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Tackling Combustor Design Problems with Large Eddy Simulation of Reacting Flows

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AG Turbo, Alstom, DFG, DST, KW21, Siemens

Overview

Gas turbine combustor design challenges

- stability
- emissions

This talk

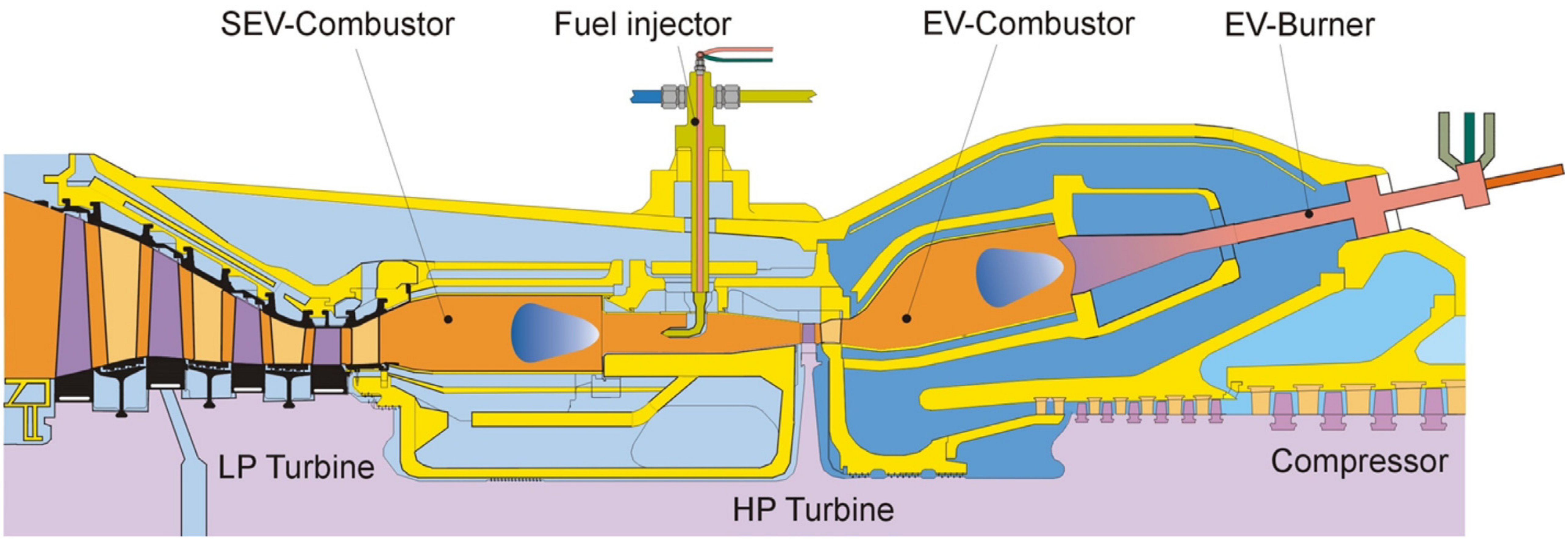
- mixing and auto-ignition in turbulent flow
- flame dynamics from system identification
- spray dispersion, evaporation & combustion

reacting flow

control & optimization,
code coupling

multi-physis, multi-scale

Sequential combustion in Alstom GT24/26

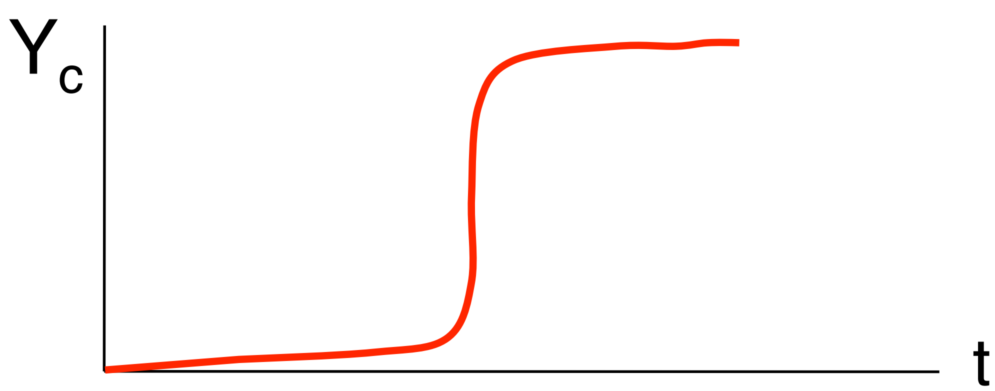


multi-stream mixing in swirling, turbulent flow

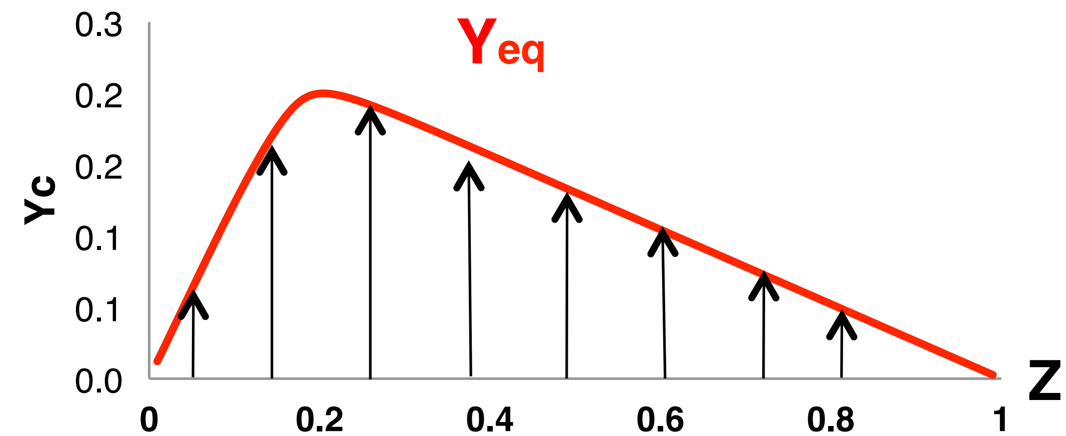
auto-ignition & flame propagation

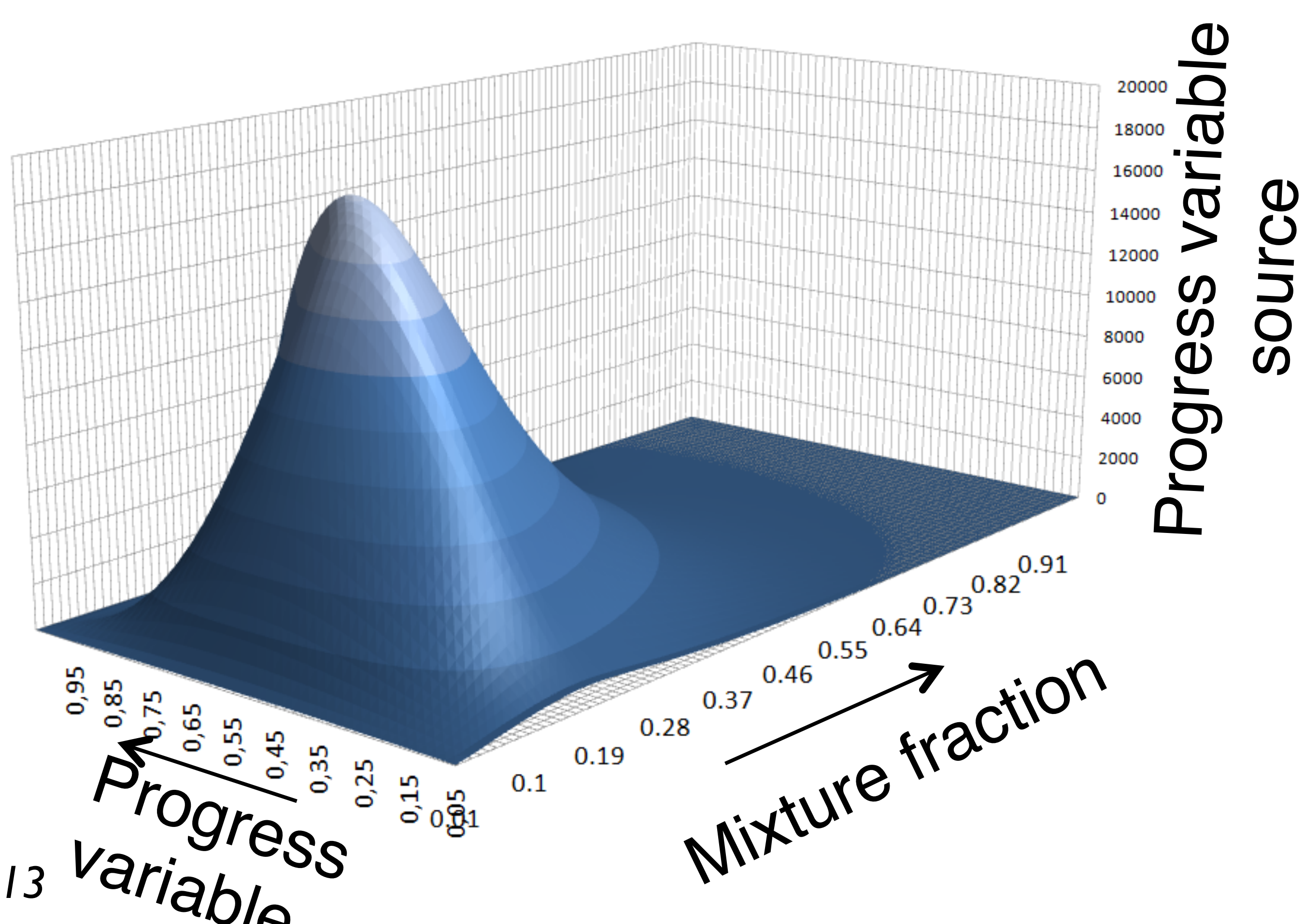
Composite PV lookup from PSRs

$Y_c = Y_{\text{intermediate}} + Y_{\text{product}}$

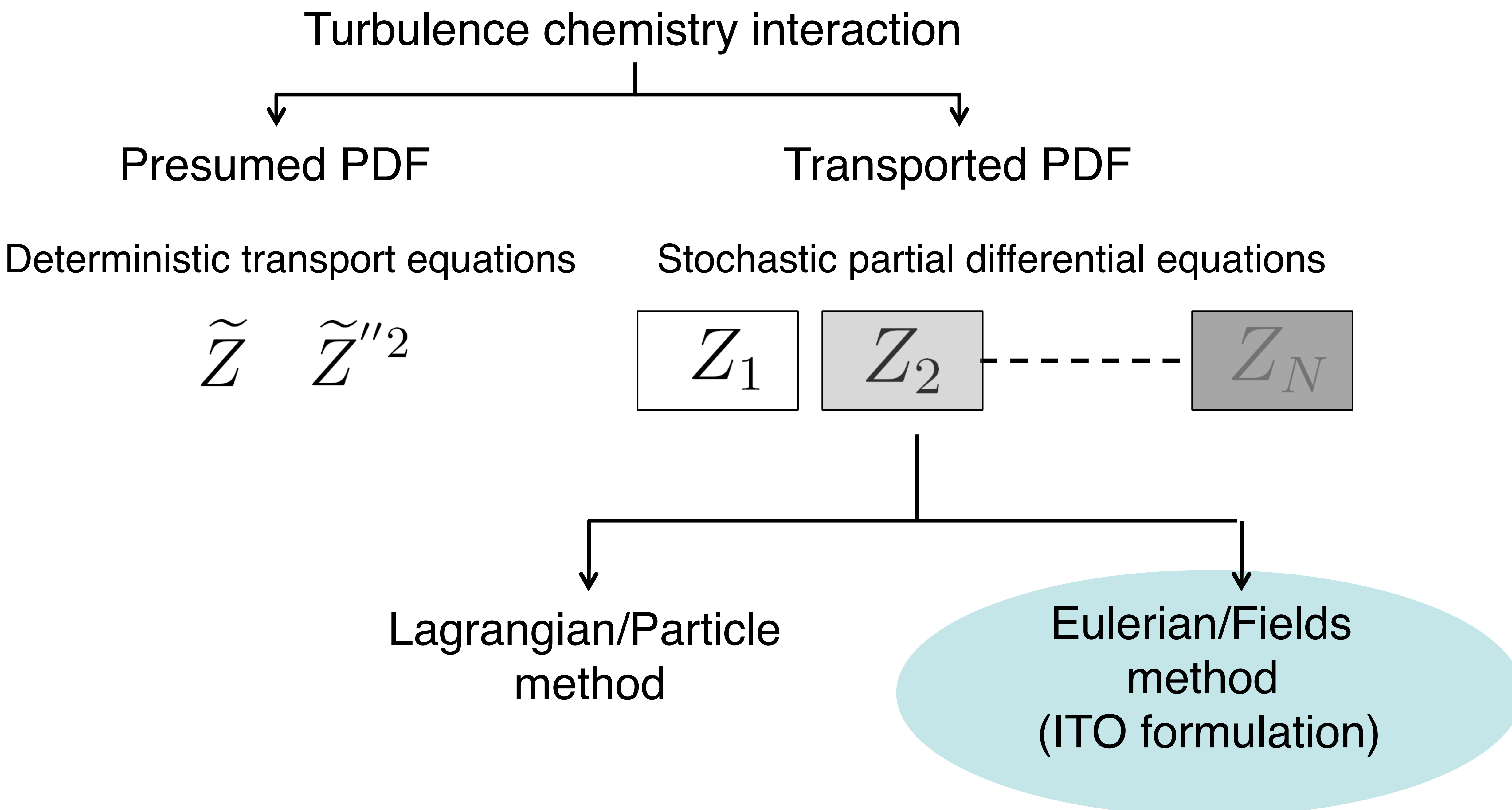


Rate of reaction progress from PSRs

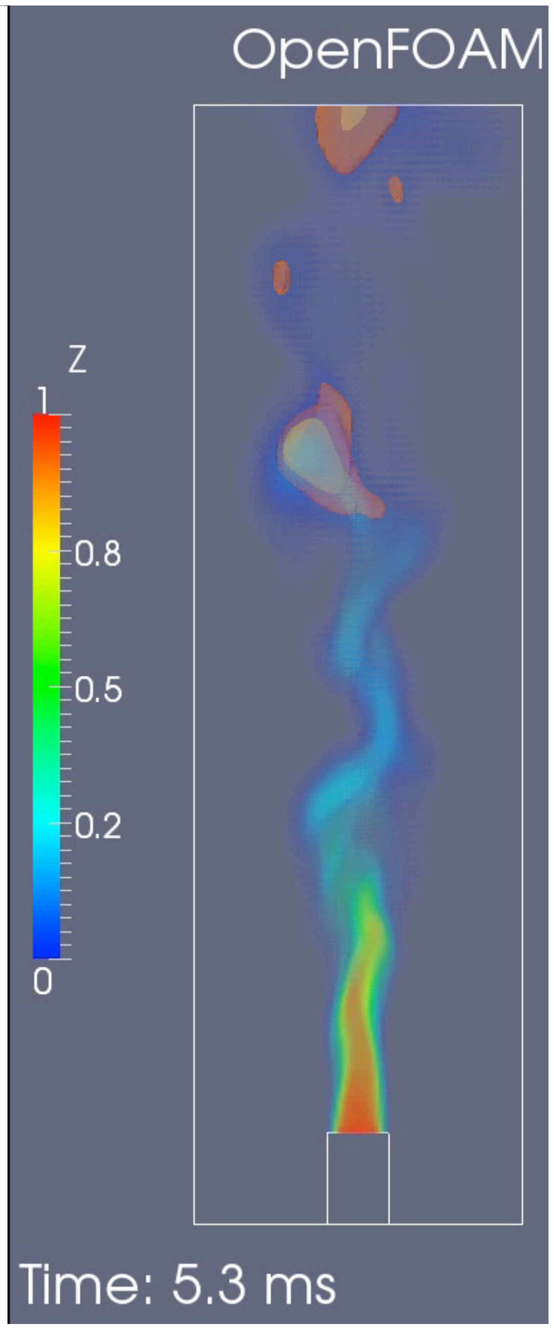




Stochastic fields for subgrid scale fluctuations



Stochastic fields, composite progress variable

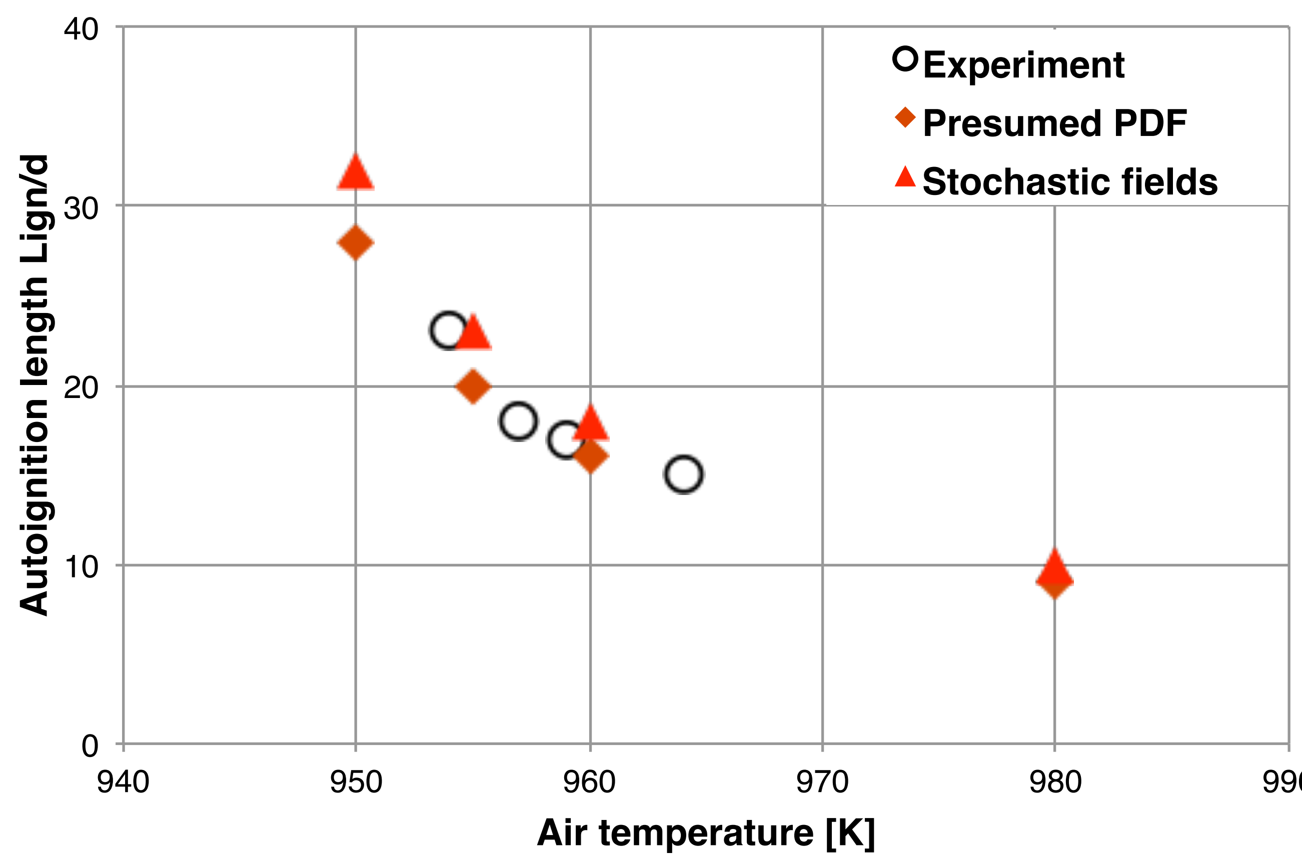


Implemented in Fluent and OpenFOAM

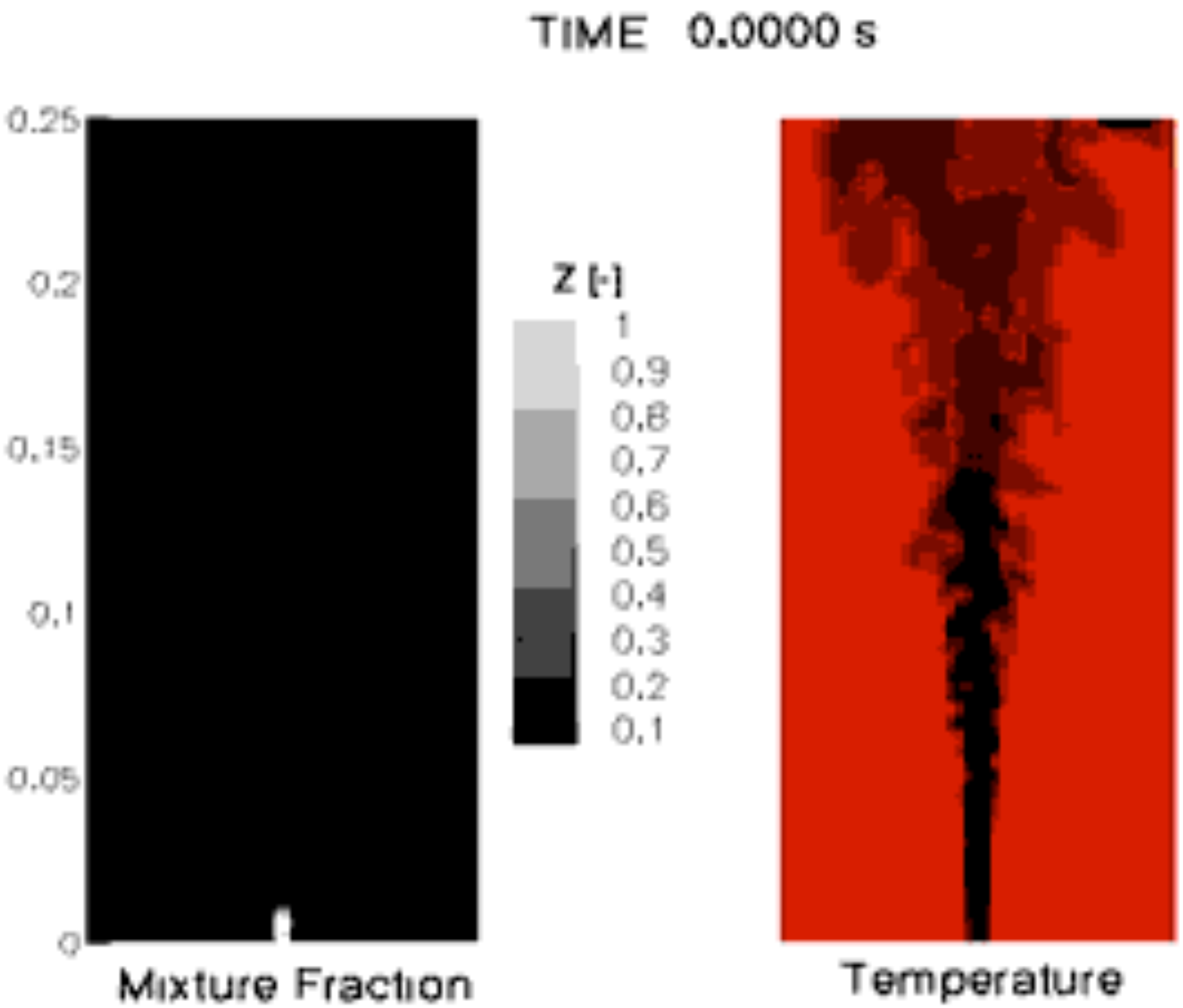
Validation:

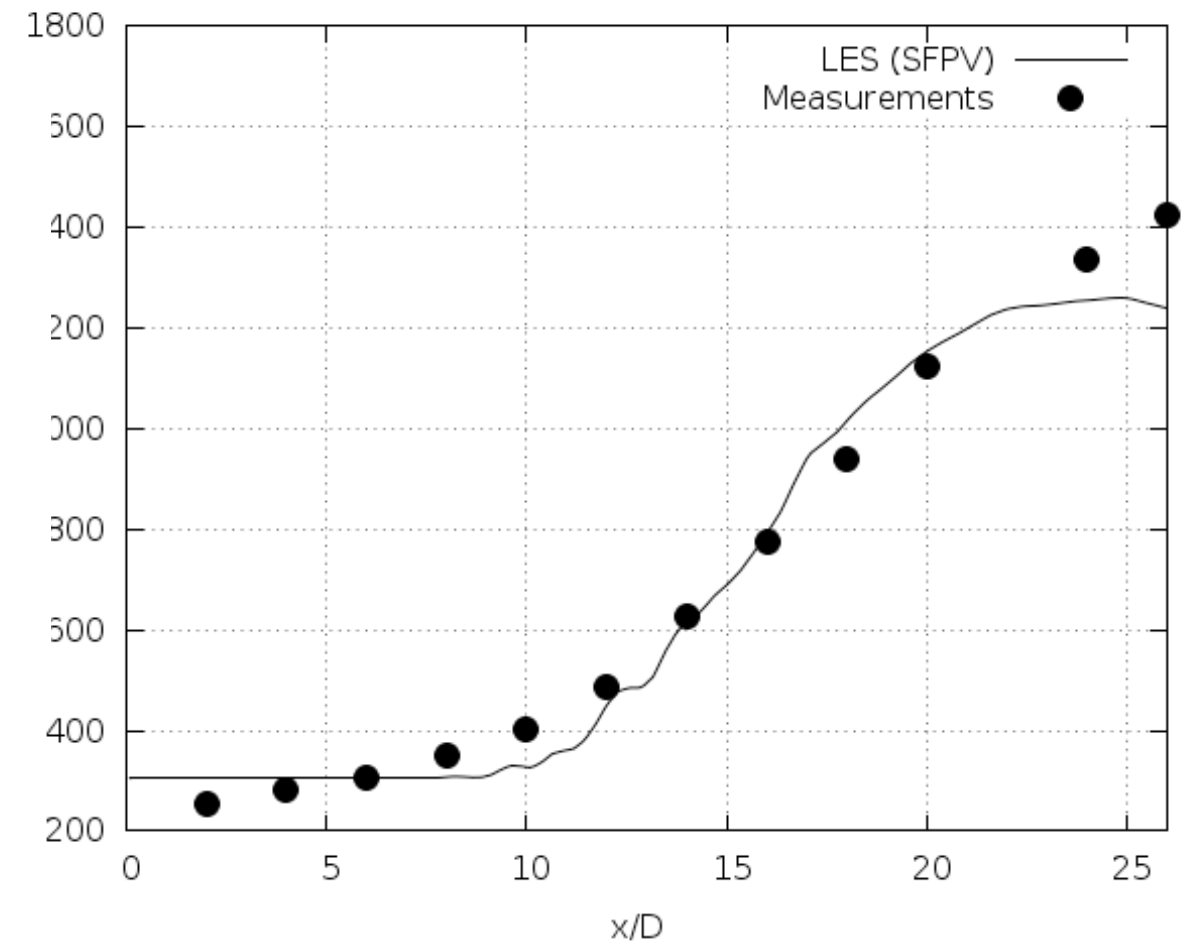
Markides & Mastorakos, Cabra, Delft, SEV

H2, n-Heptane, CH4



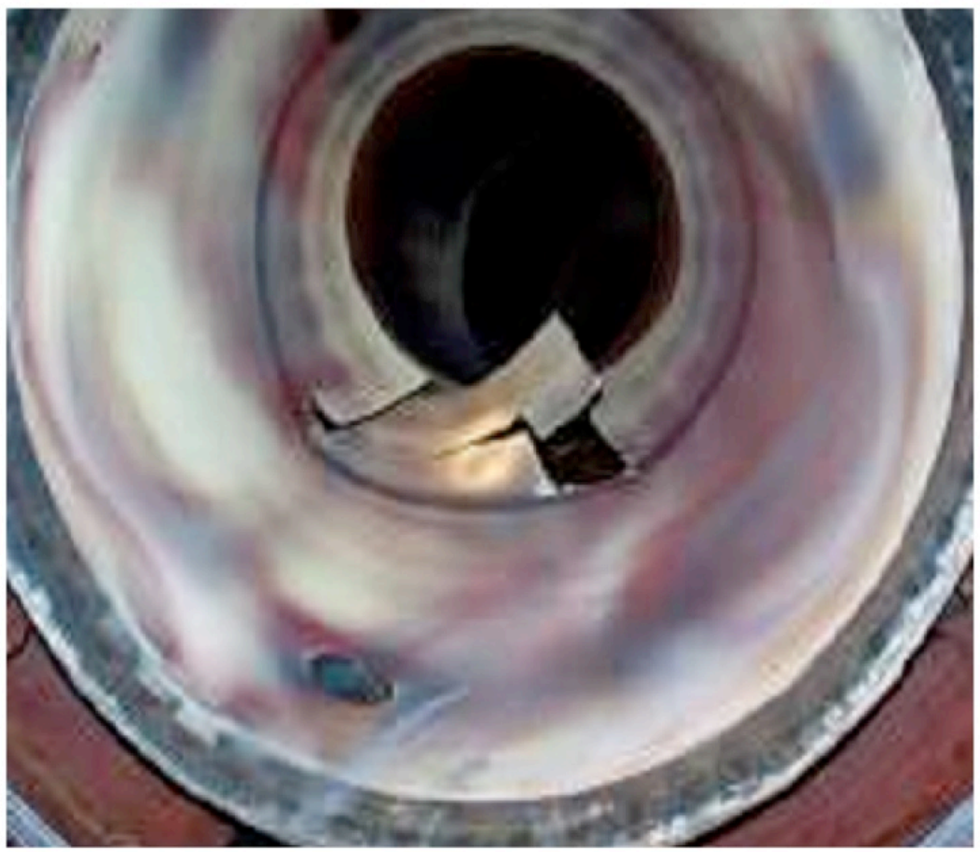
Cabra-H2-Flame with Li-Dryer mechanism





see papers by Kulkarni, Zellhuber, Collonval ...

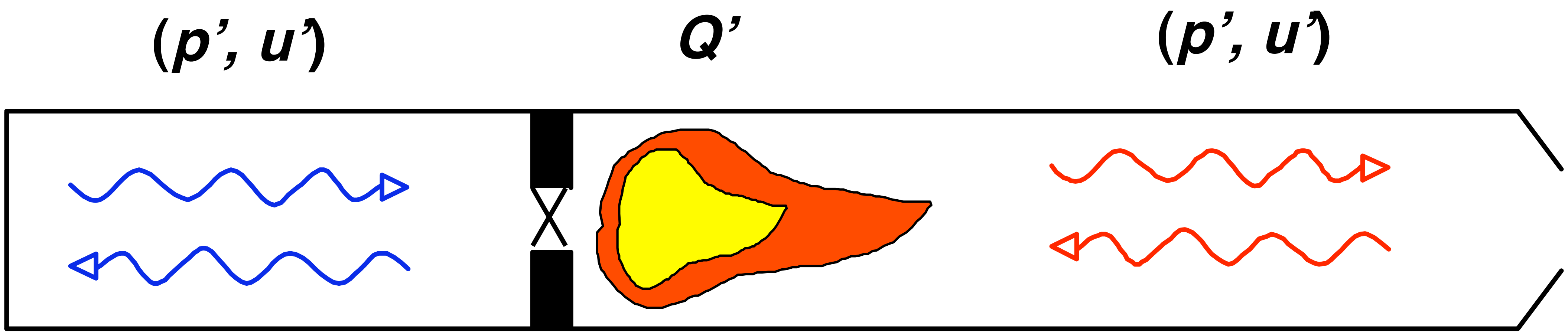
Thermo-acoustic combustion instabilities



a. Combustion liner

b. Turbine blade

Feedback between heat release and acoustics

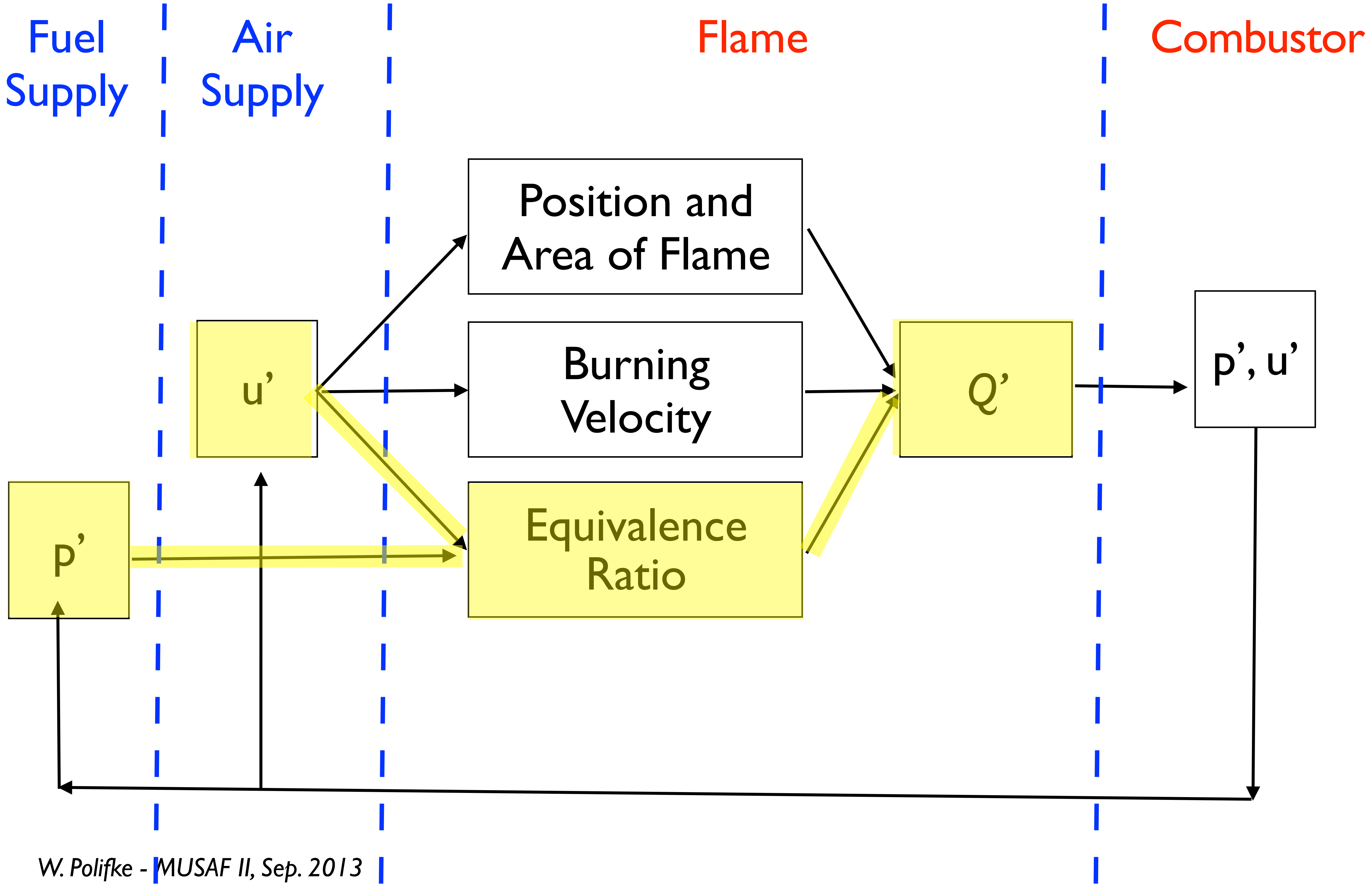


Rayleigh's criterion: Instability requires $\oint p' \, \dot{Q}' \, dt > 0$,

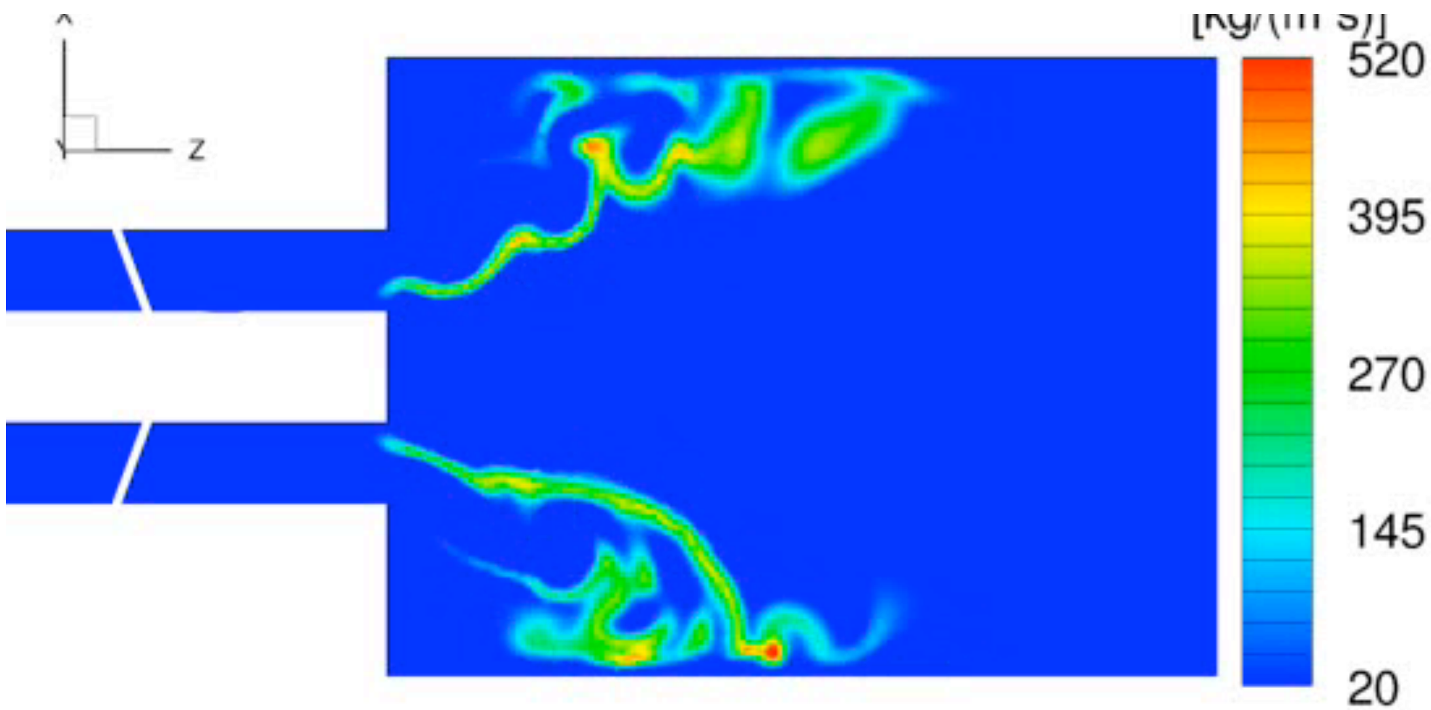
Premix flames are velocity sensitive: $\dot{Q}' = \dot{Q}'(u')$,

System acoustics controls phase $p' \leftrightarrow u'$: $Z = \dfrac{p'}{u'}$.

Multi-physics interactions with feedback



“brute force” LES for combustion dynamics?



Combustion LES captures (in principle) all relevant effects:

but:

- turbulent, reacting, compressible flow at low Ma-#
- acoustic boundary conditions !?
- wide range of length and time scales

“divide et impera”

Stability analysis by combined use of

- “system model” for combustor acoustics
- reduced order model (ROM) of heat source dynamics

This strategy may be adopted to

- network models
- state-space models
- Galerkin models
- FE/FV-based solvers for Helmholtz / APE / LEE

this is code-coupling, too !!

ROMs of input-output systems

Matrix-based methods (for state-space models)

- Truncated Balanced Realization
- Krylov methods (moment matching)

Data-based models

- PODs & Galerkin Projection
- System Identification

non-parametric model (e.g. spectral analysis)

parametric models

- *Black Box* models (e.g. time-delay models)

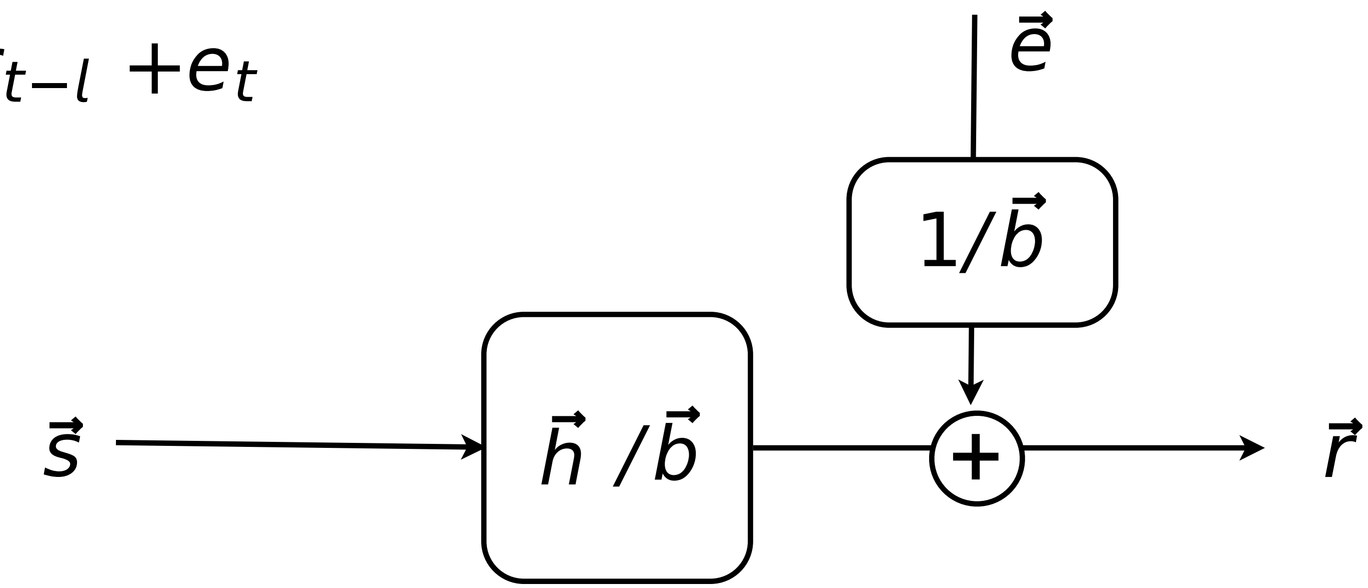
- *Gray Box* models (e.g. state space models)

Time-delay ROMs for linear systems

present response depends on present & previous signals

and previous responses ... and noise, too

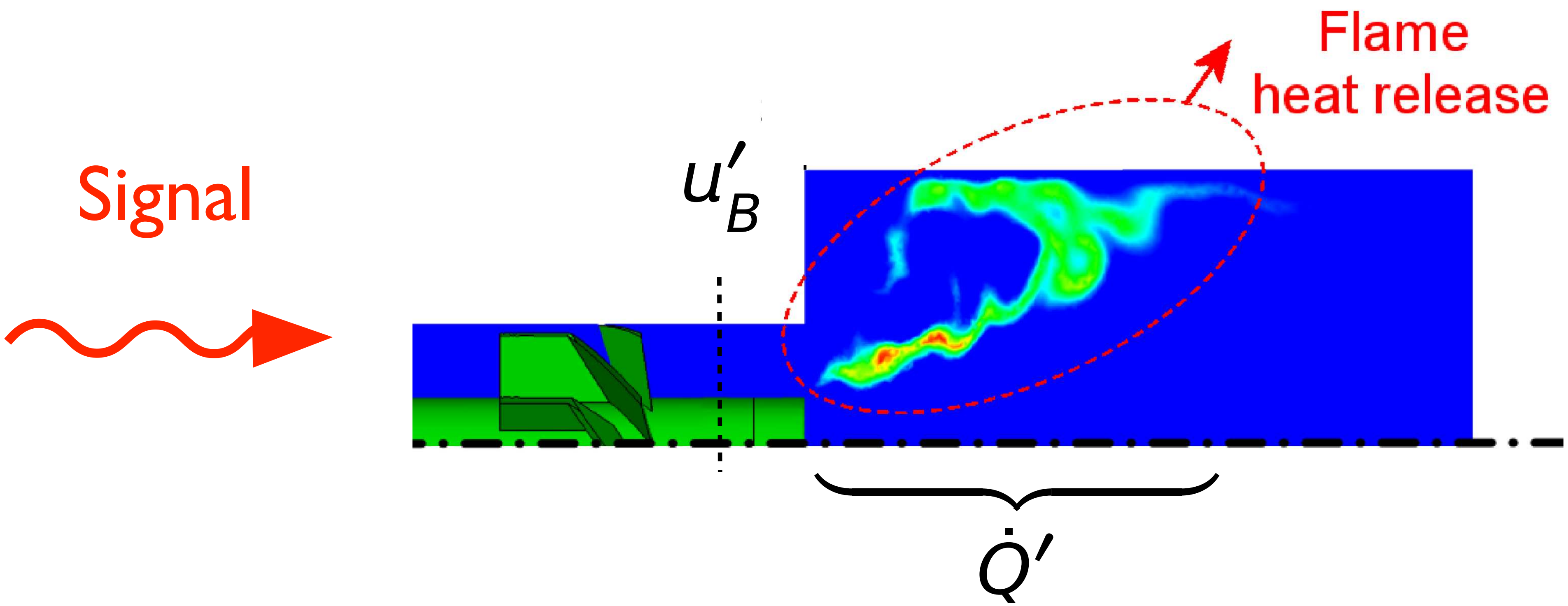
$$r_t = \sum_k h_k s_{t-k} + \sum_l b_l r_{t-l} + e_t$$



trade offs:

accuracy - uncertainty - # of coefficients - flow/flame physics

Flame transfer function from LES



Time Series $(u'_B(k\Delta t); \dot{Q}'(k\Delta t))$		Auto-correlation $\mathbf{\Gamma}$ Cross-correlation $\mathbf{c}$		Unit Impulse Response $\mathbf{h}$		Frequency Response F
s, r	⇒	$\mathbf{\Gamma}$, **c**	⇒	**h**	⇒	$F(\omega)$

$\Gamma_{ij} \sim \sum_k s_{k-i} s_{k-j}$

$c_i \sim \sum_k s_{k-i} r_k$

$\mathbf{\Gamma} \cdot \mathbf{h} = \mathbf{c}$

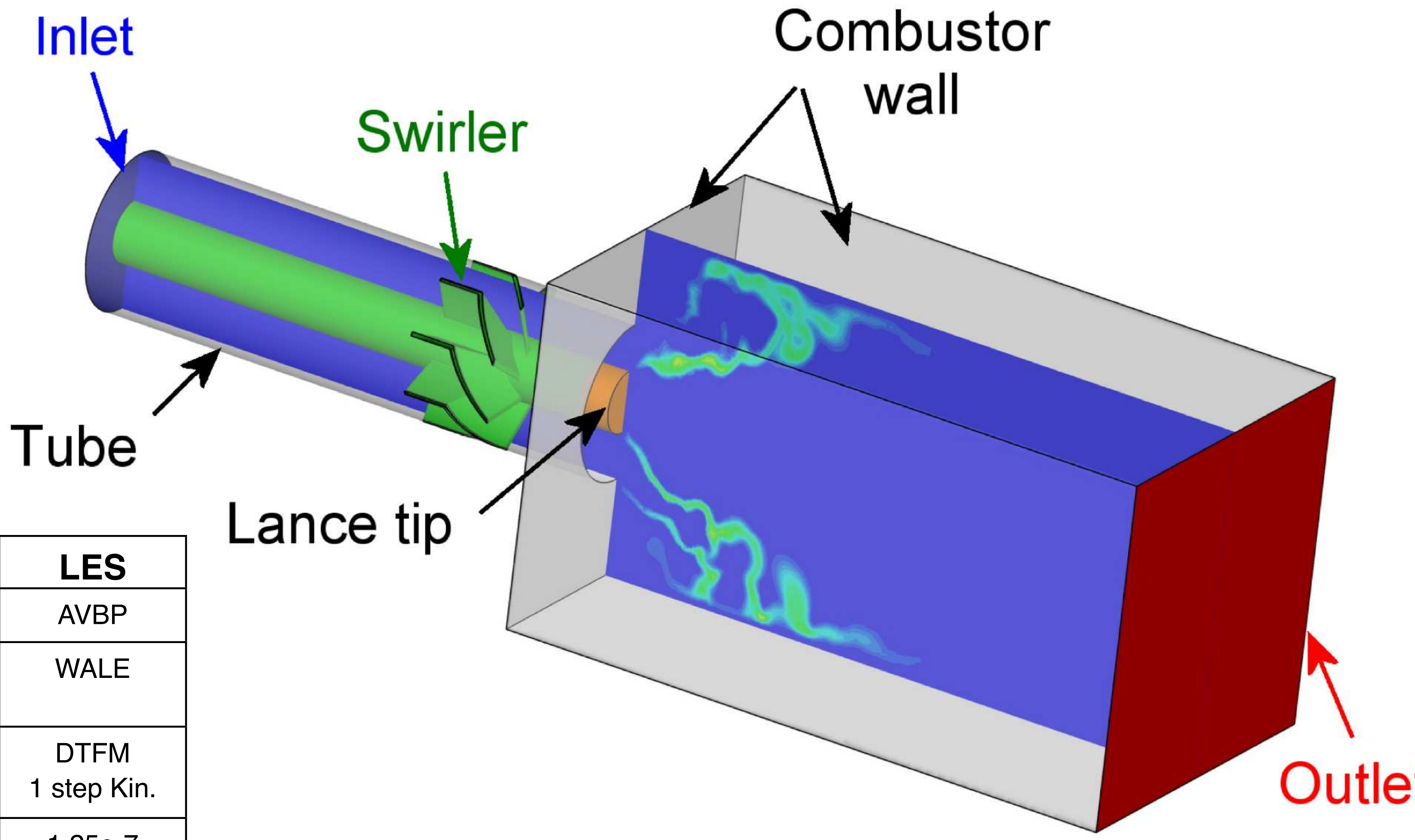
Wiener filter equation

$F(\omega) = \sum_k h_k e^{-i\omega\Delta t k}$

z-transform

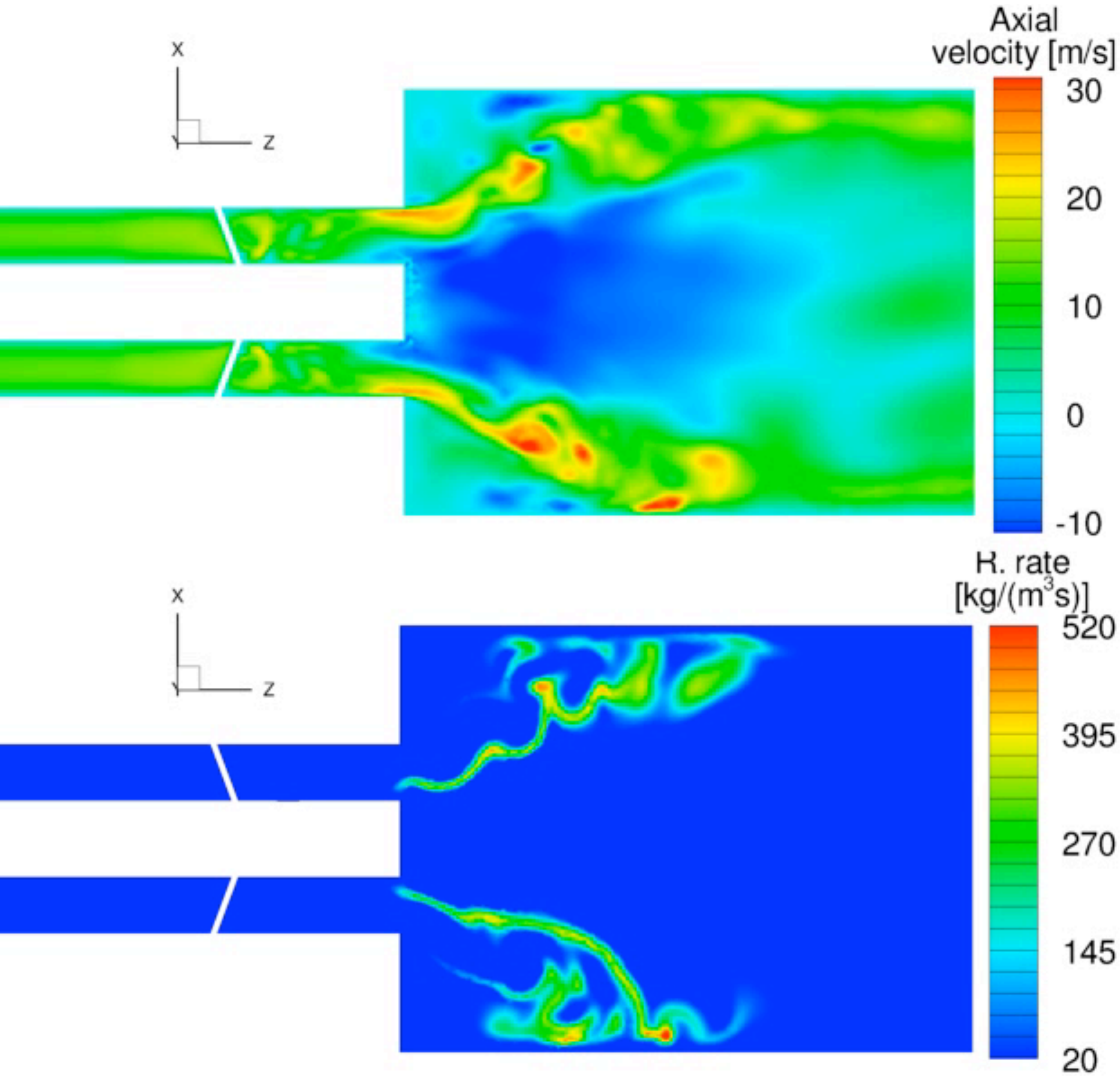
Turbulent premix swirl burner

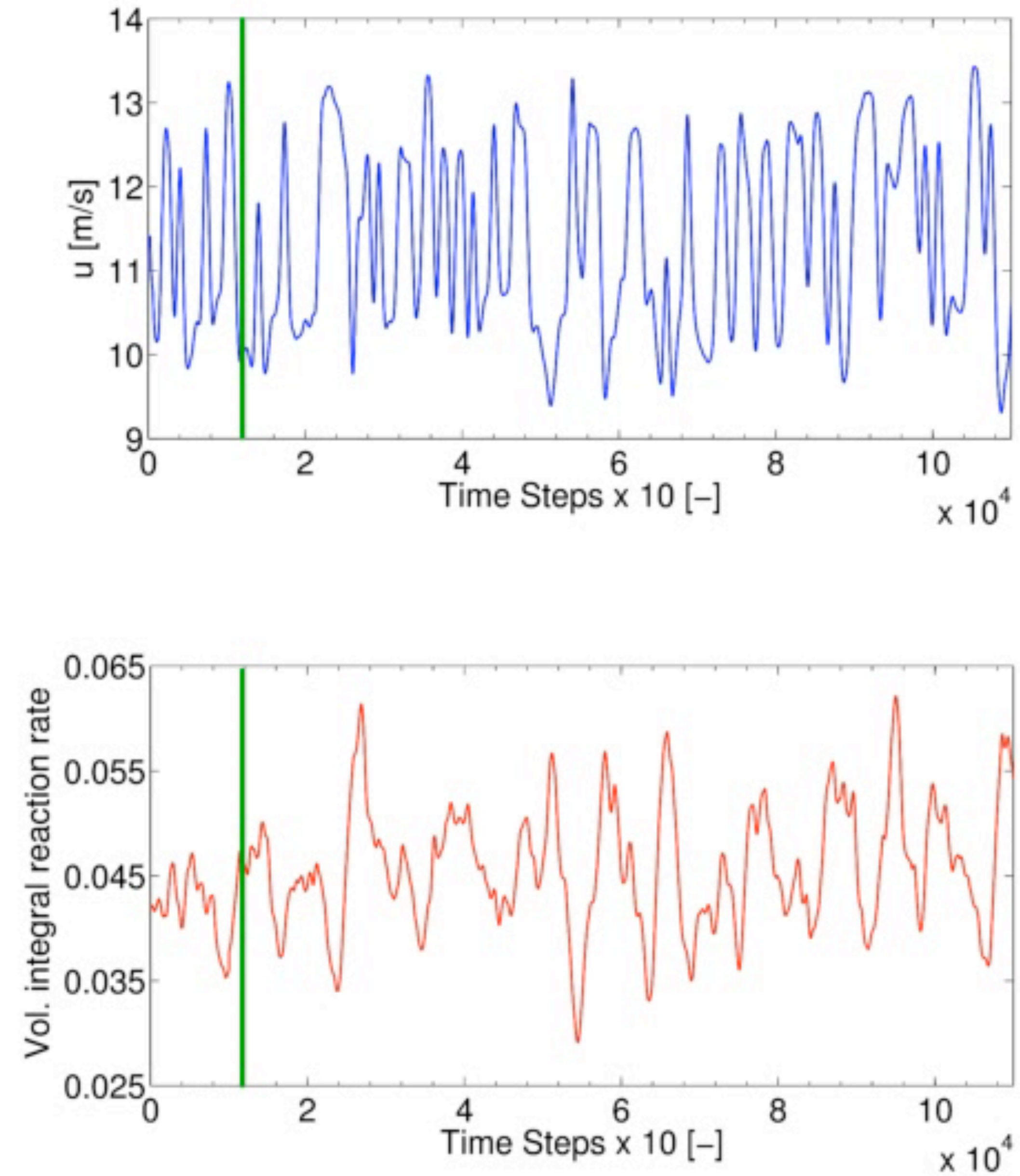
Komarek et al, '09, '10; Tay et al, '10, '11



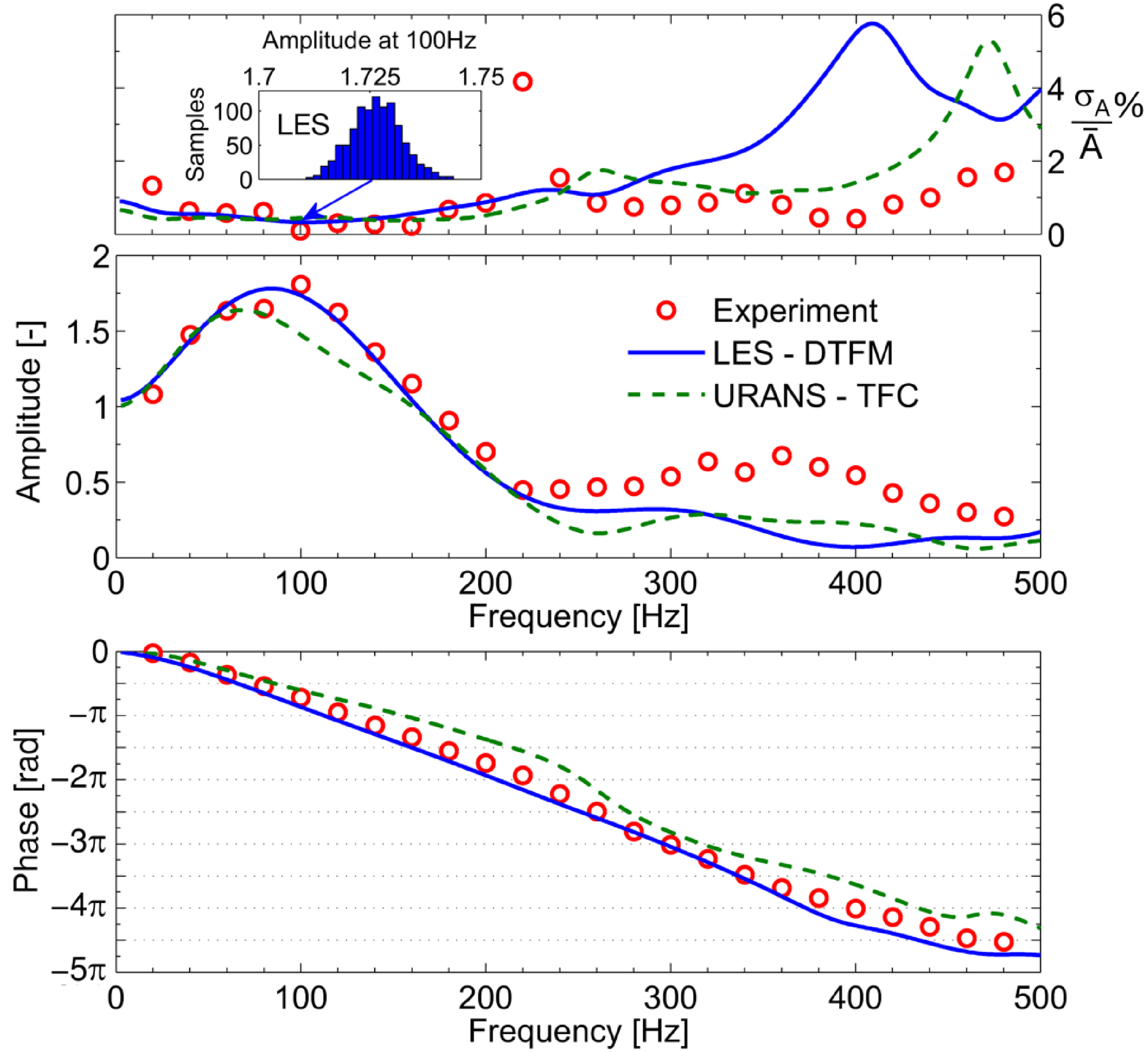
	URANS	LES
Solver	CFX	AVBP
Turb./Sub-grid model	SST	WALE
Combustion Model	TFC	DTFM 1 step Kin.
Time step [s]	5e-5	1.25e-7
Spatial/temp. Discretization	Second order	Second order

LES/SI for premix swirl burner





Validation: FTF from CFD/SI vs experiment



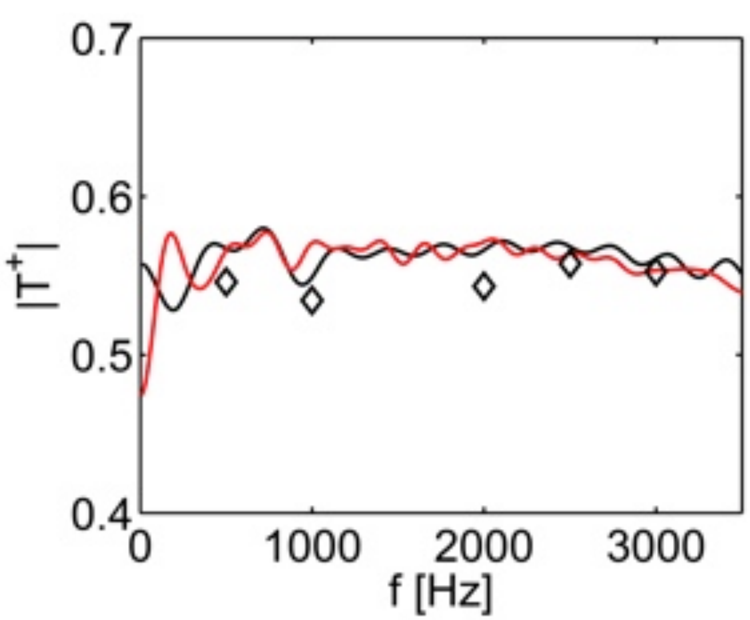
Advanced SI for low signal-to-noise

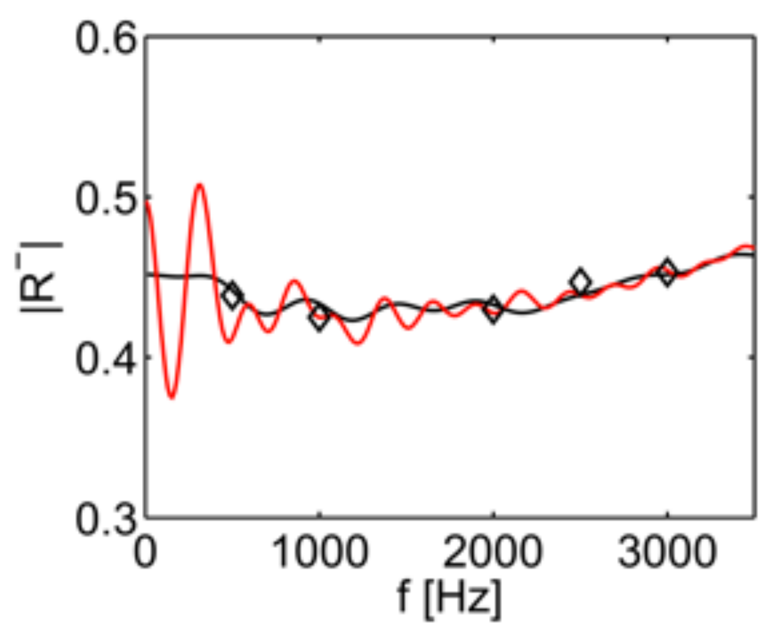
Tychonov Regularization for inversion of Wiener Filter:

$$\mathbf{h}_\alpha = \left(\Gamma^T\Gamma + \alpha^2 R R^T\right)^{-1}\Gamma^T\mathbf{c}$$

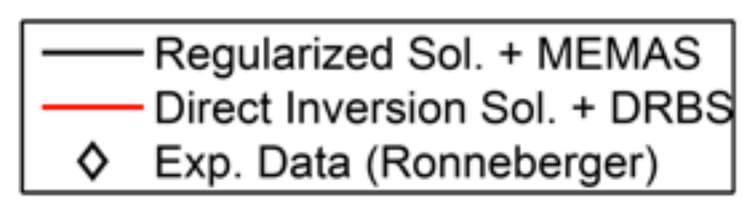
Generation of optimal excitation signals:

Daubechies wavelets → maximum entropy → non-Gaussian simulation

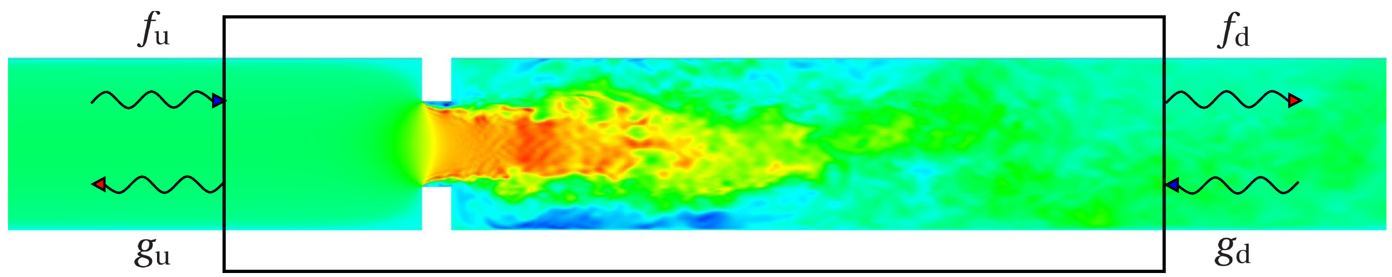


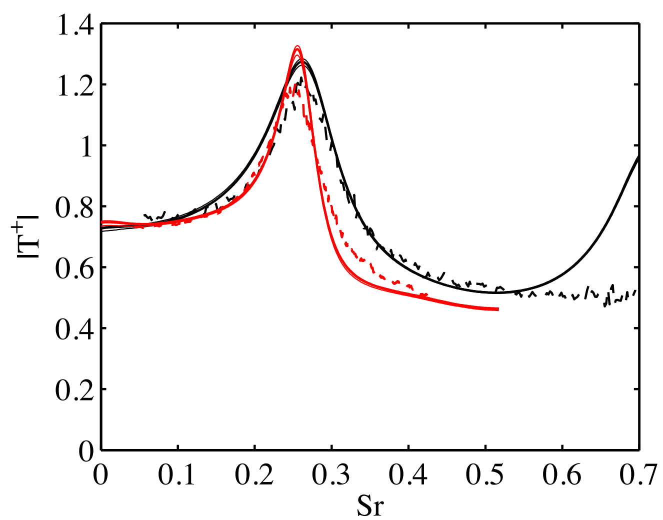


Föller & Polifke, ICSV '11: Transmission and reflection of sound at duct discontinuity

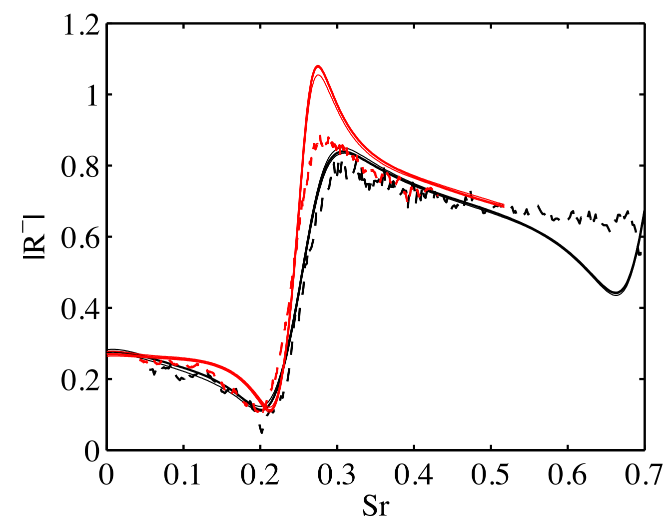


Aero-acoustic scattering at an orifice

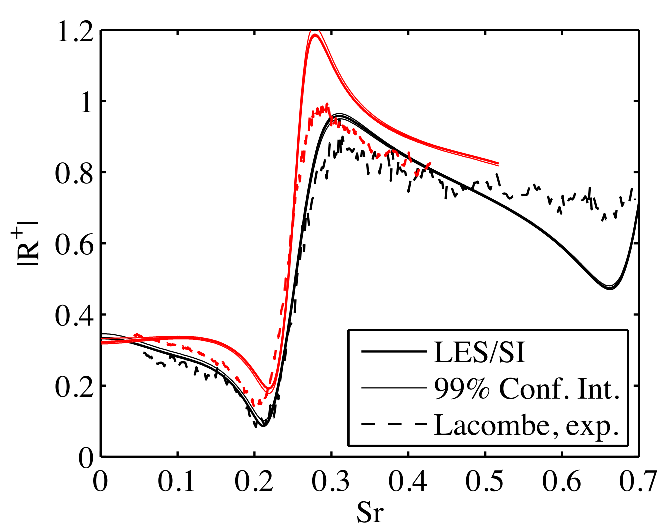




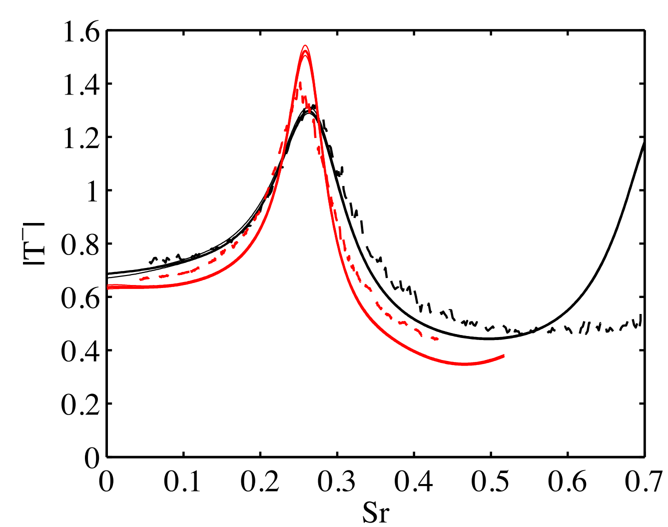
(a) upstream transmission



(b) downstream reflection



(c) upstream reflection



(d) downstream transmission

M = 0.026

M = 0.034

Lehrstuhl für THERMODYNAMIK

Summary

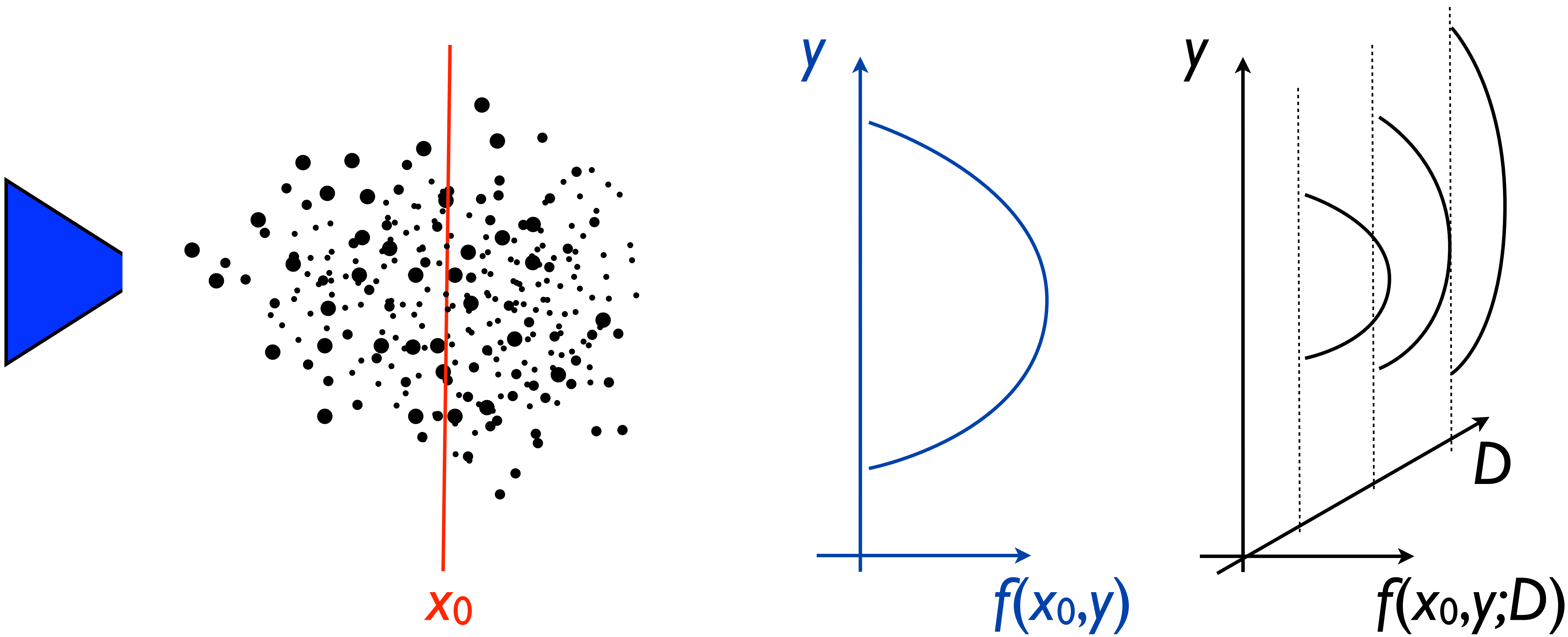
Status Quo

- LES/SI can give flame dynamics with quantitative accuracy

Ongoing work

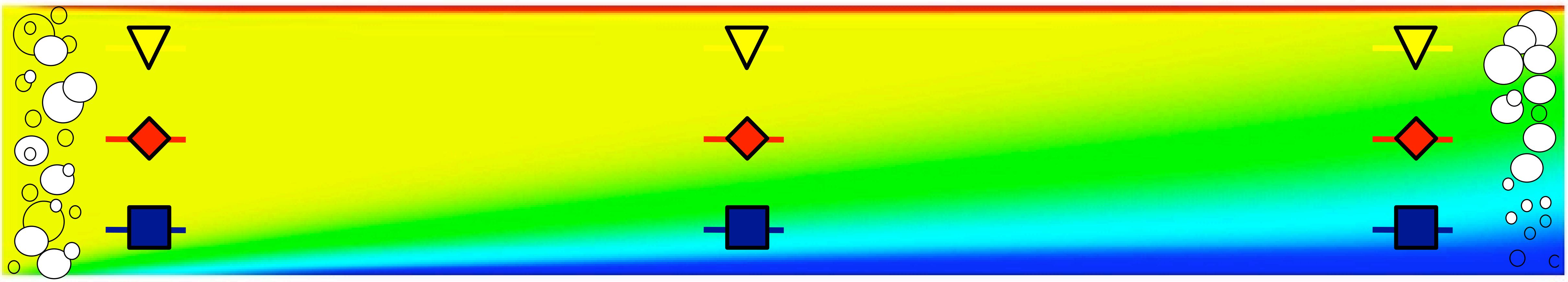
- optimal model structures for identification
- non-linear effects
- high frequencies, acoustic losses
- combustion noise
- LES model for (partially) premixed (spray) combustion

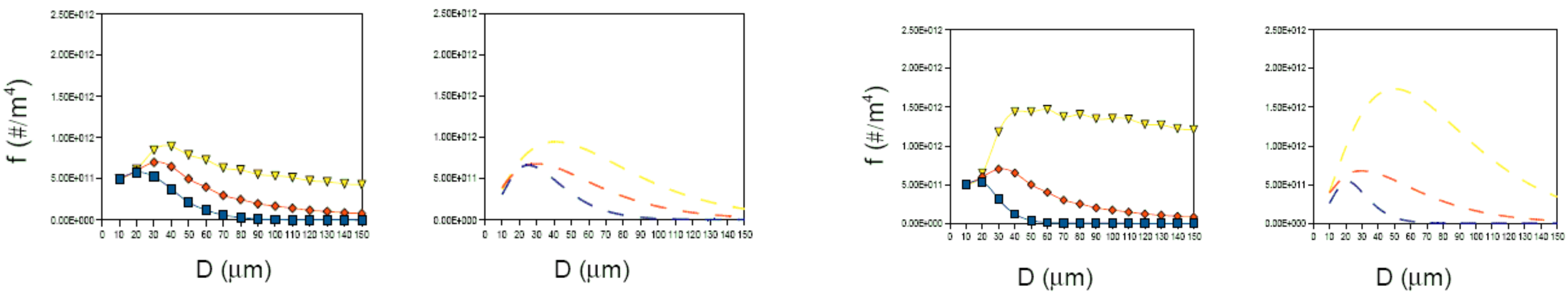
Poly-Celerity MOM for polydisperse sprays

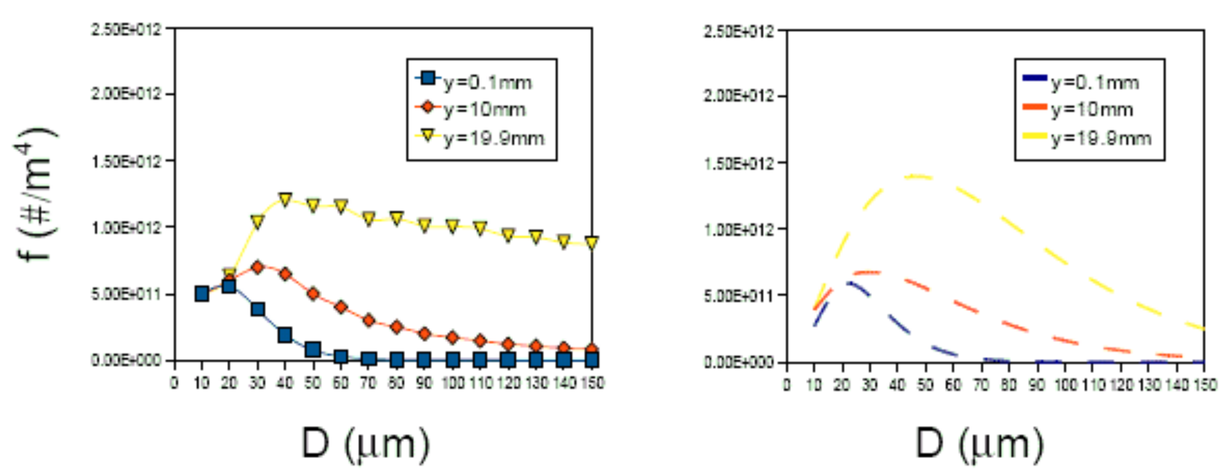


Particle number density function	$f(\vec{x}, t; D)$
k-th moment of the NDF:	$M^{(k)}(\vec{x}, t; D) = \int D^k f(\vec{x}, t; D)\, dD$
Moment transport velocity:	$u^{(k)}(\vec{x}, t; D) = \frac{1}{M^{(k)}} \int u(D) D^k f(\vec{x}, t; D)\, dD$
Fast relaxation approximation:	$u^{(k)}(\vec{x}, t; D) \approx u_c + \frac{\tau^{(k)}}{\tau_0}(u_0 - u_c),\ \tau_k \sim \frac{M^{(k+2)}}{M^{(k)}}$

Test case: sedimentation of bubbles
(Carneiro et al)

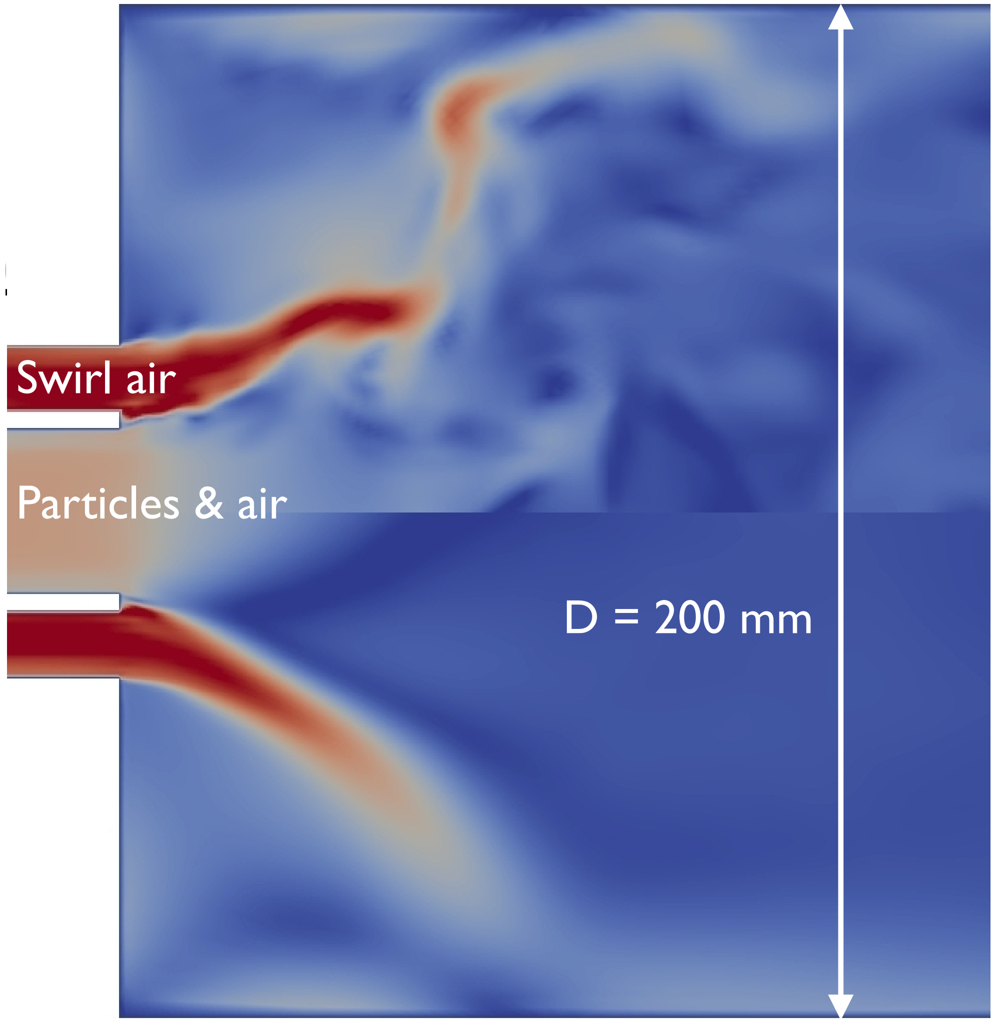




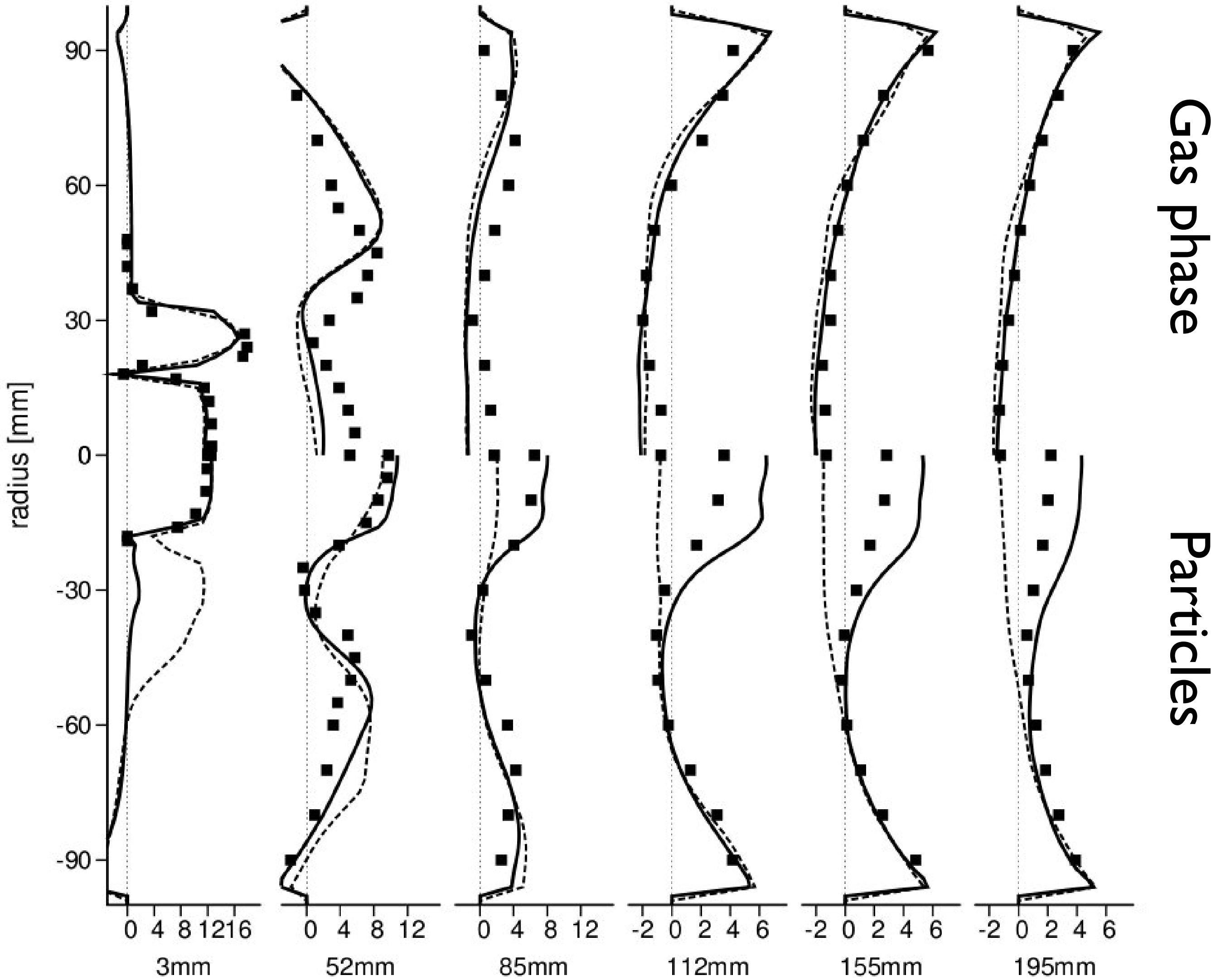


Polydisperse multi-phase turbulent swirl flow

Experiments (Sommerfeld & Qiu, '91) vs. LES (Dems et al, 2012)



Axial velocities



Conclusions

Large Eddy Simulation is relevant for R&D in industry

Industrial applications imply special modelling requirements

Reduced Order Models can be an interesting alternative to *code-coupling* for multi-physics, multi-scale problems

Thank you !