Simulation of Bluff-Body Stabilized Flames with PeleC, an Exascale Combustion Code

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Turbulence and Energy Systems Laboratory
UNIVERSITY OF COLORADO **BOULDER**

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Problem Overview

In many high-speed systems, maintaining stable combustion is a challenge

Campbell & Chambers (1994)

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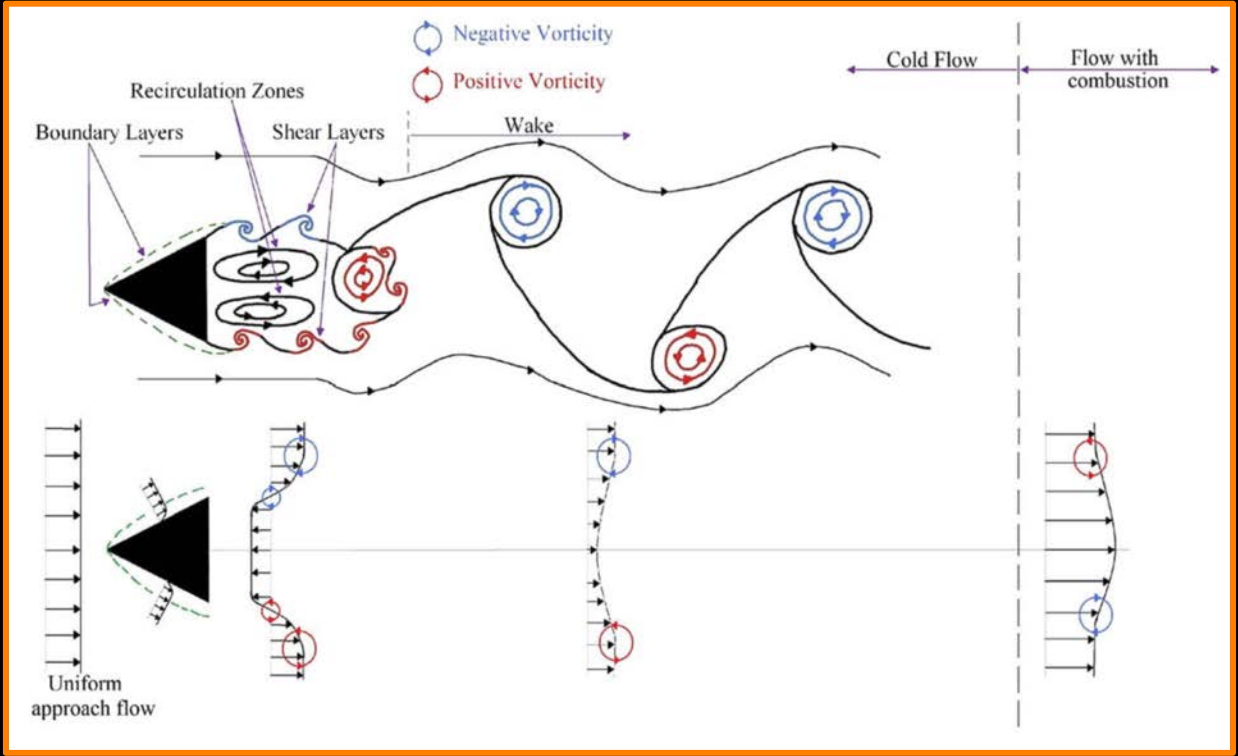
Accurately capturing the physics of these zones with low-resolution codes is an ongoing challenge

We use Blue Waters to perform high-resolution simulations

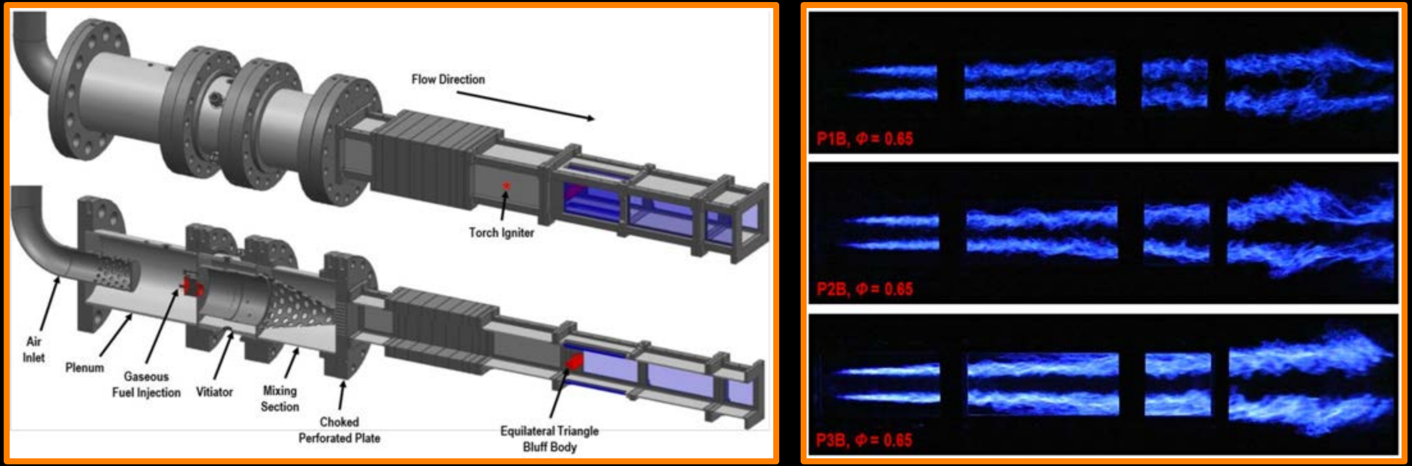
Campbell & Chambers (1994)

Turbulent Combustion Dynamics



Shanbhogue, Husain, Lieuwen (PECS, 2009)

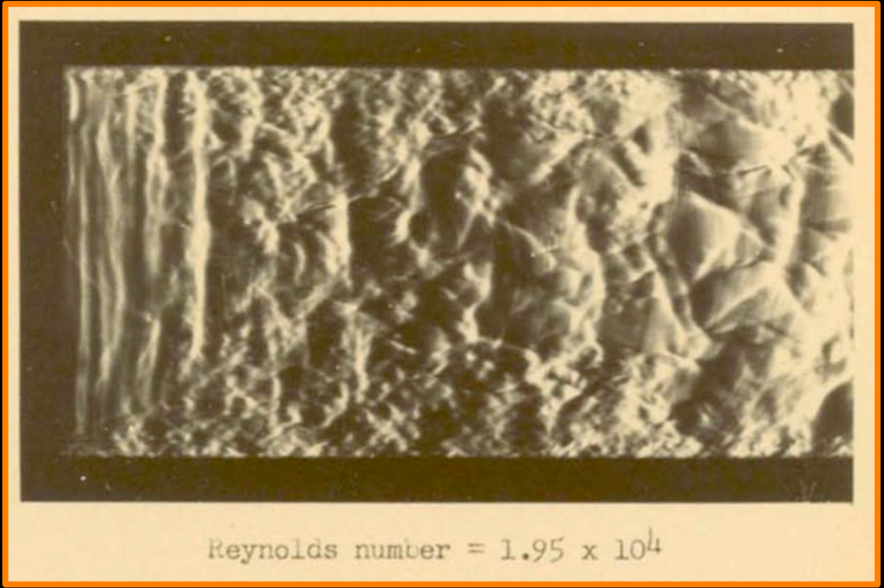
The Air Force Research Laboratory Case



Paxton et al. (AIAA, 2019)

- Flame stabilization by bluff bodies goes back to the first half of the 20th century
- The AFRL experiments are currently ongoing
- Matching computational and experimental results remains a challenge

Problem Overview: The AFRL Case



Methane flame stabilized on a circular rod, Zukoski (1954)

- Where can simulations realistically compare against experimental data?
- A common computational shortcut is to use a smaller spanwise domain with periodic boundary conditions in that direction
- There is very little in the literature on aspect ratio and spanwise boundary effects for these cases

PeleC

Exascale Combustion Code

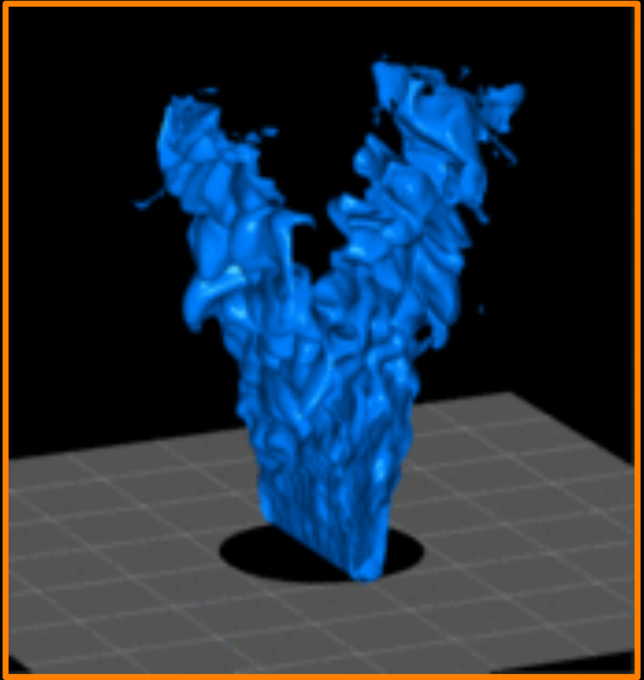
- Developed at LBNL, NREL, and ANL for performance on current and future supercomputers
- Direct Numerical Simulations (DNS) of turbulence-chemistry interactions in conditions relevant to practical combustion devices
- Embedded Boundary (EB) capability for modeling device structure
- Adaptive Mesh Refinement (AMR) built on the AMReX framework

(https://amrex-codes.github.io)

PeleC: Built on AMReX

Block-Structured AMR

- Increase efficiency by focusing on dynamically important regions
- For the cold flow we refine on cut cells (the bluff body) and vorticity magnitude.
- For reacting cases we are currently also refining on intermediate species
- We see orders of magnitude speedup over static refinement



(https://amrex-codes.github.io)

Non-Reacting Convergence:

Intent:

- Study effects of AMR on convergence of bluff-body flow simulation: “how much refinement do we need?”
- Understand effects of varying aspect ratio: “how wide a domain do we need?”

Cases:

Aspect Ratio

Levels of AMR

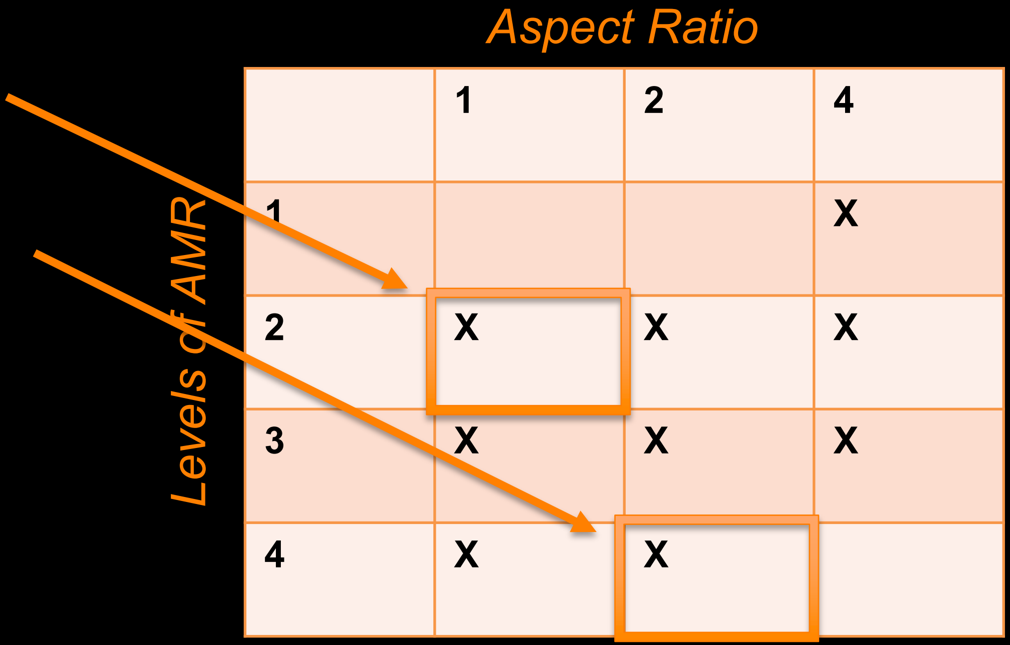
	1	2	4
1			X
2	X	X	X
3	X	X	X
4	X	X	

Non-Reacting Convergence:

Computational Cost:

- Cheapest: run on 4 nodes, ~100 node-hours
- Most expensive: run on 80 nodes, ~20,000 node-hours.
- Good weak scaling in this range on Blue Waters.
- Scaling is limited by AMR refinement level and criteria

Cases:

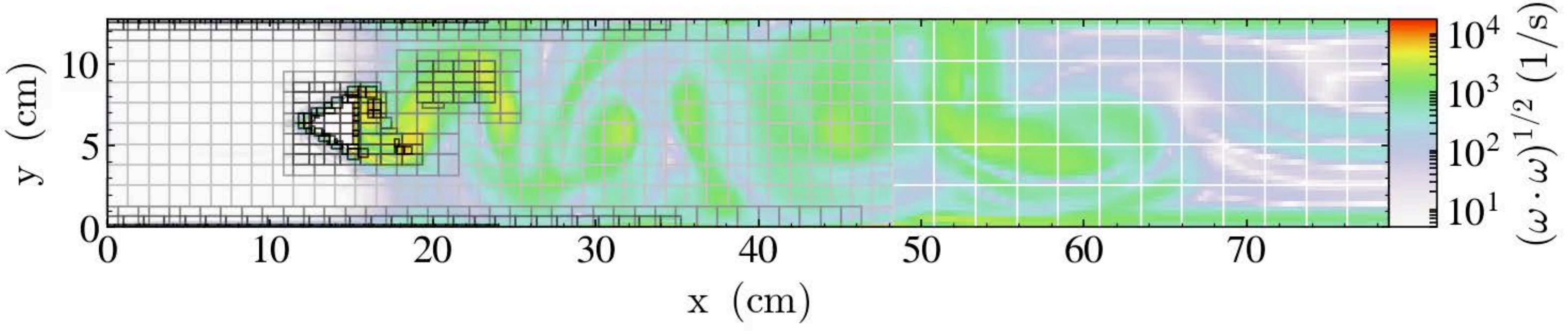


Aspect Ratio

Levels of AMR

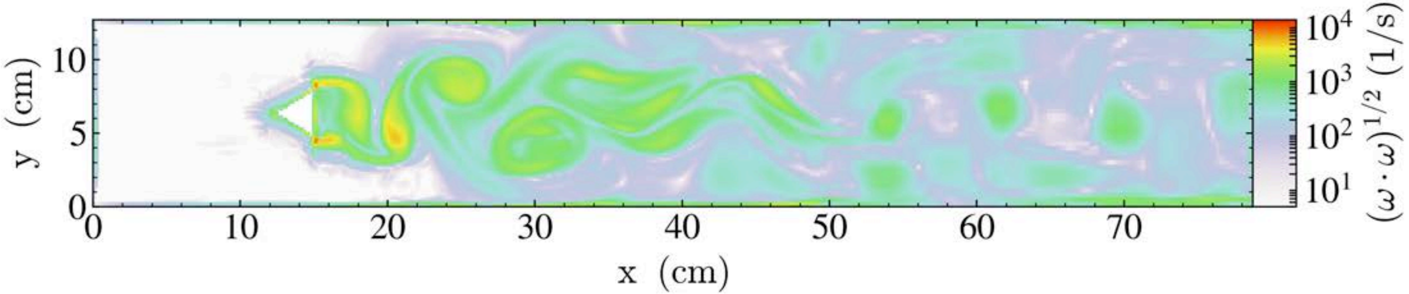
	1	2	4
1			X
2	X	X	X
3	X	X	X
4	X	X	

AMR In Action

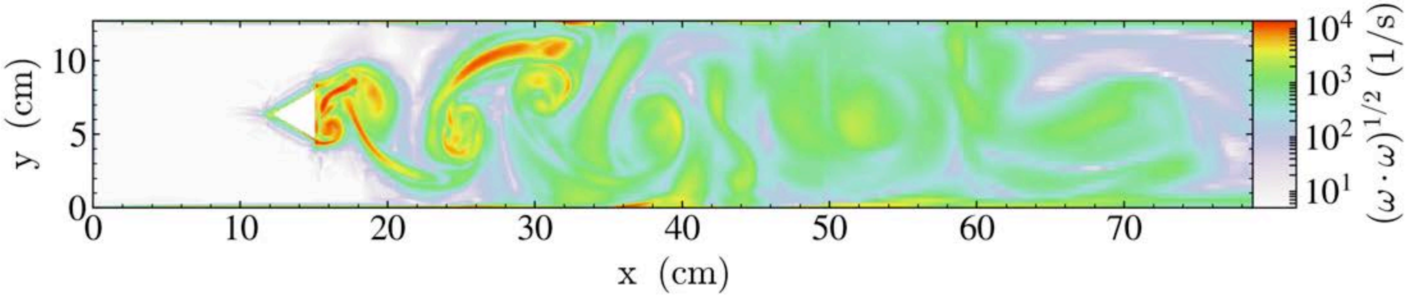


Increasing AMR Levels and Local Resolution

1 AMR Level

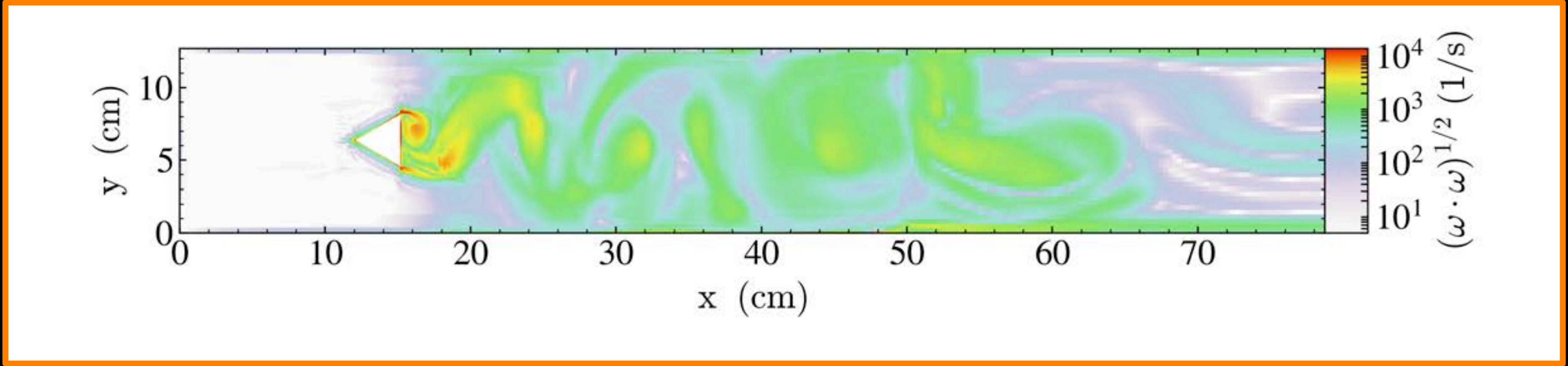


2 AMR Levels

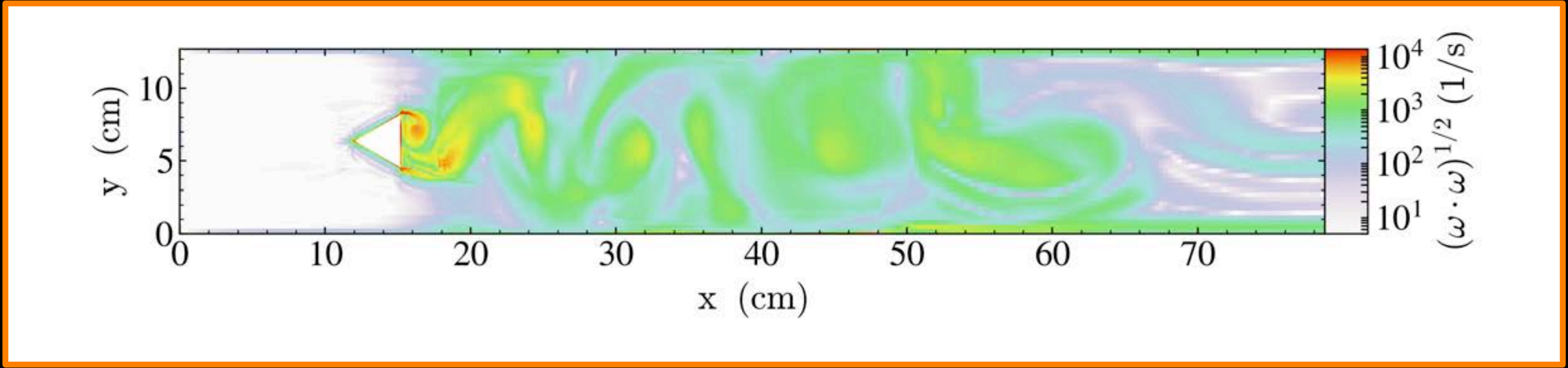


Increasing AMR Levels and Local Resolution

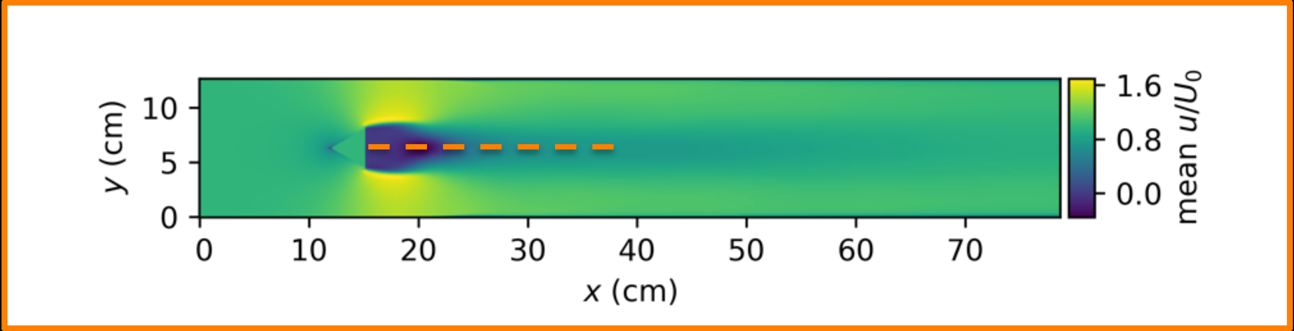
3 AMR Levels

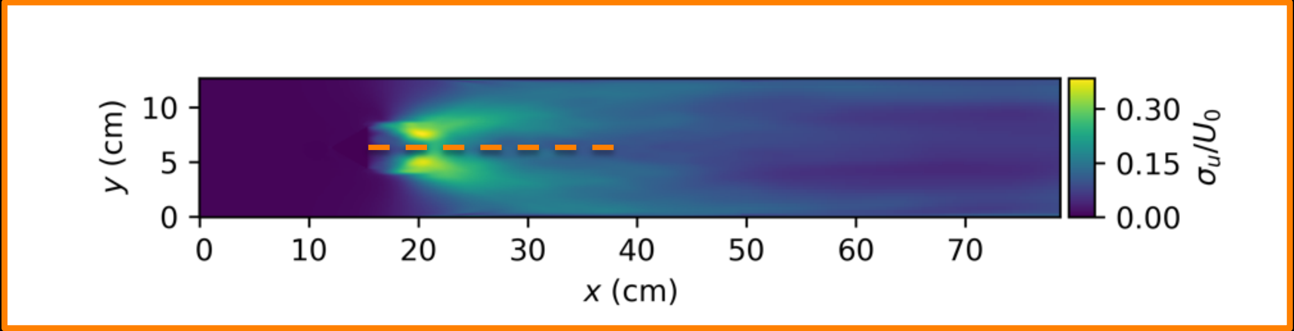


4 AMR Levels

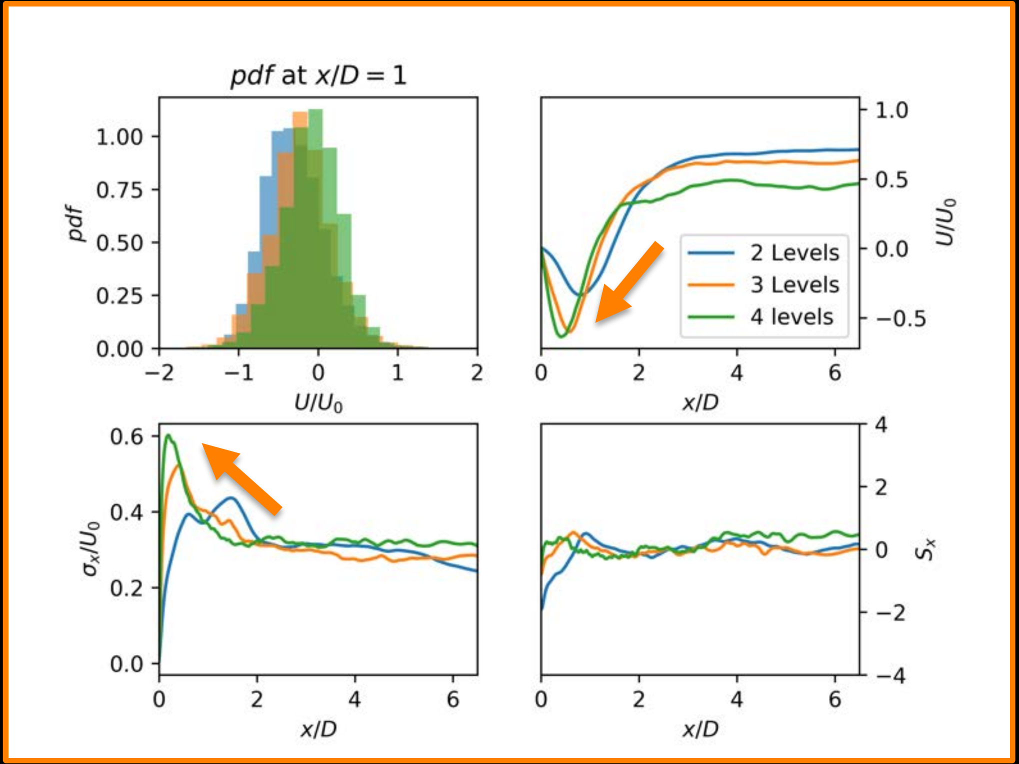


Time-Averaged Velocity Fields





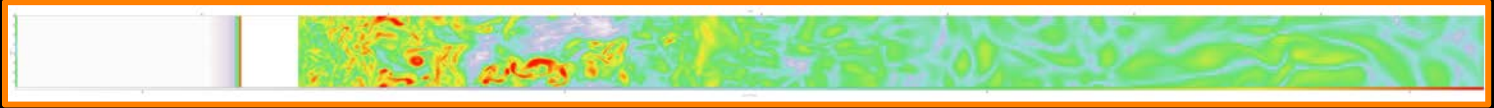
AMR Resolution and Convergence: X-Velocity Statistics



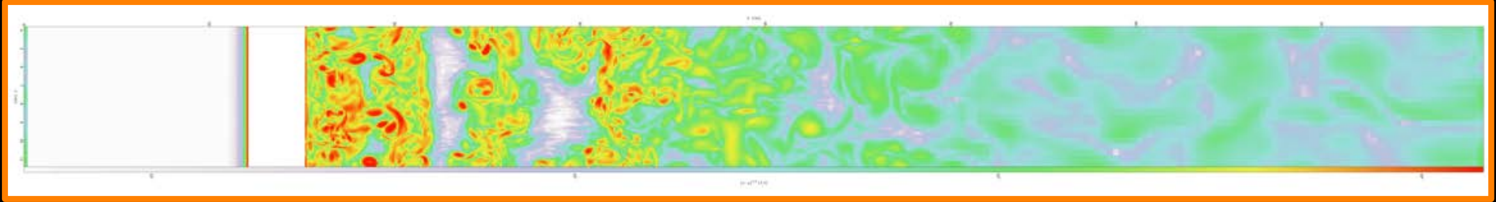
- X-velocity normalized by inflow bulk velocity U_0
- Aspect ratio of 2
- Plots show:
  - PDF from recirculation zone
  - Mean x-velocity
  - Standard deviation
  - Skewness

Aspect Ratio Comparison

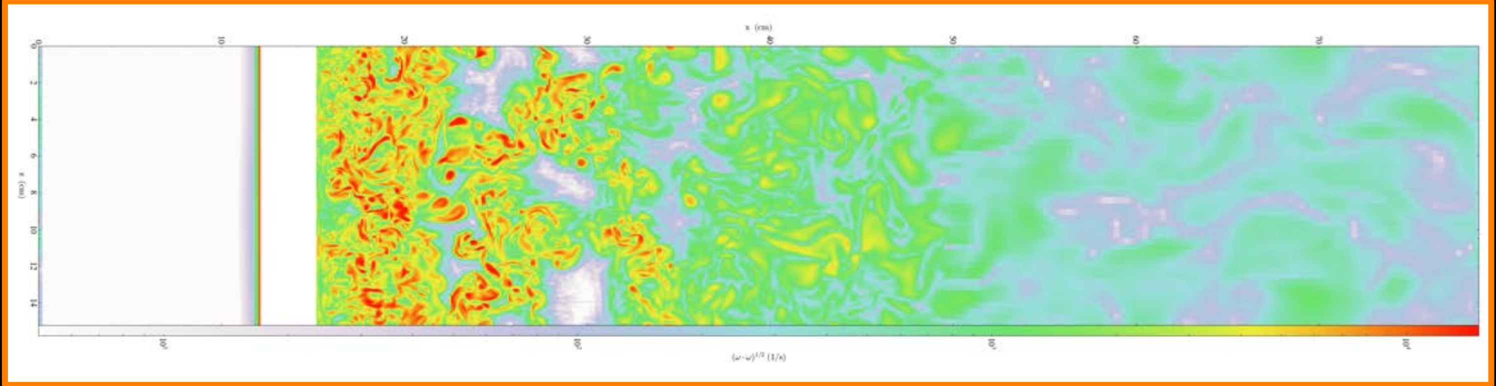
AR 1



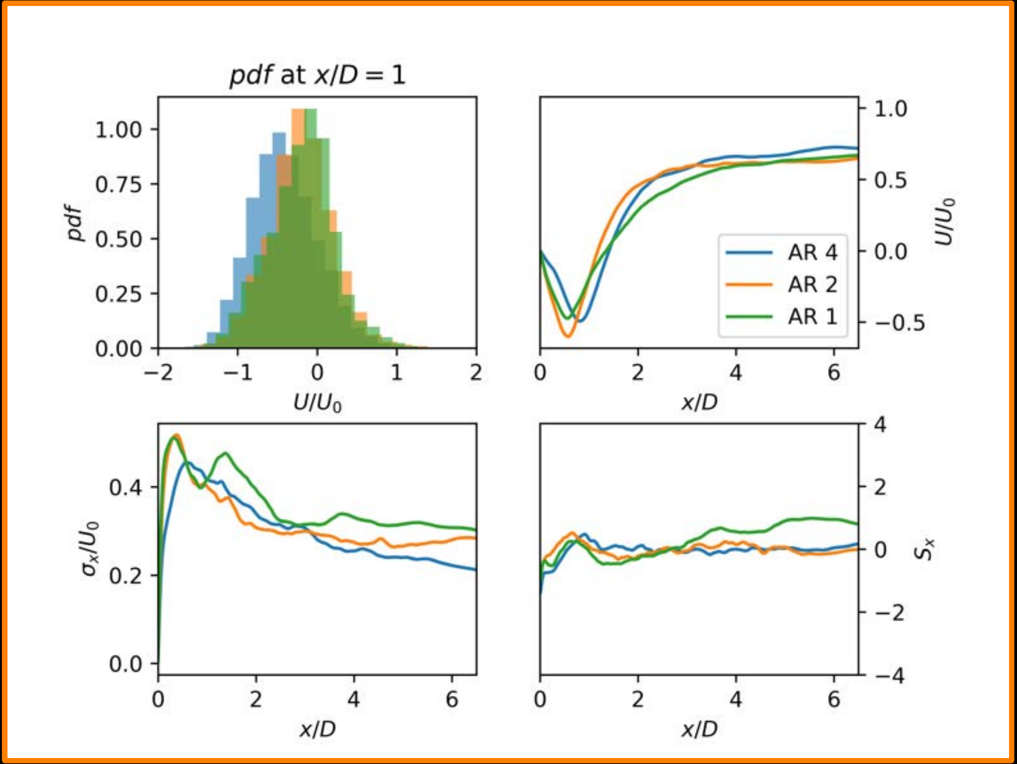
AR 2



AR 4



Aspect Ratio: X-Velocity Statistics



- X-velocity normalized by inflow bulk velocity U_0
- 3 AMR levels
- Plots show:
    - PDF from recirculation zone
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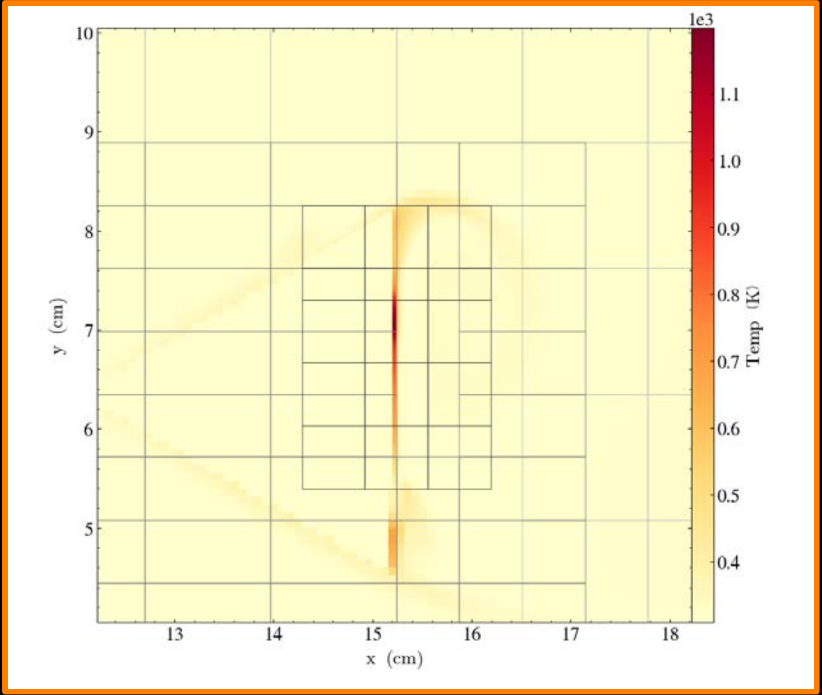
Work in Progress: Reactions



- Isothermal bluff body heated to 600K
- Premixed H2-air, inflow at 310K
- Hot spot is forming and intermediate species are produced
- Combustion has been unstable

Summary

- AMR is accurately capturing the physics of interest, providing high-resolution simulations at reduced cost compared with static refinement
- 3 levels of AMR are resolving the large-scale dynamics relevant to maintaining combustion
- Observed differences between full and reduced aspect-ratio domains are minimal
- Combustion in simulations with embedded boundaries and AMR is a work in progress and the current focus.

Acknowledgements

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Citations

- Campbell, J.F. and Chambers, J.R., 1994. Patterns in the sky: natural visualization of aircraft flow fields.
- Shanbhogue, S.J., Husain, S. and Lieuwen, T., 2009. Lean blowoff of bluff body stabilized flames: Scaling and dynamics. *Progress in Energy and Combustion Science*, *35*(1), pp.98-120.
- Paxton, B.T., Fugger, C.A., Rankin, B.A. and Caswell, A.W., 2019. Development and Characterization of an Experimental Arrangement for Studying Bluff-Body-Stabilized Turbulent Premixed Propane-Air Flames. In *AIAA Scitech 2019 Forum* (p. 0118).
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Questions?