CITIES, ENERGY AND CLIMATE CHANGE: COMPLEXITY AND MODELLING

Alan Wilson

Centre for Advanced Spatial Analysis

University College London

INTRODUCTION

- understanding the form, functioning and evolution of cities is critical for future work on energy and climate change
- much progress has been made in understanding the mathematics and the computer science of complex systems and urban modelling is in the vanguard of this
- what is needed now is to carry our present expertise into the domain of a new problem

A METROPOLITAN SYSTEM

Population | Economy

Employment | Jobs
Use of services | Products and services

Interactions
(Transport and Communications)

statics/steady state ‘physiology’/dynamics-DNA

- modelling urban development and evolution is one of the grand challenges of 21C science
- we can now see that we have been at the leading edge of complexity science for a number of years; and the wider developments will now help us
- how can we apply it to energy and climate change?

BACKGROUND: THE HERITAGE FROM THE 1960s ONWARDS

– interaction models
– Lowry and beyond
– demographics
– input-output – which did include the incorporation of energy flows
– the ‘dynamics’ hypothesis: the evolution of structure
– micro-simulation and agent-based modelling
– information systems/GIS/visualisation/geodemographics/IGIS
– economic foundations: Alonso, Herbert and Stevens, Anas, Krugman,.....; still a multi-centric challenge
– applications – e.g. interaction models as location models

Layers of disaggregation

- upper layer modelling as a framework – particularly in relation to possible rates of development:
  - nations within the international system
  - regions within a nation
  - cities within a region/nation
  - intra-urban
- demography and input-output dominate the upper layers; interaction and spatial structure models, the lowest.

A modelling framework

Principal sectors:

- Population
- Housing
- Public services such as schools and hospitals
- Retail services
- Capacity in the economy – buildings, offices, equipment etc
- Government

The principal spatial interactions are:

- The journey to work
- Population to housing
- Population to public services
- Population to retail centres
- Business to public services
- Business to retail services
- Business to business
- Government (spending) to population, public services, retail services and the economy

This leads to the following definitions of key variables:

- P_i^m, the number of type m people in zone i
- H_i^k, the number of type k houses in zone i
- V_j^n, the capacity of type-n consumer services in j; F_j^{mn}, the take-up (on a suitable measure – school places e.g.) by m-type people
- W_j^n, the capacity of type-n retail facilities in j; D_j^{mn}, the take-up of these facilities by m-type people
- Q_j^n, the capacity of the n^{th} economic sector in zone j; X_j^n, the product of sector n in j
- G_j^n, government spend in j.

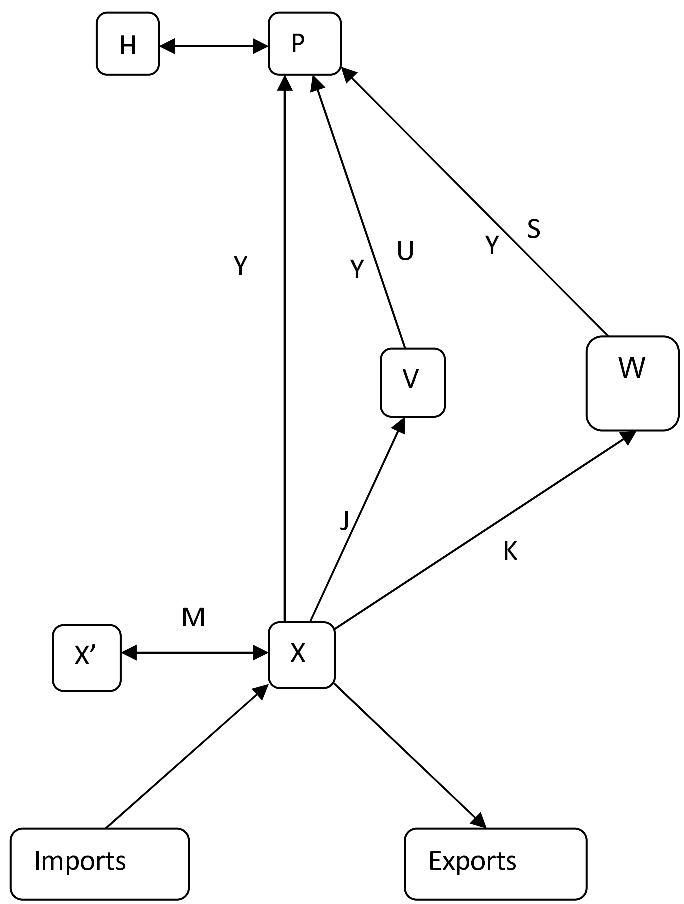
The main interaction variables are:

- Y_{ij}^{mVn}, Y_{ij}^{mWn}, Y_{ij}^{mQn}, the flows to work in sectors V, W and Q from population group m in zone i to sector n in zone j for V, W and Q respectively;
- N_{ij}^{mnk}, the allocation of type m people who work in sector n in j to type k houses in i;
- U_{ij}^{mn}, the flow of type m people in zone i to consumer services of type n in j;
- S_{ij}^{mn}, the flow to retail facilities of type n;
- J_{ij}^{mn}, the flow of goods from sector m in i to the consumer services sectors n in j;
- K_{ij}^{mn}, the flow of goods from sector m in i to the retail services sectors n in j;
- M_{ij}^{mn}, the flow of goods from sector m in i to sector n in j.

Input-output table

	P	H	V	W	X	G	Exports	Output totals
P			Y	Y	Y	T^P		
H	N					T^H		
V	U					T^V		F
W	S					T^W		D
Q			J	K	M	T^Q	Exp	X
G	G^P	G^H	G^V	G^W	G^Q			
Imports					Imp			
Input totals								

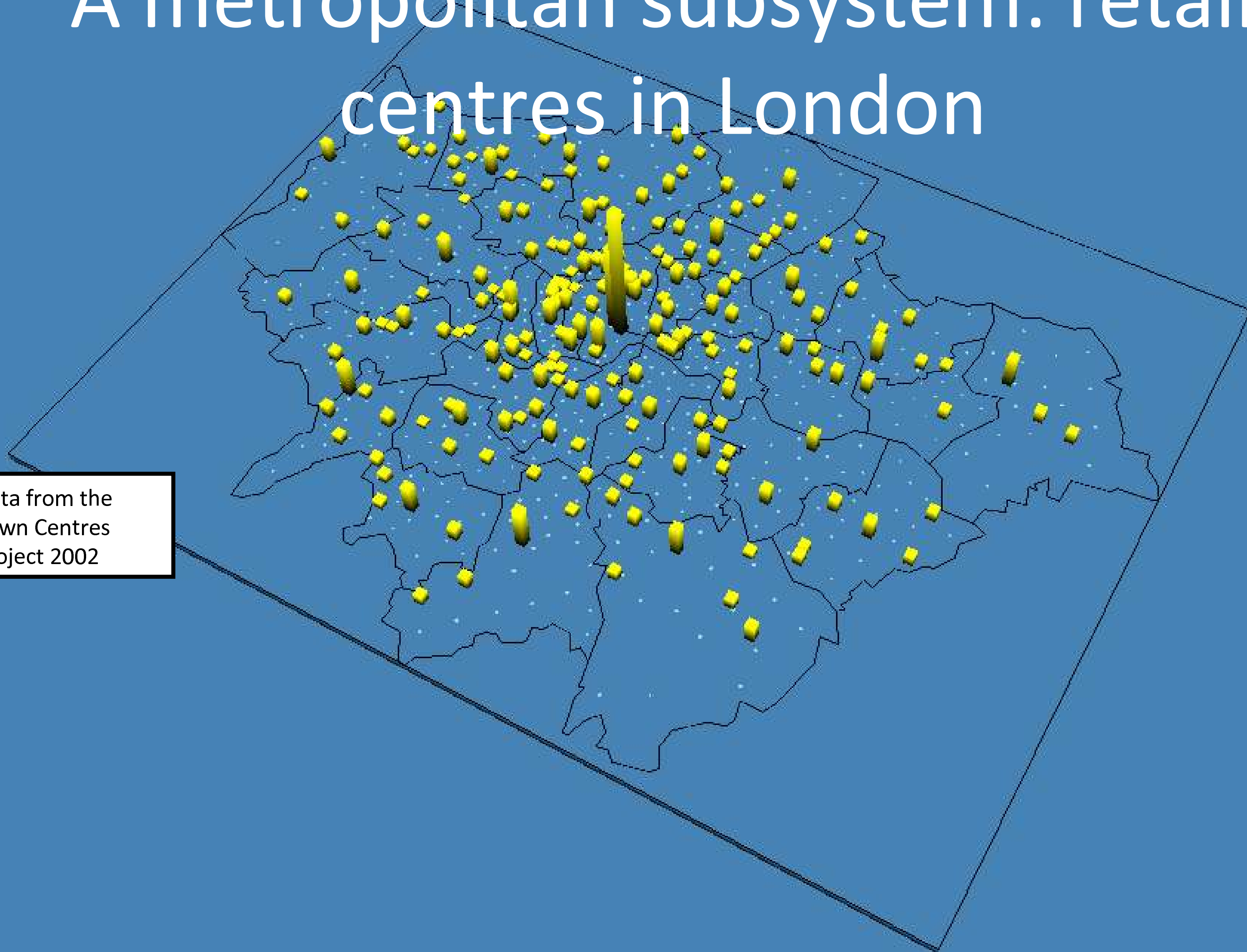
A system diagram



- it is straightforward, if complicated, to represent a megalopolis in this way; there will be
  a) activities at locations
  b) interactions
  c) both on more slowly changing structures
- a) and b) represent the ‘physiology’ of the system; c) the ‘DNA’-based system evolution

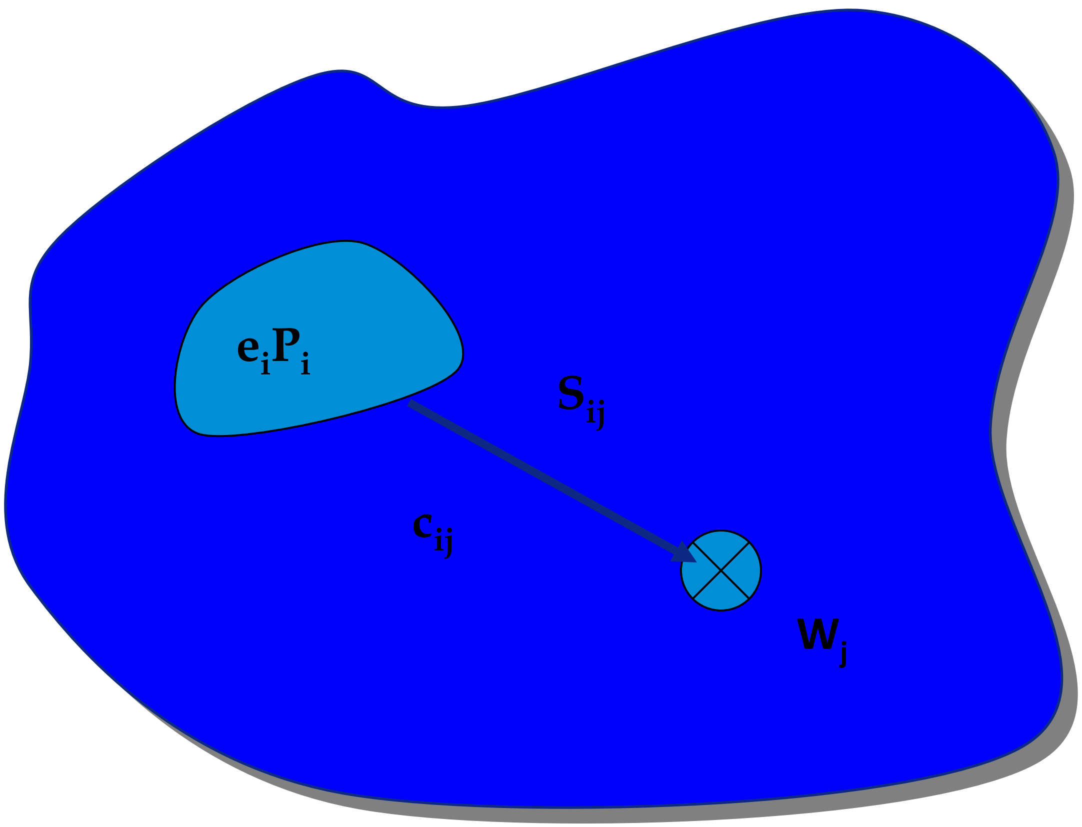
- the model will be nonlinear and so we should recognise that there will be:
  - multiple equilibrium solutions
  - path dependence
  - phase transitions
  - implications for forecasting capabilities
- to fix ideas, consider an example

A metropolitan subsystem: retail centres in London



Data from the Town Centres Project 2002

Retail as a model archetype: variable definitions



$e_i P_i$ - demand in zone i

W_j - attractiveness of zone j

S_{ij} - flows between i and j

c_{ij} - cost of travel between i and j

Spatial interaction

$$S_{ij} = A_i e_i P_i W_j^{\alpha} \exp(-\beta c_{ij})$$

where

$$A_i = \Sigma_k W_k^{\alpha} \exp(-\beta c_{ik})$$

and

$$D_j = \Sigma_i S_{ij}$$

which is

$$D_j = \Sigma_i [e_i P_i (W_j)^{\alpha} \exp(-\beta c_{ij}) / \Sigma_k (W_k)^{\alpha} \exp(-\beta c_{ik})]$$

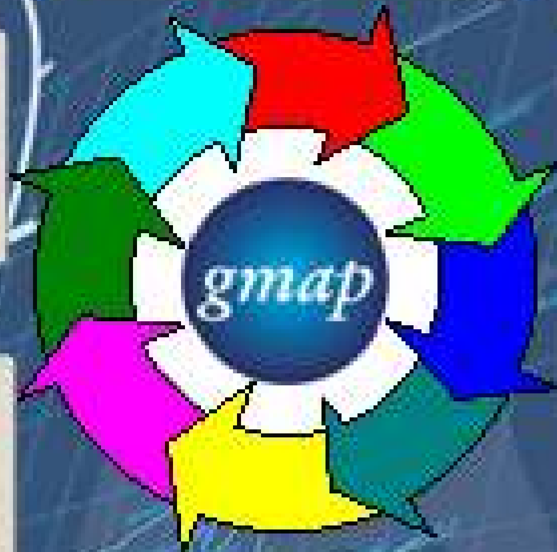
Sector specialists

Financial Services

Halifax, Nationwide,
Alliance & Leicester,
Bank of Scotland, Co-op

Automotive

Ford, Jaguar, Mazda,
Volvo, Land Rover,
Daimler-Chrysler



Retail Petroleum

Exxon Mobil, BP,
Total Fina

Telecoms

Telewest, Marconi,
THUS, OnCue,
Bulldog

Retail

Asda, Dixons,
Sainsbury's, Oxfam
IKEA, Our Price

Other

Aventis,
Warner-Lambert,
DTI, Leeds TEC

The evolution of structure

Let the cost of running a retail centre be $C_j(W_j)$. Then, the structural dynamics can be presented as

$\Delta W_j(t, t+1) = \varepsilon[D_j(t) - C_j(t)]W_j(t)$

which is, essentially, the Lotka-Volterra equation

Then

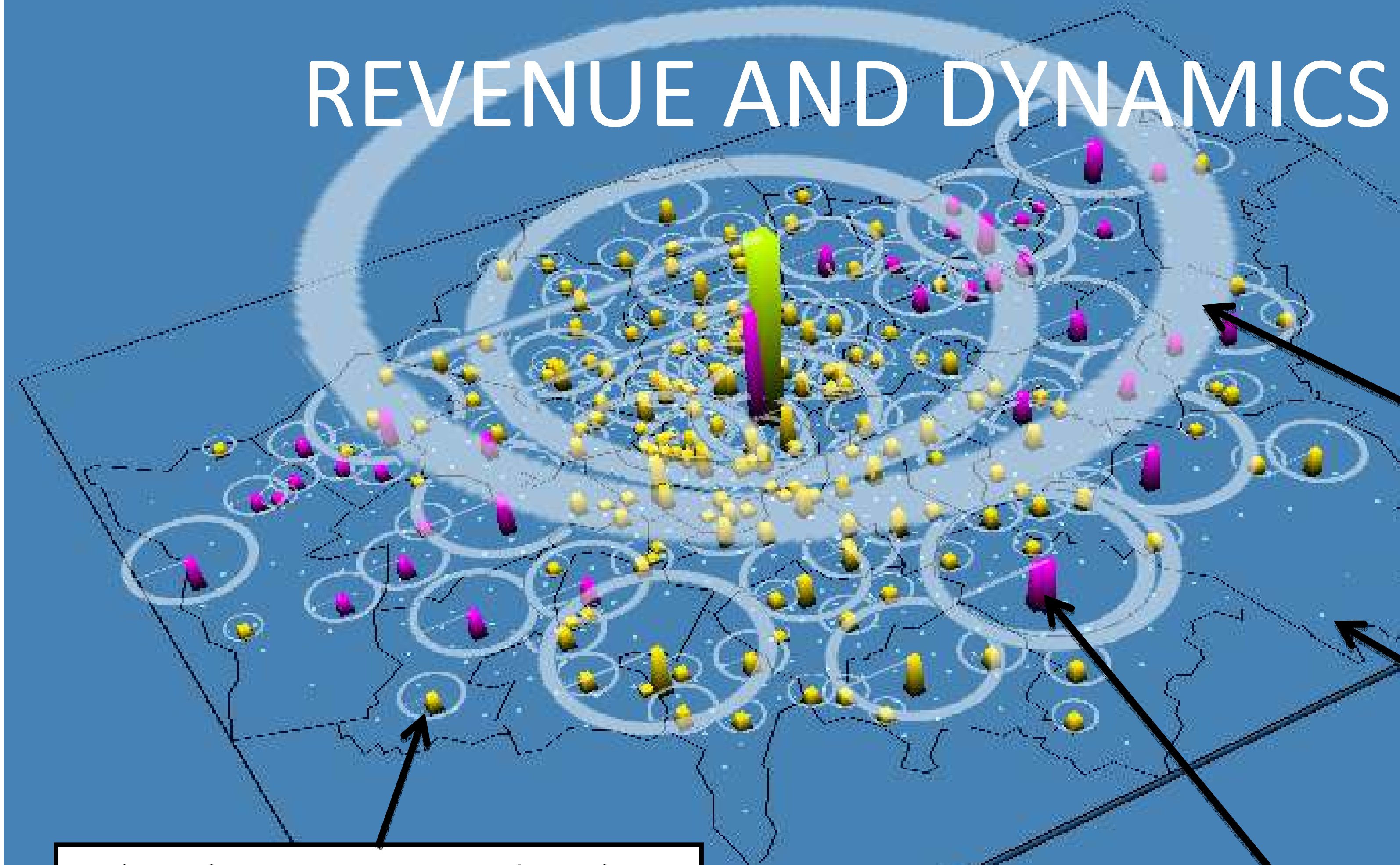
$D_j = C_j = KW_j$

at equilibrium

That is:

$\Sigma_i\{e_i P_i W_j^{\alpha} \exp(-\beta c_{ij})/\Sigma_k W_k^{\alpha} \exp(-\beta c_{ik})\} = k_j W_j$

REVENUE AND DYNAMICS



The ring above each retail centre j is proportional to the current value of D_j

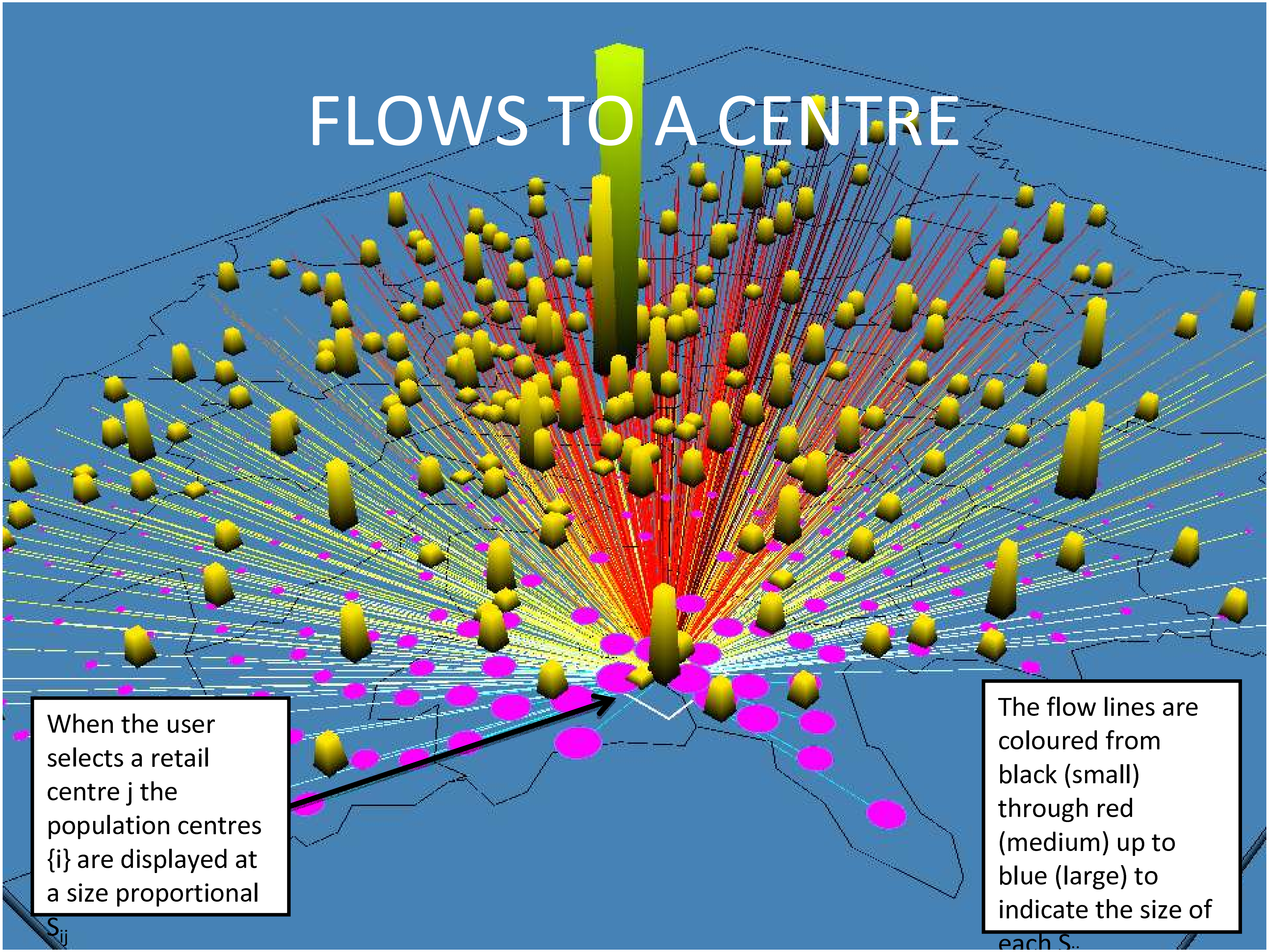
Each population centre i is shown as a blue circle

Each retail centre j is represented as a three dimensional block with:

- Height proportional to W_j
- Colour and tapering indicating whether the ΔW_j is positive (green / wider top), zero (yellow / straight sides) or negative (red / tapered to a point)

We mark centres whose direction of growth is reversed by the normalising factor using purple (forced to shrink) or cyan (forced to grow)

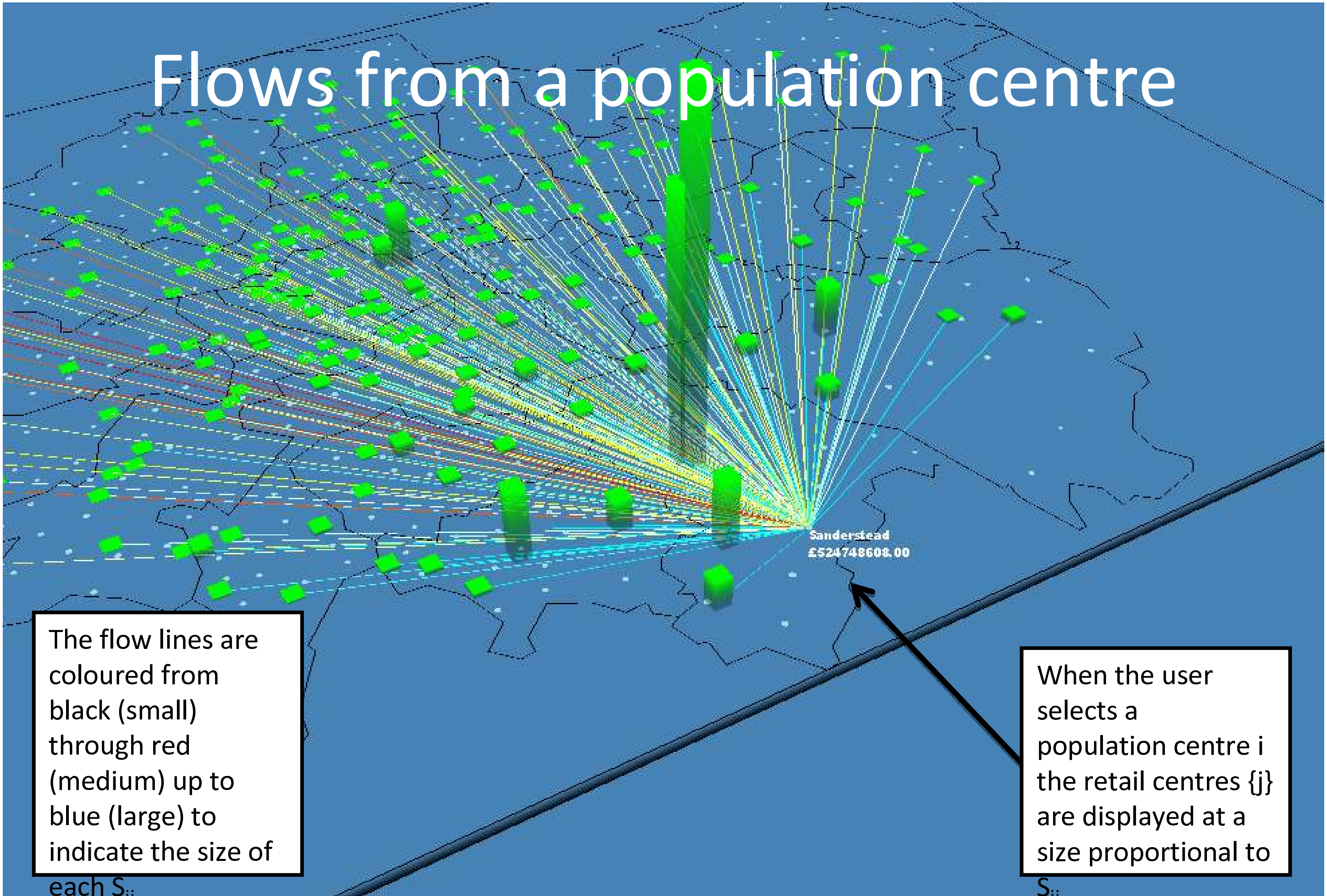
FLOWS TO A CENTRE



When the user selects a retail centre j the population centres {i} are displayed at a size proportional S_{ij}

The flow lines are coloured from black (small) through red (medium) up to blue (large) to indicate the size of each S_{ij}

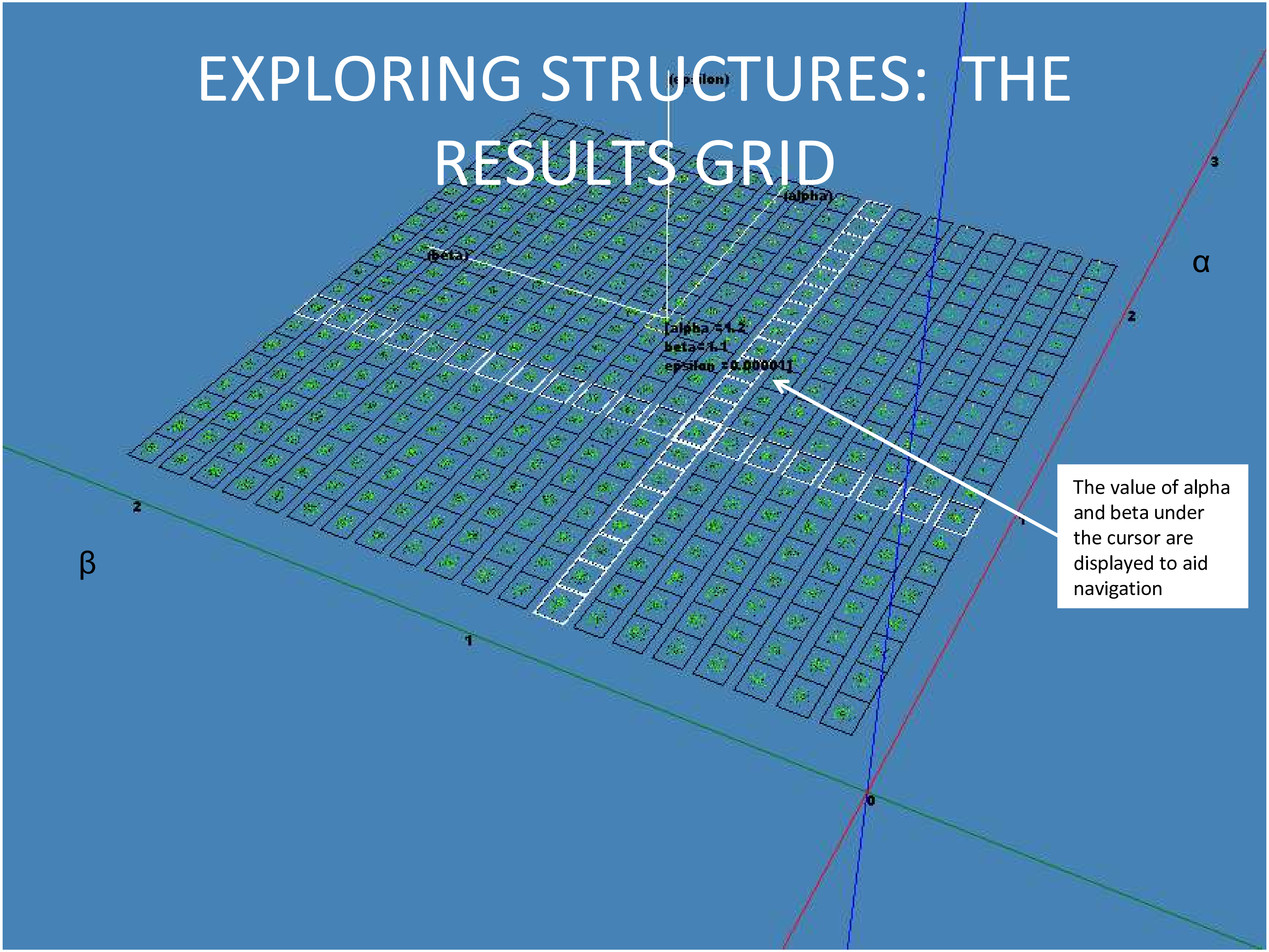
Flows from a population centre



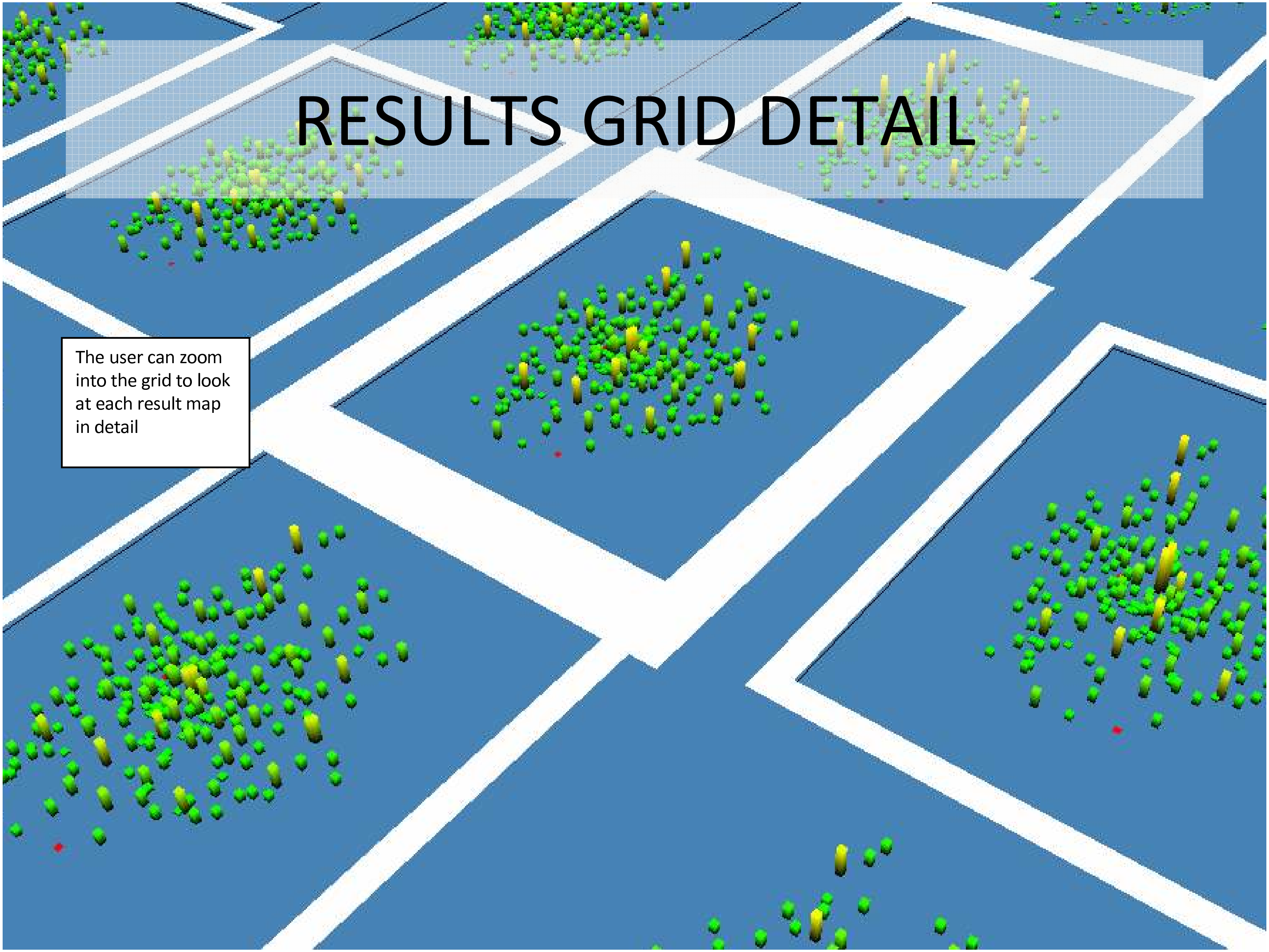
The flow lines are coloured from black (small) through red (medium) up to blue (large) to indicate the size of each S_{ij}

When the user selects a population centre i the retail centres {j} are displayed at a size proportional to S_{ij}

EXPLORING STRUCTURES: THE RESULTS GRID

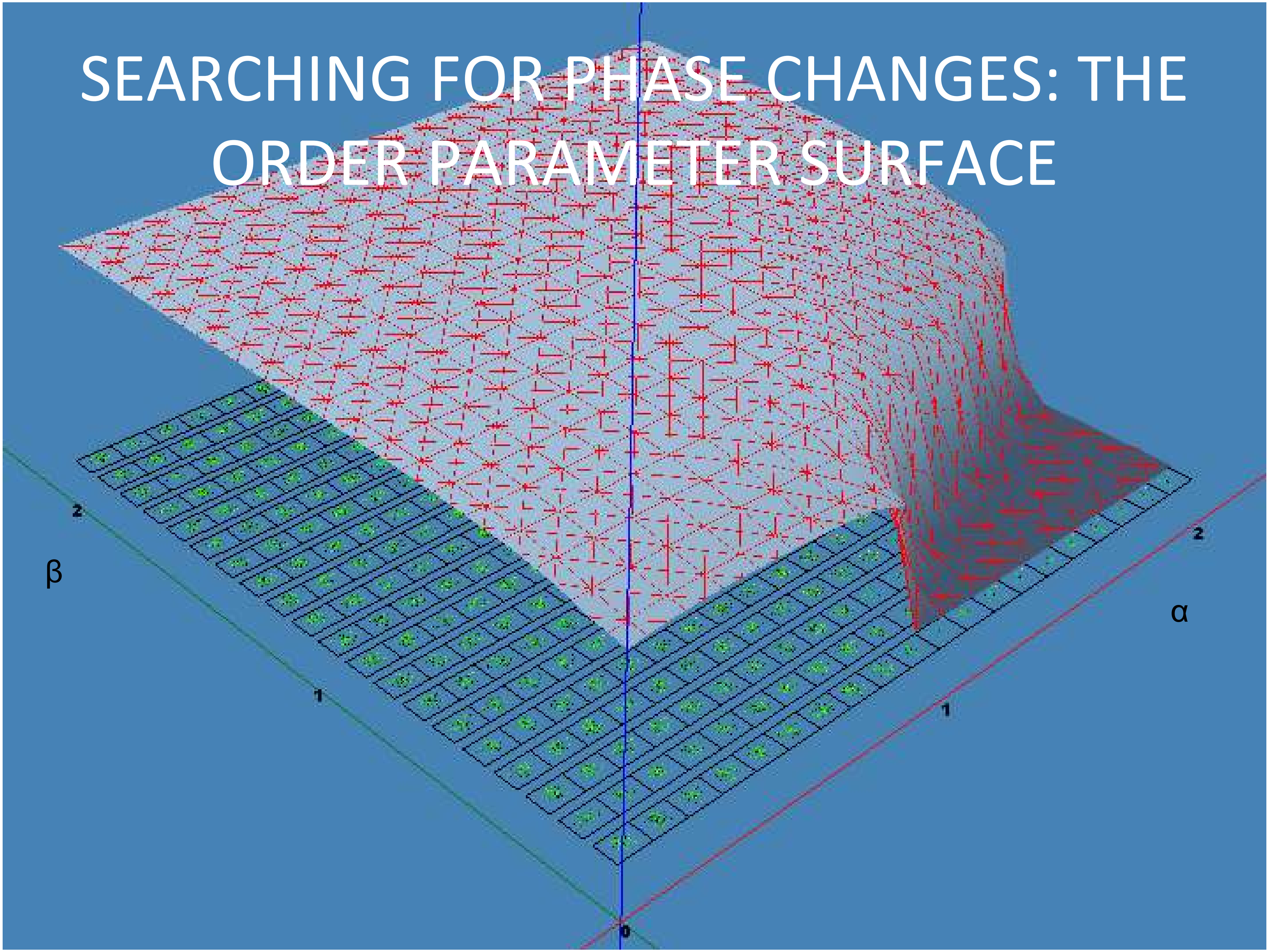


RESULTS GRID DETAIL

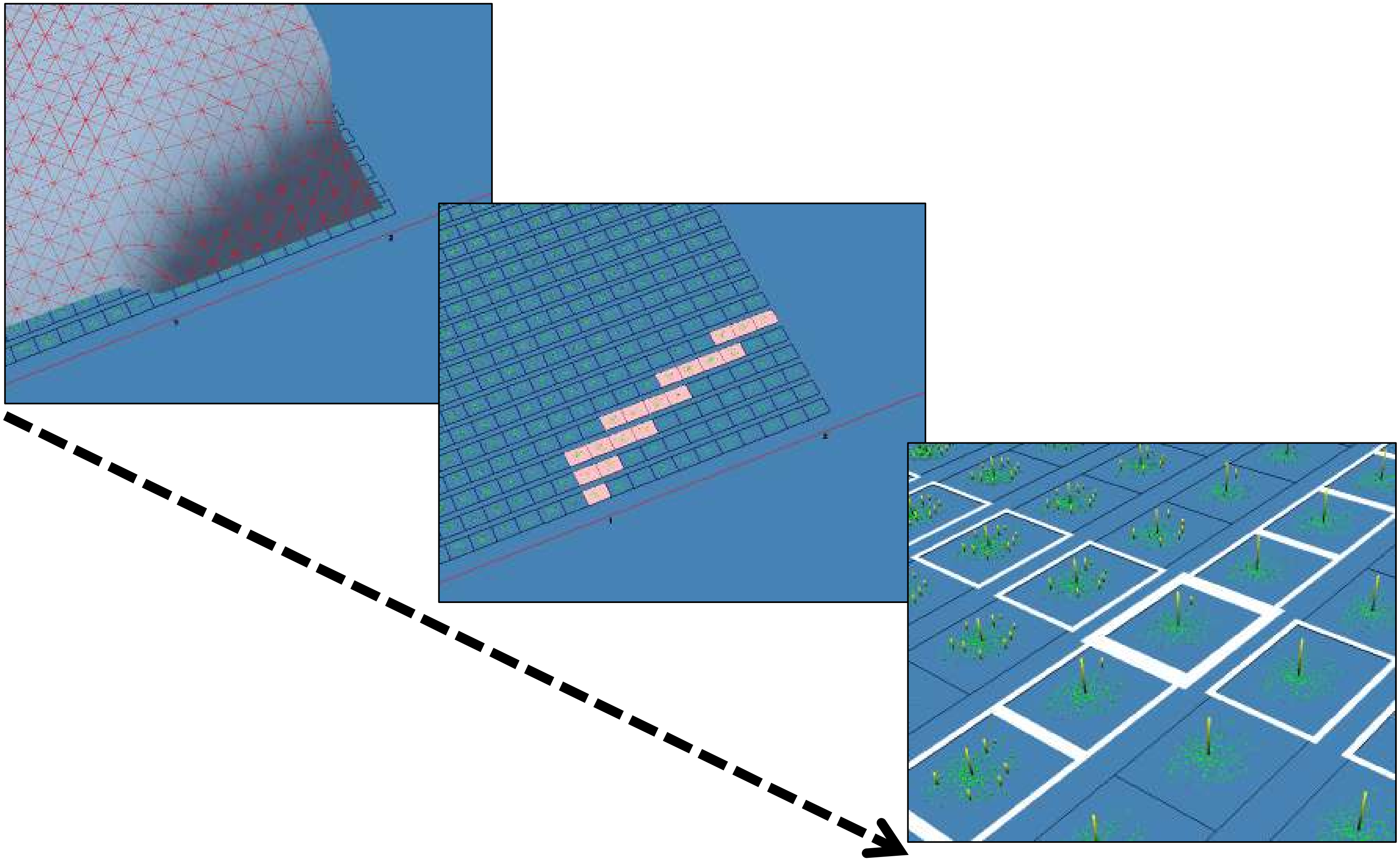


The user can zoom into the grid to look at each result map in detail

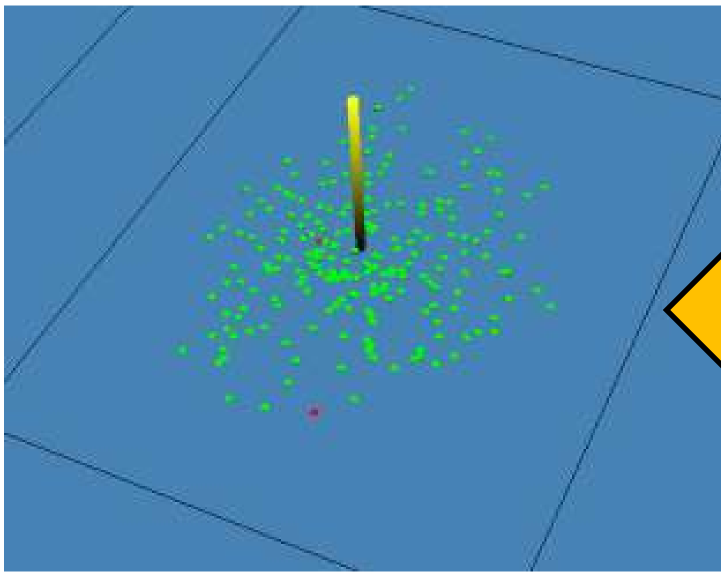
SEARCHING FOR PHASE CHANGES: THE ORDER PARAMETER SURFACE



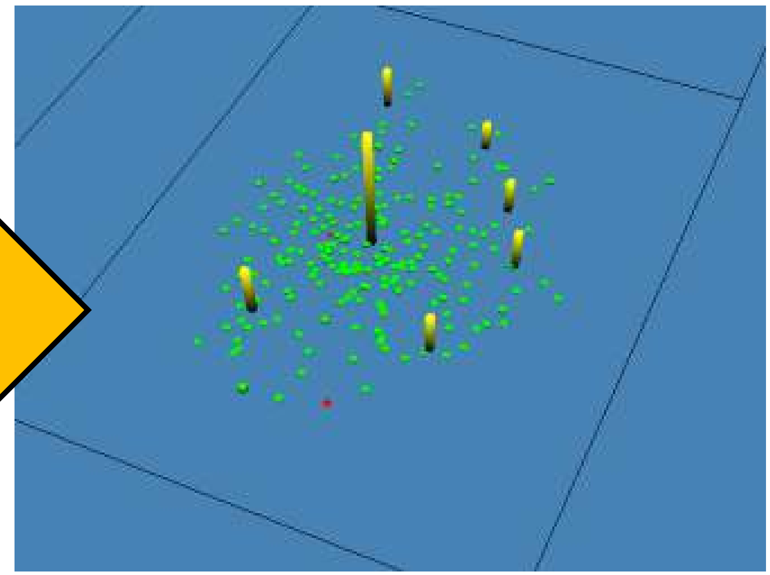
IDENTIFYING A POSSIBLE PHASE TRANSITION



PARAMETER SETS EITHER SIDE OF A PHASE TRANSITION



[α=1.6, β=0.4]



[α=1.6, β=0.5]

A big leap: urban/megalopolitan 'DNA'

- a state vector: {P, H, V, W, X, L, p, c, G}
- recall 'path dependence':
  - development can be seen as constrained by the initial conditions
  - then see the structural variables – the initial conditions - as the 'DNA'
- what are the development 'possibilities' for current DNA?
- can we see how to 'adjust' the DNA
  - either to avoid an end state
  - or to move towards one?

Applications to metropolitan criticality

- consider:
  - climate change
  - sustainability
  - we have to learn how to represent these as possible changes in model variables or parameters: an oil crisis would be an obvious example – to be represented as a steep rise in the β-parameter
- we could then explore changes in (a) the ’physiology’ – the fast dynamics and (b) structural changes – the slow dynamics

THE RESEARCH AGENDA

- establish the basics: access to data, presentation, analysis, modelling, planning
- then set up the model for case studies:
  - layers of disaggregation
  - the ‘physiology’
  - the evolution of structure
    - phase transitions: the drivers; developing the mathematics
    - urban typologies based on underlying structures: the ‘DNA’ argument
  - linking models to the big picture
- implications for planning