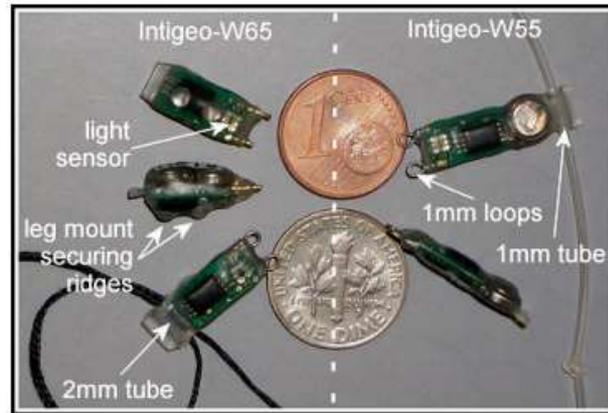


- К.В.Кавокин
- ФТИ им. Иоффе, СПбГУ и ИЭФБ им. Сеченова

Загадка магнитного компаса перелётных птиц





Всеволод Афанасьев,
British Antarctic Survey



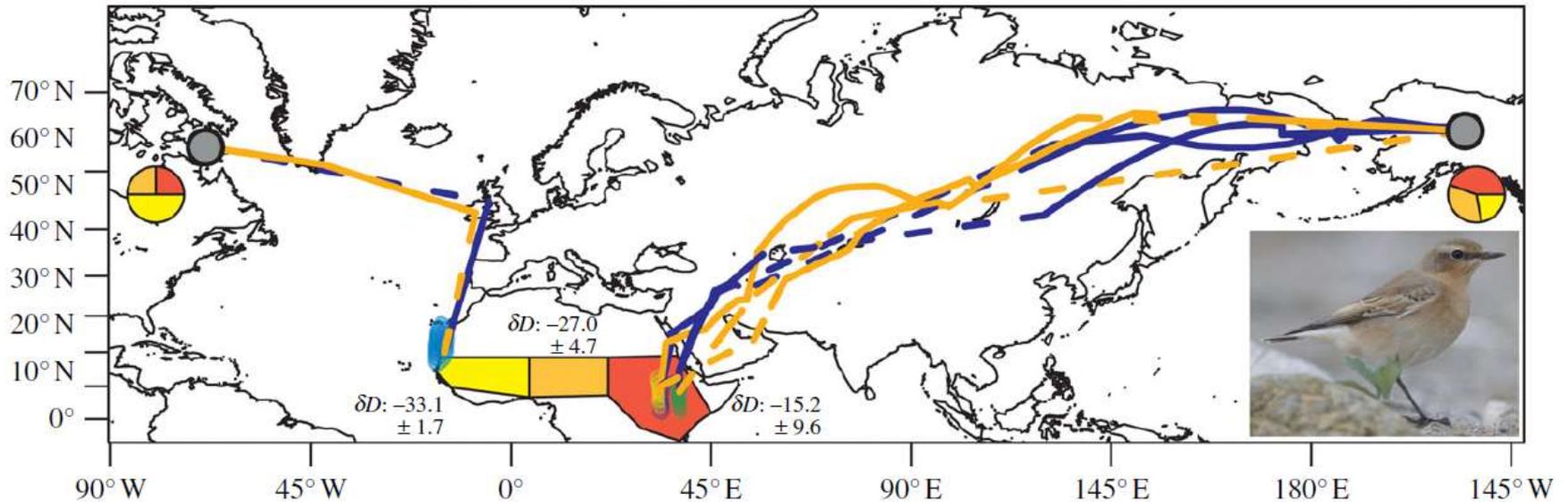
Геолокатор на чернозобике



Осенняя и весенняя миграция дупеля (*Gallinago media*)

Åke Lindström, Thomas Alerstam, Peter Bahrenberg, Robert Ekblom, James W. Fox, Johan Råghall and Raymond H. G. Klaassen

Journal of Avian Biology 46: 001–014, 2015



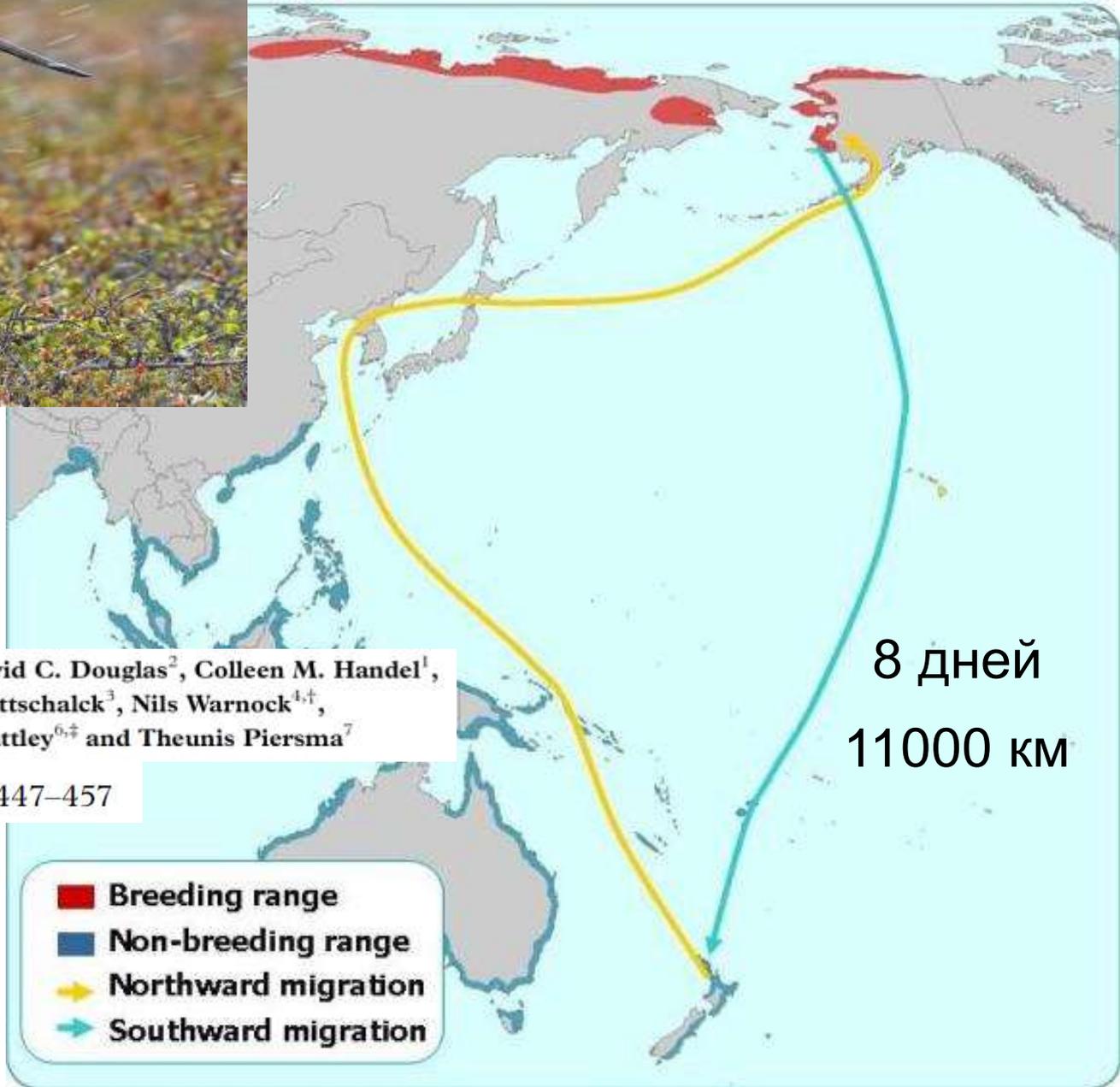
Маршруты миграции каменки (*Oenanthe Oenanthe*)

Franz Bairlein¹, D. Ryan Norris², Rolf Nagel¹,
 Marc Bulte¹, Christian C. Voigt³, James W. Fox⁴,
 David J. T. Hussell⁵ and Heiko Schmaljohann^{1,*}

Biol. Lett. (2012) 8, 505–507



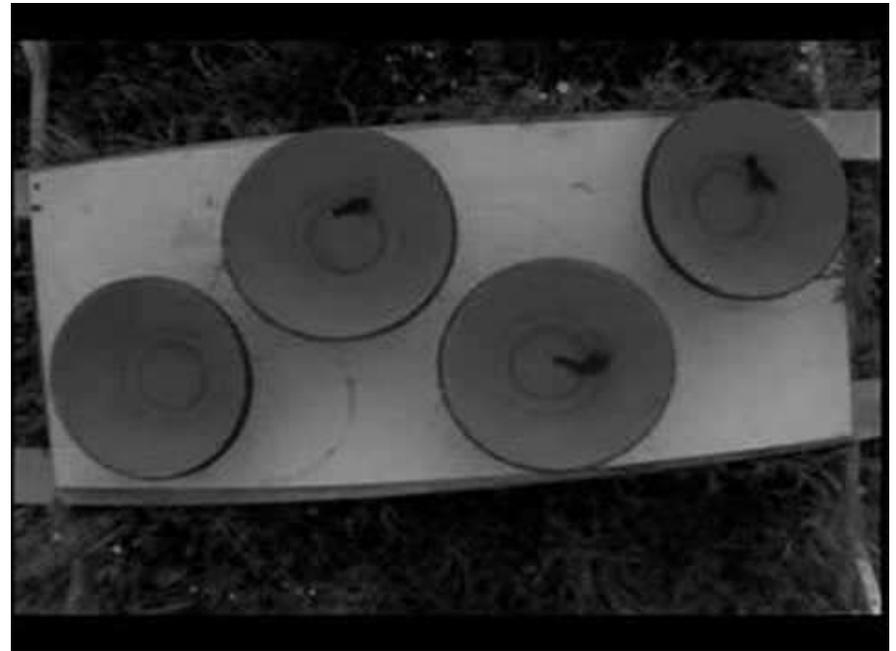
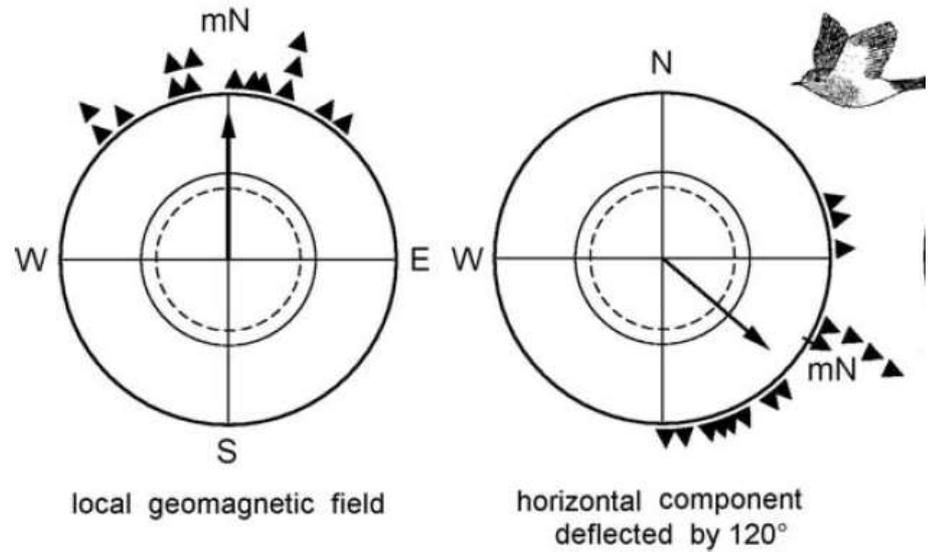
Малый веретенник (*Limosa lapponica*)



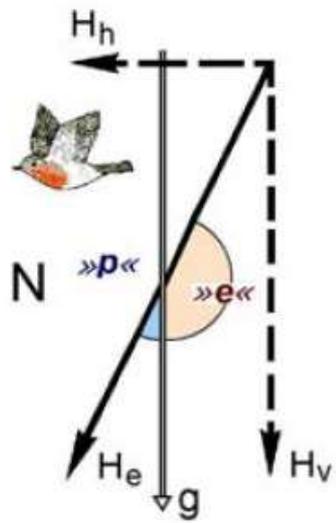
Robert E. Gill Jr^{1,*}, T. Lee Tibbitts¹, David C. Douglas², Colleen M. Handel¹,
Daniel M. Mulcahy¹, Jon C. Gottschalck³, Nils Warnock^{4,†},
Brian J. McCaffery⁵, Philip F. Battley^{6,‡} and Theunis Piersma⁷

Proc. R. Soc. B (2009) 276, 447–457

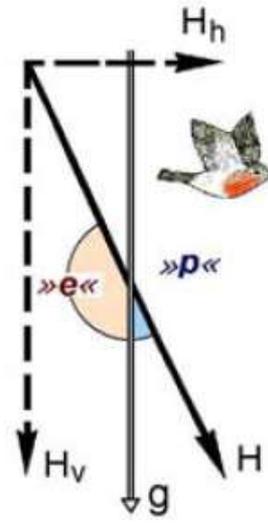
Wolfgang Wiltschko



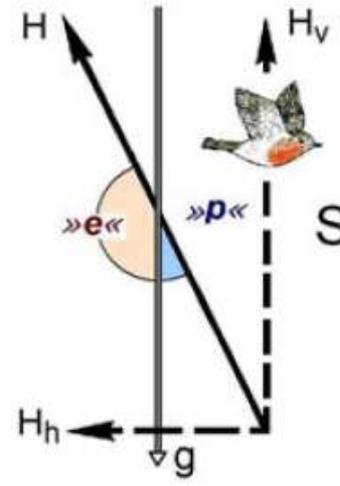
Wiltschko W, Wiltschko R. 1972. Magnetic compass of European robins. *Science* 176:62–64



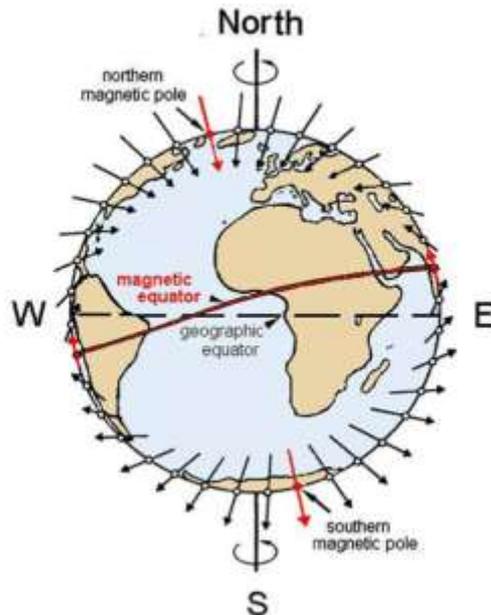
local
geomagnetic field



horizontal component
reversed



vertical component
inverted



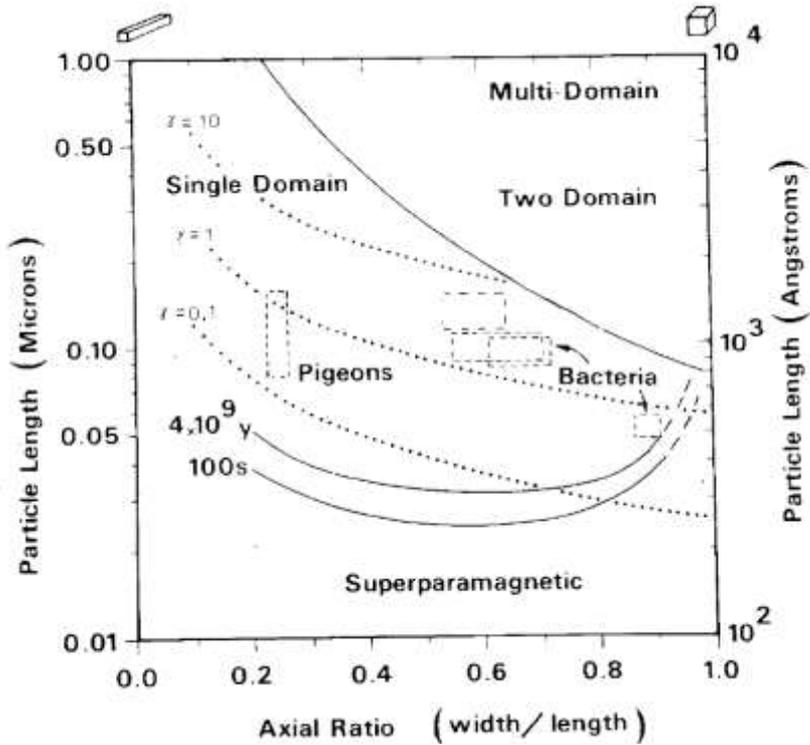
Inclination compass
(quadratic detector of
magnetic field components)

$$f\left(\sum_{i,j} A_{ij} B_i B_j\right)$$

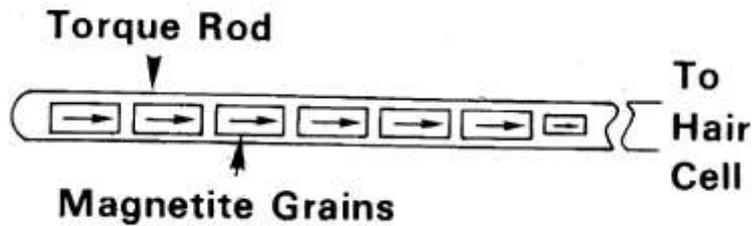
$$B_Z B_X$$

$$B_Z B_Y$$

Магниторецептор, использующий постоянные магниты



Joe Kirshvink



Kirschvink, Gould 1981

Magnetite defines a vertebrate magnetoreceptor

Carol E. Diebel^{*†}, Roger Proksch^{‡§}, Colin R. Green^{||}, Peter Neilson[‡]
& Michael M. Walker^{*}

NATURE | VOL 406 | 20 JULY 2000 | www.nature.com

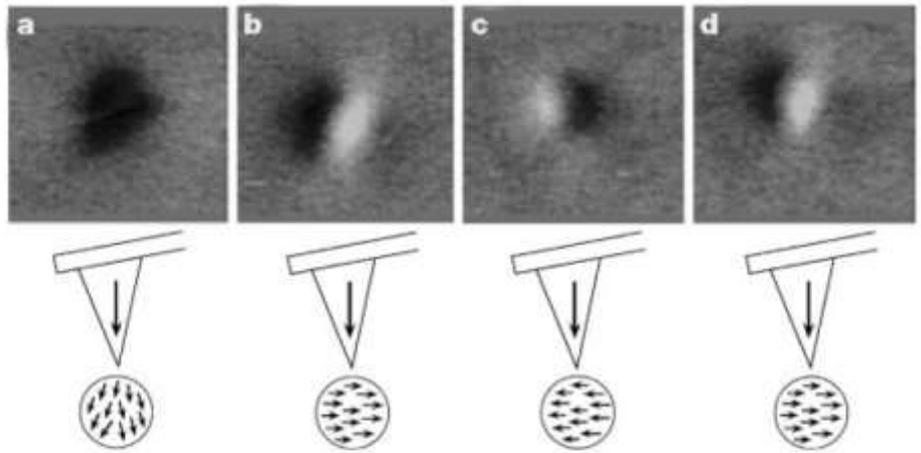
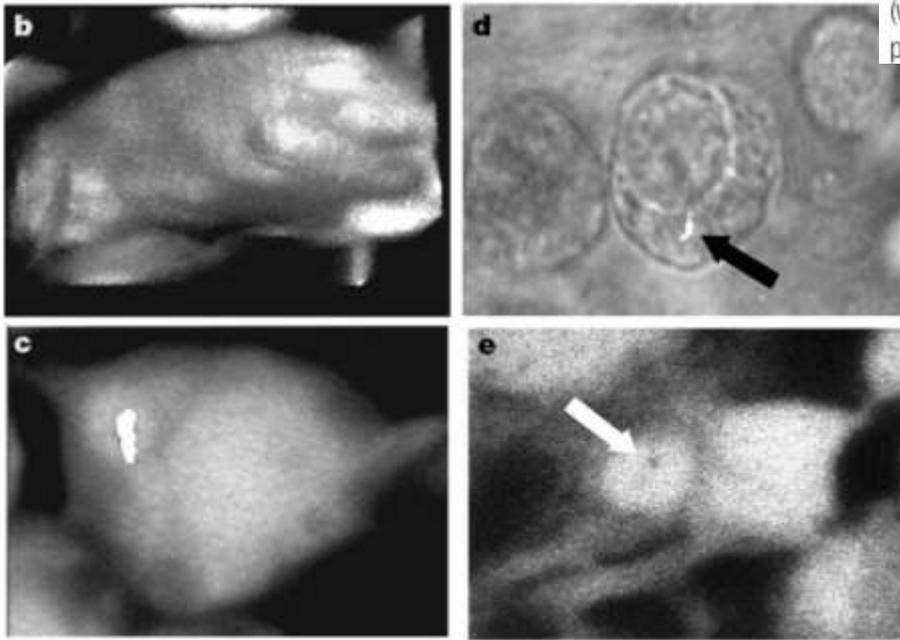
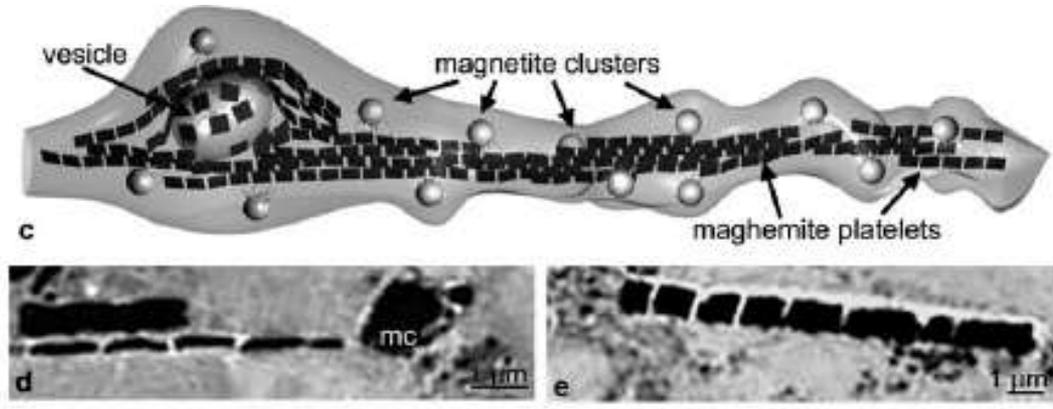


Figure 3 MFM images that show the response of a putative single magnetic particle (within trout tissue) in the presence of an applied field. The magnetic field applied in the plane of the sample was +1.4, +150, -150 and +130 mT for images **a-d**, respectively.



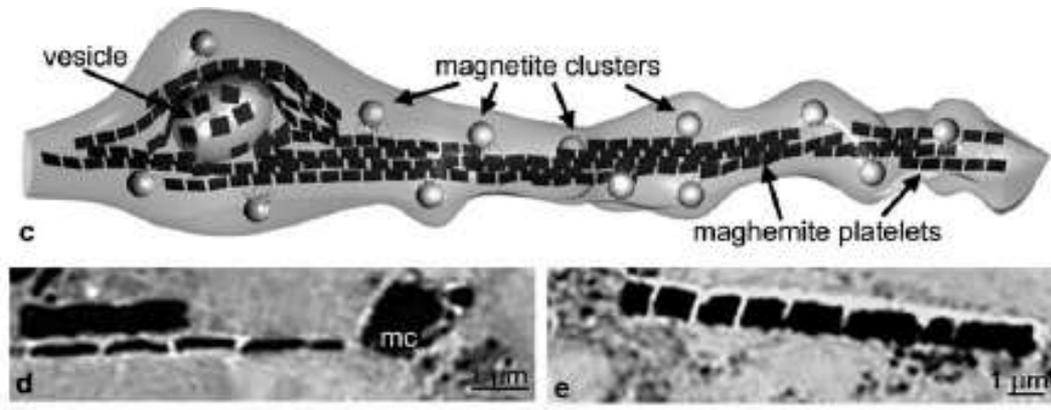
Rainbow trout *onchorinchus mykiss*
(микижа)

Iron-oxide magnetic particles in pigeon beak



Gerta Fleissner, Branko Stahl, Peter Thalau, Gerald Falkenberg, Günther Fleissner, Naturwissenschaften 2007

Iron-oxide magnetic particles in pigeon beak



Gerta Fleissner, Branko Stahl, Peter Thalau, Gerald Falkenberg, Günther Fleissner, *Naturwissenschaften* 2007

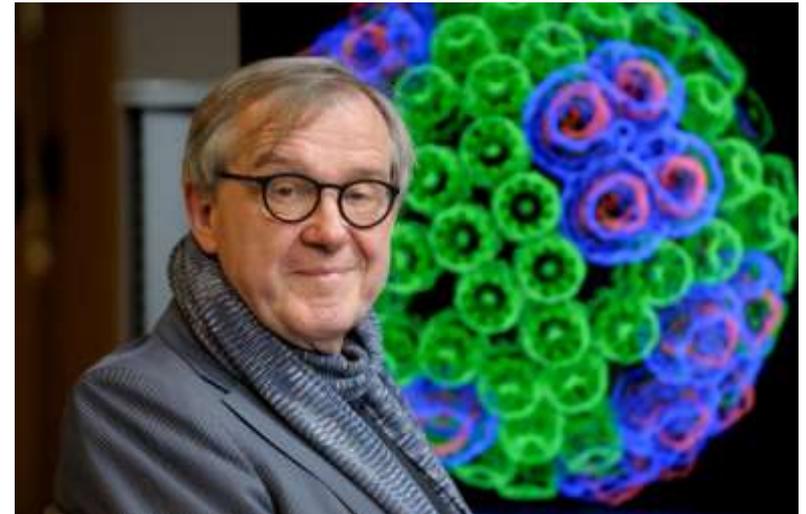
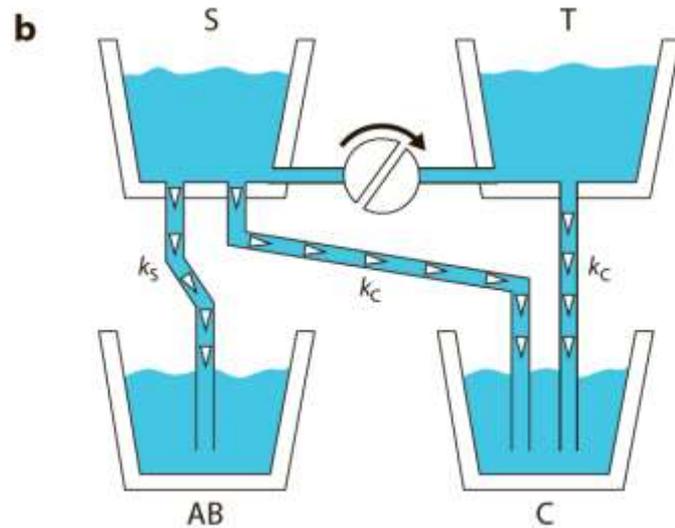
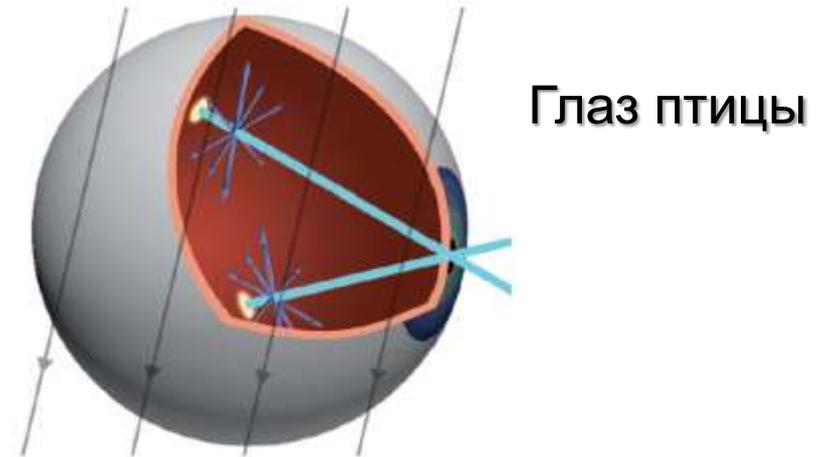
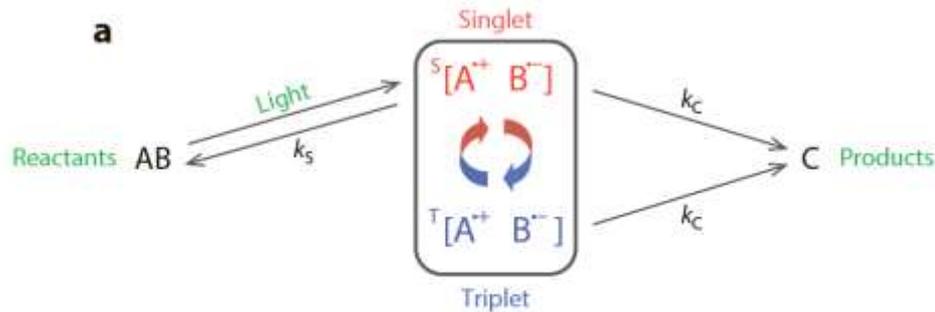
LETTER

doi:10.1038/nature11046

Clusters of iron-rich cells in the upper beak of pigeons are macrophages not magnetosensitive neurons

Christoph Daniel Treiber¹, Marion Claudia Salzer¹, Johannes Riegler², Nathaniel Edelman¹, Cristina Sugar¹, Martin Breuss¹, Paul Pichler¹, Herve Cadiou³, Martin Saunders⁴, Mark Lythgoe², Jeremy Shaw⁴ & David Anthony Keays¹

Radical pair reaction in cryptochrome

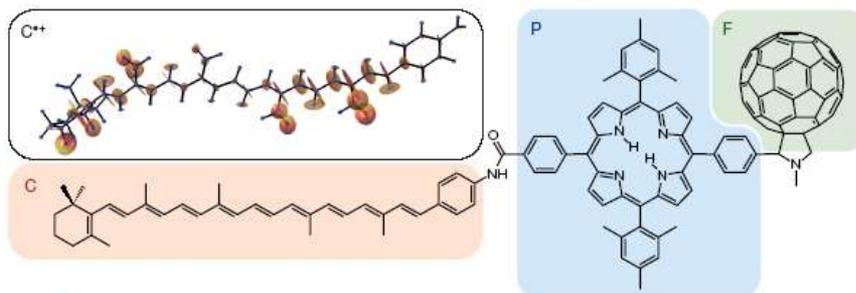


Schulten K, Swenberg CE and Weller A.

A biomagnetic sensory mechanism based on magnetic field modulated coherent electron spin motion. Z. Phys. Chem. (NF). 1978.

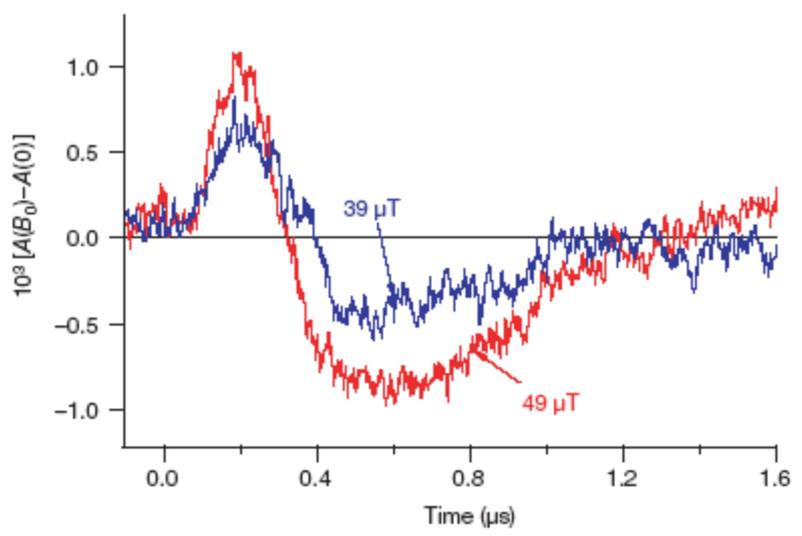
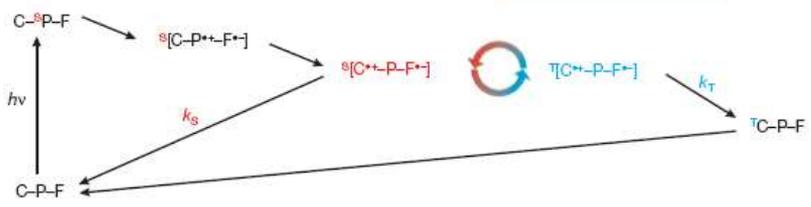
Ritz T., Adem S., Schulten K. 2000. A model for photoreceptor-based magnetoreception in birds // Biophys. J. V. 78. № 2. P. 707–718.

“Chemical compass”



K. Maeda, K. B. Henbest, F. Cintolesi, I. Kuprov, C. T. Rodgers, P. A. Liddell, D. Gust, C.R. Timmel, P. J. Hore,

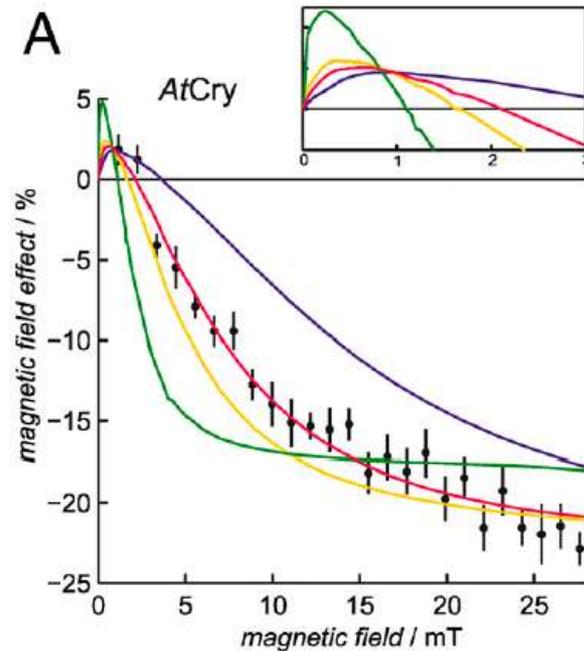
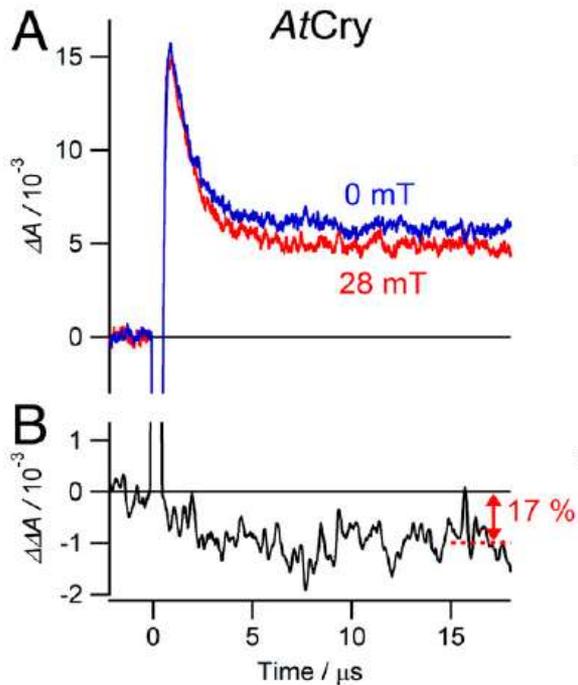
Nature **453**, 387 (2008)



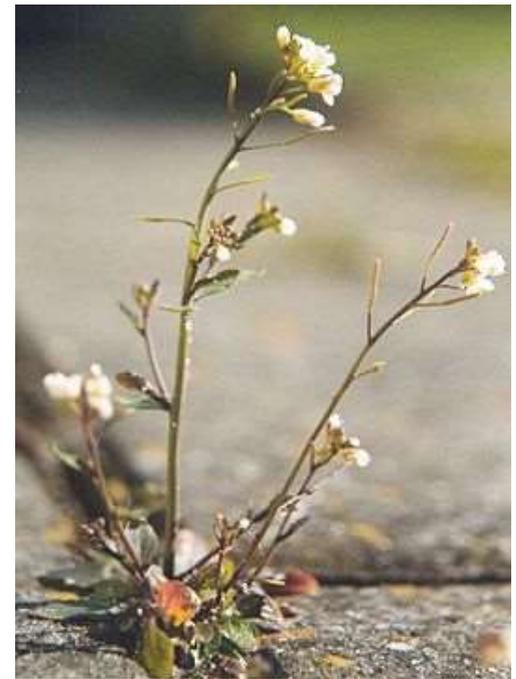
P.J.Hore

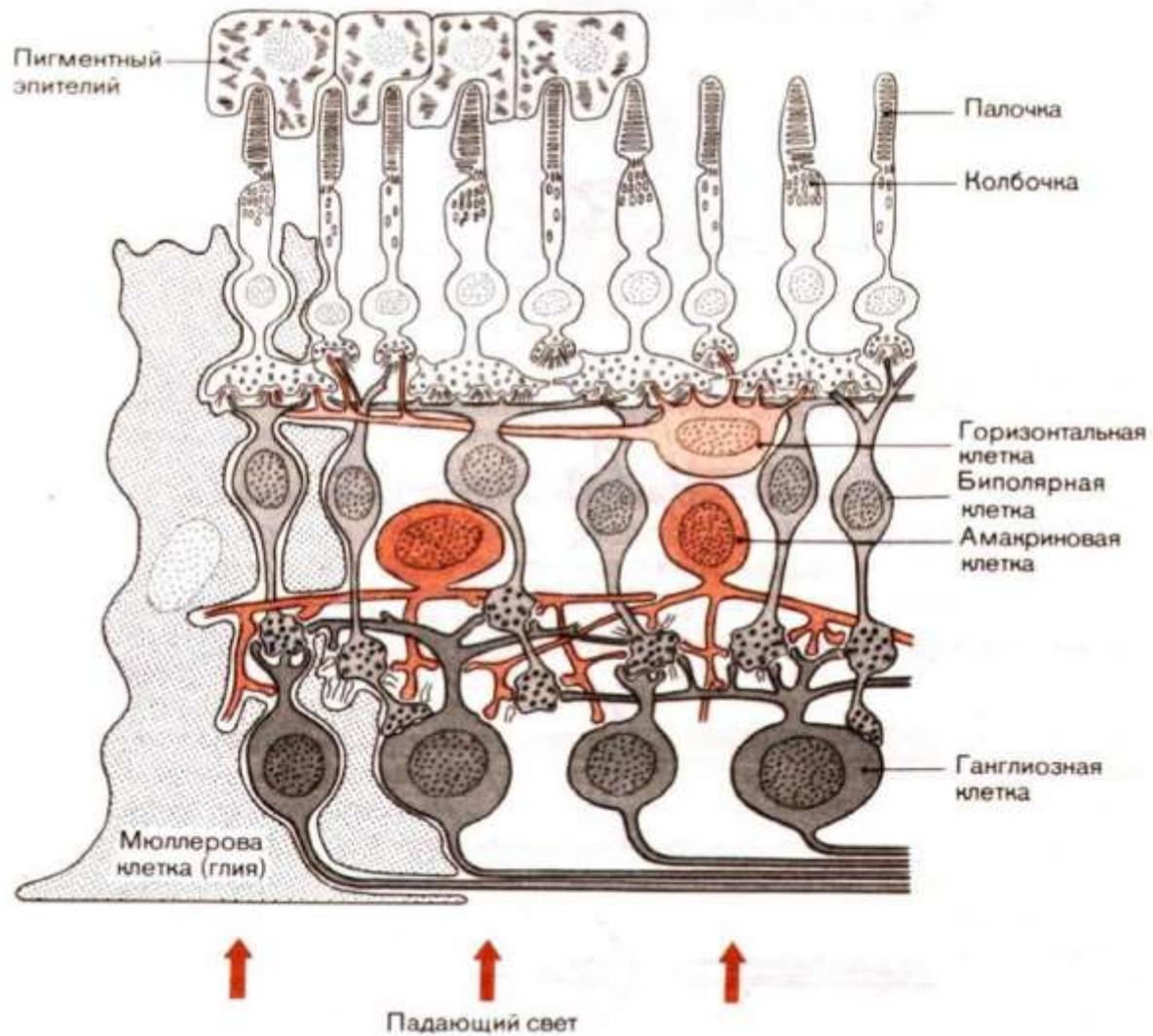
Kiminori Maeda^{a,1}, Alexander J. Robinson^{a,1}, Kevin B. Henbest^e, Hannah J. Hogben^b, Till Biskup^b, Margaret Ahmad^{c,d}, Erik Schleicher^e, Stefan Weber^e, Christiane R. Timmel^{a,2}, and P. J. Hore^{b,2}

4774–4779 | PNAS | March 27, 2012 | vol. 109 | no. 13



Arabidopsis thaliana
(резуховидка Таля)

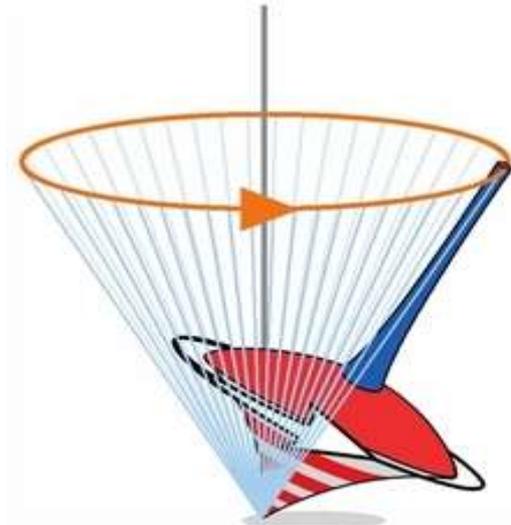
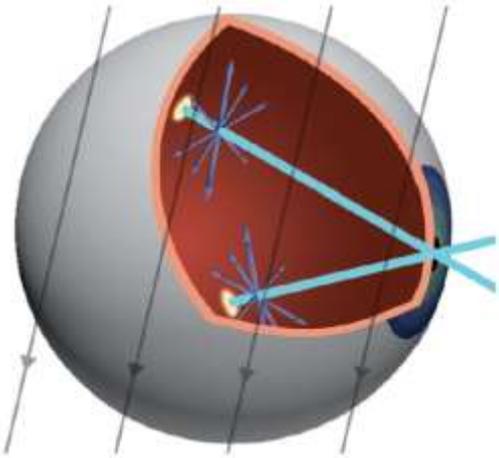




Устройство сетчатки позвоночных

“Probe and reference” model

Глаз птицы \vec{B}



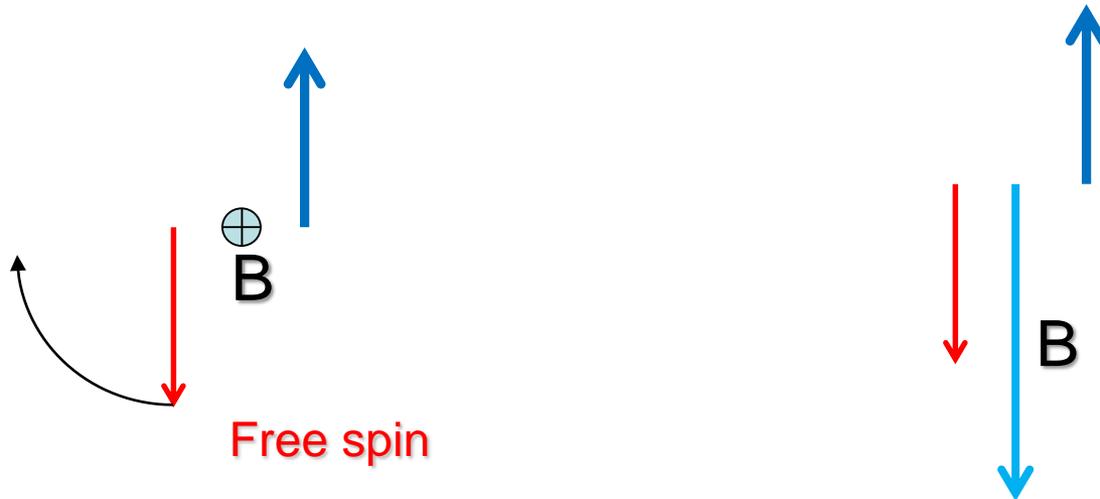
Привязан
к оси
молекулы

Свободно
вращается

$$f_B = \gamma_e B$$

$$\gamma_e = \frac{\mu_B}{\pi \hbar} \approx 28 \text{ Hz} / \text{nT}$$

“Probe and reference” model



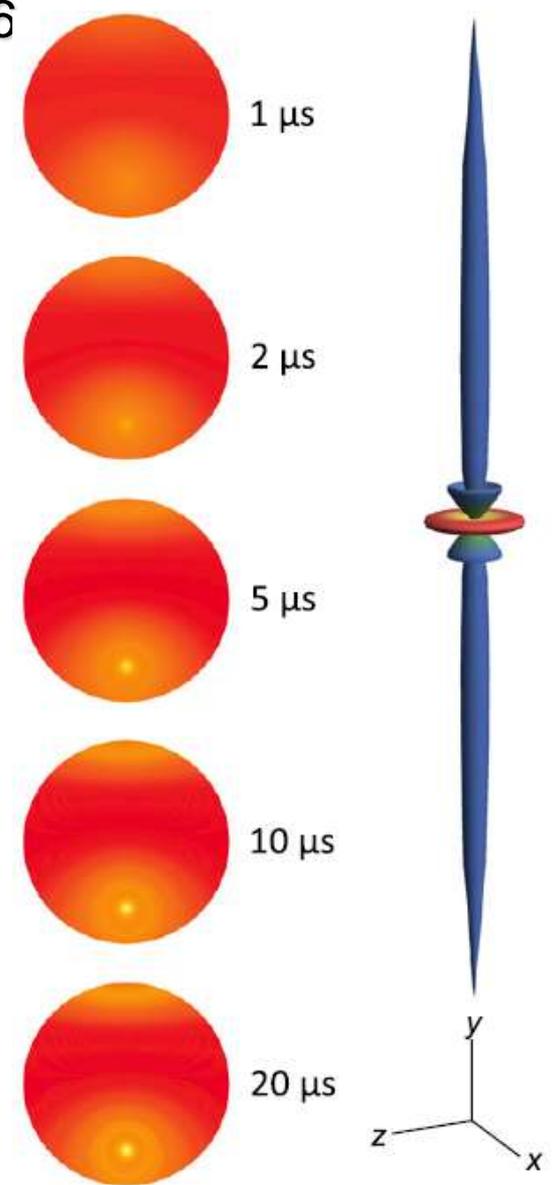
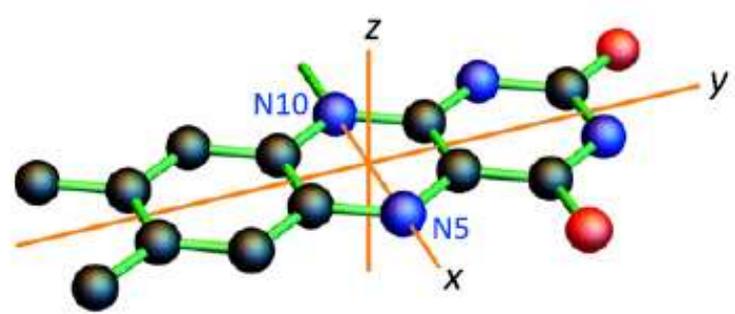
Магнитное поле производит заметный эффект, если

$$\tau_S > (2\pi f_B)^{-1}$$

τ_S - время спиновой релаксации

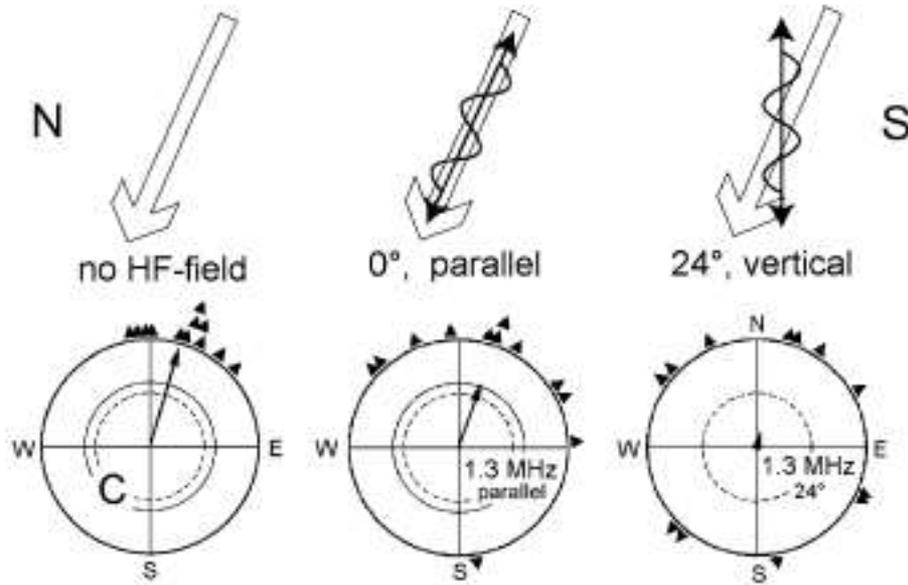
для $B=0.5 \text{ G}$ $\tau_S > 0.1 \mu\text{s}$

Hiscock, H.G., Worster, S., Kattnig, D.R., Steers, C., Jin, Y., Manolopoulos, D.E., Mouritsen, H., and Hore, P.J. 2016
The quantum needle of the avian magnetic compass.
Proc. Natl. Acad. Sci. USA **113**, 4634–4639.



Experiments with oscillatory magnetic fields.

Ritz et al, 2004; Thalau et al, 2005; Ritz et al, 2009



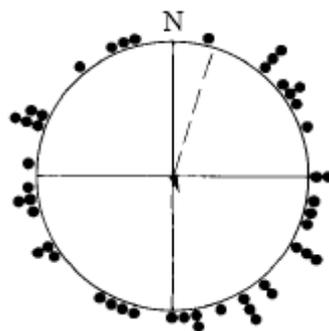
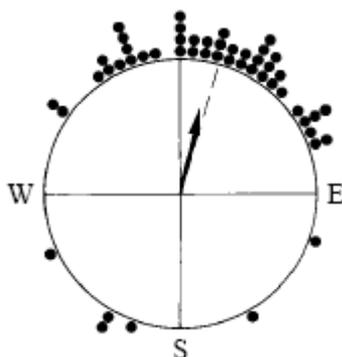
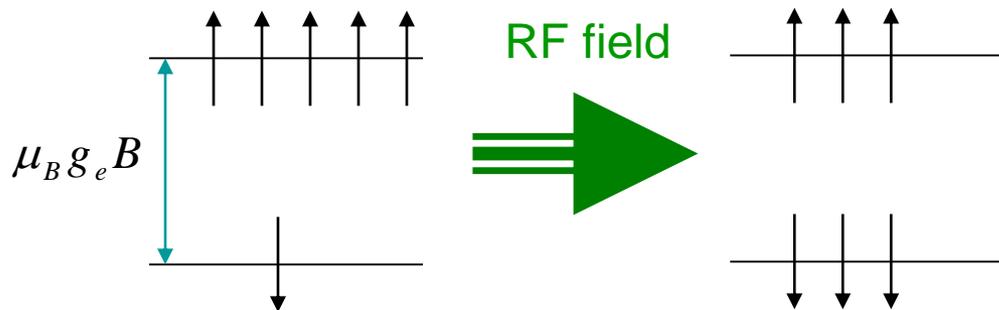
RF magnetic field
results in desorientation!

Broadband 0.1-10MHz, 85nT
monochromatic: 1.315MHz, 7MHz,
(and other frequencies in between
0.1 and 7 MHz), <500nT

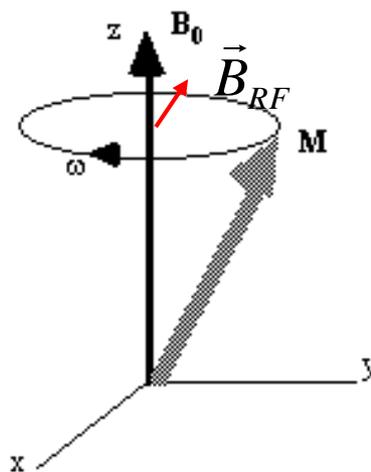
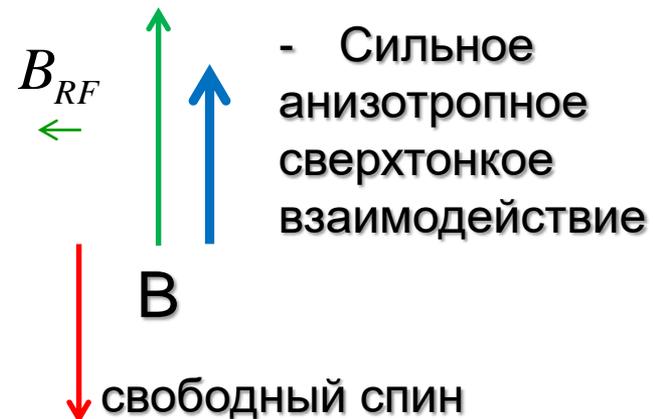


T.Ritz

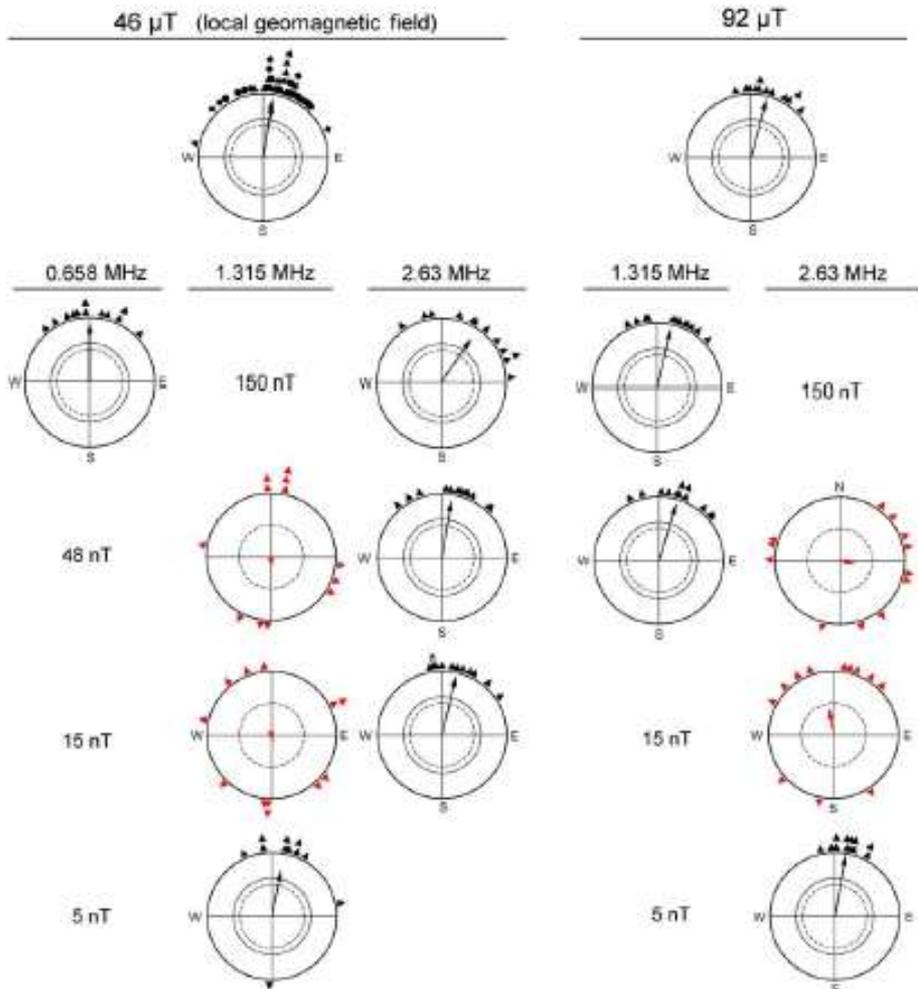
Electron spin resonance



Пример:

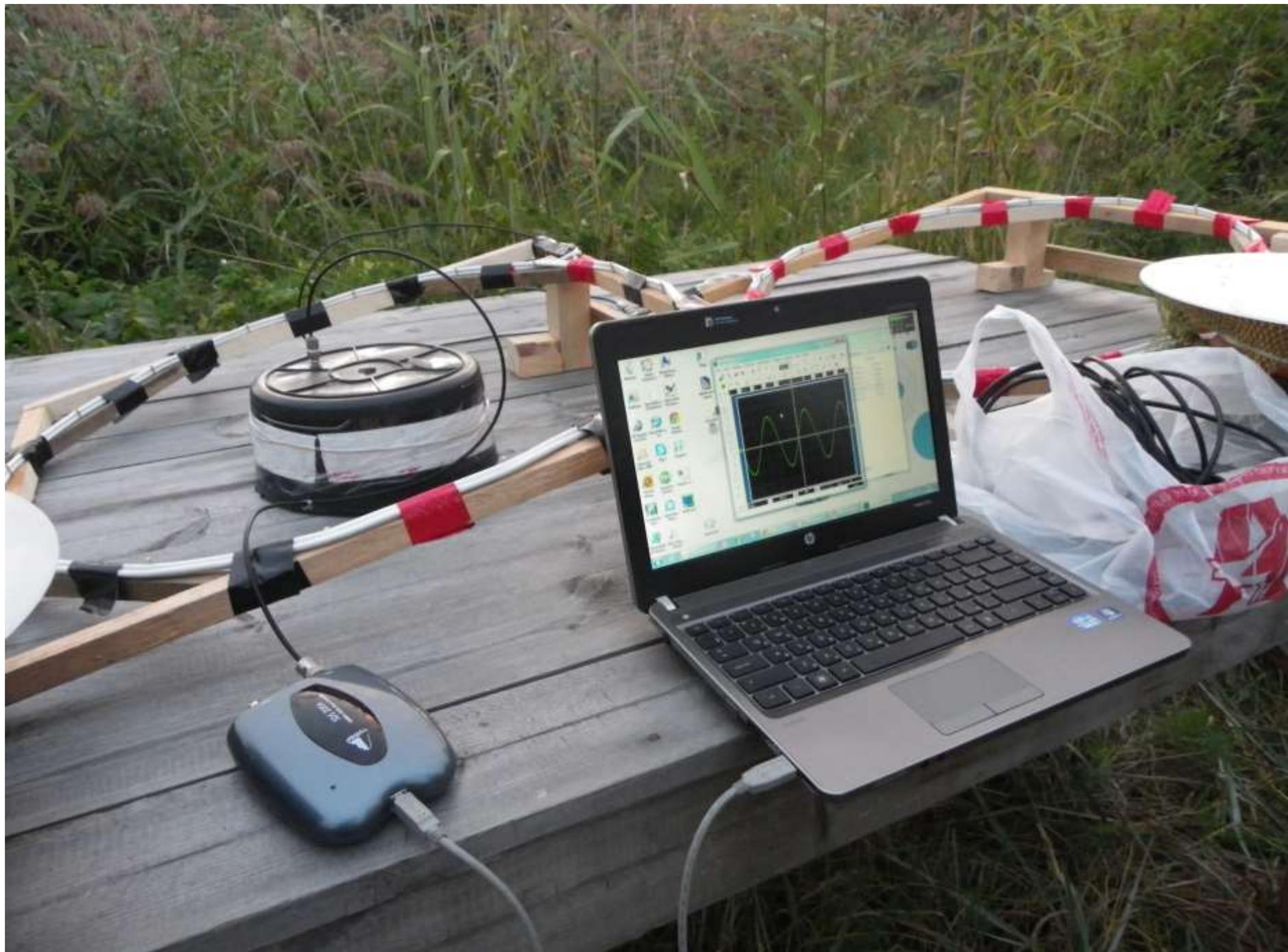


$$f_{RF} = \gamma_e B_{RF}$$



Ritz, T., Wiltschko, R., Hore, P. J., Rodgers, C. T., Stapput, K., Thalau, P., Timmel, C. R., and Wiltschko, W.,
 Magnetic compass of birds is based on a molecule with optimal directional sensitivity,
Biophys. J. (2009)

Kavokin KV. The puzzle of magnetic resonance effect
 on the magnetic compass of migratory birds. *Bioelectromagnetics*. 2009. 30: 402–410



Биологическая станция «Рыбачий» ЗИН РАН, Куршская коса

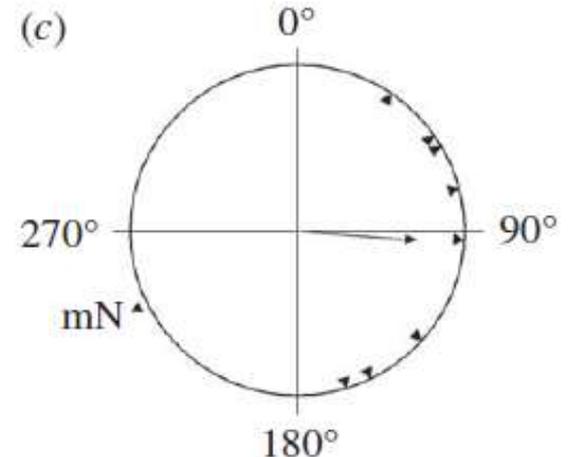
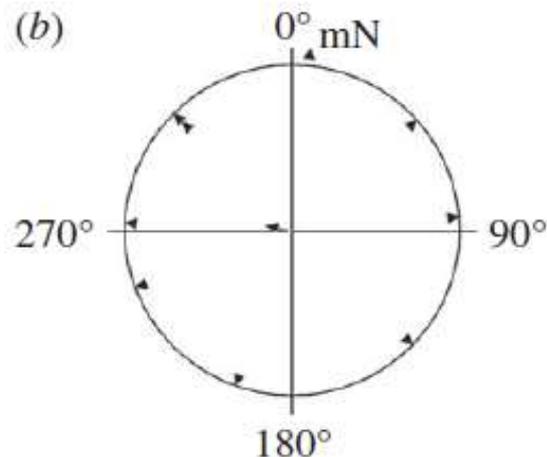
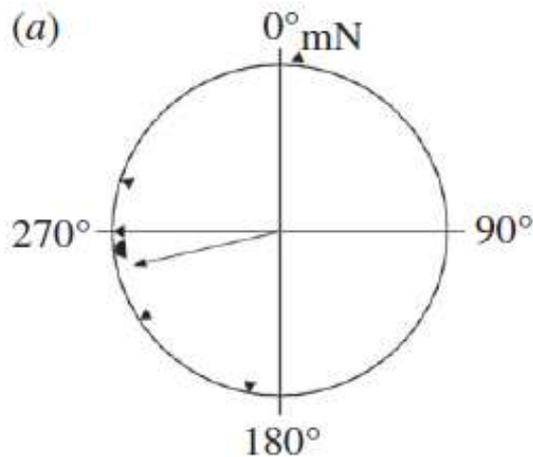


Magnetic orientation of garden warblers (*Sylvia borin*) under 1.4 MHz radiofrequency magnetic field

Kirill Kavokin, Nikita Chernetsov, Alexander Pakhomov, Julia Bojarinova, Dmitry Kobylkov and Barot Namozov

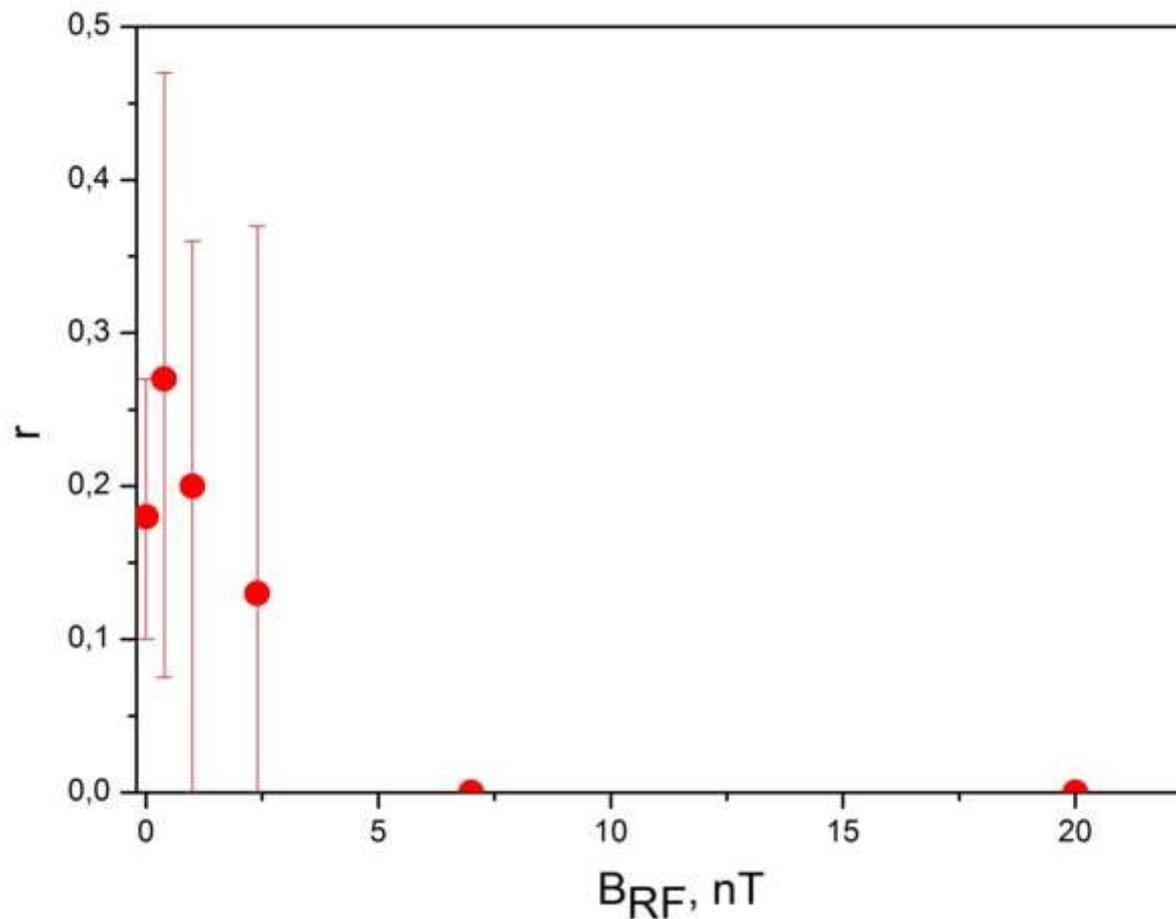
J. R. Soc. Interface 2014 **11**, 20140451, published 18 June 2014

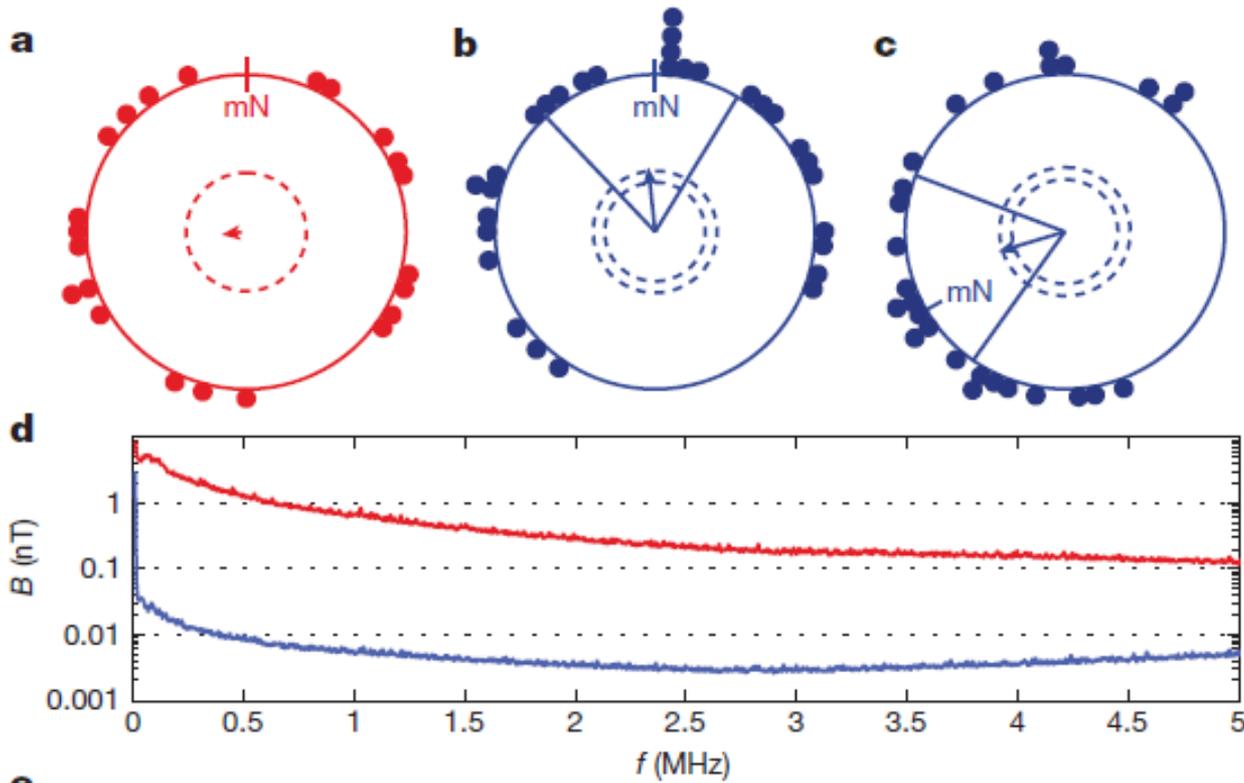
$$B_{RF} = 190 \text{ nT} \quad \alpha = 30^\circ \quad f = 1.403 \text{ MHz}$$



Very weak oscillating magnetic field disrupts the magnetic compass of songbird migrants

A. Pakhomov^{1,2}, J. Bojarinova^{2,3}, R. Cherbunin^{2,3}, R. Chetverikova³, F. Grigoriev³, K. Kavokin^{2,3,4}, D. Kobylkov⁵, R. Lubkovskaja³, N. Chernetsov^{1,2,3}





Engels S, Schneider N-L, Lefeldt N, Hein CM, Zapka M, et al. 2014. Anthropogenic electromagnetic noise disrupts magnetic compass orientation in a migratory bird. *Nature* 509:353–56

Ritz T, Thalau P, Phillips JB, Wiltschko R and Wiltschko W.
Resonance effects indicate a radical-pair mechanism for avian magnetic compass.
Nature. 2004. **429**: 177–180.

Ritz T, Wiltschko R, Hore PJ., Rodgers CT, Stapput K, Thalau P, Timmel CR
and Wiltschko W.
Magnetic compass of birds is based on a molecule with optimal directional sensitivity.
Biophys. J. 2009 **96**: 3451–3457.

Ritz T, Ahmad M, Mouritsen H, Wiltschko R and Wiltschko W.
Magnetic compass orientation of migratory birds
in the presence of a 1.315 MHz oscillating field.
Naturwissenschaften. 2005. **92**: 86–90.

Engels S, Schneider NL, Lefeldt N, Hein CM, Zapka M, et al.
Anthropogenic electromagnetic noise disrupts magnetic compass orientation
in a migratory bird.
Nature. 2014. **509**: 353–56

Kavokin K, Chernetsov N, Pakhomov A, Bojarinova J, Kobylkov D, Namozov B.
Magnetic orientation of garden warblers (*Sylvia borin*) under 1.4 MHz radiofrequency
magnetic field.
J. R. Soc.Interface. 2014. **11**: 20140451

Скорость переходов между спиновыми состояниями электронов под действием шумового магнитного поля прямо пропорциональна его спектральной мощности :

$$W_B = (\gamma_e)^2 \langle B_{RF}^2 \rangle (2\pi\Delta f)^{-1}$$

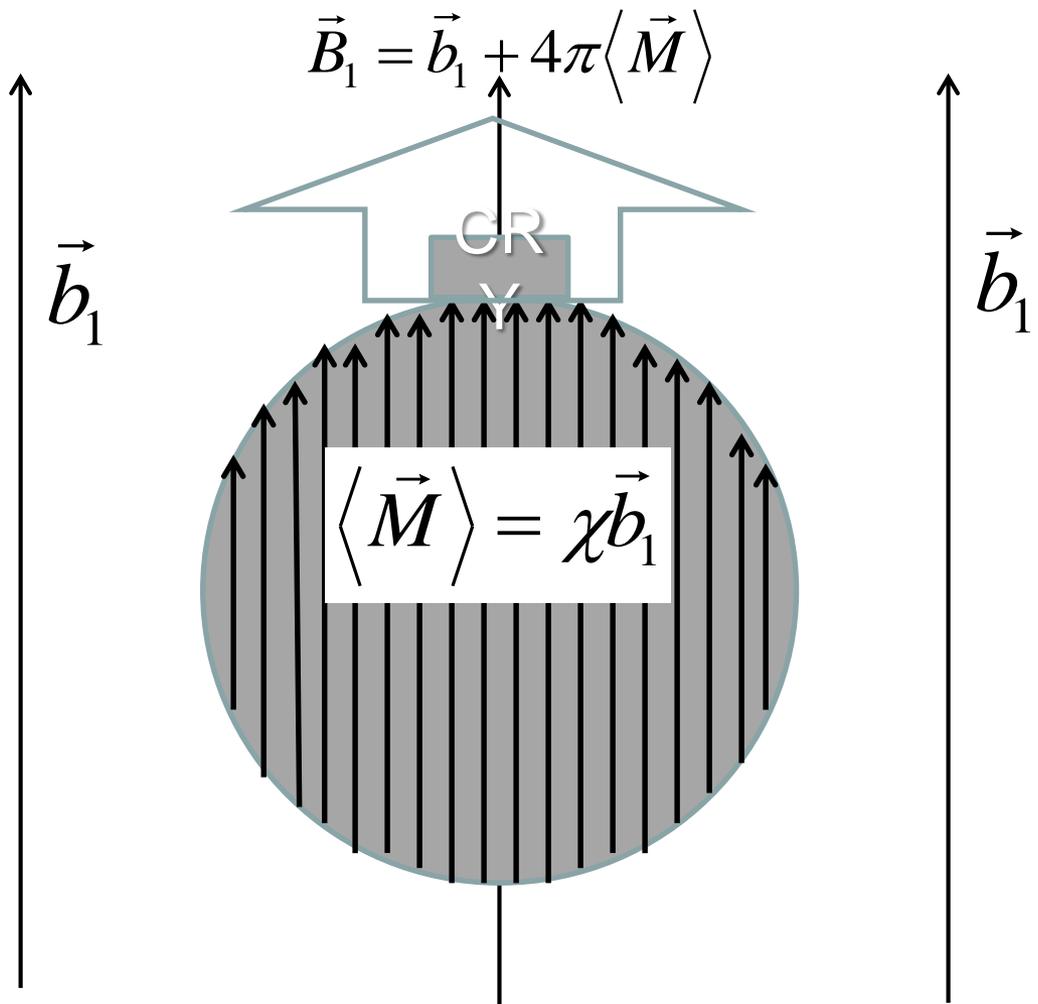
По результатам экспериментов : $W_B \approx 0.5 \text{ s}^{-1}$

Расчёт скорости переходов между спиновыми состояниями электронов в криптохроме под действием внутренних флуктуирующих полей, создаваемых магнитными моментами ядер:

Kattnig DR, Solov'yov I, Hore PJ.

Electron spin relaxation in cryptochrome-based magnetoreception. Phys.Chem.Chem.Phys. 2016. **18**: 12443-12456.

$$W_{HF} \approx 10^6 \text{ s}^{-1}$$



Безразмерная восприимчивость суперпарамагнитной частицы магнетита

$$\nu = \frac{4\pi M(B)}{B} = \frac{4\pi\mu^2}{3k_B T V} = \frac{4\pi M_S^2 V}{3k_B T} \approx 2500$$

(при размере 50 нм)

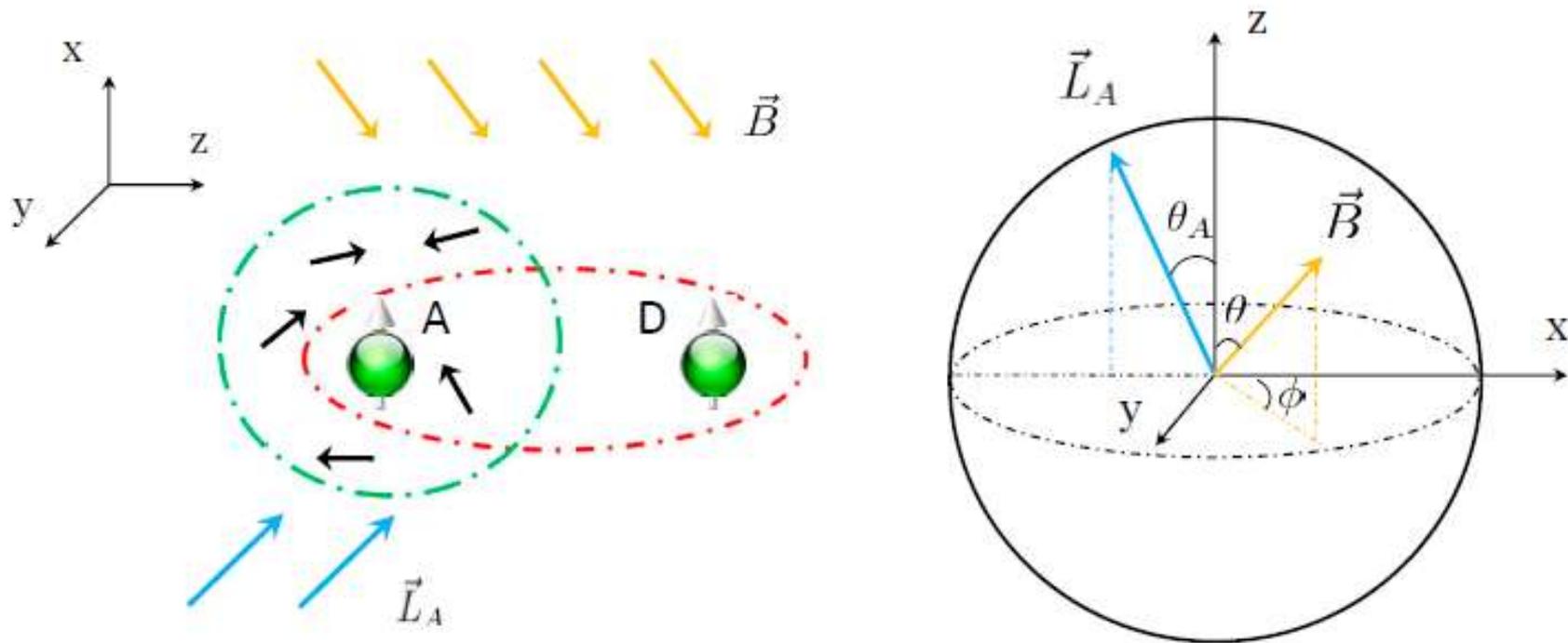
Казалось бы, прекрасно...

Quantum probe and design for a chemical compass with magnetic nanostructures

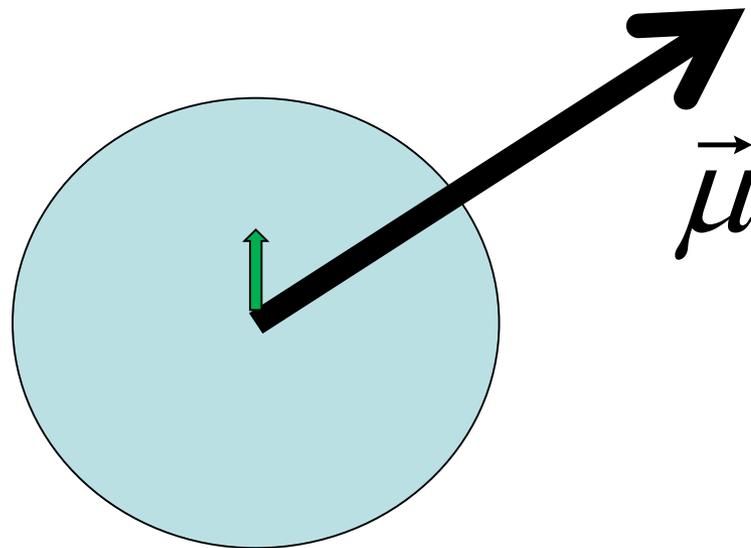
Jianming Cai

Institut für Quantenoptik und Quanteninformation der Österreichischen Akademie der Wissenschaften, Innsbruck, Austria

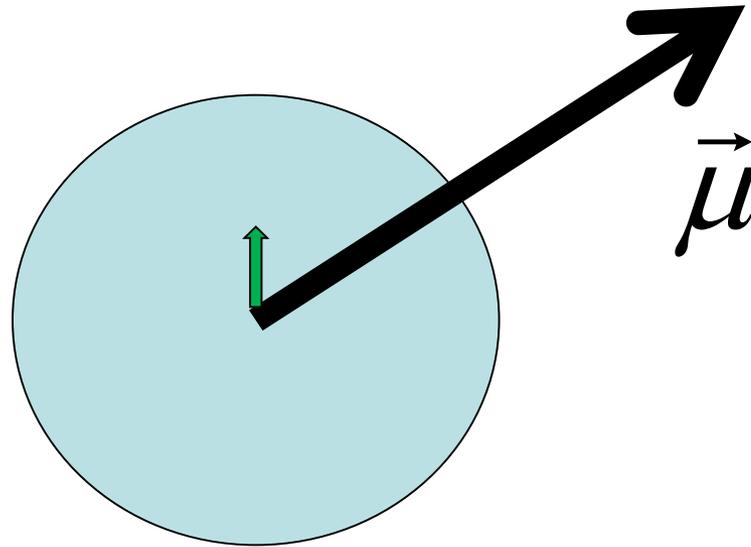
(Dated: March 2, 2011)



Но не надо забывать о флуктуациях!



Но не надо забывать о флуктуациях!



...которые, правда, размазаны по частоте

$$\Delta f = \frac{1}{2\pi\tau} \quad \tau \approx 10^{-9}$$

Спектральная плотность флуктуаций

$$\langle \mu_z^2 \rangle_\omega = \frac{\mu^2}{3} \frac{2\tau}{1 + \omega^2 \tau^2}$$

Мнимая часть восприимчивости

$$\alpha_z''(\omega) = \frac{\mu^2}{3k_B T} \frac{\omega \tau}{1 + \omega^2 \tau^2}$$

вещественная часть восприимчивости

$$\alpha_z'(\omega) = \frac{\mu^2}{3k_B T} \frac{1}{1 + \omega^2 \tau^2}$$

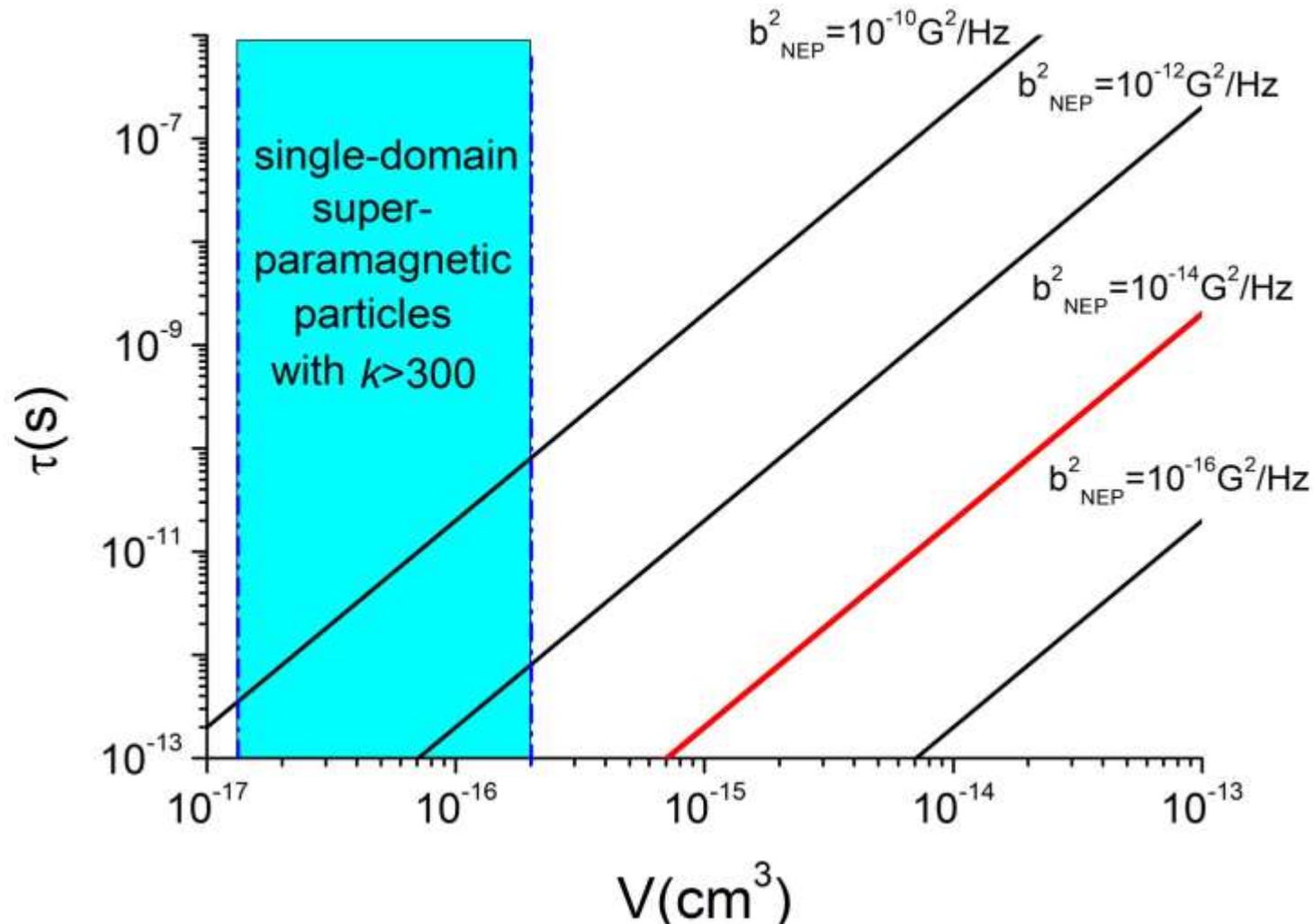
$$|\alpha_z(\omega)| = \sqrt{\alpha_z'^2(\omega) + \alpha_z''^2(\omega)} = \frac{\mu^2}{3k_B T} \frac{1}{\sqrt{1 + \omega^2 \tau^2}}$$

приведенная ко входу

спектральная плотность шума

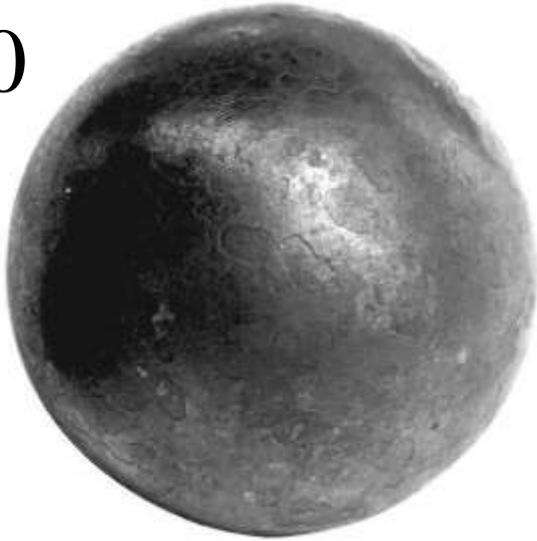
$$b_{eq}(\omega) = \frac{\sqrt{\langle \mu_z^2 \rangle_\omega}}{|\alpha_z(\omega)|} = \frac{k_B T}{\mu} \cdot \sqrt{6\tau}$$

К.Кавокин, «Can a hybrid chemical-ferromagnetic model of the avian compass explain its outstanding sensitivity to magnetic noise?»
- принята в PLOS ONE



Энергия анизотропии

$$E_A = 0$$

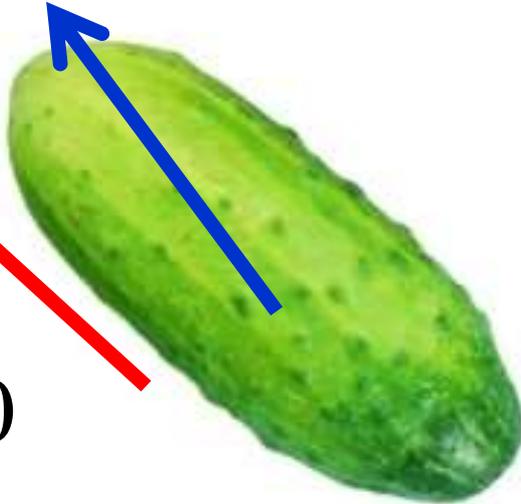


$$E_A = \frac{AVM_Z^2}{2}$$



Поле анизотропии

$$B_A$$



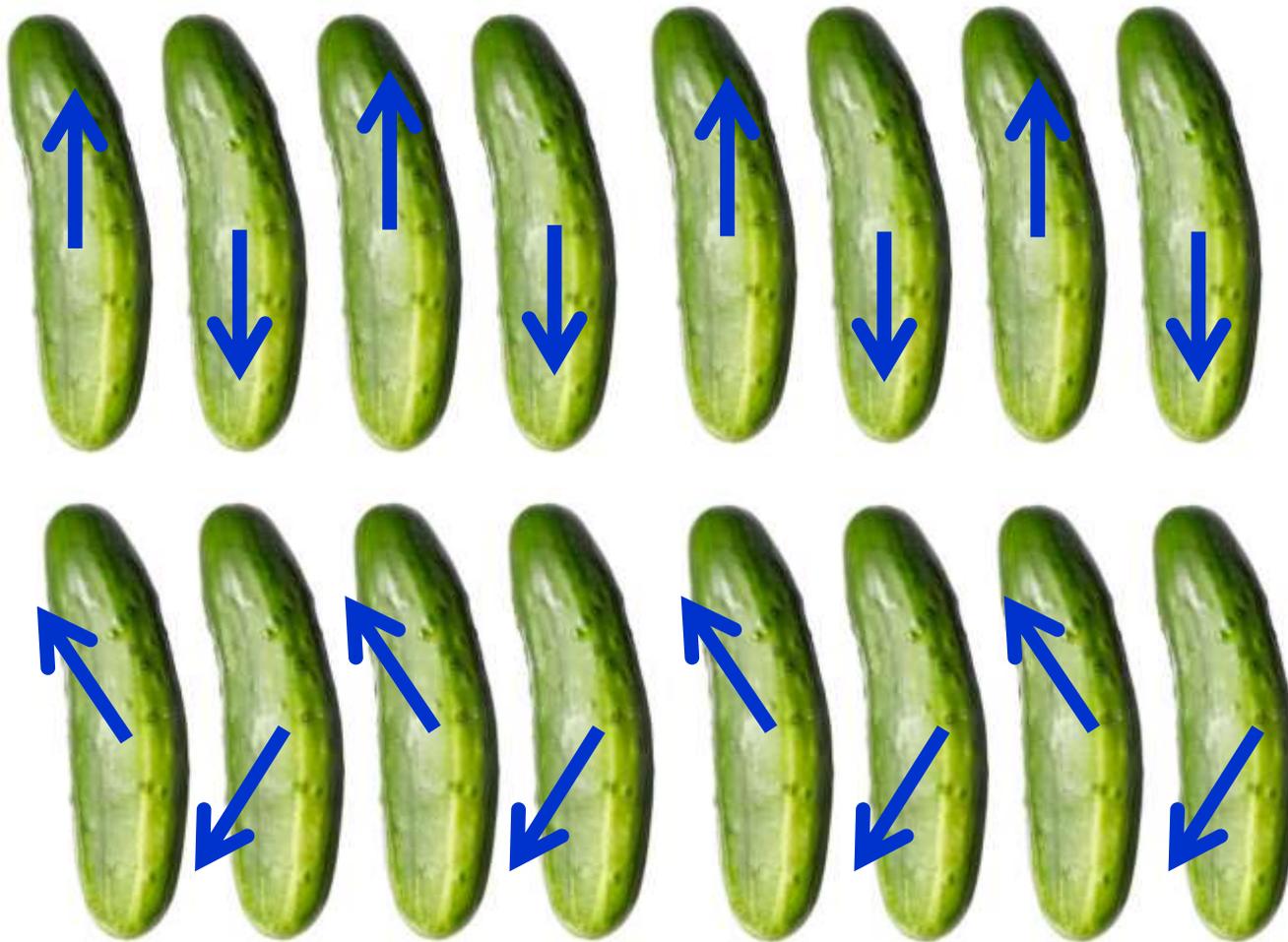
$$E_A < 0$$

$$E_A > 0$$

Магнитодипольное взаимодействие:

$$E_{MD} = -\frac{1}{r^3} \left(\vec{\mu}_1 \vec{\mu}_2 - 3 \frac{(\vec{\mu}_1 \cdot \vec{r}_{12})(\vec{\mu}_2 \cdot \vec{r}_{12})}{r_{12}^2} \right)$$





Мягкая мода

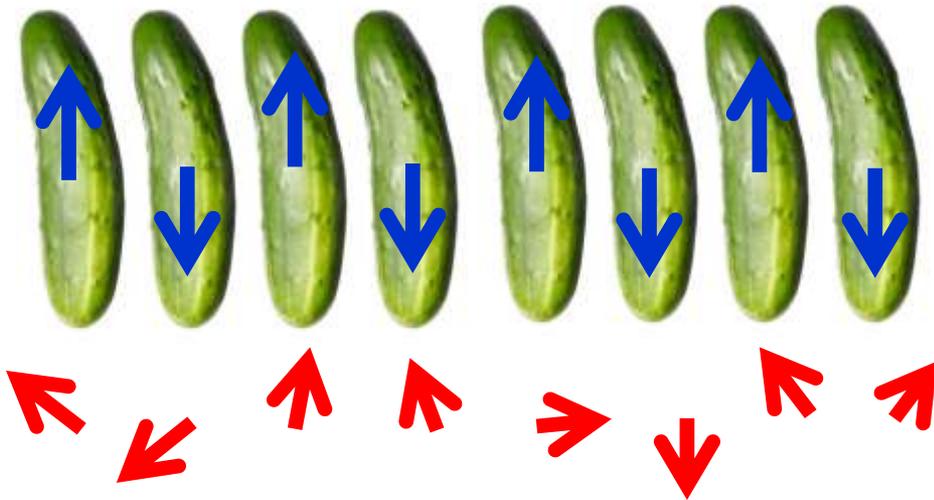
$$\omega_{SM} = \gamma_e \sqrt{B_A (B_A - B_{dd})}$$

спектральная плотность флуктуаций

$$\langle \mu_{SM}^2 \rangle_{\omega} \propto \left[\frac{\tau}{1 + (\omega - \omega_{SM})^2 \tau^2} + \frac{\tau}{1 + (\omega + \omega_{SM})^2 \tau^2} \right]$$

В области низких частот

$$\langle \mu_{SM}^2 \rangle_{\omega} \propto \frac{1}{\omega_{SM}^2 \tau_{SM}}$$

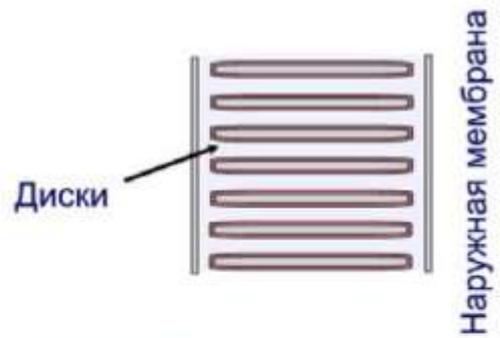
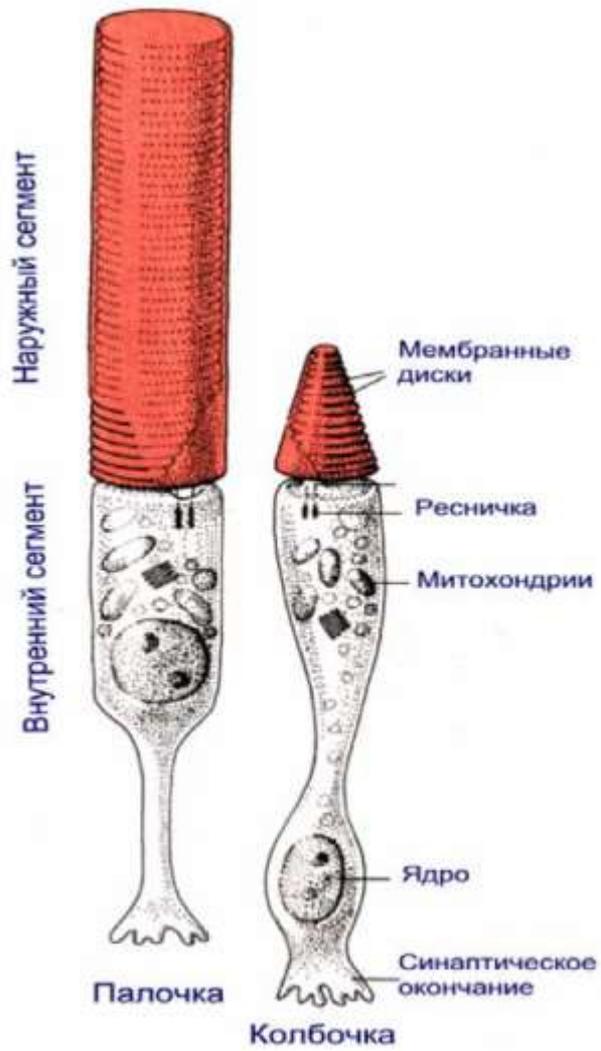


Для коллективной моды

$$b_f^* \approx b_f / \sqrt{N}$$

Время релаксации момента коллективной моды в N раз дольше!

\vec{b}_f - случайные магнитные поля, вызывающие релаксацию магнитных моментов



Что надо запомнить:

1. Магнитный компас у птиц есть!

2. Что бы вам ни говорили, никто в точности не знает, как он устроен

3. Исследование механизмов магниторецепции – вполне осмысленное поле деятельности для физика

