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On Mixing and Shaking: Structure and Dynamics of Turbulent Stratified Flames

M. Sweeney (Cambridge)
H. Han (Cambridge)
K. Kim (Cambridge)
R. Barlow (Sandia)
M. Dunn (Sandia/Sydney)
A. Dreizler (TU Darmstadt)
M. Euler (TU Darmstadt)
G. Kuenne ((TU Darmstadt)
L.Vervisch (CORIA)
P. Domingo (CORIA)
S. Nambully (CORIA)
A. Kempf (TU Duisburg)
F. Proch (TU Duisburg)
B. Fiorina (EM2C)
R. Mercier (EM2C)
S. Hochgreb

ECM 2013, Lund, 25-28, 2013

Sandia National Laboratories

TECHNISCHE UNIVERSITÄT DARMSTADT

EPSRC Engineering and Physical Sciences Research Council

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PEOPLE

The two limits of flame combustion

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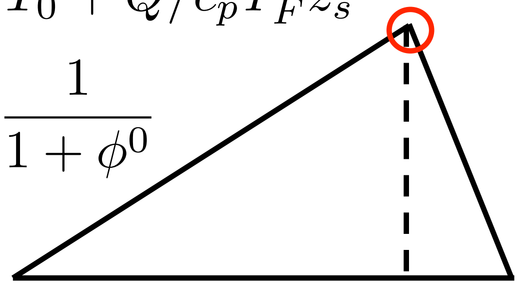
diffusion

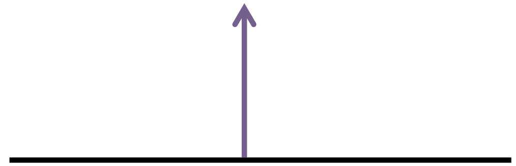
$$T_s = T_0 + Q/c_p Y_F^0 z_s$$

$$z_s = \frac{1}{1+\phi^0}$$

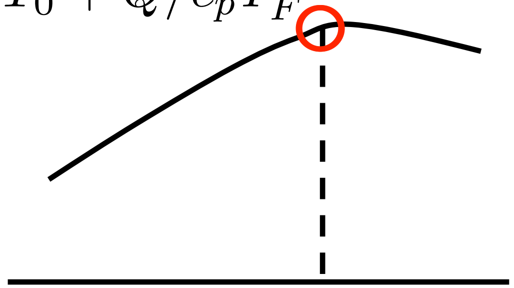


High NOx, Soot
Good dynamic range

premixed



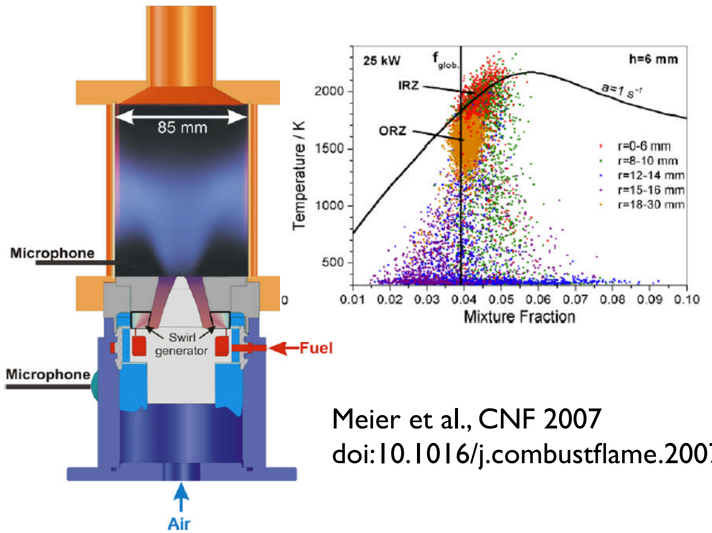
$$T_s = T_0 + Q/c_p Y_F^0$$



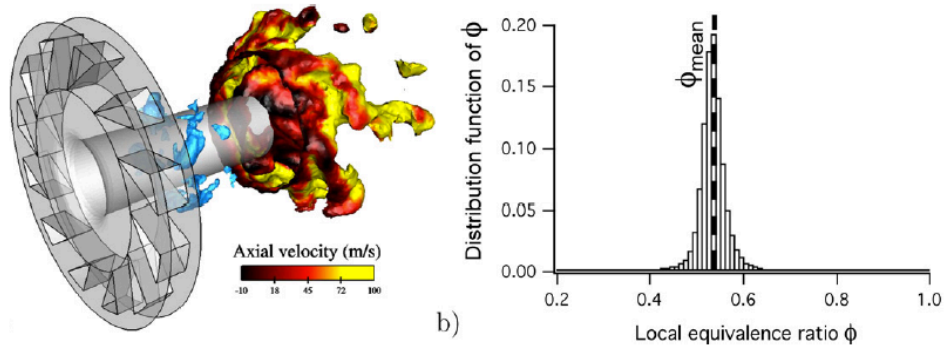
$$\phi^0 = s\frac{Y_F^0}{Y_O^0}$$

Low NOx, soot, CO
Narrow dynamic range

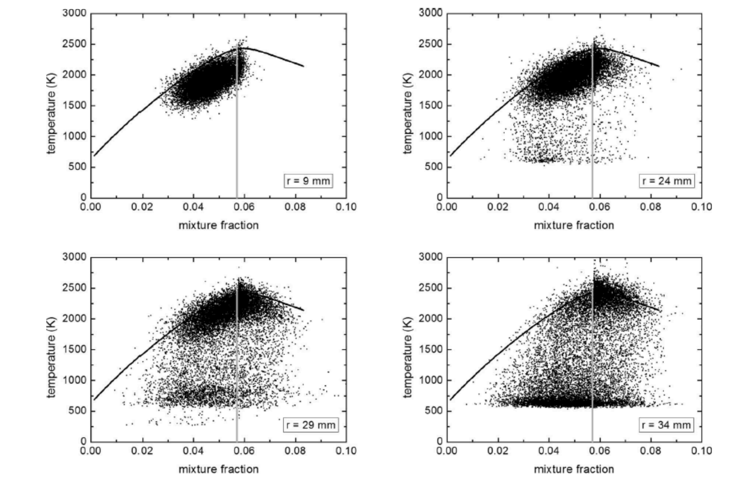
Stratified/technically premixed flames



Meier et al., CNF 2007
doi:10.1016/j.combustflame.2007.04.002

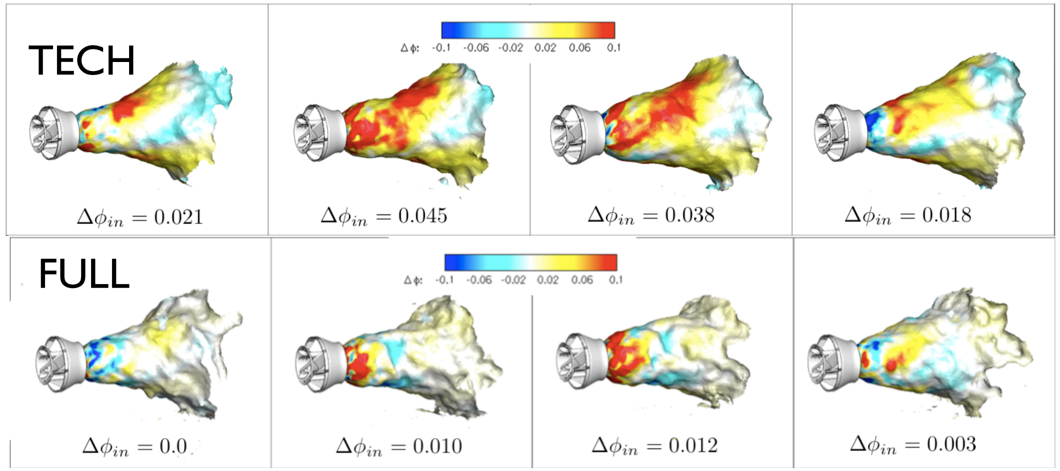


Sengissen et al, 2007
doi:10.1016/j.combustflame.2007.02.009



EV burner

Ax et al, JGTPP, 2010
doi: 10.1115/1.3205033



Hermeth et al, PCI 34 (2013)
doi: 10.1016/j.proci.2012.07.013

The two limits of flame combustion

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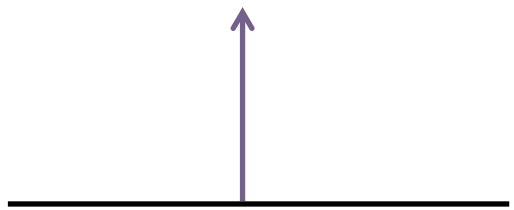
diffusion

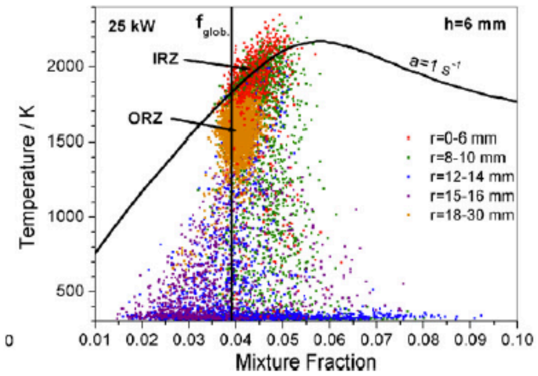
oxidizer

fuel

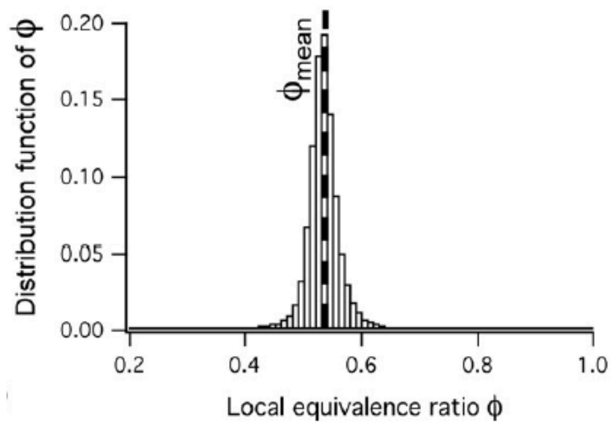
premixed



fuel + oxidizer



Meier et al., CNF 2007
doi:10.1016/j.combustflame.2007.04.002



Ax et al, JGTPP, 2010
doi: 10.1115/1.3205033

Are models for stratified flames adequate?

Why should we think stratified flames might be different?

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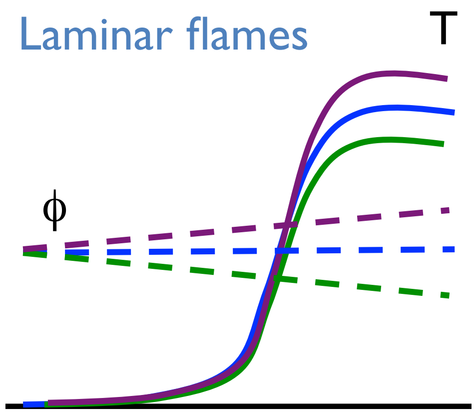
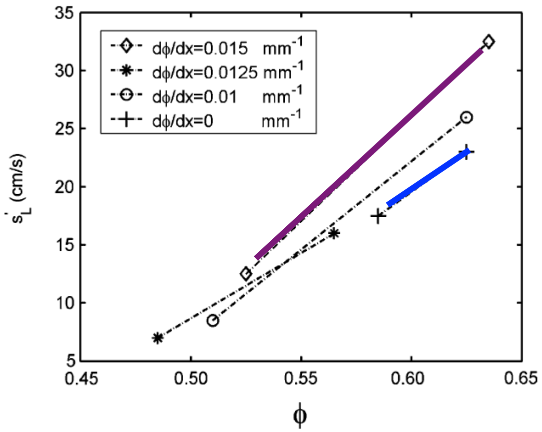
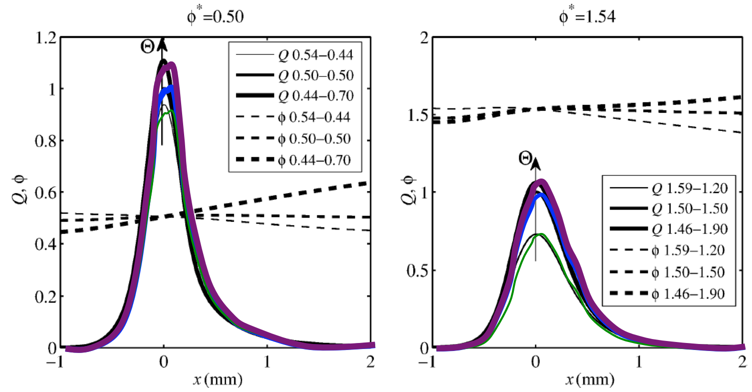
Laminar flames



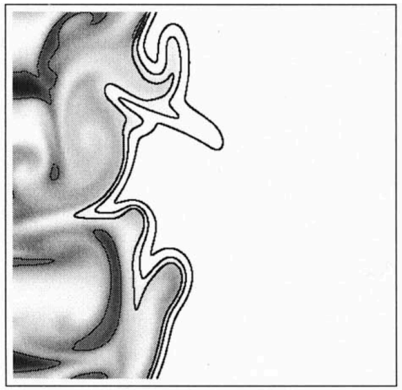


Kang & Kyritsis, CST, 177 (2005)
DOI: 10.1080/00102200500240836

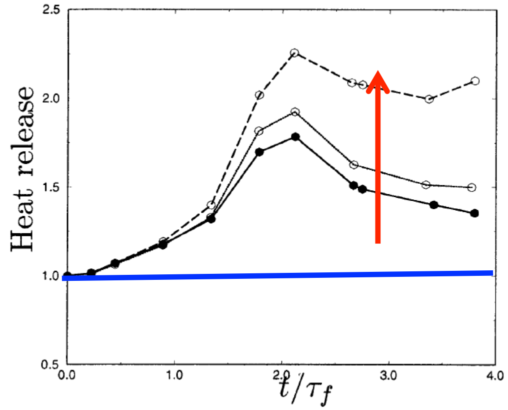


Zhou & Hochgreb, CNF,160 (2013)
DOI:10.1016/j.combustflame.2013.01.023

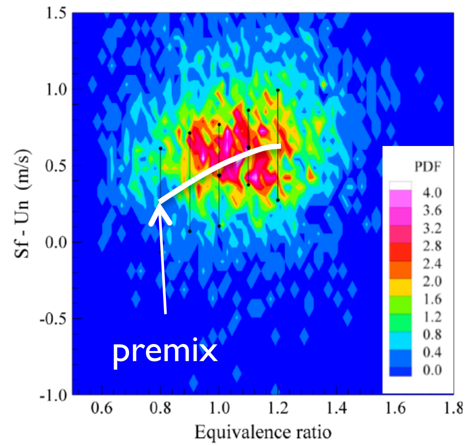
Turbulent flames



Propane mass fractions at $t/\tau_f = 4$



Jimenez et al, CNF 128:1–21 (2002)

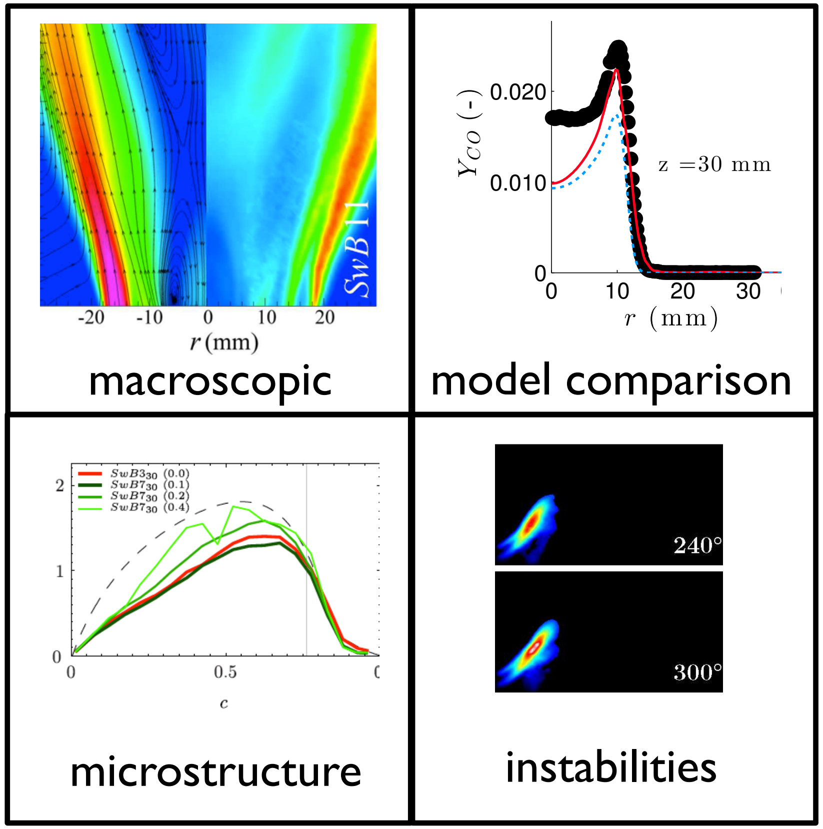


(b) $S_f - U_n$ vs. ϕ (1 ms)

Pasquier, N. et al.,
PCI 31(2007) 1567-1574
Doi:10.1016/j.proci.2006.07.118

Higher rates of heat release in lean flames for the same mean/local ϕ

Outline: Effects of Stratification



Outline: Effects of Stratification

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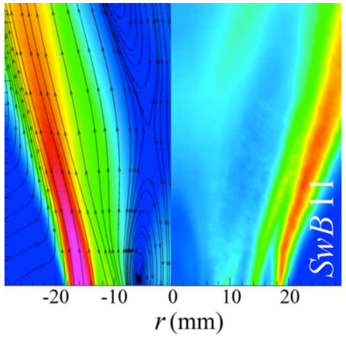
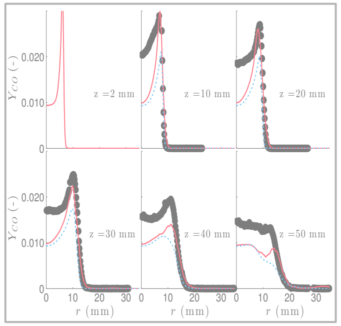
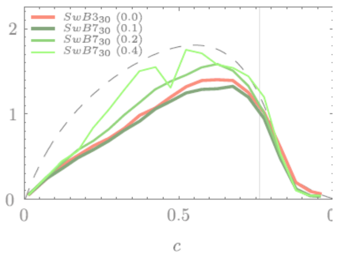


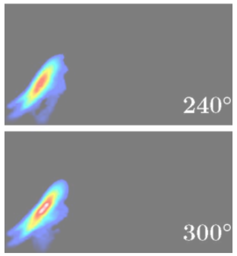
macroscopic



model comparison



microstructure



instabilities

Many contributors to the topic

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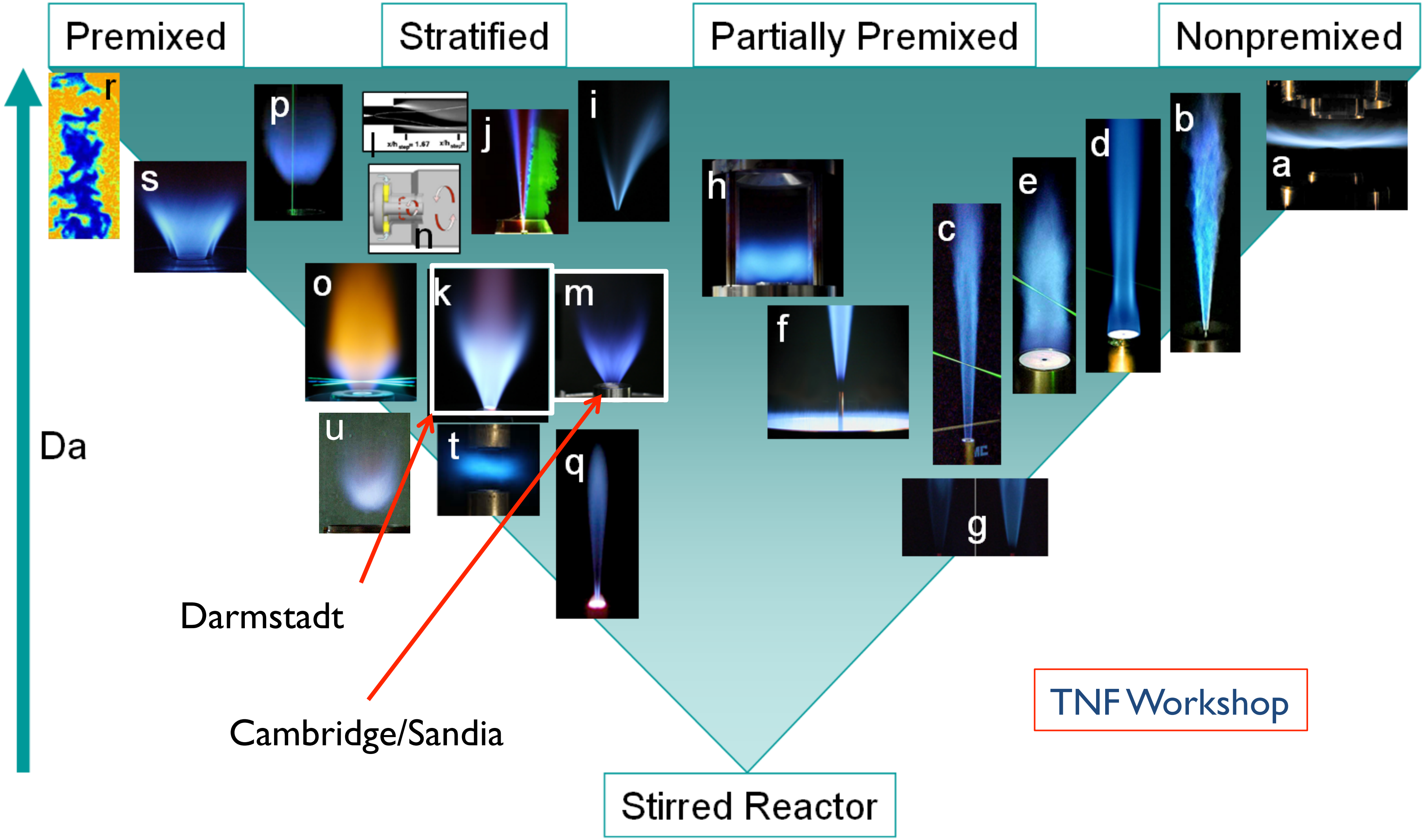
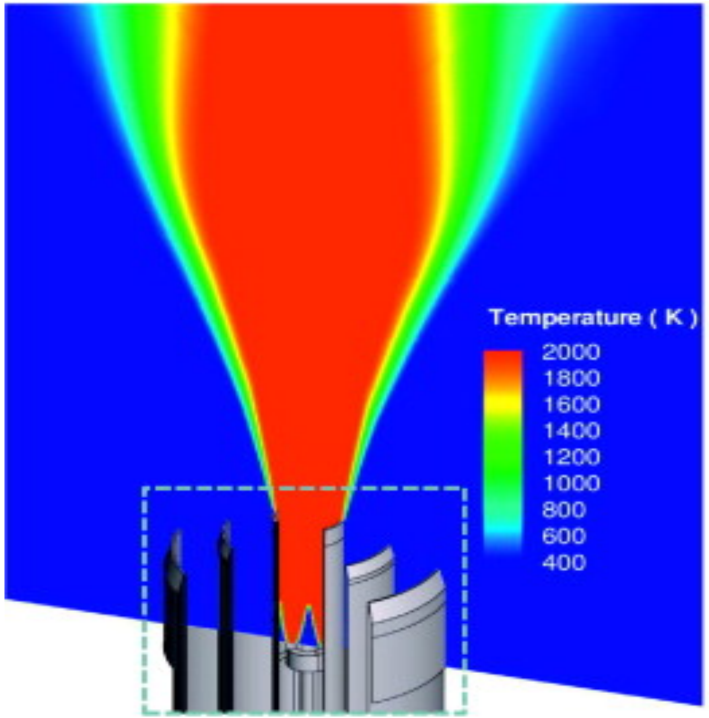
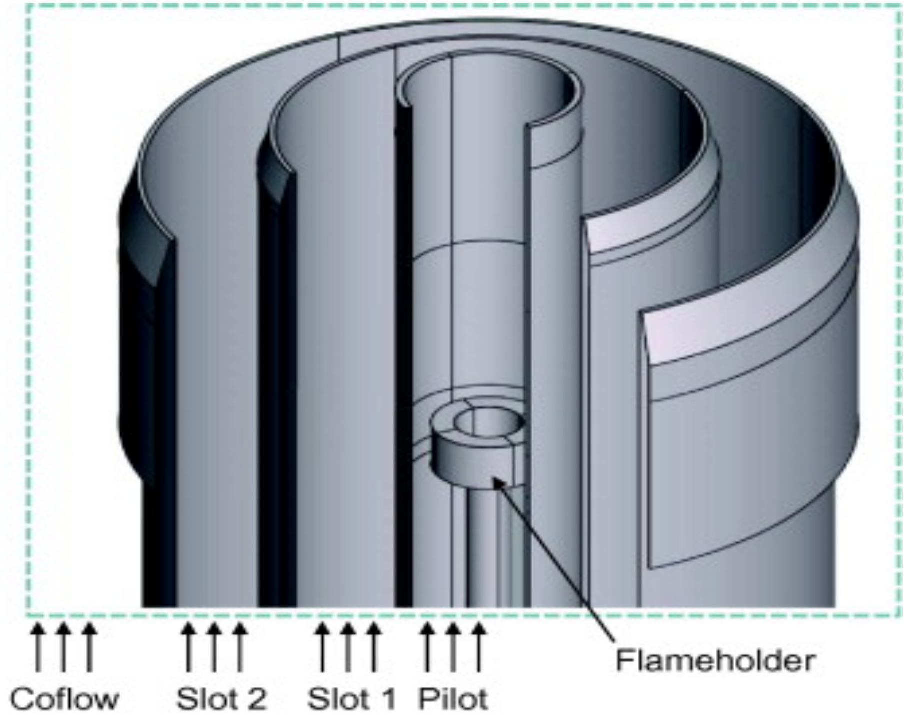


TUD Stratified Flame



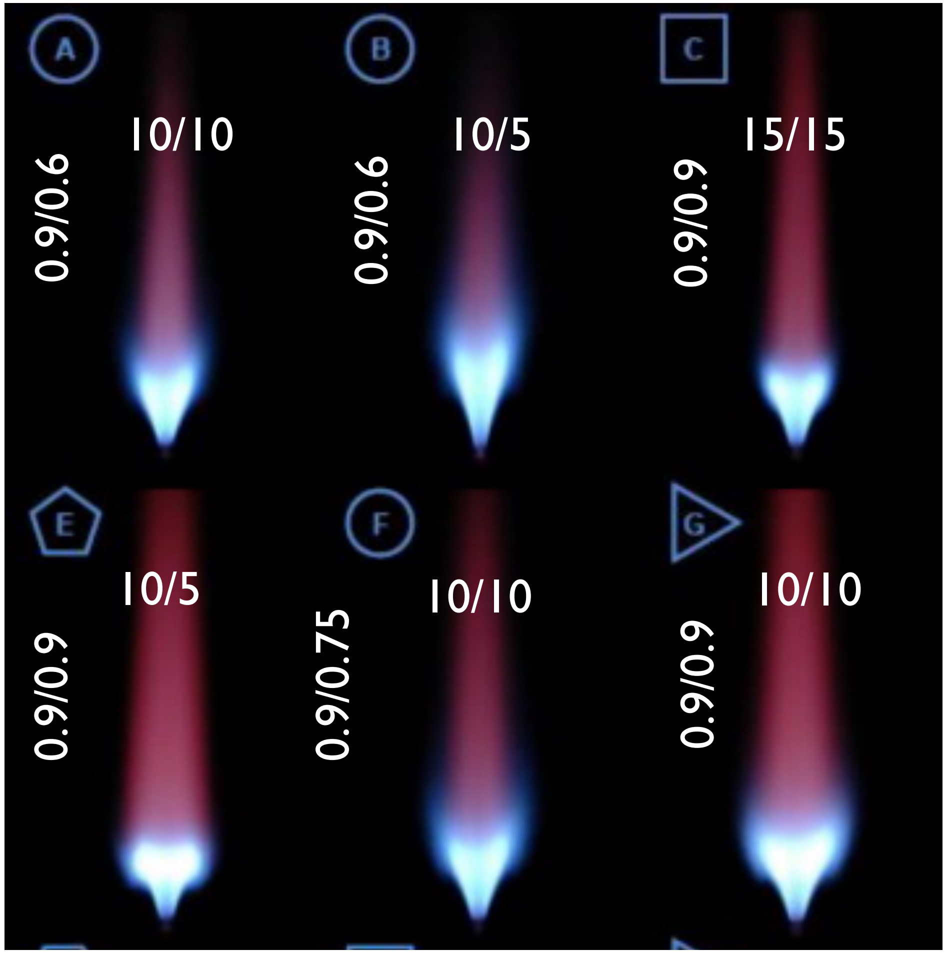


Seffrin et al, C&F157 (2010)
Boehm et al, PCI 33 (2011)
Kuenne et al, C&F 159 (2012), ECM (2013)

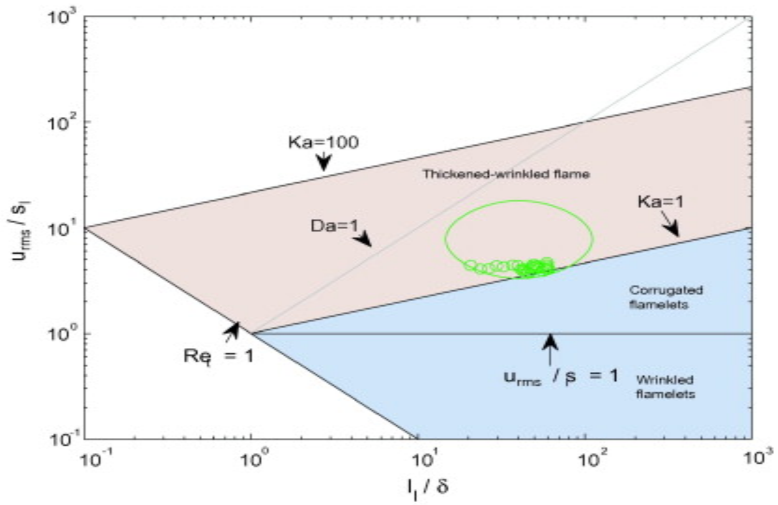
TUD Stratified Flame Properties

U

ϕ

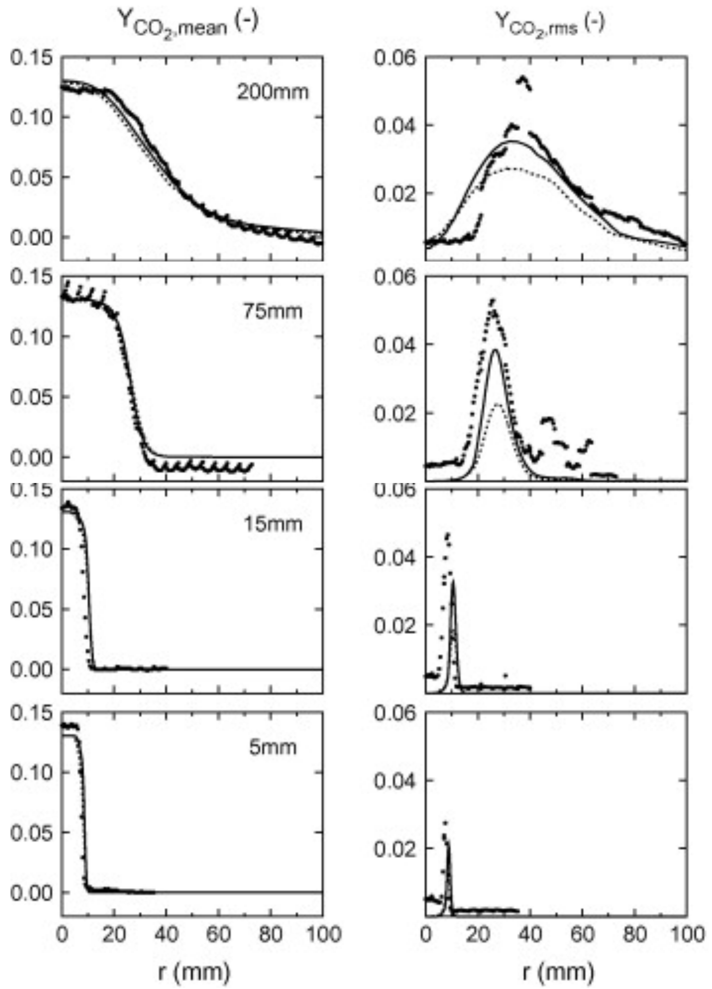


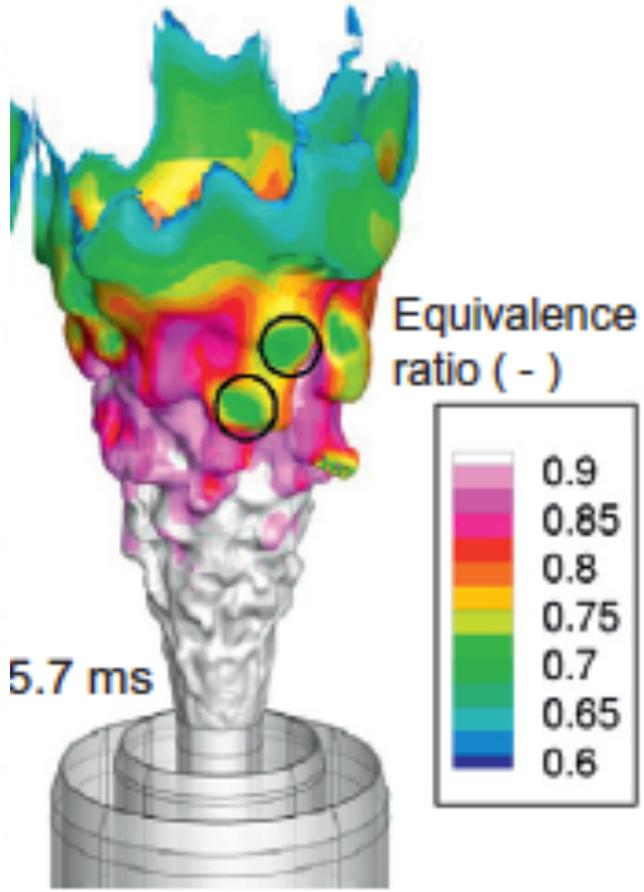
U (m/s)	5-20
u'/S_L (-)	0.35-0.9
Re_{h1}	13-26k
$Ka = (\delta_T/h)^2$	1.2-2.1
Da	50-80



Seffrin et al, CNF157 (2010)

Comparison of model and experiment TUD stratified flame



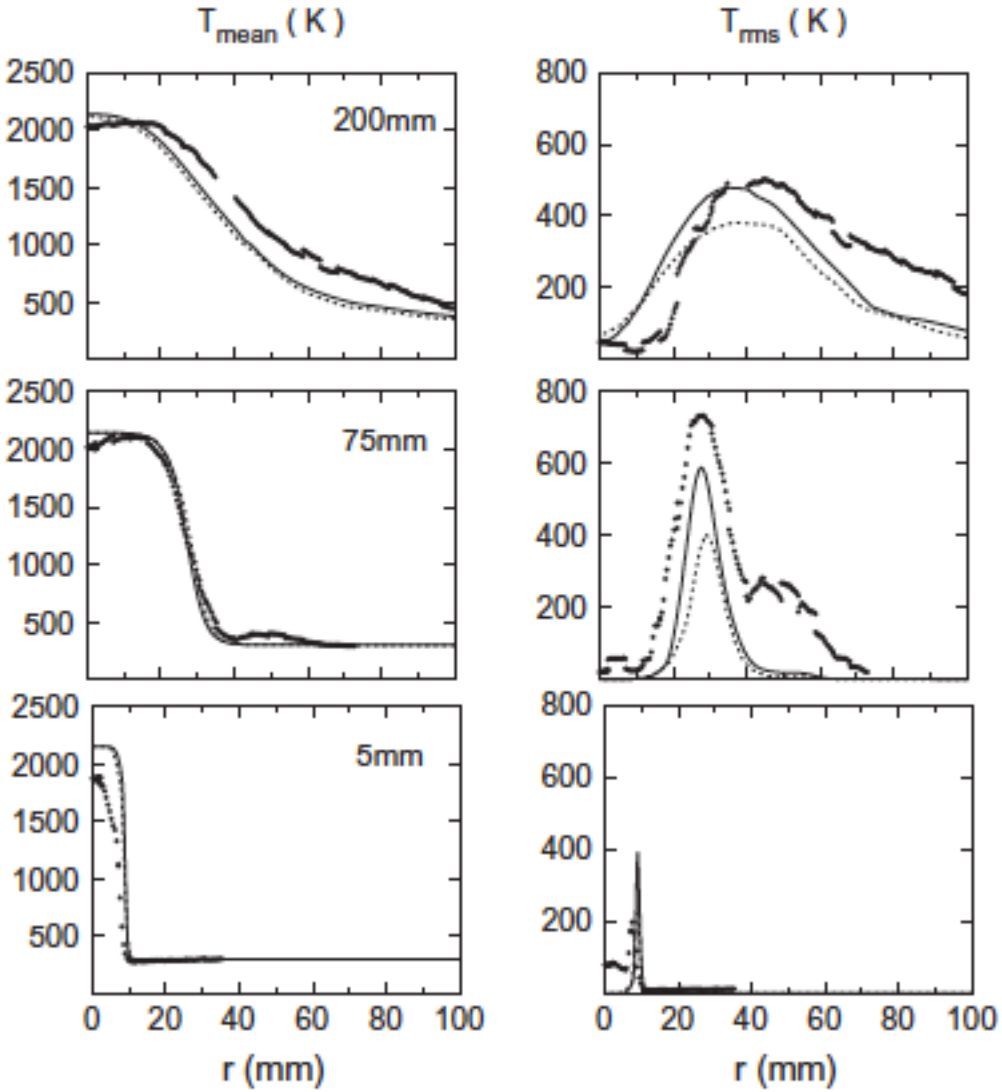


FGM model
Thickened flame
Local cell ϕ

TSF-A-r
10 m/s no shear
ϕ_i/ϕ_o = 0.9/0.6

Kuenne et al, Combustion and Flame Volume 159, Issue 8 2012
doi: 10.1016/j.combustflame.2012.02.010

Comparison of model and experiment – TUD stratified flame



FGM model
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10 m/s no shear
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Kuenne et al, Combustion and Flame Volume 159, Issue 8 2012

Velocity predictions and model
Shear cases

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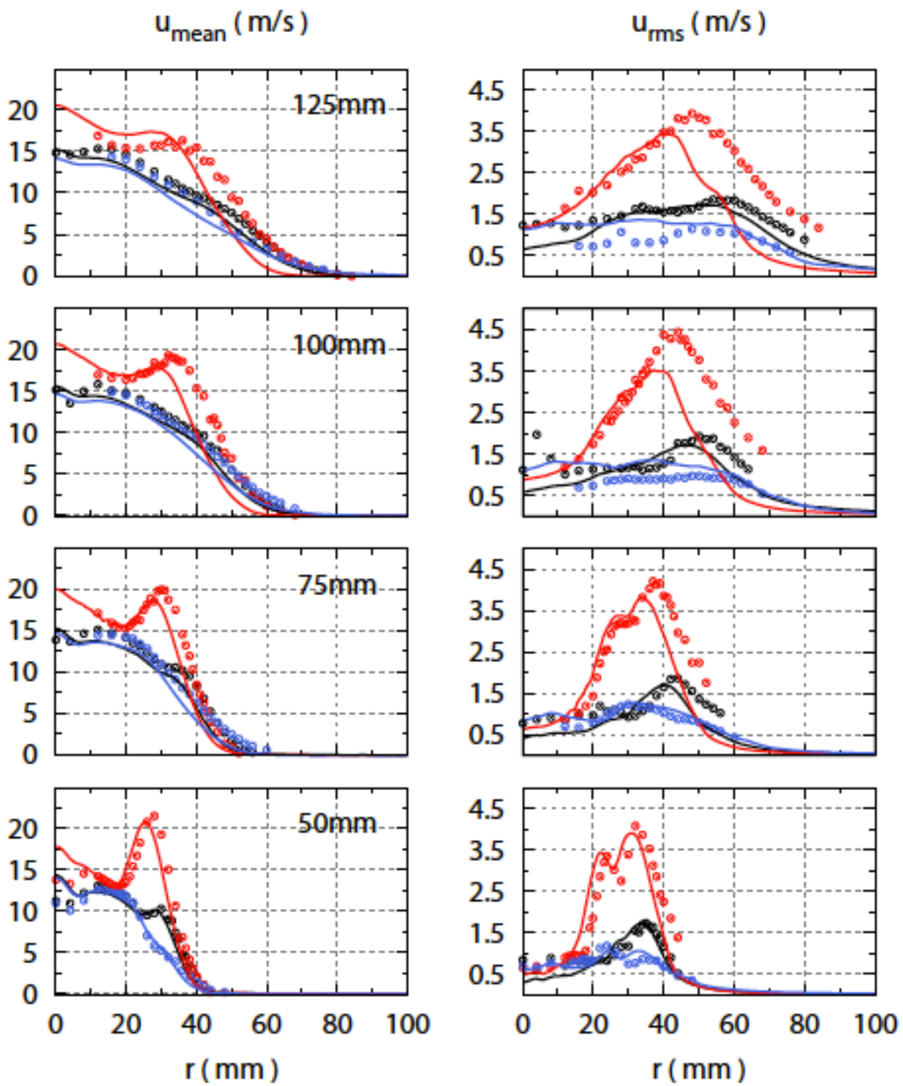


FGM model
Thickened flame
Local cell ϕ

Ui/Uo (m/s)

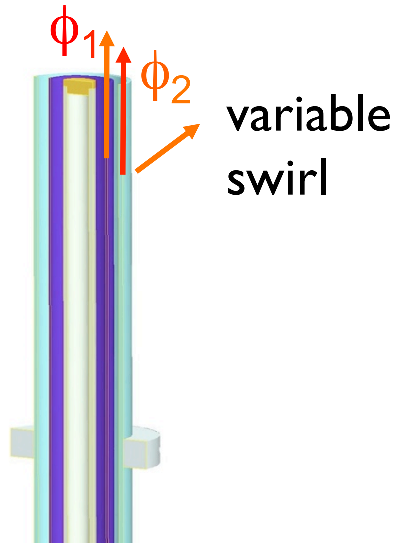
10/10
10/5
10/20

Kuenne et al., ECM 2013
Kuenne et al, CNF, 159 (2012)
doi:10.1016/j.combustflame.2012.02.010

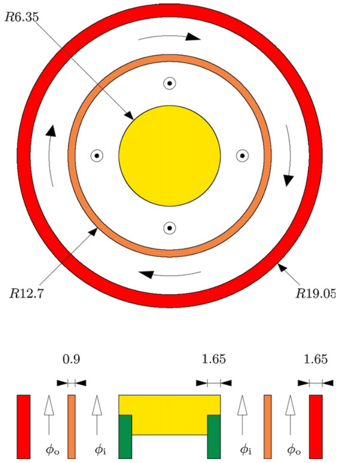
More data and simulations underway

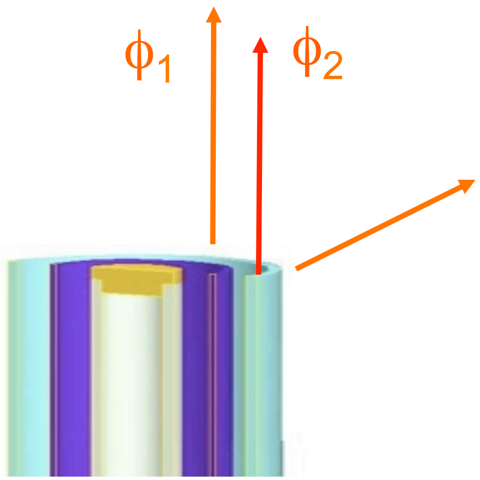
Sandia-Cambridge Stratified Swirl Burner

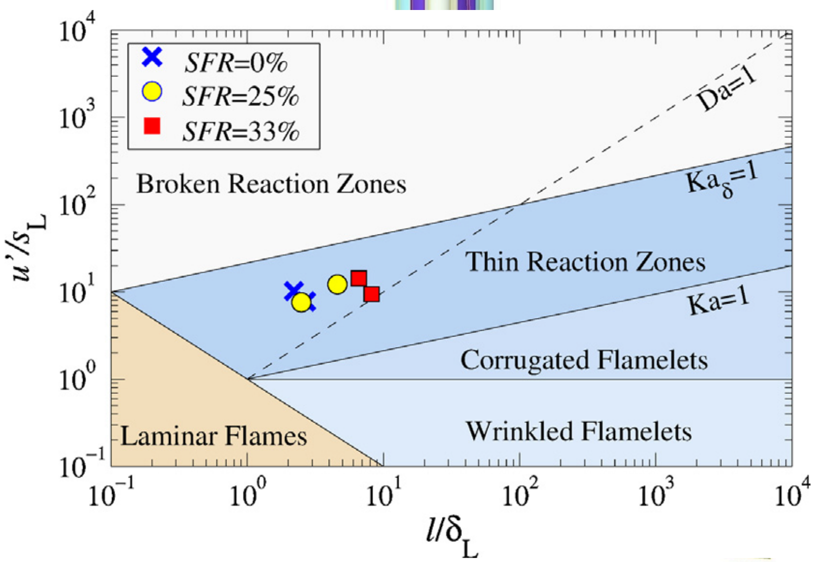
U_1 (m/s)	8.3	U_2 (m/s)	18.7
u'/U (-)	0.2-0.4	u'/S_L (-)	4-8
Re_{h1}	5690	Re_{h2}	11500
L_t (mm)	~9	Re_t	100-500
Da	0.6-1.0	$Ka = (\delta_T/\eta)^2$	7.6-48



Sweeney, Hochgreb, Dunn, Barlow
C&F 159 (2012) 2896–2911
C&F 159 (2012) 2912–2929
C&F 160 (2013) 322-334
C&F 33 (2011) 1419–1427







High resolution measurements: Sandia multiscalar facility

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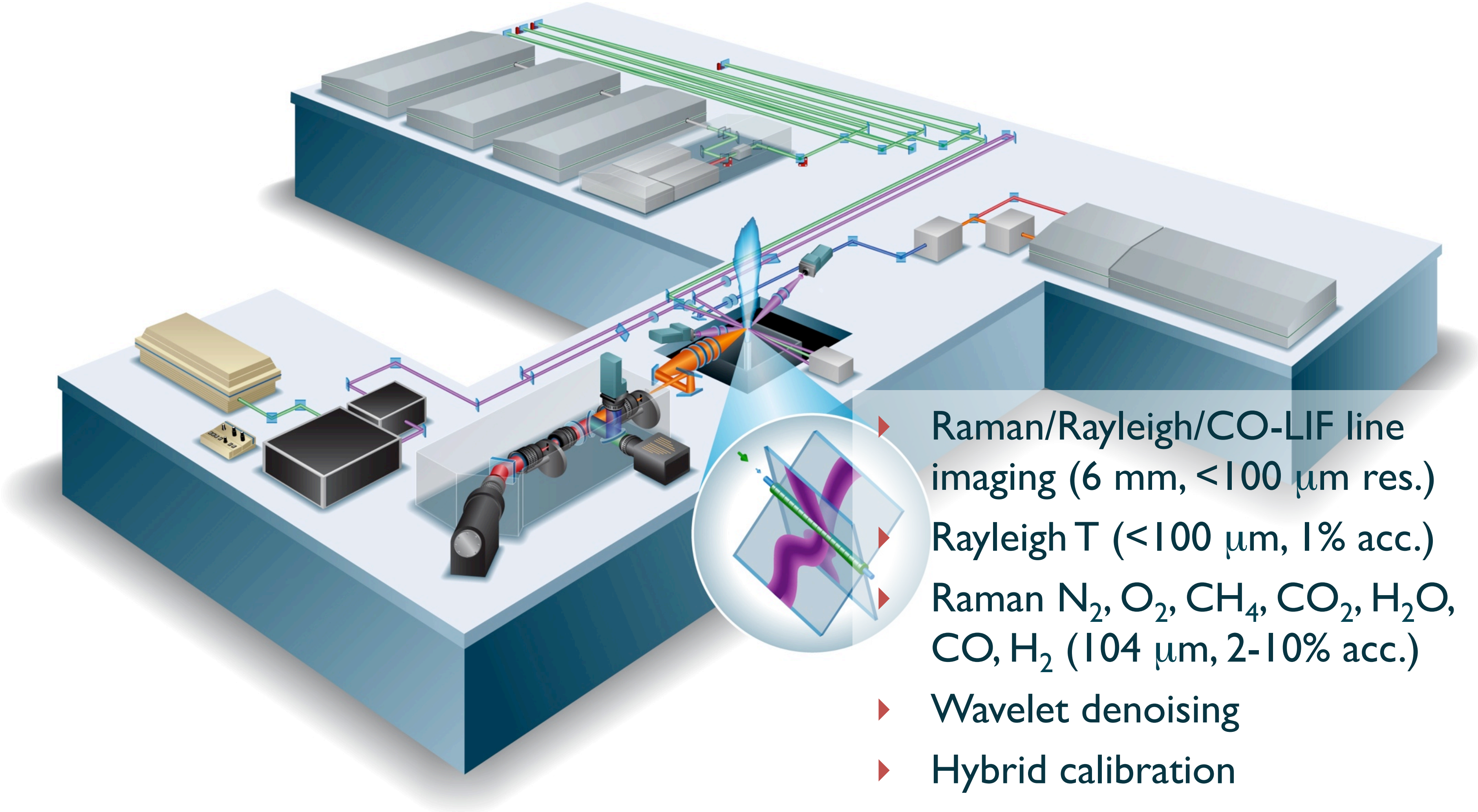
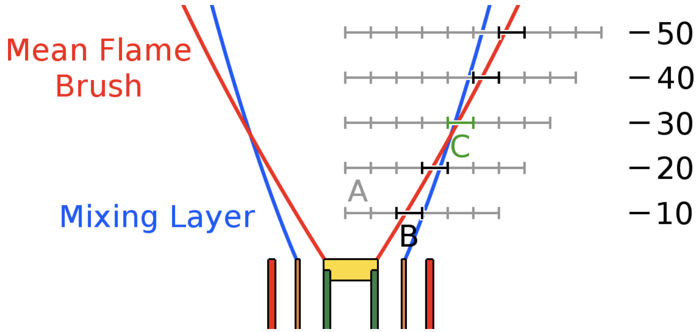
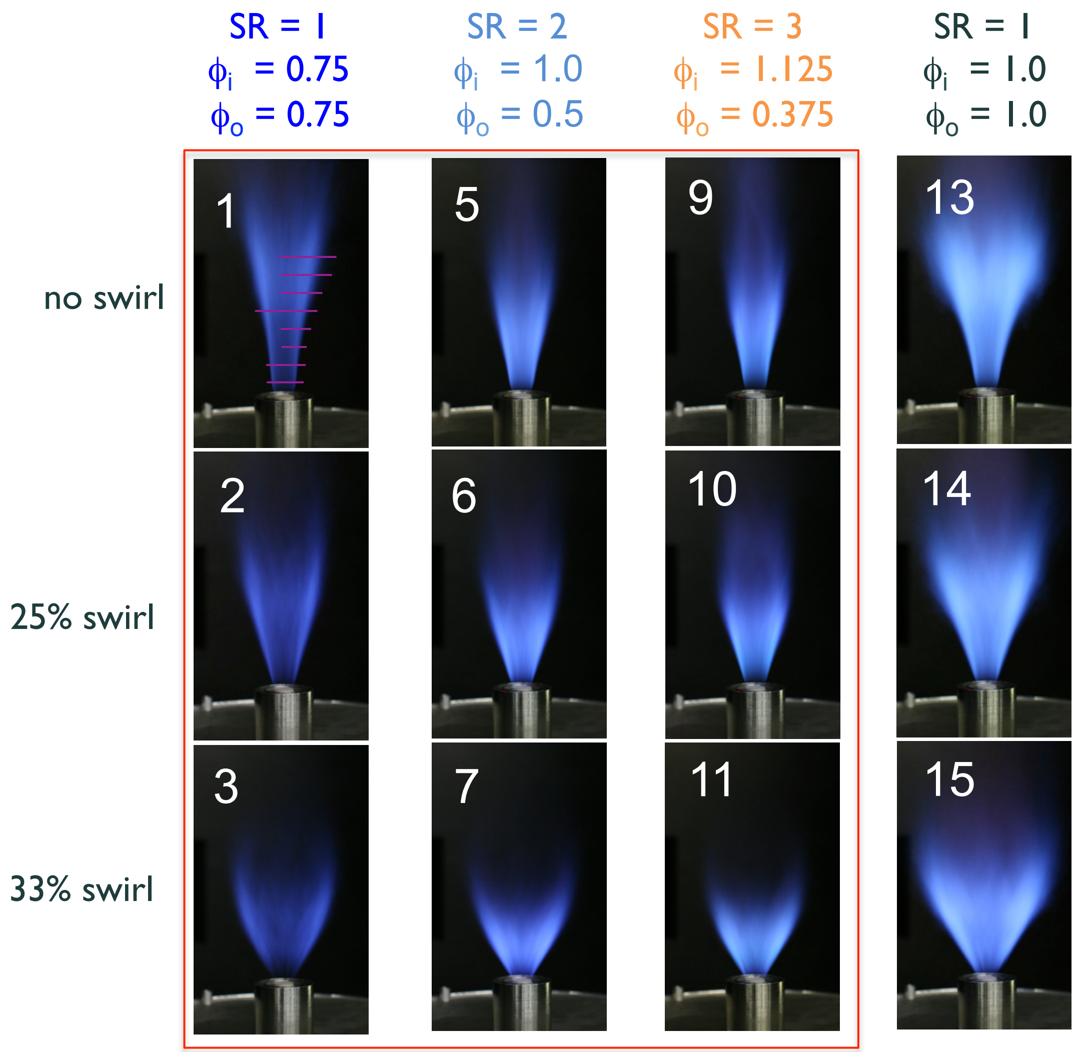


- Raman/Rayleigh/CO-LIF line imaging (6 mm, <100 μm res.)
- Rayleigh T (<100 μm, 1% acc.)
- Raman N_2, O_2, CH_4, CO_2, H_2O, CO, H_2 (104 μm, 2-10% acc.)
- Wavelet denoising
- Hybrid calibration
- Crossed OH PLIF

Sandia-Cambridge Stratified Swirl Burner





Radial profiles

- z = 10, 20, 30, …,80 mm
- 300 shots at each location, 1500 in flame brush
- 103 µm data spacing

Long records

- crossing of flame & mixing layer
- 30,000 shots
- 20 µm data spacing
- wavelet denoising

Mean velocity profiles: swirl and non-swirl

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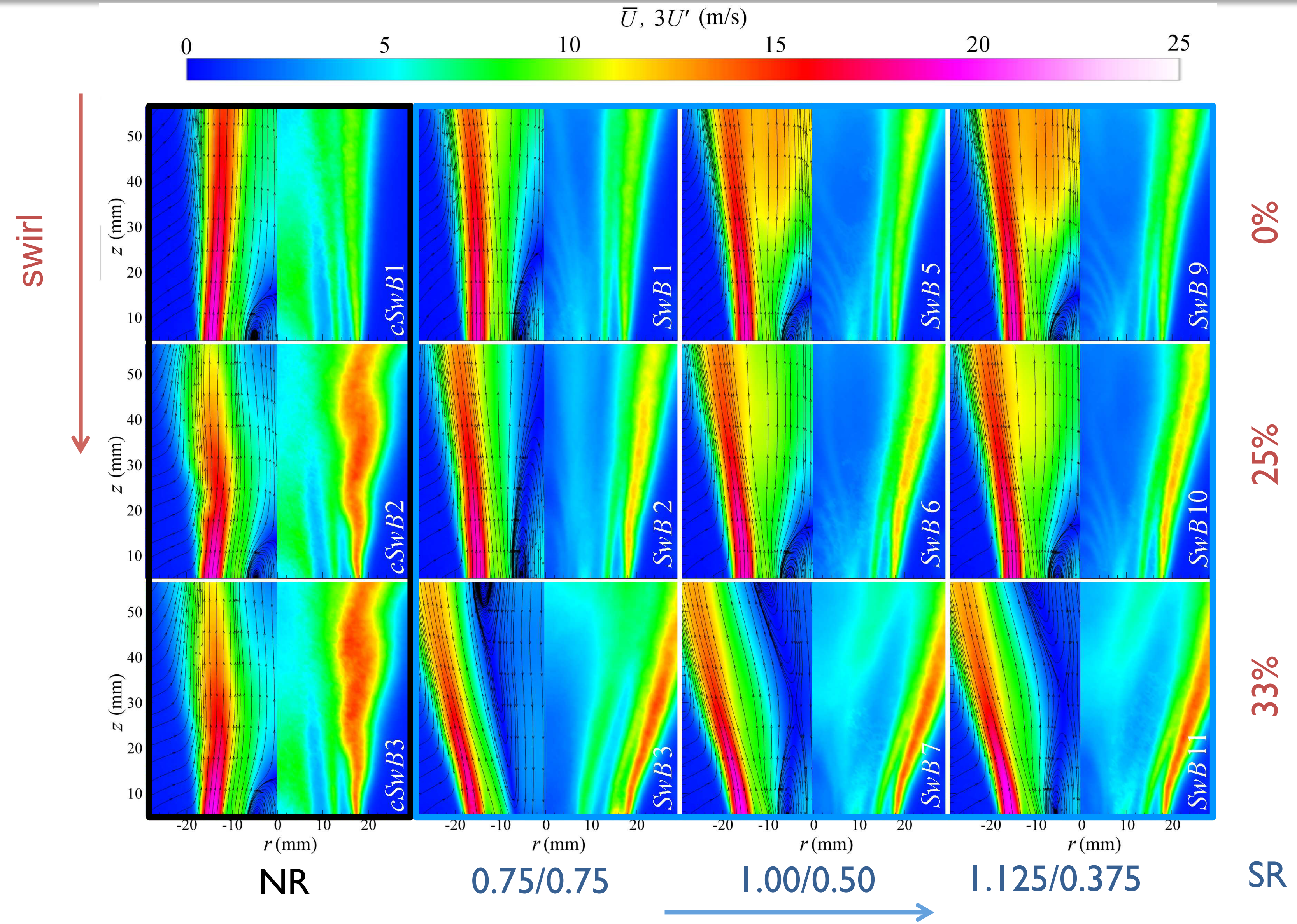

Zou & hochgreb, CNF 2013,
doi: 10.1016/j.combustflame.2013.04.007

No swirl: Favre averaged T and ϕ

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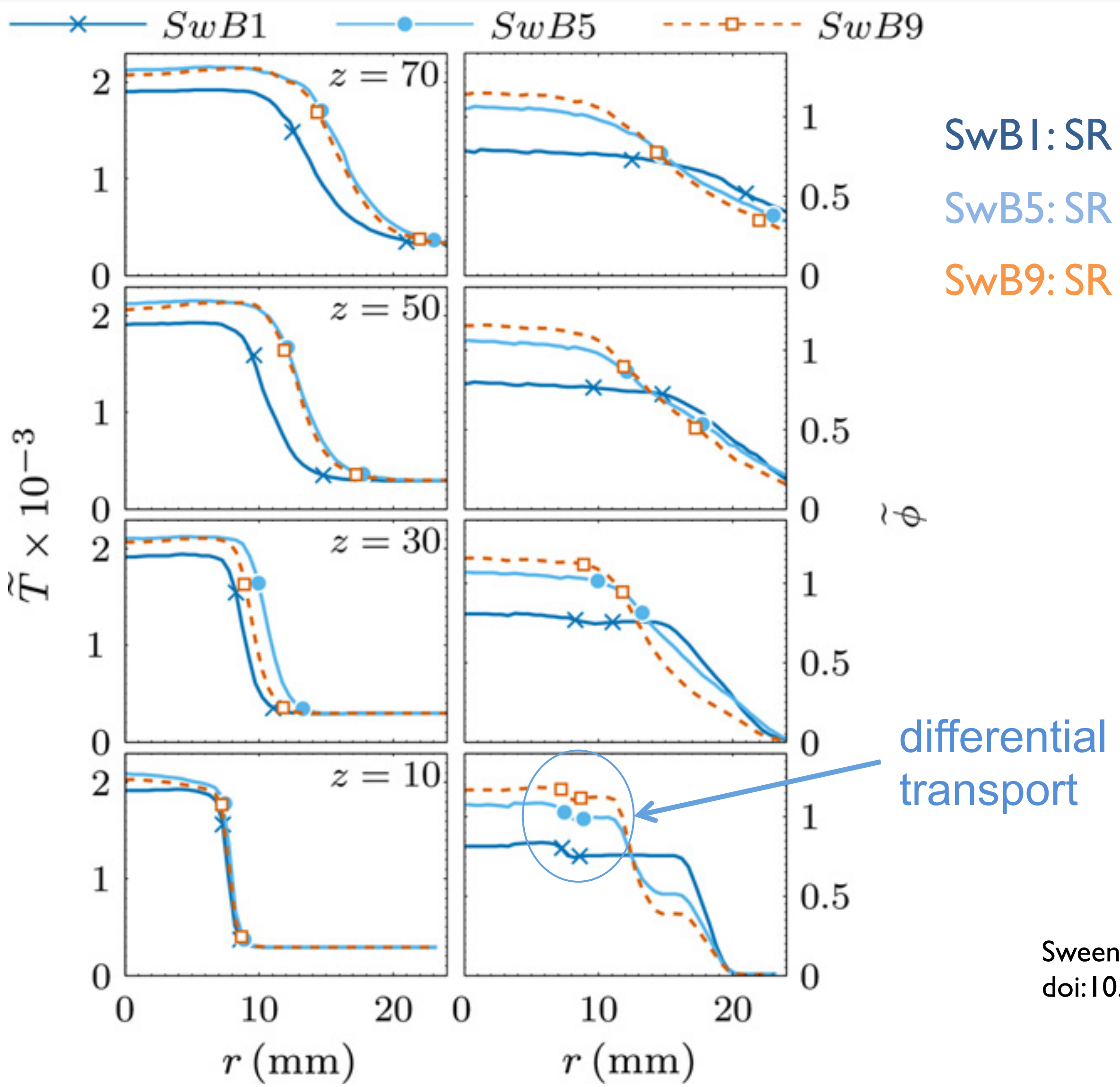


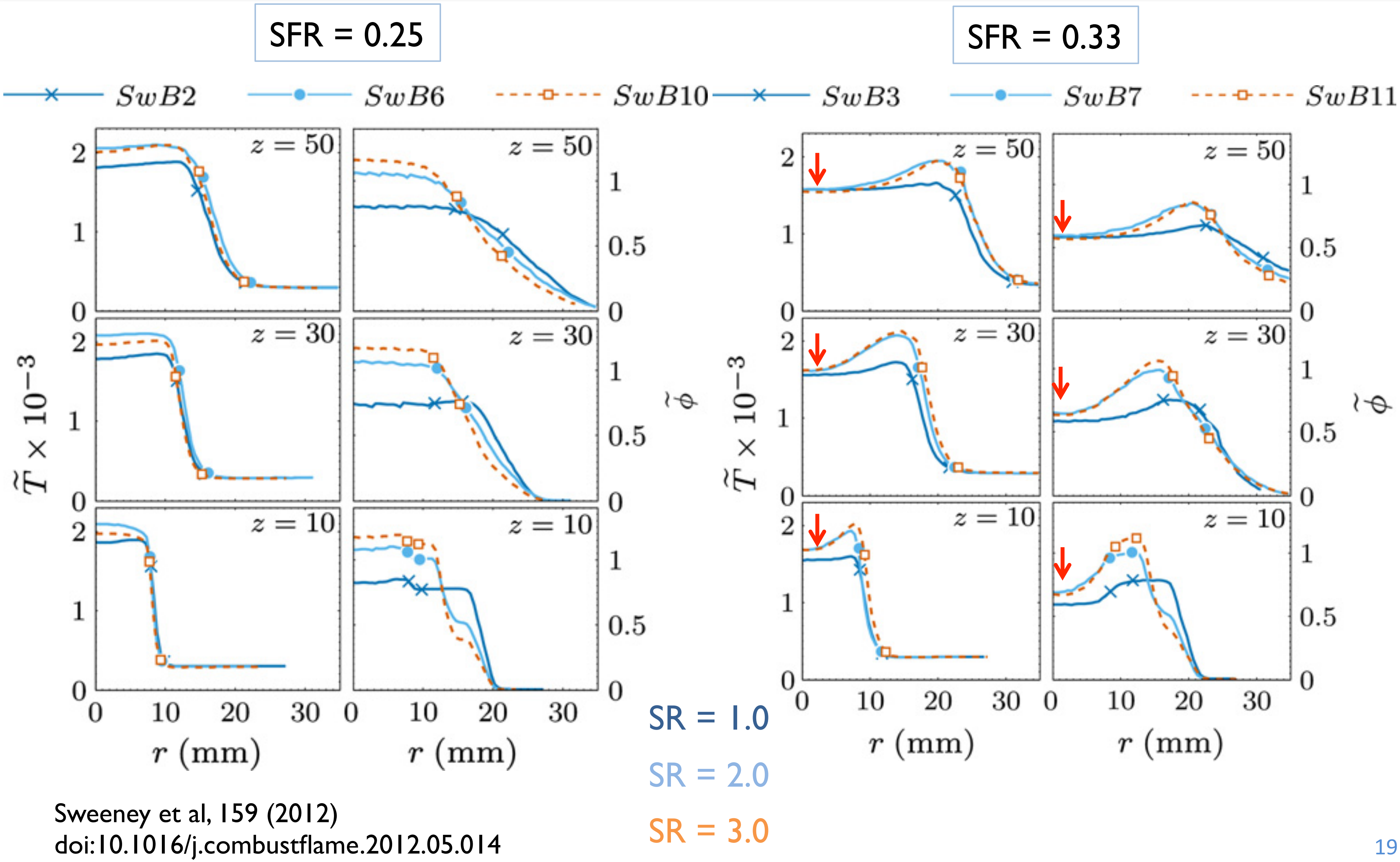
SwB1: SR = 1.0

SwB5: SR = 2.0

SwB9: SR = 3.0

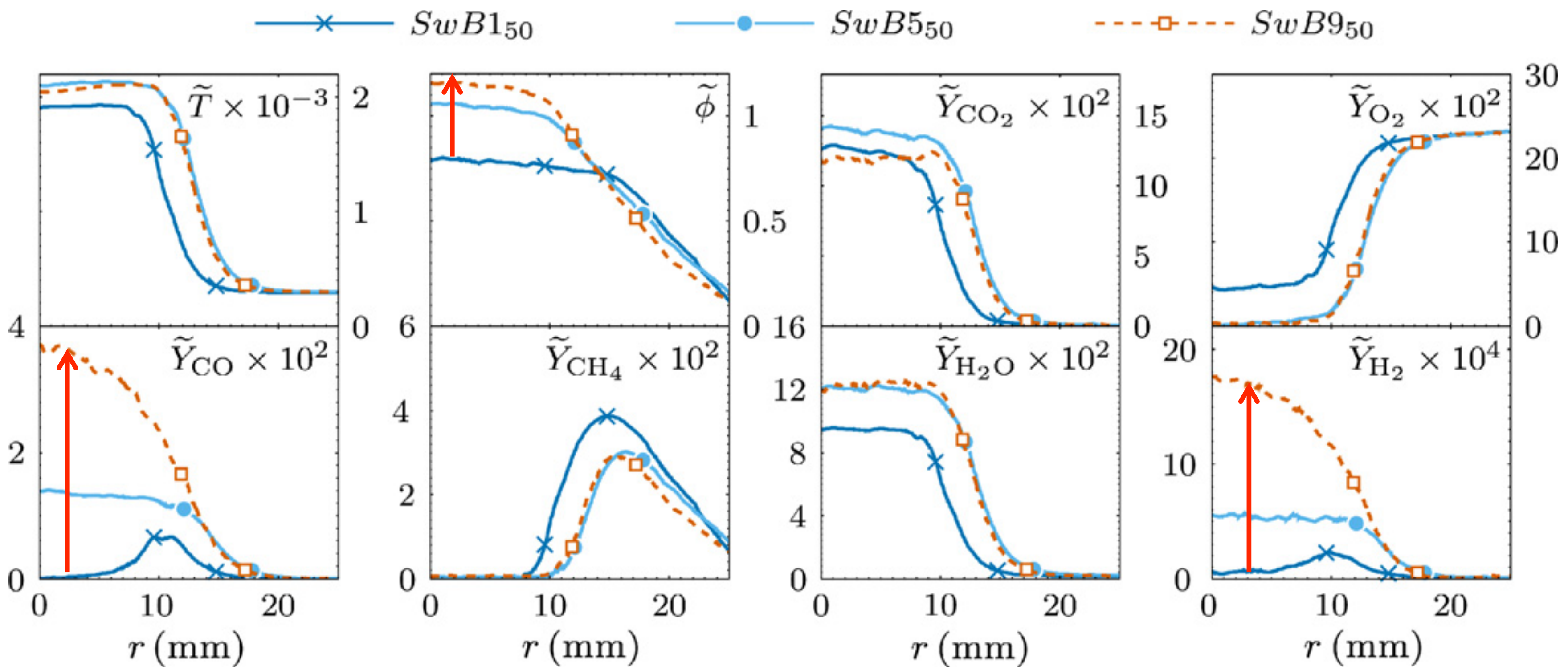
Sweeney et al, CNF 159 (2012)
doi:10.1016/j.combustflame.2012.06.001

Swirl: T and ϕ profiles



Sweeney et al, 159 (2012)
doi:10.1016/j.combustflame.2012.05.014

No swirl: Favre species profiles



z=50 mm: approximate location of mixing layer crossing

Swirl: Favre species profiles

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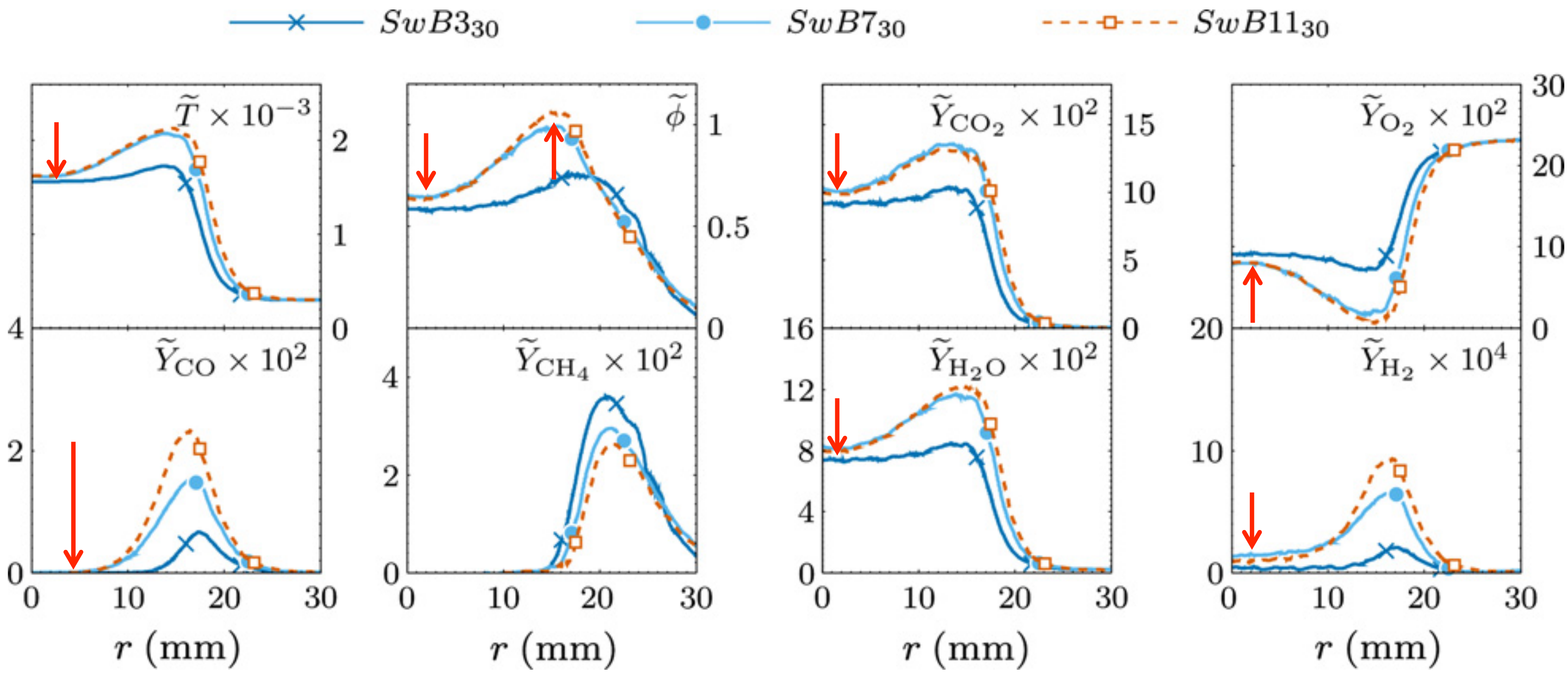
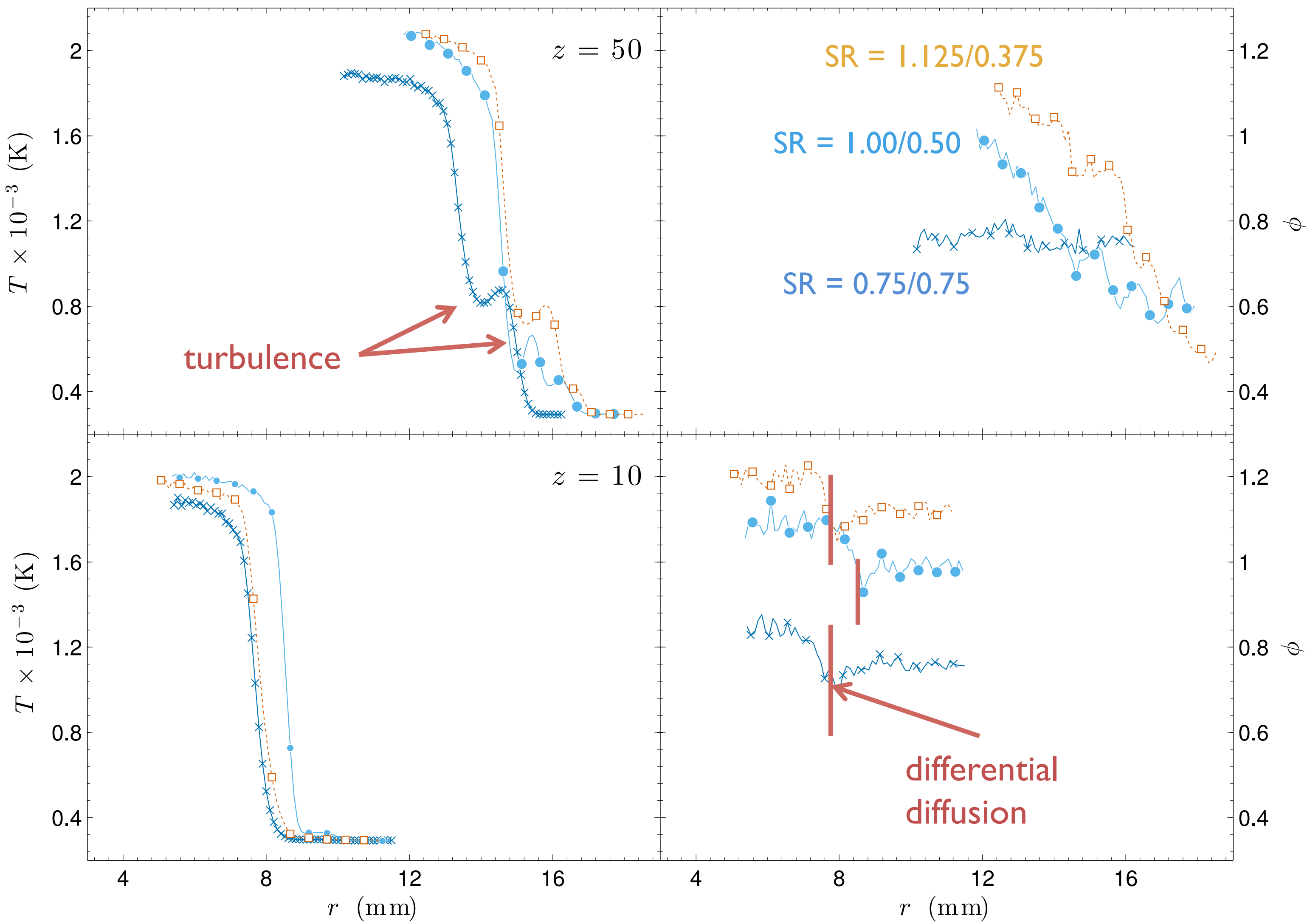


z=30 mm: approximate location of mixing layer crossing

The story of differential diffusion: Single shots



Mechanism for differential transport in bluff body stabilized burners

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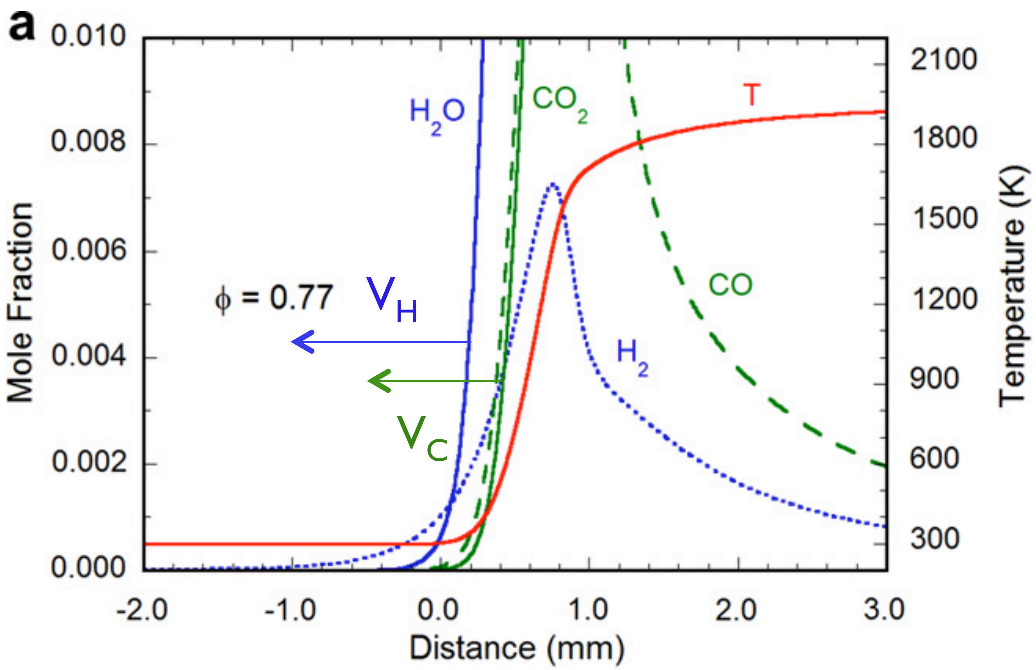
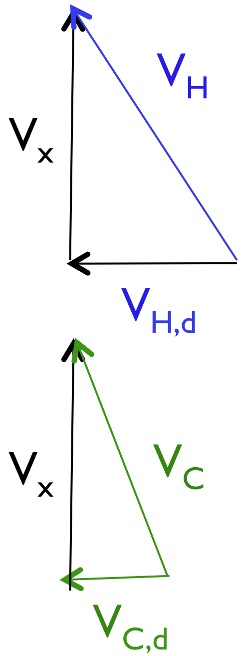
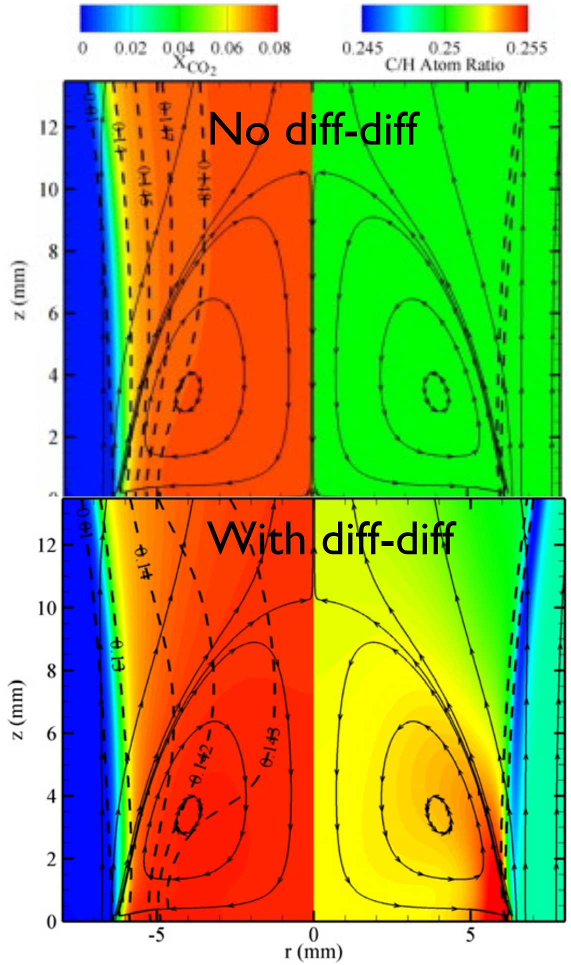


Barlow et al, C&F 159 (2012)
doi:10.1016/j.combustflame.2011.11.013



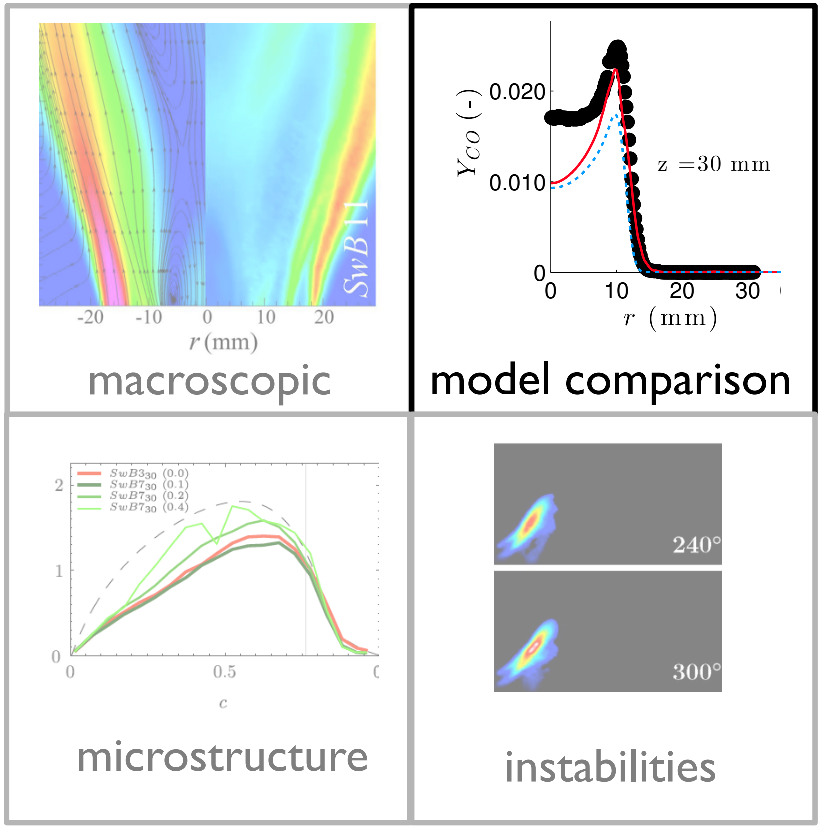


Katta & Roquemore, PCI 34 (2013)
doi:10.1016/j.proci.2012.06.033

More H than C diffuses towards the reactants
Reactants swept downstream by axial flow

Differential diffusion affects definition of ϕ at peak heat release

Outline: Effects of Stratification



Comparison with LES models

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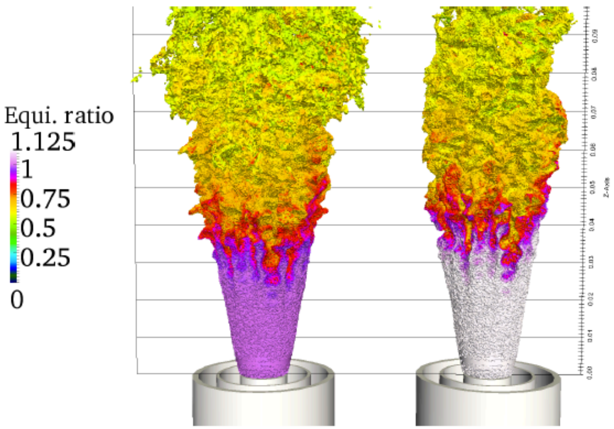
CORIA

ECP

Duisburg



[1] Nambully, Domingo, Moureau, Vervisch, C&F 2013, under review
FTF-PDF (F-TACLES [2])
Tabulated source for *differential diffusion*

Mercier & Fiorina
[2] Auzillon, P., Gicquel, O., Darabiha, N., Veynante, D. & Fiorina, B. Combustion and Flame 159 (8), 2704 – 2717. (2013)
FTF-PDF (F-TACLES)

Proch & Kempf
[3] Kuenne, G., Ketelheun, A. & Janicka, J. Combustion and Flame 158 (9), 1750-1767. (2011)
ATF-FGM

Adiabatic bluff body

LES Simulations – Premixed, No swirl

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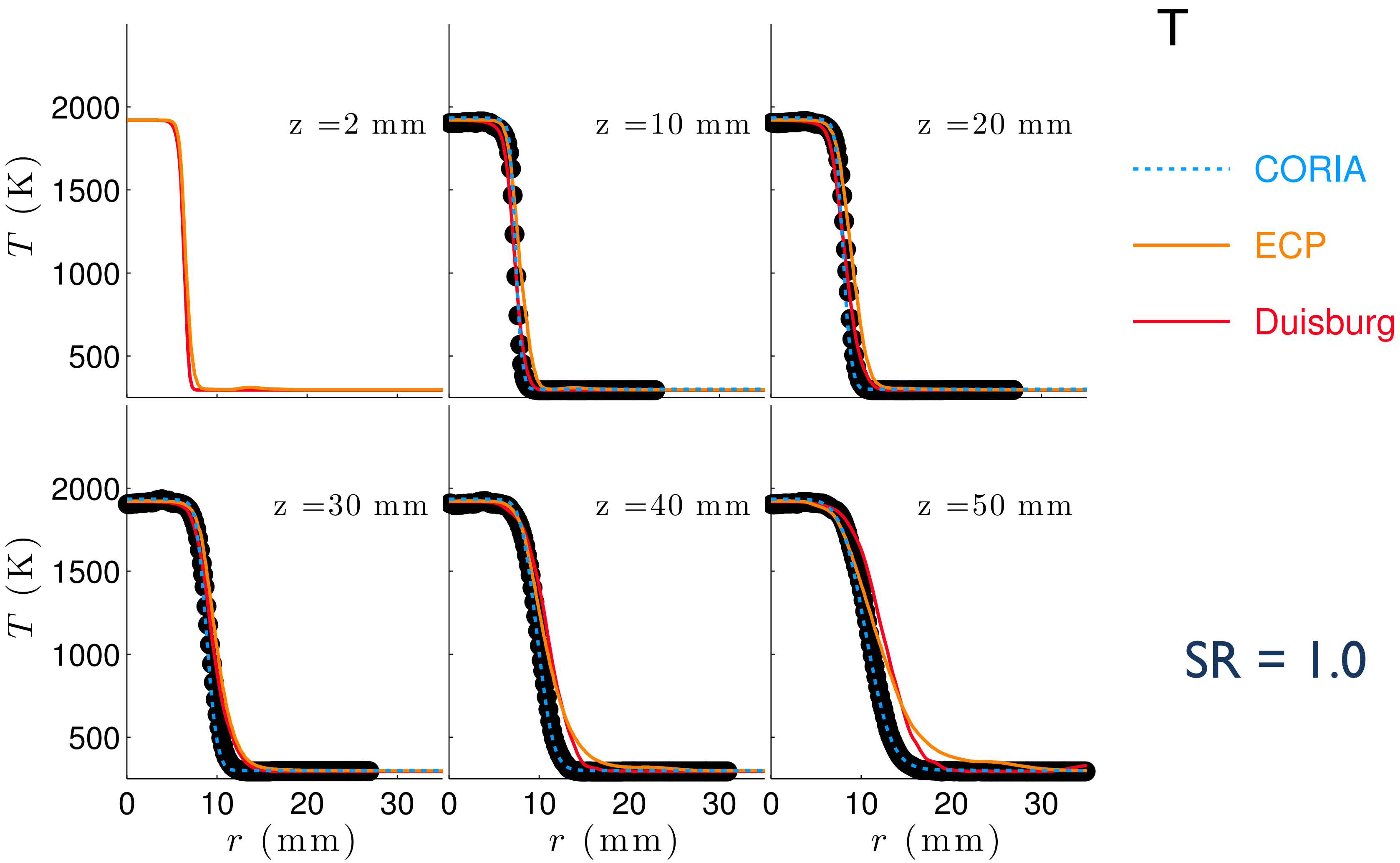

SR = 1.0

LES Simulations – Premixed, No swirl

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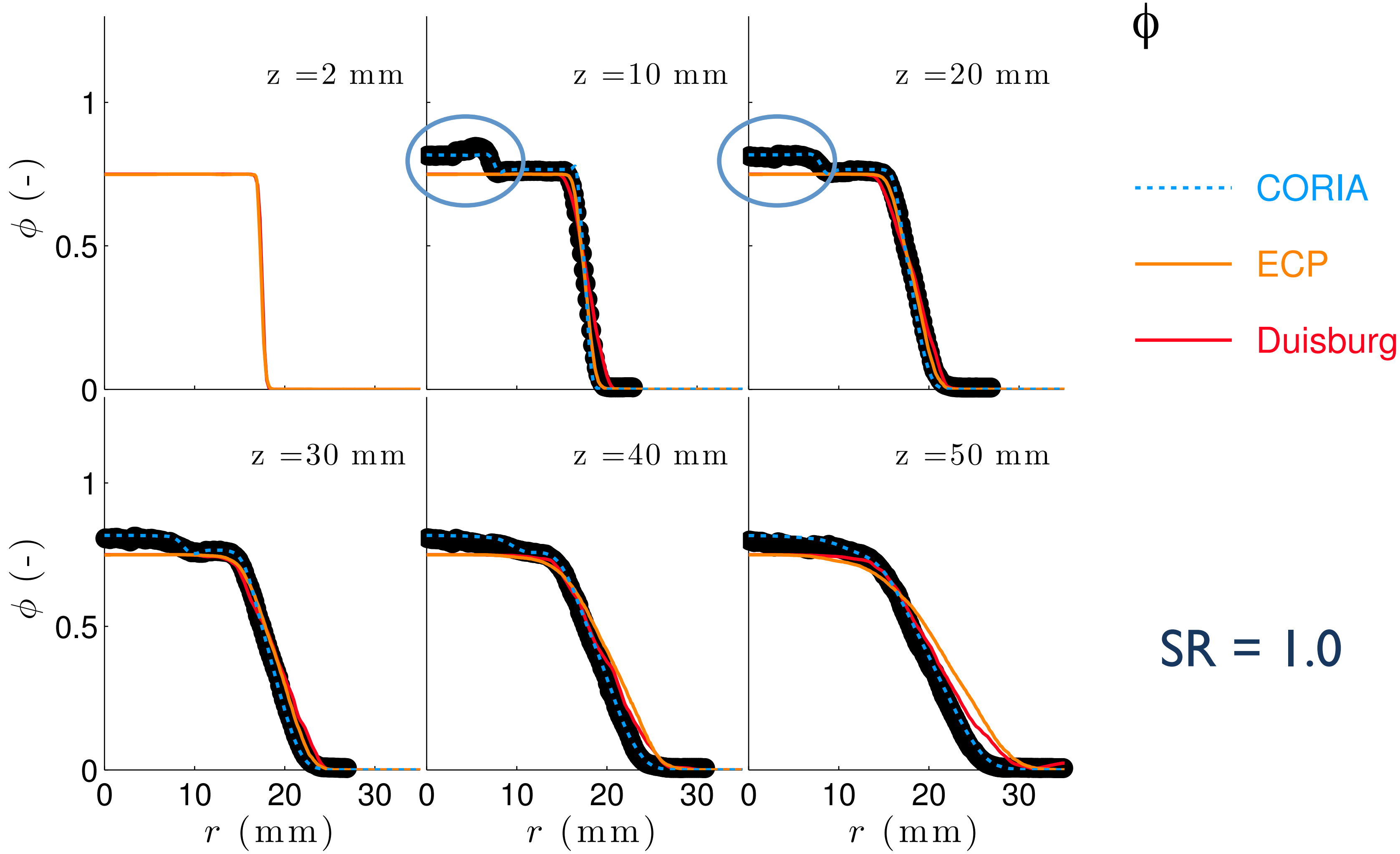
ϕ



SR = 1.0

LES Simulations – Premixed, No swirl

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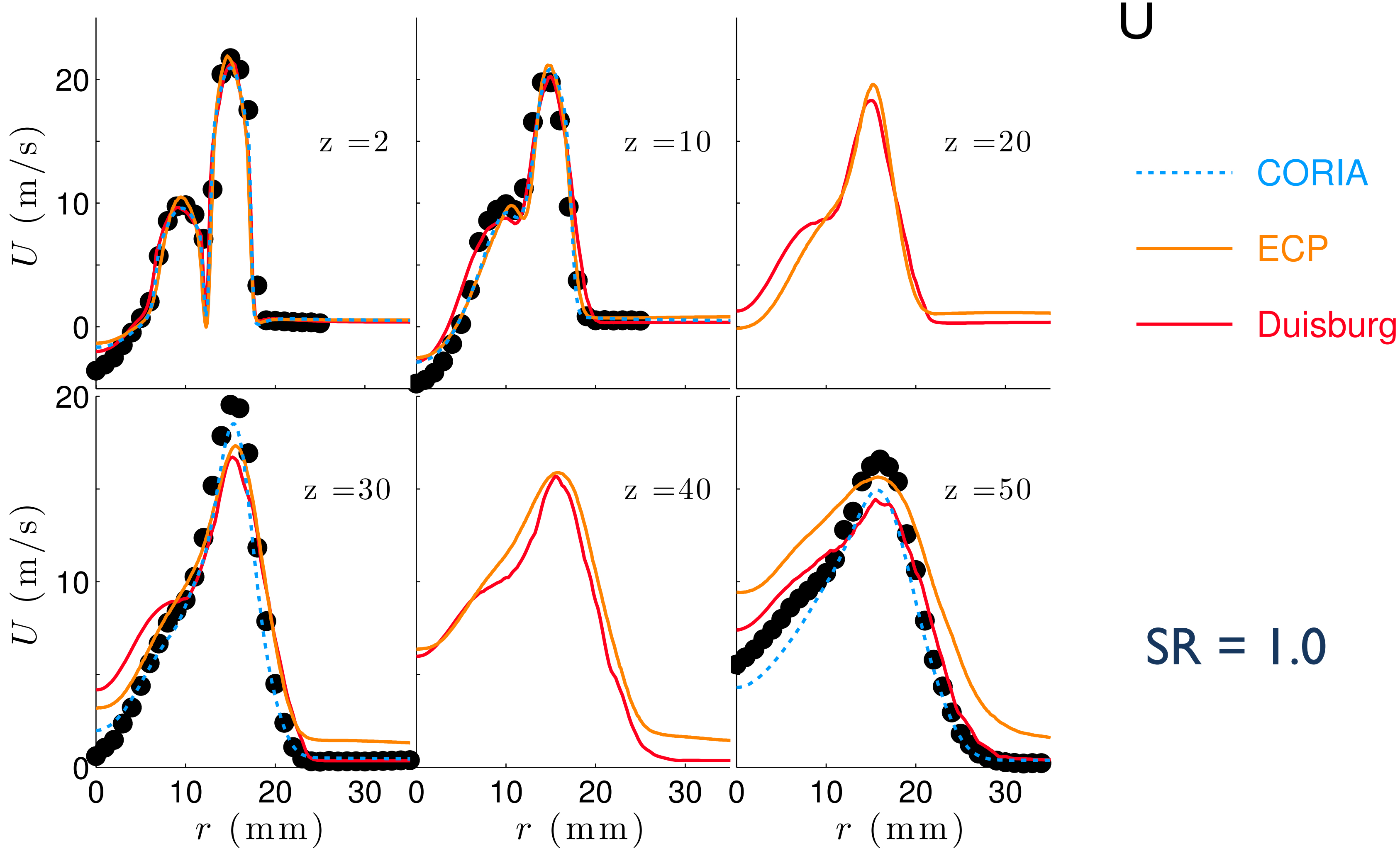
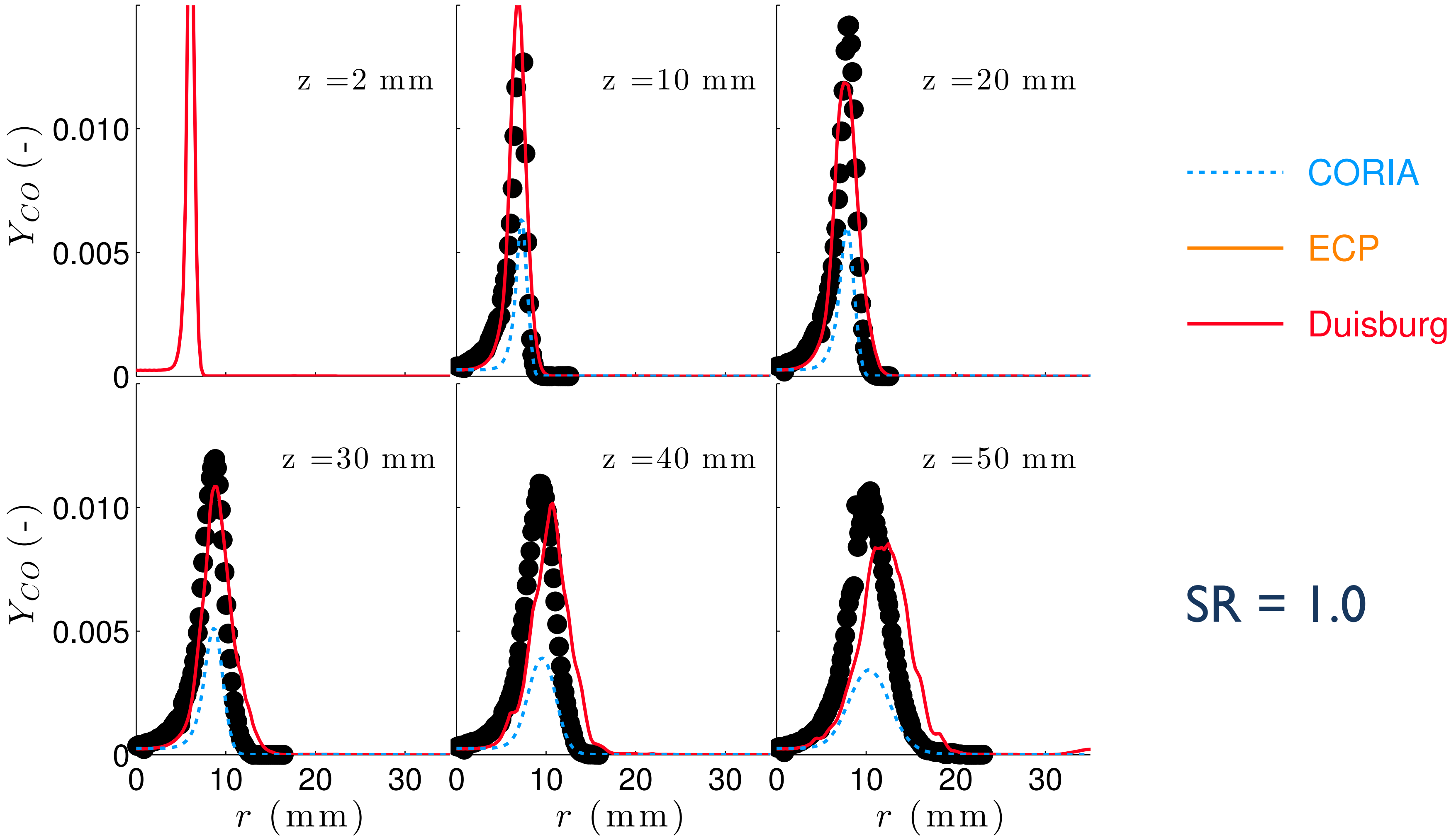


SR = 1.0

LES Simulations – Premixed, No swirl

UNIVERSITY OF CAMBRIDGE

CO

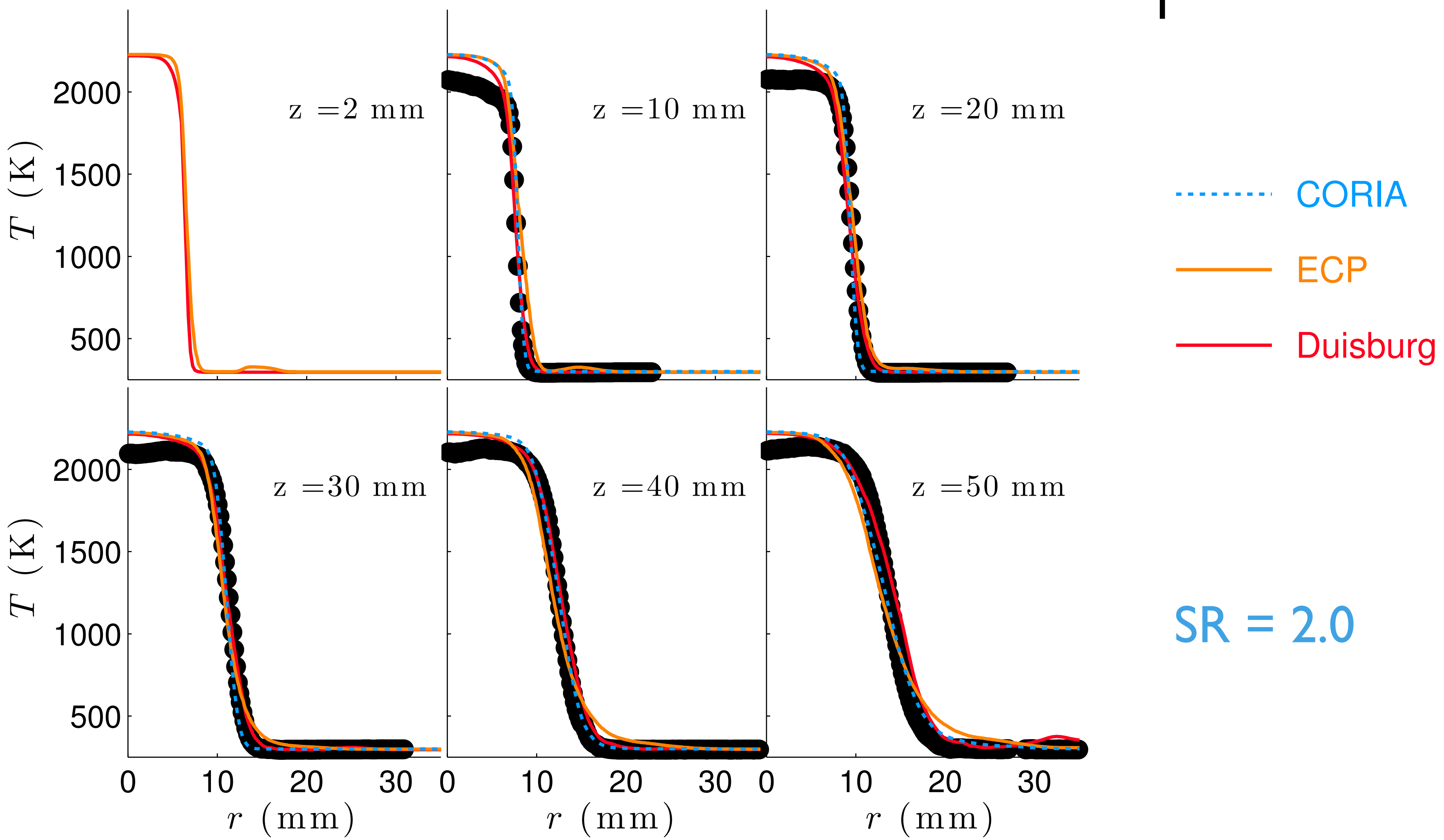


SR = 1.0

LES Simulations – SR=1.00/0.50, No swirl

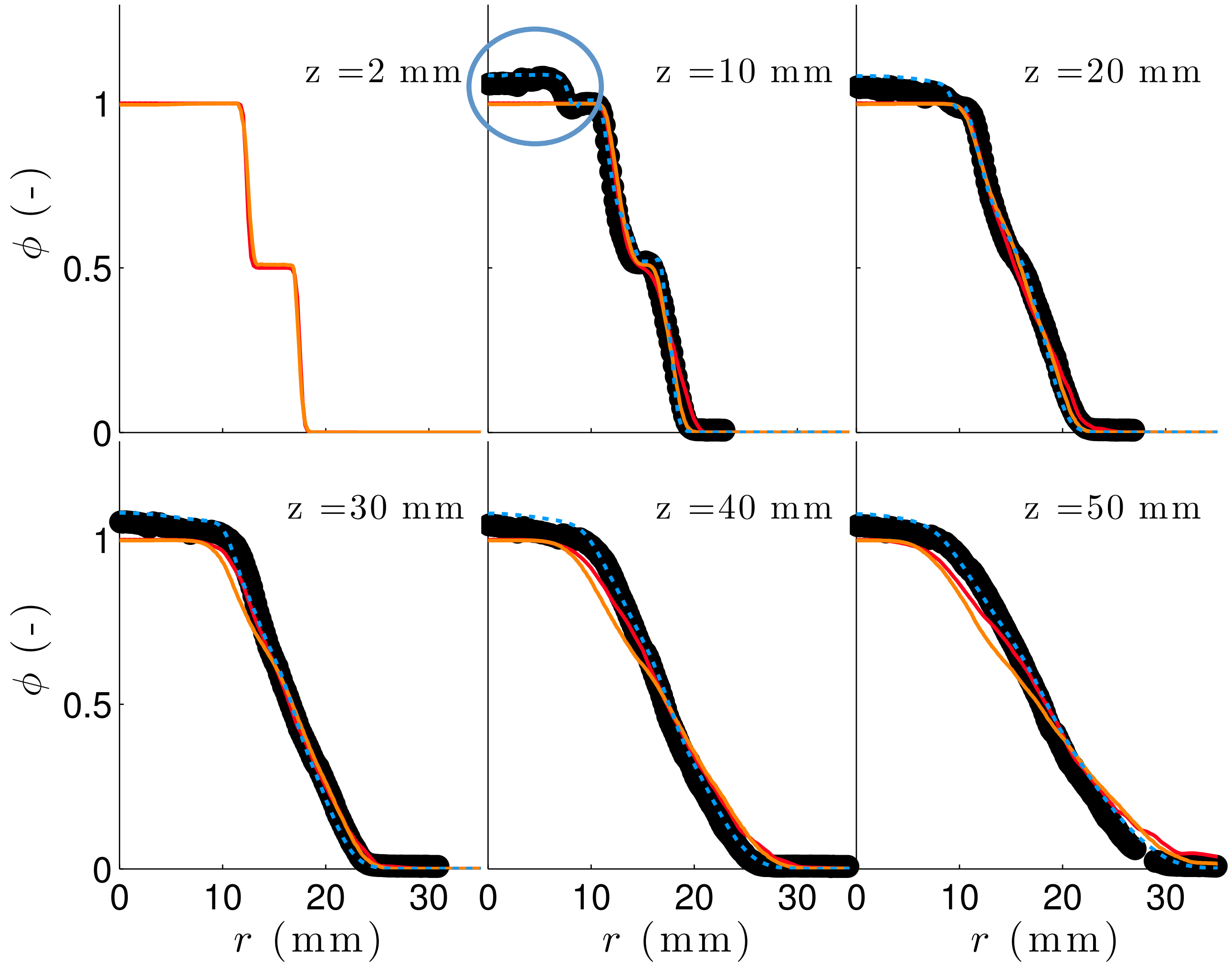
UNIVERSITY OF CAMBRIDGE

T

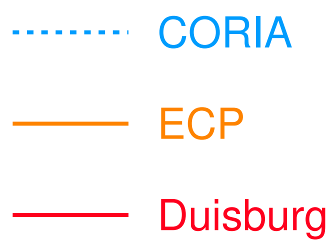


SR = 2.0

LES Simulations – SR=1.00/0.50, No swirl

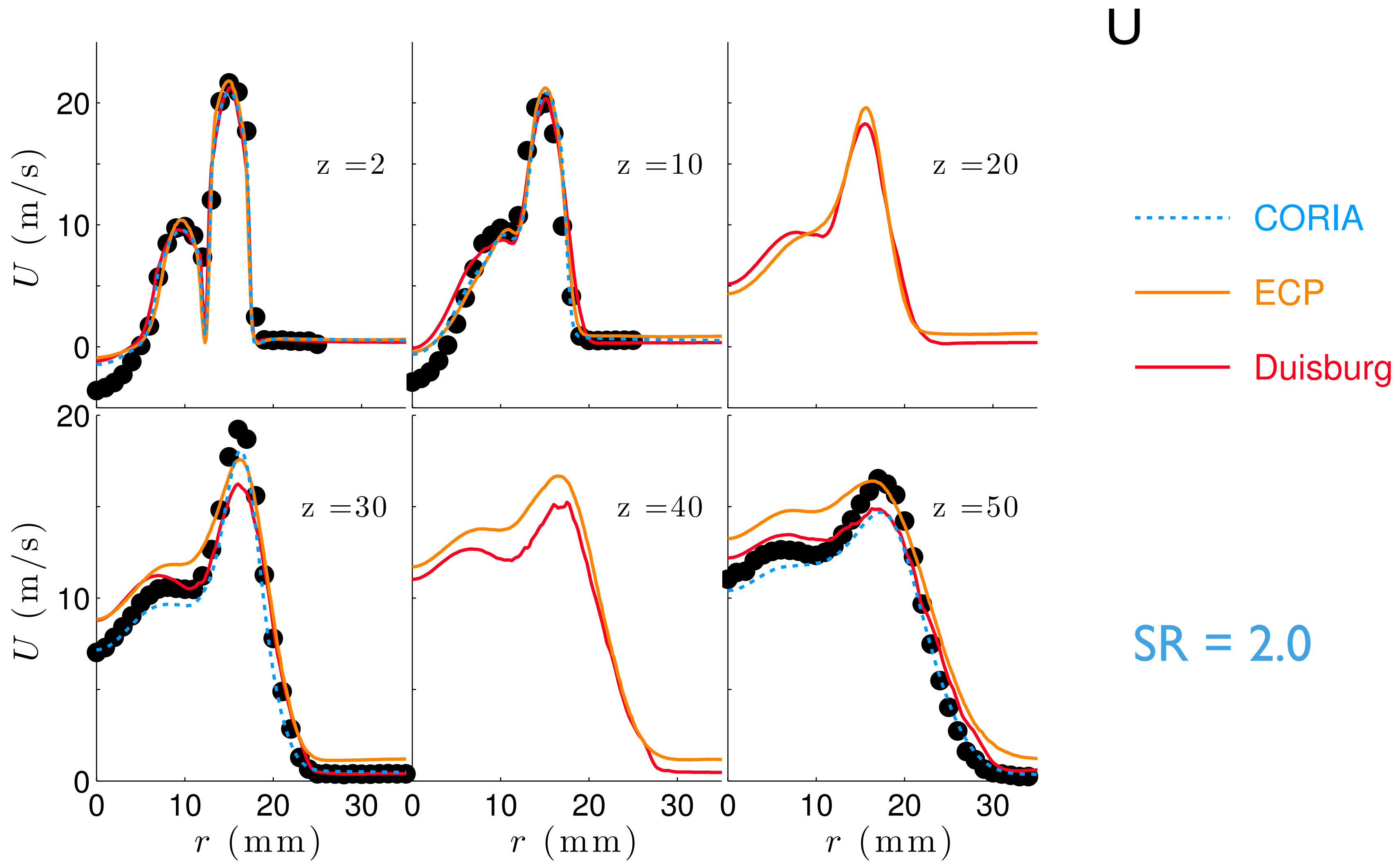


φ



SR = 2.0

LES Simulations – SR=1.00/0.50, No swirl



SR = 2.0

LES Simulations –
SR=1.00/0.50, No swirl

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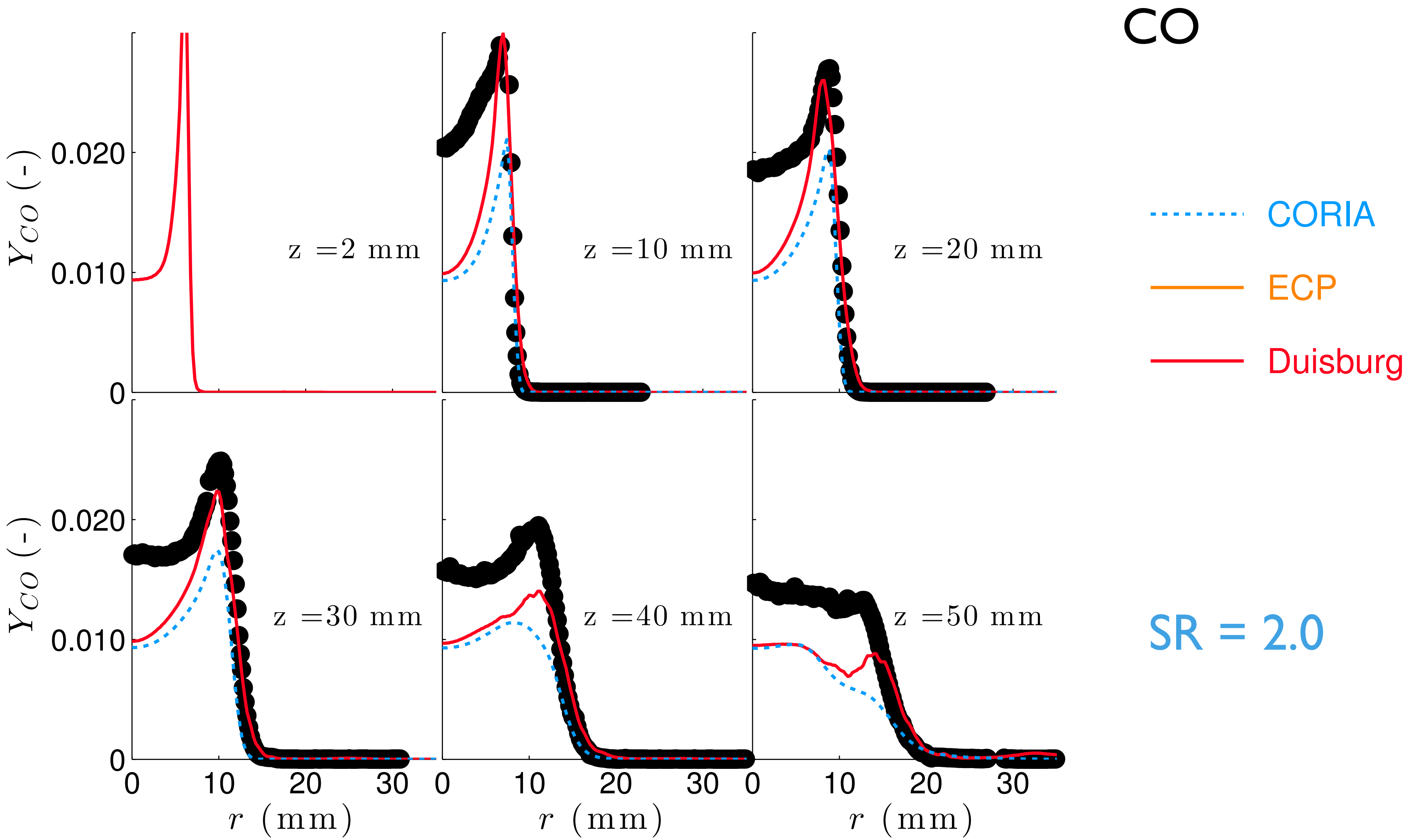
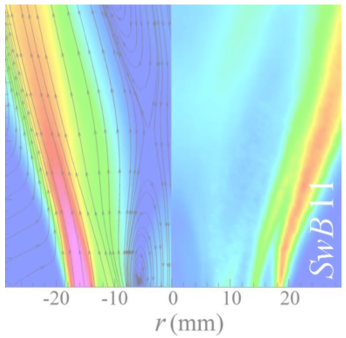
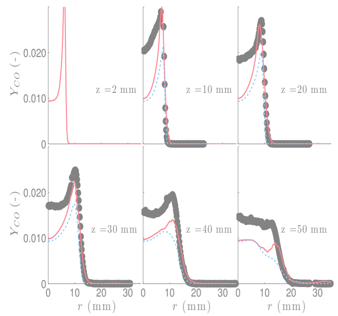


SR = 2.0

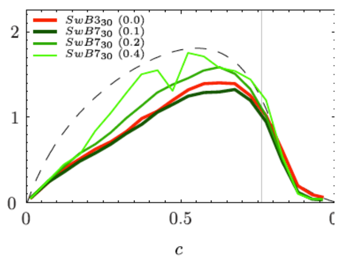
Outline: Effects of Stratification



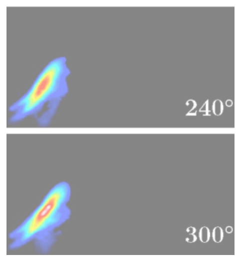
macroscopic



model comparison



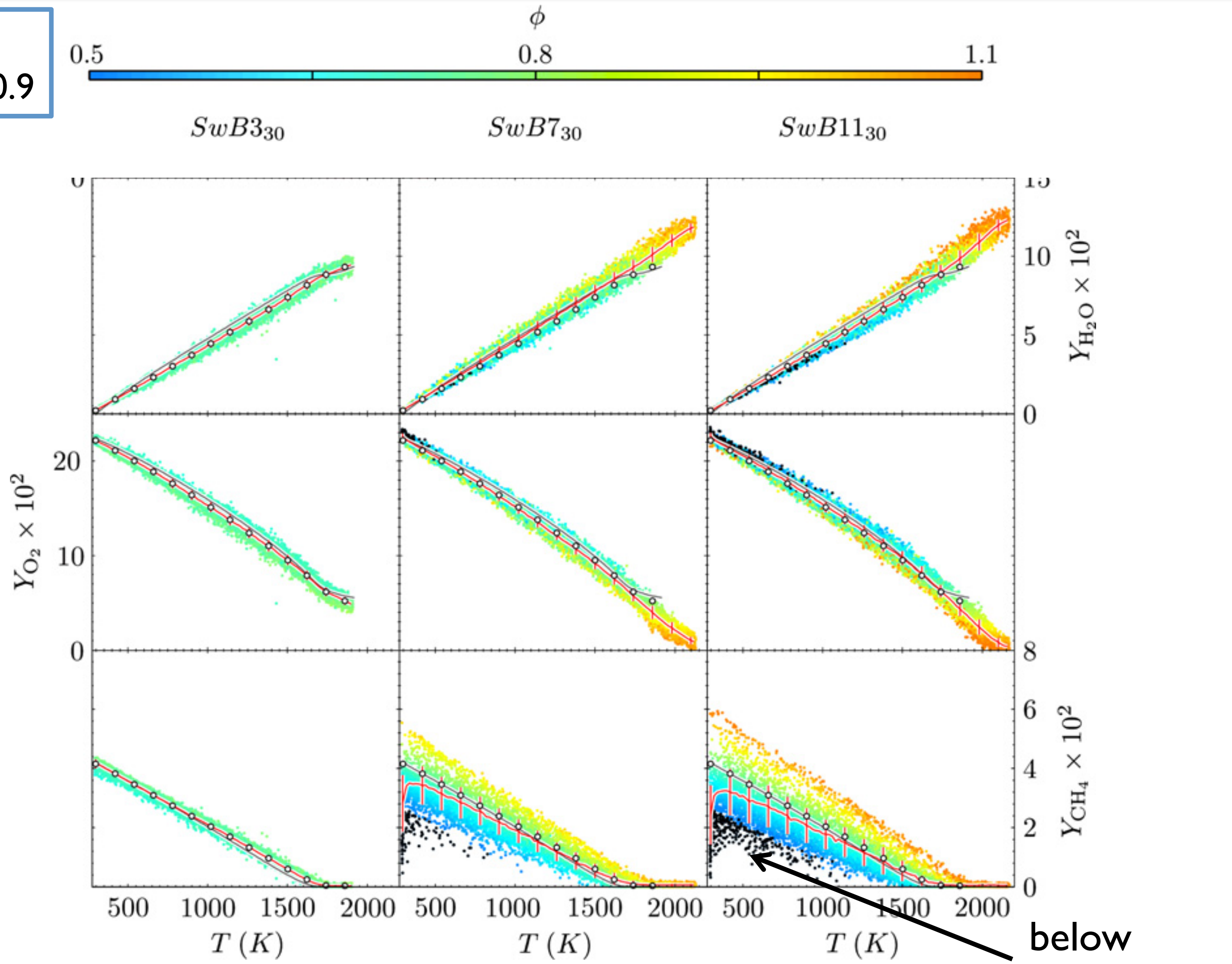
microstructure



instabilities

State space for species profiles: swirl cases

-- : mean
+ LF :0.1<Δϕ/ϕ <0.9



C&F 159 (2012) 2912–2929

State space in species profiles: swirl cases

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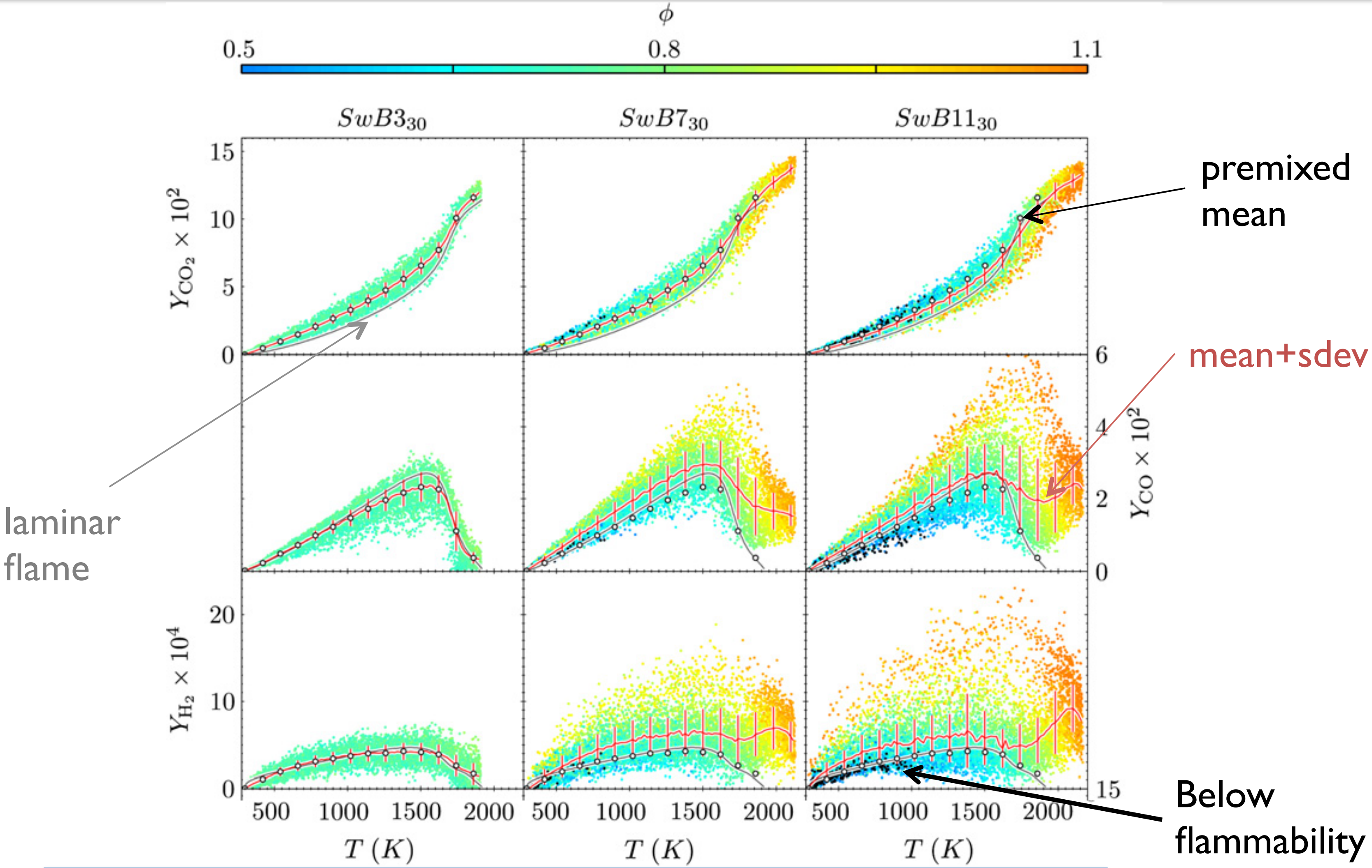
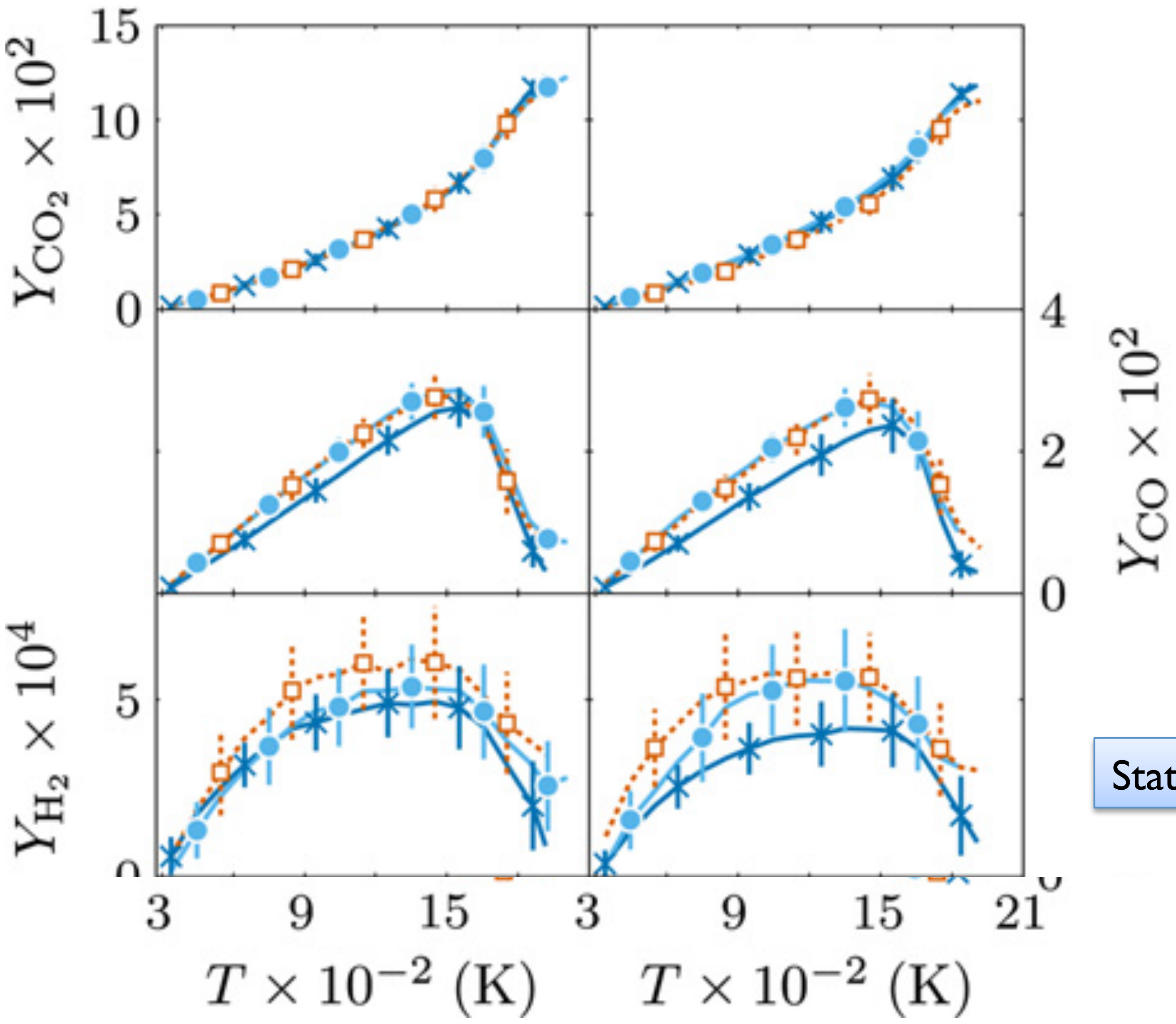


Mean flame structure well captured by laminar unstrained flame
Can we separate the effects of equivalence ratio?

Selected conditioned scalar measurements



All swirl cases
2.5% ϕ = 0.77 (premixed)

State space similar to premixed

C&F 159 (2012) 2912–2929

Microscale: local measures of reactivity: Progress of reaction, SDF and χ

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$$c = \frac{T - T_0}{T_e(\phi) - T_0}$$

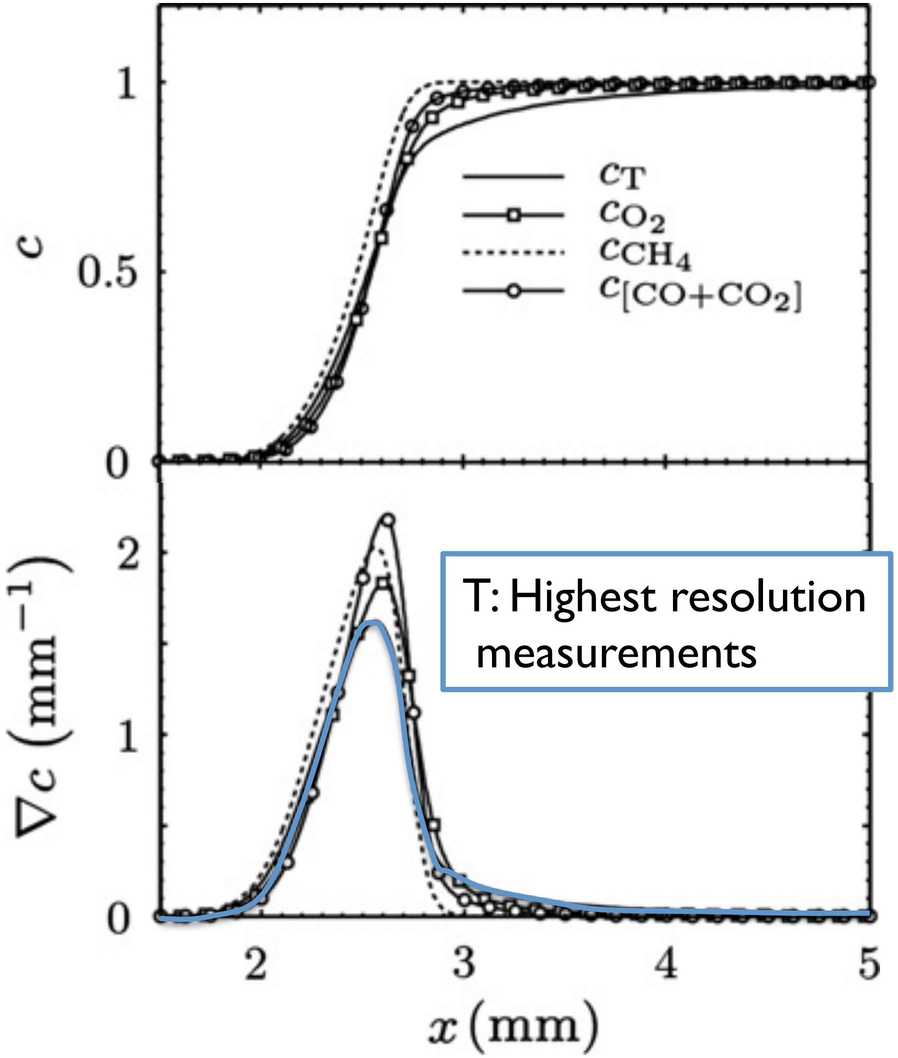
Progress of reaction
(extent of reaction completion)

∇c Surface Density Function
(local flame surface density)

$$\chi = \alpha(T)|\nabla c|^2$$

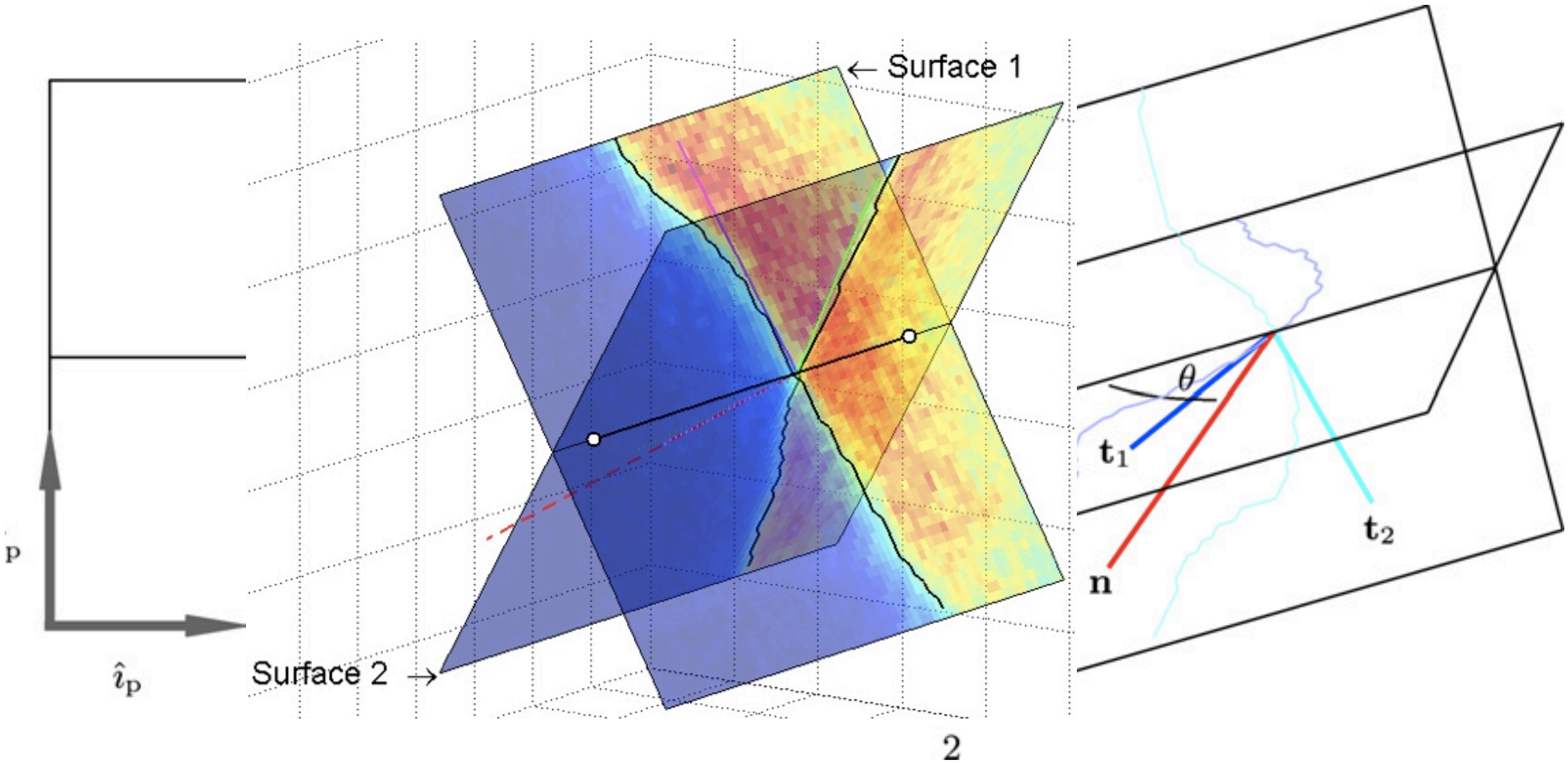
Scalar dissipation
(scales with reaction rate)

Laminar flame calculations



T: Highest resolution measurements

Gradients: two surface OH



SDF and dissipation for all cases

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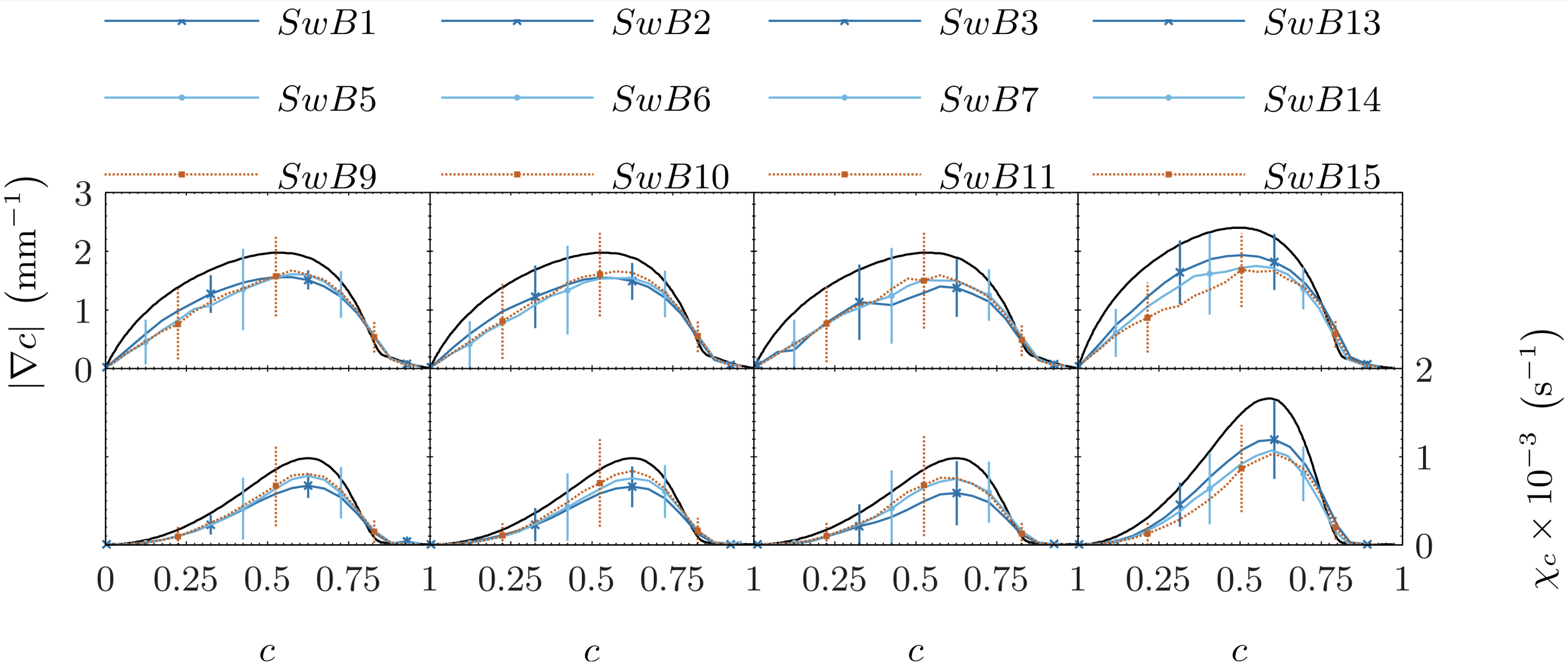

swirl 0%	25%	33%	0%
Conditioned at ϕ=0.79 Bars +/- 2.5% ϕ			ϕ = 1.0

No significant difference between premixed and stratified cases when conditioned for ϕ !

Can we separate by ϕ and its gradient ?

Conditioning ∇c on ϕ and ∇ϕ

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Select large dataset

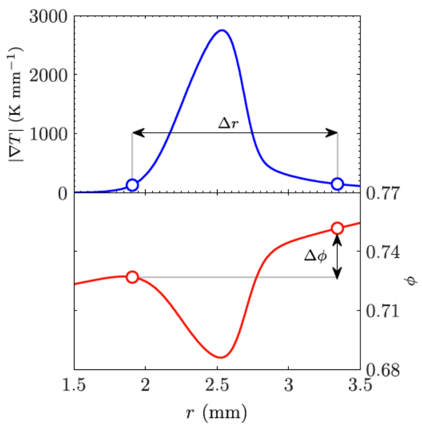
Get away from differential diffusion

De

Ch
rel

Get ϕ and **∇***ϕ* :
- ϕ interpolate between ±0.05 of temperature rise

$$\nabla\phi \approx \frac{\Delta\phi}{\Delta r}\frac{1}{\cos\theta}$$



Conditioned scalars: CO and H2 mean for $<\phi; \nabla\phi | \max(Y_{CO})>$

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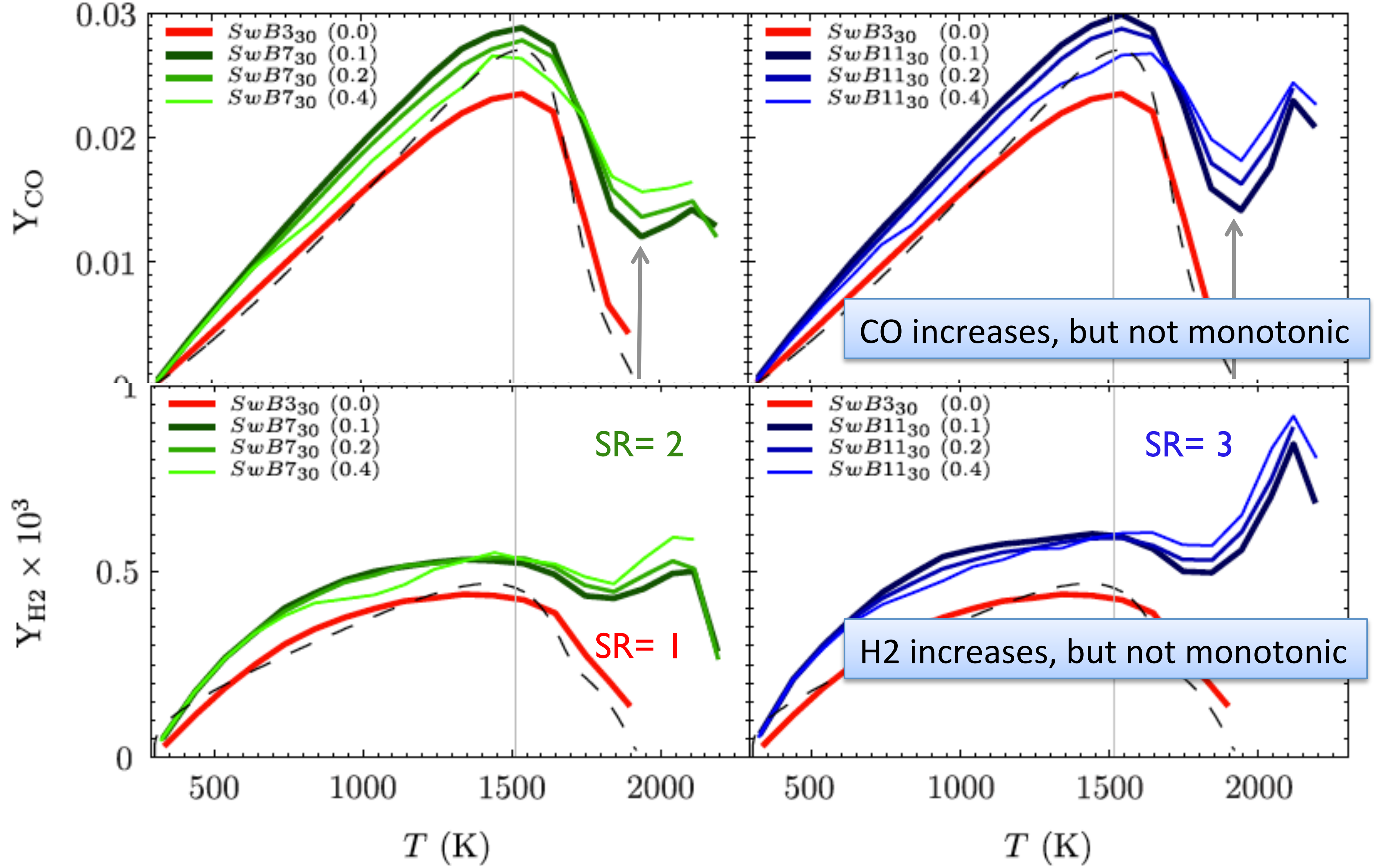

Sweeney et al, C&F 159 (2012) 2896–2911

Conditioned values: mean for <ϕ; $\nabla\phi$|max(Y_{CO})>

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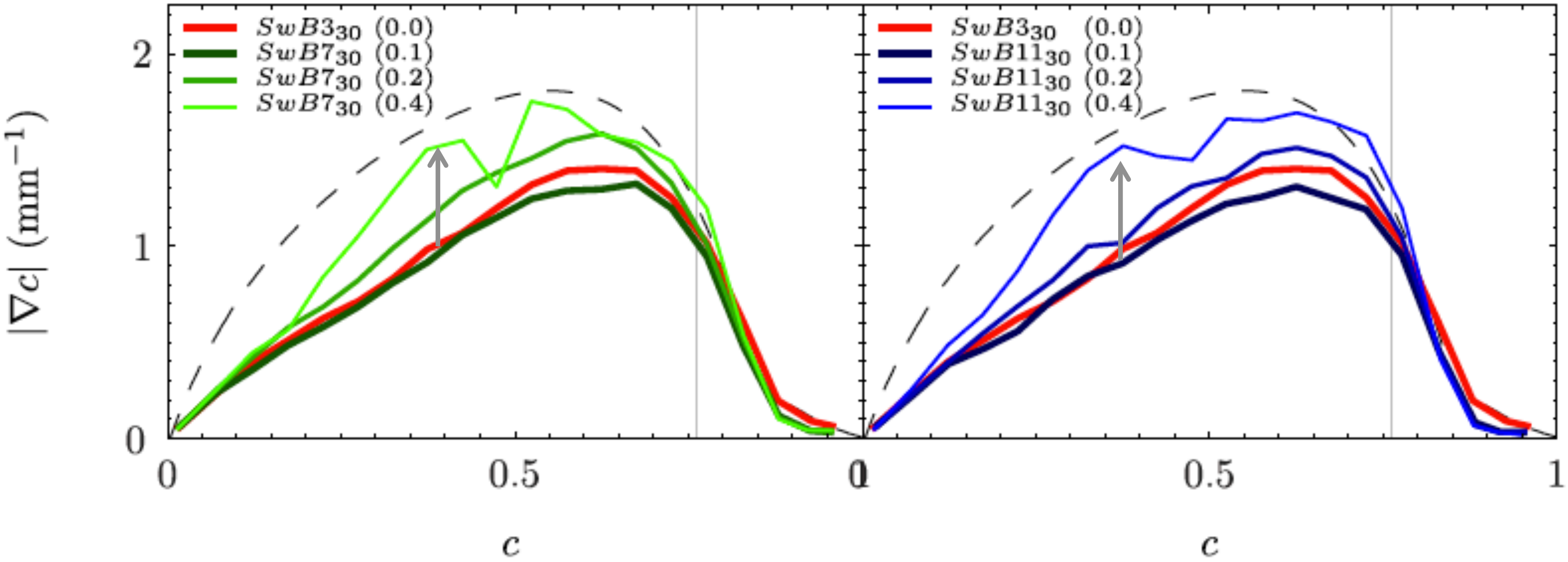
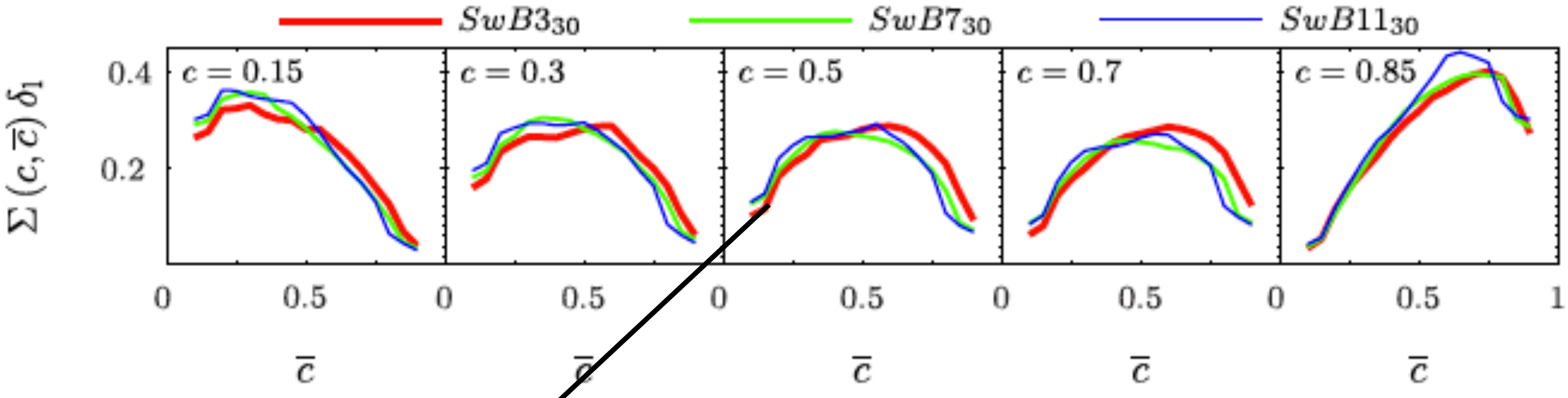


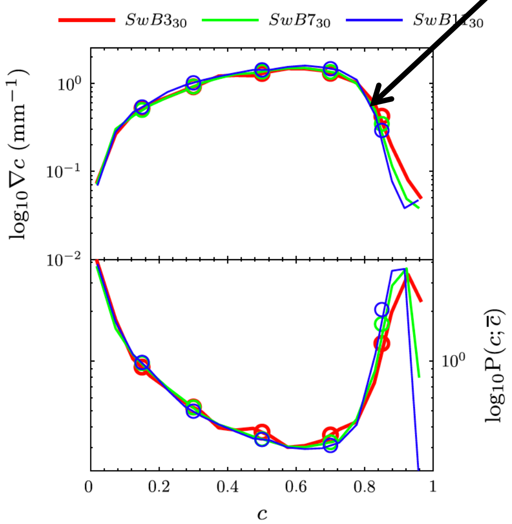
Finally! This shows that indeed, for a given ϕ at peak heat release, local stratification leads to increased gradients (and, indirectly, higher reaction rate) throughout the flame.

Effect is relatively small, and given the reduced number of events with high stratification, explains why it does not affect averages significantly

Sweeney et al, C&F 159 (2012) 2896–2911

Conditioned flame surface density





Flame surface density unchanged:

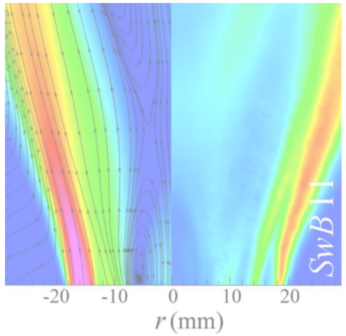
$$\Sigma(c,\bar{c}) = P(c,\bar{c}) < |\nabla c||_c > |_{\bar{c}}$$

decreases

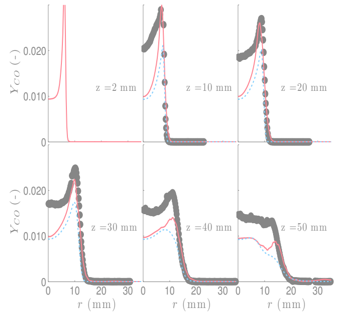
increases

Sweeney et al, C&F 159 (2012) 2896–2911

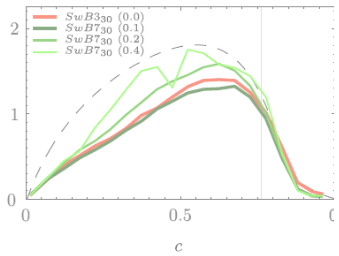
Outline: Effects of Stratification



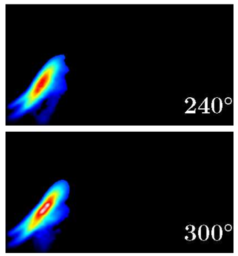
macroscopic



model comparison



microstructure



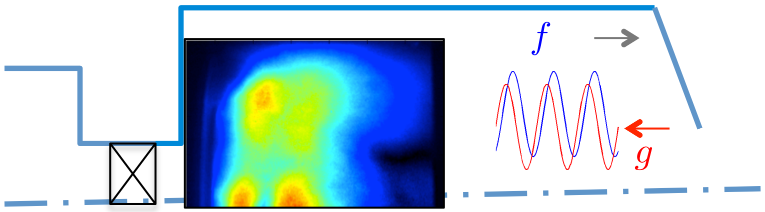
instabilities

Combustion instabilities

$$\frac{1}{p}\frac{\partial^2 p'}{\partial t^2} - \nabla \cdot \left(\frac{c^2}{p}\nabla p'\right) = (\gamma - 1)\frac{q}{p}\frac{D}{Dt}\frac{q'}{q}$$

wave propagation

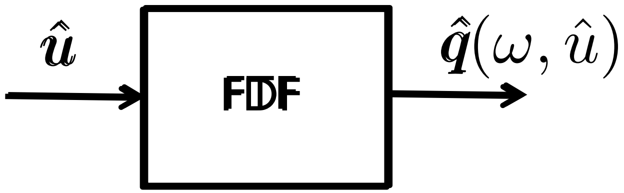
heat release rate per volume



$$F(\omega; \hat{u}/U) = \frac{\hat{q}/q}{\hat{u}/U} = G e^{-i\phi}$$

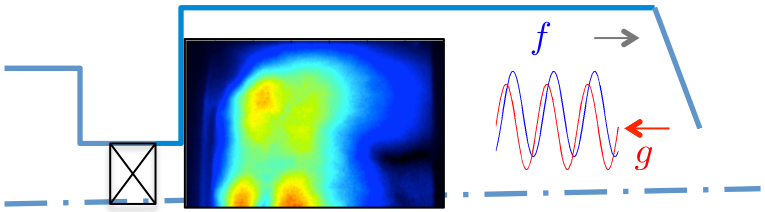
$G(\omega, \hat{u})$

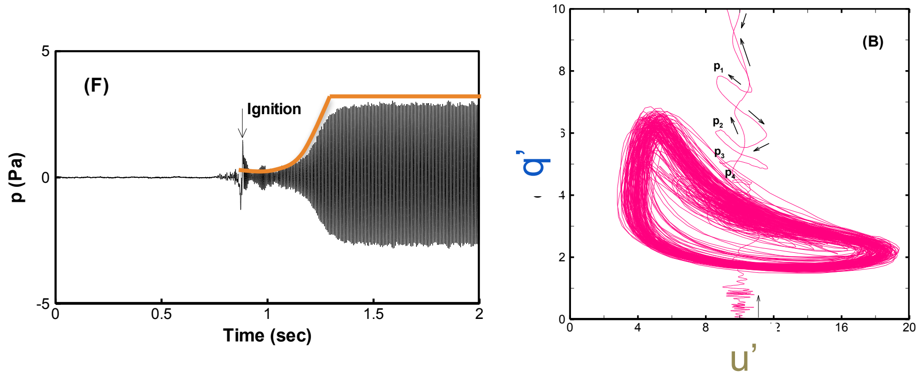
$\phi(\omega, \hat{u})$



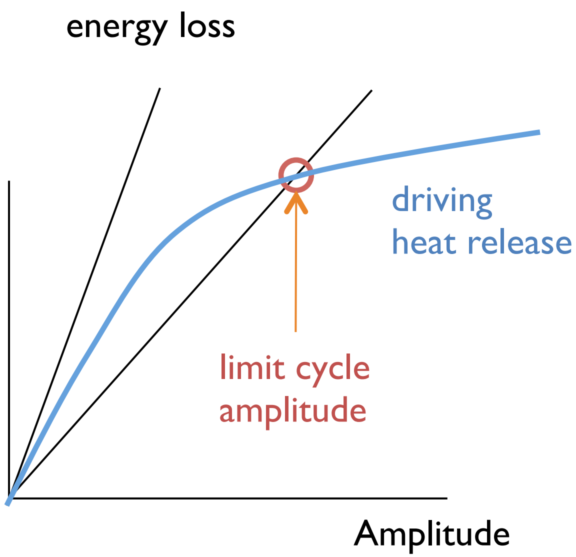
L. Crocco J. American Rocket Society 21: 163-178, 1951
L. Crocco J. American Rocket Society 22: 7-16, 1952.
N. Noiray J. Fluid Mech, 615: 139-167, 2008
A.P. Dowling J. Fluid Mech. 346:271-290, 1997

Limit cycle – the simple view





Kim & Hochgreb, Comb. Flame 159 (2012)



Self-excited periodic oscillations:

- Net result of matching possible *system* modes to existing excitation
- Limit-cycle = matching point (A,f)

Noiray et al. J. Fluid Mech, 615 (2008)

Dowling. J. Fluid Mech. 346 (1997)

Mean reacting flow fields – CERFACS simulaton

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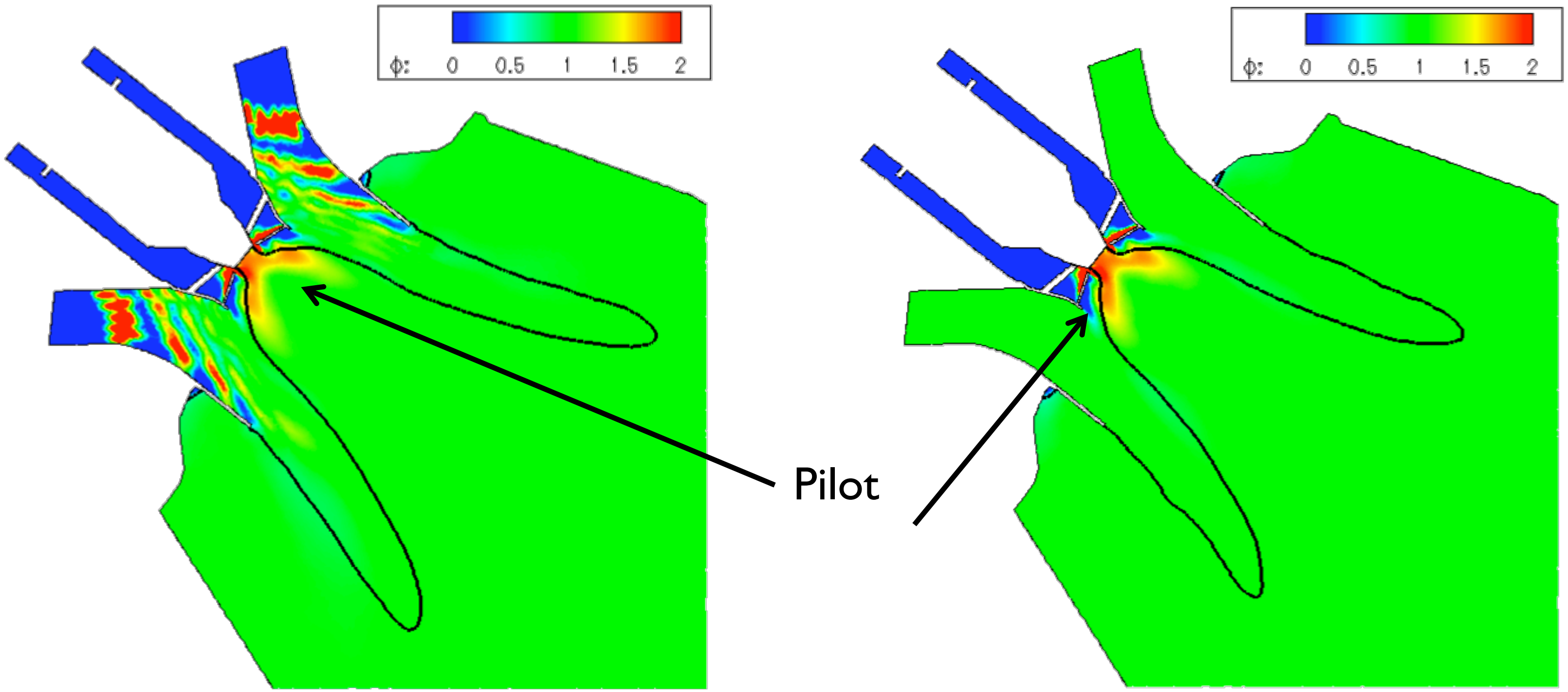
TECH

- Mixture heterogeneities in diagonal swirler
- Quasi-uniform mixture reaches the flame front

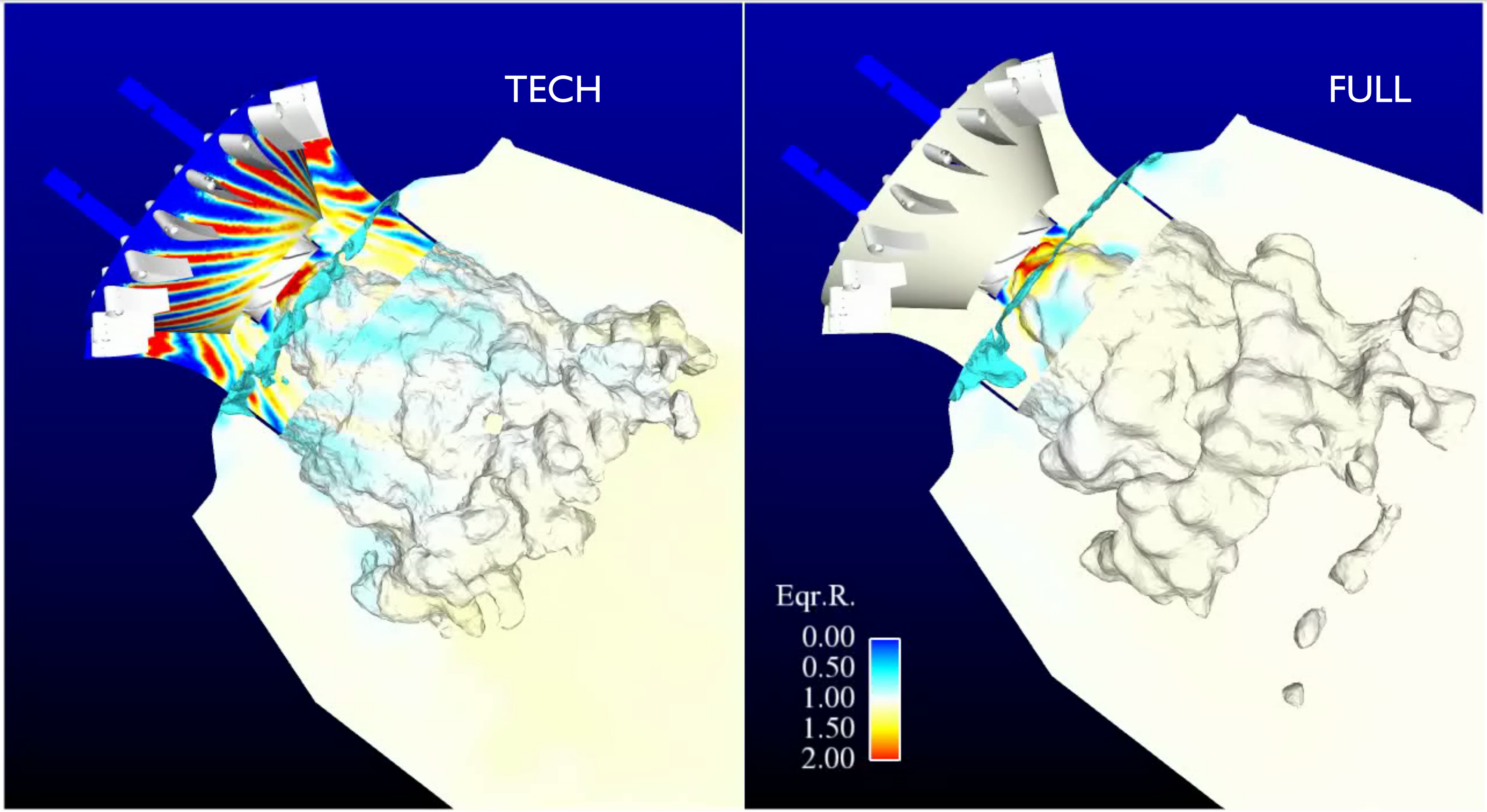
FULL

- Uniform mixture in diagonal swirler
- Similar flame



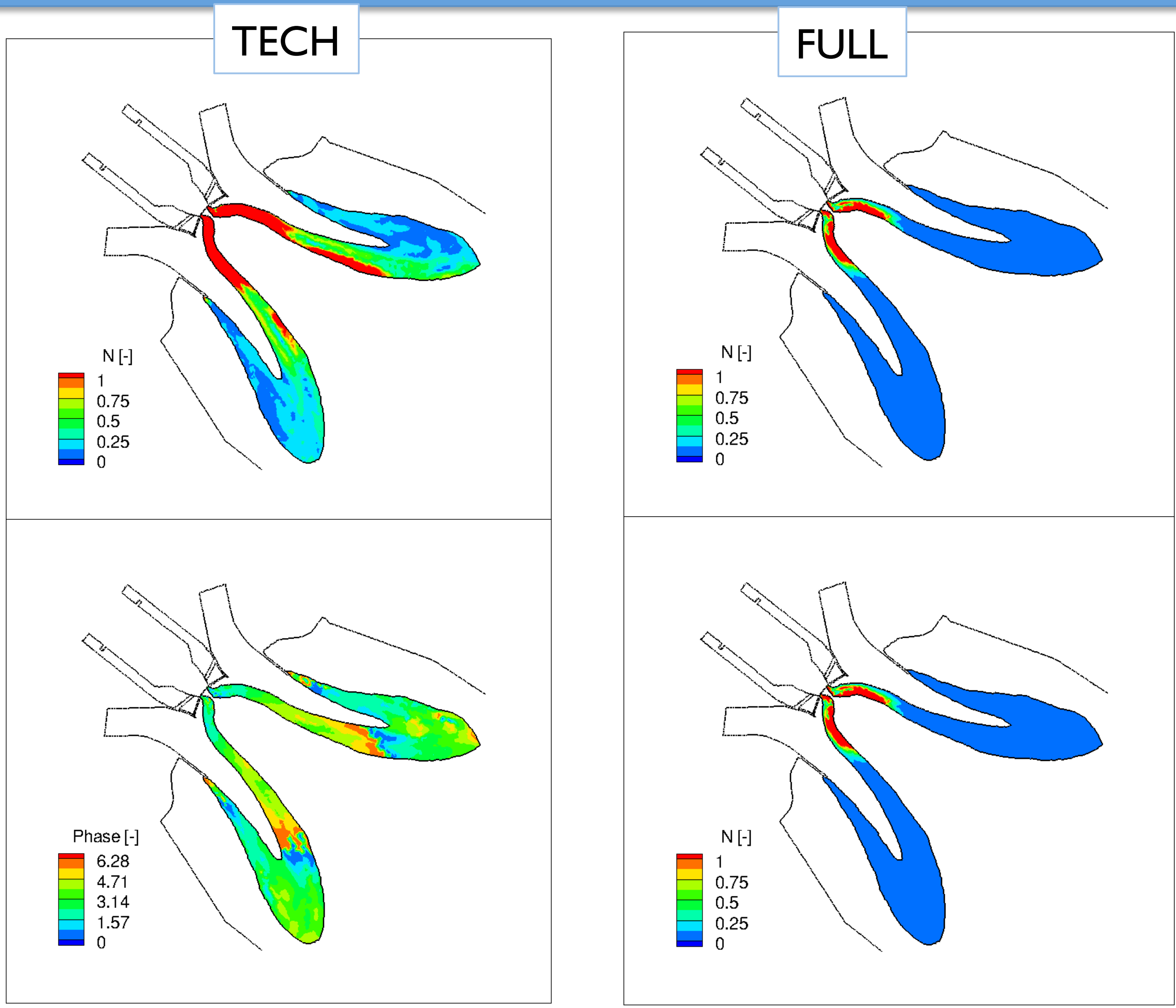
Hermeth et al., PCI 34 (2013) 3165

Equivalence ratio fluctuations



Hermeth et al., PCI 34 (2013) 3165

Local Flame Transfer Function

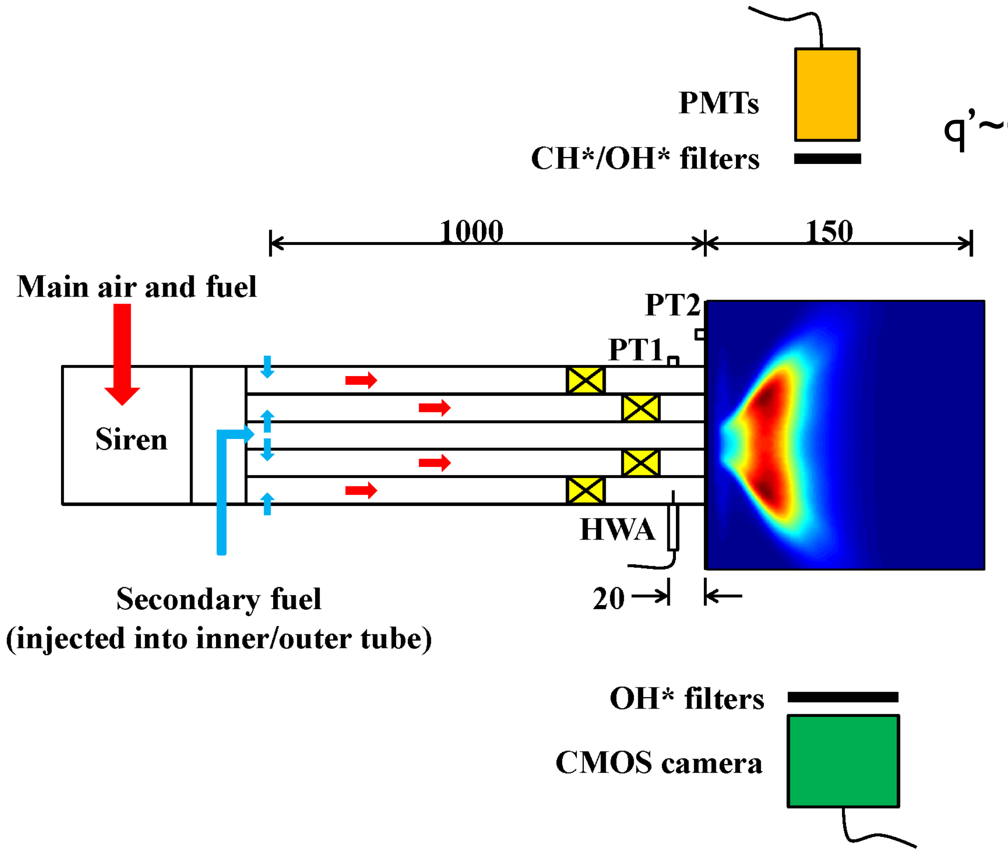


Gain

Phase

Hermeth et al., PCI 34 (2013) 3165

Model Stratified Swirl Burner
Co-annular swirl passages

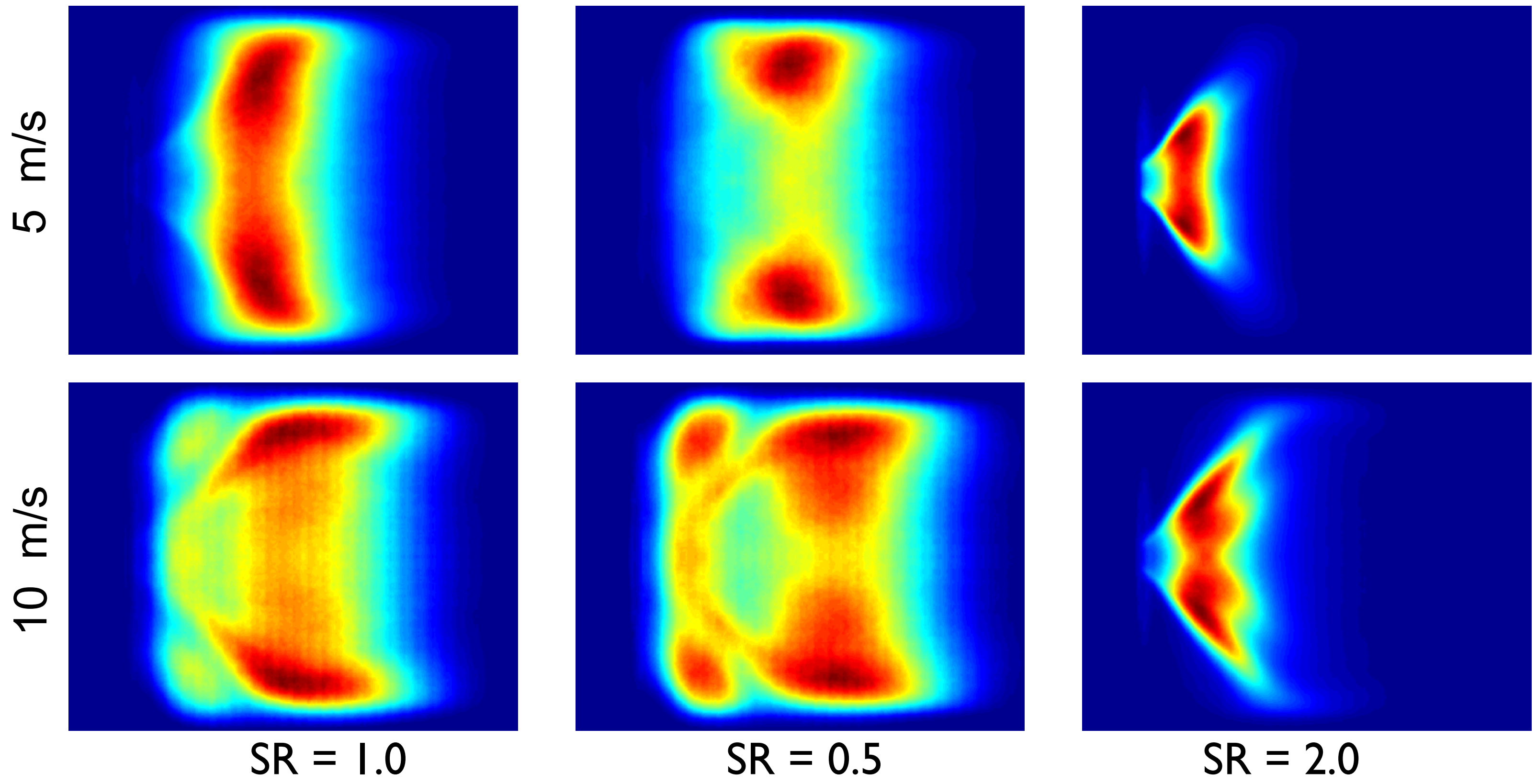


q'~OH*'

Mean ϕ (-)	0.60, 0.70, 0.80
Mean U (m/s)	5,10
SR (-)	1.0,2.0,3.0
Forcing f (Hz)	60-400

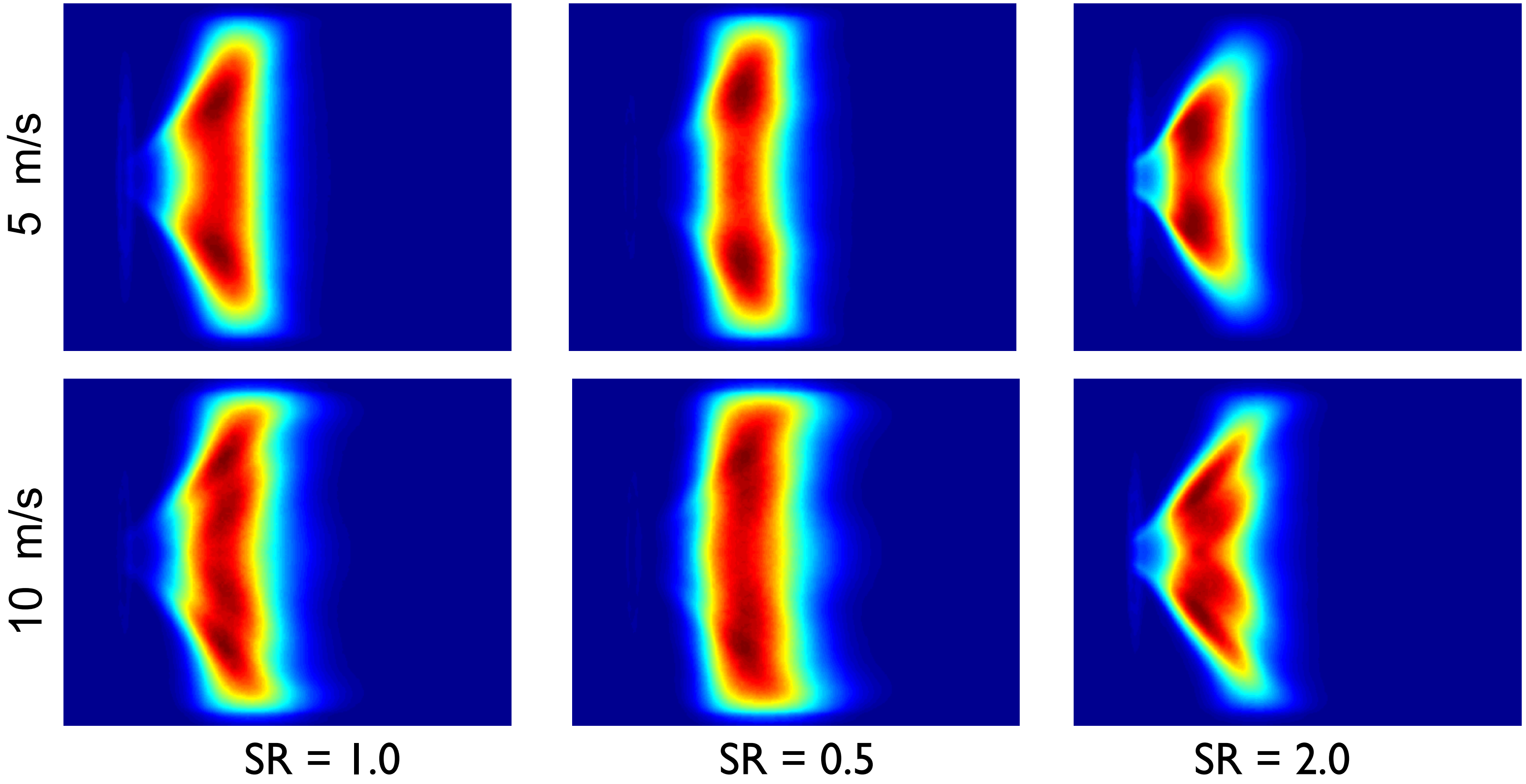
Kim & Hochgreb, C&F 2011a,b, CST 2011
Han & Hochgreb, ECM 2013

Mean Flame OH* - $\Phi_g = 0.60$



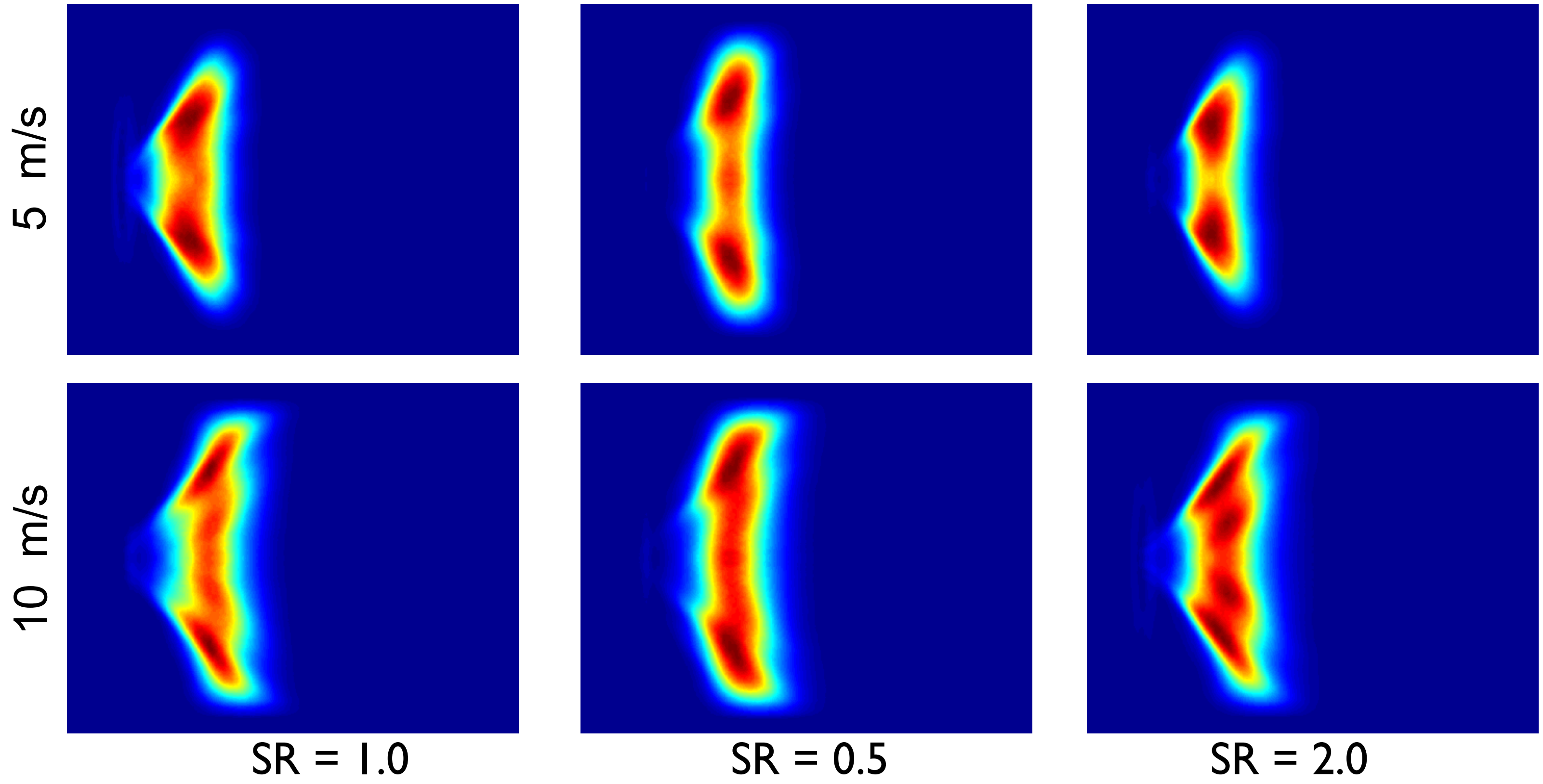
Han & Hochgreb, ECM 2013

Mean Flame OH* - Φ_g = 0.70



Han & Hochgreb, ECM 2013

Mean Flame OH* - $\Phi_g = 0.80$



Han & Hochgreb, ECM 2013

Flame Transfer Function Gain

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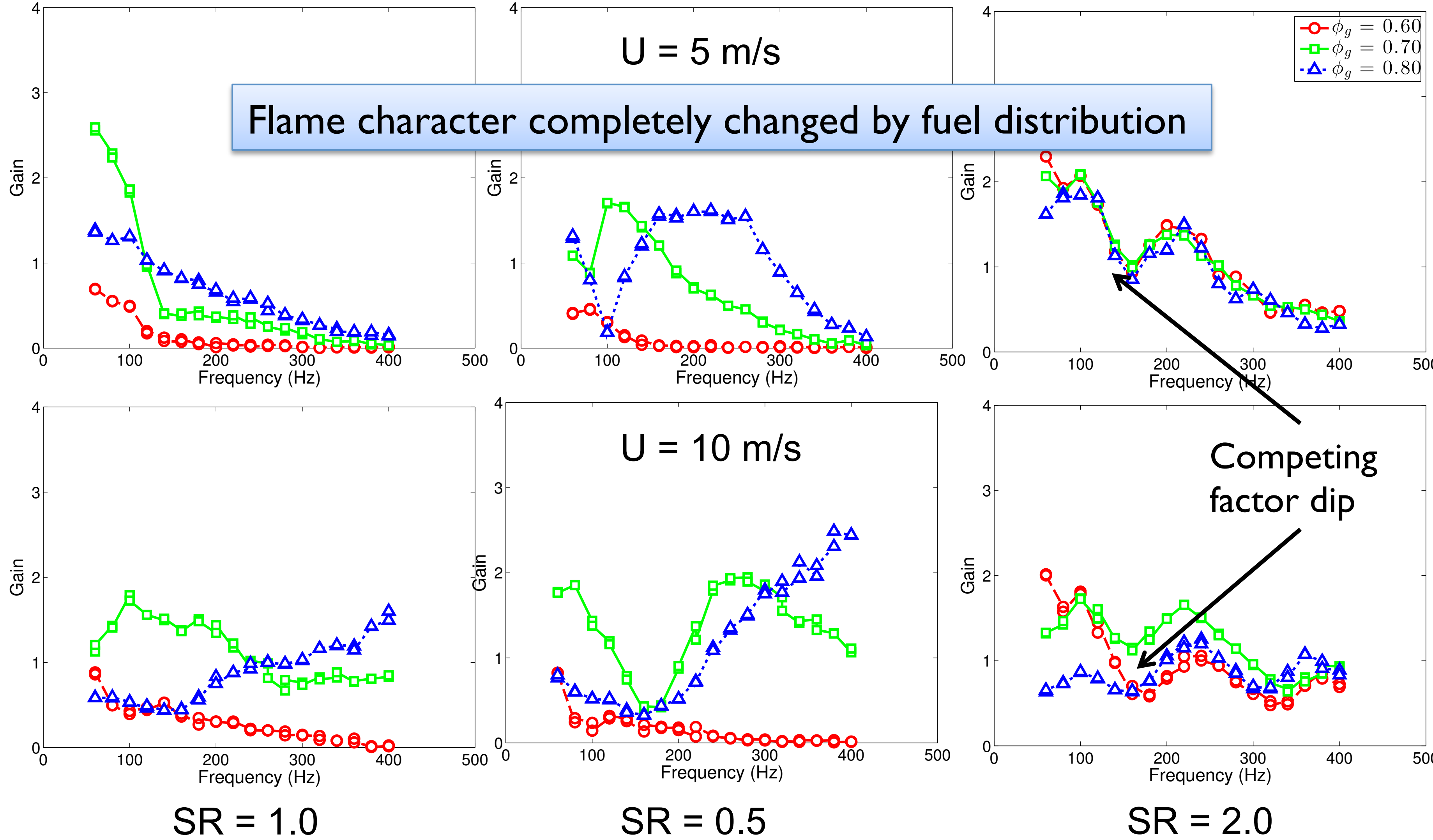
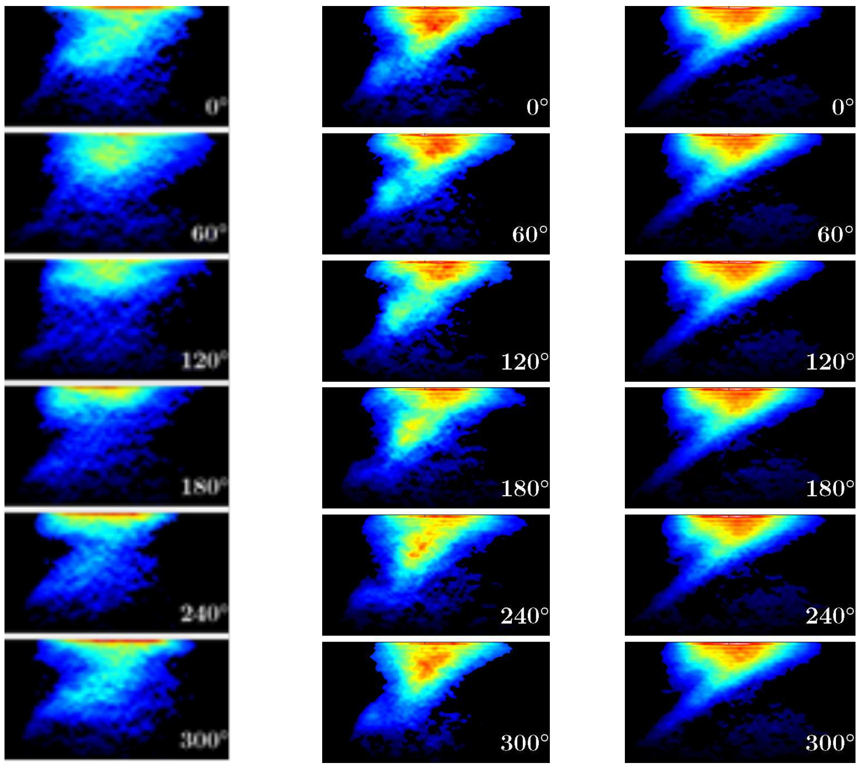


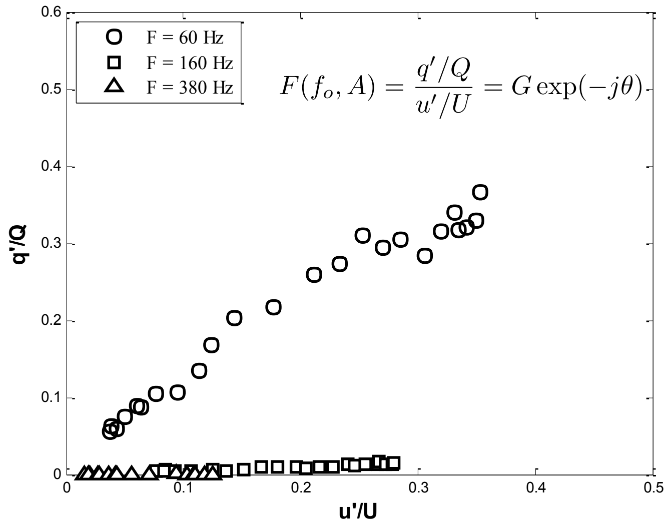
Han & Hochgreb, ECM 2013

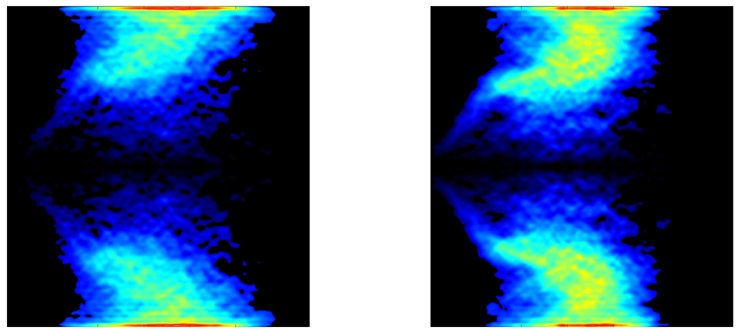
Flame behaviour - premixed

- Φ_g = 0.60, U = 5 m/s, SR = 1.0
  f_0 = 60, 160 and 380 Hz



(a) f_0 = 60 Hz (b) f_0 = 160 Hz (c) f_0 = 380 Hz



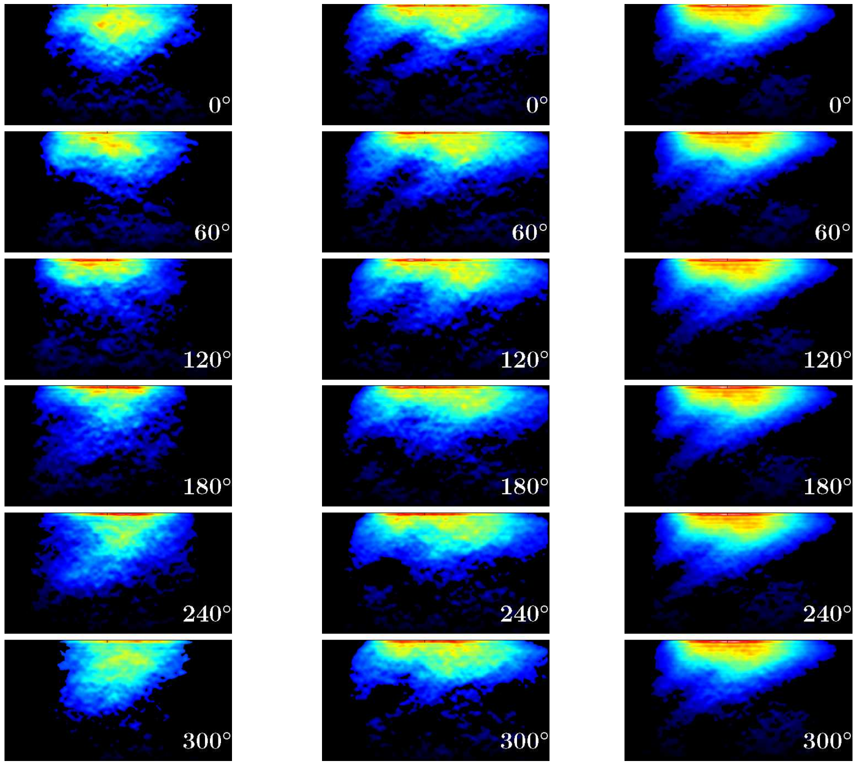


(1) u'/U= 0.1 (2) u'/U= 0.2
f_0 = 60 Hz

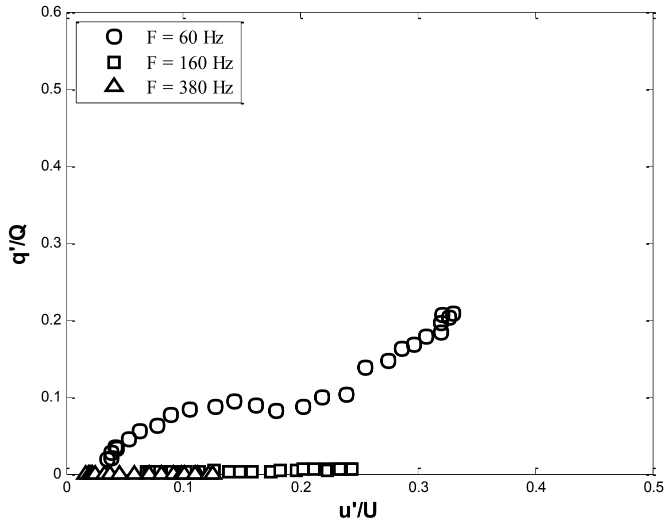
Han & Hochgreb, ECM 2013

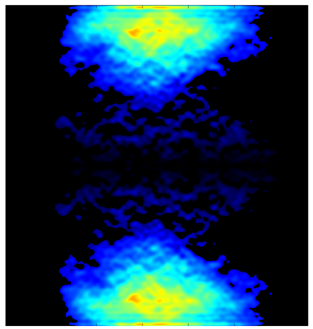
Flame behaviour – SR = 0.5

- Φ_g = 0.60, U = 5 m/s, SR = 0.5
  f_0 = 60, 160 and 380 Hz

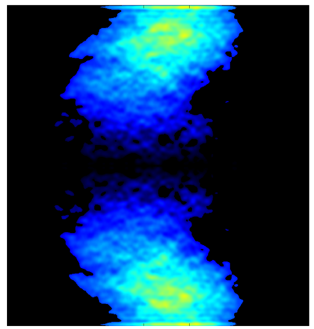


(a) f_0 = 60 Hz (b) f_0 = 160 Hz (c) f_0 = 380 Hz





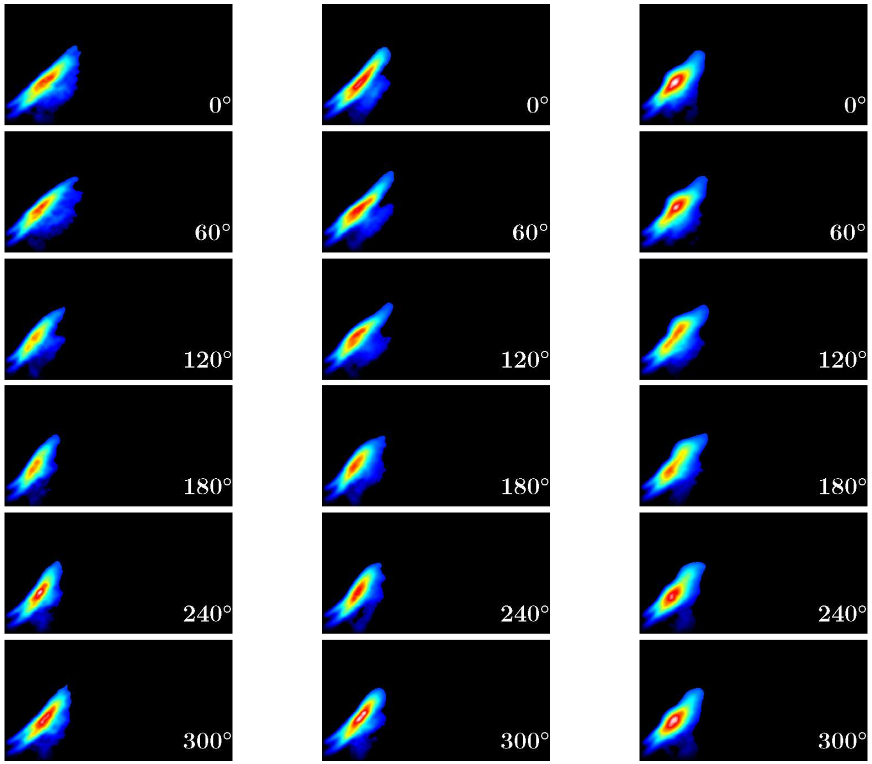
(1) u'/U= 0.1
f_0 = 60 Hz



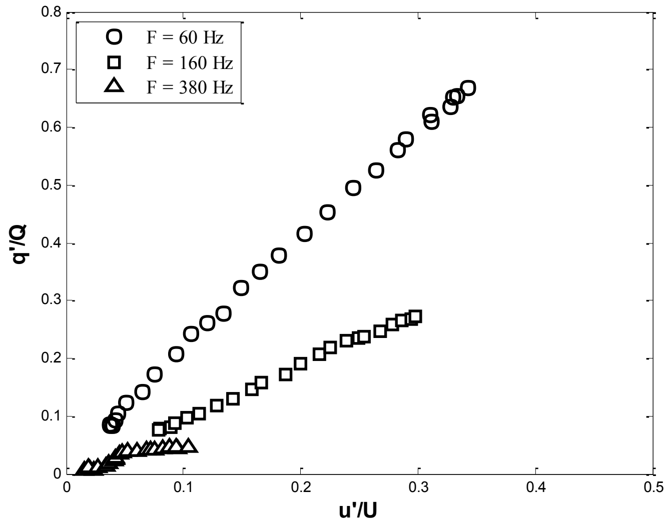
(2) u'/U= 0.2

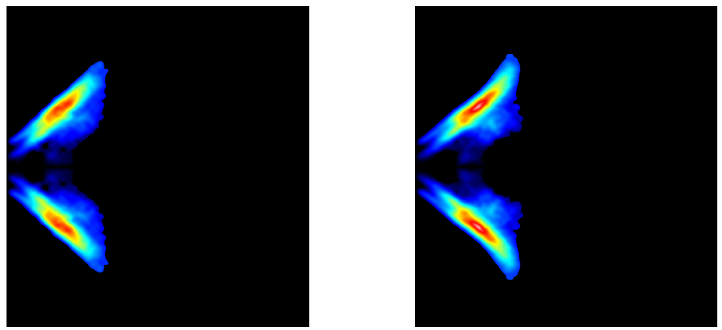
Flame behaviour – SR = 2.0

- $\Phi_g = 0.60$, U = 5 m/s, SR = 2.0
  f_0 = 60, 160 and 380 Hz



(a) f_0 = 60 Hz (b) f_0 = 160 Hz (c) f_0 = 380 Hz





(1) u'/U= 0.1 (2) u'/U= 0.2
f_0 = 60 Hz

Summary

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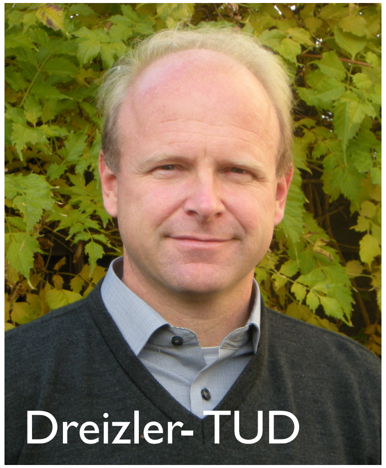
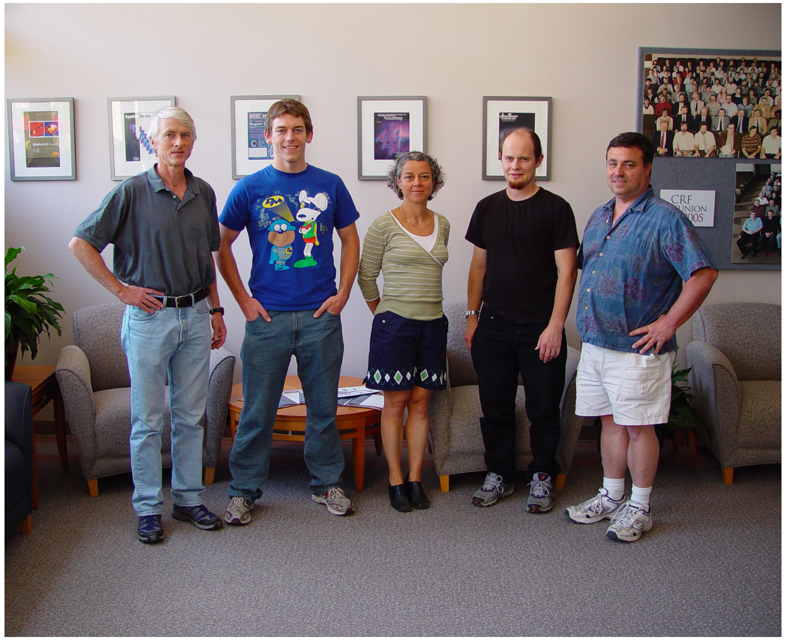
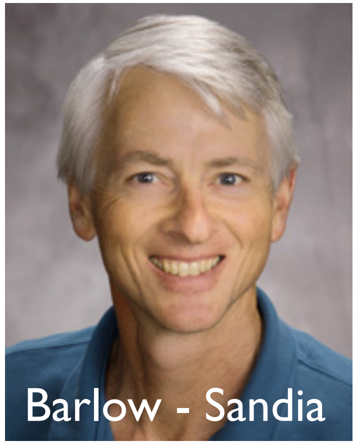
- Effects of fuel distribution on turbulent flame behaviour
  - Macrostructure – large effect, interaction with swirl
  - Microstructure – local stratification *does* affect scalars – should models incorporate the effect?
  - What about NOx and CO?
- Effects of fuel distribution on combustion instabilities
  - Location, timing of heat release
  - Sensitivity to acoustic perturbations
  - Small changes, big effects

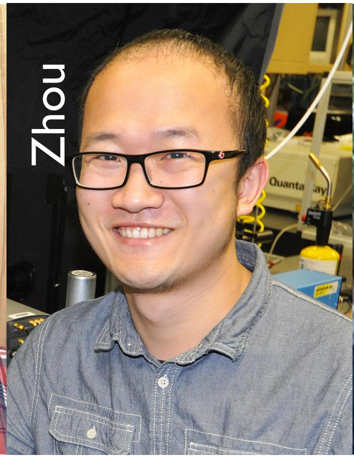
✓ Increased complexity, but great opportunities

Collaborators









Collaborators – LES Models

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