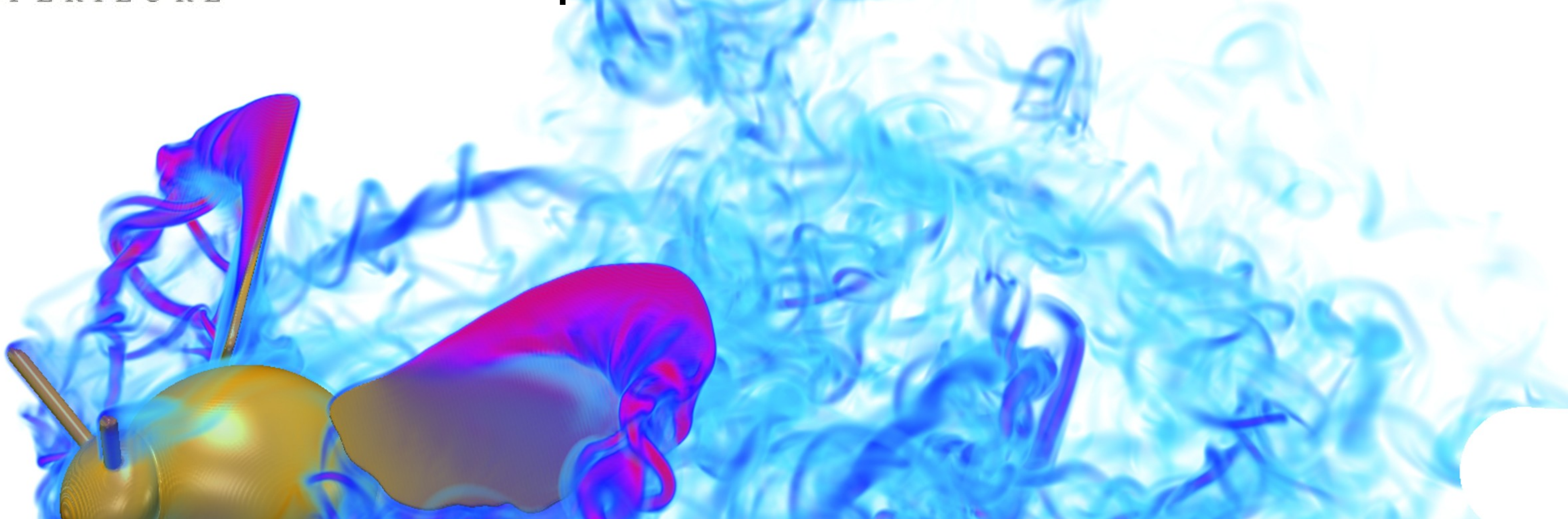
Progress with the adaptive code

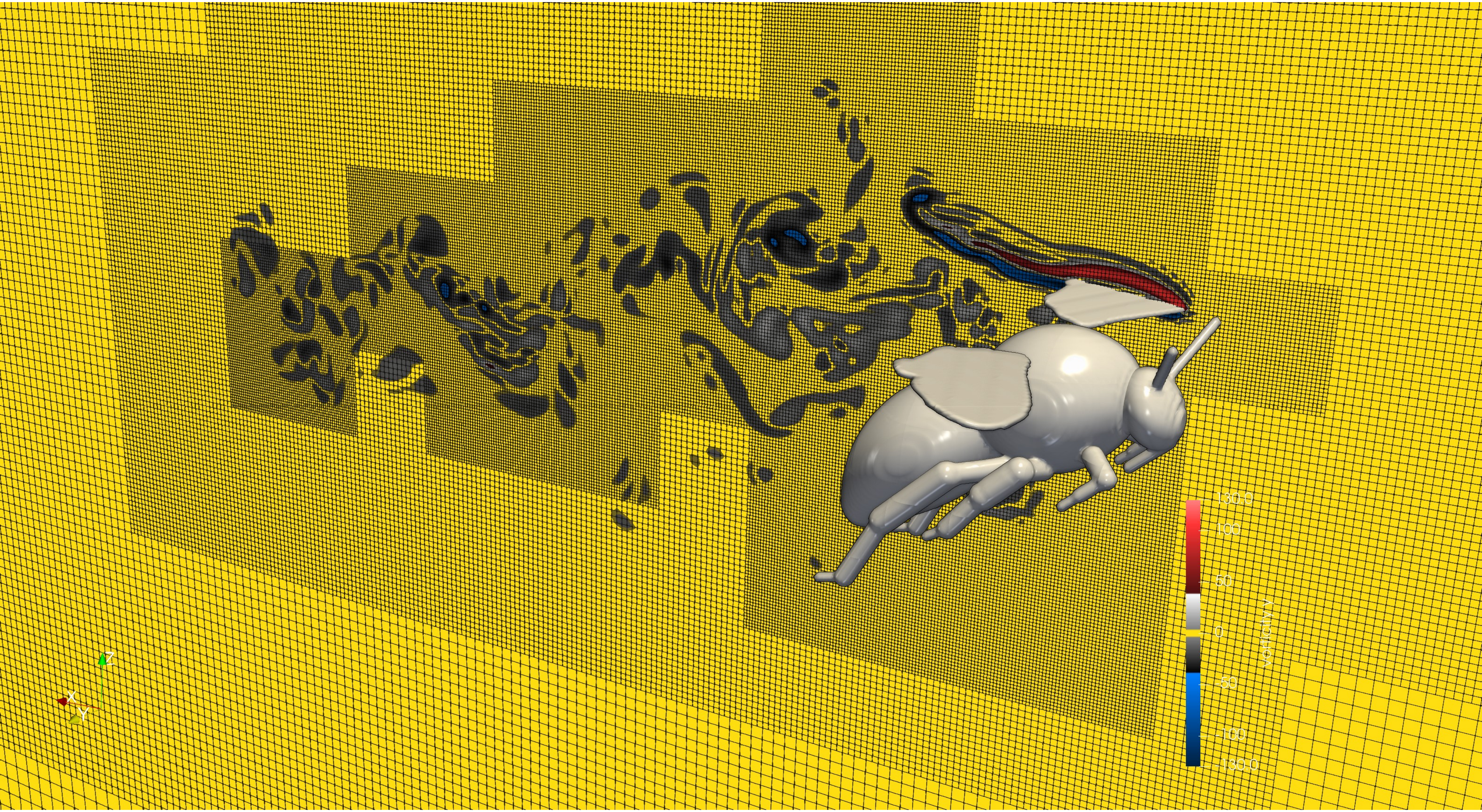
Thomas Engels

LMD UMR 8539
École Normale Supérieure

http://aifit.cfd.tu-berlin.de

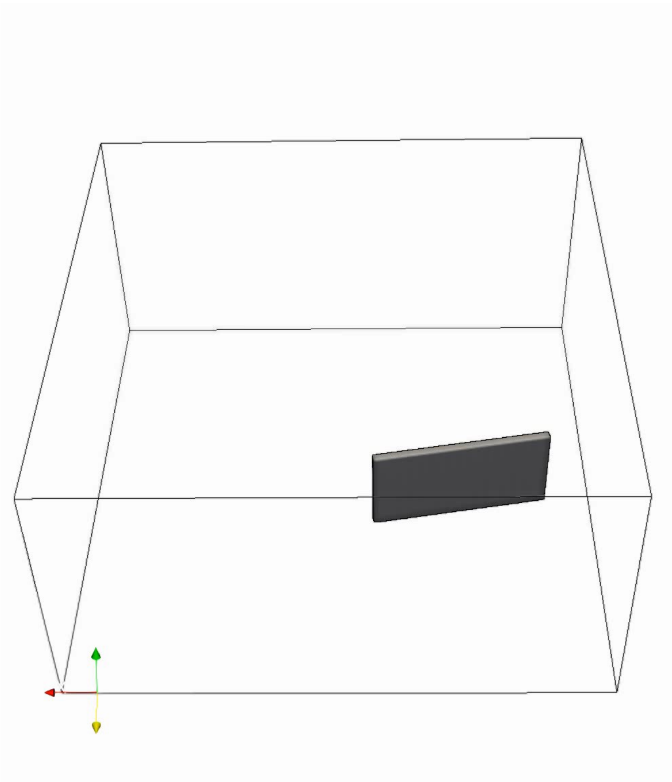


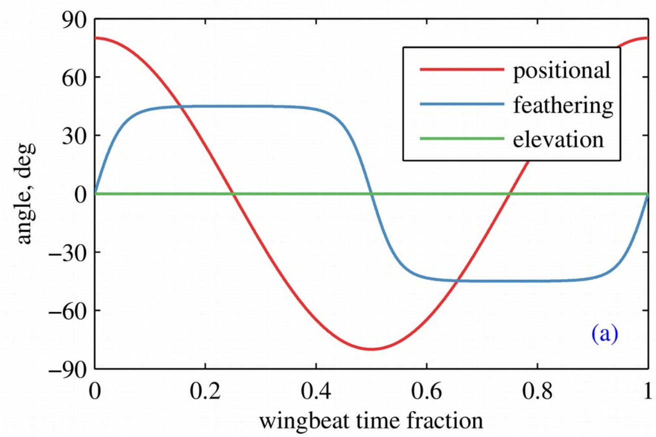
New adaptive solver

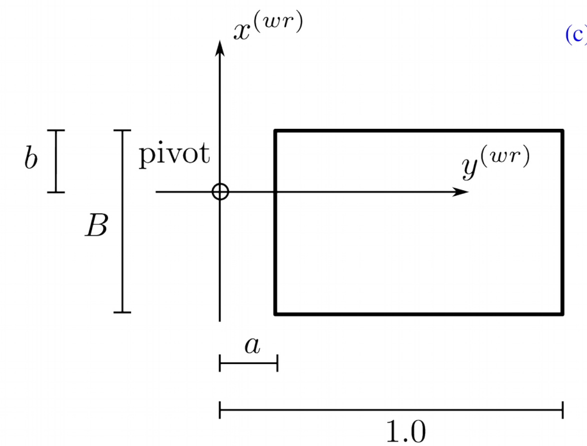


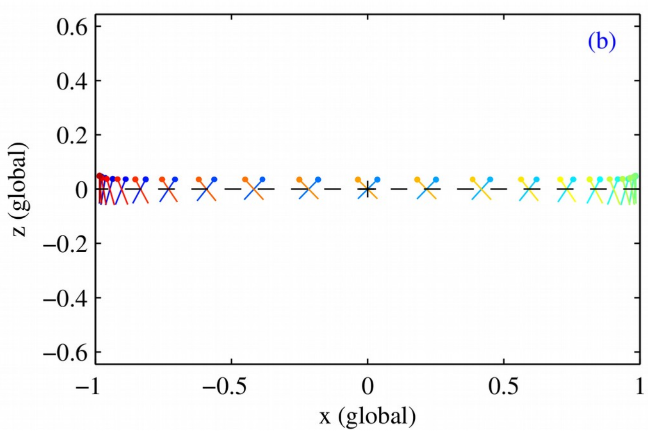
Suzuki test case

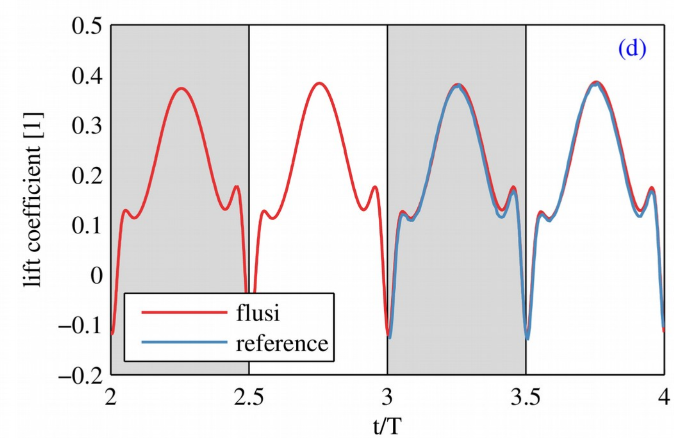
Rectangular wing, finite thickness, Re = U_tip * B / nu = 100 (very viscous)

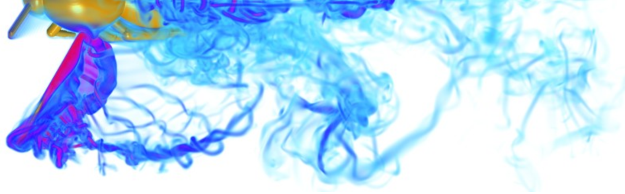




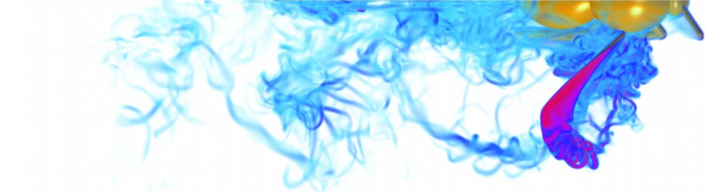








Flusi solution



Some key numbers for the Fourier solution of the problem: these are the numbers we're used to. The Flusi solution:

- Equidistant grid
- Domain size: 3 x 3 x 3R, rather small
- Perfectly incompressible fluid

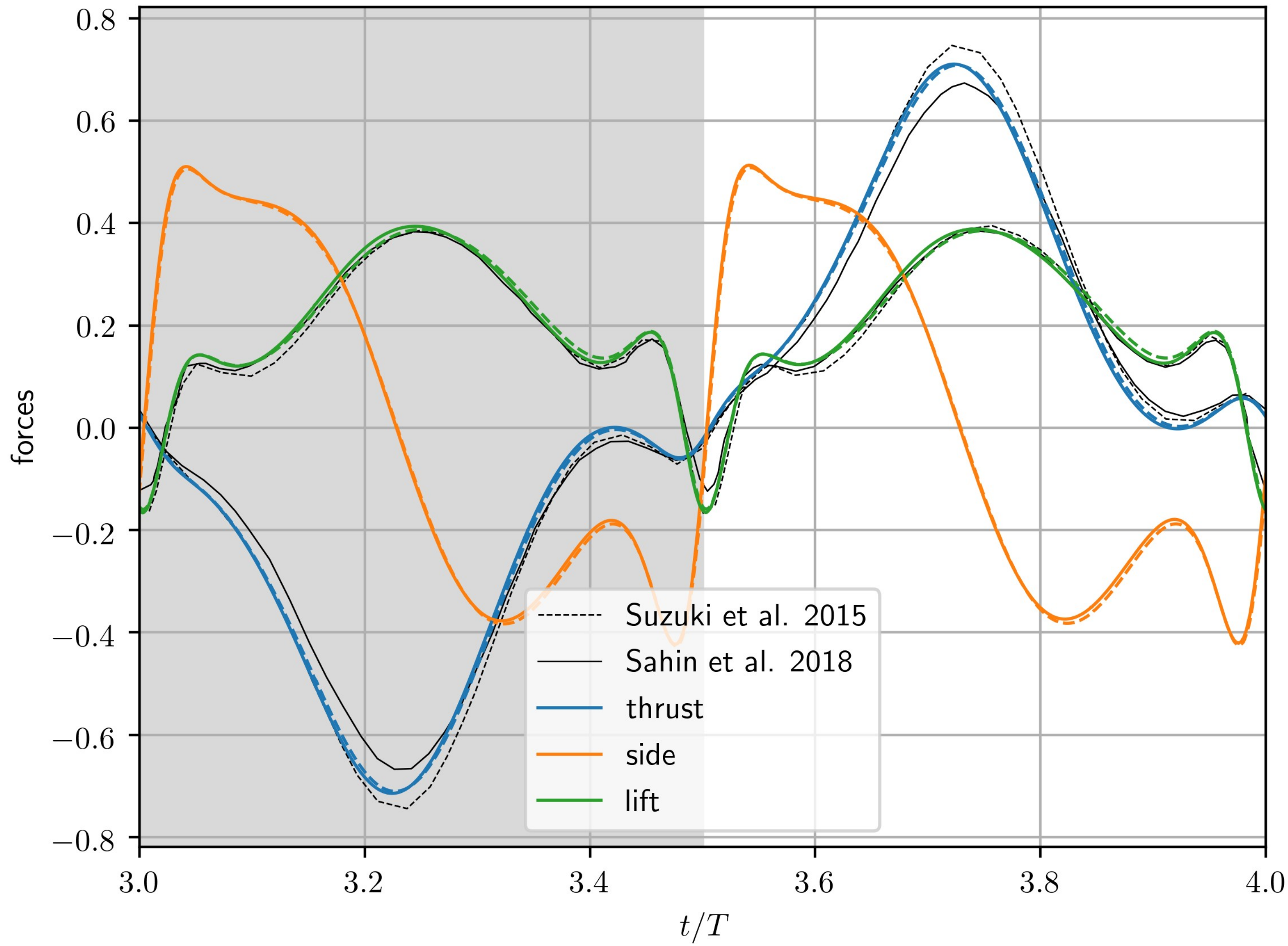
We performed two simulations:

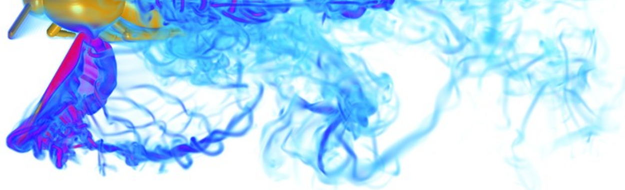
- 512 x 512 x 512, C_eta=1.25e-4, Nt=34 881,
  cost: 5709 CPUh on 1024 cores, memory 25 GB
  walltime: 5.5h
- 1024 x 1024 x 1024, C_eta=3.125e-5, Nt=59 240,
  cost: 147k CPUh on 4096 cores, memory 200 GB
  walltime: 36.4h + 16h waiting

Fourier solutions have remarkable CPU efficiency (FLOP/Mbyte) and can be highly parallelized

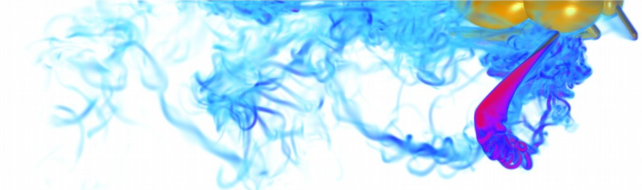
Flusi solution

Comparison of forces for 512 (- -) and 1024 (–) with Suzuki et al. 2015 and Sahin et al. 2018





Wabbit solution

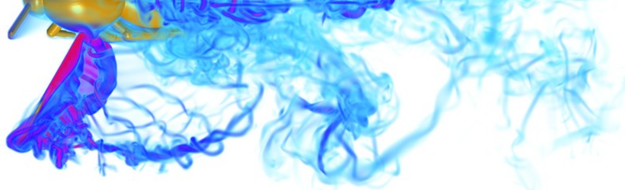


- We use the method of artificial compressibility (ACM) with a finite pseudo-speed of sound c0

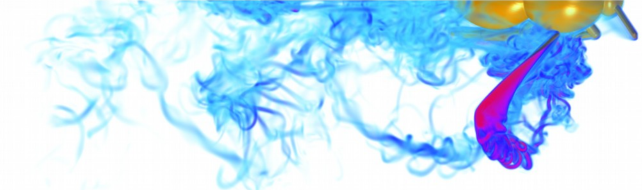
$$\partial_t \underline{u} = -\left(\underline{u}\cdot\nabla\right)\underline{u} - \nabla p + \nu\nabla^2\underline{u} - \frac{\chi}{C_\eta}\left(\underline{u}-\underline{u}_s\right) - \frac{\chi_{\mathrm{sp}}}{C_{\mathrm{sp}}}\left(\underline{u}-\underline{u}_\infty\right) \quad (1)$$

$$\partial_t p = -c_0^2\nabla\cdot\underline{u} - \gamma p - \frac{\chi_{\mathrm{sp}}}{C_{\mathrm{sp}}}\left(p-p_\infty\right). \quad (2)$$

- The traditional volume penalization method (red) is combined with a non-reflecting sponge term (blue) that removes the periodicity.
- Our computational approach is to use blocks of the same size (Bs^D)
- Parameters:
  - Speed of sound c_0
  - Porosity (penalization) c_eta
  - Maximum refinement level J
  - Multiresolution threshold epsilon
- Impulsively started motion, p=0 at the beginning
- RK4 replaced by 3rd order RK4 (Ralstons scheme) → cost neutral

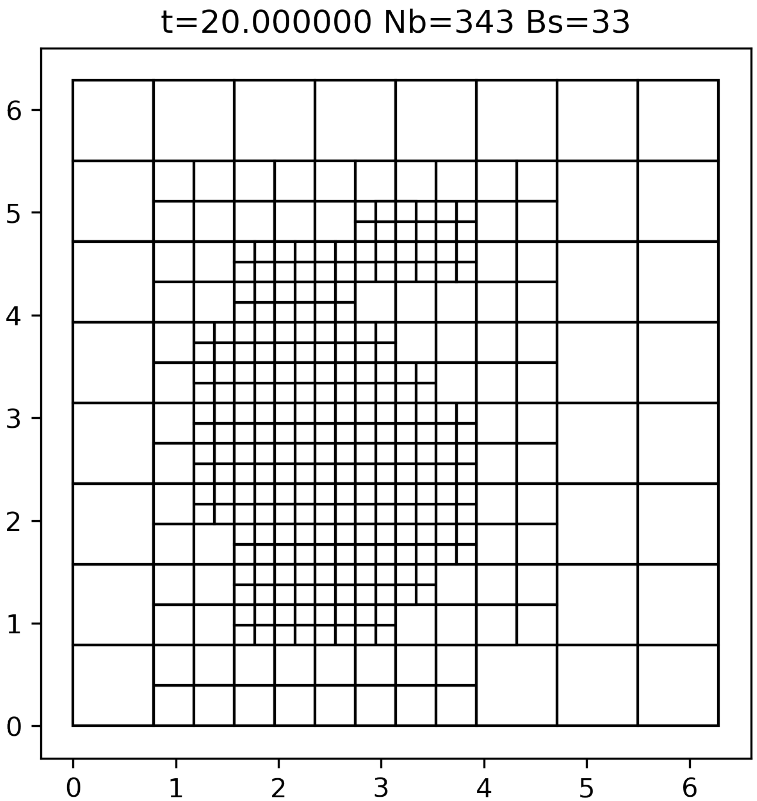


Influence of eps

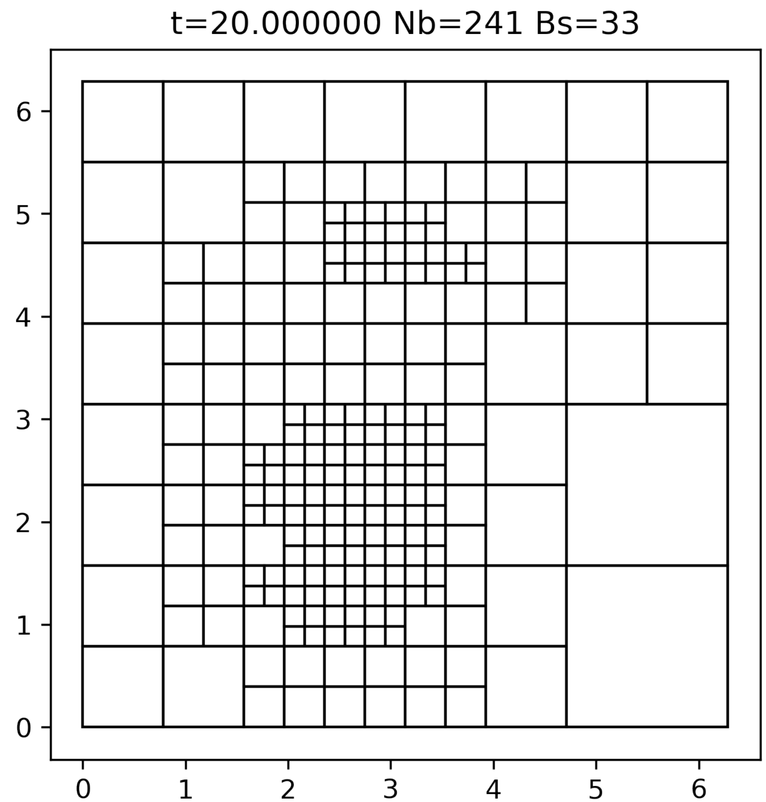


Eps controls how many fine details are retained in the representation

Eps=5e-6



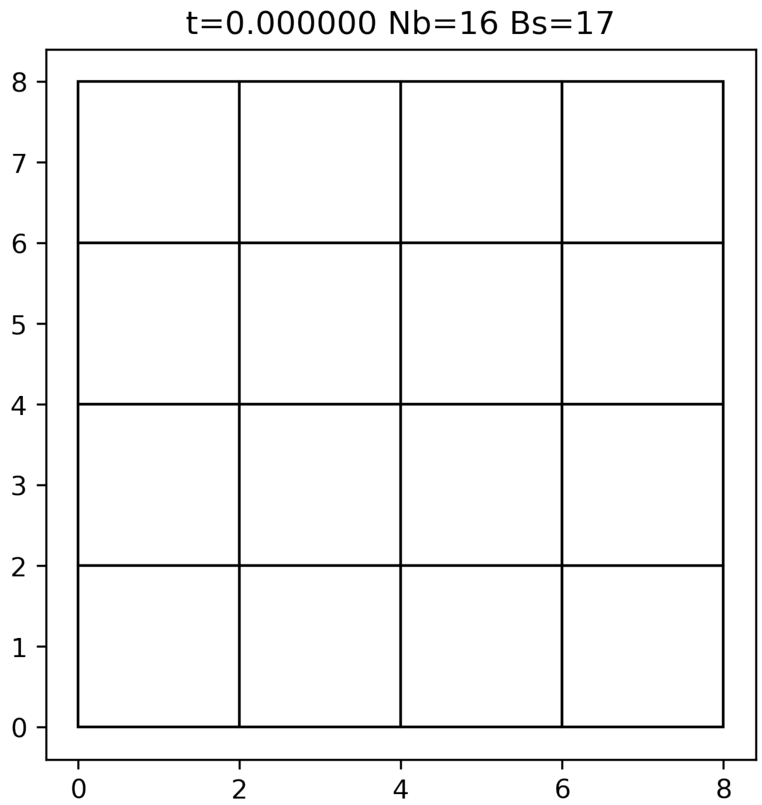
Eps=1e-4



Visualization of J

Visualization of the influence of J for a 2D cylinder flow.

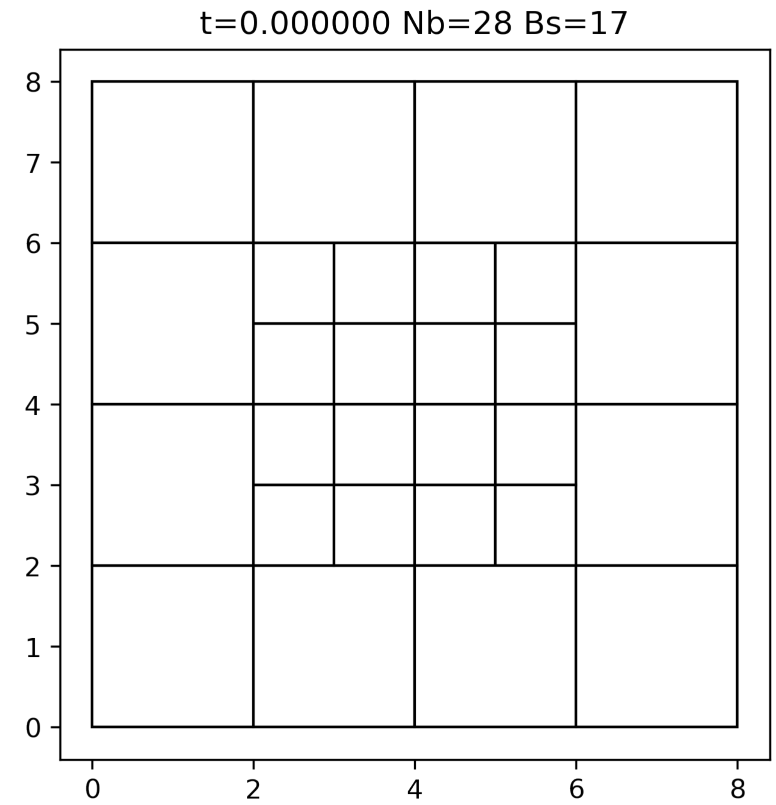
J=3



Visualization of J

Visualization of the influence of J for a cylinder flow.

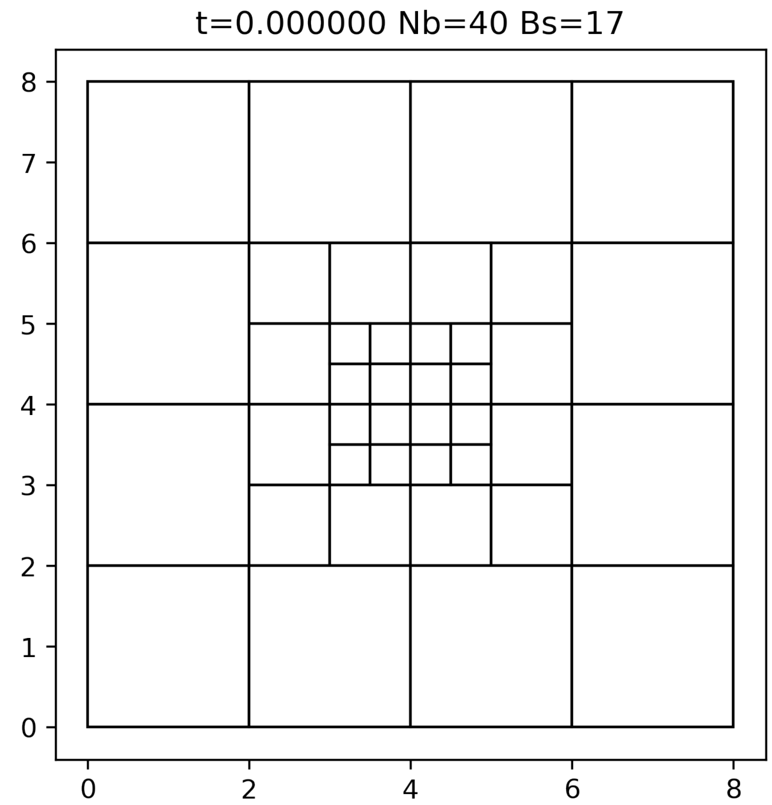
J=4



Visualization of J

Visualization of the influence of J for a cylinder flow.

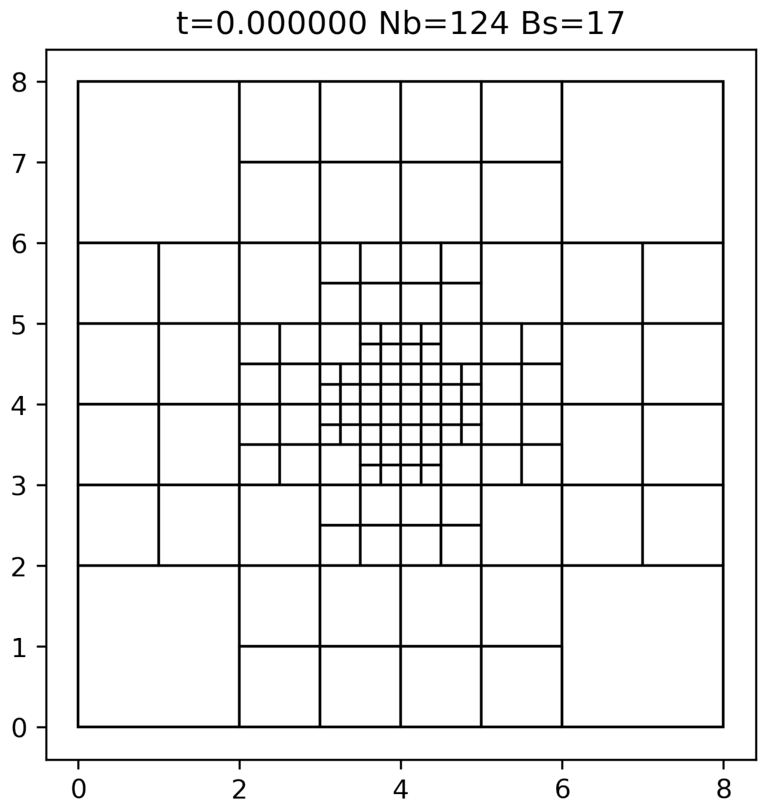
J=5



Visualization of J

Visualization of the influence of J for a cylinder flow.

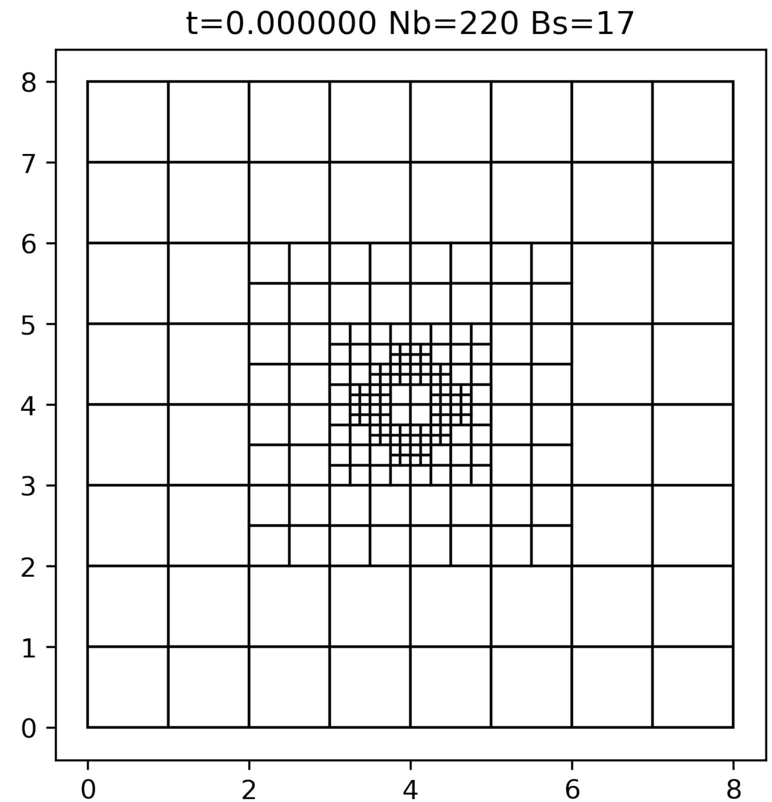
J=6



Visualization of J

Visualization of the influence of J for a cylinder flow.

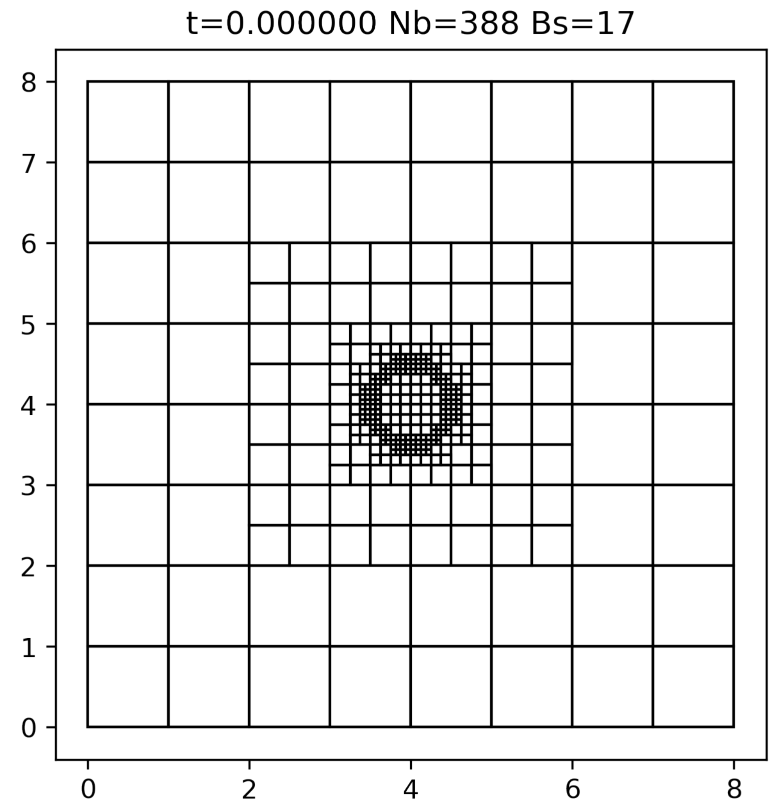
J=7



Visualization of J

Visualization of the influence of J for a cylinder flow.

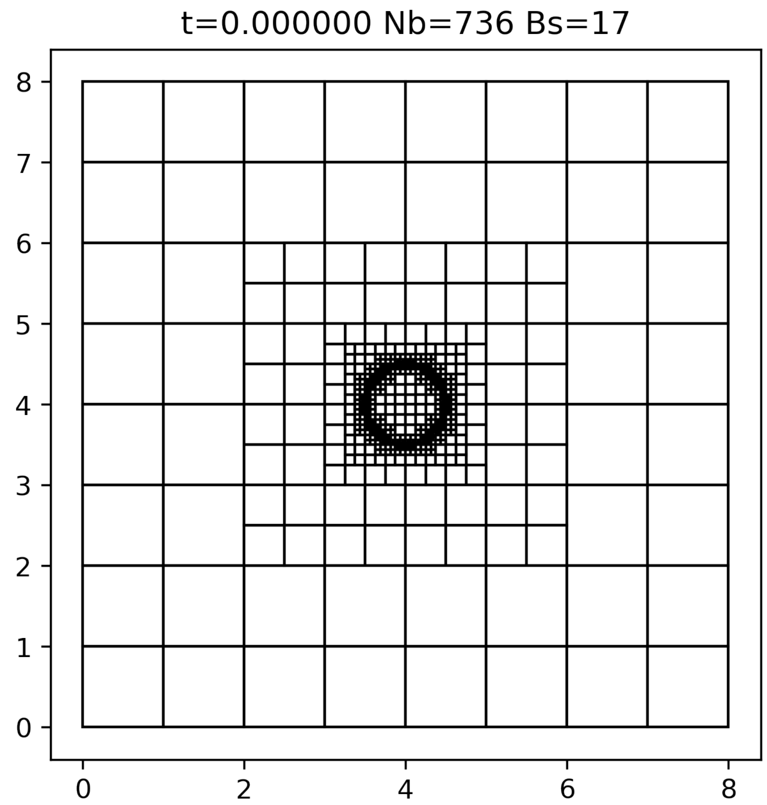
J=8



Visualization of J

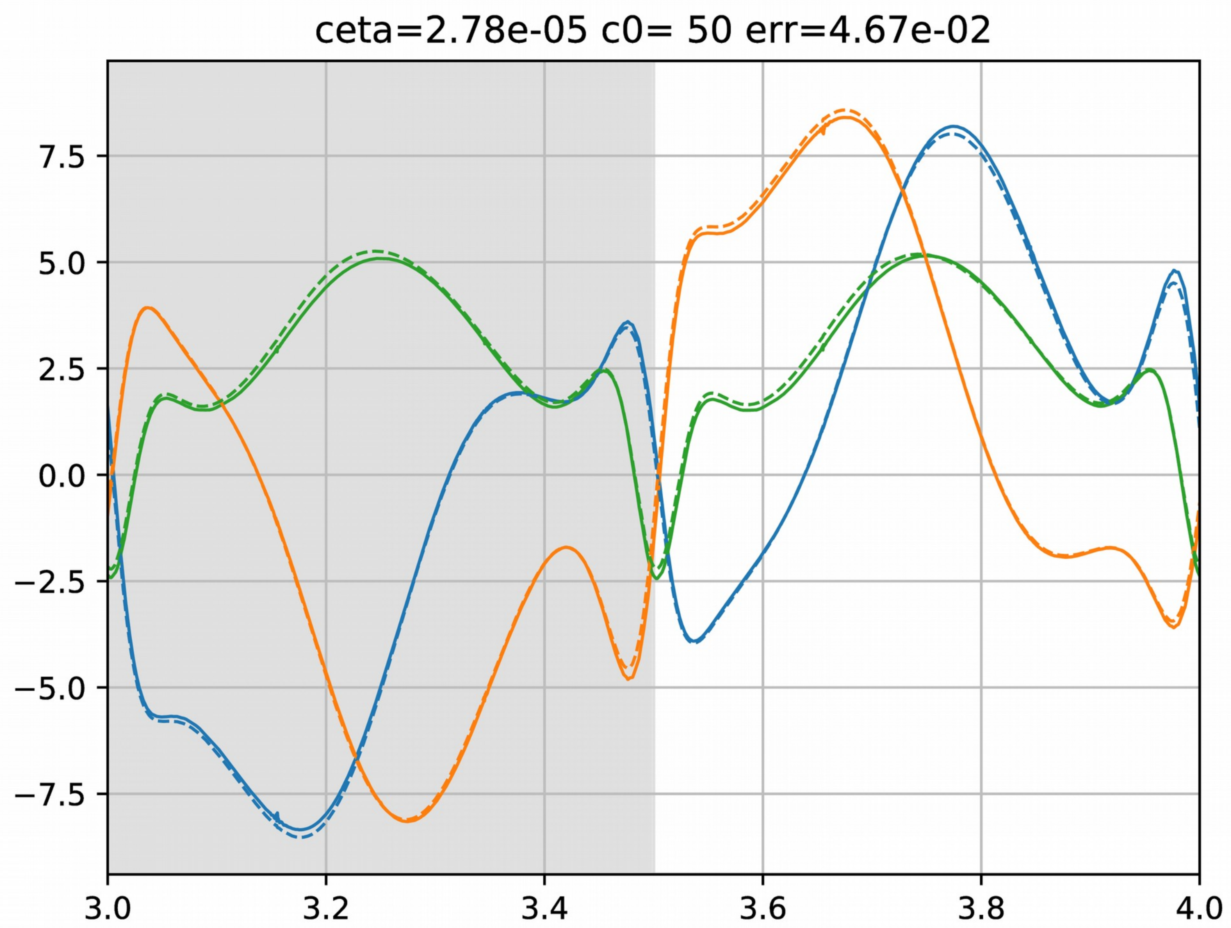
Visualization of the influence of J for a cylinder flow.

J=9

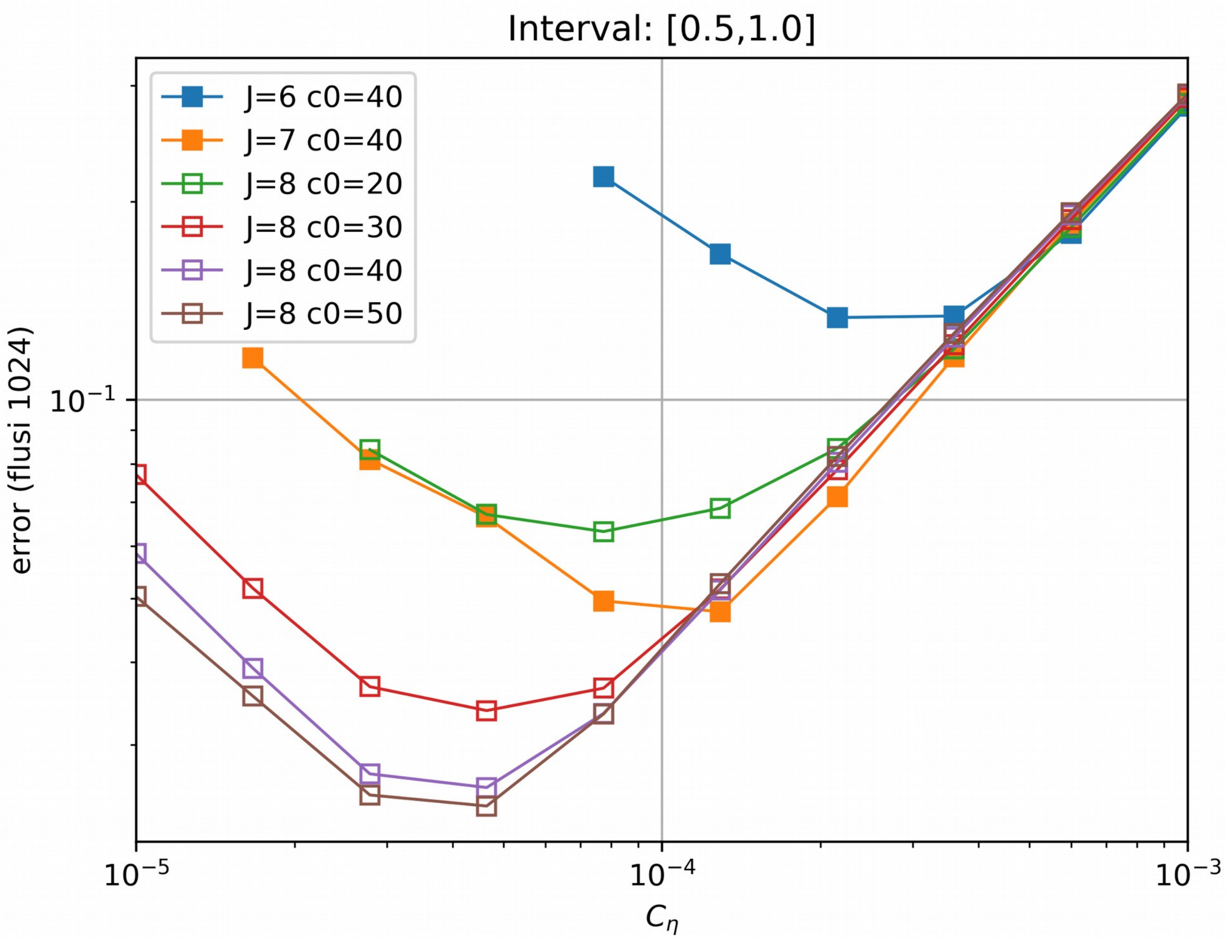


Wabbit solution (best)

- Jmax=8, c0=50 (but that does not matter) Ceta=2.78e-5
- Cost: ~10 747 CPUh on 96 cores



Wabbit convergence for suzuki



- Eps does not play a role (fixed to eps0=1e-3 here) → no turbulence
- The reference is the flusi 1024 solution because I trust it the most
- Error is computed:

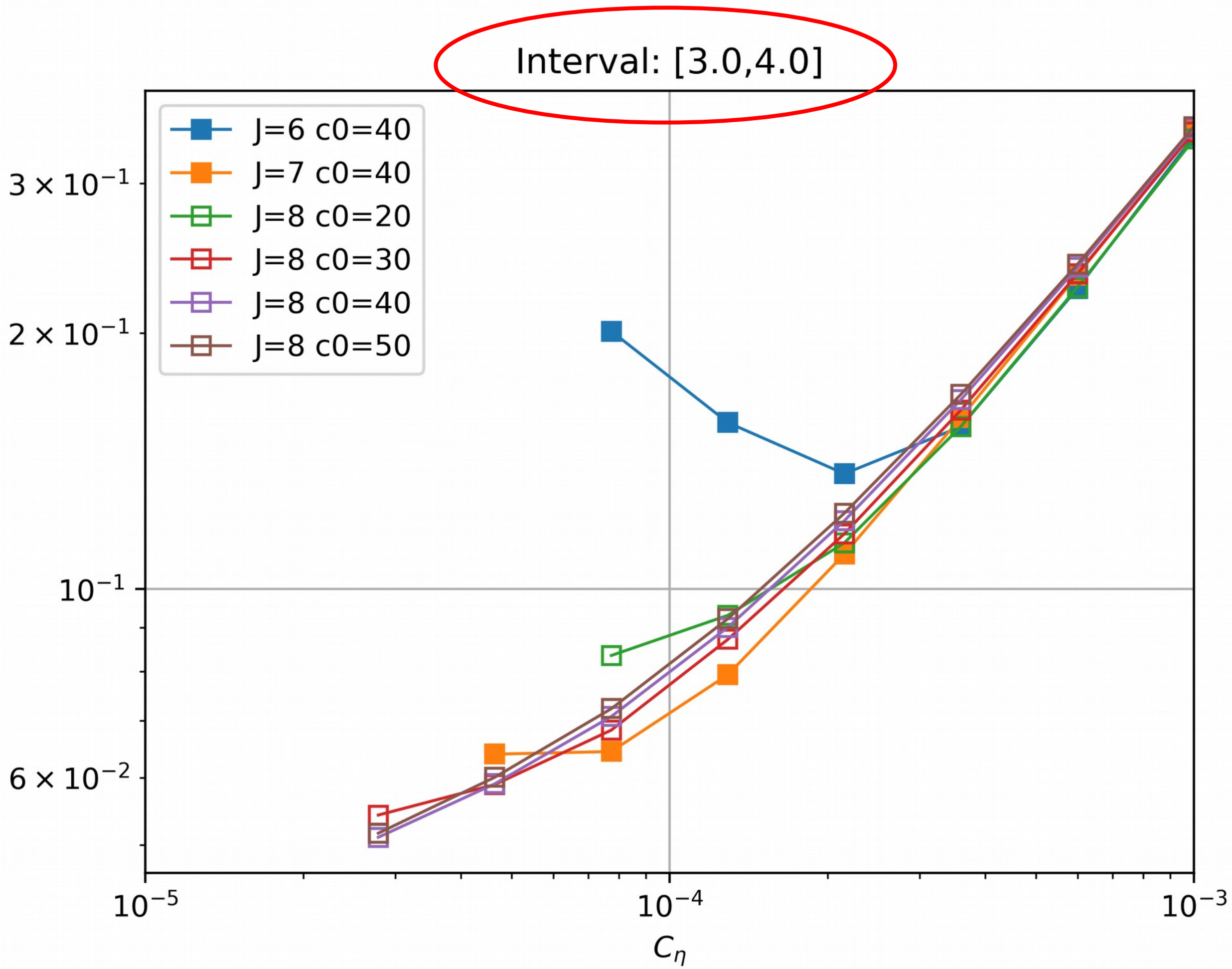
$$e_i = \frac{\int_{T0}^{T1} |f_i - f_{i,ref}|\, dt}{\int_{T0}^{T1} |f_{i,ref}|\, dt}$$

$$e = \sqrt{\sum_{i=1}^{3} e_i}$$

The interval is subject to changes as some simulations are still running.

- J=6: minimum, then error increases again (loss of regularity). For J=8 we have different values of c0.
- J=9 is not ready yet.

Wabbit convergence for suzuki



- Eps does not play a role (fixed to eps0=1e-3 here) → no turbulence
- The reference is the flusi 1024 solution because I trust it the most
- Error is computed:

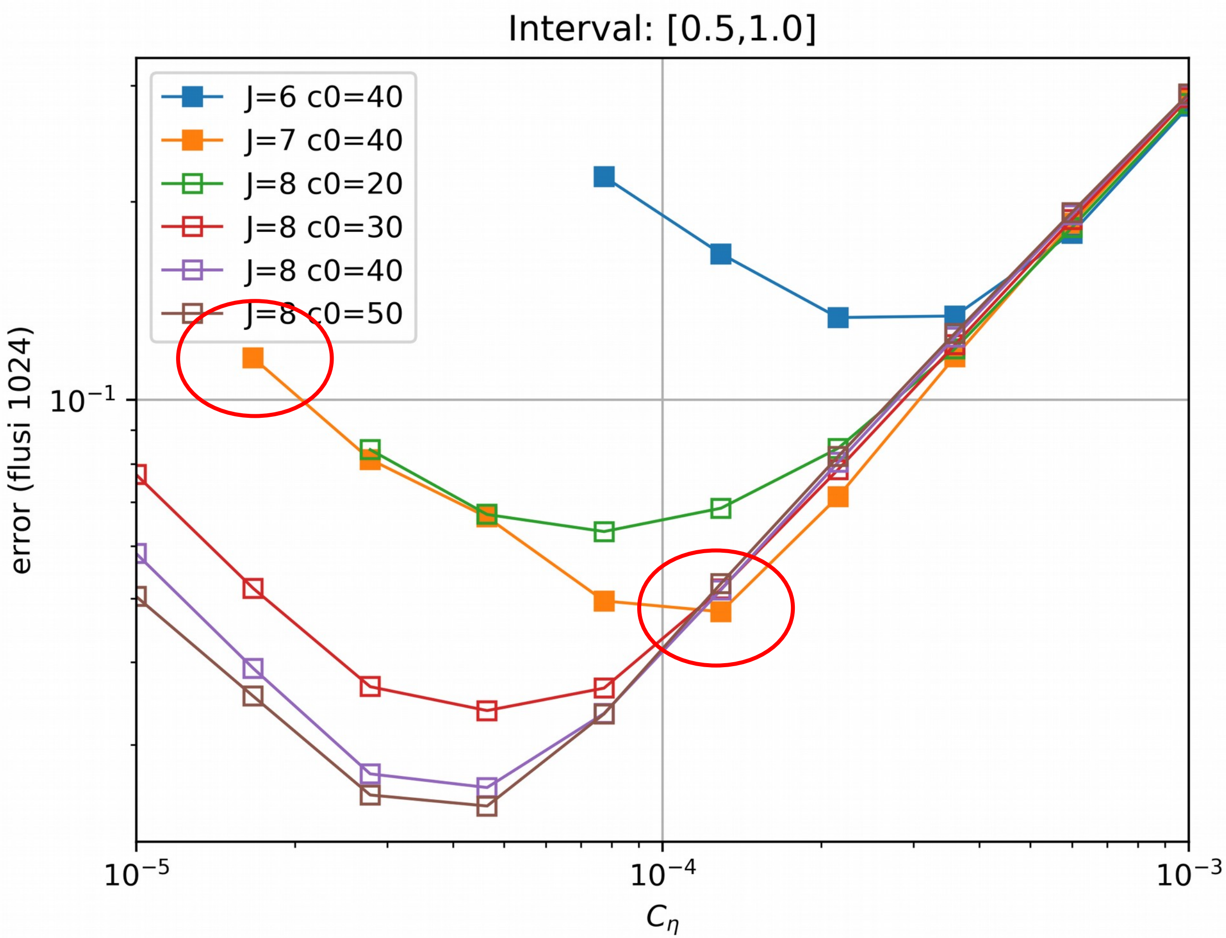
$$e_i = \frac{\int_{T0}^{T1} |f_i - f_{i,ref}| \, dt}{\int_{T0}^{T1} |f_{i,ref}| \, dt}$$

$$e = \sqrt{\sum_{i=1}^{3} e_i}$$

The interval is subject to changes as some simulations are still running.

- J=6: minimum, then error increases again (loss of regularity). For J=8 we have different values of c0.
- J=9 is not ready yet.

Wabbit convergence for suzuki



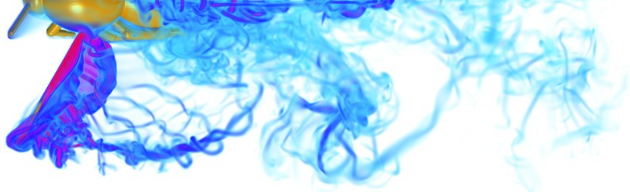
- Eps does not play a role (fixed to eps0=1e-3 here) → no turbulence
- The reference is the flusi 1024 solution because I trust it the most
- Error is computed:

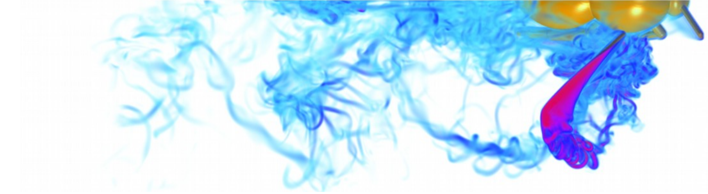
$$e_i = \frac{\int_{T0}^{T1} |f_i - f_{i,ref}|\, dt}{\int_{T0}^{T1} |f_{i,ref}|\, dt}$$

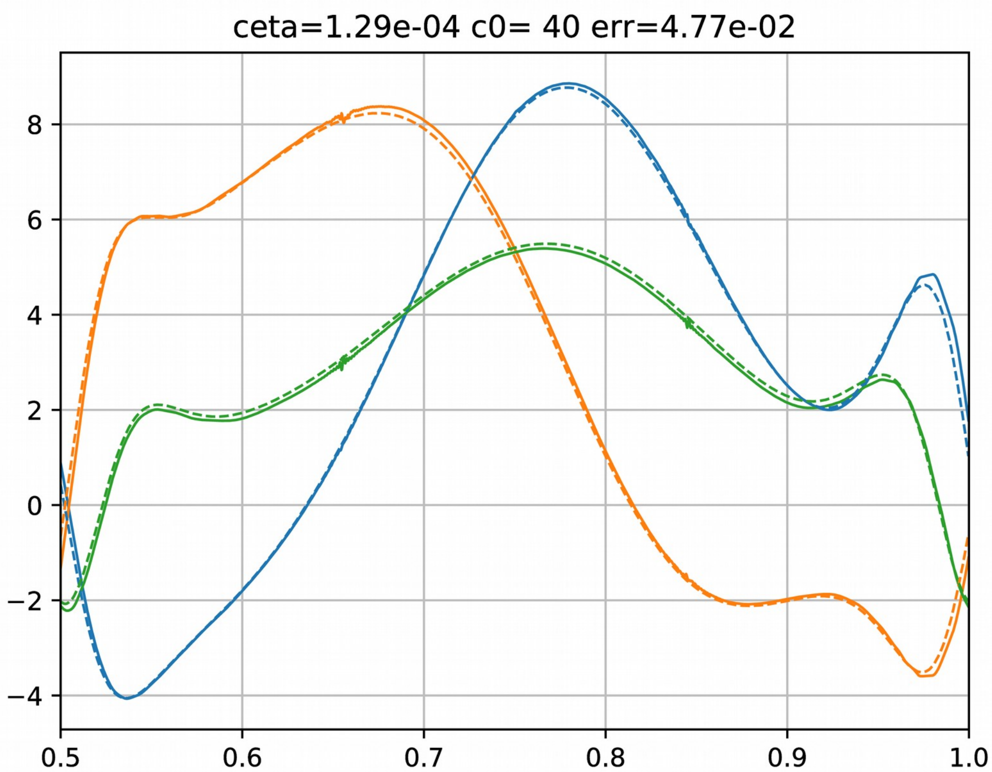
$$e = \sqrt{\sum_{i=1}^{3} e_i}$$

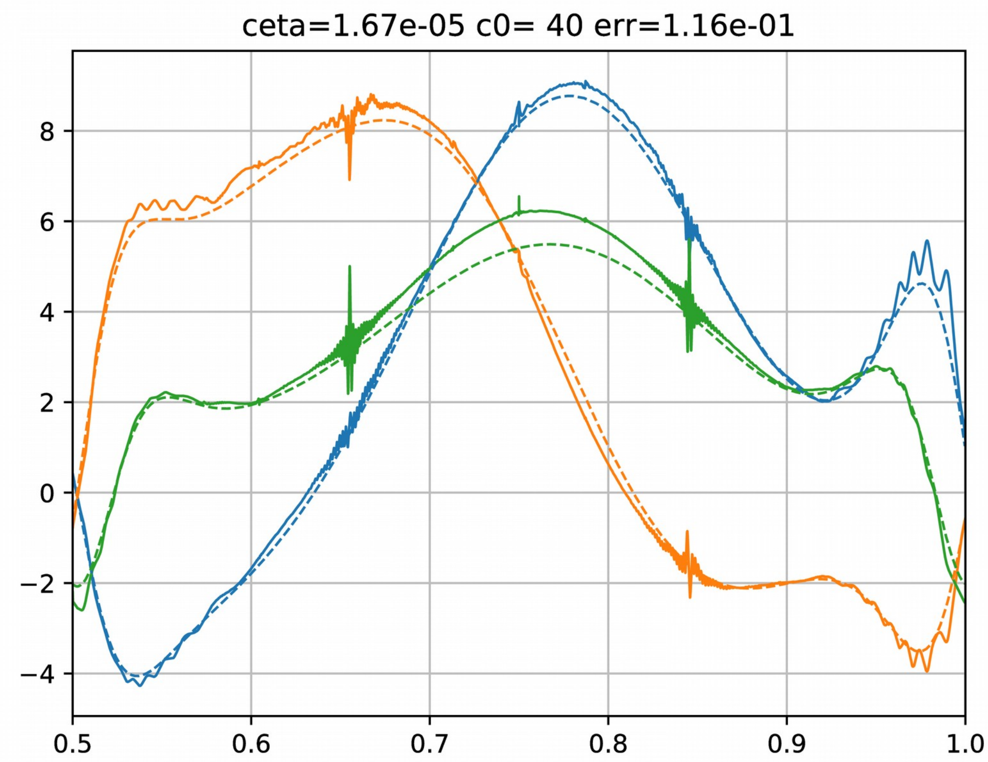
The interval is subject to changes as some simulations are still running.

- J=6: minimum, then error increases again (loss of regularity). For J=8 we have different values of c0.
- J=9 is not ready yet.



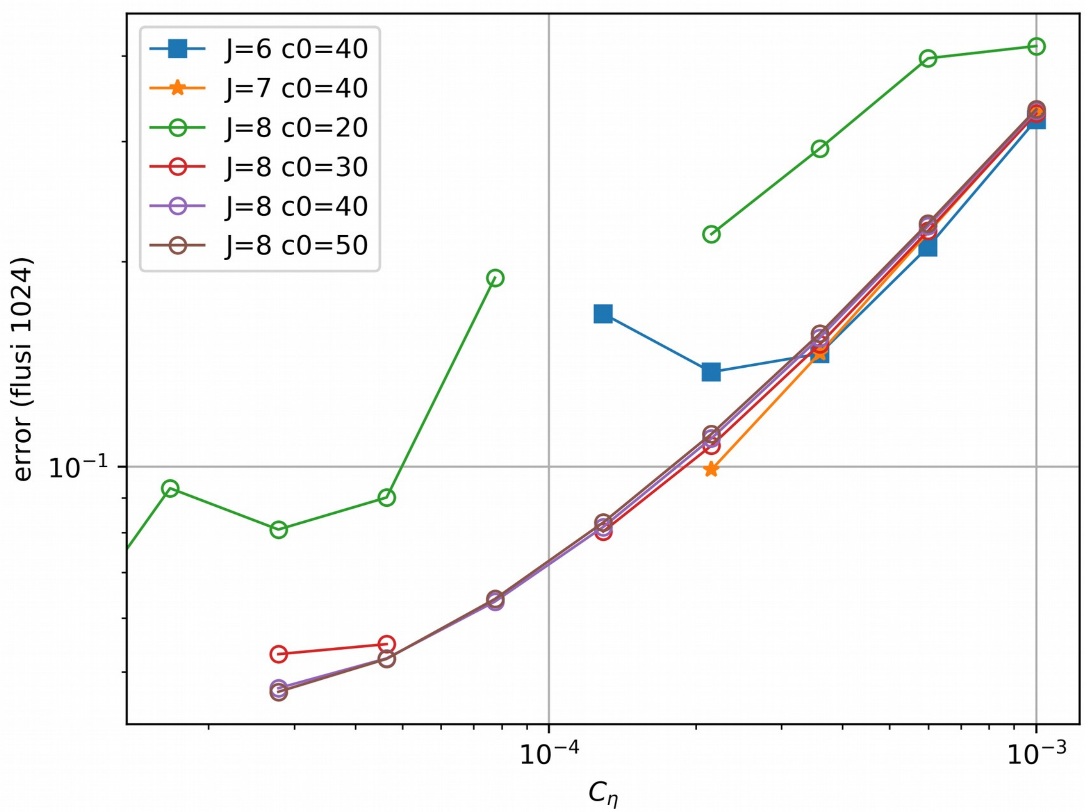



ceta=1.29e-04 c0= 40 err=4.77e-02
8
6
4
2
0
−2
−4
0.5
0.6
0.7
0.8
0.9
1.0


ceta=1.67e-05 c0= 40 err=1.16e-01
8
6
4
2
0
−2
−4
0.5
0.6
0.7
0.8
0.9
1.0

Wabbit parameter study

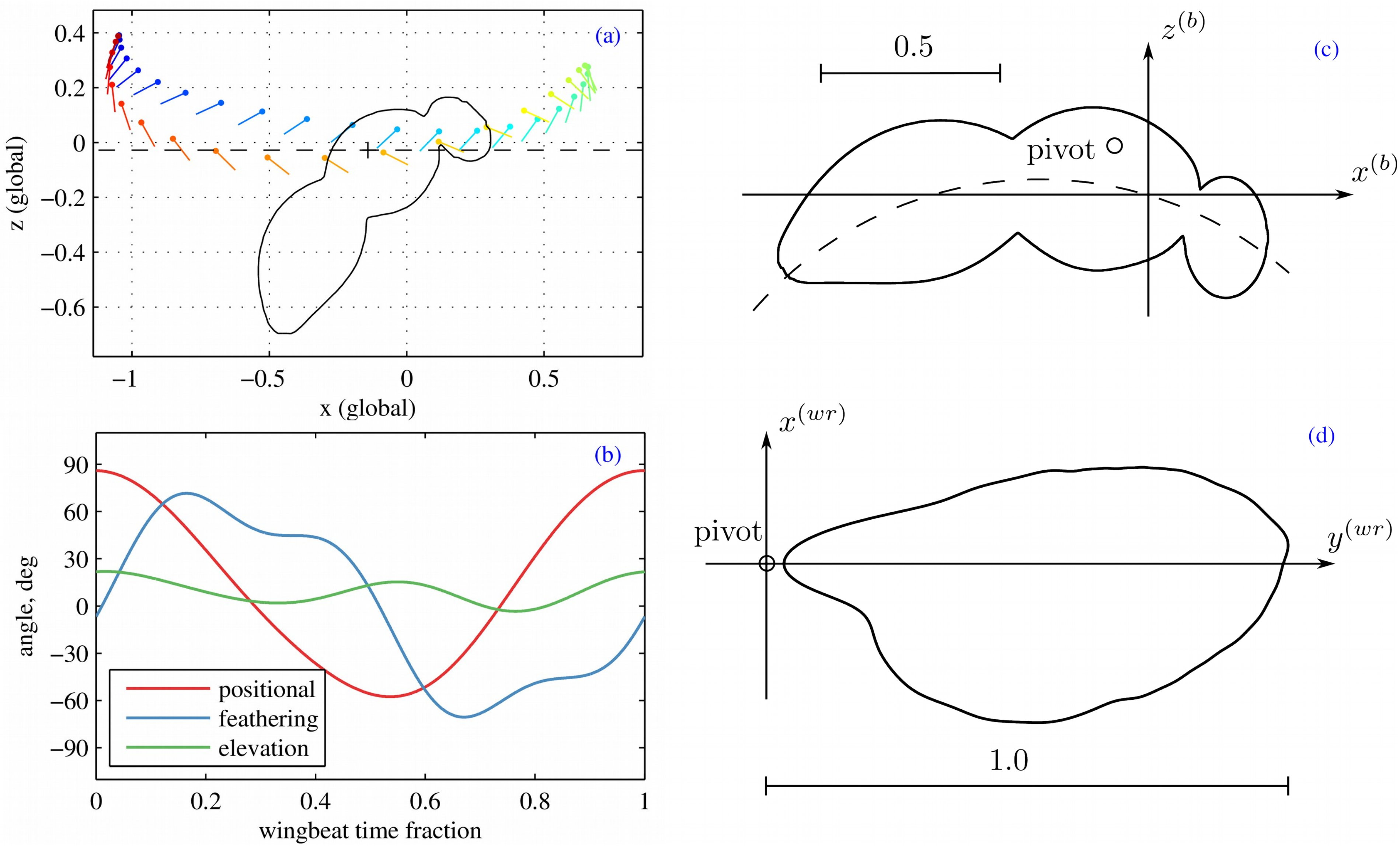
- Eps does not play a role (fixed to eps0=1e-3 here) → no turbulence



notes

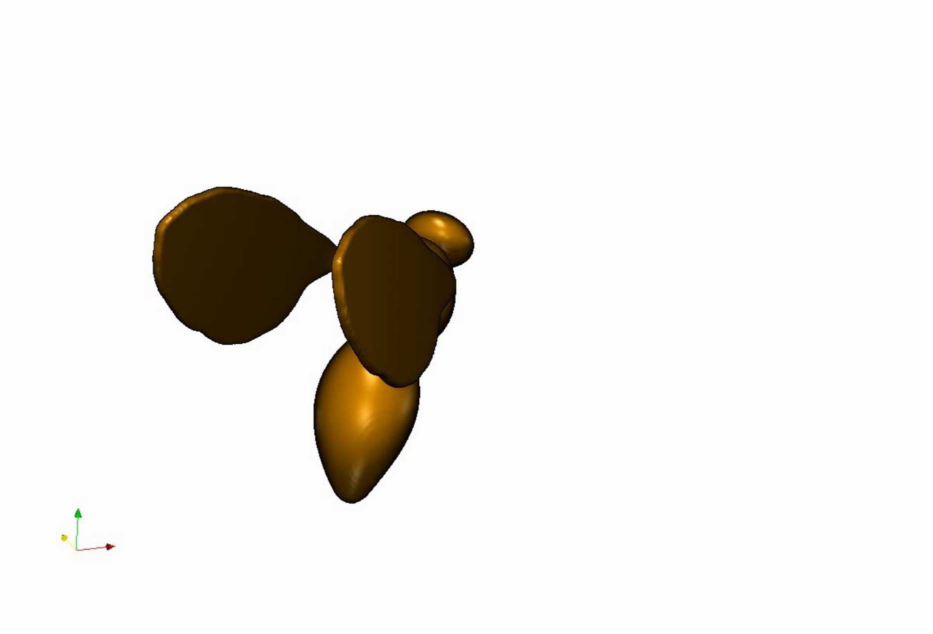
- Divergence inside the solid??
- divergence of penalization term
- Mach-number coupling unstable
- Show nblocks as a function of J: scaling very different from equidistant codes

Fruit fly (Maeda-test)

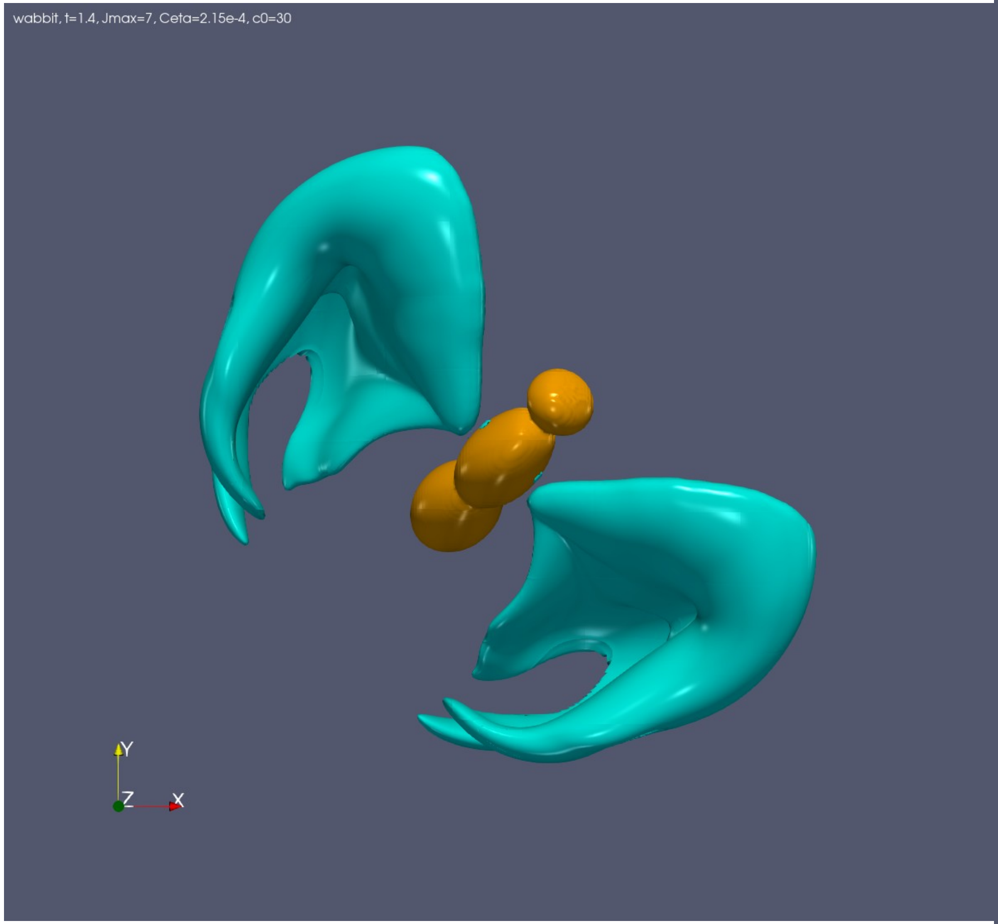


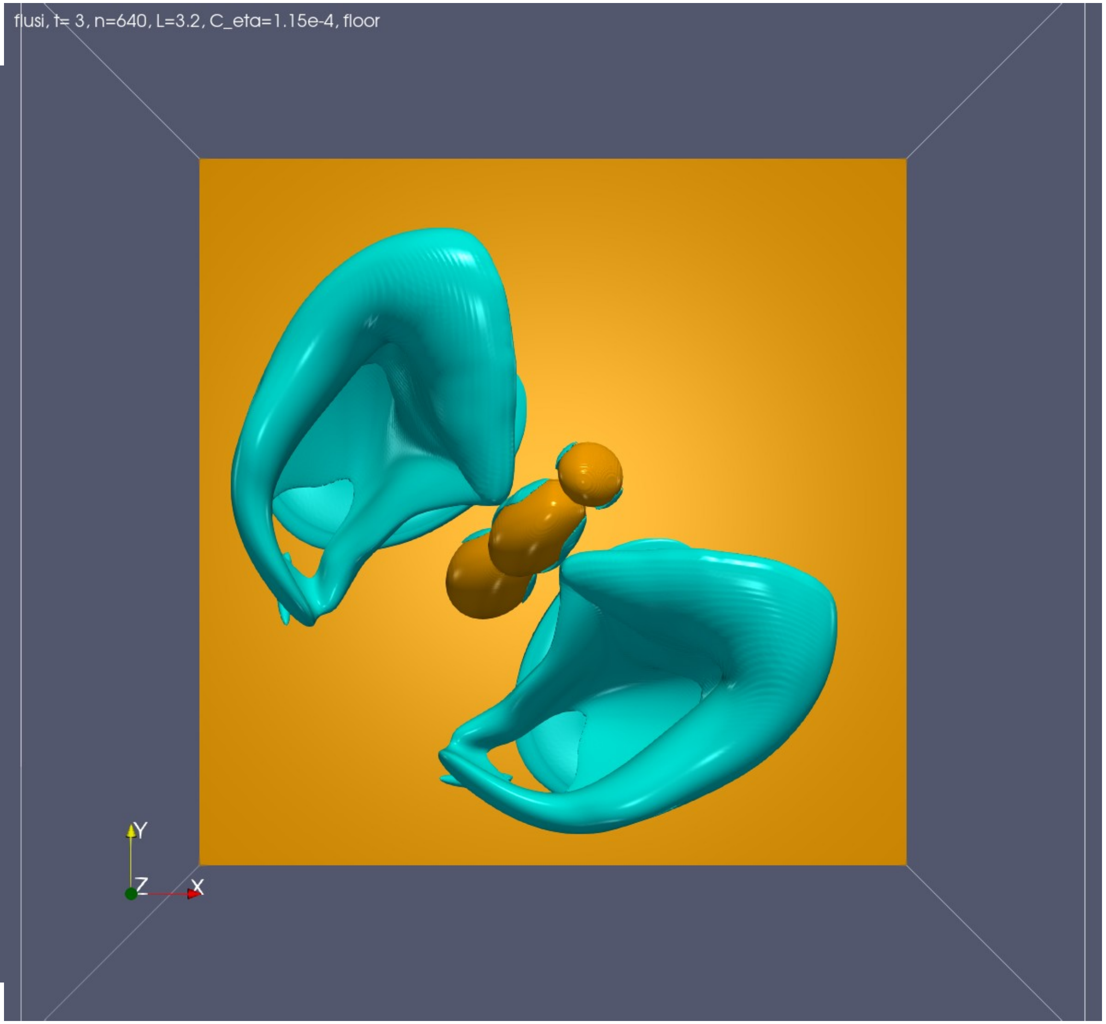
Key numbers flusi simulation

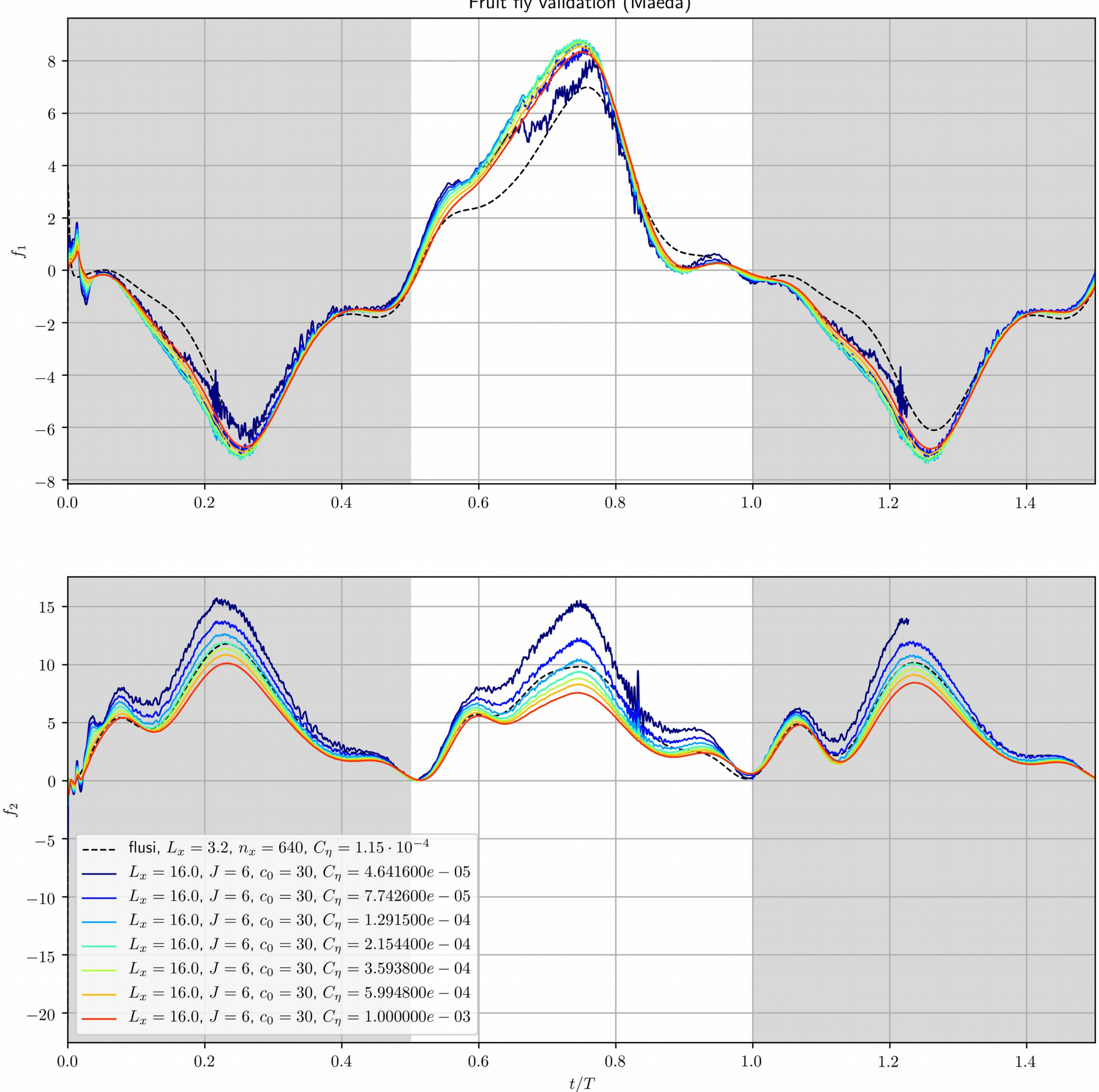
- Nu = 0.0113 (for suzuki it was nu=0.0366)
- L = 3.2
- Nx = 640
- C_eta = 1.15e-4
- Cost: ~15k CPUh
- Floor boundary condition (which was unfortunately missing in wabbit simulations right now)



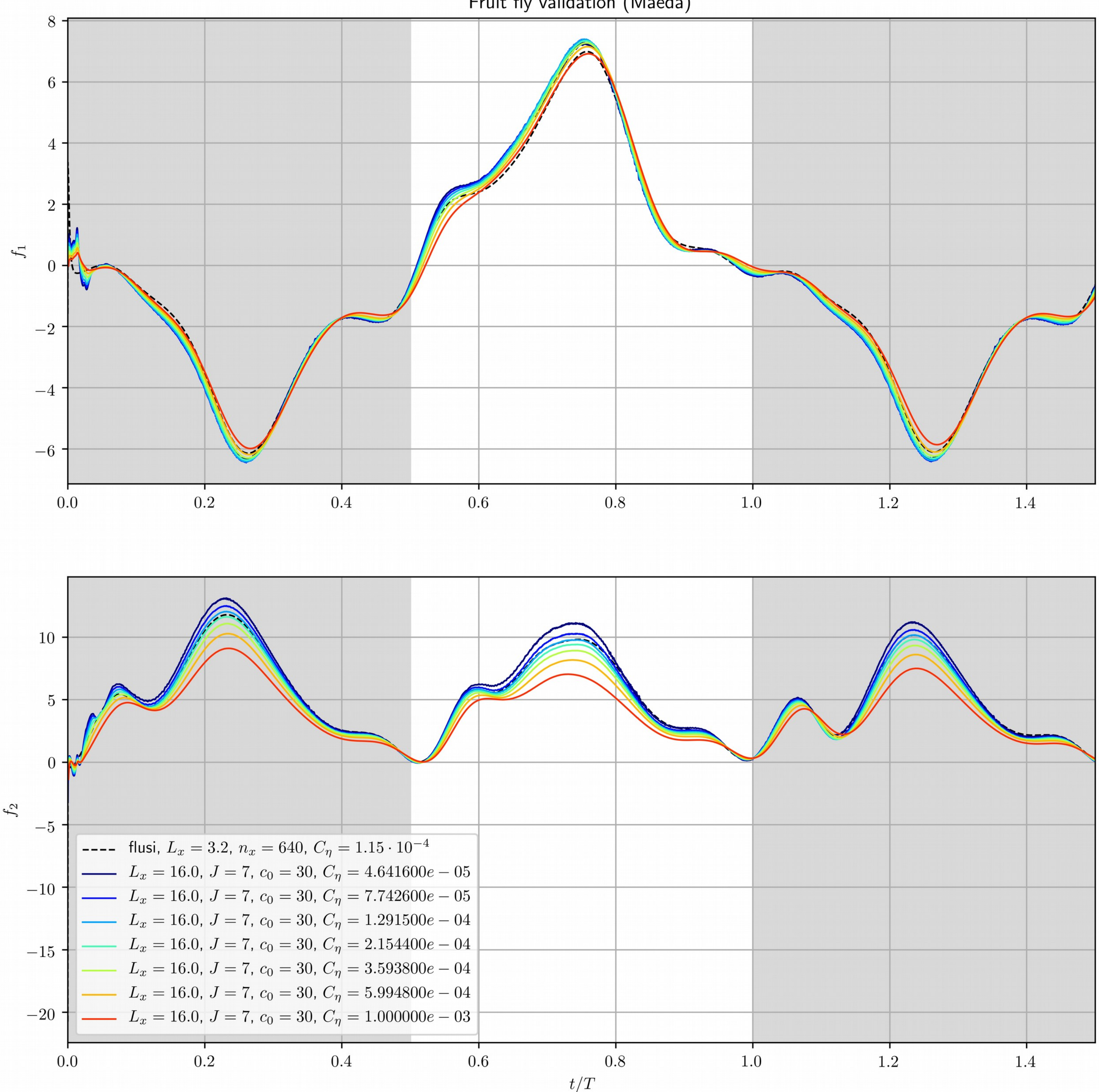
Comparison: isovor 25

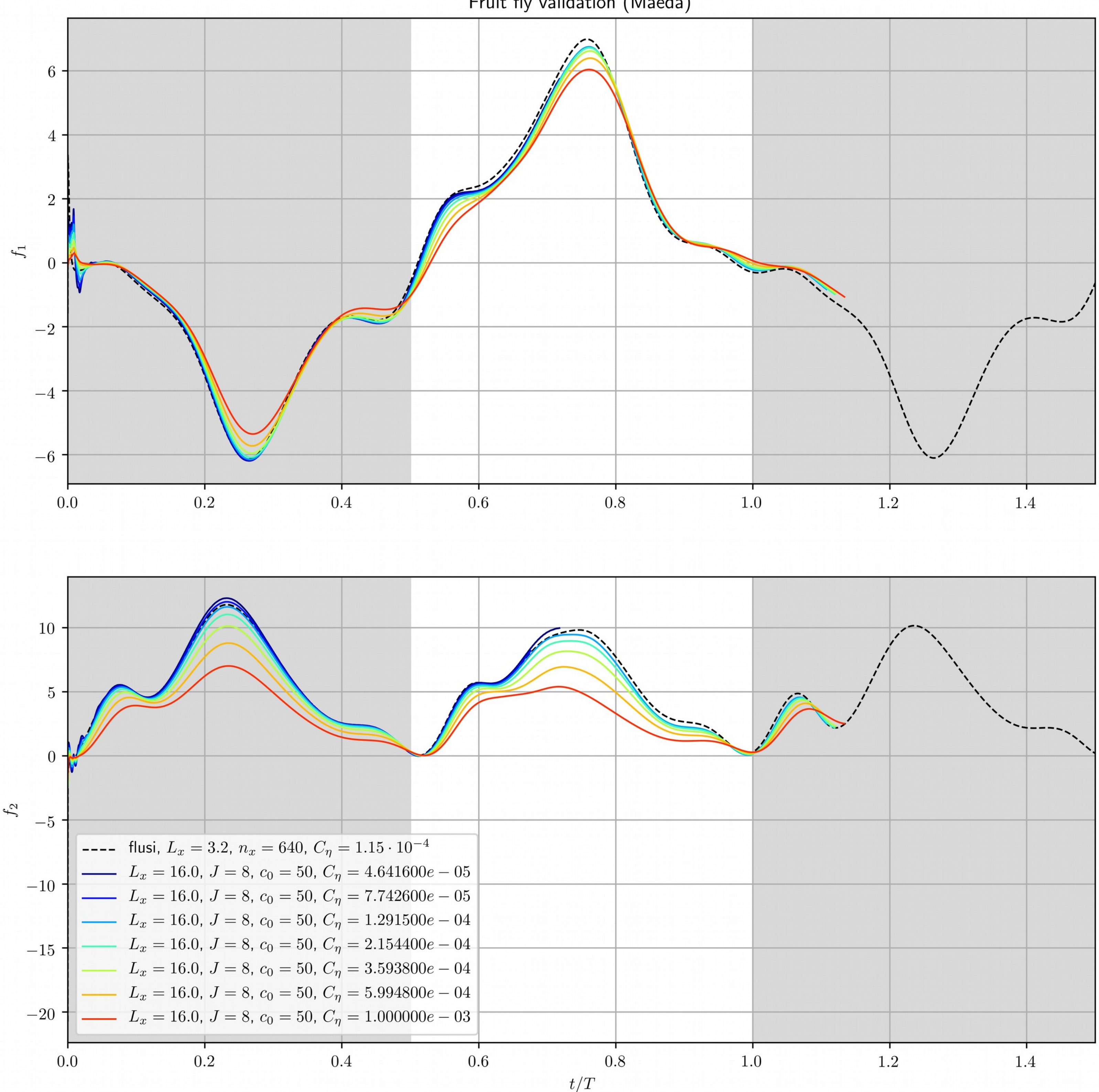




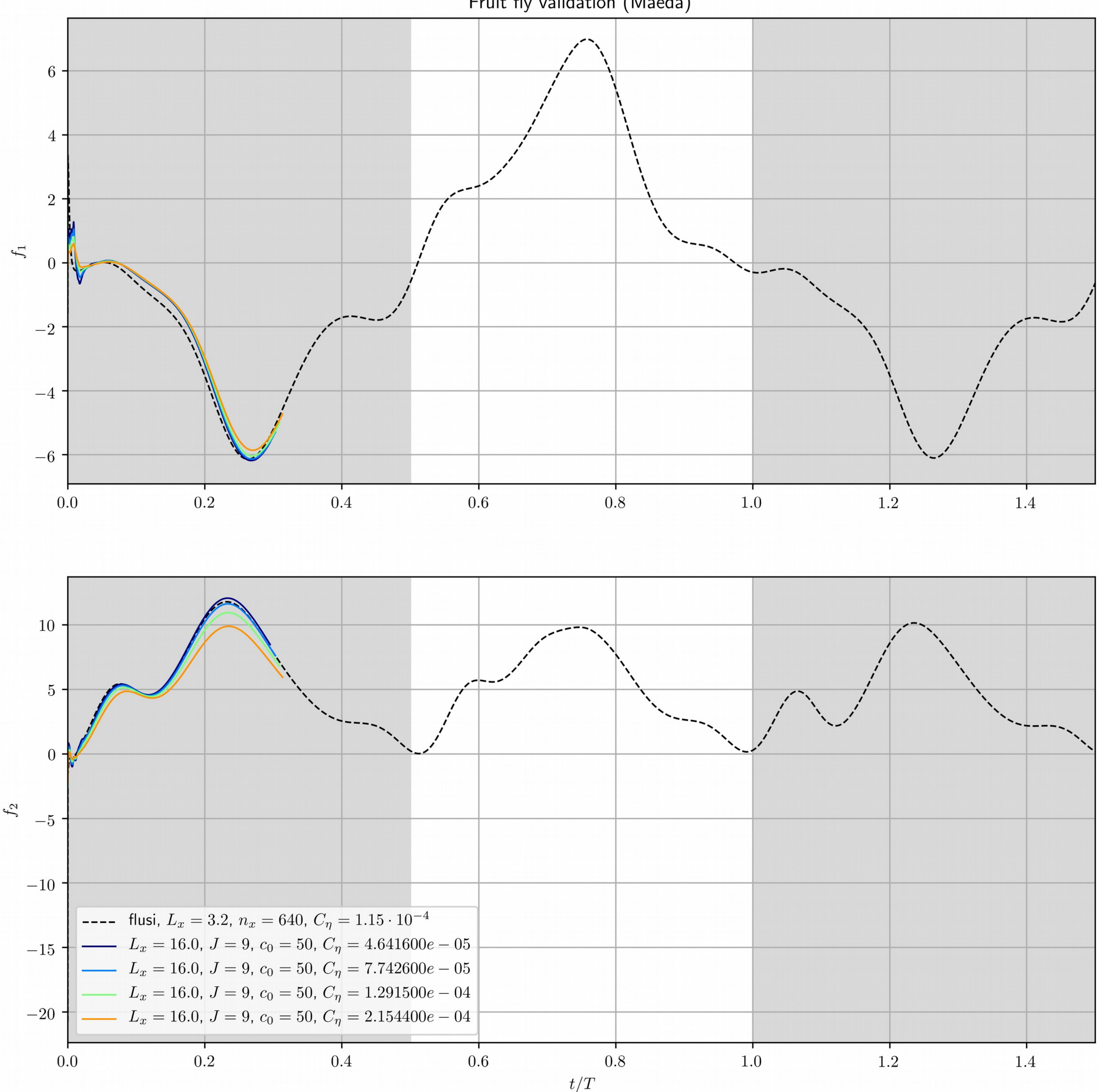


Fruit fly validation (Maeda)
f_1
f_2
t/T
flusi, $L_x = 3.2$, $n_x = 640$, $C_\eta = 1.15 \cdot 10^{-4}$
$L_x = 16.0$, $J = 6$, $c_0 = 30$, $C_\eta = 4.641600e-05$
$L_x = 16.0$, $J = 6$, $c_0 = 30$, $C_\eta = 7.742600e-05$
$L_x = 16.0$, $J = 6$, $c_0 = 30$, $C_\eta = 1.291500e-04$
$L_x = 16.0$, $J = 6$, $c_0 = 30$, $C_\eta = 2.154400e-04$
$L_x = 16.0$, $J = 6$, $c_0 = 30$, $C_\eta = 3.593800e-04$
$L_x = 16.0$, $J = 6$, $c_0 = 30$, $C_\eta = 5.994800e-04$
$L_x = 16.0$, $J = 6$, $c_0 = 30$, $C_\eta = 1.000000e-03$

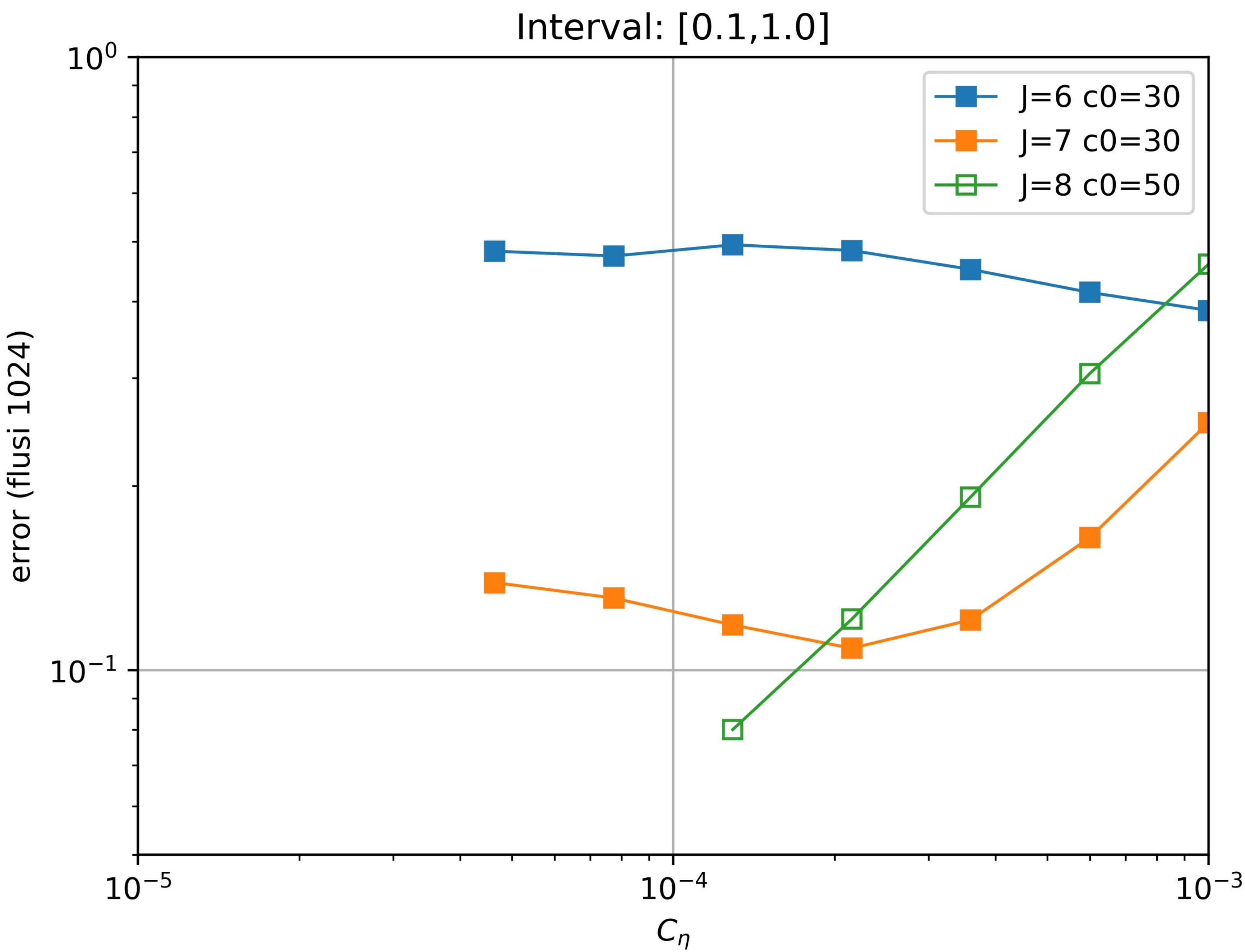

Fruit fly validation (Maeda)
f_1
f_2
t/T
flusi, $L_x = 3.2$, $n_x = 640$, $C_\eta = 1.15 \cdot 10^{-4}$
$L_x = 16.0$, $J = 7$, $c_0 = 30$, $C_\eta = 4.641600e-05$
$L_x = 16.0$, $J = 7$, $c_0 = 30$, $C_\eta = 7.742600e-05$
$L_x = 16.0$, $J = 7$, $c_0 = 30$, $C_\eta = 1.291500e-04$
$L_x = 16.0$, $J = 7$, $c_0 = 30$, $C_\eta = 2.154400e-04$
$L_x = 16.0$, $J = 7$, $c_0 = 30$, $C_\eta = 3.593800e-04$
$L_x = 16.0$, $J = 7$, $c_0 = 30$, $C_\eta = 5.994800e-04$
$L_x = 16.0$, $J = 7$, $c_0 = 30$, $C_\eta = 1.000000e-03$

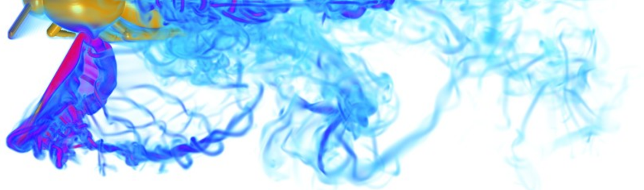


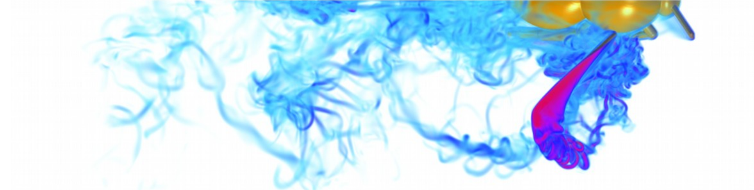
Fruit fly validation (Maeda)
f_1
f_2
t/T
flusi, $L_x = 3.2$, $n_x = 640$, $C_\eta = 1.15 \cdot 10^{-4}$
$L_x = 16.0$, $J = 8$, $c_0 = 50$, $C_\eta = 4.641600e-05$
$L_x = 16.0$, $J = 8$, $c_0 = 50$, $C_\eta = 7.742600e-05$
$L_x = 16.0$, $J = 8$, $c_0 = 50$, $C_\eta = 1.291500e-04$
$L_x = 16.0$, $J = 8$, $c_0 = 50$, $C_\eta = 2.154400e-04$
$L_x = 16.0$, $J = 8$, $c_0 = 50$, $C_\eta = 3.593800e-04$
$L_x = 16.0$, $J = 8$, $c_0 = 50$, $C_\eta = 5.994800e-04$
$L_x = 16.0$, $J = 8$, $c_0 = 50$, $C_\eta = 1.000000e-03$

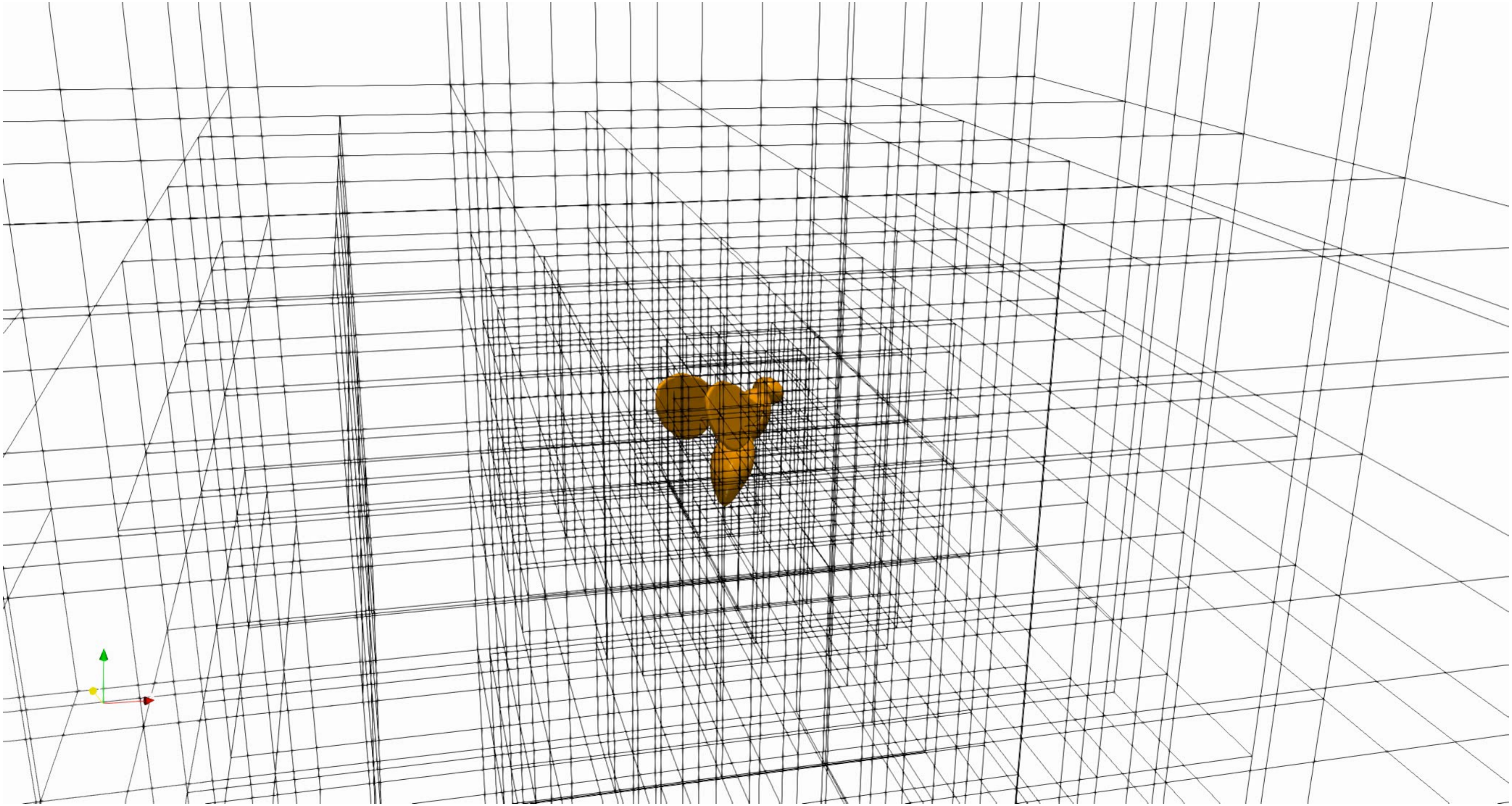


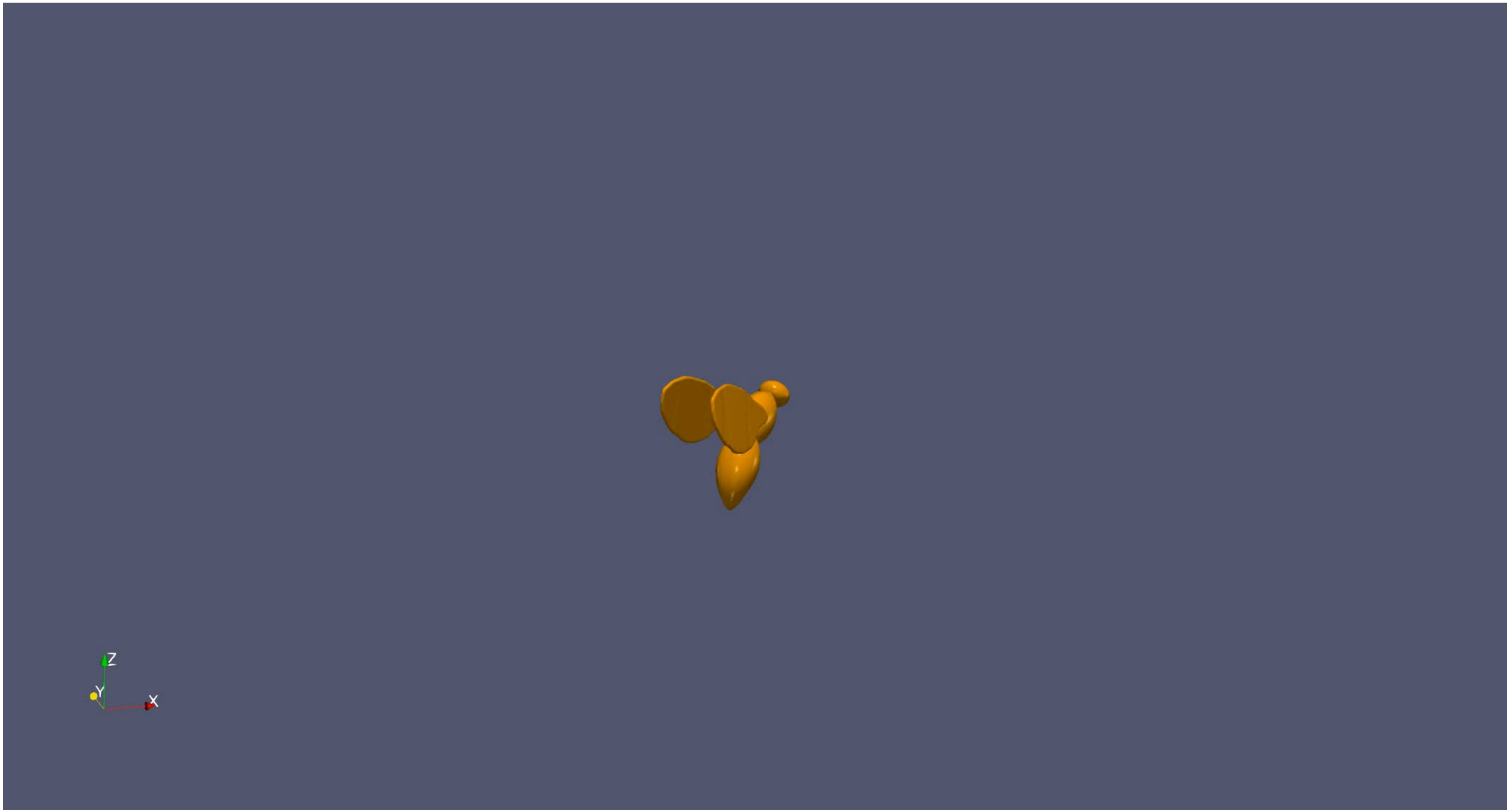
Fruit fly validation (Maeda)
f_1
f_2
t/T
flusi, $L_x = 3.2$, $n_x = 640$, $C_\eta = 1.15 \cdot 10^{-4}$
$L_x = 16.0$, $J = 9$, $c_0 = 50$, $C_\eta = 4.641600e-05$
$L_x = 16.0$, $J = 9$, $c_0 = 50$, $C_\eta = 7.742600e-05$
$L_x = 16.0$, $J = 9$, $c_0 = 50$, $C_\eta = 1.291500e-04$
$L_x = 16.0$, $J = 9$, $c_0 = 50$, $C_\eta = 2.154400e-04$

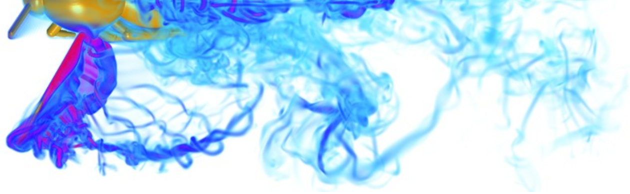

Interval: [0.1,1.0]
J=6 c0=30
J=7 c0=30
J=8 c0=50
error (flusi 1024)
10^0
10^{-1}
10^{-5}
10^{-4}
10^{-3}
C_η

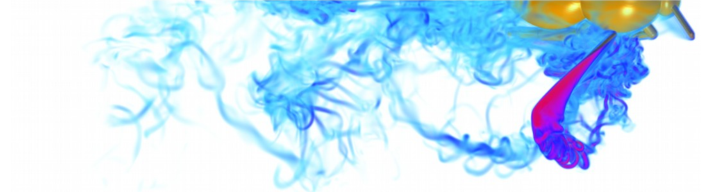


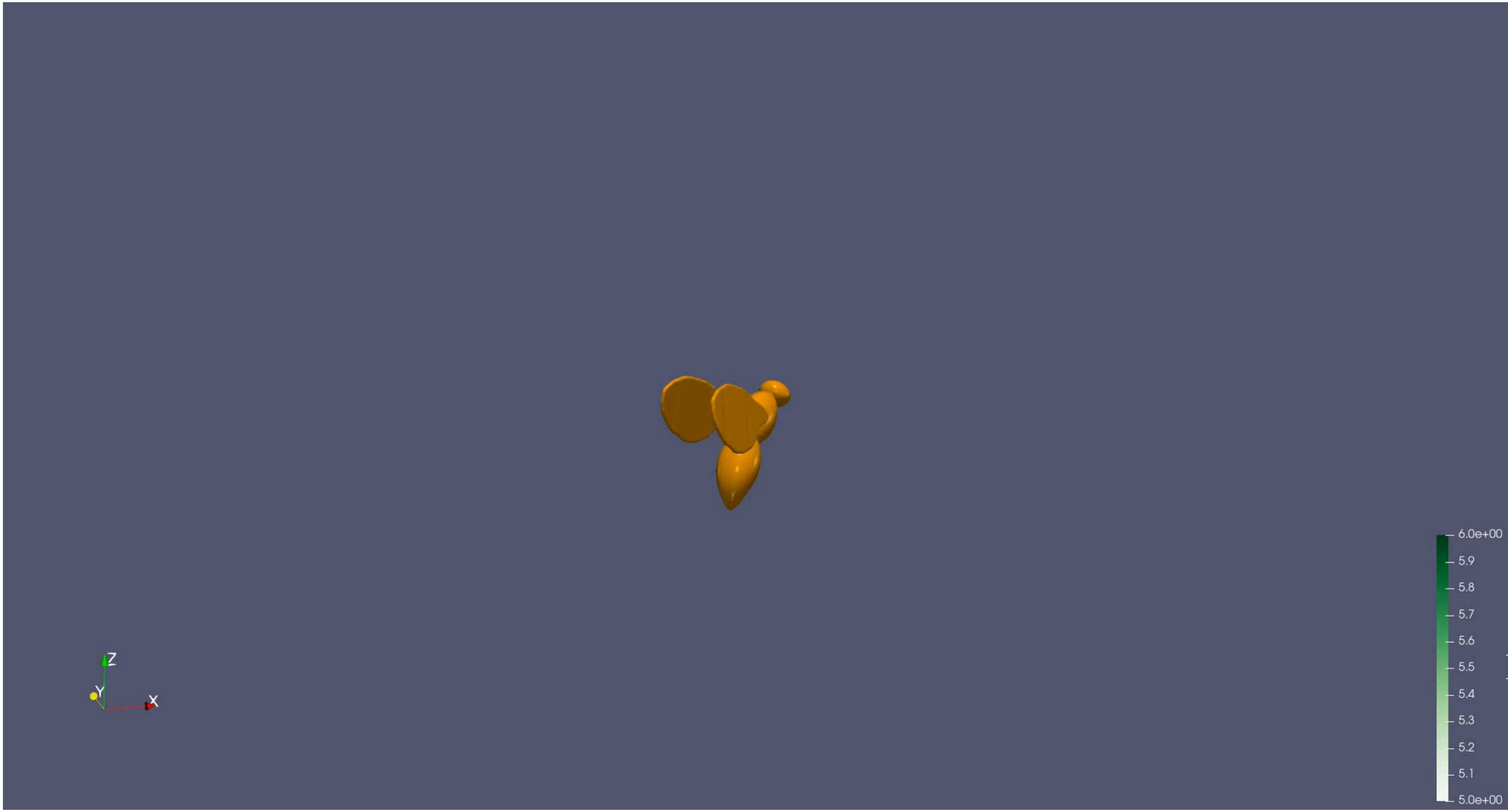





Z
Y
X






Z
Y
X
6.0e+00
5.9
5.8
5.7
5.6
5.5
5.4
5.3
5.2
5.1
5.0e+00
level

CPU time comparison

- Flusi: 15 100 CPUh on 1024 cores
- Wabbit: 1 968 CPUh on 96 cores

Next steps:

- Compute bumblebee with wabbit (turbulence: now eps plays a role), conclude validation (~2 weeks)
- For a SISC paper, a fancy test would be to simulate the fractal tree together with a bumblebee