Importance of Thermoacoustics in LES of Combustion Noise in Realistic Confined conditions

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MAMBO Workshop - ONERA Châtillon

October 18th, 2013

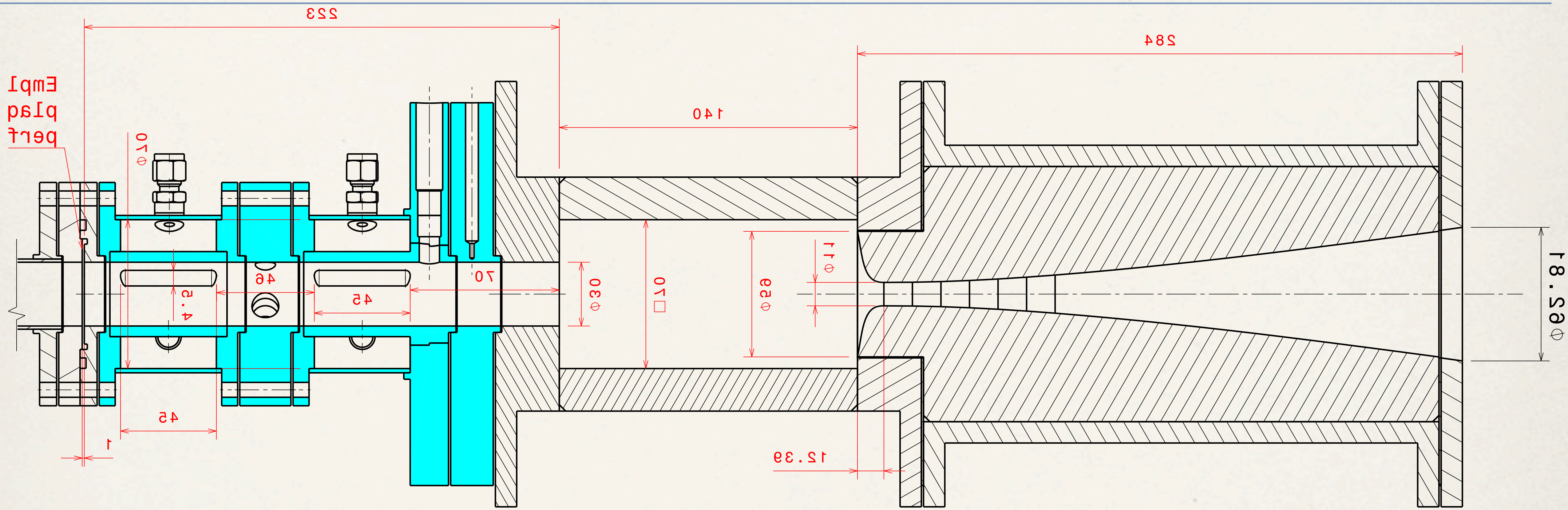
Introduction

- The study of combustion noise of realistic flames implies the need of confined lean premixed configurations
- Confined academic test cases are non dissipative, and can lead to thermoacoustic instabilities
- Thermoacoustic limit cycles can entirely mask combustion noise levels. They must be adressed in order to study combustion noise

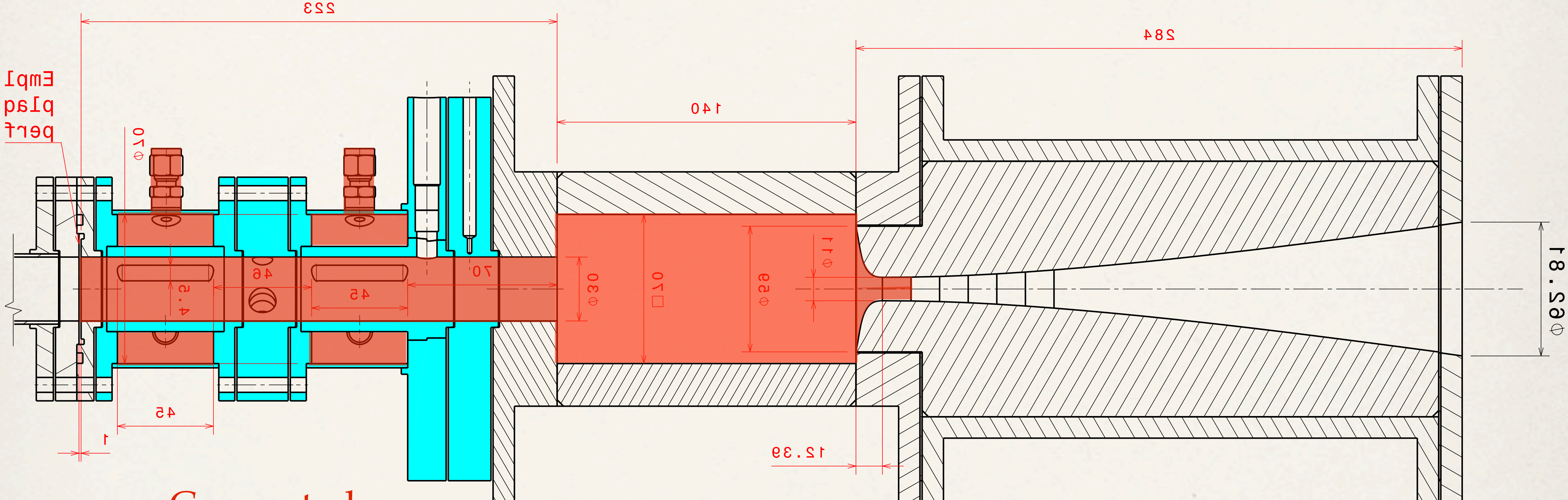
Thermoacoustic	~ 1 - 10 % P_0
Comb. noise	~ 0.01 - 1 % P_0

I - THE CESAM-HP SETUP

Geometry

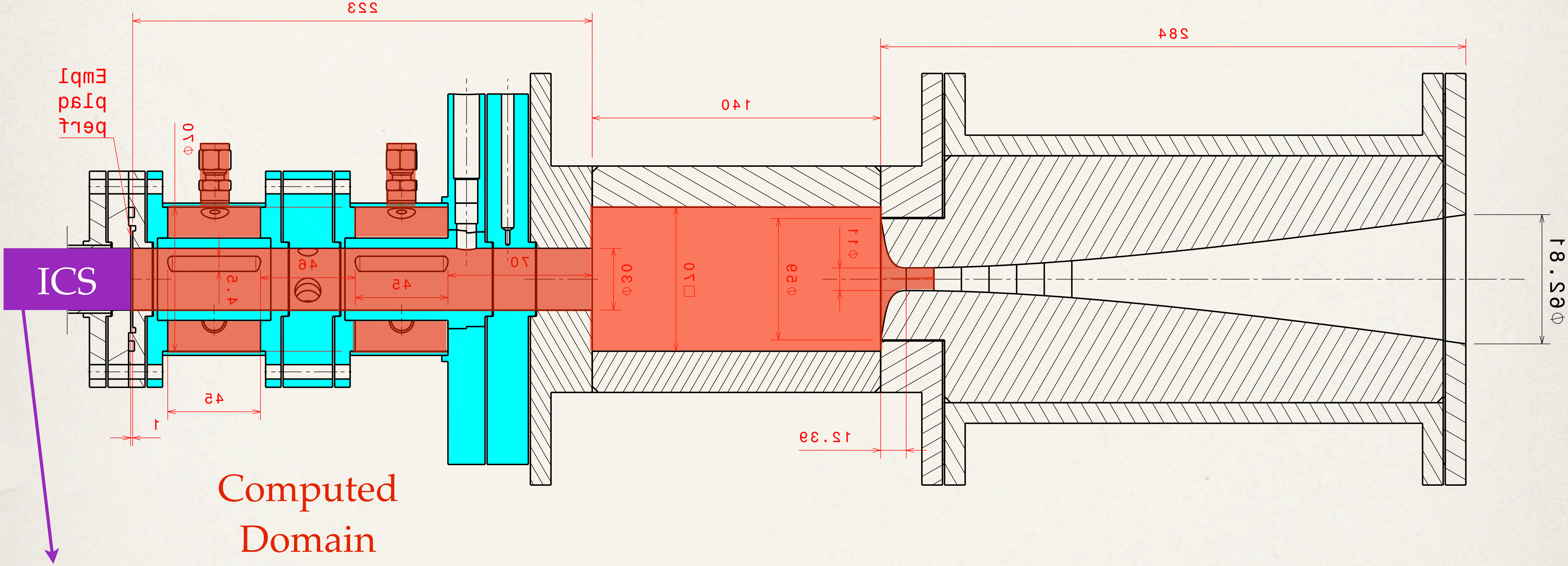


GEOMETRY



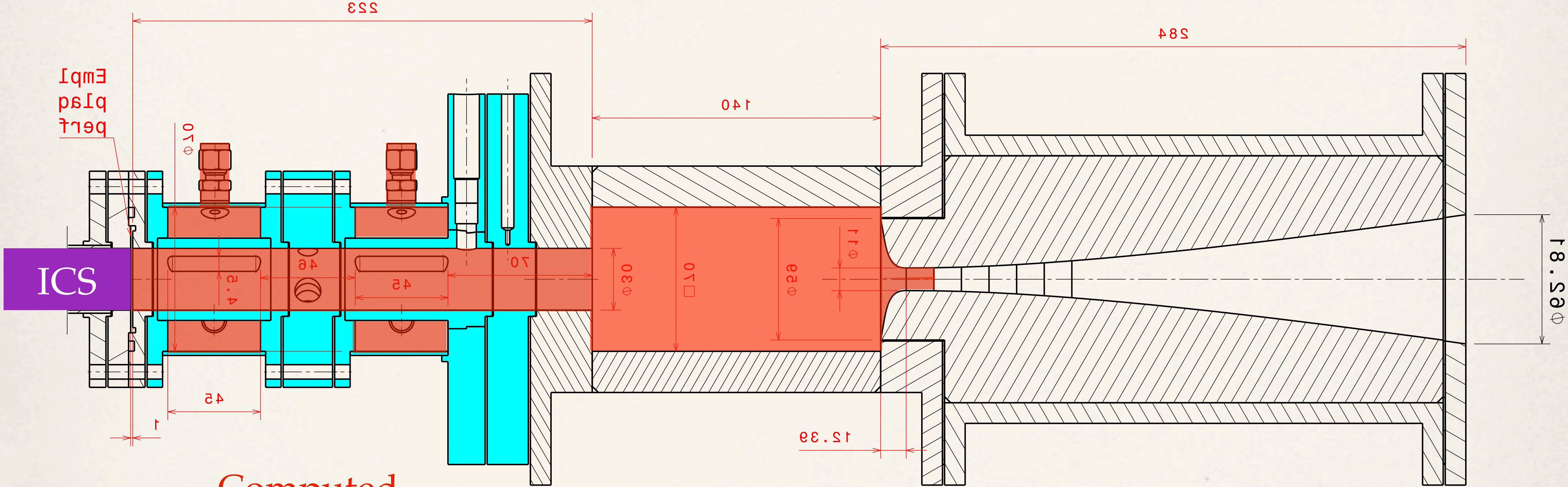
Computed Domain

Geometry



Impedance Control Machanism (ICS) developped at EM2C

GEOMETRY



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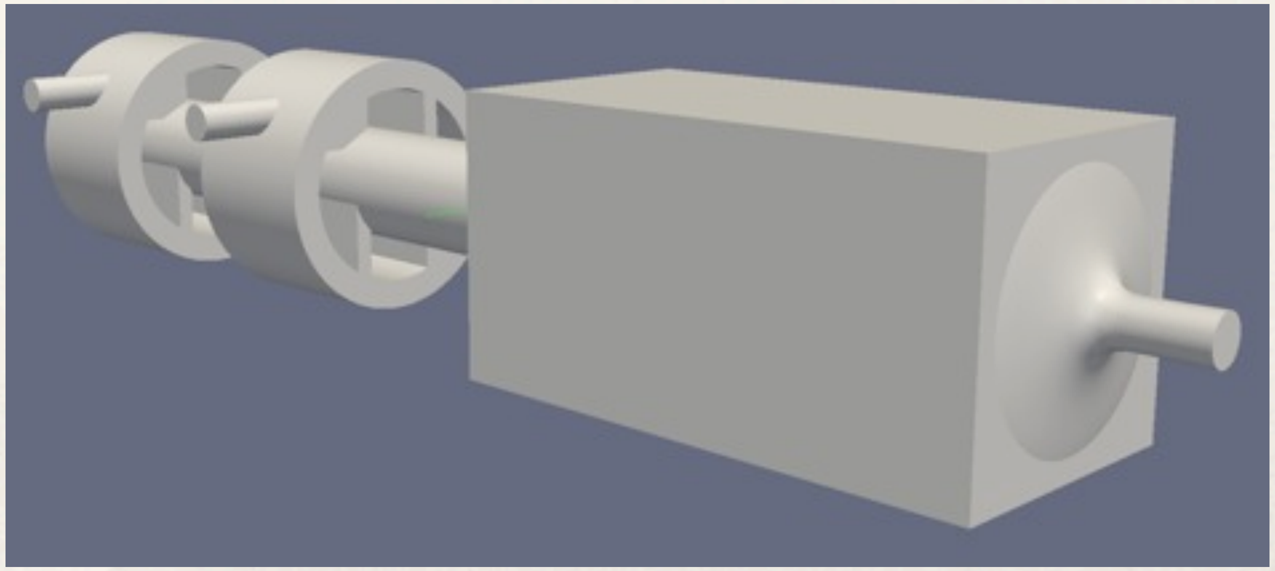

OPERATING POINT

- Test bench maximum target pressure is 2.5 bars (choked flow)
- Indirect combustion noise is strong for strong outlet Mach [1][2]
- Supersonic outlet is easier to fit numerically : no outlet impedance is needed

[1] Leyko, M., Nicoud, F., & Poinsot, T. (2009). Comparison of direct and indirect combustion noise mechanisms in a model combustor. AIAA journal, 47(11), 2709-2716.
[2] Duran, I., & Moreau, S. (2013). Solution of the quasi-one-dimensional linearized Euler equations using flow invariants and the Magnus expansion. Journal of Fluid Mechanics, 723, 190-231.

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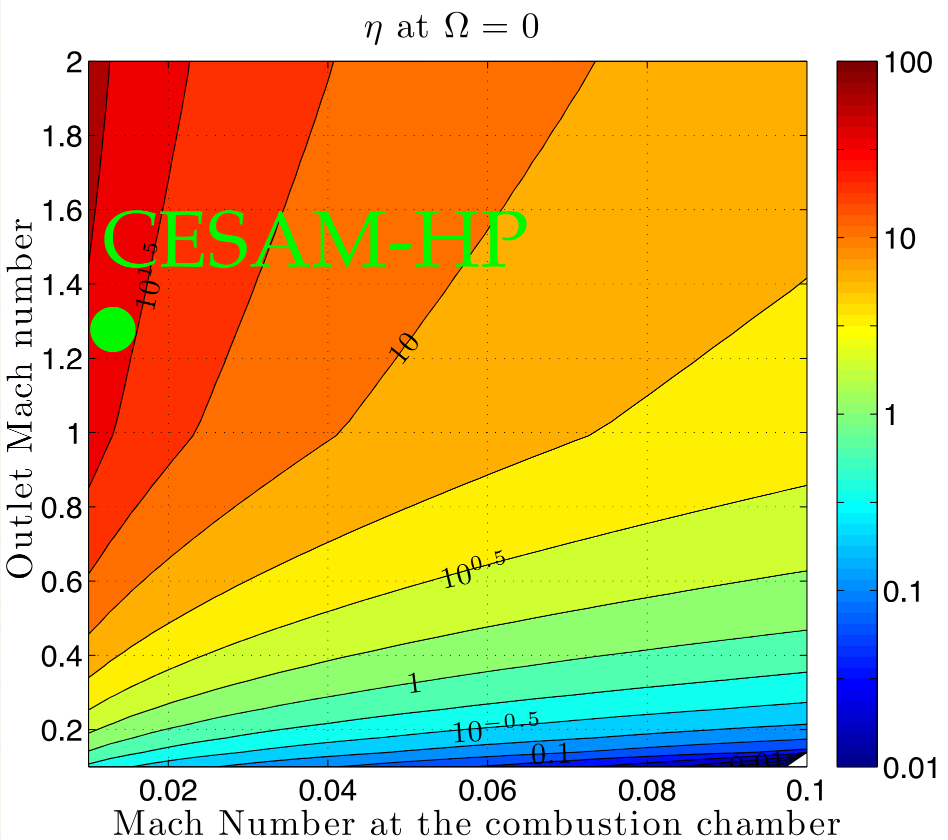

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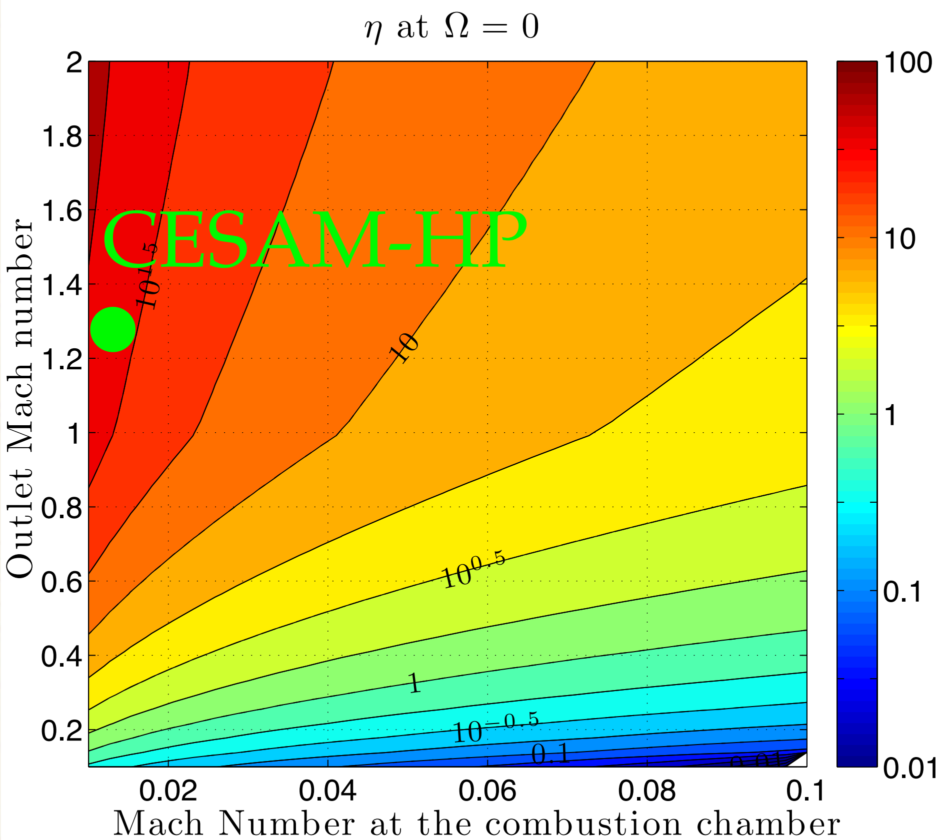

P (bars)	Tin (K)	mfr (g/s)	ϕ	Fuel
2.5	300	18	0.9	C_3H_8

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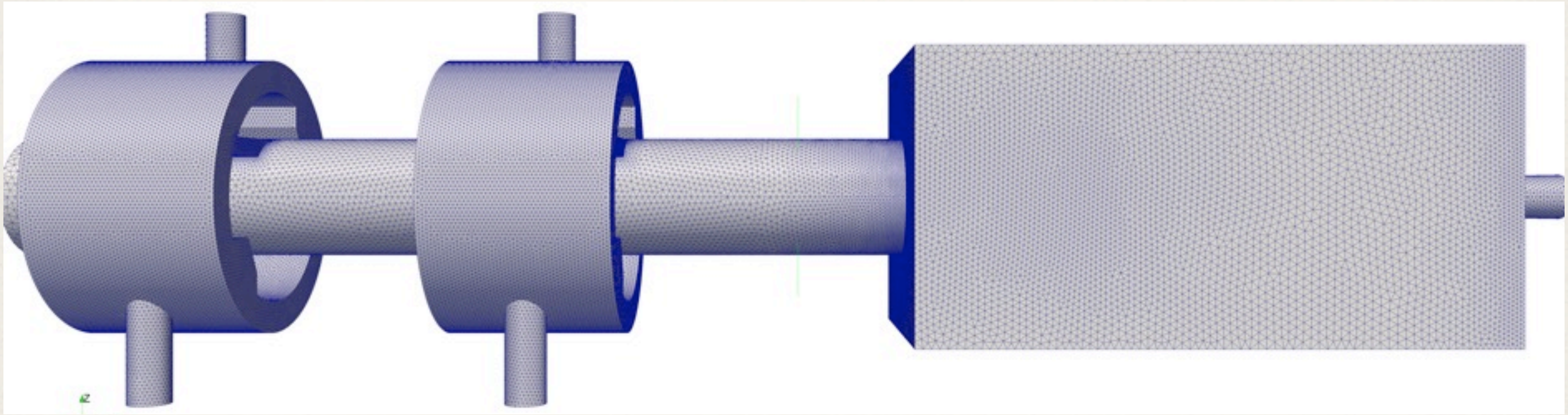
FLOW SOLVER : AVBP

Nb nodes	Nb cells	Smallest cell	Biggest cell
1 M	5 M	0.5 mm	2 mm



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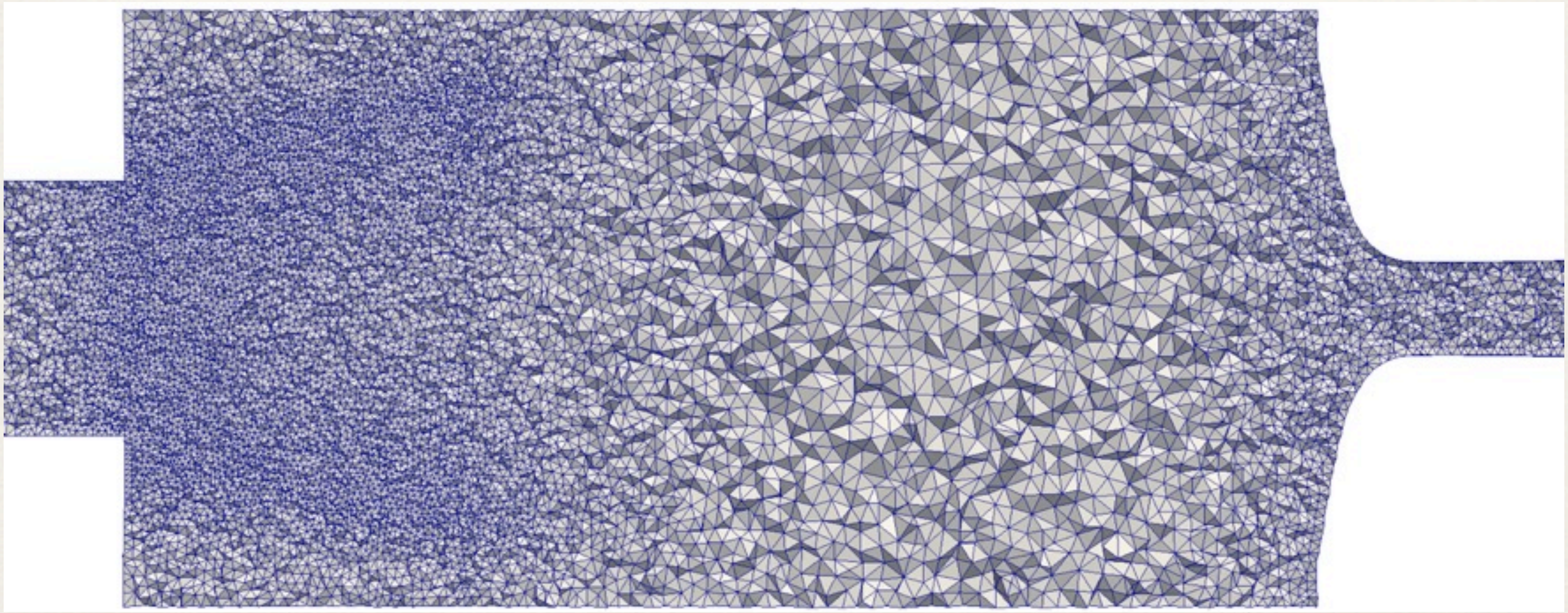

HELMHOLTZ SOLVER : AVSP [1]

- Mesh is coarser for Helmholtz solver
- Since AVSP assumes *zero Mach,* nozzle is truncated from domain. Nozzle impedance is determined using the Magnus expansion as described by Duran [1]
- Sound speed computed from mean AVBP solution

[1] Selle, L., Benoit, L., Poinsot, T., Nicoud, F., & Krebs, W. (2006). Joint use of compressible large-eddy simulation and Helmholtz solvers for the analysis of rotating modes in an industrial swirled burner. Combustion and Flame, 145(1), 194-205.

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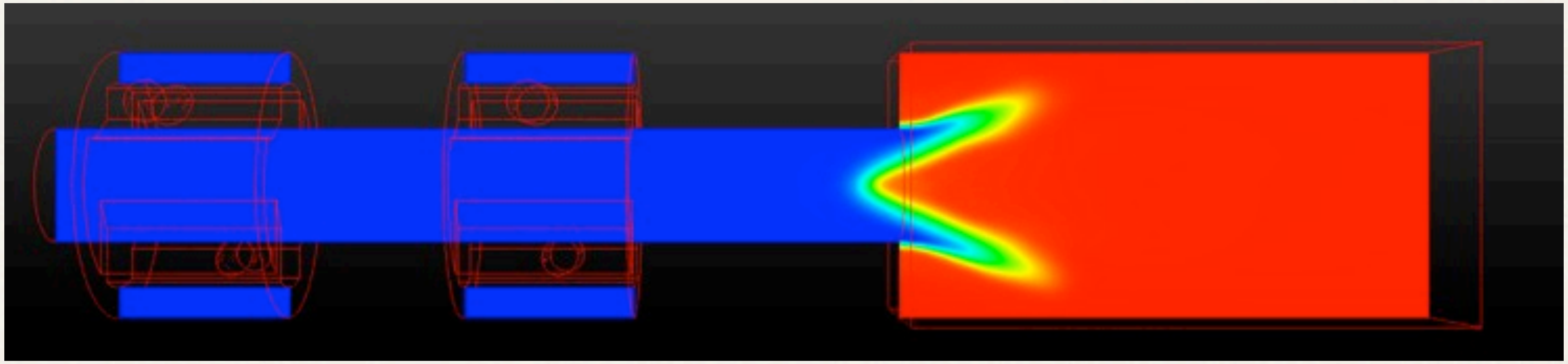

Mean sound speed

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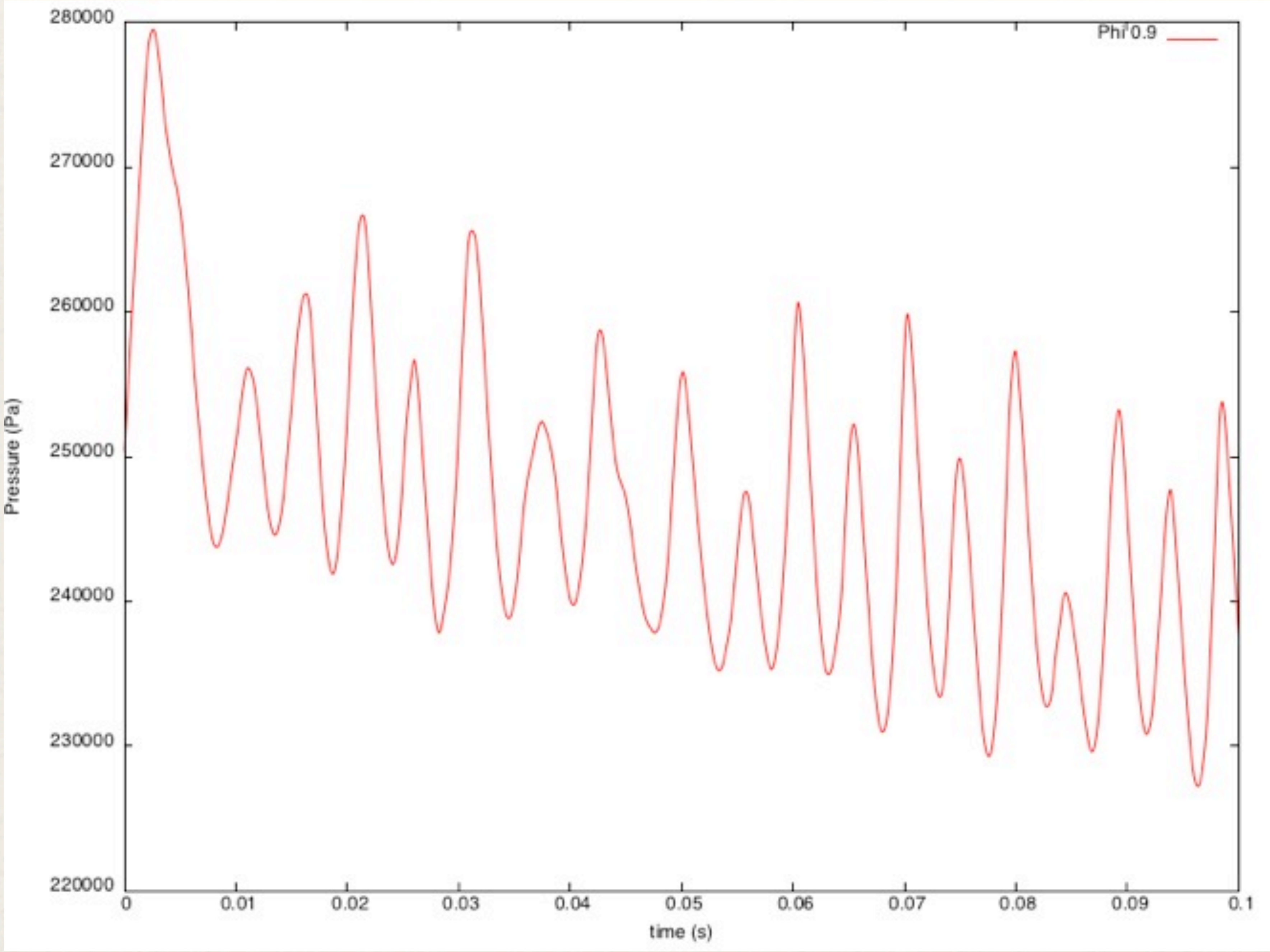
Mean Pressure (AVBP run)

- AVBP simulations are performed for the chosen operating point
- They exhibit a strong instability around 200 Hz :

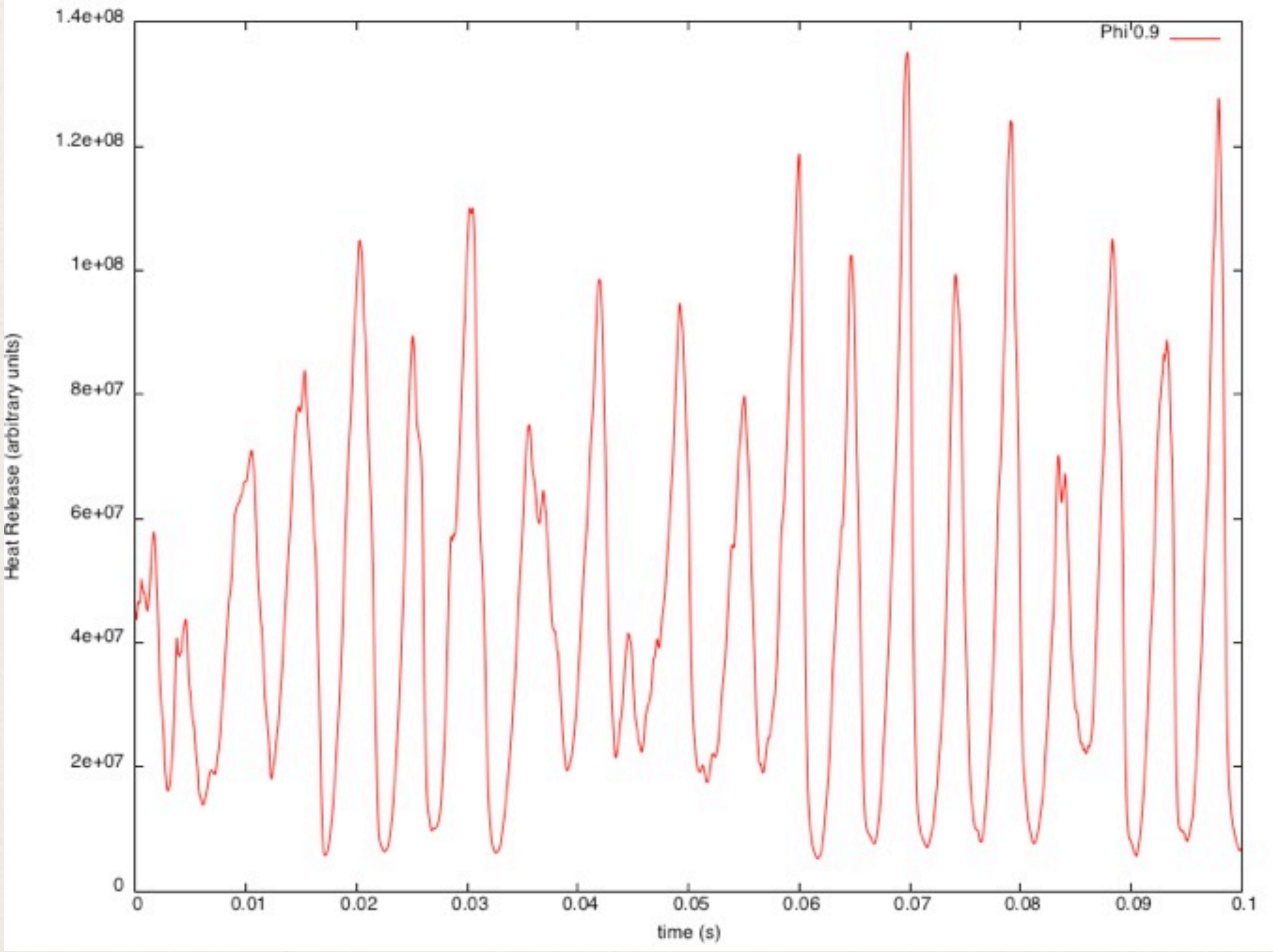
MEAN PRESSURE (AVBP RUN)



$P' \sim 5\% \ P_{mean}$

Spatial average of pressure over domain

Heat Release (AVBP run)



Spatial average of heat release over domain

$q' \sim 200\% \, q_{mean}$

Strong nonlinearity

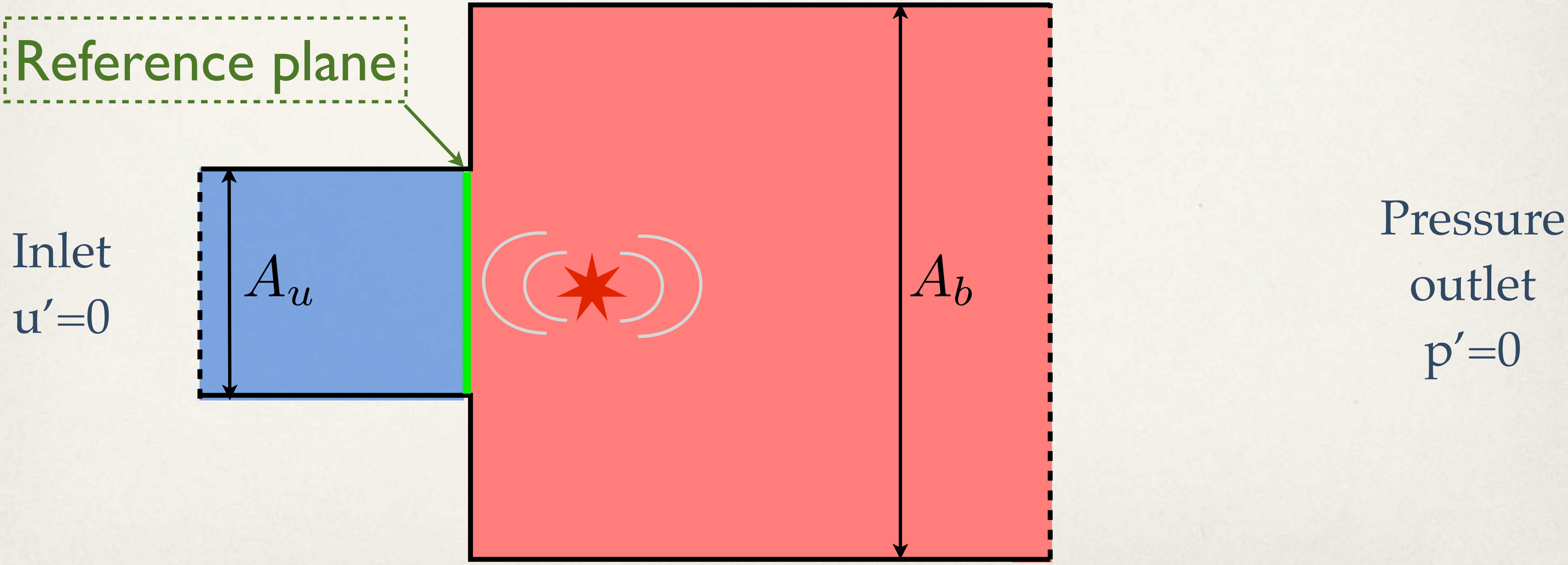
CESAM-HP : UNSTEADY SETUP?

- The CESAM-HP setup exhibits a strong instability in primary simulations
- Many possible means exist to damp this mode :
  - impedances,
  - flame dynamics,
  - heat losses...

II - Choked flow acoustics

ATMOSPHERIC COMPUTATIONS (ATM)

- Often, simple configurations have a pressure outlet (atmosphere)



Atmospheric computations (Atm)

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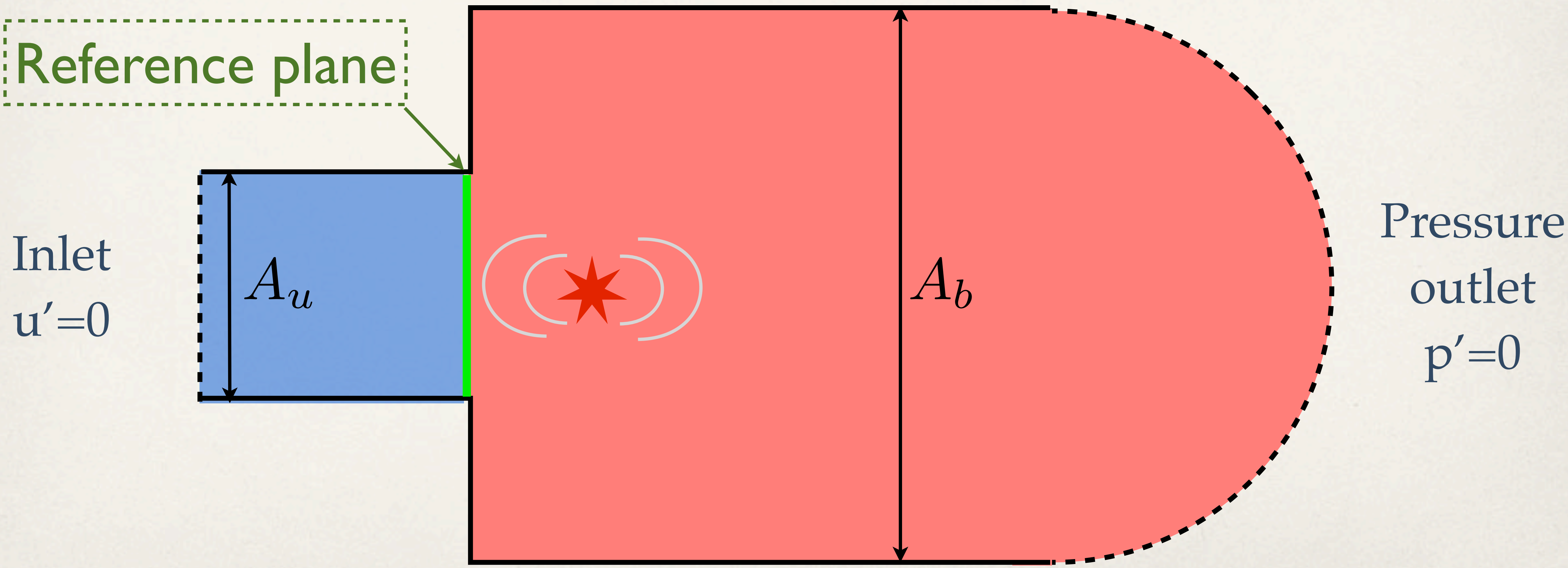
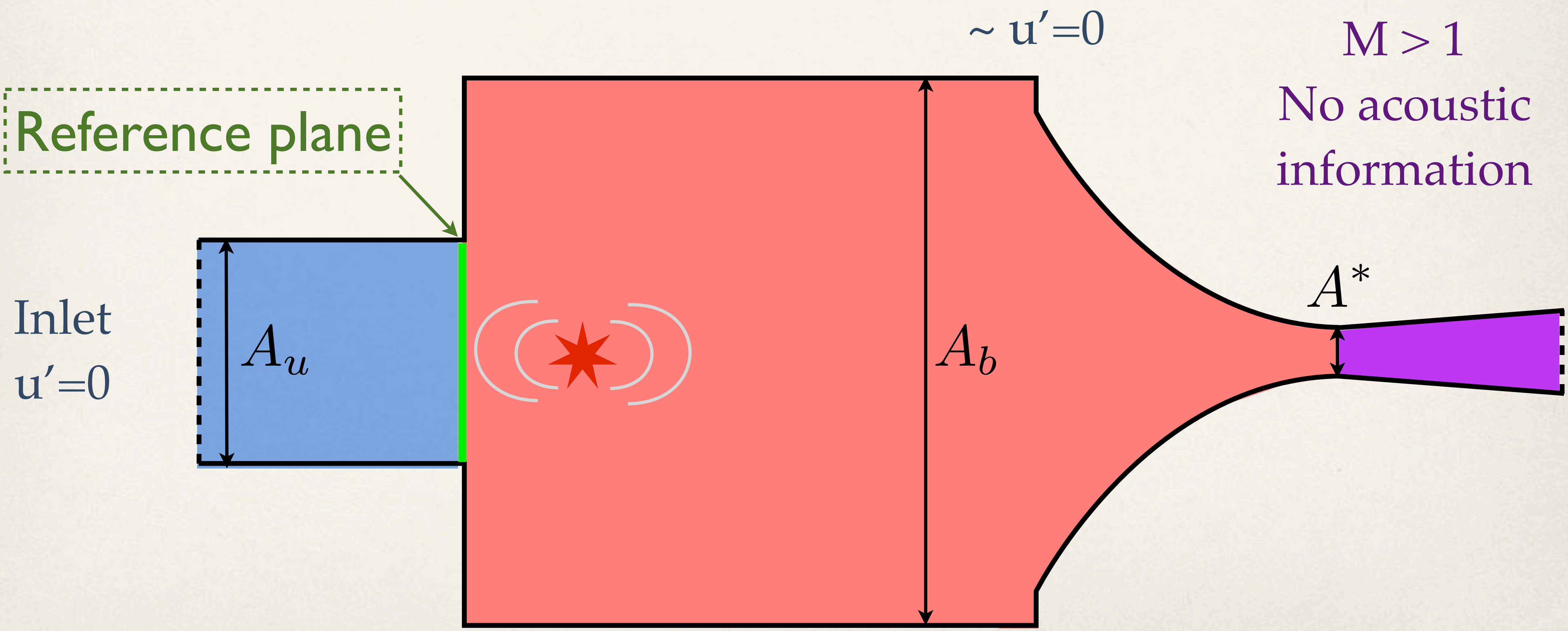
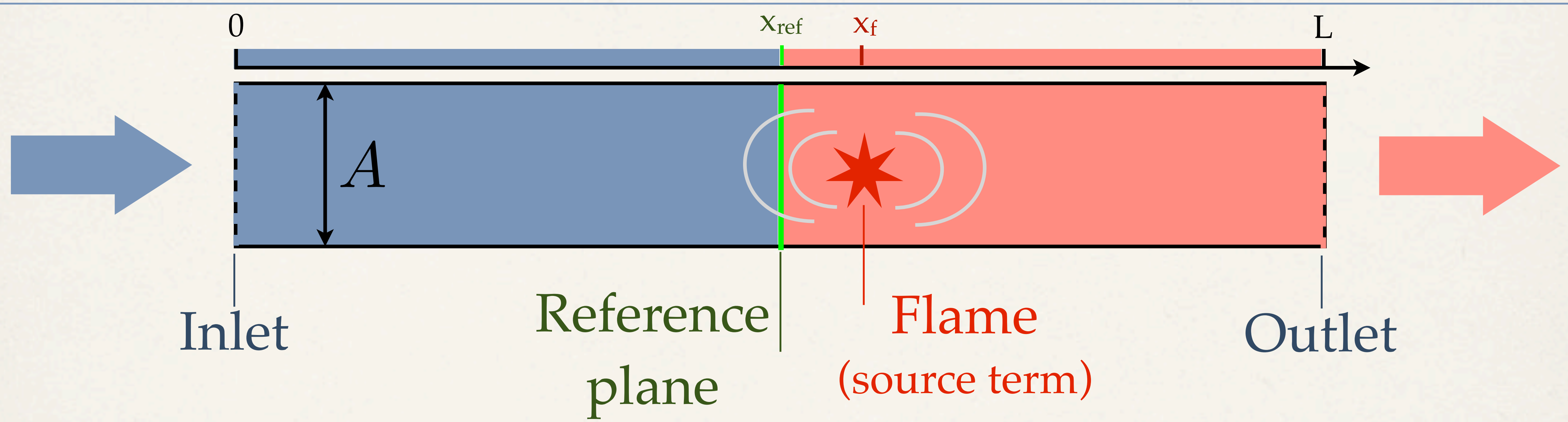


Choked flow computations (Cho)

- Adding a choked nozzle changes the outlet acoustic behavior



BASIC TUBE APPROACH TO STABILITY



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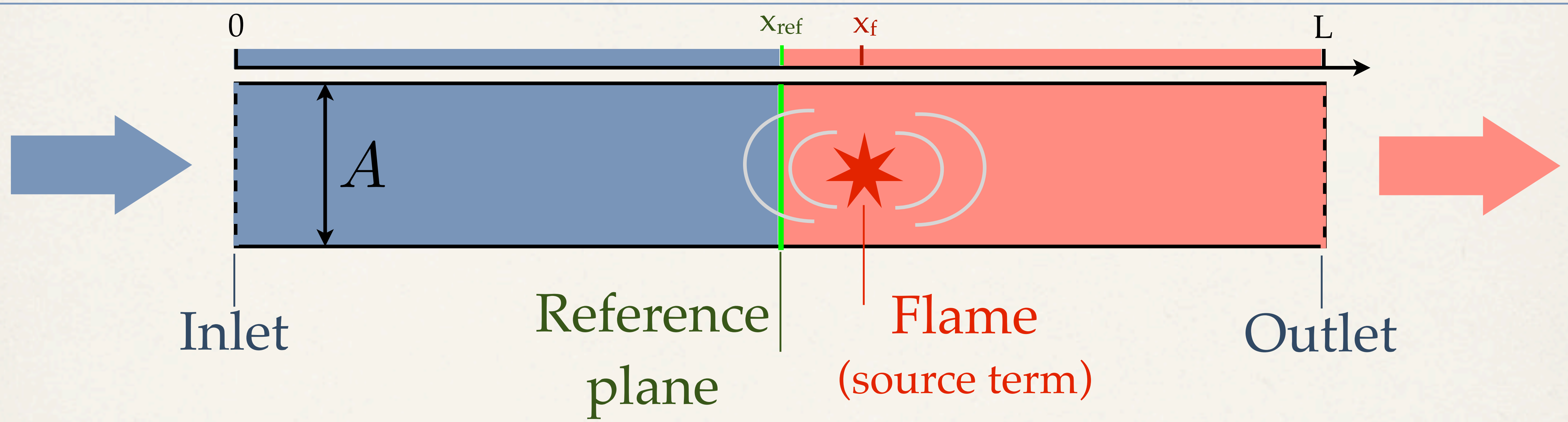

- Chamber is modeled by constant c_0 and constant A tube
- Inlet / Outlet impedances determine tube modes
- Flame (at x_f) can either excite or damp these modes

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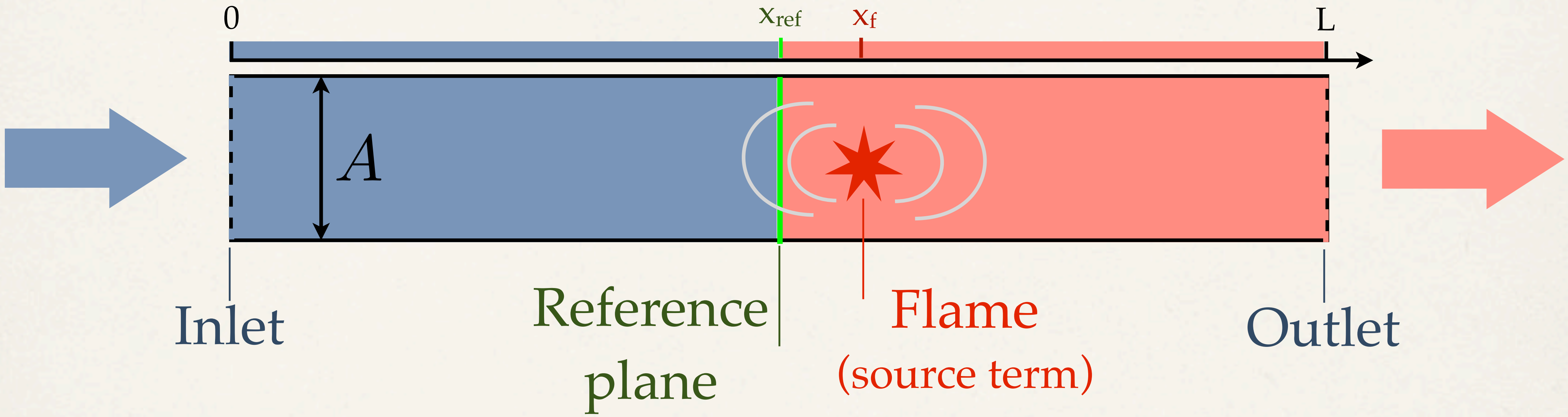


- Chamber is modeled by constant c_0 and constant A tube
- Inlet / Outlet impedances determine tube modes
- Flame (at x_f) can either excite or damp these modes
- Wave equation for the domain [1] :

$$\frac{\partial^2 p}{\partial t^2} - c_0^2 \frac{\partial^2 p}{\partial x^2} = (\gamma - 1)\frac{\partial \dot{\omega}_T}{\partial t}$$

[1] Poinsot, T., & Veynante, D. (2005). *Theoretical and numerical combustion*. RT Edwards Incorporated.

Homogenous equation

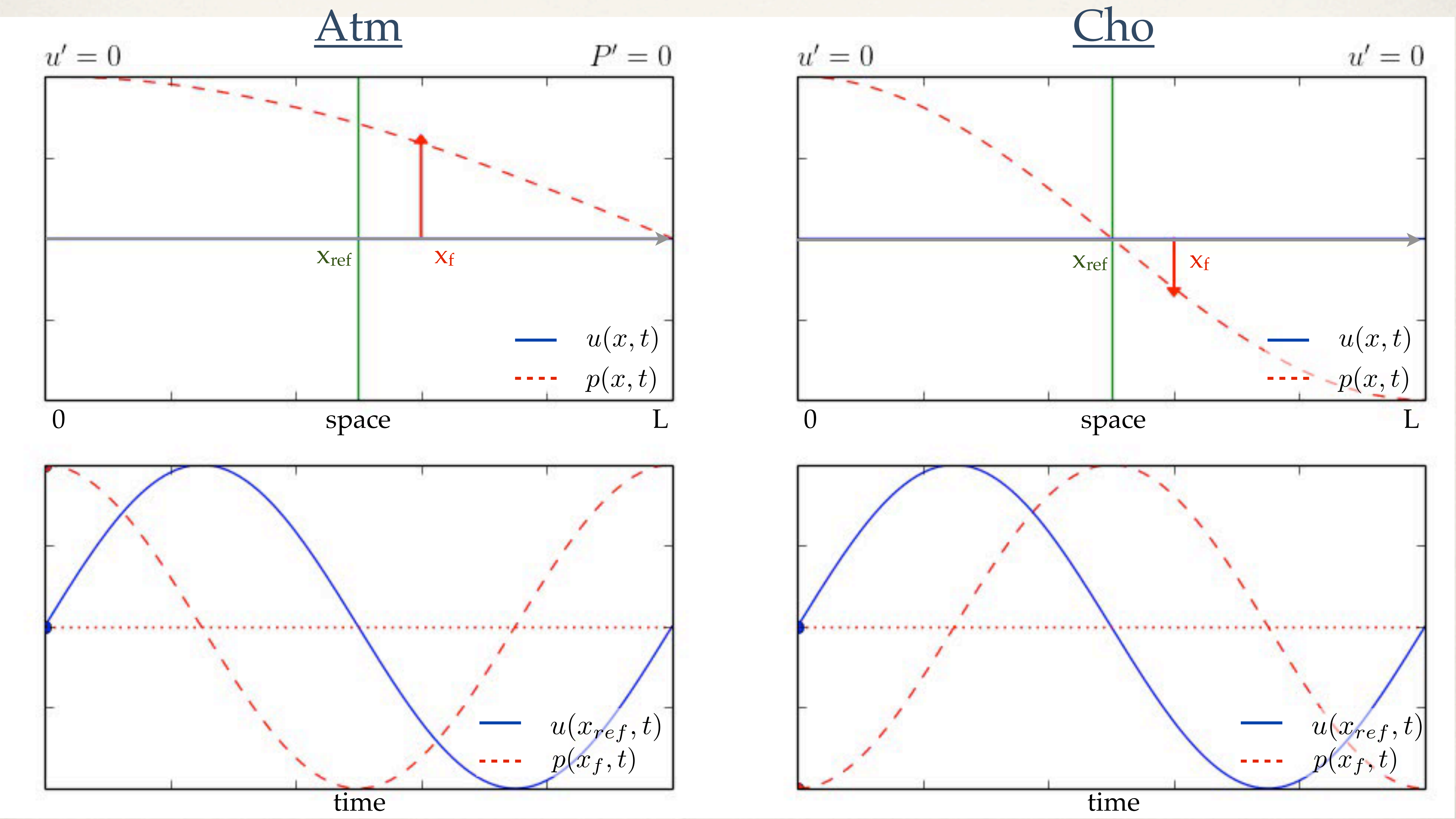
- According to inlet/outlet impedances, solutions to the homogenous equation :

$$\frac{\partial^2 p_h}{\partial t^2} - c_0^2 \frac{\partial^2 p_h}{\partial x^2} = 0$$

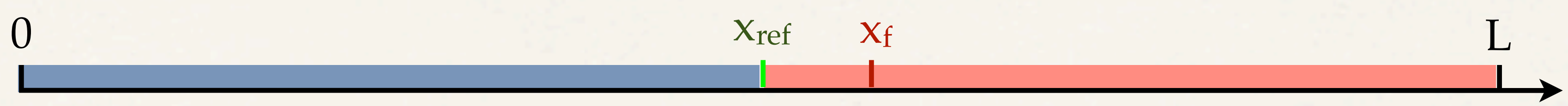
- can be easily derived (for a pressure amplitude of 1) :

Atm (p'=0 outlet)	$p_h(x,t) = cos\left(\frac{\pi}{2}\frac{x}{L}\right) cos(\omega t)$ $u_h(x,t) = \frac{1}{\rho c} sin\left(\frac{\pi}{2}\frac{x}{L}\right) sin(\omega t)$	$\omega = \frac{\pi c}{2L}$
Cho (u'=0 outlet)	$p_h(x,t) = cos\left(\pi\frac{x}{L}\right) cos(\omega t)$ $u_h(x,t) = \frac{1}{\rho c} sin\left(\pi\frac{x}{L}\right) sin(\omega t)$	$\omega = \frac{\pi c}{L}$

The animated modes



SOURCE TERM



- Classical approach for active flame modeling :

$$\frac{\gamma - 1}{\gamma p_0}\dot{\omega}_T = \begin{cases} A\ n\ u(t-\tau) & \text{if } x = x_f \\ 0 & \text{if } x \neq x_f \end{cases}$$

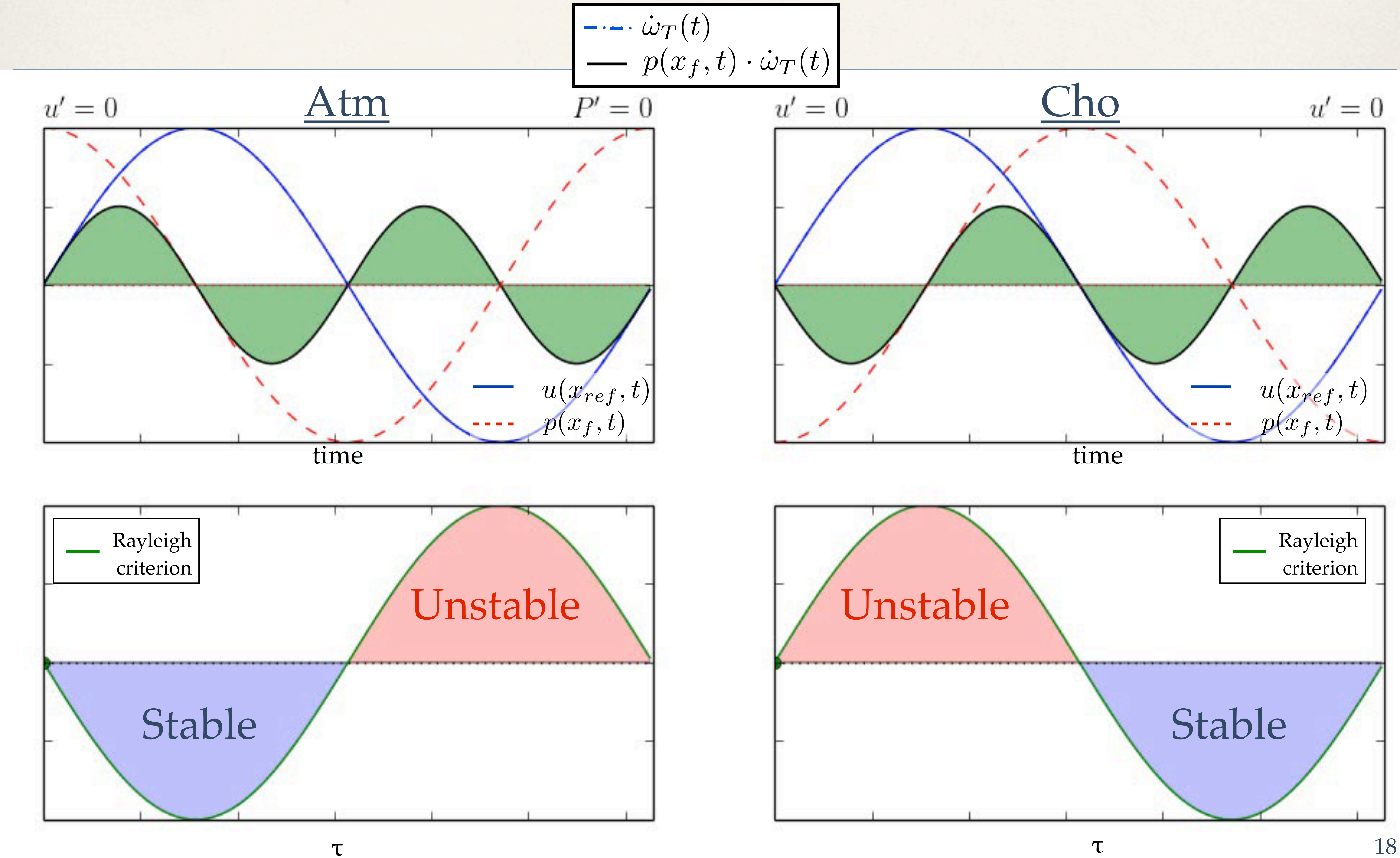
- where u is measured at x_{ref}. Hence :

$$\frac{\partial^2 p}{\partial t^2} - c_0^2 \frac{\partial^2 p}{\partial x^2} = \begin{cases} C\ \frac{\partial}{\partial t} u(x_{ref}, t-\tau) & \text{if } x = x_f \\ 0 & \text{if } x \neq x_f \end{cases}$$

- The Rayleigh criterion then predicts unstable conditions if :

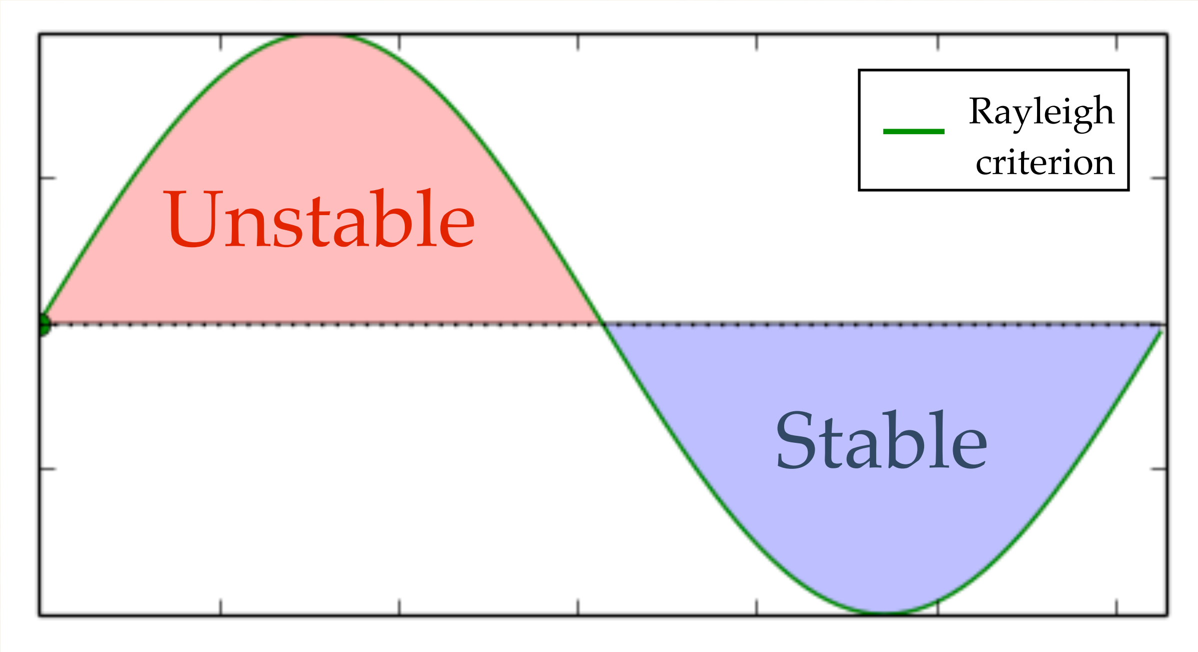
$$\int\int\int_\Omega p(x,t)\dot{\omega}_T(x,t)d\Omega > 0$$

Rayleigh criterion vs τ

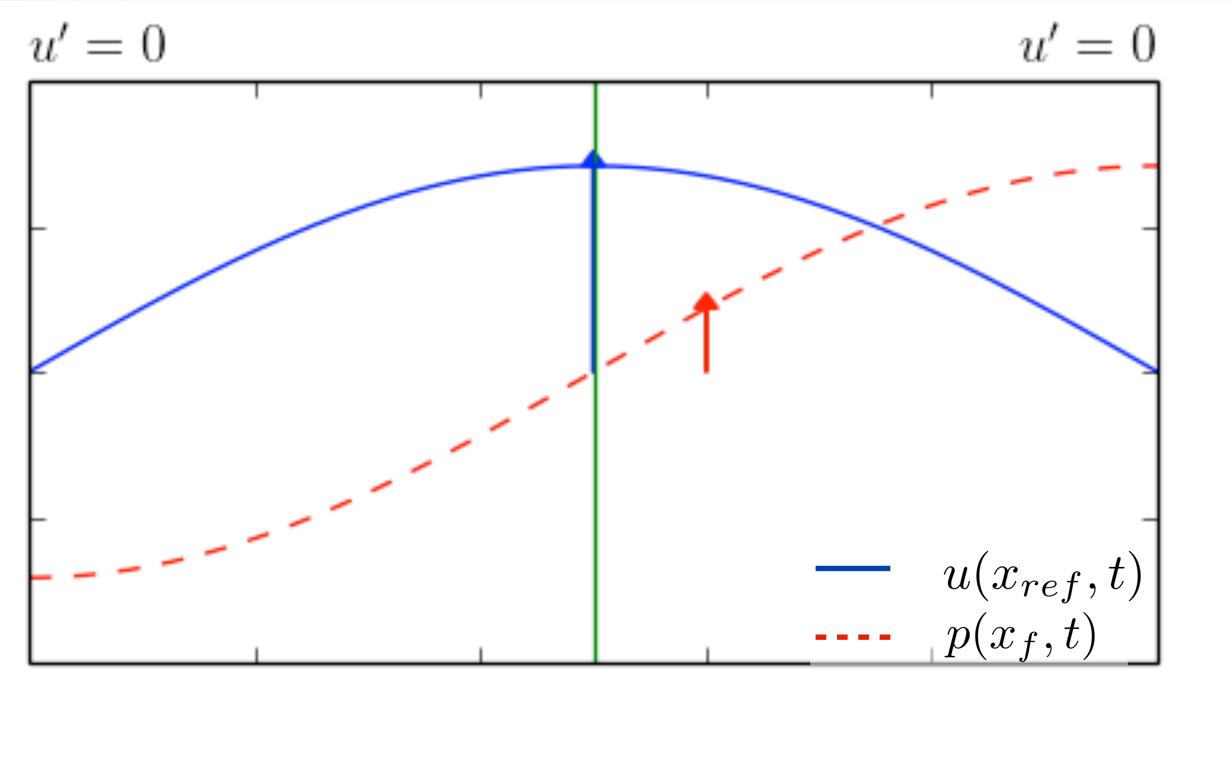


Partial Conclusion

- Instabilities are prone occur in closed choked-flow systems
- Relation between time-delay and stability is unusual :
  - ***Small*** time-delays are synonym of ***instability***
  - ***Large*** time-delays are synonym of ***stability***



Mode identification



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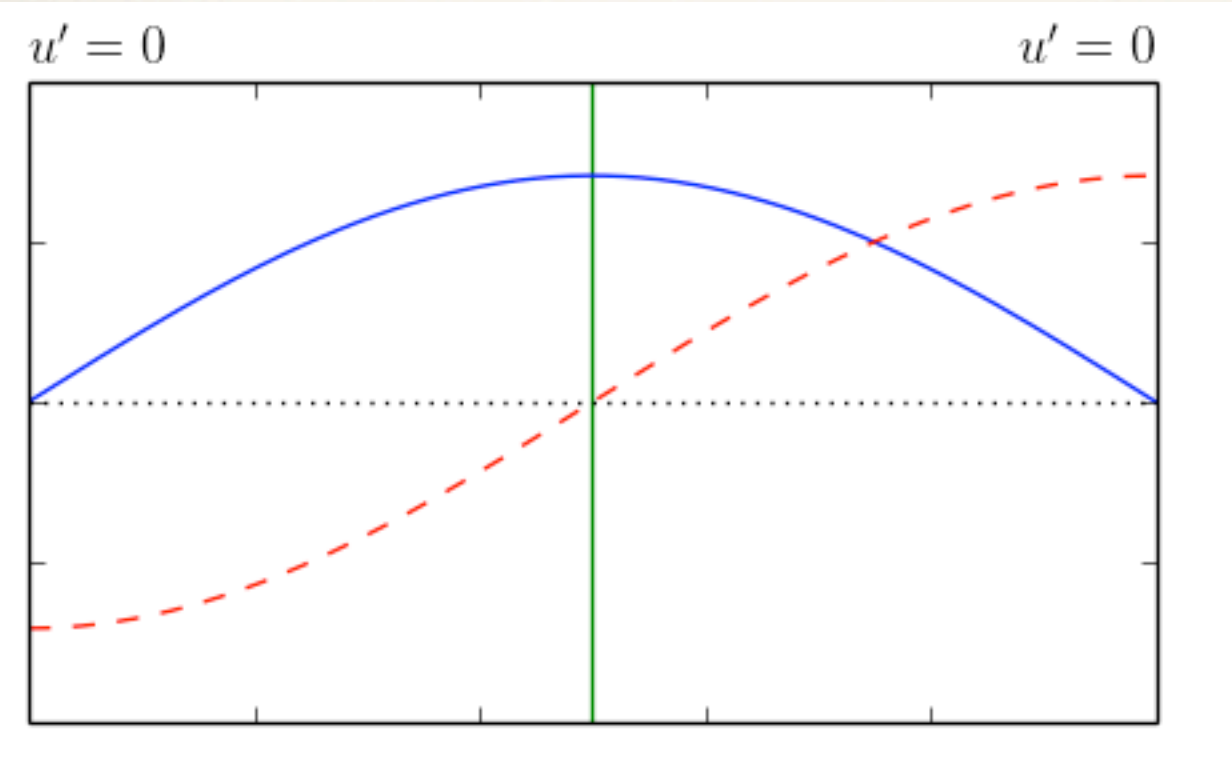
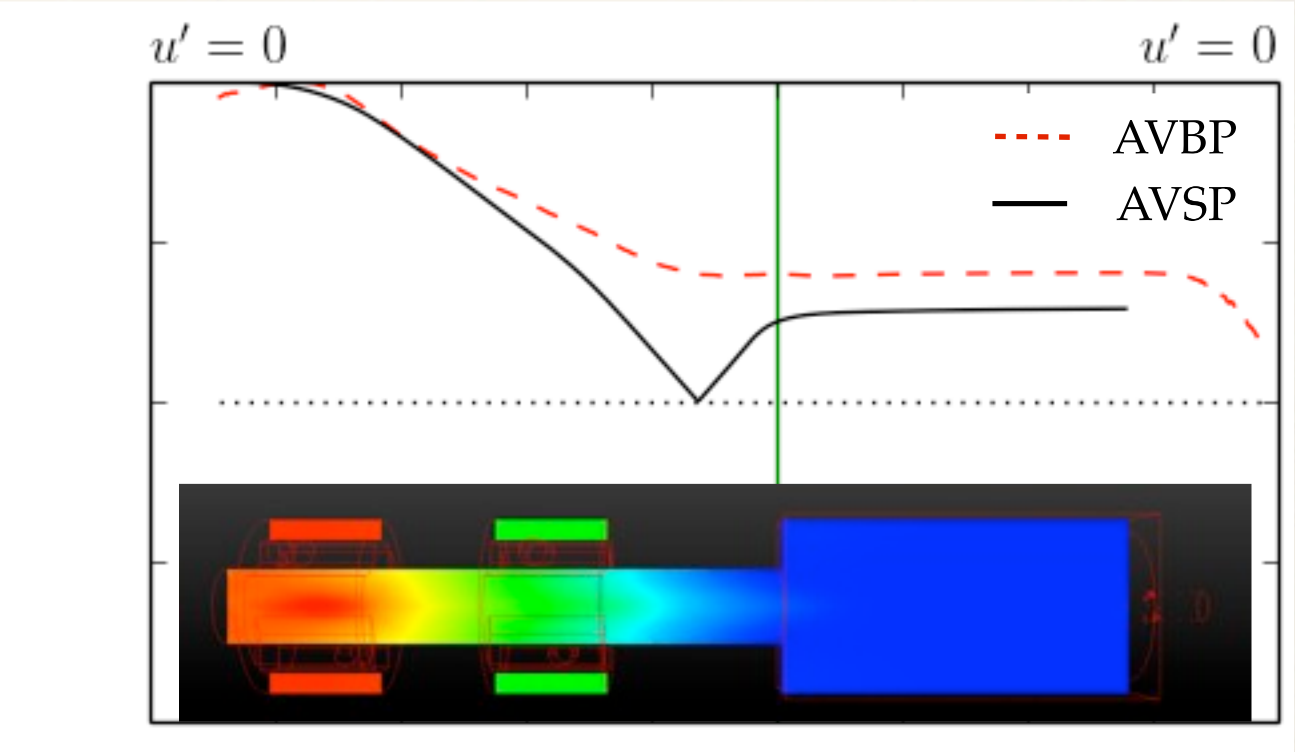
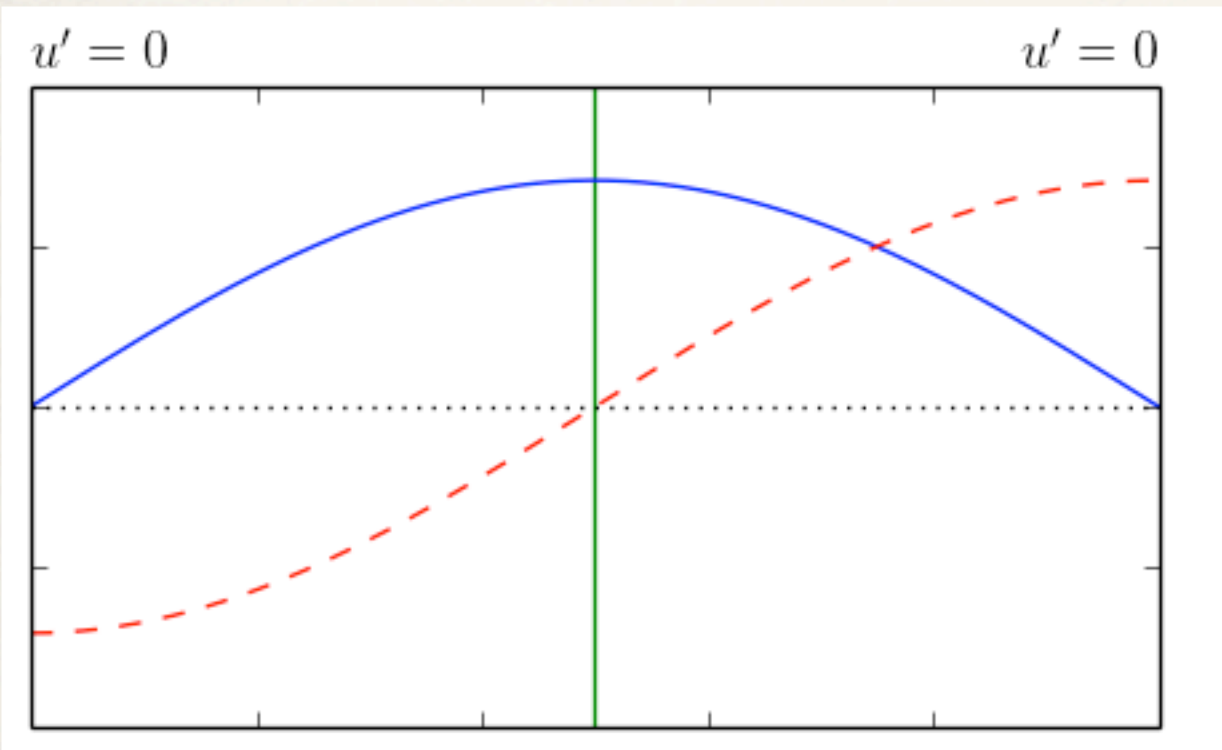


1D Approach



CESAM-HP - P_{RMS}

MODE IDENTIFICATION



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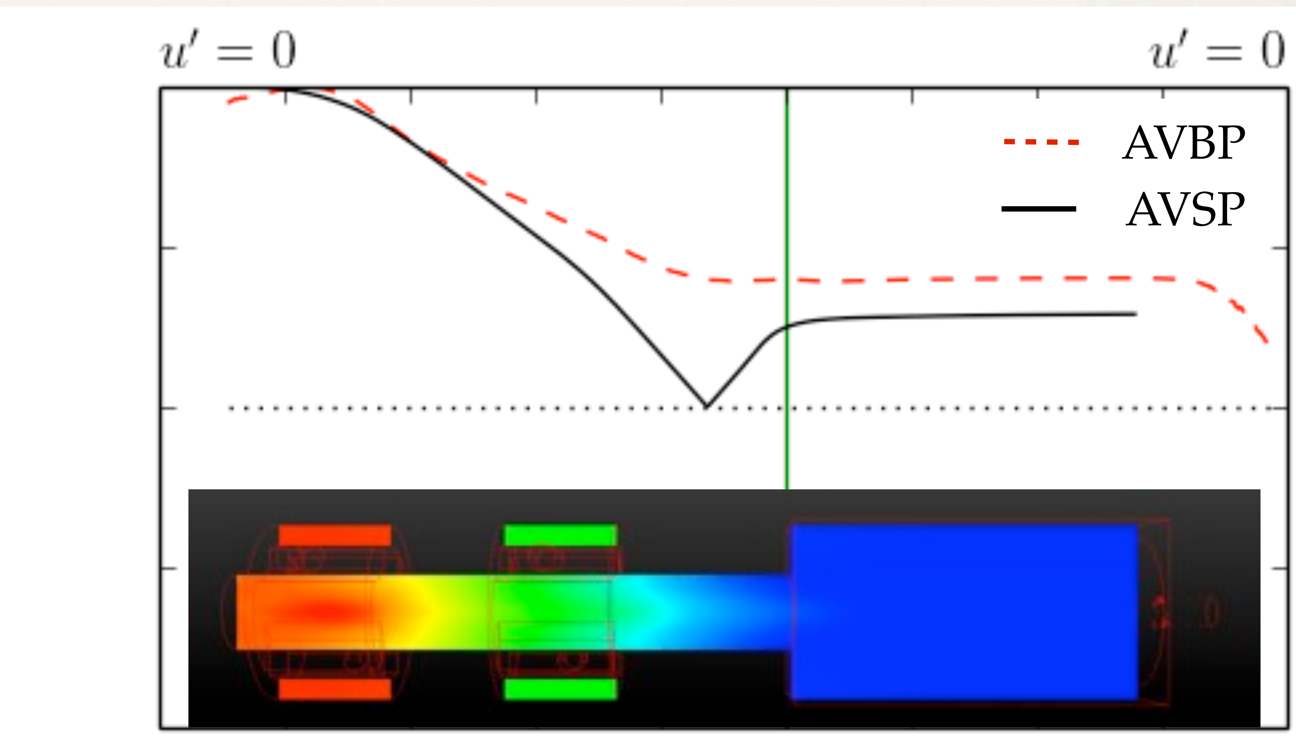
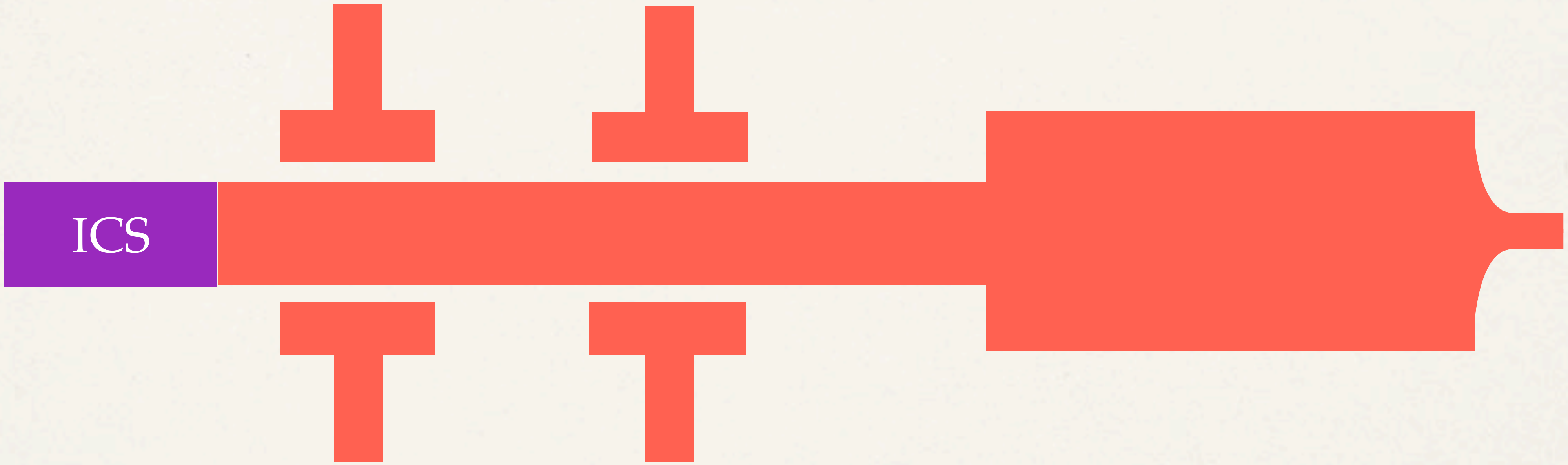


CESAM-HP - P_{RMS}

- RMS of simulations show similar longitudinal modes
- Helmholtz solver finds this mode

Playing with Impedances



- Could the ICS save us? It's where P_{RMS} is maximum
- Using «compliant walls», impedance at ICS can be drastically reduced

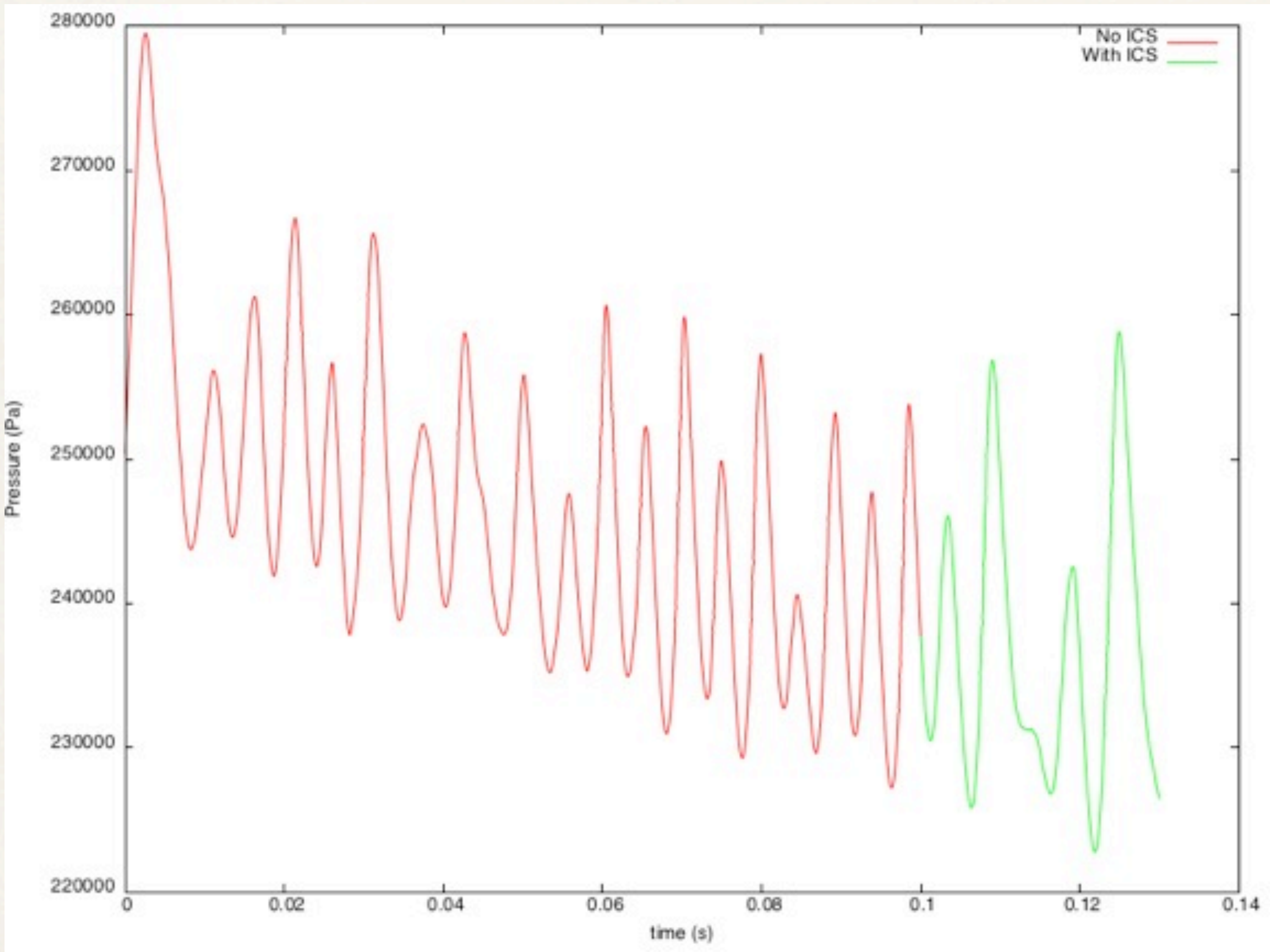
DAMPING STRATEGY : IMPEDANCE

- Pressure fluctuations are strong in the cold section

→ Idea : «open» impedances in cold section (ICS + inlets) using NSCBC compliant wall boundaries

- Results ?

Damping Strategy : Impedance



$P' \sim 5\%\ P_{mean}$

- Pressure fluctuations are still extremely high
- «Bulk» mode (constant phase in chamber) resists open impedances

Wrong Strategy?

- The mode responsible for the instability is identified
- It exists both in the chamber and in the injection system
- Killing pressure oscillations in the injection doesn't seem to be efficient to damp the mode
- Next option : work on flame dynamics

III - Towards a stable configuration

FLAME DYNAMICS

LES with
Nozzle

Initially
Very Unstable

Difficult to
stabilize

FLAME DYNAMICS

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LES without Nozzle

Quiet mean flow

Forced runs

Flame Dynamics

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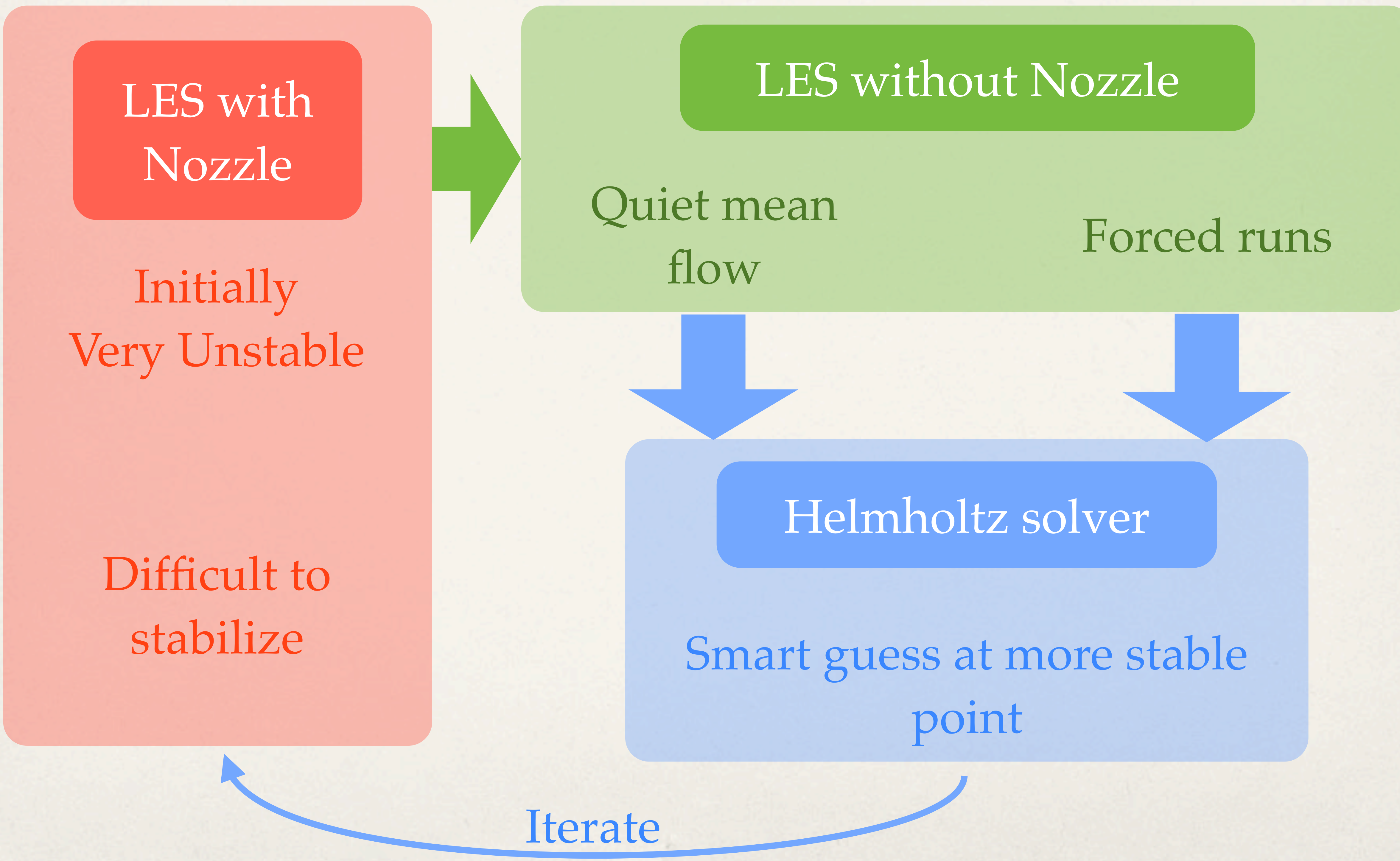
Forced runs

Helmholtz solver

Smart guess at more stable point

Flame Dynamics



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~~Nozzle~~ → Non reflecting outlet

FLAME DYNAMICS

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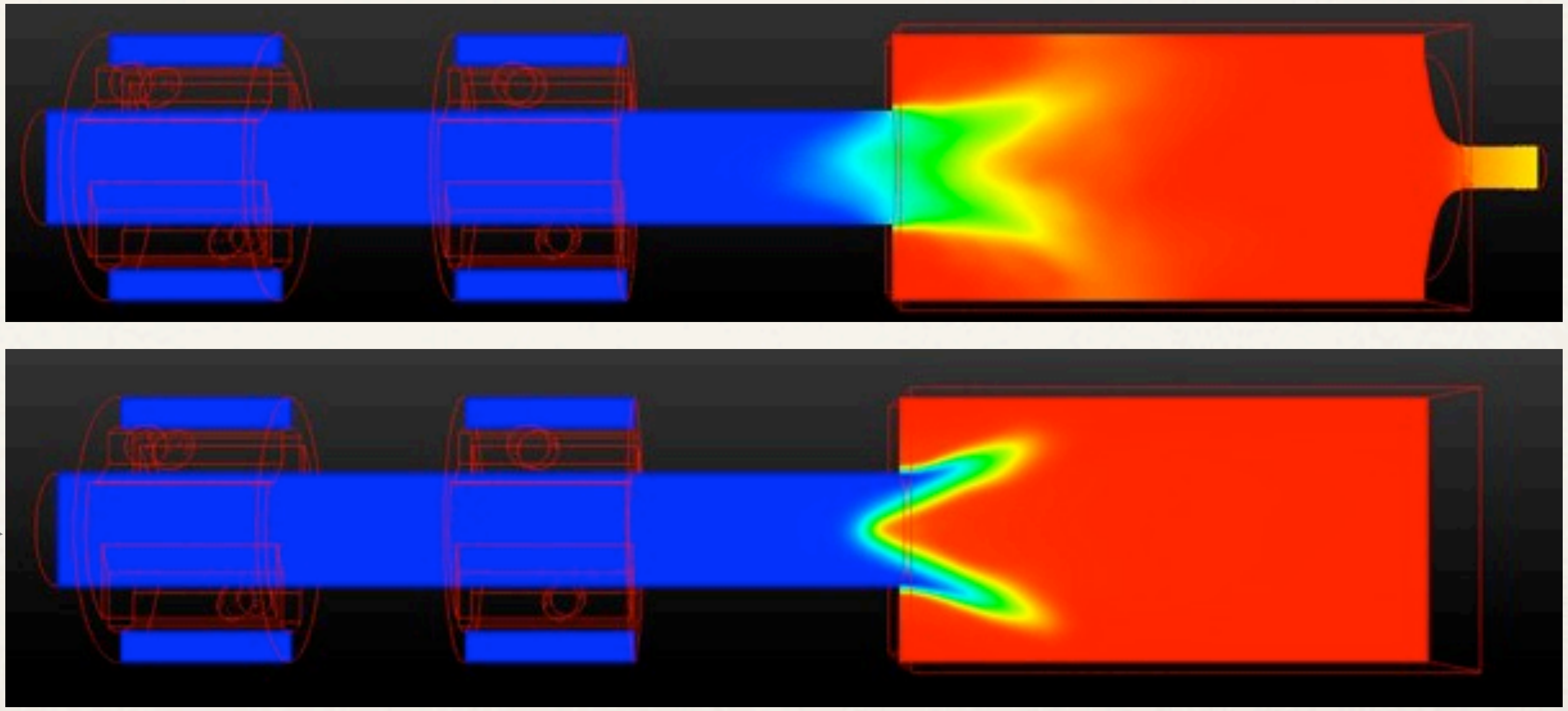
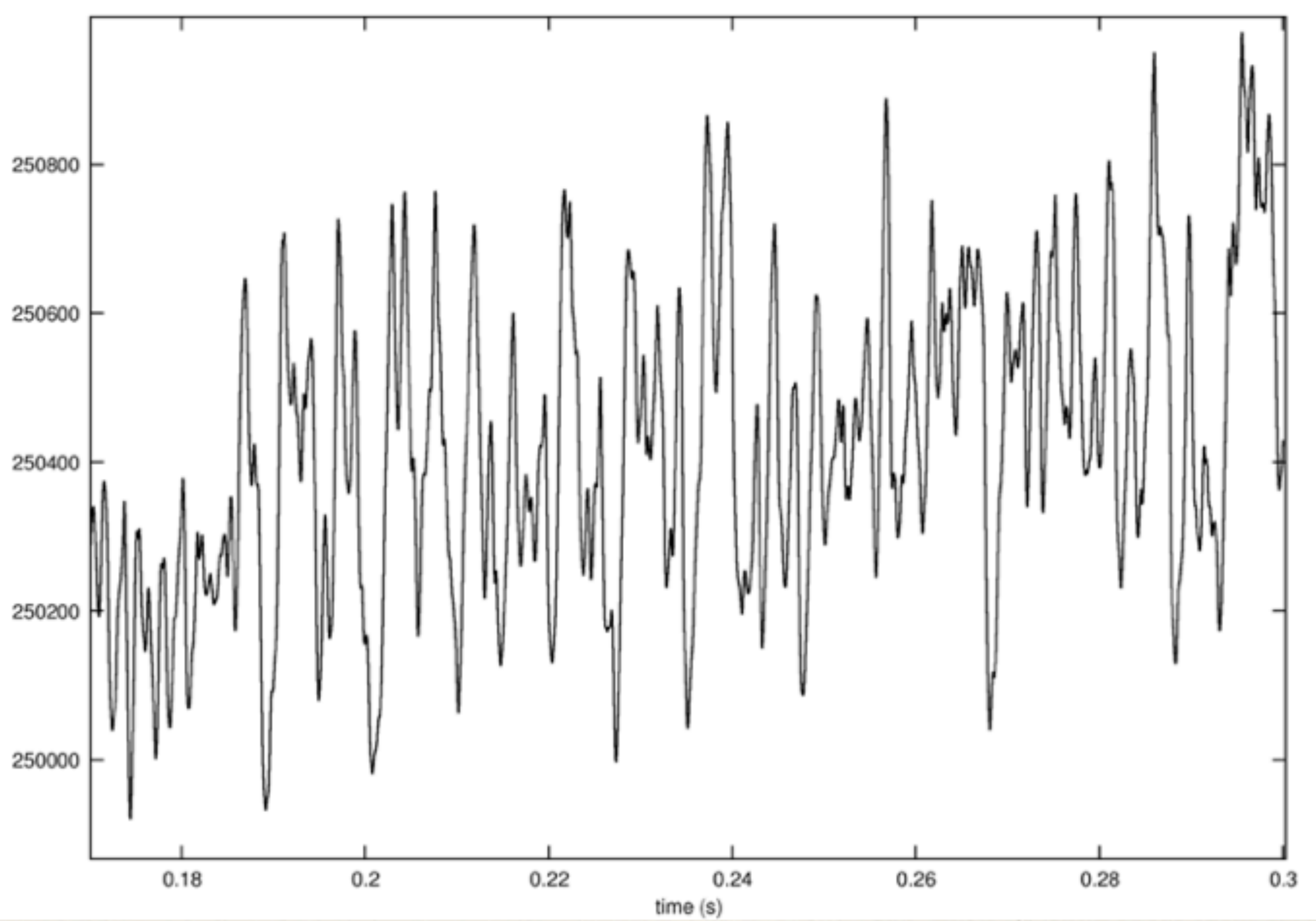


Mean Temperature

MEAN PRESSURE WITHOUT NOZZLE

Spatial average of pressure over domain



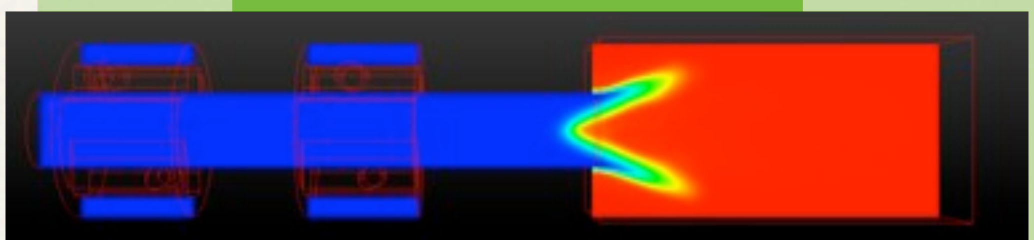
P' ~ 0.1% P_{mean}

FLAME DYNAMICS

Flame Dynamics

Stabilized no-nozzle

Flame Dynamics



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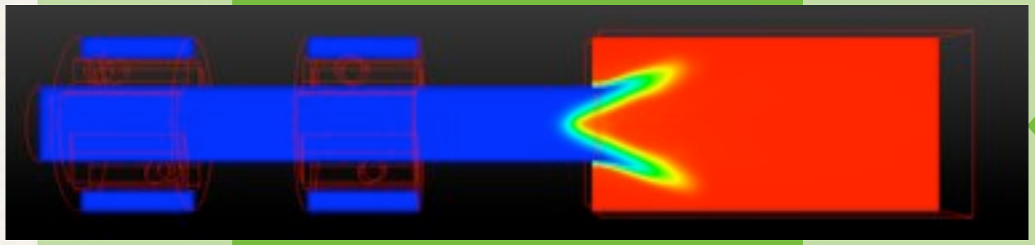

<u>Pressure forcing</u>

Frequency similar to full run instability

Flame Dynamics

Stabilized no-nozzle

Pressure forcing

Frequency similar to full run instability

Flame Transfer Function tools applied to simulation

Global value of n and τ extracted

Flame Dynamics

Stabilized no-nozzle

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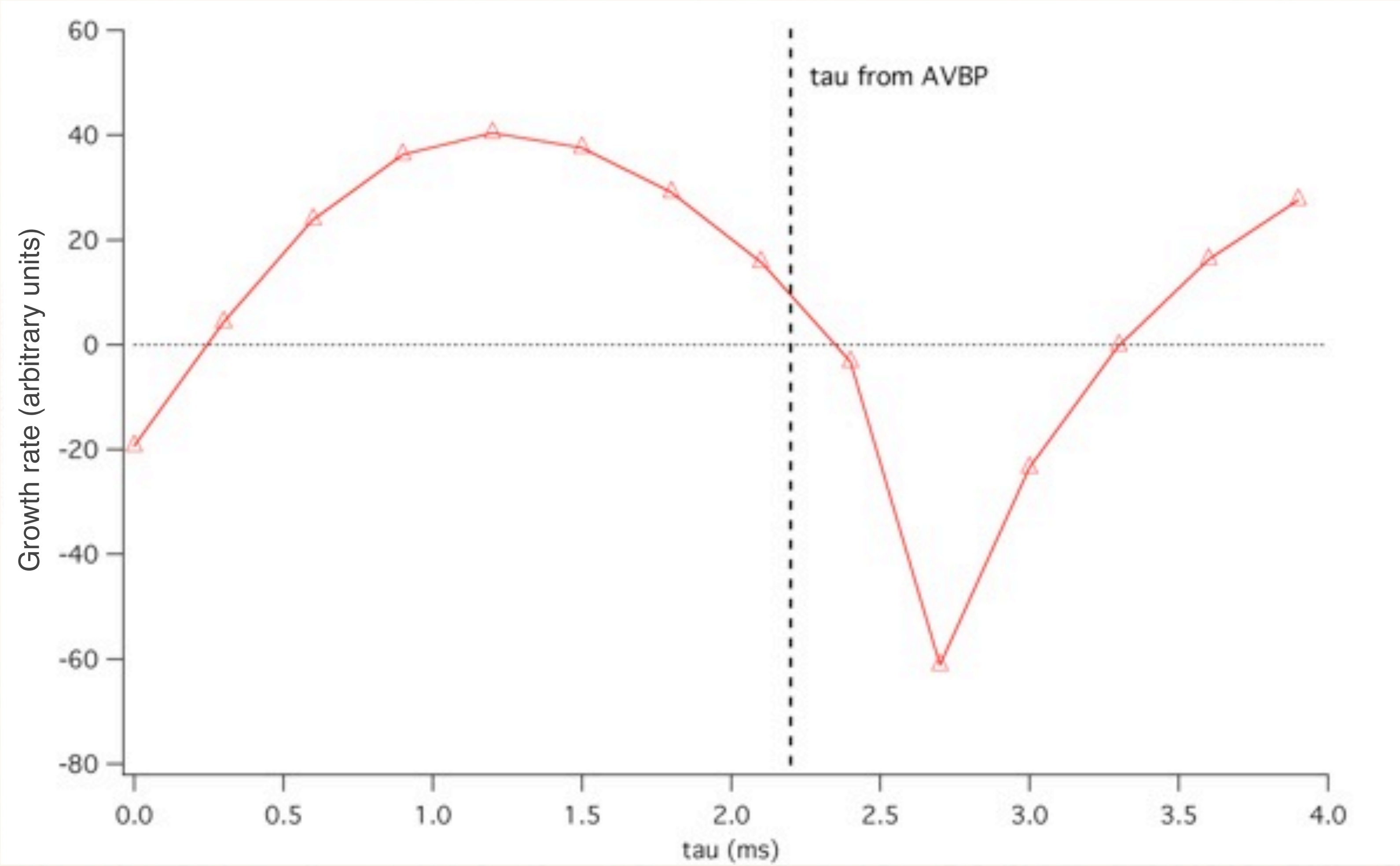
Flame Transfer Function tools applied to simulation

Global value of n and τ extracted

Helmholtz solver : AVSP

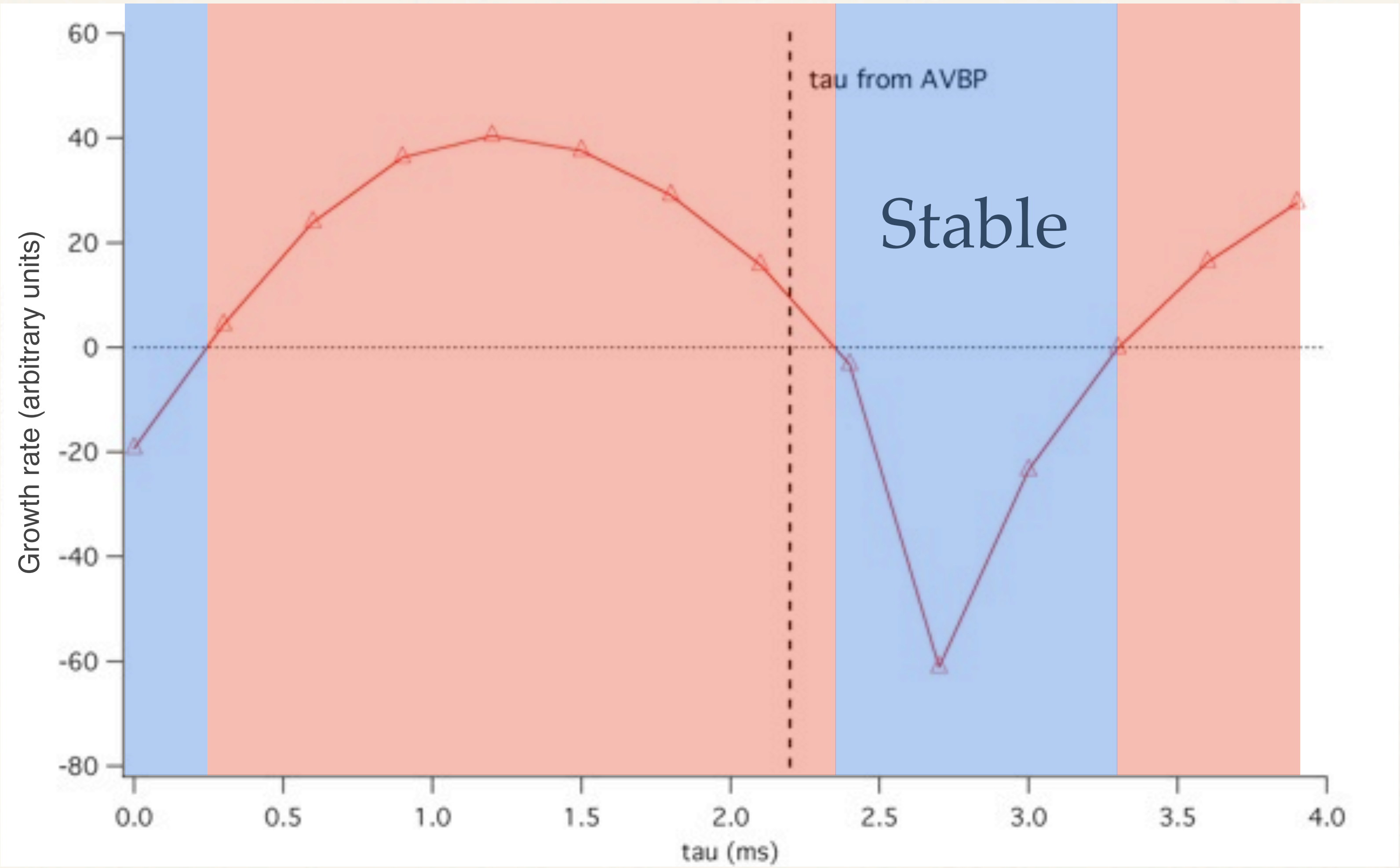
Stability map according to values of n, τ

Flame Dynamics



- Acoustic solver also predicts instability
- Stability map suggests to increase τ
- This methodology agrees with the 1D tube analysis

Flame Dynamics



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Flame Dynamics

Objective : increase τ

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Flame Dynamics

Objective : increase τ

Idea : lower flame speed s_L

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Flame Dynamics

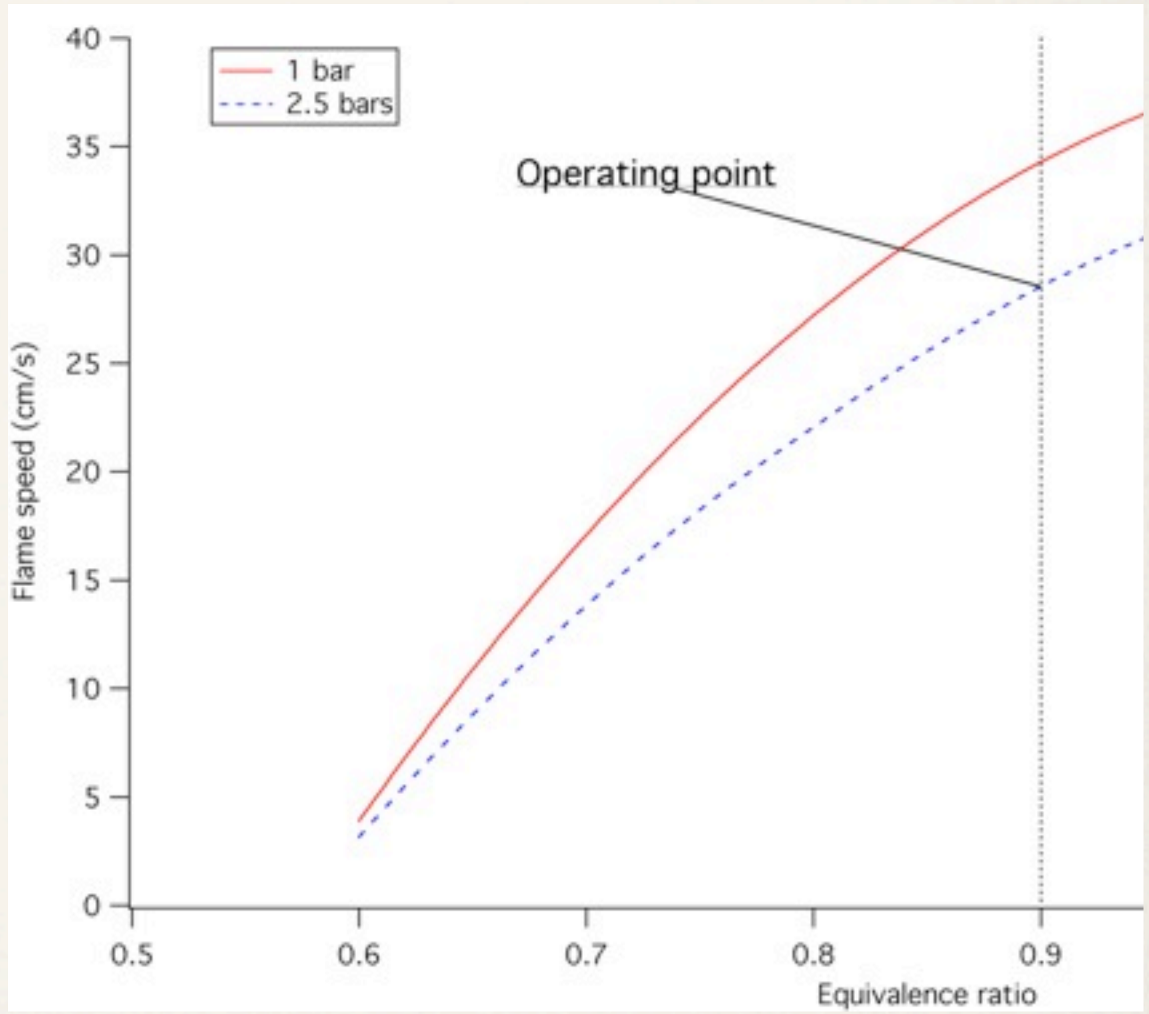
Objective : increase τ

Idea : lower flame speed s_L

$\phi = 0.9$

$s_L = 29$ cm/s

Flame speed vs ϕ [1]



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FLAME DYNAMICS

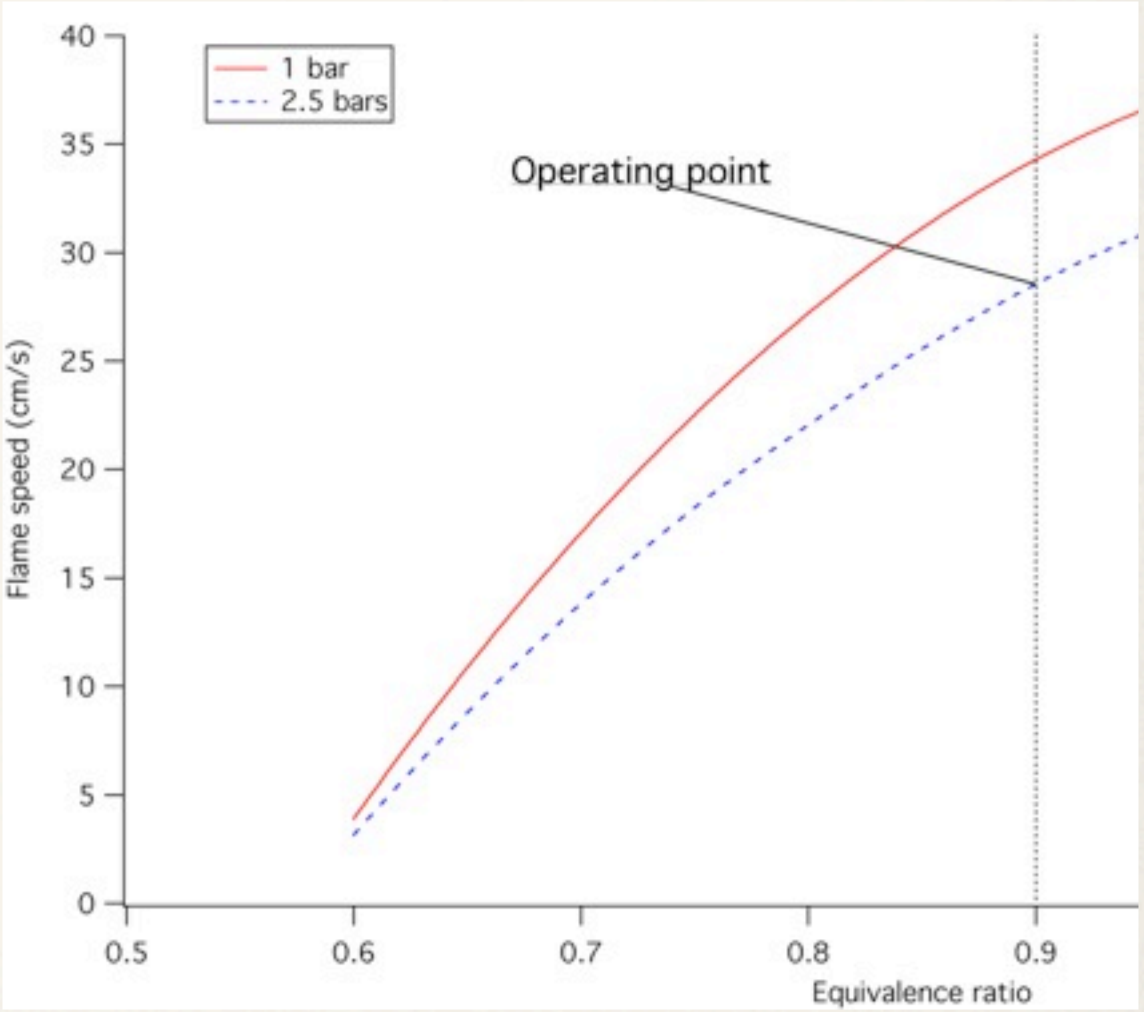
Objective : increase τ

Idea : lower flame speed s_L

$\phi = 0.9$
$s_L = 29$ cm / s

$\phi = 0.77$
$s_L = 20$ cm / s

Flame speed vs ϕ [1]



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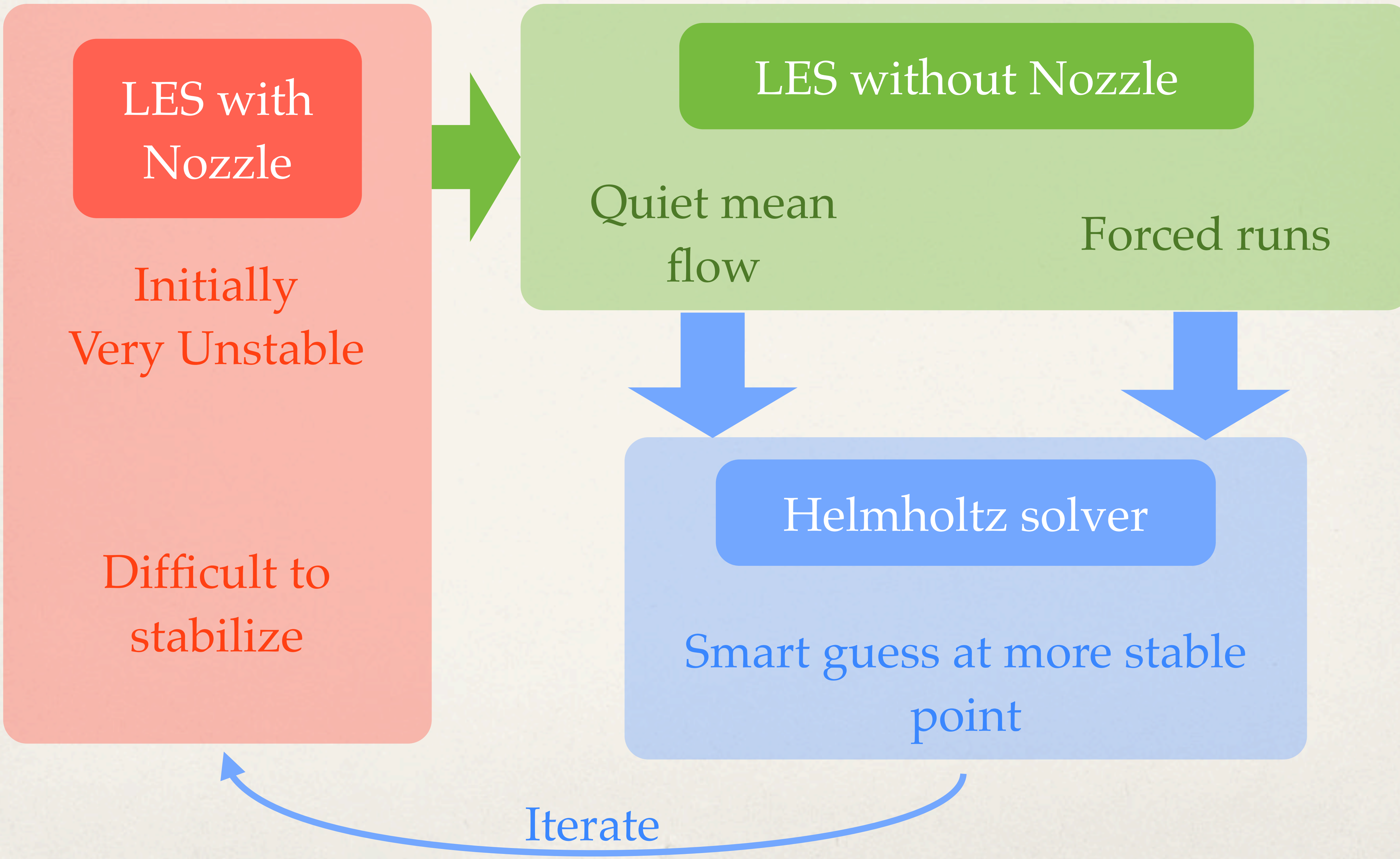

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Helmholtz solver

Smart guess at more stable point

Iterate

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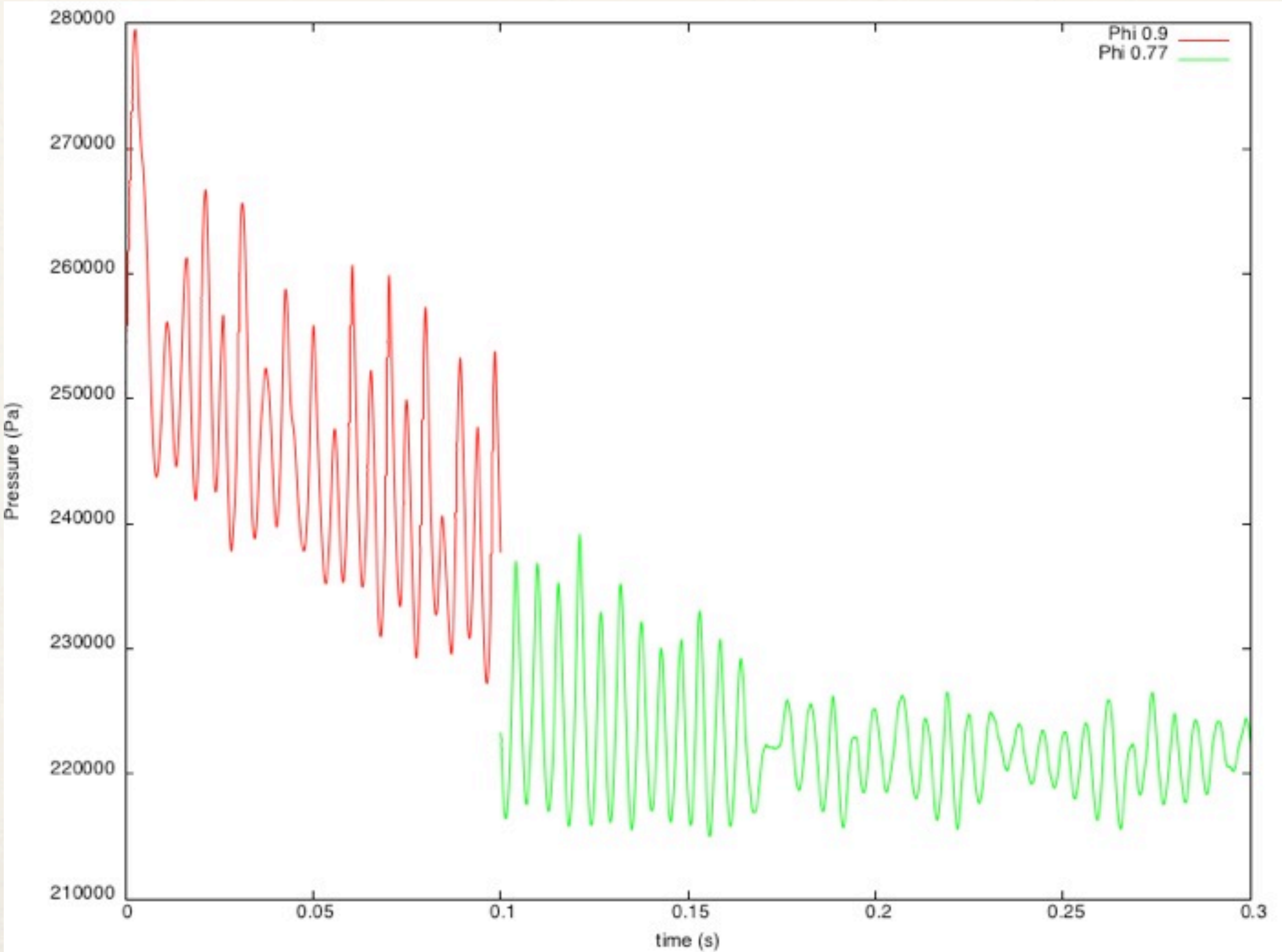
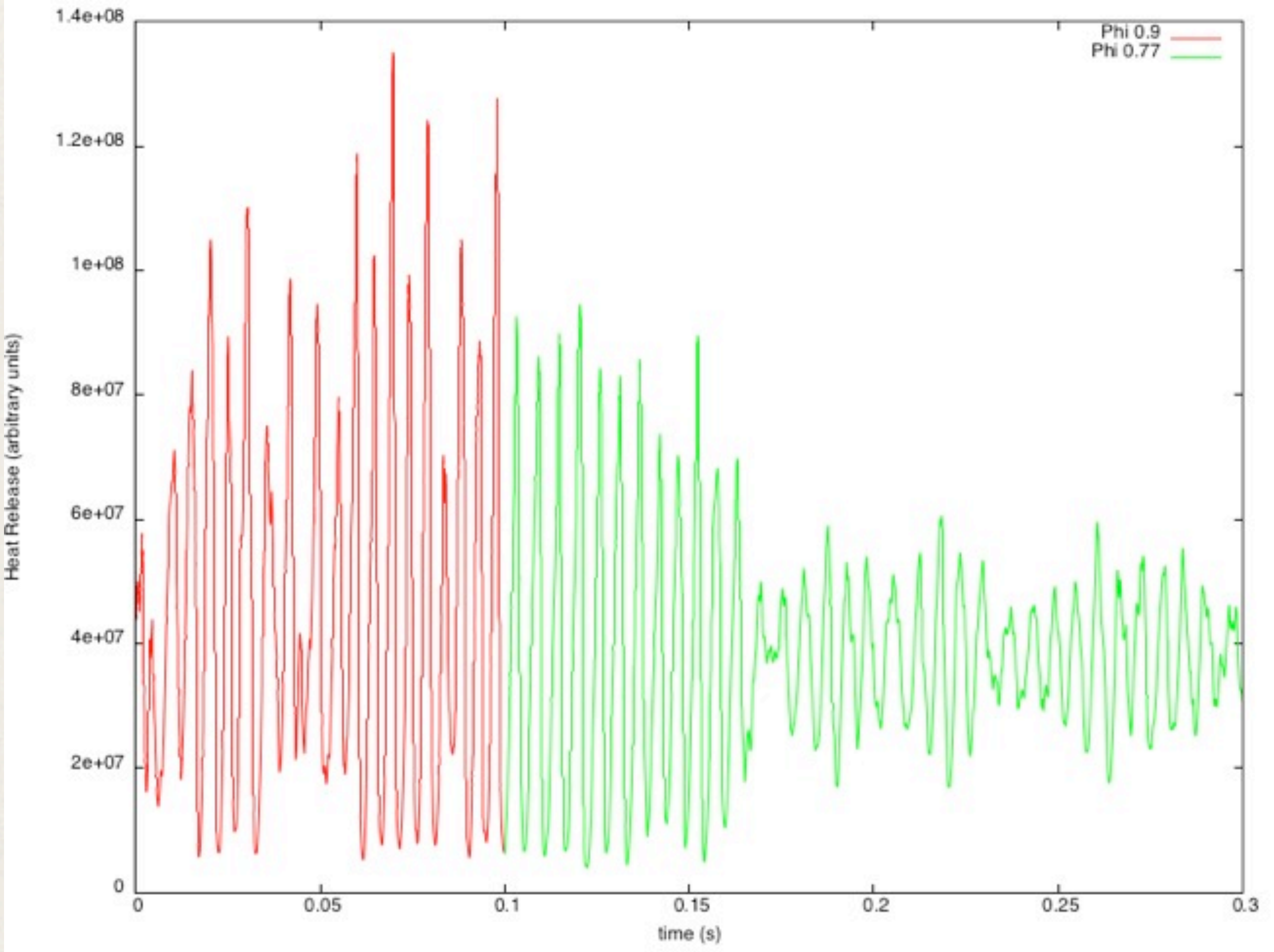
Flame Dynamics

Spatial average of pressure over domain



FLAME DYNAMICS

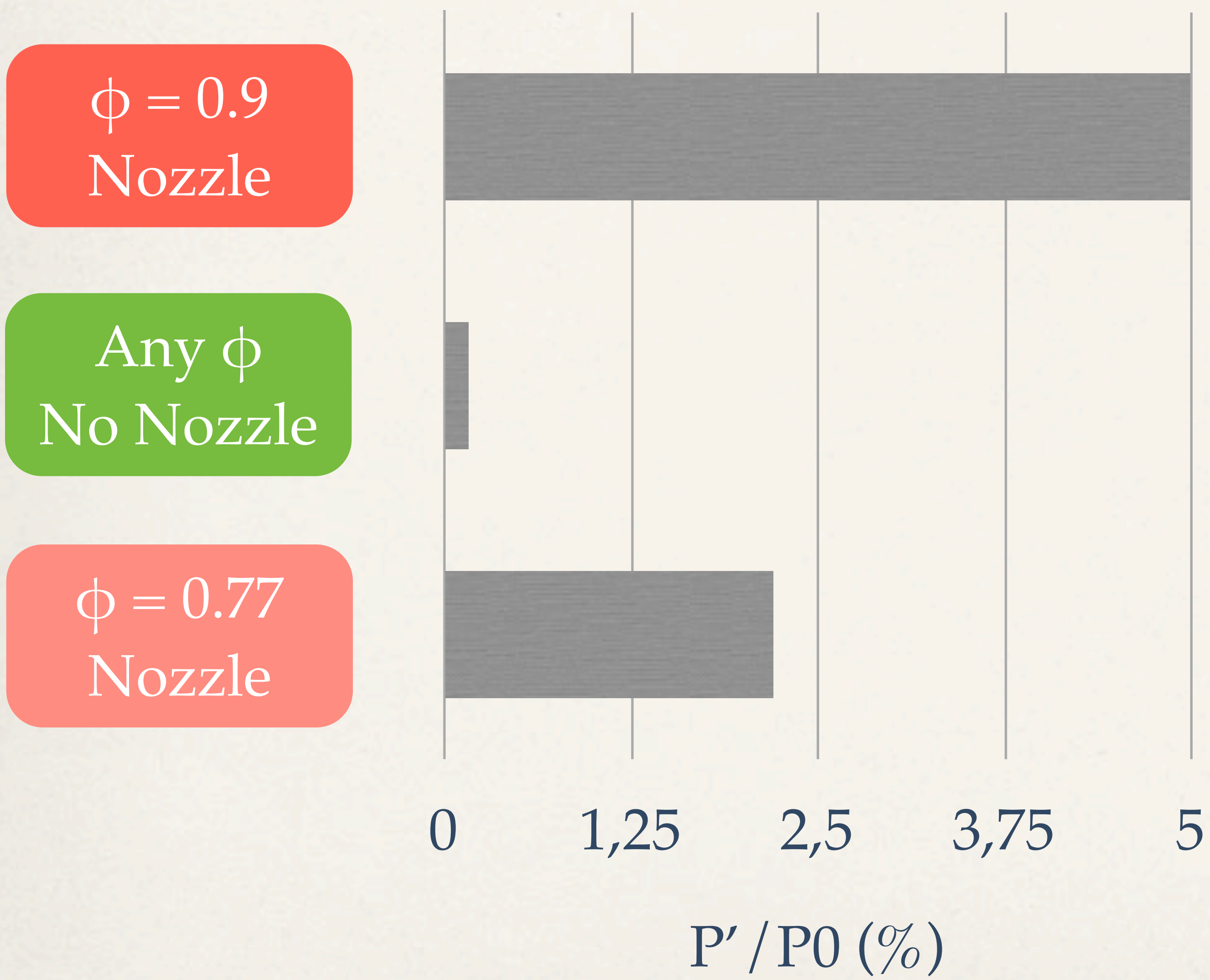
Spatial average of heat release over domain



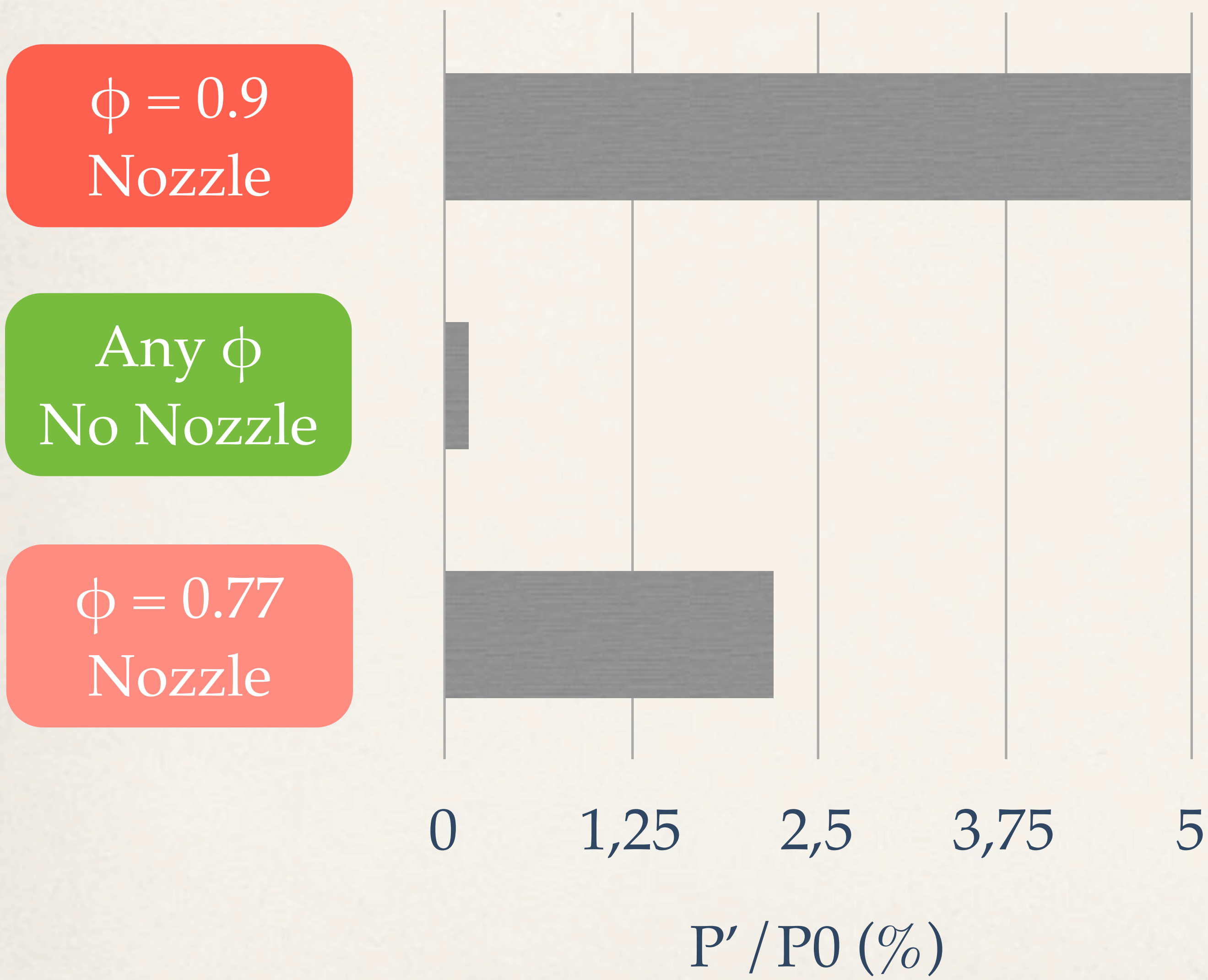
$q' \sim 50\%\ q_{mean}$

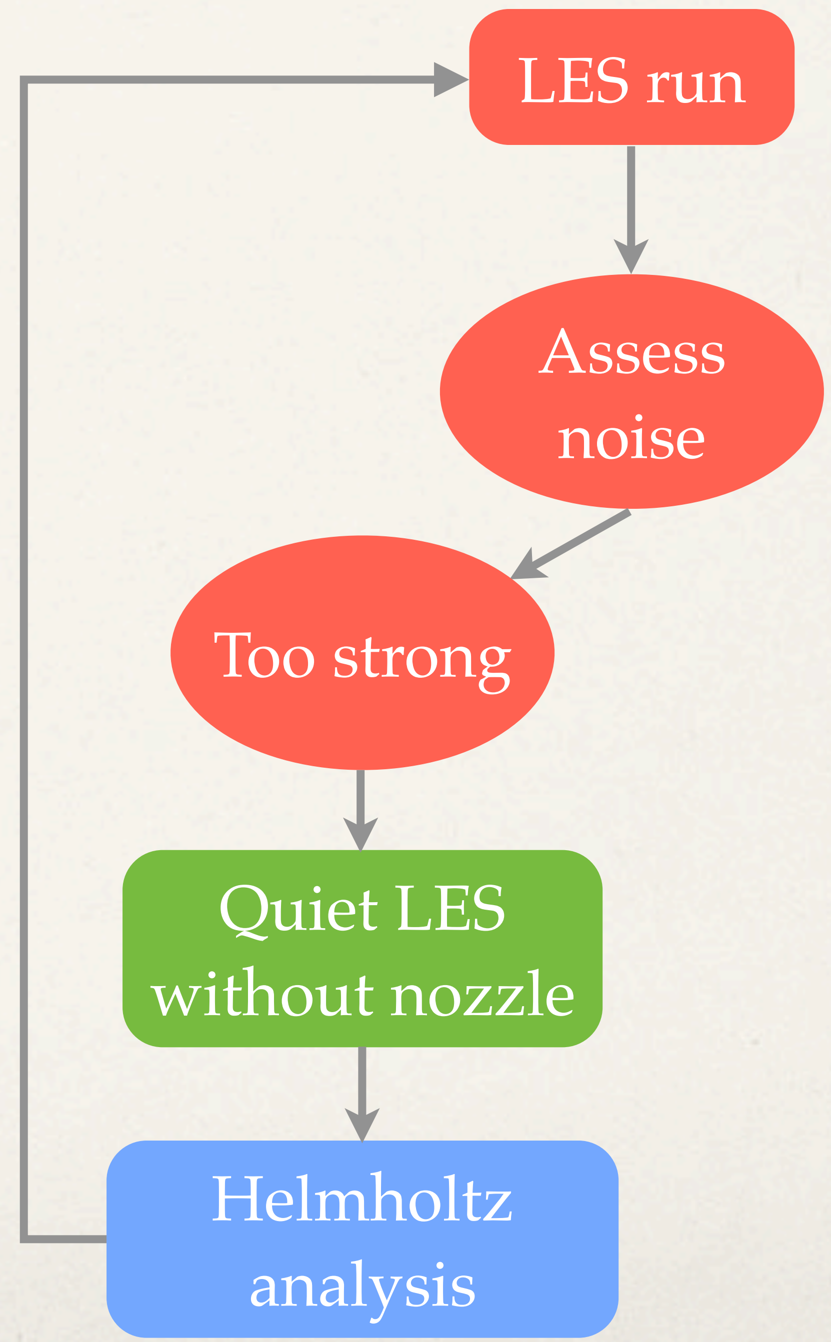
Weak nonlinearity

STRATEGY OVERVIEW

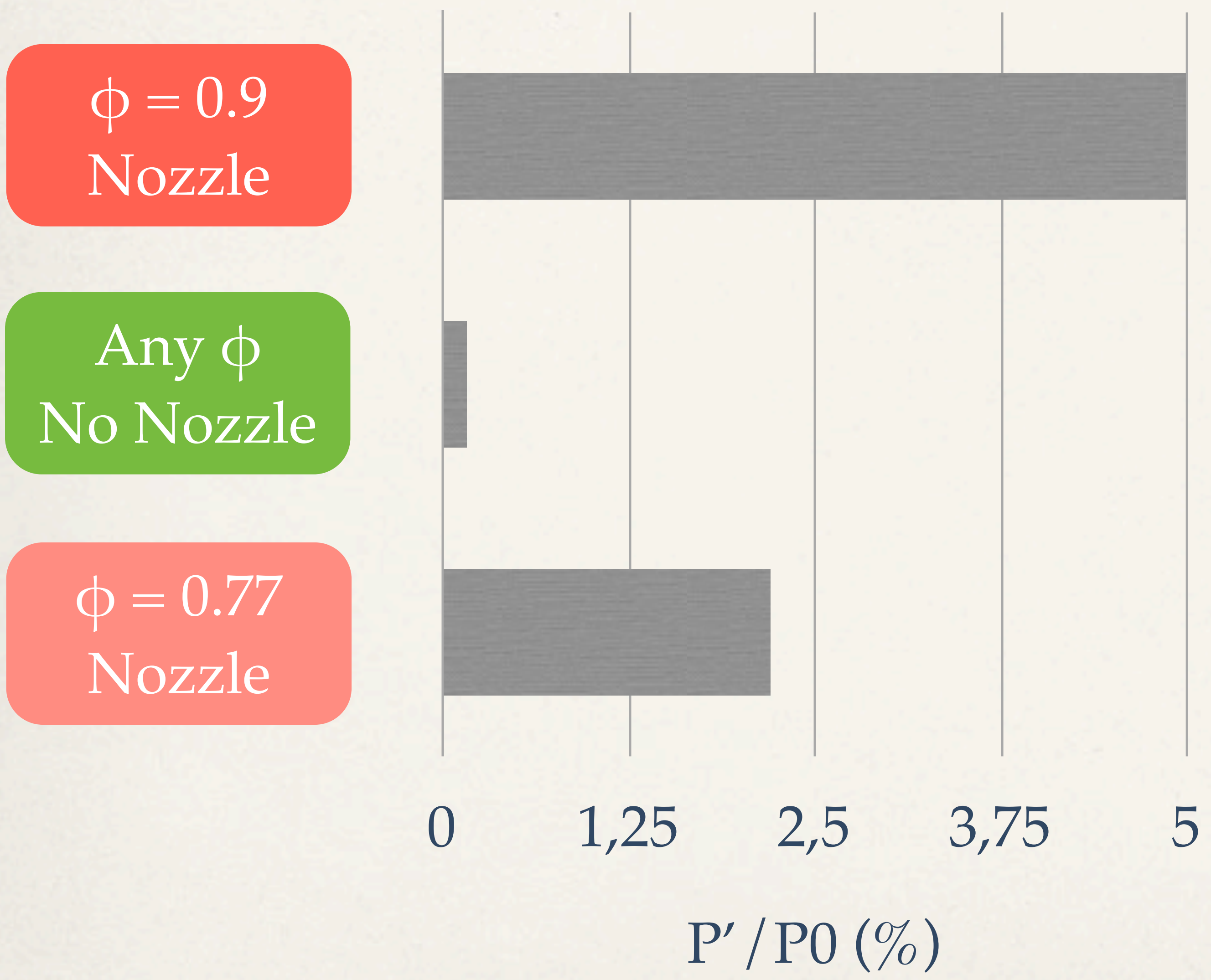


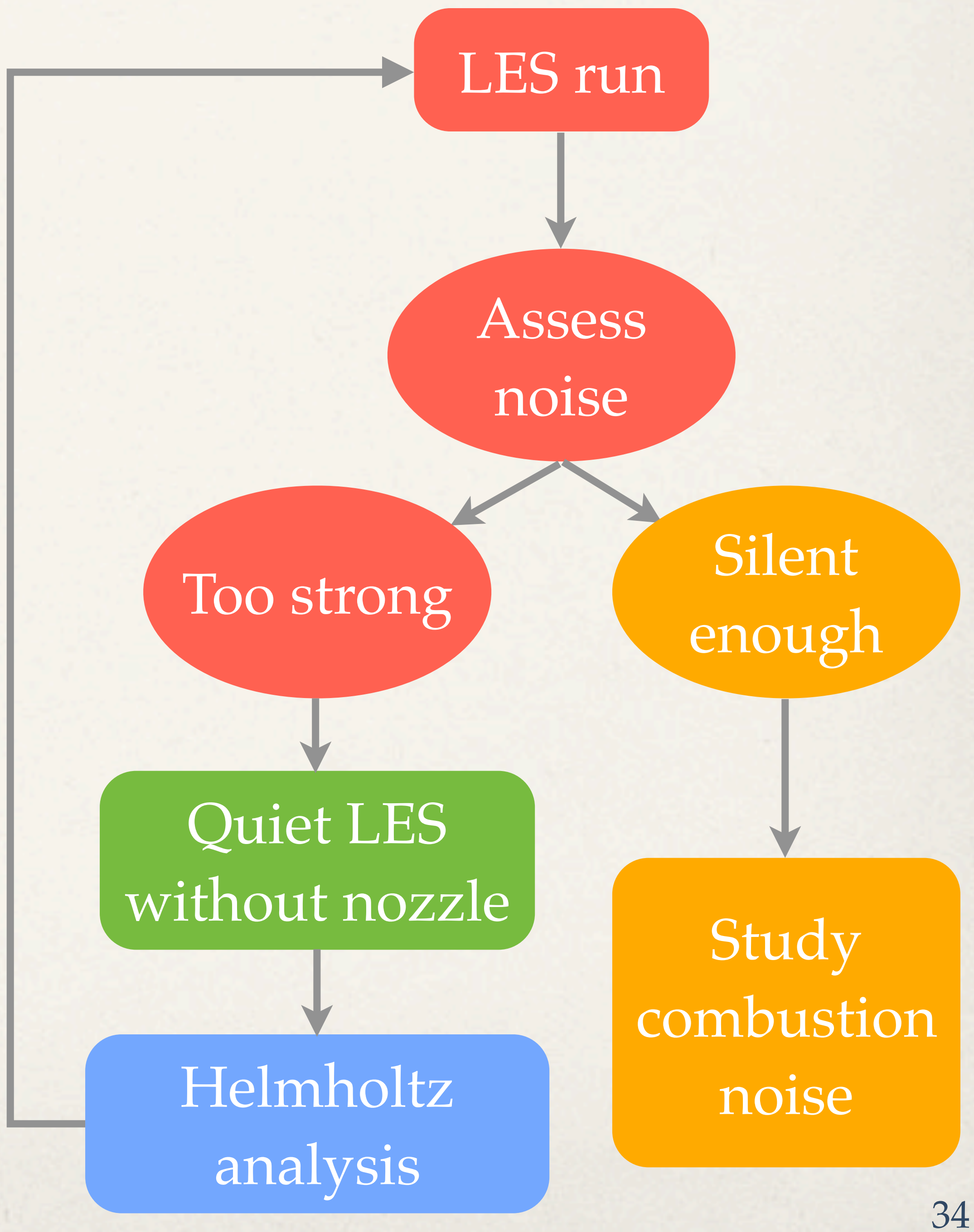
Strategy Overview





Strategy Overview





Conclusion

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- Thermoacoustic instabilities are prone to hinder the study of combustion noise in realistic academic configurations;
- The control of these instabilities cannot be done through usual academic means developped for atmospheric outlet setups;
- Nor can it be done using damping devices, as the complexity of industrial chamber dampers exceeds academic possibilities.
- A fine analysis of the specific thermoacoustic dynamics is necessary to achieve reasonable stability. It has not yet been shown however that it is enough.