Recent improvement of operational models

I. Modeling of in-ground effects

II. Modeling of atmospheric stratification and turbulence effects

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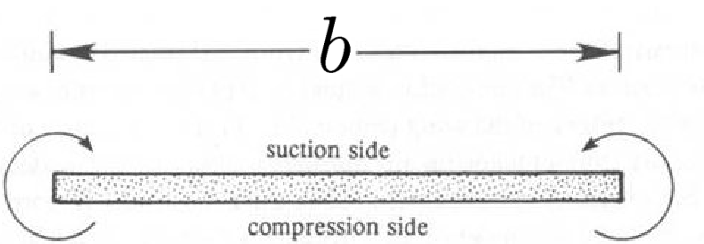
Aircraft wake vortices

$$L = \rho U_\infty b_0 \Gamma_0 = M g$$

$$\Gamma_0 = \frac{M g}{\rho U_\infty b_0}$$ circulation of WV

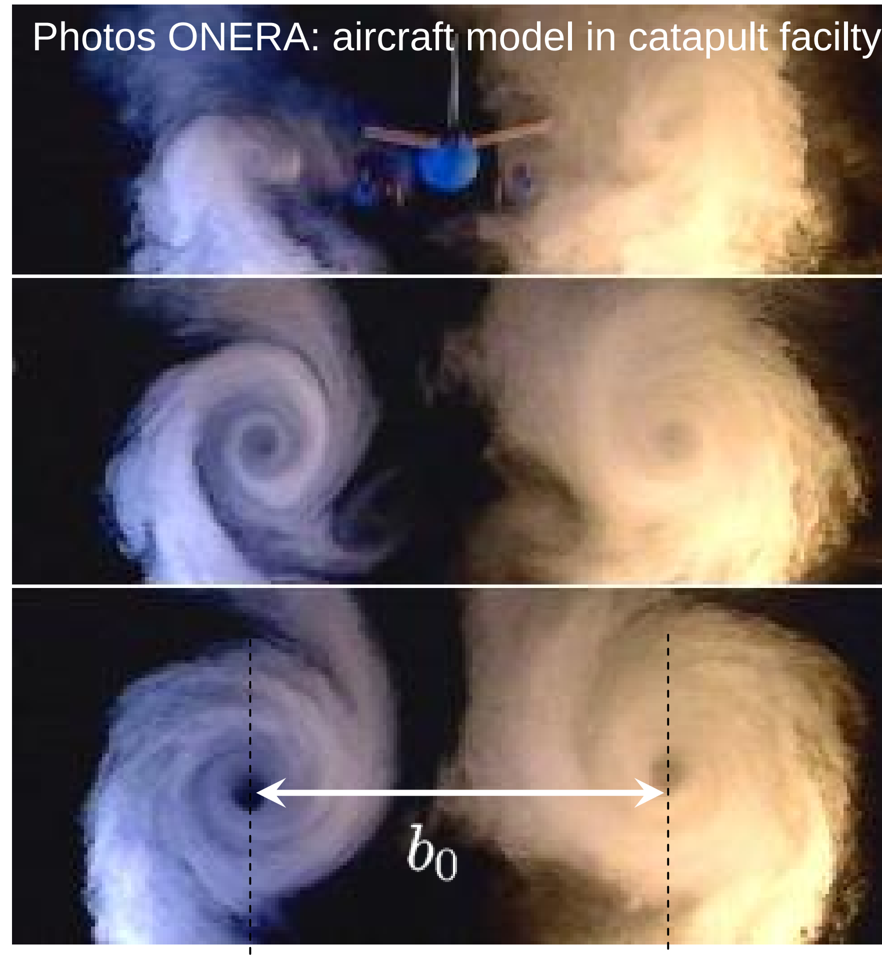
$$V_0 = \frac{\Gamma_0}{2\pi b_0}$$ sink velocity of WV

$$t_0 = \frac{b_0}{V_0}$$ reference time



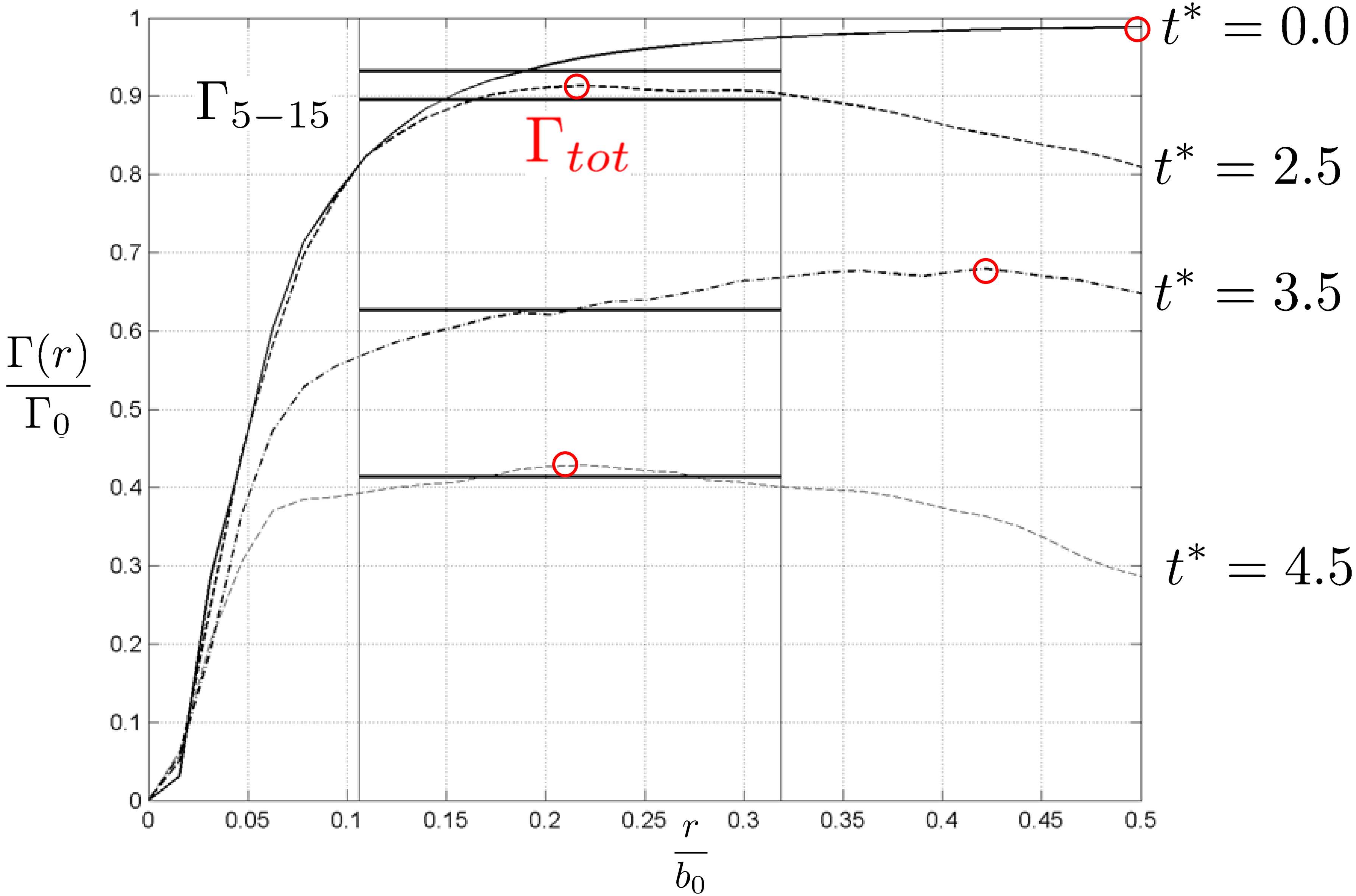
$$b_0 = 0.66 \ldots 0.92\, b$$

depending on a/c and on wing configuration



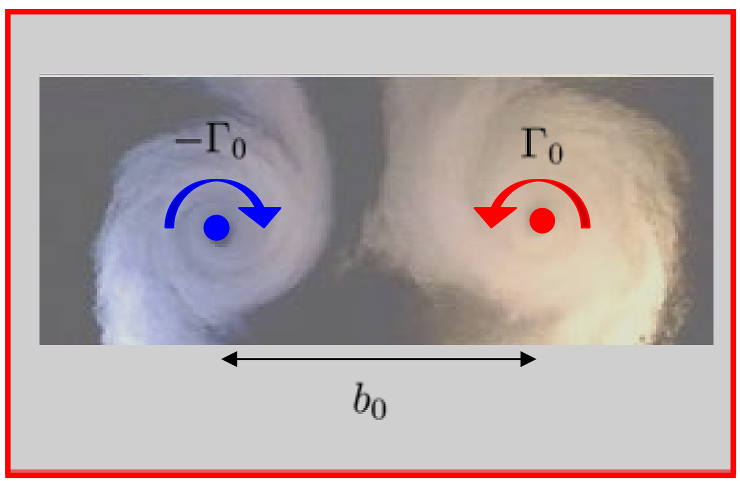
Circulation definition

$$\Gamma(r,t) = \int_0^{2\pi}\int_0^{r} \omega_x(r',\theta,t)\, r'\, dr' d\theta$$



The Deterministic wake Vortex Model (DVM)

- The DVM forecasts, in real-time, the WV behavior (transport and decay) in one computational gate, using simplified physical models.
- Each wake vortex is represented by a vortex particle (or by a set of vortex particles)
- The following effects are modeled for transport and decay:
  - Biot-Savart transport,
  - influence of the wind (wind transport, wind shear),
  - influence of atmospheric turbulence and stratification,
  - influence of the ground proximity.



Ground proximity modeling

- Use of secondary vortex particles generated close to the ground
- Interaction with the primary vortices induces :
  - the rebound,
  - an enhanced decay

- Model much improved in the framework of the FAR-Wake project (WP3- Wake Vortices In-Ground Effect)
- Recent improvements of the model to be computationally more efficient

Near Ground Effect Modeling

- Use of images vortex particles below the ground
- This is like computing $\gamma(y)$ (which would require solving a boundary integral equation)
- Correct prediction of the inviscid transport

$$d\Gamma(y) = \gamma(y)\, dy \qquad v(y, 0^+) = -\gamma(y)$$

$$v(y, 0) = 0$$

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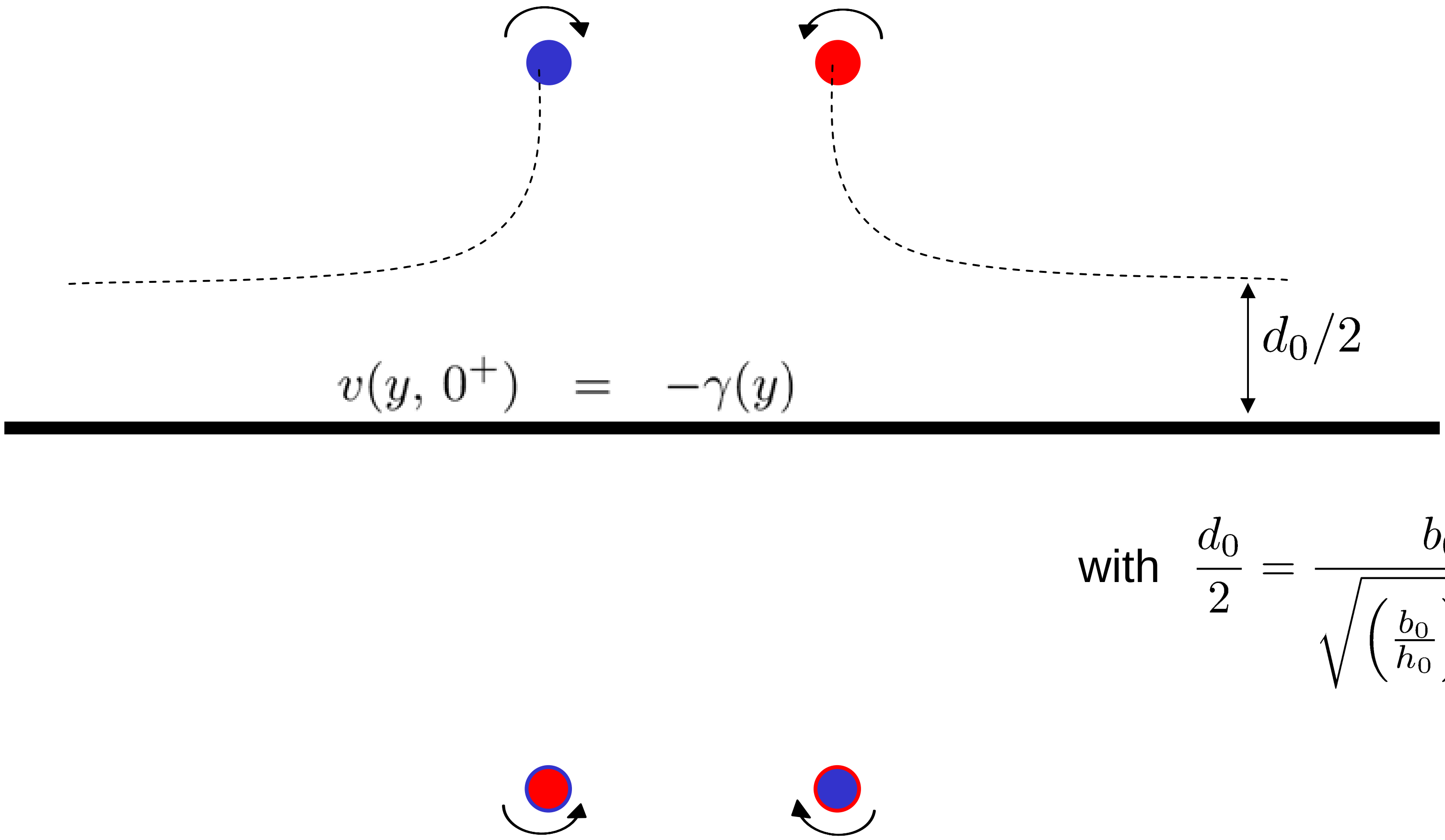


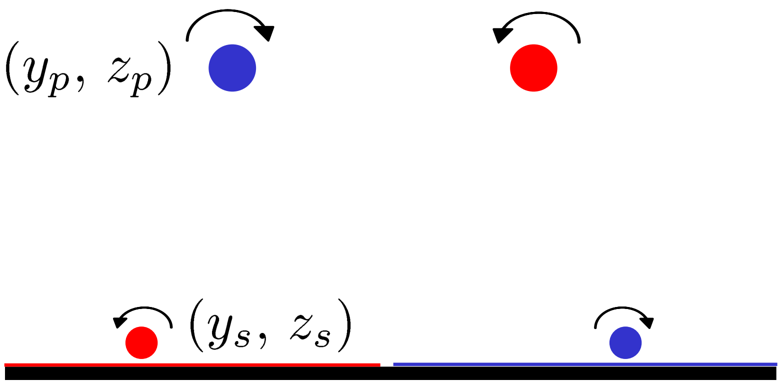
with $\dfrac{d_0}{2} = \dfrac{b_0}{\sqrt{\left(\frac{b_0}{h_0}\right)^2 + 4}}$

In-Ground Effect Modeling

Modeling of the separation of the boundary layer generated at the ground:

- At each time-step, generation of a new secondary particle when $z_p \leq \alpha_s \frac{d_0}{2}$

(typically $\alpha_s = 2.4$)



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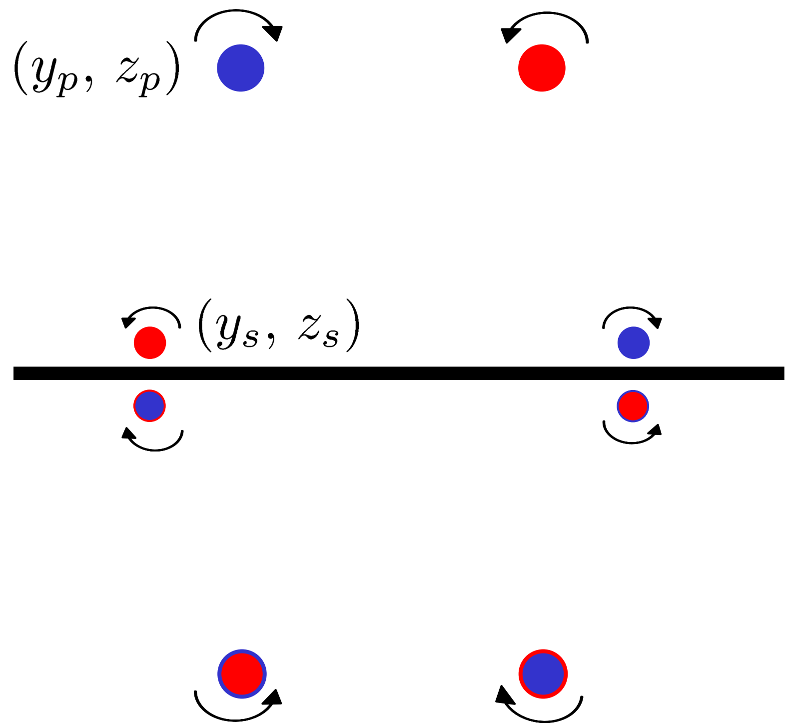
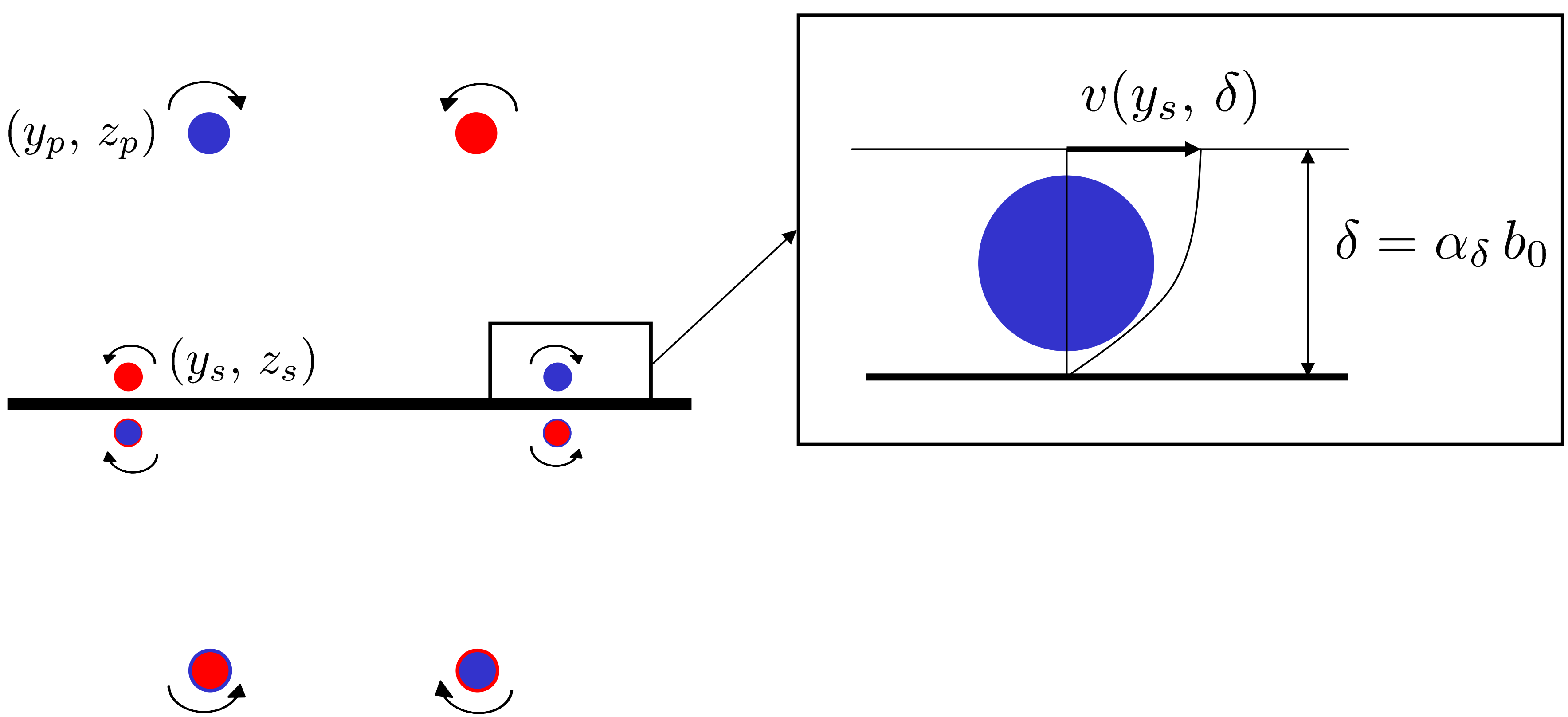


In-Ground Effect Modeling

Secondary particles characteristics are function of the whole vortex system and of the x-wind:

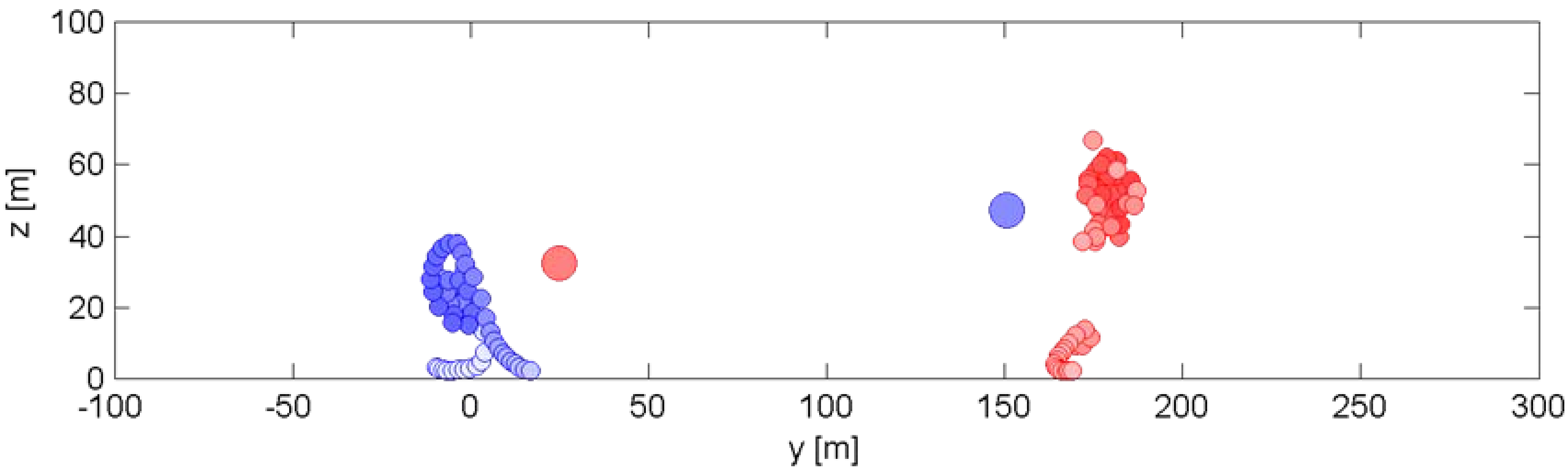
$$\begin{cases} v(y_s,\,0) &= \alpha_v\, max(v(y,\,0)) \\ \Gamma_s &= \pm\,\alpha_\Gamma\,\frac{v^2(y_s,\delta)}{2}\,\Delta t \\ z_s &= \frac{\delta}{2} \end{cases} \qquad \begin{cases} \alpha_v &= 0.82 \\ \alpha_\Gamma &= 1.5 \\ \alpha_\delta &= 0.08 \end{cases}$$



Dynamic separation of the secondary particles

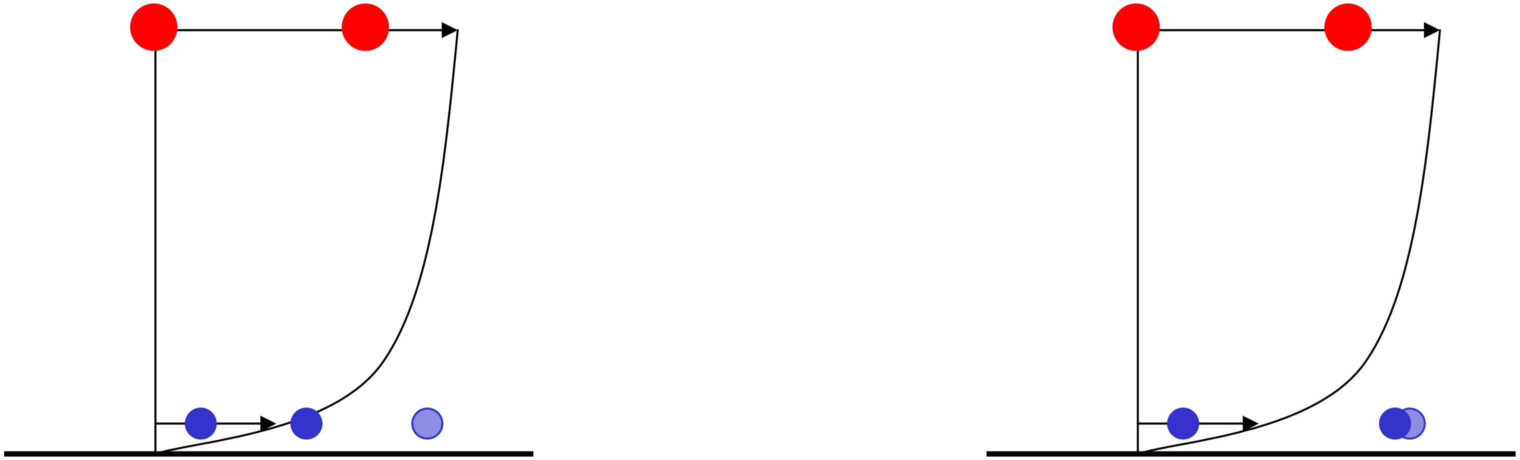
- Using Biot-Savart and wind transport:
  - The particles dynamically separate from the ground
  - They interact with the primary vortices and induce the rebound

- As the position and strength of the secondary vortex particles also depend on the x-wind, it also reproduces the asymmetric rebound



Special treatment of wind transport for particles very close to the ground

- Due to the wind profile, the wind speed very close to the ground can be a lot smaller than aloft.
- In case of strong crosswind, the secondary vortex particles would not "follow" the primary ones.
- The secondary vortex particles have then "no time" to separate.
- Solution: the wind speed, used for the secondary particles located very close to the ground (typically below 10 m), is evaluated at the primary vortex altitude.



Enhanced IGE decay model

- Model based on a “Particle Strength Exchange” (PSE) approach
- Exponential decay of both the primary and secondary particles
- The decay rate of the primary (resp. secondary) particles depends on:
  - the total secondary (resp. primary) particle circulation
  - the minimum altitude reached by the primary particles
- System applied separately to the port and starboard vortices:

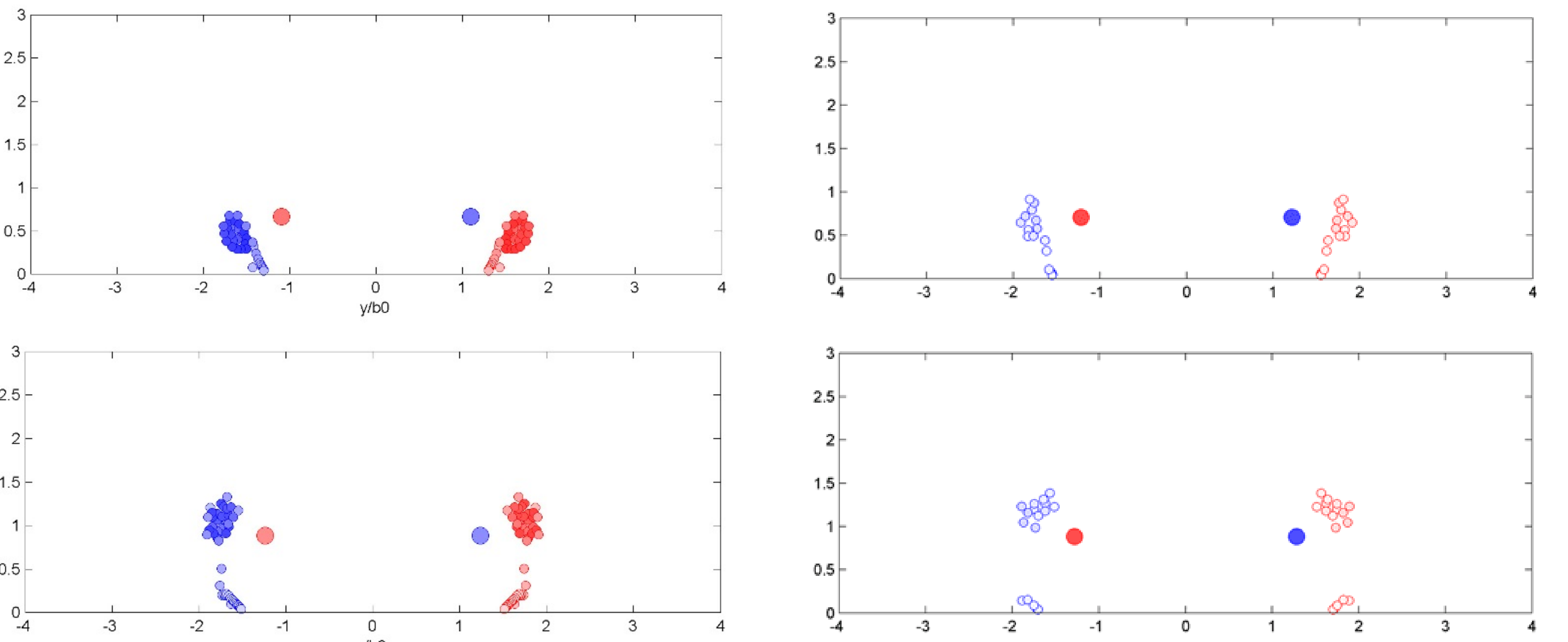
$$\begin{aligned} \frac{d\Gamma_p}{dt} &= -C_{IGE} \frac{|\sum_s \Gamma_s|}{(z_{min})^2} \Gamma_p \,, \\ \frac{d\Gamma_s}{dt} &= -C_{IGE} \frac{|\sum_p \Gamma_p|}{(z_{min})^2} \Gamma_s \,. \end{aligned}$$

$$C_{IGE} = 0.017$$

Agglomeration of secondary particles

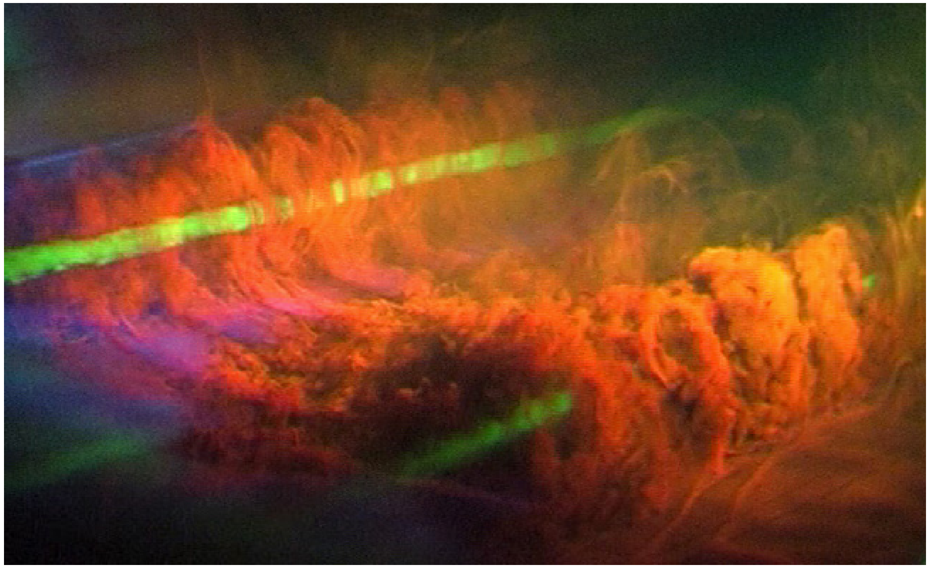
- The IGE model requires the use of several secondary vortex particles.
- Solution: agglomeration of particles
- Once a structure made of several particles reaches:
  - a sufficient size, and/or
  - a sufficient circulation,

  it is replaced by one equivalent particle



Reorganization of the secondary particles

- After the first rebound, coherent structures of secondary vorticity are no longer observed around the primary vortex.
- This is a 3-D effect => not dynamically captured by the 2-D vortex particle method.
- Model: once the primary vortex has rebound and tends to sink again, we reorganize the secondary vortex particles in a “halo” around the primary vortex.

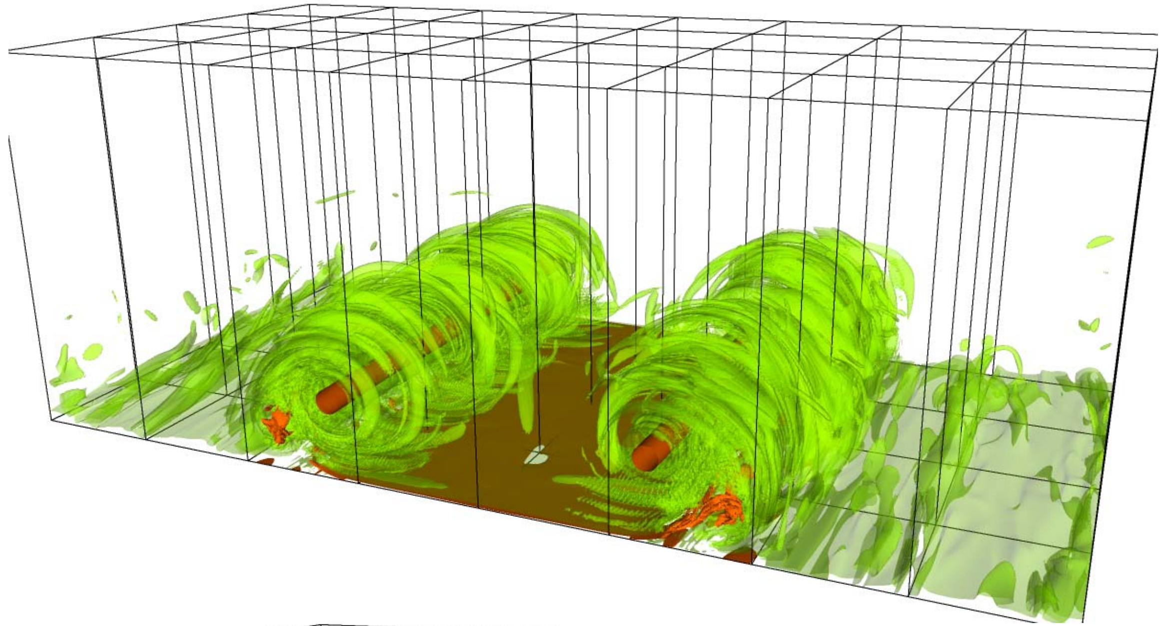


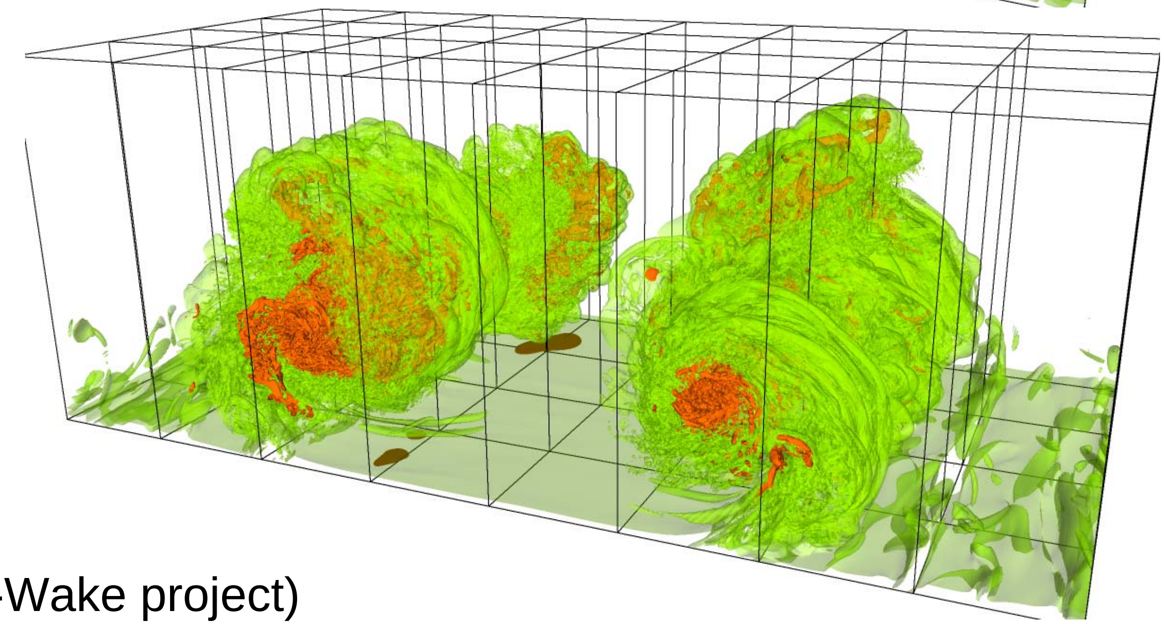
Source: UCL (FAR-Wake project)

LES of a 2VS IGE with headwind

$$h_0 = b_0$$

$$V_{\text{wind}}(h_0) = V_0$$





Source: Cenaero (FAR-Wake project)

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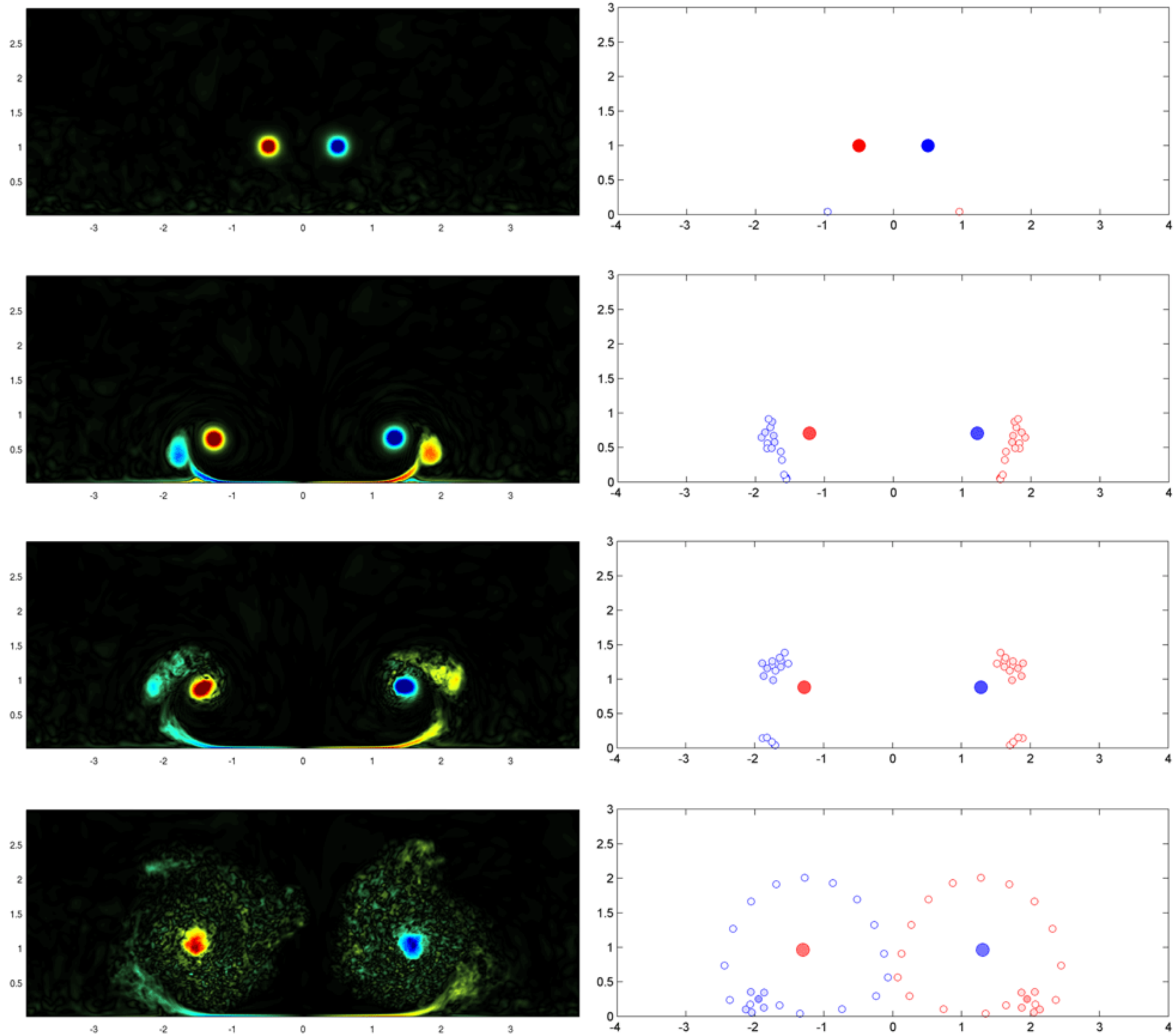
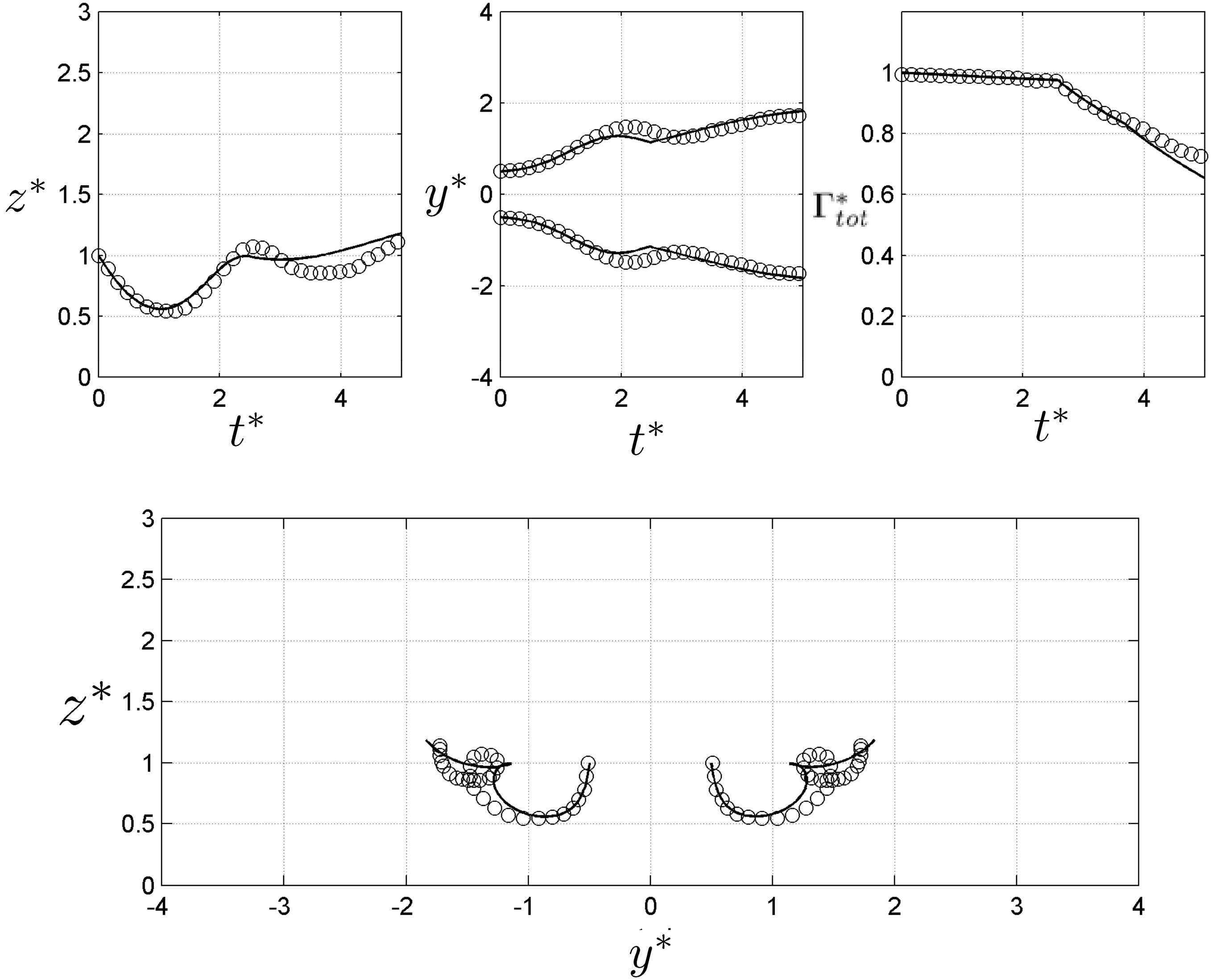
Comparison between LES and DVM results:
- case IGE with headwind

Mean axial vorticity field as computed by a LES   *Particles used in the DVM to model WV IGE*



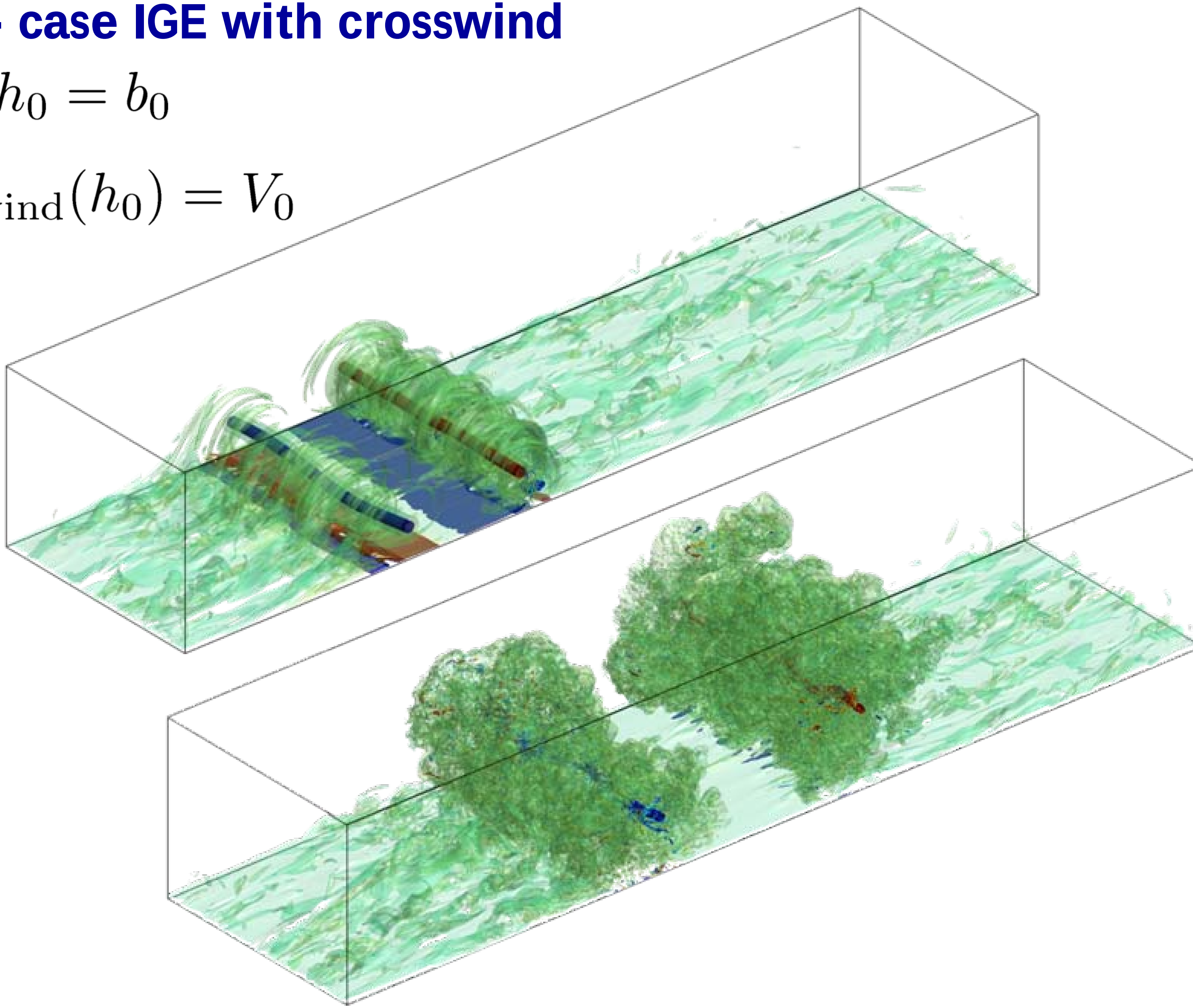
Comparison between LES and DVM results:
- case IGE with headwind



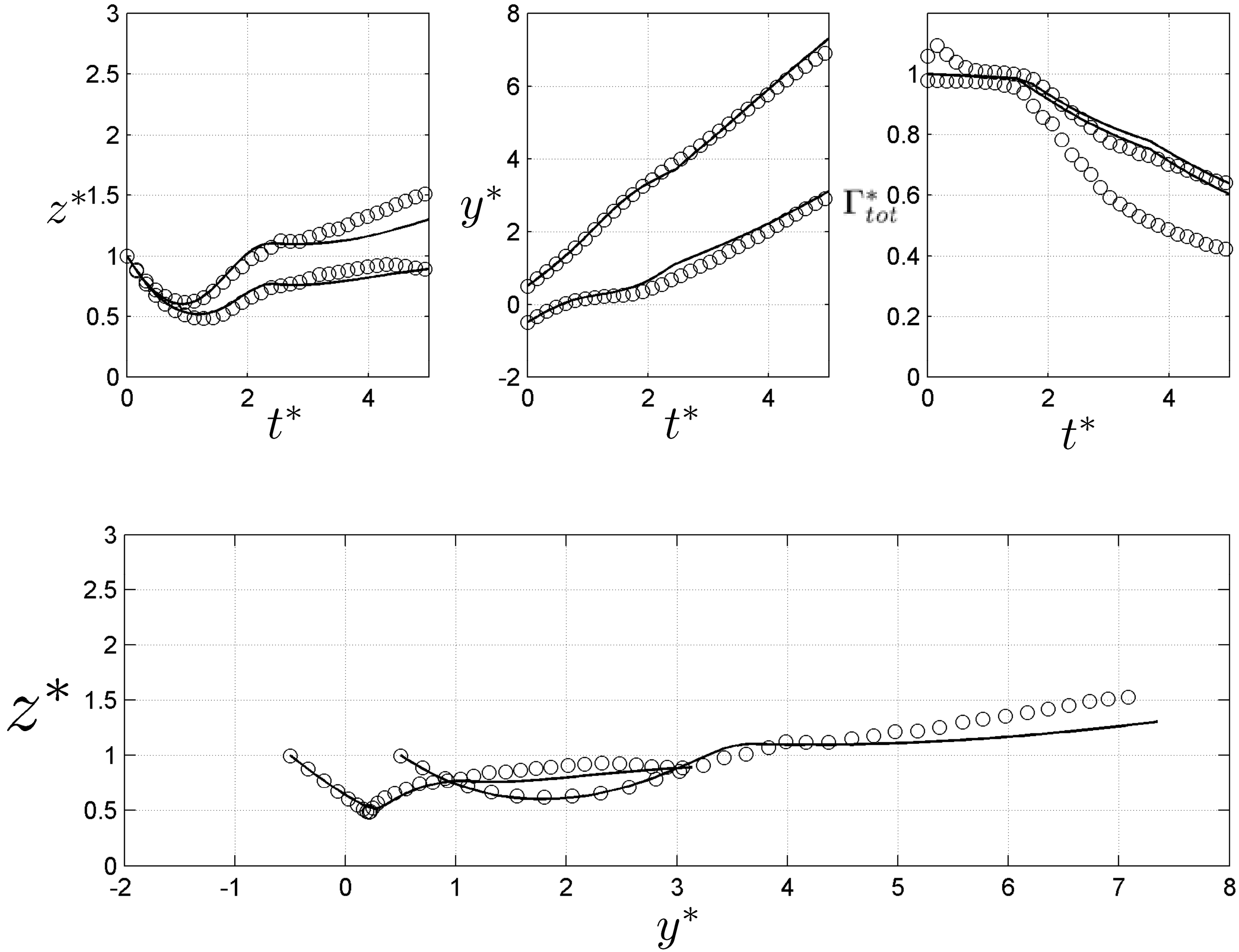
Comparison between LES and DVM results:
- case IGE with crosswind

$$h_0 = b_0$$

$$V_{\mathrm{wind}}(h_0) = V_0$$

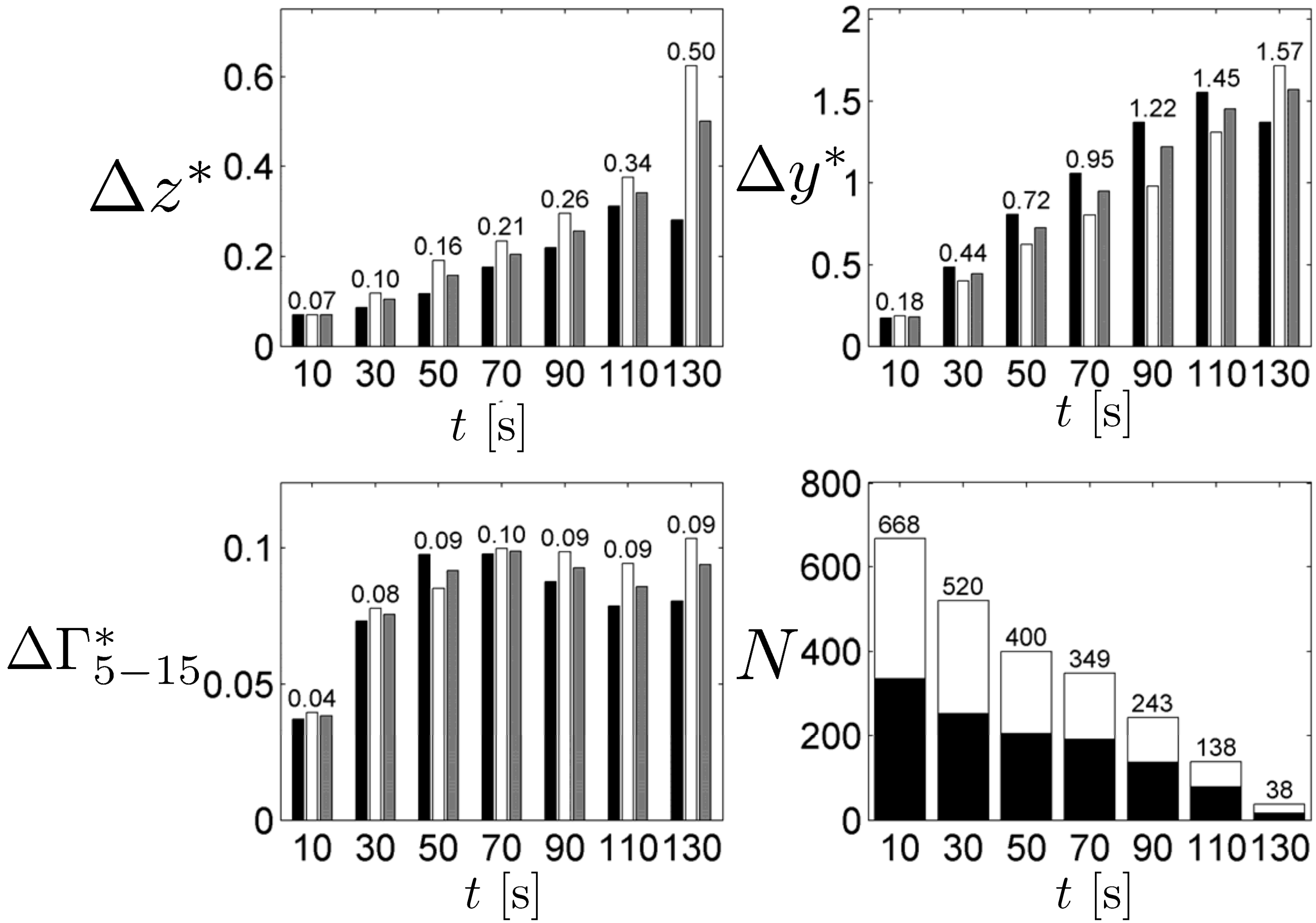


Comparison between LES and DVM results:
- case IGE with crosswind



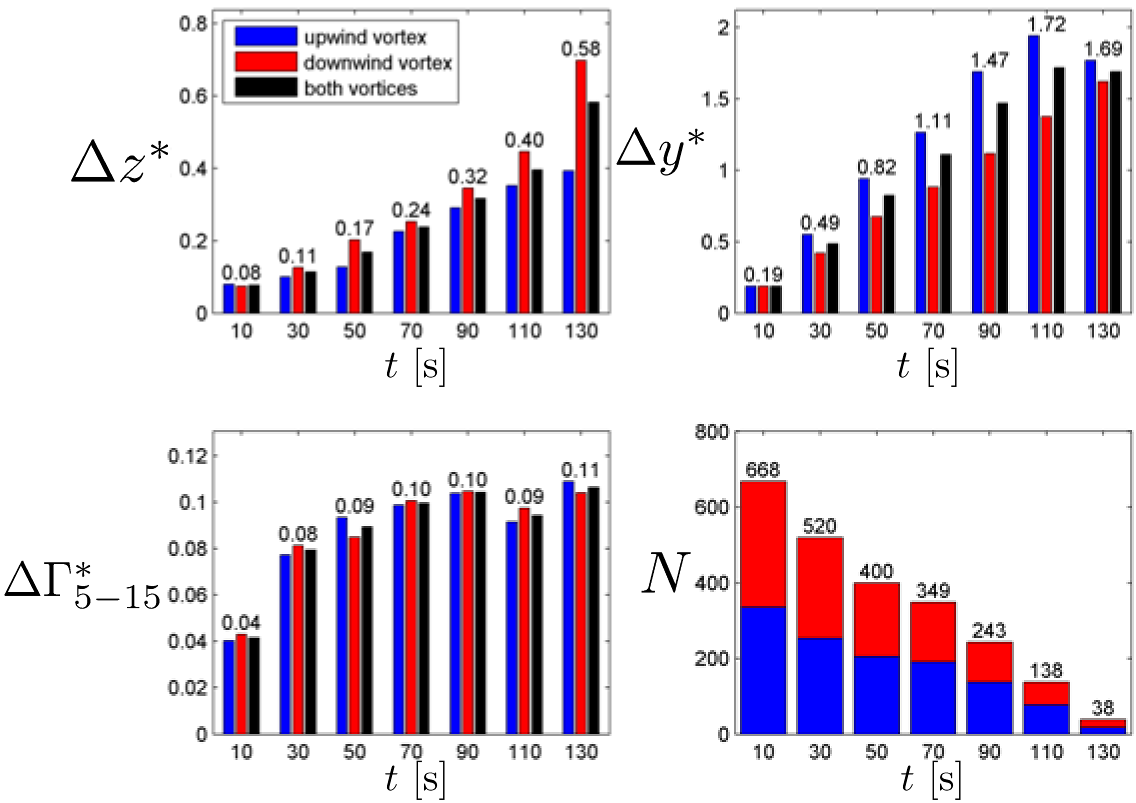
WakeFRA 2004 database

- LIDAR measurement campaign of WV generated by heavy aircraft in ground proximity (110 cases)
- Assessment using rms deviation between measurements and DVM results



WakeFRA 2004 database

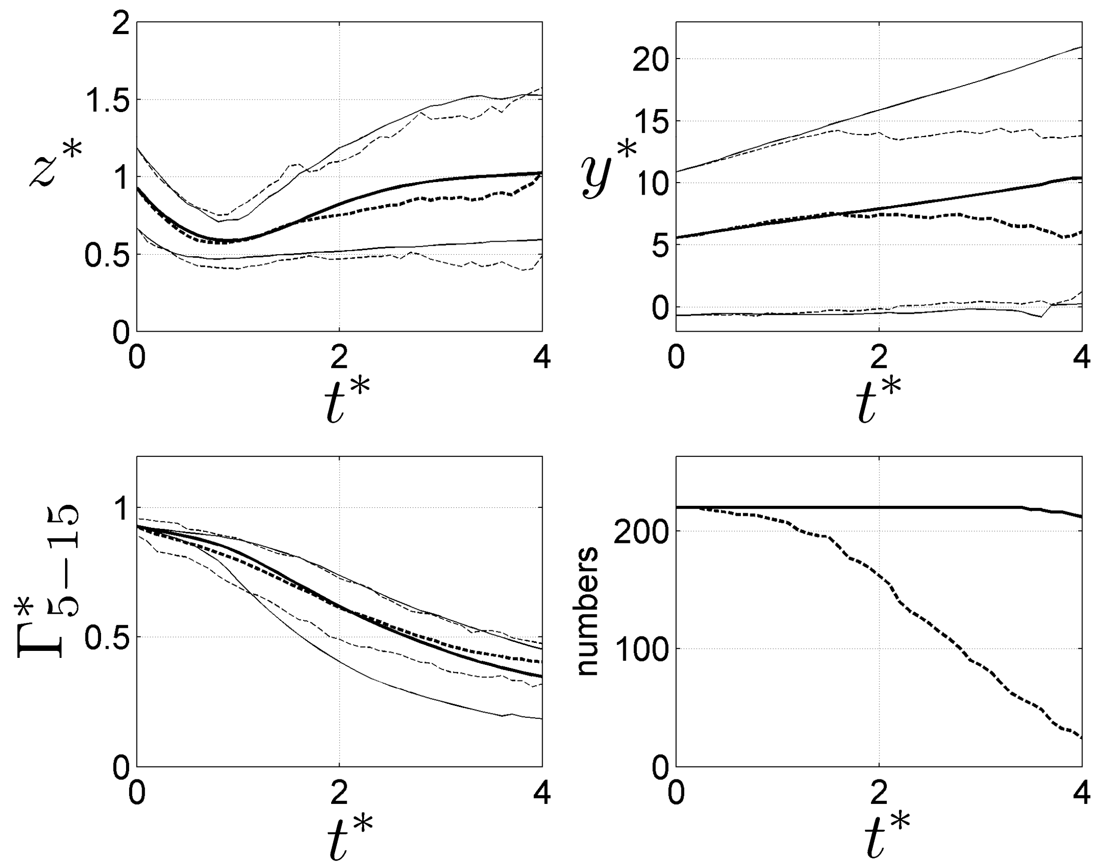
- Results using the FAR-Wake DVM version ("old")



	90 s		110 s	
	old	new	old	new
Δz^*	0.32	0.26	0.40	0.34
Δy^*	1.47	1.22	1.72	1.45
$\Delta\Gamma^*_{5-15}$	0.10	0.09	0.09	0.09

WakeFRA 2004 database

Comparison of the evolution of the mean and 90%-envelope of the whole database

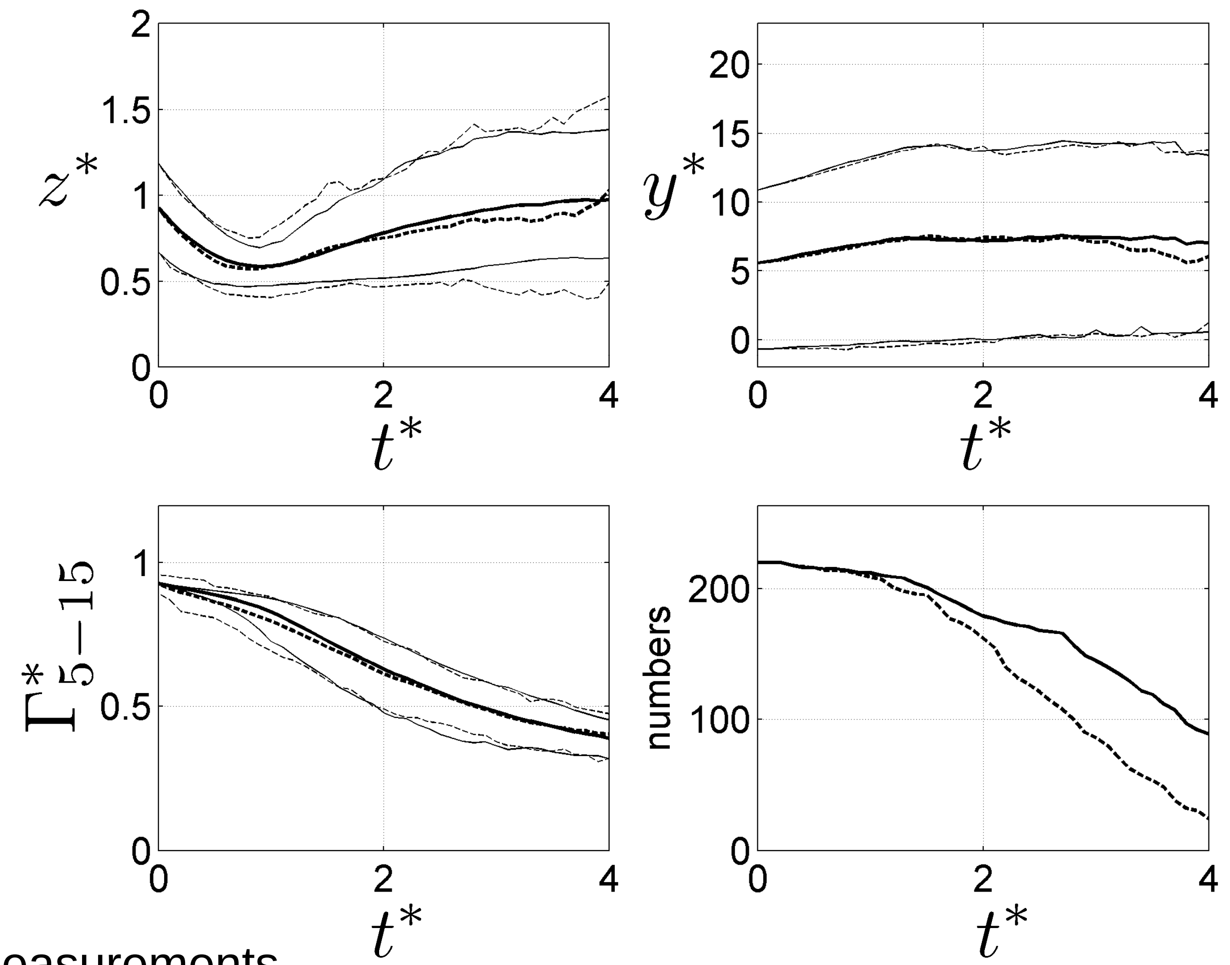


Measurements

DVM results

WakeFRA 2004 database

Use of an equivalent LIDAR-filter on the minimum and maximum measurable lateral position and minimum measurable circulation



- - - - Measurements

——— DVM results

Conclusions on the improved IGE model

- For a case of WV generated IGE, the improved IGE model uses 6 to 9 times less secondary vortex particles.
- It still mimics correctly the flow physics
- Its quality is also improved wrt the previous version.
- It is computationally much more efficient (>10).

Modeling of the effect of stratification combined with weak turbulence

- Stratification affects the transport of the vortices :
  - Rebound of the vortices due to buoyancy
  - Decrease of the vortex lateral separation for moderate N*
  - Increase of the vortex lateral separation for high N*

- Stratification also affects the vortex decay
  - Strong interaction with the turbulent baroclinic vorticity
  - For moderate N*, increase of the Crow instability growth rate

LES of WV in stratified and weakly turbulent atmosphere

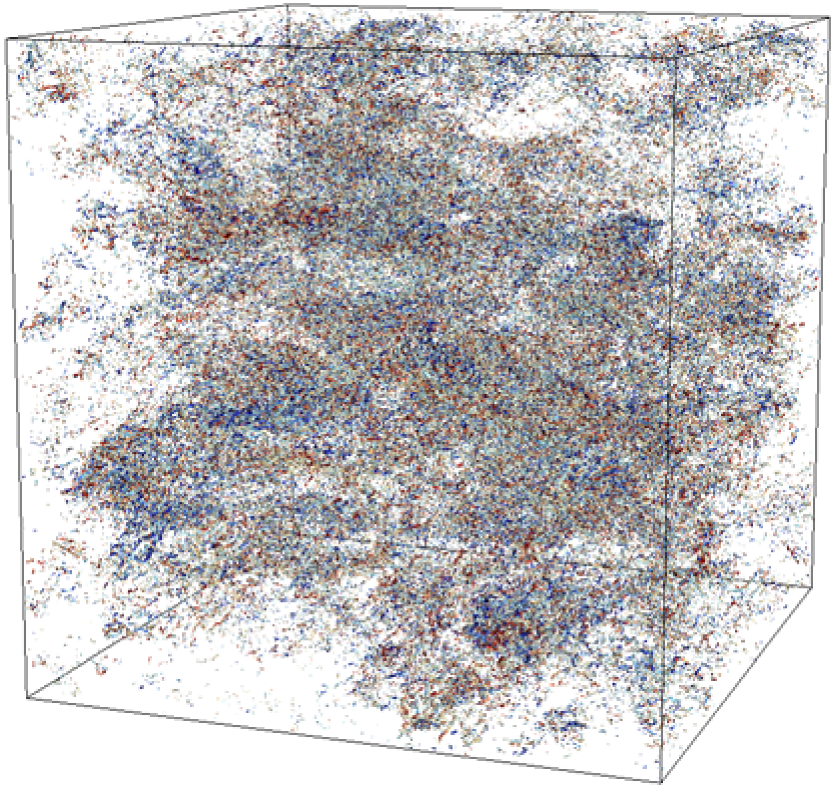
- Pseudo-spectral LES at very high $Re = \dfrac{\Gamma_0}{\nu}$ (LES using SGS model only)
- Periodic domain with possible Crow instability development
- Relatively tight vortex core ($\dfrac{r_c}{b_0} = 0.05$) with fine LES grids ($\dfrac{h}{b_0} = \dfrac{1}{64}$)
- Five stratification levels are investigated from neutral to very high:

  $N^* = 0.0,\ 0.35,\ 0.75,\ 1.0,\ 1.4$
- Two turbulence forcing levels: $\left(\dfrac{dE}{dt}\right)_f^* = \dfrac{dE}{dt}\dfrac{b_0}{V_0^3} = 2.4\,10^{-4}\ \text{and}\ 2.4\,10^{-5}$

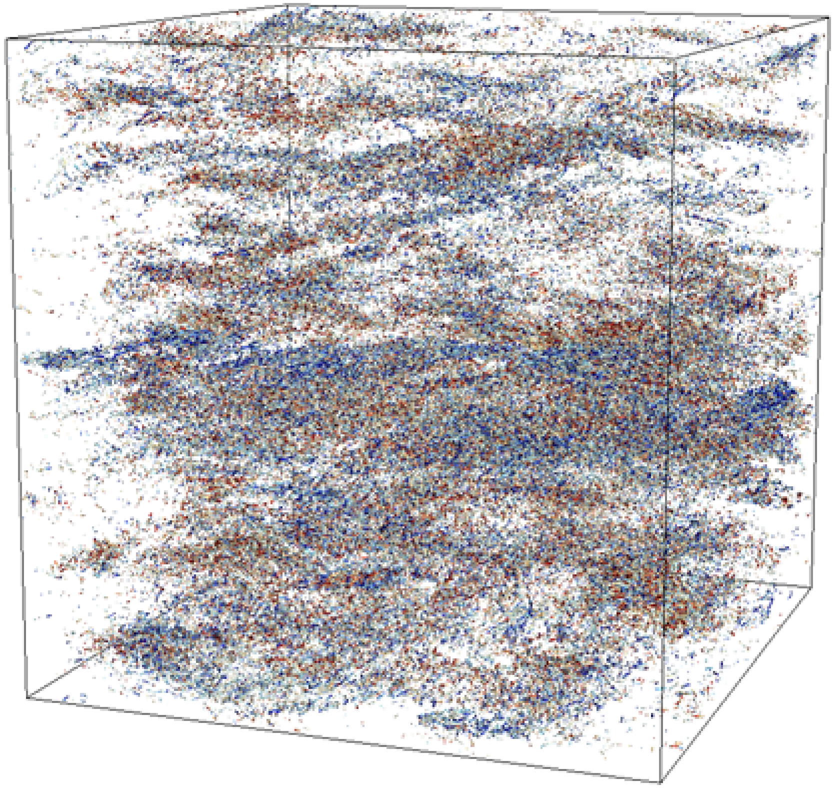
All cases correspond to a low turbulence level attained at equilibrium

Stratified turbulence

- Pre-simulations of forced stratified turbulence have been performed for the 5 considered N*, using LES
- This enables to obtain realistic background stratified and weakly turbulent fields.
- The WV will then evolve in those fields



N*=0.35



N*=1.0

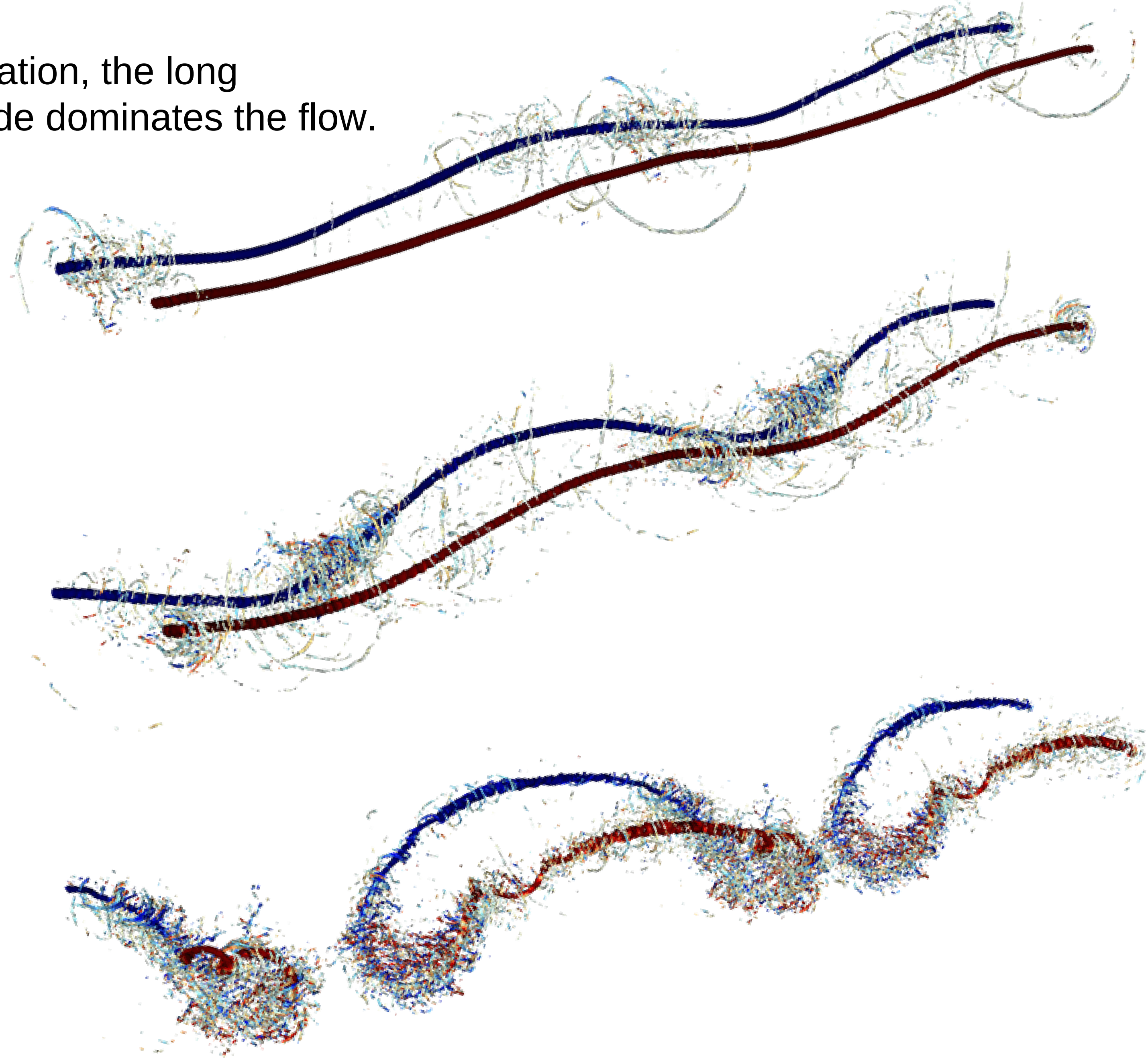
Case N*=0

Without stratification, the long wavelength mode dominates the flow.

$\tau = 3.0$

$\tau = 4.0$

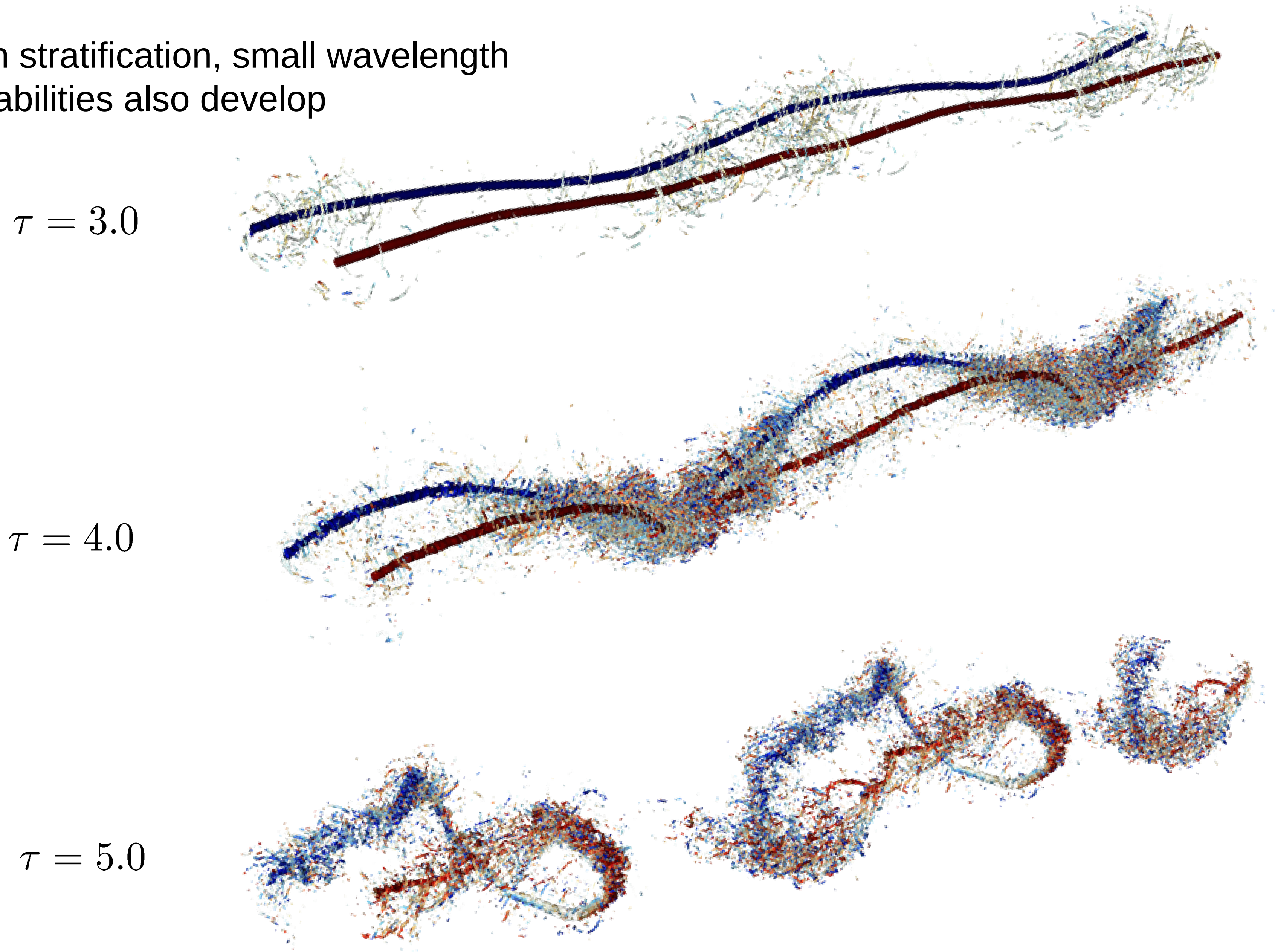
$\tau = 5.0$



Iso-λ_2 surfaces colored by the axial vorticity

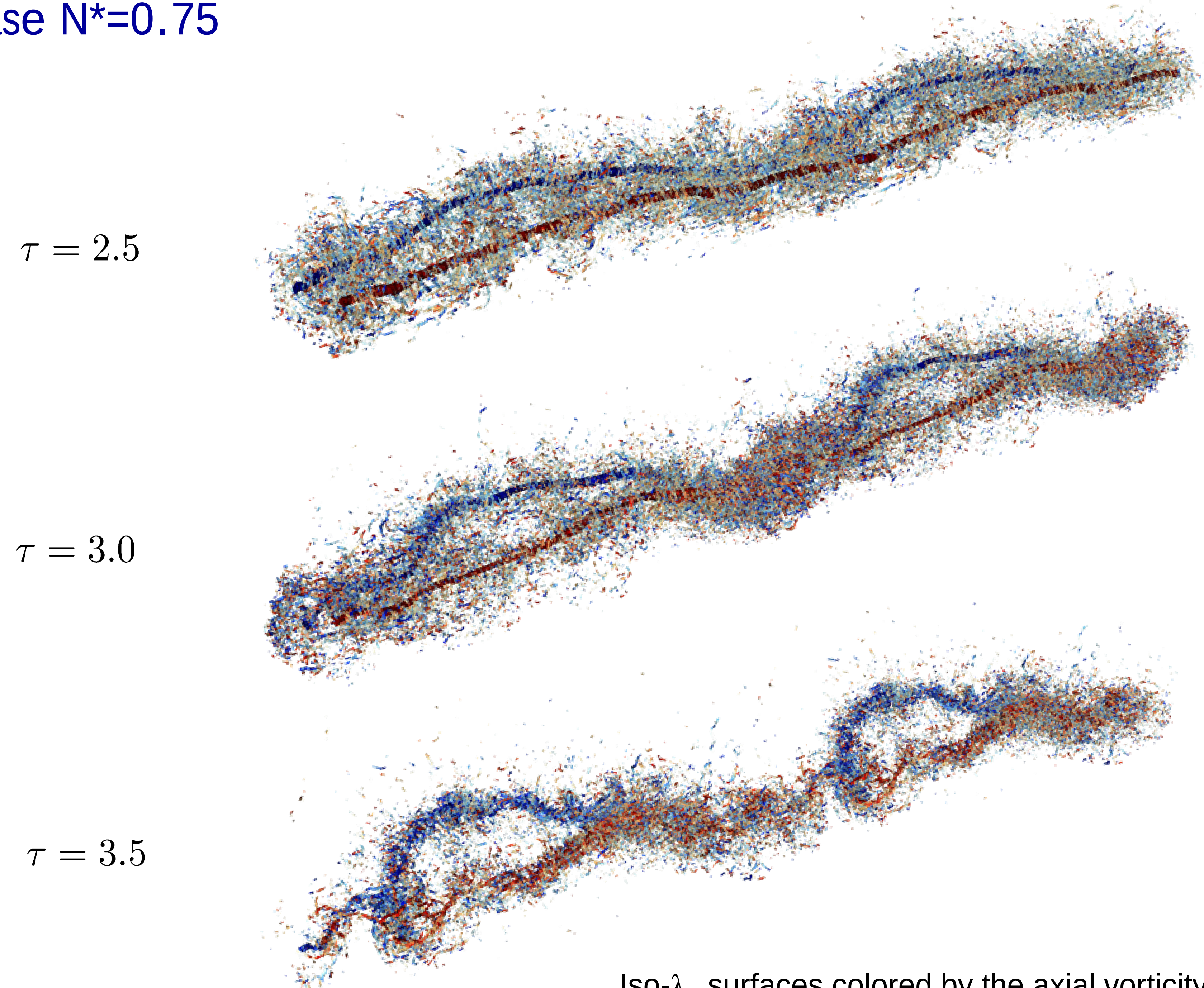
Case N*=0.35

With stratification, small wavelength instabilities also develop



Iso-λ_2 surfaces colored by the axial vorticity

Case N*=0.75



Iso-λ_2 surfaces colored by the axial vorticity

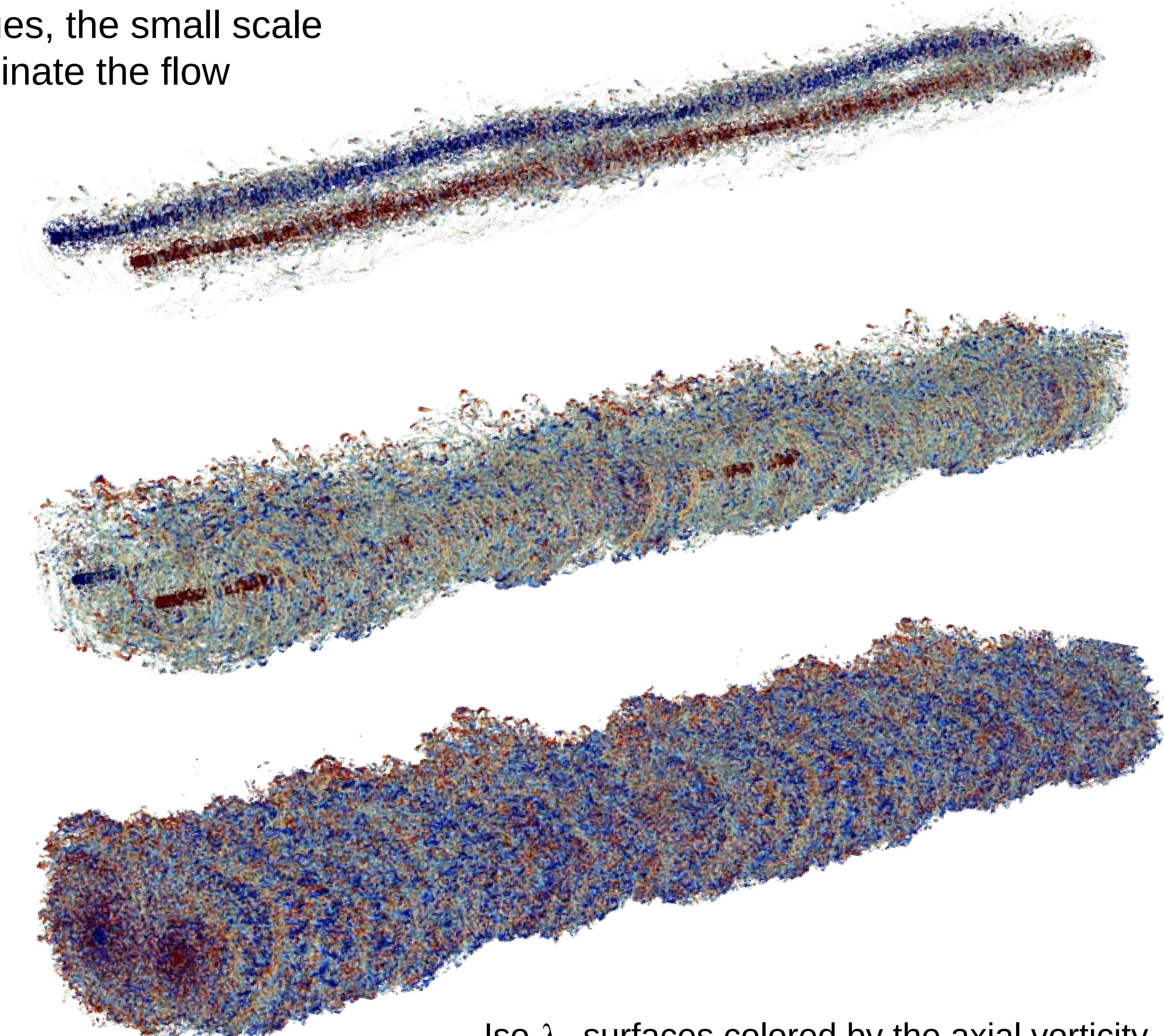
Case N*=1

For high N* values, the small scale instabilities dominate the flow

$\tau = 1.0$

$\tau = 1.5$

$\tau = 2.0$



Iso-λ_2 surfaces colored by the axial vorticity

Vortex transport modeling

- Vortex altitude evolution influenced by Biot-Savart and stratification :

$$\frac{dz^*}{dt^*} = v^*_{BS} + v^*_{str} \quad \text{with} \quad v^*_{BS}(t^*) = -\Gamma^*_{tot}(t^*)$$

- New model, improved over Saffman's model (1972) :

$$\frac{dv^*_{str}}{dt^*} = \underbrace{-(\alpha_{str}\, N^*)^2\ (z^* - h^*_0)}\ \underbrace{-\ C\, v^*_{str}}$$

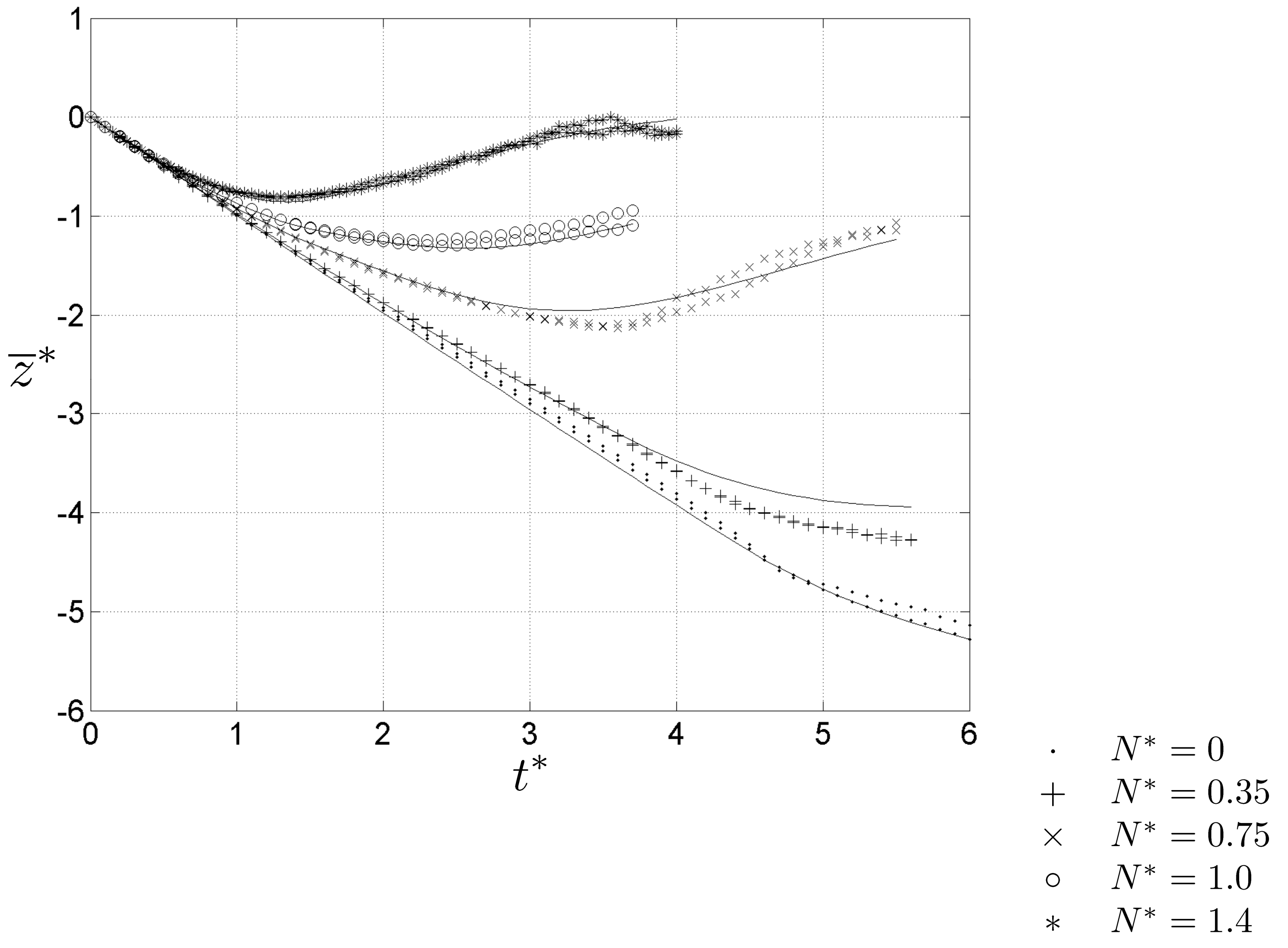
- Saffman's model: sinusoidal rebound controlled by N*

- Damping term : -modeling the effect of the reorganization of the baroclinic vorticity around the primary vortices, attenuating the rebound effect

$$\begin{cases} \alpha_{str} = 0.8 \\ C = 1.3 \\ t^*_{crit} = 1.6 \end{cases}$$

- Activated for $t^* \geq t^*_{crit}$

Comparison with LES data



Circulation decay modeling

- New time-to-demise model, based on Sarpkaya's model (2000) $t^*_{d,S}(\epsilon^*)$

$$t^*_d(\epsilon^*, N^*) = \begin{cases} t^*_{d,S} \exp\left(-C_1 \left(N^* \, t^*_{d,S}\right)^a\right) & \text{if } (N^* \, t^*_{d,S}) \leq K \\ \frac{C_2}{N^*} & \text{otherwise} \end{cases}$$

with $K = (C_1 \, a)^{-1/a}$ and $C_2 = K \exp\left(-C_1 \, K^a\right)$

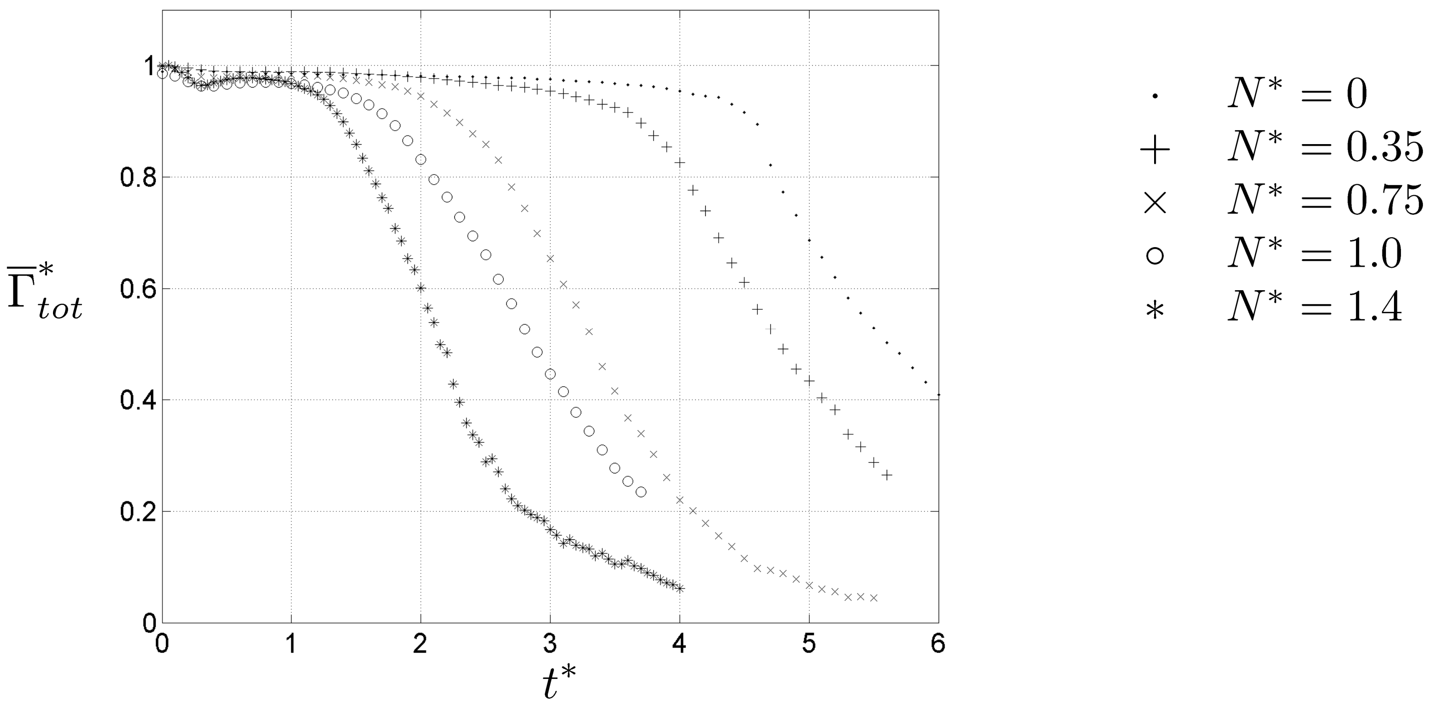
Model established so that:

a) t^*_d is a decreasing function of ϵ^* and N^*

b) for very high N^*, t^*_d is independent on ϵ^*

$$\begin{cases} a = 1.6 \\ C_1 = 0.076 \end{cases} \Rightarrow \begin{cases} K = 3.73 \\ C_2 = 2.0 \end{cases}$$

Two-phase decay model

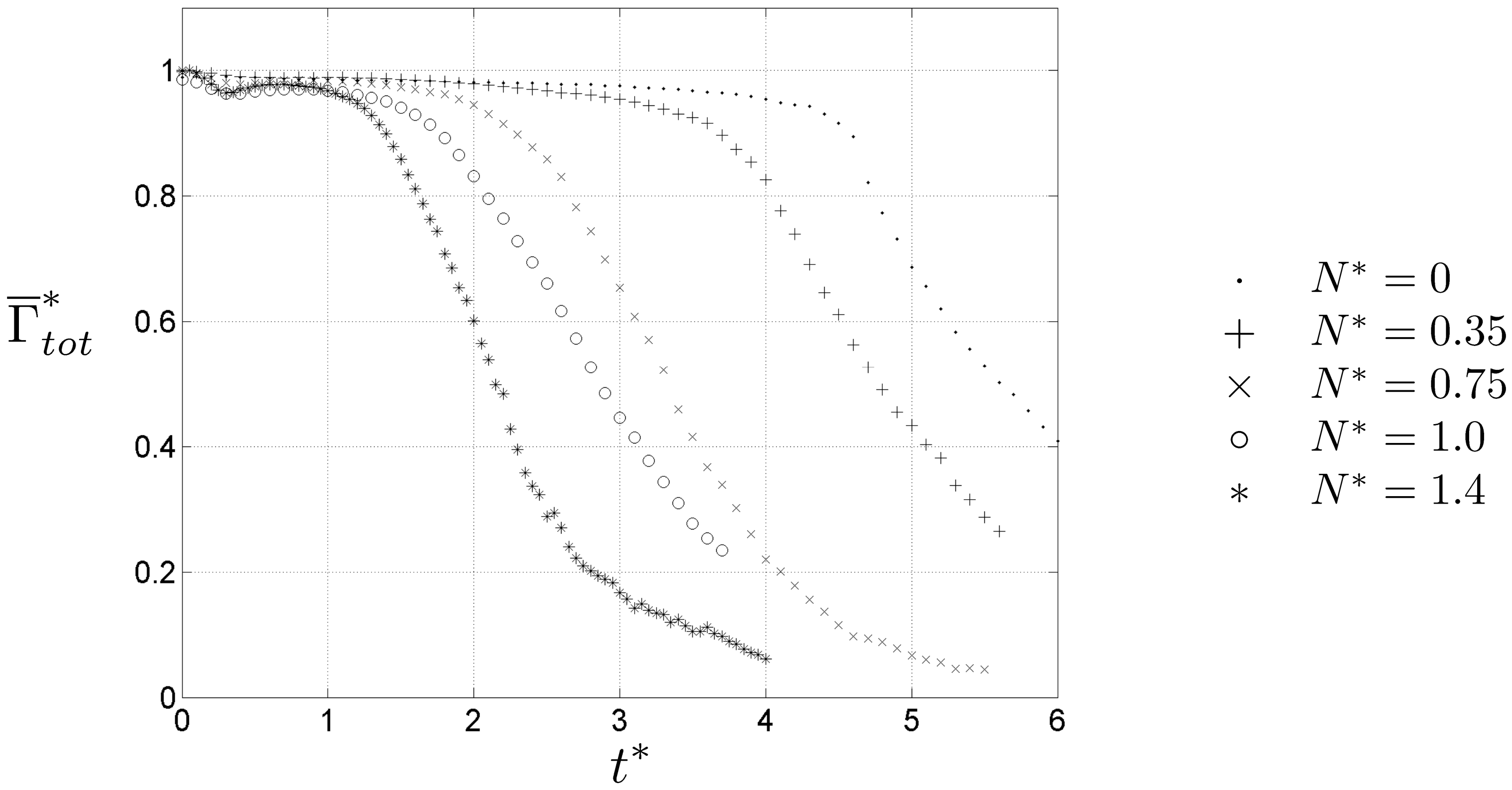


$$\frac{d\Gamma^*_{tot}}{dt^*} = \begin{cases} -\frac{c_1}{t^*_{d,S}}\Gamma^*_{tot} & \text{if } t^* \leq t^*_d \\ -\frac{c_2}{t^*_\Gamma}\Gamma^*_{tot} & \text{if } t^* \geq t^*_d \end{cases} \quad \text{with} \quad t^*_\Gamma = \begin{cases} t^*_{d,S} & \text{if } N^* = 0\,, \\ \sqrt{t^*_{d,S}\, t^*_N} & \text{otherwise.} \end{cases}$$

$$\begin{cases} c_1 & = & 0.035 \\ c_2 & = & 2.75 \\ t^*_N & = & 3.0 \end{cases}$$

Additional slow decay due to stratification

In the first decay phase, a very slow decay is observed



$$\left.\frac{d\Gamma^*_{tot}}{dt^*}\right|_{str} = (1-\beta_{str})\,(\alpha_{str}\,N^*)^2\,(z^*-h^*_0)$$

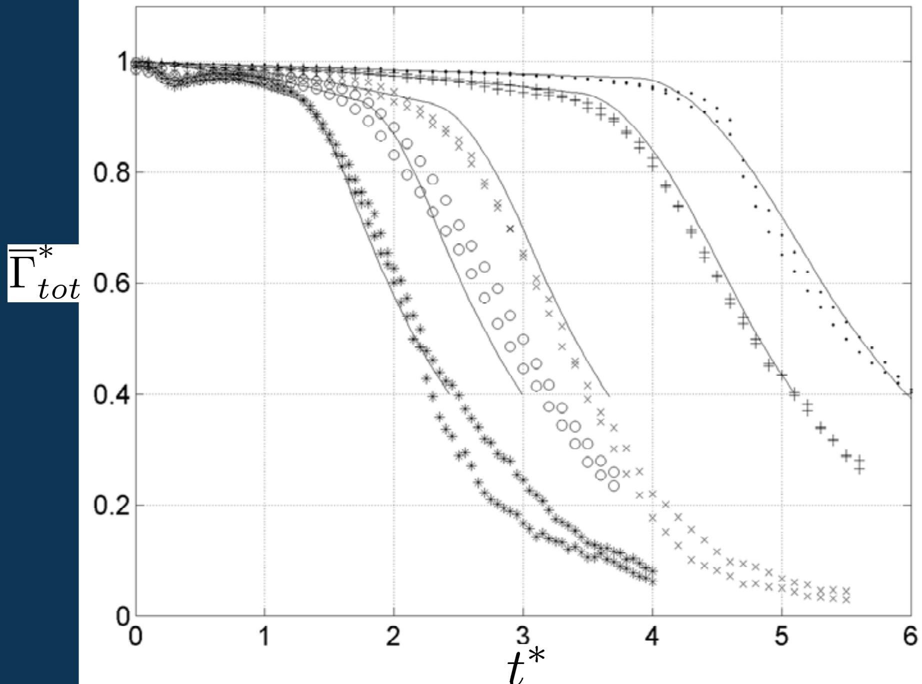
$$\frac{dv^*_{str}}{dt^*} = -\beta_{str}\,(\alpha_{str}\,N^*)^2\,(z^*-h^*_0) - C\,v^*_{str}$$

$$\begin{cases} \beta_{str} = 0.93 \\ \alpha_{str} = 0.83 \end{cases}$$

Comparison with LES data

Longitudinally-averaged circulation evolution

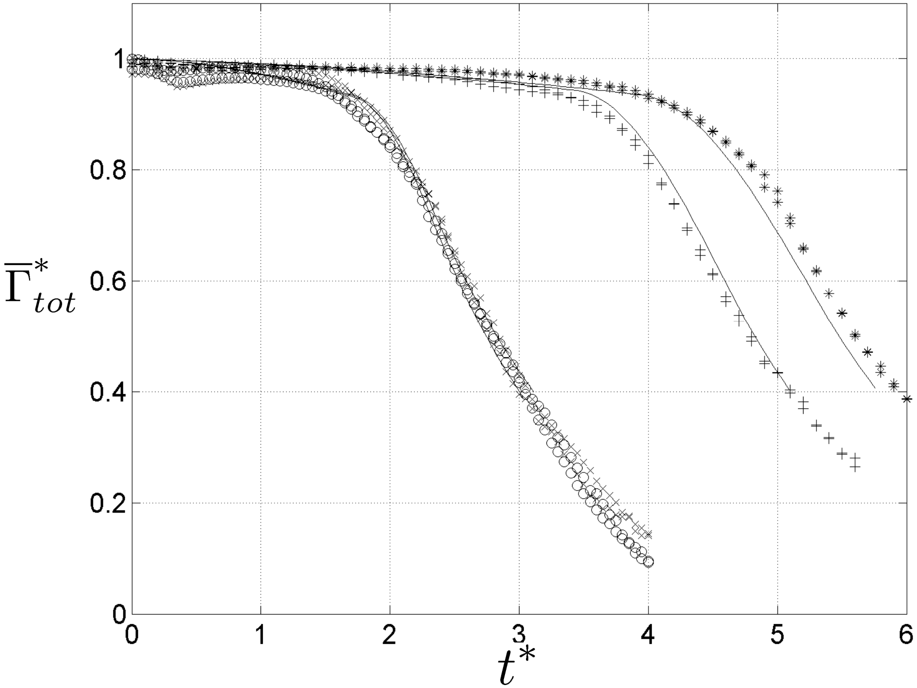
Stratification effect



	N^*
$\cdot$	0
$+$	0.35
$\times$	0.75
$\circ$	1.0
$*$	1.4

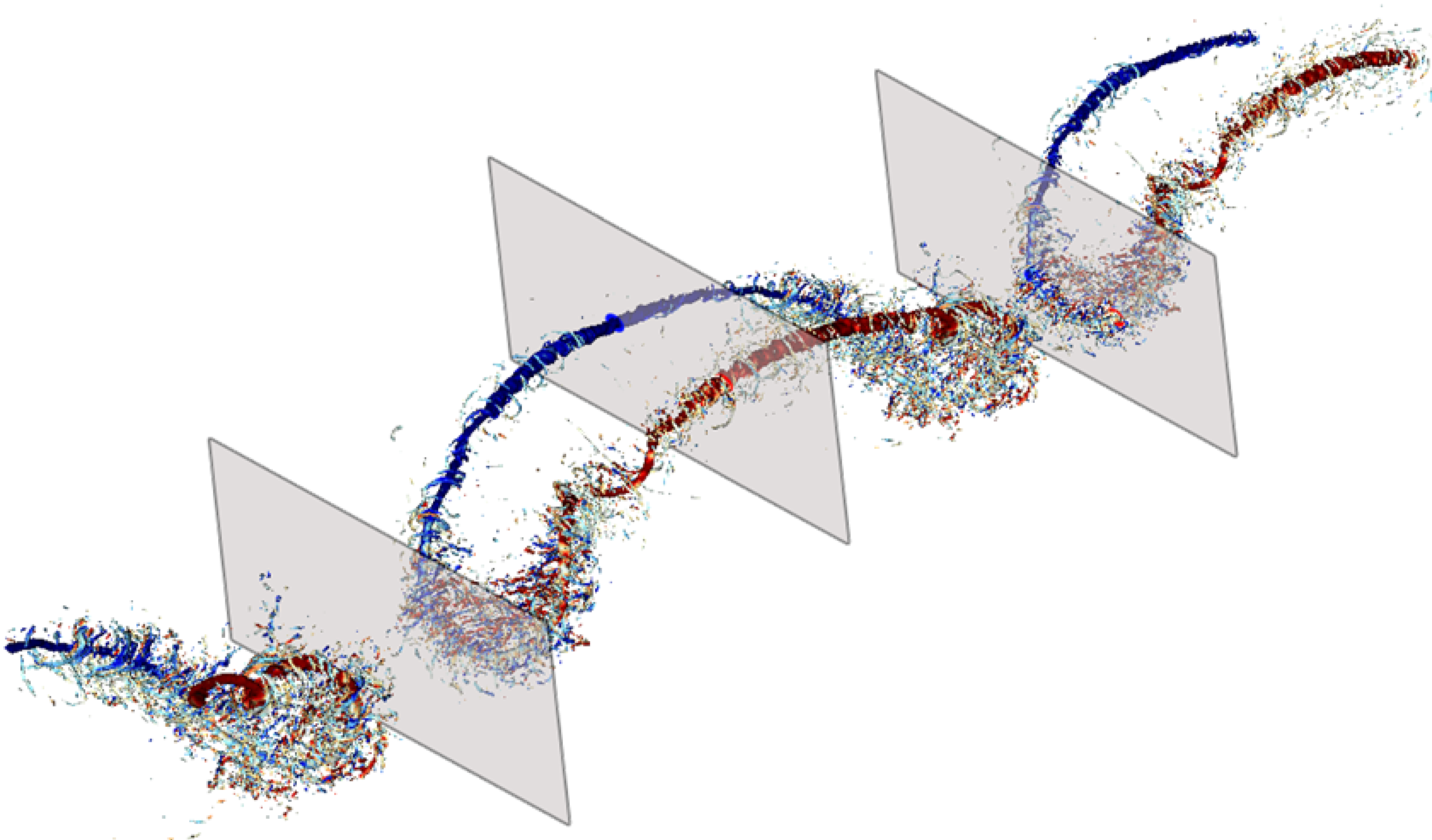
$$\epsilon^* = \frac{\epsilon\, b_0}{V_0^3} = 2.42\, 10^{-4}$$

Stratification and turbulence effects

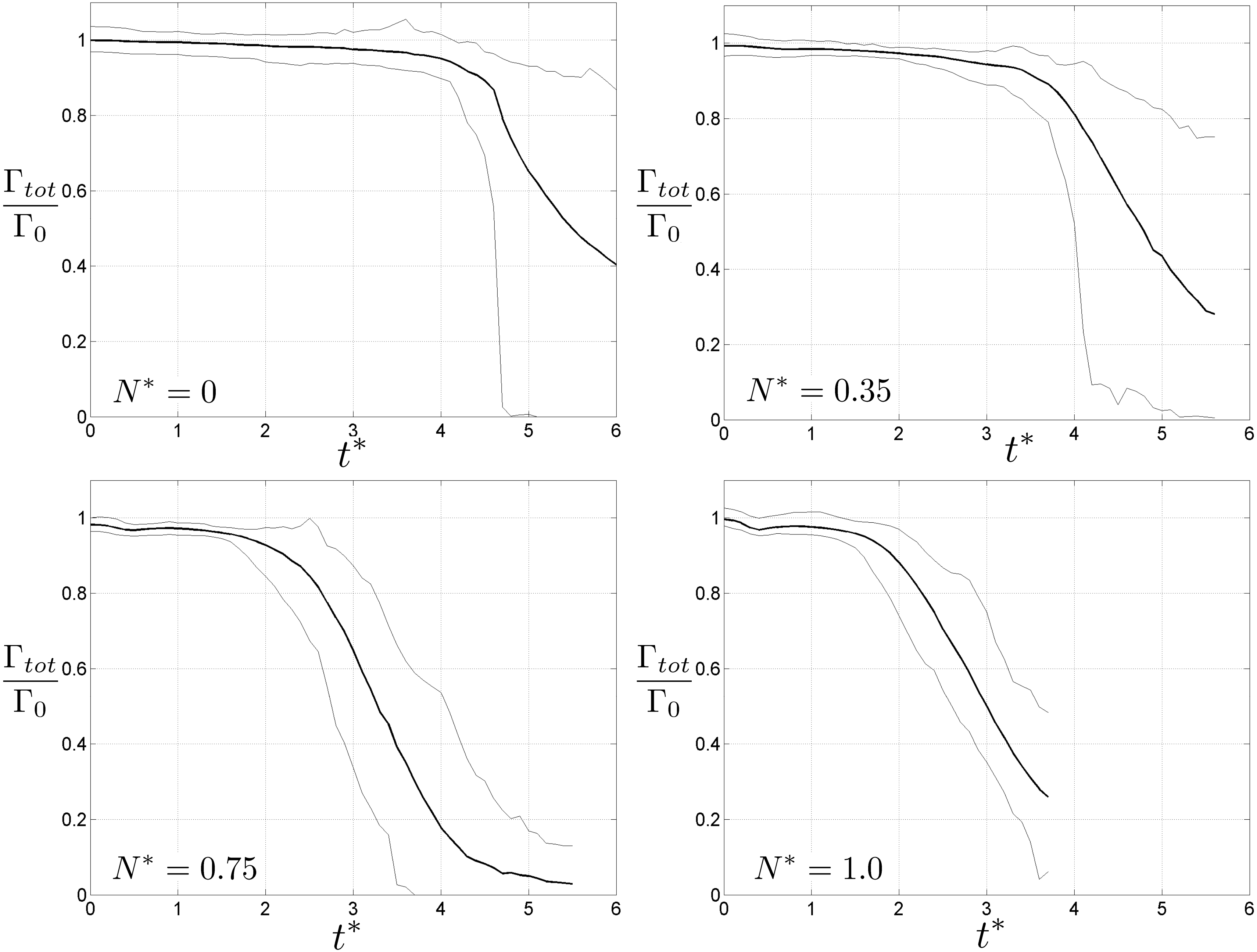


	N^*	ϵ^*
$*$	0.35	$2.42\, 10^{-5}$
$+$	0.35	$2.42\, 10^{-4}$
$\times$	1.0	$2.42\, 10^{-5}$
$\circ$	1.0	$2.42\, 10^{-4}$

Evaluation of the vortex properties in various cross-planes



Comparison of the mean and 95%-envelope circulation evolution



Vortex decay

- For low stratification levels:
  - the decay is non uniform along the vortex
  - All planes exhibit a two-phase decay with different fast decay rates
  - Second phase due to Crow linking and stratification

- For high N*:
  - The decay is much more uniform
  - Two-phase decay with almost uniform decay rate

- The model coefficients could be adapted, to be used in the PVM, to also predict the envelope behavior

  => The DVM model coefficient distribution would then be a function of the stratification level

Conclusions

- An improved IGE model was developed and integrated in the DVM
  - The model uses less particles. Hence, it is more efficient
  - Moreover, the quality of the model was improved
- An improved model of the effects of atmospheric turbulence and stratification was also developed
  - The altitude evolution model correctly reproduces the LES data
  - The new time-to-demise model takes into account the influence of both turbulence and stratification
  - The 2-phase decay model correctly reproduces the LES data
- Those new models are integrated in the DVM/PVM/WAKE4D so that it is more accurate and more efficient
- Moreover, the PVM can now use OPENMP to perform DVM runs in parallel on the different cores of a PC.

  => gain of another factor of 4 for a PC with 4 cores.