# Investigation of Smoke Characteristics by Photometric Measurements

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UNIVERSITÄT DUISBURG ESSEN
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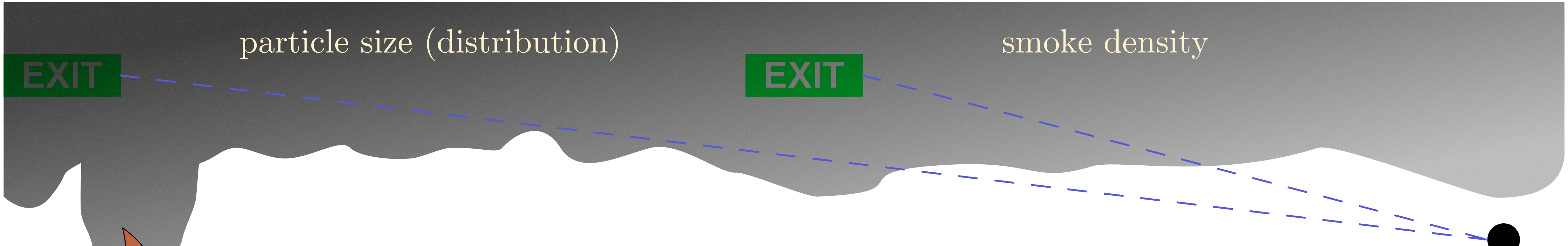
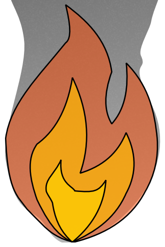
# Outline

# What is Visibility?



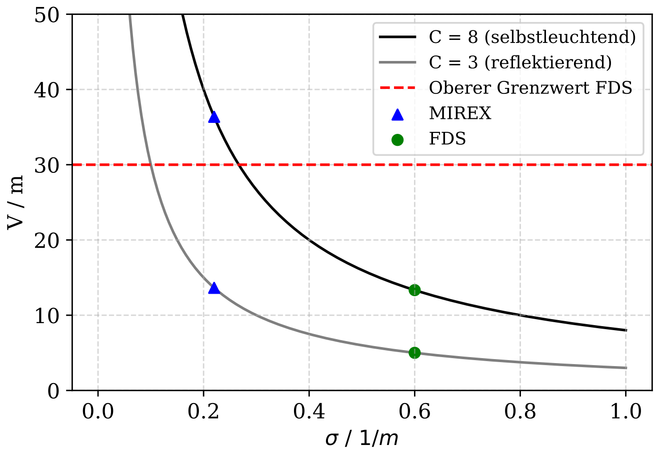



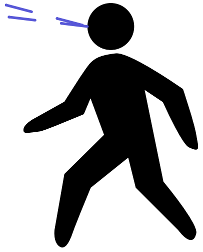
A simplification of Jin's law allows **local** prediction of visibility with CFD models:

$$V = \frac{C}{\sigma}$$

where:

- $C$: Non-dimensional constant, depending on viewed object [-]; C = 8 for light emitting sign, C = 3 for self reflecting sign
- $\sigma$: Extinction coefficient [1/m]



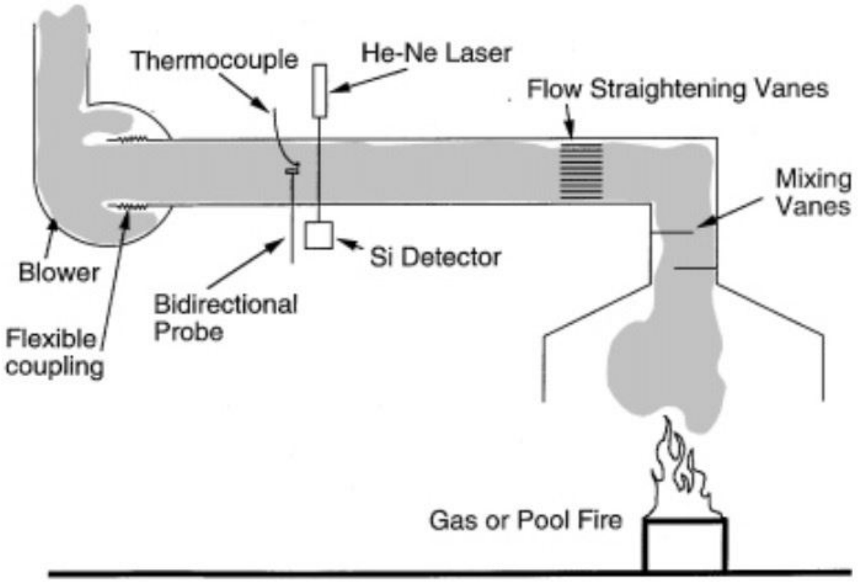
# Effects on Visibility

- Light transmission $T$ depends on mass specific extinction coefficient $K_m$, smoke density $\rho \cdot Y_s$ and the path length of light $\Delta s$

$$T = \frac{I}{I_0} = exp(-\sigma \cdot \Delta s) \qquad \sigma = K_m \cdot \rho \cdot Y_s$$

- $K_m$ and $Y_s$ usually determined by small-scale optical measurements (e.g., with a cone calorimeter) and may not be valid for modelling large-scale fires by CFD models

- Sparse data of spatial and temporal resolved extinction coefficients available




Mulholland et al., Design and Testing of a New Smoke Concentration Meter, 2000

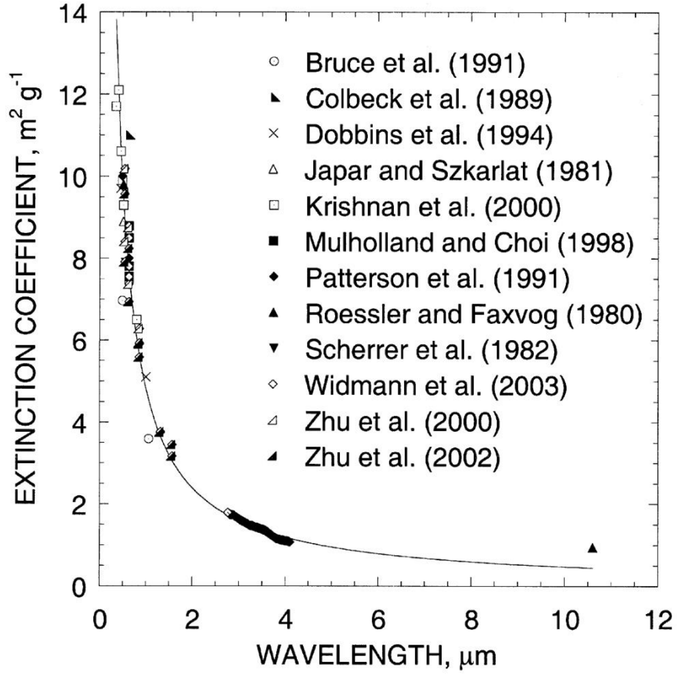
# Mass Specific Extinction Coefficient

- Widmann: correlation of $\lambda$ and $K_m$

  $K_m = 4.8081\lambda^{-1.0088}$

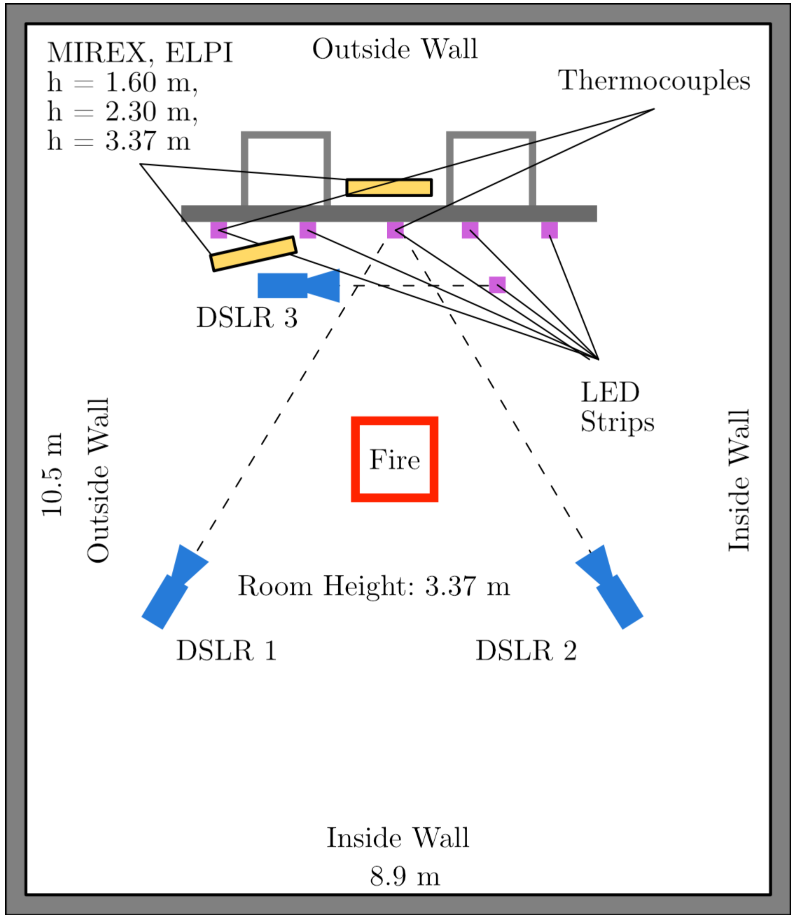
  ($K_m = 7175\, m^2/kg$ at $\lambda = 633$ nm)

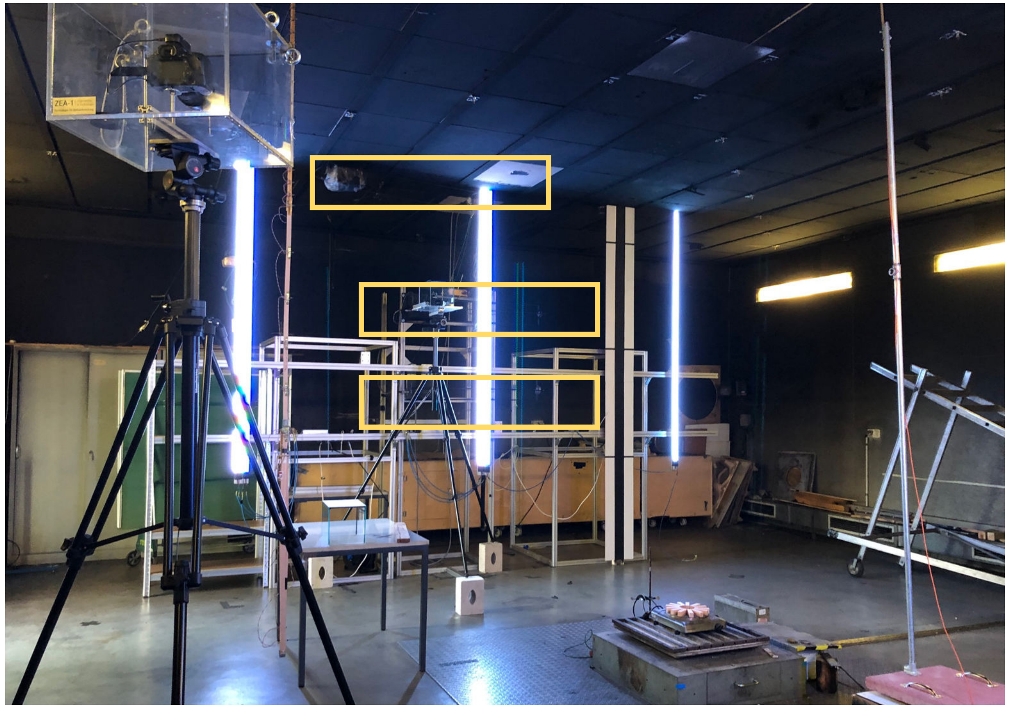
- Mullholland and Croarkin: Evaluation of seven experiments with 29 different fuels shows almost uniform mass specific extinction coefficient of $K_m = 8700\ \mathrm{m^2/kg}$ for measurements at $\lambda = 633\ \mathrm{nm}$ for well ventilated fires without smoldering and pyrolysis

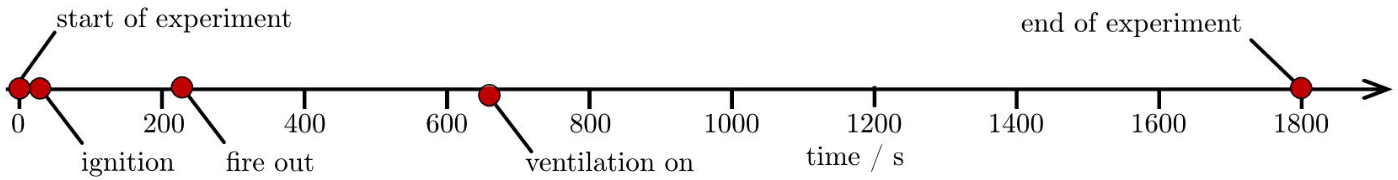



Widmann, Evaluation of the planck mean absorbtion coefficient for radiaton transport through smoke, 2003

# Experimental Setup



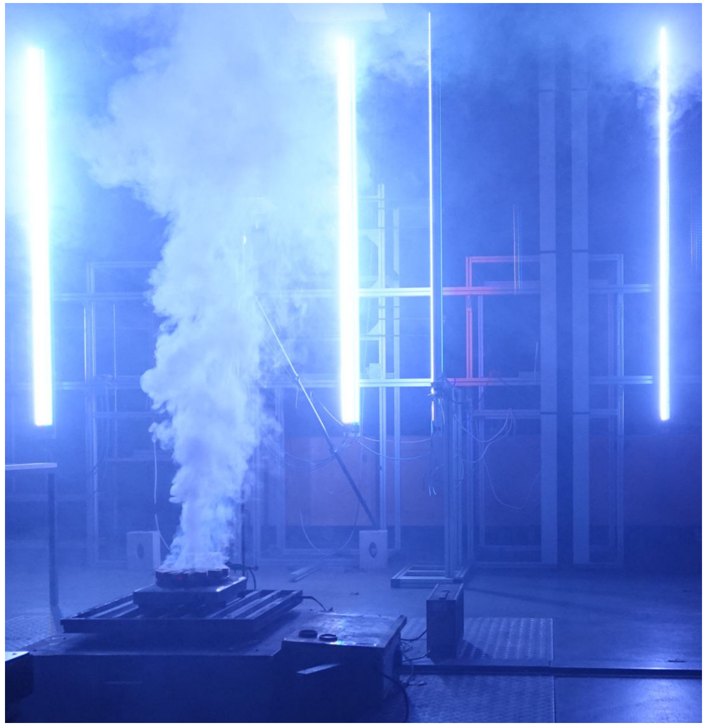





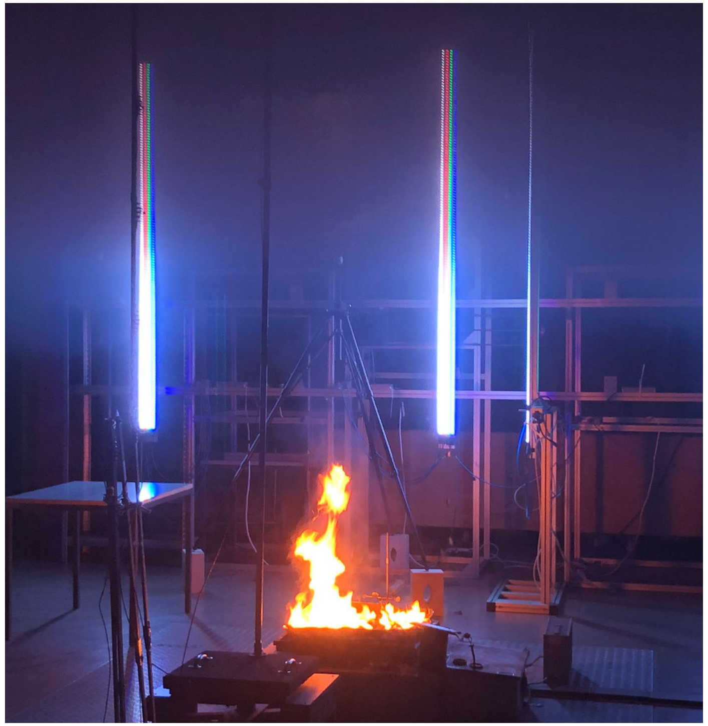
# EN 54 Test Fires

**TF 5** – n-heptane
Pool fire

**TF 2** – wood
Smoldering pyrolisis

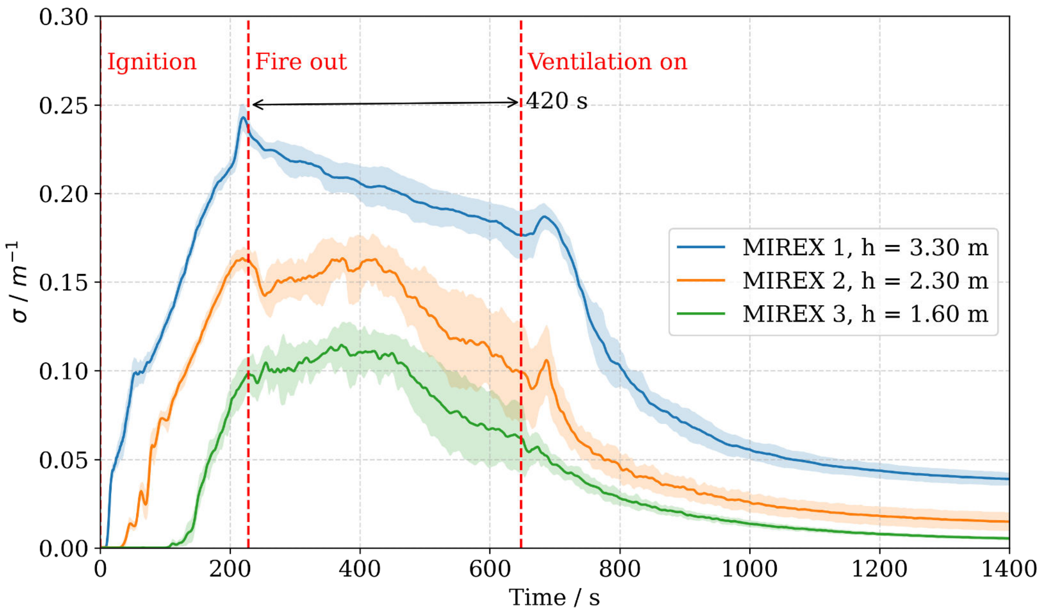


**TF 4** – polyurethane
Open plastic fire

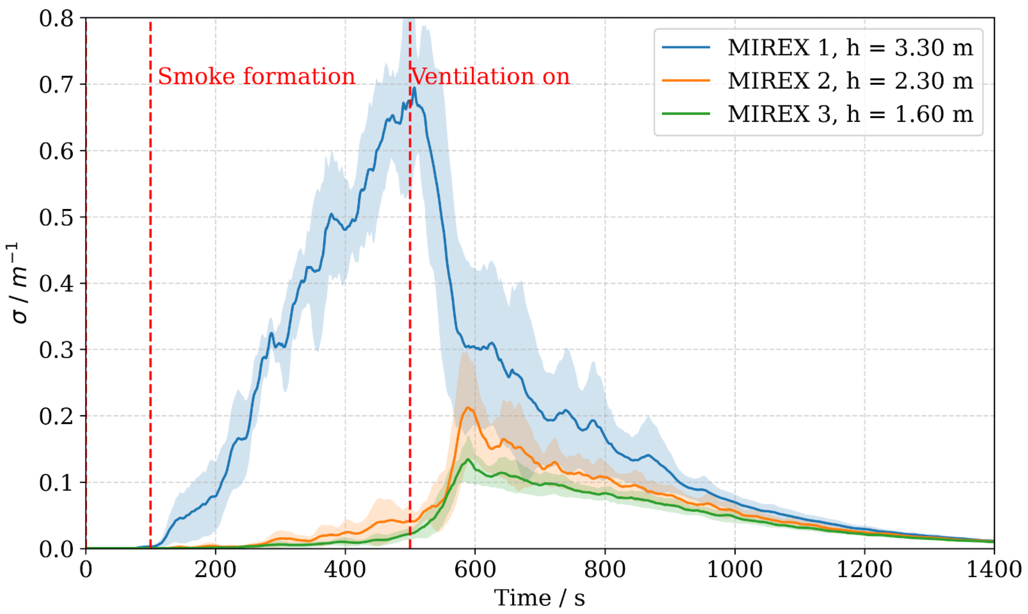


# Experimental Reproducibility

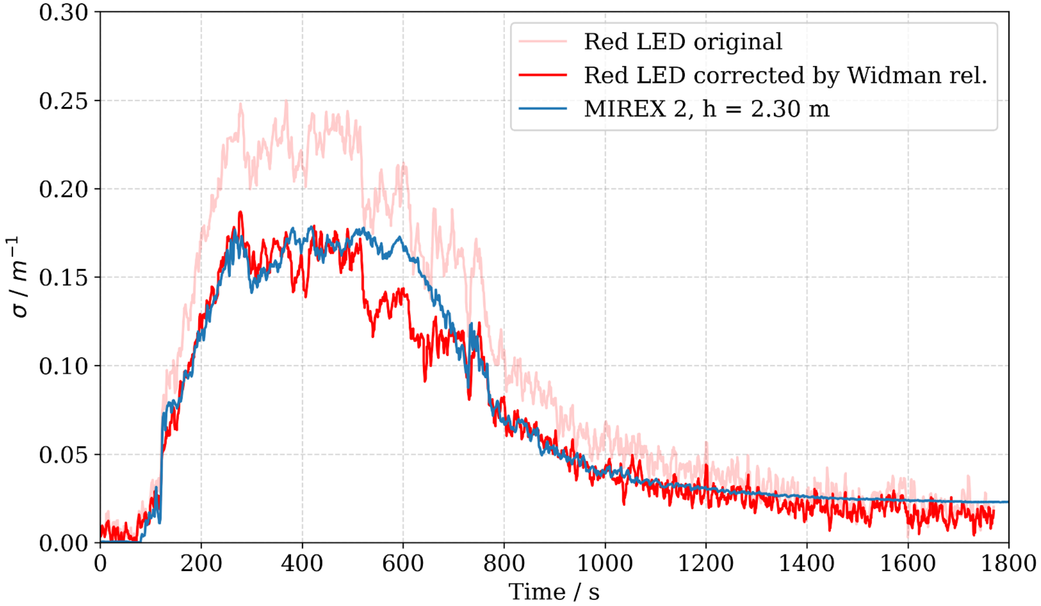
**TF 5** – n-heptane
Pool fire (17 datasets)



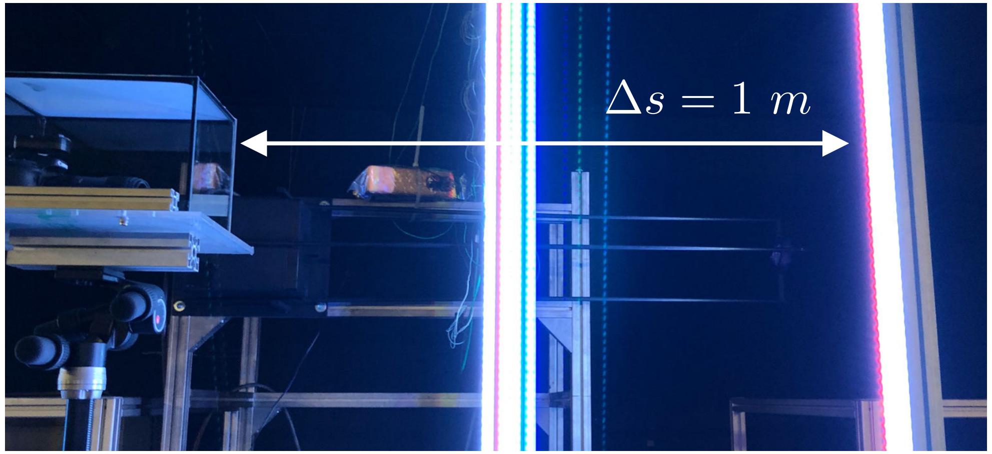

**TF 2** – wood
Smoldering pyrolisis (9 datasets)



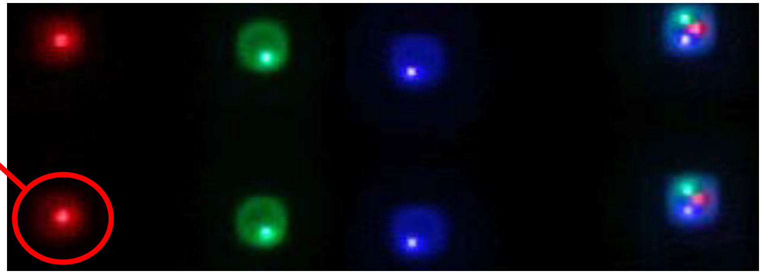
# LEDSA – Qualification of Methodology




$$\frac{\sigma_{MIREX}}{\sigma_{LED}} = \frac{K_{m,MIREX}}{K_{m,LED}} = \left(\frac{880}{630}\right)^{-1.0088} \approx 0.72$$

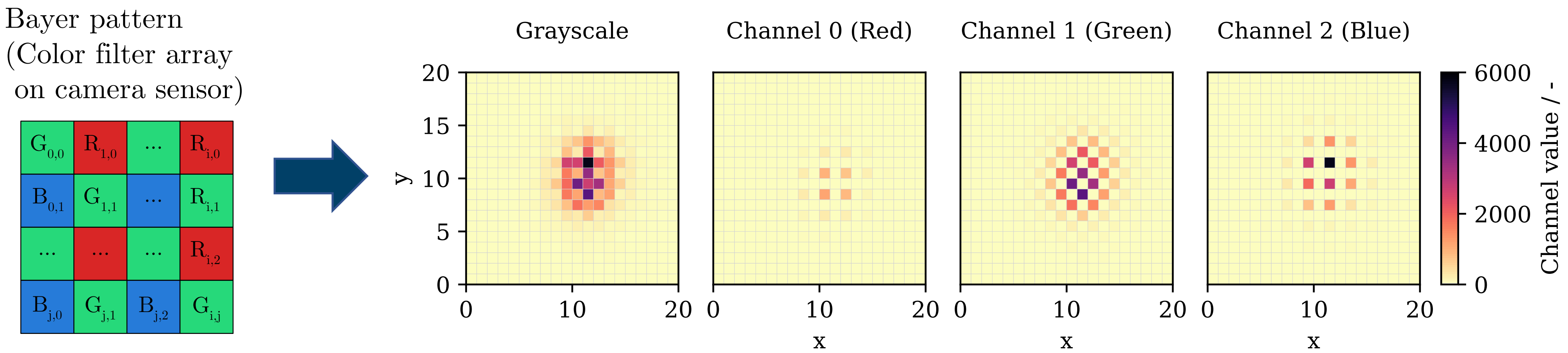



$$\sigma = \frac{-ln(\frac{I}{I_0})}{\Delta s}$$



# Measuring Transmission

- LED Intensities measured as the accumulated pixel value of a 20 x 20 pixel array




- Raw sensor data is scaled by black level $B$ and saturation point $W$ to tonal range $b$

$$P(x, y) = (S(x, y) - B) \cdot \frac{2^{b-1}}{W - B}$$

$$I = \sum_{all\ pixels} P(x, y)$$

$$I_e = \frac{I}{I_0}$$

# Spatial Discretization - Layer Model

- Modeled Intensities $I_{m,j}$ can be described as:

$$I_{m,j} = \exp\left(-\sum_{i=1}^{N_{\text{Layers}}} \sigma_i \Delta s_{i,j}\right)$$

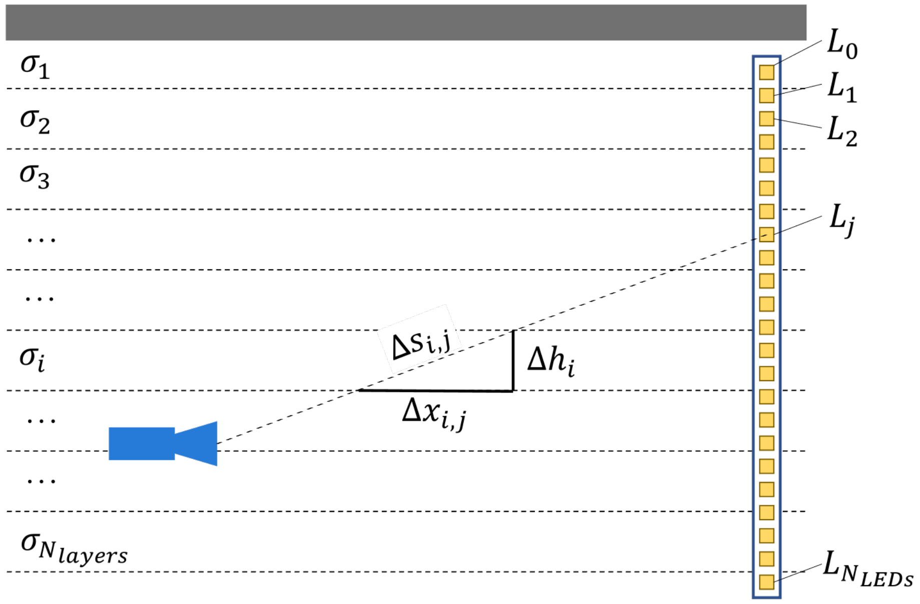
- Cost function to find extinction coefficients $\sigma_i$ that match the experimental intensities $I_{e,j}$

$$\Omega_\sigma = \underbrace{\sum_{j=i}^{N_{LEDs}} (I_{m,j} - I_{e,j})^2}_{} + \phi_s \underbrace{\sum_{j=2}^{N_{layers}-1} (\sigma_{i-1} - 2\sigma_i + \sigma_{i=1})}_{} + \phi_a \underbrace{\sum_{i=1}^{N_{layers}} \sigma_i}_{}$$

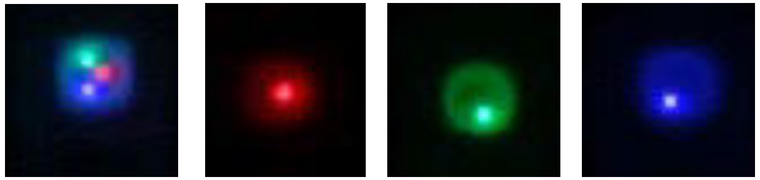
$L^2$ − norm of $I_{m,j}$ and $I_{e,j}$

Smoothness of the solution

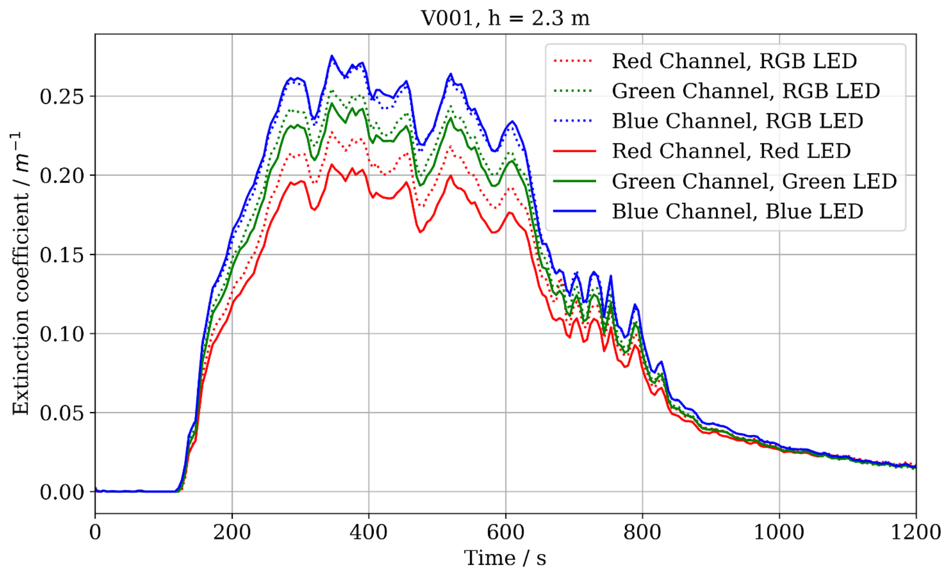
Enforce high / low values of $\sigma_i$



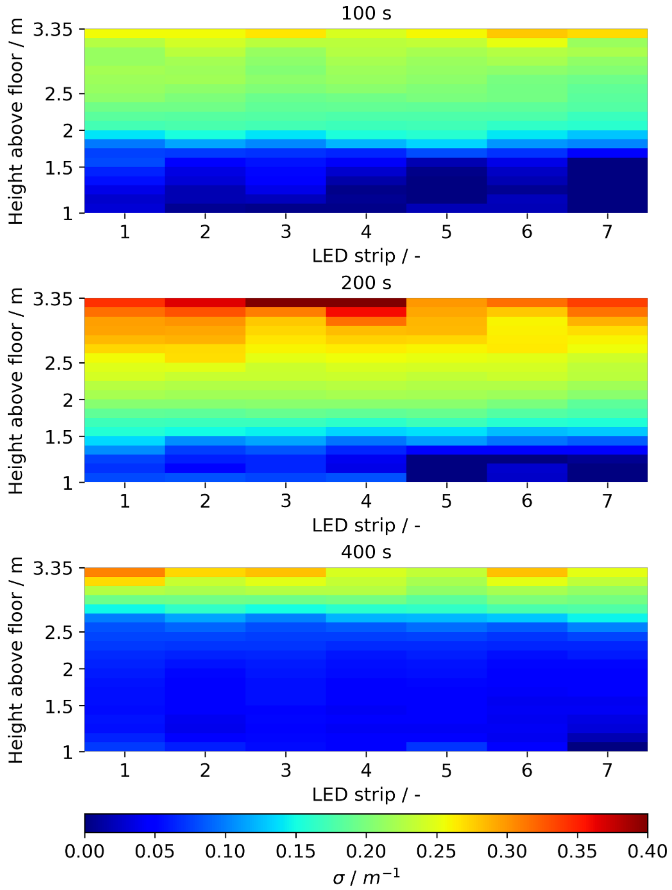
# LEDSA - Spatiotemporal Extinction Coefficients



RGB Red Green Blue



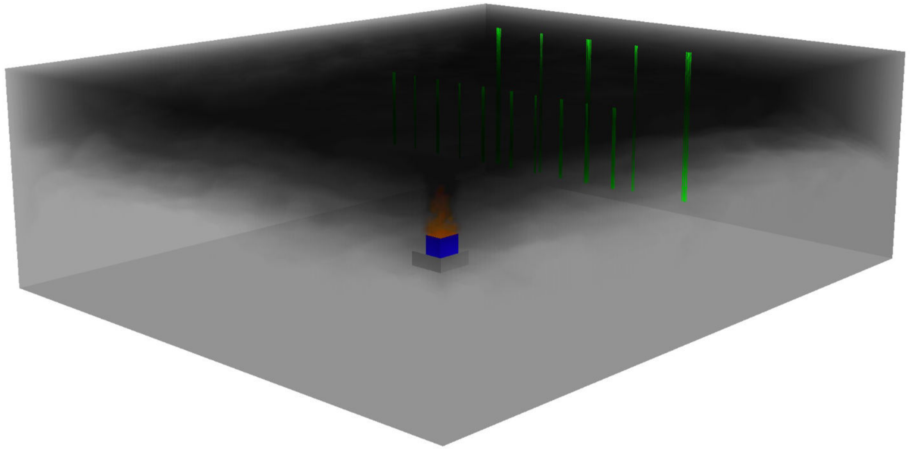

Model allows to compute spatially and temporally resolved extinction coefficients for light at different wavelengths

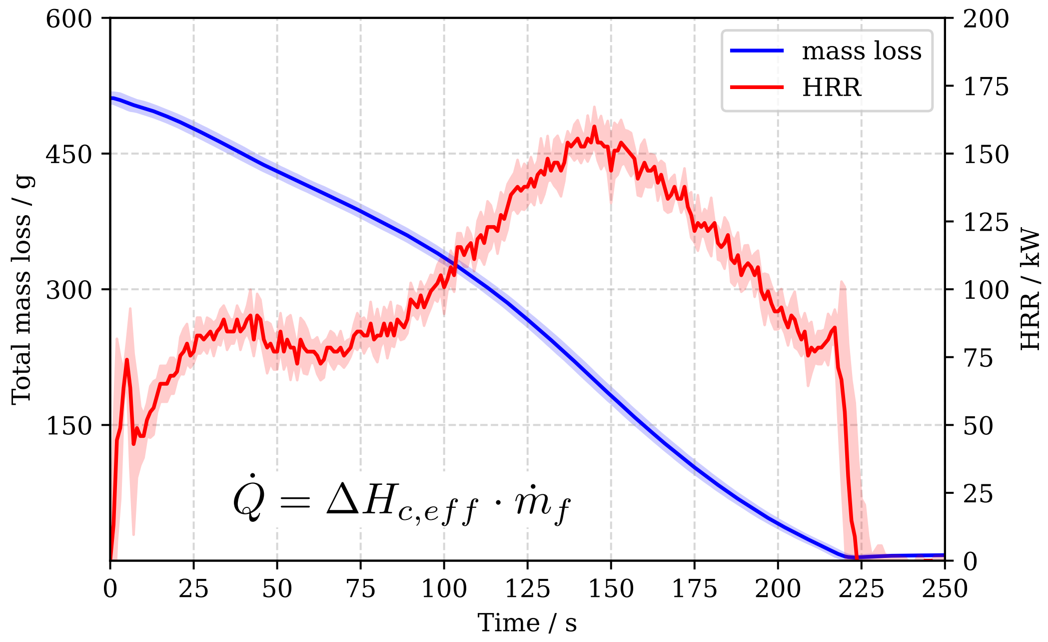


# FDS Model - TF 5

- Soot yield: $Y_S = 0.037$ (SFPE Handbook)
- Mass specific extinction coefficient:

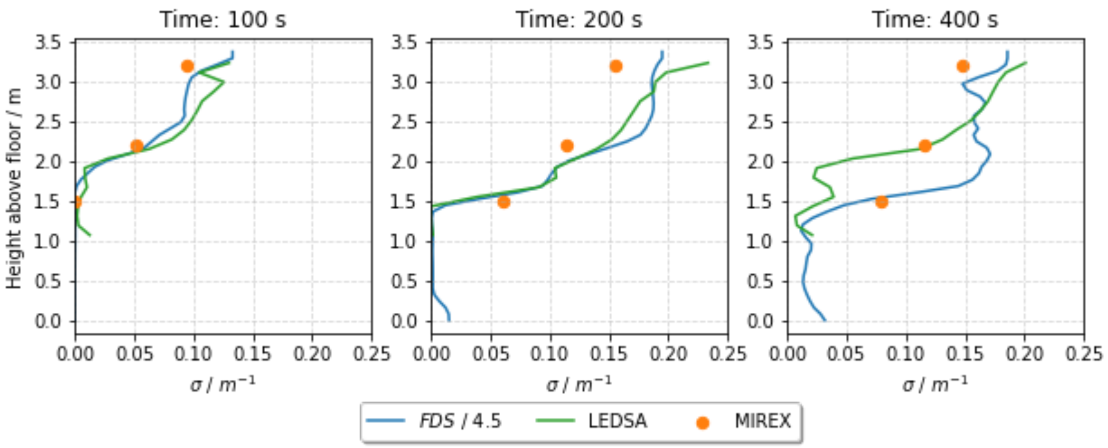
  $K_m = 8700\ \mathrm{m^2/kg}$ (FDS Default)
- Grid size: $\delta_x = 8\ \mathrm{cm}$



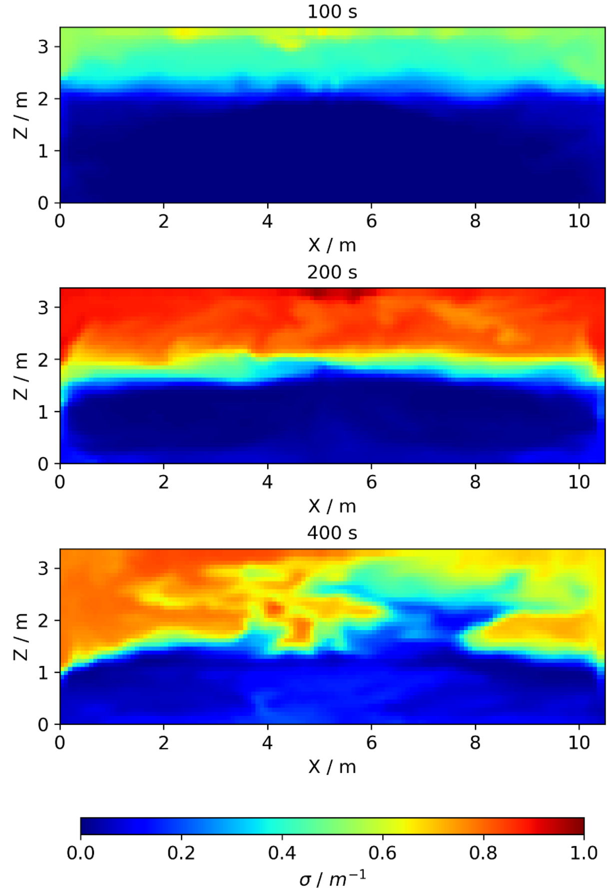


# FDS vs. Experiment - Extinction Coefficient

- FDS results reveal almost regular overestimation of $\sigma$ against (wavelength corrected) experimental data by factor 4.5
- Height profiles of $\sigma$ show similar shape in the burning period but diverge afterwards




$$\sigma = K_m \cdot \rho \cdot Y_s$$



# Conclusion and Outlook

- Especially the pool fires show a high reproducibility
- LEDSA results are in good agreement with MIREX measurements
- Overestimation of extinction coefficient by numerical models may be primarily due to input parameters than to the model itself

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- Ratio of extinction coefficients at different wavelengths may be used to draw conclusions about change in particle size (Mie Scattering Theory)

Link: Spatiotemporal measurement of light extinction coefficients in compartment fires

# Thank you!

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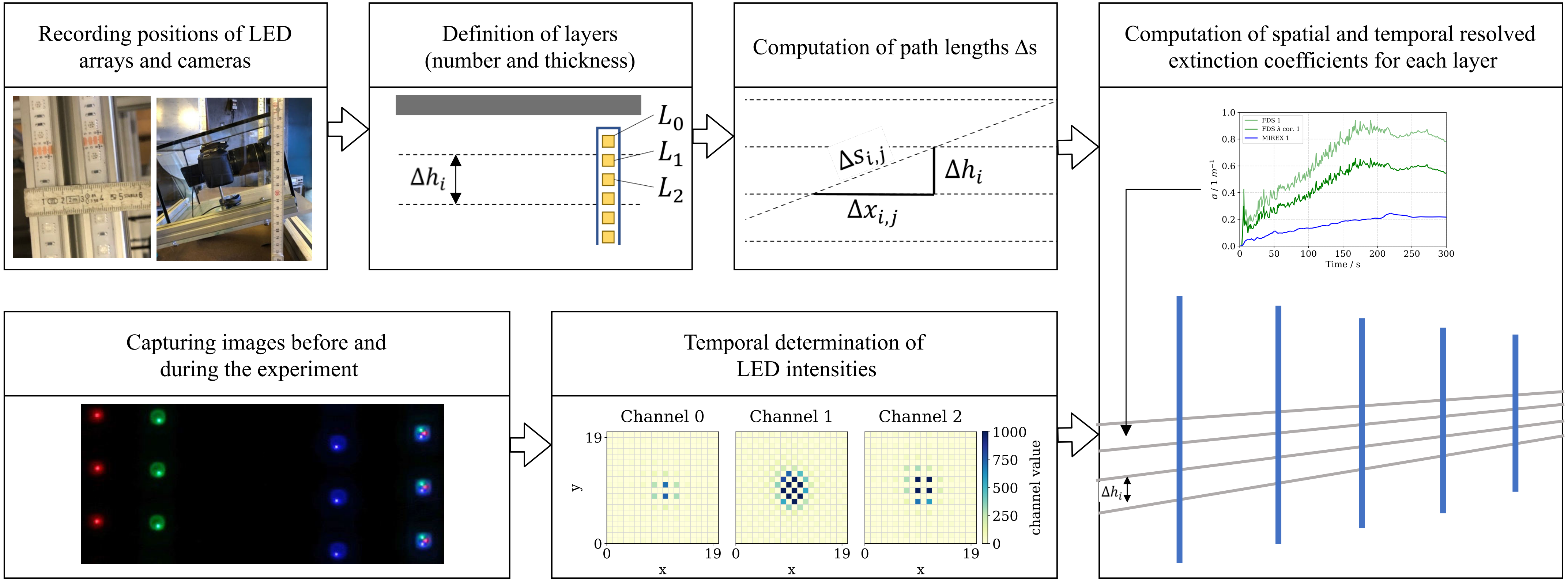
# Appendix

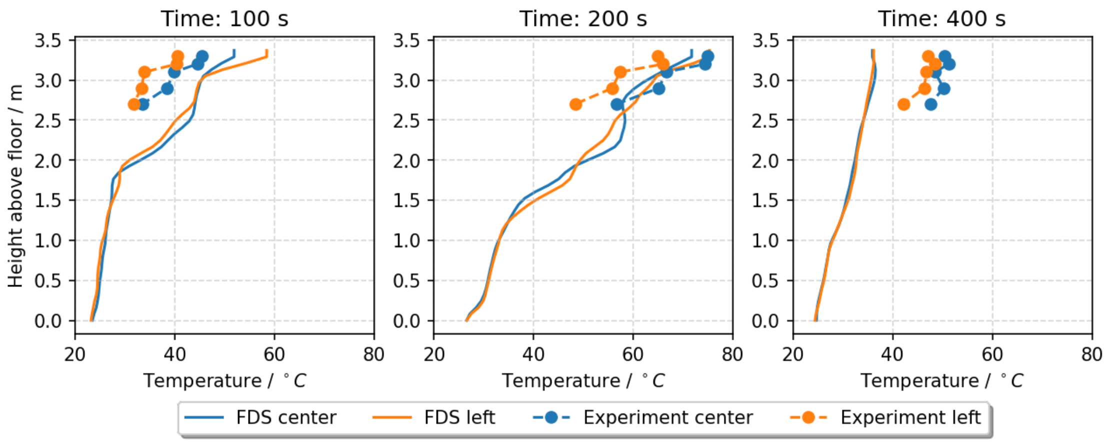
1. Data Acquisition and Analysis (LEDSA)
2. FDS vs. Experiment –Temperature
3. Temperature Dependency
4. Uncertainties of the Intrinsic LED Parameters
5. ELPI$^{+}$ - Particle Size Distribution of TF 5
6. Soot Deposition

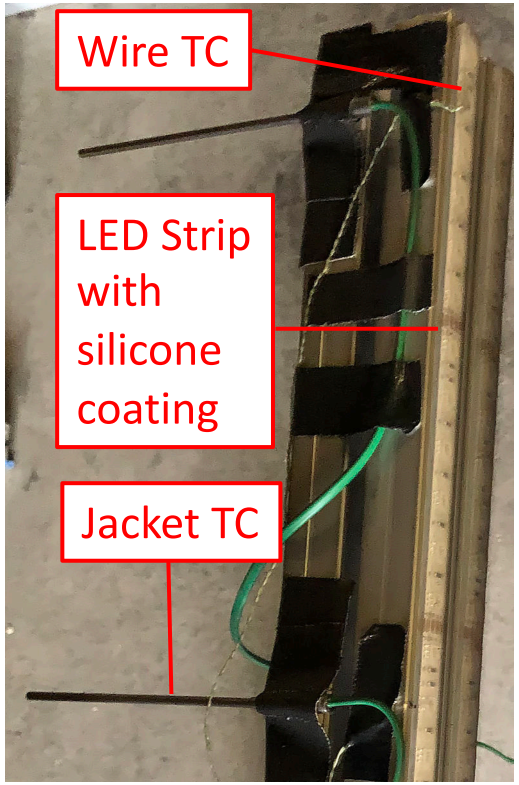
# Data Acquisition and Analysis (LEDSA)



# FDS vs. Experiment -Temperature

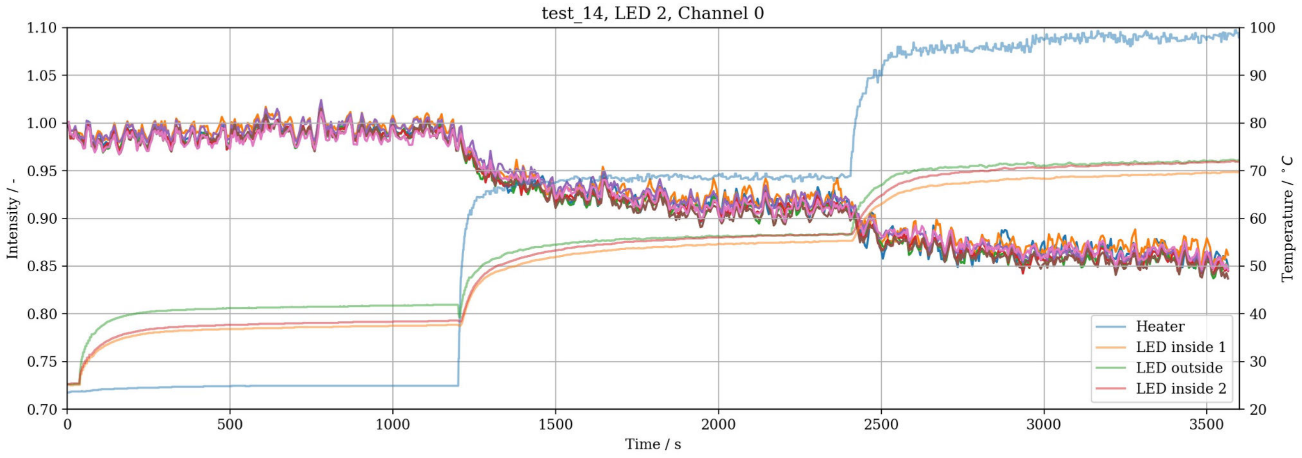
- LED surface temperature and and gas temperature were measured on the center and outer aluminum column
- Maximum measured gas temperature is similar to the simulation data but with a delay in heating and cooling due to TC inertia



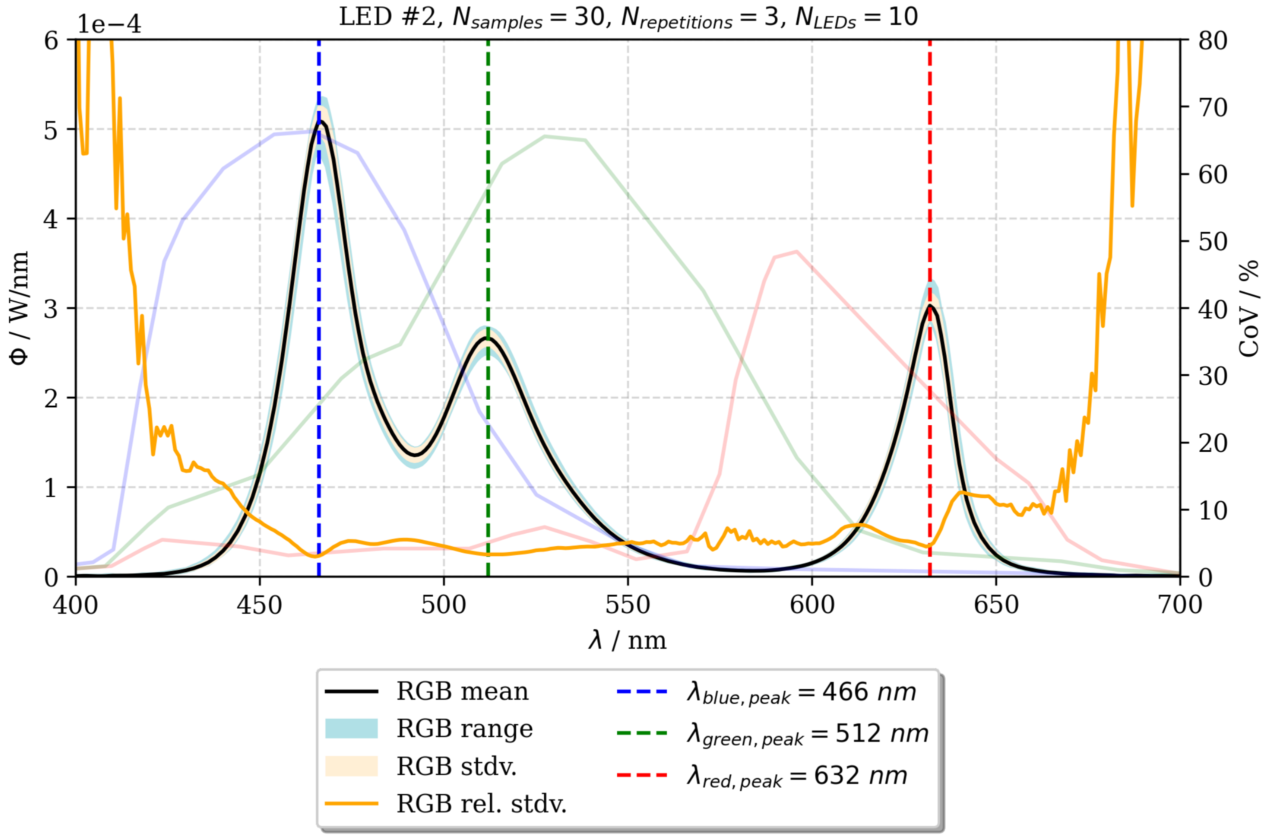
# Temperature Dependency

- Decreasing intensity of different LEDs with silicone coating was investigated under thermal stress
- More detailed investigation will be conducted under a continuous increase in temperature



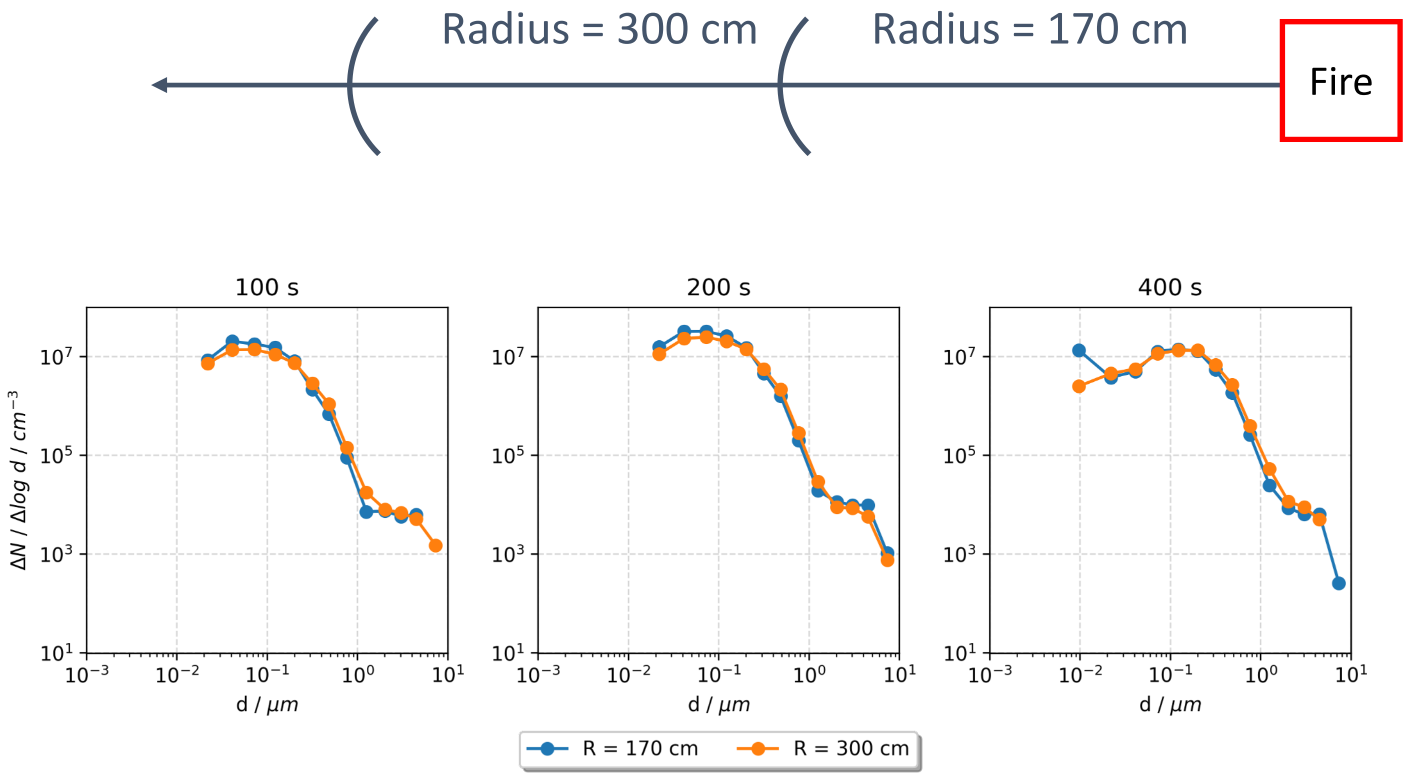

# Uncertainties of the Intrinsic LED Parameters

- Parallel measurement of RGB LEDs reveals low uncertainty
- Response spectrum of the camera has a high bandwidth and does not match the emitted spectrum of the LEDs



# ELPI⁺ - Particle Size Distribution of TF 5

- Similar size spectrum of smoke particles at different locations (horizontally)
- Aging effects on aerosols (agglomeration) may be deduced from evolution in size distribution







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# Soot Deposition