UNIVERSITY OF CAMBRIDGE

Analysis of Markers for Combustion Mode and Heat Release in MILD Combustion using DNS

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Outline

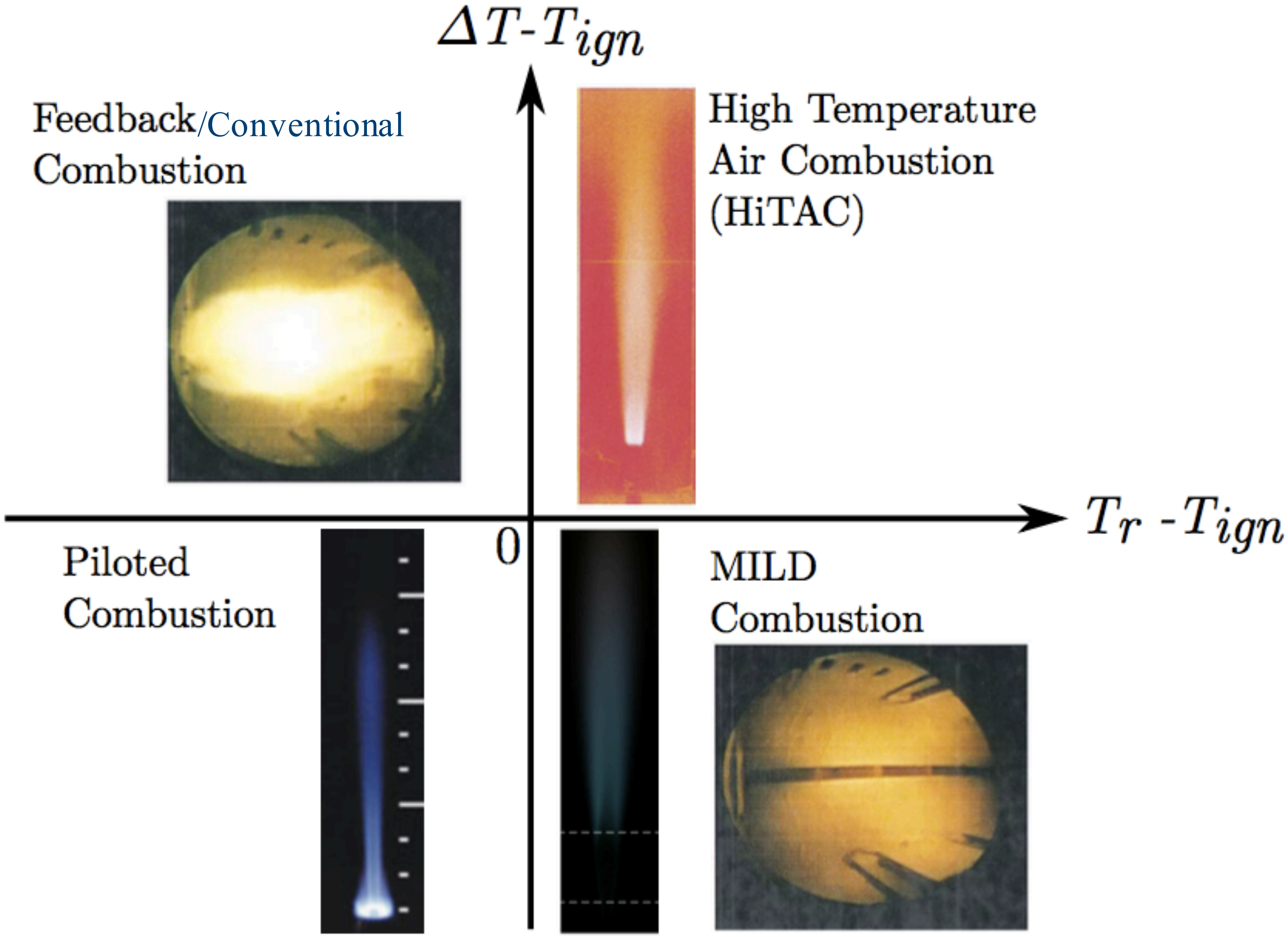
- A Brief Introduction
  - What is MILD combustion?
  - Why these markers?
- DNS Methodology
- Results
- Summary & Conclusion

Introduction

- Combustion and fossil fuels: main source of energy for the foreseeable future
- Need to improve thermal efficiency and reduce emissions – "greener – friendlier to the environment"
- Moderate or Intense Low-Oxygen Dilution (MILD) combustion: Promising concept
  - $T_r > T_{ign}$, $\Delta T < T_{ign}$, low O2 (< 5% by volume)
- Achieved using exhaust gases (recirculation, etc.)
- External/Internal recirculation
- Jet in hot co-flow or cross-flow

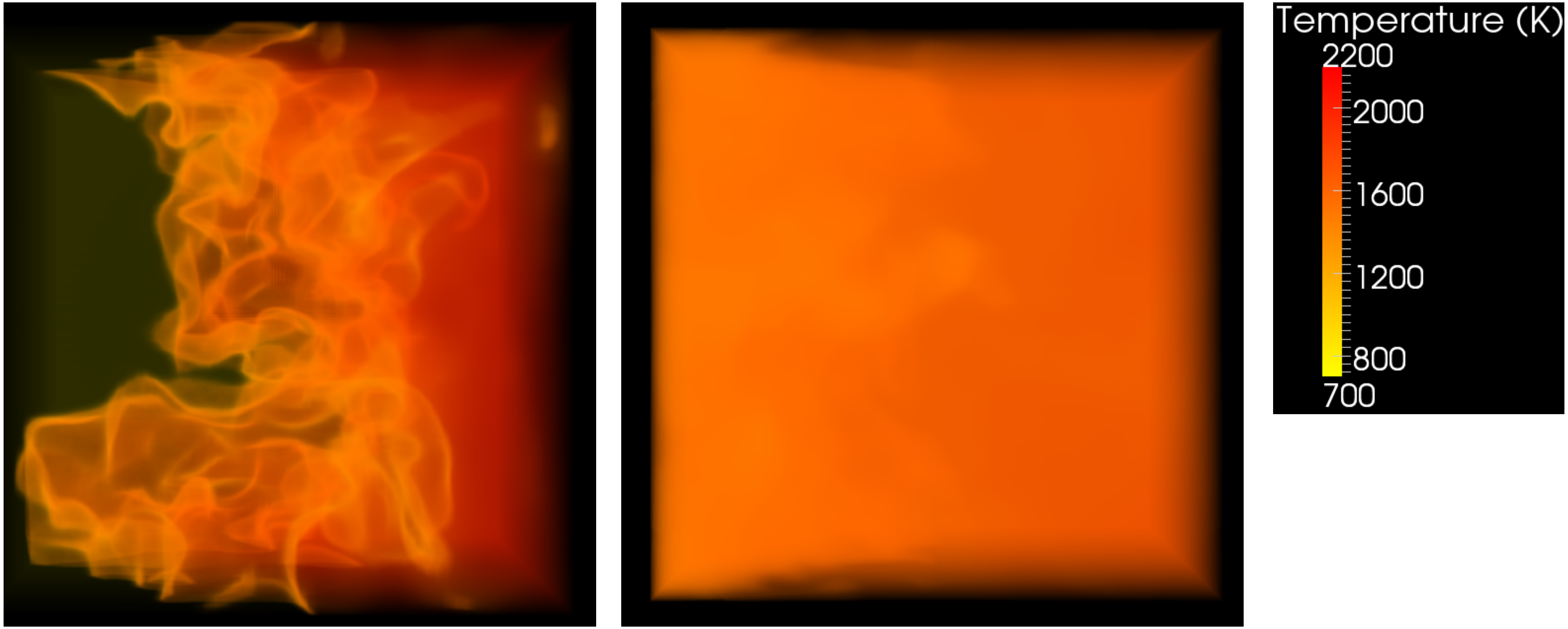
Introduction - What is MILD Combustion?

$\Delta T = T_p - T_r$



Introduction: MILD vs Conven. Comb. – from DNS

(CST 186, p. 1075 2014)



Conventional Premixed

MILD

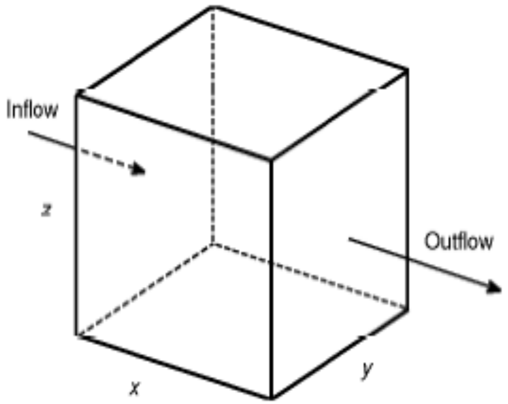
Introduction: Why HRR Markers?

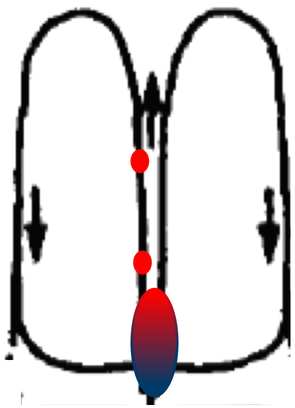
- How to identify & characterise heat releasing zones in MILD combustion?
- For conventional flames: OH, CHO, CH, CH2O, OH*, CH* and also OH x CH2O – mainly for premixed flames, also depends on ϕ
- H x CH2O worked well across ϕ (CnF 161 p. 3073, 2014)
- Would do these work for MILD or not?
- Two-scalar based marker OH x CH2O works well for premixed MILD combustion (CnF 161 p. 1063, 2014)
- OH-PLIF is commonly used in many past studies of MILD combustion
- OH* vs OH-PLIF show substantial differences (CST 186 p. 453, 2014)
- Can we assess these for non-premixed MILD combustion?

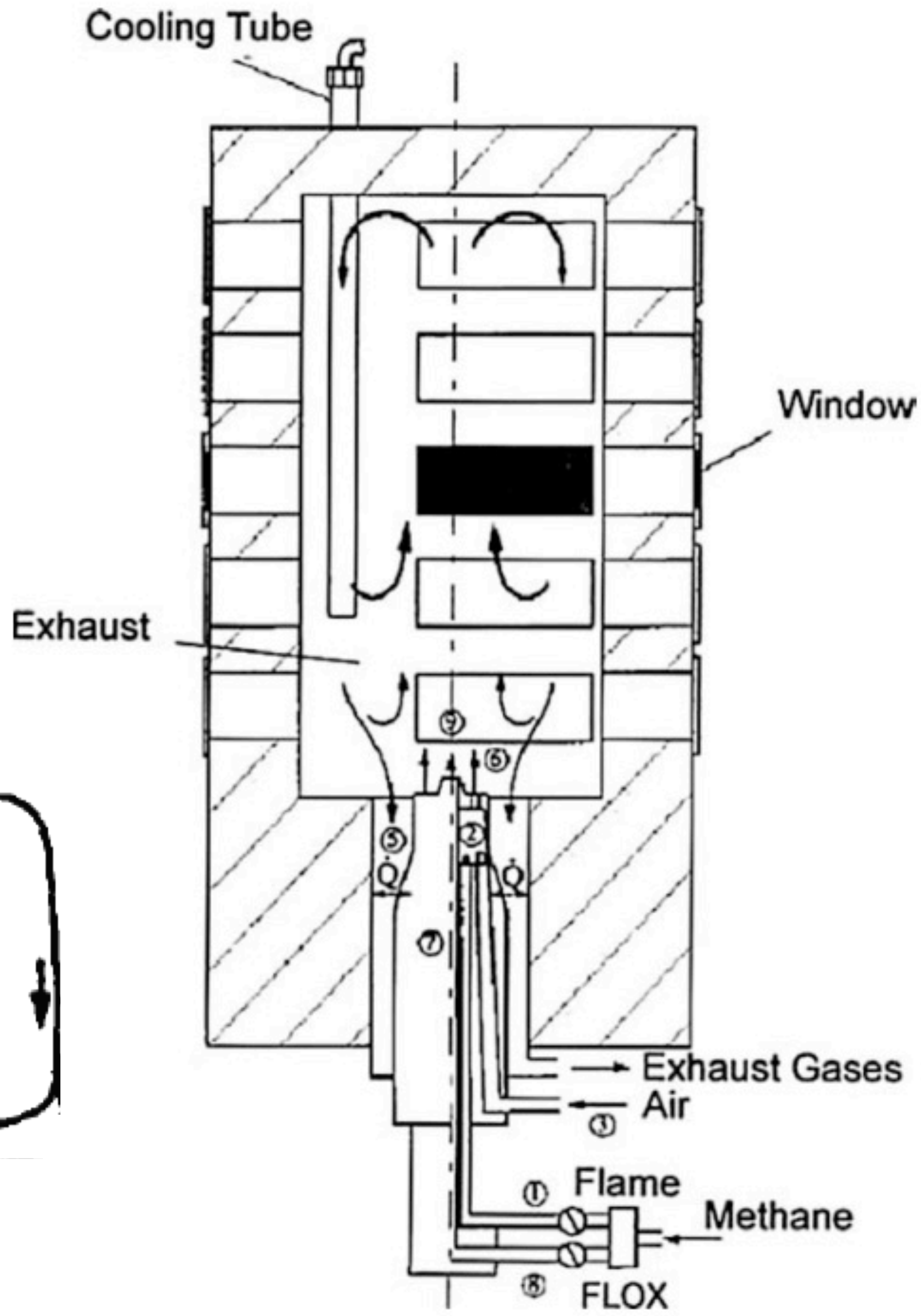
Configuration

- An example Exp. Configuration from Wunning & Wunning, PECS, 1997

Computational Domain for **DNS**

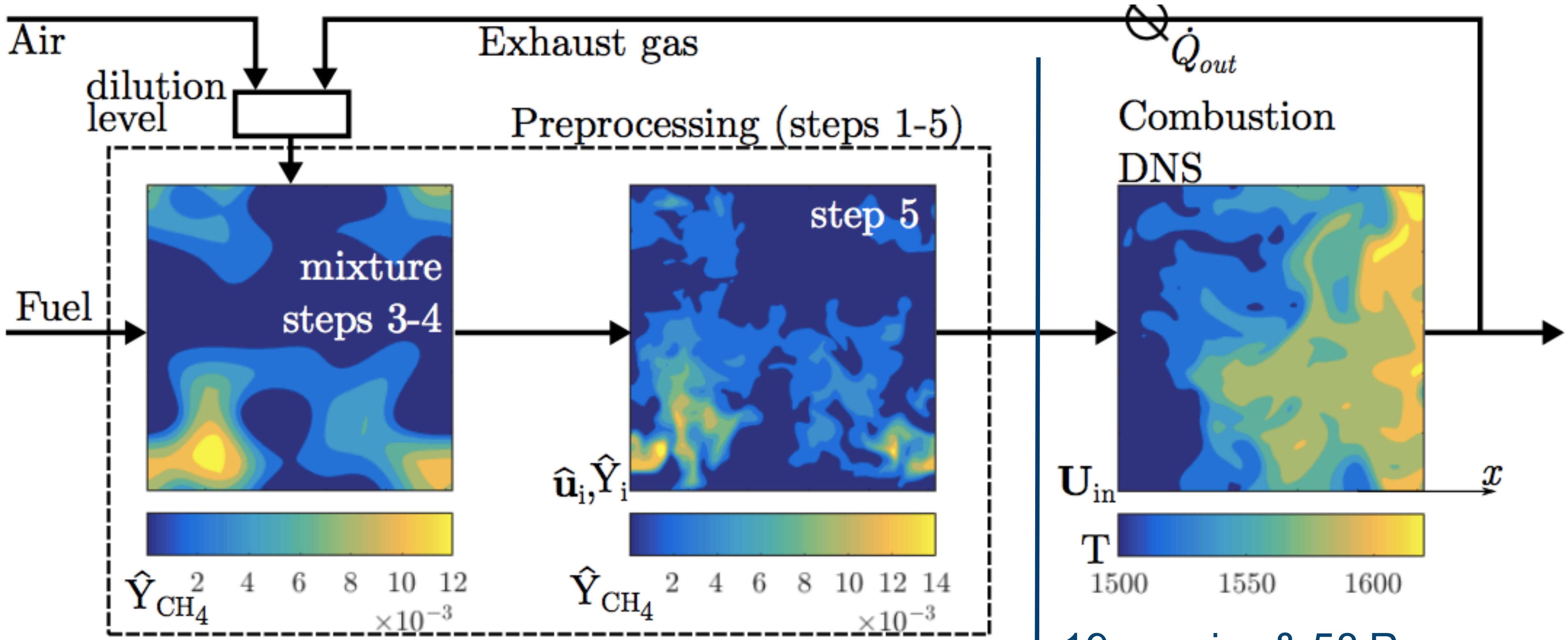






Methodology – Inflowing mixture

(PROCI 2012, CST 2014 CnF 2014, CnF 2018)



Step 1: Turbulence field generation
Step 2 to 4: Scalar fields generation
Step 5: tying turbulence & scalar fields together for consistencies

19 species & 58 Rxn CH_4/air chemistry
Includes OH* chemistry
512x512x512
First of its kind simulation

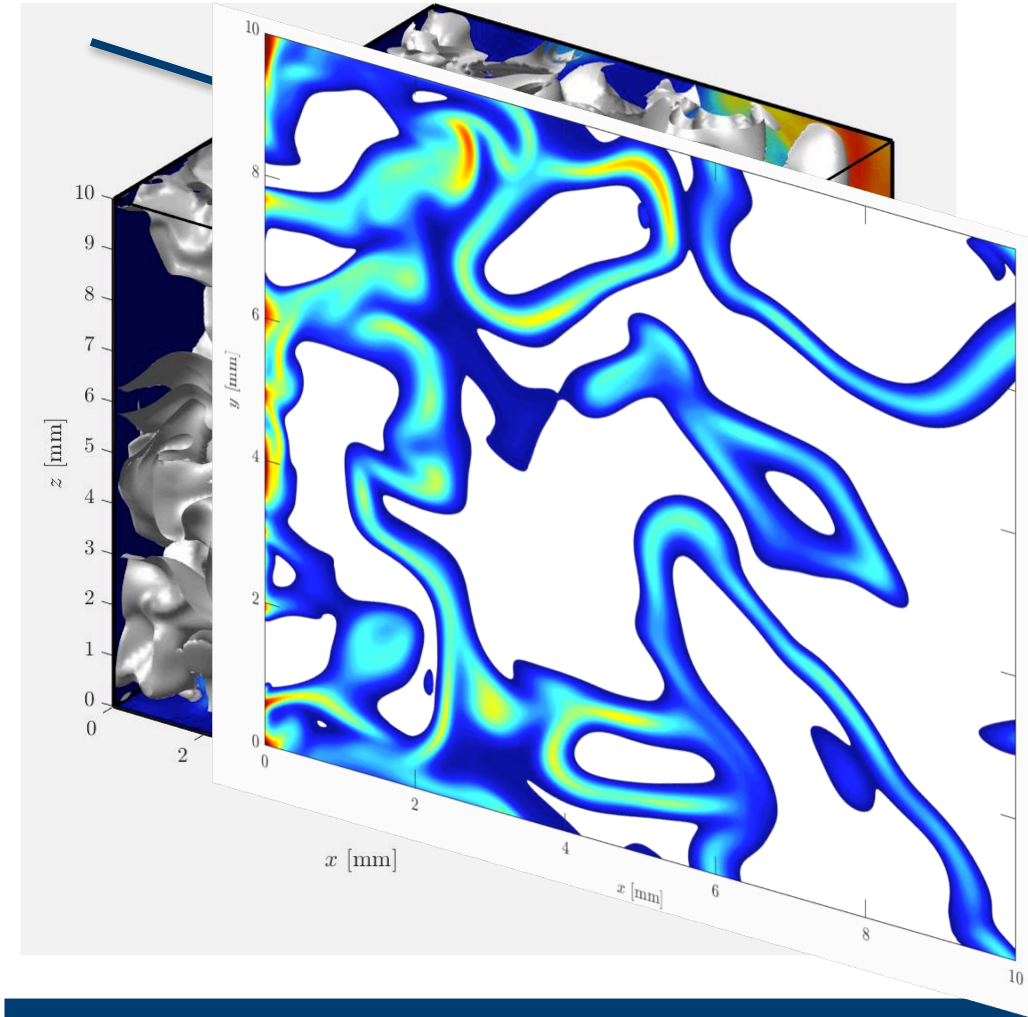
DNS Cases

Case	l_o/L_Z	$\langle X_{O2} \rangle$	X_{O2}^{max}	L_c/L_Z	$\langle Z \rangle$	Z_{st}	σ_Z	$\langle c \rangle$	σ_c
AZ1	0.60	0.0270	0.035	0.77	0.008	0.010	0.0084	0.56	0.26
AZ2	0.79	0.0285	0.035	0.99	0.008	0.010	0.0105	0.56	0.28
BZ1	0.60	0.0160	0.020	0.77	0.0046	0.0058	0.0057	0.56	0.26

- Cases with $L_c/L_Z \leq 1$ chosen as chemical length scale smaller than mixing length scale but high recirculation in MILD combustion may have $L_c/L_Z \approx 1$
- Similar turbulence field for all cases ($Re_{l_0} \approx 96$) and all are globally lean cases, $\phi = 0.8$ same as previous premixed case in [4]

[4] Minamoto & Swaminathan, CnF (2014)

Results: Visualisation



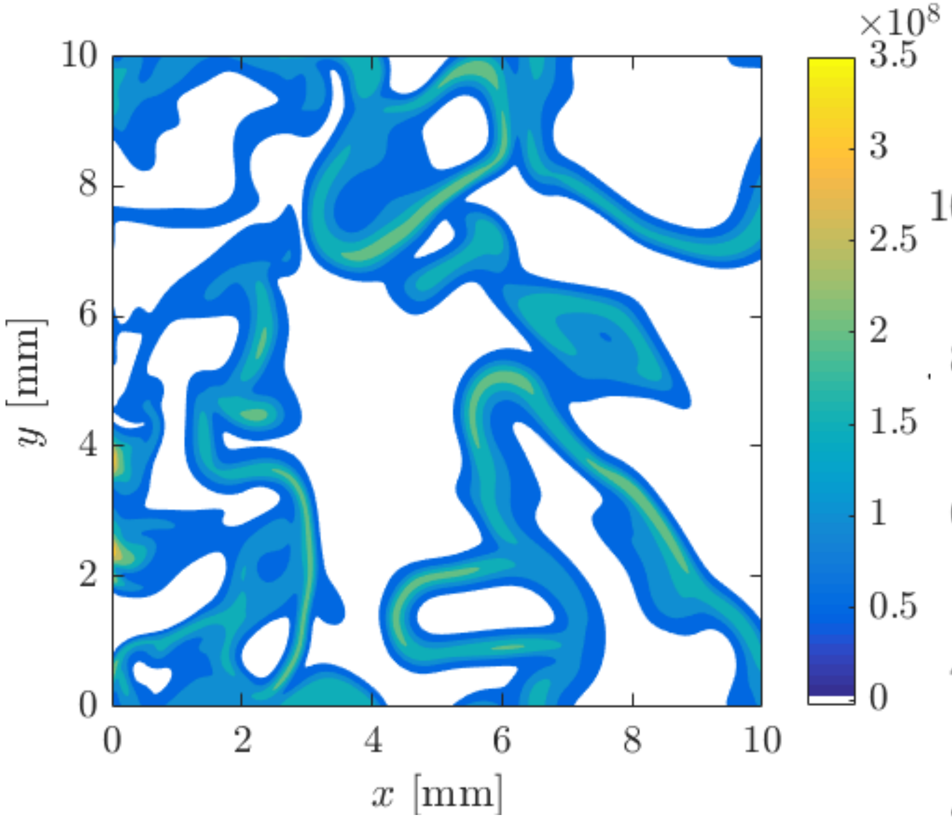
CASE AZ1:

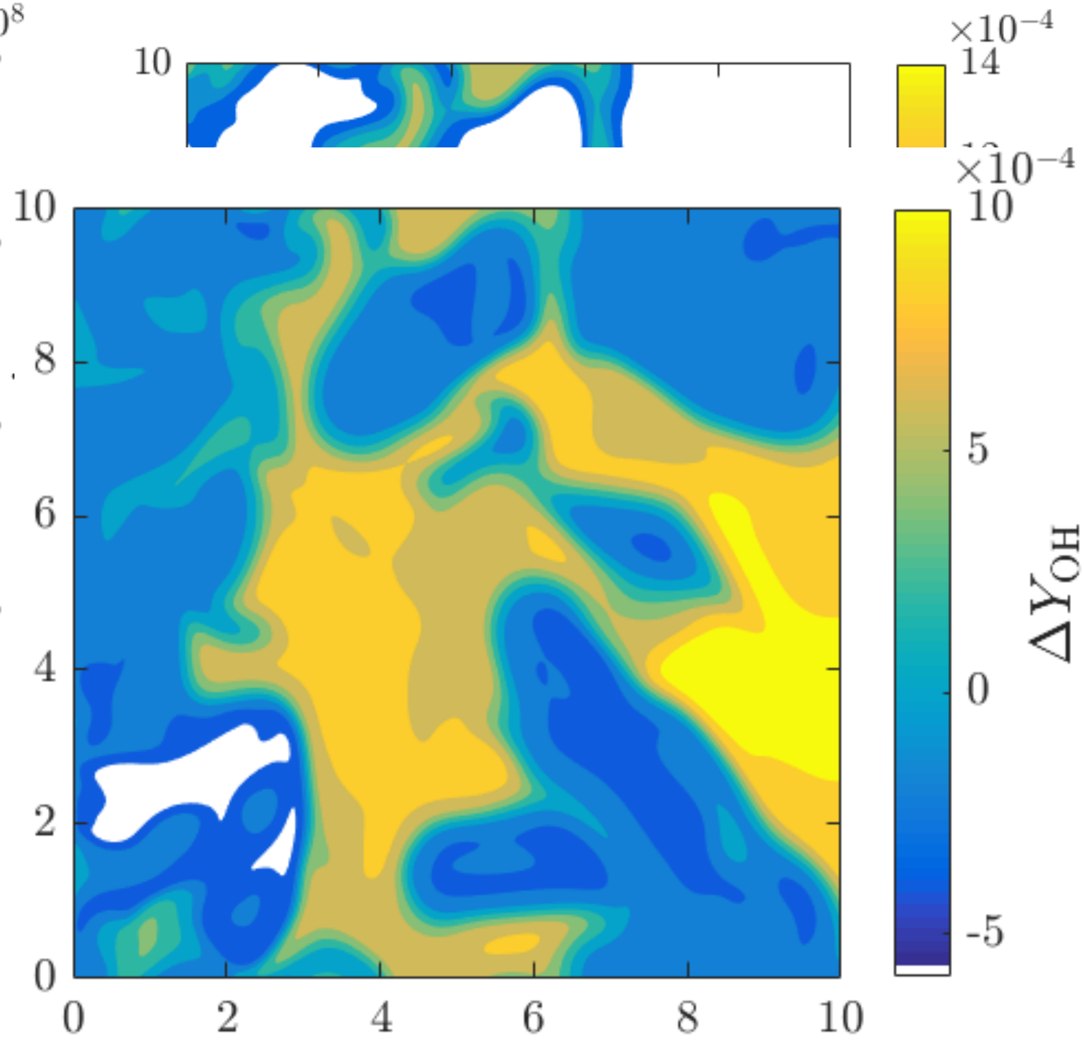
- Moderate temperature increase ($\Delta T \approx 150K$)
- Multiple & interacting reaction zones
- Significant interactions leading to thickening, reaction zones occupy wider regions & distributed => homogeneous field saw earlier
- Premixed, non-premixed and auto-ignition region – Complex dynamics - modelling??

(CnF 2018)

Results: Q, OH, etc

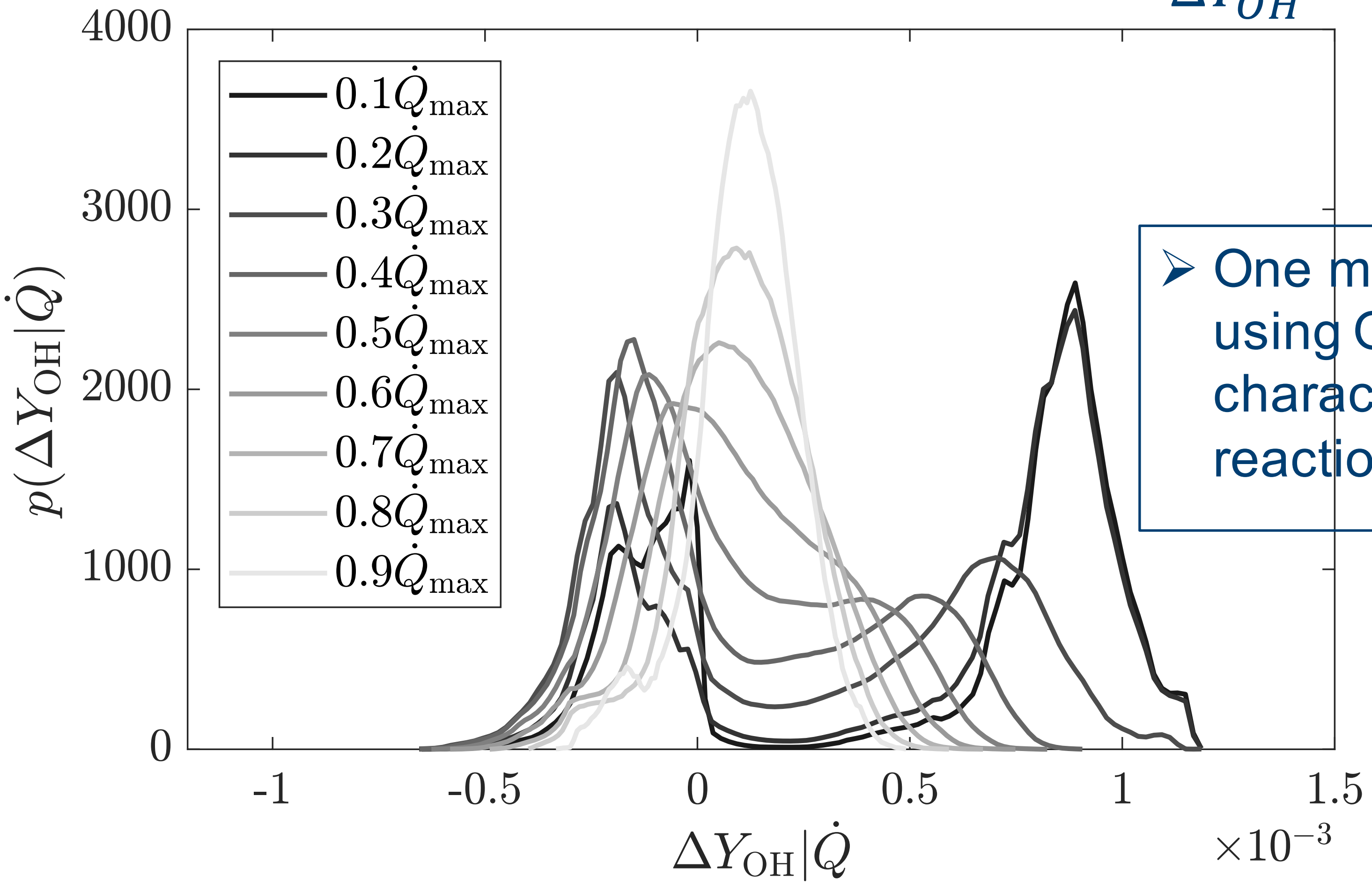
$$\Delta Y_{OH} = Y_{OH}^{R} - Y_{OH}^{CD}$$





Results: Conditional PDF of ΔY_{OH}

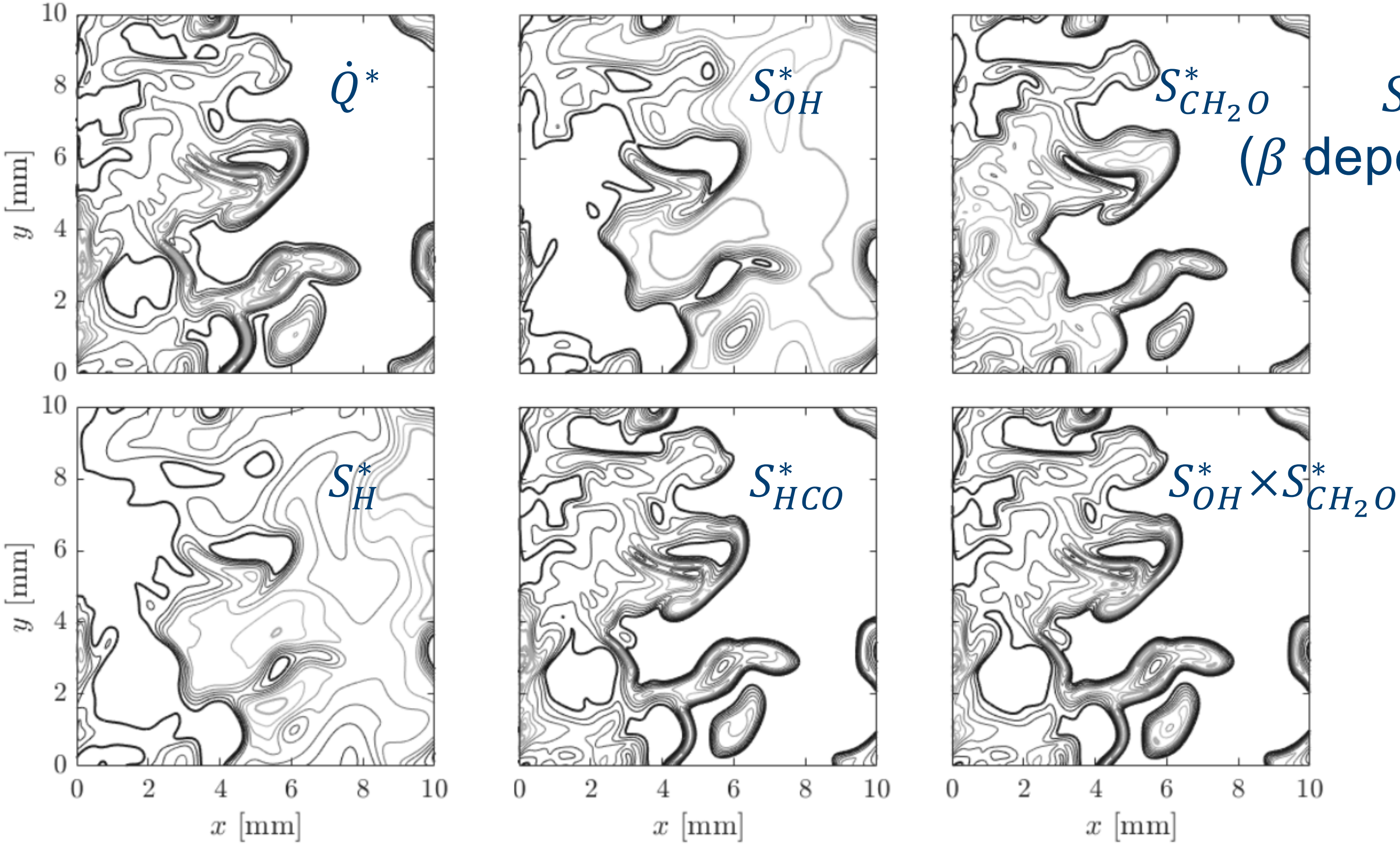
$$\Delta Y_{OH} = Y_{OH}^{R} - Y_{OH}^{CD}$$



- One must be cautious in using OH-PLIF to characterise MILD reaction zones

Results: PLIF synthesised from DNS

- Instantaneous comparison in mid x-y plane (CASE AZ1)

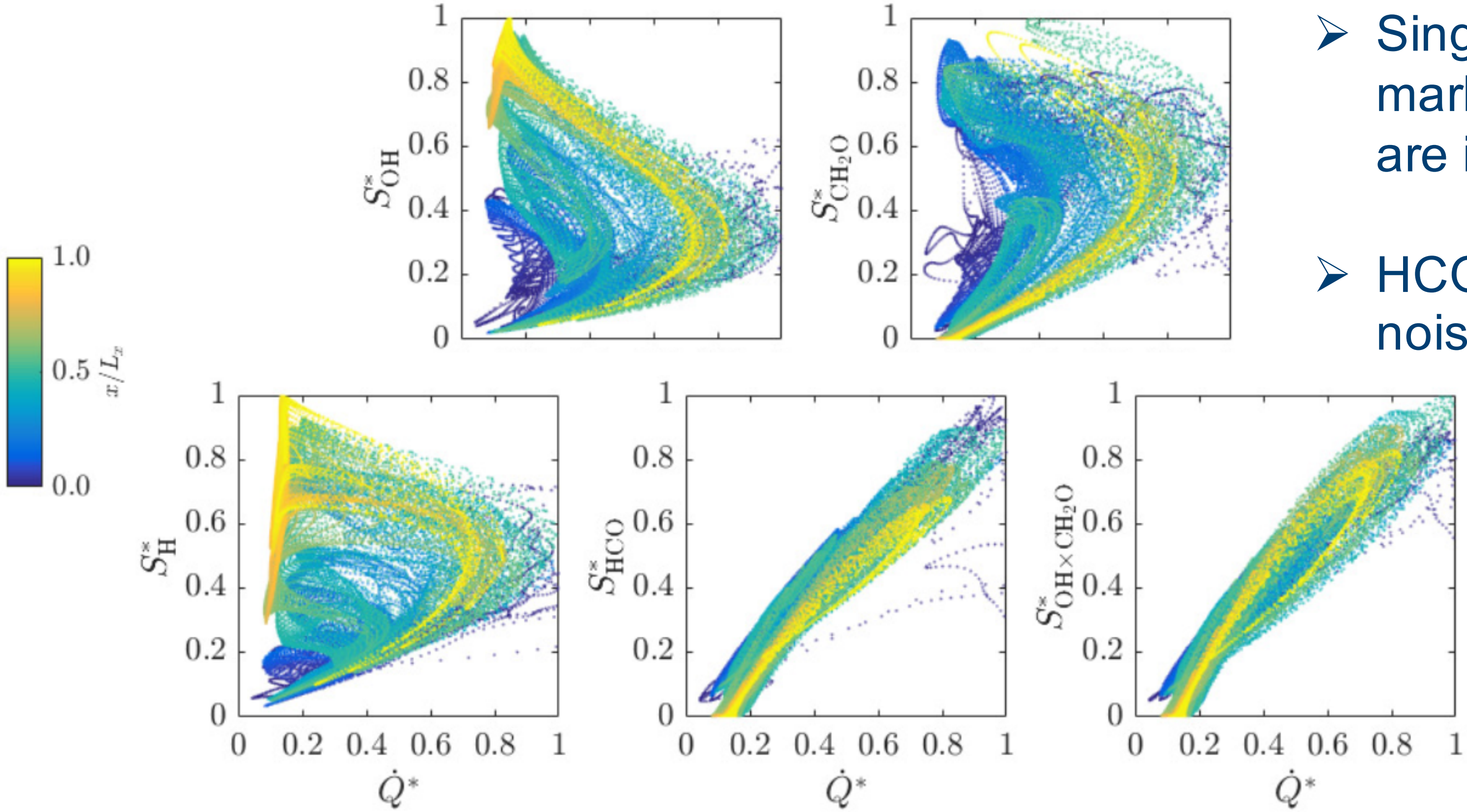


$S_\alpha \propto [\alpha] T^{1-\beta}$

(β dependent on species)

- Only HCO and $OH \times CH_2O$ capture features of HRR

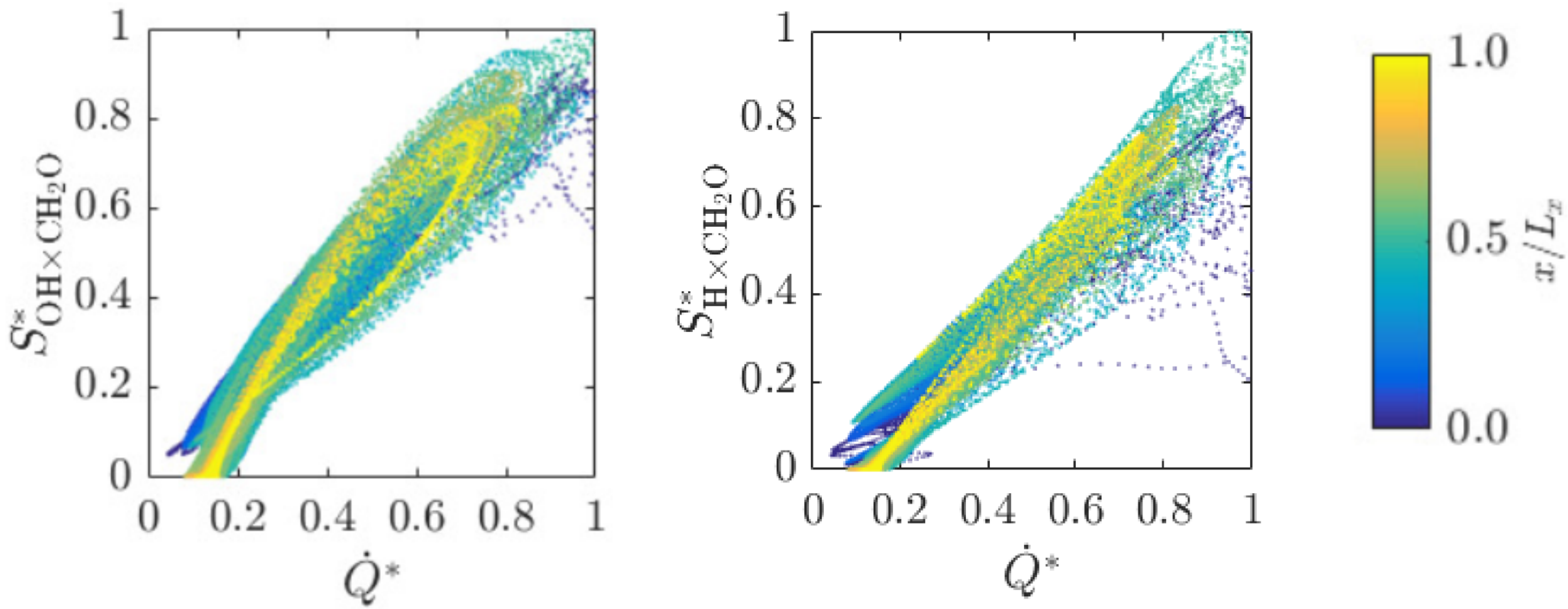
Results: Scatter plots



- Single species markers, except HCO, are inadequate
- HCO – low signal-to-noise ratio

- Two-scalar markers are good as for premixed MILD combustion

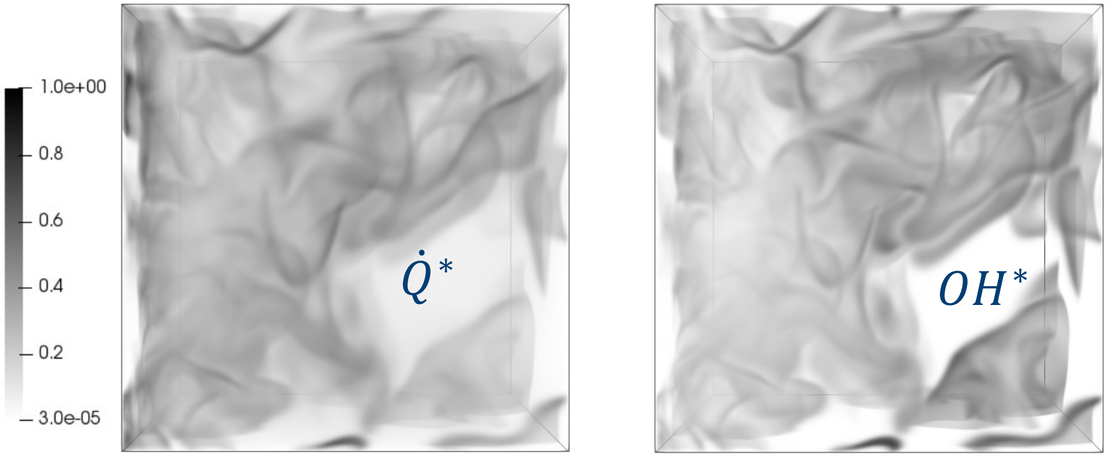
Results: Two-scalar Markers

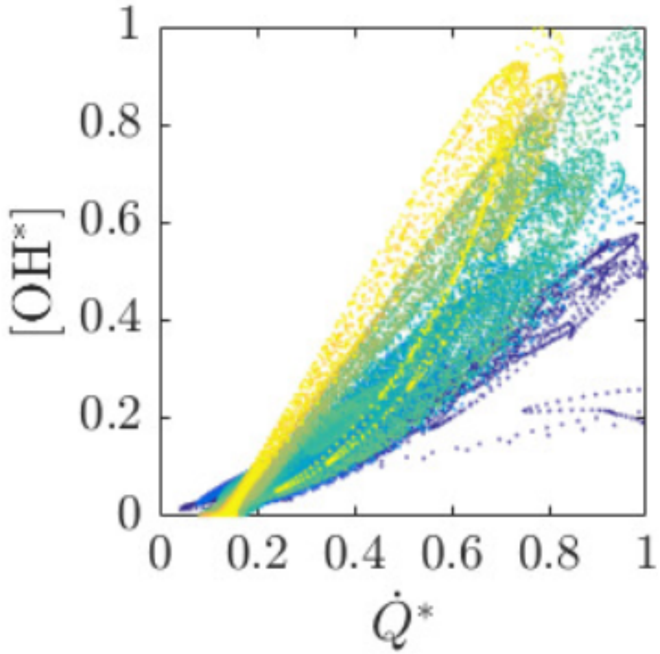


- Two-scalar markers are good
- This is for non-premixed MILD – globally lean
- Previously they were shown for premixed cases

Results: Chemiluminescent – OH*

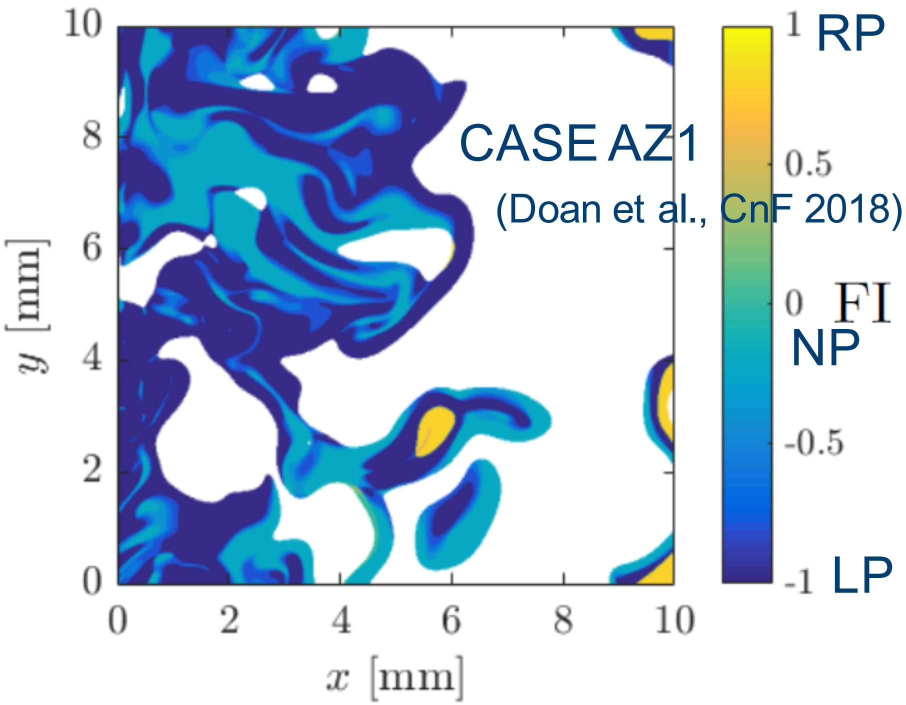
- Volume rendered image of HRR and OH^*





- Overall good correlation between HRR and OH^*, but not for fine features as it is a “Line of Sight” method

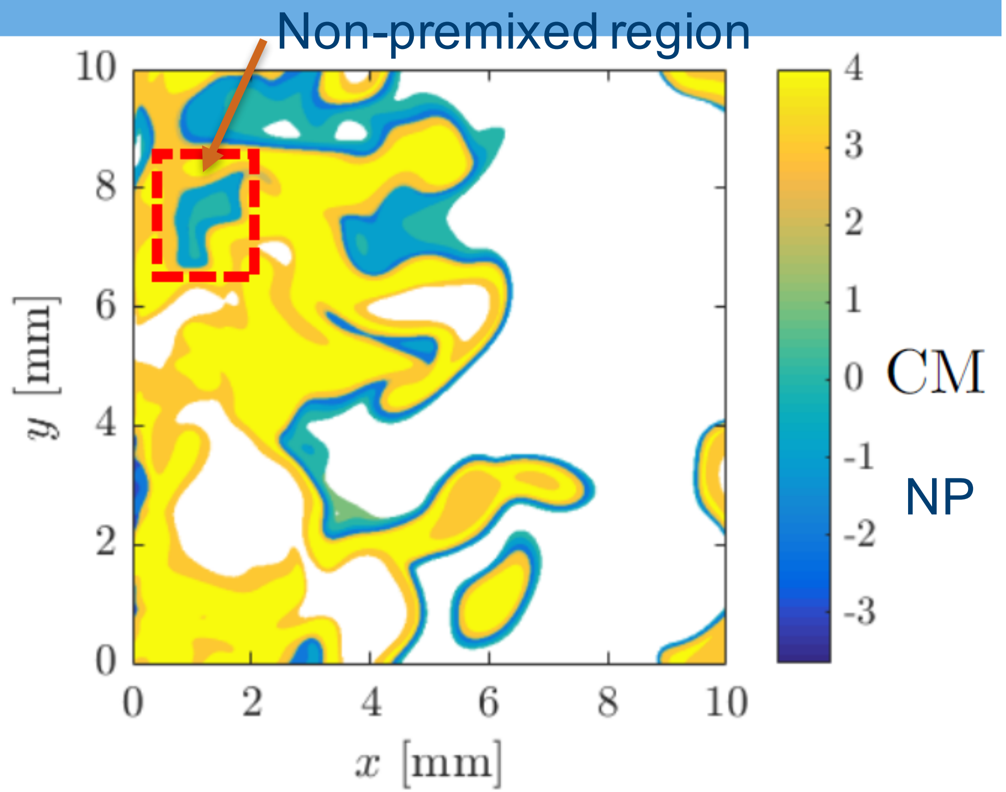
Premixed vs non-premixed identification



(Briones et al. Phys. Fluids 2006)

$$FI = \frac{Z - Z_{st}}{2|Z - Z_{st}|}\left(\frac{1 + \nabla Y_{CH_4} \cdot \nabla Y_{O_2}}{|\nabla Y_{CH_4}||\nabla Y_{O_2}|}\right)$$

Some agreement but large NP regions are misidentified as premixed



(Hartl et al. CnF 2018)

$$CM = sign\big(\Re(\lambda_e)\big)\log_{10}(1 + |\lambda_e|)$$

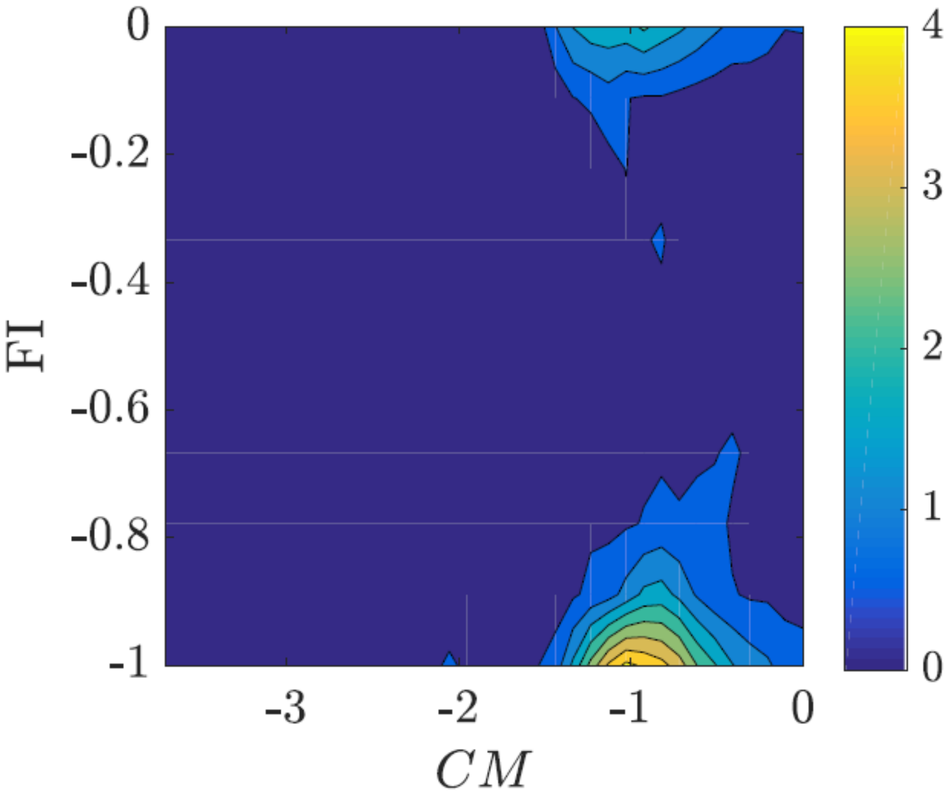
NP: $CM < 0$, with ∇Z;

PR: $CM \sim 0$, with $Z \approx 0$

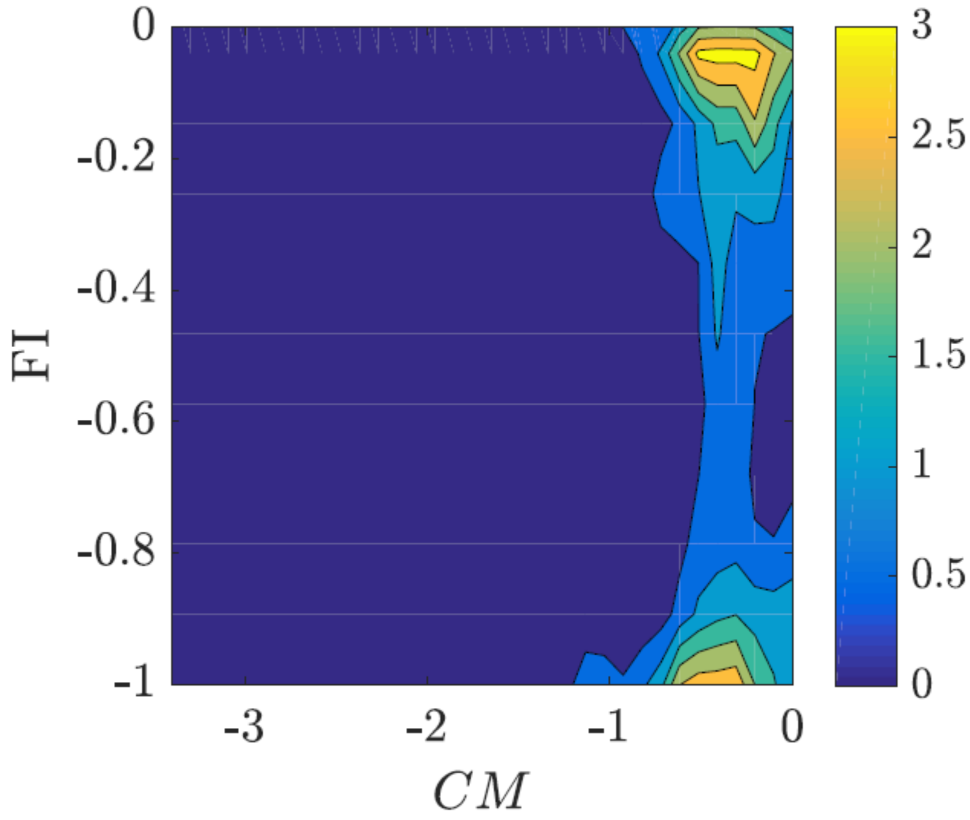
Premixed and non-premixed identification

- Joint-PDF of FI and CM focused in regions of $CM < 0$

CASE AZ1



CASE BZ1



Numerical Schlieren – conven. & MILD

- MILD combustion has mild gradients of temperature/density compared to conventional flames

- Schlieren will give unambiguous message

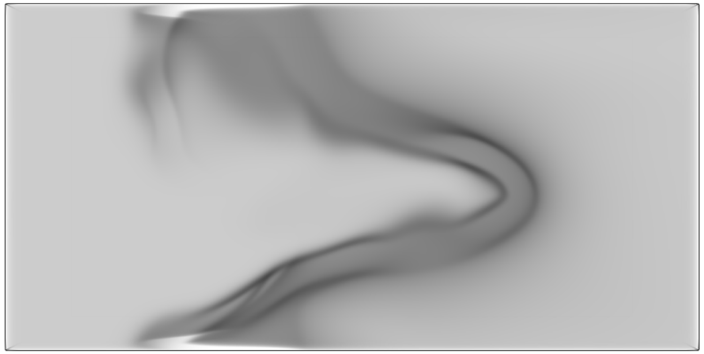
$$S(x, y) = \beta \exp\left(-\frac{\kappa\,|\nabla\rho|}{|\nabla\rho|_{\max}}\right)$$

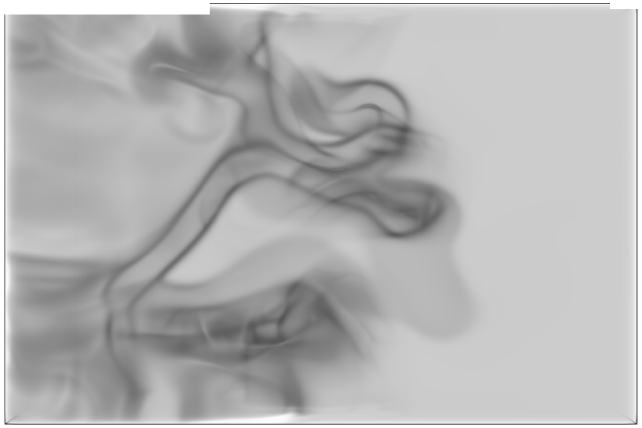
$\beta = 0.8, \kappa = 15$

(Hadjadj & Kudryavtsev 2005)

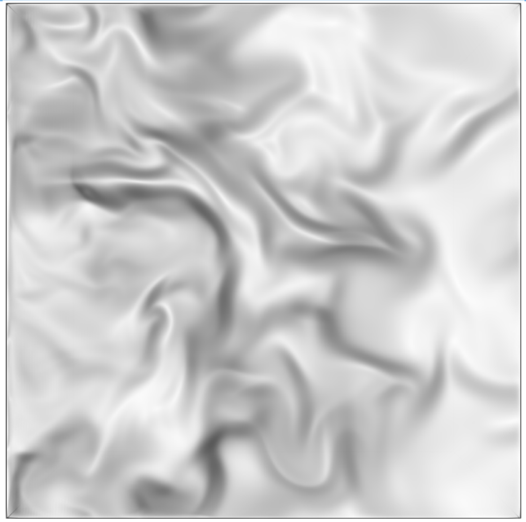
Numerical Schlieren Images

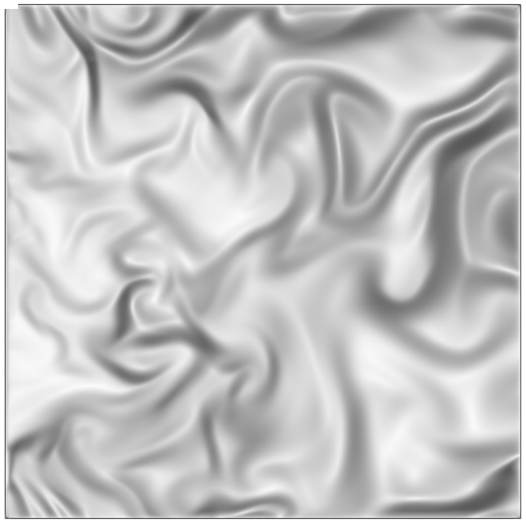
Premixed flames

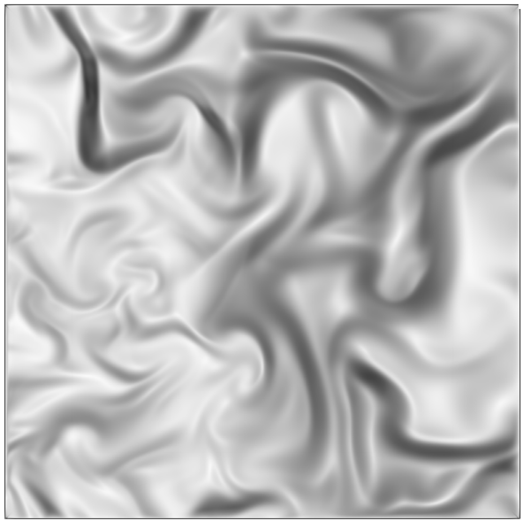


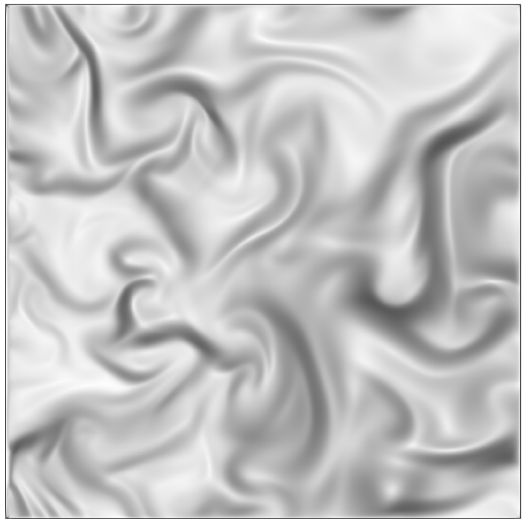


Premixed MILD









Non-premixed MILD

Conclusion

- HRR markers for MILD combustion are assessed using DNS data
  - HRR Marker
    - HCO-PLIF: good marker but has low signal-to-noise ratio
    - $OH \times CH_2O$ & $H \times CH_2O$ PLIF are good
    - OH^* chemiluminescent image: good marker (improvement over OH-PLIF)
    - Single scalar PLIF – need to be cautious
- Identification of premixed/non-premixed regions based on CEMA
  - Some level of agreement but large premixed regions are misidentified
- Schlieren – easy way of distinguishing MILD & conven. combustion, should be done first in Exps. to establish that the combustion is MILD

Questions?

Research Outcome

- Research outcome:
  - N. A. K. Doan, N. Swaminathan & Y. Minamoto. DNS of MILD Combustion with mixture fraction variations. Combustion and Flame, 189, 173-189 (2018).
  - N. A. K. Doan & N. Swaminathan. Role of radicals on MILD combustion inception. Proceedings of the Combustion Institute (2018).
  - N. A. K. Doan & N. Swaminathan. Autoignition and Flame Propagation in MILD combustion . Combustion and Flame (under review).
  - Best Use of ARCHER Award
  - Presentations at NC17, MCS2017, Symposium2018