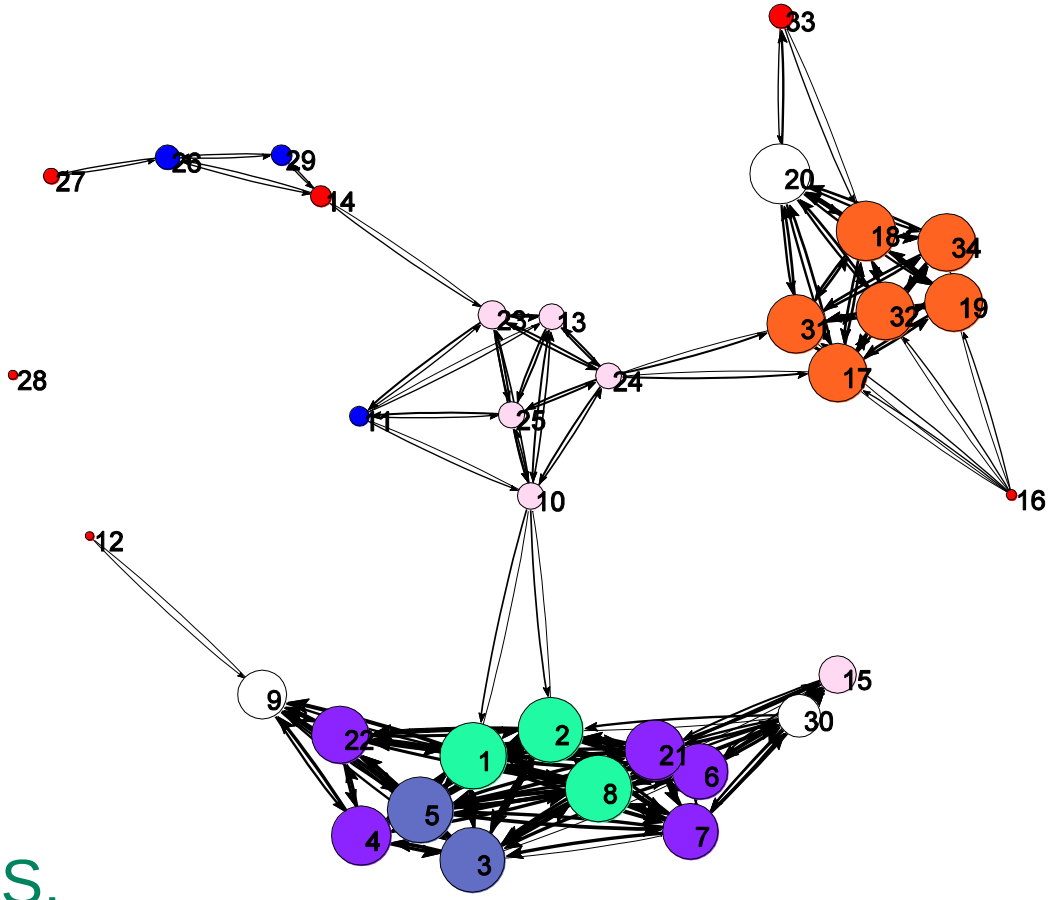
Imperial College London

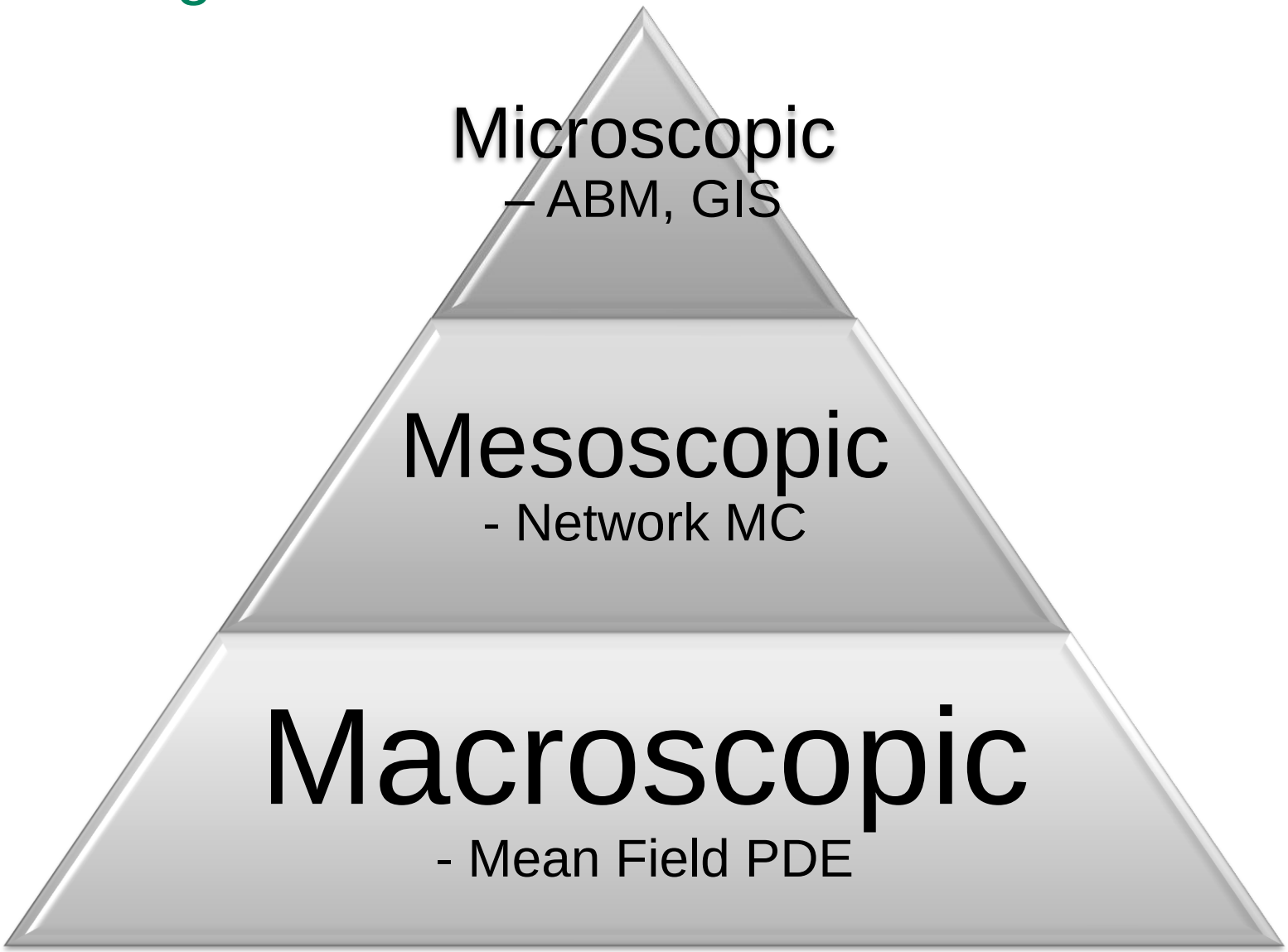
Interactions In The Aegean Bronze Age



Tim Evans
Theoretical Physics and IMS,
Imperial College London

- General Approach to Modelling in Archaeology
- Geographical Models without Networks
- Geographical Models with Networks
- Our Model - **`ariadne`**
- Summary

Modelling Scales



Site-Site Interactions

- Archaeology can be “Site Centric”
  - Regional and global interactions hard to consider
- Networks emphasise interactions

Deducing Interactions

- Artefact counts
  - Terrell 2010; Sindbæk 2007
- Texts
  - Isaksen 2006; “Anskar’s Vita” Sindbæk 2008
- Geography
  - Terrell 1977; Irwin 1983; Hage & Harary 1991; Broodbank 2000; Collar 2007; Bevan 2010

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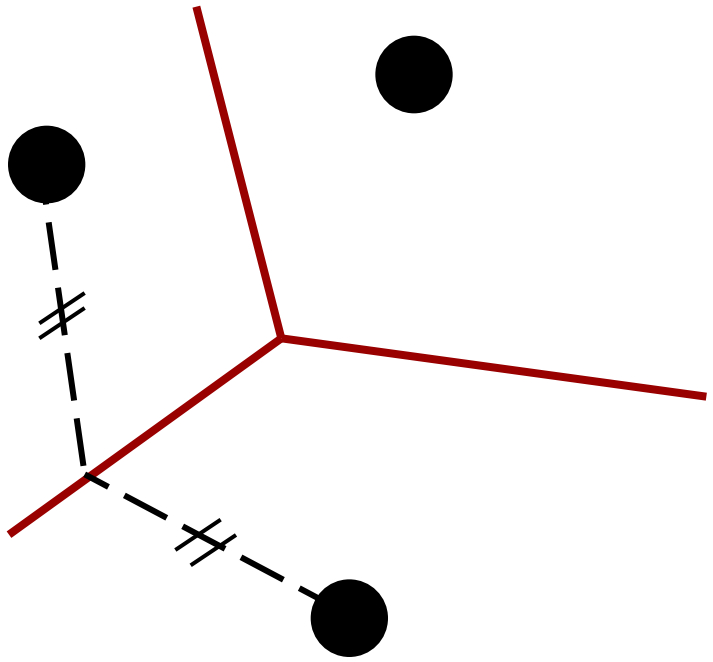
Geographical Models Without Networks

- Theissen Polygons
  - equal site sizes
- XTent
  - Theissen with variable site sizes
- Gravity Models

Theissen Polygons

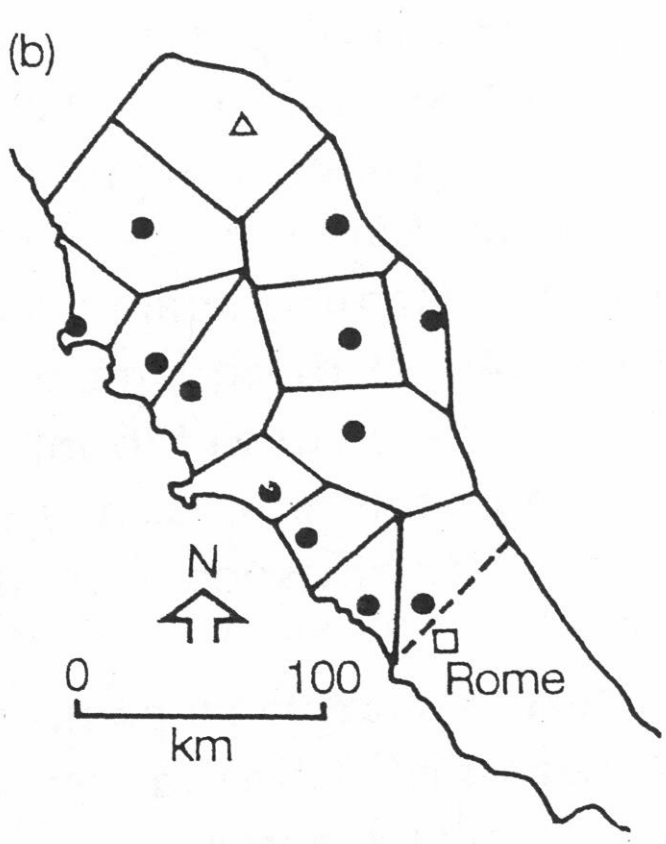
- Boundaries = Midpoint between nearest sites
- All sites equal



Theissen Polygon Example

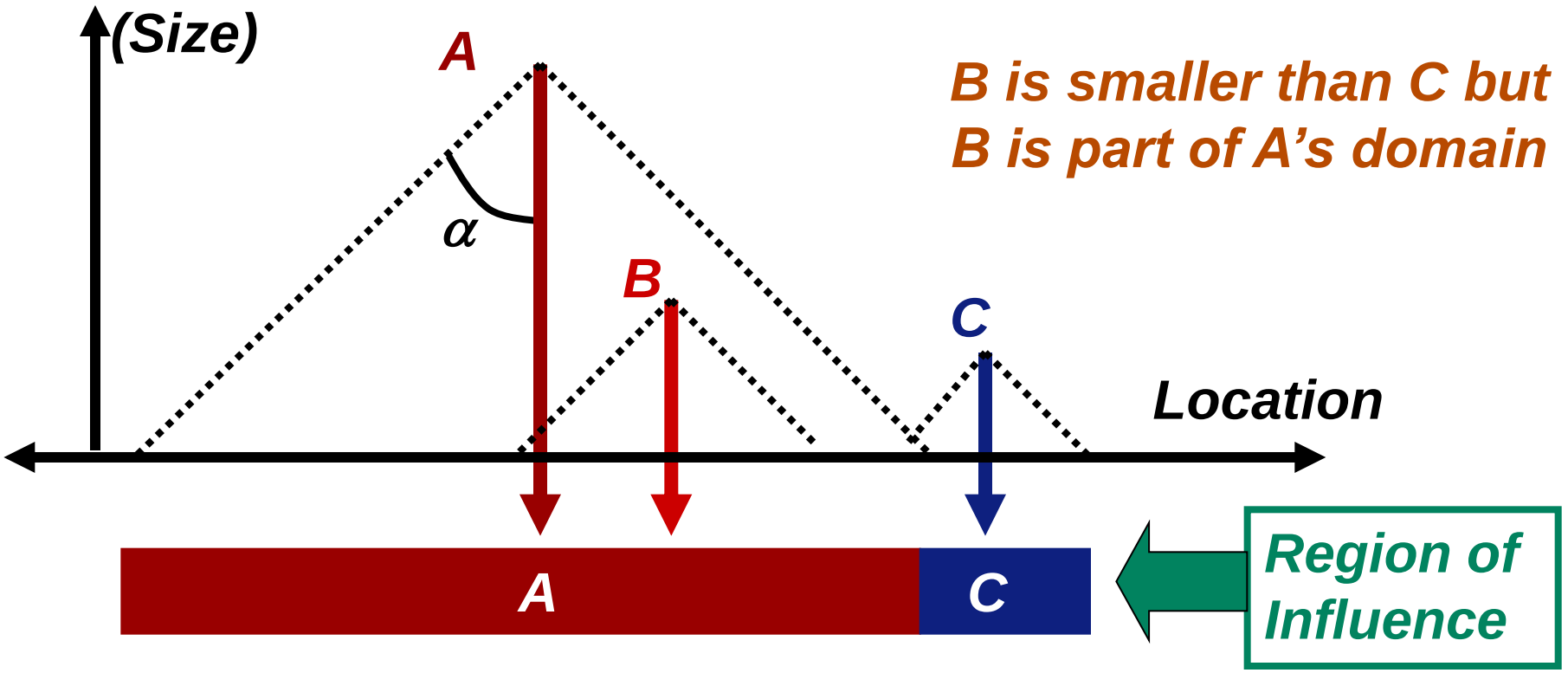
12 Etrurian Cities

[Renfrew 1975]

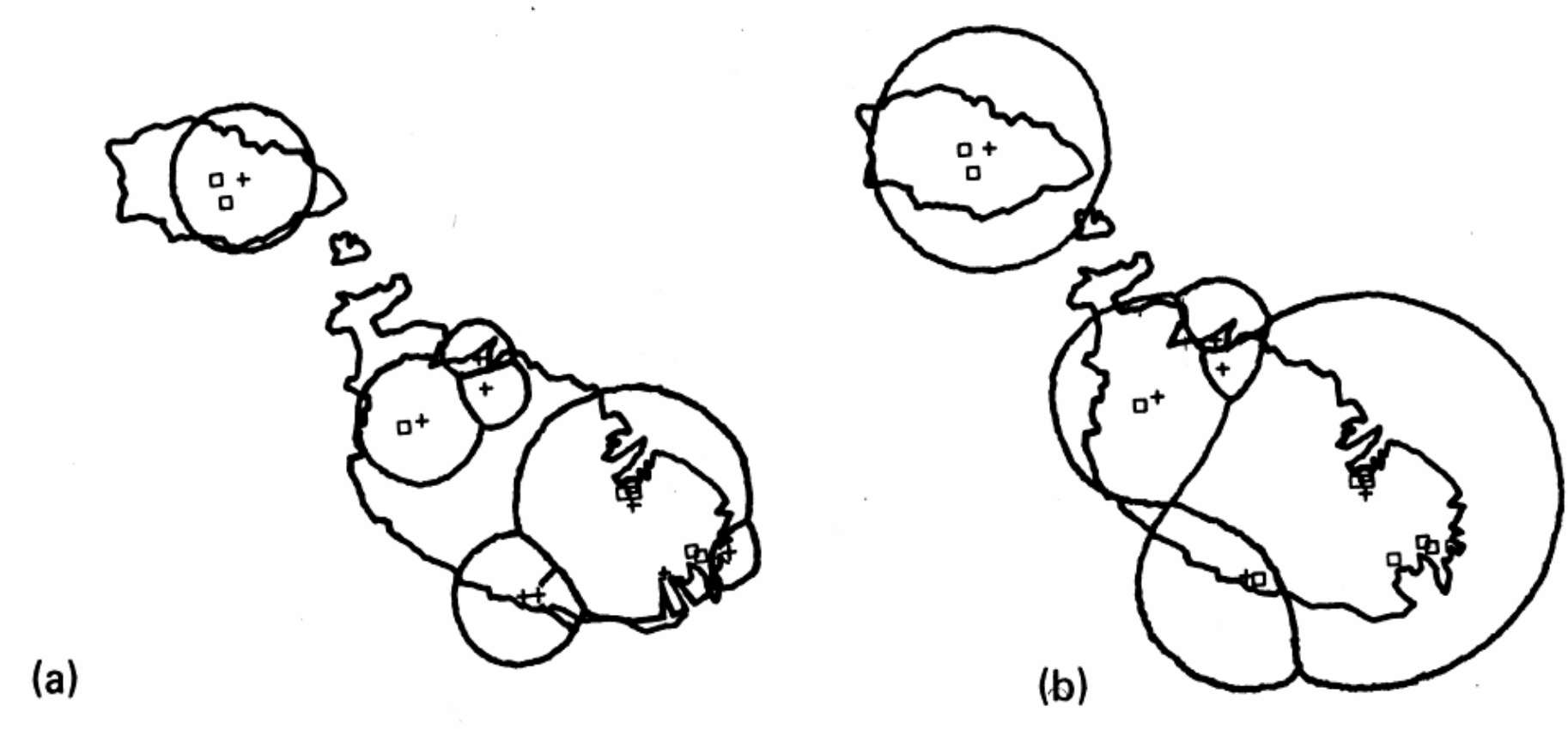


XTent Model [Renfrew & Level, 1979]

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



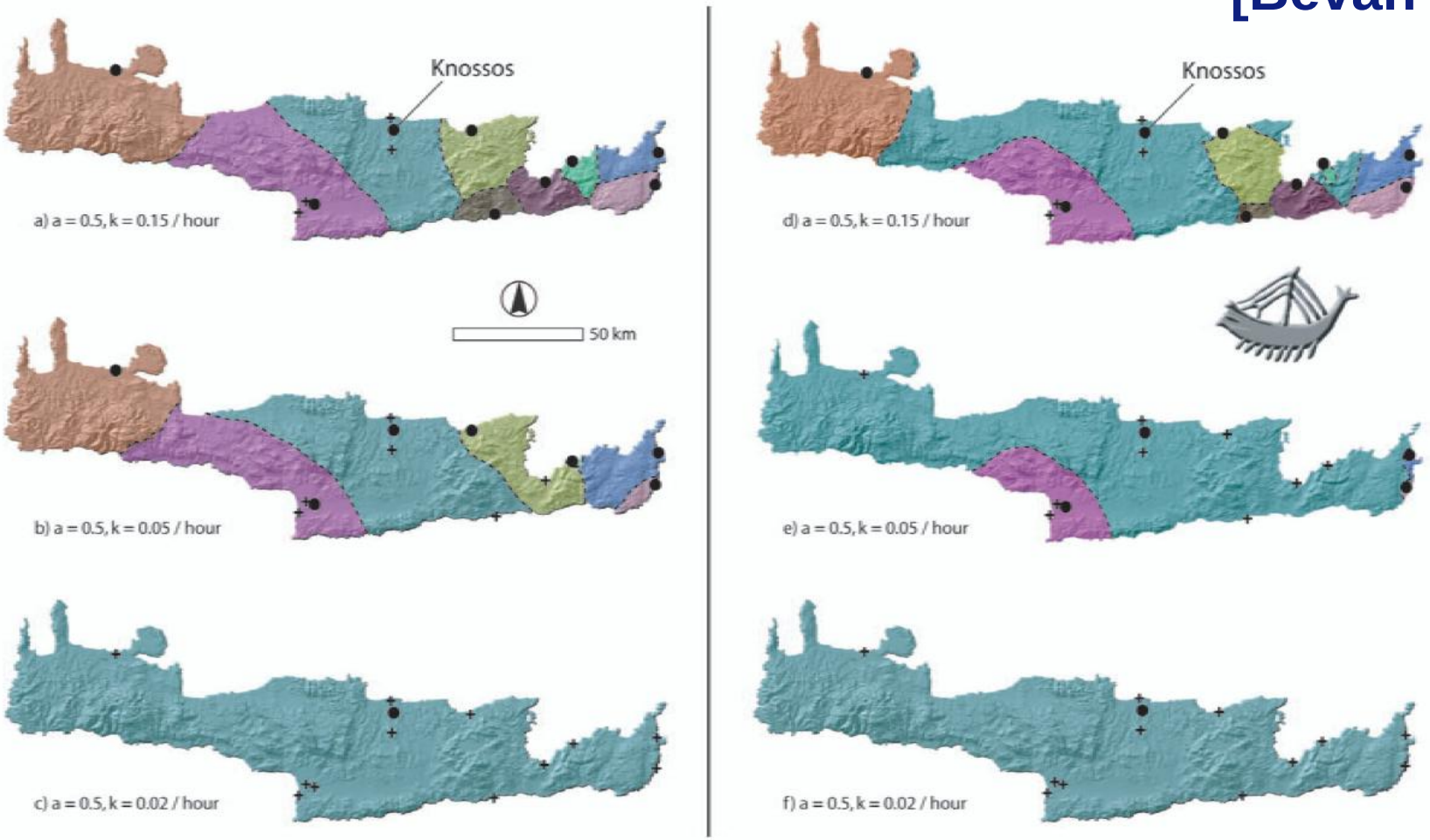
XTent model examples [Renfrew & Level, 1979]



Neolithic Temples of Malta

Xtent Neopalatial Crete (~1750BC - ~1500BC)

[Bevan 2010]



Gravity Models

- Models of modern transport systems
- First rigorous use: Casey 1955
  "Applications to traffic engineering of the law of retail gravitation"
- Site-to-Site travel costs used to predict flow

Rihll and Wilson Gravity Model Outputs

- Flow F_{ij} from i to j is

$$F_{ij} = b_i D_i \ (A_j)^{\alpha} \exp(-\beta c_{ij})$$

where α and β are model parameters

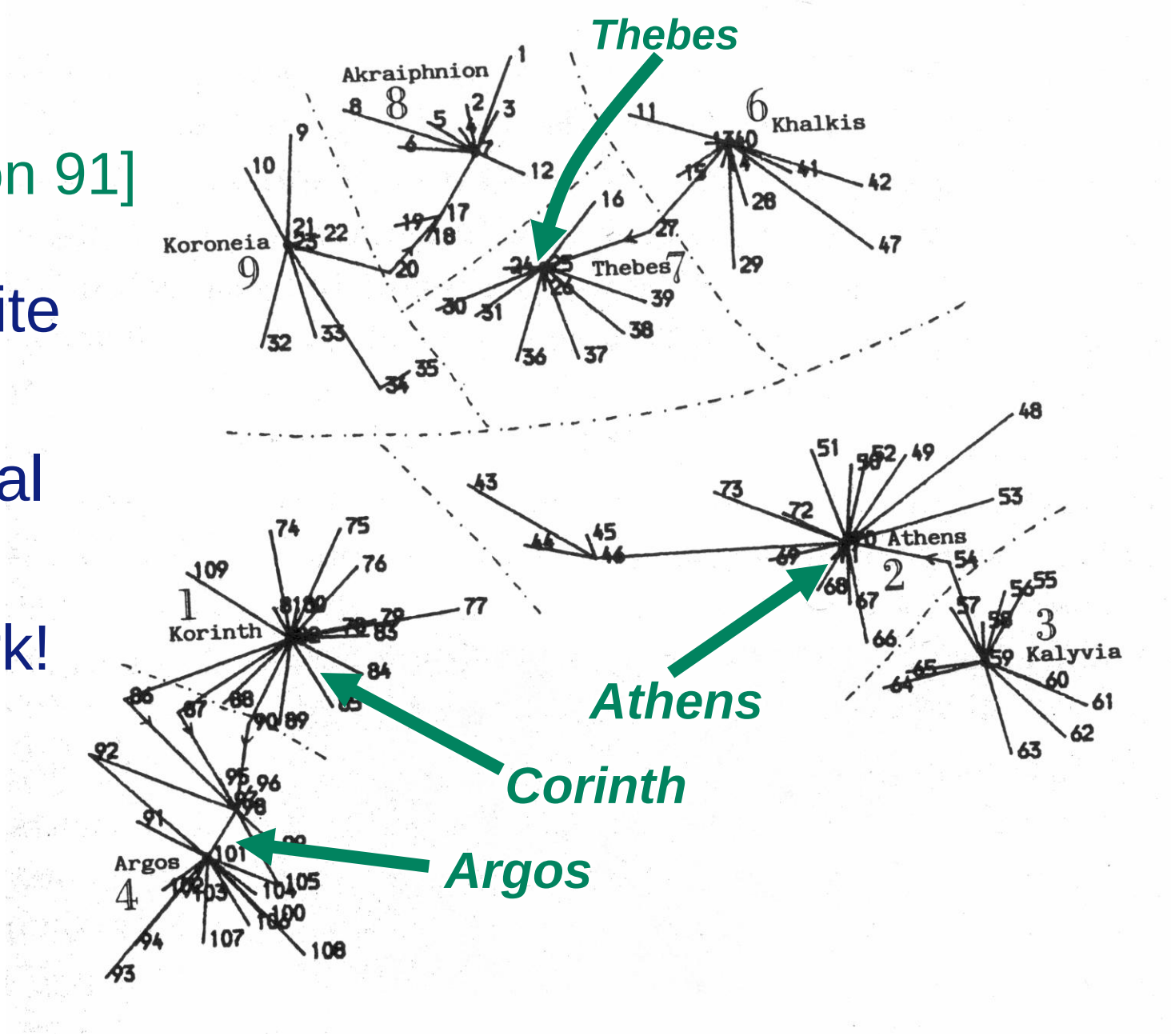
- Self consistent departure rate fixes b_i

$$\Rightarrow \quad \Sigma_j F_{ij} = D_i$$

- Departure rate D_i is either:-
  - (a) a fixed input (size of site), or
  - (b) set equal to arrival rate A_j
- Find A_j and interpret as importance of site

Results
[Rihll & Wilson 91]

- Variable site sizes
- Exponential fall off
- No network!



Summary of Models So Far

- Increasing sophistication
  - from fixed equal site sizes to variable site sizes
  - Simple crow flies separations to complicated distance metrics

⇒ Still not exploiting advantages a Network Model may provide

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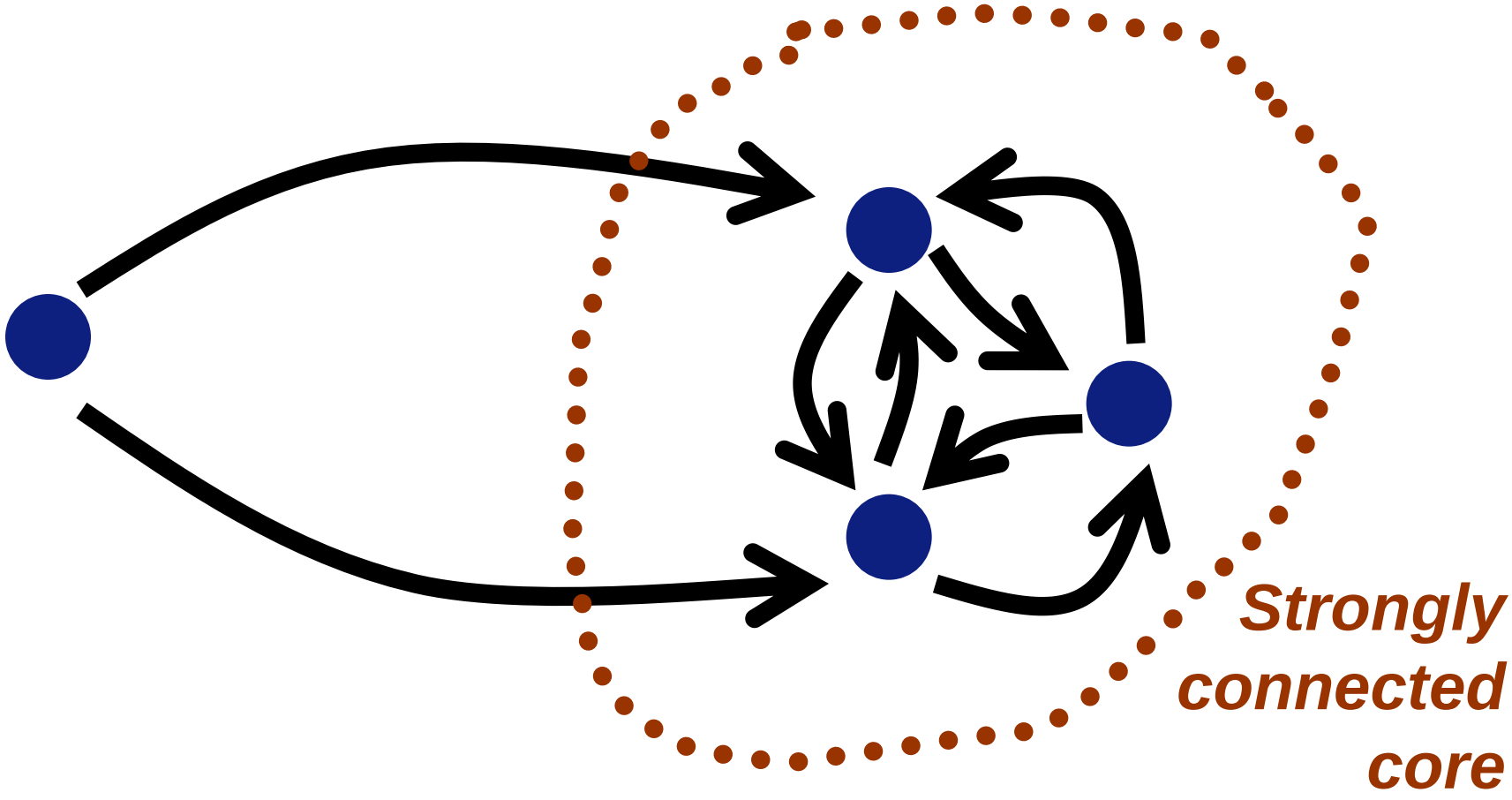
PPA - Proximal Point Analysis

- Equal sized sites
- Sites connect to ***k*** nearest neighbours
- Analyse graph
  - Often without directions on edges
  - Sometimes only local measures used *e.g. Degree*
  - Sometimes global measures used
    e.g. ranking, centrality, betweenness

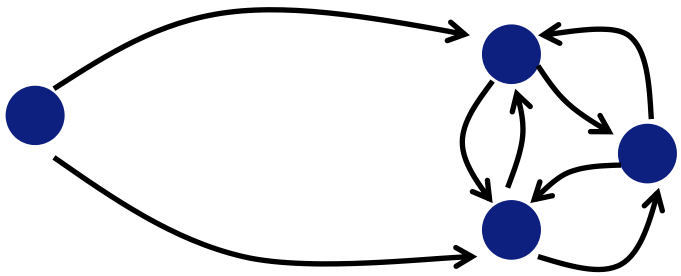
Examples: Hage & Harary 1991; Terrell 1977; Irwin 1983; Broodbank 2000; Collar 2007

PPA Example

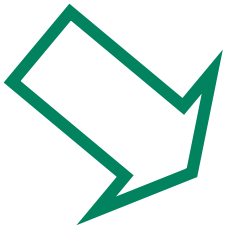
Connect each site to its ***k=2*** nearest neighbours

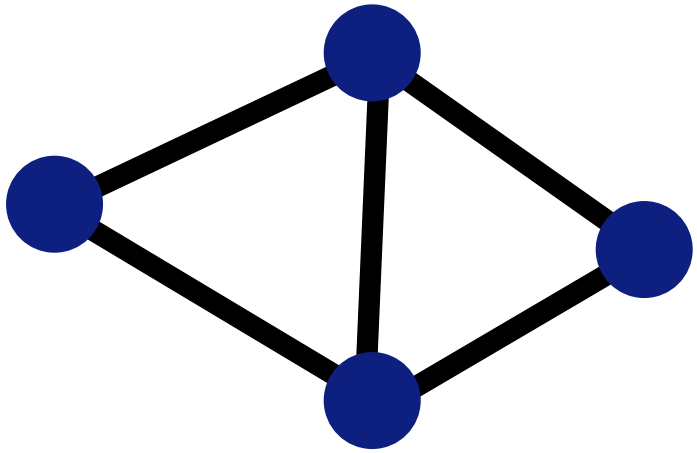


PPA Example



Ignore direction

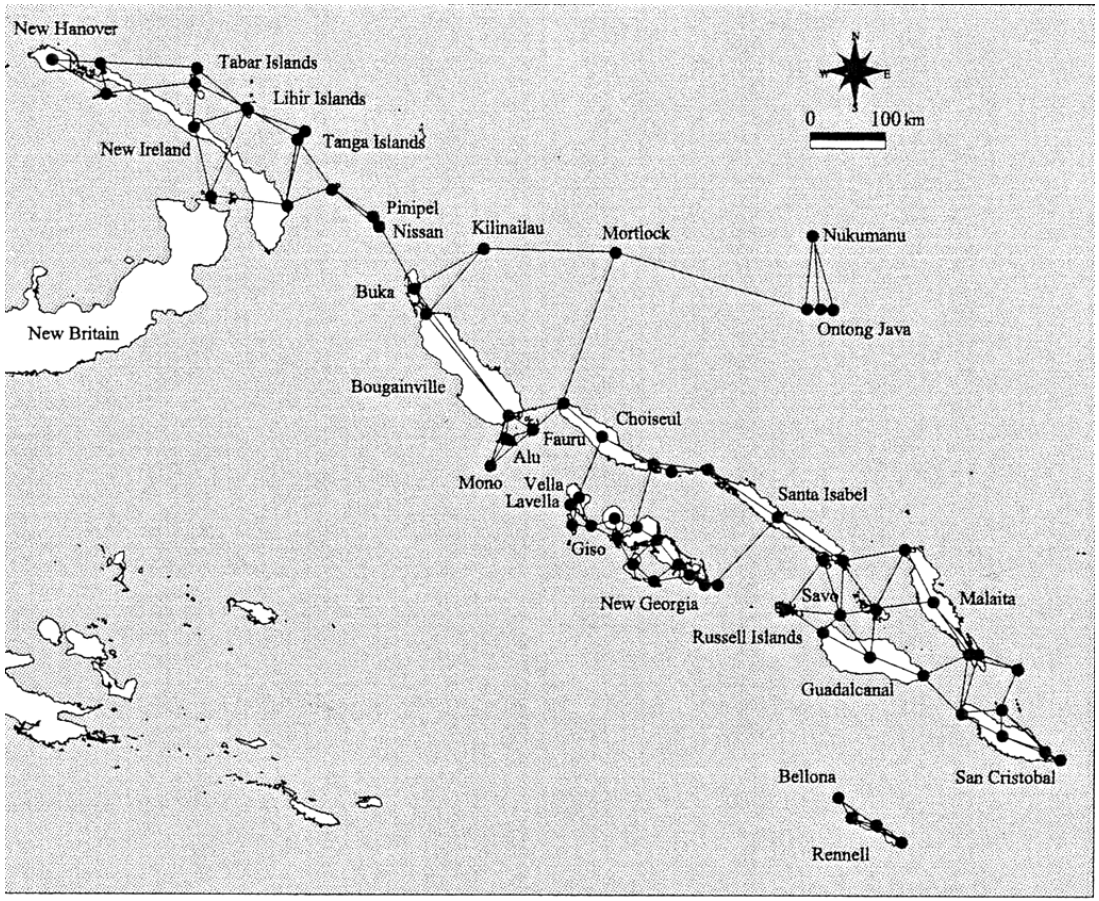




- **All edges equal**
- **Network now simply connected**

Terrell (1977)

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

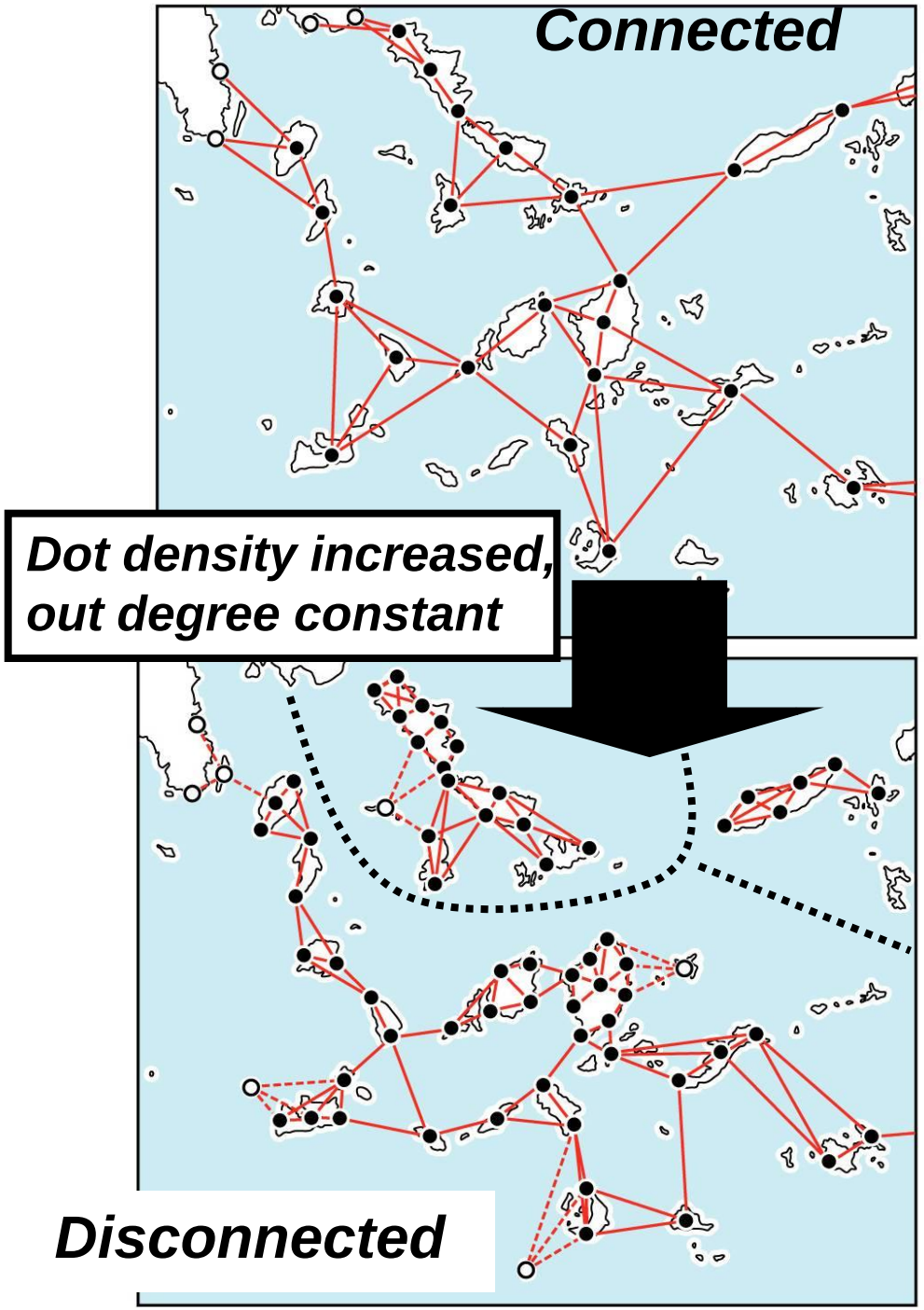


Broodbank PPA

- **Population = # vertices**

⇒Low density = connected graph

⇒High density = disconnected graph, clusters on large islands



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

Beyond these archaeological models

- The sizes of sites and their interactions never both *variable* and *interlinked*
  - *Not all sites are equal*
  - *Not all edges are equal*
- 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***

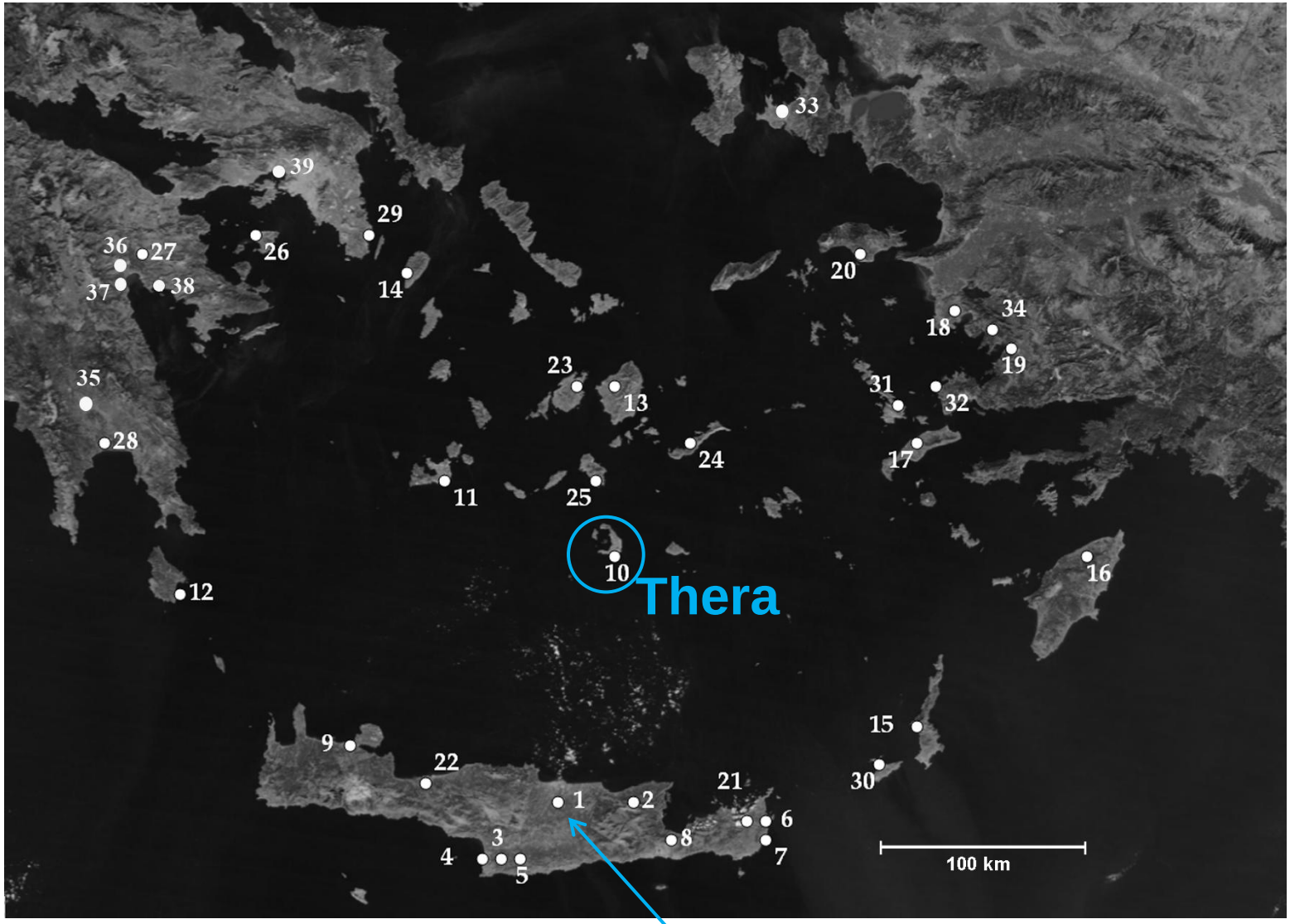
Focus: Middle Bronze Age (MBA) Aegean

- 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

Our 39 Sites

3 sizes – S, M or L



Knossos

Some Possible Questions

- **The Knossos Question**

  The palace at Knossos does not have the best local environment

- **Minoanisation**

  Spread of Minoan influence

- **Eruption of Thera**

  Relation to Minoan collapse

Network Description – Fixed Network Parameters

Network values fixed using the archaeological record are:-

- d_{ij} Fixed travel time between sites
  - Measured in ***km*** travelled by boat on open sea

- s_i Fixed site capacity (includes hinterland) = maximum local resources

Network Description – Variables, relative values

Variables whose values are found stochastically:-

- v_i Variable site occupation *fraction*
  $\Rightarrow$ Site **Weight** (S_i v_i) = Site `*population*'

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

Optimisation of what?

`Energy', resources

Isolated sites have optimal size $v_i = 0.5$

Interactions (trade) bring benefits

Increasing 'population' has a cost

Each trade link has a cost

$$H = -\kappa \sum_i 4 S_i v_i (1 - v_i) - \lambda \sum_{i,j} (S_i v_i).e_{ij} V(d_{ij}/D).(S_j v_j) + j \sum_i S_i v_i + \mu \sum_{i,j} S_i v_i e_{ij}$$

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

Supply and Demand

Interaction depends on both source and target vertices

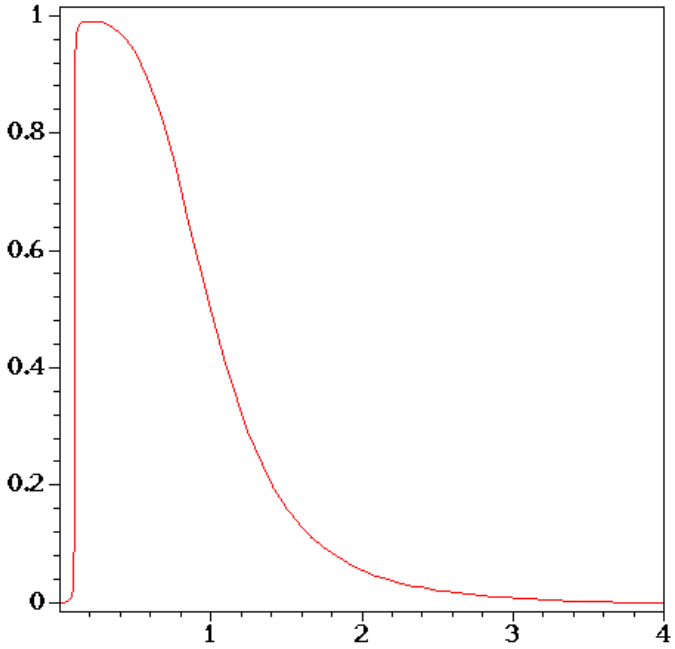
$$-\lambda \sum_{i,j} (S_i v_i).e_{ij} V(d_{ij} / D).(S_j v_j)$$

Flow from i in Gravity Models

Attraction depends on target size

Interaction Potential

$$V(x) = \frac{\Theta(x - 0.1)}{1 + x^4}$$



x=(Distance / D)

- ***D=100*** **km for sail (after 2000BC)**
- ***D=10*** **km for rowing (pre 2000BC)**
- **Friction – 3x penalty for land travel**

Coarse Graining

This model is independent of small scale details

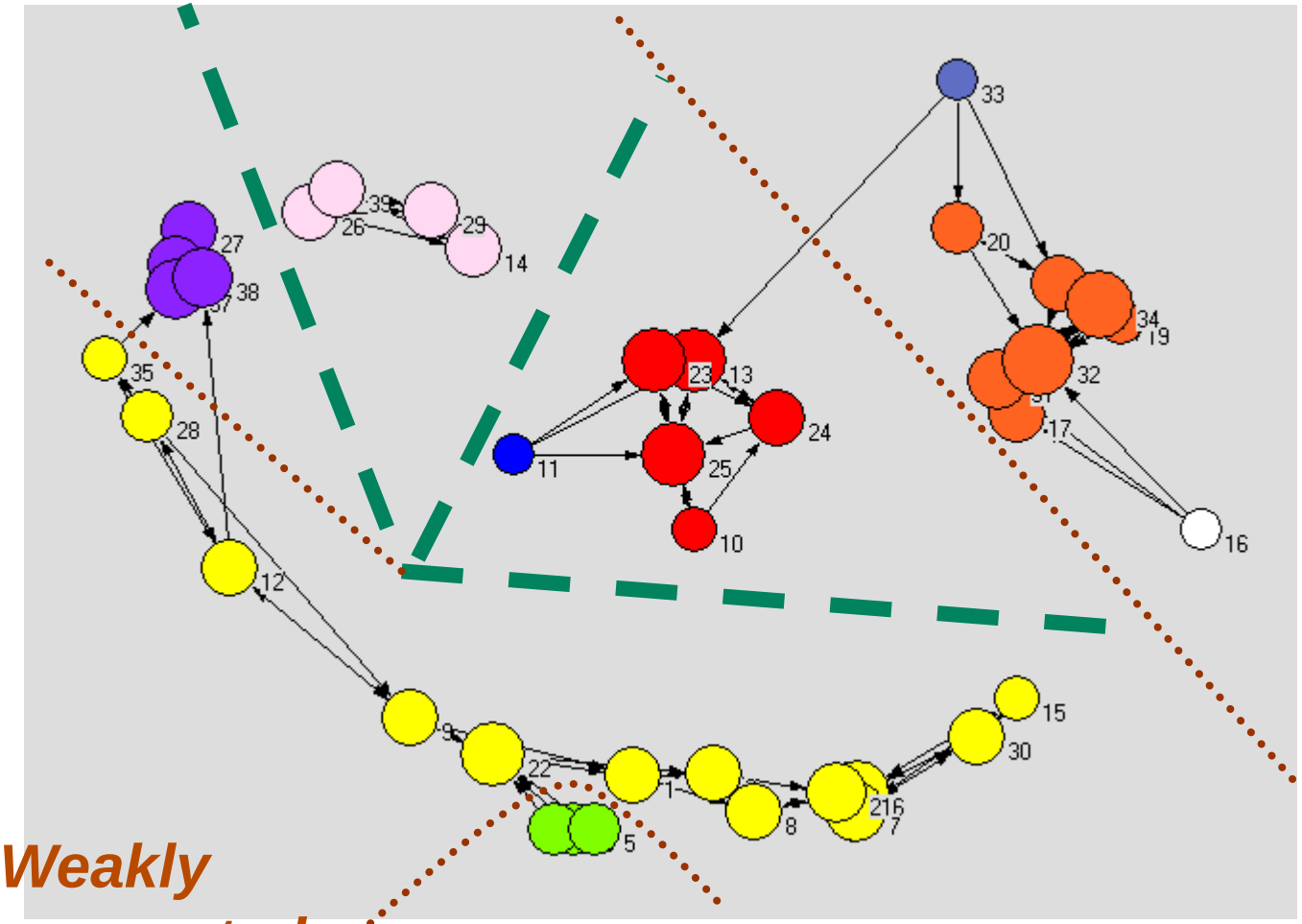
If split a site into two pieces within 10km results are exactly the same

So what does our model give us?

- Site hierarchies
- Interdependent site sizes and network edges
- Geography important but not simply nearest neighbour interactions
- Coarse graining over ***10*km** scale

⇒ Compare with PPA …

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



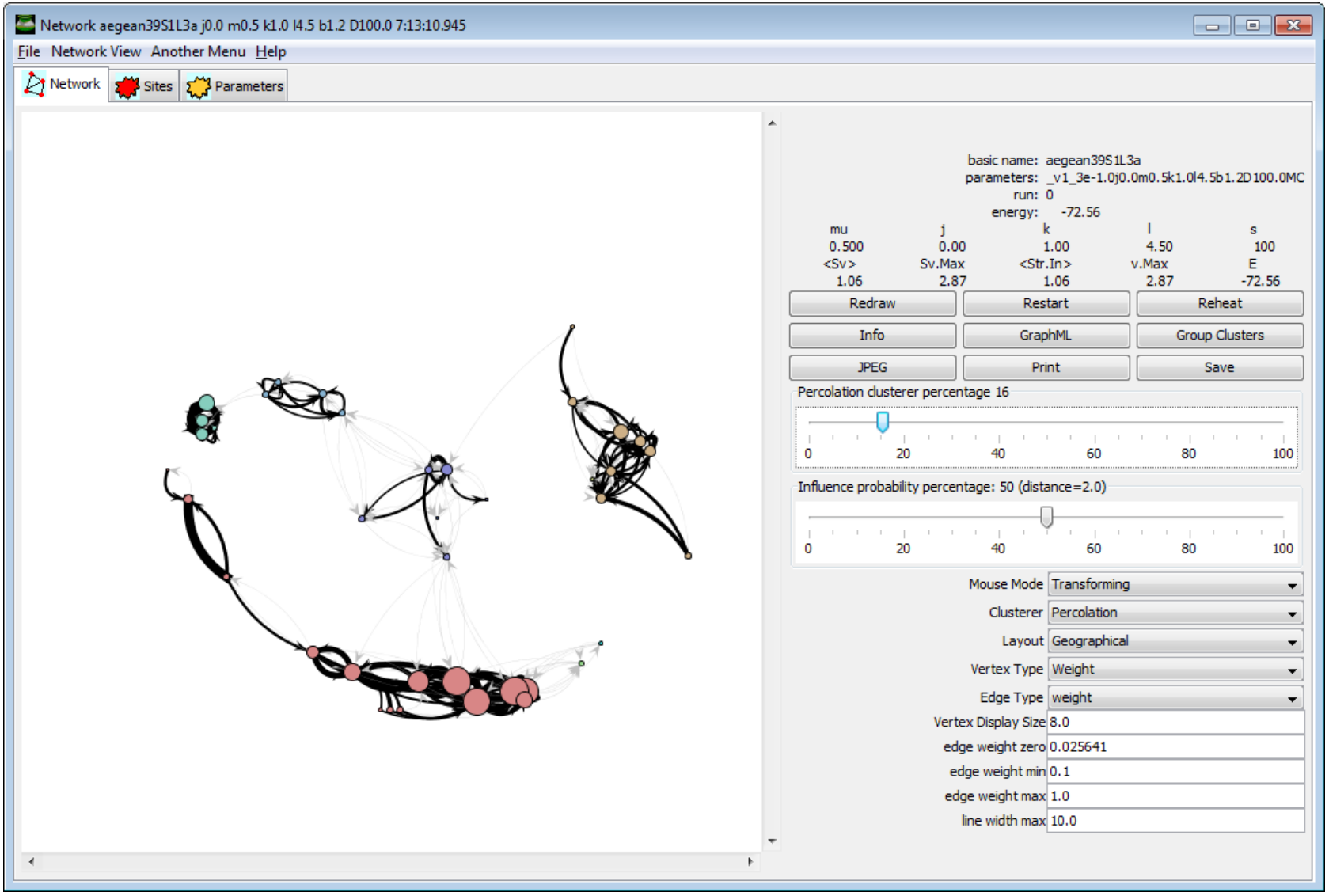
3 strongly connected regions

6 weakly connected regions

Weakly connected

Vertex size = Total Degree

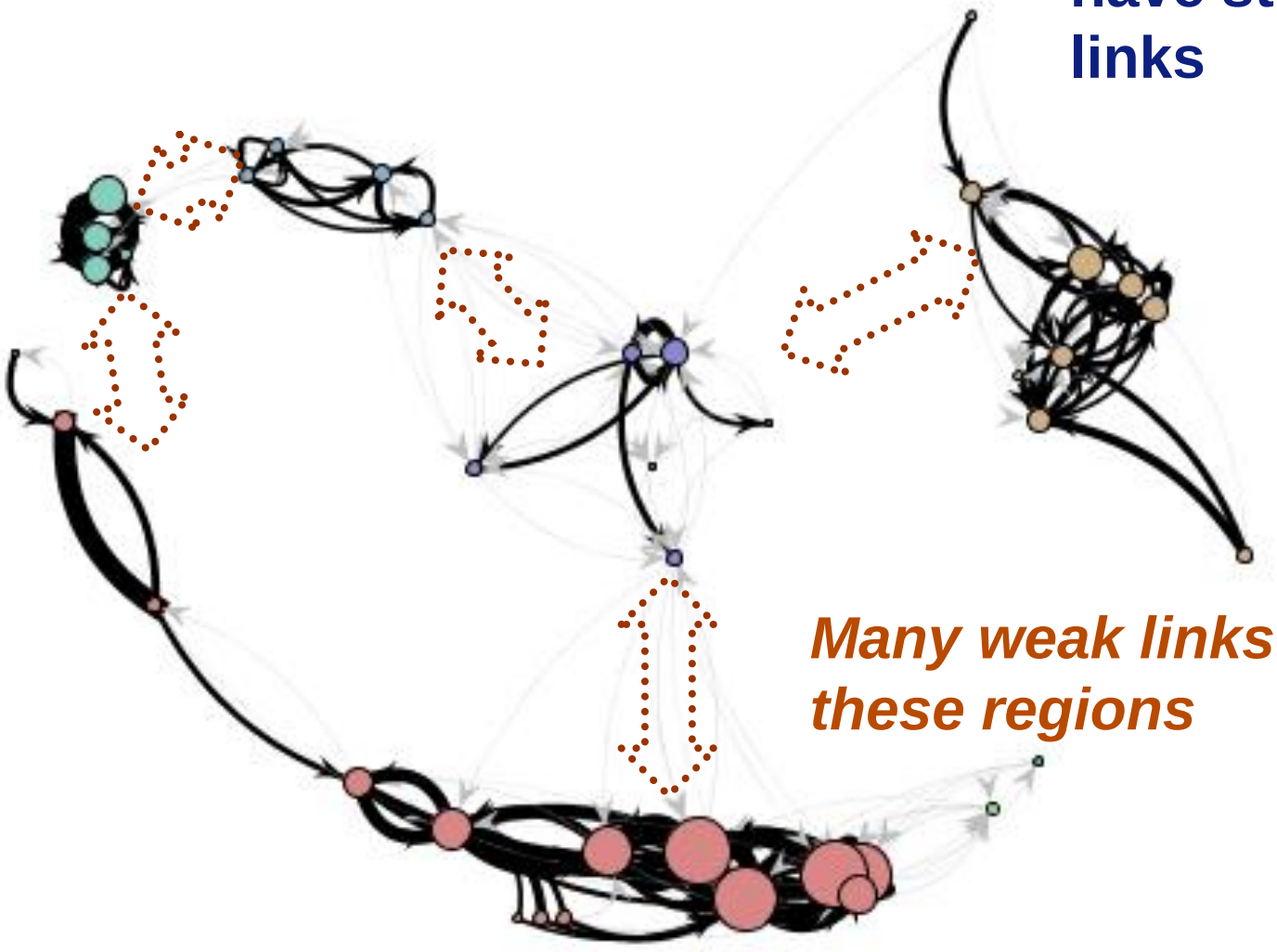
ariadne



Network in our model

Same geography

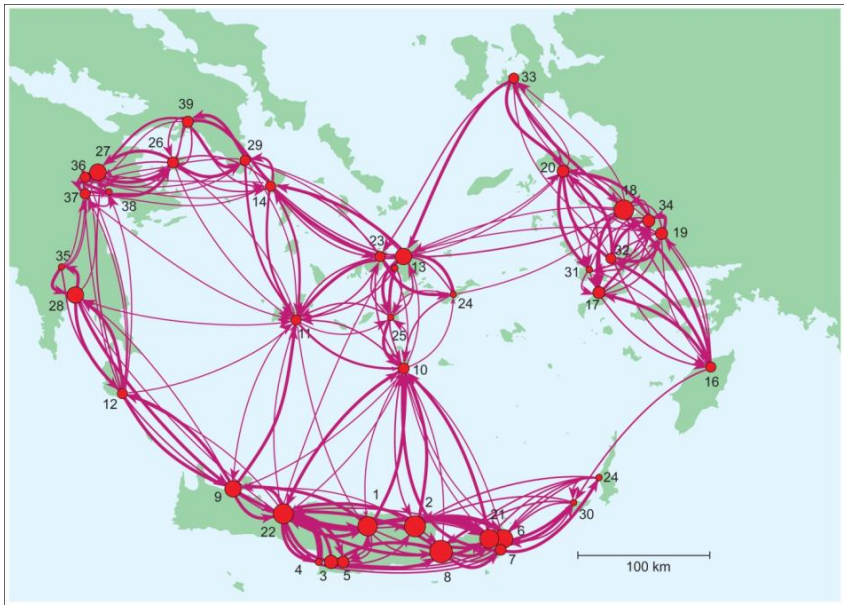
⇒ same regions have strongest links

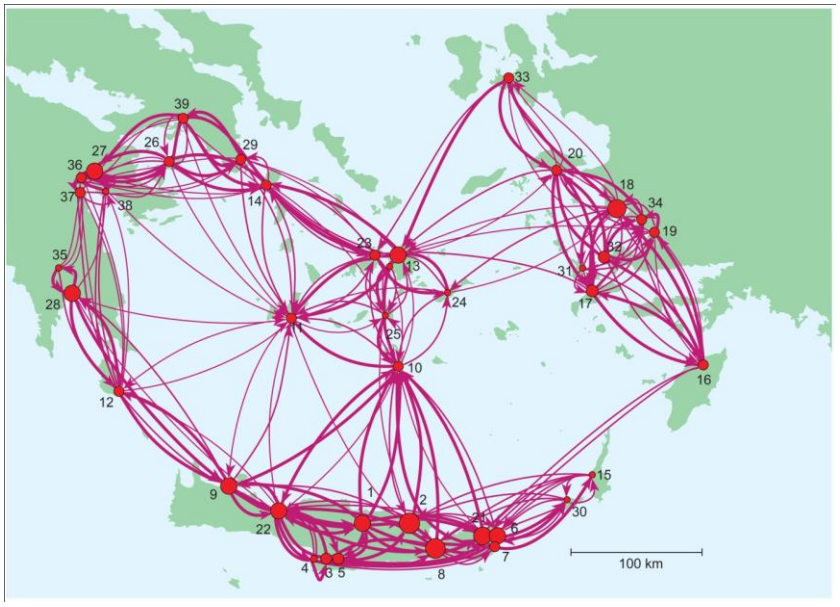


Many weak links between these regions

Vertex size = $S_i v_i$

Stochastic Variation





Same values

λ= 4.0, κ = 1.0, μ = 0.1, j = -2.0, D = 110km

Analysis

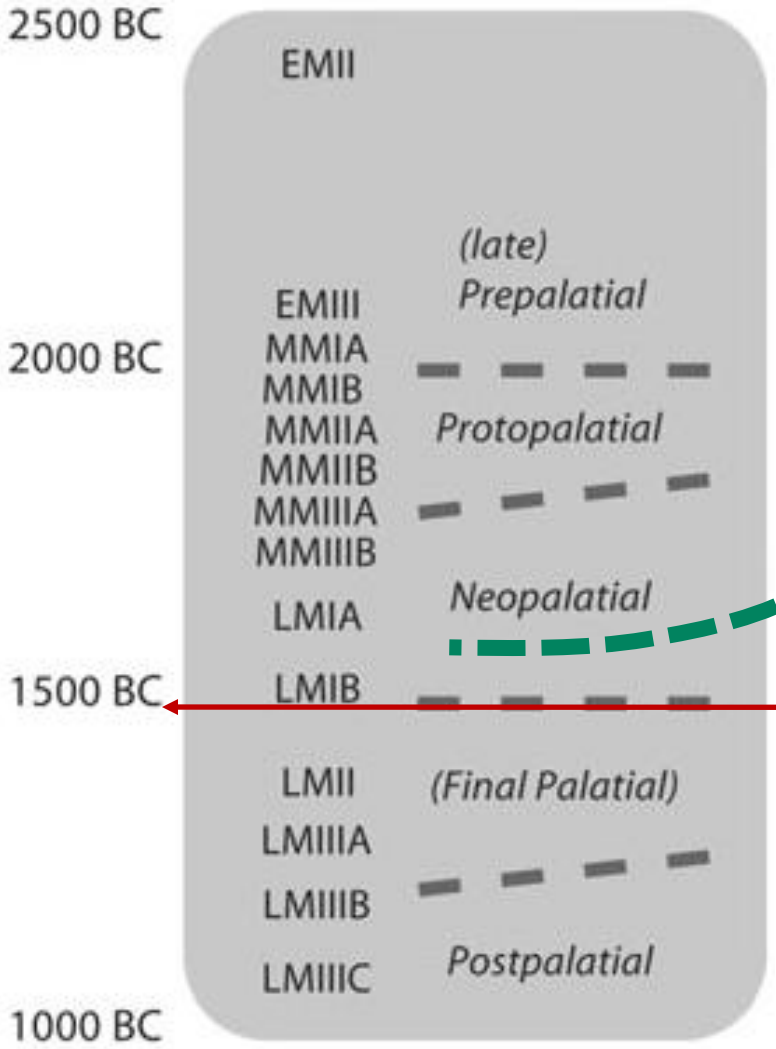
- Can not assign parameter values in model from physical data so make *comparisons* between different data sets
  - e.g. vary one parameter, hold rest fixed.

- 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. diffusion, apply cultural transmission models, ABM on this substrate.

Path Analysis

- Shortest Paths – on weighted graphs ?
  - betweenness
- Long Time Diffusion
  - PageRank
- Short Time Diffusion
  - Clustering via modularity if undirected
  - `Influence' (see sequence)
- Paths all equal
  - Biased random walks

Aegean Middle Bronze Age Chronology

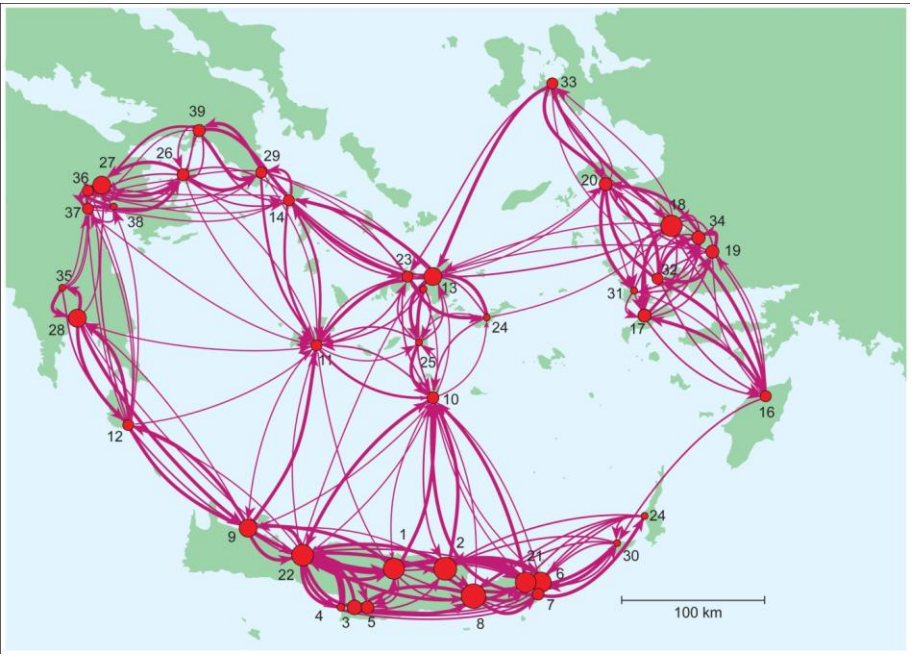


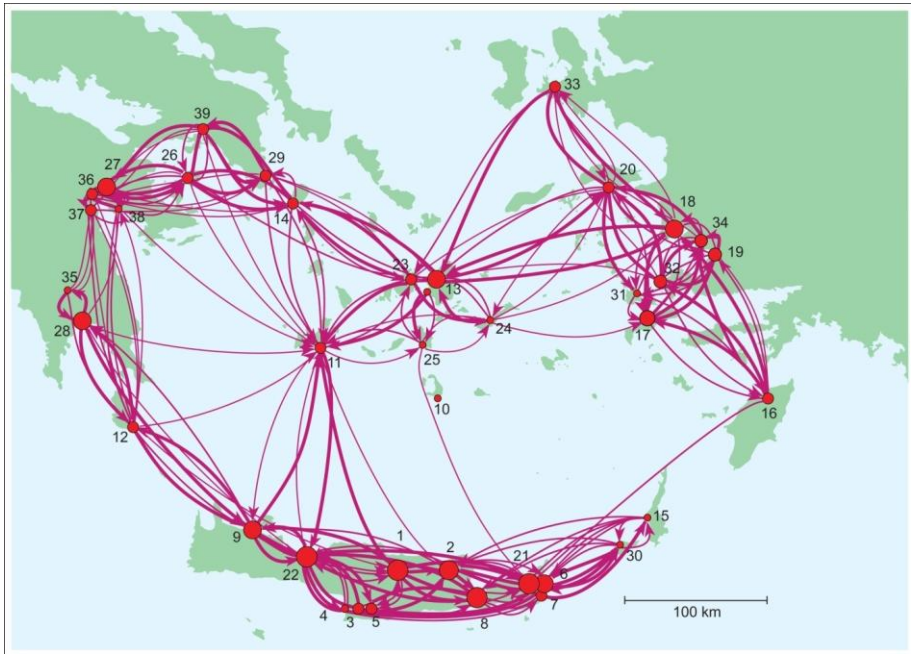
Thera errupts
~1575 BC (± 50)
– LMIA / LMIB

Minoan Collapse
~1500BC
– End of LMIB

[Bevan 2010]

Before and After the Eruption



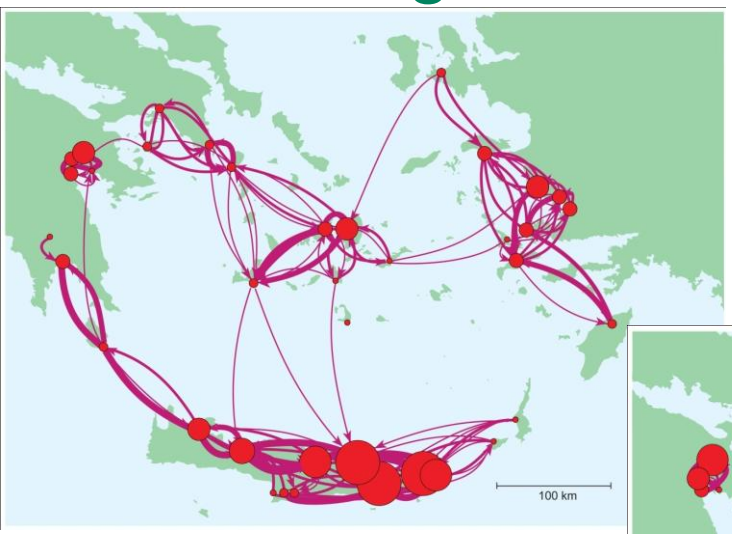


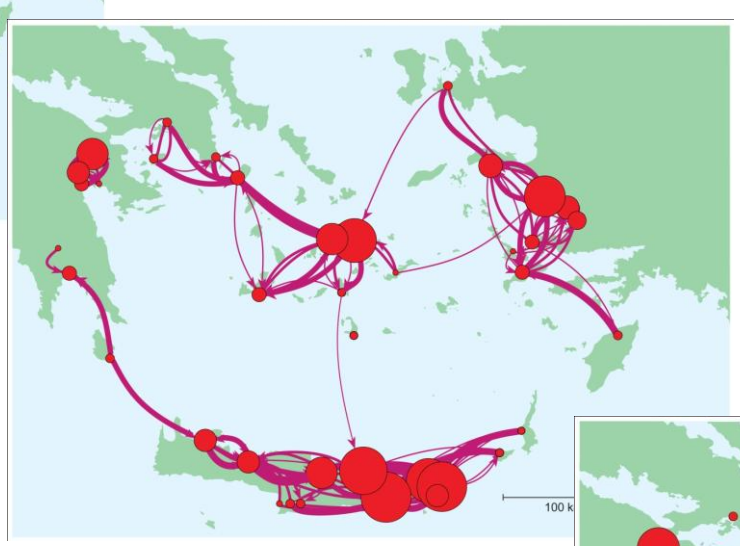
- **Total population largely unchanged**
- **Total interaction largely unchanged**

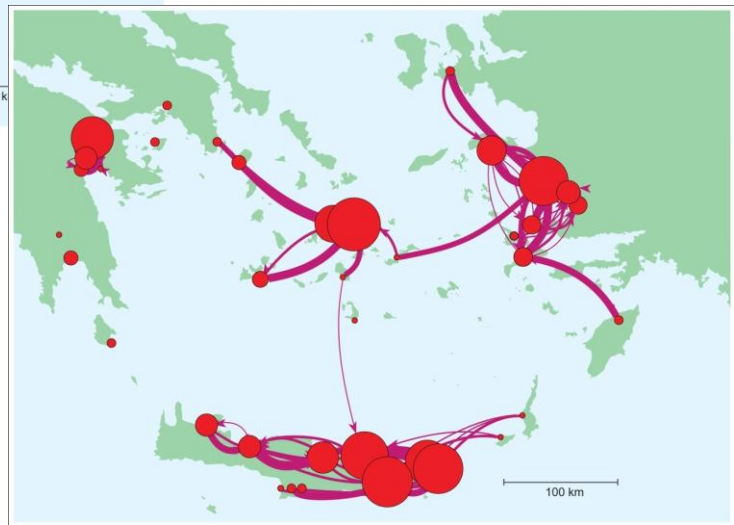
For same parameter values

λ= 4.0, κ = 1.0, μ = 0.1, j = -2.0, D = 110km

Increasing Interaction Cost post Eruption







μ increasing

- ***Fewer but stronger links***
- ***Shorter distances***

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Summary

- Very limited use of networks so far in archaeology
- Many models very simple
- Some recent studies are exploiting network analysis
- Role of geography relatively easy to study
- Comparing against finds much harder
- **Many options remain to be explored**

Acknowledgements

- All work done with
  - **Carl Knappett (Toronto)**
  - **Ray Rivers (Imperial)**

  some work also with **Edmund Hunt (Imperial)** and **Eric Beales (Toronto)**

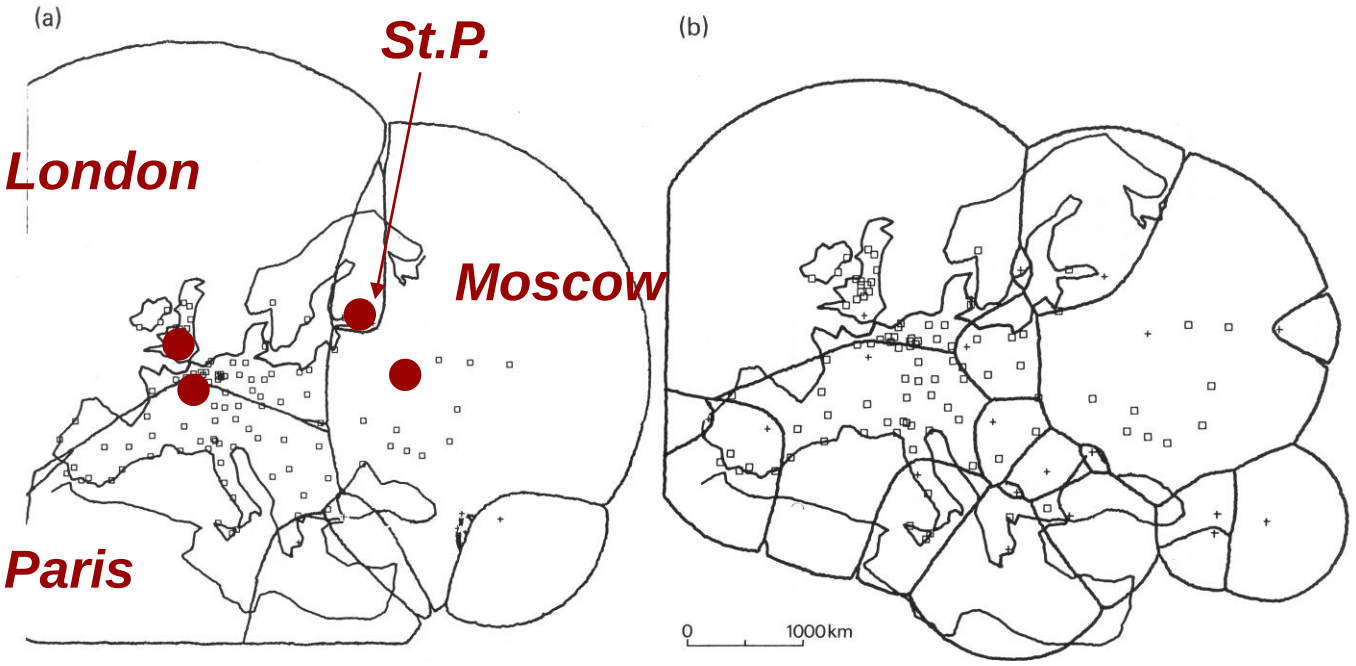
- Publications
  google “Tim Evans archaeology”

Other Material

Other Material

XTent model examples [Renfrew & Level, 1979]

European Cities 1960



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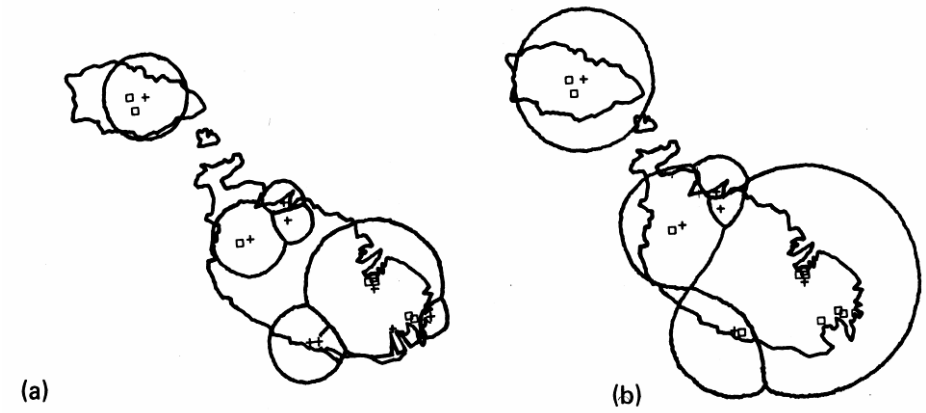

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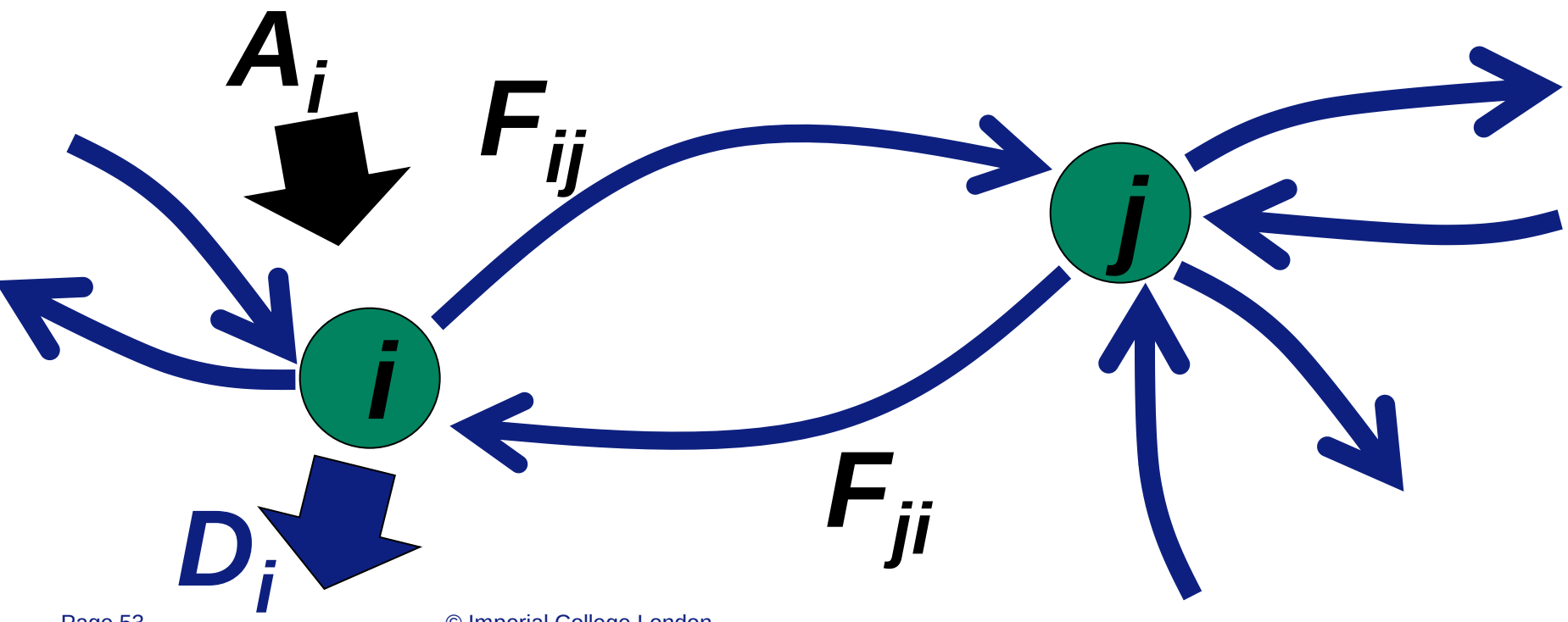
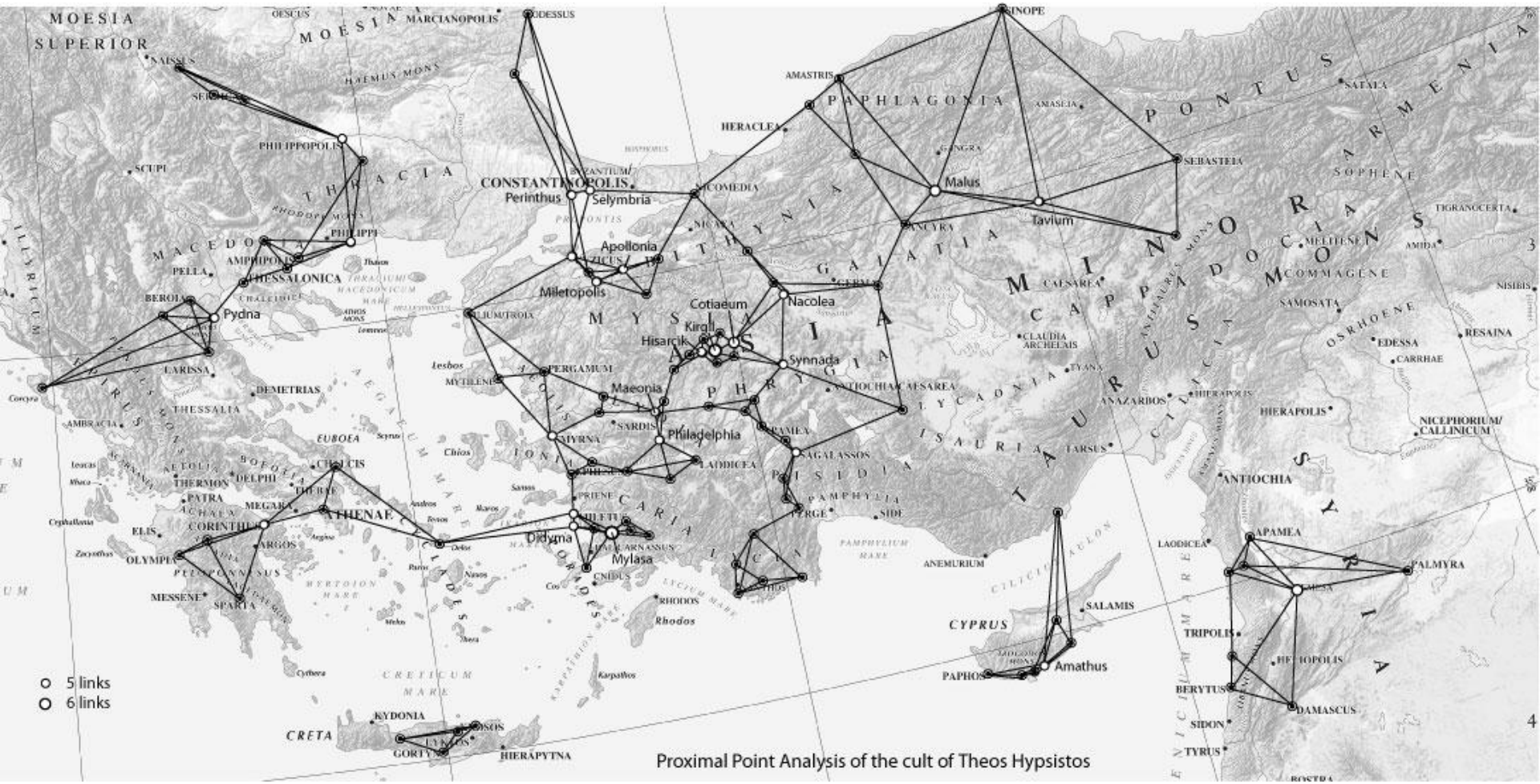
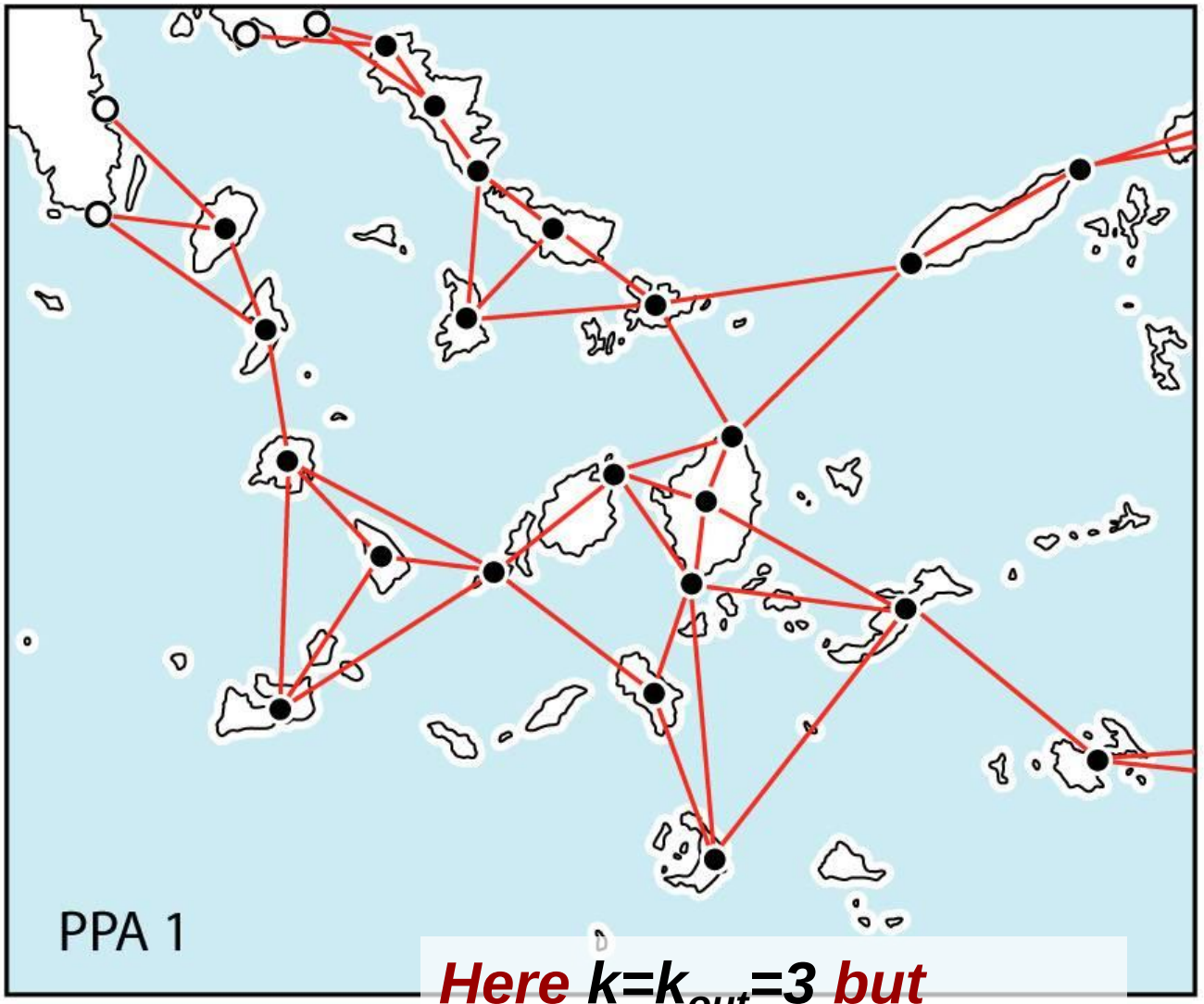


Hypsistos Cult Inscriptions (1-4c.AD)
PPA graph [Collar, 2007]



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

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



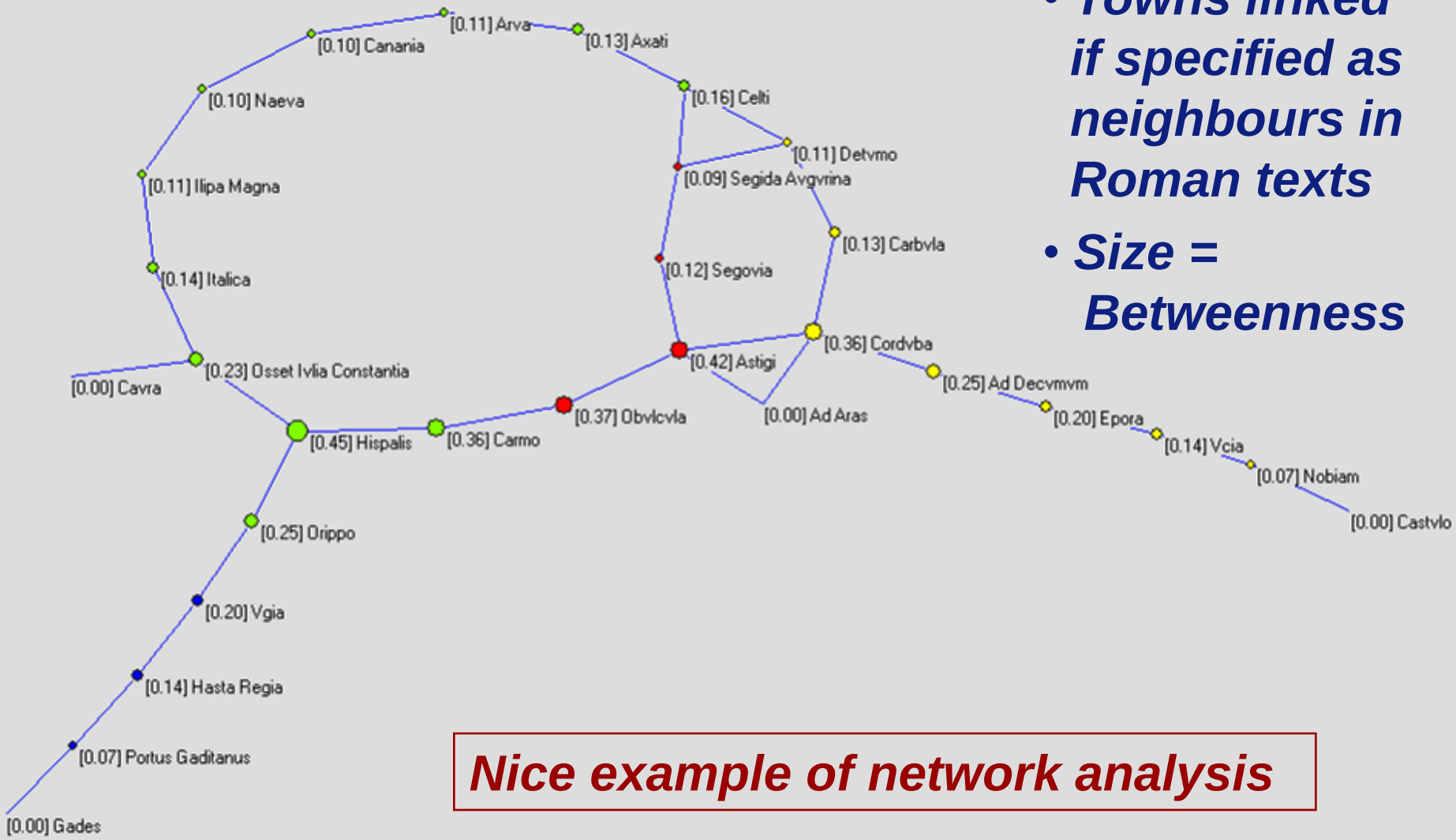
Here $k=k_{out}=3$ but direction not recorded

Networks Based on Texts

Link sites mentioned in texts

- Isaksen (2006) linked towns on the Via Augusta and river/road network based on Roman texts
- Sindbæk (2008) used travelogue "Anskar's Vita" but also uses data from finds, Viking Baltic 9th c. AD.

Isaksen (2006)

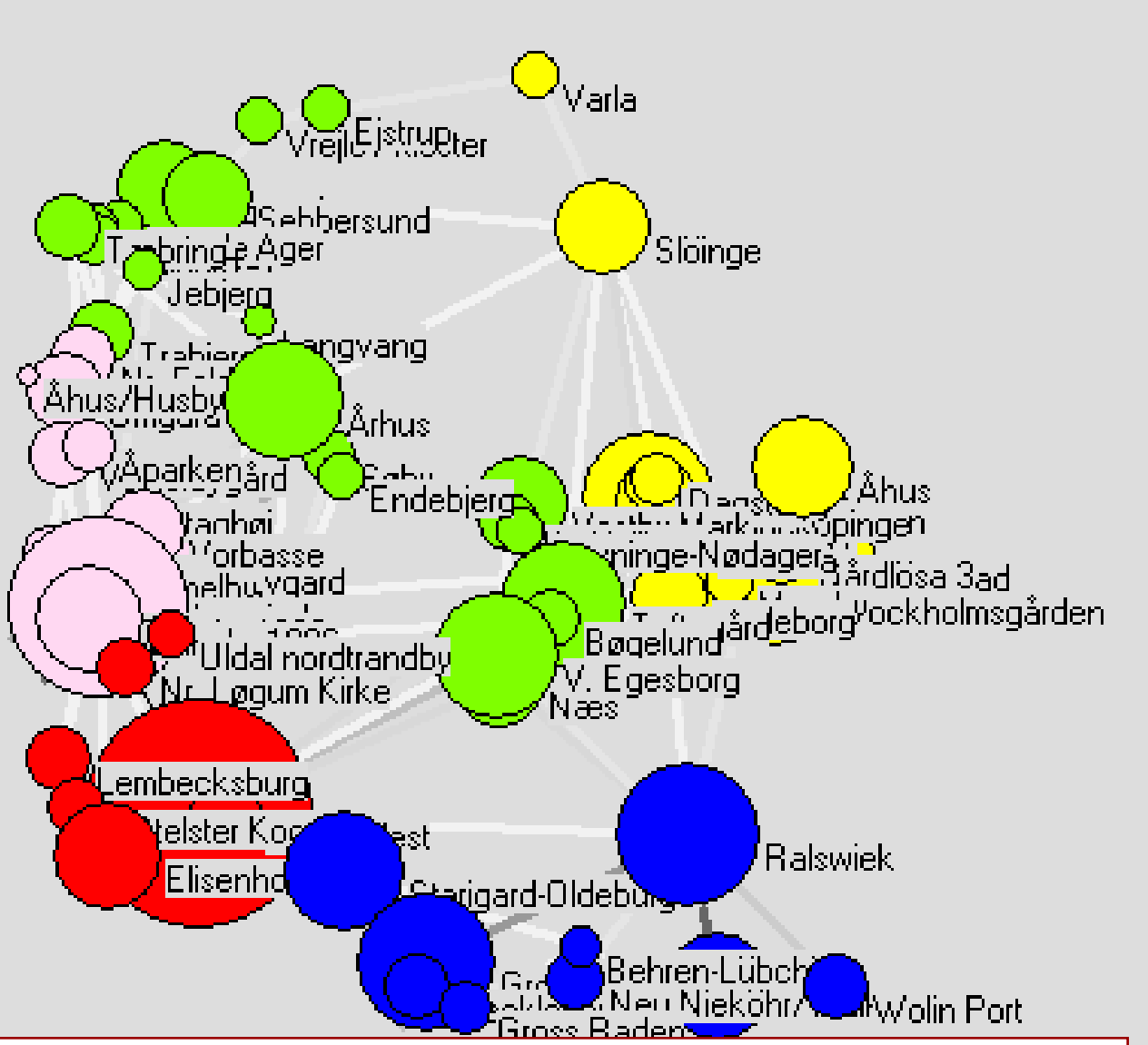


- ***Towns linked if specified as neighbours in Roman texts***
- ***Size = Betweenness***

Nice example of network analysis

[Sindbæk, 2008]

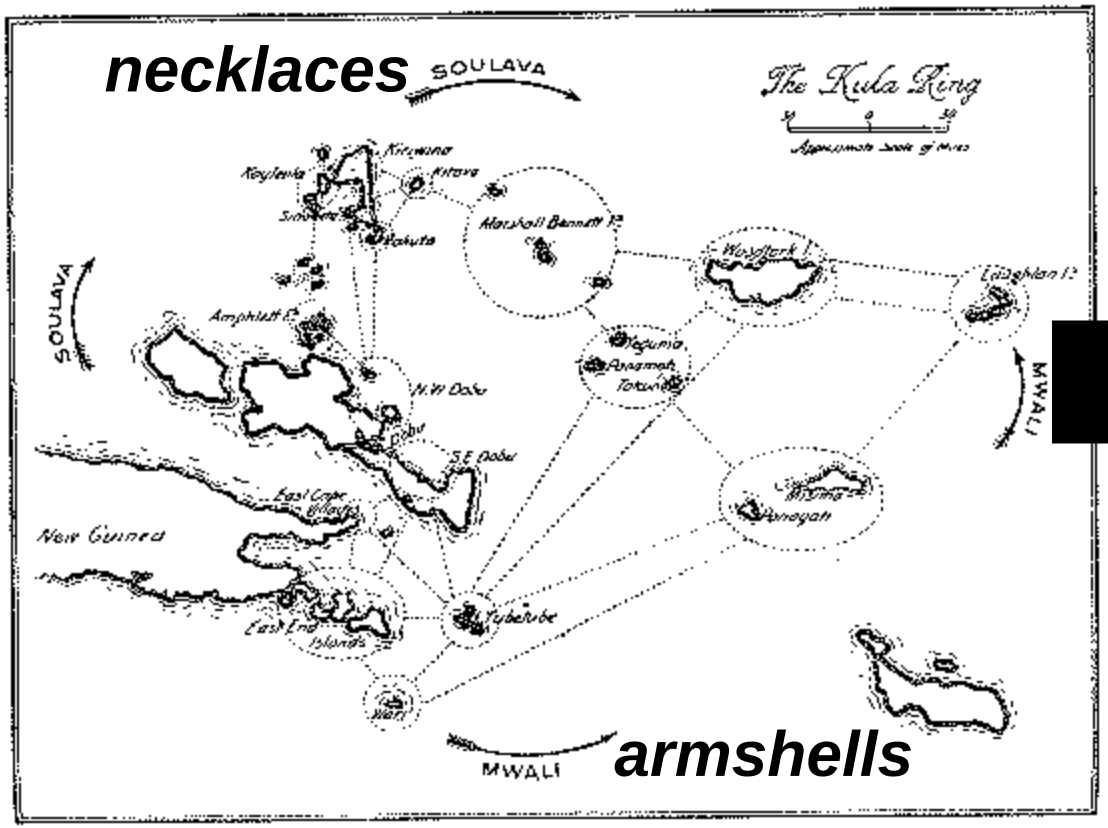
Anskar's Vita + data from finds, 9th c. AD



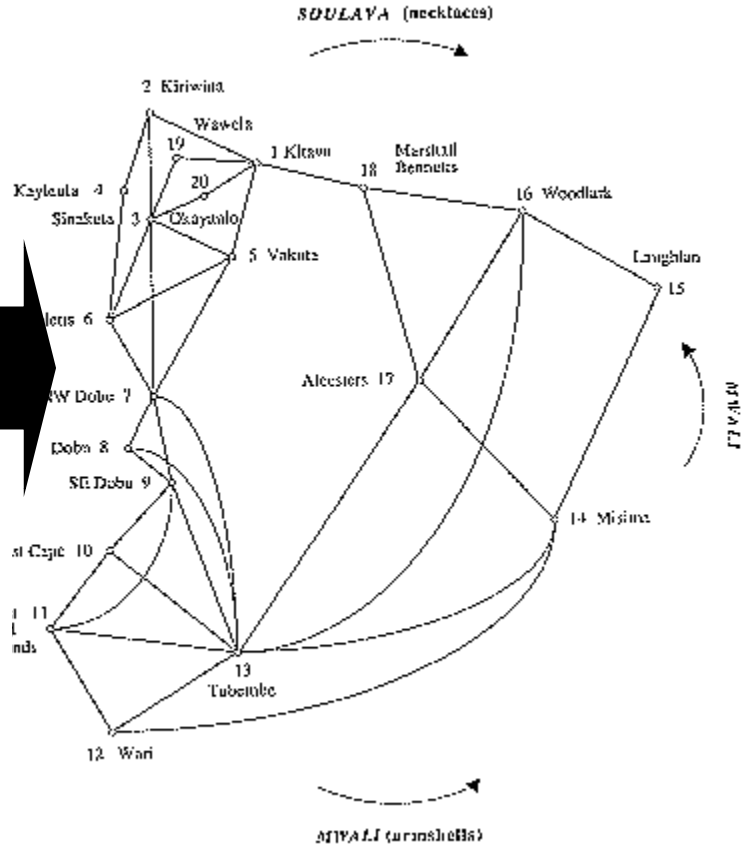
- ***More sophisticated graphs constructed from texts and finds, not a model***
- ***Some global network analysis***

Artefacts and Anthropology:- The Kula Ring

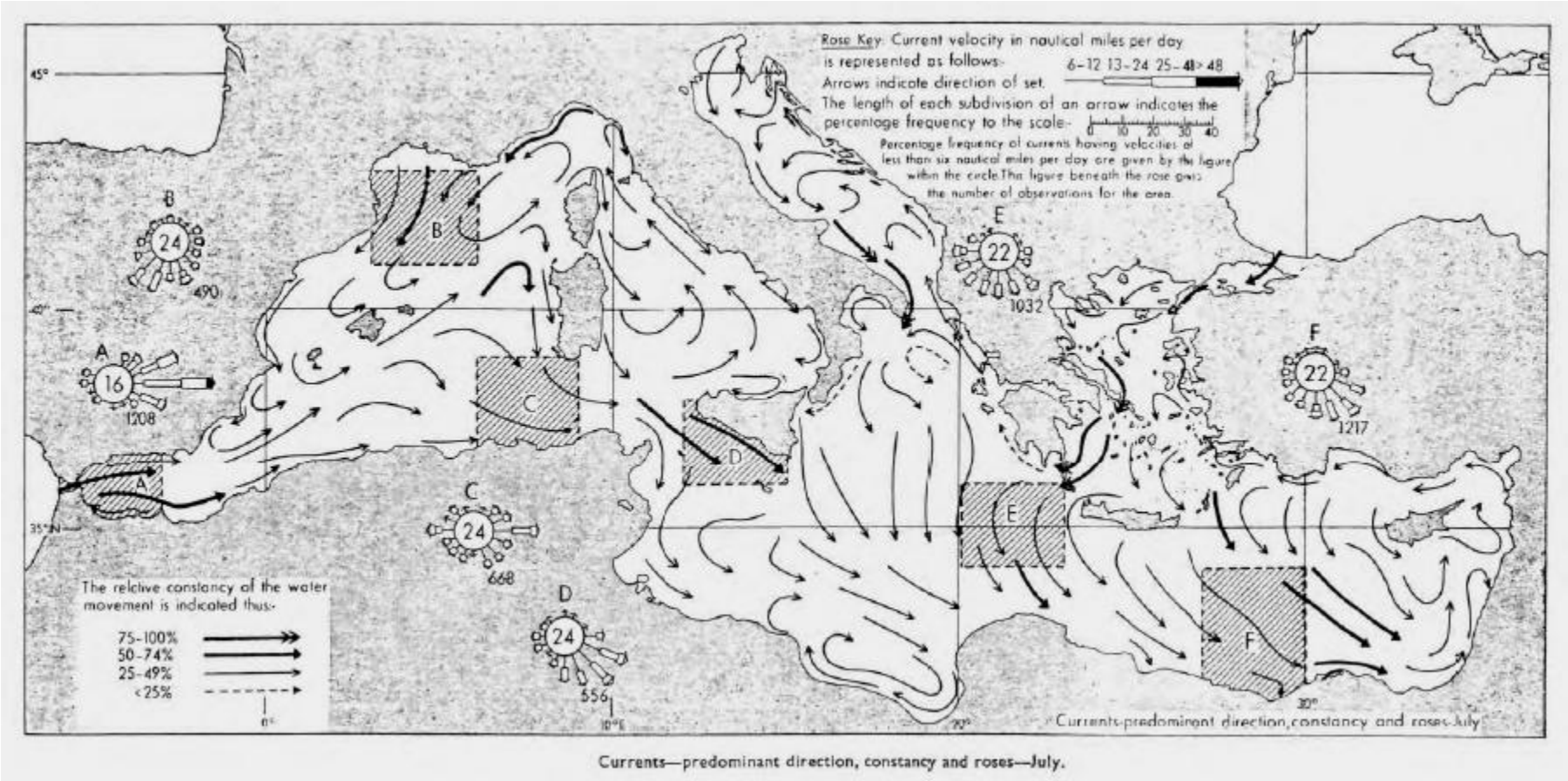
Malinowski (1922)



Hage and Harary (1991)



- Edges are exchange relations
- Random walkers probe global network properties

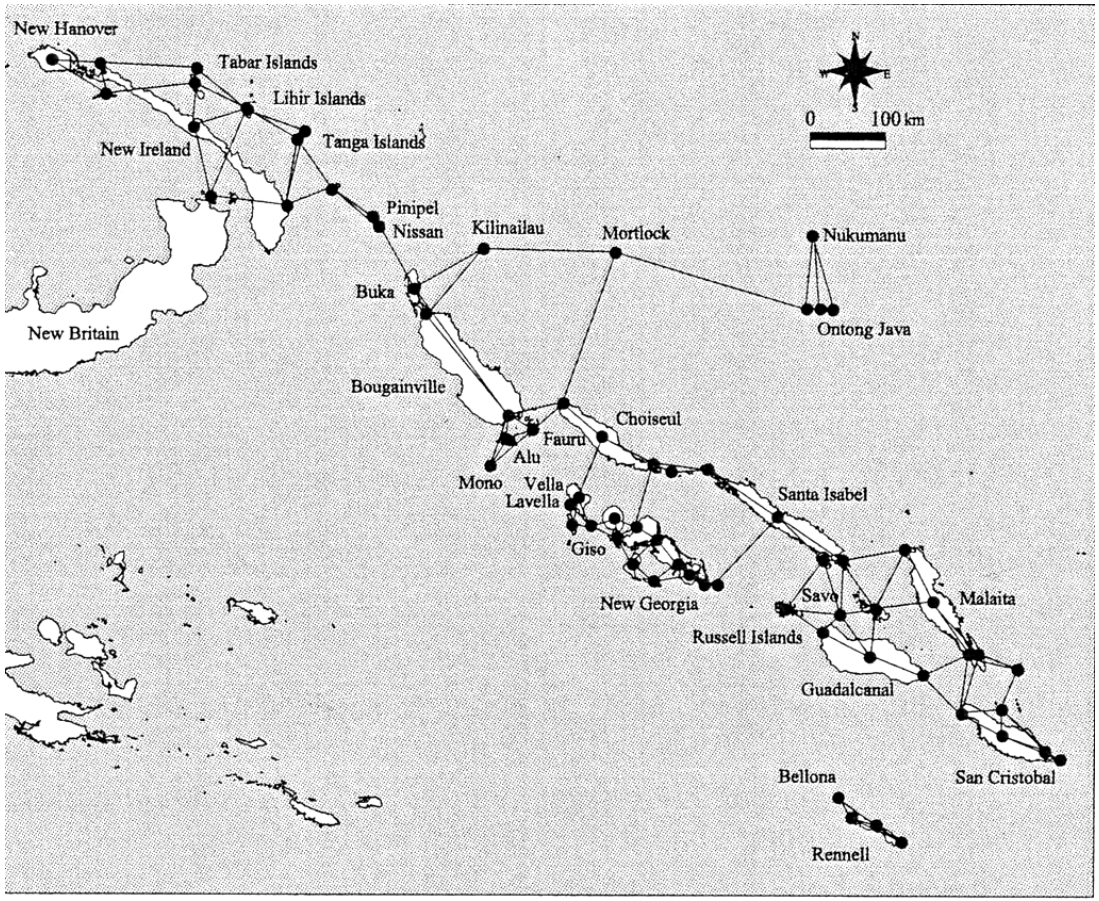


Currents—predominant direction, constancy and roses—July.

Lambrou-Phillipson, 1990

Terrell (1977)

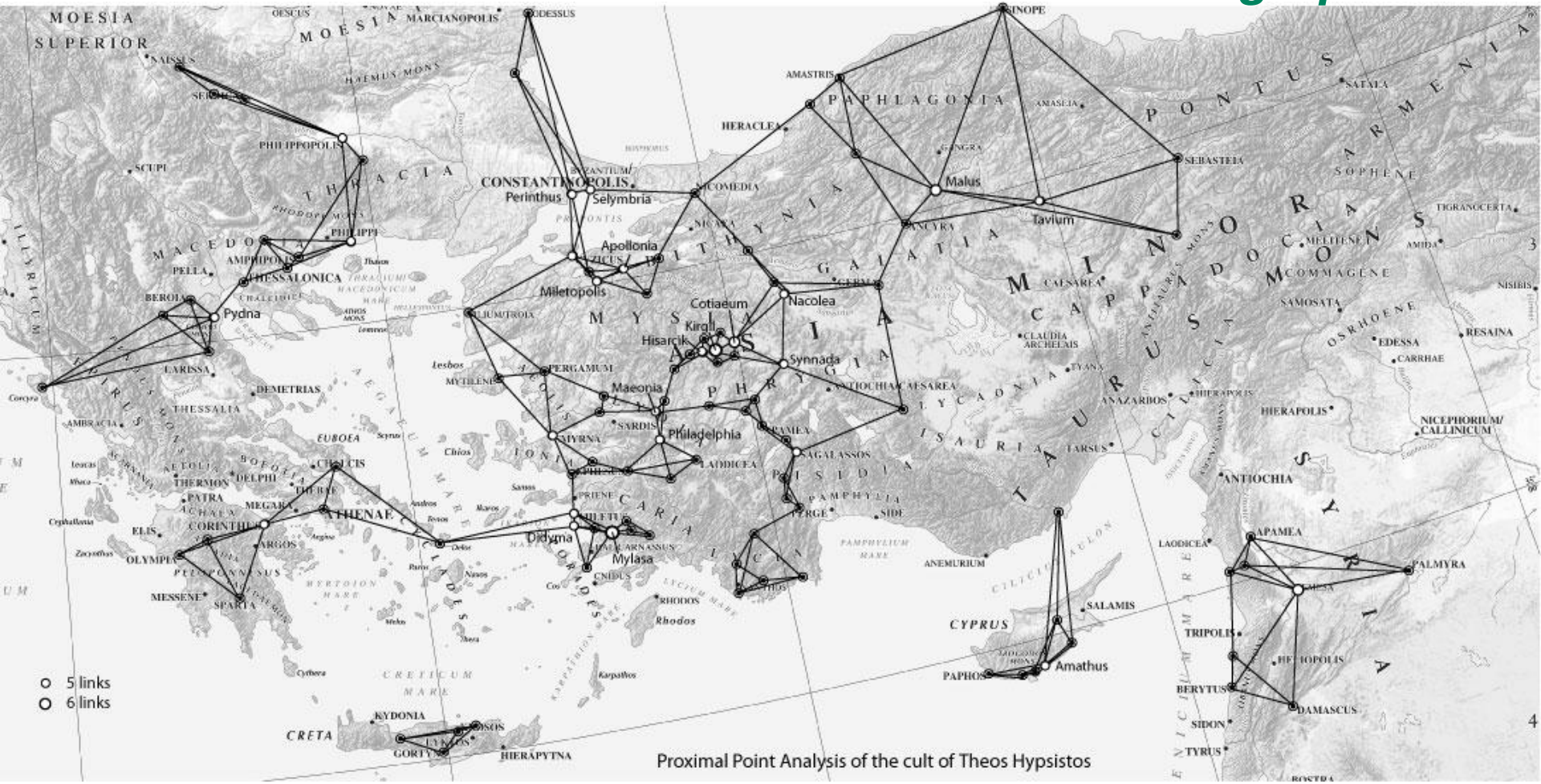
- Solomon Islands (east of Papua New Guinea)
- PPA analysis



"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

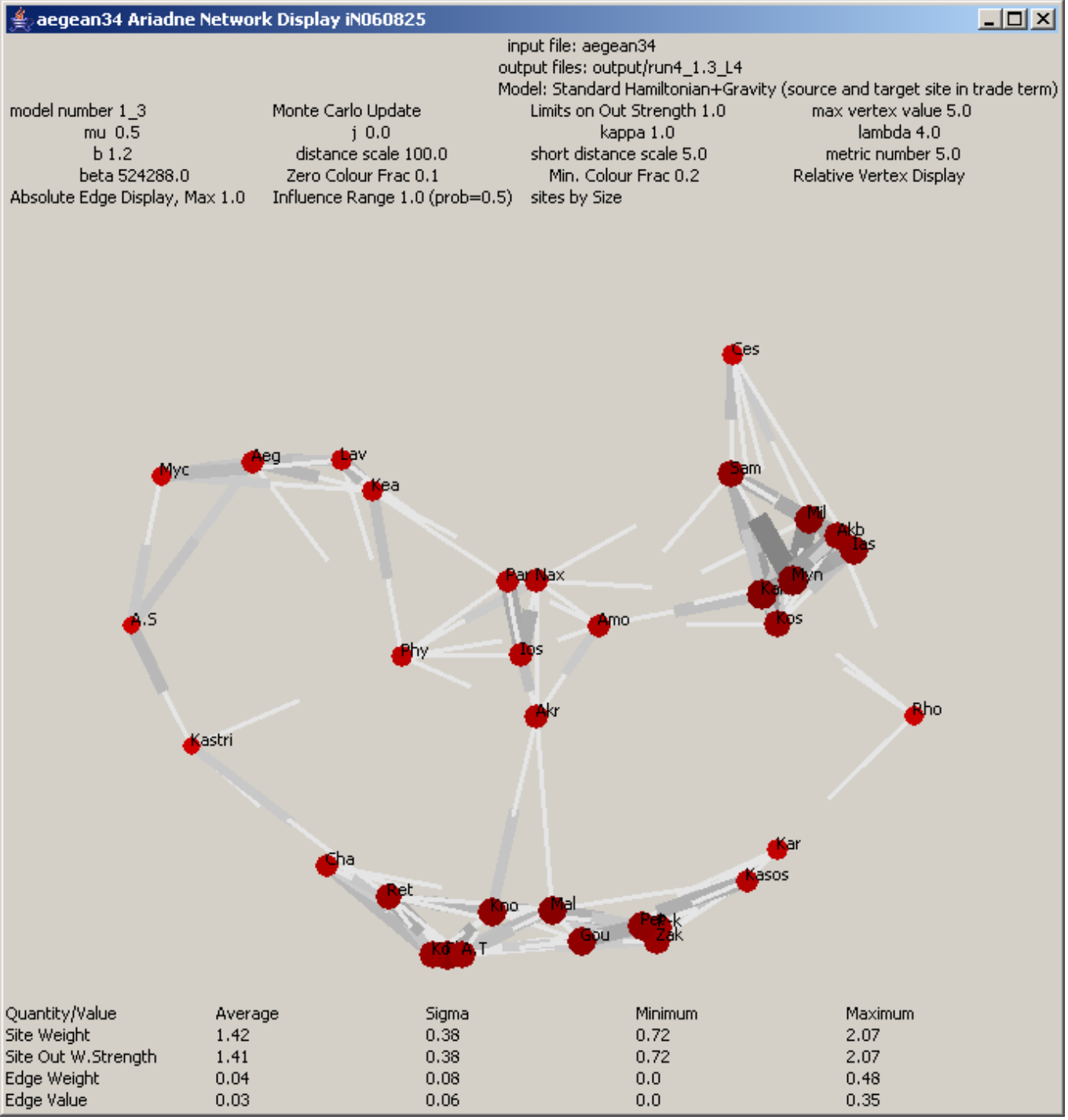


PPA – degree analysis, work in progress

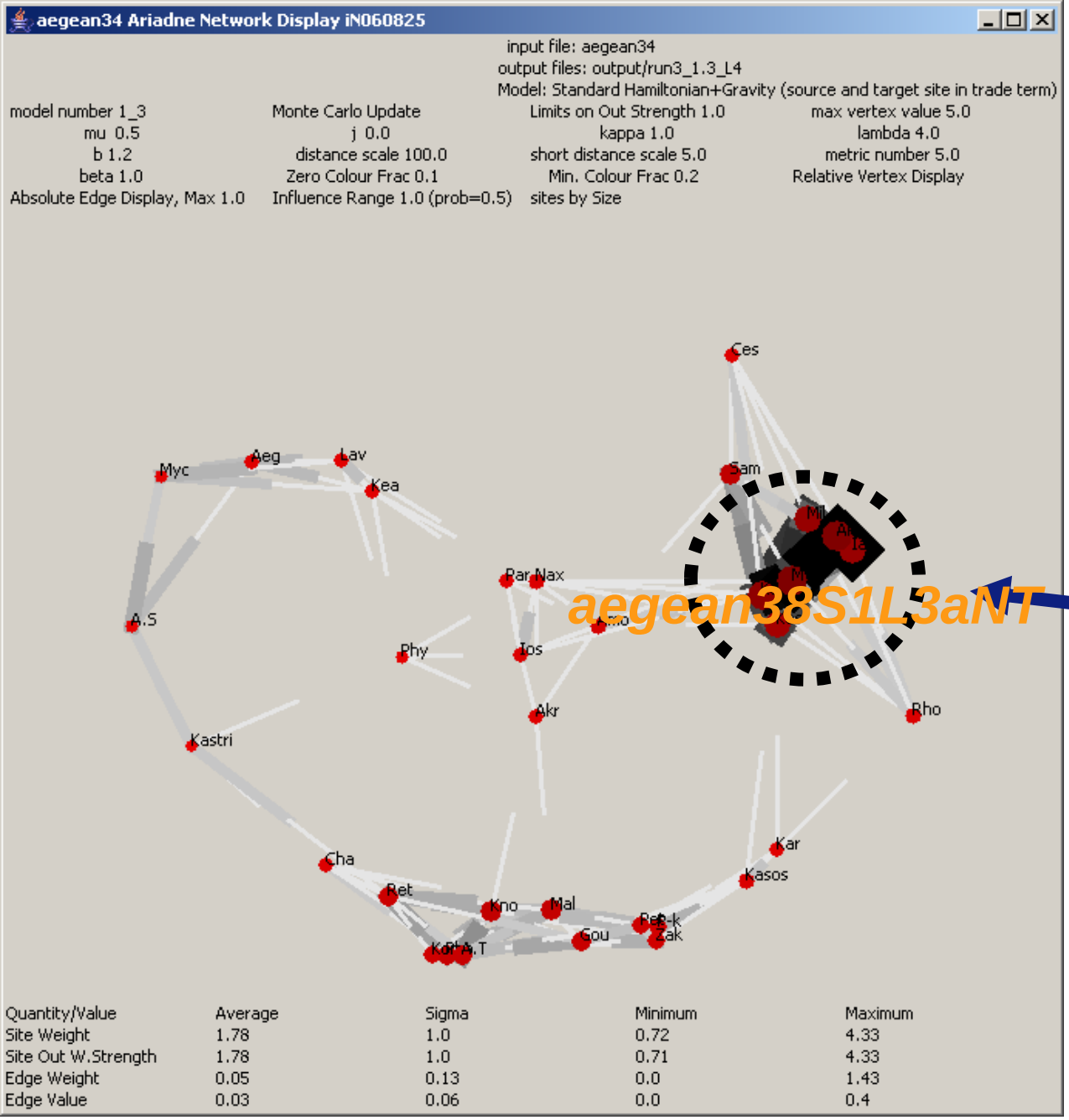
Fluctuations

- 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


aegean34 Ariadne Network Display iN060825
input file: aegean34
output files: output/run4_1.3_L4
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 0.1
Min. Colour Frac 0.2
Relative Vertex Display
Absolute Edge Display, Max 1.0
Influence Range 1.0 (prob=0.5)
sites by Size
Ces
Sam
Aeg
Lav
Myc
Kea
Mil
Akb
Ias
Par
Nax
Myn
Ka
Kos
Amo
A.S
Phy
Ios
Akr
Rho
Kastri
Kar
Kasos
Cha
Ret
Kno
Mal
Pet
Zak
Gou
Ko
A.T
Quantity/Value
Average
Sigma
Minimum
Maximum
Site Weight
1.42
0.38
0.72
2.07
Site Out W.Strength
1.41
0.38
0.72
2.07
Edge Weight
0.04
0.08
0.0
0.48
Edge Value
0.03
0.06
0.0
0.35

Atypical Run - Network



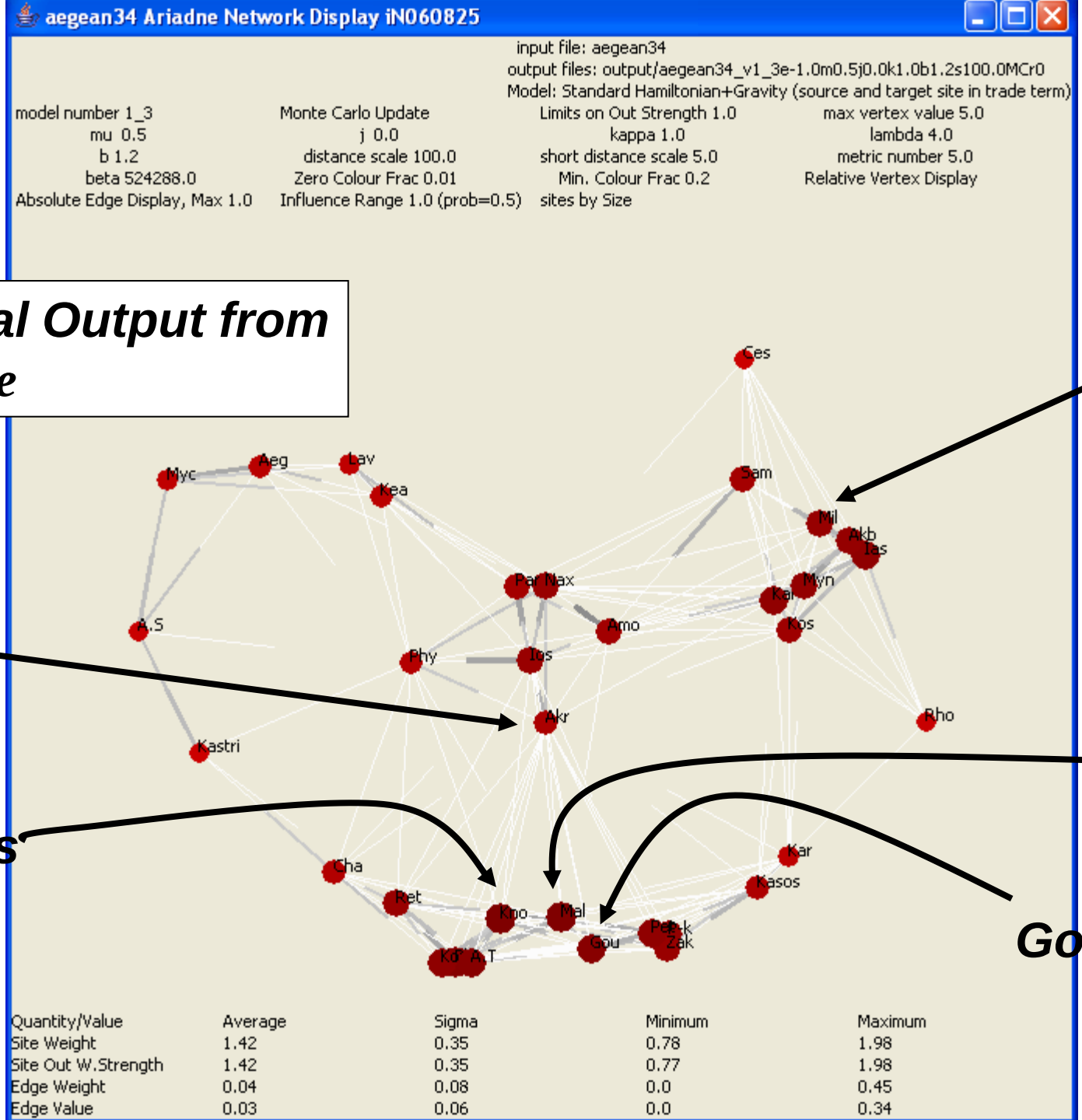
aegean38S1L3aNT

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

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

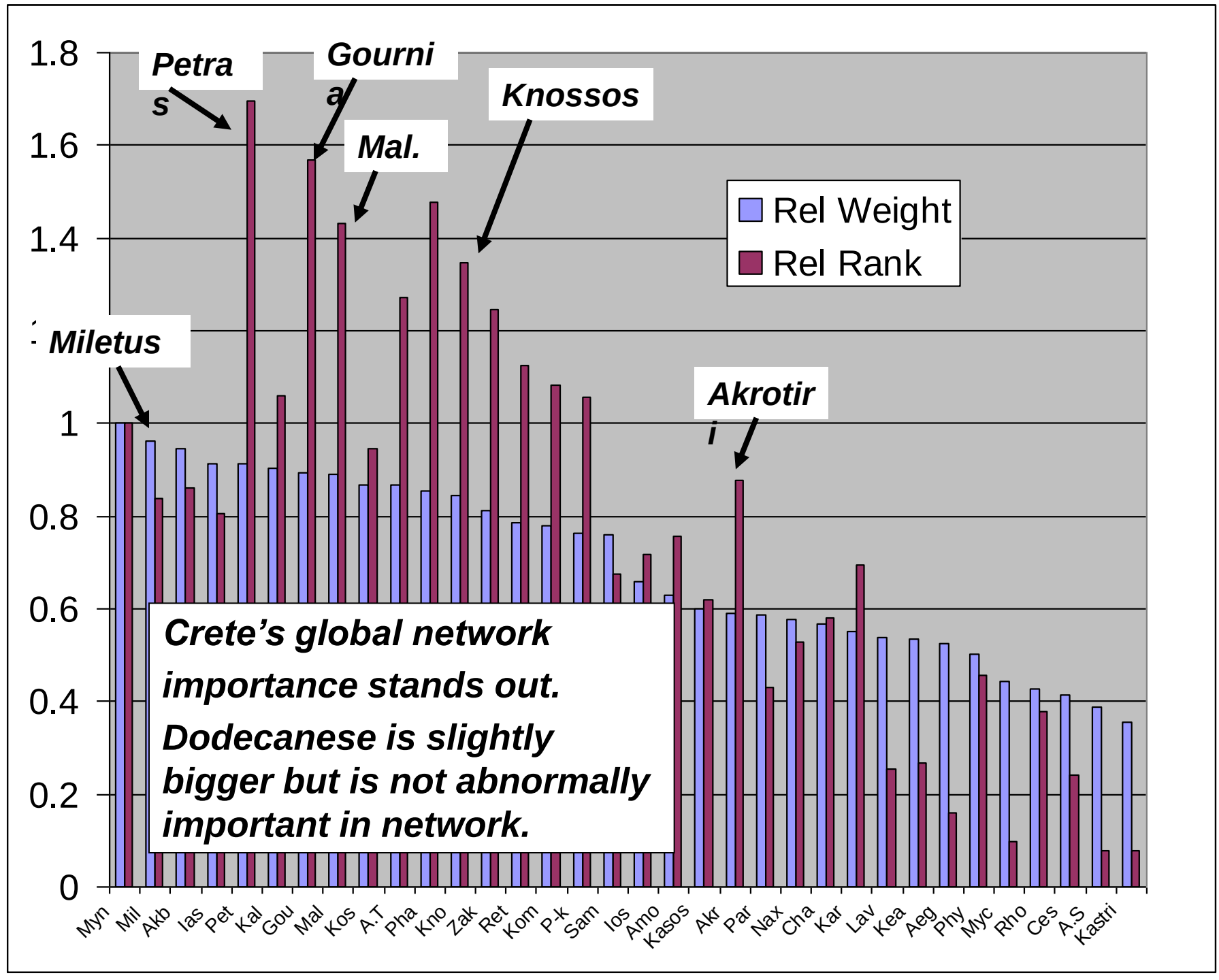
Miletus

Akrotiri

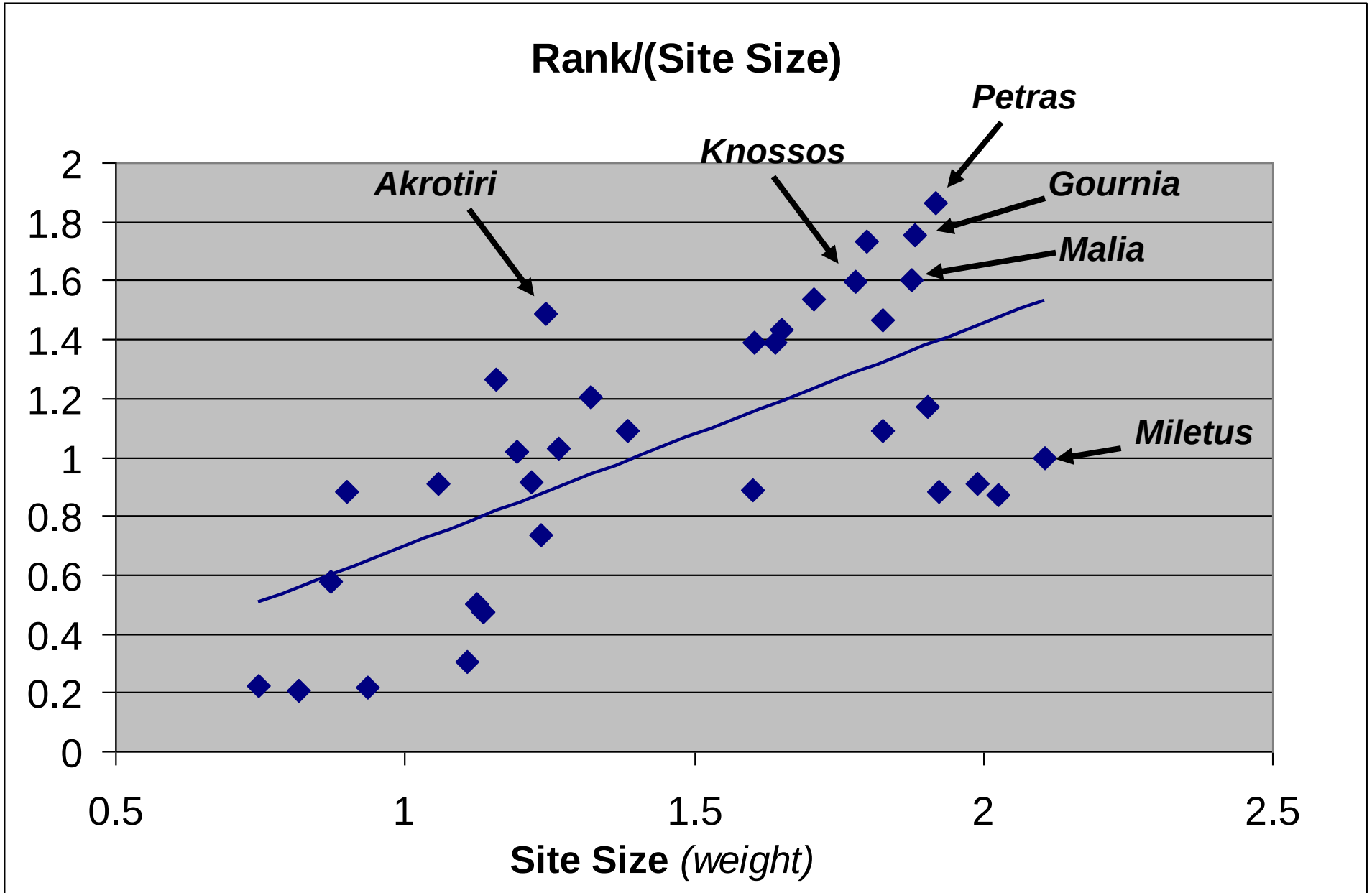
Malia

Knossos

Gournia


1.8
1.6
1.4
1
0.8
0.6
0.4
0.2
0
Petra s
Gourni a
Knossos
Mal.
Miletus
Akrotir i
Rel Weight
Rel Rank
Crete's global network importance stands out.
Dodecanese is slightly bigger but is not abnormally important in network.
Myn
Mil
Akb
Ias
Pet
Kal
Gou
Mal
Kos
A.T
Pha
Kno
Zak
Ret
Kom
P-k
Sam
Ios
Amo
Kasos
Akr
Par
Nax
Cha
Kar
Lav
Kea
Aeg
Phy
Myc
Rho
Ces
A.S
Kastri

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)