forschen.
vernetzen.
anwenden.

Karlsruhe, 18 October 2018
PM2.5 Monitoring - What‘s Next?

Comparison of optical aerosol spectrometers and low-cost photometers for monitoring the particulate exposure at workplaces

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Luftreinhaltung & Filtration

IGF

An-Institut der UNIVERSITÄT DUISBURG ESSEN

JRF MITGLIED DER Johannes-Rau-Forschungsgemeinschaft

AiF Mitglied

Background

- worldwide air pollution is a growing concern
- established measurement techniques to determine the air quality
- trend towards higher spatial and temporal resolution

http://maps.who.int/airpollution/ *Env. Sci. Technol.* **51** 6999 (2017) *Ann. Occup. Hyg.* **50** 249 (2006)

- suitable measurement techniques for a dense network needed

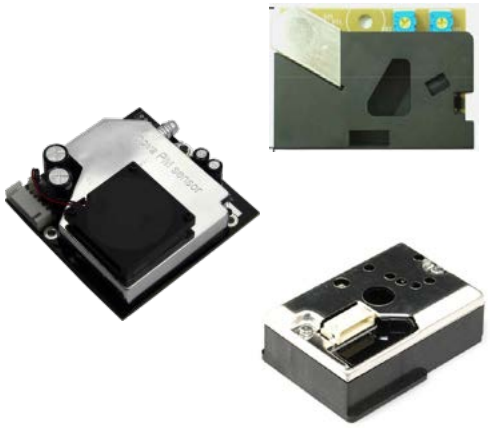
Applicability of optical techniques for air quality measurements

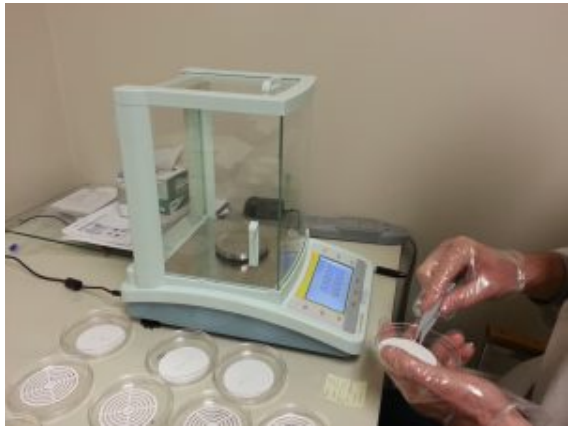
- higher temporal resolution and less maintenance than for gravimetrical analysis

- scientific instruments:
  - spectrometers (scattering of individual particles)
    → size distribution and concentration
  - high precision and accuracy
  - devices usually not very mobile
  - high costs of about 5,000 € to 50,000 €

Palas Fidas Frog certified for PM_{10} and $PM_{2.5}$ measurements

- low-cost PM sensors:
  - photometers (scattering of a particle cloud)
    → only concentration
  - a priori limited precision expected
  - sensors very small and light
  - low costs (typically < 20 €)
  - suitable for citizen science projects





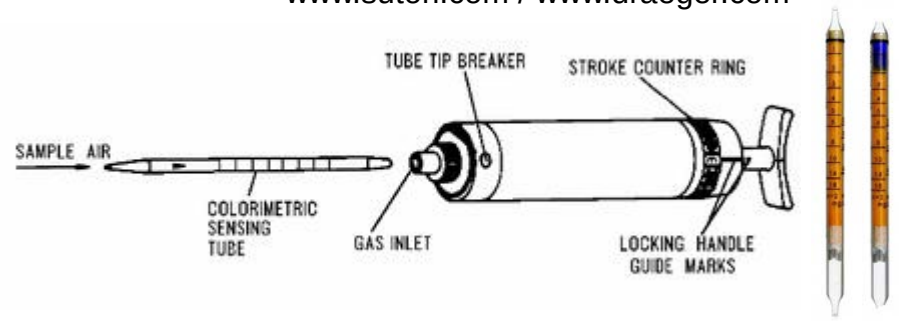
www.airzoneone.com

A brief history on air quality sensors

http://askabiologist.asu.edu

19th/20th century: canaries in coal mines to detect harmful gases

www.sutori.com / www.draeger.com



1937: Dräger tube to detect CO (today for a large variety of gases)

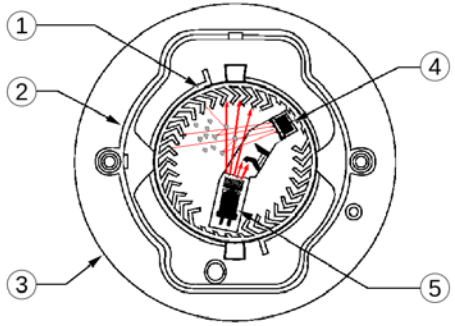
www.alphasense.com

1962: electrochemical gas sensor (today low cost)

1951: first ionization smoke detector sold in the US

www.wikipedia.org

1972: first optical smoke detector patented



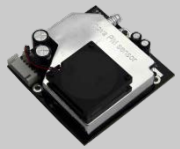
www.wikipedia.org

since ~2010: used to control mobile air cleaners (low cost)

www.philips.com / www.sparkfun.com

Types of low cost PM sensors

- large variety of sensors available on the market

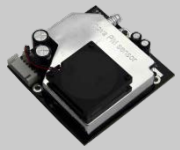
	Nova Fitness SDS011	Samyoung DSM 501	Sharp optical dust sensor	Alphasense OPC-N2
image				
size range	0.3 – 10 µm	>1 µm	not specified	0.38 – 17 µm
concentration range	0 – 1,000 µg/m³	0 – 1.4 mg/m³	25 – 500 µg/m³	ca. < 500 cm^{-3} (0.84% coincidence at 1,000 cm^{-3})
metric(s)	$PM_{2.5}$, PM_{10}	mass concentration	$PM_{2.5}$	PM_1, $PM_{2.5}$, PM_{10}, PSD (16 channels)
price	14.06 €[1] (16.40 US$)	8.28 €[1] (9.66 US$)	2.59 €[1] (3.02 US$)	ca. 400 €[2]

[1] www.aliexpress.com on 29.08.2018

[2] direct sales through Alphasense

Types of low cost PM sensors

- large variety of sensors available on the market

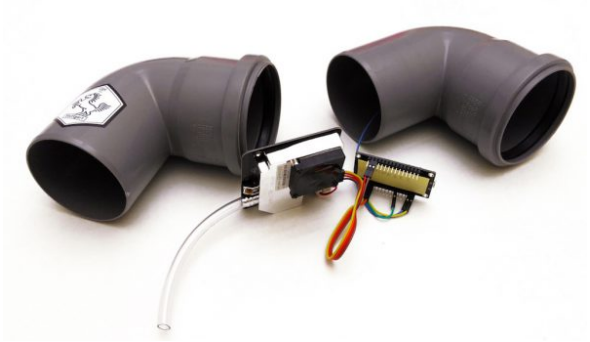
	Nova Fitness SDS011
image	
size range	0.3 – 10 µm
concentration range	0 – 1,000 µg/m³
metric(s)	$PM_{2.5}$, PM_{10}
price	14.06 €[1] (16.40 US$)

WAZ DIE ZEITUNG DES RUHRGEBIETS 16 February 2017


RHEIN-RUHR

Ich mess' meinen Feinstaub selber

Aus ein paar Kabeln und zwei Stück Abflussrohr lässt sich ein Messgerät basteln. Naturschützer bieten Info-Seminare an. Das Landesumweltamt freut sich darüber



Süddeutsche Zeitung 19 March 2017


Dreck-Sensor im Eigenbau

Eine Stuttgarter Initiative hat ein Netz aus selbstgebastelten Feinstaub-Messgeräten aufgebaut, deren Daten jederzeit im Internet abrufbar sind. So wollen die Aktivisten das Bewusstsein für Luftverschmutzung stärken

Was sind OK Labs?

Immer mehr bastelwillig Bürger wollen ihre eigenen Daten sammeln

ZEIT ONLINE 22 December 2017


Politik Gesellschaft Wirtschaft Kultur Wissen Digital Campus Arbeit Entdecken Sport ZEITmagazin mehr

Luftverschmutzung

Feinstaub in der Falle

Die gefährlichen Partikel haben neue Gegner: Hobbyforscher mit selbst gebastelten Messstationen.

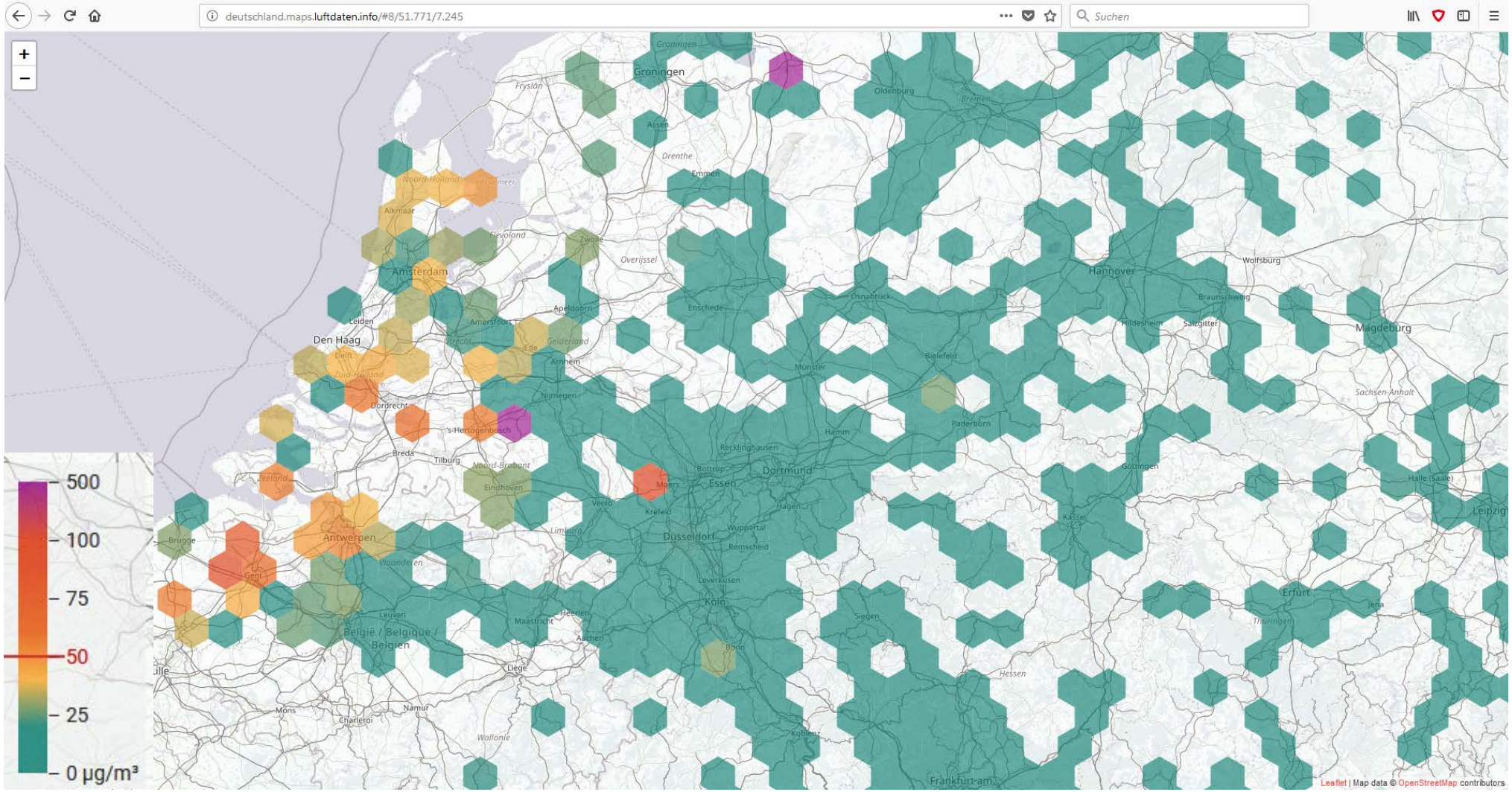
Von Ulf Schönert

- SDS011 sensors used for German citizen science projects

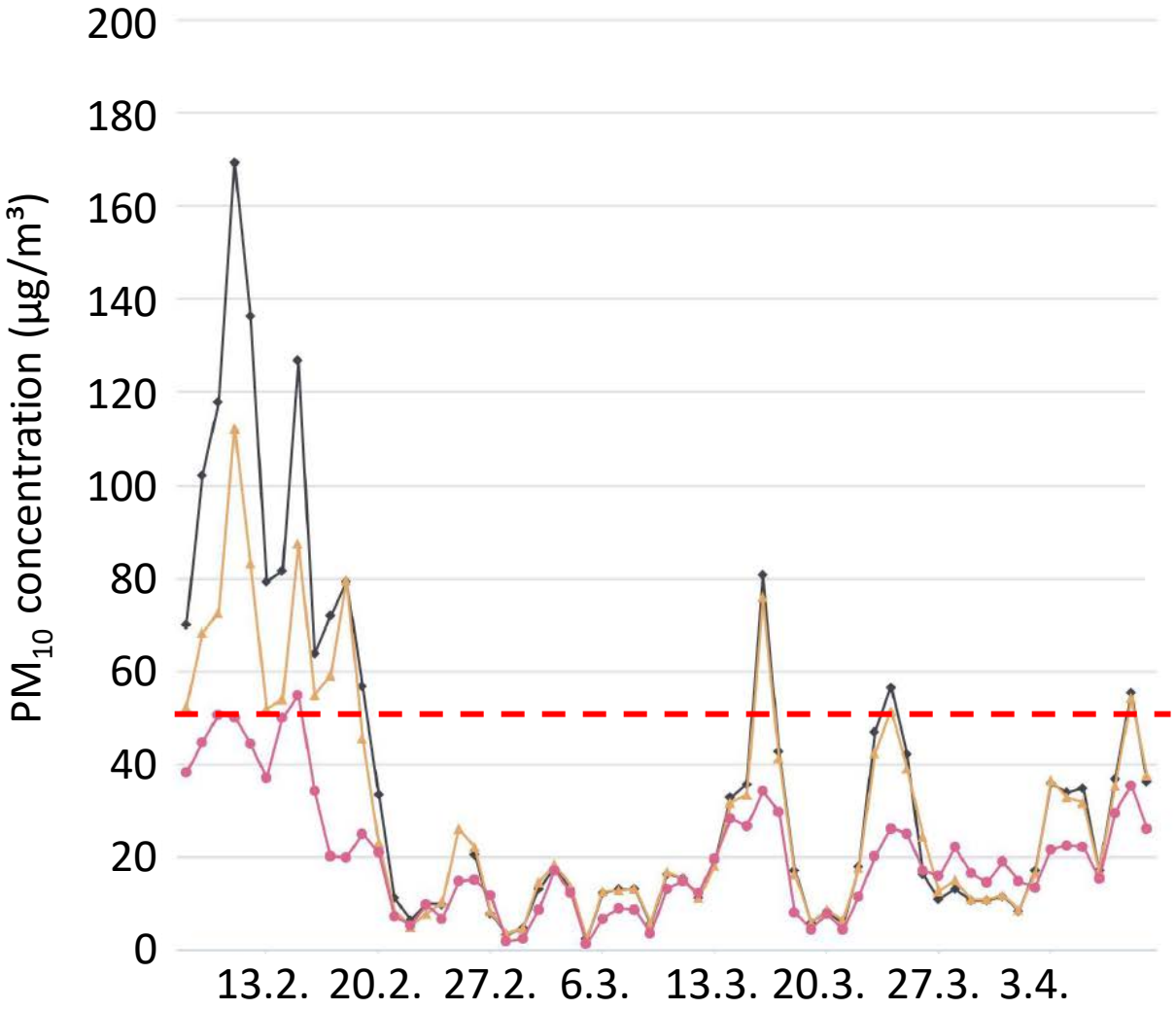
Citizen science air quality map

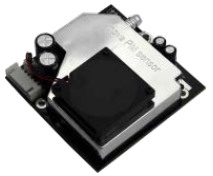
- concentrations of PM_{10} and $PM_{2,5}$ concentrations freely available

https://luftdaten.info/



Ambient PM_{10} measurements with low cost sensors





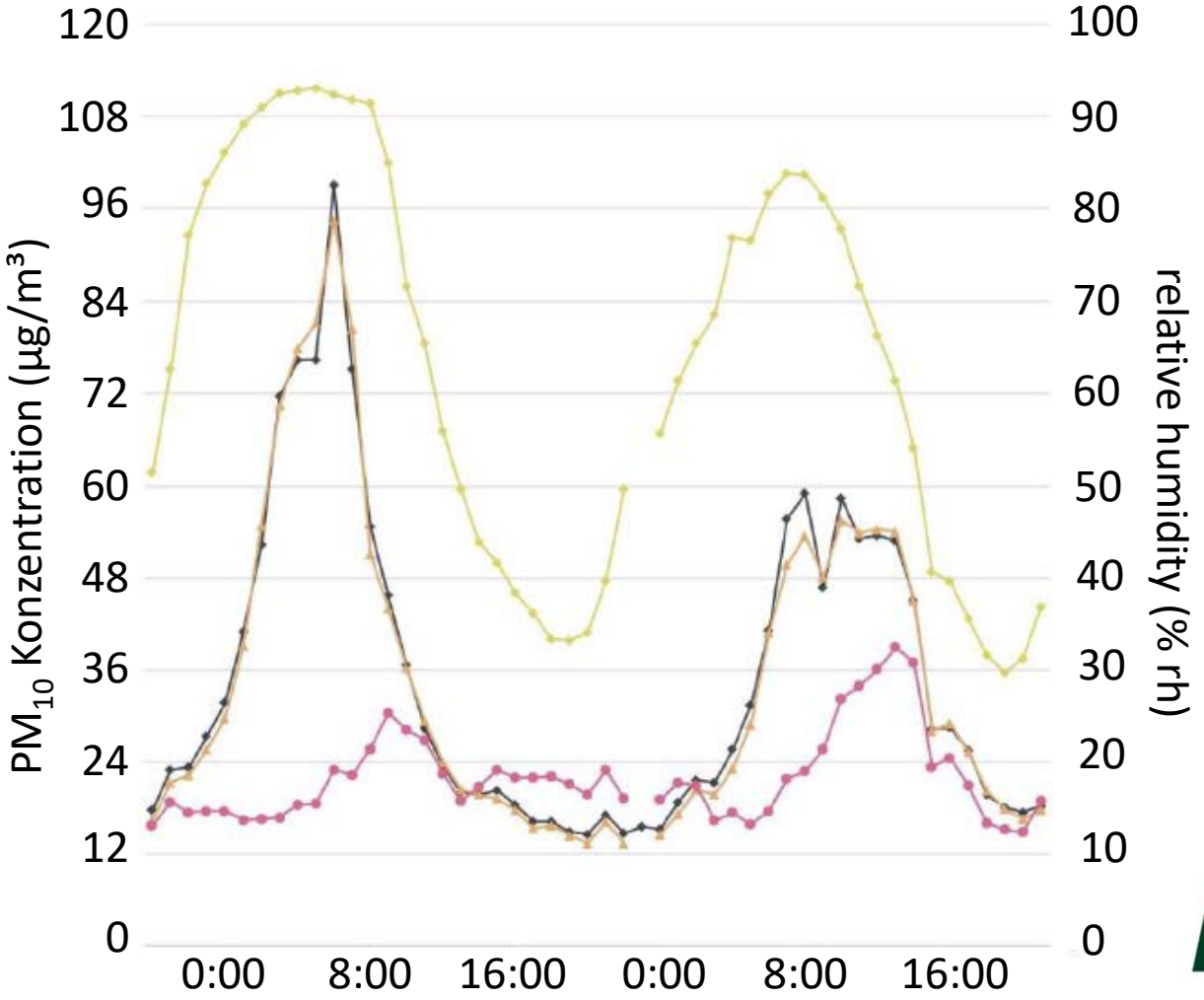
two configurations of the same sensor

optical particle counter as reference instrument

https://www4.lubw.baden-wuerttemberg.de/servlet/is/268831/messungen_mit_dem_feinstaubsensor_sds011.pdf?command=downloadContent&filename=messungen_mit_dem_feinstaubsensor_sds011.pdf

- in general good correlation, but strong deviations at certain times

Influence of the relative air humidity



LUBW

https://www4.lubw.baden-wuerttemberg.de/servlet/is/268831/messungen_mit_dem_feinstaubsensor_sds011.pdf?command=downloadContent&filename=messungen_mit_dem_feinstaubsensor_sds011.pdf

- strong deviations especially at high air humidity, similar for other low-cost sensors

Hygroscopic particle growth

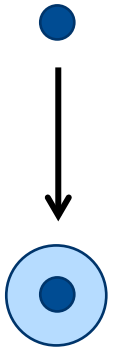
- hygroscopic particles grow by take-up of water

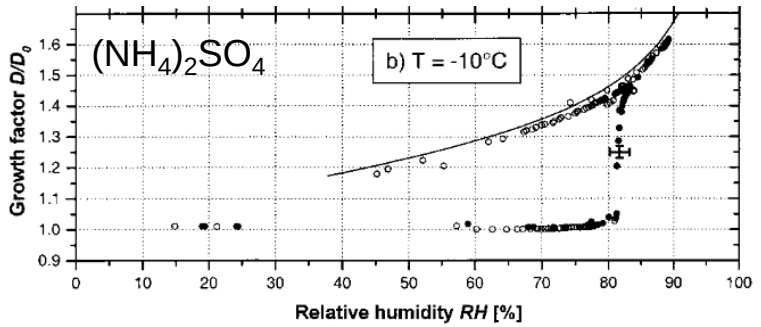
  → too high mass concentration determined

- data correction difficult (composition, size, hysteresis)
- reference measurement devices dry the aerosol
- problems with aerosol dryers at the moment

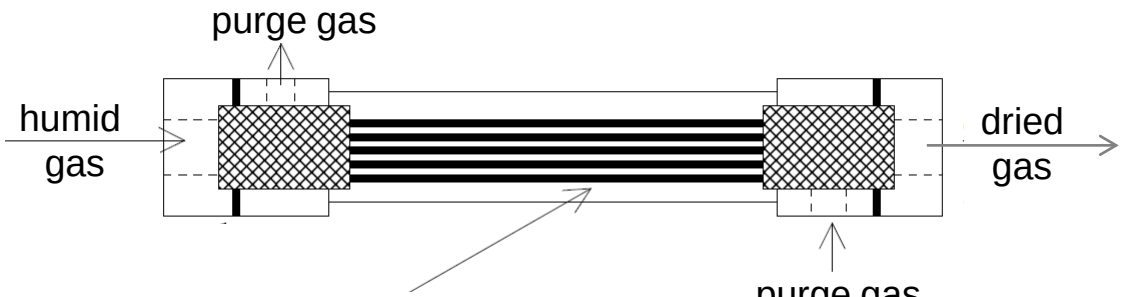
  → high pressure drop, costs, or power consumption

  → need to develop a suitable low-cost dryer





Environ. Sci. Technol. **36** 63 (2002)



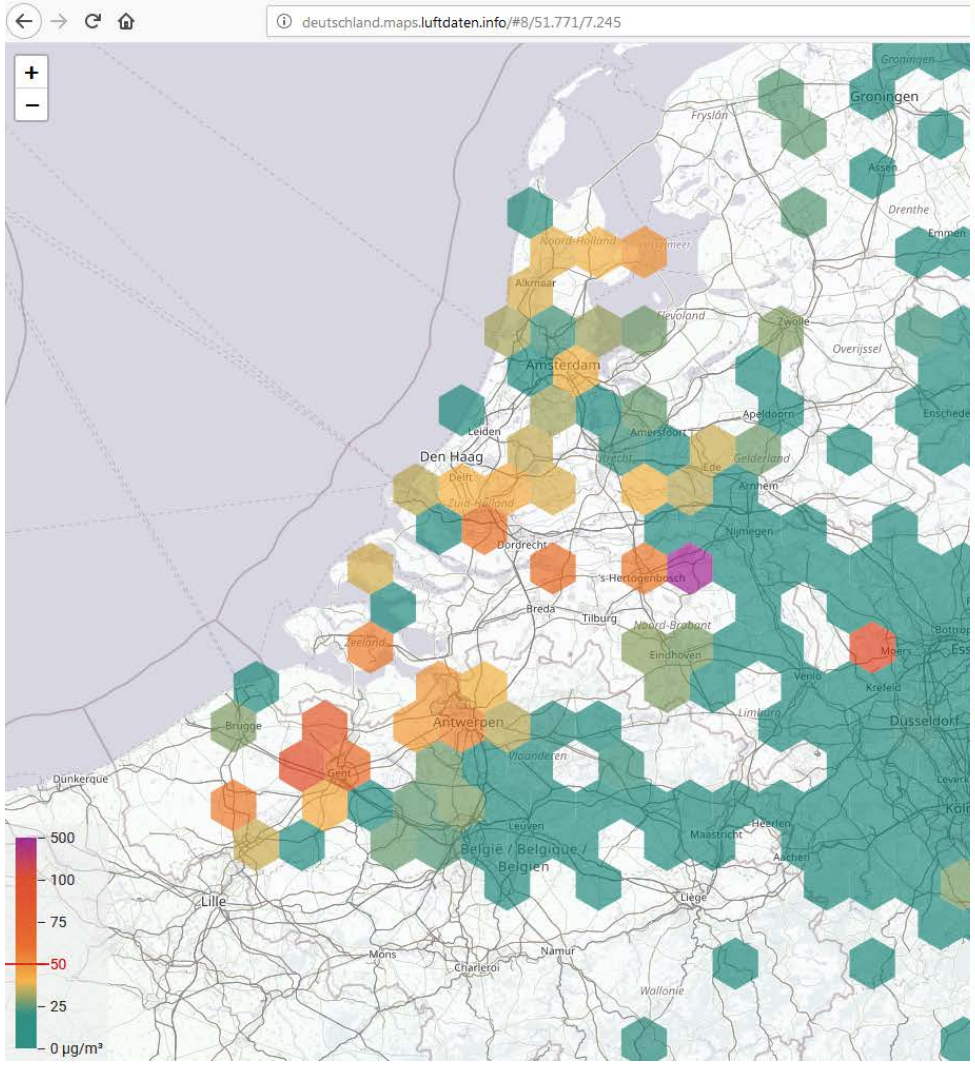
Gasmet . Ansyco
GASMESSTECHNIK & ANALYTISCHE SYSTEME

diffusion dryer

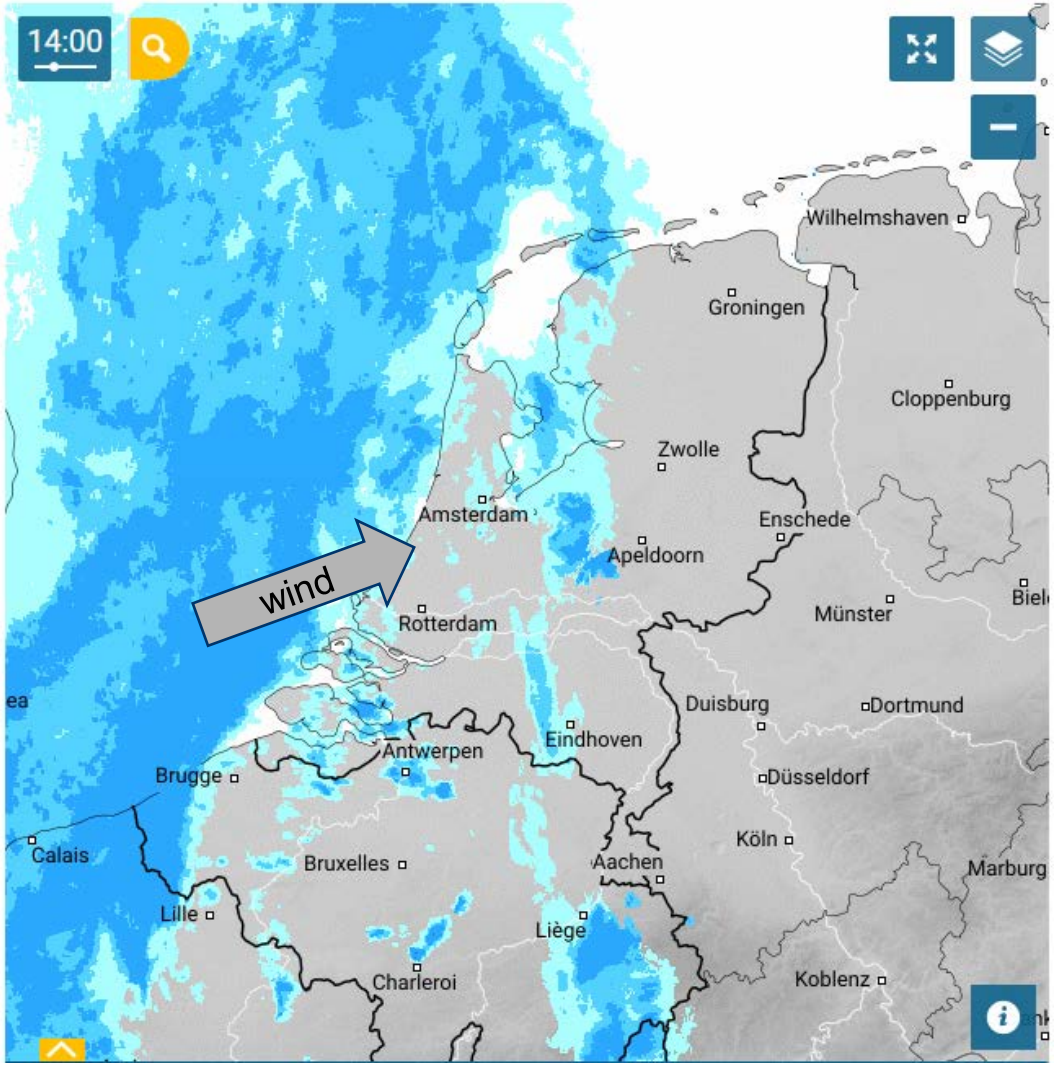
sample heating

Citizen science air quality map

- apparently high PM_x concentrations can be caused by meteorological conditions



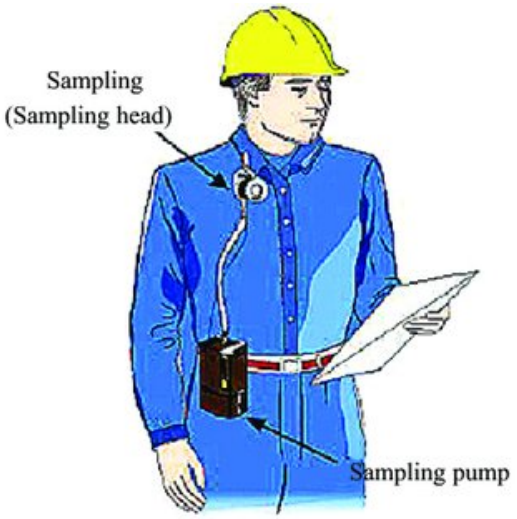
https://luftdaten.info/



www.wetteronline.de

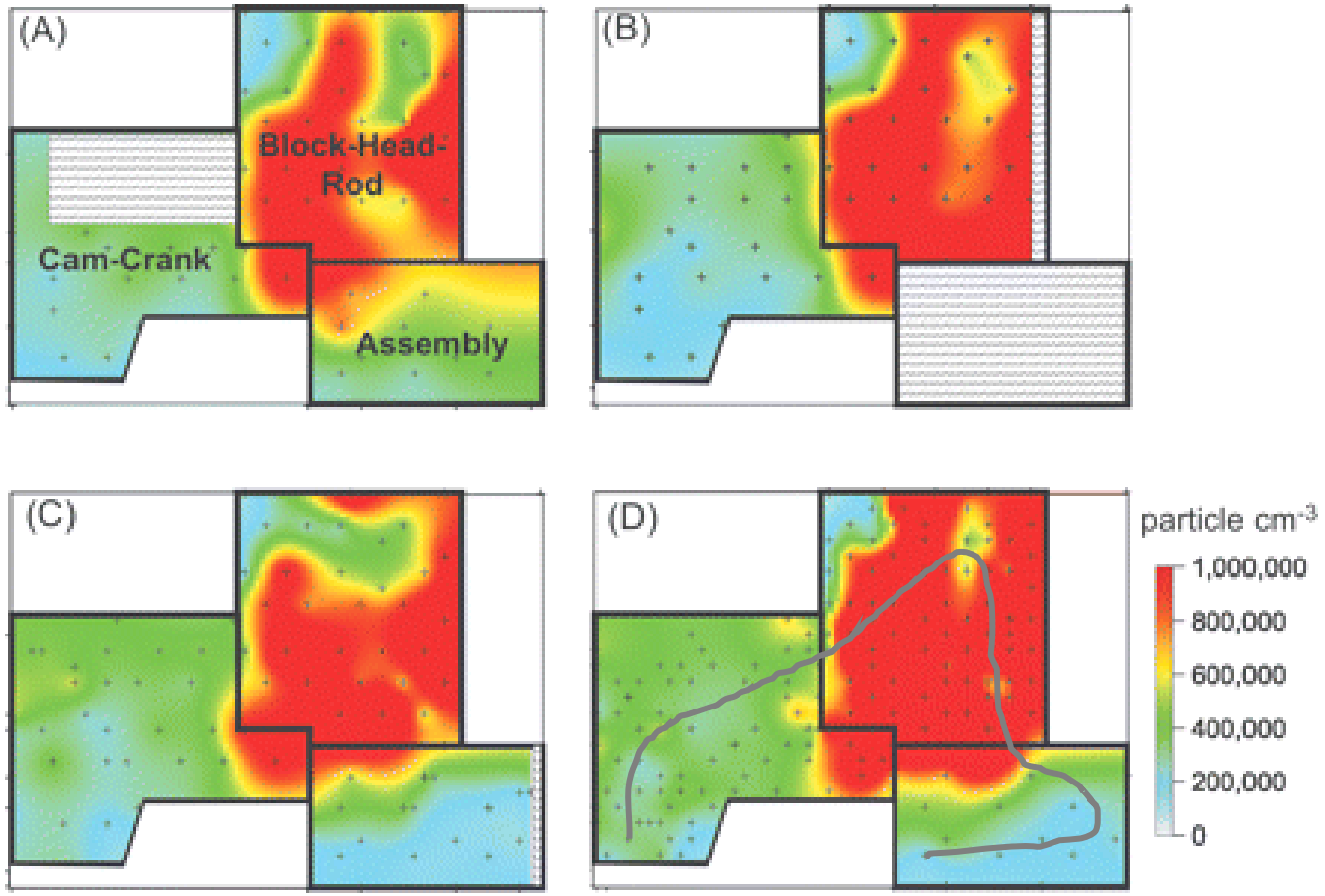
Use of optical particle counters and sensors for workplace exposure

- usually lower and less fluctuating relative humidity, particle concentrations typically higher
- German occupational exposure level (OEL) for respirable dust recently reduced to 1.25 mg/m³
- traditional gravimetric analysis reaches its limit, especially for assessing short term exposure



- optical measurement techniques offer high temporal resolution
- alternative to personal sampling: formation of a dense sensor network

Mapping workplace exposure concentrations

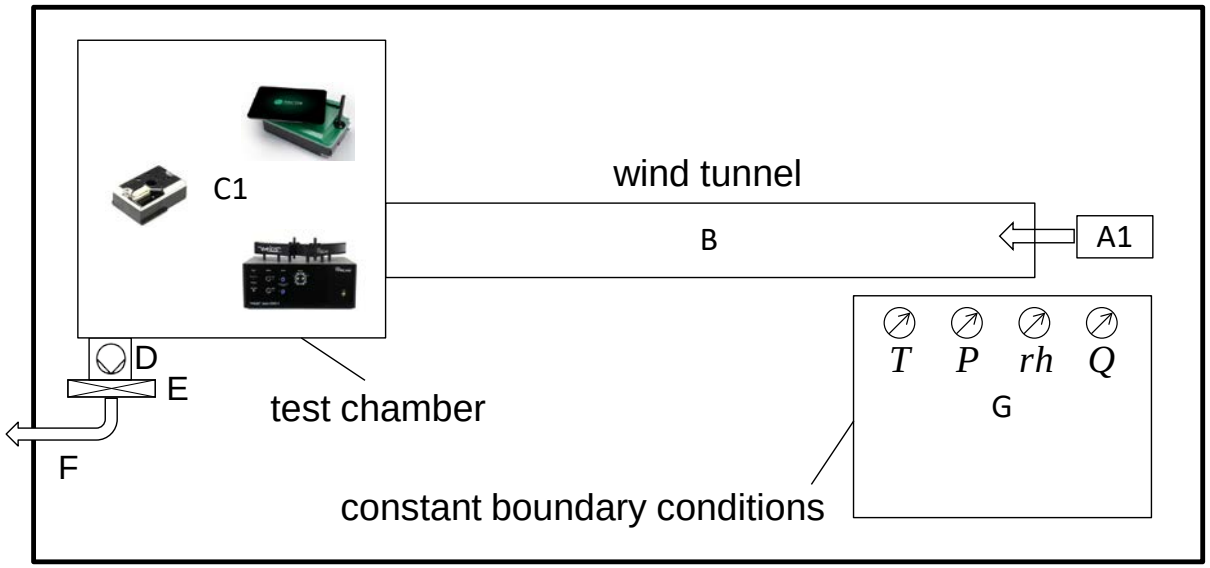


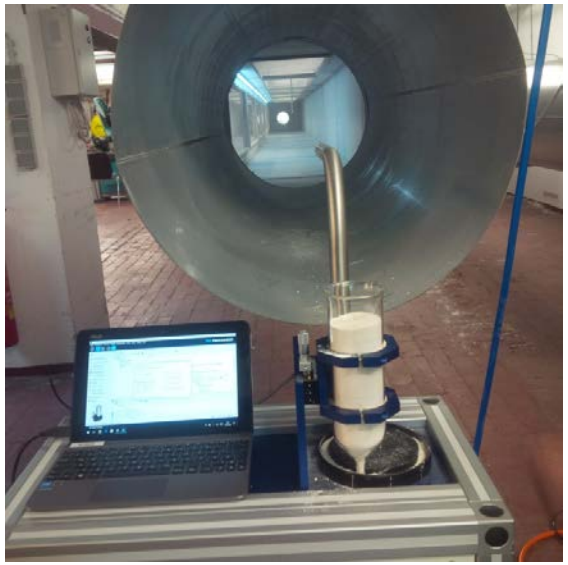
T. Peters et al. *Ann. Occup. Hyg.* **50** 249 (2006)

- measurements in a diesel engine machining and assembly facility
- expensive equipment > 50,000 €
- similar data could be obtained with low-cost sensors (50 sensors ~1,000 €)
- continuous measurements possible, important for temporal fluctuations and leak detection
- possibility to keep track of workers' motion to estimate personal exposure (e.g. iBeacon < 20 €)

Are the counters and sensors suitable for workplace aerosols?

- experiments conducted at the IGF Dortmund
  - aerosolization of powder with homemade dust feeder
  - supply into 20 m long wind tunnel, mixing with 1,800 m³/h dilution air
  - feeding into 24 m³ chamber for spatially homogenous distribution
  - all instruments measured simultaneously inside test chamber

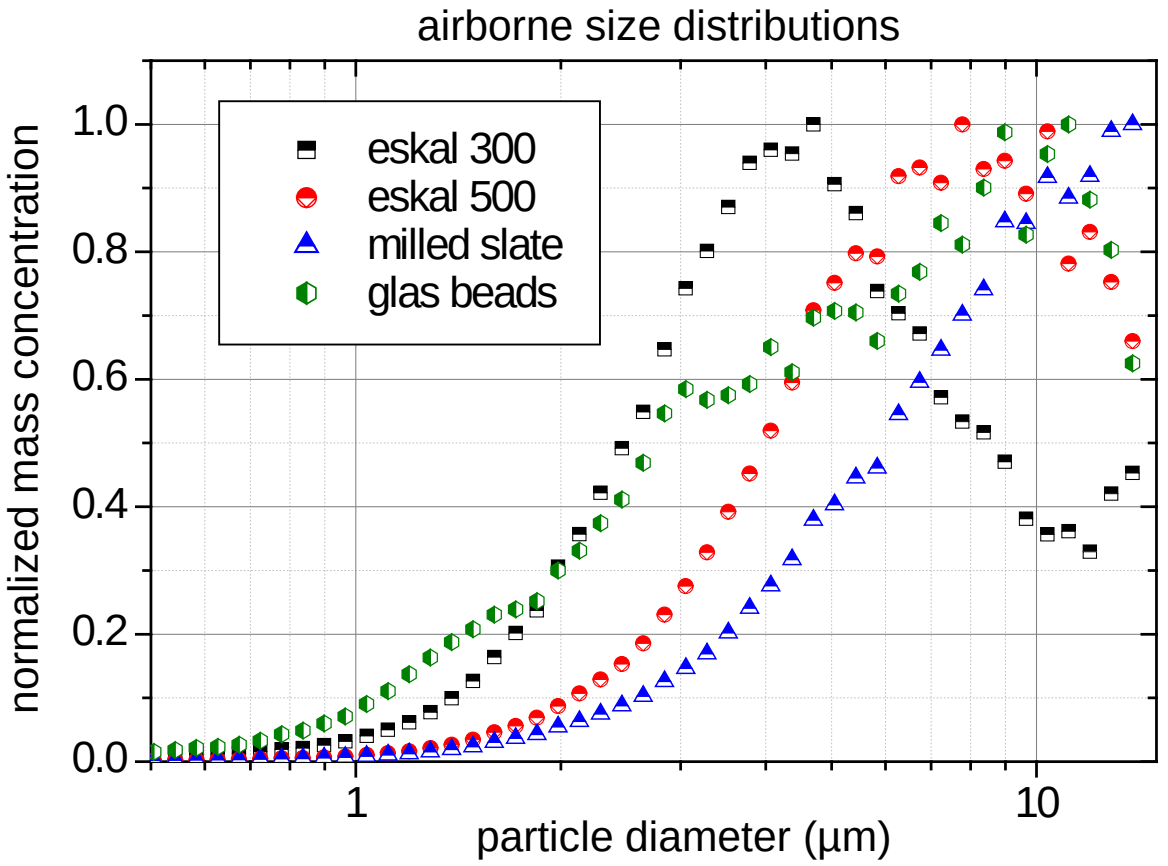




Asbach et al. *Gefahrstoffe – Reinh. Luft* **6** 252 (2018)

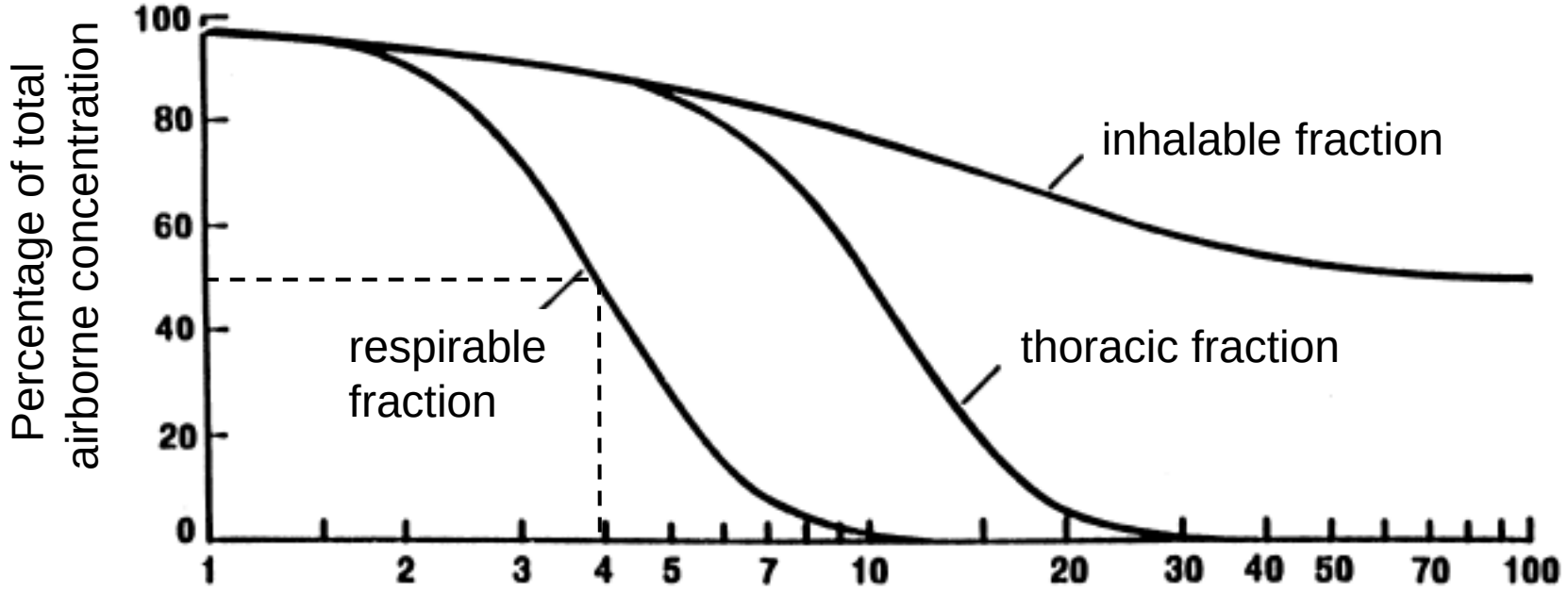
Test aerosols

- investigation of different aerosols
- eskal (KSL Staubtechnik GmbH)
  - $CaCO_3$ (calcite)
  - refractive index and density well known
  - two size distributions (eskal 300 and 500)
  - natural (white) and dyed (red or black)
- milled slate (larger particles)
- glass beads (broad size distribution)



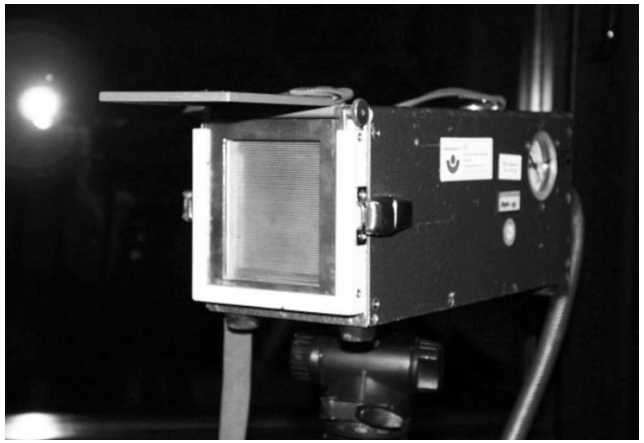
Metric and reference instrument: Respirable dust convention

- for workplaces dust able to penetrate the alveoli regulated (A-Staub, ~ PM_4)



DIN EN 481: 1993

MPG II



M. Mattenklott et al. *Gefahrstoffe – Reinh. Luft* **71** 425 (2011)

- reference sampler MPG II (horizontal sedimentation precipitator)
- mimics respirable convention curve and collects the penetrating dust on a filter
- afterwards gravimetric analysis of the filter samples

Optical instruments used in the study

Spectrometers

Fidas Frog, Palas GmbH
d_{50} = 0.18 µm
PSD, PM_1, $PM_{2.5}$, PM_4, PM_{10}

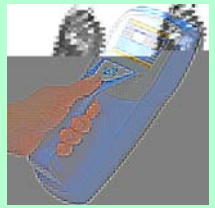
Welas digital 2500, Palas GmbH
d_{50} = 0.3 µm
PSD

OPS model 3330, TSI Inc.
d_{50} = 0.3 µm
PSD

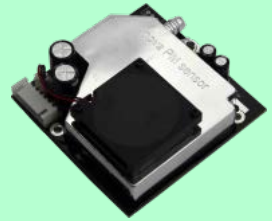
OPC model 1.108, Grimm
d_{50} = 0.3 µm
PSD

Photometers

Dusttrak DRX 8534, TSI Inc.
PM_1, $PM_{2.5}$, resp. dust, PM_{10}



SDS011, Nova Fitness
$PM_{2.5}$, PM_{10}
~15 €

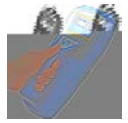


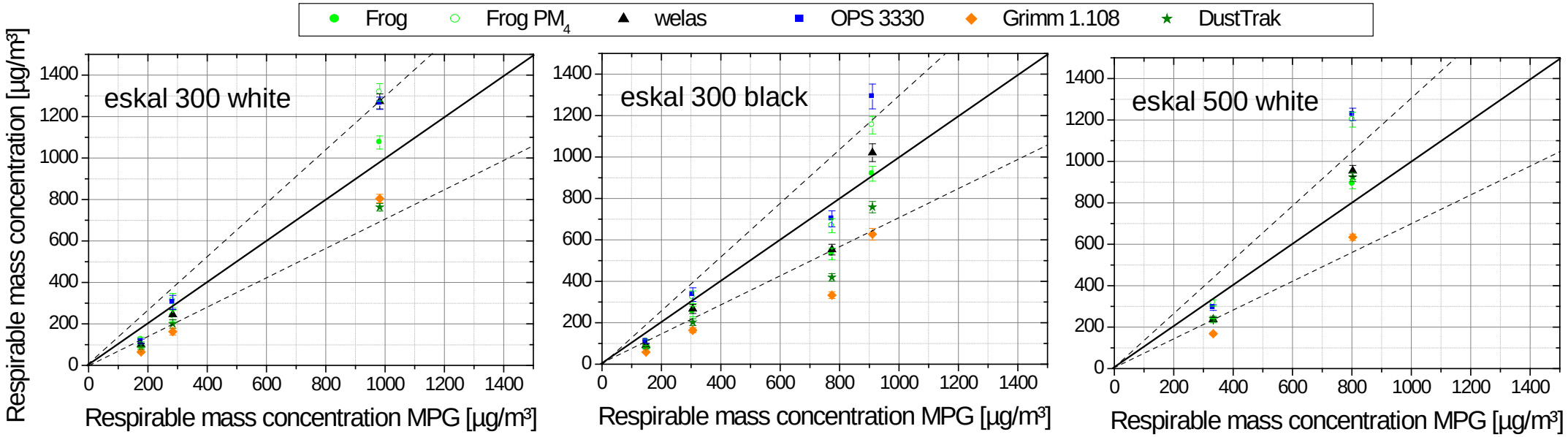
GP2Y1010AU0F, Sharp
voltage output prop. to $PM_{2.5}$
~3 €

Results for scientific instruments



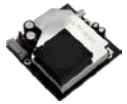


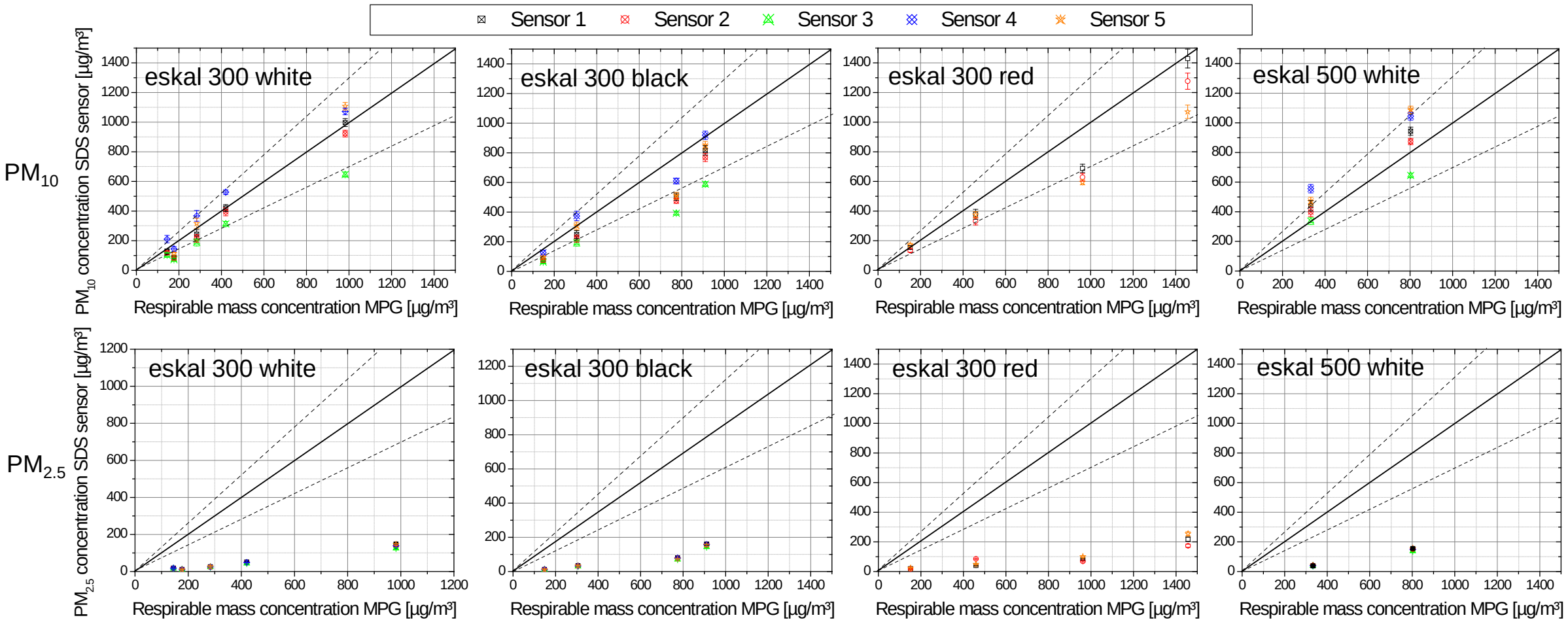




- calculation of PM_4 from number size distribution (using density and efficiency curve)
- in general good linear correlation with MPG II, acceptable accuracy of ± 30%
- no dependence on the particle size distribution (advantage of the spectrometers)
- no large influence of the imaginary part of the refractive index (absorption)

Results for low-cost SDS sensors – $CaCO_3$

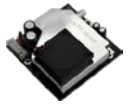


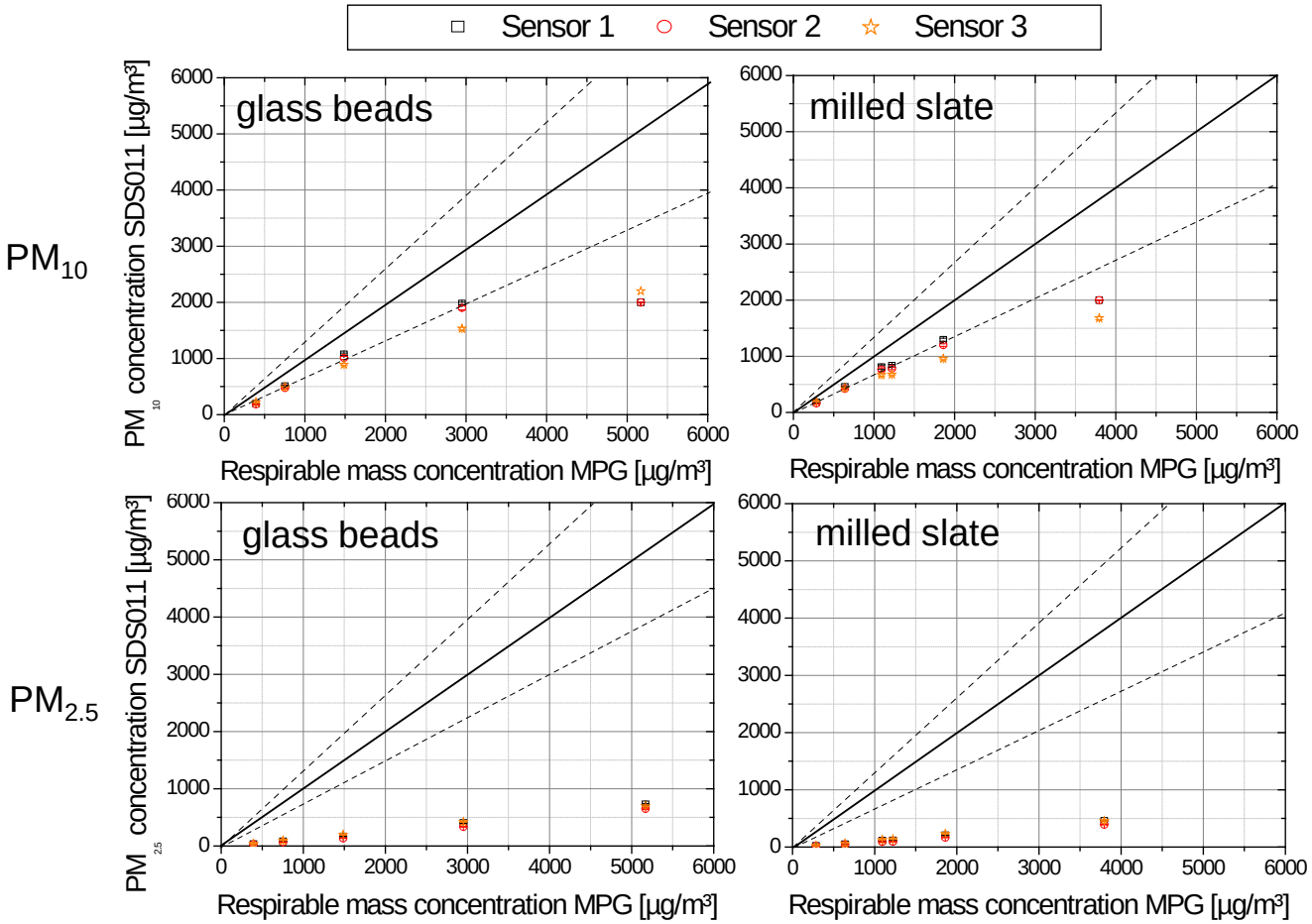


Asbach et al. *Gefahrstoffe – Reinh. Luft* **6** 252 (2018)

- PM_4 cannot be calculated for these sensors, therefore comparison with $PM_{2.5}$ and PM_{10}
- good linear correlation with MPG II, larger scatter for PM_{10}, very small scatter for $PM_{2.5}$

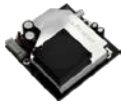
Results for low-cost SDS sensors – glass and slate

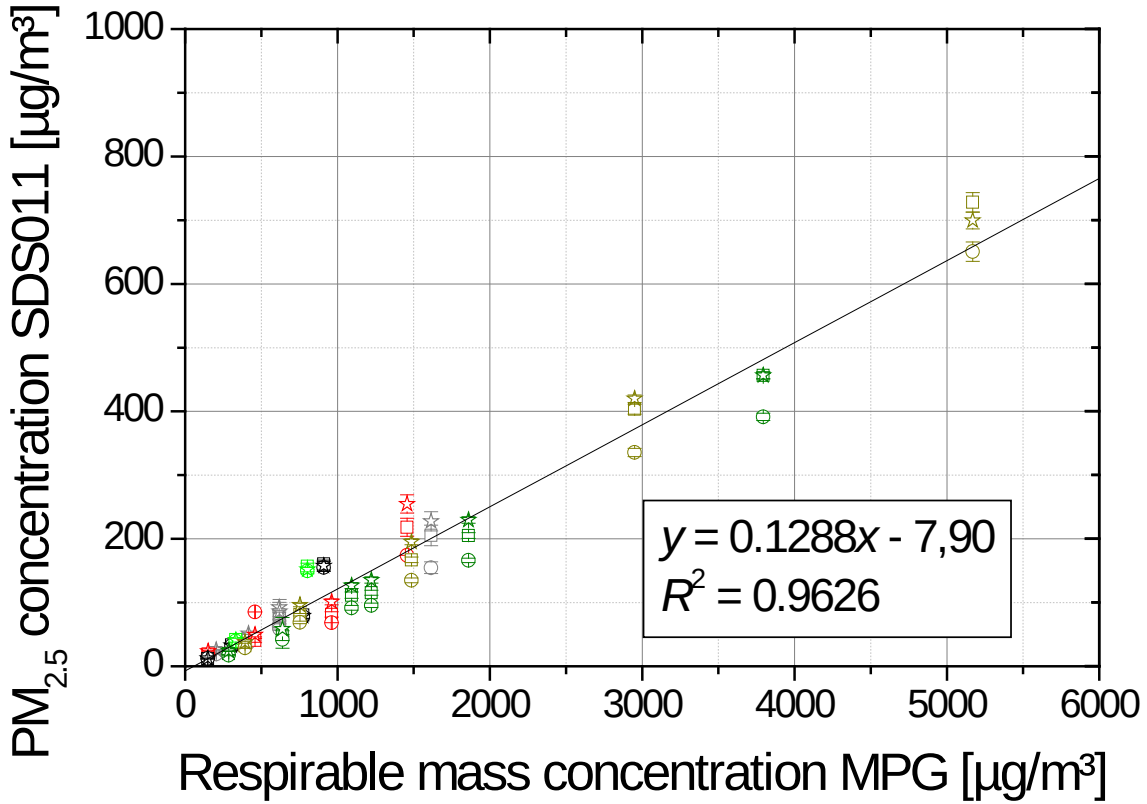


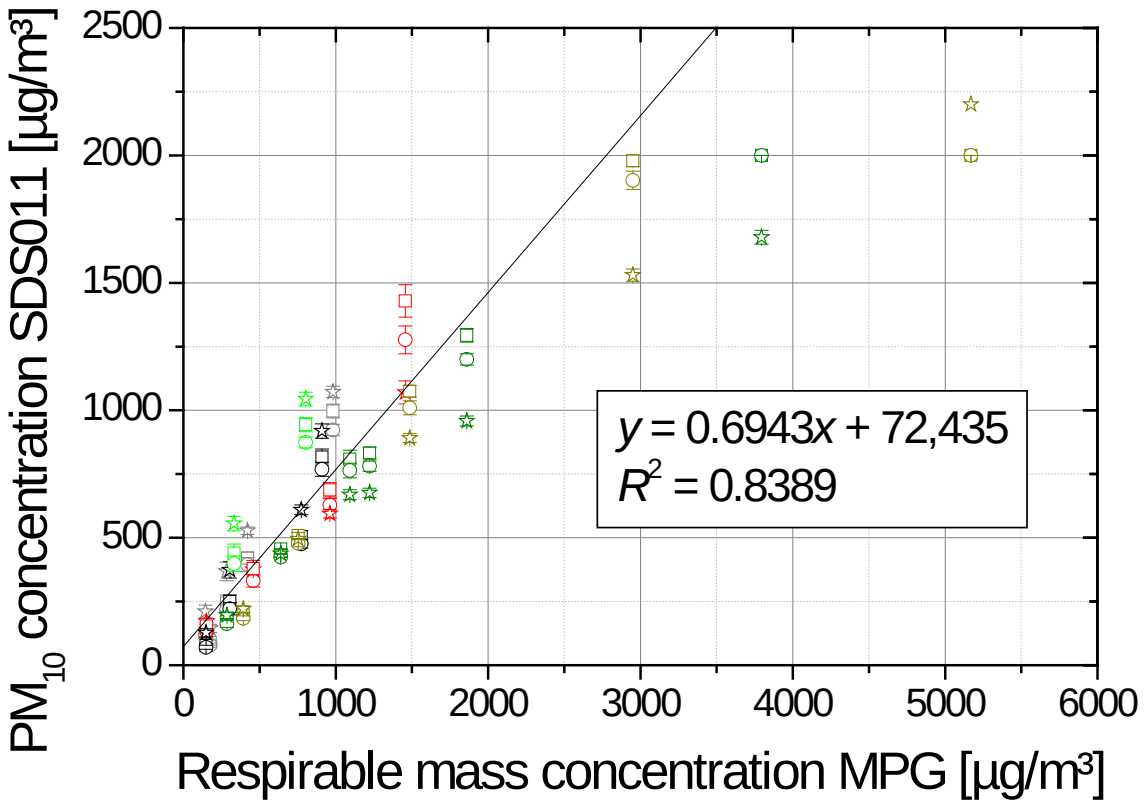


- good linear correlation with MPG II and small scatter for $PM_{2.5}$
- for PM_{10} saturation effects at high concentrations

Summary of the SDS results for all test powders





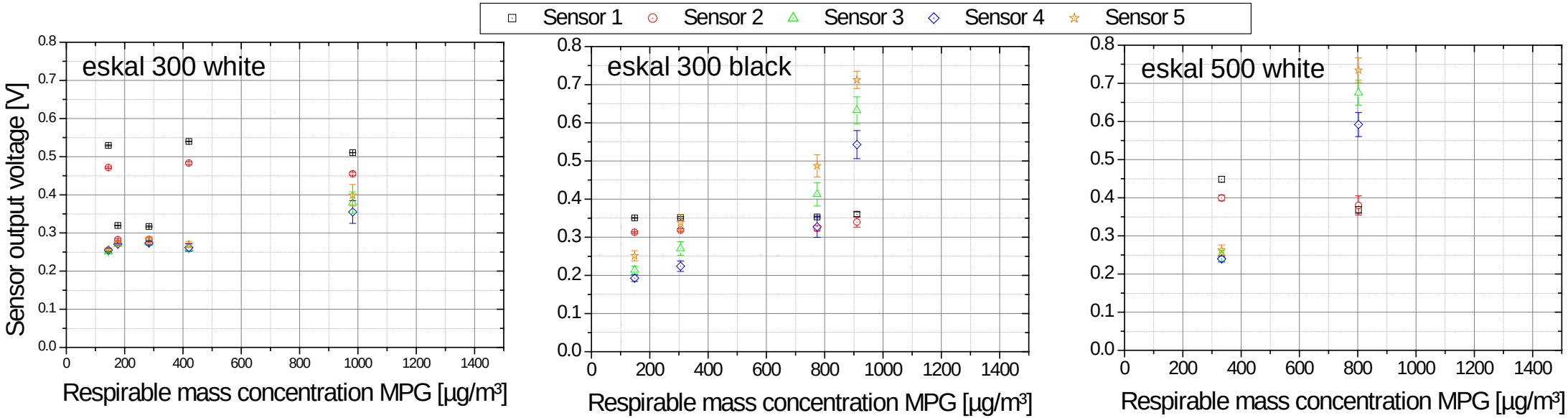


- good correlation for PM_{10} up to 2 mg/m³, saturation for higher values
- excellent linear correlation for $PM_{2.5}$ up to 5 mg/m³
- sensors could be calibrated to show PM_4 values

  → further investigations to understand this surprising result

	Sensor 1	Sensor 2	Sensor 3
eskal 300	□	○	☆
eskal red	□	○	☆
eskal black	□	○	☆
eskal 500	□	○	☆
glass beads	□	○	☆
milled slate	□	○	☆

Can we go even cheaper? – Tests with the Sharp sensor



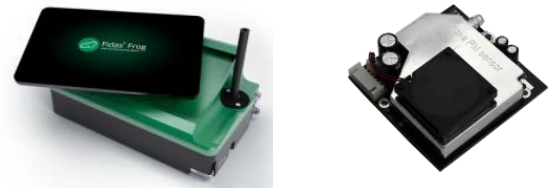
- high scatter between individual sensors
- response only to comparably high concentrations

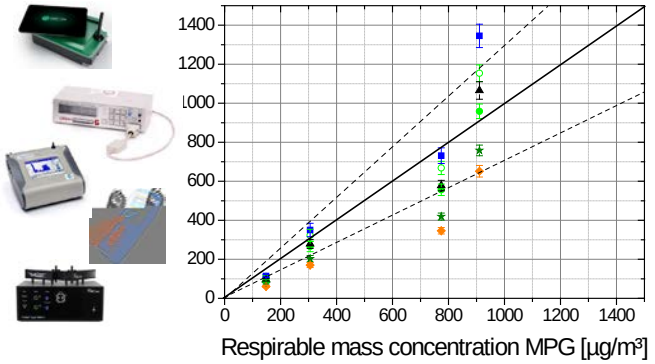
  → not applicable for workplace exposure measurements

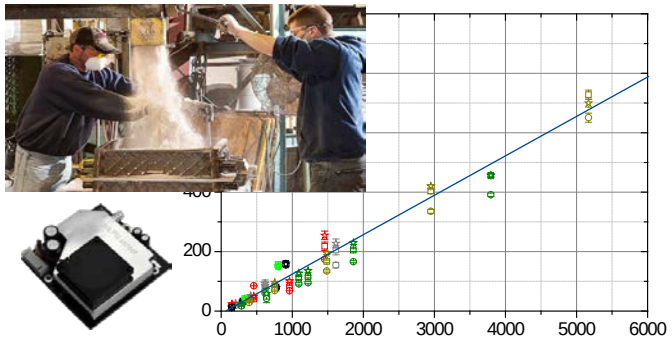
Summary

- optical particle spectrometers and photometers offer an alternative to gravimetric dust measurements
- low-cost sensors for high spatial and temporal resolution networks
- ambient measurements may be influenced by high relative humidity

  → applicability for workplace exposure measurements investigated
- for $CaCO_3$ aerosols, all scientific grade instruments agreed within ±30% with the reference instrument (MPG II)
- no major influence of particle sizes and color (refractive index)
- SDS sensor showed very repeatable results for $PM_{2.5}$
  → calibration for PM_4 seems possible
- Sharp sensor only applicable for rather high concentrations
- future measurements will include further particle sizes, shapes and refractive indices (materials)







Acknwoledgement

Further information in Asbach et al. *Gefahrstoffe – Reinh. Luft* **6** 252 (2018)

Thank you for your attention