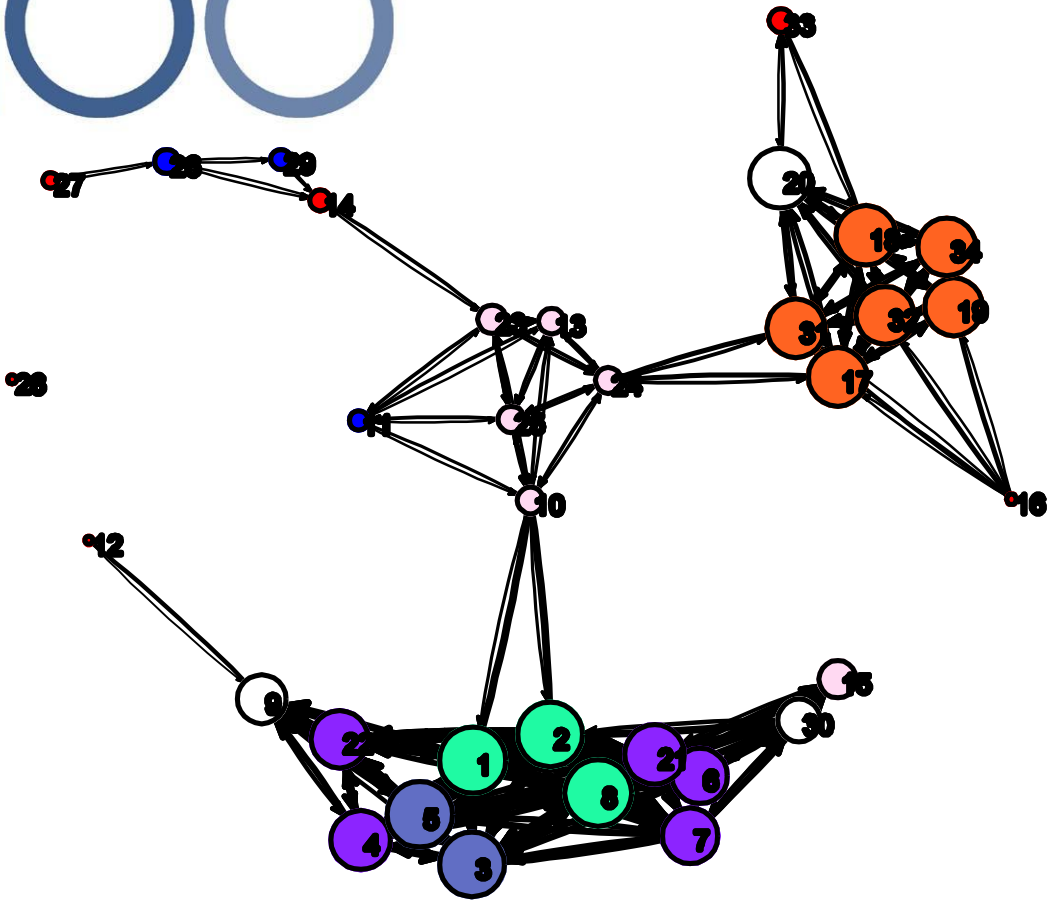
Imperial College London

100 years of living science

ECCS07 Dresden
Oct 1st – 3rd 2007

Tim Evans
Theoretical Physics

Networks in Archaeology



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Acknowledgements

- Work done with
  - **Carl Knappett (Exeter)**
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  - **Edmund Hunt (Imperial)**

- Initiated through the **ISCOM** project
  Complexity Perspectives on Innovation and Social Change
  D.Lane, D.Pumain, S. van der Leeuw and G.West (eds)
  (Springer Methodos series, 2007)

- Previous Models without Networks
- Previous Network Models
- Our Model
  - The Middle Bronze Age Aegean and the Minoans
- Summary

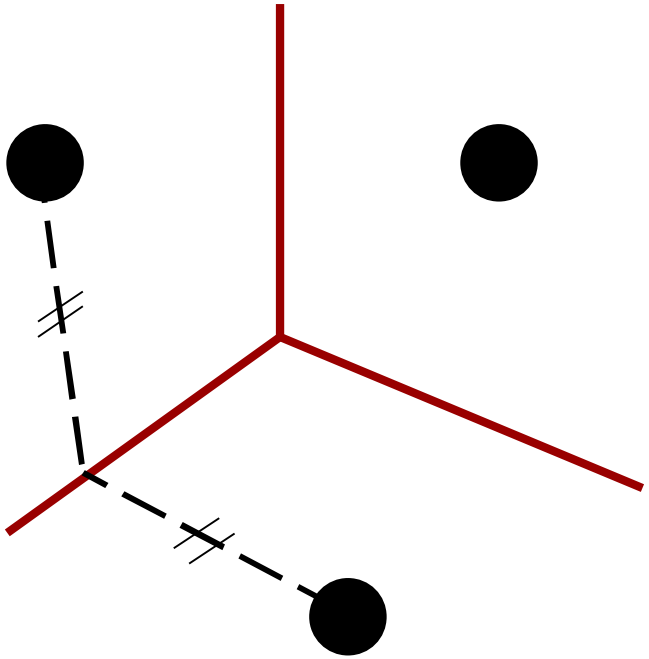
Site-Site Interactions

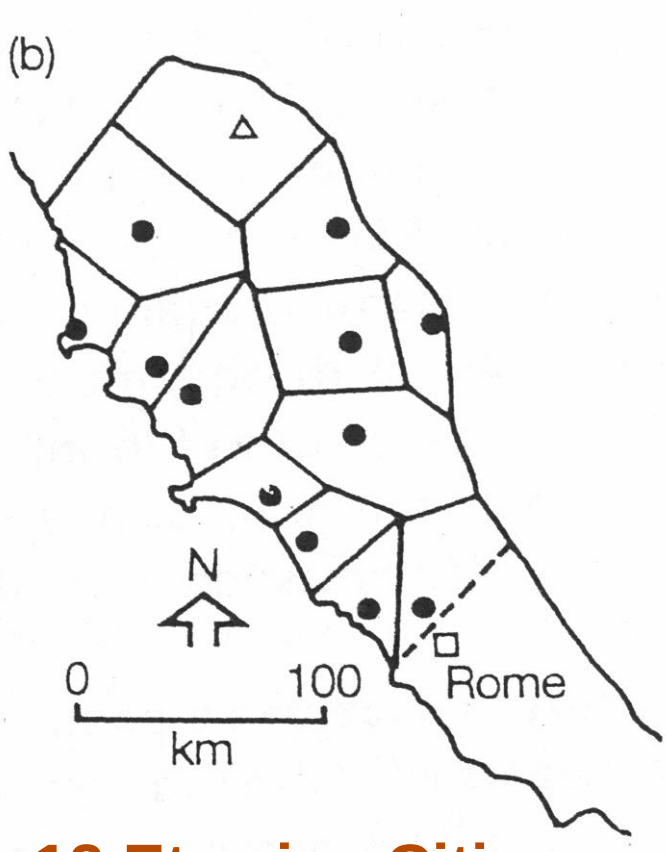
- Archaeology has given little attention to the role of interactions between sites in the generation of those sites.
  - Local (often just nearest neighbour) interactions considered sometimes but usually regional and global interactions neglected.
  - Most models use fixed site sizes

$\Rightarrow$ Network models may prove to be useful

Theissen Polygons

- Boundaries = Midpoint between nearest sites
- All sites equal

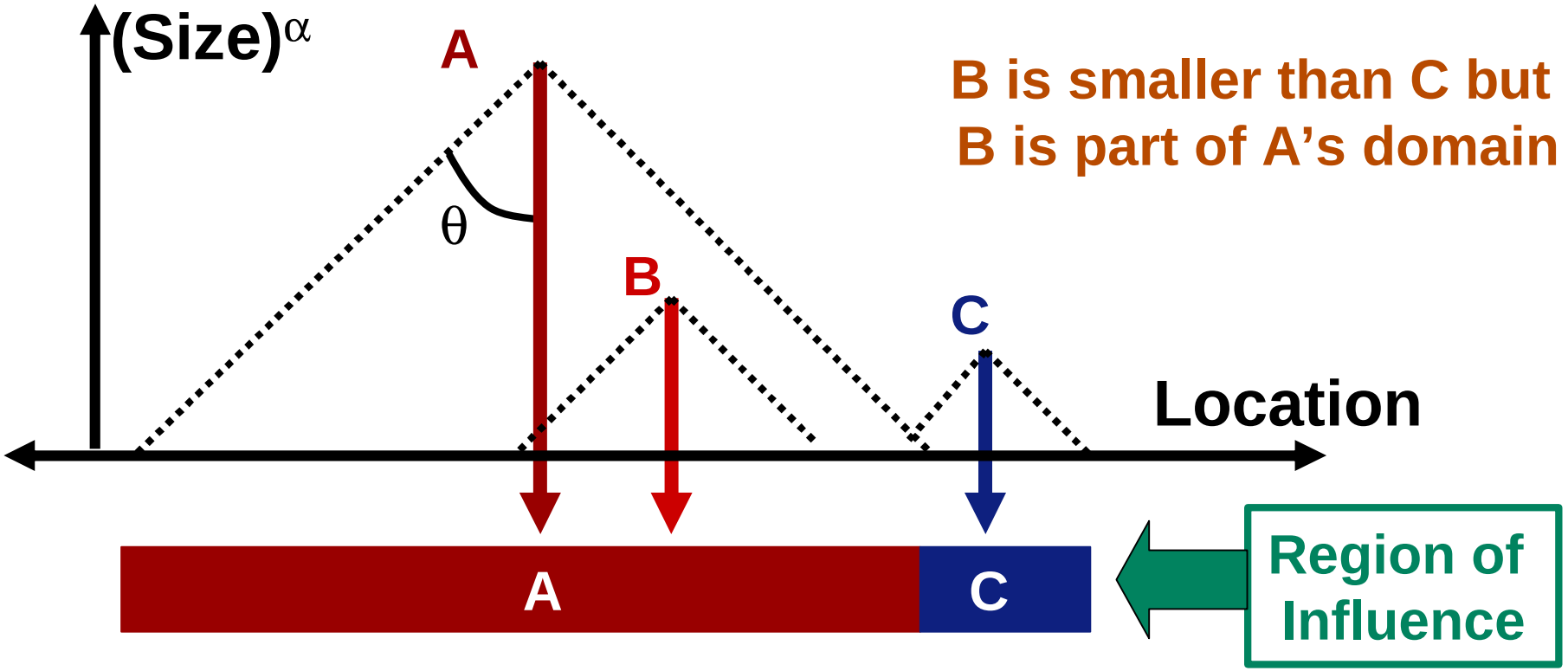




12 Etrurian Cities after Renfrew 1975

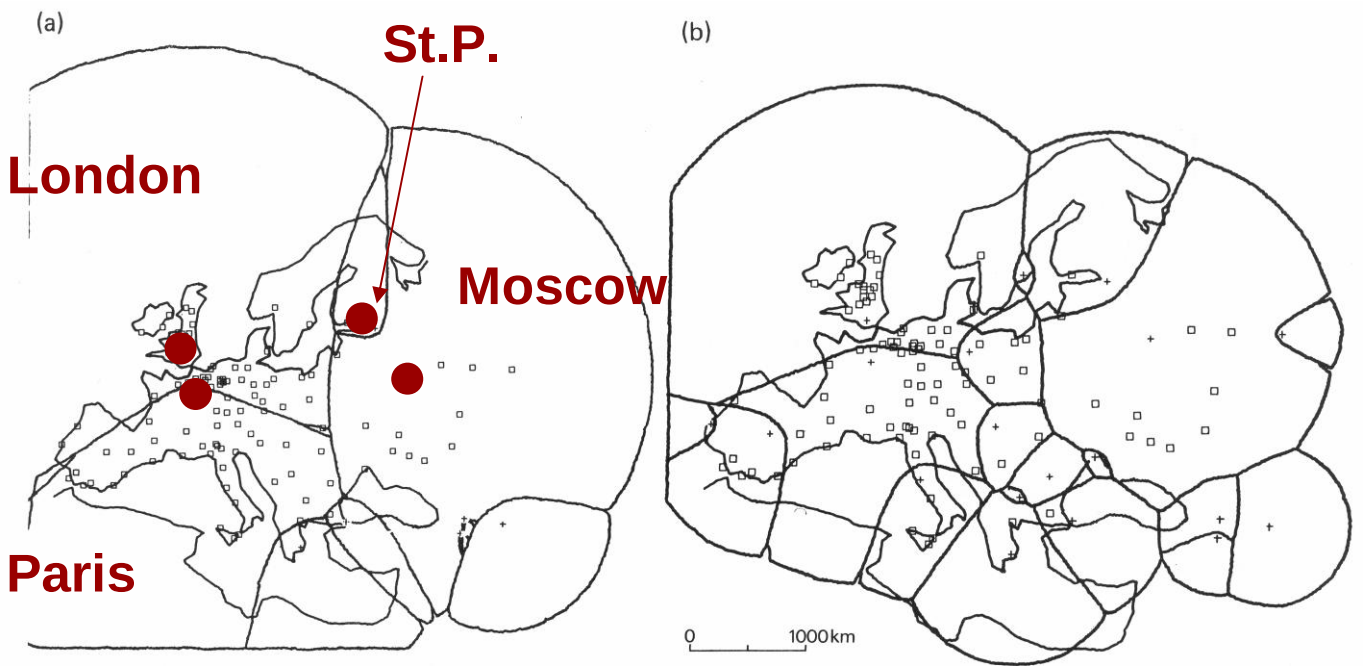
Tent Model

- Thiessen polygons for unequal but fixed size sites
- Can set influence of site as function of distance to any suitable function

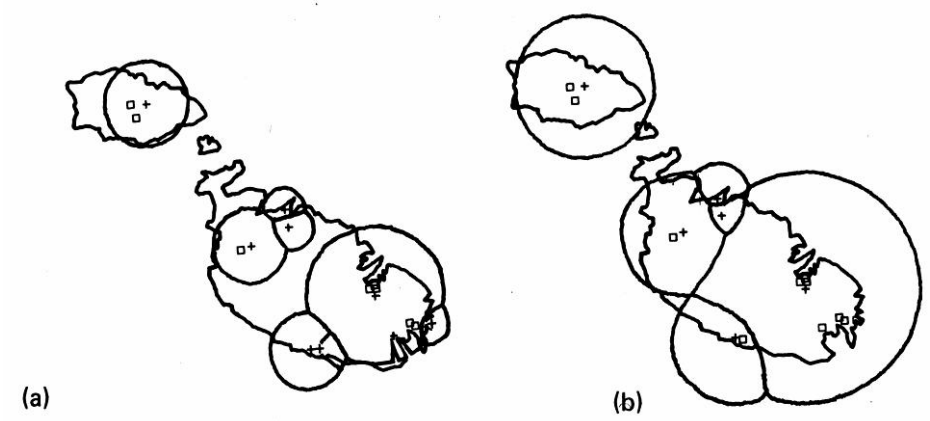


Tent model examples (Renfrew & Level, 1979)

European Cities 1960

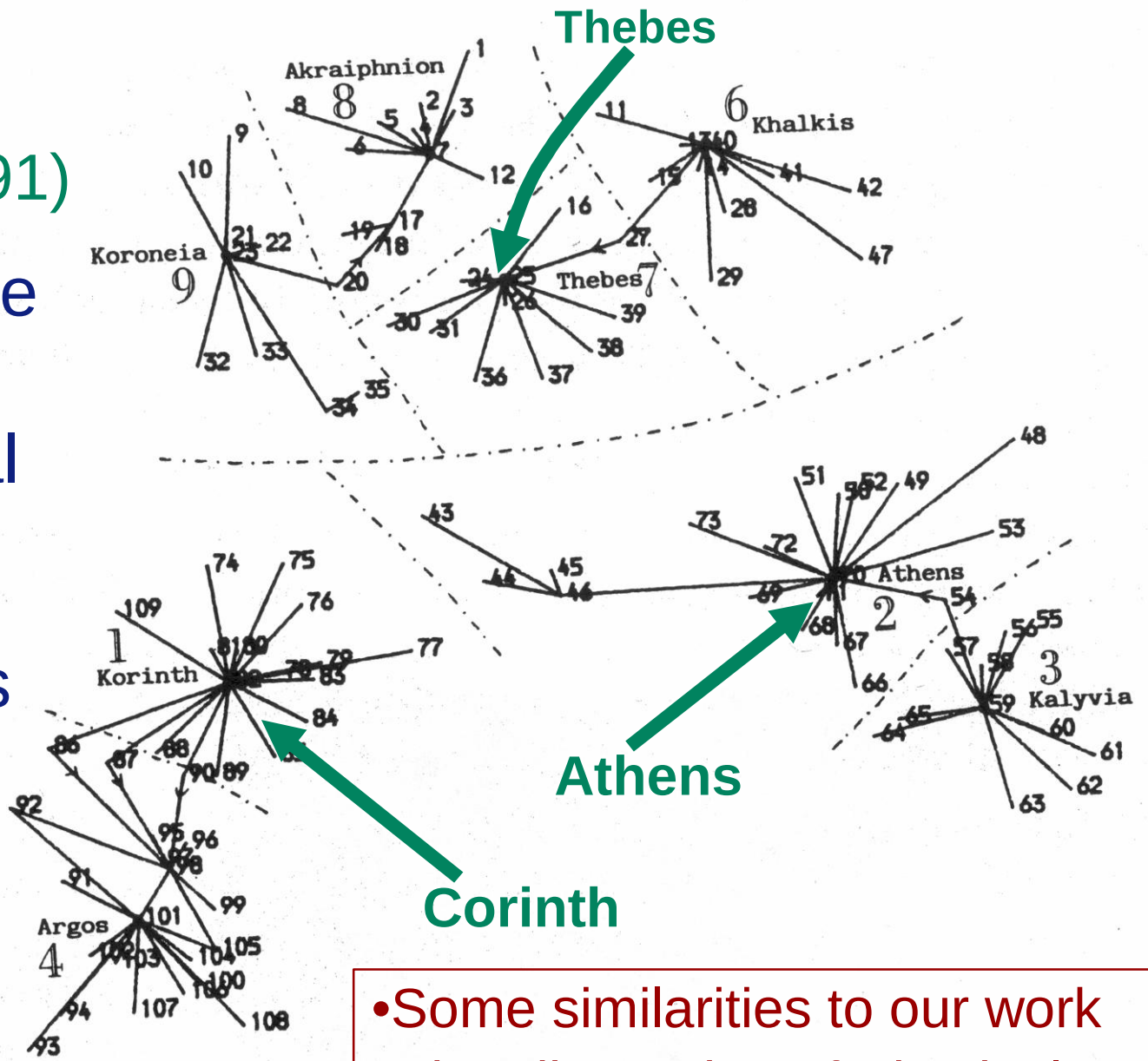


Neolithic Temples of Malta



Optimisation
(Rihll & Wilson 91)

- Variable site sizes
- Exponential fall off but fixed interactions (no dynamic edges)
- No special use of networks



- Some similarities to our work
- Nice discussion of Physical - Social science interface

Summary of Models So Far

- Increasing sophistication from fixed equal site sizes to variable site sizes
- No interactions

  or

  for Rihll and Wilson, interactions only with geographical neighbours within some effective radius

⇒ Still not exploiting advantages a Network Model may provide

- Previous Models without Networks
- Previous Network Models
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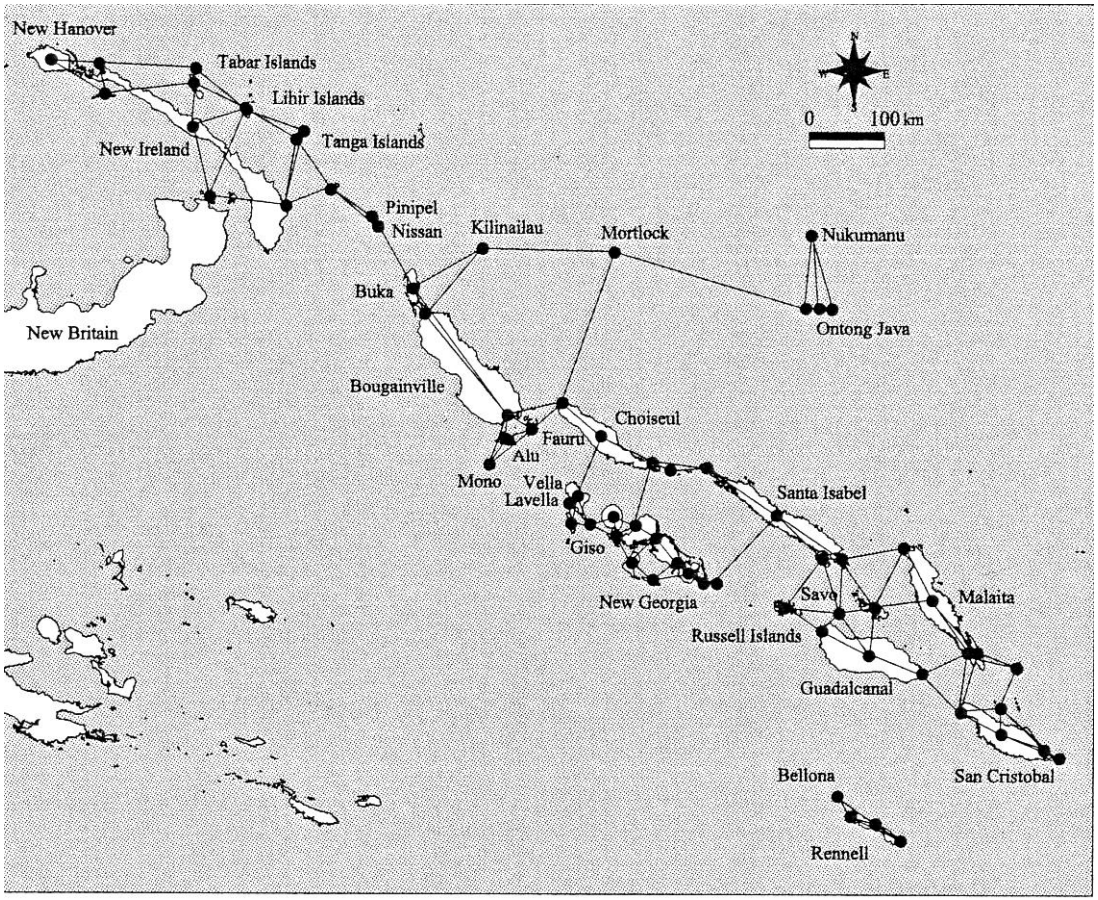
PPA - Proximal Point Analysis

- Fix sites, all considered equal
- Connect each site to ***k*** nearest neighbours
- Analyse graph
  - Often without directions on edges
  - Sometimes only local measures used *e.g. degree* but sometimes global measures used too *e.g. ranking, centrality, betweenness*

Examples: **Hage & Harary 1991 ; Terrell 1977; Irwin 1983; Broodbank 2000; Collar 2007**

Terrell (1977)

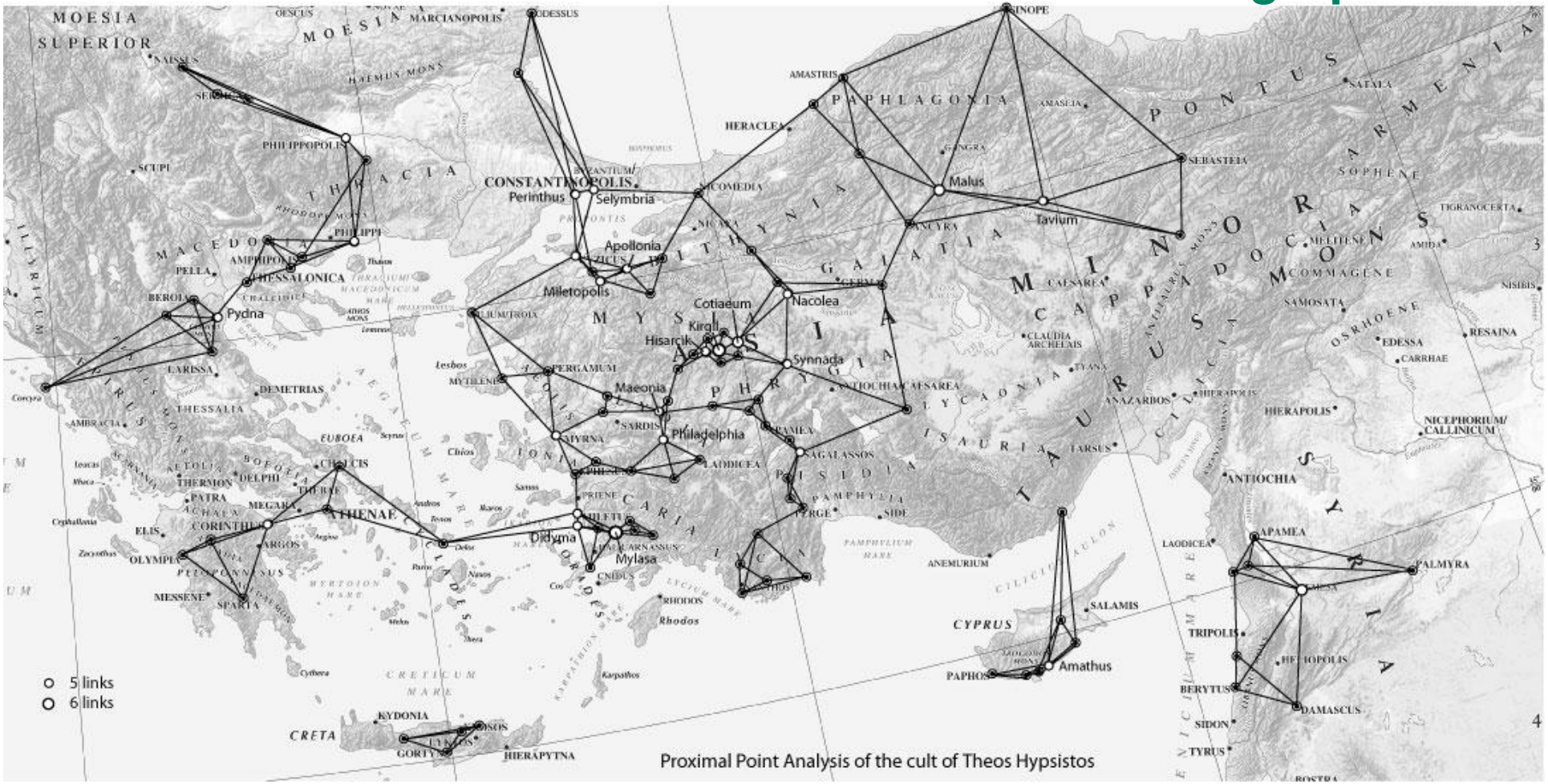
- Solomon Islands (east of Papua New Guinea)
- PPA analysis



"Networks and religious innovation: an approach to understanding the transmission of pagan monotheism"

Collar, Exeter Univ. (in prep)

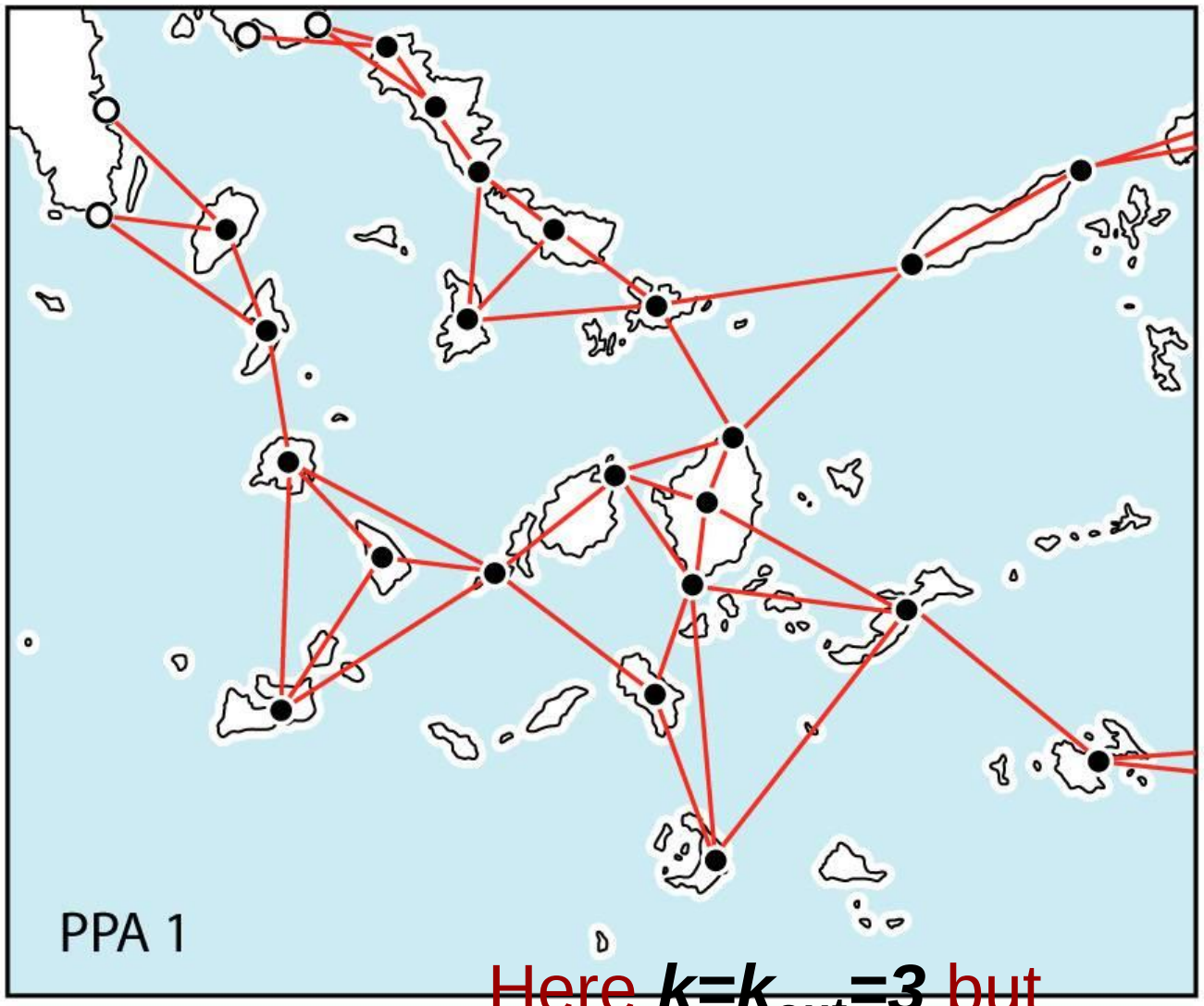
Hypsistos cult inscriptions (1-4c.AD), PPA graph



PPA – degree analysis, work in progress

Broodbank (2000) - **Early Bronze Age Cyclades**

- # vertices per island proportional to cultivable area and population density
- ***k*** outgoing edges per site connect to nearest ***k*** neighbours



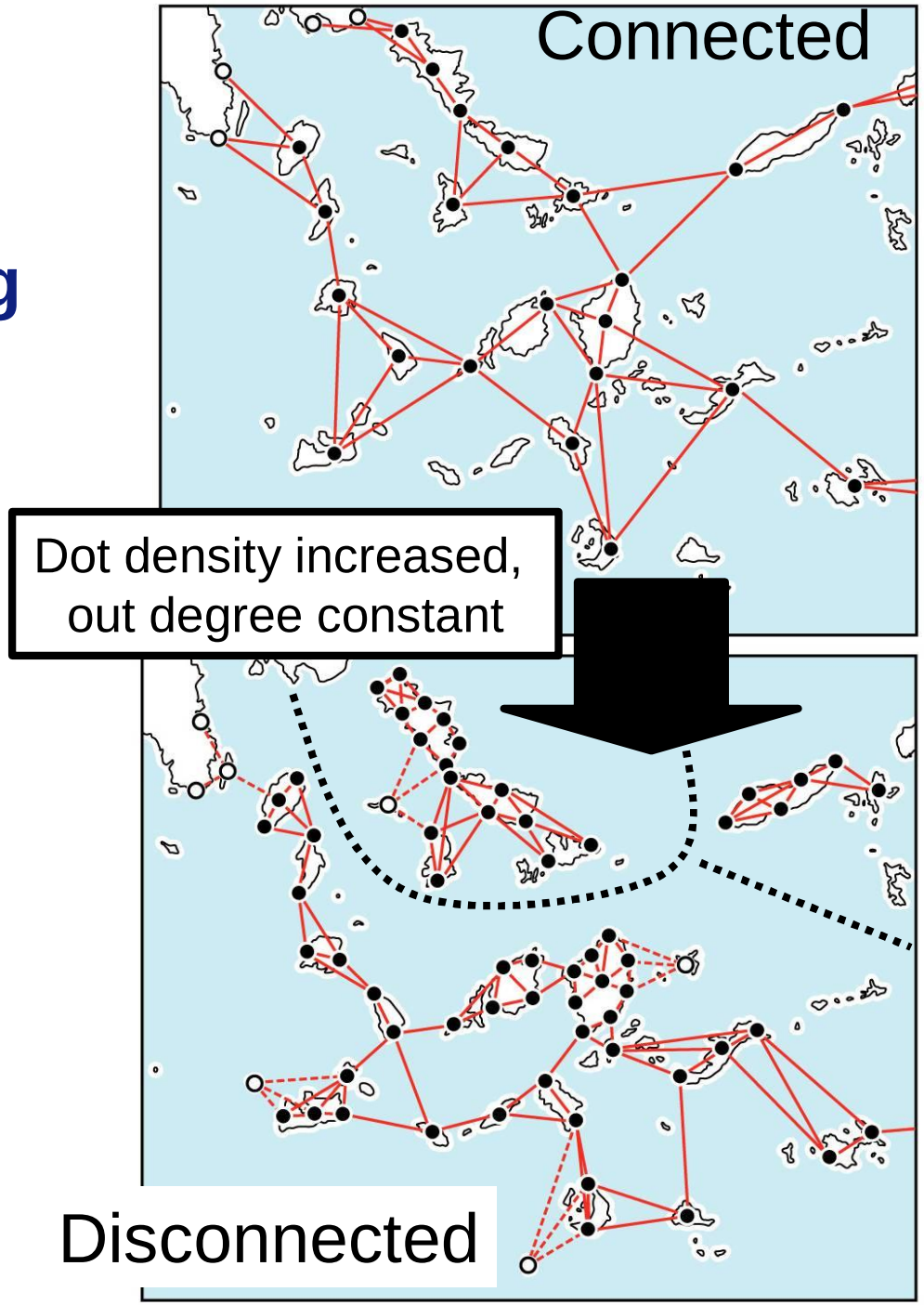
Here $k=k_{out}=3$ but direction not recorded

Broodbank PPA

- **Looks at population increases by increasing density of vertices**

⇒Low density find regional network, connected graph

⇒ High density find dense local networks centred on big islands but regional network now a disconnected graph.



Broodbank PPA (2)

- **EBA Cyclades (Early Bronze Age Aegean)**
  - **Settlements similar size**
  - **rowing ~ 10km daily**

⇒ PPA appropriate

- **More analysis is possible but perhaps not useful for such a `simple' era?**
  - **e.g. use inherent directionality of edges**

Limitations of Early Network Models

- Fixed and equal site sizes
- Edges only on or off (simple graphs)
- PPA still only considers nearest geographical neighbours

⇒Little exploitation of network structure in creating network

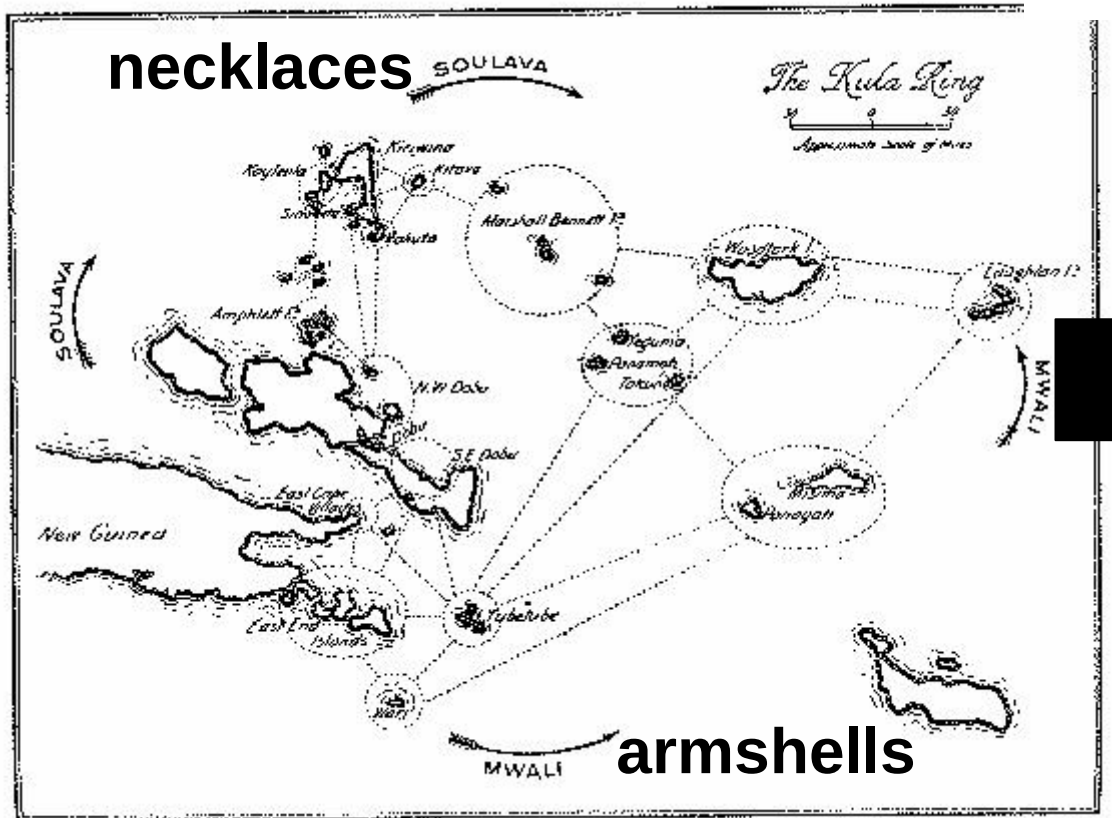
⇒ Global properties of networks and role of sites in wider network rarely studied

More Sophisticated Archaeological Network Models

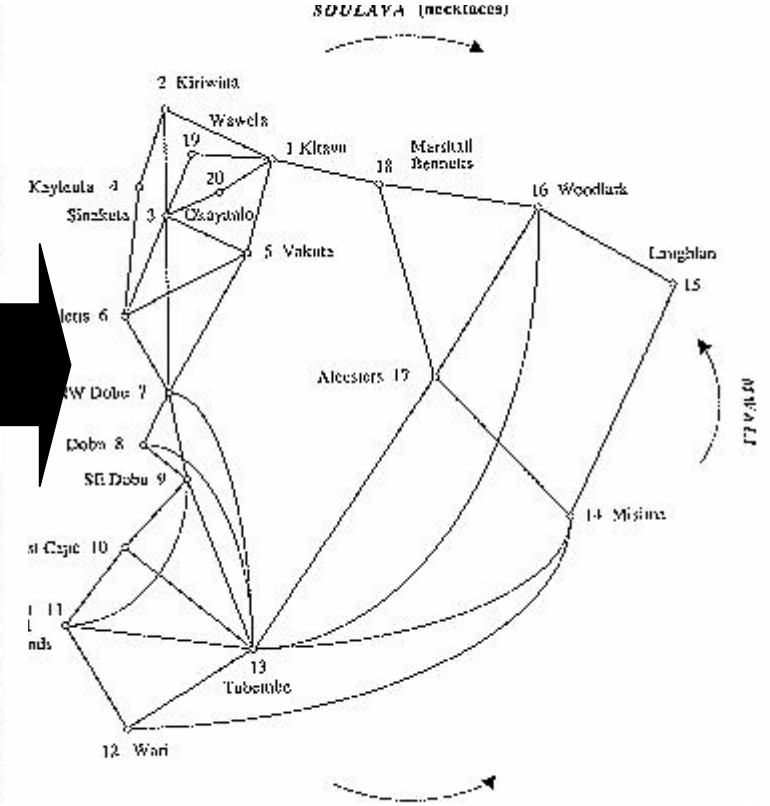
Network models have more to offer and there are examples of more sophisticated archaeological network models in the literature

Earlier Island Network:- The Kula Ring

Malinowski (1922)



Hage and Harary (1991)

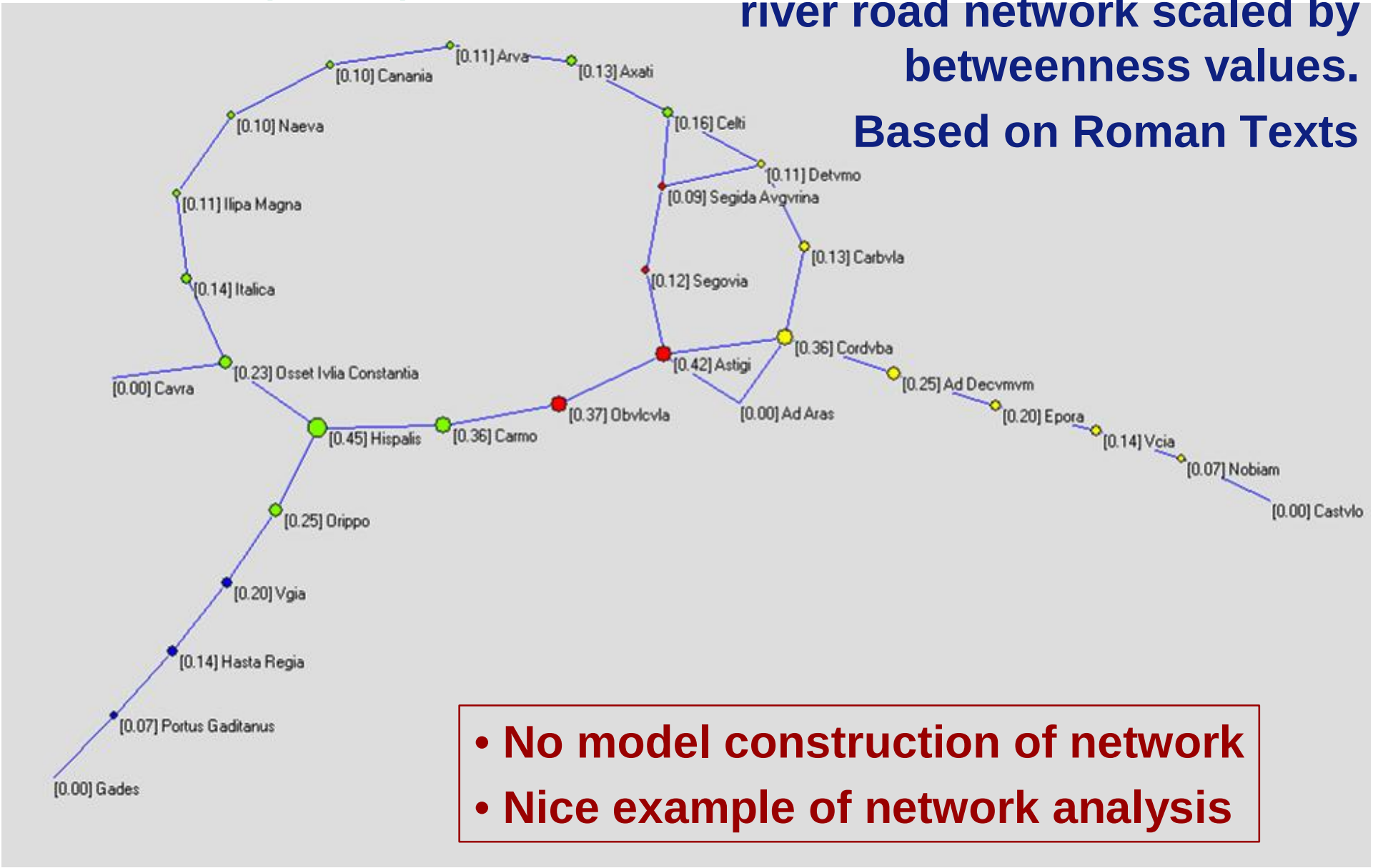


Hage and Harary formed a graph where edges are exchange relations and used random walkers to analyse the *global* properties of the system

Isaksen (2006)

Towns on the Via Augusta and river road network scaled by betweenness values.

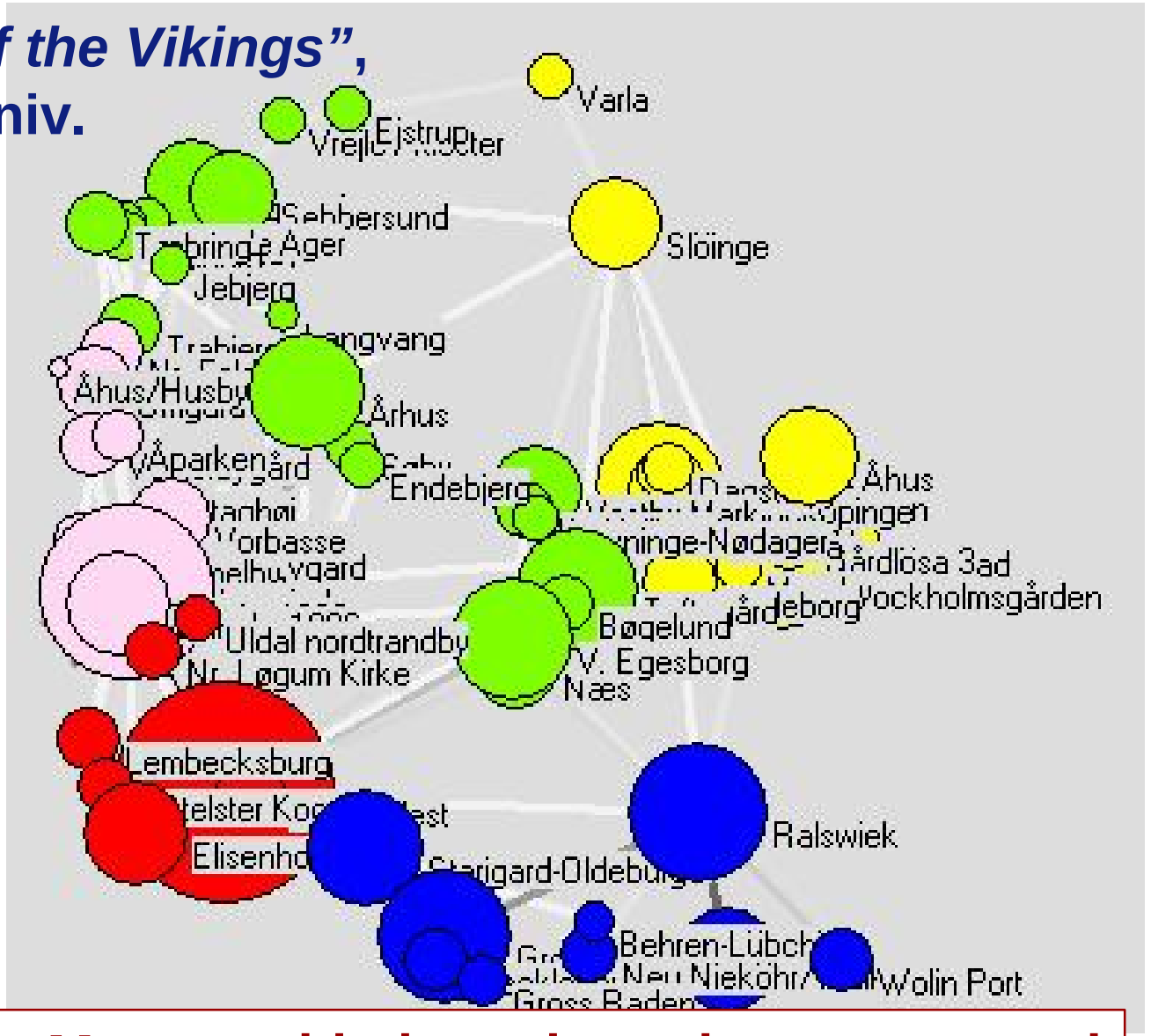
Based on Roman Texts



- **No model construction of network**
- **Nice example of network analysis**

"The Small World of the Vikings", Sindbæk, Aarhus Univ.

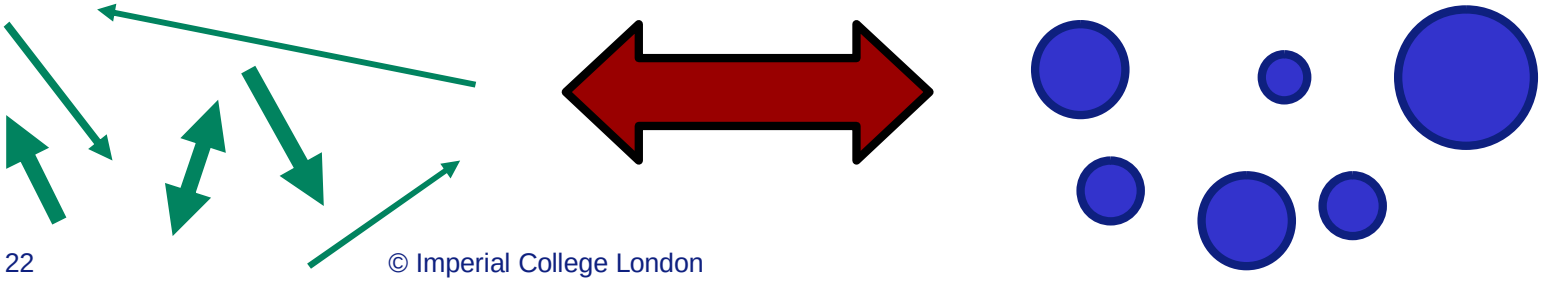
Anskar's Vita + data from finds, 9th c. AD



- **More sophisticated graphs constructed from texts and finds, not a model**
- **Some global network analysis**

Beyond these archaeological models

- The sizes of sites and their interactions never both *variable* and *interlinked*
  - *Real sites are not all identical*
  - *Real interactions are not all identical*
- Surely the regional network influences the sizes of sites *and* the site sizes determine the nature of the network?



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Island Archipelagos as an Ideal Network

- Vertices = Major Population or Resource Sites
- Edges = Exchange between sites

  - physical trade of goods *or* transmission of culture
  - direct contact *or* island hopping links

- Sea isolates communities **Natural Vertices**
- Interactions controlled by physical limitations of ancient sea travel **Simple Links**
- Coastal Sites often isolated like islands due to geography and difficulty of ancient land travel

Focus: Middle Bronze Age (MBA) Aegean

- Clear temporal delineation
  clear gaps (`dark ages') or shifts in record
  - c.2000BC distinct Minoan culture starts, sail replaces oar
  - c.1500BC end of Minoan cultural dominance

- Physically largely self contained
  - questions regarding relationship to Egyptian culture

The 34 Sites Used

Locations of 34 major sites used but their sizes are to be found

Some Possible Questions

- **The Knossos Question**
  What is the connection between macro-scale development of regional networks and the emergence of a primary centre?
  The palace at Knossos does not have the best local environment

- **Minoanisation**
  What can explain the spread of and the variability in Minoan influence across the southern Aegean c.1700 BC?

Network Description – Fixed Network Parameters

Network values fixed using the archaeological record are:-

- d_{ij} Fixed distance between sites
  - may be physical but may include penalties for prevailing winds, currents, land travel, ...
- S_i Fixed site capacity
  = maximum local resources

Network Description – Variables, relative values

Variables whose values are found stochastically:-

- v_i Variable site occupation *fraction*
  so if $v_i > 1$ then site needs external resources
  $\Rightarrow$ Site **Weight** ($S_i\, v_i$) = Site `*population*'

- e_{ij} Fractional Edge values $\mathbf{0} \leq \Sigma_j \mathbf{e_{ij}} \leq \mathbf{1}$
  $\Rightarrow$ Edge **Weights** ($S_i\, v_i\ e_{ij}$)
  = '*Trade*' (interaction) going from site ***i*** to site ***j***

Optimisation of what?

`Energy', resources

Isolated sites have optimal size $v_i = 0.5$

Trade (interactions) bring benefits

Increasing 'population' has a cost

Each trade link has a cost

$$H = -\kappa \sum_i S_i v_i (1 - v_i) - \lambda \sum_{i,j} (S_i v_i . e_{ij}) . V(d_{ij} / D) . (S_j v_j) + j \sum_i S_i v_i + \mu \sum_{i,j} S_i v_i e_{ij}$$

$$0 \le \sum_j e_{ij} \le 1 \qquad 0 \le v_i$$

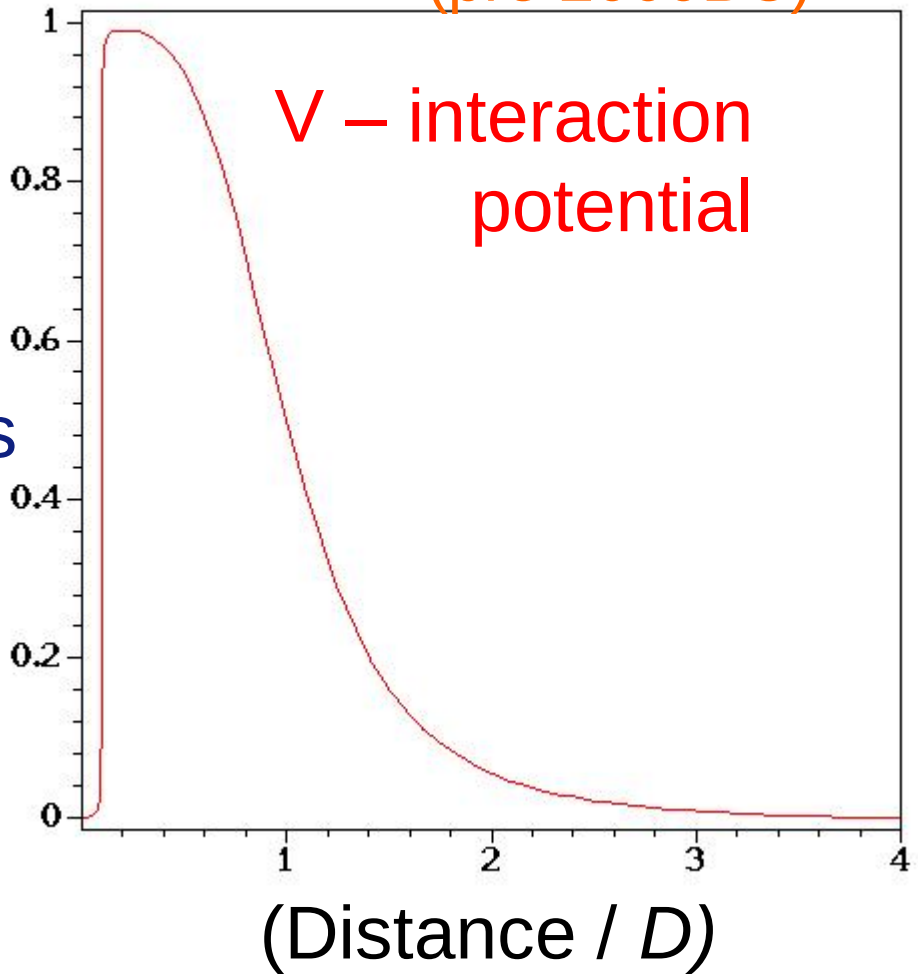
Distance Scale D

We use: D=100km for sail D=10km for rowing

(after 2000BC) (pre 2000BC)

Interaction term for each pair of sites depends on distance d_{ij} between sites such that for distances longer than a scale D the benefit is zero

i.e. no effective direct interaction

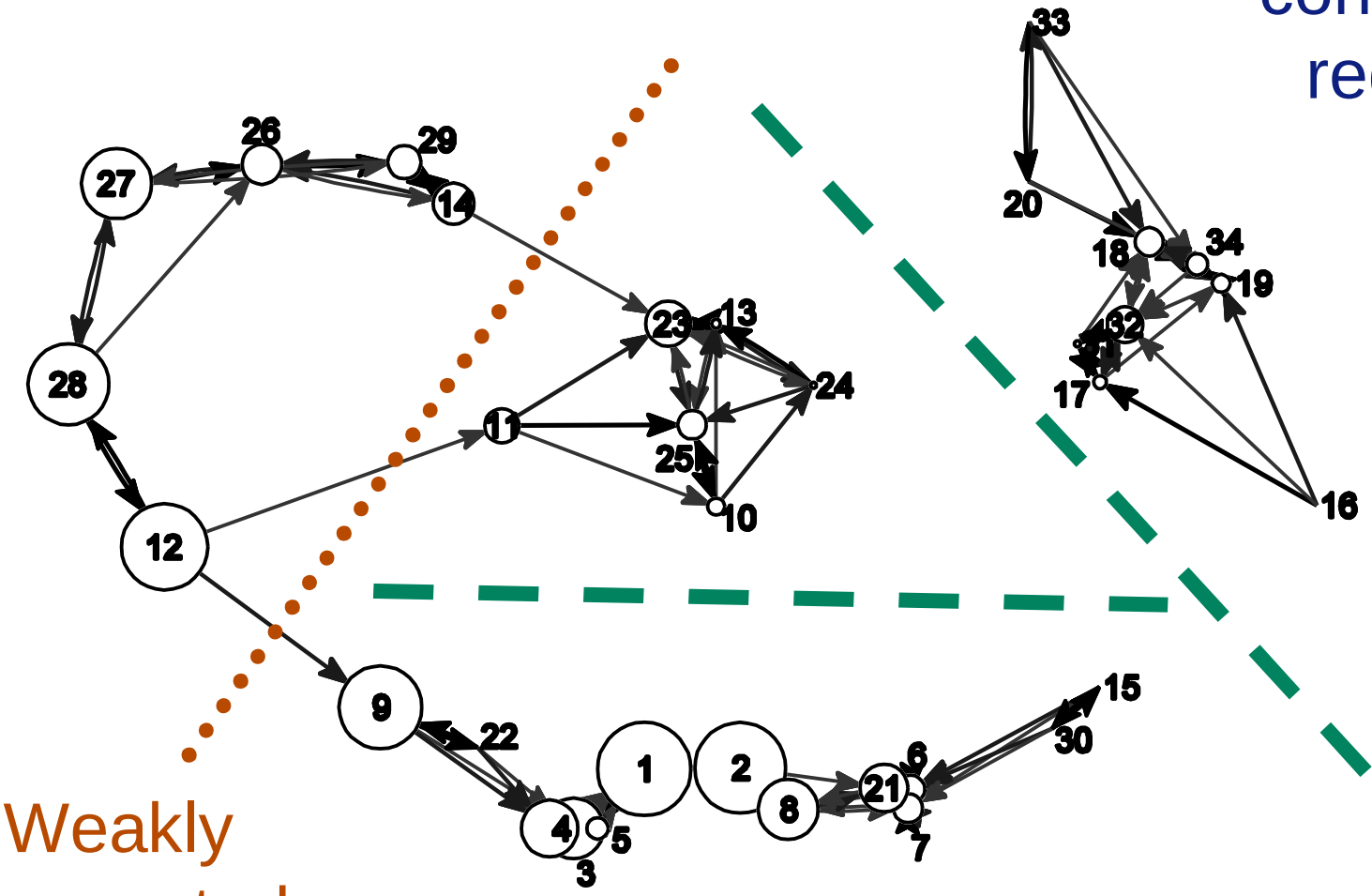


So what does our model give us?

- Site hierarchies
  - not all equal in size or in other measures of importance
- Interdependent site sizes and network edges
- Not simply nearest geographical neighbour interaction
  - Geography still important
- Regional networks can appear

⇒ Compare with PPA …

Our Sites in PPA ($k_{out}=3$)



Gives 4 strongly connected regions

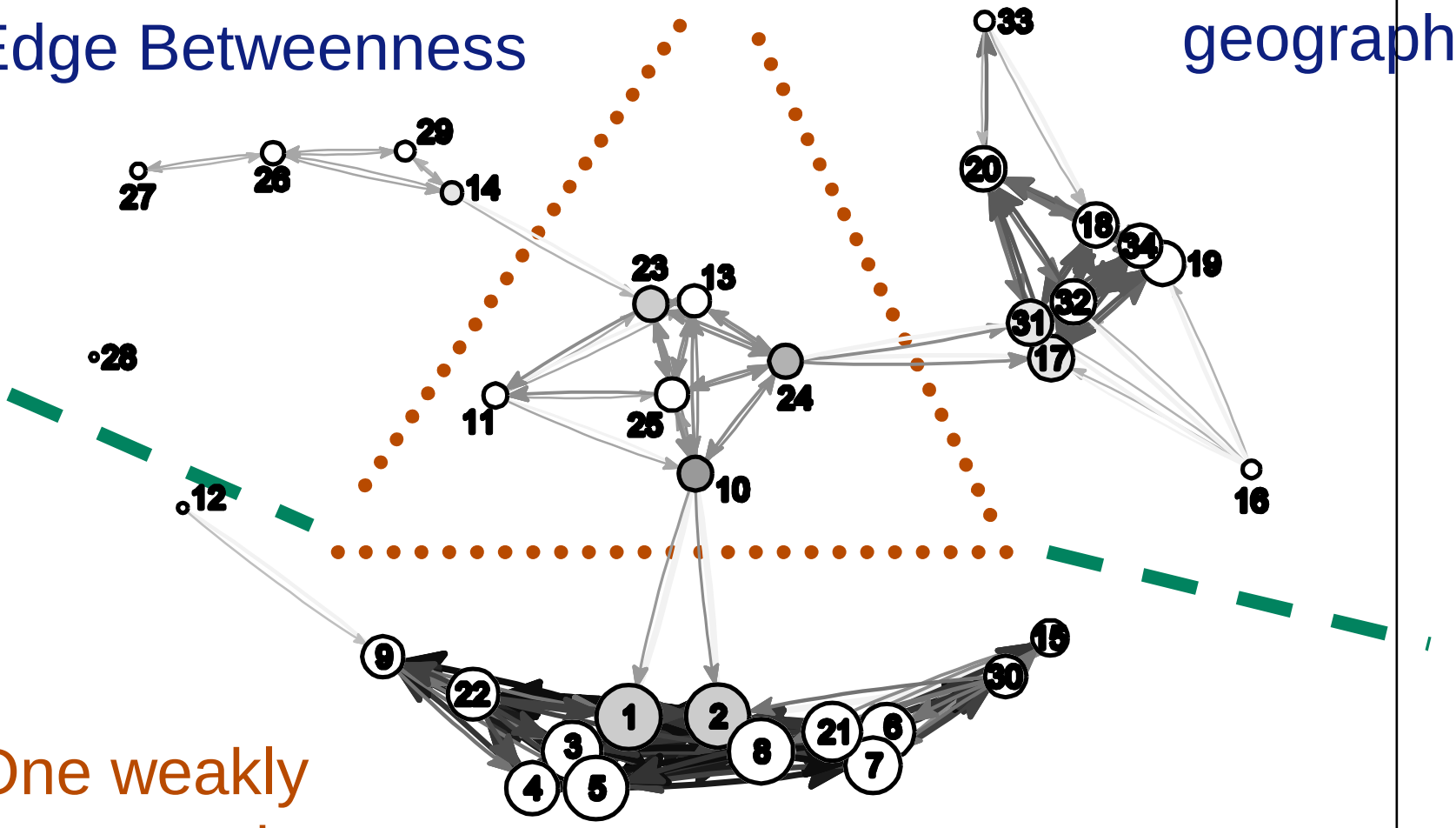
Weakly connected

Vertex size = Edge Betweenness

Network in our model

Vertex size =
Edge Betweenness

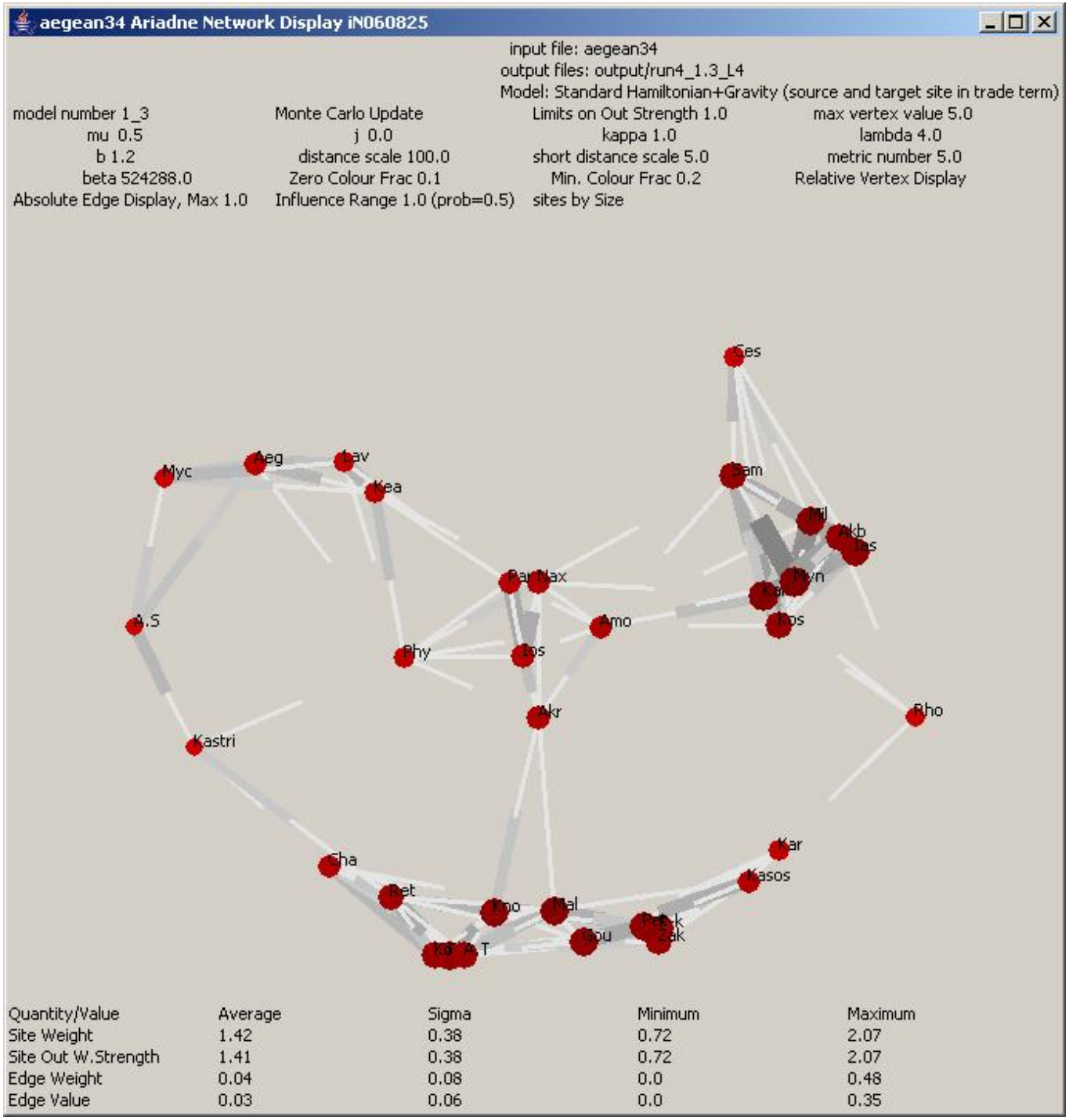
Same 4 strongly connected regions = same geography



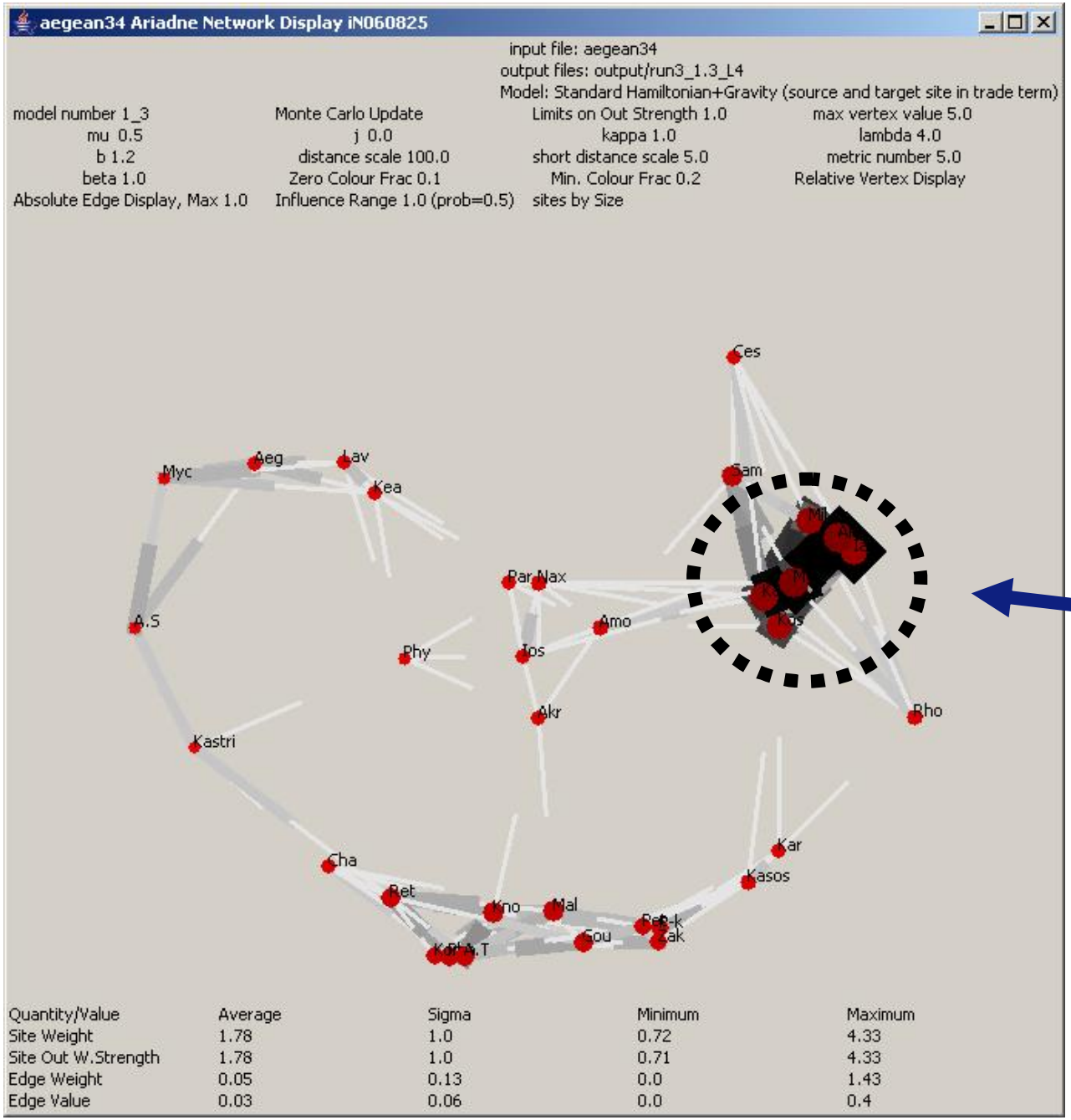
One weakly connected component,
Different vertex sizes, non-local effects

Fluctuations

- Model is not deterministic but stochastic
  - Size of fluctuations set by a ‘temperature parameter’
  - Never find the same result twice, but usually results will be similar
  - Need to interpret results in this light
    e.g. look at averages and variances



Typical Run



Atypical Run - Network

Unusually strongly connected subgraph formed outside Crete on one run out of ~40 for same parameters

Analysis

- Can not assign parameter values in model from physical data so make *comparisons* between different data sets
  - e.g. vary one parameter, hold rest fixed.

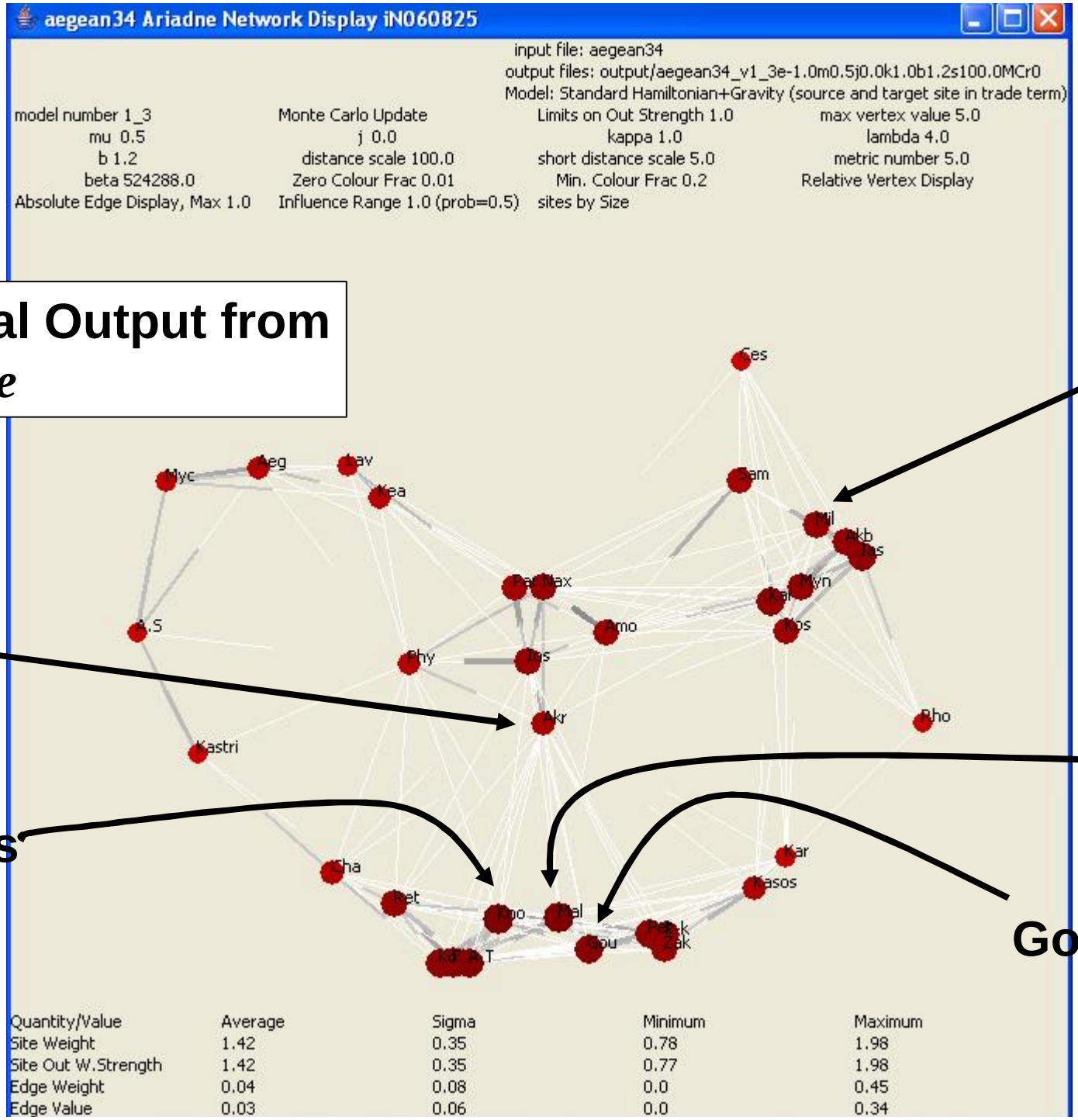
- For any given set of (reasonable) values:
  a) can analyse intrinsic network measures
     e.g. degree of vertices
  b) can perform further `games' to analyse properties
     e.g. simulate trade in physical objects,
          apply cultural transmission models.

Analysis of Single Network

- The new few slides show the analysis of one result of our model
- Look for sites which are off any general trends
- Rank = probability of random walker arriving at location, c.f. Hage & Harary 1991, Google PageRank
- Total Site Size (Weight) = ($S_i v_i$)

j=0, μ=0.5, κ=1.0, λ=4.0

Typical Output from *ariadne*



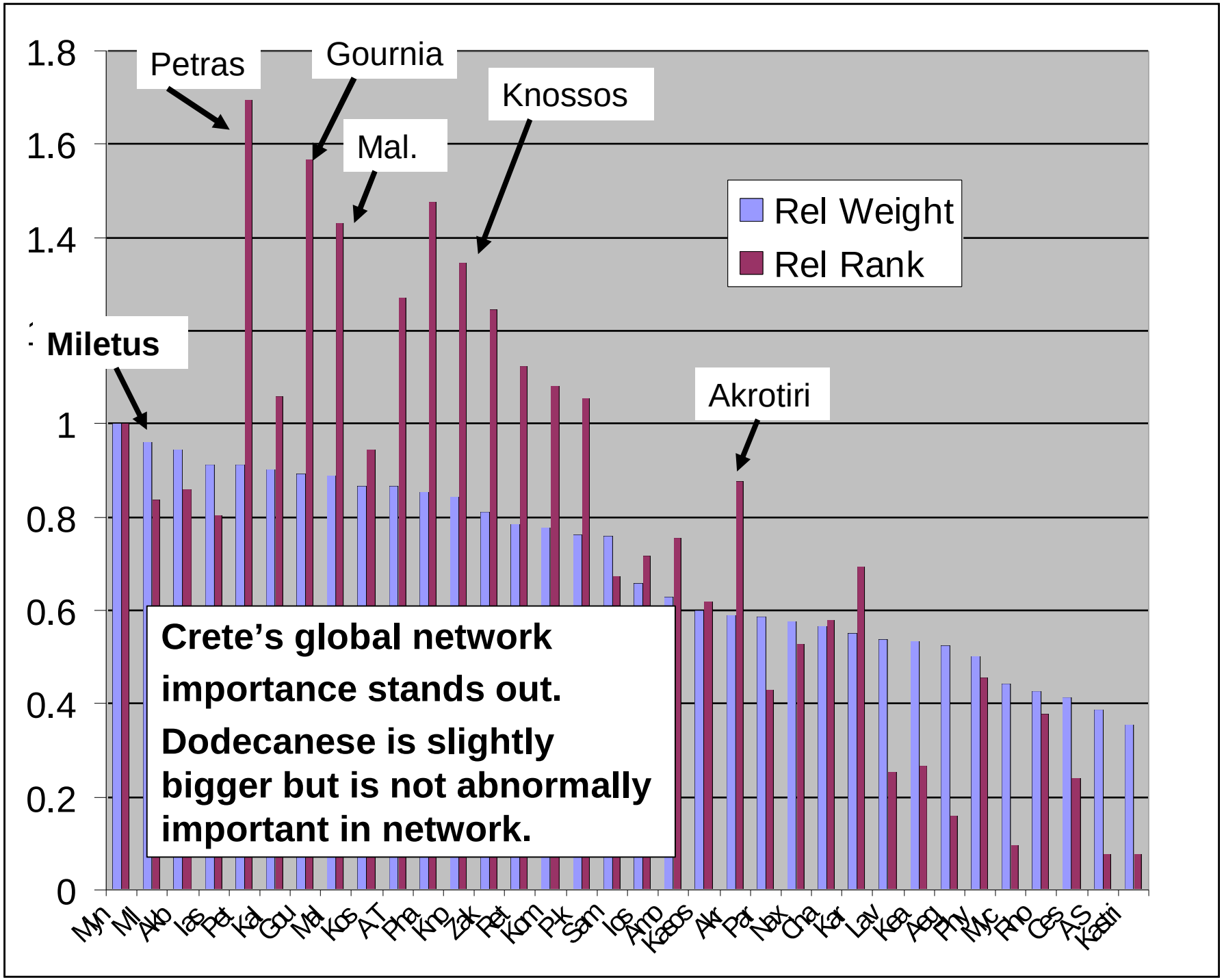
Miletus

Akrotiri

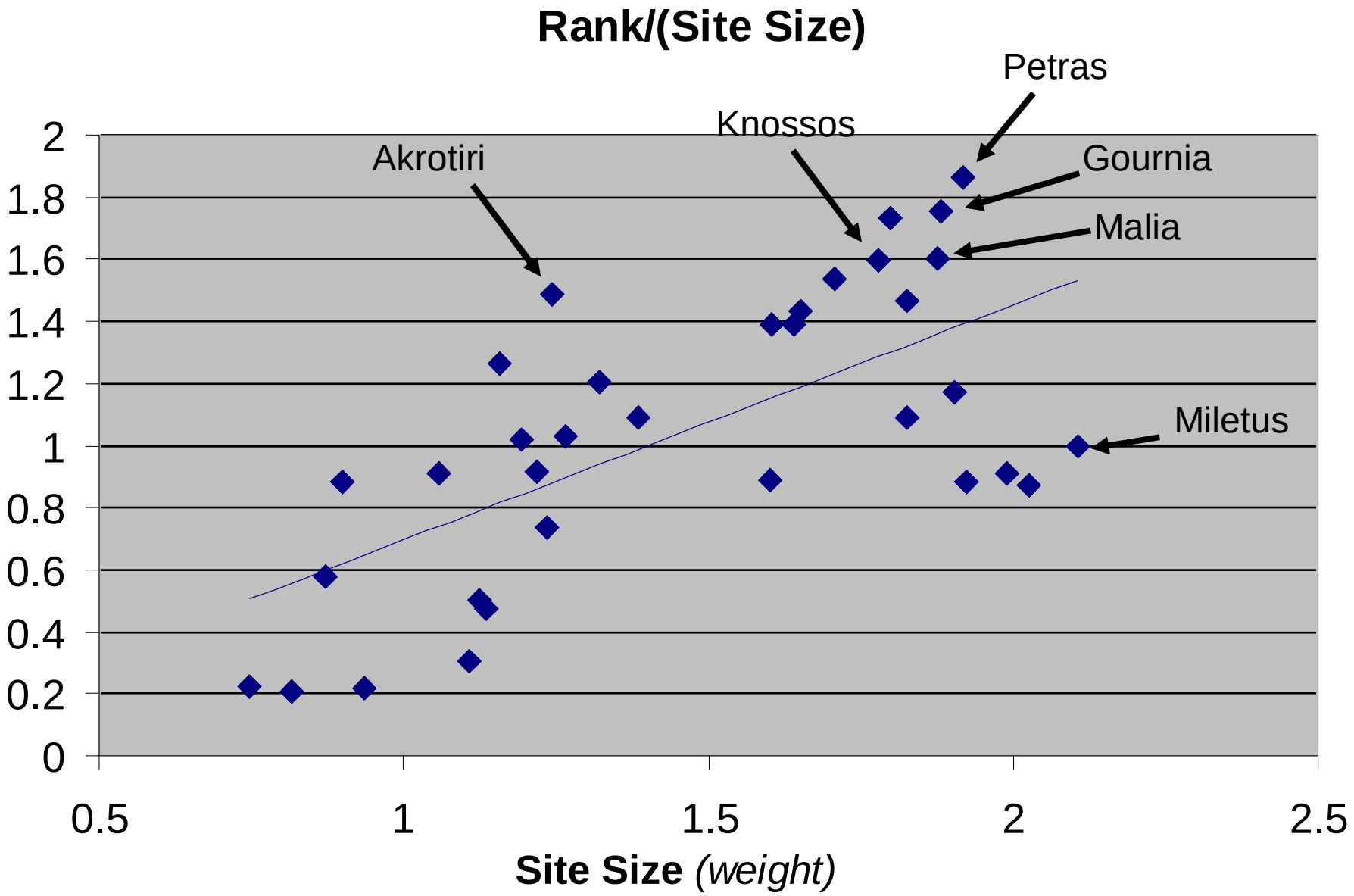
Malia

Knossos

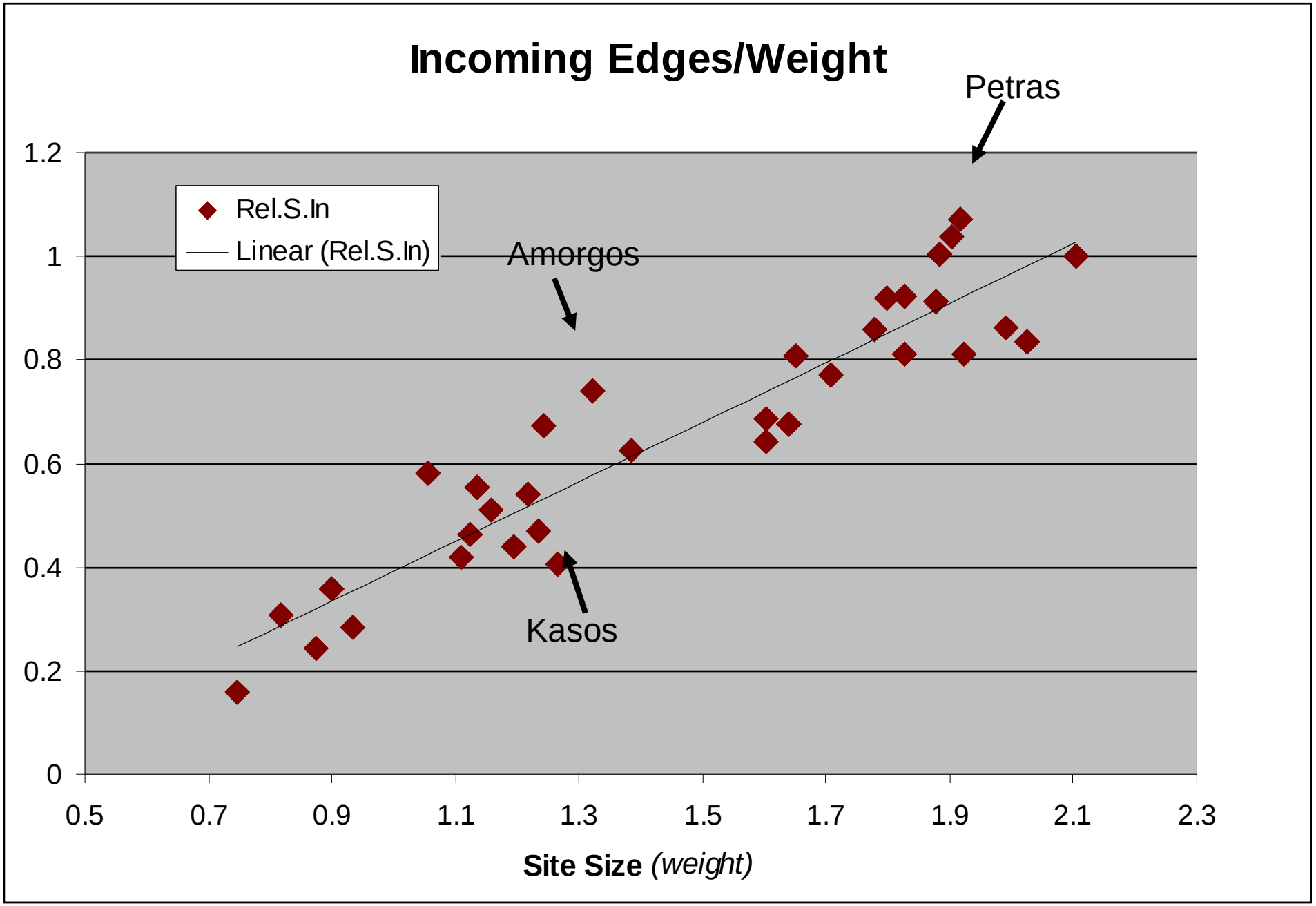
Gournia



Rank vs. Size shows Crete's is more important to the global network that its size suggests, not so for Dodecanese



Local properties often scale closely with site size (weight)



General analysis of our networks

- Big problem is that many measures of network properties are for unweighted graphs
- Fine for PPA, not for more realistic networks appropriate for more complex civilisations

Time Evolution

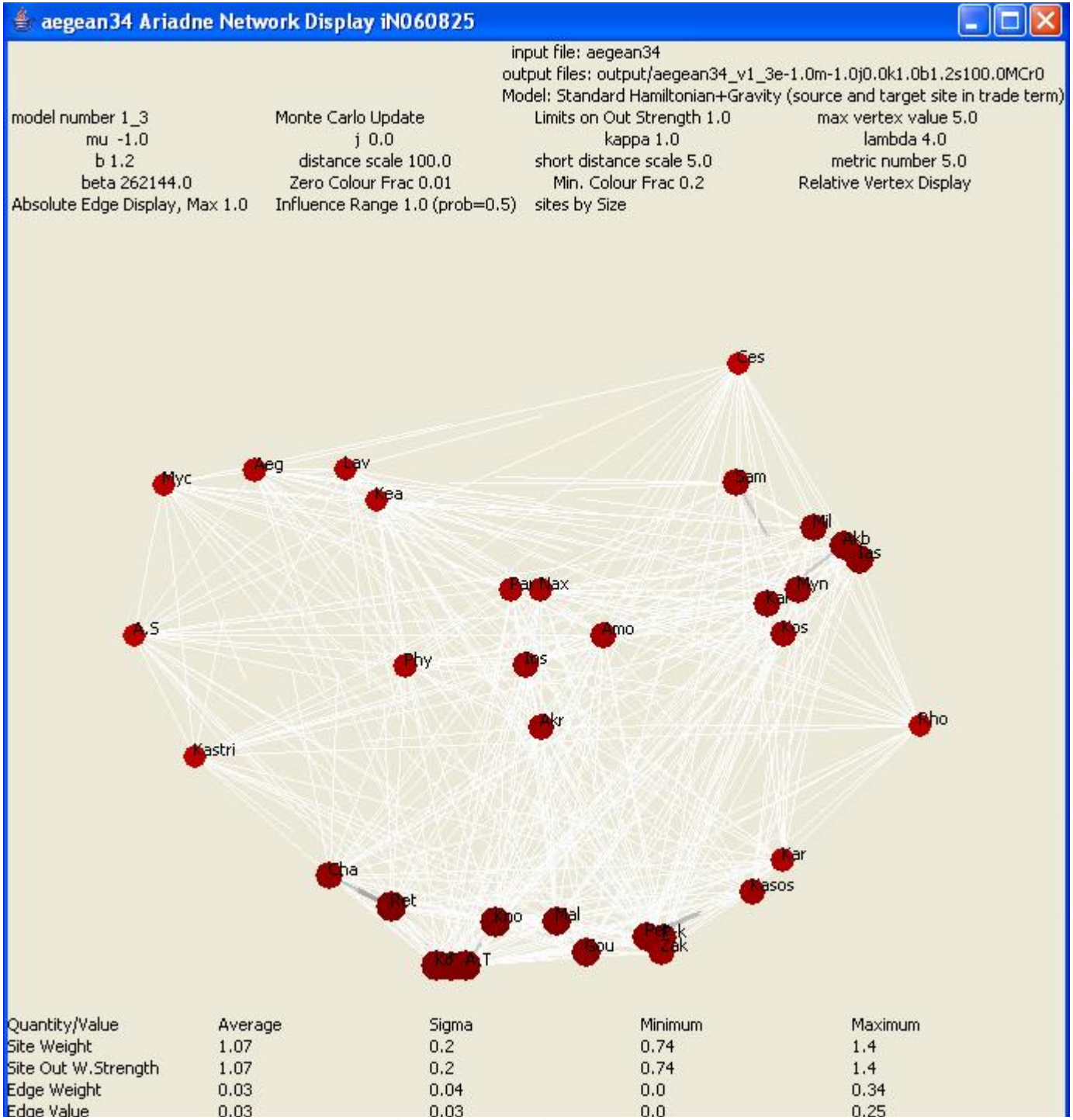
- Slow changes = adiabiatic change in parameters
  - e.g. population growth
- Fast changes = quenches
  - e.g. cataclysmic events

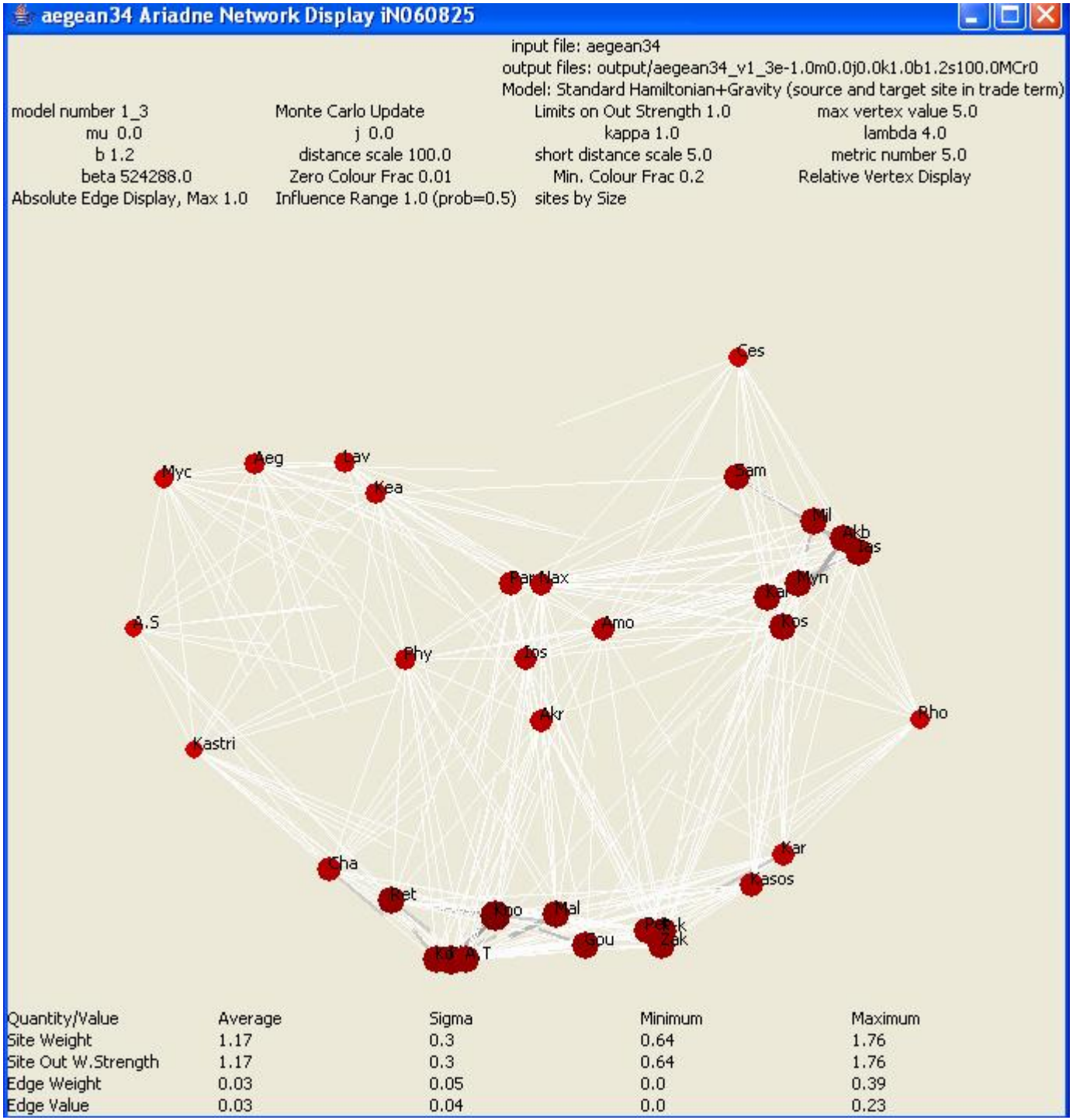
Increasing Edge Cost (μ)

Next 7 slides

- for large interaction benefits *(λ=4.0, j=0, κ=1.0)*

- Increasing μ causes edges to concentrate on decreasing profitable routes.
- The largest site size goes up while the smallest stays the same.
- Total cost in edges the same (as vertex out strength) but

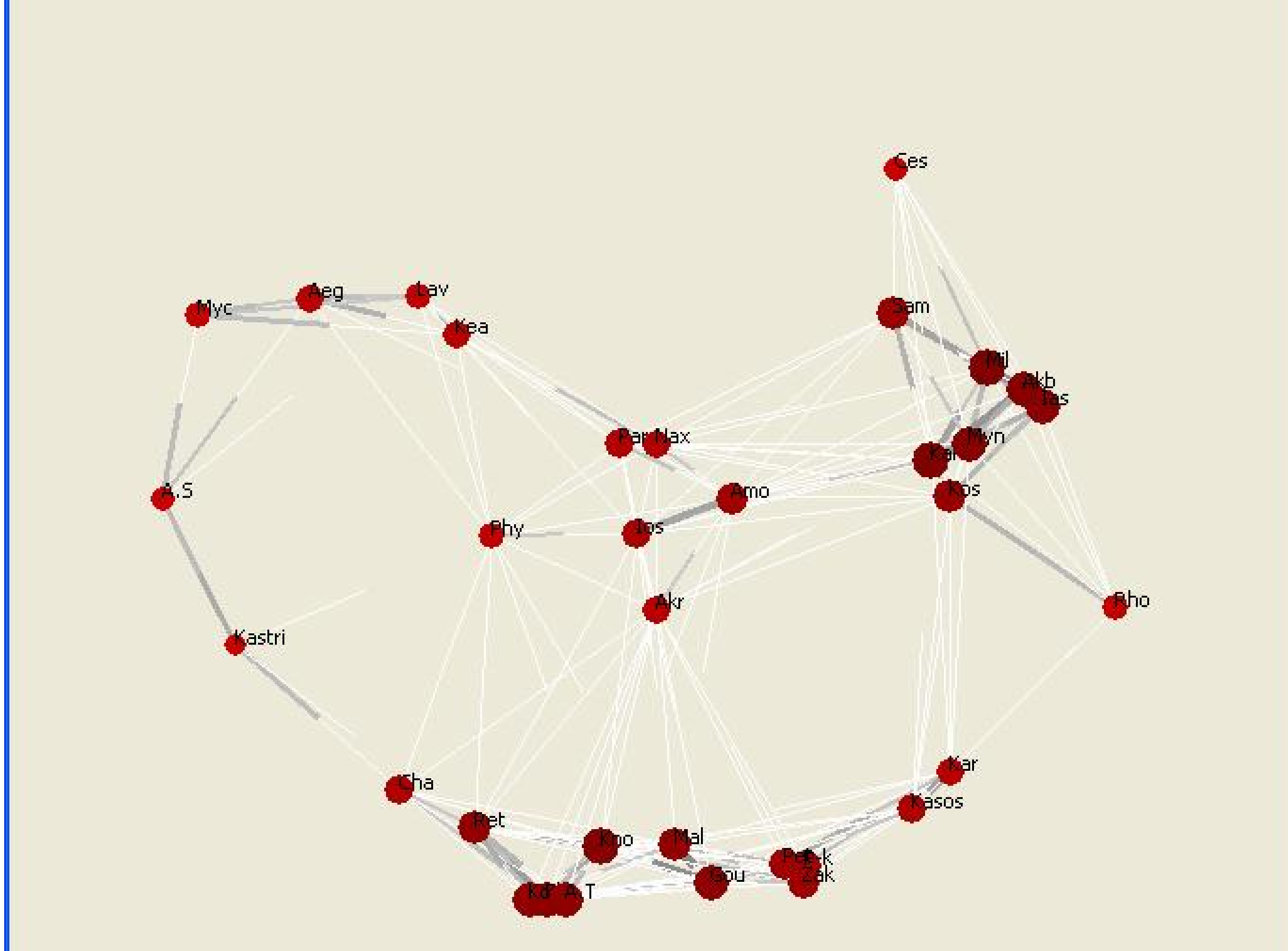




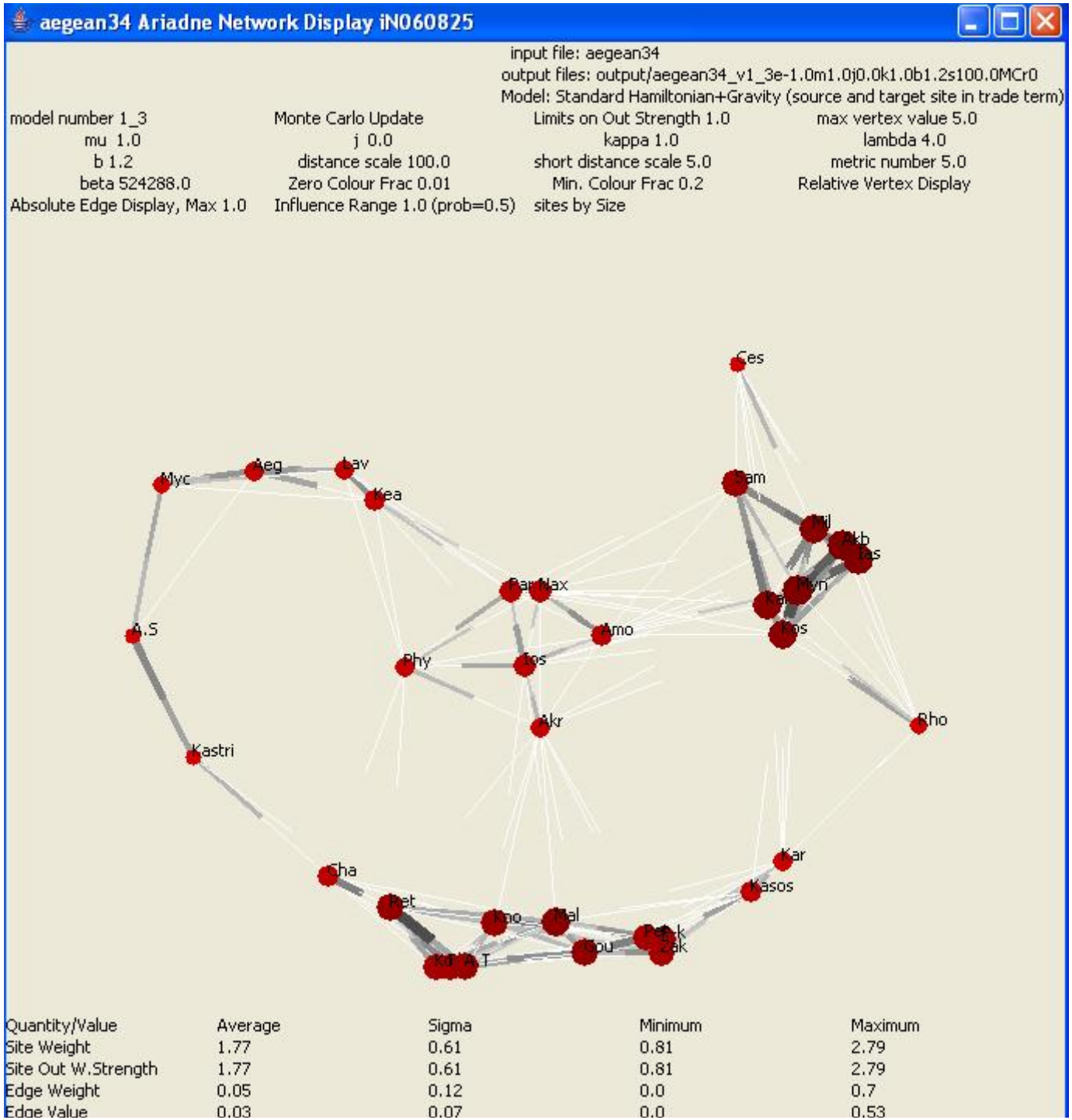
aegean34 Ariadne Network Display iN060825

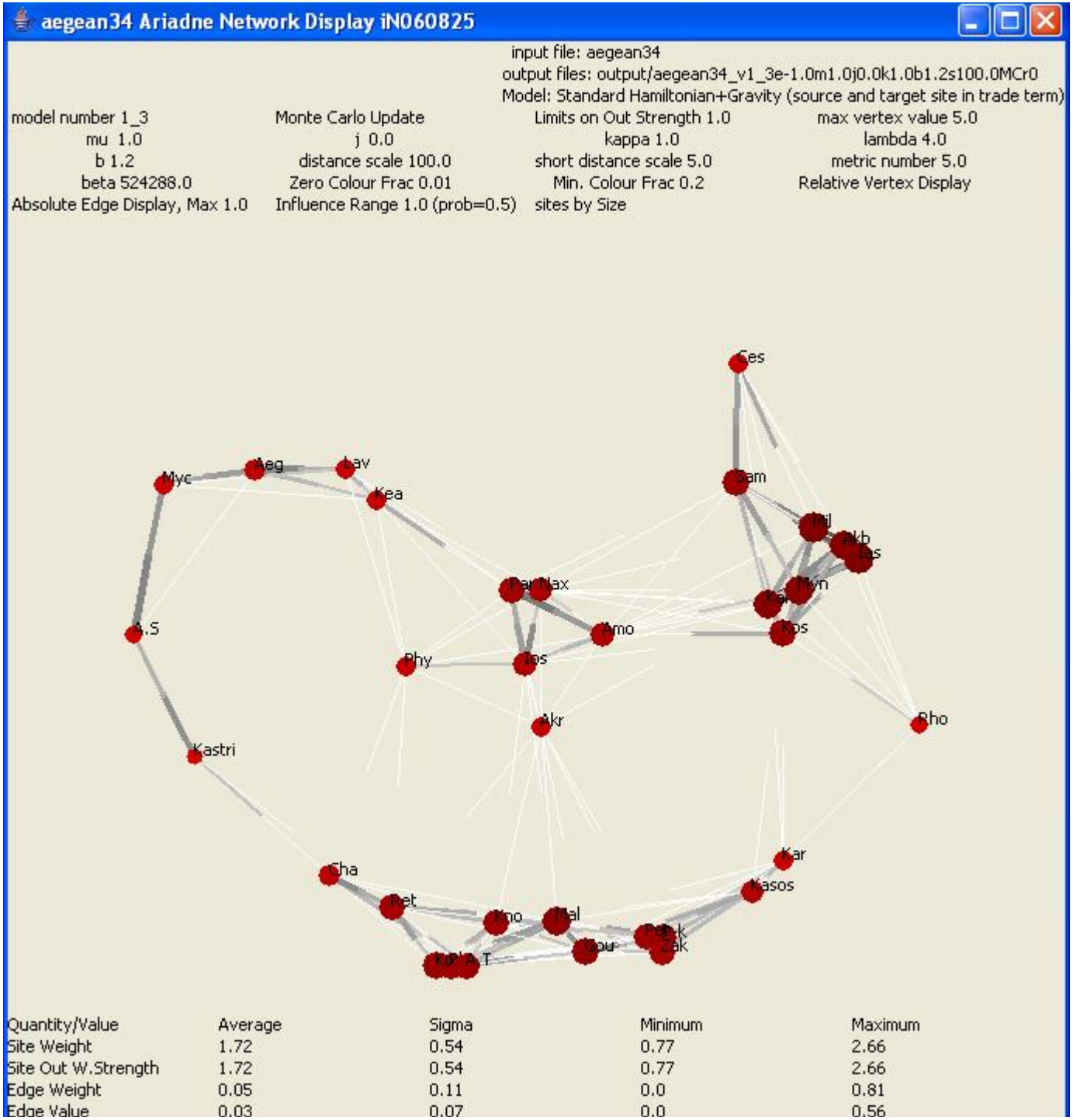
input file: aegean34
output files: output/aegean34_v1_3e-1.0m0.5j0.0k1.0b1.2s100.0MCr0
Model: Standard Hamiltonian+Gravity (source and target site in trade term)

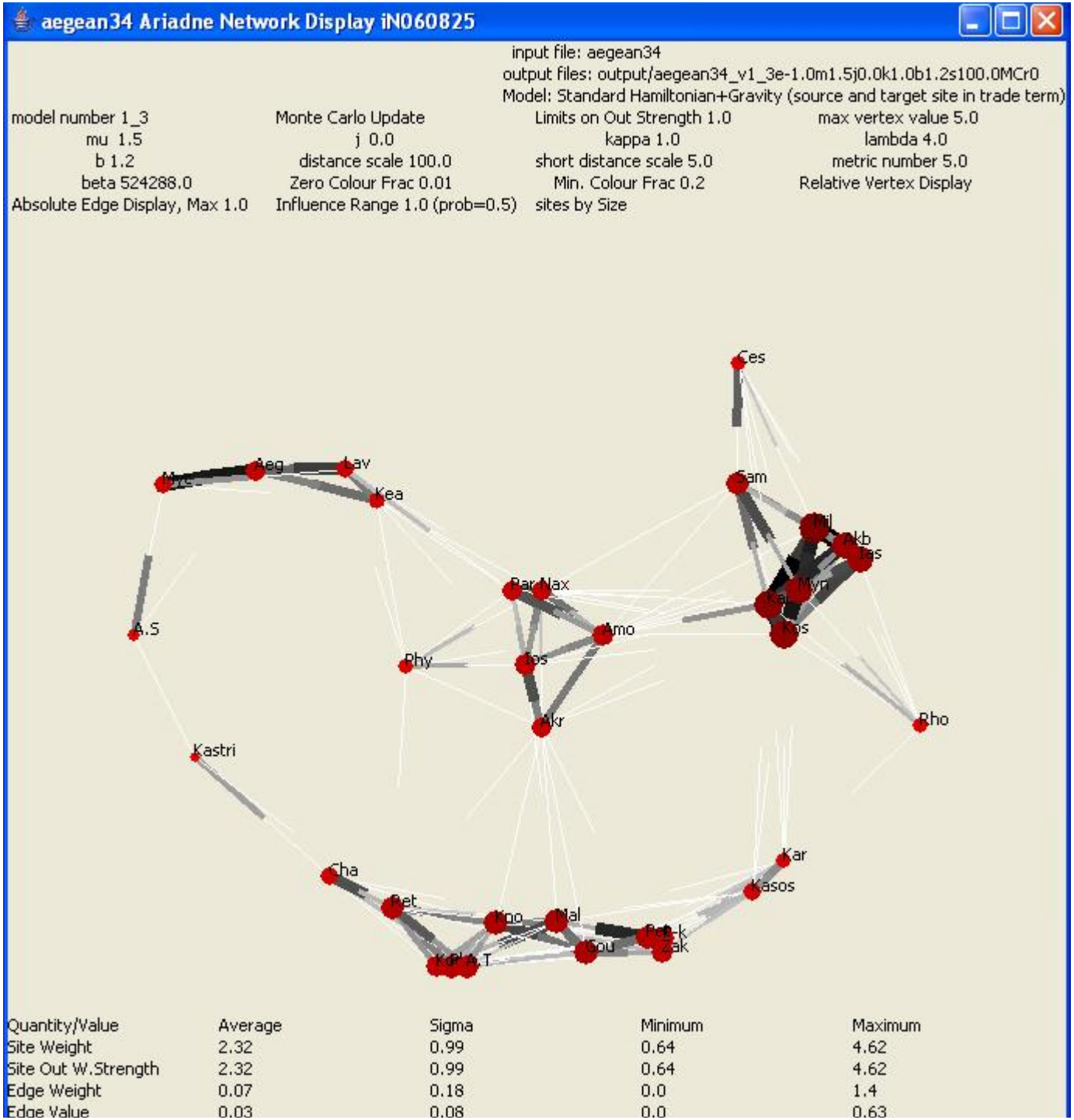
model number 1_3	Monte Carlo Update	Limits on Out Strength 1.0	max vertex value 5.0
mu 0.5	j 0.0	kappa 1.0	lambda 4.0
b 1.2	distance scale 100.0	short distance scale 5.0	metric number 5.0
beta 524288.0	Zero Colour Frac 0.01	Min. Colour Frac 0.2	Relative Vertex Display
Absolute Edge Display, Max 1.0	Influence Range 1.0 (prob=0.5)	sites by Size	

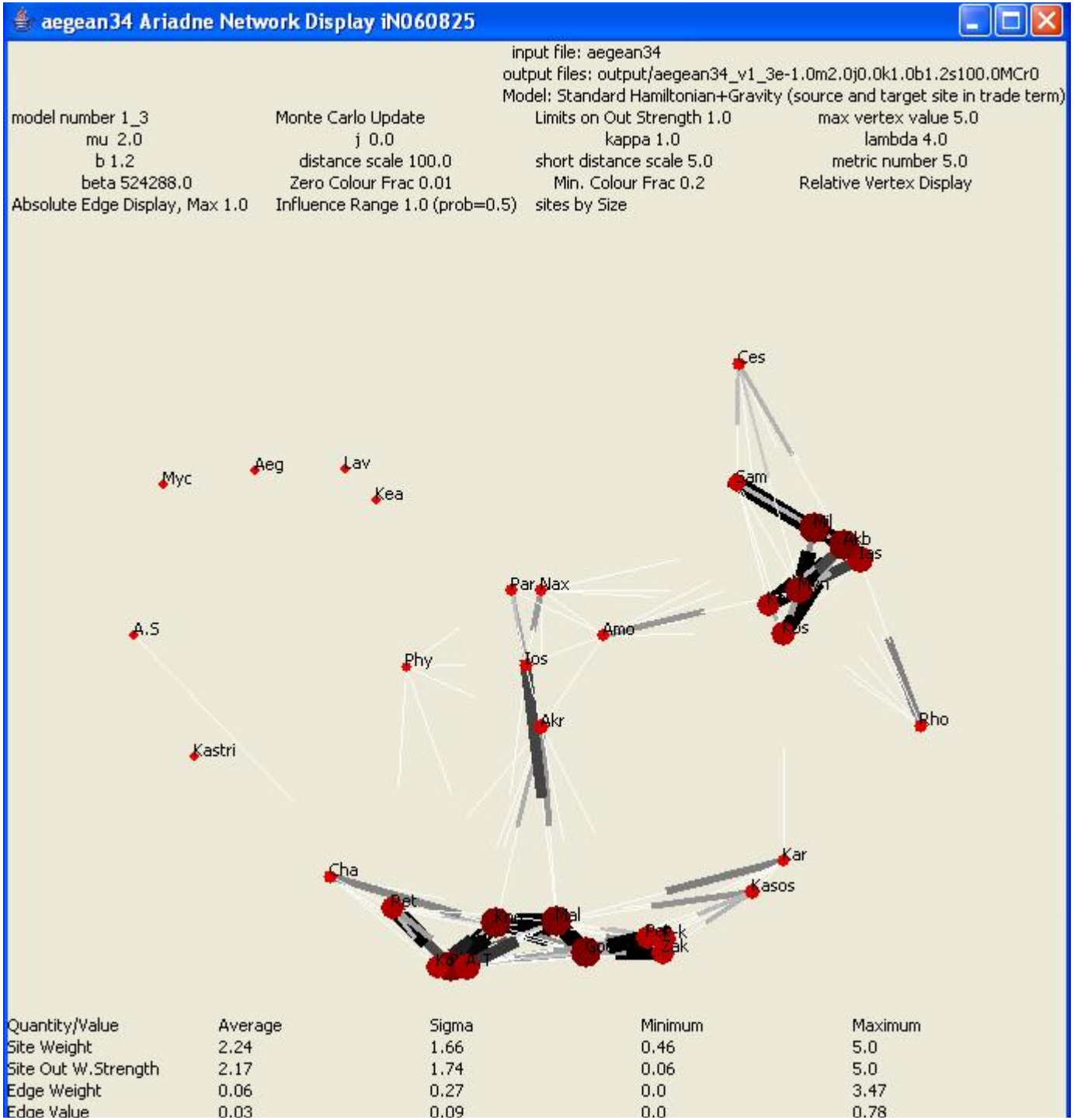


Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.43	0.37	0.79	2.03
Site Out W.Strength	1.43	0.37	0.79	2.03
Edge Weight	0.04	0.08	0.0	0.47
Edge Value	0.03	0.06	0.0	0.42





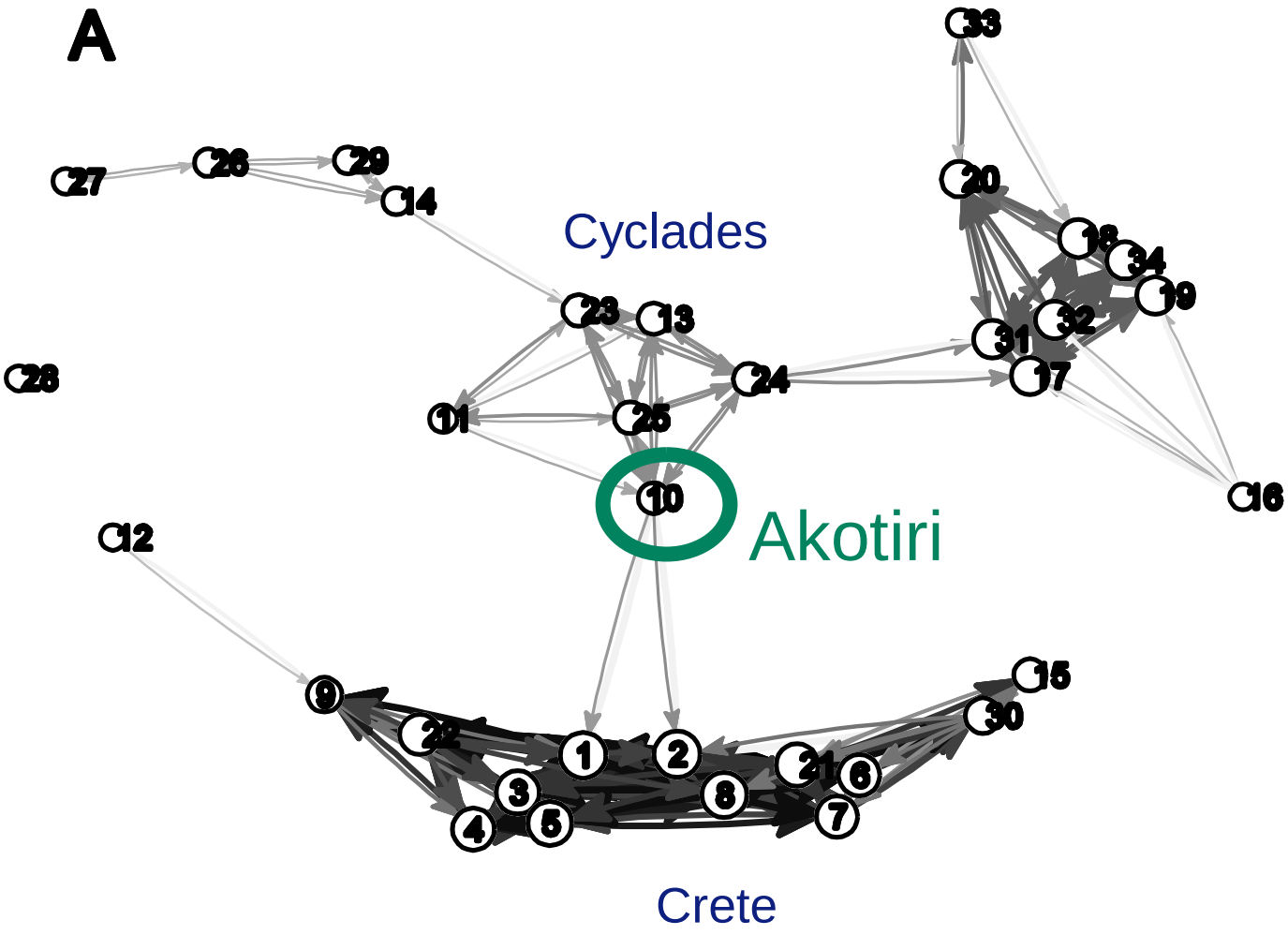




End of increasing μ sequence

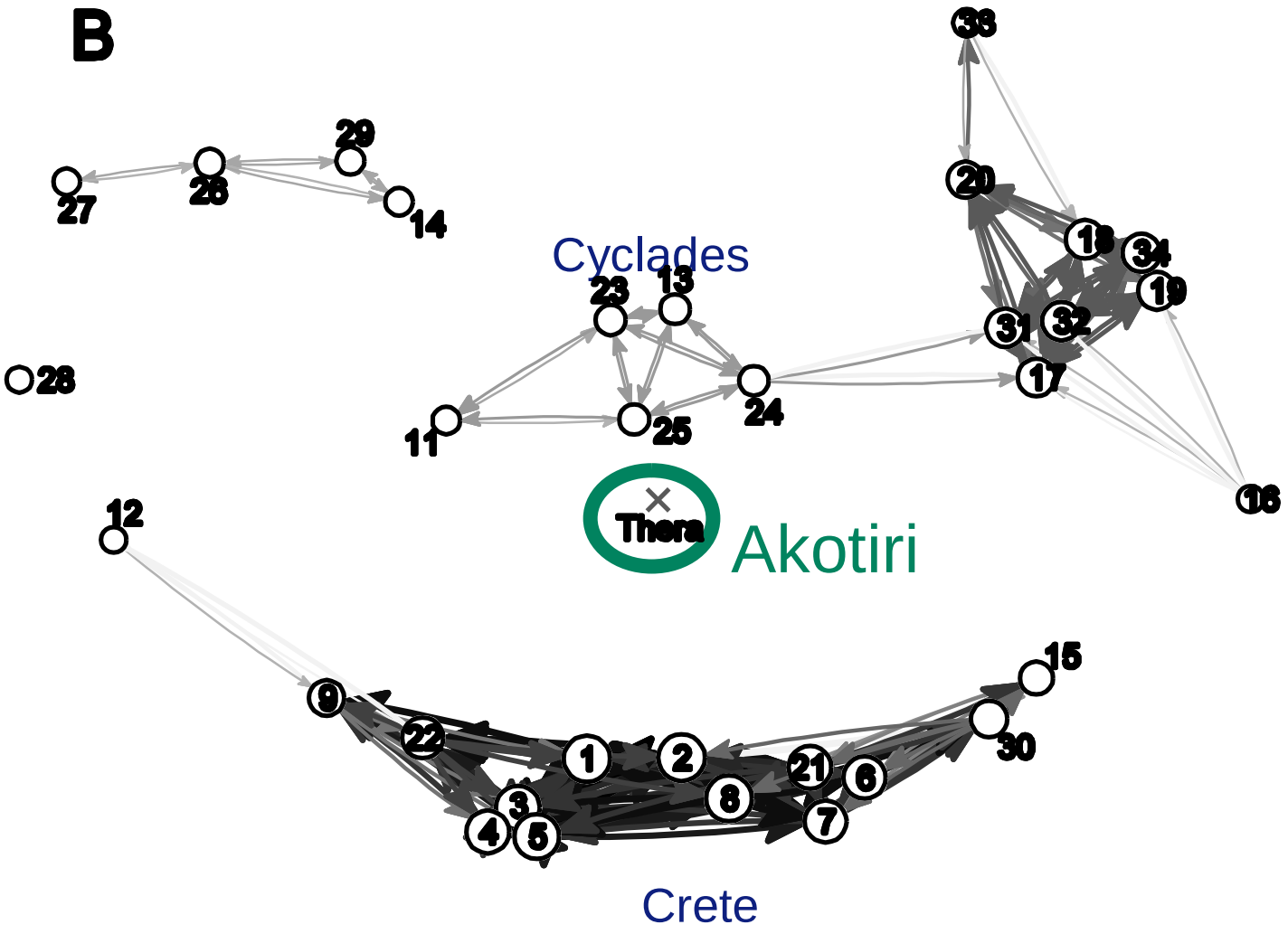
With Thera (=Santorini, ancient site Akrotiri 10)

Almost all islands have a route to each other via reasonably strong links



Without Thera (=Santorini, ancient site Akrotiri 10)

Volcantic eruption destroyed Thera around 1500BC about 50 years before end of Minoan civilisation



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Summary

- Starting to extract basic results systematically
- Some behaviour looks interesting to an archaeologist
  – Crete and Dodecanese usually form strongest clusters
- Some types of behaviour do not appear to be possible
  - Greek mainland rarely gives significant sized sites
- Some factors seem to be playing a key role
  – small differences in physical distance from Crete may be significant
- **Many options remain to be explored**
  – improve distance data, more analysis tools, more what if scenarios, EBA vs MBA, general time evolution, other data sets