Elements of a coarse-grained quantitative theory of society

macroscopic regularities and emerging principles

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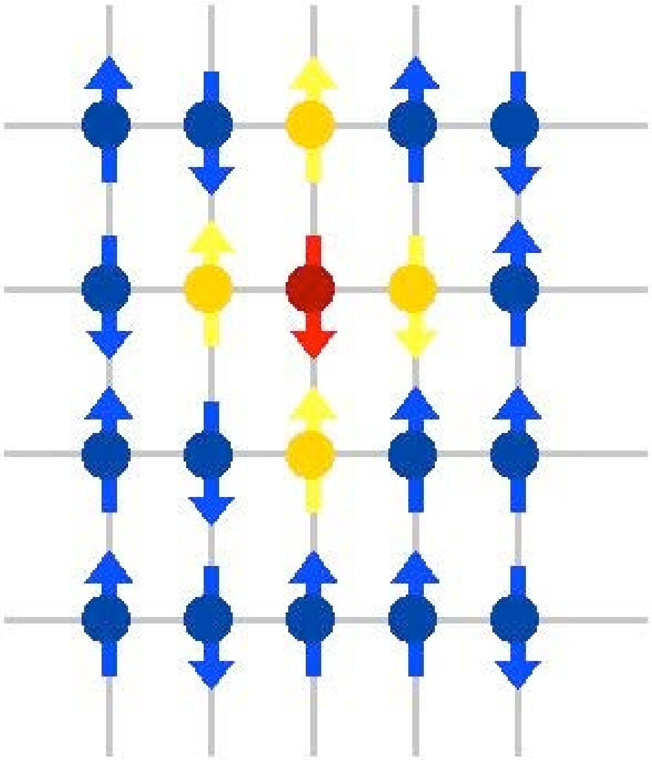
Is there a physics of human society?

	Physics	Human and Social
Elements	(elementary) particles	people
Interactions	4 elementary forces	many forms of interaction
Locality in time	yes	no, people have long memory
Locality in space	yes	no, space may not be fundamental
Stationarity	yes	no, most of the time
Universality	sometimes	maybe, we don't know
Conservation Laws:	yes	usually no
Adaptability	no	yes, people adapt and innovate permanently

From macroscopic properties to idealized microscopic models
that capture the essence of phenomena



Ising model

Predictable **Macroscopic** behavior vs. Temperature and Magnetic Field

Macroscopic empirical regularities	**Principles** abstractions	**Theory** prediction/falsification
	scientific method	
Astronomical regularities	inertia, force, gravity	Classical Mechanics
Temperature, Pressure	thermodynamics	Statistical Mechanics
flow of liquids, gases turbulence	conservation laws matter, energy, momentum	Hydrodynamics
Superconductors Superfluids	hydrodynamics, quantum phases bosons, fermions	Quantum Fluids & Condensates
Magnets	scaling, universality, RG	Critical Phenomena
Cosmological Backgrounds	Big Bang, GR	Modern Cosmology
Atoms, nuclei	relativity, quantum mechanics symmetry	Quantum Field Theory
time		**time**

Macroscopic regularities and emerging principles

non-stationarity, multiple interactions modes,
non-locality innovation, adaptation, self-similarity

Urban self similarity and growth

Bettencourt, Lobo, Kuehnert, Helbing, West PNAS 2007

Discovery and development of science and technology

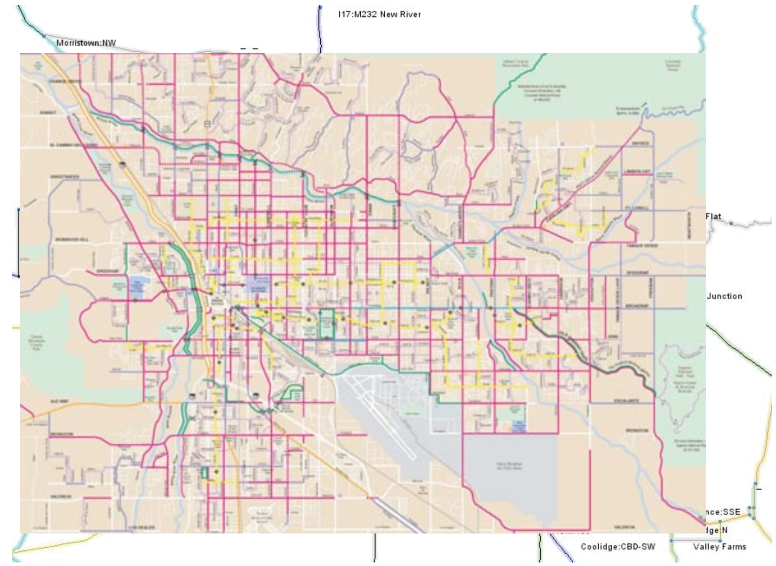
Bettencourt, Kaiser, Kaur 2007

Bettencourt, Kaur 2008

Is there are analogue between *biological* and *social* scaling?

- Metabolic Rates ~ $N^{d/(d+1)}$
  Energy/resource consumption
- Rates decrease ~$N^{-1/(d+1)}$
- Times increase ~$N^{1/(d+1)}$

Is 3> d ~2 ?



We set forth to search for data and estimate power laws:

$\mathbf{Y(N)=Y_0\, N^{\beta}}$ solution to equation: $\mathbf{Y(aN)=a^{\beta}Y(N)}$

Urban self similarity and growth

Scaling study of **urban indicators** in

USA, China and EU countries

~330, ~295 ~100 cities

Economic definition of cities [commute to work]:

Metropolitan Statistical Areas (MSAs)

Indicators:

Social and Economic quantities **β>1~1.15**

GMP, wages, income, crime, patents, AIDS incidence, walking speed

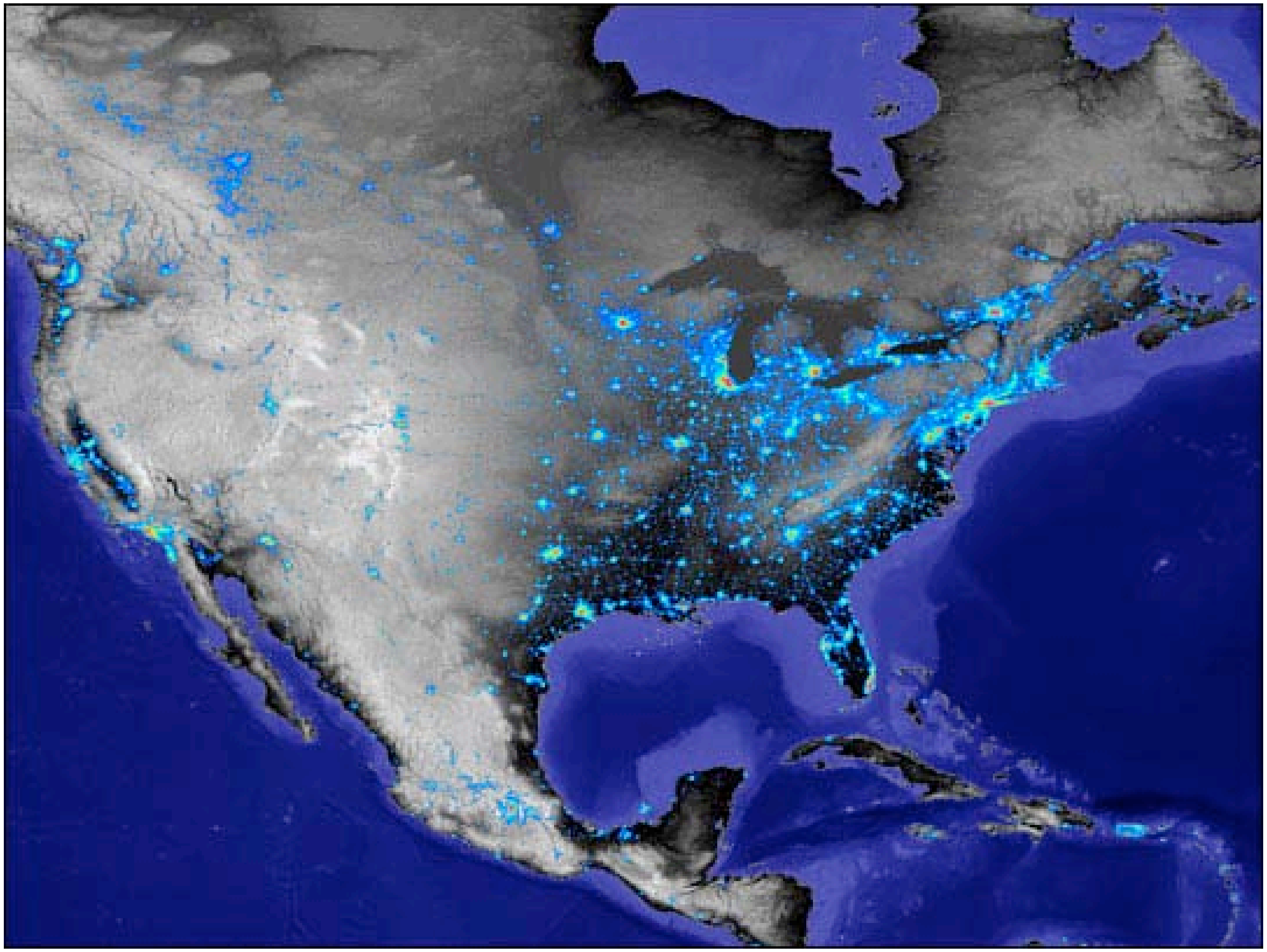
Individual need and use **β=1**

Establishments, employment, housing, household consumption

Material Infrastructure **β<1~0.8**

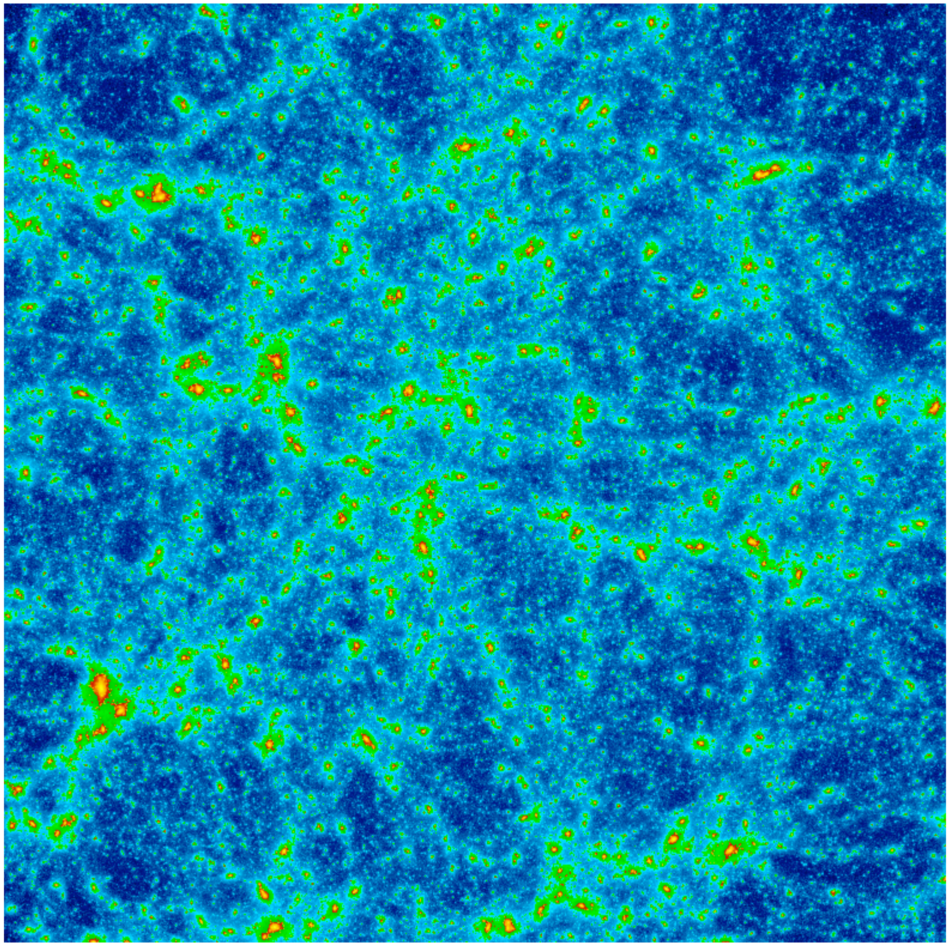
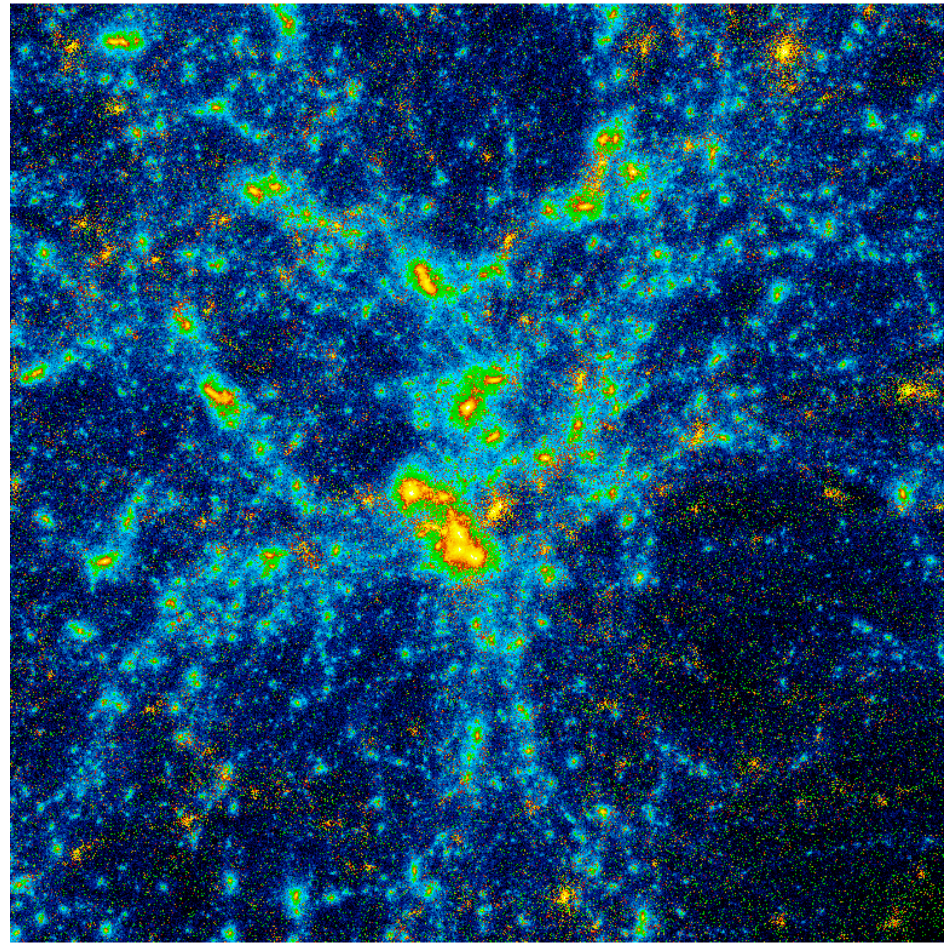
Road surface, electrical cables, gasoline sales

Urbanization is a ubiquitous, spontaneous social phenomenon



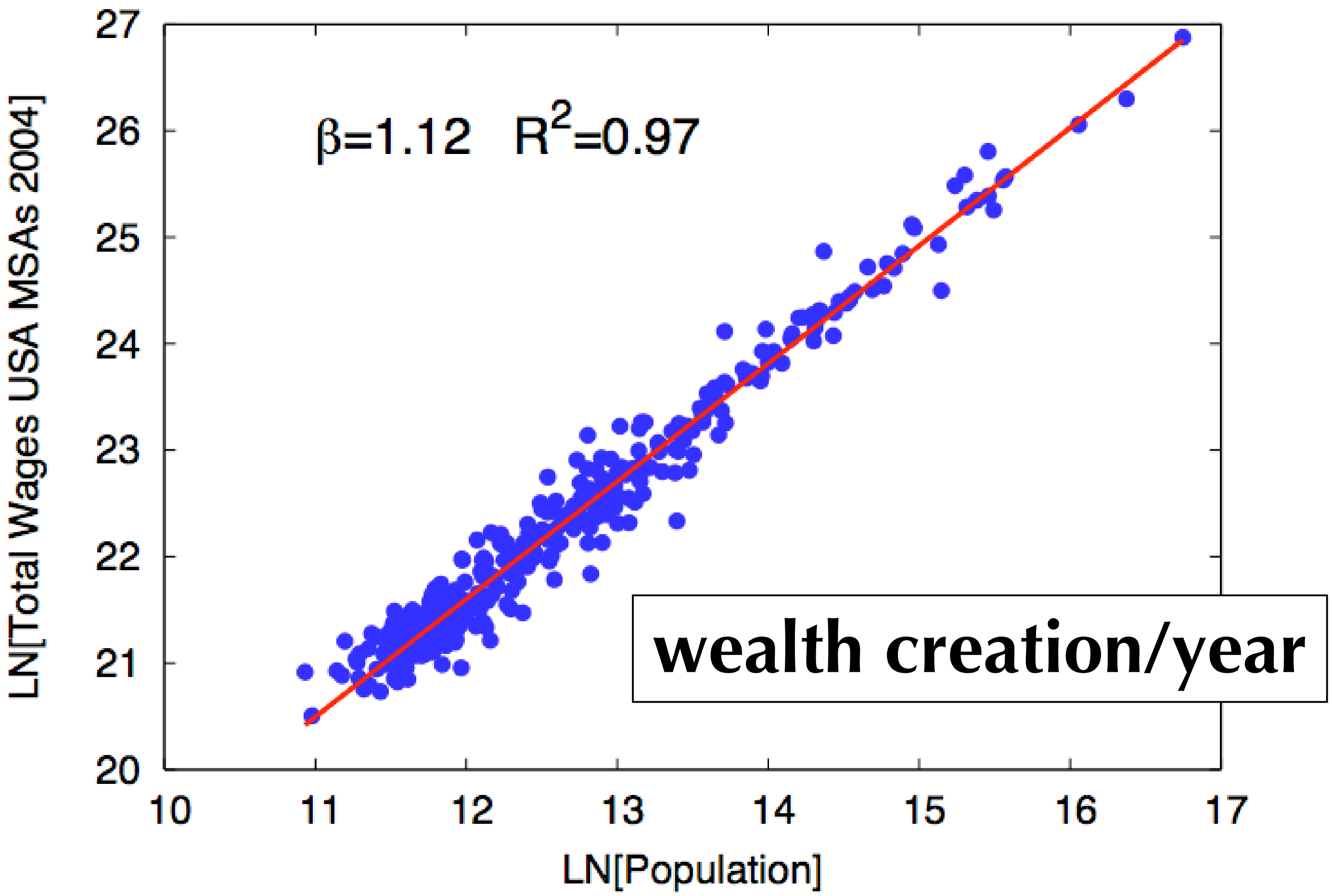
Clustering in the sky

mass and gravity

Images courtesy of M. Warren (LANL)

Increasing returns to scale in cities

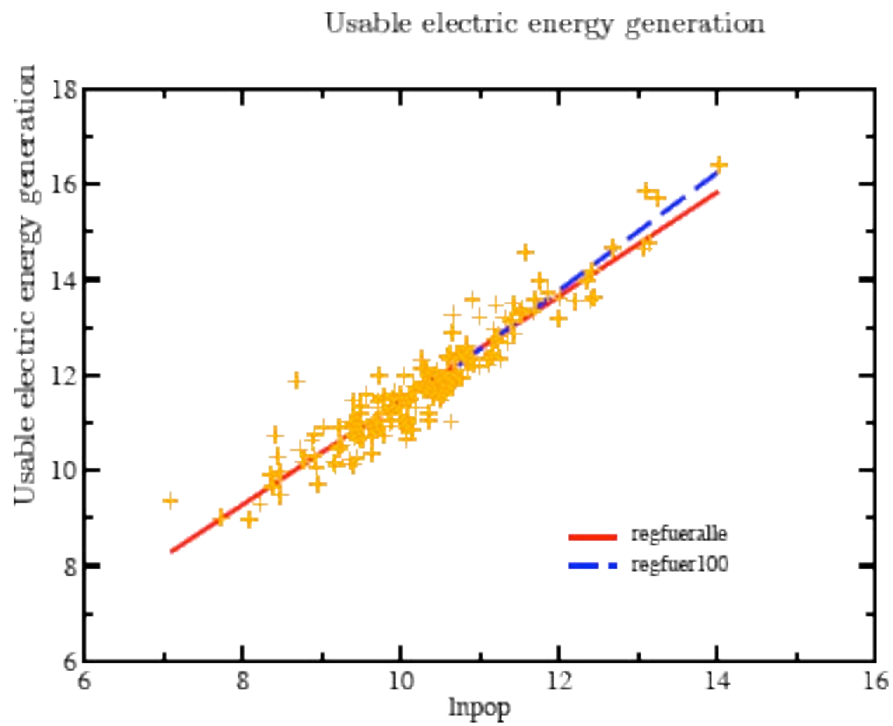


Energy consumption vs. city size

Germany: year 2002

Data source:
German Electricity Association [VDEW]

Courtesy of Christian Kuehnert & Dirk Helbing

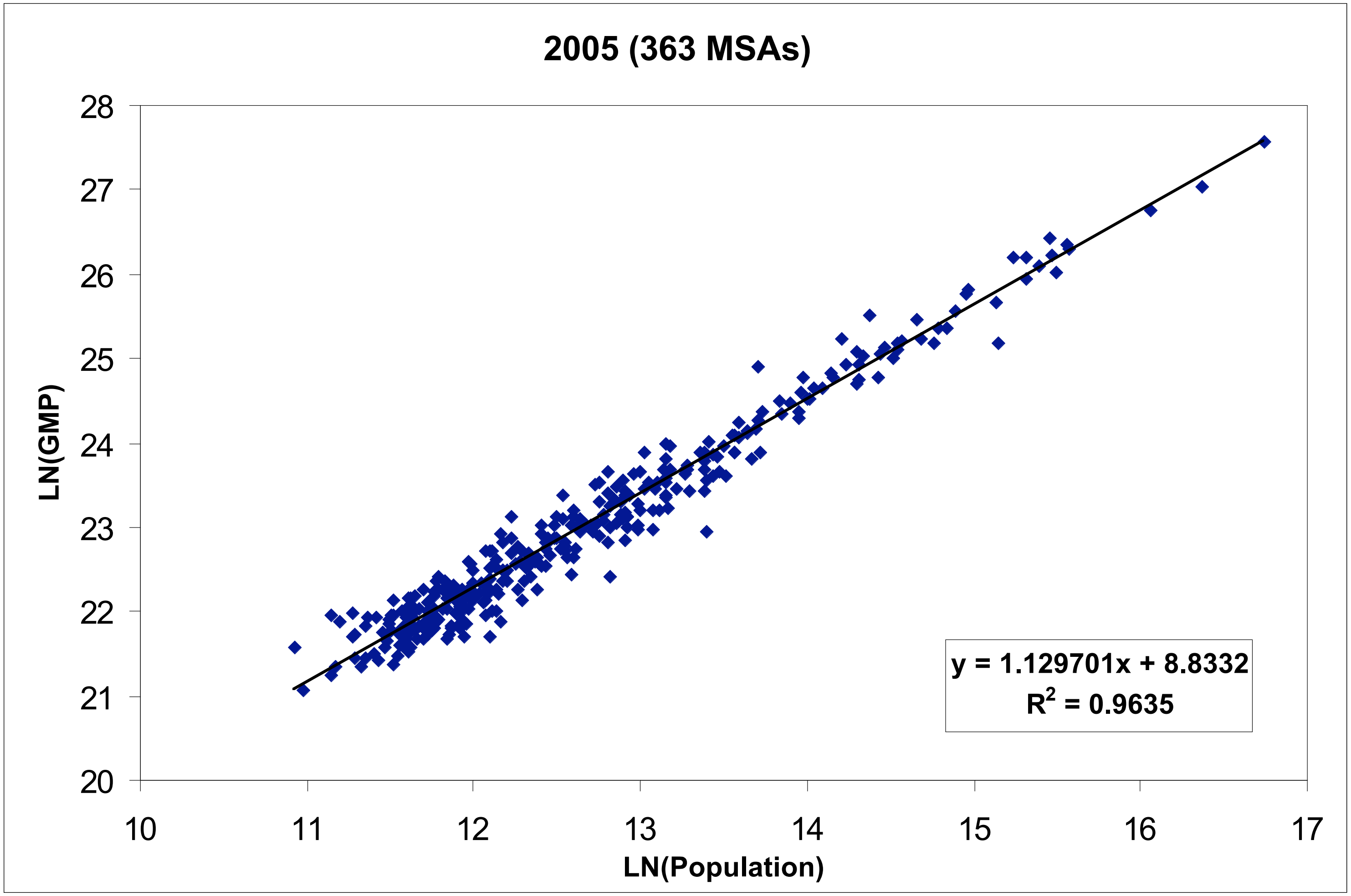


super-linear growth → usable generation

economy of scale → Length of cables

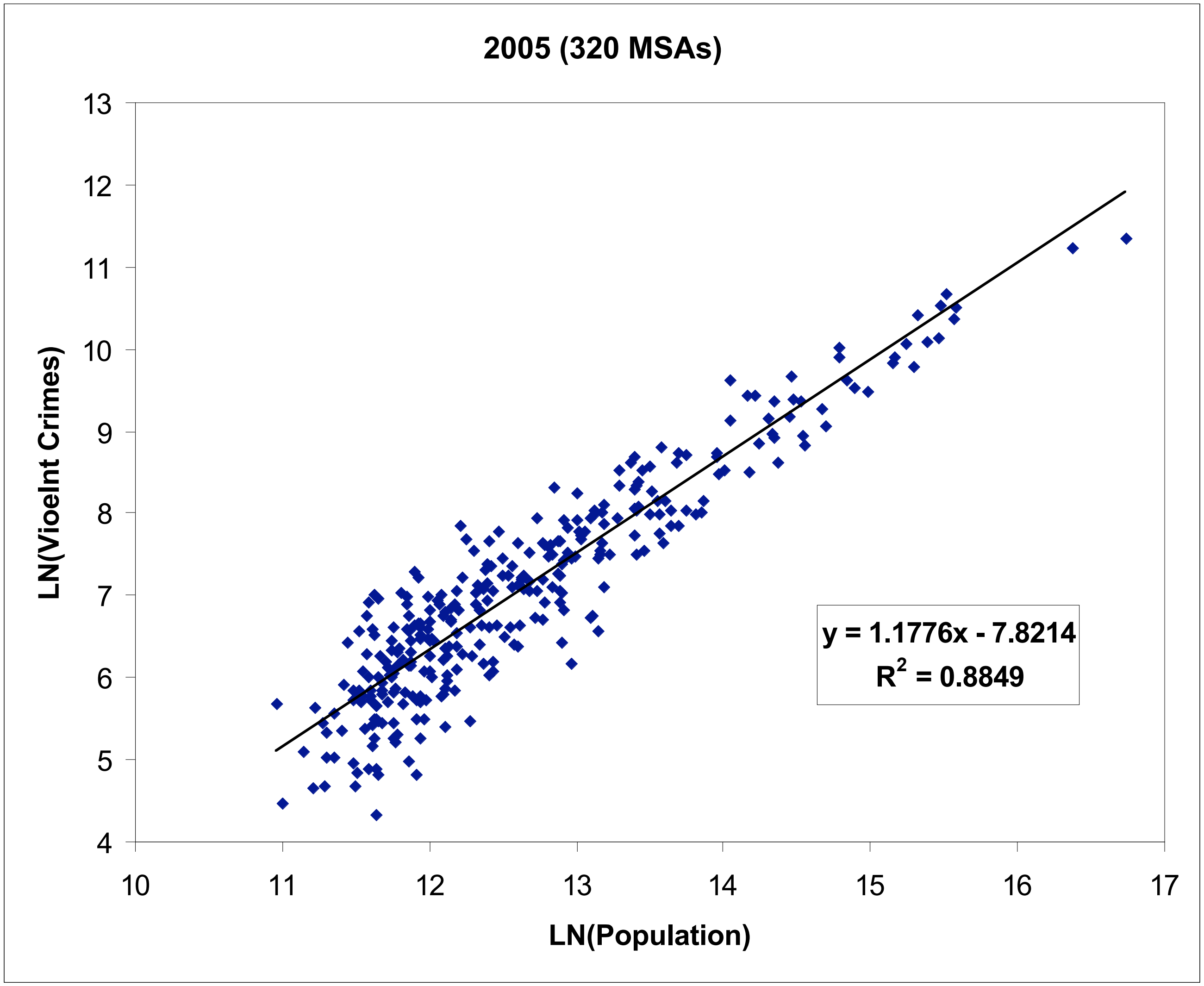
variable	exponent ± std. error for all	exponent ± std. error for first 100
net generation	1.34 ± 0.14	1.81 ± 0.24
usable generation	1.09 ± 0.03	1.24 ± 0.05
households that are end users	1.04 ± 0.02	1.09 ± 0.04
supply to households	1.00 ± 0.03	1.14 ± 0.04
end users	1.03 ± 0.02	1.08 ± 0.03
supply to end users	1.05 ± 0.03	1.16 ± 0.05
Length of cables	0.88 ± 0.03	0.90 ± 0.06
Losses	1.10 ± 0.03	1.18 ± 0.07

Gross metropolitan product of americal cities vs. population

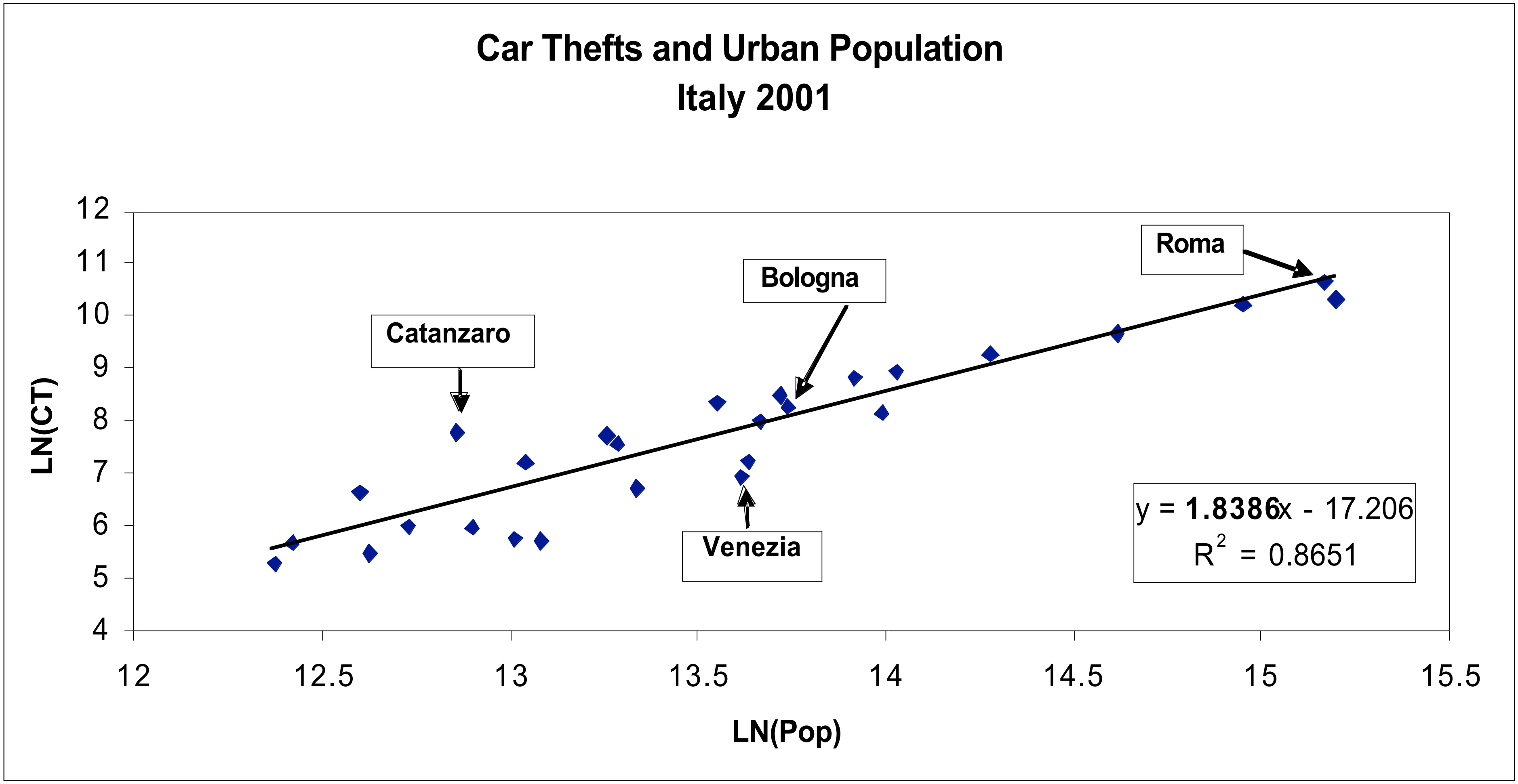


New York Cities Economy is larger than India’s

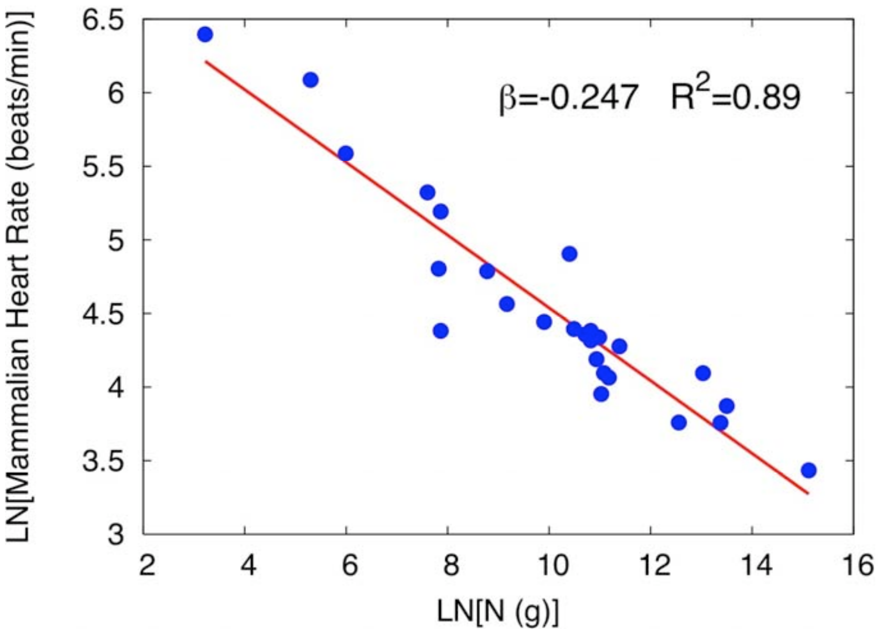
Violent crime in American cities vs. population



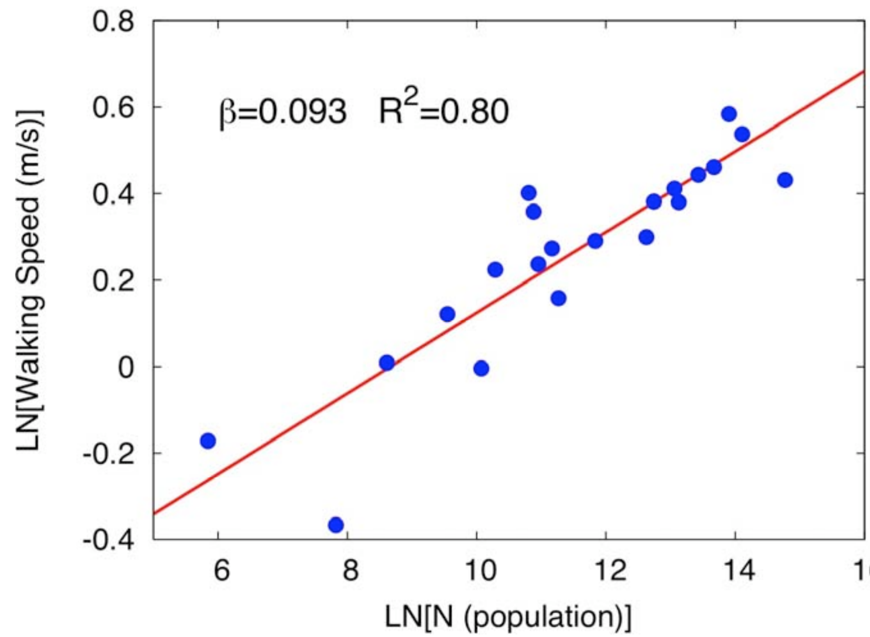
Car thefts in Italian cities vs. population



Pace of biological life vs. Pace of social life



Heart Rate vs. Body Size



Walking Speed vs. Population Size

conservation laws and growth

energy conservation:

$$R = NR_c + E_0 \frac{dN}{dt} + T\frac{dS}{dt} - p\frac{dA}{dt}$$

available resources **costs** **growth** **entropy** **expansion (sprawl)**

$$n = \frac{N}{A} = n_0 N^{\alpha}, \qquad \frac{dA}{dt} = (1-\alpha)N^{-\alpha}\frac{dN}{dt}$$

Sprawl reduces the cost of growth for smaller cities

A city may allocate its resources to creating information or to population growth

growth under scaling laws

Consider the energy balance equation:

$$R = NR_c + E_0 \frac{dN}{dt} \quad \rightarrow \quad \frac{dN}{dt} = \frac{R_a}{E_0} N^{\beta} - \frac{R_c}{E_0} N$$

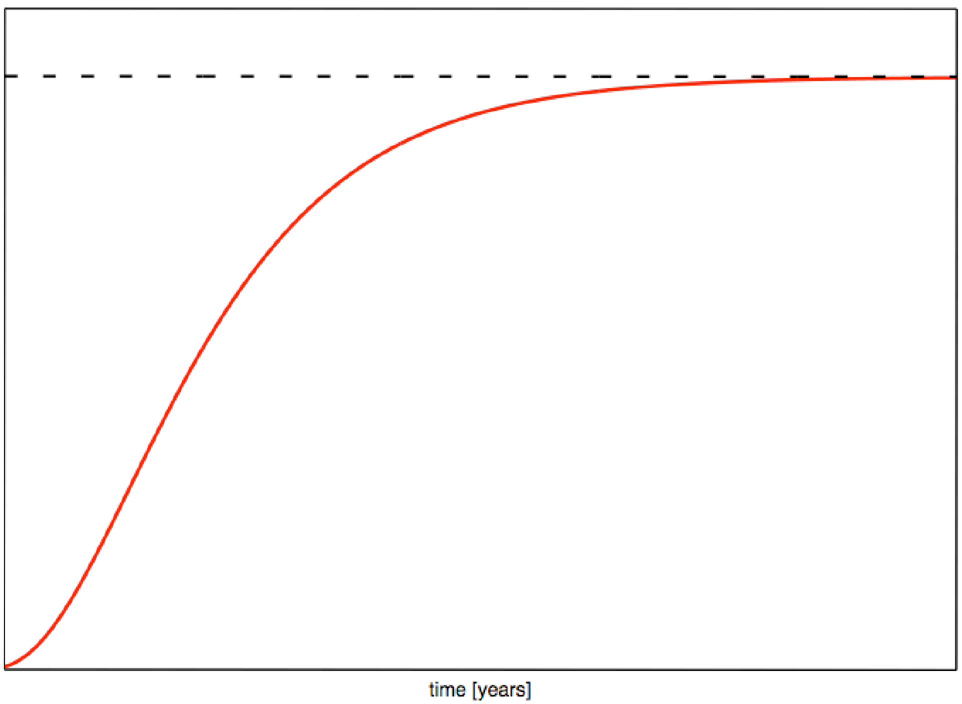
available resources (R) — **costs** (NR_c) — **growth** ($E_0 \frac{dN}{dt}$)

General Solution:

$$N(t) = \left[\frac{R_a}{R_c} + \left(N^{1-\beta}(0) - \frac{R_a}{R_c} \right) \exp[-\frac{R_c}{E_0}(1-\beta)t] \right]^{\frac{1}{1-\beta}}$$

β<1 implies limited carrying capacity

biological population dynamics

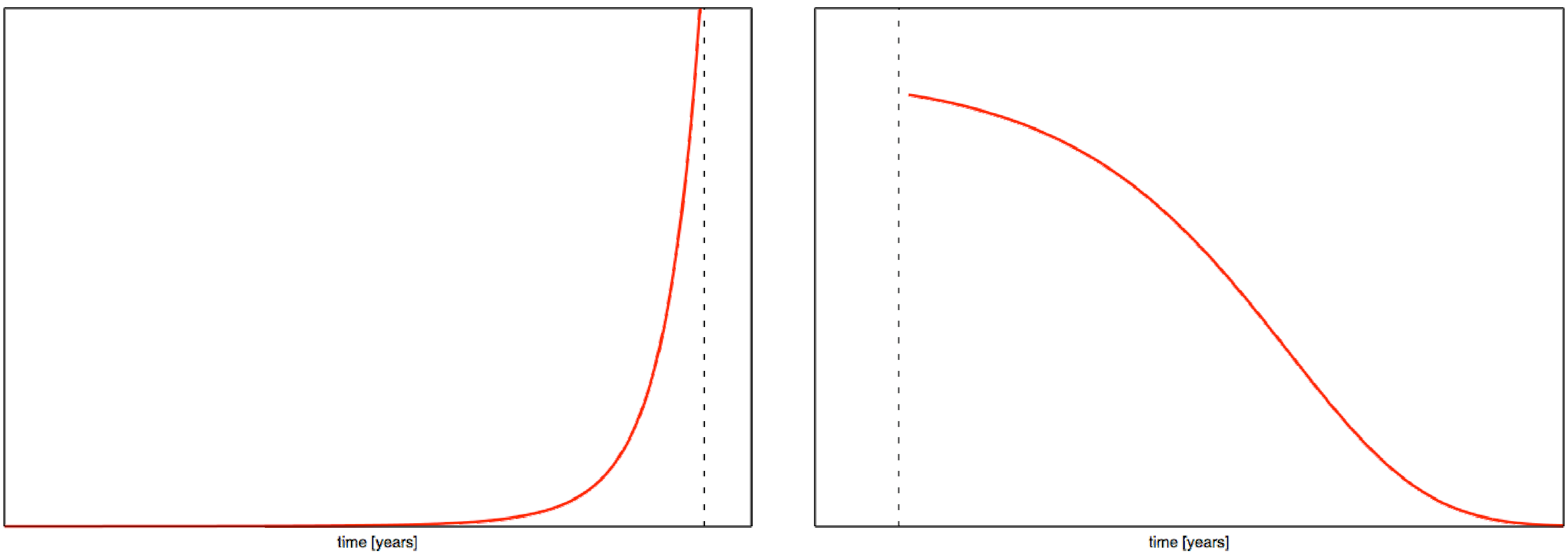


$$N_\infty = \left(\frac{R_a}{R_c}\right)^{\frac{1}{1-\beta}}$$

The dynamics is asymptotically stable **->** static equilibrium

β>1 : Finite time Boom and Collapse

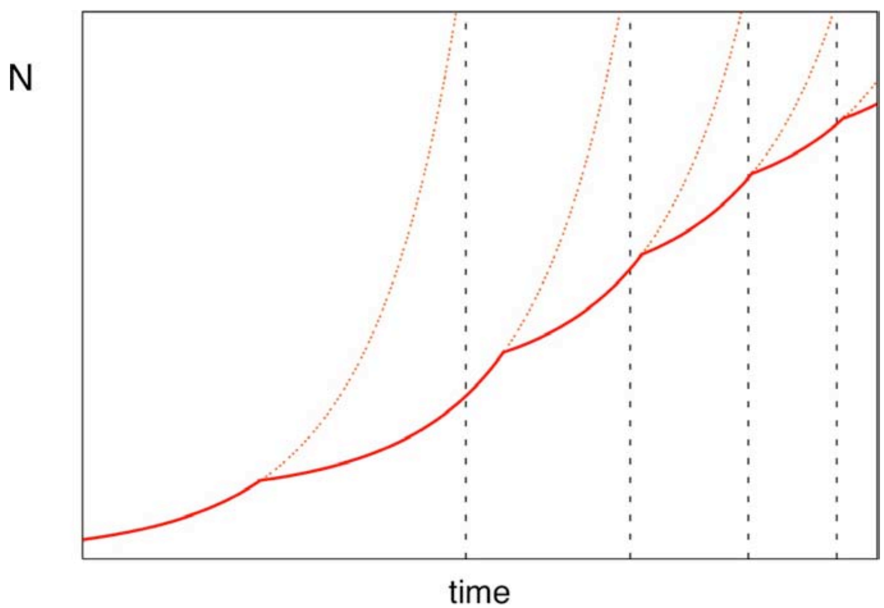
$$N(t) = \left[\frac{R_a}{R_c} + \left(N^{1-\beta}(0) - \frac{R_a}{R_c} \right) \exp[-\frac{R_c}{E_0}(1-\beta)t] \right]^{\frac{1}{1-\beta}}$$

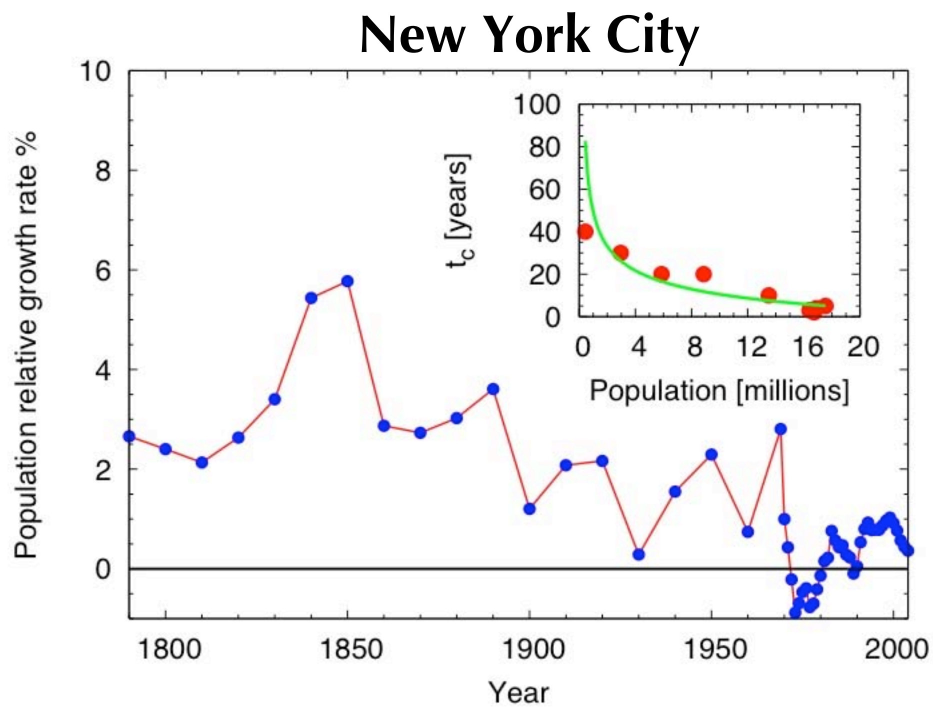


$$t_{crit} \approx \frac{E_0}{(\beta-1)R_a} N^{1-\beta}(0) \cong 50 \frac{T}{n^{\beta-1}} \quad years.$$

The dynamics is never stable in a finite population

Escaping the singularity with β>1:
cycles of successive growth & innovation





$$t_{crit} \approx \frac{E_0}{(\beta - 1)R_a} N^{1-\beta}(0) \cong 50 \frac{T}{n^{\beta-1}}\ years.$$

→ t_{crit} shortens with population size N

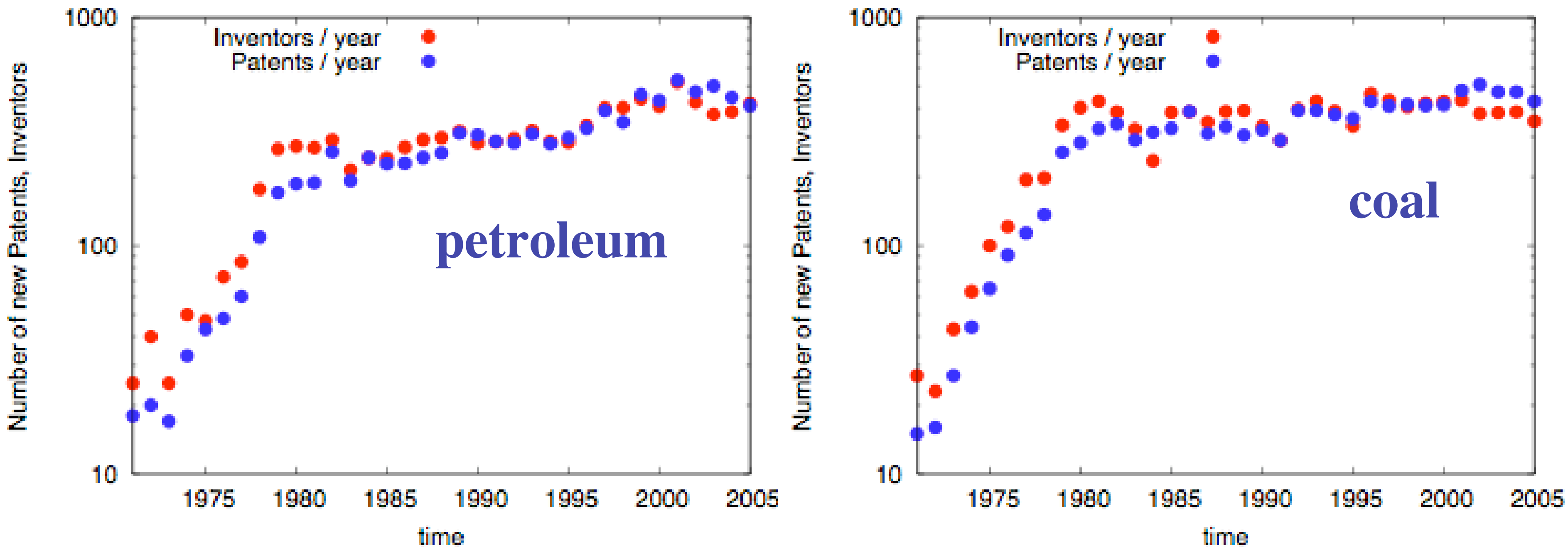
Innovation, investment, productivity in energy science and technology

World database of energy technology patents

work with Jasleen Kaur

10952	(1623)	Coal	**Fossil fuels**	23521(3829)
9224	(1297)	Petroleum		
3920	(1045)	Natural gas		
15565	(3924)	Solar	**Renewables**	28110 (6135)
9540	(1513)	Wind		
1712	(322)	Hydroelectric		
1521	(420)	Geothermal		
163	(38)	Biofuels		
829	(83)	Nuclear Fusion	**Nuclear technology**	971 (120)
157	(38)	Nuclear Fission		

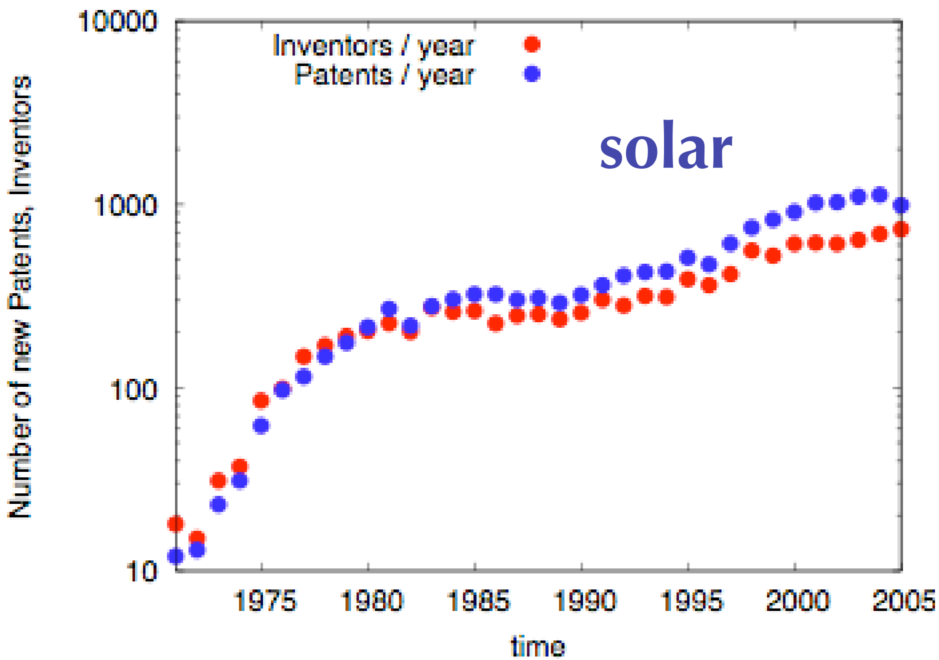
Patterns of energy innovation in time

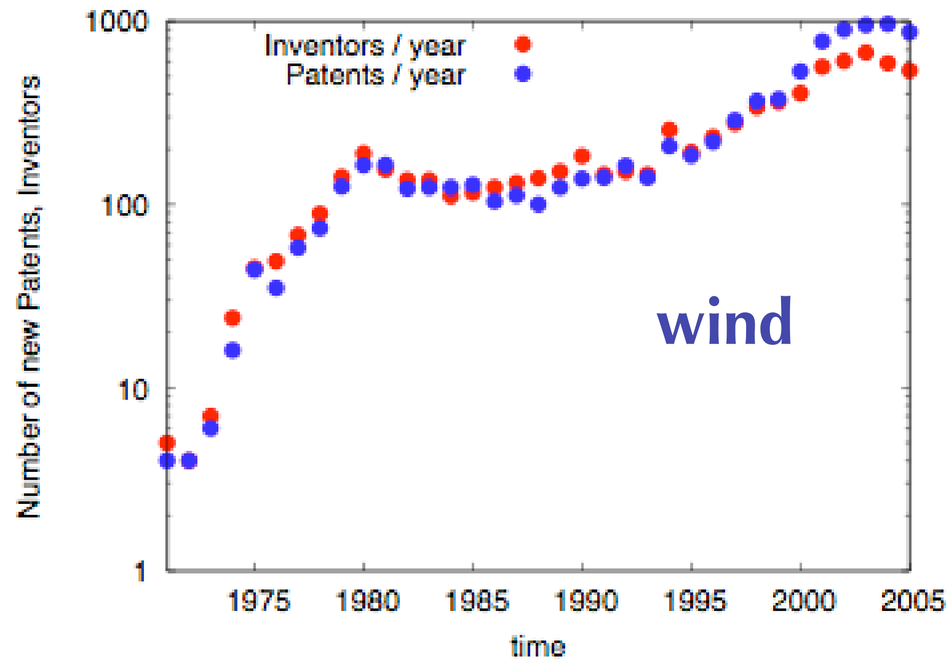


Yearly invention rates in **fossil fuel technologies**

have been ~ constant since the 80s

Patterns of energy innovation in time

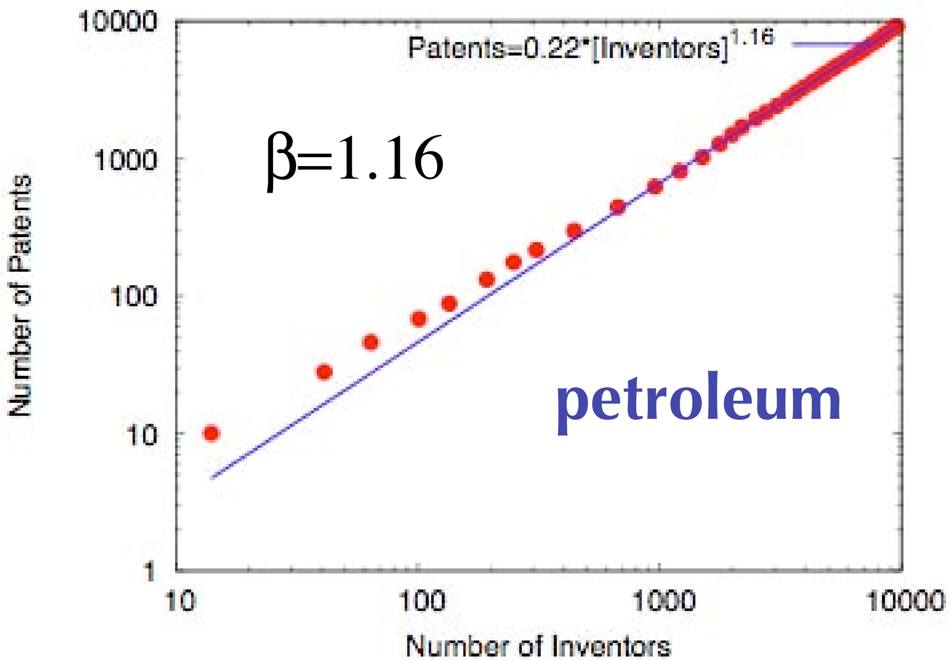


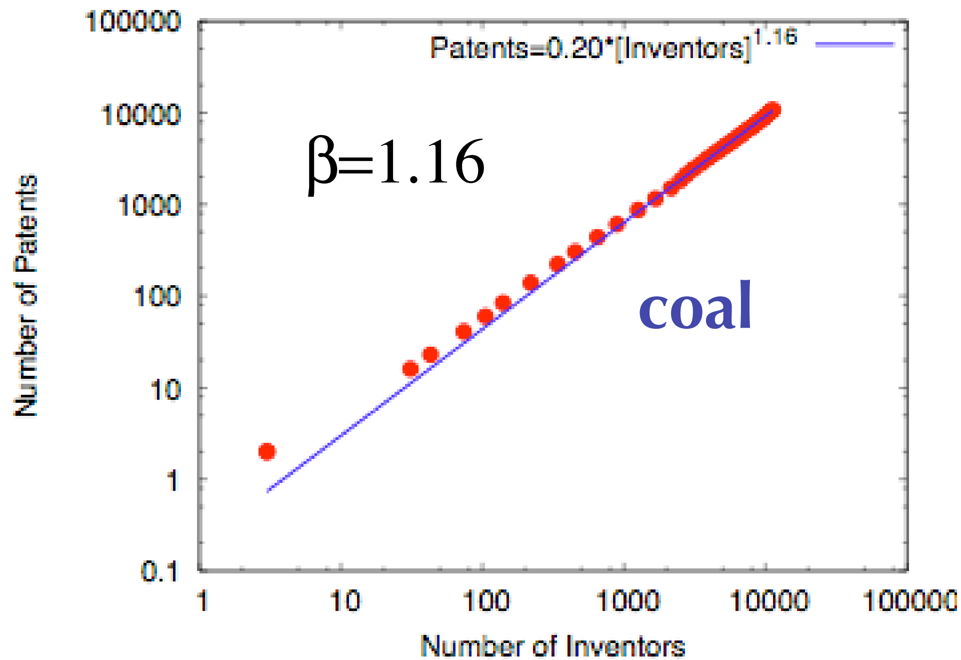


Rates of invention in **renewable technologies** have steadily increased

Marginal returns to labor

fossil fuels

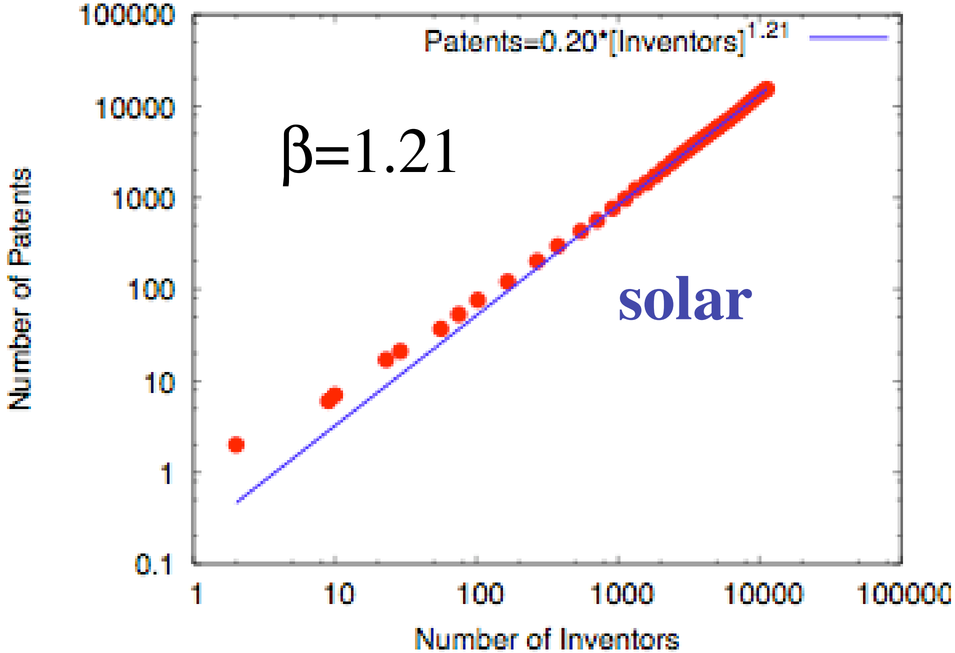


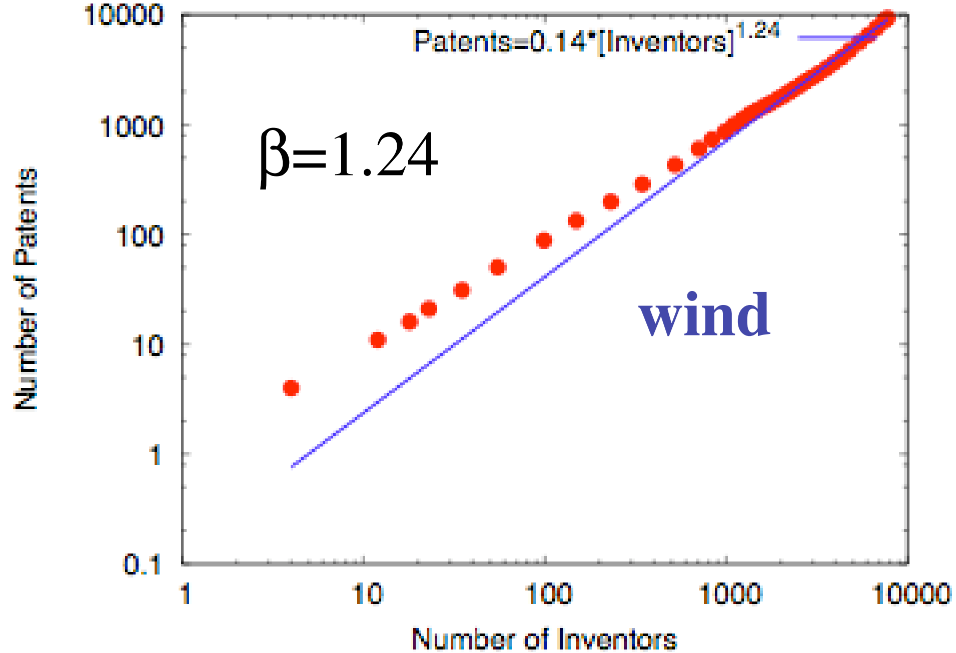


Patenting in oil and coal shows moderate increasing returns to labor

Marginal returns to labor

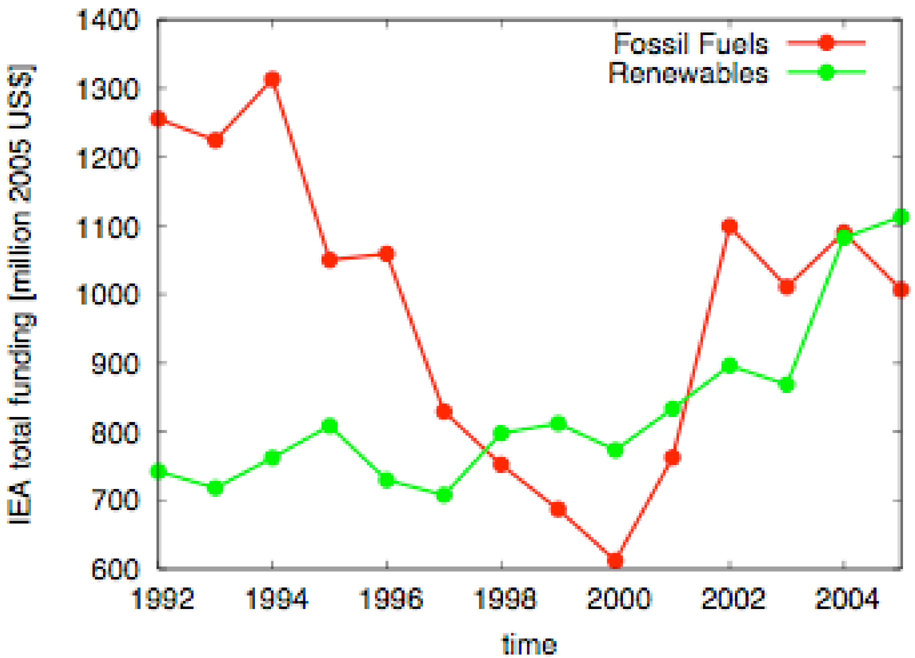
renewables

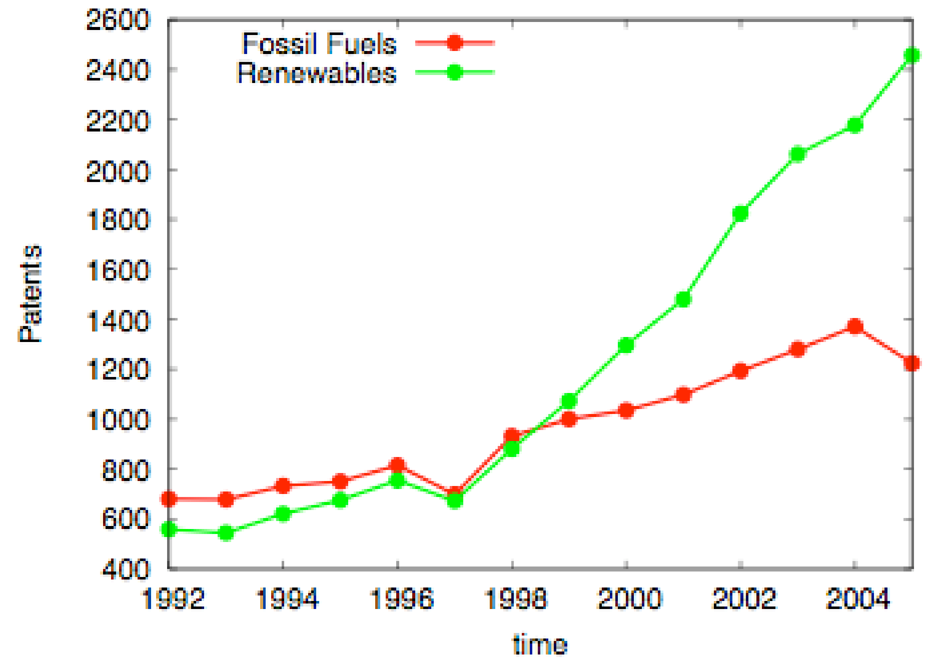




solar and wind show stronger returns to labor investments than **fossil fuel** technologies

Worldwide funding for energy R&D vs. patenting trends

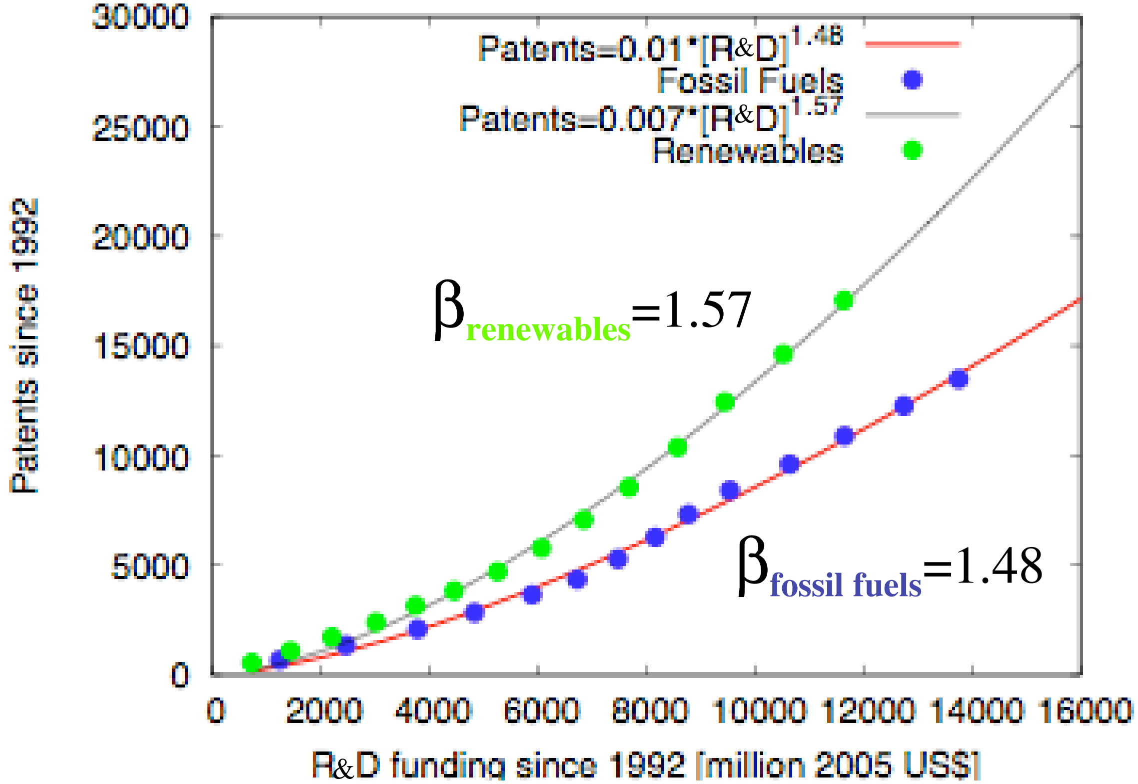




Funding data from International Energy Agency 2006 report

Renewables are overtaking **fossil fuel** technologies in terms of innovation and increasingly in R&D funding

Returns in innovation to R&D investments



Renewable technologies' patents show greater returns to R&D investment relative to **fossil fuels**

social aggregate regularities
hypotheses and theory

Despite non-stationarity, multiple interactions modes, non-locality, innovation, individual adaptation

Many empirical regularities appear as functions of **population**
or **resources** (investment, labor)
but not as simple functions of time

Increasing returns to scale ($\beta>1\sim1.15$) in **socio-economic**
variables are a universal
self-similar feature of cities, innovation

What are the essential social networks that mediate them?
What is the role of spatially optimized infrastructure networks?