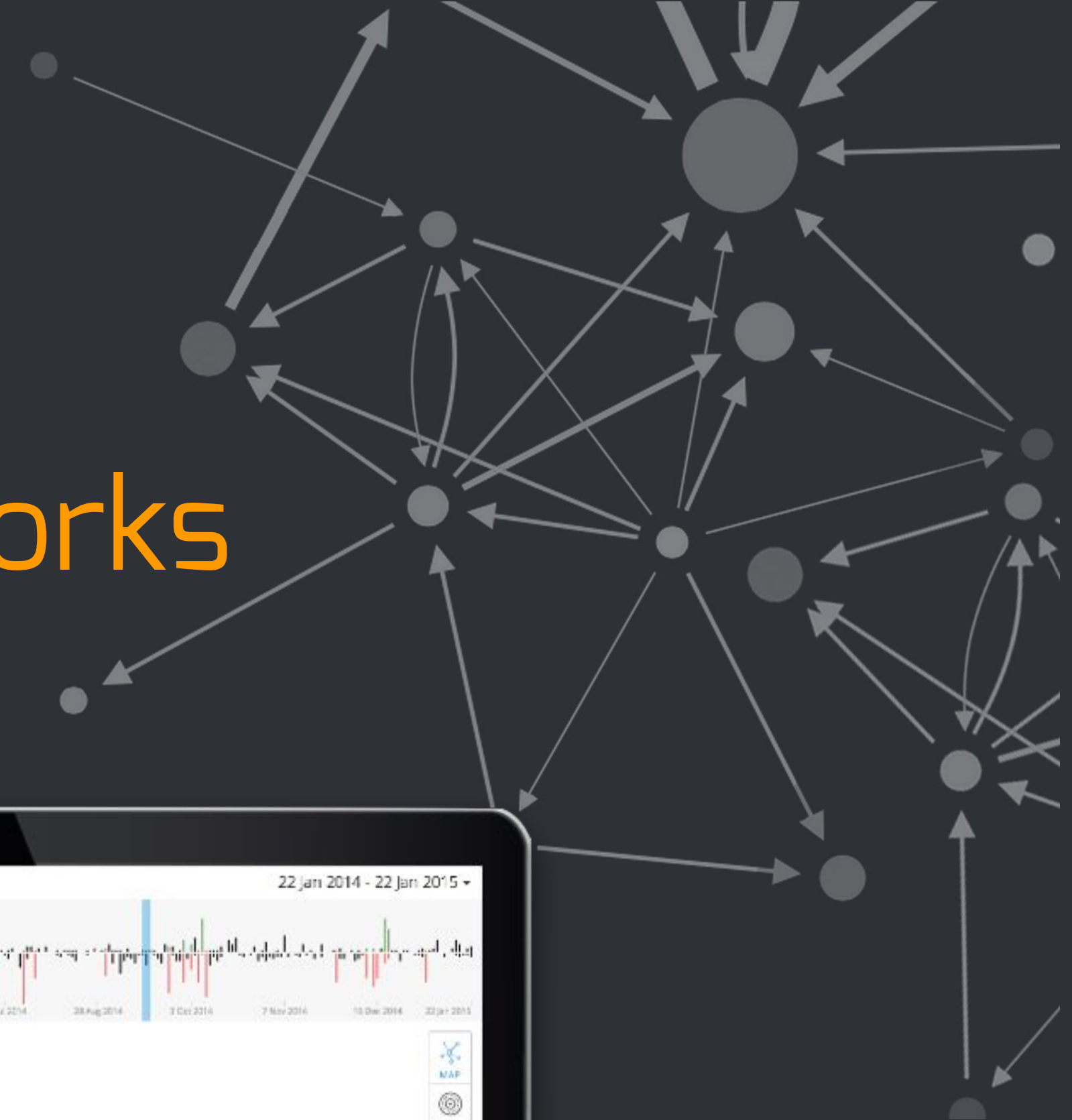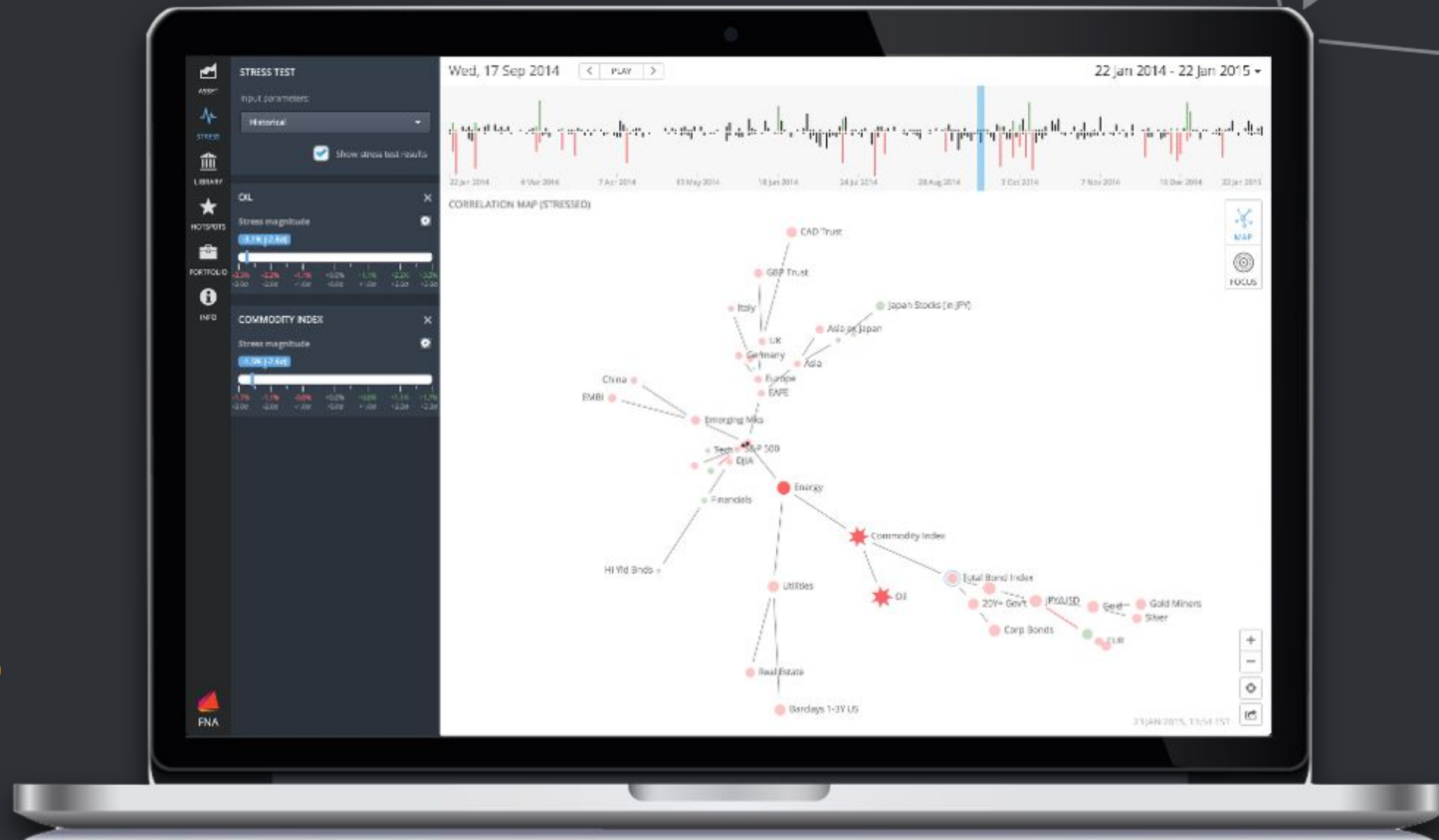# Stress Testing Correlation Networks
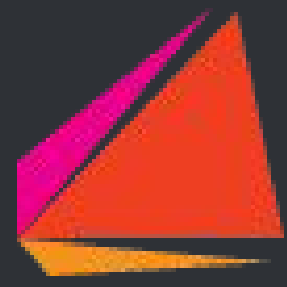
Financial Risk and Network Theory

Cambridge, 14 Sept. 2016

Kimmo Soramäki
Founder
Financial Network Analytics

www.fna.fi

Stress Testing is at the forefront of the banking regulatory agenda

Regulators are increasingly relying on *Stress Tests* to assess if the national or regional banking system is sufficiently capitalised to maintain the supply of bank lending in the face of adverse shocks
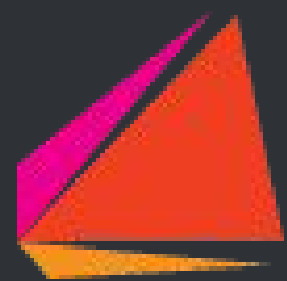
Federal Reserve

European Central Bank

EBA

Prudential Regulatory Authority

Hong Kong Monetary Authority

Network Models in Stress Testing

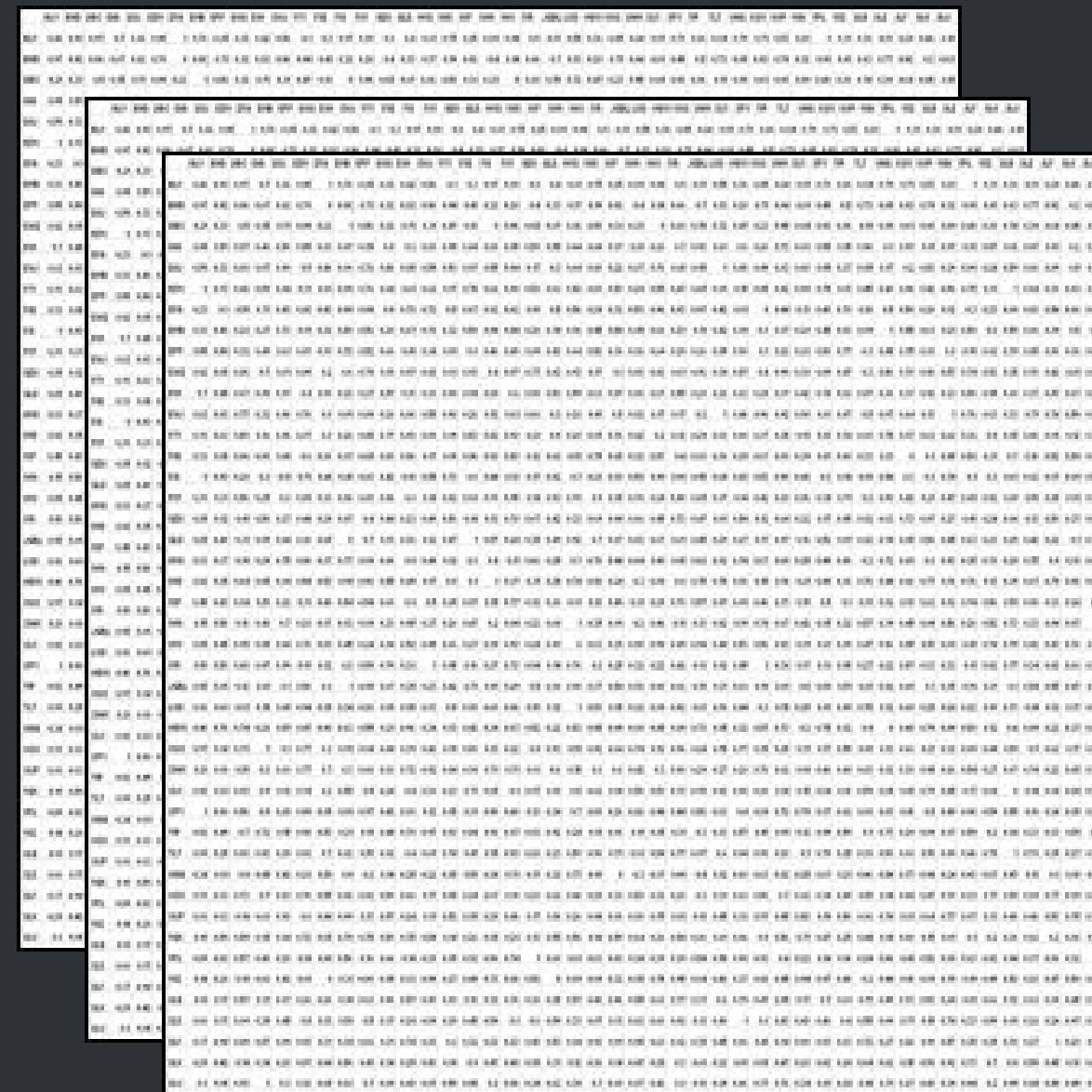| Risk	Nodes	Links	Application
Market risk	Assets, Factors, Indices	Correlations, other dependence	IFRS9, Predictive stress testing, Correlation stress testing, What if -analysis
Liquidity & Operational risk in FMIs	FMIs	Payment/Trade Flows	Infrastructure Stress Testing, FSAP
Counterparty & Systemic risk	FMIs	Exposures	Stress Testing Banking Systems

Transactions & Similarity Based Networks

Transaction: payment, trade, exposure, supply, flow, ...

Similarity: correlation, partial correlation, granger causality, transfer entropy, ...

Stress Testing Correlation Networks

We need ability to:

- Understand correlations structures of much larger scale
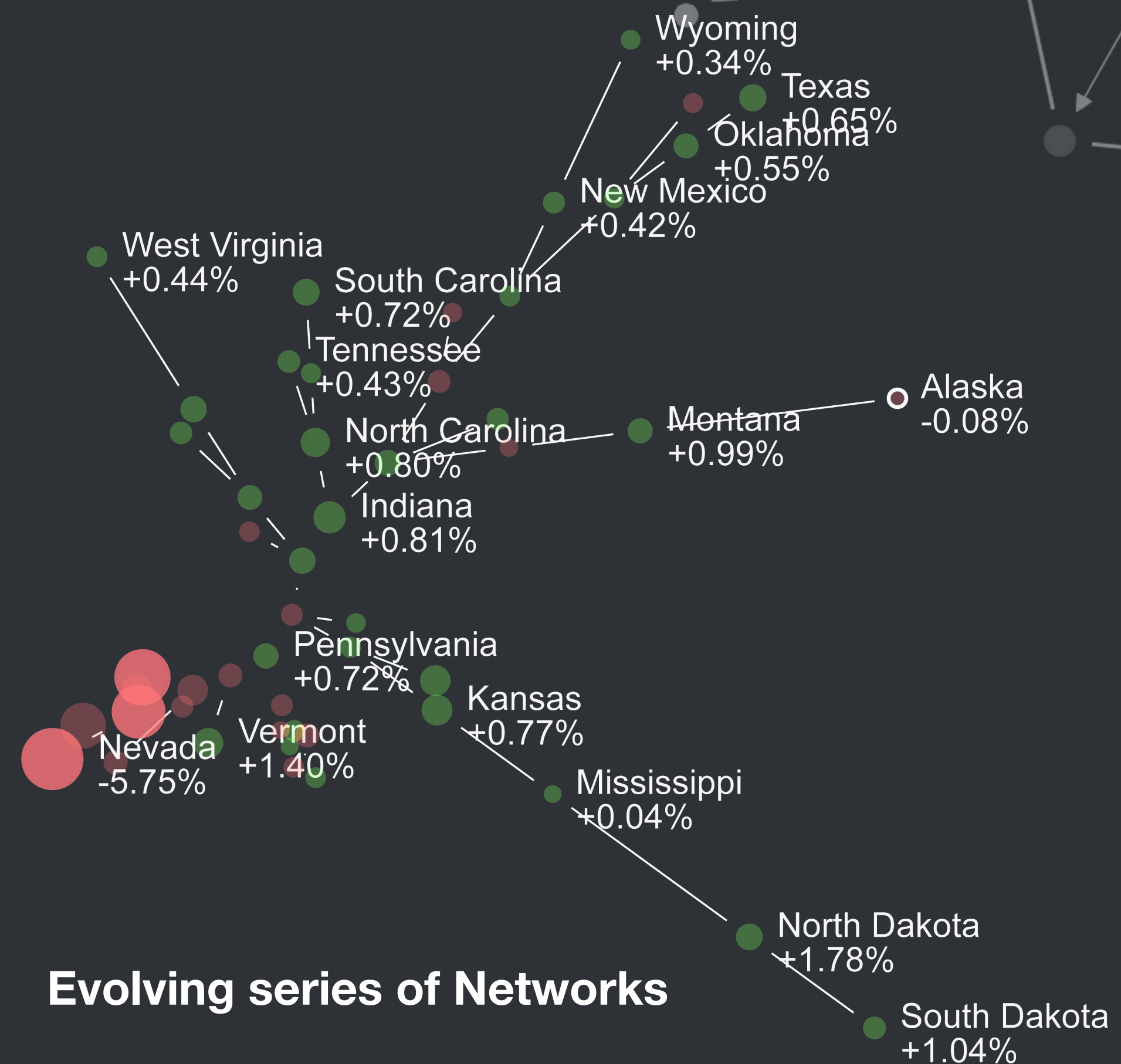- Conveniently develop plausible but severe correlation scenarios
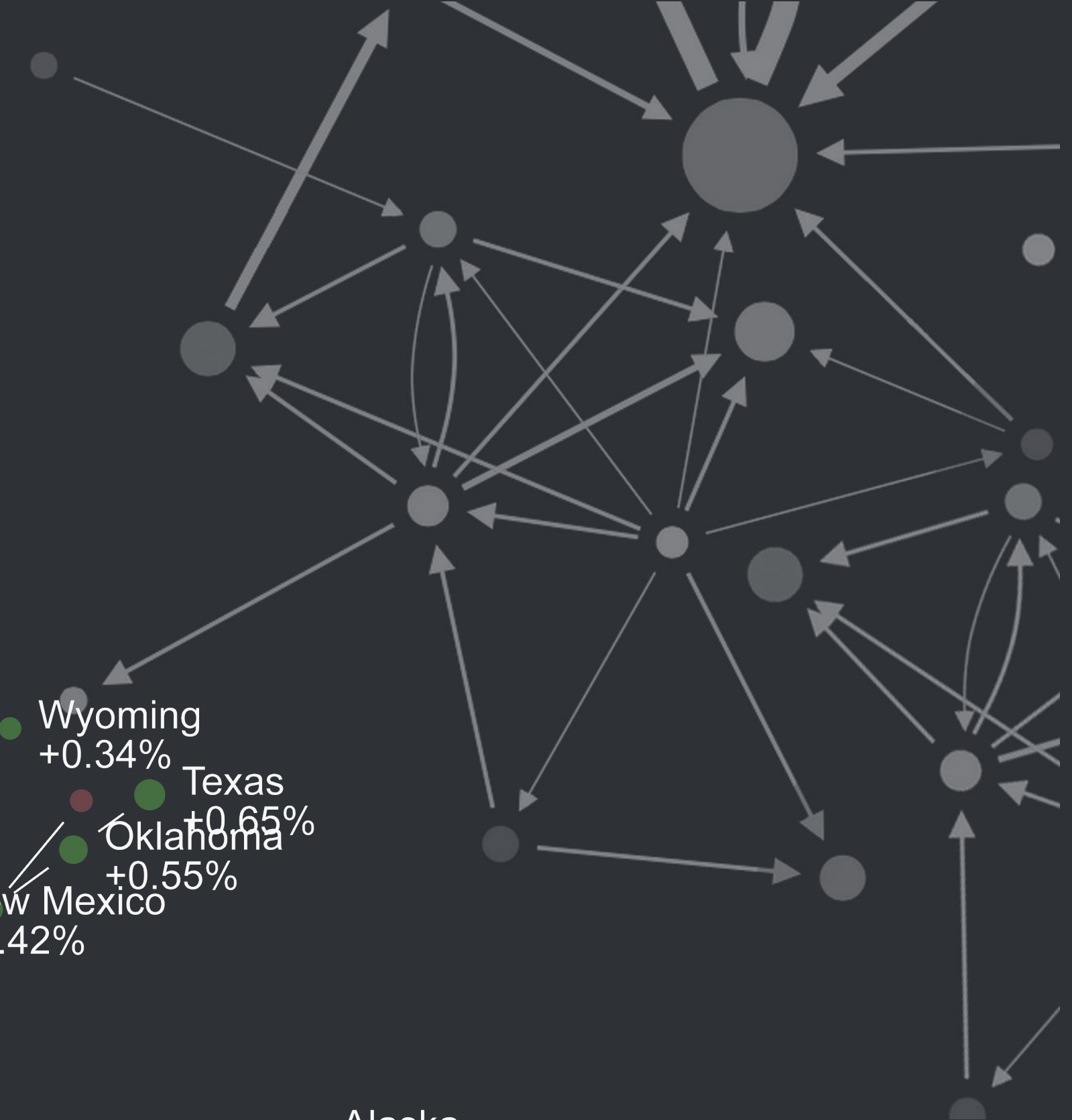
Set of large correlation matrices
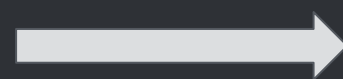
Evolving series of Networks

Wyoming
+0.34%

Texas
+0.65%

Oklahoma
+0.55%

New Mexico
+0.42%

West Virginia
+0.44%

South Carolina
+0.72%

Tennessee
+0.43%

Alaska
-0.08%

North Carolina
+0.80%

Montana
+0.99%

Indiana
+0.81%

Pennsylvania
+0.72%

Kansas
+0.77%

Nevada
-5.75%

Vermont
+1.40%

Mississippi
+0.04%

North Dakota
+1.78%

South Dakota
+1.04%

Correlation Network

We can view any matrix as a network.

We encode correlations as links between the correlated nodes/assets.

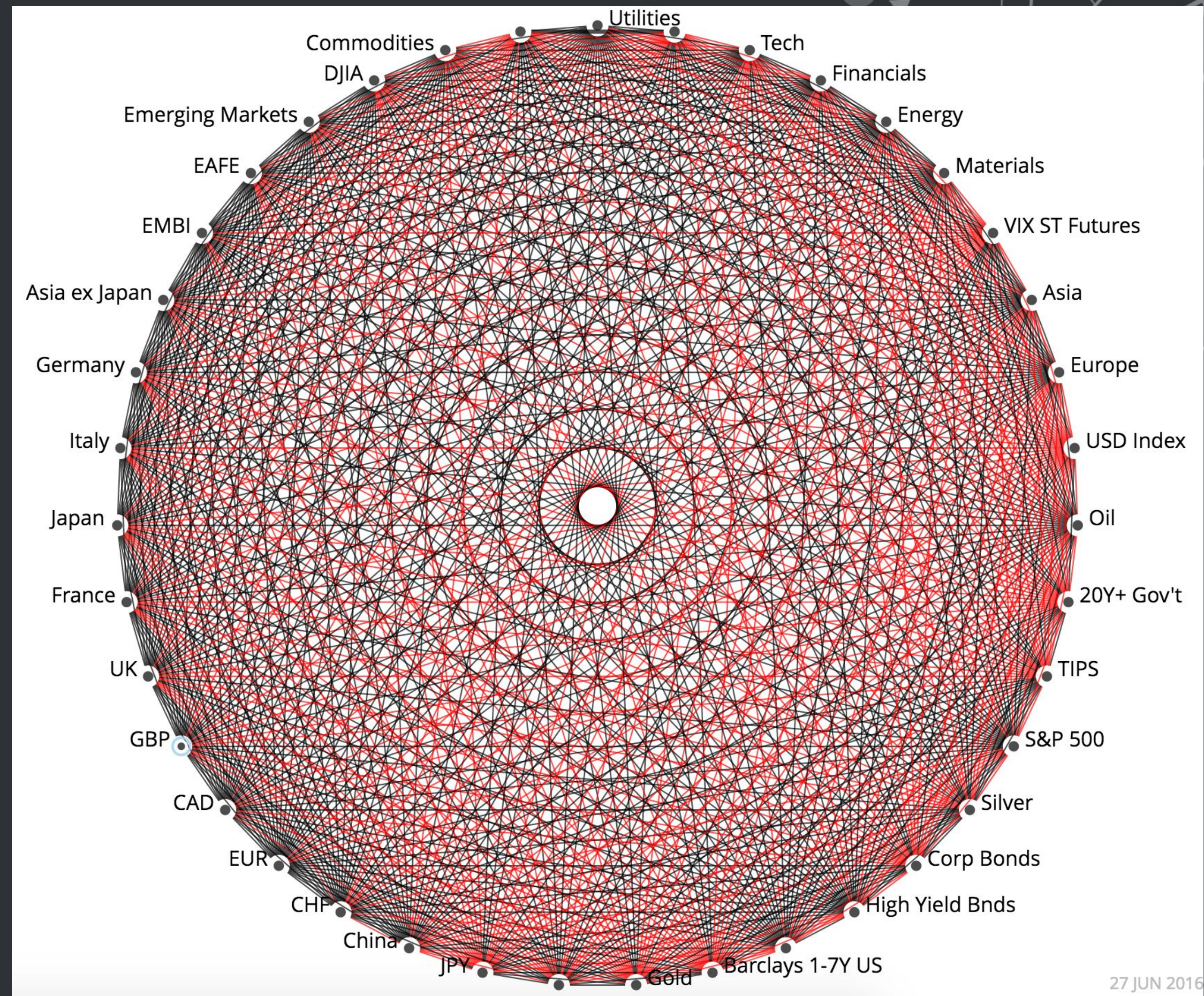Red link = negative correlation
Black link = positive correlation

However, this simple encoding does not give us much.

Significant Correlations

Not all correlations are statistically significantly different from 0.

Absence of link marks that asset is not significantly correlated (here at 95% level).

Due to the large number of estimates, we also need for multiple comparisons correction. Eg. Bonferroni or FDR.
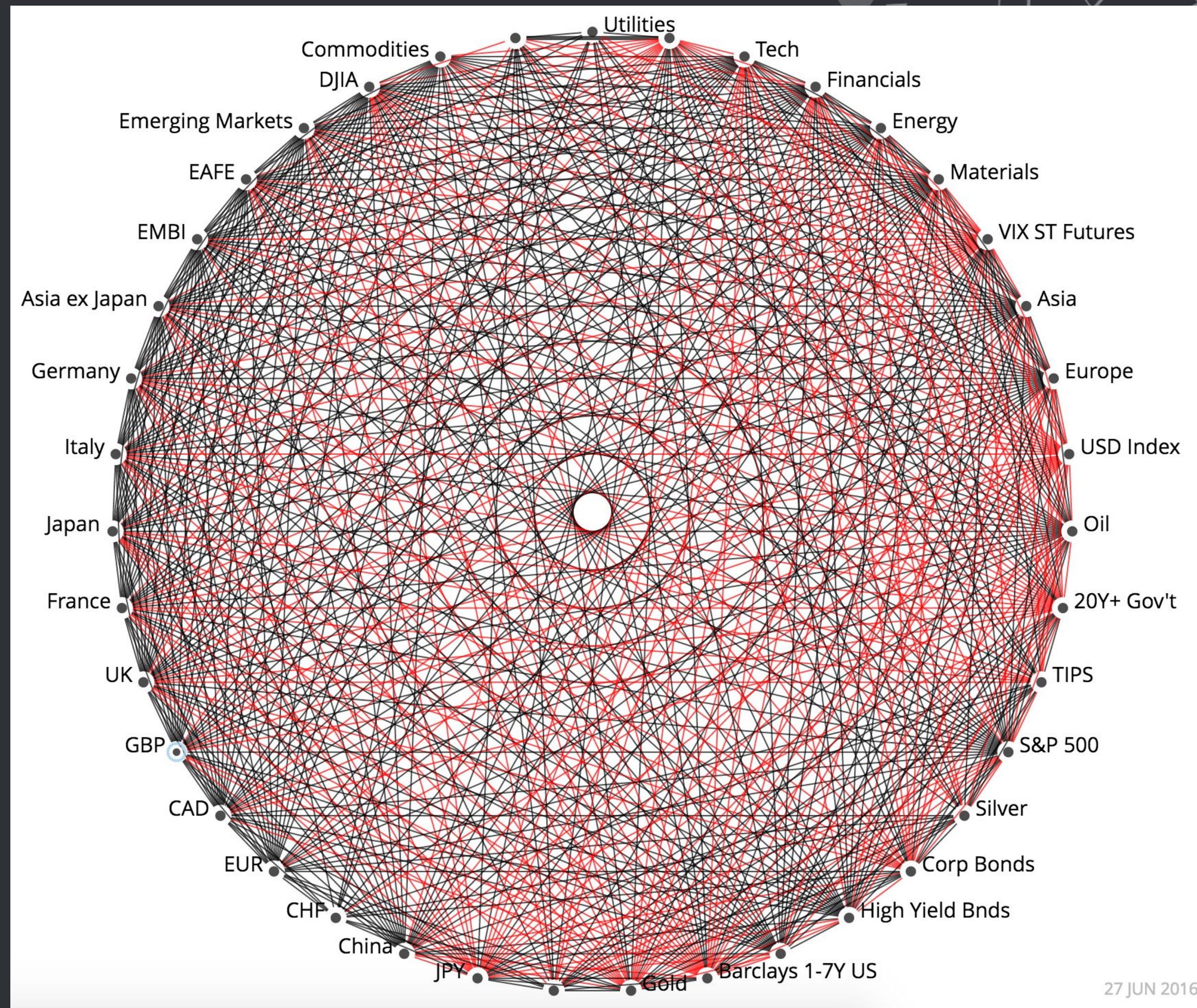
Layouts

We can use network layouts to better detect patterns from noise.

Eg we can try a Force-Directed network layout to identify clusters.
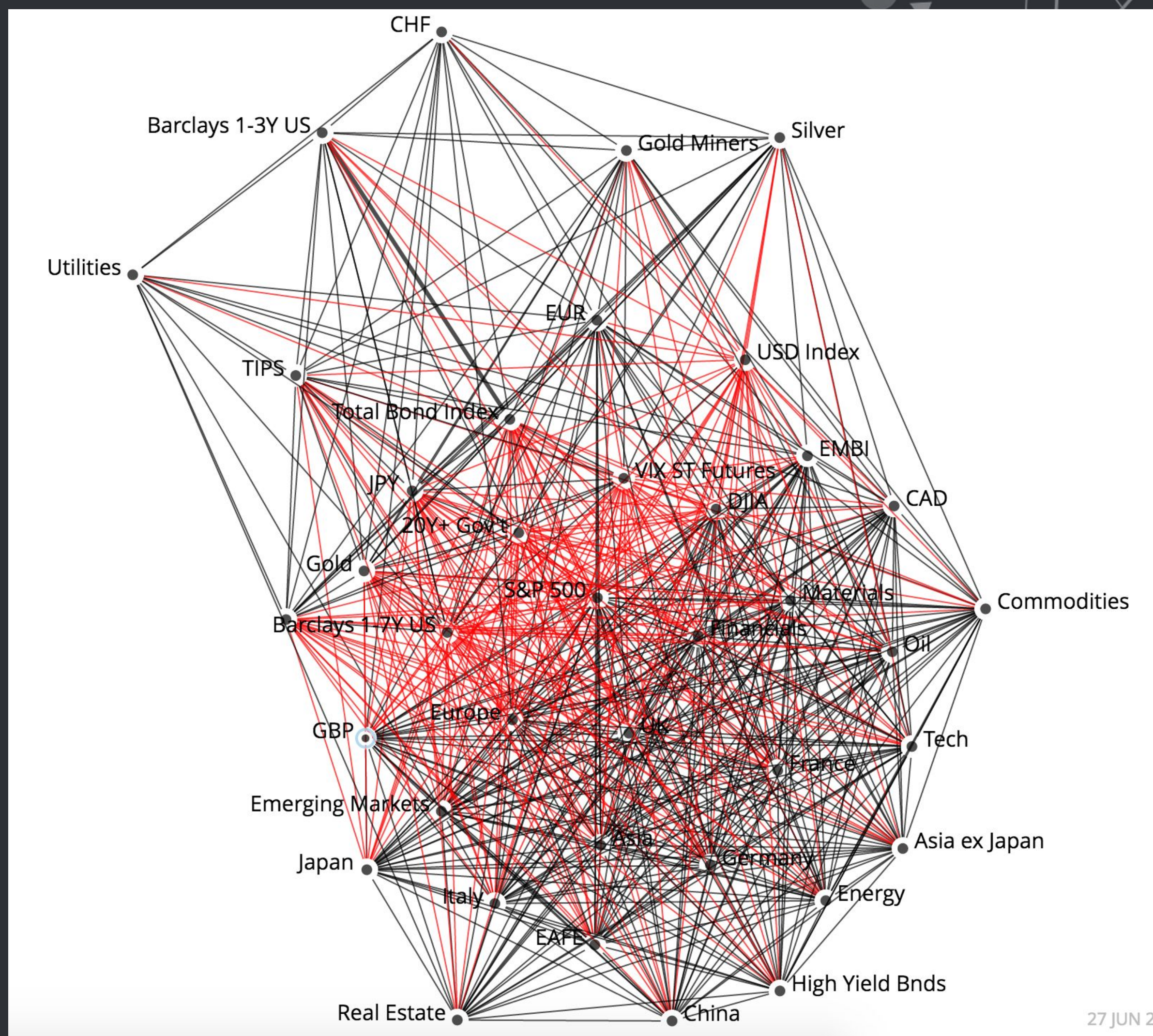
Filtering

Next, we identify the Minimum Spanning Tree and filter out other correlations (Mantegna, '99).

We need a distance function, here we look at maximum spanning tree with distance function:
`abs(cor)`

This shows us the backbone correlation structure.
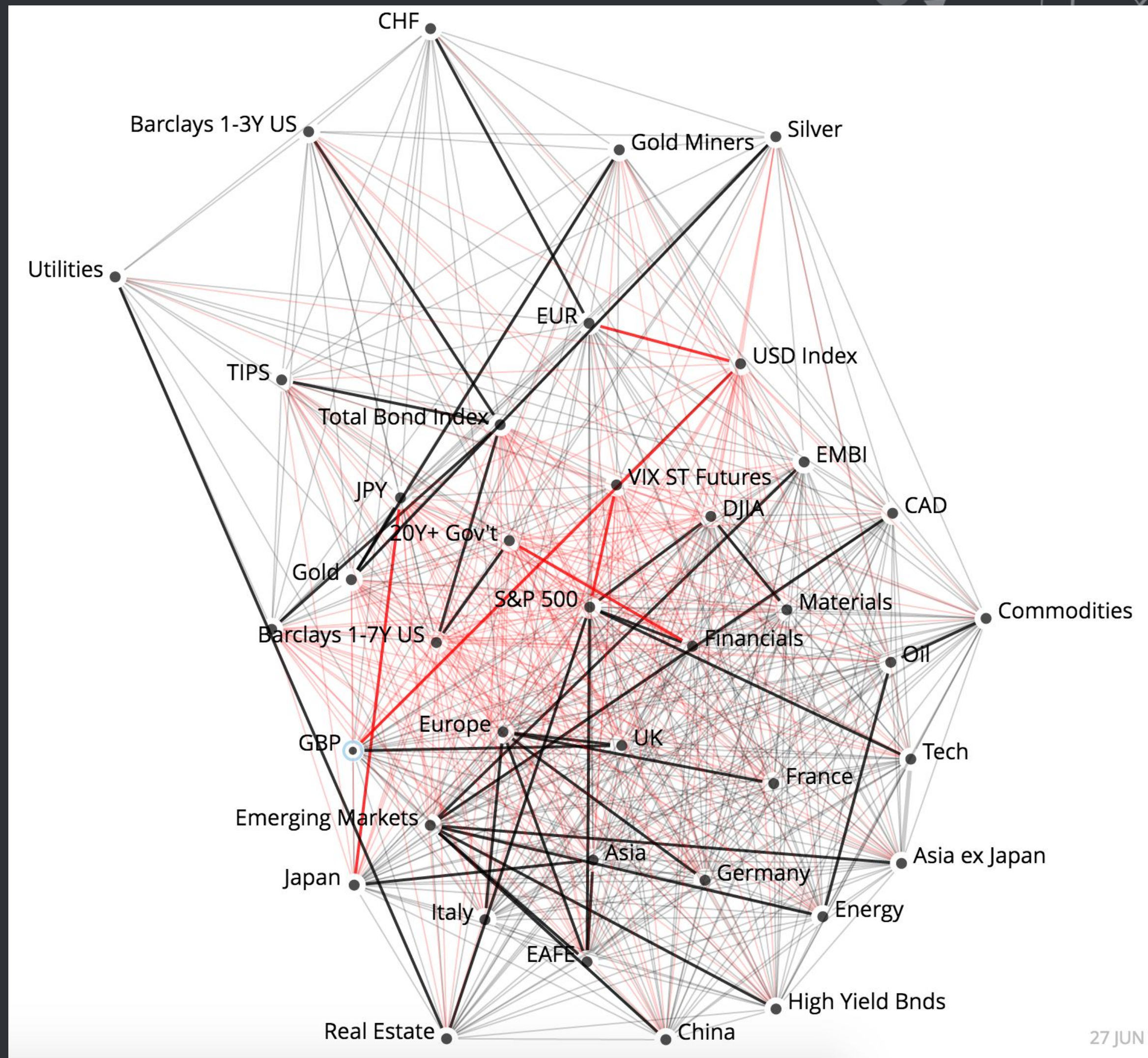
Radial Tree layout

We use a radial tree layout algorithm (Bachmeier et al. '05) that places the assets so that:

Shorter links in the tree indicate higher correlations

Longer links indicate lower correlations

As a result, we also see how the assets cluster by asset class.
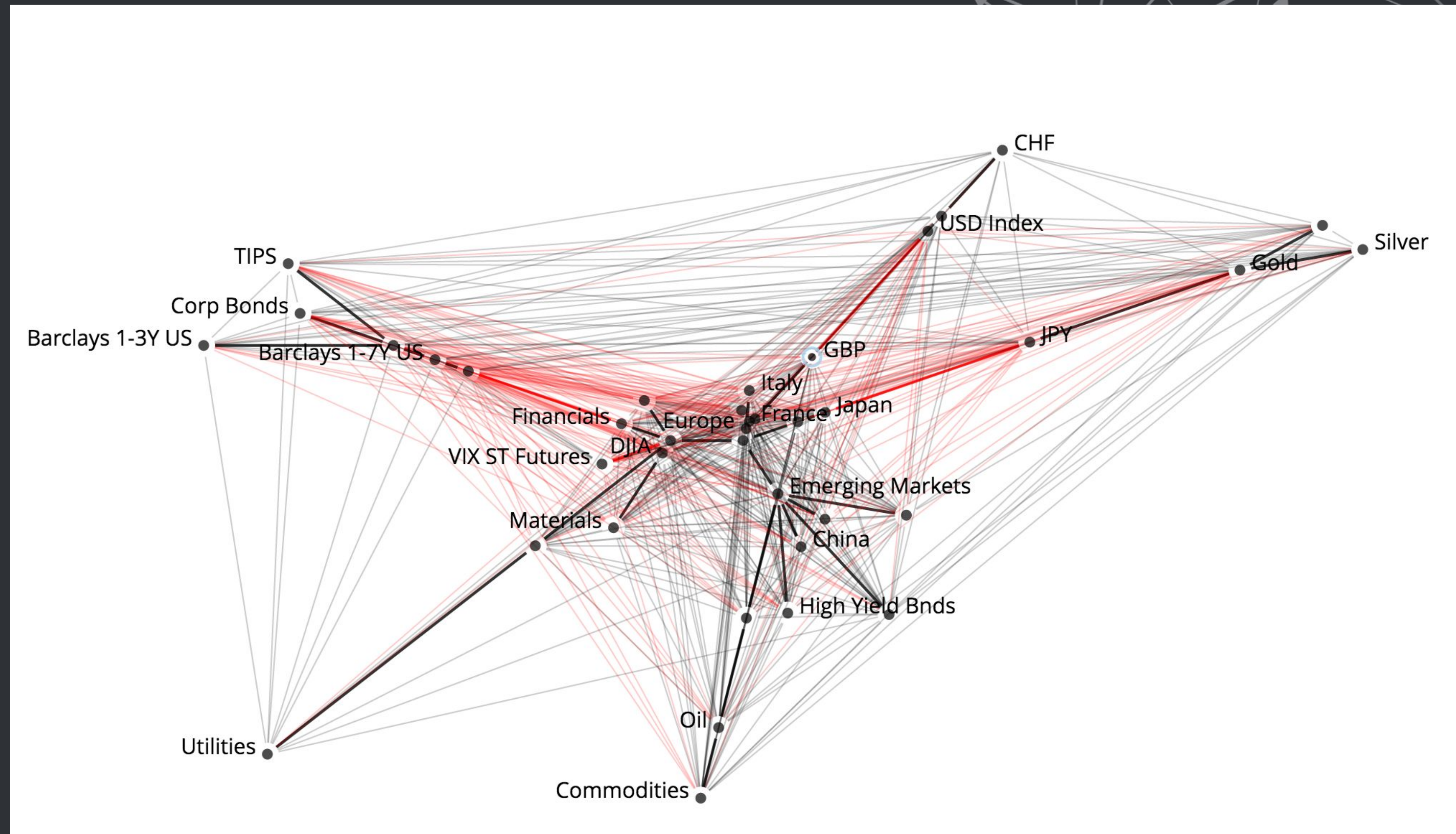
Filtering

Focus on the links in the Spanning Tree to highlight clustering structure.

Node color indicates last daily return

Green = positive

Red = negative

Node size indicates magnitude of return

Bright colors are VaR exceptions

Financial Cartography

Coordinate system

-> layout algorithm

System for visual encoding of map data

-> node sizes & colors

Dimensionality reduction & filtering

-> minimum spanning tree

Eratosthenes' map of the known world c. 194 BC

Example US Housing

ASSET
NETWORK
STRESS
LIBRARY
ALERTS
PORTFOLIO
INFO
TOUR
FNA

House Price Index Correlations

Correlations in changes of House Price Index by state. Data source: Quandl / Federal Reserve Economic Data.

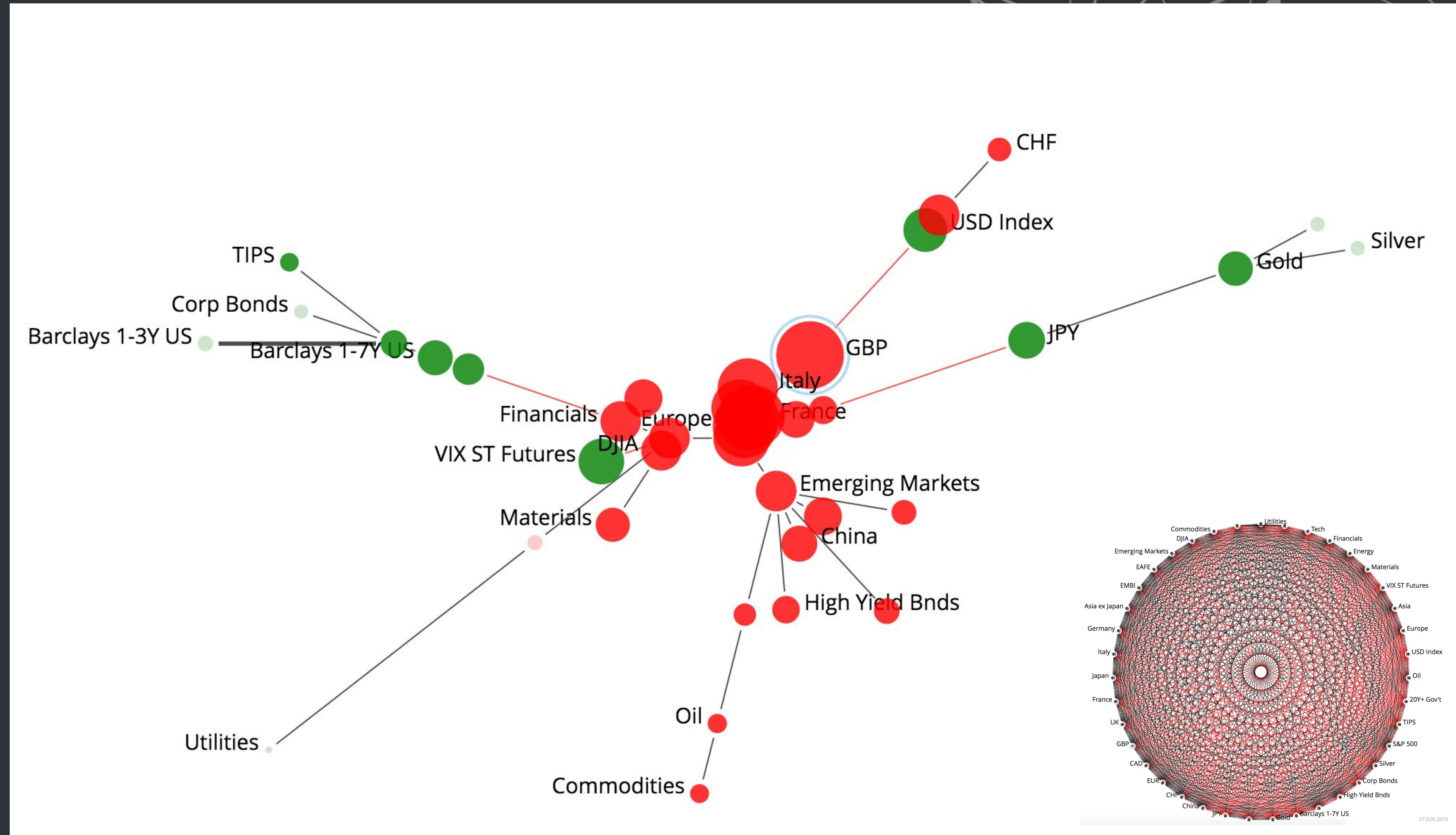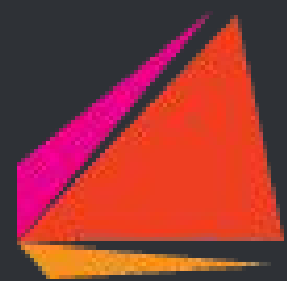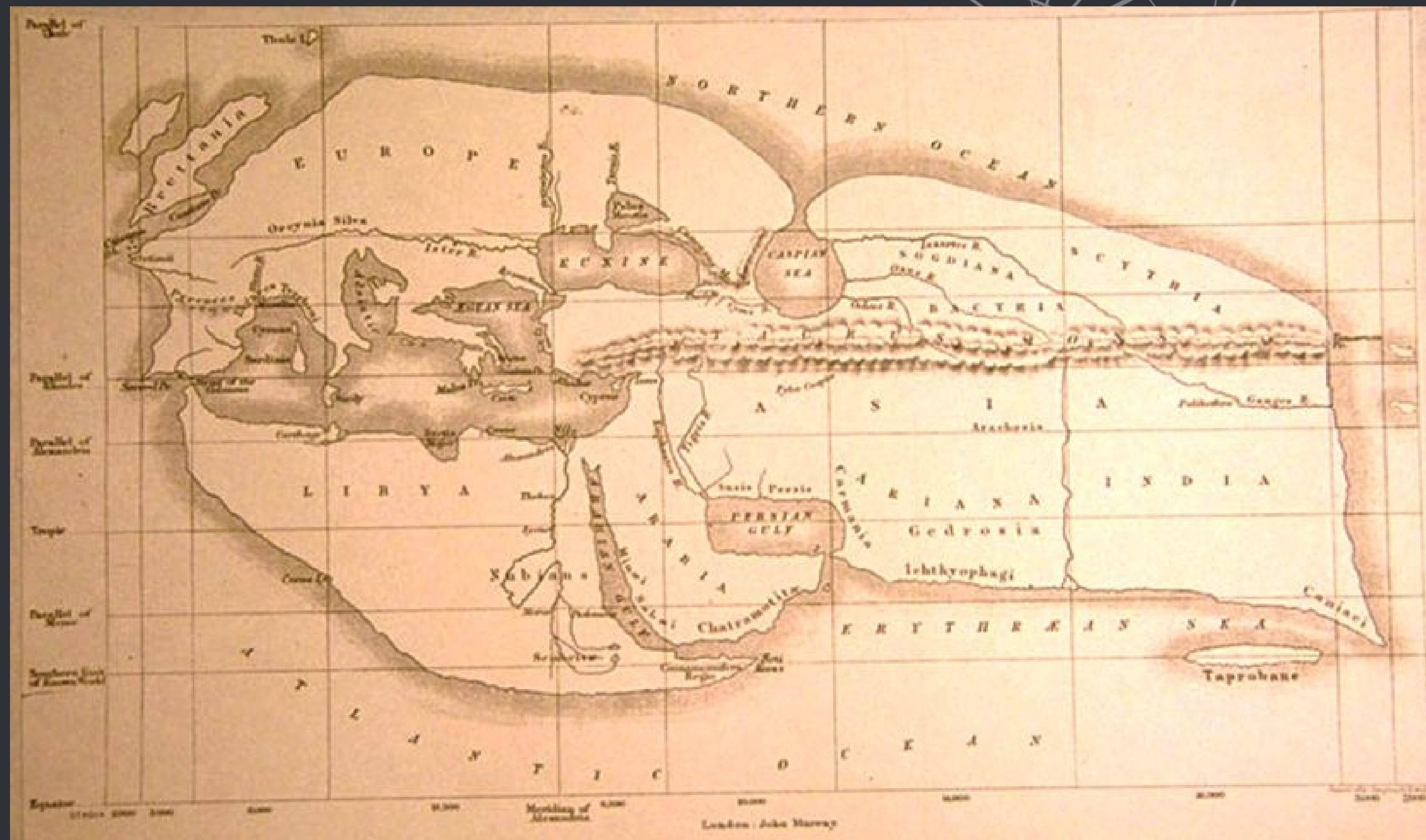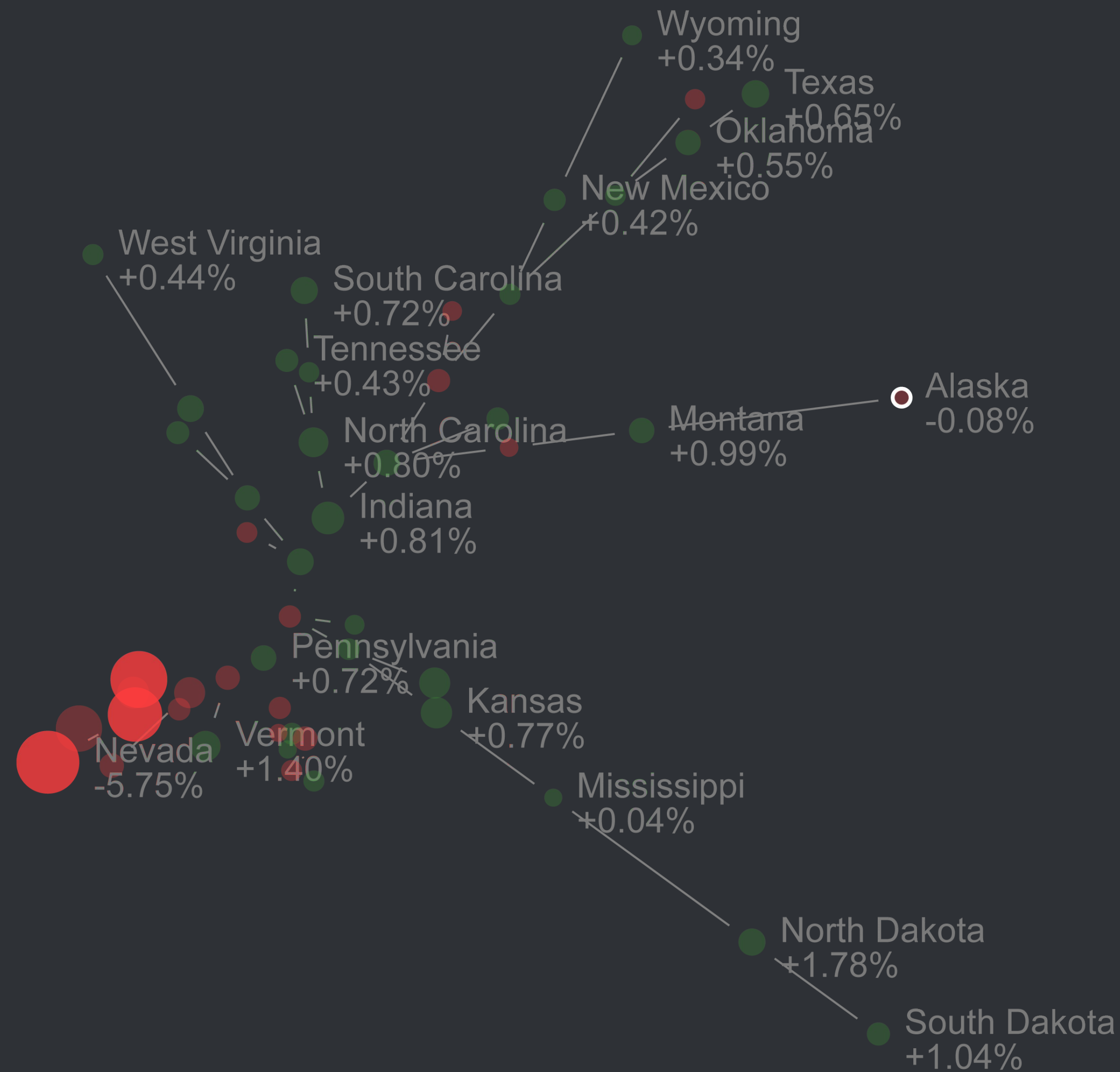The data displays a clear cascade of negative house price shocks starting in Q1 2007. Also notable is the increase in the overall level of correlations (and connectedness) from 2000 to 2014.

How to read it

Nodes represent US States. Node color reflects change in price: green is positive, and red is negative. Node size scales with the magnitude of change, bigger nodes have larger price change. Outlier movements are marked with bright colors.

Links show strongest correlations. Among these correlations, shorter link means a stronger correlation.

In this example we look at US house prices across states. We see the US states as nodes and strong correlation between house prices as link. In 2000 the tree is very spread out and prices are going slightly up. This is a time when ABS are developed with the assumption that real-estate risk can be diversified across US states.

Sat, 1 Jan 2000   < PLAY >   1 Jul 1990 - 1 Jul 2015

OUTLIER COUNT

Jan 2000   Apr 2001   Jul 2002   Oct 2003   Jan 2005   Apr 2006   Jul 2007   Jan 2009   Apr 2010   Jul 2011   Oct 2012   Jan 2014   Jul 2015

CORRELATION MAP

TREE
MAP
FOCUS

Hawaii
Idaho
Iowa
District of Columbia
Pennsylvania
South Dakota
New York
New Hampshire
Wisonsin New Jersey
Massachusetts
North Carolina
Indiana
Illinois
Virginia
Ohio Utah
Nebraska
California
West Virginia Maine Florida Arizona Washington Michigan
Colorado Oregon
South Carolina Kansas
Arkansas Wyoming Nevada
Montana
North Dakota Delaware New Mexico Mississippi
Alaska

20 JAN 2016, 10:02 EST

ALERTS 1 Oct 2003

ASSETS CORRELATIONS VOLATILITY

Range: Today 95% ▾

Top Outliers
Positive and Negative ▾

	Nevada	+2.68σ
		+5.9%
	Maryland	+2.67σ
		+5.3%
	California	+2.51σ
		+6.2%
	Florida	+2.42σ
		+4.5%
	Virginia	+2.04σ
		+4.0%
	Rhode Island	+1.99σ
		+6.3%
	Minnesota	+1.92σ
		+3.5%
	New Jersey	+1.90σ
		+4.9%
	Illinois	+1.76σ
		+3.1%

ASSET
NETWORK
STRESS
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ALERTS
PORTFOLIO
INFO
TOUR
FNA

Wed, 1 Oct 2003   ‹ PLAY ›   1 Jul 1990 - 1 Jul 2015 ▾

OUTLIER COUNT

Jan 2000 Apr 2001 Jul 2002 Oct 2003 Jan 2005 Apr 2006 Jul 2007 Jan 2009 Apr 2010 Jul 2011 Oct 2012 Jan 2014 Jul 2015

CORRELATION MAP

TREE
MAP
FOCUS

In 2003 we start to see some strong upward movements in prices in states like Nevada and we see a big cluster of bumper returns in Florida and states that have strong correlations with it.

20 JAN 2016, 10:02 EST

ASSETS   CORRELATIONS   VOLATILITY

Range: **Today 95%** ▾

Top Outliers
Positive and Negative ▾
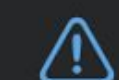
● Nevada	+4.60σ	+11.9%
● California	+3.68σ	+9.6%
● Maryland	+3.39σ	+7.1%
● Florida	+3.14σ	+6.1%
● Virginia	+3.01σ	+6.2%
● Arizona	+2.56σ	+5.8%
● New Jersey	+2.54σ	+6.5%
● Rhode Island	+2.10σ	+6.8%
● Pennsylvania	+2.09σ	+4.0%
● Minnesota	+1.85σ	+3.3%
● Delaware	+1.80σ	+5.7%
● District of Columbia	+1.68σ	

ASSET
NETWORK
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INFO
TOUR
FNA

OUTLIER COUNT

Jan 2000   Apr 2001   Jul 2002   Oct 2003   Jan 2005   Apr 2006   Jul 2007   Jan 2009   Apr 2010   Jul 2011   Oct 2012   Jan 2014   Jul 2015

CORRELATION MAP

TREE
MAP
FOCUS

Alaska
New Mexico
Wyoming   Montana
Kansas   Colorado   Alabama
Nevada
Minnesota   Oregon
District of Columbia
Virginia
California
Maryland   Ohio
Rhode Island
New Hampshire
New York
Delaware   North Carolina
Tennessee
Wisonsin   Mississippi
Arizona   Idaho
South Dakota   Kentucky   Iowa
Hawaii
North Dakota

As we move into 2004, into the peak of the housing bubble we see that most states now have outlier price changes and Nevada for example has an almost 12% rise in house prices in one quarter.

20 JAN 2016, 10:02 EST

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INFO

TOUR

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NETWORK
1 Jul 2005

≫

Positive Outliers	12
Negative Outliers	0
Scale	205.05
Number of Assets	51

☑ Center tree

SYSTEMATIC RISK
38%
38%
34%
38%

LENGTH OF TREE
18.50
15.80
15.80

ARC SURVIVAL
94%
86%

OUTLIER COUNT

Jan 2000 Apr 2001 Jul 2002 Oct 2003 Jan 2005 Apr 2006 Jul 2007 Jan 2009 Apr 2010 Jul 2011 Oct 2012 Jan 2014 Jul 2015

CORRELATION MAP

TREE

MAP

FOCUS

Alaska
New Mexico
Nevada
Wyoming
Utah
Lousiana
Oregon
Kansas
Oklahoma
Montana
Alabama
Colorado
Maine
Nebraska
North Dakota
Minnesota
District of Columbia
Illinois
Rhode Island
Virginia
Ohio
Connecticut
Florida
New Jersey
Pennsylvania
Delaware
Tennessee
Georgia
Wisonsin
Mississippi
South Carolina
Arizona
West Virginia
Michigan
Idaho
Iowa
Hawaii

As we move into 2005 we look at the length of the tree. It measures the overall correlations in this system. The shorter (smaller value) the tree, the stronger the correlations. We see that the tree has been getting shorter and shorter. The assumptions behind diversification of ABS getting eroded.

20 JAN 2016, 10:02 EST
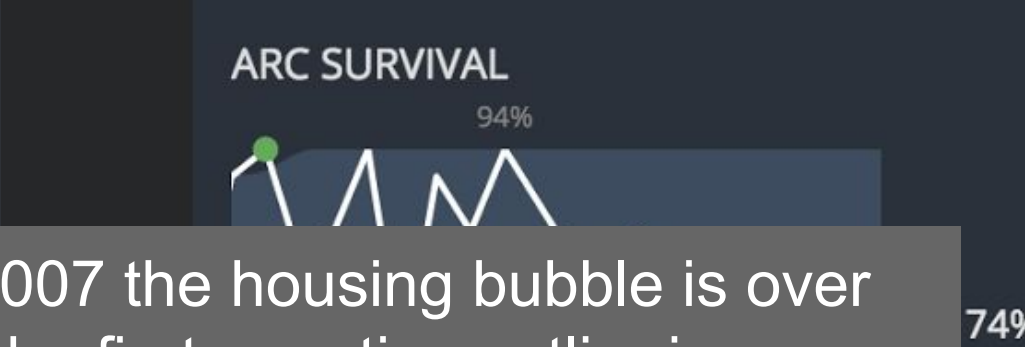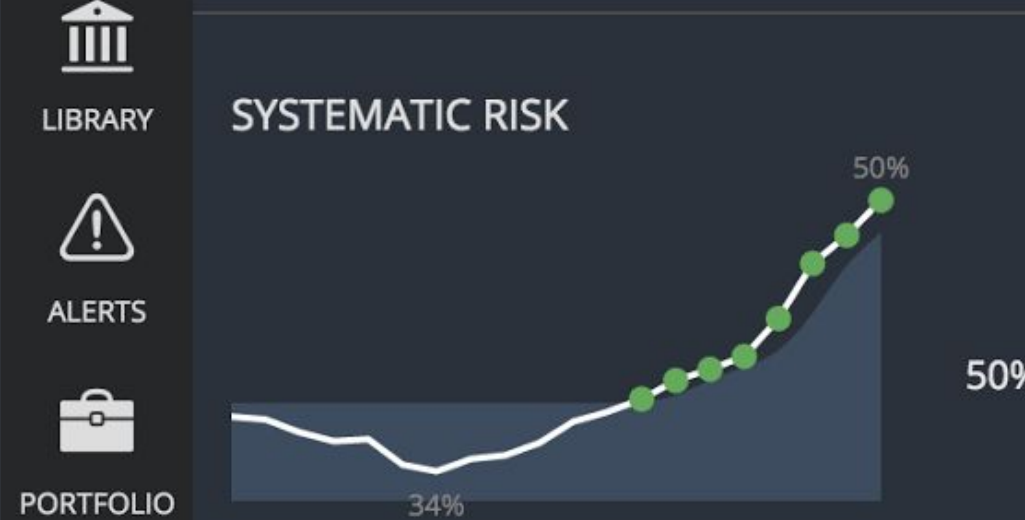
In summer 2007 the housing bubble is over and we see the first negative outlier in Florida. Most of the system has become redm, except a green branch on the left.

We also see that the tree has been getting shorter and shorter, reaching new lows each quarter. The system is becoming highly coupled.

NETWORK
1 Jul 2009
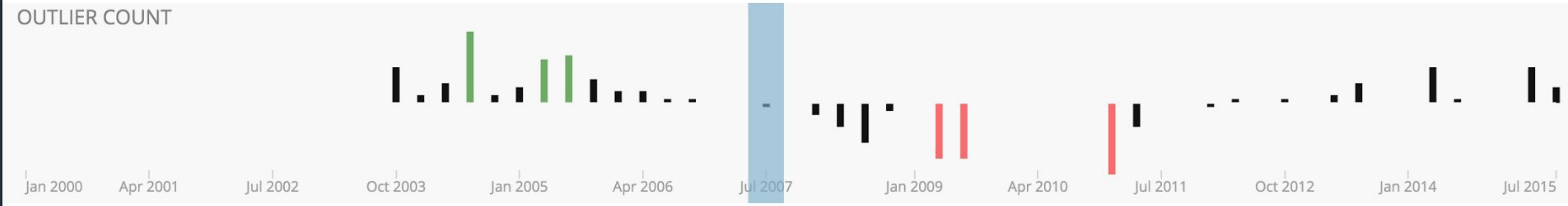
Positive Outliers — 0
Negative Outliers — 14

Scale — 375.55
Number of Assets — 51

☑ Center tree

ASSET

NETWORK

STRESS

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PORTFOLIO

INFO

TOUR

FNA

SYSTEMATIC RISK
58%

58%

35%

LENGTH OF TREE
17.17

8.29

8.29

ARC SURVIVAL
82%

Wed, 1 Jul 2009

< PLAY >

OUTLIER COUNT

0
14

14

Jan 2000   Apr 2001   Jul 2002   Oct 2003   Jan 2005   Apr 2006   Jul 2007   Jan 2009   Apr 2010   Jul 2011   Oct 2012   Jan 2014   Jul 2015

CORRELATION MAP

Jul 2009

TREE

MAP

FOCUS

Massachusetts
New Hampshire
New York
Vermont
Pennsylvania
Arizona
Delaware Florida
Virginia District of Columbia
Mississippi
Kansas
Wisonsin Missouri
Nebraska
Ohio Michigan
Indiana
Washington
Kentucky Tennessee
Oregon
Iowa
Idaho
Alabama
New Mexico
Arkansas
Lousiana Utah
Montana
Oklahoma
North Dakota
West Virginia
Alaska Wyoming
South Dakota

In 2009 we reach the peak crisis. The system has become largely red with many central states as negative outliers.

We can look at another metric on the left. Systematic risk measures how much changes in the system are driven by the largest single factor, and how much by idiosyncratic - state level - factors. We see that the system is quickly becoming governed by a single factor affecting all states.

20 JAN 2016, 10:02 EST

The same dynamics continue with the "double dip" in 2011.

ASSET

NETWORK

STRESS

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ALERTS

PORTFOLIO

INFO

TOUR

FNA

NETWORK
1 Apr 2012

Positive Outliers   1 |
Negative Outliers   0

Scale   325.54
Number of Assets   51

☑ Center tree

SYSTEMATIC RISK

50%

63%

63%

LENGTH OF TREE

11.46

7.03

7.03

ARC SURVIVAL

96%

88%
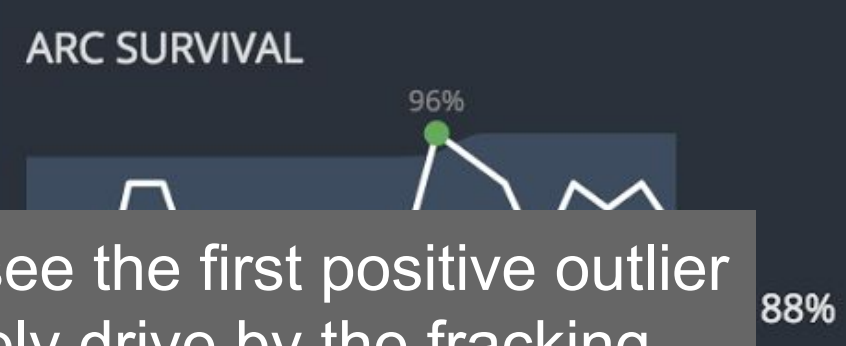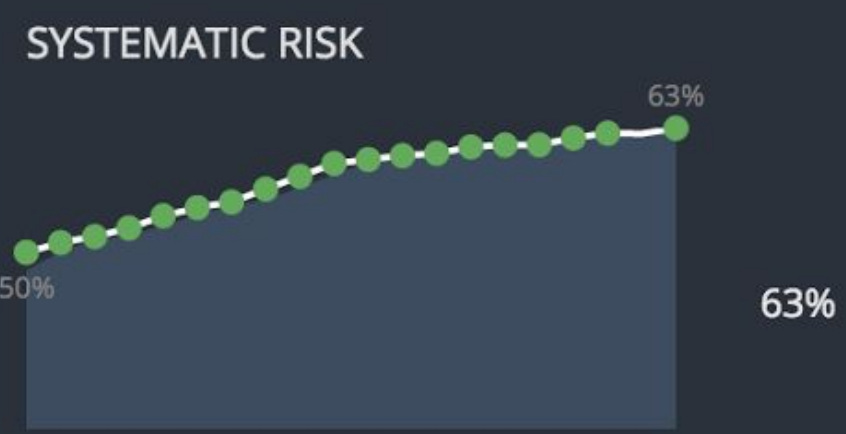
In Spring 2012 we see the first positive outlier in North Dakota, likely drive by the fracking boom. The rest of the system is still mostly negative.

OUTLIER COUNT
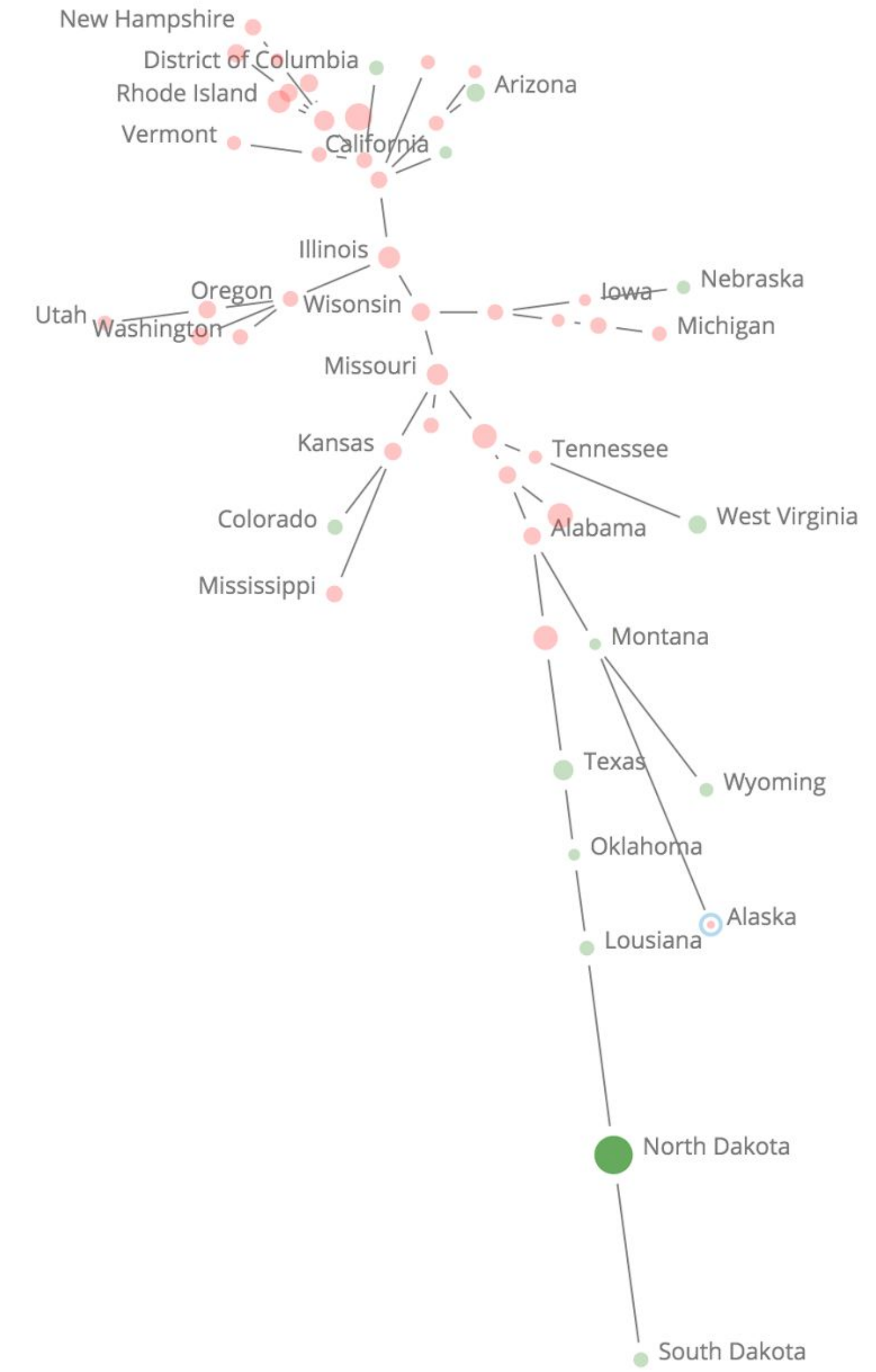
Jan 2000   Apr 2001   Jul 2002   Oct 2003   Jan 2005   Apr 2006   Jul 2007   Jan 2009   Apr 2010   Jul 2011   Oct 2012   Jan 2014   Jul 2015

CORRELATION MAP

New Hampshire
District of Columbia
Rhode Island
Arizona
Vermont
California
Illinois
Oregon
Iowa   Nebraska
Utah
Wisonsin
Washington
Michigan
Missouri
Kansas
Tennessee
Colorado
Alabama   West Virginia
Mississippi
Montana
Texas
Wyoming
Oklahoma
Alaska
Lousiana
North Dakota
South Dakota

TREE

MAP

FOCUS

+

−

20 JAN 2016, 10:02 EST

NETWORK
1 Jul 2015

Positive Outliers	4
Negative Outliers	0
Scale	466.48
Number of Assets	51

☑ Center tree

SYSTEMATIC RISK

61%
71%
71%

LENGTH OF TREE

7.43
5.40
5.40

ARC SURVIVAL

96%
88%

ASSET
NETWORK
STRESS
LIBRARY
ALERTS
PORTFOLIO
INFO
TOUR
FNA

Wed, 1 Jul 2015

< PLAY >

1 Jul 1990 - 1 Jul 2015 ▾

OUTLIER COUNT

Jan 2000   Apr 2001   Jul 2002   Oct 2003   Jan 2005   Apr 2006   Jul 2007   Jan 2009   Apr 2010   Jul 2011   Oct 2012   Jan 2014   Jul 2015

CORRELATION MAP

TREE
MAP
FOCUS

Massachusetts
New Hampshire
District of Columbia
Vermont
Hawaii
New Jersey
Pennsylvania
California
Nevada Florida
Arizona
South Dakota
Colorado
Oregon
Nebraska
Illinois
Iowa
Utah
Missouri
Ohio
Michigan
Wisonsin
Minnesota
Texas
South Carolina
North Carolina
North Dakota
Georgia
Tennessee
Lousiana
Mississippi
Arkansas
West Virginia
Montana
Wyoming
Alaska
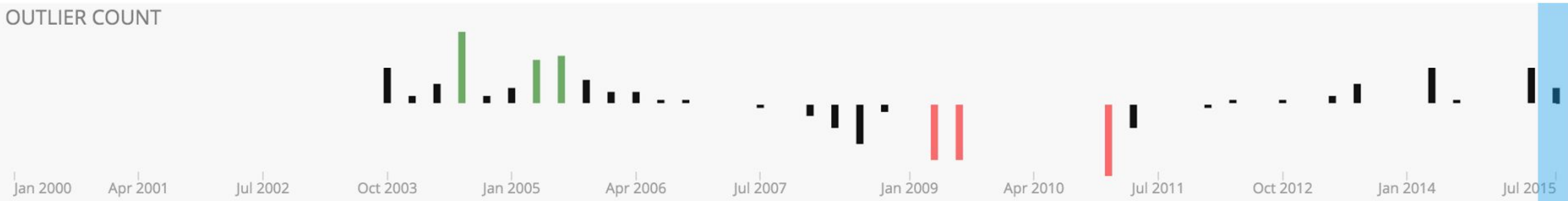
If we fast forward to the latest observation, July 2015, we see a period of positive changes in prices with outliers scattered across the network.

We also see both systematic risk and correlations at their peak. We have not returned to the pre-bubble system state but are in a very risky territory still..

20 JAN 2016, 10:02 EST

NETWORK
1 Jul 2005

Positive Outliers	12
Negative Outliers	0
Scale	121.57
Number of Assets	51

☐ Center tree

SYSTEMATIC RISK
38%
34%
38%

LENGTH OF TREE
18.50
15.80
15.80

ARC SURVIVAL
94%
86%

ASSET

NETWORK

STRESS

LIBRARY

ALERTS

PORTFOLIO

INFO

TOUR

FNA

OUTLIER COUNT

Jan 2000 · Apr 2001 · Jul 2002 · Oct 2003 · Jan 2005 · Apr 2006 · Jul 2007 · Jan 2009 · Apr 2010 · Jul 2011 · Oct 2012 · Jan 2014 · Jul 2015

CORRELATION MAP

TREE

MAP

FOCUS

Alaska

New Mexico

Nevada

Wyoming

Oregon

Utah

Lousiana

Kansas

Montana

Colorado

Nebraska

Maine

Minnesota

District of Columbia

Virginia

Missouri

Ohio

Florida

Pennsylvania

Delaware

Tennessee

Wisonsin

South Carolina

Arizona

Michigan

Idaho

Iowa

Hawaii

Then at the peak of the bubble in 2005.
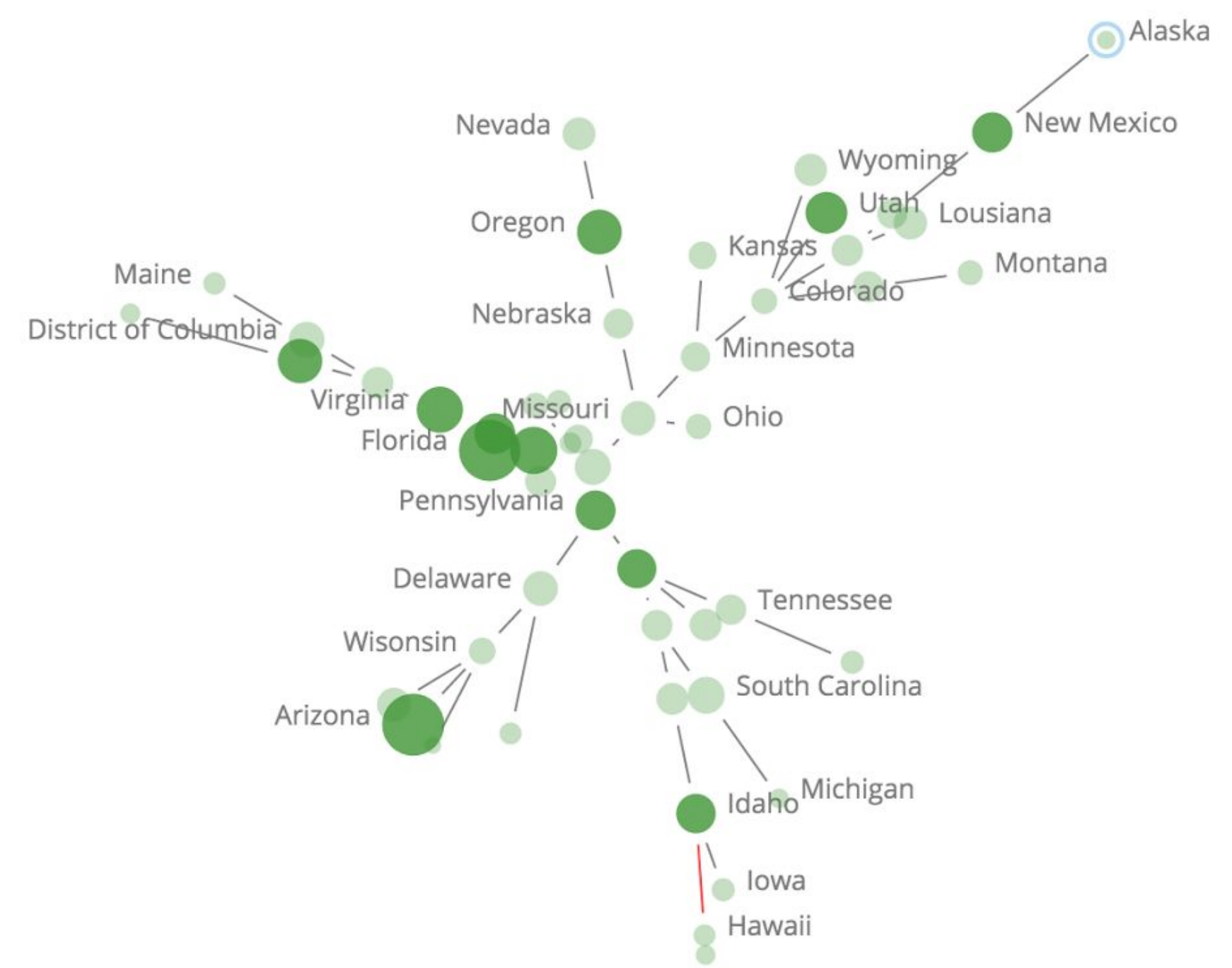
NETWORK
1 Jul 2009

»

Positive Outliers	0
Negative Outliers	14

Scale	121.57
Number of Assets	51

☐ Center tree

ASSET
NETWORK
STRESS
LIBRARY
ALERTS
PORTFOLIO
INFO
TOUR

SYSTEMATIC RISK

58%

58%

35%

LENGTH OF TREE

17.17

8.29

8.29

ARC SURVIVAL

94%

82%
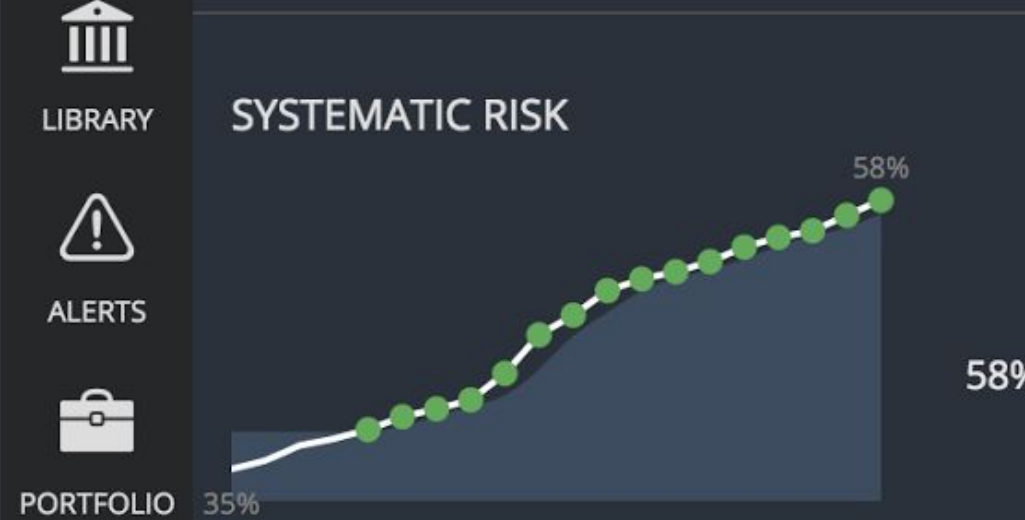
Then at the peak of the crisis in 2009.
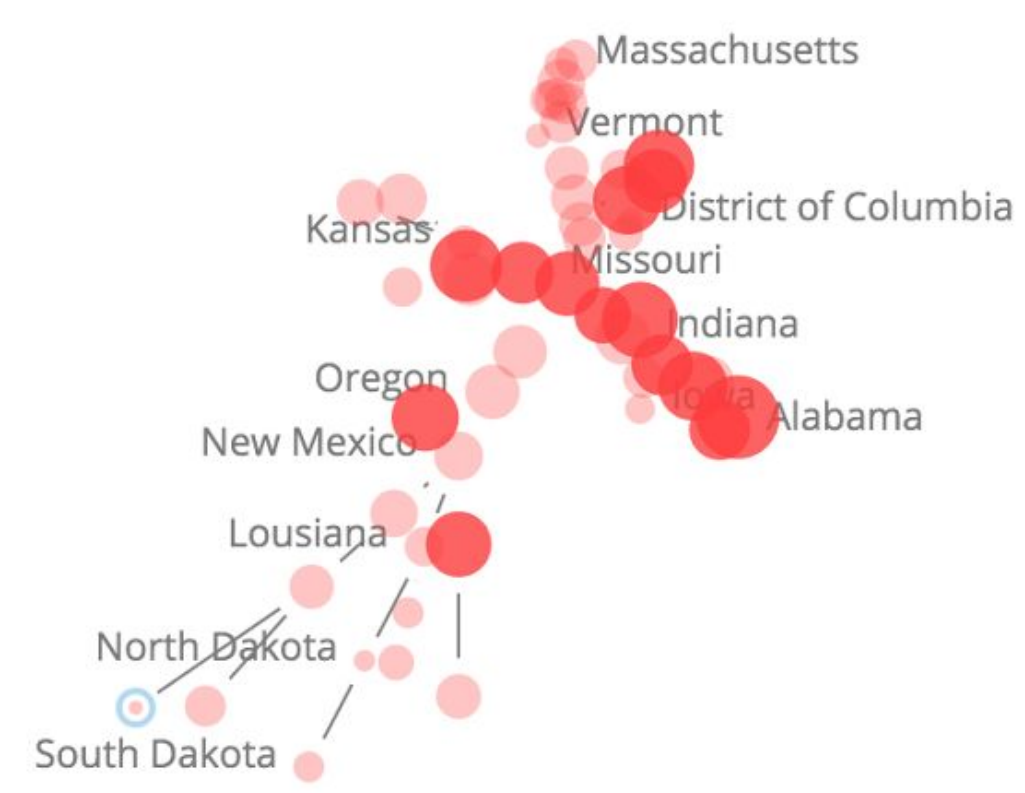
OUTLIER COUNT

0
14

| Jan 2000 | Apr 2001 | Jul 2002 | Oct 2003 | Jan 2005 | Apr 2006 | Jul 2007 | Jan 2009 | Apr 2010 | Jul 2011 | Oct 2012 | Jan 2014 | Jul 2015 |

Jul 2009

CORRELATION MAP

TREE

MAP

FOCUS

Massachusetts
Vermont
District of Columbia
Kansas
Missouri
Indiana
Oregon
Alabama
New Mexico
Lousiana
North Dakota
South Dakota

FNA

ASSET

NETWORK

STRESS

LIBRARY

ALERTS

PORTFOLIO

INFO

TOUR

FNA

Positive Outliers   4
Negative Outliers   0

Scale   121.57
Number of Assets   51

☐ Center tree

SYSTEMATIC RISK

71%

61%

71%

LENGTH OF TREE

7.43

5.40

5.40

ARC SURVIVAL

96%

88%

Wed, 1 Jul 2015   < PLAY >   1 Jul 1990 - 1 Jul 2015 ▾

OUTLIER COUNT

Jan 2000   Apr 2001   Jul 2002   Oct 2003   Jan 2005   Apr 2006   Jul 2007   Jan 2009   Apr 2010   Jul 2011   Oct 2012   Jan 2014   Jul 2015

CORRELATION MAP

TREE

MAP

FOCUS

District of Columbia
California
Arizona
Oregon
Minnesota
Lousiana
Wyoming
Alaska

Colorado
Michigan
North Dakota
Tennessee
West Virginia

And now.

The tree has shrunk during the whole period. The correlations are now stronger than ever.

Such slow moving change is hard to notice when focusing on daily events. Like in the story of the frog put in water that is gradually heated.
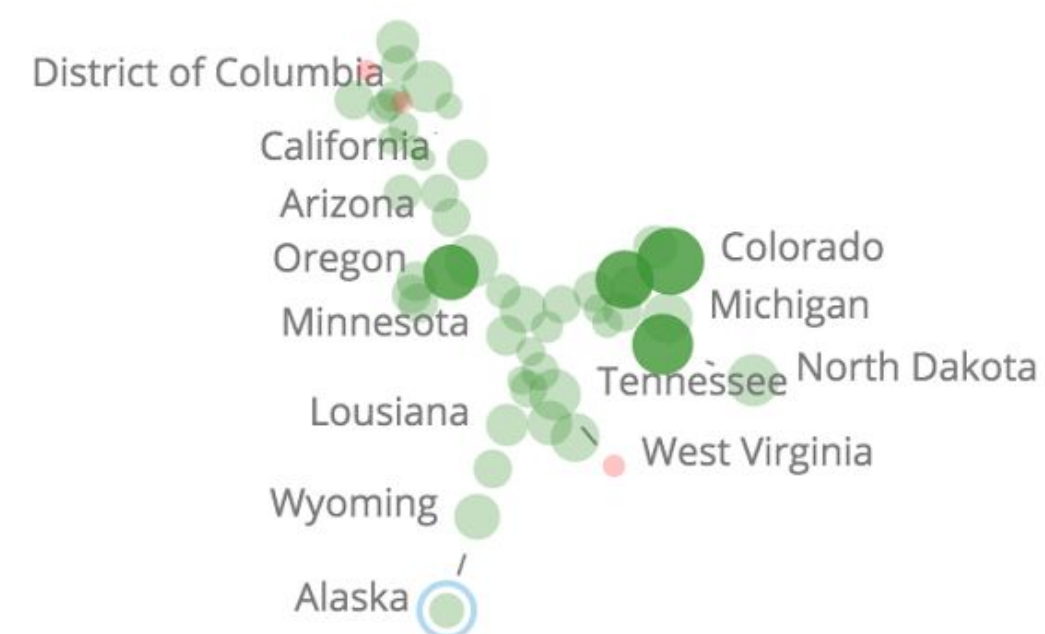
20 JAN 2016, 10:02 EST

Example: China hard landing
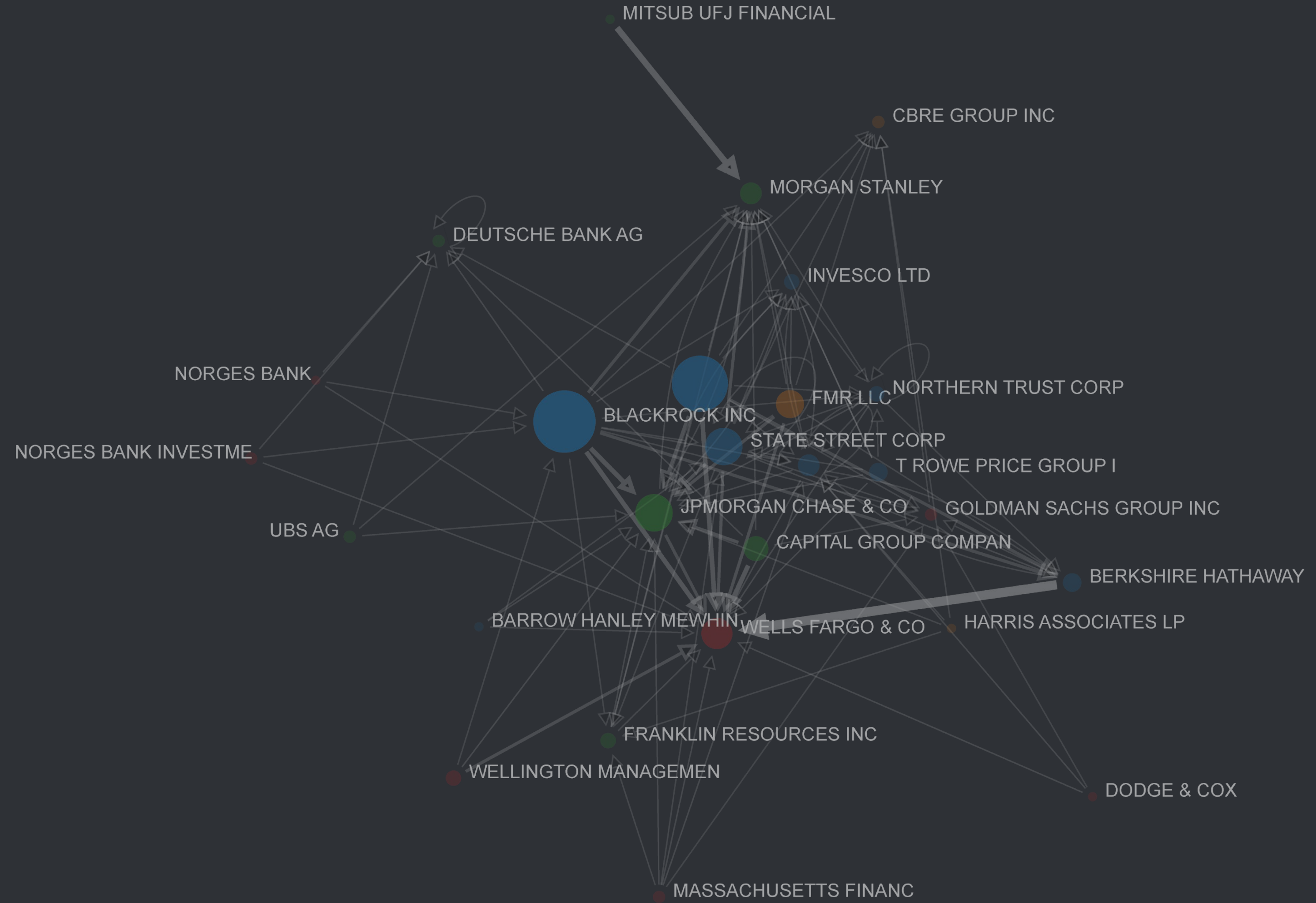
NETWORK
22 Jun 2016

Positive Outliers	0
Negative Outliers	0
Scale	249.73
Number of Assets	39

☑ Auto scale

+ Add Charts

LARGEST FACTOR ✕

45%
39%
43%

2ND LARGEST FACTOR ✕

28%
20%
22%

TREE LENGTH ✕

7.27
7.01

ASSET
NETWORK
LINK
STRESS
LIBRARY
ALERTS
PORTFOLIO
INFO
MAPPINGS

FNA

OUTLIER COUNT

24 Jun 2015   4 Aug 2015   9 Sep 2015   14 Oct 2015   18 Nov 2015   24 Dec 2015   2 Feb 2016   9 Mar 2016   14 Apr 2016   19 May 2016   24 Jun 2016

CORRELATION MAP

TREE
MAP
FOCUS

Utilities
Barclays 1-3Y US
Barclays 1-7Y US
Corp Bonds
TIPS
Silver
Gold
Gold Miners
JPY
CHF
USD Index
Commodities
Oil
Energy
EMBI
High Yield Bnds
UK
China
GBP
Japan
DJIA
Tech
CAD
Materials
VIX ST Futures
Real Estate
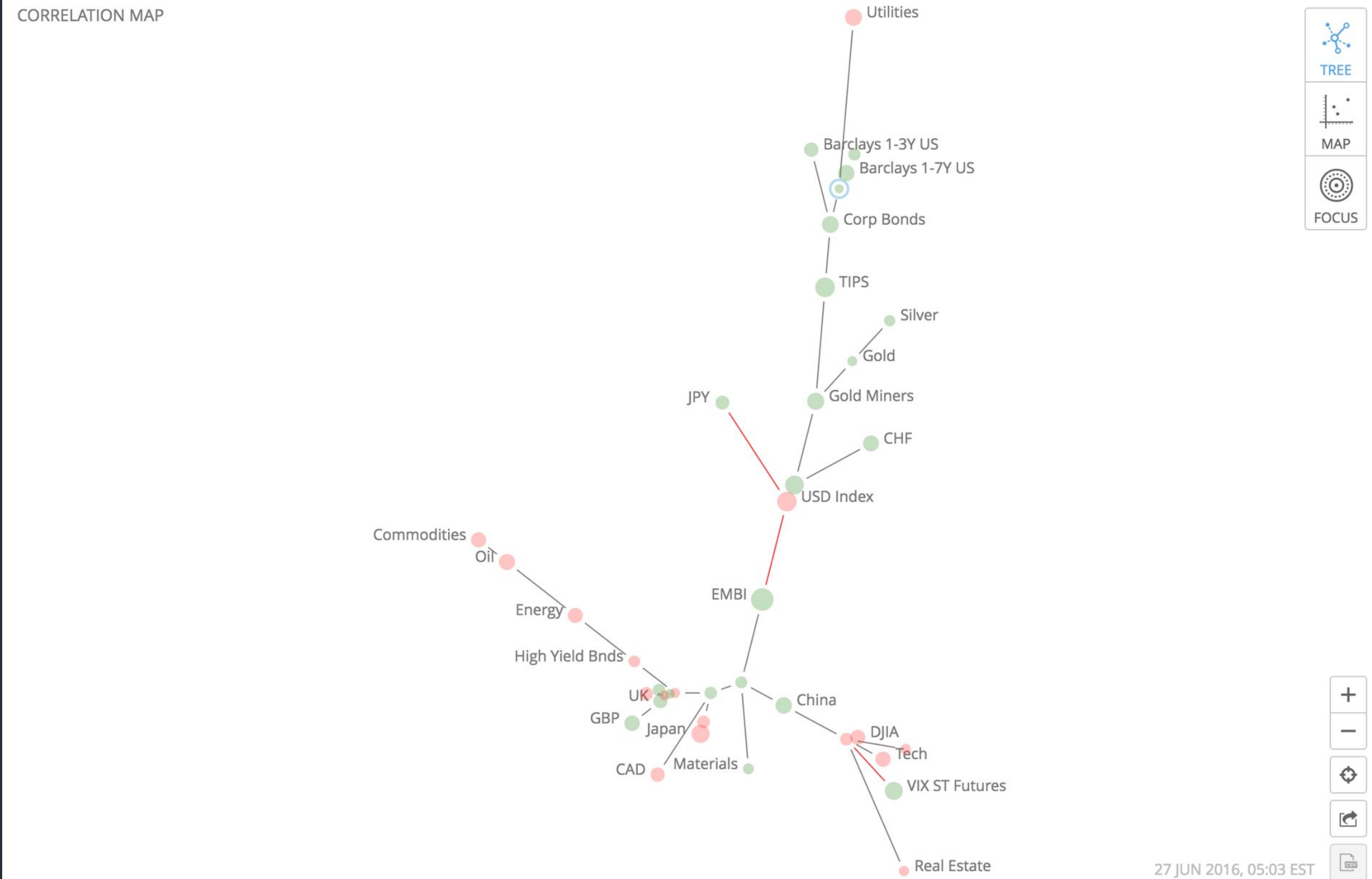
Here we see a correlation map showing the broad global markets. We see different asset classes cluster together, eg oil-energy, precious metals, bonds and equities clustered in the center.

27 JUN 2016, 05:03 EST
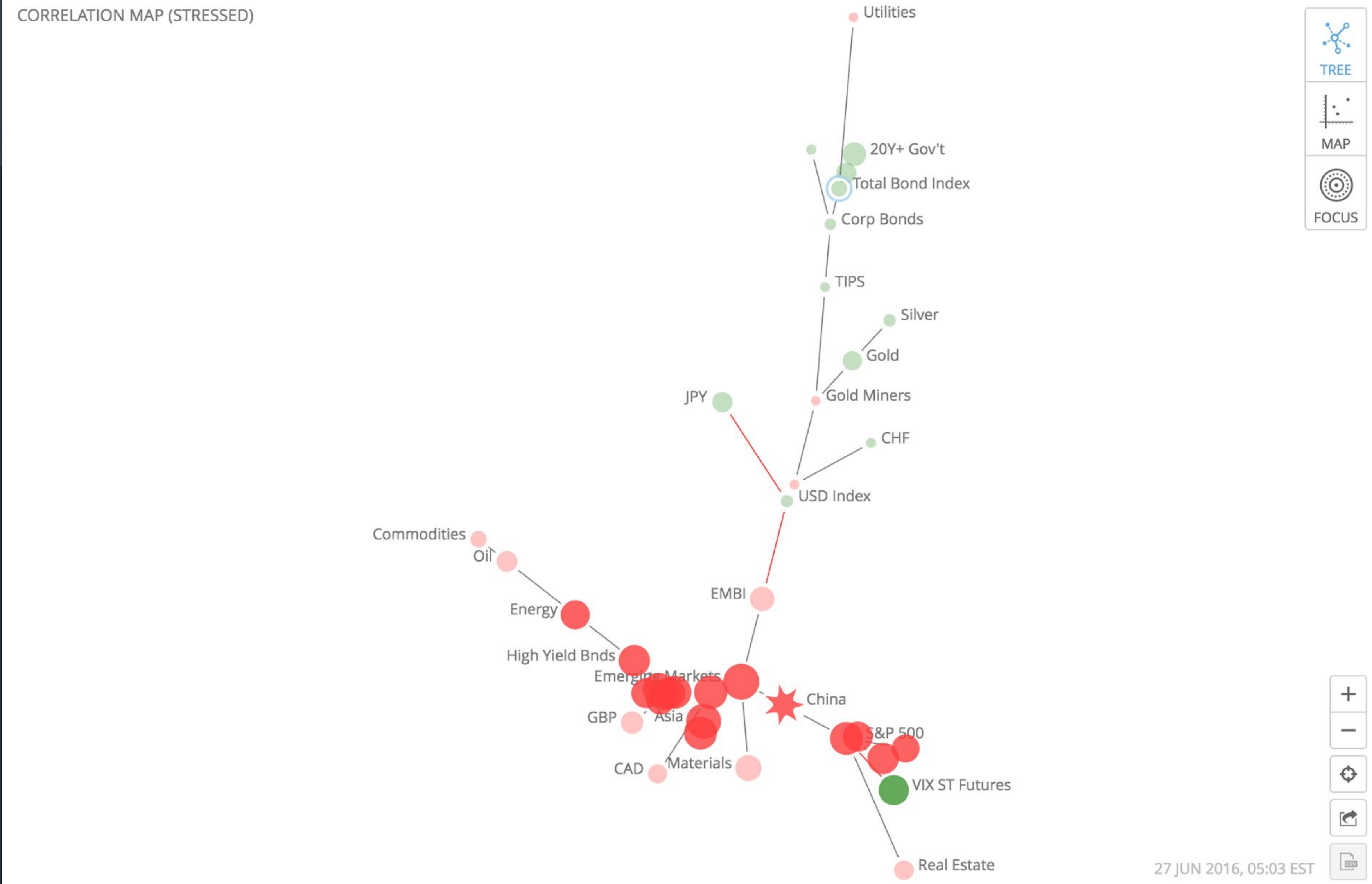
Many people are worried about China. Here we do a stress test shocking Chinese equity markets 4.5% down.

We see the impact in the network. A shock like this would, based on currently observed correlations, be accompanied by large downward movements in many markets - with VIX futures and Japanese Yean having strong positive moves.

STRESS TEST

+ Add Stress Node

▶ ADJUST MAPPING...

Input parameters:

Current Network

Correlation Scale

+0.0%

-10.0% -6.7% -3.3% +0.0% +3.3% +6.7% +10.0%

Original correlation (mean):	+0.53
Adjusted correlation (mean):	+0.53
Length of the tree:	4.68

☑ Show stress test results

CHINA ✕

Stress magnitude

-3.0σ (-7.9%)

-3.0σ -2.0σ -1.0σ +0.0σ +1.0σ +2.0σ +3.0σ
-7.9% -5.3% -2.6% +0.0% +2.6% +5.3% +7.9%

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MAPPINGS

FNA

Thu, 27 Aug 2015   ‹ PLAY ›   24 Jun 2015 - 24 Jun 2016 ▾

TREE LENGTH

8.16

24 Jun 2015   4 Aug 2015   9 Sep 2015   14 Oct 2015   18 Nov 2015   24 Dec 2015   2 Feb 2016   9 Mar 2016   14 Apr 2016   19 May 2016   24 Jun 2016 04

CORRELATION MAP (STRESSED)

GBP

Corp Bonds

CHF

USD Index

Barclays 1-7Y US

JPY

Commodities

Oil

Barclays 1-3Y US

EMBI

Germany

UK

France

China

Asia

Asia ex Japan

S&P 500

Materials

Energy

Utilities

CAD

Gold Miners

Silver

Gold
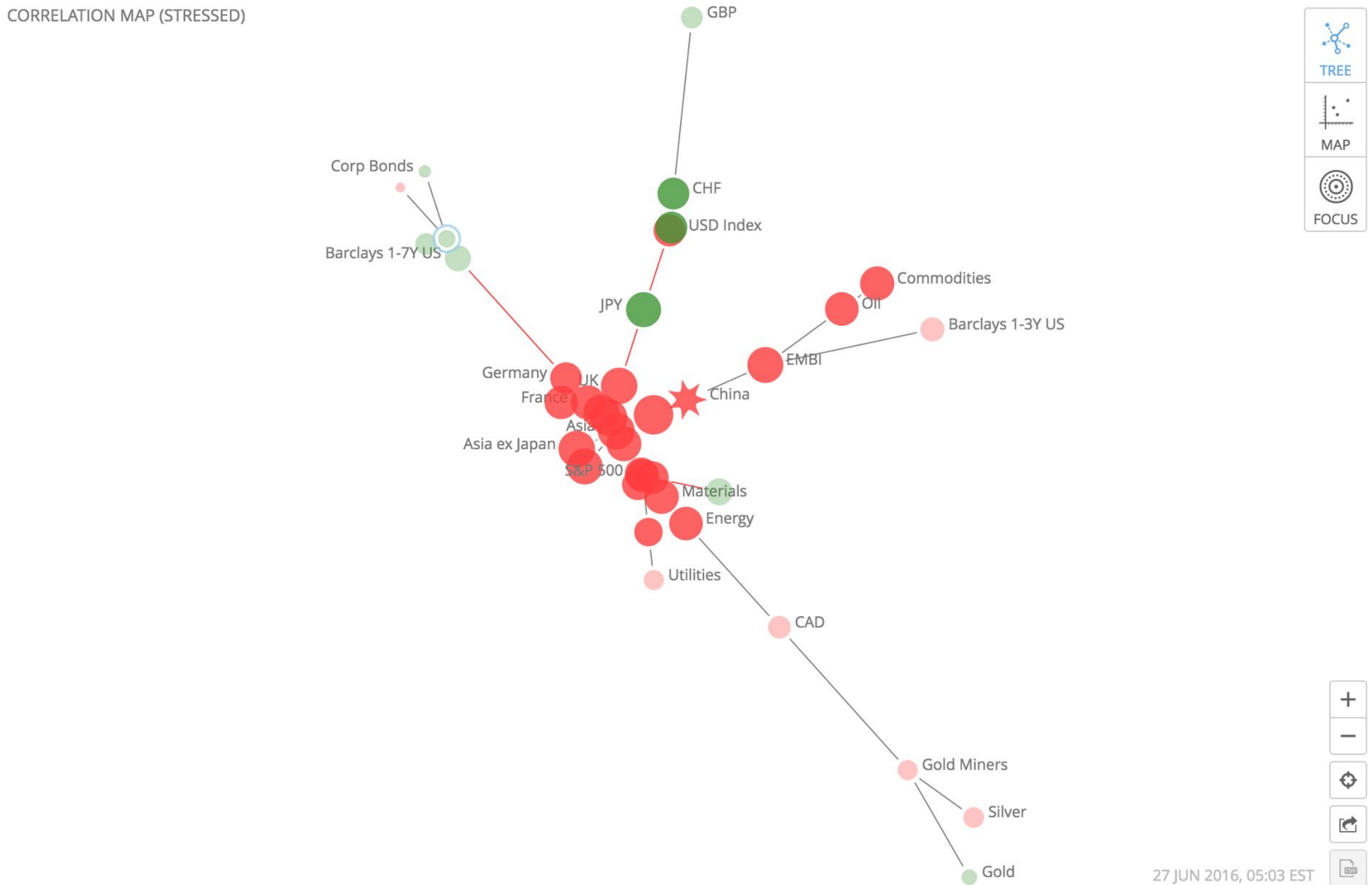
TREE

MAP

FOCUS

The impact would have been worse during the time period of strongest correlations, the August sell-off

27 JUN 2016, 05:03 EST

STRESS TEST

+ Add Stress Node ▾

▶ ADJUST MAPPING...

Input parameters:

Current Network ▾

Correlation Scale ⚙

+30.0%

-10.0% -3.3% +3.3% +10.0% +16.7% +23.3% +30.0%

Original correlation (mean):	+0.53
Adjusted correlation (mean):	+0.58
Length of the tree:	6.11

☑ Show stress test results

CHINA ✕

Stress magnitude ⚙

-3.0σ (-7.9%)

-3.0σ -2.0σ -1.0σ +0.0σ +1.0σ +2.0σ +3.0σ
-7.9% -5.3% -2.6% +0.0% +2.6% +5.3% +7.9%

ASSET

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INFO

MAPPINGS

FNA

TREE LENGTH

8.16

24 Jun 2015 4 Aug 2015 9 Sep 2015 14 Oct 2015 18 Nov 2015 24 Dec 2015 2 Feb 2016 9 Mar 2016 14 Apr 2016 19 May 2016 24 Jun 2016

CORRELATION MAP (STRESSED)

TREE

MAP

FOCUS

Corp Bonds
TIPS

GBP

Total Bond Index

CHF

Barclays 1-7Y US

JPY

Commodities

Oil

Germany

Barclays 1-3Y US

EMBI

China

Emerging Ma...
High Yield Bnds

Financials

Materials

Energy

Utilities

CAD

Gold Miners

Silver

Gold

And even worse if we also increase overall correlations from 0.53 to 0.58.
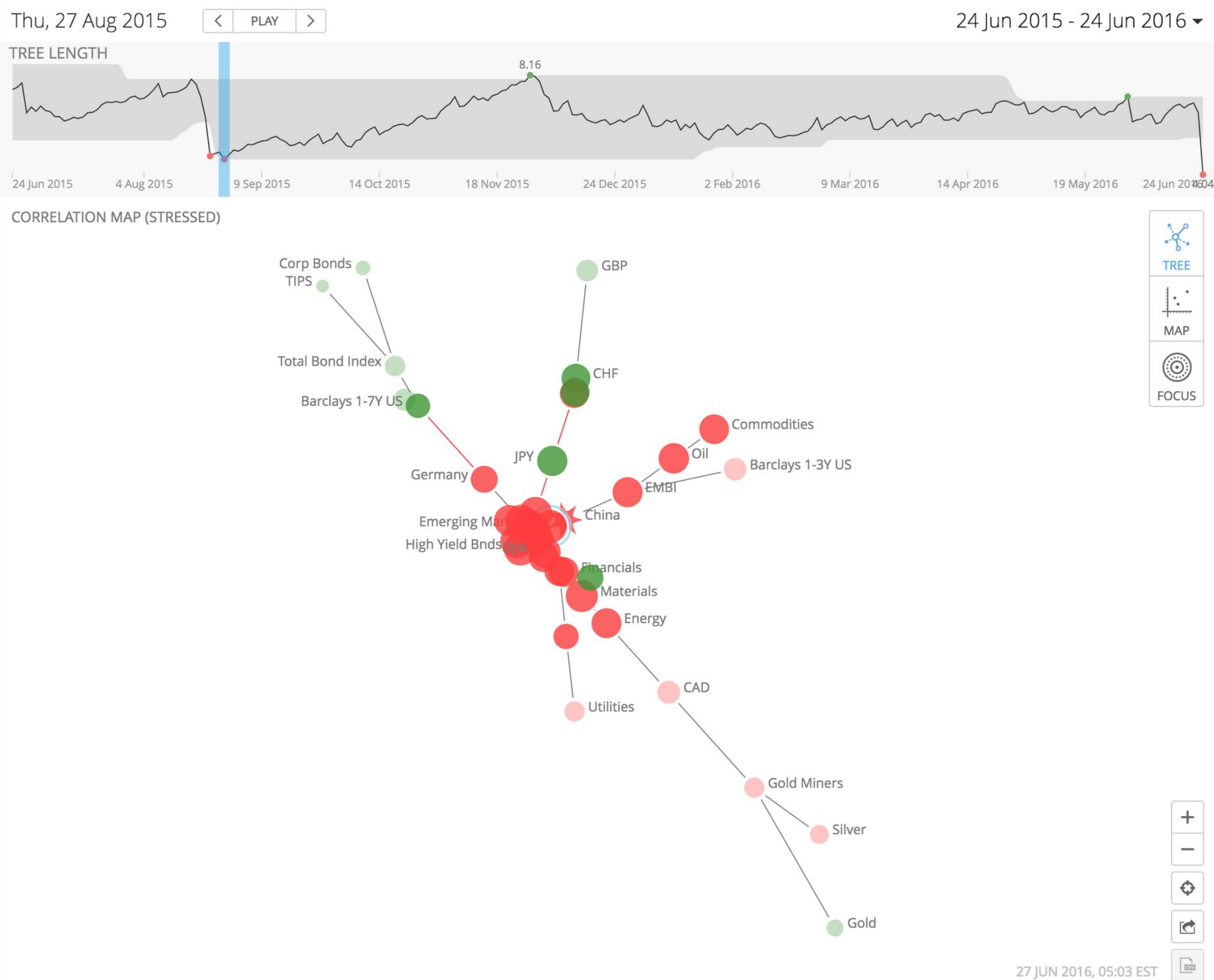
27 JUN 2016, 05:03 EST
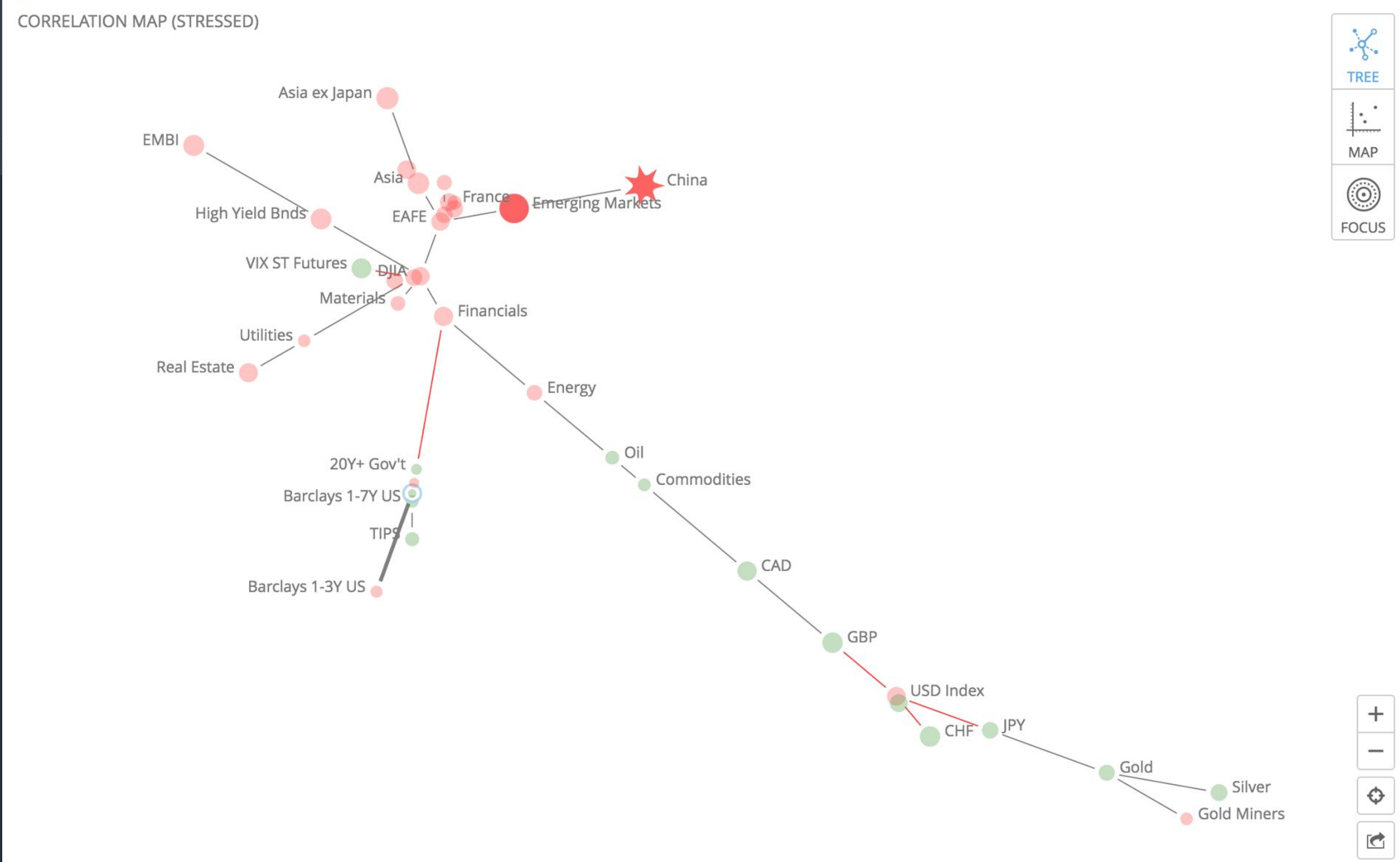
However, had we done this stress test with the correlation structure experience in early 2015, the impact would have been mostly contained to Asian markets.

China became very central in the global markets during 2015.
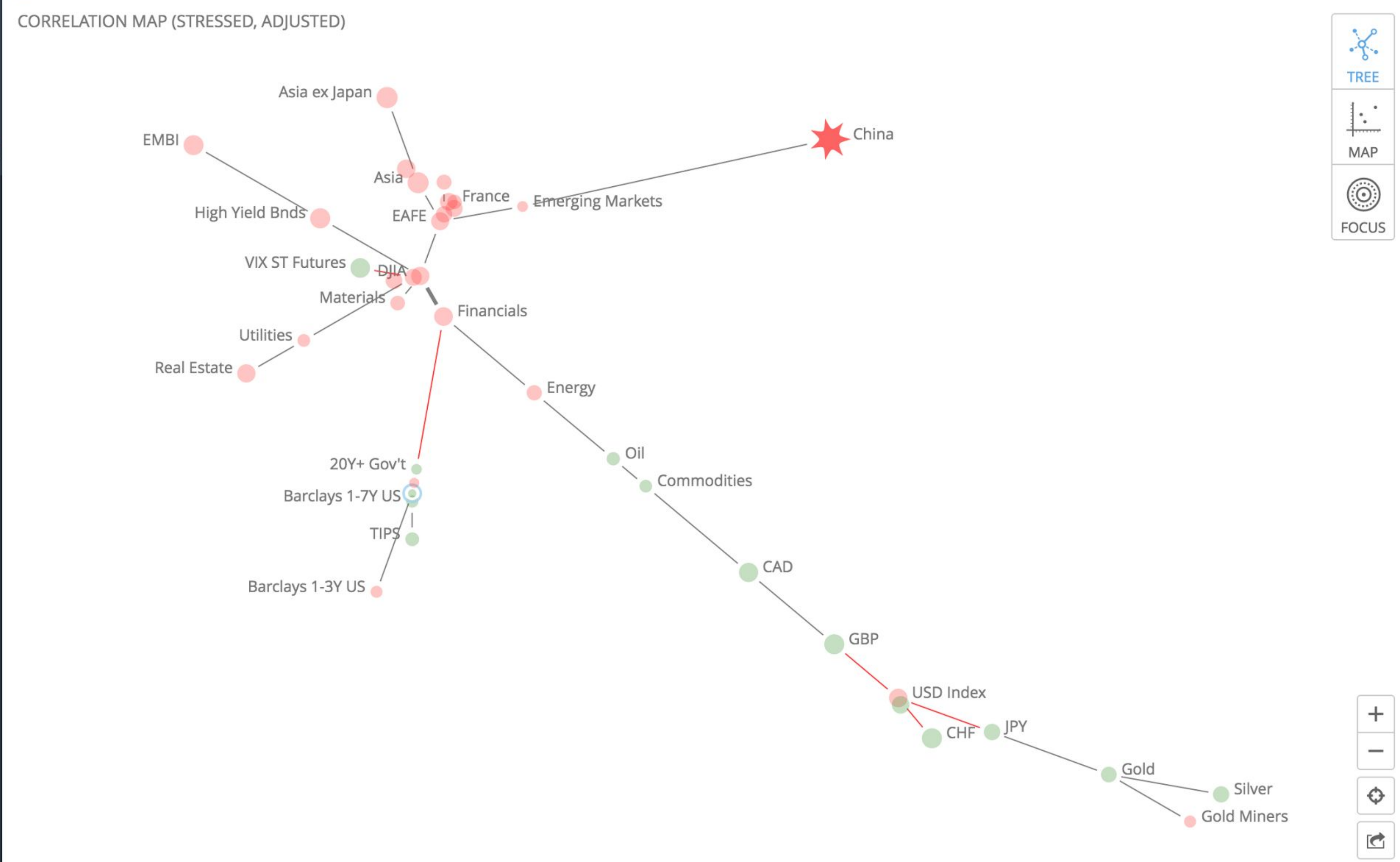
Conclusions

Visual methods based on networks allow us to:

* understand correlations structures of much larger scale than often done before.

* conveniently develop correlation scenarios based on historical structures

* create new correlation structures

-> Correlations become a subjective variable in the stress test

FNA
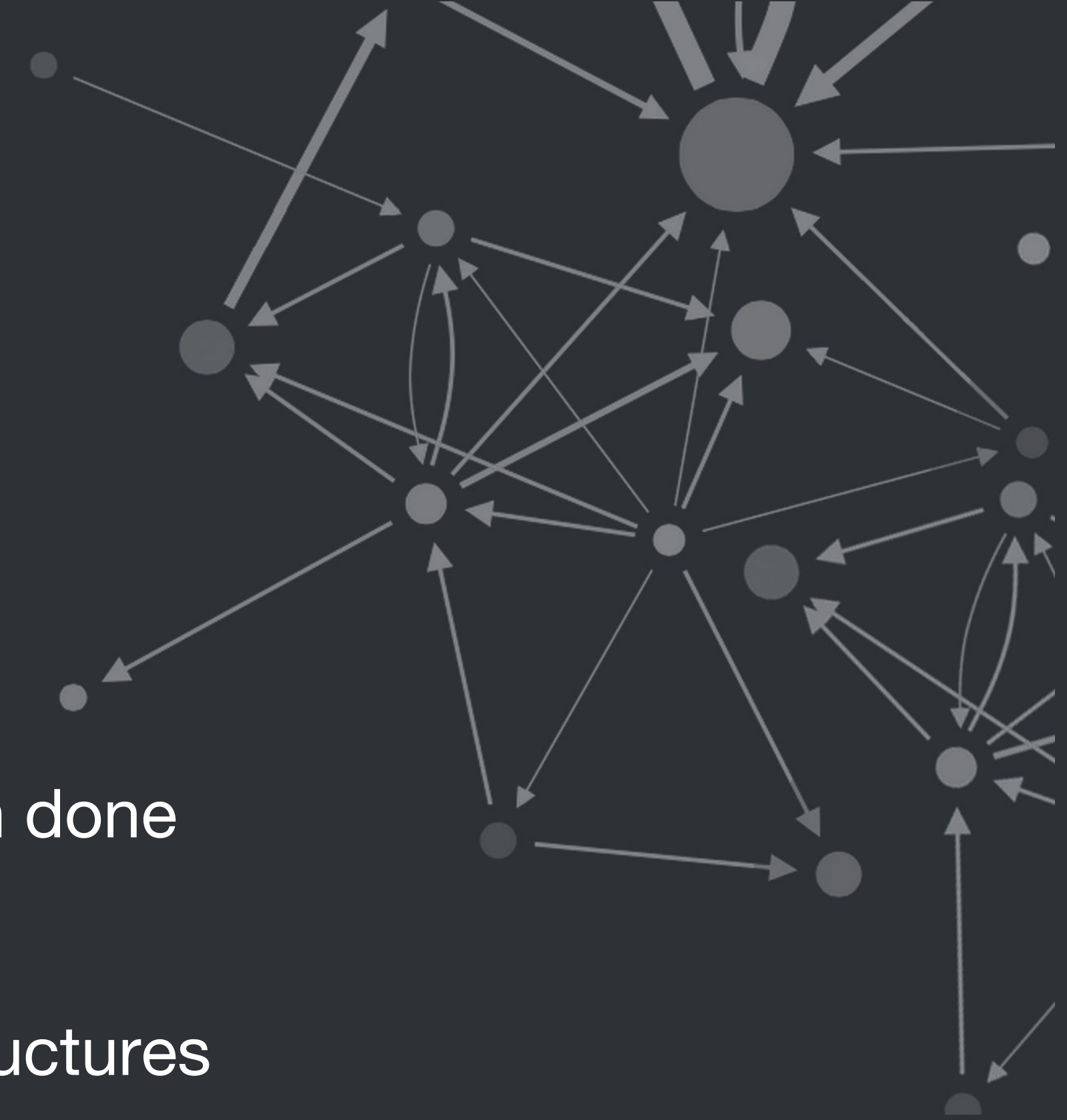
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