Solar Energy Evolution and Diffusion Studies (SEEDS)

An unprecedented industry-wide study to identify the drivers and barriers to adoption of solar, how they vary by customer segments, and how the target customer segment may shift over time.

Ben Sigrin, National Renewable Energy Laboratory
www.nrel.gov/extranet/seeds/

Agent-based models of how segregation and peer effects influence solar PV adoption

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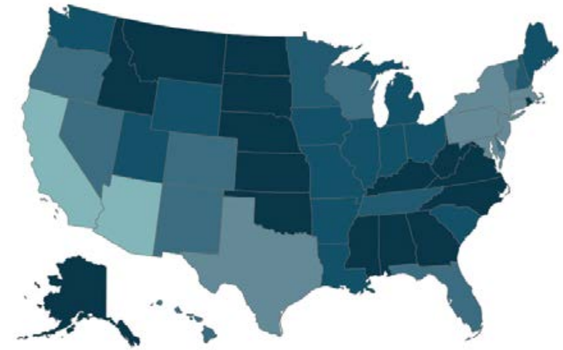
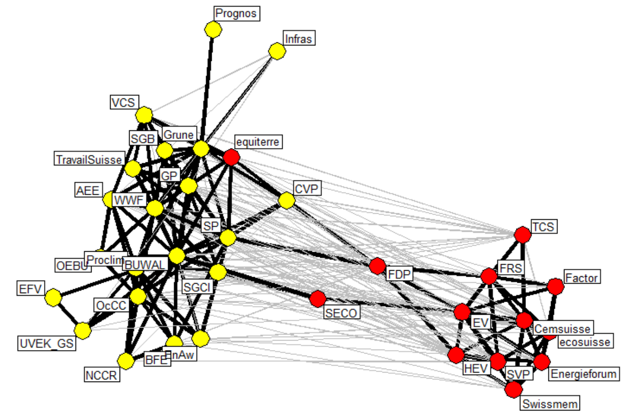
Understanding environmental consumption



- How people invest in technologies that change their ecological footprint… has important implications for sustainability!
- We have good indicators of environmental consumption, but need better theories of the mechanisms that drive these indicators.
  - Need focus on **models of individual**
- With better theory can design better programs that **exploit** factors that contribute to learning, and **overcome** factors that inhibit learning.
- This research examines how the social structures can inhibit adoption in the context of **solar PV**, given certain strategies used by PV installers.

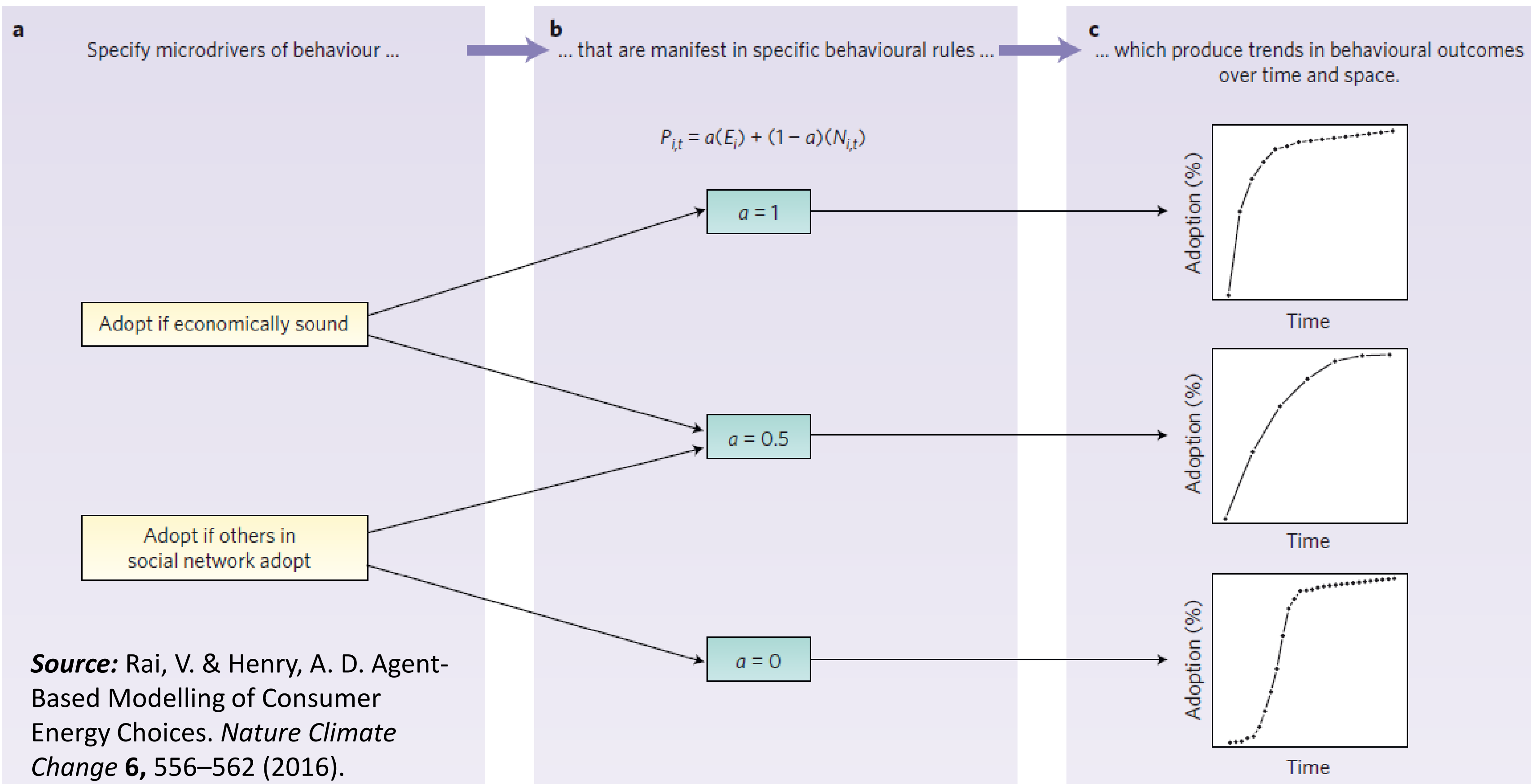
Factors influencing adoption



- Adoption dynamics are a result of factors that operate at three (at least) levels…
- …At the level of "agents" those who make adoption decisions
  - Individual propensities. Covers cognitive factors (concern, values), socioeconomic factors.
  - Social influence. People are influenced by others they share social connections (or "closeness") with. If my neighbor adopts it changes the probability that I adopt.
- … At the level of social structure
  - Social influence means that patterns of connectivity matter. Often, the factors that determine propensity also determine segregation.
- …At the level of external agents who "manipulate" adopters
  - E.g., installer behavior constrains who has an opportunity to adopt.

Role of ABM

- Agent-based models (ABM) can help us to understand and test these complex dynamics in a “virtual laboratory.”
- We can directly specify theoretical mechanisms of how people make decisions, and explore the consequences of these mechanisms.



Source: Rai, V. & Henry, A. D. Agent-Based Modelling of Consumer Energy Choices. *Nature Climate Change* **6,** 556–562 (2016).

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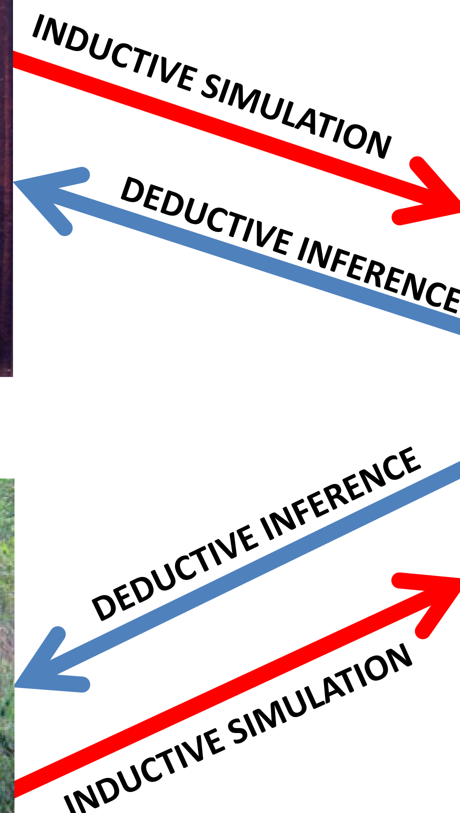
Jacob Jordaens (1593–1678) "Odysseus in der Höhle Polyphems"



Source: www.amnh.org

PV adoption in segregated networks and environmental justice

- Programs to enhance PV adoption (incentive programs, installer strategies, etc.) may have unintended consequences.
- Common wisdom is that peer effects create a social multiplier that magnify benefits of programs. Adoption "spreads" through networks and over space.
- But many social systems are segregated…
  - …Potential adopters with "high propensity" tend to influence others who already have high propensity
  - …Potential adopters with "low propensity" tend to influence others with low propensity.
- Thus programs that benefit high propensity agents may not benefit populations evenly--dampening adoption over time and creating inequities in access to innovative technologies.
- We can explore these dynamics in a theoretical ABM…

The Incentives Model

- Explores how the structures of social networks mediate the effectiveness of governmental programs;
  case of residential solar photovoltaics (PV)

- Network characteristic (e.g. network segregation) can dampen the indirect benefits of solar incentive programs that come from the social multiplier effect

- Measuring the success of incentive programs for renewable energies:
  - Adoption rates and overall adoption of renewables
  - Degree to which incentives diminish or increase structural equalities

Policy incentives for solar adoption

- **Feed-in-tariff**
  - guarantees adopters a long-term fixed rate for every kWh fed into the grid
  - reduces financial risk and amortization times
  - upfront investment necessary
  - first nationwide implemented in Germany (1991)
  - 2007: 46 jurisdictions worldwide have implemented a feed-in-tariff

- **Leasing**
  - based on third-party ownership
  - reducing or eliminating upfront costs for installing solar
  - increasing the demand and widening the range of potential adopters (Drury et al., 2012; Rai & Sigrin, 2013)
  - widely present in California

- **Seeding poorer communities**
  - free PVs for selected agents in poorer communities
  - increasing the visibility of PV within those communities
    - increasing peer effects (e.g. Bollinger & Gillingham, 2012)
    - increasing provision of information (Jager, 2006)
  - positive effects shown in pilot and experimental studies (e.g. Zhang et.al., 2014)

Hypotheses

- H1: Without incentives the difference between adoption curves of low- and high-propensity actors is larger in segregated networks than in integrated networks.

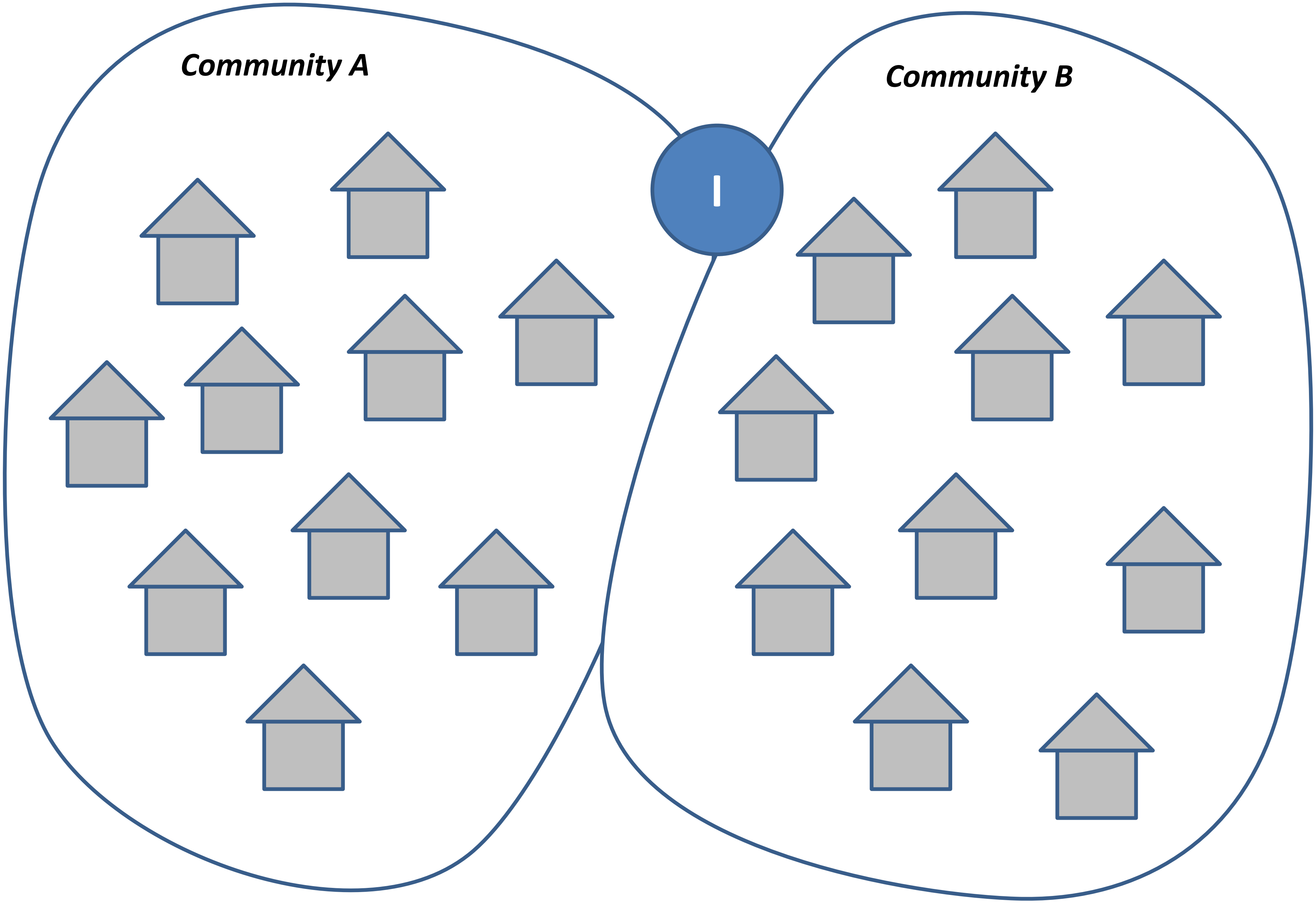
DV: Speed of adoption

- H2a: In integrated as well as in segregated networks feed-in tariffs lead to a faster uptake of installations (as compared to no incentives), through targeting the actors that are most likely to adopt (high-probability agents).

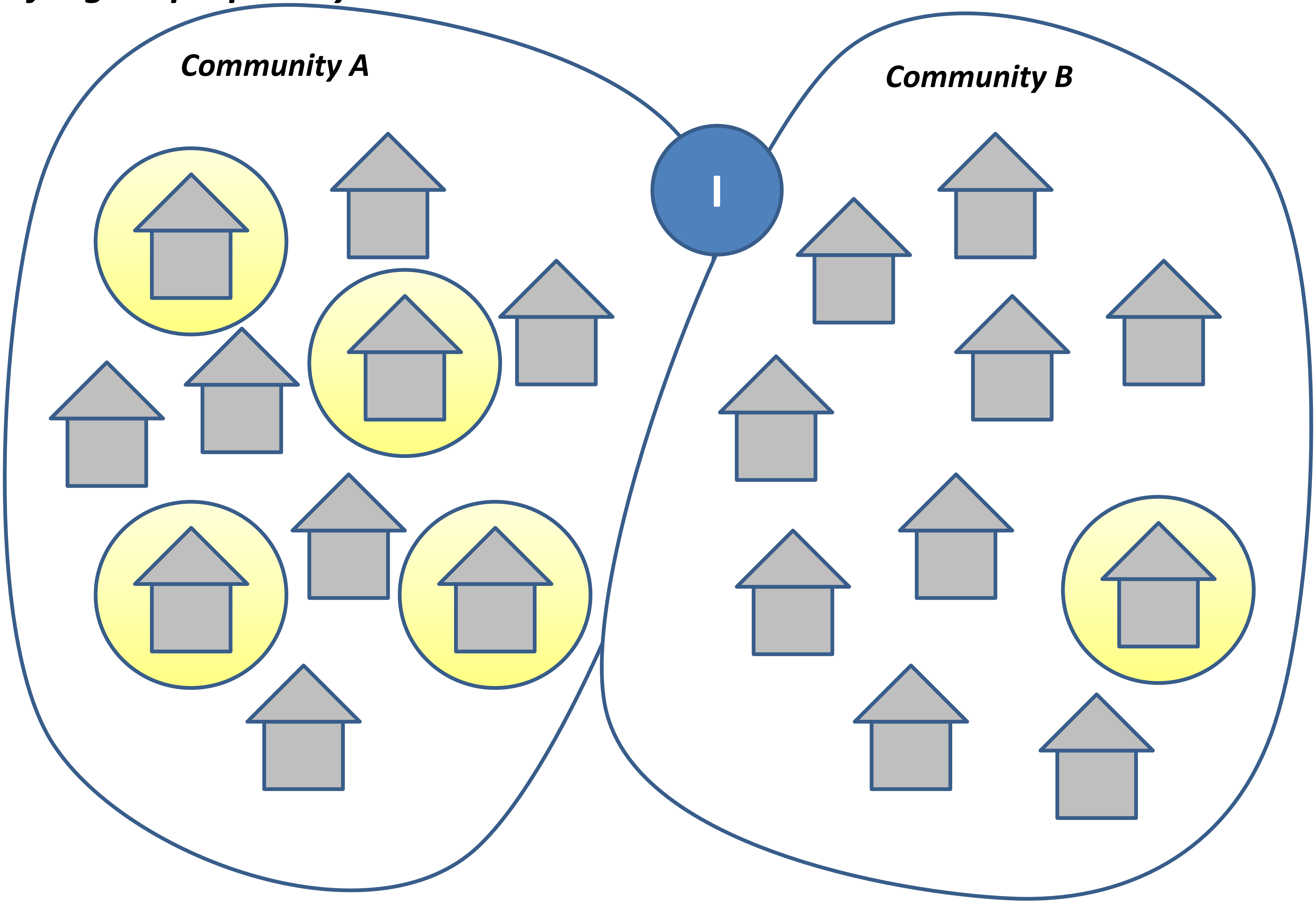
DV: Difference in adoption dynamics

- H2b: In integrated networks the difference in adoption dynamics between high- and low-probability actors does not increase significantly through the feed-in-tariff (as compared to no incentive in integrated networks).
- H2c: In segregated networks the difference in adoption dynamics between high- and low-probability actors increases significantly through the feed-in-tariff (as compared to no incentive in segregated networks).

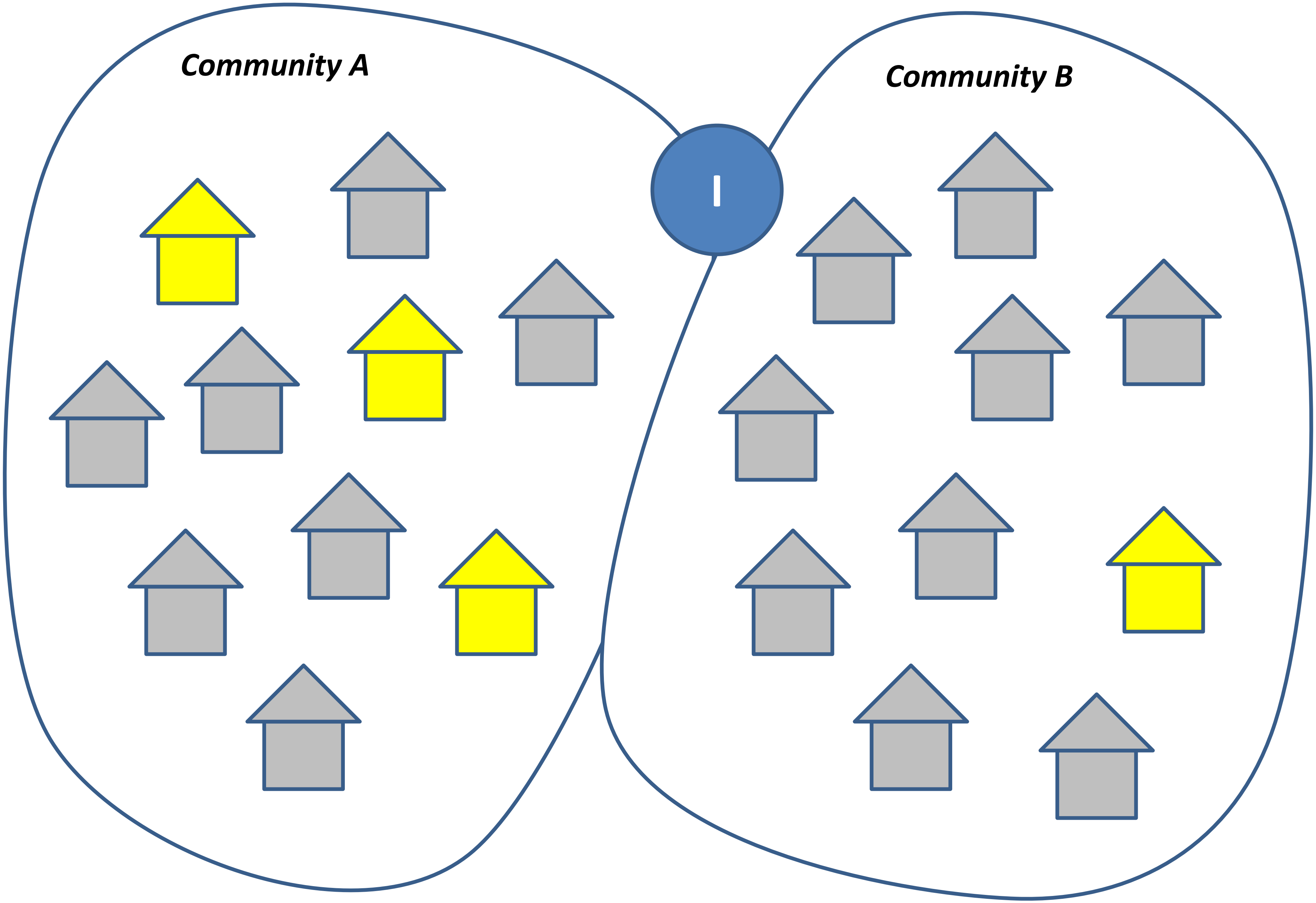
Two hypothetical communities of household "agents"…



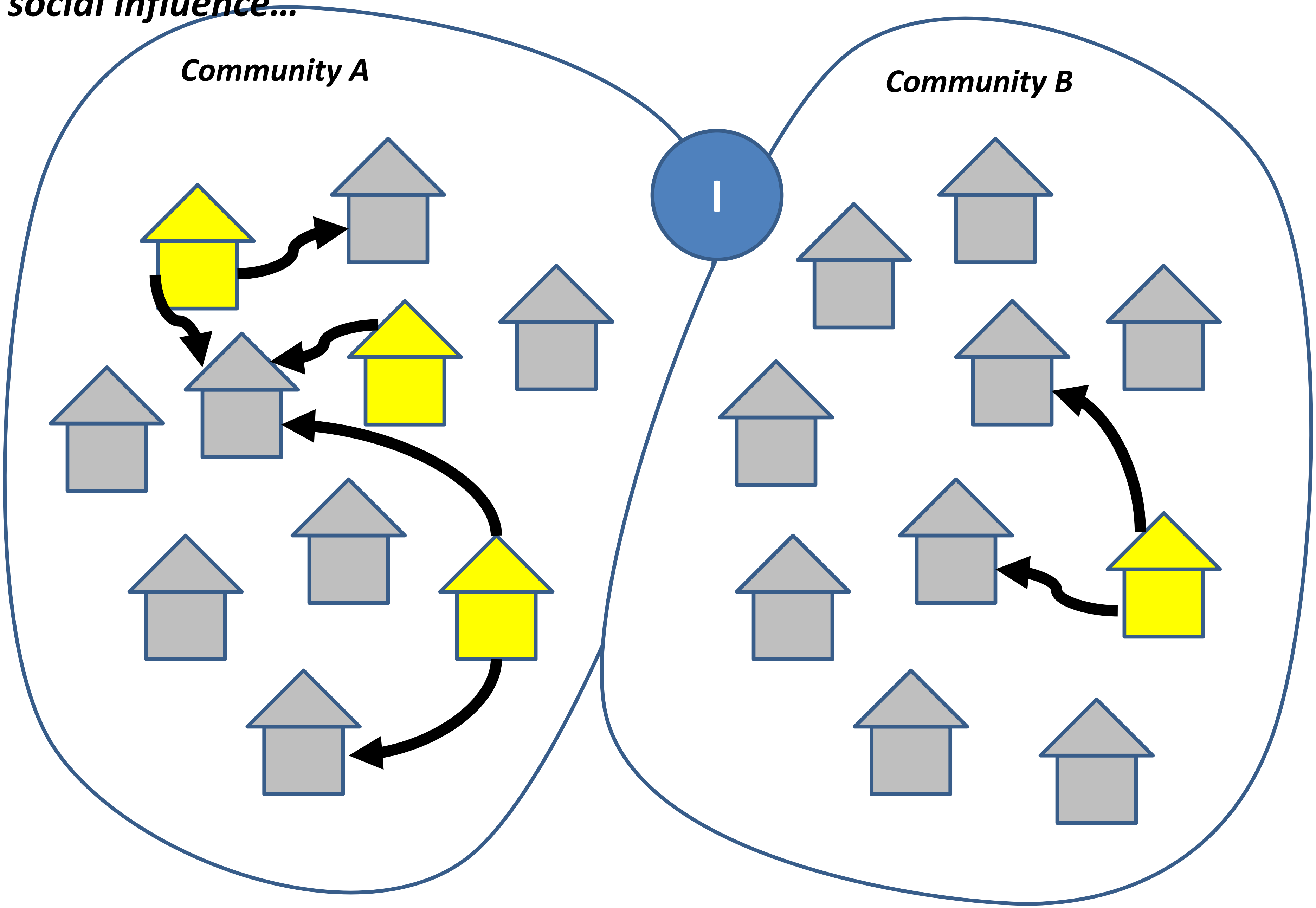
A non-adopter in Community A has higher probability of adoption because of higher propensity…



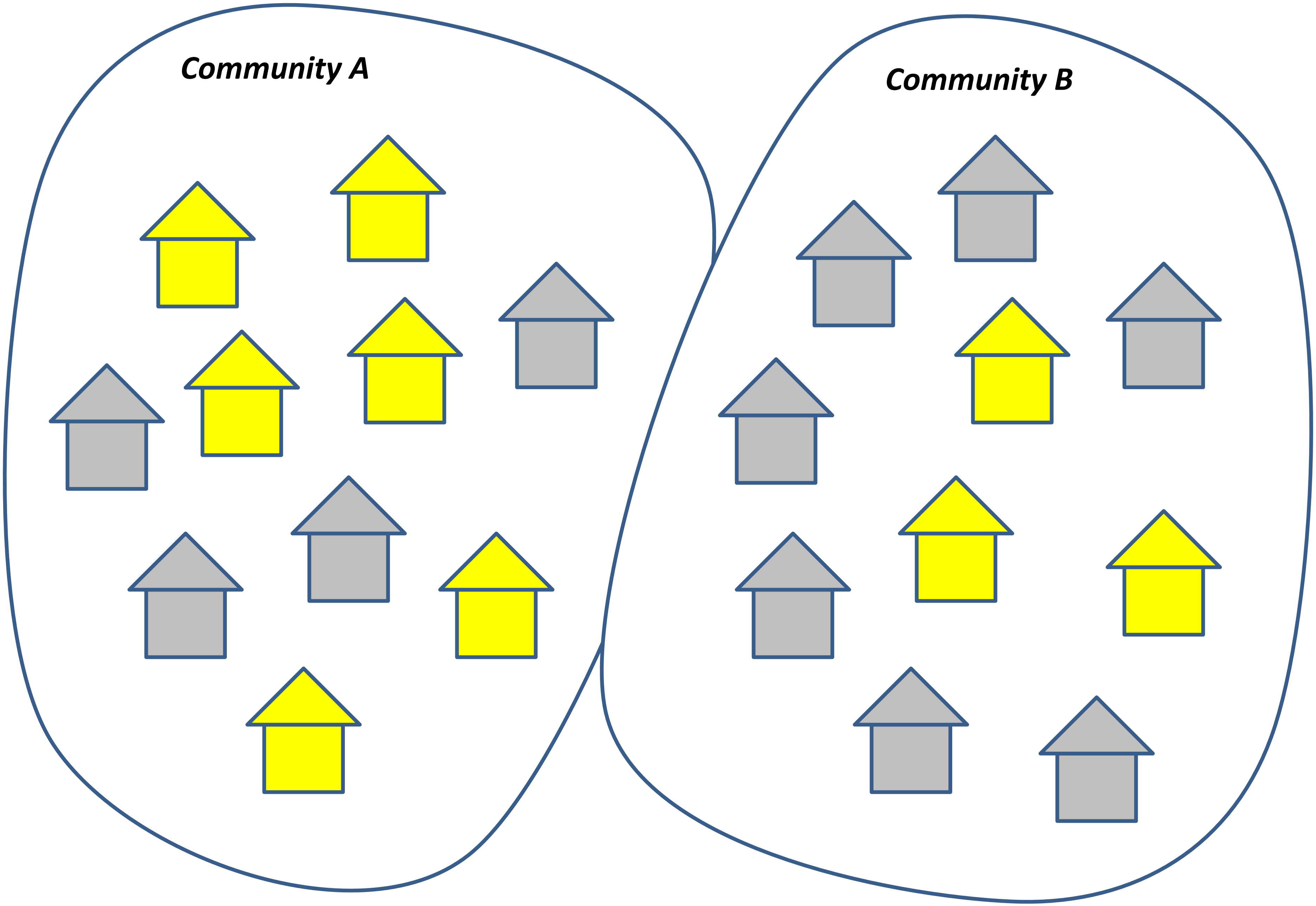
More adopters in Community A…



Probability to adopt for agents in Community A increases further through social influence…



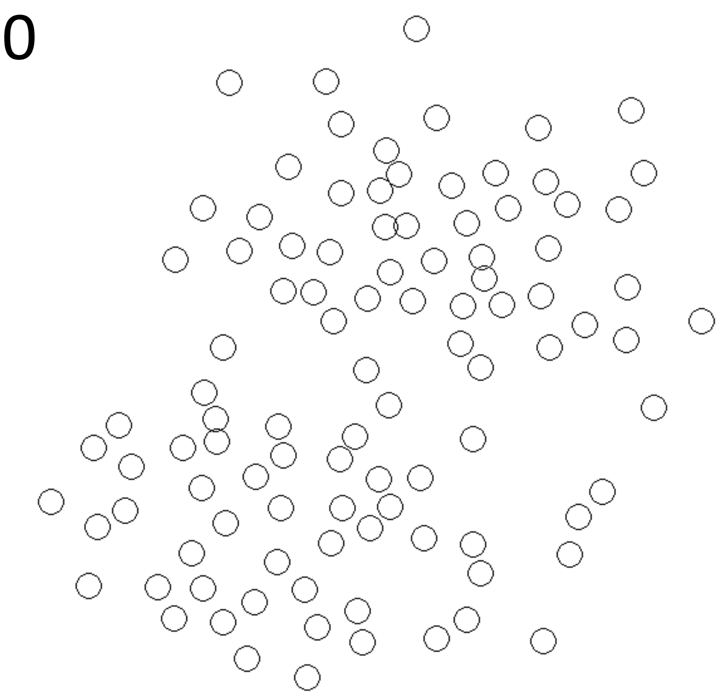
Leading to a long-term difference in adoption rates…



Agent-based Model

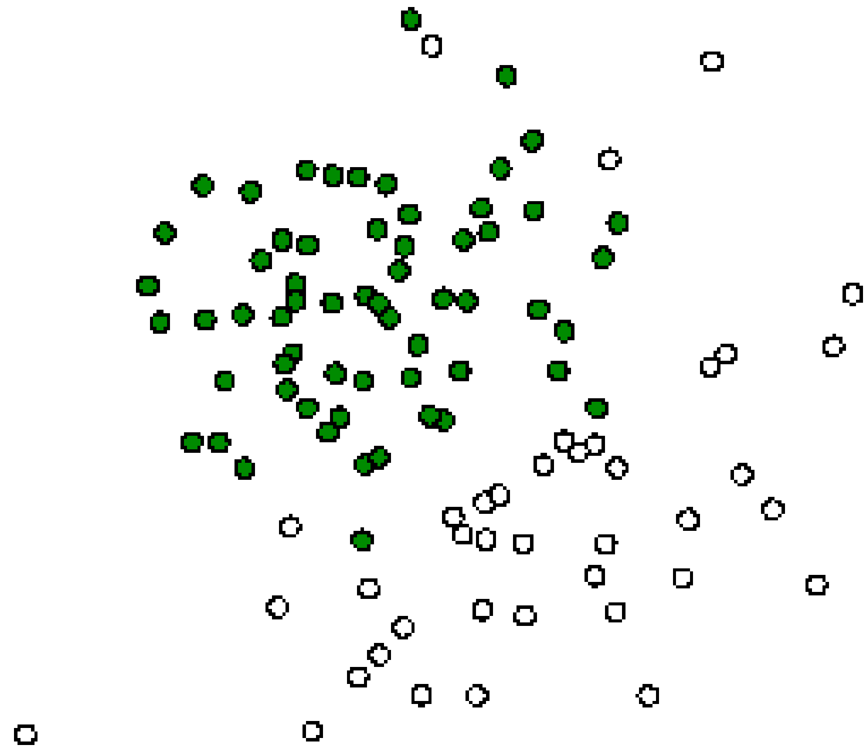
Model setup

- Repeated random simulations in R
- A system is populated with 100 agents…



Model setup

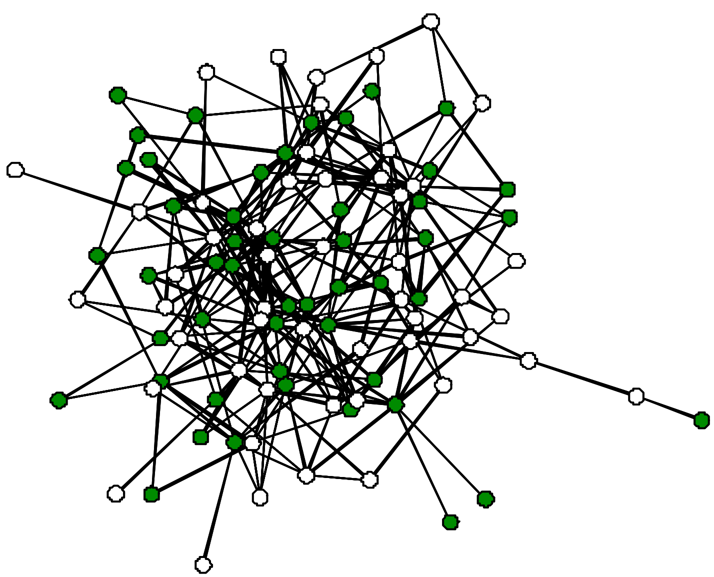
- Agents are assigned to groups with high versus low propensity.
- High propensity (white) have attribute value r = 1, low propensity (green) have value r = 0.



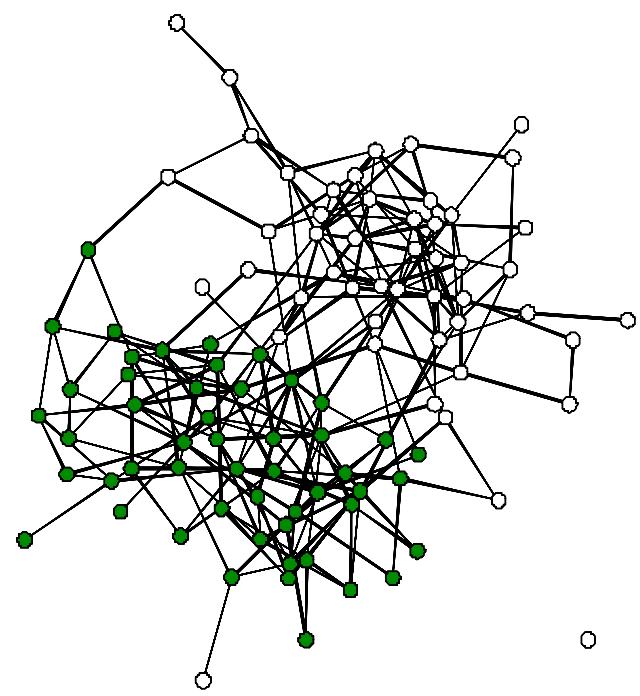
Model setup

- Agents are linked in a random network, governed by the segregation parameter ***S.***

- The larger ***S***, the more likely links occur within groups than links across groups.



Integrated Network
S=0   d=0.05



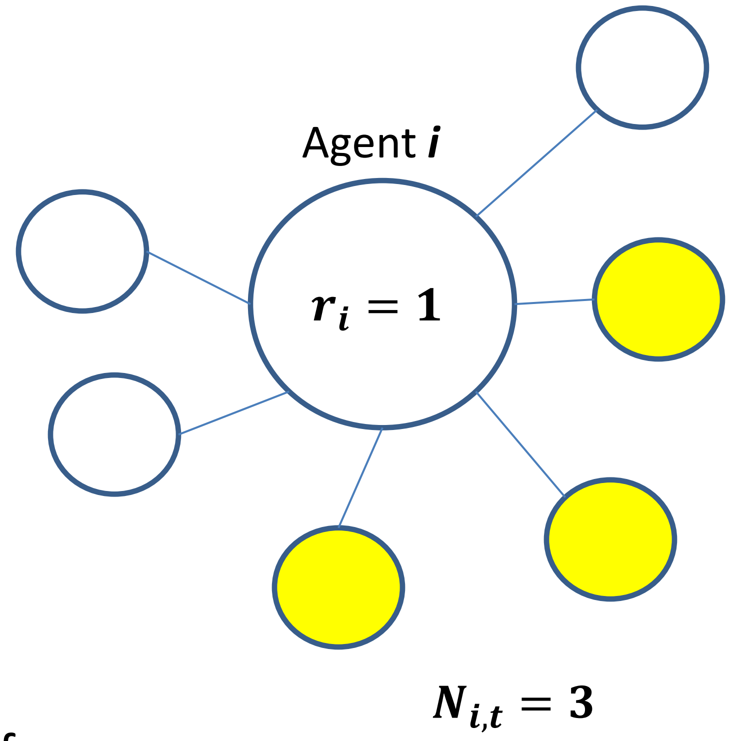
Segregated Network
S=0.75   d=0.05

Adoption decisions

- Each time step one random agent is selected
- The selected agent makes a probabilistic decision to adopt or not.

- Governed by three additional model parameters:
  - ***SI***, social influence $\in [0,1]$
  - ***P***, propensity difference $\in [0,1]$
  - $\mathbf{I_{i,s}}$, Incentive parameter

- For agent i, at time t, probability of adoption if selected is defined as a logistic function:



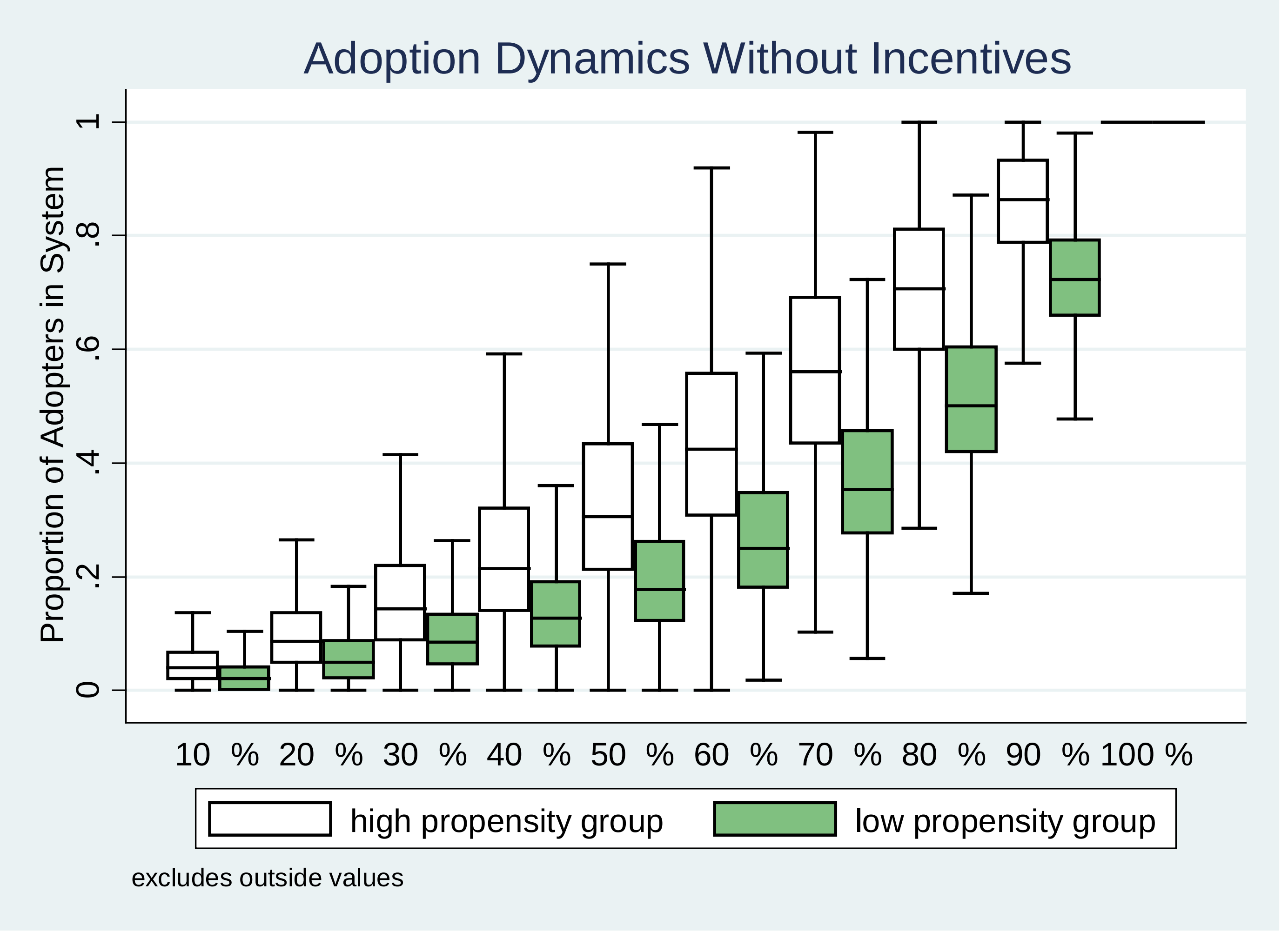
$$A(i,t) = \frac{I_{i,s}}{1 + e^{-(-2.944 + P * r_i + SI * N_{i,t})}}$$

Incentives parameter $\boldsymbol{I_{r_i,s}}$

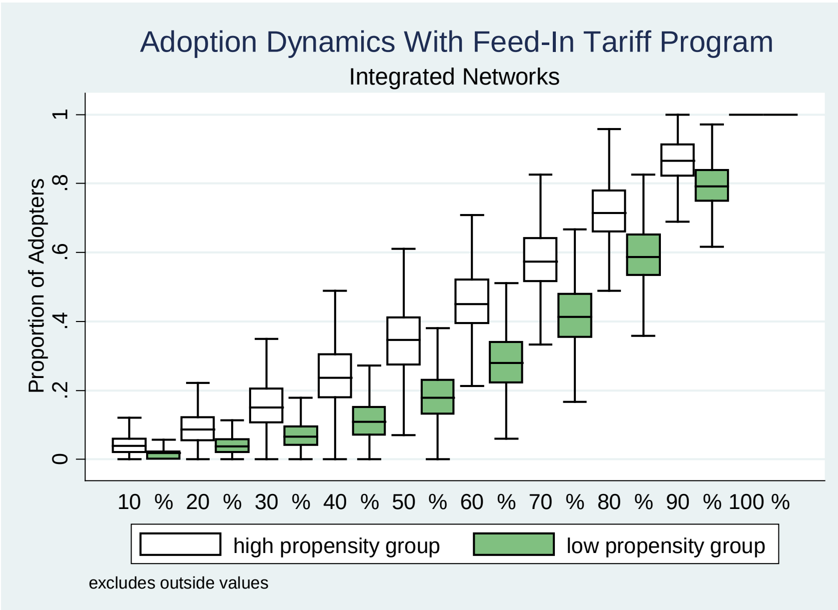
	Low propensity agents	High propensity agents
	$r_i = 0$	$r_i = 1$
Incentive	$\boldsymbol{I_{r_i,s}}$	
Feed-In Tariff	1	1.5
Leasing	1.25	1.25
Seeding (poorer households)	1.5	1

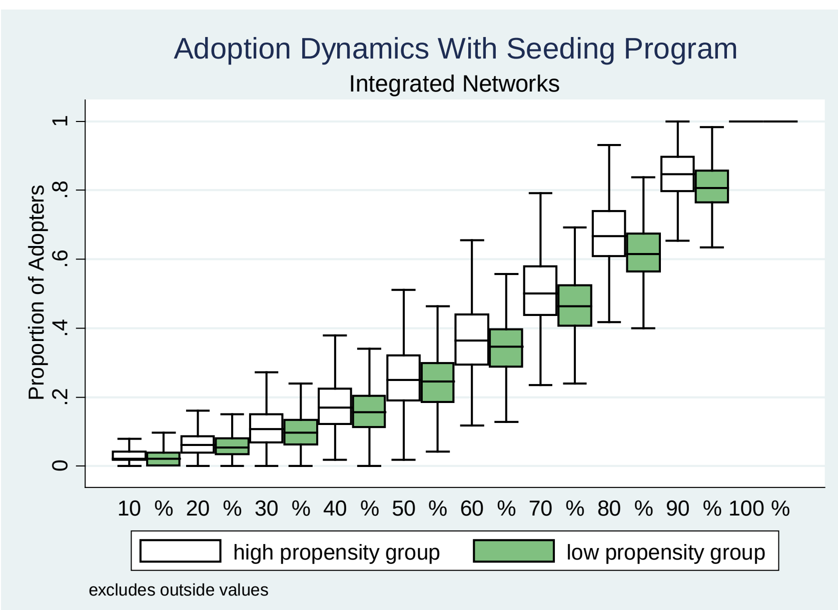
Results

Adoption dynamics without incentives

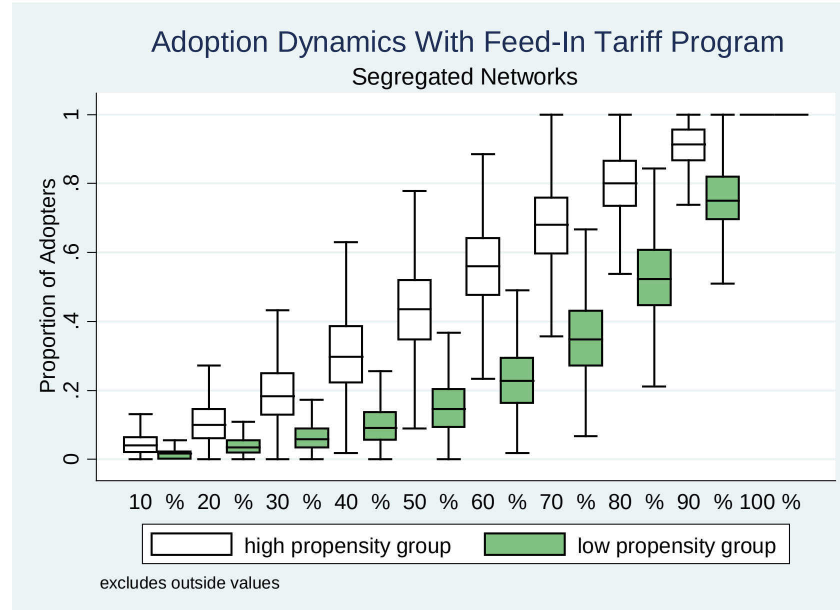


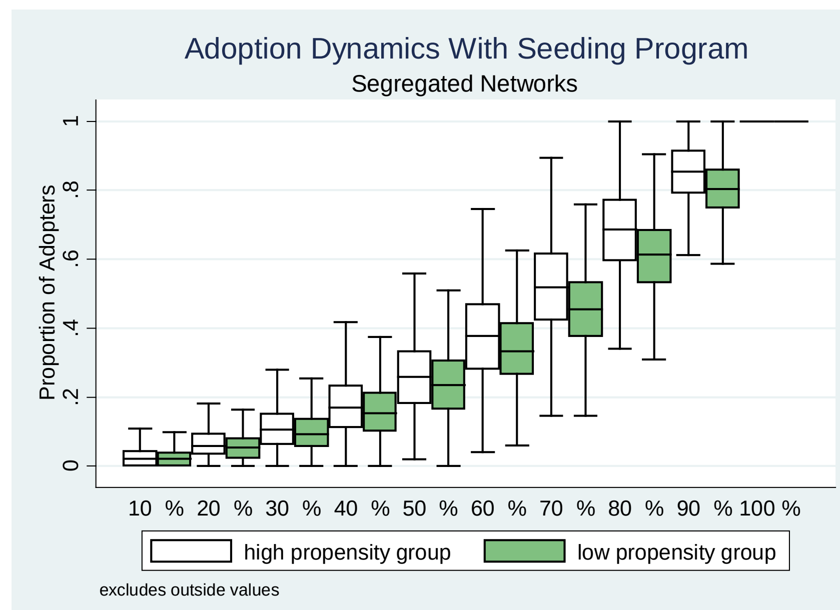
Integrated Networks





Segregated Networks





Effect of incentive programs on speed of adoption - Integrated versus segregated social networks

	DV = avg. wait time (smaller values signify faster adoption speeds)	
	Model 1: Integrated networks	Model 2: Segregated networks
Program dummy variables		
Feed-in tariffs used?	-0.415 ***	-0.394 ***
Leasing program used?	-0.366 ***	-0.413 ***
Seeding program used?	-0.282 ***	-0.362 ***
Constant coefficient	3.328 ***	3.411 ***
N	7,428 simulations	7,408 simulations
R^2	0.029	0.030

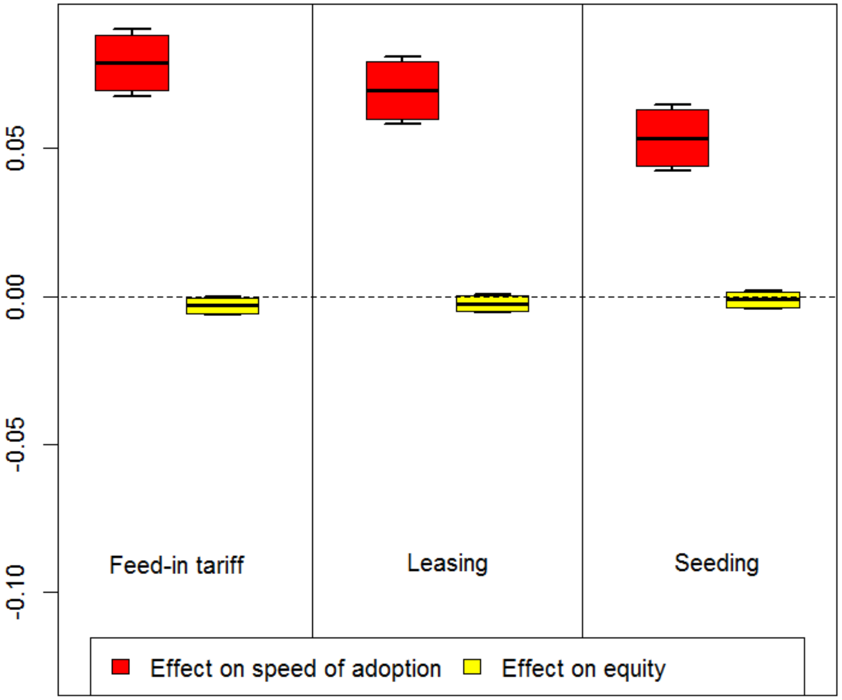
Note: Table reports results of OLS regression models with average wait time as the dependent variable. For dummy variable effects, the simulations with no incentive programs is the left-out category. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Effect of incentive programs on distributional equity - Integrated versus segregated social networks

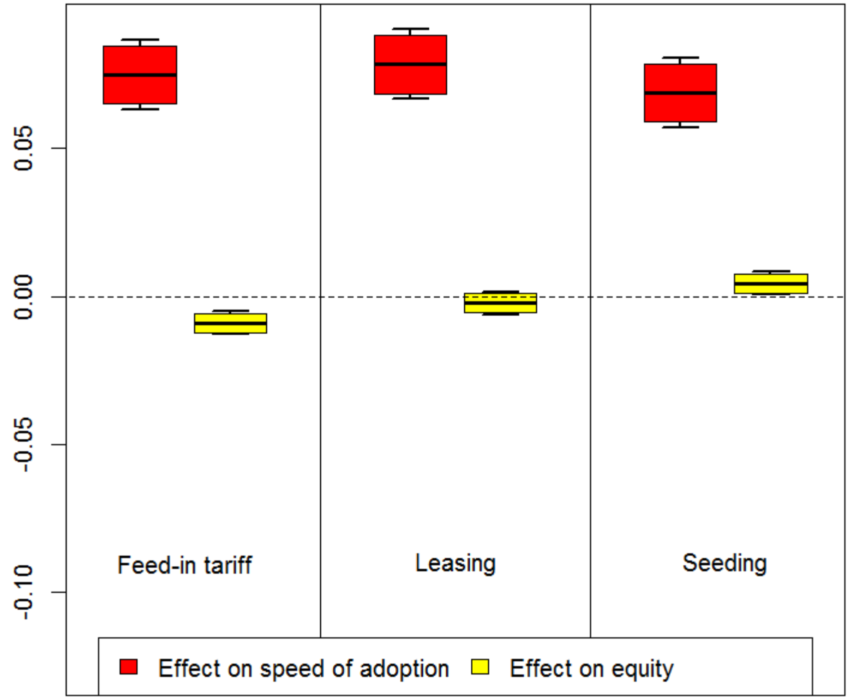
	DV = difference in avg. wait time (smaller values signify greater equity)	
	Model 1: Integrated networks	Model 2: Segregated networks
Program dummy variables		
Feed-in tariffs used?	0.008 *	0.024 ***
Leasing program used?	0.007	0.006
Seeding program used?	0.003	-0.011 *
Constant coefficient	0.037	0.056 ***
N	7,428 simulations	7,408 simulations
R^2	0.001	0.007

Note: Table reports results of OLS regression model with difference in average wait time (distributional equity) as the dependent variable. For dummy variable effects, the simulations with no incentive programs is the left-out category. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Program outcomes: Speed of adoption versus equity in segregated versus integrated networks



Integrated network



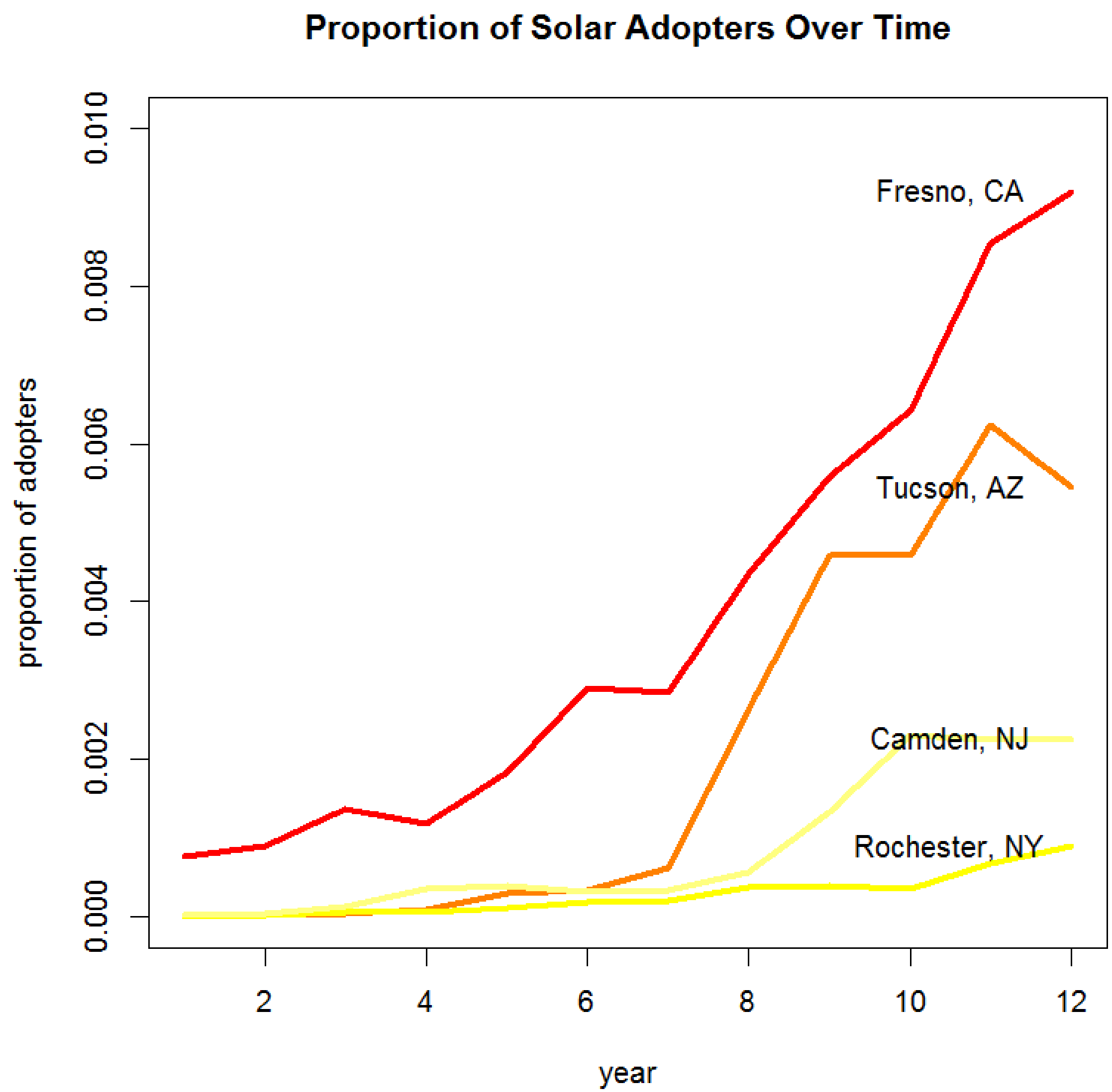
Segregated network

PV adoption in segregated networks and environmental justice

- Theoretical models are useful for showing the importance of certain factors for producing outcomes—such as the role of segregation in influencing adoption over time.
- How do these dynamics play out in the real world?
- Give a first look at a new empirical, geographically-constrained ABM of solar adoption: the “Golden Solar” model.

What is to be explained?

- Golden Solar aims to model solar adoption curves in metro regions of the U.S.



What explains adoption?

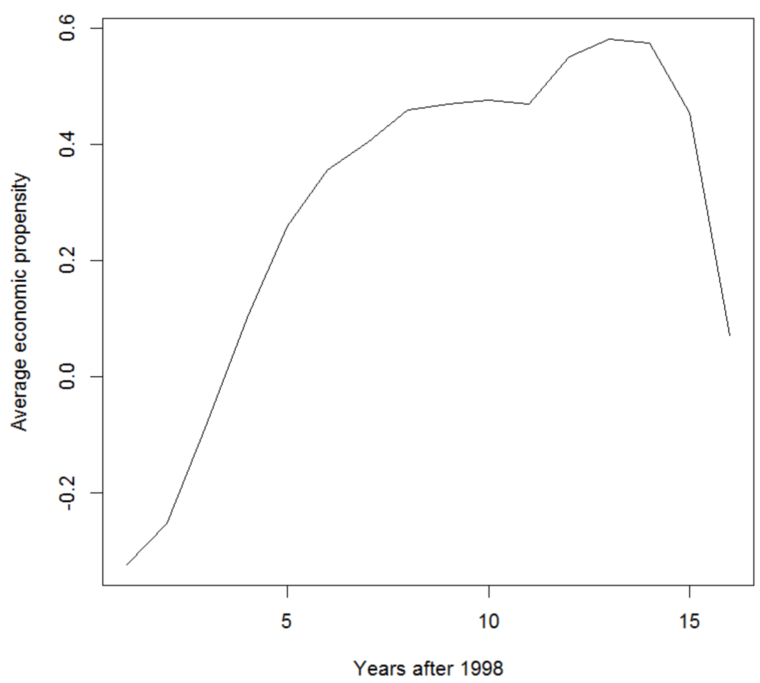
- Decisions are assumed to happen at the "house" level, and agents are assumed to make binary decisions (adopt/do not adopt) in every year.
- As with our theoretical models, decisions are assumed to be a function of three factors:
  - Economic propensity: What are the monetary motivations for solar?
  - Cognitive propensity: What are the non-monetary motivations for solar?
  - Social "closeness" to other adopters
- These factors are not so easy to measure!

Measuring economic propensity

- Economic propensity is measured using census and other secondary data on income and net (monetary) benefits of solar PV.
- Economic propensity changes as incentive programs change (see right panel – Tucson region)

$$EP = a*g(I) + (1-a)*f(B - C)$$

Variable	Meaning
a	A weighting factor between 0 and 1, set to 0.5 as a default
g(I)	I is household income, g(x) transforms income to fit the range [-1,1]
f(B-C)	Net benefits of solar transformed to fit in the range [-1,1]

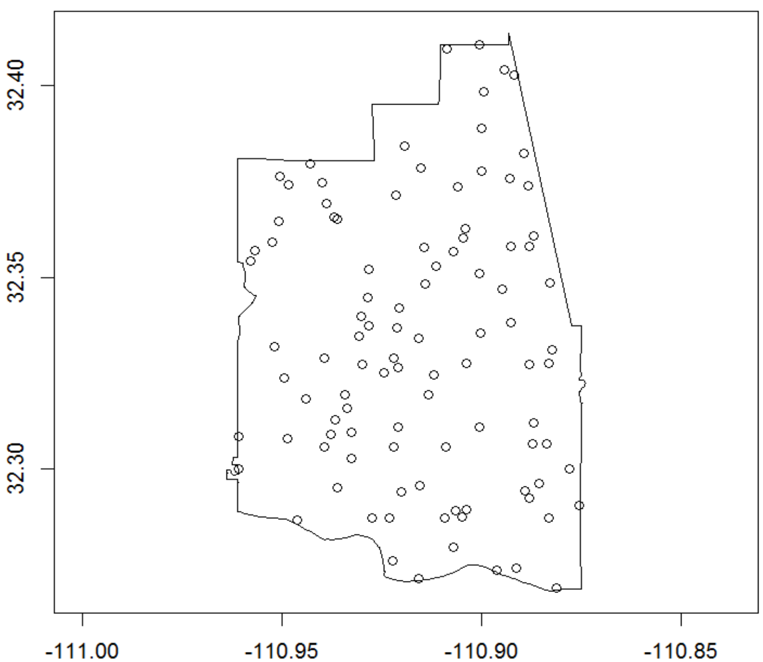


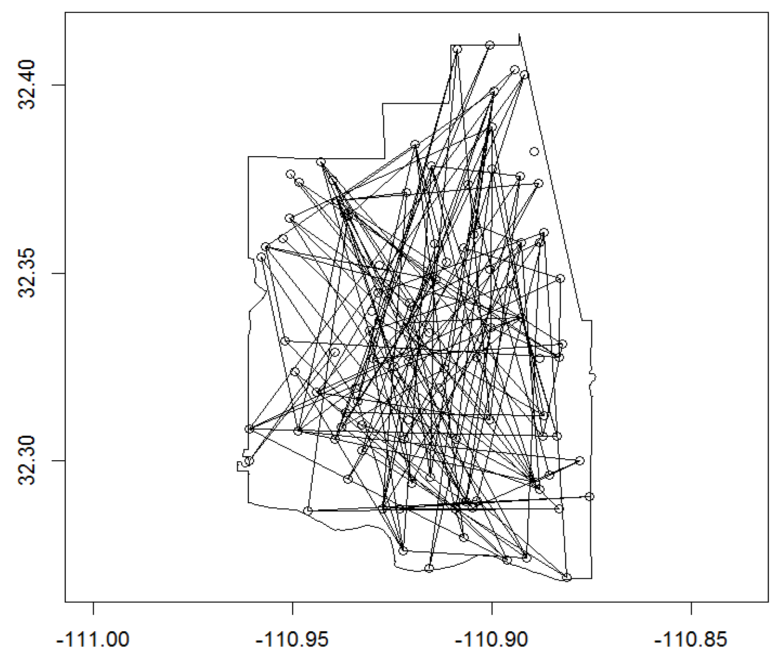
Measuring cognitive propensity

- Cognitive propensity includes all non-monetary attributes that tend to change agents' probability of adoption.
- Estimated from survey data: CP is estimated from residuals between solar adoption models with and without cognitive factors.
- The residuals are then modeled as a function of data available from the census at the zip code level.

Measuring social closeness

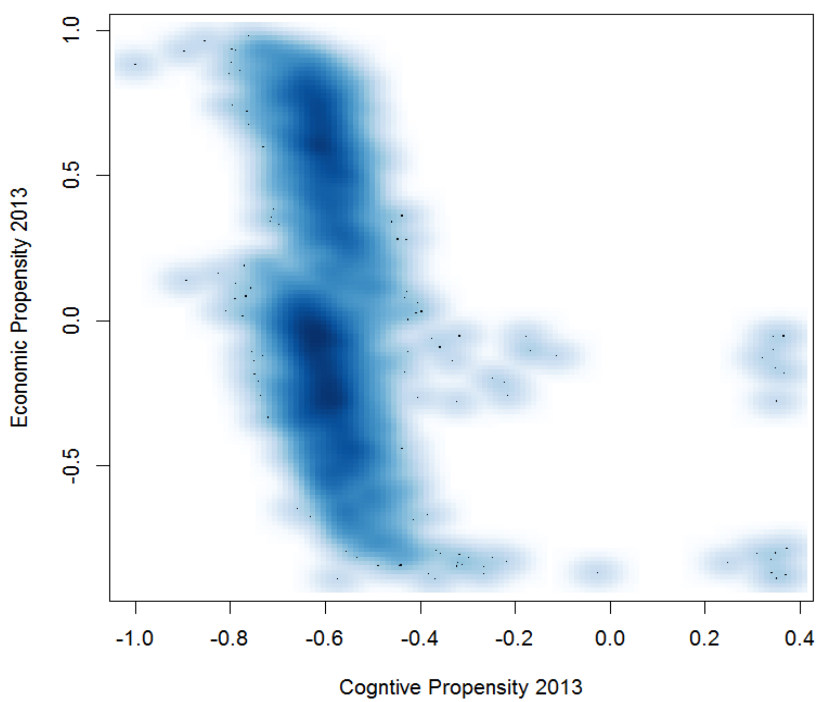
- For most regions, data on actual adopter locations are not available.
- We randomly assign agents locations within zipcodes, and represent spatial proximity as a network:



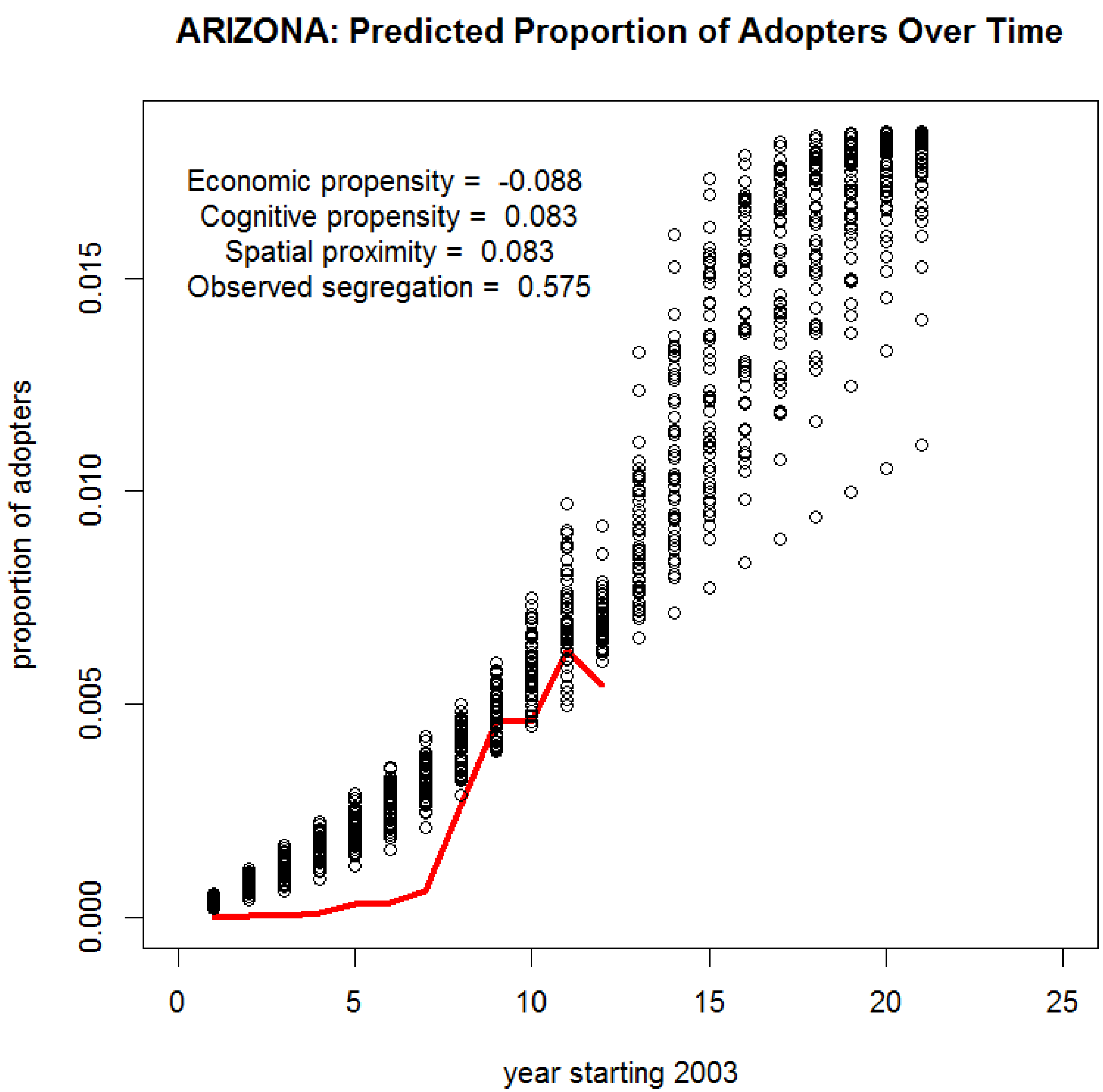


Do these systems exhibit segregation?

- Consistent with our claim in the theoretical models—that systems exhibit segregation—economic and cognitive propensities are pretty clearly clustered.
- *Economic and cognitive propensity for agents in Tucson:*



Calibrated/predicted trends over time



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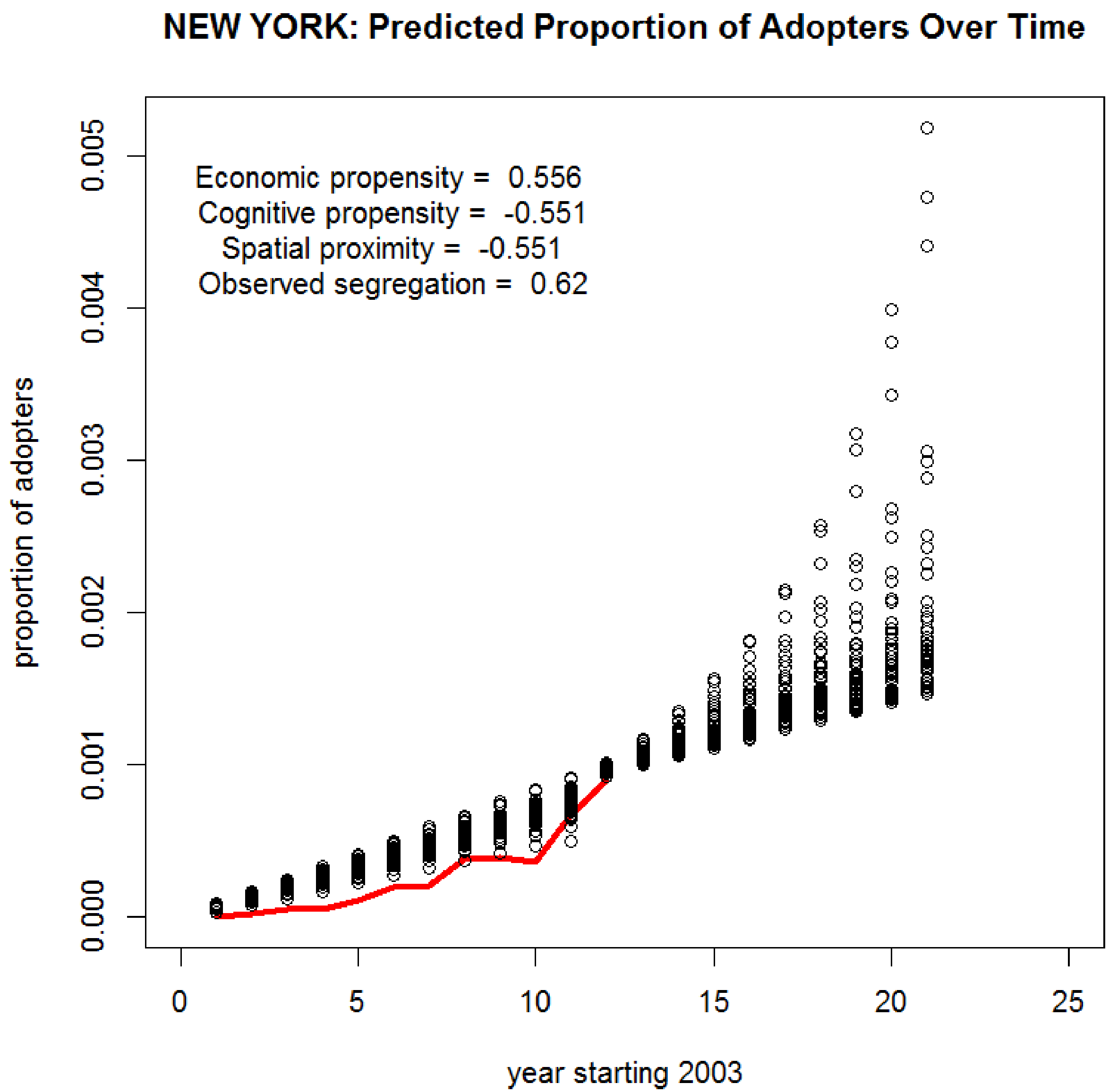

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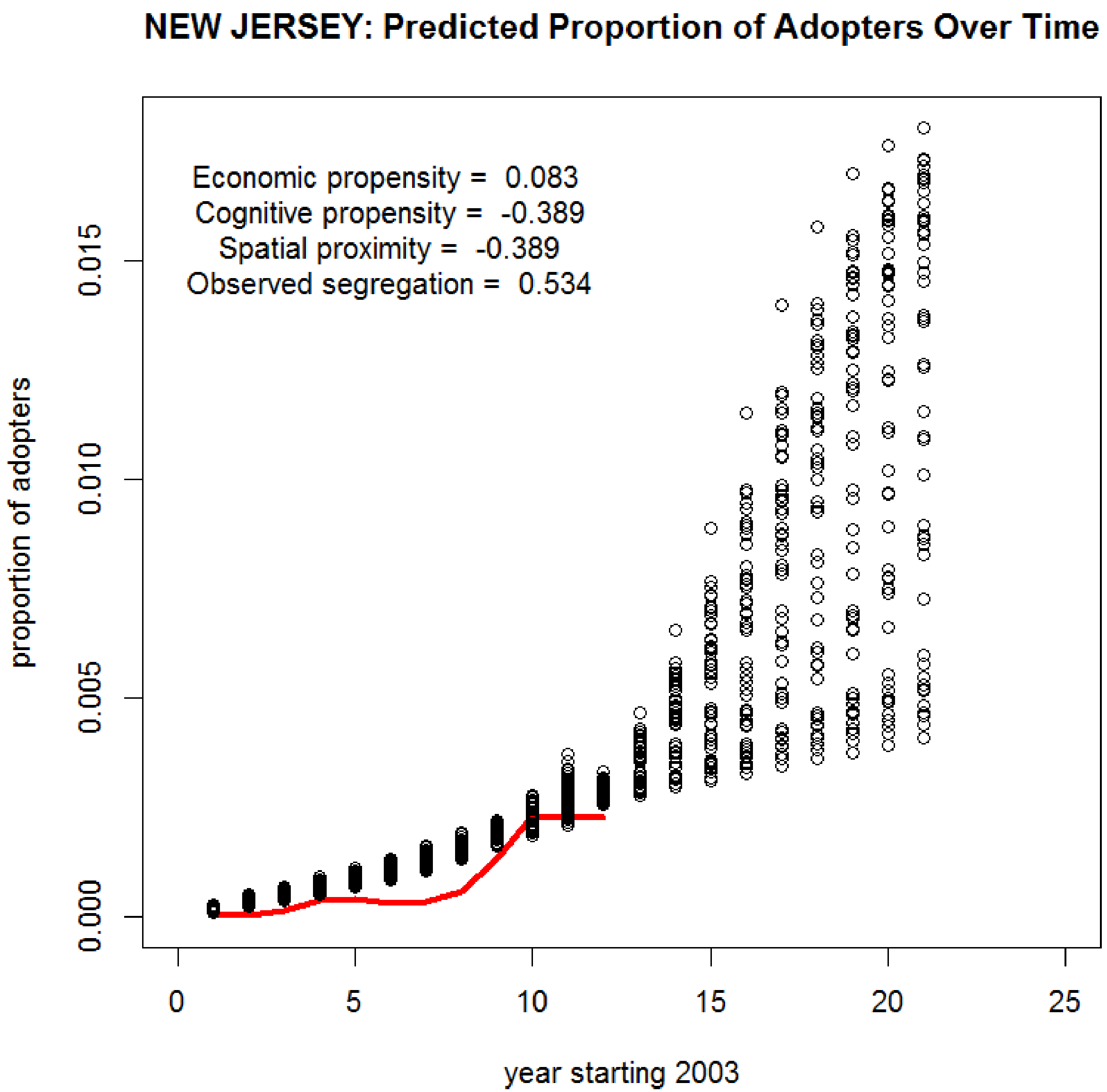
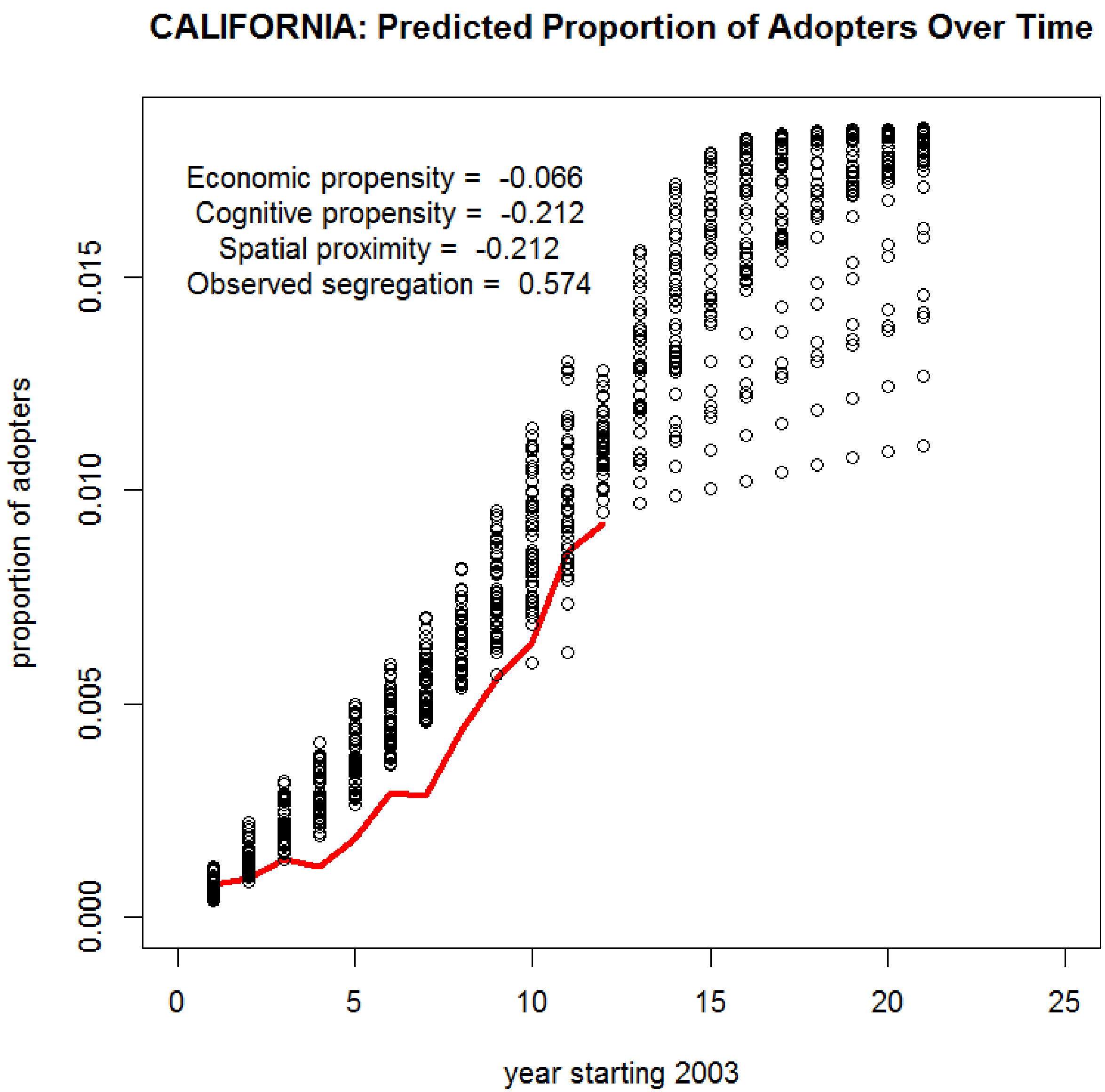


Calibrated/predicted trends over time



Future work

- The Golden Solar model will enable us to apply theoretical models in a real-world case.
- Data constraints are legion… makes it very difficult to build models!
- Preliminary results show the importance of non-economic factors, particularly spatial proximity and “cognitive” factors.
- Segregation is not of theoretical importance—it seems to be a real phenomenon and models suggest that they can transform the effectiveness of programs to enhance solar adoption.

SEEDS Webinar Series

Today	Agent-Based Models of How Segregation and Peer Effects Influence Solar PV Adoption
Wednesday, June 15	How to Get Those Considering Solar to Ultimately Make the Switch https://attendee.gotowebinar.com/register/6465548759601649410
Wednesday, June 29	Solar Aspirations and Disinclinations: Learning from 3,600 households https://attendee.gotowebinar.com/register/3200297192758389251
For More Information	Benjamin.Sigrin@nrel.gov