

# Investigation of Smoke Characteristics by Photometric Measurements



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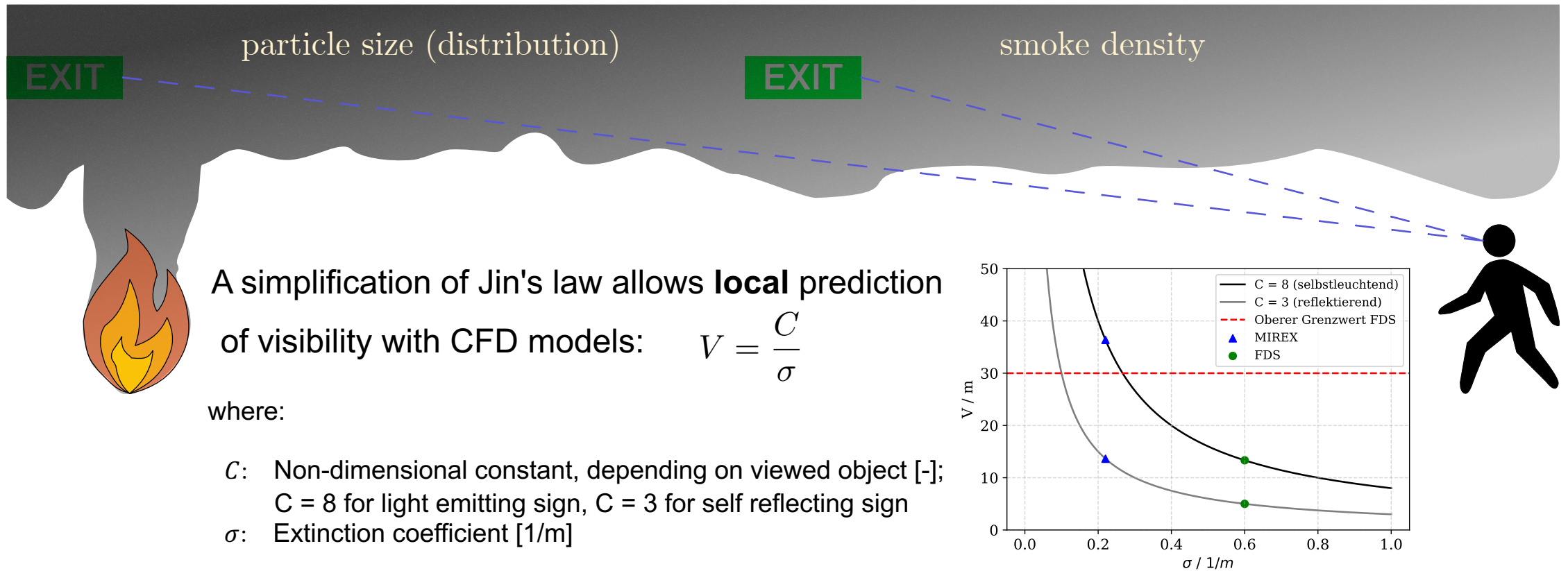


**JÜLICH**  
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# Outline

1. What is Visibility?
2. Experimental Setup
3. LEDSA - A Photometric Approach
4. Experimental Results
5. FDS vs. Experiment
6. Conclusion and Outlook

# What is Visibility?

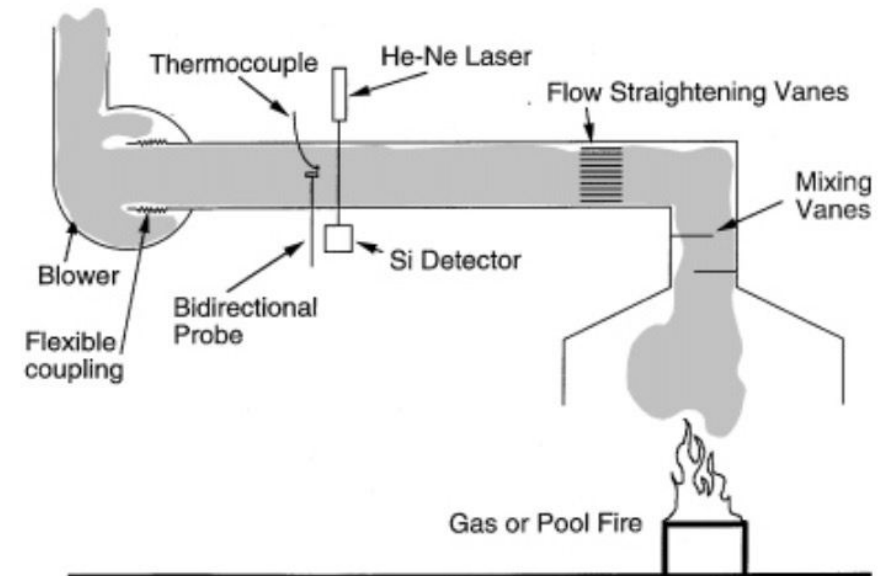


# Effects on Visibility

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

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

- $K_m$  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

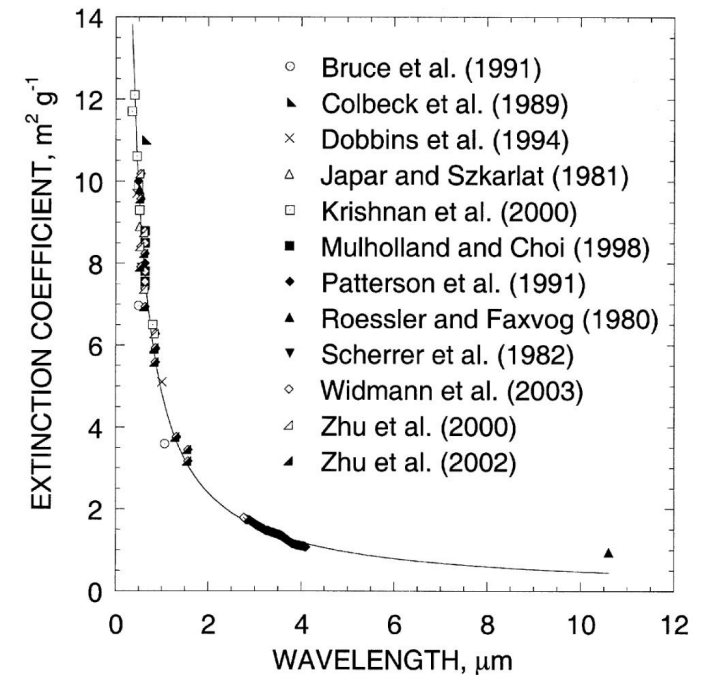
# Mass Specific Extinction Coefficient

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

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

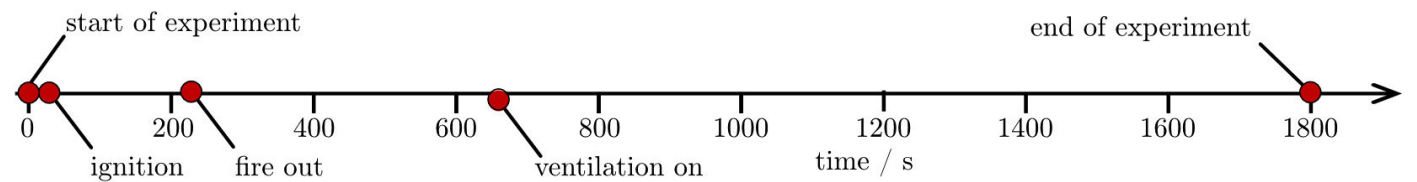
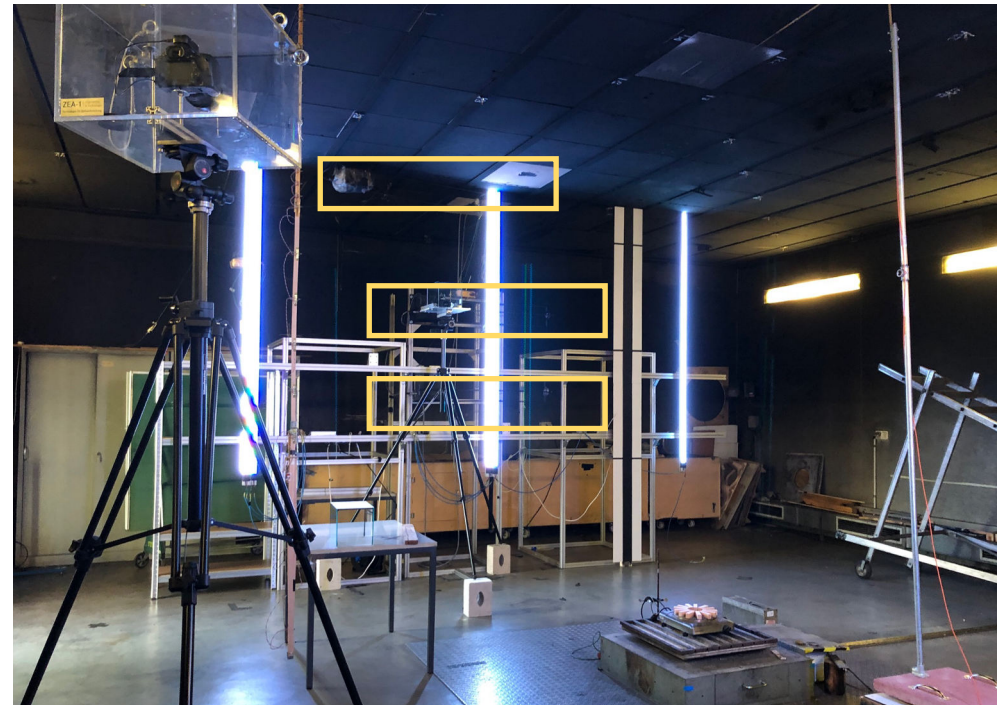
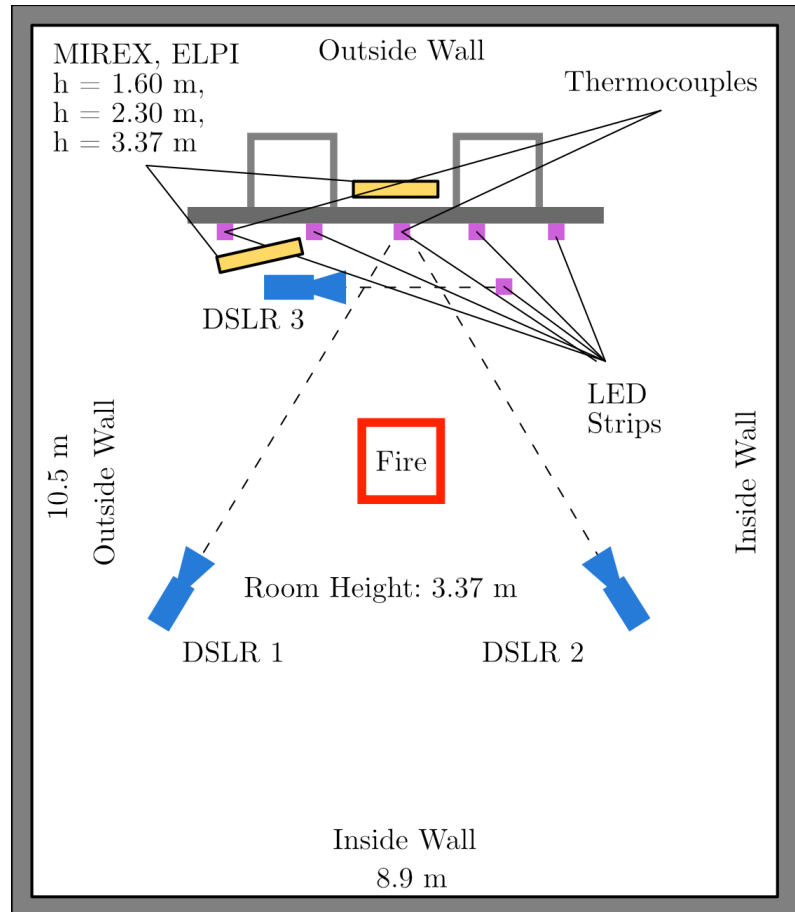
$$(K_m = 7175 \text{ m}^2/\text{kg} \text{ at } \lambda = 633 \text{ nm})$$

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



Widmann, Evaluation of the planck mean absorption coefficient for radiation transport through smoke, 2003

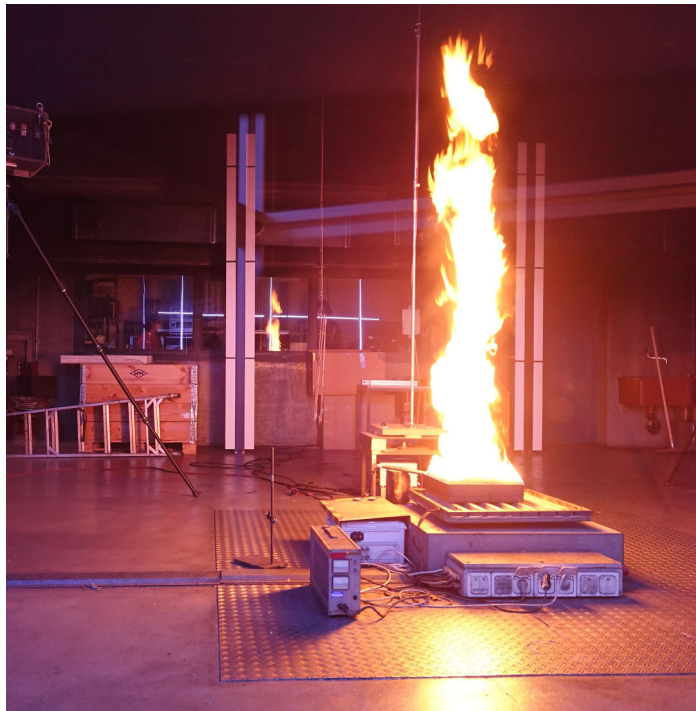
# Experimental Setup



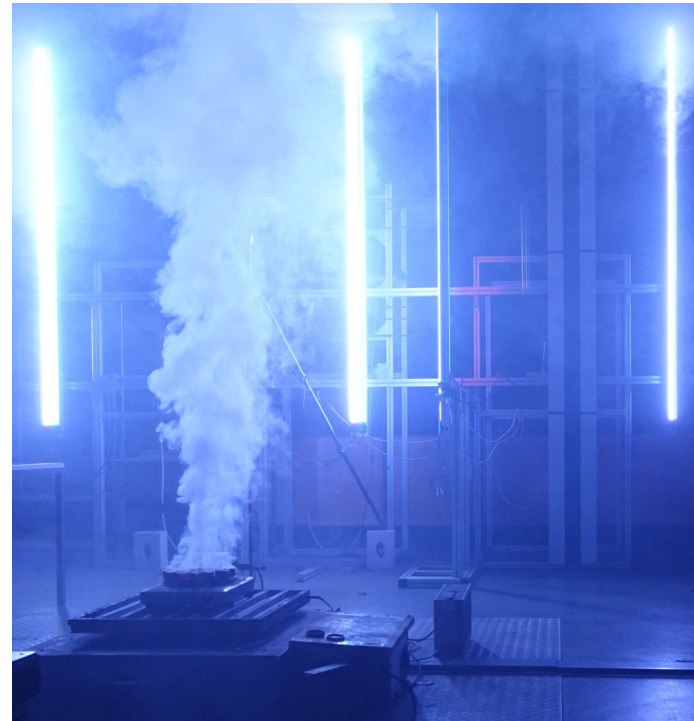


# EN 54 Test Fires

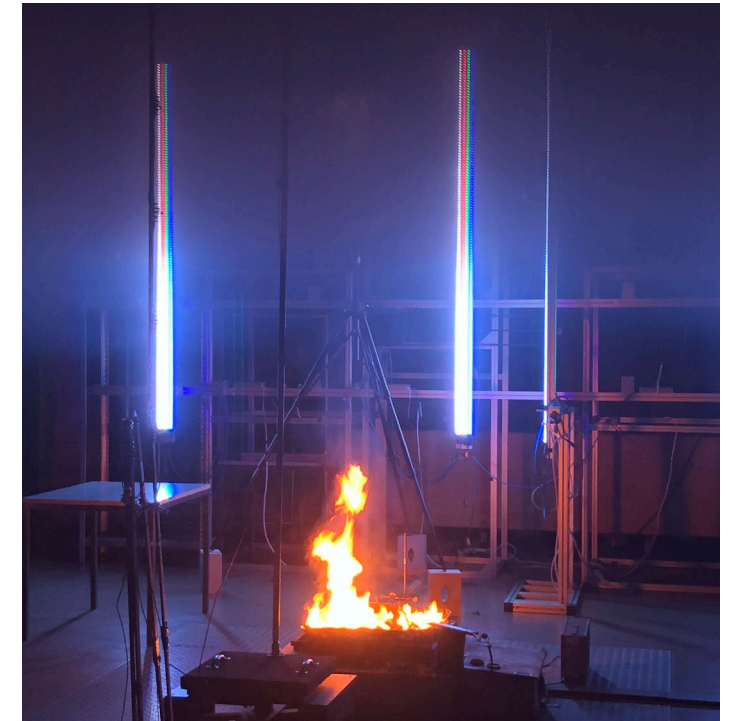
**TF 5 – n-heptane**  
Pool fire



**TF 2 – wood**  
Smoldering pyrolysis

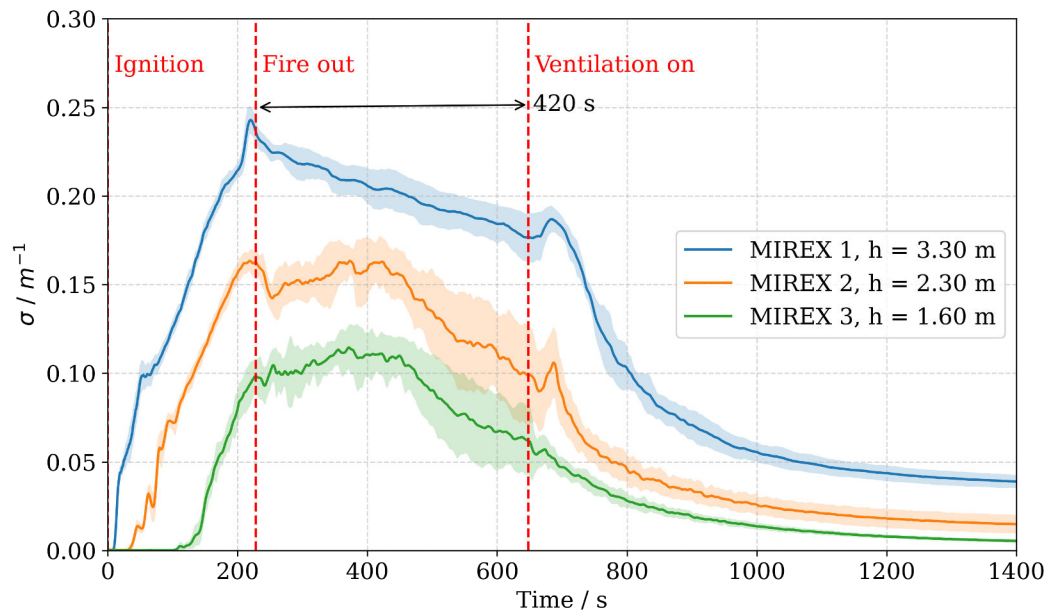


**TF 4 – polyurethane**  
Open plastic fire

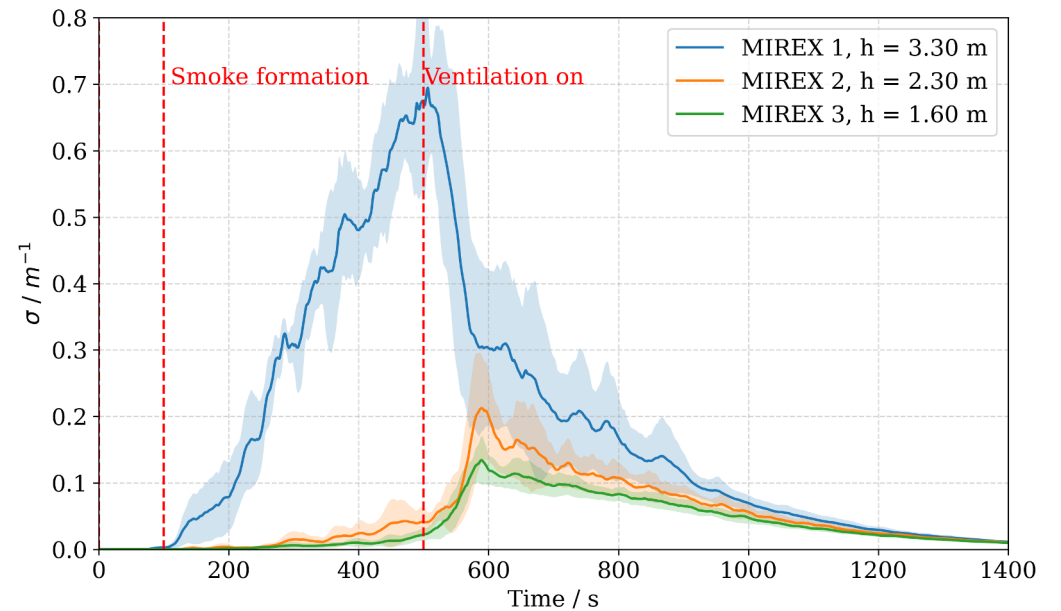


# Experimental Reproducibility

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

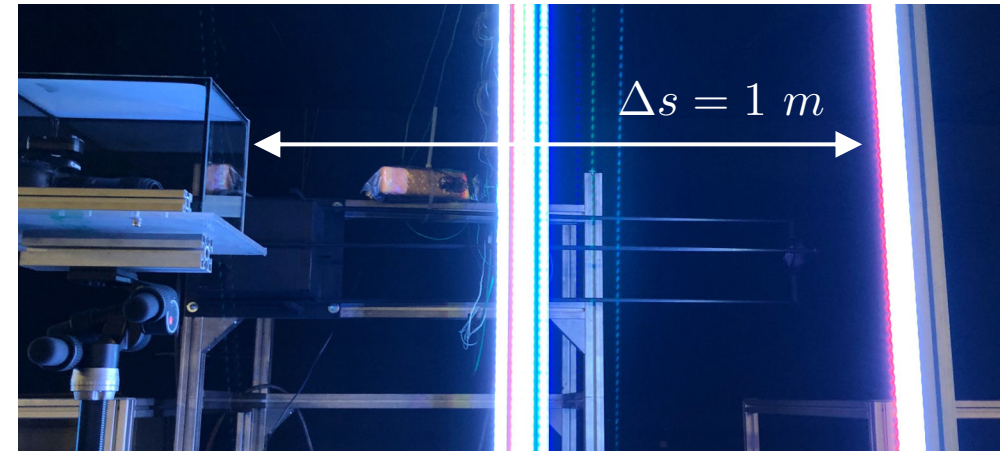
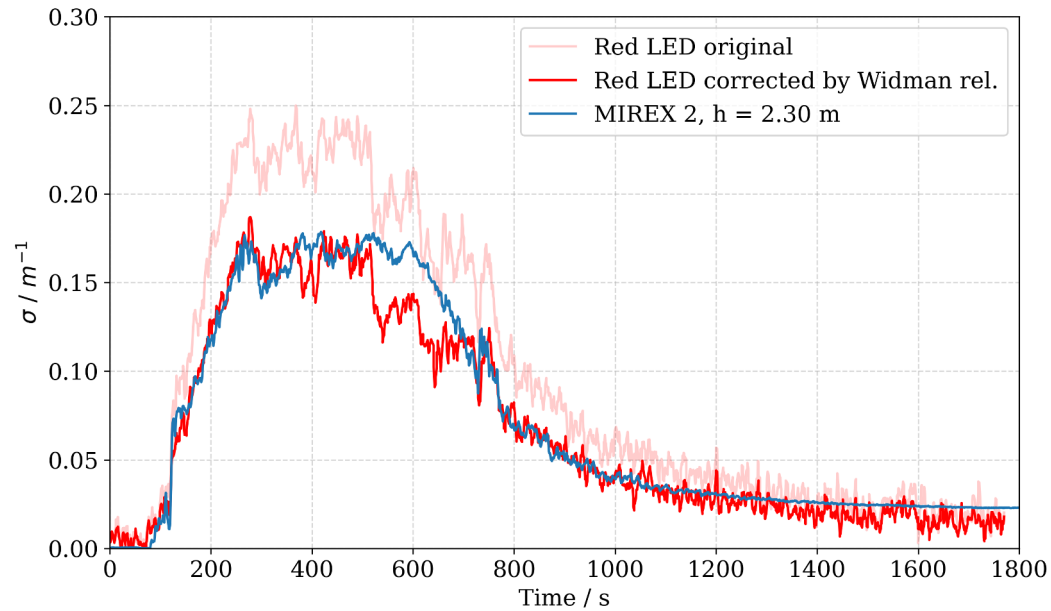


**TF 2 – wood**  
Smoldering pyrolysis (9 datasets)



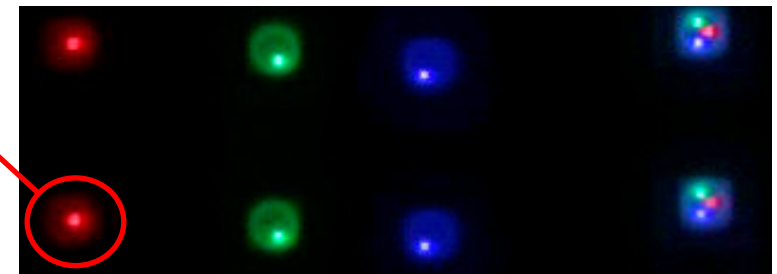


# LEDSA – Qualification of Methodology



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

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

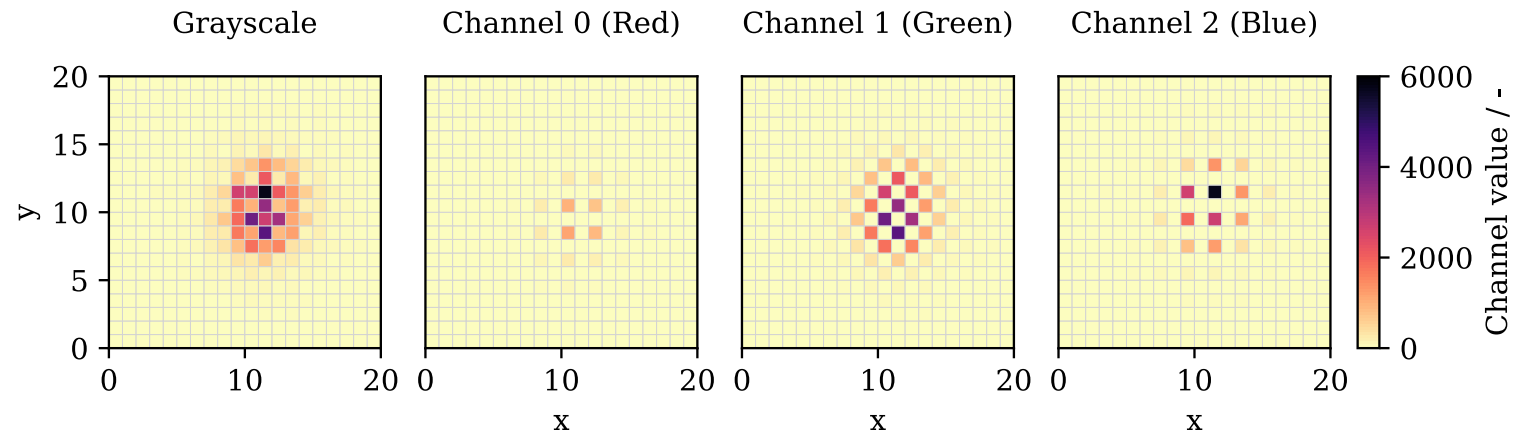


# Measuring Transmission

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

Bayer pattern  
(Color filter array  
on camera sensor)

$G_{0,0}$	$R_{1,0}$	...	$R_{1,0}$
$B_{0,1}$	$G_{1,1}$	...	$R_{1,1}$
...	...	...	$R_{1,2}$
$B_{j,0}$	$G_{j,1}$	$B_{j,2}$	$G_{ij}$



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

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

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

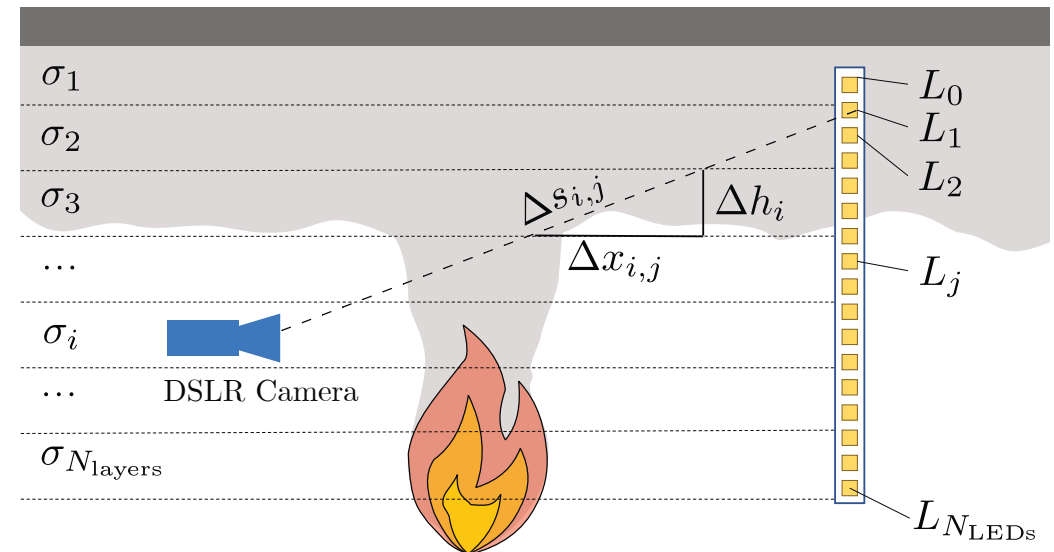
$$I_e = \frac{I}{I_0}$$

# Spatial Discretization - Layer Model

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

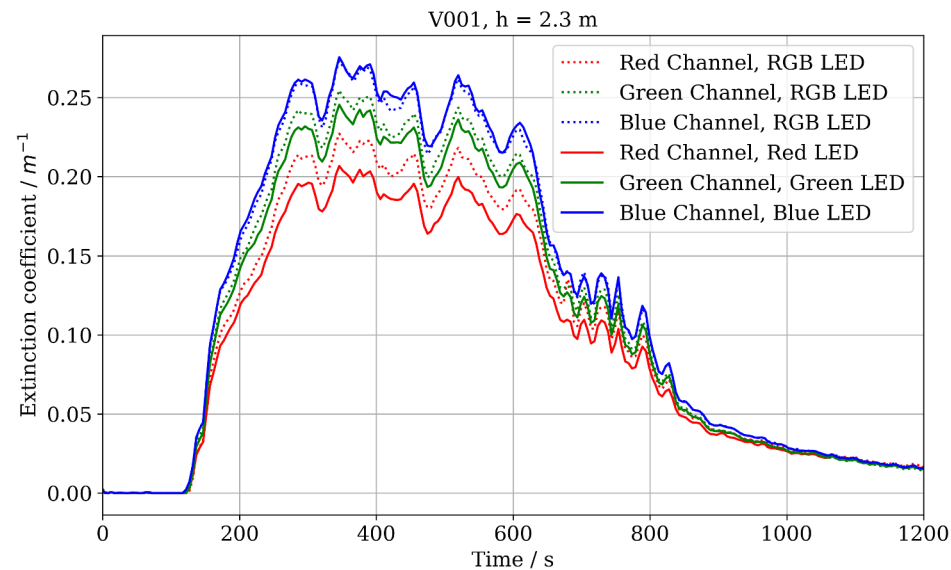
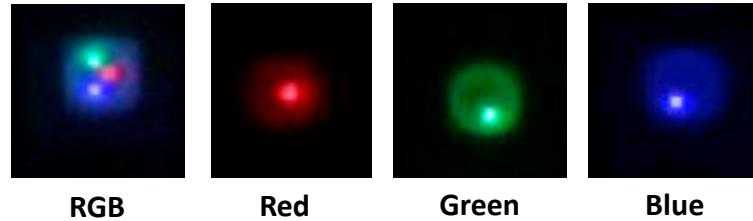
$$I_{m,j} = \exp \left( - \sum_{i=1}^{N_{\text{Layers}}} \sigma_i \Delta s_{i,j} \right)$$

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

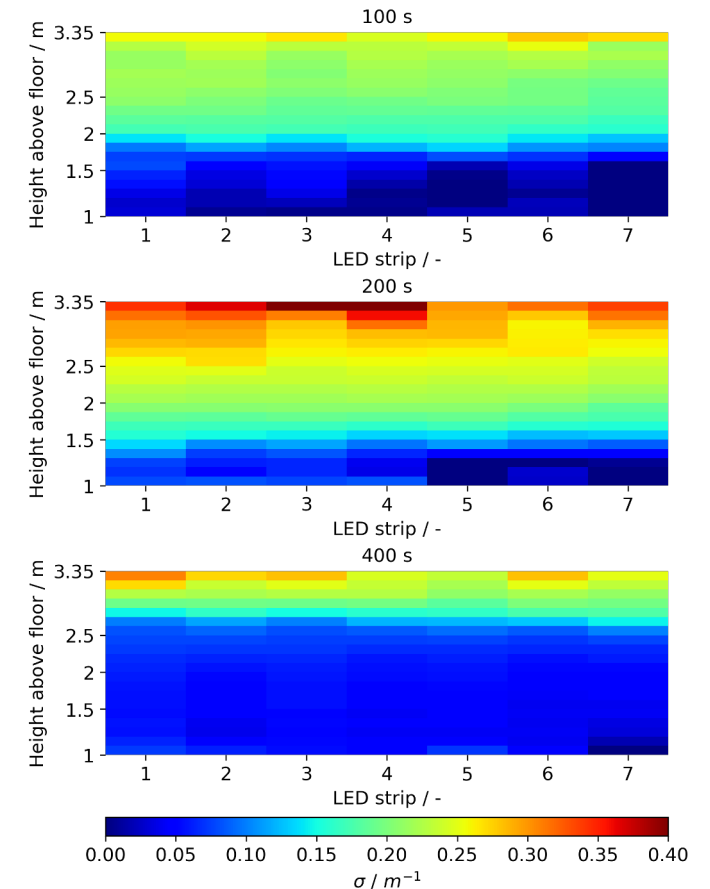


$$\Omega_{\sigma} = \underbrace{\sum_{j=i}^{N_{LEDs}} (I_{m,j} - I_{e,j})^2}_{L^2 \text{ - norm of } I_{m,j} \text{ and } I_{e,j}} + \underbrace{\phi_s \sum_{j=2}^{N_{layers}-1} (\sigma_{i-1} - 2\sigma_i + \sigma_{i+1})}_{\text{Smoothness of the solution}} + \underbrace{\phi_a \sum_{i=1}^{N_{layers}} \sigma_i}_{\text{Enforce high / low values of } \sigma_i}$$

# LEDSA - Spatiotemporal Extinction Coefficients

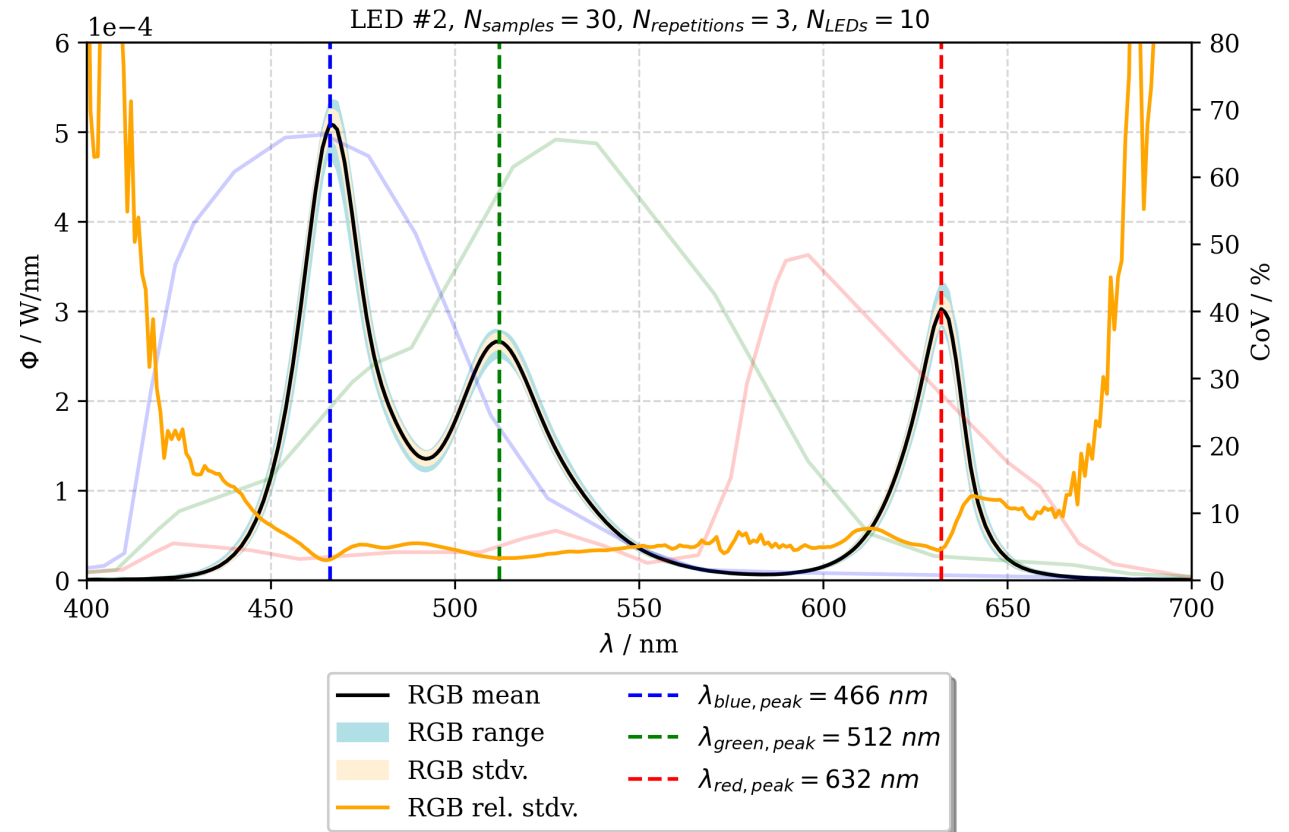


Model allows to compute spatially and temporally resolved extinction coefficients for light at different wavelengths



# Uncertainties of the Intrinsic LED Parameters

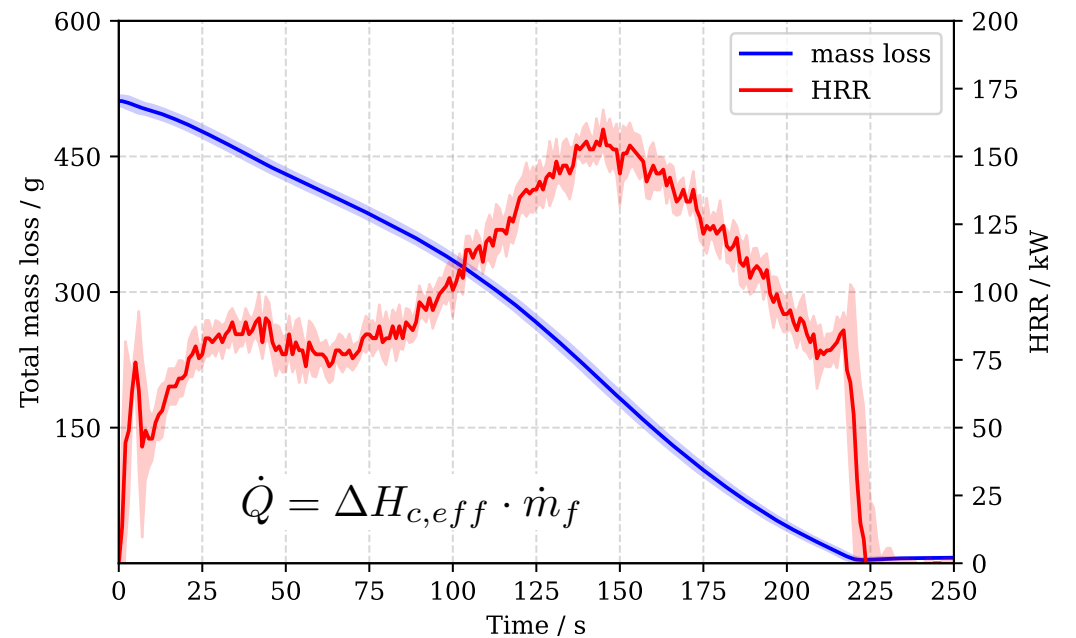
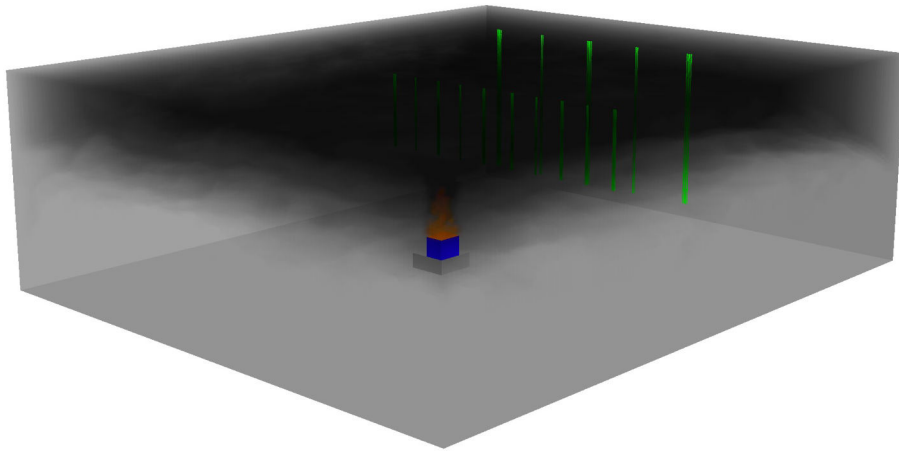
- Parallel measurement of RGB LEDs reveals low uncertainty
- Response spectrum of the camera has a high bandwidth and does not match the emitted spectrum of the LEDs





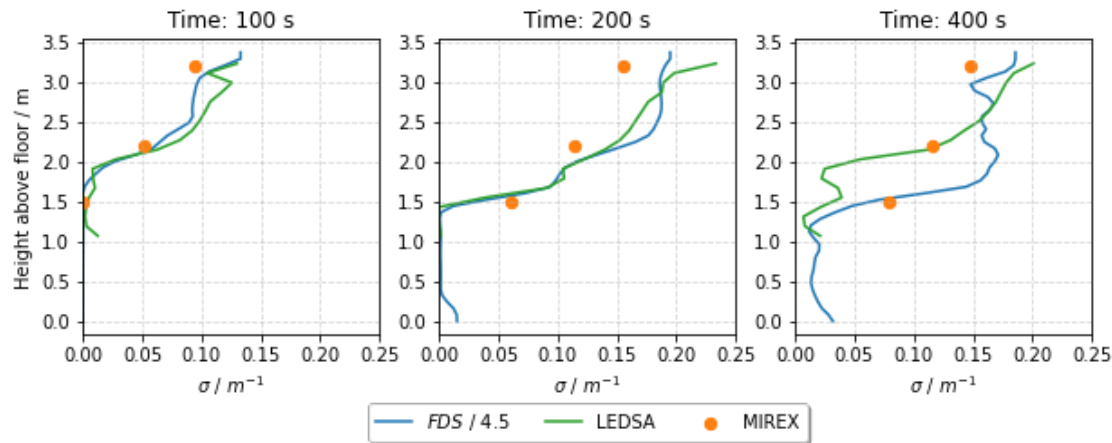
# FDS Model - TF 5

- Soot yield:  $Y_S = 0.037$  (SFPE Handbook)
- Mass specific extinction coefficient:  
 $K_m = 8700 \text{ m}^2/\text{kg}$  (FDS Default)
- Grid size:  $\delta_x = 8 \text{ cm}$

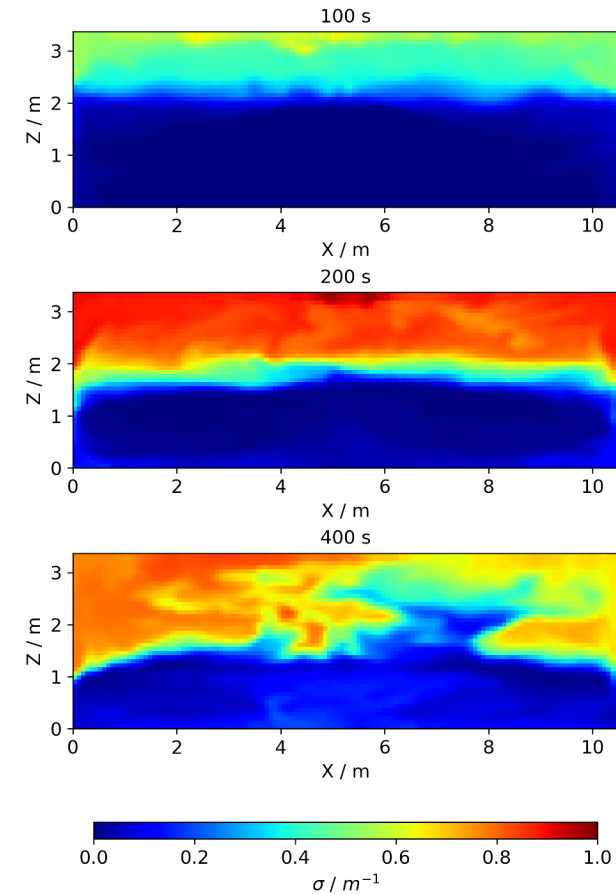


# FDS vs. Experiment - Extinction Coefficient

- 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

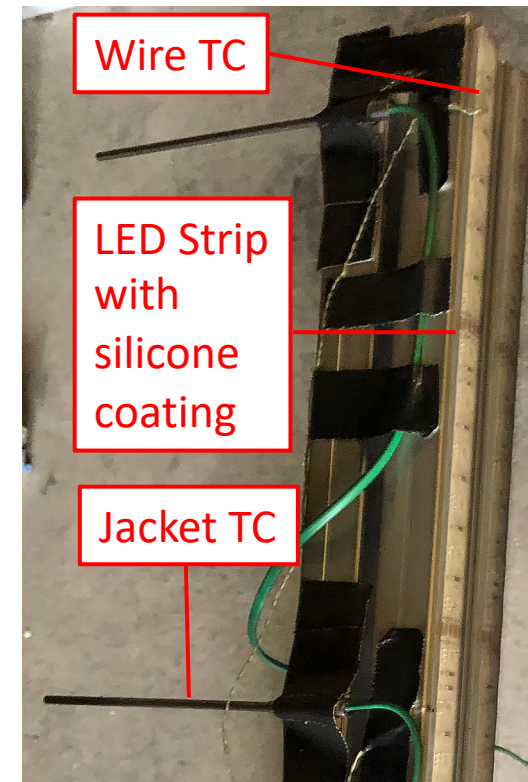
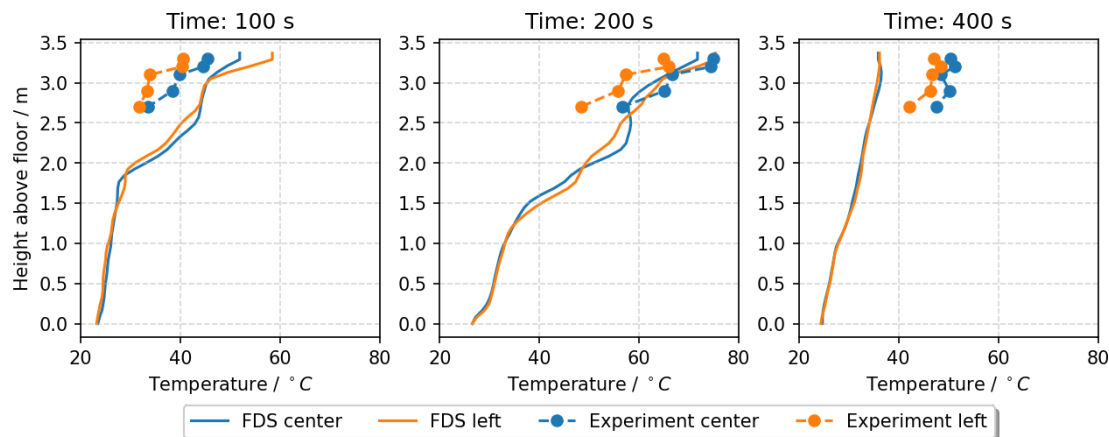


$$\sigma = K_m \cdot \rho \cdot Y_s$$



# FDS vs. Experiment -Temperature

- LED surface temperature 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



# 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

- 
- 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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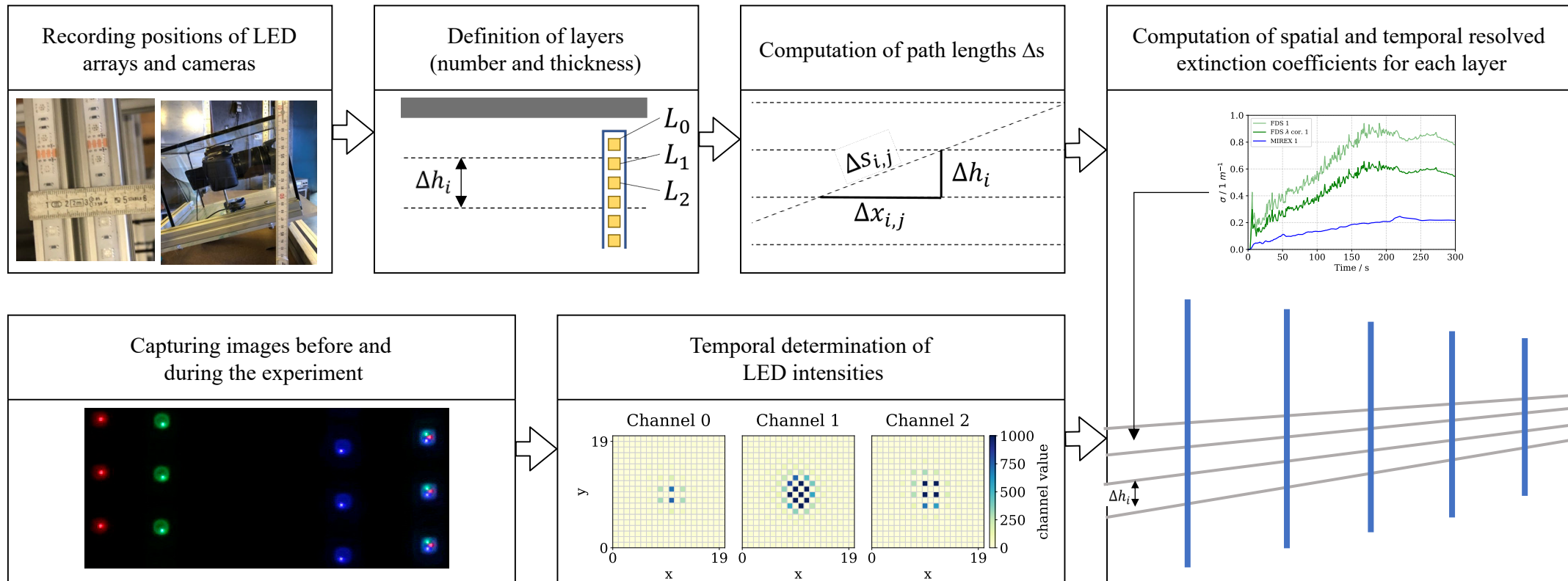


# Appendix

1. Data Acquisition and Analysis (LEDSA)
2. Temperature Dependency
3. ELPI<sup>+</sup> - Particle Size Distribution of TF 5
4. Soot Deposition

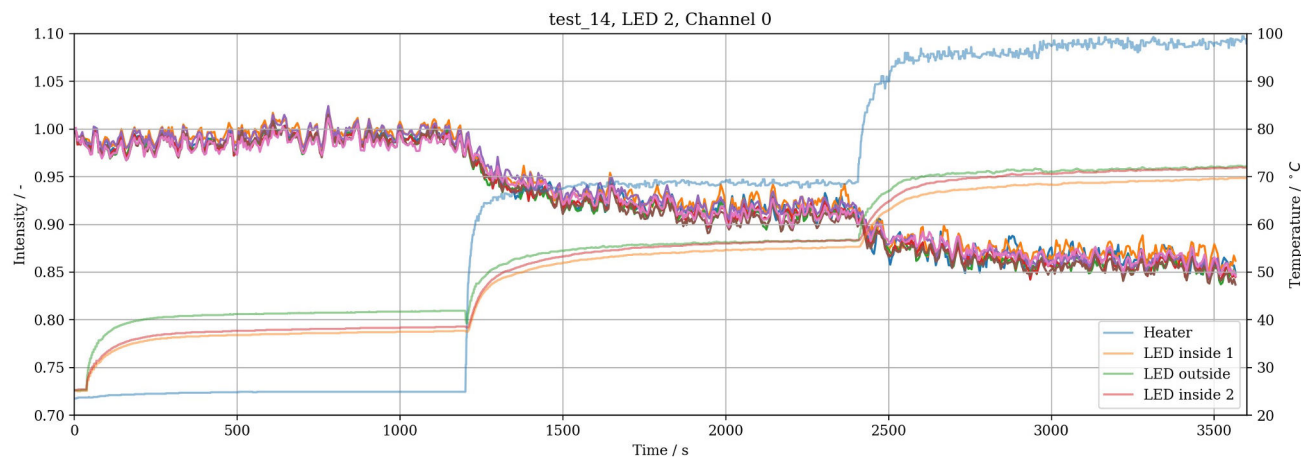


# Data Acquisition and Analysis (LEDSEA)



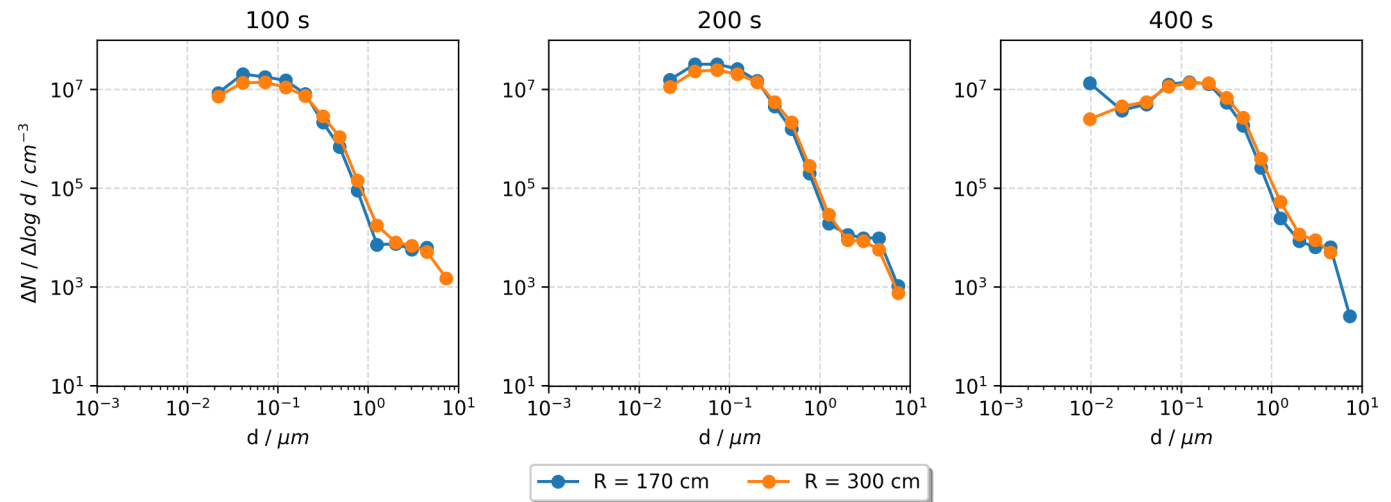
# Temperature Dependency

- 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



# ELPI<sup>+</sup> - 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



# Soot Deposition

