Universality in Open-Evolving Systems

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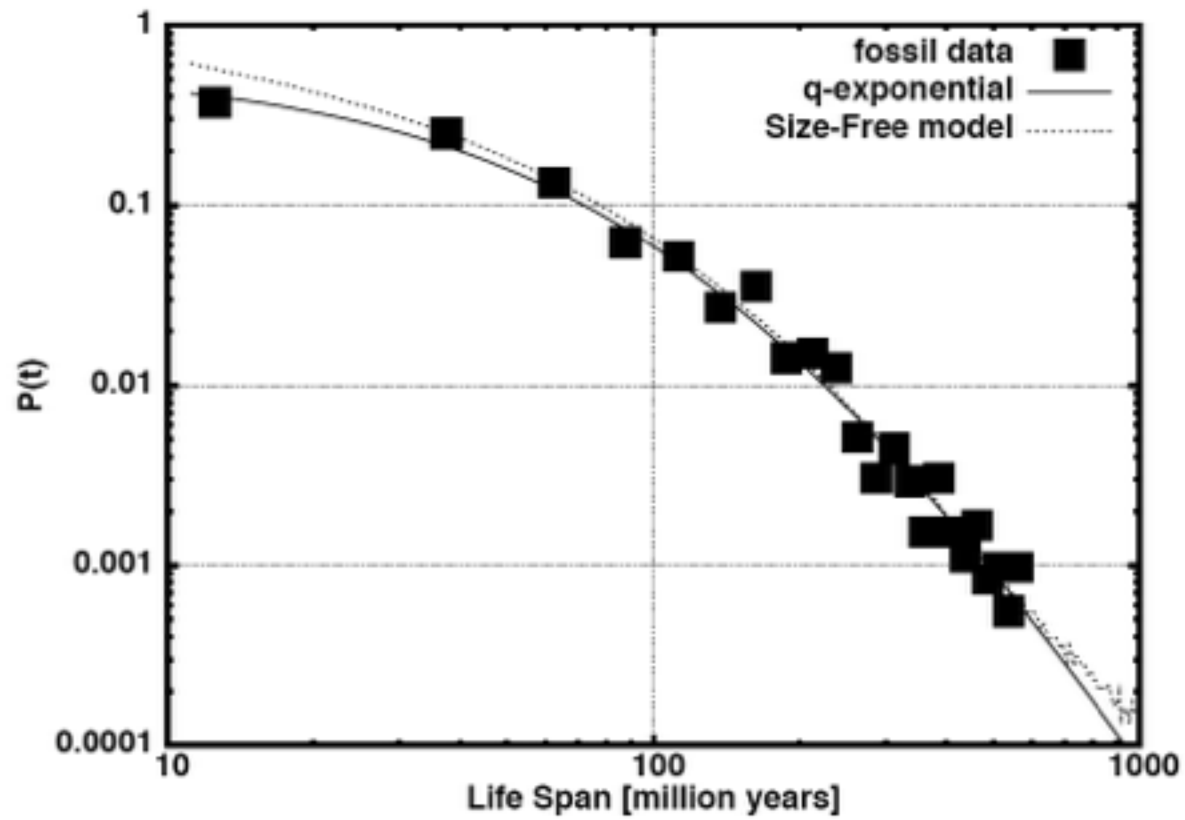
In collaboration with T. Shimada, N. Ito and P.A. Rikvold

Statistical physics of “*diverse*” & “*open*” system

Statistics of open-evolving systems

- lifetime distribution of each element
- extinction-size distribution
- intermittency in time series
- structure of the emergent system
- ….



T. Shimada et al., Int. J. Mod. Phys. C, 9 1267 (2003)

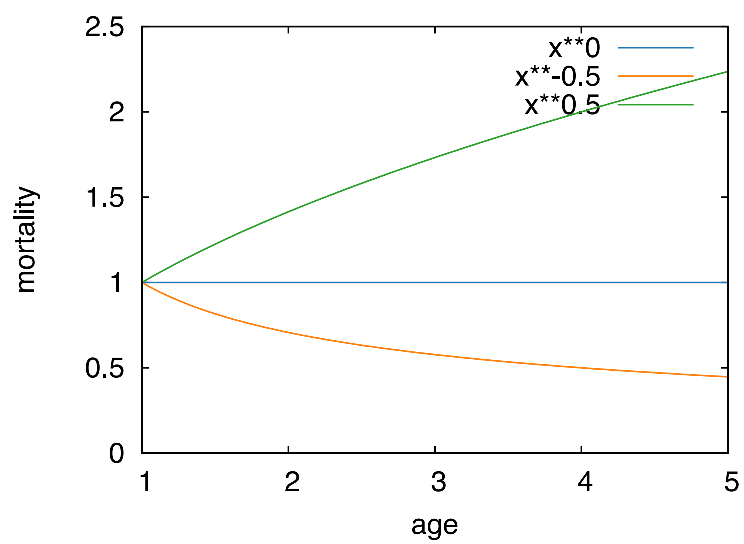
Outline of the Talk

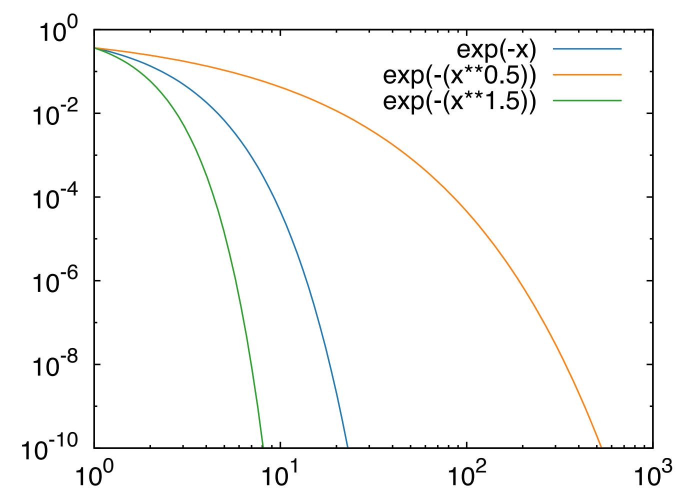
- Review on theories for lifetime distributions
- Population dynamics models
    - -> A skewed species lifetime distribution is robustly found.
- propose a minimal model to understand the underlying mechanisms
- comparison with empirical data

Theories for lifetime distributions

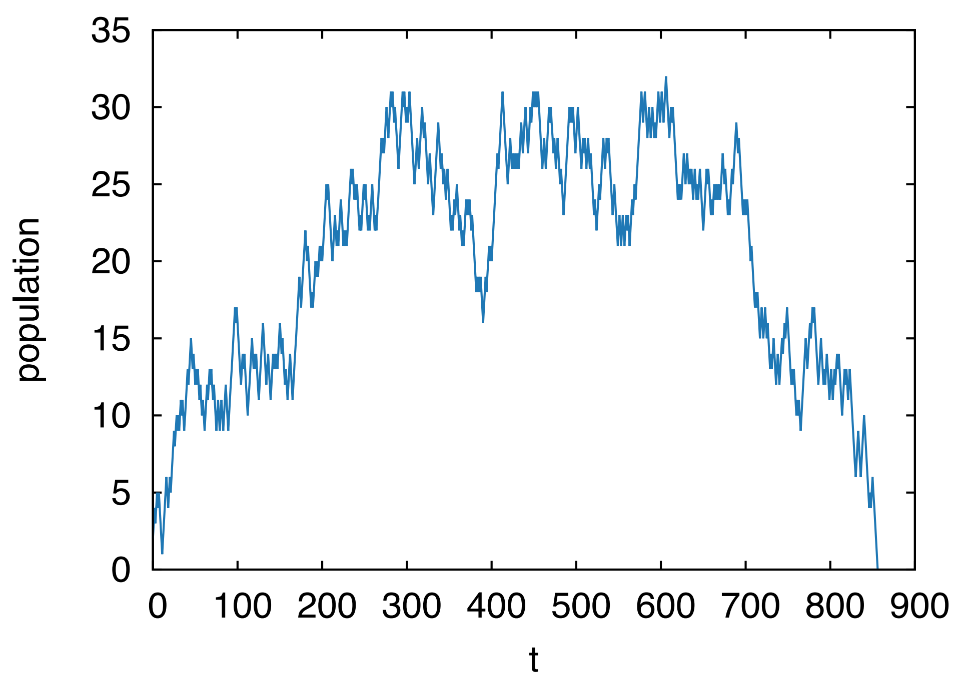
- Poisson process
  - age-independent mortality (constant failure rate) $\exp\left(-t/\tau\right)$
  - a simple exponential function
  - known as "Red-Queen" hypothesis in ecology
- age-dependent mortality
  - stretched exponential distribution (Weibull) $t^{\beta-1}\exp[-(t/\tau)^{\beta}]$
  - q-exponential distribution $[1-(1-q)(t/\tau)]^{1/(1-q)}$

$$m(t) = \frac{p(t)}{1-\int_0^t p(t)dt}$$

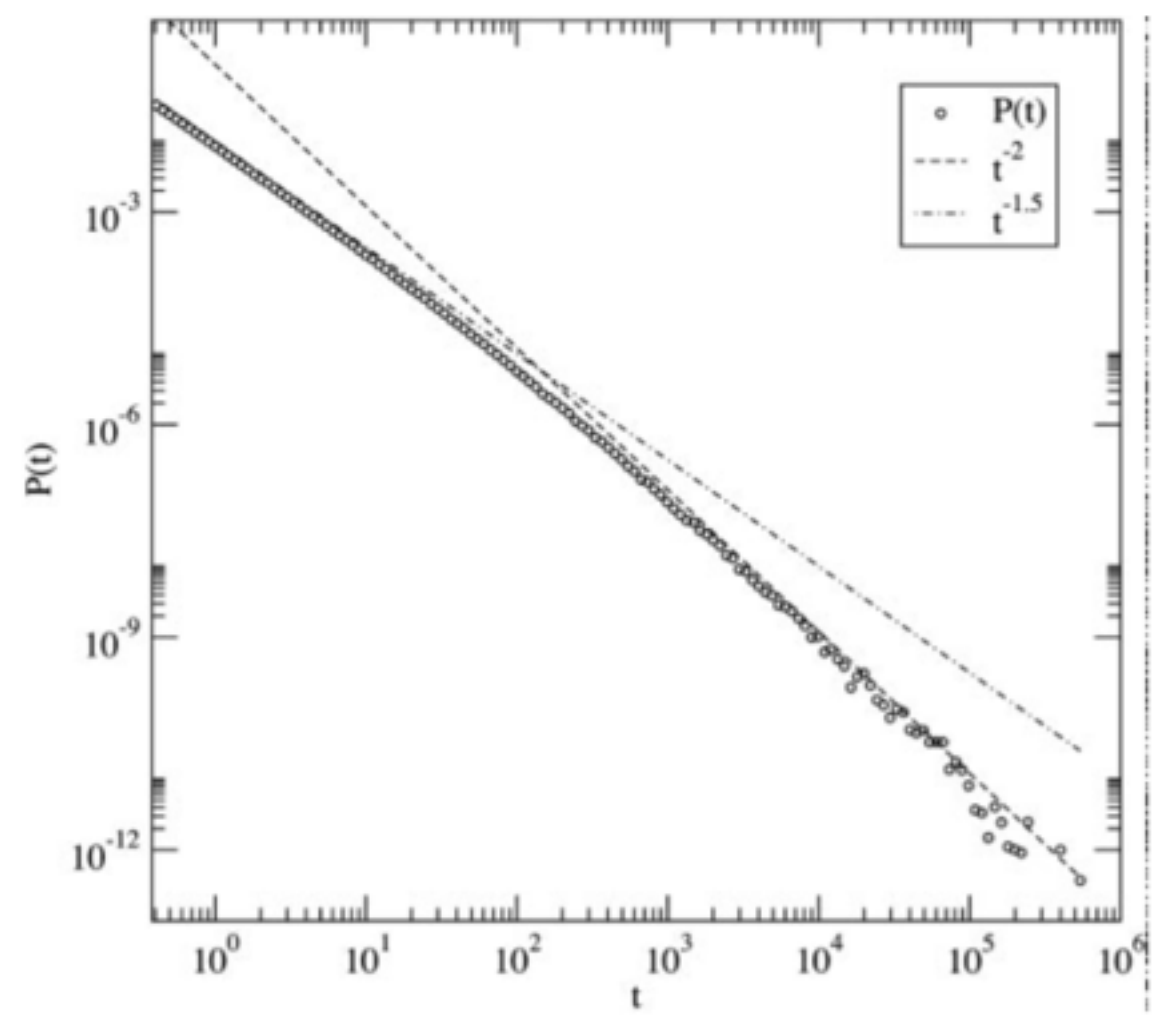




- return time distribution
  - 1-d random walk $t^{-3/2}$
  - critical branching process t^{-2}

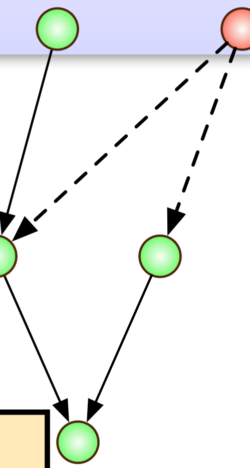


Pigolotti et al. PNAS (2005)



What about the lifetime distribution of mutually interacting systems?

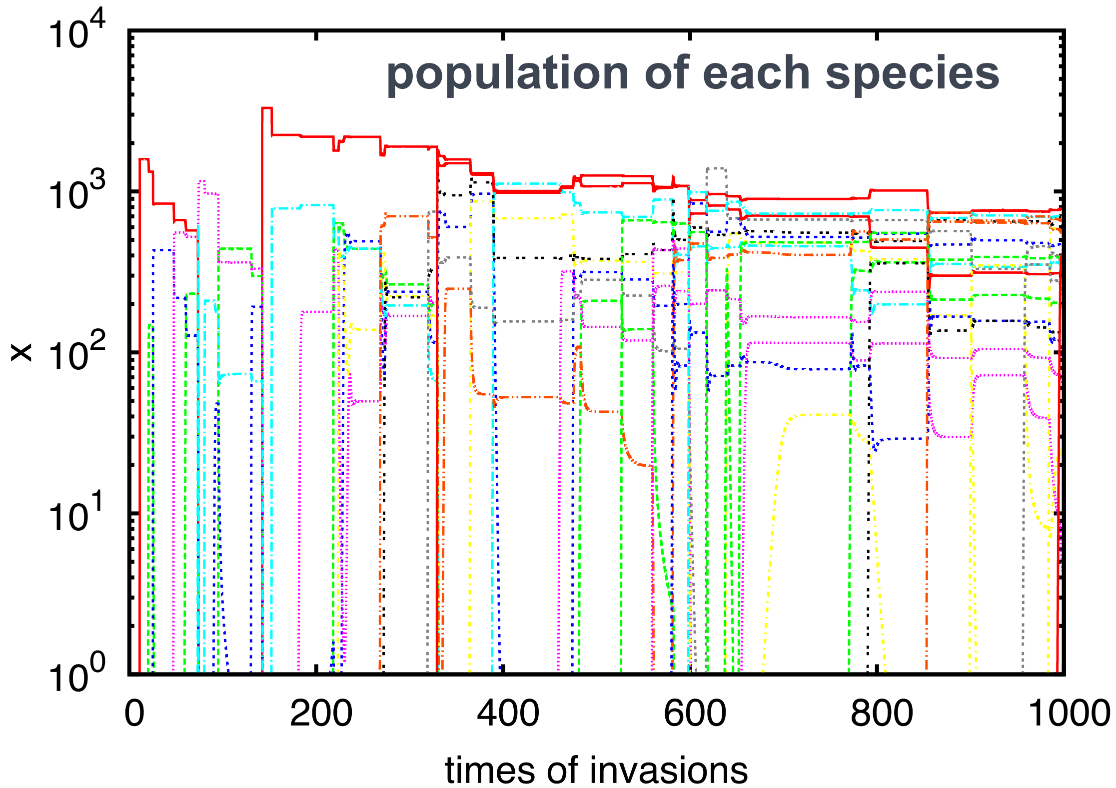
Population dynamics models

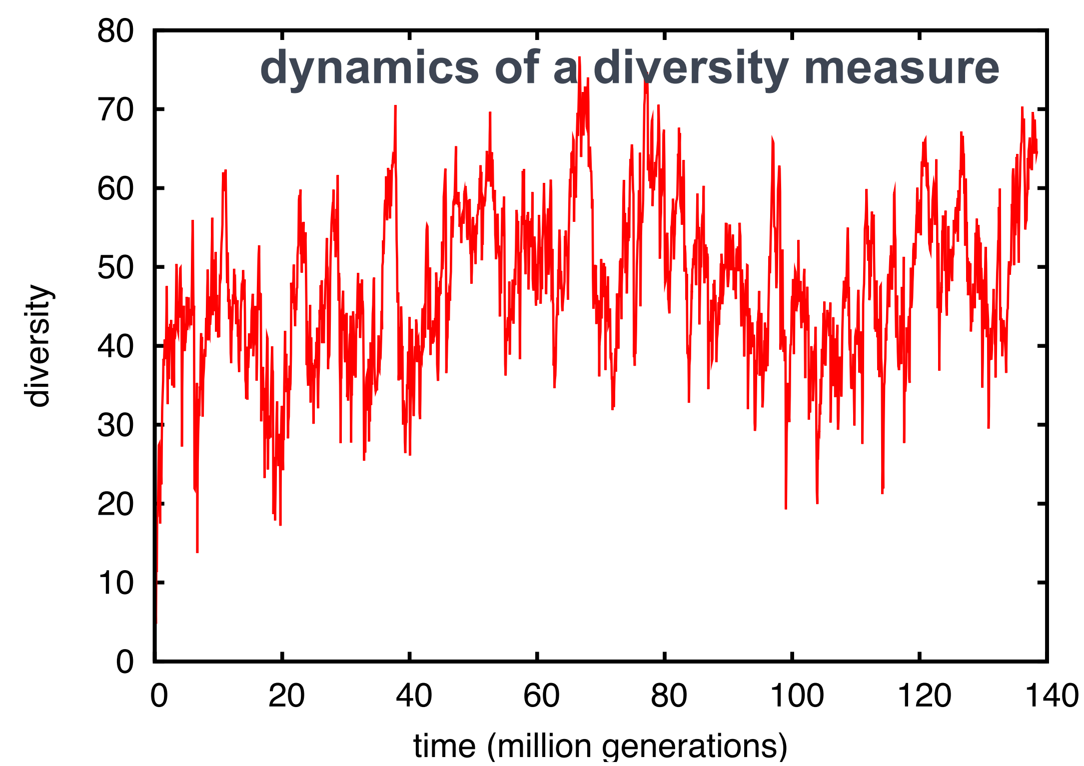


- **population dynamics models**
  - Models with two time scales:

population dynamics model (or individual based model)	+	addition of new species extinction of species

$$\dot{x}_i = f(\{x_j\}, \dots)$$





various forms of population dynamics

Since we do not know an established model,
we tried to find a universality shared for various models.

Y. Murase et al., J.Theor.Biol., **264**, 663 (2010)
Y.Murase et al.,Phys. Rev. E, **81**, 041908 (2010)

Scale-invariant model

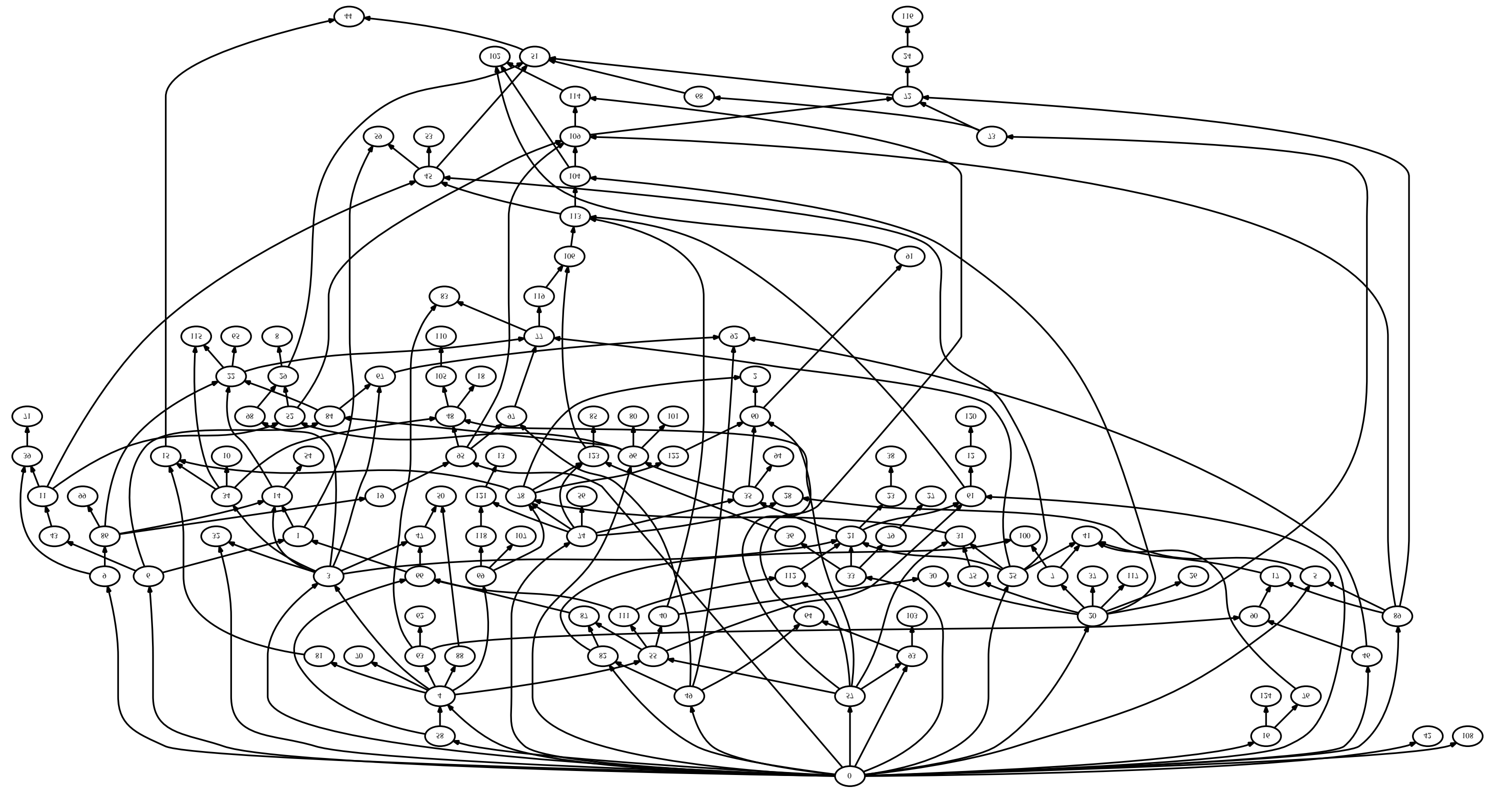
$$\dot{x}_i = -b_i x_i + \sum_{a_{ij}<0} a_{ij} x_i^{\lambda} x_j^{(1-\lambda)} + \sum_{a_{ij}>0} a_{ij} x_i^{(1-\lambda)} x_j^{\lambda}$$

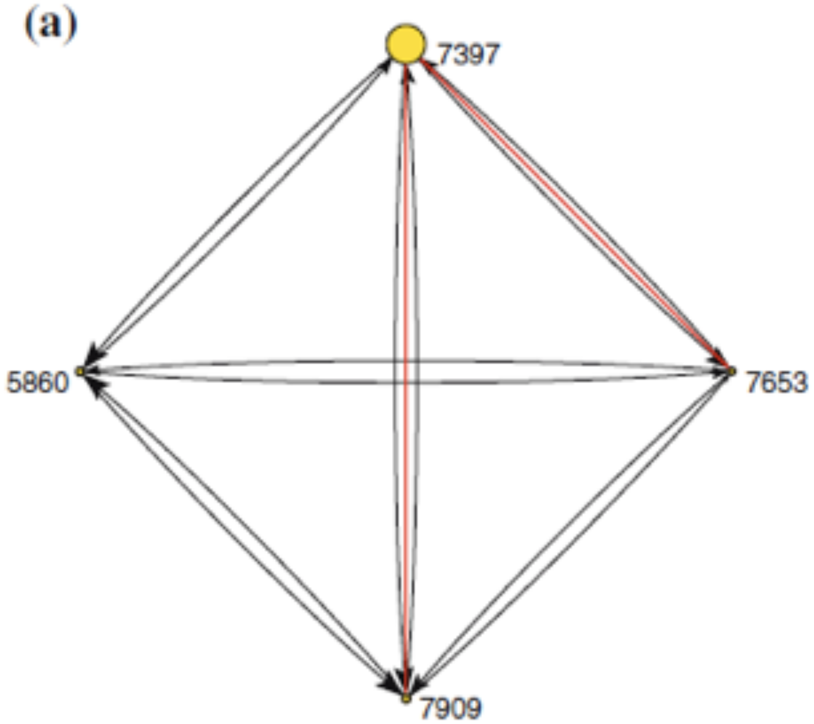
Tangled-Nature model A

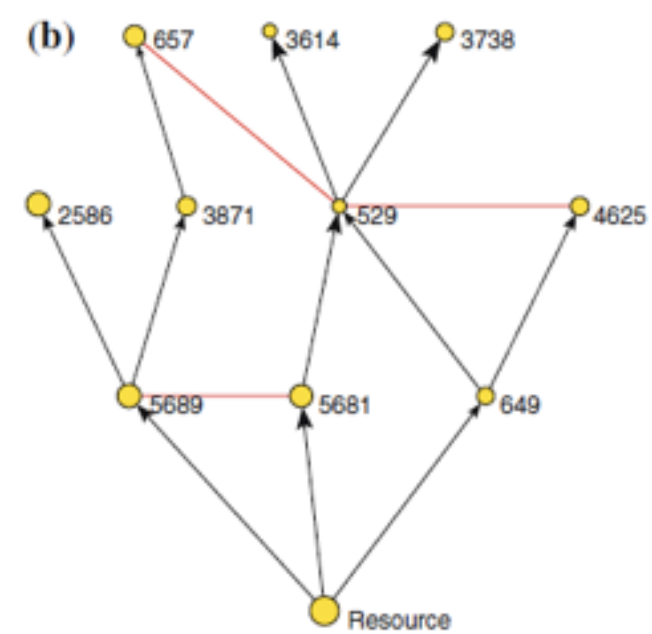
$$\Delta_I(R, \{n_J(t)\}) = \sum_J \underbrace{M_{IJ} n_J(t)/N_{tot}(t)}_{\text{interaction with } J\text{'th species}} - \underbrace{N_{tot}(t)/N_0}_{\text{globally applied suppression}}$$

Tangled-Nature model B

$$\Delta_I(R, \{n_J(t)\}) = \underbrace{-b_I}_{\text{birth cost}} + \underbrace{\eta_I R/N_{tot}(t)}_{\text{coupling to external resource}} + \sum_J \underbrace{M_{IJ} n_J(t)/N_{tot}(t)}_{\text{interaction with } J\text{'th species}}$$

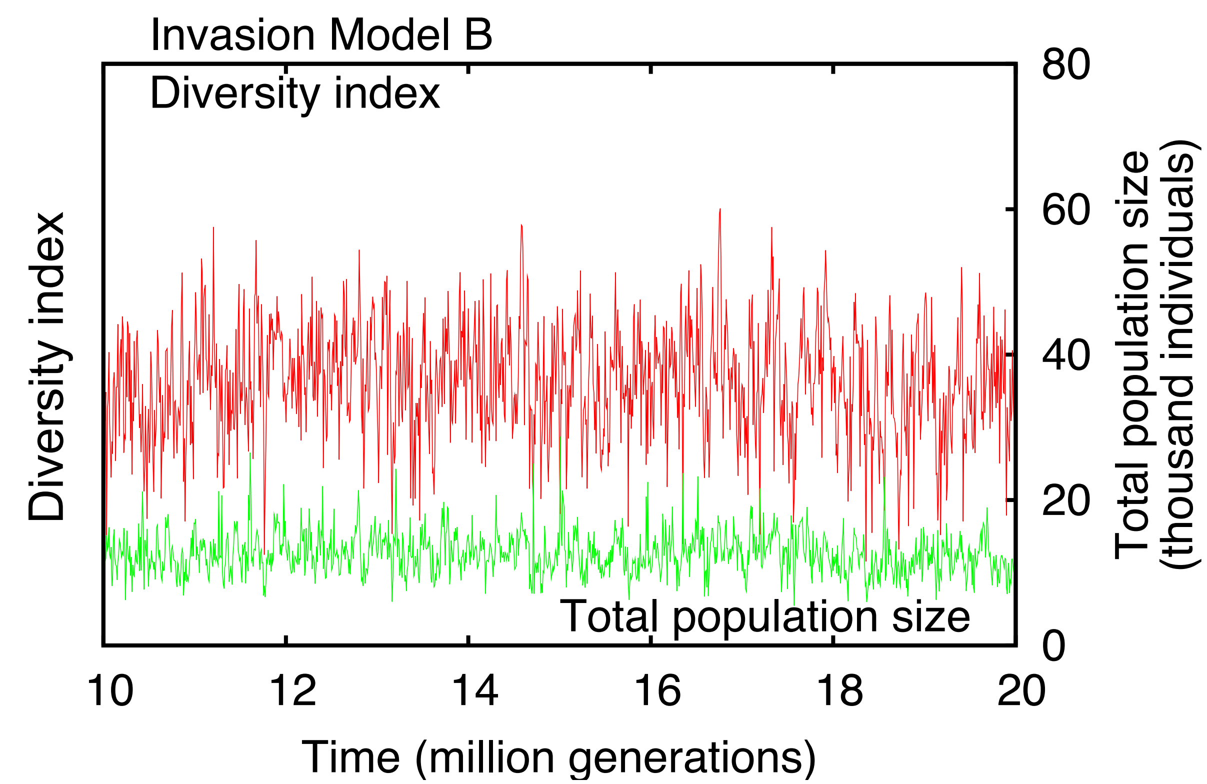


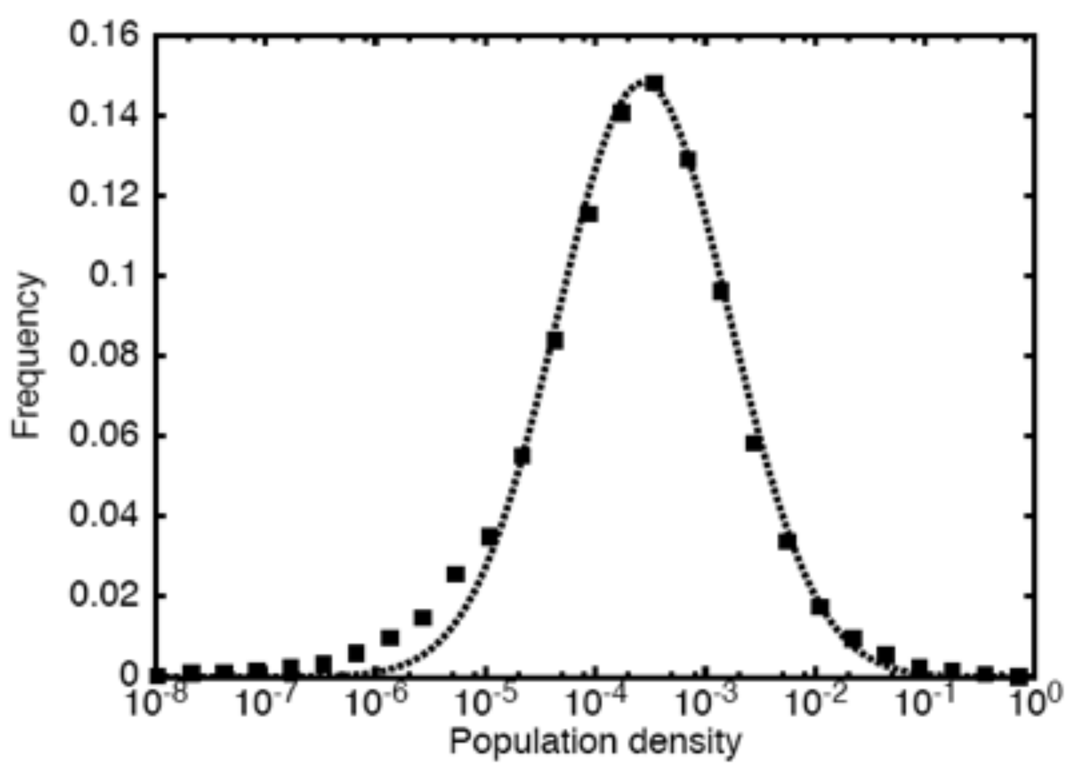

(a)
7397
5860
7653
7909

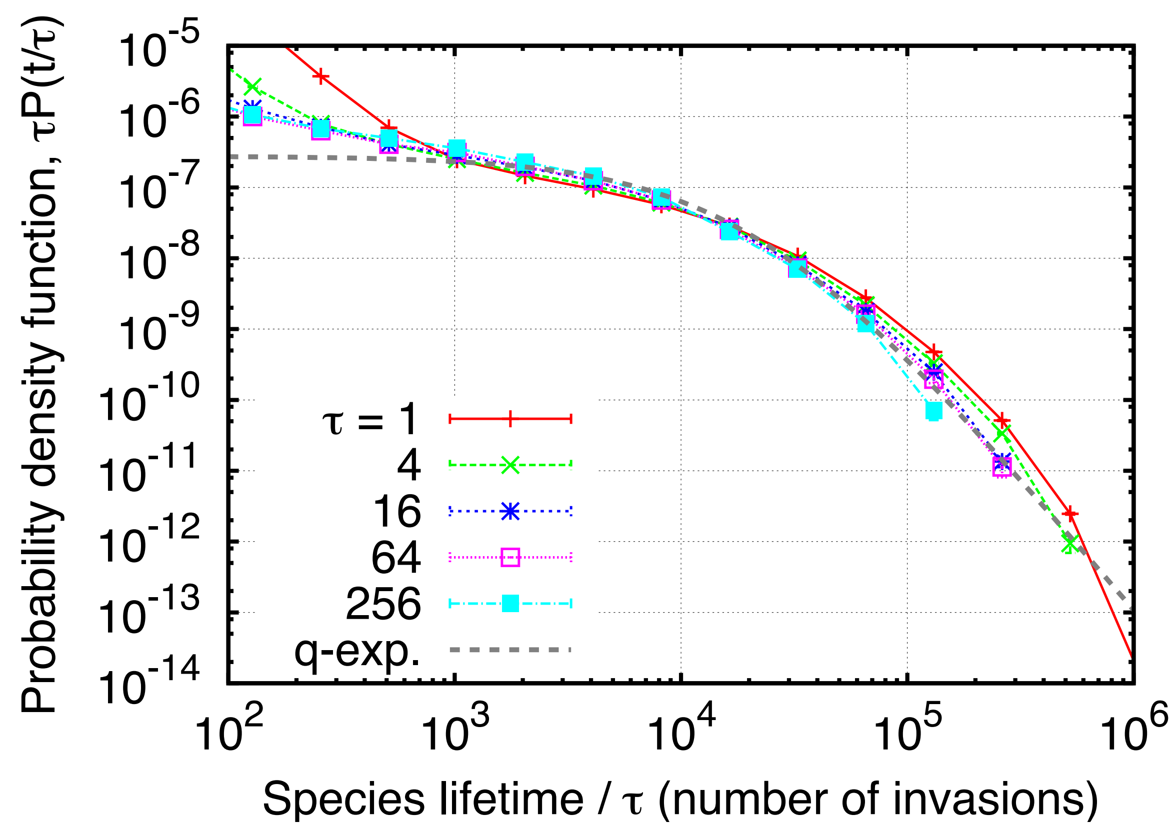

(b)
657
3614
3738
2586
3871
529
4625
5689
5681
649
Resource

Commonly observed pattern

- For all models
  - $1/f^2$ fluctuations of N
  - Skewed species-lifetime distribution
  - exponential extinction-size distribution
  - log-normal like population distribution

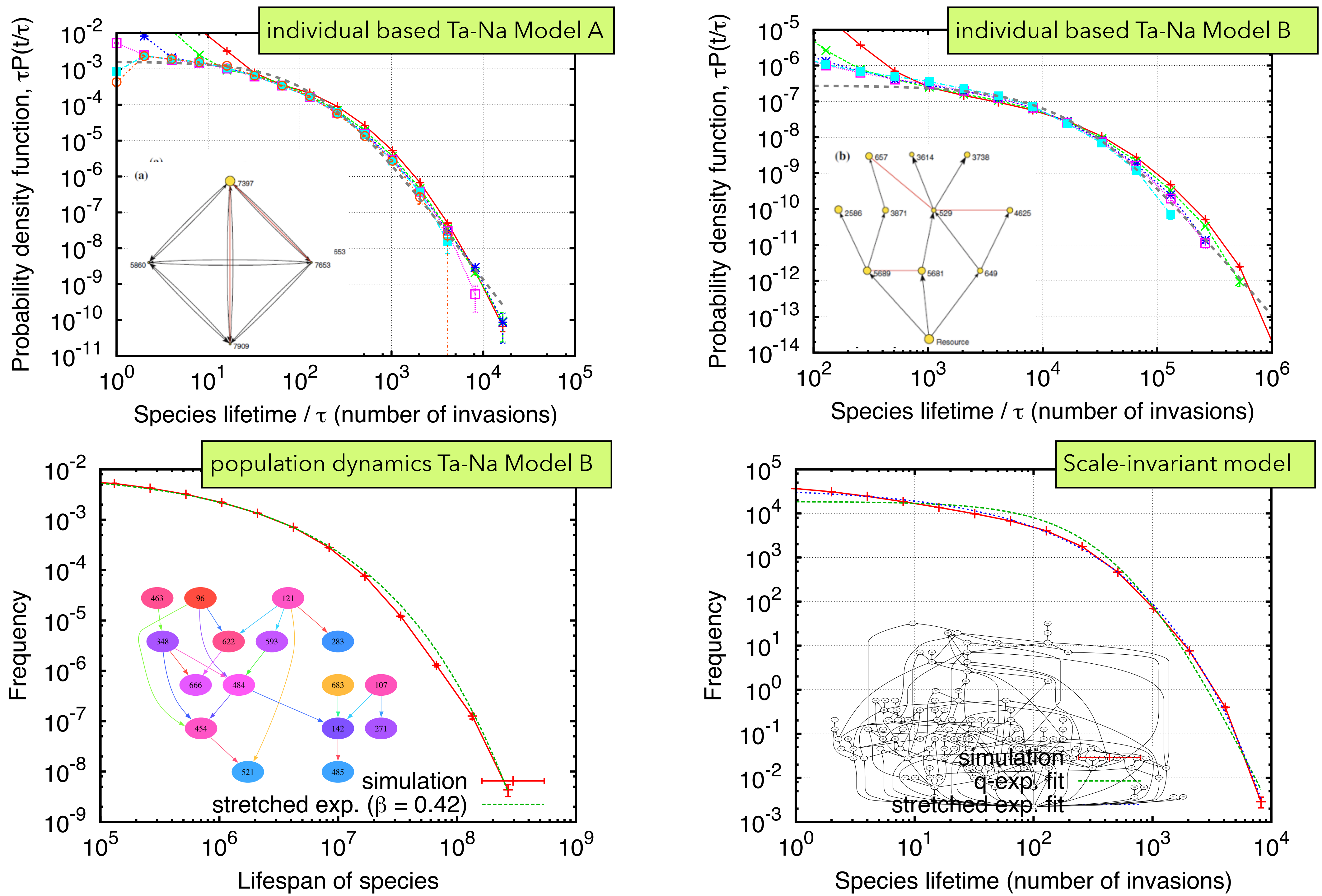






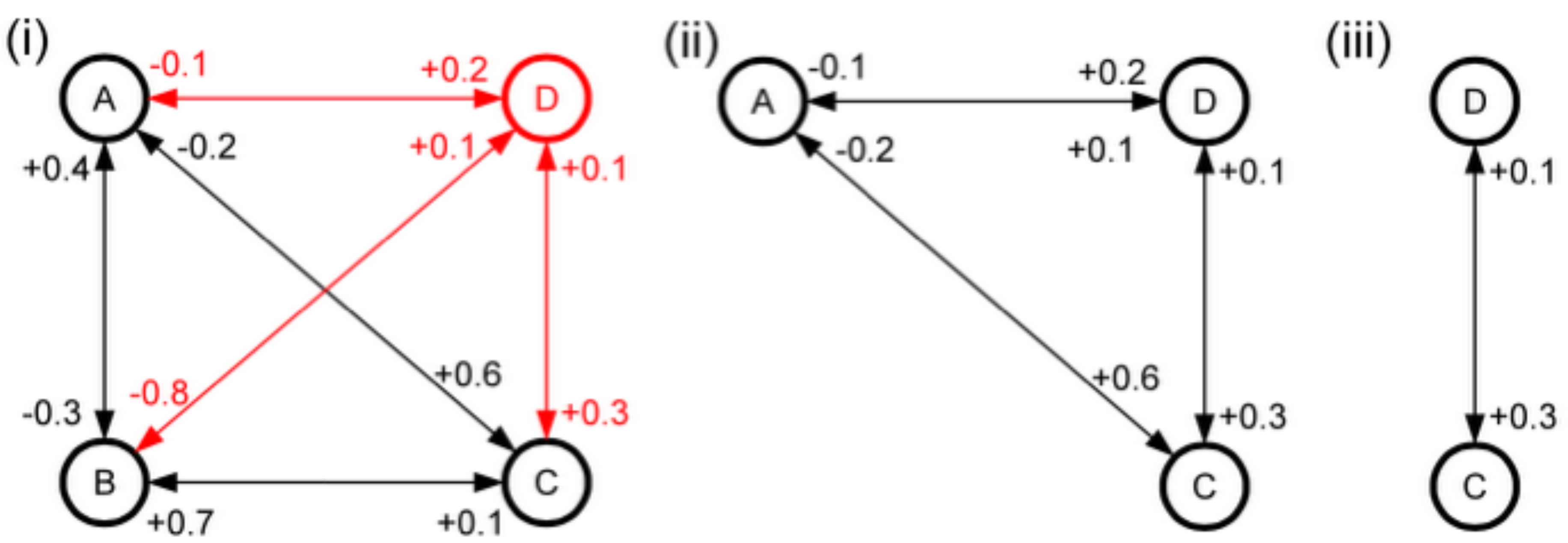
Lifetime distribution for population dynamics models

Skewed profile is universal for various population dynamics models



Dynamical Graph Model

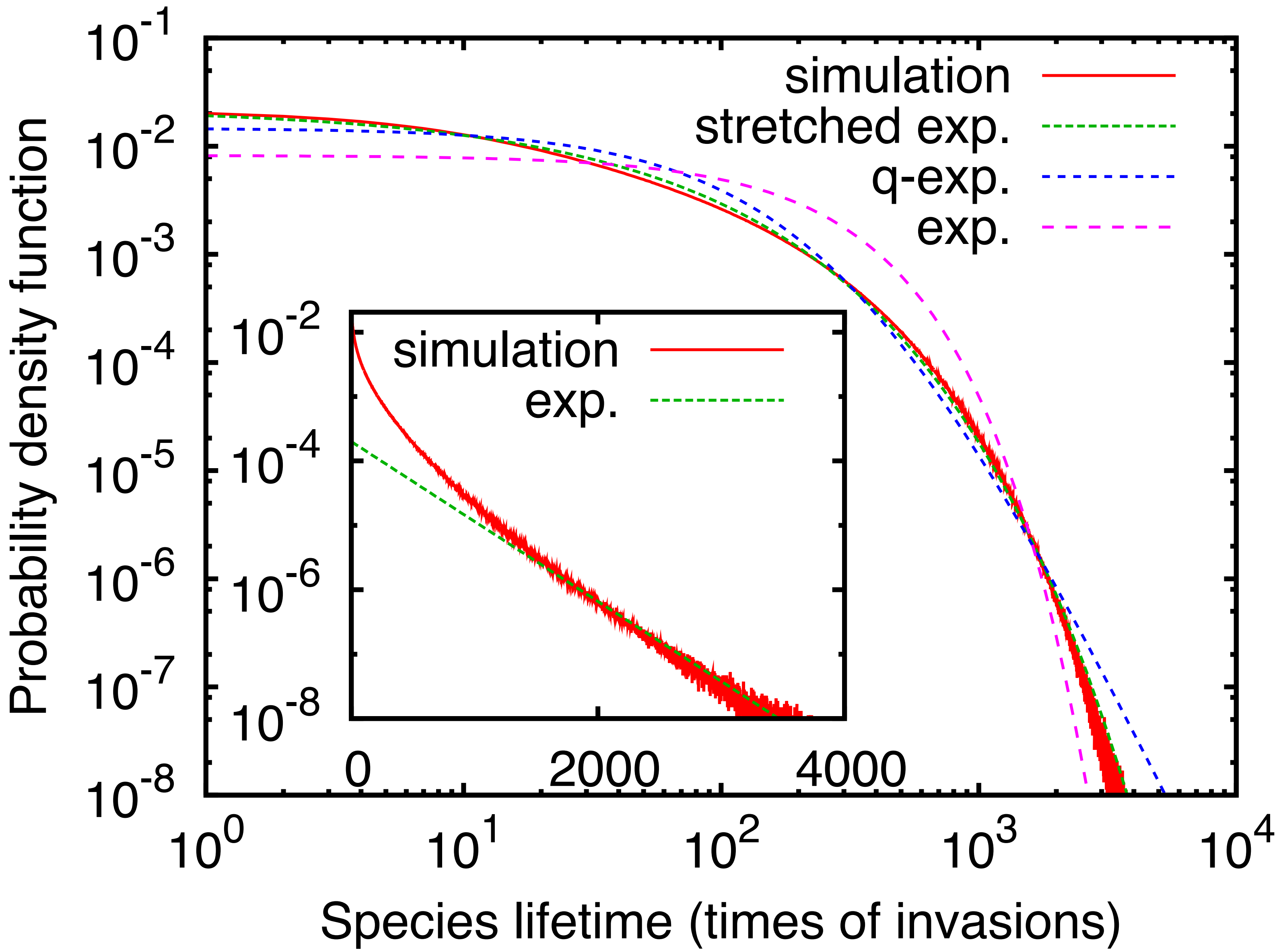
- System is represented by a weighted and directed graph.
- Interspecies interaction is denoted by a_{ij}.
- If $\Sigma a_{ij} \geqq 0$, species *I* can survive. (Σa_{ij} = fitness of *i*'th species: f_i)
- a_{ij} takes a random number drawn from a Gaussian distribution with probability *c*. (With 1-c, a_{ij} is zero.)



Y. Murase et al., New J. Phys., 12, 063021 (2010)

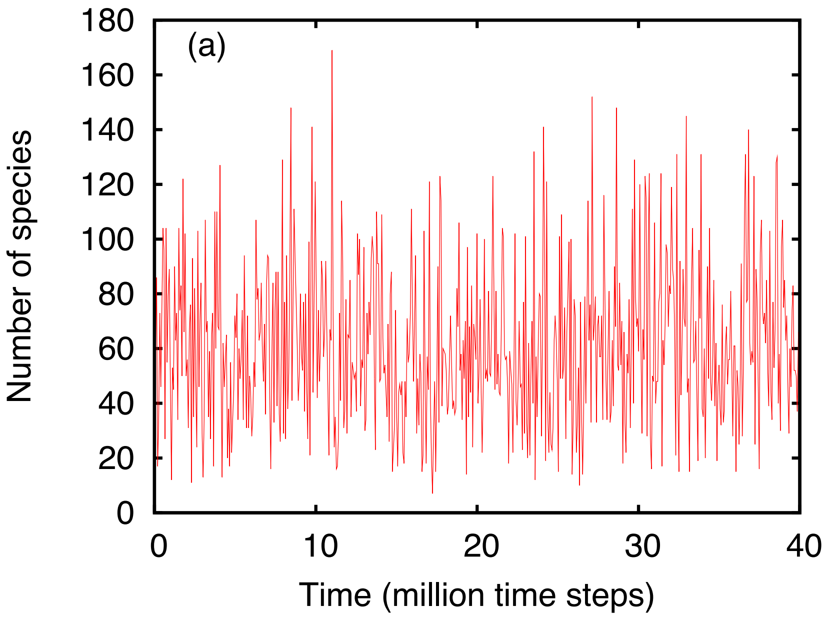
Lifetime Distribution of DG model

- neither simple exponential or simple power law



$$P(t) \propto \exp\left(-(t/\tau)^{\beta}\right)$$

$$\beta = 0.54$$

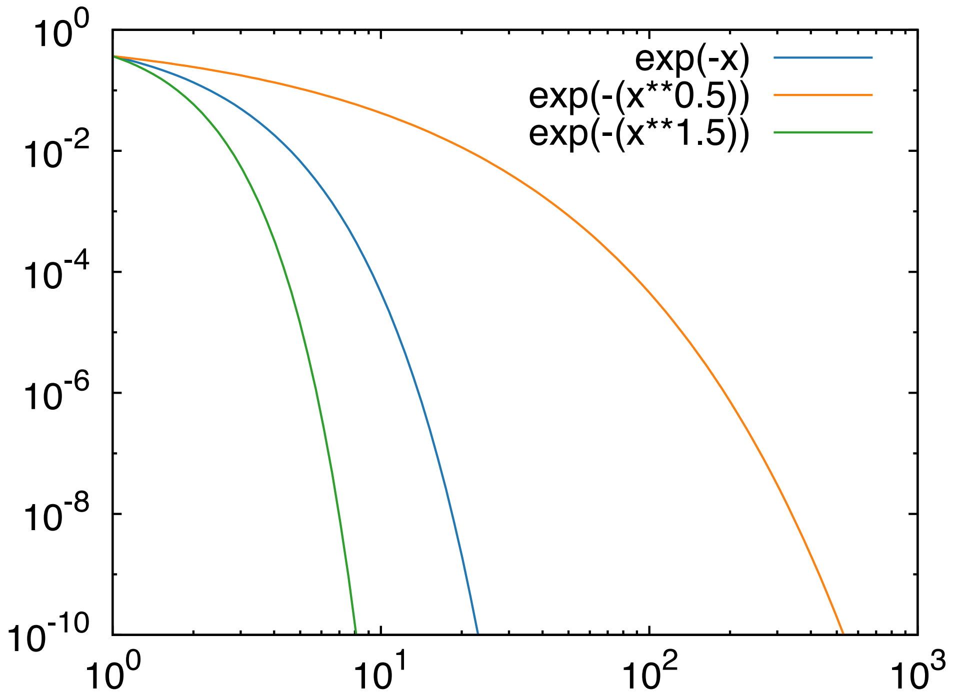


well fitted by a stretched exponential function with exponent 1/2

What is the origin of the profile?

- If we assume the mortality function $t^{-1/2}$, we get a stretched exponential distribution.

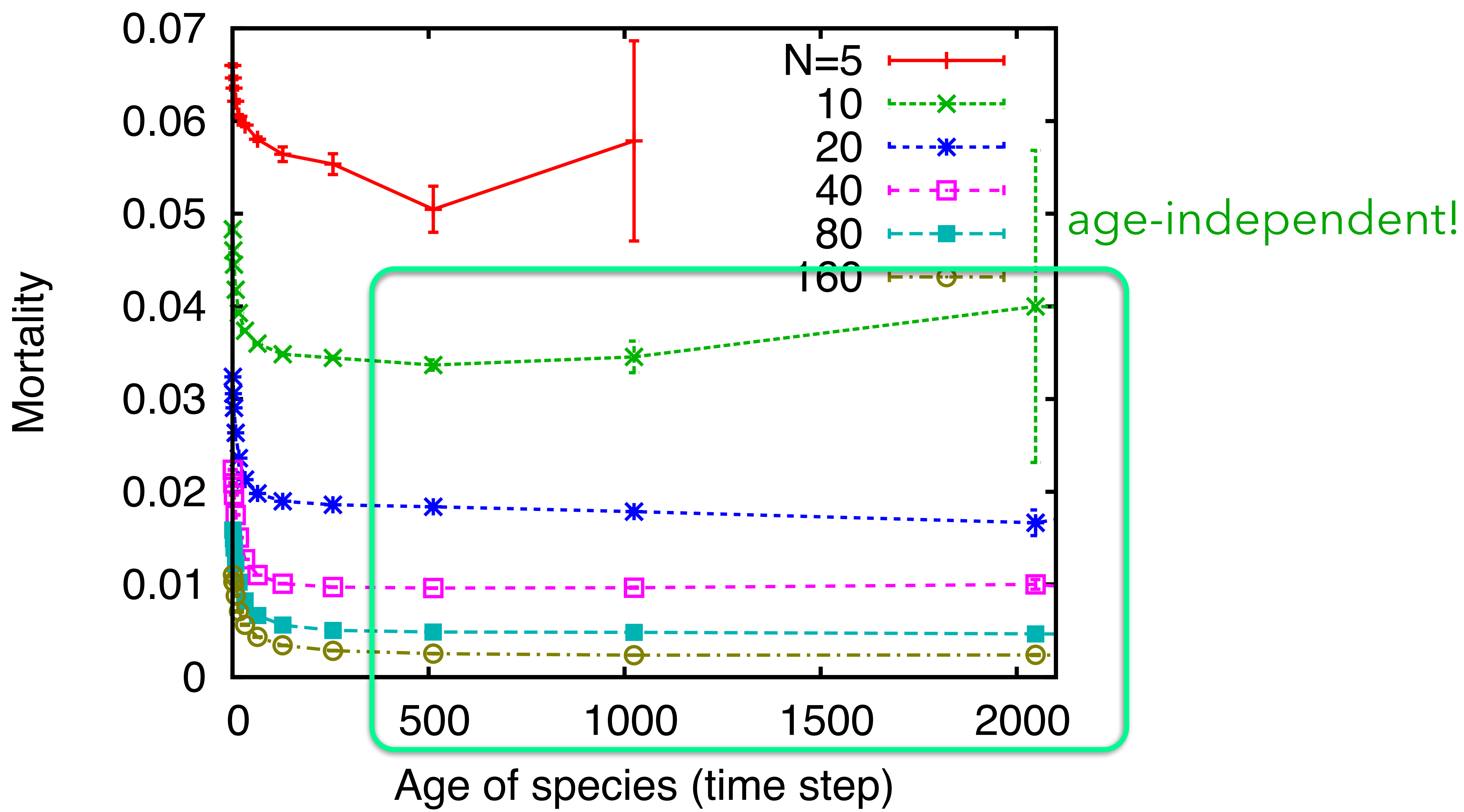
$$m(t) = \frac{p(t)}{1 - \int_0^t p(t)dt}$$



Does long-living species have advantages to survive??

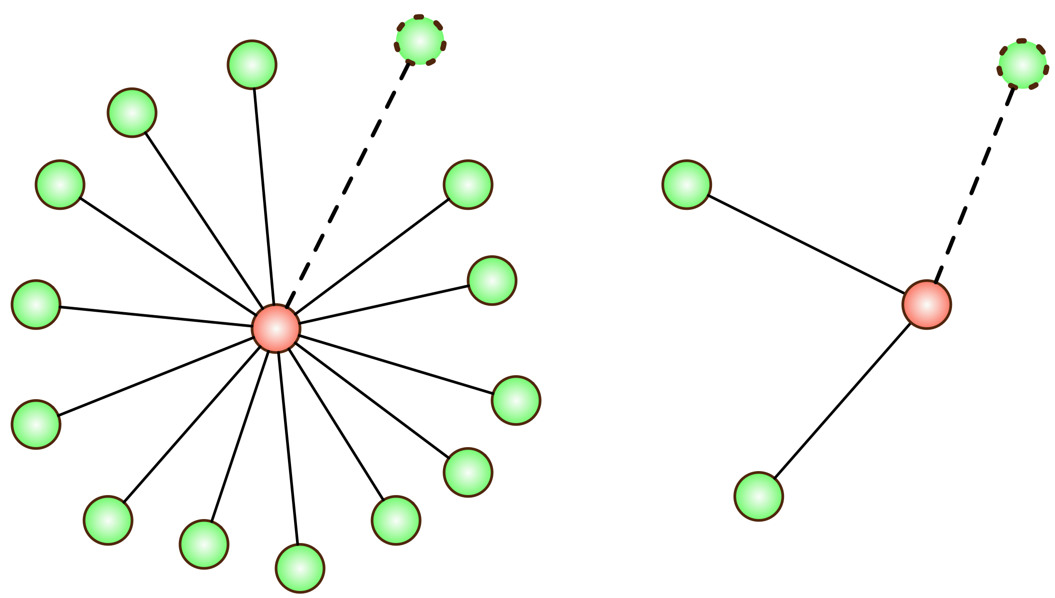
Mortality is age-independent

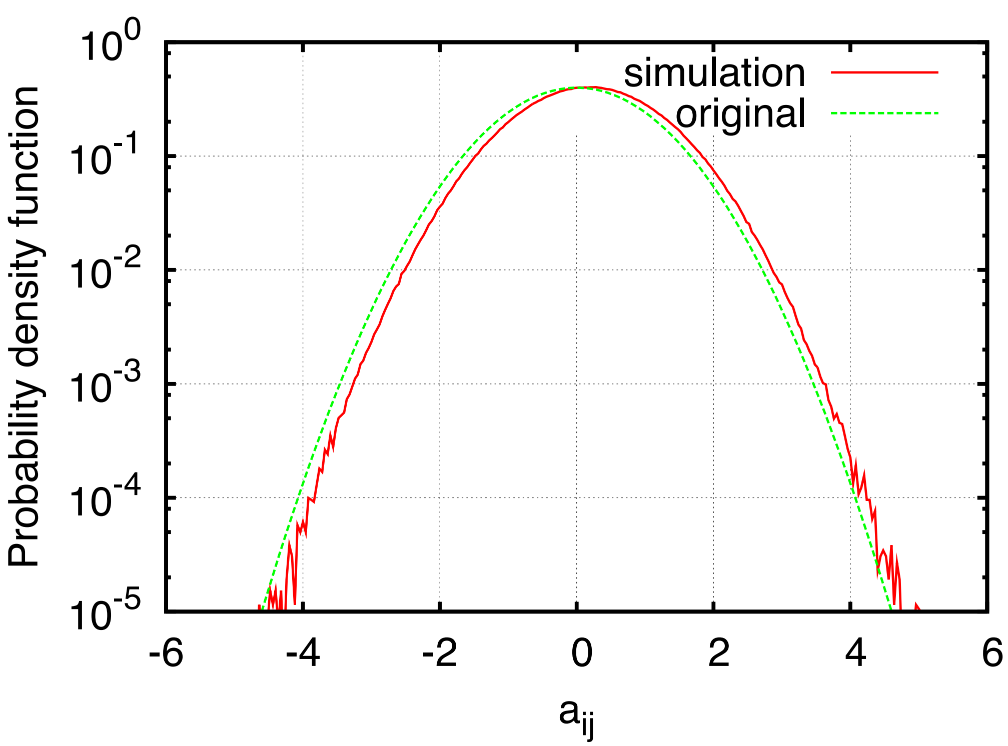
Mortality is not dependent on age, but N.



Origin of 1/N dependence of mortality

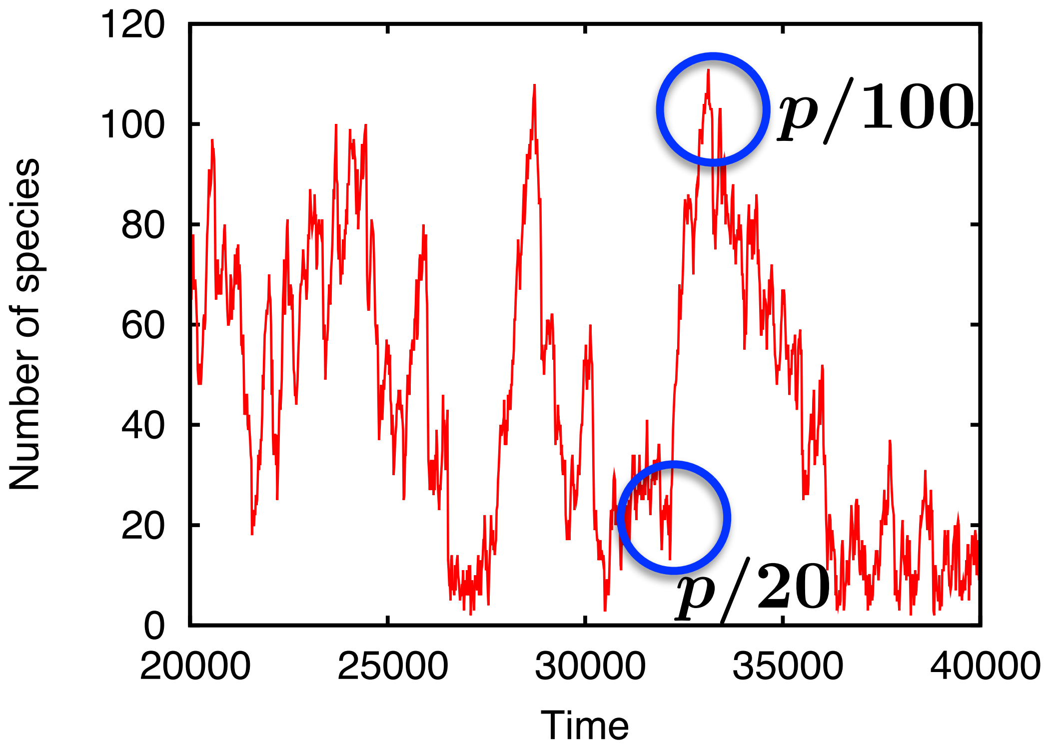
- fitness changes by immigration and extinction
  - changes in f_i caused by immigrant is **neutral**
    - → this yields $t^{-3/2}$ (does not have a time scale)
  - changes in f_i caused by extinction is **negative**
    - this is because f_i is positive by model definition
    - → **negative drift is proportional to 1/k (~1/cN)**





Modified Red-Queen Hypothesis

- Assumption: random walk in *N* space + "Red-Queen" hypothesis



$$p(N) \propto \exp(-bN)$$

$$e^{-t/\tau}$$

$$\text{mortality} \propto 1/N \qquad \tau \propto N$$

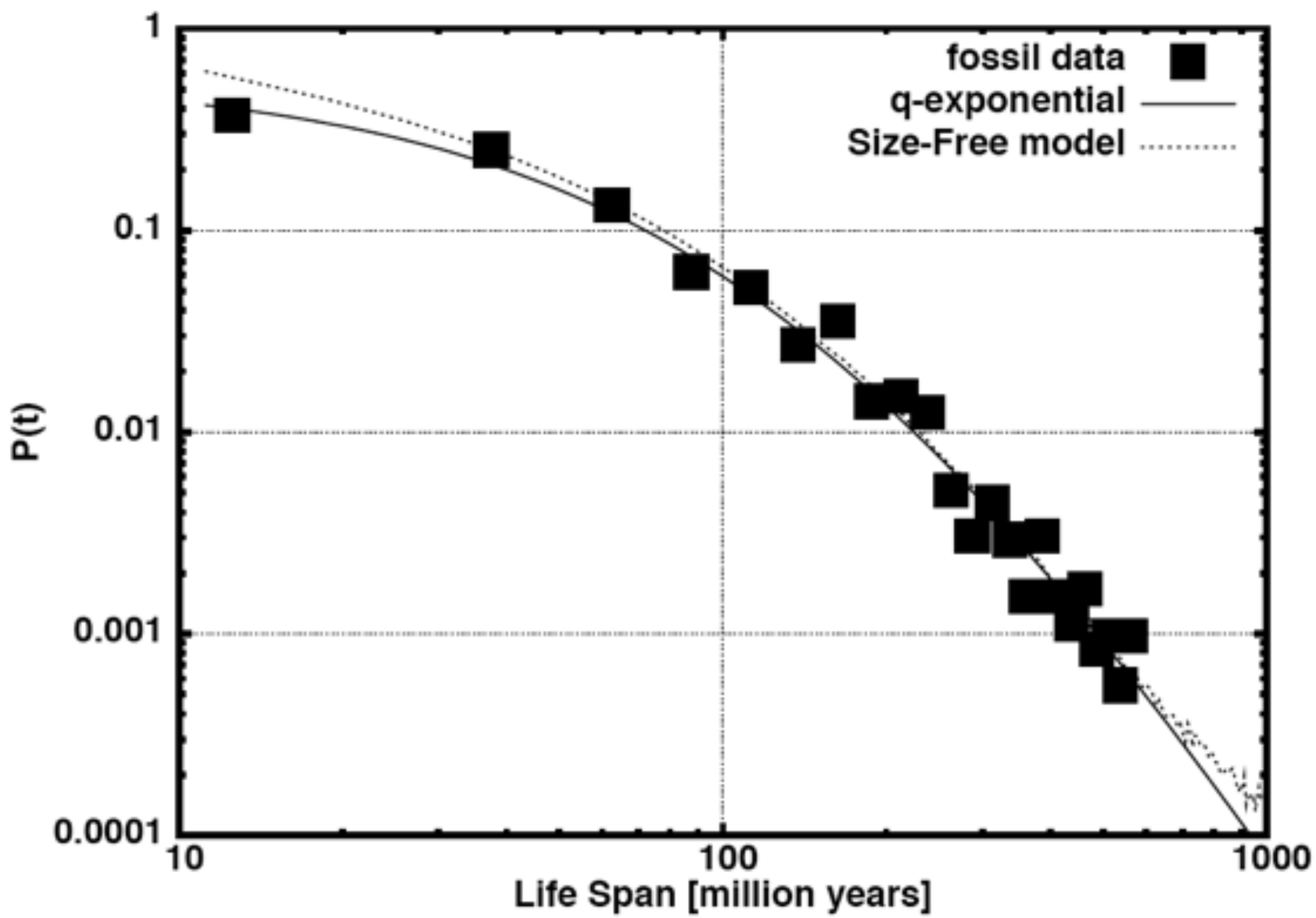
$$\begin{aligned} p(t) &= \int_0^\infty \frac{\exp(-t/\tau)}{\tau} b \exp(-b\tau) d\tau \\ &= 2bK_0(2\sqrt{bt}) \\ &\approx \sqrt{\pi}(bt)^{-1/4} \exp(-2\sqrt{bt}) \qquad (t \gg 1) \end{aligned}$$

Stretched exponential function with exponent 1/2 is obtained by modified Red-Queen hypothesis

Comparison with Empirical Data

Ecosystem : lifetime of families

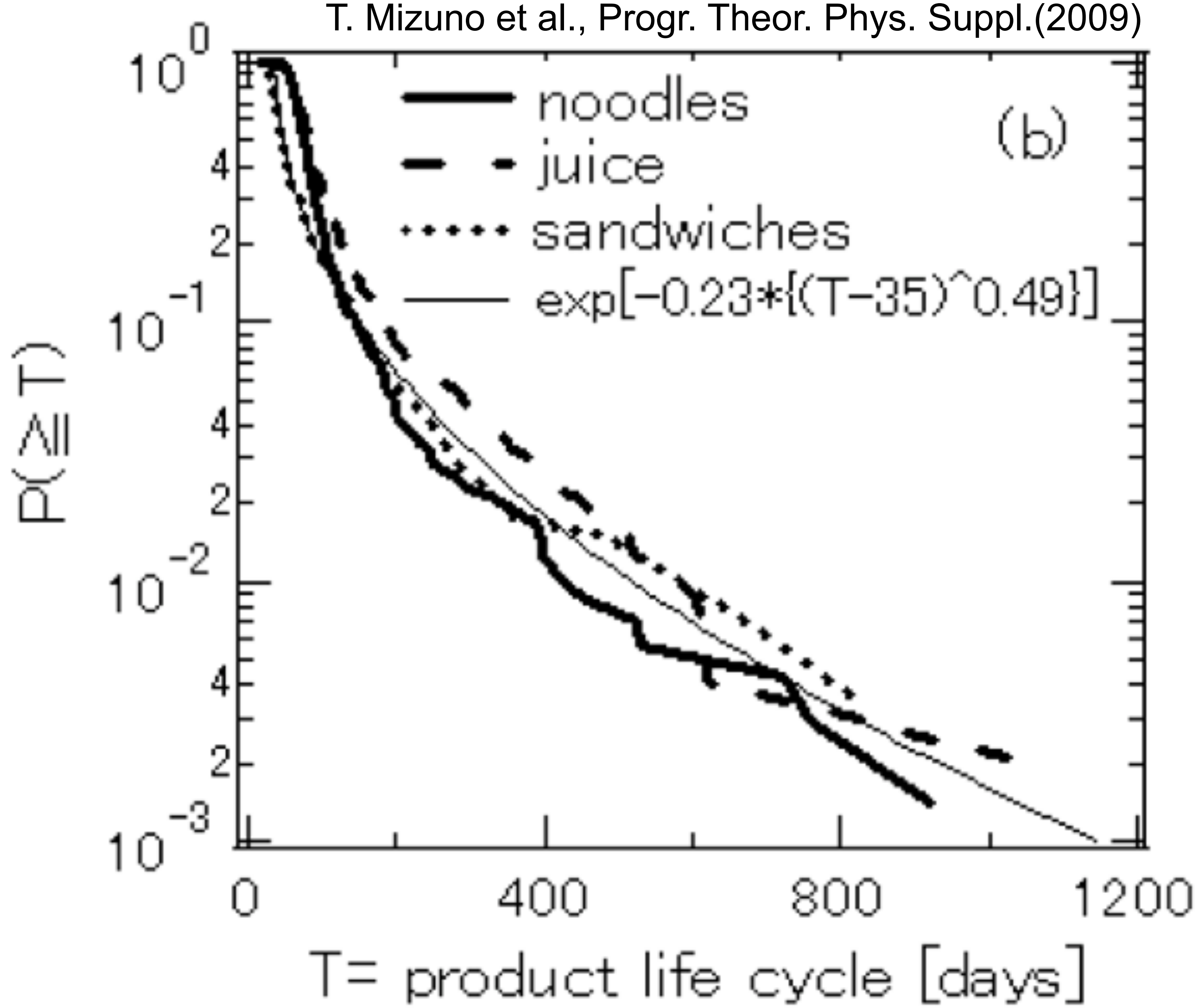
lifetime distribution of families



T. Shimada et al., Int. J. Mod. Phys. C, **9** 1267 (2003)

Product lifecycle of convenience stores

T. Mizuno et al., Progr. Theor. Phys. Suppl.(2009)



lifetime distribution of bankrupted firms

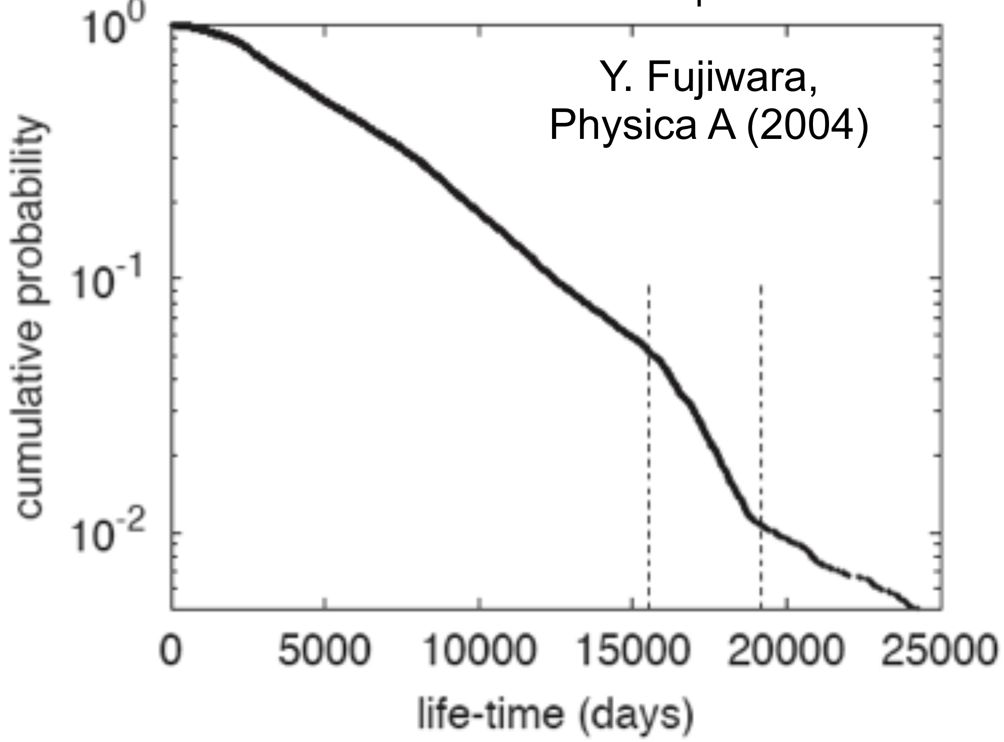
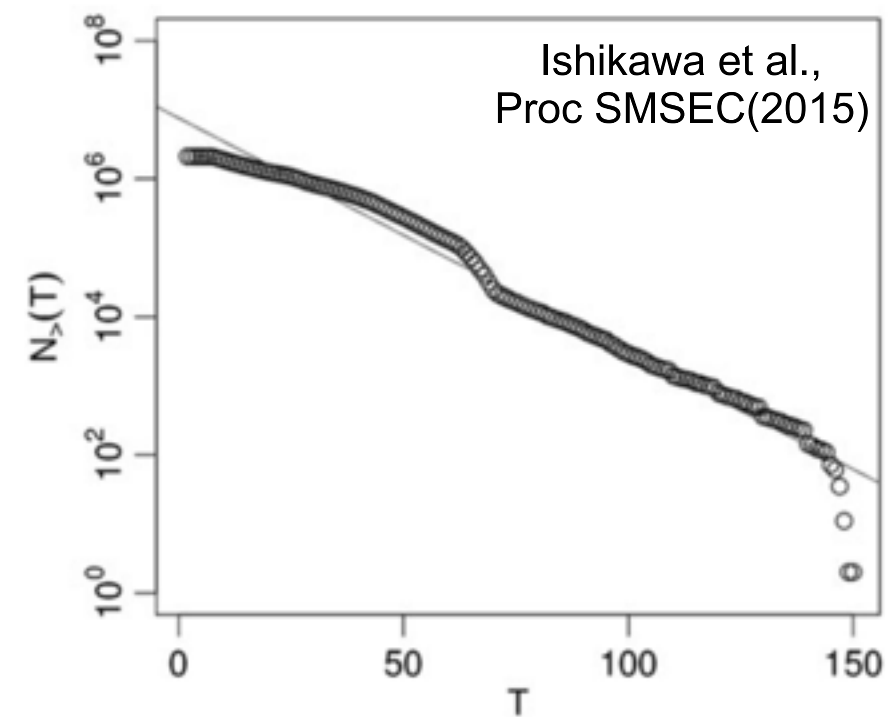
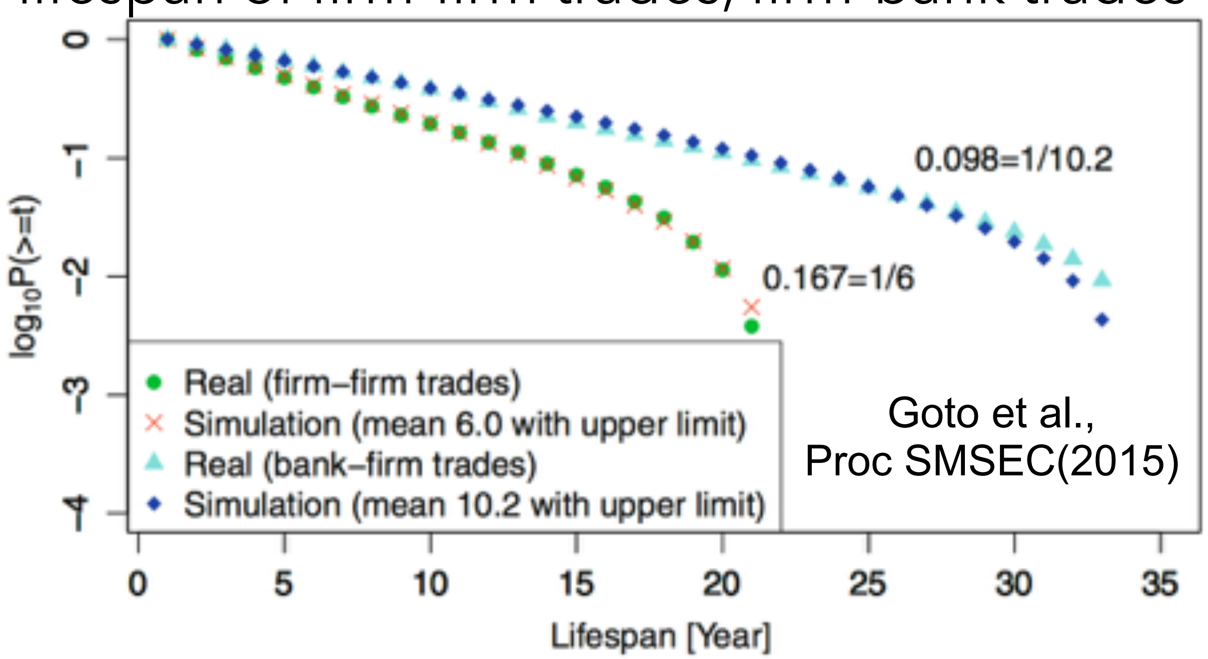
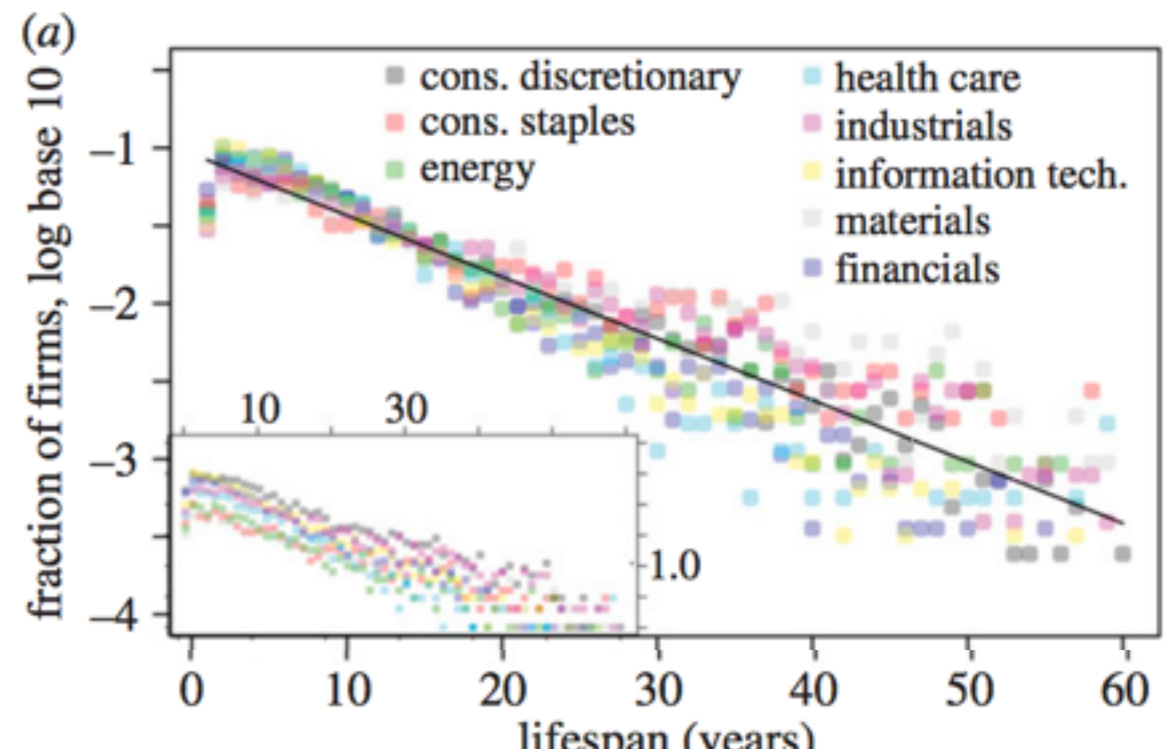


Fig. 17.1 Cumulative age distribution $N_>(T)$ of firms in Japan included in database ORBIS. Horizontal axis is firm age T, and vertical axis is number of firms whose age exceeds T



lifespan of firm-firm trades, firm-bank trades

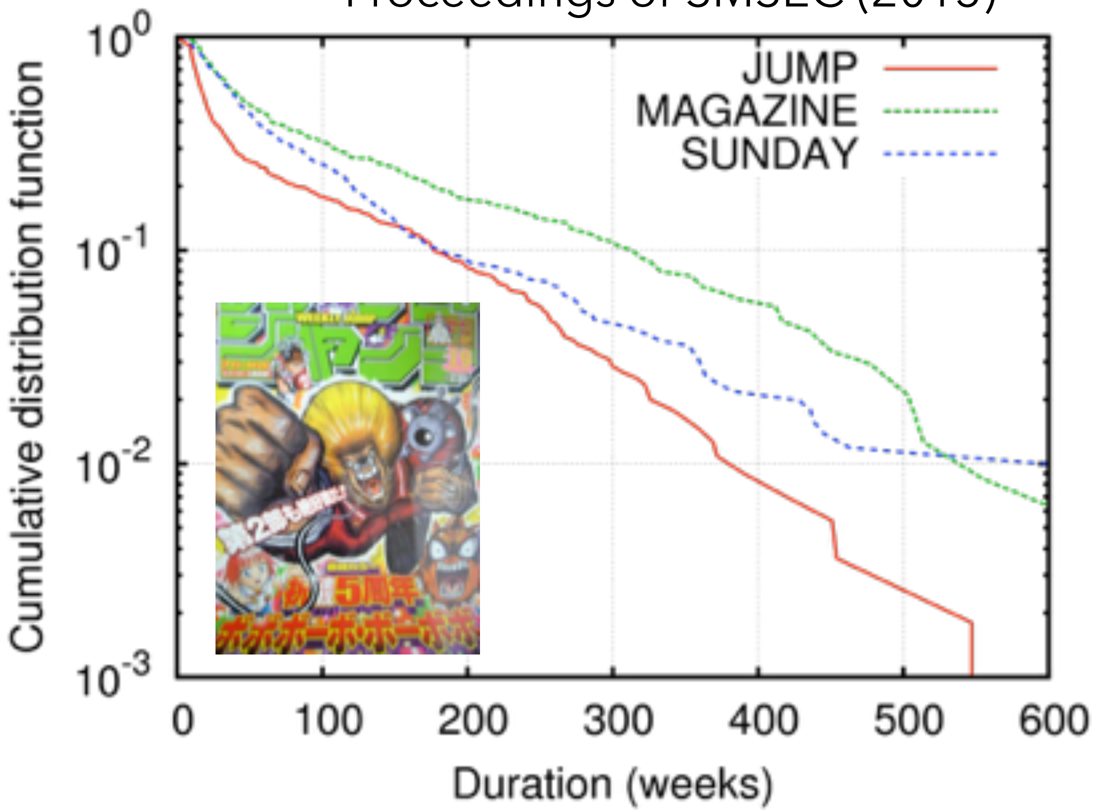




Maldaine et al.,
J. Roy. Soc. Interface(2015)

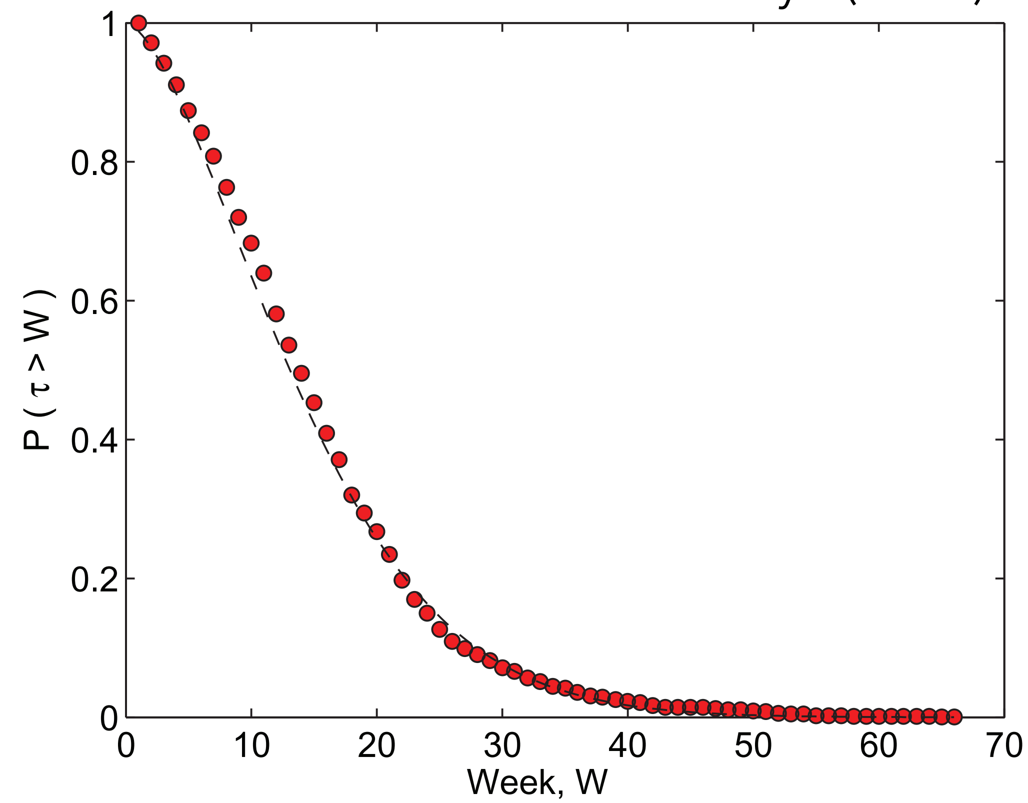
Comics

Y. Murase,
Proceedings of SMSEC (2015)



Movies

R.K. Pan,
New J. Phys. (2010)

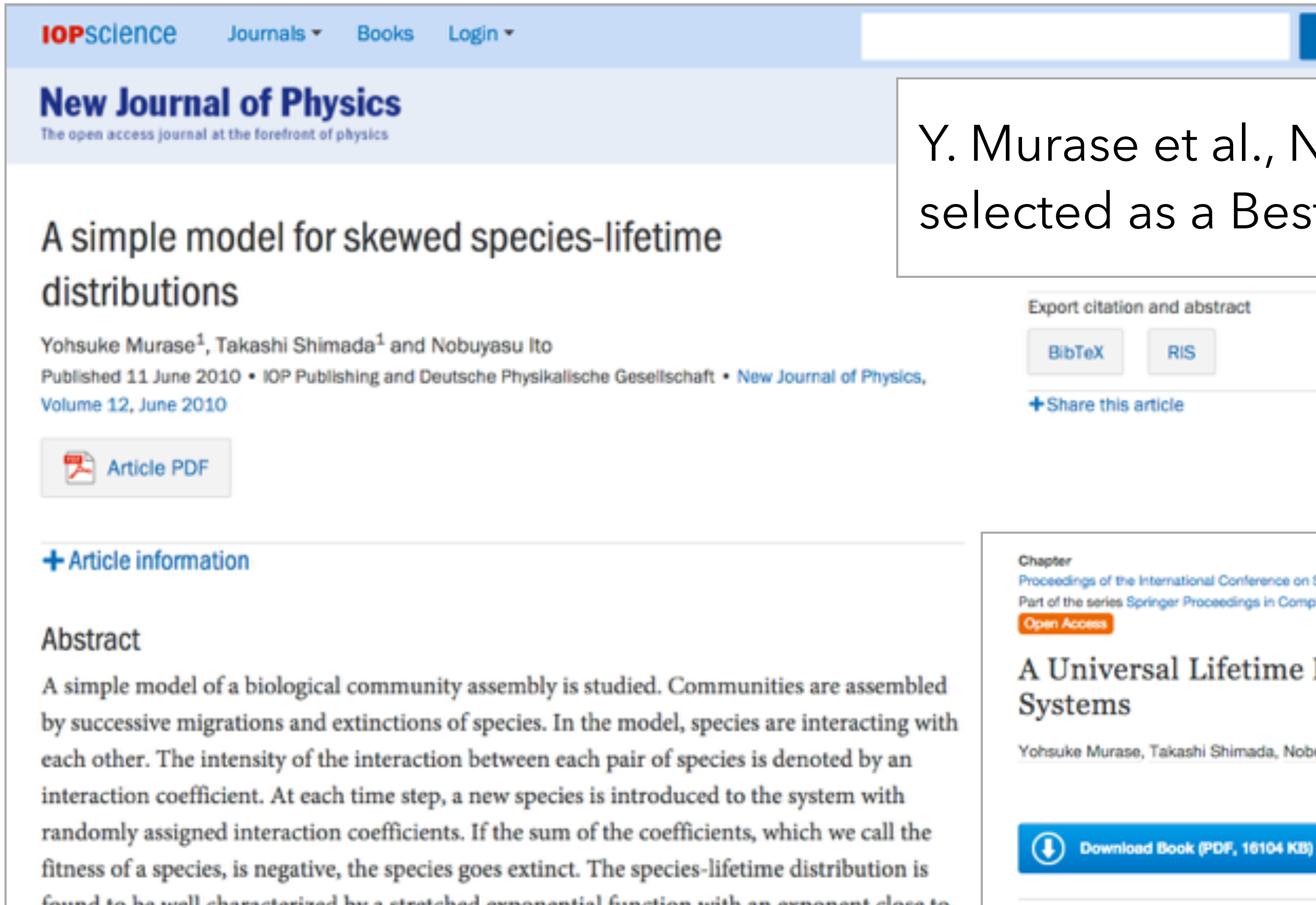


We found a few example showing the “skewed” lifetime distribution although exponential distribution is also common.

Conclusions

- **Stretched exponential function with exponent 1/2** is universally observed for various multi-species models.
- We proposed a new theory, **modified Red-Queen hypothesis**, to interpret the skewed lifetime distribution.
- **Age-independent mortality** is not excluded if a lifetime distribution has a heavier tail than exponential.

References



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A simple model for skewed species-lifetime distributions

Yohsuke Murase[1], Takashi Shimada[1] and Nobuyasu Ito

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Abstract

A simple model of a biological community assembly is studied. Communities are assembled by successive migrations and extinctions of species. In the model, species are interacting with each other. The intensity of the interaction between each pair of species is denoted by an interaction coefficient. At each time step, a new species is introduced to the system with randomly assigned interaction coefficients. If the sum of the coefficients, which we call the fitness of a species, is negative, the species goes extinct. The species-lifetime distribution is found to be well characterized by a stretched exponential function with an exponent close to

Y. Murase et al., New J. Phys., 12, 063021 (2010)
selected as a Best Paper 2010 by IOP

Chapter

Proceedings of the International Conference on Social Modeling and Simulation, plus Econophysics Colloquium 2014

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Abstract

...butions of social entities, such as enterprises, products, and media contents, are one ...ental statistics characterizing the social dynamics. To investigate the lifetime ... mutually interacting systems, simple models having a rule for additions and deletions ... investigated. We found a quite universal lifetime distribution for various kinds of inter-...ons, and it is well fitted by a stretched-exponential function with an exponent close to ...se a "modified Red-Queen" hypothesis to explain this distribution. We also review empirical studies on the lifetime distribution of social entities, and discuss the applicability of the model.

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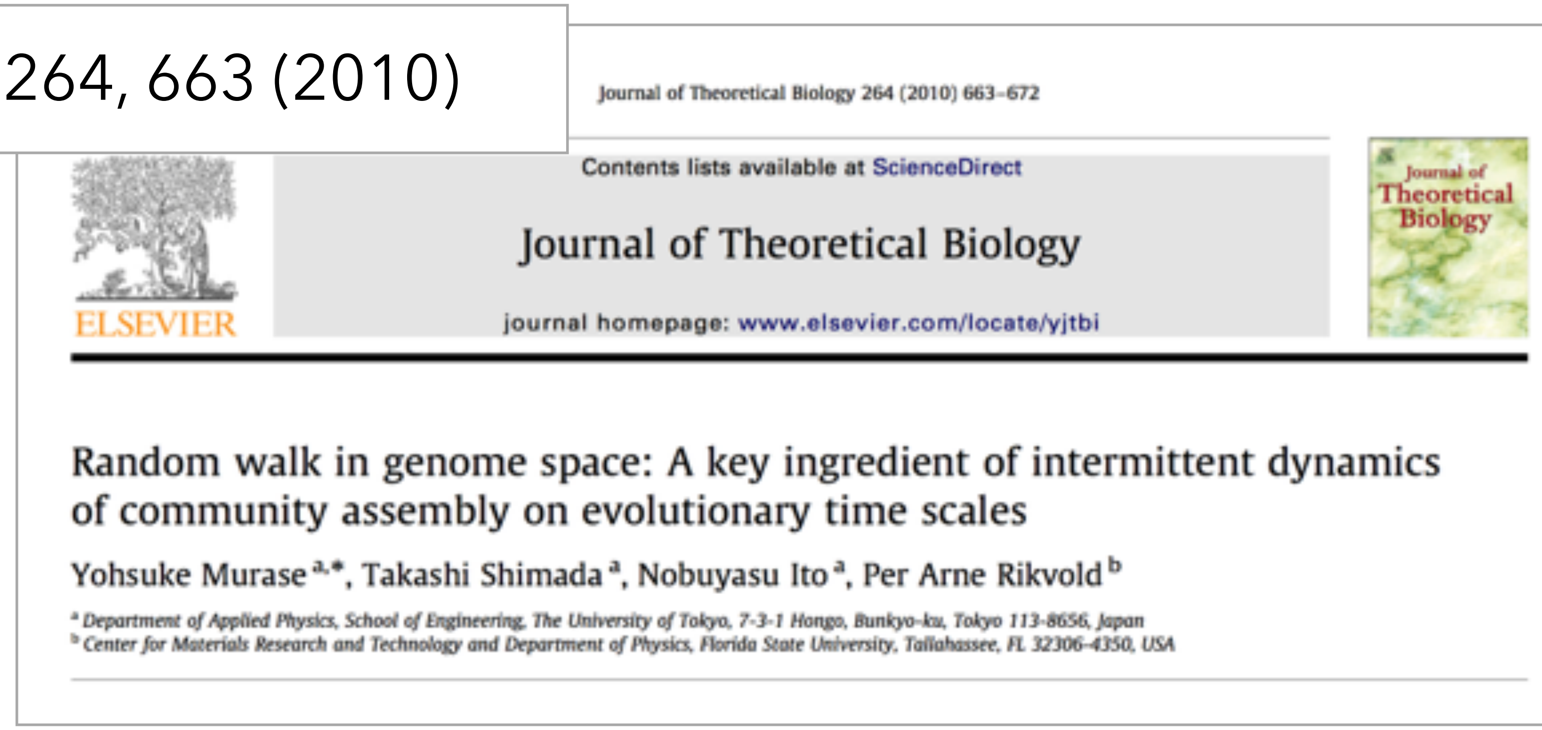

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Random walk in genome space: A key ingredient of intermittent dynamics of community assembly on evolutionary time scales

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https://github.com/yohm/dynamical_graph_model