CURRENT STATUS DLR PARTICIPANT ID: 019

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Spatial discretization

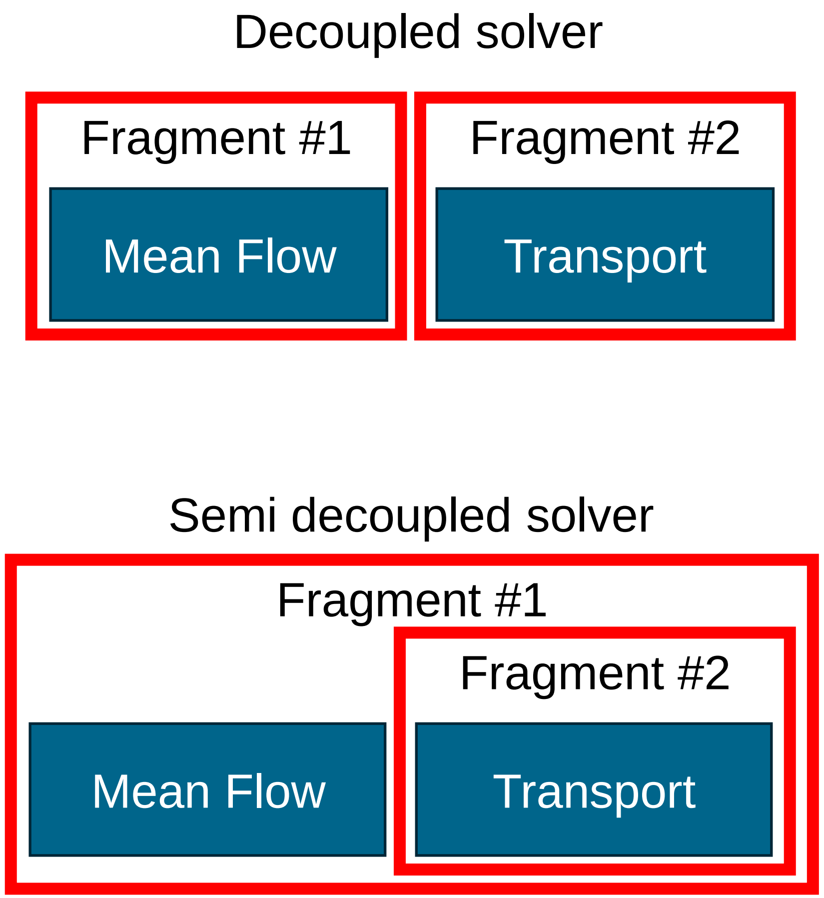
- CFD Software by ONERA, DLR and Airbus (CODA)
- SAneg turbulence model
- 2^{nd} order FV cell-centered
- Extended Green-Gauss gradients
  - Spline quintic limiter for the mean flow with smooth region attenuation
  - Unlimited turbulence

Solution strategy

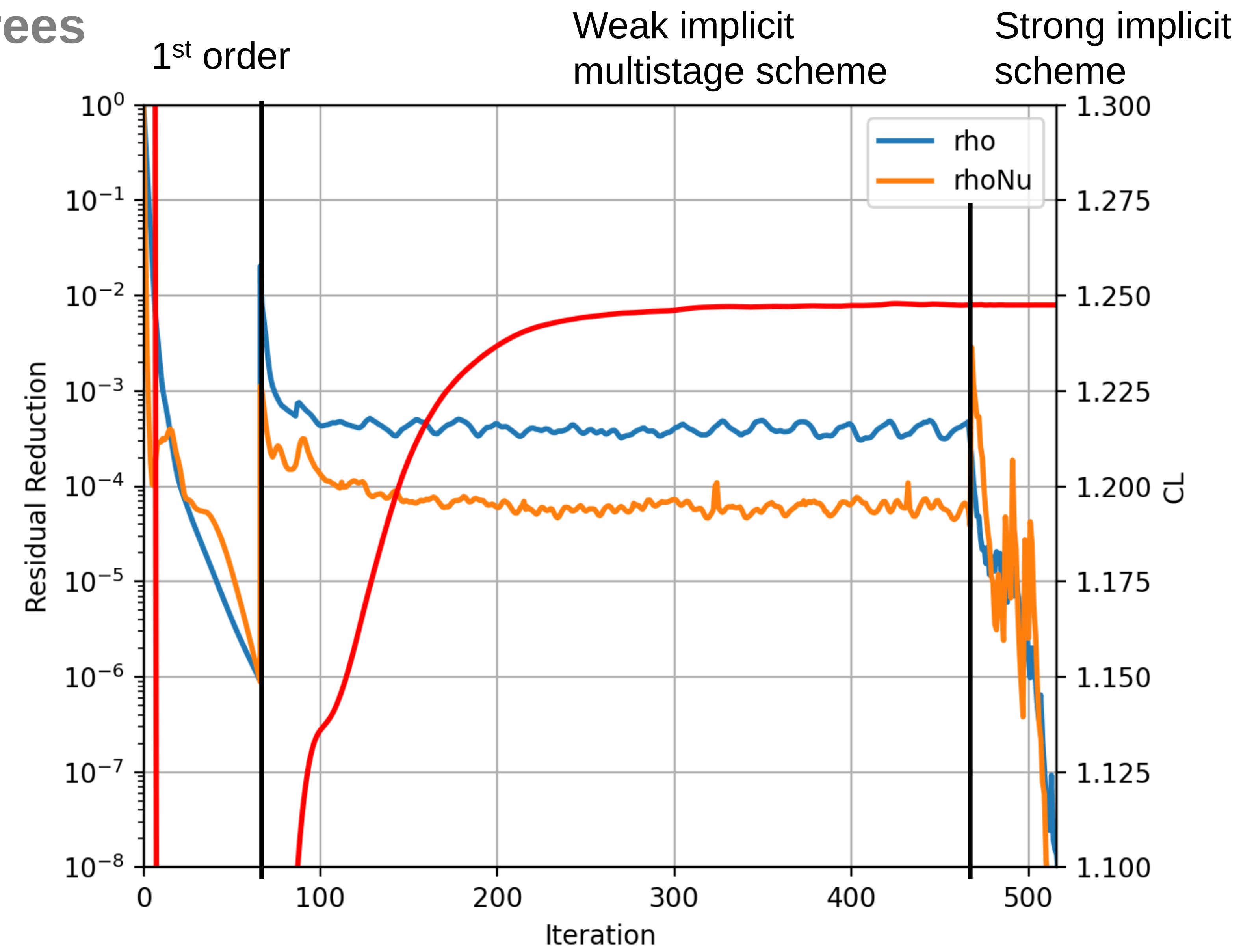
- Two stage solution approach
  1. Weak implicit multistage scheme
  2. Strong implicit Linearized Euler
     - SER-CFL ramping with CFL $\rightarrow \infty$ as residual approach 0
- Semi-decoupled time integration
  1. Full PDE
  2. Turbulence equations
- Strong linear solver
  1. GMRES
  2. Field Split
  3. Jacobi
  4. Process local ILU
- Iteration is stopped after density and turbulence residual have converged 8 order of magnitude compared to the free-stream residual

Semi-decoupled time integration

- Problems:
  - We need the decoupled solver to have non-exploding residuals for this test case
  - The fully decoupled solver struggles to converge to machine precision
- Solutions:
  - Switch to fully coupled solver in the latest stage
    - Not always stable
  - A hybrid between fully coupled and fully decoupled

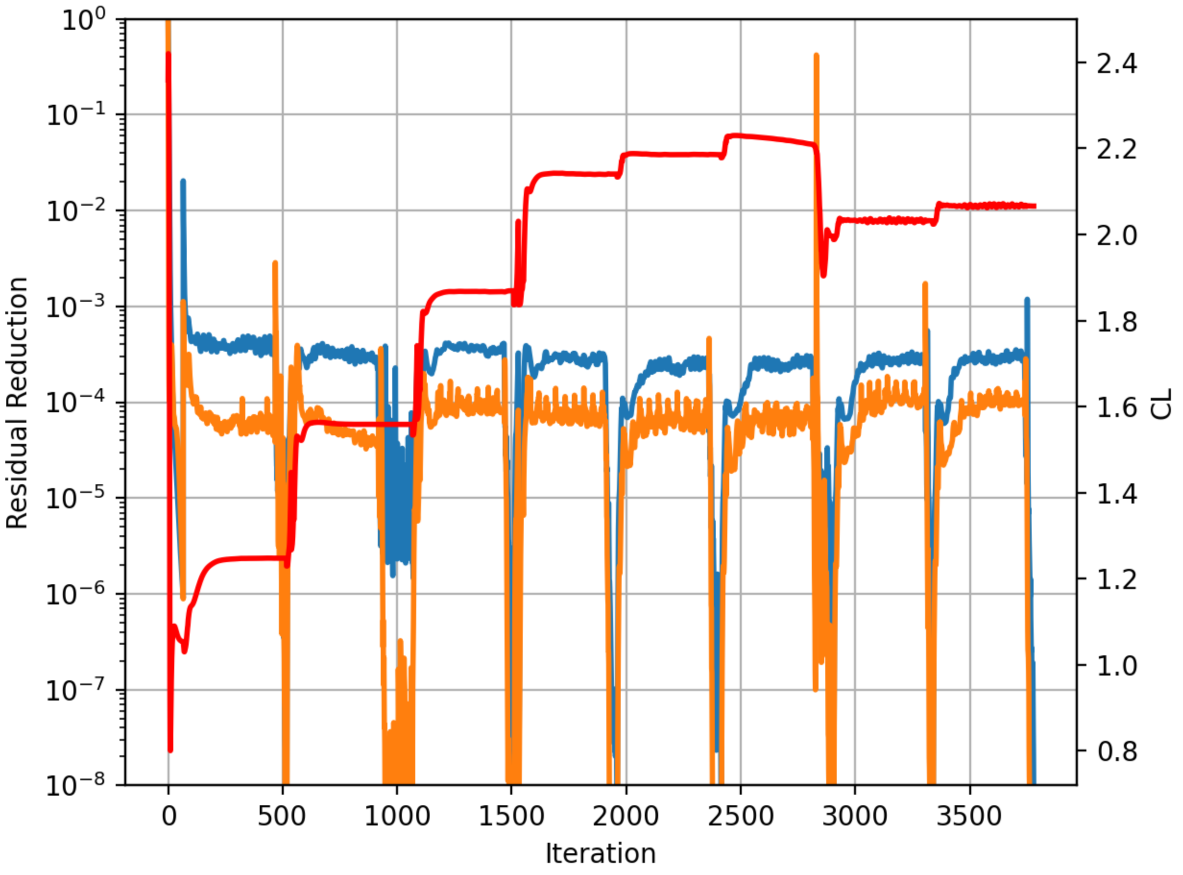


Example convergence history
Mesh A, 27 degrees



Example convergence history
Mesh D

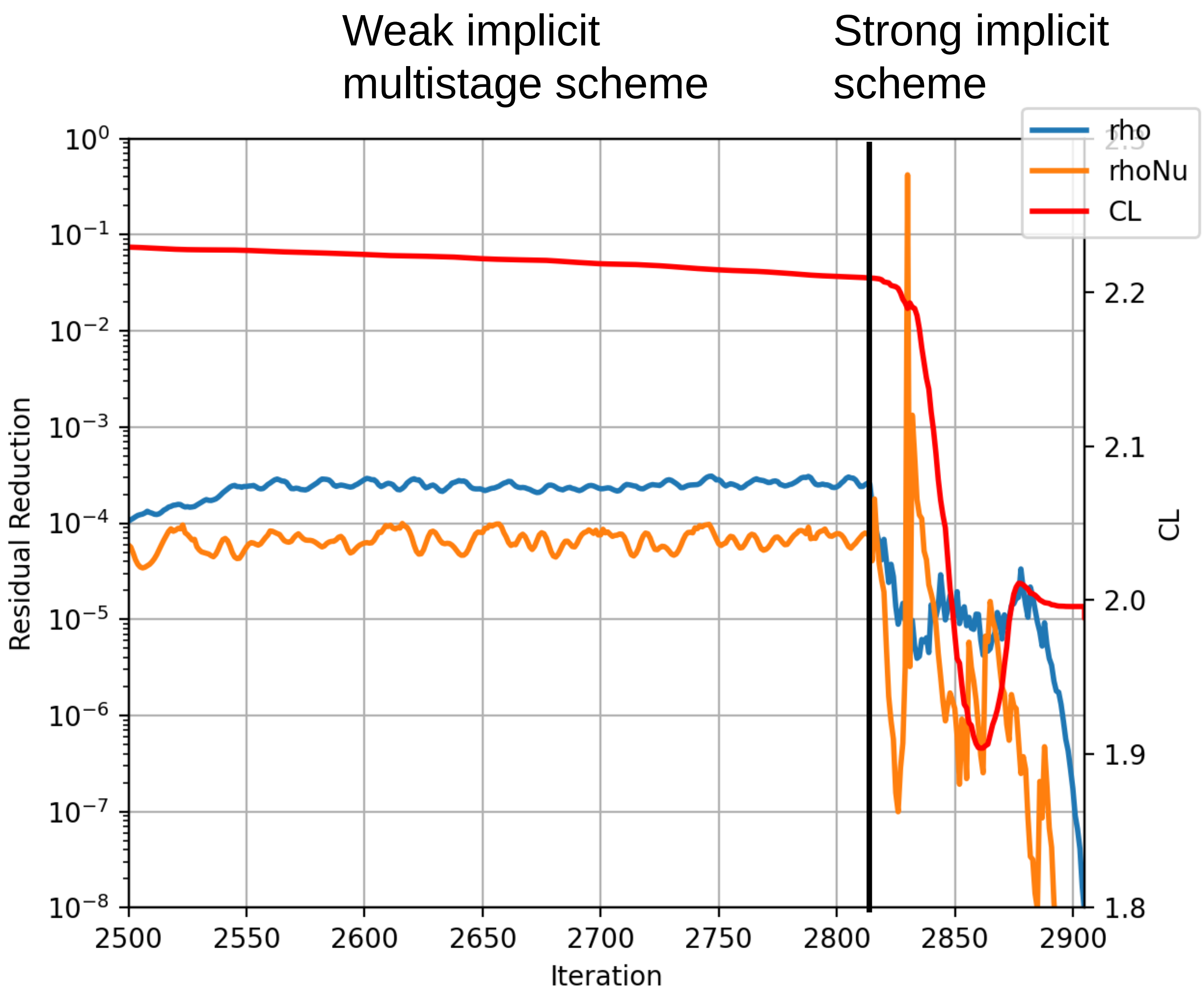
- Several additional angles of attack are considered to better examine Λ-separation
  - 10, 15, 20, 25, 26, 27, 28, 29, [30]
- All AoA (except for 15 degrees) are converged 8 orders of magnitude in density and turbulence variable (and all others but not shown)
- In practice warm starts/α-continuation is used but cold starts work as well
- This generalizes also to all coarser meshes



Example convergence history
Mesh D, 27 degrees

- In the weak implicit stage, no Λ-Separation is present
- Downward trend in the lift can be observed
- In the strong implicit stage, after a sharp increase in the turbulence variable Λ-separation appears

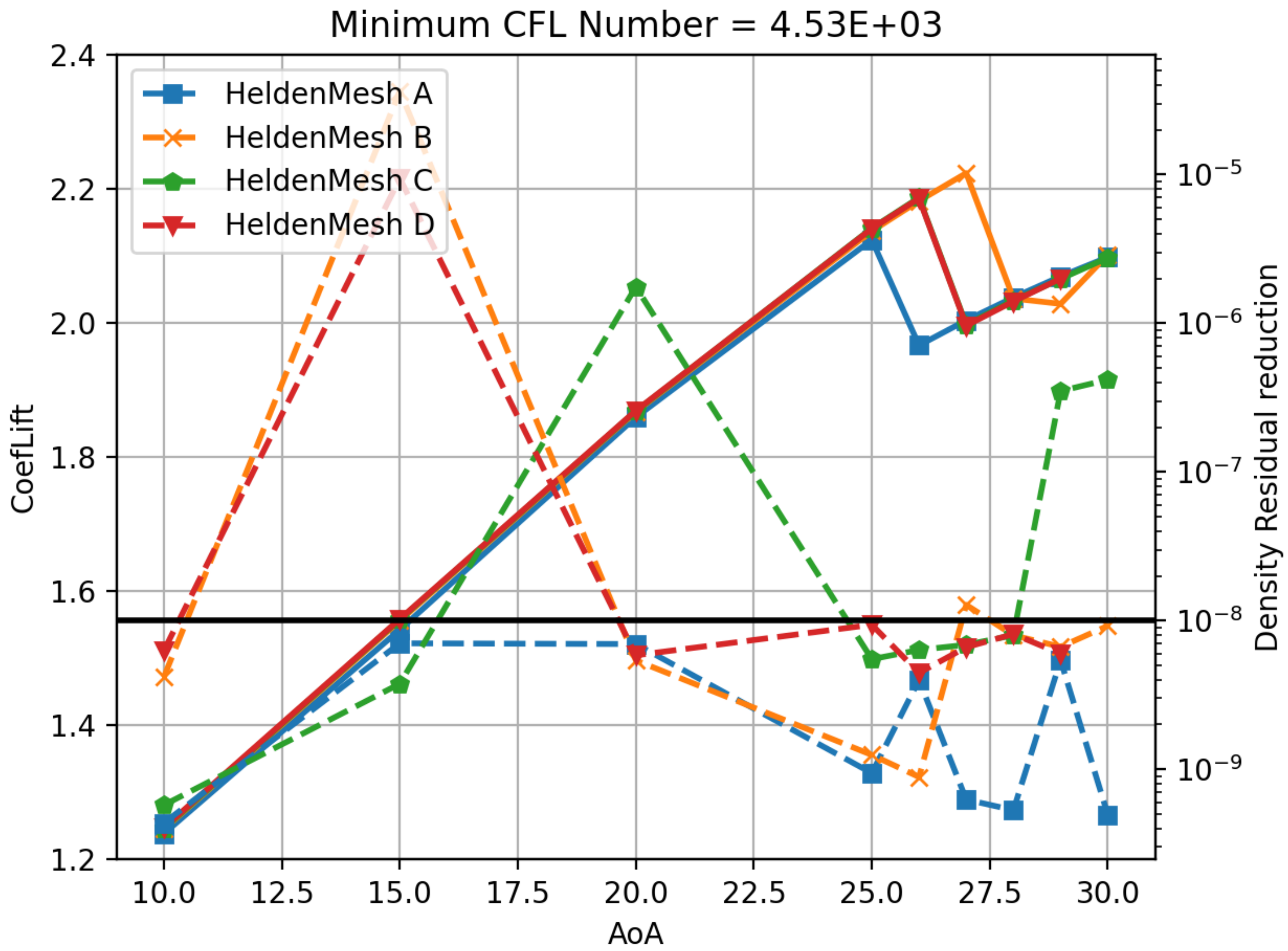
=> Λ-separation for an iteratively converged solution on a sufficiently fine mesh



Full polar

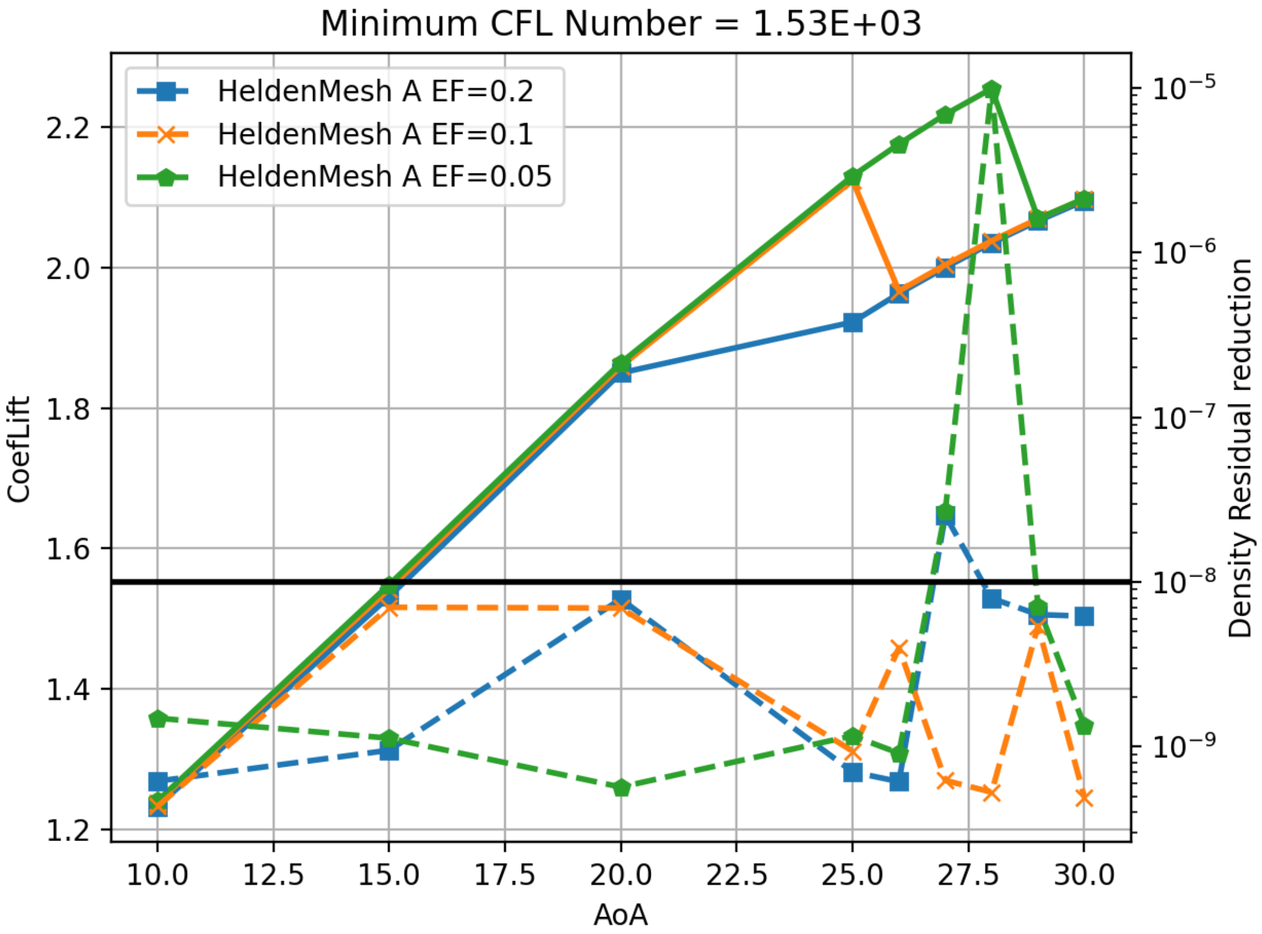
- Full polar computations on the 4 coarsest meshes
- Almost all angles of attacks are converged
  - Sometimes 15, 20 degrees struggle
  - Post stall can be difficult
  - Minimum CFL number of all datapoints is still quite high
  - Results are the same for hot and cold starts
- Finer meshes move Λ to higher AoA in general, Mesh B is an outlier
- A converged solution either has fully developed Λ or none

→Hypothesis: Excessive (numerical) dissipation can trigger Λ, which is a binary effect



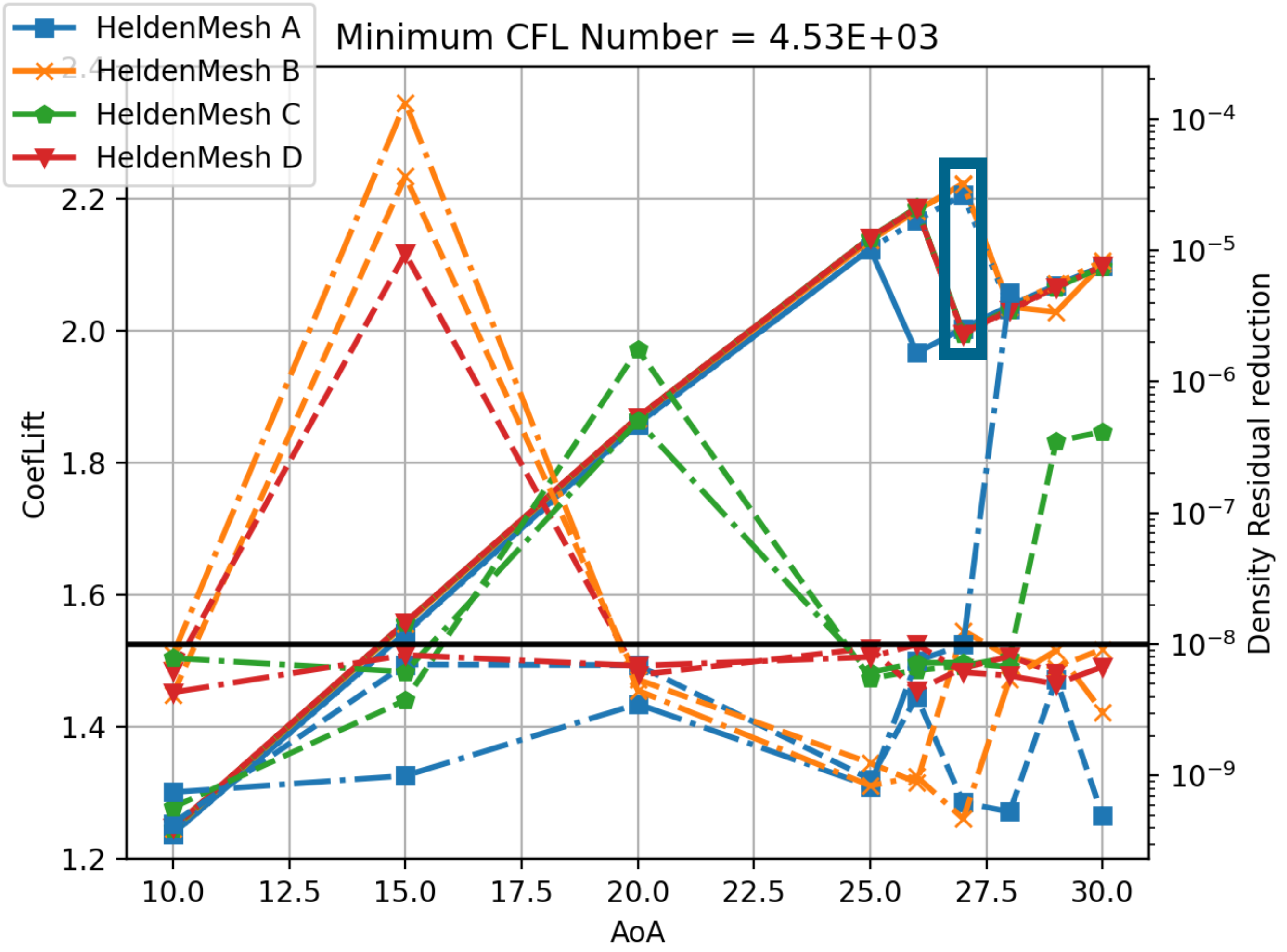
Λ-separation for varying numerical dissipation

- Use entropy-fix fraction (EF) to control numerical dissipation
  - On Mesh A
- All datapoints except $C_{L_{max}}$ of EF=0.05 are converged
- Increasing EF triggers earlier Λ-separation
- Decreasing EF leads to later Λ-separation
- => Lower dissipation might be beneficial, but brings stability issues (EF<0.05 did not converge)

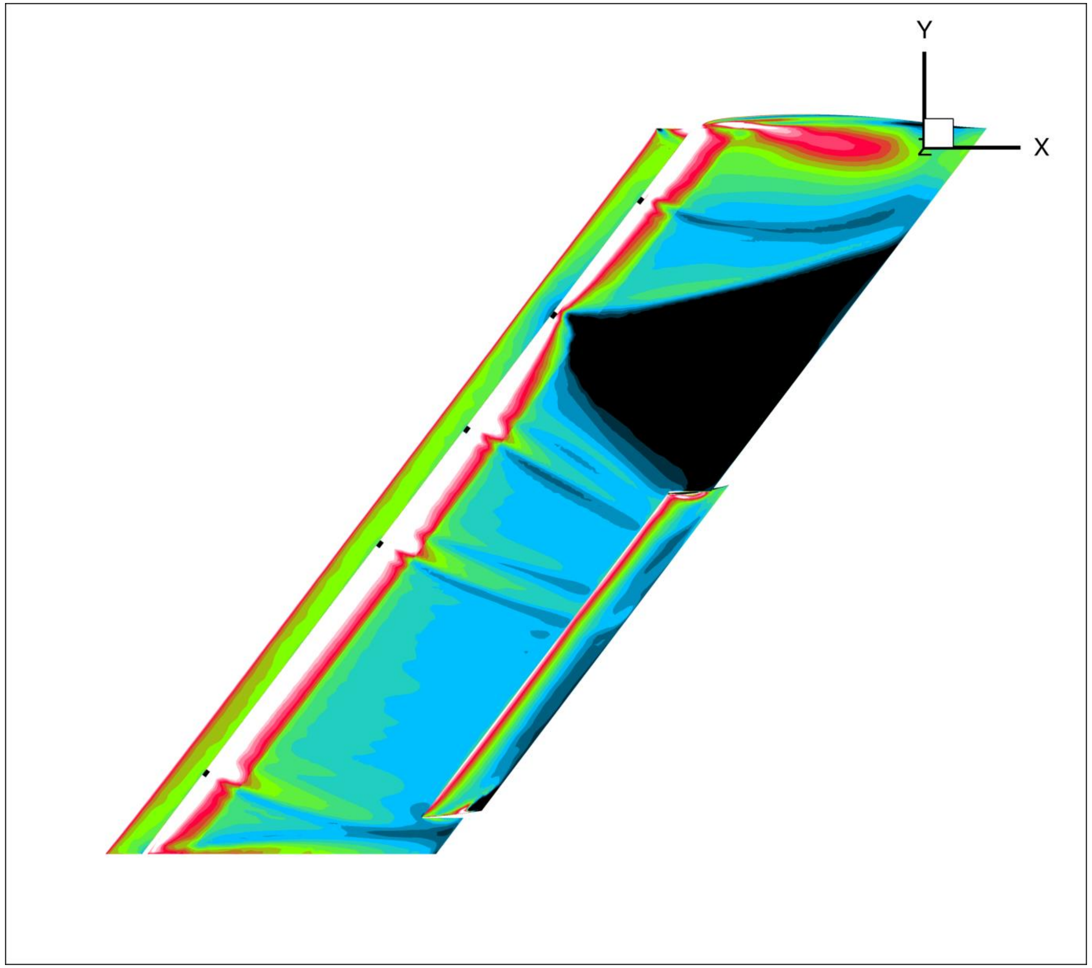


Influence of limiting on Λ-separation

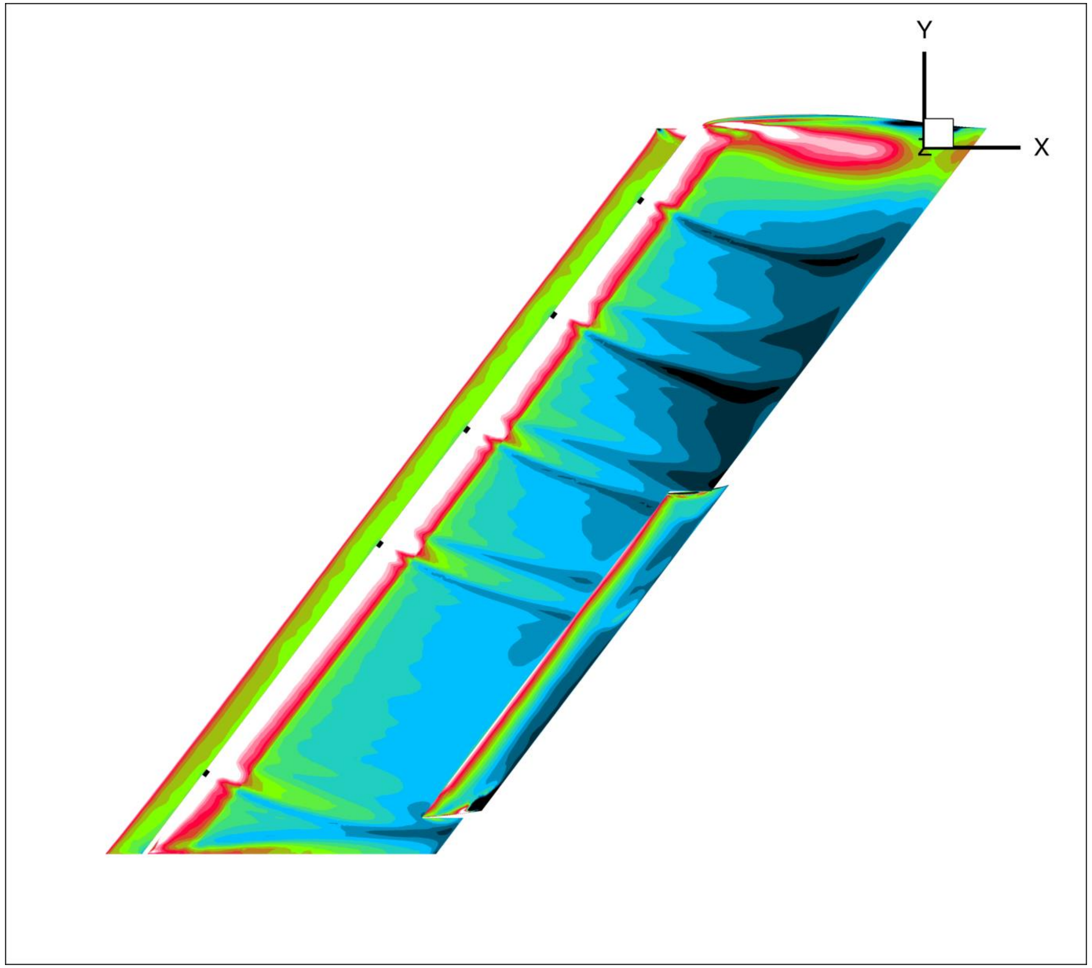
- Completely remove limiting
- Similar convergence levels as the limited computations
  - Faster in terms of wall clock time
- Strong influence on especially the coarsest mesh
- Finer meshes show no influence



Influence of limiting on Λ-separation
27 degrees Mesh A



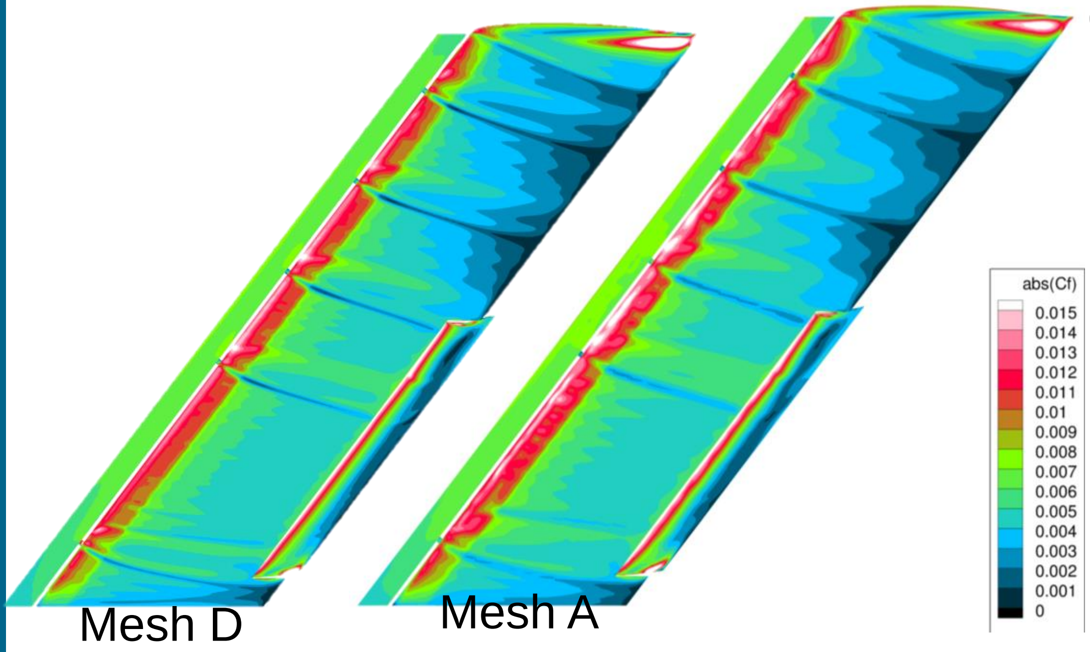
Limiting

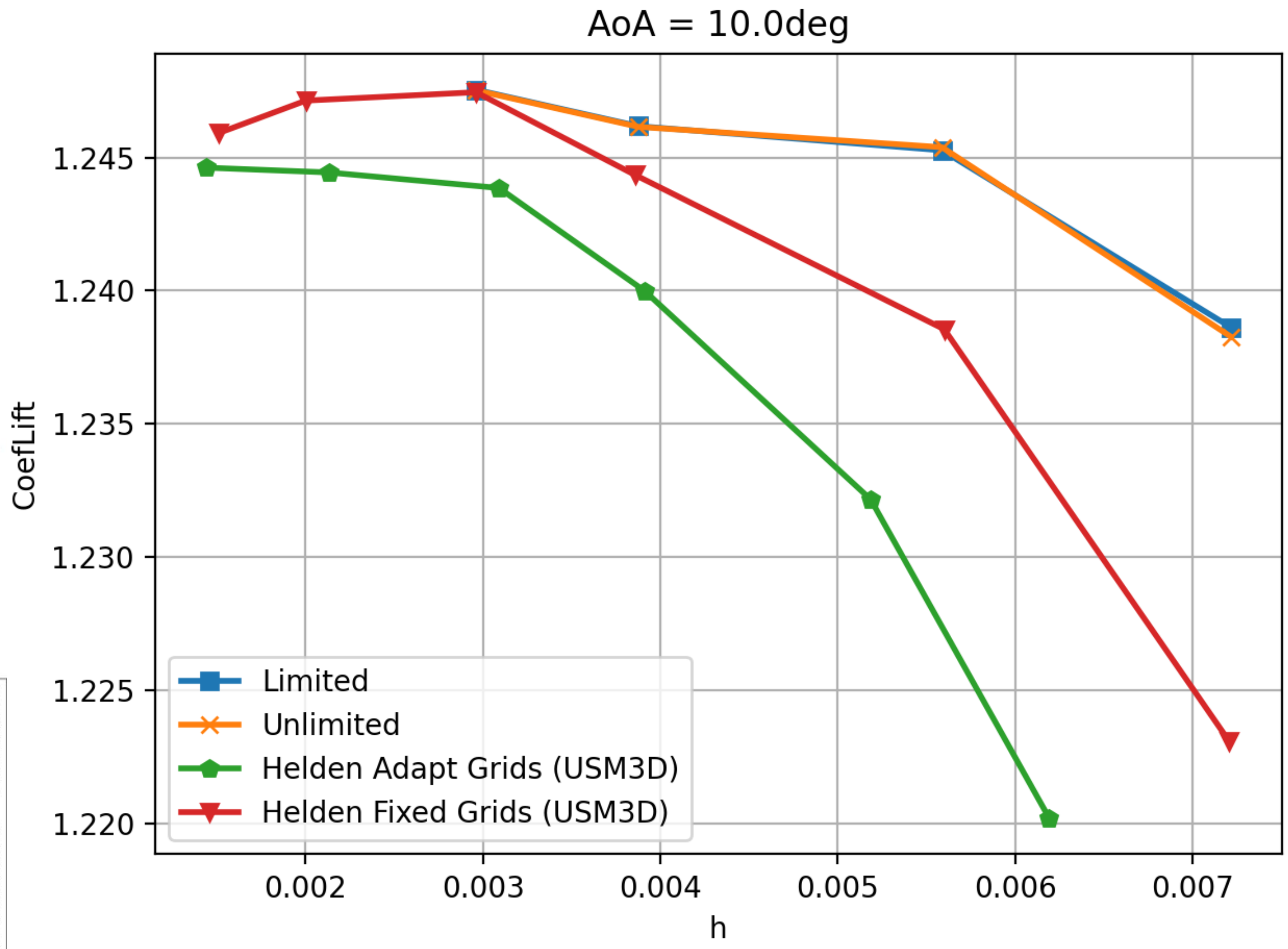


No Limiting

Spatial convergence 10 degrees

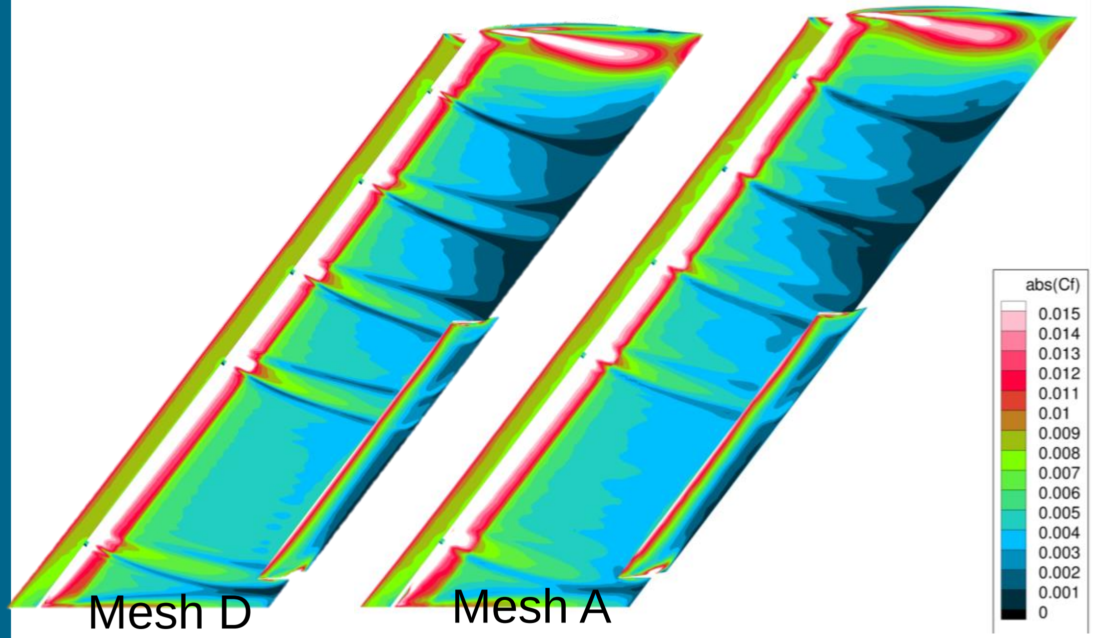
- Very good agreement between limited and unlimited gradients
- Good agreement on Mesh D with USM3D results

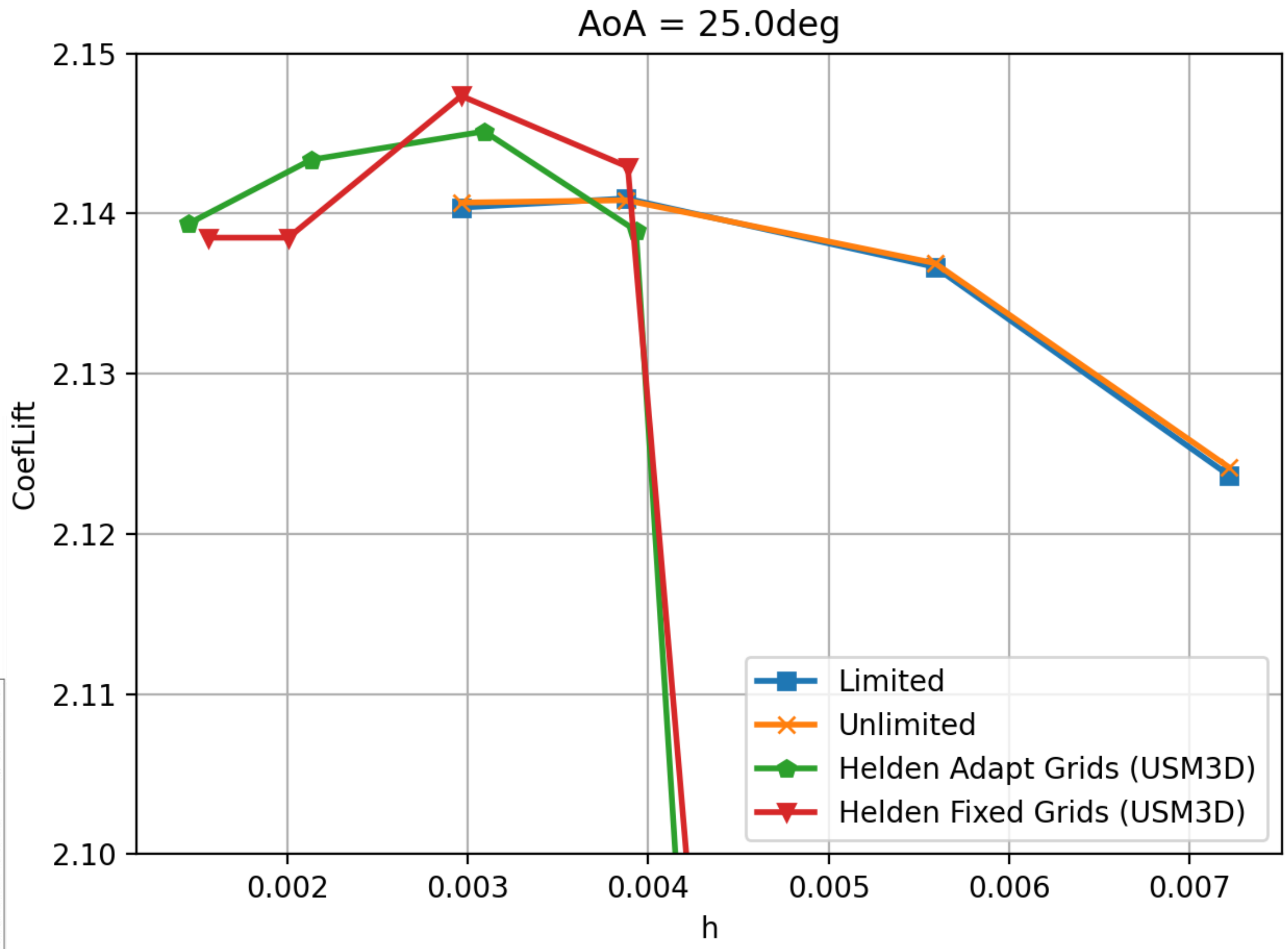




Spatial convergence 25 degrees

- Very good agreement between limited and unlimited gradients
- Good agreement with USM3D

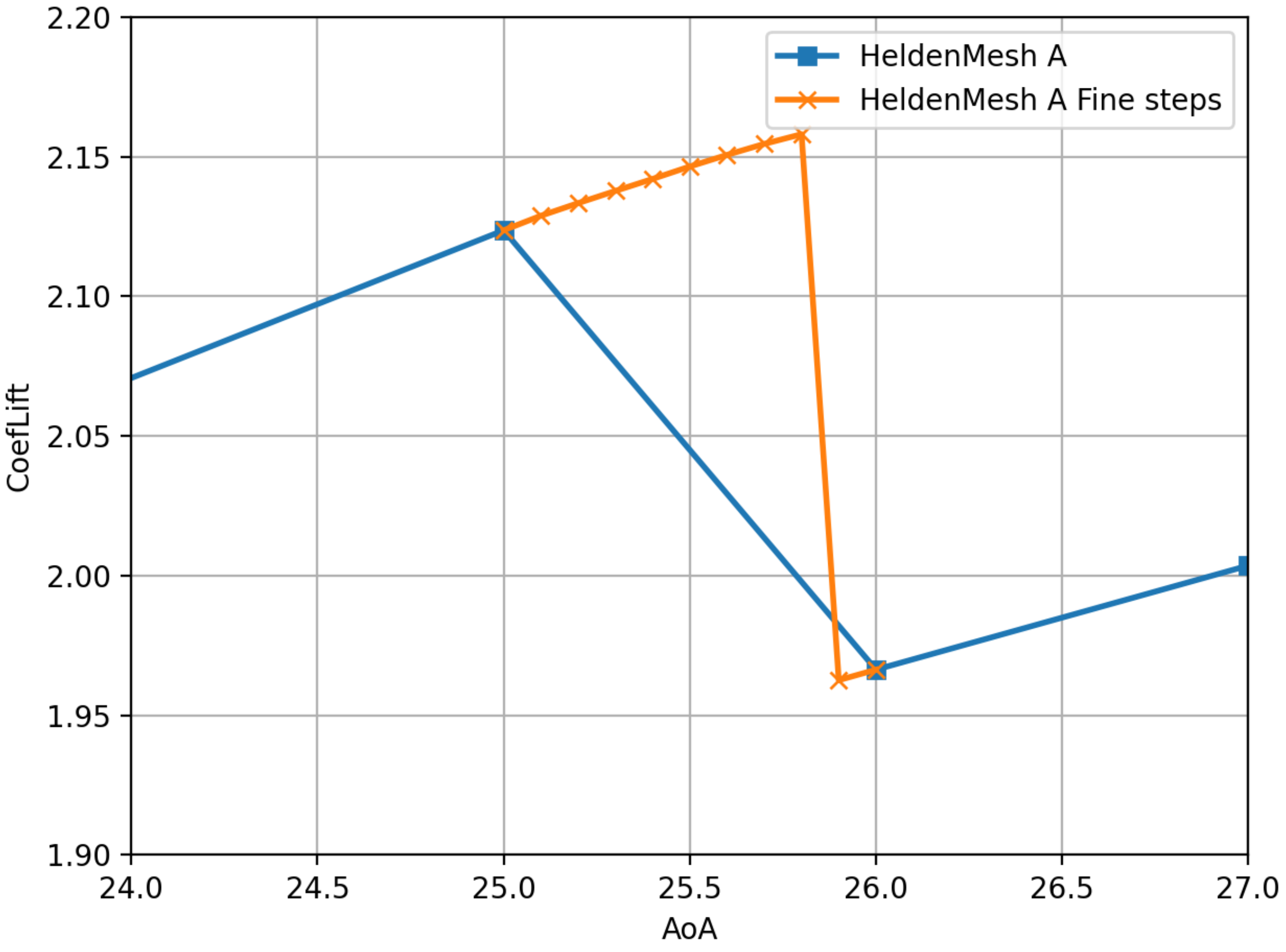




Sharpness of Λ-separation

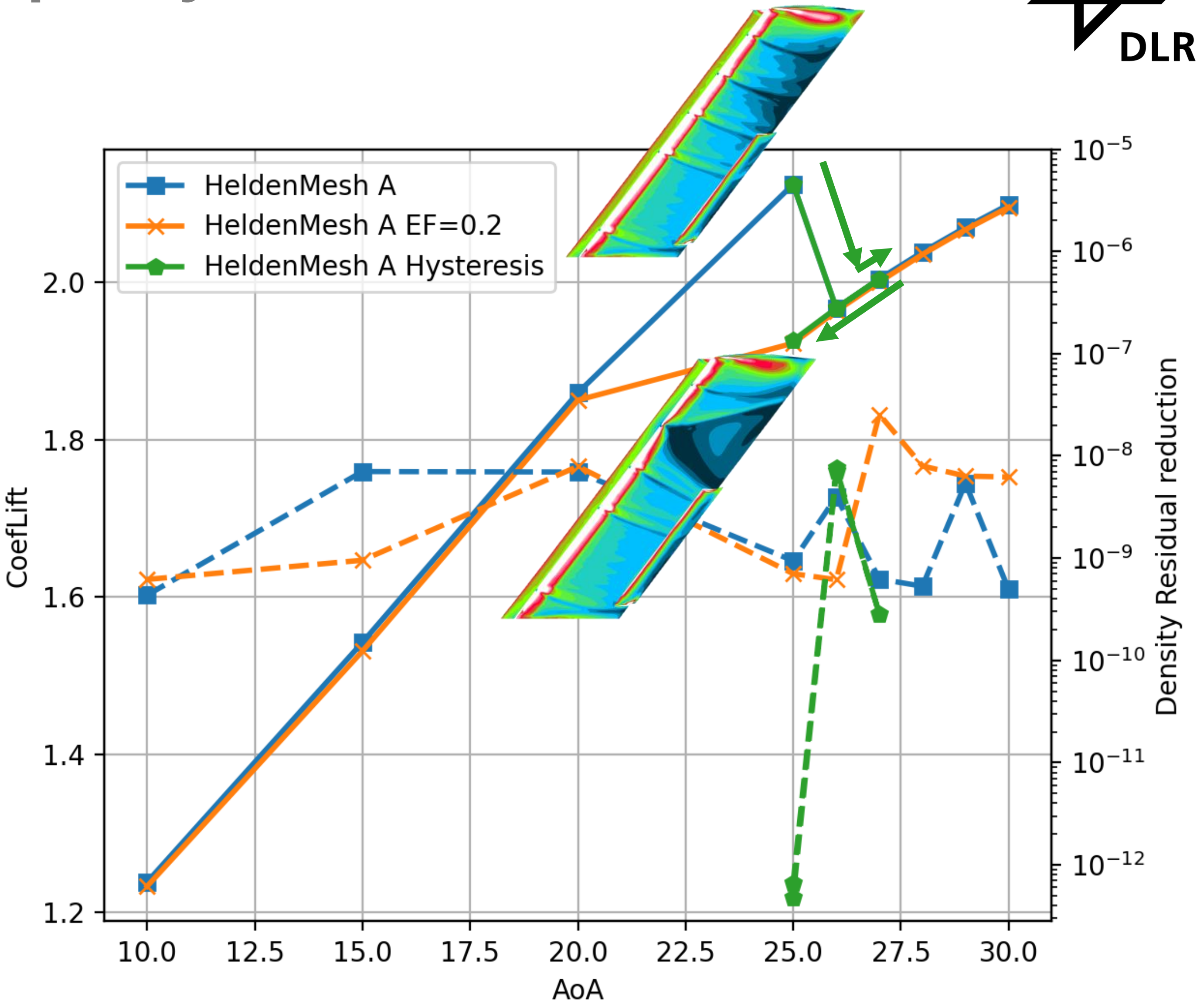
- 0.1deg angle of attack steps for Mesh A between 25 and 26 degrees
- Warm starts from previous angle of attack

- There is no gradual change to Λ-separation
- Λ-separation is a binary effect



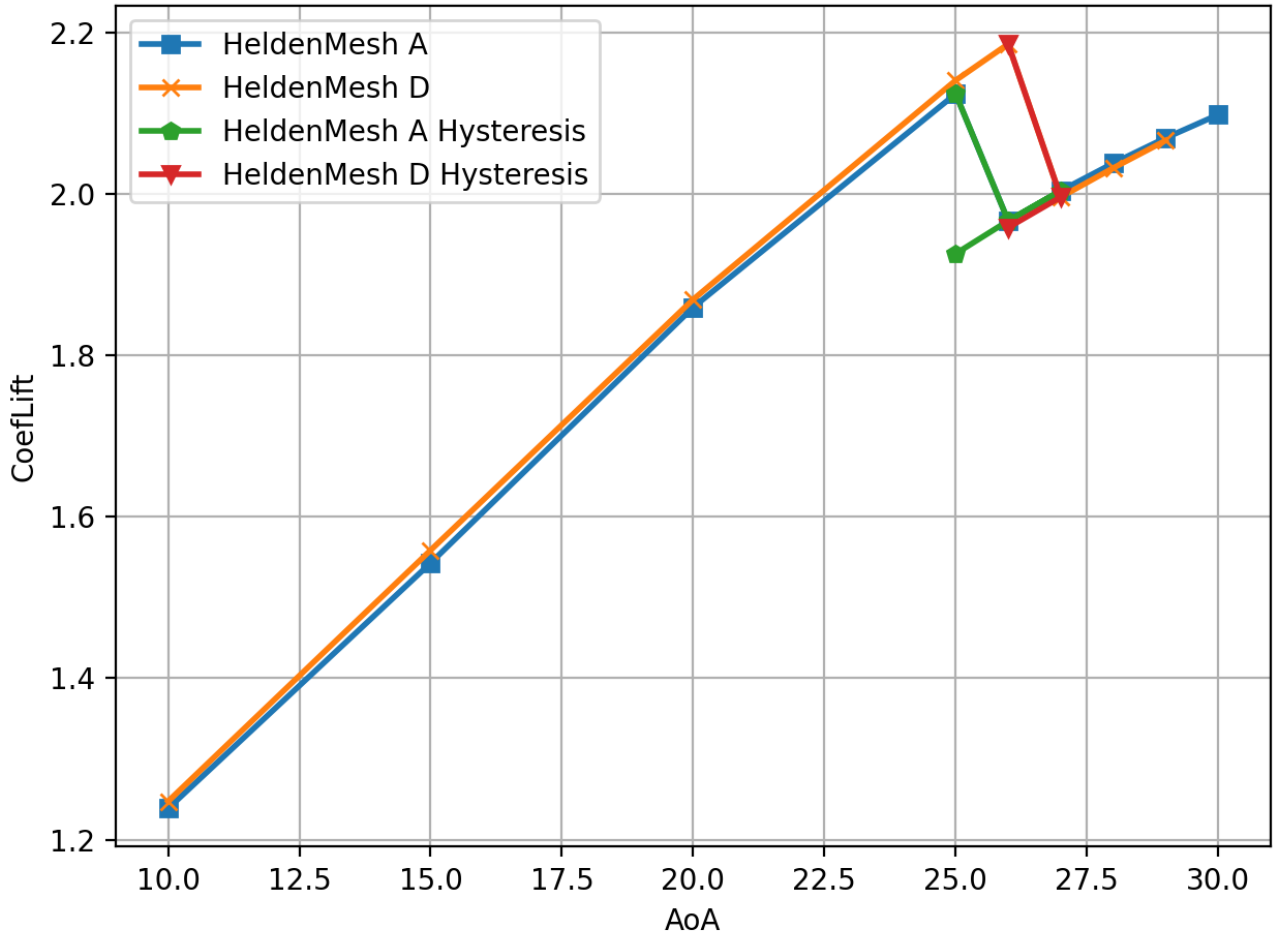
Hysteresis effects and multiplicity of solutions

- Polar that introduces Λ-separation which then tries to recover
  - 25 →26 → 27 → 26 → 25
- Warm starts of each angle of attack from the previous angle of attack
- Attached flow is not recovered and 2 different converged solutions are obtained on the same mesh for the same numerical settings
- Both solutions at 25 degrees are converged 12 orders of magnitude



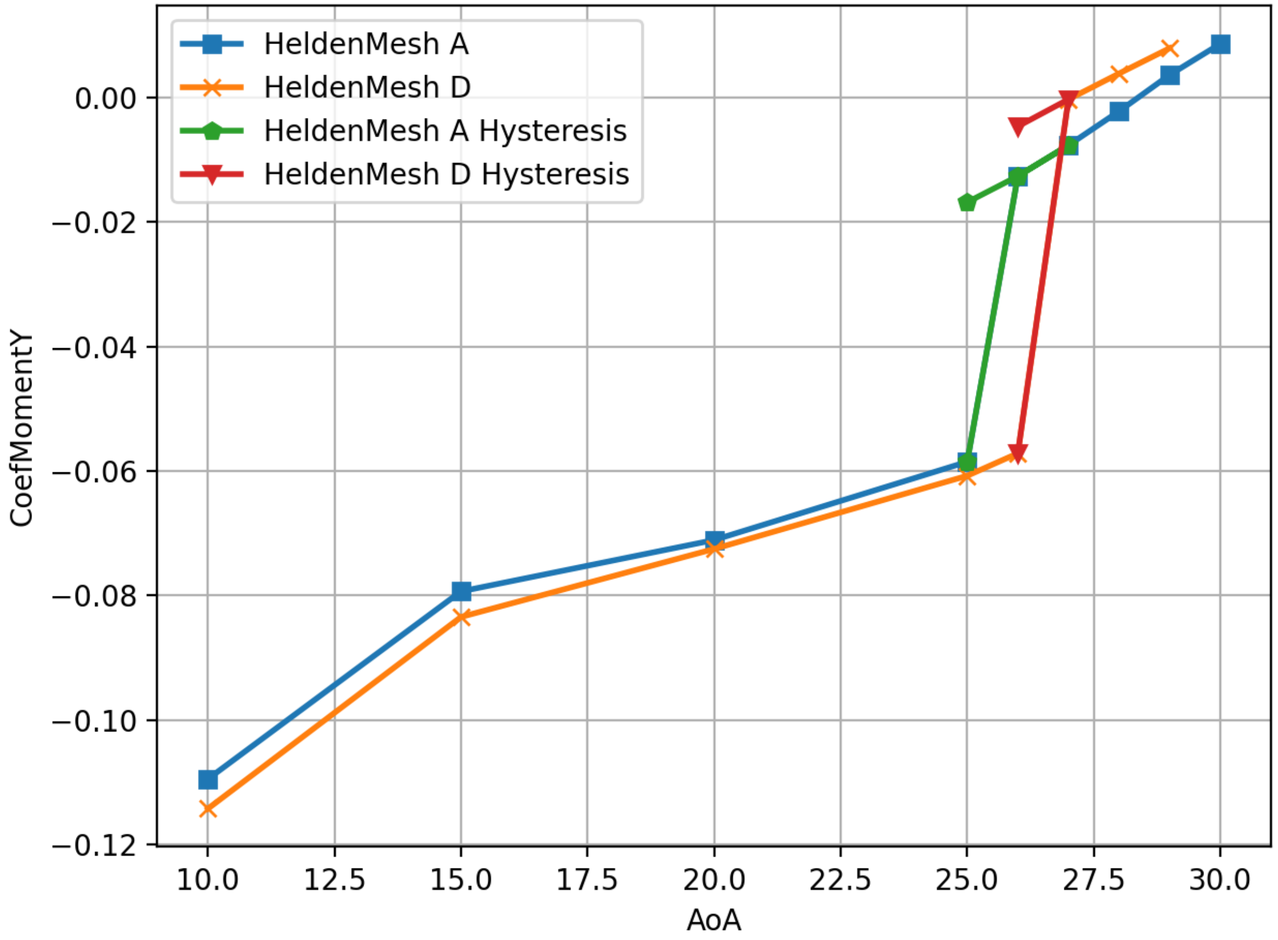
Multiplicity of solutions on fine meshes

- Polar on mesh level D
  - 26 → 27 → 26
- 12 order of residual reduction
- Multiple solutions exist also on the fine mesh



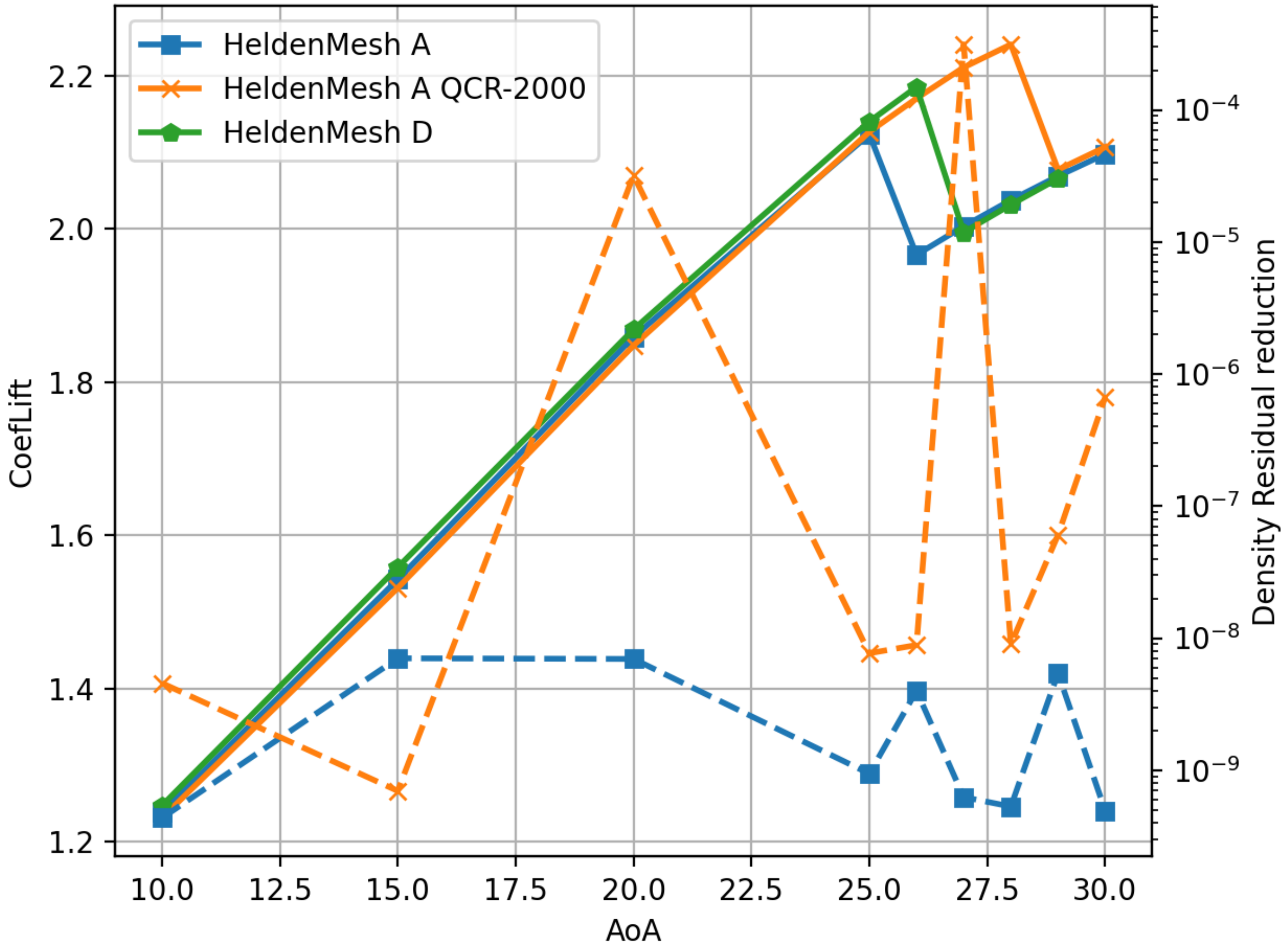
Multiplicity of solutions on fine meshes

- Polar on mesh level D
  - 26 → 27 → 26
- 12 order of residual reduction
- Multiple solutions exist also on the fine mesh
- Visible in the moment coefficient
- Similar difference between fine and coarse mesh for both separated and attached solutions



QCR-2000

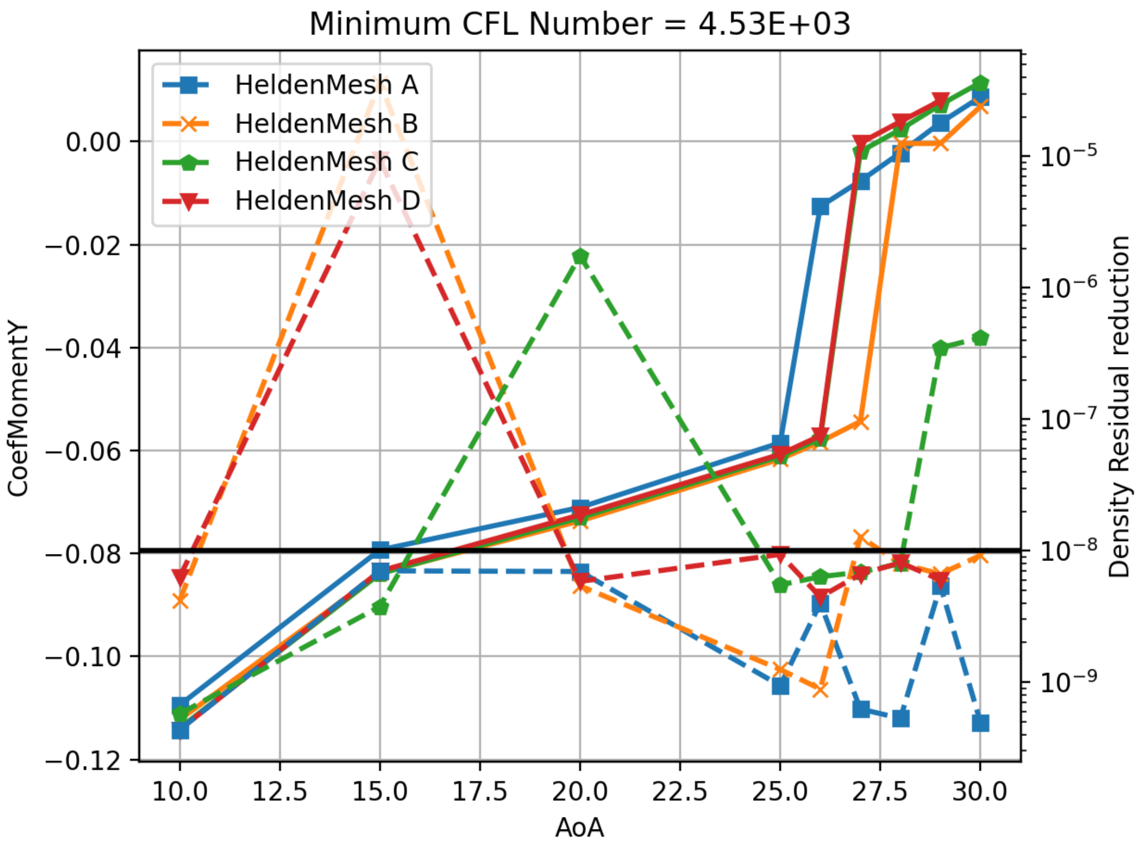
- Convergence issues with QCR-2000 for some angles of attack
- QCR-2000 delays Λ even more than just higher mesh resolution
- Full Λ is still present at some point for a converged solution



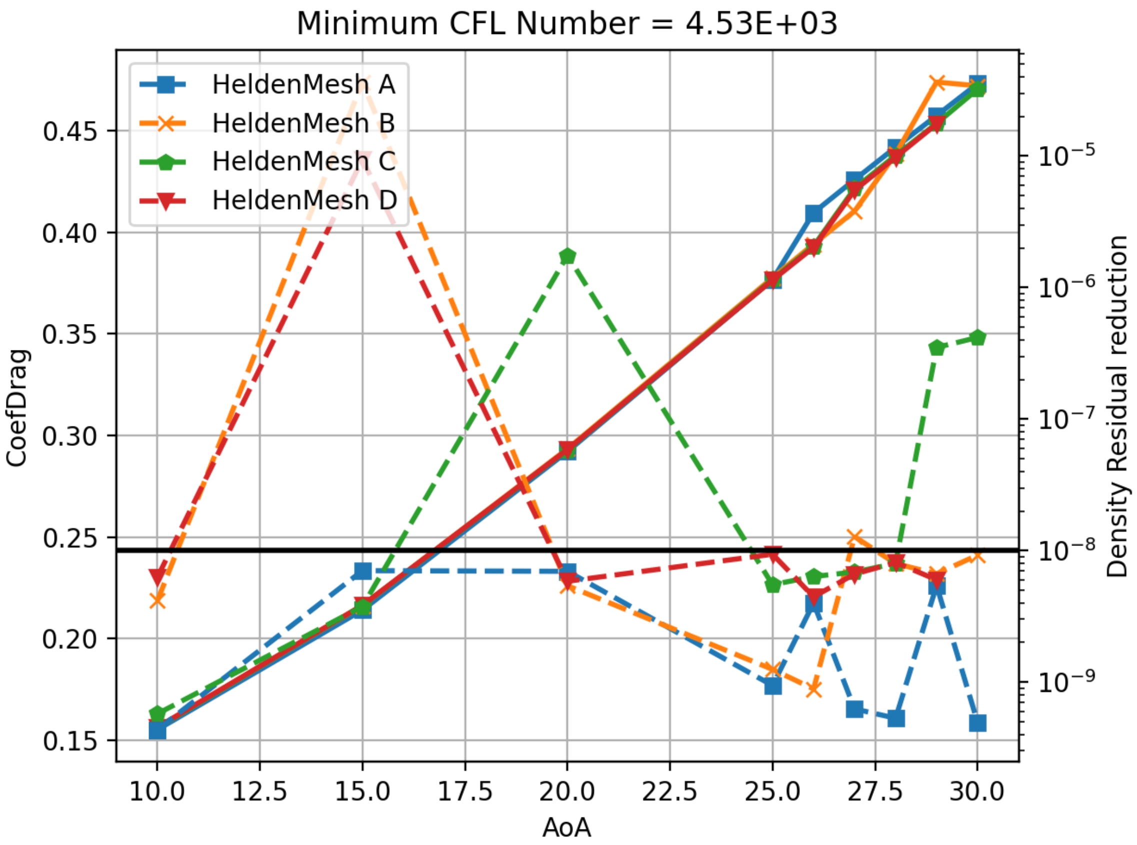
Take aways

- Λ-separation can occur for iteratively converged computations
  - SAneg
  - SAneg-QCR2000
- Lower dissipation delays Λ-separation
  - Lower entropy fix fraction in convection scheme
  - Finer meshes
  - Less limiting
- Λ-separation happens on all meshes up to level D
- Λ-separation is a binary effect without a smooth transition
- Λ-separation is most likely one of potentially many solutions on a single grid

Additional polars



AoA



Mesh convergence 28 degrees