Quantifying long-term evolution of intra-urban spatial interactions

Lijun SUN[1,2]

[1]Future Cities Laboratory, Singapore-ETH Centre
[2]Dept. of Civil Eng., National University of Singaproe
sunlijun@nus.edu.sg
https://sites.google.com/site/sunlijun1988/

Quantifying long-term evolution of intra-urban spatial interactions

Jian Gang Jin, Shanghai Jiao Tong University
Kay W. Axhausen, ETH Zurich
Der-Horng Lee, National University of Singapore
Manuel Cebrian, University of Melbourne

Quantify spatial interaction

- Created by individuals' trips for work, school, shopping and other social activities, intra-urban movement is a crucial part of these spatial interactions. It exhibits strong spatial and temporal patterns, which play an important role in urban planning and traffic forecasting.

- Taking travel demand as an example, previous work has focused on developing models to estimate current and predict future interaction intensity based on social and infrastructural input for planning purposes.

- Despite the observations telling us that 'near things are more related than distant things' geographically, studies trying to integrate the infrastructure and interaction layers have remained limited by the lack of detailed longitudinal data measuring change at high spatial and temporal resolutions

Quantify spatial interaction

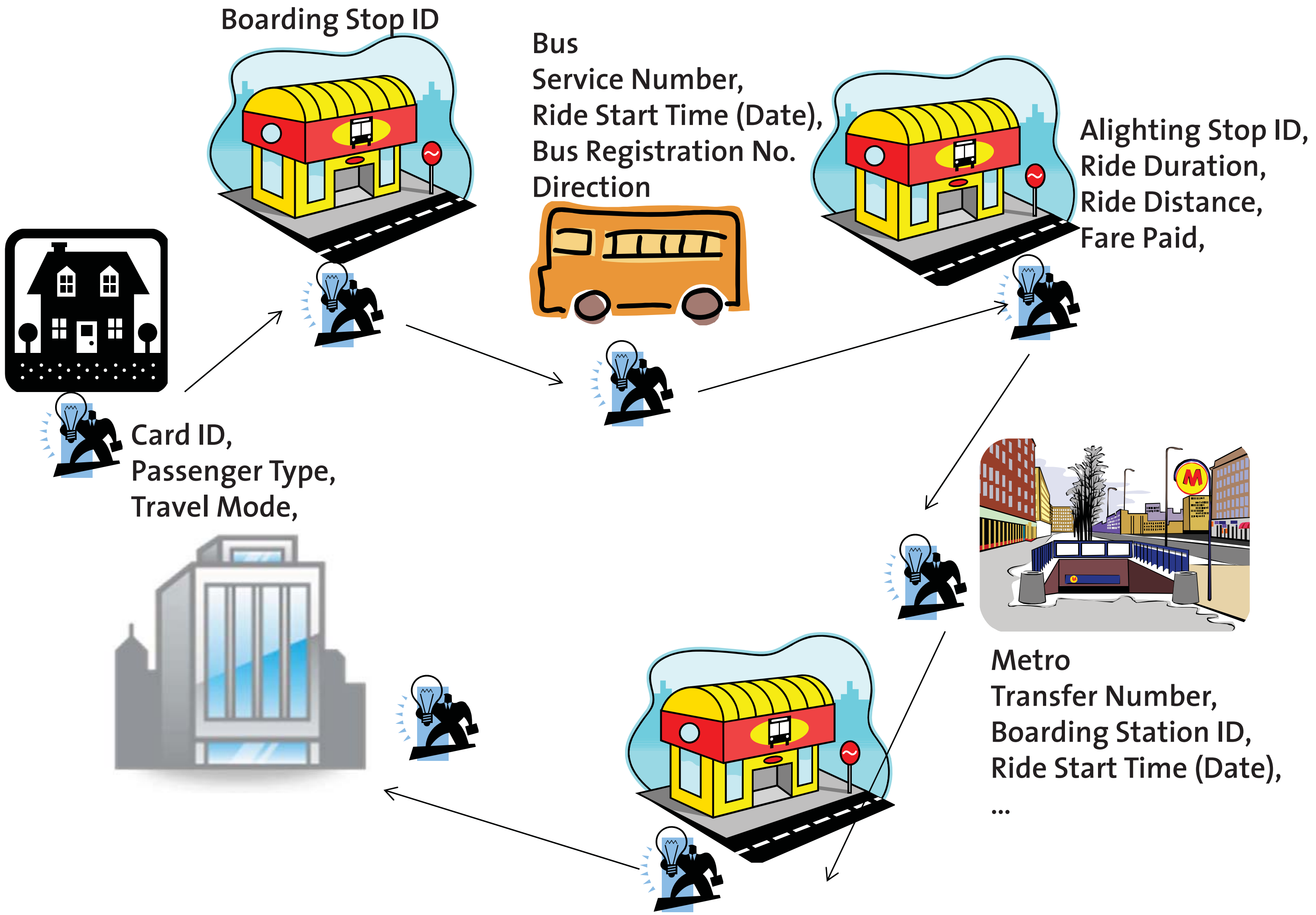
- The real impact of infrastructure systems may not be visible in static or aggregated mobility measures
- Quantify the evolution of urban spatial interactions: natural variance and transportation infrastructure change

Quantify spatial interaction

- The real impact of infrastructure systems may not be visible in static or aggregated mobility measures
- Quantify the evolution of urban spatial interactions: natural variance and transportation infrastructure change
- **DATA?**
- **Household interview survey, GPS, Cellphone ….**

Smart card data

- City-scale smart card data (Singapore)



Smart card data

- City-scale smart card data (Singapore)

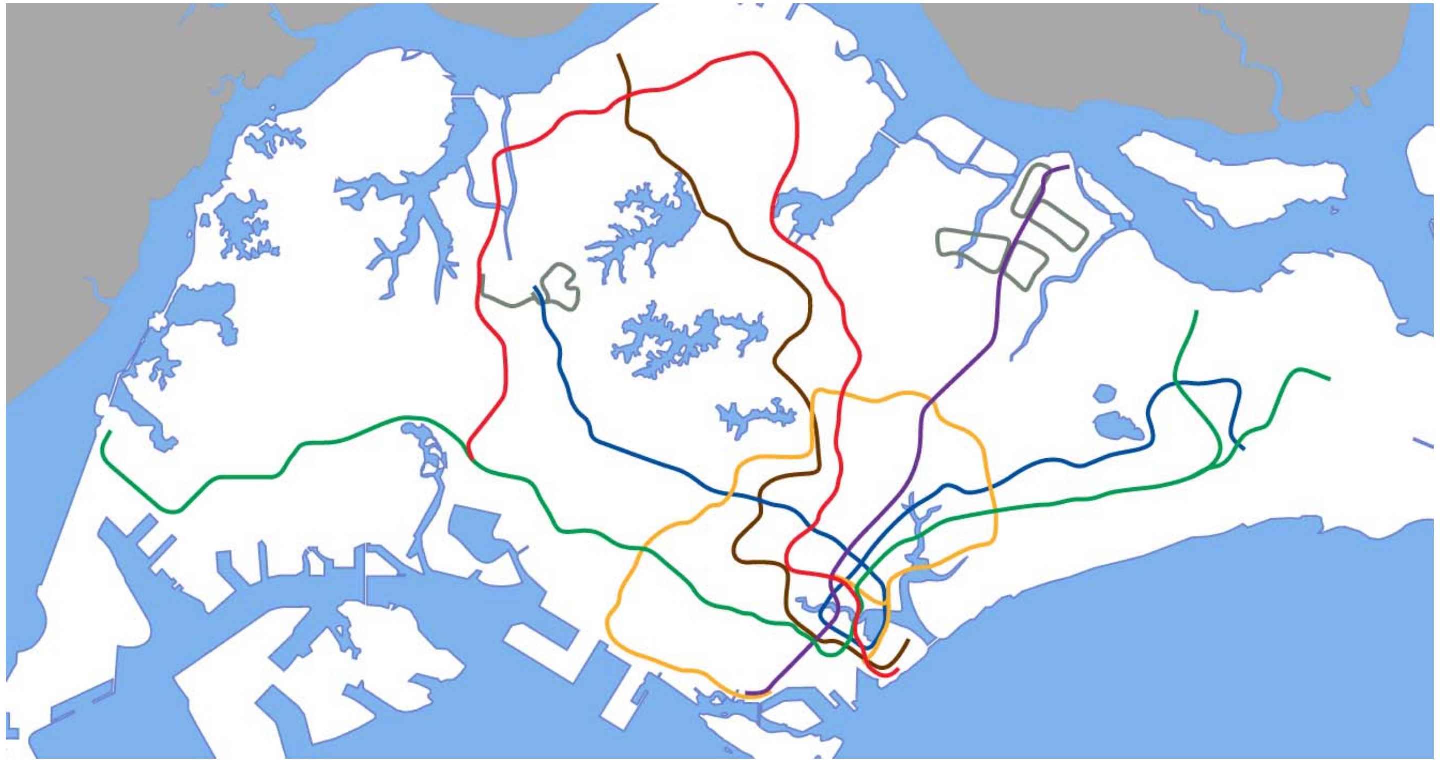
- covering more than 96% of transit use (the rest is made by cash)
- Capturing more than 63% of total mobility in Singapore (household interview travel survey)

Smart card data

- City-scale smart card data (Singapore)

- covering more than 96% of transit use (the rest is made by cash)
- Capturing more than 63% of total mobility in Singapore (household interview travel survey)

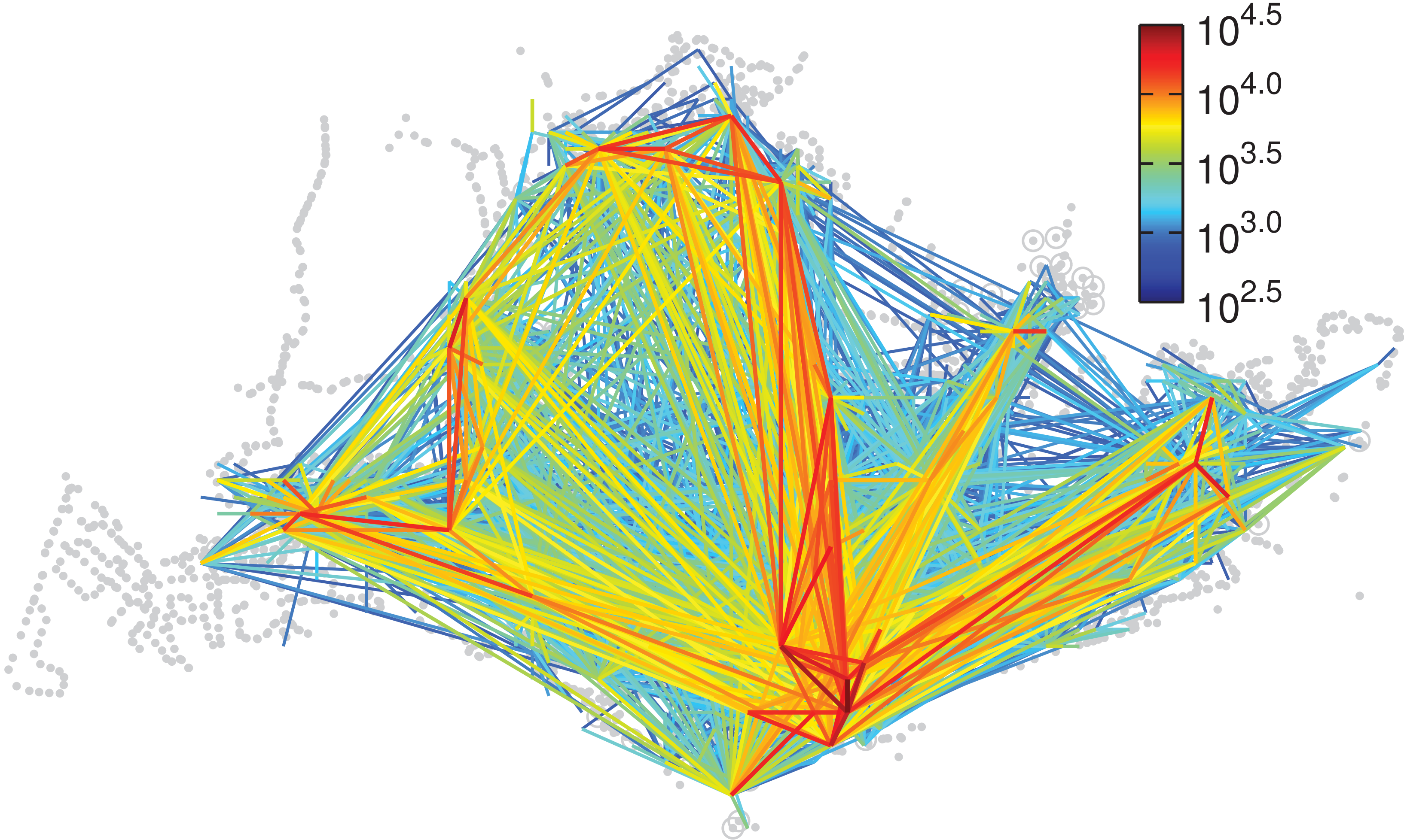
- In 2011, April 11 to April 15
- In 2012, March 19 to March 23
- In 2013, April 4 to April 12



Structure of transit movement network

- Divide study area (Singapore) into zones of 500m x 500m
- Aggregated spatial interaction network across weekdays

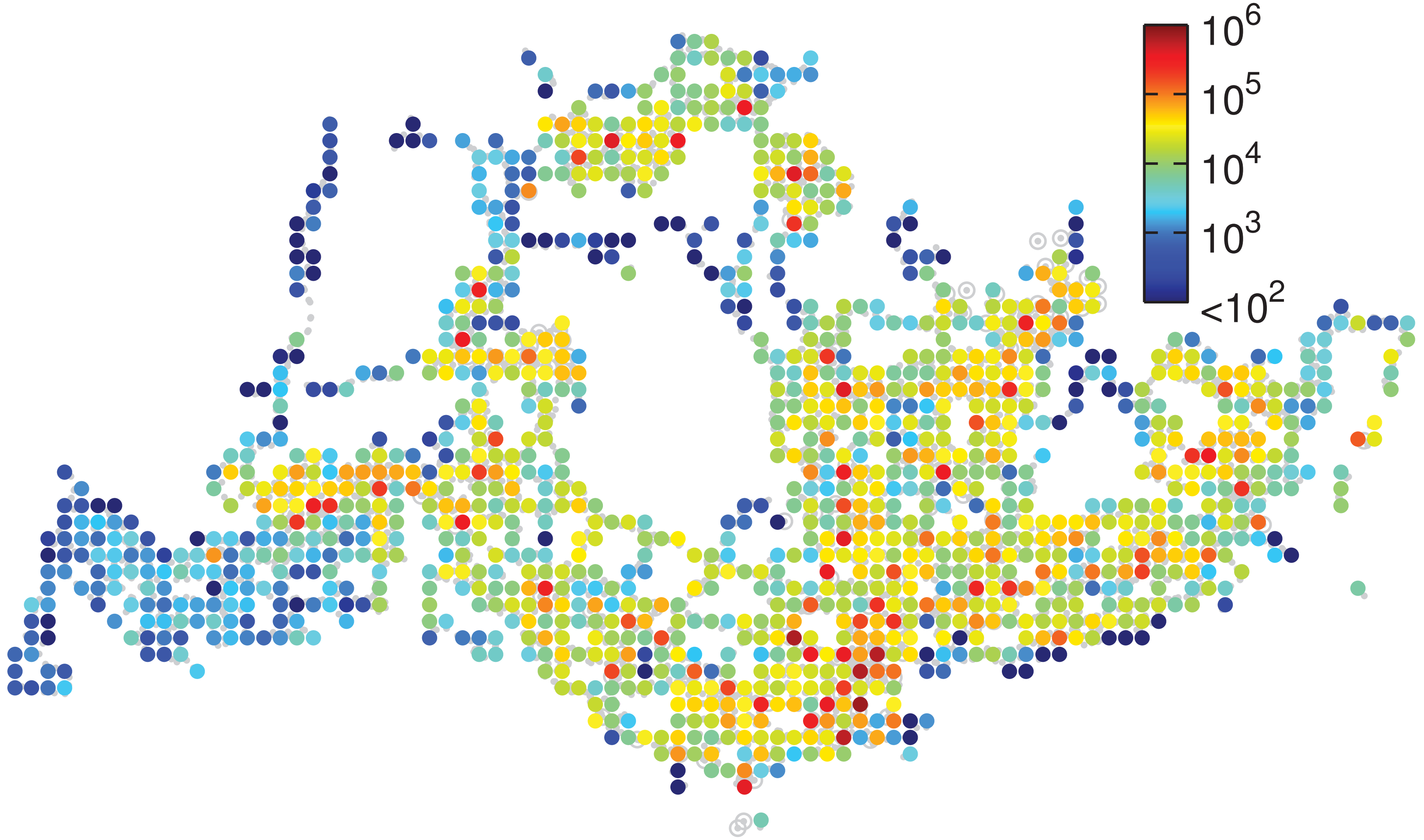
- Top 1% edges (intensity-pax)



Structure of transit movement network

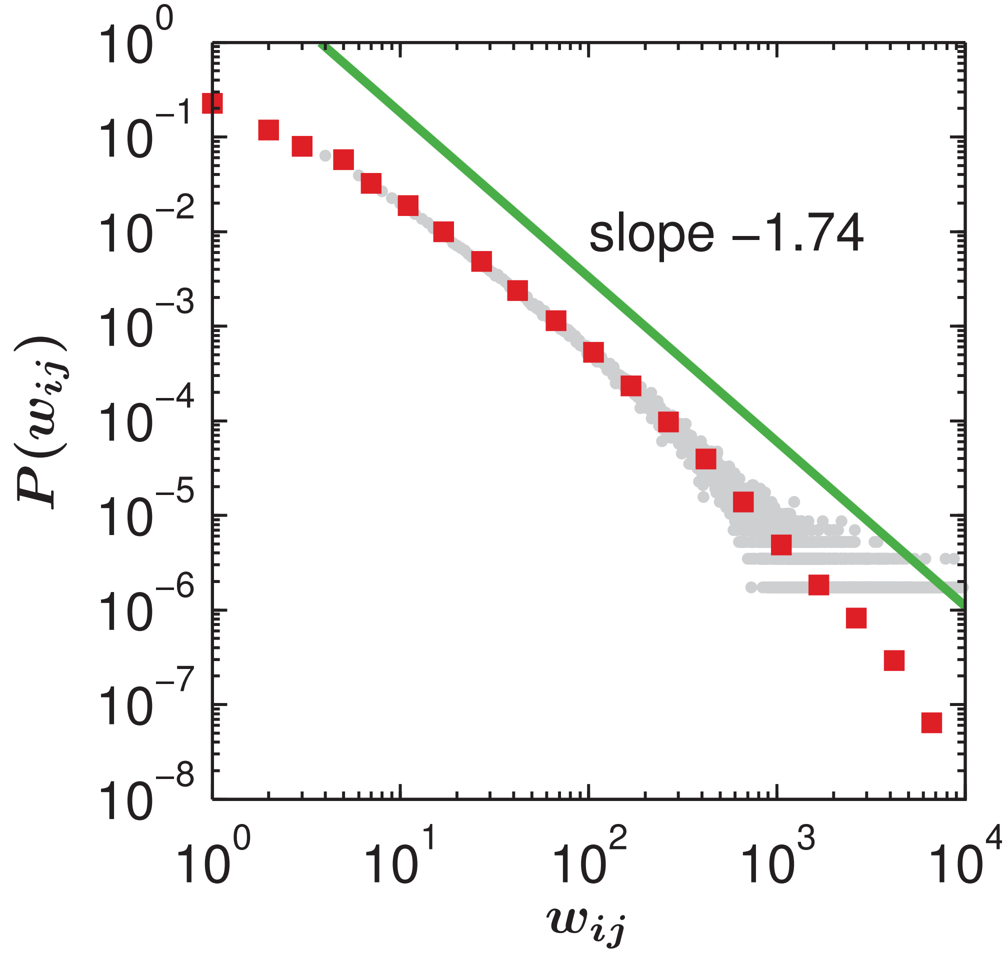
- Divide study area (Singapore) into zones of 500m x 500m
- Aggregated spatial interaction network across weekdays

- Node strength distribution



Structure of transit movement network

- Divide study area (Singapore) into zones of 500m x 500m
- Aggregated spatial interaction network across weekdays
- Interaction intensity $P\left(w_{ij}\right)$



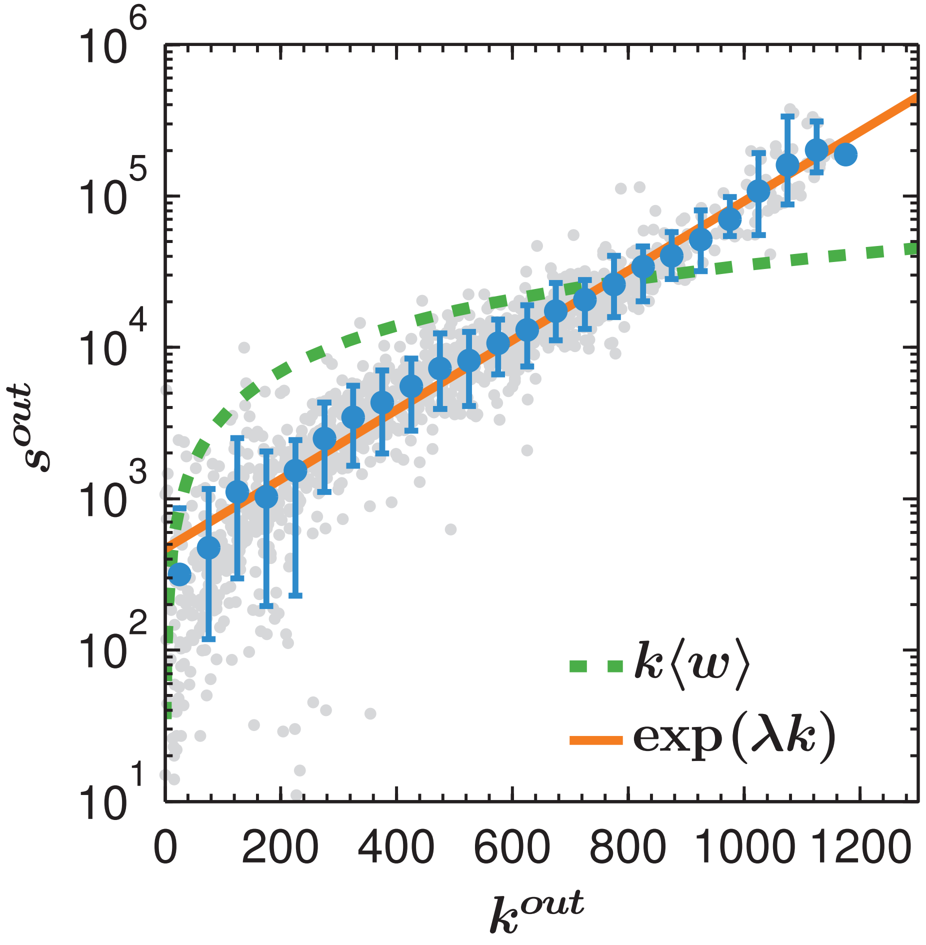
Structure of transit movement network

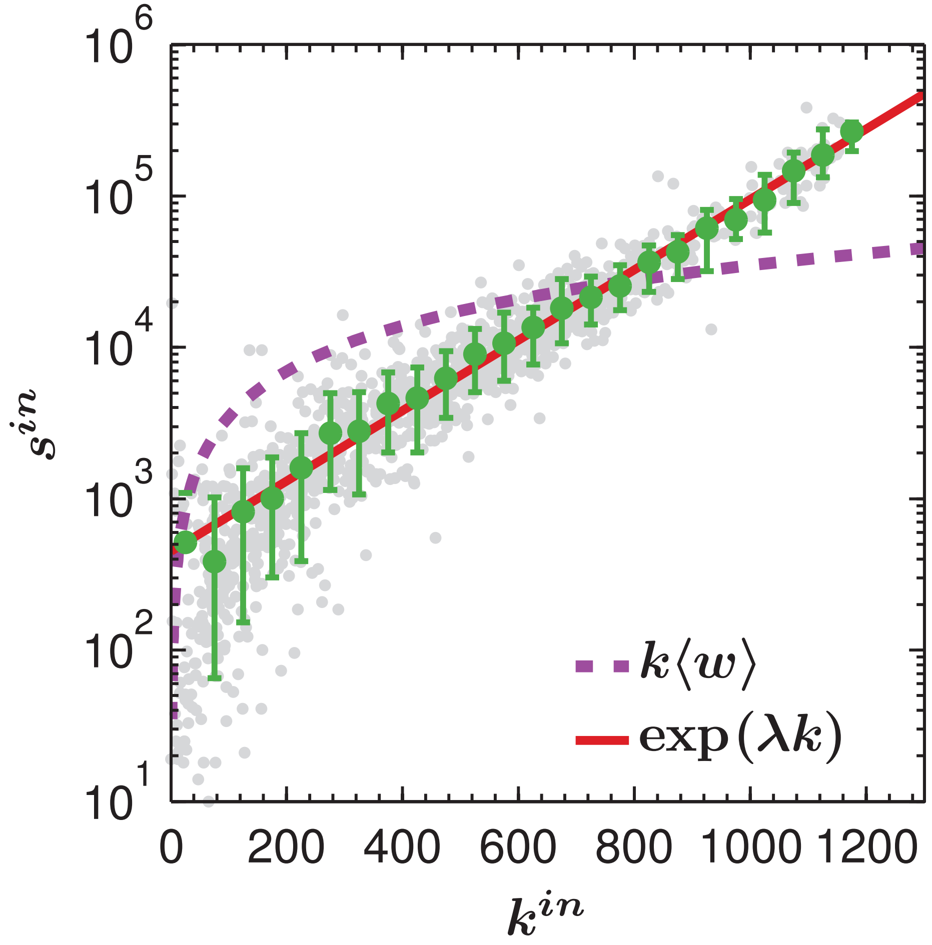
- Spatial networks
- Power-law on node strength v.s node degree

$$s(k) \sim k^{\beta}$$

$$s(k) \sim \exp(\lambda k)$$

$$s(k) \sim k\langle w \rangle$$





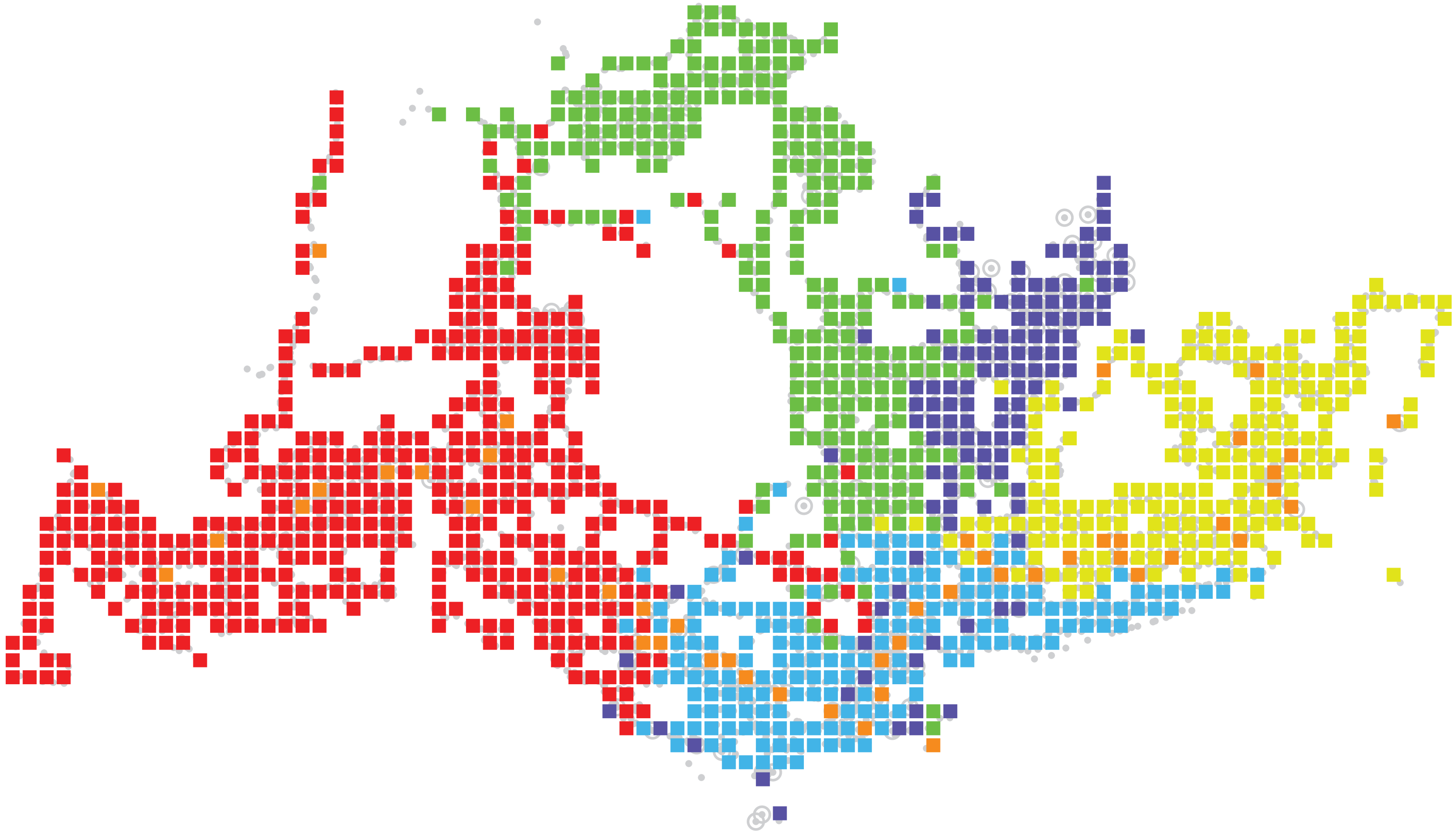
Community structure

- **Maximize Q-modularity**

$$Q = \frac{1}{W} \sum_{ij} \left(w_{ij} - w'_{ij} \right) \delta \left(c_i, c_j \right)$$

- Louvain method

Blondel VD, Guillaume J-L, Lambiotte R, & Lefebvre E (2008) Fast unfolding of communities in large networks. Journal of Statistical Mechanics: Theory and Experiment (10):P10008.



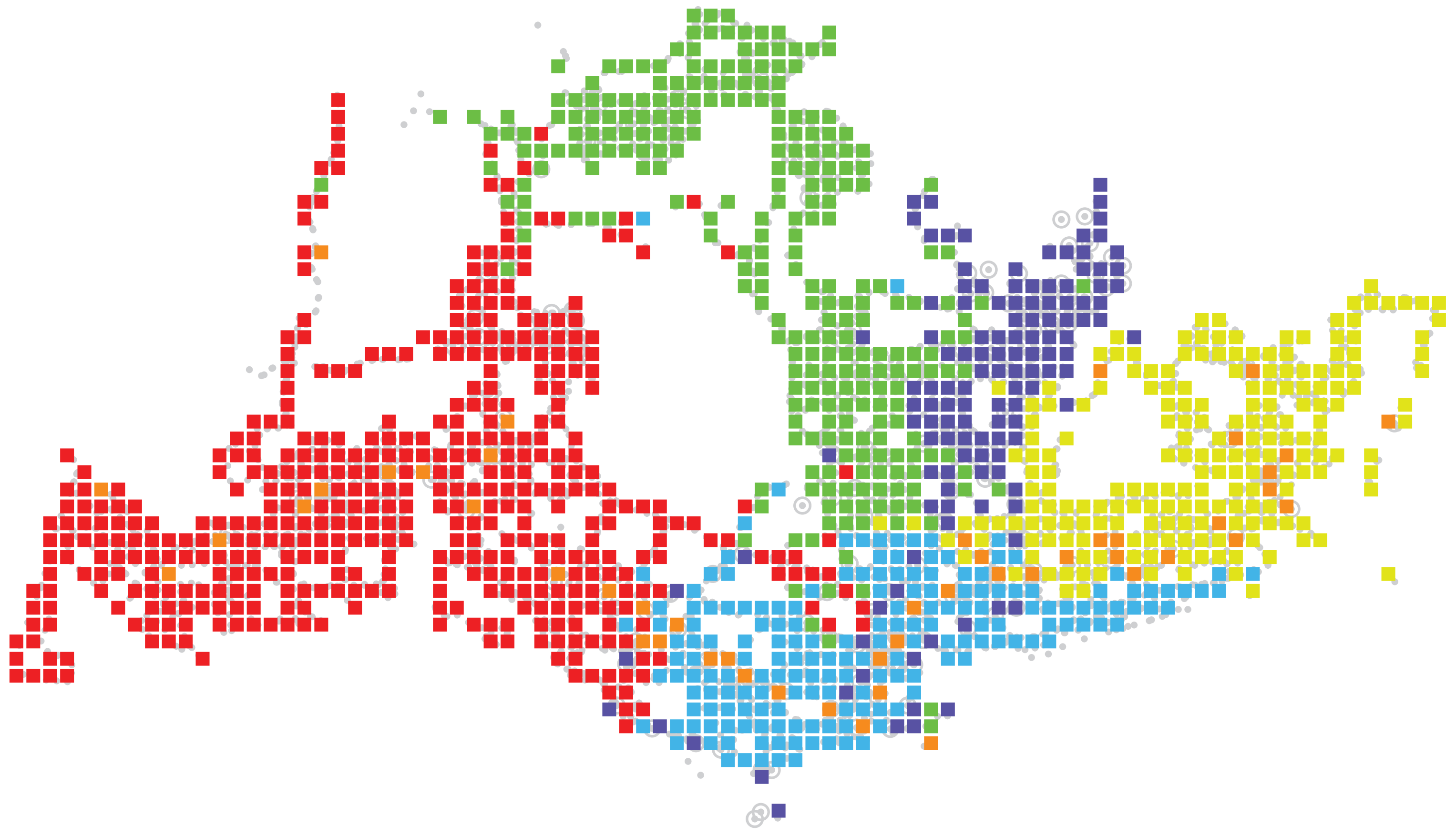
Community structure

- **Maximize Q-modularity**

$$Q = \frac{1}{W}\sum_{ij}\left(w_{ij} - w'_{ij}\right)\delta\left(c_i, c_j\right)$$

- Louvain method

- We still miss the temporal evolution of these inherited community structure.



Community structure

- **Maximize modularity**

$$Q = \frac{1}{W} \sum_{ij} \left(w_{ij} - w'_{ij} \right) \delta \left(c_i , c_j \right)$$

- Divide all transit journeys into groups according to their transaction times.

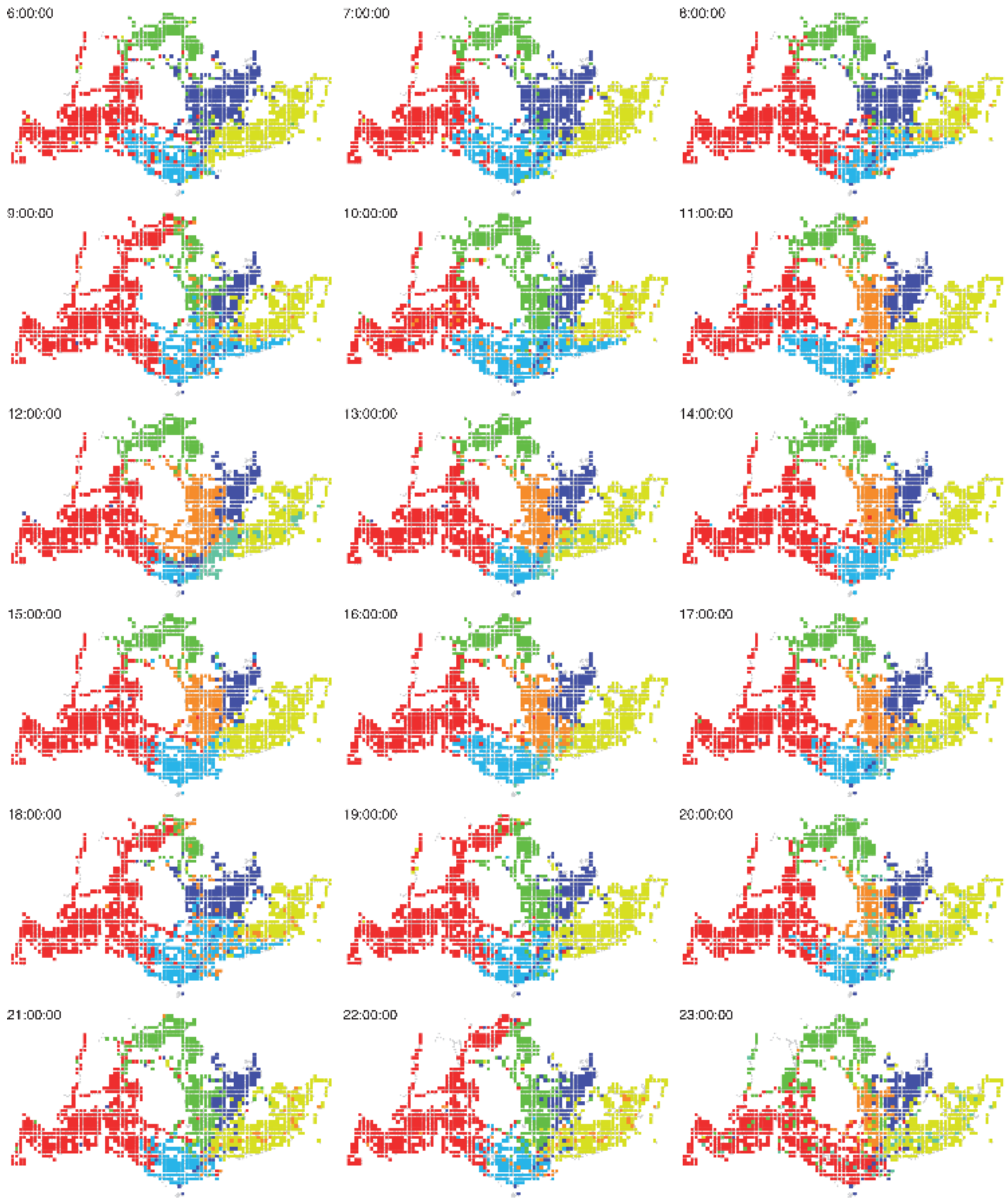
Community structure

- **Maximize modularity**

$$Q = \frac{1}{W}\sum_{ij}\left(w_{ij} - w'_{ij}\right)\delta\left(c_i, c_j\right)$$

- Divide all transit journeys into groups according to their transaction times.

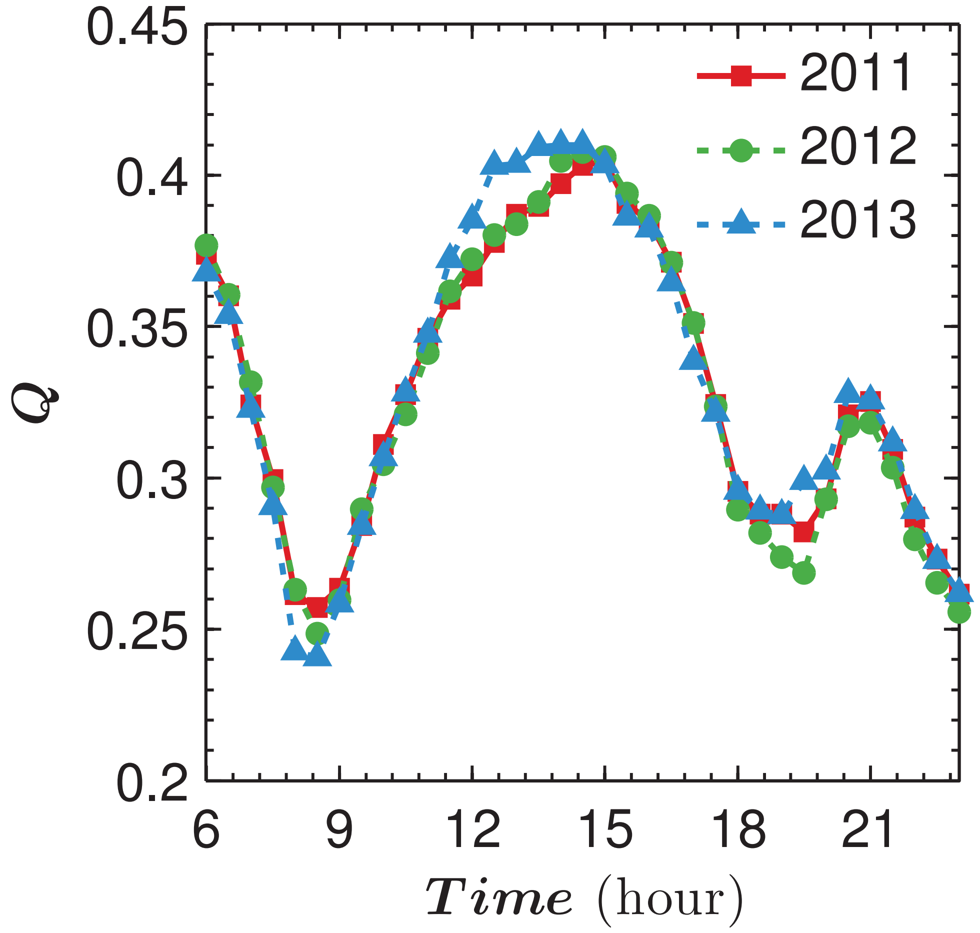
- Applying community detection for aggregated interaction network in each hour



Temporal change

- Applying community detection for aggregated interaction network in each hour

- **The temporal change of modularity**

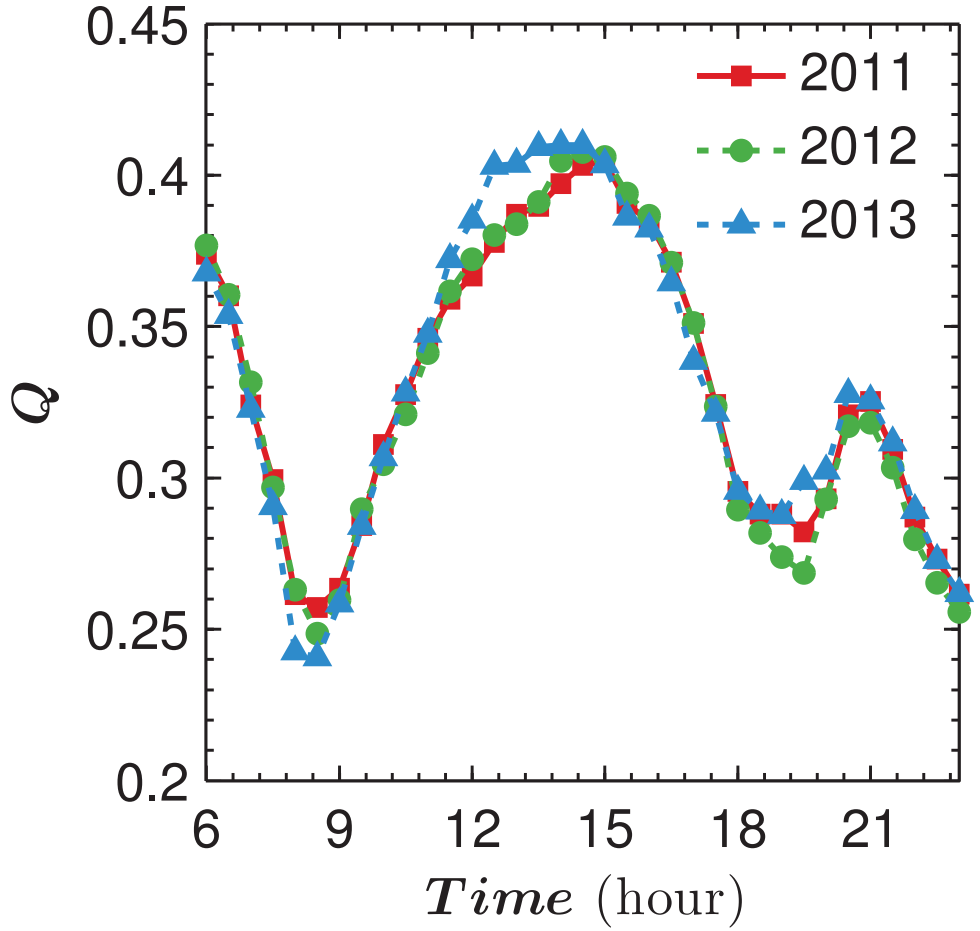


Temporal change

- Applying community detection for aggregated interaction network in each hour

- The temporal change of modularity

- A high degree of similarity across years

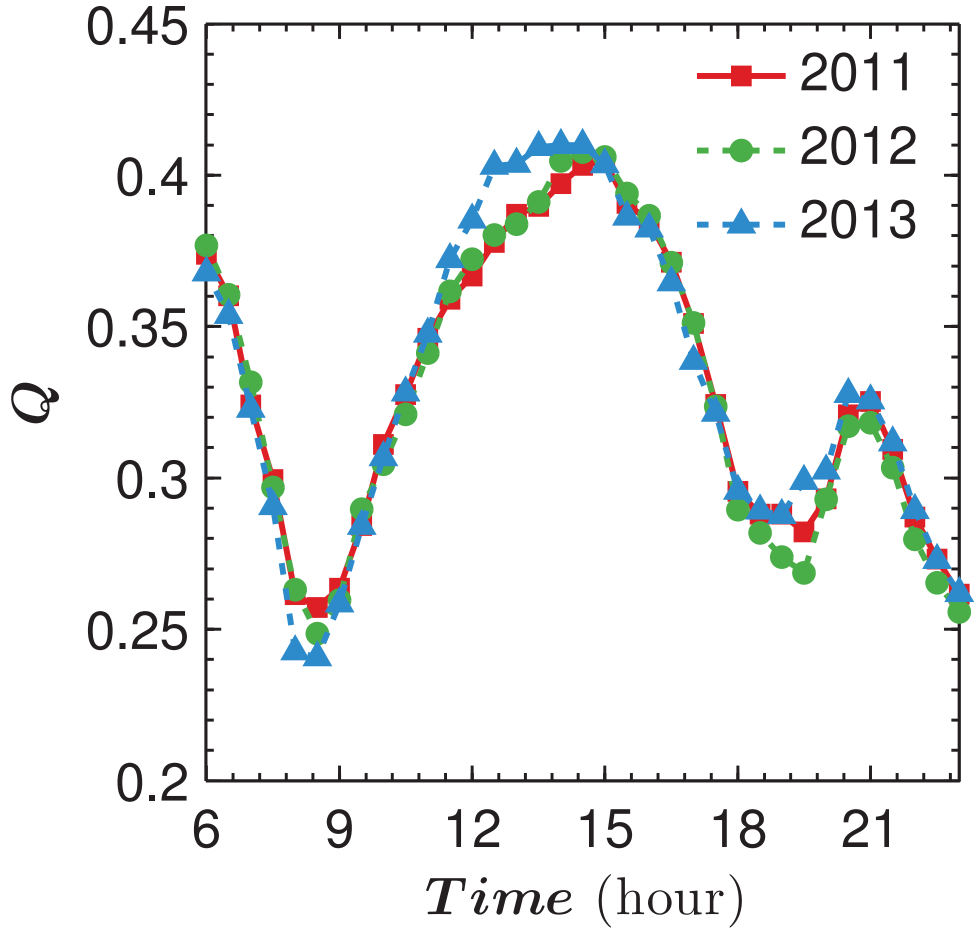


Temporal change

- Applying community detection for aggregated interaction network in each hour

- **The temporal change of modularity**

- **Travel behaviour?**

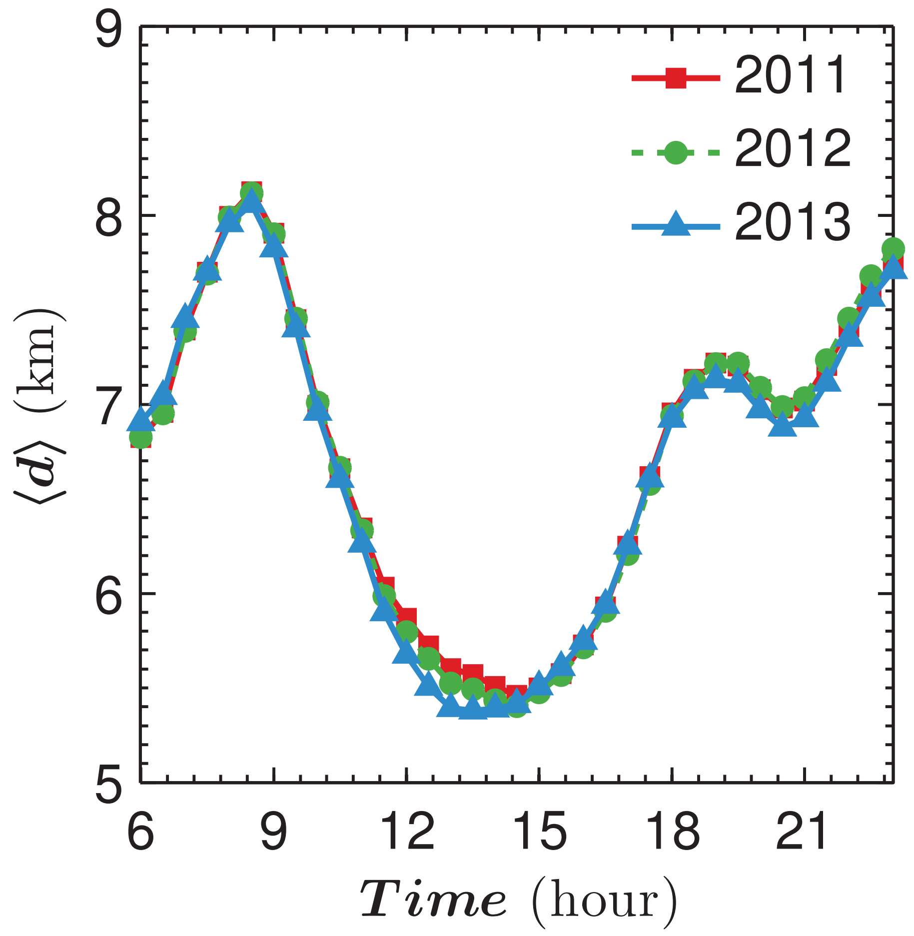


Temporal change

- Applying community detection for aggregated interaction network in each hour

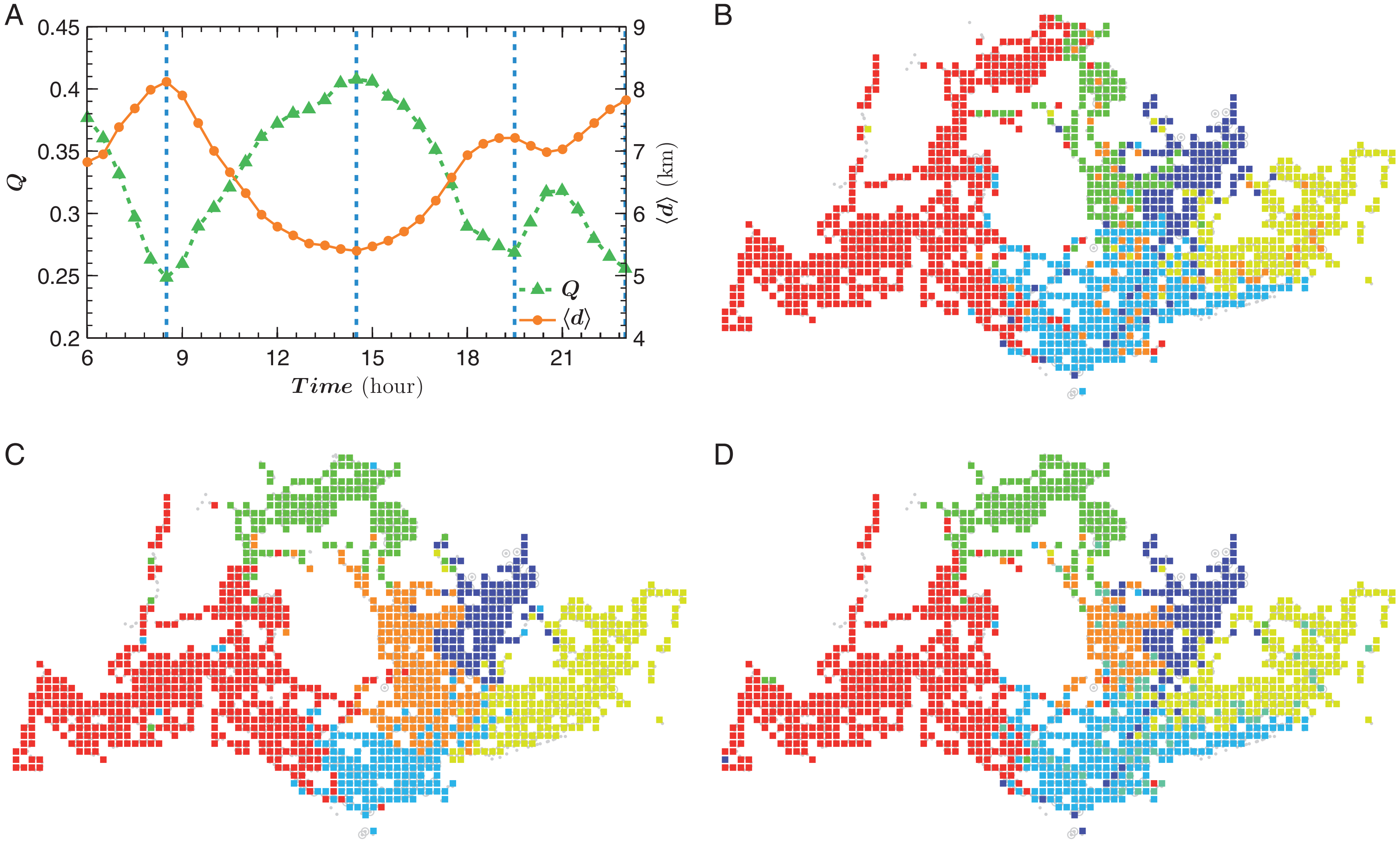
- The temporal change of modularity

- The temporal change of avg travel distance
- (displacement)
- Another high degree of similarity



Temporal change

- Applying community detection for aggregated interaction network in each hour



8:30 am

2:30 pm

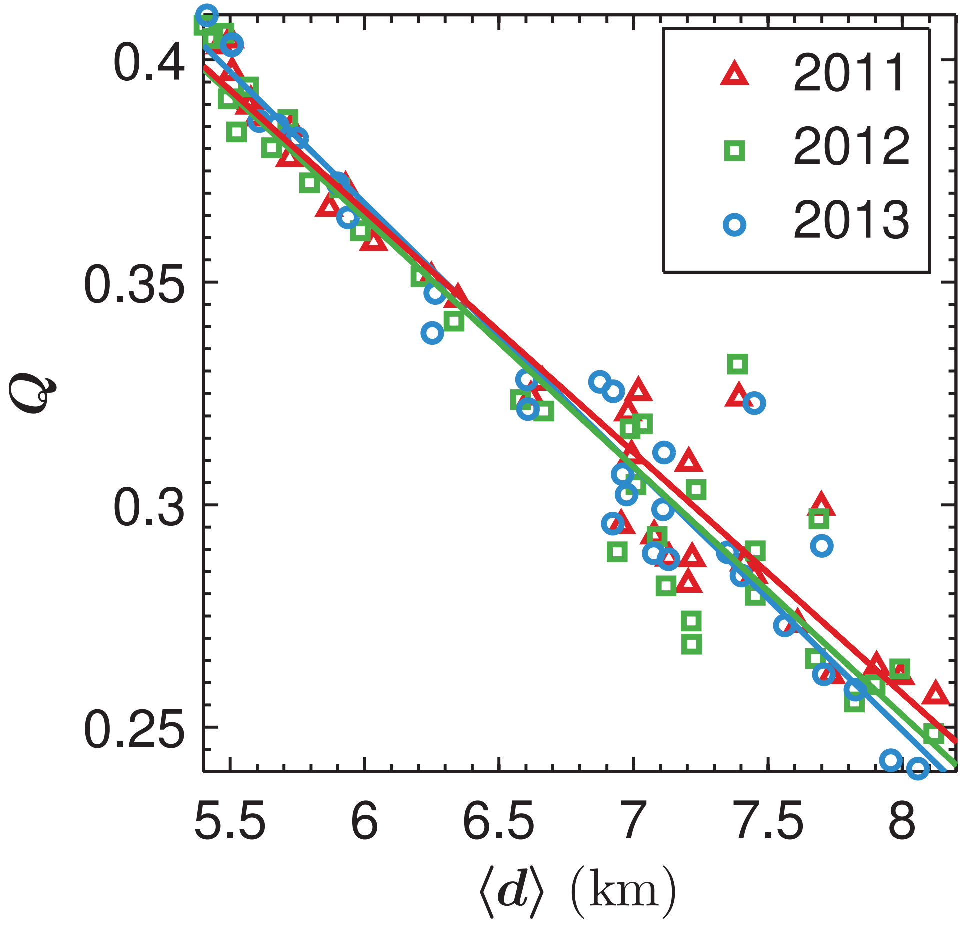
7:30 pm

Temporal change

- Applying community detection for aggregated interaction network in each hour
- The temporal change of modularity
- The temporal change of travel distance

$$Q \sim \alpha \langle d \rangle$$

$$\alpha_{11} = -0.69 \quad \rho = -0.97$$
$$\alpha_{12} = -0.70 \quad \rho = -0.96$$
$$\alpha_{13} = -0.72 \quad \rho = -0.98$$

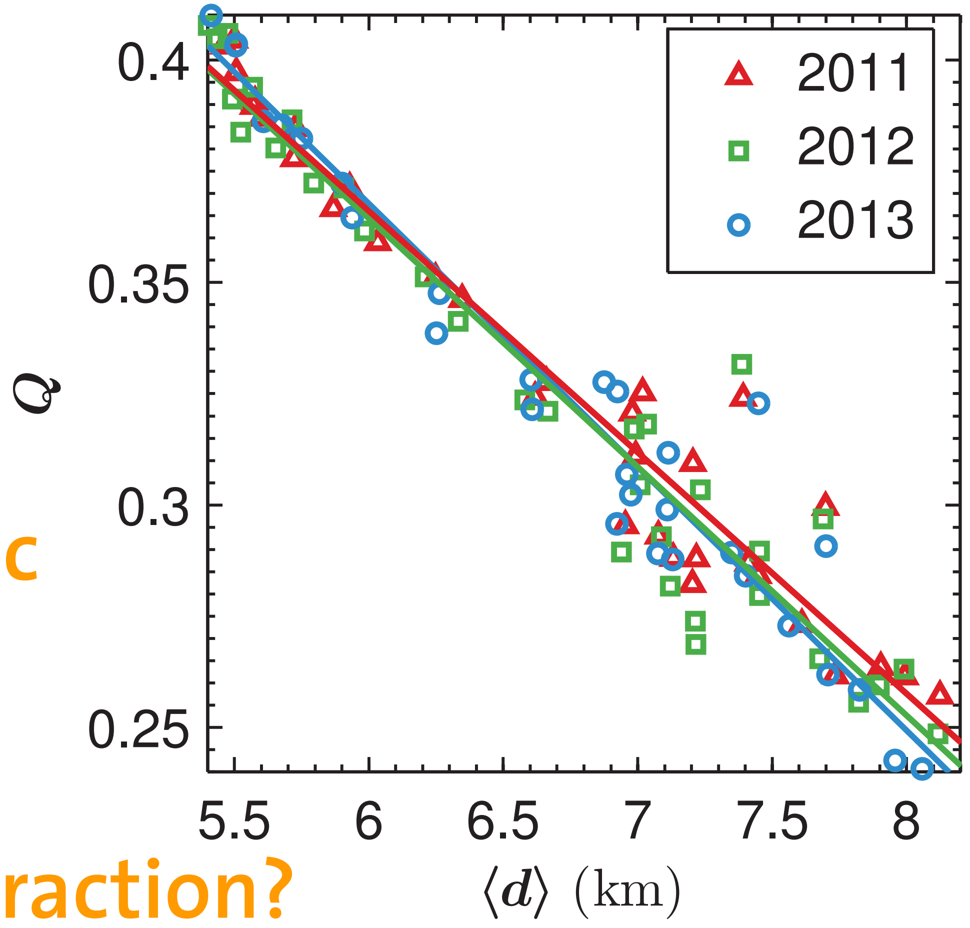


Temporal change

- Applying community detection for aggregated interaction network in each hour

- The temporal change of modularity
- The temporal change of travel distance

- Temporal variation of collective movement plays a crucial role in expressing the dynamic community structures



- The impact of travel distance on spatial interaction?

Impact of distance on spatial interaction

- Quantify the variation of two distance-related measures

- Degree of heterogeneity of bi-directional flows
- (for OD pairs with $w_{ij}, w_{ji} > 0$)

$$\theta_{ij} = \max\{w_{ij}, w_{ji}\} / \min\{w_{ij}, w_{ji}\}$$

- **We may expect that θ_{ij} is independent from distance.**

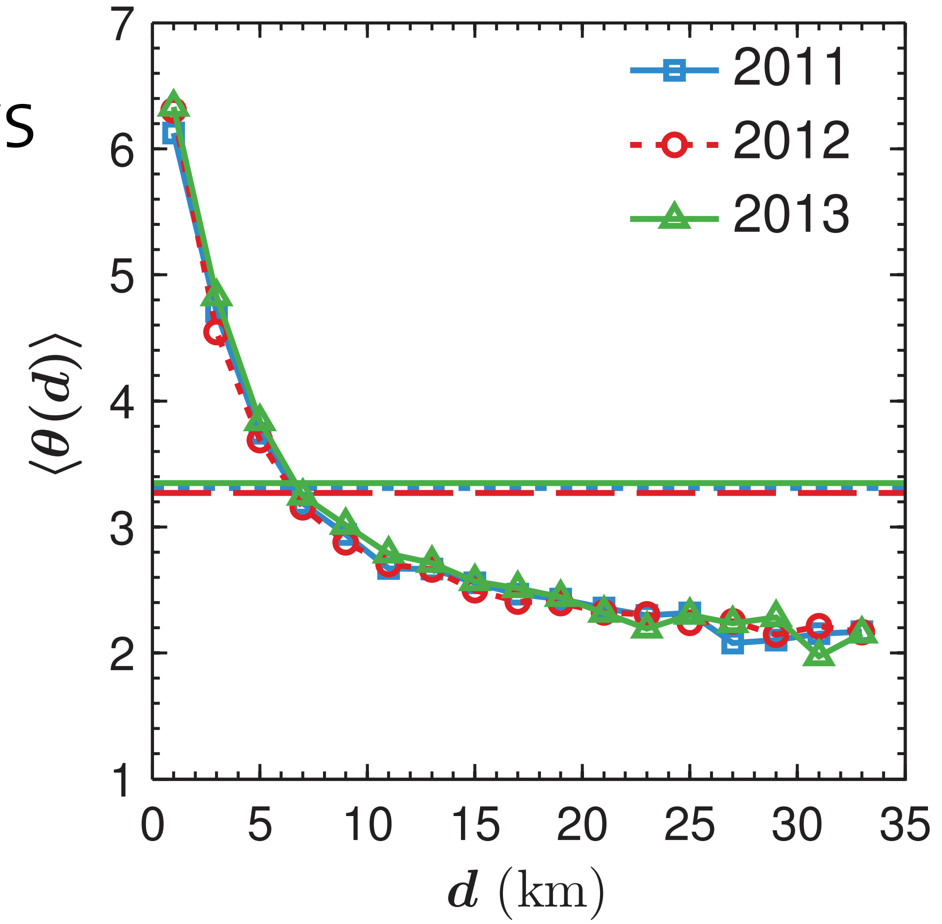
Impact of distance on spatial interaction

- Quantify the variation of two distance-related measures

- Degree of heterogeneity of bi-directional flows
- (for OD pairs with $w_{ij}, w_{ji} > 0$)

$$\theta_{ij} = \max\{w_{ij}, w_{ji}\} / \min\{w_{ij}, w_{ji}\}$$

- Average $\langle \theta \rangle$ *vs* d
- Consistent reduction, indicating that bi-directional flows become more balanced



Impact of distance on spatial interaction

- Quantify the variation of two distance-related measures

- Degree of heterogeneity of bi-directional flows
- (for OD pairs with $w_{ij}, w_{ji} > 0$)

$$\theta_{ij} = \max\{w_{ij}, w_{ji}\} / \min\{w_{ij}, w_{ji}\}$$

- Not sufficient to show homogeneity at individual level
- Using card ID

Impact of distance on spatial interaction

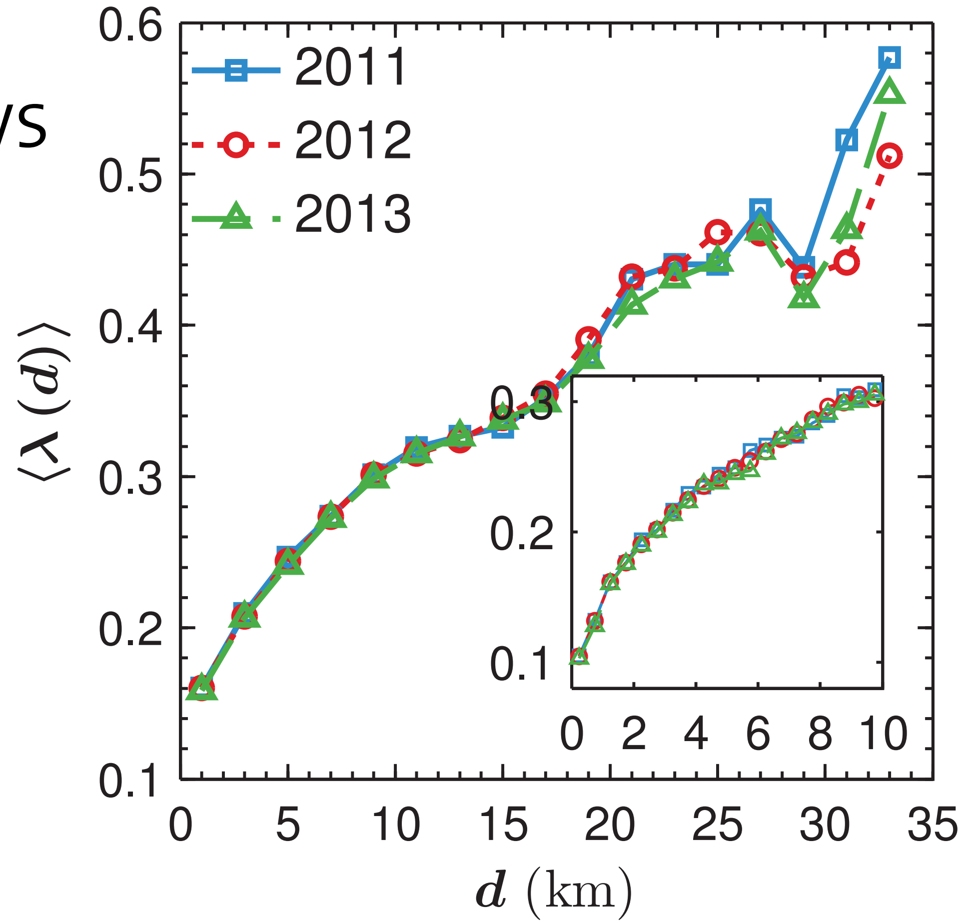
- Quantify the variation of two distance-related measures

- Degree of heterogeneity of bi-directional flows
- (for OD pairs with $w_{ij}, w_{ji} > 0$)

$$\theta_{ij} = \max\{w_{ij}, w_{ji}\} / \min\{w_{ij}, w_{ji}\}$$

- Jaccard index (another consistent trend)

$$\lambda_{ij} = |W_{ij} \cap W_{ji}| / |W_{ij} \cup W_{ji}|$$



- **Shorter travel distances are associated with higher exploration; and previously visited locations are more preferred for long distance journeys.**

How spatial interactions shape a city

- With time-varying interactions during a day, the resulting structural communities should be changing simultaneously over time (such as the continuous changing of boarders and emergence of new communities).

- **To quantify it, we define neighbourhood variability γ_i of zone i between the sub-networks at t_1 and t_2 as:**

$$\gamma_i(t_1,t_2)=1-\frac{|C_i(t_1)\cap C_i(t_2)|}{|C_i(t_1)\cup C_i(t_2)|}$$

Palla G, Barabási A-L, & Vicsek T (2007) Quantifying social group evolution. *Nature* 446(7136):664-667.

- $\gamma_i(t_1,t_2)$ **is close to one if the community zone i belongs does not change from t1 to t2.**

How spatial interactions shape a city

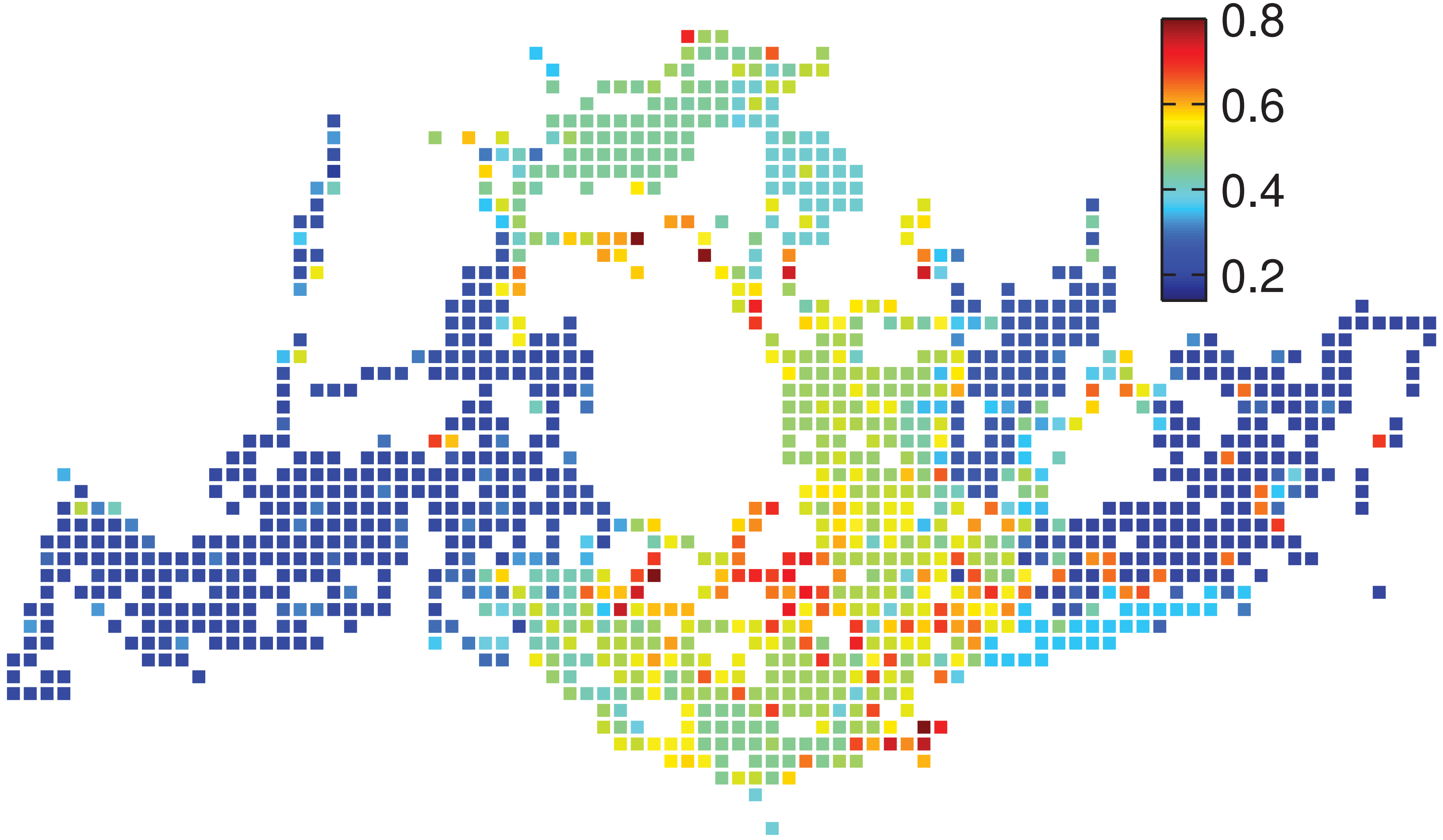
- With time-varying interactions during a day, the resulting structural communities should be changing simultaneously over time (such as the continuous changing of boarders and emergence of new communities).

- **Using continuous observations (hourly), we quantify the overall spatial evolution of zone i by calculating mutability as average neighbourhood variability from t_0 to t_{max} (6am to 11pm):**

$$\phi_i = \frac{\sum_{t=t_0}^{t_{max}-1} \gamma_i(t, t+1)}{t_{max} - t_0}$$

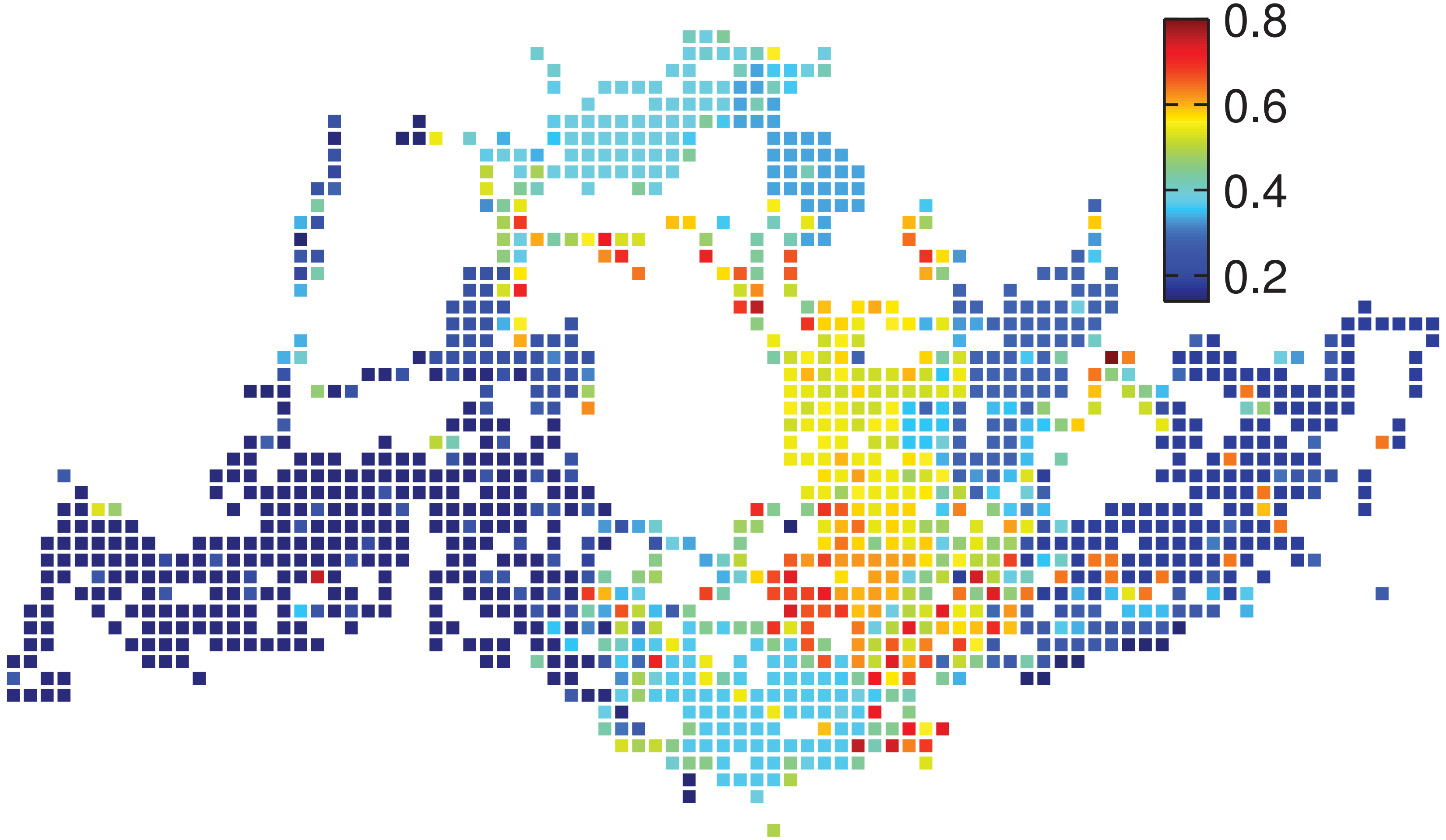
How spatial interactions shape a city

- **Spatial distribution of mutability - 2011**



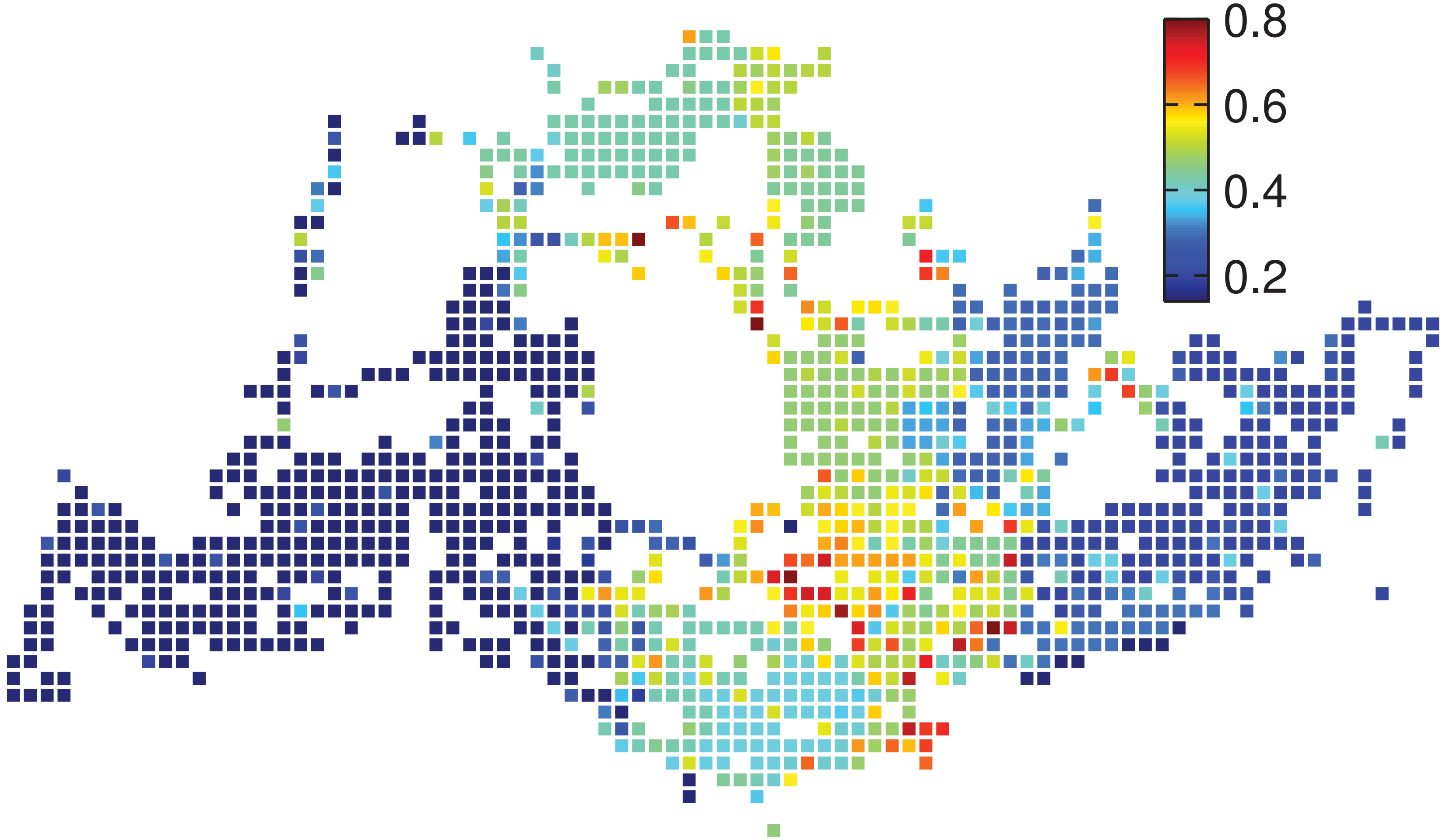
How spatial interactions shape a city

- **Spatial distribution of mutability - 2012**



How spatial interactions shape a city

- **Spatial distribution of mutability - 2013**



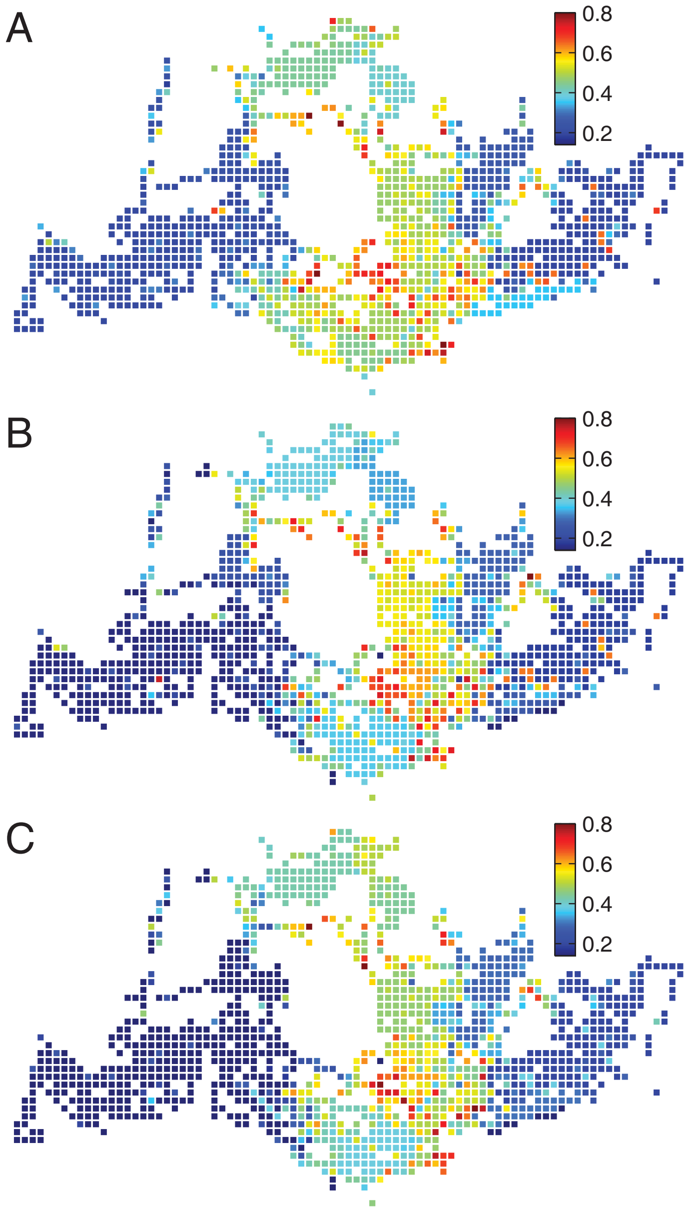
How spatial interactions shape a city

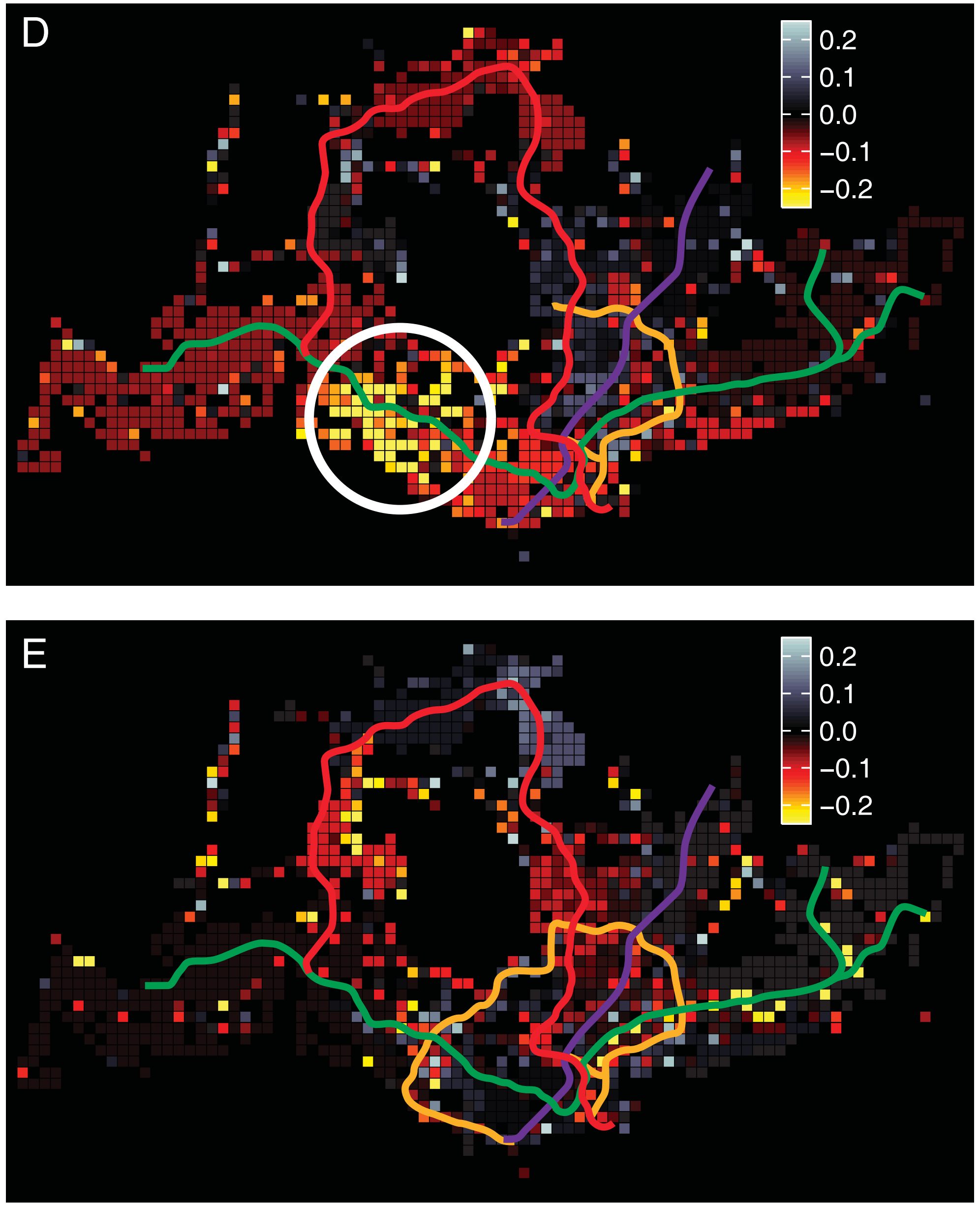
- **Quantify the differences**

$$\Delta\phi^1 = \phi_{i,12} - \phi_{i,11}$$

$$\Delta\phi^2 = \phi_{i,13} - \phi_{i,12}$$

- **Region affected by the new CCL metro service**





How spatial interactions shape a city

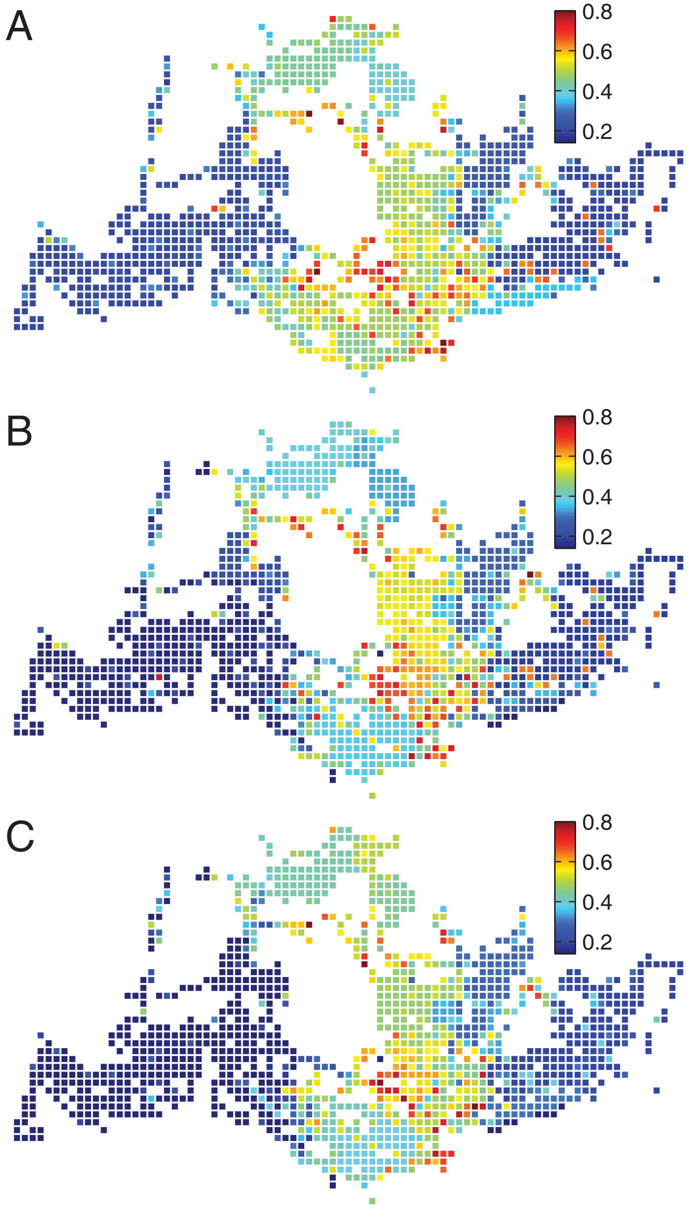
- Quantify the differences

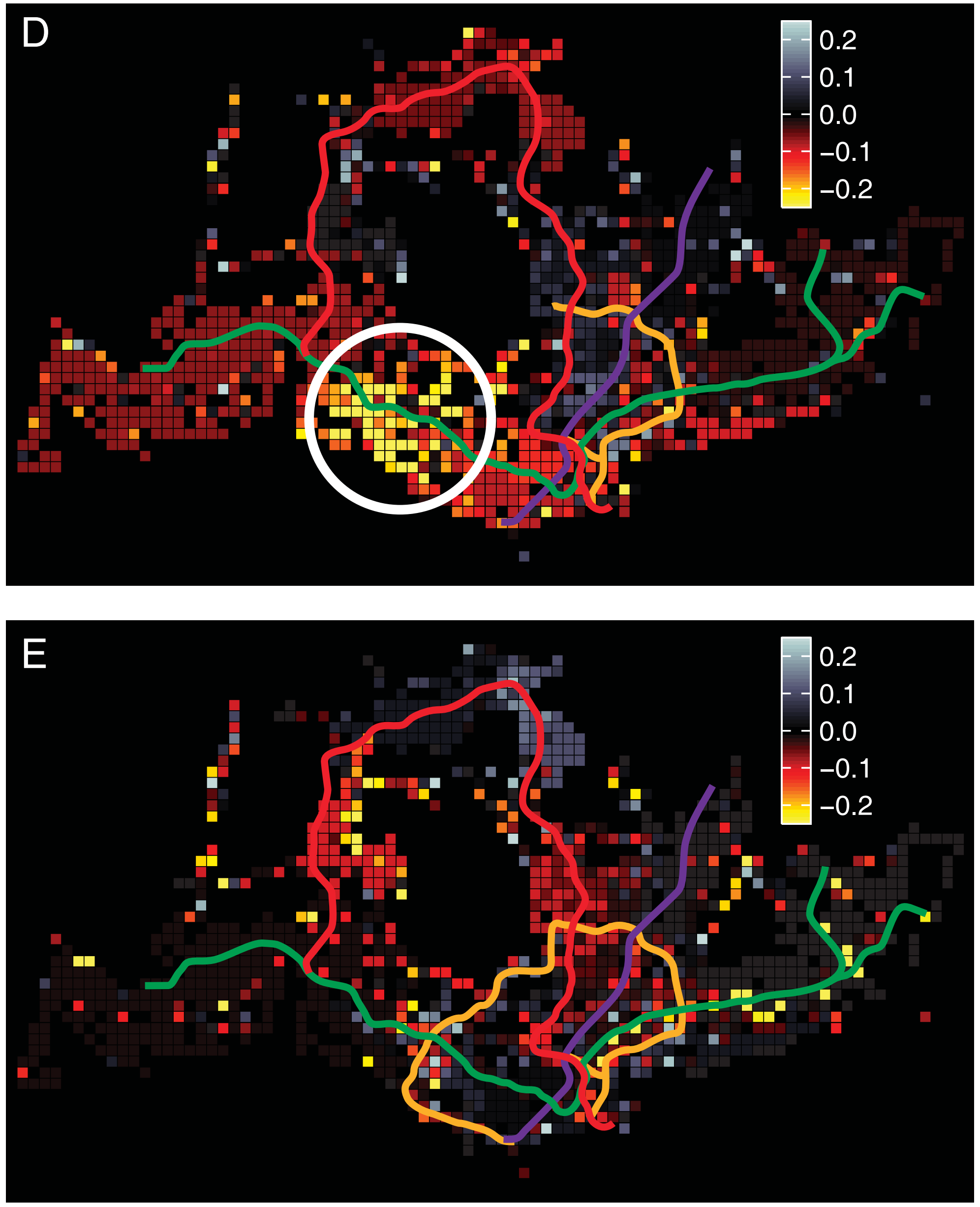
$$\Delta\phi^1 = \phi_{i,12} - \phi_{i,11}$$

$$\Delta\phi^2 = \phi_{i,13} - \phi_{i,12}$$

- Compare $\Delta\phi$ in region with others

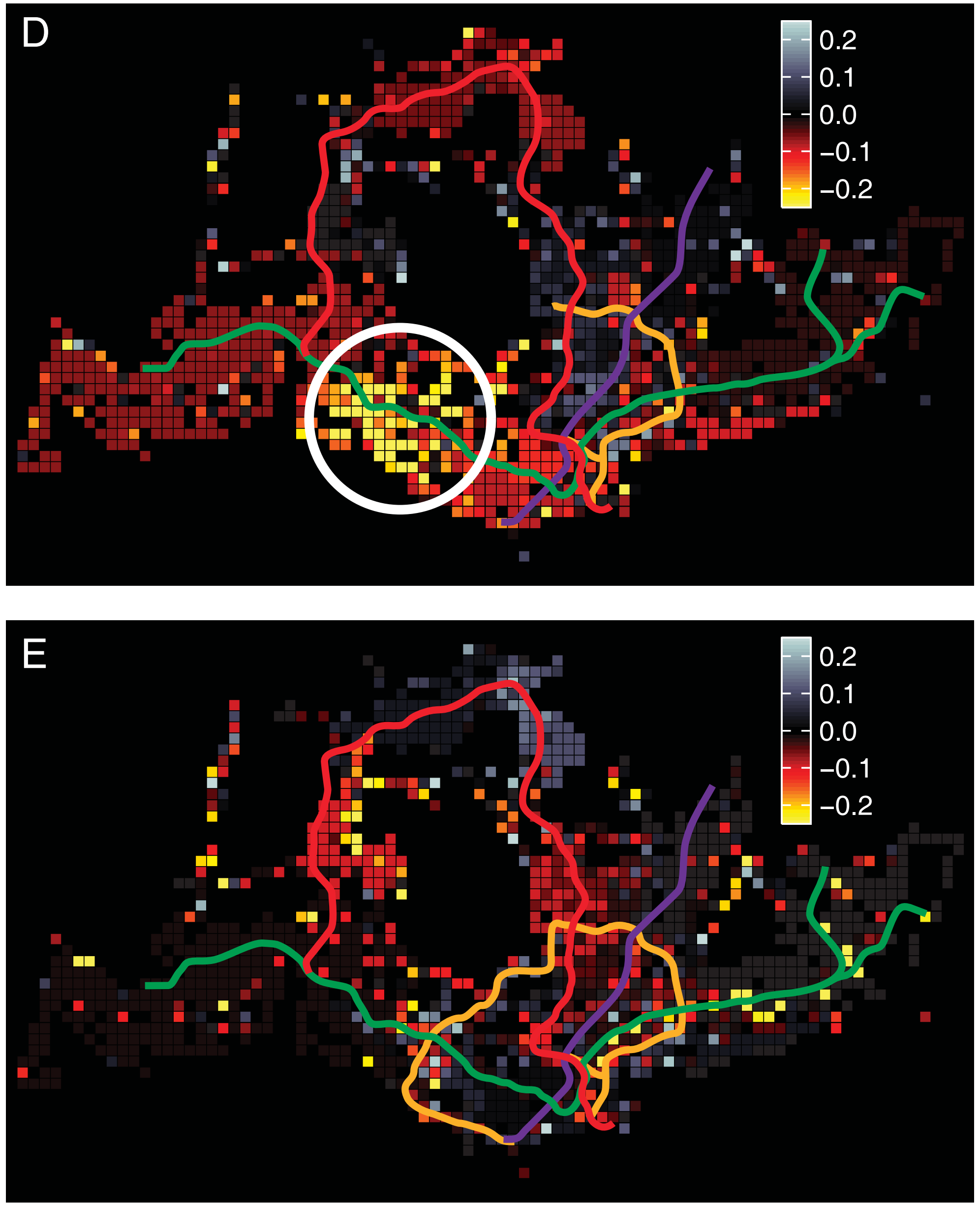
- $P<10^{-4}$ (Wilcoxon rank-sum)
- $P=0.213$ (Wilcoxon rank-sum)





How spatial interactions shape a city

- The completion of Stage 2 (the western half of the circle line) allows commuters to shorten their trips when traveling from north/central/south to west and vice versa and reduces their travel times, enhancing the connectivity between the nearby region and western community. This matches our observation in mutability change very well.



Discussion

- The evolution of urban structure with these temporal interactions is merely revealed before, as it is not possible to distinguish fluctuations from the natural variability in the city's mobility from large deviations and real changes using either coarse-grained or short-time scales mobility data.

Discussion

- The evolution of urban structure with these temporal interactions is difficult: to distinguish fluctuations from the natural variability in the city's mobility from large deviations and real changes using either coarse-grained or short-time scales mobility data.

- Despite Singapore being a dynamic, fast-changing city, we show that human mobility displays patterns invariant across the years, even when seeing a large infrastructure project.

Discussion

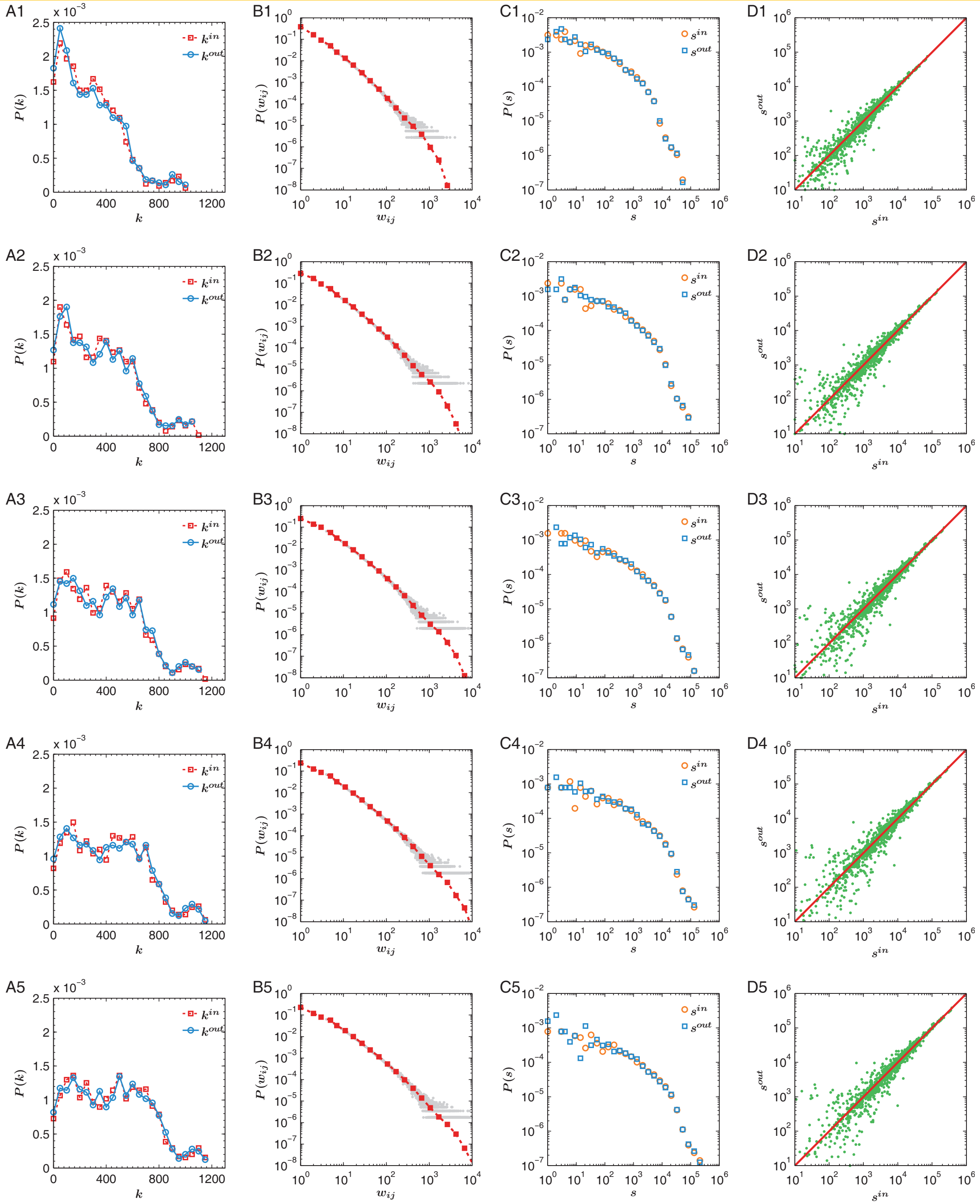
- The evolution of urban structure with these temporal interactions is merely revealed before, as it is not possible to distinguish fluctuations from the natural variability in the city's mobility from large deviations and real changes using either coarse-grained or short-time scales mobility data.
- Despite Singapore being a dynamic, fast-changing city, we show that human mobility displays in aggregate patterns invariant across the years, even when seeing a large infrastructure project.
- Notably, despite other structural and behavioral dynamic indicators being almost consistent and indistinguishable over the long-term, we do observe a significant difference of mutability. It is sensitive to the differences in mobility caused by major transportation infrastructure change, showing the evolving borders in community structure, and with this the way people interact to shape, sustain or reform a city.

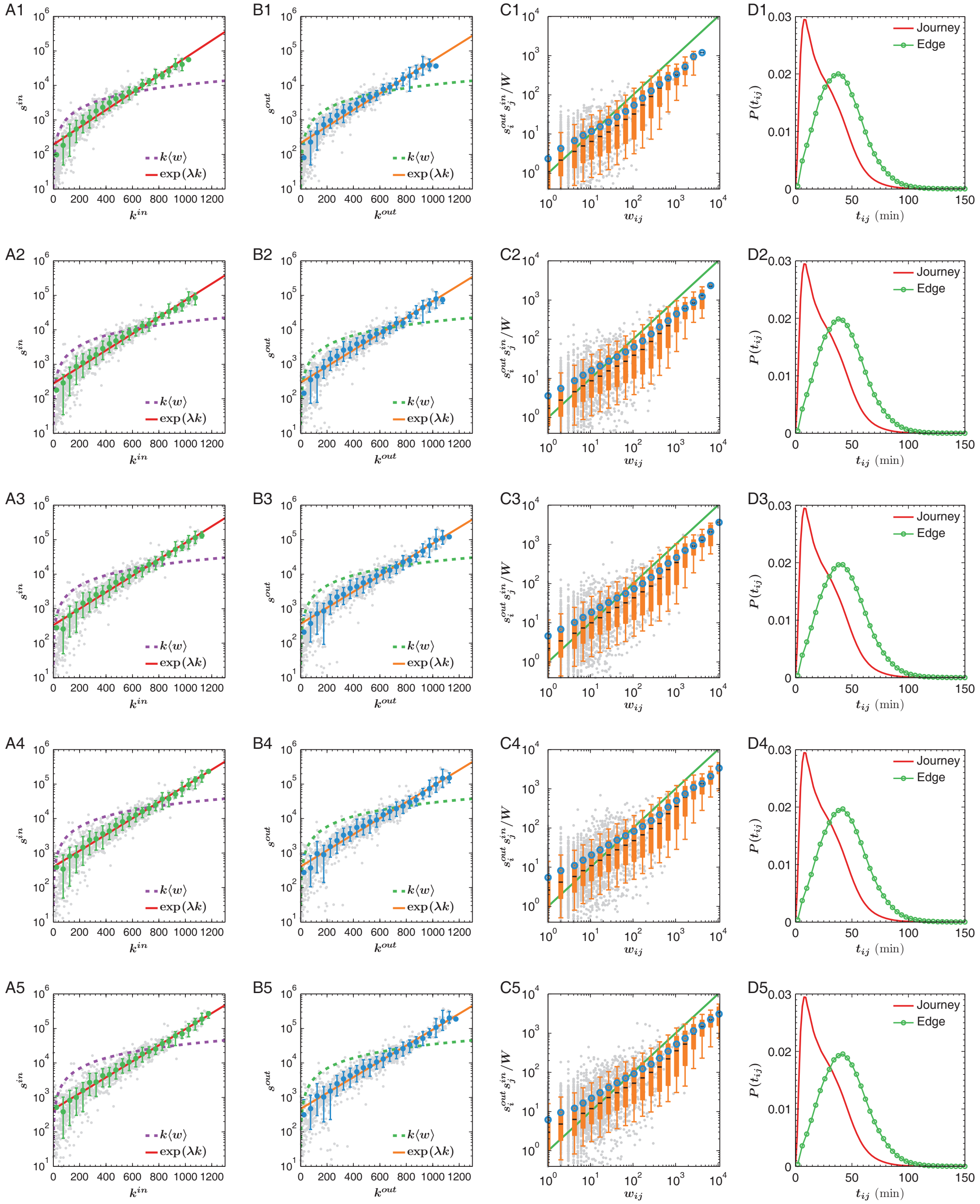
Thank you!

SUN Lijun

Future Cities Laboratory, Singapore-ETH Centre
Dept. of Civil Eng., National University of Singapore
sunlijun@nus.edu.sg
https://sites.google.com/site/sunlijun1988/

Appendix – evolution of aggregated networks





Appendix -