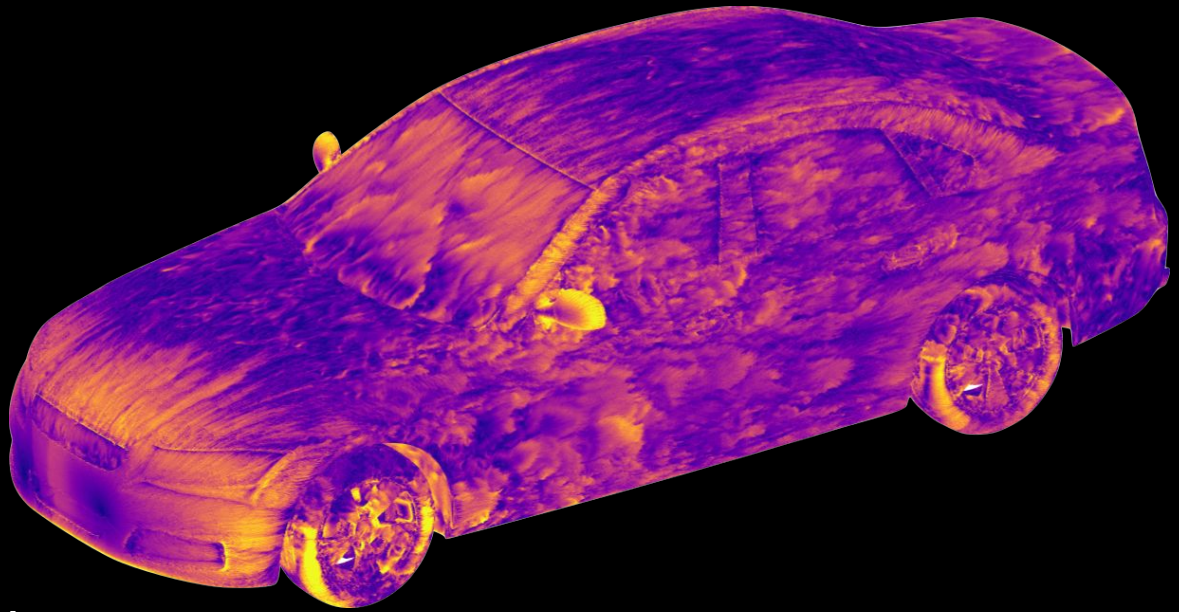
High Order Spectral Element Method: DrivAer



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8–9 October 2026 · DAMA Technopole, Bologna, Italy

5th Automotive CFD Prediction Workshop

The Team

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Large Scale Computational Fluid Dynamics

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Samuel Gomez Gonzalez



Oriol Lehmkuhl



Samuel Limonchi Colomina



Herbert Owen

Is SEM suitable for complex geometries?

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Advantages

- **High-Order Accuracy**
  - Smooth solutions
  - Superior precision per degree of freedom
- **Low Numerical Dispersion**
  - Highly effective for wave propagation problems
- **Curved physical boundaries**
- **Computational Efficiency**
  - Gauss-Lobatto-Legendre (GLL) quadrature

Disadvantages

- **Challenging Mesh Generation**
- **Hexahedral mesh**

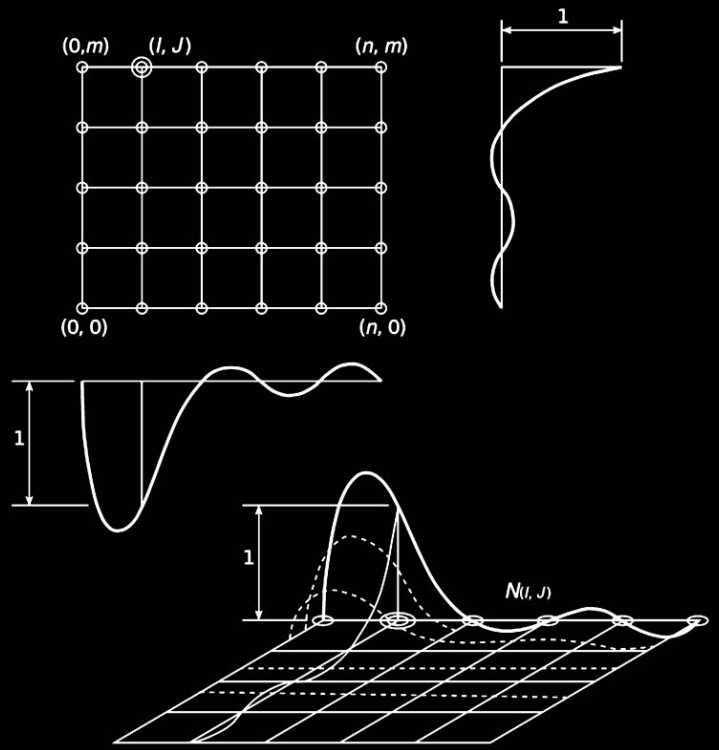


Fig. 1. Schematic detailing how a nodal shape function can be constructed by combining the one-dimensional Lagrange polynomials.

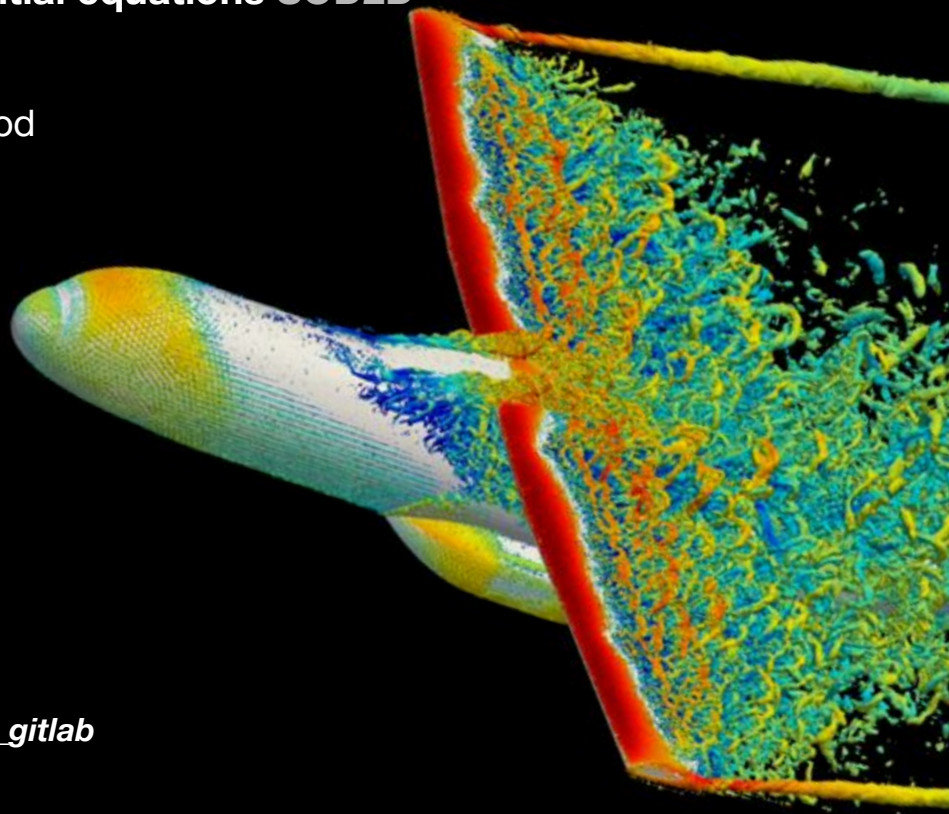
Sod2d

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Spectral high-Order coDe 2 solve partial Differential equations SOD2D

Gasparino et al. (2024)

- Continuous Galerkin spectral-finite element method
- Incompressible and compressible formulations
- Advanced high-order low-dissipation schemes
- Native Fortran accelerated with OpenACC/CUDA
- Matrix-free formulation



SOD2D

https://gitlab.com/bsc_sod2d/sod2d_gitlab

Numerical Model

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- High pass filter by ***O.Lehmkuhl (2026)***
- Two point flux scheme by ***Ranocha (2018)***
- Strong-Stability Preserving Runge-Kutta, explicit temporal scheme
- Vreman subgrid-scale model
- Equilibrium wall model by ***Reichardt (1951)***

$$u^+ = \frac{1}{\kappa}\ln\left(1+\kappa y^+\right) + 7.8\cdot\left(1 - e^{-y^+/11} - \frac{y^+}{11}\cdot e^{-0.33y^+}\right)$$



1. 1D filter (M-orthonormal modal basis)

$$\mathsf{A} = \mathsf{L}^T\mathsf{M}\mathsf{L} = \mathsf{C}\mathsf{C}^T, \quad \mathsf{Q} = \mathsf{L}\mathsf{C}^{-T}, \quad \mathsf{F} = \mu\,\mathsf{Q}\mathsf{W}\mathsf{Q}^T\mathsf{M} + (1-\mu)\mathsf{I}, \quad \mathsf{H} = \mathsf{I} - \mathsf{F}$$

with $\mathsf{W} = \mathrm{diag}(1,\ldots,1,\omega_N)$ and $\omega_N = \omega_N(N)$.

2. 3D extension (tensor product, element-wise)

$$\mathbf{u}_e^f = (\mathsf{F}_\xi \otimes \mathsf{F}_\eta \otimes \mathsf{F}_\zeta)\,\mathbf{u}_e$$

3. Local relaxation

$$\tilde{\mathbf{u}}_e = \mathbf{u}_e - \phi_e\,\mathsf{H}_{3D}\,\mathbf{u}_e, \qquad \phi_e = \frac{1}{C\,b_e + 1}$$

4. Modal sensor

$$\ln w_m^d = \ln a - \sigma^d(m-1), \qquad b_e = \frac{\min(|\sigma^\xi|,|\sigma^\eta|,|\sigma^\zeta|)}{\sigma_{\mathrm{ref}}}$$

where w_m^d is the modal energy fraction in direction d.

5. C^0 reassembly (lumped mass)

$$\mathbf{u}_I^{\mathrm{new}} = \frac{\sum_e \tilde{\mathbf{u}}_{e,a}\,\mathrm{gpvol}_{e,a}}{\sum_e \mathrm{gpvol}_{e,a}}$$

Applied to $\mathbf{q} = \rho\mathbf{u}$, ρ and E; the sensor is evaluated on the entropy variable η.

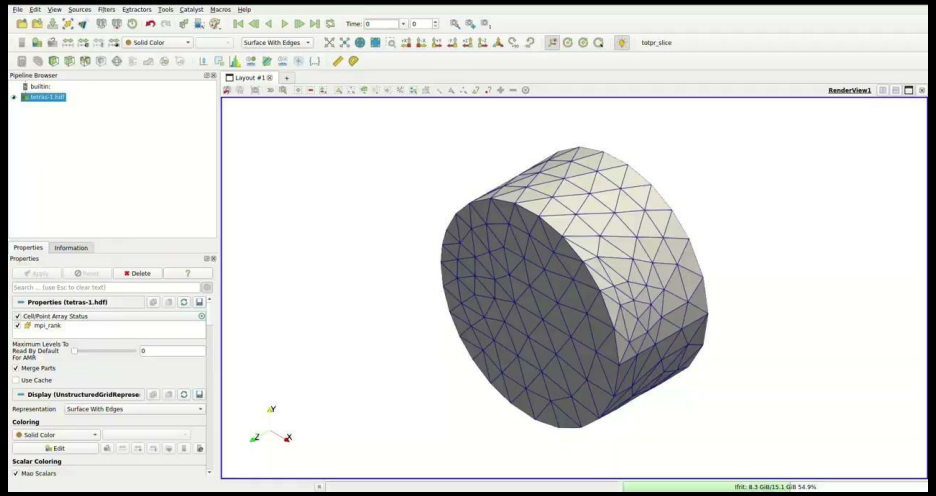
Mesh Workflow

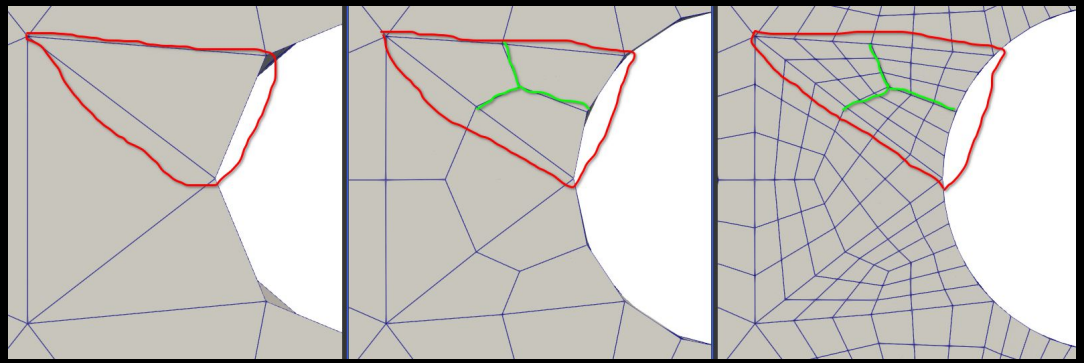
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Full Hexa meshes

- **ANSA**
  - Initial P2 tetra mesh
- **Mesh Elevation SFC partitioning**

  Splitting to hexas and Improvement
  - SFC partitioning
  - Splitting to hexas
  - P-elevation

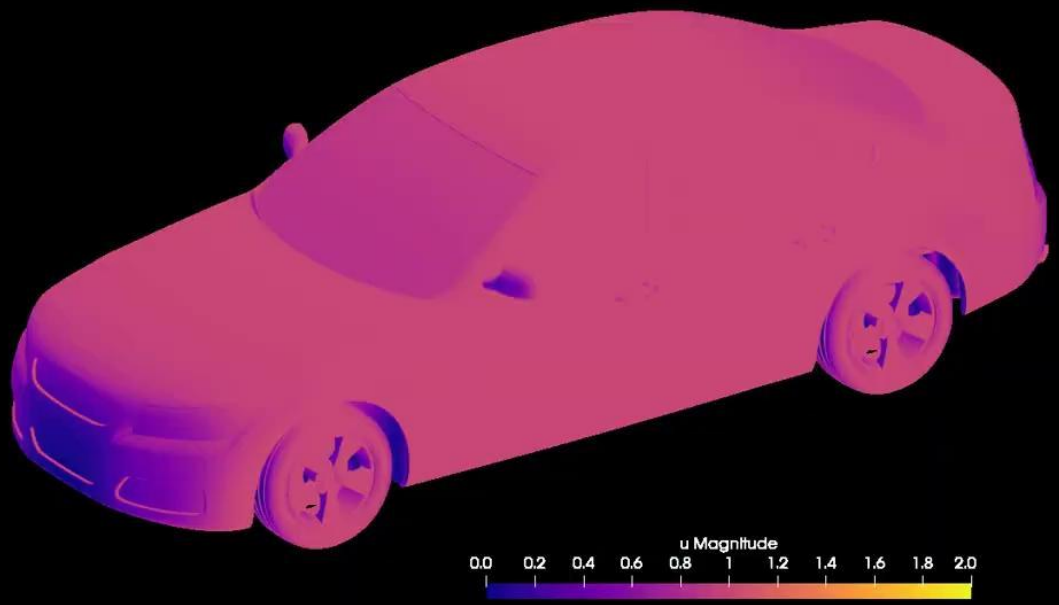






Initial simulation

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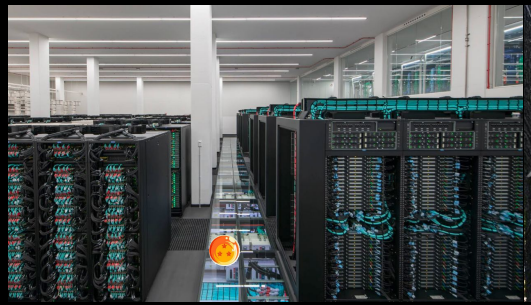


- 144M nodes - 17M elems - P2

100 hours per time unit - 32 GPU's

The quest for an affordable DrivAer

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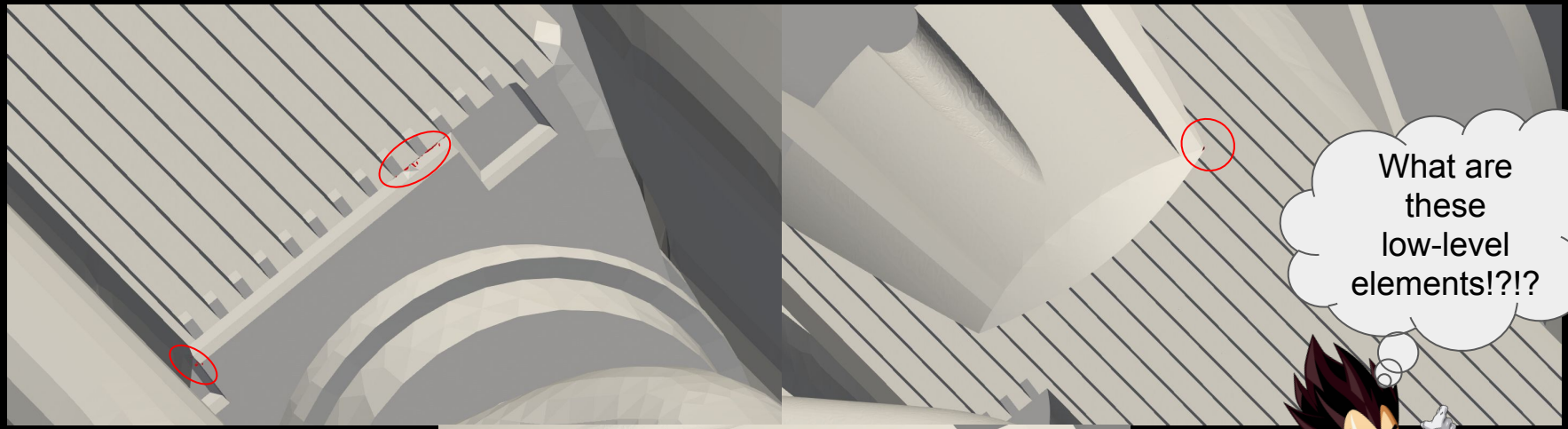



The Summoning



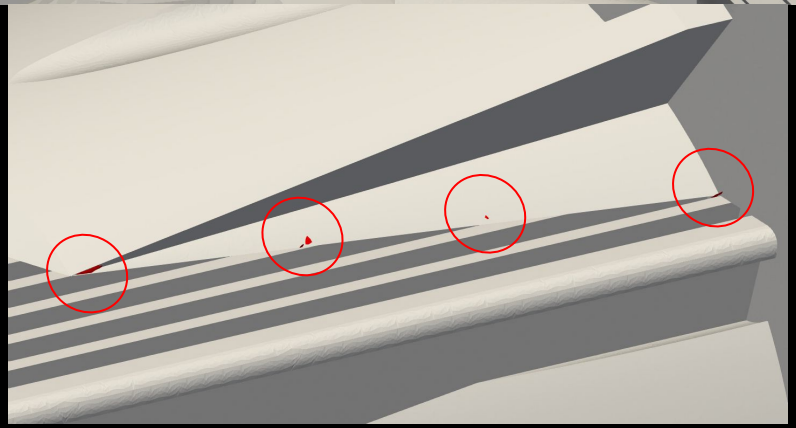
Mesh Improvements

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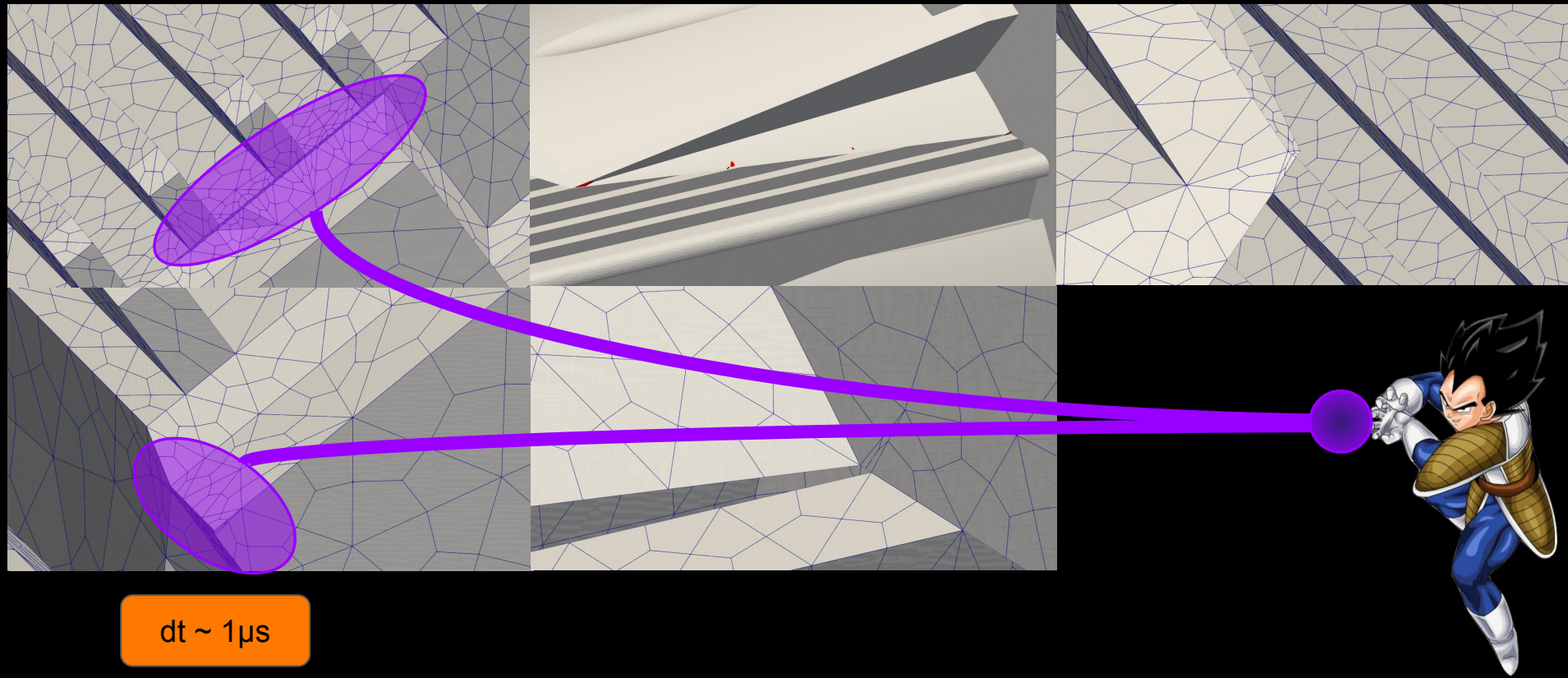
dt ~ 1μs





Mesh Improvements

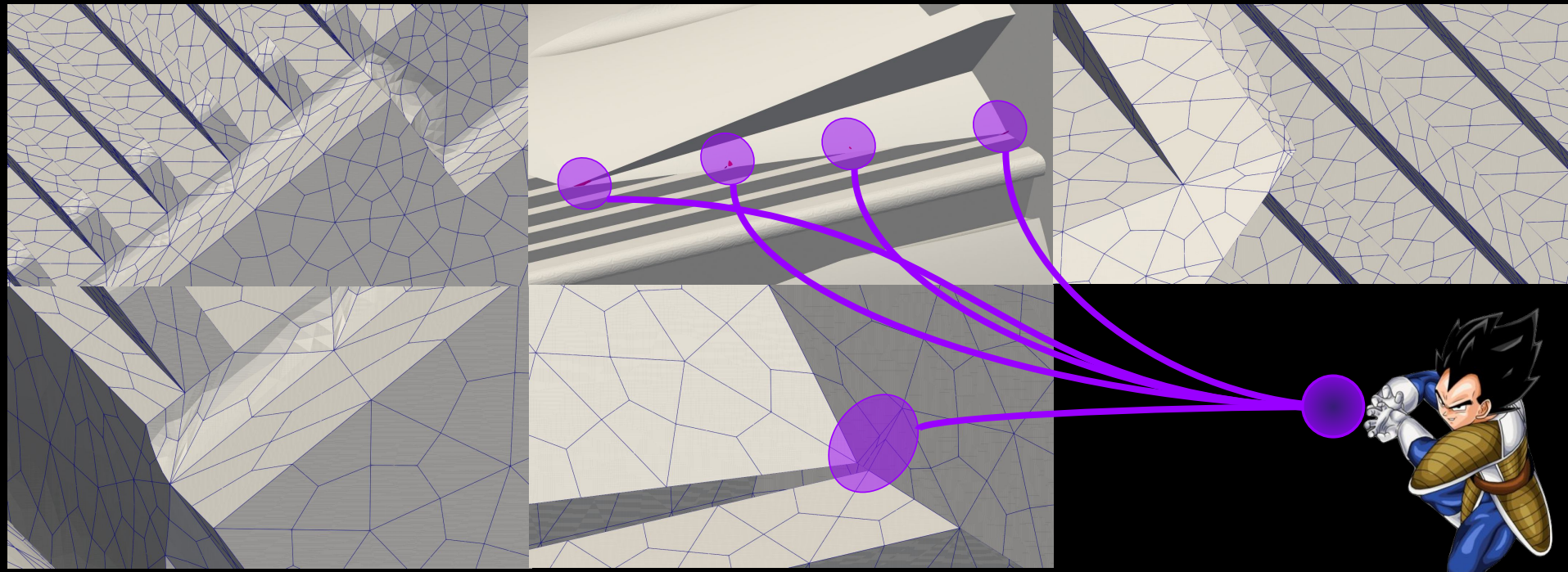
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dt ~ 1μs

Mesh Improvements

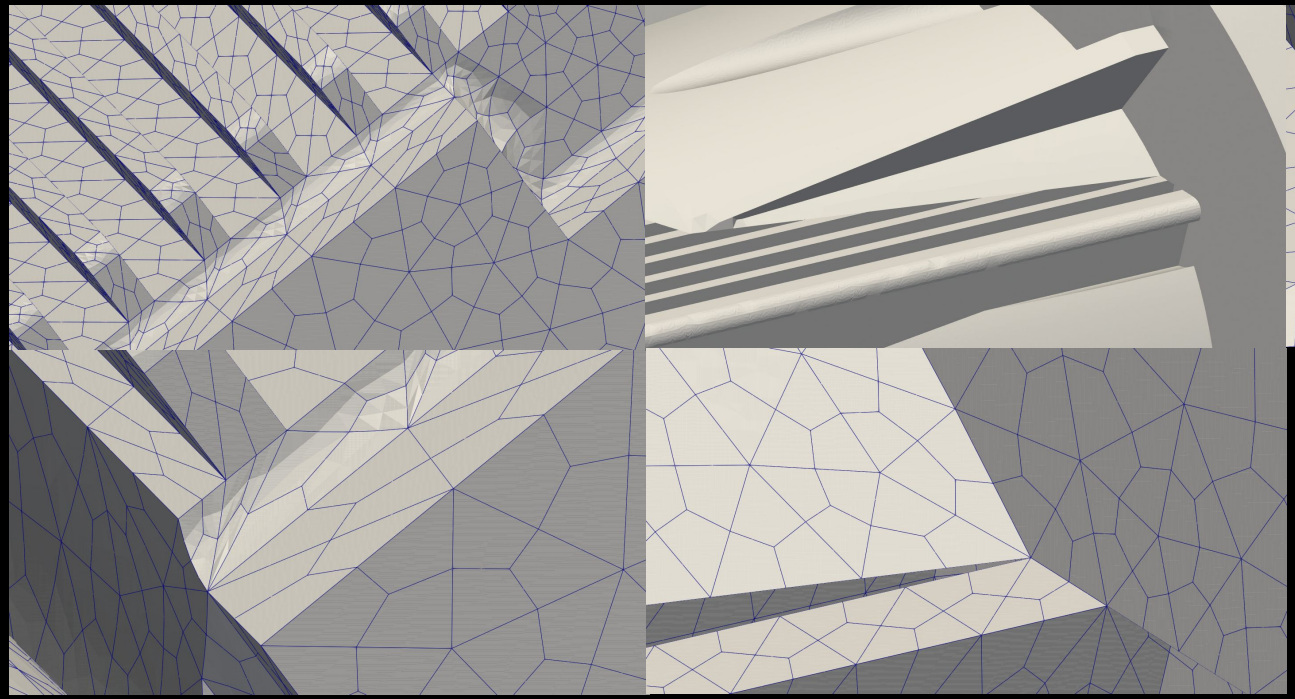
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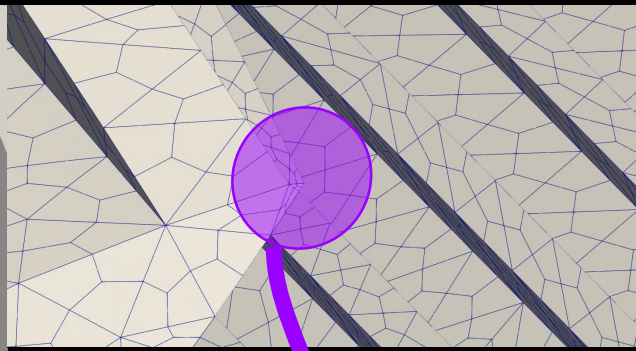


dt ~ 1μs → dt ~ 2μs

Mesh Improvements

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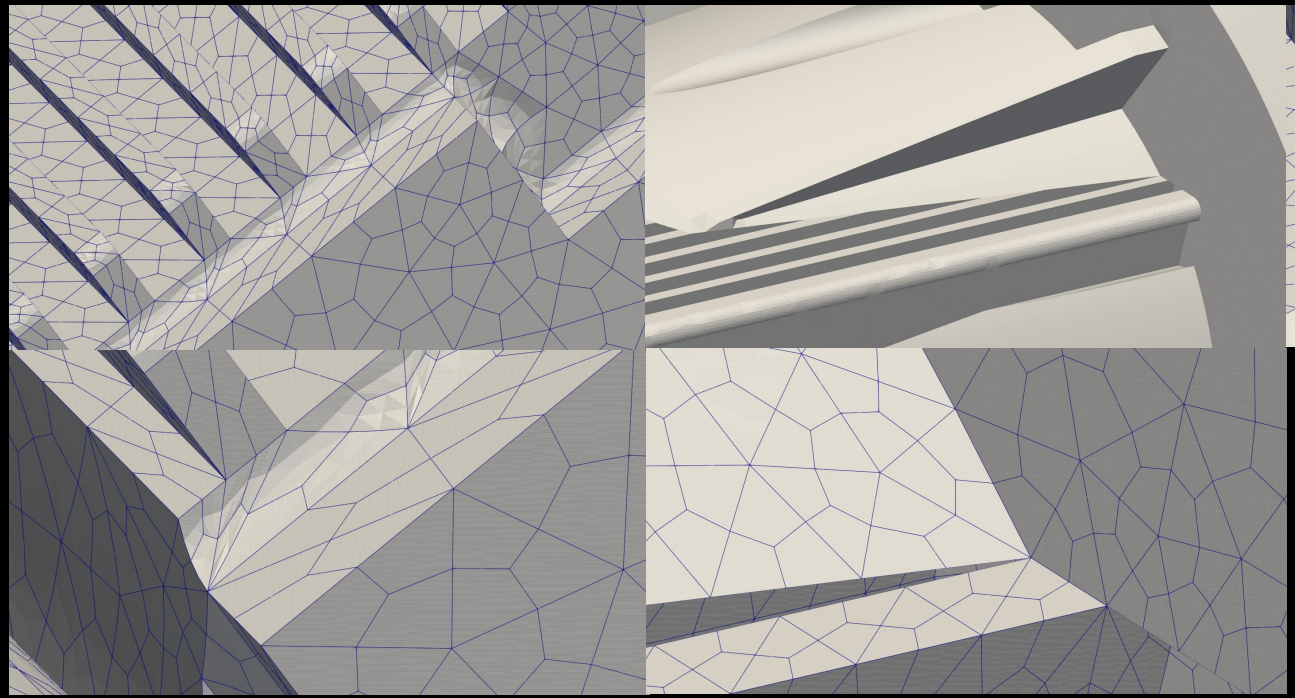




dt ~ 1μs → dt ~ 2μs → dt ~ 3μs

Mesh Improvements

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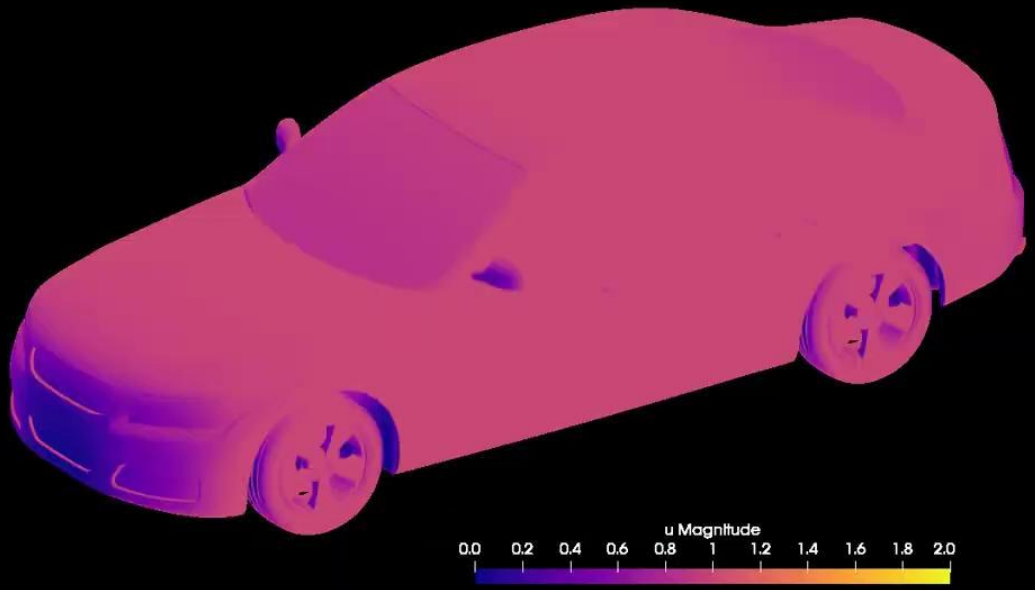




dt ~ 1μs → dt ~ 2μs → dt ~ 3μs → dt ~ 3.5μs

Improved simulation

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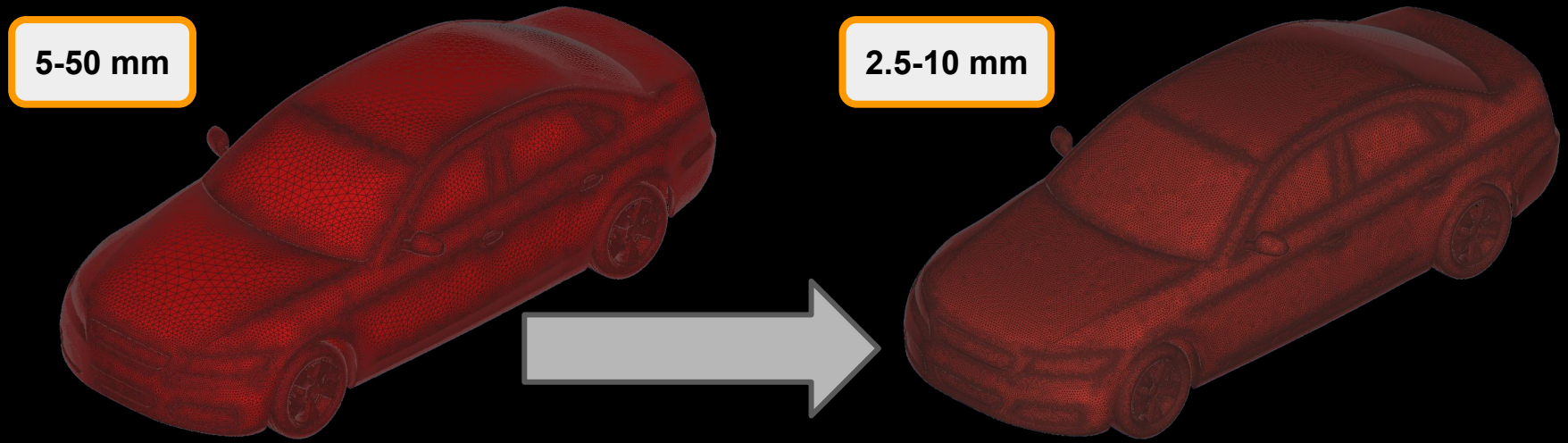


- 143M nodes - 16.8M elems - P2

32 hours per time unit - 32 GPU's

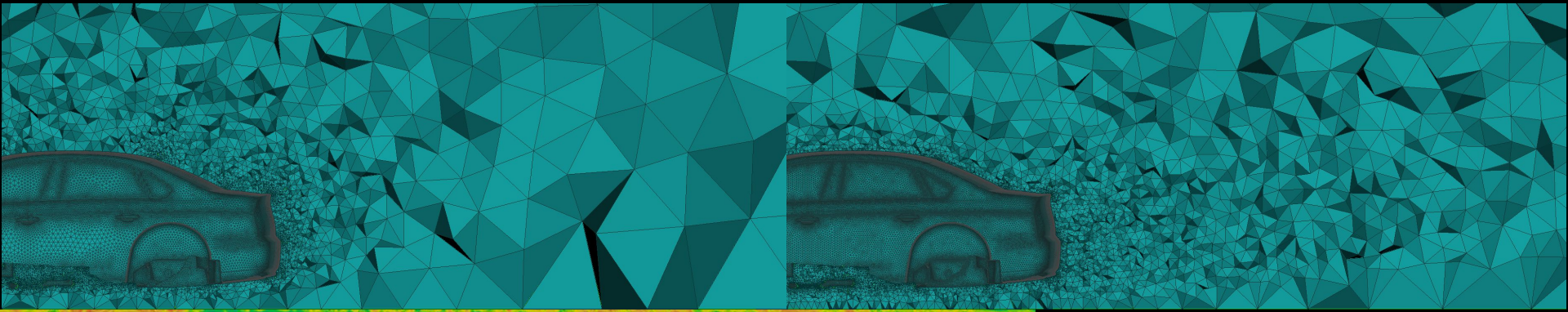
Mesh refinements

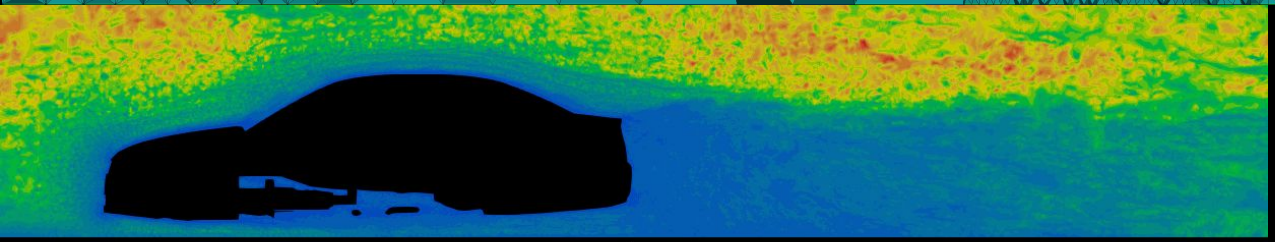
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Mesh refinements

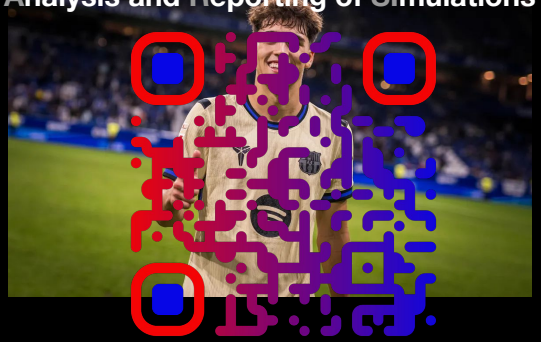
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$$h = 2\left(\frac{\epsilon}{\max_i |\lambda_i(\nabla^2|\mathbf{u}|)|}\right)^{\frac{1}{p+1}}$$

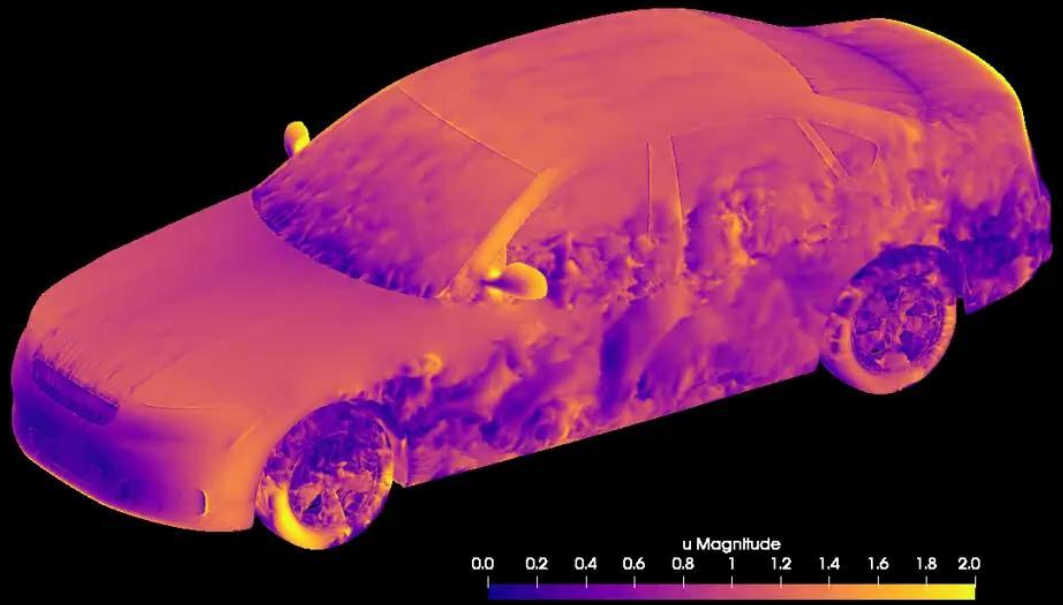
Python module: Quick Visualization, Analysis and Reporting of SImulations



pyQvarsi

Refined simulation

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- 210M nodes - 24.5M elems - P2

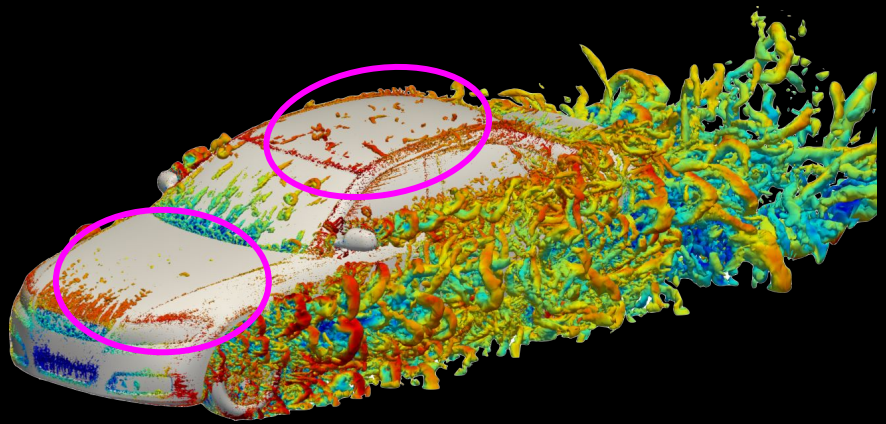
48 hours per time unit - 32 GPU's

Refined simulation

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- ***Where are the turbulent structures?***

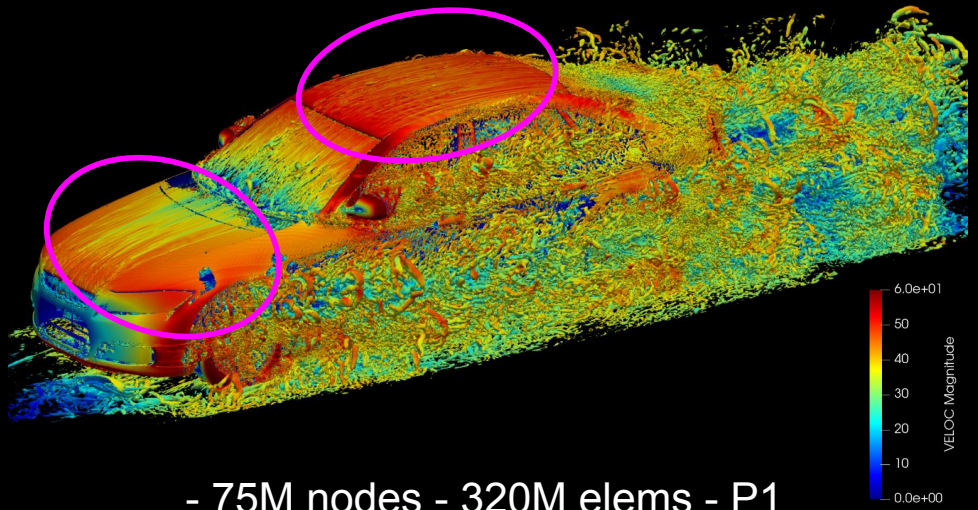
Sod2d



- 210M nodes - 24.5M elems - P2

48 hours per time unit - 32 GPU's

Alya (AutoCFD2)



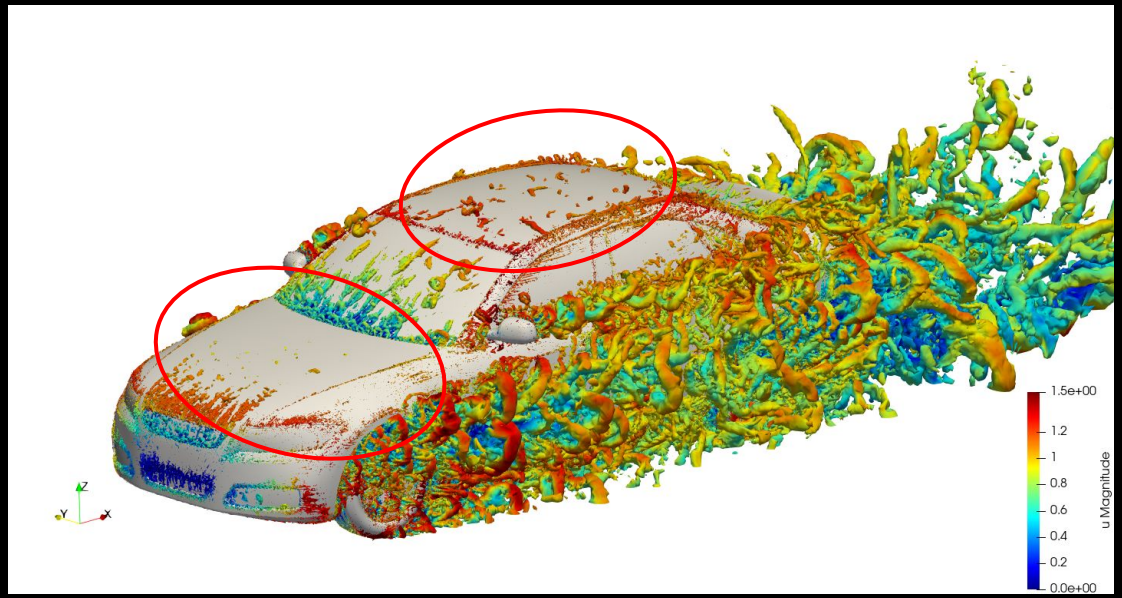
- 75M nodes - 320M elems - P1

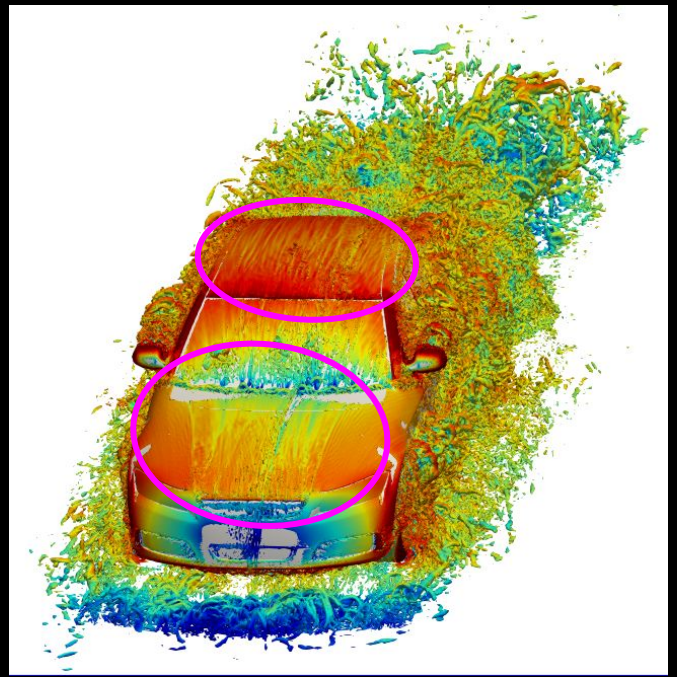
100 hours per time unit - 2300 CPU's

Refined simulation

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- *Q sod*

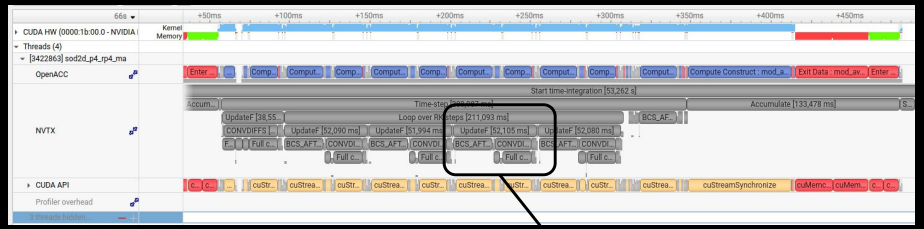


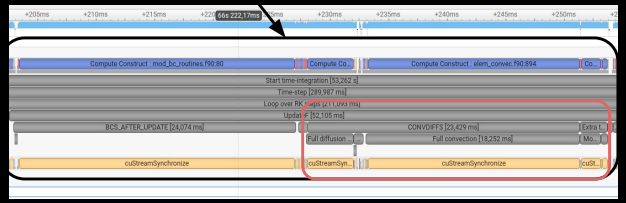


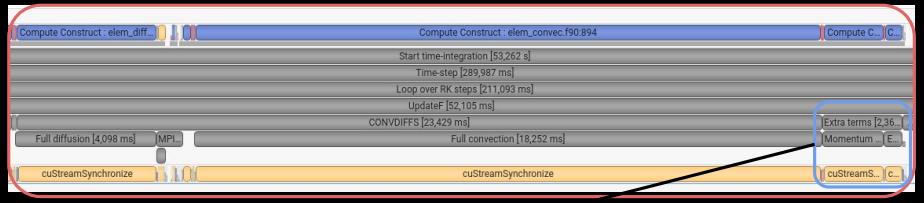
Code Implementation: Kernel Optimization

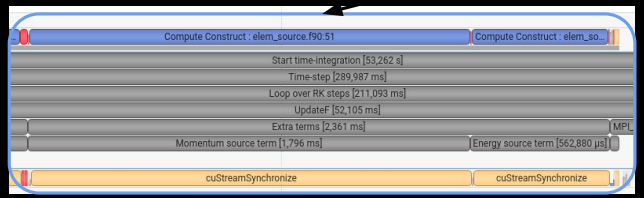
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Before









After



	Master [ms]	Opt. [ms]
Time Step	293	82
Accum	138	3
BCs	24	0.3
Conv.	18	4.4
Diff.	4	3.8

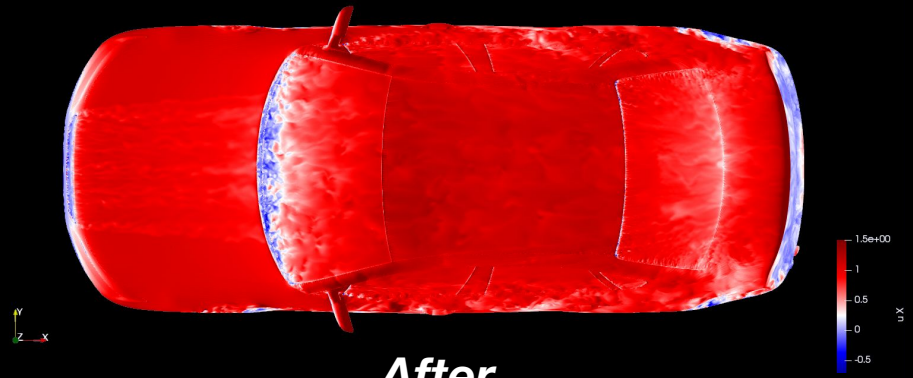
≈ x4 Faster!!!!

By @Jordi Muela and @Oriol Lehmkuhl

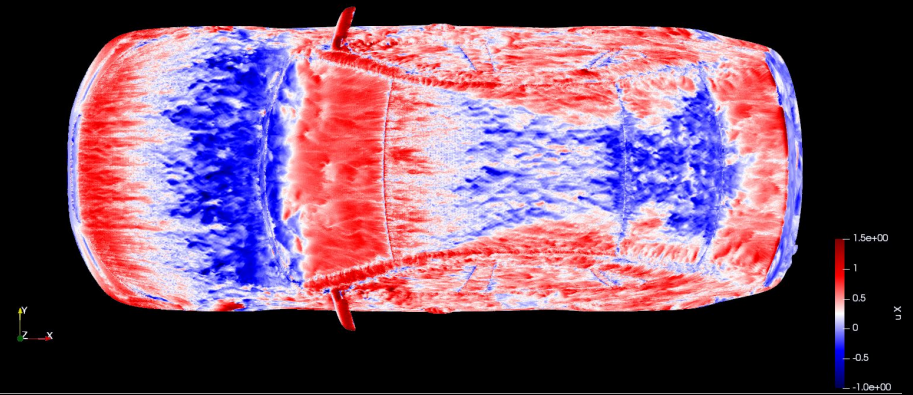
Code Implementation: Near Wall Filtering Behaviour

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Before



After




```
!$acc parallel loop gang private(ipoin,ul,tmpI,tmpJ,tmpK,n,isoI,isoJ,isoK,m,inode,in_m,ii,s1,s2,s3)
do ielem = 1, nelem

   !$acc loop vector
   do inode = 1, nnode
      ipoin(inode) = connec(ielem,inode)
      !$acc loop seq
      do idime = 1, ndime
         ul(inode,idime) = u(ipoin(inode),idime)
      end do
   end do

   phi0 = 1.0_rp/(19.0_rp*blend(ielem) + 1.0_rp)
   phi  = phi0

   if (filter_bnd_damp(ielem) < 1.0_rp) then
      if (phi0 < 0.05_rp) then
         phi = filter_bnd_damp(ielem)*phi0
      end if
   end if

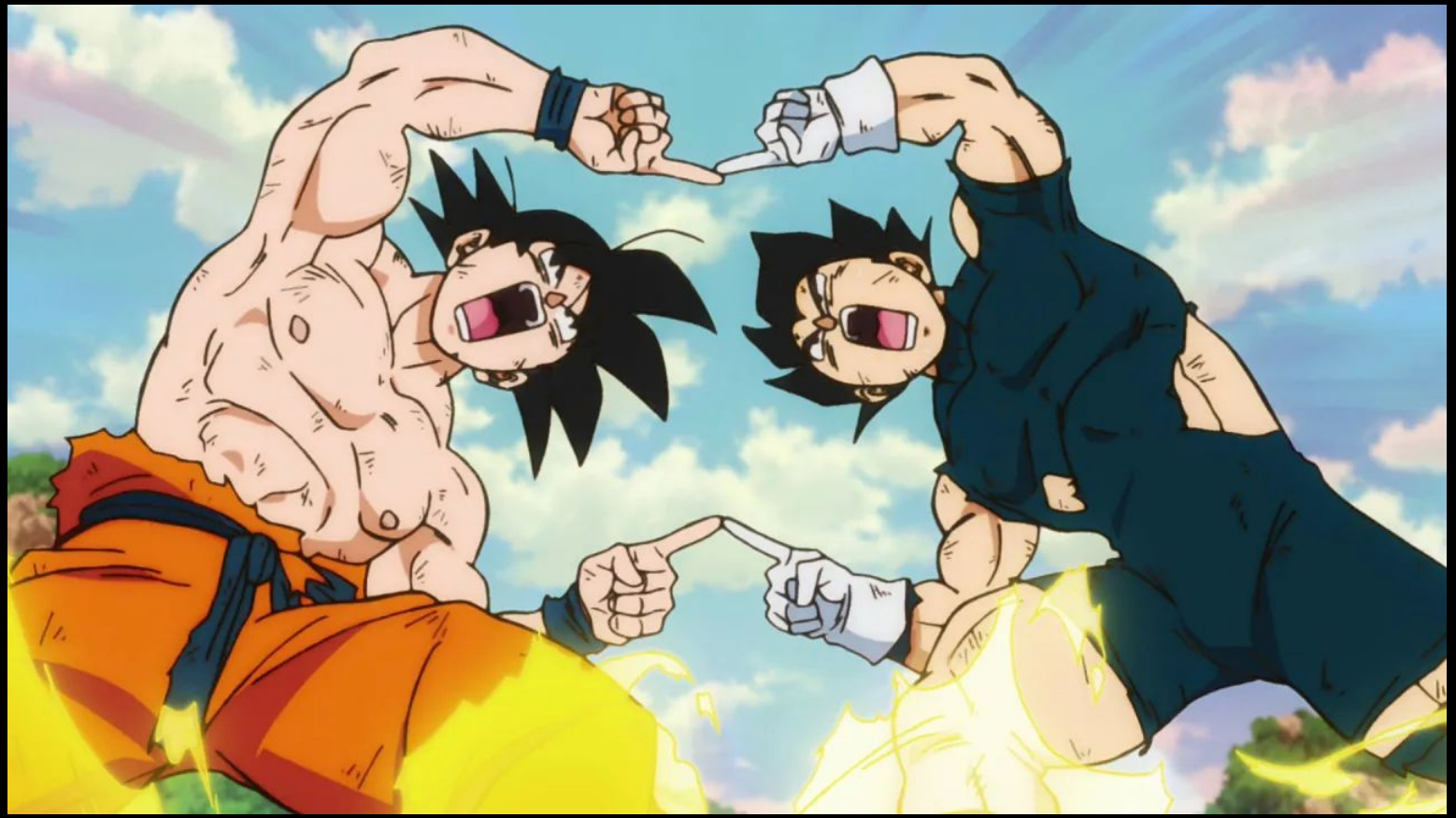
   n = porder + 1
```

Dumping mechanism in the first element touching a boundary, removing the filtering if the Mossier sensor is ***0.05*** or less (above is consider to be a shock touching the wall).

By @Oriol Lehmkuhl

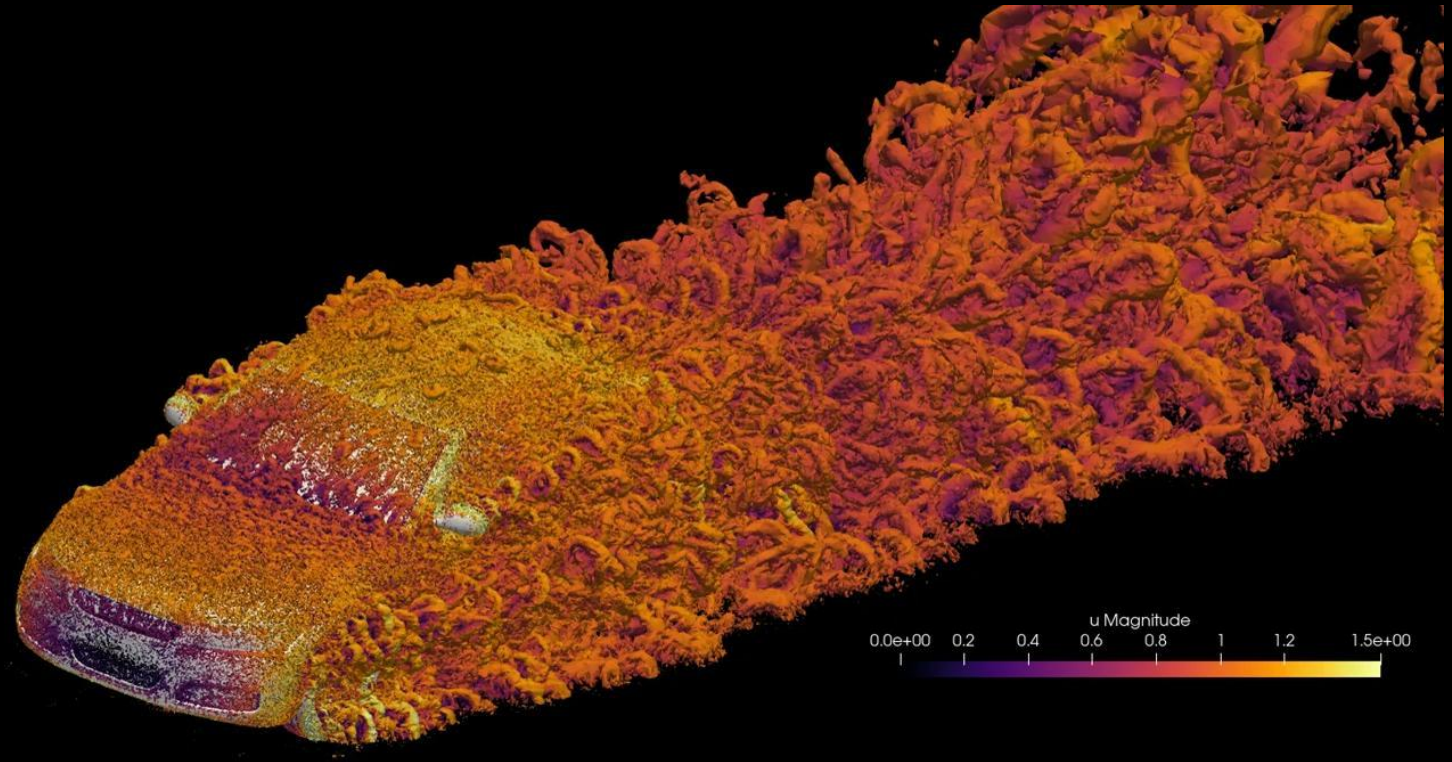
Mesh + code + filter improvements

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Mesh + code + filter improvements

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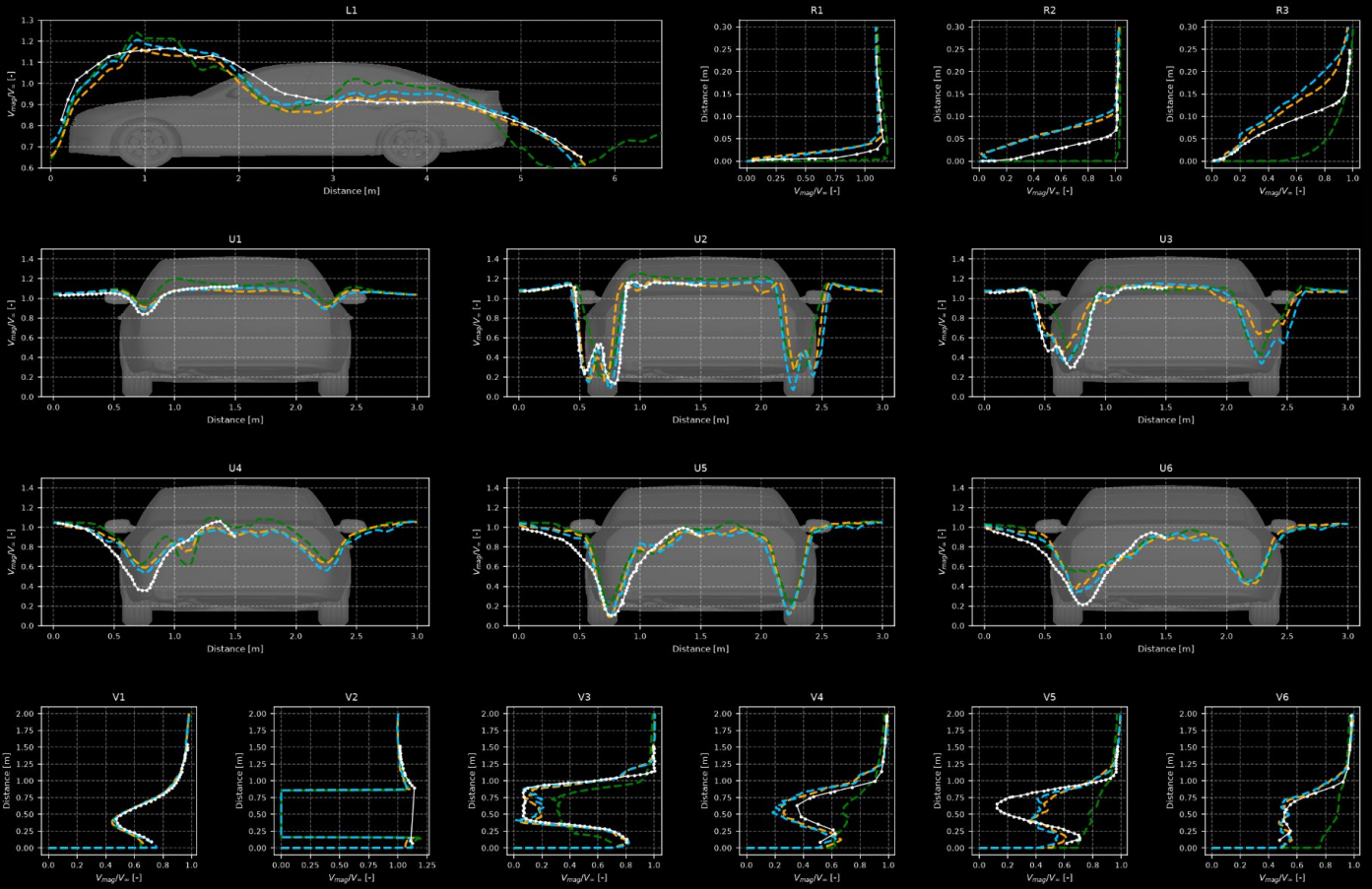


- 690M nodes - 24.5M elems - P3

43 hours per time unit - 32 GPU's

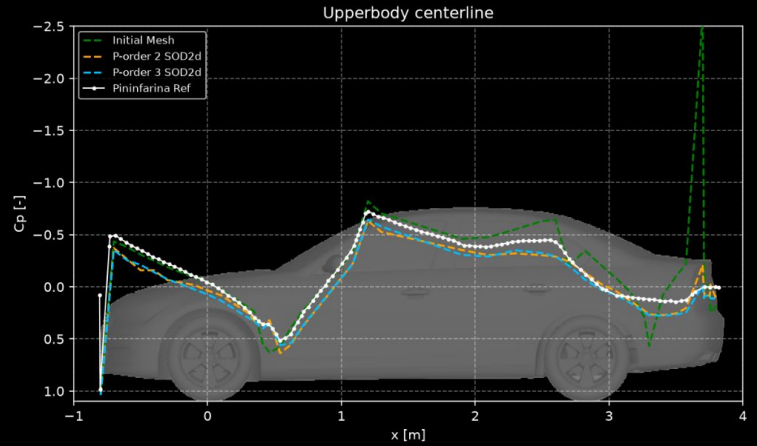
Results: Velocity Profiles

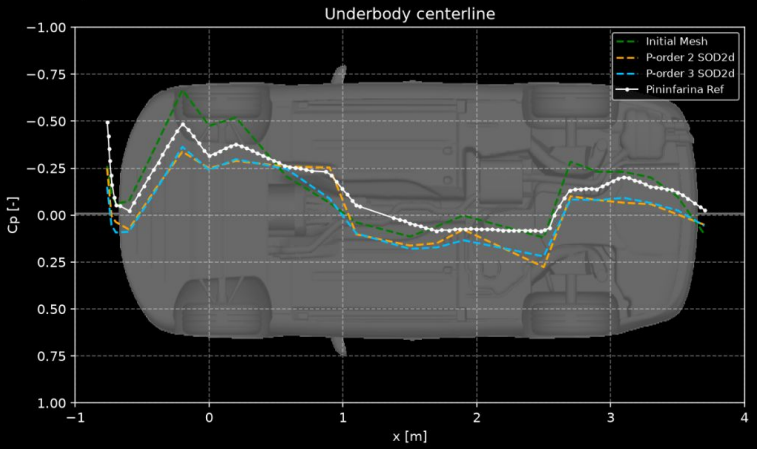
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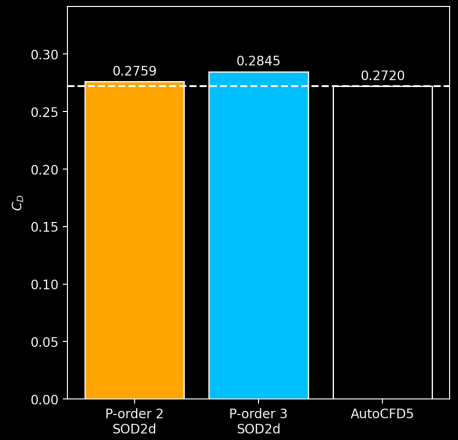


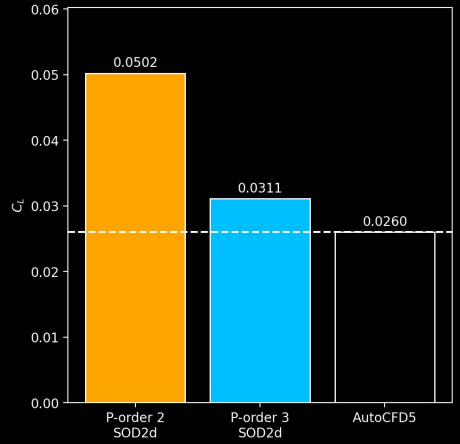
Results: Pressure and Aerodynamics Coefficients

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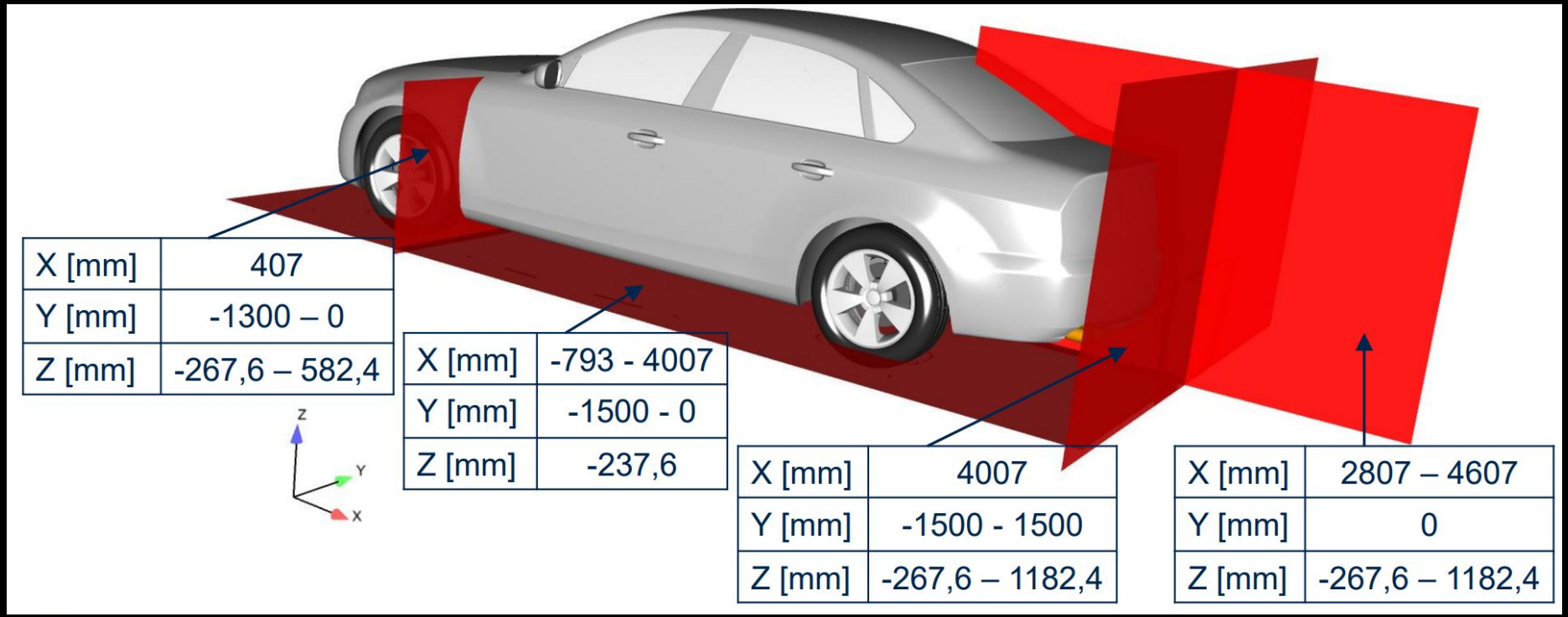






Results: Flowfield Measurements

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X [mm]	407
Y [mm]	-1300 – 0
Z [mm]	-267,6 – 582,4

X [mm]	-793 - 4007
Y [mm]	-1500 - 0
Z [mm]	-237,6

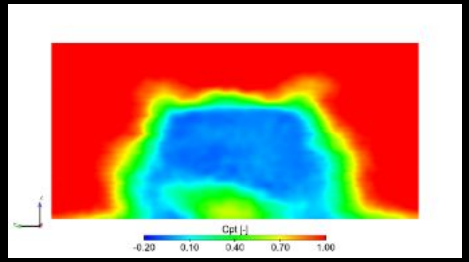
X [mm]	4007
Y [mm]	-1500 - 1500
Z [mm]	-267,6 – 1182,4

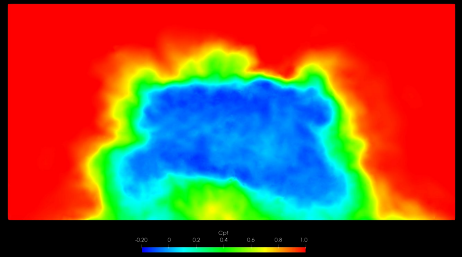
X [mm]	2807 – 4607
Y [mm]	0
Z [mm]	-267,6 – 1182,4

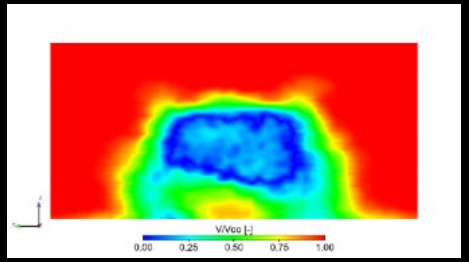
Results: Flowfield Measurements $x = 4\ m$

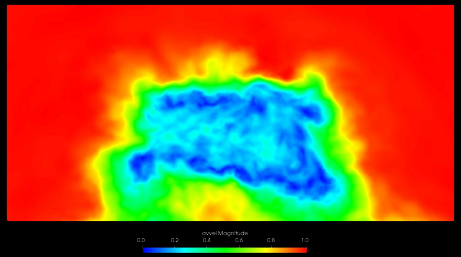
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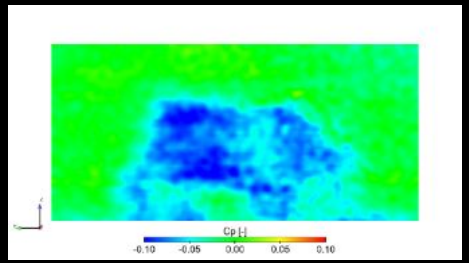
P-order 3 SOD2d
Pininfarina Ref

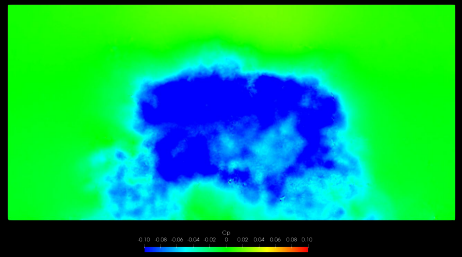


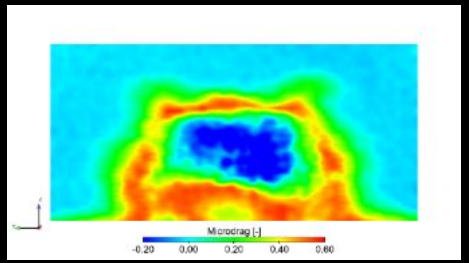


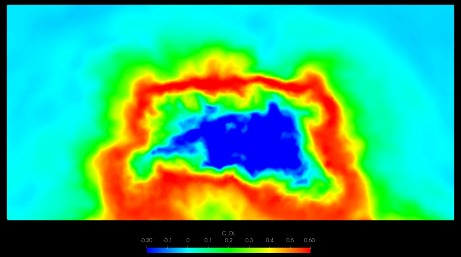








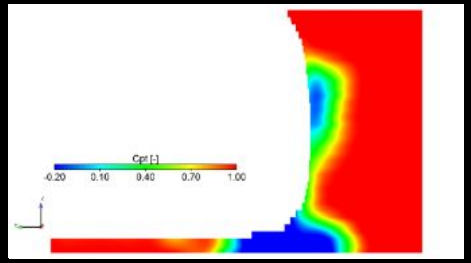


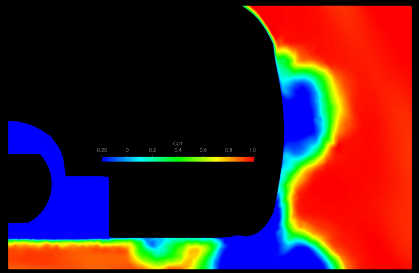


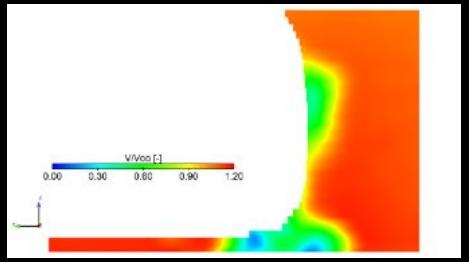
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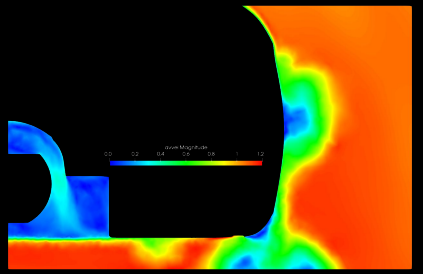
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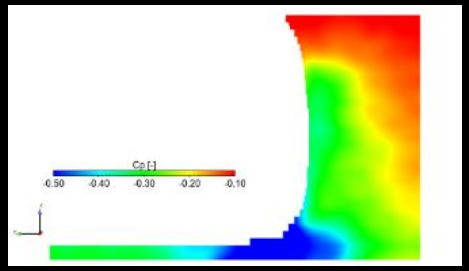
P-order 3 SOD2d
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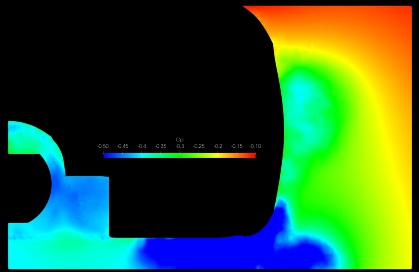


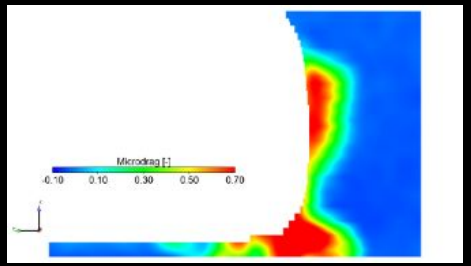


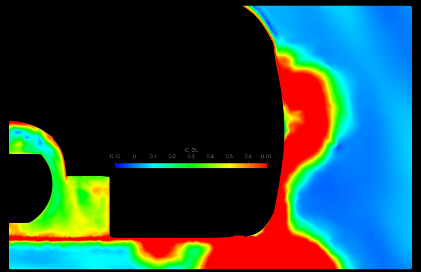








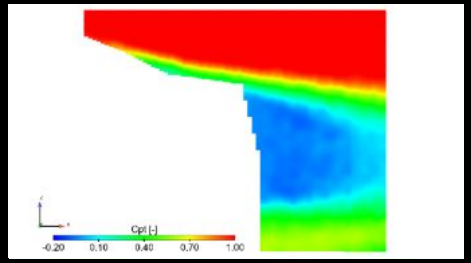


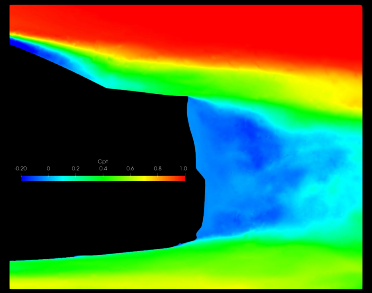


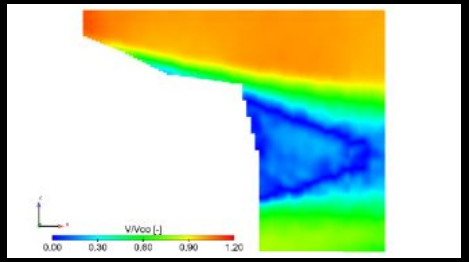
Results: Flowfield Measurements $y = 0\ m$

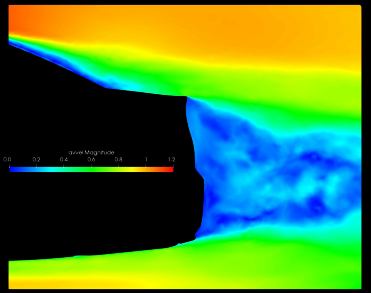
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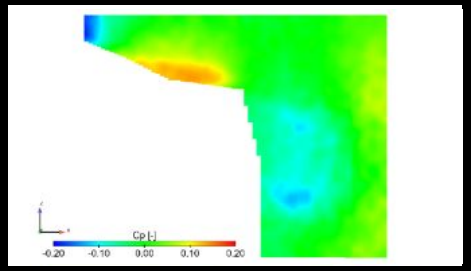
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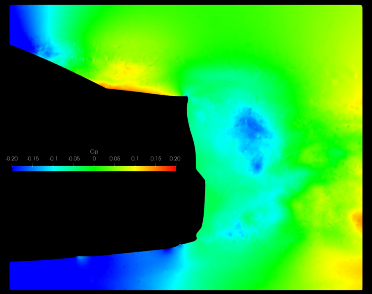


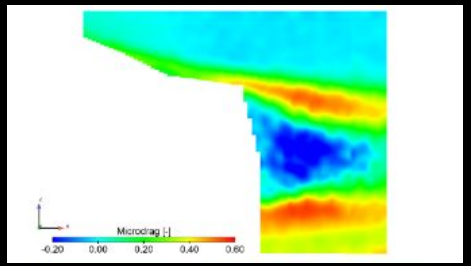


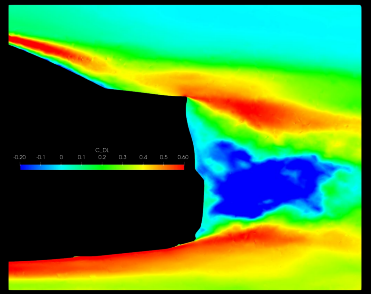












Conclusions

- **Meshing remains challenging**
  - **ANSA + MESSI** relaxes the meshing constraints
  - **Minimal** geometric **modifications** alleviate time-stepping restrictions
  - **AMR is essential** to properly distribute nodes in the relevant regions
  - **Anisotropic layers could** further reduce the number of nodes
- **Complex geometries remain computationally expensive for LES + SEM**
  - **Affordable** within a fortnight (depending on available resources)
  - **Reasonable agreement** of velocity profiles, pressure distributions, and flow fields **with experimental data**
  - **Accurate prediction of force coefficients**



Thanks for your attention!

Questions?

samuel.limonchi@bsc.es
oriol.lemhkuhl@bsc.es
samuel.gomez@bsc.es
herbert.owen@bsc.es