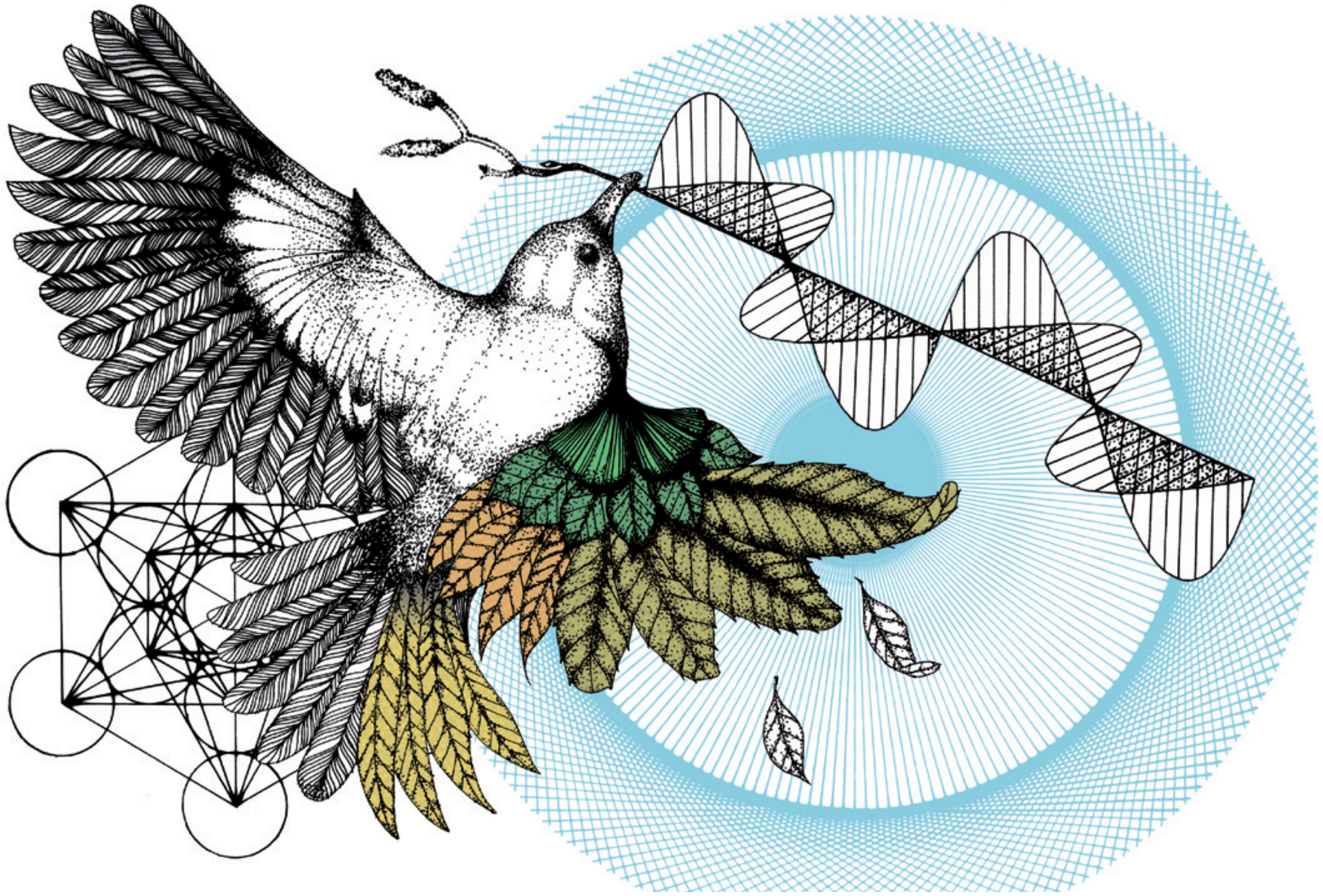


the dawn of Quantum Biology

Hsiu-Hau Lin
National Tsing Hua Univ.

outline

- introduction to quantum biology
- photosynthesis
- olfactory receptors
- theory and predictions
- conclusions

quantum biology

REVIEW ARTICLE

| DOI: 10.1038/NPHYS2474

nature physics

Nature Physics **9**, 10 (2013)

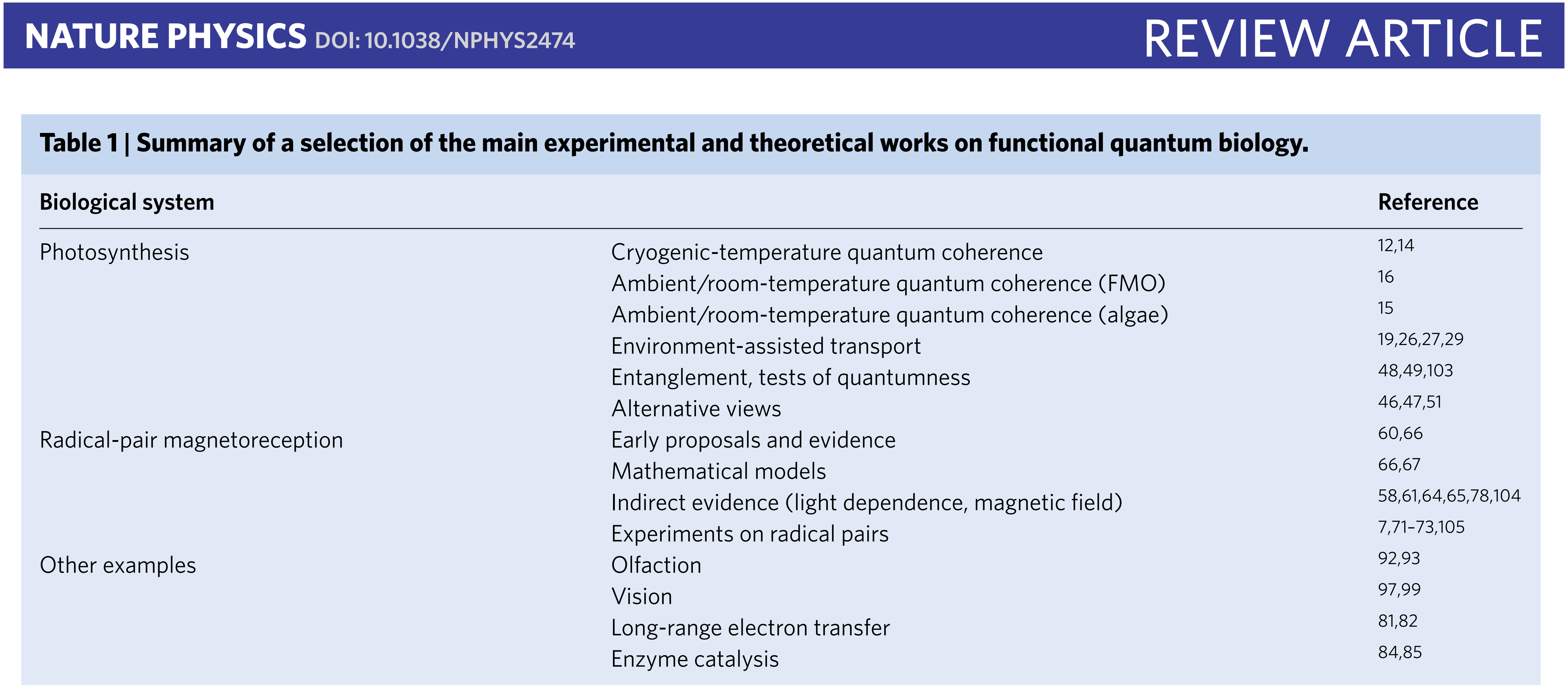
Quantum biology

Neill Lambert[1]★, Yueh-Nan Chen[2], Yuan-Chung Cheng[3], Che-Ming Li[4], Guang-Yin Chen[2]
and Franco Nori[1,5]★

Recent evidence suggests that a variety of organisms may harness some of the unique features of quantum mechanics to gain a biological advantage. These features go beyond trivial quantum effects and may include harnessing quantum coherence on physiologically important timescales. In this brief review we summarize the latest results for non-trivial quantum effects in photosynthetic light harvesting, avian magnetoreception and several other candidates for functional quantum biology. We present both the evidence for and arguments against there being a functional role for quantum coherence in these systems.

Can we find quantum coherence in biology?

potential candidates



NATURE PHYSICS DOI: 10.1038/NPHYS2474 REVIEW ARTICLE

Table 1 | Summary of a selection of the main experimental and theoretical works on functional quantum biology.

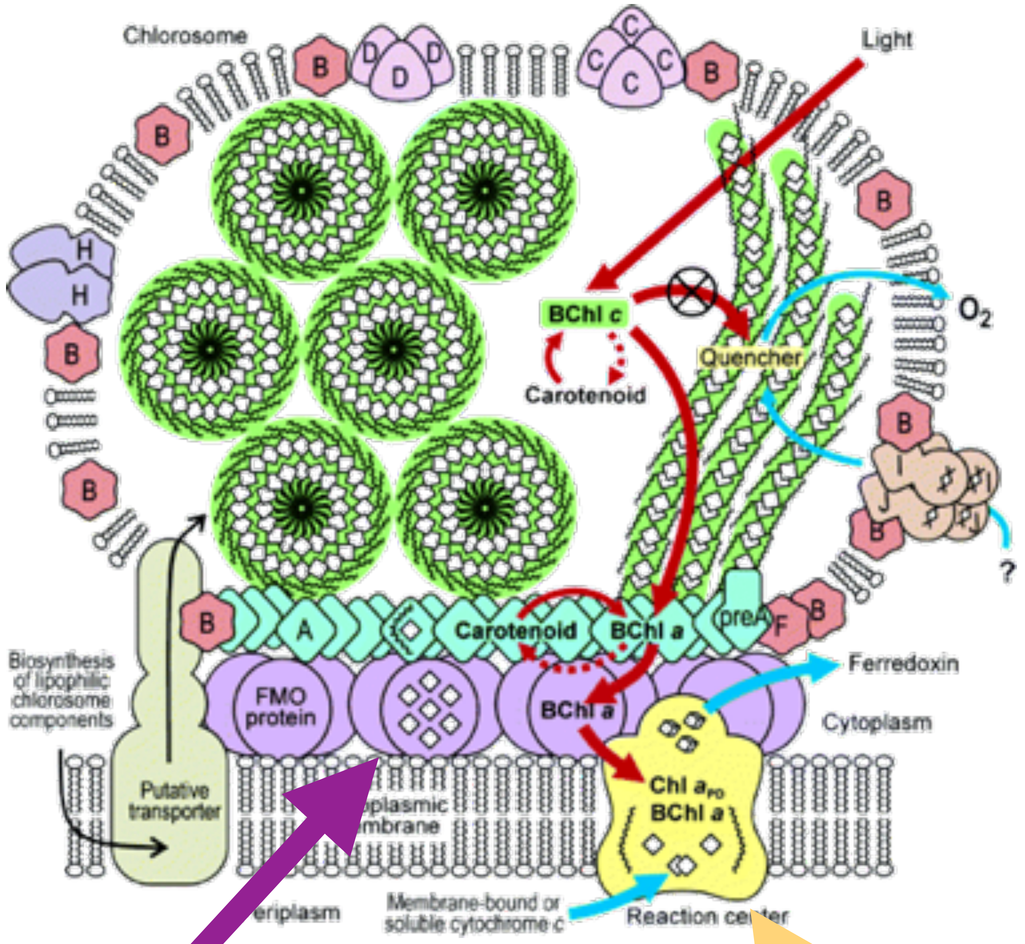
Biological system		**Reference**
Photosynthesis	Cryogenic-temperature quantum coherence	12,14
	Ambient/room-temperature quantum coherence (FMO)	16
	Ambient/room-temperature quantum coherence (algae)	15
	Environment-assisted transport	19,26,27,29
	Entanglement, tests of quantumness	48,49,103
	Alternative views	46,47,51
Radical-pair magnetoreception	Early proposals and evidence	60,66
	Mathematical models	66,67
	Indirect evidence (light dependence, magnetic field)	58,61,64,65,78,104
	Experiments on radical pairs	7,71–73,105
Other examples	Olfaction	92,93
	Vision	97,99
	Long-range electron transfer	81,82
	Enzyme catalysis	84,85

Focus on photosynthesis and olfaction in this talk.

photosynthesis

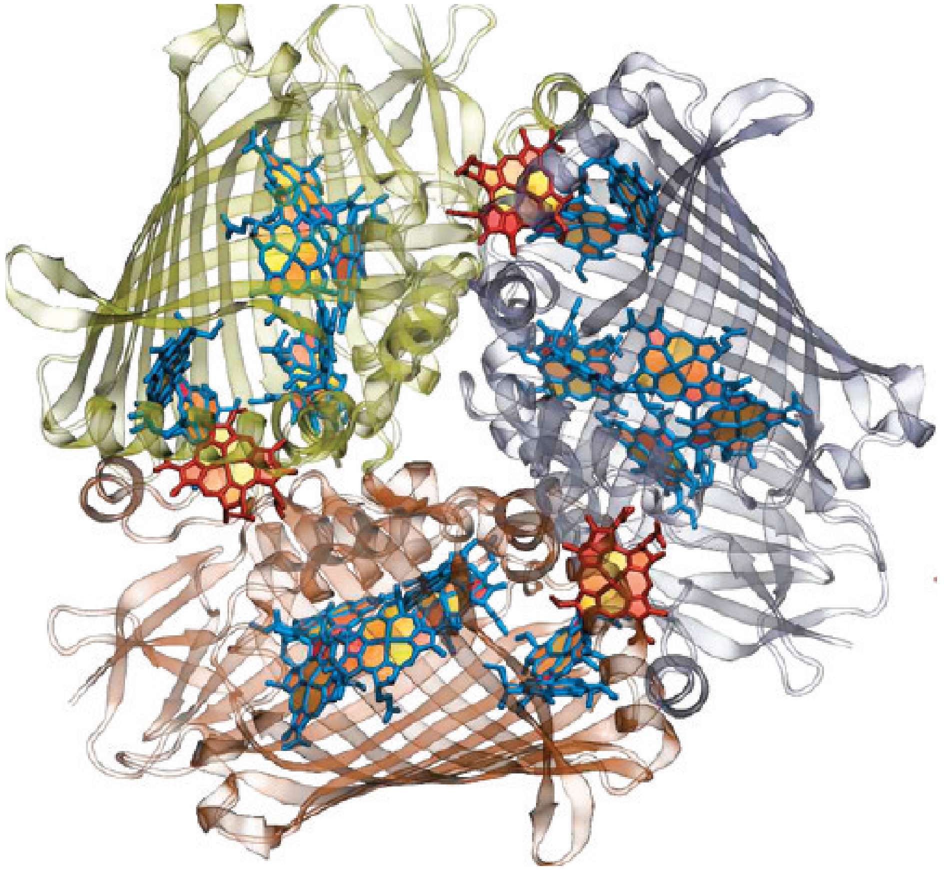
FMO complex

Chlorosome complex



FMO complex

reaction center



FMO is a trimer with 7 pigments inside each monomer.

exciton transport

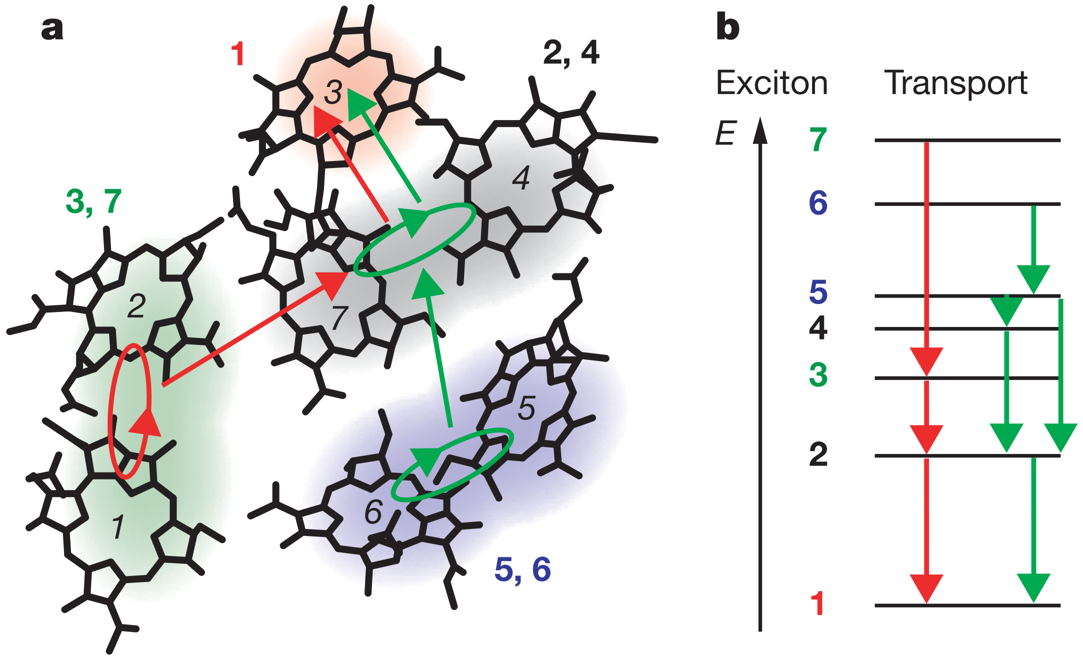
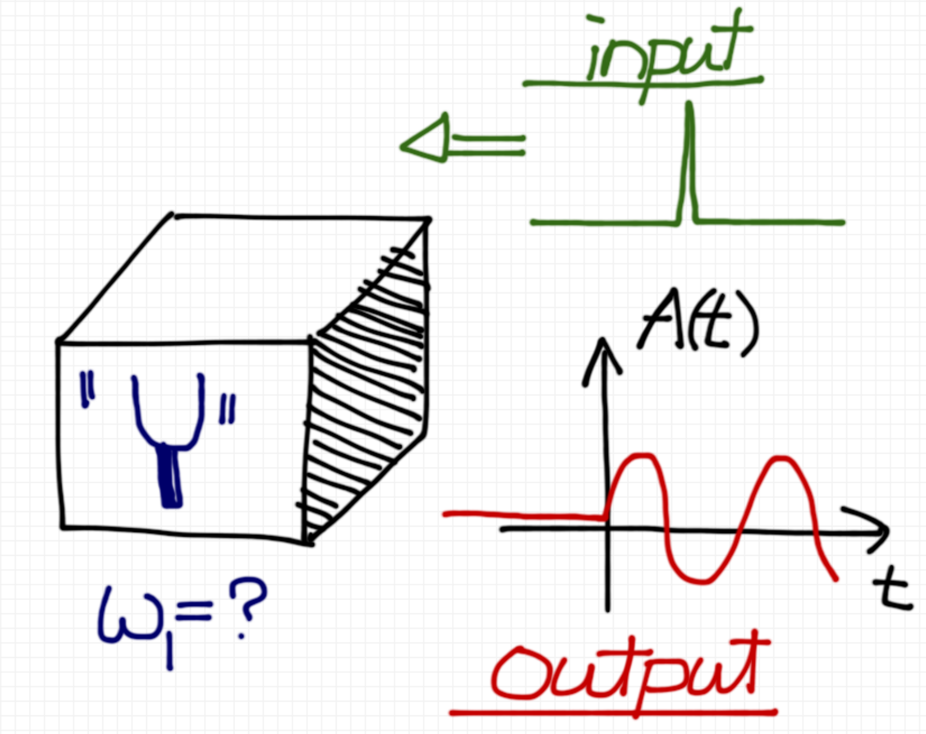


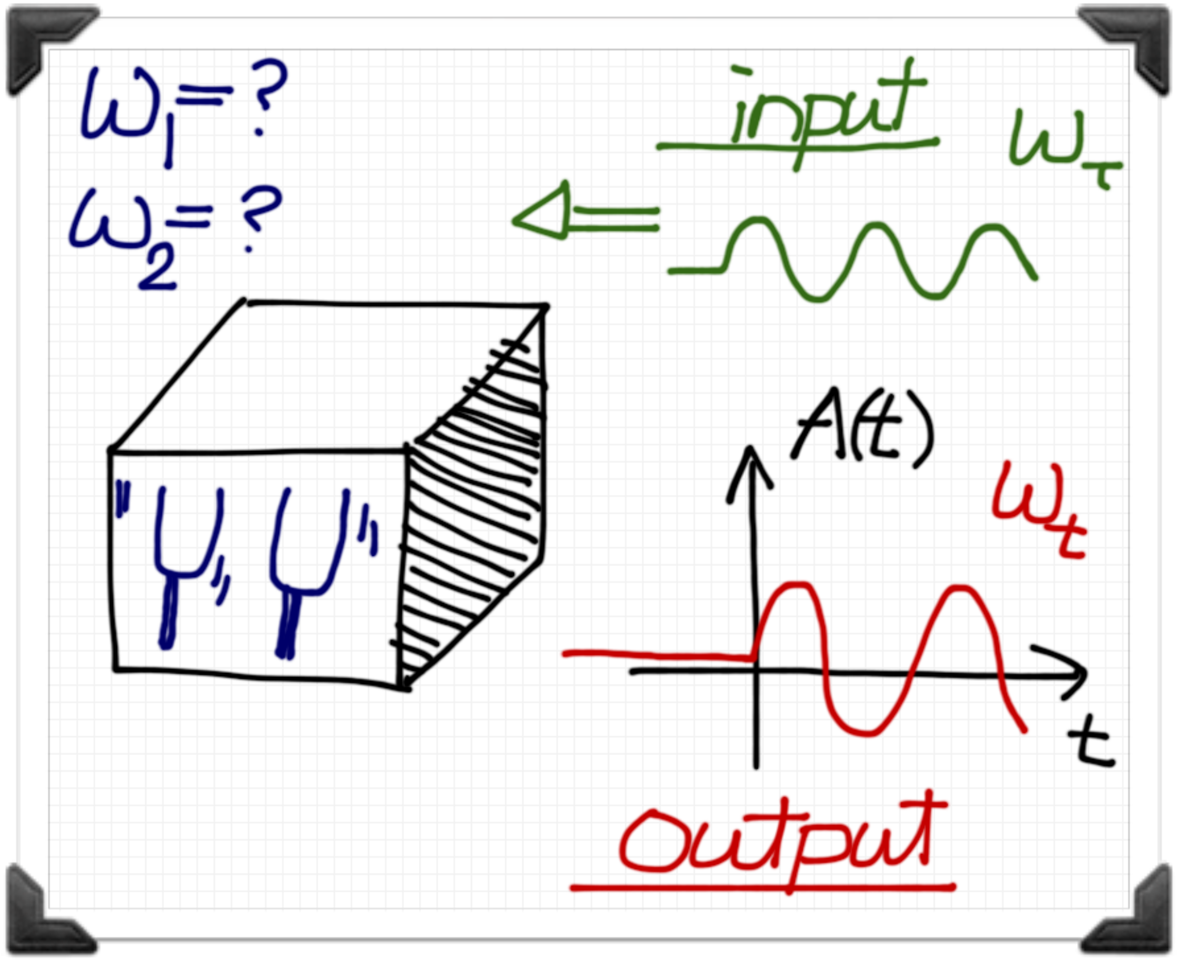
Figure 2 Exciton delocalization and energy transport. **a**, The FMO structural arrangement of the seven BChl molecules (italic numbers) is overlaid qualitatively with the delocalization patterns of the different excitons (coloured shading, bold numbers). Two main photoexcitation transfer pathways are indicated by red and green arrows. **b**, The energy transport is not just a simple process of stepwise energy decrease from one level to the next level below; rather, intermediate states are left out if they have insufficient spatial overlap with potential transfer partners.

Nature **434**, 625 (2005)

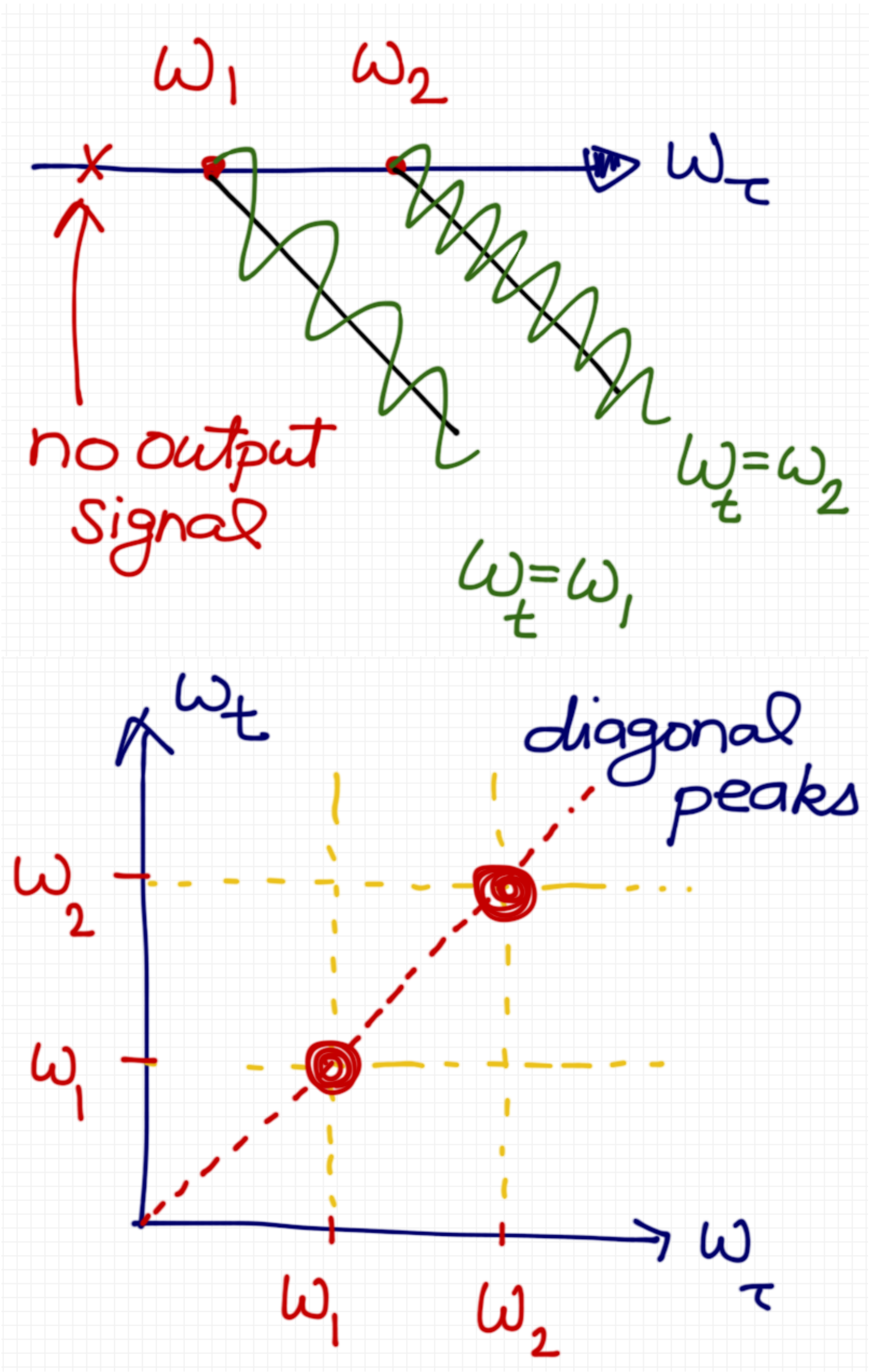


Can we detect the excitonic states by simple pump-probe experiments?

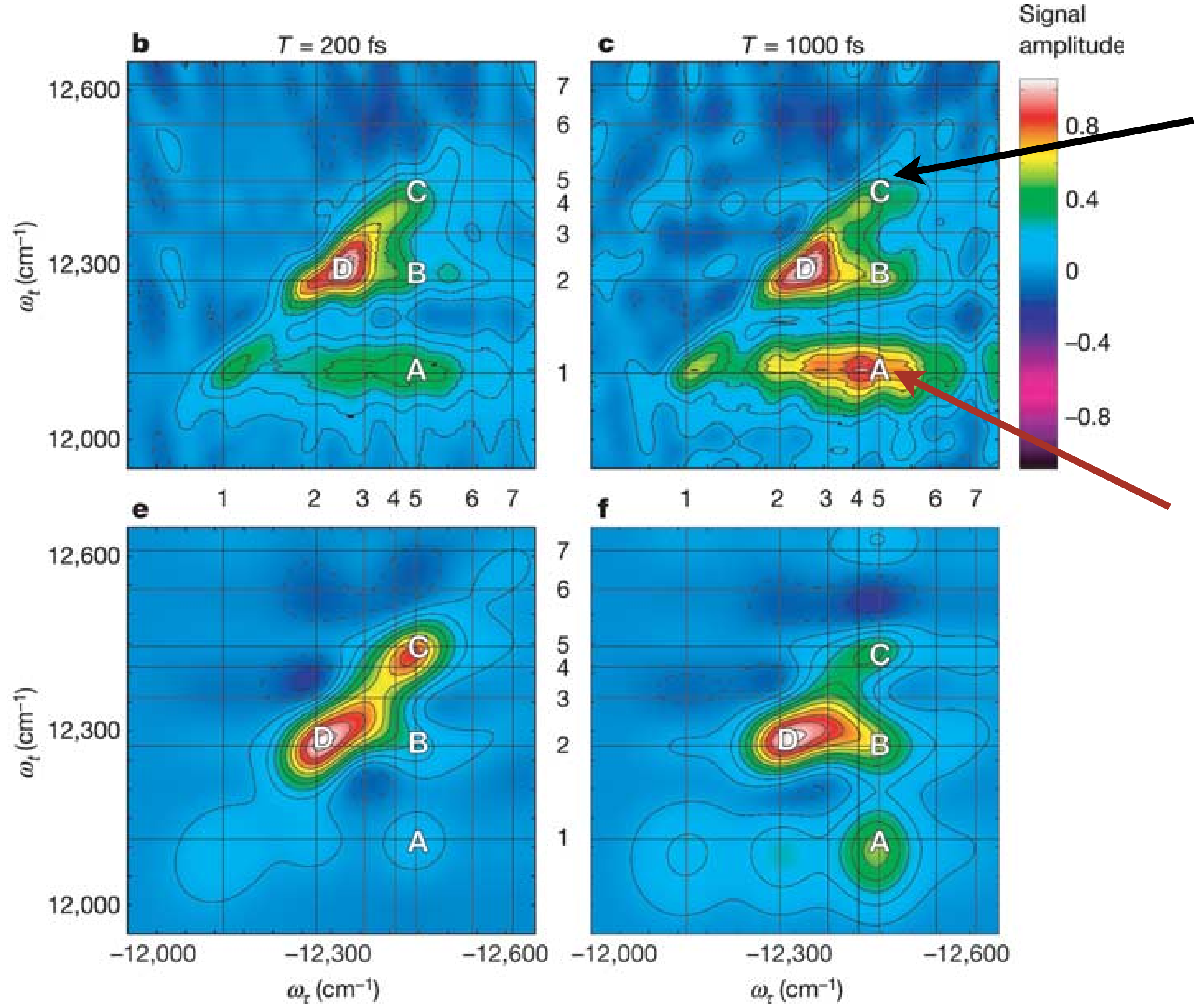
pump and probe



On resonance, the output frequency echoes the input frequency.



off-diagonal peaks



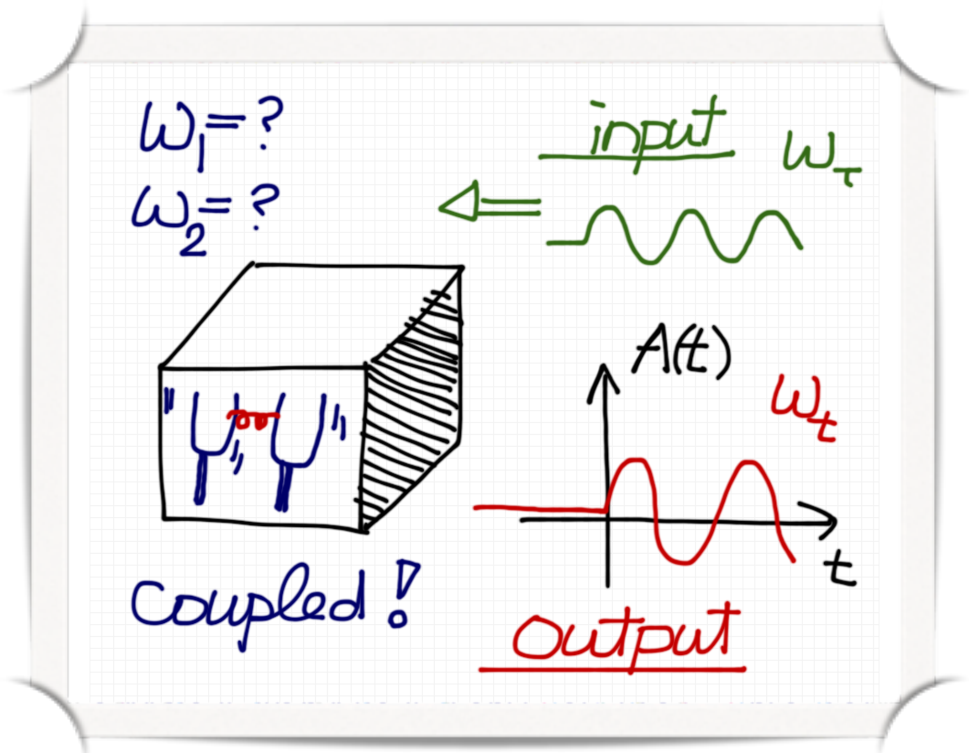
Diagonal peaks (C,D) expected.

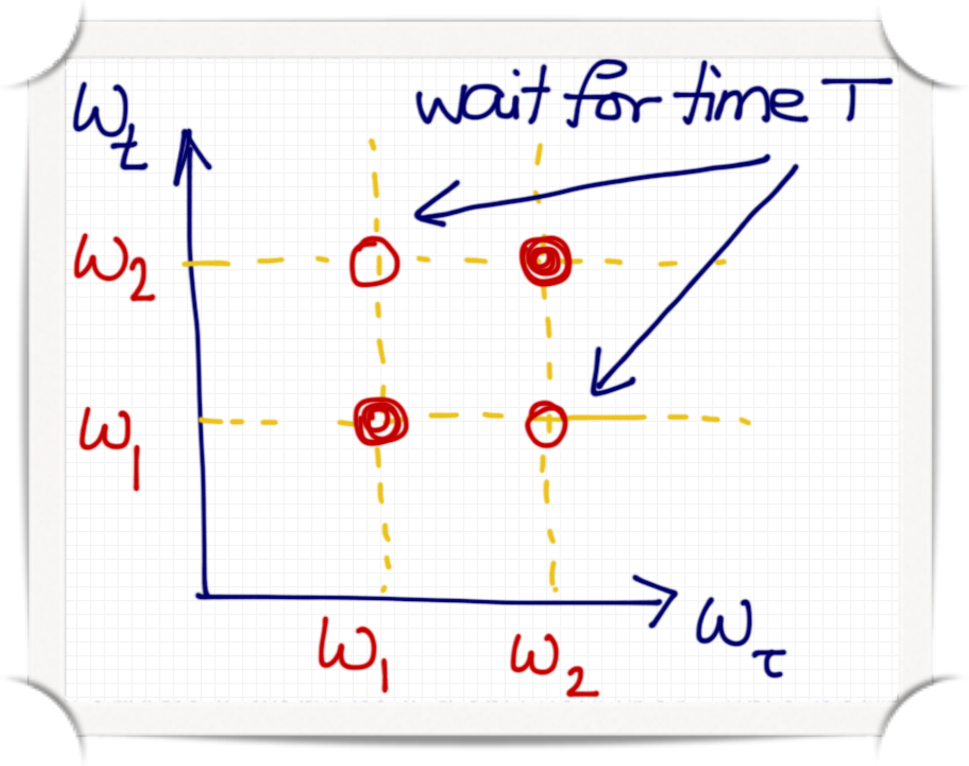
Off-diagonal peaks (A,B) show up... What happens?

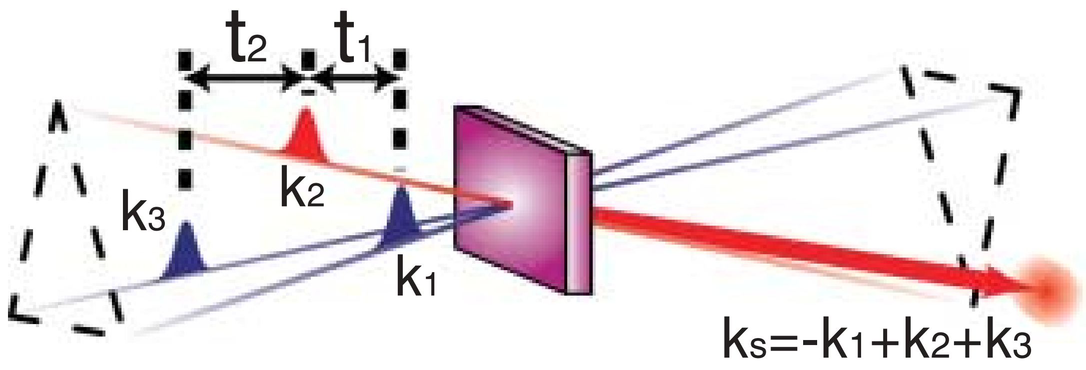
Nature **434**, 625 (2005)

The real biological systems seem to be more complicated. Off-diagonal peaks show up!

three-pulse pump-probe







Three-pulse pump-probe:

The first two pulses pump and entangled two excitonic states and the third one probe the entangled dynamics.

quantum coherence

Science **316**, 1462 (2007)

Coherence Dynamics in Photosynthesis: Protein Protection of Excitonic Coherence

Hohjai Lee, Yuan-Chung Cheng, Graham R. Fleming*

The role of quantum coherence in promoting the efficiency of the initial stages of photosynthesis is an open and intriguing question. We performed a two-color photon echo experiment on a bacterial reaction center that enabled direct visualization of the coherence dynamics in the reaction center. The data revealed long-lasting coherence between two electronic states that are formed by mixing of the bacteriopheophytin and accessory bacteriochlorophyll excited states. This coherence can only be explained by strong correlation between the protein-induced fluctuations in the transition energy of neighboring chromophores. Our results suggest that correlated protein environments preserve electronic coherence in photosynthetic complexes and allow the excitation to move coherently in space, enabling highly efficient energy harvesting and trapping in photosynthesis.

So, quantum coherence is detected in FMO complex by pump-probe photon echo experiment.

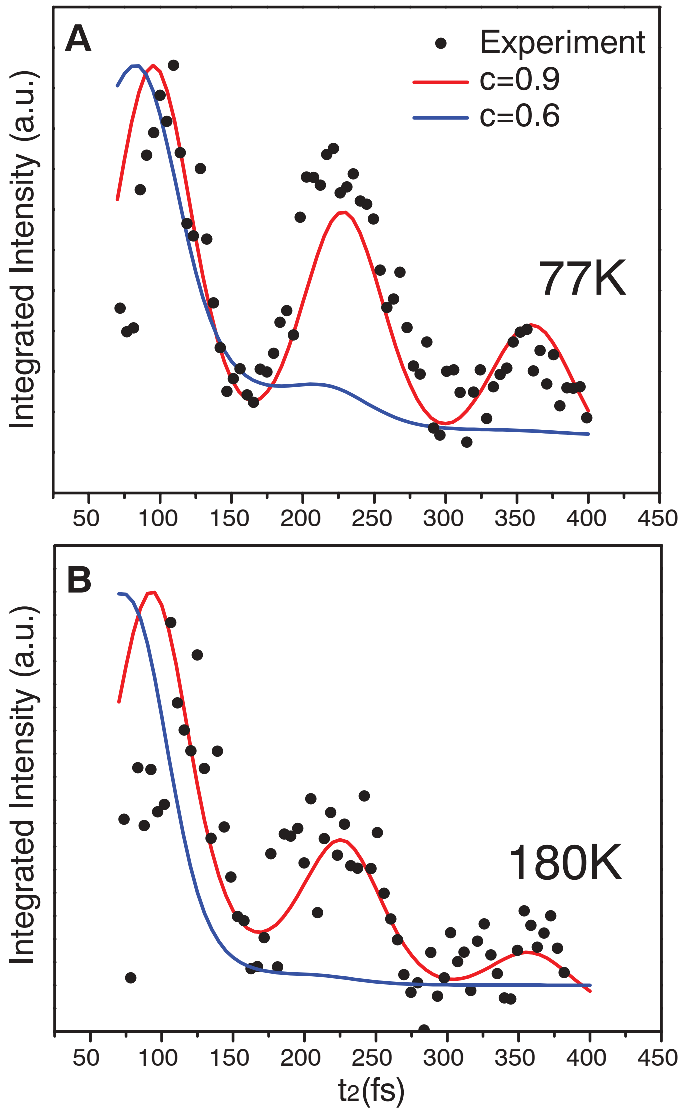
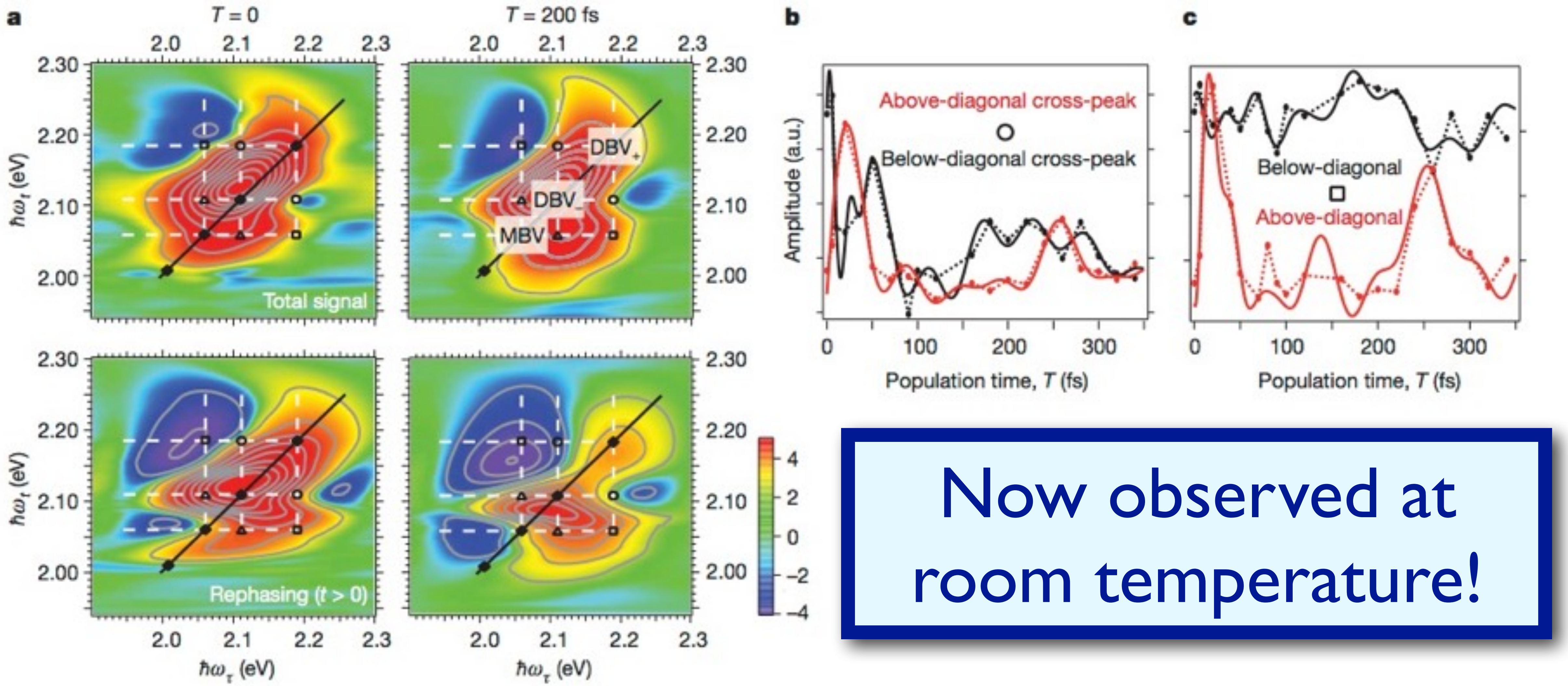


Fig. 3. Integrated echo signals as a function of t_2 at $t_1 = 30$ fs. Because the system evolves as a coherence between the H and B excitons during the t_2 period, this plot represents the dephasing dynamics of the $|B\rangle\langle H|$ coherence. Measurements at 77 K (**A**) and 180 K (**B**) are shown in solid circles, and the theoretical curves are shown in red ($c = 0.9$) or blue ($c = 0.6$) lines. a.u., arbitrary units.

at ambient temp

Nature **463**, 644 (2010)

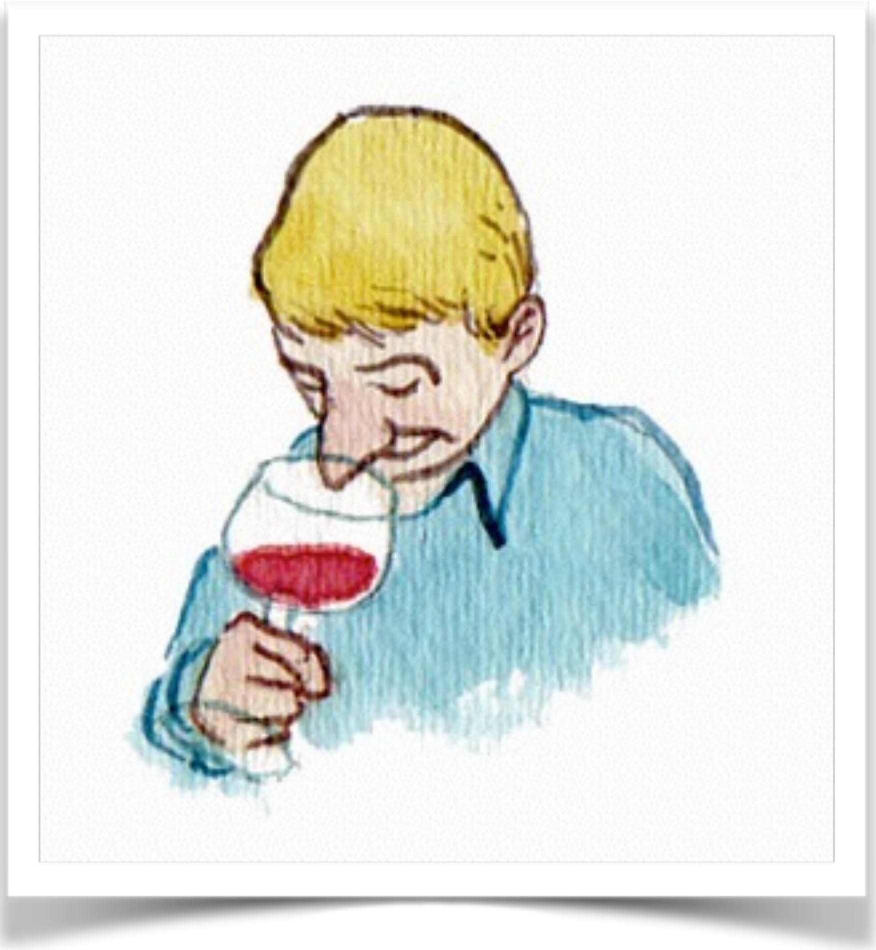


Now observed at room temperature!

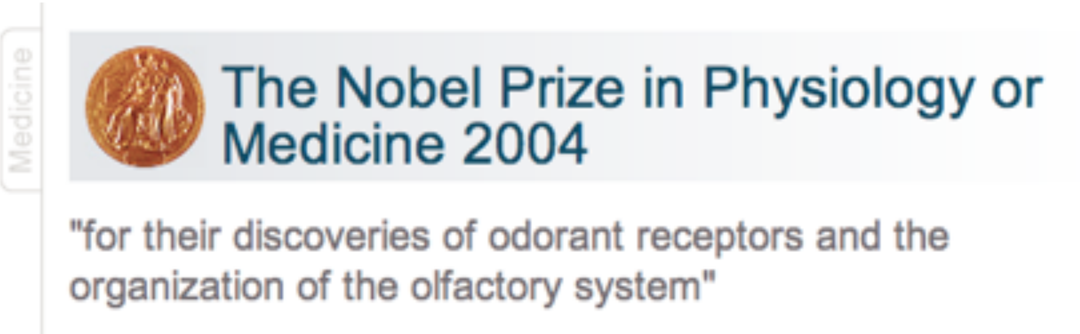
Figure 2 | Two-dimensional photon echo data for PC645. a, The left column shows the total real 2DPE spectrum recorded for PC645 at zero waiting time ($T = 0$), together with the rephasing contribution to this signal. The right column shows the data for $T = 200$ fs. The 2DPE spectra show the signal intensity on an arcsinh scale (colour scale, arbitrary units) plotted as a function of coherence frequency ω_τ and emission frequency ω_t. **b,** Intensity of the DBV dimer cross-peaks (open circle) as a function of time T. **c,** Intensity of the MBV–DBV$_+$ cross-peaks (open square) as a function of time T. The dashed lines interpolate the data points (solid circles). The solid line is a fit to a sum of damped sine functions (Supplementary Information). a.u., arbitrary units.

olfactory receptors

how do we smell?



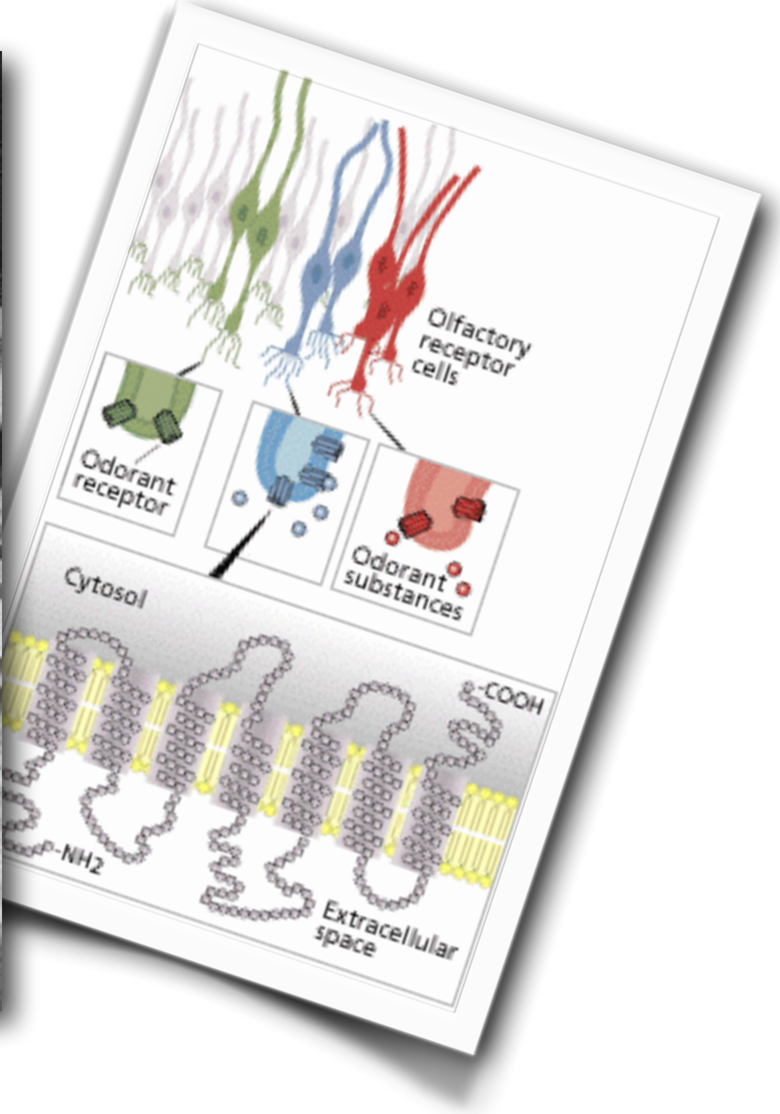
odorant receptors



The Nobel Prize in Physiology or Medicine 2004

"for their discoveries of odorant receptors and the organization of the olfactory system"

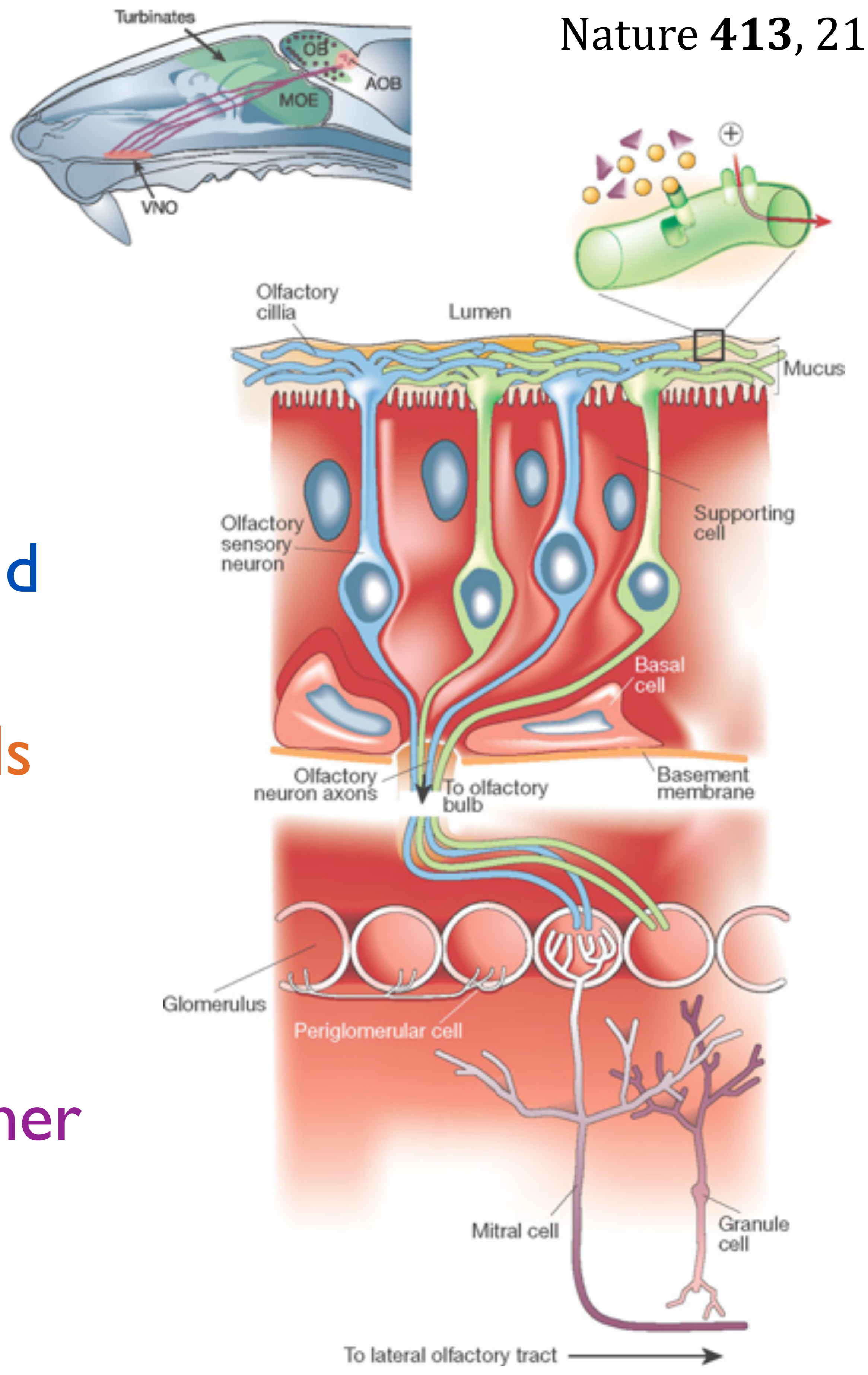
Linda **Buck** and Richard **Axel** discovered olfactory receptors in 1991.



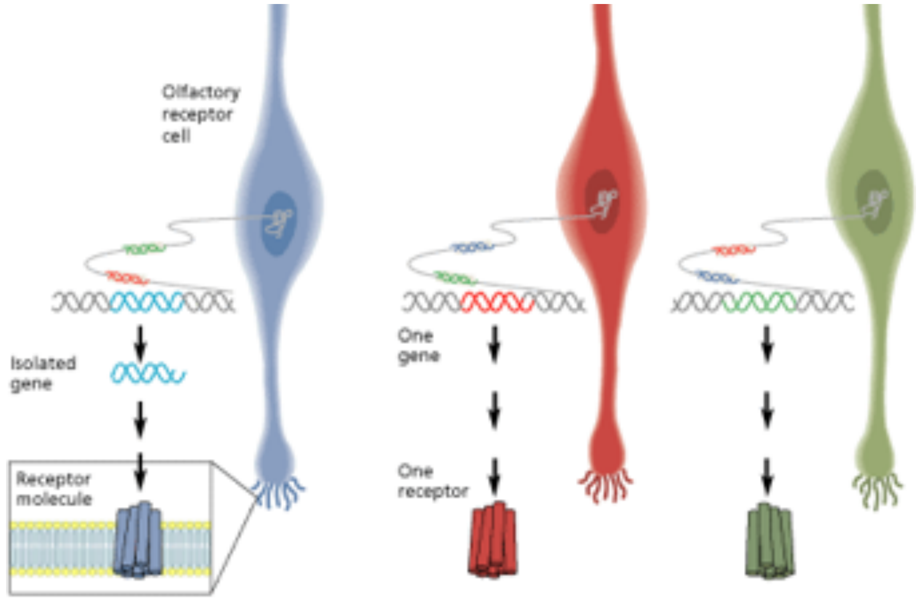
olfaction pathway

Nature **413**, 211 (2001)

- Odorant molecules bind to receptors
- Olfactory receptor cells are activated
- Signals are relayed in glomerulus
- Final processing in higher regions of the brain



many, many receptors...



Identification of genes

The genes encoding the receptor molecules were isolated and identified.

An unexpected finding!

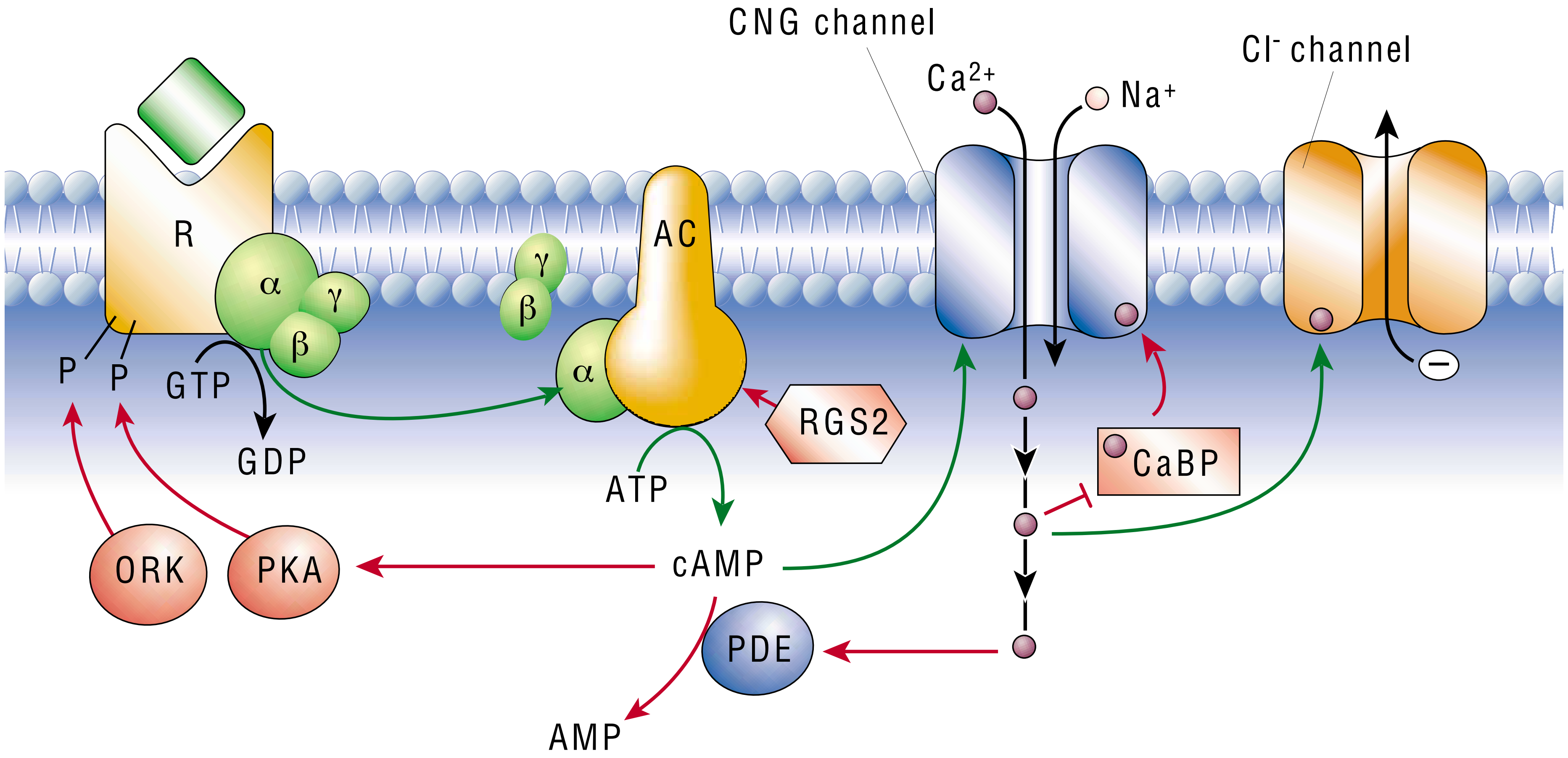
Every single olfactory receptor cell expresses one and only one gene of all the genes that code for olfactory receptor molecules.

It is now known that there are about 350 functional odorant receptors in human being and twice more for all (including inactive) odorant receptors.

This number of genes specific to the olfactory system is about 3% of our whole genome, second only to those of the immune system.

neuron activation

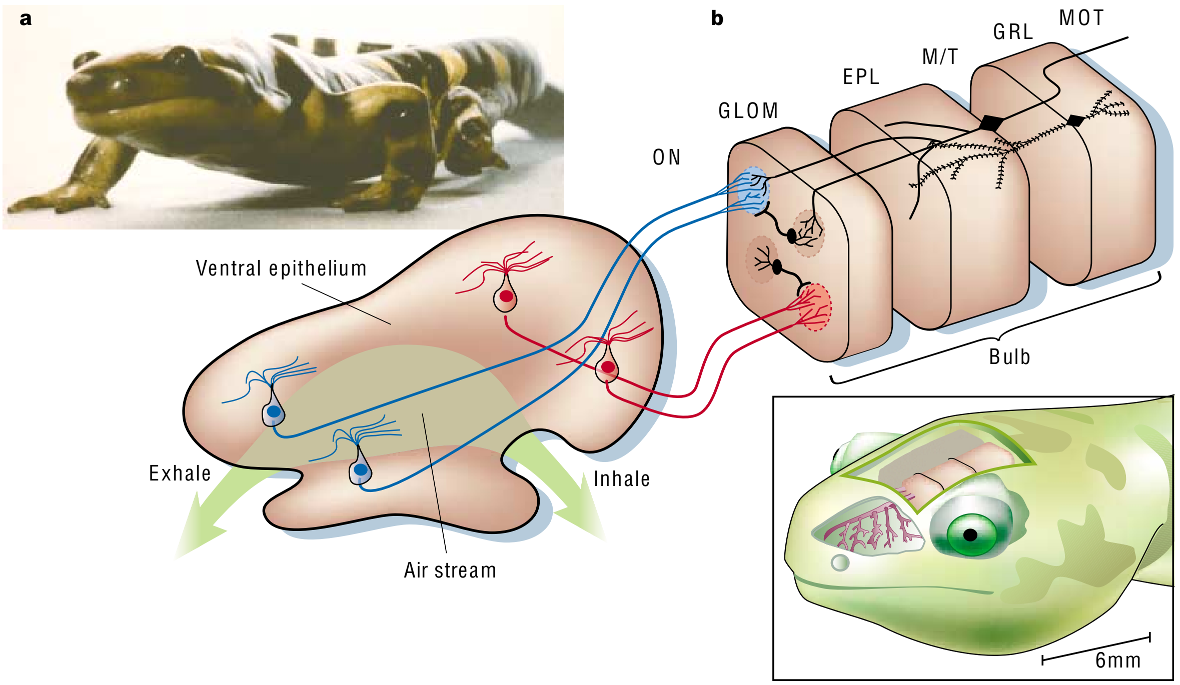
Nature **413**, 211 (2001)

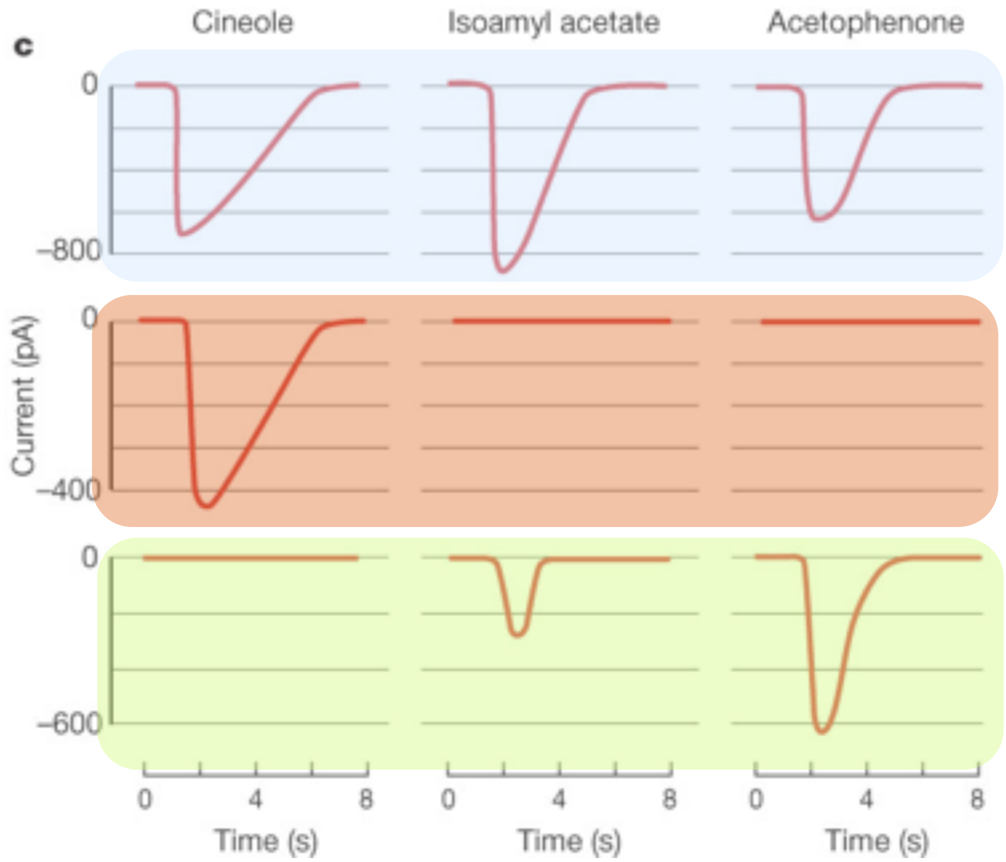


Odorant triggers the receptor. The receptor releases the G-protein. The G-protein generates cAMP which controls the channel and activate the olfactory neuron cell.

spelling out “smell”

Nature **417**, 336 (2002)



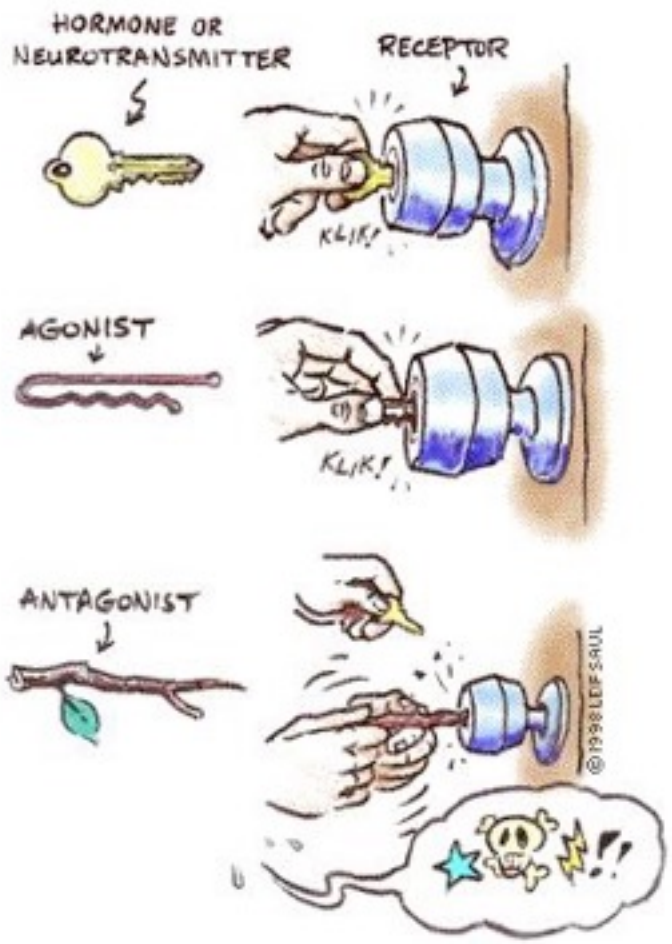


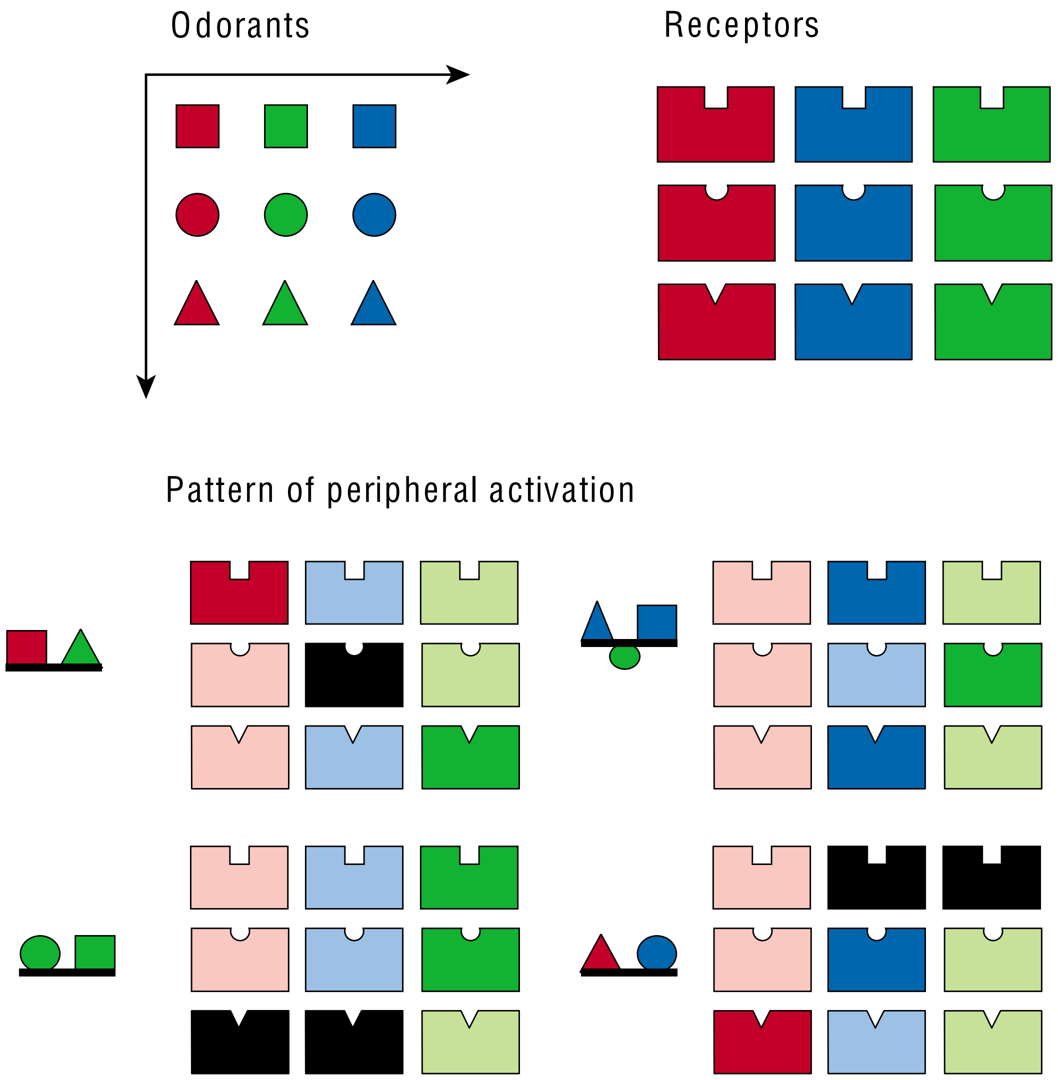
An odorant molecule can trigger multiple receptors and a receptor can be triggered by different odorant molecules.

Thus, ***smell*** is a complicated foreign language....

shape theory

The Shape theory of Olfaction states that the sensation of smell is due to a lock and key mechanism by which a scent molecule fits into olfactory receptors in the nasal lamina of the nose.

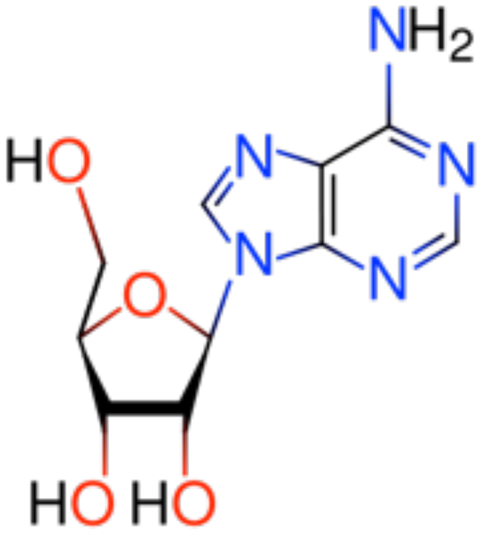




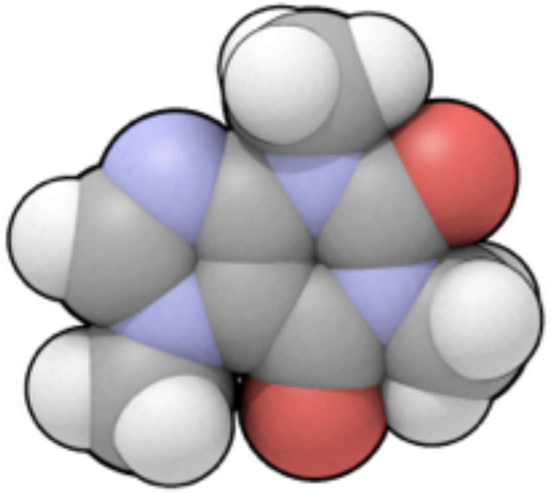
Nature **413**, 211 (2001)

antagonist: coffee

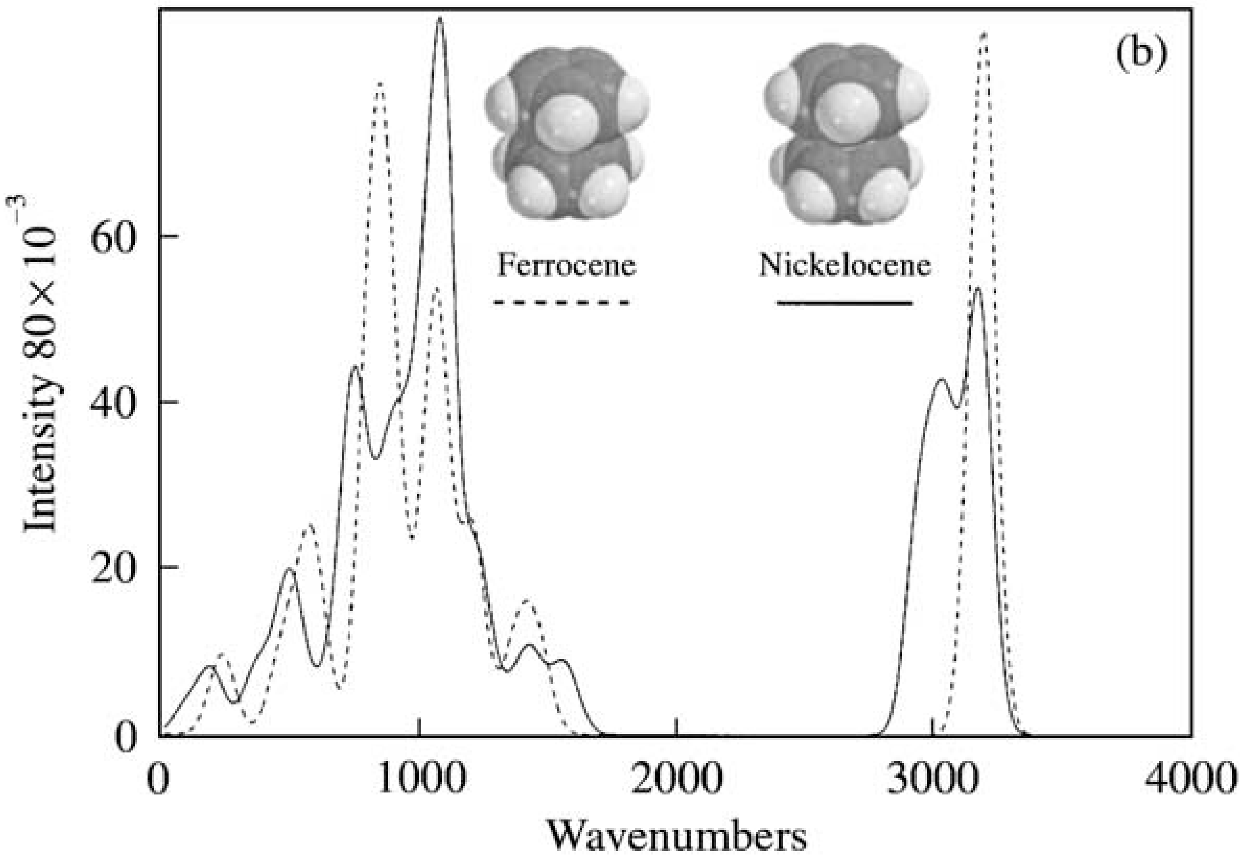
Caffeine



Adenosine



Adenosine is an agonist, triggering signal to suppress neuron activities and cause the sleepy feeling. **Caffeine** competes with adenosine and sticks to the receptor site to prevent the signal for activity suppression.



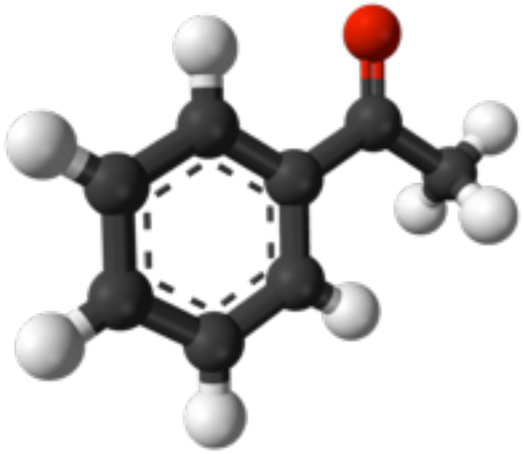
vibration theory

The vibration theory of olfaction, proposed by Luca Turin (1996), originates from the earlier work of Dyson who suggested that the olfactory receptors might detect molecular vibrations.

no isotope effect

BRIEF COMMUNICATIONS

A psychophysical test of the vibration theory of olfaction



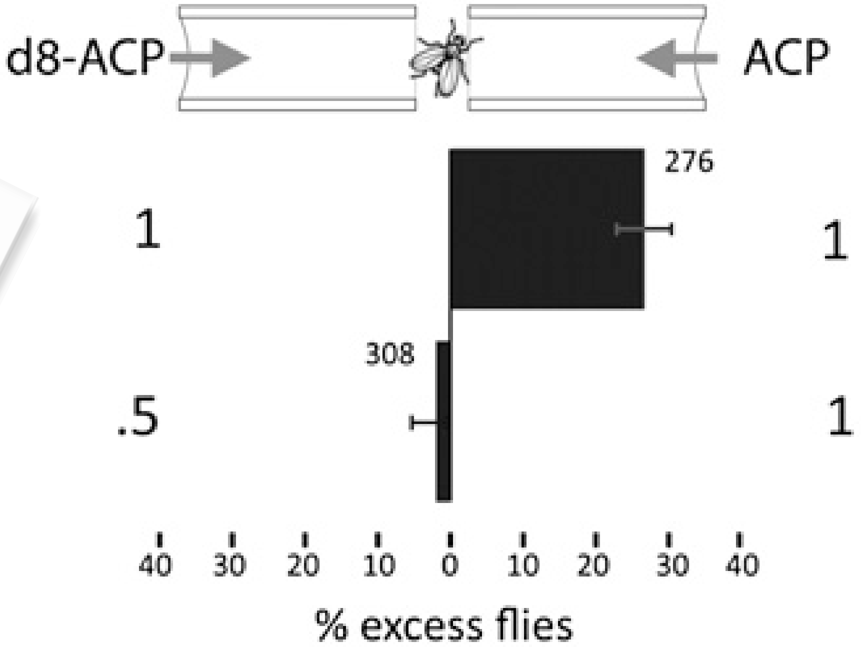
Andreas Keller & Leslie B Vosshall

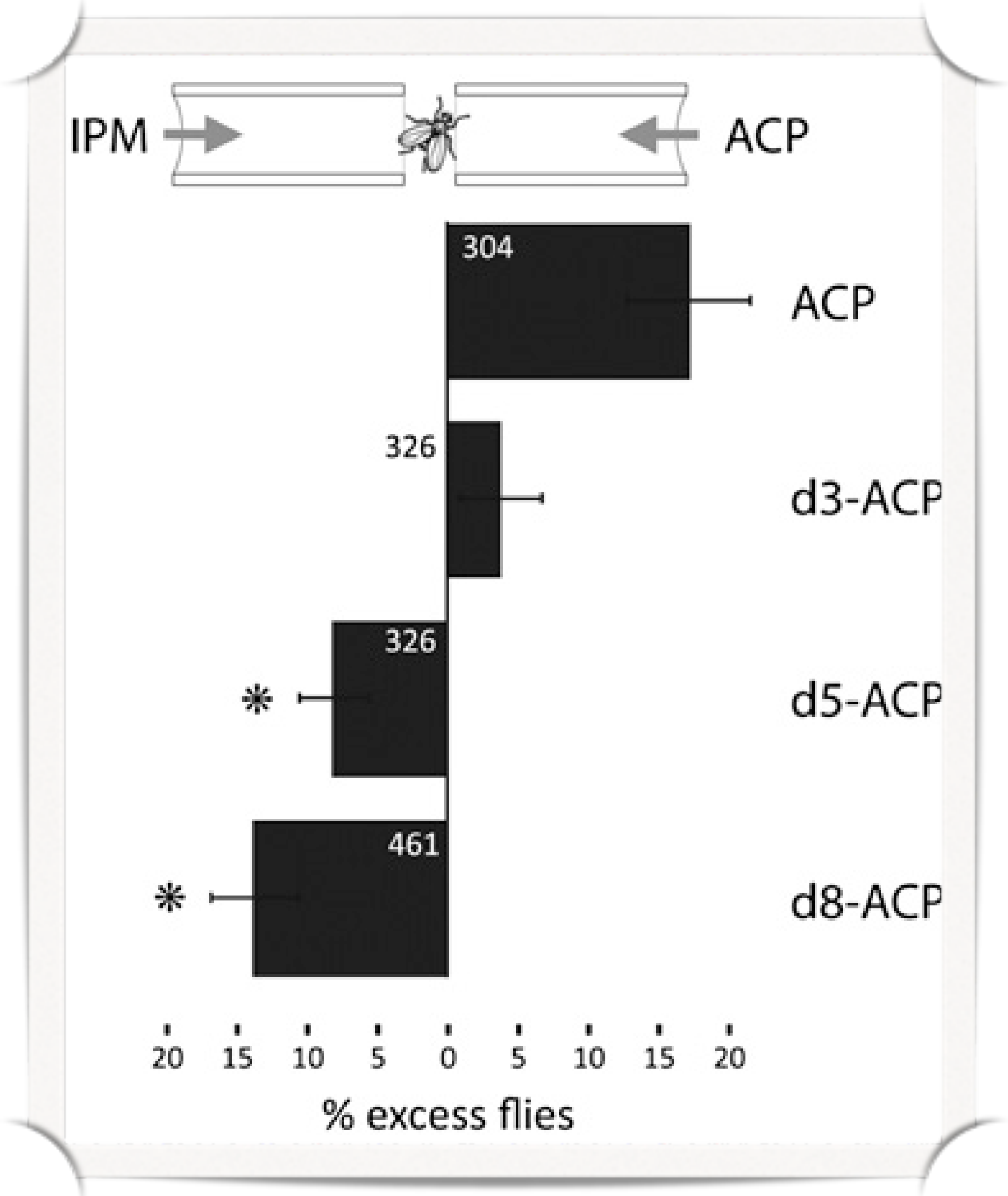
At present, no satisfactory theory exists to explain how a given molecule results in the perception of a particular smell. One theory is that olfactory sensory neurons detect intramolecular vibrations of the odorous molecule. We used psychophysical methods in humans to test this vibration theory of olfaction and found no evidence to support it.

NATURE NEUROSCIENCE VOLUME 7 | NUMBER 4 | APRIL 2004

fruit flies can smell

PNAS **108**, 3797 (2011)

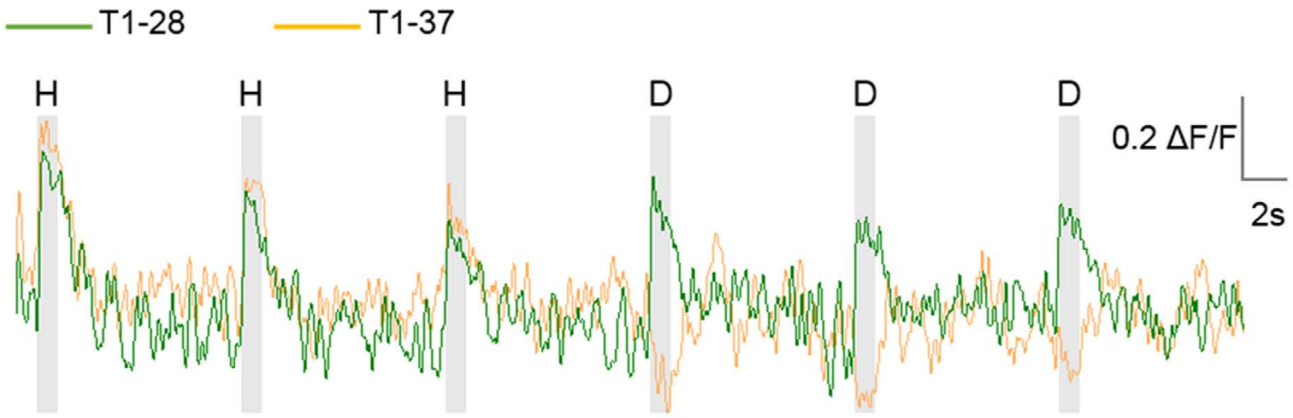




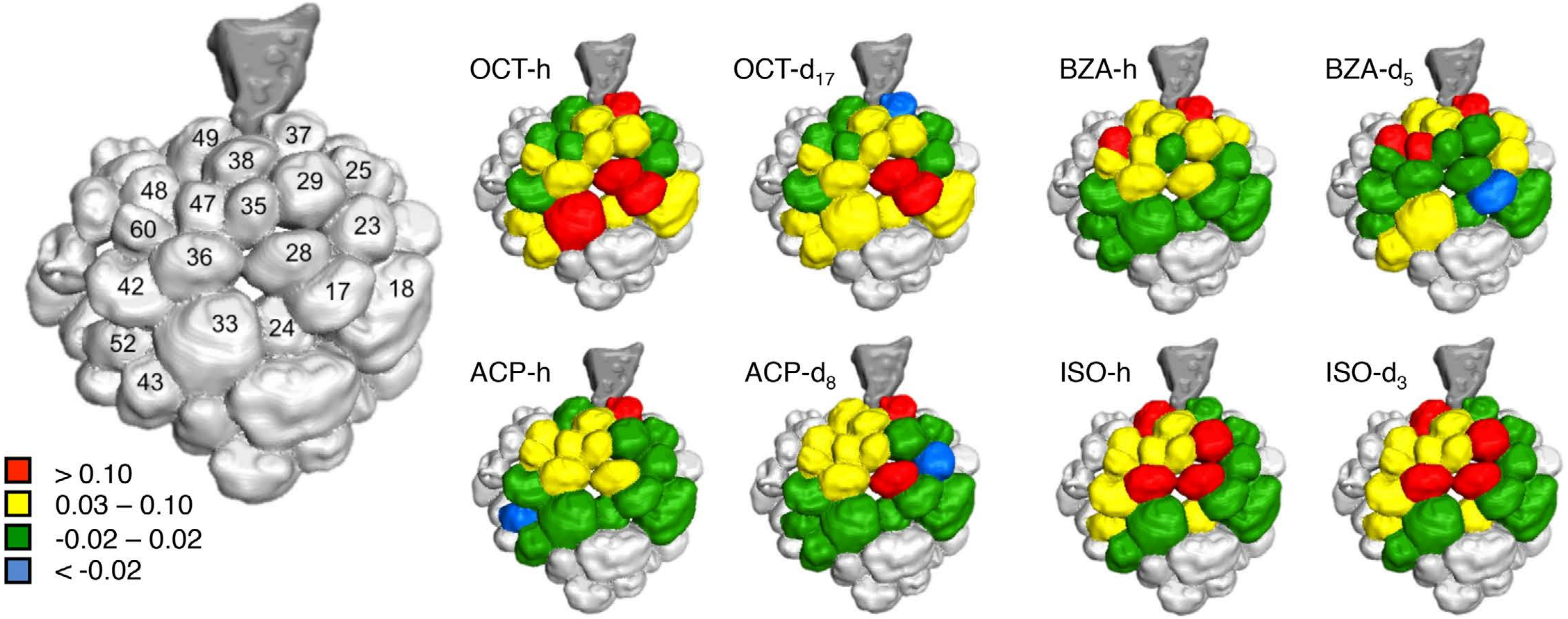
Unlike Vosshall’s negative results, fruit flies can distinguish the deuterated and un-deuterated acetophenone.

so are bees!

Scientific Reports **6**, 21893 (2016)



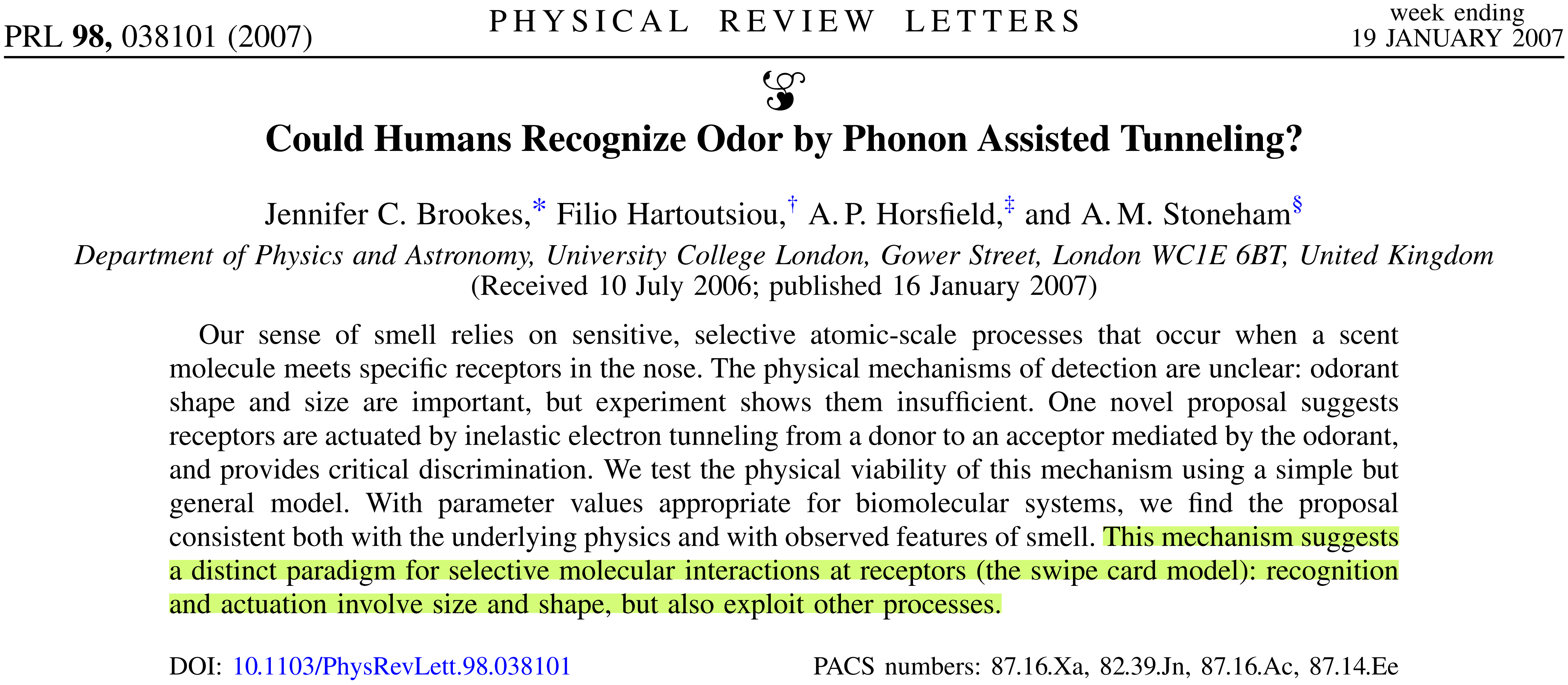
Isotope effect found in induced glomerular responses.



quantize

the shape theory

the first model



PRL **98,** 038101 (2007)
PHYSICAL REVIEW LETTERS
week ending
19 JANUARY 2007

Could Humans Recognize Odor by Phonon Assisted Tunneling?

Jennifer C. Brookes,* Filio Hartoutsiou,† A. P. Horsfield,‡ and A. M. Stoneham§
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

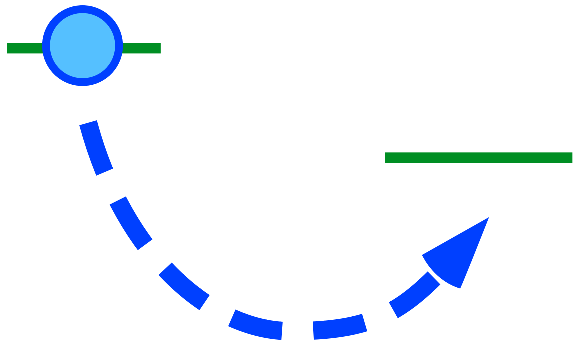
(Received 10 July 2006; published 16 January 2007)

Our sense of smell relies on sensitive, selective atomic-scale processes that occur when a scent molecule meets specific receptors in the nose. The physical mechanisms of detection are unclear: odorant shape and size are important, but experiment shows them insufficient. One novel proposal suggests receptors are actuated by inelastic electron tunneling from a donor to an acceptor mediated by the odorant, and provides critical discrimination. We test the physical viability of this mechanism using a simple but general model. With parameter values appropriate for biomolecular systems, we find the proposal consistent both with the underlying physics and with observed features of smell. This mechanism suggests a distinct paradigm for selective molecular interactions at receptors (the swipe card model): recognition and actuation involve size and shape, but also exploit other processes.

DOI: 10.1103/PhysRevLett.98.038101 PACS numbers: 87.16.Xa, 82.39.Jn, 87.16.Ac, 87.14.Ee

model receptor

First of all, the receptor is modeled as a two-level system with the finite energy gap. Besides, there exists a bare tunneling between the donor and the acceptor states.

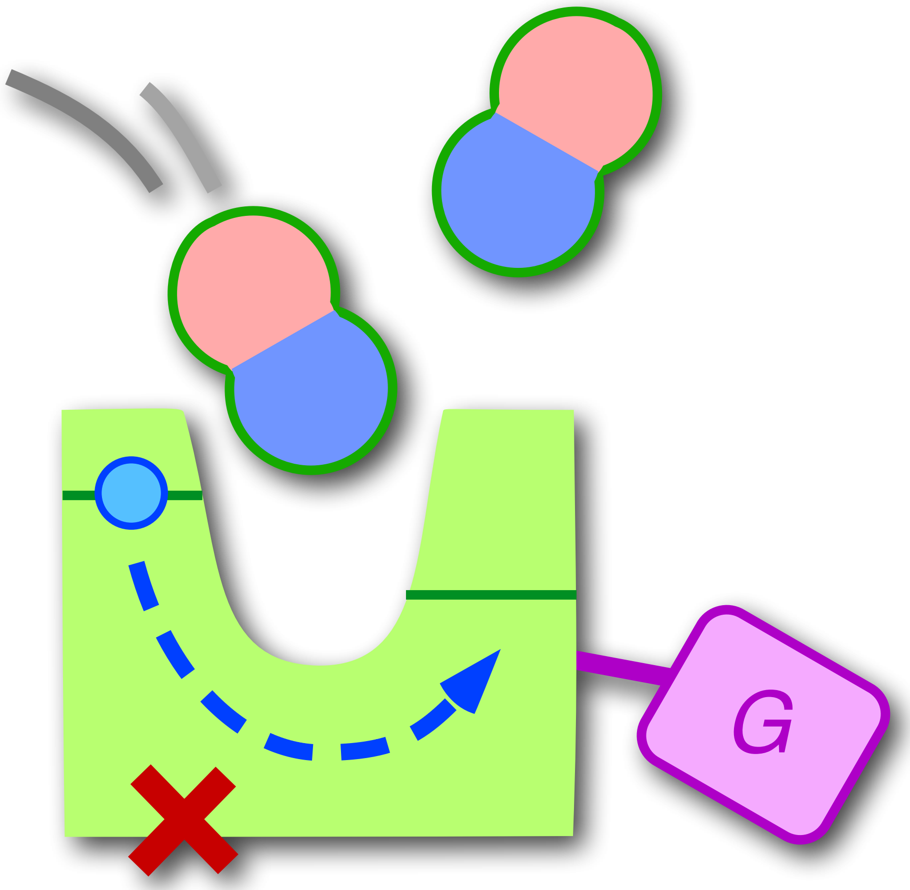


$$\boxed{H_R = \frac{\Delta}{2}\sigma_z + \gamma\sigma_x}$$

OFF state

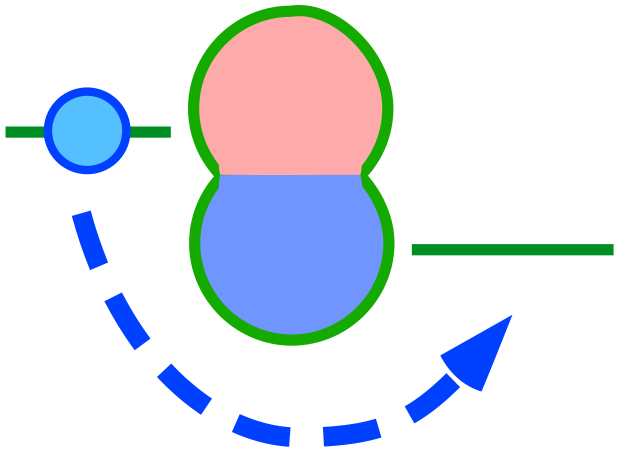
Two different conformations of the receptor correspond to the OFF/ON states. The OFF state has a higher energy.

$$\boxed{\Delta = E_{OFF} - E_{ON}}$$



Quantum tunneling is suppressed by the presence of finite energy gap between OFF and ON states.

model odorant



The odorant is modeled as a simple oscillator and the coupling between the receptor and the odorant is assumed to be linear:

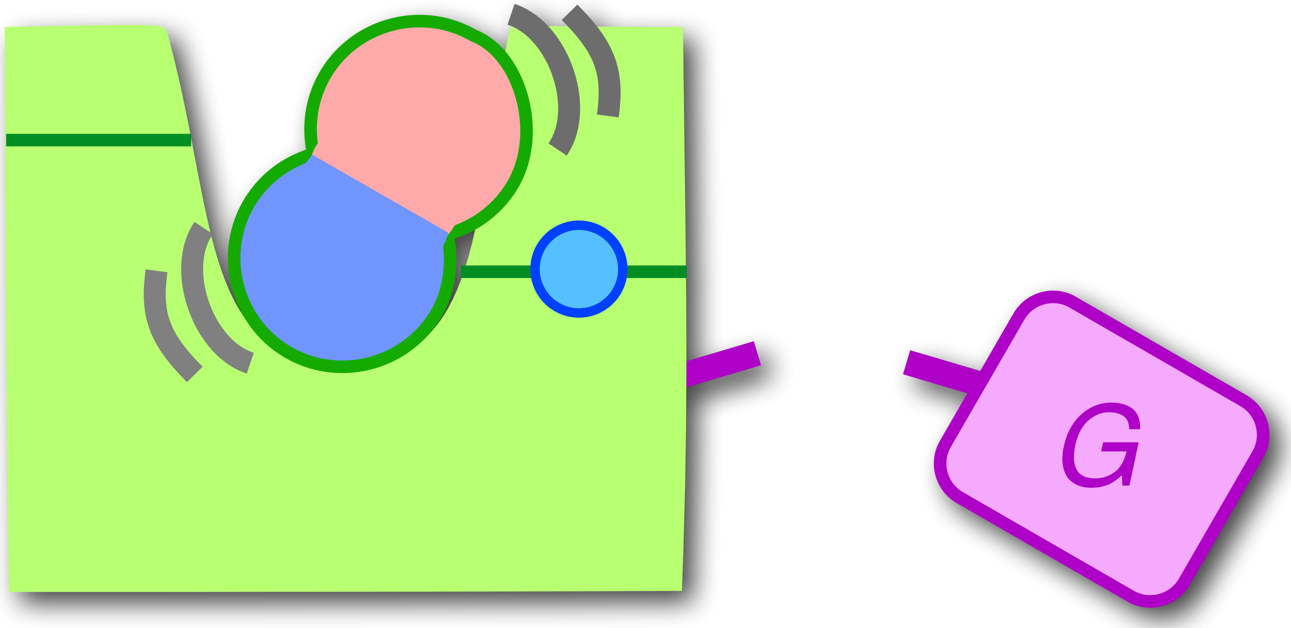
$$H_{R-o} = g\,\sigma_z(b + b^\dagger) + \hbar\Omega\left(b^\dagger b + \frac{1}{2}\right)$$

ON state

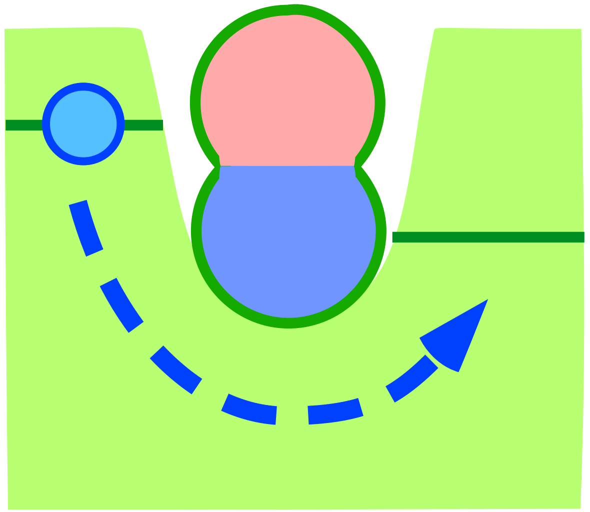
If the resonance condition is matched, the receptor tunnels to the (lower-energy) ON state while the odorant molecule is in the excited state.

$$\boxed{\hbar\omega_O \approx \Delta}$$

The tunneled charge triggers the G-protein cascade.



model environment



The environment is modeled as a thermal bath of simple harmonic oscillators that couple to the receptor in a similar way.

$$H_{R-env} = \sum_q g_q \, \sigma_z (b_q + b_q^\dagger) + \hbar\omega_q \left(b_q^\dagger b_q + \frac{1}{2} \right)$$

induced response

It was claimed in Stoneham's PRL that, "after standard approximations", the tunneling rate is

$$\frac{1}{\tau_n} = \frac{2\pi}{\hbar}\gamma^2\sigma_n \frac{1}{\sqrt{4\pi kT\lambda}} \exp\left[-\frac{(\epsilon_n - \Delta + \lambda)^2}{4kT\lambda}\right]$$

Here $\epsilon_n = n\hbar\Omega$ is the excitation energy of the odorant. The coupling to the odorant molecule gives rise to the Huang-Rhys factor,

$$\sigma_n = \frac{S^n}{n!}e^{-S} = \frac{(2g/\hbar\Omega)^{2n}}{n!}e^{-(2g/\hbar\Omega)^2}.$$

Similarly, one can define $S_q = (2g_q/\hbar\omega_q)^2$ for each oscillator in the thermal bath. The reorganization energy is

$$\lambda = \sum_q \hbar\omega_q S_q$$

Sensing scents. M. Maumus's advertising poster for the perfume Nelombo (1932).

Hum, "standard approximations", that should be quite easy...

chew on literature

ORIGINAL RE

A Spectroscopic

Reception

Luca Turin

Department of Anatomy and

WC1E 6BT, UK

Correspondence to be sen

College London, Gower St

Abstract

A novel theory of prima

shape of the molecules

providing a detailed a

tunnelling. Elements

G-protein. Means of

given of correlations

molecules of very si

acetophenone and

structure. This fac

suggests instead

Introduction

Putative olfactory

(Buck and Axel,

Raming et al.,

involve a G-pro

(for review see S

which receptor

basis of odou

pointed out,

evidence (Bee

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VOLUME 43, NUMBER 2

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MAY, 195

n Reactions Involving Electron Transfer. I*

Marcus

nstitute of Brooklyn, Brooklyn, New York

ly 28, 1955)

he electrostatic contribution to the free energy of formation of
e intermediate state from the reactants, ΔF^*, is thereby obtained
terms of known quantities, such as ionic radii, charges, and the
dard free energy of reaction.
is intermediate state X^* can either disappear to reform the
nts, or by an electronic jump mechanism to form a state X
ch the ions are characteristic of the products. When the
rocess is more probable than the former, the over-all
rate is shown to be simply the rate of formation of the
ate state, namely the collision number in solution multi-
p$(-\Delta F^*/kT)$. Evidence in favor of this is cited. In a
antitative comparison, given elsewhere, with the
no arbitrary parameters are needed to obtain reason-
t of calculated and experimental results.

ta on isotopic exchange reactions having
ms is that the entropy of activation of
large and negative. It is of interest
tions were between ions of like sign.
at a reorganization of the solvation
he reacting ions occurred prior to
believed that this would con-
to the entropy of activation. It
e reorganization would involve
e solvent attached to the ions,
olve an increase in entropy.
entropy of activation there
negative term. It was sug-
e to the low probability of
ugh a solvation barrier,
n the intermediate state.
s interesting treatment
using the values given

Eyring, J. Phys. Chem. 58,
ne of these data in their
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sidered there.
as incomplete in that only one
tate in the reaction was considered.
d that this state involving the reorganized
y produce products, but not reform the reactants.
her would occur by an electron jump process, the latter
a disorganizing motion of the solvent.) It is shown later that
this omission can significantly affect the role played by the
electronic jump process.
The number of times per second that the electron in one of the
reactants struck the barrier was not included in the over-all calcu
lation. Effectively, this made electron tunnelling appear abo
thousand-fold less frequent than would otherwis
estimated.

Gehlen and

a)Contribution No. 8799.

J. Chem. Phys. 99 (2), 15 July 1993 0021-9606/93/99(2)/969/10/$6.00 © 1993

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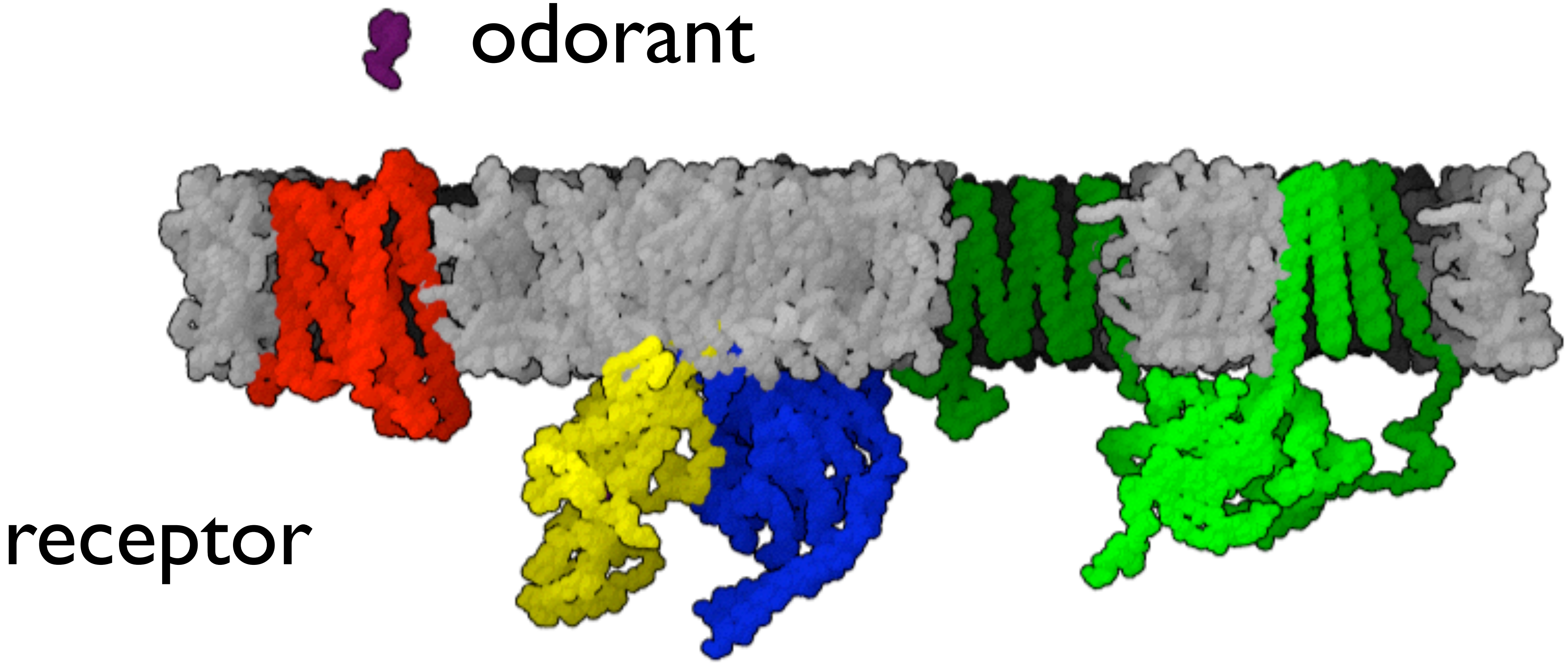
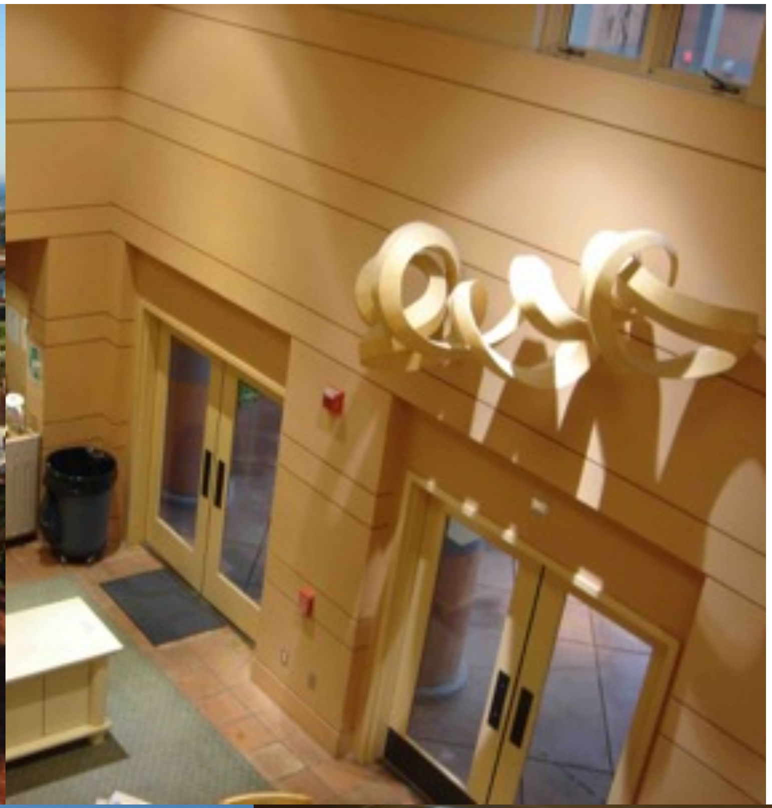
ducking-induced tunneling



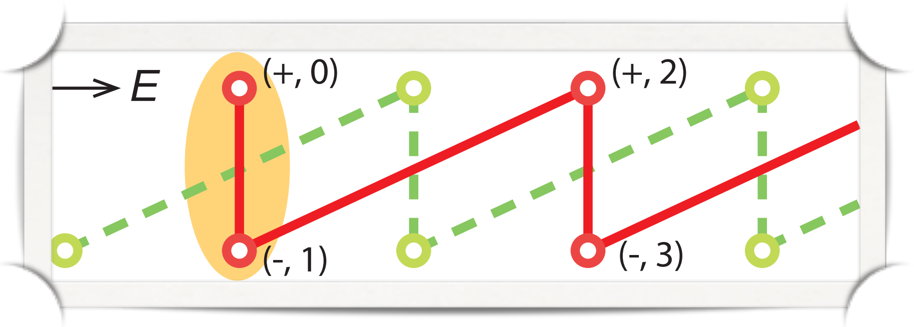
Odorant: Numerical methods in quantum chemistry.
Receptor: Modeling with analytic/numeric solutions.

Smell @ KITP

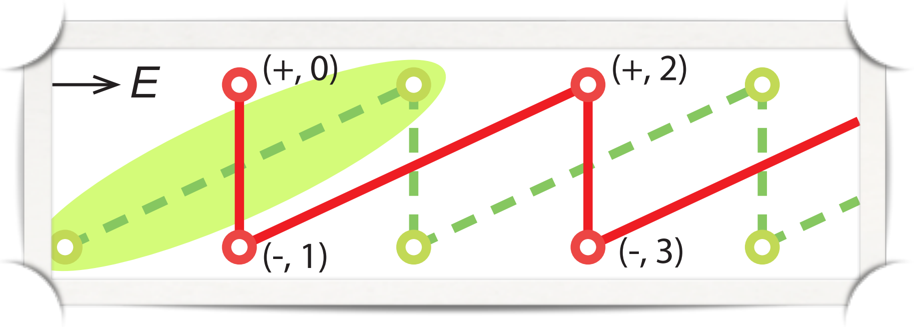


(c) Elena Nikanorova

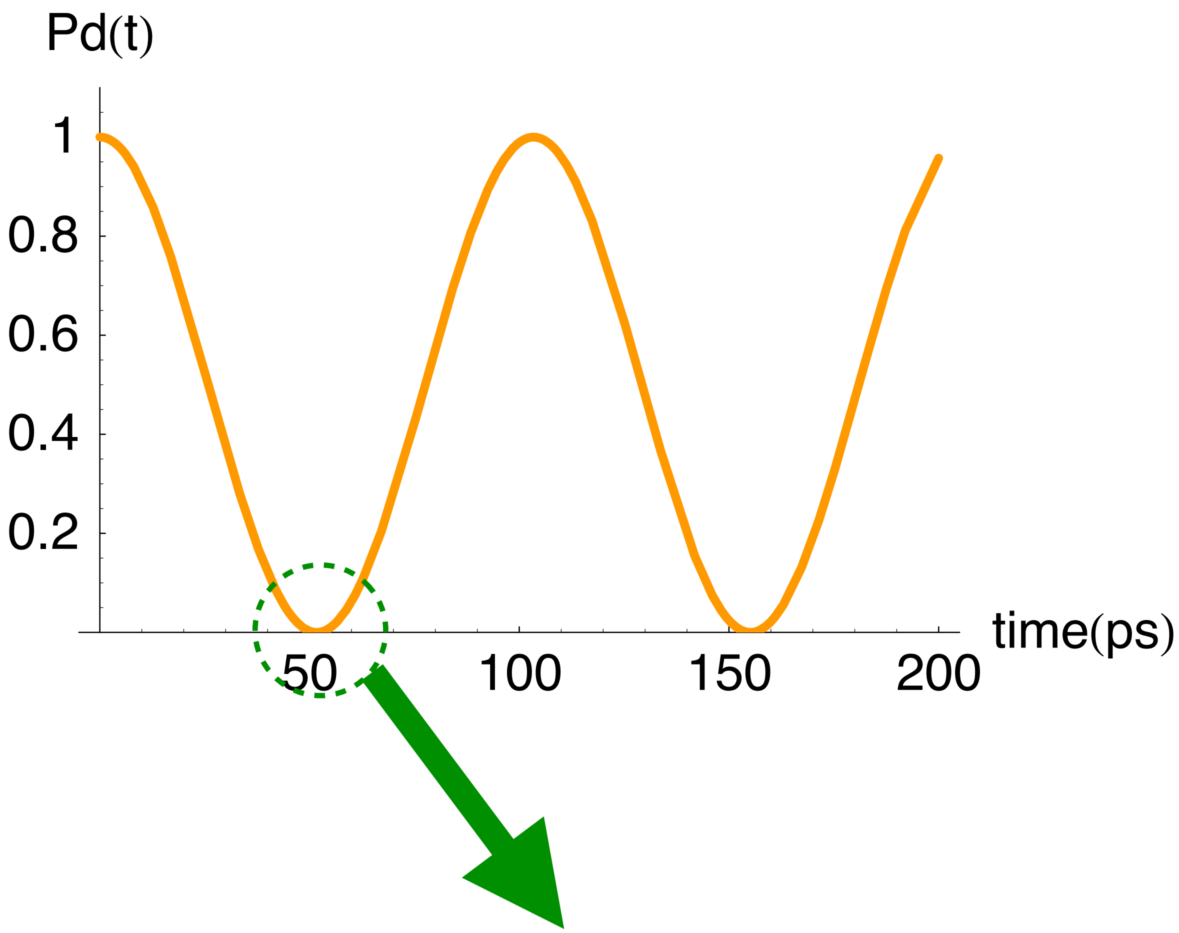
Dyson equation in q-bio



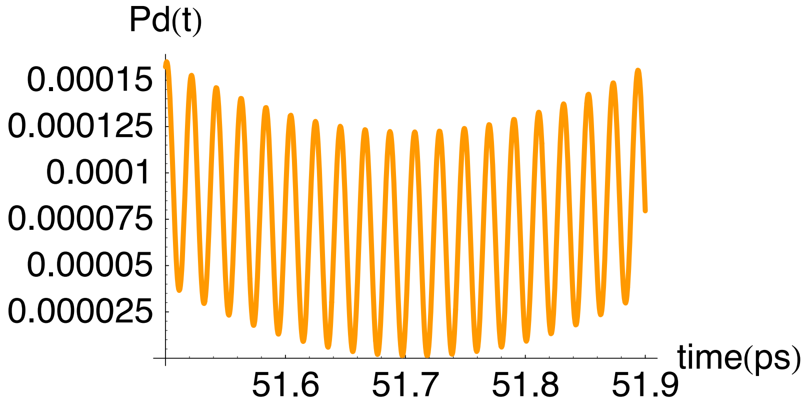
main oscillation



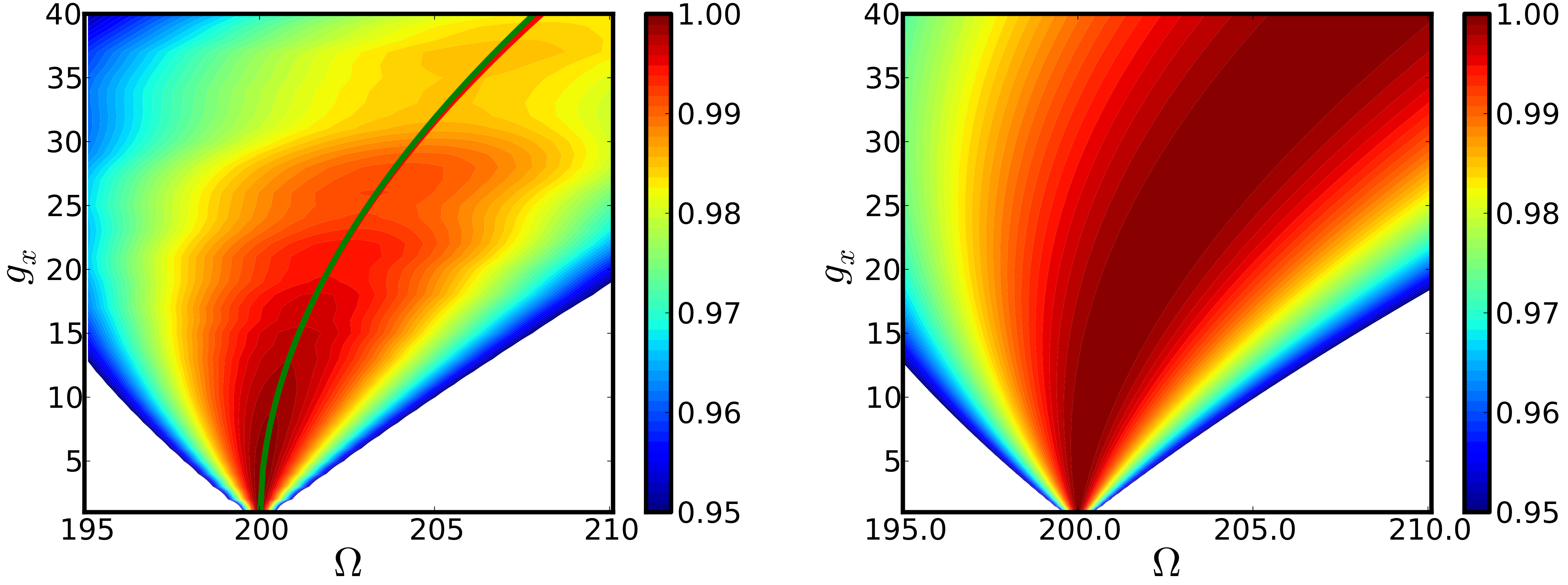
sub oscillation



One can use **Dyson equation** to derive the **effective two-state Hamiltonian** by tracing out the remaining states.



robust 2-state receptor



The numerical result for the receptor-odorant dynamics is well captured by the effective two-state Hamiltonian.

exact formula

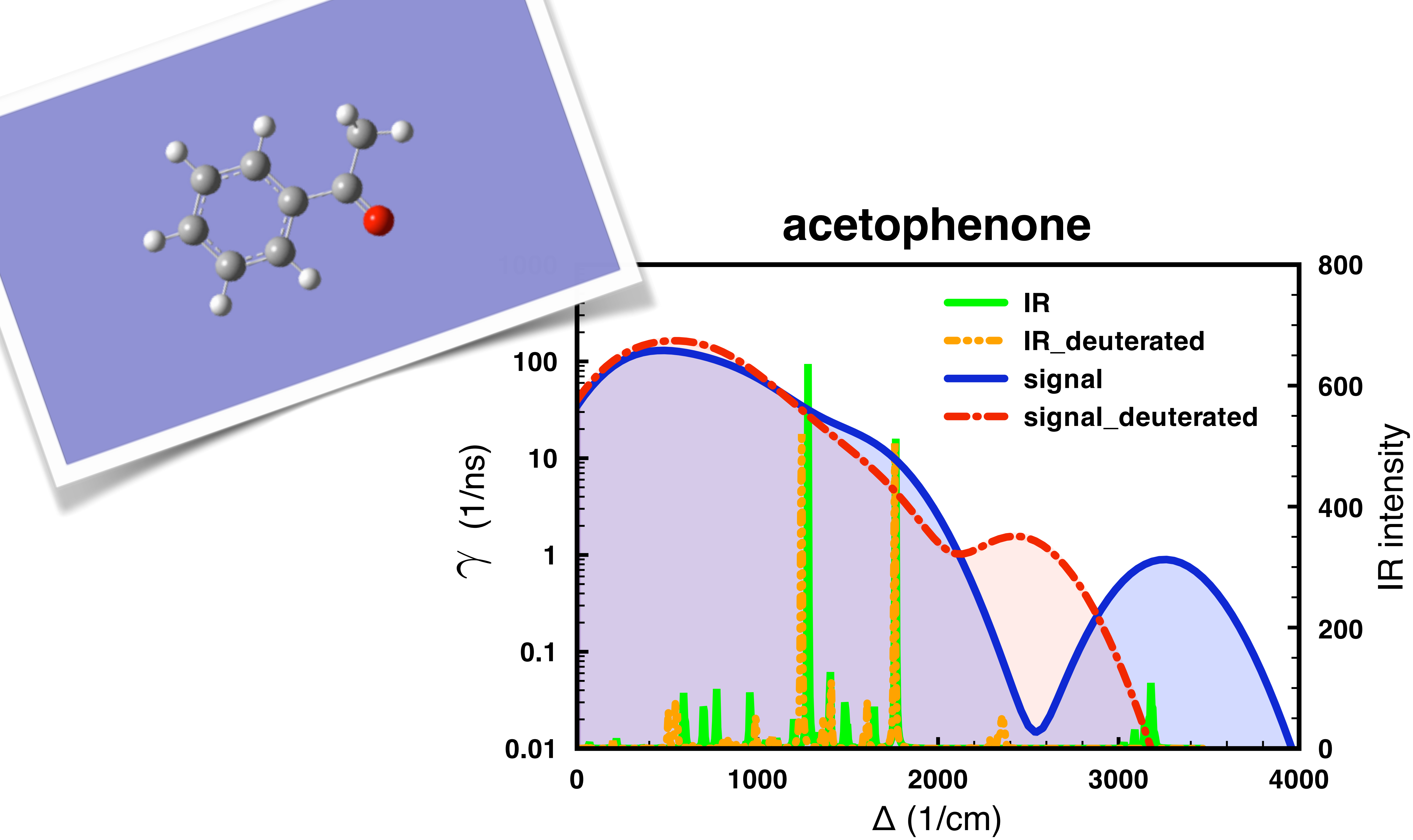
Fermi’s golden rule + path integral + Green’s function leads to the exact formula for the tunneling rate:

$$\boxed{\frac{1}{\tau_n} = \frac{2\pi}{\hbar}\gamma^2\sigma_n \int_{-\infty}^{\infty} \frac{dt}{2\pi\hbar} e^{-i(\epsilon_n - \Delta)t/\hbar} \prod_q F_q(t)}$$

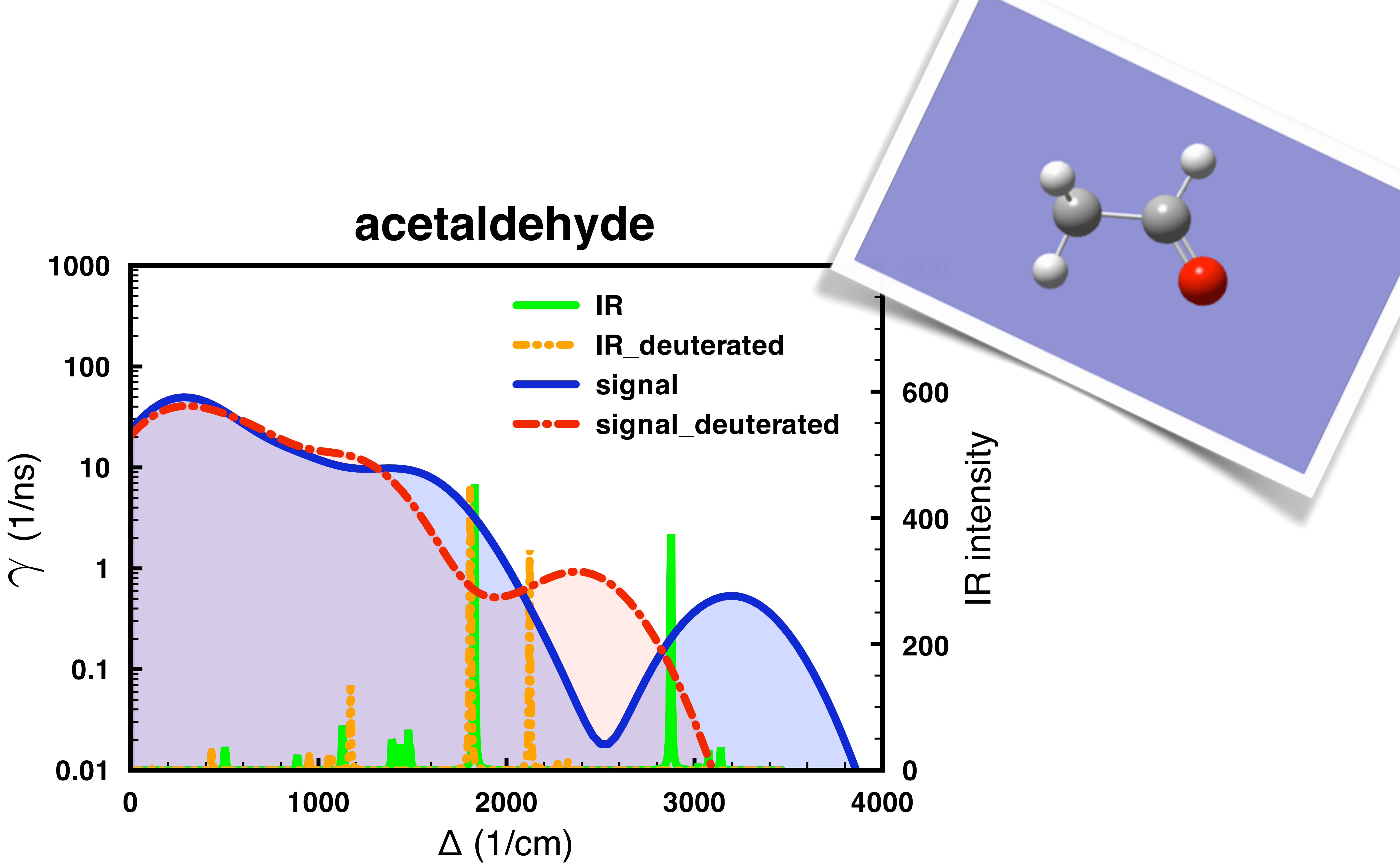
The correlation function is $F_q(t) = \langle D_q(t) D_q^\dagger(0)\rangle$ with the displacement operator defined as $D_q(t) \equiv e^{[2g_q/\hbar\omega_q][b_q(t) - b_q^\dagger(t)]}$ and can be computed exactly

$$F_q(t) = \exp\left[-iS_q \sin\omega_q t - S_q(2n_q + 1)(1 - \cos\omega_q t)\right],$$

where $S_q = (2g_q/\hbar\omega_q)^2$ is the dimensionless distortion.



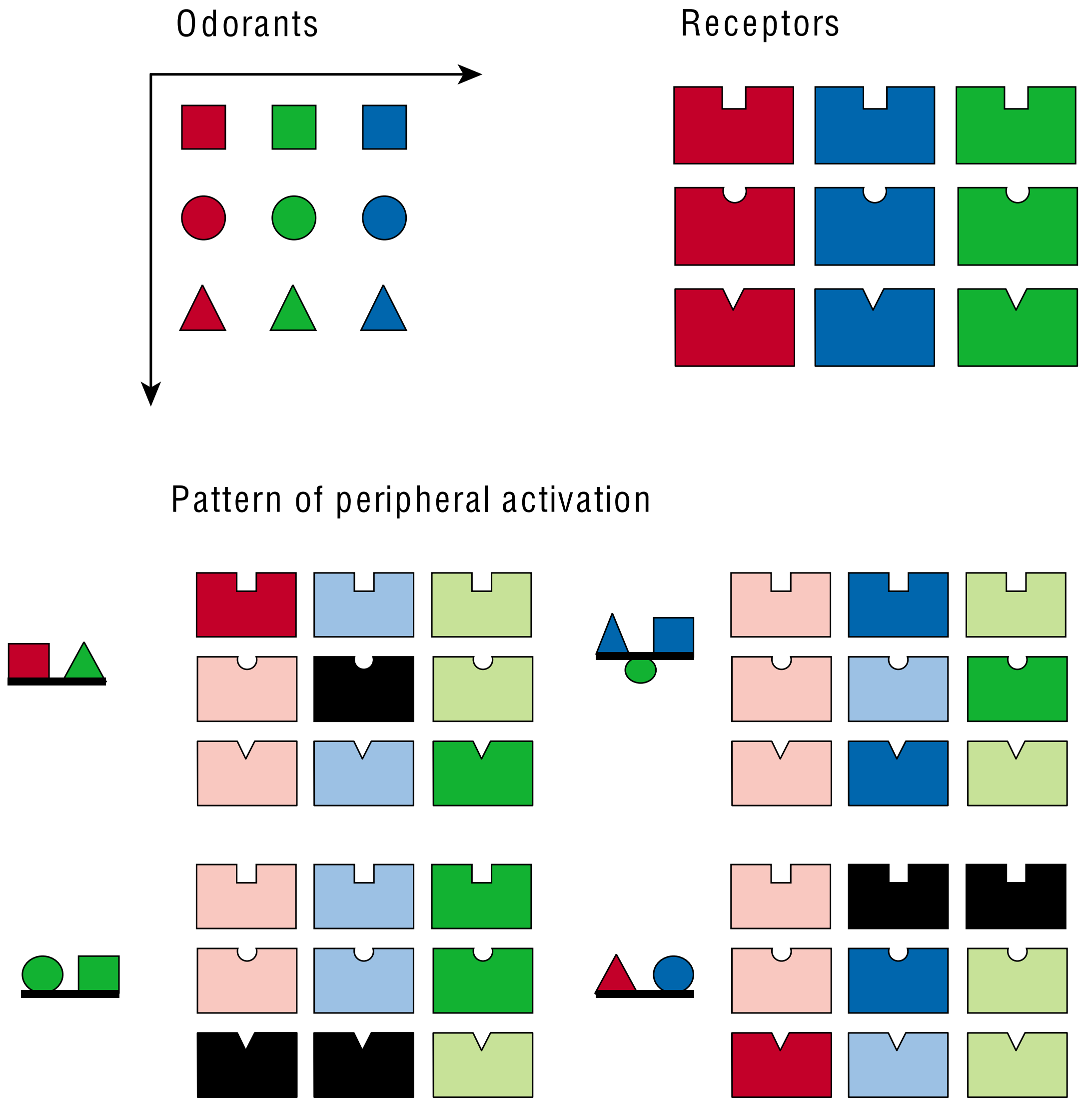
Acetophenone: except the local stretching model, no significant mode-shift -- weak isotope effect?

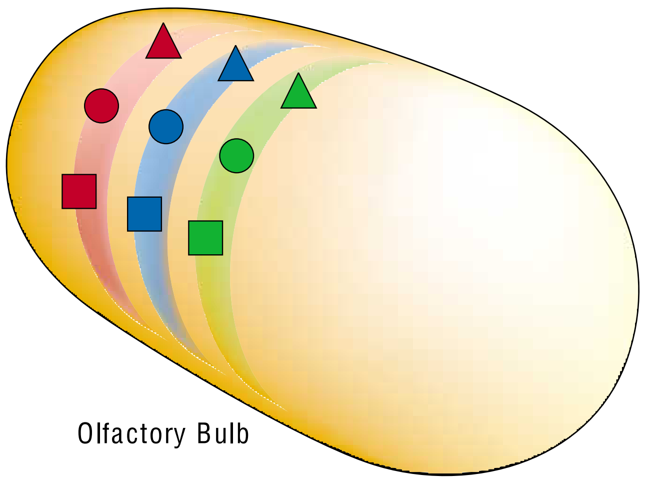


Acetaldehyde: significant mode-shift when replacing hydrogens by deuterium -- strong isotope effect?

codes in the nose?

Nature **413**, 211 (2001)





In addition to the **molecular shape**, what else molecular features are picked up by the odorant receptor?

conclusions

- quantum coherence is spotted in biology.
- the theory of olfaction is not yet complete
- quantize "shape theory" of olfactory receptor lead to "vibration theory".
- isotope effect, olfaction profile and more to be explored in the future...