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# Direct Numerical Simulation of Multi-Injection Mixing and Combustion at Compression Ignition Engine Conditions

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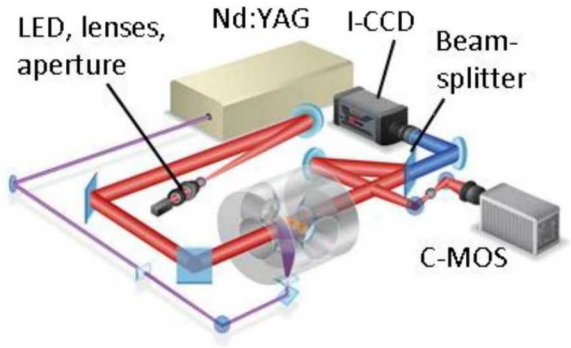
# Scientific Problem

## Application

www.challenger.com

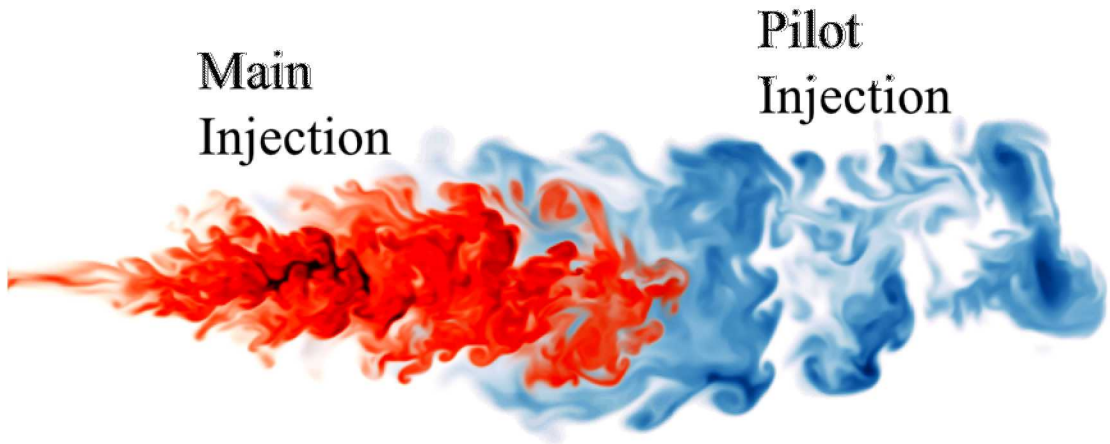
http://insideunmannedsystems.com

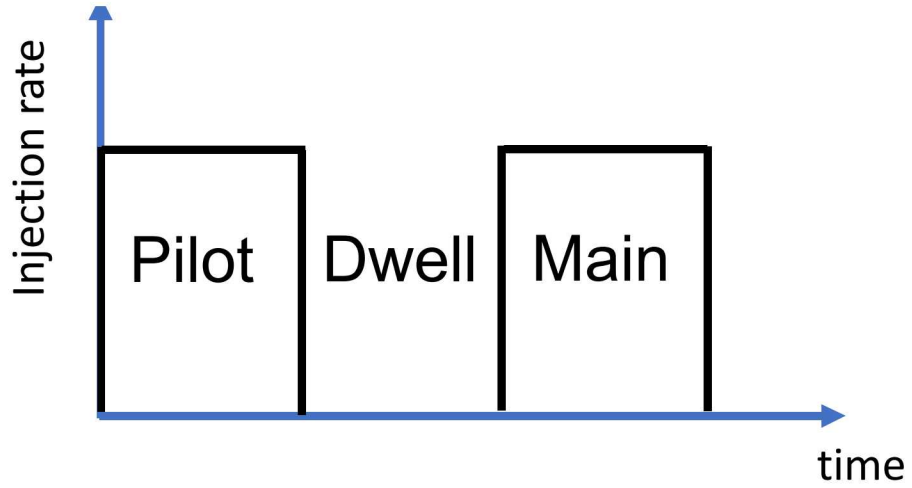
## Experiment




*Skeen et al., SAE IJE, 2015.*

## Simulation



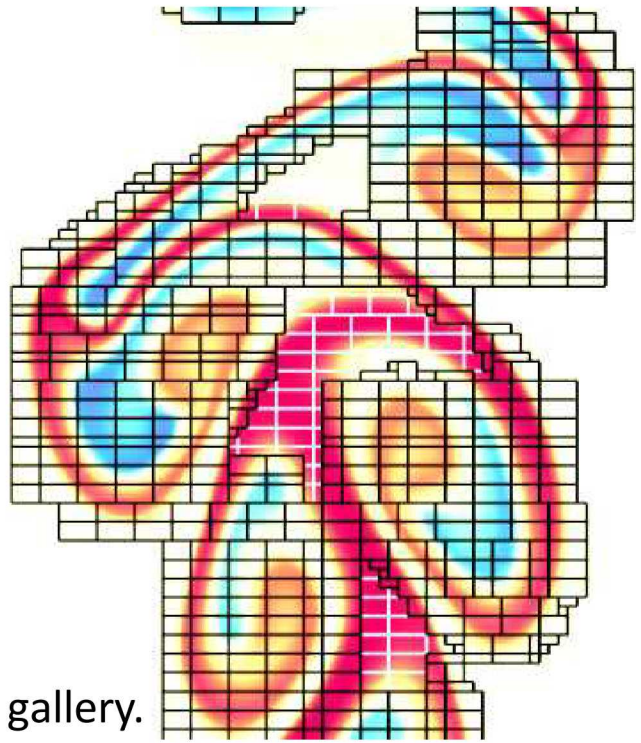




How does the presence of the pilot injection alter the ignition of the main injection?

# PeleLM Code & Numerical Setup

- PeleLM – low-Mach adaptive mesh refinement code based on AMReX
- Spectral deferred correction scheme for fluid dynamics-chemistry coupling
- Current multi-physics development: spray, soot, radiation

- Refinement based on temperature gradient, vorticity & ‘flame species’
- Typical resolution O(1-10micron)
- Typical size of simulation:
  1B cells (O(100)B cells without AMR)
- 35 species reduced n-dodecane mechanism (Yao et al., 2017; Borghesi et al., 2018)
- Downscaled conditions compared to experiment/device (Dalakoti et al., 2017)



Emmett et al., arxiv, 2018. E. Motheau AMReX gallery.

# Cases

www.challenger.com

## Ground operation

High-pressure, 60atm
Moderate temperature, 900K
Exhaust gas recirculation, 15% $O_2$
Pilot 0.5 ms, dwell 0.5 ms, main 0.5 ms
Multi-injection to improve mixture formation, reduce emissions

http://insideunmannedsystems.com

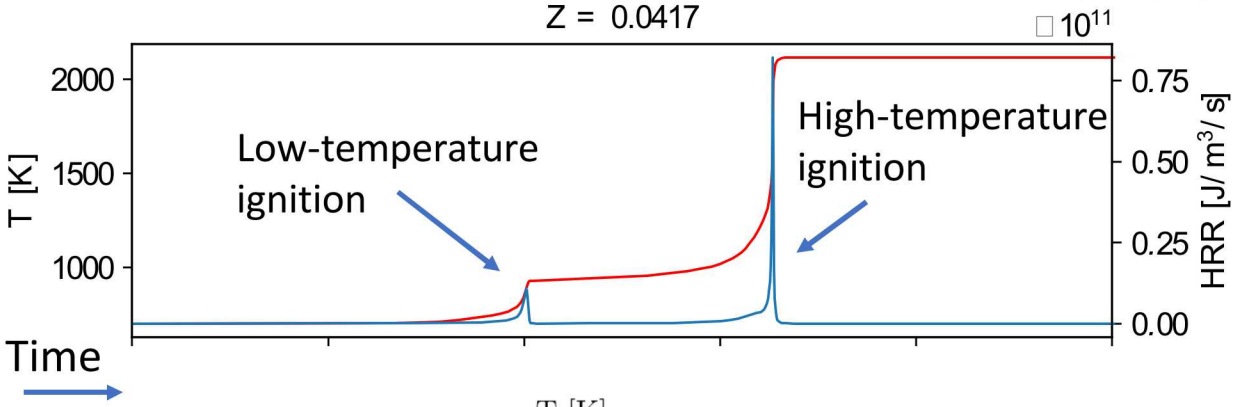
## High-altitude operation (UAV)

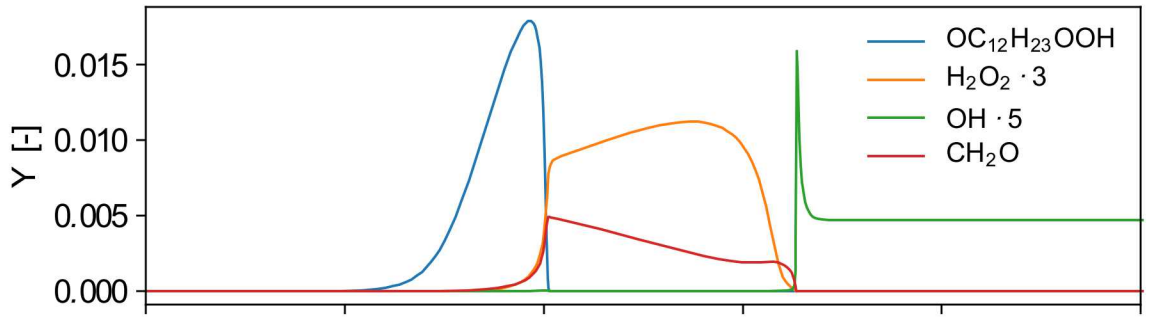
Moderate pressure, 10atm
**Low temperature, 750K**
No exhaust gas recirculation, 21% O2
Pilot 0.208ms ms, dwell 0.992 ms, main 1.138 ms
Multi-injection to reduce signature (IR, smoke), improve ignition reliability, improve operation with various fuels

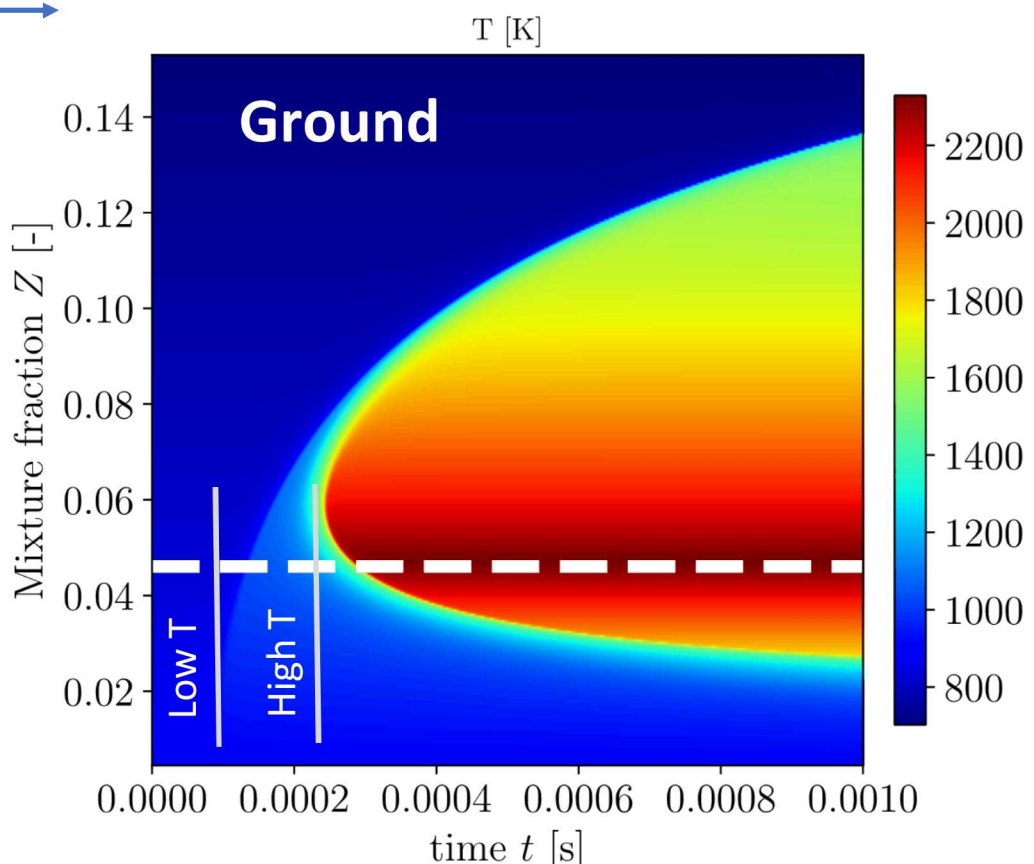
Conditions lead to significantly different ignition processes

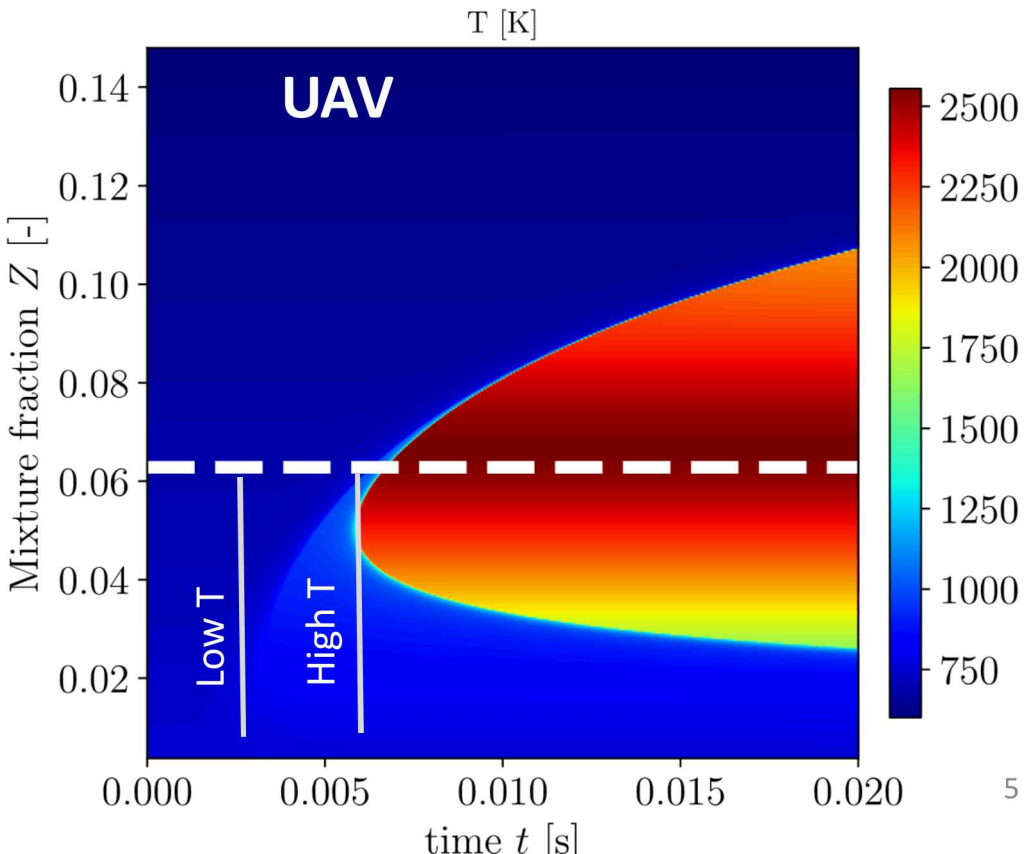
# Ground and UAV operation - 0D ignition

Exemplary ignition sequence

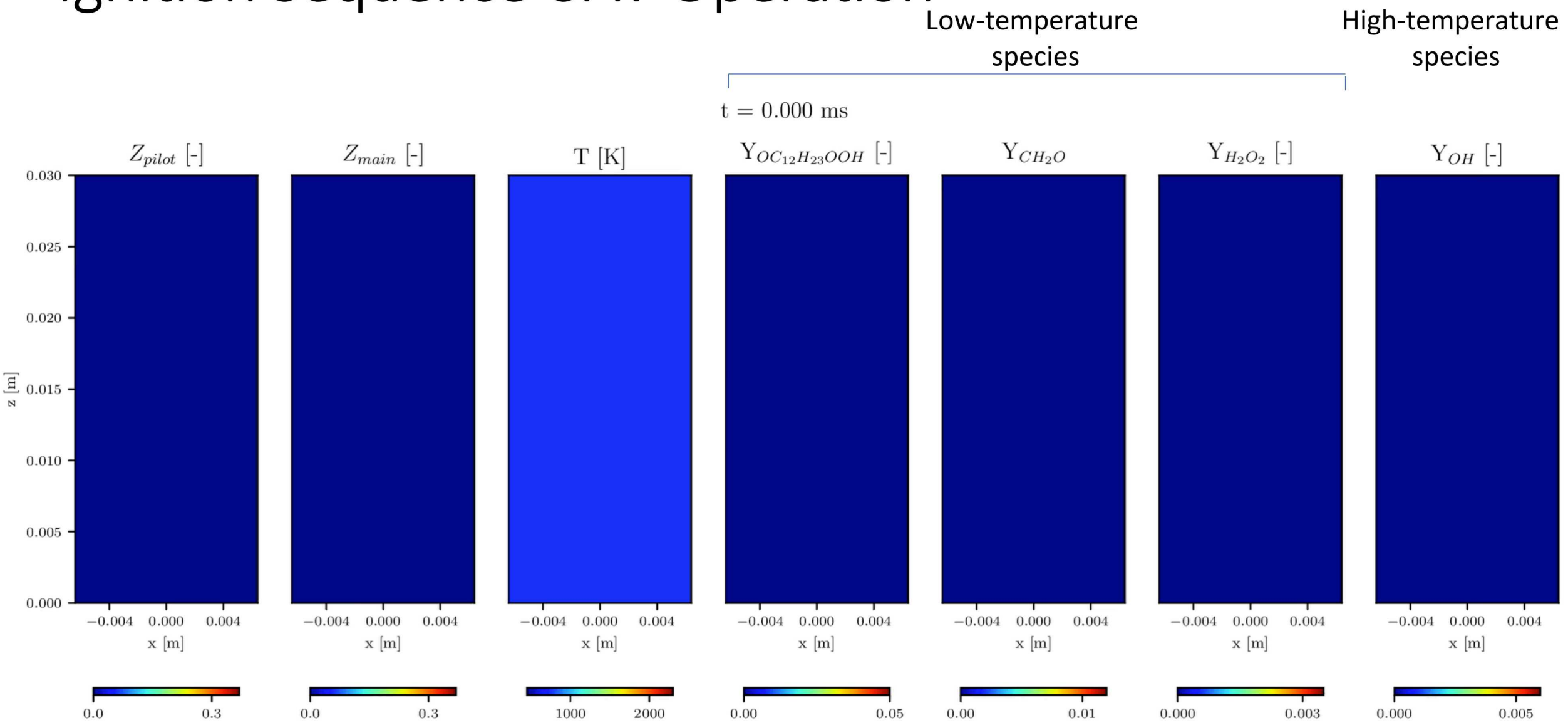


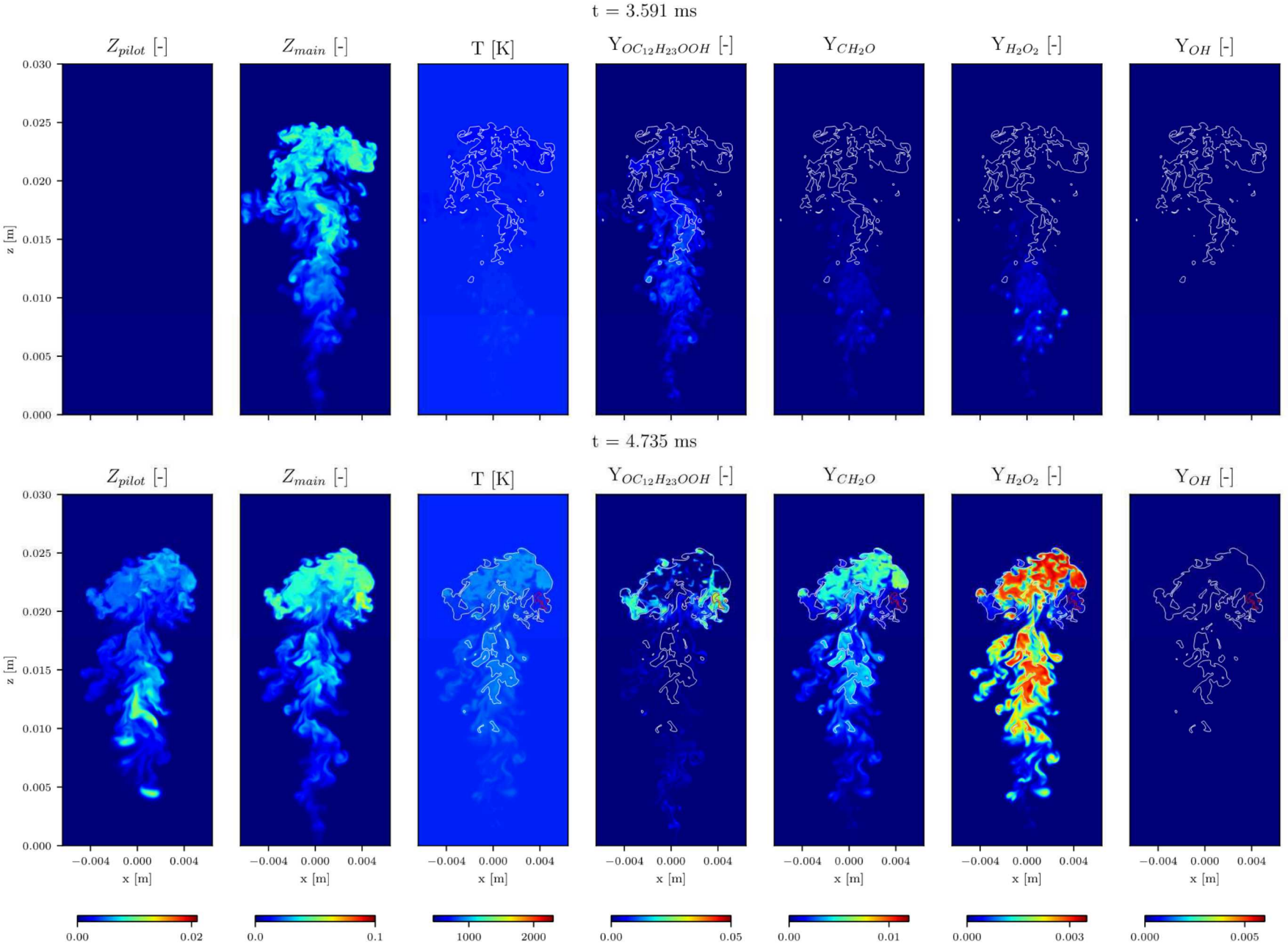



# Ignition Sequence UAV Operation




Mixture fractions track fluid from individual injections (two additional transport equations)

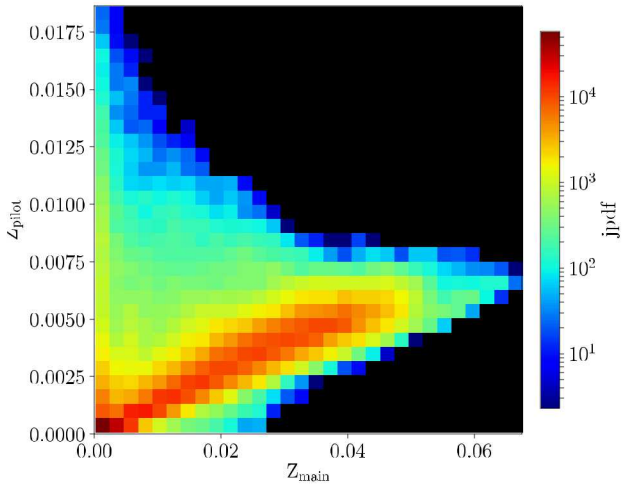
# Ignition Sequence UAV Operation - 3.6ms




Without pilot

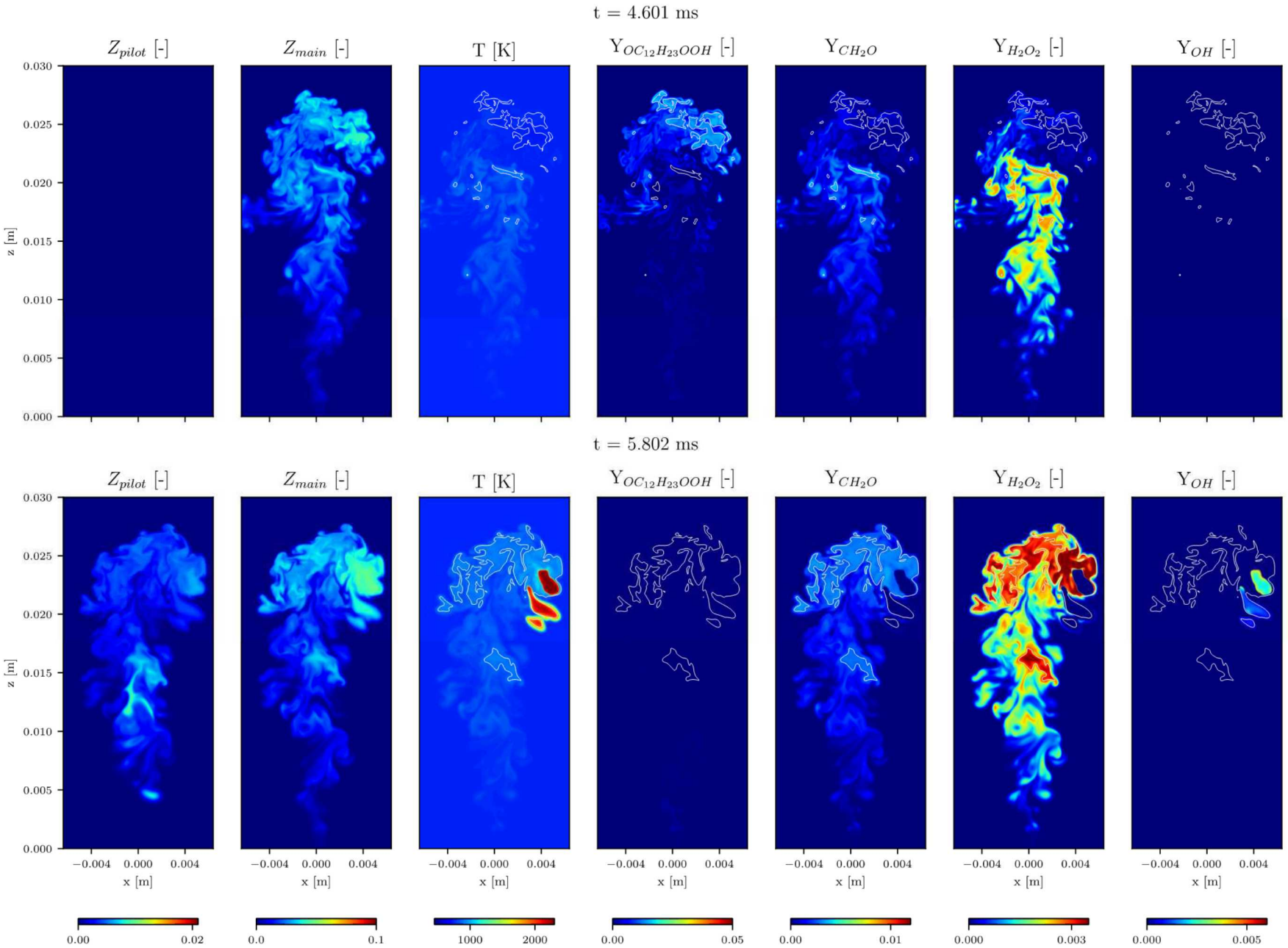
With pilot

JPDF of the mixture fractions




Strong correlation
→ well mixed

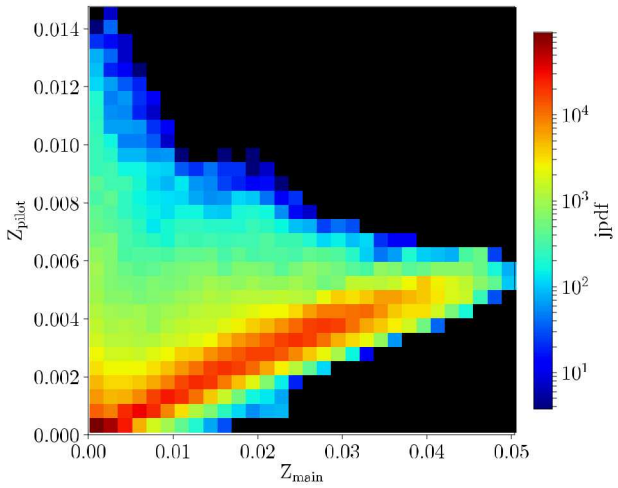
# Ignition Sequence UAV Operation - 4.6ms




Without pilot

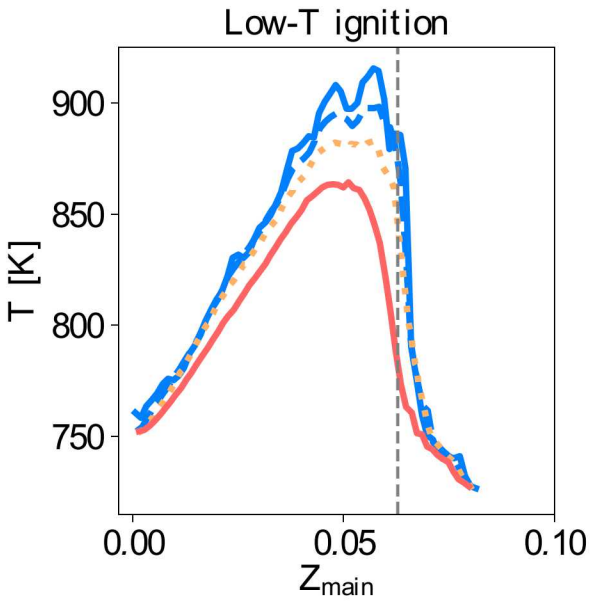
With pilot

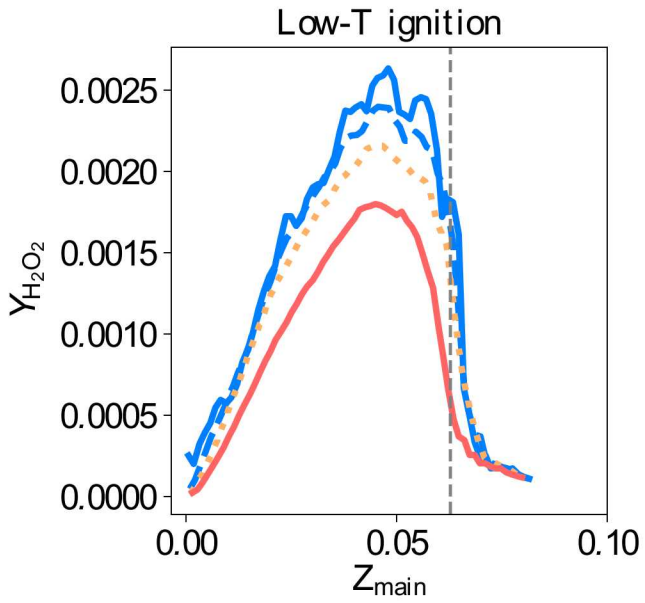
JPDF of the mixture fractions

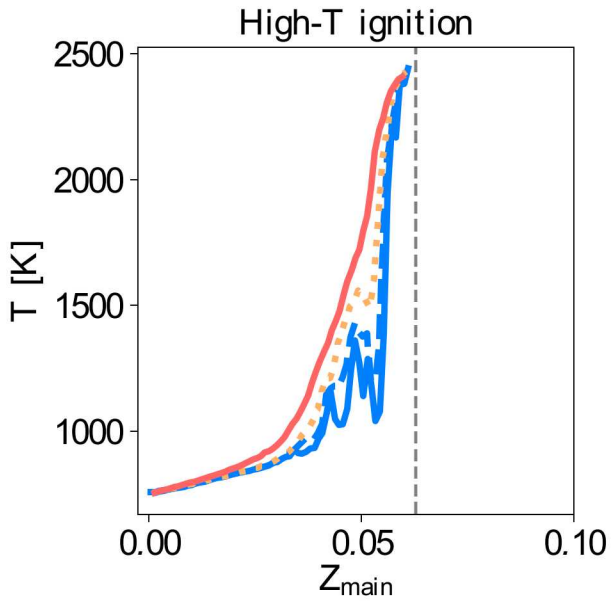


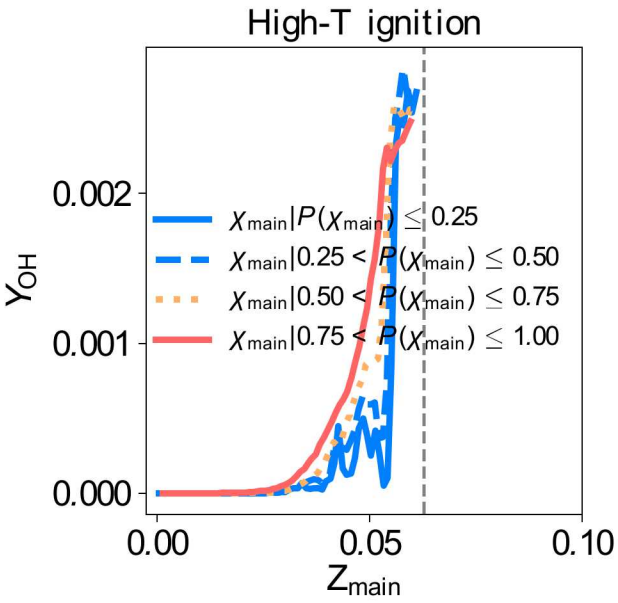

Strong correlation
→ well mixed

# Influence of mixing on ignition




- High scalar dissipation rates inhibit low-temperature ignition
- High scalar dissipation rates enhance high-temperature ignition

# Chemical Explosive Mode Analysis

- Eigen-analysis of the Jacobian of the local chemical source term

$$\frac{D\boldsymbol{\omega}(\mathbf{y})}{Dt} = \mathbf{J}_\omega \frac{D\mathbf{y}}{Dt} = \mathbf{J}_\omega(\boldsymbol{\omega} + \mathbf{s}), \quad \mathbf{J}_\omega = \frac{\partial \boldsymbol{\omega}}{\mathbf{y}}$$

diffusion

reaction

$$\lambda_e = \mathbf{b}_e \cdot \mathbf{J}_\omega \cdot \mathbf{a}_e$$

- CEM is associated with $\lambda_e$ that has a positive real part
- Projection onto CEM to distinguish reaction or diffusion dominated regions

$$\mathbf{b}_e \frac{D\boldsymbol{\omega}(\mathbf{y})}{Dt} = \mathbf{b}_e \cdot \mathbf{J}_\omega \frac{D\mathbf{y}}{Dt} = \lambda_e \mathbf{b}_e \cdot (\boldsymbol{\omega} + \mathbf{s}) \quad \frac{D\phi_\omega}{Dt} = \lambda_e \phi_e + \lambda_e \phi_s + \frac{D\mathbf{b}_e}{Dt} \cdot \boldsymbol{\omega}(\mathbf{y})$$

- Combustion mode indicator

$$\alpha = \phi_s / \phi_w$$

$-1 \leq \alpha \leq 1$ : auto-ignition (AI)

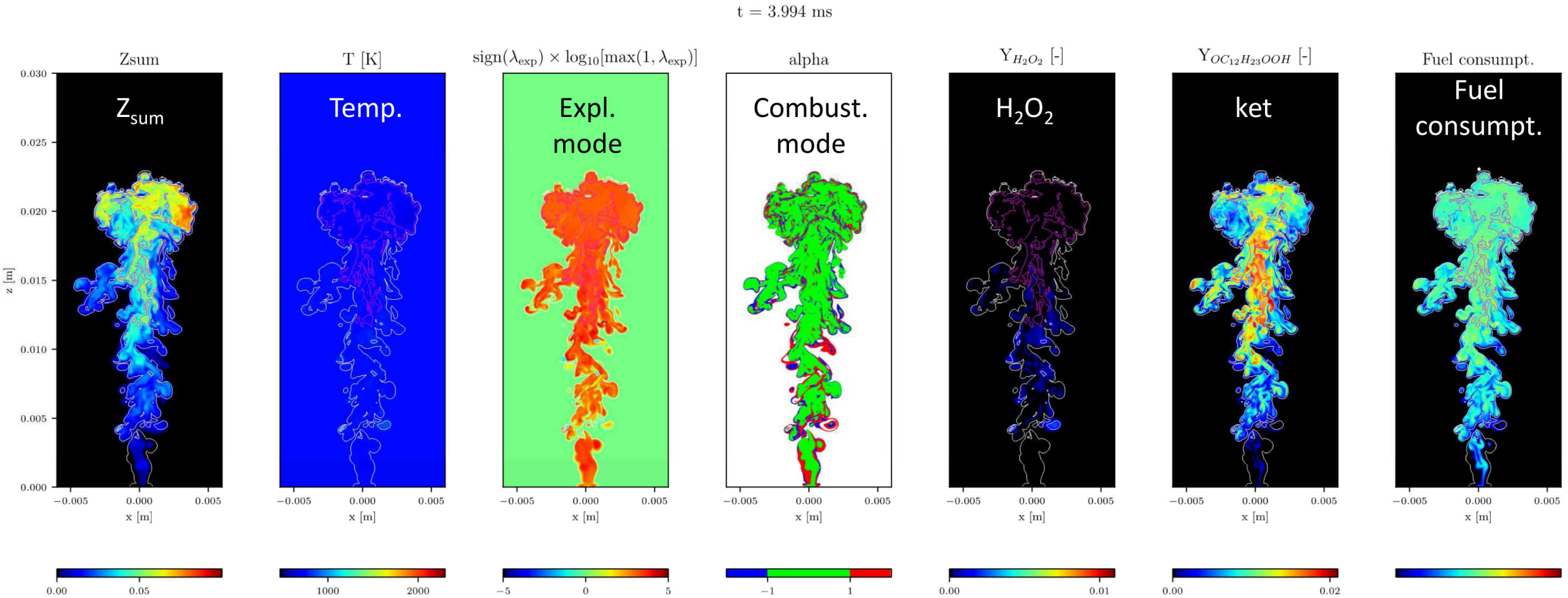
$\alpha < -1$ : diffusion dominates (extinction)

$\alpha > 1$ : flame propagation

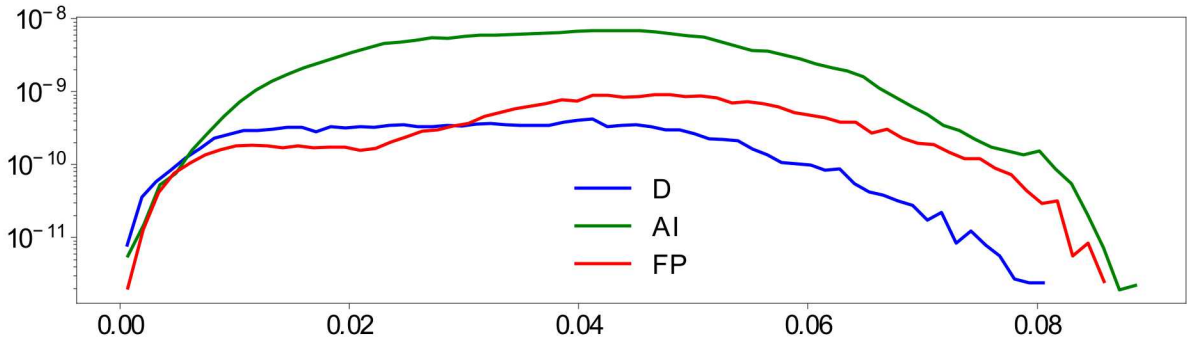


Lu et al., JFM, 2010; Chao et al., PROCI, 2019.

# Chemical Explosive Mode Analysis – 4ms

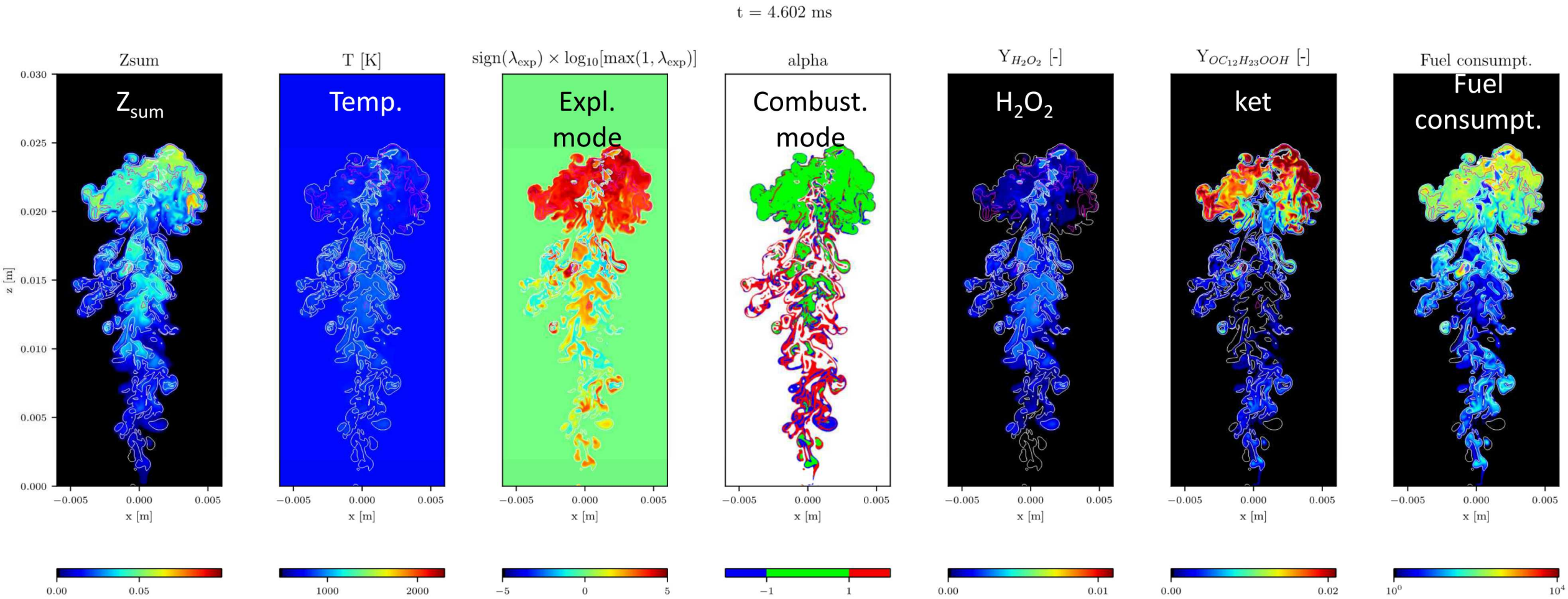



Integrated fuel consumption rate conditioned on $Z_{sum}$ and combustion mode

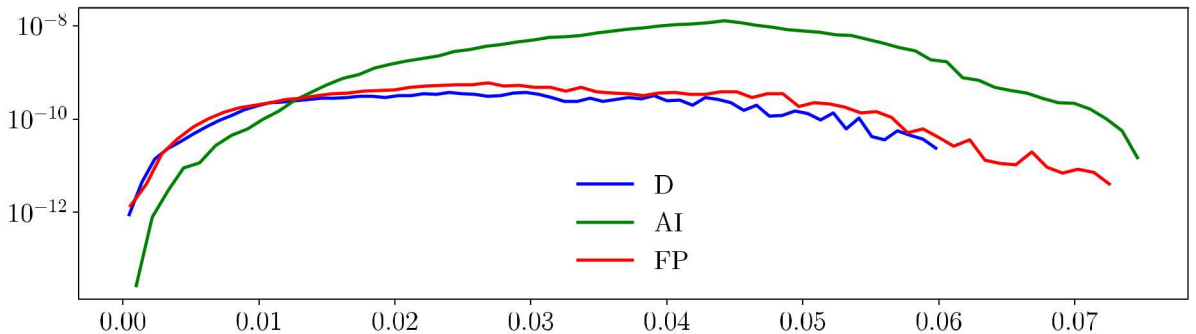



**Preliminary**
requires further research for two-stage ignition

# Chemical Explosive Mode Analysis – 4.6ms



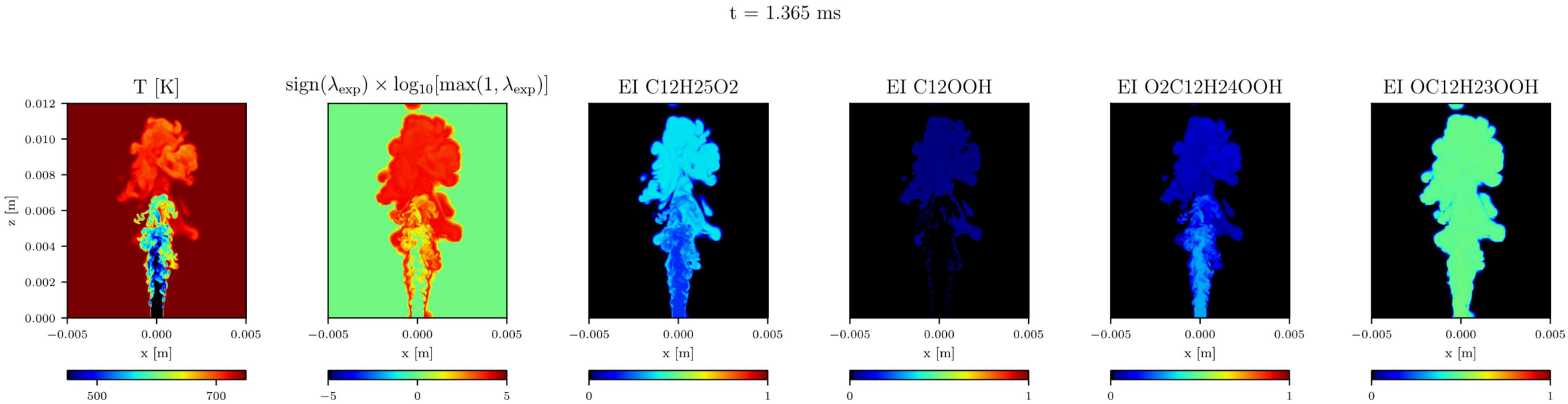

Integrated fuel consumption rate conditioned on $Z_{sum}$ and combustion mode




**Preliminary**
requires further research for two-stage ignition

# Chemical Explosive Mode Analysis – Explosion Indices

## Species with largest explosion indices




- Time when pilot and main injection start to interact
- Explosion index reveals species importance for auto-ignition

# Conclusions

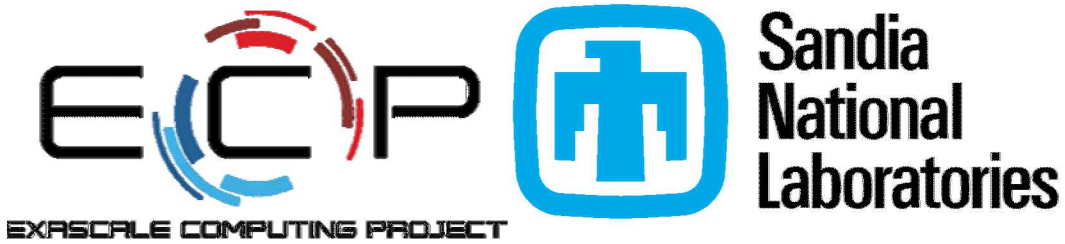
- PeleLM works very well for multi-injection ignition cases
- Differences in temperature/pressure conditions lead to very different ignition behavior

**Ground operating conditions**

- Strong mixing inhibits ignition of first injection, promotes ignition of second injection

**UAV conditions**

- Pilot injection does not ignite prior to mixing with main injection for UAV operation
- Pilot supplies low-temperature species that enhance ignition of the second injection
- CEMA provides information on combustion modes (preliminary) – fuel consumption overall dominated by auto-ignition during low-temperature ignition




# Thank you for your attention

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