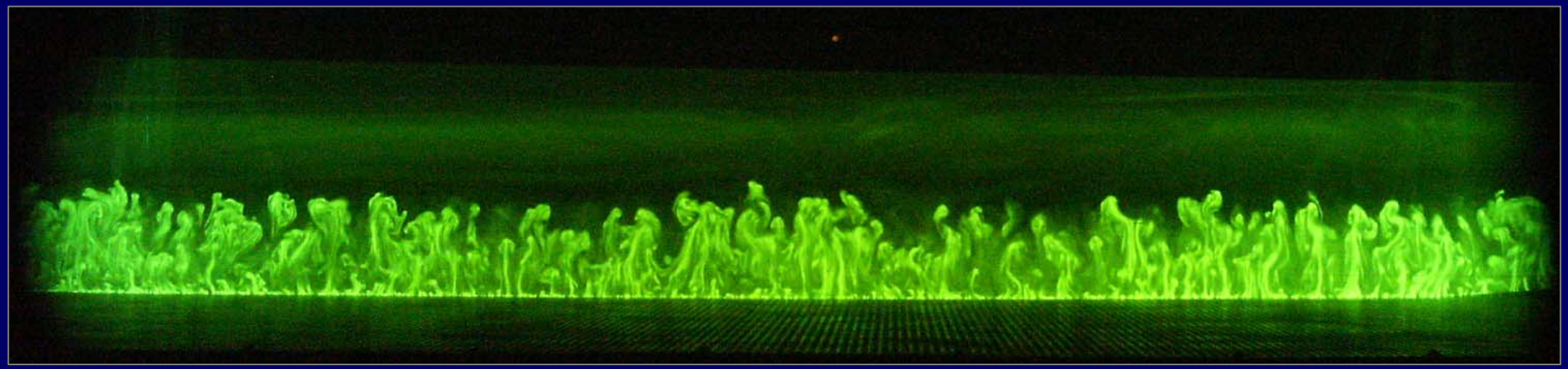
Jonker,Duynkerke,Cuypers, JAS, 1999

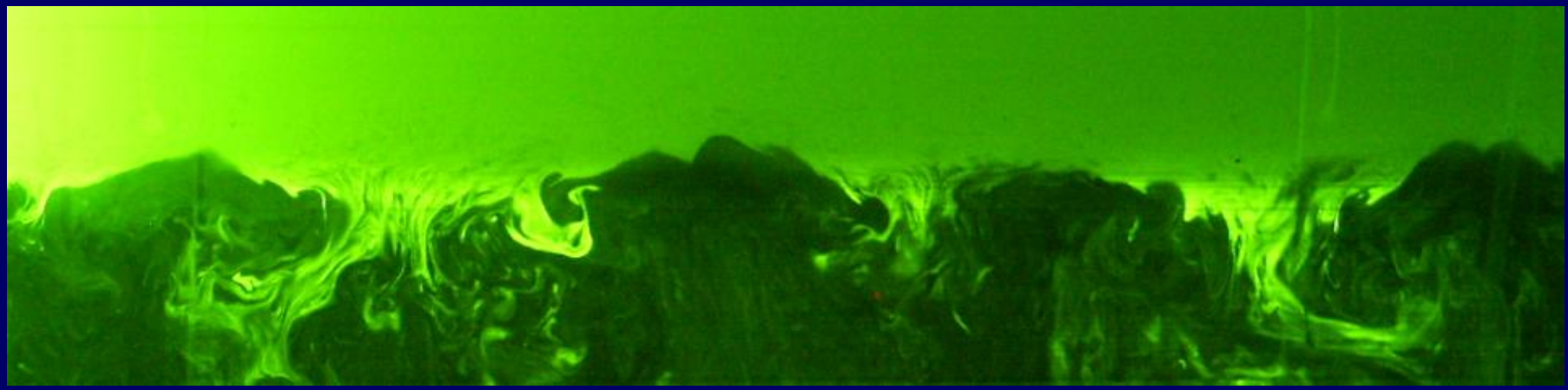
Saline convection tank
Laser Induced Fluorescence (LIF)

Han van Dop, IMAU
Mark Hibberd, CSIRO
Jos Verdoold,
Thijs Heus,
Esther Hagen



Laser Induced Fluorescence

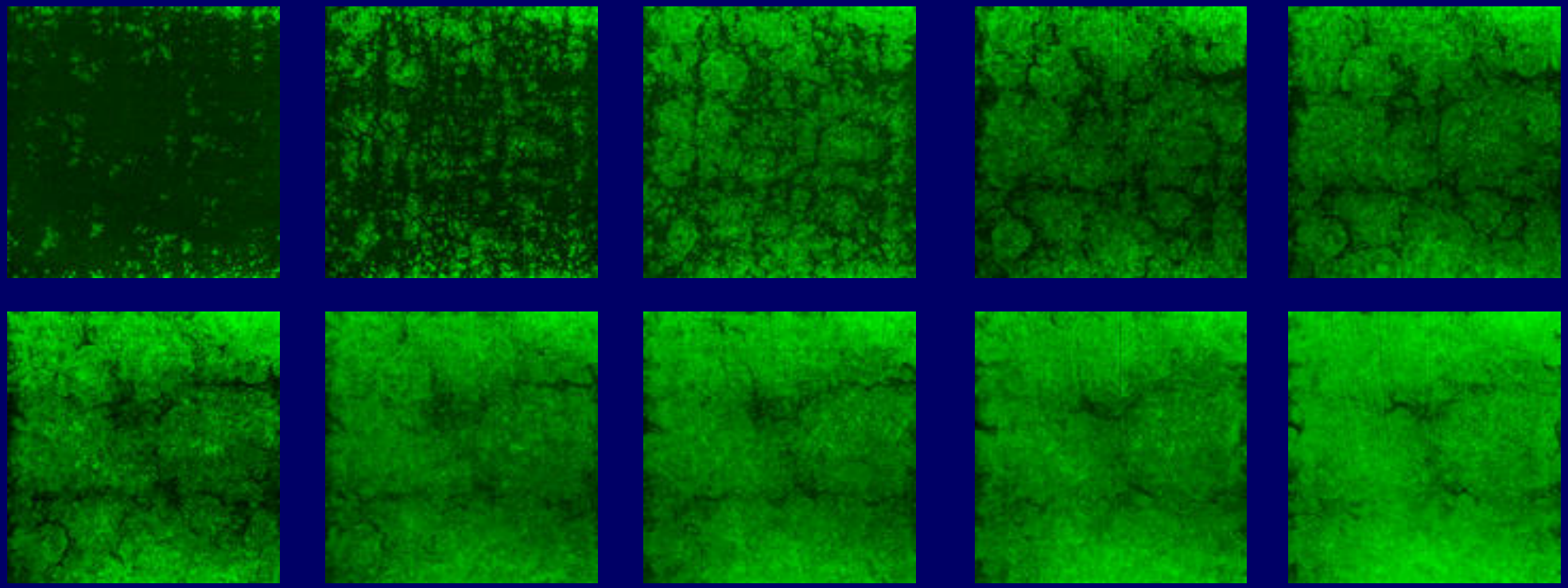




Laser Induced Fluorescence (LIF)

"bottom-up" tracer

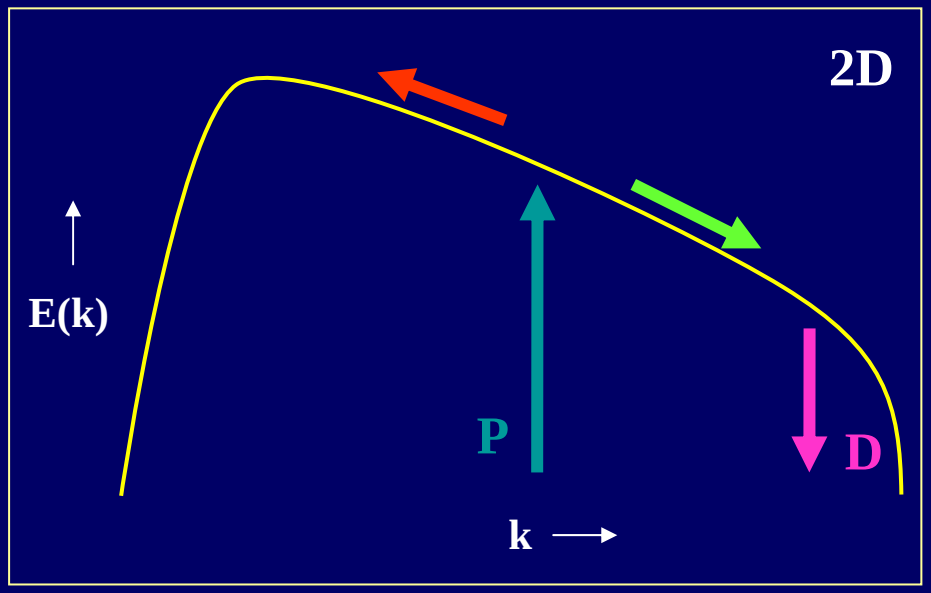
- boundary layer depth structure

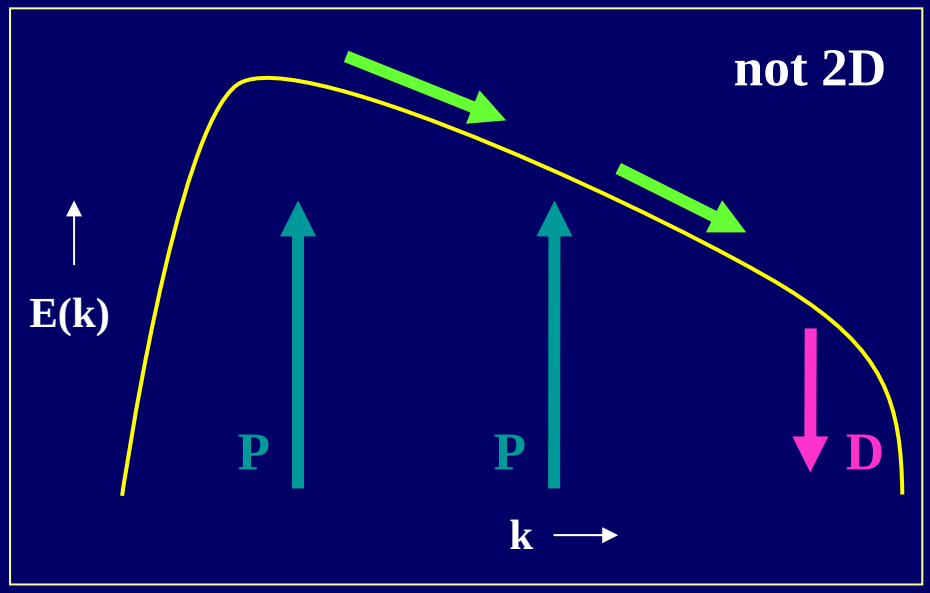


(see also van Dop, et al. BLM 2005)

(Verdoold, Delft, 2001)

Inverse Cascade?





2-D or not 2-D: that's the question!

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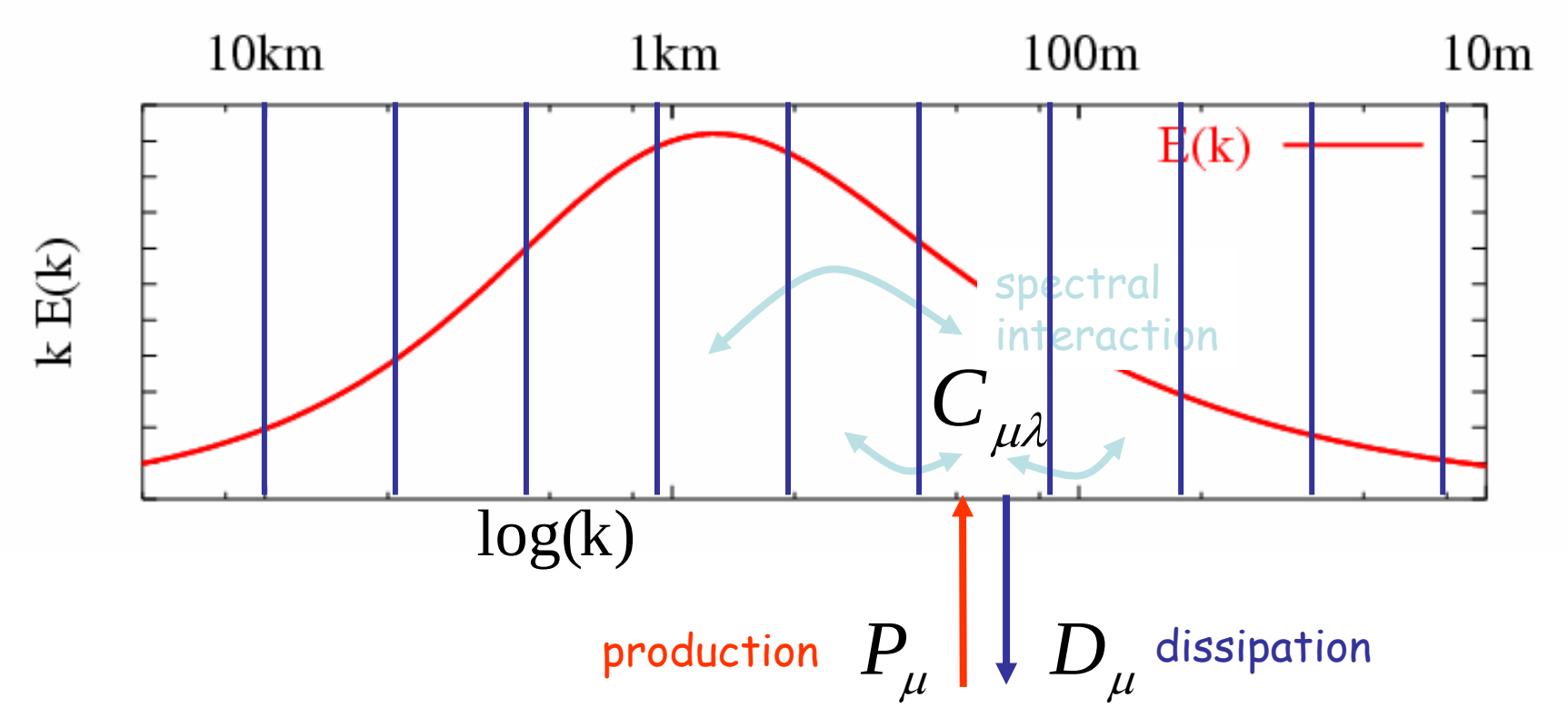
$$c = \bar{c} + c' \longrightarrow \frac{d}{dt}\overline{c'^2} = P - D$$

variance budget

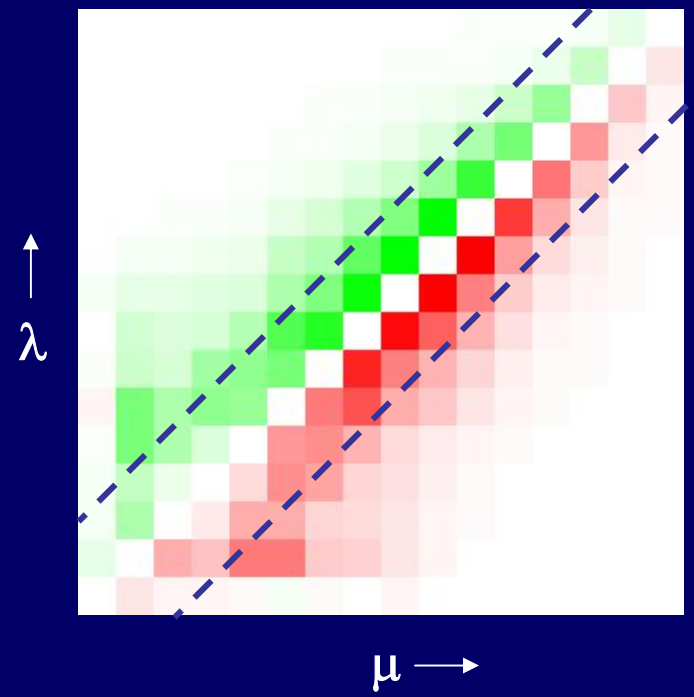


$$c = \bar{c} + c_1 + c_2 + \ldots + c_n \longrightarrow \frac{d}{dt}\overline{c_\mu^2} = P_\mu - D_\mu + \sum_\lambda C_{\mu\lambda}$$

scale by scale variance budget

Scale Interaction Matrix $C_{\mu\lambda}$

16 sections



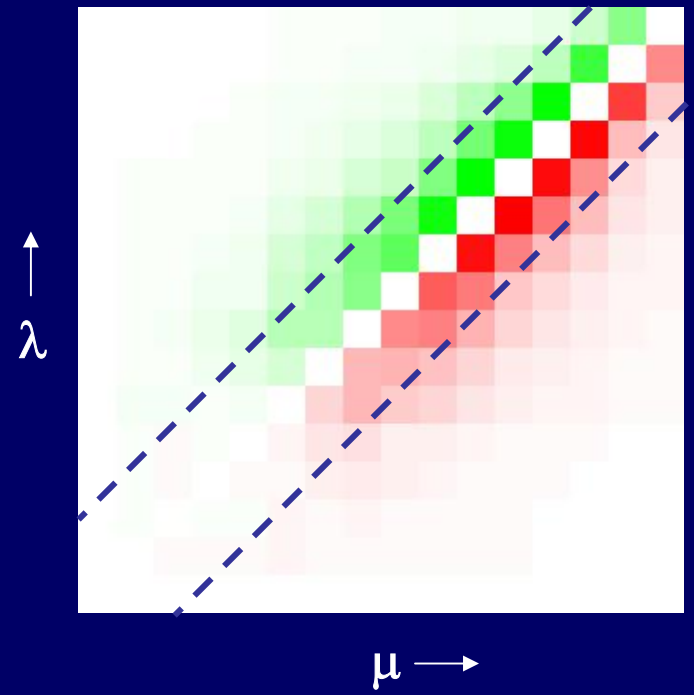
source

sink

passive scalar

Scale Interaction Matrix $C_{\mu\lambda}$

16 sections

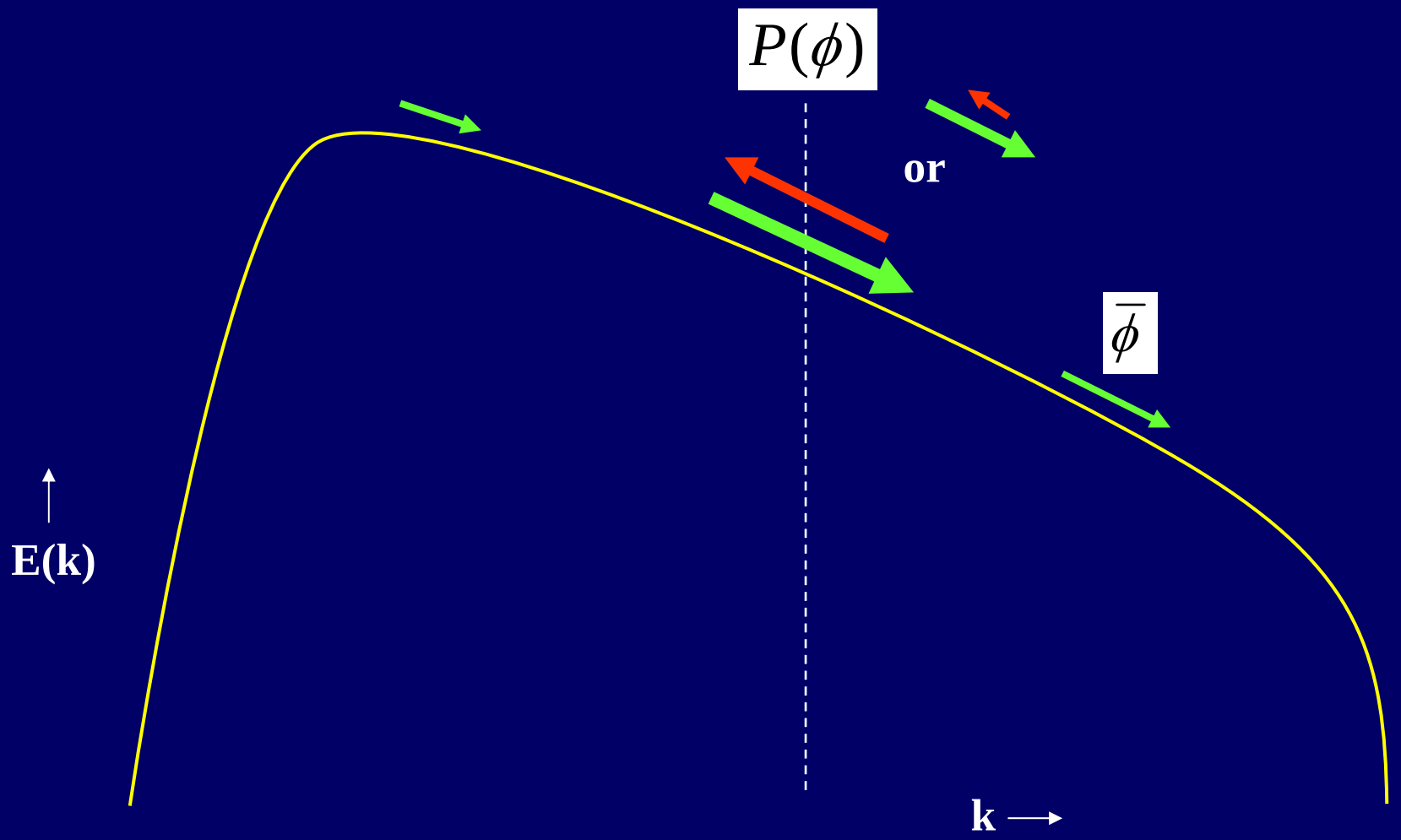


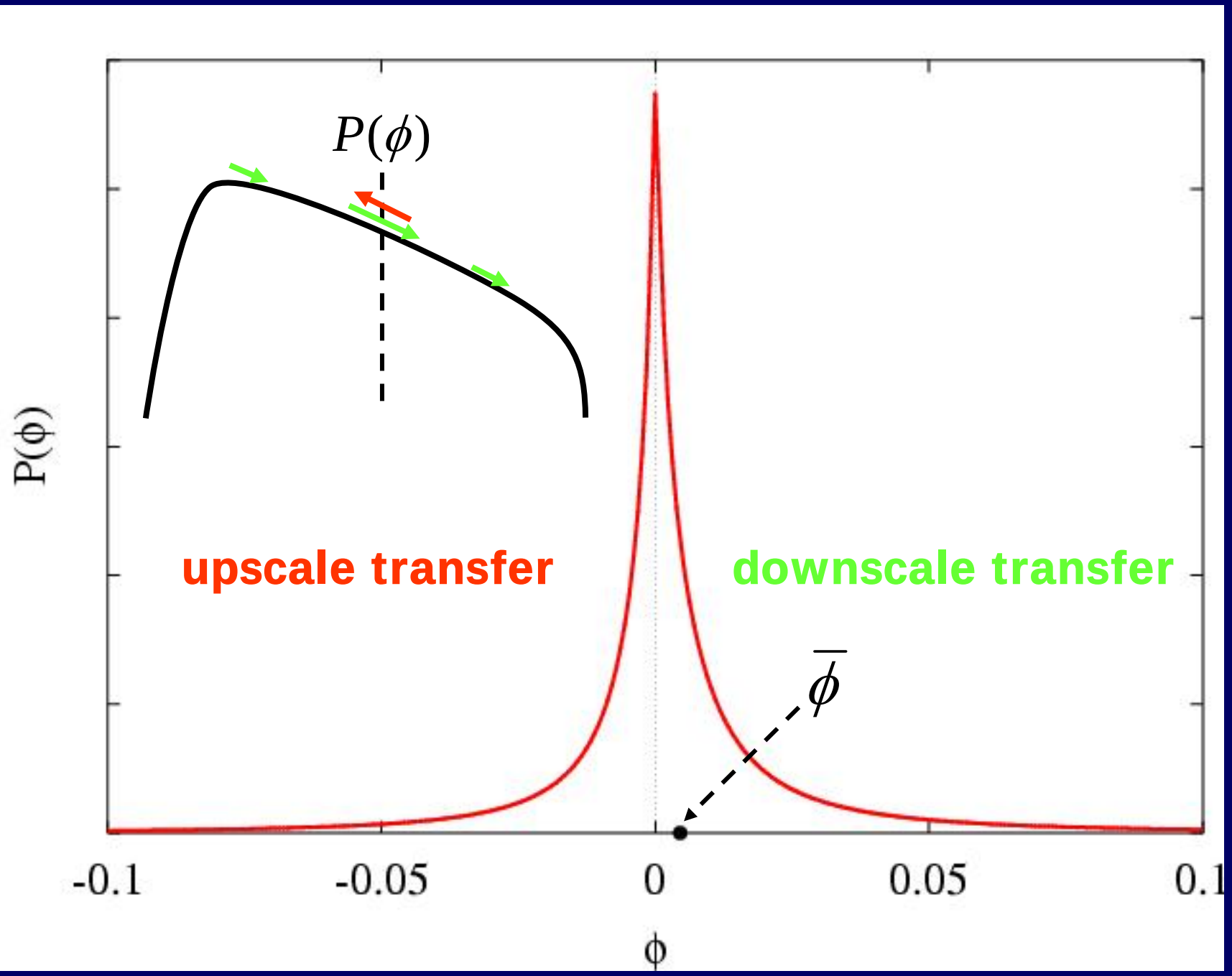
source

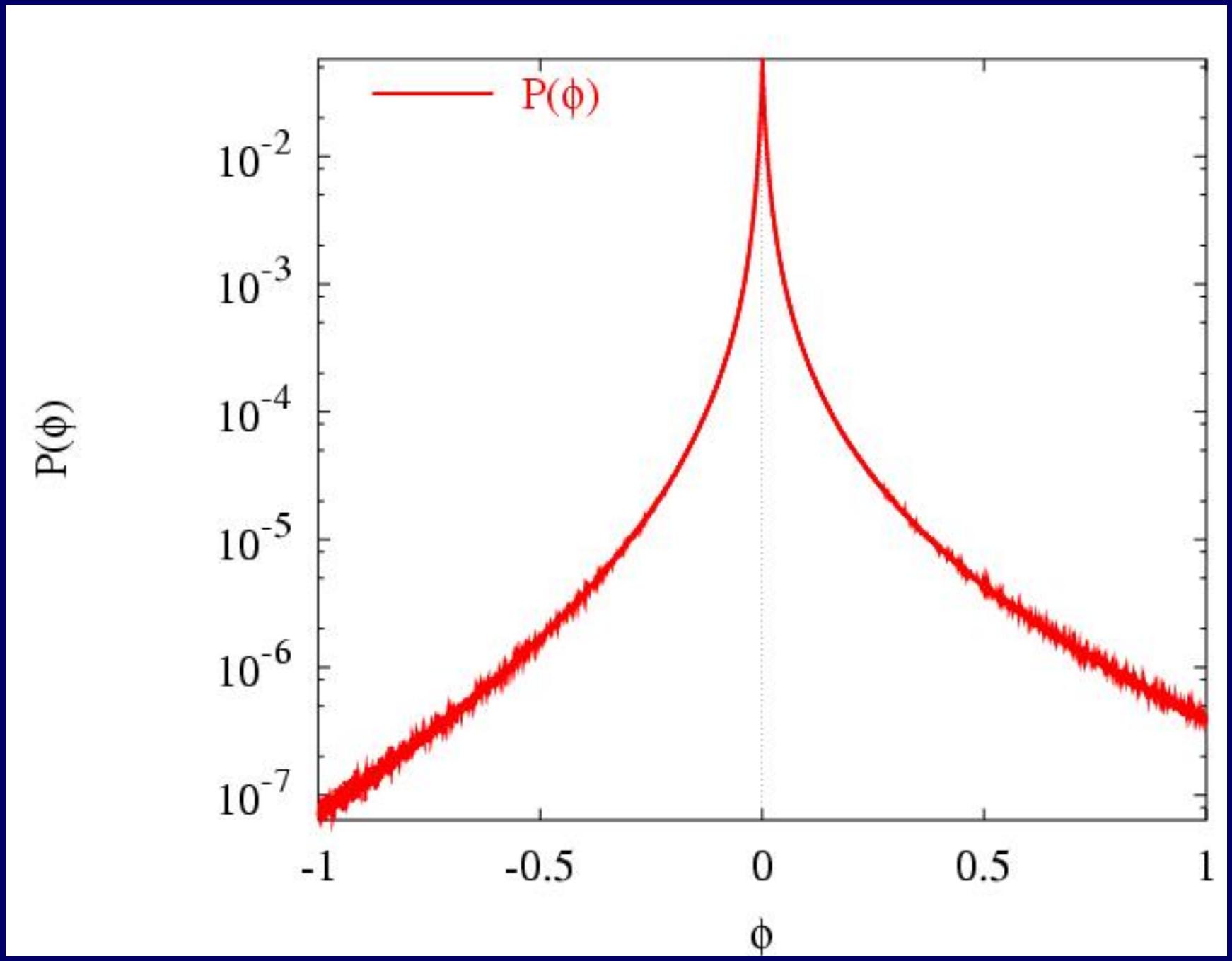
sink

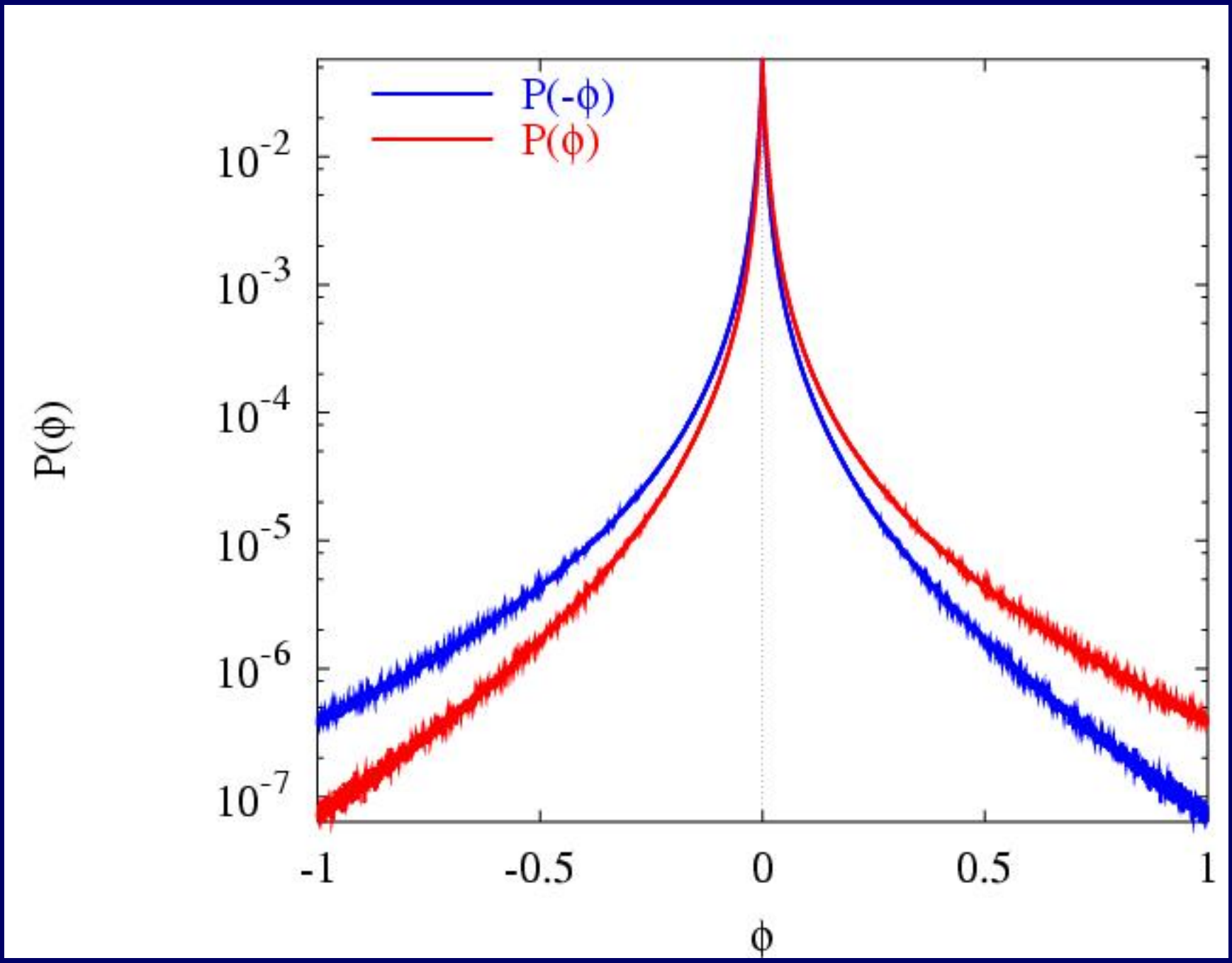
temperature

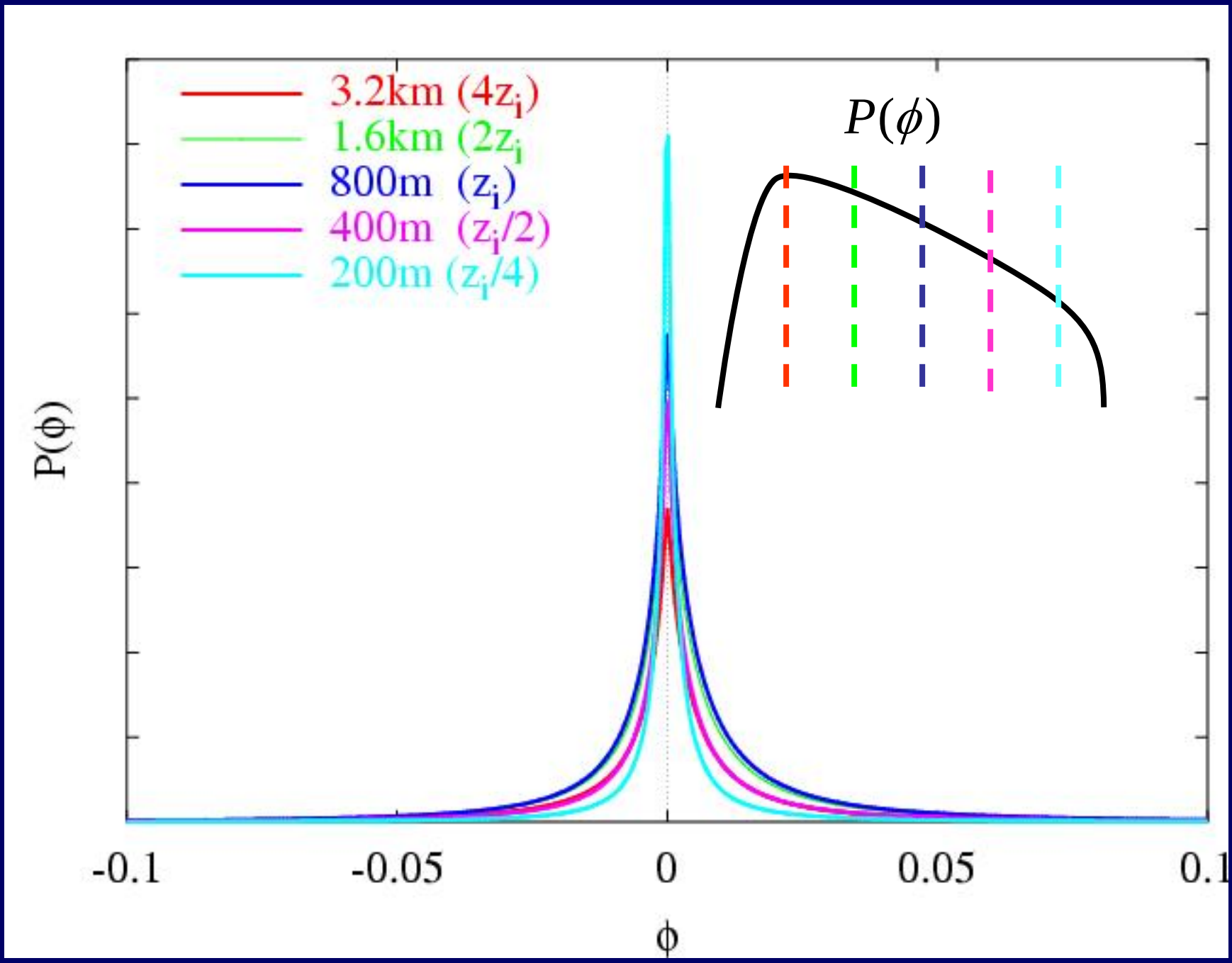
pdf of spectral flow f

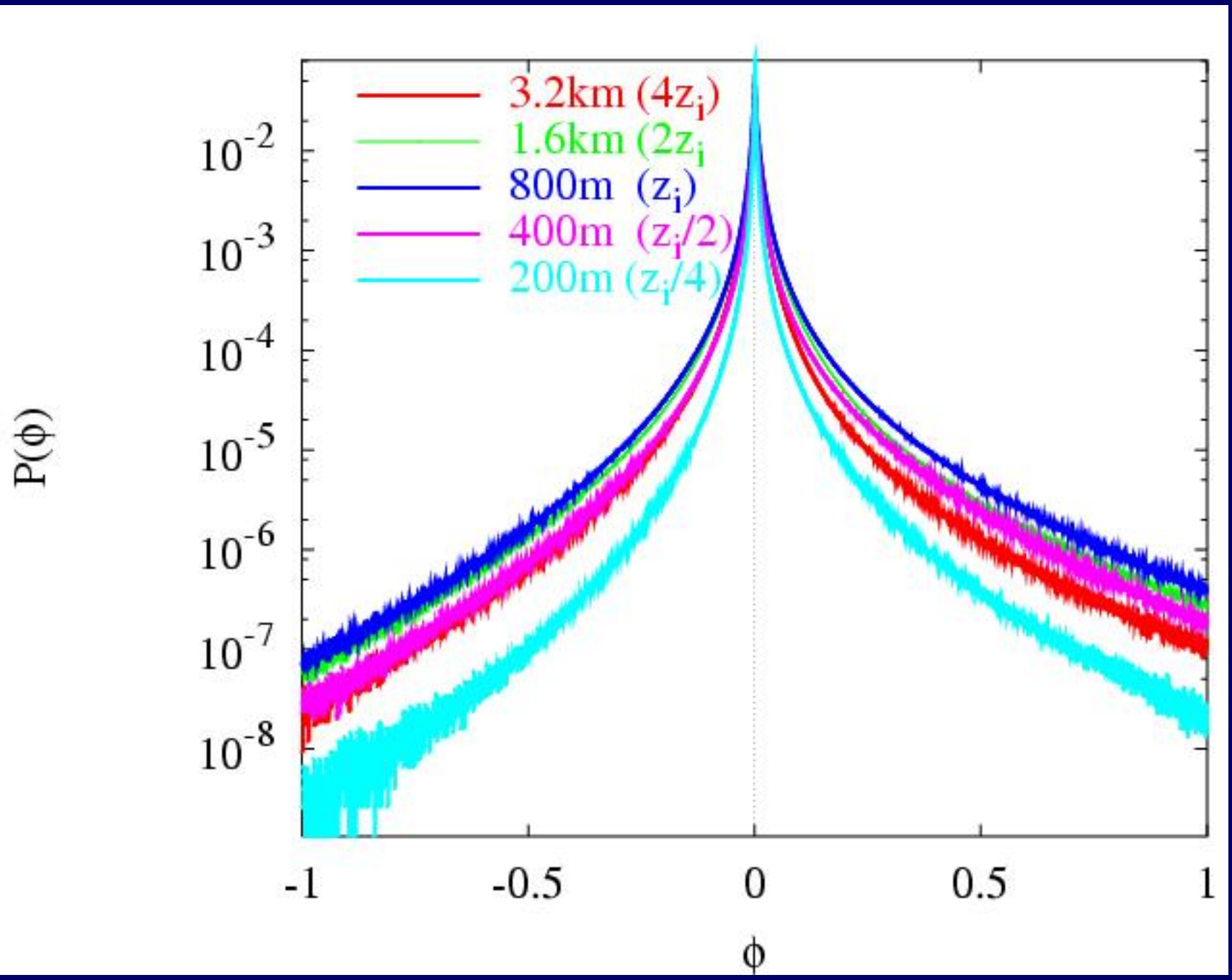



$P(\phi)$
P(ϕ)
upscale transfer
downscale transfer
$\bar{\phi}$
-0.1
-0.05
0
0.05
0.1
ϕ


P(ϕ)
P(ϕ)
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
-1
-0.5
0
0.5
1
ϕ


P(-ϕ)
P(ϕ)
P(ϕ)
10-2
10-3
10-4
10-5
10-6
10-7
-1
-0.5
0
0.5
1
ϕ


3.2km (4z_i)
1.6km (2z_i
800m (z_i)
400m (z_i/2)
200m (z_i/4)
P(ϕ)
P(ϕ)
-0.1
-0.05
0
0.05
0.1
ϕ


3.2km (4z_i)
1.6km (2z_i
800m (z_i)
400m (z_i/2)
200m (z_i/4)
P(ϕ)
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
-1
-0.5
0
0.5
1
ϕ

Intermediate Conclusions

1) the formation of **dominating** mesoscale fluctuations is an integral part of PBL dynamics!

2) latent heat and radiation are **not** essential

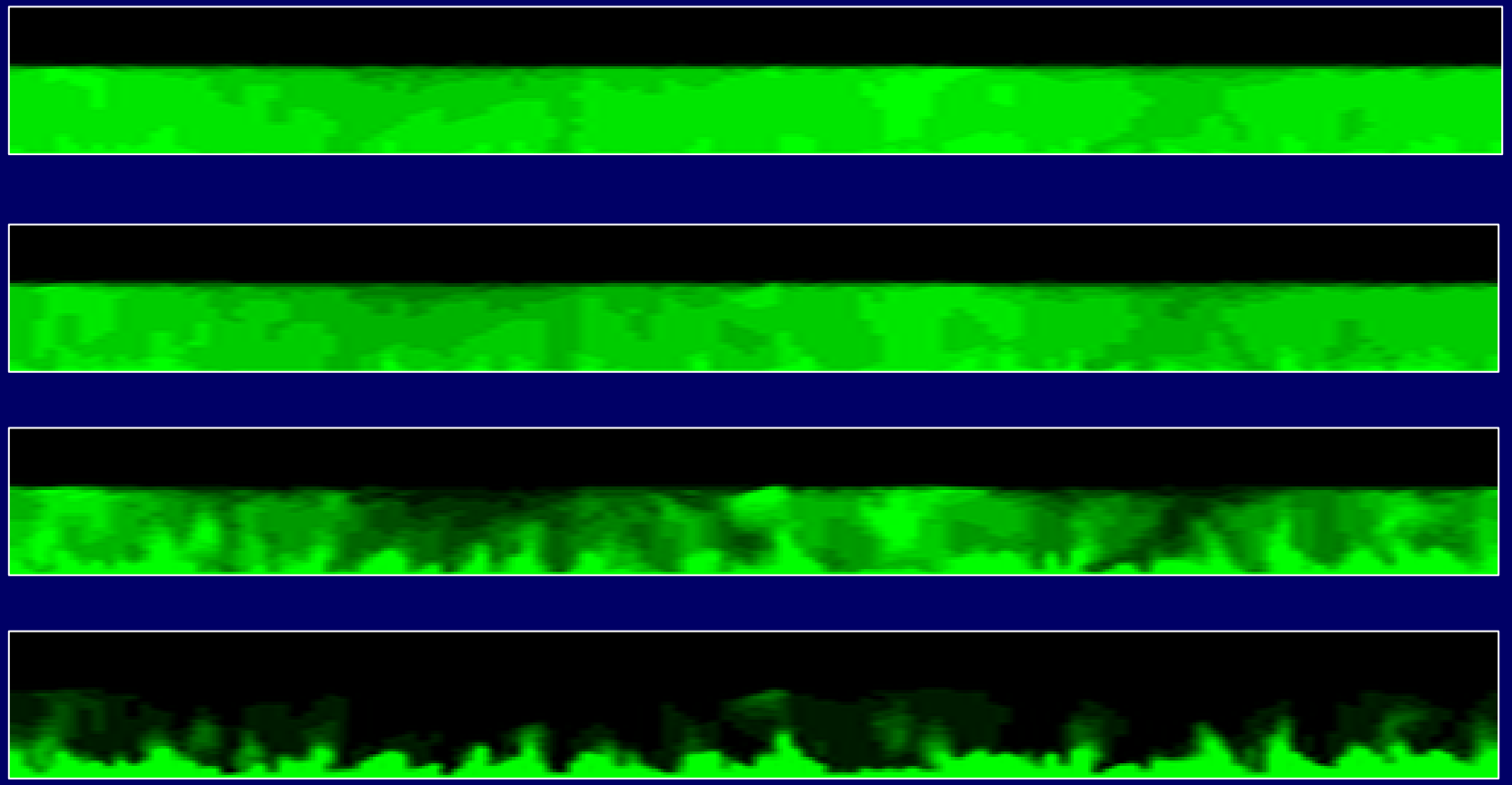
3) budgets show: no inverse cascade

- ~~latent heat release~~
- ~~radiative cooling~~
- ~~entrainment~~
- ~~inverse cascade~~

$$\frac{d}{dt}c = -jc$$

LES of reacting species:
Side view at $\mathbf{t = 40\ t_*}$ (10hr)

$$\mathrm{Da} = \frac{t_{\mathrm{turb}}}{t_{\mathrm{chem}}} = j\,t_*$$



Da=10^{-2}

Da=10^{-1}

Da=10^{0}

Da=10^{1}

(Jonker, Vila, Duynkerke, JAS 2004)

Spectral Model

$$\frac{d}{dt}E_c(k) = -E_{wc}(k)\frac{\partial \overline{c}}{\partial z} - D_c k^2 E_c(k) - j E_c(k) - S(k)$$

production **dissipation** **chemistry** **spectral transfer**

Leith (1967)

$$S(k) = -\frac{d}{dk}\left[k^{13/2}\frac{d}{dk}\left(k^{-3}\sqrt{W(k)}E_c(k)\right)\right]$$

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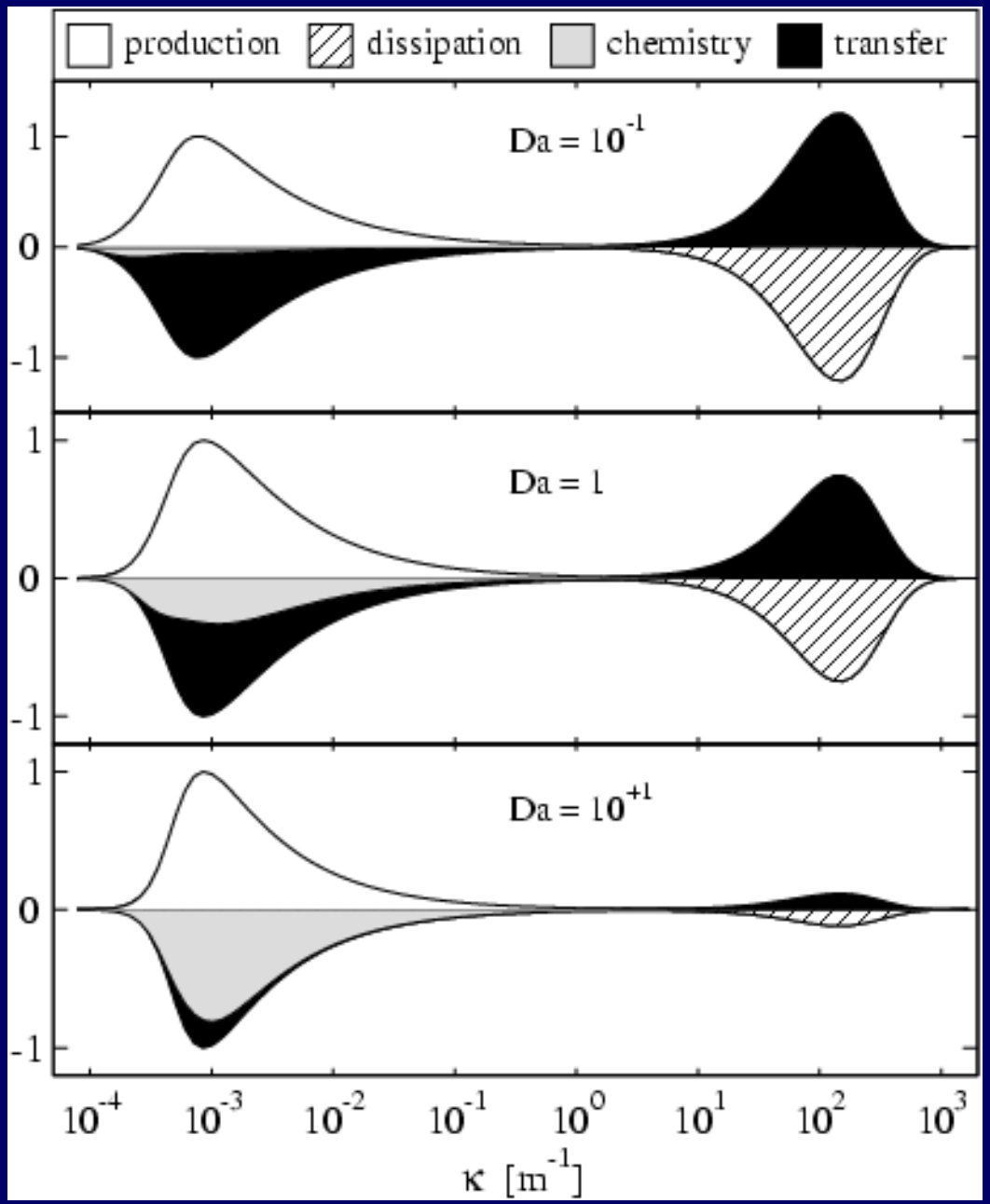
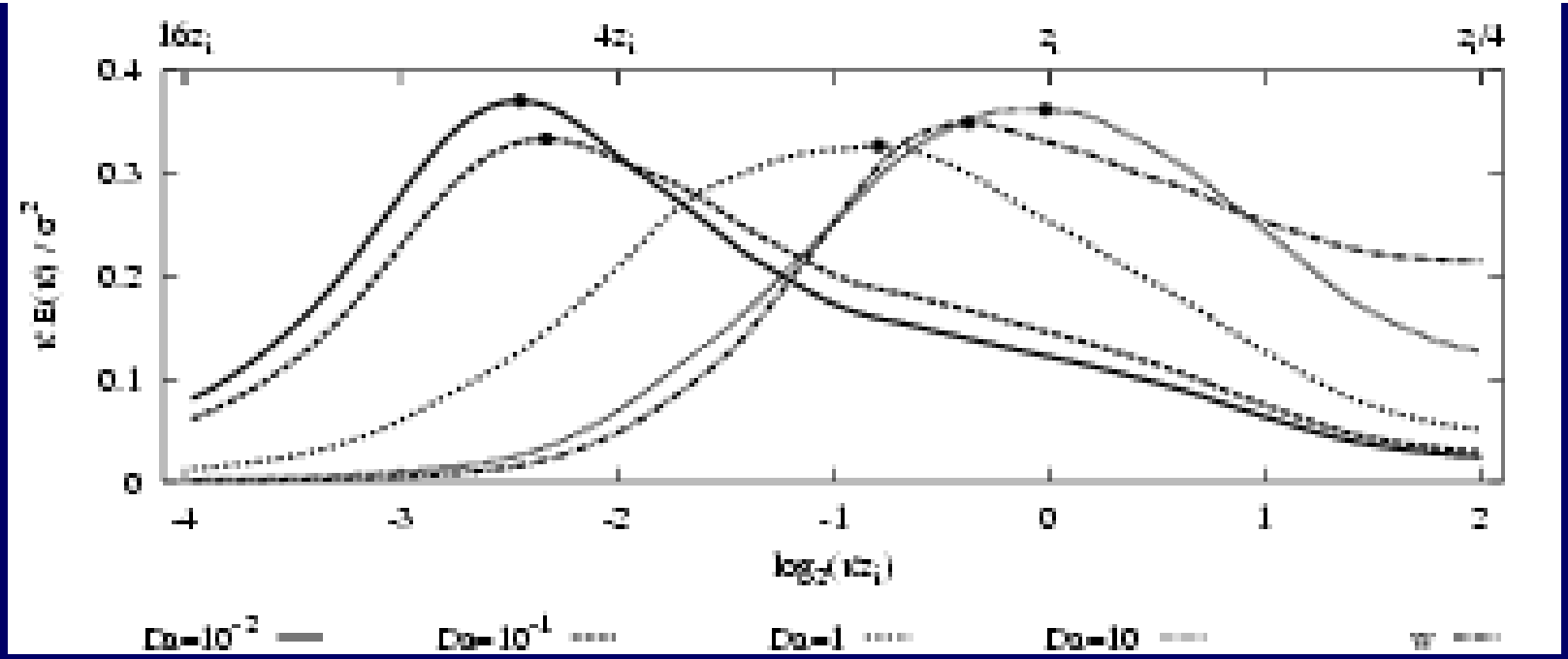
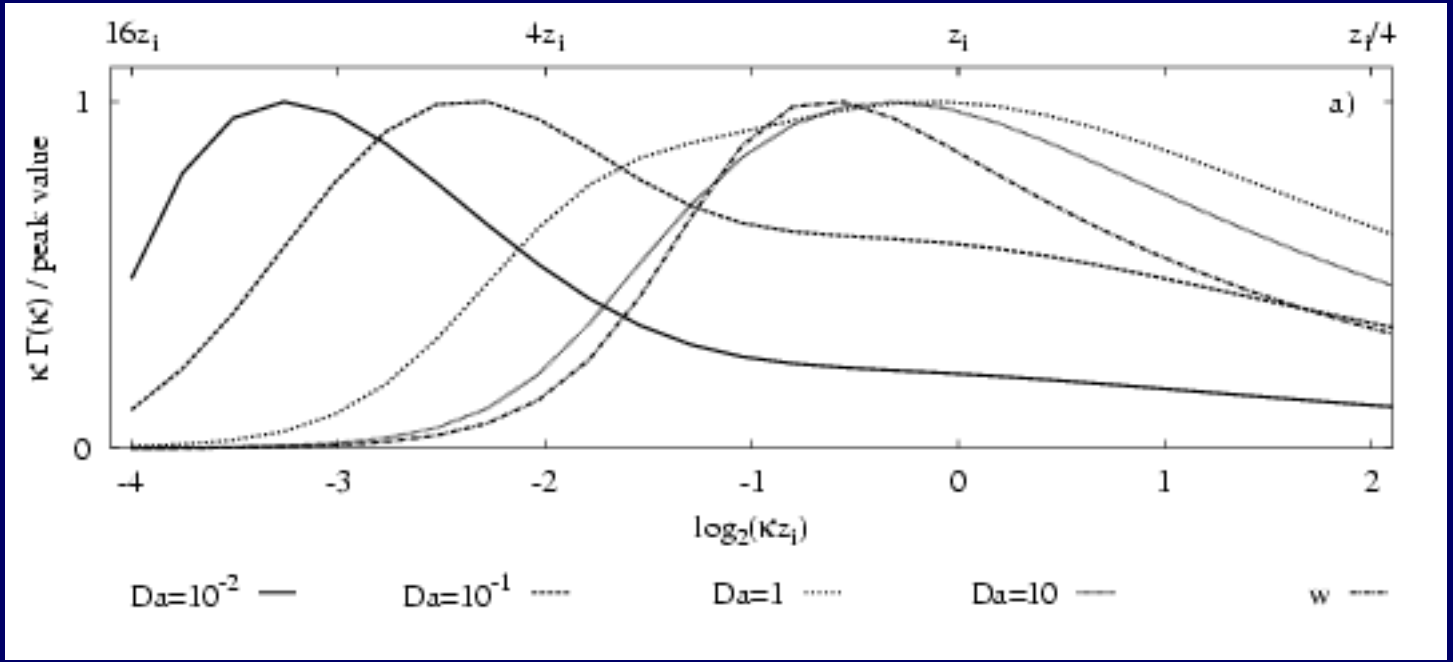


(Jonker, Vila, Duynkerke, JAS 2004)


16z_i
4z_i
z_i
z_i/4
0.4
0.3
0.2
0.1
0
κ E(κ) / σ²
-4
-3
-2
-1
0
1
2
log₂(κz_i)
Da=10⁻²
Da=10⁻¹
Da=1
Da=10
w


16z_i
4z_i
z_i
z_i/4
a)
1
0
κ Γ(κ) / peak value
-4
-3
-2
-1
0
1
2
log₂(κz_i)
Da=10⁻²
Da=10⁻¹
Da=1
Da=10
w

Spectral Model: scale analysis ...

$$\frac{d}{dt}E_c(k) = -E_{wc}(k)\frac{\partial \overline{c}}{\partial z} - D_c k^2 E_c(k) - j E_c(k) - S(k)$$

production **dissipation** **chemistry** **spectral transfer**

$$P(k) \sim \sqrt{W(k)E_c(k)}\,\frac{c_*}{z_i} \quad = \quad kE_c(k)\sqrt{kW(k)} \sim S(k)$$

$$\Rightarrow \qquad E_c(k) \sim k^{-3}$$

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Conclusions

1) the formation of **dominating** mesoscale fluctuations is an integral part of PBL dynamics!

2) latent heat and radiation are **not** essential
(but speed up the process considerably)

3) budgets: no inverse cascade on average.
significant backscatter (on all scales)

4) production: ineffective (slow), but spectral transfer is just as ineffective

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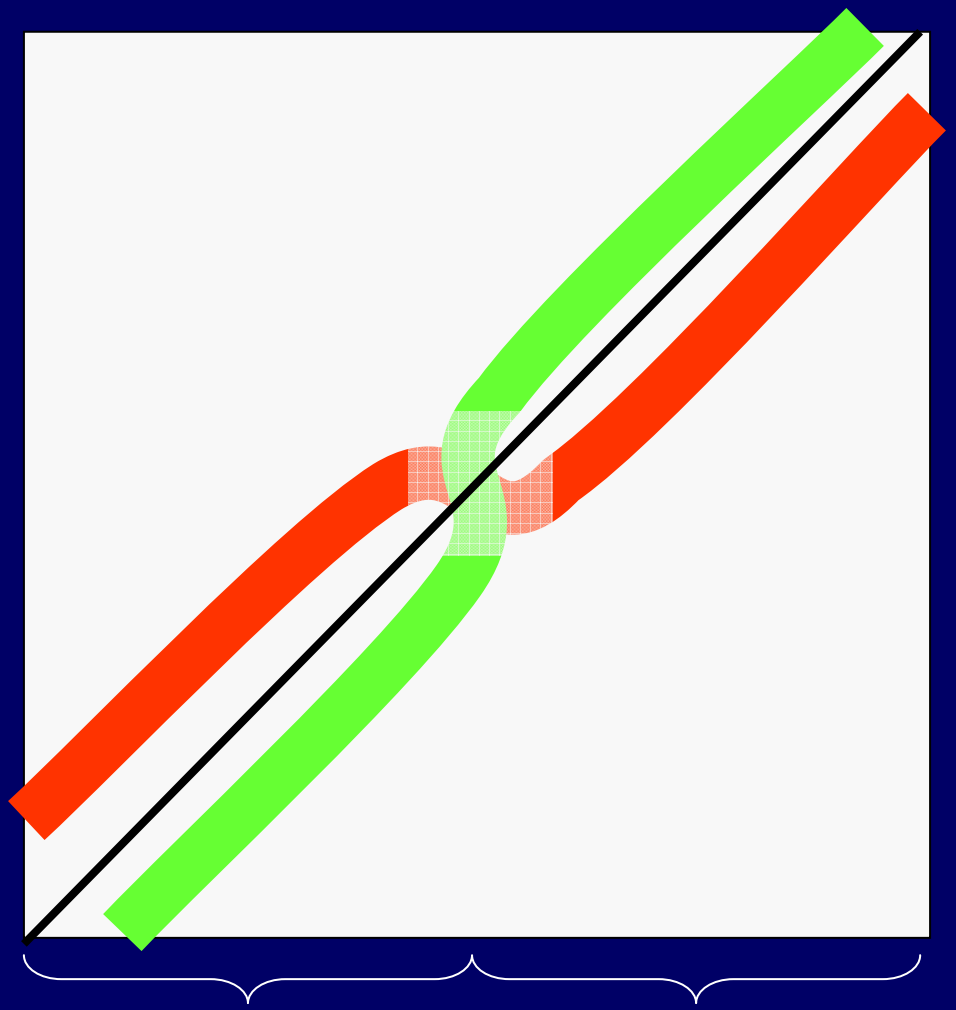
cross-over between 2D and 3D turbulence (?)



2D
upscale cascade

3D
downscale cascade