Topological structure of the hippocampal code

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Hippocampus and space coding

- Hippocampus is essential for:
  - Forming new memories

    Sequentially consistent memory maps
  - Spatial behavior, spatial memory

    Hippocampal damage results in difficulties in

    - navigation and navigation planning (Poucet et. al.1997)
    - imagining spatial scenes (Hassabis, 2007)
    - sequential goal tasks (Wallenstein, 2004)
  - Electrophysiology – place cells

Space and trajectory reconstruction

Trajectory reconstruction:

1. Record the spike trains
2. Estimate *locations* of preferred spiking
3. Decode animal's position from new spike trains based on these estimates

(Brown et. al 1998)

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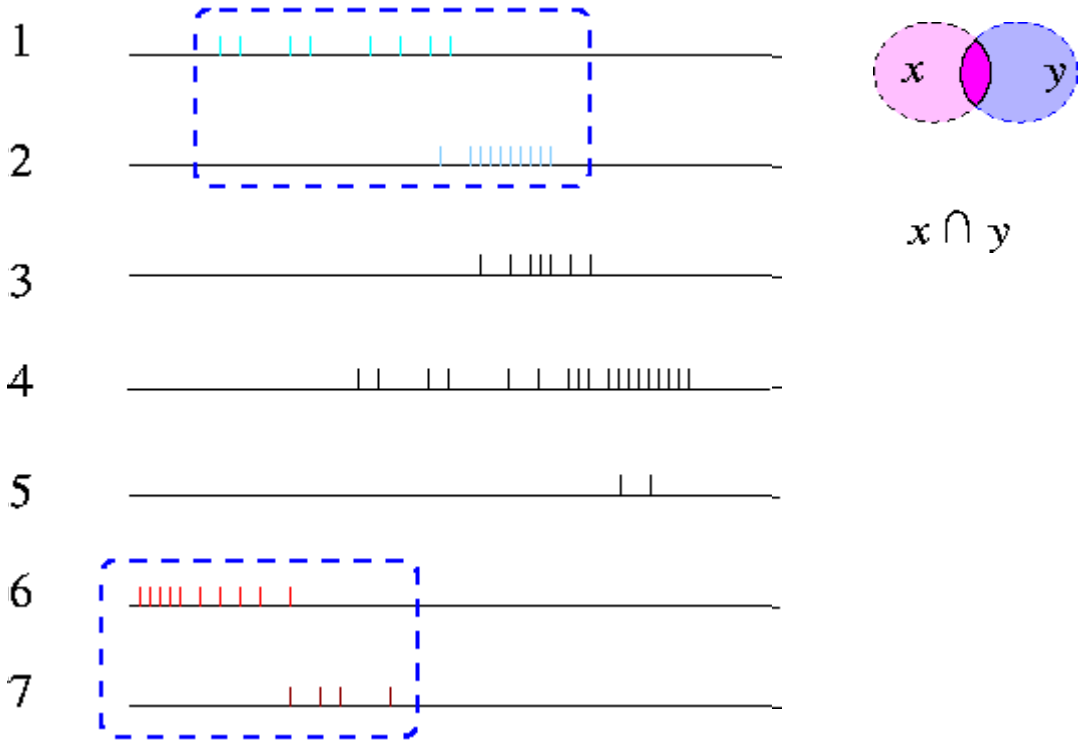
- The analysis is based on *external* geometric information
- What if the external "place" tags are removed?

Spikes → Space reconstruction



$x \cap y$

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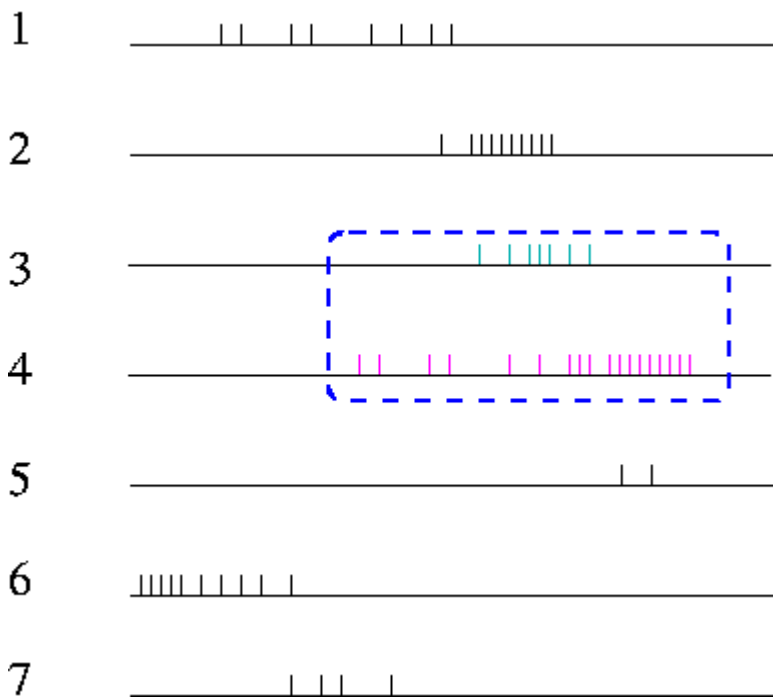

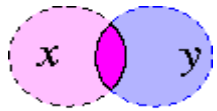

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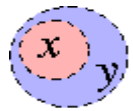

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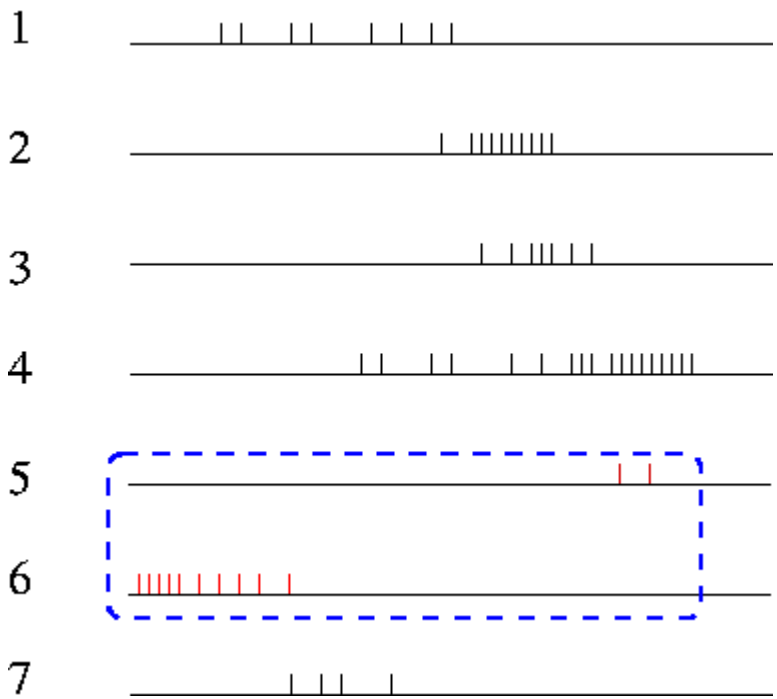
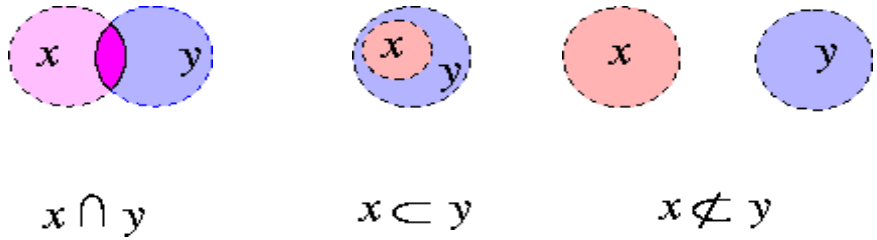
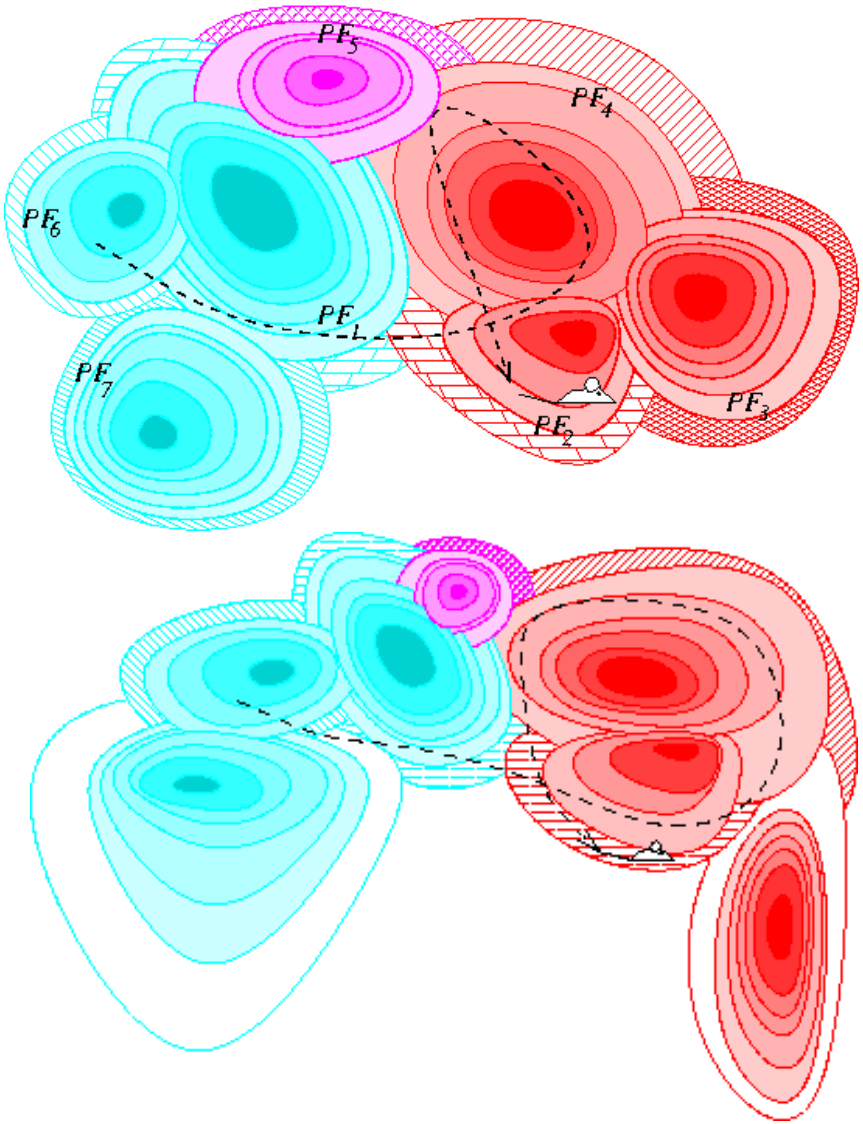
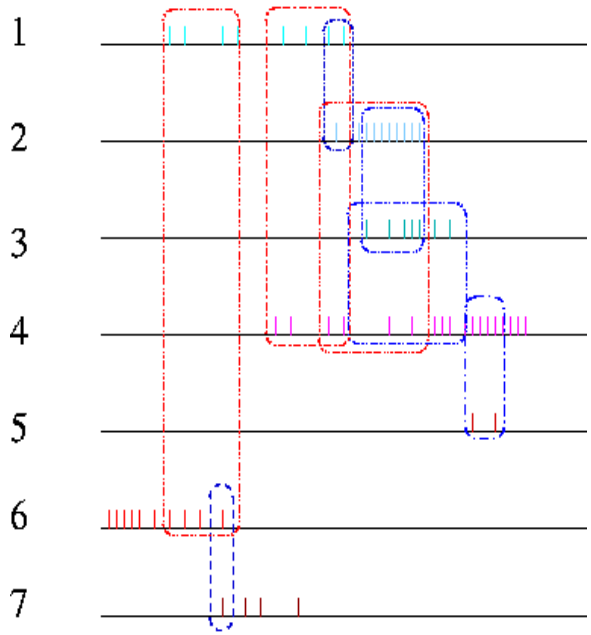




Spiking activity encodes relationships between spatial regions

Global topology of the environment





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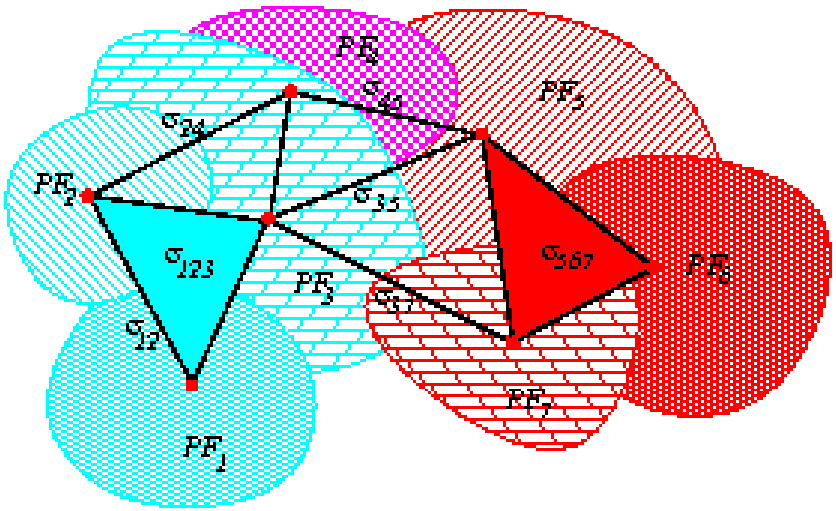
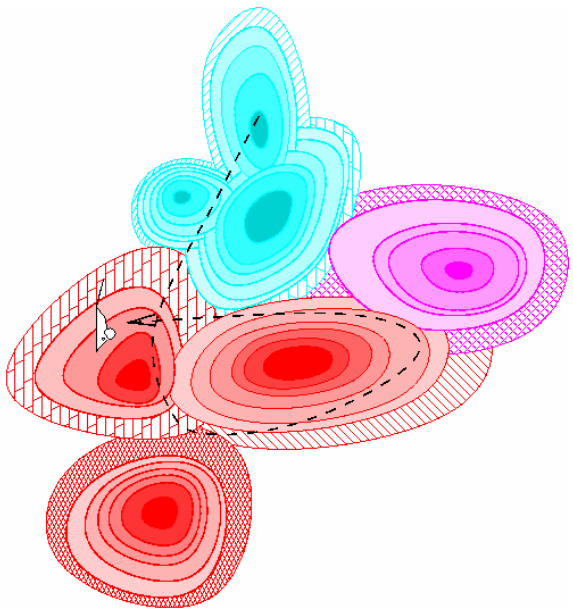
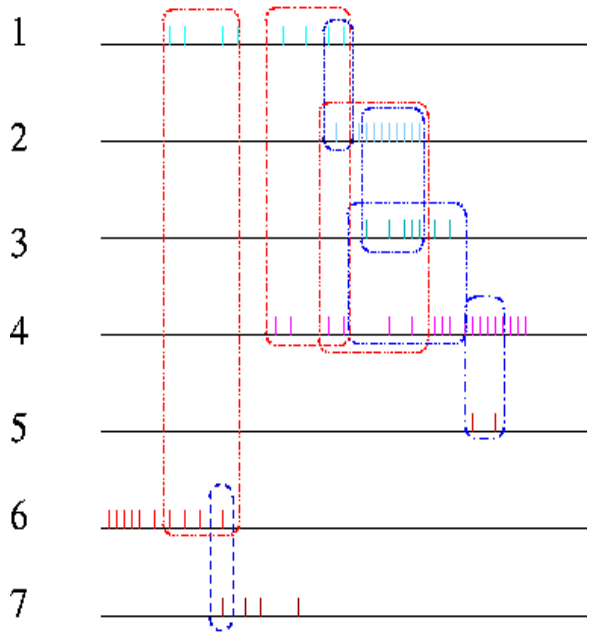




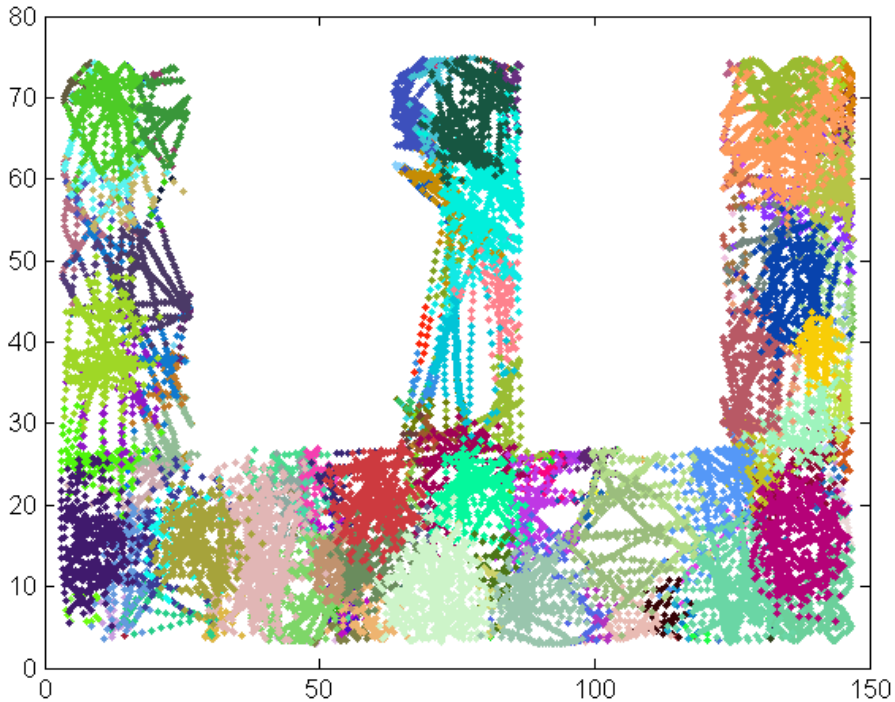


↑

A *topological* structure,
compatible with *many geometries*.

Local analysis - Region Connection Calculus

W-track, 200 place fields



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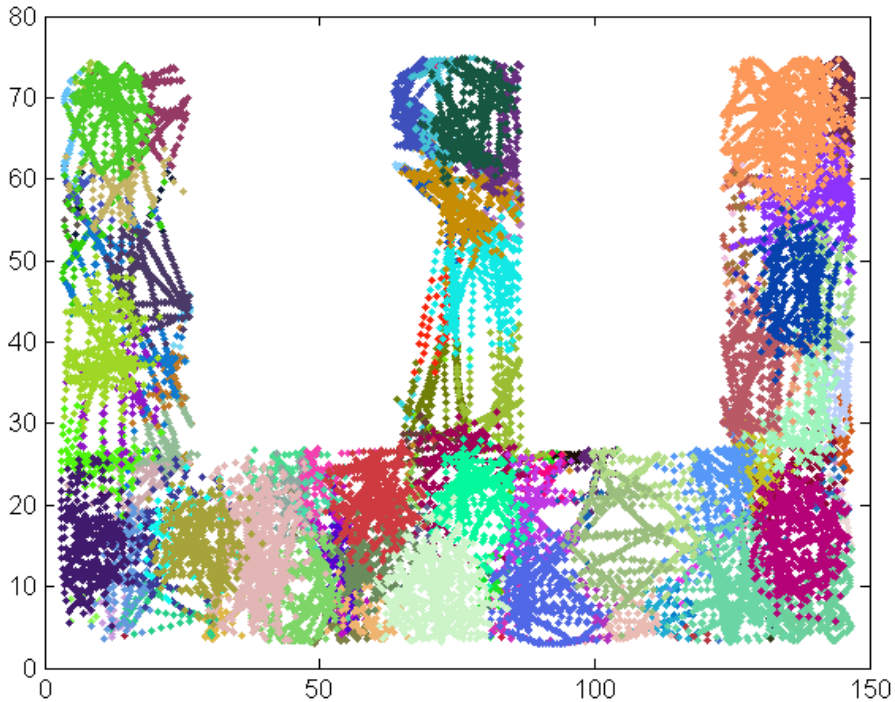

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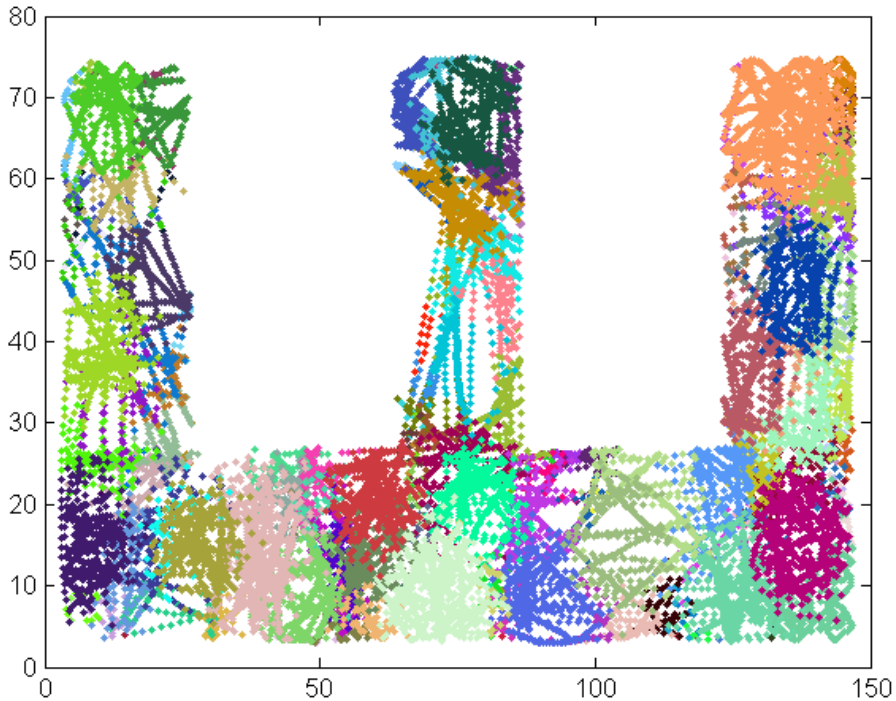

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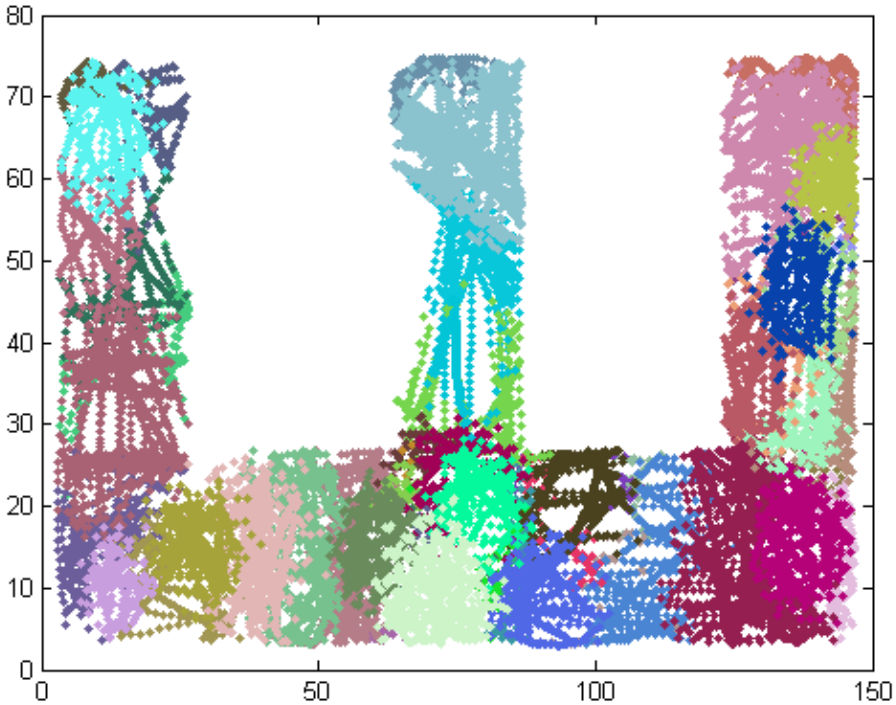

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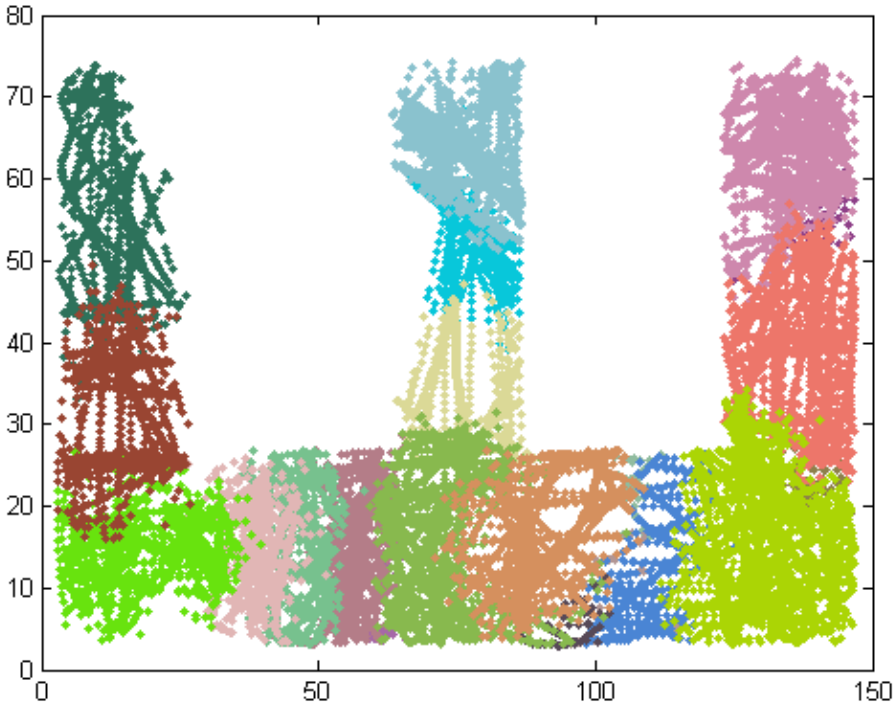

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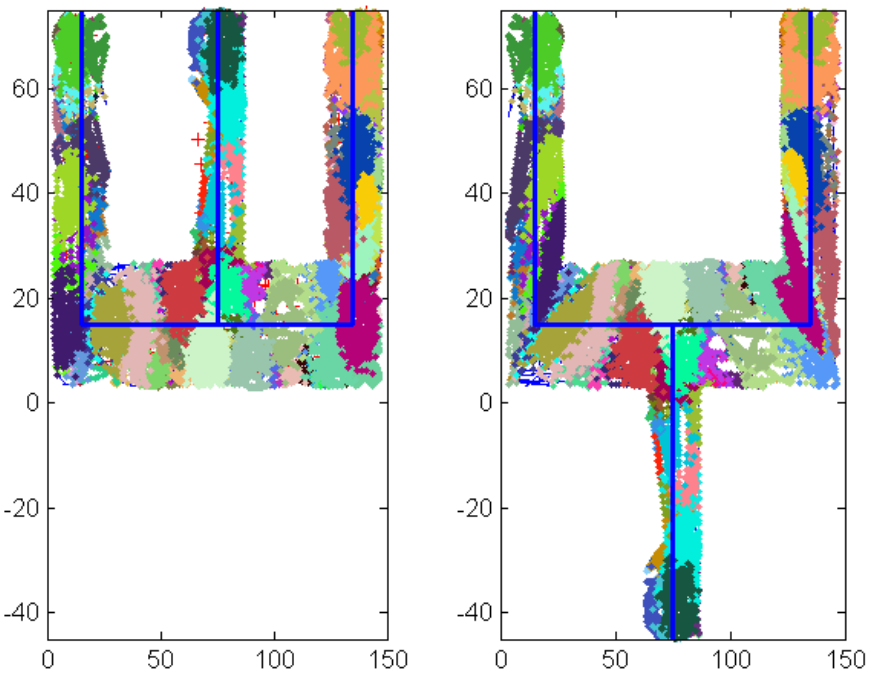

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• It is a "*topological" shape – geometric "tags" are not introduced*

Yu. Dabaghian et al, (ACM GIS 2007).

What do hippocampal cells represent?

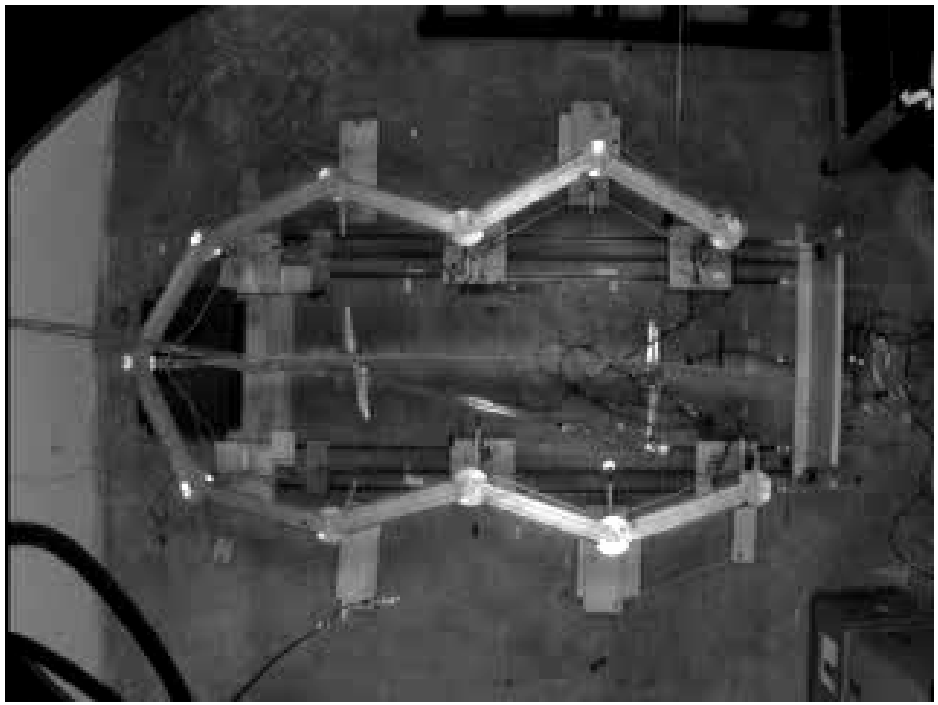
What sort of spatial information can be extracted from the hippocampal cells by the downstream neurons?

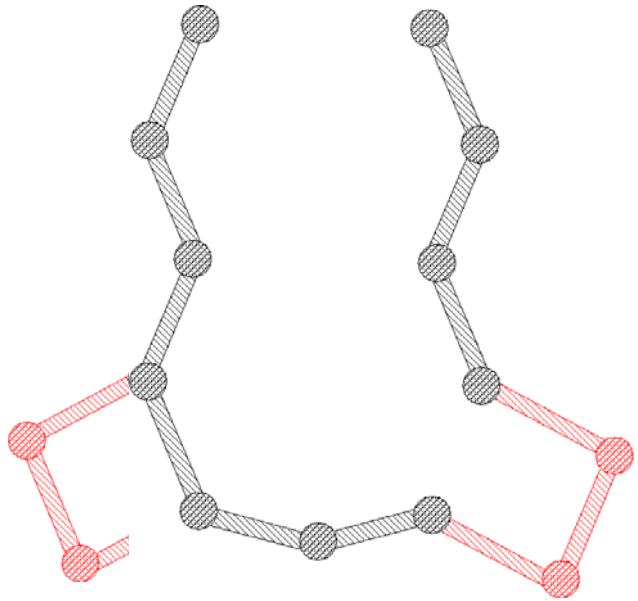
- Topology?
  - Spatial order, spatial connectivity
- Affine structure?
  - Qualitative measure of relative directions
- Metric?
  - A quantitative description of spatial scales

Current opinion: place cells form a basis of *metrical* navigation

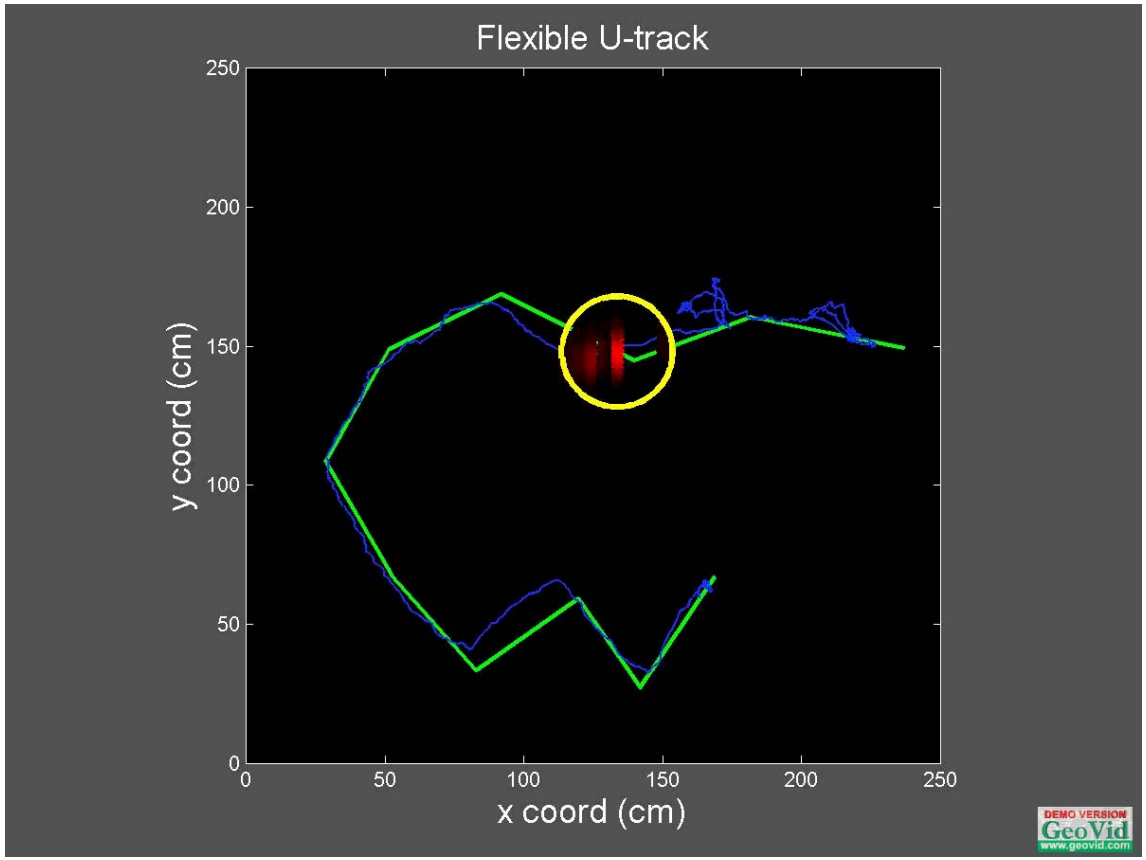
Topology or geometry?

Experimental test of topological hypothesis:
Flexible environments: testing geometric invariance



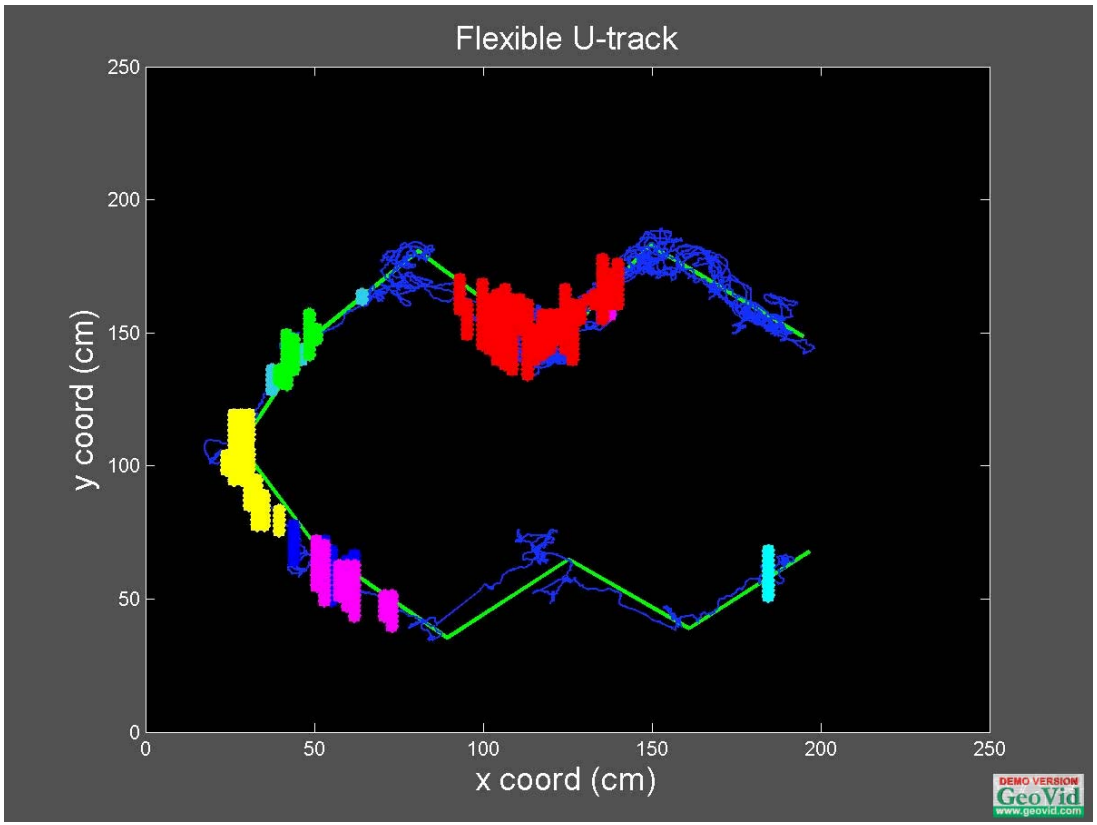


Place fields are geometrically invariant



- Place field locations move in the 2D space
- Linear position along the track is preserved
- Place fields do not appear to be controlled by the rat's path integration mechanism

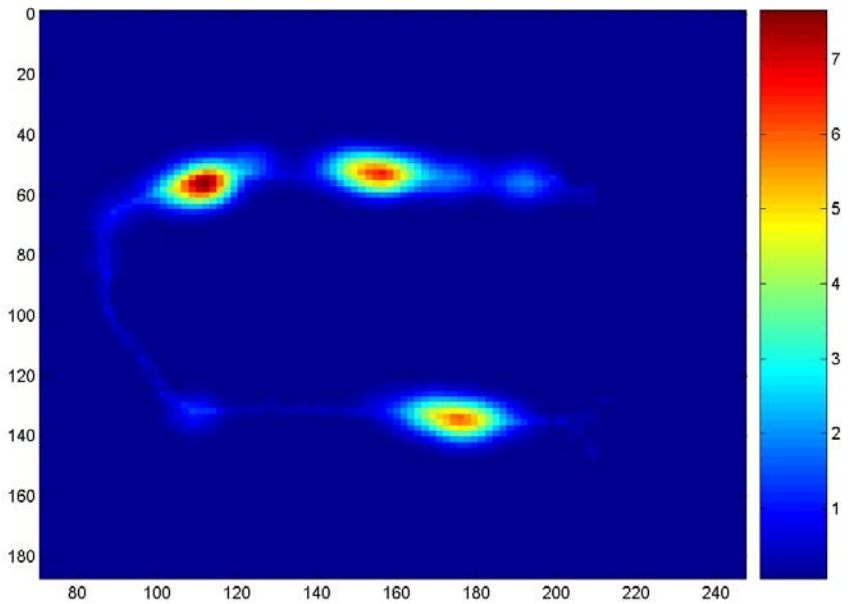
Relative order of the place fields is preserved

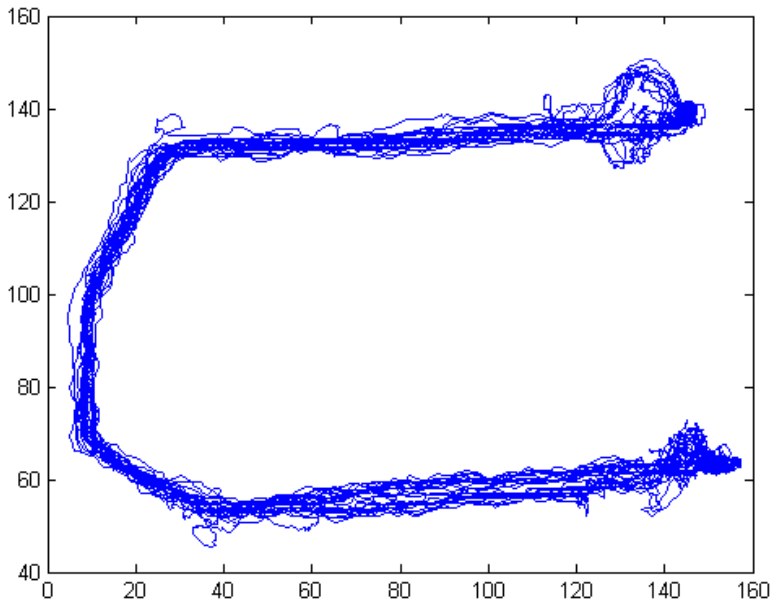


The place field pattern along the track is *invariant* with respect to the track geometry transformations

Relative order of the place fields is preserved

run 1





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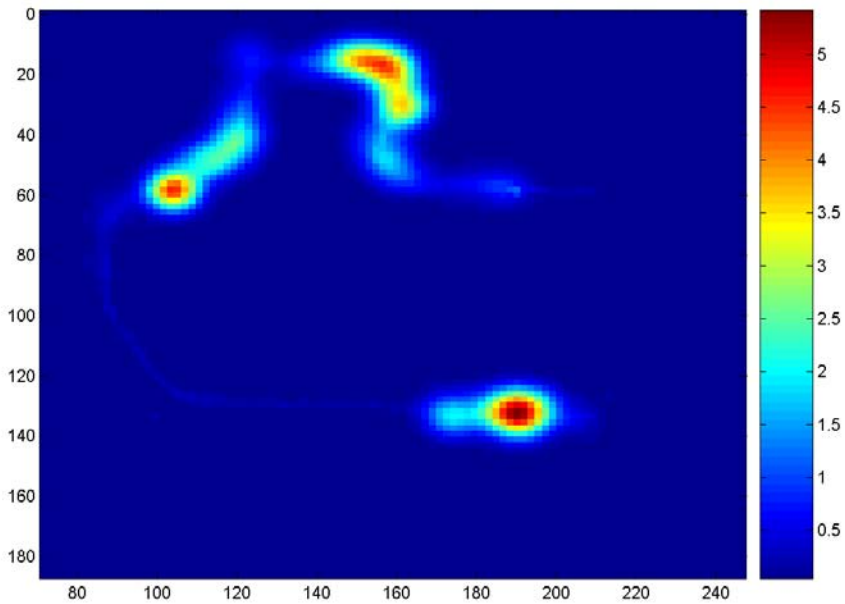
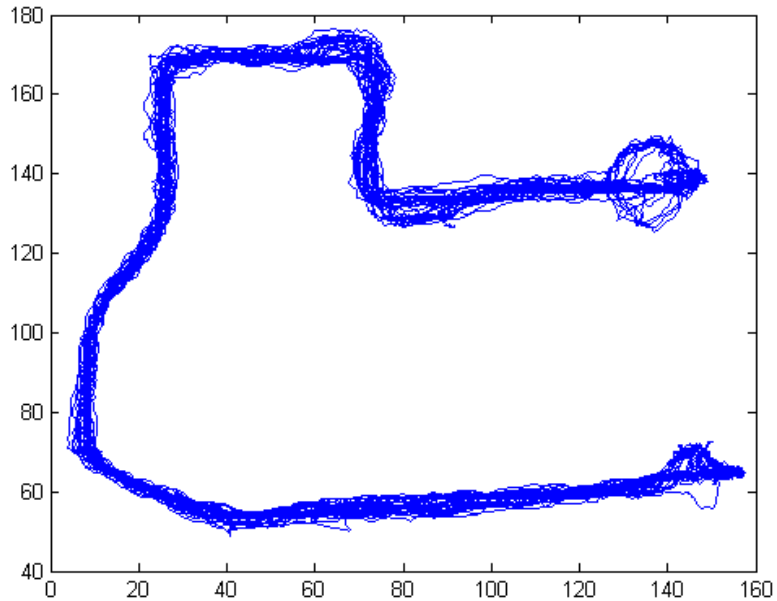
run 2





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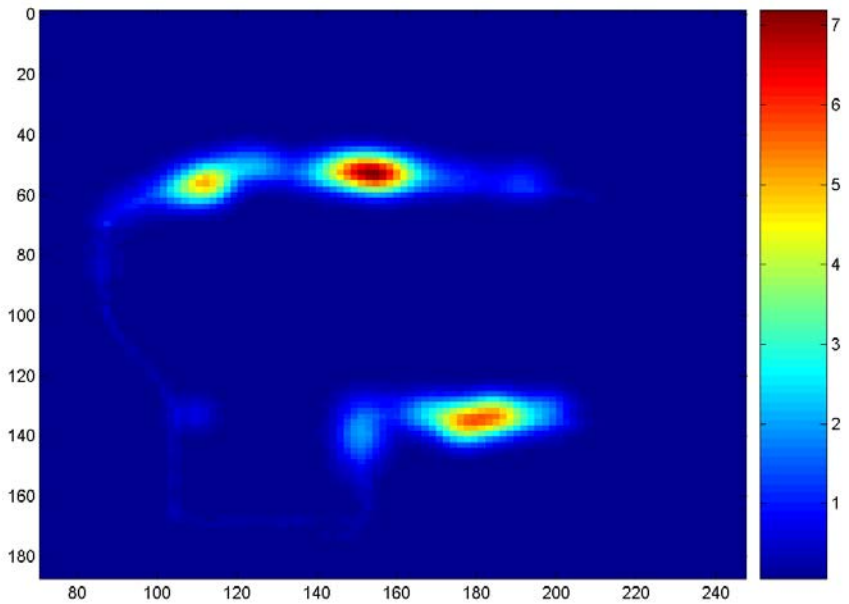
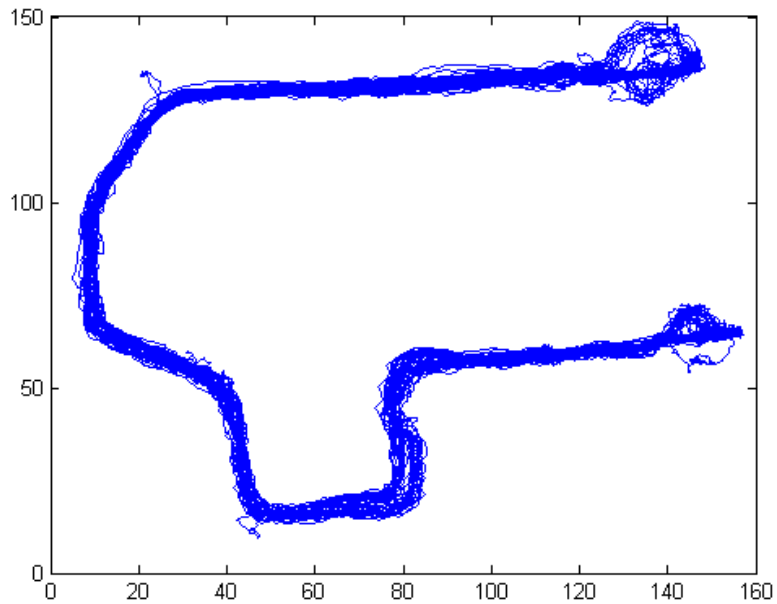
run 3





Hippocampal code seems to represent the relative "order of places", – the topology of the space

Ordered places → topological spaces

- The analysis of ordered activity of the hippocampal cells allows to reconstruct both the *global* and the *local* topology of the space

•*Further development:* it is possible to *build a space*, as a mathematical object, given the semantics of the hippocampal system

- *Theoretical framework – Pointfree Topology*
  - *Formal Topology*; *Region Connection Calculus* (RCC)
  - *Spatial "primitives" are regions (not points!) defined via the observables – spikes and spike trains*
  - *The task is to build the appropriate "proximity structure" on them*

- *Result: a set of ordered places can be interpreted as a topological space*
  - *place cell activity patterns are sufficient to form a topological space,*
  - by construction this space is *consistent with animal's spatial behavior*

Conclusions

- Topological coding: a way of understanding hippocampal functions

Spatial memory

Episodic memory

Relational learning

Space coding specifics

-- topological arrangements of memory elements

- Based on the hippocampal cell activity analysis it is possible to:
  - *identify* the topological characteristics of the environment
  - *build a pointfree topological space* based on spike patterns
    - By construction this space is *consistent with animal's spatial behavior*
    - We speculate that this space provides *a framework for cognitive spatial representation and spatial reasoning*

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