

Elimination of systemic risk in financial markets

Stefan Thurner



MEDICAL UNIVERSITY
OF VIENNA



SANTA FE INSTITUTE



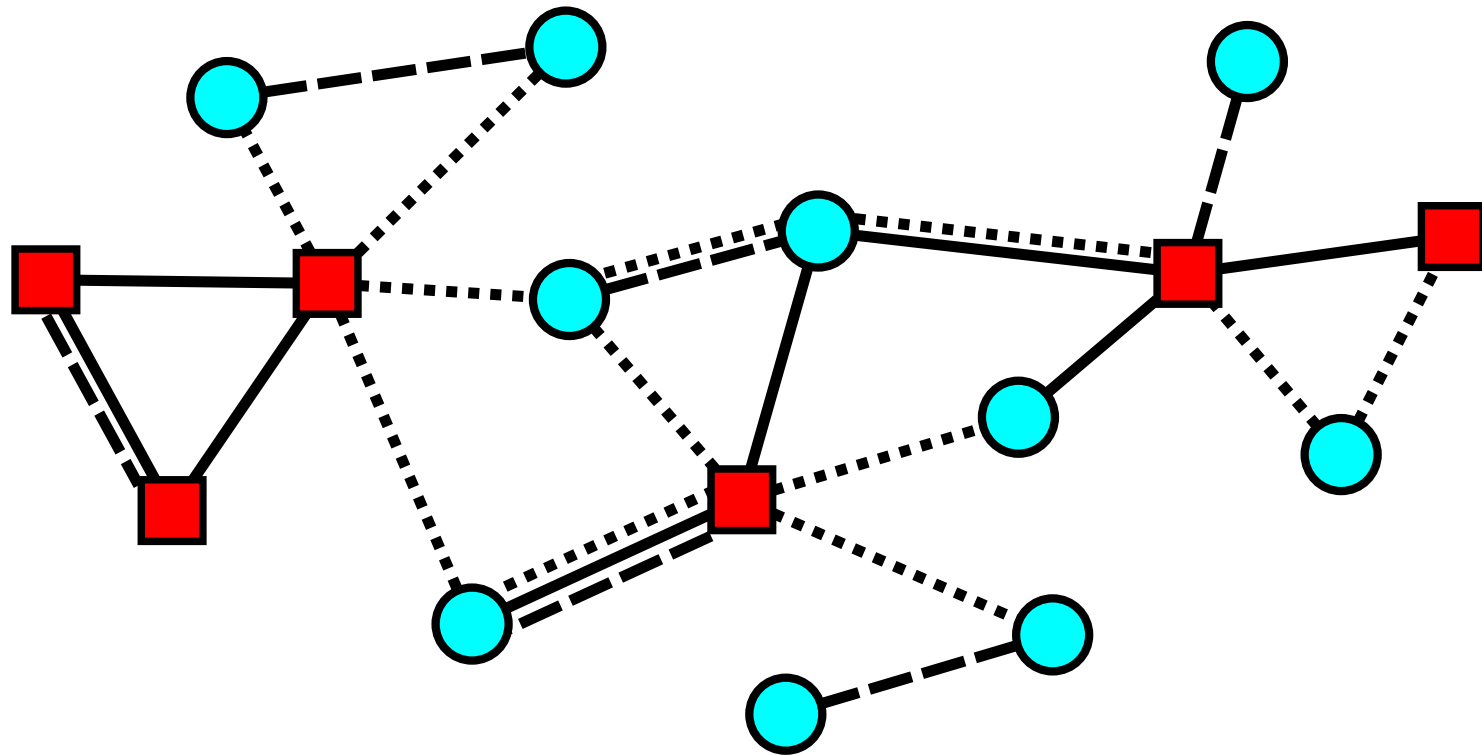
COMPLEXITY
SCIENCE
HUB
VIENNA

www.complex-systems.meduniwien.ac.at

www.santafe.edu

with Anton Pichler
Sebastian Poledna
Peter Klimek
Serafin Martinez-Jamarillo
Jose-Luis Molina Balboa
Marco van der Leij

Control Complex Systems?



- nodes i characterized by states, $\sigma_i(t) = C_i(t)$
- links multiplex network, $M_{ij}^\alpha(t)$

Complex system=co-evolving multiplex network

$$\frac{d}{dt}\sigma_i^\alpha(t) \sim F \left(M_{ij}^\alpha(t), \sigma_j^\beta(t) \right)$$

and

$$\frac{d}{dt}M_{ij}^\alpha(t) \sim G \left(M_{ij}^\alpha(t), \sigma_j^\beta(t) \right)$$

- states are observable (big data) – **reality**
- networks are observable (big data) – **invisible reality**

Complex systems are unstable

most complex systems are stochastic

statistics of complex systems is the **statistics of power laws**

- many large outliers – outliers are normal
- non-managability

details matter

Breaking complexity

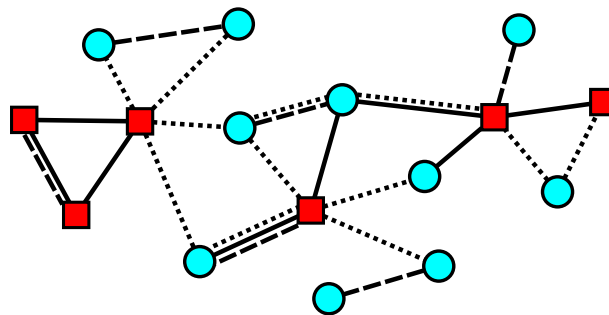
- if understand co-evolution \rightarrow we may break complexity

by controlling every component – tame complexity (cut off power law tails)

- if we forget a detail \rightarrow might lose control

The three types of financial risk

- **economic risk:** investment in business idea does not pay off
- **credit-default risk:** you don't get back what you have lent
- **systemic risk:** system stops functioning due to local defaults and subsequent (global) cascading



Credit-default risk

if I lend something – there is risk that I will not get it back

estimate for credit-worthiness: assets–liabilities

- **management:** capital requirements for lending

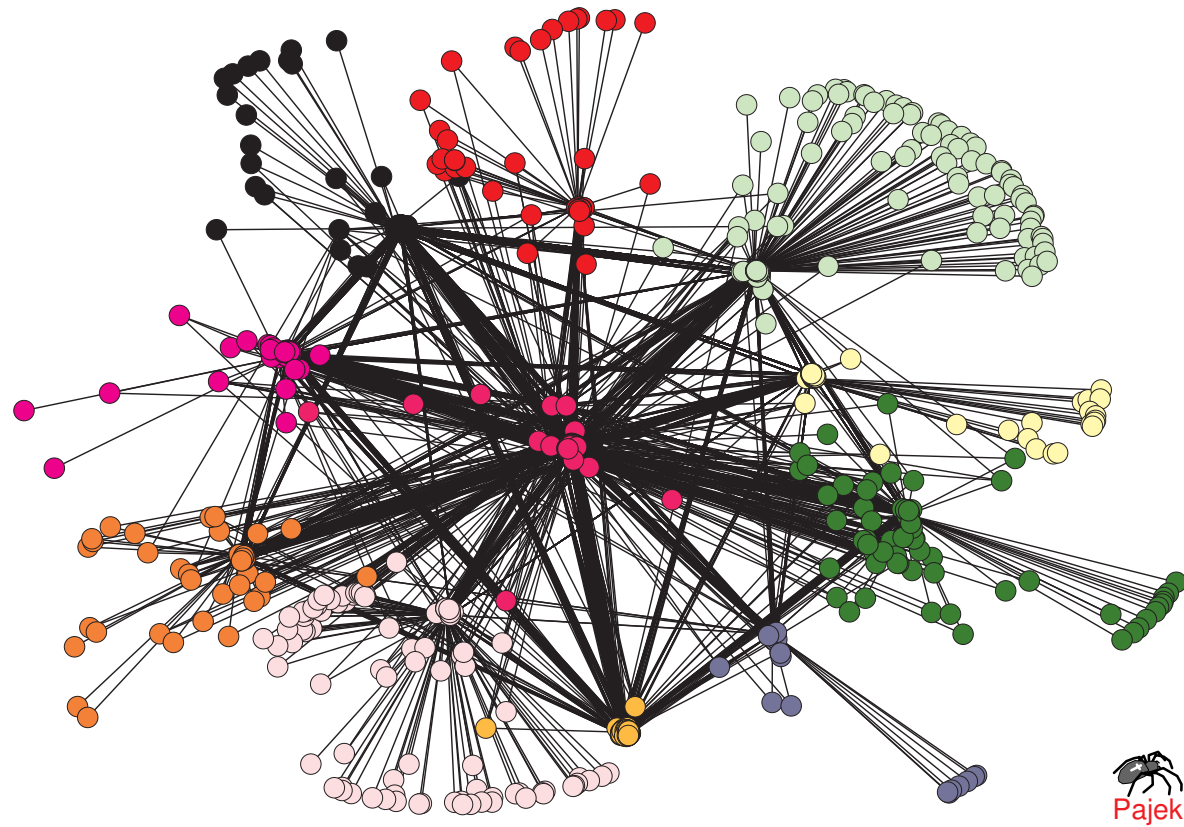
→ Basel-type regulation

Systemic risk

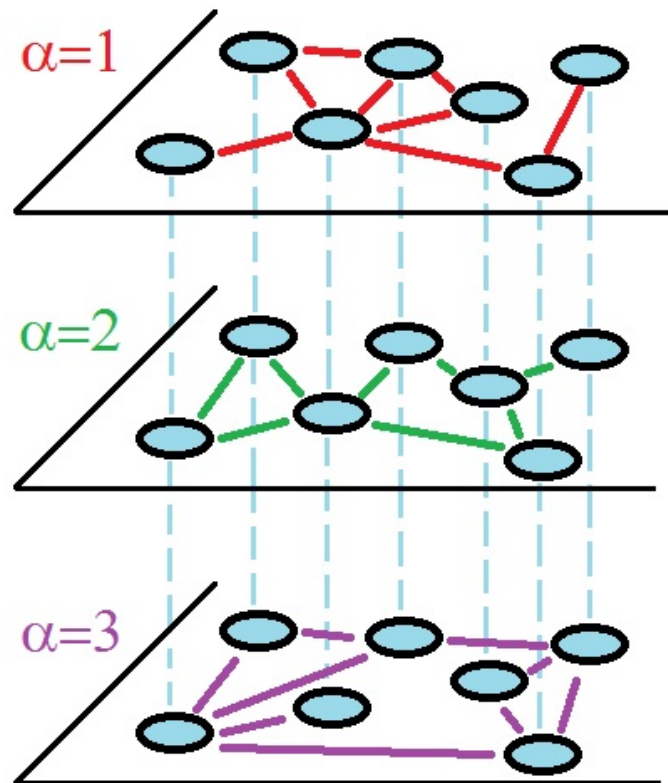
- risk that significant fraction of financial network defaults
 - systemic risk **is not the same** as credit-default risk
 - banks care about credit-default risk
 - banks have no means to manage systemic risk
- role of regulator: **manage systemic risk**
- incentivise banks to think of SR

The 2 origins of systemic risk

- **synchronisation of behaviour:** herding, fire sales, margin calls, various amplification effects – may involve networks
- **networks of contracts:** this is what the financial system is



Systemic risk is created on multiplex networks



layer 1: lending–borrowing loans

layer 2: derivative networks

layer 3: collateral networks

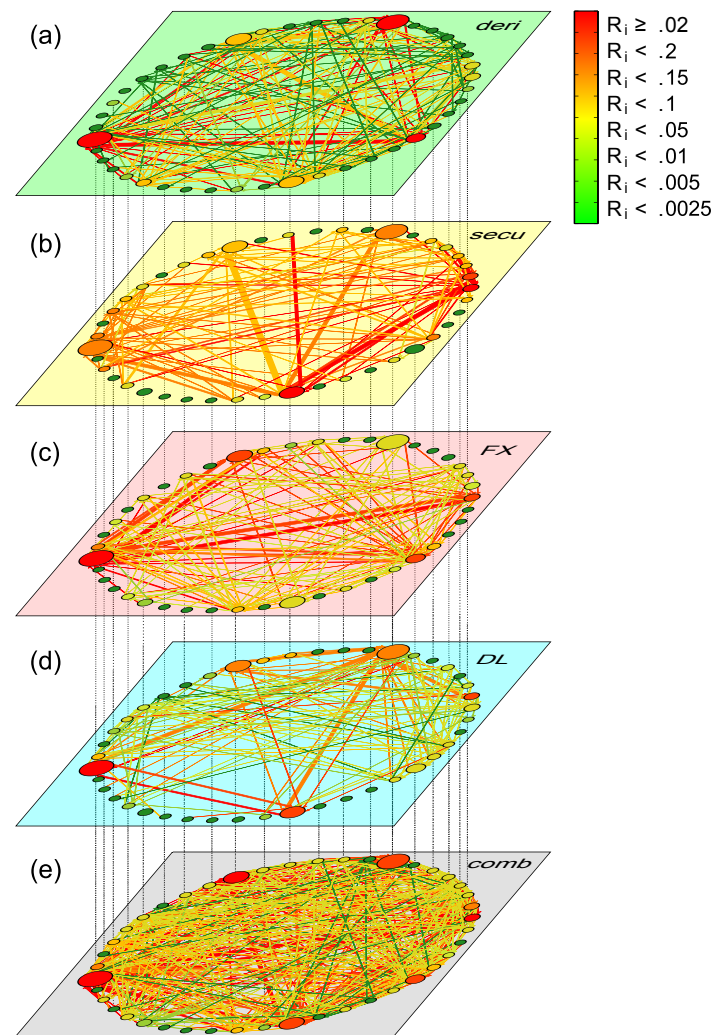
layer 4: securities networks

layer 5: cross-holdings

layer 6: overlapping pfolios

layer 7: liquidity: over-night loans

layer 8: FX transactions



Quantification of SR

Systemic risk – quantification

Wanted: systemic risk-value for every financial institution

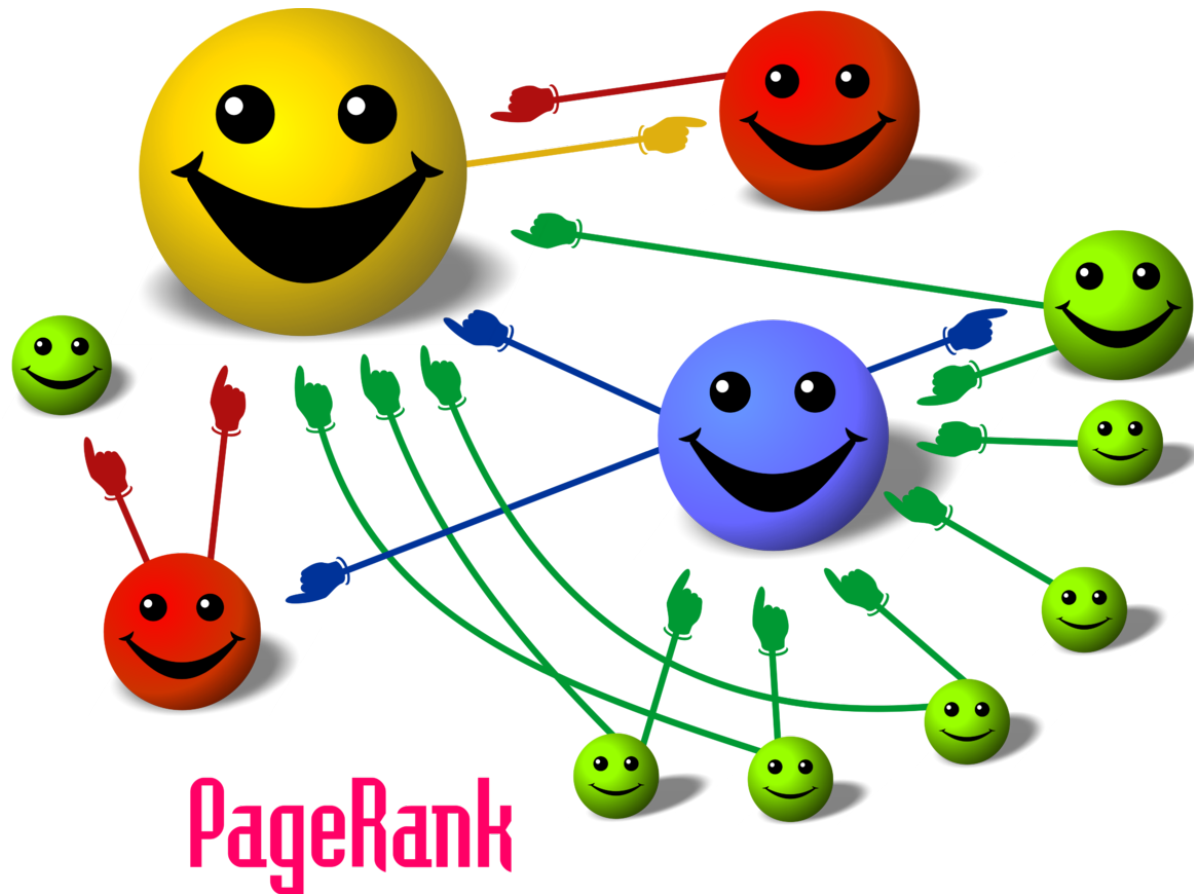
given: entire network

Google has similar problem: value for importance of web-pages

→ page is important if many important pages point to it

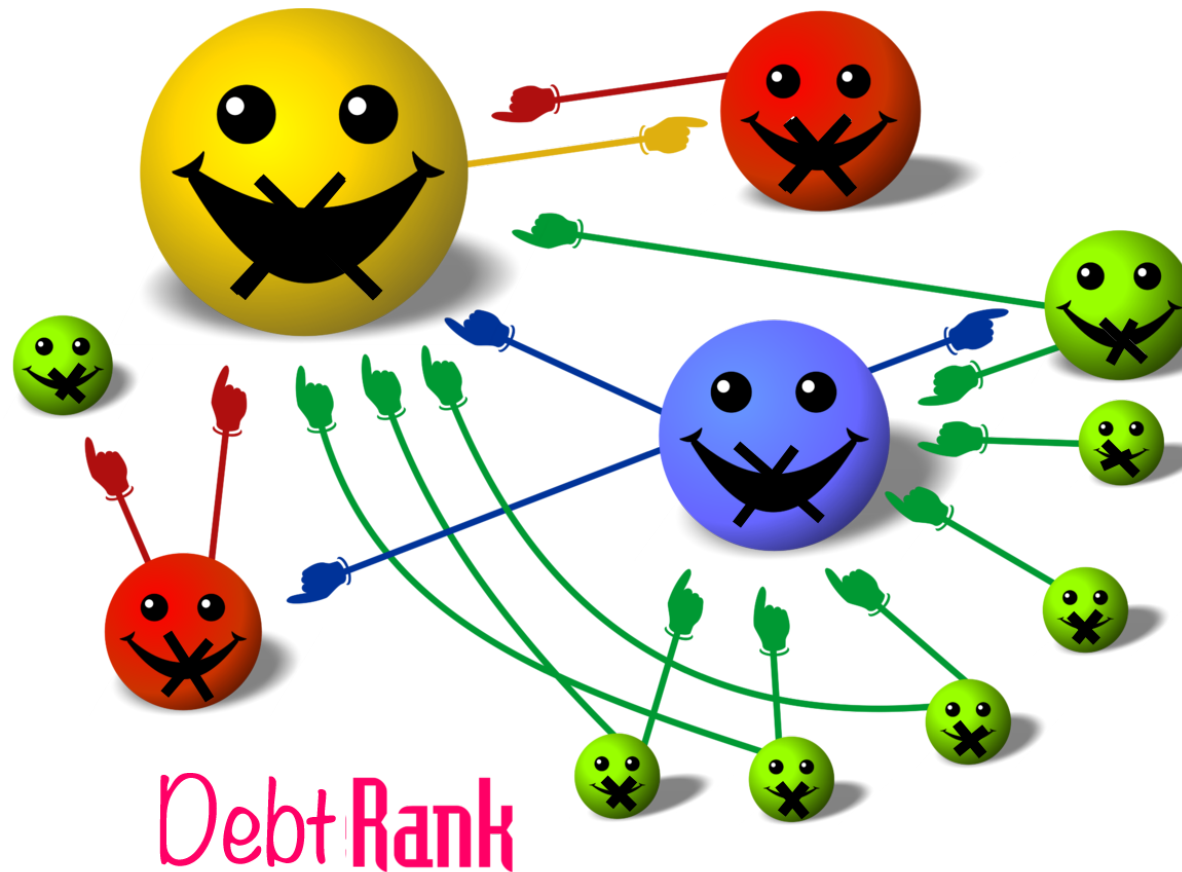
→ number for importance → **PageRank**

page is **important** if many **important** pages point to it



source Wikipedia cc-license

institution **system. risky** if **system. risky** institutions lend to it



Systemic risk factor – DebtRank R

... is a “different Google” – adapted to context of systemic risk
(S. Battiston et al. 2012)

superior to: eigenvector centrality, page-rank, Katz rank ...

Why?

- **economic value** in network that is affected by node's default
- capitalization/leverage of banks taken into account
- cycles taken into account: no multiple defaults

DebtRank

- recursive method
- corrects Katz rank for loops in the exposure network
- if i defaults and can not repay loans, j loses L_{ij} . If j has not enough capital to cover that loss $\rightarrow j$ defaults
- asset-liability network: L_{ij}
- exposure network: $W_{ij} = \min \left[1, \frac{L_{ij}}{C_j} \right]$
- outstanding loans: $L_i = \sum_j L_{ji}$, and $v_i = L_i / \sum_j L_j$
- impact of bank i on neighbors: $I_i = \sum_j W_{ij} v_j$

- impact on nodes at distance two and higher \rightarrow recursive

$$I_i = \sum_j W_{ij} v_j + \beta \sum_j W_{ij} I_j$$

If the network W_{ij} contains cycles the impact can exceed one
 \rightarrow DebtRank (S. Battiston et al. (2012))

DebtRank II

- simulate distress: take set of nodes that fail: S_f
- after fail: simulate over time t
- nodes have two state variables, $h_i(t) \in [0, 1]$ and $s_i(t) \in \{Undistress, Distress, Inactive\}$
- Dynamics: $h_i(t) = \min \left[1, h_i(t-1) + \sum_{j|s_j(t-1)=D} W_{ji} h_j(t-1) \right]$

$$s_i(t) = \begin{cases} D & \text{if } h_i(t) > 0; s_i(t-1) \neq I \\ I & \text{if } s_i(t-1) = D \\ s_i(t-1) & \text{otherwise} \end{cases}$$

- DebtRank of set S_f (set of nodes in distress), is

$$R_S = \sum_j h_j(t)v_j - \sum_j h_j(1)v_j$$

Measures distress in the system, excluding initial distress. If S_f is a single node, DebtRank measures its systemic impact on the network.

- DebtRank of S_f containing only the single node i is

$$R_i = \sum_j h_j(t)v_j - h_i(1)v_i$$

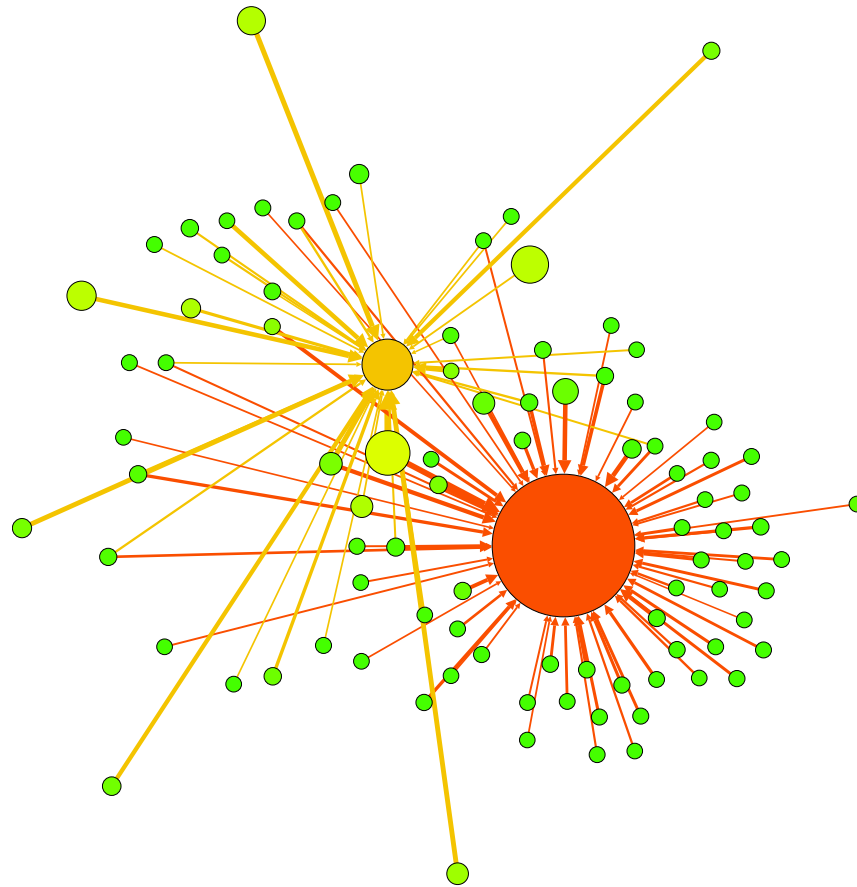
Systemic risk of nodes

Input: Network of contracts between banks

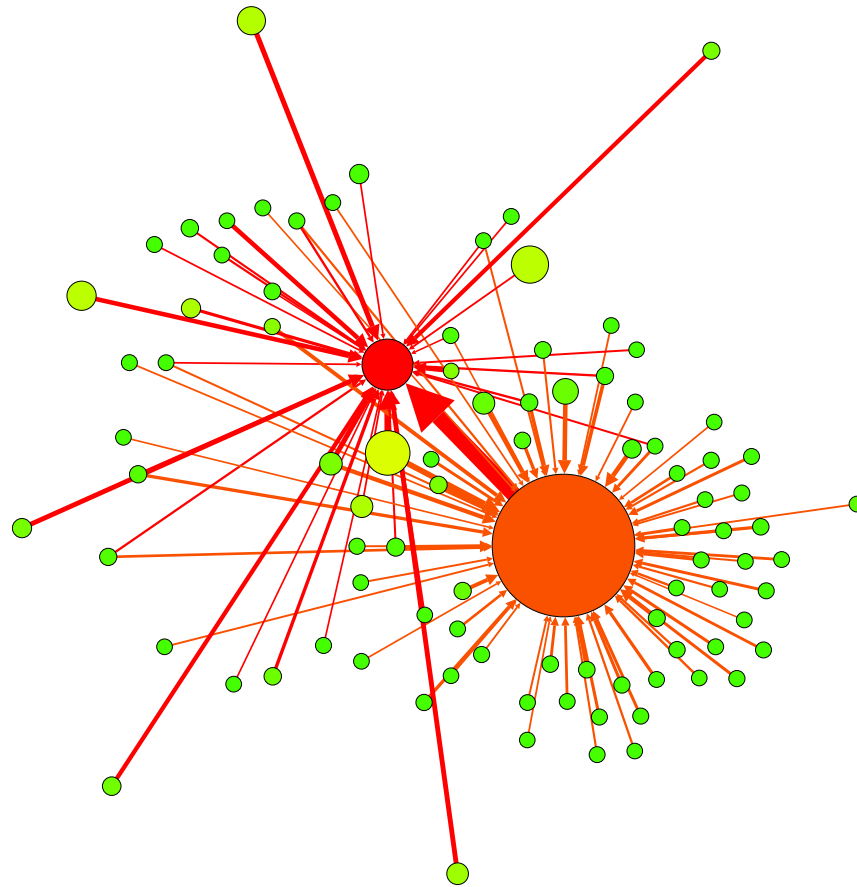
Compute = DebtRank; think of a complicated first eigenvector

Output: all banks i get damage value R_i (% of total damage)

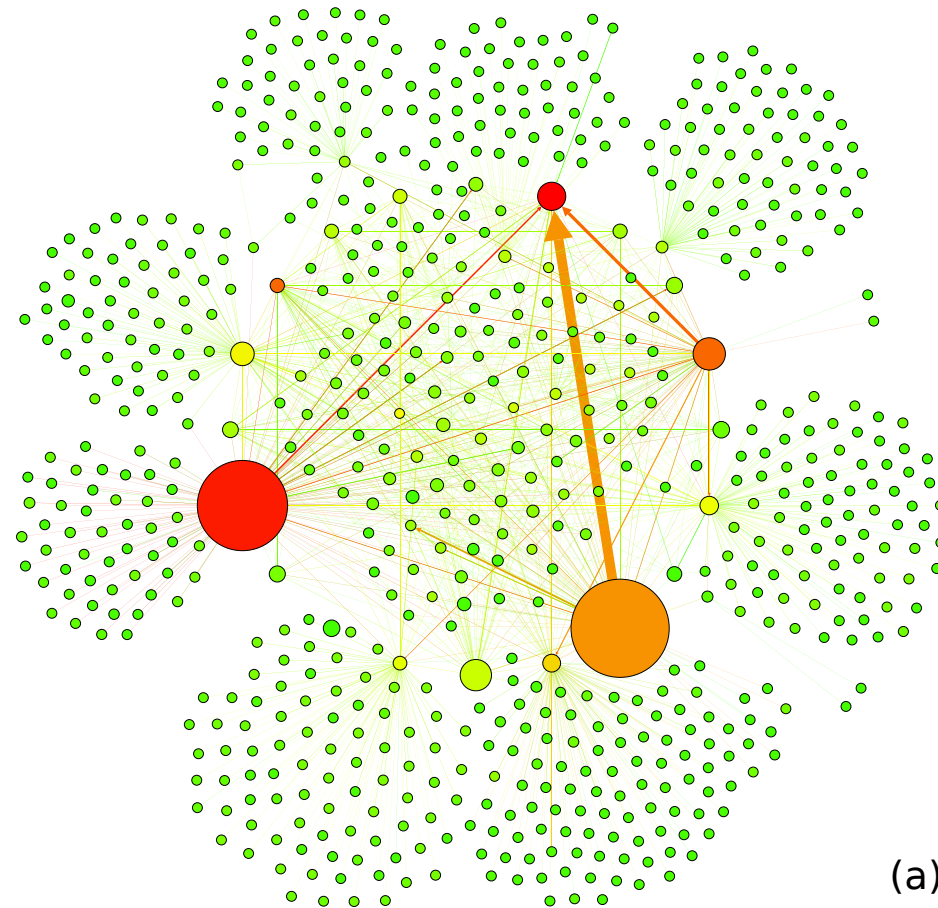
Systemic risk spreads by borrowing



Systemic risk spreads by borrowing



DebtRank Austria Sept 2009

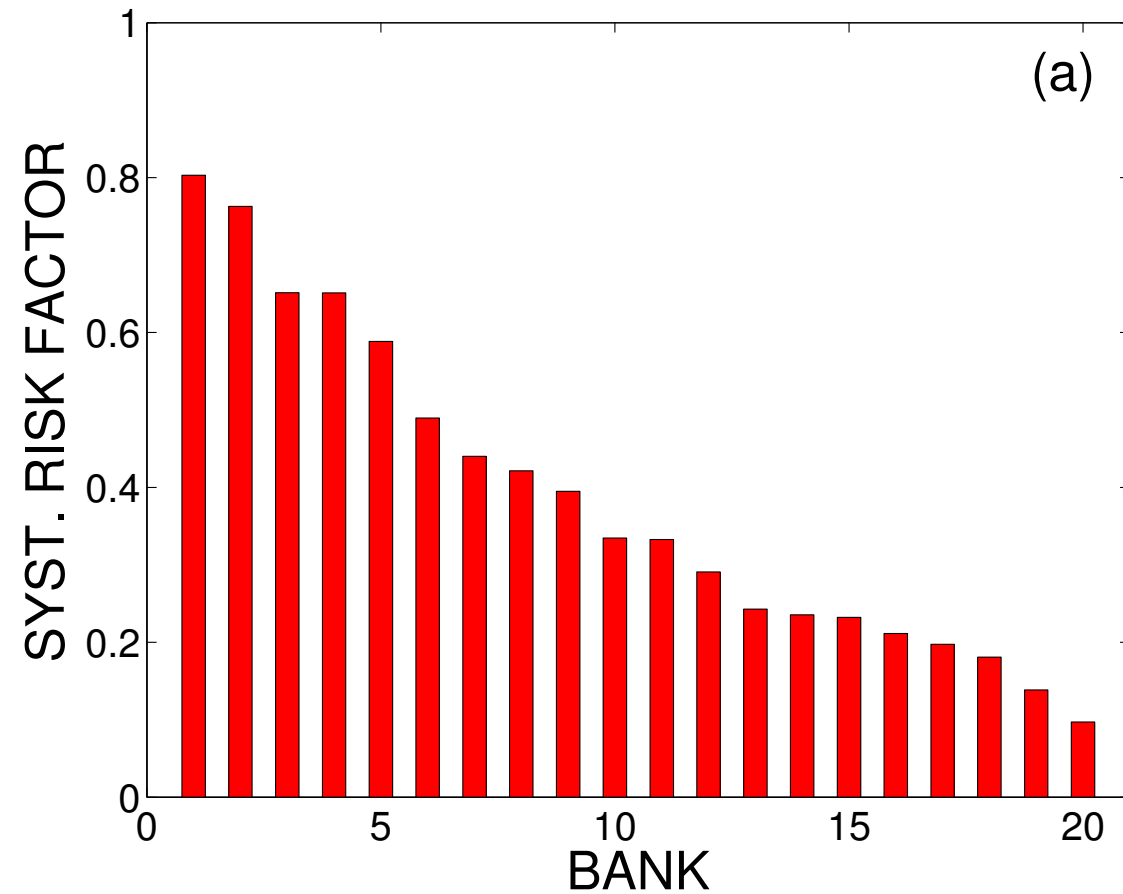


note: size is **not proportional** to systemic risk

note: **core-periphery** structure

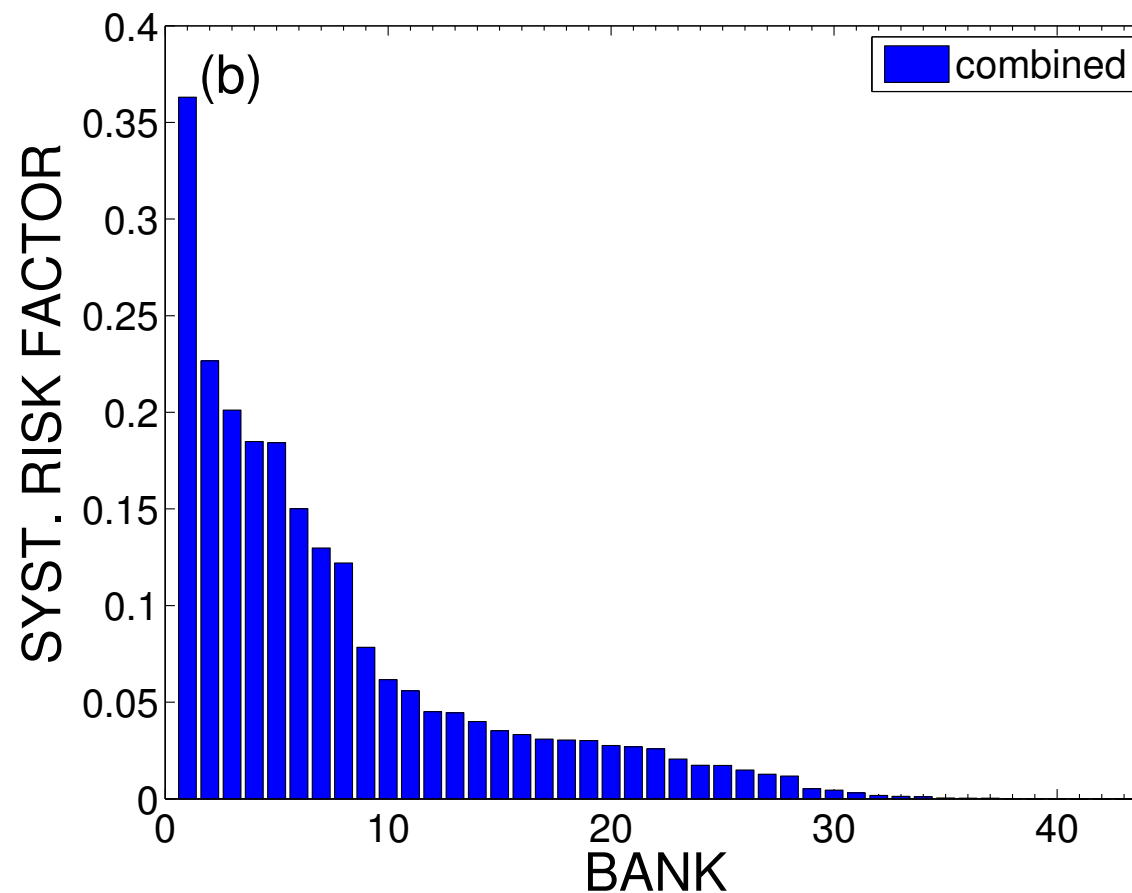
Systemic risk profile

Austria



Systemic risk profile

Mexico*



*with Serafin Martinez-Jaramillo and his team at Banco de Mexico, 2014

How big is the next financial crisis?

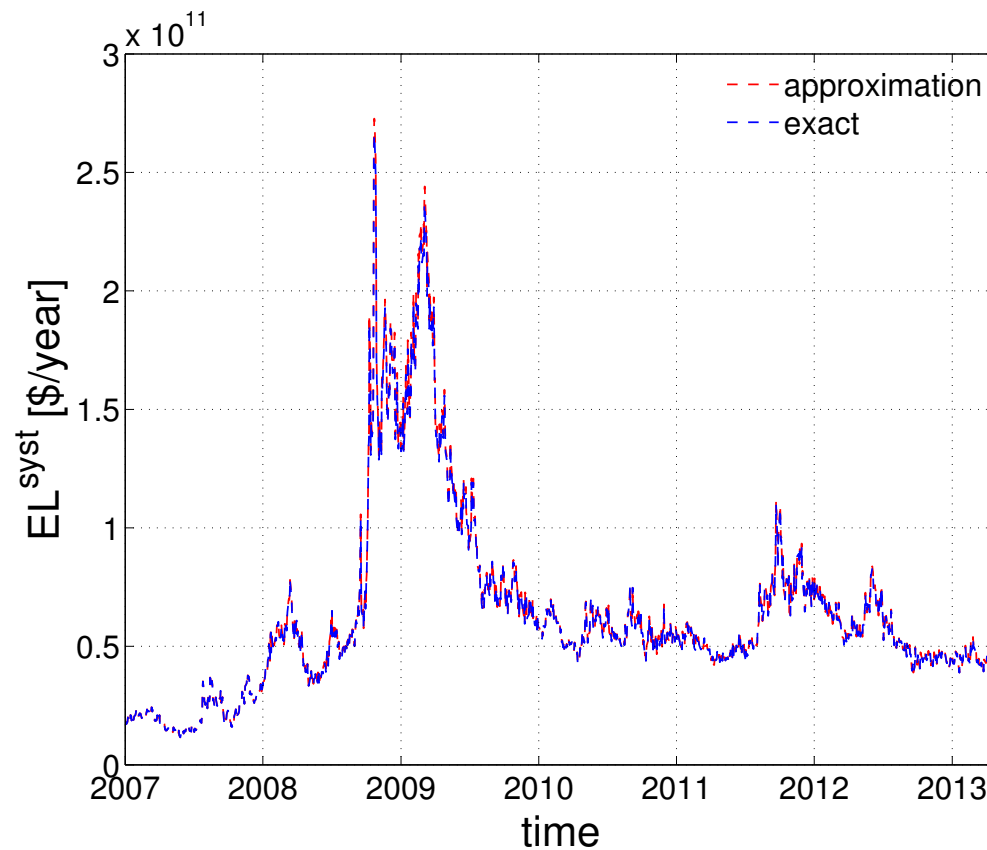
Expected systemic loss [Euro / Year]

$$\text{Expected systemic loss} = \sum_i p_{\text{default}}(i) \cdot \text{DebtRank}(i)$$

$$\text{Expected loss}(i) = \sum_j p_{\text{default}}(j) \cdot \text{Loss-given-default}(j) \cdot \text{Exposure}(i,j)$$

$$\begin{aligned}
\text{EL}^{\text{syst}} &= V \sum_{S \in \mathcal{P}(B)} \prod_{i \in S} p_i \prod_{j \in B \setminus S} (1 - p_j) (R_S) \\
&\approx V \sum_{S \in \mathcal{P}(B)} \prod_{i \in S} p_i \prod_{j \in B \setminus S} (1 - p_j) \left(\sum_{i \in S} R_i \right) \\
&= V \sum_{i=1}^b \underbrace{\left(\sum_{J \in \mathcal{P}(B \setminus \{i\})} \prod_{j \in J} p_j \prod_{k \in B \setminus (J \cup \{i\})} (1 - p_k) \right)}_{=1} p_i R_i \\
&= V \sum_{i=1}^b p_i R_i
\end{aligned}$$

Expected systemic loss index: error

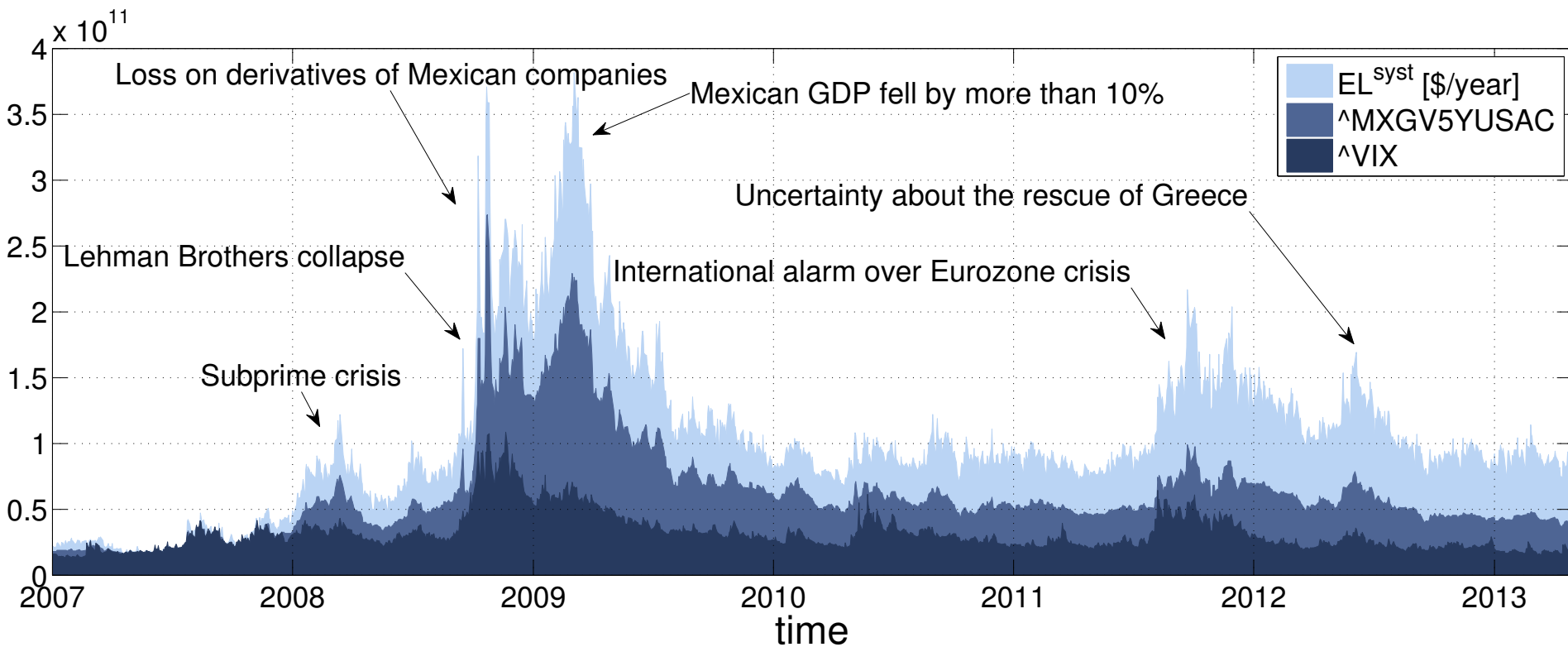


Compare to expected loss for individual banks

$$\text{Expected loss}(i) = \sum_j p_{\text{default}}(j) \cdot \text{Loss-given-default}(j) \cdot \text{Exposure}(i,j)$$

note: this is used in standard stress testing

Expected systemic loss index for Mexico*



*with Serafin Martinez-Jaramillo and team at Banco de Mexico, 2014

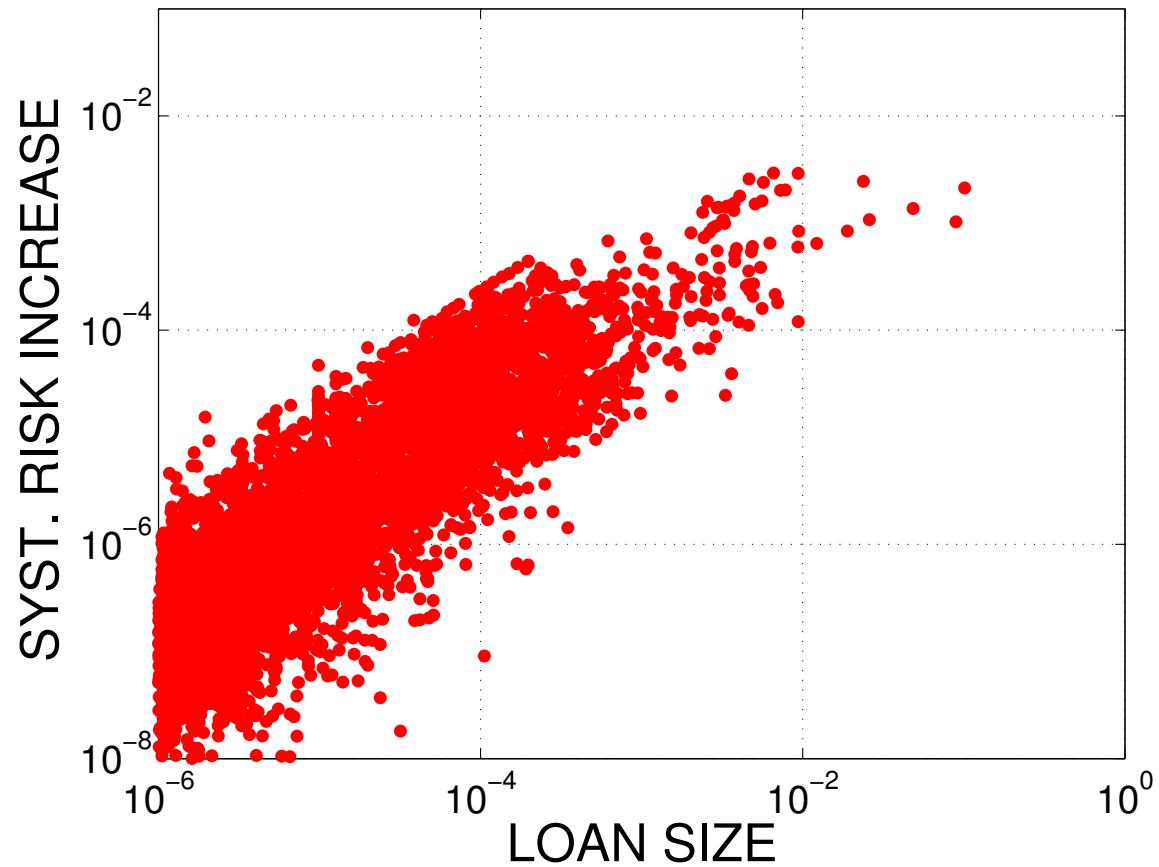
Expected systemic loss index

- expected losses per year within country in case of severe default and NO bailout
 - rational decision on bailouts
- allows to compare countries
- allows to compare situation of country over time
 - are policy measures taking action in Spain? in Greece?

Observation

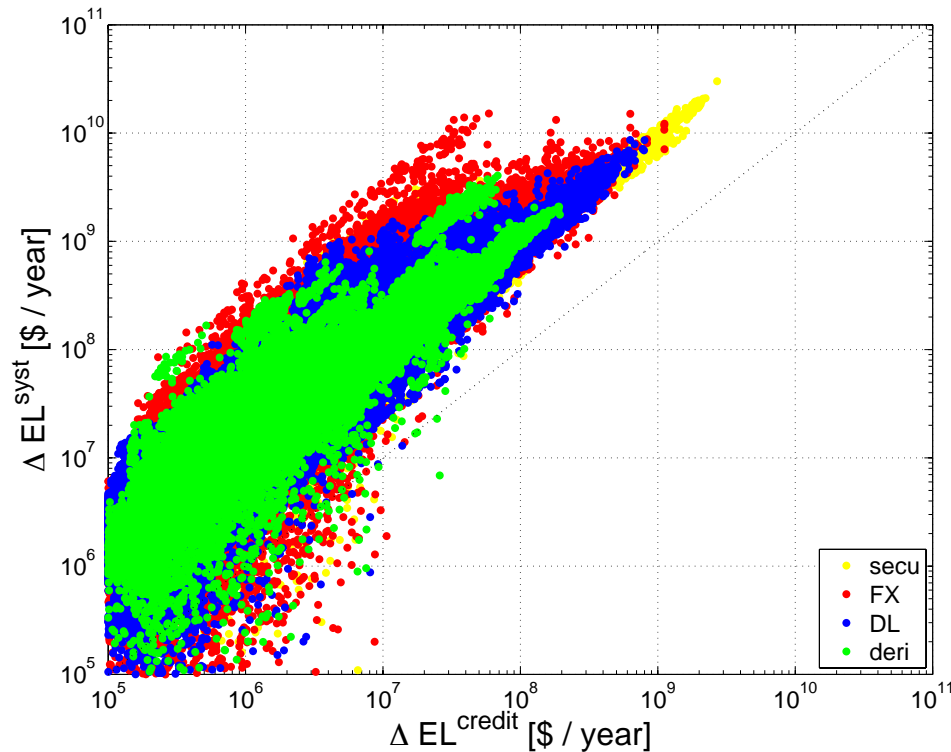
Systemic risk of a node changes with **every** transaction

Austria all interbank loans



note orders of magnitude !

Systemic risk in Mexican data



$\Delta EL^{syst} > \Delta EL^{credit} \rightarrow$ defaults **do not only affect lenders**
but involves third parties

systemic risk is an externality

Management of systemic risk

- systemic risk is a network property
- manage systemic risk: **re-structure financial networks** such that cascading failure becomes unlikely / impossible

systemic risk management
=
re-structure networks

Systemic risk elimination

- systemic risk spreads by borrowing from risky agents
- how risky is a transaction? → increase of expected syst. loss
- ergo: restrict transactions with high systemic risk

→ **tax those transactions** that increase systemic risk

Systemic risk tax

- tax transactions according to their systemic risk contribution
 - agents look for deals with agents with low systemic risk
 - liability networks **re-arrange** → eliminate cascading

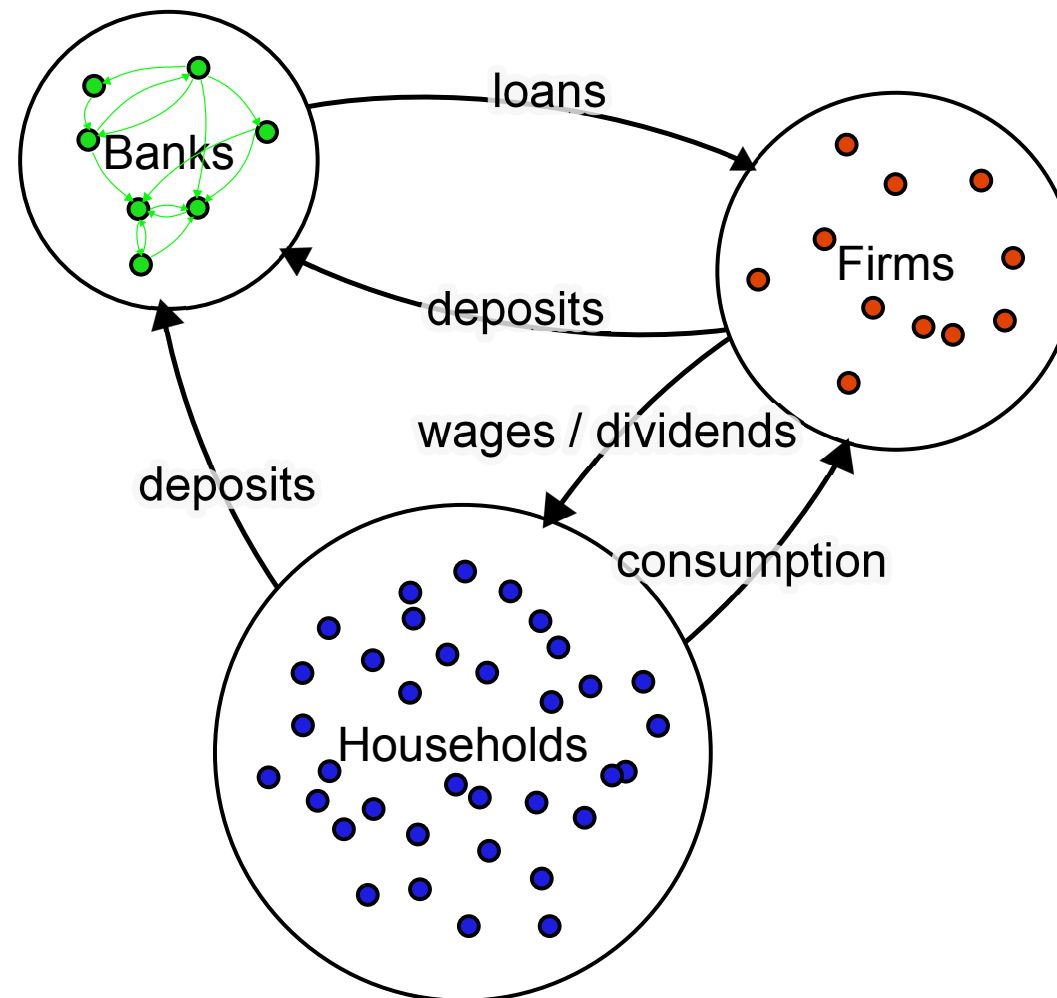
no-one should pay the tax – tax serves as incentive to re-structure networks

- size of tax \propto expected systemic loss of transaction (society is neutral)
- if system is risk free: no tax
- **credit volume MUST not be reduced by tax**

Self-stabilisation of systemic risk tax

- those who can not lend become systemically safer
 - those who are safe can lend and become unsafer
 - → new equilibrium where systemic risk is distributed evenly across the network (cascading minimal)
- self-organized critical

To test efficacy of tax: Crisis Macro-Financial Simulator (schematic)



The agents

- **firms:** ask bank for loans: random size, maturity τ , $r^{\text{f}-\text{loan}}$
 - firms sell products to households: realise profit/loss
 - if surplus → deposit it bank accounts, for $r^{\text{f}-\text{deposit}}$
 - firms are bankrupt if insolvent, or capital is below threshold
 - if firm is bankrupt, bank writes off outstanding loans
- **banks** try to provide firm-loans. If they do not have enough
 - approach other banks for interbank loan at interest rate r^{ib}
 - bankrupt if insolvent or equity capital below zero
 - bankruptcy may trigger other bank defaults
- **households** single aggregated agent: receives cash from firms (through firm-loans) and re-distributes it randomly in banks (household deposits, r^{h}), and among other firms (consumption)

For comparison: implement Tobin-like tax

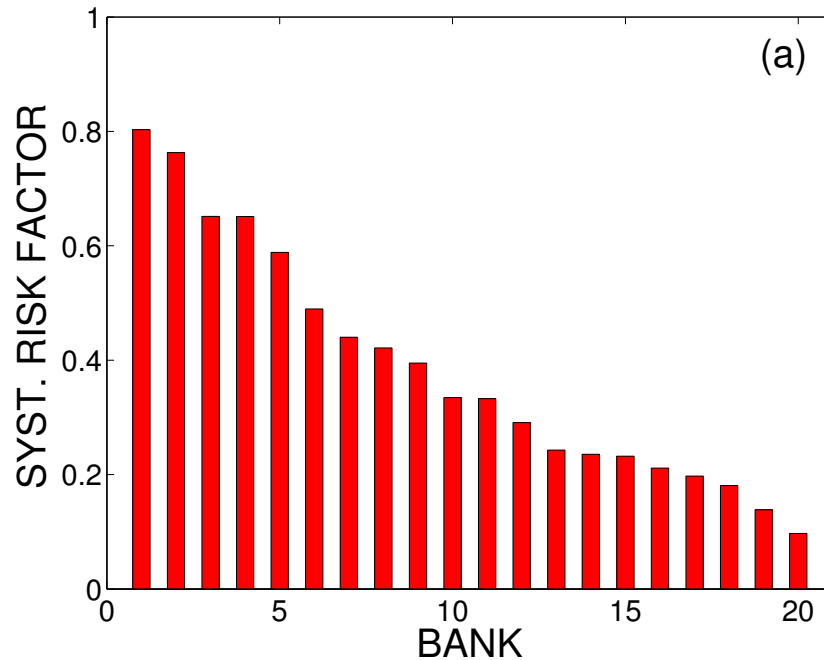
- tax all transactions regardless of their risk contribution
- 0.2% of transaction ($\sim 5\%$ of interest rate)

Comparison of three schemes

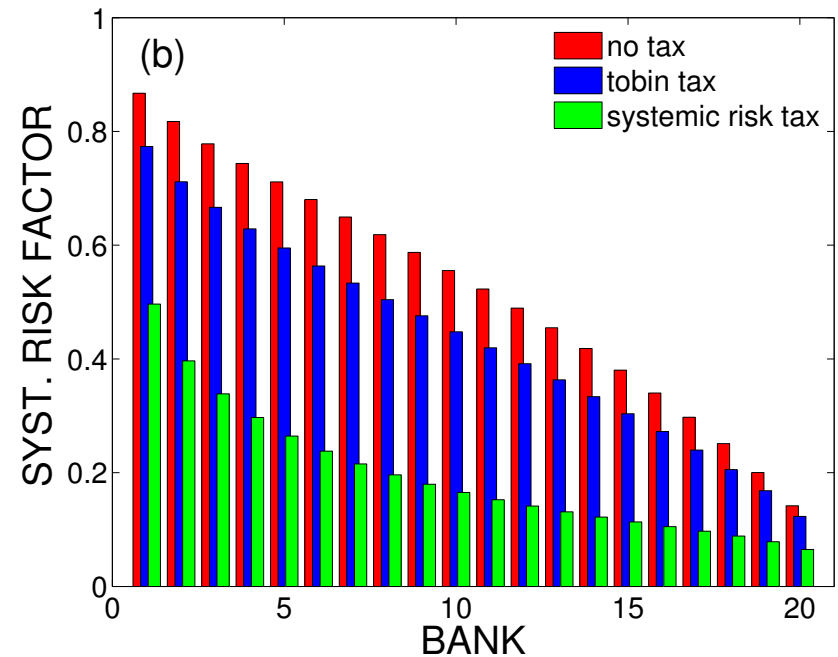
- No systemic risk management
- Systemic Risk Tax (SRT)
- Tobin-like tax

Model results: Systemic risk profile

Austria

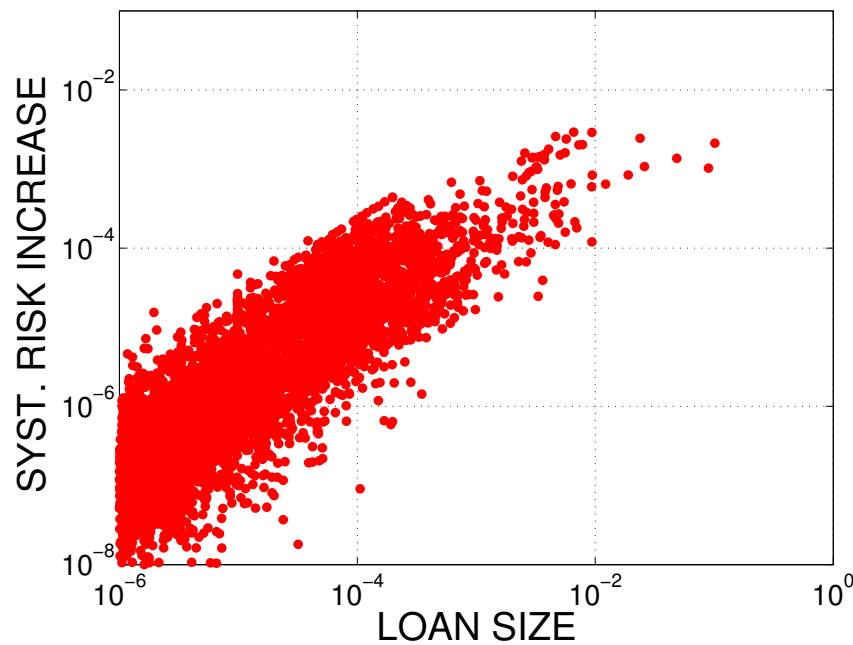


Model

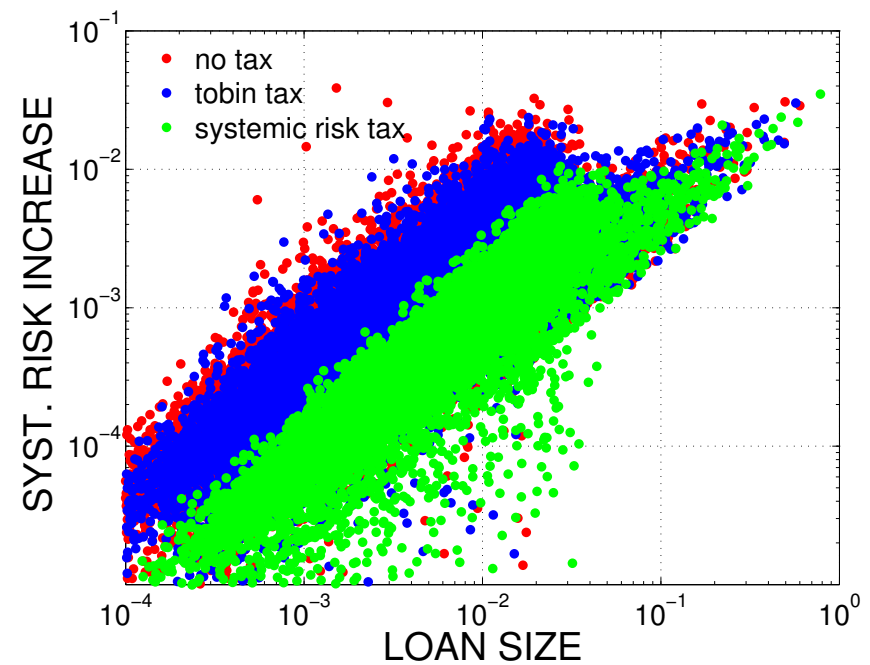


Model results: Systemic risk of individual loans

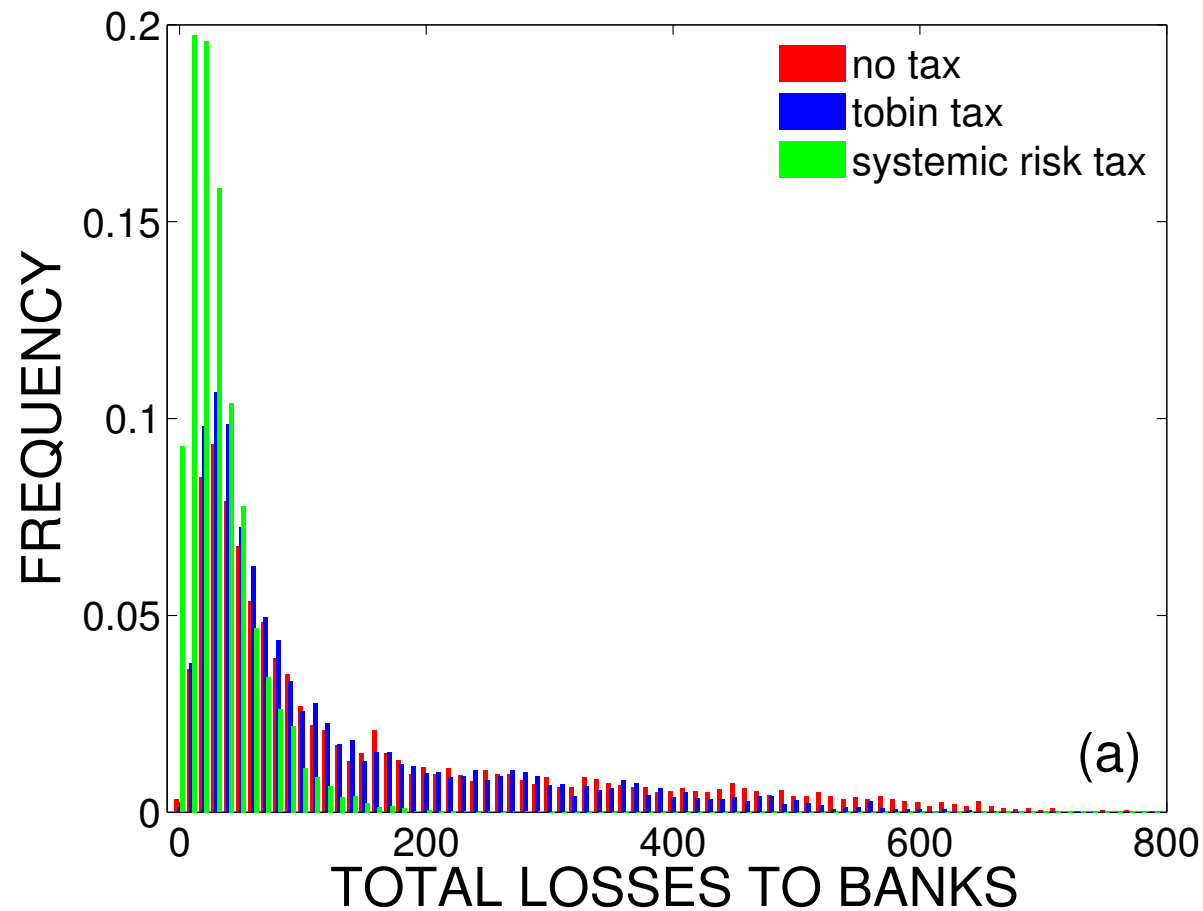
Austria



Model

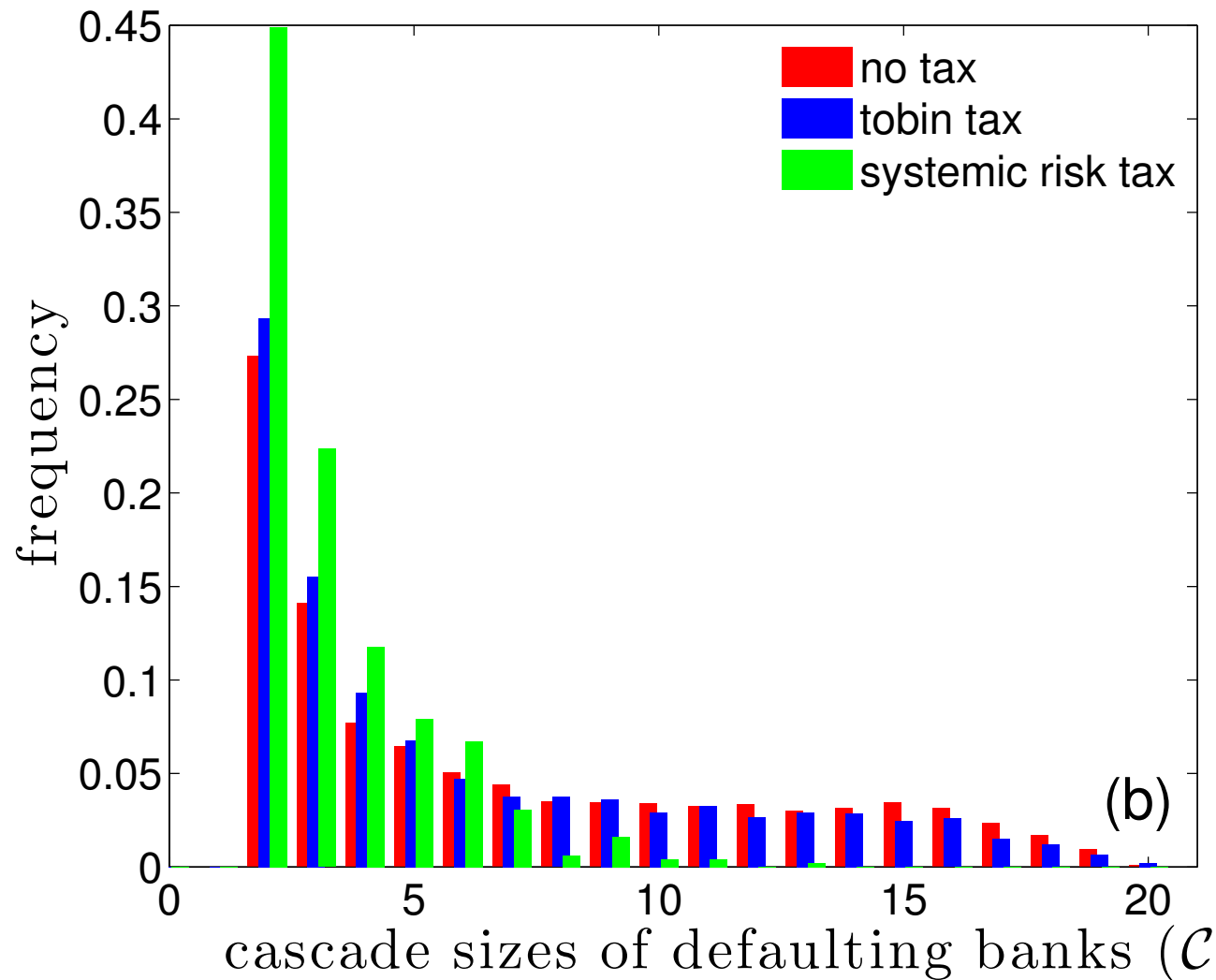


Model results: Distribution of losses

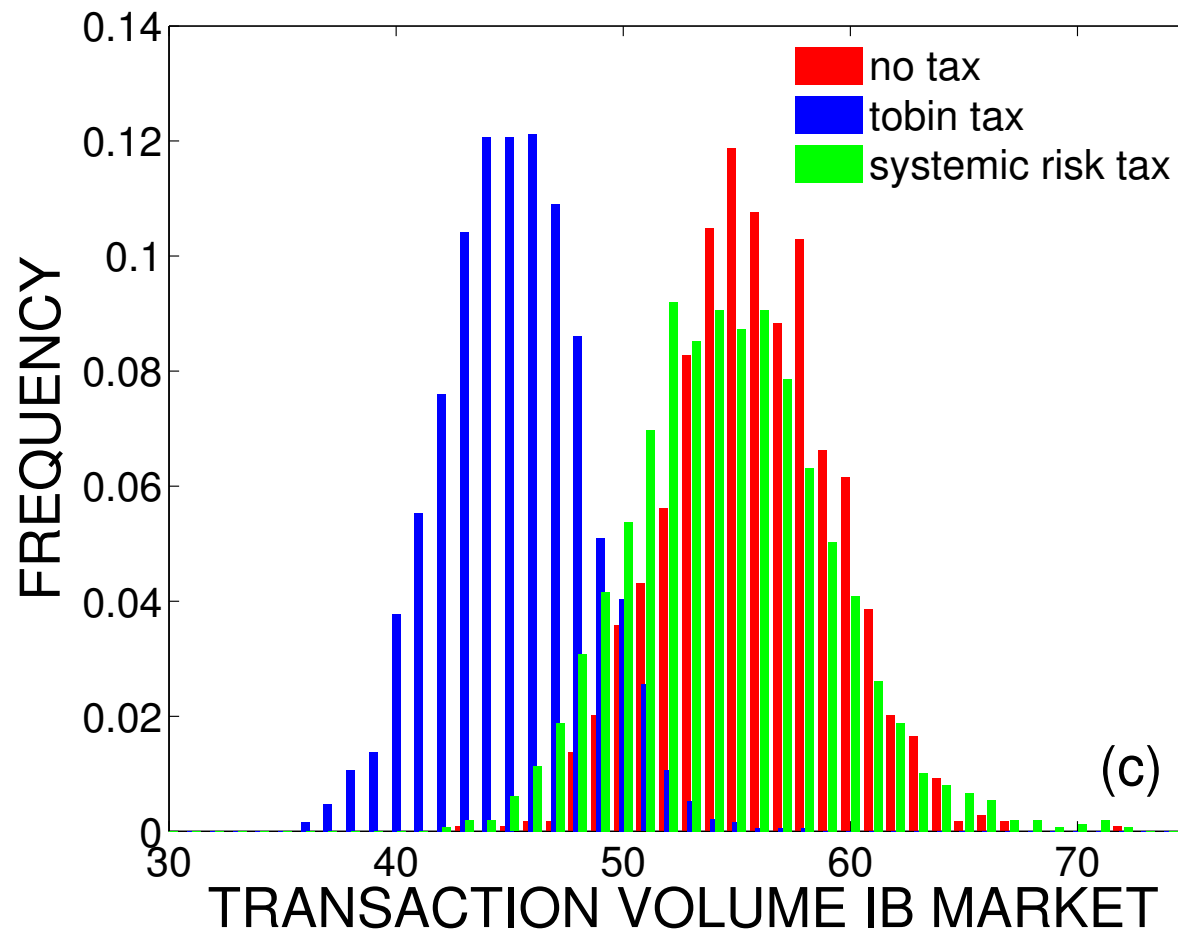


SRT eliminates systemic risk. How?

Model results: Cascading is suppressed



Model results: Credit volume



Tobin tax reduces risk by reducing credit volume

Mathematical proof:

SR-free equilibrium under SRT exists

M. Leduc, S. Thurner, J Economic Dynamics and Control 82 (2017) 44

Proposition *Systemic Risk under Systemic Risk Tax.*

Let $(\mathcal{B}_t, \mathcal{L}_t, \mathbf{P})$ be a market for liquidity at time t . Given a net exposure matrix \bar{A}_{t-1} at time $t - 1$, let $\bar{A}_t^{*,\mathcal{T}}$, $\bar{A}_t^{*,\kappa}$ and \bar{A}_t^* be the net exposure matrices formed at time t with a SRT \mathcal{T} , with a Tobin-like tax κ and without tax by the equilibrium matchings $\mu_t^{*,\mathcal{T}}$, $\mu_t^{*,\kappa}$ and μ_t^* , respectively. Then,

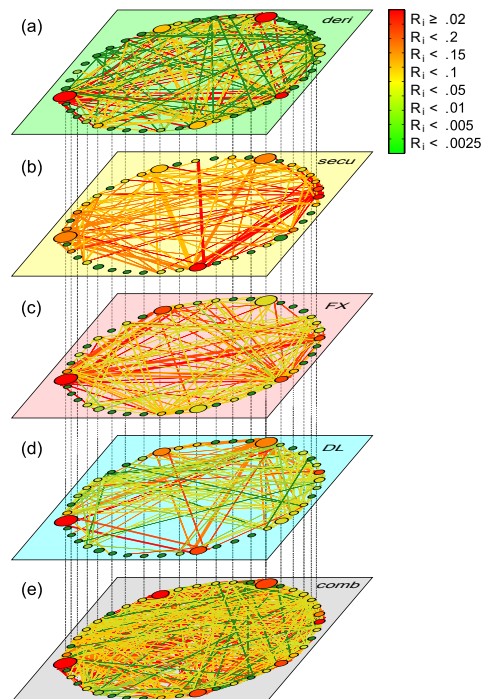
- (i) for any $\mu_t^* \in \mathcal{EQ}_t$, such that $Vol(\mu_t^*) = \nu$, there exists \mathcal{T} such that $ESL(\bar{A}_t^{*,\mathcal{T}}, \vec{E}_t) \leq ESL(\bar{A}_t^*, \vec{E}_t)$ and $Vol(\mu_t^{*,\mathcal{T}}) \geq Vol(\mu_t^*)$; In particular, there exists \mathcal{T} such that $\mu_t^{*,\mathcal{T}}$ is systemic risk efficient.
- (ii) for any $\mu_t^{*,\kappa} \in \mathcal{EQ}_t^\kappa$, such that $Vol(\mu_t^{*,\kappa}) = \nu$, there exists \mathcal{T} such that $ESL(\bar{A}_t^{*,\mathcal{T}}, \vec{E}_t) \leq ESL(\bar{A}_t^{*,\kappa}, \vec{E}_t)$ and $Vol(\mu_t^{*,\mathcal{T}}) \geq Vol(\mu_t^{*,\kappa})$.

What could go wrong?

Challenges – what could go wrong?

- **SRT is useless if not all countries participate** – arbitrage possibilities for non-participating countries – same as for any transaction tax
- **Basel III takes care of Systemic Risk?**
- **the interbank network is not the relevant one** – role of derivatives, mutual cross-holdings, overlapping pfs, etc. → apply SRT to other multiplex layers

Systemic risk multiplex of Mexico Sep 30 2013



layer 1: derivatives network

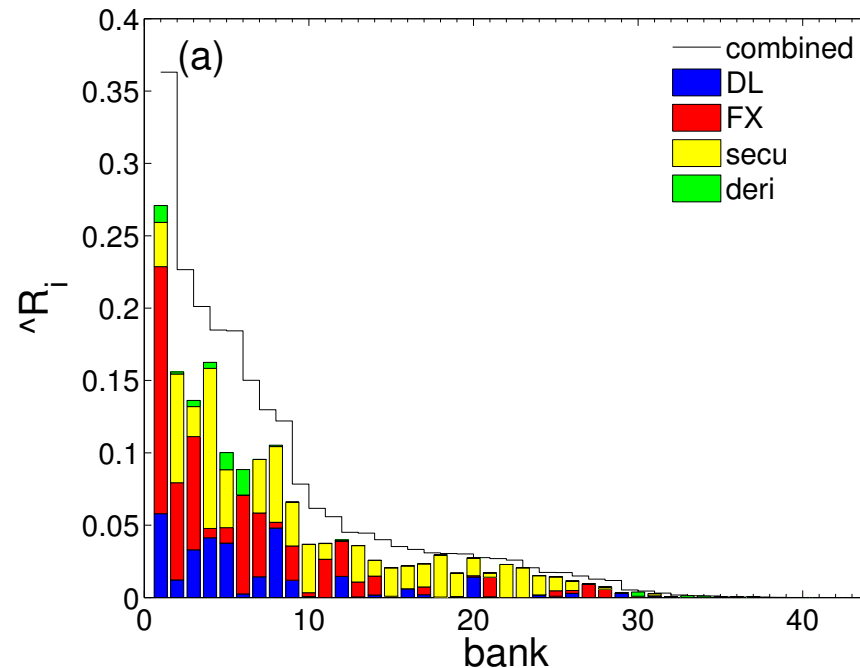
layer 2: network of cross holdings

layer 3: foreign exchange exposures

layer 4: network of deposits and loans

layer 5: combined exposures

Risk profile in the various layers



systemic risk profile for different layers

DebtRank \hat{R}_i^α stacked for banks. Jan 2, 2007 – May 30, 2013

Basel III does not reduce SR

Basel III

- Indicator approach: **five categories** (equal weights ω^i): size, interconnectedness, financial institution infrastructure, cross-jurisdictional activity and complexity. Sub-indicators (equal weights)

$$S_j = \sum_{i \in I} \omega^i \frac{D_j^i}{\sum_j^B D_j^i} 10000$$

Bucket	Score range	Bucket thresholds	Higher loss-absorbency requirement
5	D-E	530-629	3.50%
4	C-D	430-529	2.50%
3	B-C	330-429	2.00%
2	A-B	230-329	1.50%
1	Cutoff point-A	130-229	1.00%

- **Cross-jurisdictional activity (20%)**

Cross-jurisdictional claims 10%

- **Size (20%)**

Cross-jurisdictional liabilities 10%

Total exposures for use in Basel 20%

III leverage ratio

- **Interconnectedness (20%)**

Intra-financial system assets 6.67%

Intra-financial system liabilities 6.67%

Securities outstanding 6.67%

Assets under custody 6.67%

- **Substitutability / financial institution infrastructure (20%)**

Payments activity 6.67%

Underwritten transactions in debt and equity markets 6.67%

(Notional) OTC derivatives 6.67%

- **Complexity (20%)**

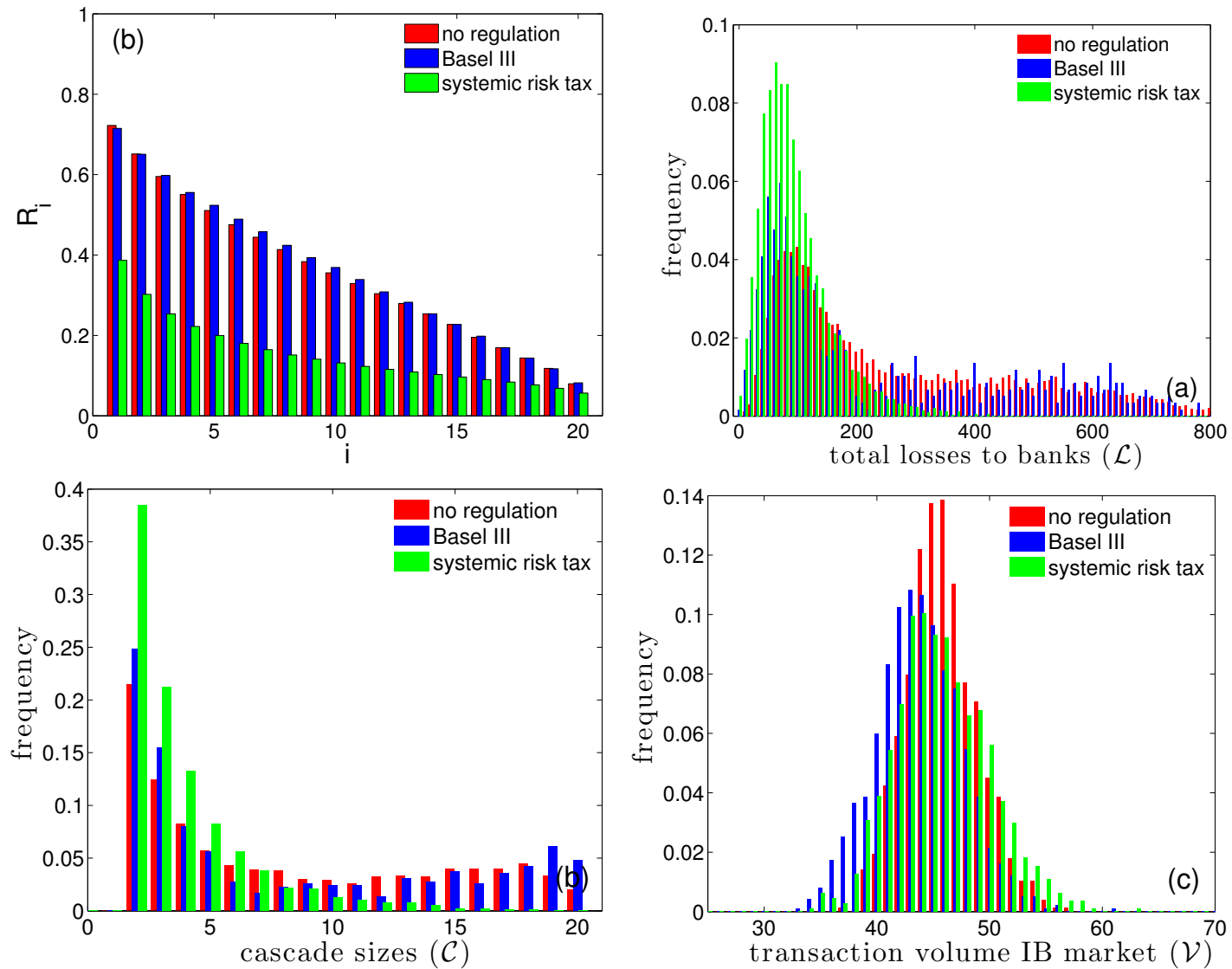
Level 3 assets 6.67%

Trading and available-for-sale securities 6.67%

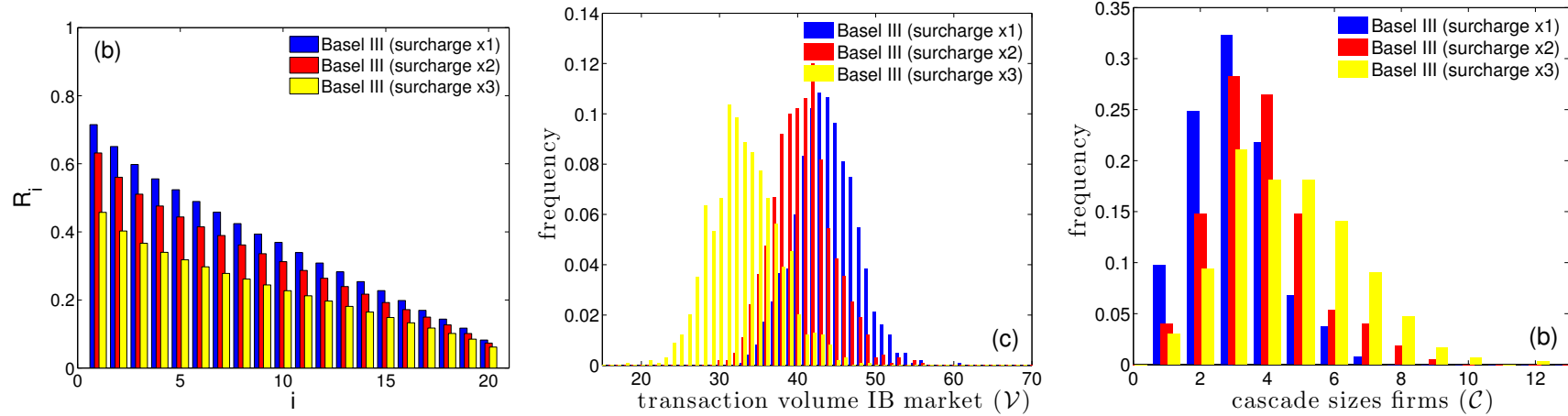
Basel III

- **Size:** total exposures of banks
- **Interconnectedness:** use directed and weighted networks
- **Substitutability/ financial institution infrastructure:** payment activity of banks. The payment activity is measured by the sum of all outgoing payments of banks.
- **Complexity:** not modelled (weight 0)
- **Cross-jurisdiction activity:** not modelled (weight 0)

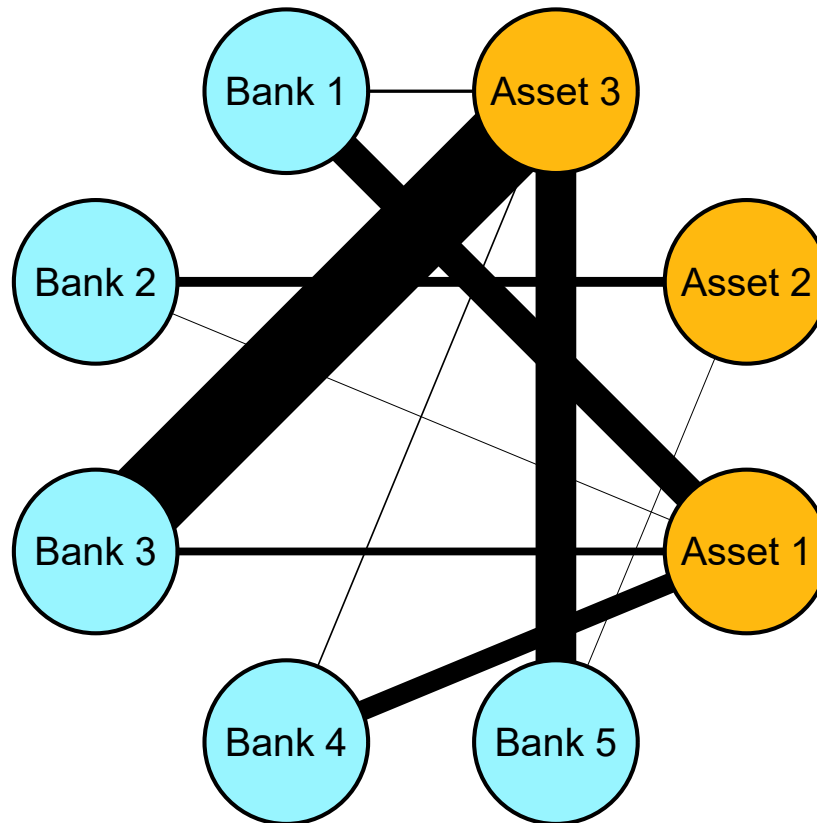
Basel III does not reduce SR !



Basel III works under tremendous costs



Overlapping portfolios



Market depth and linear price impact

- market depth $D_k = c \frac{\langle \text{vol}_k \rangle_{\text{day}}}{\sigma_k}$
- total portfolio value of bank i , $V_i = \sum_k \beta_{ki} p_k$

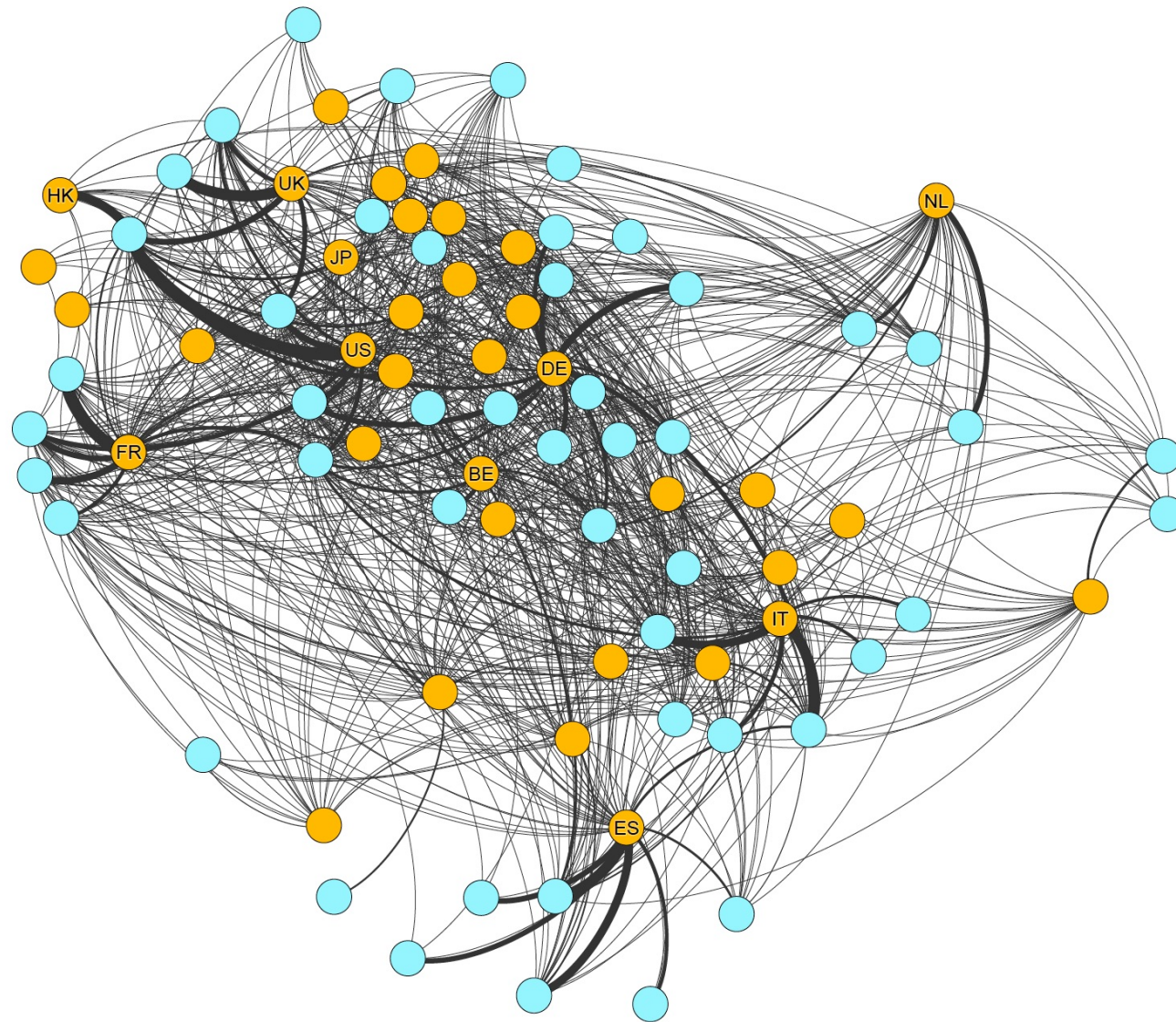
If bank i sells V_{ki} of asset k , price is depressed by $\frac{V_{ki}}{D_k}$

If bank j owns V_{kj} of asset $k \rightarrow$ face loss of $V_{kj} \frac{V_{ki}}{D_k}$

$$\rightarrow W_{ij} = \sum_{k=1}^K V_{kj} V_{ki} \frac{1}{D_k}$$

European stress testing data 2016 (EBA)

- 51 relevant European banks (49 included in analysis)
- 44 sovereign bond investment categories (36 included)



Re-organize networks directly

Minimize SR, subject to portfolios get better

Quadratically Constrained Quadratic Programming problem

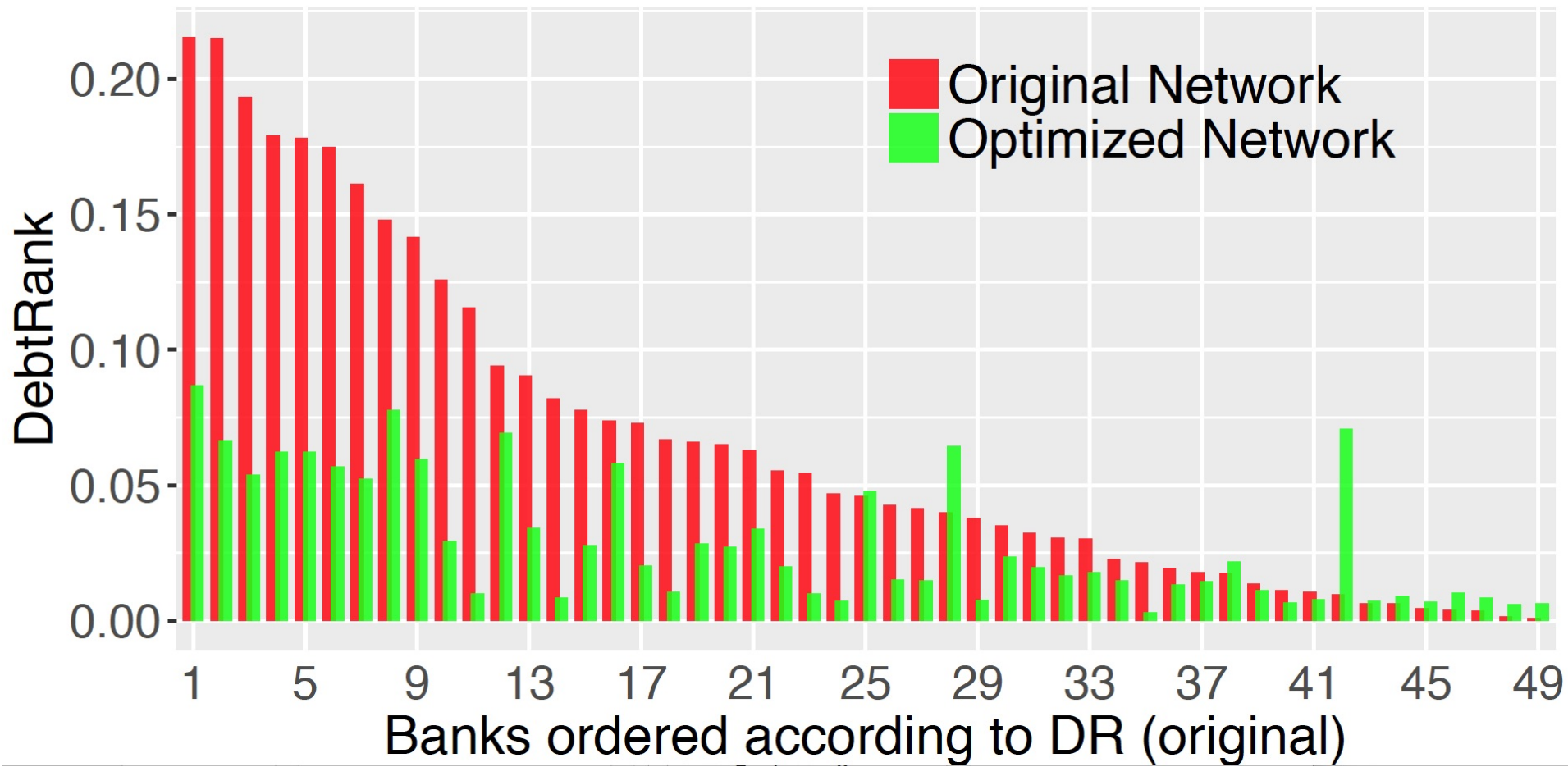
$$\min_{V_{ki} \geq 0 \forall k, i} f(x) = \sum_i \sum_j \frac{1}{C_j} \sum_k V_{ki} V_{kj} \frac{1}{D_k}$$

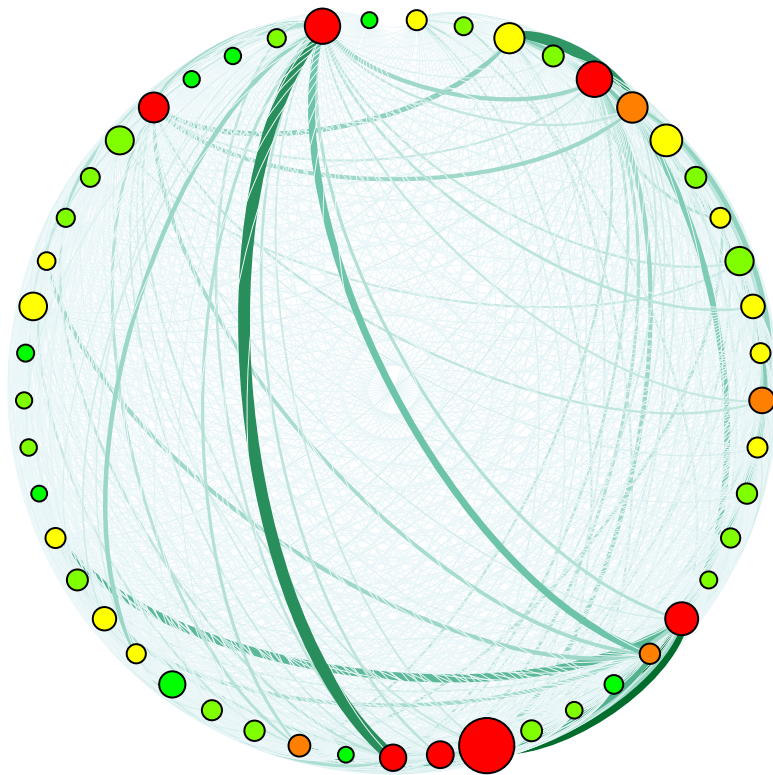
$$\text{subject to } V_i = \sum_k V_{ki}, \quad \forall i,$$

$$S_k = \sum_i V_{ki}, \quad \forall k,$$

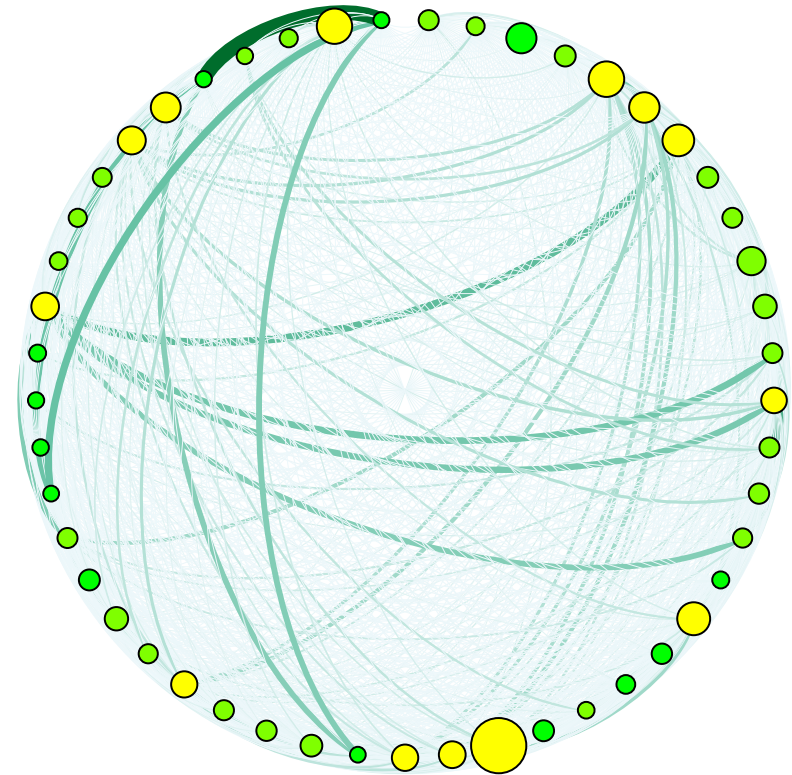
$$\tilde{r}_i \leq \sum_k V_{ki} r_k, \quad \forall i, \text{ return not less}$$

$$\tilde{\sigma}_i^2 \geq \sum_k \sum_l V_{ki} V_{li} \sigma_{kl}^2, \quad \forall i, \text{ variance not more}$$

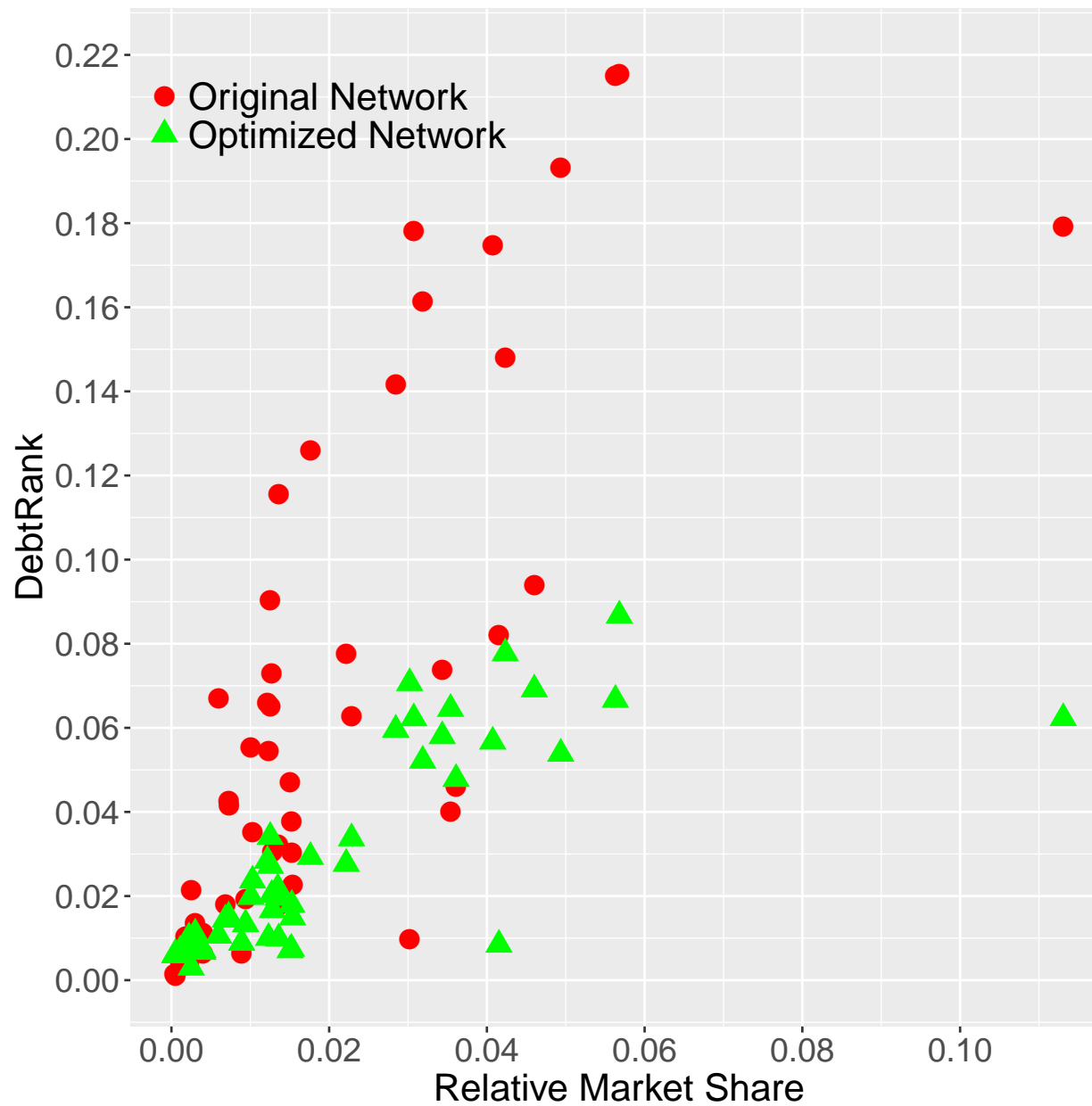




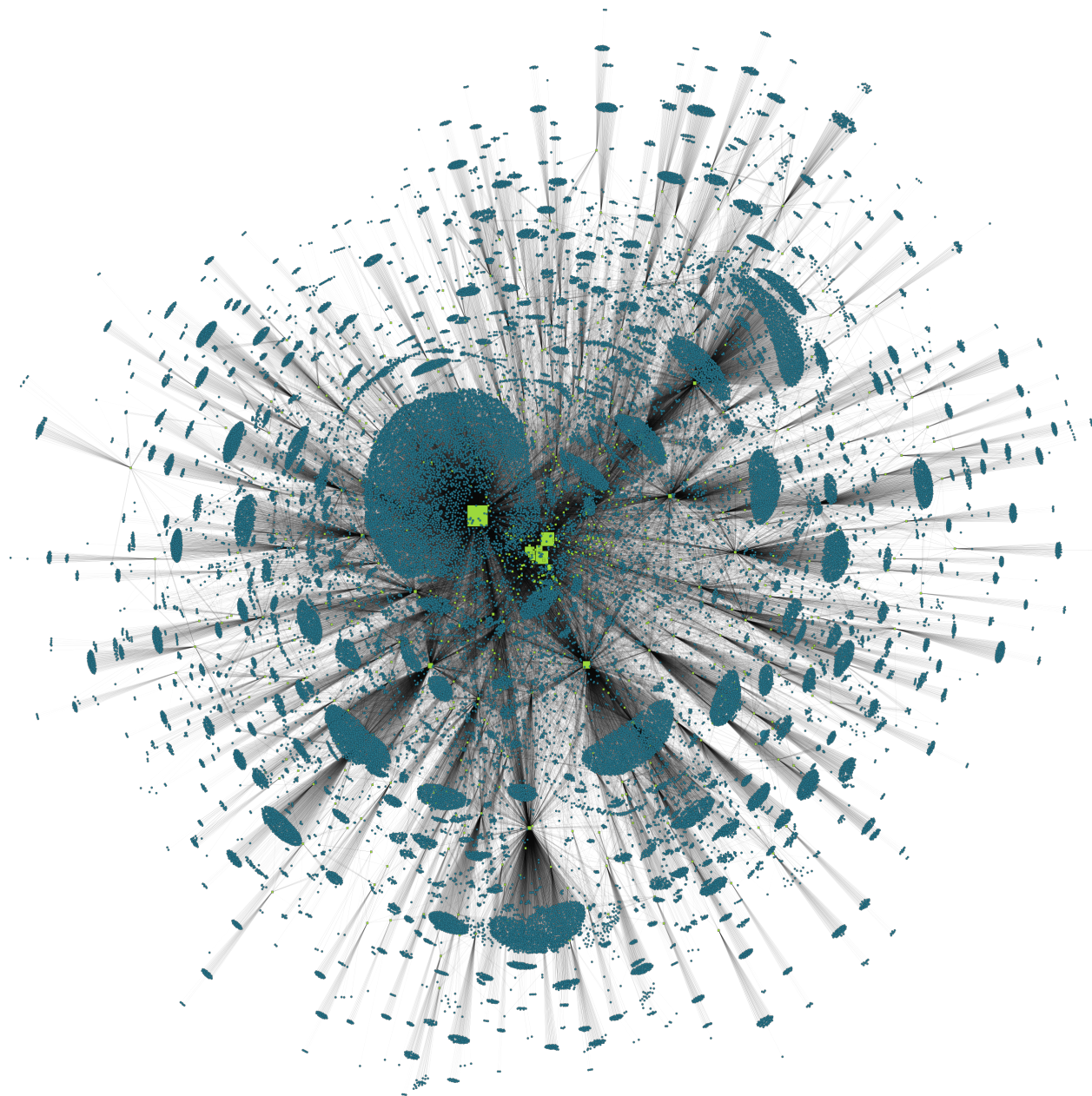
original network



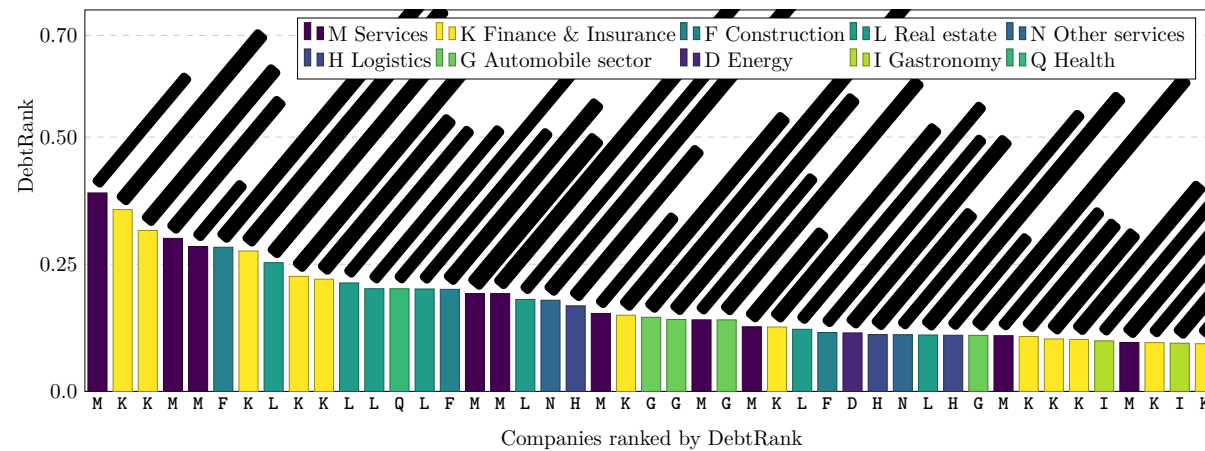
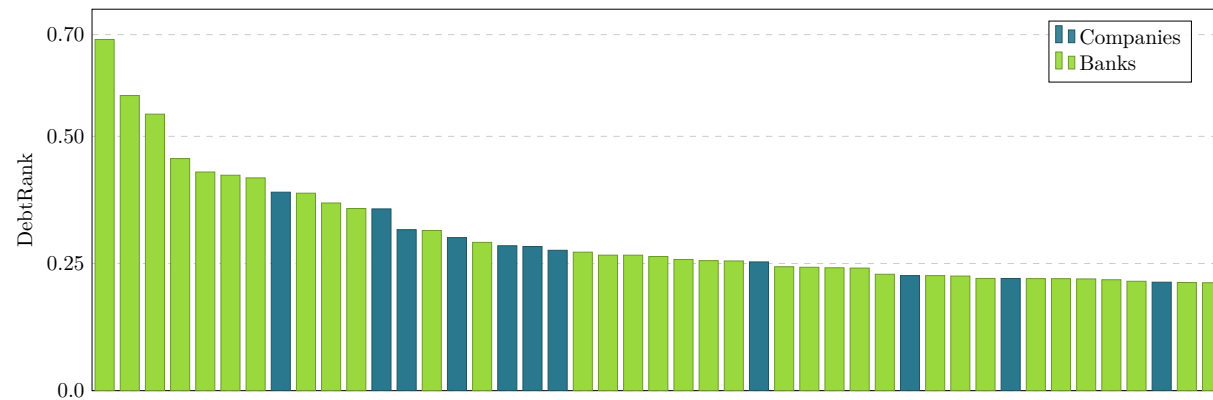
after optimization



Credit network of small nation



SR of companies



Message

more than half of the total financial SR comes from companies

Conclusions

- systemic risk is a network property – endogenously created
- can be measured for each institution / transaction
- can be eliminated by SRT (networks don't allow for cascading)
- SRT should **not be payed!** – evasion re-structures networks
- SRT does not reduce credit volume; **re-ordering** transactions
- Basel III as planned does not work – 3 fold works – costly
- SR requires a multi-layer network framework
- SR tax is technically feasible
- SR can be drastically reduced as a optimization problem

Collaborators

Sebastian Poledna, IIASA

Anton Pichler, Oxford

Abraham Hinteregger, MUW

Doyne Farmer, Oxford

Matt Leduc, IIASA

Serafin Martinez-Jamarillo, Banco de Mexico

Jose-Luis Molina Balboa, Banco de Mexico

S. Thurner, J.D. Farmer, J. Geanakoplos
Quantitative Finance 12 (2012) 695

S. Thurner, S. Poledna
Scientific Reports 3 (2013) 1888

S. Poledna, S. Thurner, J. D. Farmer, J. Geanakoplos
J Banking and Finance 42 (2014) 199

P. Klimek, S. Poledna, J.D. Farmer, S. Thurner
J Economic Dynamics and Control 50 (2014) 144

S. Poledna, J.L. Molina-Borboa, M. van der Leij, S. Martinez-Jaramillo, S. Thurner
J Financial Stability 20 (2015) 70

S. Poledna, S. Thurner
Quantitative Finance 16 (2016) 1599

S. Poledna, O. Bochmann, S. Thurner
J Economic Dynamics and Control 77 (2017) 230

M. Leduc, S. Thurner
J Economic Dynamics and Control 82 (2017) 44

Alternatives to systemic risk tax

- Mandatory CDS
- Markose: taxes banks – not transactions – according to eigenvalue centrality

Problem 1 eigenvector is not economically reasonable number

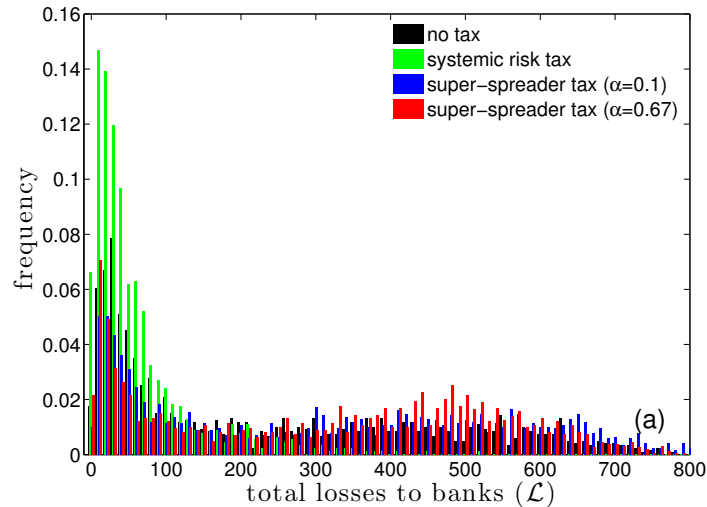
Problem 2 blind to cycles in contract networks

Problem 3 absurd size (up to 30% of capital)

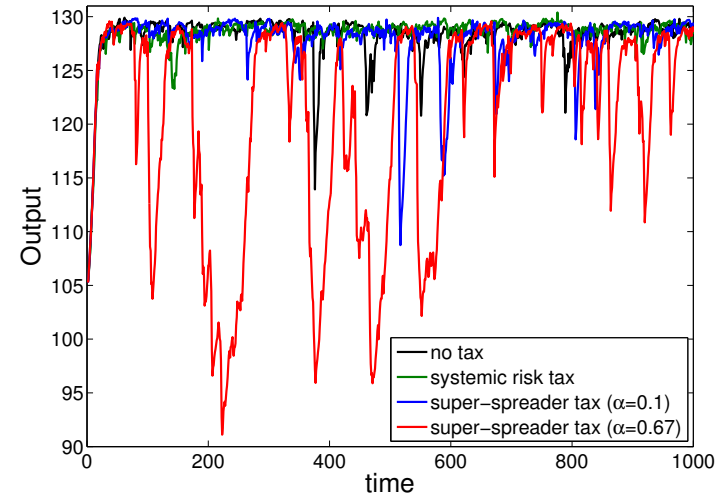
- Tax size: misses small SR institutions, SR improvement at tremendous economic cost

Markose proposal in macro-financial ABM

Losses



Output (GDP)



	No tax	SRT	SST ($\alpha=0.1$)	SST ($\alpha=0.67$)
Output	128.458 ± 1.792	128.382 ± 2.038	127.506 ± 3.278	106.877 ± 20.706
Unemployment	0.0017 ± 0.0102	0.0020 ± 0.0121	0.0059 ± 0.0204	0.1520 ± 0.1533
Credits (firms)	128.174 ± 18.990	121.435 ± 17.303	120.193 ± 19.397	87.943 ± 29.958
Interest (firms)	0.0238 ± 0.0015	0.0243 ± 0.0016	0.0241 ± 0.0017	0.0248 ± 0.0023

Statistical measures

- CoVAR: descriptive – not predictive!
- SES, SRISK: related to leverage and size
- DIP: market based – markets do not see NW-based SR

pro data publicly available, easy to implement

contra 'conditional' hard to define without knowledge of networks, descriptive, non-predictive