Imperial College London

Informal Summer Workshop on

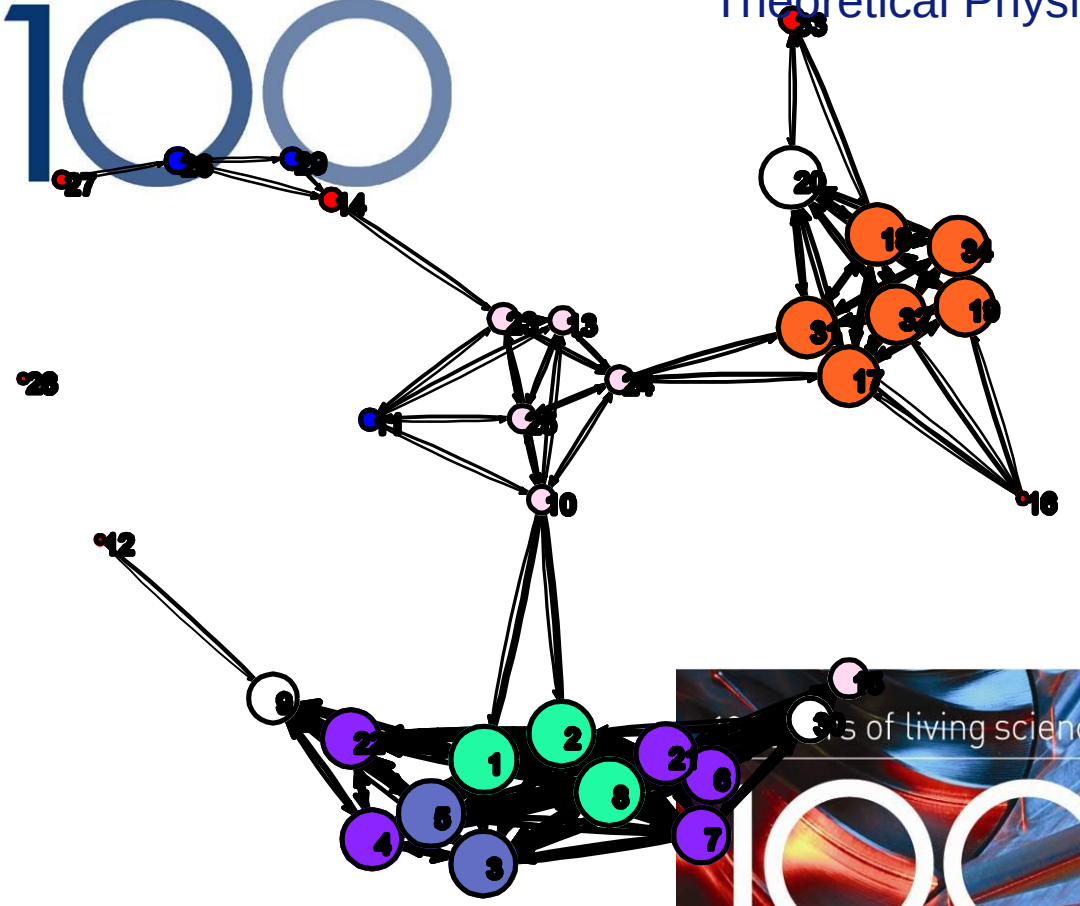
Complex Networks and Social Dynamics

Espoo 31st Aug.-2nd Sept. 2007

Tim Evans

Theoretical Physics

Networks in Archaeology



e.g. see **ISCOM** project
Evans, Knappett, Rivers
"Physical and Relational Networks in the Aegean Bronze Age"
(ed.s D.Lane et al. 2007)

www.ic.ac.uk/people/t.evans

- Archaeology and Physics
- Previous Models
  - Without networks
  - With Networks
- Our Model
  - The Middle Bronze Age Aegean and the Minoans
- Summary

Archaeology seen by a physicist

- Events/Experiments
  - Details of history never repeated
  - Must assume some universal principles exist
- Uncontrolled Fluctuations
  - Chance events may obscure underlying trends
    e.g. weather, great leaders, volcanoes
- Data
  - Impossible to collect all data
  - Data expensive and slow to collect
  - Impossible to avoid unknown systematic bias
    e.g. some sites under modern settlements,
    some data survives better in some places than others

Physicist's approach to Archaeology

- Statistical Physics
  - Allows for uncertainties in input data
  - Allows for chance events
- Model Robustness
  - Precise scaling properties of model reflecting some basic features
  - Wide range of parameter values give similar results
- Statistical Outputs
  - Results interpreted statistically not deterministically

Modelling Cycle

ARCHAEOLOGY DATA

Set direct parameters

Inputs

MODEL

Output Filter

Set remaining parameters

Output Checks

Consistency check

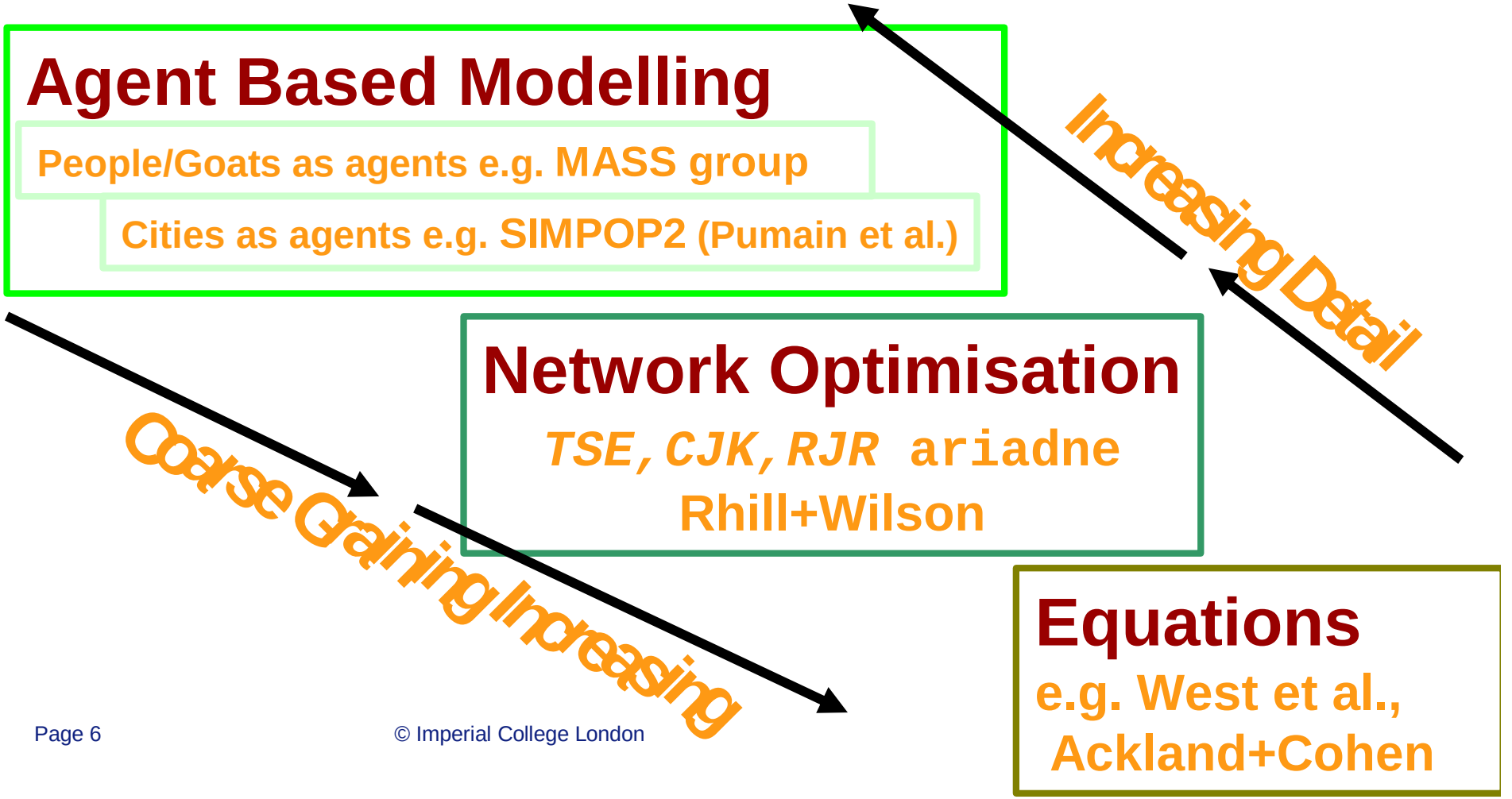
Predictions

```
//        double [] [] distance  = new double [numberSites][num

//        double DijkstraMaxDist;
        StatisticalQuantity siteDistanceStats;

        IslandCulture networkCulture;
        double culturePSiteCopy = 0.45;
        double culturePCopy =0.45;
        double culturePInnovate =0.05;
        double cultureTimeScale=10000.0;

        // update records
        updateRecord edgeU = new updateRecord() ;
        updateRecord verte R= new updateRecord() ;
        // General parameters
        TimMessage
//infolevel=message.
        int
        int outputM
        double vertexMaximum;
//        double modelNumbe
        ModelNumber modelN ber;
//        int modelNumber.
//        int modelNumber.minor;
          boolean
//
//        boolean modelNumber.bit2;

        // Display
        double zeroColourF ac=0.03;
        double minColourFr =0.1;
        int siteWeightFact r = 20;
        int edgeWidthFacto = 10;
        boolean newNetworkDisplaySyle = false;
        double DisplayMaxVertexScale=0.0; //<=0 then display ve
                                          // else display vertice
        double DisplayMaxEdgeScale=1.0;   //<=0 then display ed
                                          // else display edges r
        int DisplayVertexType=0; // 0=size, 1 = rank;
```

Modelling Scales

Several approaches when studying settlement patterns, many take *settlements* as the core unit.

- e.g. see EU ISCOM project [Lane et al. (ed.s) 2007]



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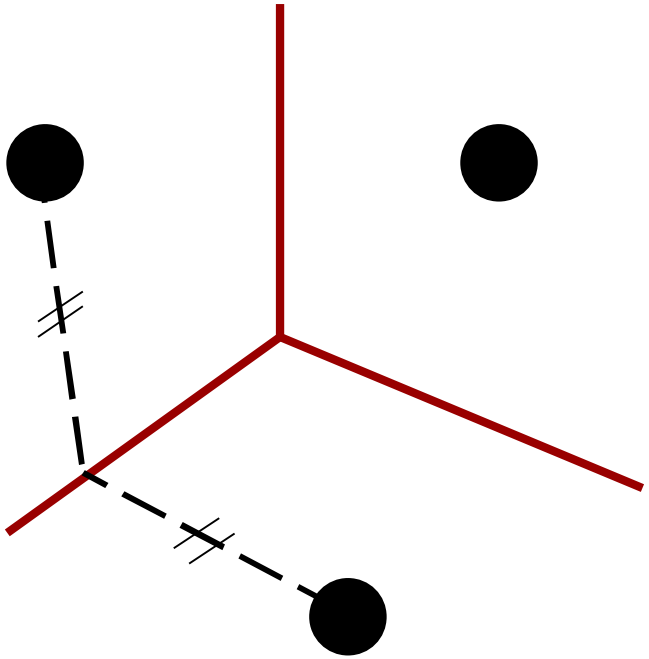
Site-Site Interactions

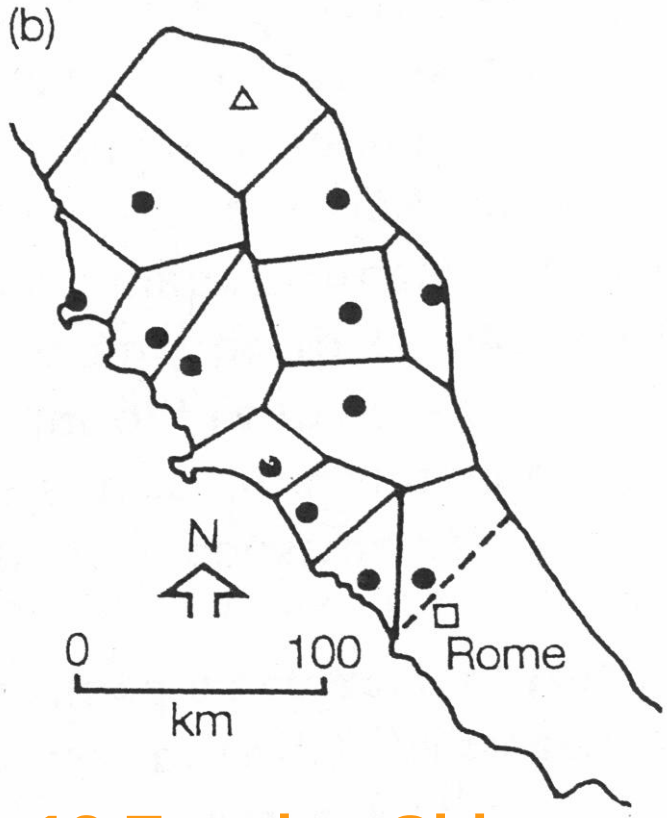
- Archaeology has given little attention to the role of interactions between sites in the generation of those sites.
  - Local (often just nearest neighbour) interactions considered sometimes but usually regional and global interactions neglected.
  - Most models use fixed site sizes

$\Rightarrow$ Network models may prove to be useful

Theissen Polygons

- Boundaries = Midpoint between nearest sites
- All sites equal

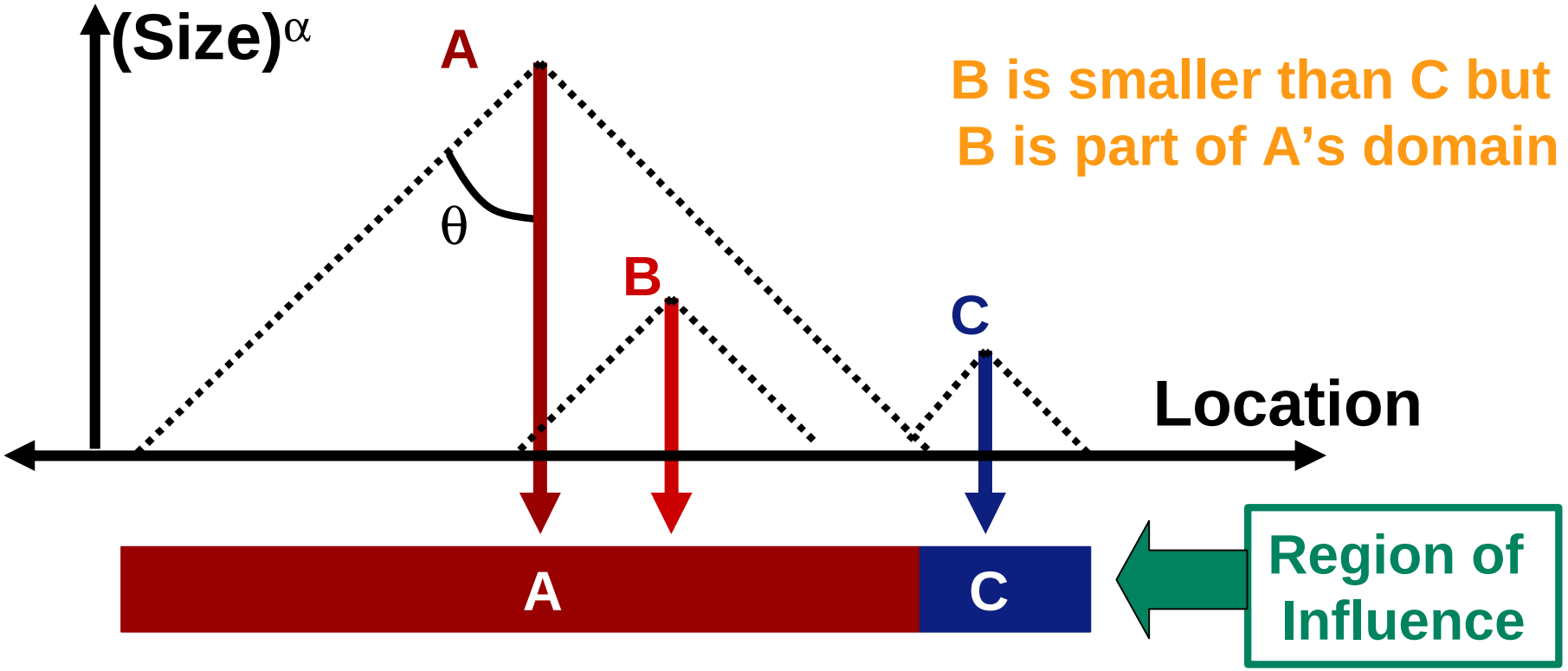




12 Etrurian Cities after Renfrew 1975

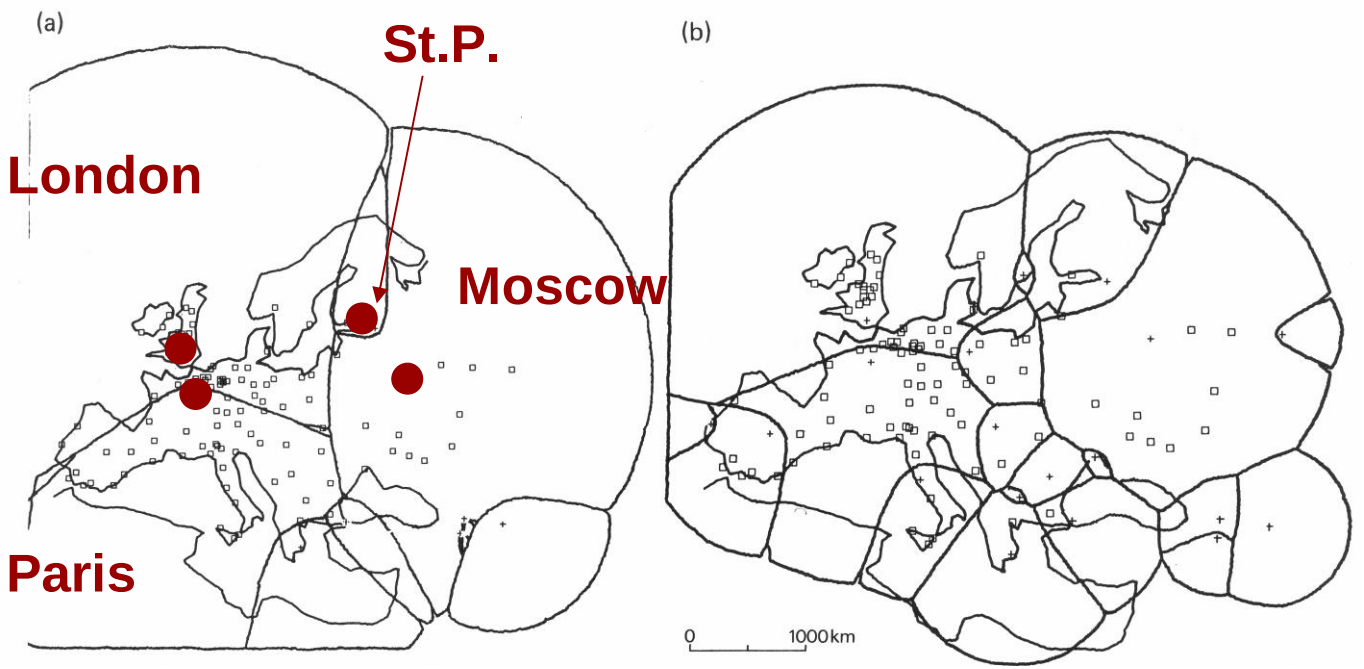
Tent Model

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

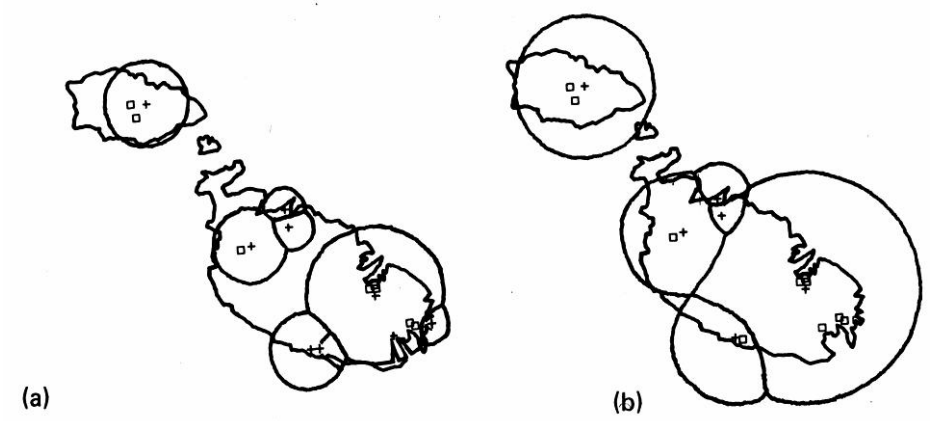


Tent model examples (Renfrew & Level, 1979)

European Cities 1960



Neolithic Temples of Malta



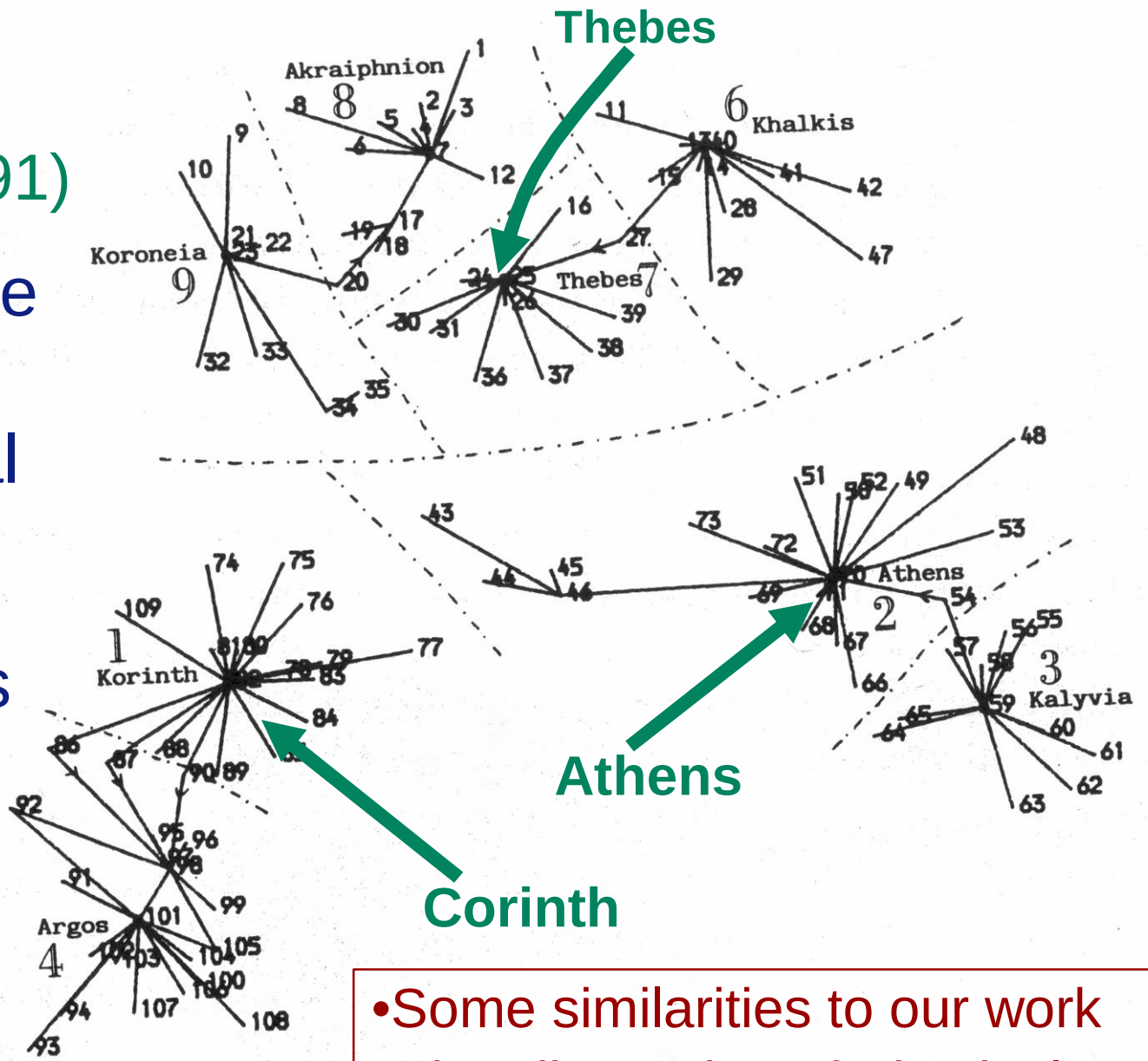
Limitations of Early Models

- Focus on Sites
- Fixed Site Sizes
- Interactions with nearest geographical neighbours only

*** Network models may prove to be useful

Optimisation
(Rhill & 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

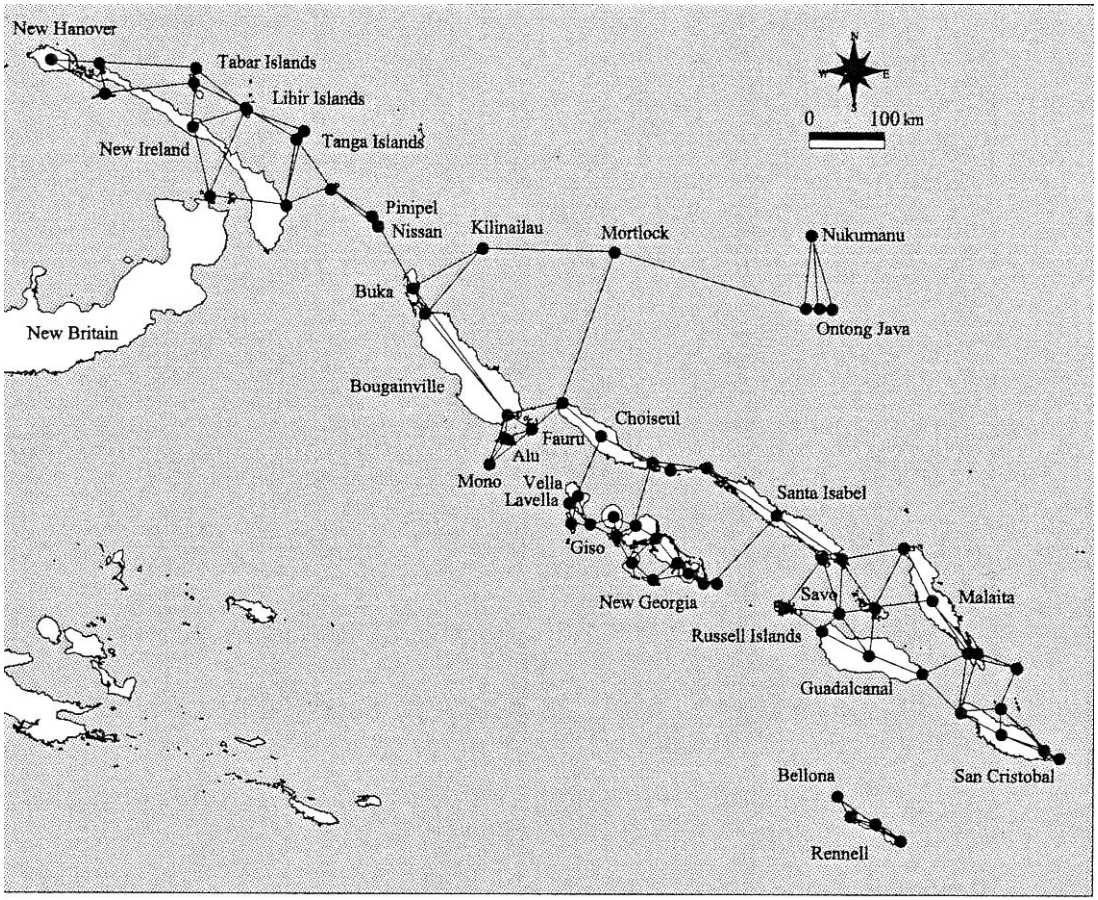
PPA - Proximal Point Analysis

- Fix sites, all considered equal
- Connect each site to three 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)

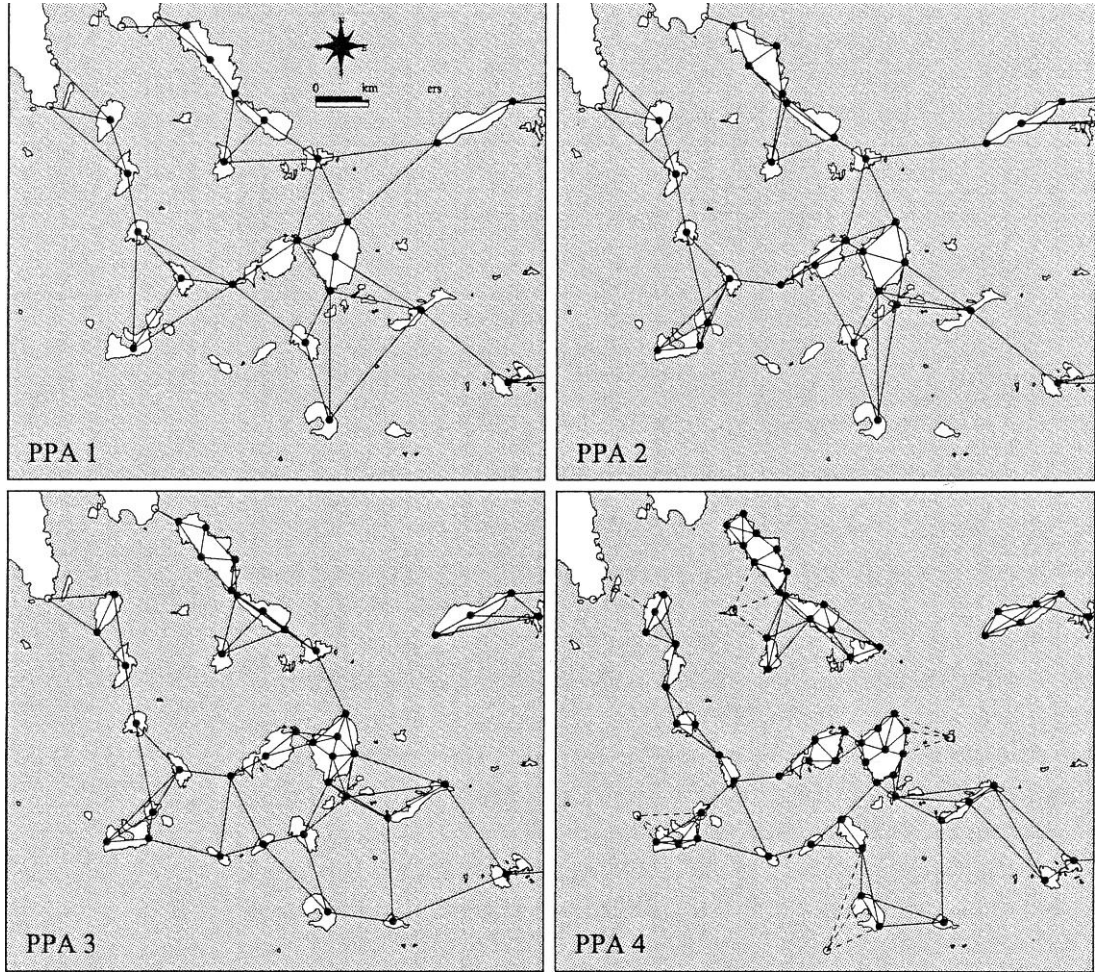
- Solomon Islands (east of Papua New Guinea)
- PPA analysis



Broodbank (2000)

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

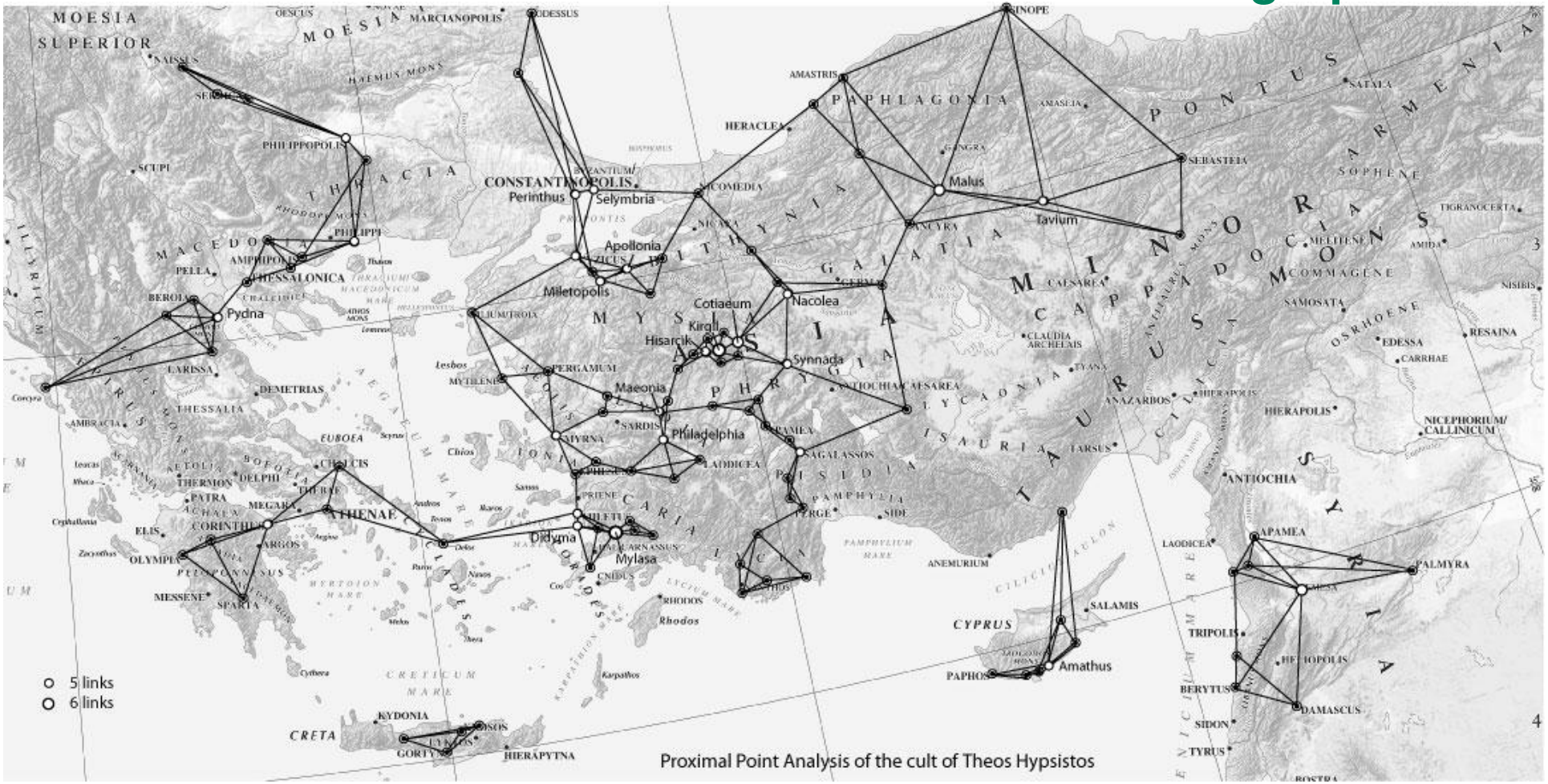
⇒ PPA very appropriate, more analysis possible but is it useful?



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

Collar, Exeter Univ.

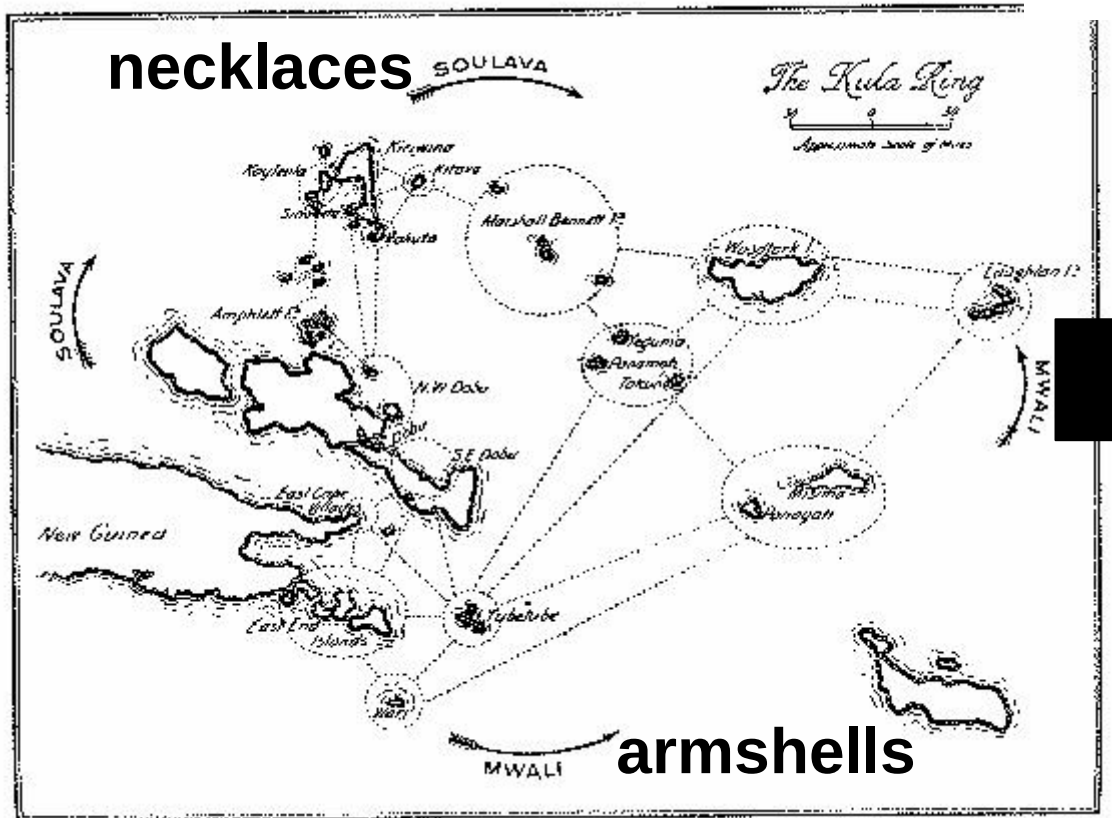
Hypsistos cult inscriptions (1-4c.AD), PPA graph



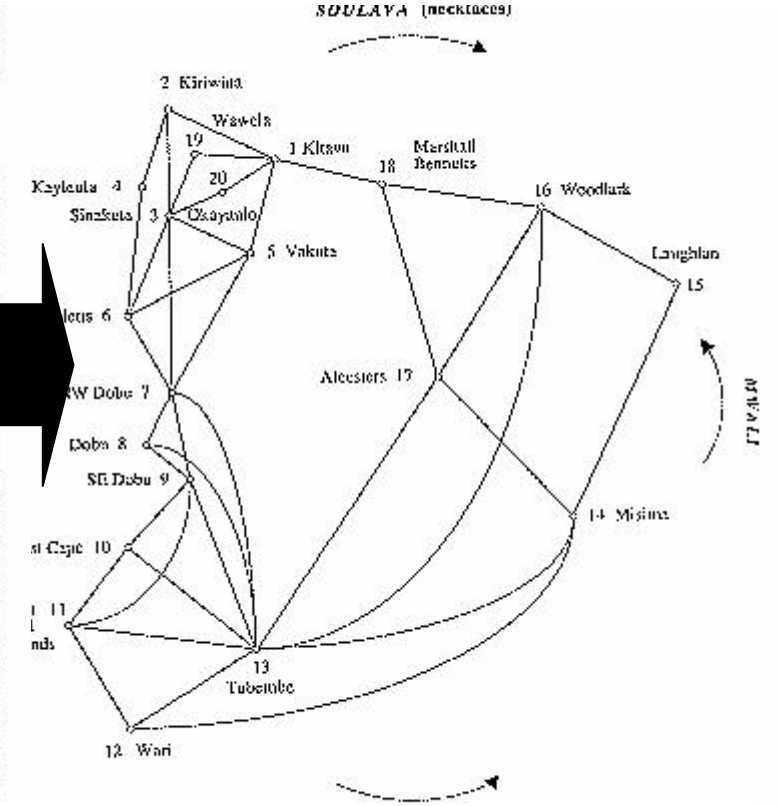
PPA – degree analysis, work in progress

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

Limitations of Early Network Models

- Still fixed site sizes
- Edges only on or off (simple graphs)
- PPA still only considers nearest geographical neighbours

⇒Little exploitation of network structure in creating network

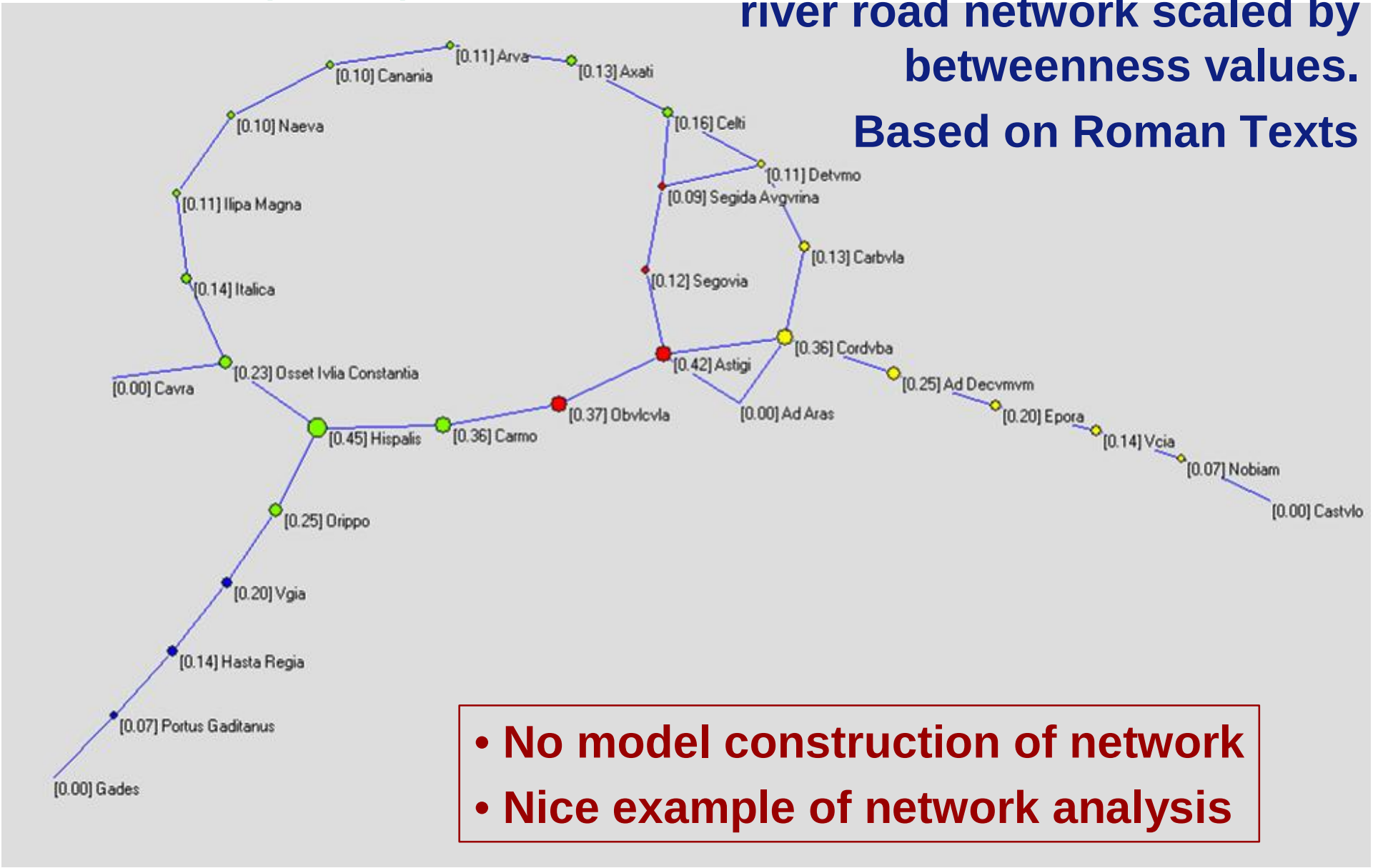
⇒ Global properties of networks and role of sites in wider network rarely studied

*** Network models have more to offer …

Isaksen (2006)

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

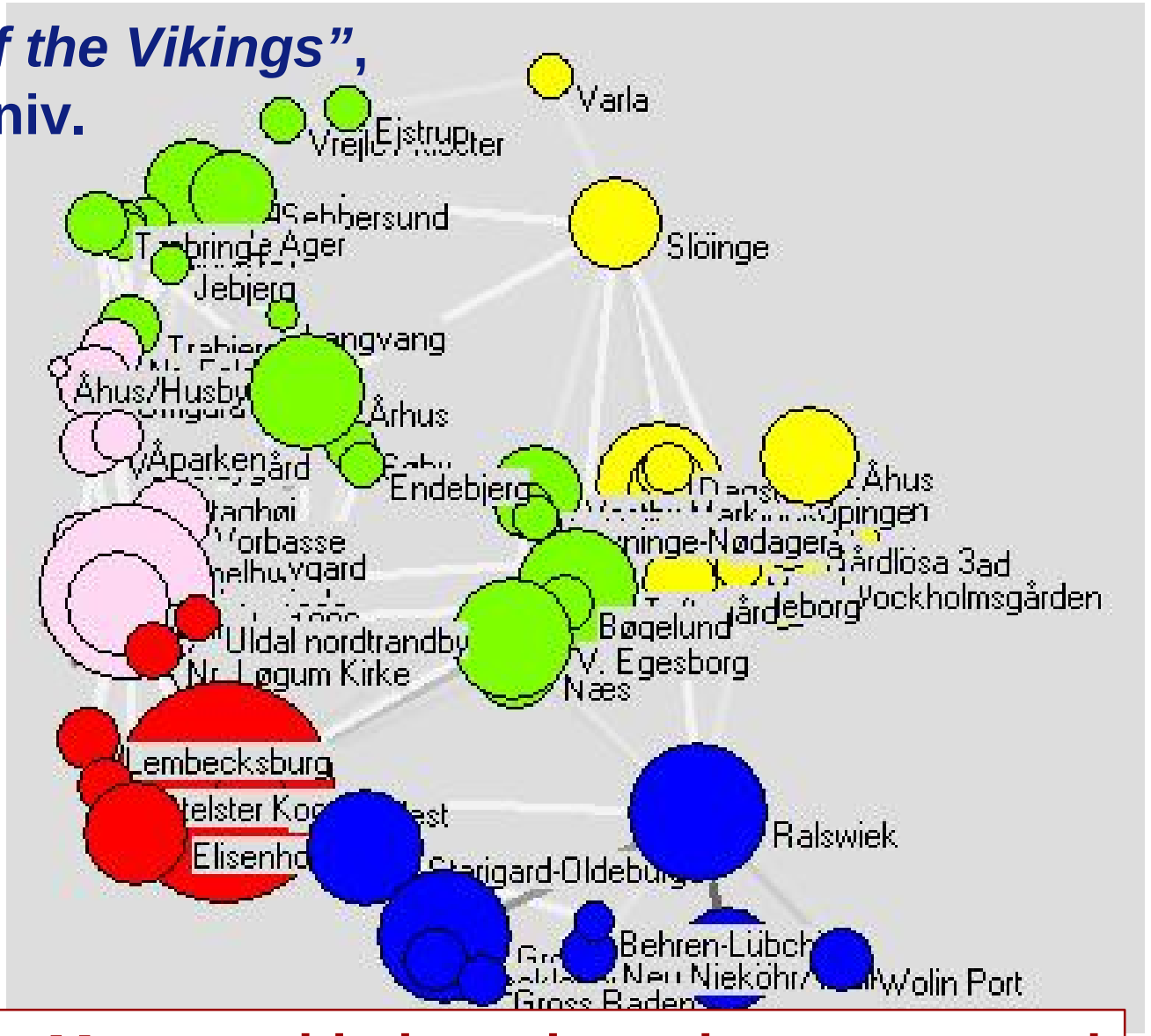
Based on Roman Texts



- **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**

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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

`Minoa'

A reconstruction on show in Chania, Crete

See A.Simandiraki (2005) for commentary on the modern context of this reconstruction

Some 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

$$H =$$

Isolated sites have optimal size $v_i = 0.5$

$$-\kappa \sum_i S_i v_i (1 - v_i)$$

Trade (interactions) bring benefits

$$-\lambda \sum_{i,j} (S_i v_i . e_{ij}) . V(d_{ij} / D) . (S_j v_j)$$

Increasing 'population' has a cost

$$+ j \sum_i S_i v_i$$

Each trade link has a cost

$$+ \mu \sum_{i,j} S_i v_i e_{ij}$$

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

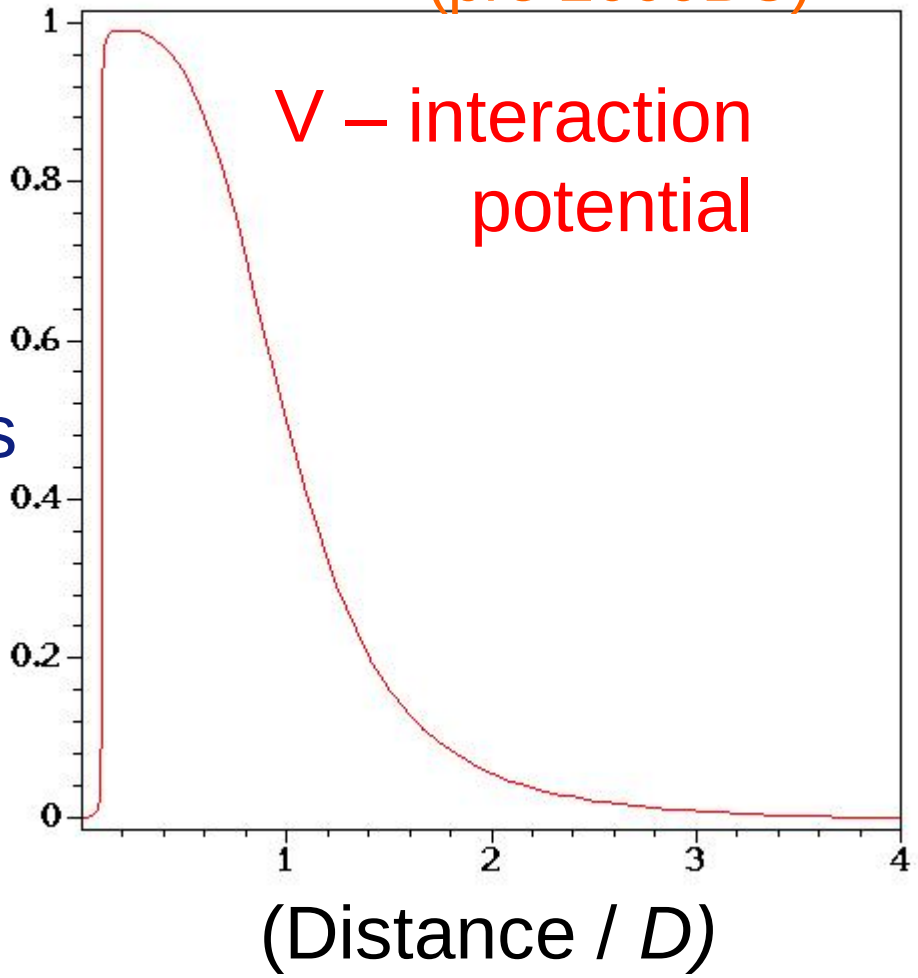
Distance Scale D

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

(after 2000BC) (pre 2000BC)

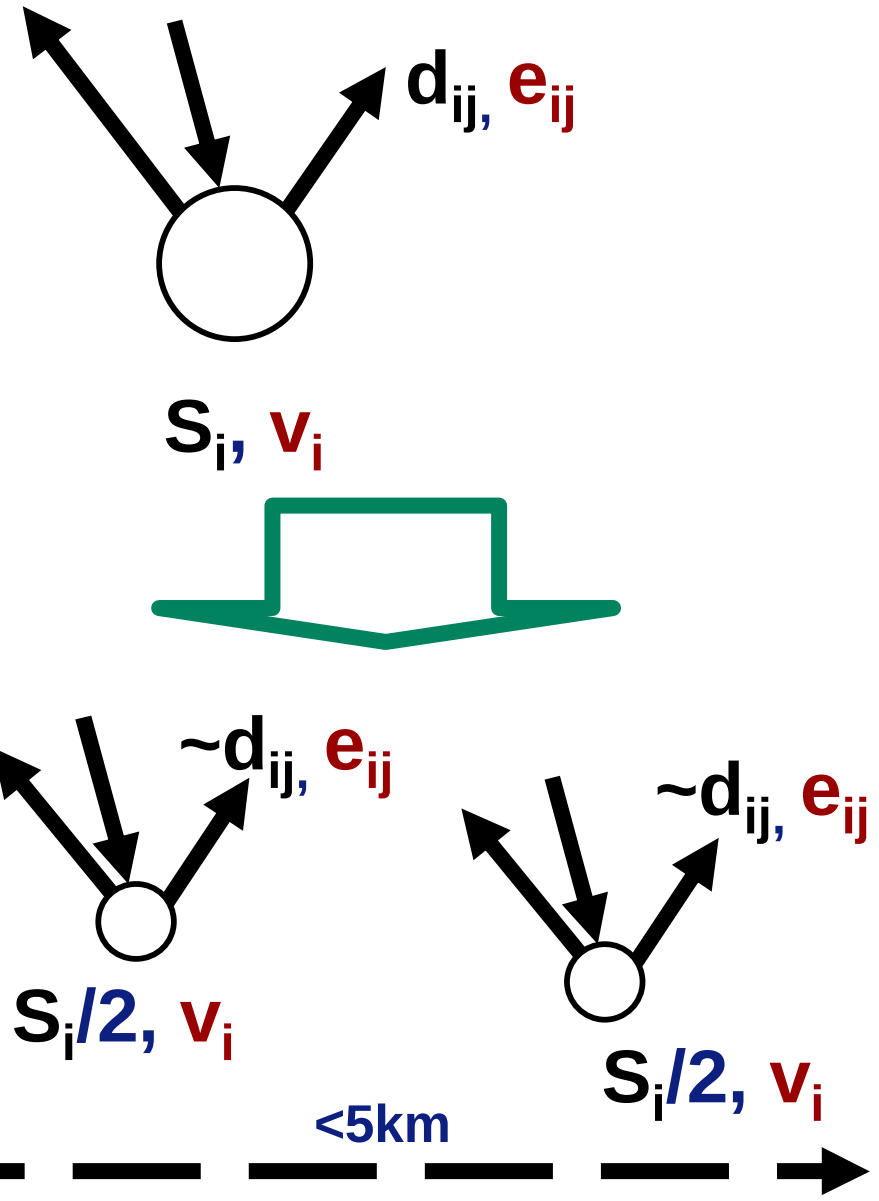
Interaction term for each pair of sites depends on distance d_{ij} between sites such that for distances longer than a scale D the benefit is zero

i.e. no effective direct interaction



Scaling Properties

- Splitting a site into two sites (total fixed capacity unchanged) at approximately the same location gives exactly the same answer *provided* we allow no interactions between these sites
  ⇒ short distance cut off imposed



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

Analysis

- Working with 34 major known sites
- 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.

  This represents slow evolution where system remains in effective equilibrium.
- For any given set of (reasonable) values:

  a) can analyse intrinsic parameters

  b) can perform further `games' to analyse properties e.g. simulate trade in physical objects, cultural transmission models.

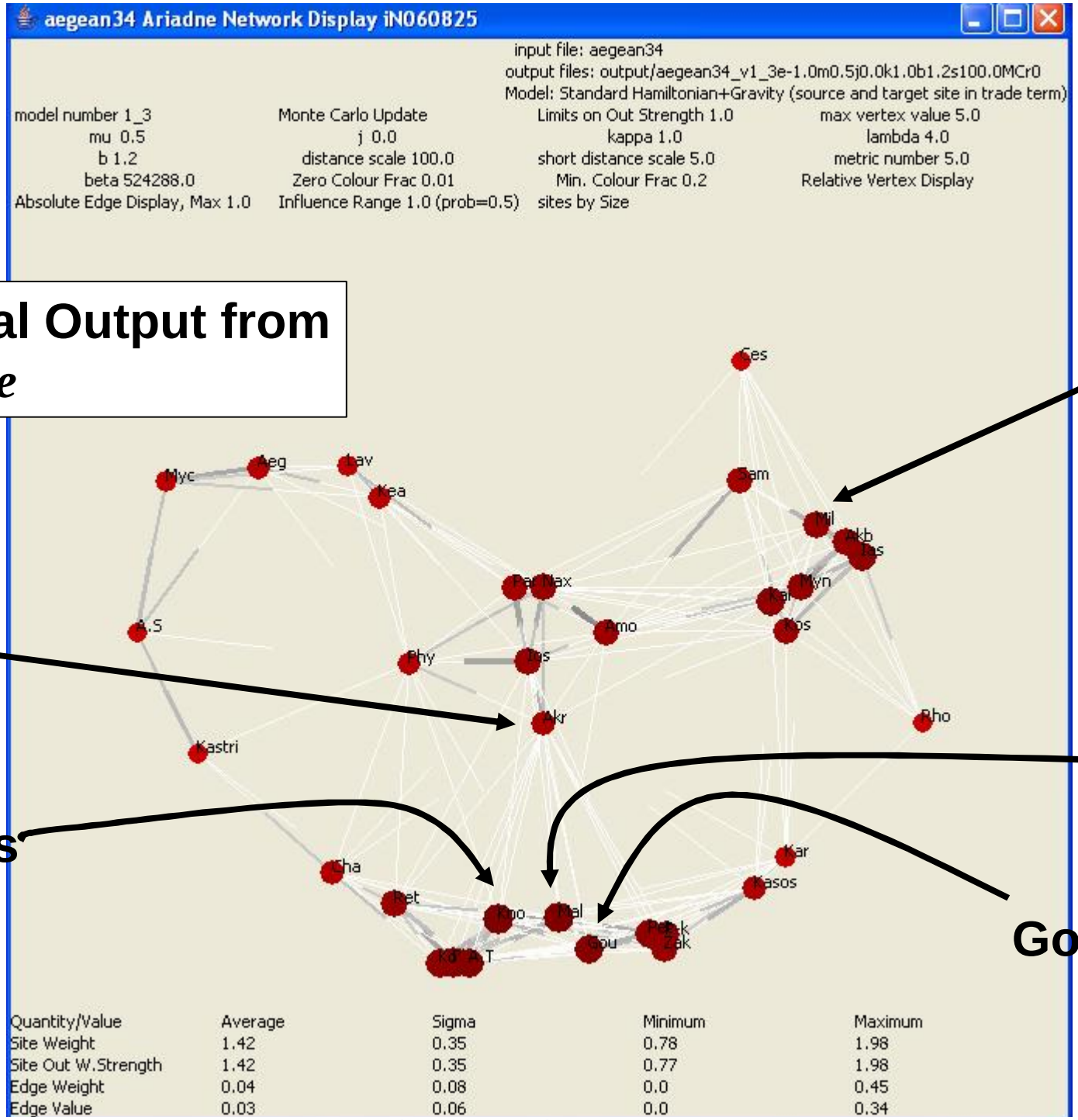
The 34 Sites Used

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*



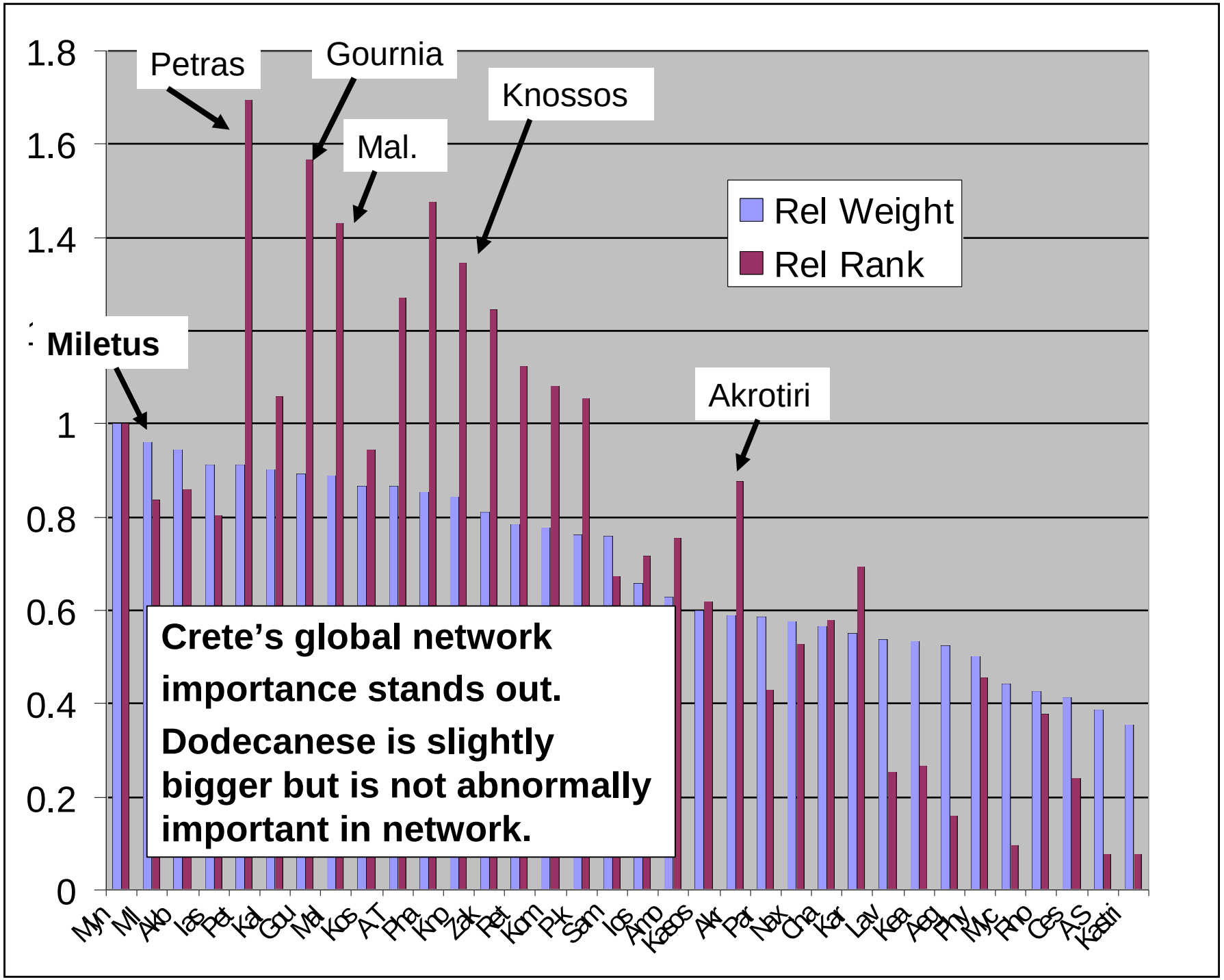
Miletus

Akrotiri

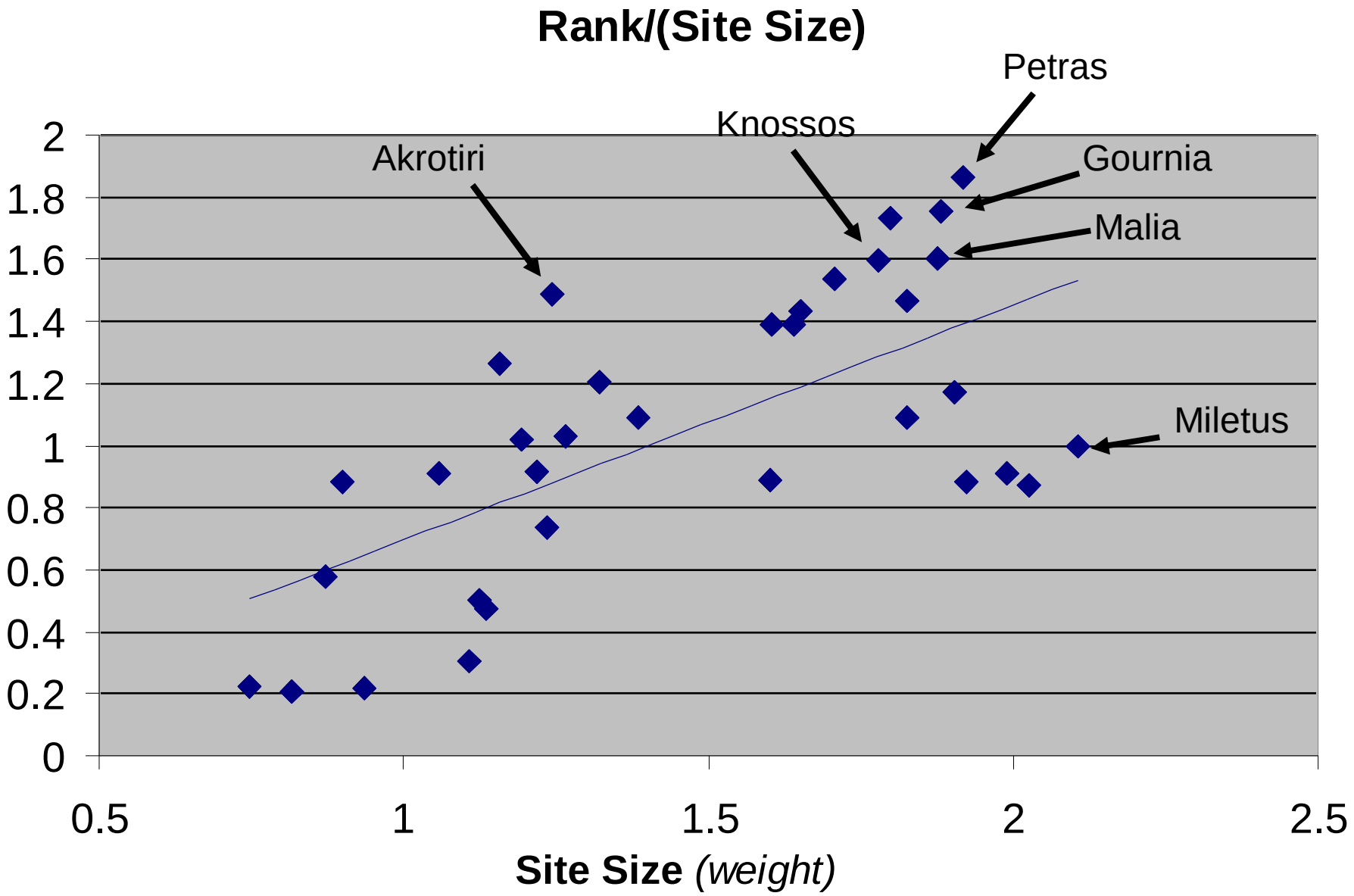
Malia

Knossos

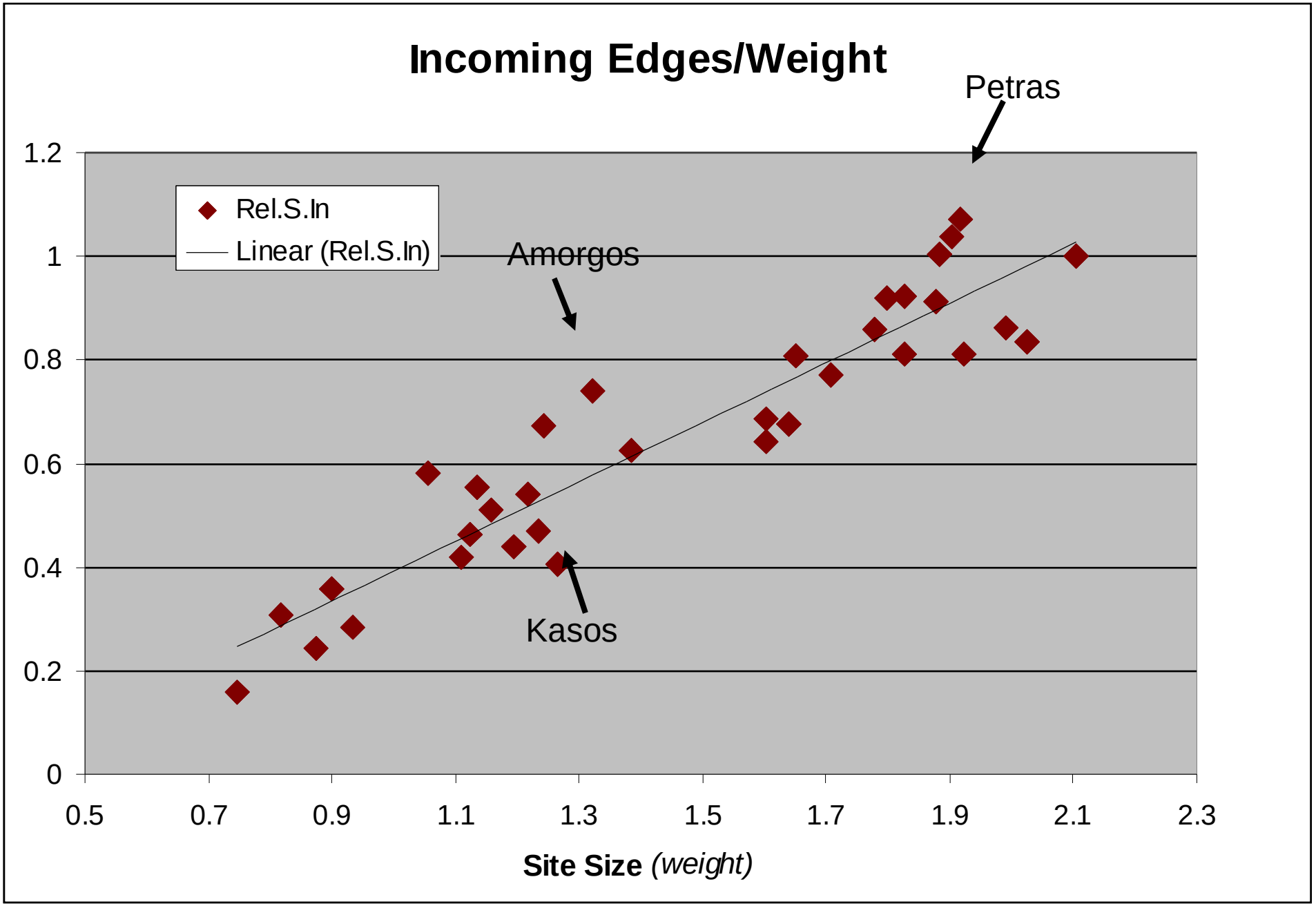
Gournia

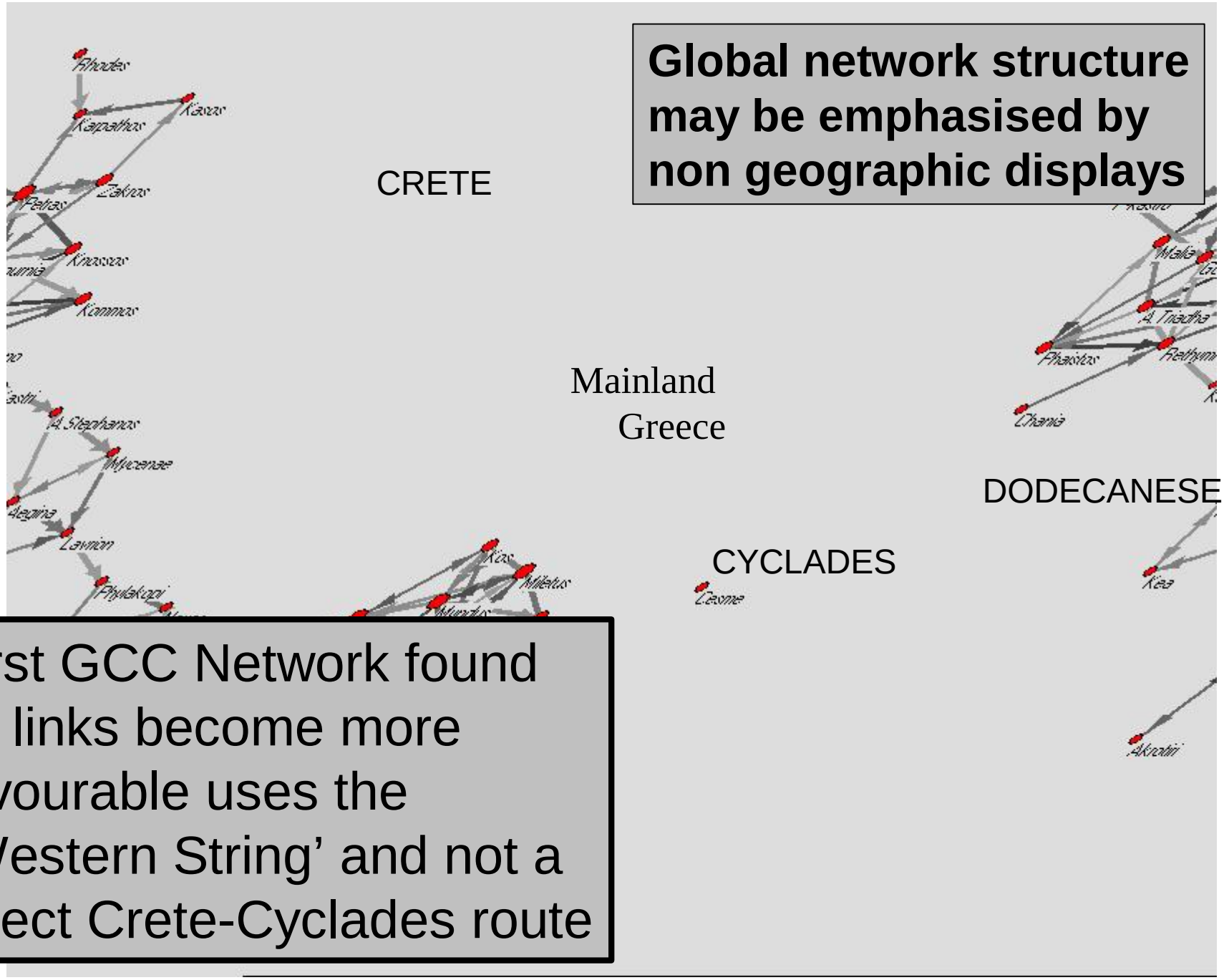


Rank vs. Size shows Crete's is more important to the global network that its size suggests, not so for Dodecanese



Local properties often scale closely with site size (weight)



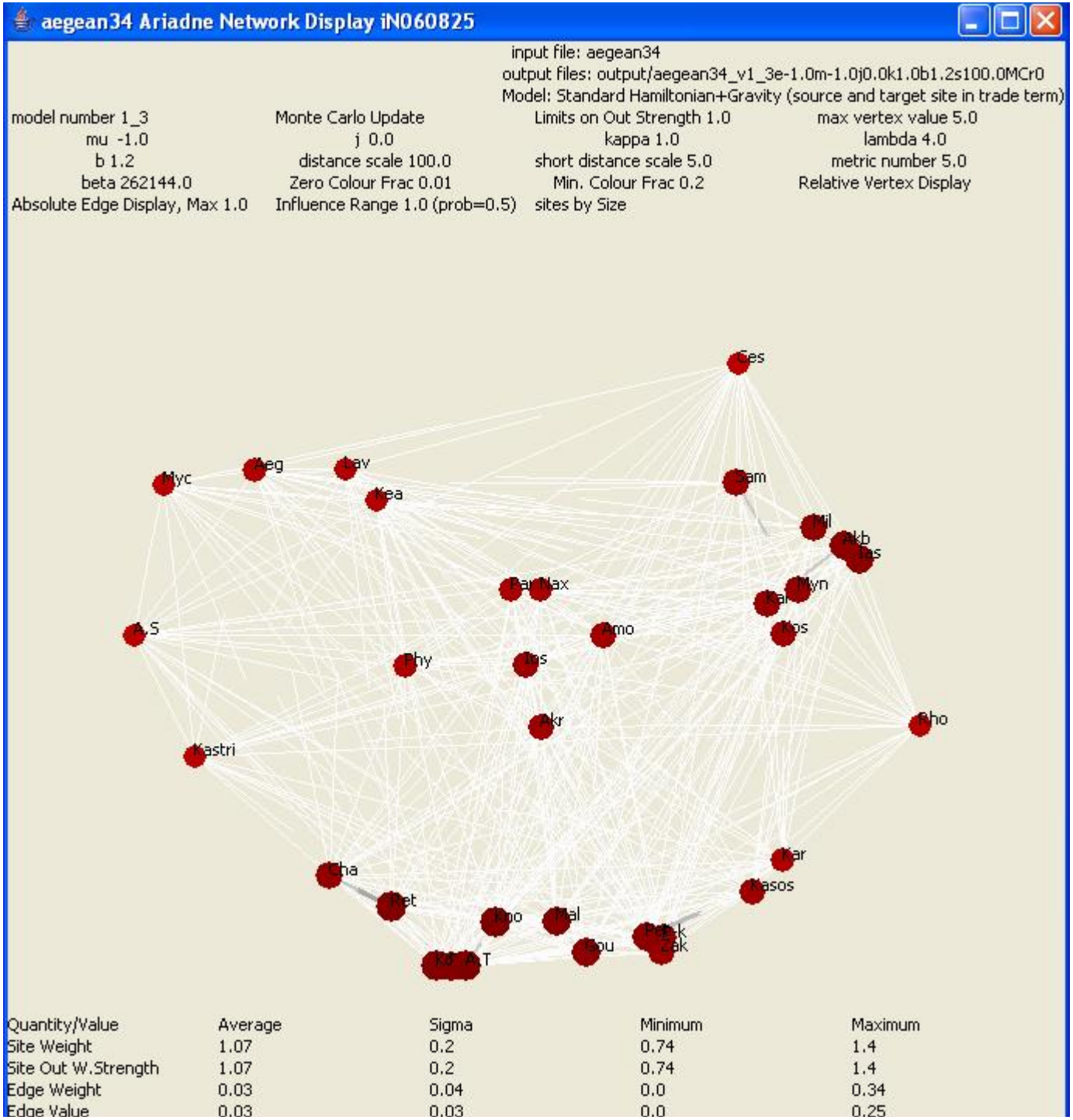


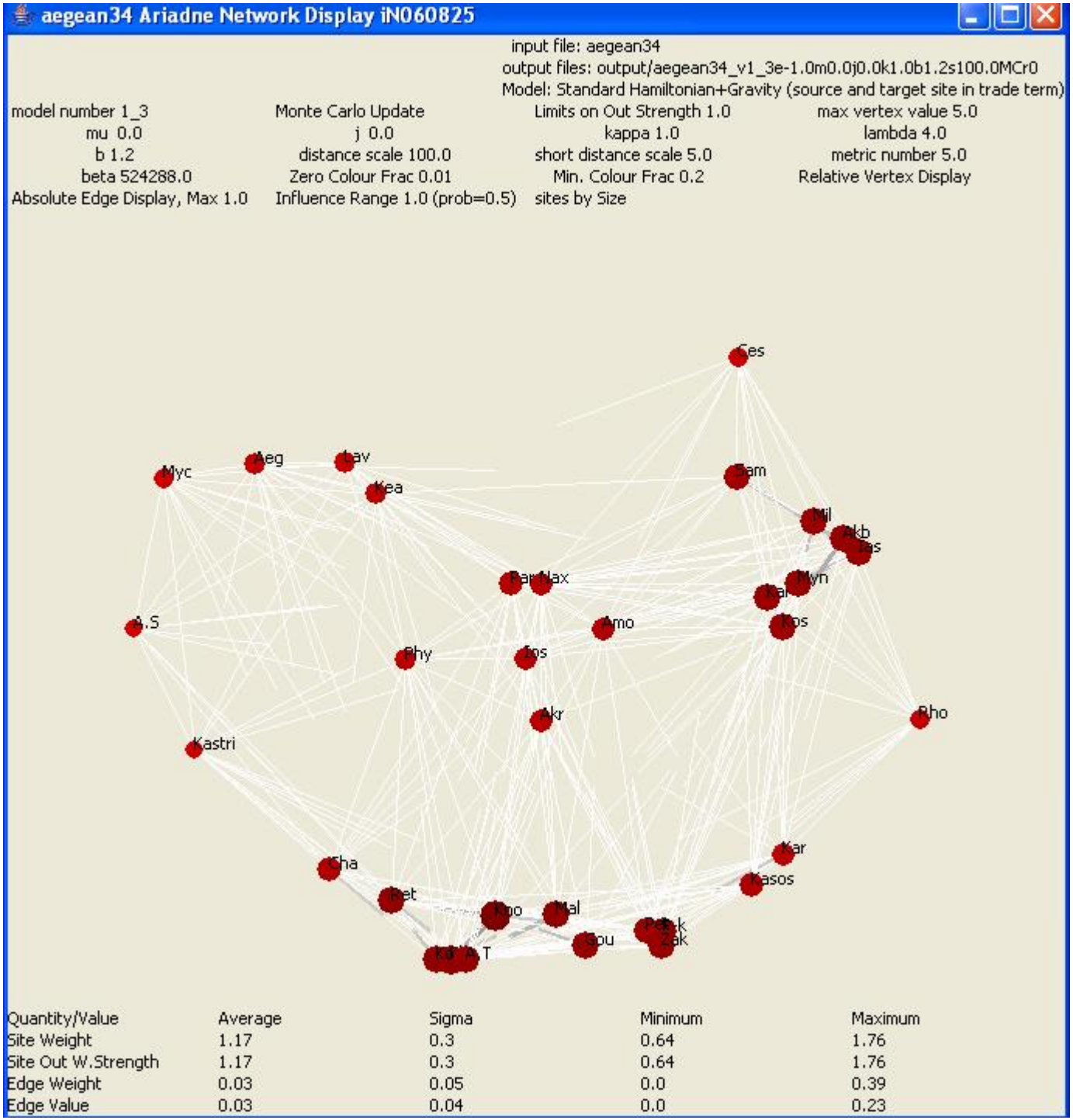
Increasing Edge Cost (μ)

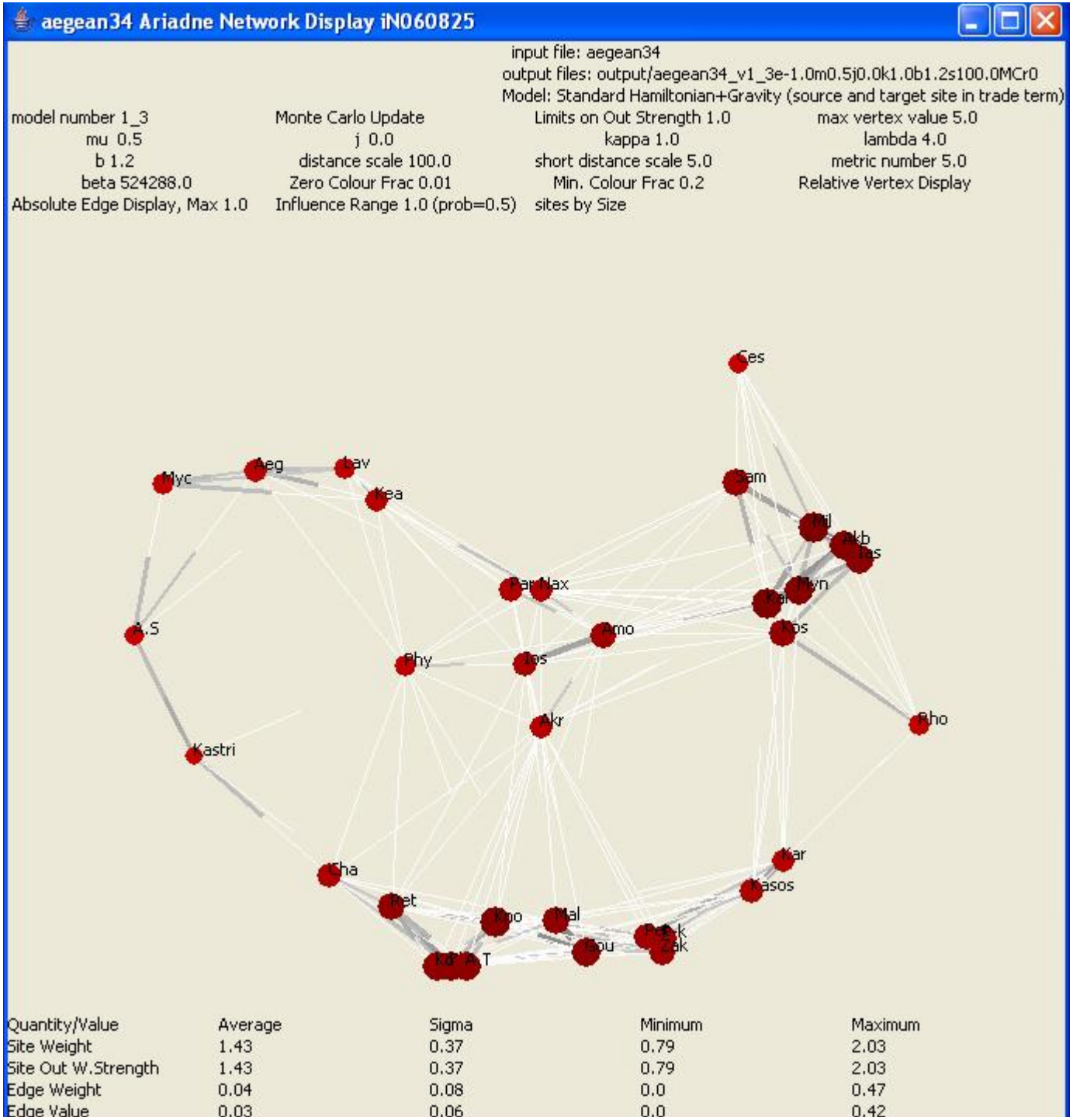
Next 7 slides

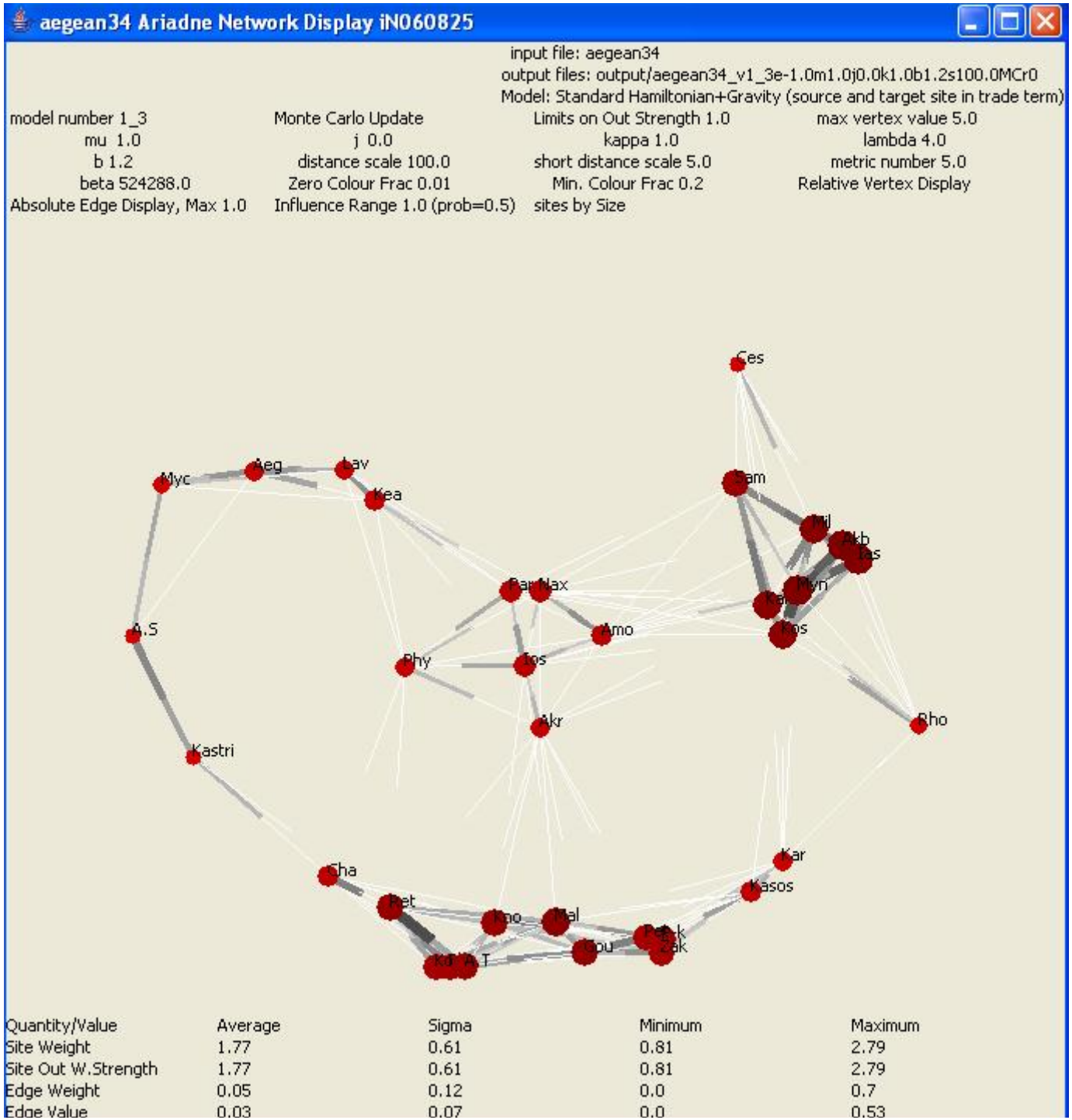
- for large interaction benefits *(λ=4.0, j=0, κ=1.0)*

- 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

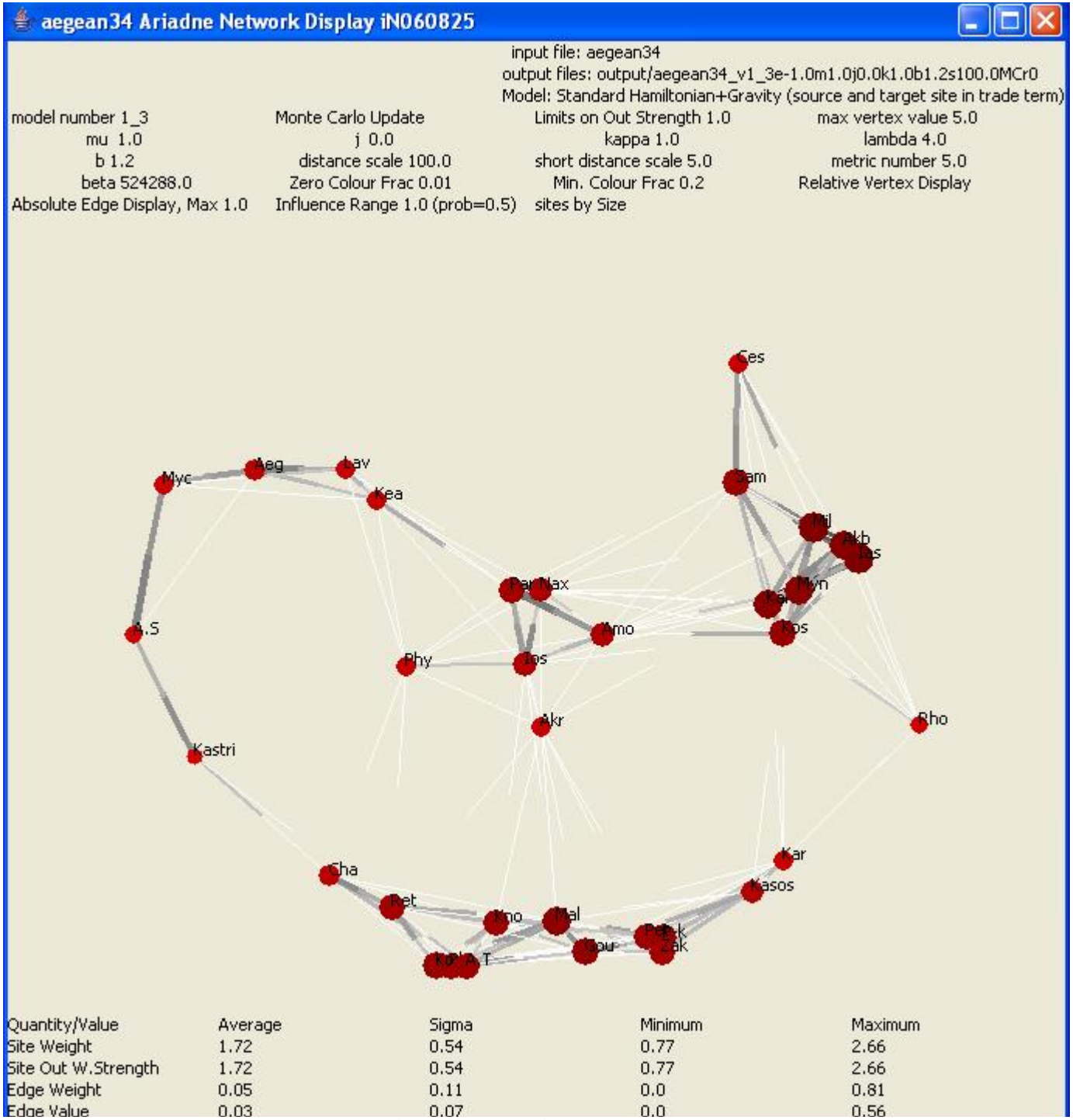


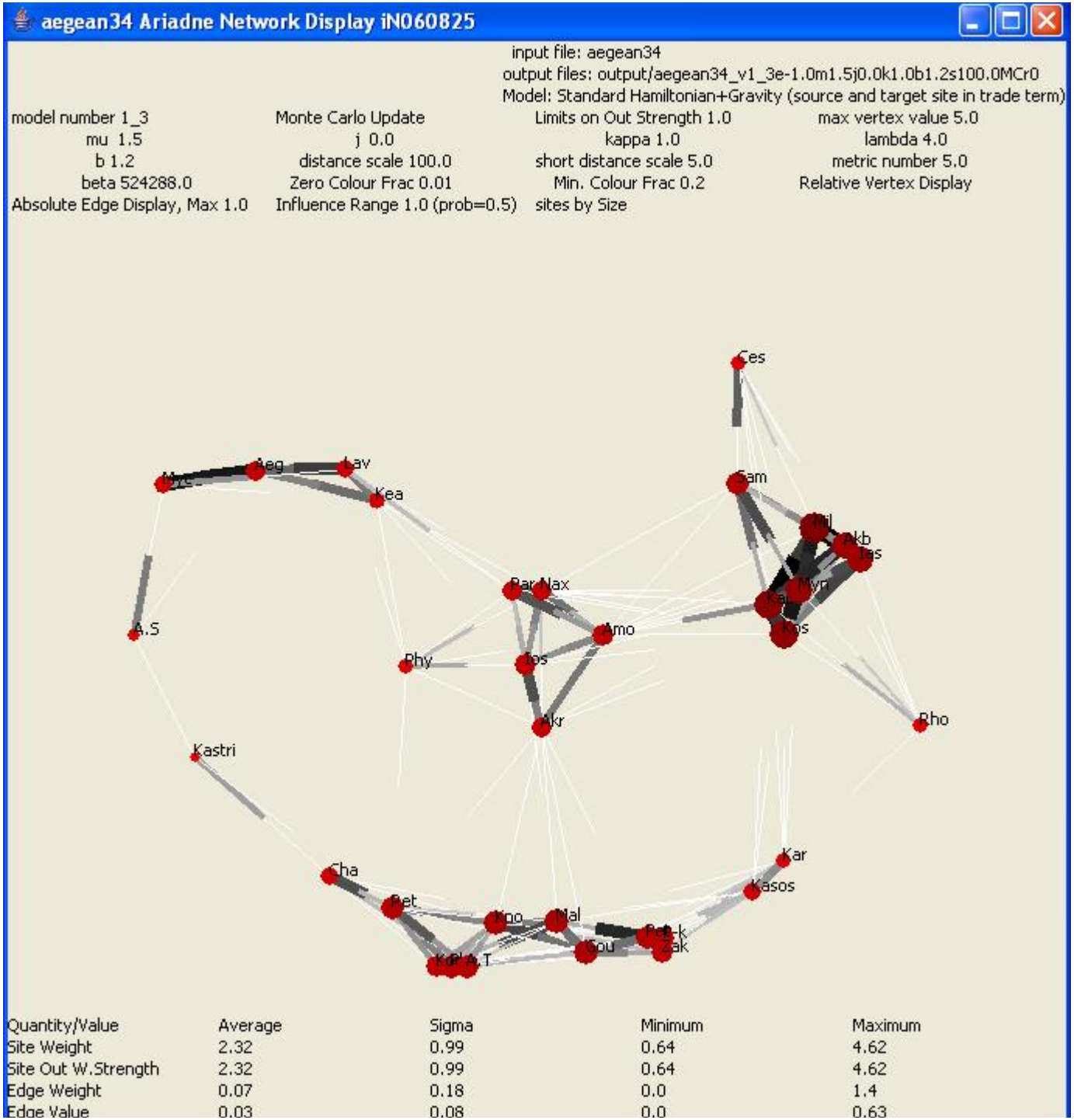


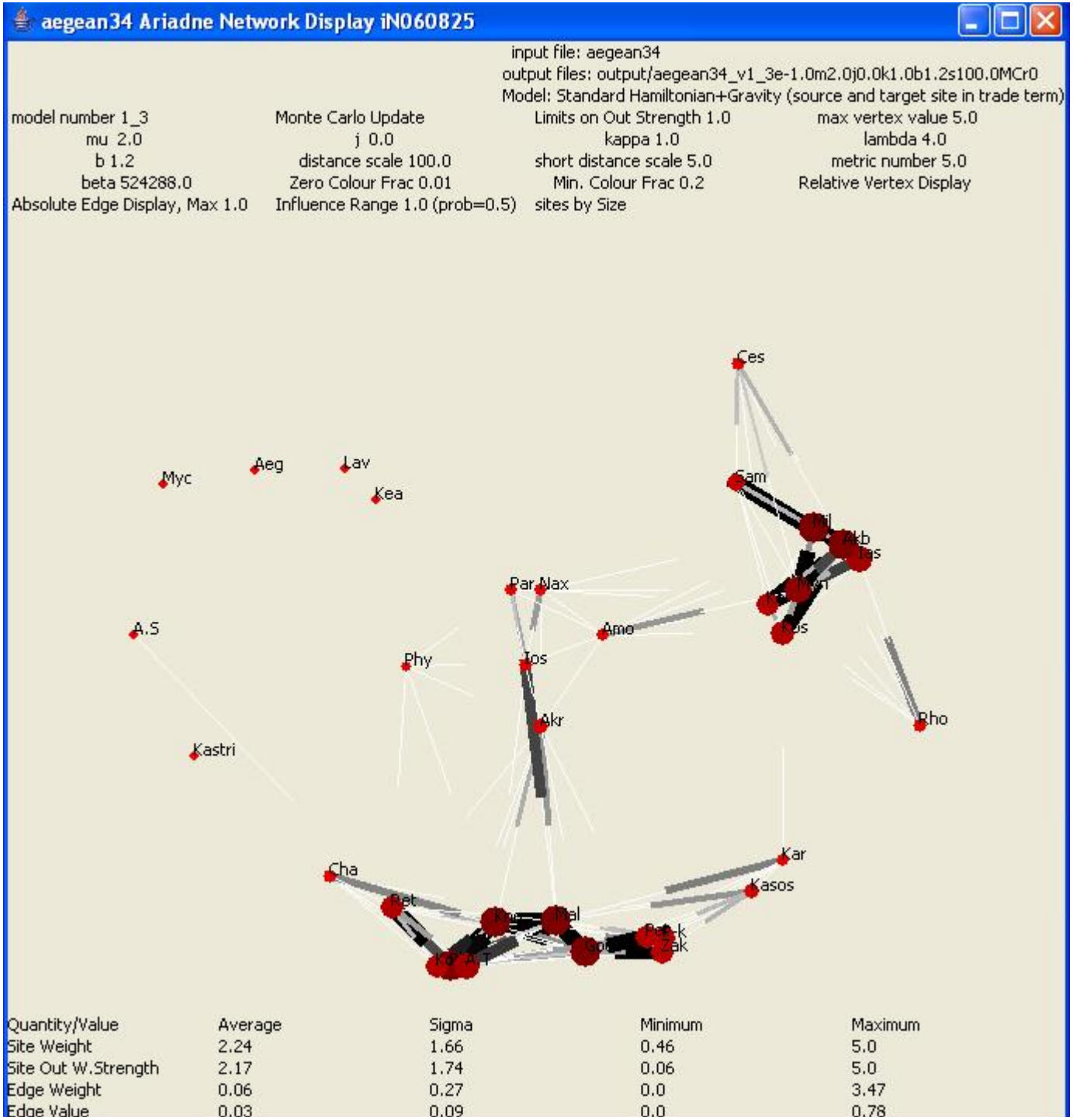




Quantity/Value	Average	Sigma	Minimum	Maximum
Site Weight	1.77	0.61	0.81	2.79
Site Out W.Strength	1.77	0.61	0.81	2.79
Edge Weight	0.05	0.12	0.0	0.7
Edge Value	0.03	0.07	0.0	0.53

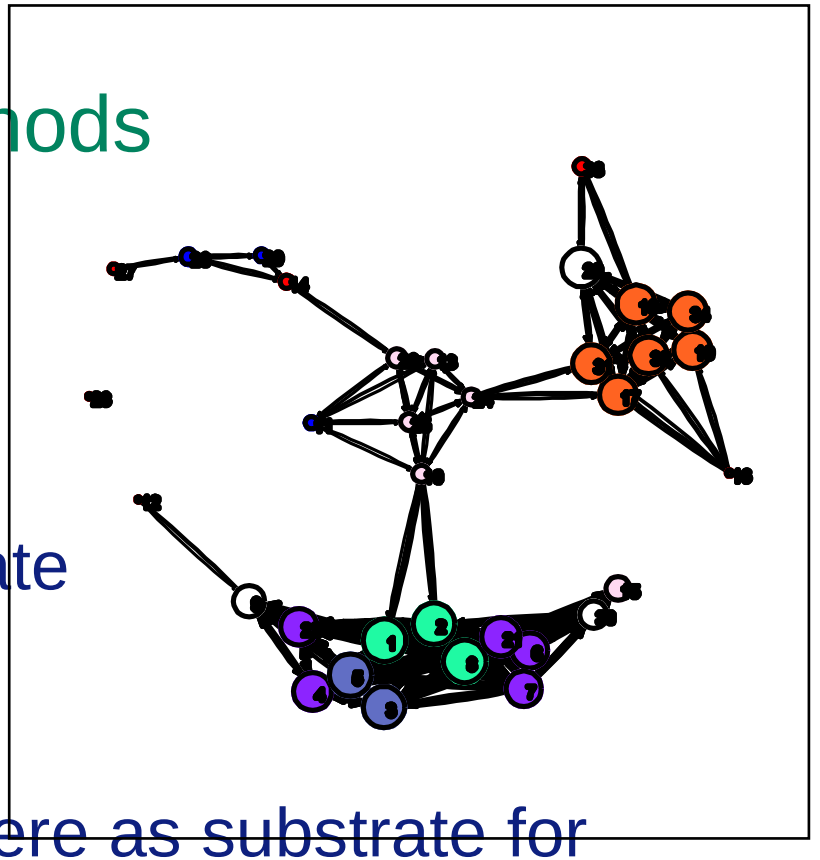






End of increasing μ sequence

Minoanisation Analysis Methods



- **Diffusion**
  Use random walkers doing variable short range walks to assess how ideas can percolate through system.
- **Cultural Transmission**
  Use the networks produced here as substrate for well known models of cultural transmission (Bentley & Shennan 2003) and language transmission (Stauffer et al. 2006)
  - based on copying (drift) and innovation (mutation) processes

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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