# A new experimental database for the investigation of soot in a model scale swirled combustor under perfectly premixed rich conditions

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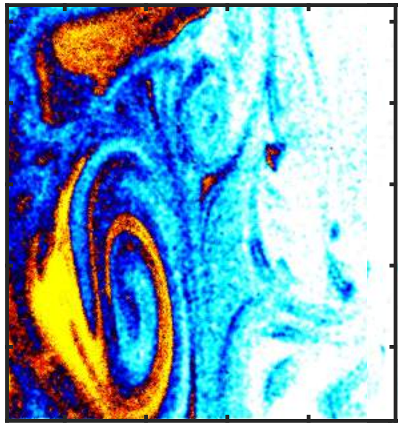
S. Candel, B. Franzelli



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*Dublin, 2018*

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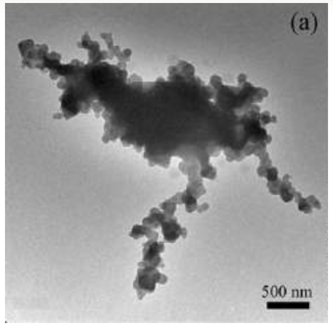
Paris-Saclay, 91192 Gif-sur-Yvette, France

# Introduction

1) Soot are dangerous and harmful:
- Environment[2]
- Human health[3]




TEM images of a soot particle [1]

2) **But** crucial role of soot in industrial burners
- Thermal radiation of soot is highly effective for glass or metal melting in large industrial applications

→ Need for a better understanding of soot production to guide modeling efforts

But there are numerous difficulties:
- Experimentally: small particles with high intermittency; optical properties not perfectly known and highly dependent on fuel and operating conditions
- Numerically: multi-physics and multi-scale phenomenon

***[1] Li, W., & Shao, L***. (2009). Transmission electron microscopy study of aerosol particles from the brown hazes in northern China. ***J. Geophys. Res. Atmos***, *114*(D9).

***[2] T.C Bond et al.*** (2013) Bounding the role of black carbon in the climate system: A scientific assessment. ***J. Geophys. Res. Atmos***., 118, 5380–5552,

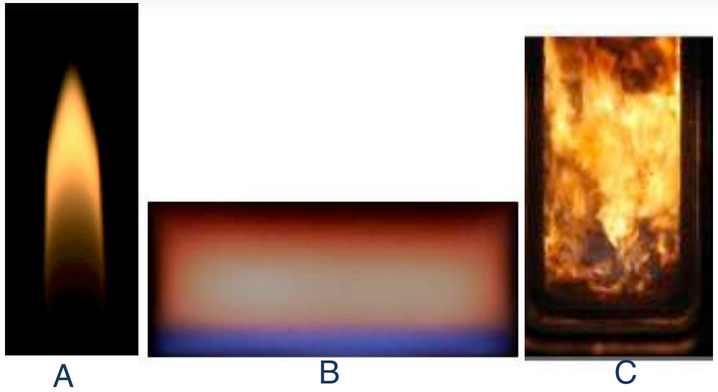
***[3] Pascal M et al.*** (2016) Impacts de l'exposition chronique aux particules fines sur la mortalité en France continentale et analyse des gains en santé de plusieurs scénarios de réduction de la pollution atmosphérique ***Santé publique France***

# Introduction

Numerous studies already exist on soot characterization:

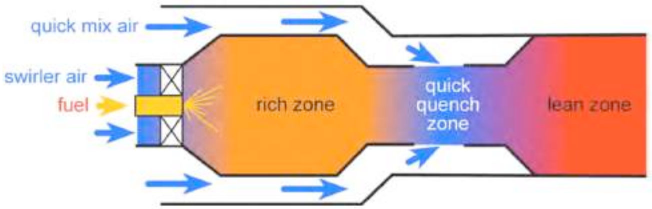
- A) Laminar diffusion flame[1]/good predictability[1]
- B) Laminar premixed flame[2]/good predictability[3]
- C) Turbulent diffusion flame[4]/difficult challenge ($f_v$)[5]
- D) **Turbulent premixed flame:** no experimental data and

a single LES of a turbulent premixed sooting flame [6]




But this configuration presents several advantages:

- No air/fuel mixing effect → direct study of effects such as equivalence ratio or turbulence on soot production
- Perfectly premixed condition is interesting for numerical validation
- Useful for Rich-Quench-Lean concepts for NOx reduction





***[1] Smooke, M., et al***, 2005. Soot formation in laminar diffusion flame. ***Combust. Flame***, 143 (4), pp. 613–628.

***[2] Betrancourt, C. et al***, 2017. Investigation of the size of the incandescent incipient soot particles in premixed sooting and nucleation flames of n-butane using LII, HIM, and 1 nm-SMPS. ***Aerosol Sci. Technol.***, 51 (8), pp. 916–935.

***[3] Abid, A.D.***, et al, 2009. Quantitative measurement of soot particle size distribution in premixed flames–the burner-stabilized stagnation flame approach. ***Combust. Flame*** 156.10 : 1862-1870.

***[4] Geigle, K. P.et al,*** 2011. Experimental analysis of soot formation and oxidation in a gas turbine model combustor using laser diagnostics. ***J. Eng. Gas Turbines Power***, 133 (12).

***[5] Rodrigues, P. et al,*** 2018. Coupling an LES approach and a soot sectional model for the study of sooting turbulent non-premixed flames. ***Combust. Flame***, 190, 477-499.

***[6] El-Asrag, H. et al,*** 2007. Simulation of soot formation in turbulent premixed flames. ***Combust. Flame***, *150*(1-2), 108-126.

# Introduction

1) EM2Soot configuration
2) Study of a typical operating point
3) Effects of operating conditions on soot production

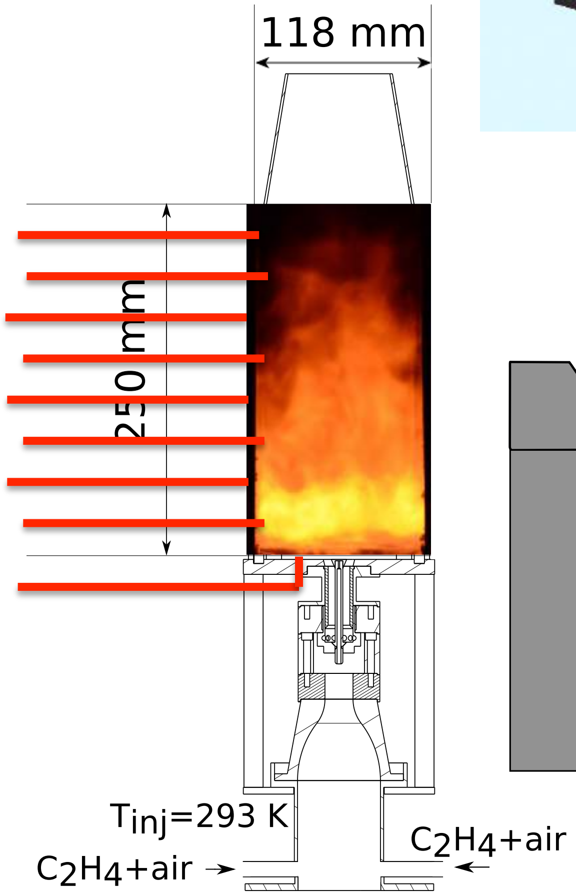
# EM2Soot configuraton

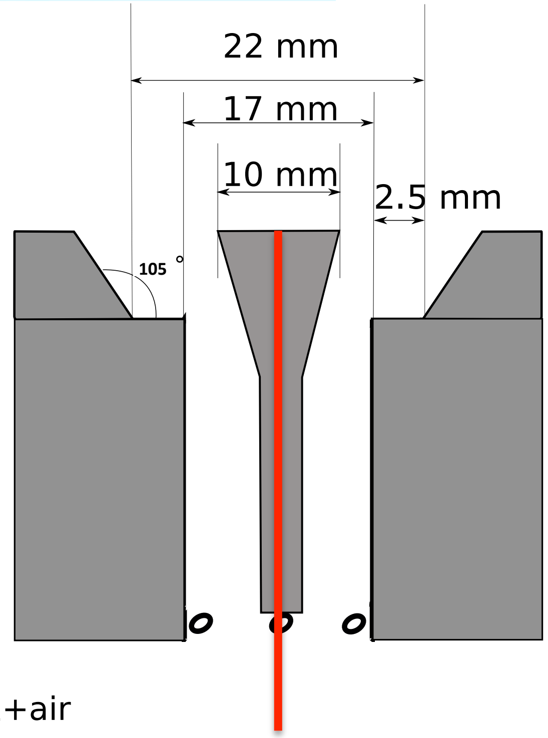
***Characteristics:***

- Perfectly premixed (ethylene/air) swirled flame
- Quartz confinement
- 12 thermocouples for wall and gas temperature measurements

***Several challenges:***

- Stabilization of a rich premixed swirled flame with a new injector design
- Important role of the combustion chamber temperature (issue for repeatability)
- Fast obscuration of quartz (< 2 min)
- Relatively low soot volume fraction (detection issues)




*Injector design*

# Content

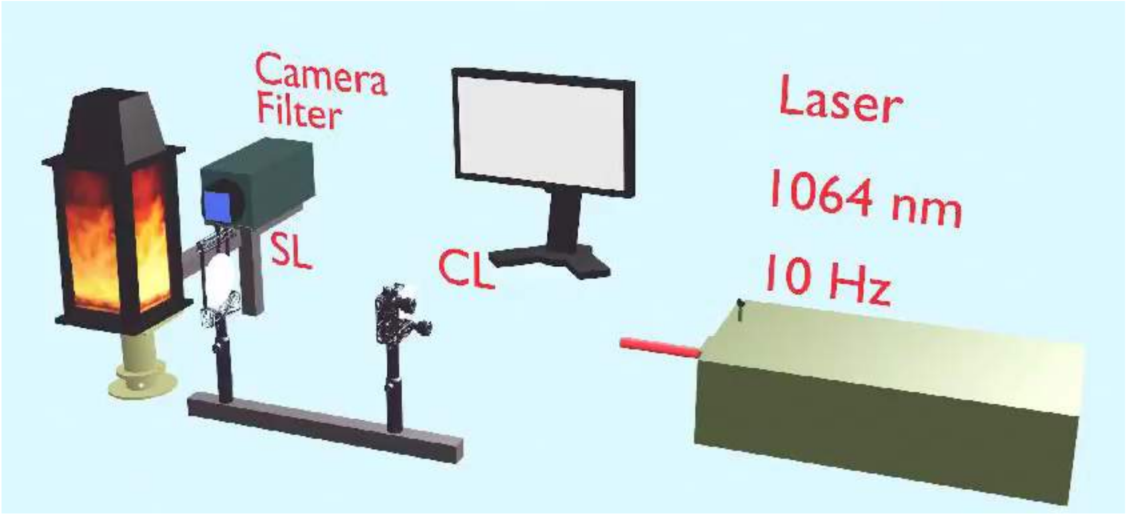
1) EM2Soot configuration

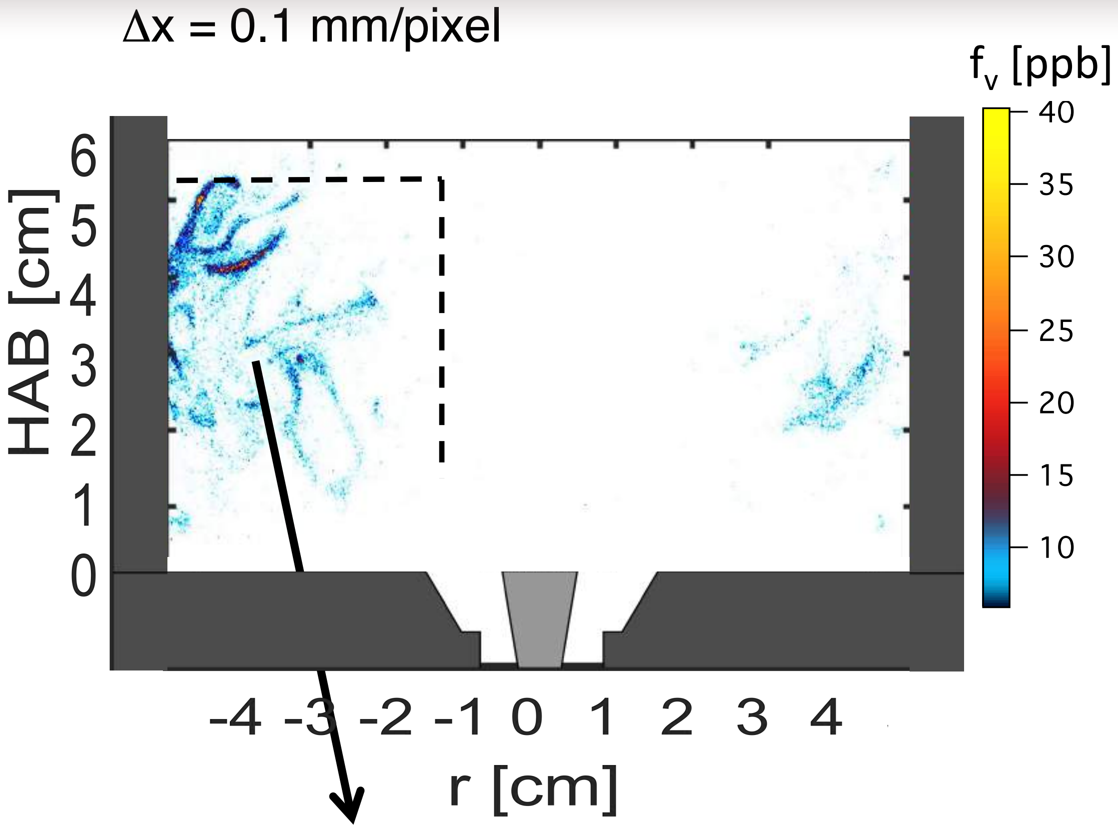
2) Study of a typical point (P=15 kW, $\phi$=2.1)

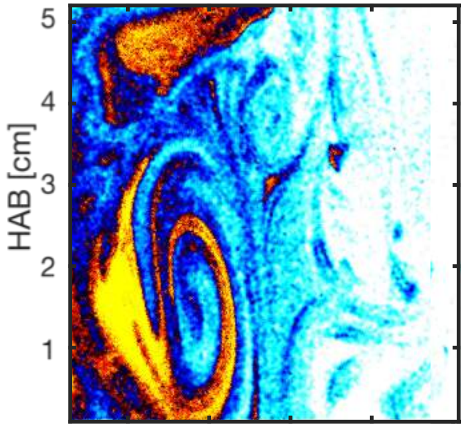
- Laser Induced Incandescence (LII) for soot volume fraction
- Light scattering for soot imaging
- PIV for flow velocity measurements
- OH chemiluminescence for flame reaction zone

3) Effects of operating conditions on soot production

# Soot volume fraction measurements (LII)[1]



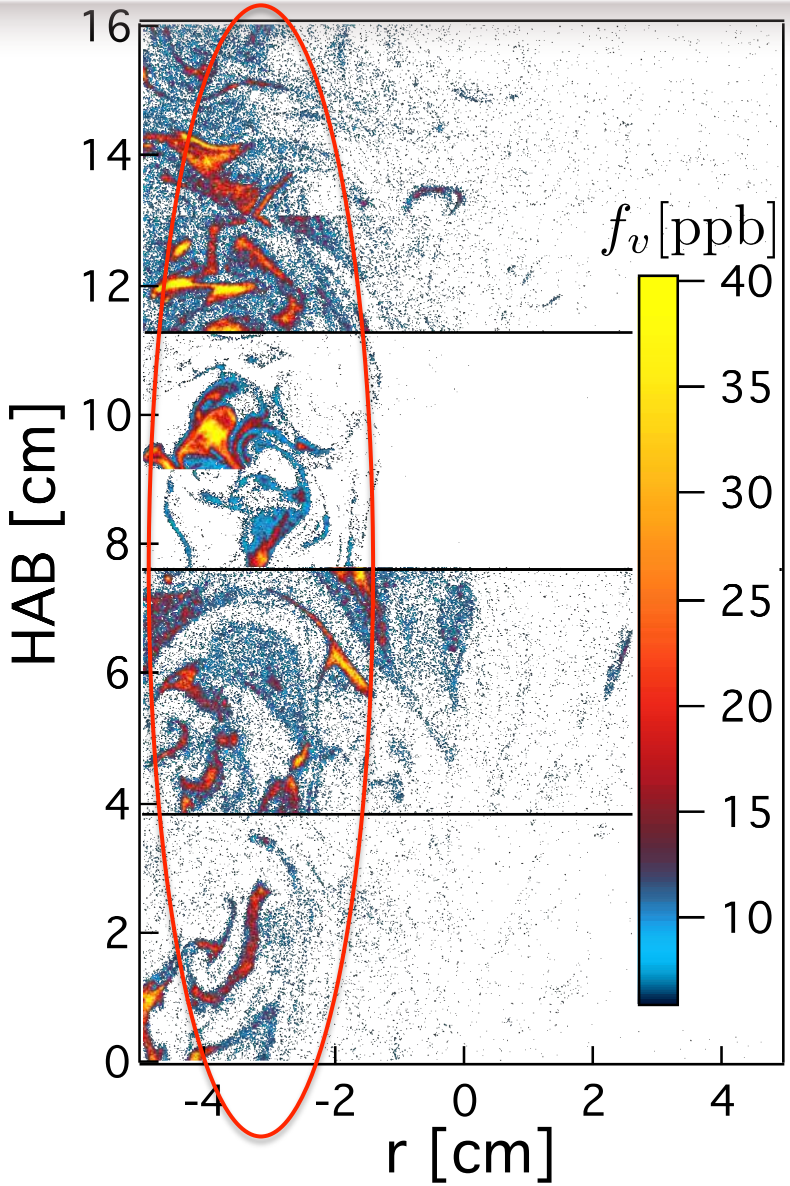




- Wrinkled filament of soot visible along the wall with large-scale soot structure
- High temporal and spatial intermittency
- Strong interaction with turbulent eddies
- Ligamentary structure (thickness ≈ 1 mm)

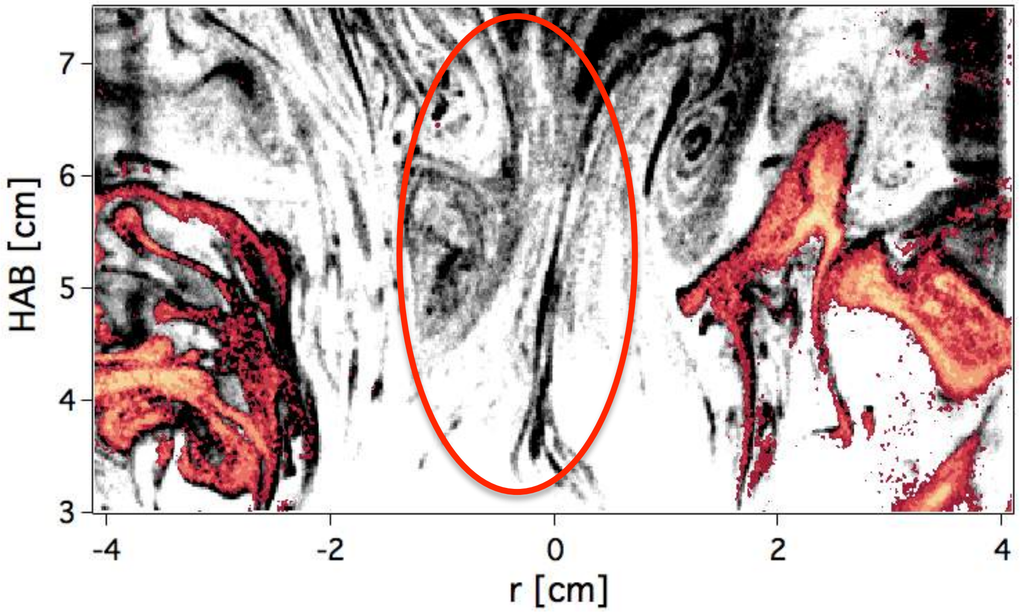

*[1] **Roussillo, M. et al.***, 2018. “Experimental investigation of soot production in a confined swirled flame operating under perfectly premixed rich conditions*”. **Proc. Combust. Inst (2018)***

# Soot volume fraction measurements (LII)[1]




*LII signal (soot volume fraction) is mainly detected close to the wall*

But.... Light scattering signal in the middle is detected




*Simultaneous LII (red)/light scattering (black) experiments at 532 nm*

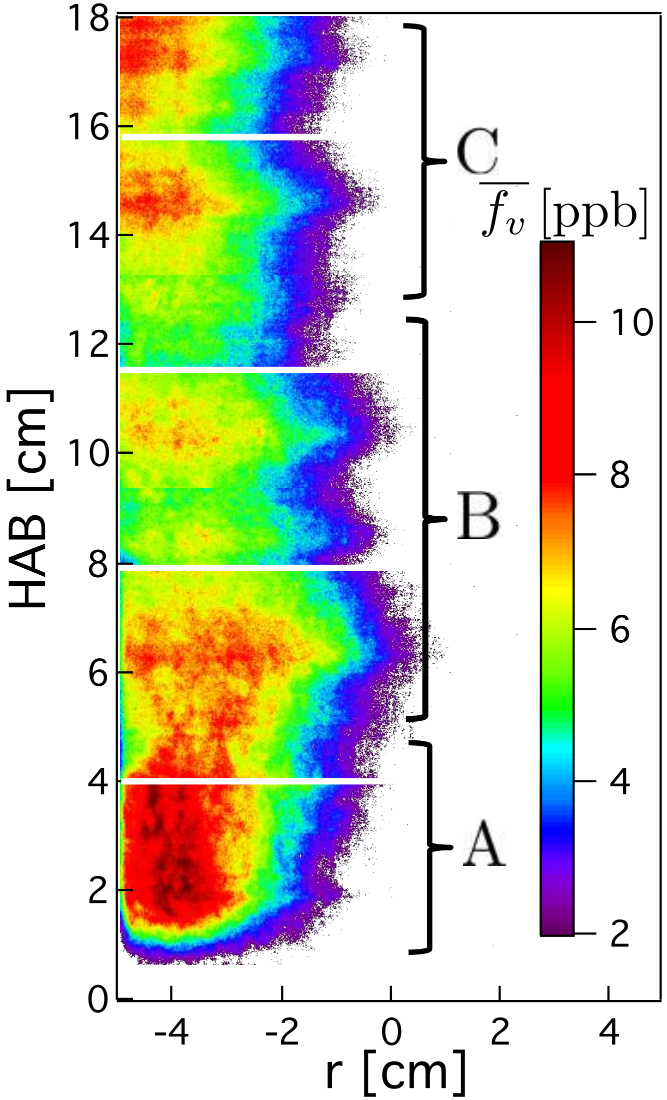
Soot is also present in the central region, two possibilities:

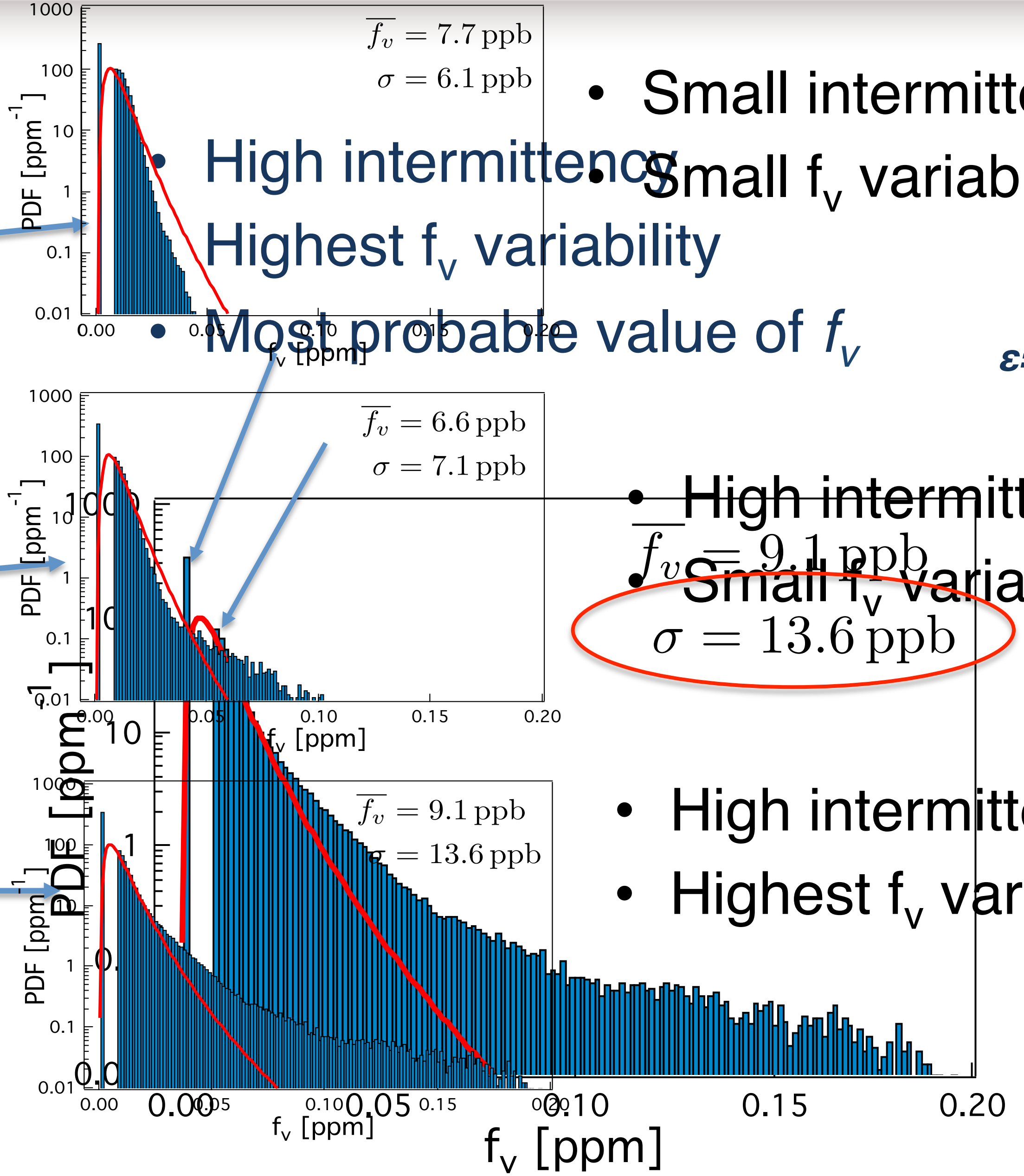
- ***Small number of large particles***
- ***Big number of nuclei***

**What about mean soot volume fraction along the wall ?**

# Soot volume fraction measurements (LII)[1]

Mean soot volume fraction distribution is monotonic along HAB?




- High intermittency
- Highest $f_v$ variability
- Most probable value of $f_v$

- Small intermittency
- Small $f_v$ variability

*ε=7.5 ppb*

- High intermittency
- Small $f_v$ variability

$\overline{f_v} = 9.1$ ppb

$\sigma = 13.6$ ppb

- High intermittency
- Highest $f_v$ variability

*Mean soot volume fraction from 300 uncorrelated images*

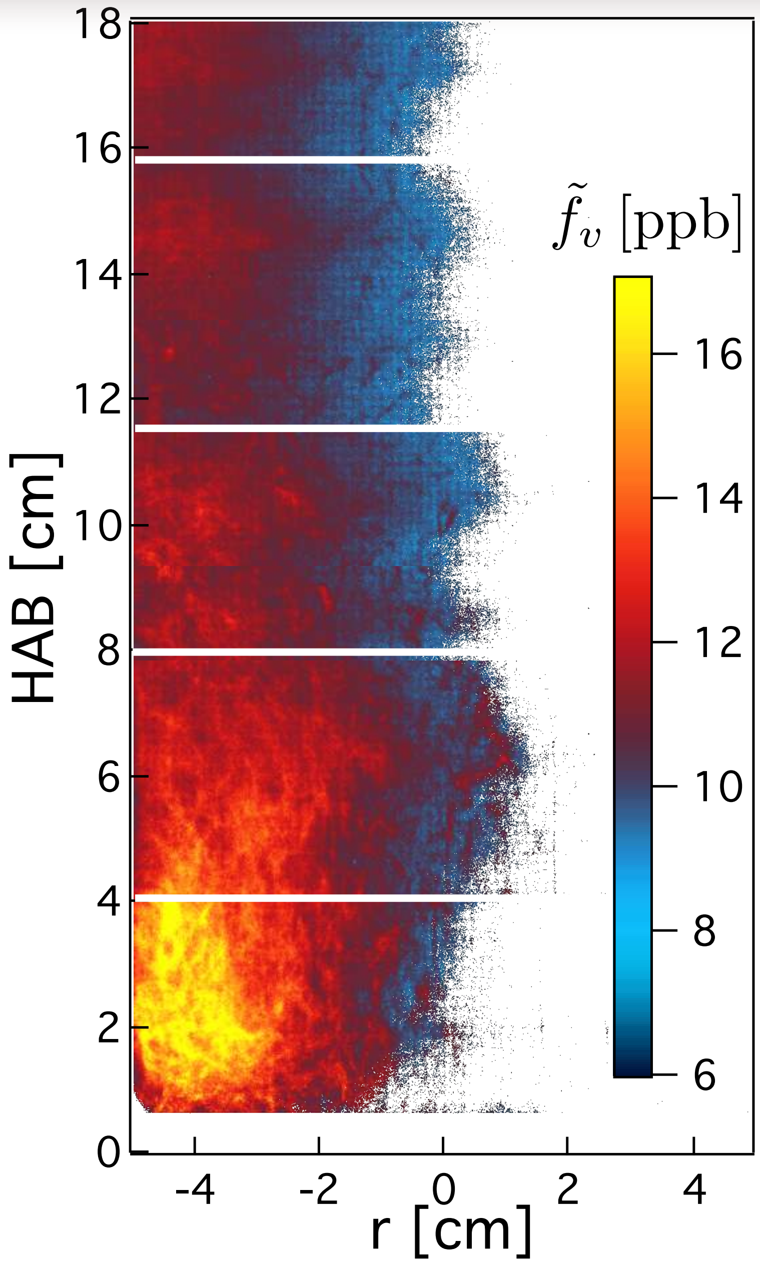
# Intermittency affects results interpretation

*Weighted mean to account for the intermittency index I*

$$\widetilde{f}_v(x,y) = \frac{\sum_{t=1}^{N_t} f_v(x,y,t) I(x,y,t)}{\sum_{t=1}^{N_t} I(x,y,t)}$$

$$\mathcal{I}(x,y,t) = \begin{cases} 0 & \text{if} \quad f_v(x,y,t) < \epsilon \\ 1 & \text{if} \quad f_v(x,y,t) \geq \epsilon \end{cases}$$

***ε=7.5 ppb***

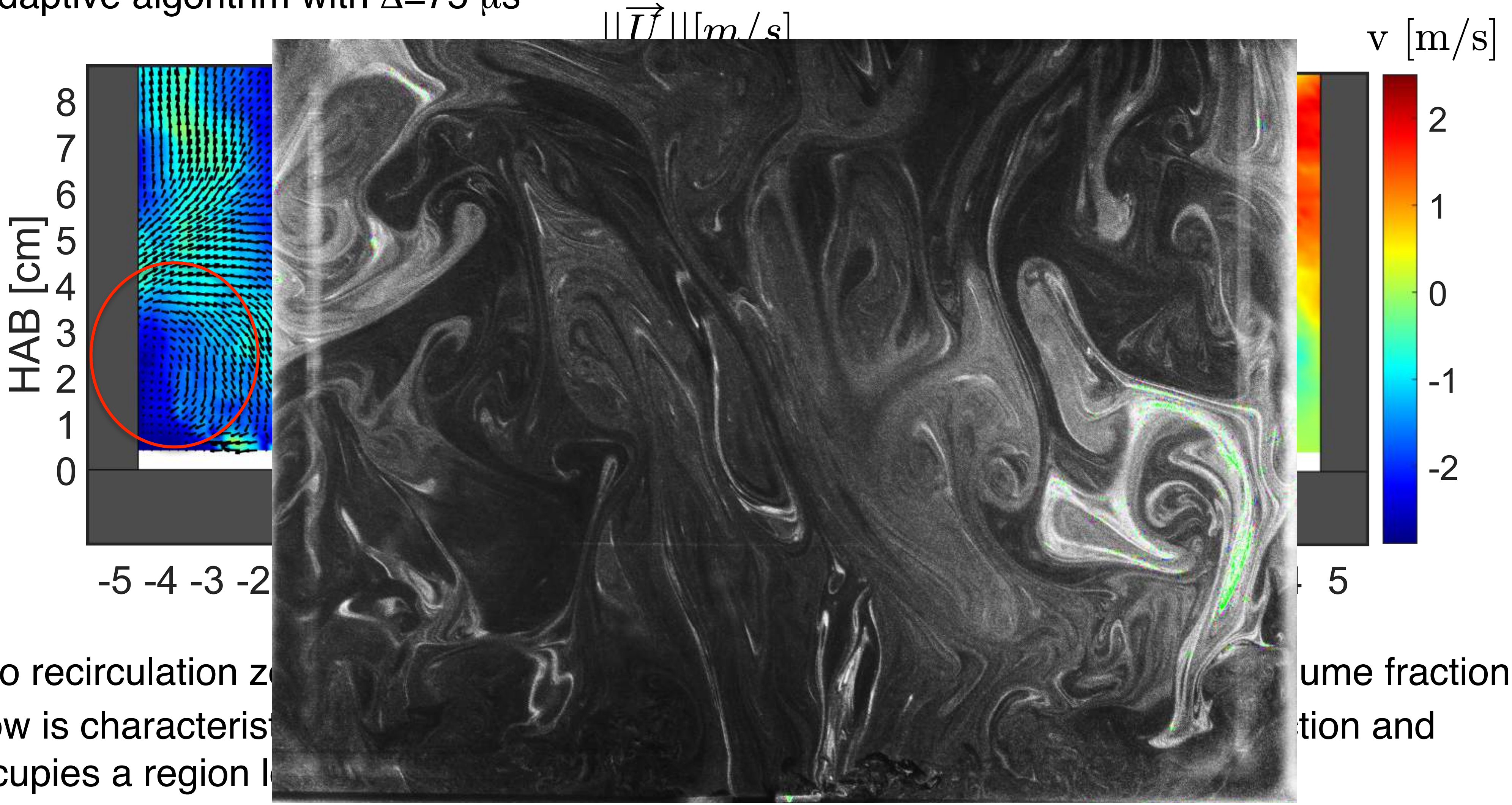



Intermittency has a major impact on soot production ➔ the weighted mean is evolving monotonically in the axial direction

# PIV results

PIV measurements under reactive conditions are carried out using soot particles as tracers

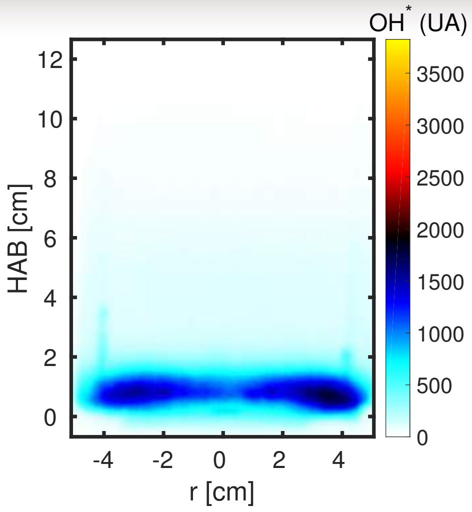
- A narrow band filter is used to filter out high flame luminosity on the second frame
- Adaptive algorithm with Δ=75 μs




- Two recirculation z ume fraction
- Flow is characterist tion and occupies a region l

[1] ***Degeneve, A. et al,*** 2018. ***ASME 2018 (2018)***

# Information on the flame reaction zone OH



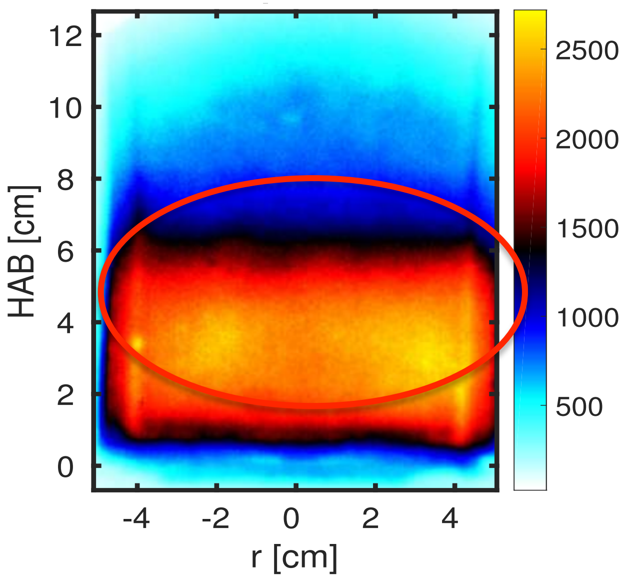

**ϕ=1.48 (non sooting)**

Reaction zone close to the injector backplane with this injector design[1]

OH detection is no longer possible due to :

- ***Low OH concentration for rich conditions***
- ***Black body radiation of soot particles and filter parasitic transmission in infrared (rebound)***

**ϕ=1.7 (sooting)**




Hypothesis: OH reaction zone remains close to the injector backplane for all the operating conditions


***[1]* Jourdaine, P et al** "Effect of quarl on N2 -and CO2 -diluted methane oxy-flames stabilized by an axialplus-tangential swirler". ***In ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition***

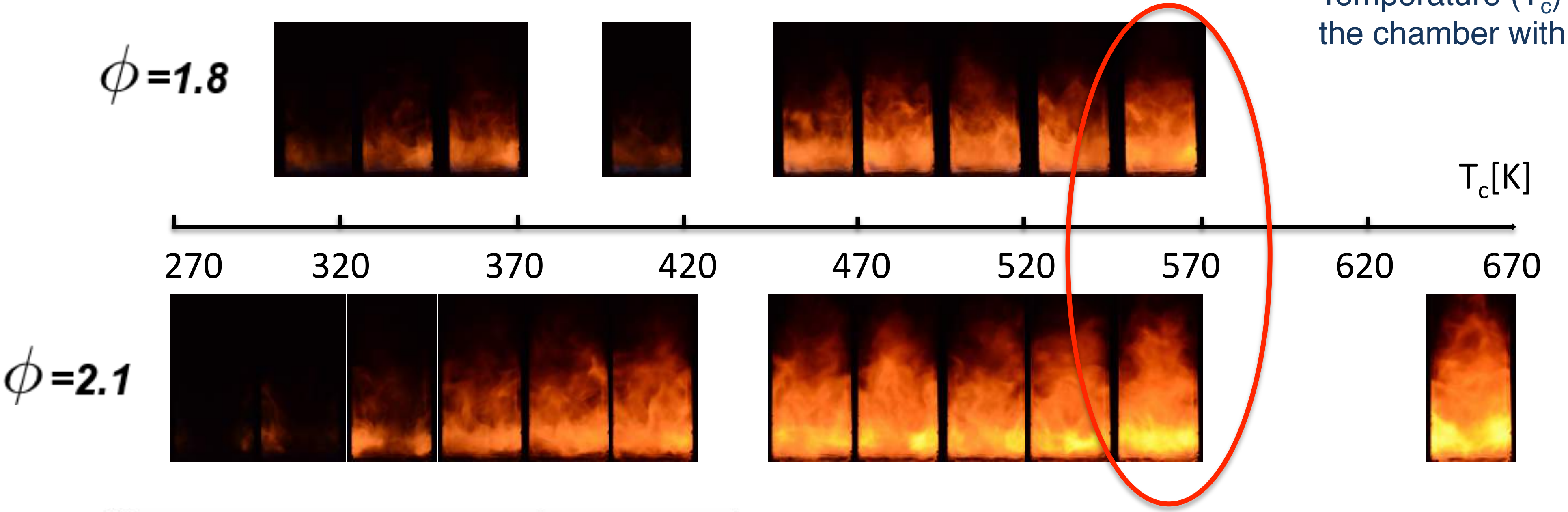
***[2] Panoutsos, C.et al.***, 2009. "Numerical evaluation of equivalence ratio measurement using OH *and CH chemiluminescence in premixed and nonpremixed methane–air flames". **Combust. Flame***, 156 (2), pp. 273–291

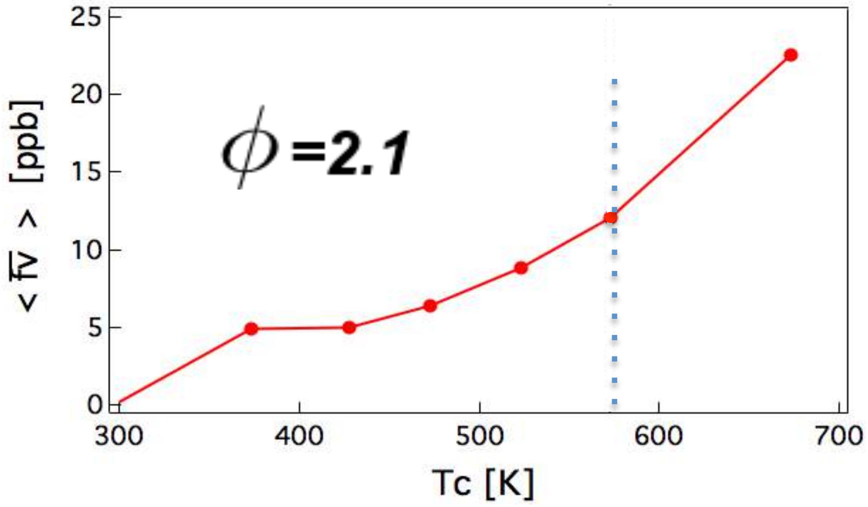
# Content

1) EM2Soot configuration
2) Study of a typical operating point
3) Effects of operating conditions on soot production

# Effect of wall temperature [1]

Temperature ($T_c$) is reached after preheating of the chamber with a lean flame

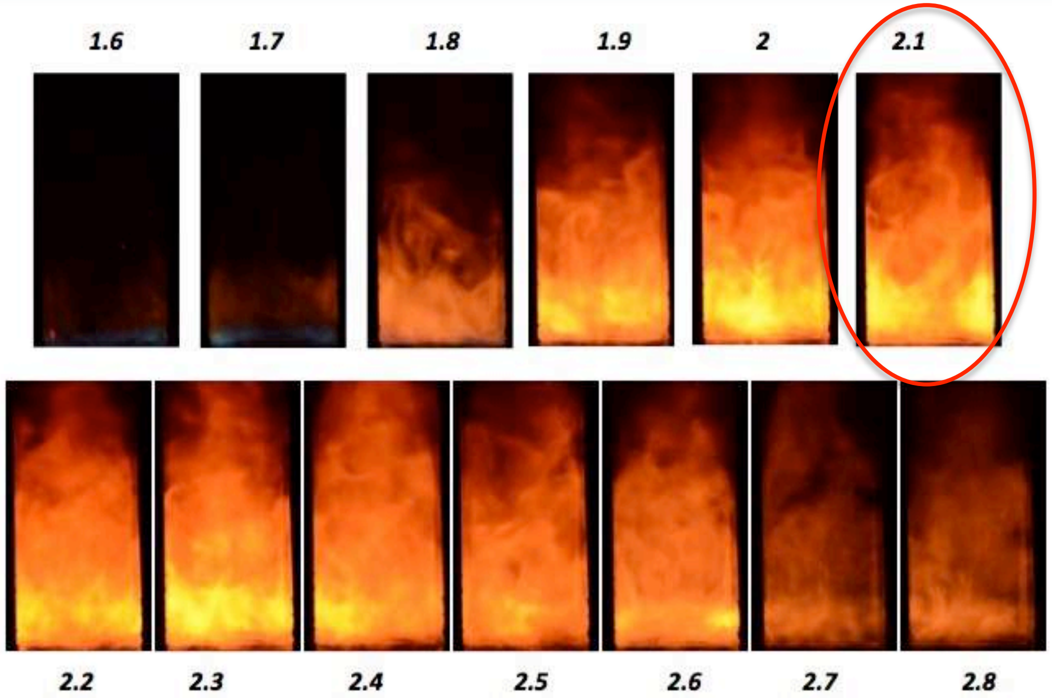


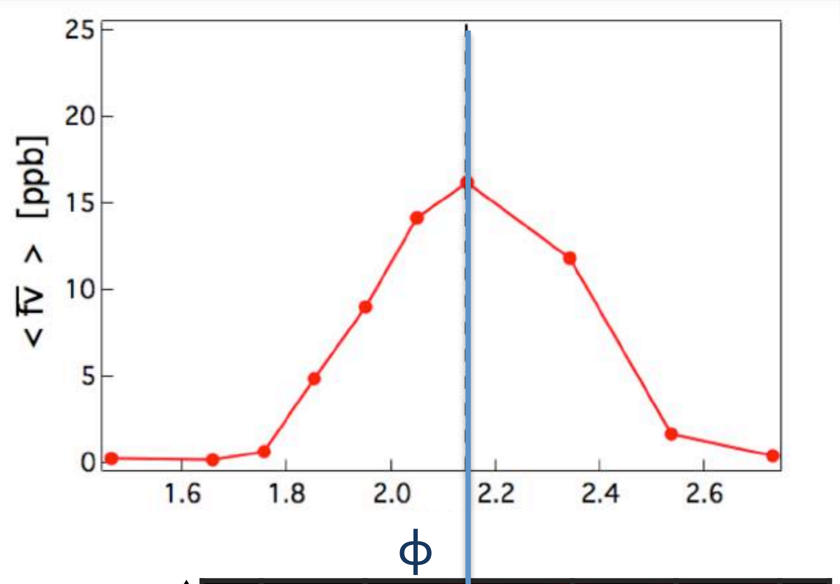

- Strong link between the wall temperature on soot production detected both qualitatively and quantitatively
- All experiments are then carried out with an initial temperature of $T_c$=570 K, assuring a good repeatability, a sufficient soot production and a quasi-steady thermal state during experiments $\Delta T$= 15 K

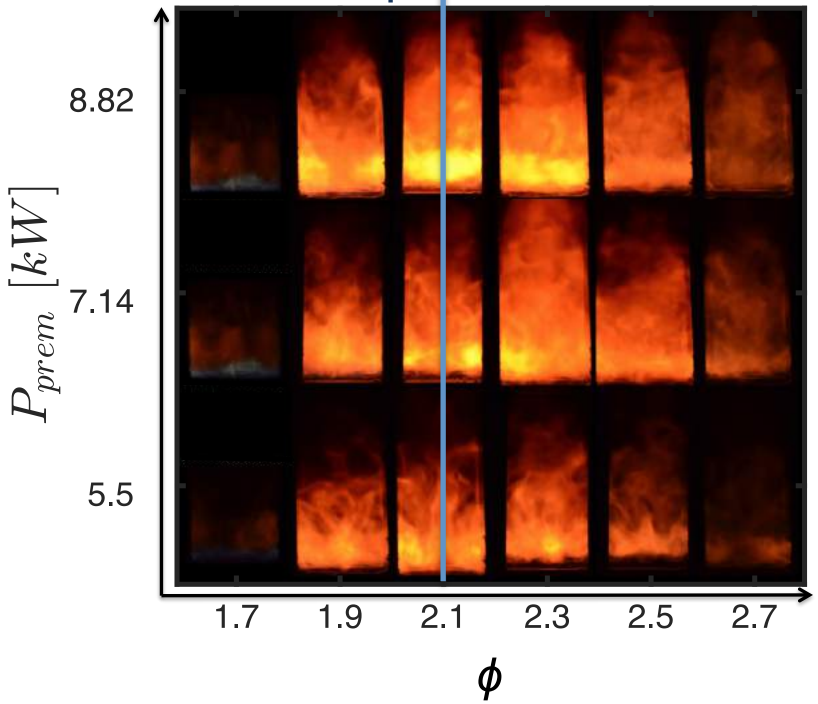

***[1] Roussillo, M. et al,*** 2017. “A new experimental database for the investigation of soot in a model scale swirled combustor under perfectly premixed rich conditions”. ***ASME 2018 (2018)***

# Effect of equivalence ratio




- A critical equivalence ratio for maximum soot production close to 2.1 is measured
- Fair agreement between LII measurements and visual aspect of flame evolution with the equivalence ratio
- Scalable for all studied powers



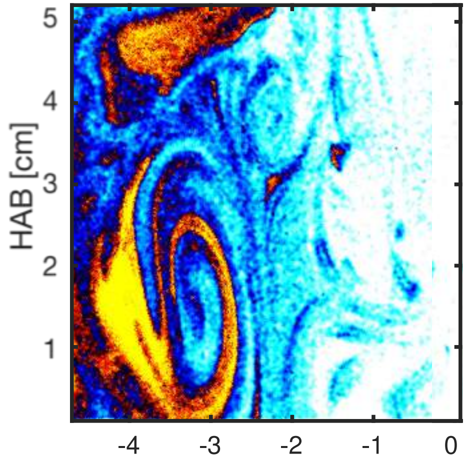



# Conclusion

- First quantitative measurements of soot in turbulent premixed sooting flames
- High correlation between quartz temperature and soot production was highlighted
- Soot volume fraction is measured mainly along the wall but soot particles are present everywhere in the burner
- Effects of equivalence ratio and flame power on soot production have been discussed
- PIV measurements using soot particles as tracers have been carried out in reactive conditions

*Future work:*

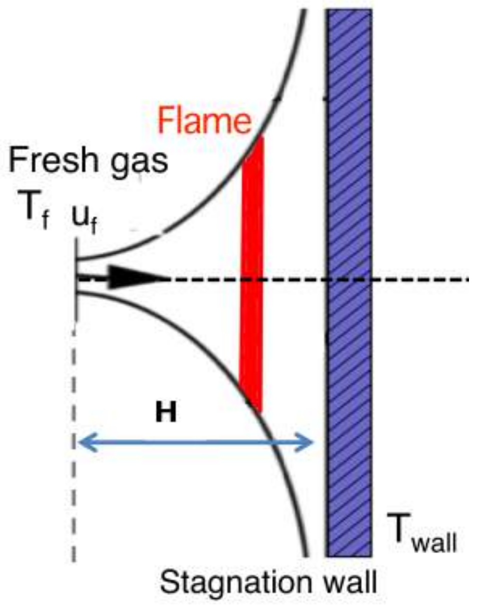
- New confinement to measure LII signal along the wall
- Temperature measurement by LIP
- Slightly different injector to modify the injector and chamber aerodynamic
- Simulations




**ACKNOWLEDGMENT**

Support from G.Legros and J.Bonnety (UPMC) for the LII calibration through the MAE technique is gratefully acknowledged. This study is supported by the Air Liquide, CentraleSupelec and CNRS Chair on oxycombustion and heat transfer for energy and environment and by the OXYTEC project, grant ANR-12-CHIN-0001 of the French Agence Nationale de la Recherche.

# First simulation: burner-stabilized stagnation (BSS)

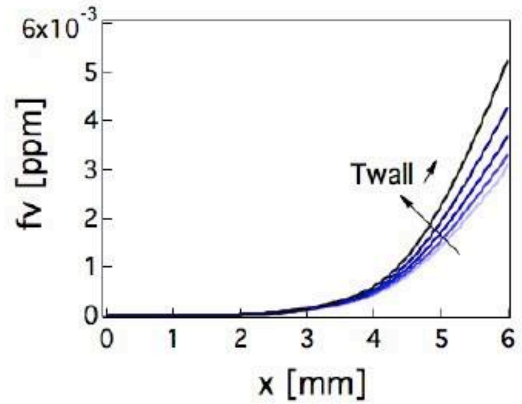



Advantages

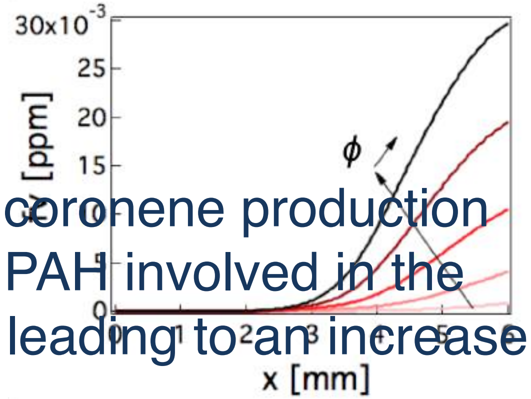
- Fast to simulate
- REGATH
- Well-known configuration[1-2]

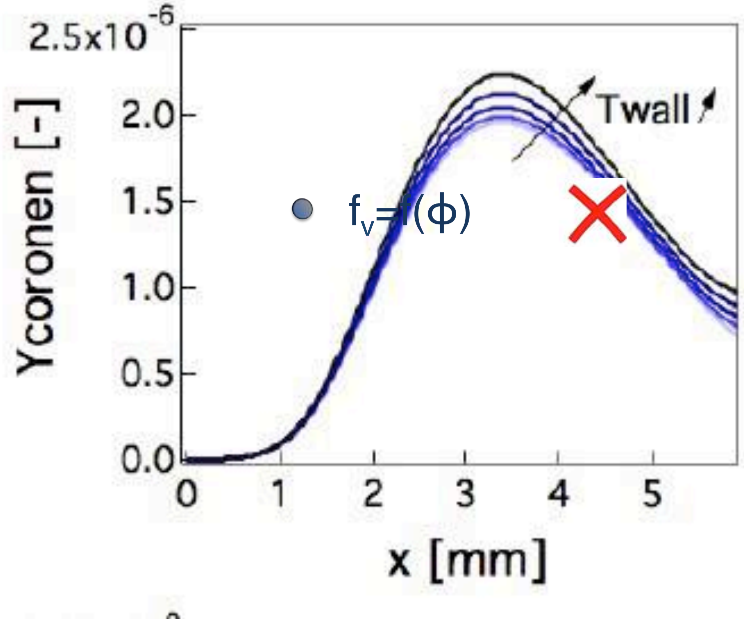
Drawbacks

- Laminar model
- 1-D simulation




$T_{wall}$ =300, 400, 500, 600, 700 K




- $f_v = f(\phi)$

$T_{wall}$ increases with coronene production which is one of the PAH involved in the nucleation process leading to an increase of $f_v$

This model cannot account for the interactions between the flame, turbulent eddies and soot production


***[1] Abid, A. D. et al.***, 2009. "Quantitative measurement of soot particle size distribution in premixed flames–the burner-stabilized stagnation flame approach". ***Combust. Flame***, 156 (10), pp. 1862–1870.

***[2] Lindstedt, R. et al***, 2013. "Modeling of soot particle size distributions in premixed stagnation flow flames". ***Proc. Combust. Inst.***, 34 (1), pp. 1861–1868.

# Nomenclature

Rich premixed condition, two flames are present

Exhaust flame

$$P_{exh} = \dot{m}_{exhaust\ fuel} PCI_{C_2H_4}$$

Premixed flame

$$P_{prem} = \dot{m}_{fuel}^{stochio} PCI_{C_2H_4}$$

$P_{tot} = P_{ex} + P_{prem}$

$$\phi = \frac{P_{tot}}{P_{prem}}$$

***EM2Soot is fully characterized by $\phi$ and $P_{prem}$***



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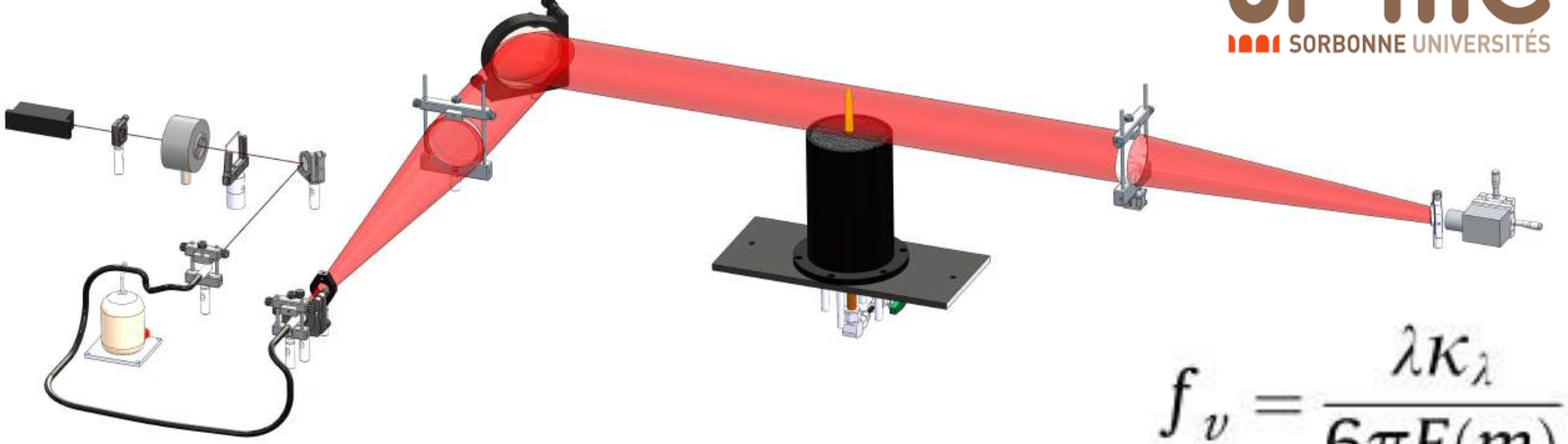
# Effect of wall temperature

As soot production is extremely linked with the temperature of preheating, a working method had to be implemented:

# MAE [1] on a laminar configuration [2]

*MAE [4] (Modulated Absorption Emission Technique):*



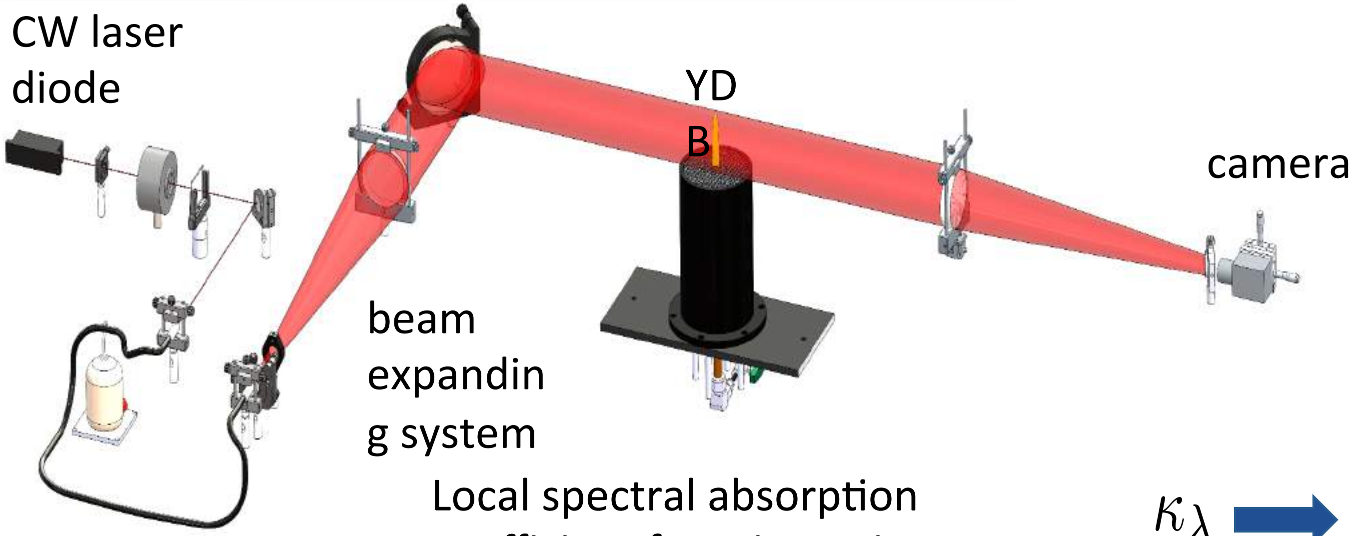
$$f_v = \frac{\lambda K_\lambda}{6\pi E(m)}$$

- Measurements of $f_v$ and T in laminar axisymmetric flames based on absorption measurements
- Non-applicable in turbulent flames (cf deconvolution process)
- Main sources or errors linked with the high variability of E(m)

***[1] Legros, G et al.***(2015). Simultaneous soot temperature and volume fraction measurements in axis-symmetric flames by a two-dimensional modulated absorption/emission technique. *Combustion and Flame*, *162*(6), 2705-2719

***[2] Franzelli, B. et al.***, 2018. "Muti-diagnostic soot measurements in a laminar diffusion flame to assess the ISF database consistency*"*. ***Proc. Combust. Inst***

# MAE [1] on a laminar configuration [2]




Local spectral absorption coefficient from incoming energy with-w/o laser/flame:

$$\kappa_\lambda \rightarrow f_v = \frac{\lambda \kappa_\lambda}{6\pi E(m)}$$

**Operating conditions**

$\lambda = 645\text{nm}$ $E(m) = 0.38$

*Filter* $645 \pm 2\text{nm}$

*Line-of-sight measurements*

*In-house deconvolution*

**Uncertainties**

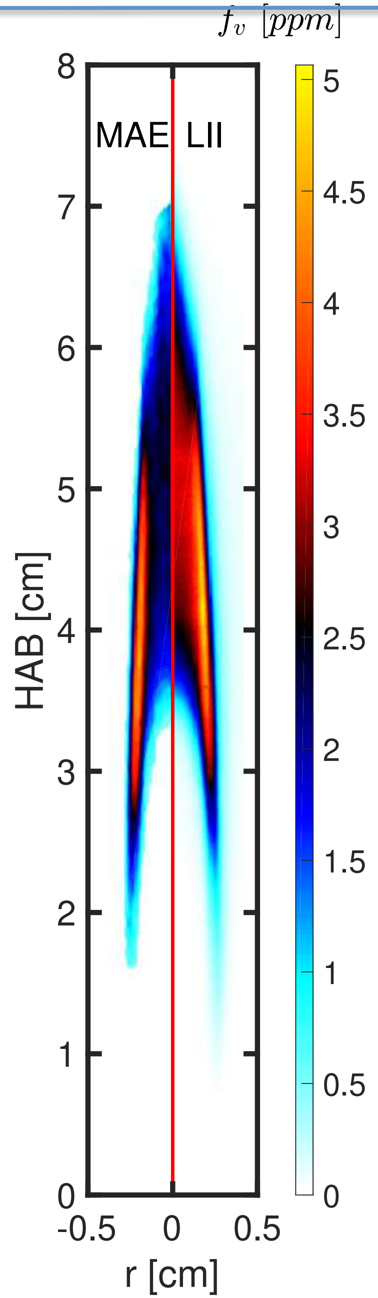
Factor 2: E(m)

2.5% (Santoro flame)

***[1] Legros, G et al.***(2015). Simultaneous soot temperature and volume fraction measurements in axis-symmetric flames by a two-dimensional modulated absorption/emission technique. *Combustion and Flame*, *162*(6), 2705-2719

***[2] Franzelli, B. et al.***, 2018. "Muti-diagnostic soot measurements in a laminar diffusion flame to assess the ISF database consistency". ***Proc. Combust. Inst***

# Calibration of LII with MAE [1] on a laminar configuration [2]




Calibration is carried out by comparing LII and MAE measurements in the wings of the flame in order to neglect:

- LII self-absorption
- MAE errors along the r=0 axis due to the deconvolution process

# How intermittency affects results interpretation

Soot is a highly intermittent phenomenon[1,2]:

*Intermittency index*

$$\Omega(x,y) = 1 - \frac{1}{N_t}\sum_{t=1}^{N_t}\mathcal{I}(x,y,t)$$

with $\mathcal{I}(x,y,t) = \begin{cases} 0 & \text{if} \quad f_v(x,y,t) < \epsilon \\ 1 & \text{if} \quad f_v(x,y,t) \geq \epsilon \end{cases}$

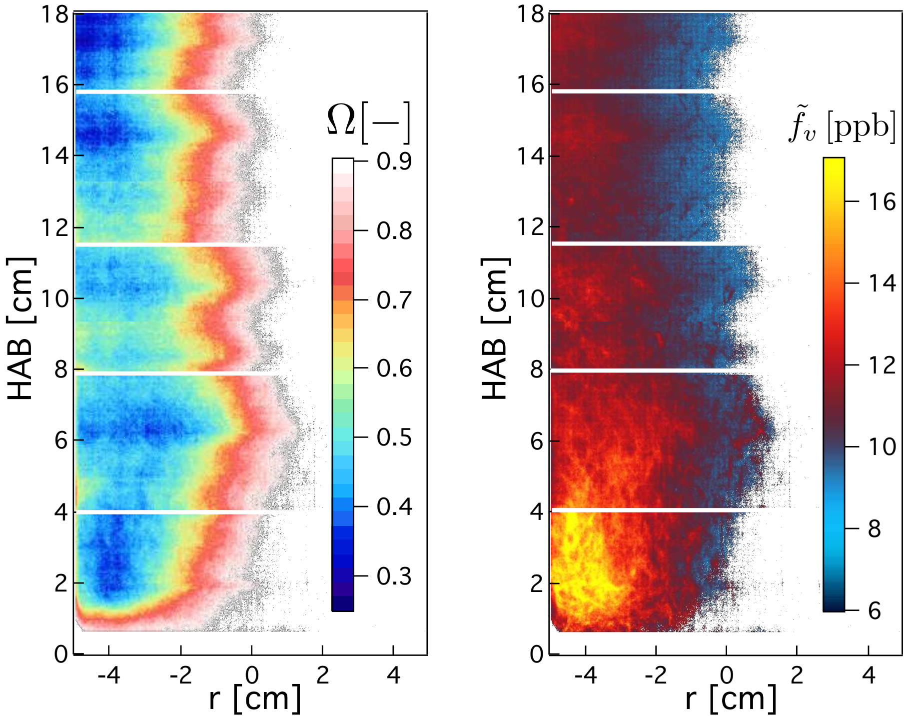
*Weighted mean to take into account the intermittency index*

$$\widetilde{f_v}(x,y) = \frac{\sum_{t=1}^{N_t} f_v(x,y,t)I(x,y,t)}{\sum_{t=1}^{N_t} I(x,y,t)}$$

*Low intermittency*

*ε=7.5 ppb*

*Medium intermittency*

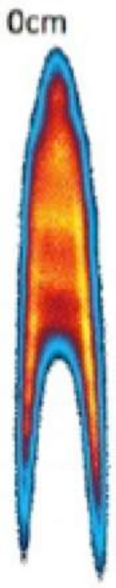



*Higher weighted mean in the lower region*

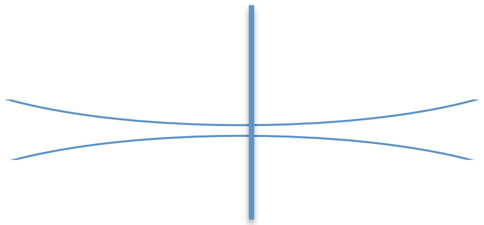

[1]**Qamar, N. H. et al** (2009). Soot volume fraction in a piloted turbulent jet non-premixed flame of natural gas. ***Combust. and Flame***, 156(7), 1339-1347.

[2] **Roussillo, M.et al.**, 2018. "Experimental investigation of soot production in a confined swirled flame operating under perfectly premixed rich conditions". ***Proc. Combust. Inst. (submitted)***

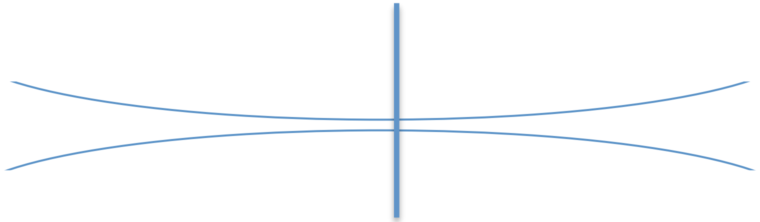
# Effect of focal length on LII measurements





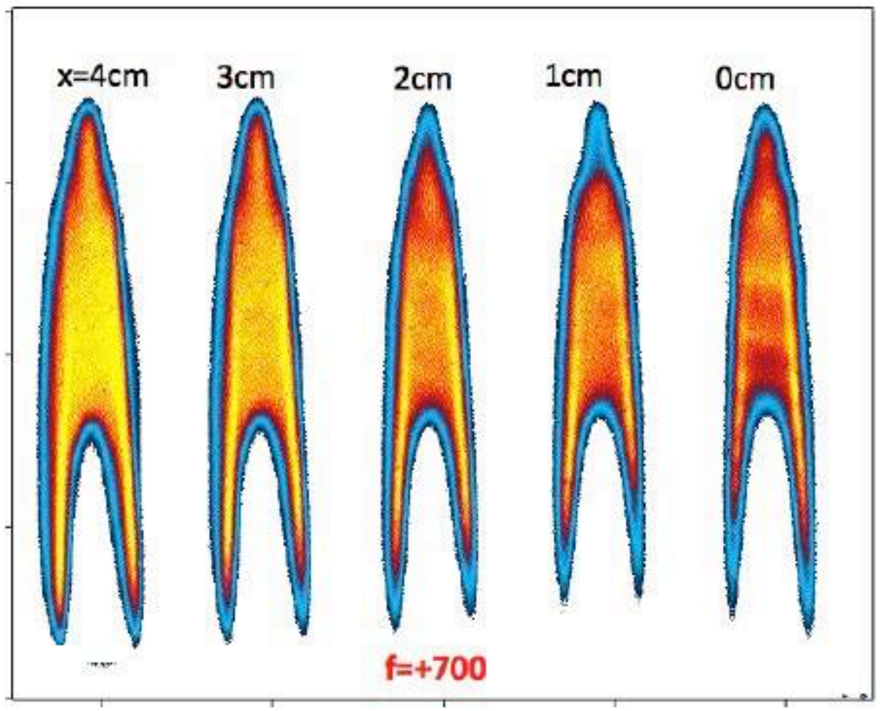


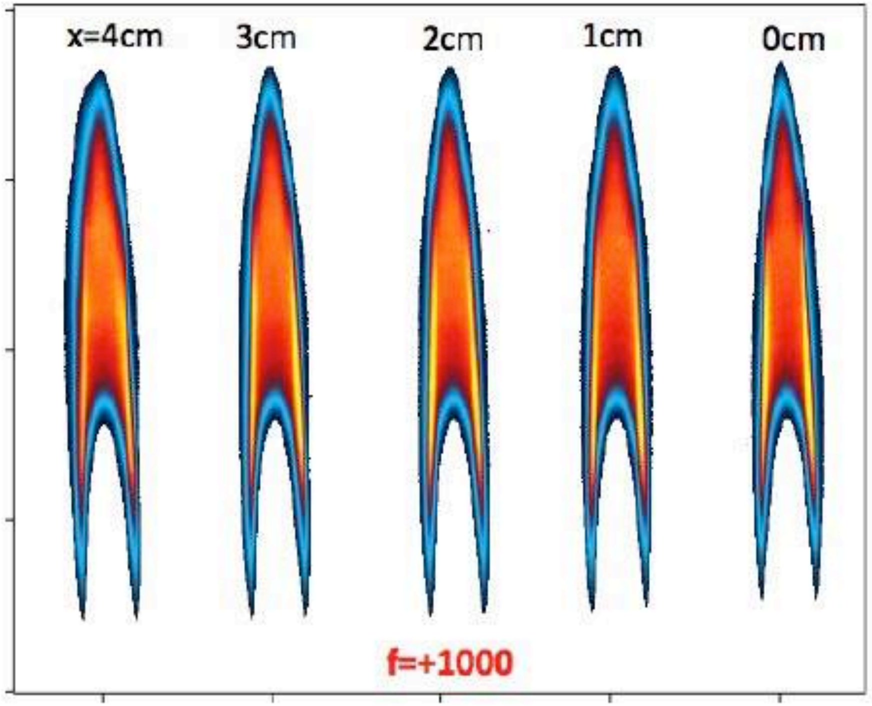
f=700 mm

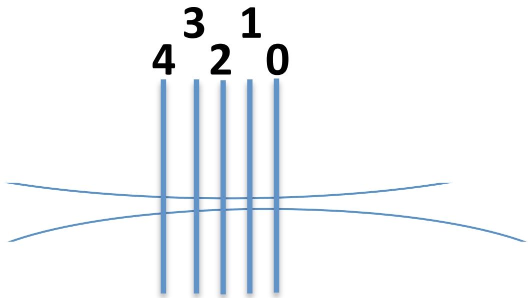


f=1000 mm

# Effect of focal length on LII measurements

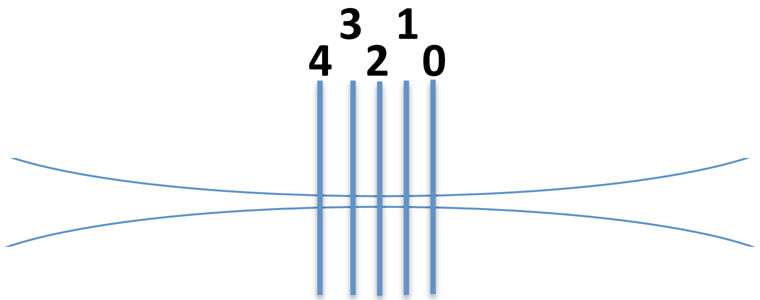



Focus point=0

f=700 mm




Focus point=0

f=1000 mm