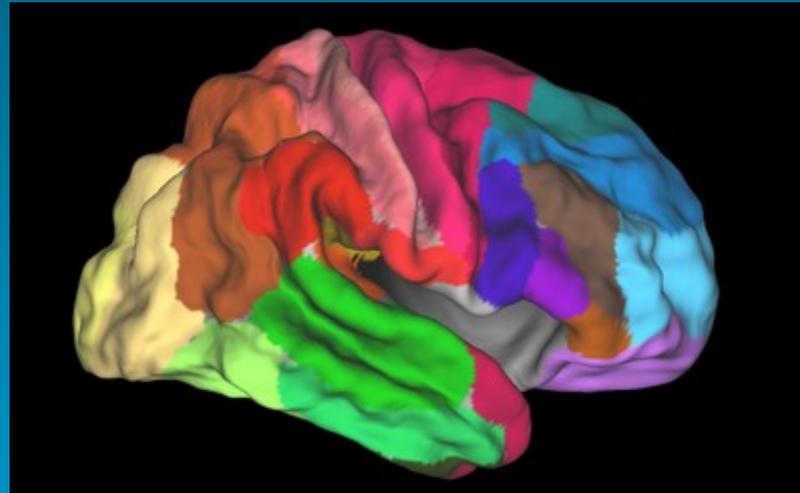




SISSA



limbo



J Stefan Institute, Ljubljana

January 29, 2014

Alessandro Treves



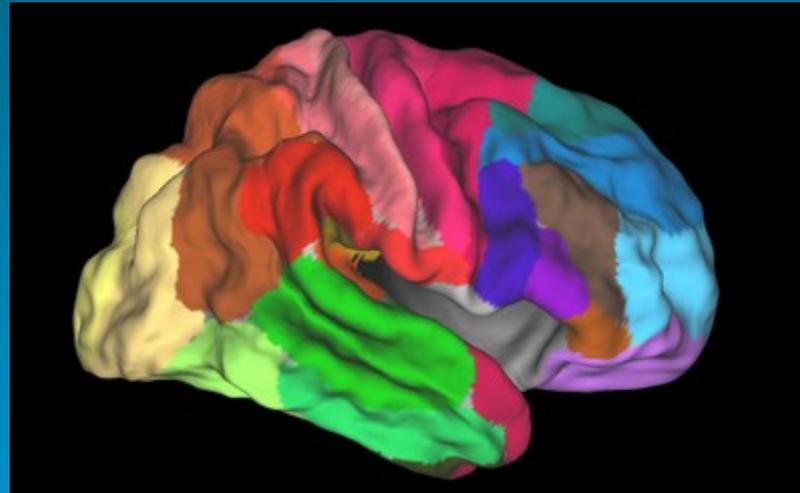
SISSA

# SPACEBRAIN

where in our inner space,  
among its **multiple** areas,  
do we construct our internal  
representations of outer space?



limbo

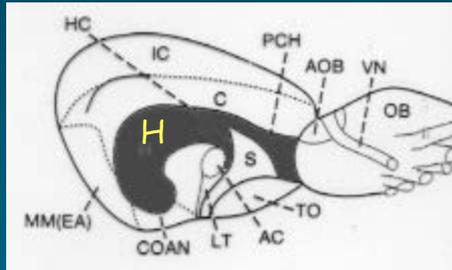


J Stefan Institute, Ljubljana

January 29, 2014

Alessandro Treves

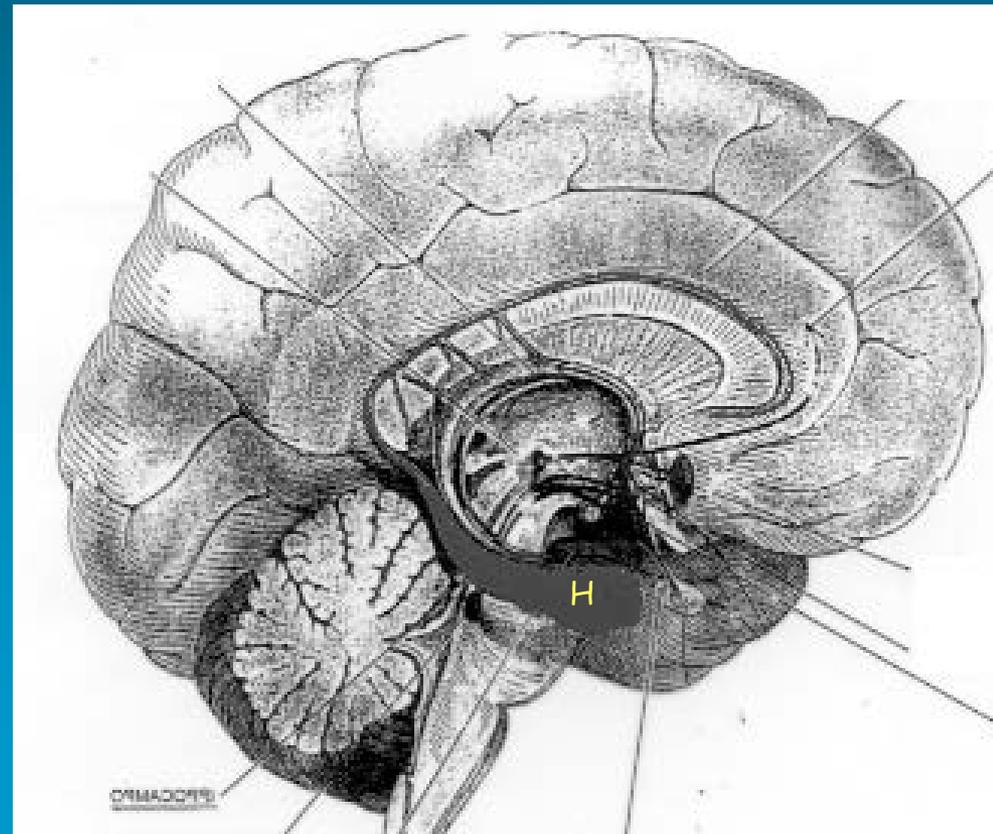
# THE HIPPOCAMPUS



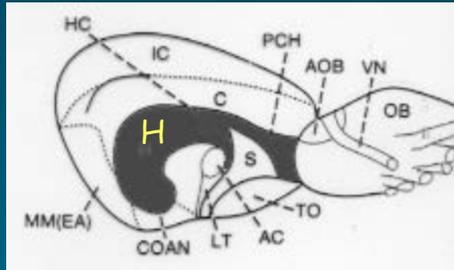
opossum

a structure which remains stable and self-similar across mammalian species

human



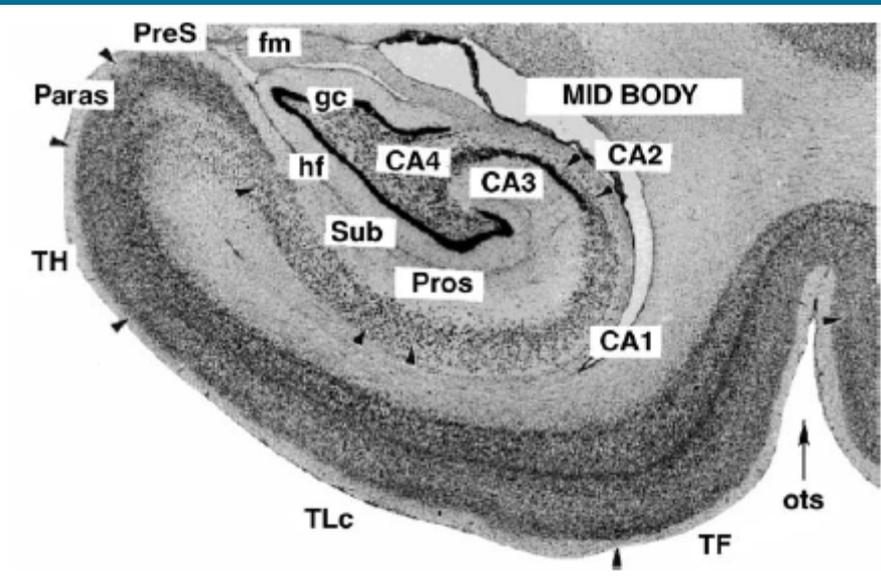
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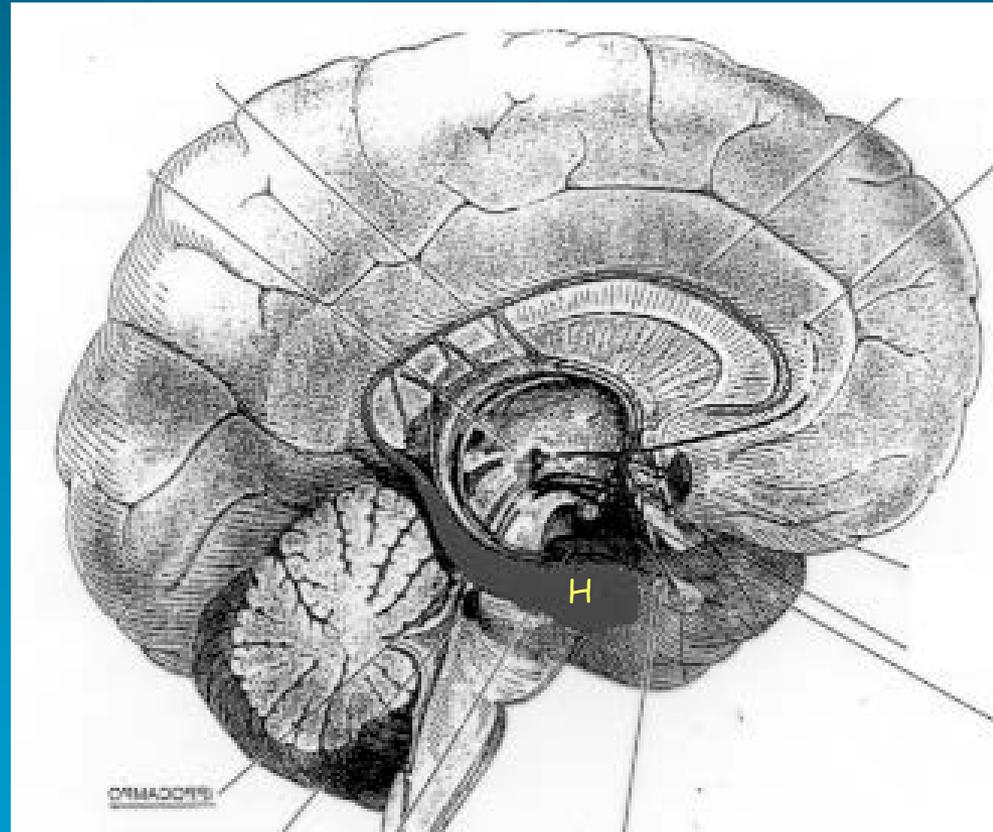
opossum

a structure which remains stable and self-similar across mammalian species

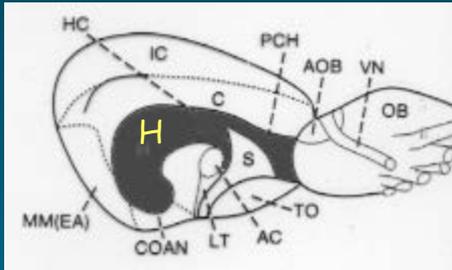
human



monkey



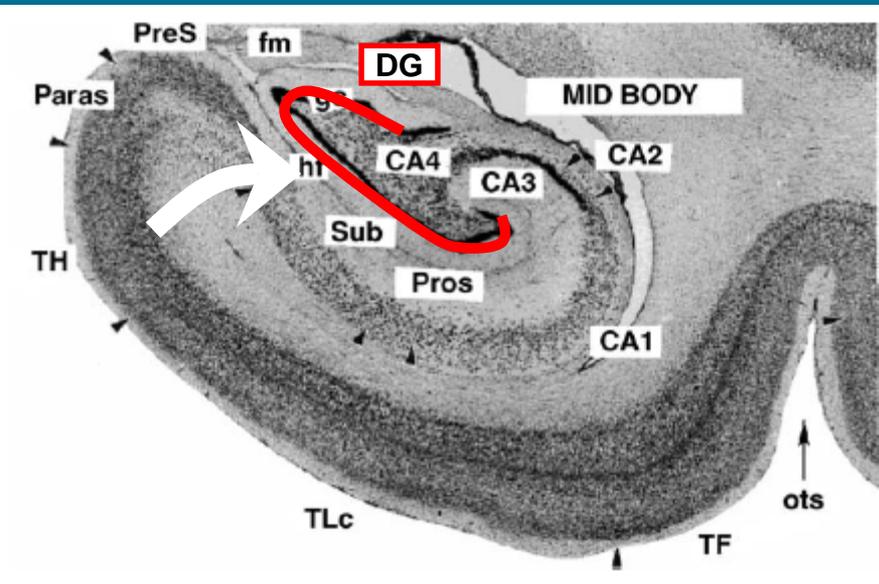
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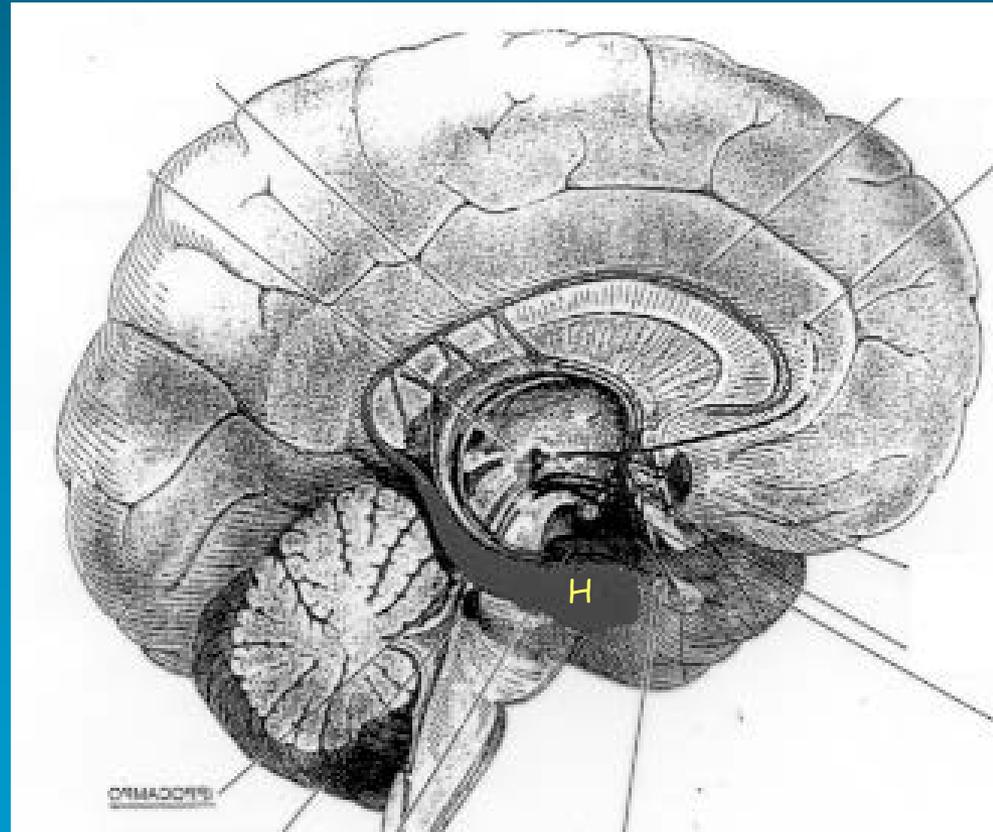
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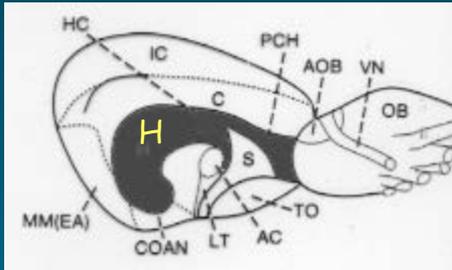
human



monkey



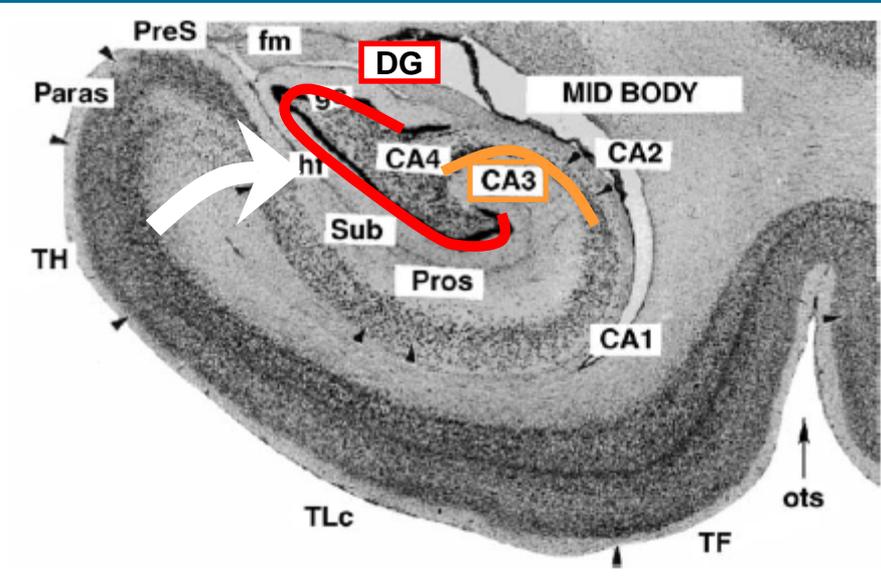
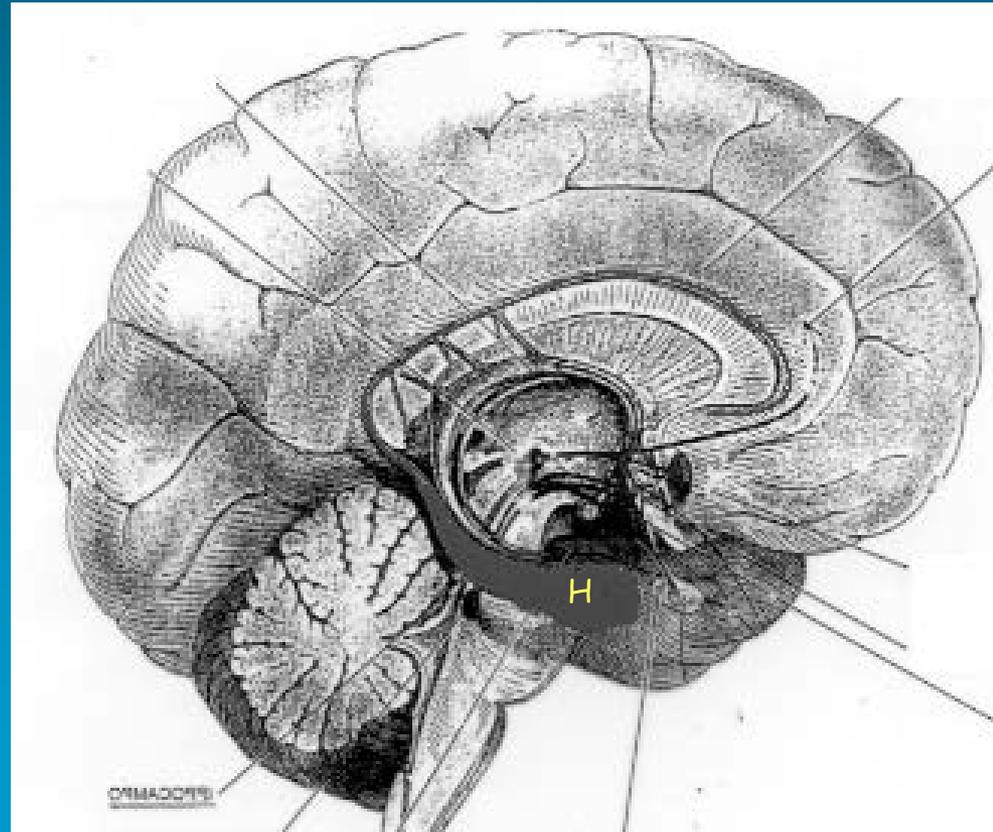
# THE HIPPOCAMPUS



opossum

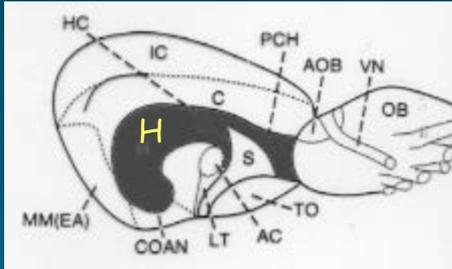
a structure which remains stable and self-similar across mammalian species

human



monkey

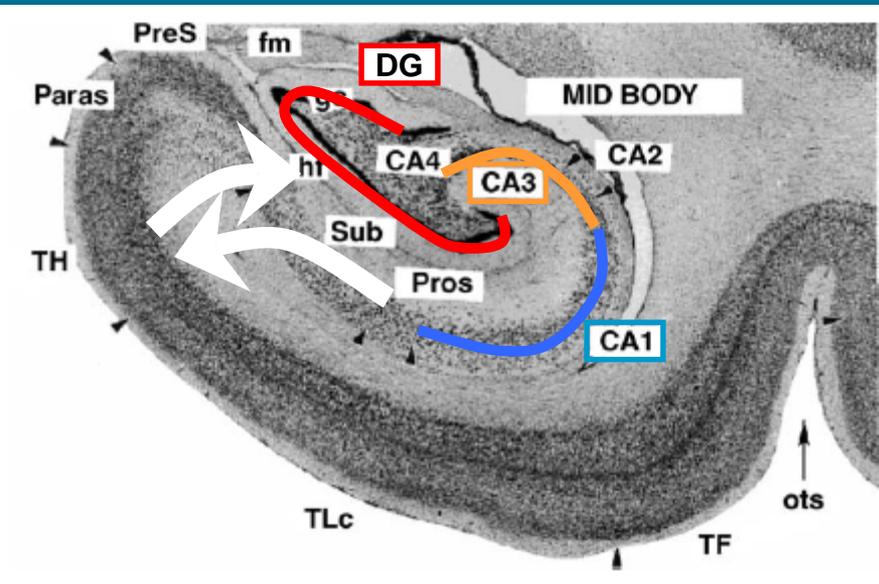
# THE HIPPOCAMPUS



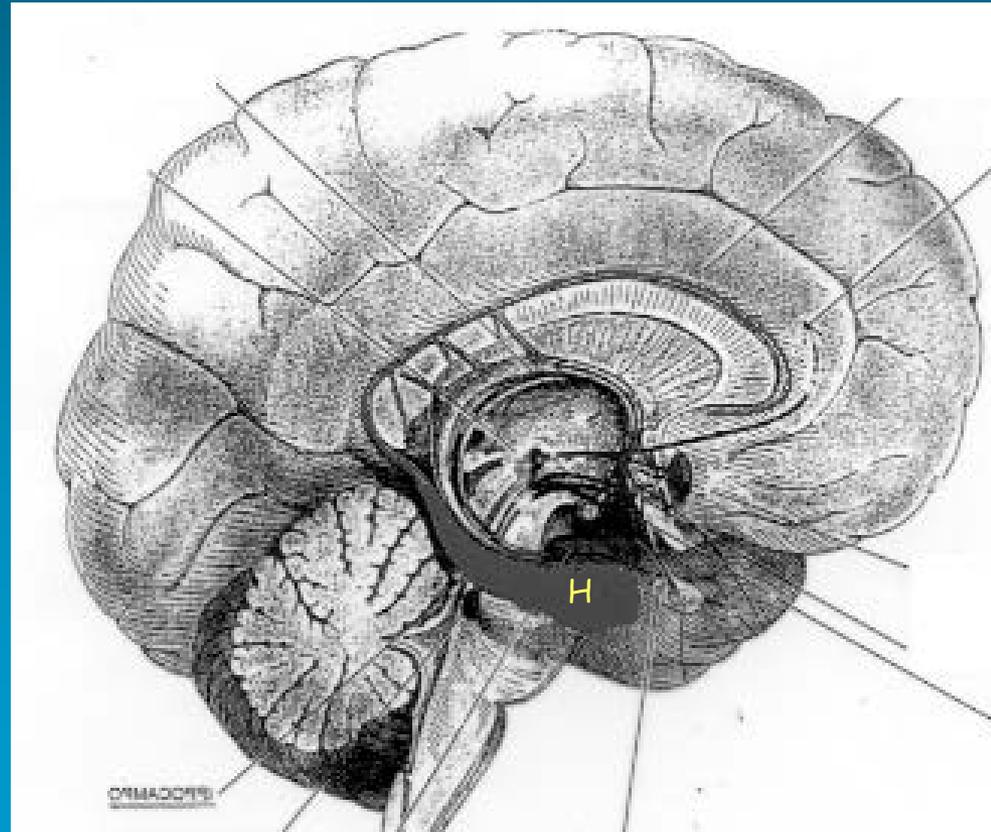
opossum

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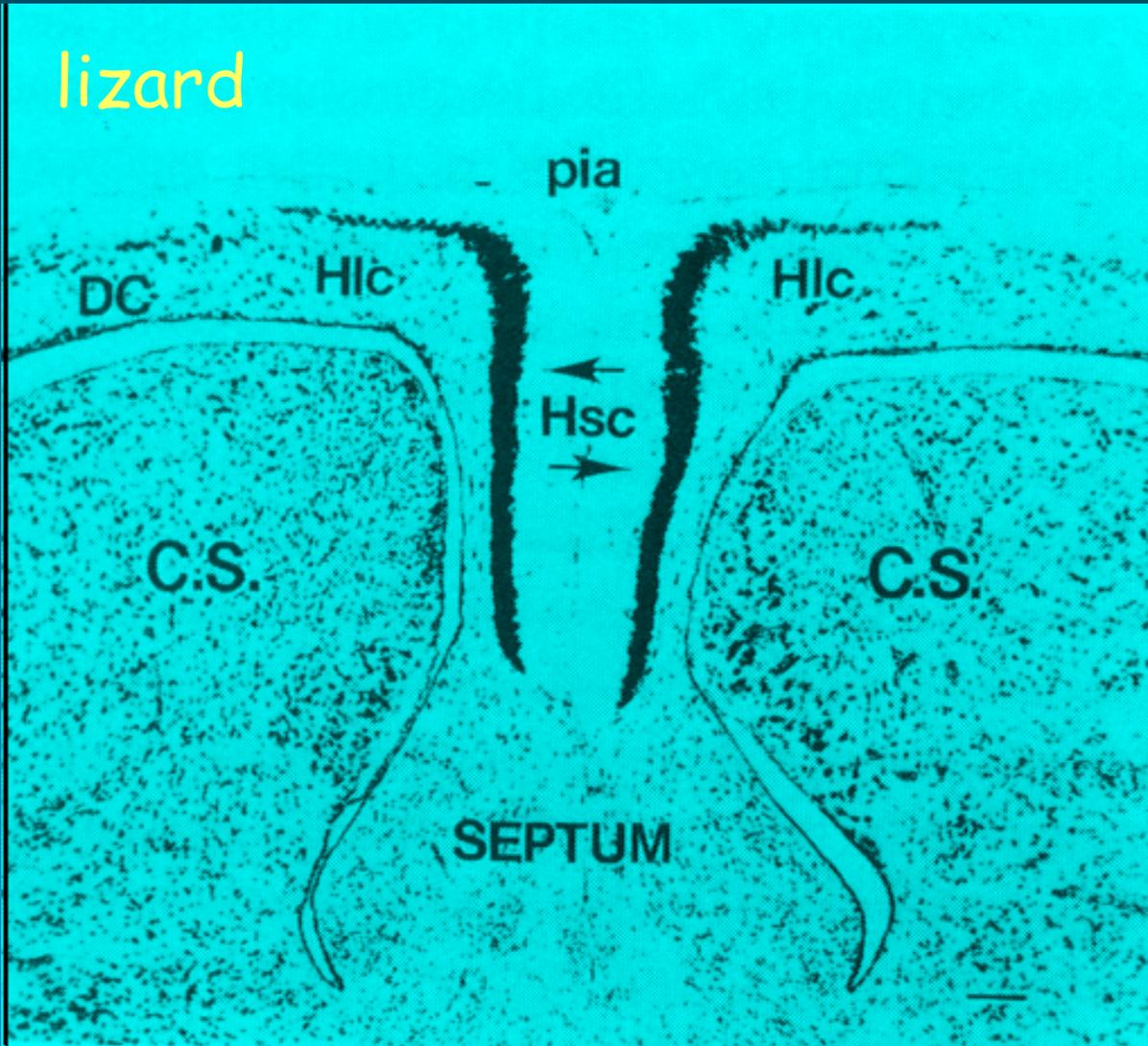


monkey

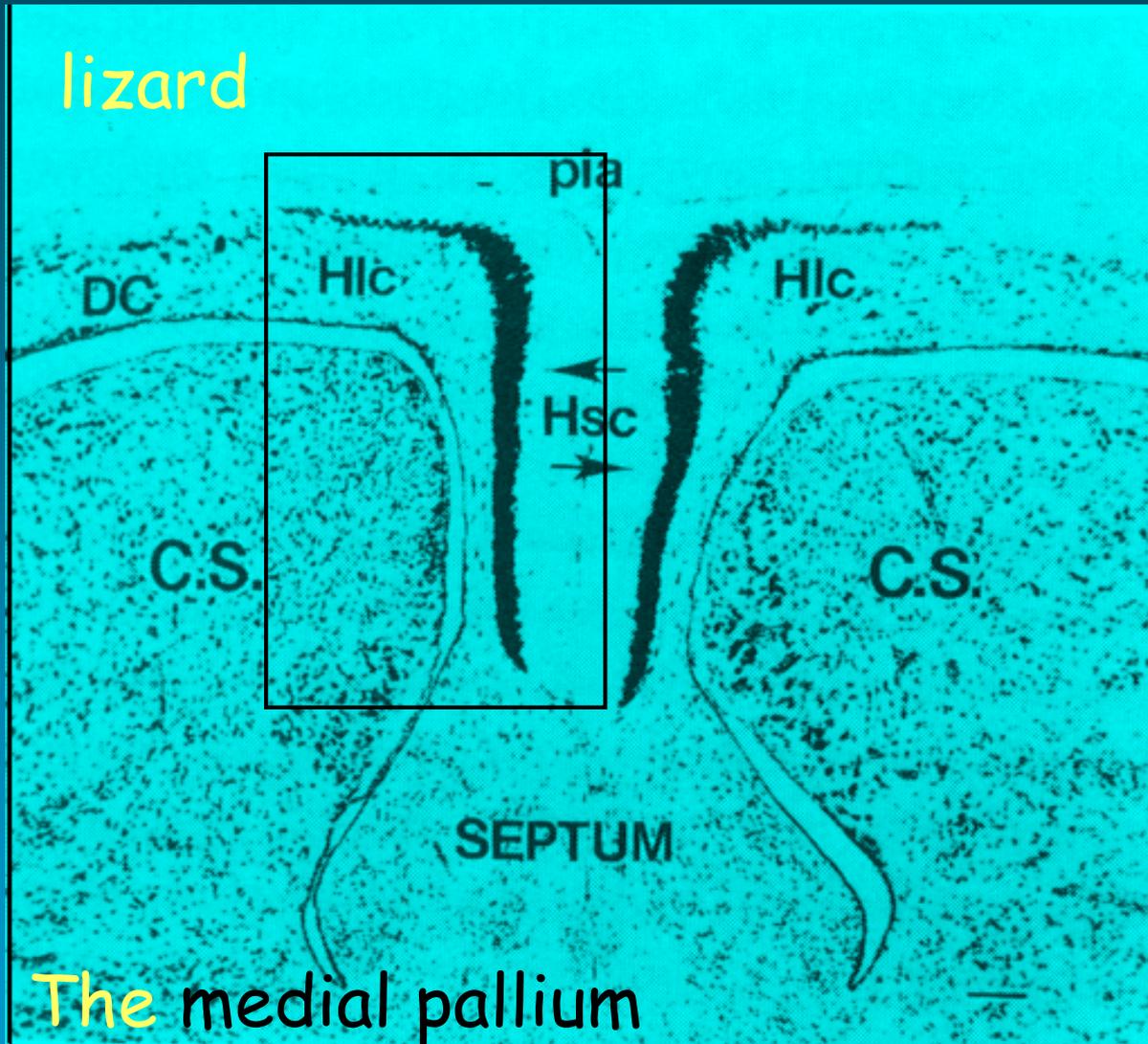


but... has it always been like that?

lizard



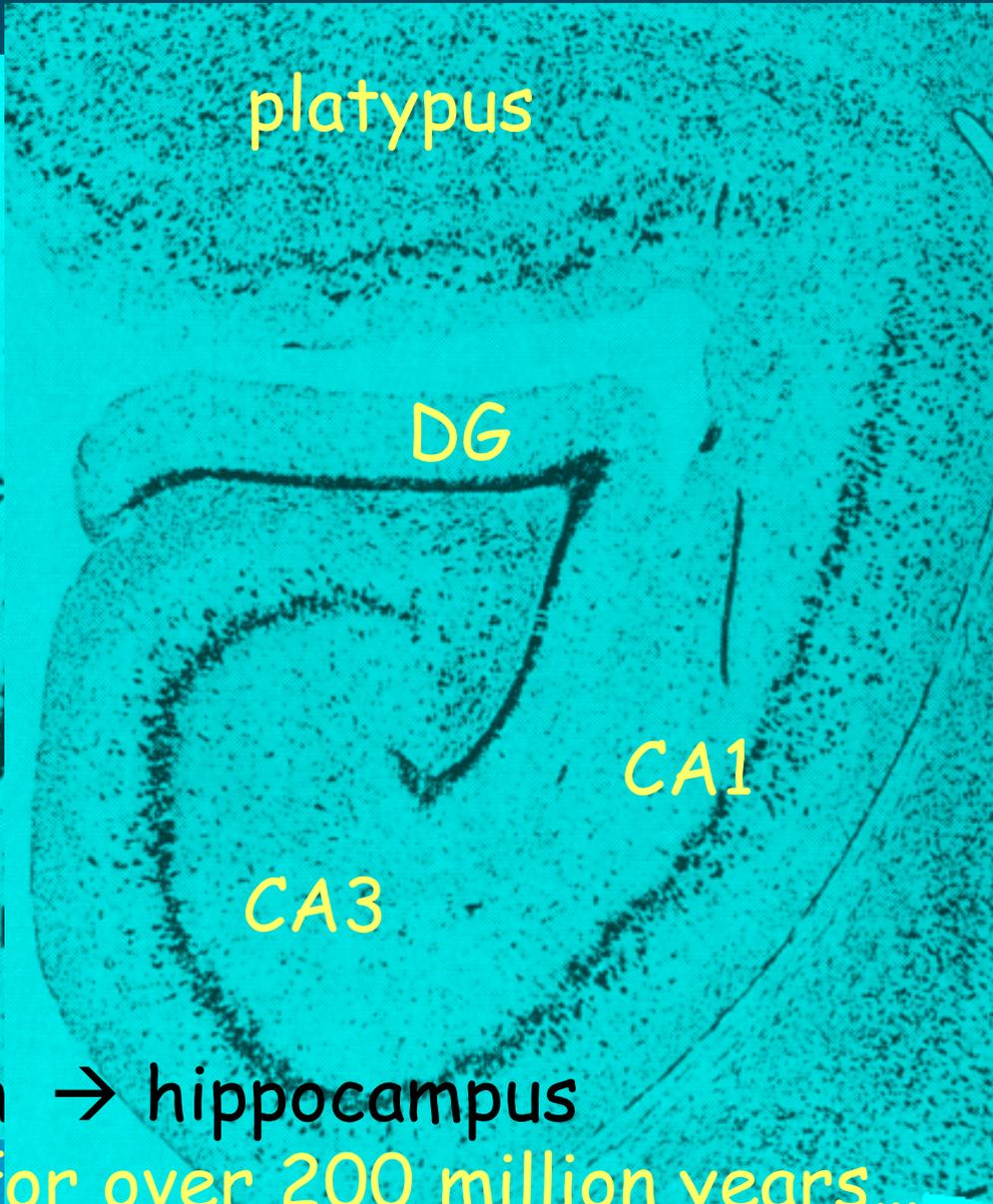
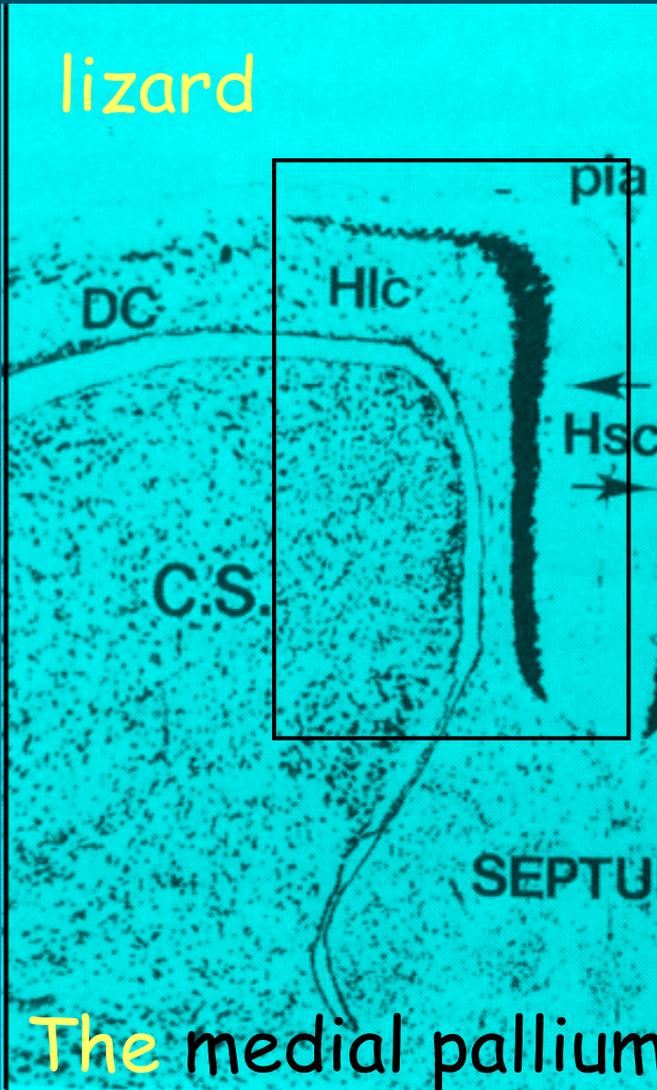
but... has it always been like that?



The medial pallium

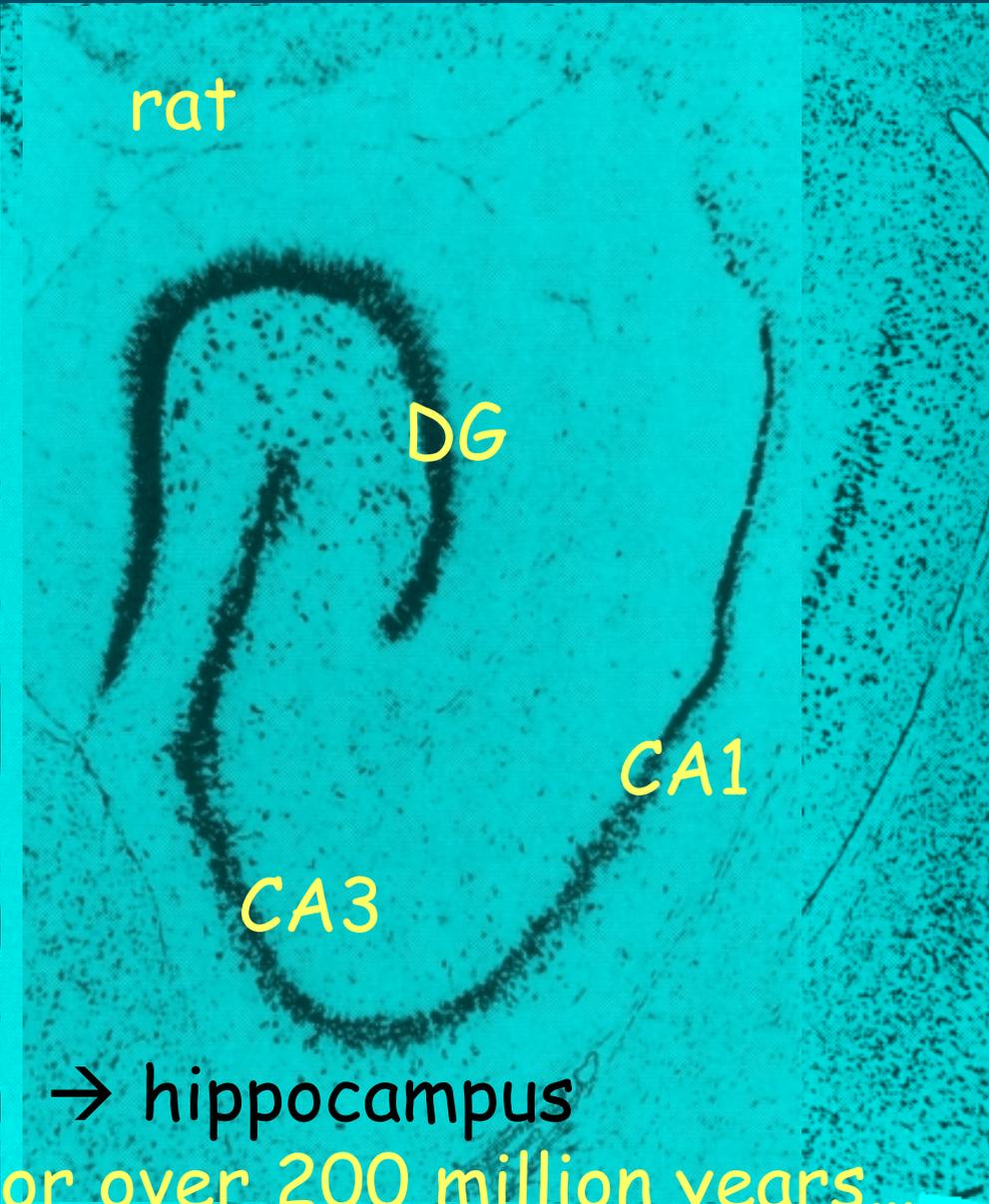
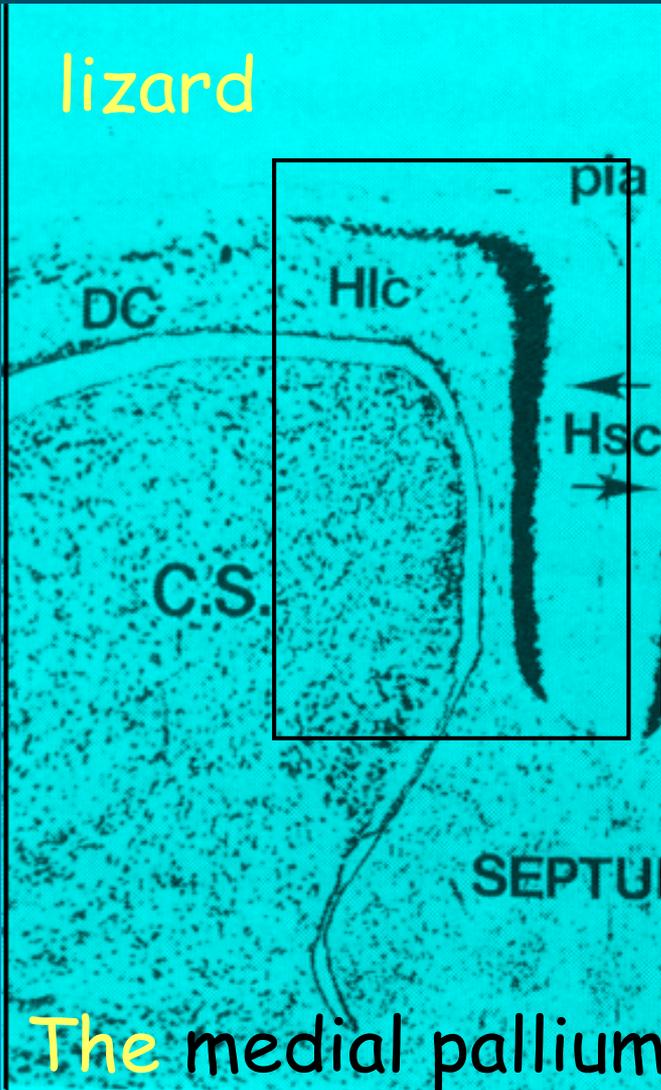
has been with us for over 300 million years...

but... has it always been like that?



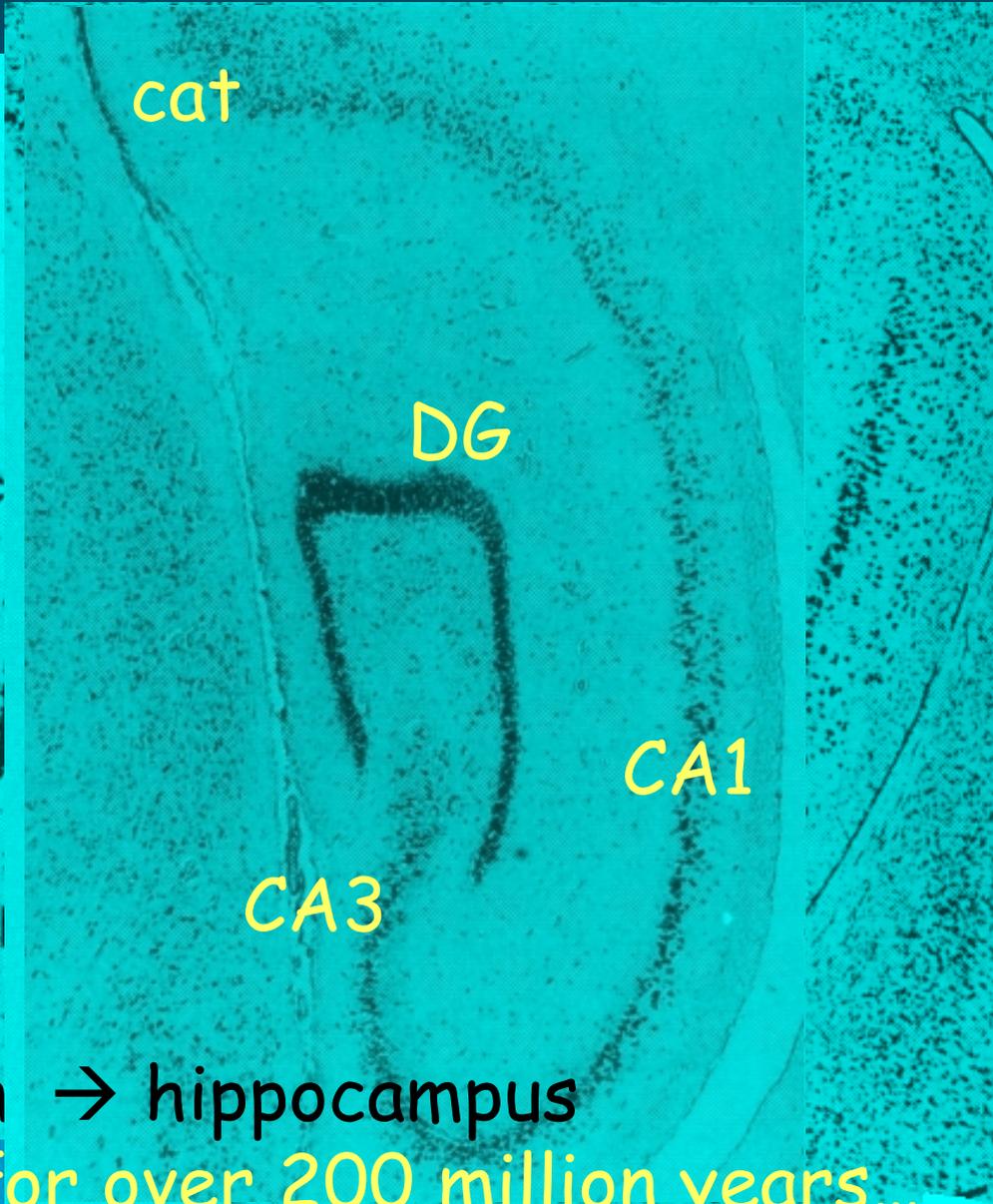
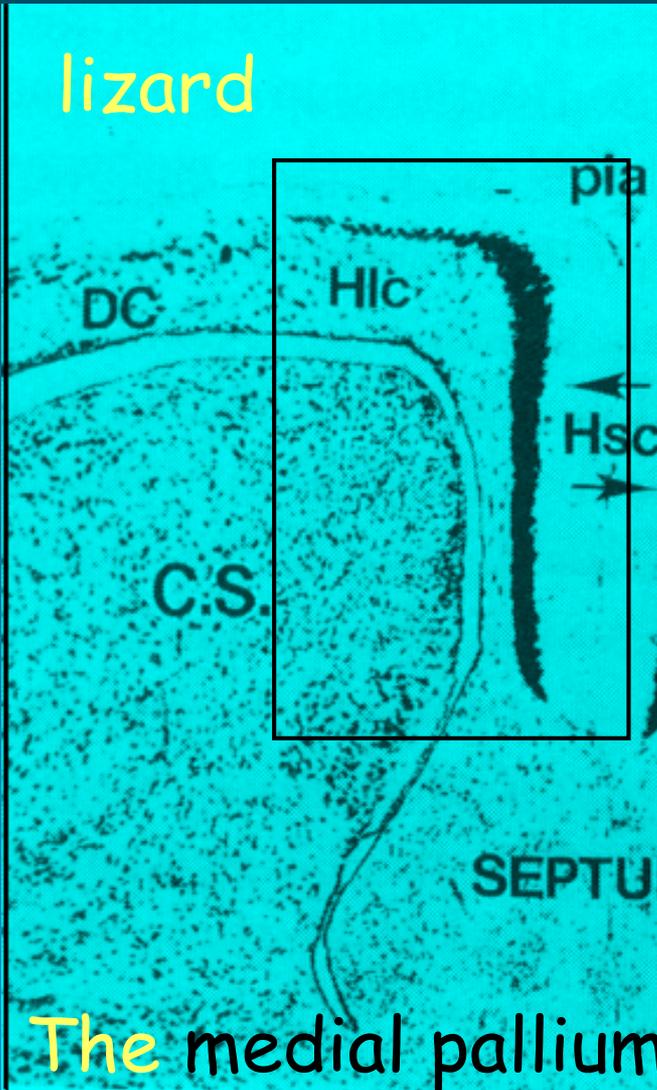
The medial pallium → hippocampus  
has been with us for over 200 million years...

but... has it always been like that?



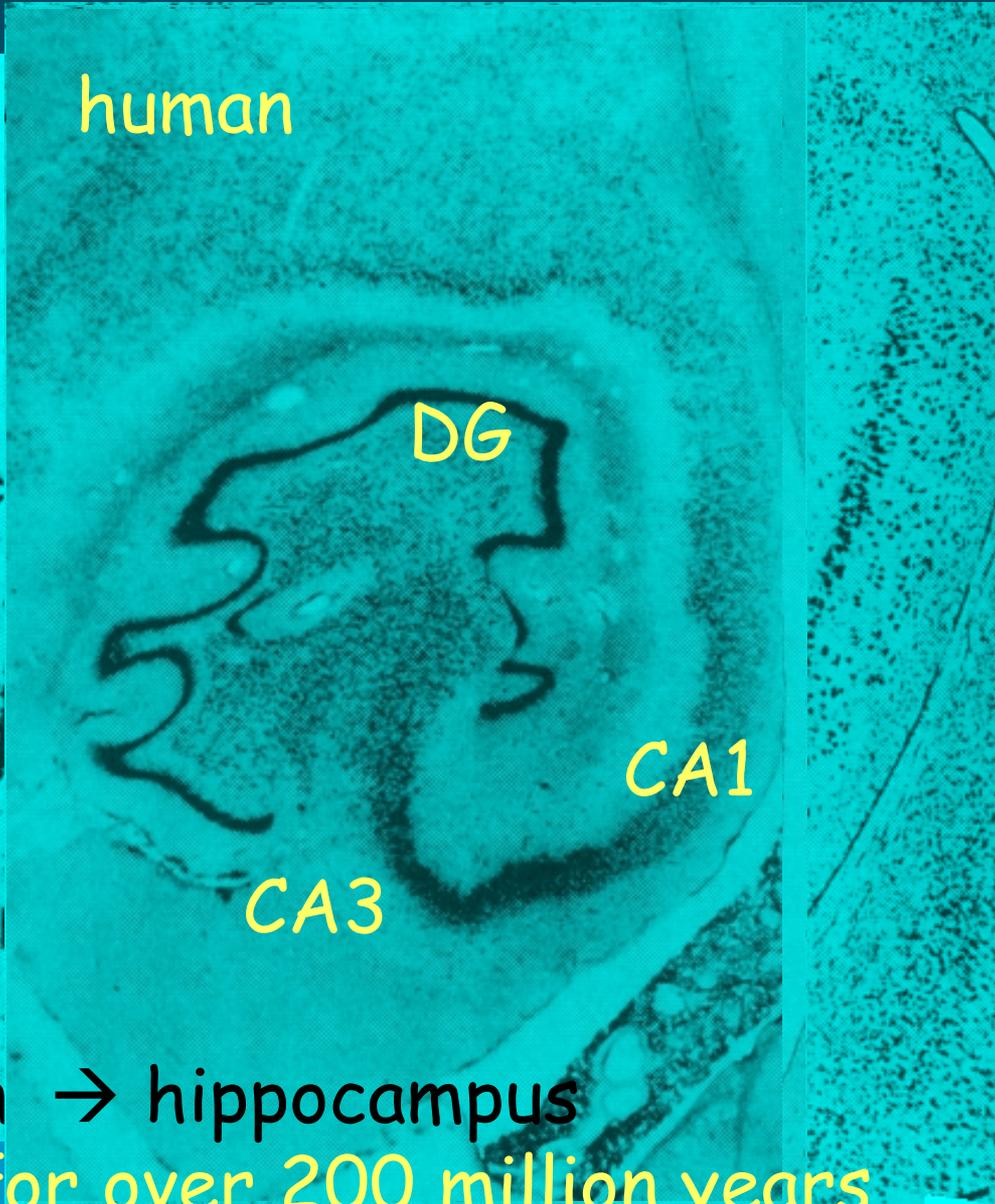
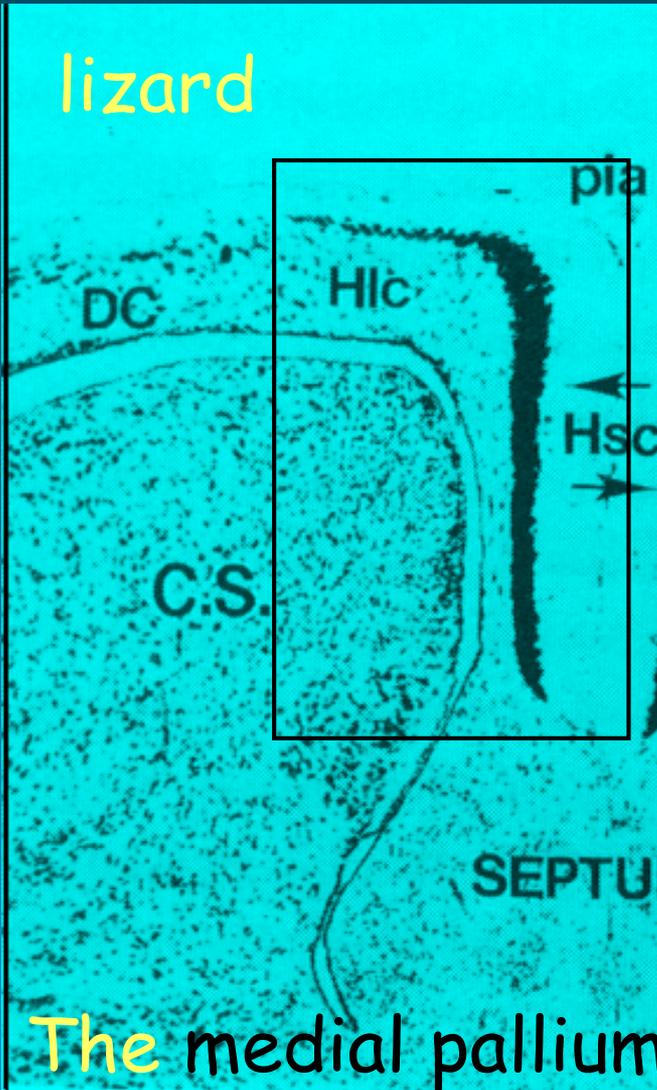
The medial pallium → hippocampus  
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but... has it always been like that?



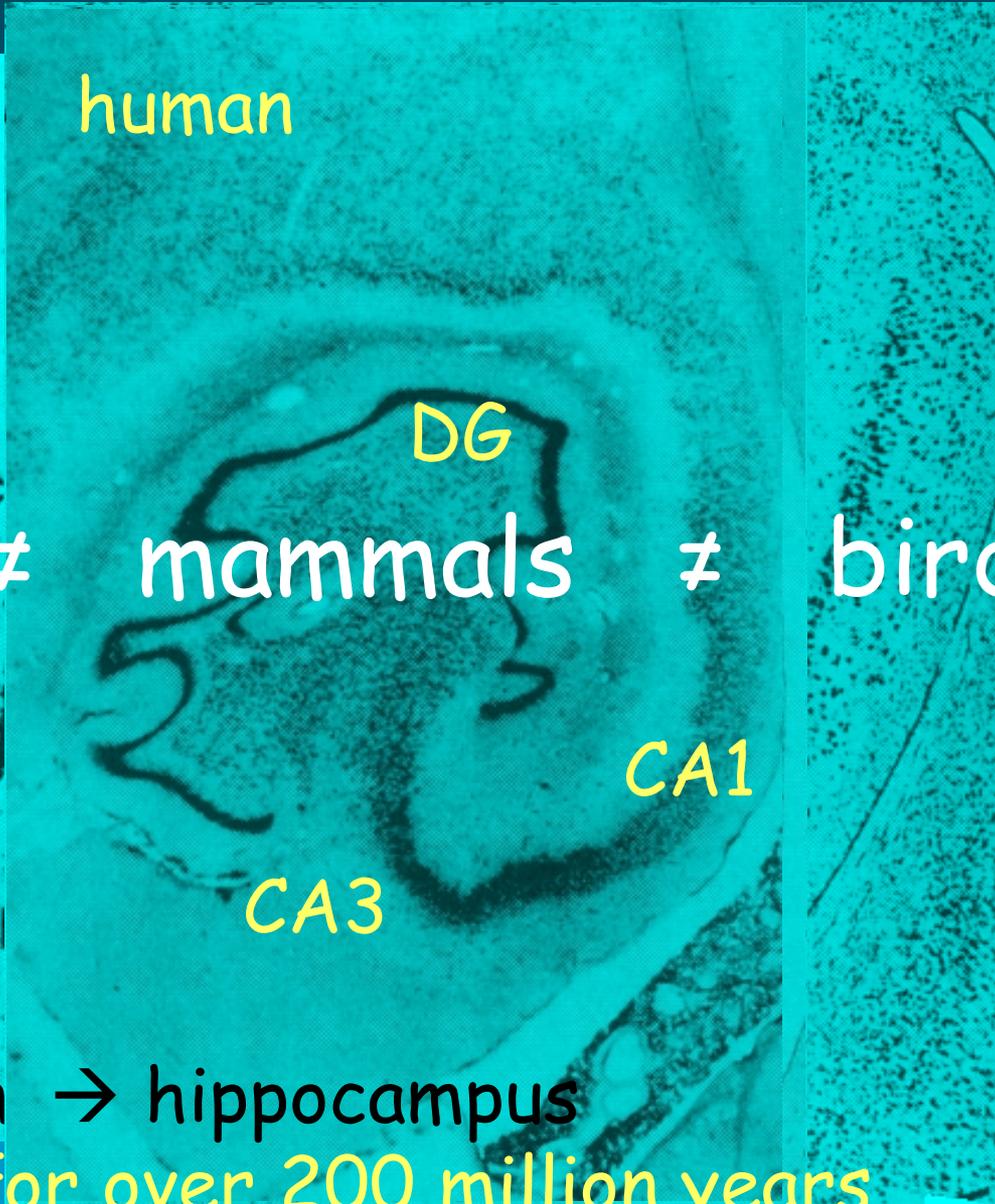
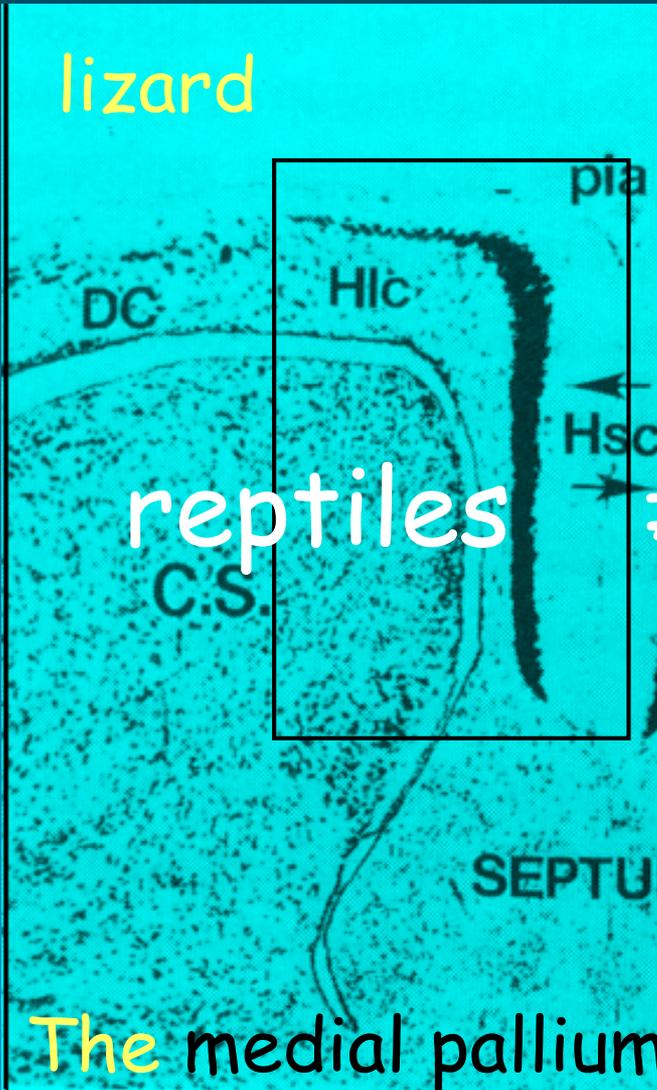
The medial pallium → hippocampus  
has been with us for over 200 million years...

but... has it always been like that?



The medial pallium → hippocampus  
has been with us for over 200 million years...

but... has it always been like that?



reptiles ≠ mammals ≠ birds

The medial pallium → hippocampus  
has been with us for over 200 million years...

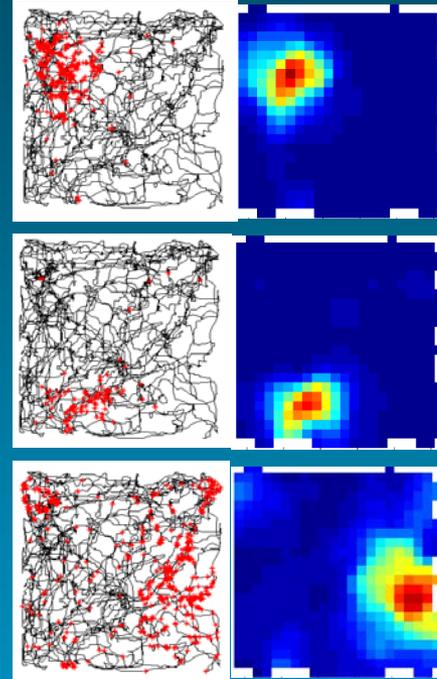
Is the hippocampus what we use to navigate?



# Is the hippocampus what we use to navigate?



John O'Keefe  
1971  
Univ Coll London  
SPACEBRAIN



place  
cells!

# Is the hippocampus what we use to navigate?

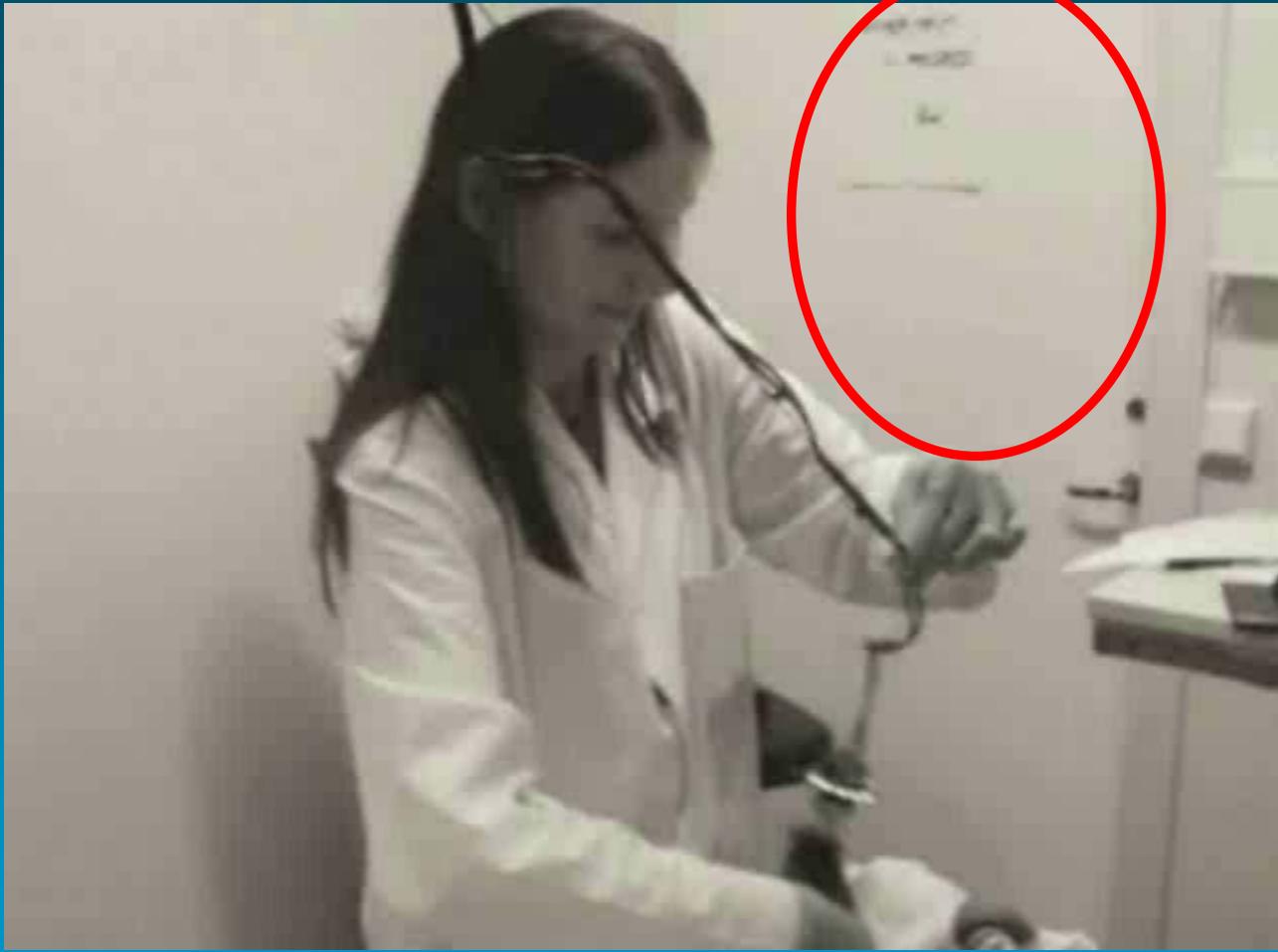


...or is it used to recollect from the past salient episodes of our lives?

# Laura and a rat



# Laura and a rat



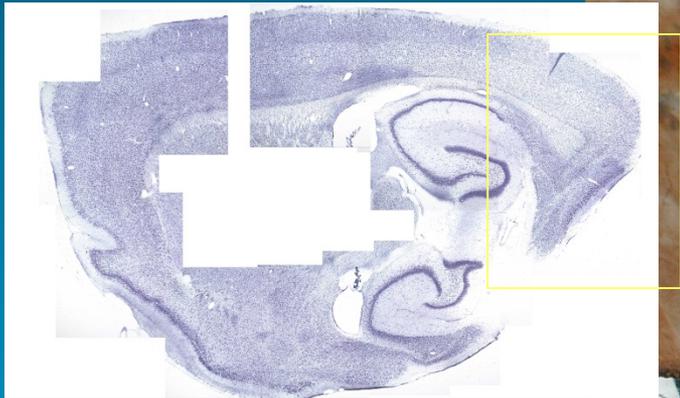
Place cells

# Neurophysiology

Edvard & May-Britt Moser  
Centre for the Biology of Memory  
NTNU, Trondheim, Norway

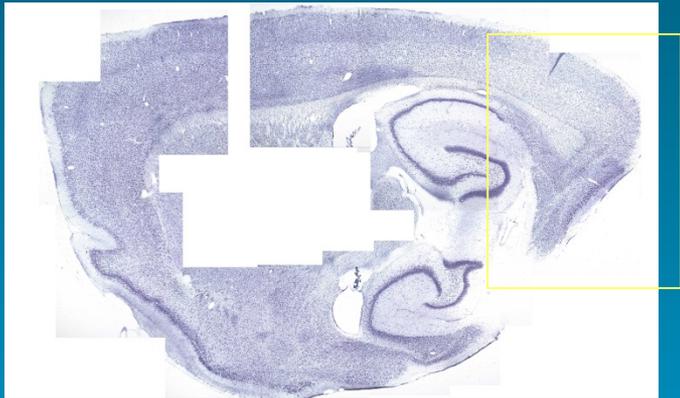


# Neurophysiology + Neuroanatomy



Marianne Fyhn  
in the Mosers' lab  
with Menno Witter  
(Science, 2004)

# Neurophysiology + Neuroanatomy

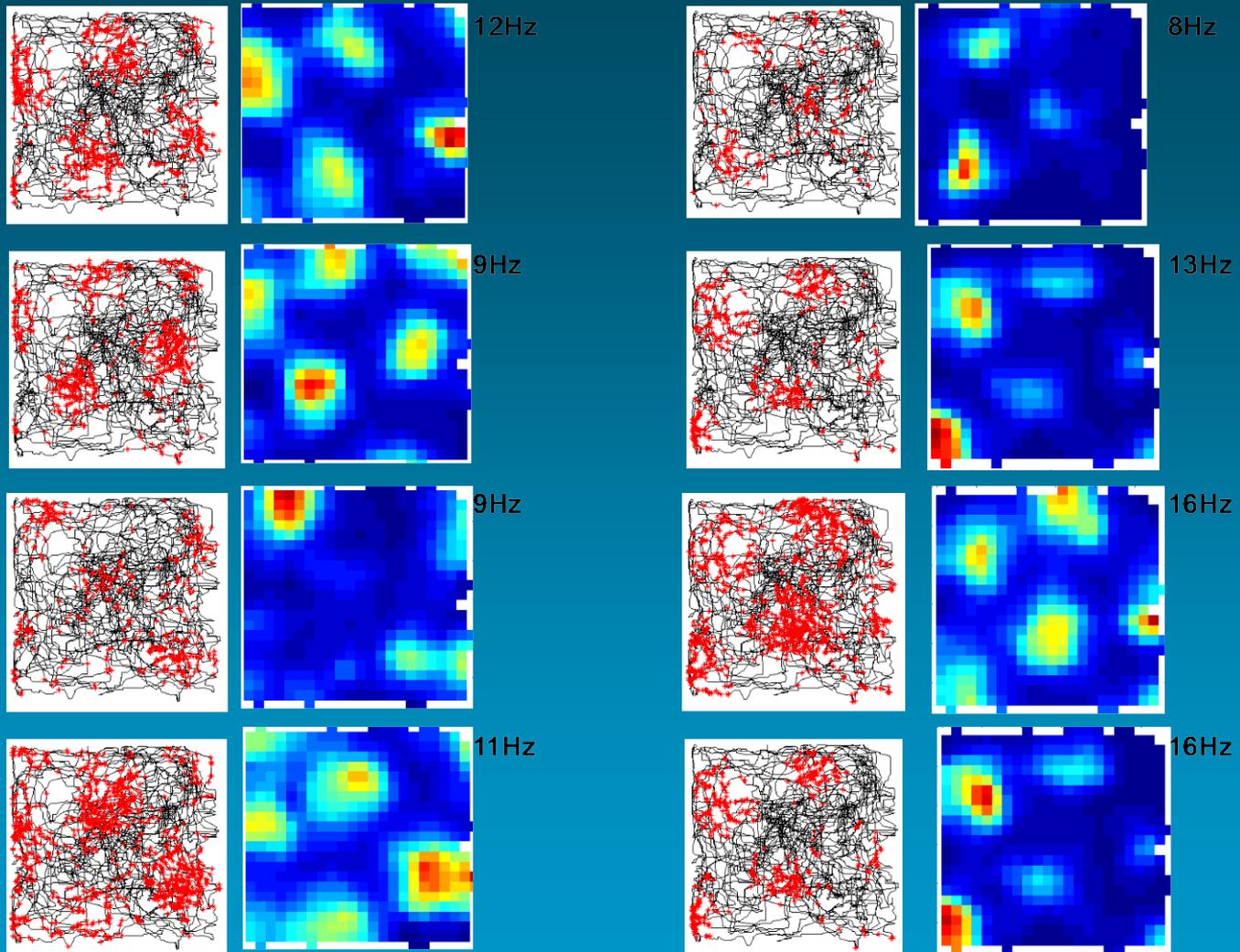


Marianne Fyhn  
in the Mosers' lab  
with Menno Witter  
(Science, 2004)



Electrodes  
were placed in  
layers II and  
III of caudal  
medial  
entorhinal  
cortex (which  
projects to  
dentate/CA3  
and to CA1,  
respectively)

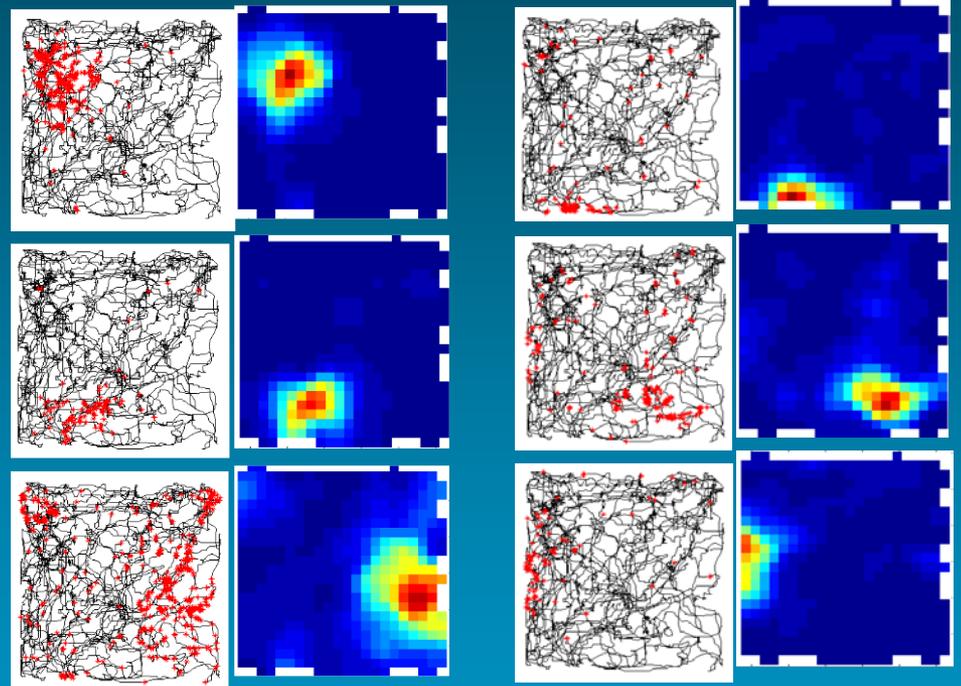
10073\_170103\_04:



Cells in dorsal medial entorhinal cortex have multiple dispersed fields

# Multiple place fields in entorhinal cortex become single fields in CA3

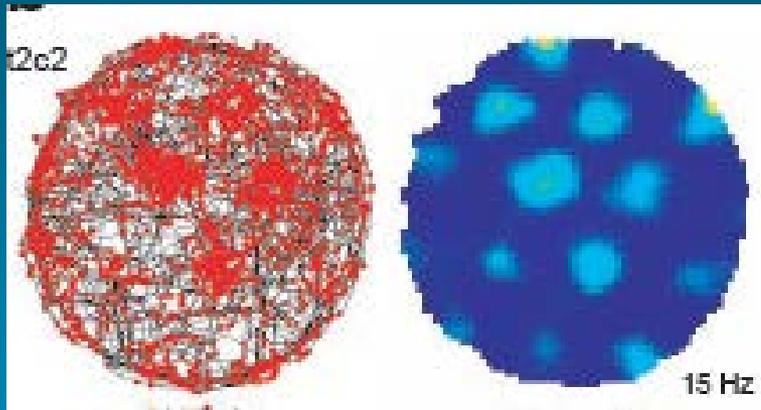
Target location in dorsal CA3



Torkell Hafting  
(with Marianne Fyhn  
et al in the Mosers' lab  
Nature, 2005)

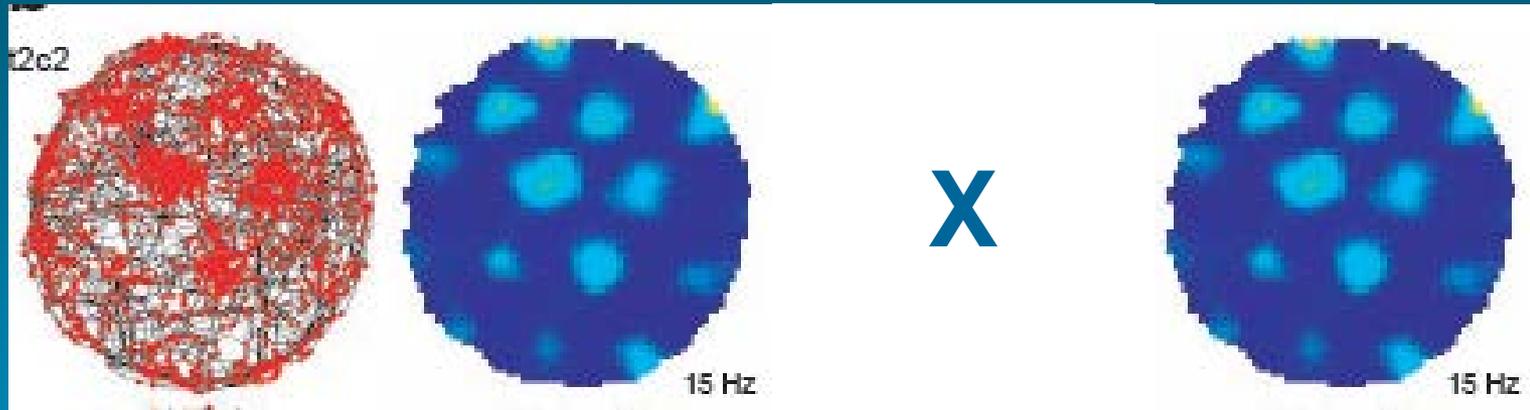
Torkell Hafting  
(with Marianne Fyhn  
et al in the Mosers' lab  
Nature, 2005)

recorded units in a  
larger environment

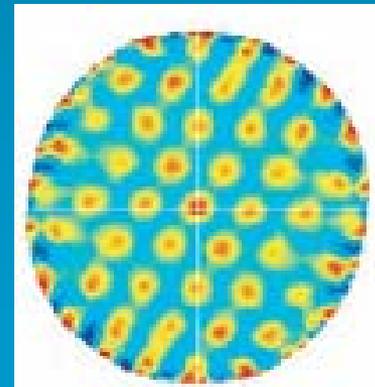


Torkell Hafting  
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Nature, 2005)

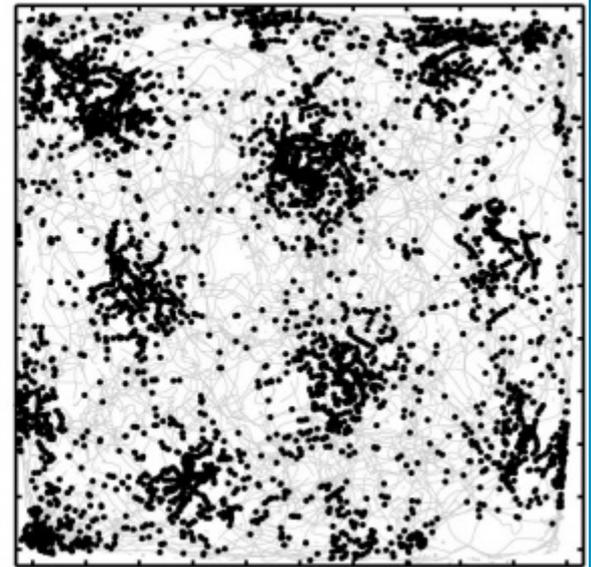
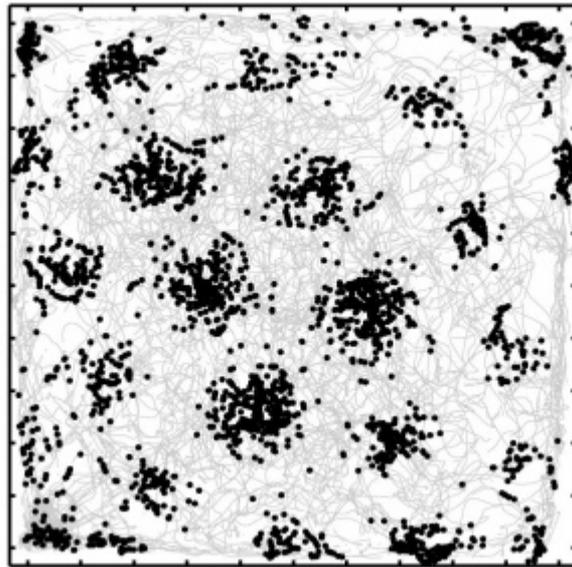
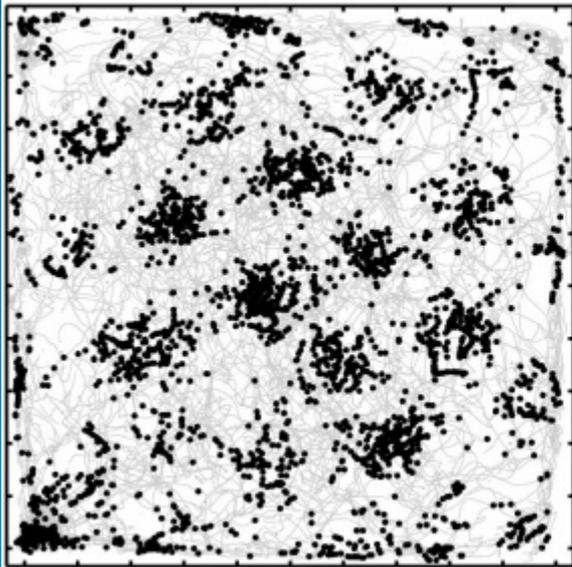
recorded units in a  
larger environment  
and looked at the map  
autocorrelation



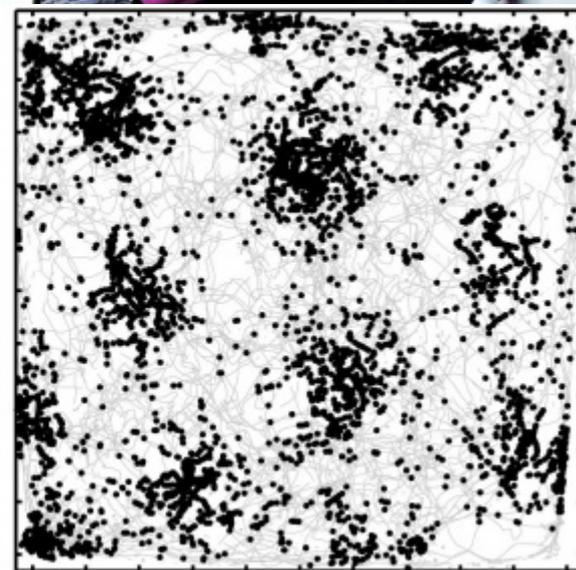
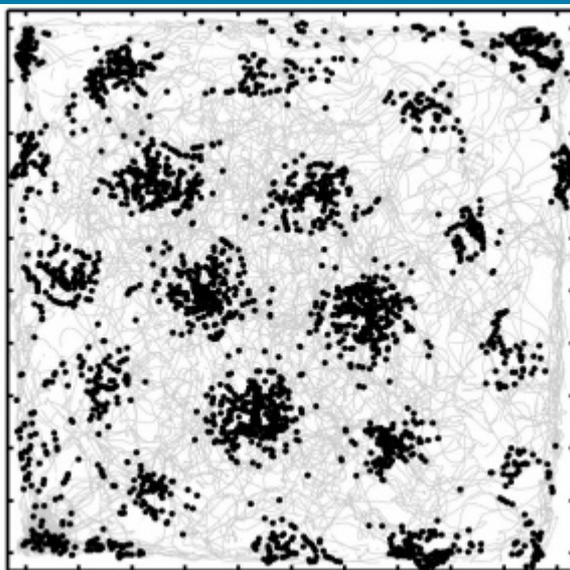
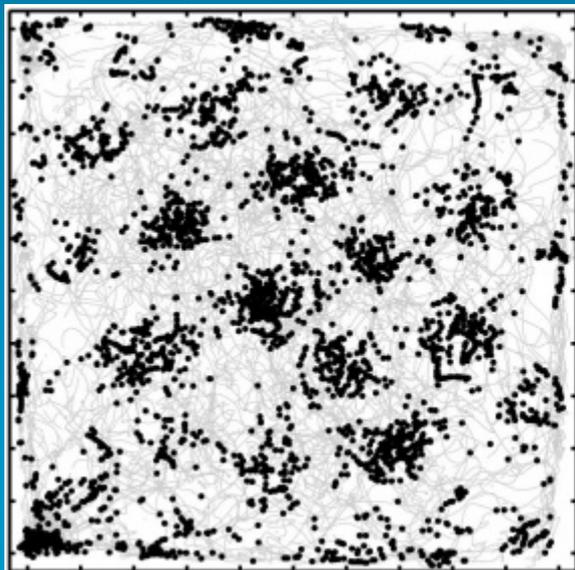
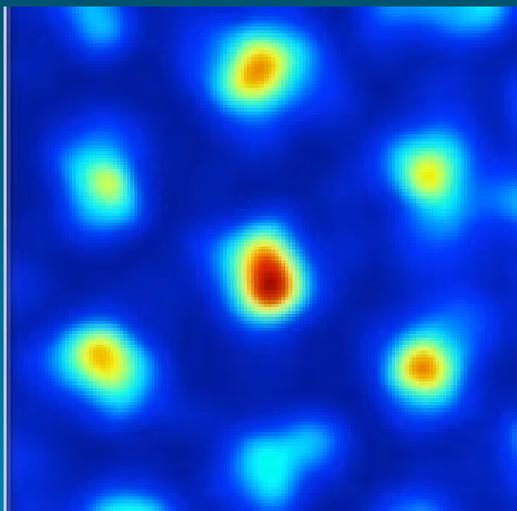
Grid cells !



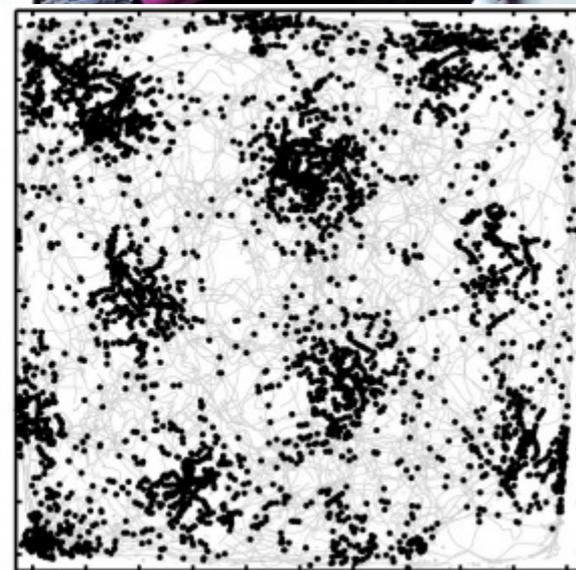
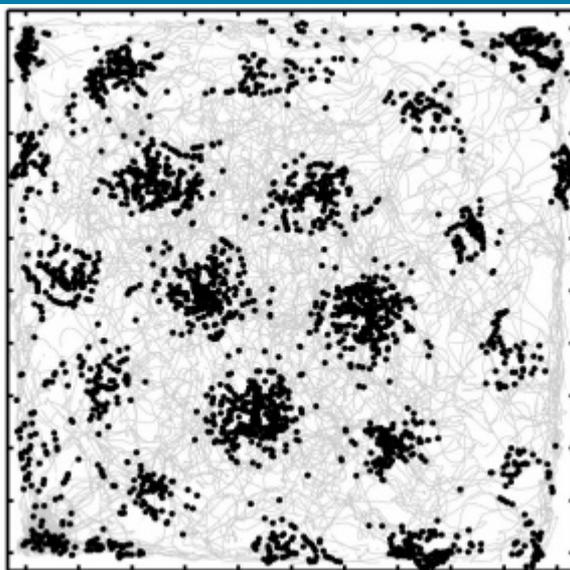
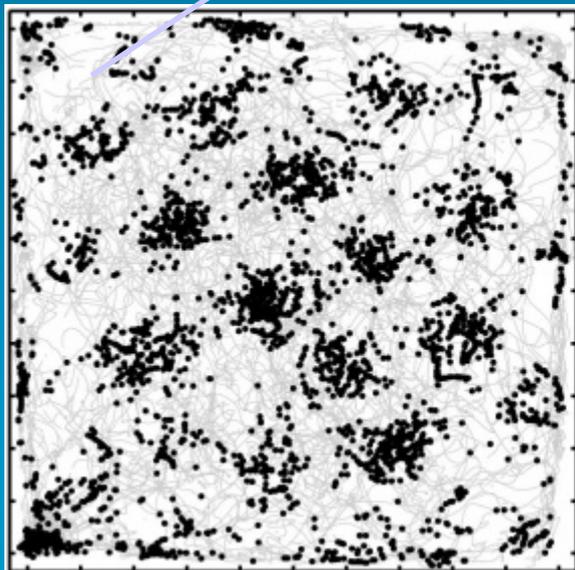
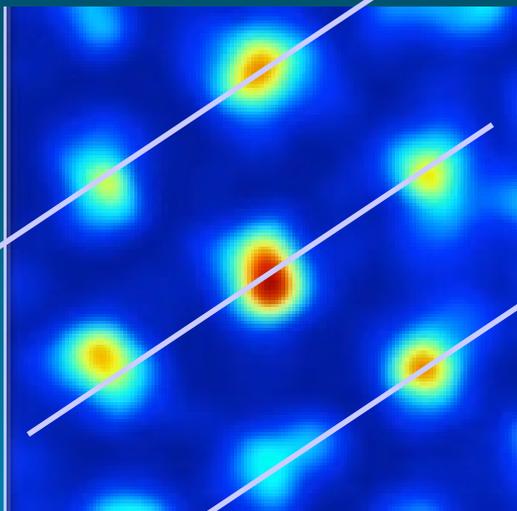
Just look at one grid cell...



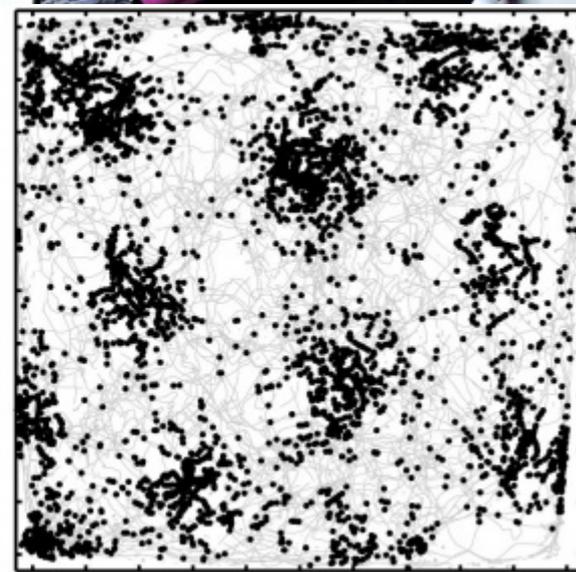
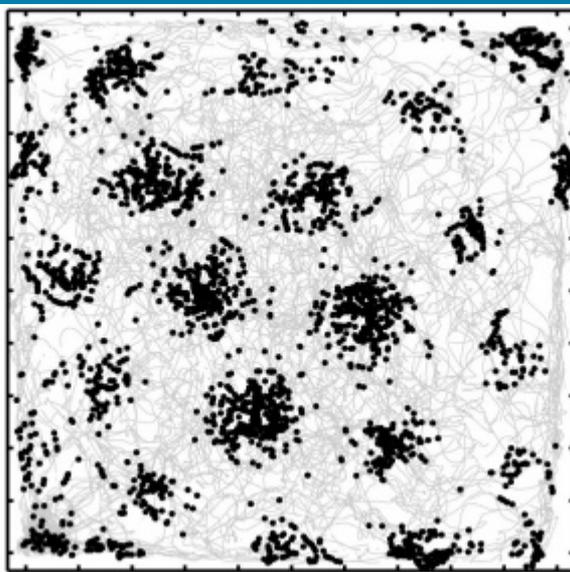
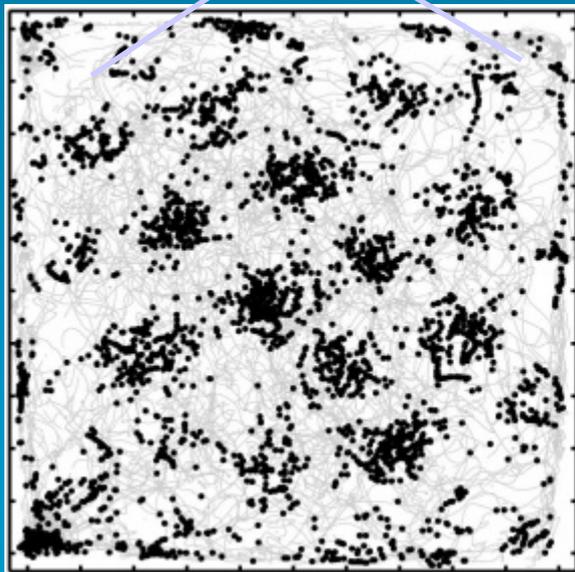
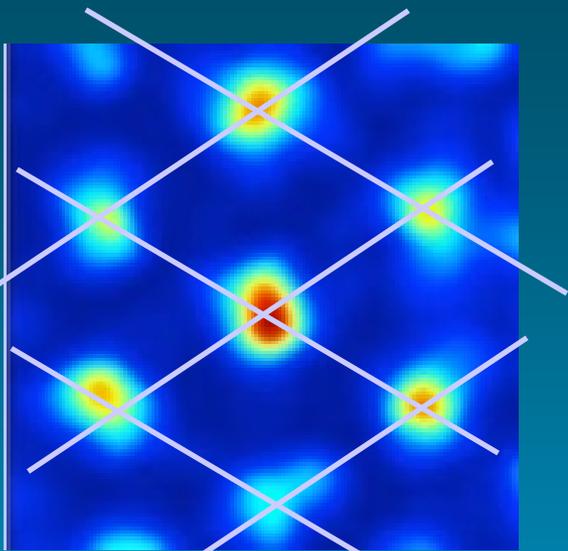
Just look at one grid cell...



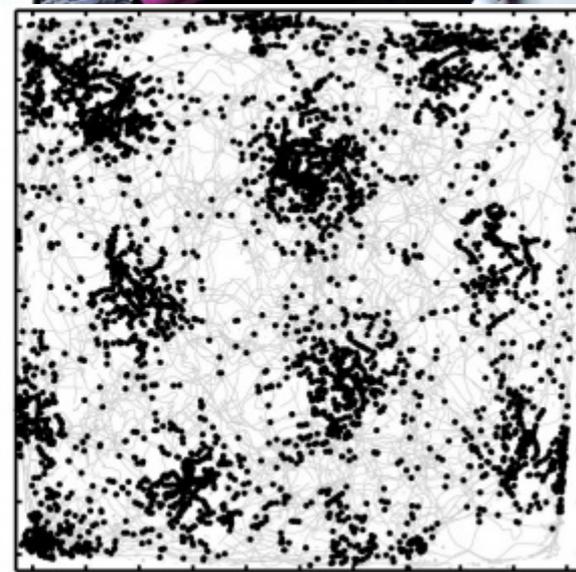
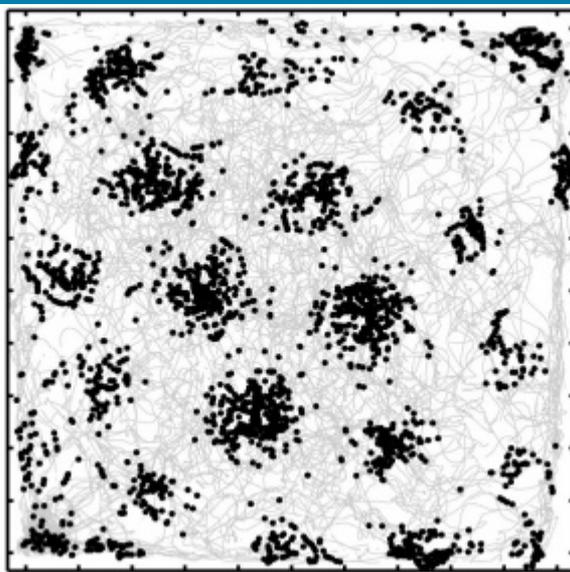
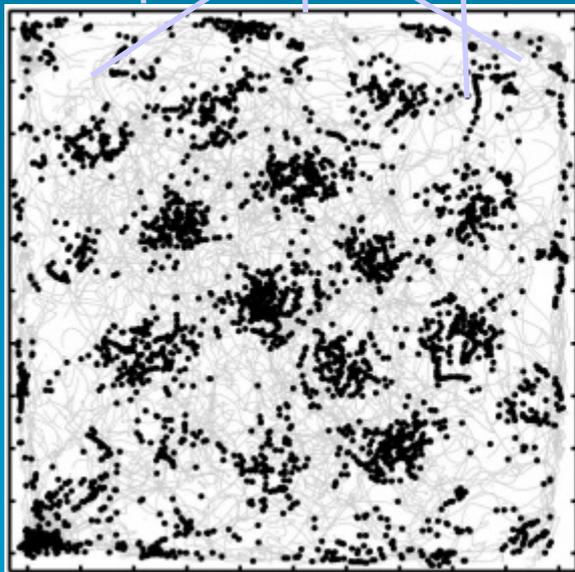
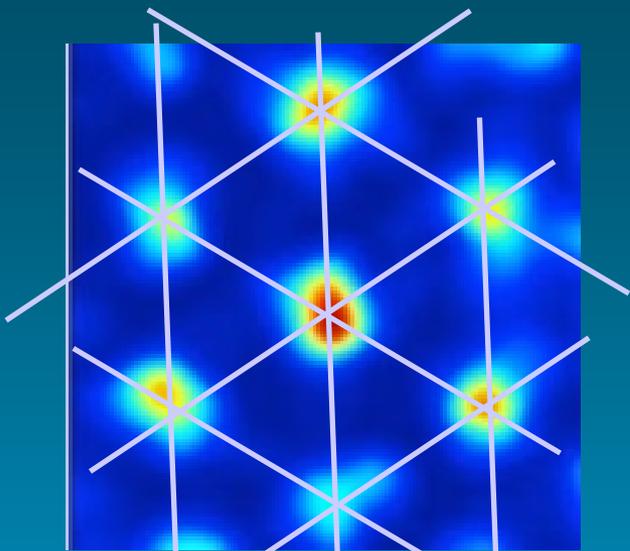
Just look at one grid cell...



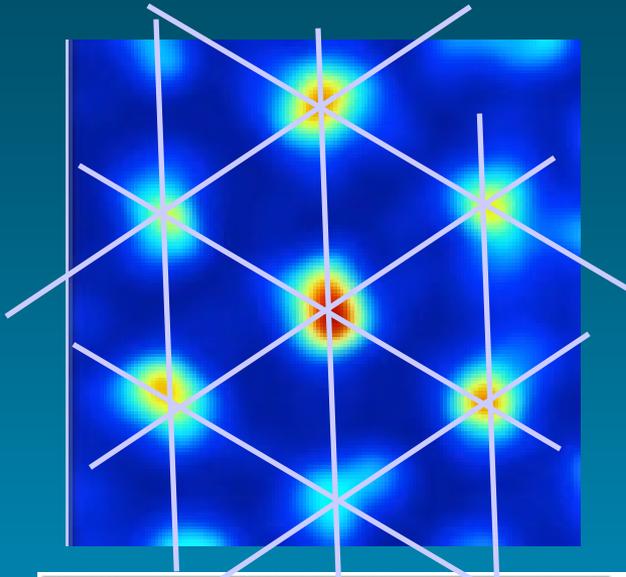
Just look at one grid cell...



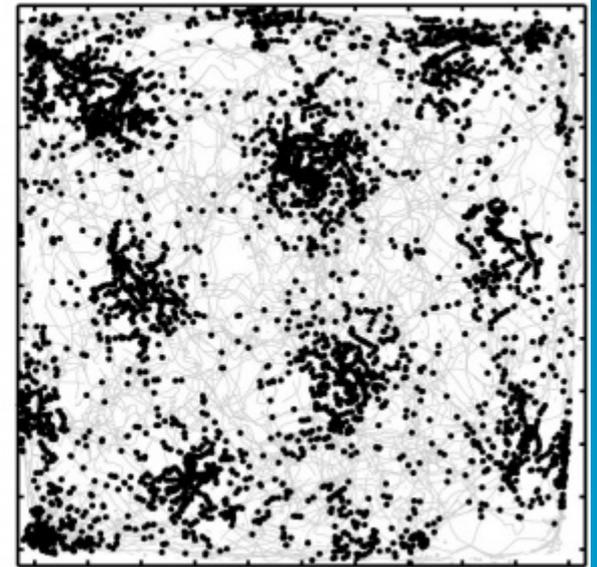
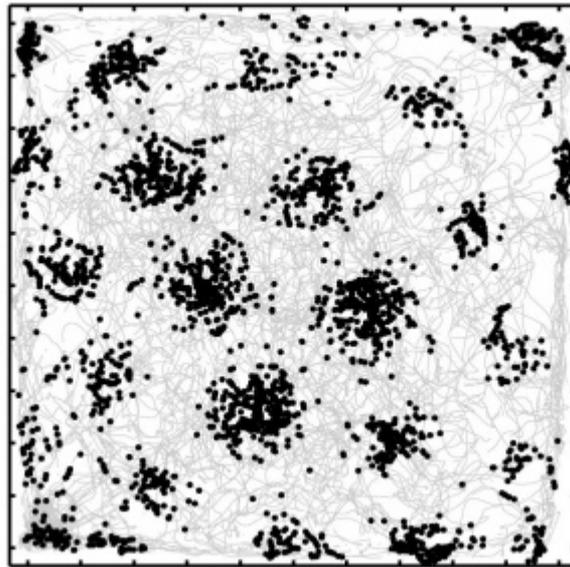
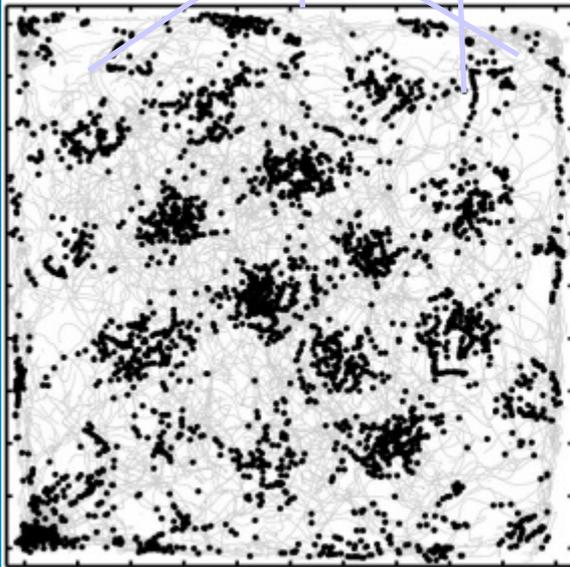
Just look at one grid cell...

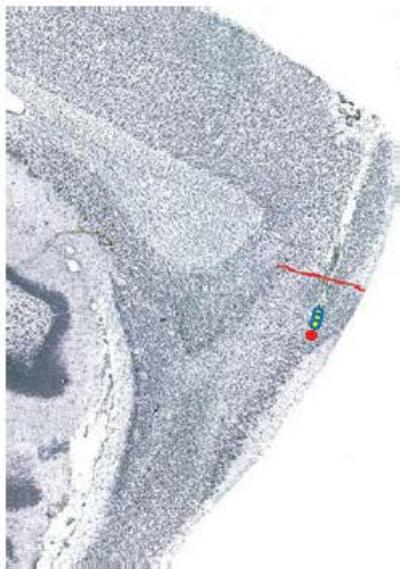
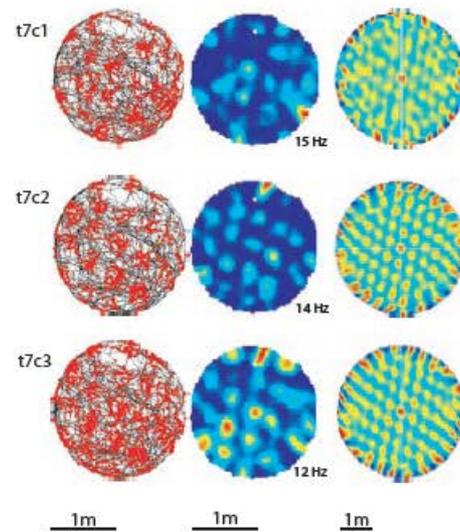
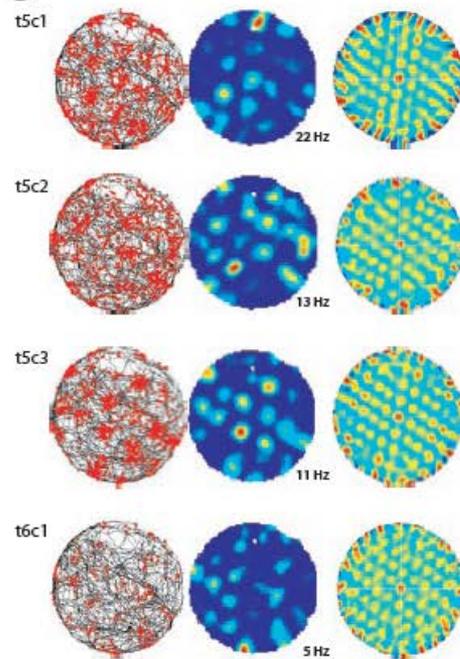
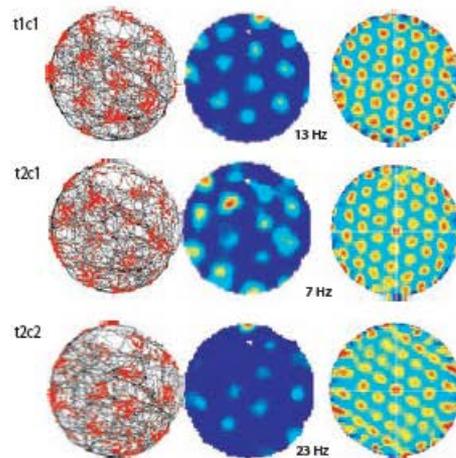
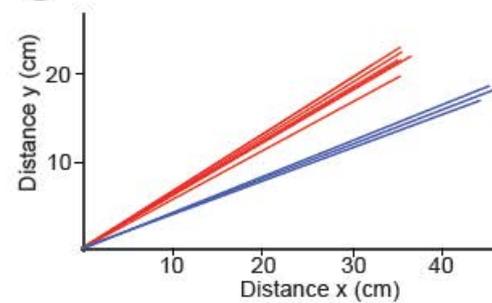
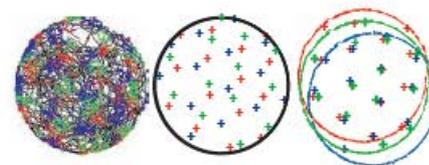


Just look at one grid cell...

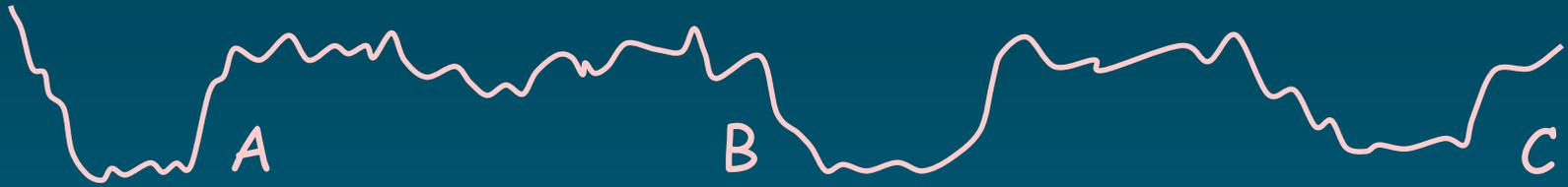


Is it just more beautiful than a place cell, more metrical, more...

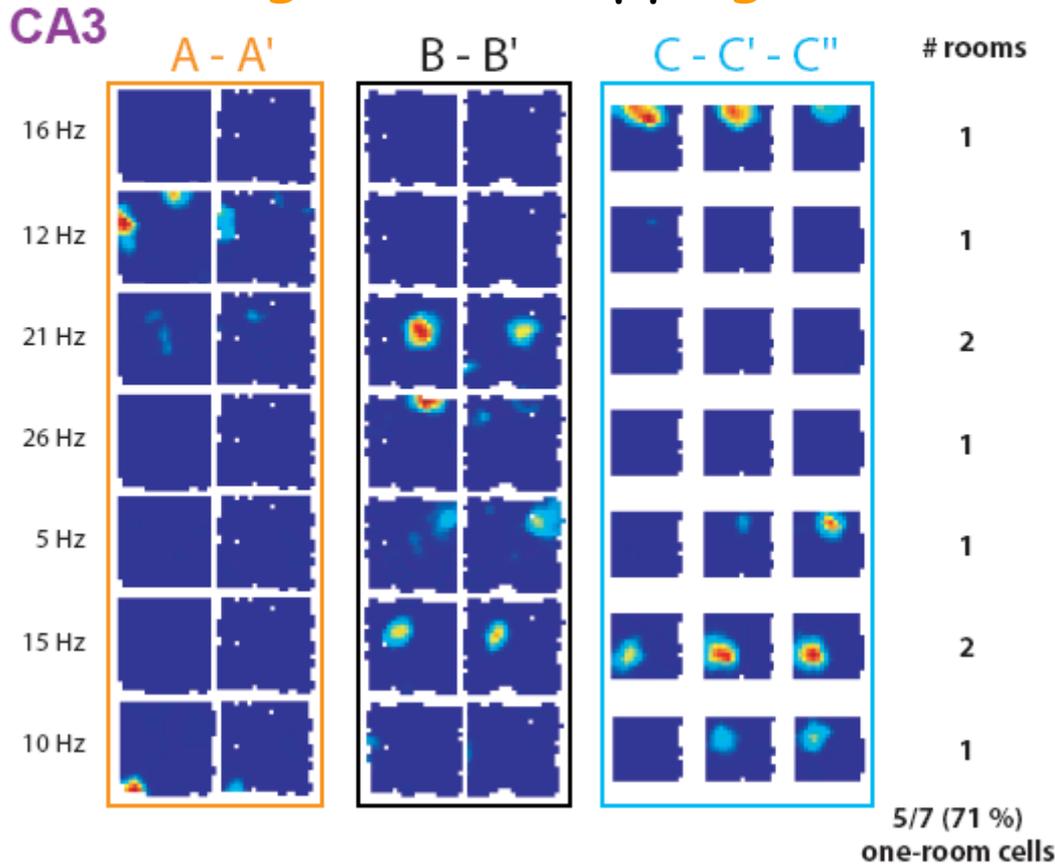


**a****b****c****d****e****f**

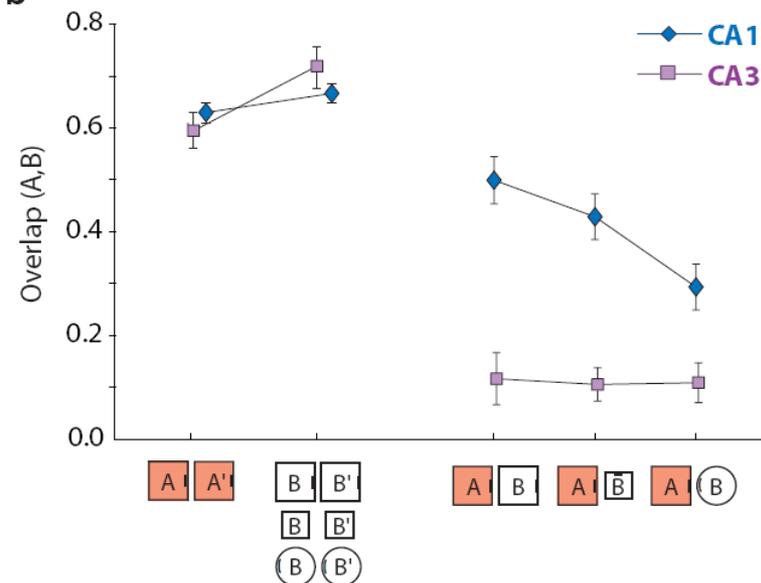
# Consider what happens in the hippocampus when changing context



'global remapping'

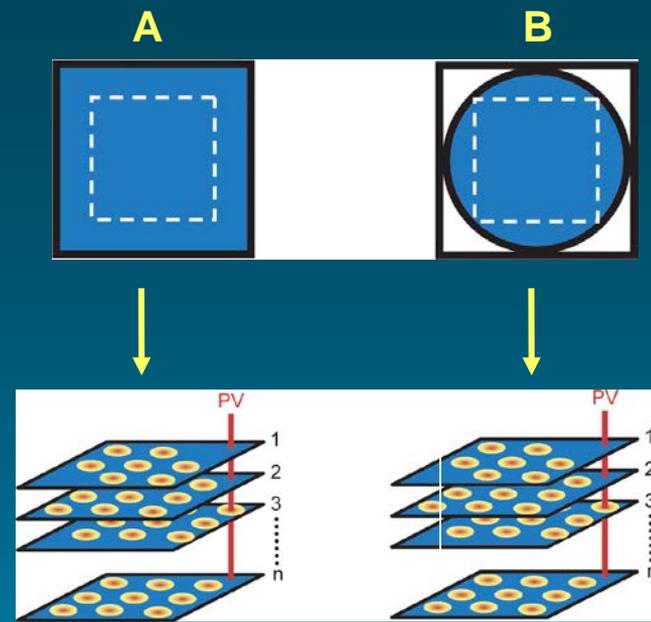


CA3 charts can be described as a (discrete?) number of continuous attractors, with minimal overlap among them



# Neurophysiology + Neural Computation

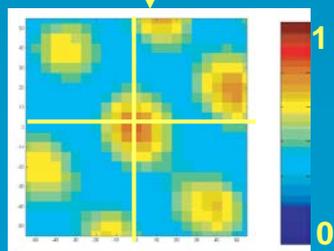
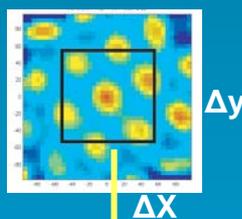
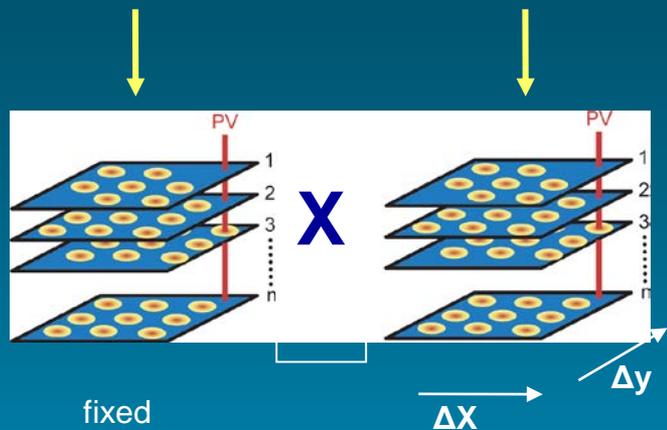
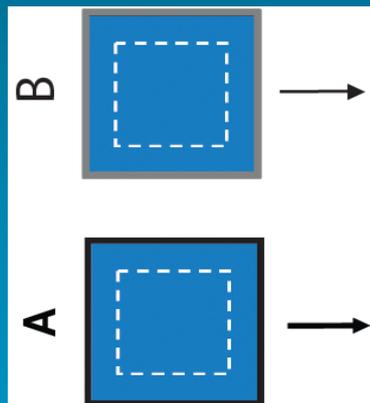
Matrices of population vectors  
were cross-correlated between  
two boxes



Marianne, Torkel, AT +  
Moser (Nature, 2007)

# Neurophysiology + Neural Computation

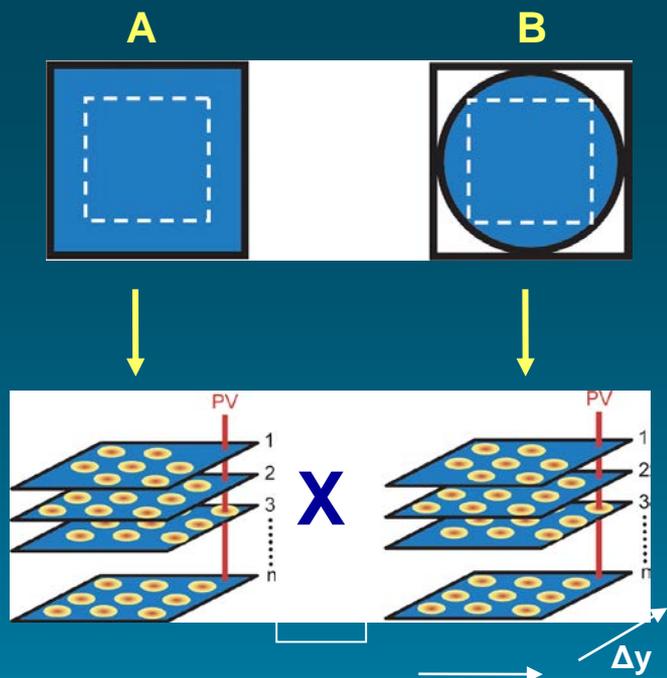
Matrices of population vectors were cross-correlated between two boxes



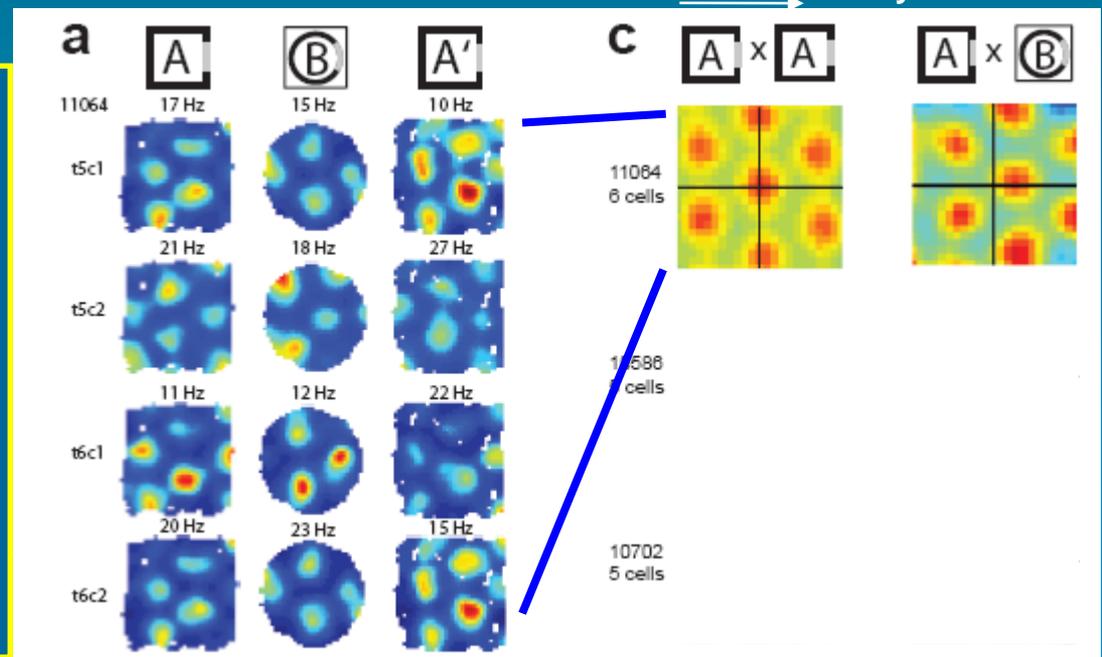
Marianne, Torkel, AT + Mosers (Nature, 2007)

# Neurophysiology + Neural Computation

Matrices of population vectors were cross-correlated between two boxes

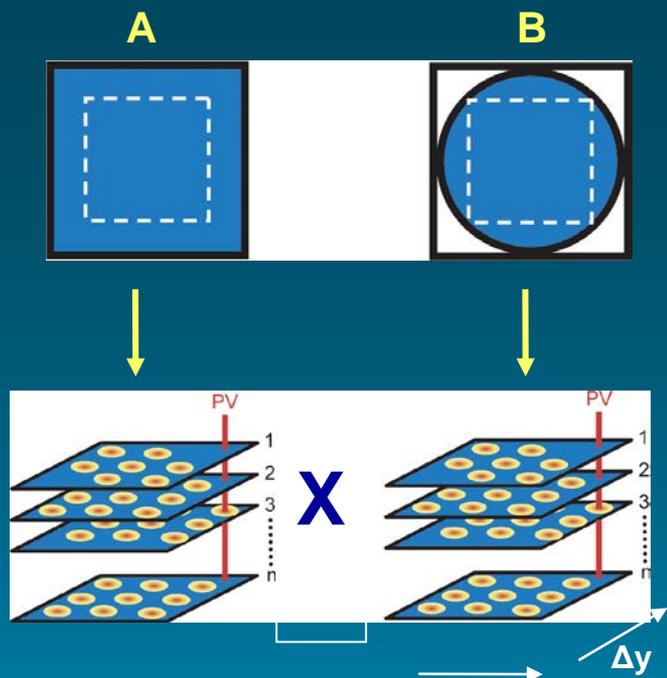


coherent displacement of the entorhinal map during global remapping in the hippocampus!

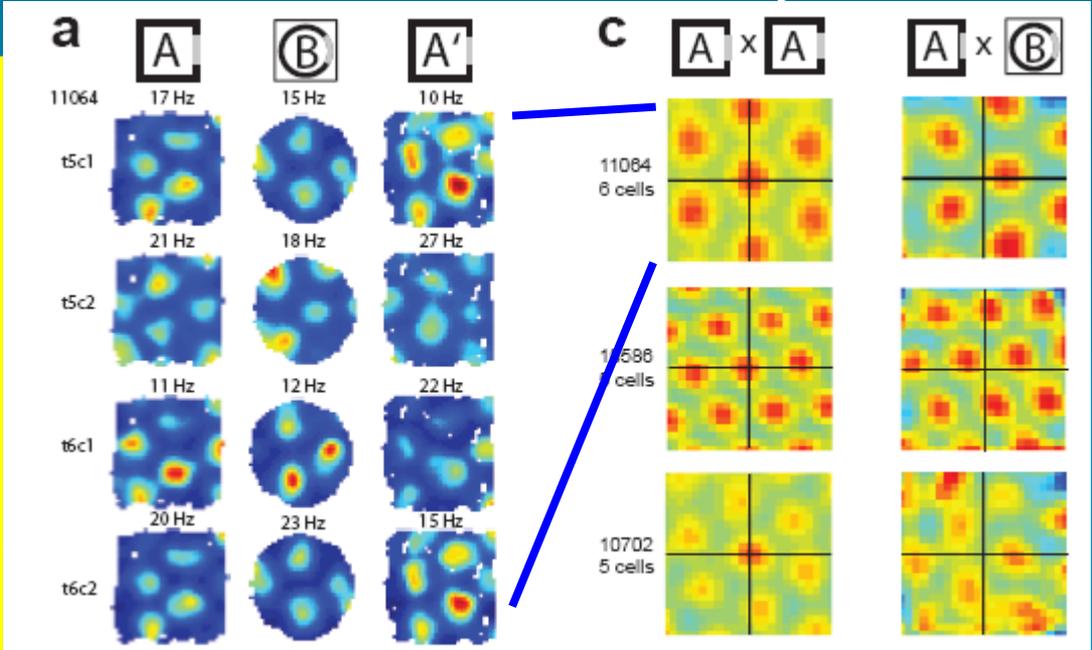


# Neurophysiology + Neural Computation

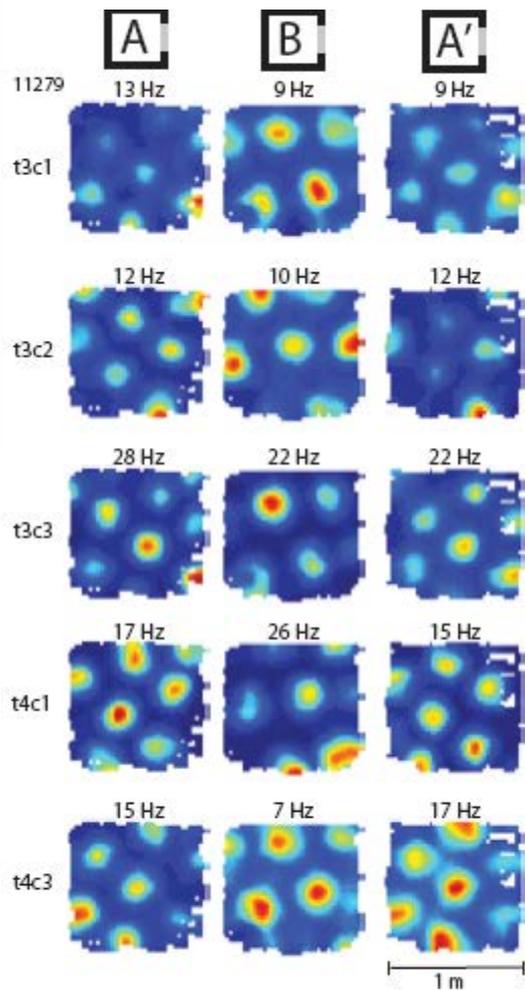
Matrices of population vectors were cross-correlated between two boxes



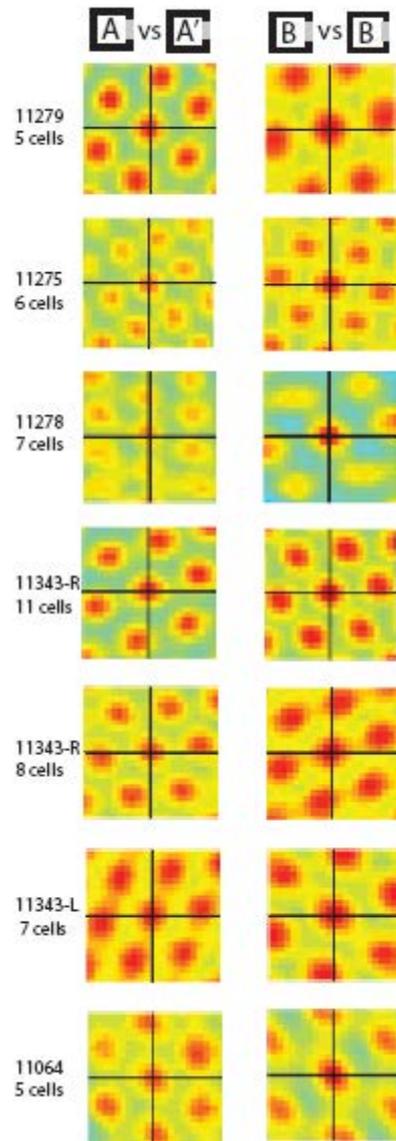
coherent displacement of the entorhinal map during global remapping in the hippocampus!



## 2 rooms:



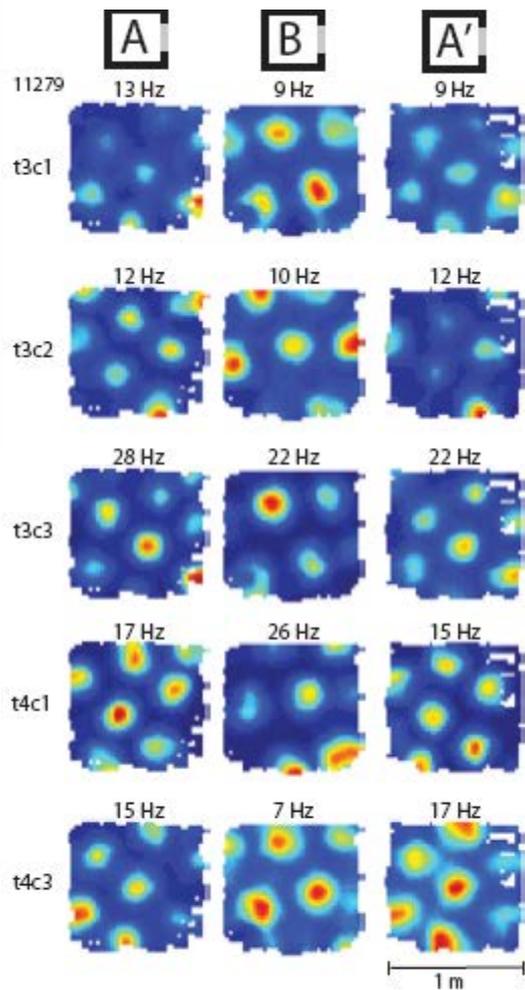
## same



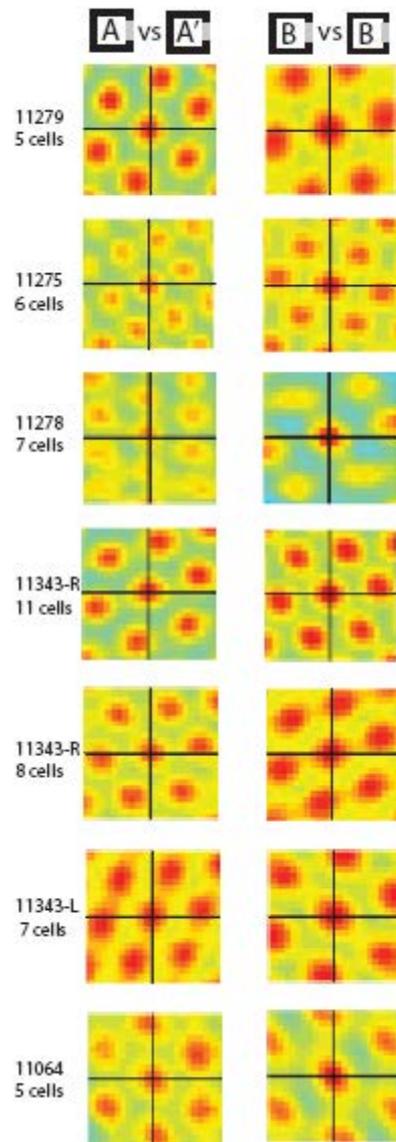
## different



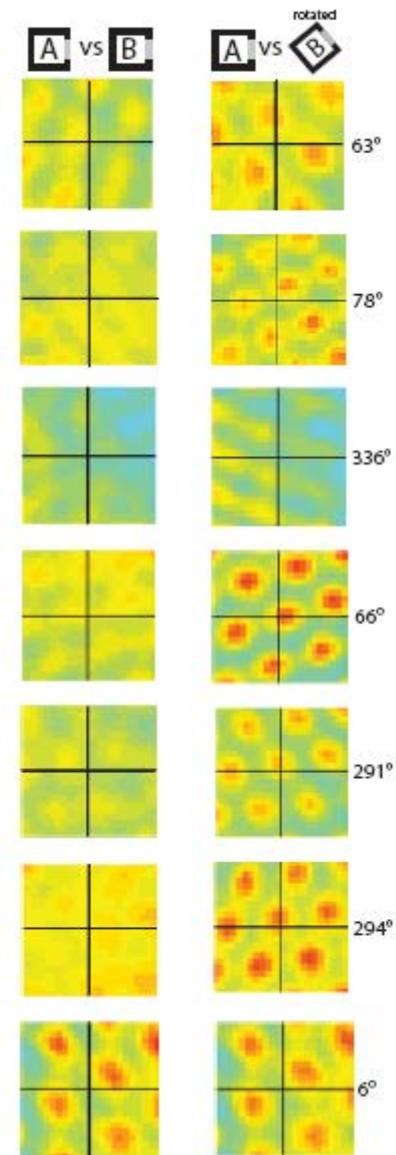
## 2 rooms:



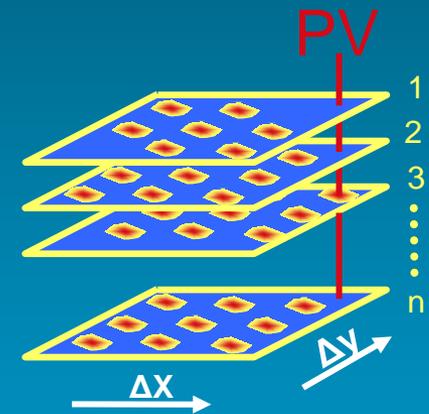
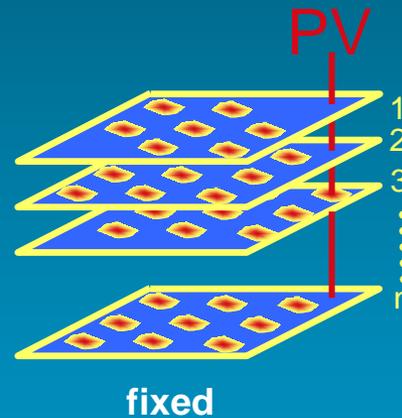
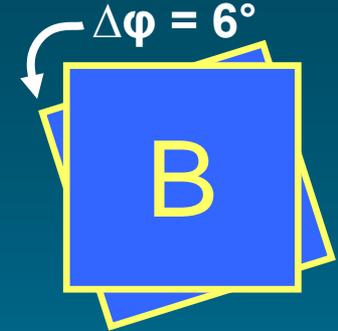
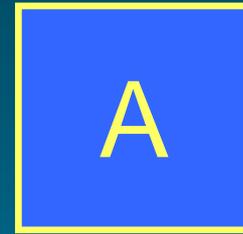
## same



## different

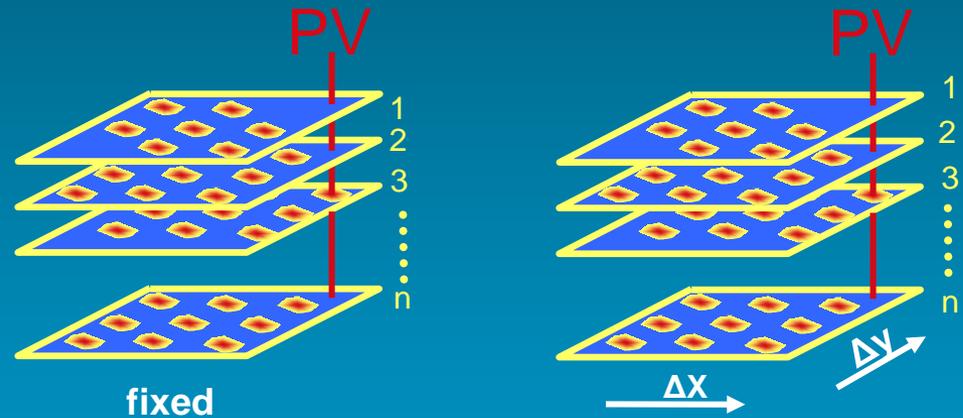
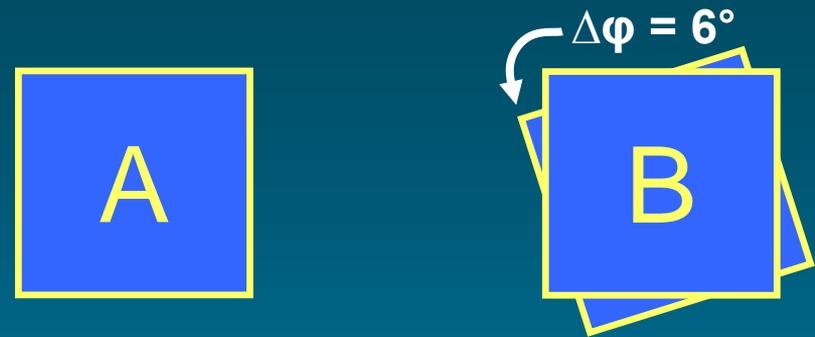


The coherence between grid maps in two rooms is observed only after a rotation of one map relative to the other



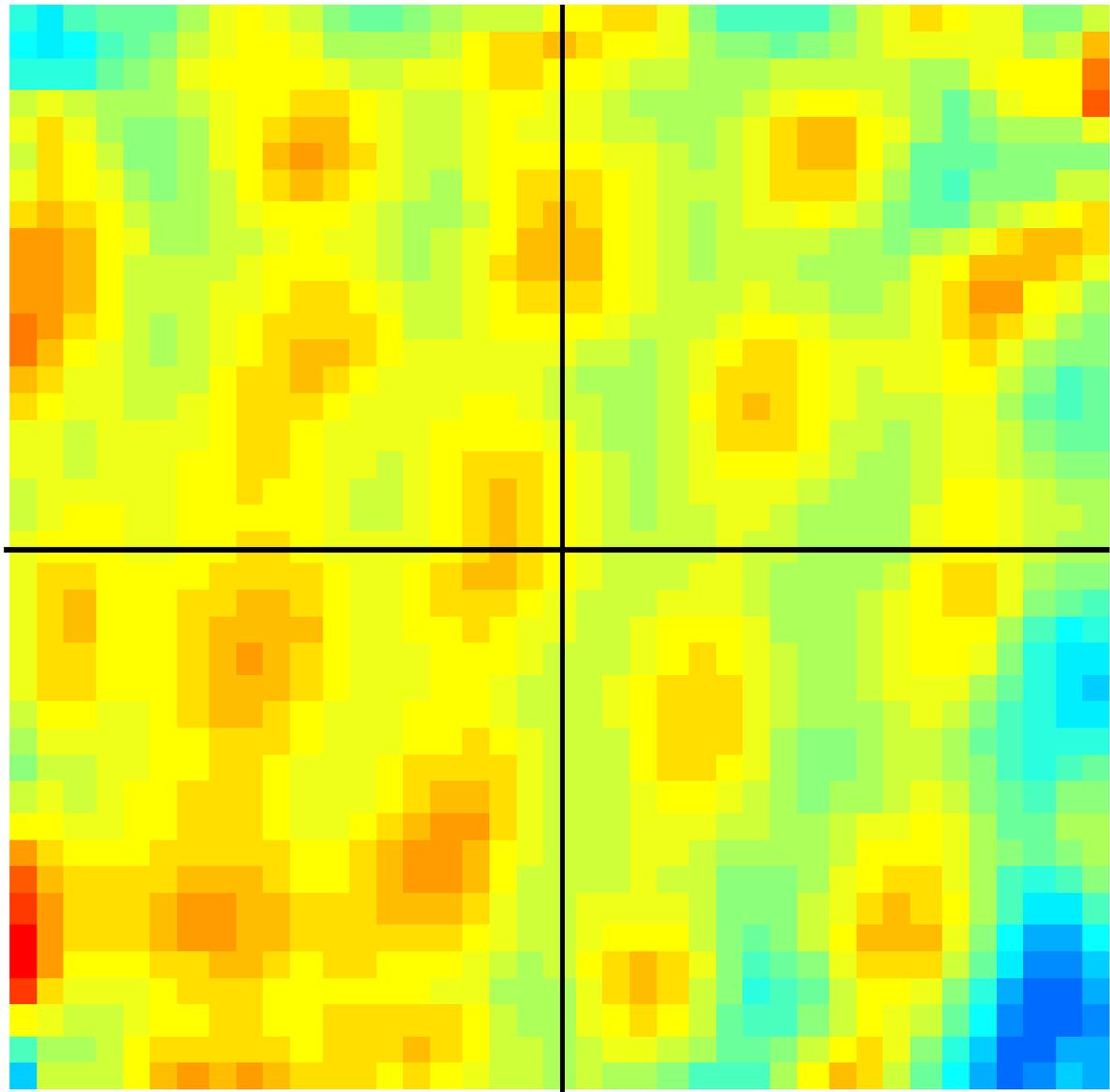
$$PV(A) \times PV(B) \Delta\phi$$

The coherence between grid maps in two rooms is observed only after a rotation of one map relative to the other



The local ensemble translates / rotates as a rigid structure ...kept together by recurrent connections ?

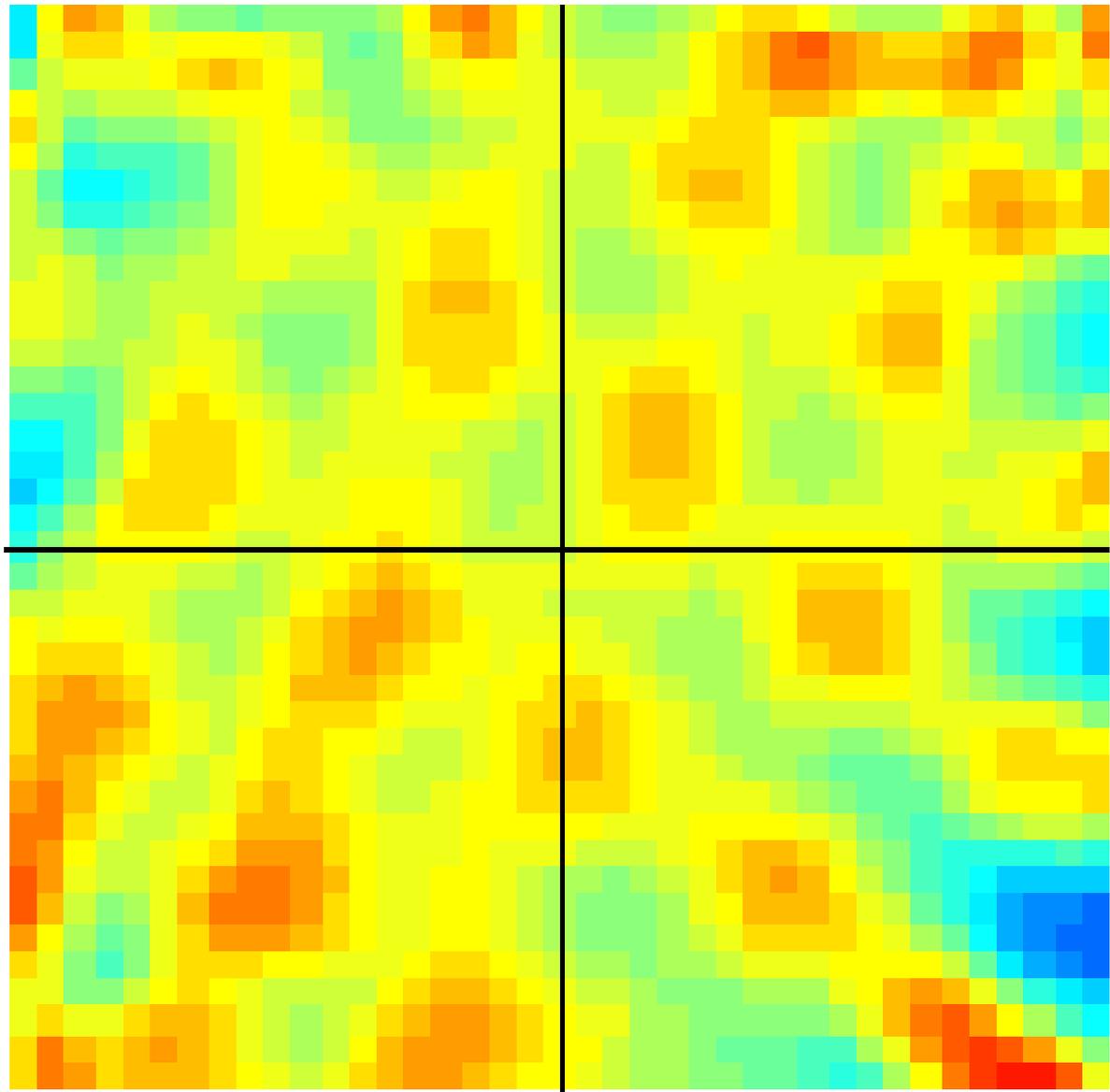
$$PV(A) \times PV(B) \Delta\phi$$



Thus, the intrinsic structure of the map (spacing, orientation, spatial phase) is retained,

i.e. a single map may be applied rigidly in all environments

..millimeter paper



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i.e. a single map may be applied rigidly in all environments

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Many models have been proposed..

Grid cell model	Position representation	Updating mechanism
Conklin and Eliasmith (2005)	Torus attractor, single bump	Direction-conjunctive cells
O'Keefe and Burgess (2005)	[Torus attractor, single bump]	[Direction-modulated recurrent connections]
Fuhs and Touretzky (2006)	Aperiodic attractor, multi-bump	Direction-conjunctive cells
McNaughton et al. (2006)	[Torus attractor, single bump]	[Direction-conjunctive cells]
Blair et al. (2007)	[Theta grids]	–
Burgess et al. (2007)	Sinusoid phase difference	Frequency modulation
Gaussier et al. (2007)	Firing rates as coordinates	Firing rate modulation
Giocomo et al. (2007)	Sinusoid phase difference	Frequency modulation
Guanella et al. (2007)	Twisted-torus attractor, single bump	Dynamic recurrent connections
Blair et al. (2008)	[Biased ring attractor phase difference]	[Direction-conjunctive cells]
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Hasselmo and Brandon (2008)	Firing rate	Frequency modulation
<b>Most models require an engineer inside the brain to set them up</b>		
Burak and Fiete (2009)	Torus and aperiodic attractors, multi-bump	Direction-conjunctive cells
Mhatre et al. (2012)	[Unbiased ring attractor]	[Direction-conjunctive cells]
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Welday et al. (2011)	[Biased ring attractor phase difference]	[Direction-conjunctive cells]

Many models have been proposed..

Grid cell model

Position representation

Updating mechanism

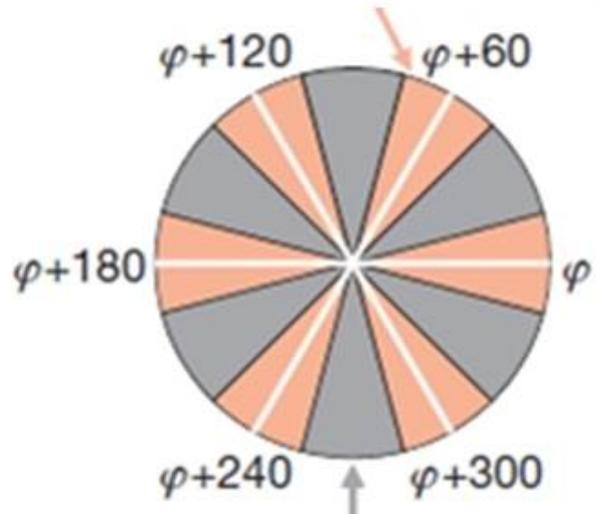
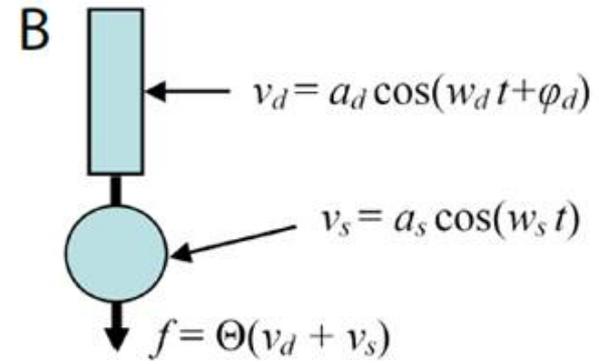
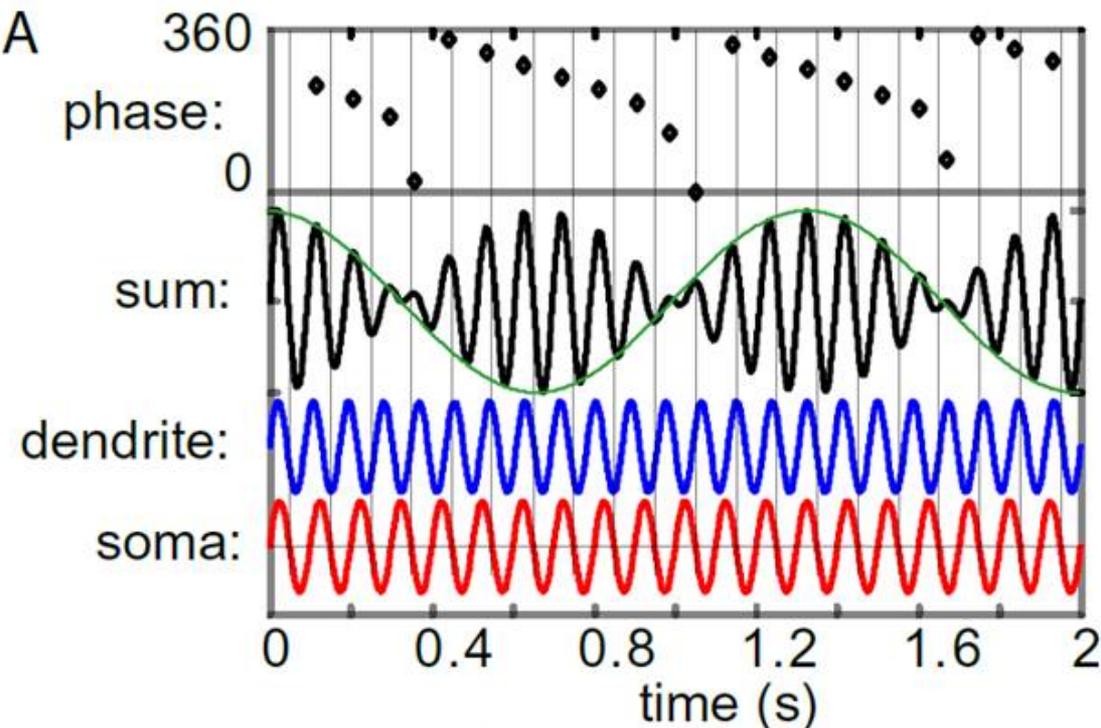
Conklin and Eliasmith (2005)  
O'Keefe and Burgess (2005)

Torus attractor, single bump  
[Torus attractor, single bump]

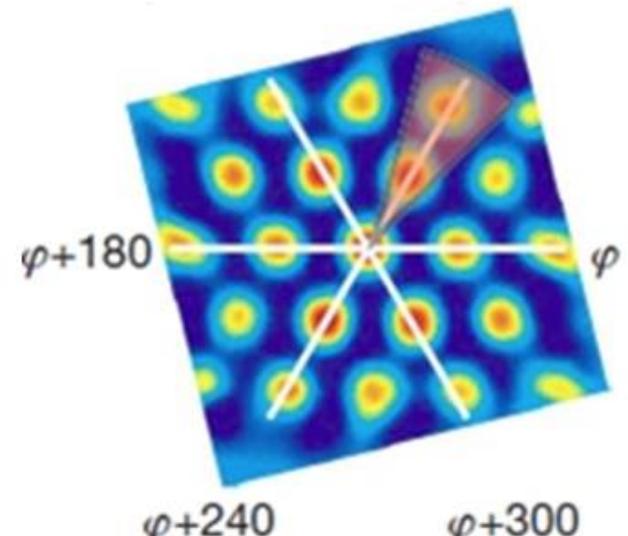
Direction-conjunctive cells  
[Direction-conjunctive cells]

modulated  
connections]  
conjunctive cells  
conjunctive  
odulation  
odulation  
odulation  
urrent  
conjunctive  
odulation  
odulation  
odulation

# Oscillator interference



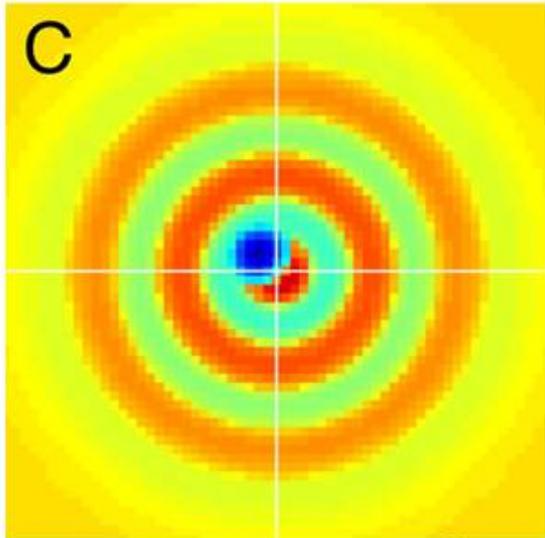
60 +  
120 +  
180 =



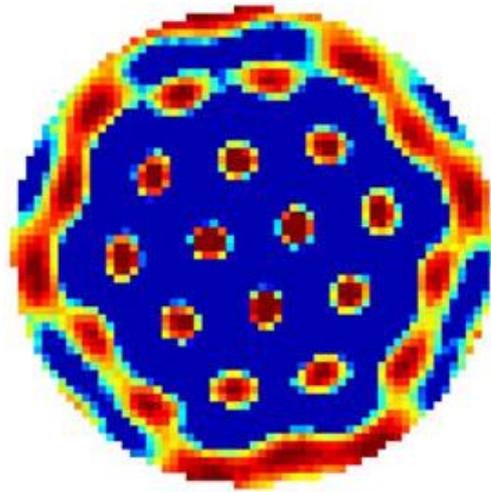
em up  
conjunctive cells  
conjunctive  
ency  
conjunctive cells  
conjunctive

Many models have been proposed..

Grid cell model	Position representation	Updating mechanism
Conklin and Eliasmith (2005)	Torus attractor, single bump	Direction-conjunctive cells
OKeefe and Burgess (2005)	[Torus attractor, single bump]	[Direction-modulated]



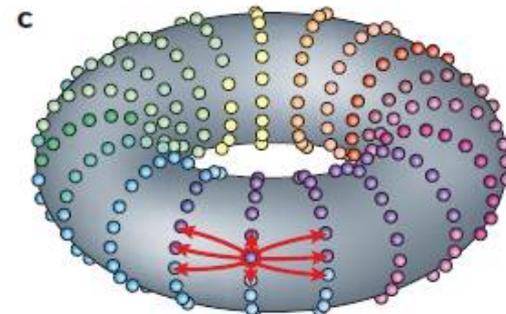
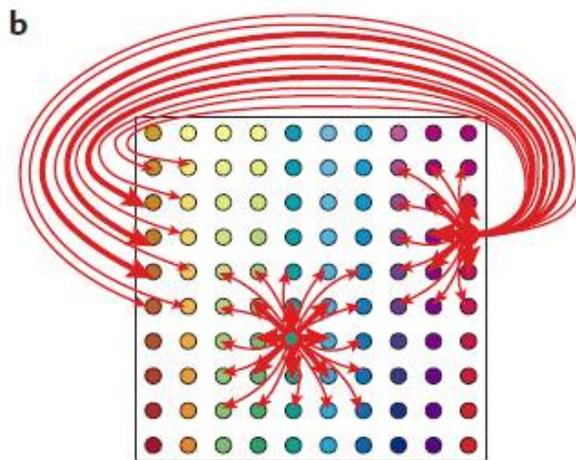
Connection weights



Firing rate map

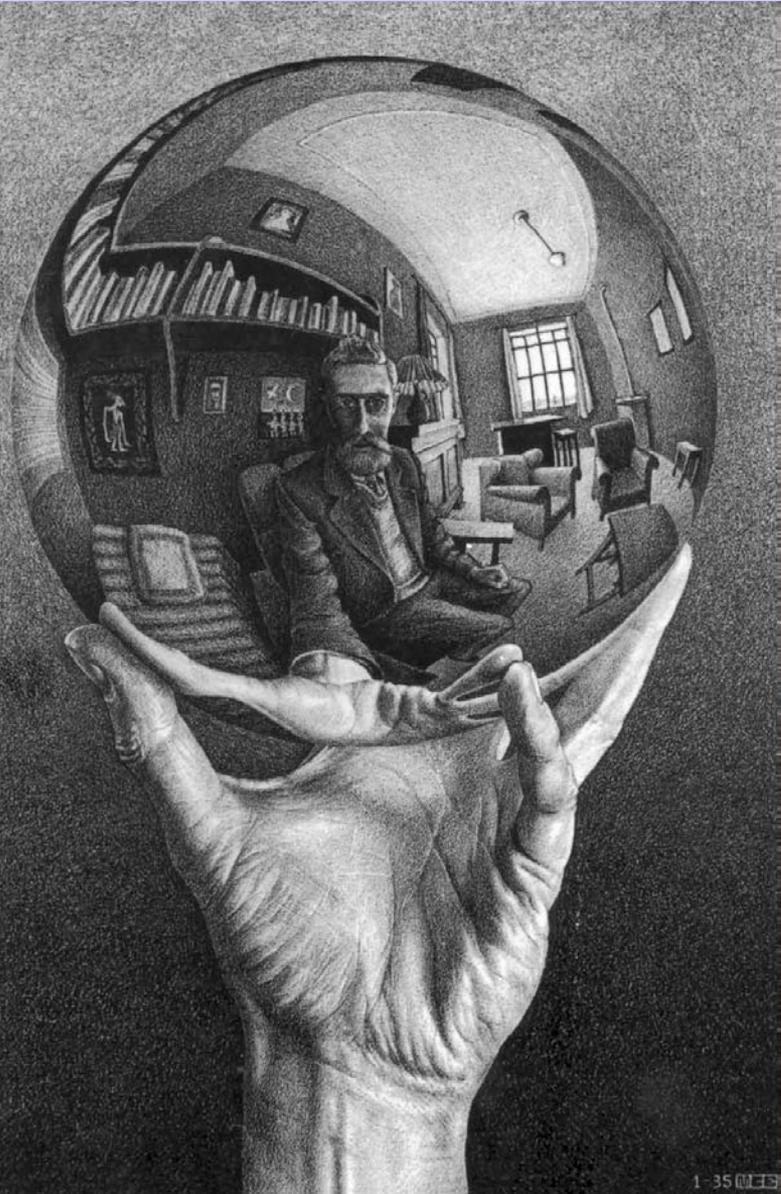
# Recurrent Network creating a single Continuous Attractor

Solving both  
**boundary & periodicity**  
problems in  
one shot



Direction-conjunctive cells
[Direction-modulated]
connections]
conjunctive cells
conjunctive
odulation
odulation
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urrent
conjunctive
odulation
odulation
odulation
<b>em up</b>
conjunctive cells
conjunctive
ency
conjunctive cells
conjunctive

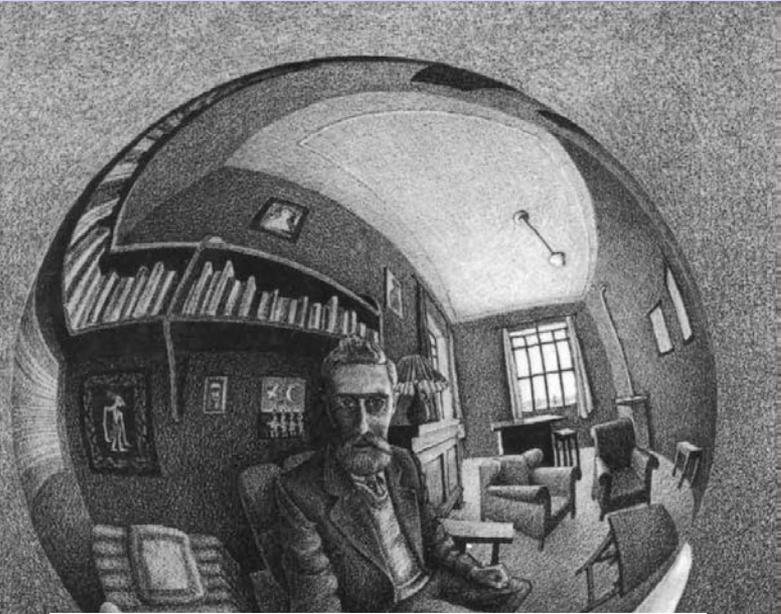
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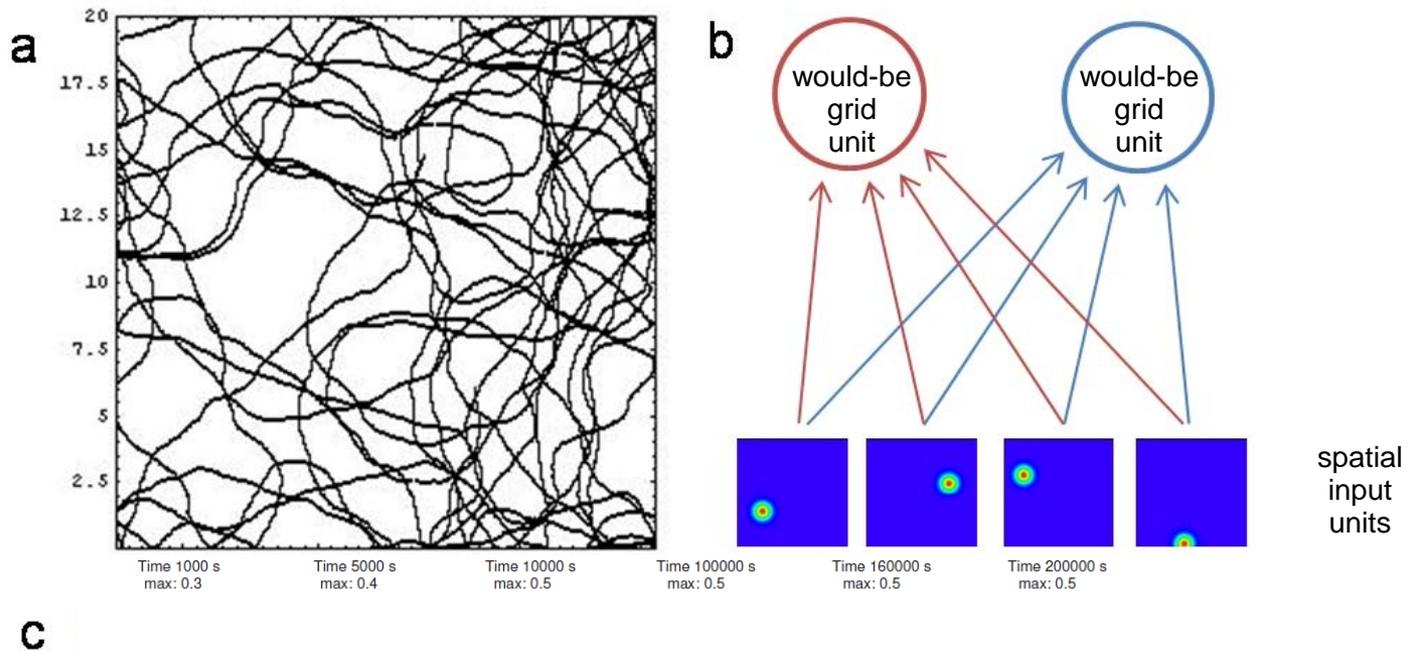
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Hasselmo (2008)	Sinusoid phase difference	Frequency modulation
Hasselmo and Brandon (2008)	Firing rate	Frequency modulation
Kropff and Treves (2008)	Place cells	<b>Self-organization</b>
Burak and Fiete (2009)	Torus and aperiodic attractors, multi-bump	Direction-conjunctive cells
Mhatre et al. (2012)	[Unbiased ring attractor]	[Direction-conjunctive cells]
Zilli and Hasselmo (2010)	Non-phase attractor	Frequency modulation
Navratilova et al. (2012)	Attractor	Direction-conjunctive cells
Welday et al. (2011)	Attractor p	Non-conjunctive

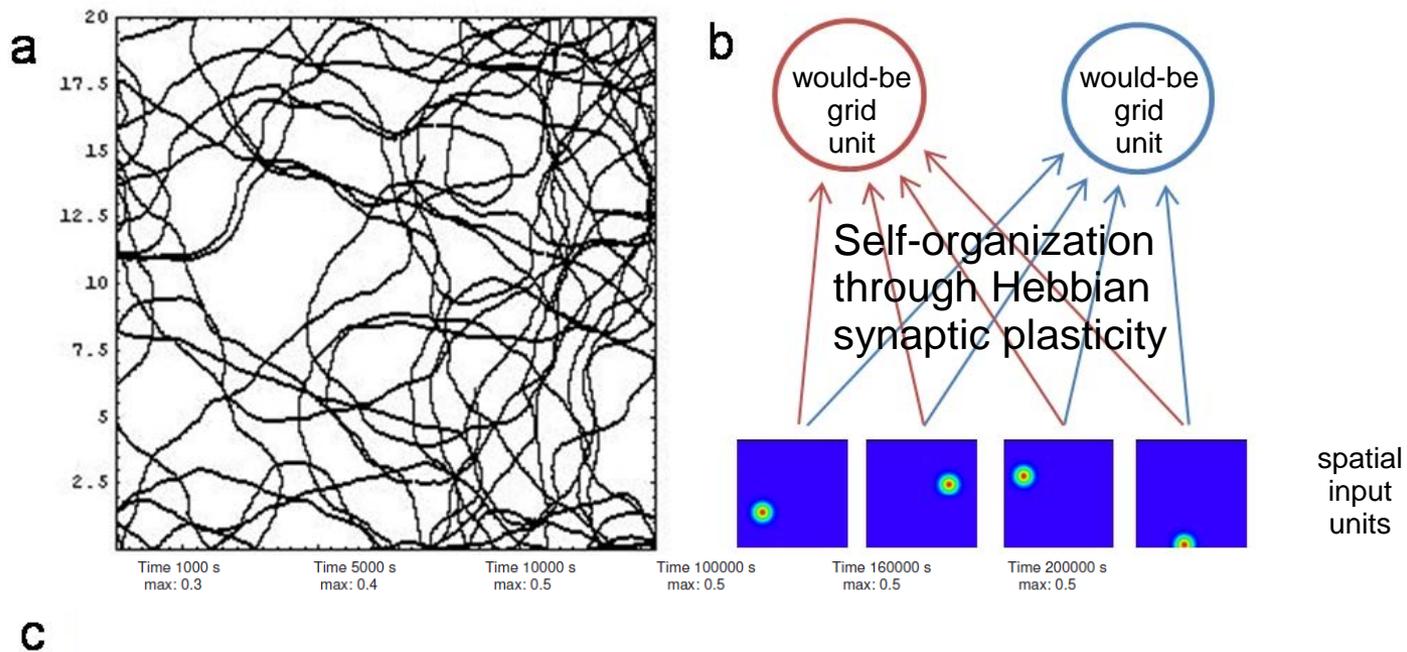


# Grid cells may slowly self-organize averaging, over many trajectories, the effect of neuronal fatigue (firing rate adaptation) : an example of pattern formation



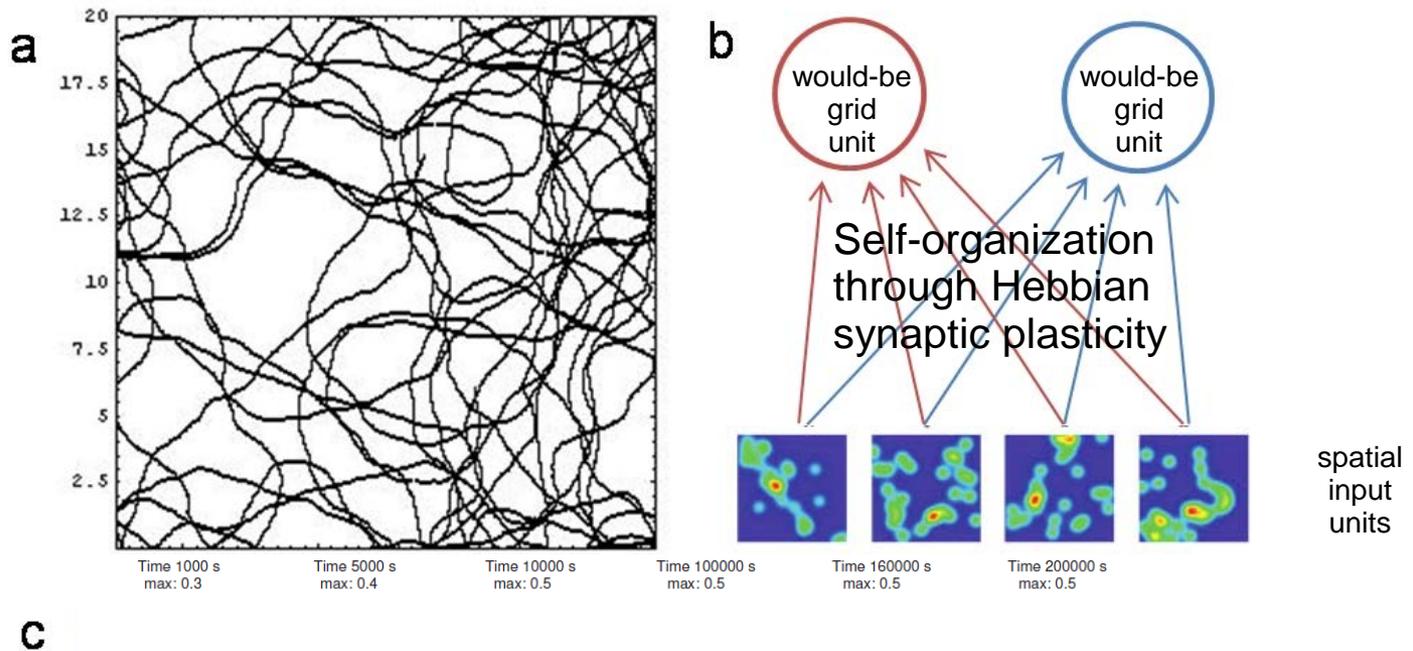
# Grid cells may slowly self-organize

averaging, over many trajectories, the effect of neuronal fatigue (firing rate adaptation) : **an example of pattern formation**

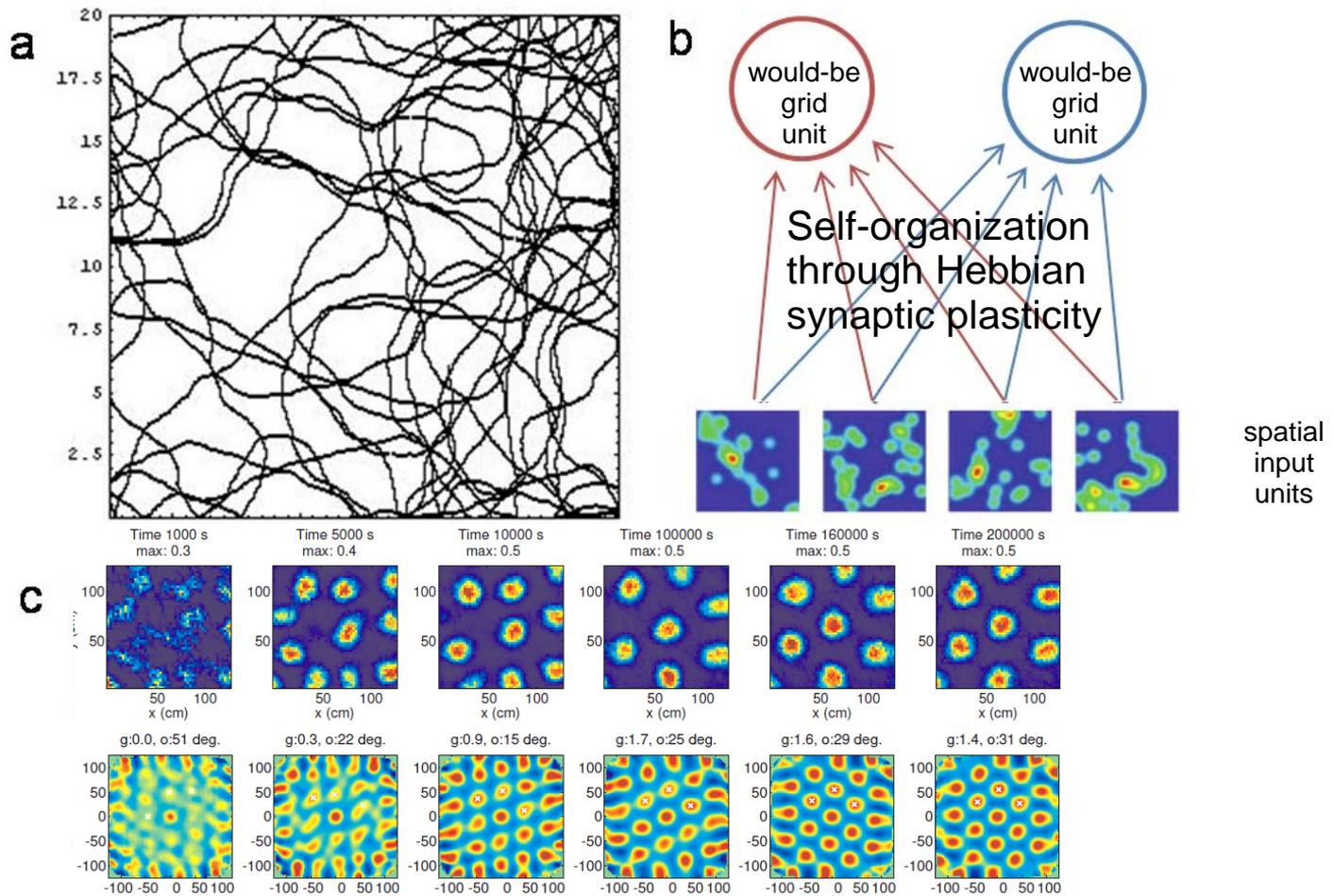


# Grid cells may slowly self-organize

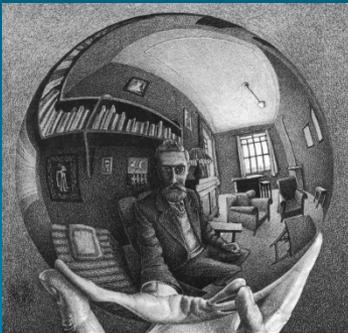
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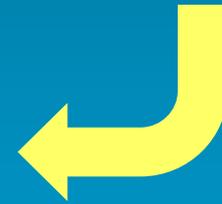
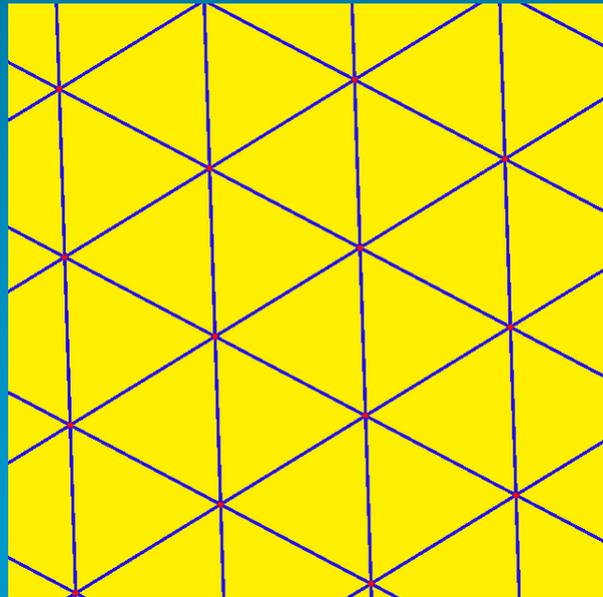
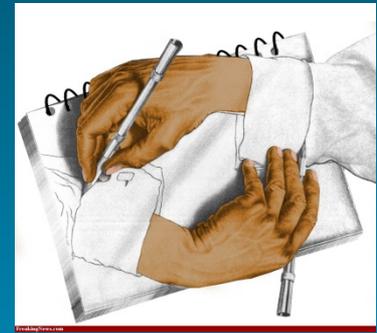
# Grid cells may slowly self-organize averaging, over many trajectories, the effect of neuronal fatigue (firing rate adaptation) : an example of pattern formation



# How to decide which model is right?



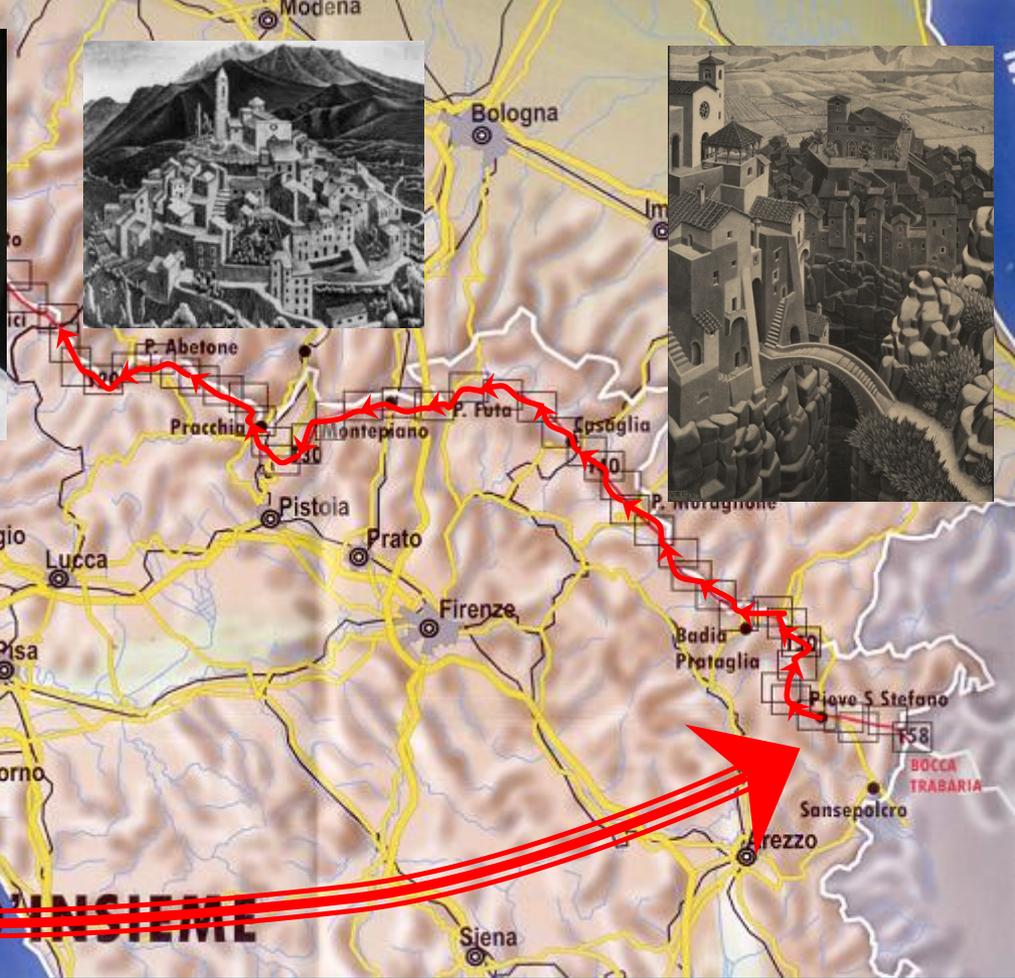
In a plain box,  
with nothing inside  
all models work fine







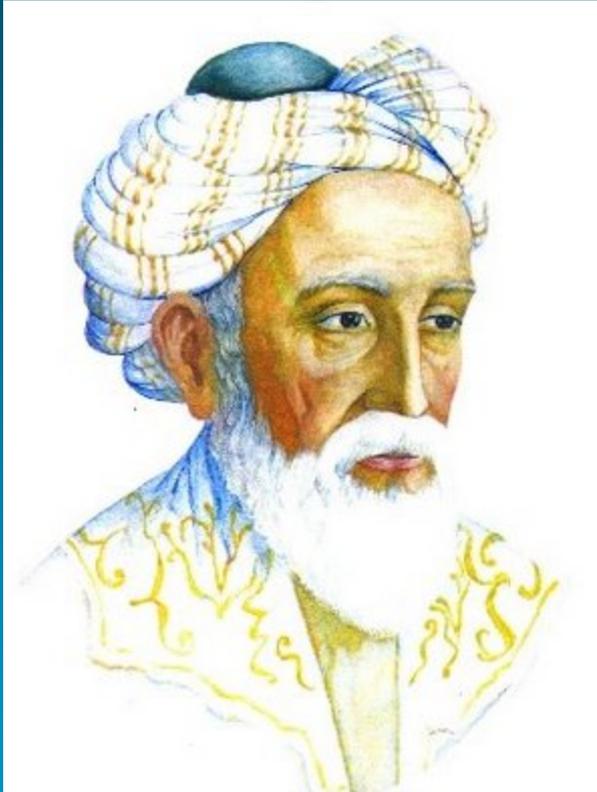
## Grande Escursione Appenninica



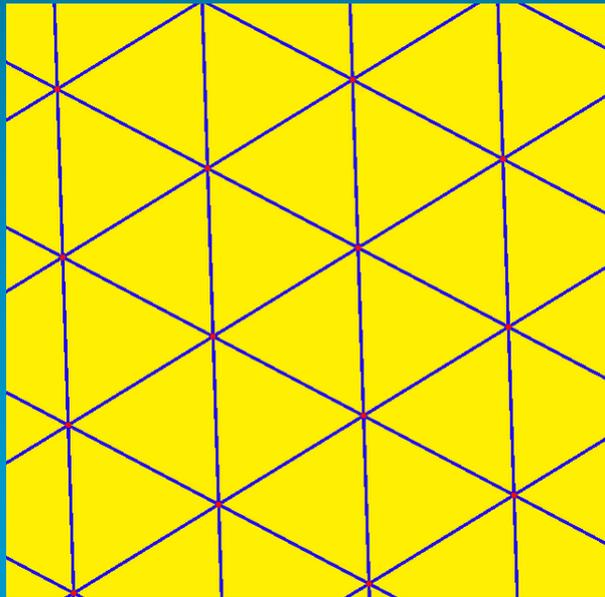
# Grande Escursione Appenninica

..no straight lines

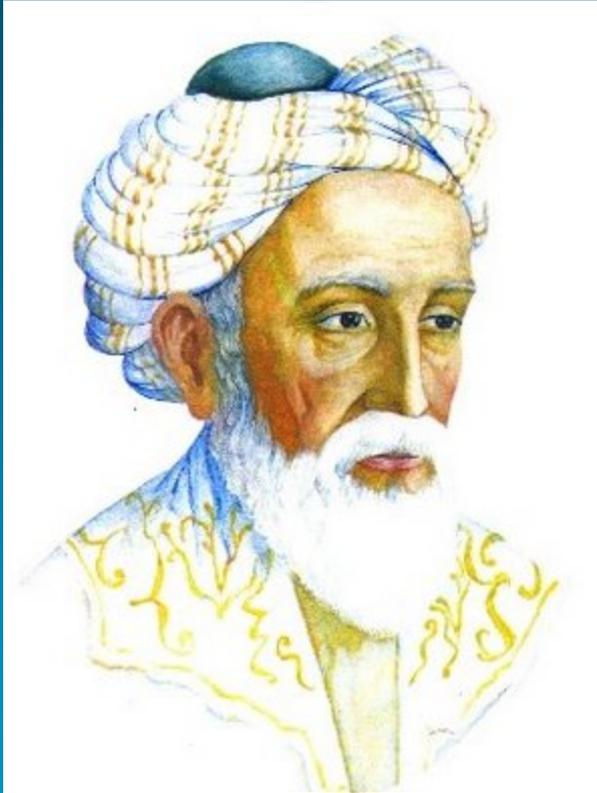
Is it true that  
through a given  
point there can only  
be one parallel line?



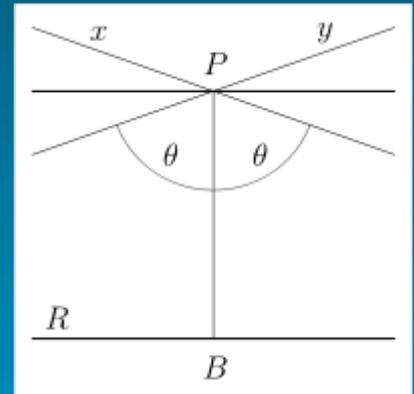
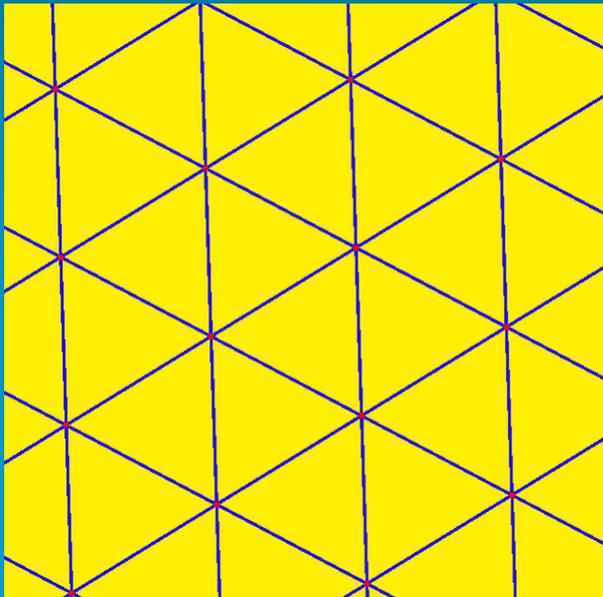
Omar Khayyam  
ca. 1080



Is it true that  
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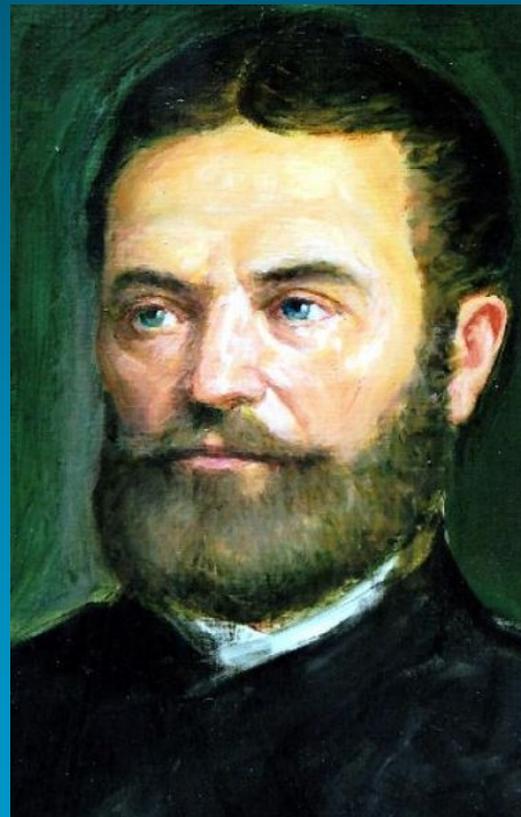
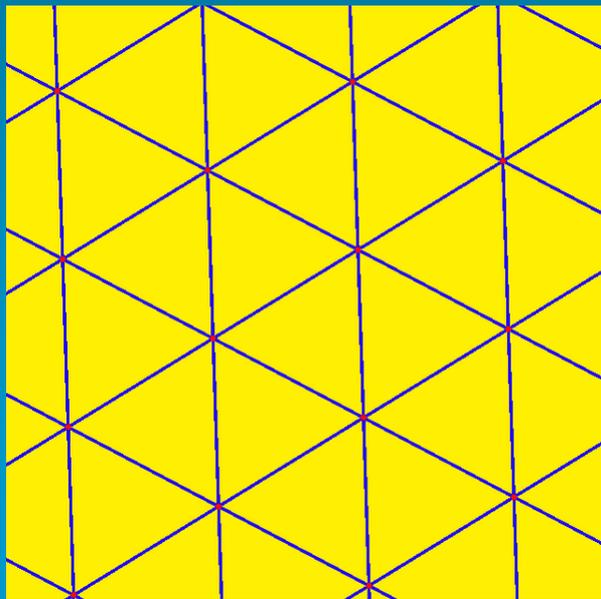


mmmhh...  
...thinking about it...  
...no!  
There can be more

ca. 1830



Lobachevsky

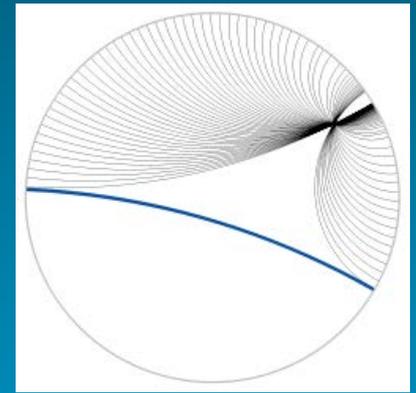


Bolyai

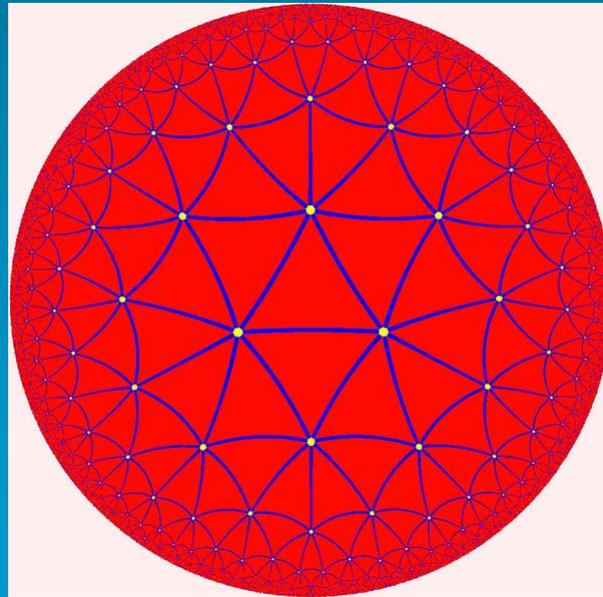
In fact !  
It all depends what  
you mean with  
*a line*  
Think of projecting it..



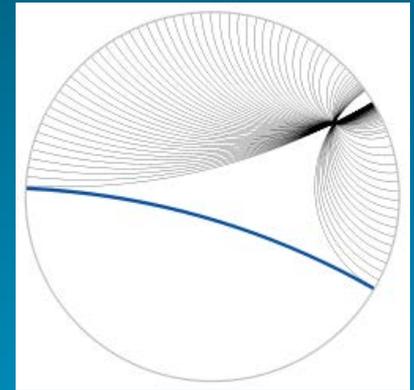
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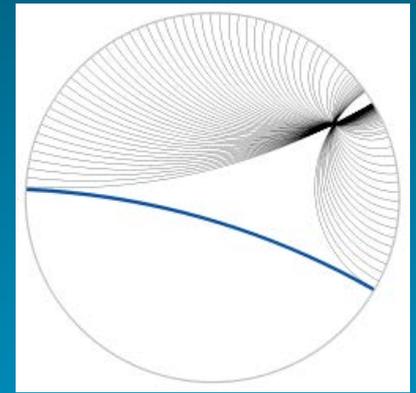
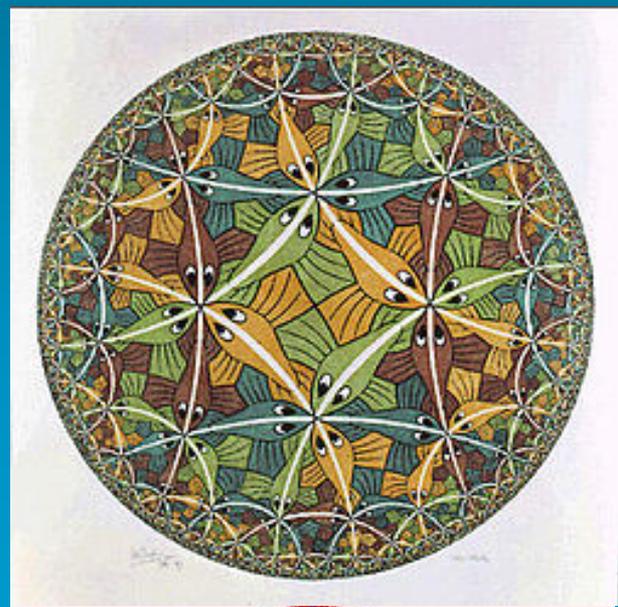
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Hyperbolic disk



In fact !  
It all depends what  
you mean with  
*a line*  
Think of projecting it..



Hyperbolic disk

I need to construct  
something tangible,  
a physical model  
in 3 dimension

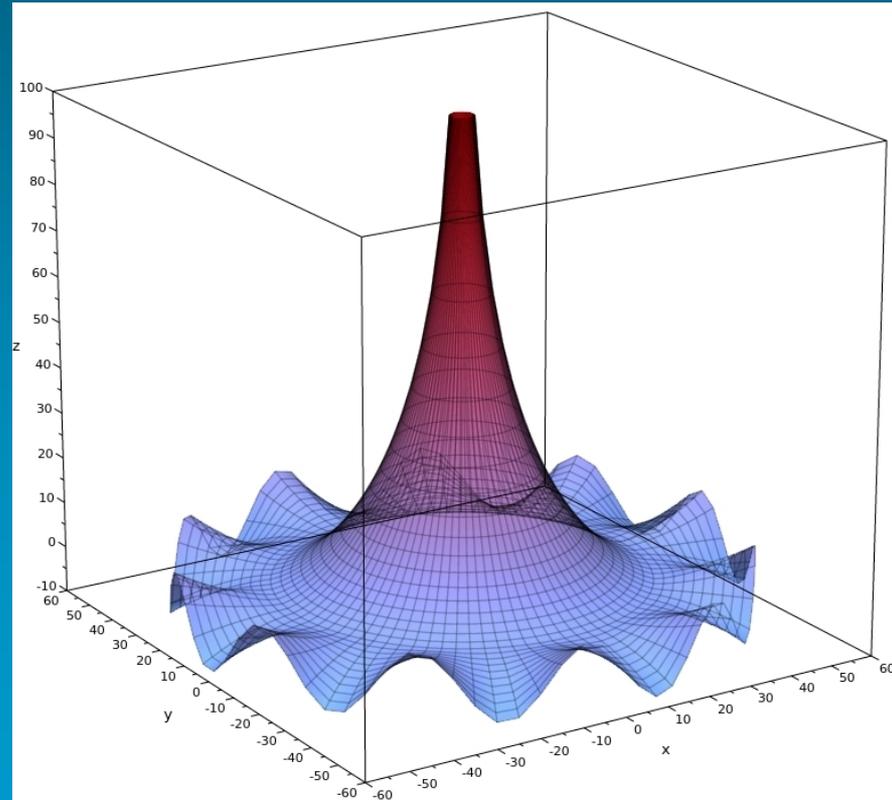




Hyperbolic  
"pseudosphere"

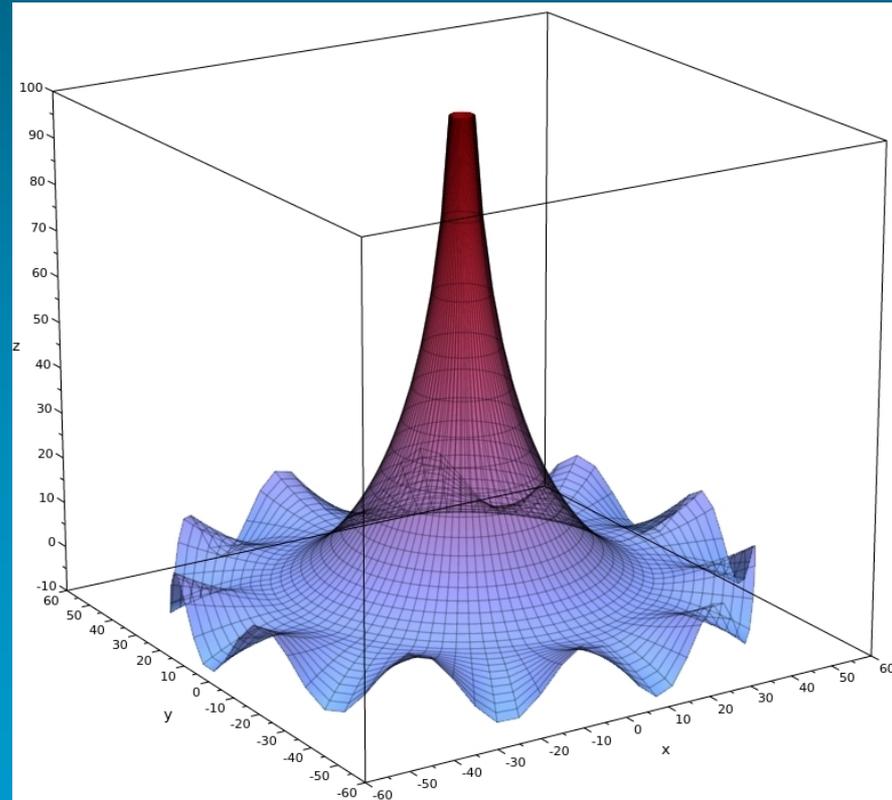


Hyperbolic  
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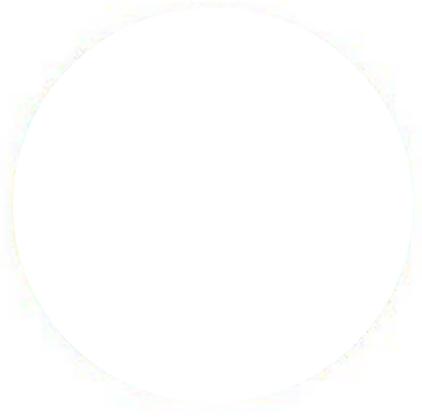
Hyperbolic  
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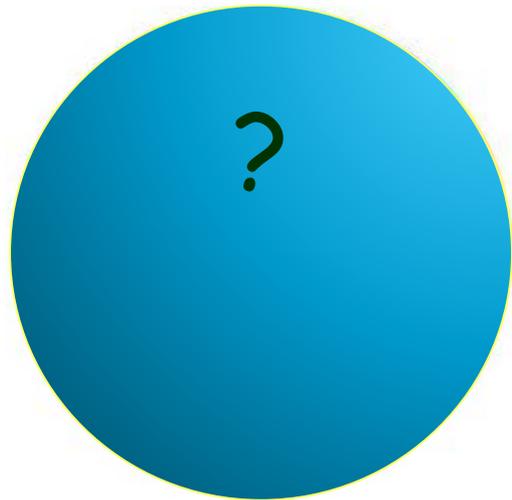
..a simpler experimental test of the adaptation model is to raise rodents either in or on a ball



Federico  
on the ball



what do we  
expect to see  
on the ball?



..a simpler experimental test of the adaptation model is to raise rodents either in or on a ball

## Spherical harmonics

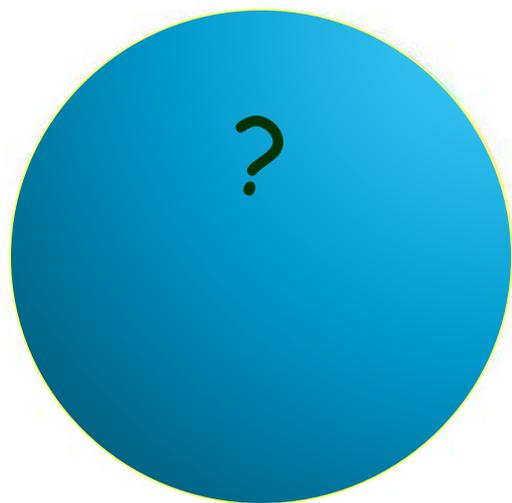
$$\Psi_{l^*}(r) = \sum_{l=0, l^*} \sum_{m=0, m^*} a_{lm} Y_l^m(r)$$



Federico  
on the ball

$$\begin{aligned} \Psi_6(\theta, \varphi) &= d[cY_0^0 + [aY_6^0 + \frac{b}{2}(Y_6^{-5} - Y_6^5)]] \\ &= d[\frac{c}{2}\sqrt{\frac{1}{\pi}} + \\ &\quad + [\sqrt{\frac{143}{137\pi}} \frac{1}{32} * (231 \cos^6(\theta) - 315 \cos^4(\theta) + 105 \cos^2(\theta) - 5) + \\ &\quad + \frac{143}{137\pi} \frac{21}{6} * \cos(5\varphi) \sin^5(\theta) \cos(\theta)]] \end{aligned} \quad (9)$$

what do we  
expect to see  
on the ball?



..a simpler experimental test of the adaptation model is to raise rodents either in or on a ball

## Spherical harmonics



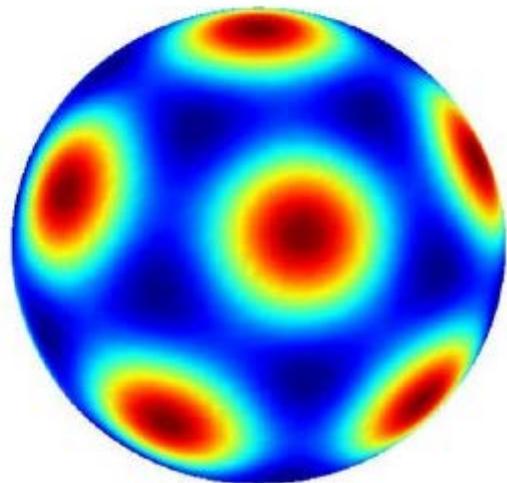
Federico  
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12 fields,  $l=6$



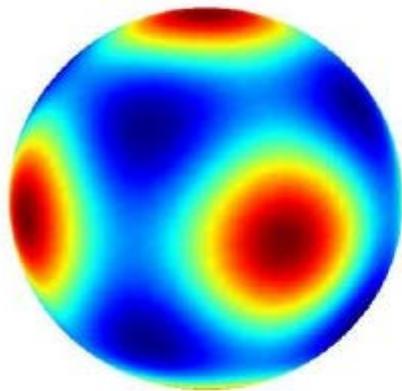
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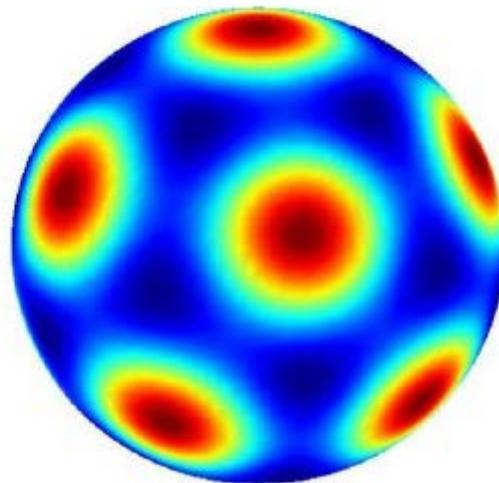


Federico  
on the ball

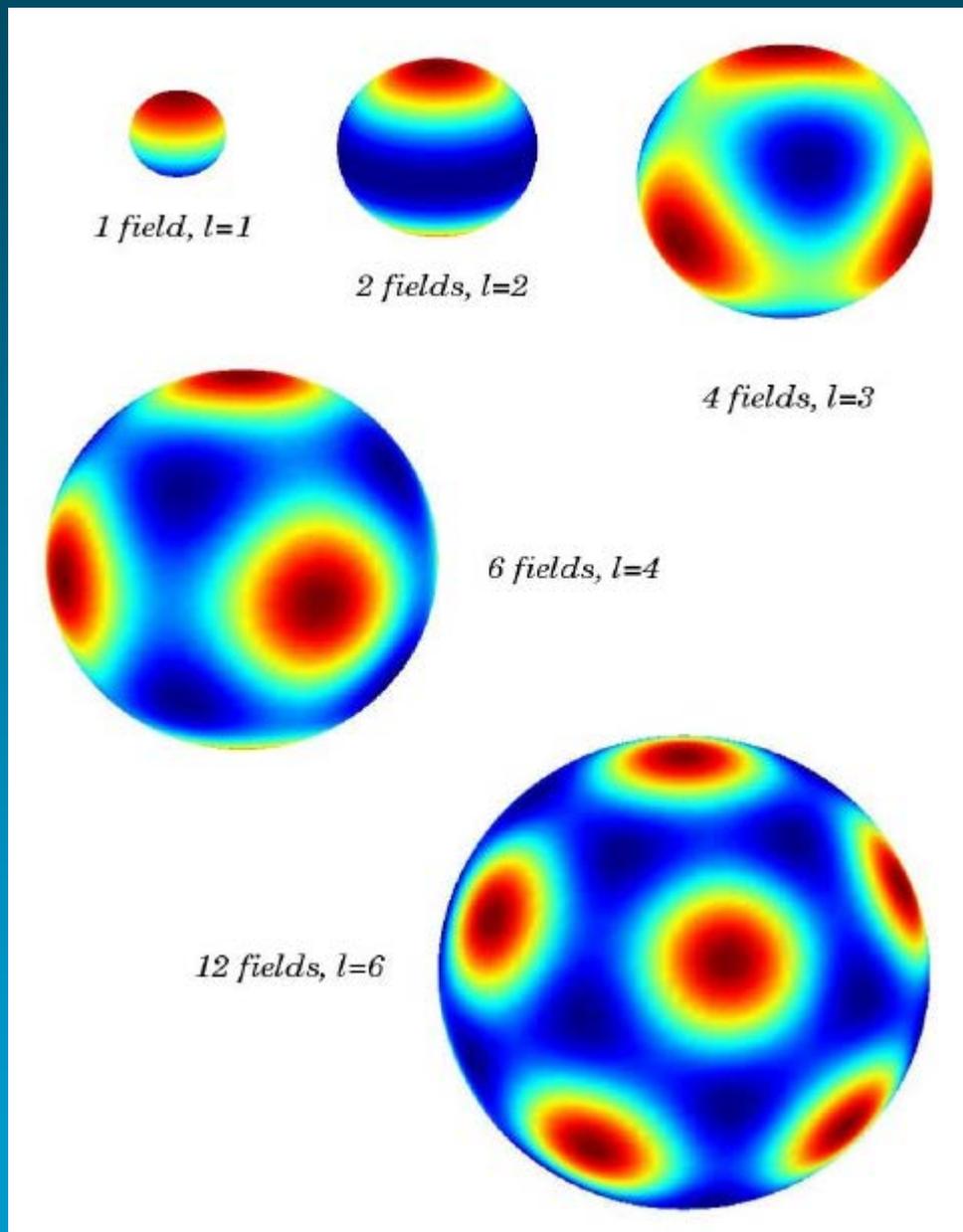


*6 fields, l=4*

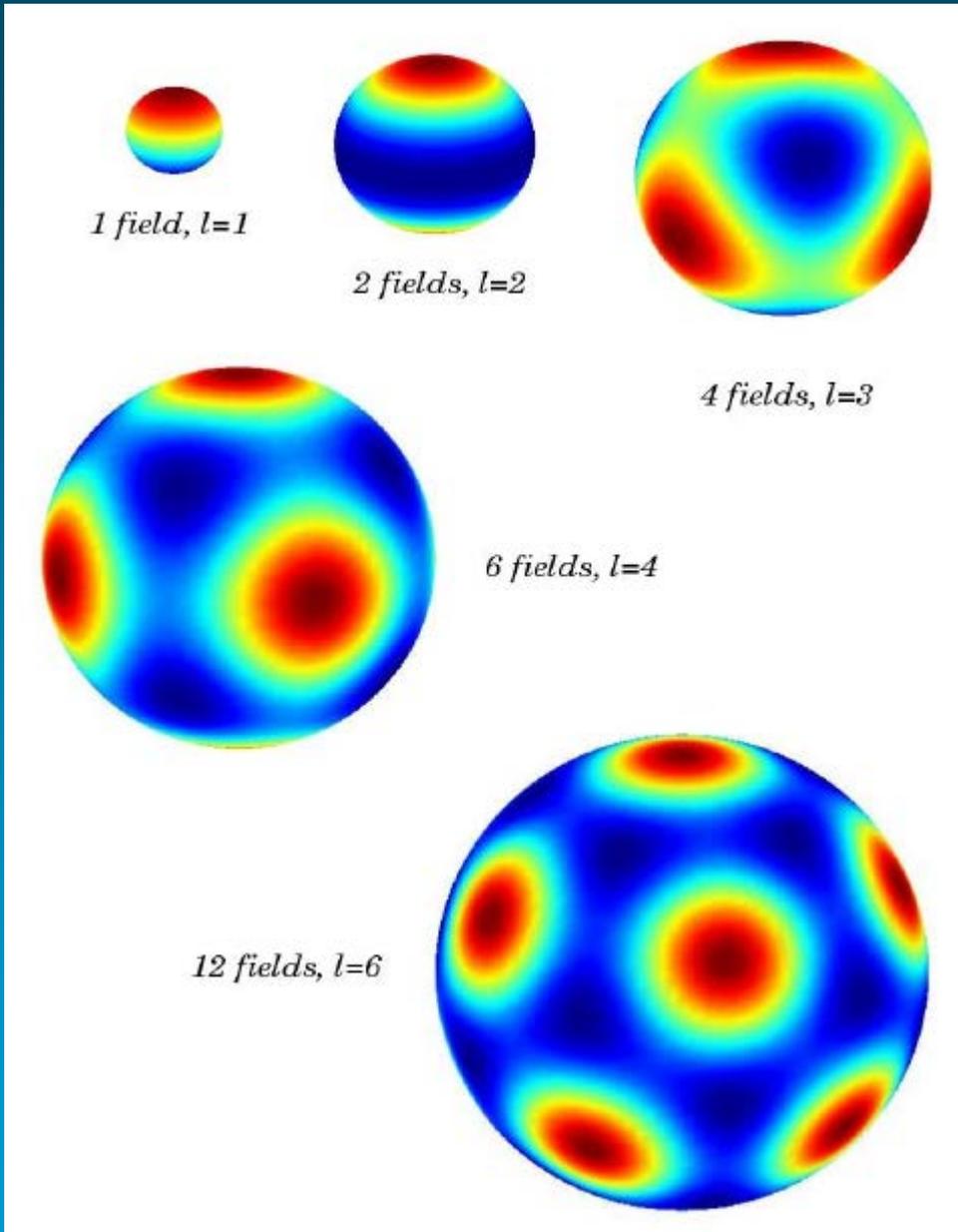
*12 fields, l=6*



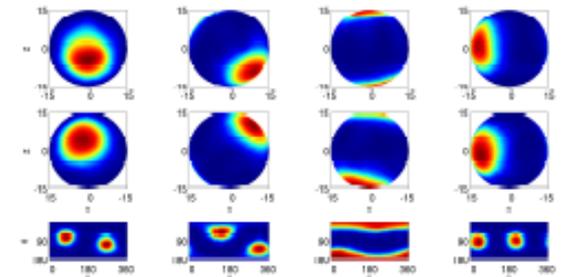
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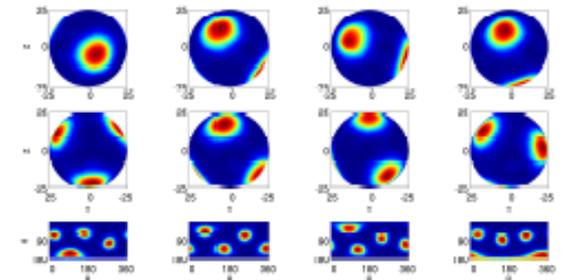
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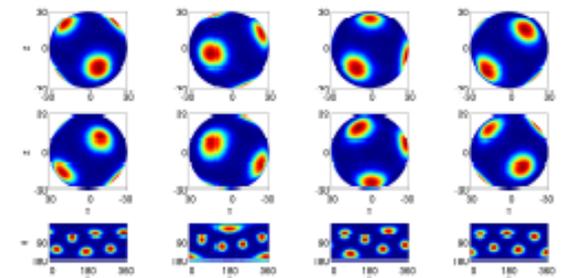
(b)  
 $R = 15\text{cm}$



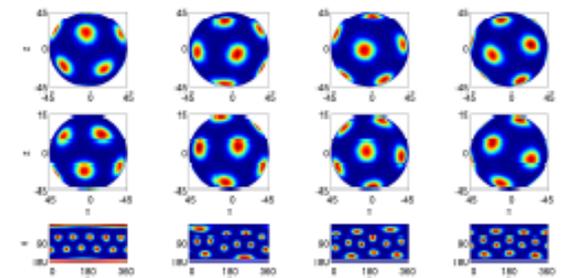
(c)  
 $R = 25\text{cm}$



(d)  
 $R = 30\text{cm}$

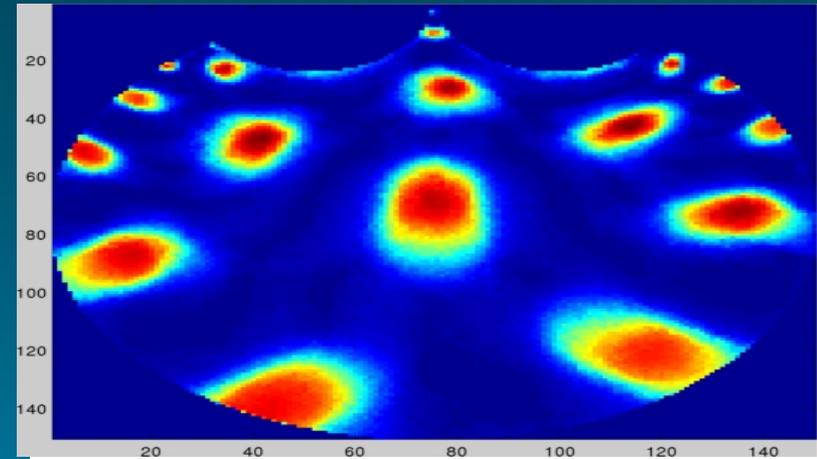
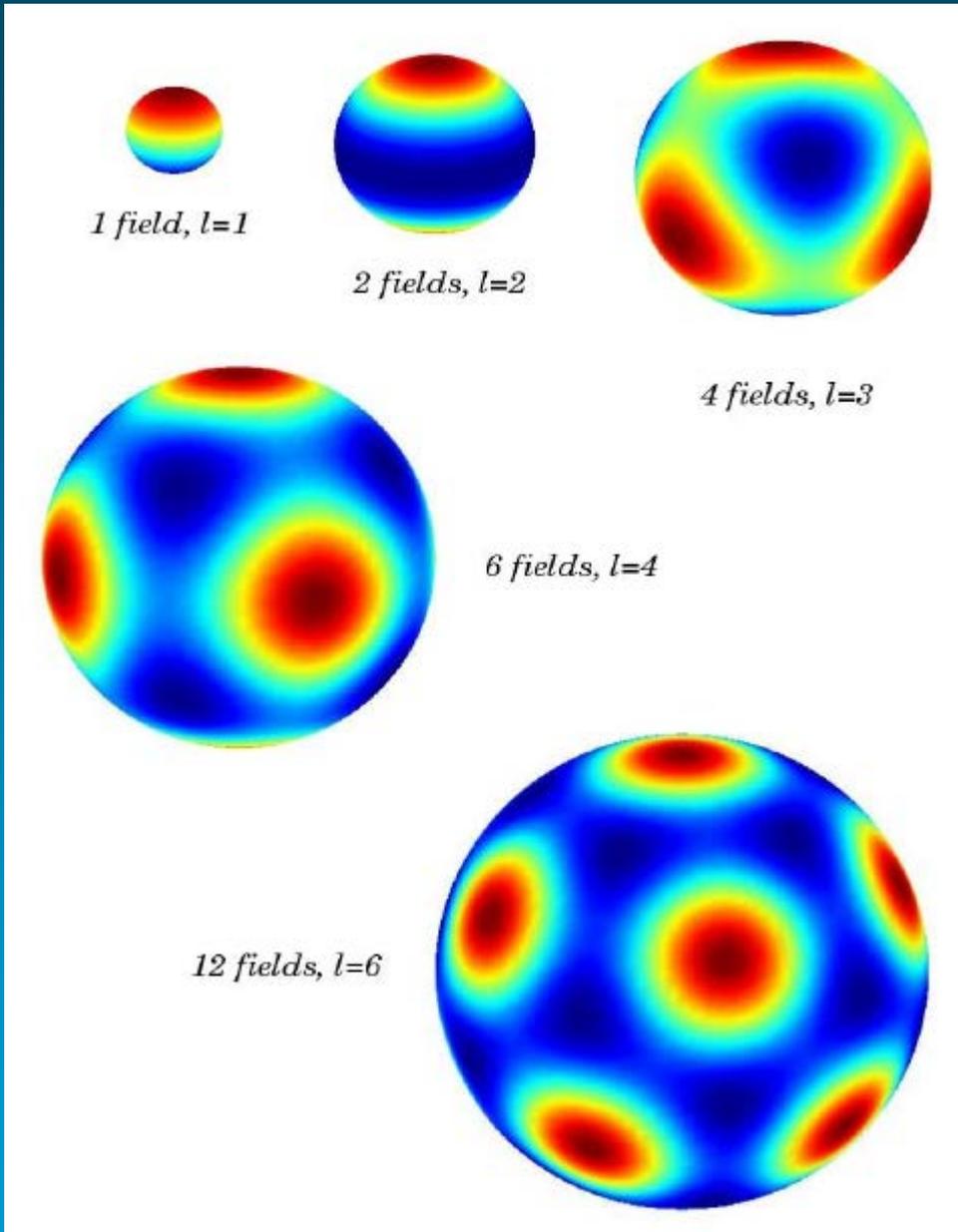


(e)  
 $R = 45\text{cm}$



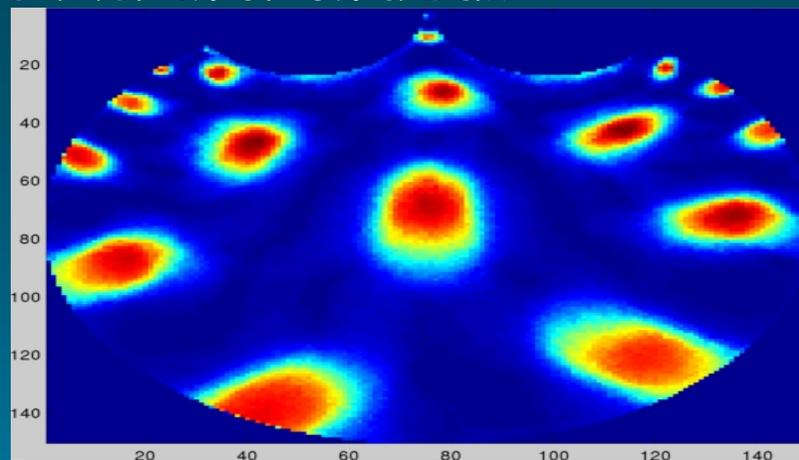
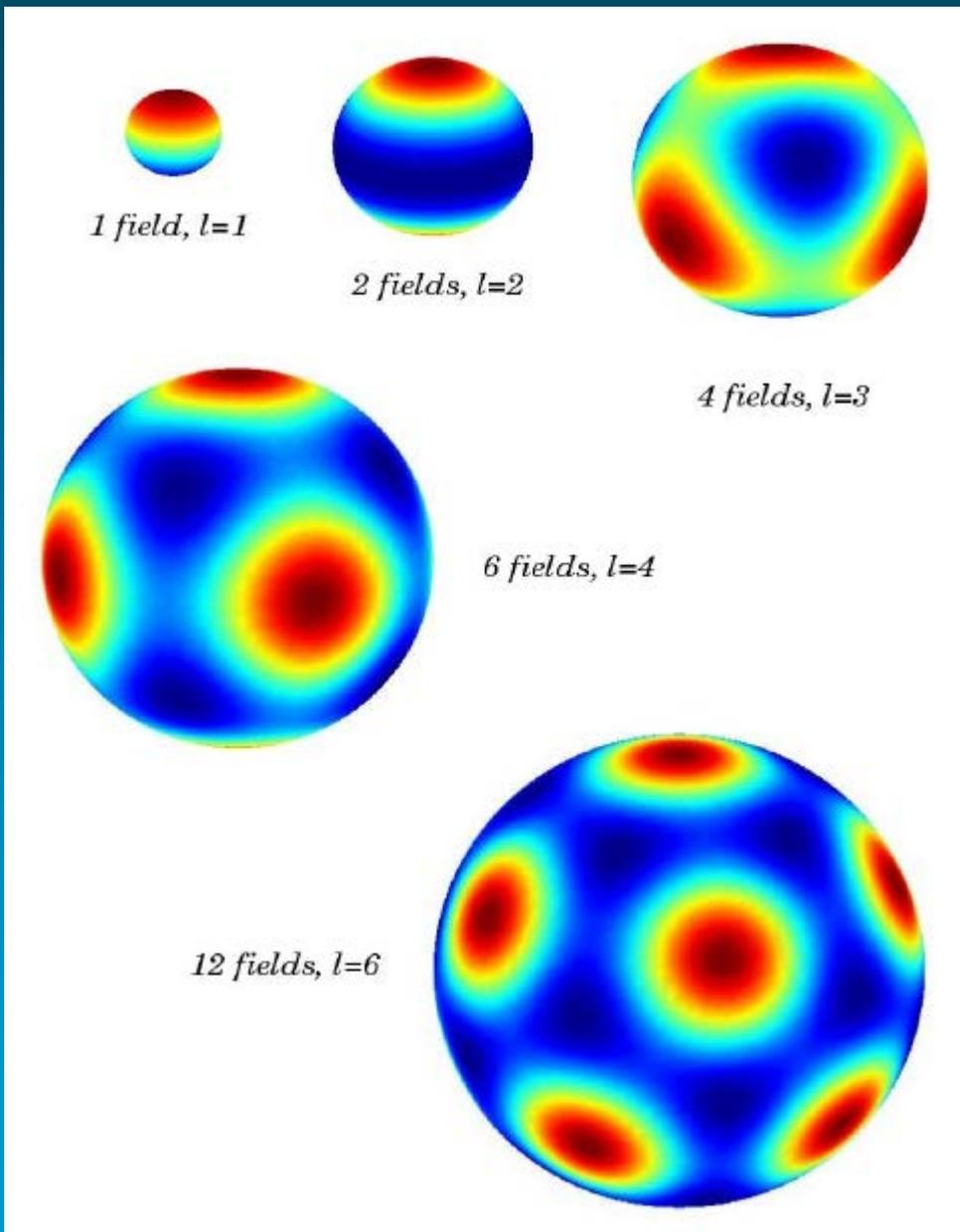
Simulations  
confirm  
the analysis

..a simpler experimental test of the adaptation model is to raise rodents either in or on a ball



Francesca  
& Eugenio  
on a **hyper**  
ball

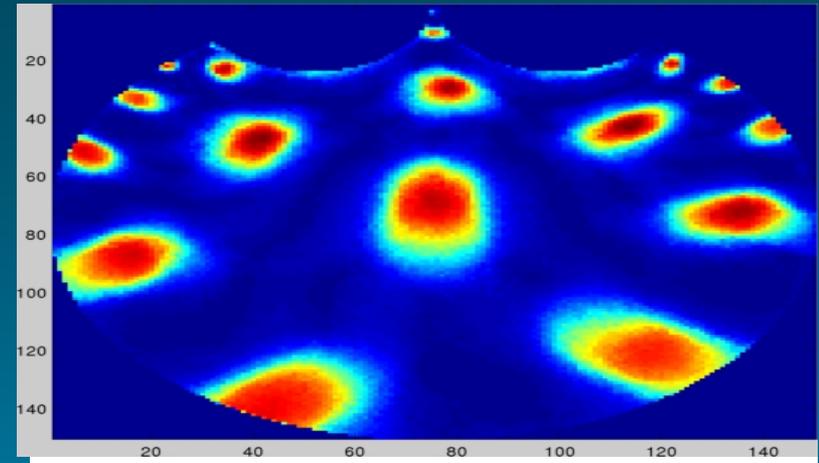
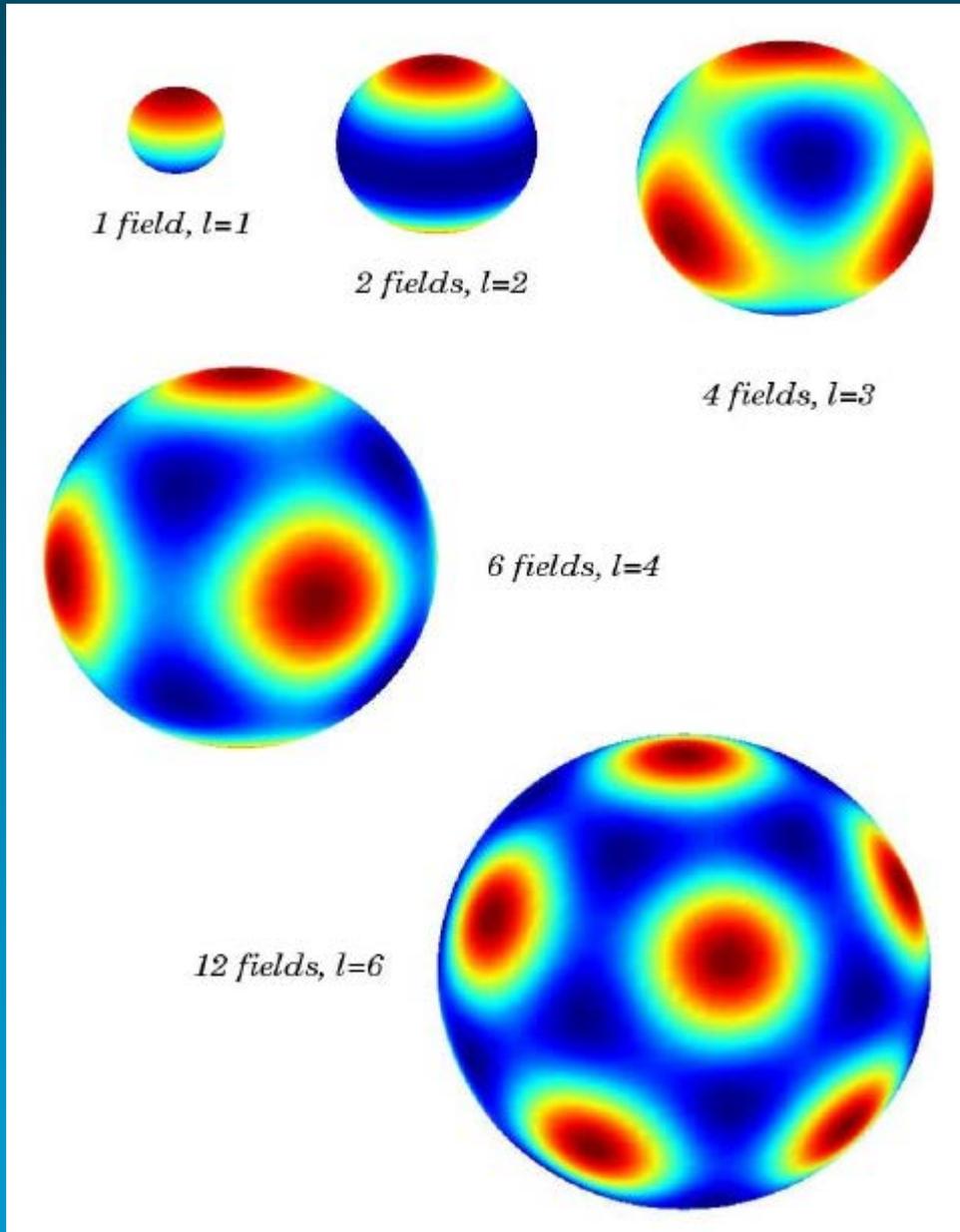
..a simpler experimental test of the adaptation model is to raise rodents either in or on a ball



Francesca  
& Eugenio  
on a **hyper**  
**ball**

from 0 to 1, 3, 4, 5, **6**, 7, ...  
nearest neighbours

..a simpler experimental test of the adaptation model is to raise rodents either in or on a ball



Ingvild in Trondheim

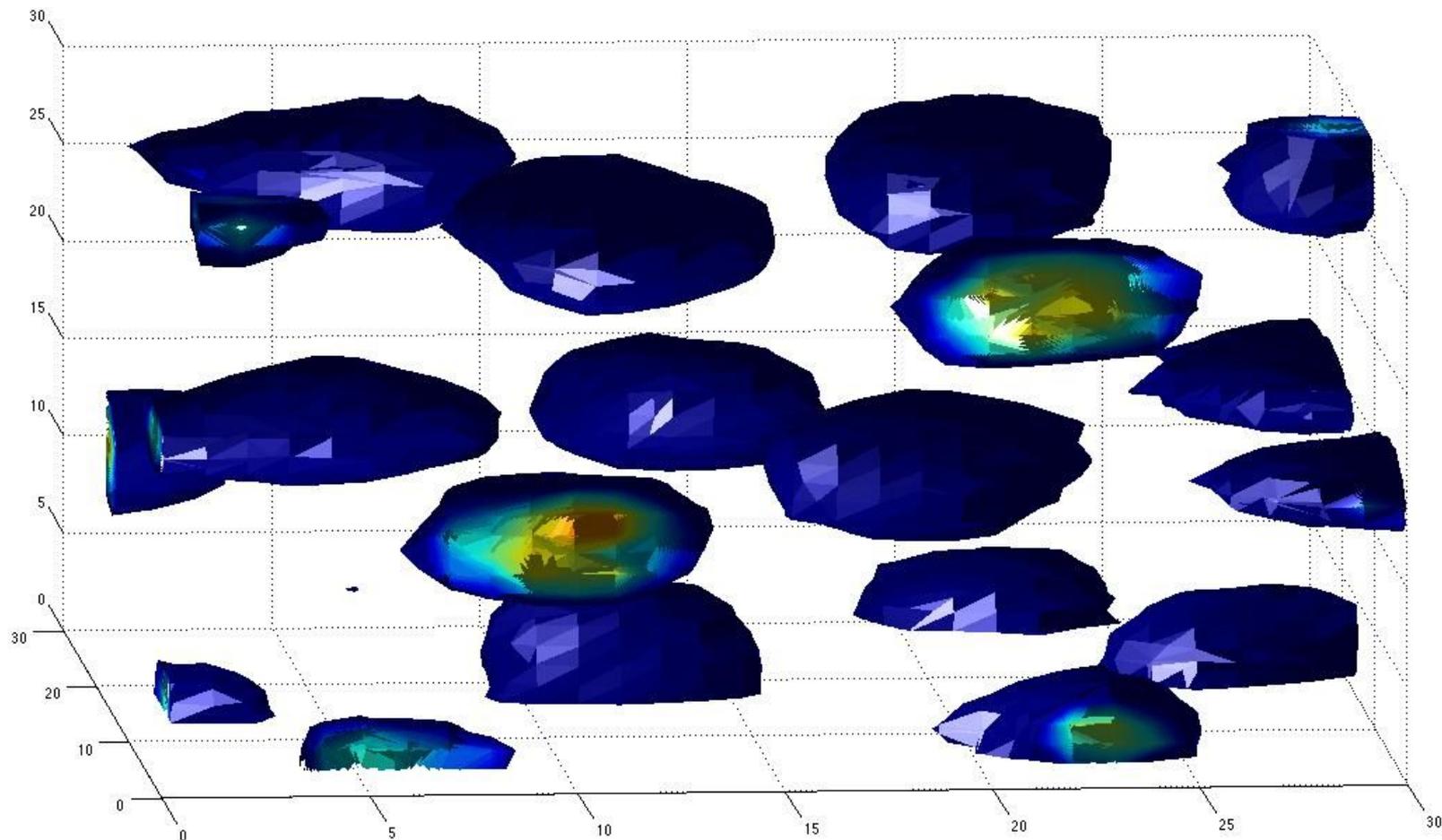
# What to expect in 3D?

(soon to be discovered by Nachum Ulanovsky)



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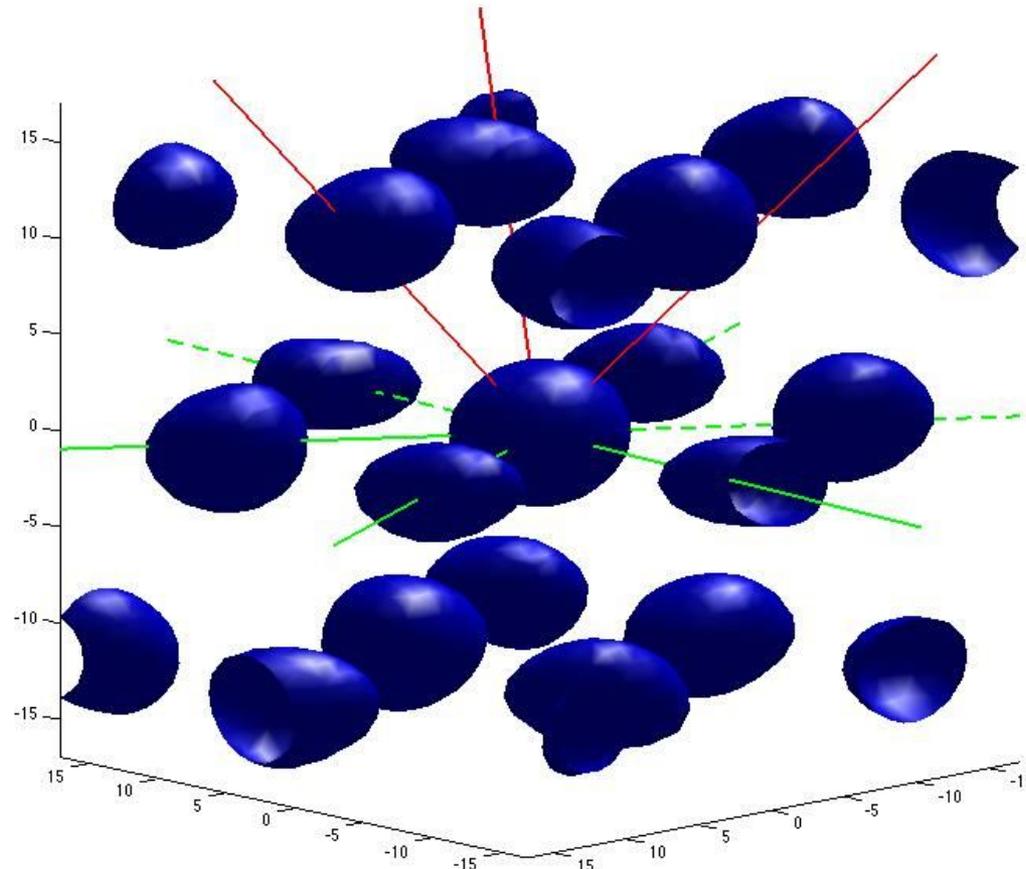


# What to expect in 3D?

(soon to be discovered by Nachum Ulanovsky)



FCC  
lattice



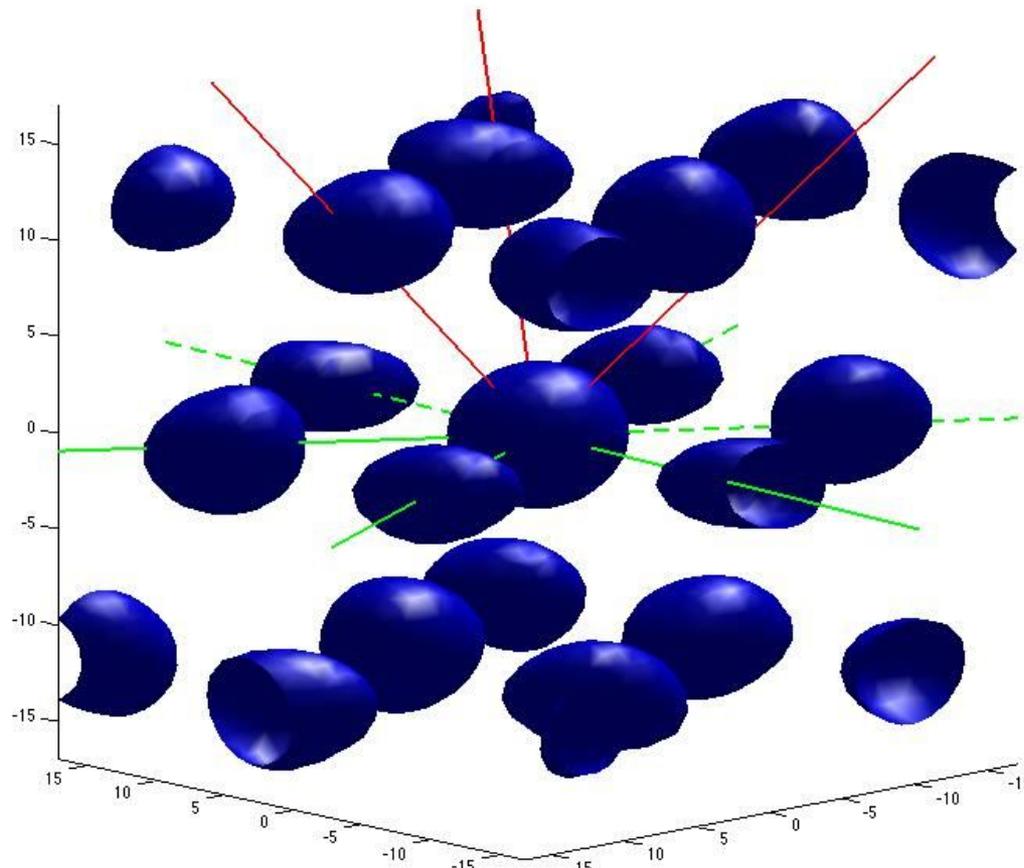
(or HCP  
or mixed)

# What to expect in 3D?

(soon to be discovered by Nachum Ulanovsky)



FCC  
lattice



(or HCP  
or mixed)

Rather than Euclides or Kant, the space of one's experience

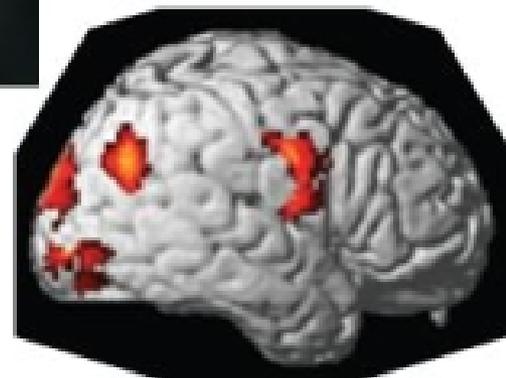
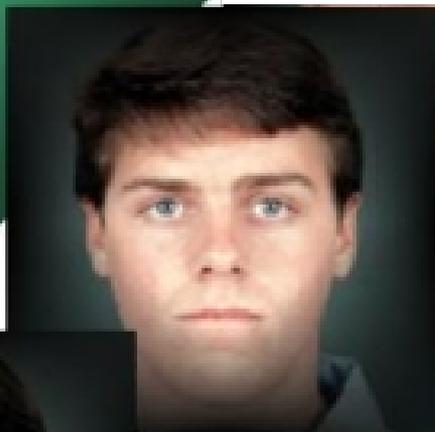
expression

# Free-energy landscape

identification

prediction

?



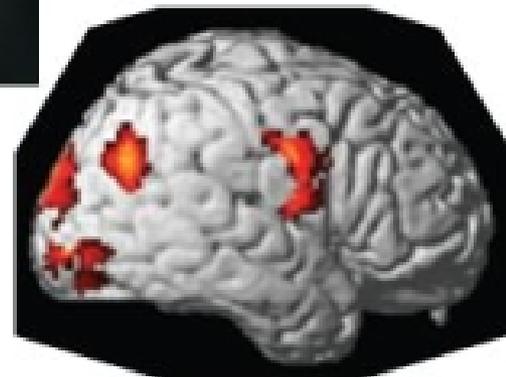
identity

expression

Free-energy  
landscape

identification

prediction



identity

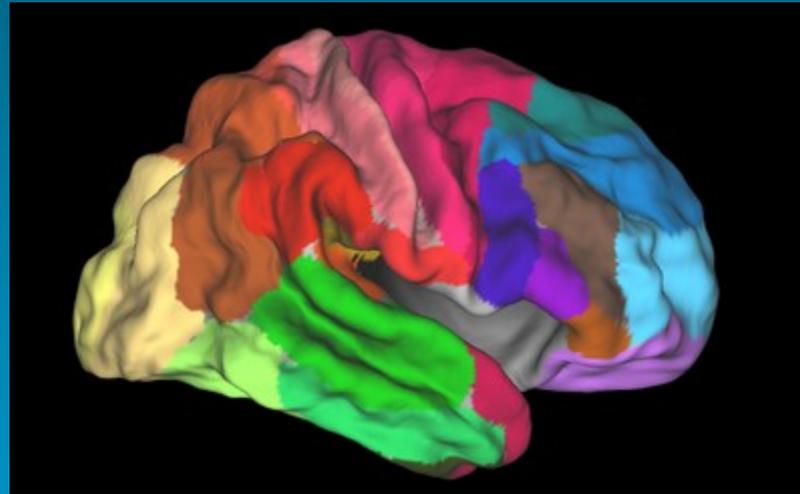


SISSA

GRidmap  
is looking for a self-organizing  
**postdoc**,  
who wants to understand navigation  
in unexplored spaces



limbo



MICA

MASTER IN COMPLEX ACTIONS

**NEXT GENERATION LEADERS**