This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2019-1651C

Turbulent Combustion Simulation and In Situ Analytics on Titan and Summit with S3D-Legion

Jacqueline H. Chen[1], Elliott Slaughter[2], Wonchan Lee[3], Sean Treichler[4], Michael Bauer[4], Konduri Aditya[1], Hemanth Kolla[1], Pat McCormick[5] and Alex Aiken[3]

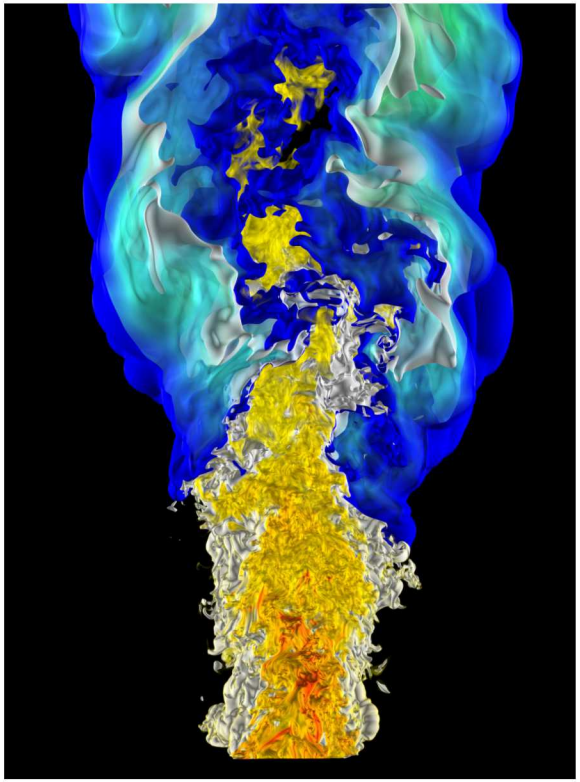
[1]Sandia National Laboratories

[2]SLAC National Accelerator Laboratory

[3]Stanford University

[4]NVIDIA

[5]Los Alamos National Laboratory



1st R-CCS Symposium, February 18-19, 2019

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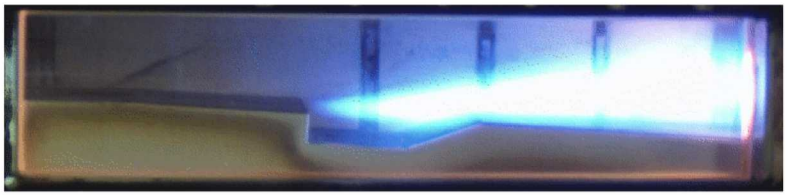
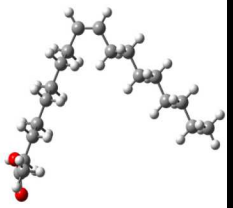
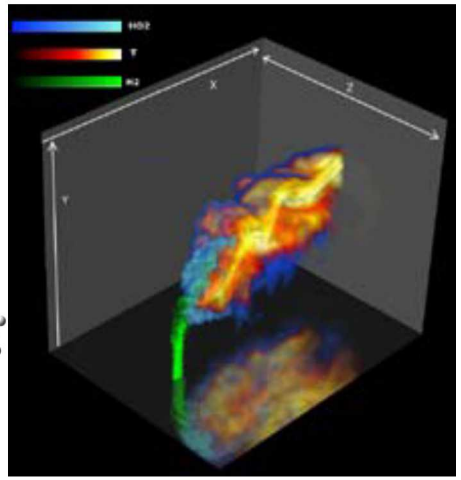
Exascale Simulation of Turbulent Combustion

- Fundamental insights into multi-physics in highly turbulent flames to formulate physics-based LES models

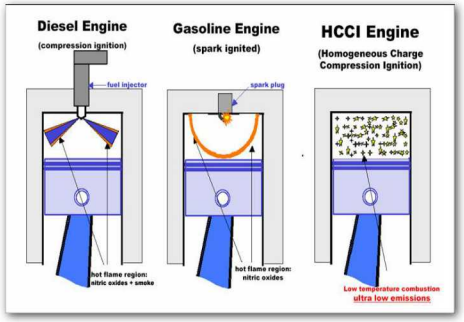


- High Reynolds number, high pressure, large turbulent velocity fluctuations, compressibility
  - LES SGS closures inherited from nonreacting flows
  - Multi-scale energy transfer processes
  - Complex thermo-chemical trajectories through flames and ignition fronts – structural differences to 'laminar flamelets'



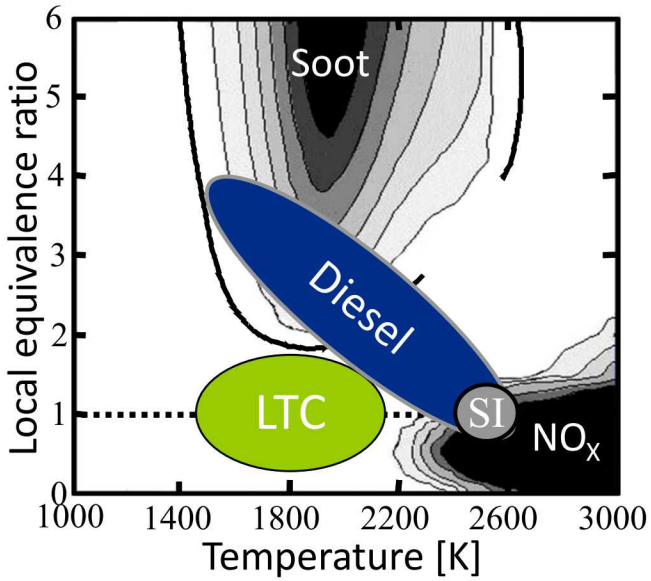


- High-fidelity direct numerical simulation (DNS) and hybrid DNS/LES methodologies
  - sufficient chemical fidelity to differentiate effects of fuels where there is strong turbulence-chemistry interactions
  - complex flows

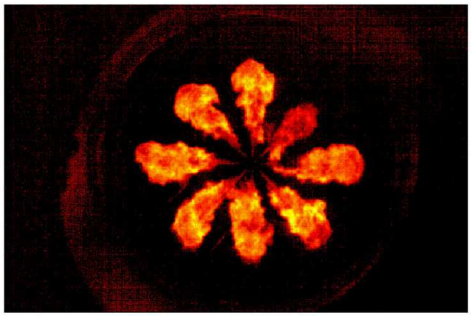


EXASCALE COMPUTING PROJECT

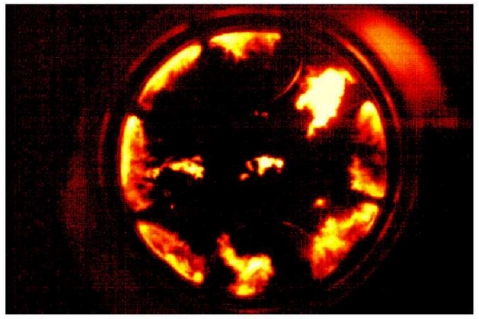
Autoignition in Engines

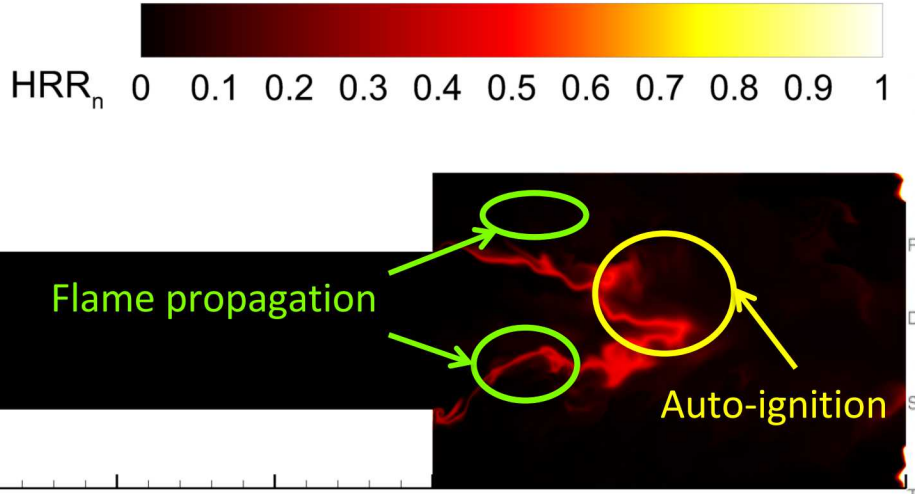


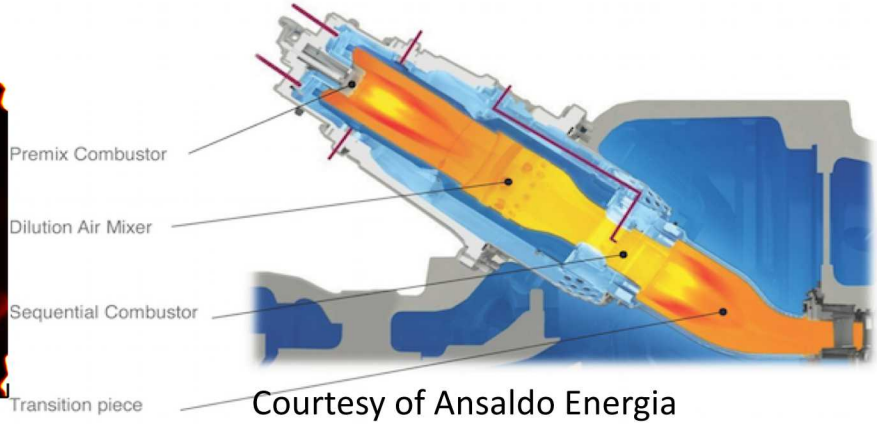
Conventional diesel *



Early injection PCCI



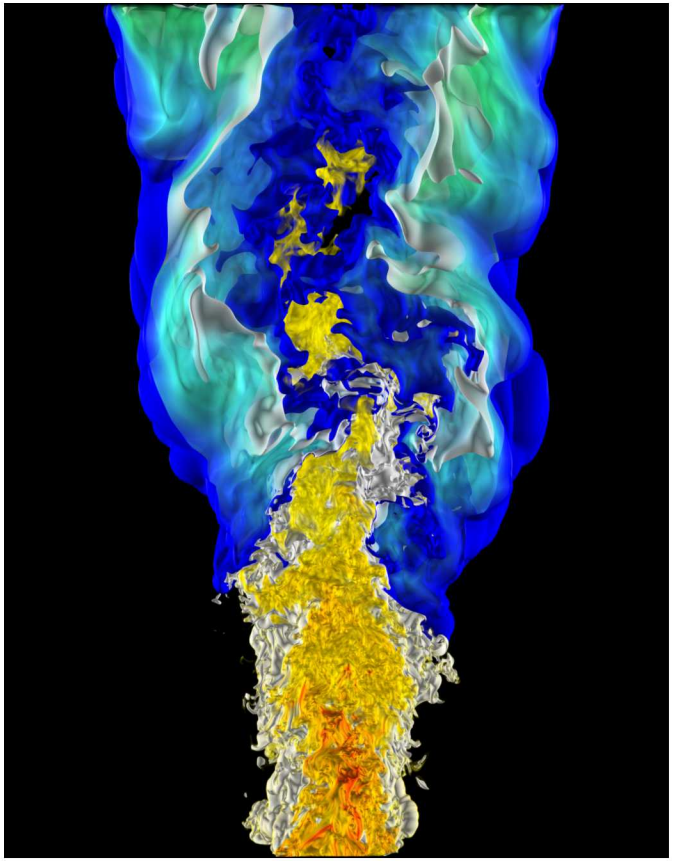




Courtesy of Ansaldo Energia

Fundamental Turbulence-Chemistry Interactions Motivated by Advanced Engines

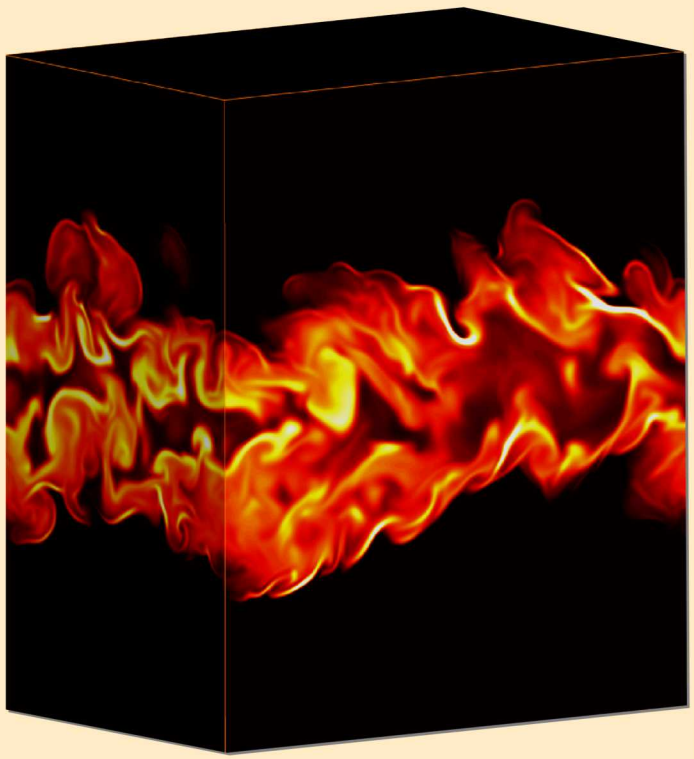
- Higher fuel efficiency and lower emissions driving combustion towards more **fuel lean, partially-premixed conditions**
- **Mixed-regime combustion**
- **Multi-Stage autoignition - sensitivity to fuel chemistry and preferential diffusion**
- **Multi-scale interactions and backscatter**



Lifted dimethyl ether jet flame at 5 bar stabilized on cool flame ignition intermediate, flame marker OH (blue); methoxymethylperoxy (ignition marker (yellow)

Direct Numerical Simulation – S3D

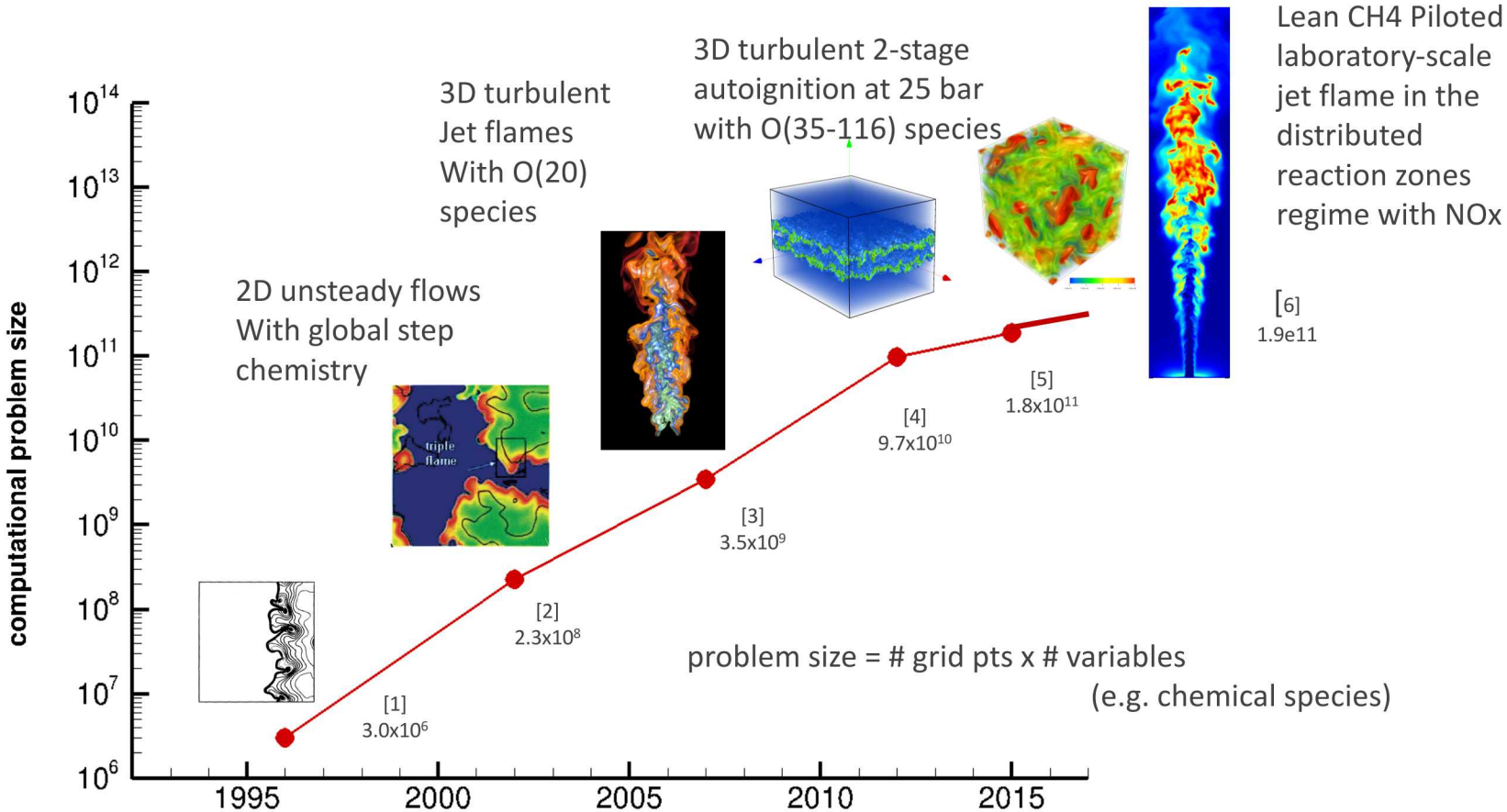
- DNS of turbulent reacting flows
- Solves compressible reacting Navier-Stokes, total energy and species continuity equations
- High-order finite-difference methods
- Detailed reaction kinetics and molecular transport models
- Lagrangian particle tracking (tracers, spray, soot)
- In situ analytics and visualization
- Refactored for multi-threaded, many core heterogeneous architectures



DNS provides unique fundamental insight into the chemistry-turbulence interaction

Chen *et al.*, *Comp. Sci. Disc.*, 2009

Computational intensity of DNS scales with Moore's Law



[1] T. Echekki, J.H. Chen, *Comb. Flame*, 1996, vol.106.
[2] T. Echekki, J.H, Chen, *Proc. Comb. Inst.*, 2002, vol. 29.
[3] R. Sankaran, E.R. Hawkes, J.H. Chen, *Proc. Comb. Inst.*, 2007, vol. 31.
[4] E.R. Hawkes, O. Chatakonda, H. Kolla, A.R. Kerstein, J.H. Chen, *Comb. Flame*, 2012, vol. 159.
[5] 2015 submission for Gordon Bell prize
[6] H. Wang, E. Hawkes, J. H. Chen, Comb. Flame 2017

Outline:

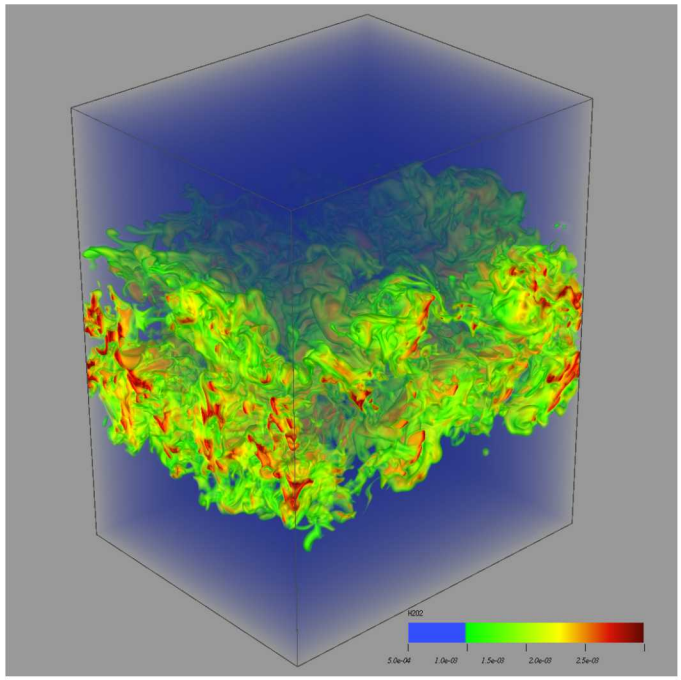
- DNS of tubulent combustion with complex flow at the petascale:
  - DNS of turbulent autoigniting n-dodecane diesel jets
  - DNS of flame stabilization behind a backwards facing step
  - DNS of reheat combustion in staged gas turbines
- Path to exascale combustion simulations (2021-2023)
  - Adaptive mesh refinement
  - Programming models
  - Composable in situ workflow (analytics, machine learning)
  - Anomaly detection

DNS of a Turbulent Autoigniting n-Dodecane Jet at 25 Bar

Giulio Borghesi[1], Alex Krisman[1], Tianfeng Lu[2] and Jackie Chen[1]

[1]Combustion Research Facility, Sandia National Laboratories

[2]University of Connecticut

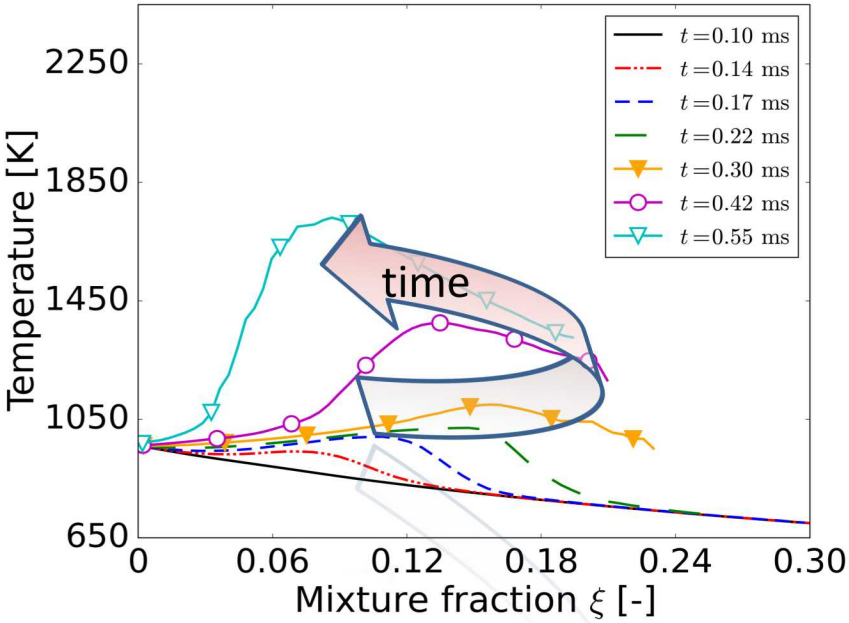


Ketohydroperoxide mass fraction

Borghesi et al. Combustion and Flame, 2018

Background and Objective

- Low-temperature combustion (LTC) aims at increasing fuel efficiency and reducing emissions
- Under LTC conditions, combustion occurs in a mixed mode and in multiple ignition stages
- Ignition is now very sensitive to the fuel chemistry, especially to the low temperature reactions branch



Question: How does transport and low-temperature chemistry affect ignition in low-temperature diesel combustion?

Background on high-temperature ignition

- Homogeneous PSR calculations show the existence of x value, x_m, where ignition delay has a minimum;
- Flamelet simulations show the ignition delay increases with scalar dissipation N until a critical value is reached;
- In practical systems, ignition occurs at locations close to x_m where N is low. The ignition delay is longer than in PSR;
- **Question:** which features of high-T ignition carry over to low-T ignition?

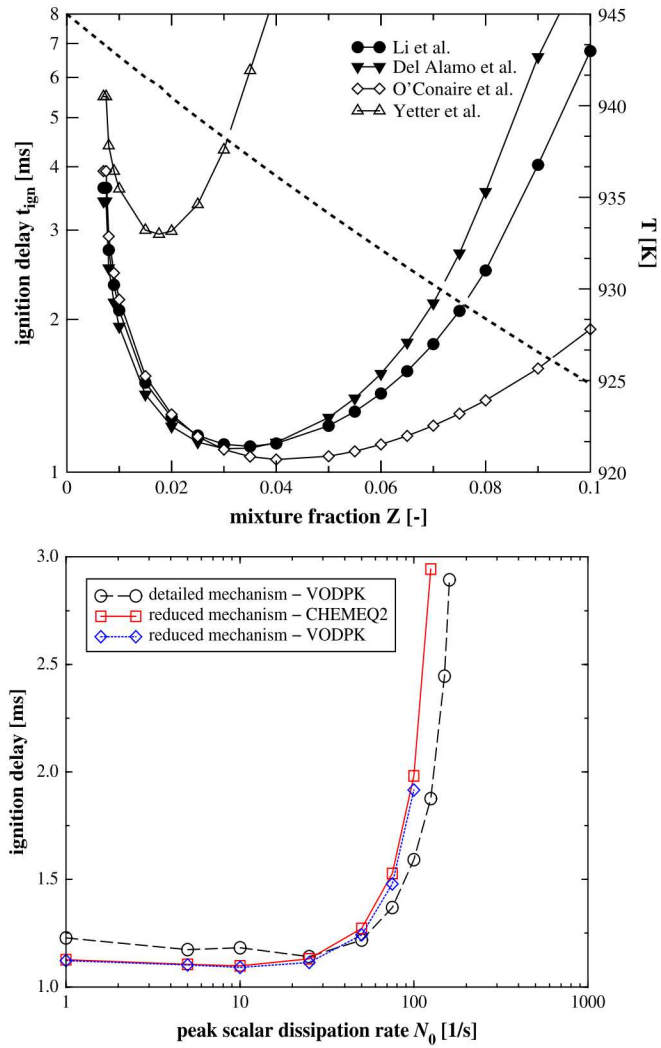
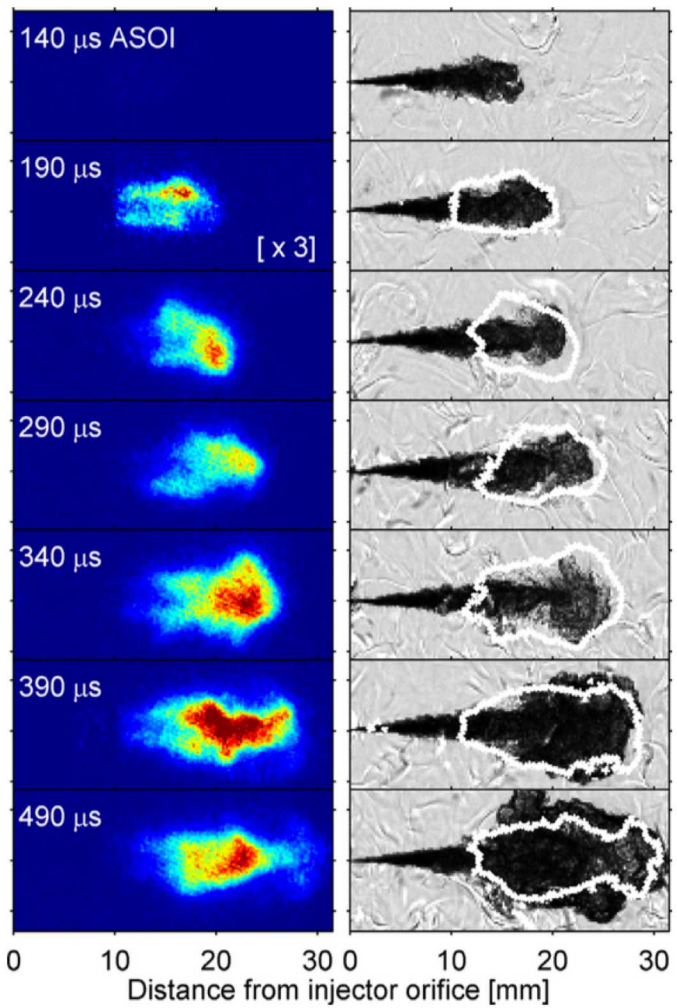


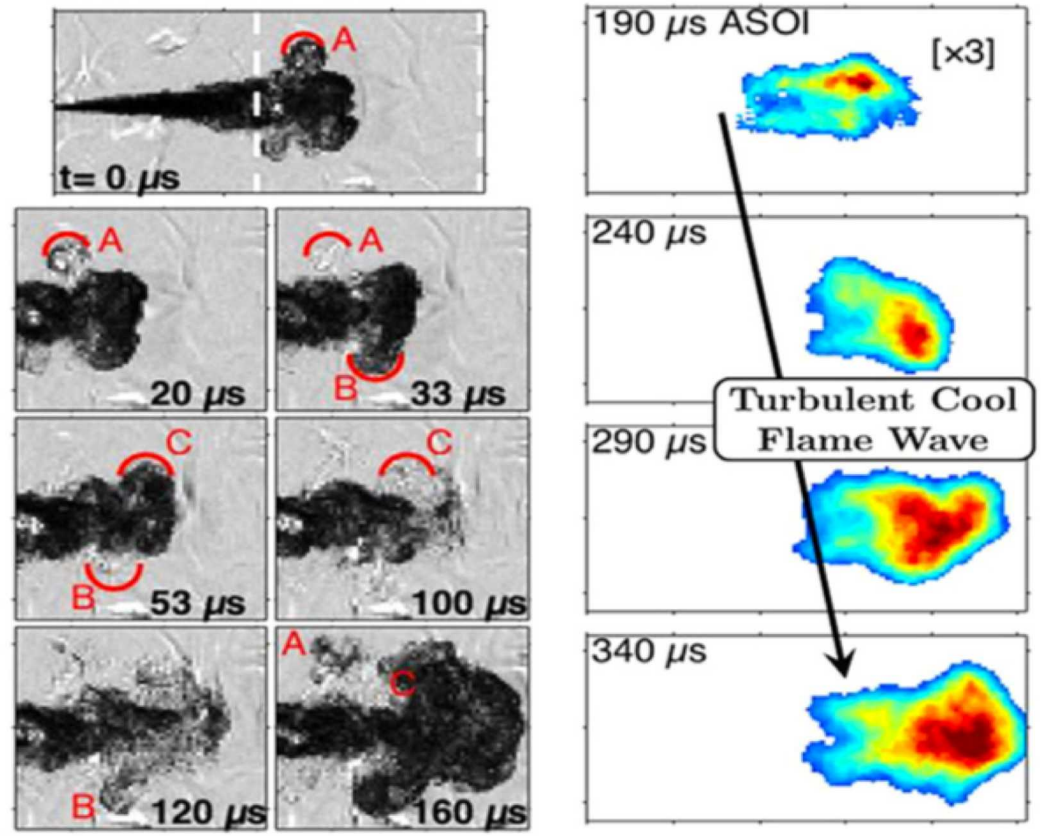
Figure: ignition delay time in PSR and in nonpremixed flamelet simulation[1]

[1] E. Mastorakos, PECS (2009), pp. 57-97

Low Temperature Diesel Combustion Experiments – Engine Combustion Network



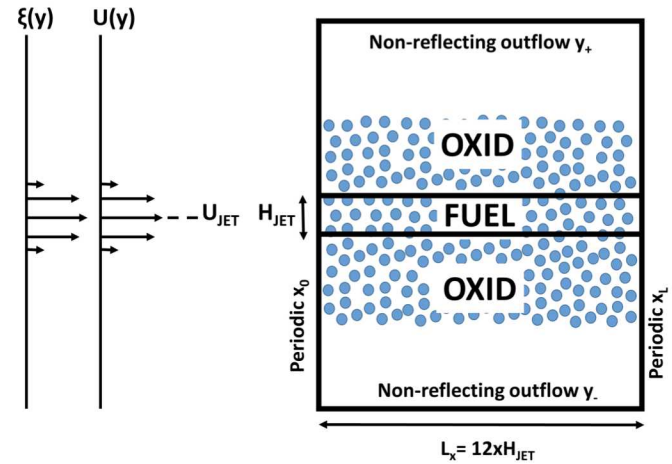
Skeen et al., PROCI 35 (2015) 3167-3174



Dahms et al., PROCI 36 (2017) 2615-2623

DNS Configuration and Physical Parameters

- **Pressure:** 25 bar
- **Air stream:** 15% X_{O2}+85% X_{N2}, T=960 K
- **Fuel stream:** *n*-dodecane at ξ=0.3, T=450 K
- **Kinetics:** 35-species non-stiff reduced (Lu)
- **Fuel jet velocity:** 21 m/s, Re_j = 7000, Re_t ~ 950
- **Code and cost:** S3D Legion, 60M CPUh
- **Setup:**
  - 3 billion grids
  - 3 microns spatial grid resolution
  - Dimensions: 3.6 mm x 14.0 mm x 3.0 mm
  - 1 ms of physical time with 4 ns timesteps to observe ignition and propagation of burning flames throughout the domain
  - BCs: X and Z periodic, Y NSCBC outflows



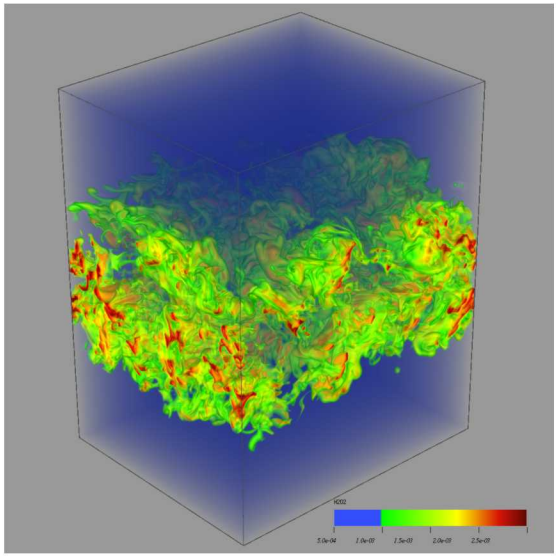
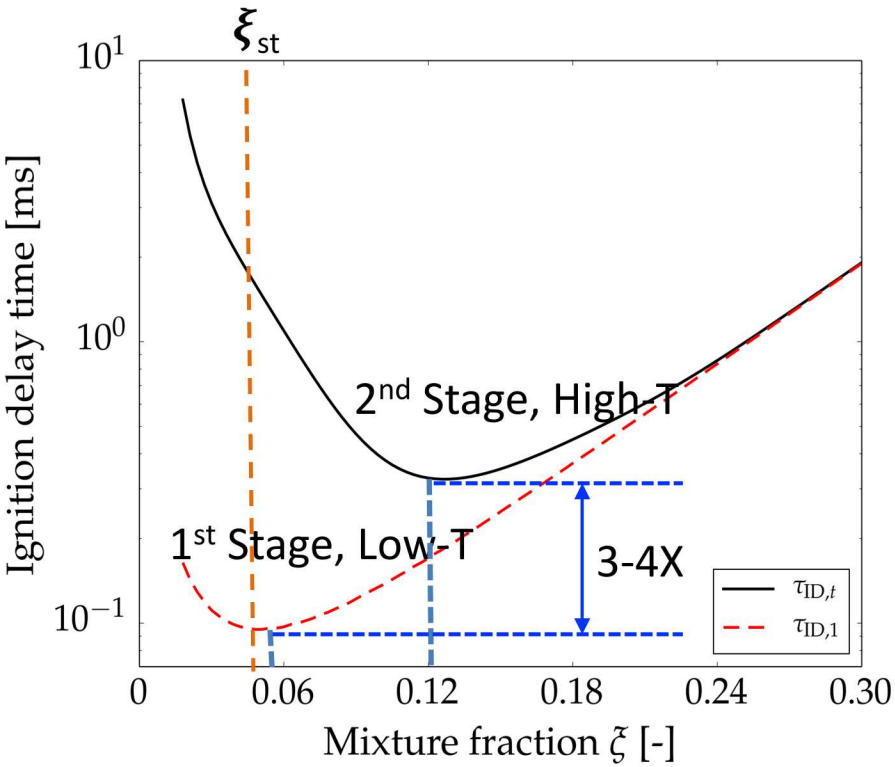
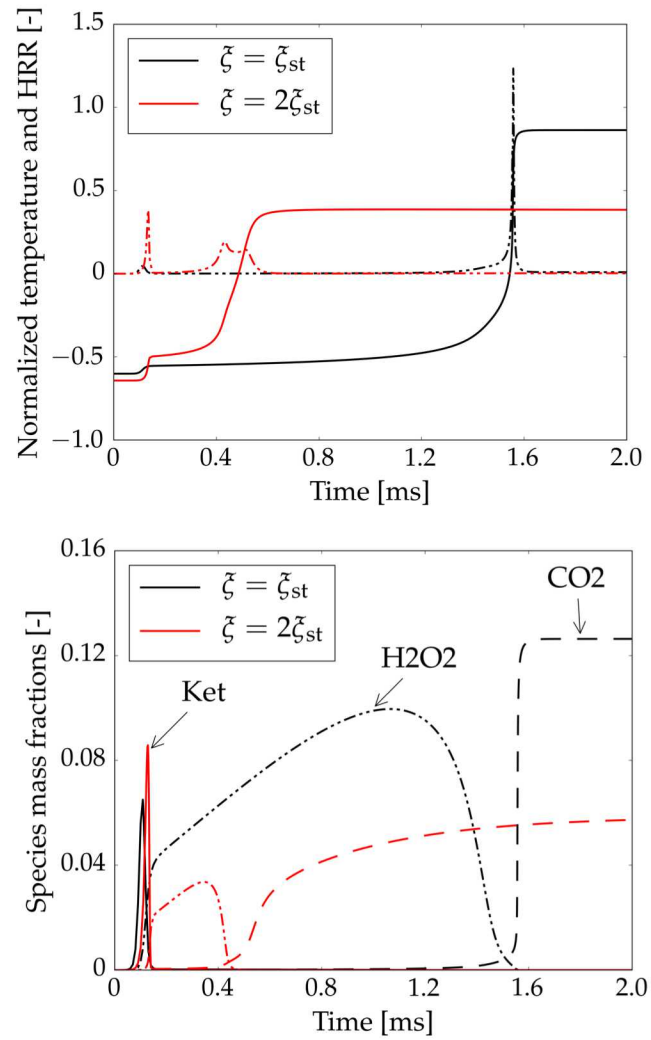


Figure: H_2O_2 mass fraction at t=0.17 ms after start of reactions

Homogeneous Multi-Stage Autoignition

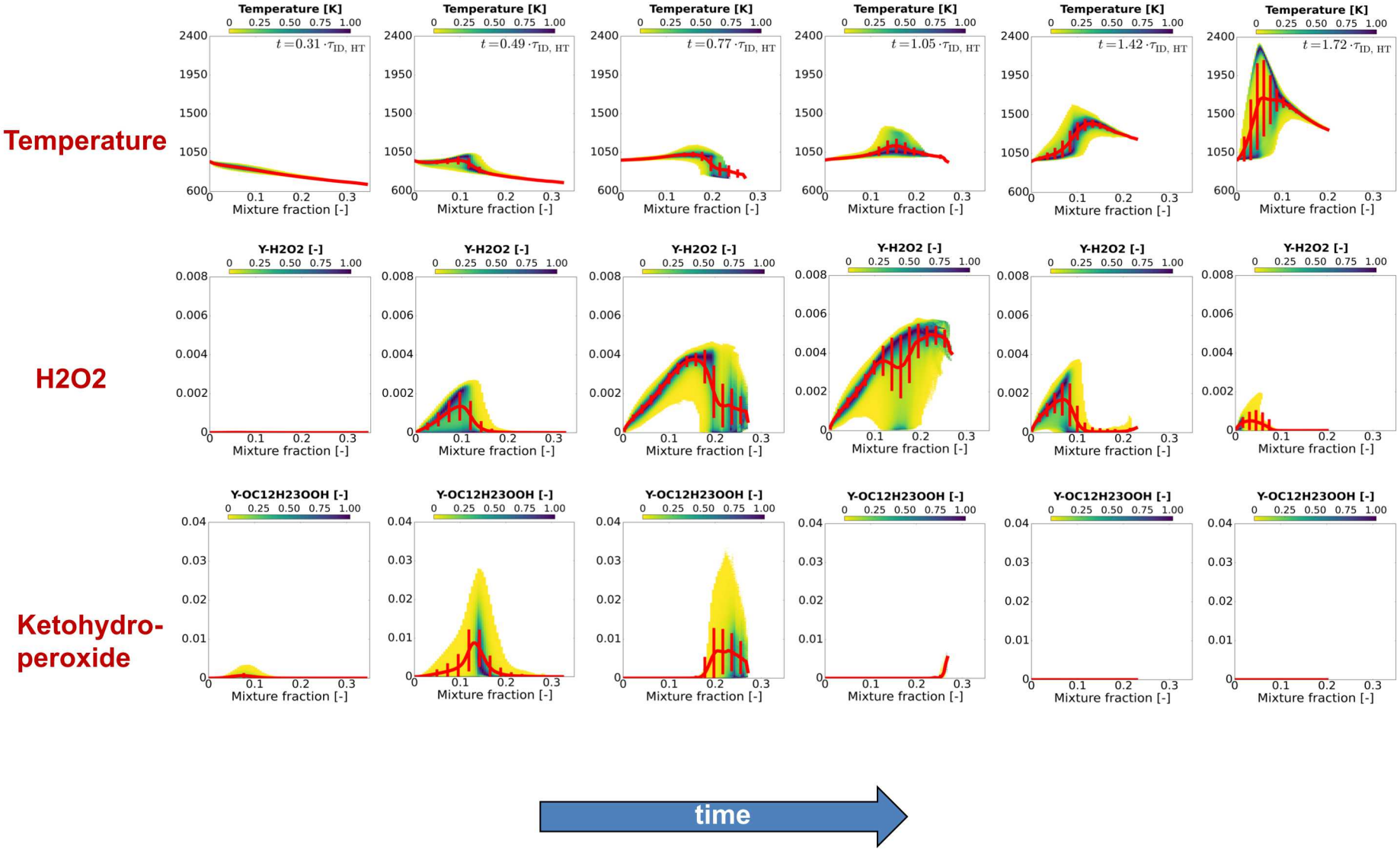


Homogeneous ignition delay time

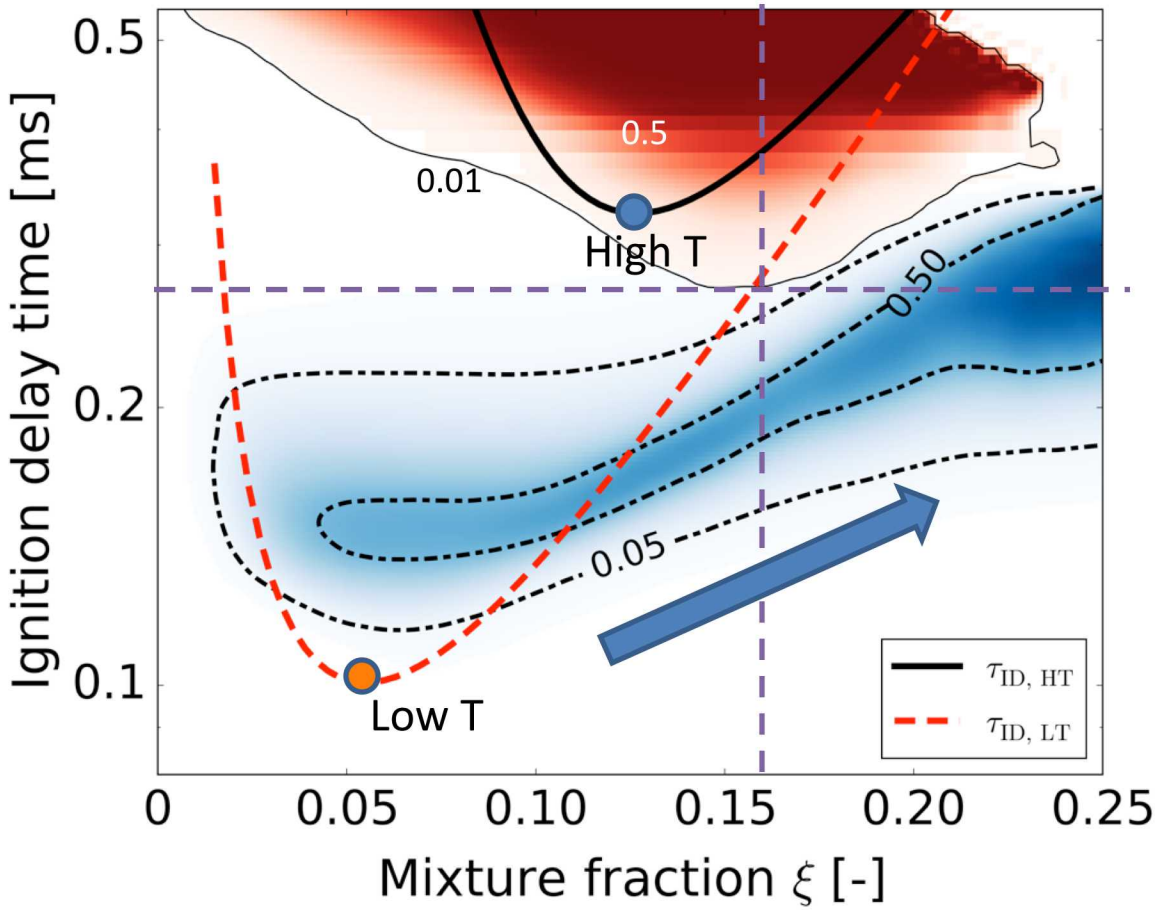


Temporal evolution of selected reactive scalars

Conditional statistics reveal ignition dynamics

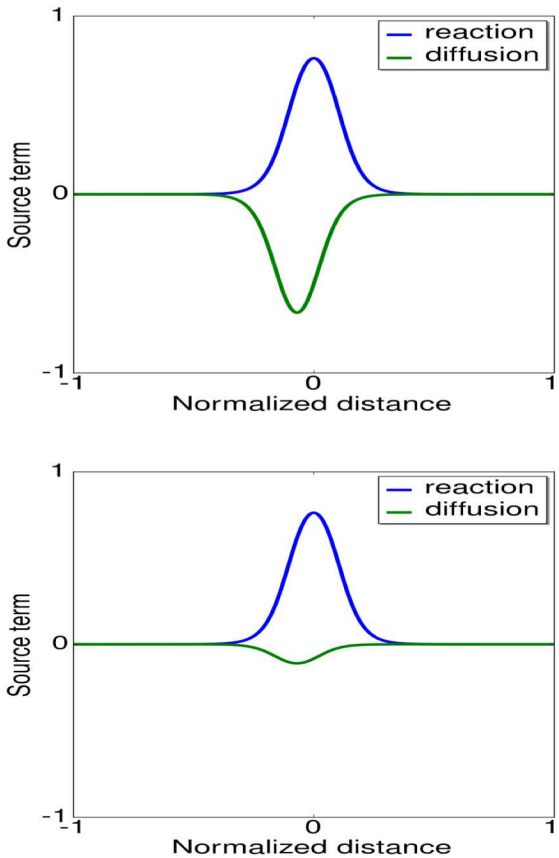


Turbulent versus homogeneous ignition



Low-T and high-T ignition in jet can be faster and than in a PSR !

Propagation mechanism for low-T reaction front



Sketch of reaction / diffusion balance along normal for KET for flame and ignition kernel

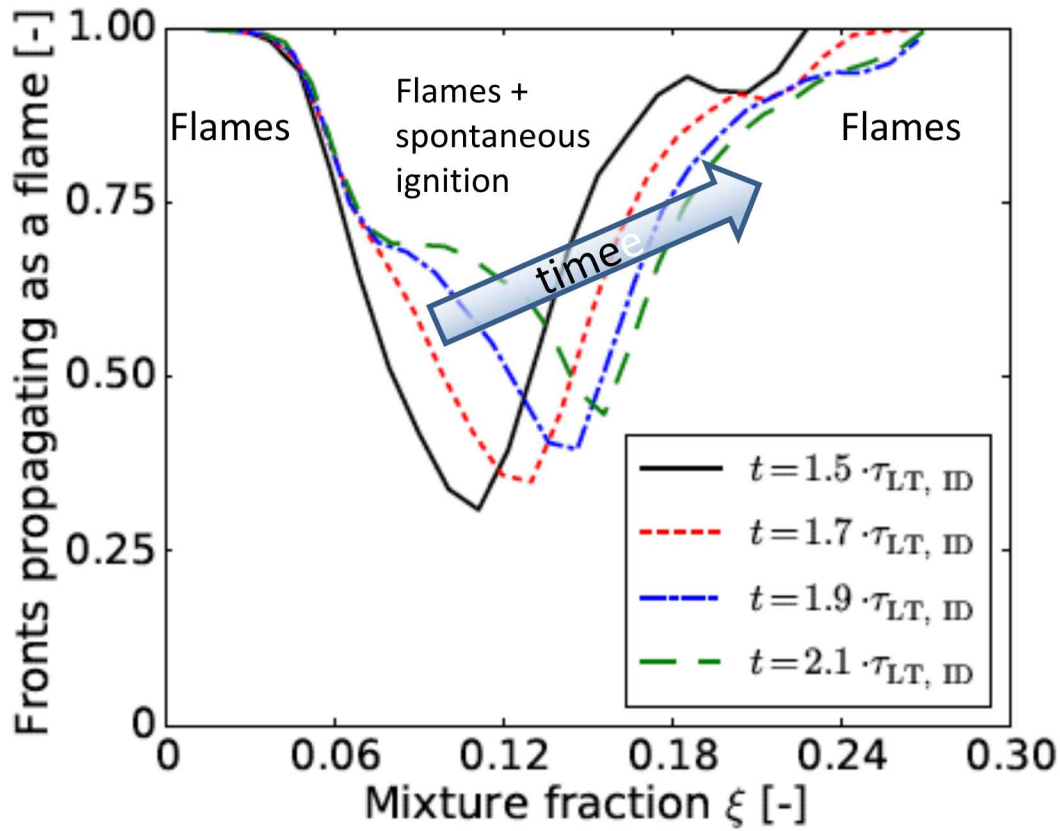
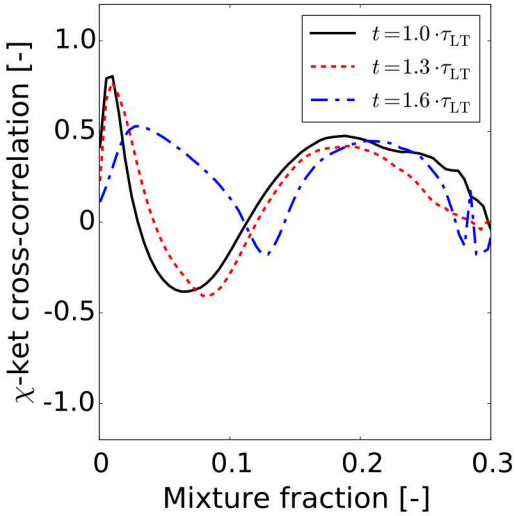
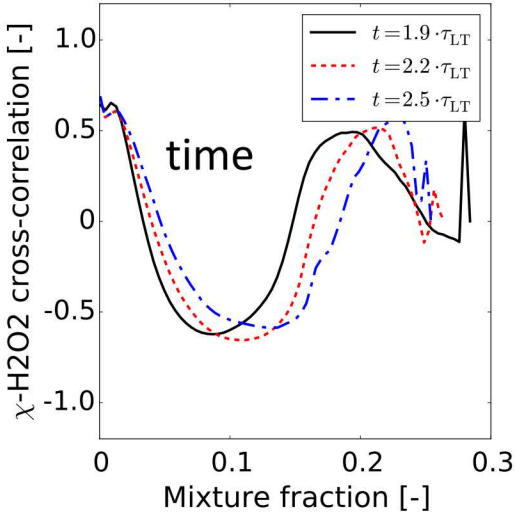


Figure: Fraction of reactive low-T fronts propagating as a flame

Low-T fronts propagate through diffusively supported flame

Effect of Scalar Dissipation Rate on Low Temperature Ignition





Effect of Scalar Dissipation Rate on High-Temperature Ignition

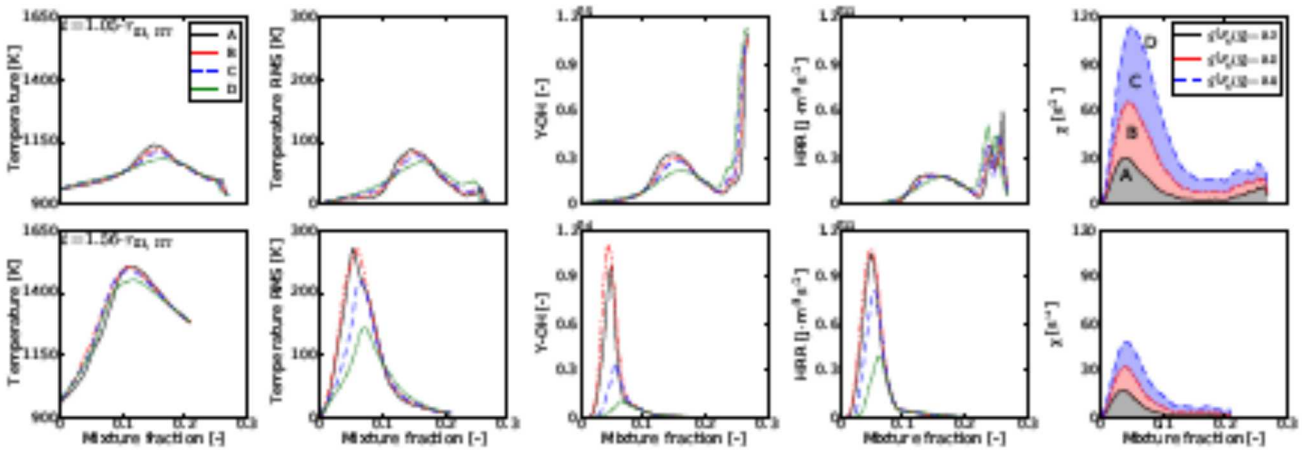


Figure 14: Conditional averages of temperature (first column), temperature root-mean-square (second column), Y_{OH} (third column) and HRR (fourth column), the conditioning being on ξ and χ, at selected instants during second-stage ignition. The intervals of χ that were used to condition the reactive scalars are shown in the last column.

Combustion Modes During Ignition Transients

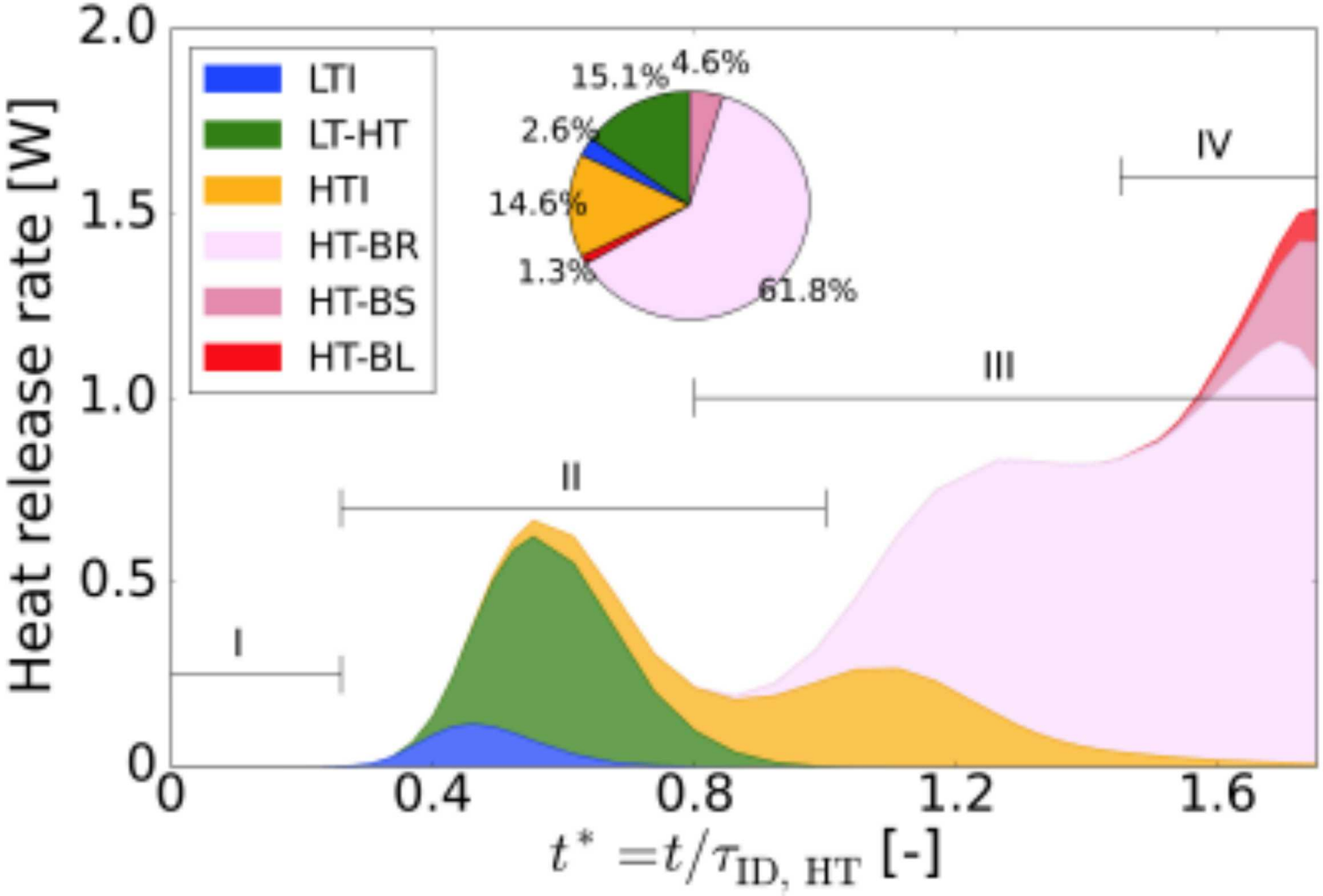


Figure 19: Contributions to heat release rate from different combustion modes during the ignition transient

Conclusions

- Low-temperature reactions create the conditions for high-temperature ignition to occur faster than under homogeneous conditions;
- Low-temperature front appears to propagate through a diffusively supported cool flame;
- High scalar dissipation appears to delay low-temperature ignition; however, it leads to faster ignition at very rich mixture conditions;
- High-T ignition starts at conditions richer-than-homogeneous conditions (ξ=0.16 compared to ξ=12). Edge flames are seen to form around ξ_{st}. High-T flame ignites mainly by propagation of rich premixed flames following hot ignition to ξ_{st}.

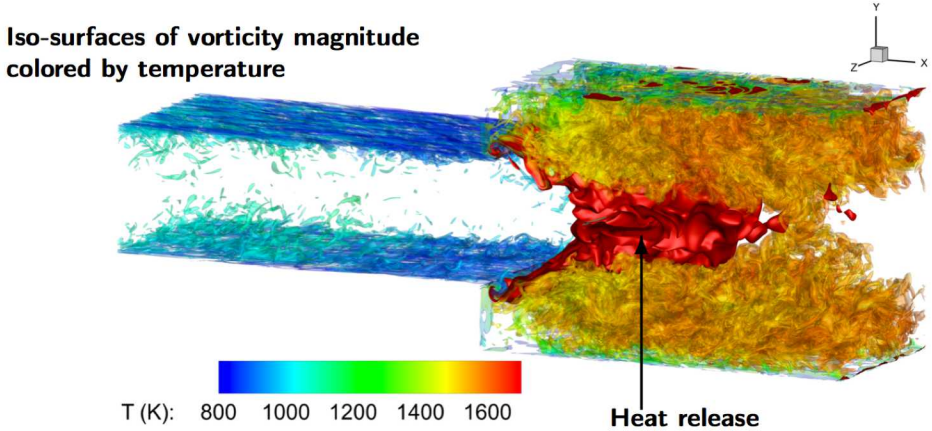
Future work

- Need to characterize low-T flames (e.g. speed, thickness, etc.);
- In present simulations, low- and high-T ignition are well separated. Are there ambient conditions where there is greater overlap?
- What is the effect of dwell time in multi-injection diesel combustion, ie. the effect of the low-T ignition intermediates from pilot on the primary injection ignition? How does ambient temperature affect this?
- What is the effect of spray injection on mixture formation?
- How is soot generated on the rich side and eventually oxidized?

Direct Numerical Simulation of flame stabilization assisted by auto-ignition at *reheat* conditions

Konduri Aditya[a], Andrea Gruber[b], Mirko Bothien[c] and Jacqueline H. Chen[a]

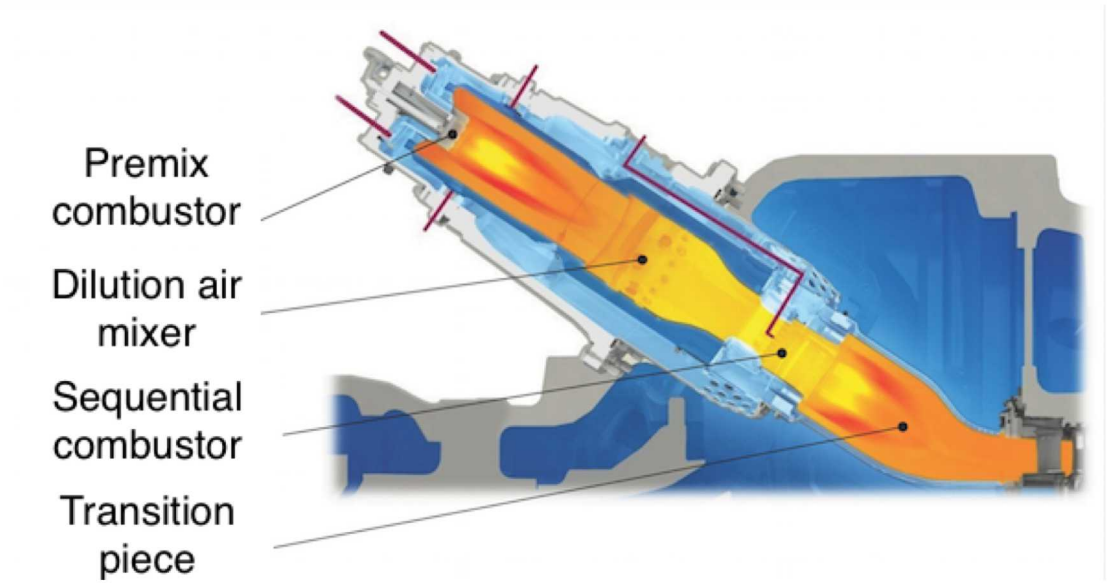
[a]Combustion Research Facility, Sandia National Laboratories, Livermore, CA, USA
[b]SINTEF Energy Research, Trondheim, Norway
[c]Ansaldo Energia, Baden, Switzerland



Acknowledgements:
Basic Energy Sciences, Office of Science, DOE
OLCF, NERSC, Norwegian CCS Research Centre (NCCS)

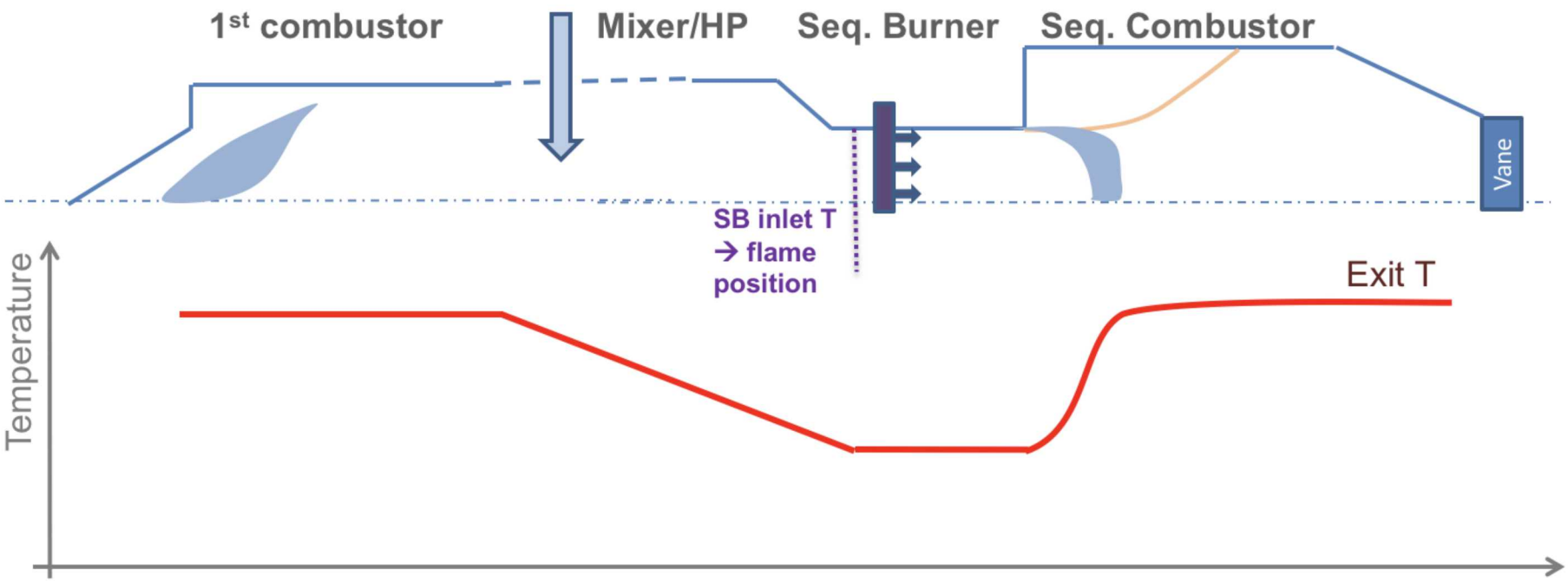
Aditya et al. PCI 2018

Staged gas turbine combustion



- Originally developed by ABB for high efficiency, load flexibility and low emissions
- Recently improved and simplified (reduced cost) for the H-class GT36
- First (premix) combustion stage based on flame propagation
- Second (sequential) combustion stage based on auto-ignition

Staged gas turbine combustion

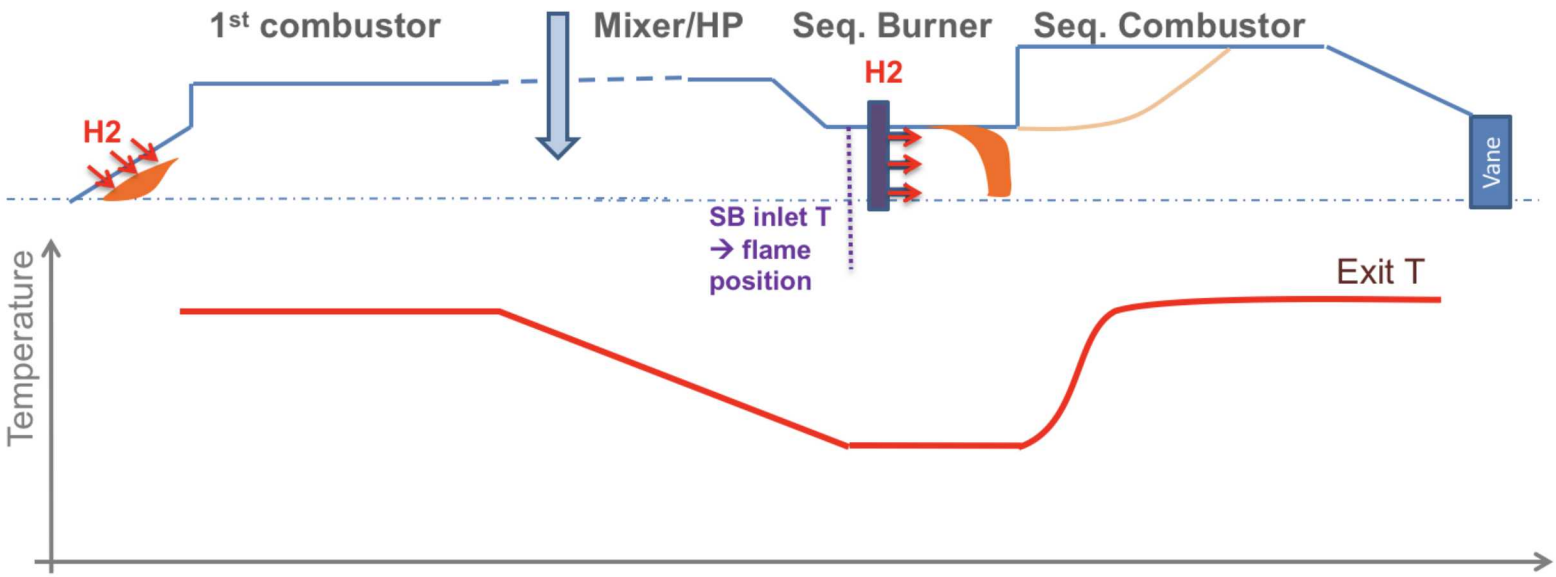


- Adjusting firing temperature of 1st stage allows control of t_{ign} in 2nd stage

Staged gas turbine combustion

Hydrogen fuel

- Flashback in 1st stage
- Early auto-ignition in 2nd stage

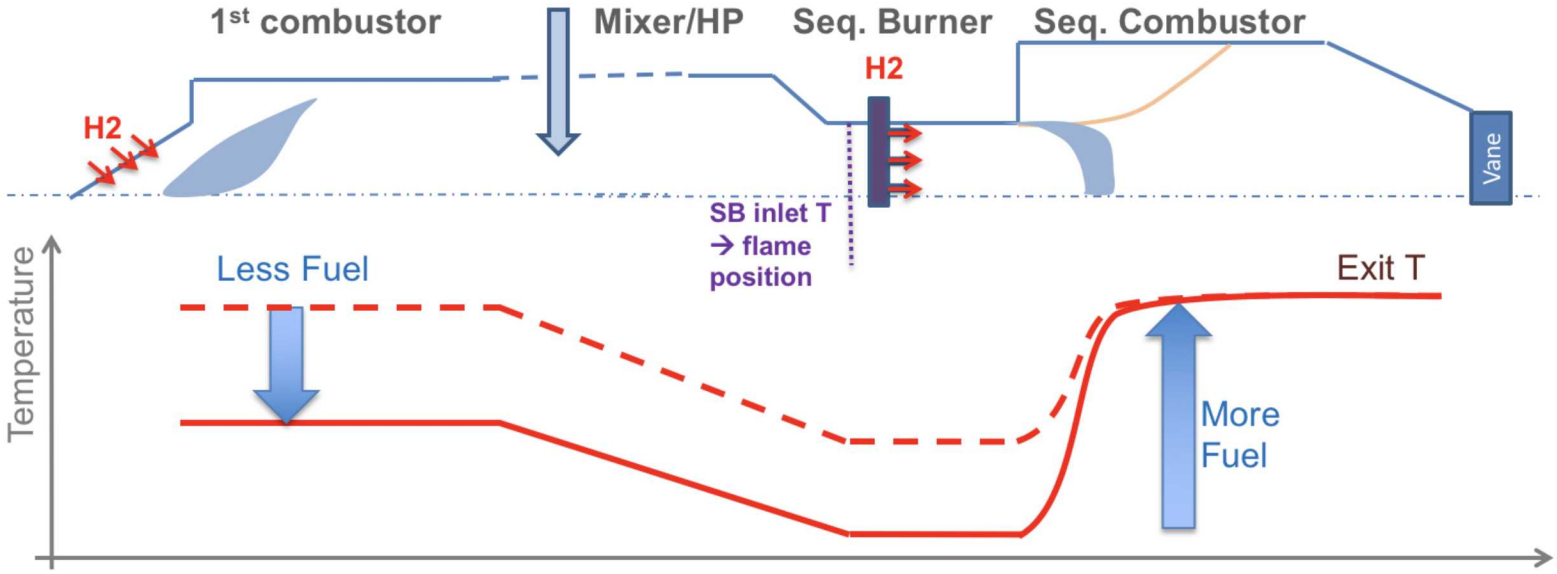


- 2nd stage is mainly auto-ignition stabilized
- 2nd stage inlet temperature needs to be decreased and not 2nd stage flame temperature

Staged gas turbine combustion

Hydrogen fuel

- Flashback in 1st stage
- Early auto-ignition in 2nd stage



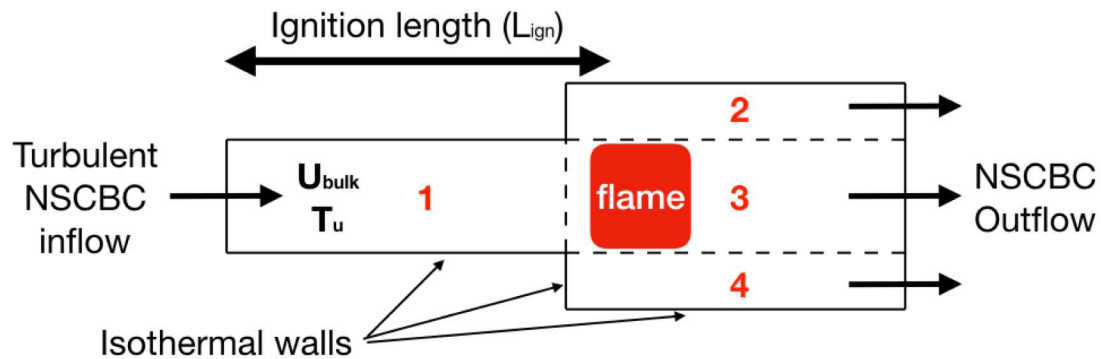
- 2nd stage is mainly auto-ignition stabilized
- 2nd stage inlet temperature needs to be decreased and not 2nd stage flame temperature
- 1st stage de-rating is compensated by shifting fuel to 2nd stage

Reheat burner

DNS of idealized reheat burner configuration from Ansaldo Energia

Operating conditions:

- Inlet temperature: ~ 1100 K
- Pressure: ~ 20 atm



Scaled conditions:

- Mean inlet temperature:
- Pressure: 1 atm
- Fuel: hydrogen

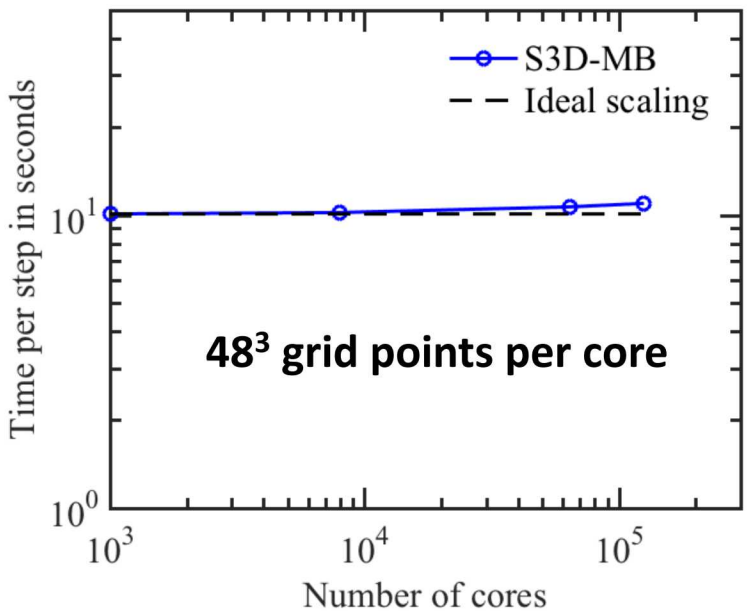
Objective:

- Understand the flame stabilization
- Identify the modes of combustion
- Quantify the role of auto ignition

S3D - Multiblock

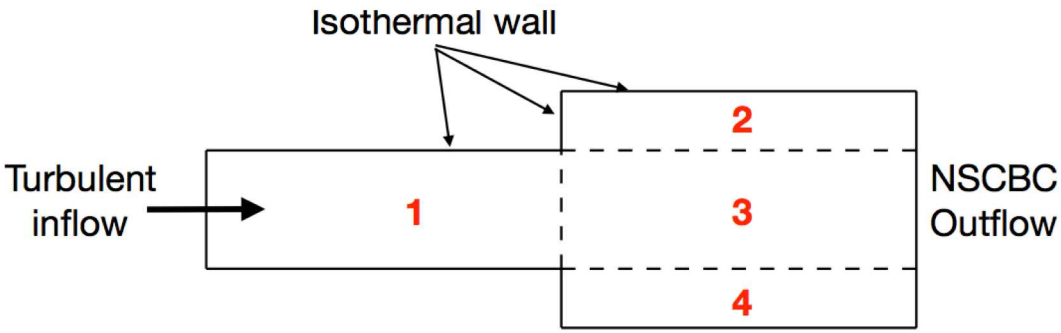
- Mildly complex geometry enabled by multi-block DNS capability
- Construct geometries by assembling several cuboidal blocks (like Lego)
- Compressible formulation (J. H. Chen et al., CSD 2009)
- Spatial derivatives: 8th order CD schemes & 10th order filter
- Time integration: 4th order Runge-Kutta
- Mixture averaged transport model

Weak scaling on Titan



Code scales well on hundreds of thousands of processors

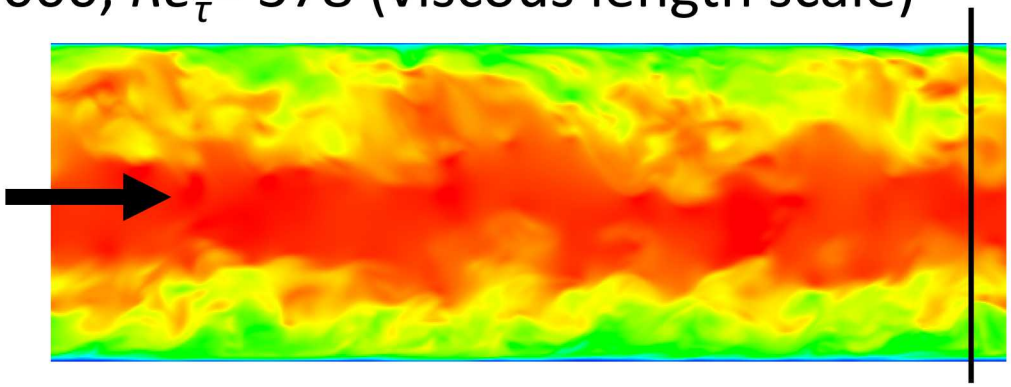
Simulation details



1.25 billion grid points
20 million CPU hours
$Re_b = 13000$

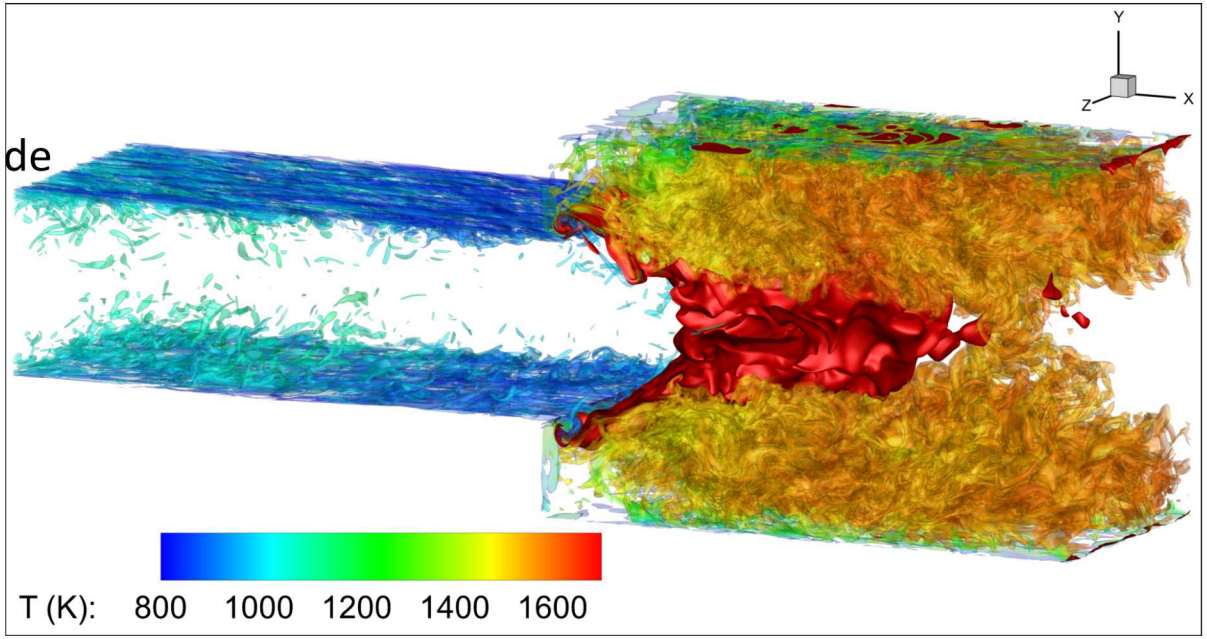
- **Chemical mechanism:** 9 species hydrogen-air (Li et al., 2004)
- **Inflow composition:** premixed H2 + O2 + N2 + H2O (ϕ = 0.35)
- Ubulk = 200m/s, u' = 20m/s, T_{inlet} = 1100K, T_{wall} = 750K
- **Inflow profile:** feed from DNS of a fully developed channel flow,

$Re_b \sim 13,000$, $Re_\tau = 378$ (viscous length scale)



Feed data sampling plane

Iso-surfaces of vorticity magnitude colored by temperature

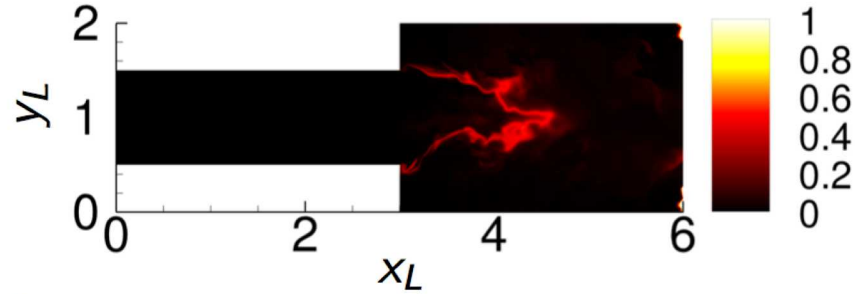


Two combustion configurations are observed:

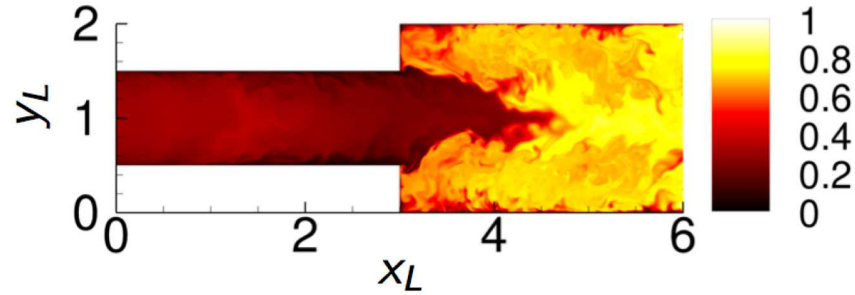
- Design state: mainly auto-ignition in the combustion chamber
- Intermittent auto-ignition state: ignition in mixing section

Design combustion state

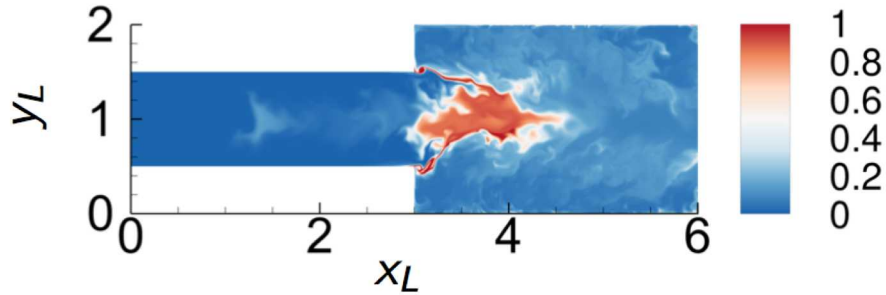
Heat release rate



Temperature



Mass fraction of HO_2



Combustion modes:

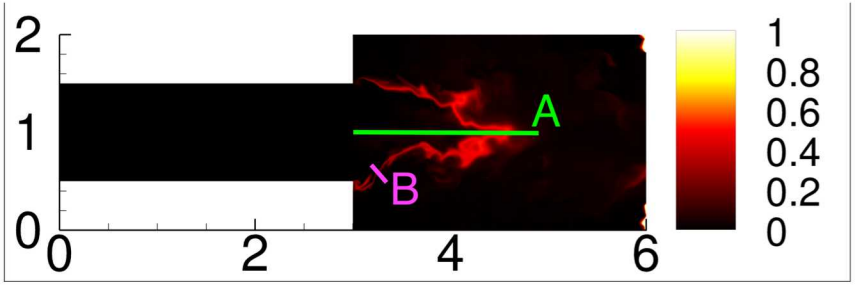
- Autoignition along center-line
- Flame propagation near corners
- HO2: indicative of chain branching

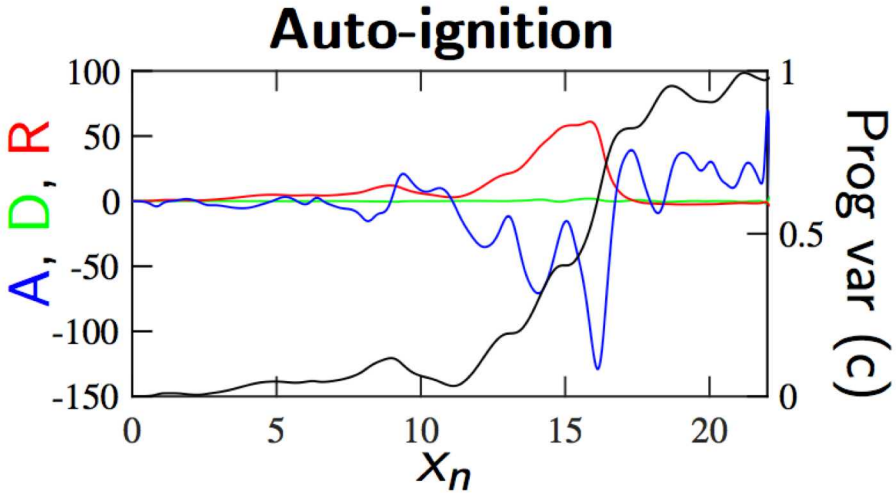
Transport budget analysis

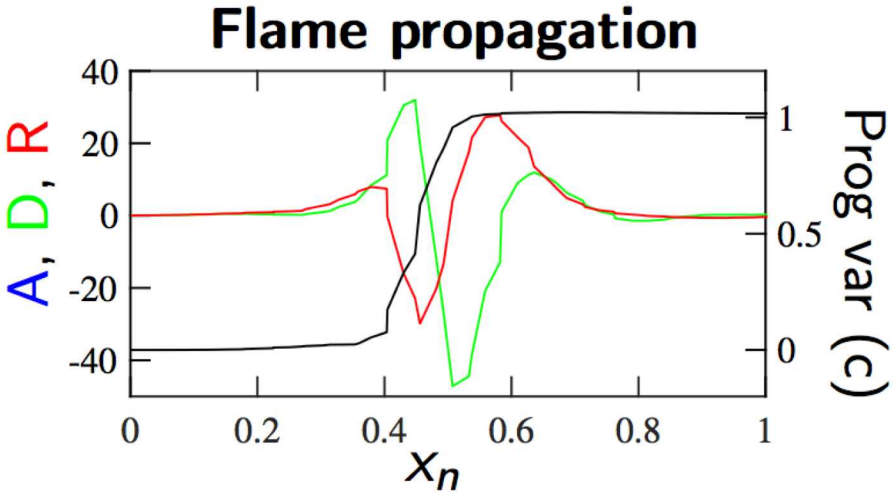
$$\frac{\partial(\rho Y_{OH})}{\partial t} = -\nabla_\beta \cdot (\rho Y_{OH}\mathbf{u}_\beta) - \nabla_\beta \cdot (\rho Y_{OH}\mathbf{V}_{\beta,OH}) + W_{OH}\dot{\omega}_{OH}$$

Advection Diffusion Reaction

- Auto-ignition: balance between advection and reaction
- Flame propagation: balance between diffusion and reaction





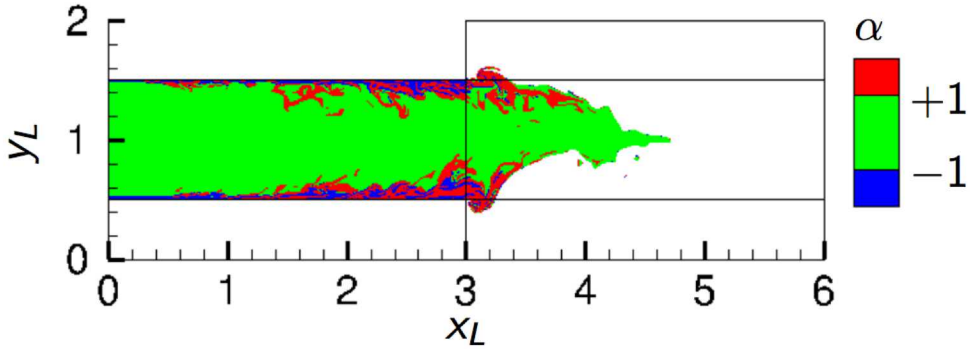


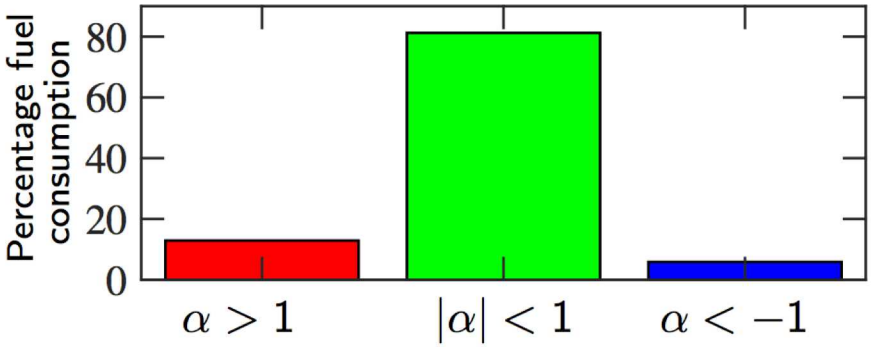
Chemical Explosive Mode Analysis

- $\alpha = \phi s / \phi \omega$: ratio of the projected non-chemical source term and the projected chemical source term (C. Xu et al., PROCI 2018)

Three mode are identified:

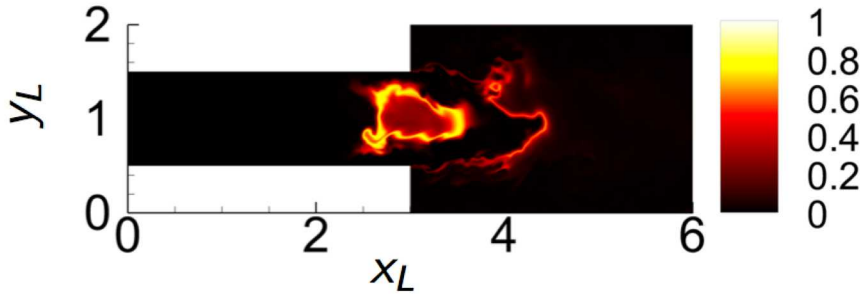
- Assisted-ignition ($\alpha > 1$): diffusion significantly promotes reaction
- Auto-ignition ($-1 < \alpha < 1$): chemistry plays a dominant role
- Extinction zone ($\alpha < -1$): diffusion dominates chemistry and suppresses ignition



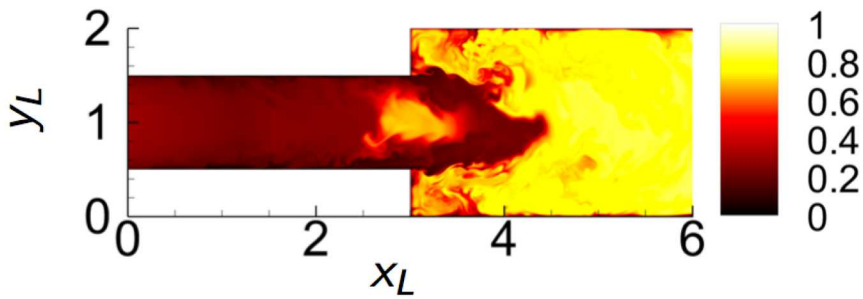


Intermittent auto-ignition state

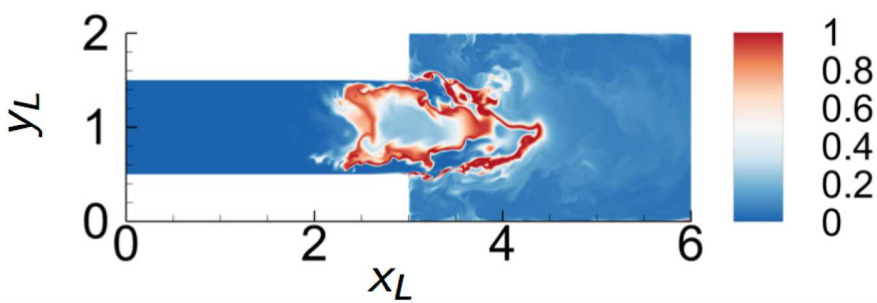
Heat release rate



Temperature

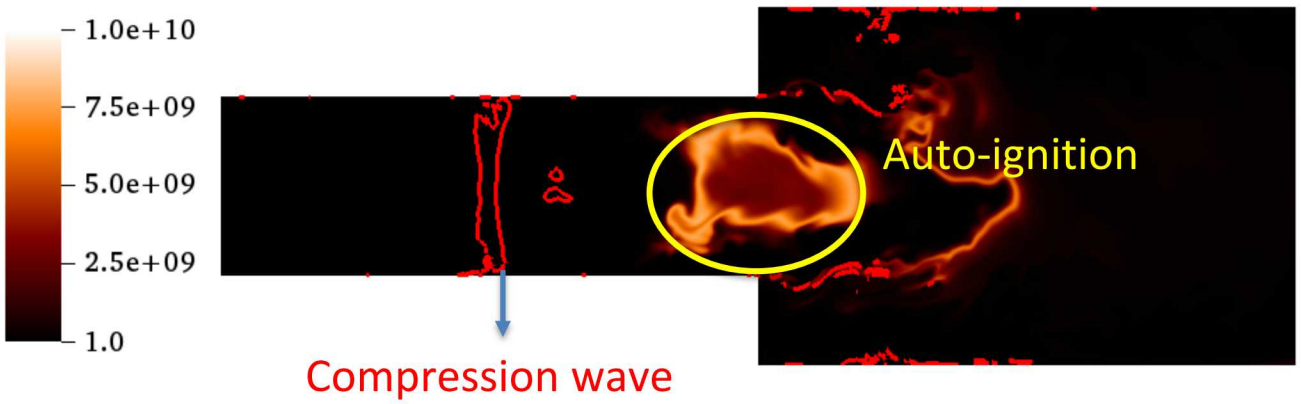


Mass fraction of HO_2

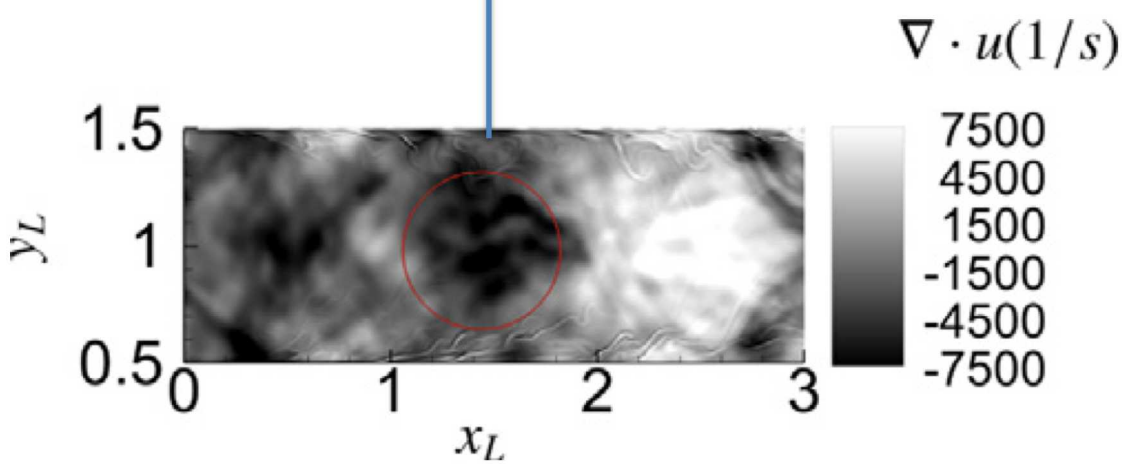


- Early auto-ignition in the mixing section
- Ignition kernel advects downstream
- Occurs intermittently

Intermittent auto-ignition state



Contours of heat release



Contours of instantaneous dilatation

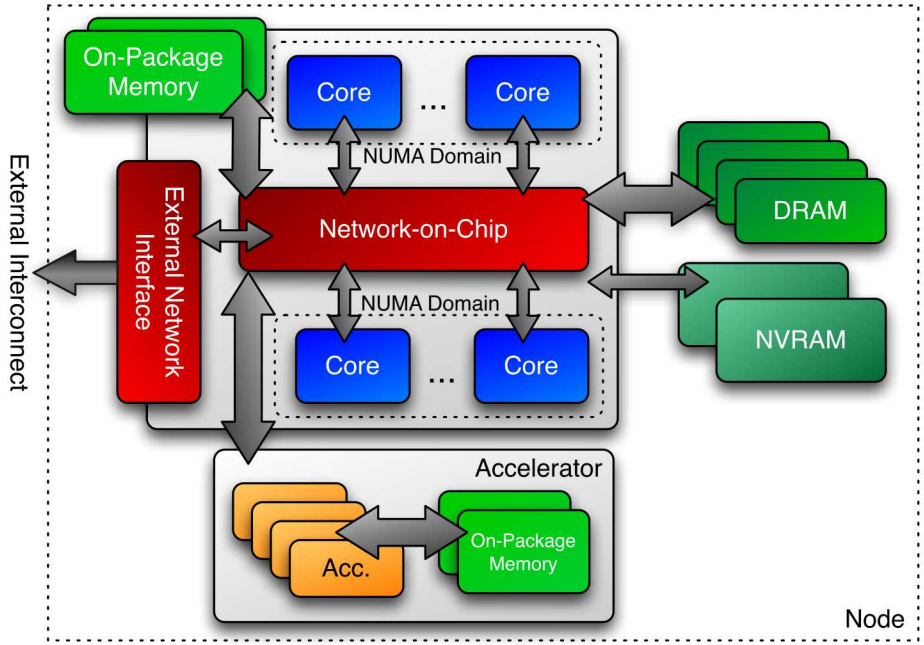
- Local rise in pressure due to intermittent constructive interference pattern
- Increases local temperature by 20-30 K
- High reactivity of hydrogen
- Decrease in ignition delay time (30%)

Conclusions

- Performed DNS of a reheat burner at scaled conditions
- Two states of hydrogen/air combustion have been observed:
  - design state: flame propagation and auto-ignition in the combustor
  - intermittent auto-ignition in mixing section
- Premature auto-ignition arises due to pressure (and following temperature) rise in mixing section
- Quantified the contribution of different modes towards heat release using chemically explosive mode analysis (CEMA)
- Future work:
  - characterize the unstable flame behavior and the conditions leading to it
  - find the inlet conditions for statistically stationary reheat flame
  - perform 2D and 3D simulations with varying fuel composition and its stratification

Constraints imposed by exascale architecture

- **Power:** primary design constraint for future HPC system design
- **Cost:** Data movement dominates: optimize to minimize data movement
- **Concurrency:** Exponential growth of parallelism within chips
- **Locality***:* must reason about data locality and possibly topology
- **Memory Scaling**: Compute growing 2x faster than capacity or bandwidth,
  Heterogeneity: Architectural and performance nonuniformity

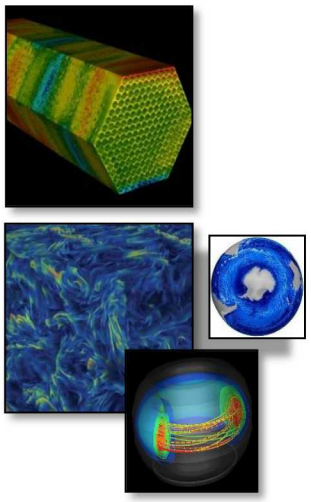


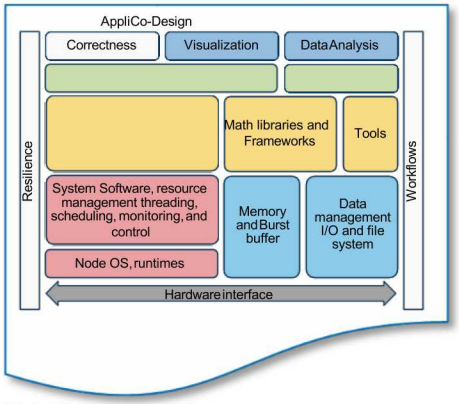
Conceptual model of future HPC node

Express data locality and independence, express massive parallelism, minimize data movement and reduce synchronization, detect and address faults

DOE Exascale Computing Project (ECP) adopts a holistic approach that uses co-design and integration to achieve capable exascale in 2021-2023

Application Development	Software Technology	Hardware Technology	Exascale Systems
Science and mission applications	Scalable and productive software stack	Hardware technology elements	Integrated exascale supercomputers



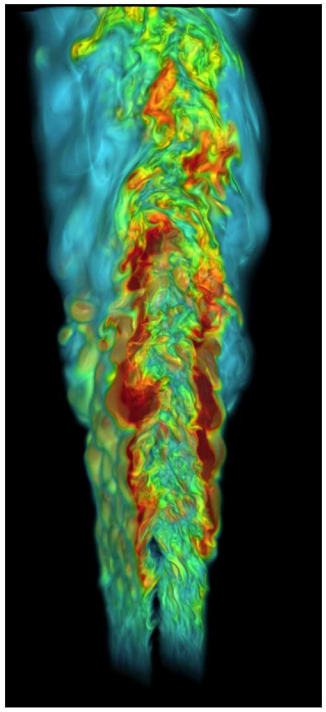


ECP's work encompasses applications, system software, hardware technologies and architectures, and workforce development

From Paul Messina's ASCAC talk April 19, 2017

EXASCALE COMPUTING PROJECT

ECP application: Transforming Combustion Science and Technology Through Exascale Simulation (Pele)



S3D: multi-block compressible reacting DNS multi-physics validation: spray, soot, radiation

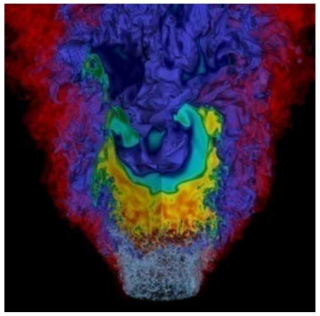
Effects of reactivity stratification at:

- high pressure
- high turbulence
- fuel blends

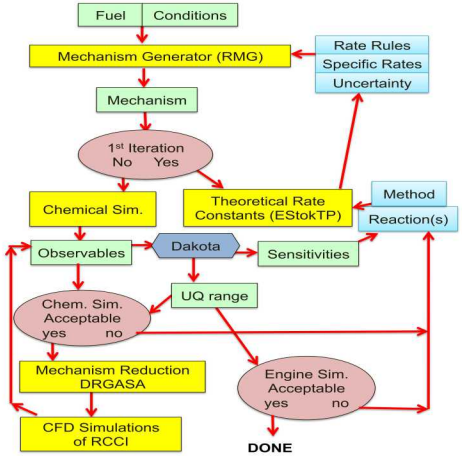
on:

- ignition delay
- combustion rates
- emissions

Pele: Block-structured adaptive mesh refinement, multi-physics: spray, soot, and radiation, real gas, complex geometry

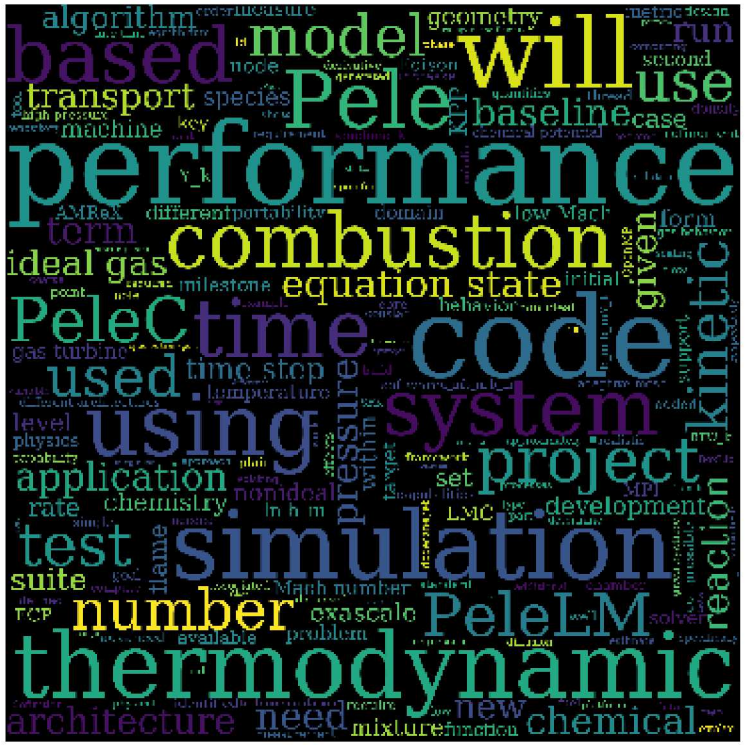


Automated Mechanism Generation

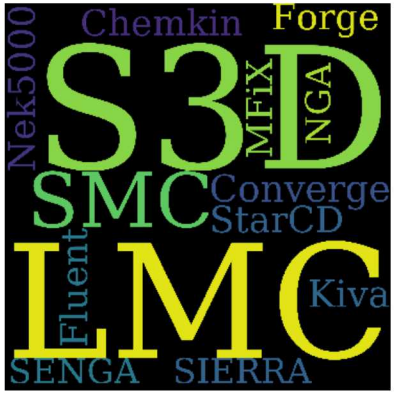


The Pele Project

Transforming Combustion Science and Technology with Exascale Simulations

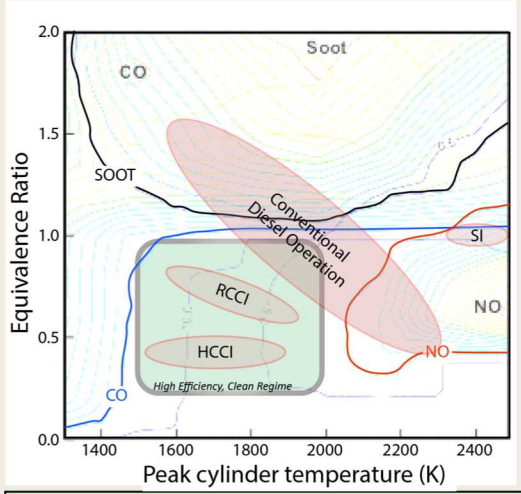


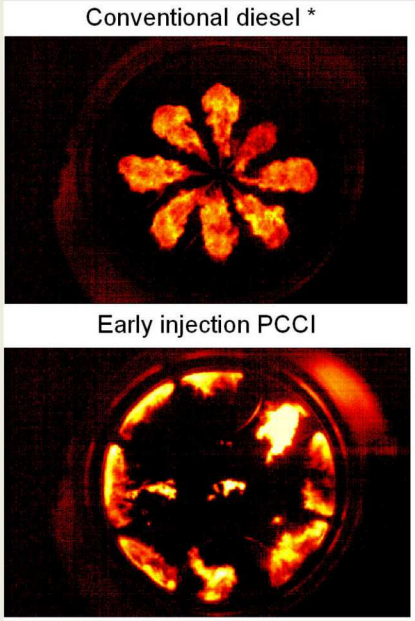
- Use exascale platforms to solve first of exascale-era combustion problems
- Anchored in basic research needs: requirements driven by gas phase chemical kinetics research questions
- turbulence chemistry interaction in conditions *motivated by IC engine and gas turbine research*
- provide a path for development of scalable design codes suitable for exascale hardware



Challenge Problem - Motivation

Advanced combustion regimes (LTC)

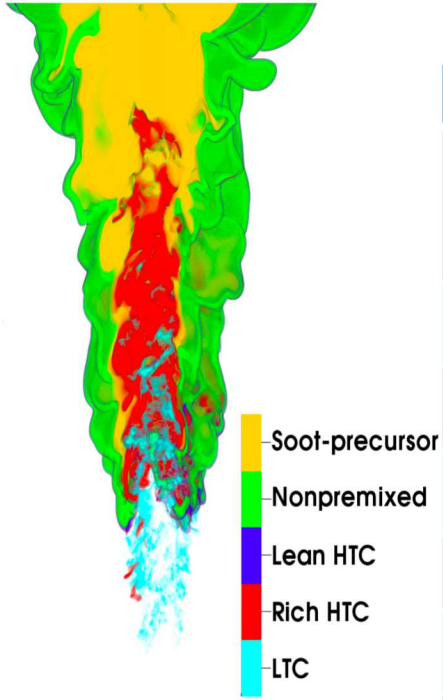




PCCI/HCCI – load limitations
Requires precise charge preparation and combustion control mechanisms
(for auto-ignition and combustion timing)

Adapted from content provided by University of Wisconsin Engine Research Center

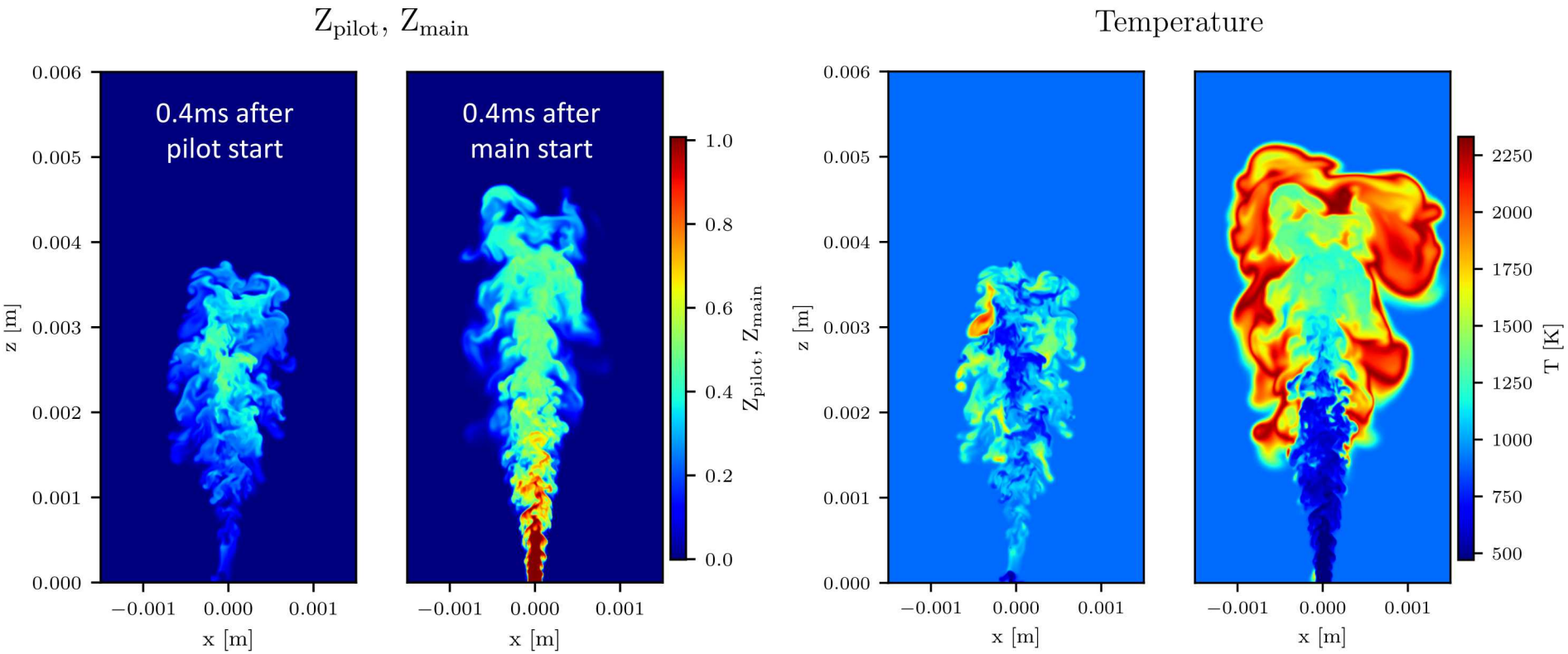
High Fidelity DNS and Hybrid DNS/LES of RCCI Diesel Combustion



DNS of a ndodecane spatially evolving turbulent diesel jet flame at 60 bar, combustion modes, Dalakoti et al. 2018

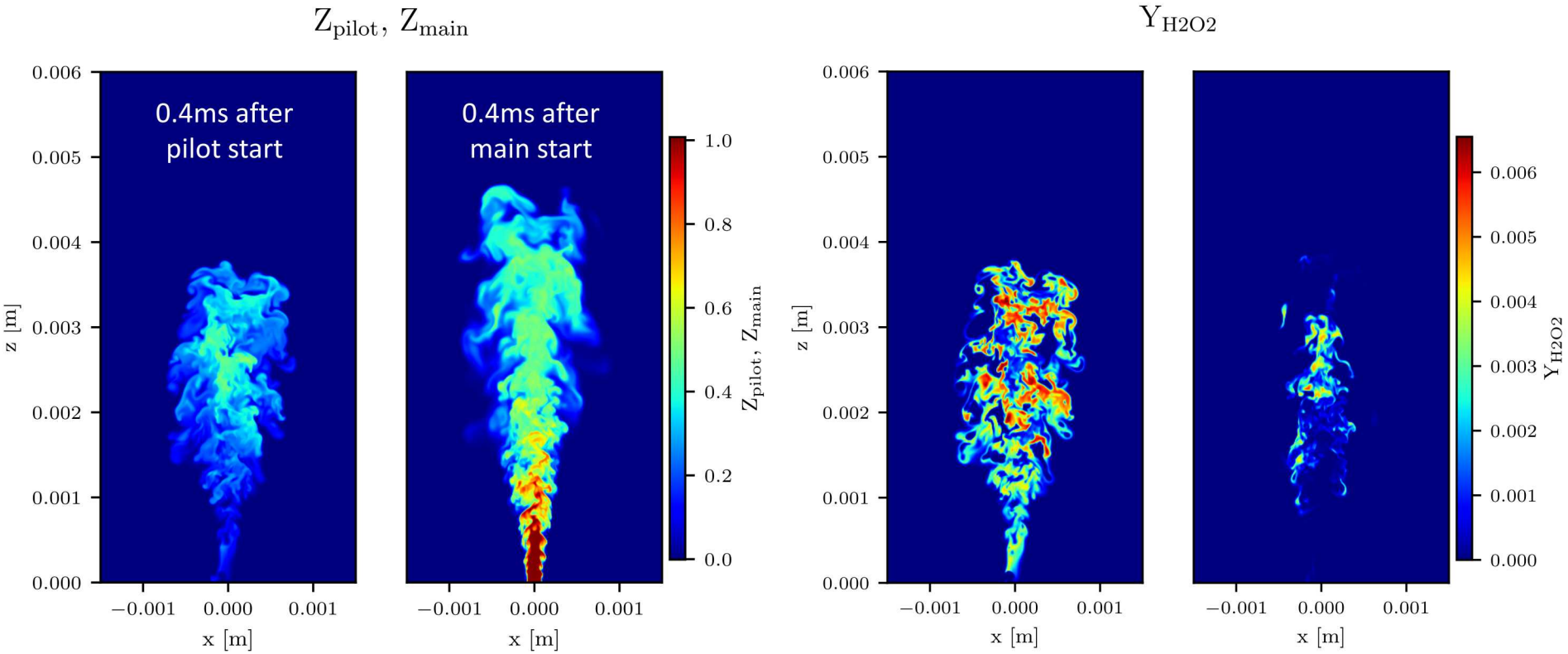
Characteristic / Need	Approach
Impulsively started jets with disparate scales between fronts and turbulence. (Outer scales: 10cm, ms Inner timescales: microns, ns)	Dynamic adaptive mesh refinement
High speed injection followed by subsonic conditions downstream	Compressible and low-Mach capabilities
Long time horizons to set up turbulence for studying fundamental TCI	Hybrid DNS/LES [Non-reacting LES, DNS for flame]
Lean, rich, and low temperature chemistry critical in multi-stage ignition and formation of soot precursors.	Accurate and detailed thermochemistry.
Liquid fuel injection	Lagrangian spray model
Coupling between mixture preparation and emissions	Detailed kinetics including emissions, sectional model for soot with radiation
Mixture preparation dependent on re-entrainment of combustion products	Realistic piston dish and cylinder wall geometry
Performant on exascale architecture	

Comparison at 0.4ms after pilot/main injection start



Pilot: 0.26ms, dwell: 0.17ms, main: 0.74ms
left: times w.r.t pilot start (0.4ms total time), right: times w.r.t. main start (0.83ms total time)

Comparison at 0.4ms after pilot/main injection start



Parallel Programming 101 - Productivity

Functionally correct application code

Mapping to target machine

Extraction of para

anagement of ata transfers

Task scheduling Latency hiding

Data-Dependent Behavior

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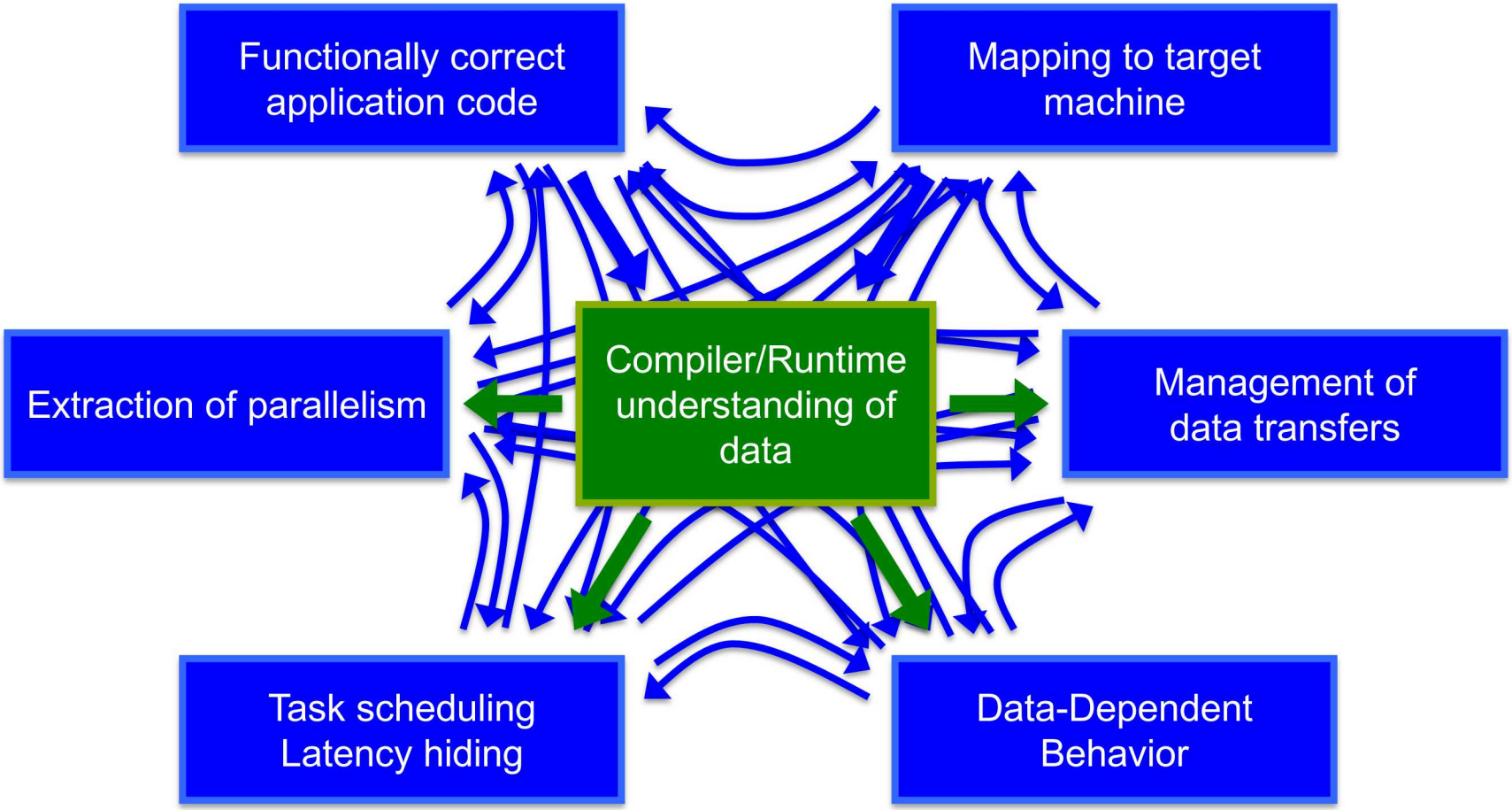
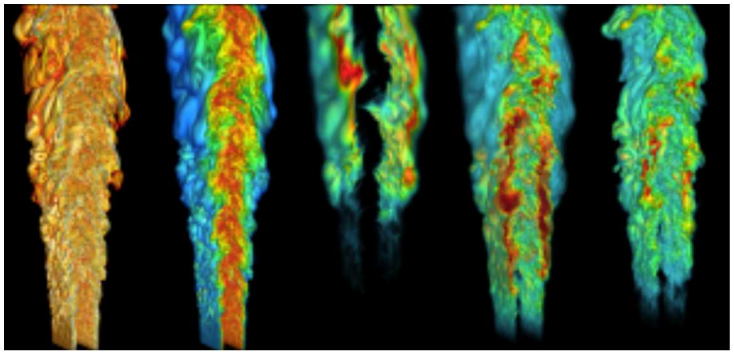
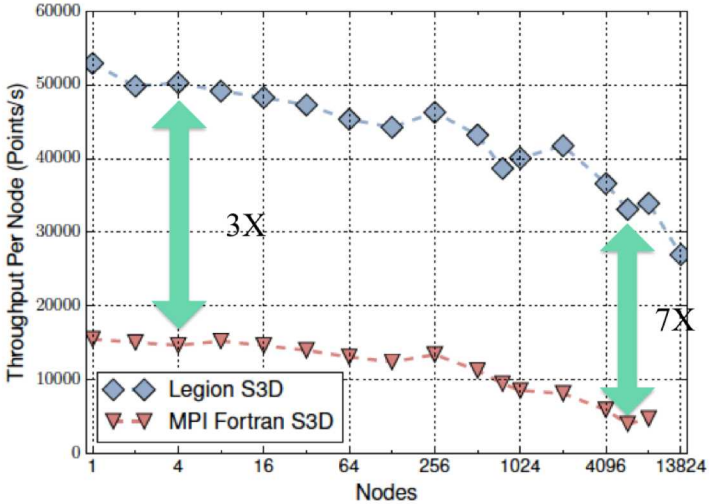
Parallel Programming 101



Legion Programming System

- A data-centric parallel programming system
- A programming model for heterogeneous, distributed machines
  - Automates many aspects of achieving high performance, such as extracting task- and data-level parallelism
  - Automates details of scheduling tasks and data movement (*performance optimization*)
  - Separates the specification of tasks and data from the mapping onto a machine (*performance portability*)
- Legion application example: S3D (ASCR ExaCT)
  - Production combustion simulation
  - Written in ~200K lines of Fortran
  - Direct numerical simulation using explicit methods





S3D performance Legion vs. MPI

Legion Programming System applied to S3D

- A data-centric parallel programming system
- A programming model for heterogeneous, distributed machines
  - Automates many aspects of achieving high performance, such as extracting task- and data-level parallelism
  - Automates details of scheduling tasks and data movement (*performance optimization*)
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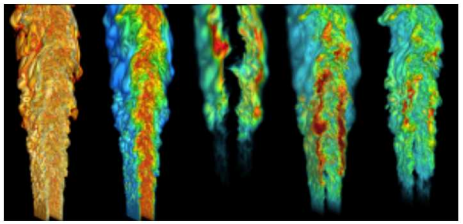
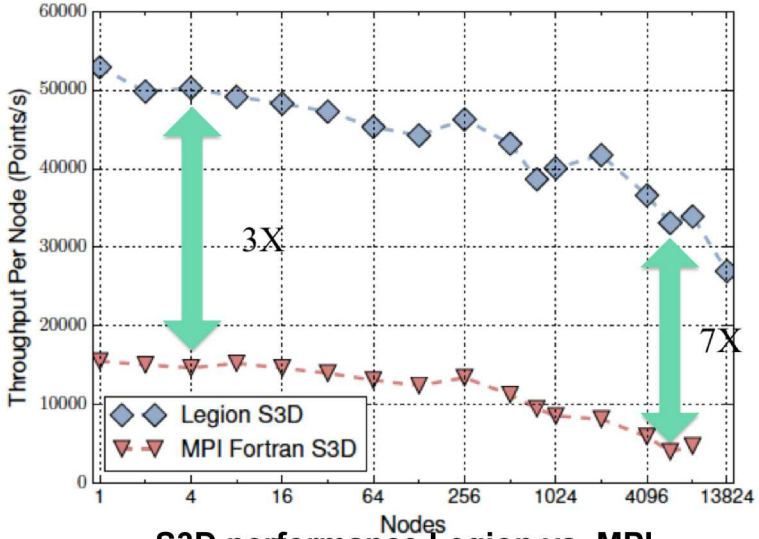


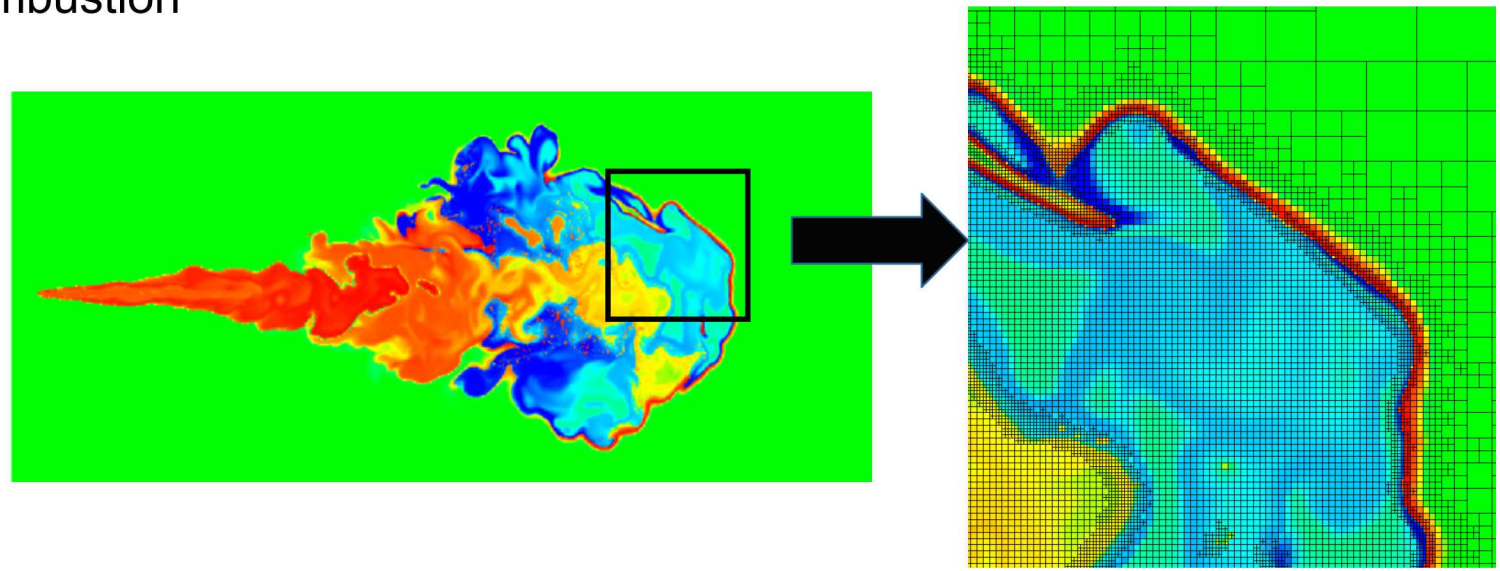


S3D performance Legion vs. MPI

S. Treichler et al., "S3D-Legion: An Exascale Software for Direct Numerical Simulation (DNS) of Turbulent Combustion with Complex Multicomponent Chemistry," CRC Book on Exascale Scientific Applications: Programming Approaches for Scalability Performance and Portability, 2017.

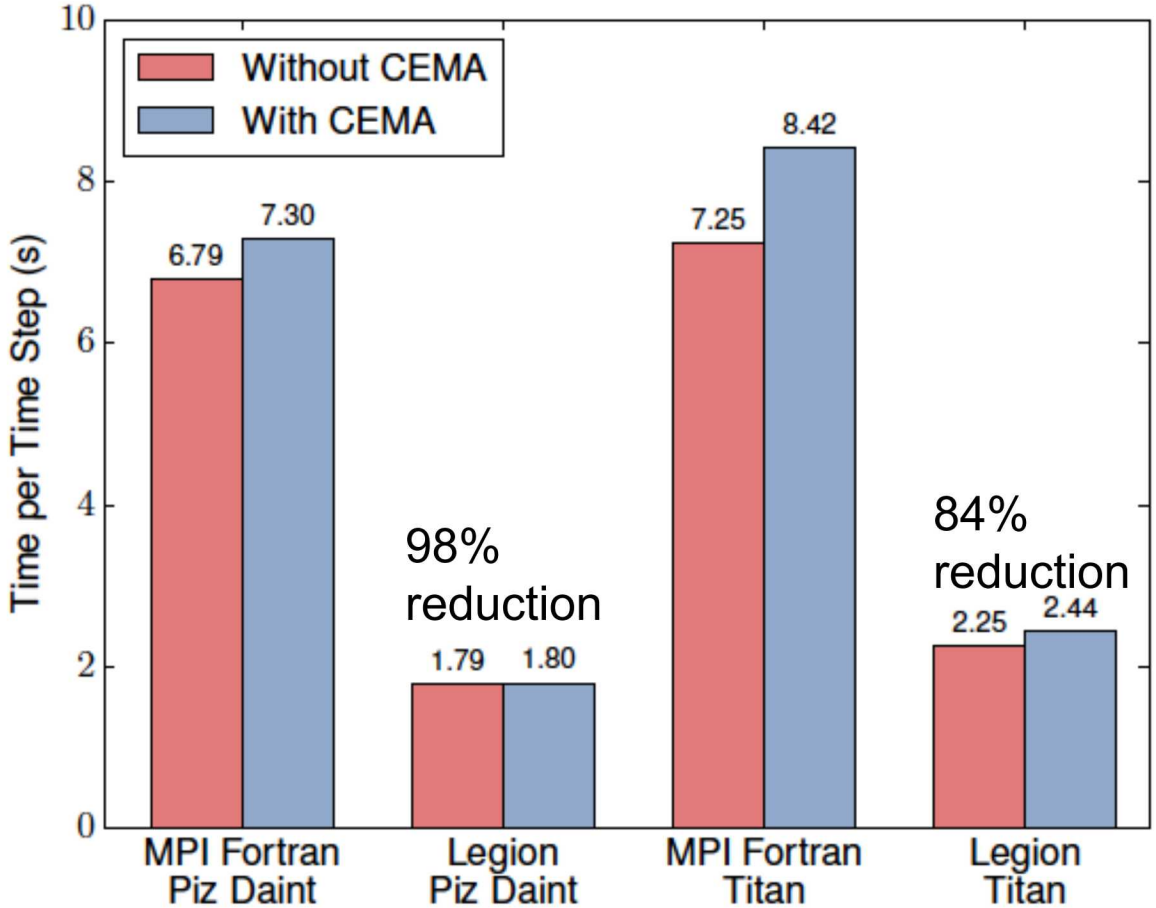
In-situ Data Analytics in Legion
Chemical Explosive Mode Analytics (CEMA)

- CEMA: eigenvalue solve on the reaction rate Jacobian to determine the mode of combustion



- Run CEMA at each time step as a diagnostic to steer mesh refinement
- CEMA computation takes longer than a single explicit RK stage (6 stages/timestep)
- Dividing CEMA across RK stages and interleaving with other computation so as not to impact other critical operations would be hard to schedule manually
- Asynchronous task execution, schedule CEMA on CPU resources
- Interoperate Fortran CEMA with Legion code – took a day to implement

Execution Overhead of In-situ Analytics (CEMA) in S3D-Legion (Titan & Piz Daint)



Legion S3D Lessons Learned

- Legion
  - S3D shows potential of data-centric, task-based models
  - Enables new simulation capabilities (physics, and in situ analytics)
  - Code is easier to modify and maintain
    - Ports are just new mappings, easy to tune for performance
    - New functionality usually just means new tasks
    - Legion will figure out the dependences and scheduling
    - Productivity requires higher level abstraction layer for scientists to write in

- Co-Design and ECP
  - The Legion/S3D experience is a tribute to co-design
  - Computer and computational scientists worked closely
  - Major progress on important problems resulted

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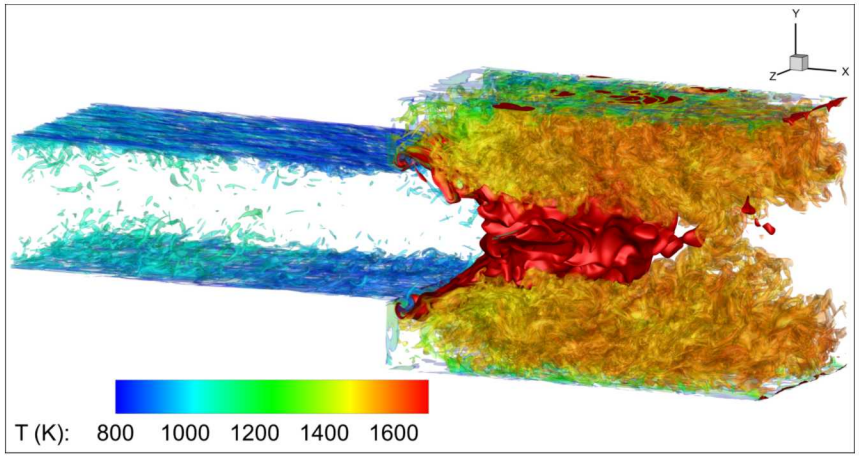
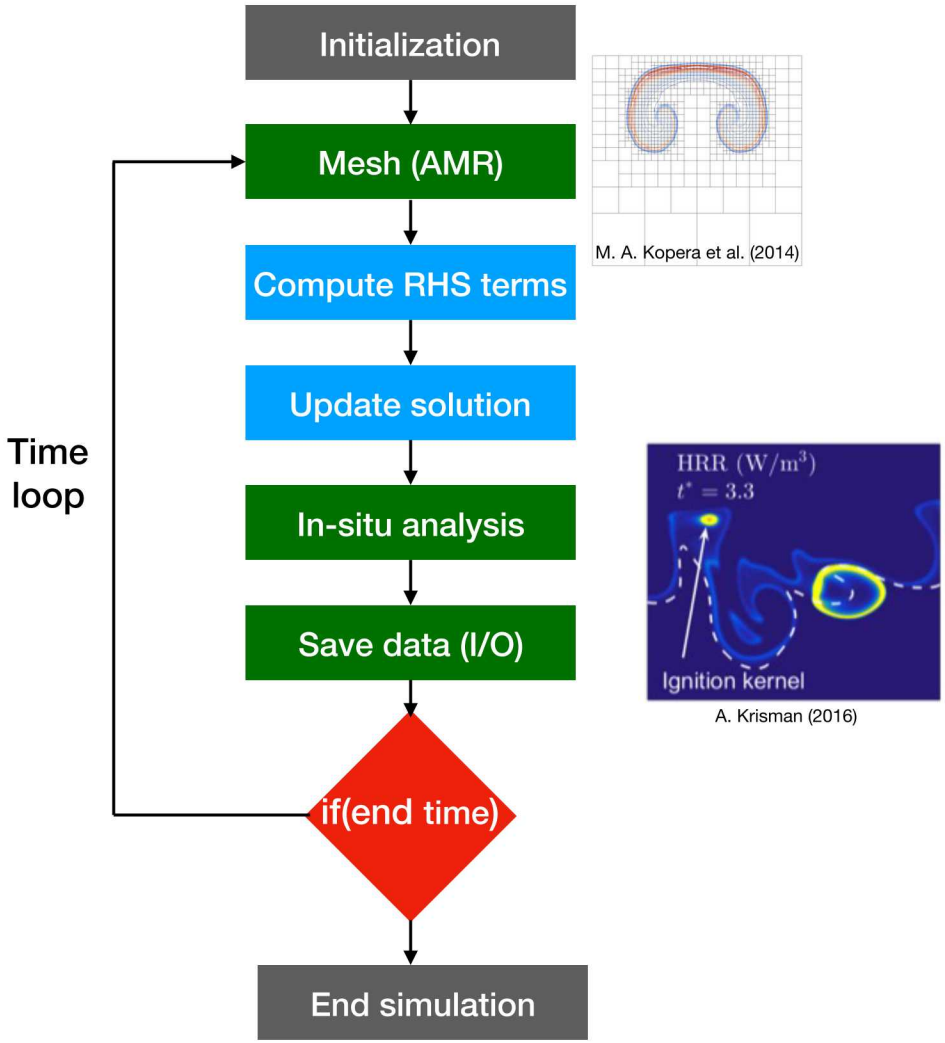
Anomaly Detection in Combustion simulations

Iso-surfaces of vorticity magnitude colored by temperature



- Direct numerical simulations: resolve all the scales in space and time
- **Attributes:**
  - Multi-variate: ~10 – 100 variables; multi-scale
  - High resolution data of smoothly varying functions
- Massively parallel solvers (e.g. S3D Chen at al. (CSD 2009))
  - computationally expensive (tens millions of CPU hours)
  - large amount of data (~ 100 TB)
- Exascale (millions processing elements): need efficient workflows

Simulation workflow

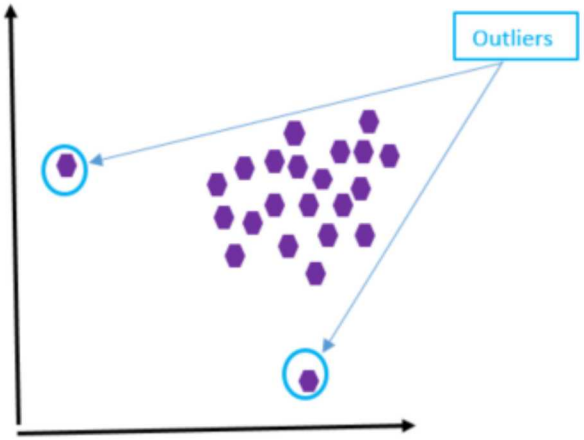


M. A. Kopera et al. (2014)

A. Krisman (2016)

Methods

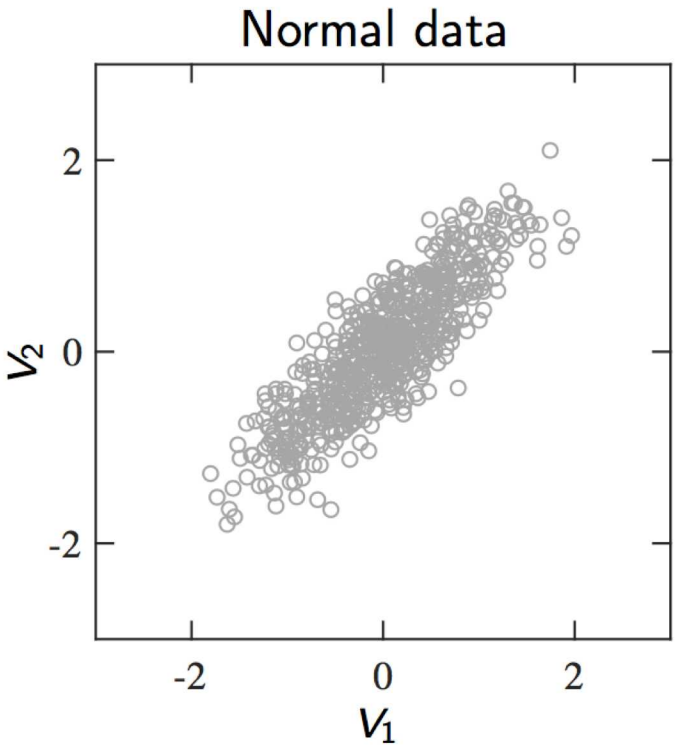
- k-nearest neighbors
  - compute “mean” distance from k nearest neighbors
- Local outlier factor
  - compute outlier score based on local density
- Supervised learning methods (e.g. neural networks)
  - regression and classification

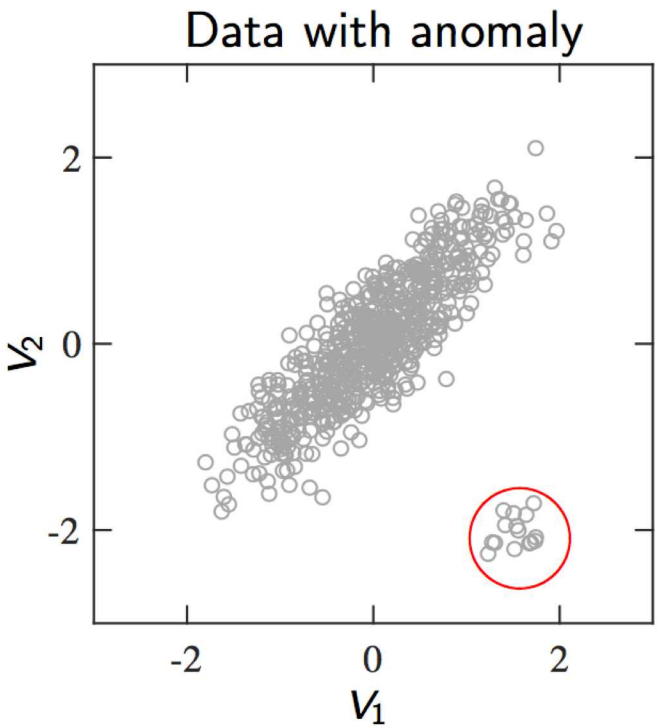


Not efficient and expensive to compute

Idea

- Bivariate dataset

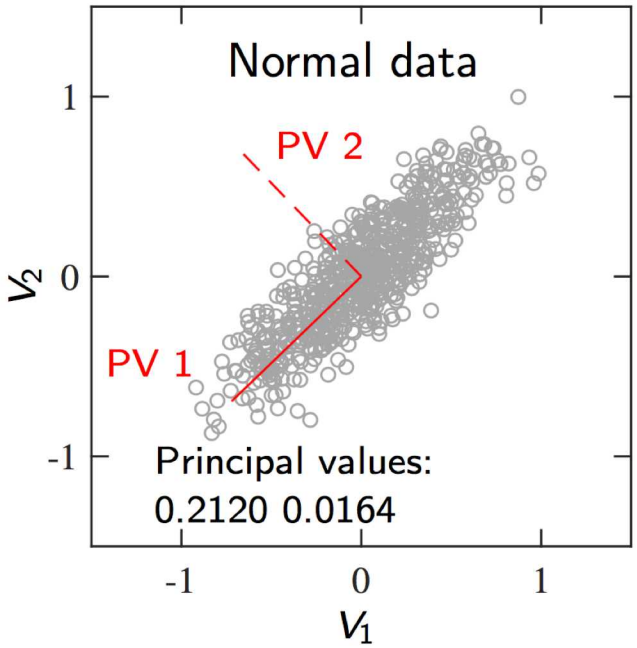


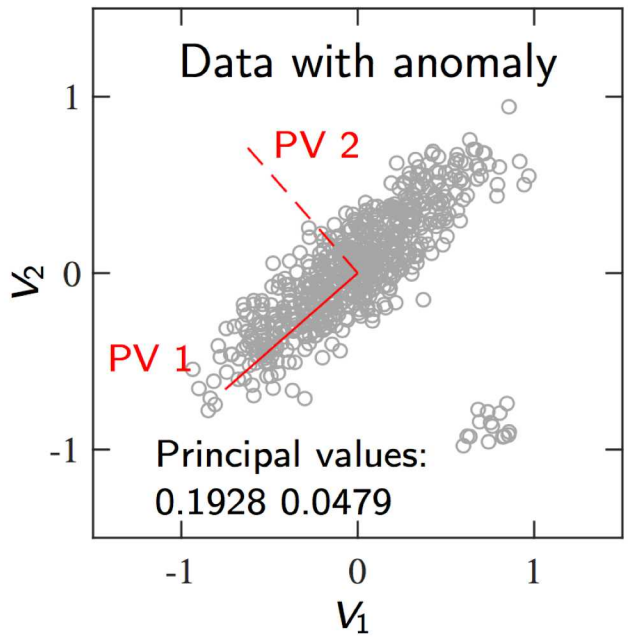


- Characterize the data distribution: principal component analysis
- Change in distribution: effects the magnitude of principal value and orientation of principal vectors

Principal component analysis

- Scale the data: with mean and maximum
- Compute the co-variance matrix (second order joint moment)
- Perform Eigen decomposition to obtain the principal values and vectors





- Mainly captures variance
- **Need to look at higher order moments to capture extreme events**

Fourth order joint moment

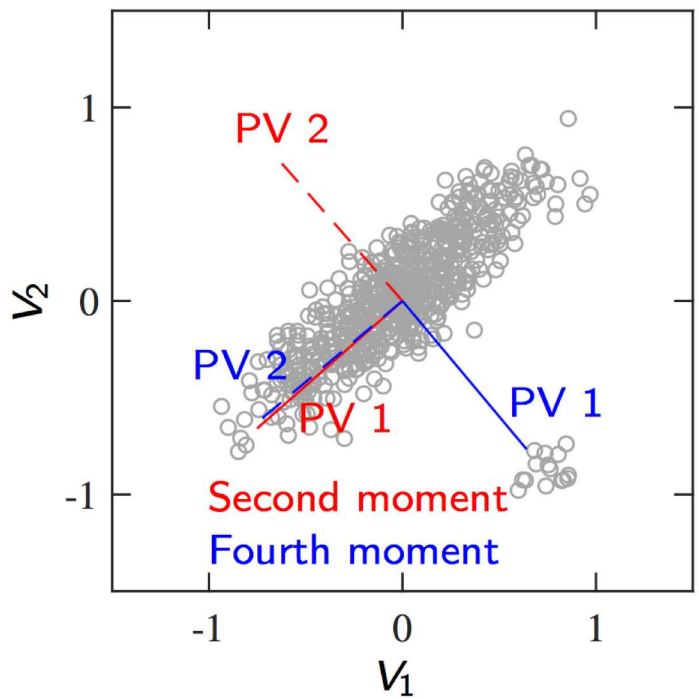
Kurtosis: measure of "either existing outliers (for the sample kurtosis) or propensity to produce outliers (for the kurtosis of a probability distribution)" (P. H. Westfall, 2014)

- Compute the fourth joint moment (cumulant tensor, T)

$$\begin{aligned}\mathcal{T} &= \mathbb{E}[v \otimes v \otimes v \otimes v] - \mathbb{E}[v_{i_1} v_{i_2}]\mathbb{E}[v_{i_3} v_{i_4}] \\ &\quad -\mathbb{E}[v_{i_1} v_{i_3}]\mathbb{E}[v_{i_2} v_{i_4}] - \mathbb{E}[v_{i_1} v_{i_4}]\mathbb{E}[v_{i_2} v_{i_3}], \quad 1 \leq i_1 \ldots i_4 \leq k\end{aligned}$$

- Decompose the fourth order symmetric tensor
  - Tensor size (N_f^4), N_f : number of features
  - Matricize the tensor and perform SVD (A. Anandkumar et al., JMLR 2014)
- Obtain principal kurtosis values and vectors

Anomaly detection

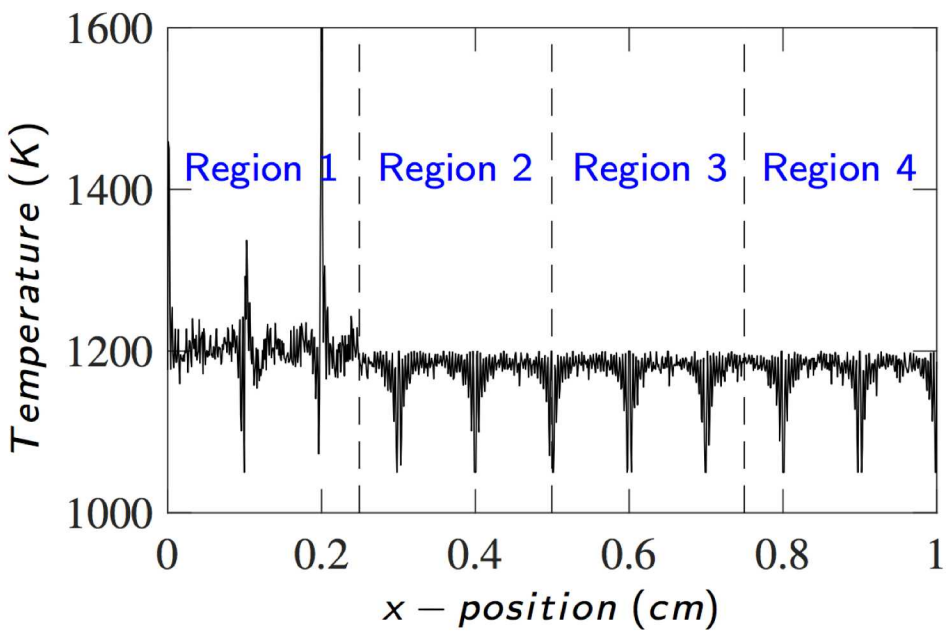


- First principal kurtosis vector aligns in the direction of anomalies
- Can be used to characterize extreme events

Combustion test case

Consider a simple problem with a 1D domain

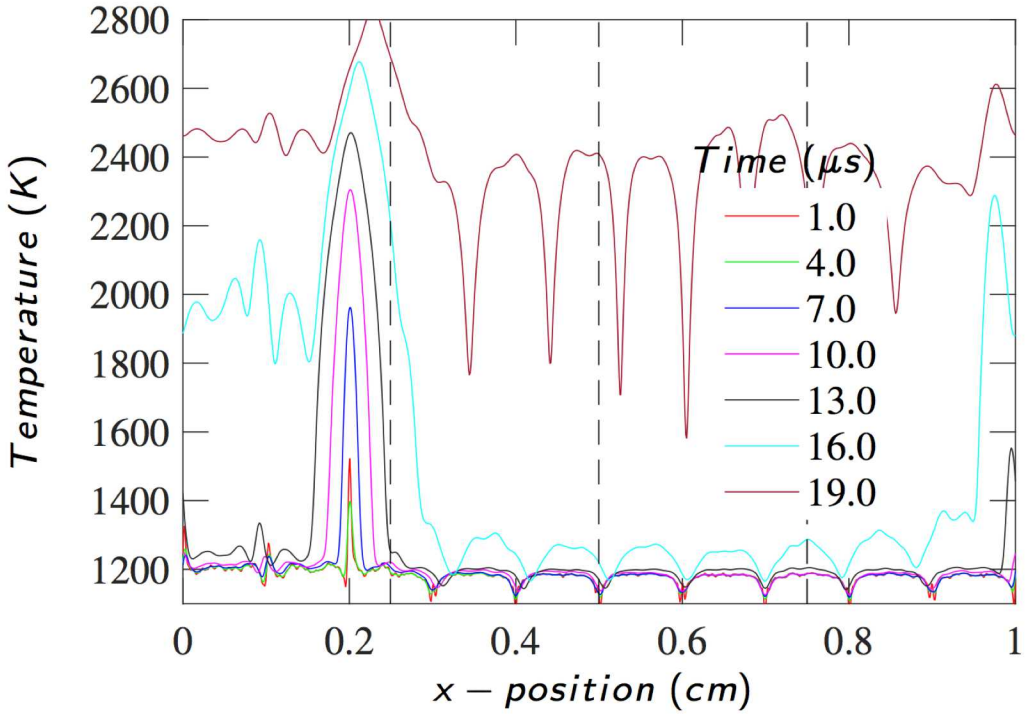
- Initial condition



- Fuel-air composition: premixed – $0.6CO + 0.4H_2 + 0.5(O_2 + 3.76N_2)$
- Solver: scalable reacting flow code S3D (J. H. Chen et al., CSD 2009)
- Number of subdomains: $N_d = 4$
- Time-steps: $\Delta t = 0.001\ \mu s$
- Number of checkpoints: $N_t = 20$, interval: 1 μs

Auto-ignition solution

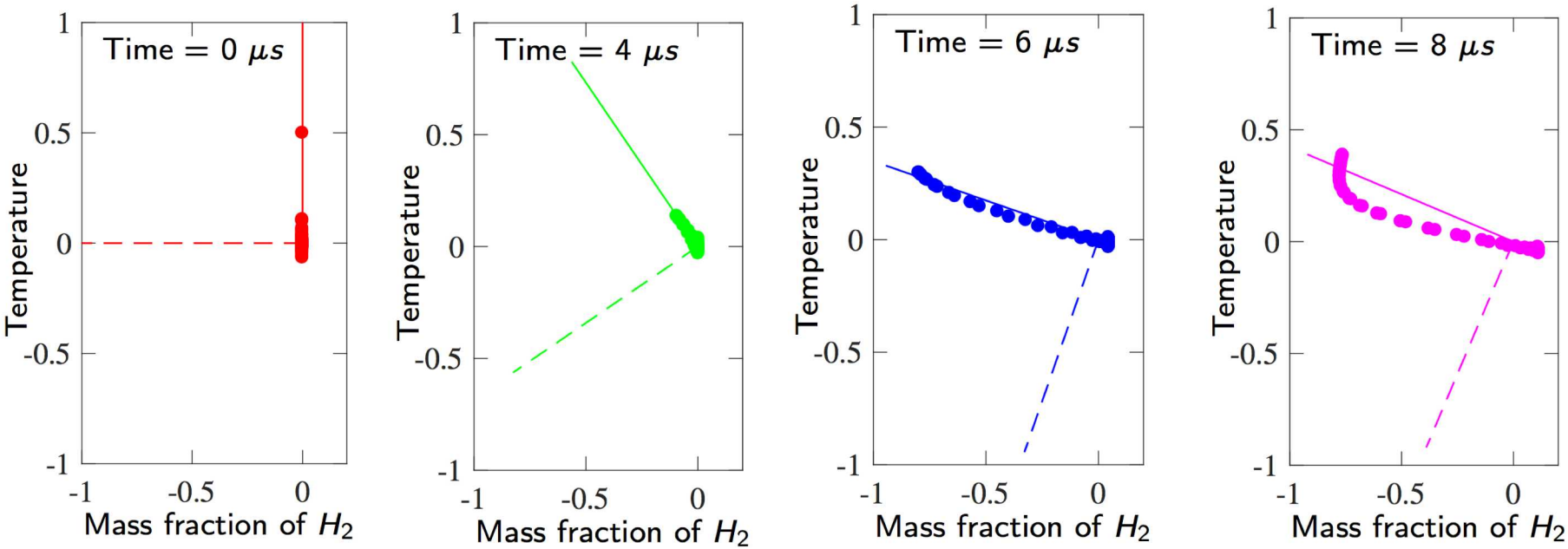
- Time evolution of temperature



- Early ignition occurs in Region 1: spatial anomaly
- Eventually ignites in Regions 4, 2 and 3

Results

Time evolution of principal vectors in Region 1 (axes: scaled)



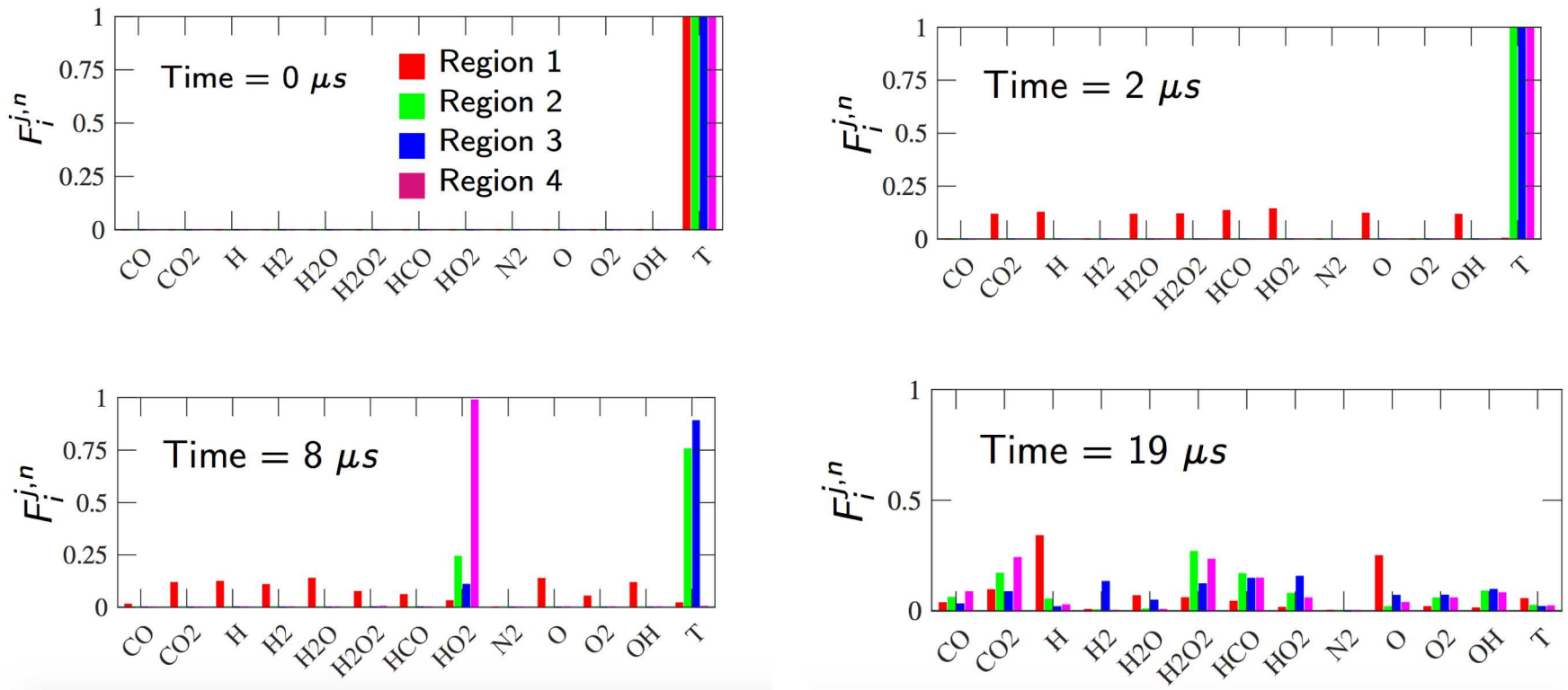
Feature moment metrics

- Number of features: N_f = 13 (12 species + temperature), index i
- Number of subdomains: N_d = 4, index j
- Number of time steps: N_t = 20, index n
- Project the principal vectors weighted by the principal values onto the features to obtain the feature moment metrics ($F_i^{j,n}$)

$$F_i^{j,n} = \frac{\sum_{k=1}^{N_f} \lambda_k \left(\hat{e}_i \cdot \hat{v}_k\right)^2}{\sum_{k=1}^{N_f} \lambda_k}$$

- $\hat{e} \cdot \hat{v}$ is effectively the i-th entry in the k-th vector $\hat{v}_k$
- Property: $\sum_{i=1}^{N_f} F_i^{j,n} = 1, \ \forall\, j, n$

Results



- FMMs distribute across different features when ignition (anomaly) occurs

Anomaly metrics

Identify spatial and temporal anomalies

- Statistical signature: distribution of feature moment metrics changes
- **Hellinger distance:** a symmetric measure of difference between two discrete distributions *P* and *Q*

$$D_{PQ} = \frac{1}{\sqrt{2}}\sqrt{\sum_i (\sqrt{p_i} - \sqrt{q_i})^2}$$

- **Spatial metric:** compare each FMM distribution with the average

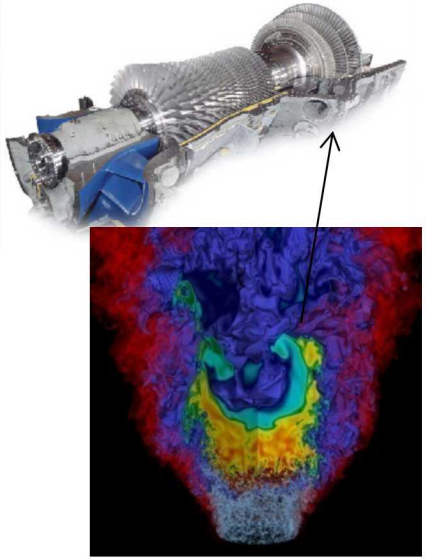
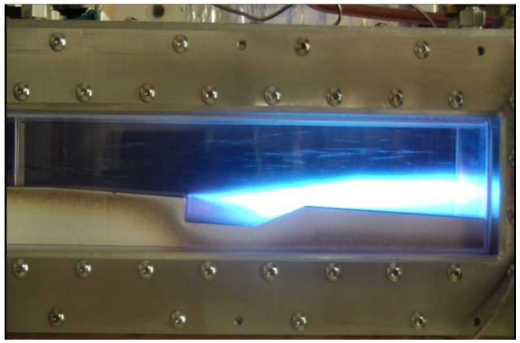
$$M_1^n(j) = \frac{1}{\sqrt{2}}\sqrt{\sum_{i=1}^{N_f}\left(\sqrt{F_i^{j,n}} - \sqrt{\overline{F}_i^n}\right)^2}$$

- **Temporal metric:** compare FMM distribution between successive time steps

$$M_2^j(n) = \frac{1}{\sqrt{2}}\sqrt{\sum_{i=1}^{N_f}\left(\sqrt{F_i^{j,n}} - \sqrt{F_i^{j,n-1}}\right)^2}$$

Results

- Proposed an unsupervised anomaly detection algorithm
- Verified the idea using synthetic and auto-ignition data
- Future work:
  - in-situ implementation of the algorithm into the massively parallel direct numerical simulation solver (S3D)
  - evaluate scalability
  - apply the algorithm to detect anomalies in other scientific phenomena

Exascale Targets: Science at Relevant Conditions

- **Hybrid DNS/LES (near DNS) with dynamic adaptive mesh refinement, multi-physics (sprays, soot, radiation at high pressure) in geometry**
- **Reactivity Stratified Compression Ignition IC Engines** - multi-stage, high pressure autoignition of a liquid hydrocarbon fuel blend, soot formation
- **Natural Gas IC Engines – ignition and knock**
- **Scramjets** – cavity stabilized shear driven lean turbulent premixed flames, effect of products recirculation coupled with high Re, high Ka, compressible flames
- **Gas Turbines** – swirl stabilized spray combustion gas turbines with lean premixed combustion, flame stabilization, nitric oxide emissions, thermo-acoustics
- **Include in-situ analytics & visualization**