Universal Geometric Structure of Epidemic Spreading Across Scales

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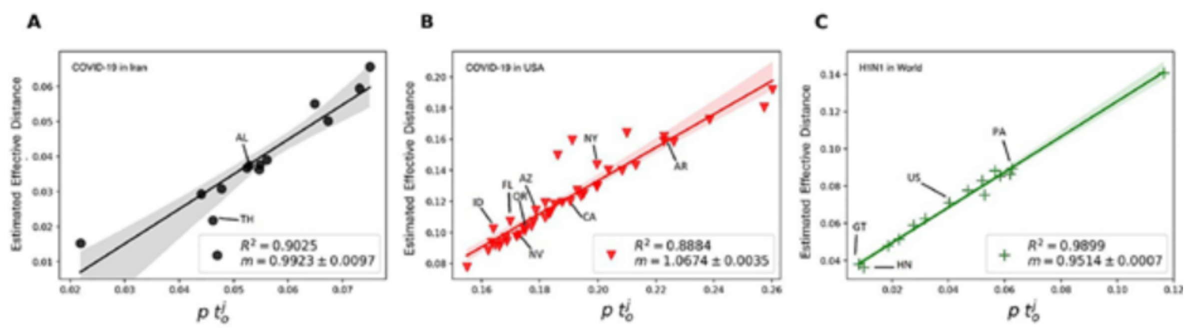
Understanding when and where an epidemic begins, and how it propagates across heterogeneous networks, requires linking dynamics across multiple spatial and temporal scales. In modern mobility systems, contagion unfolds through a complex interplay between local infection dynamics and large-scale movement patterns, making it challenging to infer global spreading behavior from partial observations. In this work, we develop a mathematical framework for epidemic spreading on meta-population networks that explicitly integrates intra-population infection processes with inter-population mobility flows.

By linearizing the coupled dynamical system at the early stage, we derive analytical expressions that enable the identification of the spatiotemporal origin of an outbreak—the epidemic "Big Bang"—including both its source location and initiation time. This approach provides a principled way to reconstruct early-stage dynamics from limited data. Building on this formulation, we introduce an effective distance that encodes the geometry induced by mobility patterns. When contagion dynamics are expressed in this metric, the spread of infection exhibits a universal linear structure, revealing a striking simplification of otherwise complex dynamics.

Remarkably, this emergent geometric representation is largely independent of disease-specific parameters, such as the basic reproduction number, and remains robust across different classes of mobility networks. This suggests that large-scale spreading patterns are governed by renormalization factors based on network structure and epidemiological factors. From this perspective, contagion exhibits a clear multi-scale organization: heterogeneous mesoscopic subpopulation dynamics collectively give rise to a universal macroscopic geometric law, effectively bridging local interactions and global behavior.

We validate the proposed framework using empirical data from COVID-19 and H1N1 outbreaks, demonstrating that even sparse observational snapshots are sufficient to reconstruct spreading pathways and infer outbreak origins with high accuracy, see Figure. Beyond epidemiology, our results highlight how network structure and dynamics jointly generate universal laws of propagation, offering a unifying viewpoint for analyzing complex systems across scales. This framework opens new avenues for data-driven inference, real-time monitoring, and the design of effective intervention strategies in networked systems.



Reference:

Babazadeh Maghsoodlo, Y., Safaeesirat, A. Ghanbarnejad, F. The Big Bang of an epidemic: a metapopulation approach to identify the spatiotemporal origin of contagious diseases and their universal spreading pattern. Sci Rep 15, 5809 (2025).