# European Network on New Sensing Technologies for Air Pollution Control and Environmental Sustainability - *EuNetAir*

## COST Action TD1105

## 2nd International Workshop *EuNetAir* on

## *New Sensing Technologies for Indoor and Outdoor Air Quality Control*

**ENEA - Brindisi Research Center, Brindisi, Italy, 25 - 26 March 2014**

# Enabling High Resolution Urban Pollution Monitoring through Mobile Sensor Networks


**Adrian Arfire**, Alcherio Martinoli

**External Expert** / adrian.arfire@epfl.ch

**EPFL ENAC IIE DISAL / Switzerland**



COST is supported by the EU Framework Programme

ESF provides the COST Office through a European Commission contract

# Overview

**Motivation**

Research and Development Plan

Conclusions

# Urban Air Pollution

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Air pollution in urban areas is a global concern

- affects quality of life and health
- urban population is increasing

Air pollution is highly location-dependent

- traffic chokepoints
- urban canyons
- industrial installations

Air pollution is time-dependent

- rush hours
- weather
- industrial activities

# Air Pollution Monitoring

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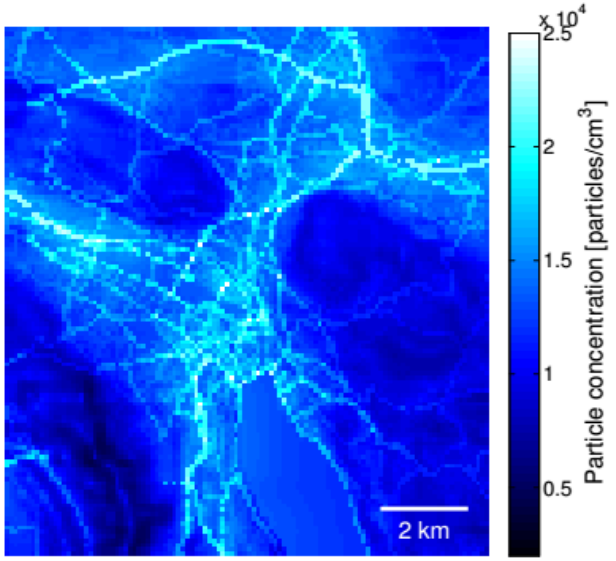
Accurate location-dependent and real-time information on air pollution is needed

Officials

- environmental engineers: location of pollution sources
- municipalities: creating incentives to reduce environmental footprint
- public health studies

Citizens

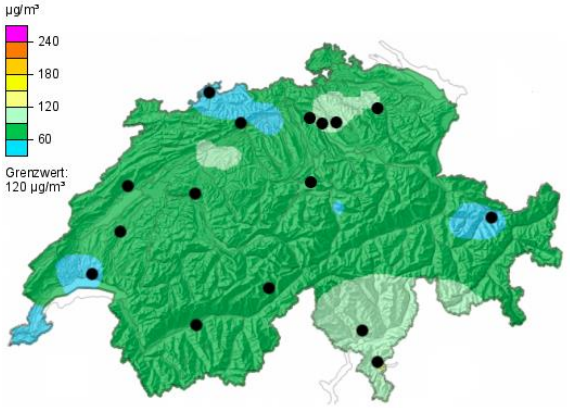
- advice for outside activities
- assessment of long-term exposure
- pollution maps



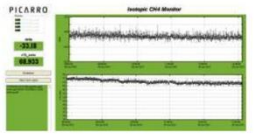

OpenSense ultra fine particle levels map in Zürich during winter months

# Monitoring Today

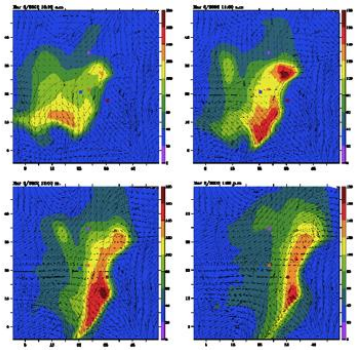
Stationary and expensive stations




Sparse sensor network (NABEL)

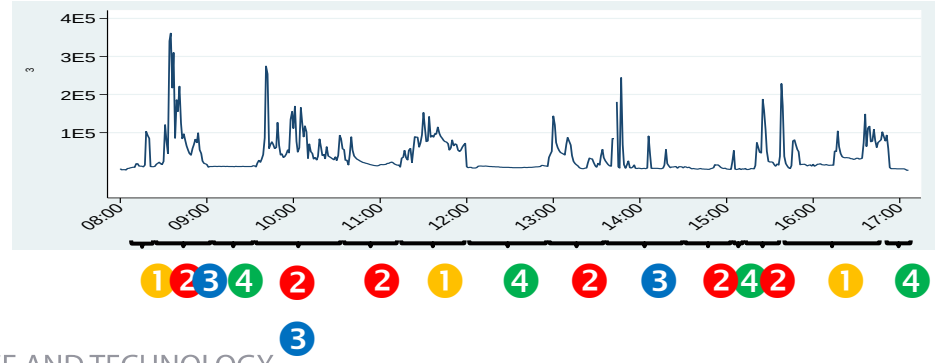




Expensive mobile high fidelity equipment



Coarse models (mesoscale = 1km²)


Personal exposure with specialized punctual studies



# Data Validation through Measurements and Modelling over Multiple Scales

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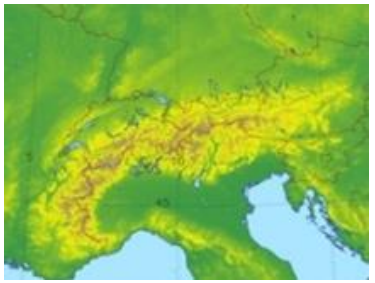
## Sensor Data

Crowd-sensors, mobile sensors, monitoring stations

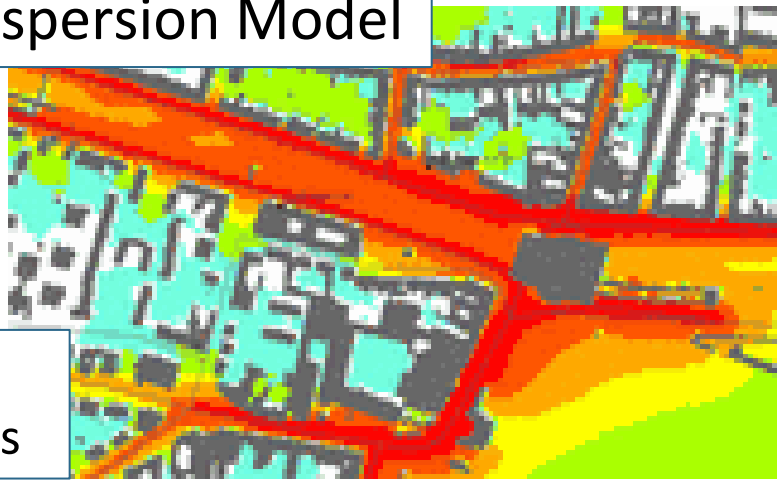


## Model Input

Terrain, meteorology, source strength, background



## Lagrangian Dispersion Model



High resolution urban atmospheric pollution maps

# Consortium

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## Nano-Tera OpenSense

**PI: Karl Aberer – LSIR, EPFL**

- management of sensor data, peer data & reputation-based trust
- Team: Julien Eberle, Thanasis Papaioannou, Sofiane Sarni, Saket Sathe

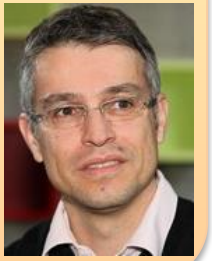
Co-PIs:

**Boi Faltings – LIA, EPFL**

- model-based & case-based reasoning, constraint programming, distributed problem solving
- Team: Jason Lee

**Alcherio Martinoli – DISAL, EPFL**

- data-driven & model-based design, optimization for distributed intelligent systems, sensor & actuator networks
- Team: Adrian Arfire, Alexander Bahr, Emmanuel Droz, Ali Marjovi



**Lothar Thiele – TIK, ETHZ**

- design, engineering methodologies, tools for embedded systems & software
- Team: Jan Beutel, David Hasenfratz, Olga Saukh, Christoph Walser

**Martin Vetterli – LCAV, EPFL**

- communication & signal processing for sensor networks
- Team: Guillermo Barrenetxea, Andrea Ridolfi

# Consortium

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## Nano-Tera OpenSense2

**PI: Alcherio Martinoli – DISAL, EPFL**
- data-driven & model-based design, optimization for distributed intelligent systems, sensor & actuator networks

Co-PIs:

**Boi Faltings – LIA, EPFL**
- model-based & case-based reasoning, constraint programming, distributed problem solving

**Karl Aberer – LSIR, EPFL**
- management of sensor data, peer data & reputation-based trust

**Lothar Thiele – TIK, ETHZ**
- design, engineering methodologies, tools for embedded systems & software

**Andreas Krause – LAS, ETHZ**
- learning and adaptive systems, crowdsourcing

**Lukas Emmenegger – EMPA**
- management of NABEL Network, chemistry-transport & Lagrangian modeling

**Murielle Bochud – IUMSP, CHUV**
- health studies, methodological support, large scale population-based studies

**Michael Riediker – IST Lausanne**
- exposure and toxicokinetic modeling, exposure assessment, occupational health studies

# Supported by Industry, Government and Research

| | | |
|---|---|---|
| VBZ | Transportation in Zürich | Public company |
| TL | Transportation in Lausanne | Public company |
| SensorScope | Sensor networks | Industry |
| Anaximen | Air quality monitoring | Industry |
| PSA | Car manufacturer | Industry |
| Wicked Devices | Air quality sensing | Industry |
| IBM | IT and Smarter Cities | Industry |
| SGX SensorTech | Gas sensing | Industry |
| Naneos | Particle detection | Industry |
| Swiss TPH | Air pollution and health studies (SAPALDIA) | Research |
| UGZ | Air quality and health in Zürich | Government |
| DSE | Environmental protection in Lausanne | Government |
| FOEN | Federal air pollution monitoring (NABEL) | Government |

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# OpenSense: Deployments

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**10 streetcars in Zurich & 10 buses in Lausanne**

- CO, $NO_2$, $O_3$, $CO_2$, UFP, temperature, humidity
- Active sniffing & closed sampling system in Lausanne
- Localization: GNSS for trams, augmented GNSS for buses
- Communication: GPRS


**At NABEL stations in Dübendorf & Lausanne**

- Calibration and sensor drift evaluation
- Testing new sensors

**On top of C-Zero electric vehicle**

- 100% electric, flexible mobility
- system test bed, targeted investigation tool

**On top of "LuftiBus"**

- Since March 2013, covers whole Switzerland

# OpenSense: Deployments

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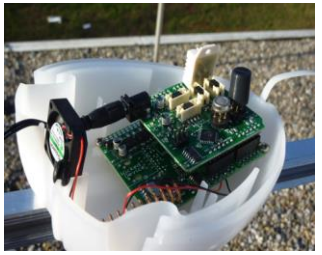
**10 streetcars in Zurich & 10 buses in Lausanne**



… in OpenSense2:

Integrated air quality measurement platform:

- Institutional stations (NABEL, Ostluft)
- OpenSense infrastructure
  - Maintained and upgraded
  - Integration of cutting edge sensing technologies ($NO_2$ laser-based sensing device developed in IrSens2)
- Personal and portable sensors
  - Heterogeneous devices and data
  - Human activity assessment, lifestyle and health data

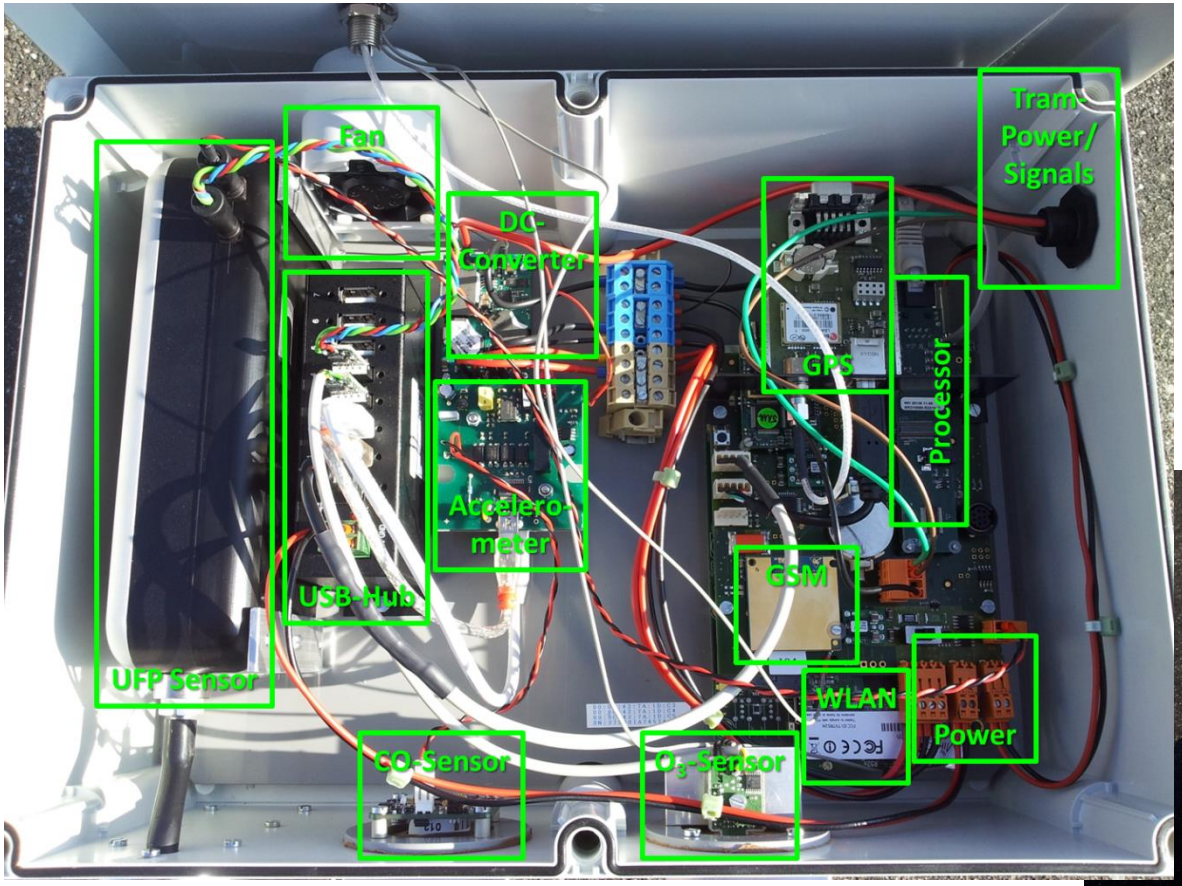





cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

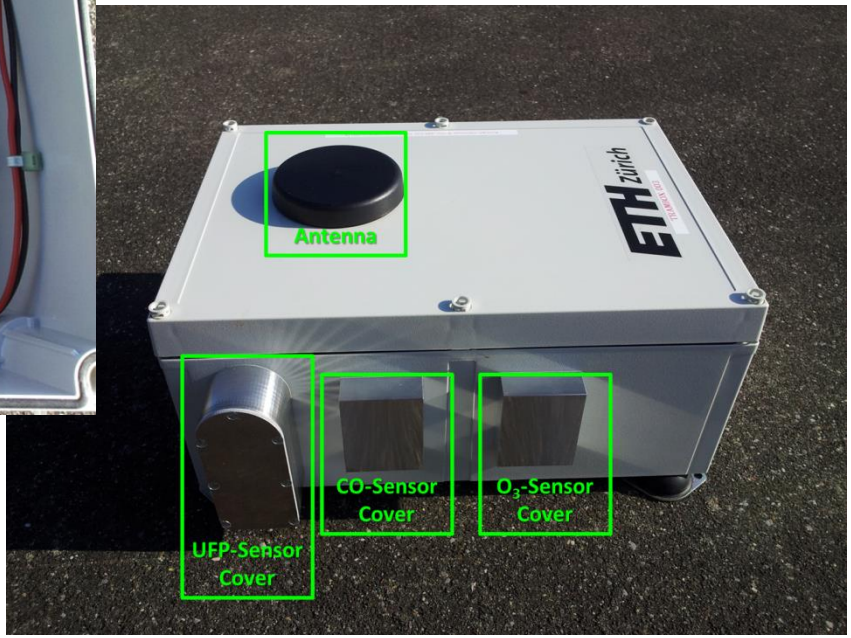
LUNGE ZÜRICH
Hilft. Informiert. Wirkt.
VBZ Züri Linie
EMPA
CITROËN
TRACE
tl Transports publics de la région lausannoise

# OpenSense: Zurich Node




*Inside the OpenSense Zurich node*


*Installation on top of VBZ Cobra tram*




*OpenSense Zurich node*

# OpenSense: Lausanne Node

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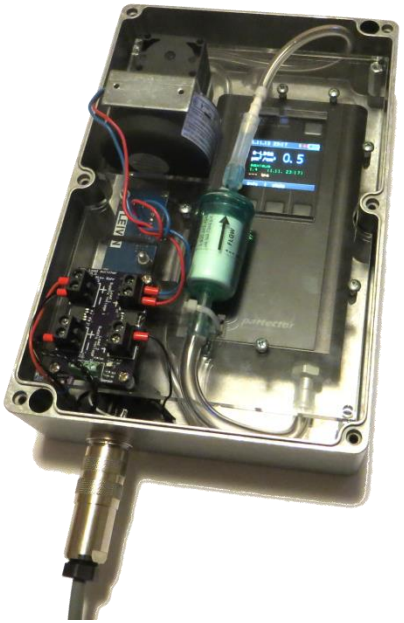
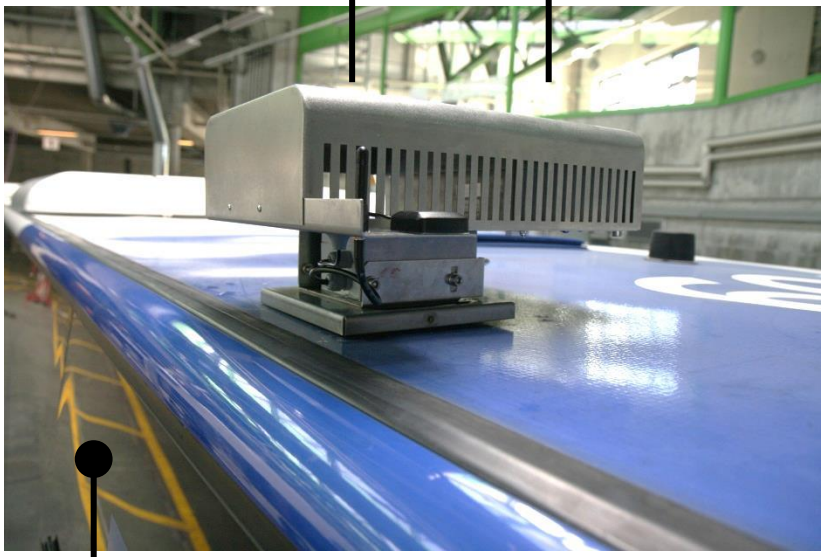
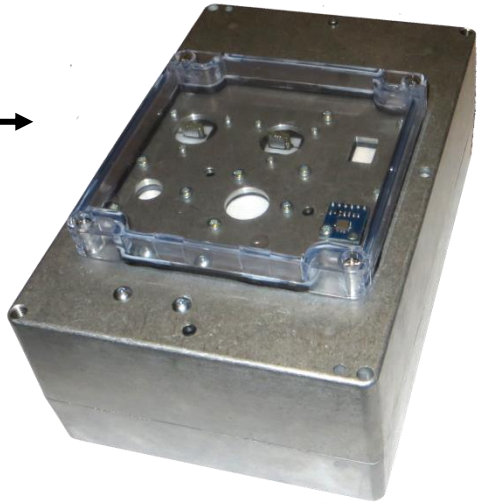
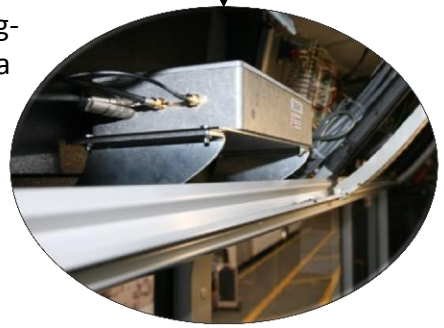






**Particle sampling module**

- Ultrafine particle measurements using Naneos Partector
- Measures directly lung-deposited surface area



**Enhanced localization & logger**

- mounted inside bus
- Fused GPS, gyro and vehicle speedpulses
- Accurate sample geolocation even in difficult urban landscapes
- GPRS communication

**Gas sampling module**

- CO, $NO_2$, $O_3$, $CO_2$, temperature & relative humidity
- Hybrid active sniffer/closed chamber sampling operation
- Enables absolute concentration mobile measurements

# Leveraging Cutting Edge Micro- / Nano-Technology Developed by Project Partners

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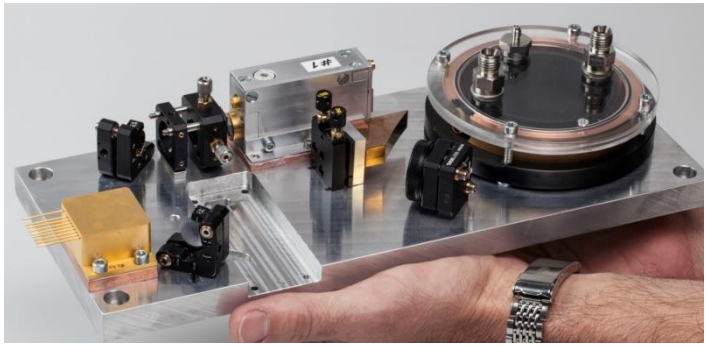


Prototype $NO_2$ laser-based sensor from IRSense2 (L. Emmenegger, co-PI); expected deployment on a Zurich tram: Spring 2014


MiniDisc and Partector UFP detectors invented by M. Fierz (FHNW and Naneos GmBh)

Key industrial partners in sensing technology (SGX SensorTech, Corcelles, Switzerland, E. Germain, CEO)

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

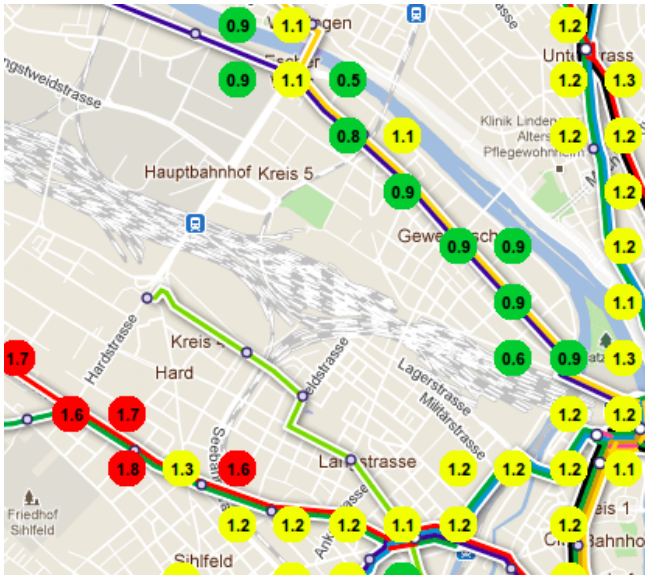
naneos particle solutions gmbh

EMPA

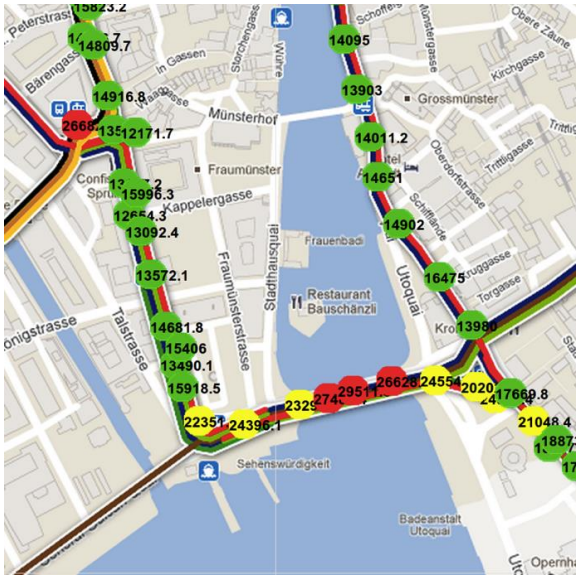
n|w Fachhochschule Nordwestschweiz

SGX SENSORTECH

# Pollution Data – Zurich Deployment




CO concentration

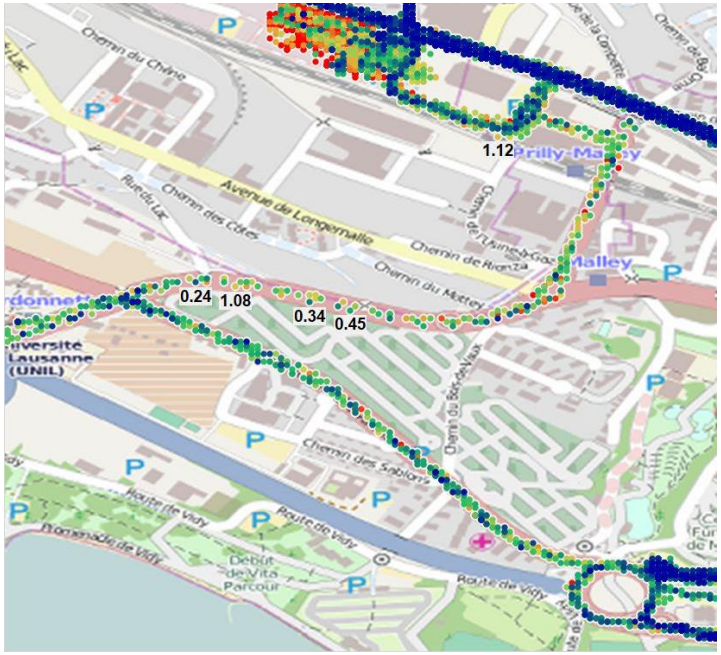



UFP concentration

[Keller et al., SenseApp 2012]

| Pollutant | # of Measurements | Sampling rate | Time Period |
|---|---|---|---|
| UFP | 56.000.000 | 5s | 22 months |
| Ozone | 8.900.000 | 20s | 22 months |
| CO | 5.300.000 | 20s | 22 months |

# Pollution Data – Lausanne Deployment



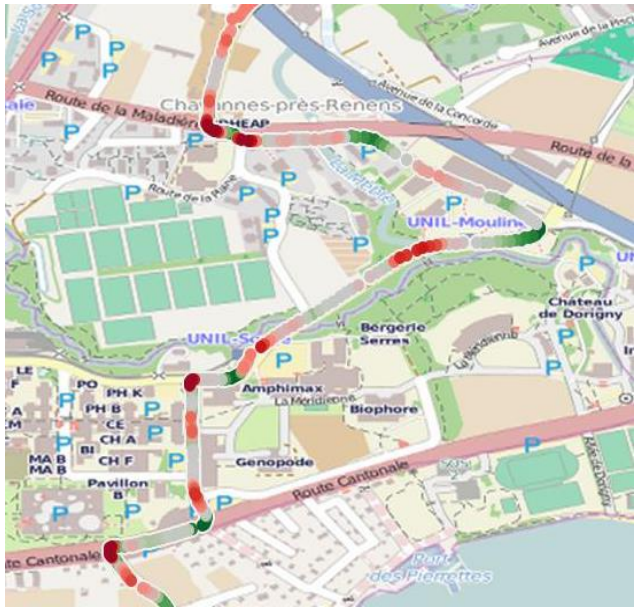

CO concentration


UFP concentration

[Arfire, unpublished, 2014]

| Pollutant | # of Measurements | Sampling rate | Time Period |
|---|---|---|---|
| UFP | 9.151.000 | 1s | 3 months |
| Ozone | 2.488.000 | 15s | 5 months |
| [CO, NO2, CO2] | 10.930.000 | 5s | 5 months |

# Mobility Data – Lausanne Deployment




Gyro yaw rate


X-axis acceleration
& vehicle context

[Arfire, unpublished, 2014]

Coverage of Lausanne region

| Measurement | # of Measurements | Sampling rate | Time Period |
|---|---|---|---|
| [GPS, gyroscope] | 52.207.000 | 1s | 5 months |
| [odometer, accelerometer] | 211.767.000 | 0.25s | 5 months |
| vehicle context info | 751.000 | event-driven | 5 months |

# OpenSense: Mobility Modeling

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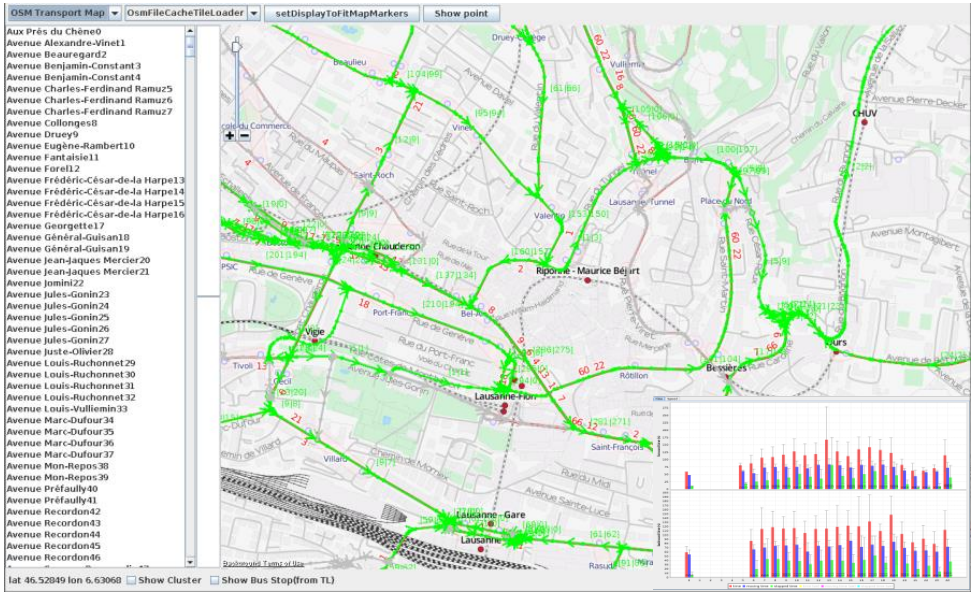
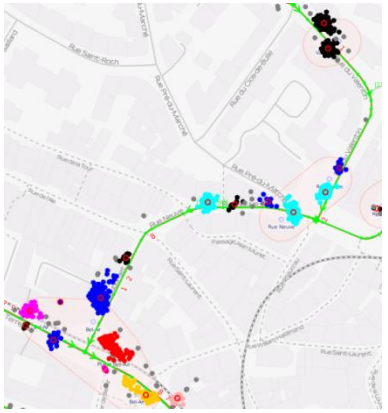
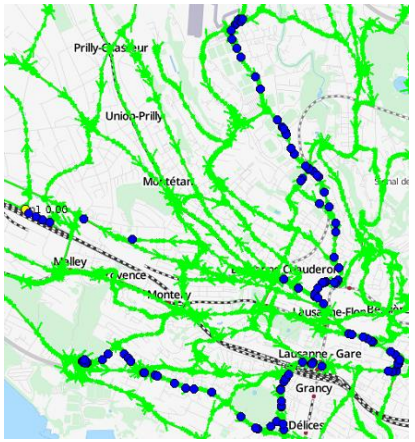
**Public transport simulation framework**

- Statistical data-driven modeling of road links in Lausanne
- Data sources:
  - public transport network topology
  - enhanced localization module
  - context data from vehicle communication bus (current line, destination, stop information)
- Allows the generation of vehicle trajectories for given scenarios (bus line, time of day etc.)



*Modeling vehicle stops (bus stops, junctions, traffic lights etc.)*




*Generating vehicle trajectories*

# OpenSense: Mobility Modeling

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- Statistical data-driven modeling of road links in Lausa
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  - public transp topology
  - enhanced loc
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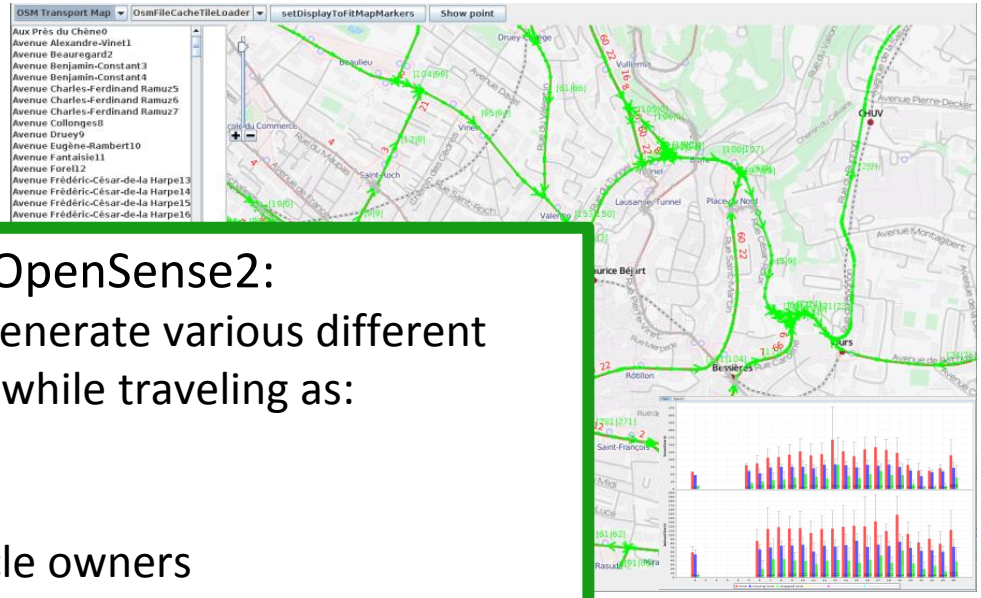
- Allows the generation of vehicle trajectories for given scenarios (bus line, time of day etc.)

… in OpenSense2:

- Participants can generate various different mobility patterns while traveling as:
  - pedestrians
  - cyclists
  - private vehicle owners
- Utilitarian approach needed to deal with the trade-off between model complexity and accuracy




*Modeling vehicle stops (bus stops, junctions, traffic lights etc.)*


*Generating vehicle trajectories*

# OpenSense: Data Quality

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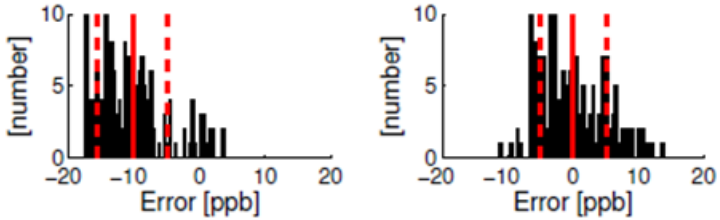
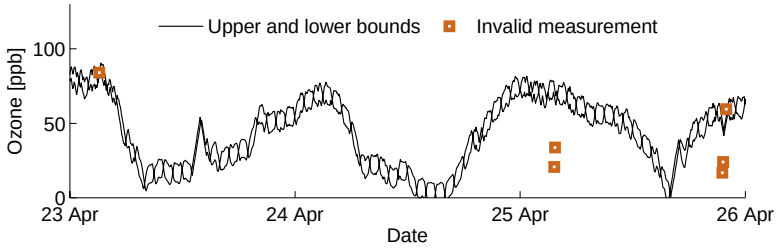
- **Automatic Sensor Calibration**
  - Based on temporal and spatial closeness of two sensors
    - Close measurements are similar
    - Measurement closeness depends on locality of a physical process
  - Evaluated calibration algorithms in static and mobile settings
- **Sensor Fault Detection**
- **Measurement Accuracy Bounds**
  - Use sensor and phenomenon models
- **Outlier detection**




*Periodic calibration improves data quality from 10.5±5.3ppb to 4.2±5.1ppb. Mean error after calibration is 0.*




*Augment every sensor reading with accuracy bounds. Allows detecting outliers.*

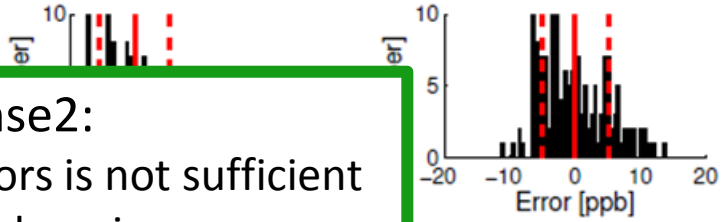
# OpenSense: Data Quality

- **Automatic Sensor Calibration**
  - Based on tem… closeness of …
    - Close me…
    - Measure… on locali…
  - Evaluated ca… static and m…
- **Sensor Fault …**
- **Measuremen…**
  - Use sensor a… phenomenon models
- **Outlier detection**

… in OpenSense2:

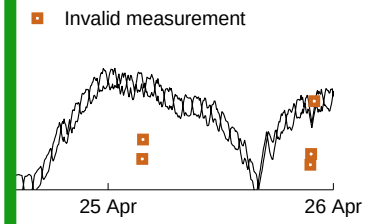
Evaluation of individual sensors is not sufficient

- Sensor calibration for crowdsensing:
  - Using OpenSense infrastructure to provide numerous calibration points
- Assign data with data quality signatures
  - Model-based data validation
  - Real-time data quality assurance
- People are less reliable than well-tested hardware
  - Introduce reputation tools




$O_3$: calibrated.

*…roves data quality …to 4.2±5.1ppb. …alibration is 0.*




*Augment every sensor reading with accuracy bounds. Allows detecting outliers.*

# OpenSense: High-resolution Maps

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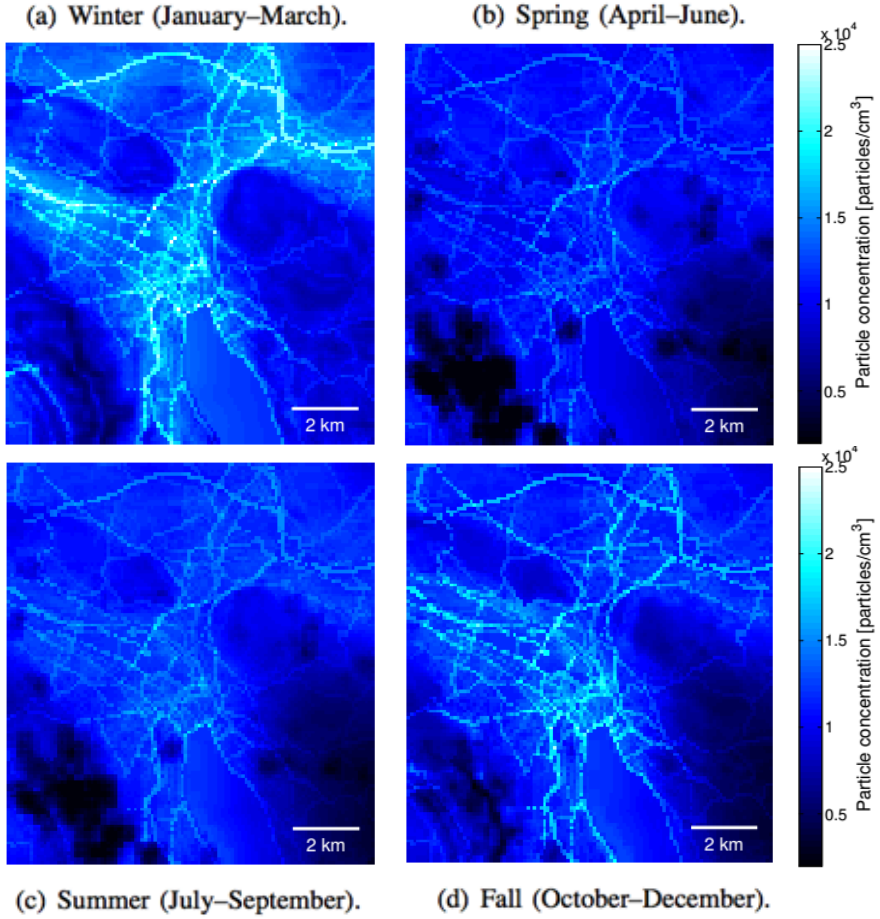
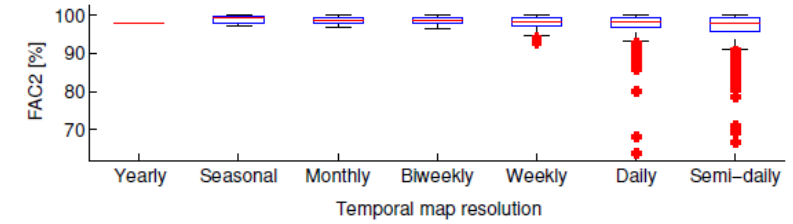
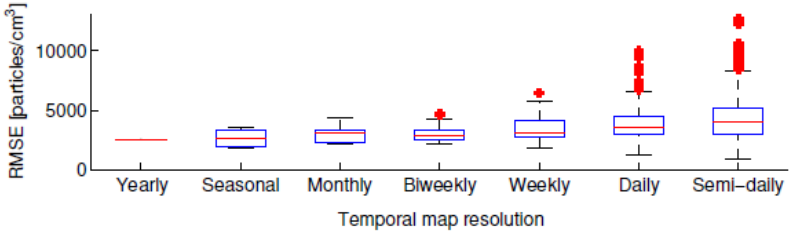
Ultrafine particle air pollution maps with 100x100m resolution



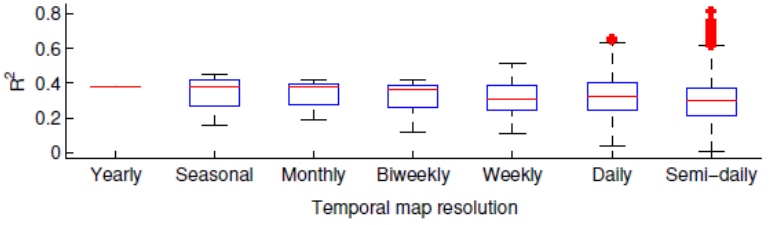

Accurate pollution maps with yearly to weekly temporal resolution




(a) Factor of 2 statistic (FAC2).



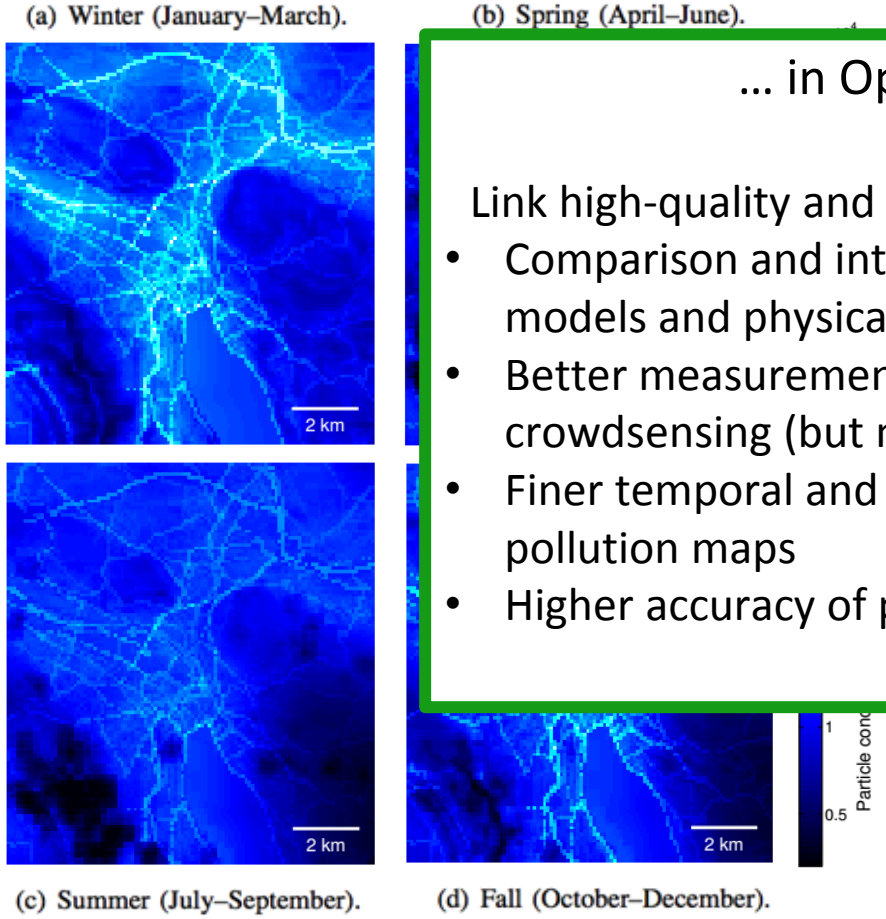

(b) Root-mean-square error (RMSE).




(c) Coefficient of determination ($R^2$).

# OpenSense: High-resolution Maps

Ultrafine particle air pollution maps with 100x100m resolution

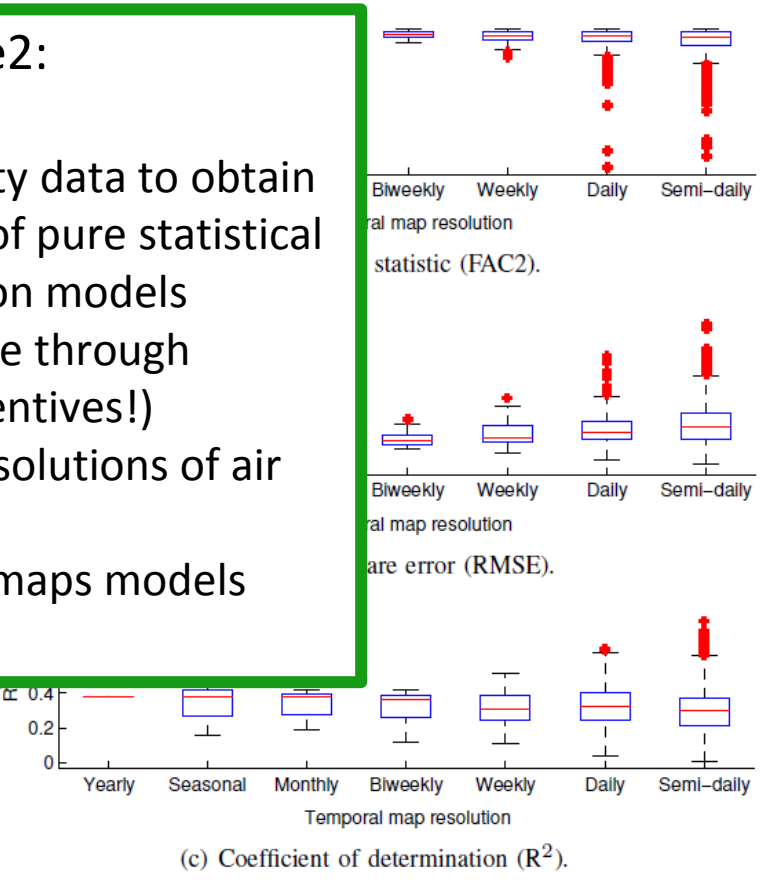



Accurate pollution maps with yearly to weekly temporal resolution

… in OpenSense2:

Link high-quality and low-quality data to obtain

- Comparison and integration of pure statistical models and physical dispersion models
- Better measurement coverage through crowdsensing (but needs incentives!)
- Finer temporal and spatial resolutions of air pollution maps
- Higher accuracy of pollution maps models



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**Conclusions**

# CONCLUSIONS

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## In OpenSense

- long-term deployments for air monitoring in the both Zurich and Lausanne
- gathered large amount of data (pollution & mobility)
- techniques to evaluate data quality & calibrate sensors on the fly
- first stage models for mobility simulation & high resolution pollution mapping

## In OpenSense2

- integrate new data sources (institutional & private devices)
- deal with less predictable mobility, unreliable data, incentives
- sensor selection / energy cost
- integration of physical dispersion models

# Q&A