Convective Waves in Thermoacoustic Combustion Instability

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Montestigliano, Italy

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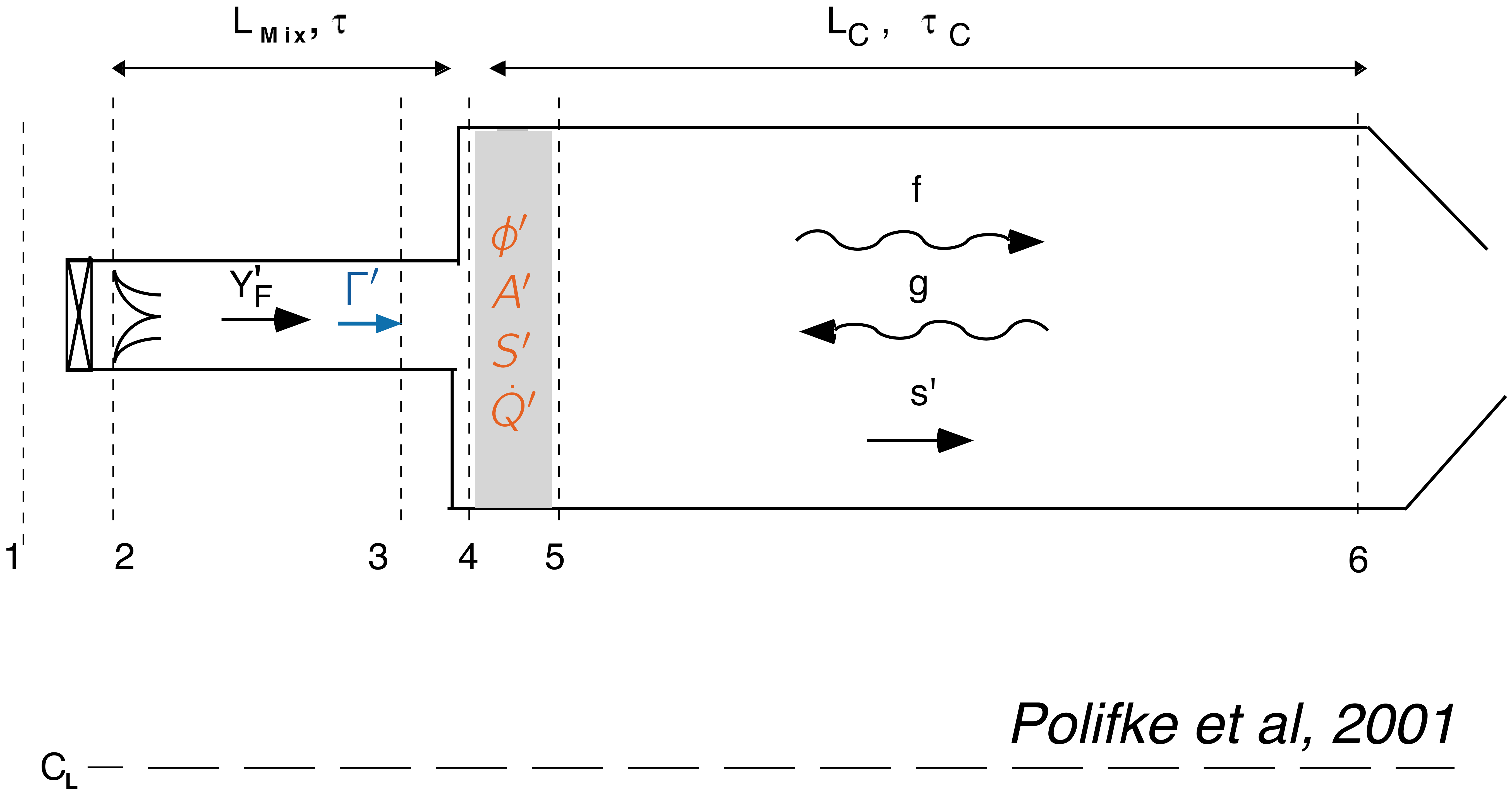
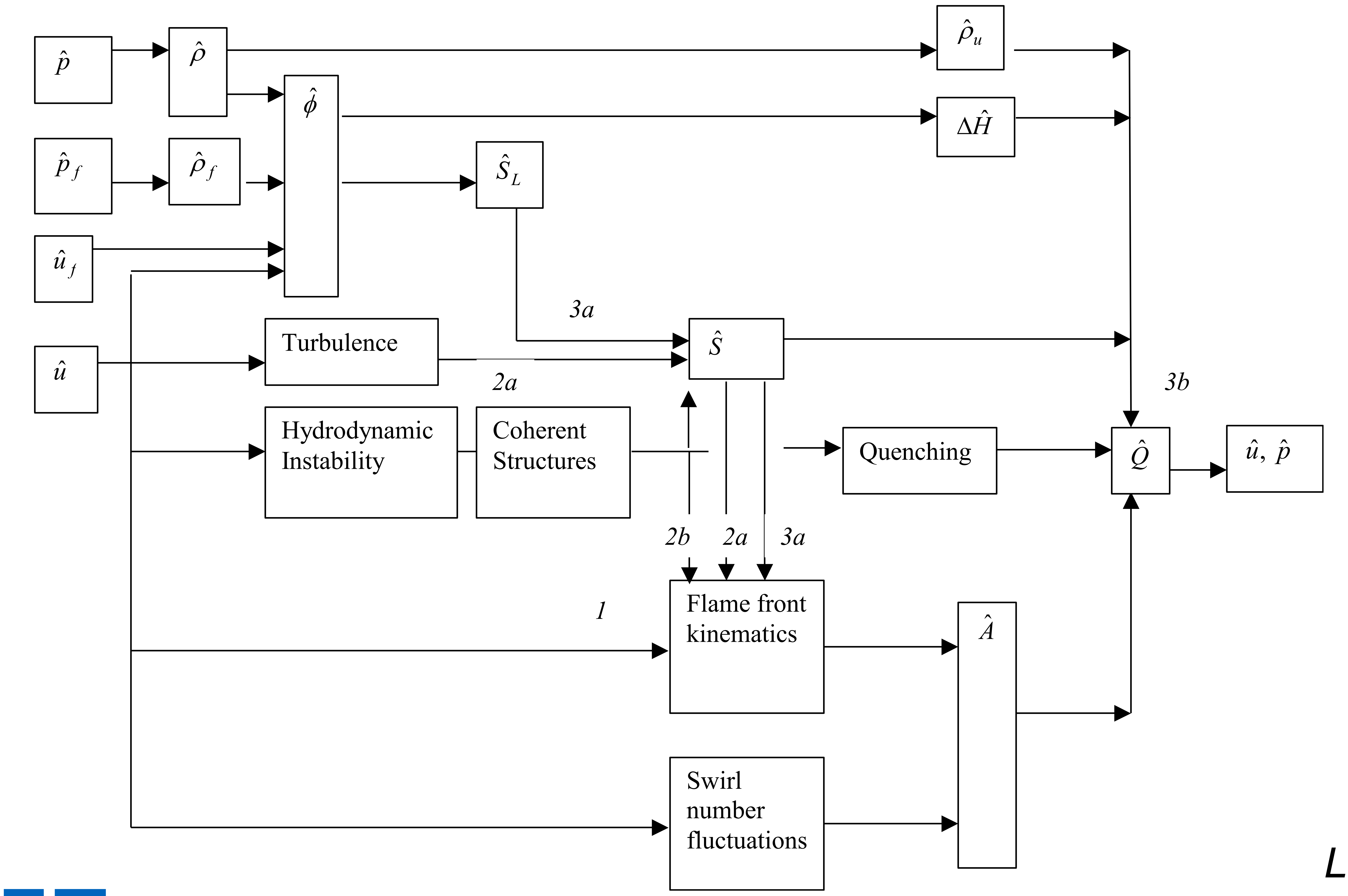


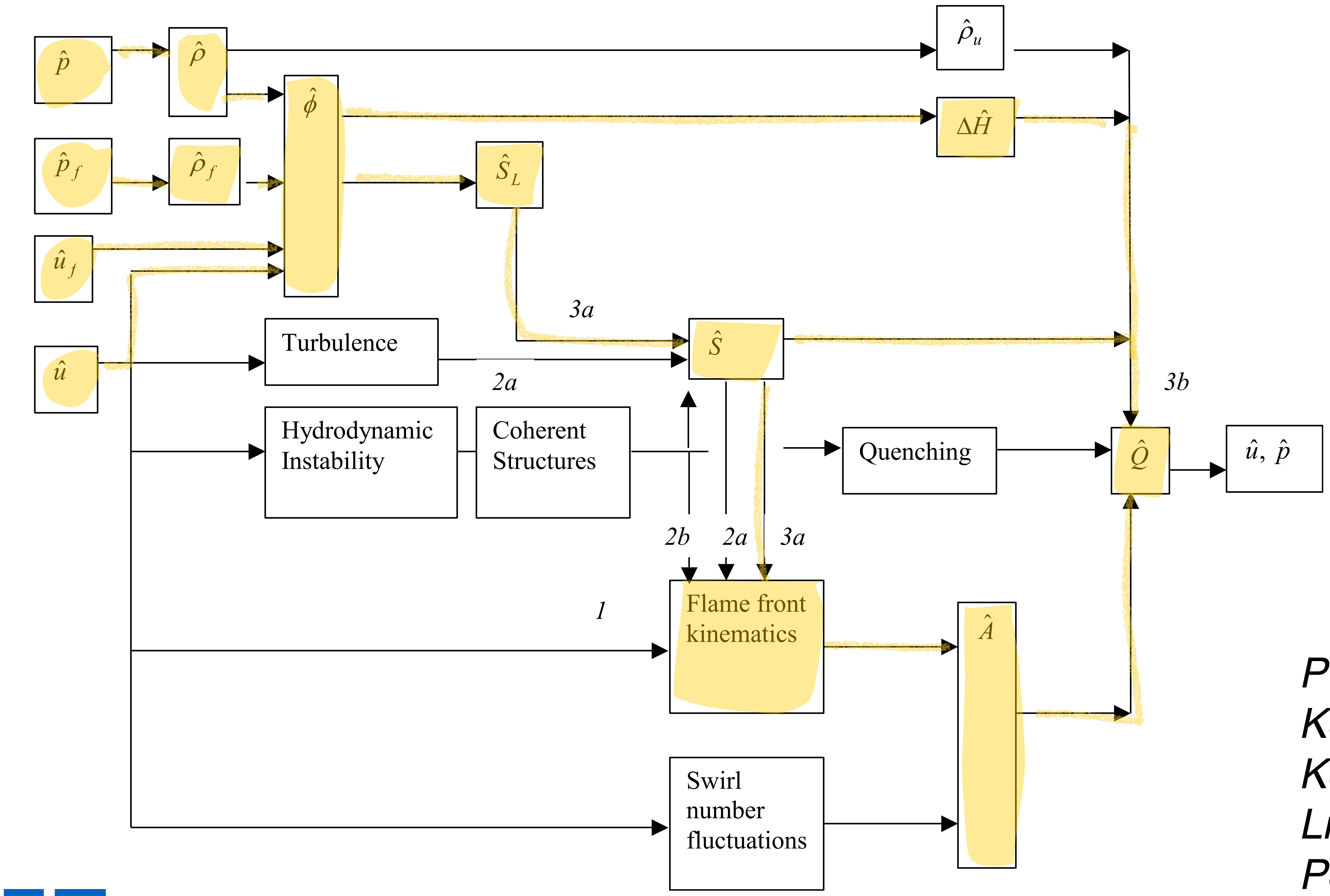
Polifke et al, 2001

Feedback interactions between a wide variety of acoustic and convective waves contribute to thermoacoustic combustion instability



Lawn and Polifke 2004

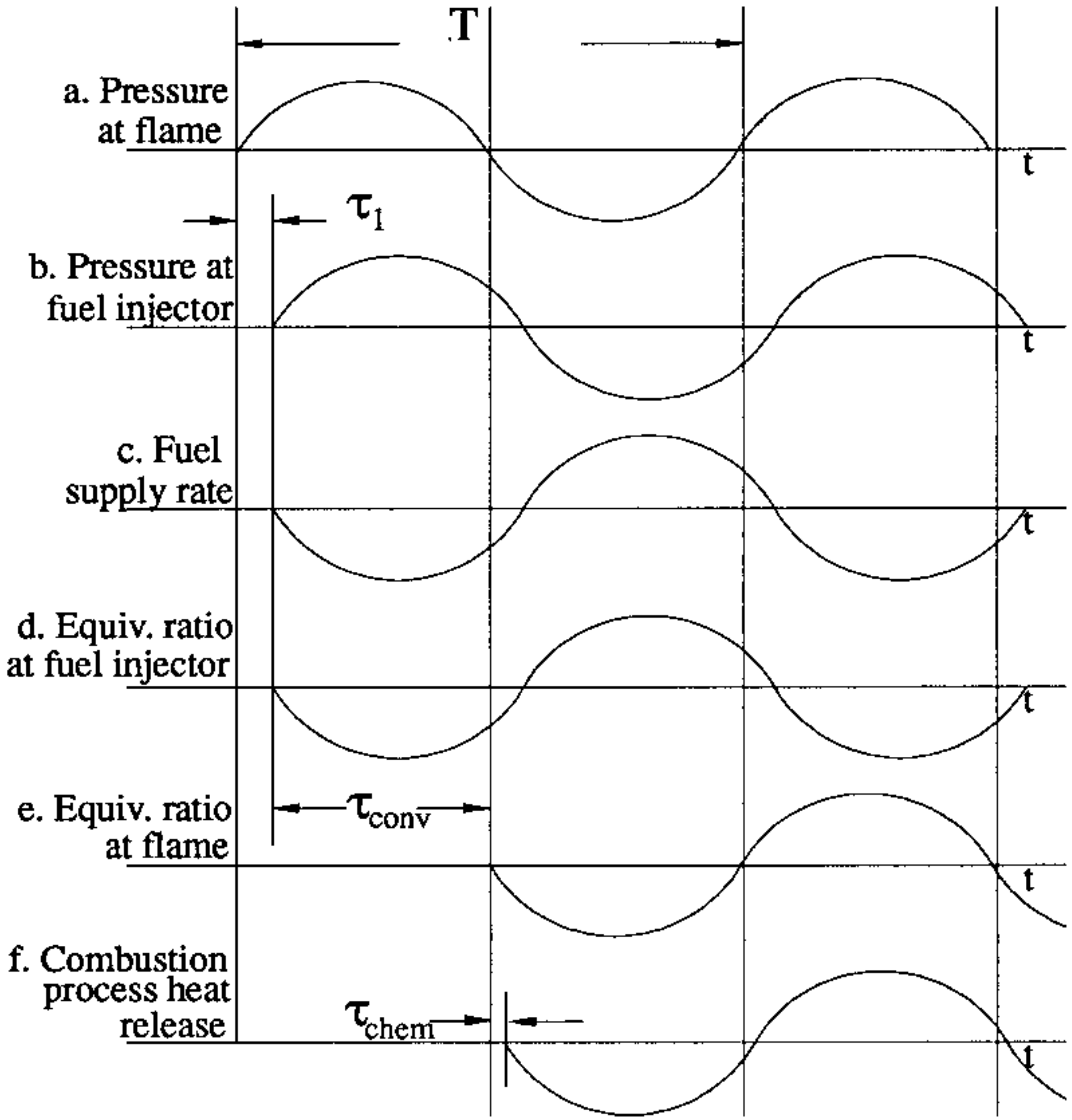
Fluctuations of pressure or velocity at the fuel injector modulate after a time delay the equivalence ratio at the flame and thereby heat release rate

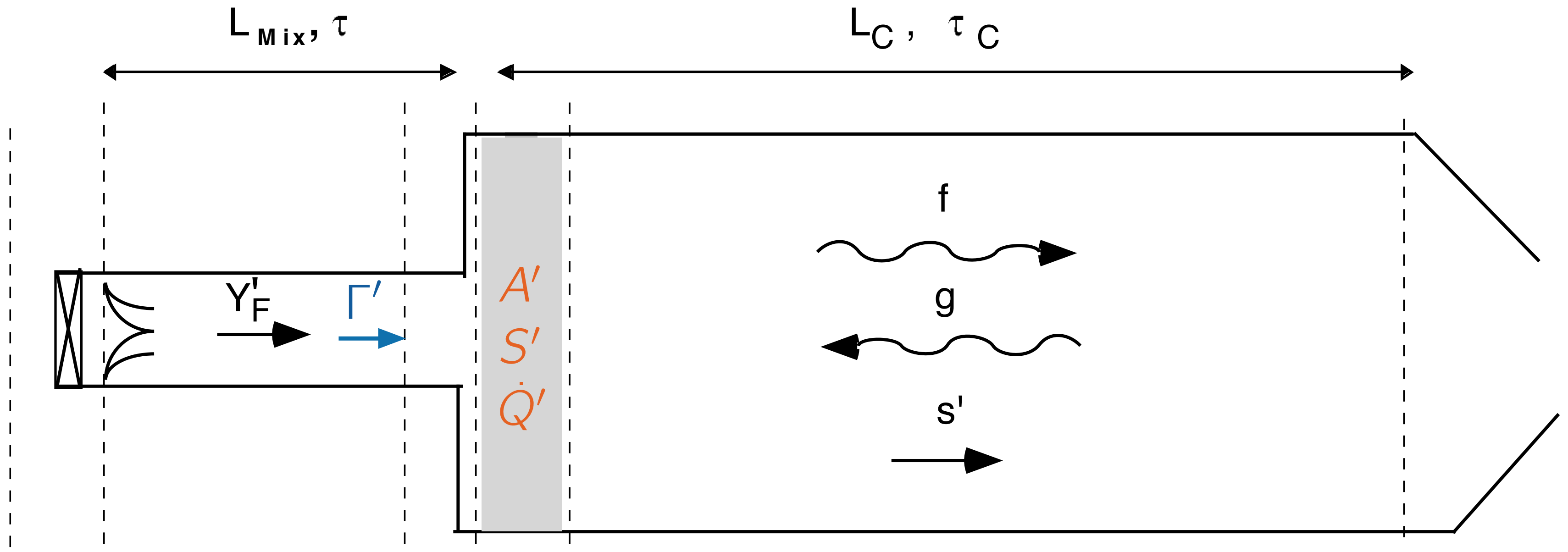


Putnam, 1971
Keller et al. 1985
Keller 1995
Lieuwen and Zinn, 1998
Polifke et al. 2001
Sattelmayer 2003

The relative phases between pressure, fuel supply rate, equivalence ratio and heat release rate determine the sign of the Rayleigh index

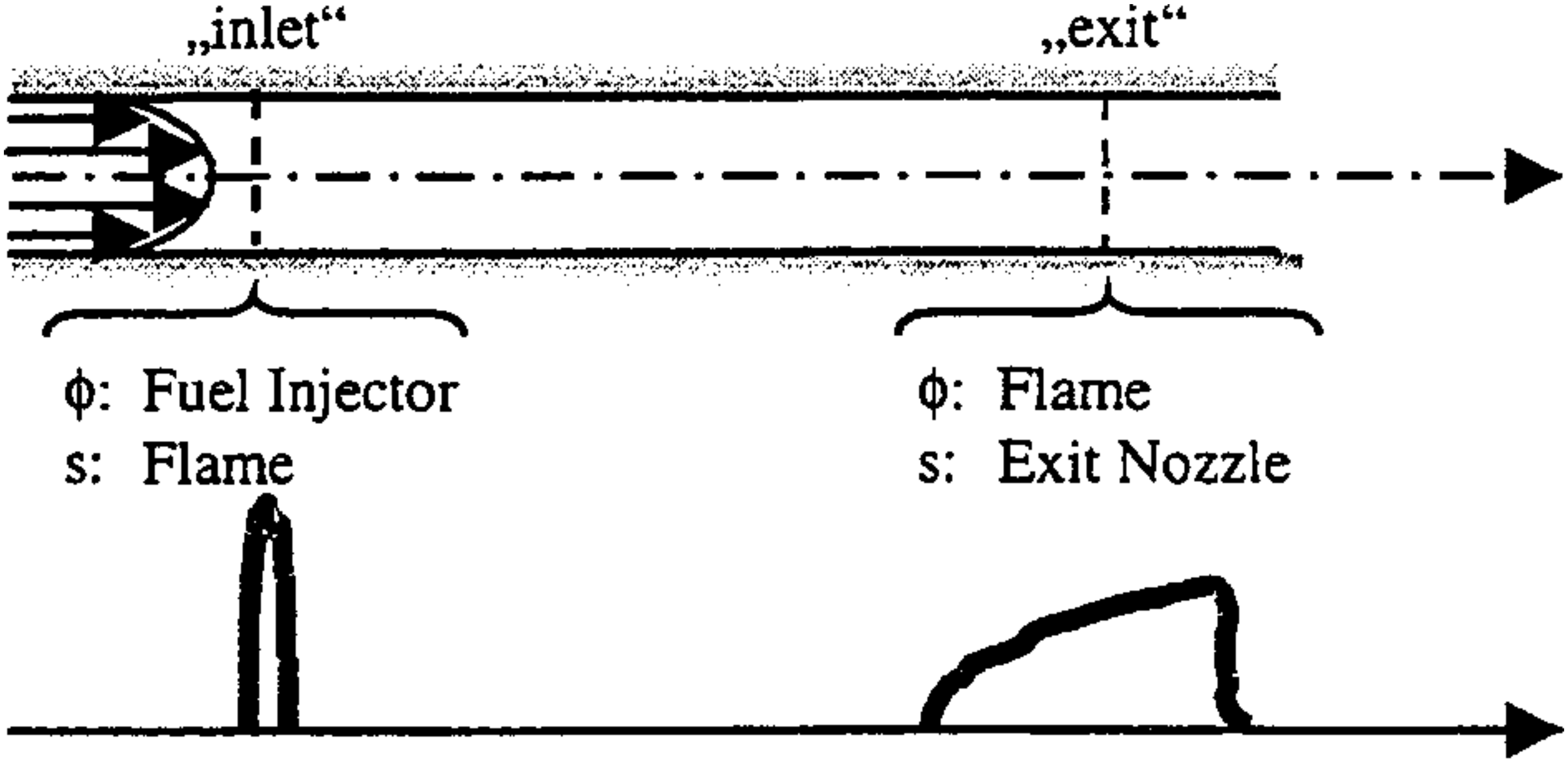
For a compliant fuel injector:





Lieuwen and Zinn 1998

Shear dispersion or *distributed fuel injection* or an *elongated / distorted flame* will result in a distribution of fuel transport time lags



Sattelmayer, 2003

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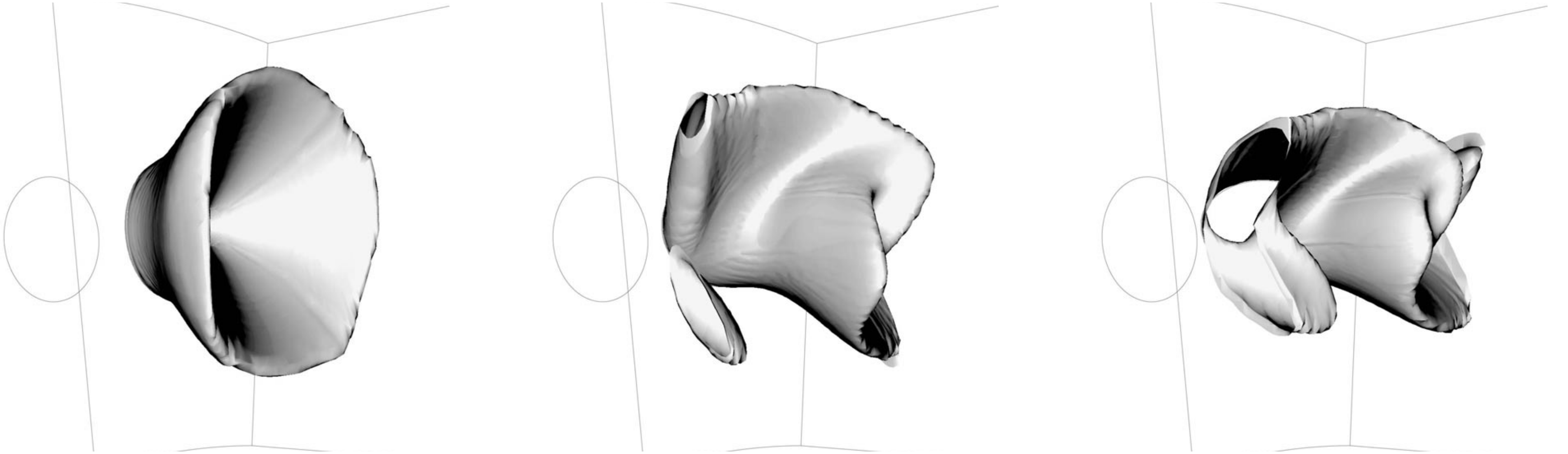
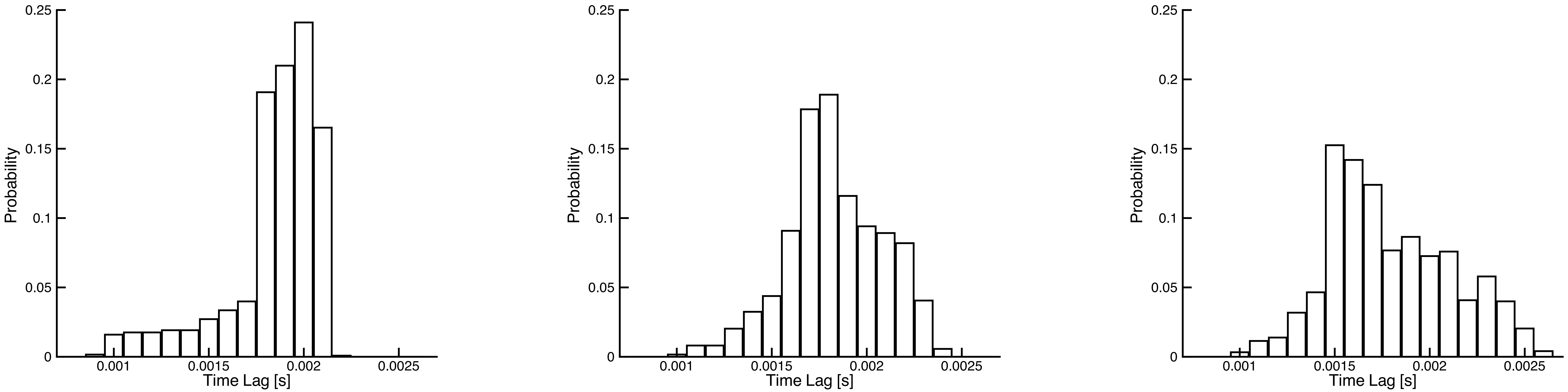




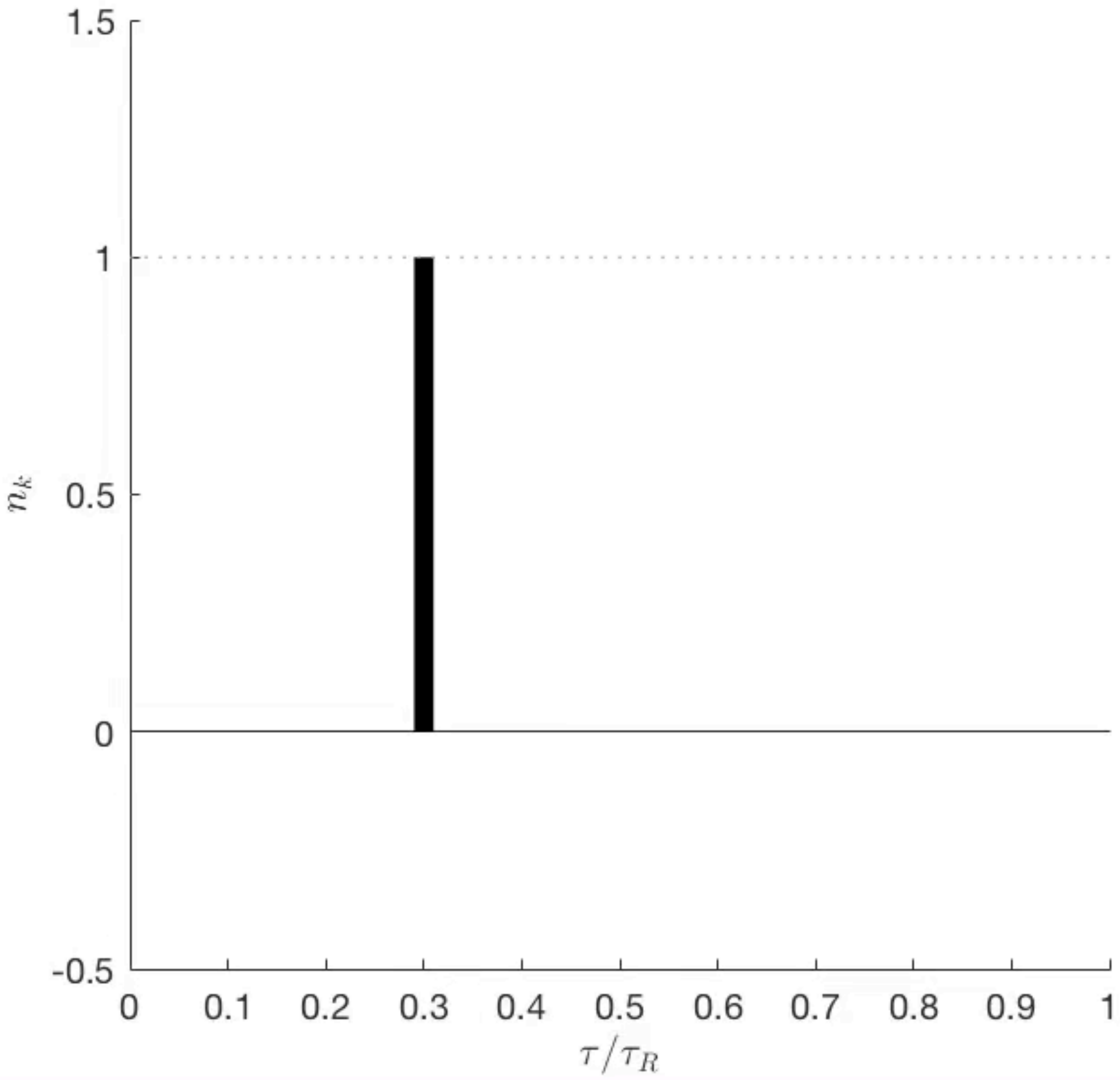
Kopitz and Polifke, 2001

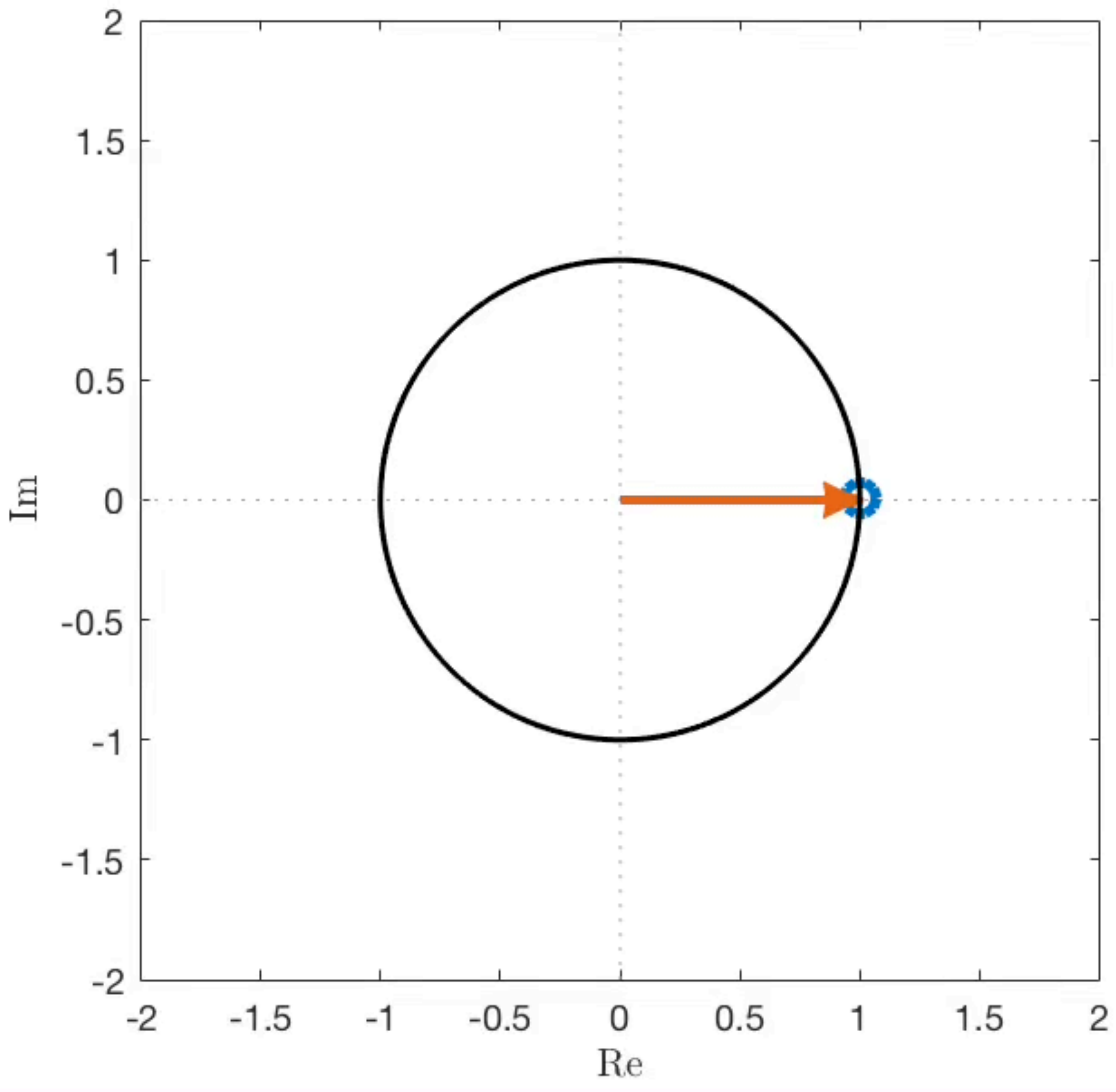
A distribution of time delays reduces the response at higher frequencies

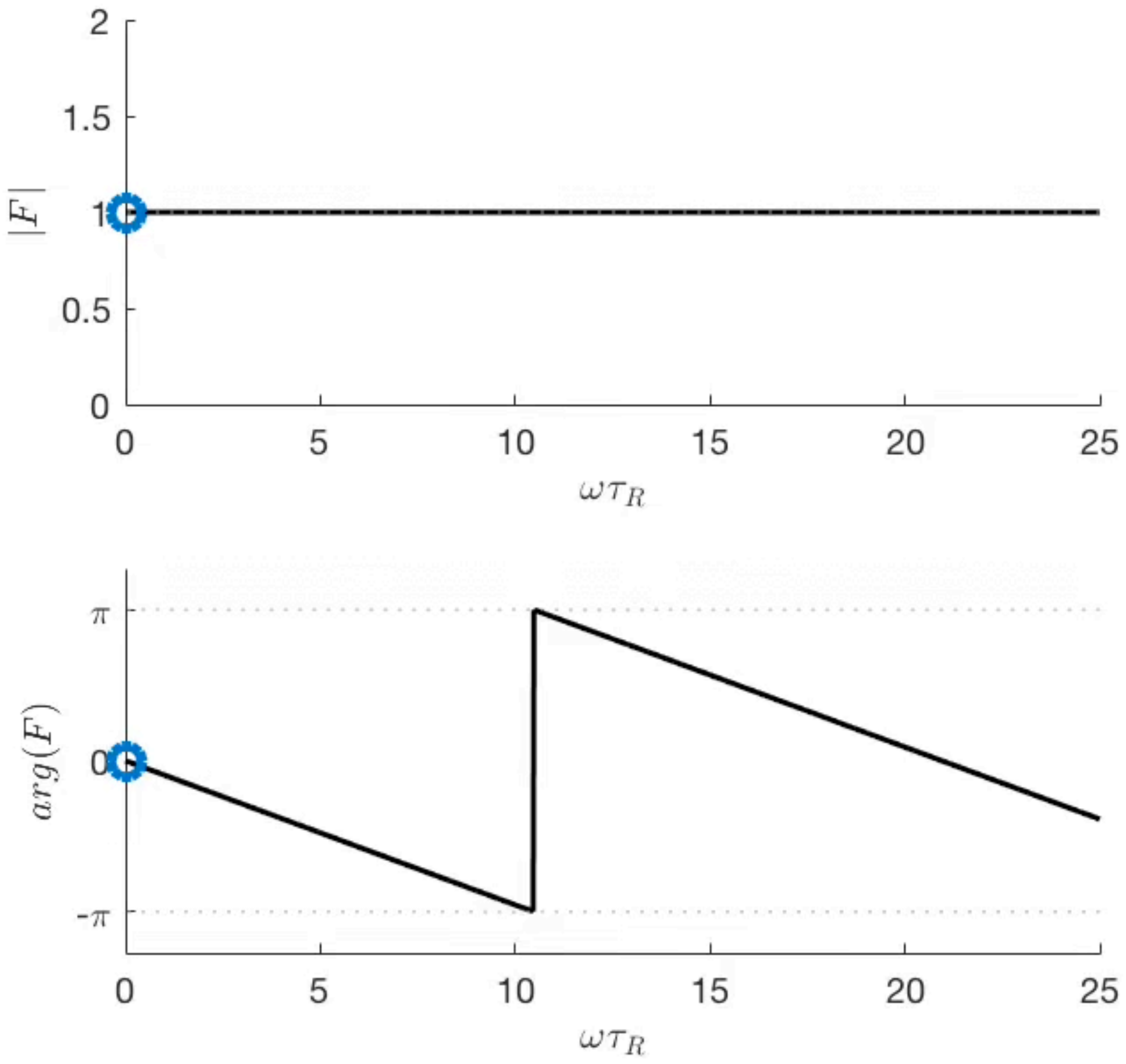
Unit Impulse Response h_k

Flame Transfer Function

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







Polifke, 2020

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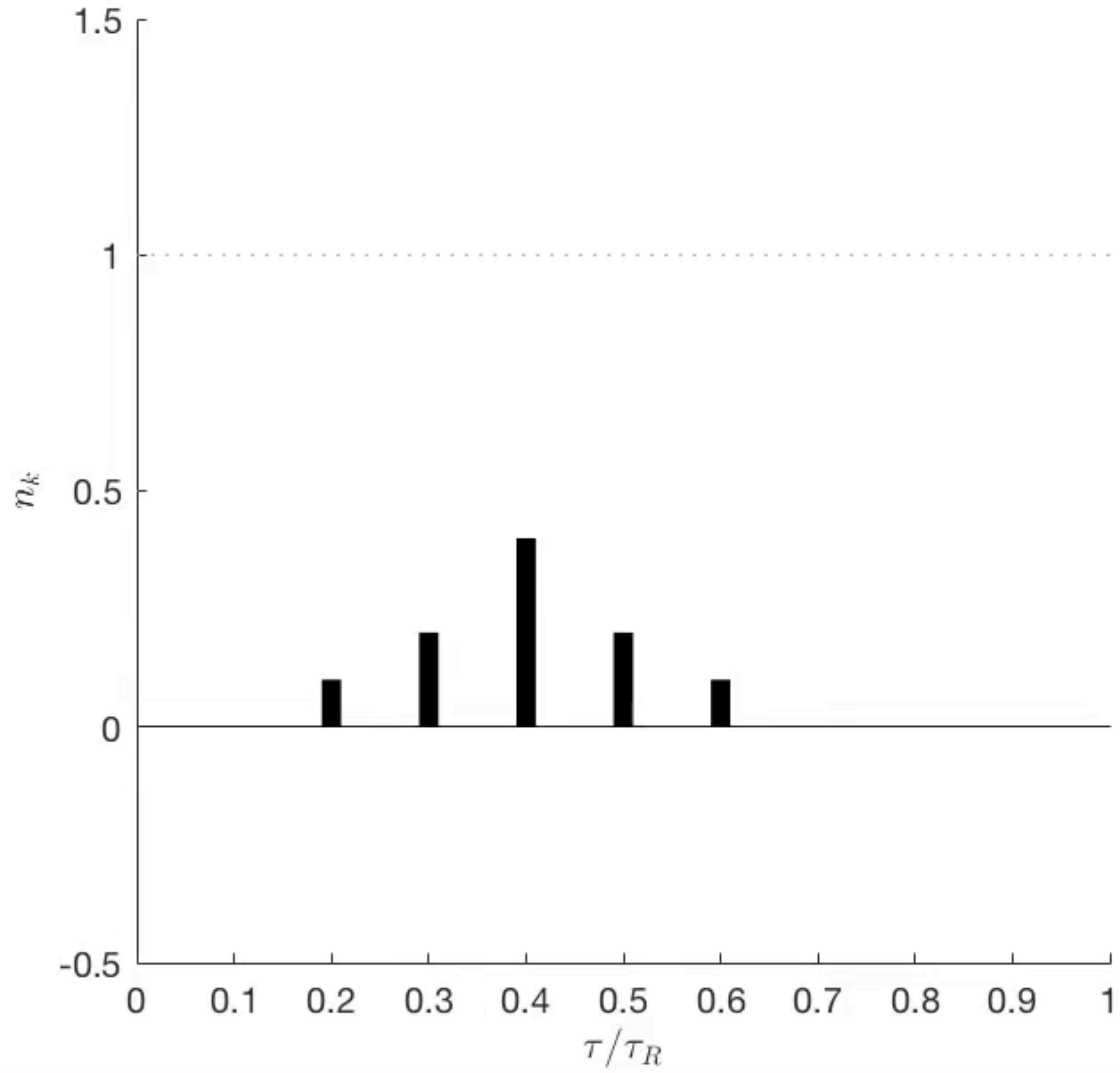

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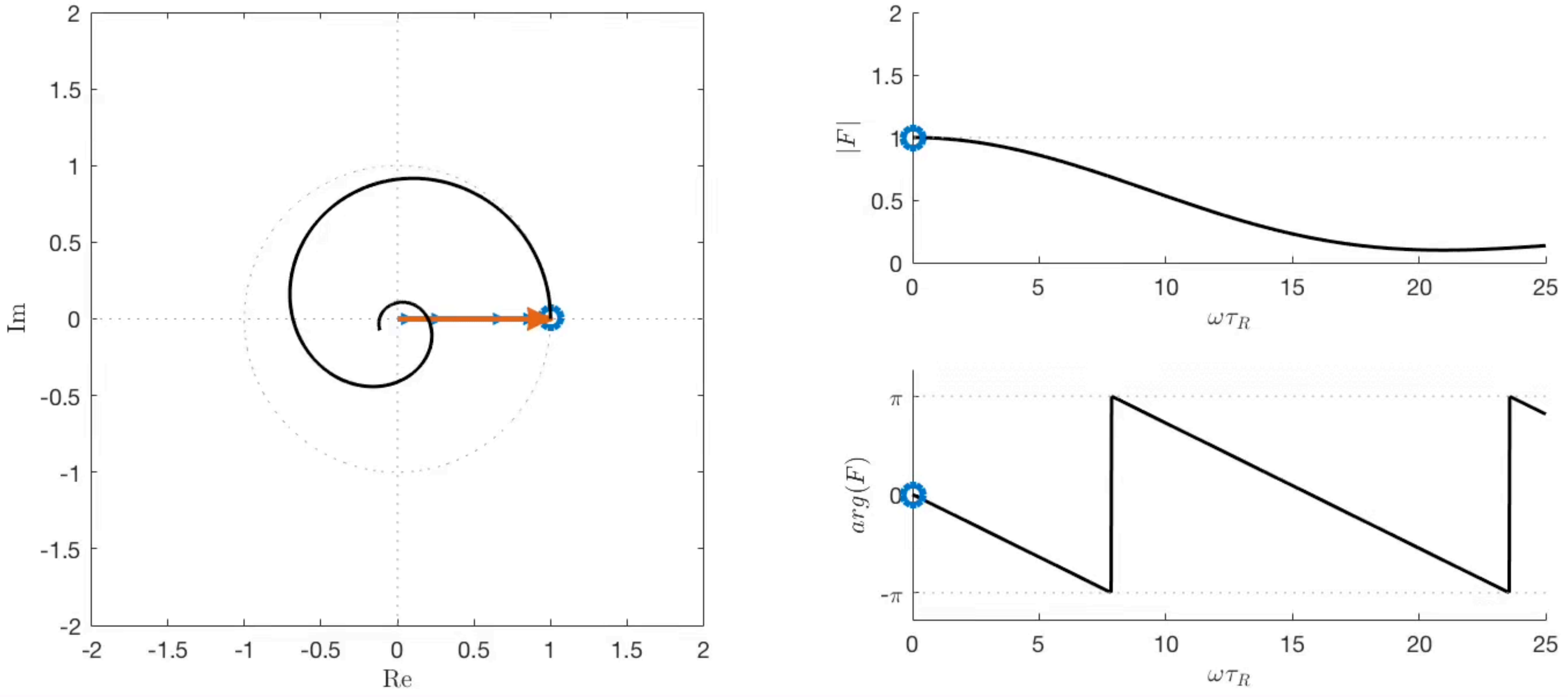
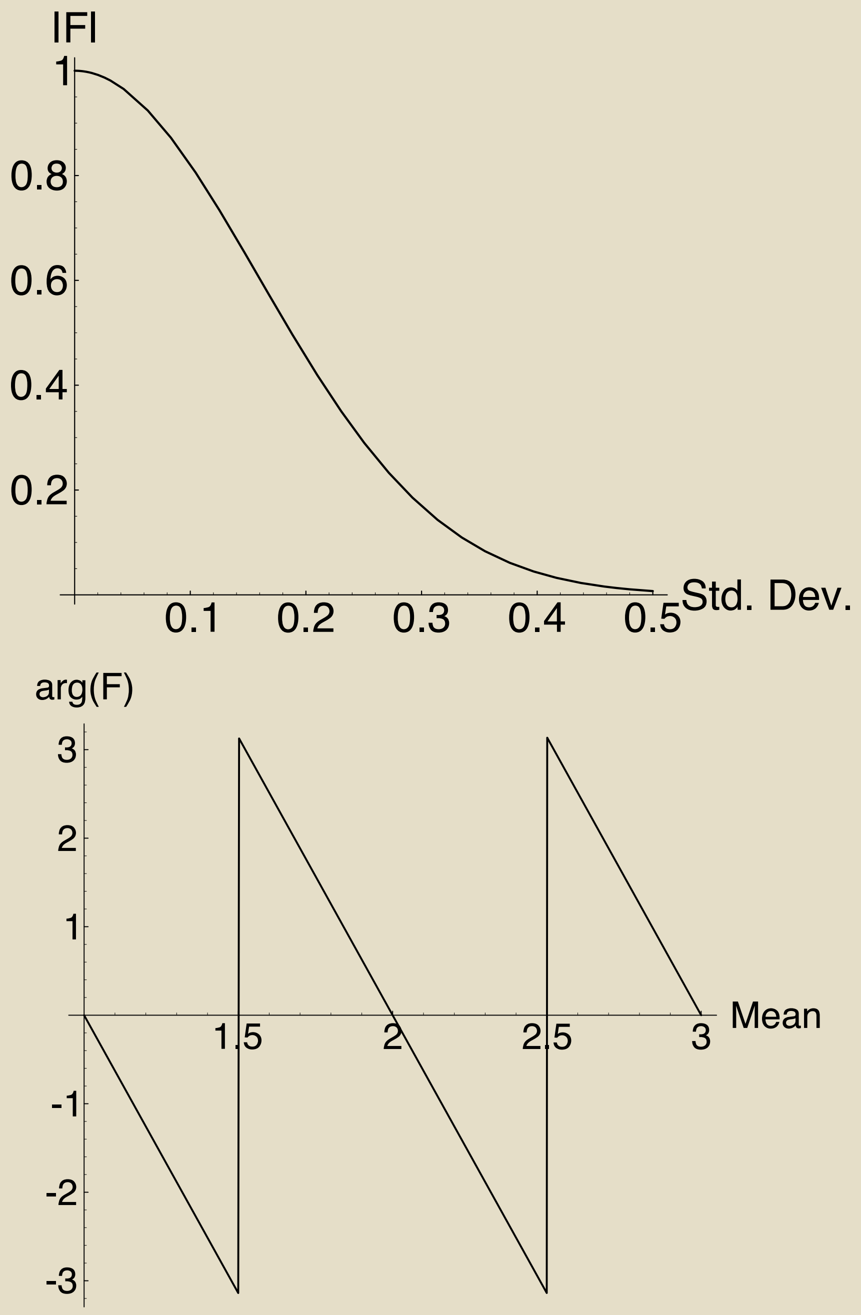


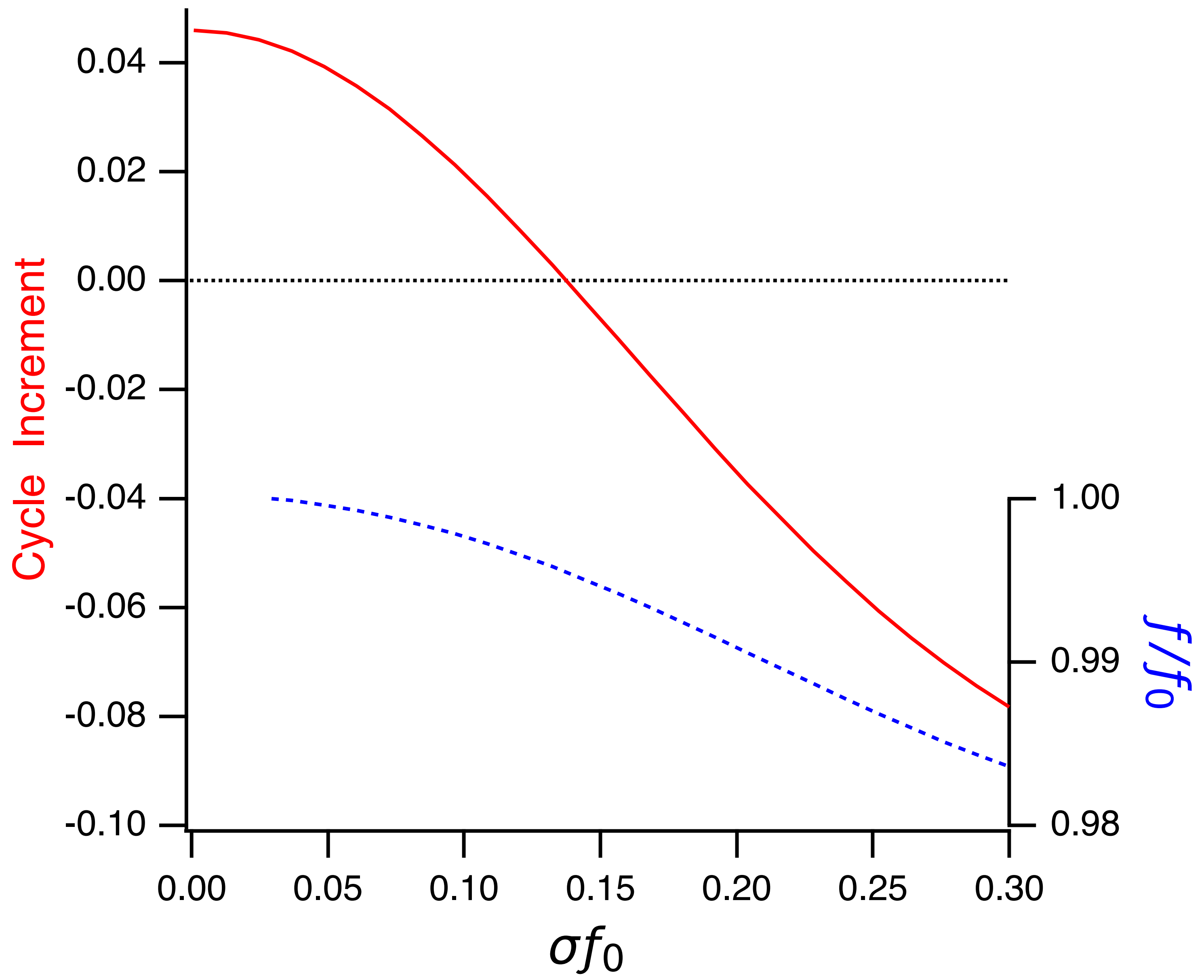
Polifke, 2020

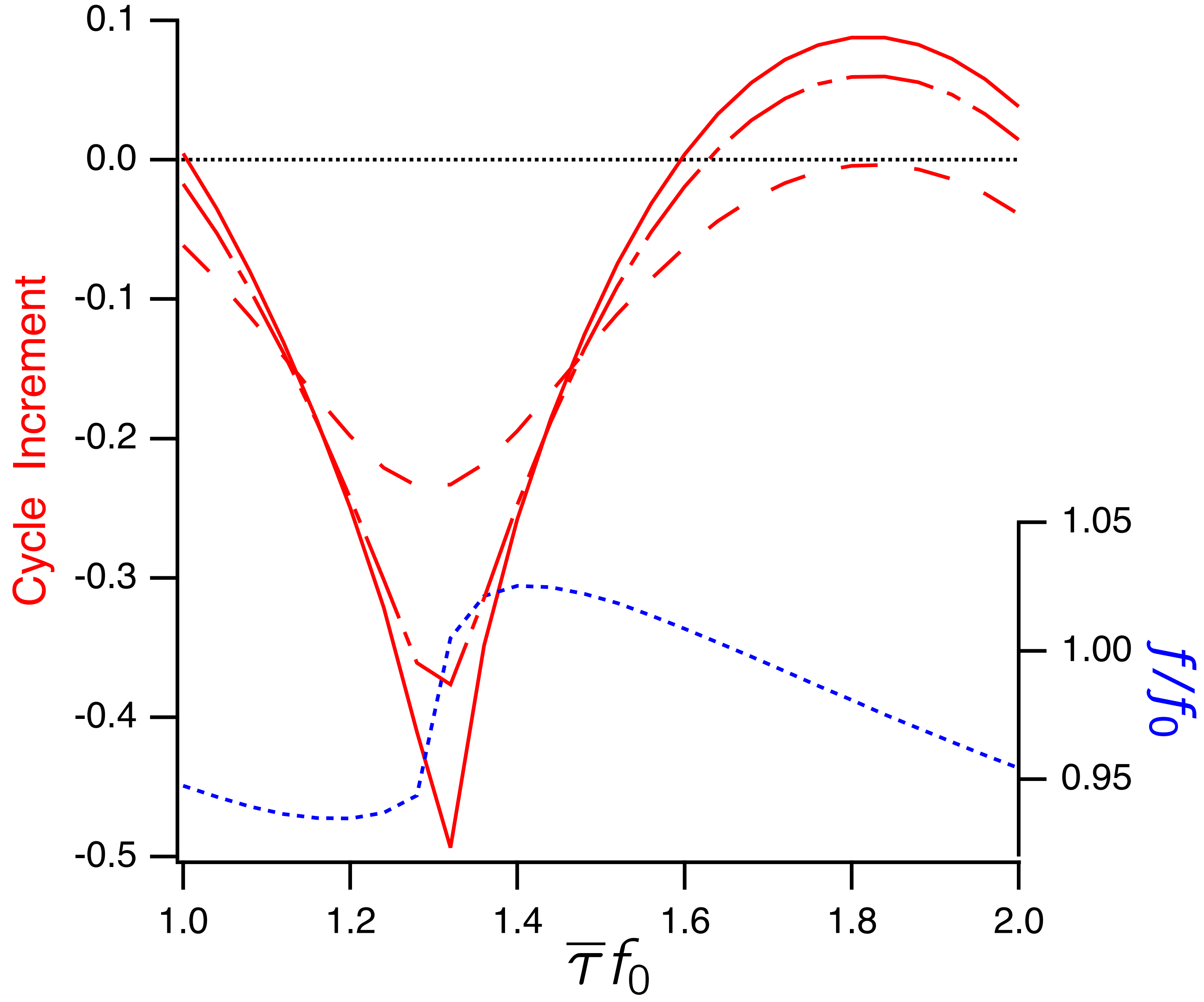
Distributed delays tend to stabilize combustion instabilities – but the mean delay is more important

Gaussian distribution of time delays:



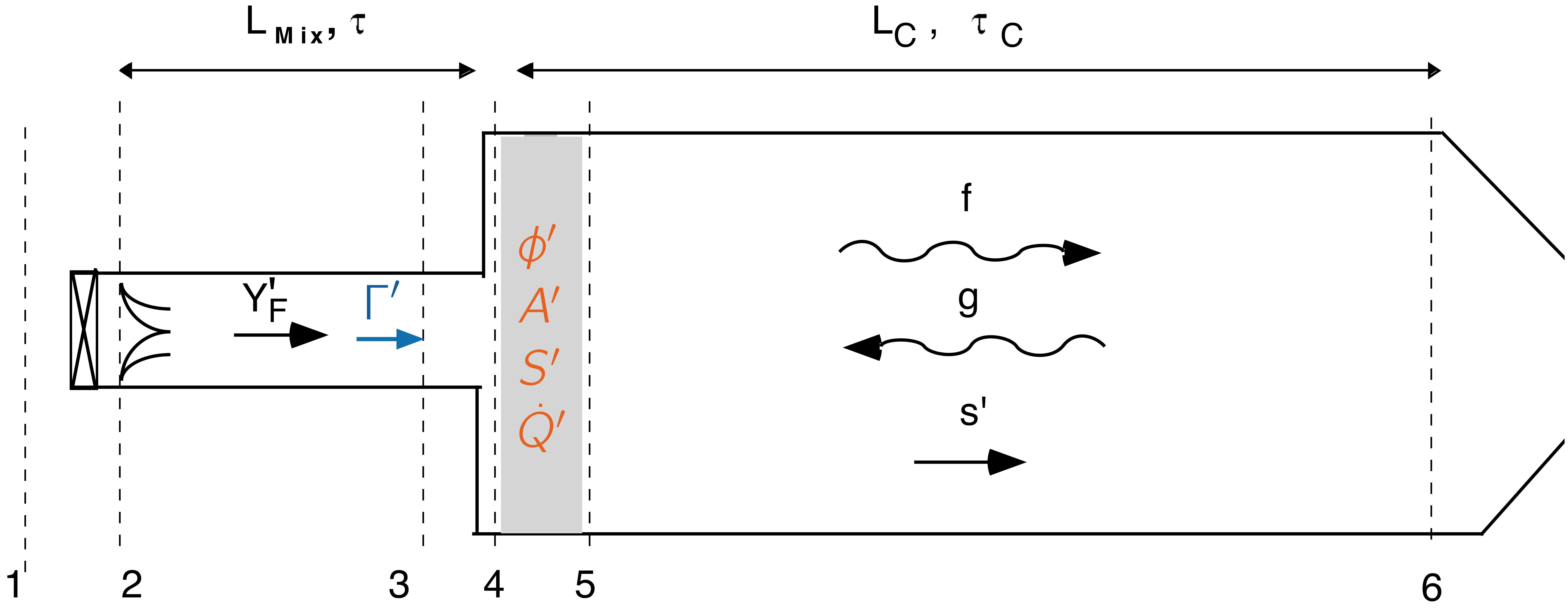
Change in growth rate and frequency with mean and width of time delay distributions:





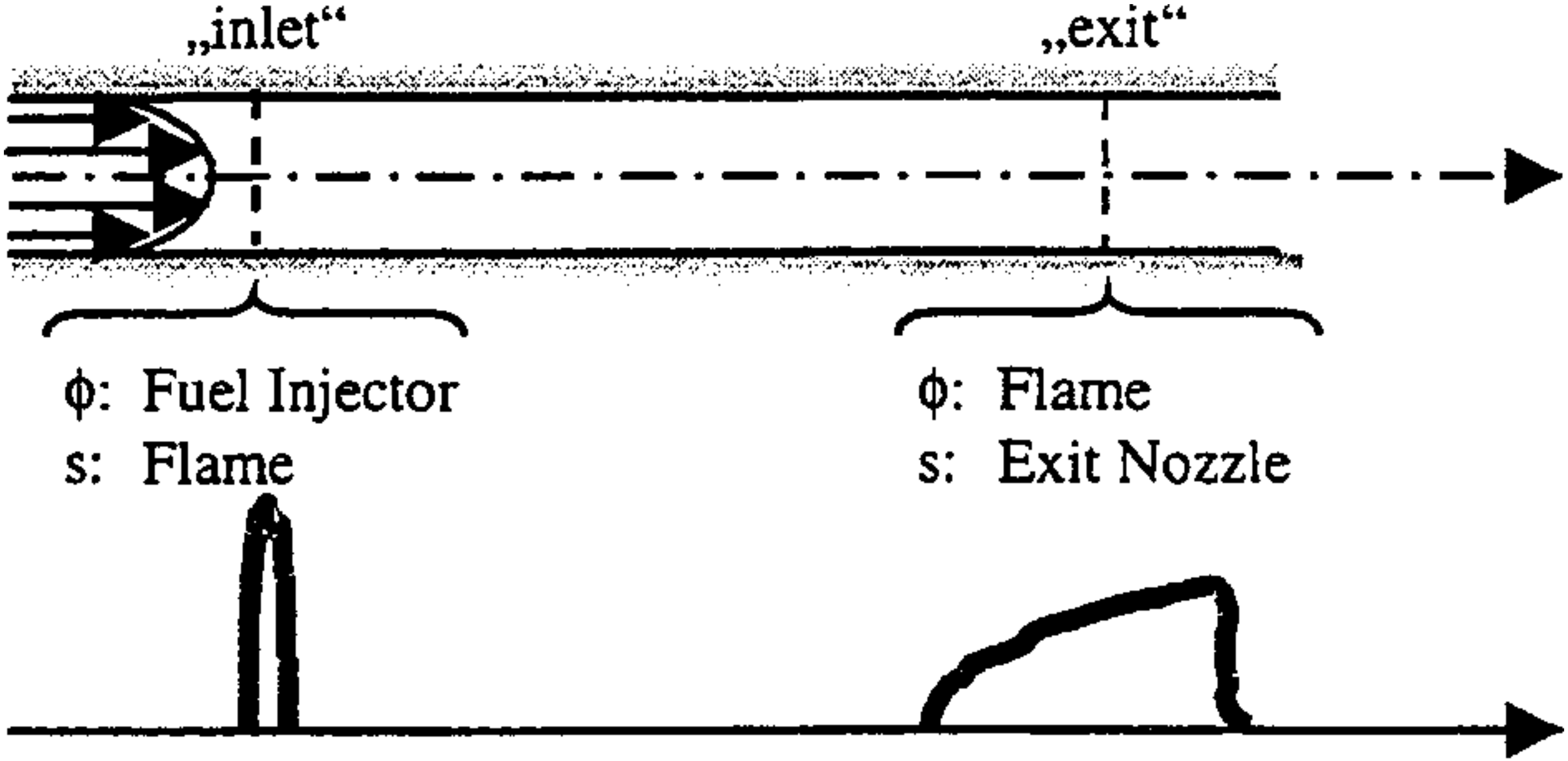
Kopitz and Polifke, 2001

Fluctuations of equivalence ratio at the flame will give rise to entropy waves, which may contribute to thermoacoustic instability or combustion noise



Keller et al. 1985
Keller 1995
Polifke et al. 2001
Sattelmayer 2003

Shear dispersion or *distributed fuel injection* or an *elongated / distorted flame* will result in a distribution of entropy transport time lags



Sattelmayer, 2003
Morgans, 2013
Wassmer, 2018

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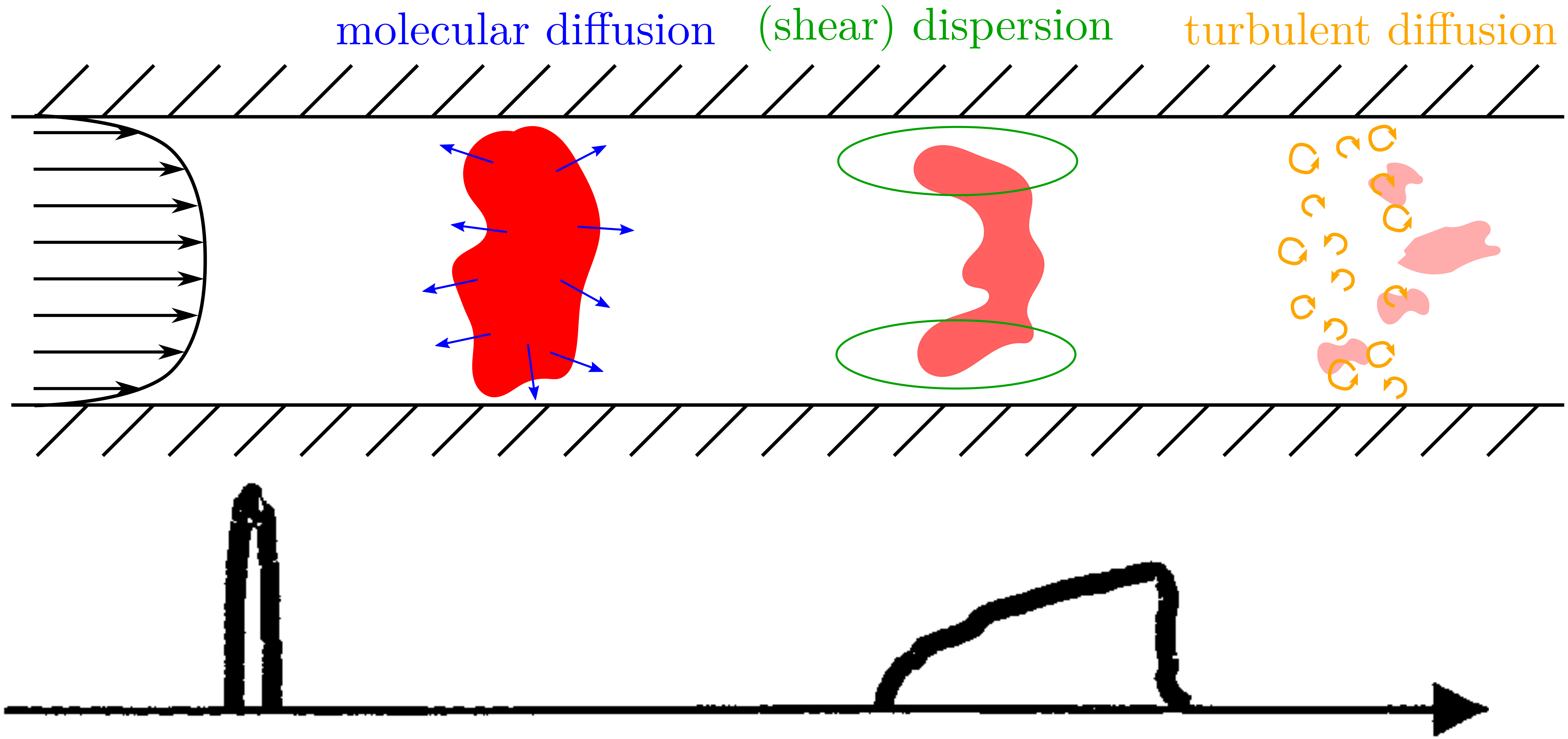
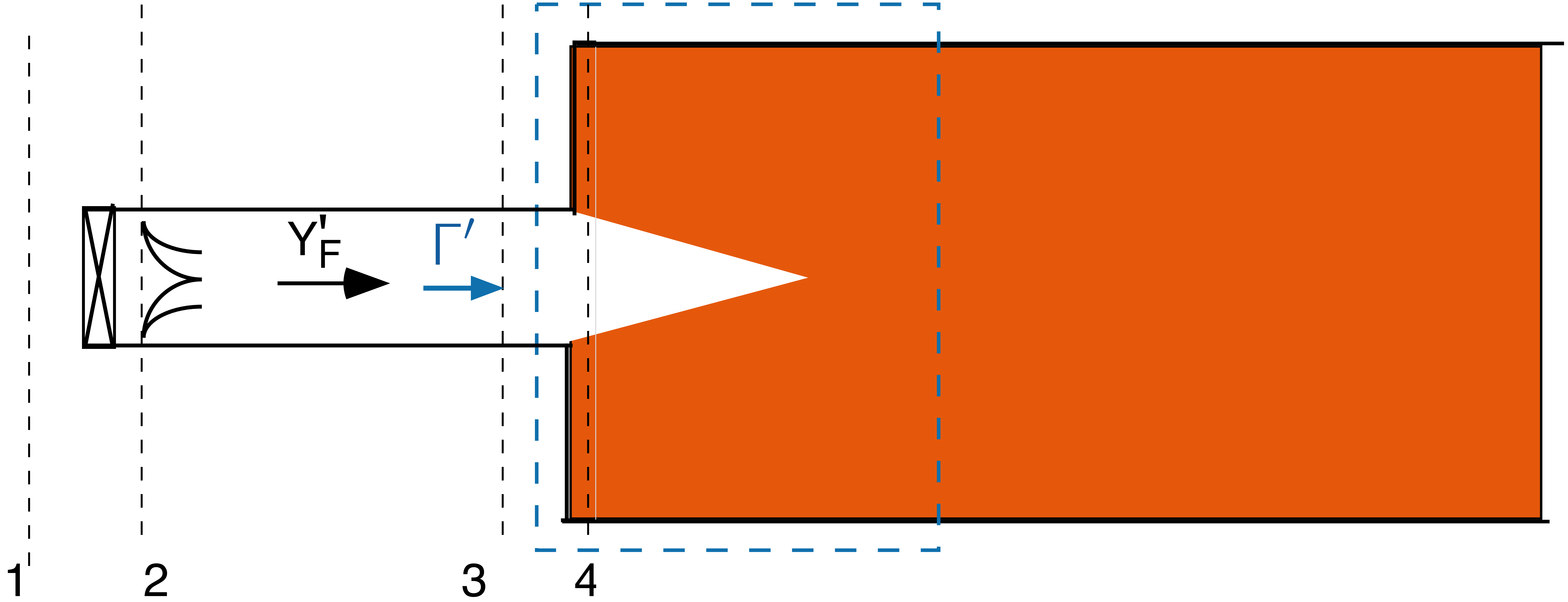


Sattelmayer, 2003
Morgans, 2013
Wassmer, 2018

Don’ be fooled by the 2nd Law of Thermodynamics – $s' \neq \frac{\dot{Q}'}{T}$



Polifke et al., 2001,
Strobio Chen et al., 2016, 2017

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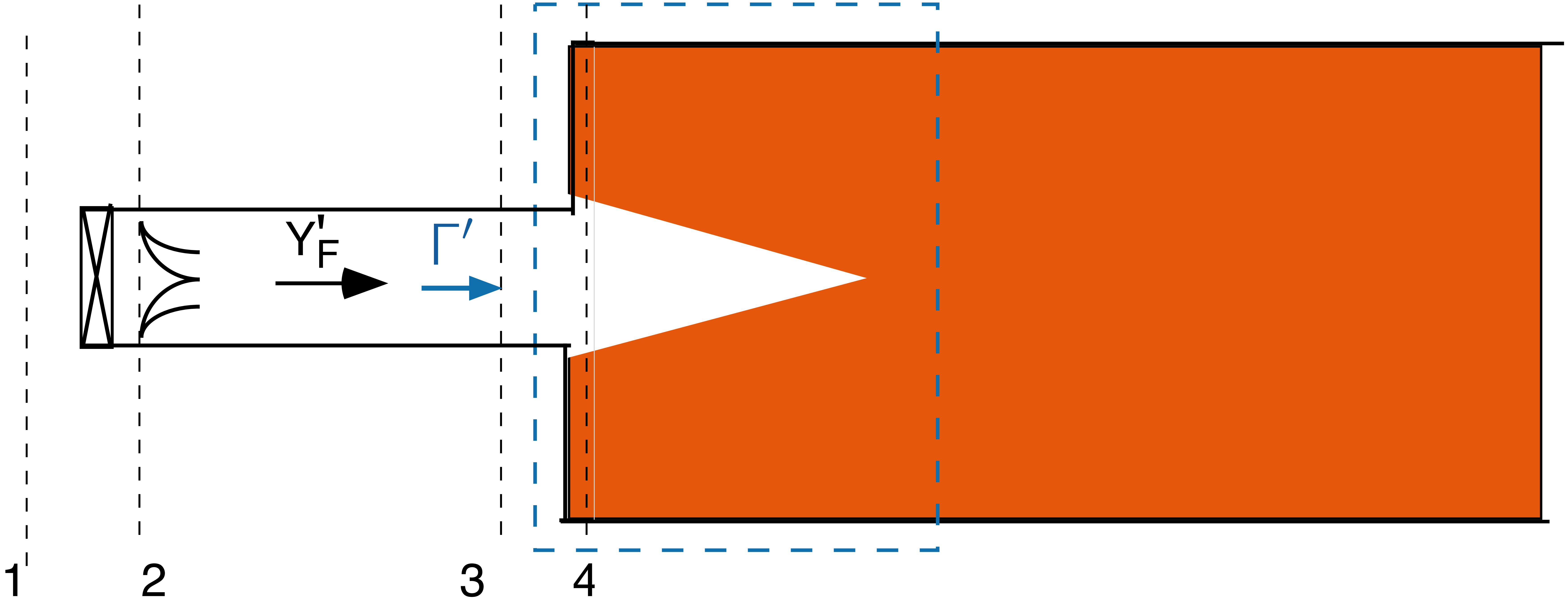
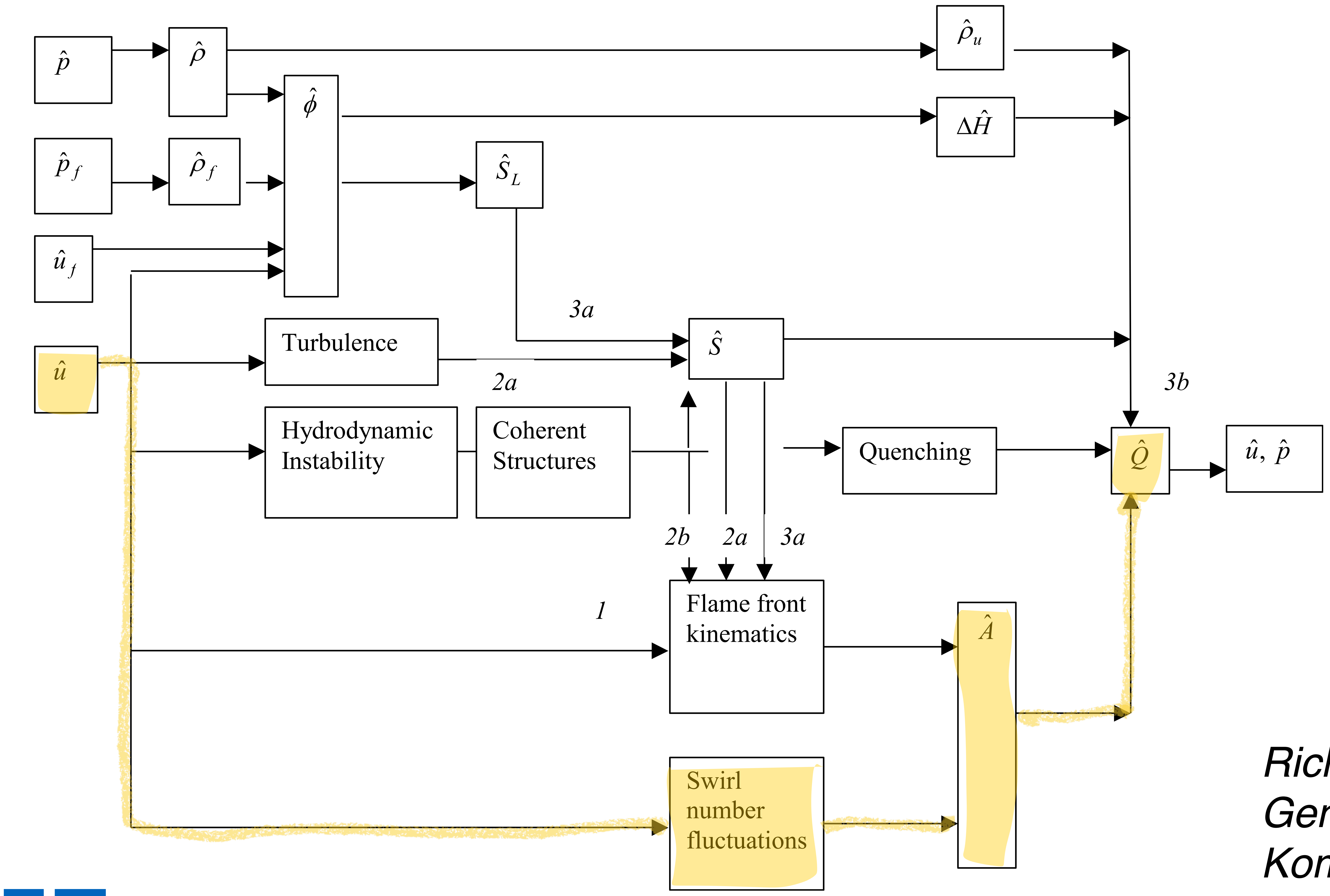


$$\int_V \rho s dV = \int_{\partial V} \rho s \vec{u} \cdot d\vec{A} + \int_V \frac{\dot{q}}{T} dV$$

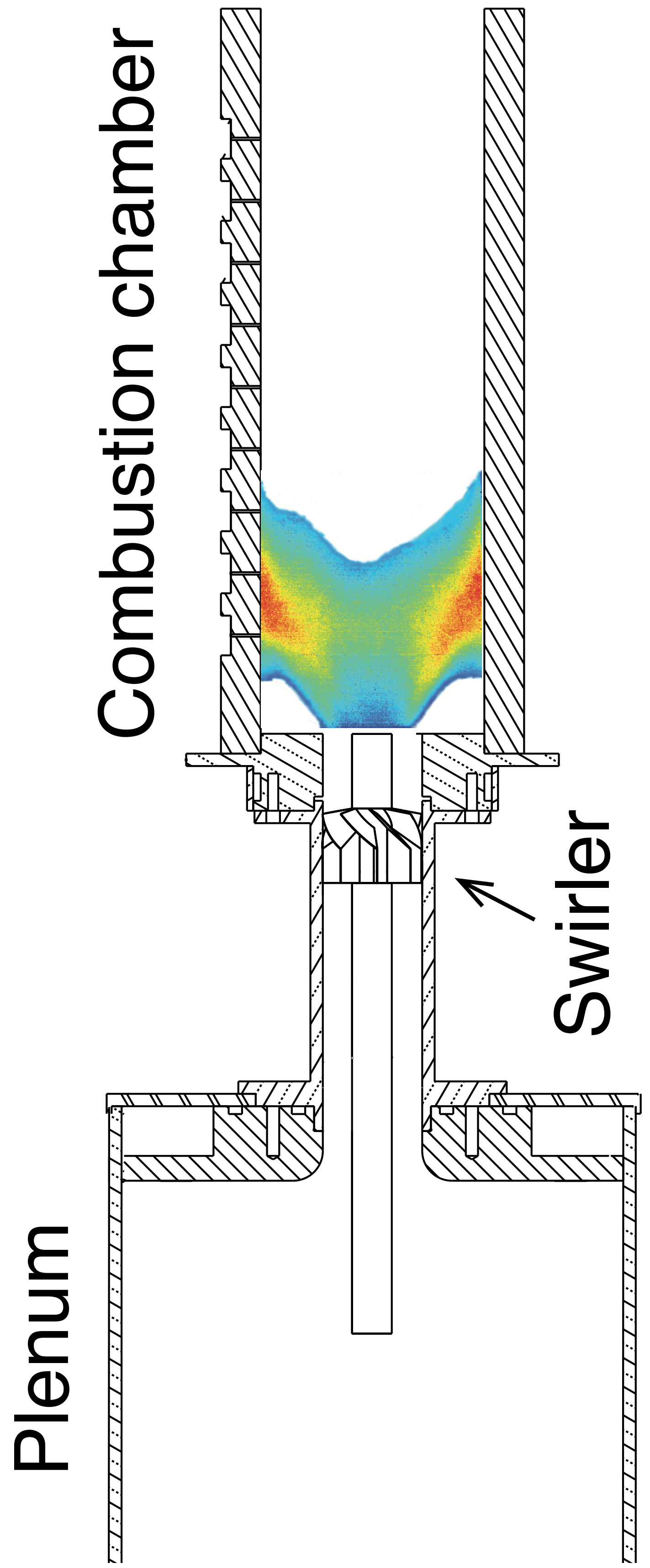
Polifke et al., 2001,
Strobio Chen et al., 2016, 2017

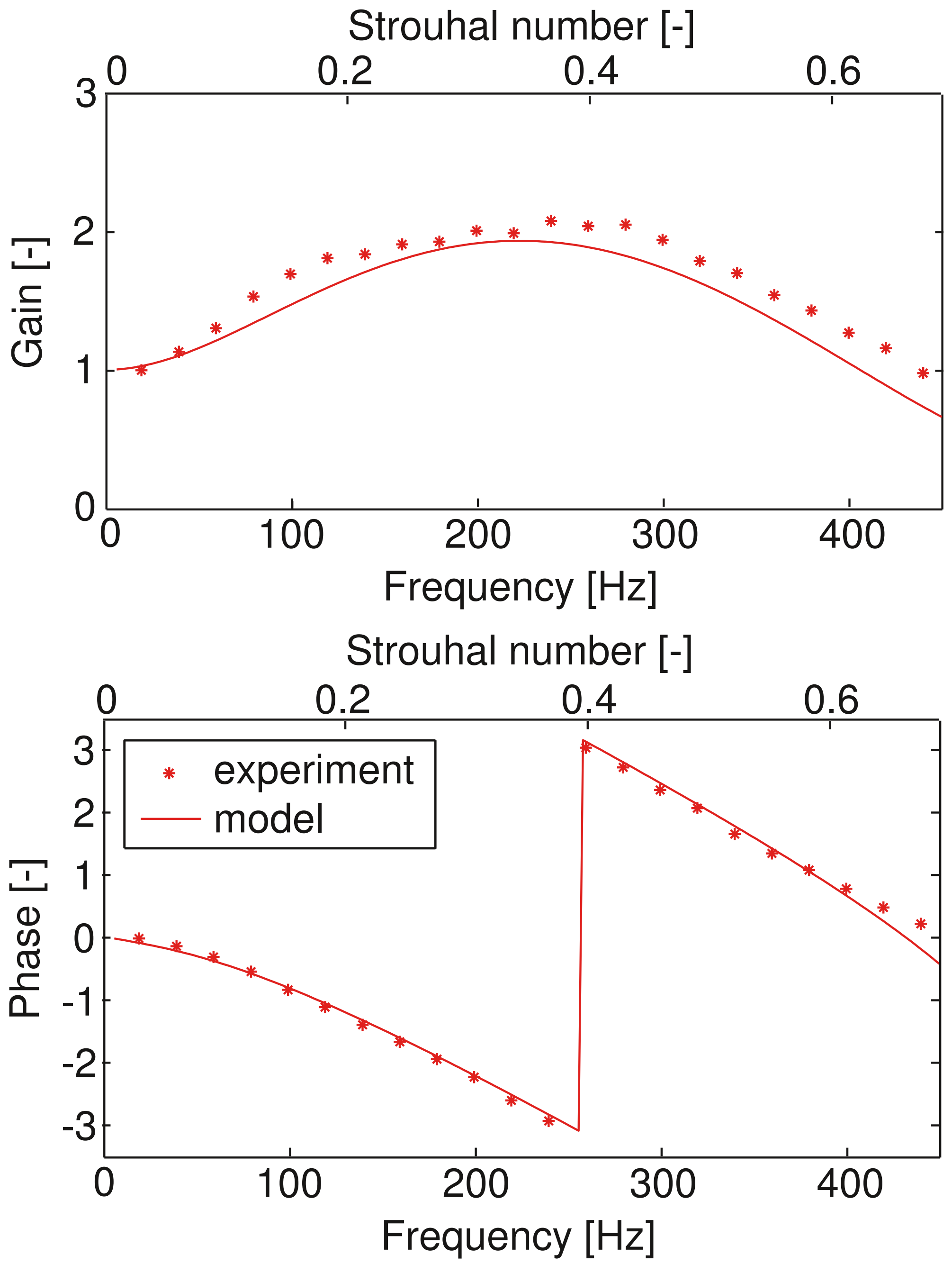
Flow oscillations across a swirl generator will result in „swirl waves", which may induce fluctuations of heat release rate



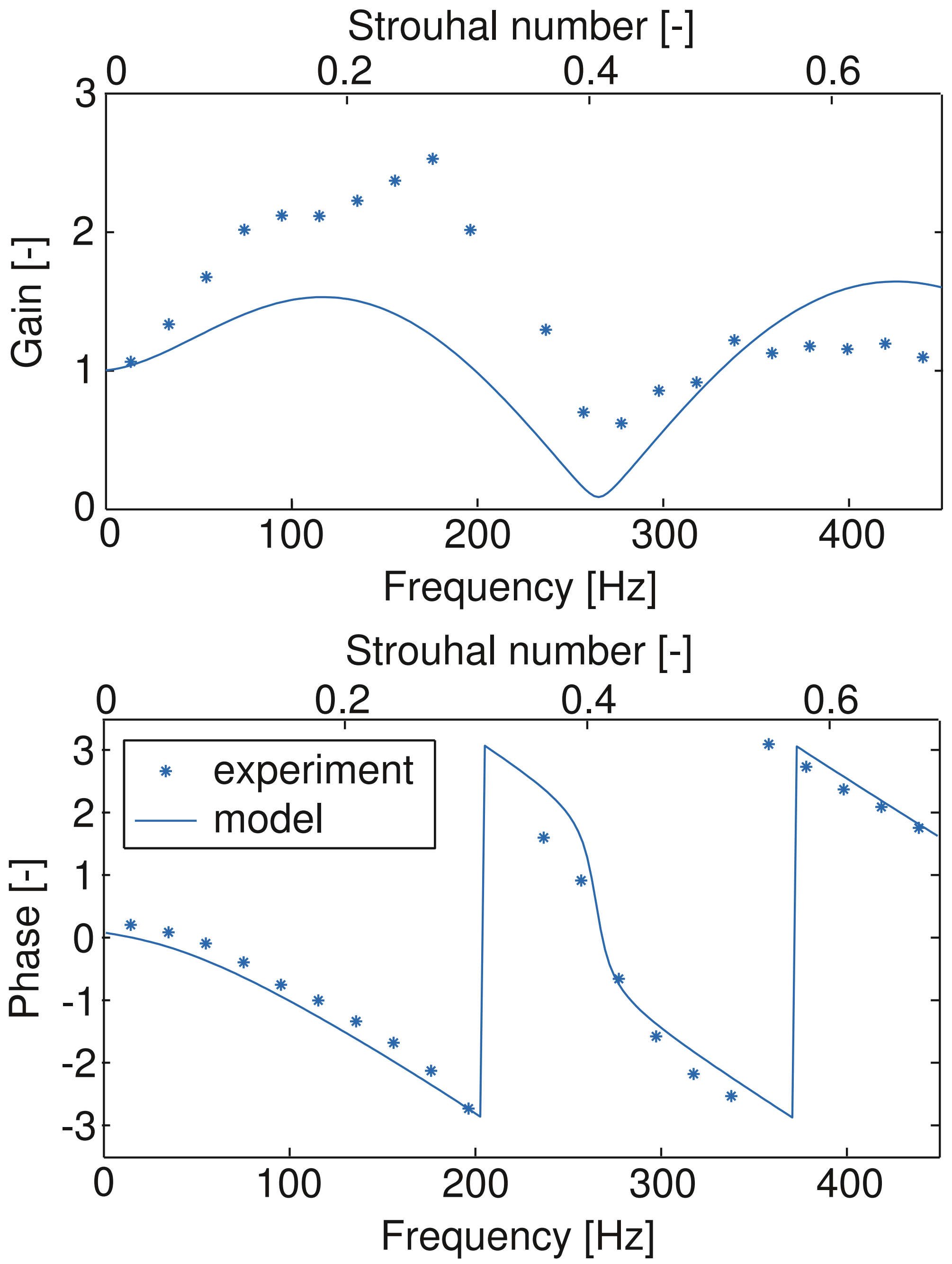
Richards et al, 1999
Gentemann et al, 2004
Komarek and Polifke, 2009
Palies et al, 2010

Con-/destructive superposition of the respective responses to swirl and velocity perturbations shapes the overall flame response (FTF) of the BRS burner

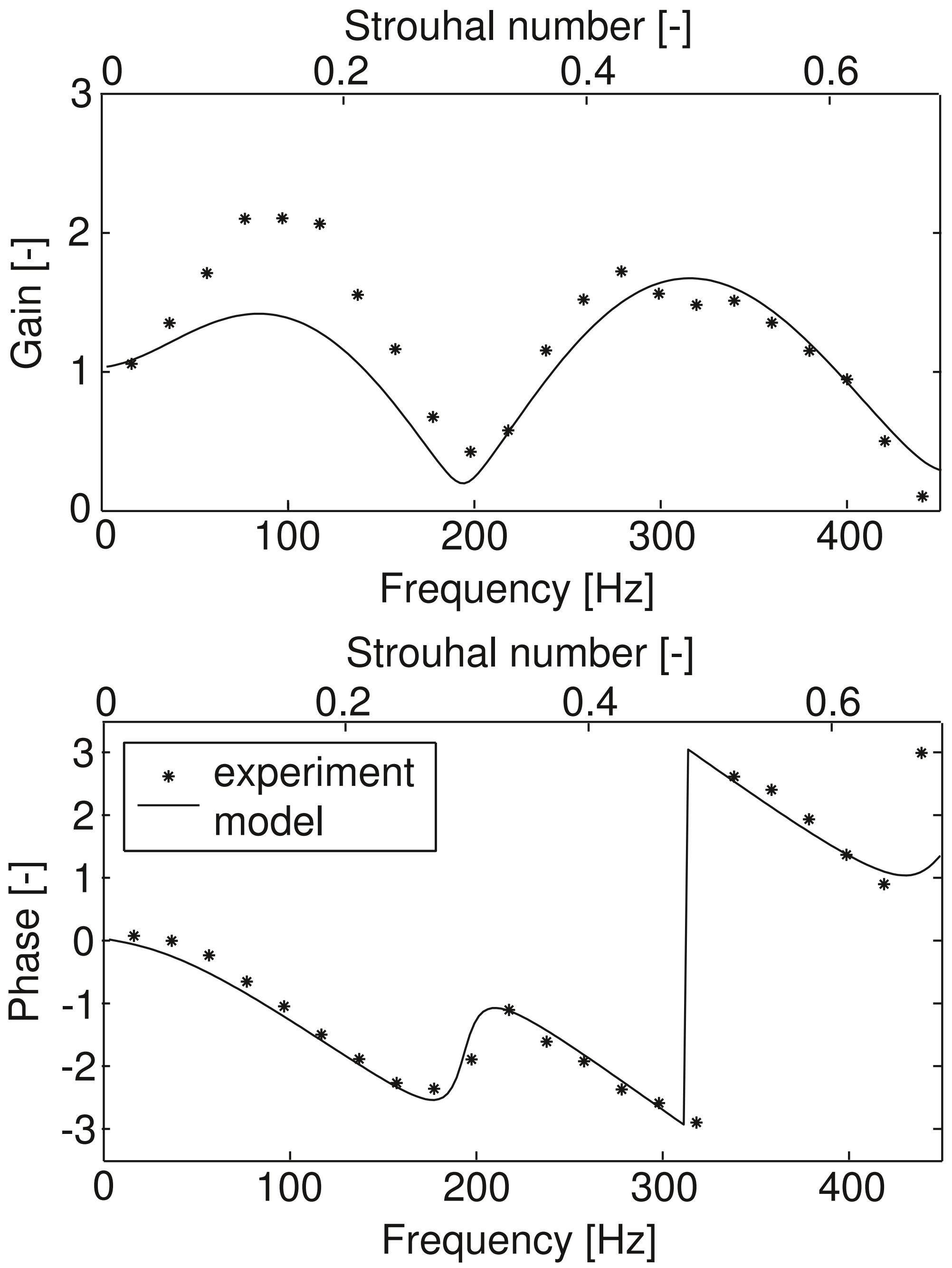




(a) Swirler at $\Delta x = 30\mathrm{mm}$



(b) Swirler at $\Delta x = 90\mathrm{mm}$



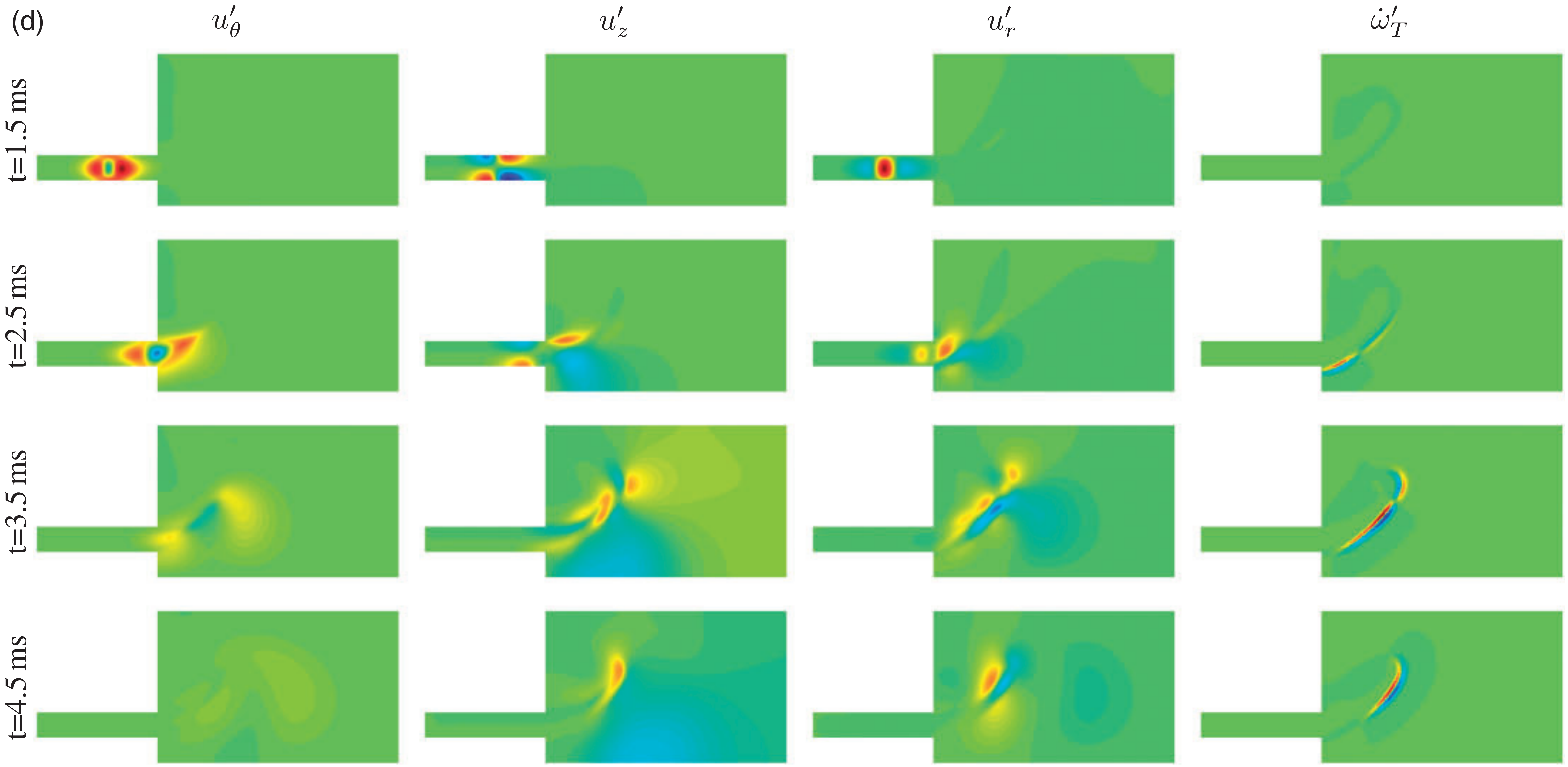
(c) Swirler at $\Delta x = 130\mathrm{mm}$

A simple model for the flame resonse: triple $n - \tau - \sigma$

$$h_k = \underbrace{\frac{1}{\sigma_1\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{k\Delta t-\tau_1}{\sigma_1}\right)^2}}_{\text{response to mass flow rate}} + \underbrace{\frac{1}{\sigma_2\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{k\Delta t-\tau_2}{\sigma_2}\right)^2} - \frac{1}{\sigma_3\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{k\Delta t-\tau_3}{\sigma_3}\right)^2}}_{\text{response to circulation}},$$

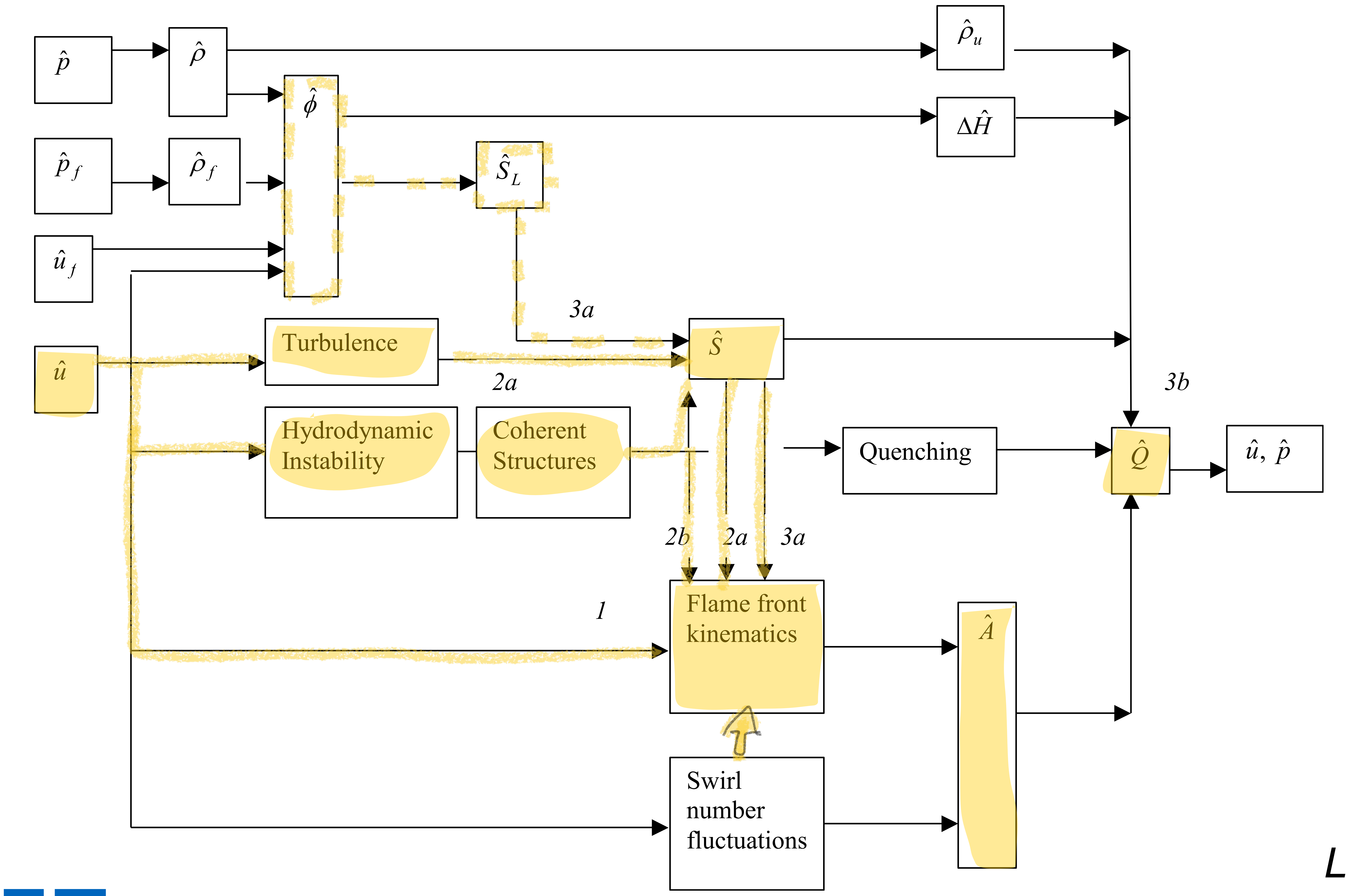
Komarek and Polifke, 2009

Swirl waves are not „convective waves”, but *inertial waves* with non-convective propagation speed and axial as well as radial components



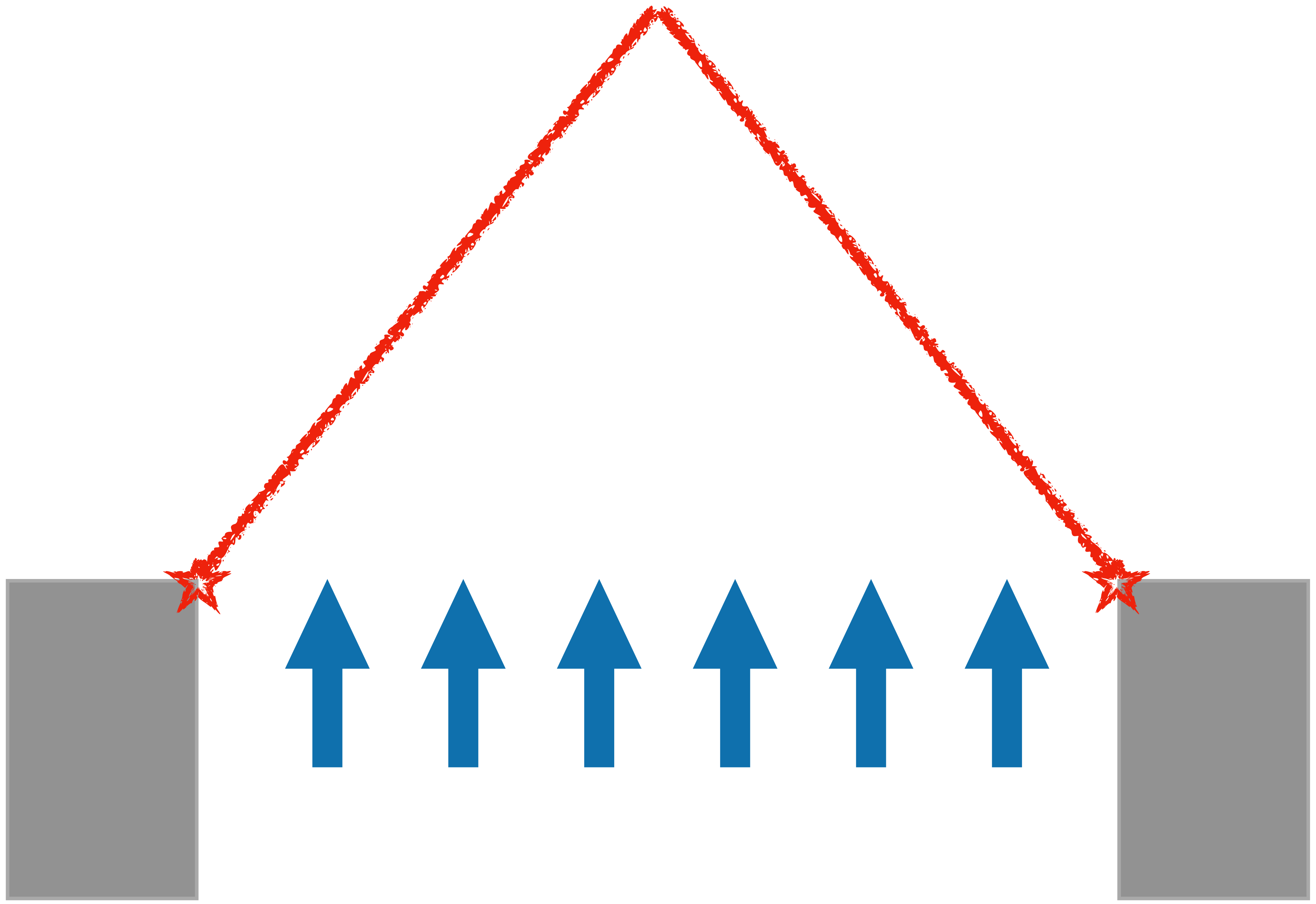
Albayrak et al. 2017, 2019

Front Kinematics

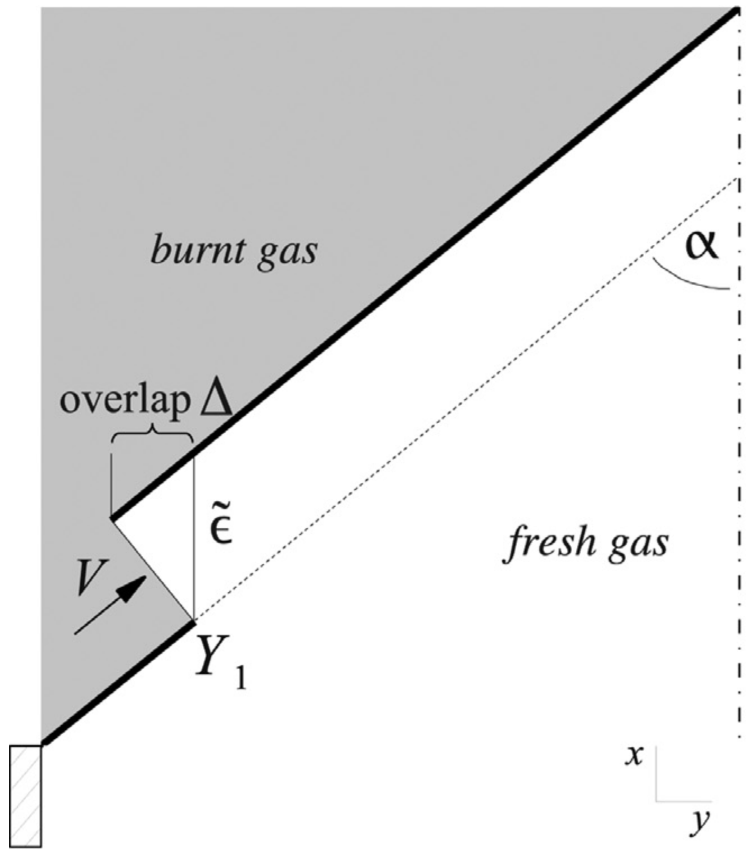


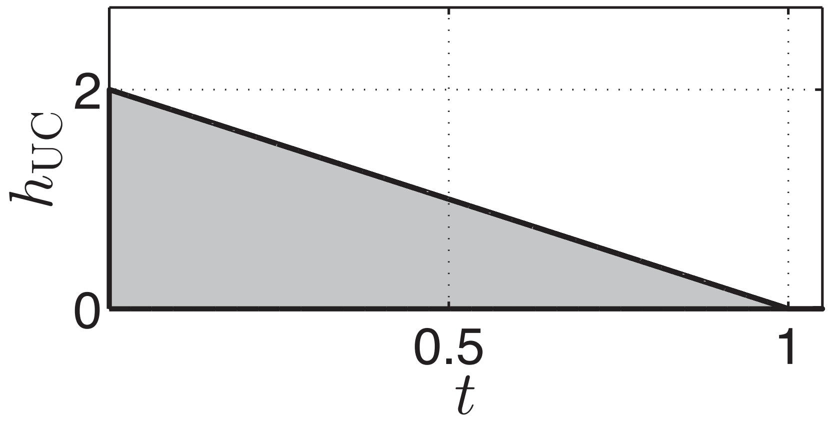
Lawn and Polifke 2004

An flow perturbation disturbs the kinematic balance between convection, diffusion and reaction in a flame



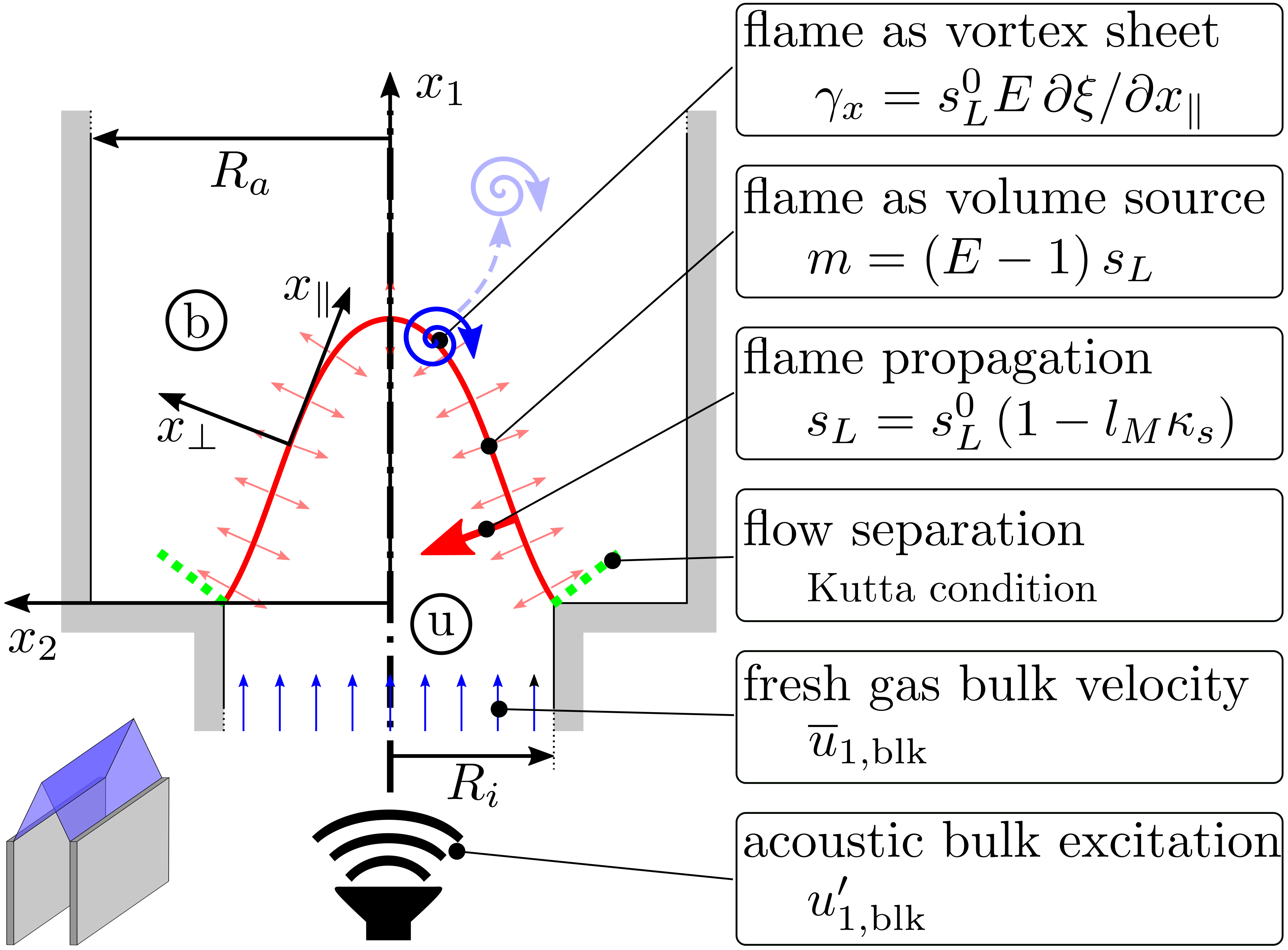
After the perturbation, the original flame shape is restored convectively, which results in a delayed response of heat release rate





Blumenthal et al, 2013

A premixed flame front is not merely convected by the flow, but also acts on the flow: decrease in density & generation of vorticity



flame as vortex sheet
$\gamma_x = s_L^0 E\,\partial\xi/\partial x_\parallel$

flame as volume source
$m = (E-1)\,s_L$

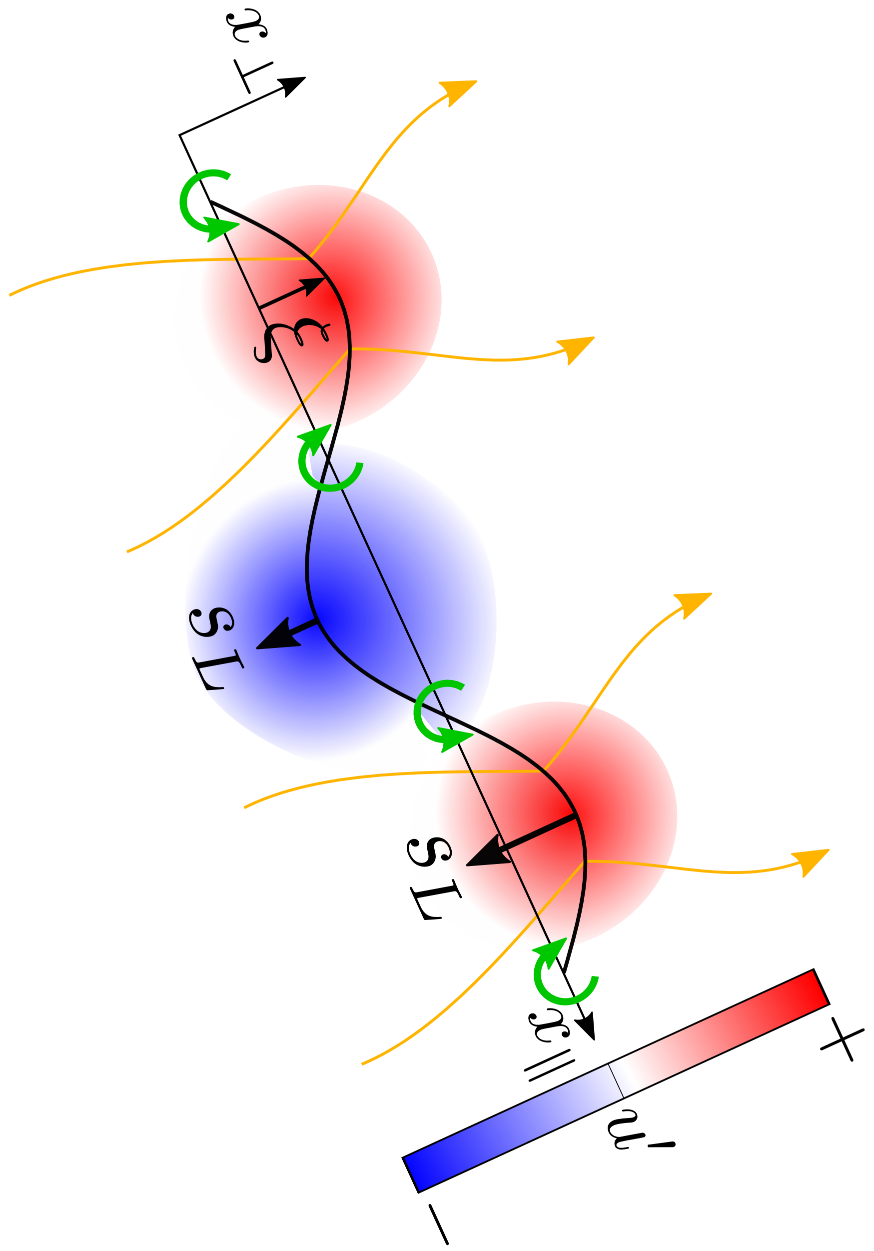
flame propagation
$s_L = s_L^0\,(1 - l_M \kappa_s)$

flow separation
Kutta condition

fresh gas bulk velocity
$\overline{u}_{1,\mathrm{blk}}$

acoustic bulk excitation
$u'_{1,\mathrm{blk}}$

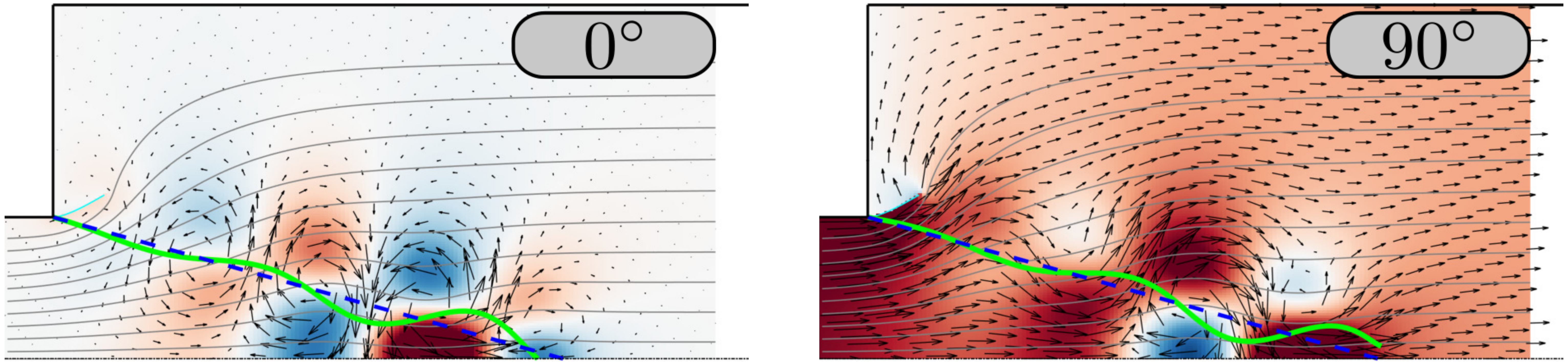
Flame front wrinkles are amplified by vorticity generated by the wrinkles:



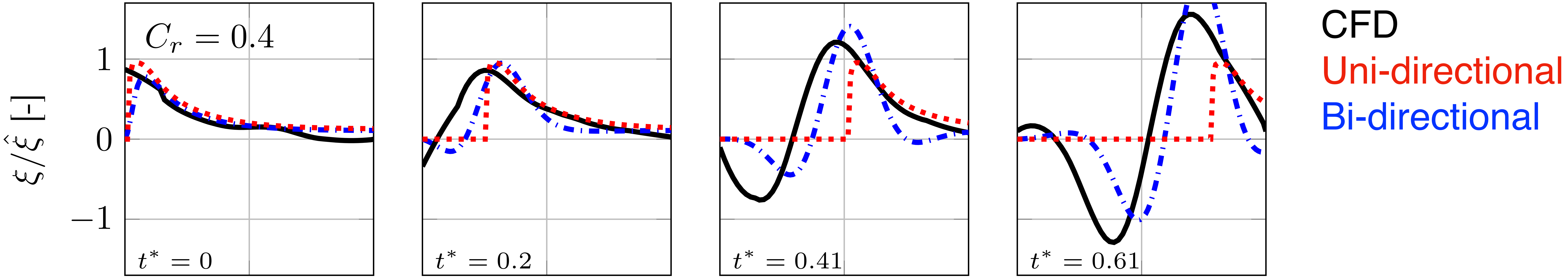
Steinbacher and Polifke 2022

Flame-flow interactions have a significant impact on the flame response

Harmonic forcing:



Flame displacement after impulse forcing with/out bi-direction coupling



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