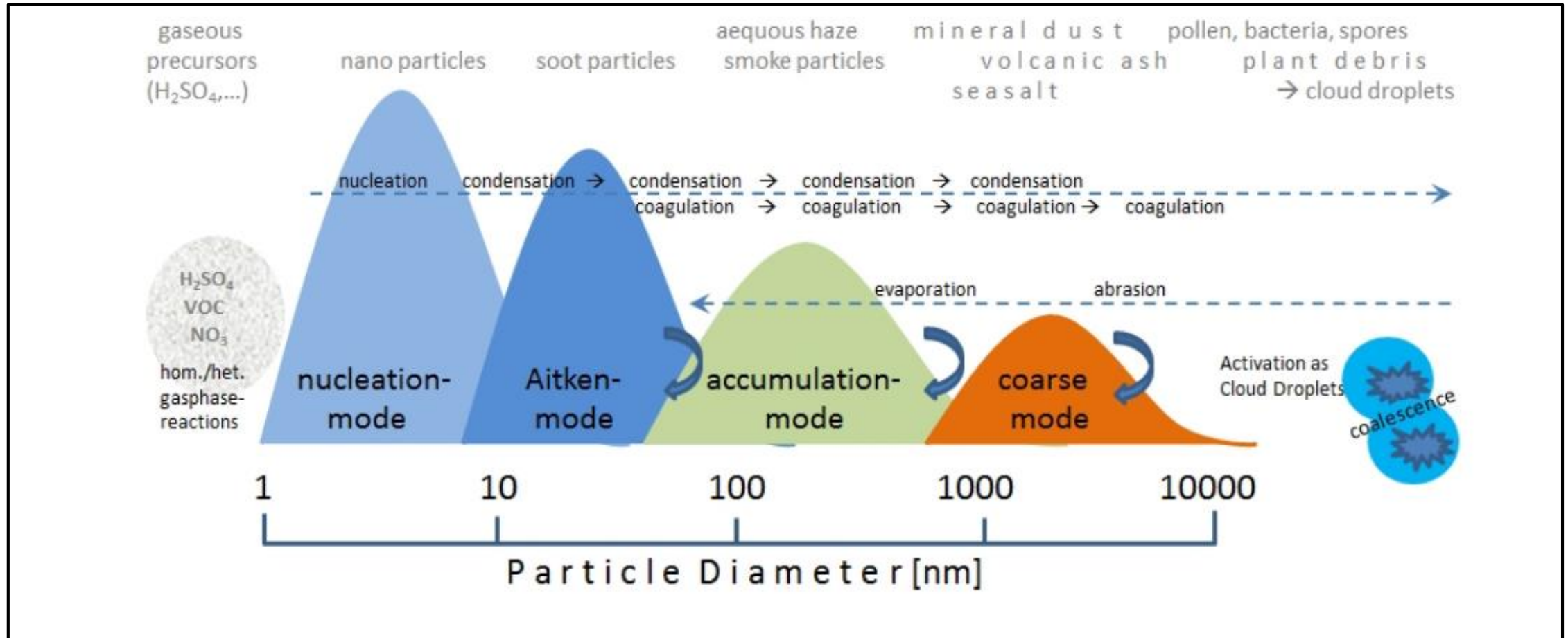


Ultrafine particles and $PM_{2.5}$ – are they representative of each other?

Dr. Josef Cyrys, Alexandra Schneider, Regina Pickford, Kathrin Wolf and Annette Peters

Helmholtz Munich - Institut für Epidemiologie

Size-fractions of airborne particles

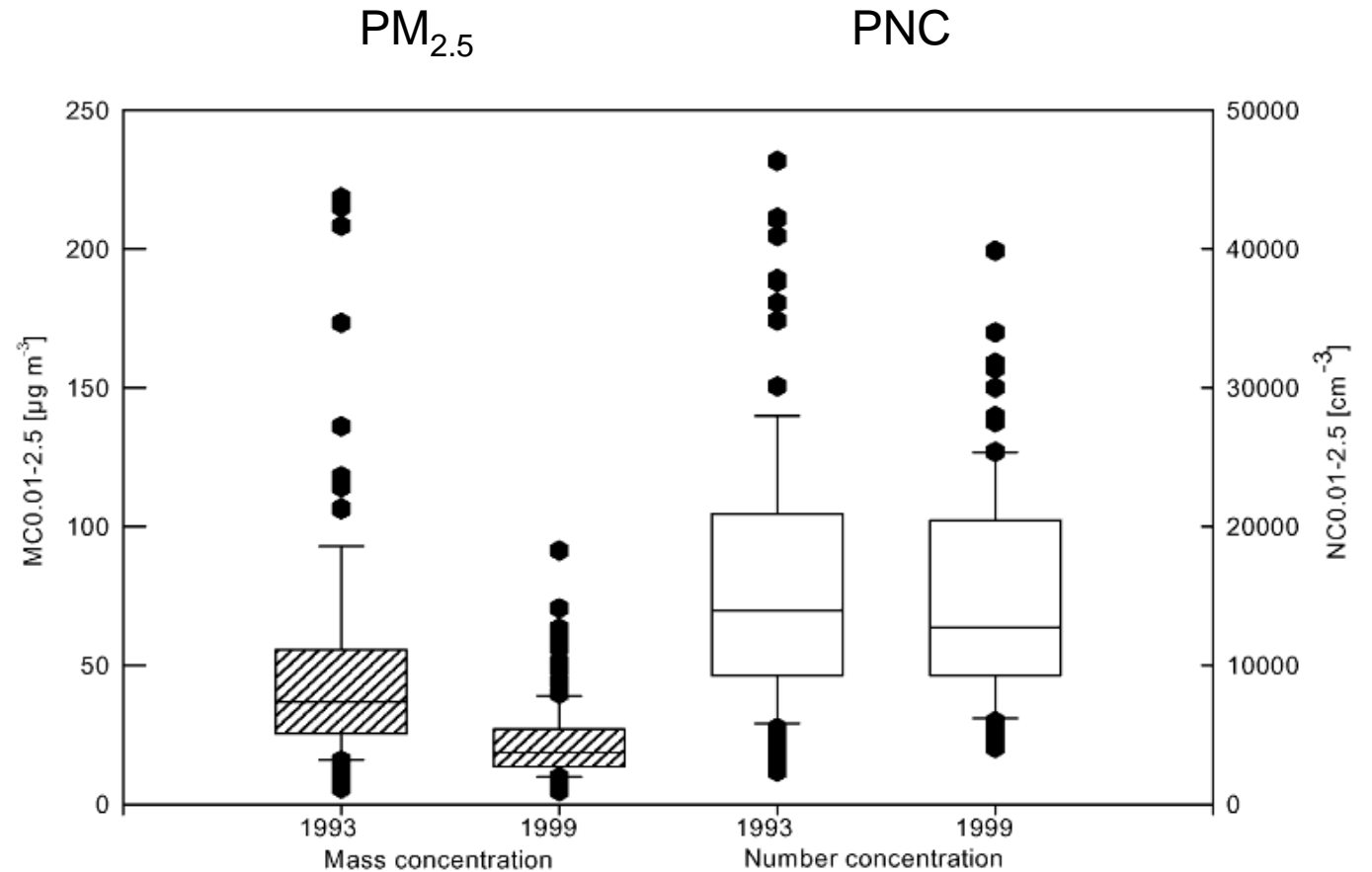


↳ Exposure to UFP (particle number concentration) in ambient air compared to PM_{2.5} (mass concentration)

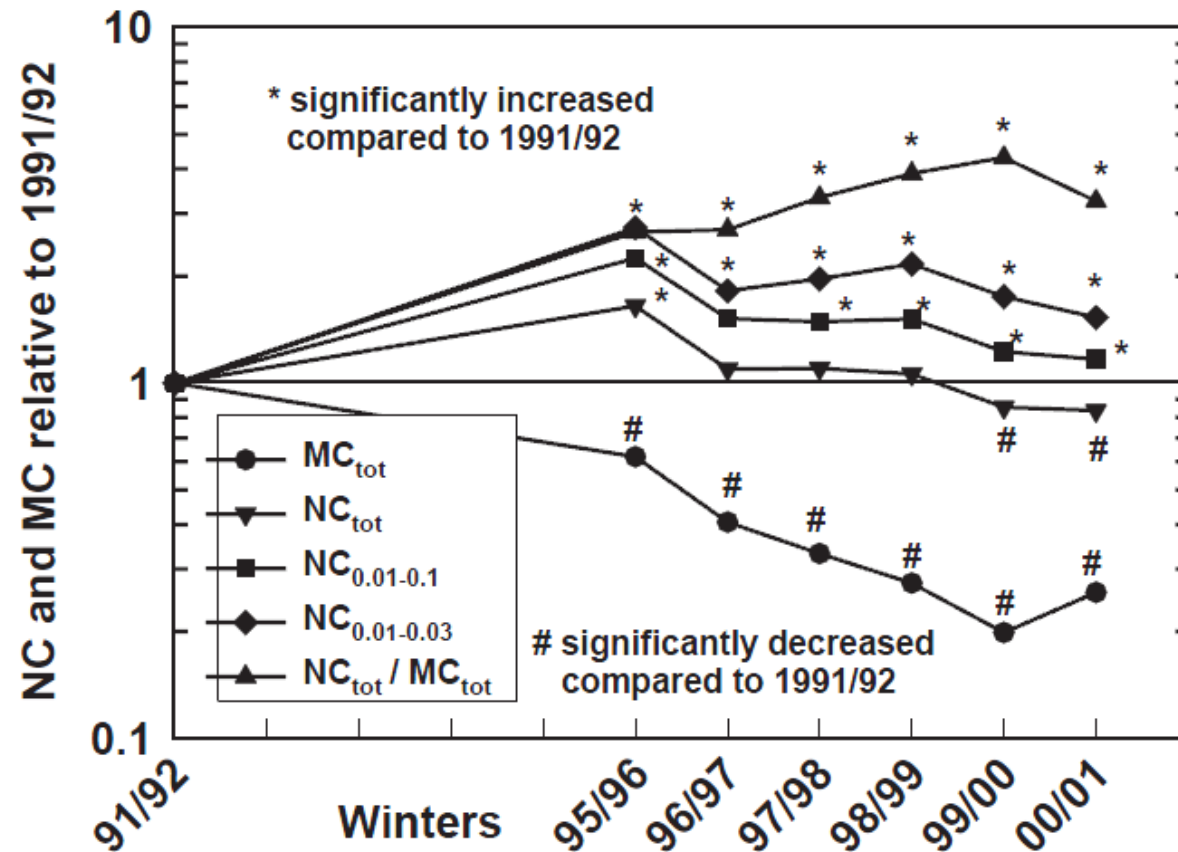
Different temporal trends of UFP and PM_{2.5} in the ambient air (East Germany in the 1990s)



Fig. 1. A map of Germany with the study area (Hettstedt, Bitterfeld and Zerbst).



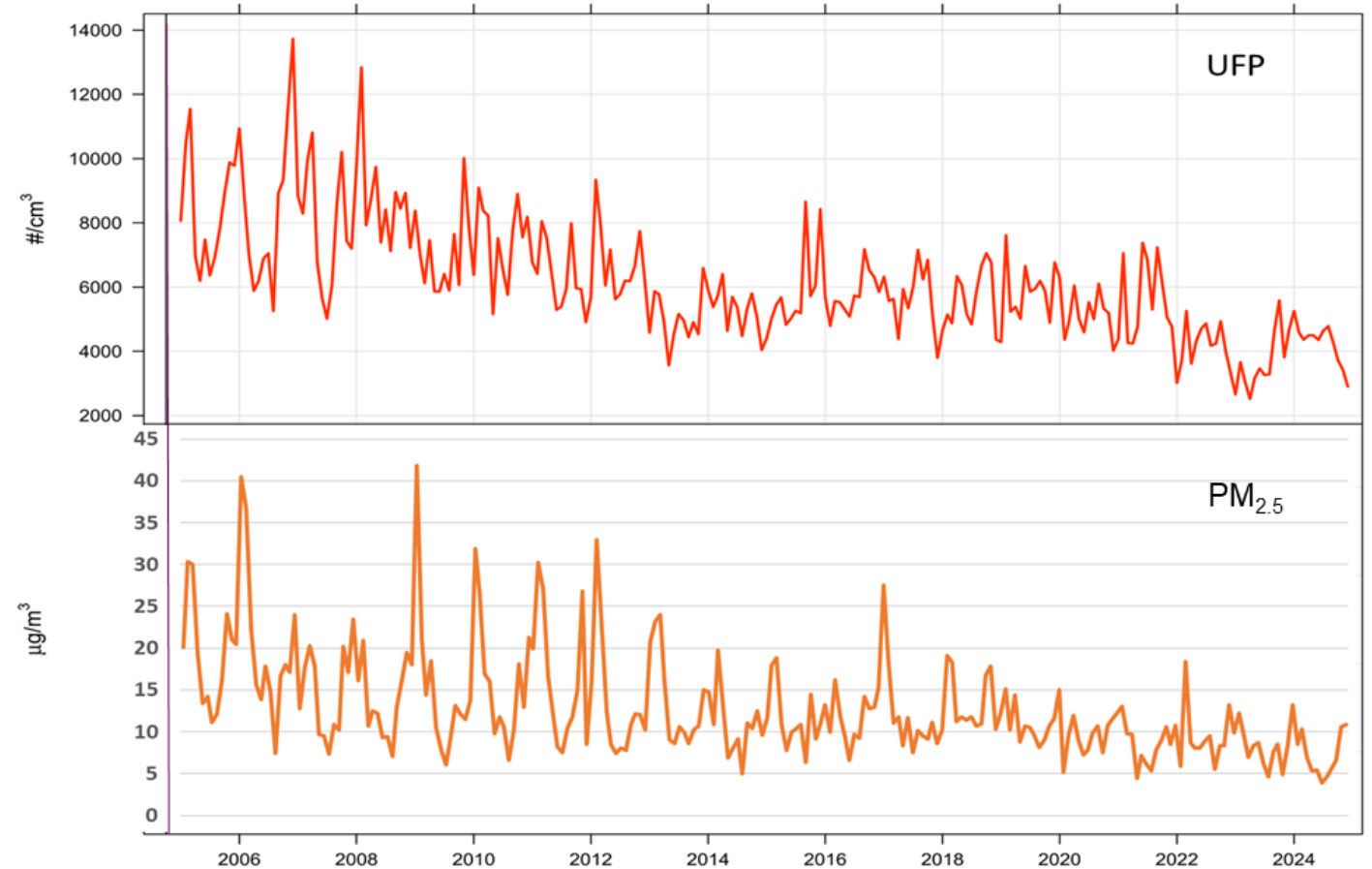
Different temporal trends of UFP and PM_{2.5} in the ambient air (East Germany in the 1990s)



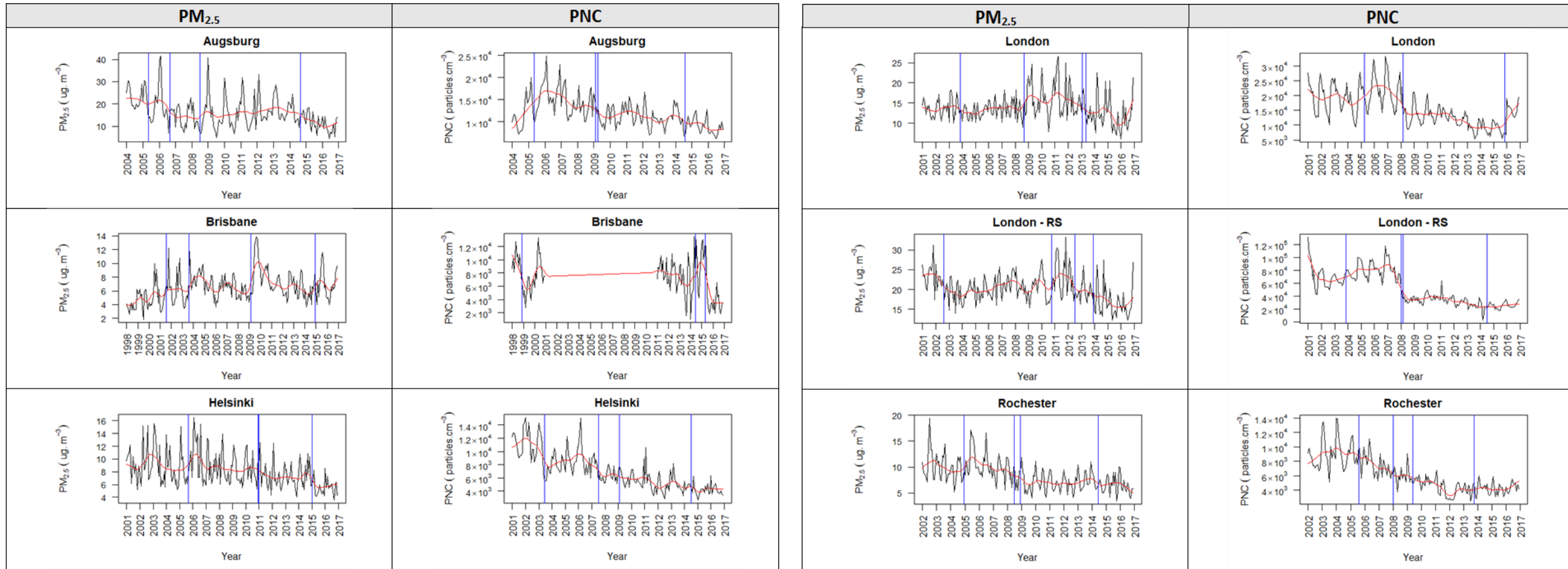
Temporal trends of UFP and PM_{2.5} in the ambient air: Augsburg 2005 - 2025



Aerosol measurement station Augsburg



Long term trends in PM_{2.5} and PNC in five cities around the world



Long term trends in PM_{2.5} and PNC in five cities around the world

The long-term trends in PM_{2.5} and PNC in five cities were assessed with regard to the changing climates and regulatory policies

This study has clearly shown that PM_{2.5} and PNC were influenced differently by the impacts of the changing climate and by the mitigation measures

The planning and implementing of urban air quality management will be more effective and efficient if both PM_{2.5} and PNC are considered

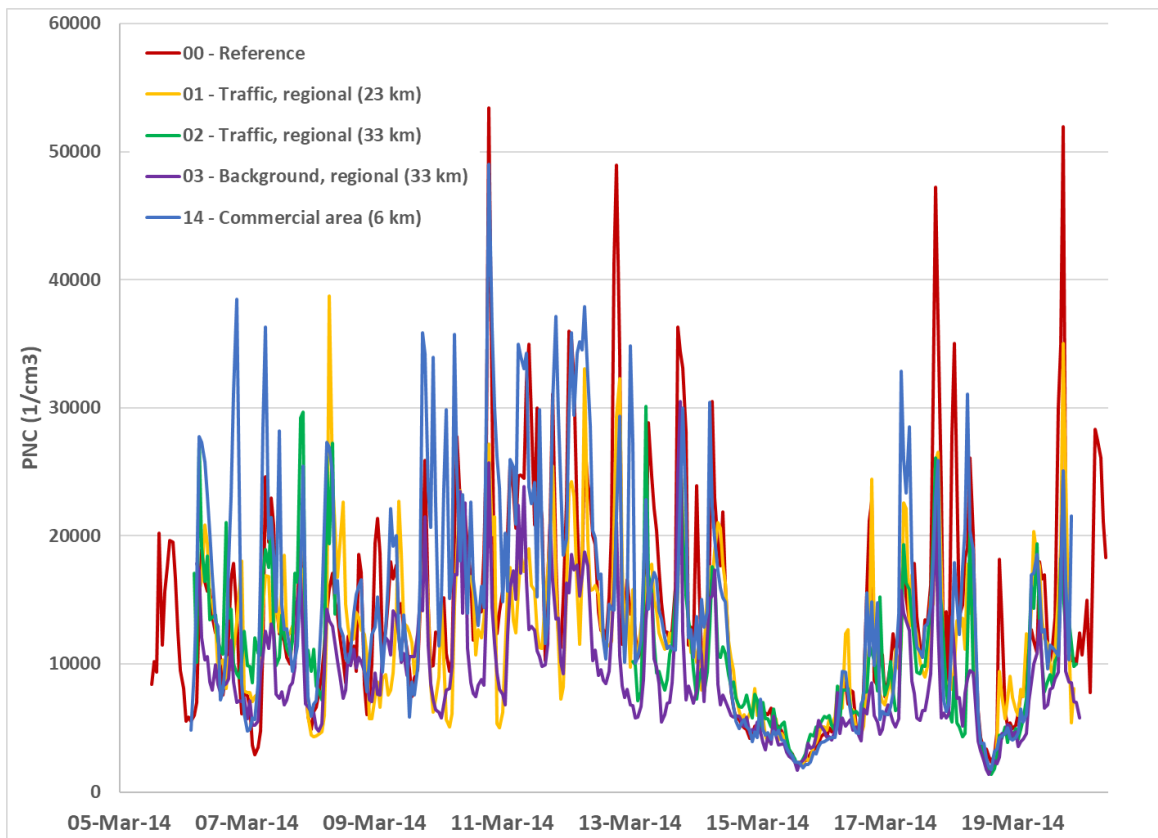
A separate regulatory standard for particulate mass and number would be a positive step in abating negative health and environment effects



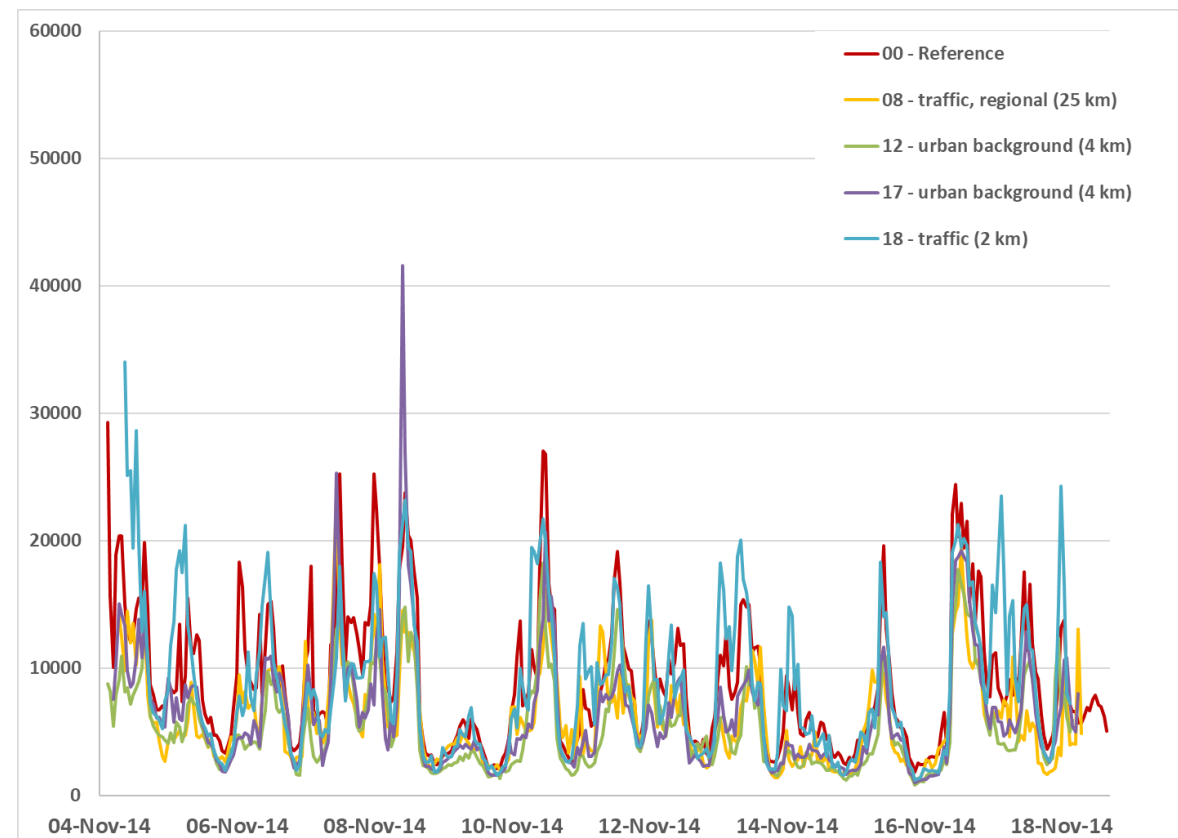
Long-term trends in PM_{2.5} mass and particle number concentrations in urban air: The impacts of mitigation measures and extreme events due to changing climates

Alma Lorelei de Jesus ^{a,1}, Helen Thompson ^b, Luke D. Knibbs ^c, Michal Kowalski ^d, Josef Cyrus ^d, Jarkko V. Niemi ^e, Anu Kousa ^e, Hilkka Timonen ^f, Krista Luoma ^g, Tuukka Petäjä ^g, David Beddows ^h, Roy M. Harrison ^{i,2}, Philip Hopke ^{j,3}, Lidia Morawska ^{a,*}

ULTRA3 study: Strong temporal correlation between the sites

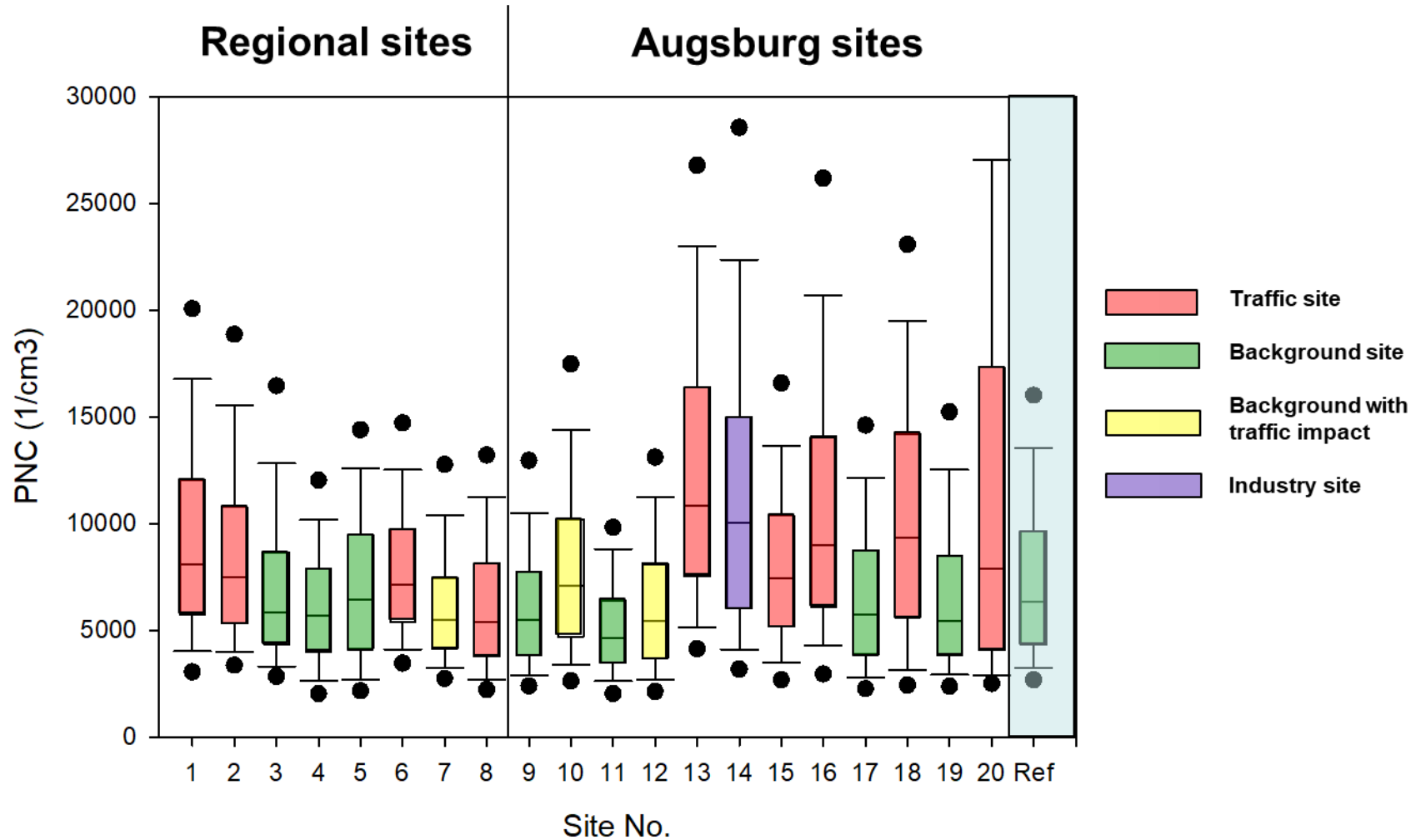


Reference vs.	01 - Traffic, regional	02 - Traffic, regional	03 - Background, regional	14 - Commercial area
Pearson r	0.78	0.74	0.75	0.75

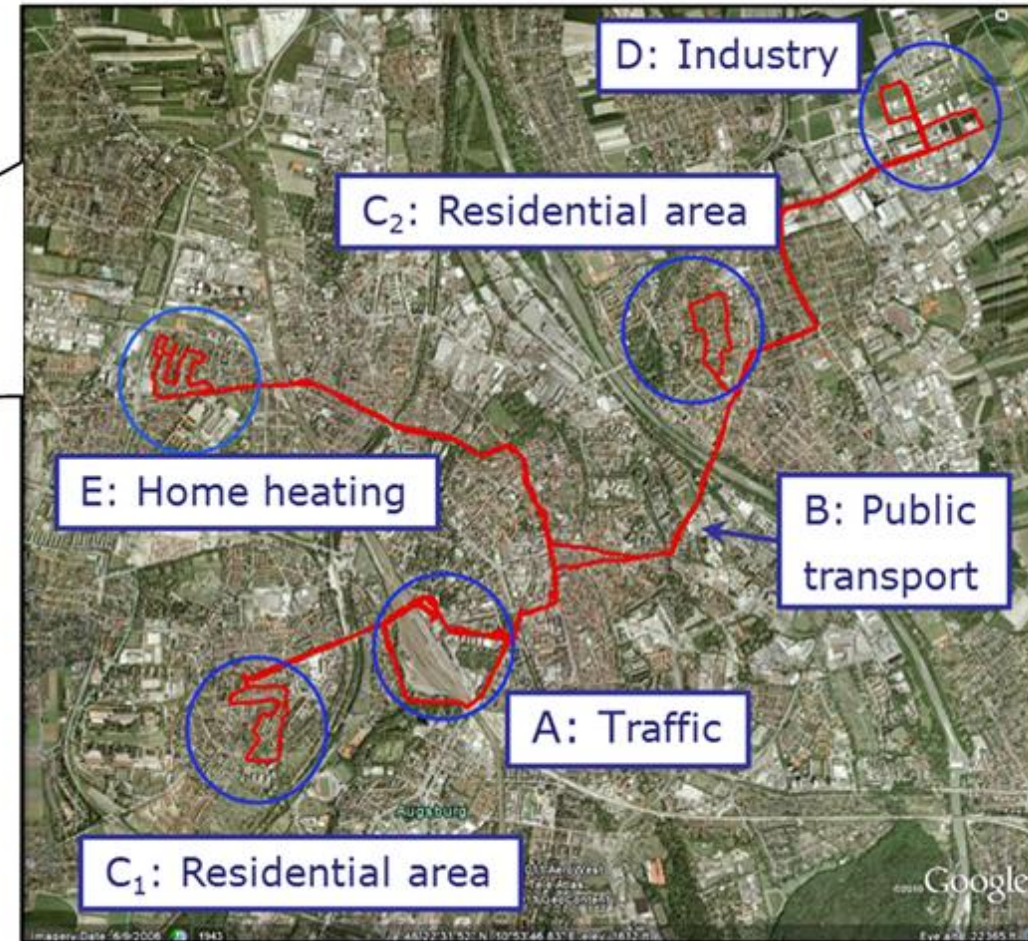


Reference vs.	08 - Traffic, regional	12 - urban background	17 - urban background	18 - traffic
Pearson r	0.79	0.91	0.90	0.83

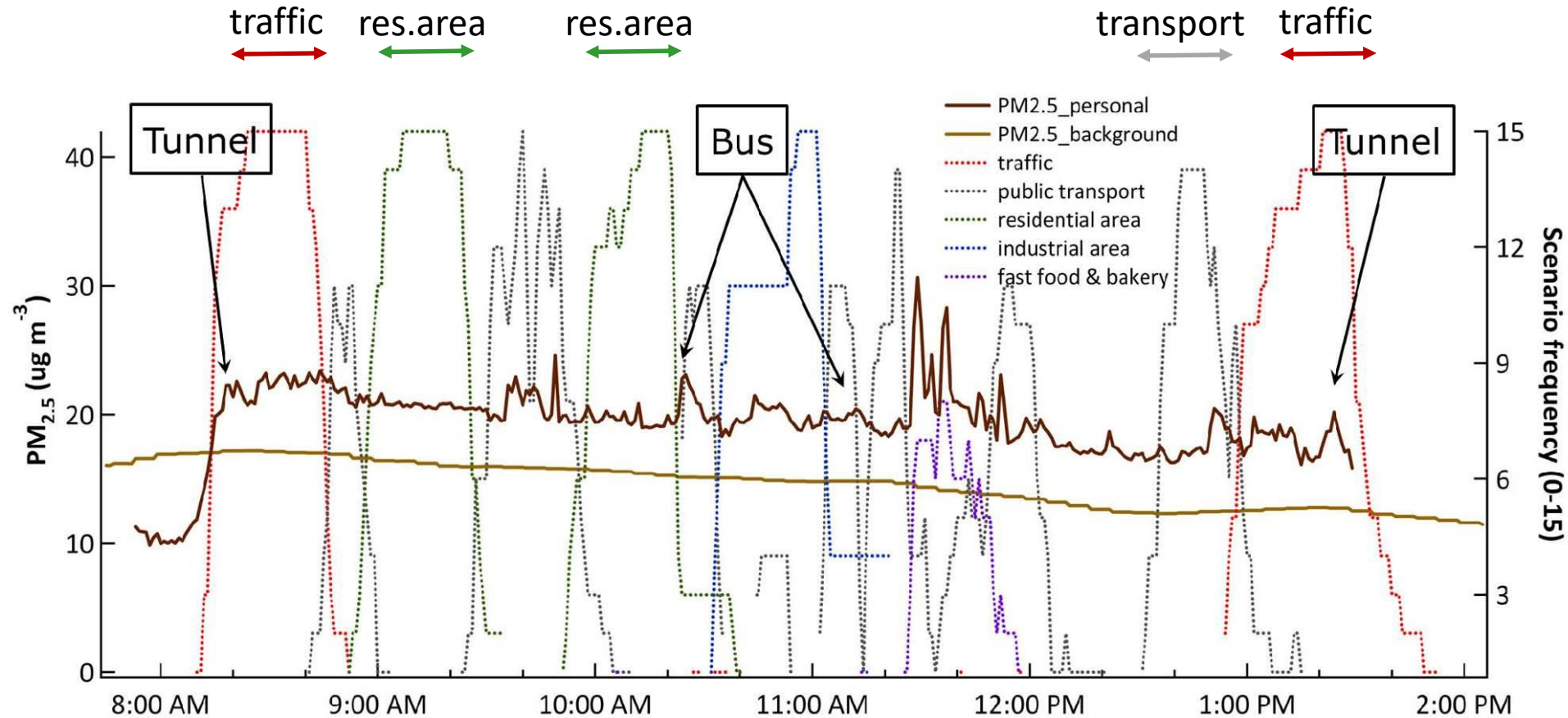
ULTRA3 study: Large spatial variability in the urban area of Augsburg and region of Augsburg



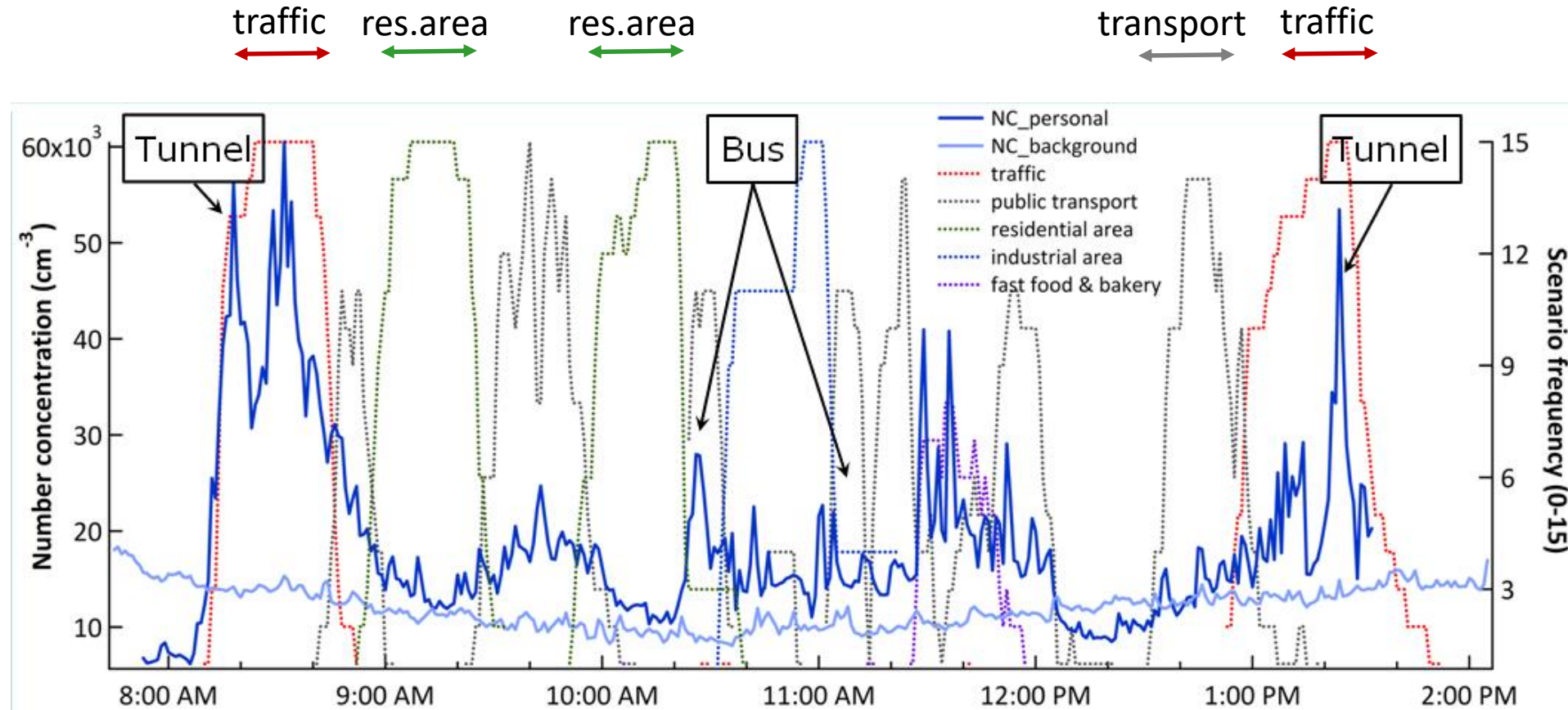
Personal exposure to UFP and PM_{2.5} in different microenvironments



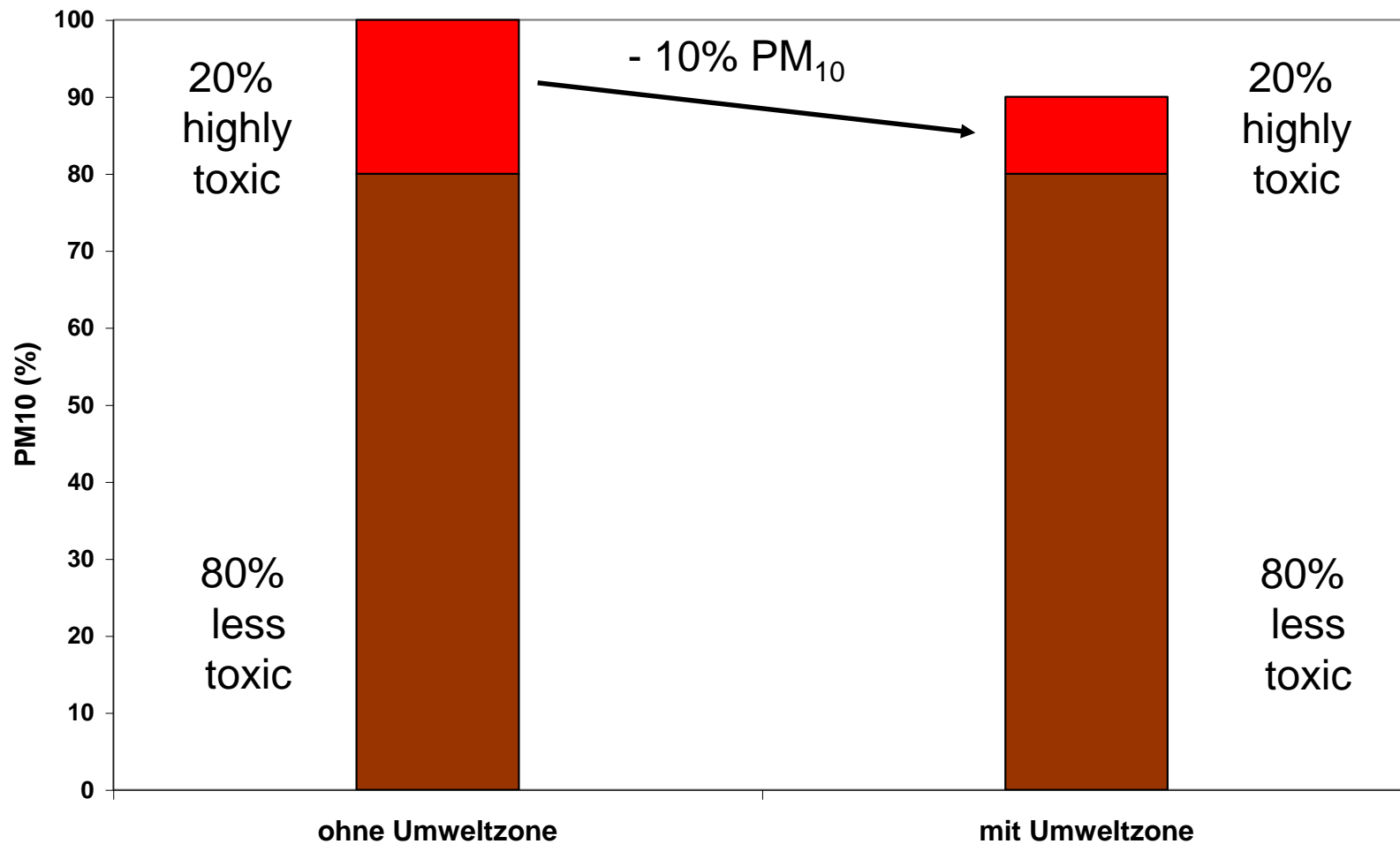
Temporal and spatial variation of personal PM_{2.5} (averaged for spring)



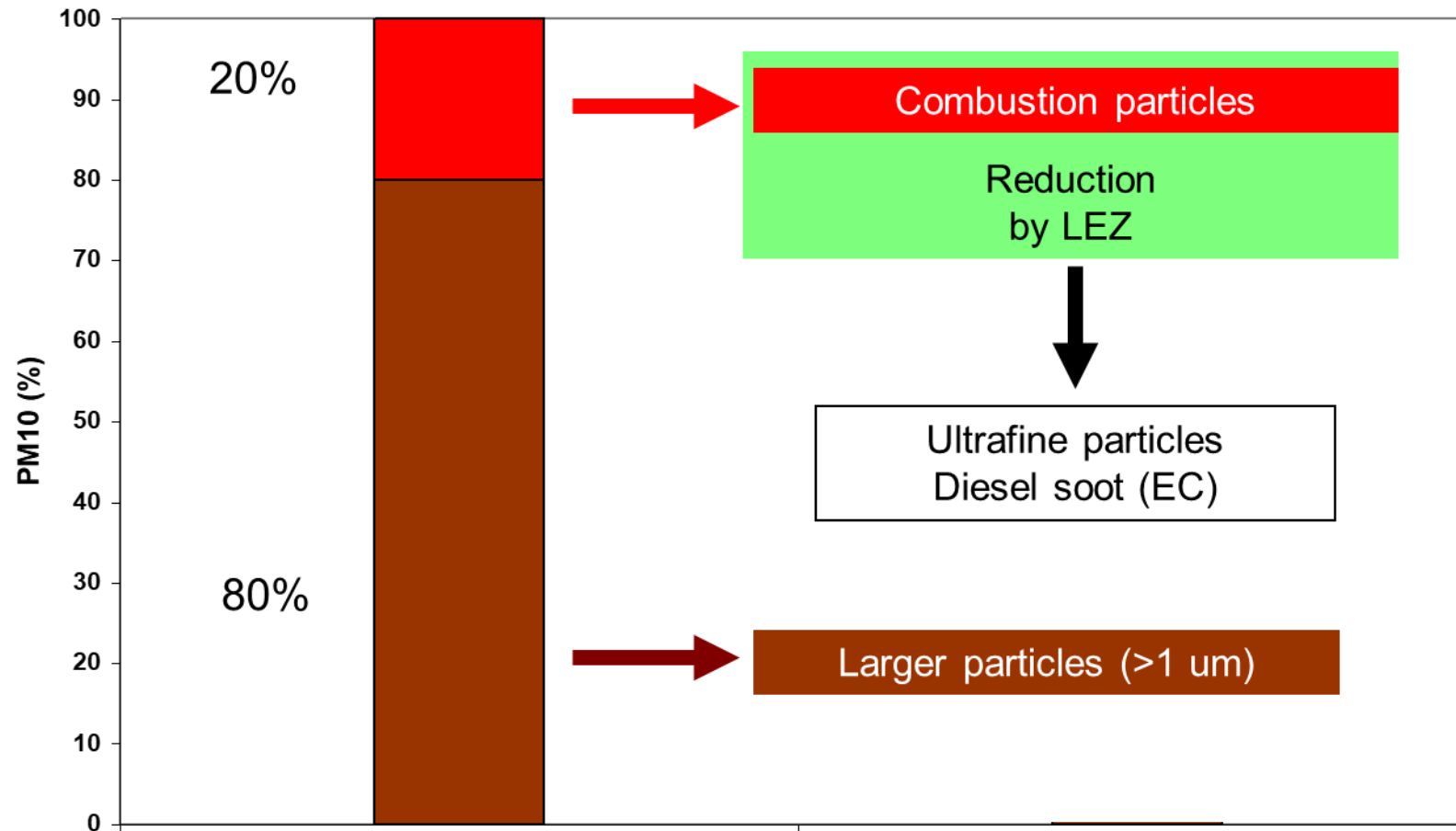
Temporal and spatial variation of personal PNC (averaged for spring)



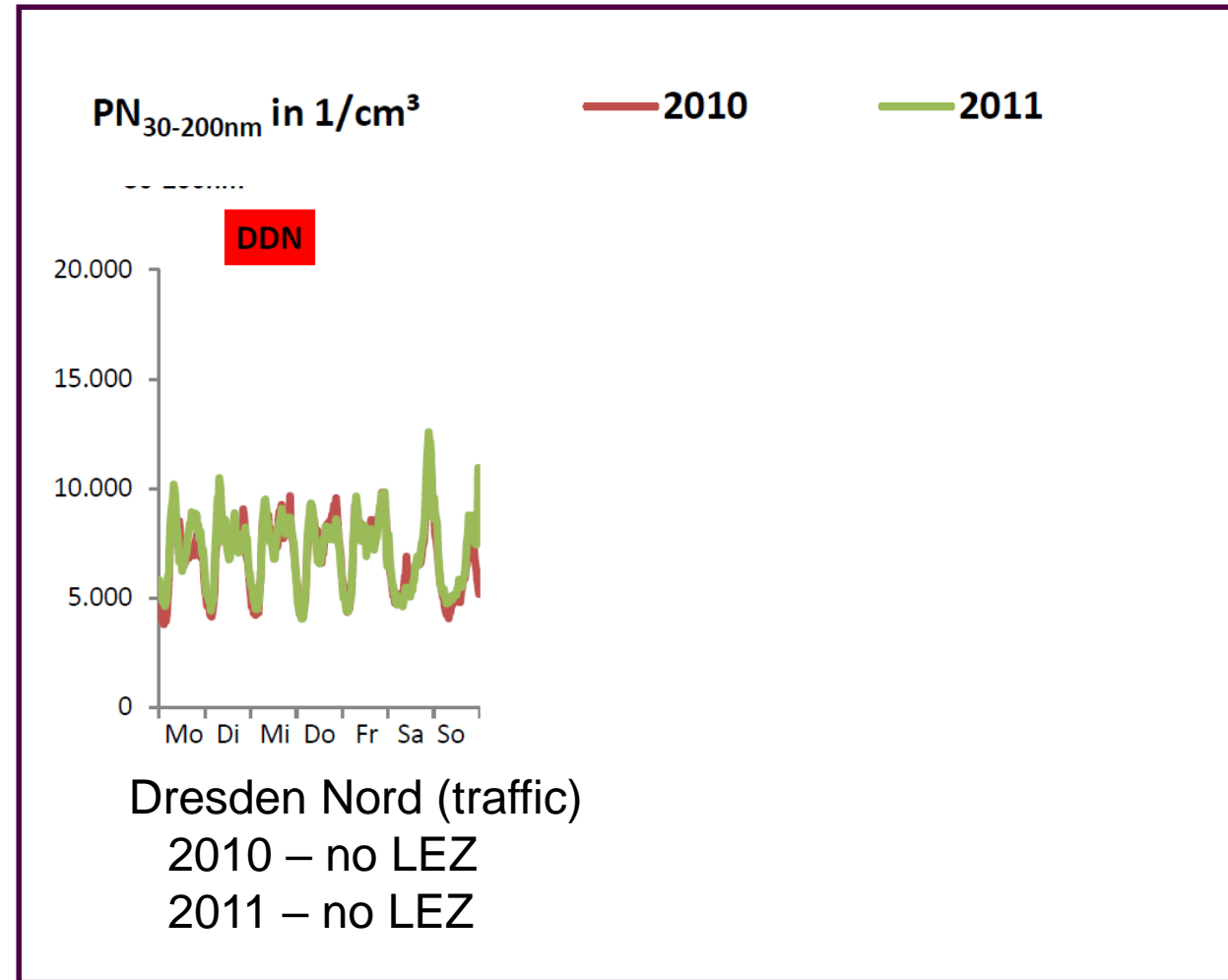
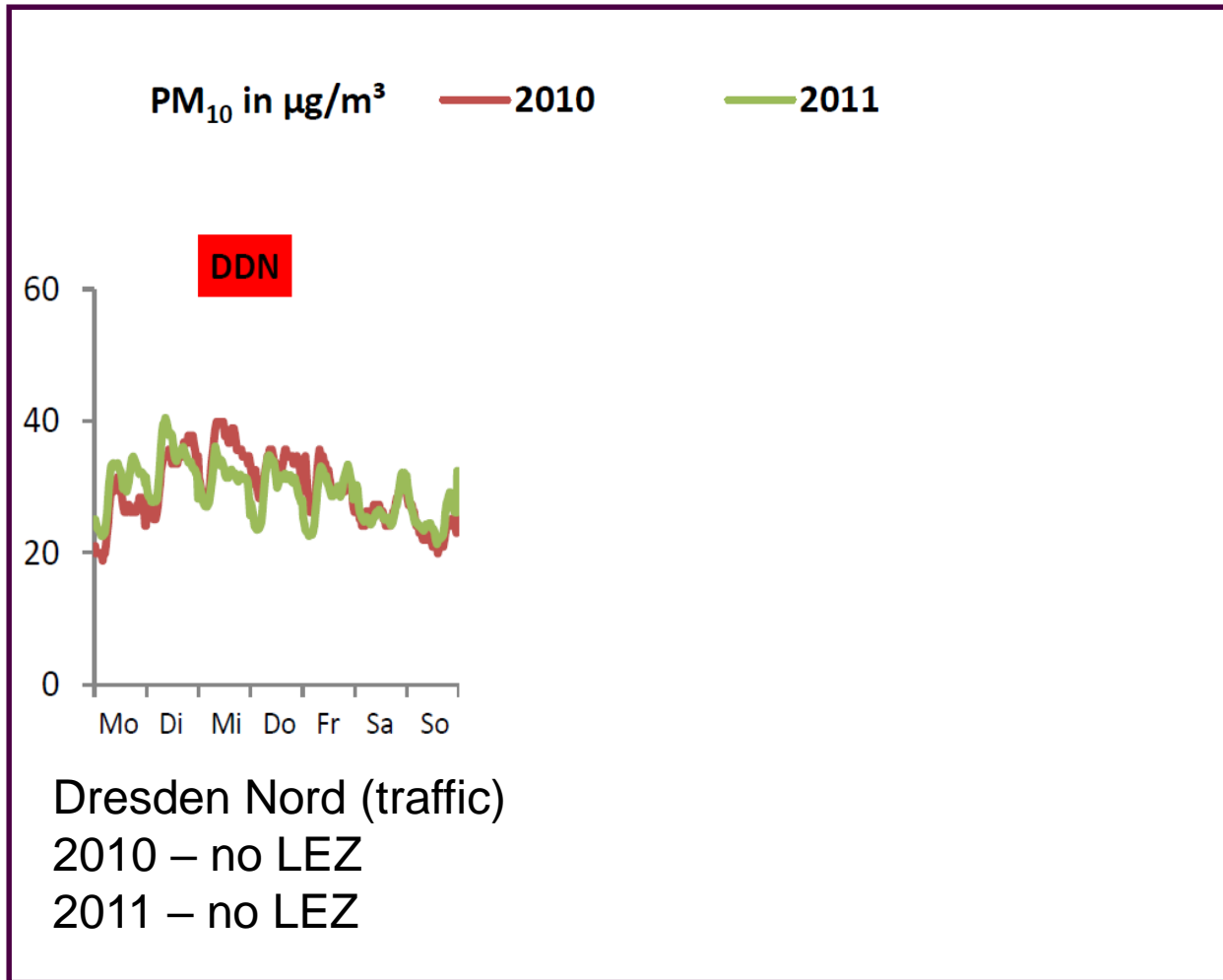
A reduction of PM₁₀ by 10% results in a 50% reduction of combustion-related PM fraction



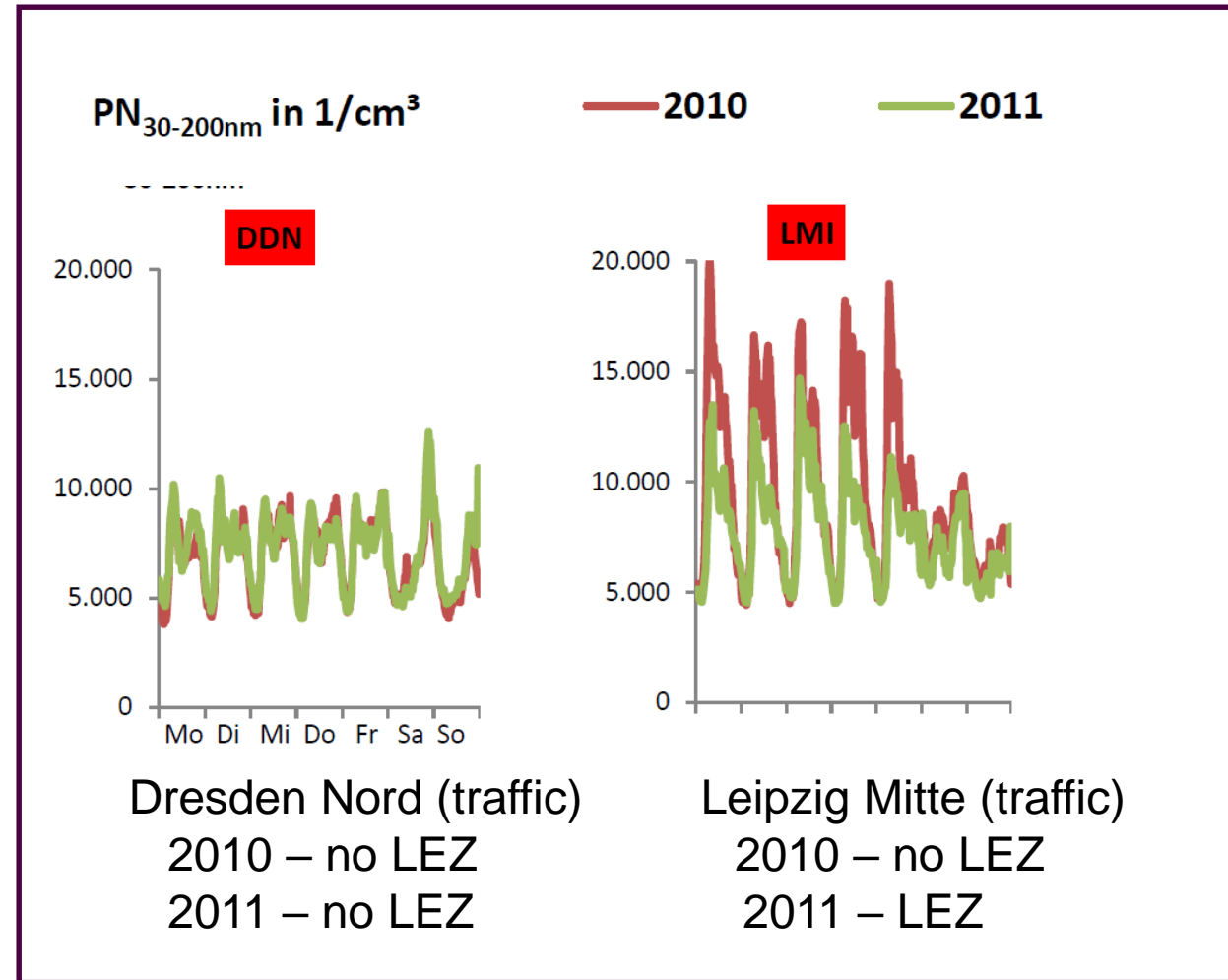
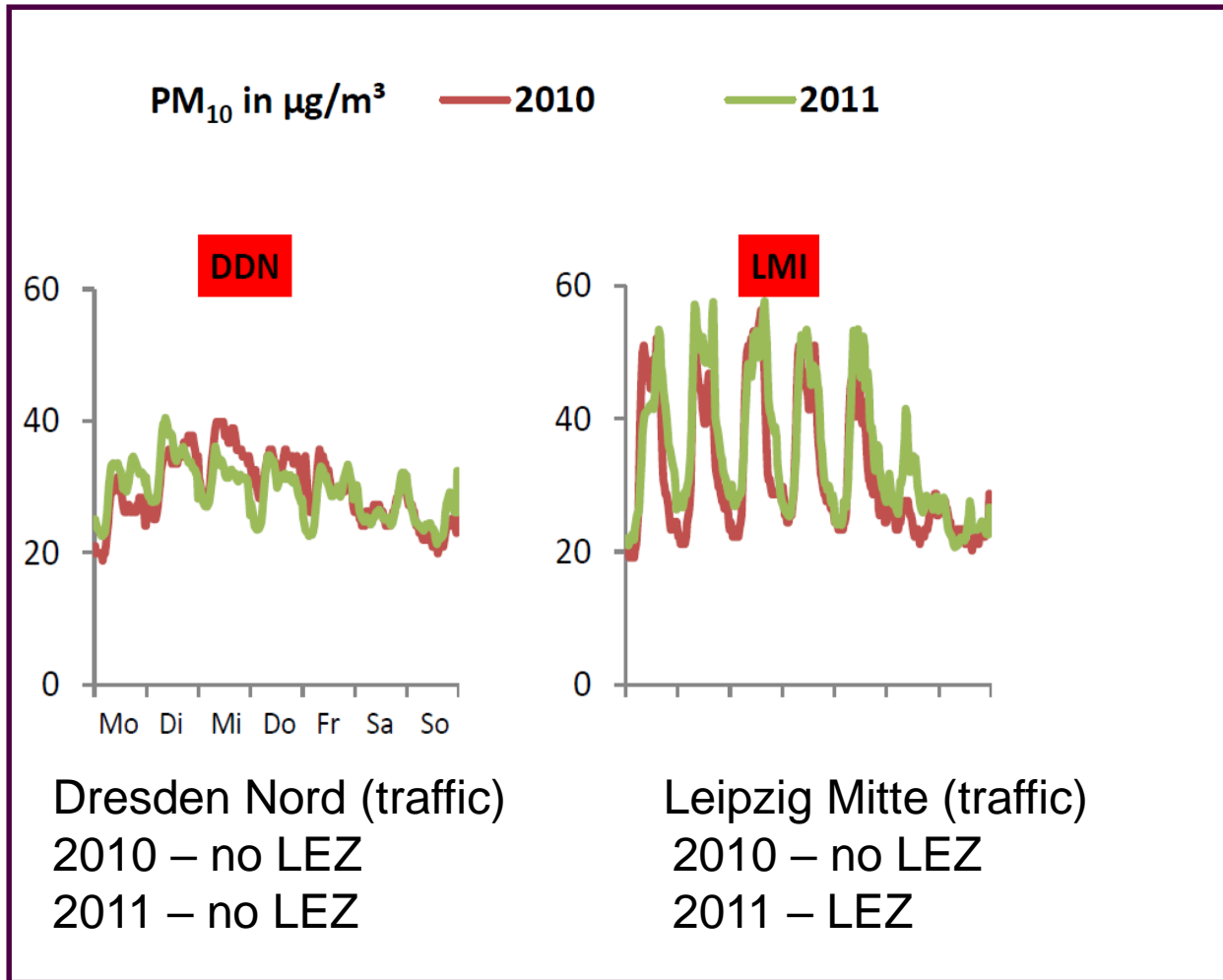
Hypothetical impact of the LEZs assuming that combustion related particles comprise 20% of the PM₁₀ fine particles



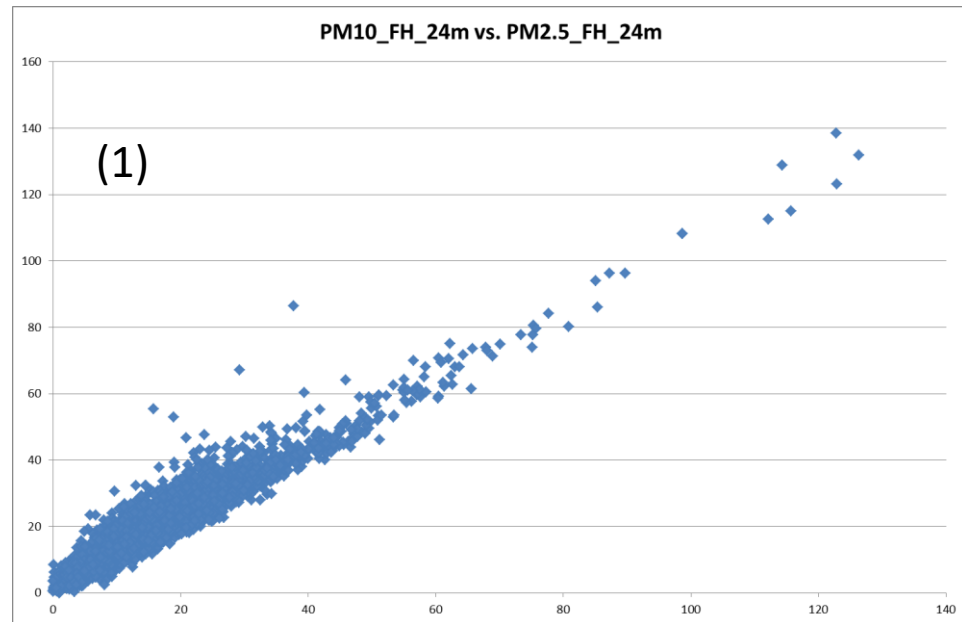
UFP is a better indicator of traffic related air pollutants compared to $PM_{2.5}$: Low Emission Zone in Leipzig



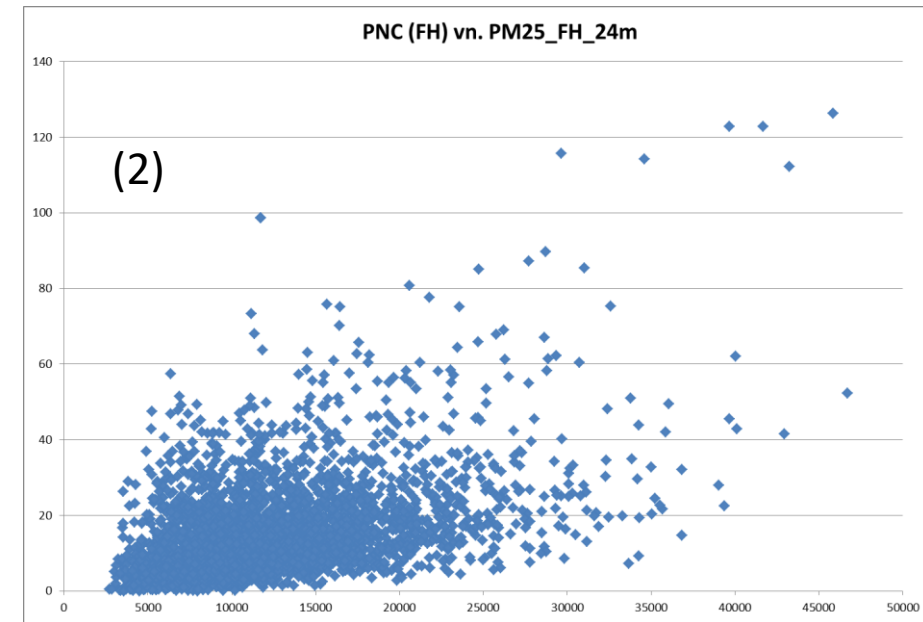
UFP is a better indicator of traffic related air pollutants compared to PM_{2.5}: Low Emission Zone in Leipzig



Temporal correlation between (1) PM_{10} - $PM_{2.5}$ and (2) UFP - $PM_{2.5}$ (hourly means, 2015)

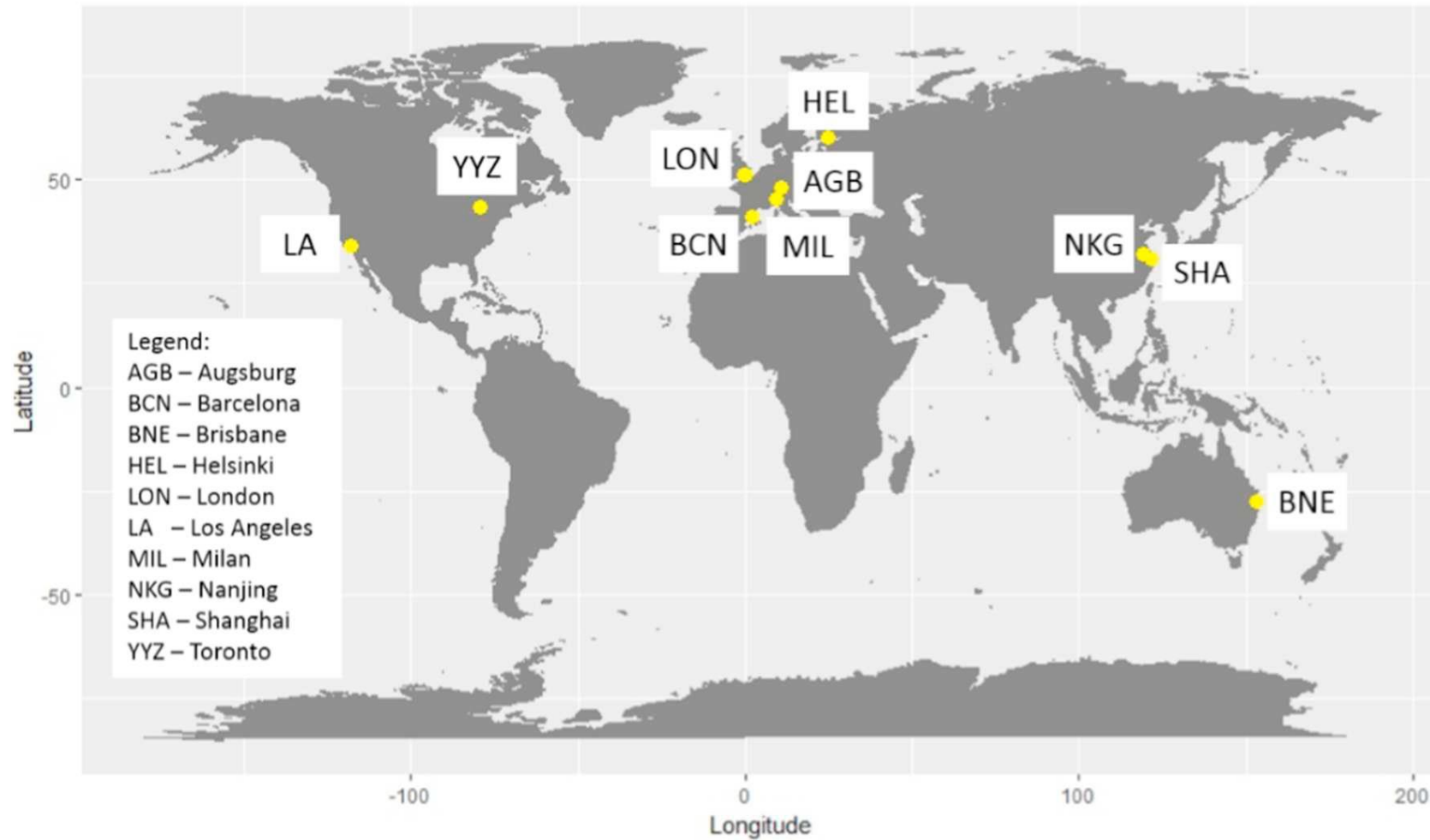


PM_{10} vs. $PM_{2.5}$



UFP vs. $PM_{2.5}$

Ultrafine particles and PM_{2.5} in the air of cities around the world: Are they representative of each other?



Correlation of the raw and log-transformed hourly PNC and PM_{2.5} values by city

UFP vs. PM_{2.5}

UFP vs. PM_{2.5}

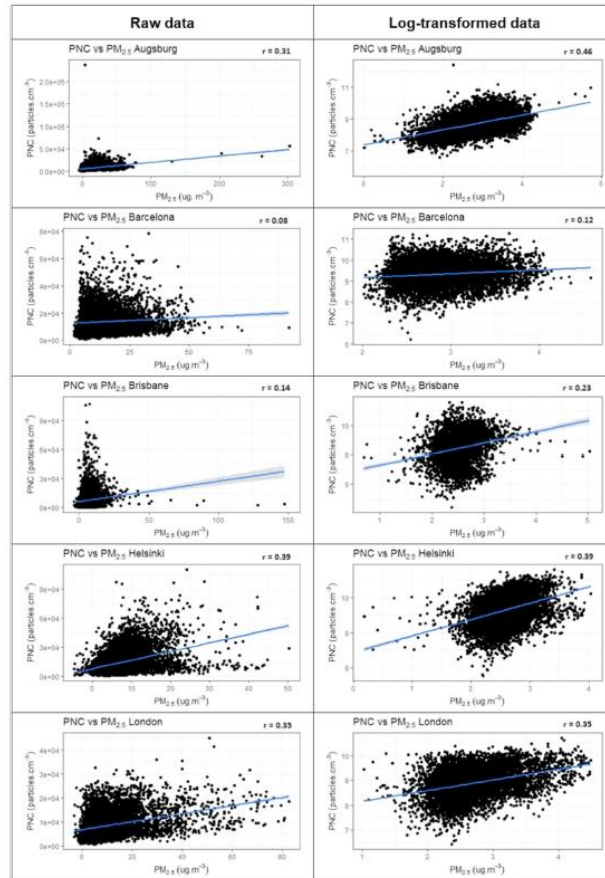
r=0.31

r=0.08

r=0.14

r=0.39

r=0.35



r=0.07

r=0.31

r=0.19

r=0.53

r=0.16

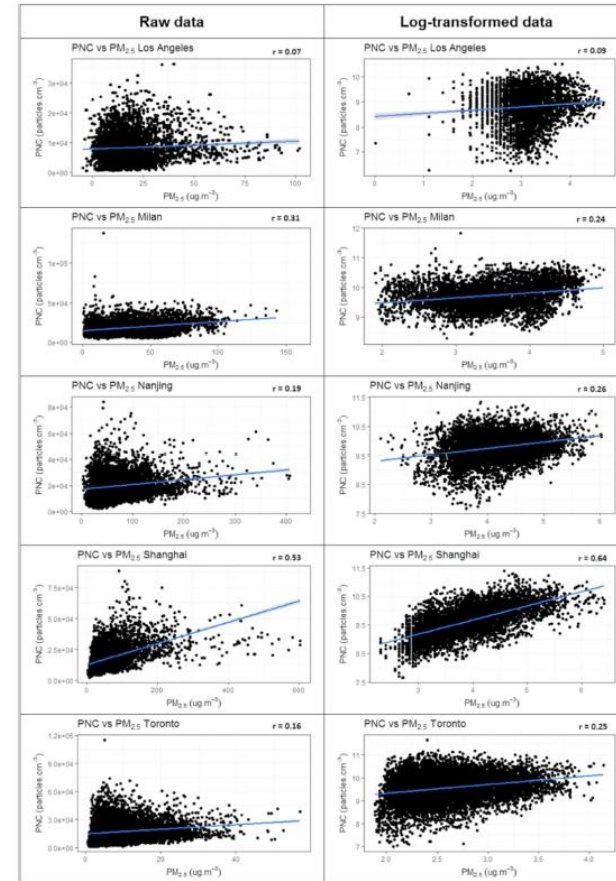
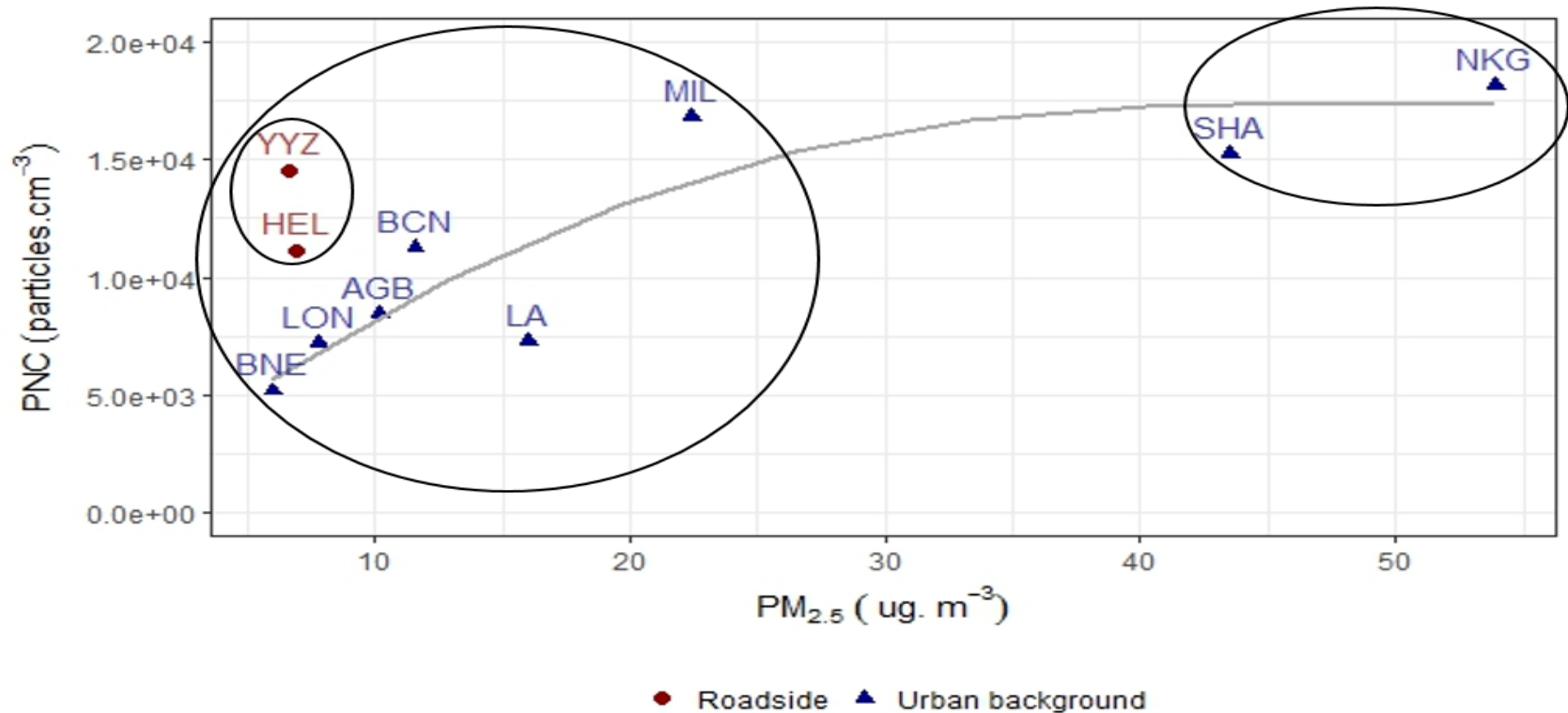


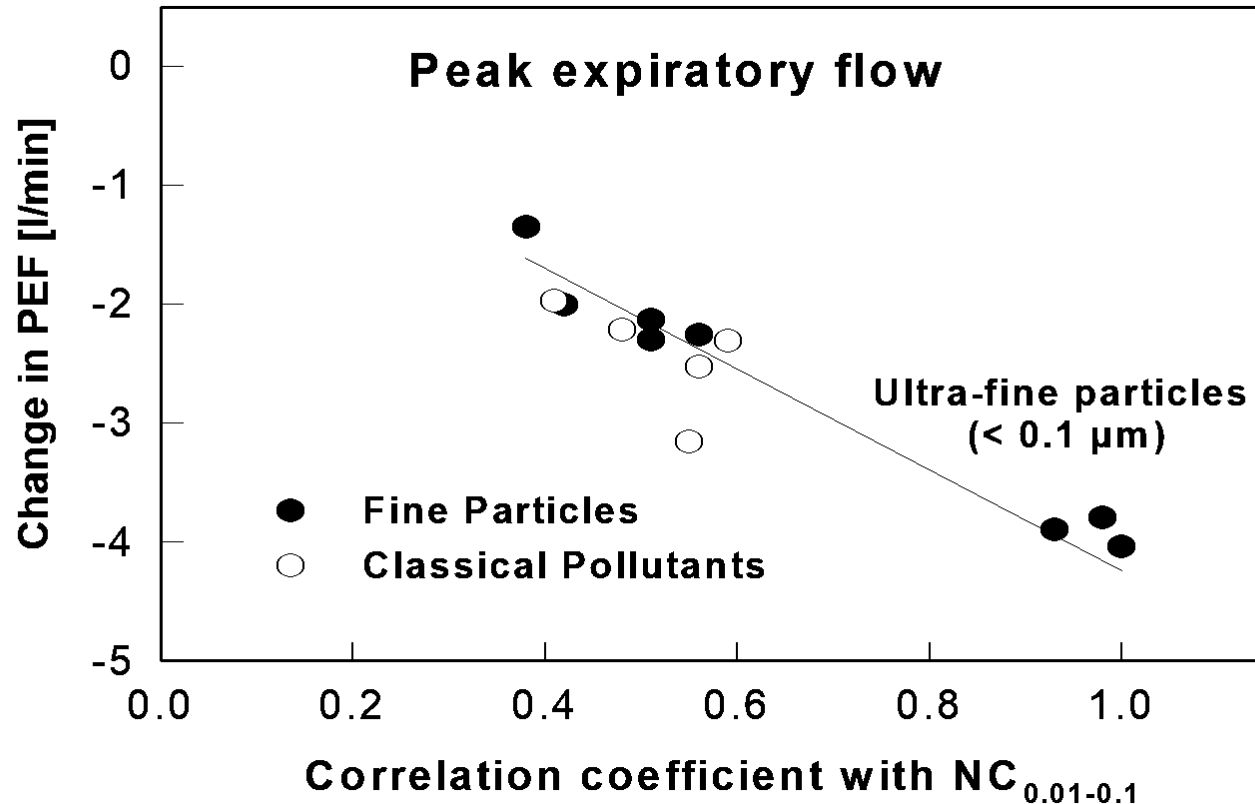
Fig. 8. (continued)

Annual median of the hourly PNC and PM_{2.5} in the air of cities around the world



↳ Which properties are unique for ultrafine particles compared to $PM_{2.5}$?

Where the evidence started: Panel study in asthmatics



Decreased lung function on days with high ultrafine particles

UFP Study in Erfurt (1995 – 1998)



RESEARCH REPORT

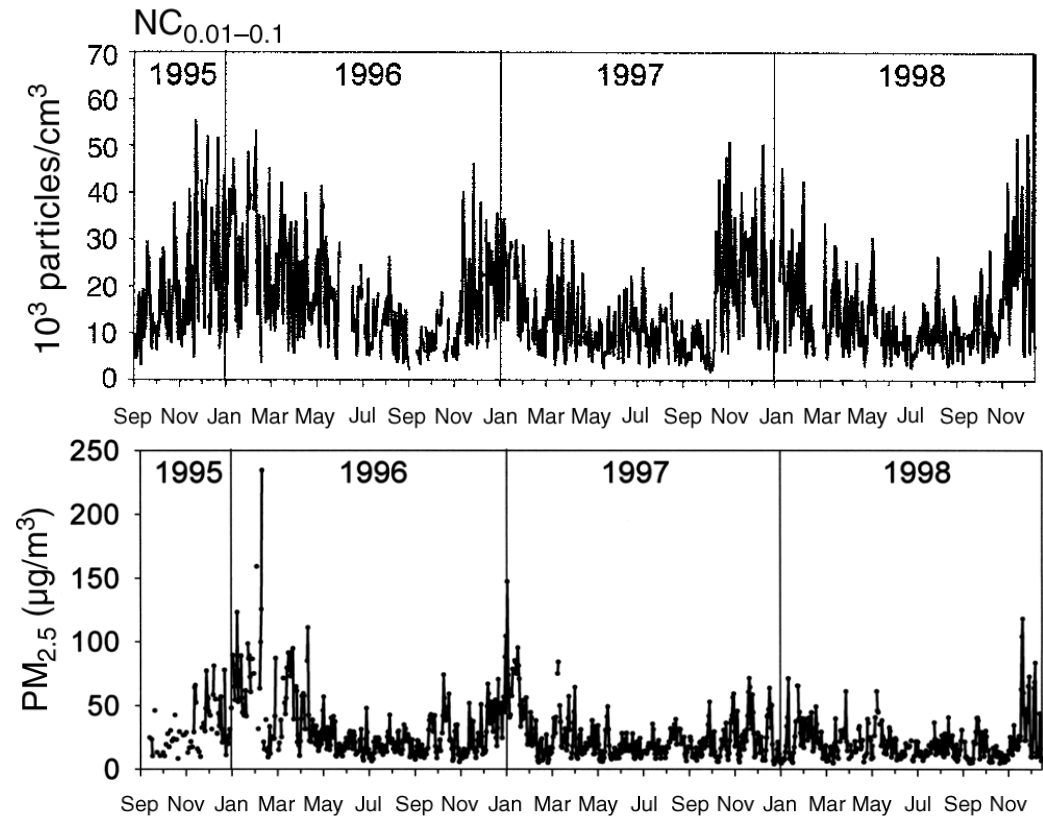
HEALTH
EFFECTS
INSTITUTE

Number 98
November 2000

Final Version

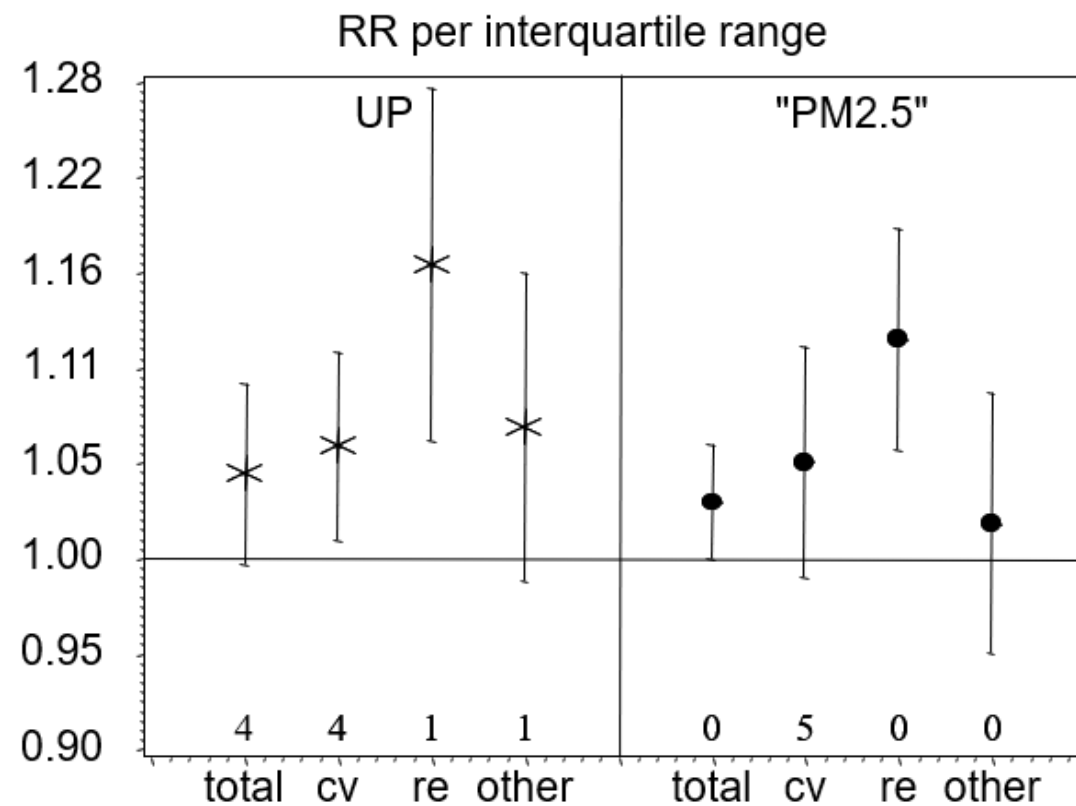
Daily Mortality and Fine and Ultrafine Particles in Erfurt, Germany Part I: Role of Particle Number and Particle Mass

H-Erich Wichmann, Claudia Spix, Thomas Tuch, Gabriele Wölke,
Annette Peters, Joachim Heinrich, Wolfgang G Kreyling, and
Joachim Heyder



UFP Study in Erfurt (1995 – 1998)

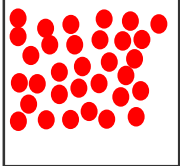
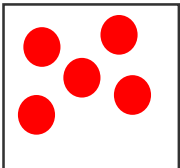
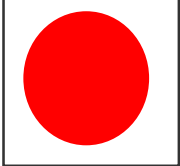
- Strongest association with respiratory diseases (re)
- The effect estimate was stronger for UFP
- The effect estimates of UFP and PM_{2.5} remain almost unchanged in "two-pollutant models"



Evidence from toxicological studies

- The first evidence of the health effects related to exposure to UFPs came from animal and in vitro toxicological studies.
- Evidence from studies on animals suggested that UFPs might penetrate more deeply into the lung and might be more toxic than larger particles (Oberdörster et al. 1990; Ferin et al. 1992)
- Oberdörster and colleagues (1992) instilled 20 nm titanium dioxide particles in the tracheas of rats and found that increased pulmonary toxicity was associated with the surface area of the particles
- It was postulated that the number of UFPs is a more relevant exposure metric than their mass, because of their larger surface area (Oberdörster et al. 1995)
- Other investigators confirmed that surface area is a potentially important interface by which particles interact with biological systems and help to transport toxic metals or chemicals adsorbed on the particles (Donaldson et al. 2005; Kreyling et al. 2006a; Maier et al. 2008)

Number and surface area of monodisperse particles of unit density and mass concentration of $10 \mu\text{g m}^{-3}$

	PM	\emptyset	Mass [$\mu\text{g m}^{-3}$]	Number [cm^{-3}]	Surface [$\mu\text{m}^2 \text{cm}^{-3}$]
PM _{0.02} 	PM _{0.02}	20 nm	10	~2.400,000	3016
PM _{0.1} 	PM _{0.1}	100 nm	10	~19,100	600
PM _{2.5} 	PM _{2.5}	2.5 μm	10	1,2	24

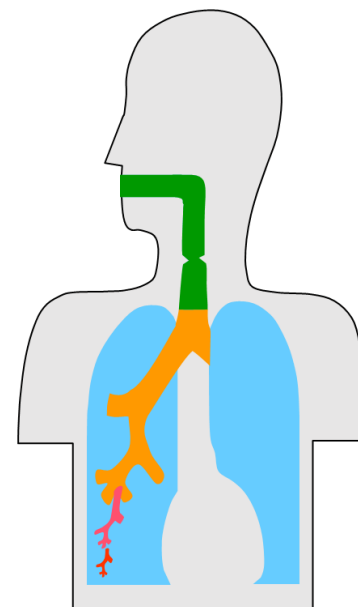
A measured PM_{2.5} mass concentration of $10 \mu\text{g/m}^3$ for example, might contain as many as 2.4 million 20-nm particles/cm³, but could also be represented by a single 2.5 μm particle (Oberdörster et al. 1995)

UFPs have different properties when compared with PM

The different properties of UFPs when compared with larger particles make this particle fraction of great concern because of their potential adverse human health effects.

- They deposit with higher efficiency in the alveolar region and to a lesser extent in the larger airways

Inhalable Particles: Upper airways and nasal cavities (PM ₁₀ . Ø < 10 µm)
Fine Particles: lower air ways and alveoli (PM _{2.5} . Ø < 2.5 µm)
Clearance: Mucociliar transport, macrophages, translocation into the blood (< 200 nm)

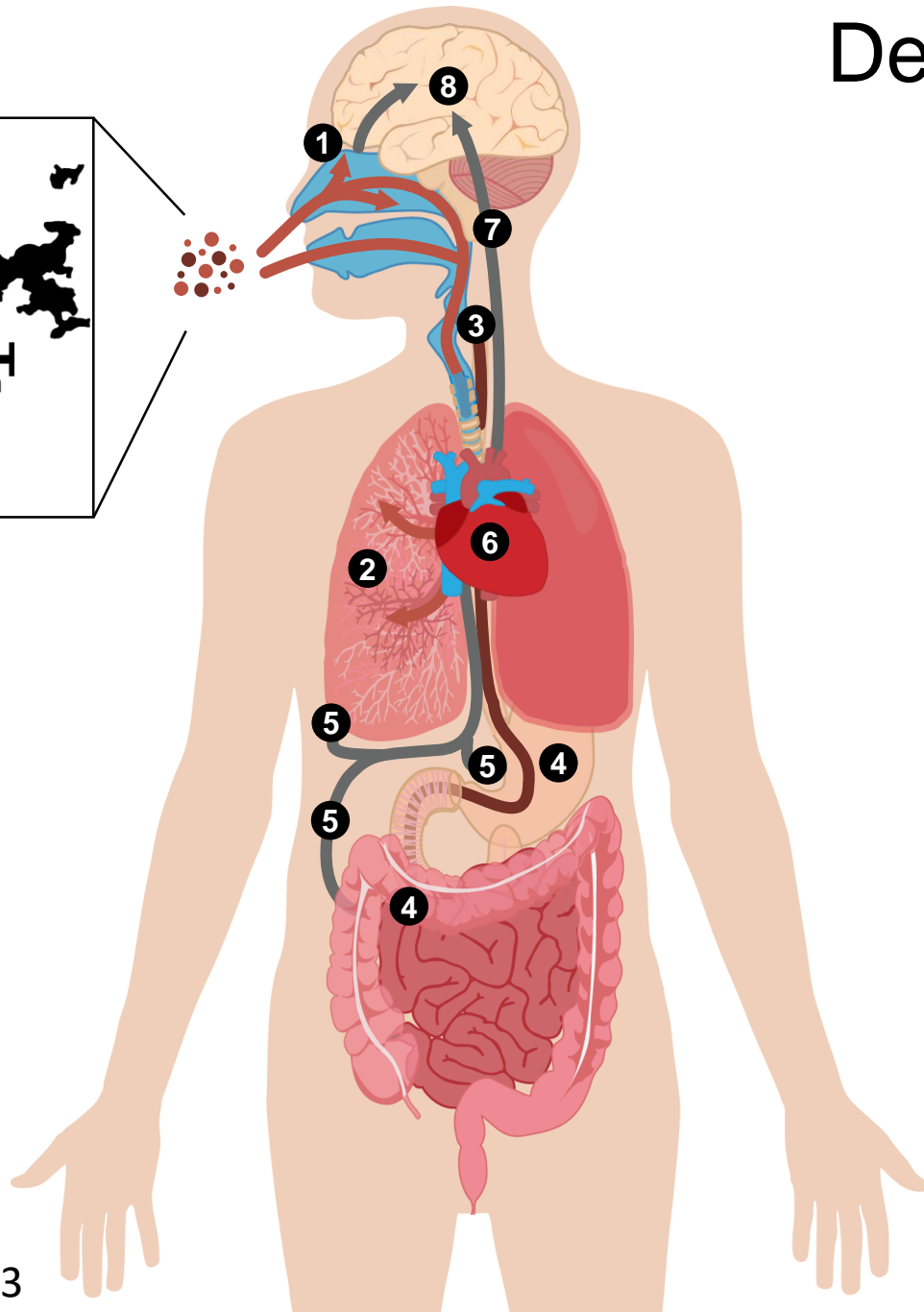
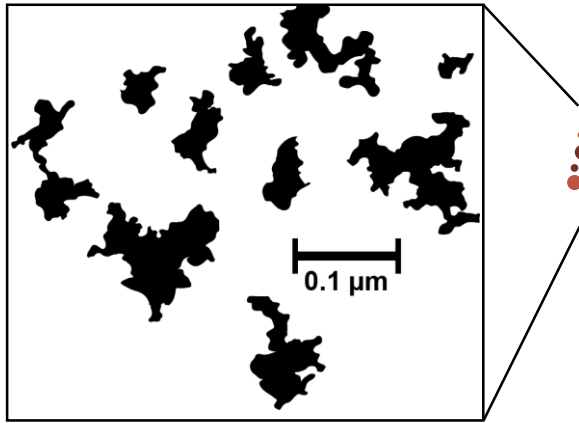


UFPs have different properties when compared with PM

The different properties of UFPs when compared with larger particles make this particle fraction of great concern because of their potential adverse human health effects.

- They deposit with higher efficiency in the alveolar region and to a lesser extent in the larger airways
- They potentially translocate into cells (and consequently into extra-pulmonary organs) through diffusion mechanism

Deposition and mechanisms

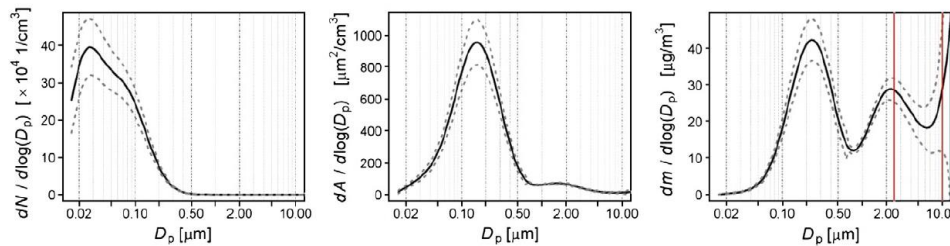


- 1 Ultrafine particles (UFP) deposited in the nasal cavity translocate to the brain via the olfactory nerve
- 2 Particles deposited in the lung activate the immune system
- 3 Particles are swallowed after clearance from the lung or deposition in the upper airways
- 4 Particles reach the gastrointestinal tract
- 5 UFP and constituents translocate into the blood stream
- 6 UFP and constituents pass the heart
- 7 UFP and constituents from different organs reach the brain vasculature
- 8 UFP and constituents induce localized and diffuse inflammatory responses, protein misfolding, glial and vascular dysfunction, and neuronal degradation

UFPs have different properties when compared with PM

The different properties of UFPs when compared with larger particles make this particle fraction of great concern because of their potential adverse human health effects.

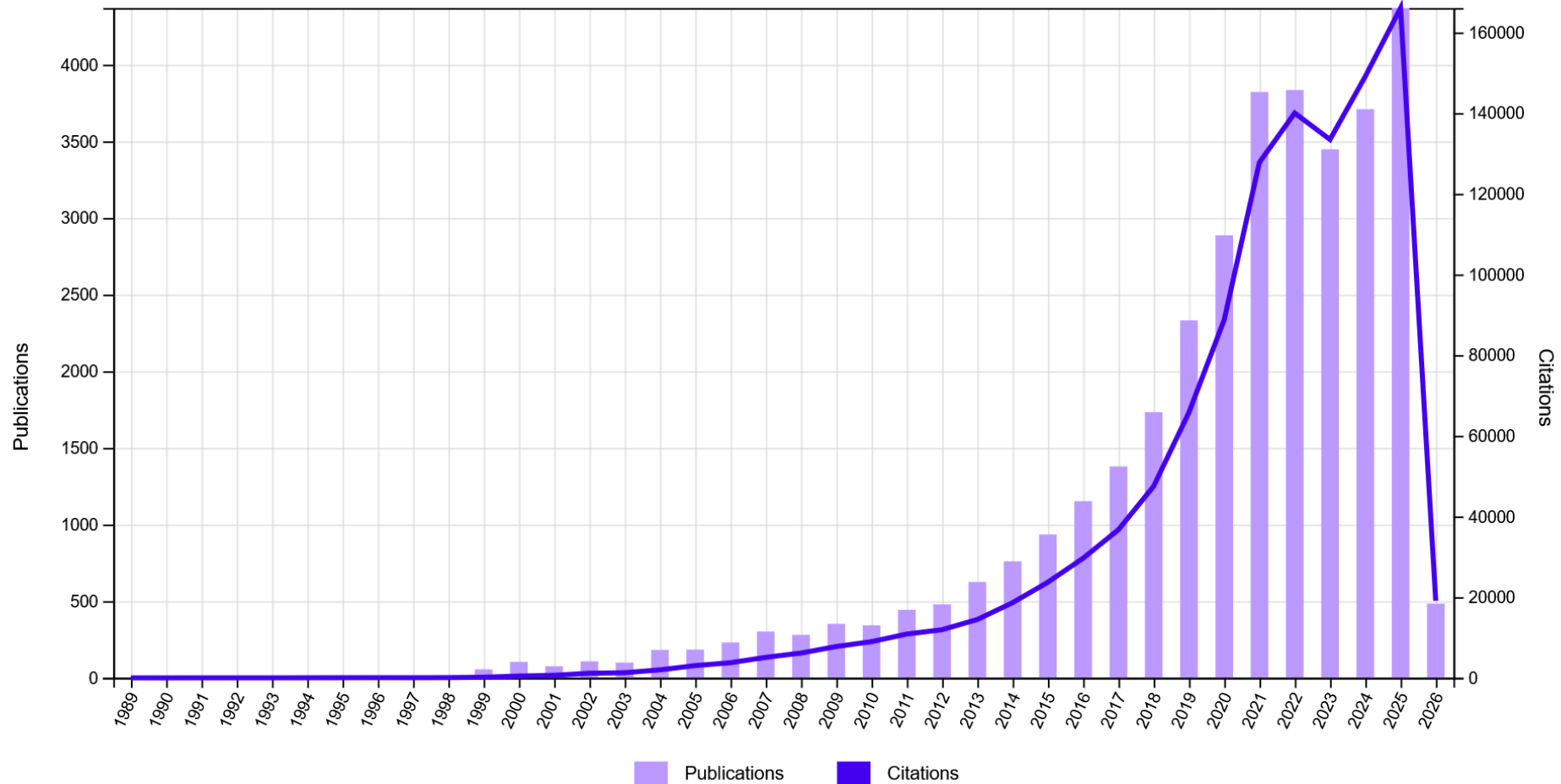
- They deposit with higher efficiency in the alveolar region and to a lesser extent in the larger airways
- They potentially translocate into cells (and consequently into extra-pulmonary organs) through diffusion mechanism
- They have little mass but high number and surface area concentration



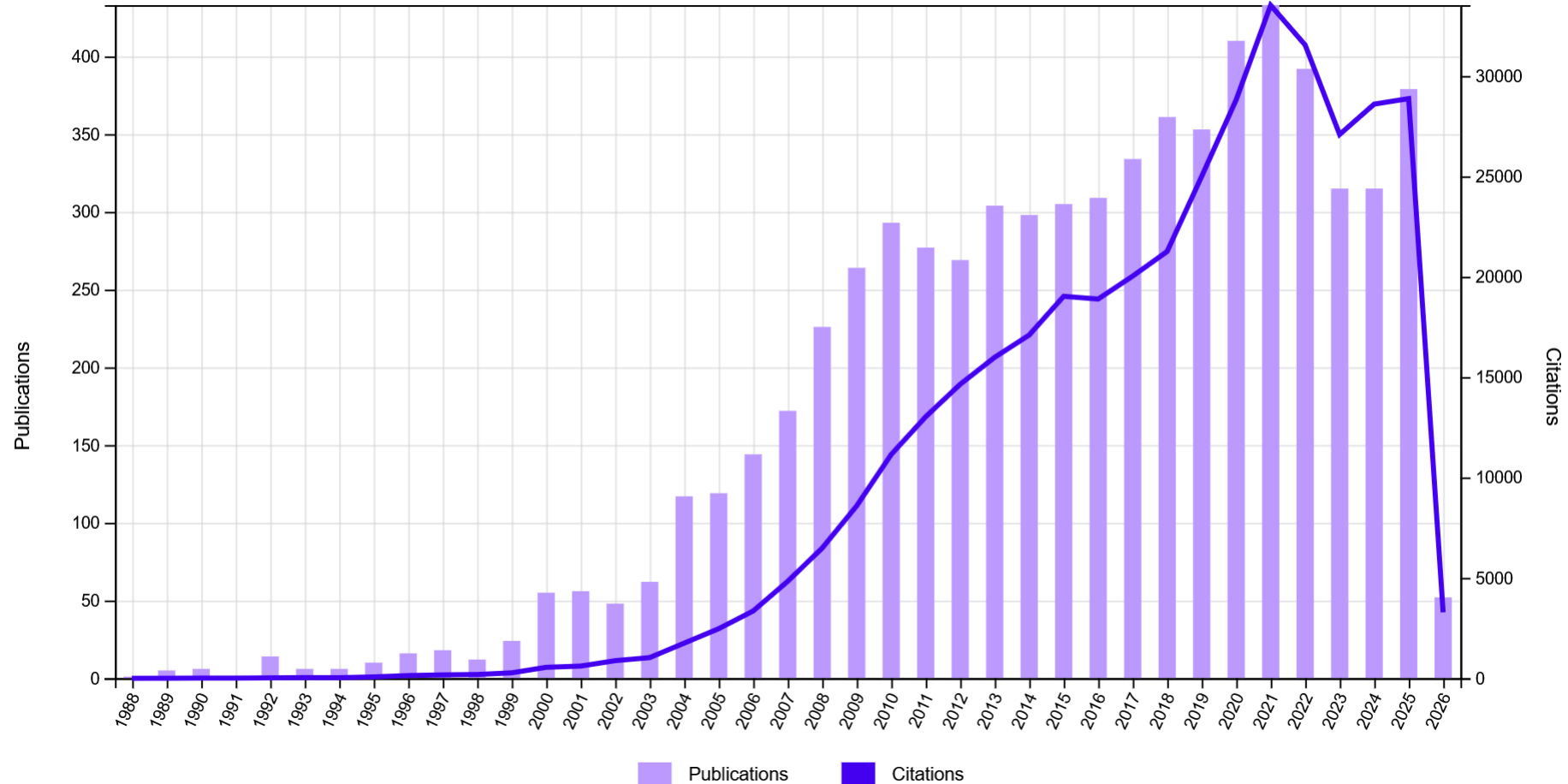
Harrison et al. 2010

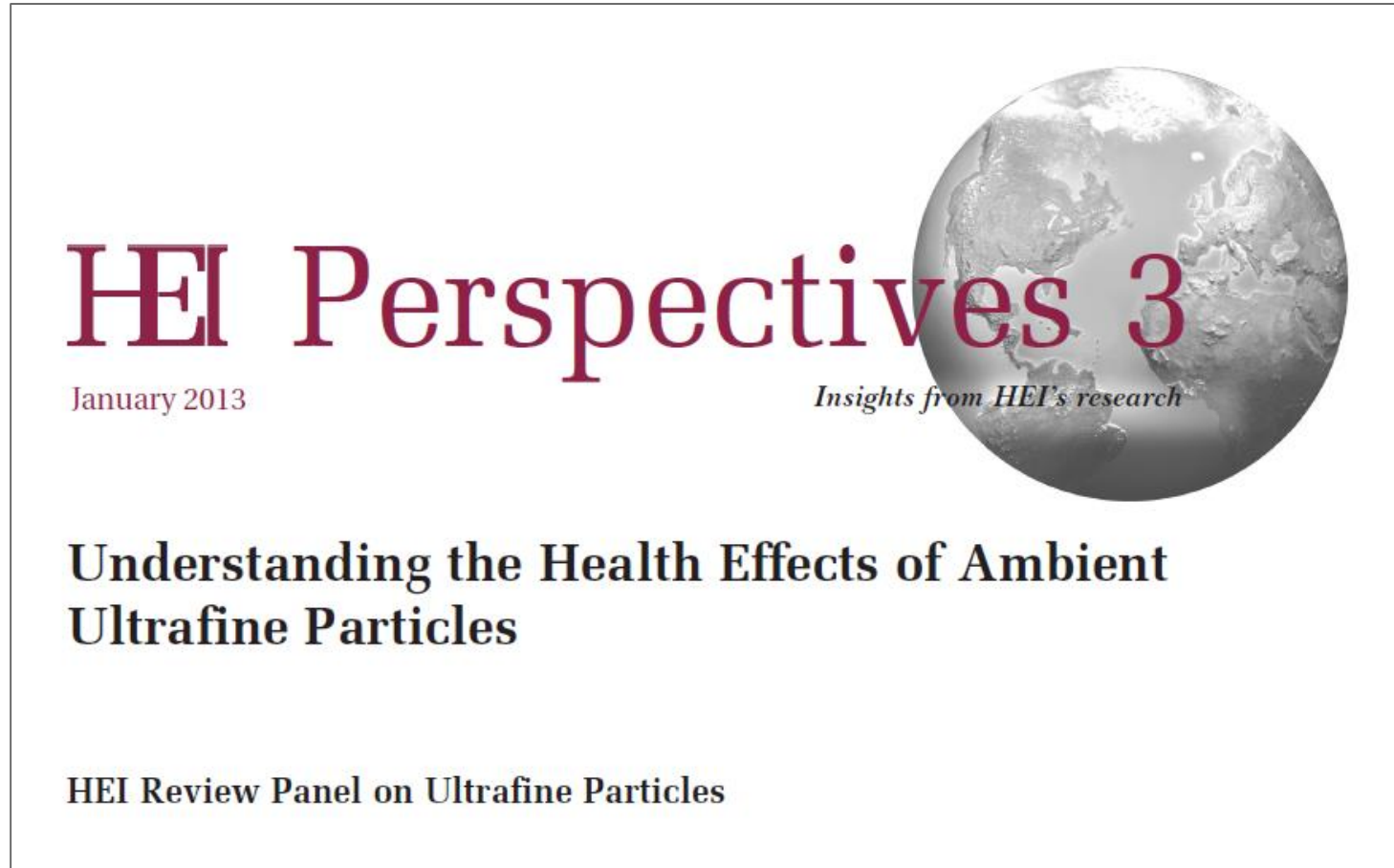
↳ What do we know today
about health effects of
ultrafine particles?

Number of publications for PM_{2.5} and “Health”



Number of publications for *Ultrafine particles* and *Health*





The image shows the cover of the journal 'HEI Perspectives 3'. The title is in a large, dark red serif font. To the right of the title is a circular grayscale image of the Earth. Below the title, the date 'January 2013' is on the left and the subtitle 'Insights from HEI's research' is on the right. The main article title 'Understanding the Health Effects of Ambient Ultrafine Particles' is centered below the journal title. At the bottom of the cover, it says 'HEI Review Panel on Ultrafine Particles'.

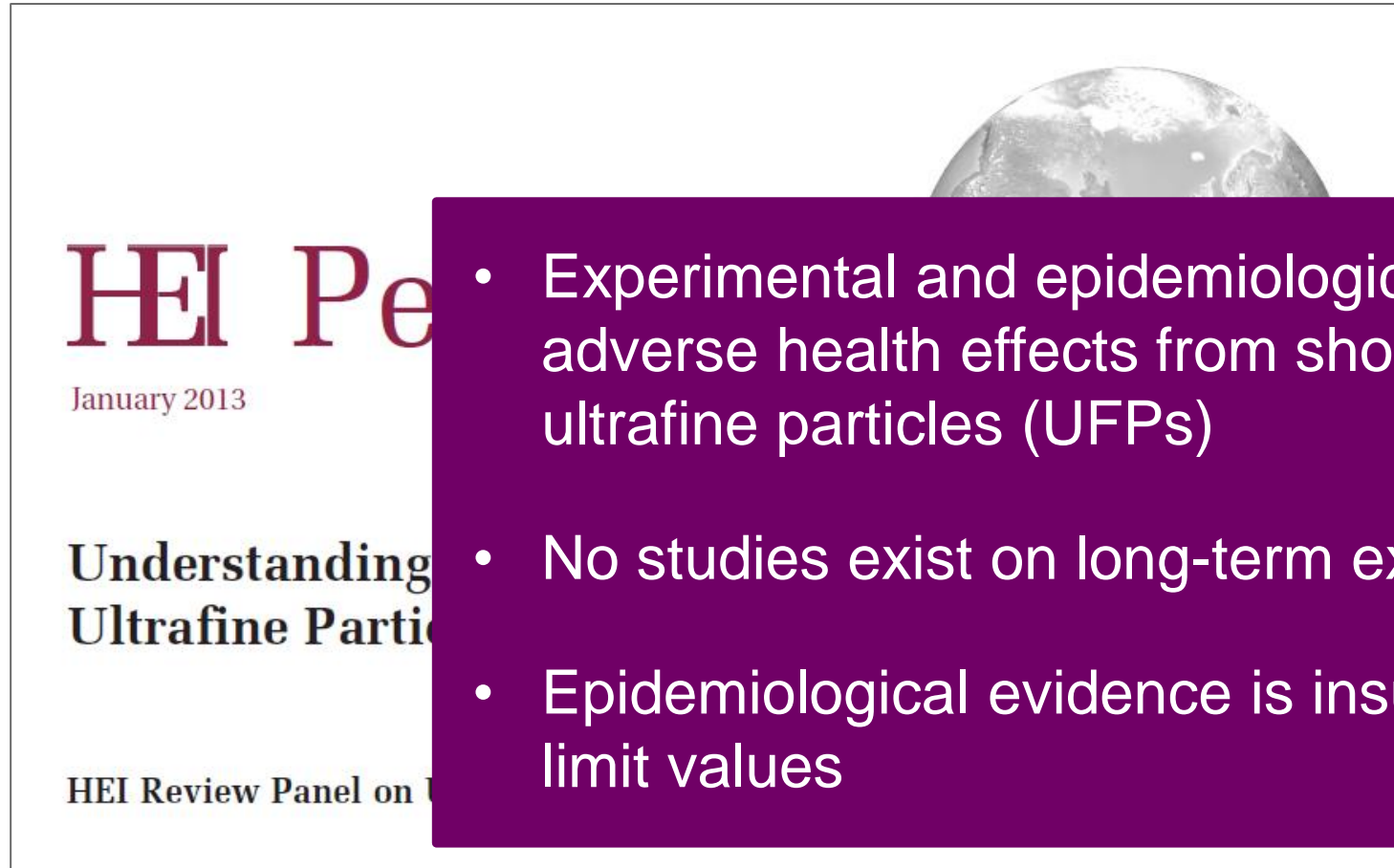
HEI Perspectives 3

January 2013 *Insights from HEI's research*

Understanding the Health Effects of Ambient Ultrafine Particles

HEI Review Panel on Ultrafine Particles

2013: Health Effects Institute Review

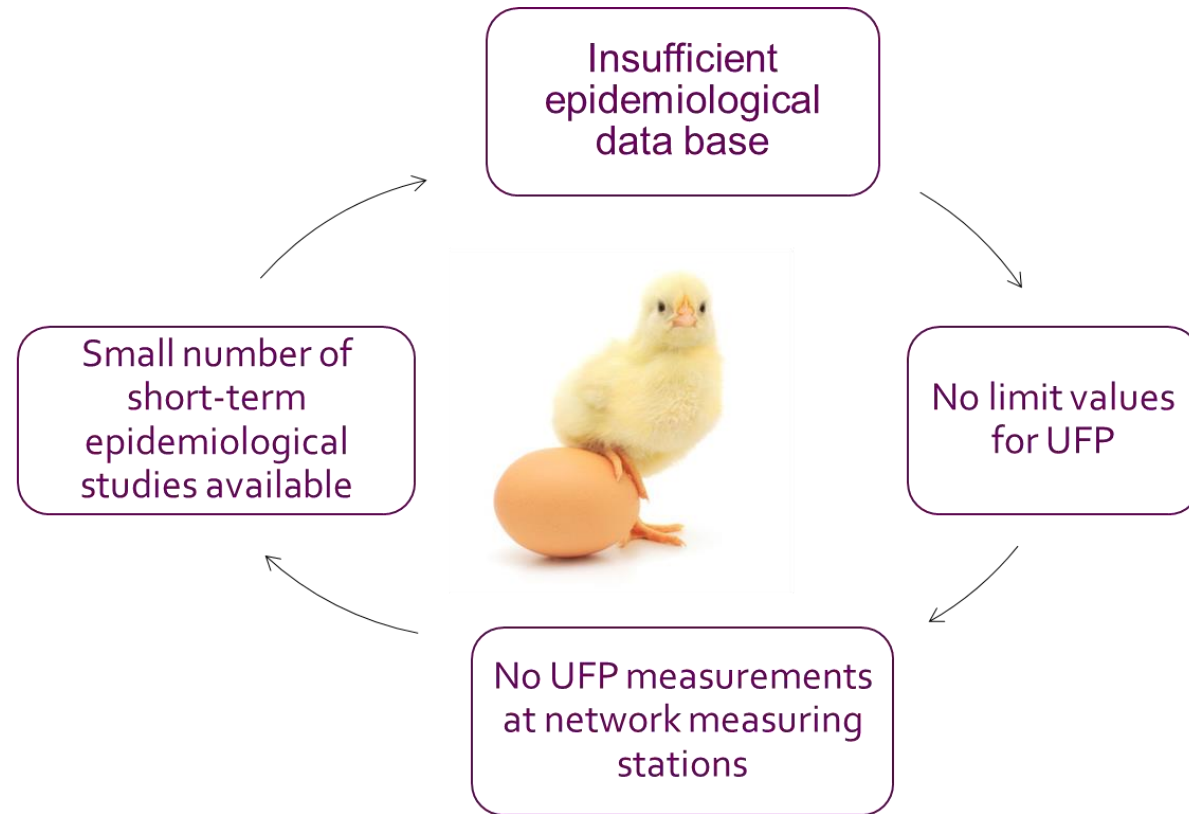


- Experimental and epidemiological studies indicate adverse health effects from short-term exposure to ultrafine particles (UFPs)
- No studies exist on long-term exposure
- Epidemiological evidence is insufficient to establish limit values

REVIHAAP: Review of evidence on health aspects of air pollution for guidance of EU policy

On UFPs:

- There is **increasing**, though as yet **limited**, epidemiological **evidence** on the association between **short-term exposures** to ultrafine particles and ... health.
- Clinical and toxicological studies have shown that ultrafine particles (in part) act through mechanisms **not shared with larger particles** that dominate mass-based metrics, such as $PM_{2.5}$ or PM_{10} .



The UFP challenge: chicken and egg problem

2019: Systematic Literature Review (UBA & BAfU)

Design	Studienanzahl	%
Langzeit	gesamt=10	
Fall-Kohortenstudie	1	1.2%
Fall-Kontrollstudie	1	1.2%
Kohortenstudie	4	4.7%
Querschnittsstudie	4	4.7%
Short-Term	gesamt =75	
Kohortenstudie	4	4.7%
Querschnittsstudie	4	4.7%
Panelstudie (Querschnitt)	1	1.2%
Panelstudie (wiederholte Messungen)	31	36.5%
Case-crossover	8	9.4%
Scripted exposure	16	18.8%
Zeitreihenstudien	11	12.9%
Gesamt	85	100.0%

2019: Systematic Literature Review (UBA & BAfU)

Design	Studienanzahl	%
Langzeit		
Short-Term		
Panelstudie		
Gesamt	85	100.0%

- Progress since 2013
- Conclusions from the 2013 HEI report not substantially changed
- Most evidence for subclinical endpoints, particularly cardiopulmonary endpoints and inflammation
- Evidence for the independence of UFP effects is limited
- Highly exposed sites need to be investigated, e.g., near roads and airports

Ultrafine Particles and Health – Epidemiological Evidence

	1997-2011	2011-2017	Sum
Long-term Exposure			
Mortality	0	1	1
Morbidity	0	4	4
Emergency/hospital call/admission	0	0	0
Subclinical	0	5	5
All	0	10	10
Short-term Exposure			
Mortality	11	7	18
Morbidity/ Emergency/hospital call/admission	15	5	20
(Respiratory) Symptoms	8	11	19
Subclinical	52	55	107
All	86	78	164
Total	86	88	174

WHO global air quality guidelines (2021)

- The body of epidemiological evidence has grown, and two systematic reviews have assessed scientific research papers published from 1997 to 2017 (HEI, 2013; Ohlwein et al., 2019), documenting the rising number of studies being conducted
- However, various UFP size ranges and exposure metrics were used, preventing a comparison of results across studies (US EPA, 2019)
- The **lack of long-term studies** was assessed as the most important factor of uncertainty in the evaluation of the health effects of UFP
- Therefore, there was a consensus in the guideline development group that **the body of epidemiological evidence was not yet sufficient** to formulate an air quality guideline level



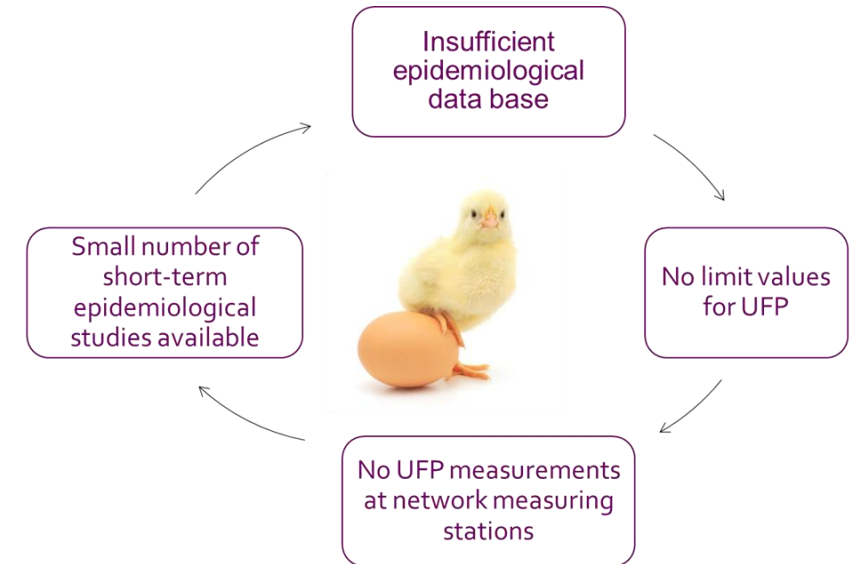
WHO Good Practice Statement on Ultrafine Particles

- Quantify ambient UFP in terms of PNC for a size range with a lower limit of ≤ 10 nm and no restriction on the upper limit.
- Expand the common air quality monitoring strategy by integrating UFP monitoring into the existing air quality monitoring.
- Distinguish between low and high PNC to guide decisions on the priorities of UFP source emission control. Low PNC can be considered $< 1\ 000$ particles/cm³ (24-hour mean). High PNC can be considered $> 10\ 000$ particles/cm³ (24-hour mean) or $20\ 000$ particles/cm³ (1-hour mean).
- Utilize emerging science and technology to advance approaches to the assessment of exposure to UFP for their application in epidemiological studies and UFP management.



EU Air Quality Directives (2024/2881/EC)

- From 2030 onwards, it will be mandatory to set up so-called supersites
- Supersites are monitoring stations designed to measure:
 - regulated air pollutants
 - not regulated air pollutants or parameters (UFPs, black carbon (BC), ammonia (NH₃), oxidative potential of particles)
- As a contribution to the scientific understanding of the effects of UFP on human health, and to improve the data basis for epidemiological studies, the Air Quality Directive calls for set up of additional monitoring sites for UFPs



Summary (exposure)

- UFPs have little mass but high number and surface area concentration
- PNC is particularly affected by local sources, with a major contribution from traffic and NPF. $PM_{2.5}$ is attributed to predominant local meteorological conditions and regional transport; a high PNC does not mean a high $PM_{2.5}$, and vice versa
- The correlation between these two metrics is weak, especially if the sources contributing to each metric are different or contribute to their bulk concentrations in different proportions
- It means, control measures aiming to reduce $PM_{2.5}$ do not automatically reduce UFPs. Consequently, regulating $PM_{2.5}$ does not imply a low level of risk to UFP exposure, especially in zones near roadways, airports or railways
- Exposure to UFPs and $PM_{2.5}$ differ in time and space, the spatial variation is more pronounced for UFPs
- The high degree of spatial variation in UFP concentrations is both an opportunity and a challenge for scientists trying to estimate population exposure to UFPs for health studies, particularly for long-term studies:
 - Variation in concentrations of a pollutant is essential to investigate whether pollutant exposures may be related to variations in health outcomes
 - The high spatial variability makes it more difficult to rely on measurement strategies that have been adequate for more spatially homogenous particulate fractions like $PM_{2.5}$ (exposure can be more represented by a city-wide average or by a central site monitor over a longer time period)

Summary (epidemiology)

- UFPs deposit with higher efficiency in the alveolar region and to a lesser extent in the larger airways
- They are not well recognized and cleared by macrophages in the alveolar space
- They potentially translocate into cells (and consequently into extra-pulmonary organs) through diffusion mechanism
- The different properties of UFPs when compared with larger particles make this particle fraction of great concern because of their potential adverse human health effects.
- As early as the 1990's, the use of both PNC and $PM_{2.5}$ in epidemiological studies was recommended because of the poor correlation between the two metrics
- Epidemiological studies suggest independent short- and long-term health effects
- Studies on long-term health effects are rare
- It is recommended to keep daily levels below 10 000 particles cm^{-3} to avoid health effects
- Monitoring both PNC and $PM_{2.5}$ is essential to fully grasp the health impact associated with the inhalation of ambient PM

Ultrafine particles and $PM_{2.5}$ –
are they representative of each other?

Answer: Ultrafine particles and $PM_{2.5}$ are
not representative of each other



Thank you!



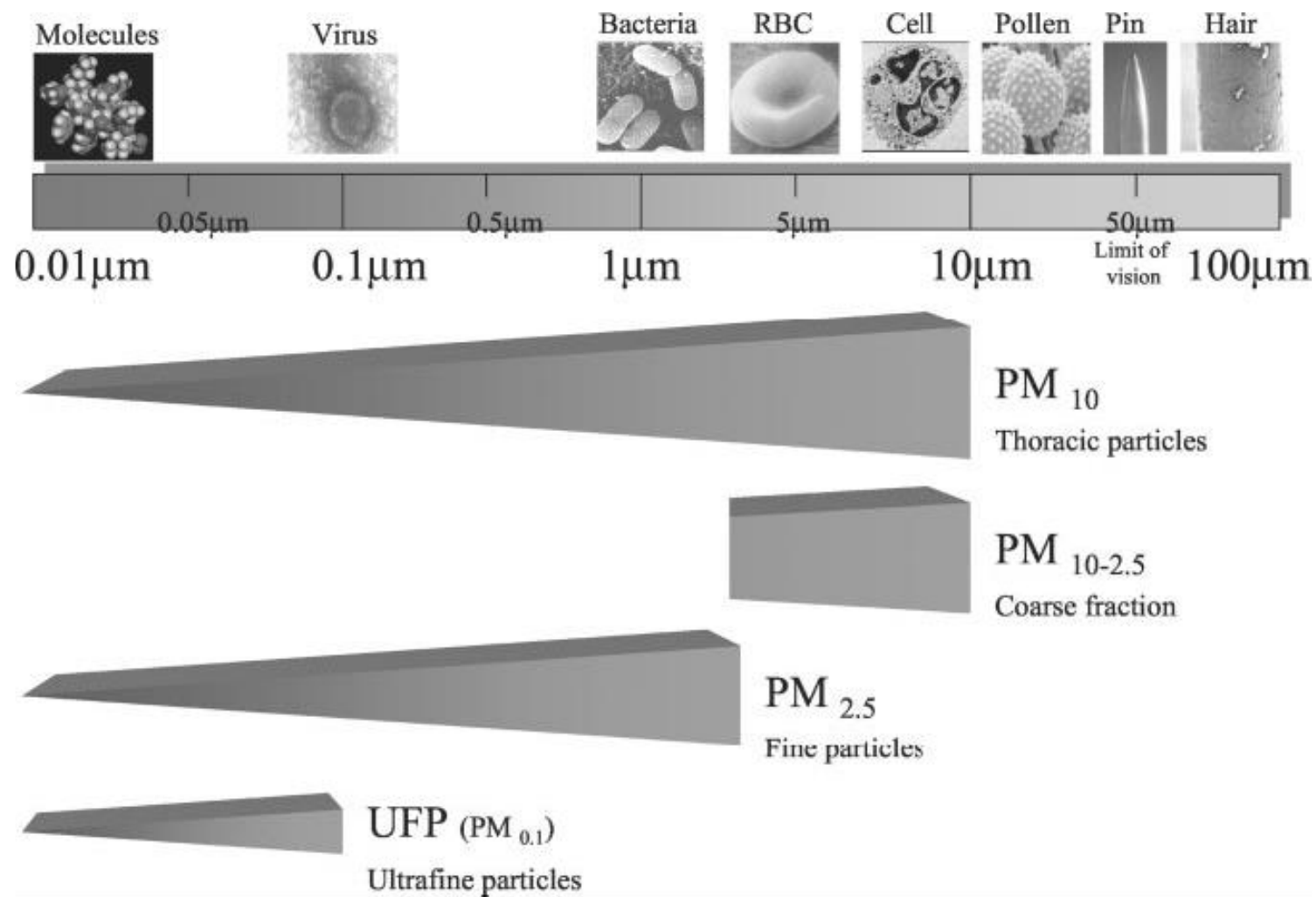
Questions ???

josef.cyrys@helmholtz-munich.de

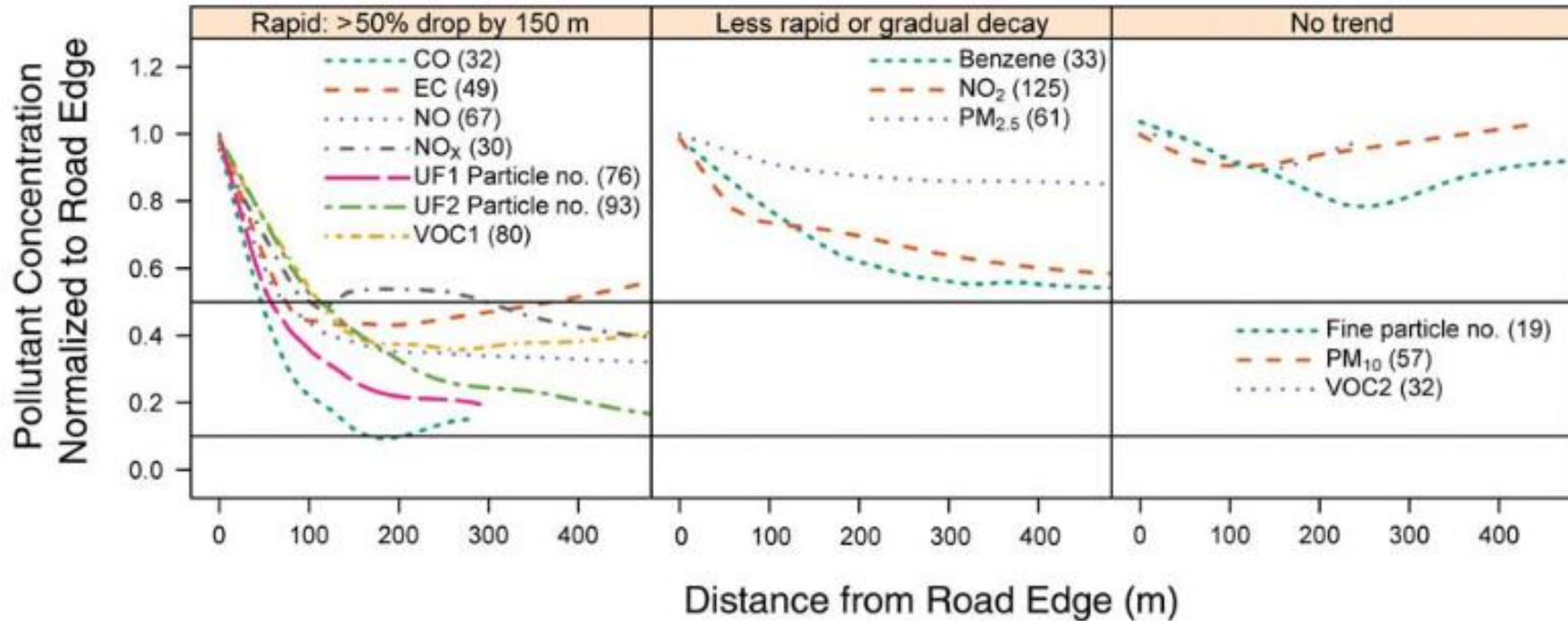
+49 89 3187-4156

Size definition for PM (particulate matter)

- Defined by size
 - ❖ Fine particles $< 10 \mu\text{m}$ (PM_{10})
 - ❖ Fine Particles $< 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$)
 - ❖ Ultrafine particles $< 100 \text{ nm}$ (UFP)
- Different particle composition
- Fine particles already regulated, whereas no limit values have been set for UFP by now.



Gradients in UFPs and other traffic-related pollutants as a function of distance from roadways



New systemic review on short term effects of UFPs and mortality

Environmental Research 286 (2025) 122780



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journal homepage: www.elsevier.com/locate/envres



Review article

Systematic review and meta-analysis on short-term concentrations of ambient ultrafine particles and natural, cardiovascular and respiratory mortality



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New systemic review on short term effects of UFPs and mortality

1 *Letter to the Editor: Health effect studies of ultrafine air pollution—Are we missing the*
2 *forest for the trees?*¶¶

3 ¶¶

4 Maximilian Schwarz^a, Regina Pickford^a, Josef Cyrys^a, Susanne Breitner-Busch^{a,b}, Annette
5 Peters^{a,b}¶¶

6 ¶¶

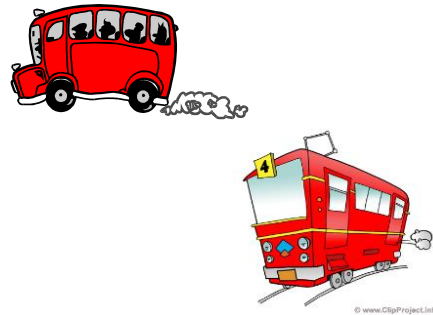
7 ^a: Institute of Epidemiology, Helmholtz-Zentrum München - German Research Center for
8 Environmental Health (GmbH), Neuherberg, Germany¶¶

9 ^b: Institute for Medical Information Processing, Biometry, and Epidemiology, Faculty of
10 Medicine, LMU Munich, Munich, Germany¶¶

11 ¶¶

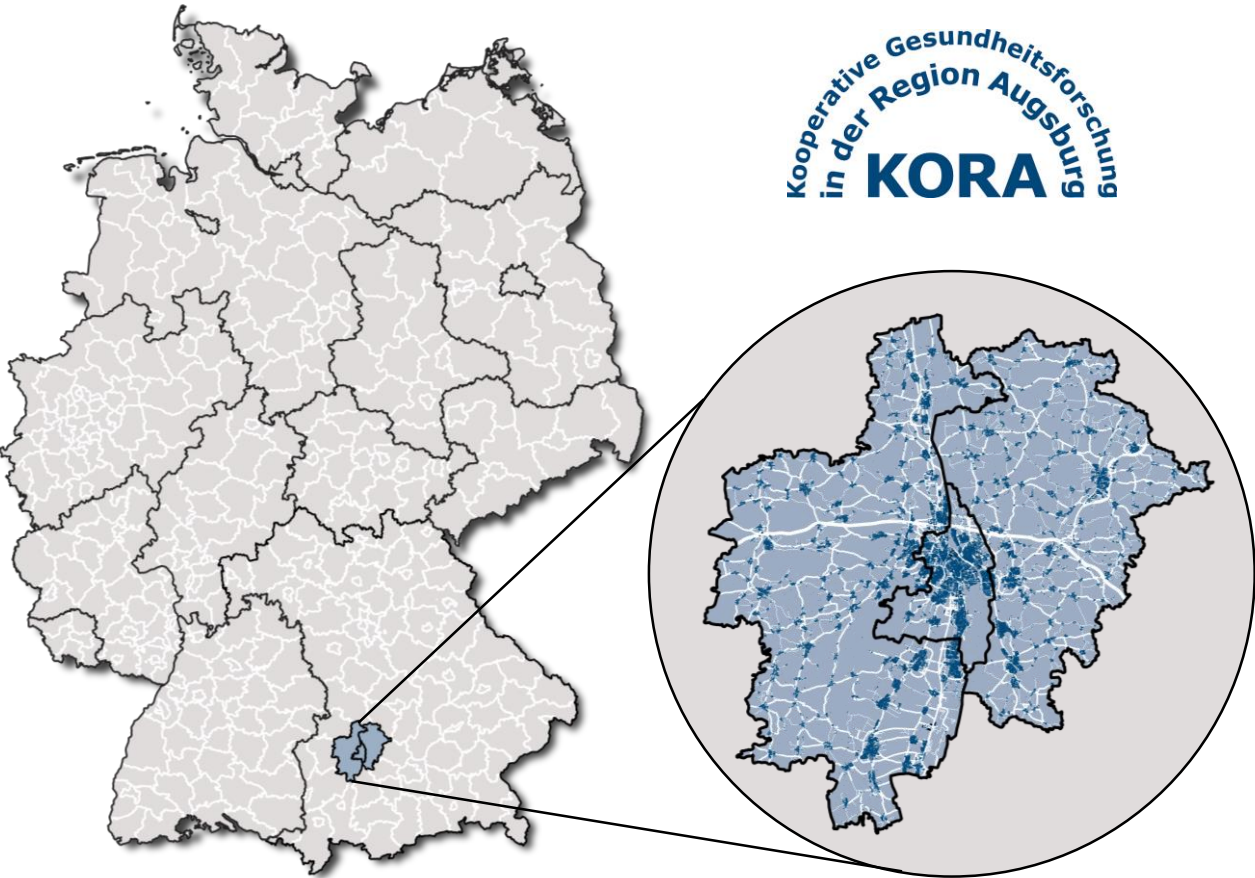
Case study I: Personal vs. ambient: Study methods

- personal measurements of $PM_{2.5}$, BC, PNC
- ambient measurements of $PM_{2.5}$, BC, PNC
- GPS coordinates
- time-activity questionnaire
- 1 researcher
- 5 main exposure scenarios

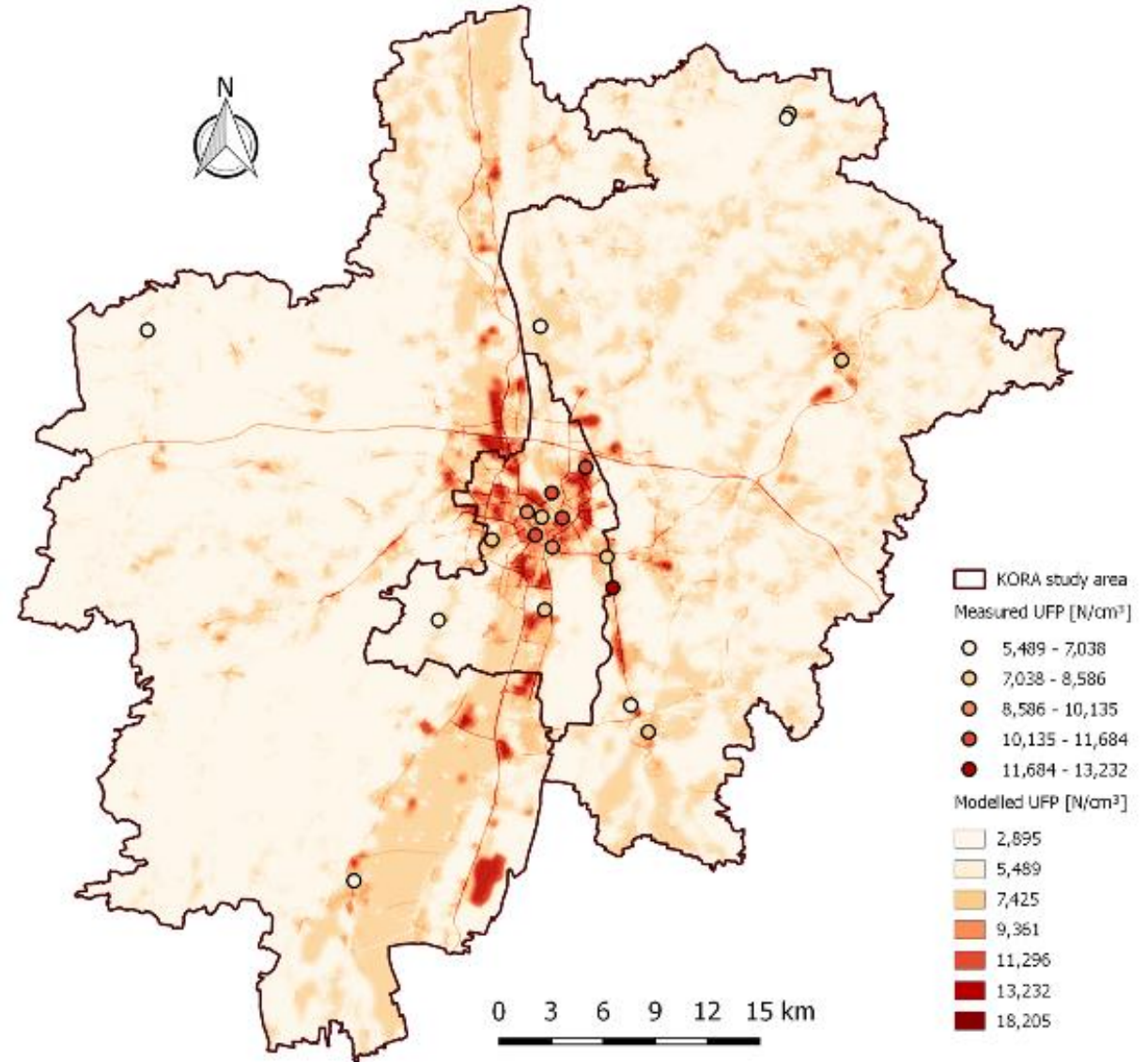


Landuse regression-based modelling of UFP

Kooperative Gesundheitsforschung
in der Region Augsburg
KORA



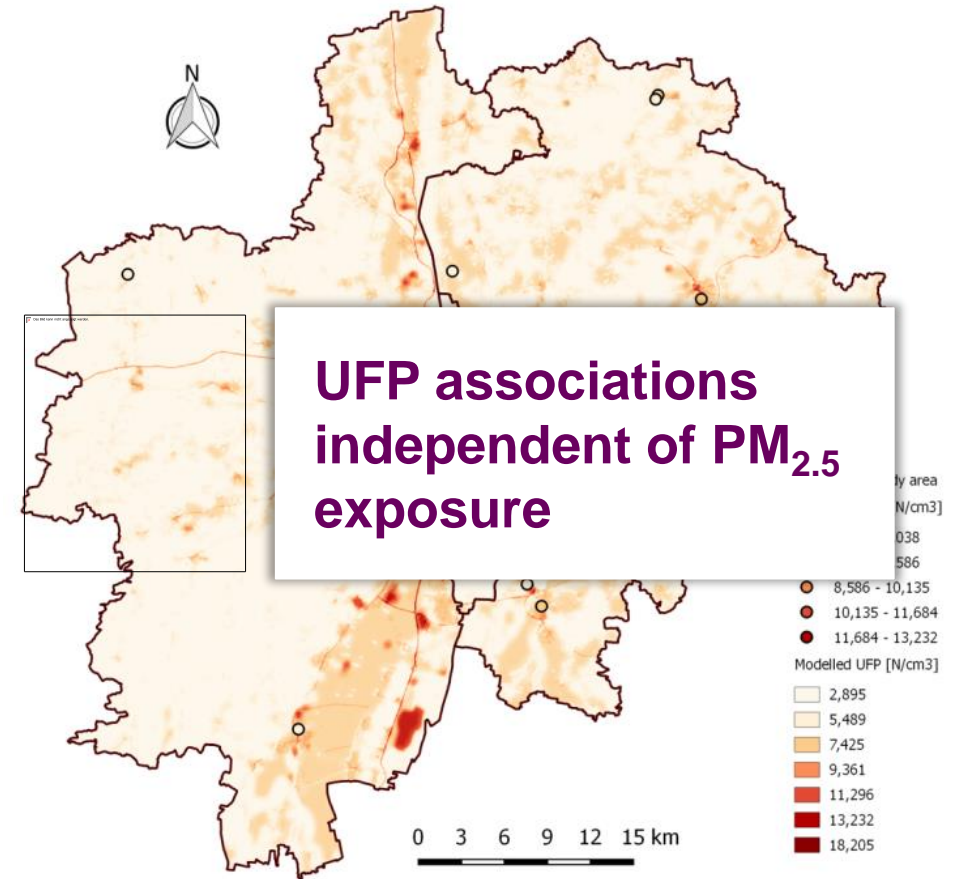
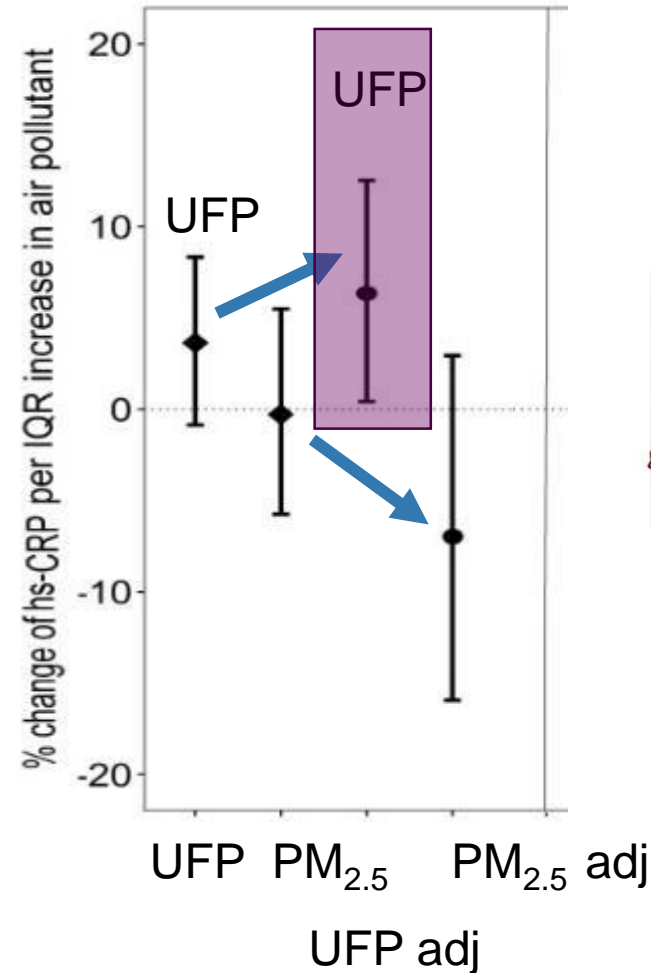
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Wolf et al., 2017

Long-term UFP exposure is associated with inflammation

- Annual average UFP concentrations
- Assigned to the residential locations
- 2,252 participants



Wolf et al., 2017
Pilz et al., 2018

Long-term UFP is associated with cardiovascular disease

- Annual average UFP concentrations at the residence
- ~27,000 participants

UFP associations independent of PM_{2.5} or NO₂ exposure

