Surrounded by a Cloud of Dust:
Particle Resuspension in Indoor Environments

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Lyles School of Civil Engineering & Herrick Laboratories, Purdue University
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PURDUE UNIVERSITY

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

"You know what I am?
I'm a dust magnet!"[1]

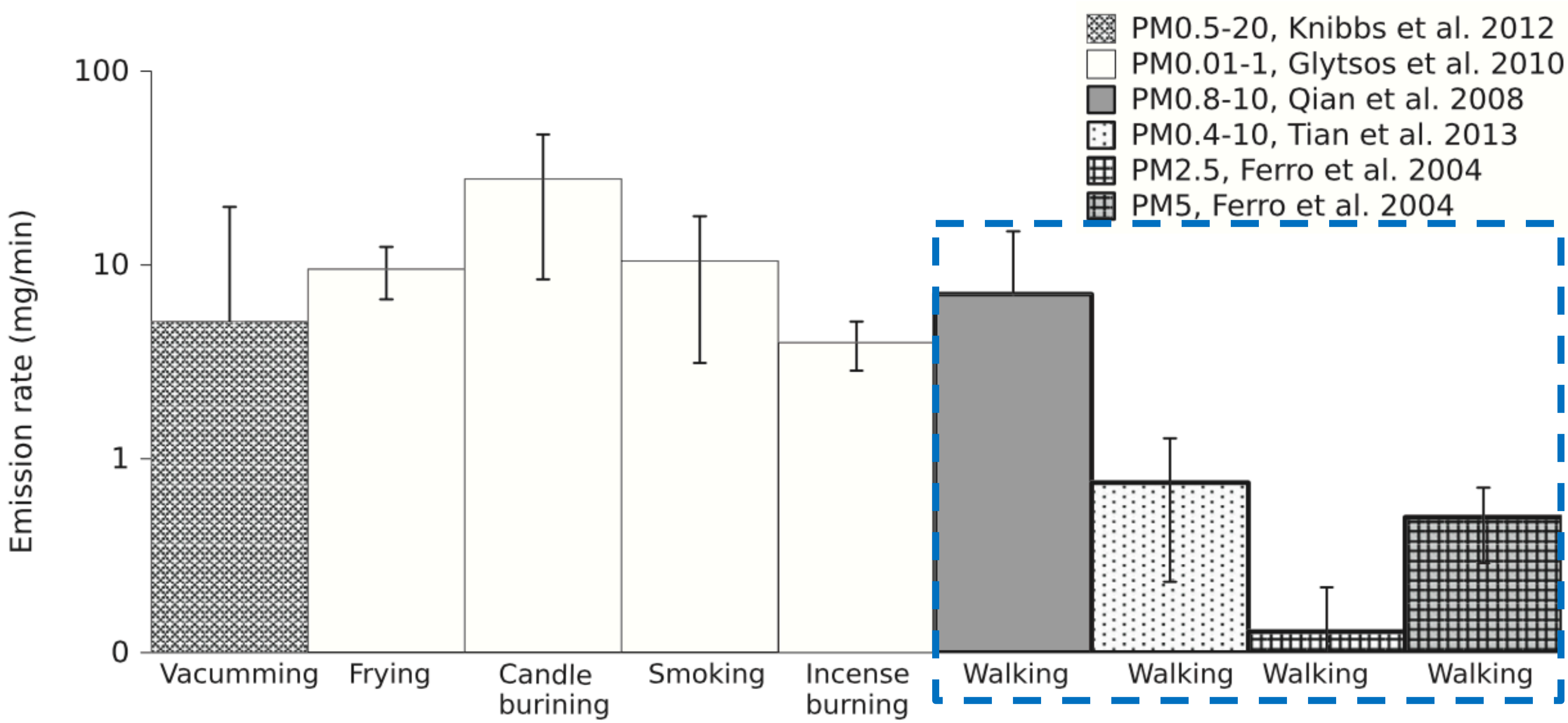
[1]: Peanuts comic, November 25, 1959; image: http://www.peanuts.com/wp-content/themes/desktop-theme-peanuts/images/characters/round/pigpen.png

Human movements, activity patterns & occupancy

my Finnish neighbor's baby, Rolle

images: http://cdn.c.photoshelter.com/img-get/I0000jDpWdk_4SJM/s/600/600/AAA4863.jpg, http://www.consumerreports.org/content/dam/cro/news_articles/health/CRO_health_SleepStory_1-14.jpg, http://www.trbimg.com/img-52bb9e87/turbine/la-1640202-me-1217-belmont-high-004-ik-jpg-20131225/2048/2048x1286, http://i.huffpost.com/gen/859155/original.jpg.

Big particulate(s) matter



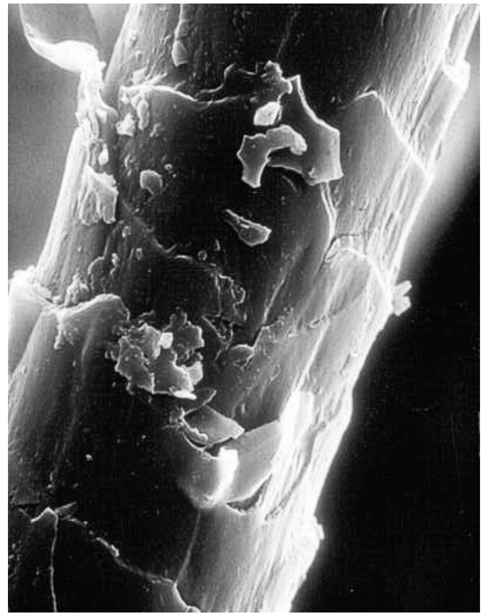
E for PM_{10} due to walking* ~ 1 to 10 mg/min

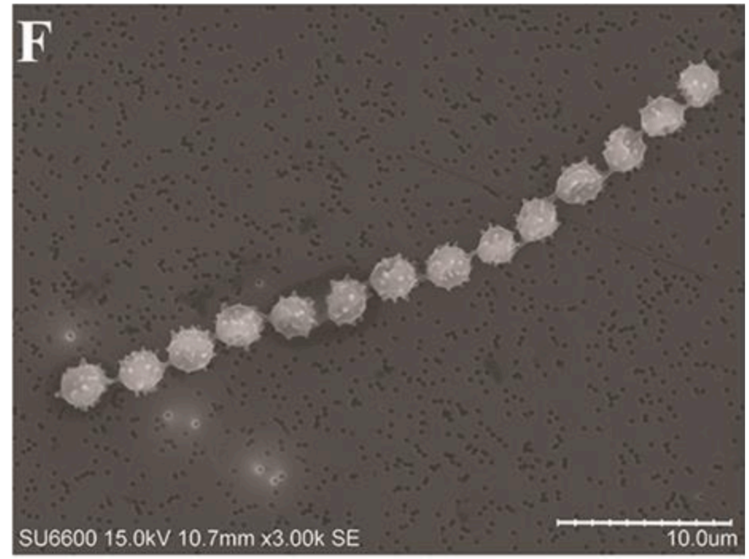
~ 10 to 100 kg of indoor dust particles < 10 μm resuspended in one's lifetime

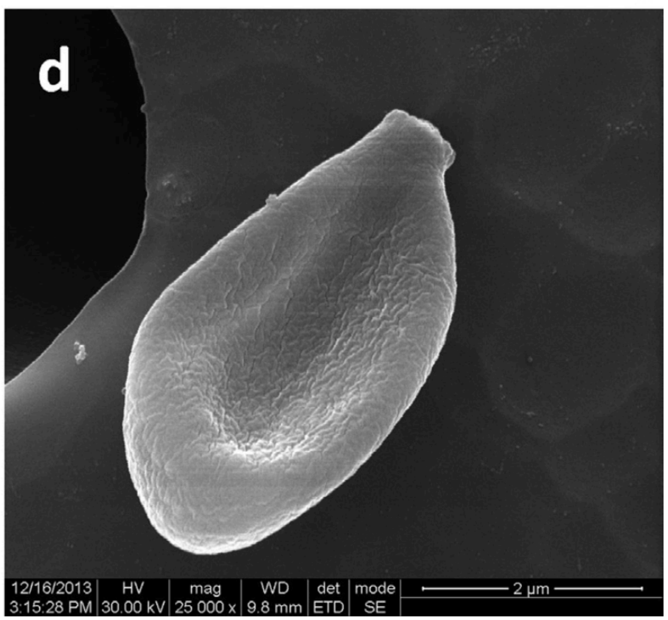
*as surrogate for other activities, considering varying level of movement intensity: *E* for 2-4 h, 0.1*E* for 8 h, 0.01*E* for 12-14 h, 78 y lifespan

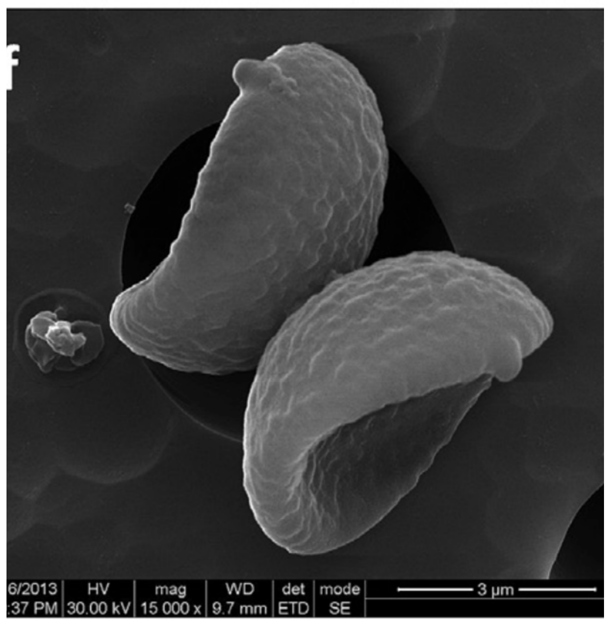
Figure from: Qian, J. et al. (2014). Walking-Induced Particle Resuspension in Indoor Environments. *Atmos. Environ*. 89:464-481.

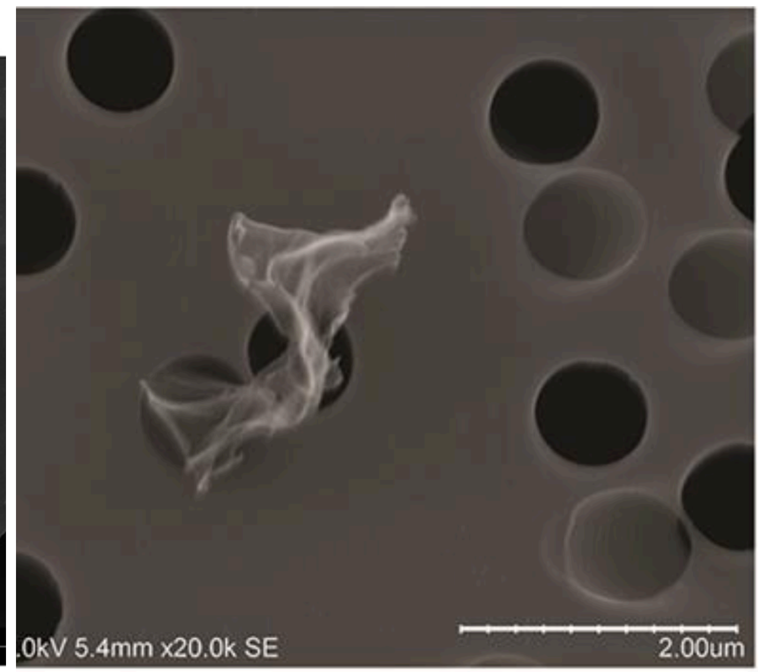
Resuspension = a source mechanism for all of the "stuff" in house dust











Images from: Afanou, K.A. et al. (2015). *Aerosol Sci. Technol*. 49:423-435., Valsan, A.E. et al. (2015). *Atmos. Environ*. 89:464-481., http://www.mayindoorair.com/photo-gallery/

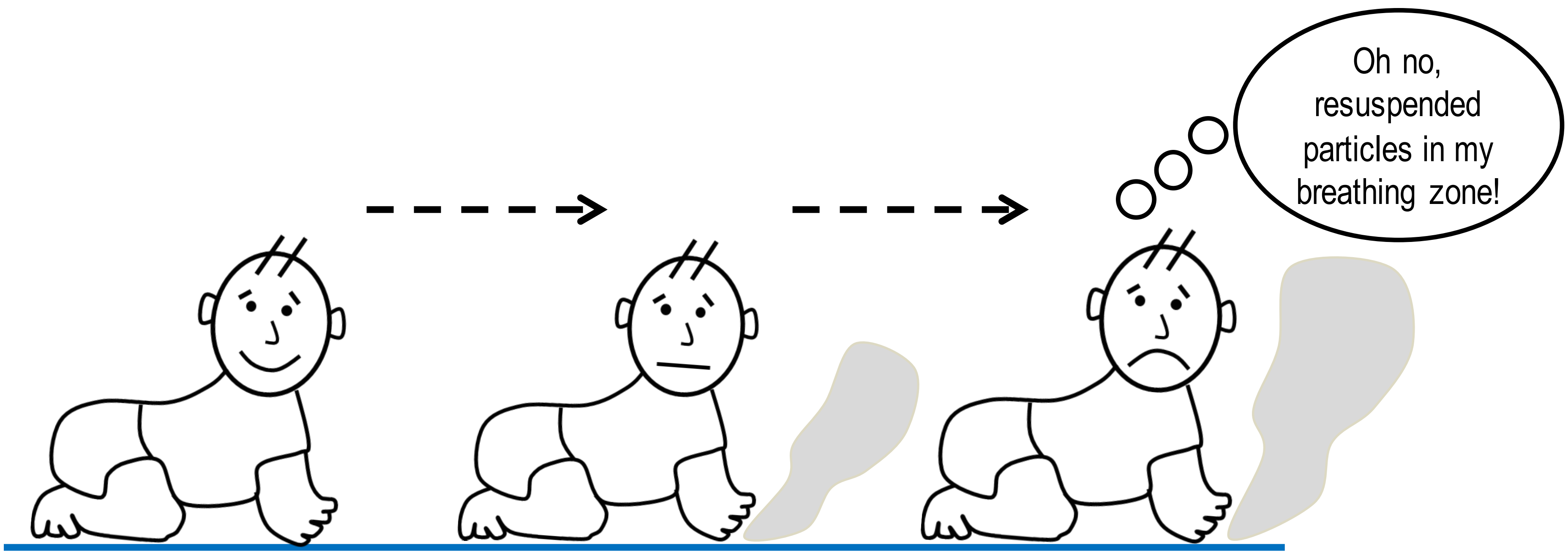
Exposure to resuspended particles

infants & the near-floor microenvironment: crawling, playing on carpet – little is known

the walking particle cloud: can induce self-exposure & exposure of others

mattress dust & the sleep microenvironment – 1/3rd of our life

occupational workplace exposures – contaminated clothing



From wind-blown dust to the mechanical foot: a timeline of seminal studies

Corn and Stein (1965)

Wen and Kasper (1989)

Nicholson (1993)

Thatcher and Layton (1995): Haagen-Smit Prize

Karlsson et al. (1999)

Montoya and Hildemann (2001)

Ibrahim et al. (2003)

Ferro et al. (2004)

Gomes et al. (2007)

Qian and Ferro (2008)

Rosati et al. (2008)

Mukai et al. (2009)

Tian et al. (2014)

Re-entrainment of Particles from a Plane Surface

MORTON CORN, Ph.D., and FELIX STEIN

University of Pittsburgh, Graduate School of Public Health, Pittsburgh, Pennsylvania

Image from: Tian, Y. et al. (2014). A Comparative Study of Walking-Induced Dust Resuspension Using a Consistent Test Mechanism. *Indoor Air.* 24:592-603.

Mechanistic approach – material-balance model

air $$V\frac{dC_j}{dt} = S_j - C_j\left(\beta_j V + Q\right)$$

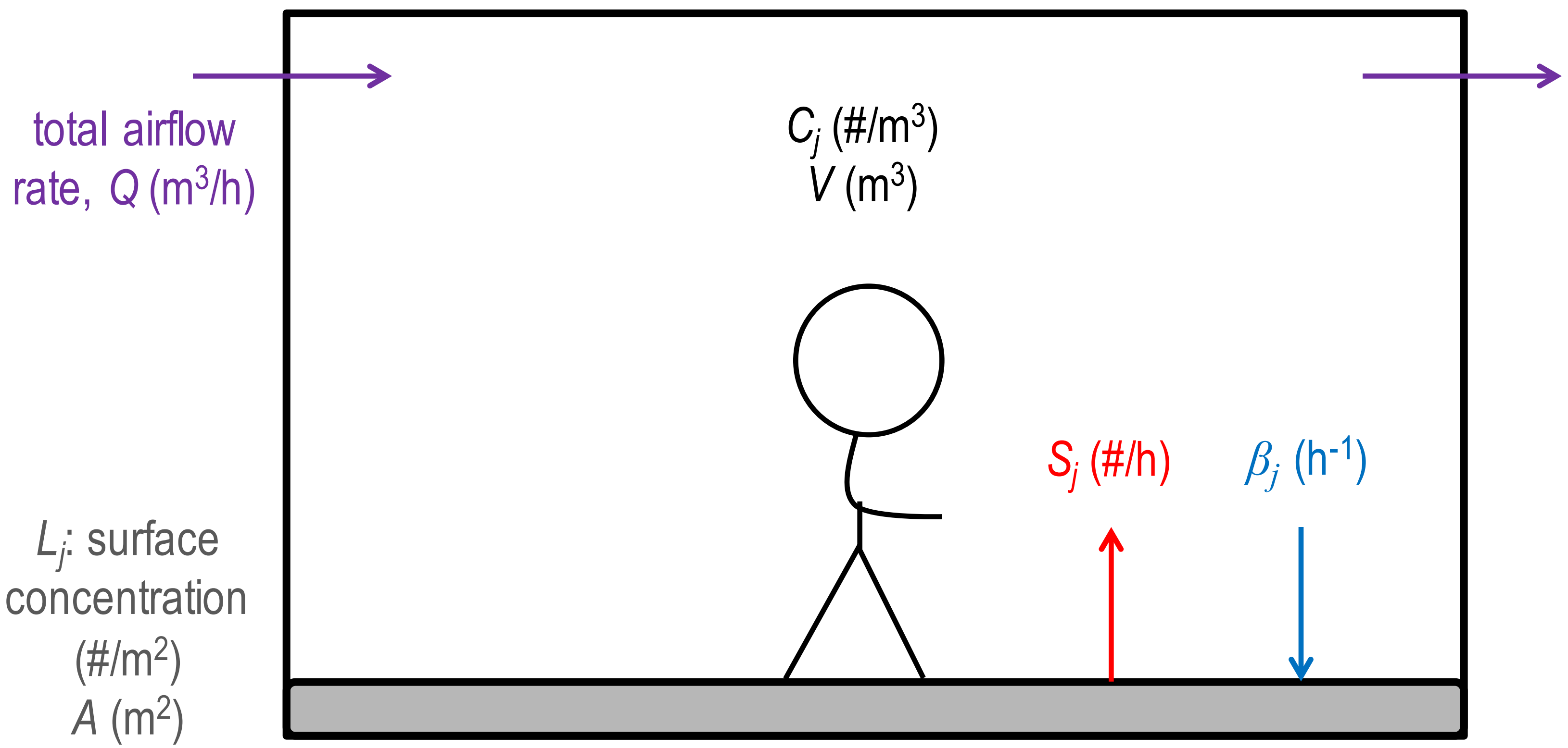
dust $$A\frac{dL_j}{dt} = C_j\beta_j V - S_j$$

source term, S_j (#/h)

emission rate: E_j (#/h) – not linked to dust

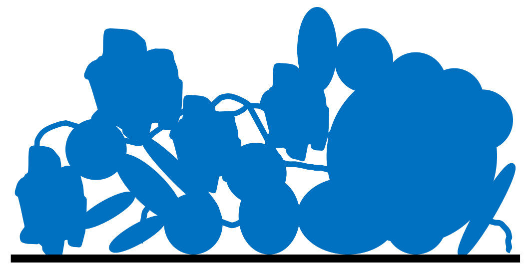
resuspension rate: $RR_j{*}L_j{*}A$ – RR_j (h^{-1})

resuspension fraction: $r_j{*}L_j{*}A{*}f$ – r_j (-) & f (movement frequency, h^{-1})



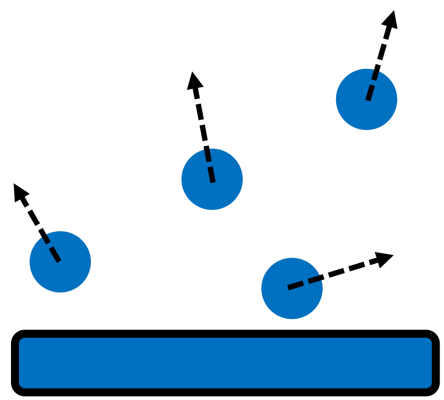
linking resuspension to exposure

dust



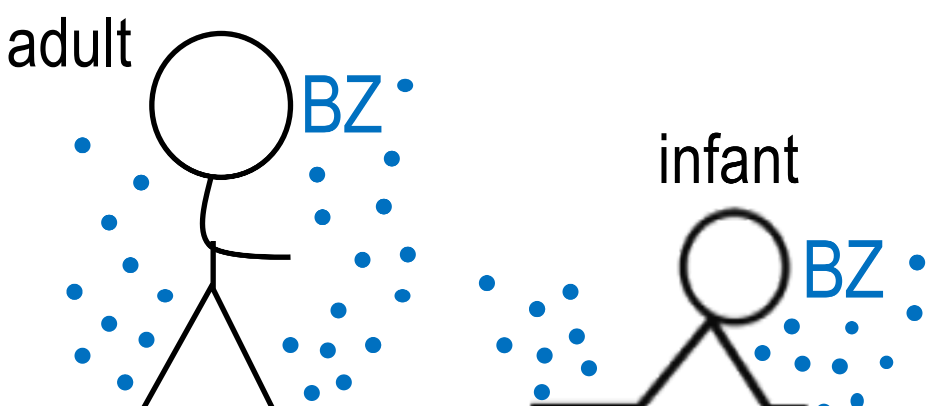
L_j & volume fraction/dlogD_p
composition & morphology
deposit structure
adhesion
indoor surface

dust to air



E_j, RR_j, r_j
dN/dlogD_p & time
type of human movement
removal forces
occupancy

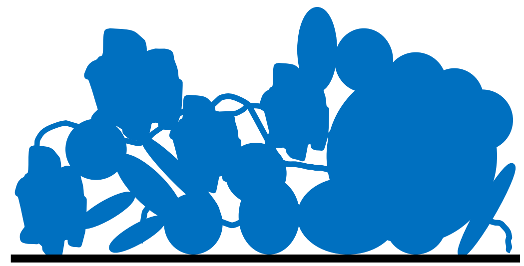
air to BZ



vertical variation
airborne particle transport
airflow patterns
exposure assessment

linking resuspension to exposure

dust



L_j & volume fraction/dlogD_p
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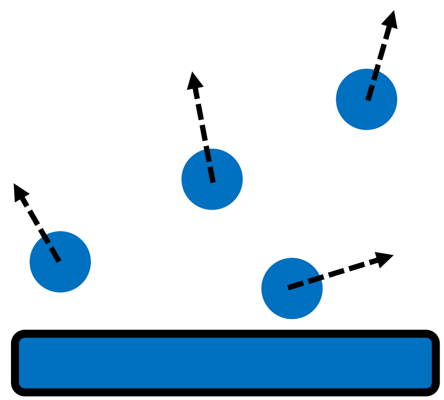

E_j, RR_j, r_j
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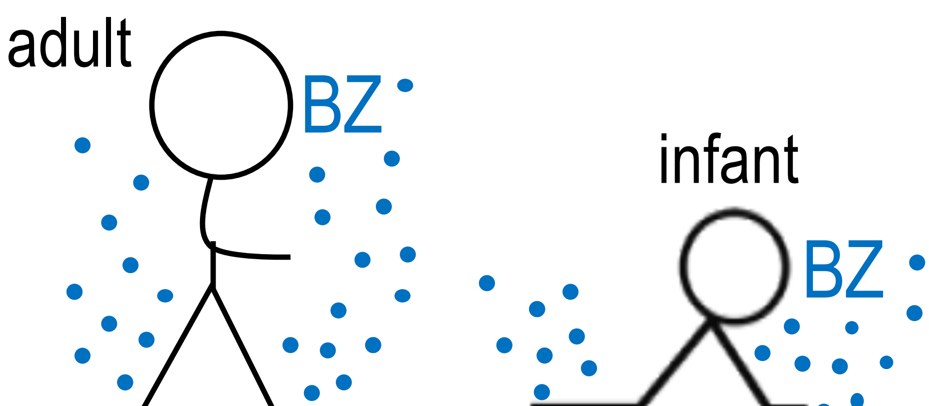


vertical variation
airborne particle transport
airflow patterns
exposure assessment

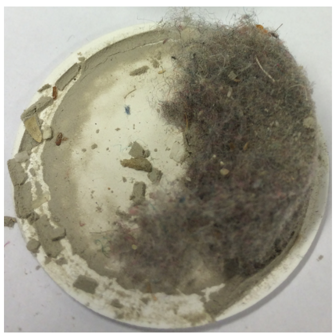
Dust: need for size-resolved dust data from all indoor surfaces (L_j)

→ floor & mattress dust: commonly collected in epidemiological studies, e.g. analysis for SVOCs and microorganisms

→ little data on size distribution by number, volume/mass fraction, e.g. via laser diffraction, SEM

→ how does dust collection affect fragile agglomerates?

→ novel surface dust collection techniques



dust loads on indoor surfaces (g/m^2): large variability

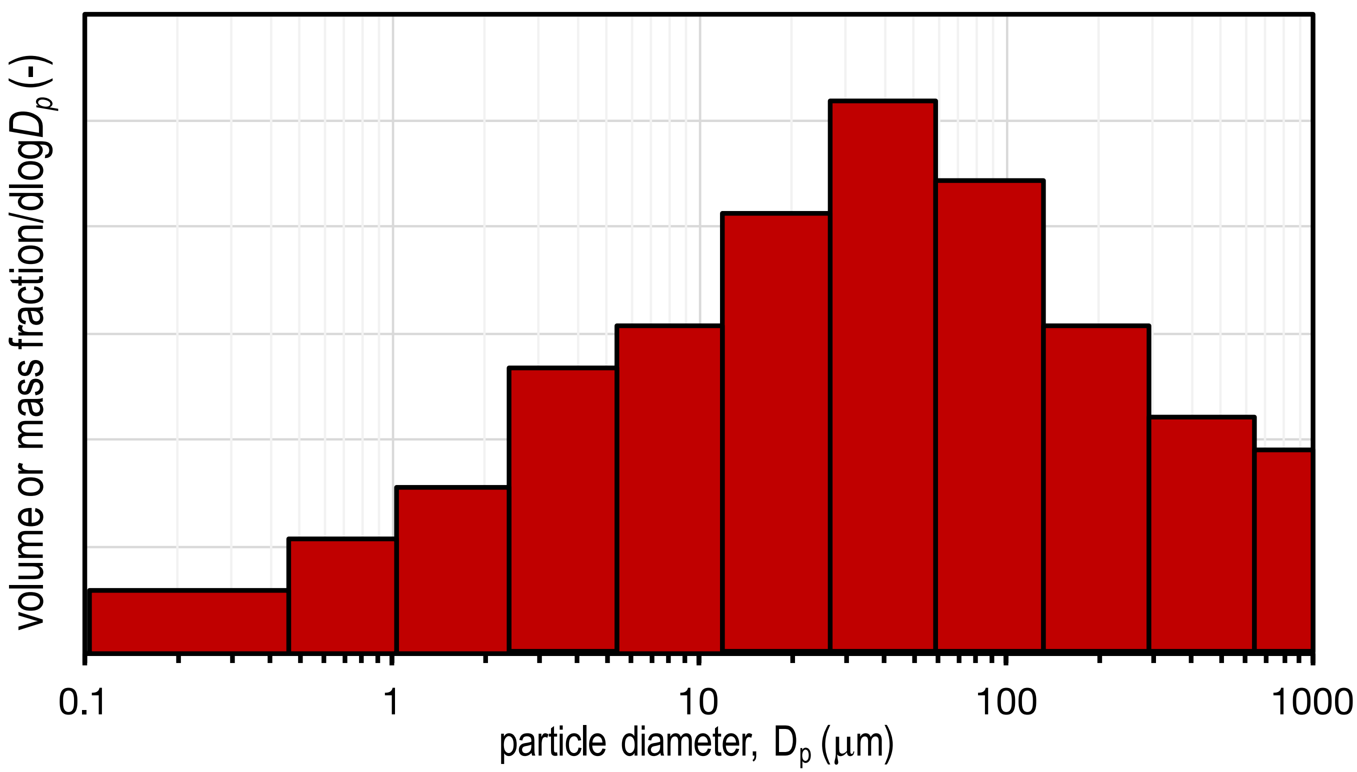
hard floor: 0.1 to 10

carpet: 1 to 100

ventilation duct: 1 to 100

mattress: 0.1 to 1

clothing: ?



note: above figure is for illustrative purposes and is not actual data

Dust: improving physical characterization of indoor dust

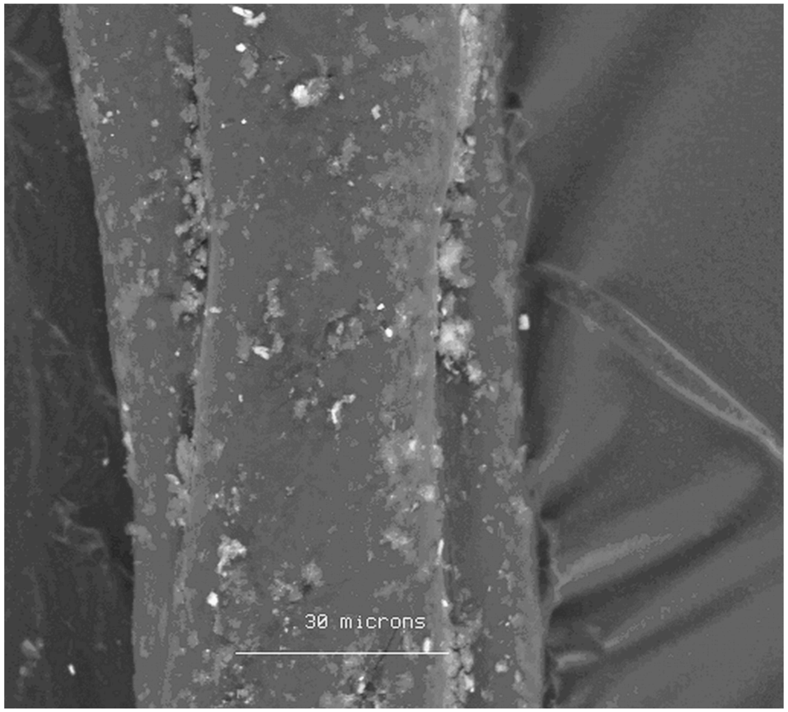
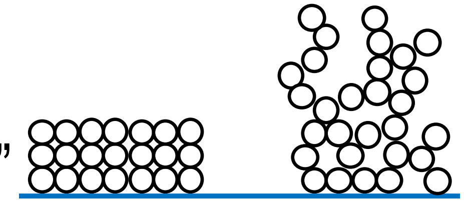


Image from: Rosati, J. et al. (2008). Resuspension of Particulate Matter from Carpet Due to Human Activity. *Aerosol Sci. Technol*. 42(6):472-482.

→ tools: microscopy, modeling

→ porosity: "cake-like" vs. "fluffy"



→ agglomeration of < 10 μm particles

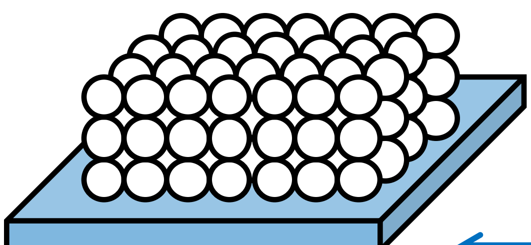
→ particle-surface & particle-particle interactions

→ formation over time

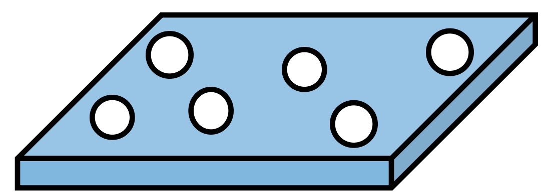
→ mass transfer of SVOCs within porous deposit?

→ *how do we influence structure?*, e.g. compression of carpet/fabric fibers, cleaning activities

multilayer

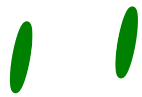
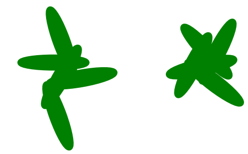


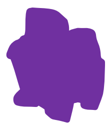
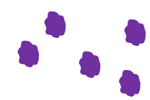
monolayer

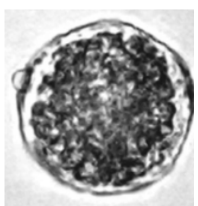
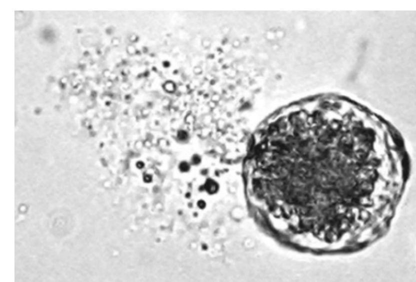


Dust: considerations for biological particles & their adhesion to indoor surfaces

spectrum of shapes, surface features, aerodynamic diameters, electrostatic charge & extent of agglomeration/adhesion with other microbes in dust


single bacterial cells ⟷ bacterial agglomerates



fungal spores ⟷ fungal fragments



pollen grains ⟷ pollen fragments



abiotic particle (e.g. mineral dust) with microbes attached

Pollen image from: Miguel, A.G. et al. (2006). Meteorological Influences on Respirable Fragment Release from Chinese Elm Pollen. *Aerosol Sci. Technol*. 40:690-696.

Dust: particles on fabric fibers (clothing, bedding), what do we know?

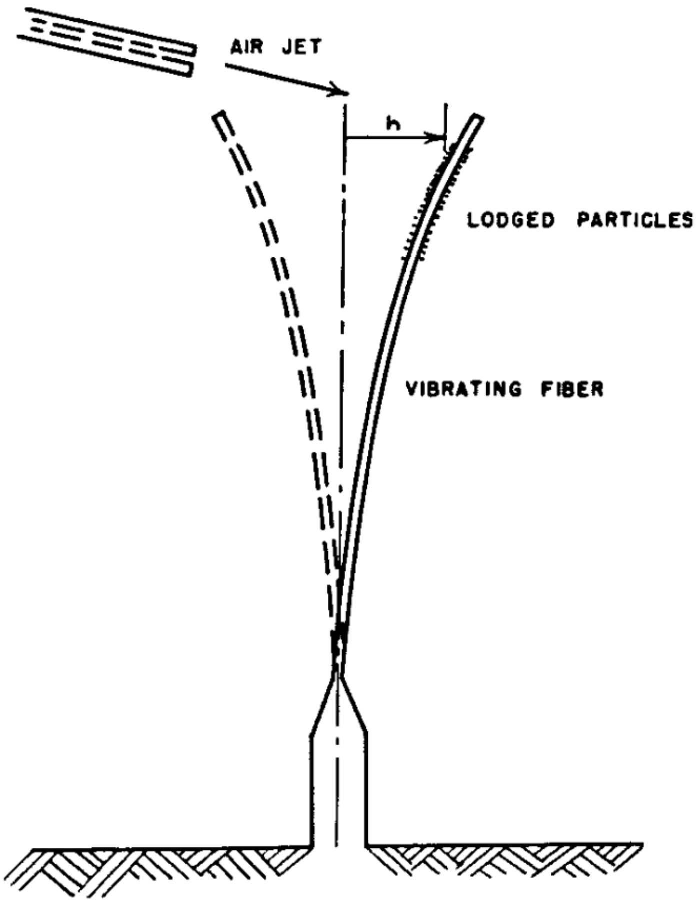
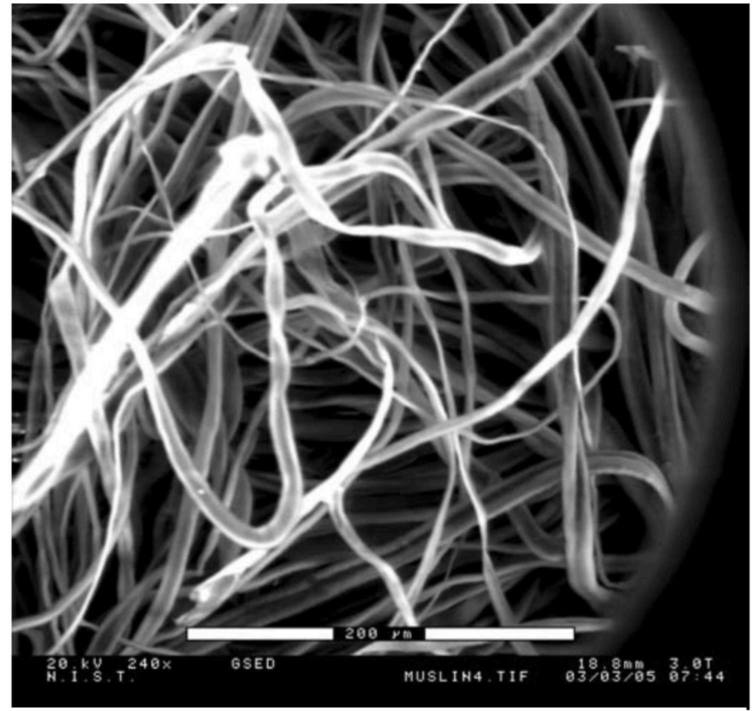
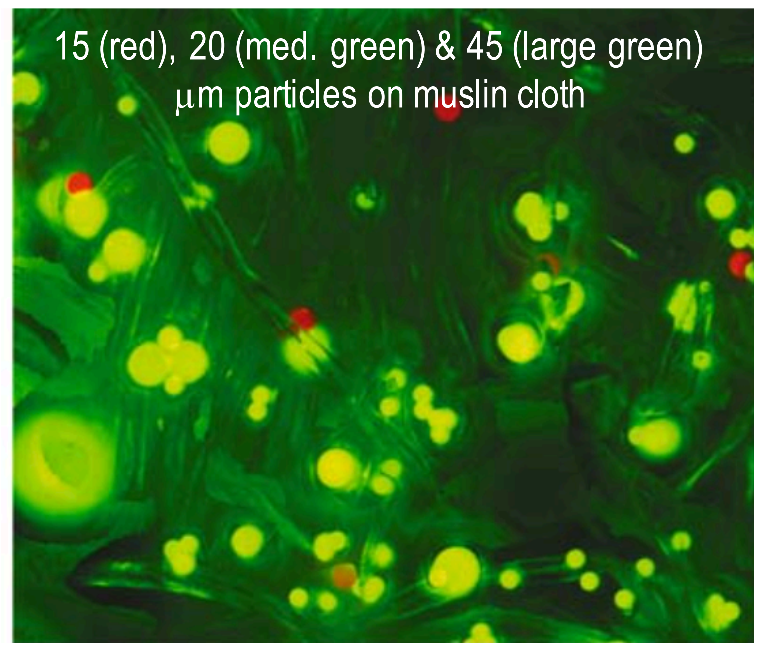


FIGURE 15. Vibrating fiber

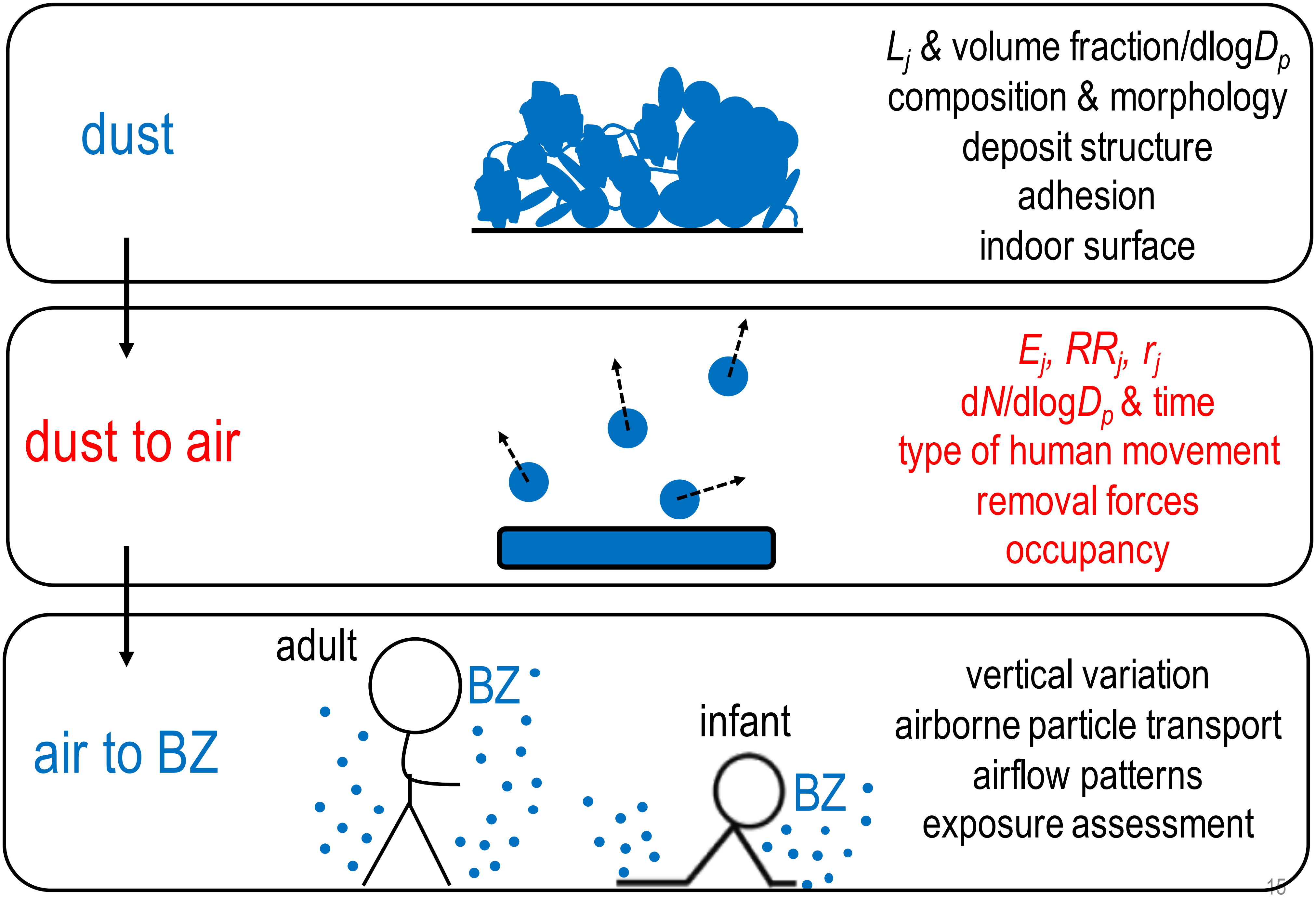
Above image from: Larsen, R.I. (1958). The Adhesion and Removal of Particles Attached to Air Filter Surfaces. *AIHA J.* 19(4):265-270.

Right images from: Fletcher, R. et al. (2008). Measurements of Air Jet Removal Efficiencies of Spherical Particles from Cloth and Planar Surfaces. *Aerosol Sci. Technol.* 42(12):1052-1061.





linking resuspension to exposure



Dust to air: walking

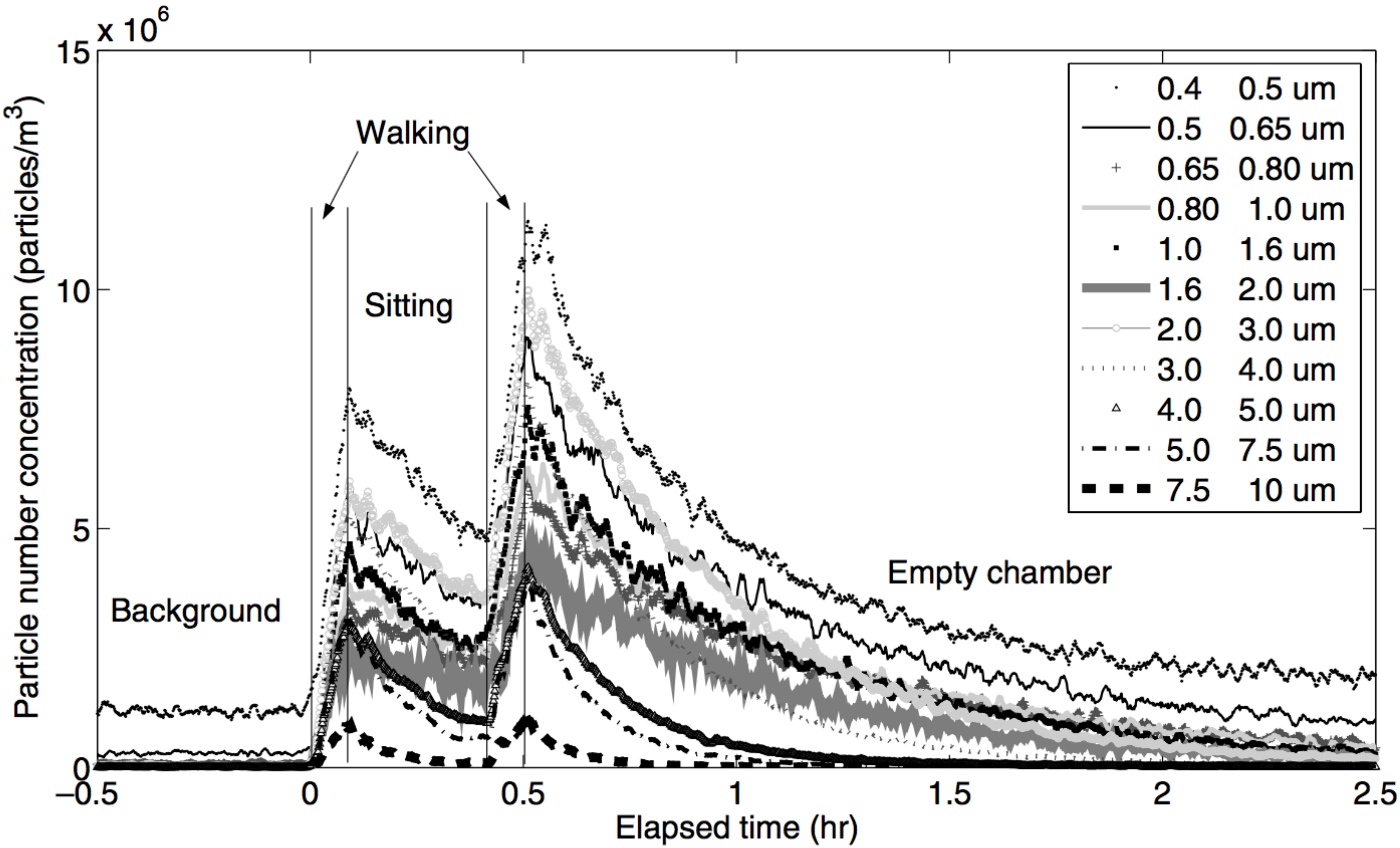
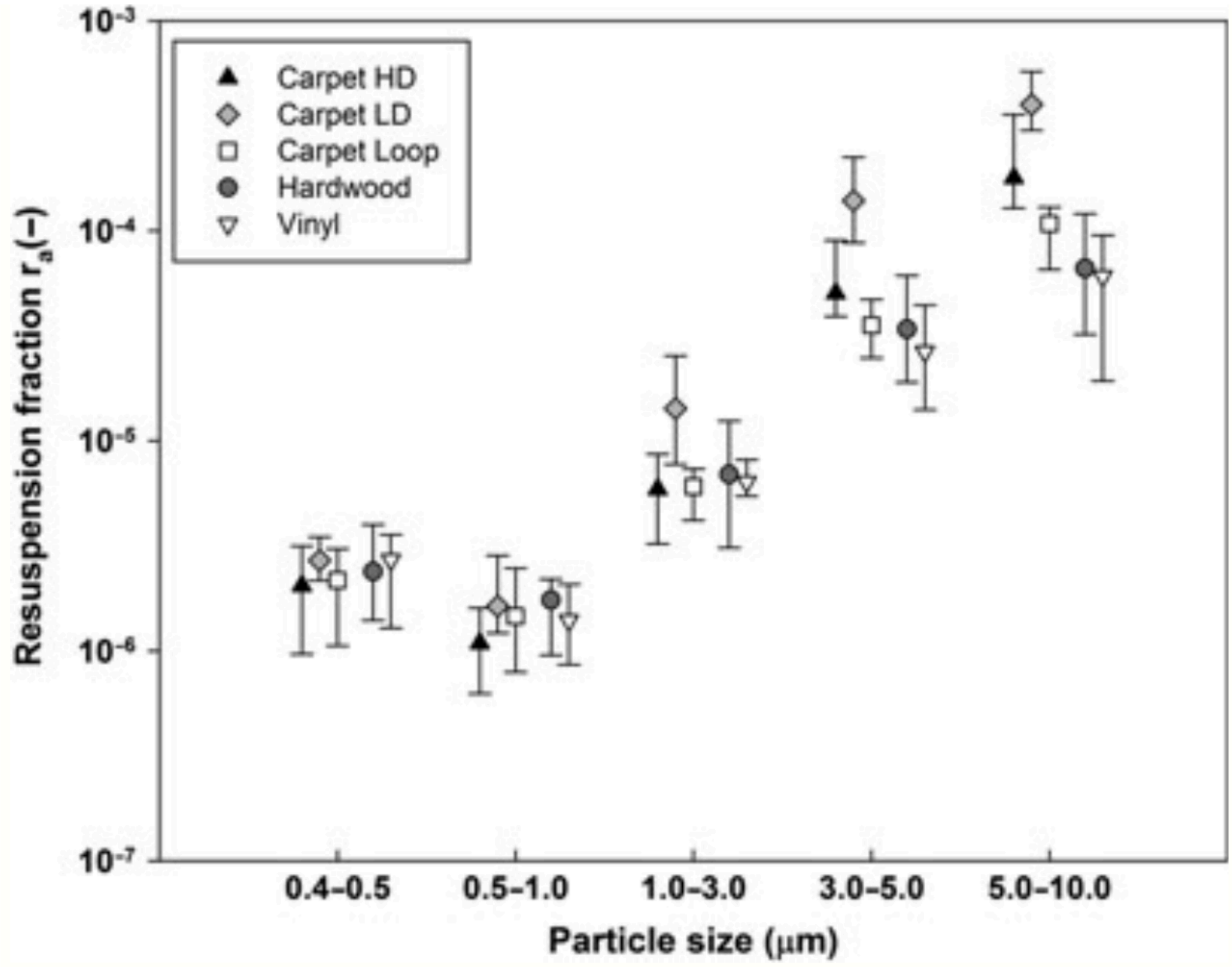


Figure from: Qian, J. and Ferro, A. (2008). Resuspension of Dust Particles in a Chamber and Associated Environmental Factors. *Aerosol Sci. Technol.* 42(7):566-578.

Dust to air: walking – flooring type is key (r_j)



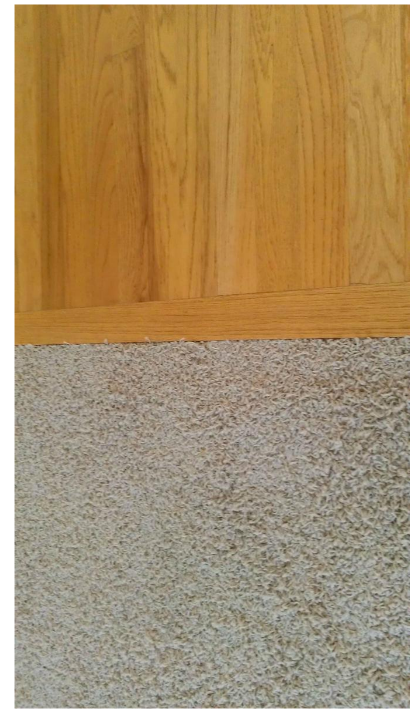


Figure from: Tian, Y. et al. (2014). A Comparative Study of Walking-Induced Dust Resuspension Using a Consistent Test Mechanism. *Indoor Air*. 24:592-603.
Image: http://i.imgur.com/POUMeTz.jpg?1

Dust to air: sleeping – experimental chamber study

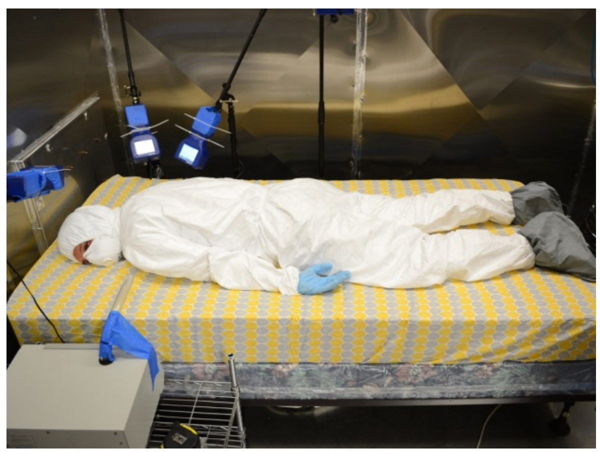
routine of five movements, 10 volunteers, dust loads of 0.1 and 1 g/m^2

M1

M2

M3

M3

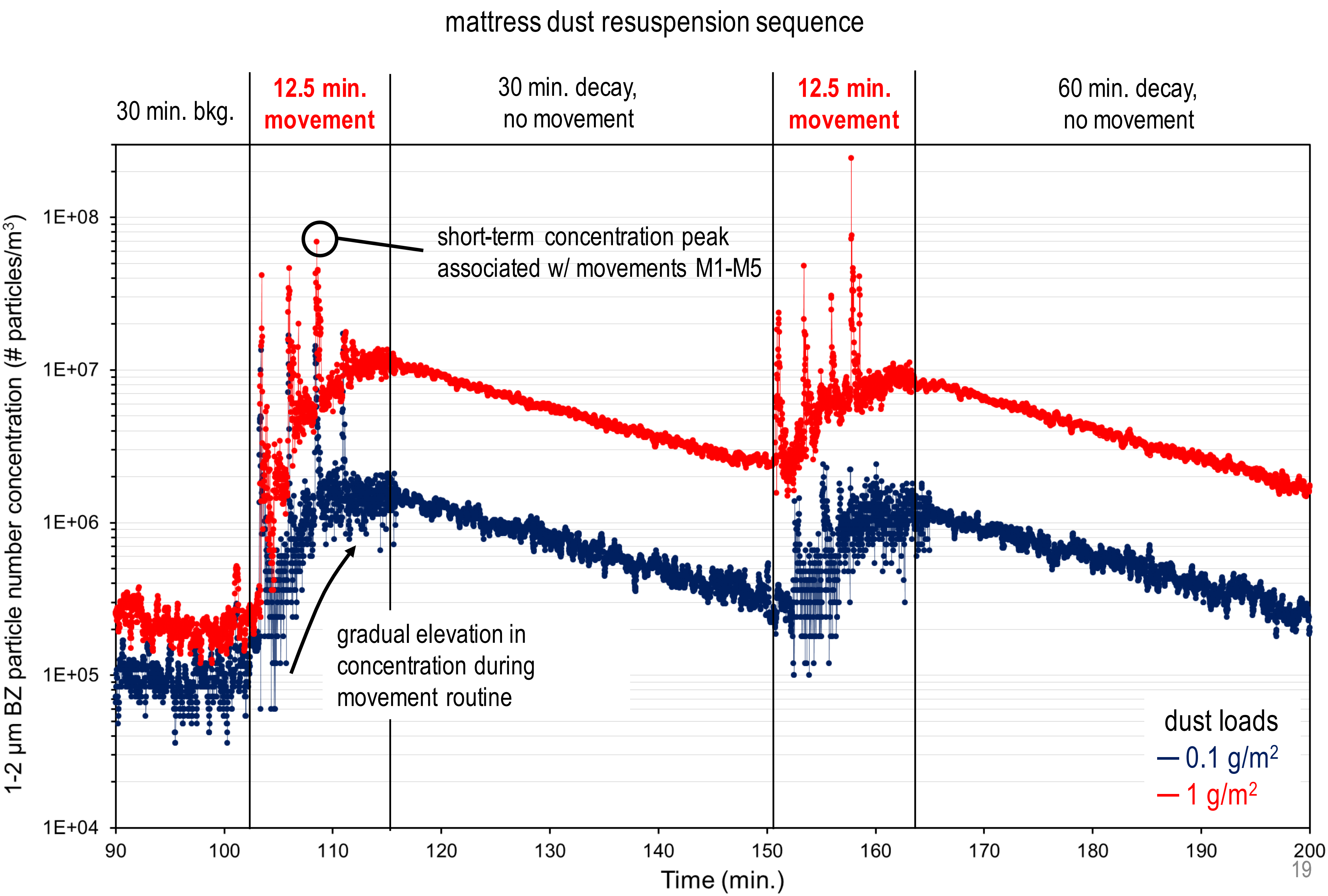


M4

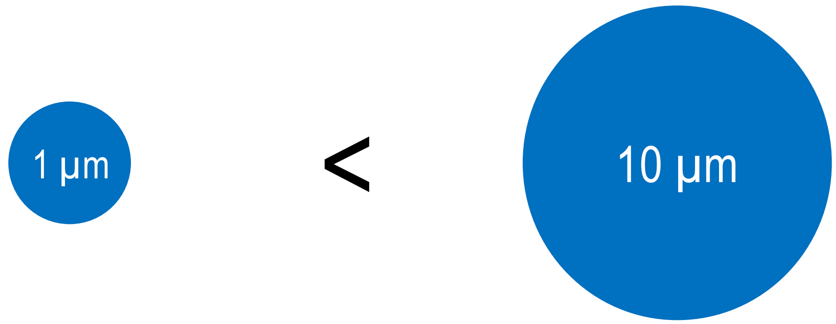
M5

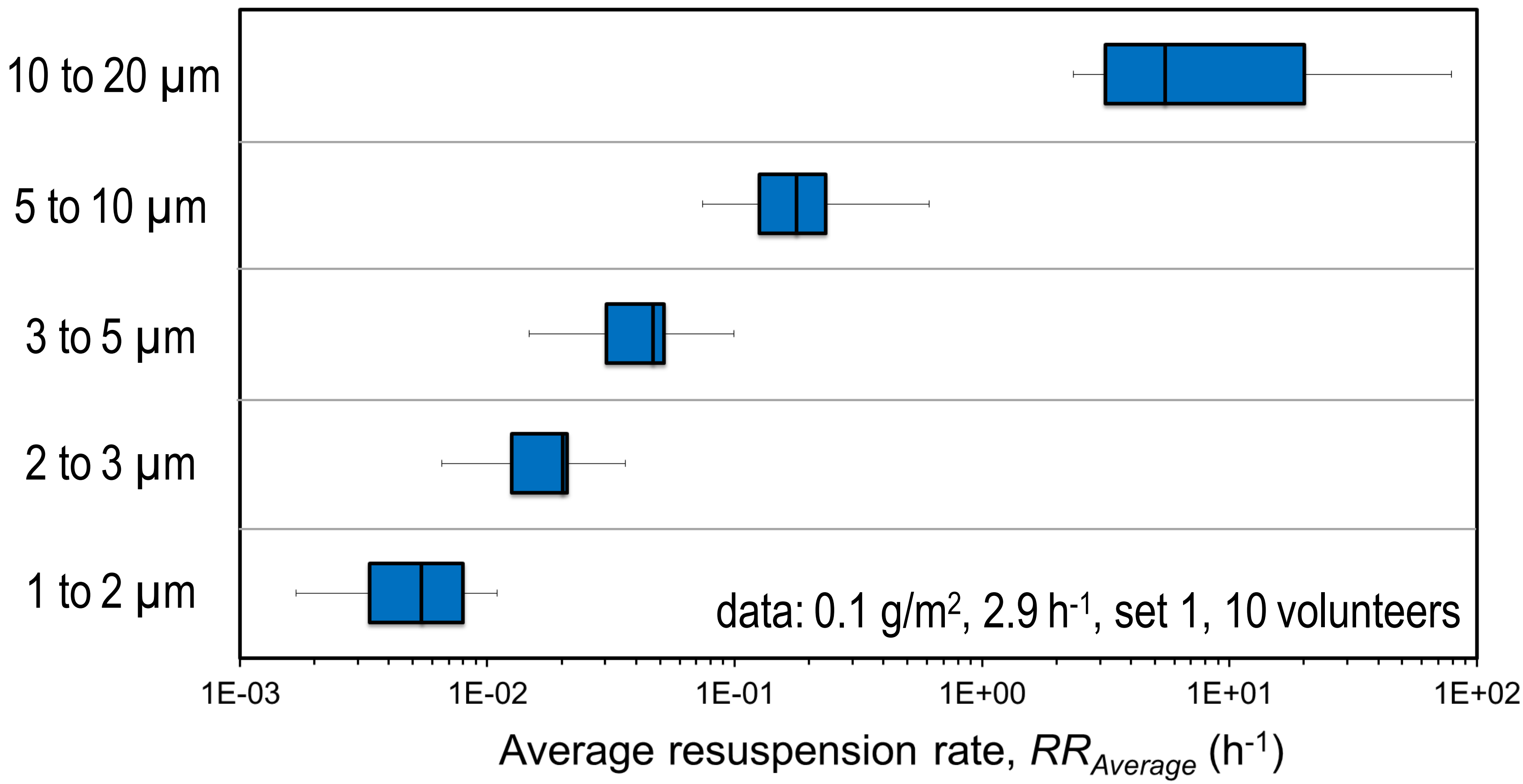
Boor, B.E. et al. (2015). Characterizing Particle Resuspension from Mattresses: Chamber Study. *Indoor Air*. 25:441-456.

Dust to air: sleeping – inhaling while sleeping

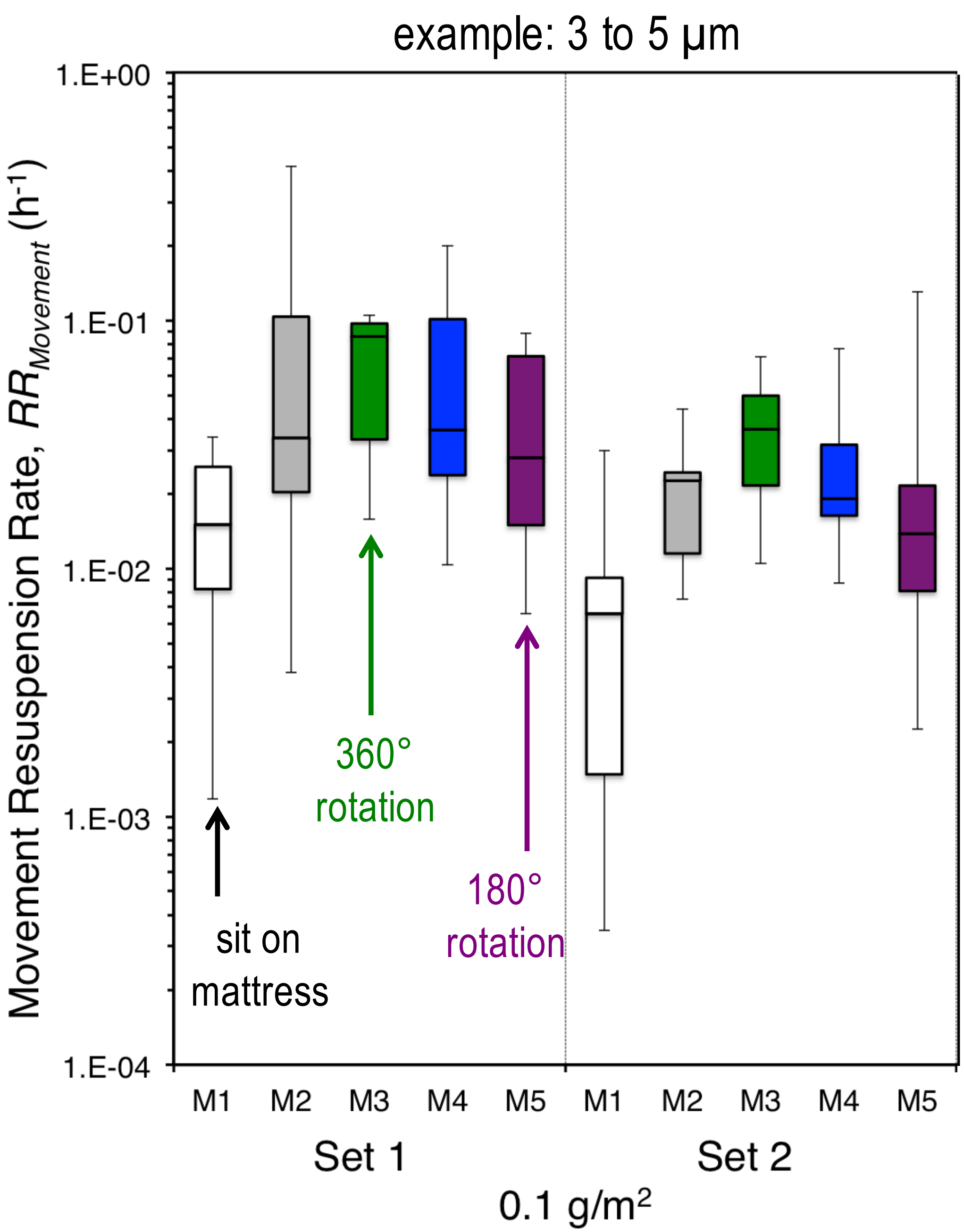


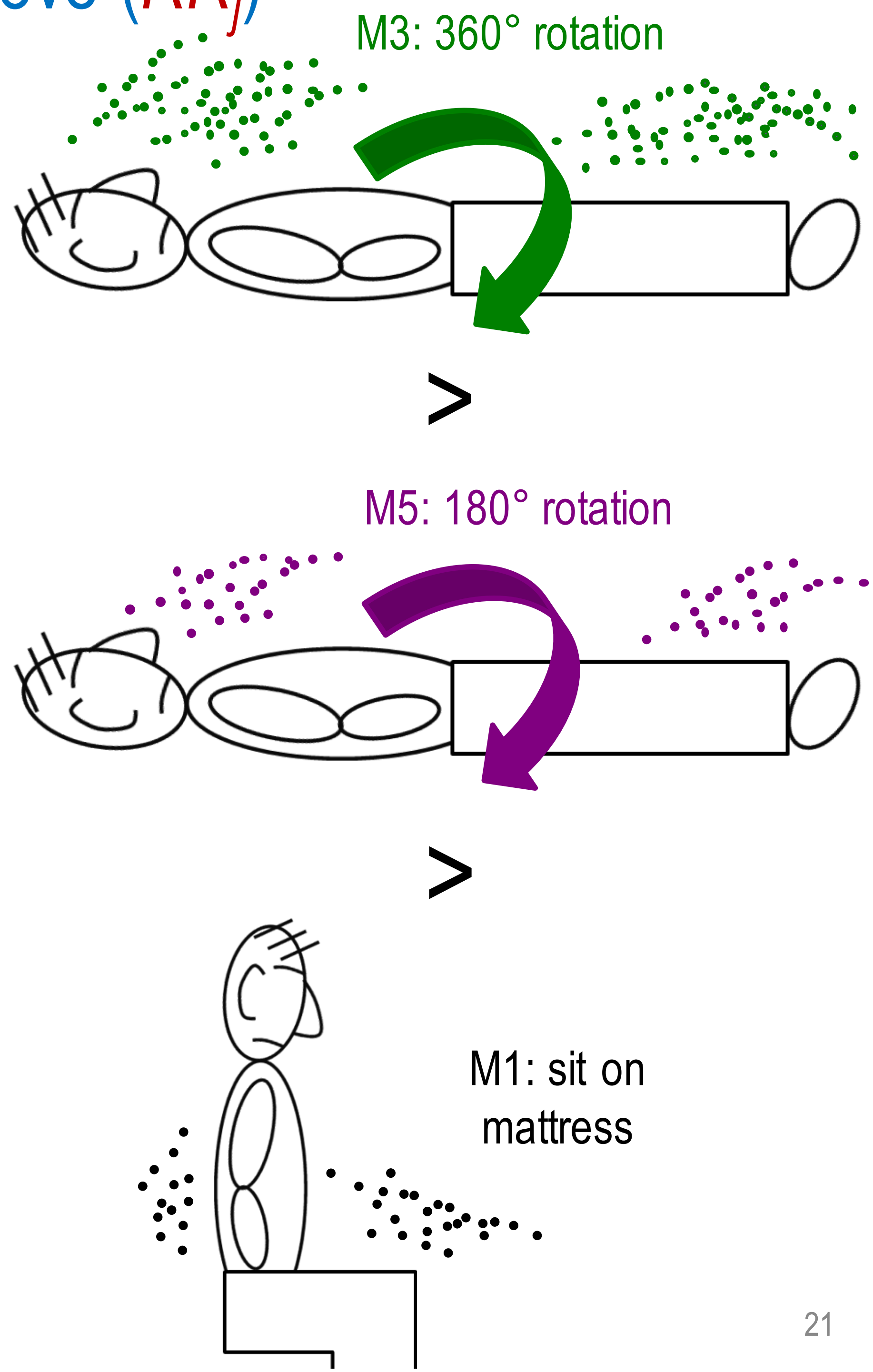
Dust to air: sleeping – resuspension rate (RR_j)



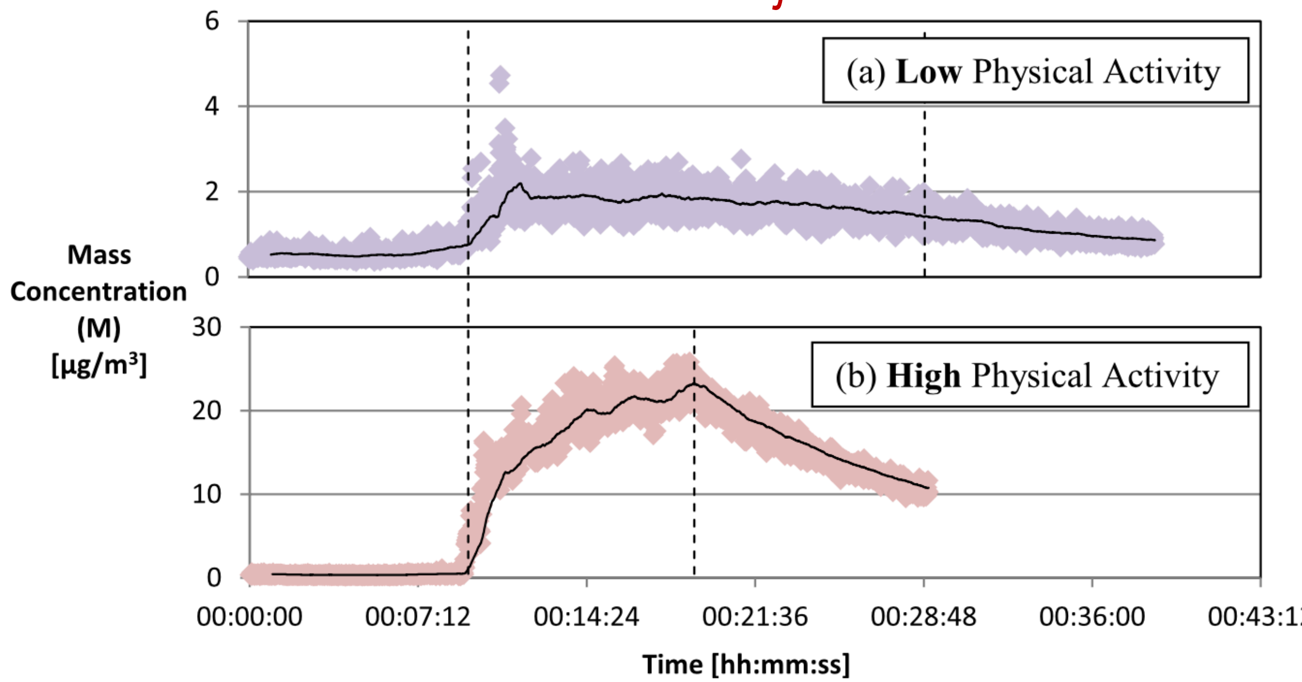


Dust to air: sleeping – the way you move (RR_j)

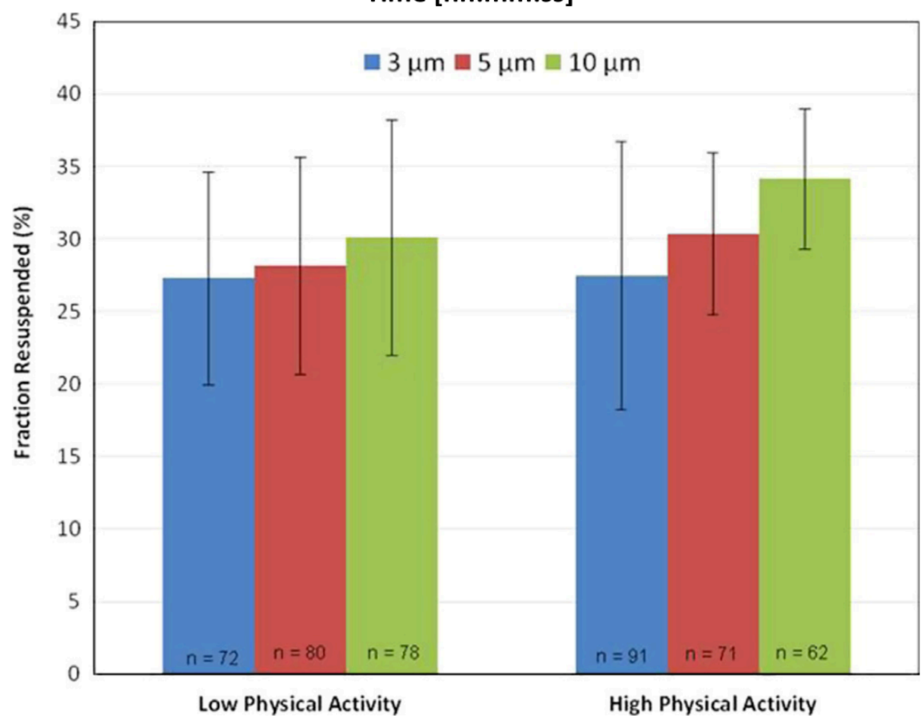




Dust to air: clothing – Irish dancing to a Reel (r_j)



Above figures from: McDonagh, A. and Byrne, M.A. (2014). The Influence of Human Physical Activity and Contaminated Clothing Type on Particle Resuspension. *J. Environ. Radio.* 127:119-126.

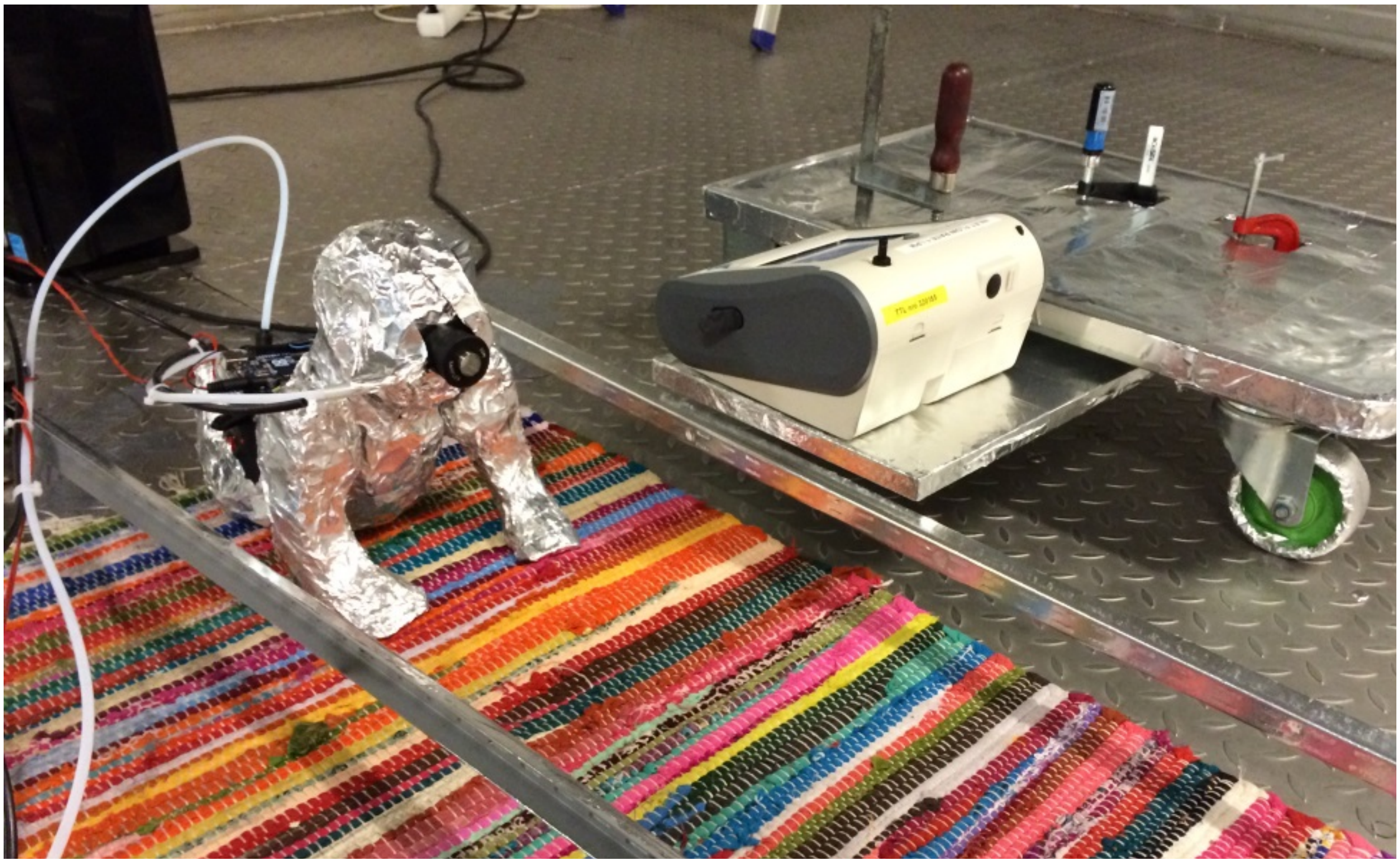


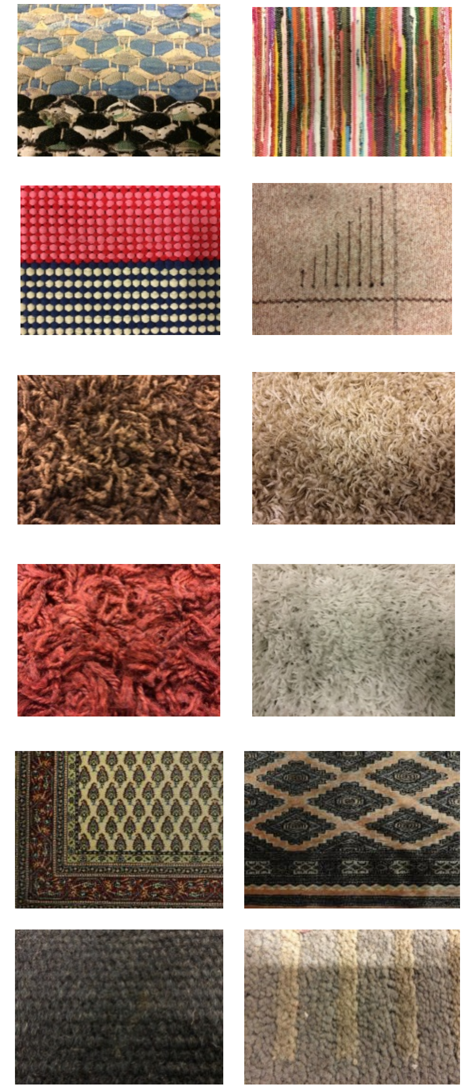
Right figure from: McDonagh, A. and Byrne, M.A. (2014). A Study of the Size Distribution of Aerosol Particles Resuspended from Clothing Surfaces. *J. Aerosol Sci.* 75:94-103

Dust to air: crawling – experimental chamber study

4 kg simplified mechanical crawling infant
real-time aerosol sampling in infant BZ and bulk air (not shown)
IOM inhalable sampler (~PM_{100}) for qPCR/NGS analysis

12 carpets borrowed from Helsinki residents





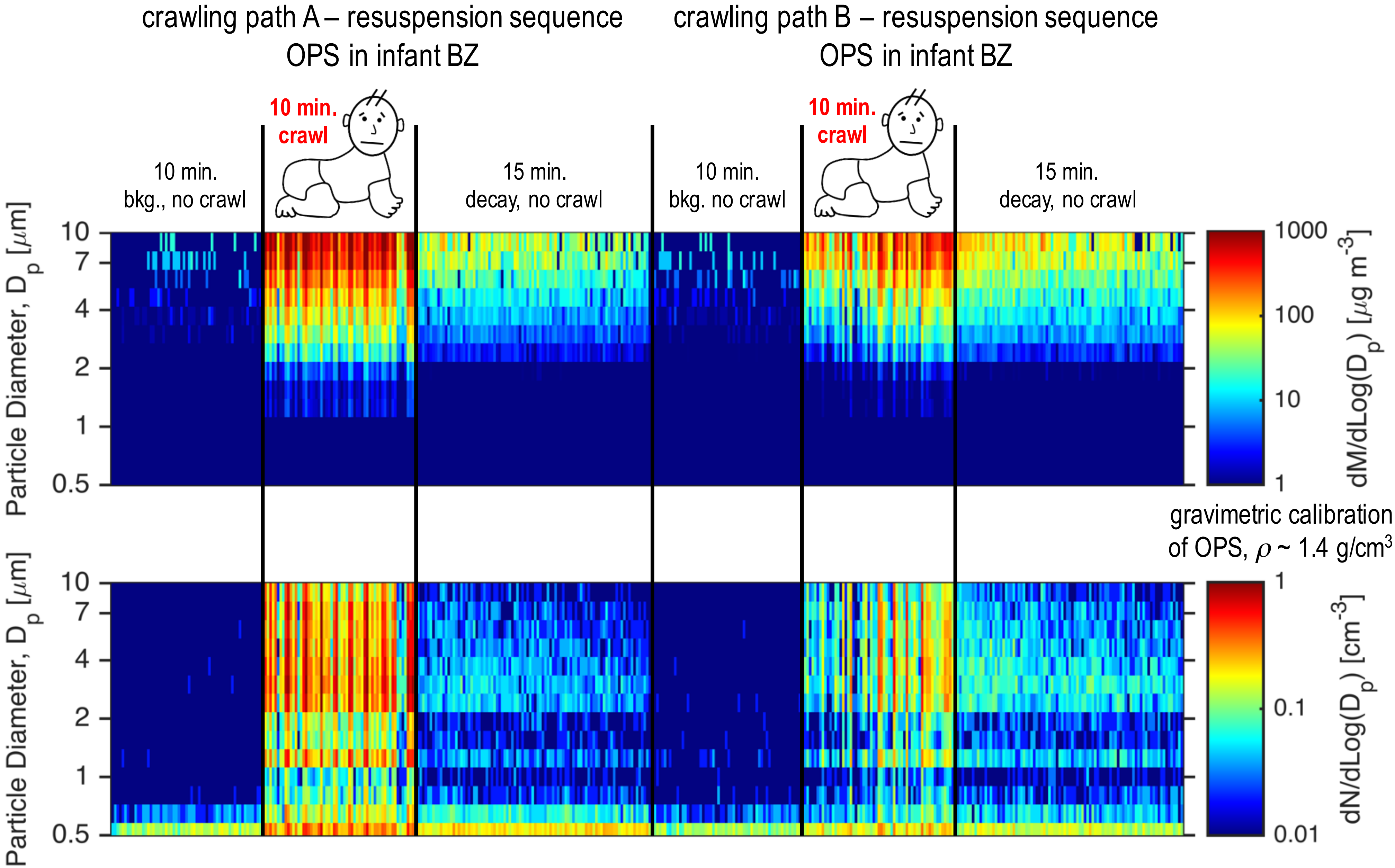
Dust to air: crawling – resuspension in real-time

video links:

https://vimeo.com/107277872

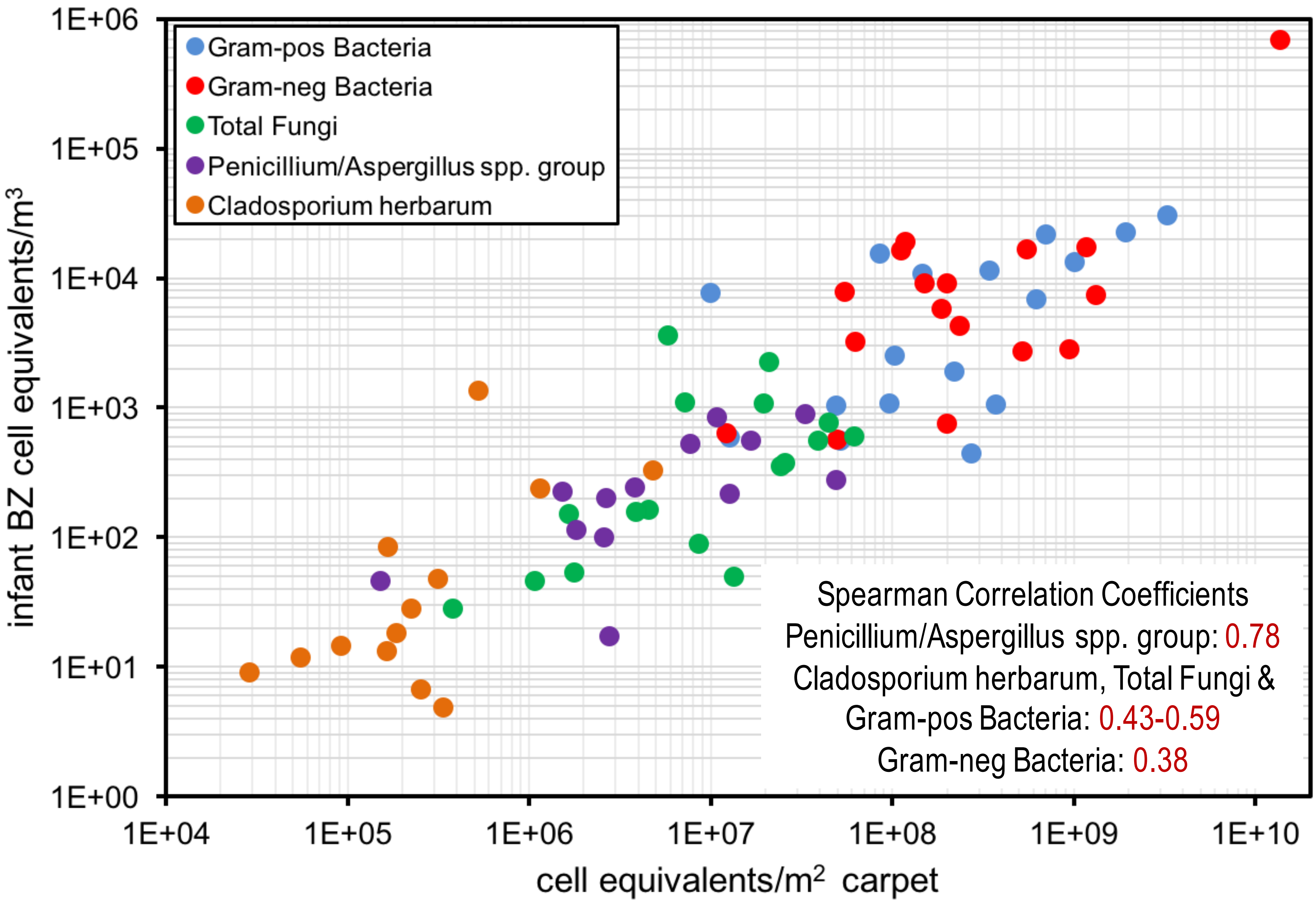
https://vimeo.com/107076687

Dust to air: crawling – “the infant playpen effect”



Dust to air: crawling – linking microbes in dust to infant BZ

large variation in microbial concentrations in infant BZ & surface dust across 12 + [5] = 17 carpets
analysis of qPCR data by Martin Täubel, Finnish National Institute for Health & Welfare



Dust to air: transient behavior – real-time bioaerosols

LIF: laser-induced fluorescence (UV-APS, WIBS, BioScout)
FBAP: fluorescent biological aerosol particle, dN_F/dlogDp

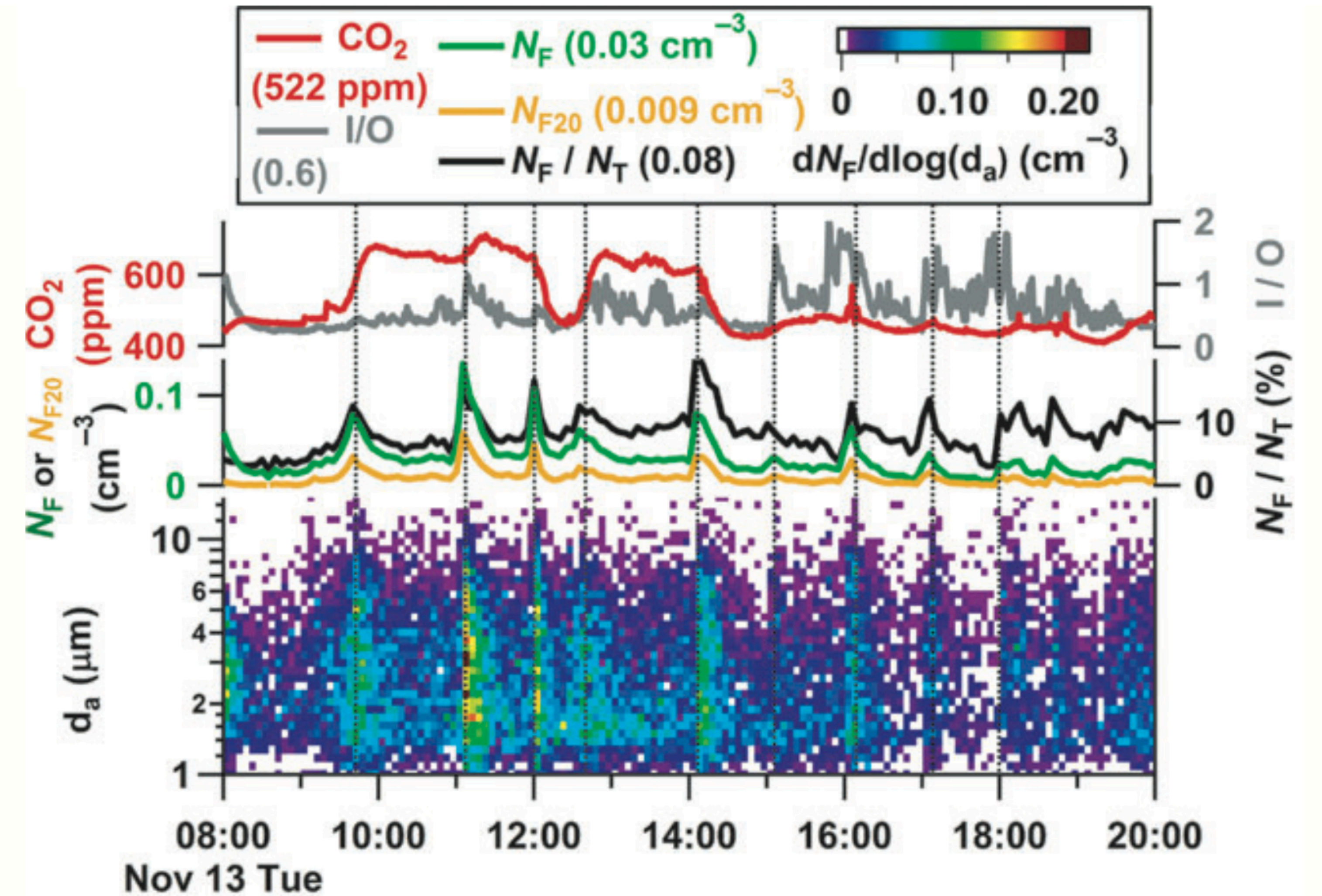
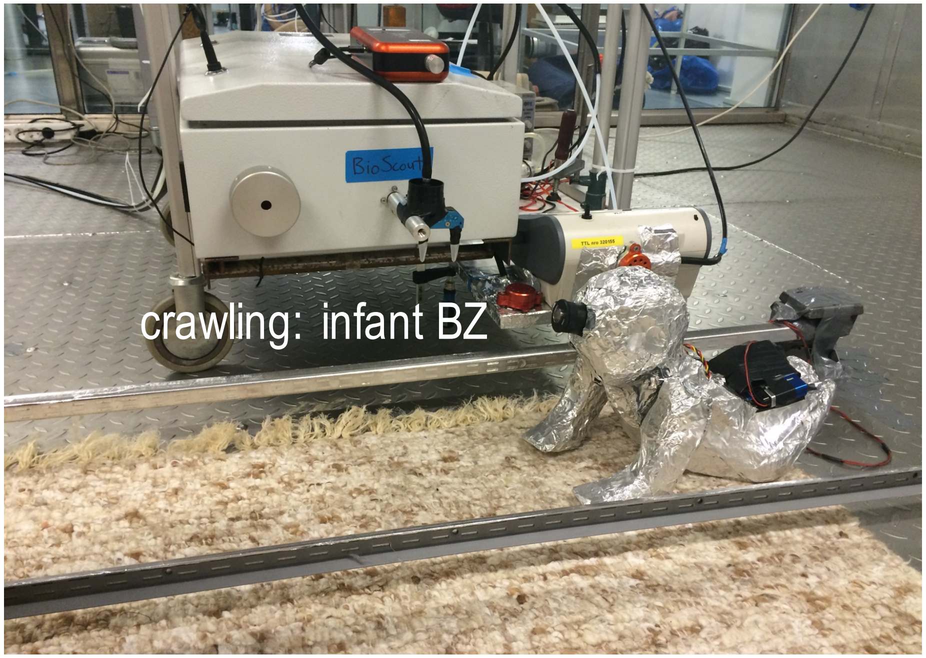
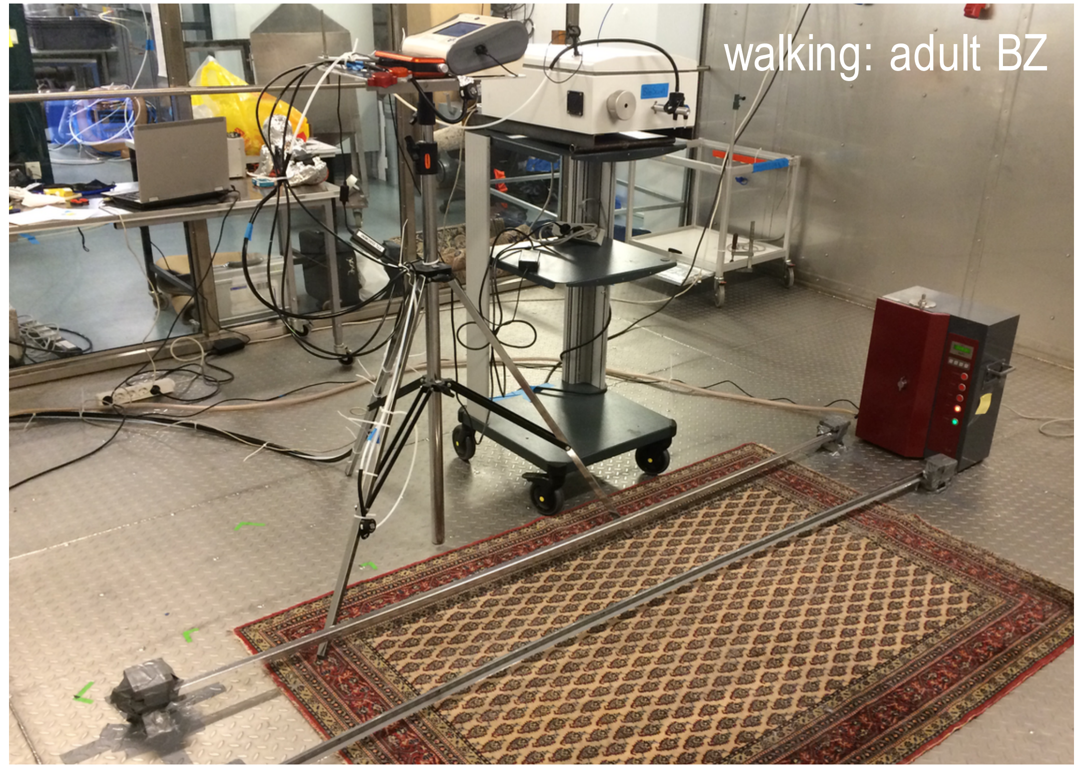
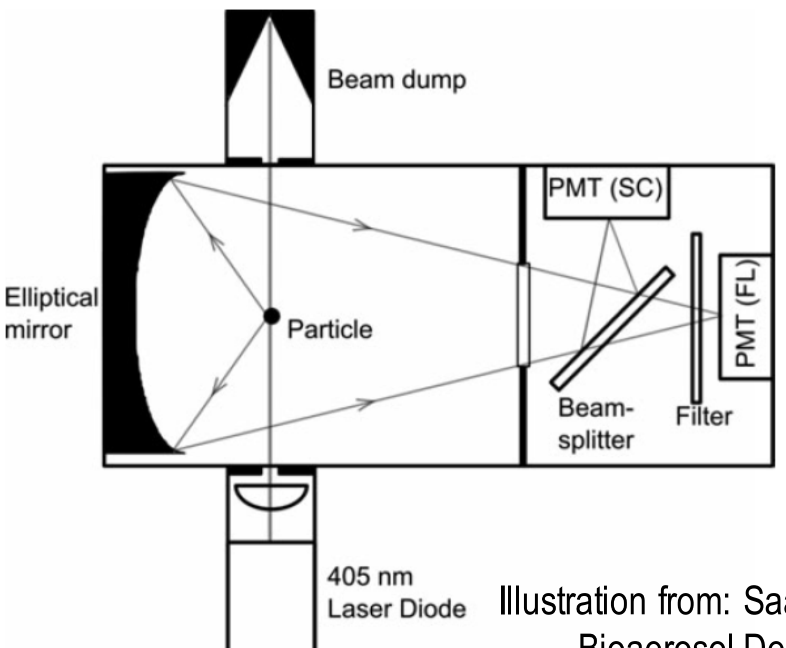


Figure from: Bhangar, S. et al. (2014). Size-Resolved Fluorescent Biological Aerosol Particle Concentrations And Occupant Emissions in a University Classroom. *Indoor Air.* 24:604-617.

Dust to air: transient behavior – baby bot meets BioScout



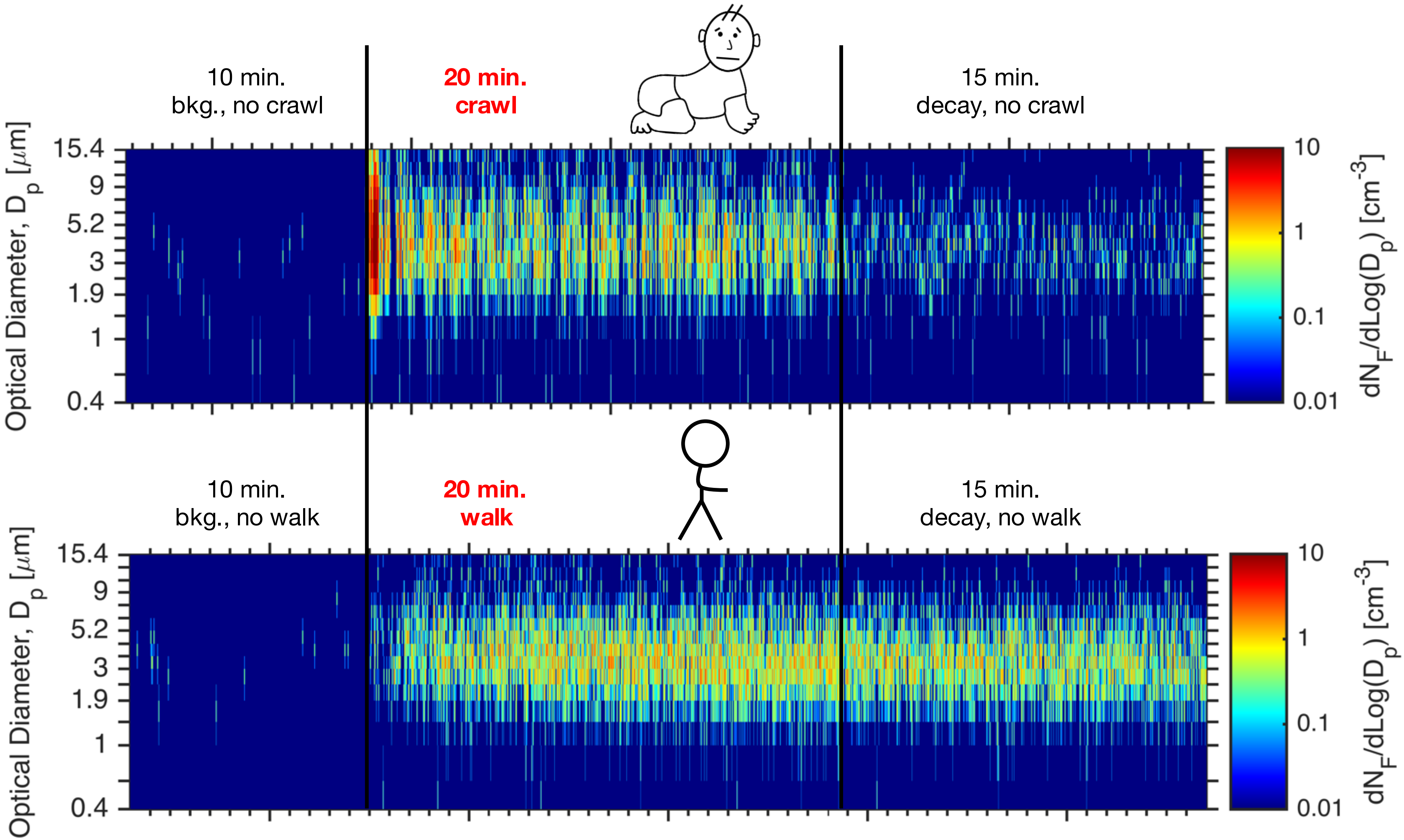




BioScout operational principle:
405 nm excitation (Laser Diode)
> 442 nm emission band
0.4 to 15.4 µm, 1 Hz

Illustration from: Saari, S. et al. (2014). Performance of Two Fluorescence-Based Real-time Bioaerosol Detectors: BioScout vs. UVAPS. *Aerosol Sci. Technol.* 48(4):371-378.

Dust to air: transient behavior – FBAPs: crawling vs. walking



Dust to air: transient behavior – classifying bioaerosols in real-time

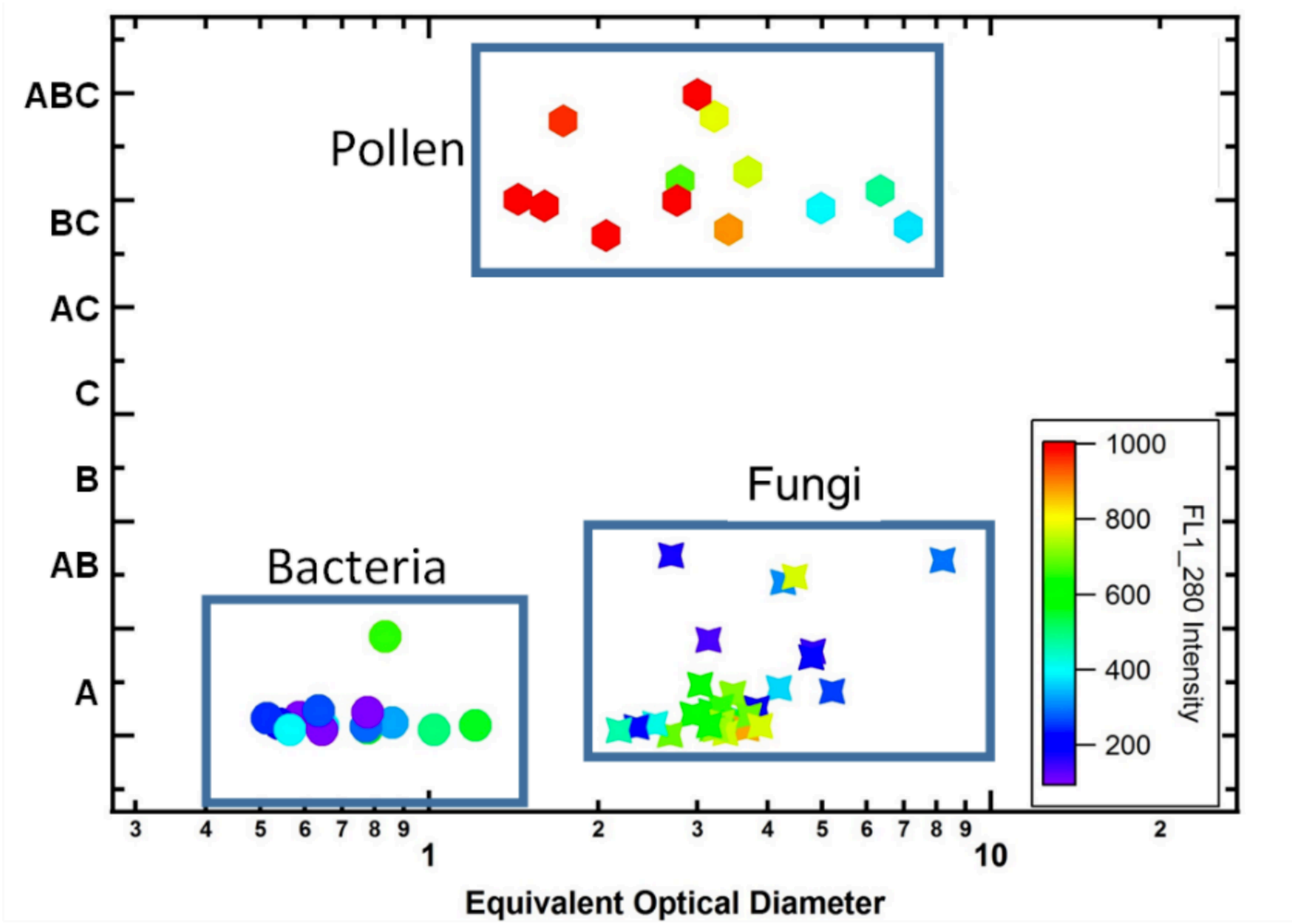


Figure from: Hernandez, M. et al. (2016). Composite Catalogues of Optical and Fluorescent Signatures Distinguish Bioaerosol Classes. *Atmos. Meas. Tech. Discuss.* doi:10.5194/amt-2015-372.

Dust to air: transient behavior – observing particle detachment w/ high speed imaging

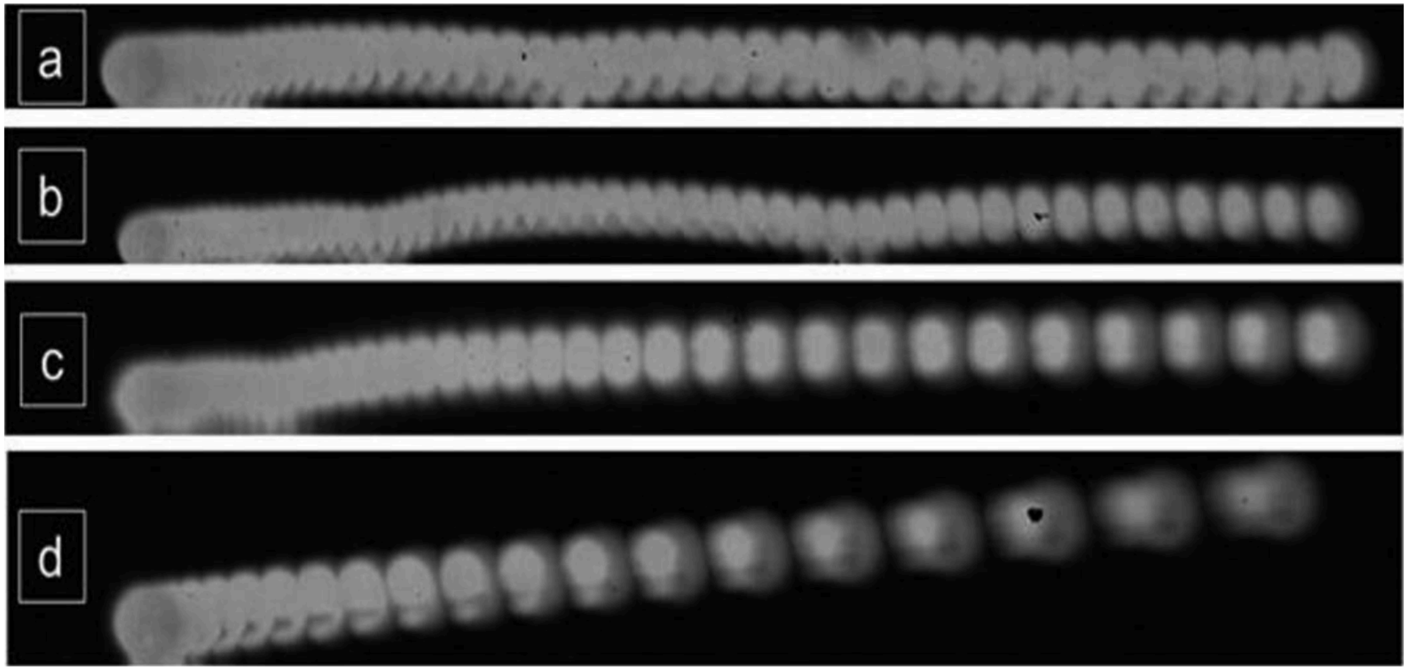


Figure from: Kassab, A.S. et al. (2013). High Resolution Study of Micrometer Particle Detachment on Different Surfaces. *Aerosol Sci. Technol.* 47:351-360.

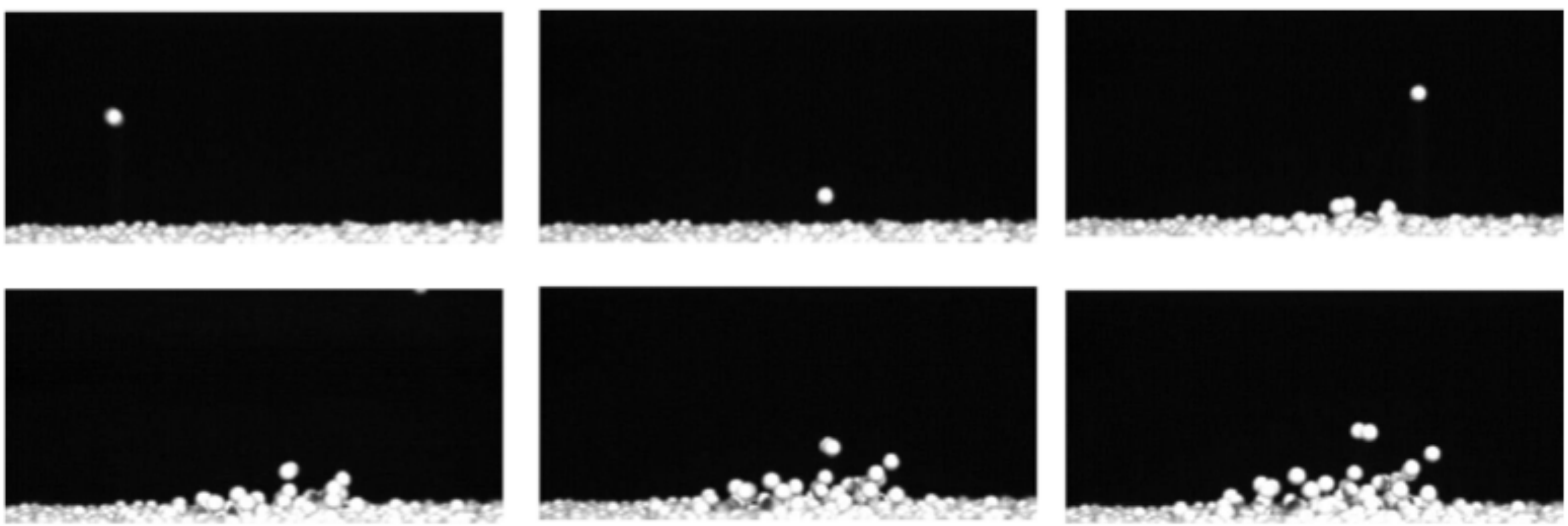
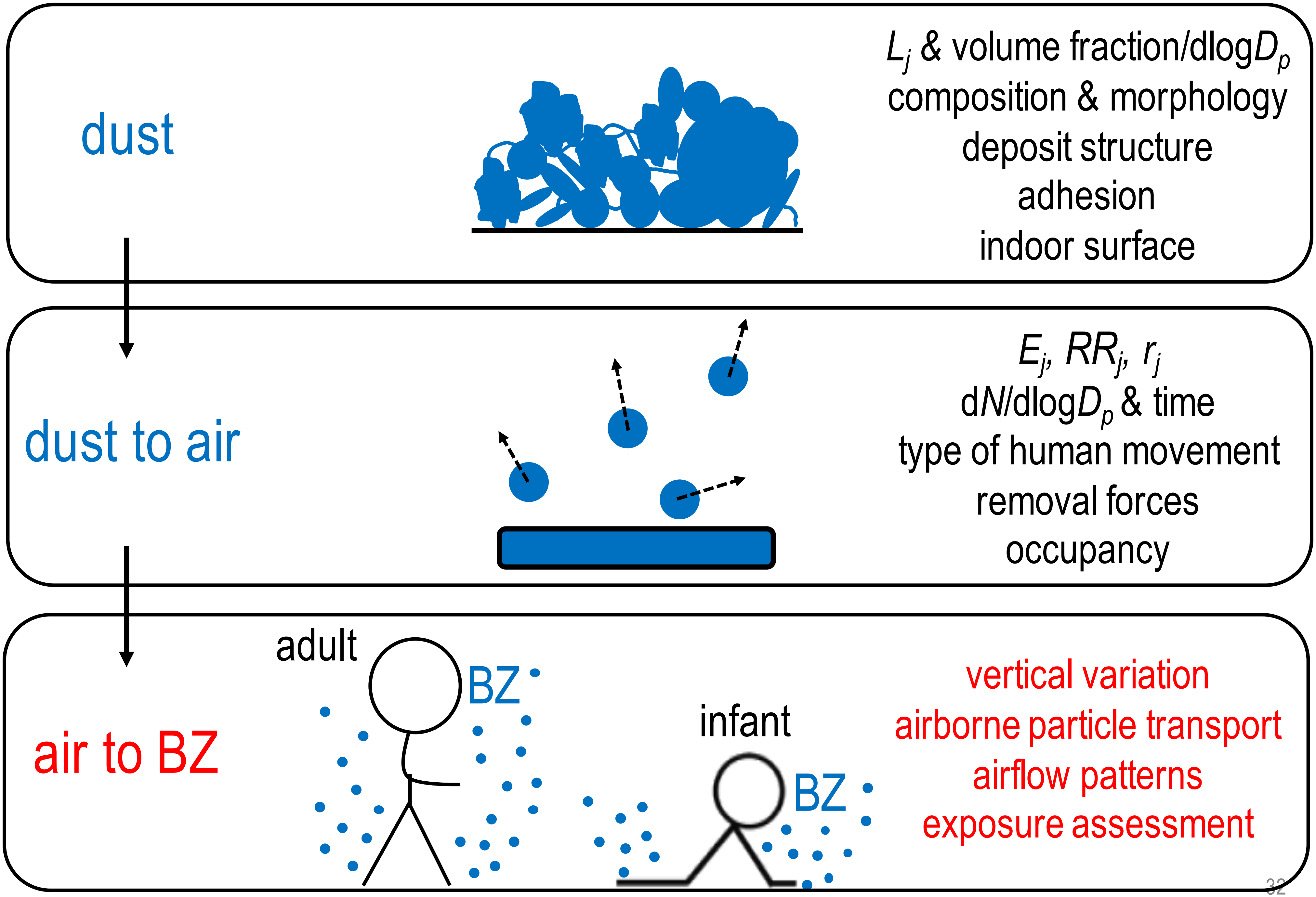
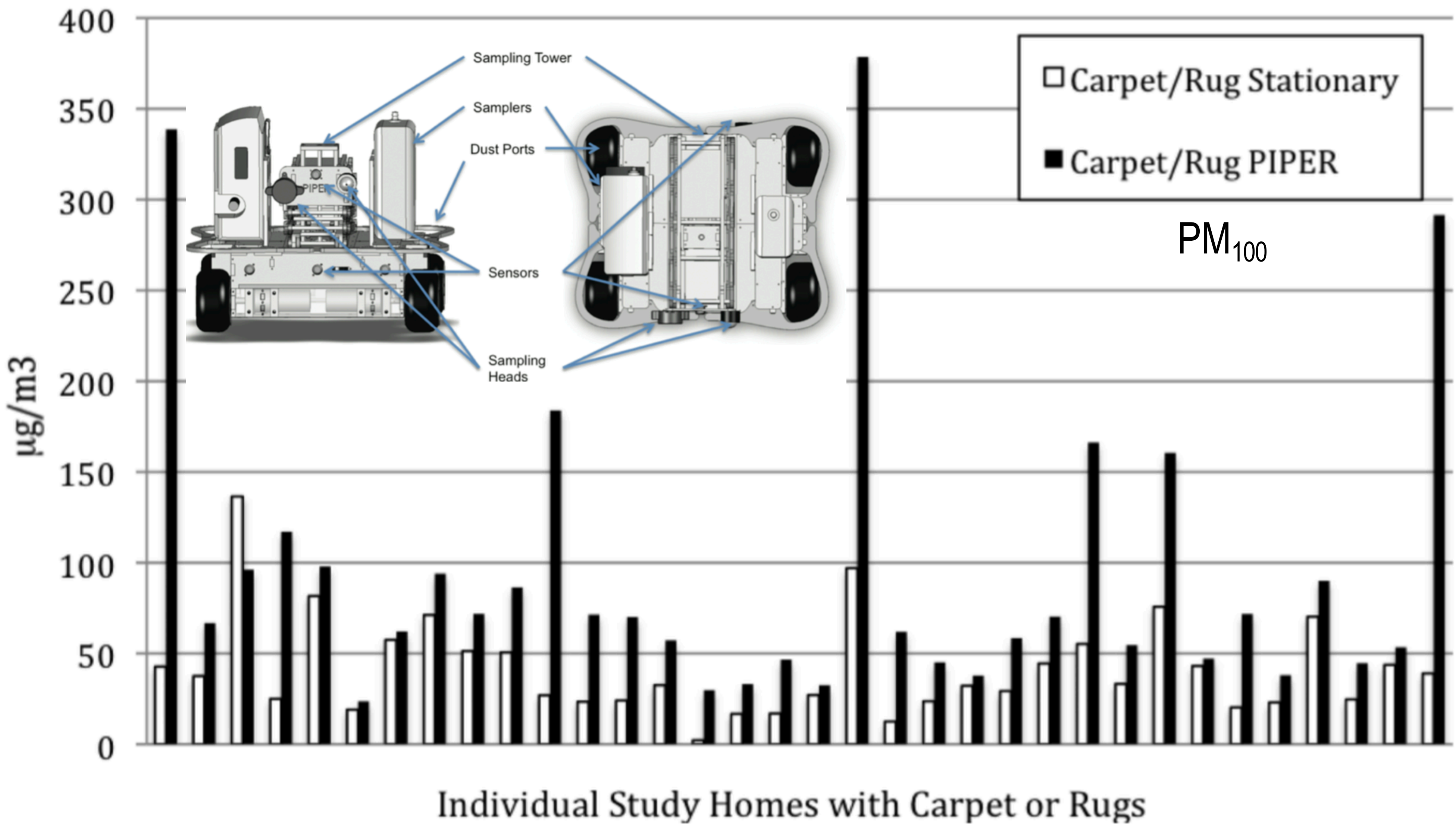


Figure from: Beladjine et al. (2007) by Kok et al. (2012). The Physics of Wind-Blown Sand and Dust. *Rep. Prog. Phys.* 75:106901

linking resuspension to exposure

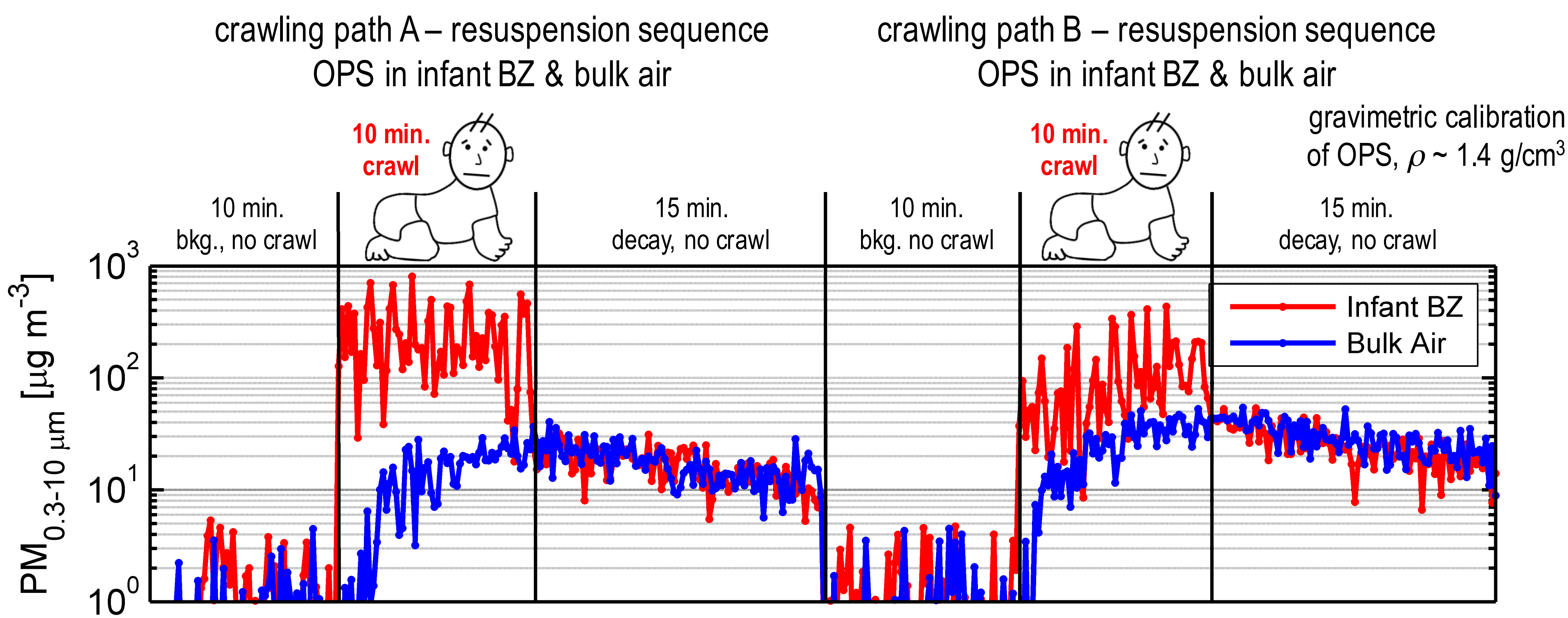


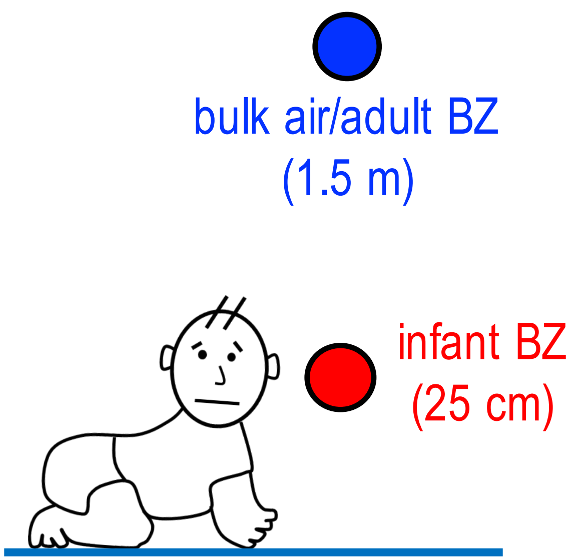
Air to BZ: vertical variation – infants: the PIPER study



Figures from: Shalat, S.L. et al. (2011). Development and In-Home Testing of the Pretoddler Inhalable Particulate Environmental Robotic (PIPER Mk IV) Sampler. *Environ. Sci. Technol.* 45:2945-2950.

Air to BZ: vertical variation – the infant near-floor microenvironment

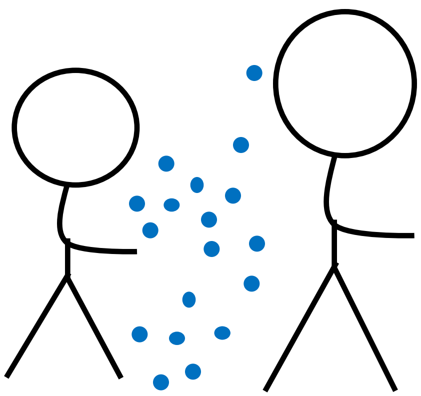




microbial group	ratio of cell equivalents/m^3 in infant BZ to bulk air/adult BZ (mean, range)
Penicillium/Aspergillus spp. group	7.9 (4.1-13)
Total Fungi	9.4 (3.0-20)
Gram-pos bacteria	21 (4.8-47)
Gram-neg bacteria	13 (1.1-43)
PM_{100} ($\mu g/m^3$)	4.6 (1.3-12)

Air to BZ: vertical variation – adults and their height

short > tall



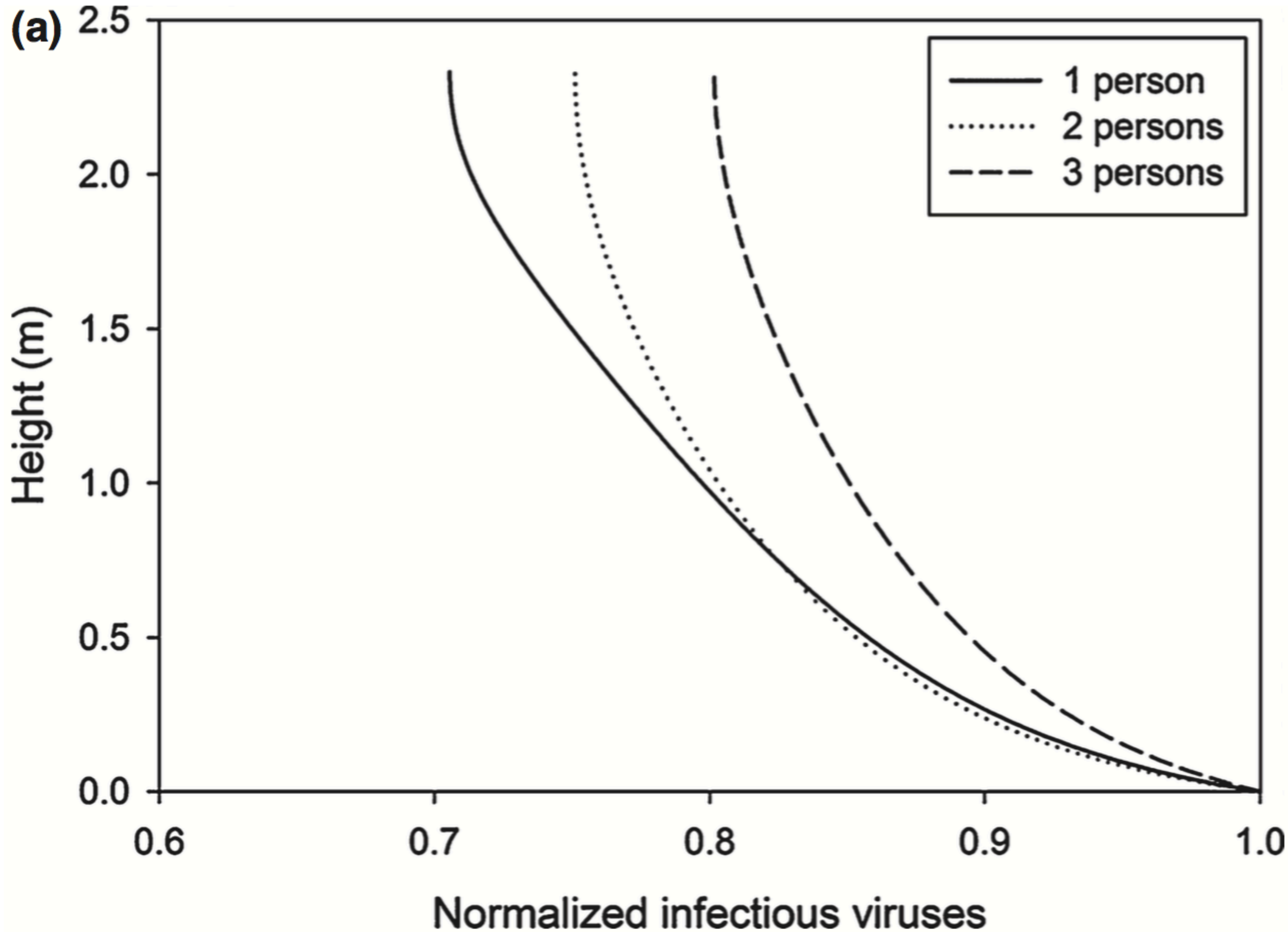
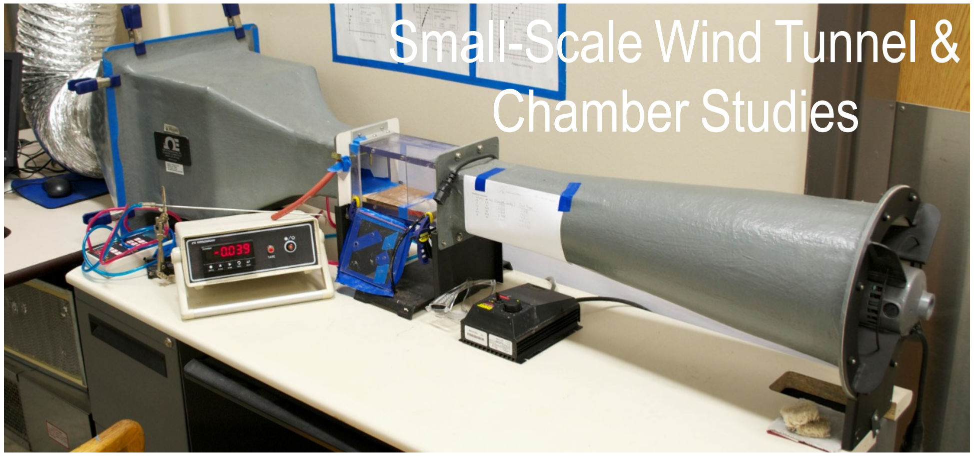
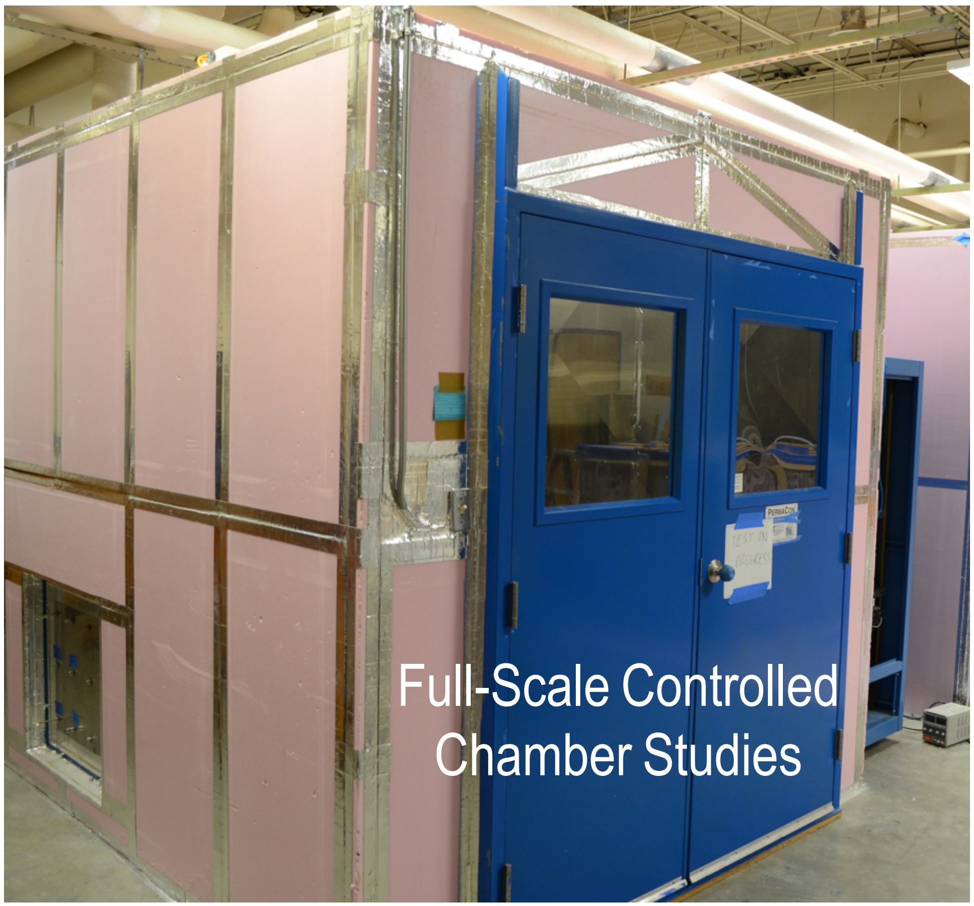


Figure from: Khare, P. and Marr, L.C. (2015). Simulation of Vertical Concentration Gradient of Influenza Viruses in Dust Resuspended by Walking. *Indoor Air.* 25:428-440.

Dust to Air to BZ: need for integrated measurements across all scales



Small-Scale Wind Tunnel & Chamber Studies



Full-Scale Controlled Chamber Studies

Living Laboratories at Purdue CHPB

Living Lab Office Space

ReNEWW Residential Test House at Purdue

Pigpen knows:
indoor particle resuspension – a fascinating research domain with many areas remaining to be explored.

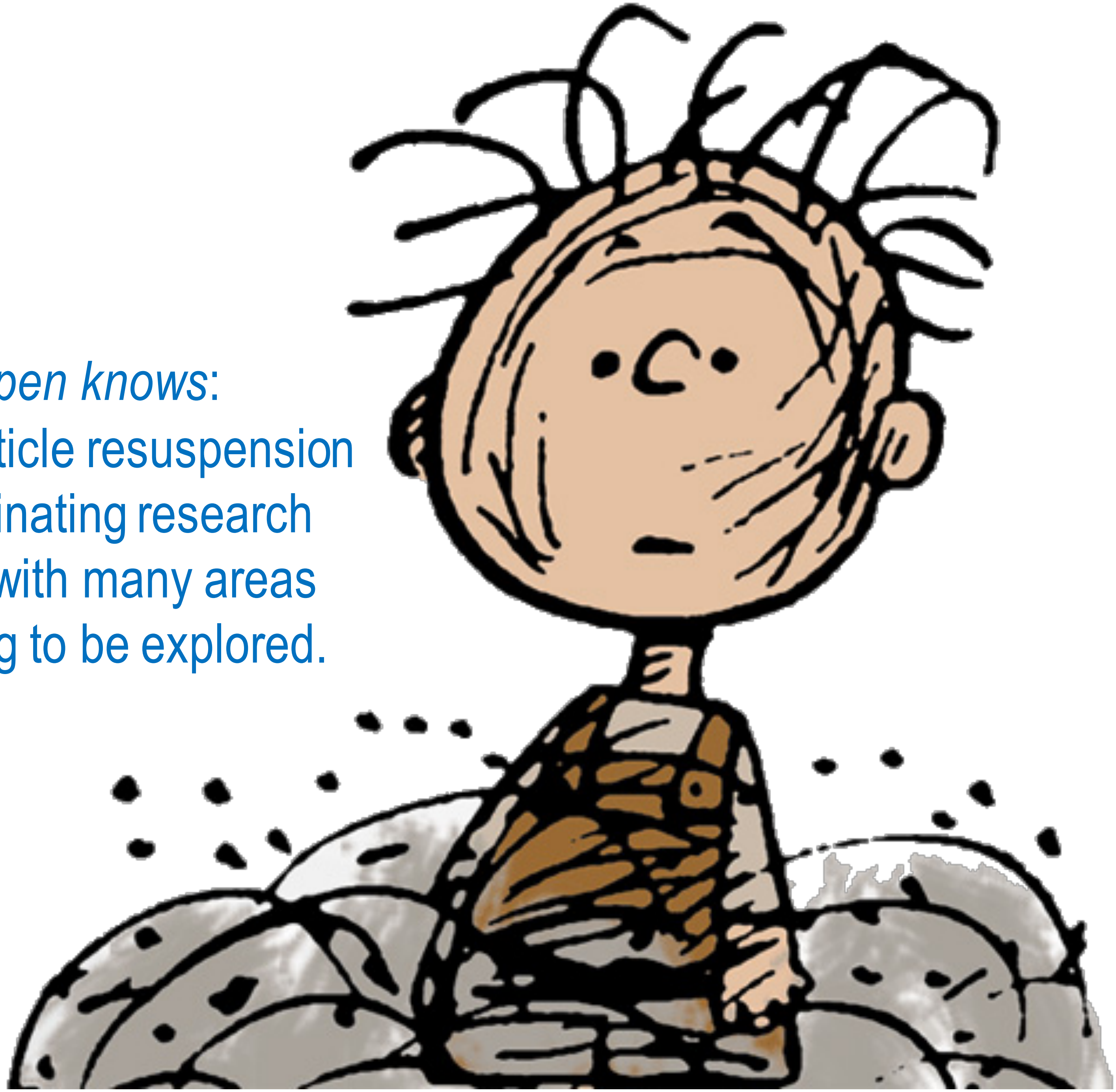


image: http://www.peanuts.com/wp-content/themes/desktop-theme-peanuts/images/characters/round/pigpen.png

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Tampere University of Technology: Sampo Saari


Thank You!
Any Questions?
Helsinki, Finland, Summer 2015