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Multi-diagnostic soot measurements in a laminar diffusion flame to assess the ISF database consistency

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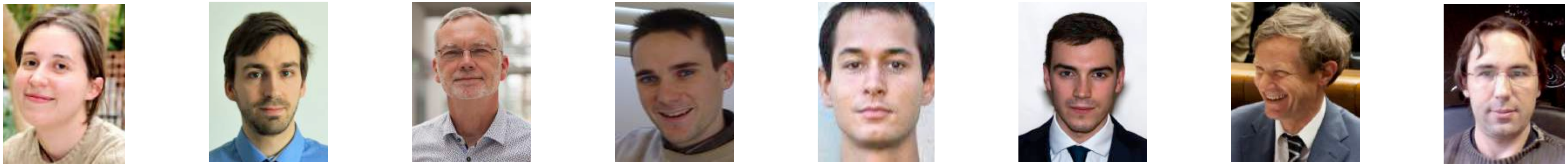

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Fundamental understanding of soot production

Control of soot release is required:

1. Full understanding of soot formation and oxidation processes
2. Accurate modeling of soot

➔ Accurate experimental database is needed!

$(1-X_{N2})\ C_2H_4 + X_{N2}\ N_2$

YALE DIFFUSION BURNER (YDB) – ISF workshop

Comparisons of experimental and numerical methods from different laboratories

- Experimental uncertainties
- Extensive experimental database
- Model validation

OBJECTIVES
Variability of experimental data on f_v , T and d_p: new measurements vs literature

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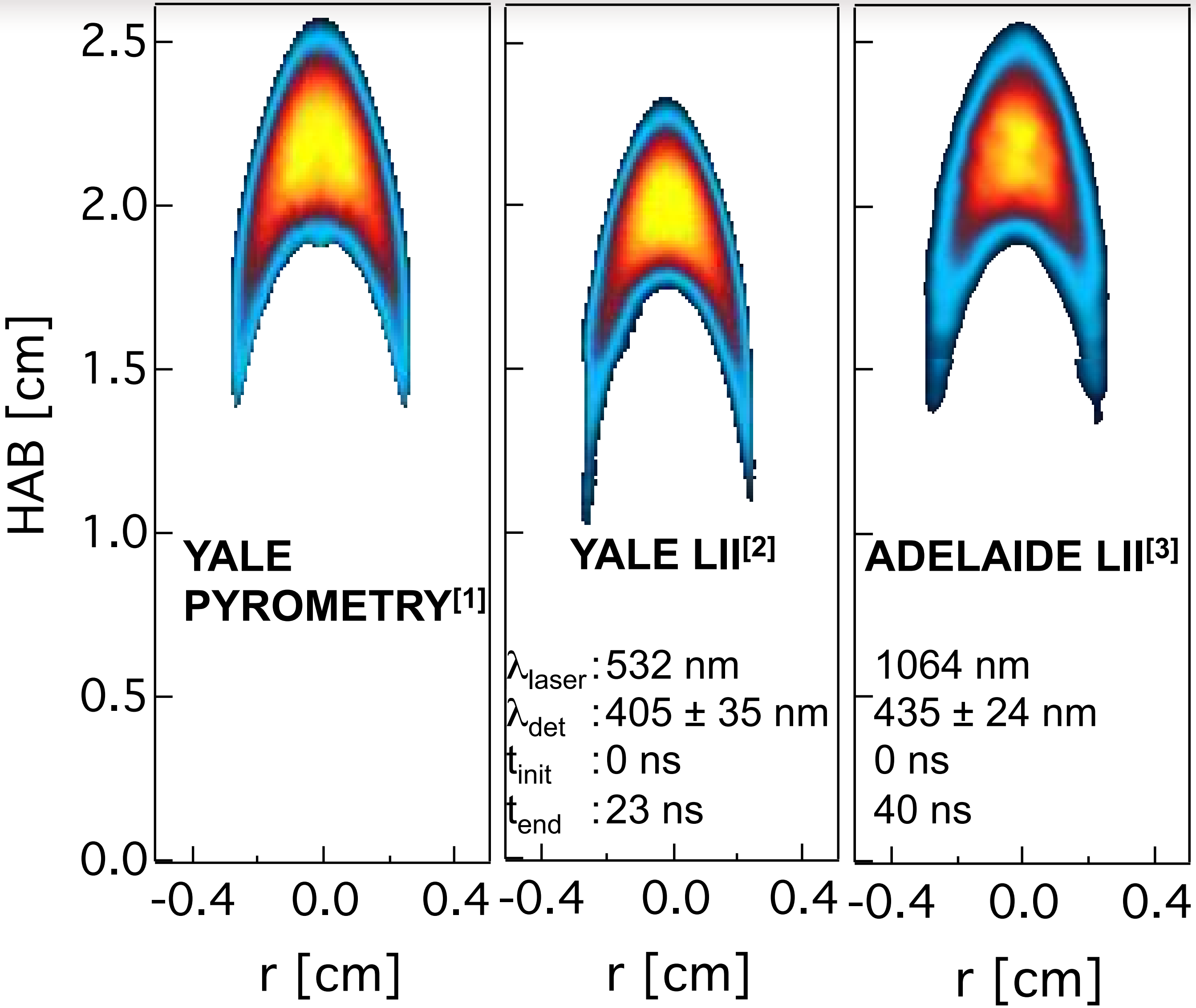
Sooting Yale Coflow Diffusion Flames, available at http://guilford.eng.yale.edu/yalecoflowflames/ (2016). M.Smooke,M.Long,B.Connelly,M.Colket,R.Hall,Combust.Flame143 (2005) 613–628.

f_v variability observed in literature



	YALE LII[2]	ADELAIDE LII[3]
λ_{laser}	:532 nm	1064 nm
λ_{det}	:405 ± 35 nm	435 ± 24 nm
t_{init}	:0 ns	0 ns
t_{end}	:23 ns	40 ns

Same flame (X_{N2}=32%) **BUT** different teams, techniques and optical setups:

- Shorter flame for YALE LII
- Same max f_v value (0.25ppm) BUT Adelaide LII calibrated with YALE LII

What is the variability on f_v, T and d_p? What are the sources of errors?

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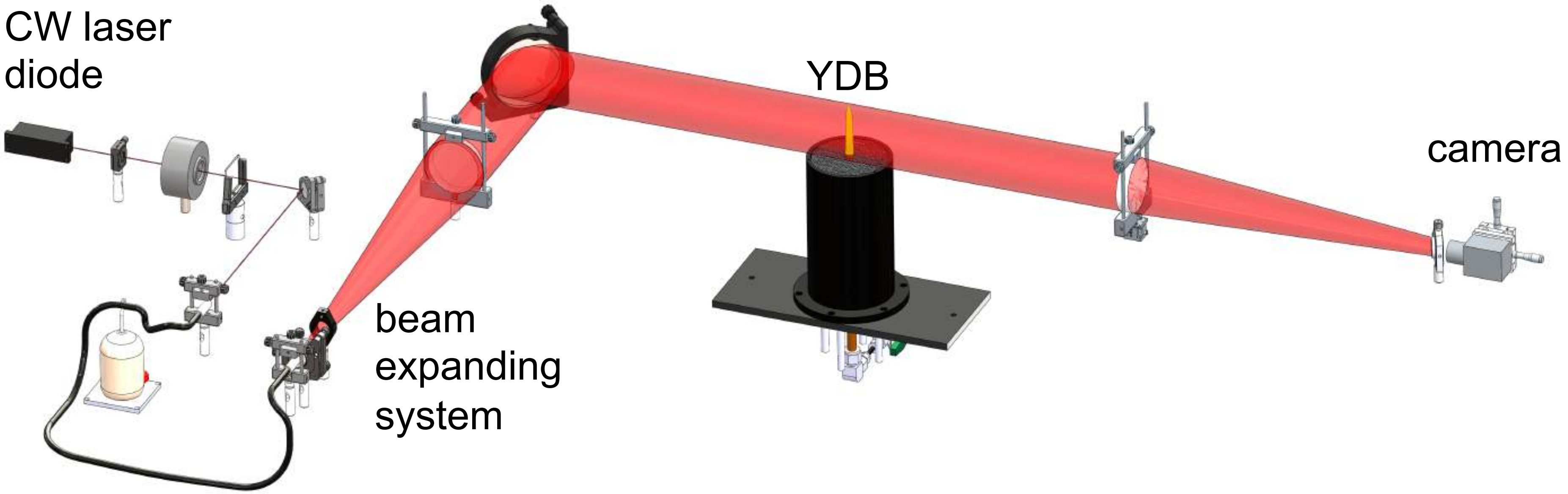
[1] P. B. Kuhn et al., Proc. Combus.Inst. 33 (2011).
[2] M.Smooke et al.,Combust.Flame143 (2005).
[3] K. K. Foo et al., Combust. Flame 181 (2017).

Content

- Experimental Setup (LII and MAE)
- Soot volume fraction comparison
- TiRe-LII results for primary particle diameter

Modulated Absorption/Emission technique[1]



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

$\lambda = 645\text{nm}$

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

$E(m) = 0.38$

Line-of-sight measurements
In-house deconvolution

Uncertainties

Factor 2: *E(m)*

2.5% (Santoro flame [1])

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[1] G. Legros et al., Combust. Flame (2015).

Laser Induced Incandescence (LII)

Operating conditions

Laser $\lambda = 1064\text{nm}$
$0.45\,\text{J/cm}^2$ (9ns)

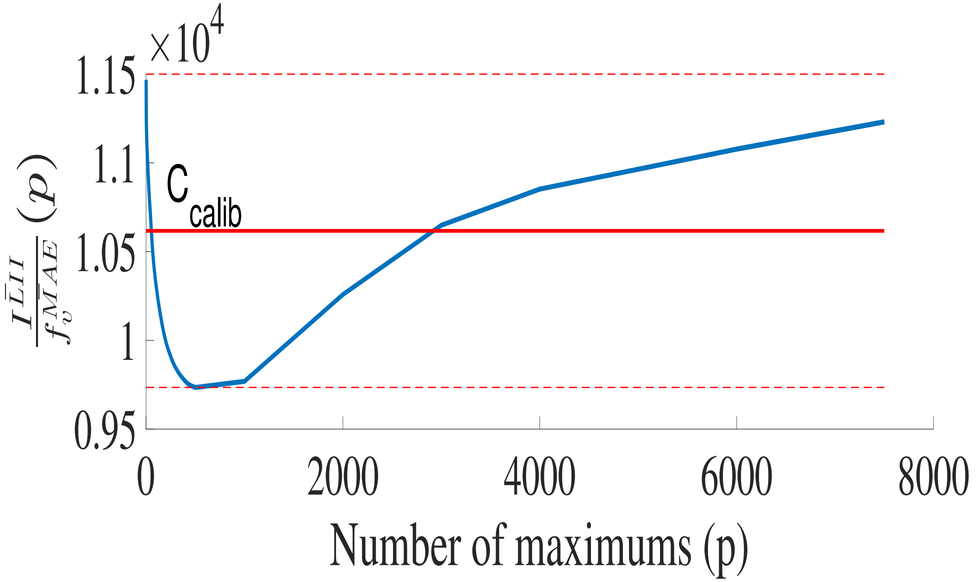
Camera $t_0 = 0\text{ns}$
$\Delta t = 25\text{ns}$

Sheet $f_1 = +1000\text{mm}$
$f_2 = -50\text{mm}$
$7\text{cm} \times 0.35\text{mm}$

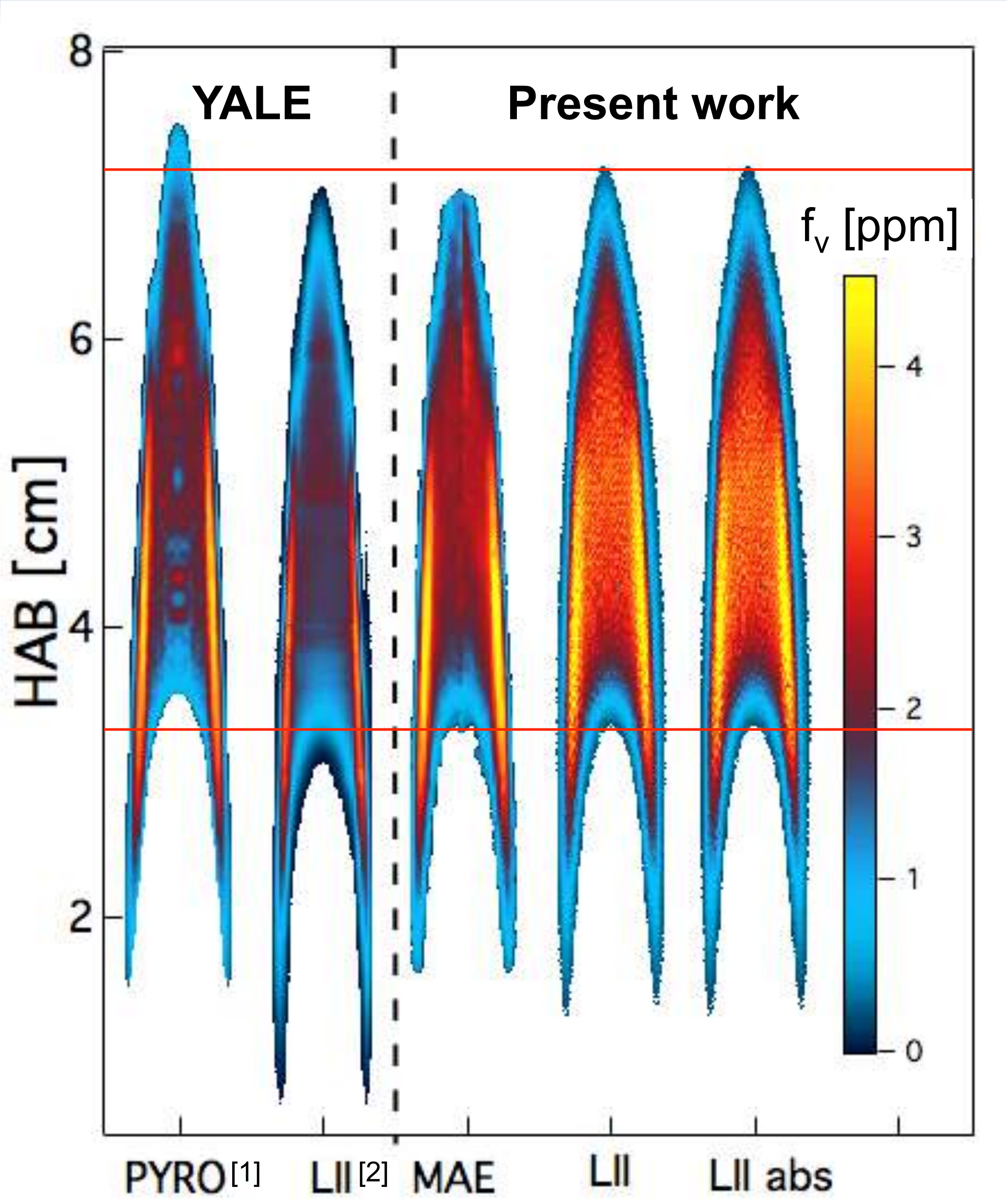
Filter $425 \pm 25\text{nm}$

Uncertainties

- **4% of peak LII signal (flame variability)**
- **Laser light absorption**
  Only half side of results is considered (laser absorption)
- **Calibration procedure**
  How? Considering the first p maximum
  How many p? p=100 in the wings of the flame
  10% of C_{calib} $I^{\text{LII}} = C_{\text{calib}} f_v^{\text{MAE}}$
- **Self-absorption of LII signal**
  5% in the middle of the flame



Comparison on f_v with state-of-the-art data[1,2]



- Flame length variability

  Operating conditions effect?

- Similar qualitative trend

  High f_v in wings

- Different max. values

  YALE-PYRO: 4.3 ppm
  YALE-LII: 4.0 ppm
  MAE: 4.6 ppm
  LII: 5.0 ppm
  LII_{absorp}: 5.1 ppm

25 % difference !!

➔ ***Impact of calibration technique and post-processing?***

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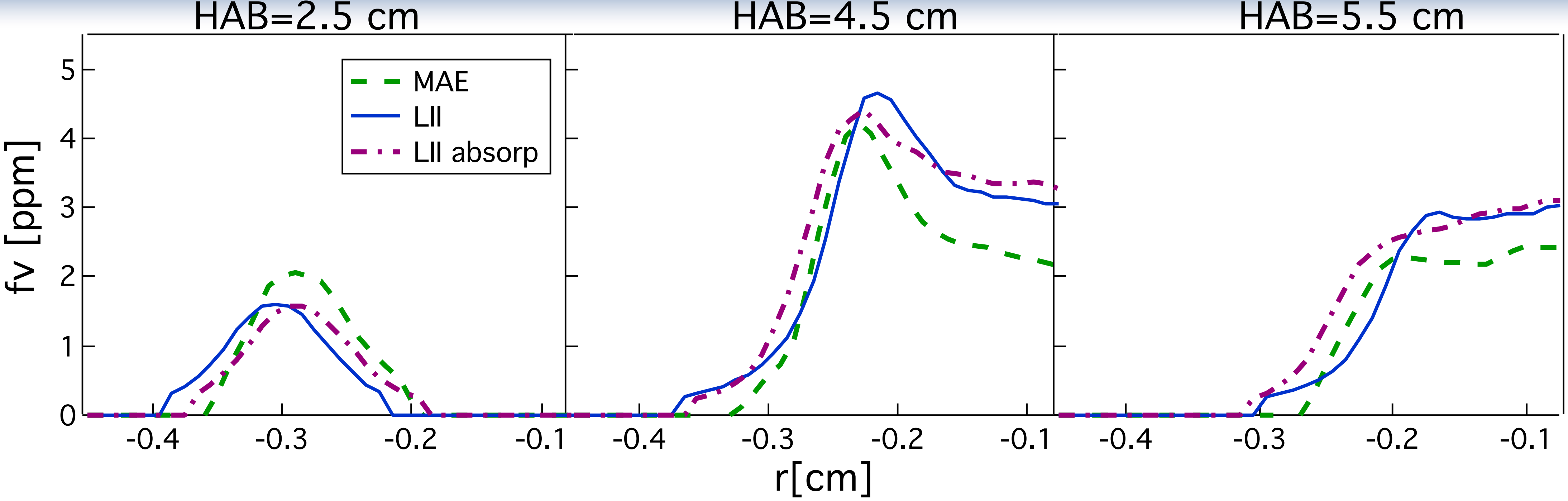
[1] P. B. Kuhn et al., Proc. Combus. Inst. 33 (2011).
[2] M.Smooke et al., Combust. Flame.143 (2005).

LII VS MAE



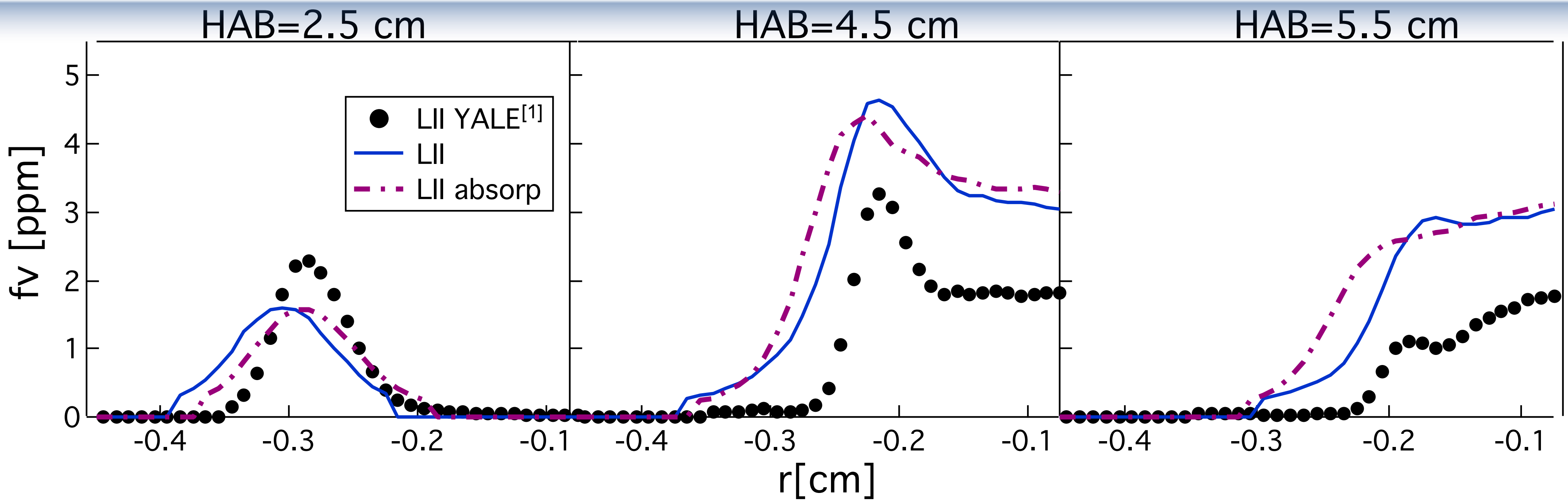
FIRST-TIME COMPARISON BETWEEN MAE AND LII

- Similar trends
- Good agreement in wings (calibration zone) but discrepancies on centerline

  MAE deconvolution error?
- Small differences between LII and $\text{LII}_{\text{absorp}}$

  Auto-absorption is negligible here (low optical thickness)

LII VS LII-YALE[1]



COMPARISON ON LII RESULTS FROM TWO TEAMS

Relevant differencies due to:

- Experimental uncertainties?
- Different flame lengths ?
- Choice of laser wavelengths for LII ?

  $\lambda = 1064\text{nm vs } \lambda = 532\text{nm}$
- Choice of E(m)? $E(m) = 0.38\text{nm vs } E(m) = 0.45\text{nm}$
- LII filter?
- Calibration technique?

Qualitative agreement among techniques and teams BUT quantitative differences!!!

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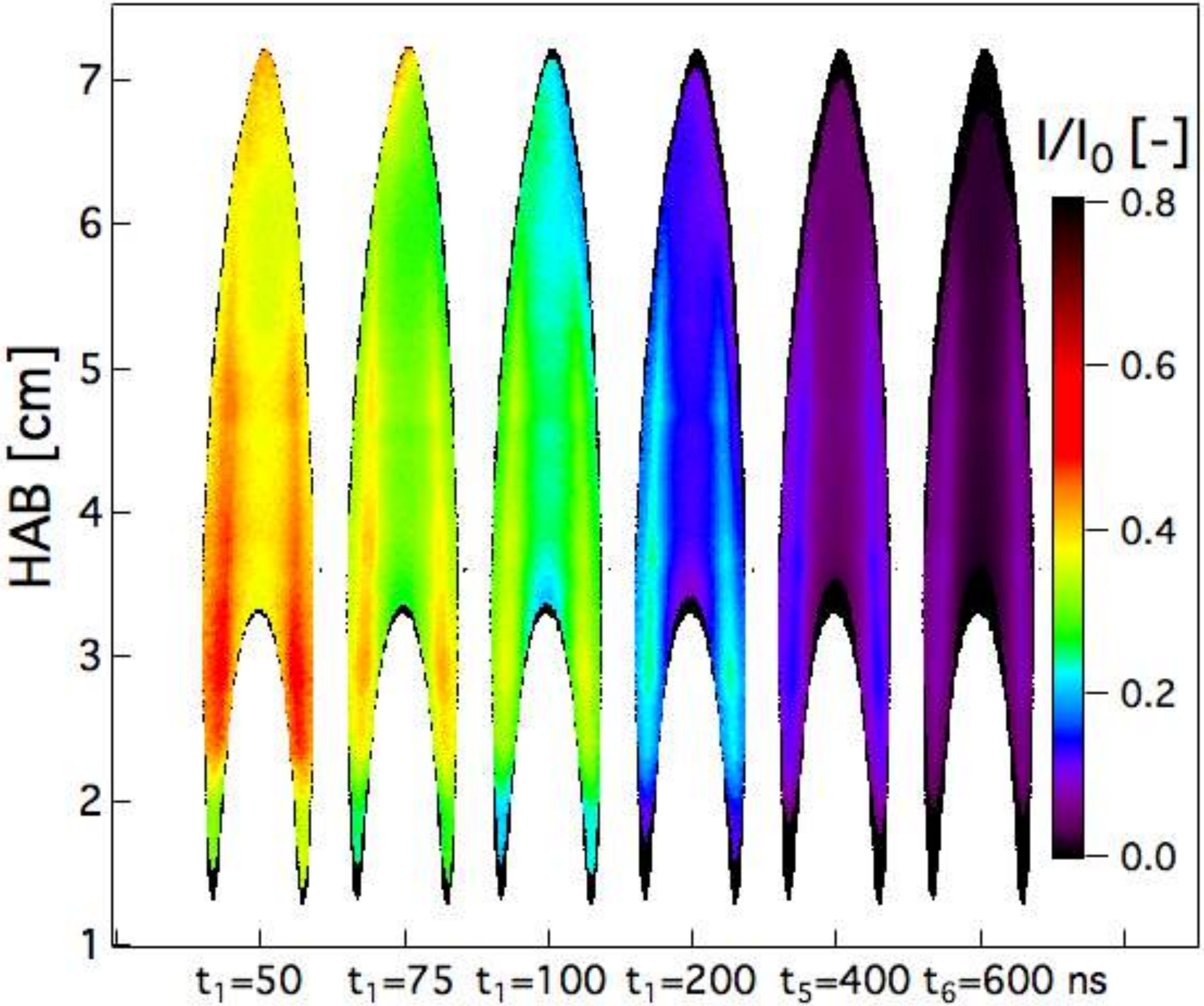
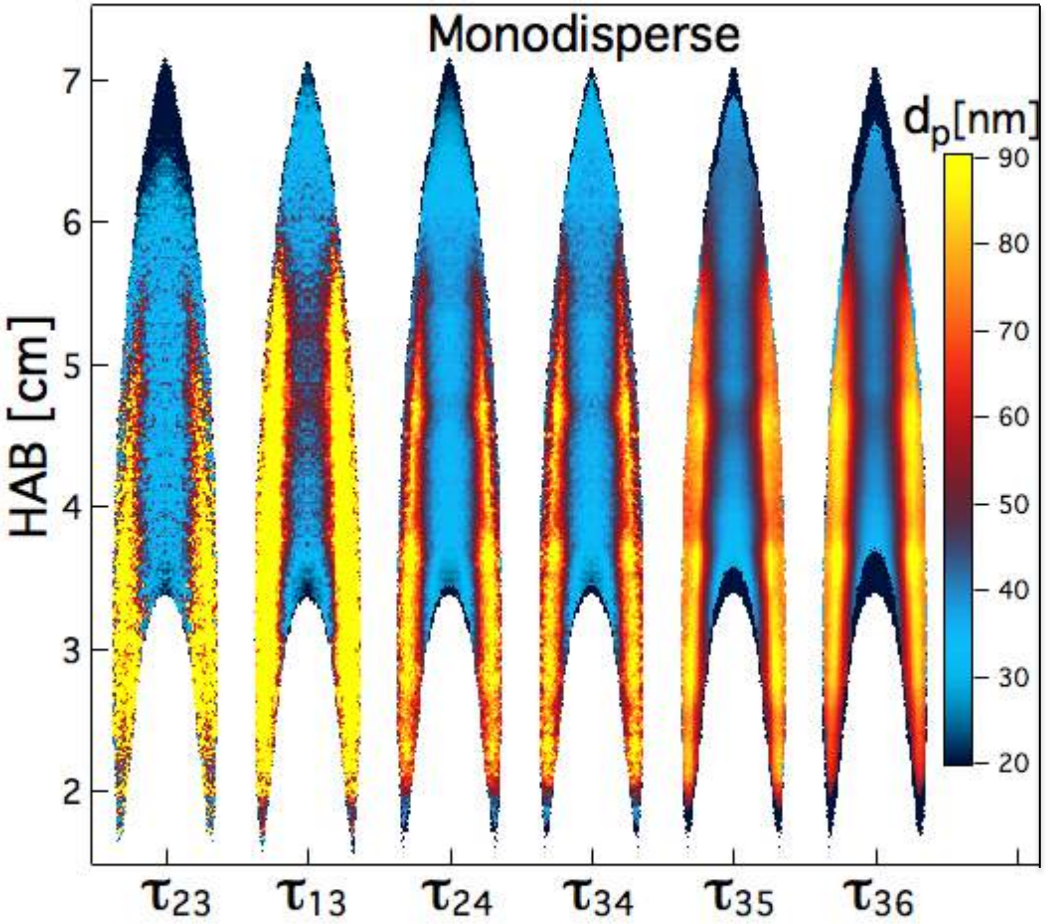
[1] P. B. Kuhn et al., Proc. Combus.Inst. 33 (2011).

Time-resolved LII for primary particles d_p



- PPSD (primary particle size distribution) varies in space
- Big d_p particles are expected in the flame outer region

Monodisperse reconstruction



1) Look-up table from LII decay signal simulations (LIISim-Web tool) $\tau_{ij}^{\mathrm{mod}}(d_p)$

Assumptions:

- *T=1700 K*
- *Spherical particles*
- *Monodisperse*

2) d_p is choosen so that it minimizes

$$\mathcal{F}(d_p) = [\tau_{ij}^{\mathrm{exp}} - \tau_{ij}^{\mathrm{mod}}(d_p)]^2$$

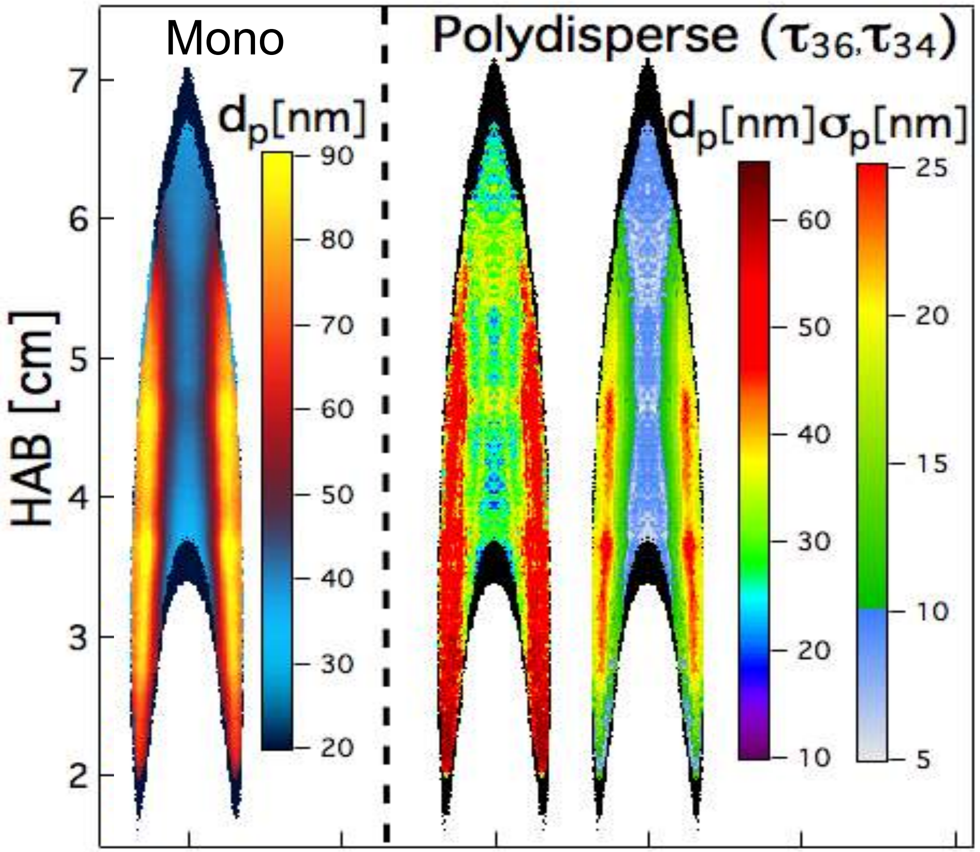
with $\tau_{ij} = (t_i - t_j)/(\ln(I_j) - \ln(I_i))$

- Largest d_p in wings, smallest d_p on centerline.
- Results depend on (i,j): *high gating delays to avoid vaporization effect but information on smallest d_p may be lost (black regions)*

➔ this choice depends on investigated PPSD.

LIISim-Web available at http://web.liisim.com/ (Updated 2016).
M. Hofmann et al, ECM (2017).

Polydisperse reconstruction



1. Look-up table from LII decay signal simulations (LIISim-Web tool)

Assumptions:

- *T=1700 K*
- *Spherical particles*
- *Presumed log-normal PPSD population*

$$\tau_{ij}^{\mathrm{mod}}(d_p,\sigma)$$

2. d_p, σ are choosen so that they minimize

$$\mathcal{F}(d_p,\sigma)=[\tau_{ij}^{\exp}-\tau_{ij}^{\mathrm{mod}}(d_p,\sigma)]^2$$

Comparing mono and poly:

- Higher d_p for mono in wings (where σ is high = poly PPSD)
- Similar d_p in centerline (where σ is small = mono PPSD)

➔ Already observed on Santoro flames[1]

Uncertainties[1]:
- Const. temperature: 4% τ
- Shielding effect: 30% d_p and 5% σ

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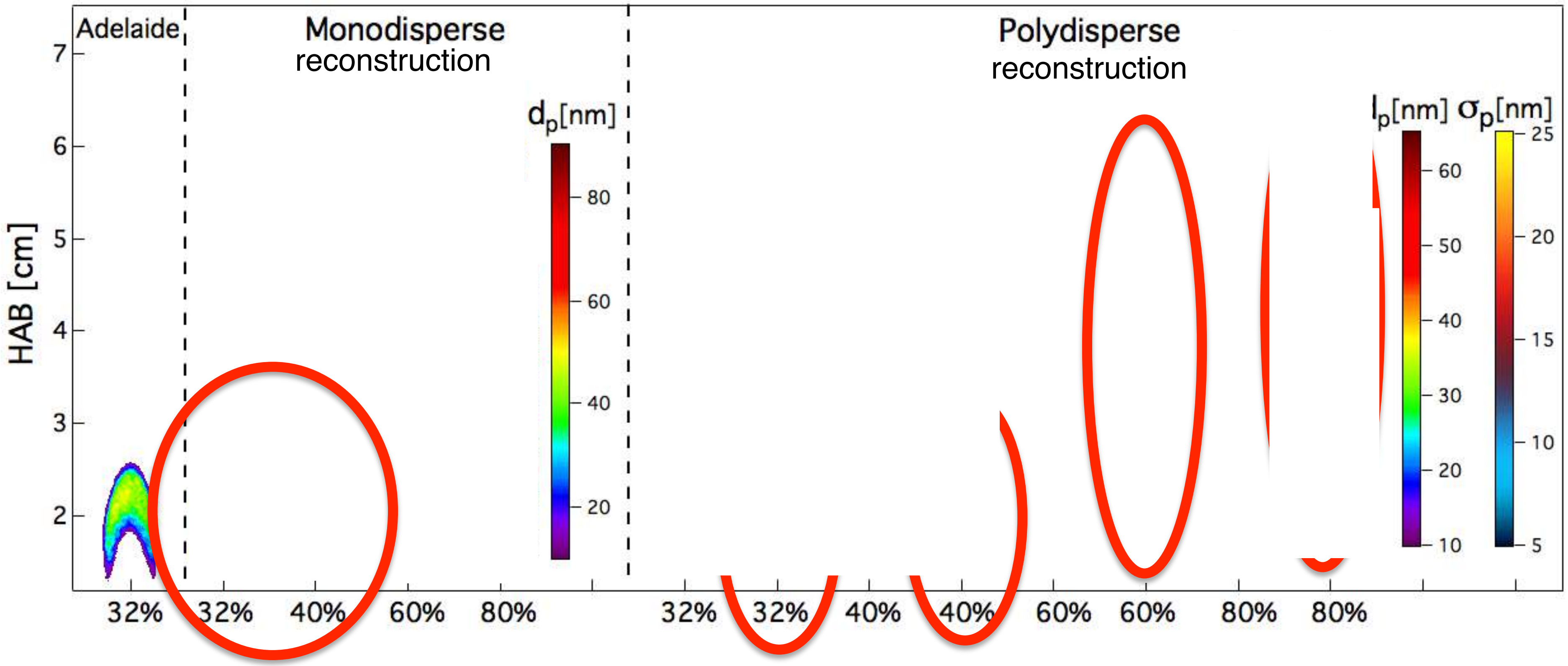
[1] L. Chen et al. Appl. Phys (2017).

Effect of dilution



- 32%-40%: Homogeneous $d_{p,}$
- 60%-80%: High d_p

COMPARISON ON 32% CASE

- Adelaide[1]: 50 nm
- Here: 30 nm

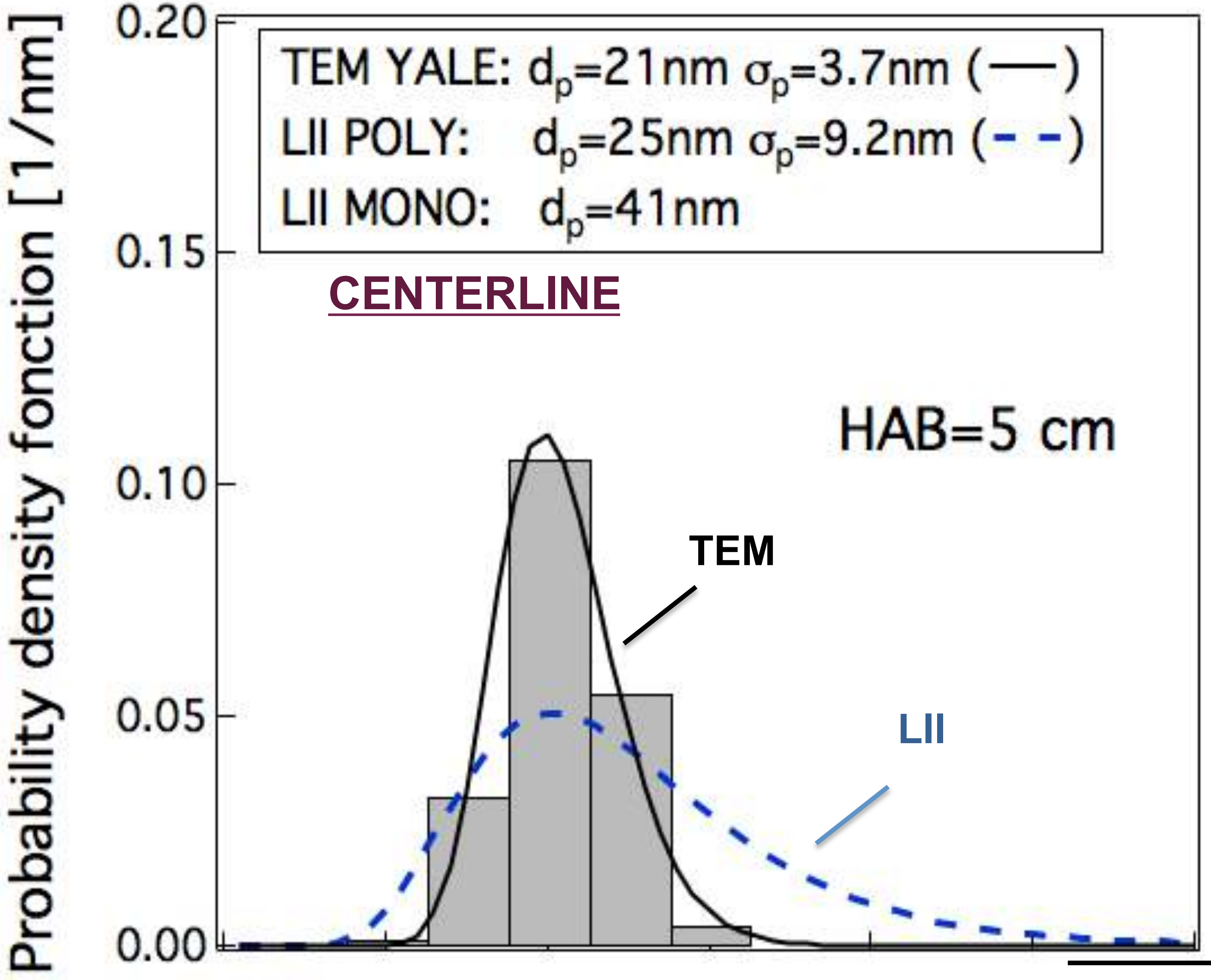
TEM (80%): d_p < 50nm

Measurements?
Post-processing?
LII models for table?

Raw data should always be provided to allow pertinent comparisons

[1] K. K. Foo et al., Combust. Flame (2017)

TR-LII vs TEM (Transmission Electron Microscopy)[1]



- Qualitative agreement with LII
- LII overestimates d_p and σ vs TEM (better agreement with poly than mono)

UNCERTAINTIES:

- Shielding effect: 30% d_p and 5% σ
- PPSD is log-normal?
- Effective d_p (LII) vs measured d_p (TEM)

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[1] N.J. Kempema et al, Appl. Phys. B (2016).

[2] L. Chen et al. Appl. Phys (2017).

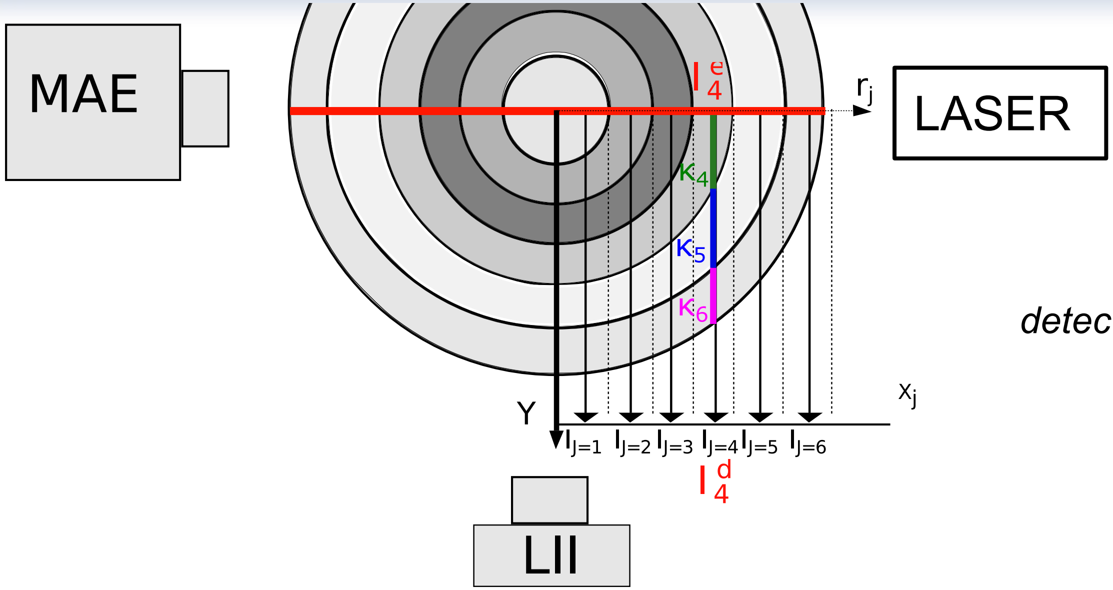
Conclusions

- Qualitative agreement among techniques and results obtained by different research teams for f_v but quantitative differences
- d_p correlates with f_v: by increasing fuel flow rate, d_p and σ increase;
- With monodisperse assumption, d_p field is qualitatively retrieved but its value is largely overestimated;
- High variability of PPSD with diagnostics and post-processing methods.

- Need for a cross comparison between multiple data sets
  - ➔ consistent database for sooting flames
- Provide access to measured, post-processed and modeled signals
  - ➔ better understanding of the discrepancies

ACKNOWLEDGMENT
This study has been 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.

Accounting for self-absorption of LII signal



Deconvolution process inspired from MAE technique

$$I^d_{4l} = I^e_{4l} \exp\left(-\sum_{m=4}^{6} A^{\mathrm{OP}}_{4m} k_{ml}\right)$$

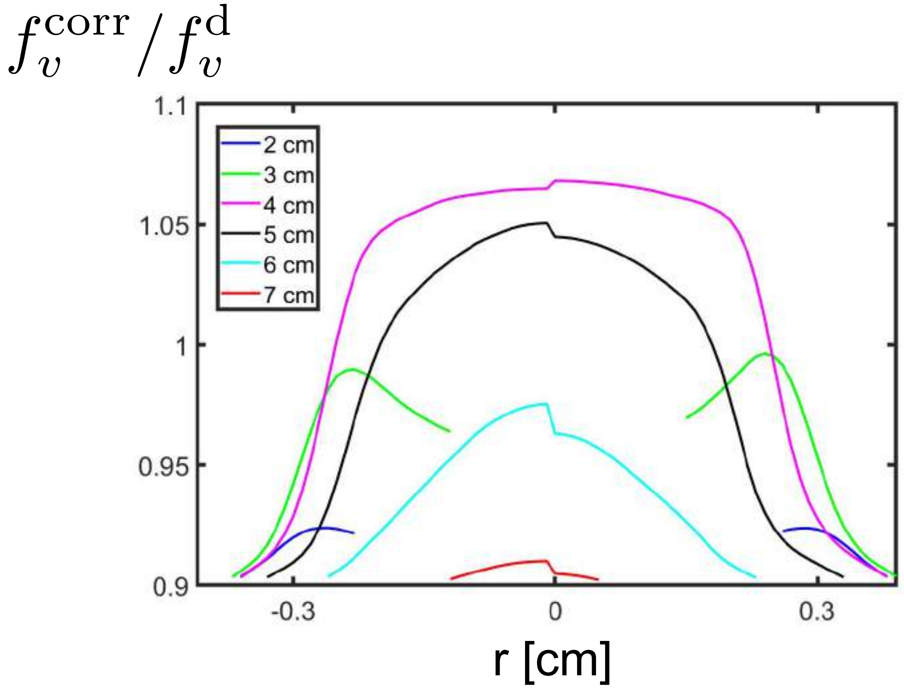
detected

emitted

optical path length

absorp. coeff.

Correcting the detected LII signal knowing the absorption field from f_v with an iterative procedure



- Signal has to be recalibrated
  (C_{calib} varies of 10%)
- 10% modification of f_v
  ➔ neglected in the following

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[1] M. Roussillo et al., ECM (2017).

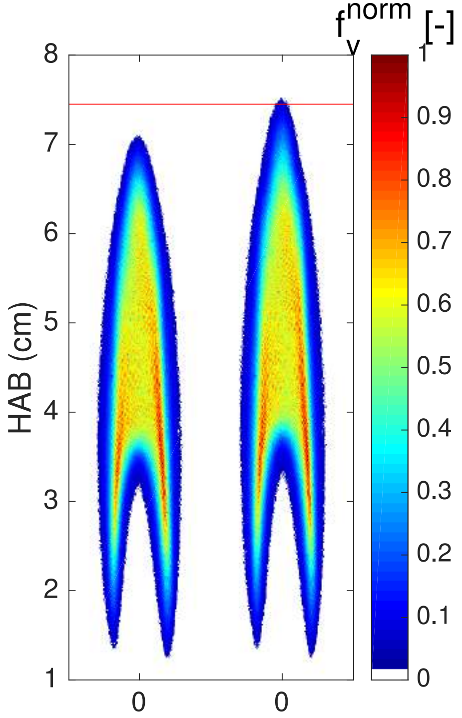
Flame sensitivity is a first source of errors

- **Flame flickering**: 4% flame luminosity
- **Flow rate** uncertainties:
  mass flow rate from inner diameter, bulk velocity and mass flow rate controller

$$d_f^{\mathrm{real}} = 3.9\mathrm{mm} \neq d_f^{\mathrm{nom}} = 4.0\mathrm{mm}$$

4% flow rate ➔ 6 mm flame length=10 %

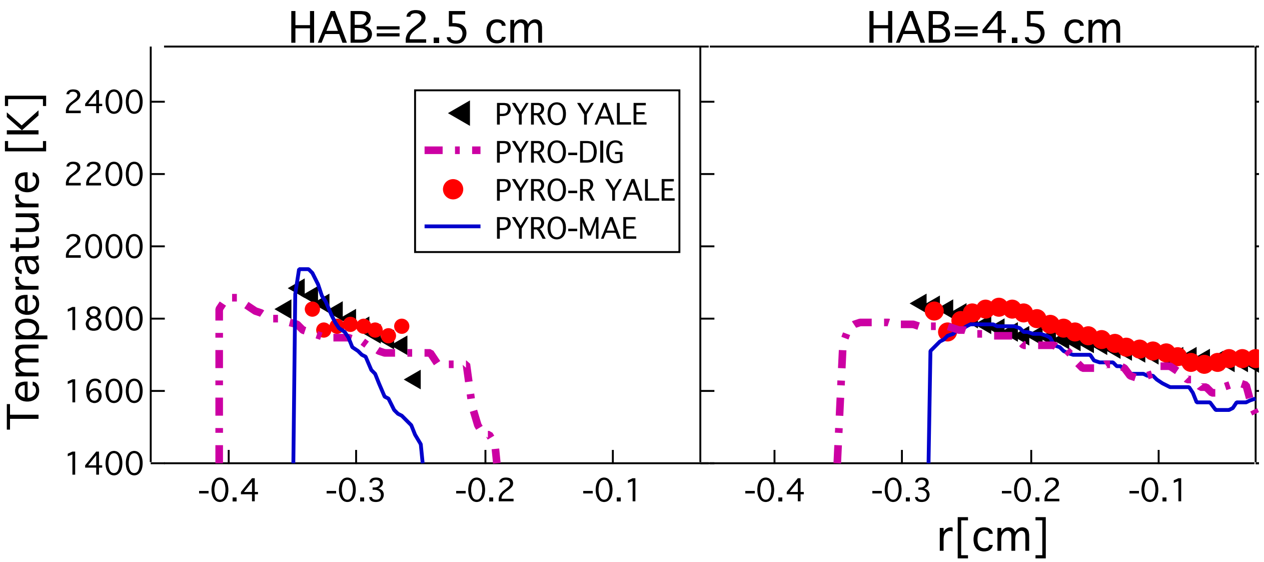
- **Inner tube position** with respect to air co-flow:
  Not indicated in the publications (here 0.5 mm)



- *Mass flow rate:*
- *275 vs 286 g/min*

What about the experimental procedure, associated setup and data post-processing?

Comparison on *T* with state-of-the-art data[1]



Color ratio pyrometry using a digital camera

PYRO YALE
PYRO DIG
R-PYRO YALE

constant soot opt. prop.

2C-pyrometry from MAE fields

PYRO-MAE

$\lambda_1 = 645\mathrm{nm}, \lambda_2 = 785\mathrm{nm}$

It accounts for soot self-absorption

- Similar results with pyrometry (~100 K)
- PYRO-DIG on a wider radial region (already observed for new LII)
- PYRO-MAE needs high f_v to obtain k_λ ➔ smaller detection region

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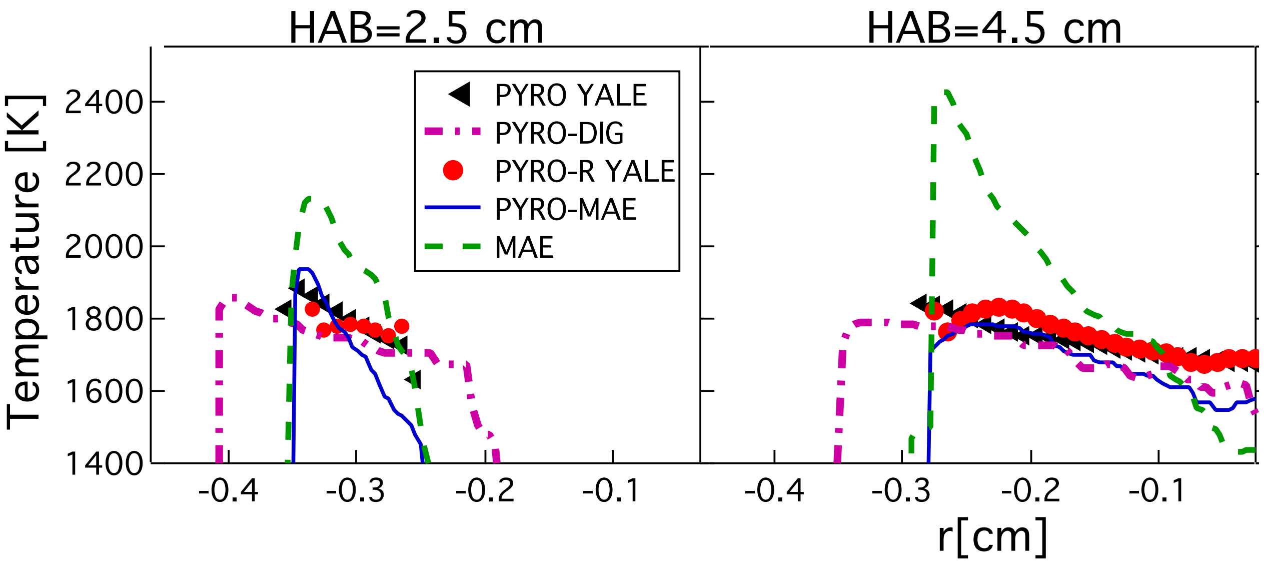
[1] P. B. Kuhn et al., Proc. Combus.Inst. 33 (2011).

Comparison on *T* with state-of-the-art data[1]



Color ratio pyrometry using a digital camera

PYRO YALE
PYRO DIG
R-PYRO YALE

constant soot opt. prop.

2C-pyrometry from MAE fields

PYRO-MAE

MAE technique

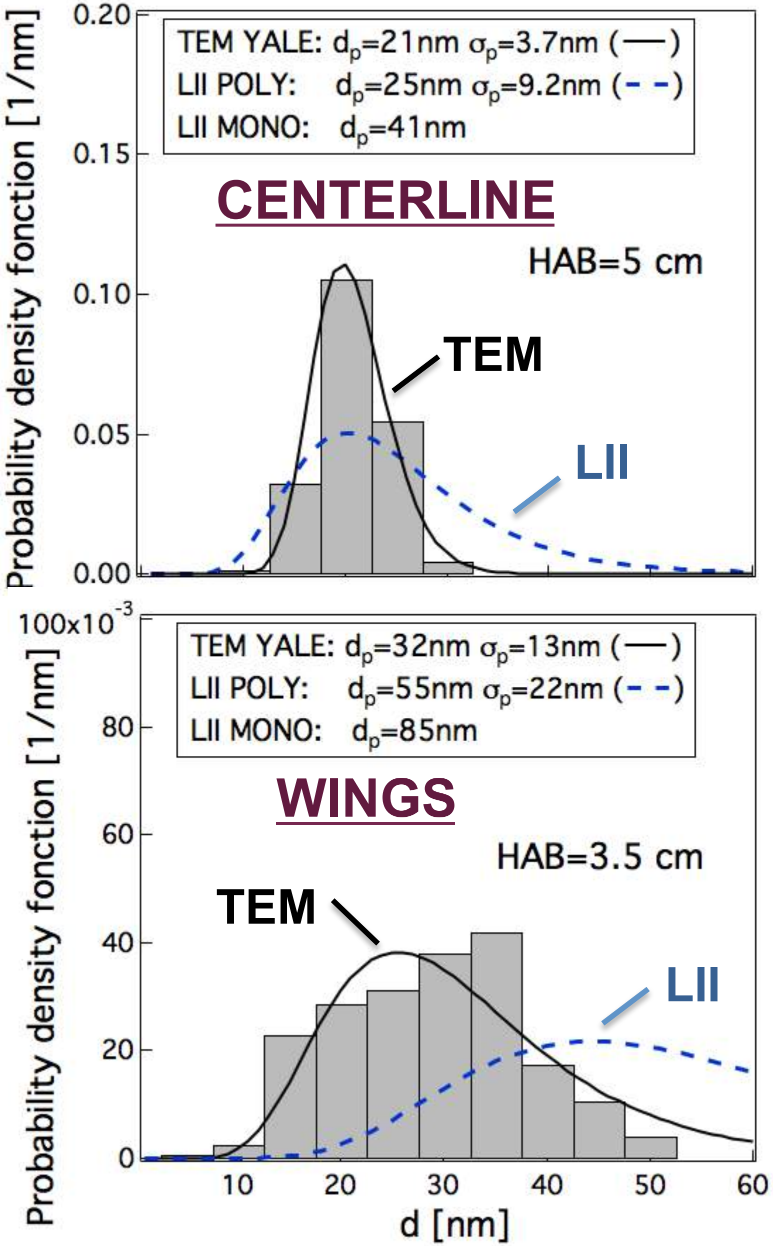
No calibration or modeling to correlate f_v and k_λ

- Similar results with pyrometry (~100 K)
- PYRO-DIG on a wider radial region (already observed for new LII)
- PYRO-MAE needs high f_v to obtain k_λ ➔ smaller detection region
- MAE: high *T* in the wings (from simulations *T<2150 K*)
  ➔ affected by low optical thickness and sharp *T* gradients here

(N.B.: MAE validation on Santoro flame -> smoother gradients)

[1] P. B. Kuhn et al., Proc. Combus.Inst. 33 (2011).

TR-LII vs TEM (Transmission Electron Microscopy)[1]



- TEM: Higher d_p and σ in wings than centerline
  - -qualitative agreement with LII
- LII overestimates d_p and σ vs TEM (better agreement with poly than mono)
- Similar to results obtained on the Santoro flame[2]

UNCERTAINTIES:

- Position of TEM probe:
  - 0.5 mm in r ➔ 30% d_p
- Shielding effect: 30% d_p and 5% σ
- PPSD is log-normal?
- Effective d_p (LII) vs measured d_p (TEM)

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[1] N.J. Kempema et al, Appl. Phys. B (2016).

[2] L. Chen et al. Appl. Phys (2017).