On dispersion, preferential concentration and settling of inertial particles in (stratified) turbulence

Herman Clercx

with _Marleen van Aartrijk_ and _Michel van Hinsberg_

Fluids and Flows group, Physics Department

Eindhoven University of Technology

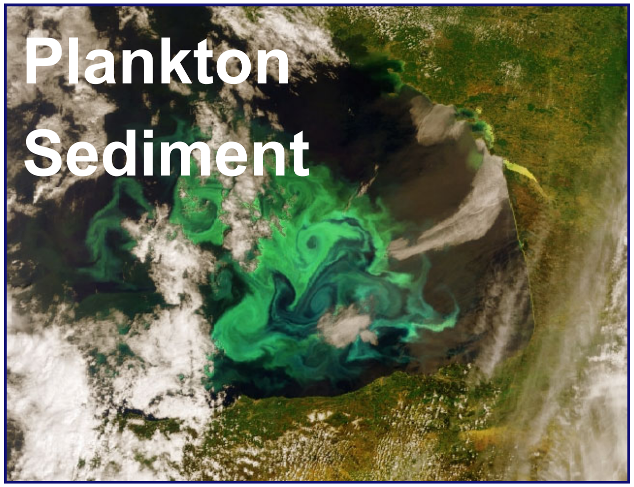
The Netherlands

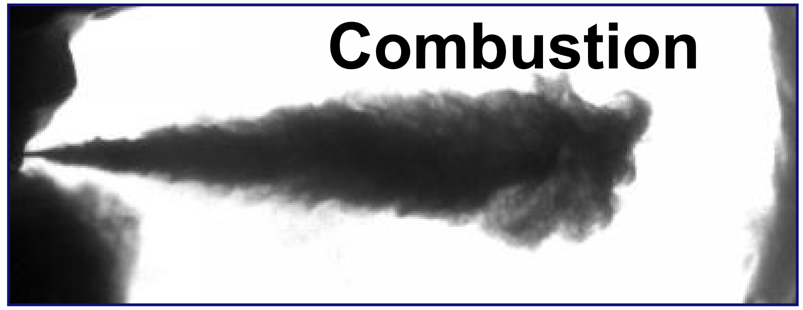
J.M. Burgerscentrum

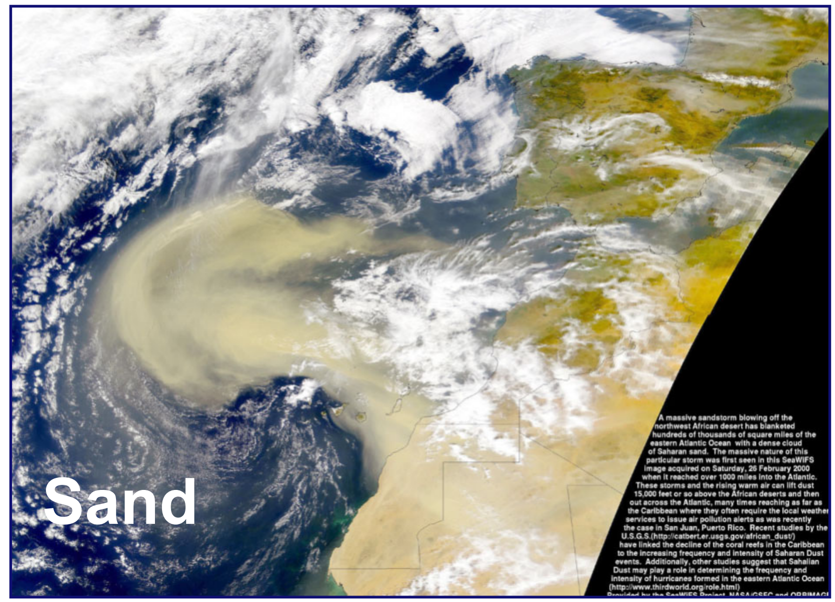
Technische Universiteit Eindhoven
University of Technology

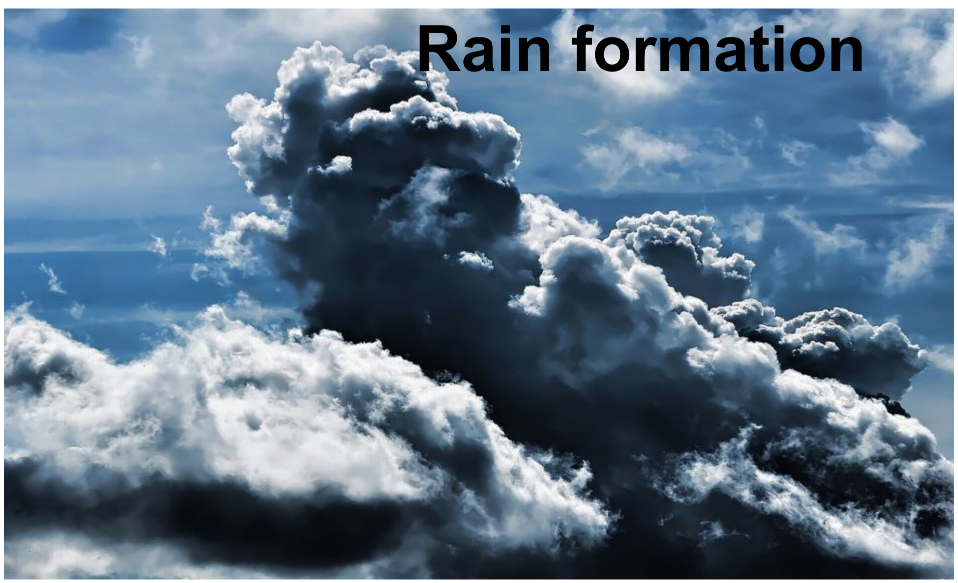
Where innovation starts

Introduction

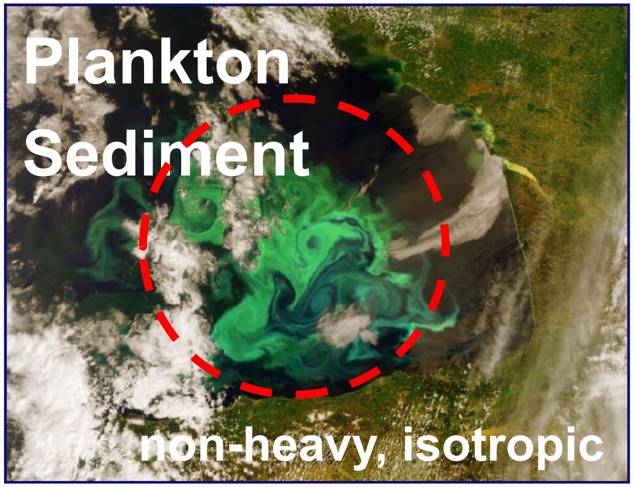






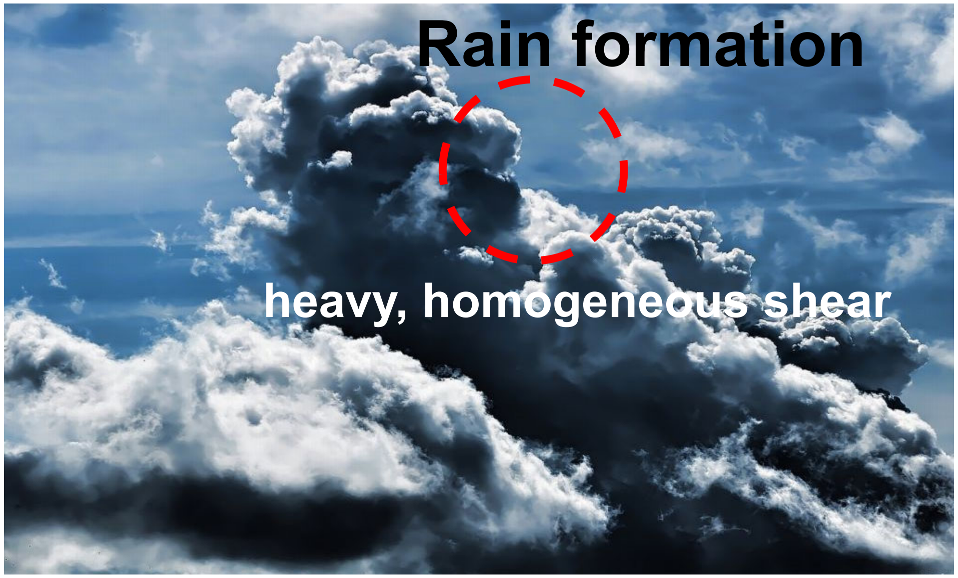


Introduction



Focus on the statistics of many-particle systems

Need to use point-particle approximation

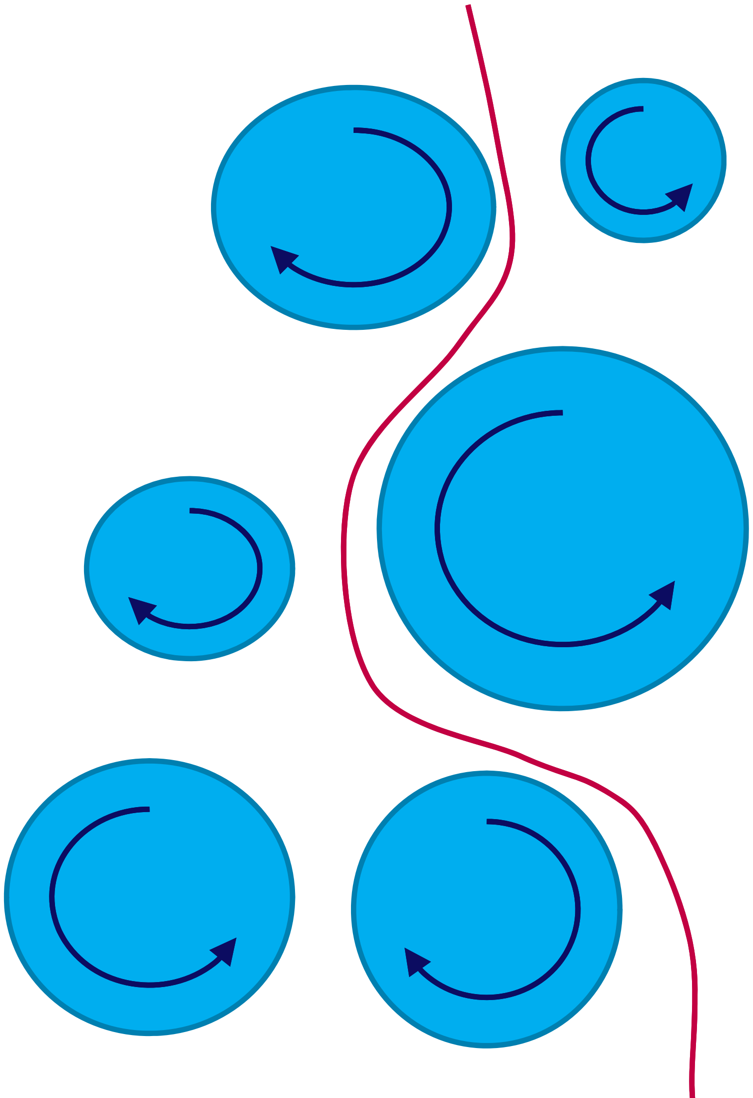


Role of:
- hydrodynamic forces
- shear
- stratification

Contents

- Settling of non-heavy particles in HIT
- Horizontal drift in HST (heavy particles)
- Inertial particle dispersion in stratified turbulence
- Non-heavy inertial particles in stratified turbulence
- Concluding remarks

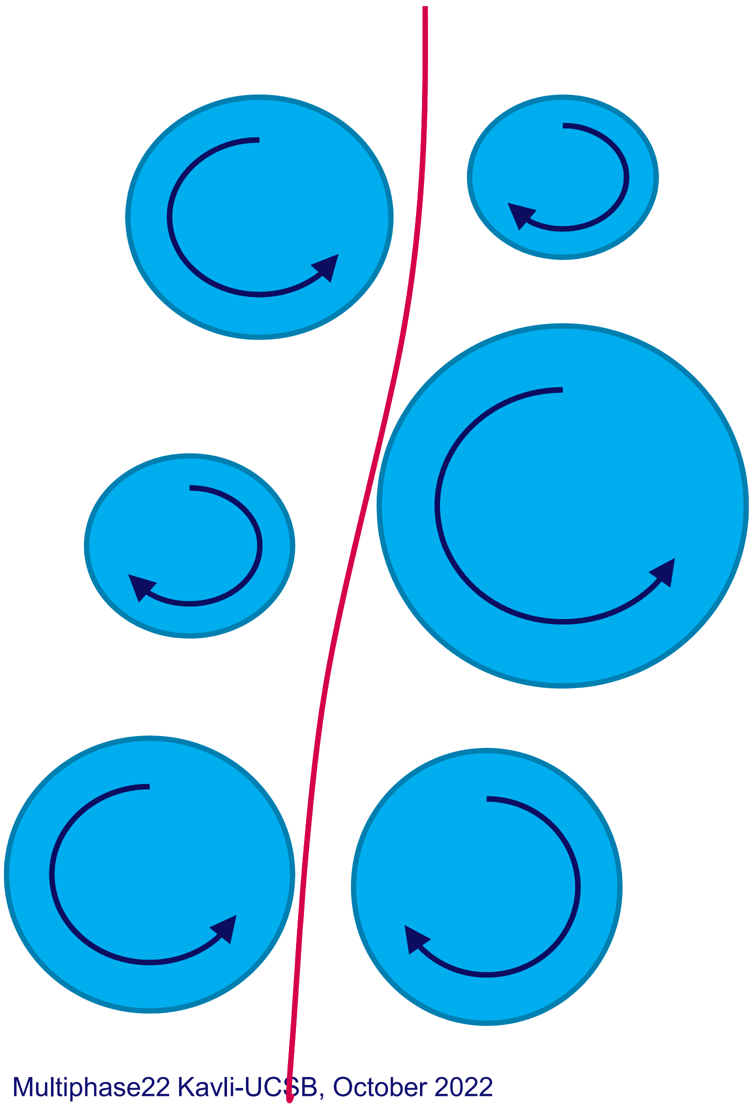
Settling of non-heavy particles



St ~ 1: Enhanced settling velocity of heavy particles by preferential sweeping

Wang and Maxey, JFM **256**, 27 (1993)

Settling of non-heavy particles



St ~ 1: Enhanced settling velocity of heavy particles by preferential sweeping

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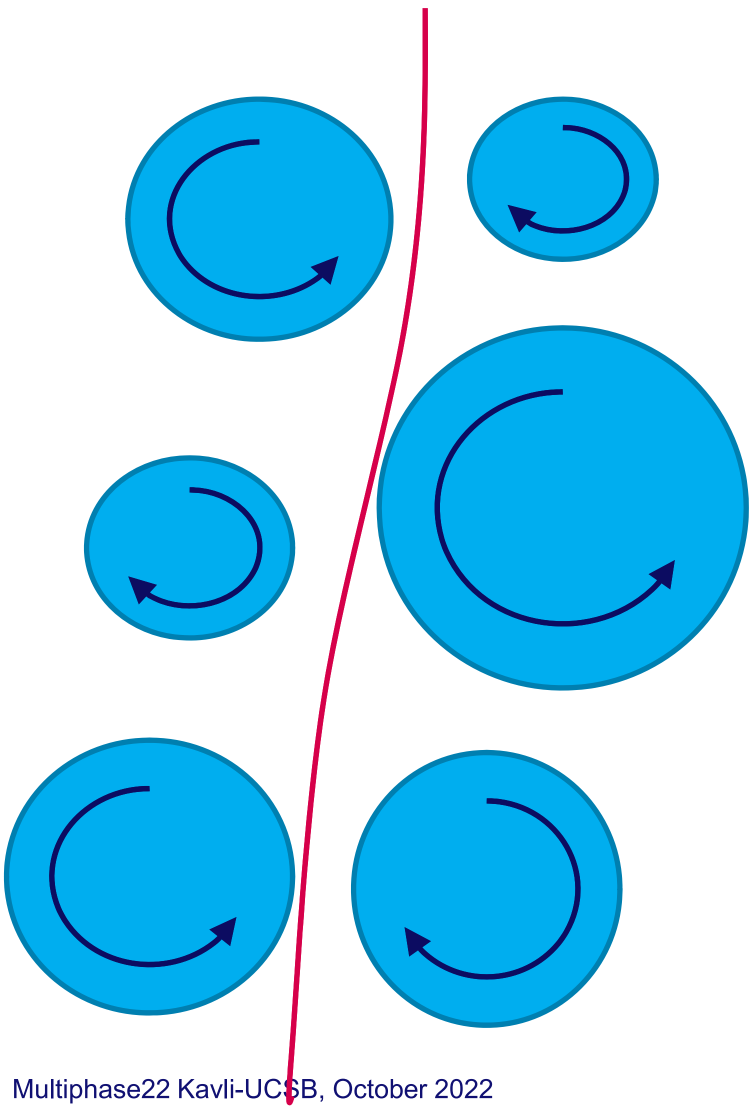
St >> 1: Heavy particles fall almost straight without noticing details of the flow structure

No enhanced settling velocity due to lack of preferential sweeping

Settling of non-heavy particles



St ~ 1: Enhanced settling velocity of heavy particles by preferential sweeping

Wang and Maxey, JFM **256**, 27 (1993)

St >> 1: Heavy particles fall almost straight without noticing details of the flow structure

No enhanced settling velocity due to lack of preferential sweeping

But what about non-heavy particles?

Elgobashi and Truesdell, JFM **242**, 655 (1992)
Armenio and Fiorotto, PoF **13**, 2437 (2001)
Van Aartrijk and Clercx, PoF **22**, 013301 (2010)

Settling of non-heavy particles

Starting point:

- Direct Numerical Simulations of the incompressible Navier Stokes equations
- Based on a pseudo spectral code on a triple periodic domain

Biferale, Lanotte, Scatamacchia & Toschi, JFM **757**, 550 (2014)

Forcing scheme:
Lamorgese, Caughey & Pope, **PoF** 17, 015106 (2005)

- Shear implemented by the Rogallo algorithm

Deforming reference frame (keeping periodic BCs, and periodically remeshing. R.S. Rogallo, NASA Report # NASA-TM-81315 (1981)

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Settling of non-heavy particles

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Forcing scheme:
Lamorgese, Caughey & Pope, **PoF** 17, 015106 (2005)

- Efficient Lagrangian particle tracking algorithm

Van Hinsberg, Ten Thije Boonkkamp, Toschi & Clercx, SIAM JSC **34**, B479 (2012)
Van Hinsberg, Ten Thije Boonkkamp, Toschi & Clercx, PRE **87**, 043307 (2013)

- Heavy and small particles → only Stokes drag and gravity

$$\frac{d\mathbf{u}_p}{dt} = \frac{1}{\tau_p}(\mathbf{u} - \mathbf{u}_p) - g\mathbf{e}_z$$

$$St = \frac{\tau_p}{\tau_\eta}$$

Settling of non-heavy particles

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} = 6\pi a\mu\left(\mathbf{u}-\mathbf{u}_p\right) + m_f \frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} - (m_p - m_f)g\mathbf{e}_z$$

$$+\frac{1}{2}m_f\left(\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} - \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t}\right) + 3\sqrt{3\mu a m_f}\int_{-\infty}^{t}\frac{\mathrm{d}\mathbf{u}(\tau)/\mathrm{d}\tau - \mathrm{d}\mathbf{u}_p(\tau)/\mathrm{d}\tau}{\sqrt{t-\tau}}\mathrm{d}\tau$$

$$= \mathbf{F}_{\mathrm{St}} + \mathbf{F}_{\mathrm{P}} + \mathbf{F}_{\mathrm{G}} + \mathbf{F}_{\mathrm{AM}} + \mathbf{F}_{\mathrm{B}}.$$

Maxey-Riley equation

Maxey and Riley, PoF **26**, 883 (1983)

$a \ll \eta$ and $Re_p \ll 1$, $\phi \ll 1$

With Faxén correction MR is acceptable for $a \leq 8\eta$

see, e.g., Calvazarini *et al.*, Phys D **241**, 237 (2012)

Van Hinsberg, Ten Thije Boonkkamp & Clercx, JCompP **230**, 1465 (2011)
Van Hinsberg, Clercx & Toschi, PRE **95**, 023106 (2017)

Settling of non-heavy particles

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{dt}} = 6\pi a\mu\,(\mathbf{u}-\mathbf{u}_p) + m_f \frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}} - (m_p - m_f) g\mathbf{e}_z$$

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$a \ll \eta$ and $Re_p \ll 1$, $\phi \ll 1$

Basset, *Treatise on Hydrodynamics*, 1888
Michaelides, J. Fluids Eng. **125**, 209 (2003)

For alternative formulations see:
Mei, Exp. Fluids **22**, 1 (1996)
Magnaudet & Eames, ARFM **32**, 659 (2000)

For effects due to nonlinear drag and lift forces see

Van Hinsberg, Ten Thije Boonkkamp & Clercx, JCompP **230**, 1465 (2011)
Van Hinsberg, Clercx & Toschi, PRE **95**, 023106 (2017)

Settling of non-heavy particles

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{dt}} = 6\pi a\mu\,(\mathbf{u}-\mathbf{u}_p) + m_f \frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}} - (m_p - m_f)g\mathbf{e}_z$$

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$$\frac{\mathrm{d}\mathbf{u}_p}{\mathrm{dt}} = \frac{\mathbf{u}-\mathbf{u}_p}{\tau_p^*} + \beta\frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}} - (1-\beta)\,g\mathbf{e}_z + \sqrt{\frac{3\beta}{\pi\tau_p^*}} \int_{-\infty}^{t} \frac{\mathrm{d}\mathbf{u}(\tau)/\mathrm{d}\tau - \mathrm{d}\mathbf{u}_p(\tau)/\mathrm{d}\tau}{\sqrt{t-\tau}} \mathrm{d}\tau$$

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Settling of non-heavy particles

$$\frac{d\mathbf{u}_p}{dt} = \frac{\mathbf{u}-\mathbf{u}_p}{\tau_p^*} + \beta\frac{D\mathbf{u}}{Dt} - (1-\beta)g\mathbf{e}_z + \sqrt{\frac{3\beta}{\pi\tau_p^*}}\int_{-\infty}^{t}\frac{d\mathbf{u}(\tau)/d\tau - d\mathbf{u}_p(\tau)/d\tau}{\sqrt{t-\tau}}d\tau$$

$$= \mathbf{F}^*_{St} + \mathbf{F}^*_{P} + \mathbf{F}^*_{G} + \mathbf{F}^*_{B},$$

$$\tau_p^* = \left(1+\frac{1}{2R_\rho}\right)\tau_p = \frac{3}{3-\beta}\tau_p \; ,$$

$$\beta = \frac{3}{2R_\rho+1} \; .$$

$R_\rho = \rho_p/\rho_f$

$\tau_p^* = a^2/(3\beta\nu)$

R_ρ	∞	1000	100	10	2	1.2	1	0
β	0	0.0015	0.0149	0.1429	0.6	0.8824	1	3

Settling of non-heavy particles

$$\frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} = \frac{\mathbf{u}-\mathbf{u}_p}{\tau_p^*} + \beta\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} - (1-\beta)\,g\mathbf{e}_z + \sqrt{\frac{3\beta}{\pi\tau_p^*}}\int_{-\infty}^{t}\frac{\mathrm{d}\mathbf{u}(\tau)/\mathrm{d}\tau - \mathrm{d}\mathbf{u}_p(\tau)/\mathrm{d}\tau}{\sqrt{t-\tau}}\mathrm{d}\tau$$

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$$\beta = \frac{3}{2R_\rho+1}\ .$$

$R_\rho = \rho_p/\rho_f$

(τ: typical flow time scale)

$$St^* = \frac{\tau_p^*}{\tau}\ ,$$

$$Sv^* = \frac{U_s}{U} = \frac{\tau_p^*(1-\beta)g}{U}$$

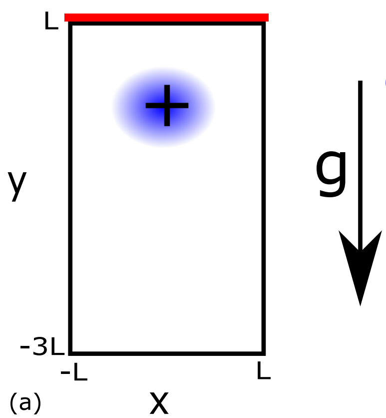
terminal settling velocity: $U_s = \tau_p^*(1-\beta)g$

(Sv: normalized settling number)

R_ρ	∞	1000	100	10	2	1.2	1	0
β	0	0.0015	0.0149	0.1429	0.6	0.8824	1	3

Settling of non-heavy particles

$$U_s = \tau_p^*(1-\beta)g$$



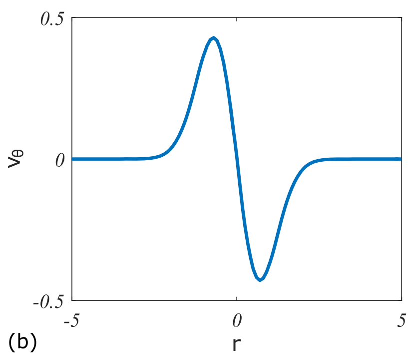
(a)

clockwise circulation

$$v_\theta(r) = \omega_0 r \left[\exp\left(-\frac{r^2}{R^2}\right) \right]$$

$$\omega(r) = 2\omega_0 \left(1 - \frac{r^2}{R^2}\right) \exp\left(-\frac{r^2}{R^2}\right)$$

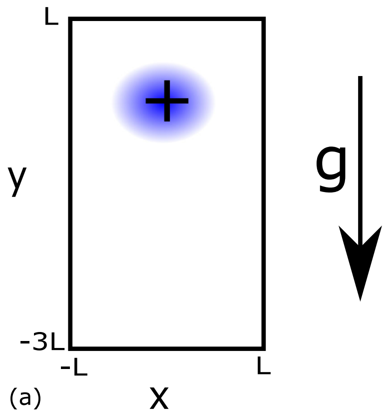
isolated vortex!



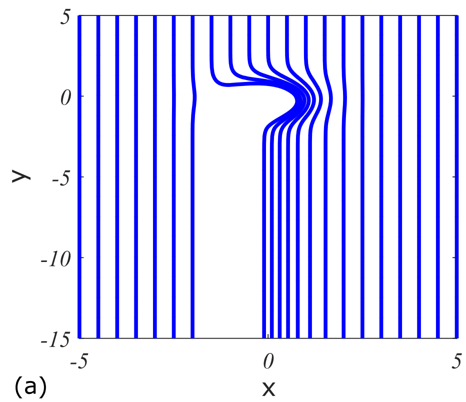
(b)

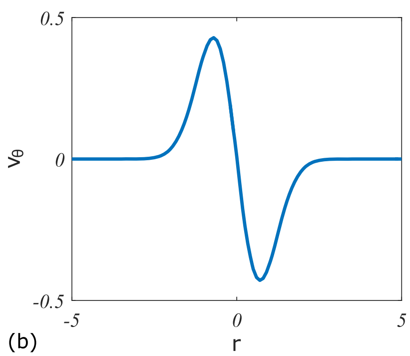
$\tau = 1/|\omega_0|$ and $U = R|\omega_0|$

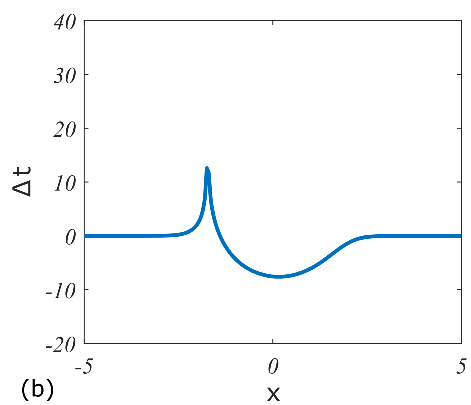
Settling of non-heavy particles



St=0.5 , Sv=0.2





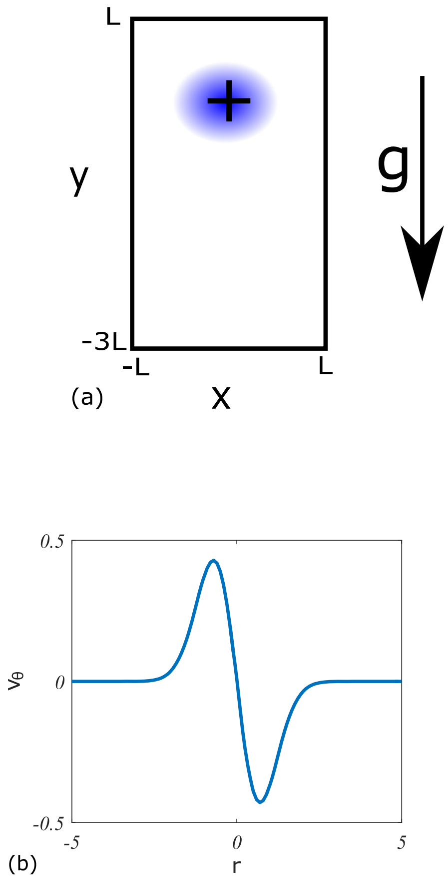


$$\Delta t = t_f - 4L/U_s$$

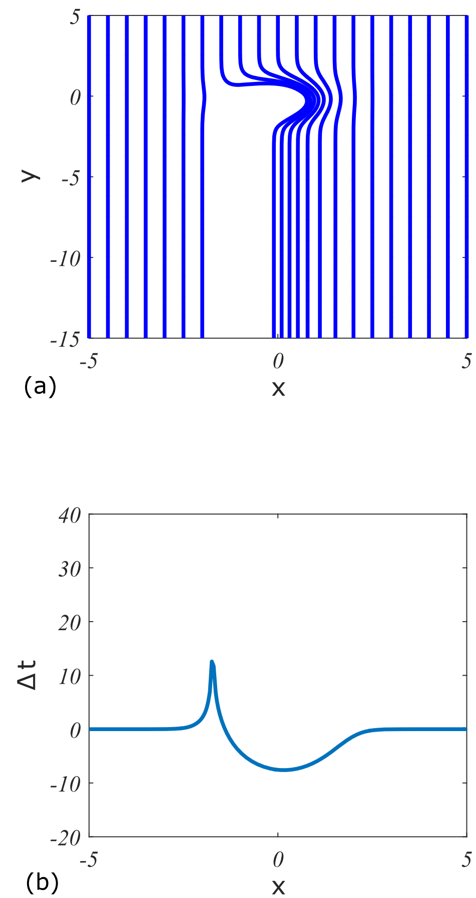
$\Delta t < 0$ faster

$\Delta t > 0$ slower

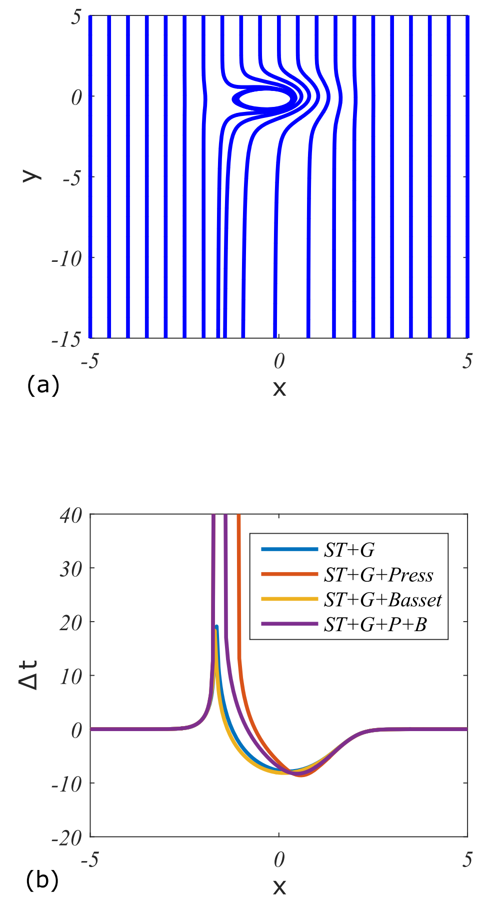
Settling of non-heavy particles



St=0.5 , Sv=0.2

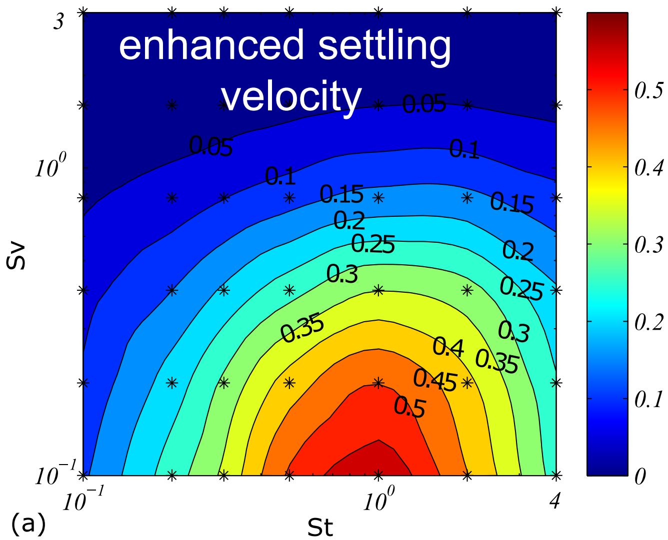


St*=2.0 , Sv*=0.4, R_ρ=1.2

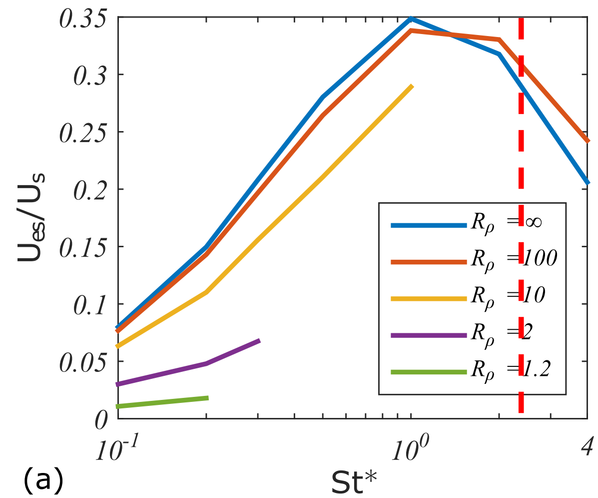


$$\Delta t = t_f - 4L/U_s$$

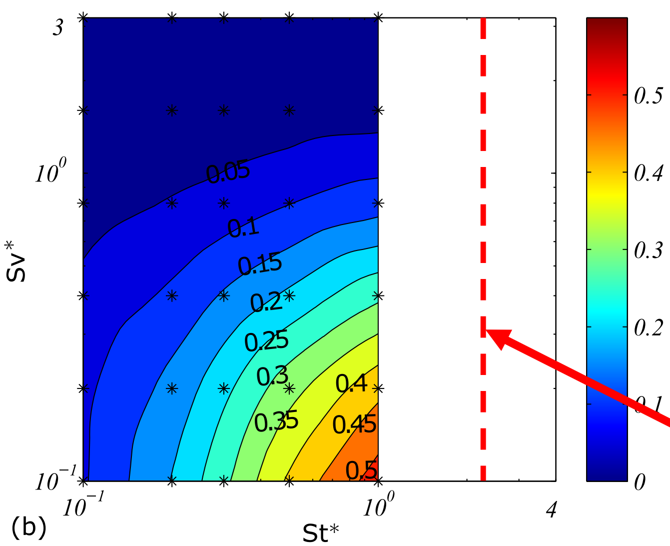
Settling of non-heavy particles



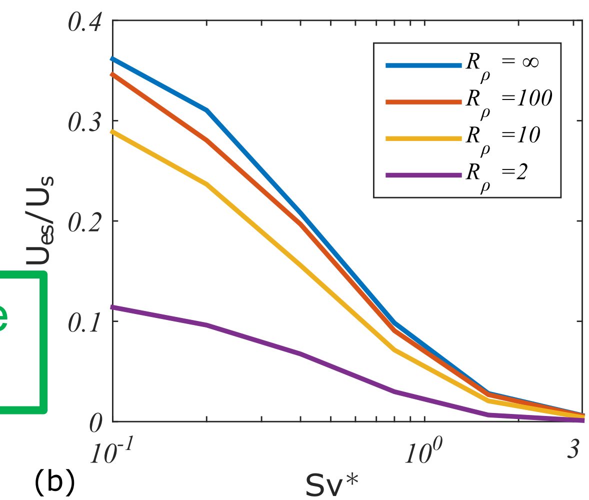
$R_\rho=\infty$



Sv*=0.4



$R_\rho=10$



St*=0.3

due to pressure gradient force!

left from dashed line: a/η sufficiently small for $R_\rho=10$

Settling of non-heavy particles

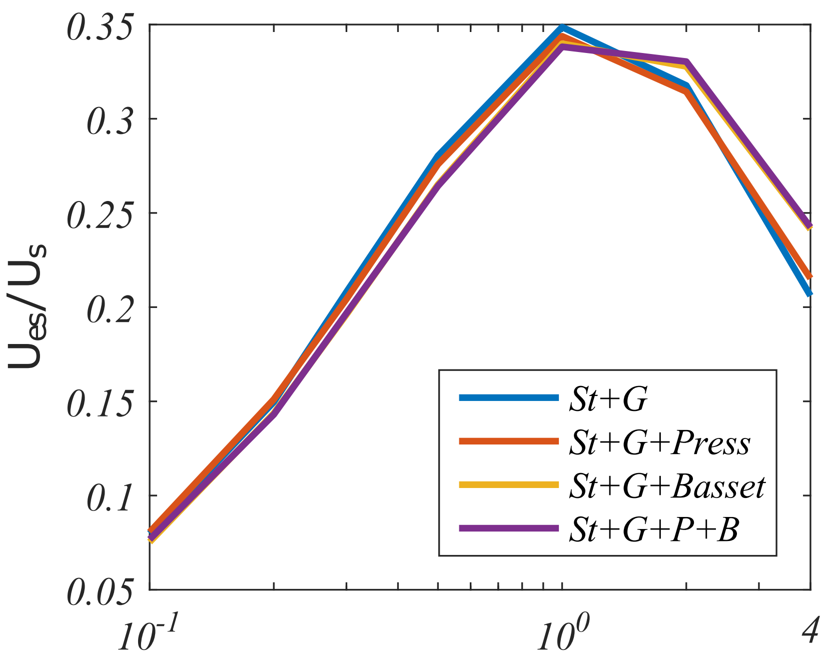
$$\frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} = \frac{\mathbf{u}-\mathbf{u}_p}{\tau_p^*} + \beta\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} - (1-\beta)\,g\mathbf{e}_z + \sqrt{\frac{3\beta}{\pi\tau_p^*}}\int_{-\infty}^{t}\frac{\mathrm{d}\mathbf{u}(\tau)/\mathrm{d}\tau - \mathrm{d}\mathbf{u}_p(\tau)/\mathrm{d}\tau}{\sqrt{t-\tau}}\mathrm{d}\tau$$

$$= \mathbf{F}^*_{\mathrm{St}} + \mathbf{F}^*_{\mathrm{P}} + \mathbf{F}^*_{\mathrm{G}} + \mathbf{F}^*_{\mathrm{B}},$$

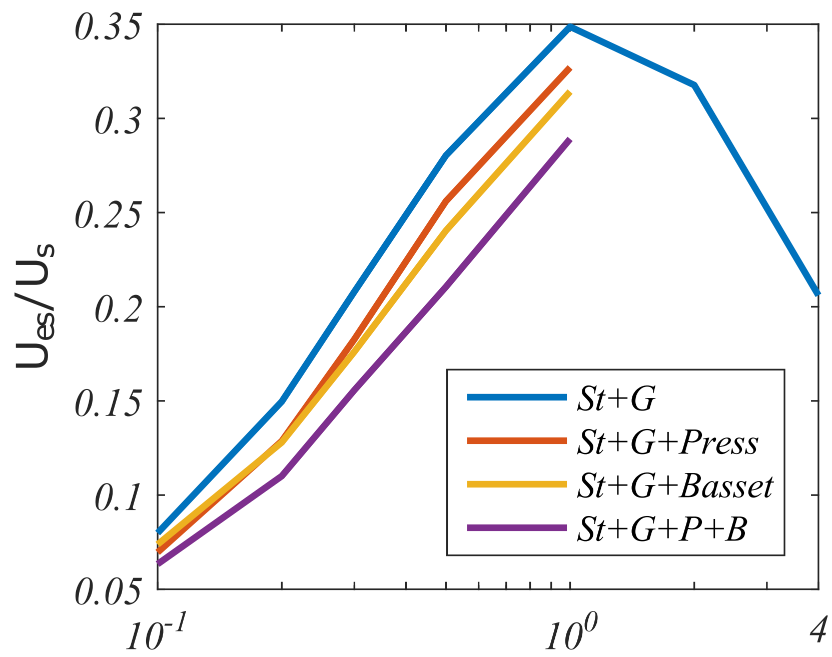
St = Stokes
P = pressure
G = gravity
B = Basset (history)

due to pressure gradient force, but …

Settling of non-heavy particles



(a)



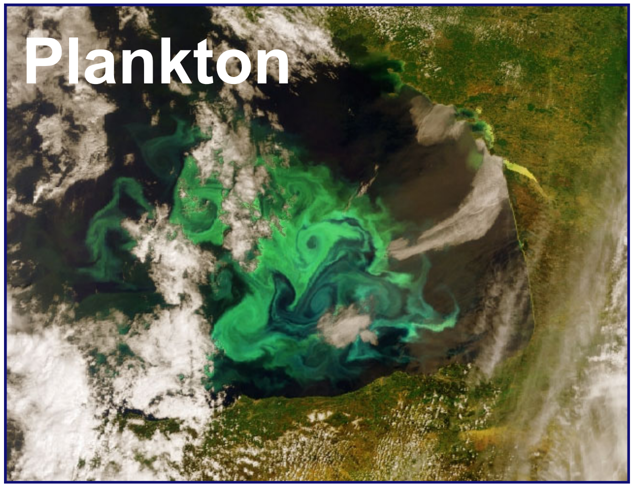
(b)

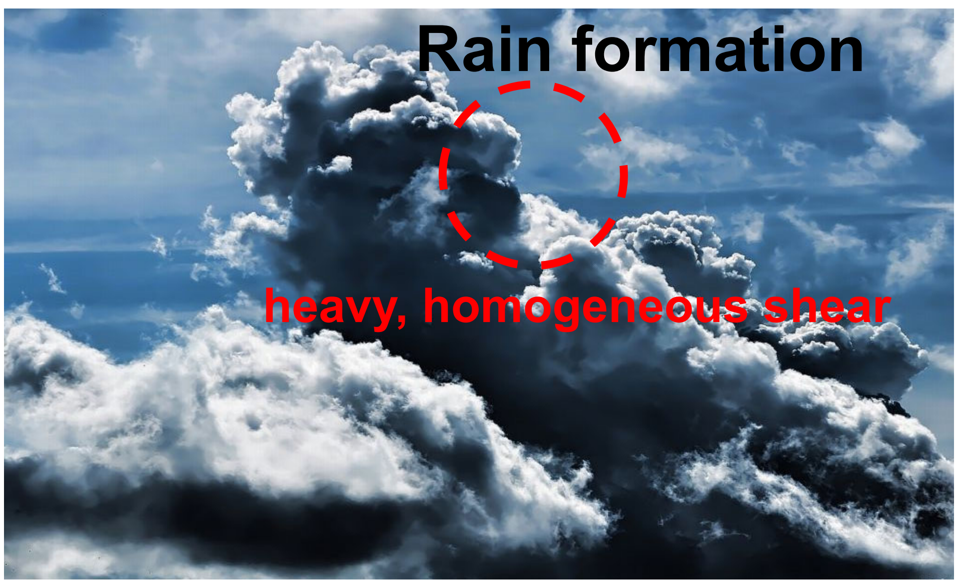
Sv*=0.4
R_ρ=100

Sv*=0.4
R_ρ=10

Horizontal drift in HST*

* HST = Homogeneous Shear Turbulence



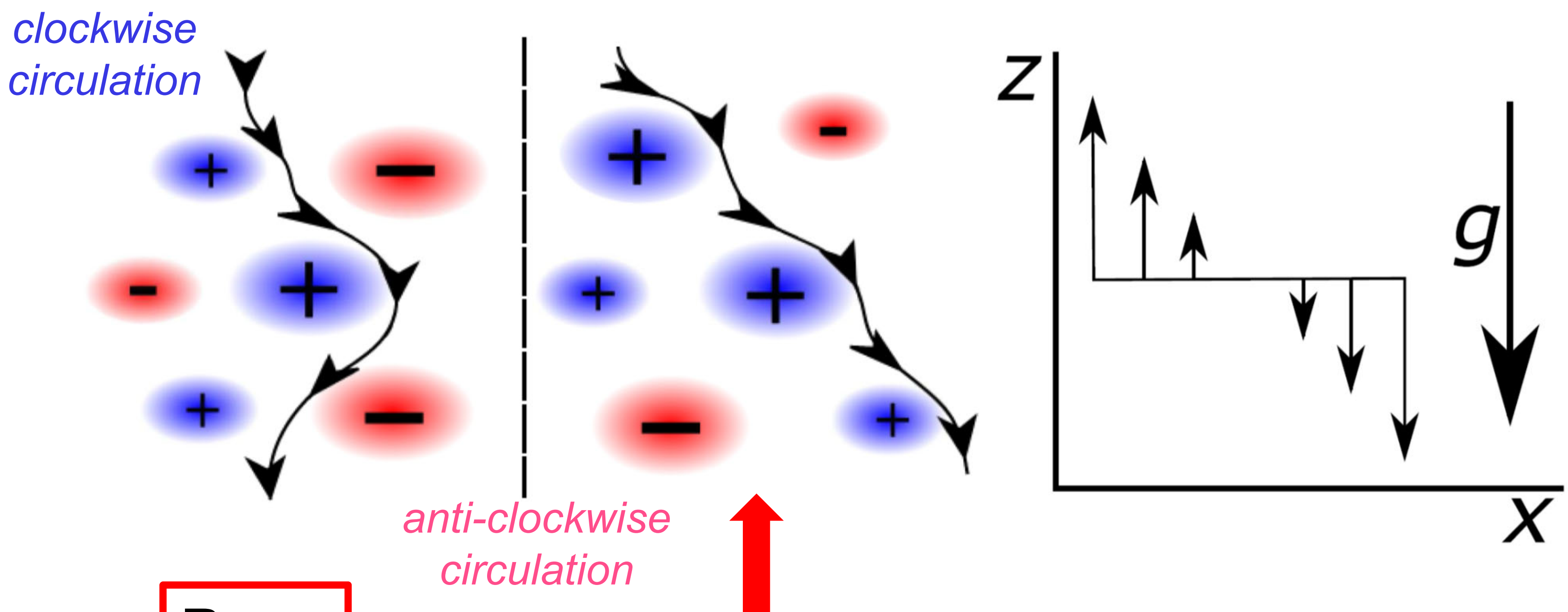


Need to use point-particle approximation

Role of:
- hydrodynamic forces
- **shear**
- stratification

Horizontal drift in HST*

* HST = Homogeneous Shear Turbulence



$R_\rho = \infty$

$$\frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} = \frac{1}{\tau_p}(\mathbf{u} - \mathbf{u}_p) - g\mathbf{e}_z$$

+ shear contribution

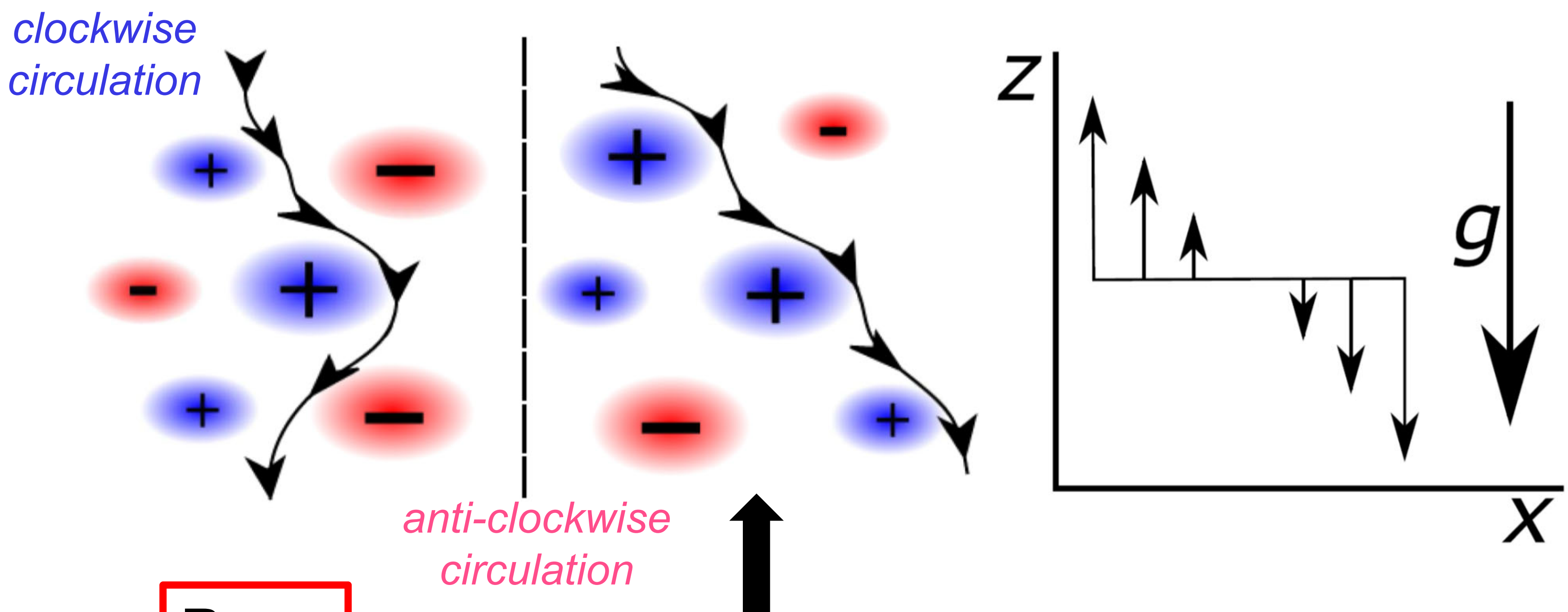
Due to shear: introduction of mean vorticity

Some previous works:

Shotorban & Balachandar, PoF **18**, 065105 (2006)
Nicolai, Jacob, Gualtieri & Piva, JPCS **318**, 052009 (2011)
Gualtieri, Picano & Casciola, JFM **629**, 25 (2009)

Van Hinsberg, Clercx & Toschi, PRL **117**, 064501 (2016)

Horizontal drift in HST



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+ shear contribution

Due to shear: introduction of mean vorticity

Do particles get a horizontal drift velocity?

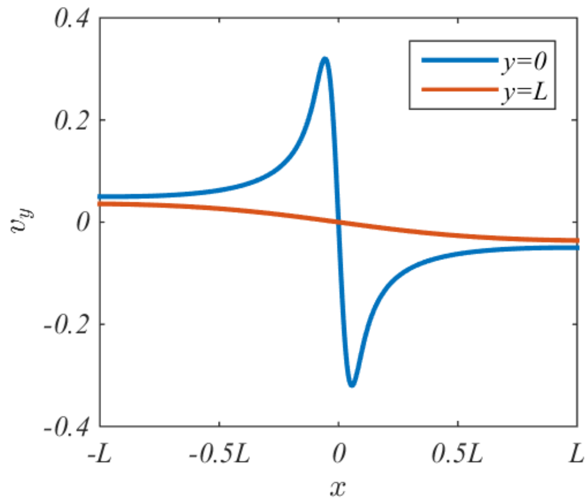
Van Hinsberg, Clercx & Toschi, PRL **117**, 064501 (2016)

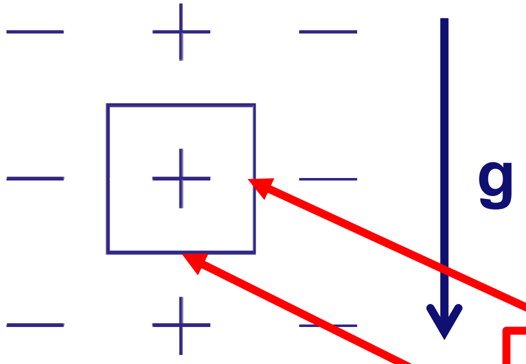
Horizontal drift in HST

Gaussian patch of vorticity

$$\omega(r) = \exp\left(-r^2\right)$$

$$v_\theta(r) = \frac{1}{2r}\left(1 - \exp\left(-r^2\right)\right)$$

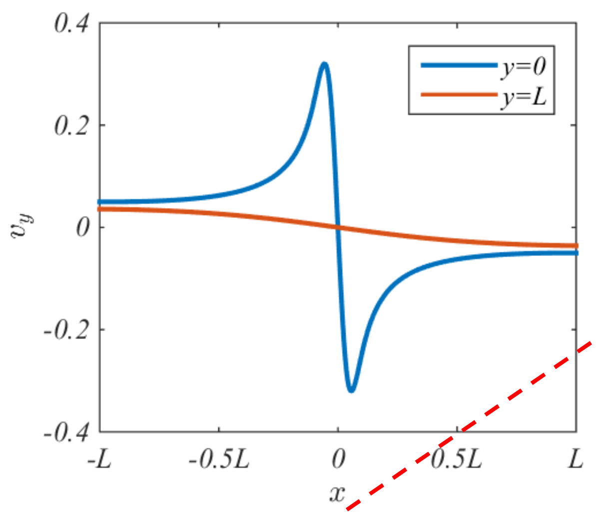


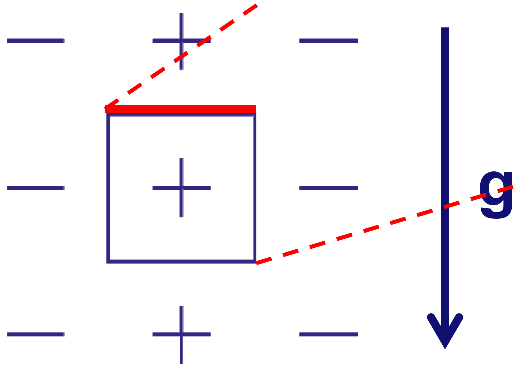


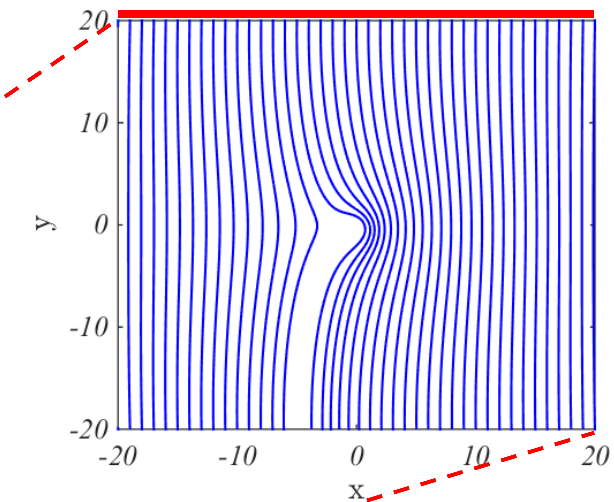
no horizontal velocities at boundaries

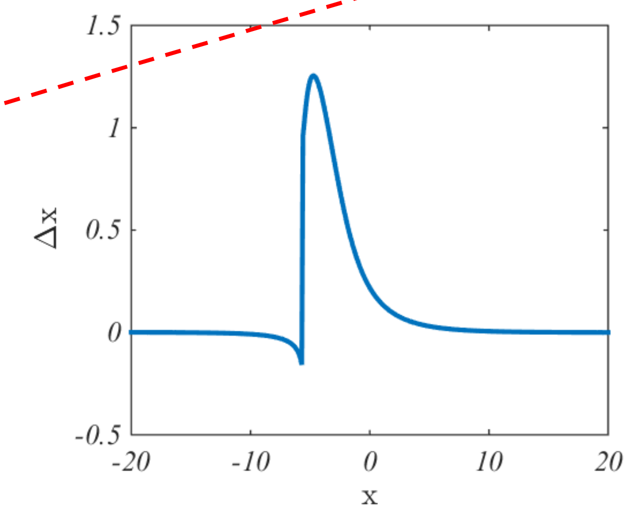
Horizontal drift in HST

Gaussian patch of vorticity



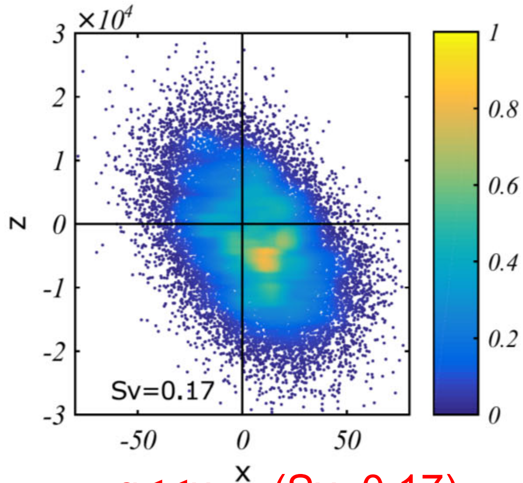




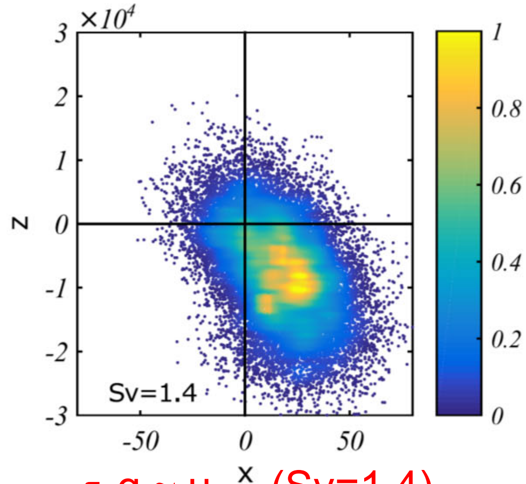


Horizontal drift in HST

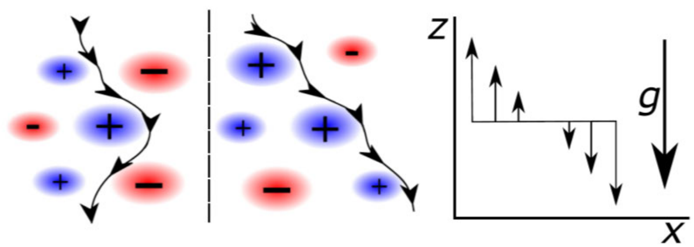
St=3.2 Scatter plot of inertial particle dispersion (with respect to initial position)



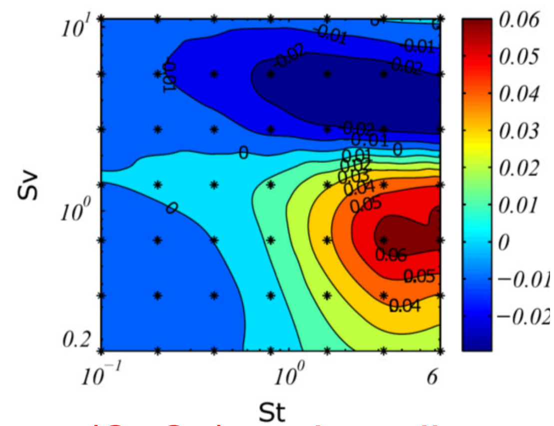
$\tau_p g << u_{rms}$ (Sv=0.17)



$\tau_p g \approx u_{rms}$ (Sv=1.4)



HIT HST

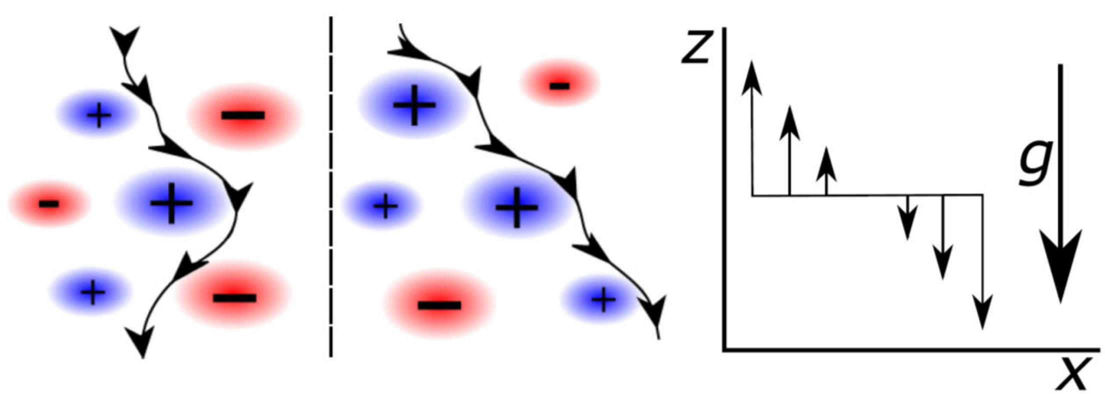


(St,Sv) regime diagram of horizontal drift velocity

Van Hinsberg, Clercx & Toschi, PRL **117**, 064501 (2016)

First set of conclusions

- Going from heavy to non-heavy particles first F_B affects settling and subsequently F_P comes into play
- F_B enhances settling for large St and reduces it for smaller St
- F_P only decreases settling
- Need to include hydrodynamic forces (according to MR)
- Homogeneous shear results in horizontal drift

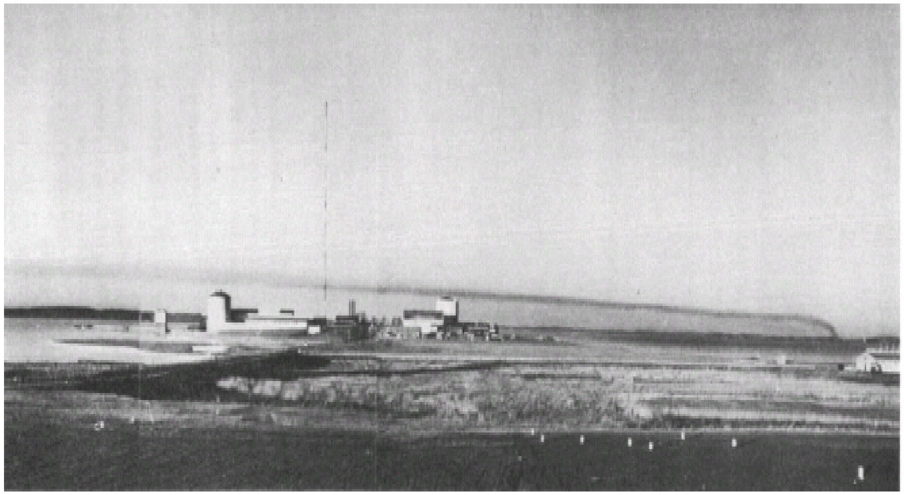


Technische Universiteit Eindhoven University of Technology

Transport in stratified turbulence

Algal blooms

Aerosol dispersion



Transport in stratified turbulence

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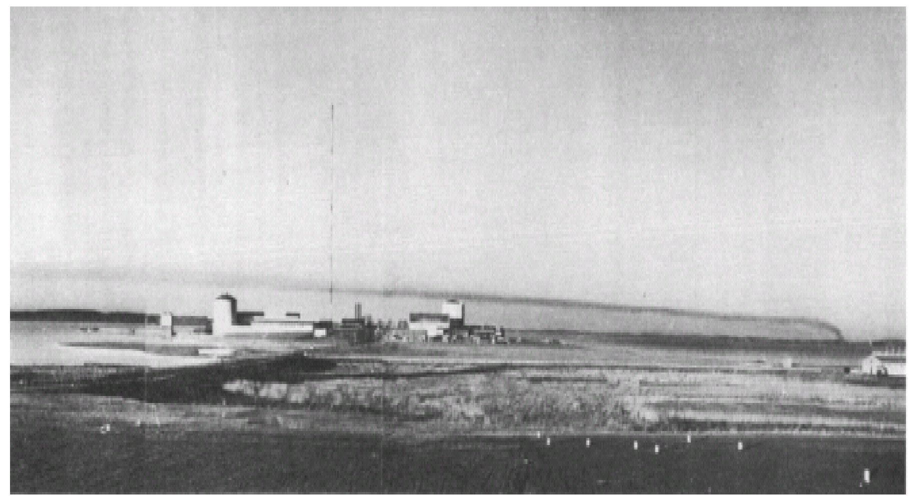
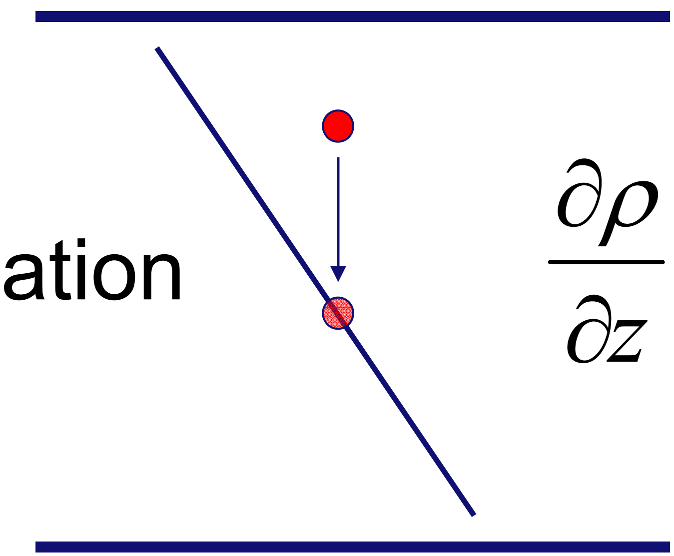


How is particle dispersion affected by the particle's inertial properties?

Does preferential concentration persist for small particle-to-fluid density ratios?

How is preferential concentration affected by stratification?

Methods: Eulerian part



$$\frac{\partial \rho}{\partial z} < 0$$

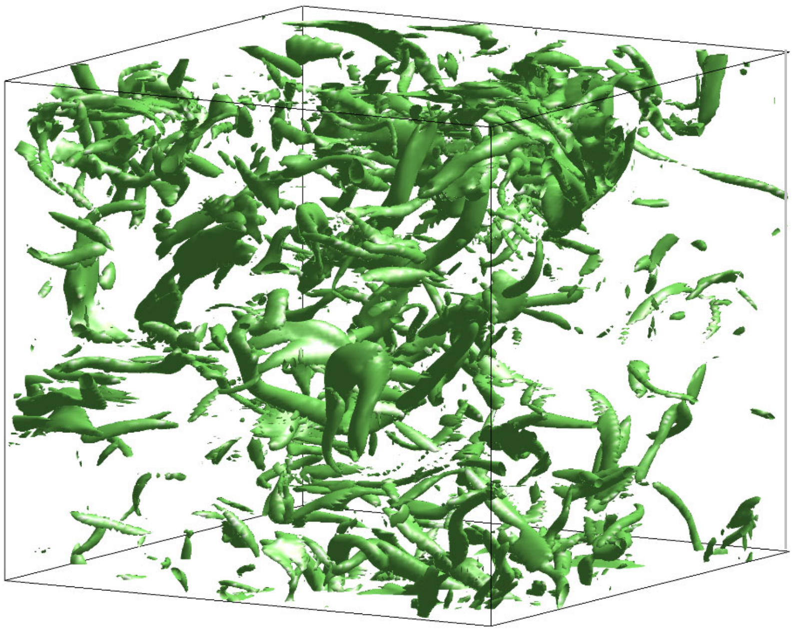
- Boussinesq approximation
- Periodic domain
- 128^3 (and 256^3)
- Forced DNS
- Parallel
- Buoyancy frequency N:

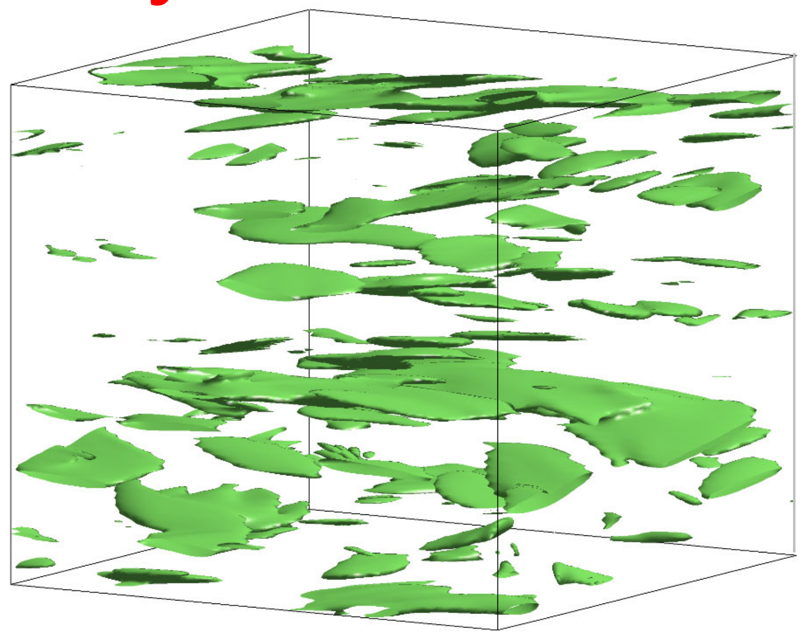
$$N = \left(-\frac{g}{\rho_0} \frac{\partial \rho}{\partial z} \right)^{1/2}$$

Code provided by: Winters, MacKinnon & Mills, JAOT **21**, 69 (2004)

Methods: Eulerian part

Isovorticity



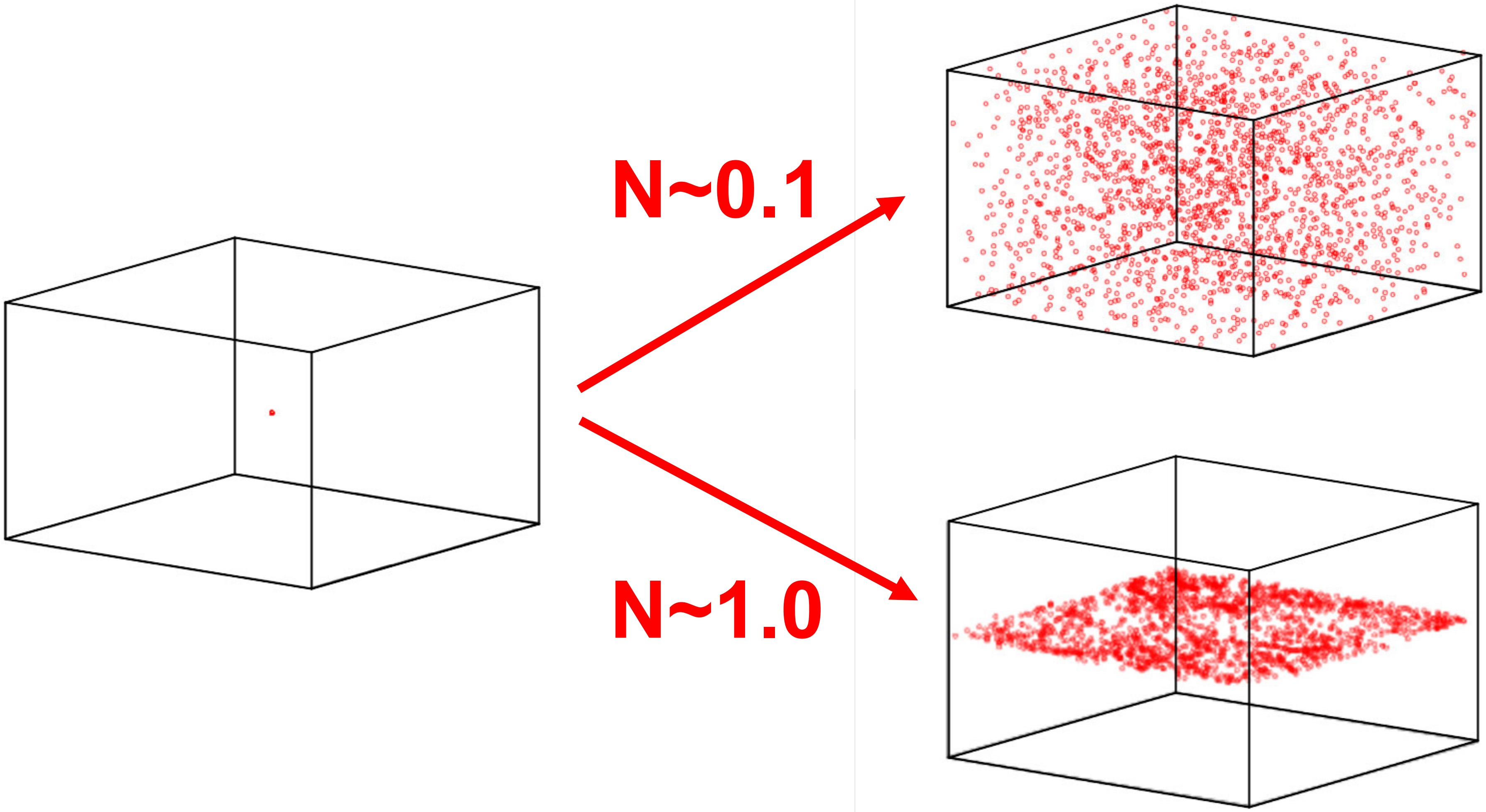


N~0.1 (s^{-1}) N~1 (s^{-1})

$Re_\lambda \approx 90\text{-}170$

Methods: Lagrangian part

Dispersion in Forced Stratified Turbulence



Methods: Lagrangian part

Dispersion and mean-squared displacement

$$\overline{x^2} = 2\overline{u'_p{}^2}\int (t-\tau)R(\tau)d\tau$$

Taylor (1921)

$$\overline{x^2}(t) \approx \overline{u'^2}t^2 \qquad t \to 0$$

ballistic

$$\overline{x^2}(t) \approx 2\overline{u'^2}T_L t \qquad t \to \infty$$

diffusive

Methods: Lagrangian part

Inertia effect on dispersion

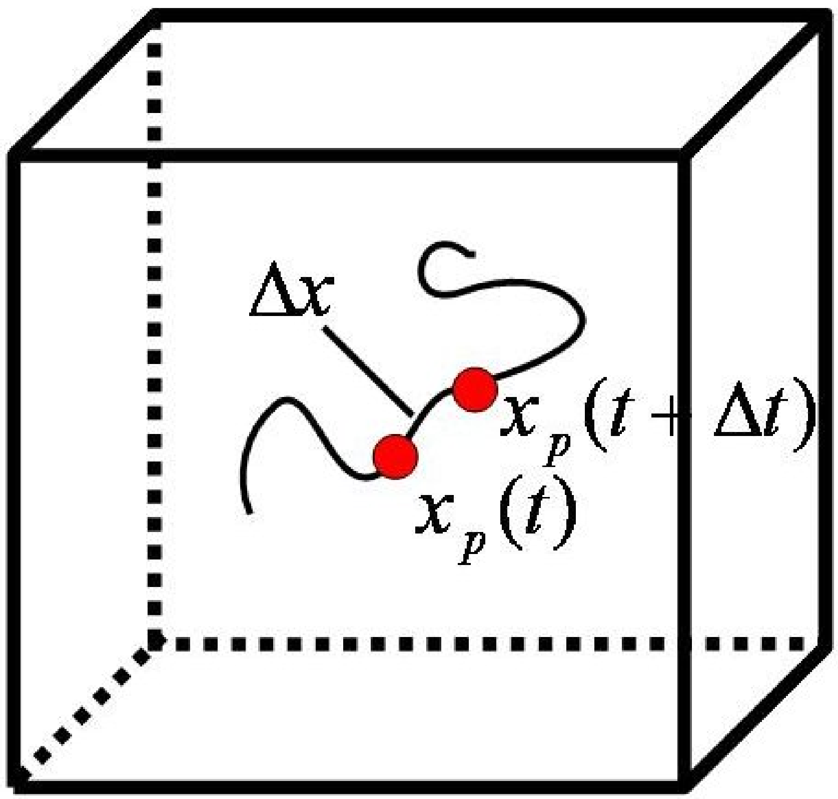
$$\overline{x^2} = 2\overline{u'_p{}^2}\int (t-\tau)R(\tau)d\tau$$

Taylor (1921)

- Increasing inertia → $\overline{u'_p{}^2}\downarrow$ → decreasing dispersion
- Increasing inertia → memory, $R(\tau)\uparrow$ → increasing dispersion
- Dispersion optimum around $\tau_p = \tau_K$ (iso)

Methods: Lagrangian part

DNS – Lagrangian part



$$\frac{d\vec{x}_p}{dt} = \vec{u}_p$$

$$\frac{d\vec{u}_p}{dt} = \ldots\ldots$$

Methods: Lagrangian part

DNS – Lagrangian part

Maxey-Riley equation

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{dt}} = 6\pi a\mu\left(\mathbf{u}-\mathbf{u}_p\right) + m_f \frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}} - (m_p - m_f) g \mathbf{e}_z$$

$$+\frac{1}{2} m_f \left(\frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}} - \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{dt}}\right) + 3\sqrt{3\mu a m_f} \int_{-\infty}^{t} \frac{\mathrm{d}\mathbf{u}(\tau)/\mathrm{d}\tau - \mathrm{d}\mathbf{u}_p(\tau)/\mathrm{d}\tau}{\sqrt{t-\tau}} \mathrm{d}\tau$$

$$= \mathbf{F}_{\mathrm{St}} + \mathbf{F}_{\mathrm{P}} + \mathbf{F}_{\mathrm{G}} + \mathbf{F}_{\mathrm{AM}} + \mathbf{F}_{\mathrm{B}}.$$

M.R. Maxey and J.J. Riley, *Phys. Fluids* **26**, 883 (1983).

Methods: Lagrangian part

DNS – Lagrangian part

Maxey-Riley equation: heavy particles

$$\frac{\rho_p}{\rho_f} \gg 1$$

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} = 6\pi a\mu\left(\mathbf{u}-\mathbf{u}_p\right) + m_f \frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} - (m_p - m_f)g\mathbf{e}_z$$

$$+\frac{1}{2}m_f\left(\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} - \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t}\right) + 3\sqrt{3\mu a m_f}\int_{-\infty}^{t}\frac{\mathrm{d}\mathbf{u}(\tau)/\mathrm{d}\tau - \mathrm{d}\mathbf{u}_p(\tau)/\mathrm{d}\tau}{\sqrt{t-\tau}}\mathrm{d}\tau$$

$$= \mathbf{F}_{\mathrm{St}} + \mathbf{F}_{\mathrm{G}}$$

M.R. Maxey and J.J. Riley, *Phys. Fluids* **26**, 883 (1983).

Methods: Lagrangian part

DNS – Lagrangian part

Maxey-Riley equation: … and without gravity

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} = 6\pi a\mu\left(\mathbf{u}-\mathbf{u}_p\right) + m_f\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} - (m_p - m_f)g\mathbf{e}_z$$

$$+\frac{1}{2}m_f\left(\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} - \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t}\right) + 3\sqrt{3\mu a m_f}\int_{-\infty}^{t}\frac{\mathrm{d}\mathbf{u}(\tau)/\mathrm{d}\tau - \mathrm{d}\mathbf{u}_p(\tau)/\mathrm{d}\tau}{\sqrt{t-\tau}}\mathrm{d}\tau$$

$$= \mathbf{F}_{\mathrm{St}}$$

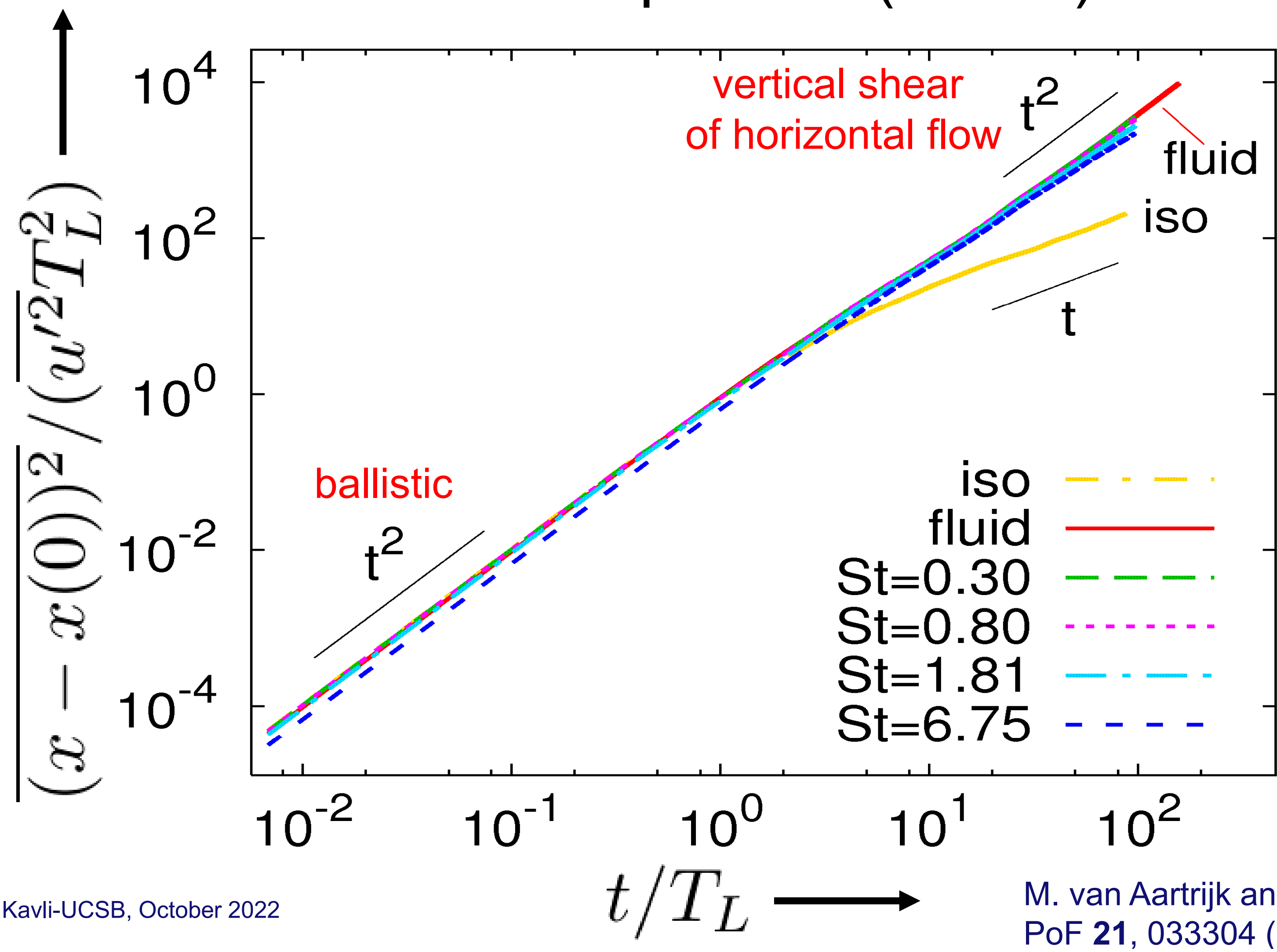
$$\frac{\rho_p}{\rho_f} \gg 1$$

$$\tau_p = \frac{(\rho_p/\rho_f)\, d_p^2}{18\nu} \qquad St = \frac{\tau_p}{\tau_k}$$

M.R. Maxey and J.J. Riley, *Phys. Fluids* **26**, 883 (1983).

Inertial particles in stratified turbulence

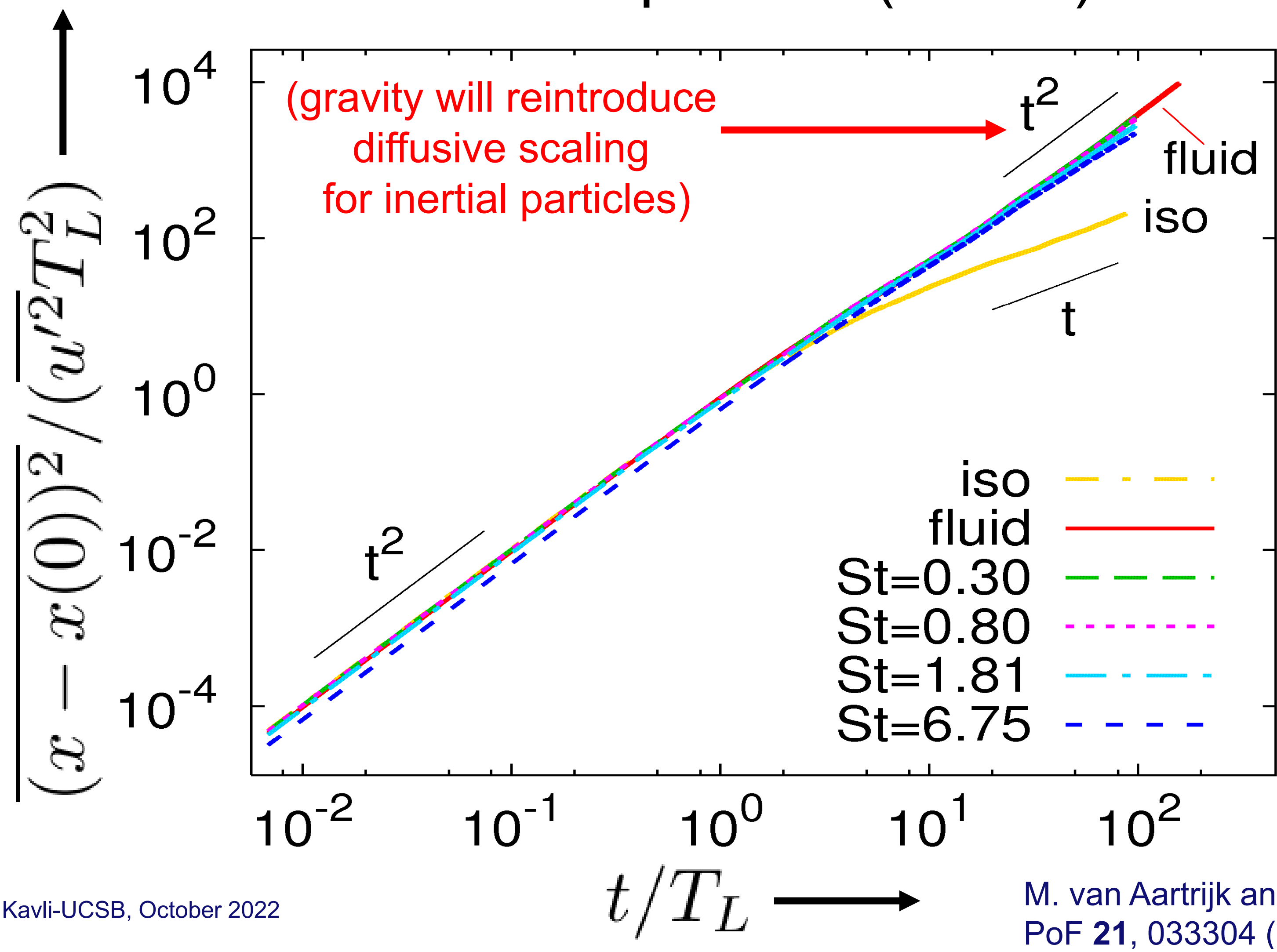
Horizontal dispersion (N~0.3)



M. van Aartrijk and H.J.H. Clercx, PoF **21**, 033304 (2009)

Inertial particles in stratified turbulence

Horizontal dispersion (N~0.3)

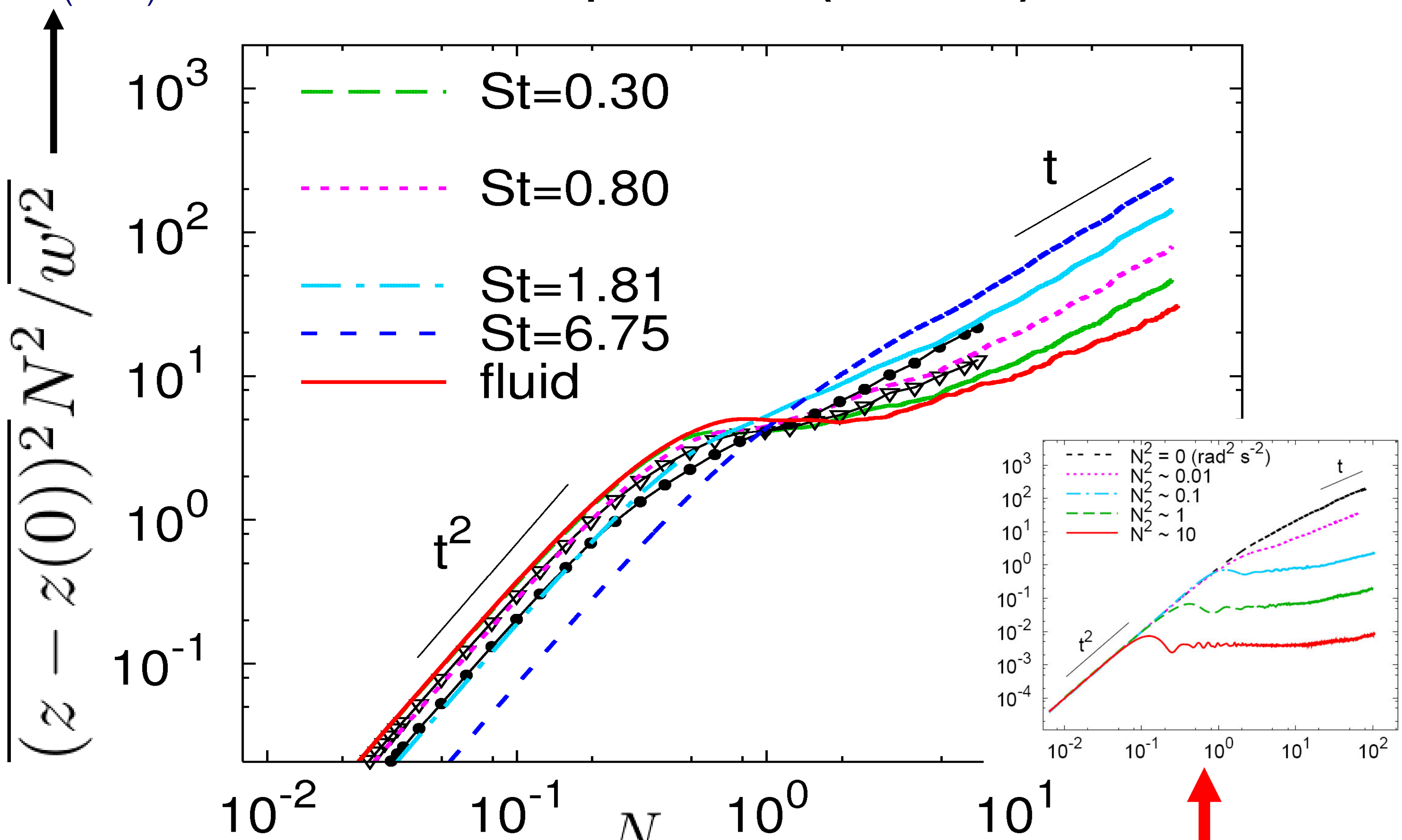


M. van Aartrijk and H.J.H. Clercx, PoF **21**, 033304 (2009)

Inertial particles in stratified turbulence

Van Aartrijk & Clercx,
PoF **21**, 033304 (2009)

Vertical dispersion (N~0.3)

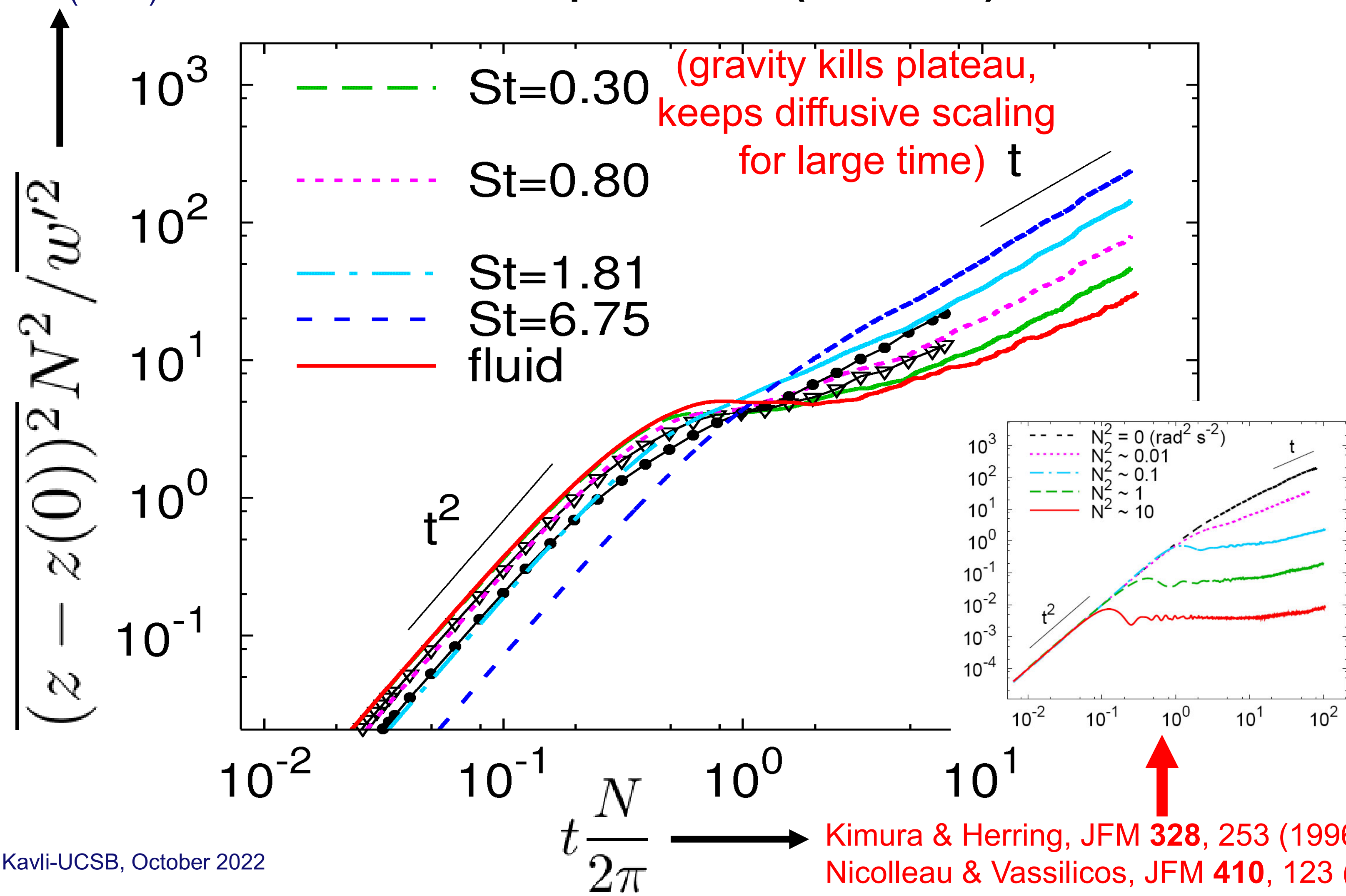


Kimura & Herring, JFM **328**, 253 (1996)
Nicolleau & Vassilicos, JFM **410**, 123 (2000)

Inertial particles in stratified turbulence

Van Aartrijk & Clercx, PoF **21**, 033304 (2009)

Vertical dispersion (N~0.3)



Kimura & Herring, JFM **328**, 253 (1996)
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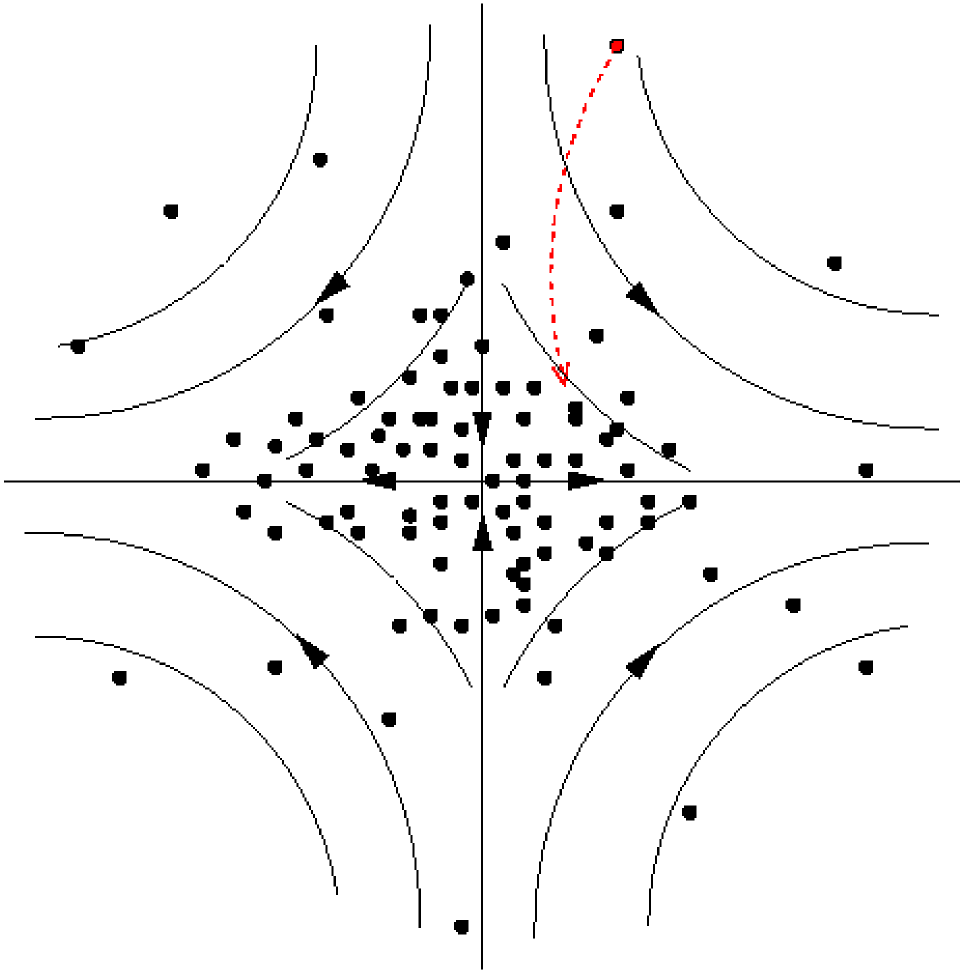
Inertial particles in stratified turbulence

Preferential concentration

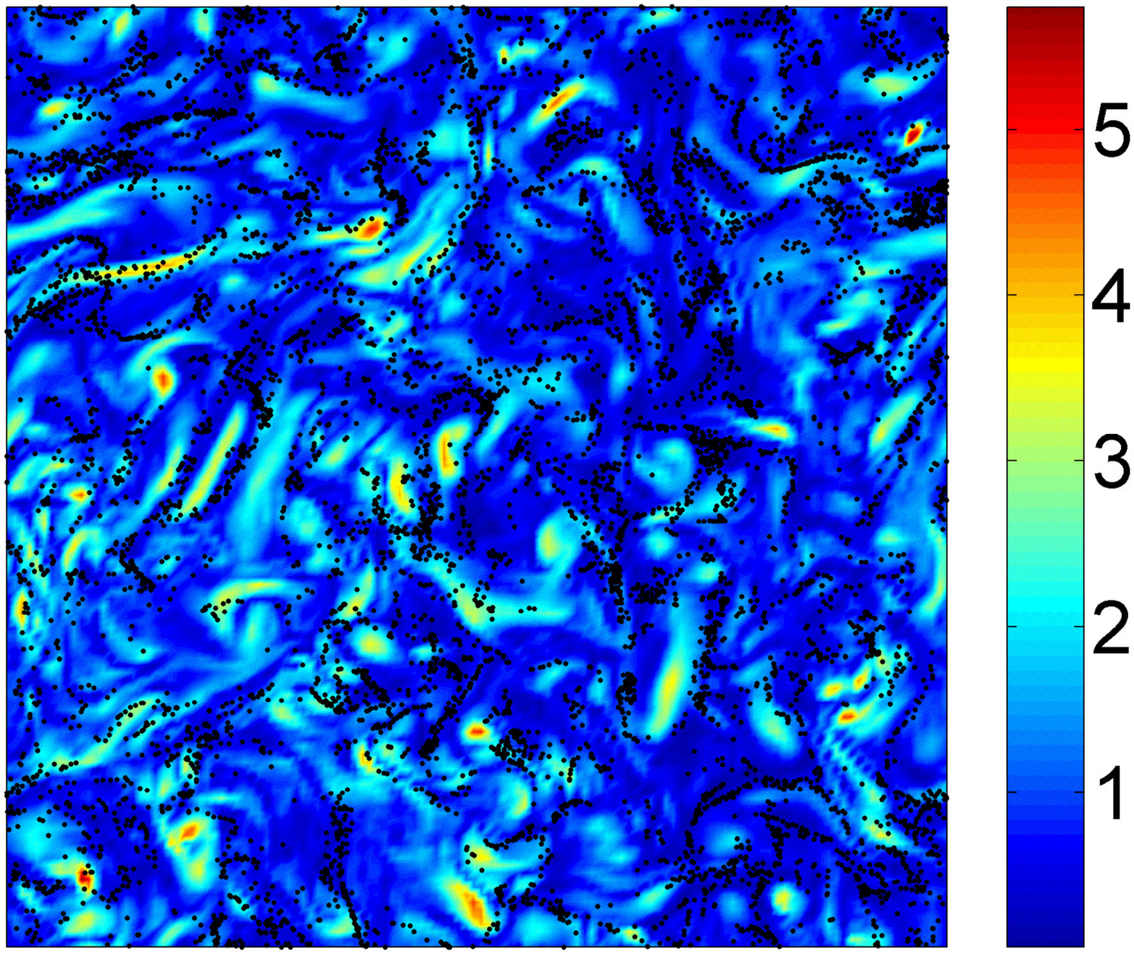


$$\frac{\rho_p}{\rho_f} > 1$$

high strain,
low vorticity

Inertial particles in stratified turbulence

Preferential concentration



isotropic turbulence

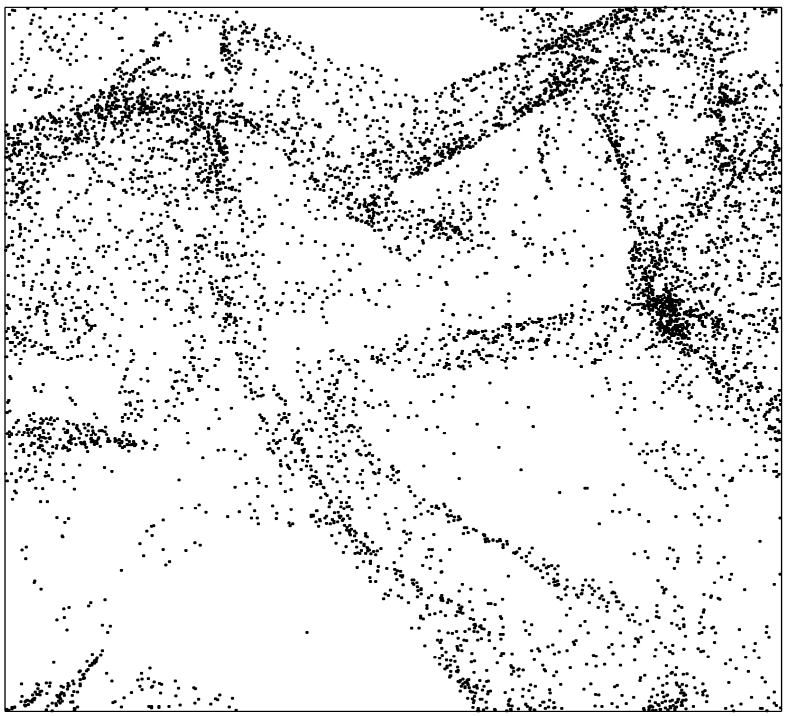
strain dominated

vorticity dominated

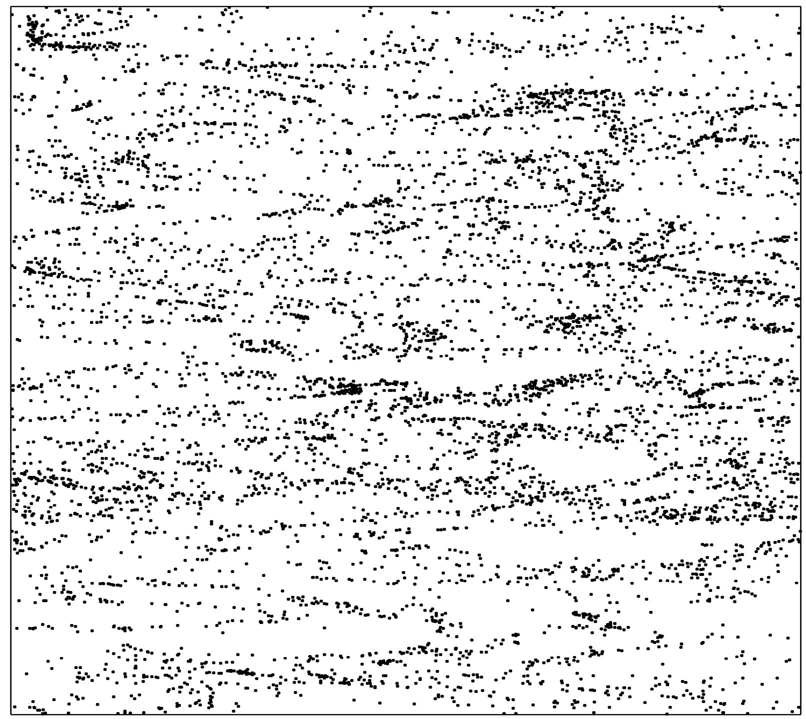
Inertial particles in stratified turbulence

Preferential concentration

stratified turbulence



horizontal



vertical

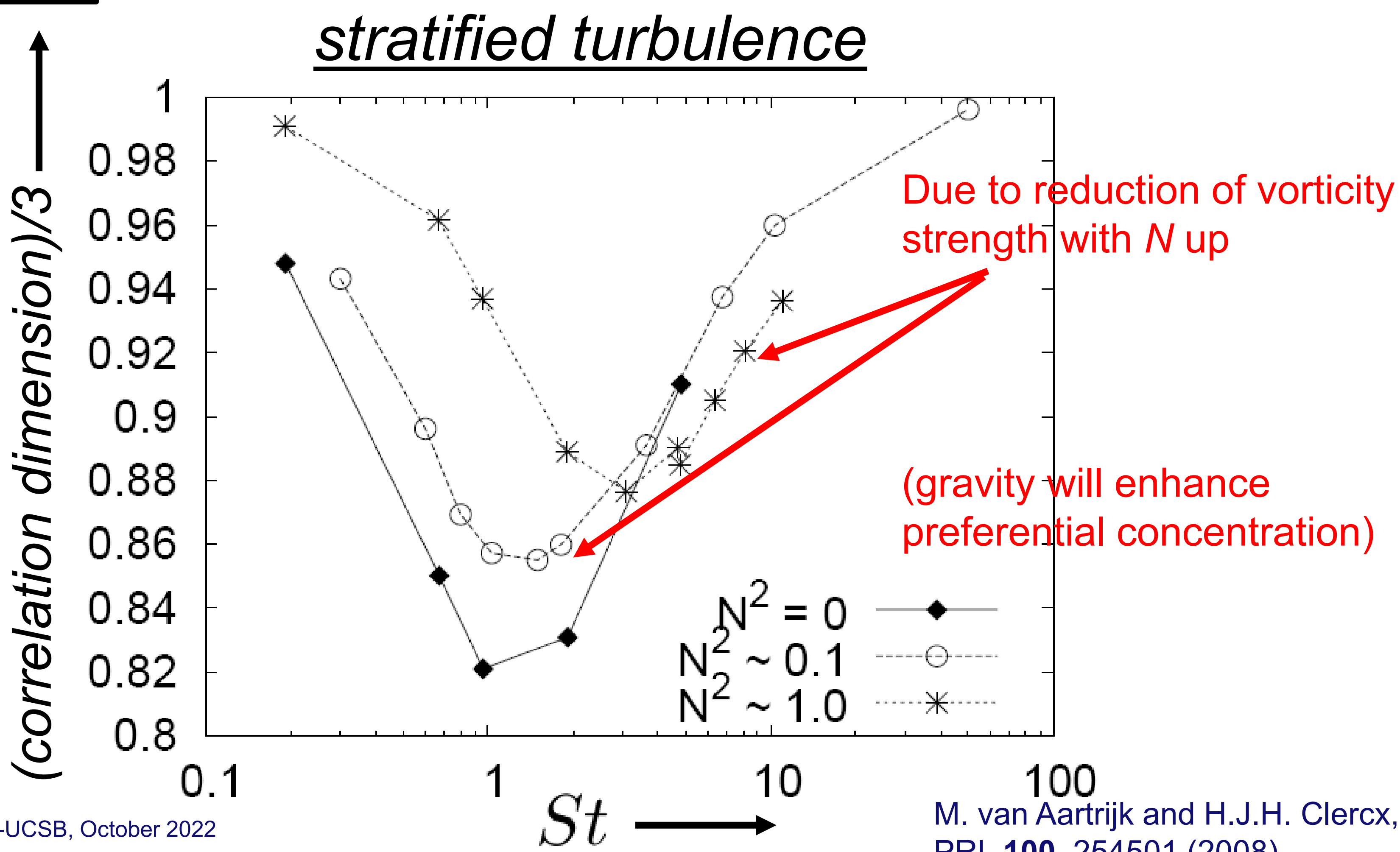
$N \sim 1\,(s^{-1})$

M. van Aartrijk and H.J.H. Clercx, PRL **100**, 254501 (2008)

Inertial particles in stratified turbulence

$P_2(r) \sim r^D$

Preferential concentration



M. van Aartrijk and H.J.H. Clercx, PRL **100**, 254501 (2008)

Non-heavy particles in stratified turbulence

DNS – Lagrangian part

Maxey-Riley equation: light or non-heavy particles

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{dt}} = 6\pi a \mu \left(\mathbf{u} - \mathbf{u}_p\right) + m_f \frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}} - \cancel{(m_p - m_f) g \mathbf{e}_z}$$

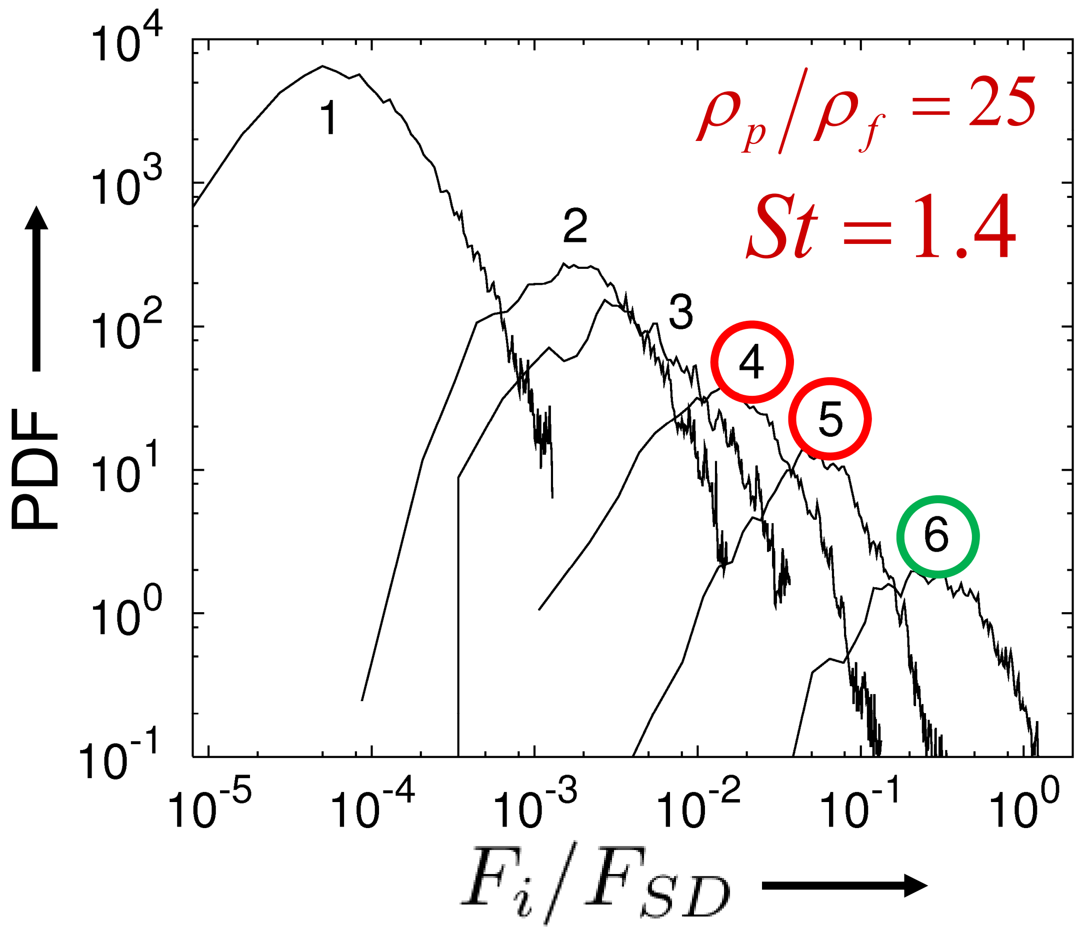
$$+ \frac{1}{2} m_f \left(\frac{\mathrm{D}\mathbf{u}}{\mathrm{Dt}} - \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{dt}} \right) + 3\sqrt{3\mu a m_f} \int_{-\infty}^{t} \frac{\mathrm{d}\mathbf{u}(\tau)/\mathrm{d}\tau - \mathrm{d}\mathbf{u}_p(\tau)/\mathrm{d}\tau}{\sqrt{t-\tau}} \mathrm{d}\tau$$

$$= \mathbf{F}_{\mathrm{St}} + \mathbf{F}_{\mathrm{P}} + \qquad \mathbf{F}_{\mathrm{AM}} + \mathbf{F}_{\mathrm{B}}.$$

M.R. Maxey and J.J. Riley, *Phys. Fluids* **26**, 883 (1983).

Non-heavy particles in stratified turbulence

Forces on the particles (N~0.3)



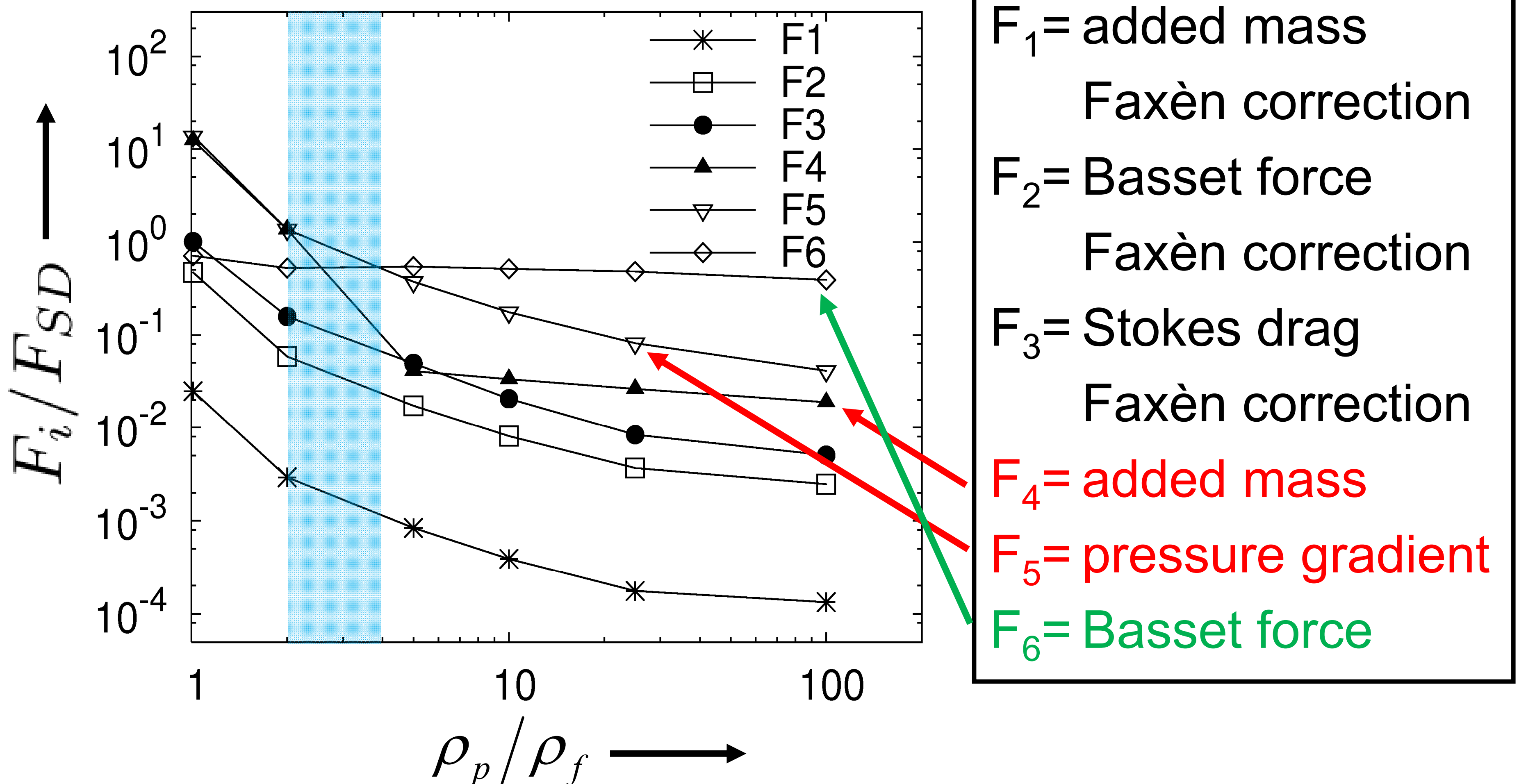
F_1= added mass
Faxèn correction
F_2= Basset force
Faxèn correction
F_3= Stokes drag
Faxèn correction
F_4= added mass
F_5= pressure gradient
F_6= Basset force

Non-stratified: V. Armenio and V. Fiorotto, PoF **13**, 2437 (2001)

M. van Aartrijk and H.J.H. Clercx, PoF **22**, 013301 (2010)

Non-heavy particles in stratified turbulence

Forces on the particles (N~0.3)

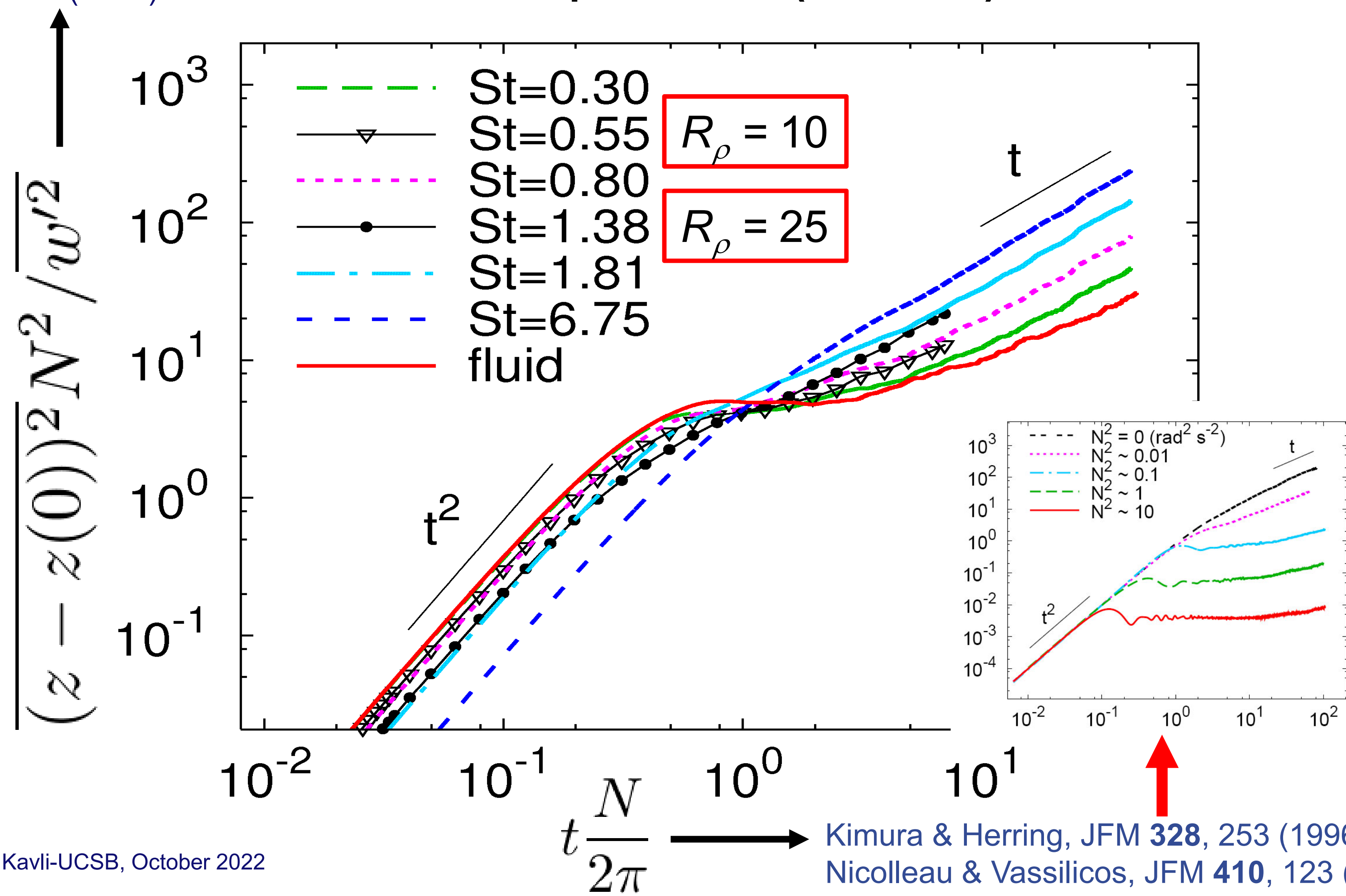


M. van Aartrijk and H.J.H. Clercx,
PoF **22**, 013301 (2010)

Non-heavy particles in stratified turbulence

Van Aartrijk & Clercx,
PoF **21**, 033304 (2009)

Vertical dispersion (N~0.3)



Kimura & Herring, JFM **328**, 253 (1996)
Nicolleau & Vassilicos, JFM **410**, 123 (2000)

Second set of conclusions

- Stratification enhances horizontal dispersion and reduces vertical dispersion (confirmation)

- Inertia has negligible influence on horizontal and increases long-time vertical dispersion in stratified turbulence

- Stratification affects preferential concentration

- Better vertical mixing of light particles compared to heavy particles (iso+strat) and full MR needed

Thanks to many colleagues involved in particles in turbulence in Eindhoven,
in particular with regard to this work:
Jan ten Thije Boonkkamp, Federico Toschi,
Marleen van Aartrijk and Michel van Hinsberg.