Theory of spin mechatronics

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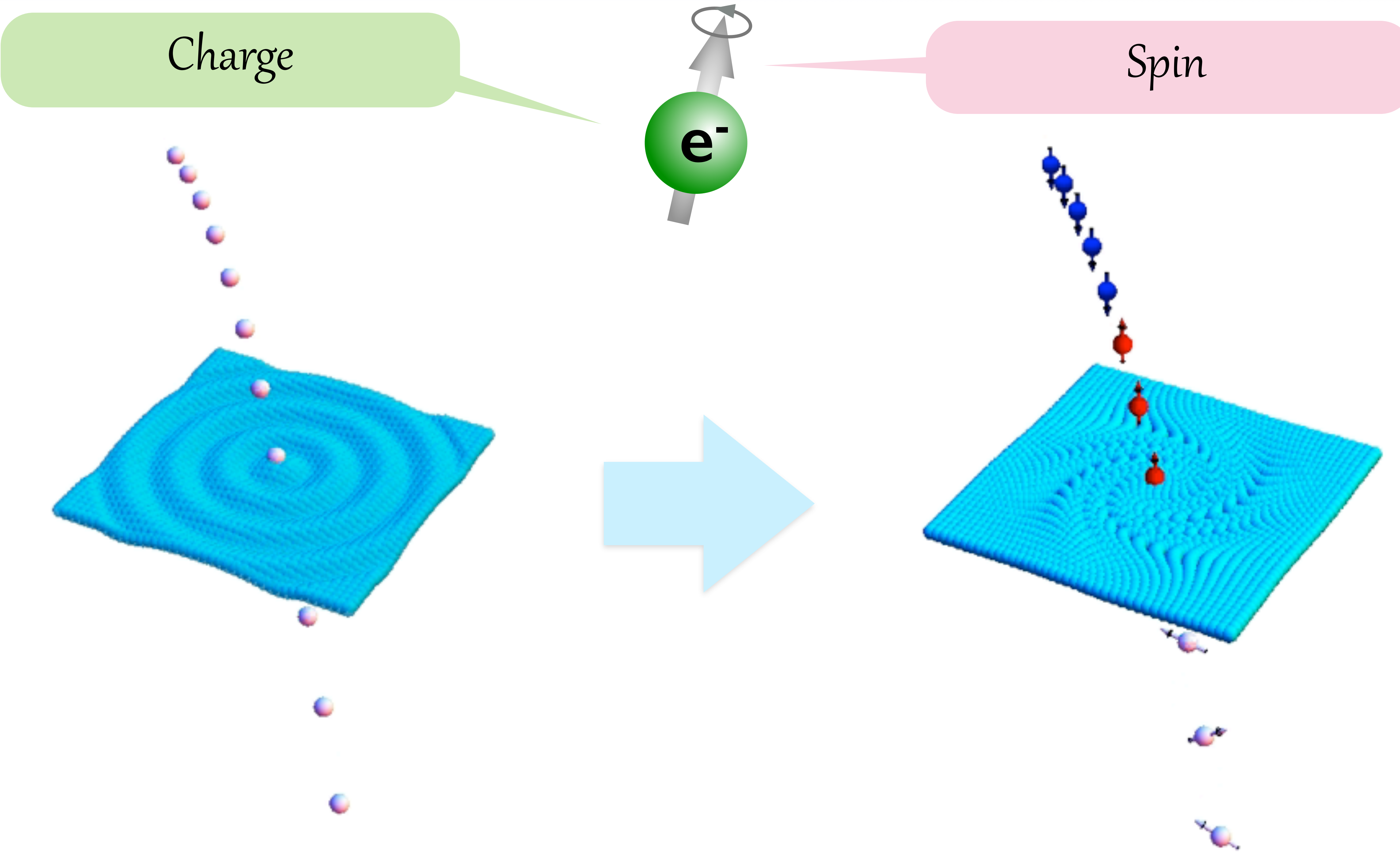
in collaboration with

J. Ieda, S. Maekawa [theory]

H. Chudo, K. Harii, M. Ono, R. Takahashi, E. Saitoh [experiment]

From mechatronics to “spin mechatronics”



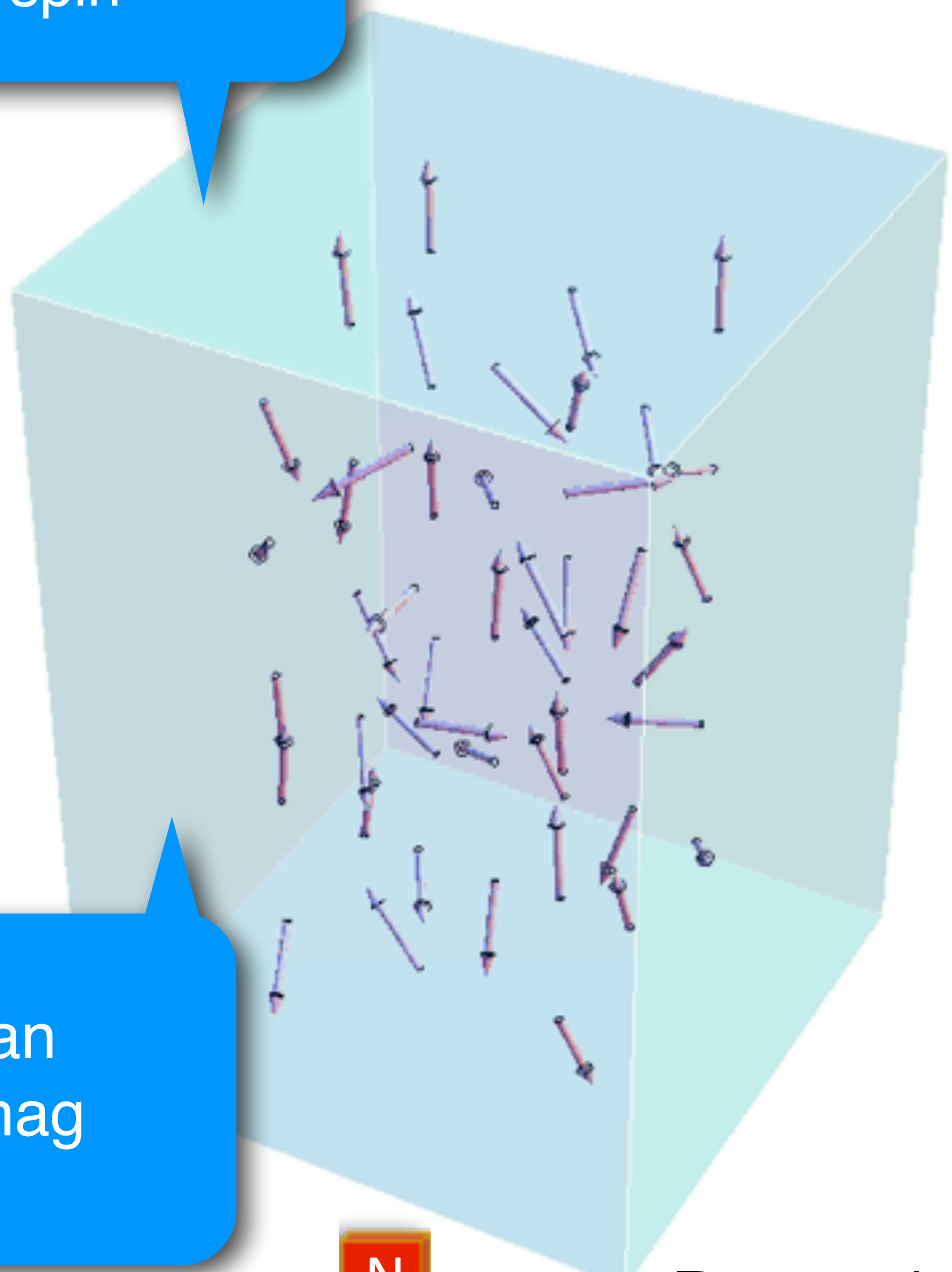
Charge current & mechanical motion

<u>Spin current & mechanical motion</u>

Angular momentum conversion
between spin and mechanical rotation

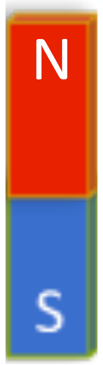
Einstein-de Haas (1915): Rotation by magnetization

Wheel = spin



Ayako-san
＝ Ferromag

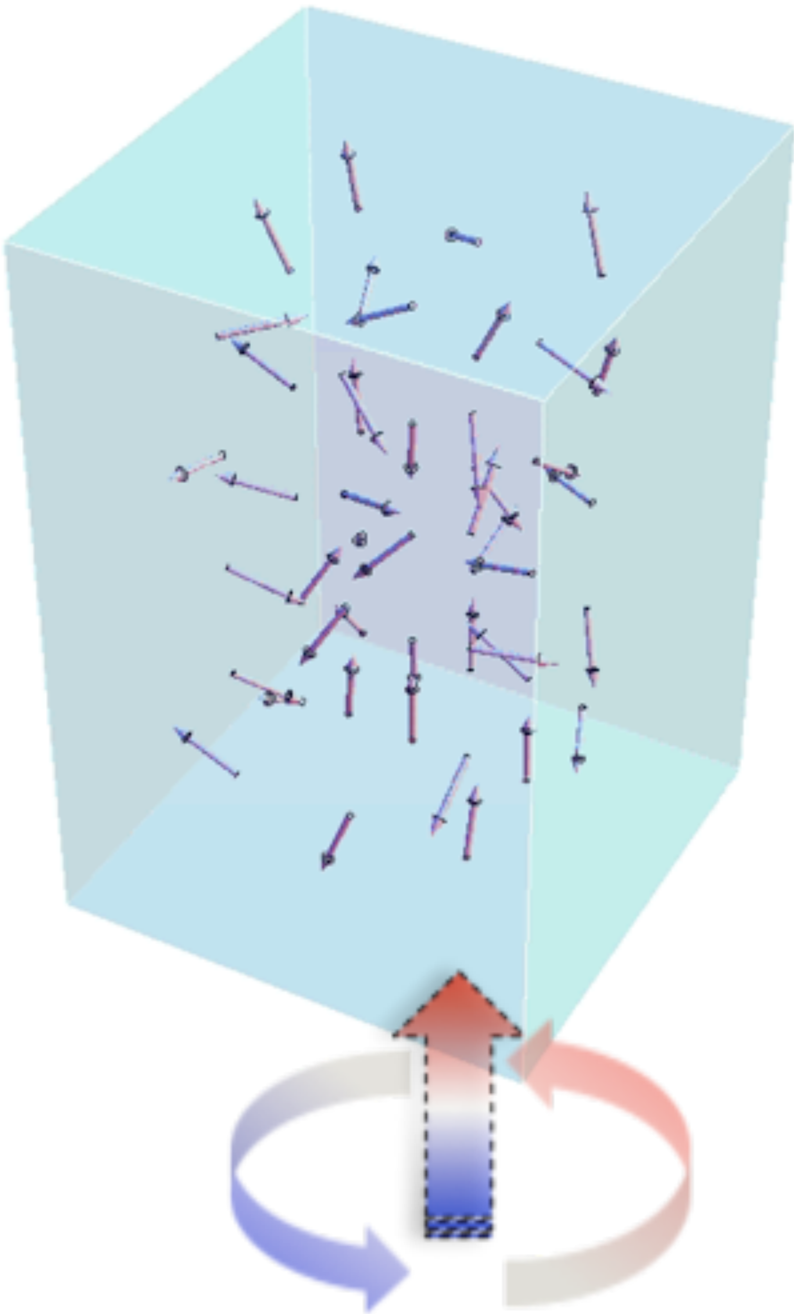
Arm = Magnet



Determined
g~2 for electron
before Quantum
Mechanics

Magnetization by rotation: Barnett effect (1915)

$$H_{\text{Spin-rotation}} = S \cdot \Omega$$



Rotation ~ Magnetic field

$$H = L \cdot \Omega$$ [L : angular momentum, Ω : rotation frequency]

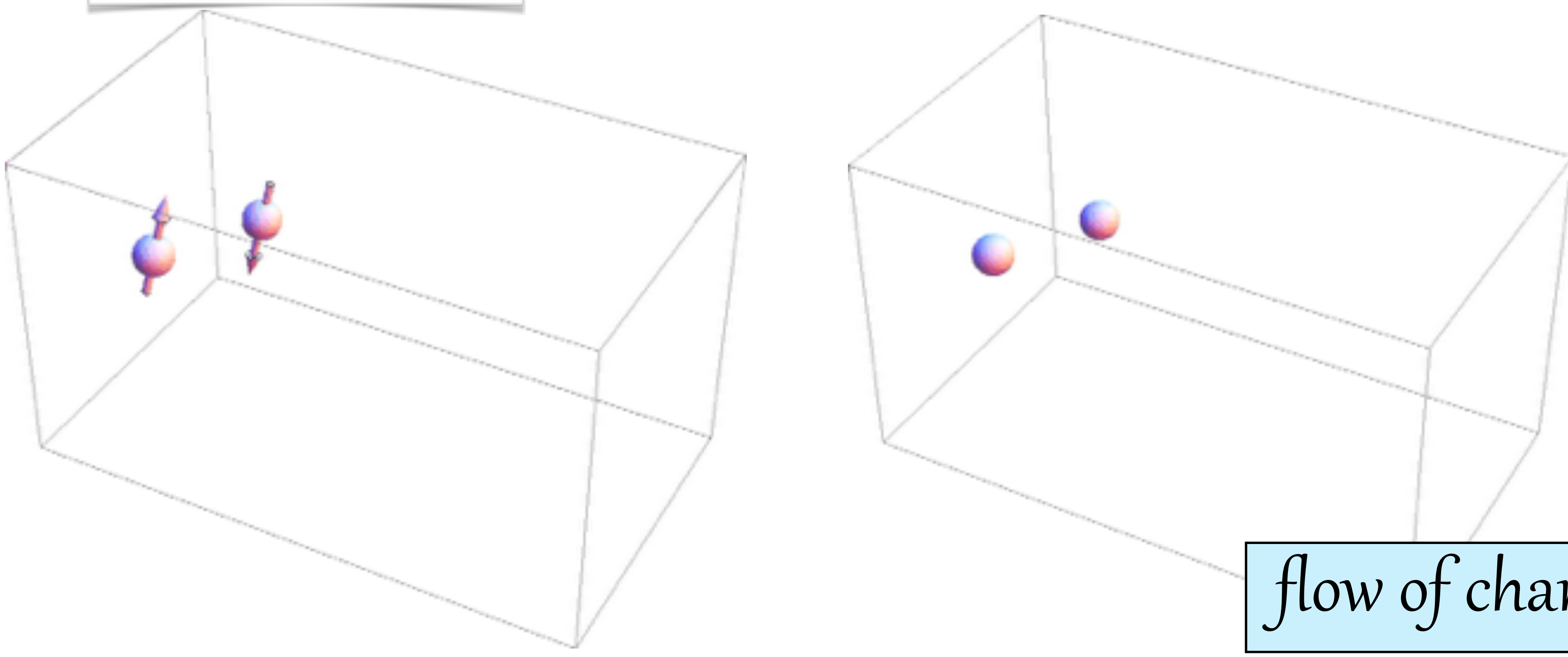
$$H_{\text{Zeeman}} = S \cdot \gamma B$$

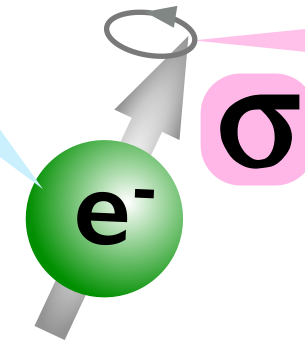
$$B_{\Omega} = \frac{\Omega}{\gamma}$$ [$\gamma = \frac{e}{m}$: gyromagnetic ratio]

$$H_{\text{Spin-rotation}} = S \cdot \Omega$$

Charge current and spin current

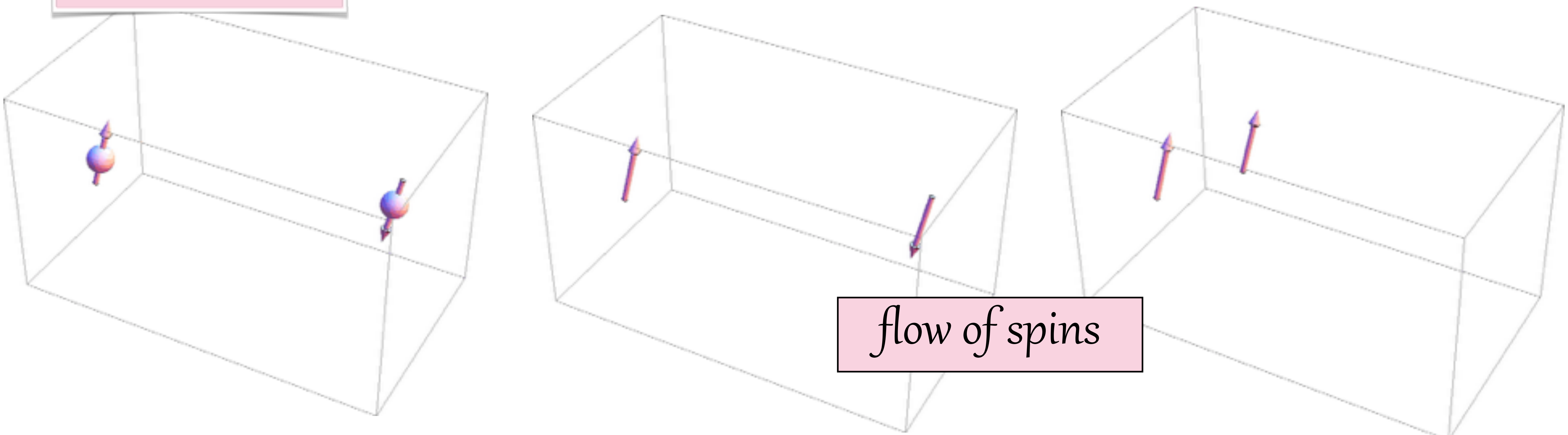
Charge current





flow of charges

Spin current

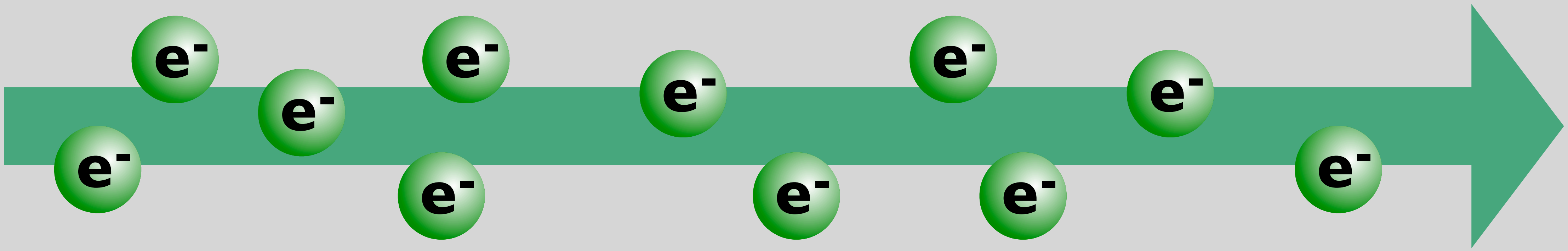


flow of spins

Spin current is fragile

Charge current:
conserved

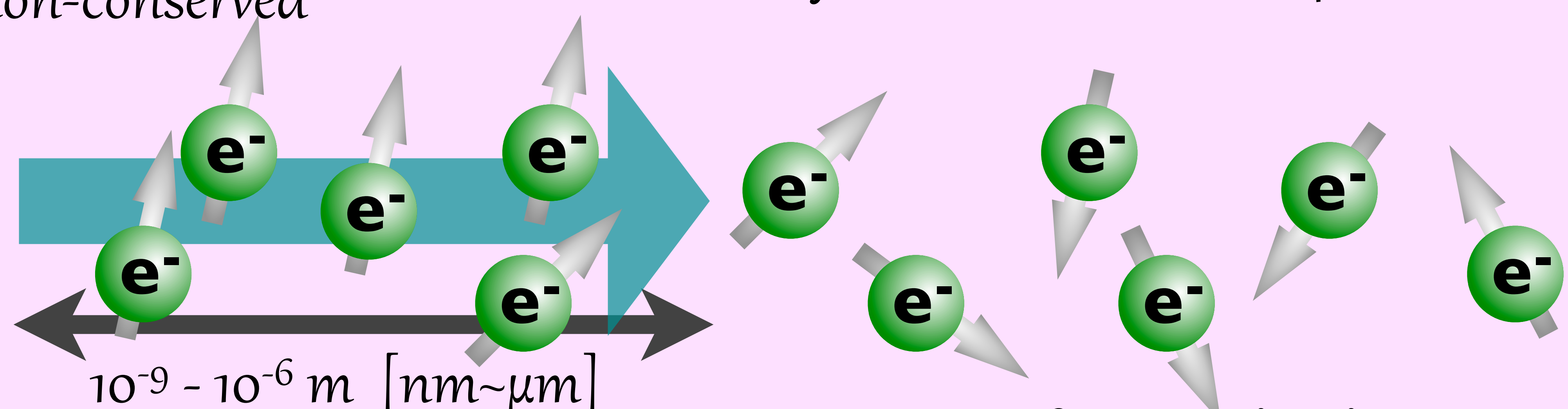
→ can travel infinite distance



Easy to control → Electronics in 20th century

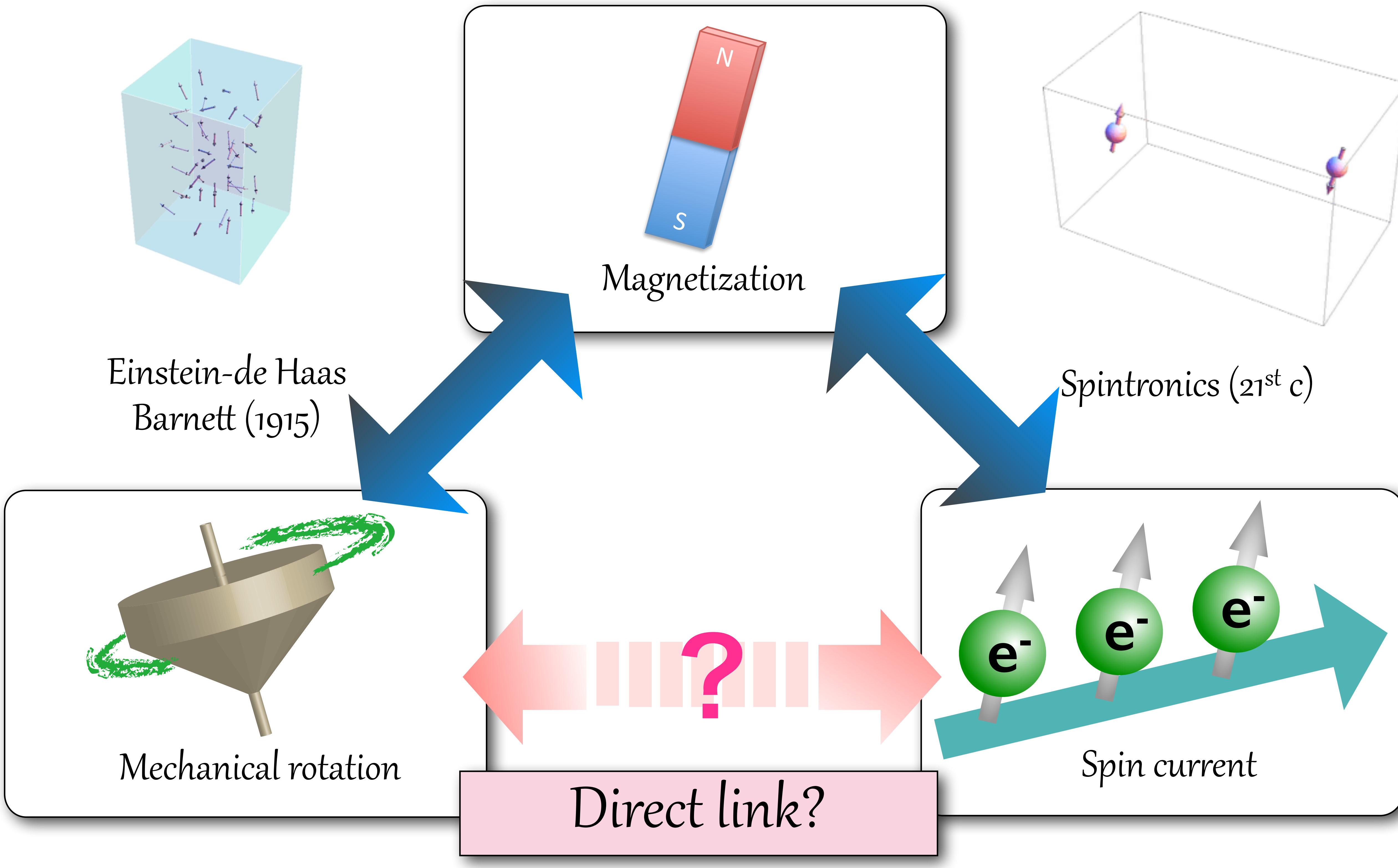
Spin current:
non-conserved

→ can travel only short distance [nm~μm]

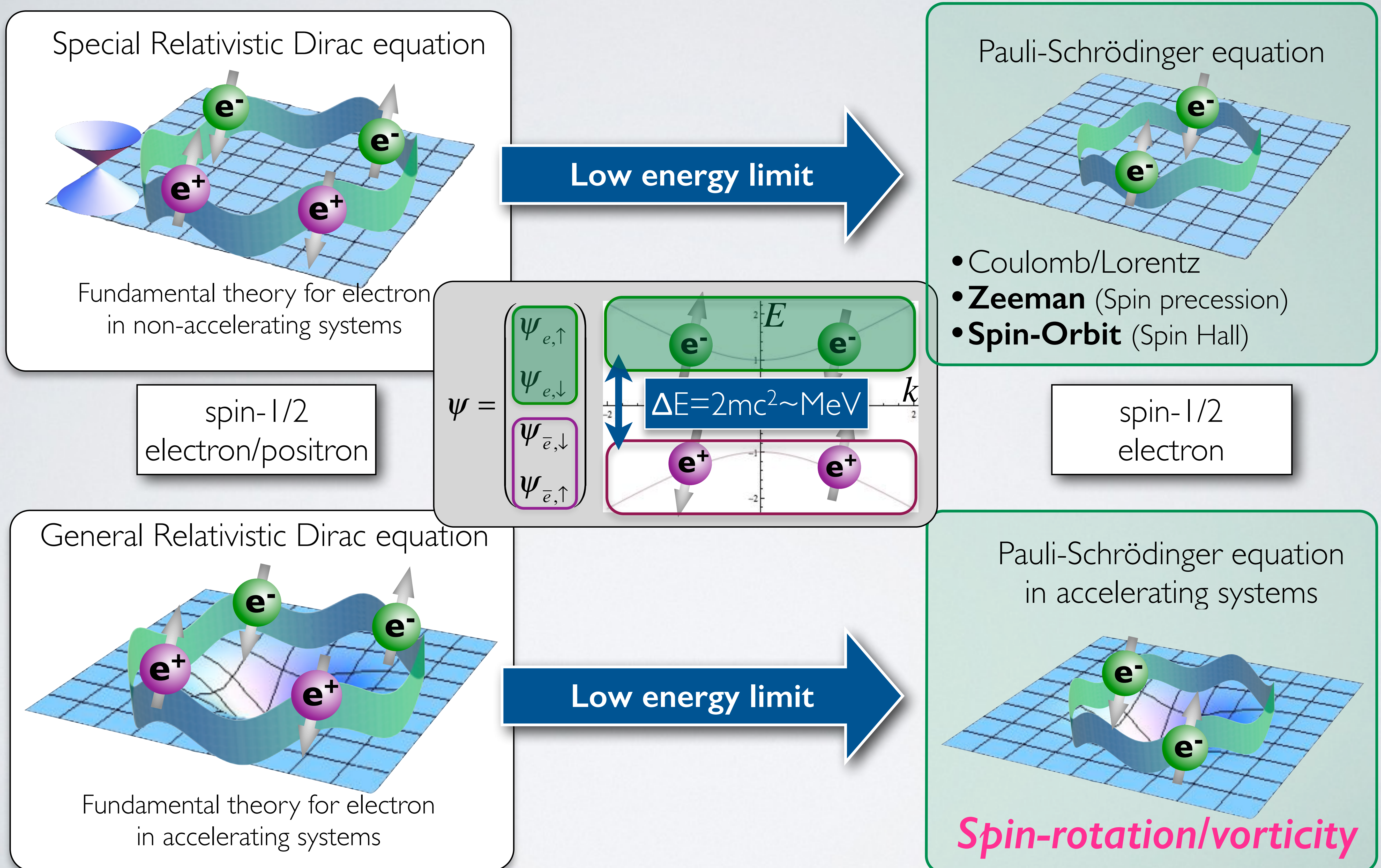


Recent progress of nanotechnology in spintronics allows us to utilize spin current!

Motivation

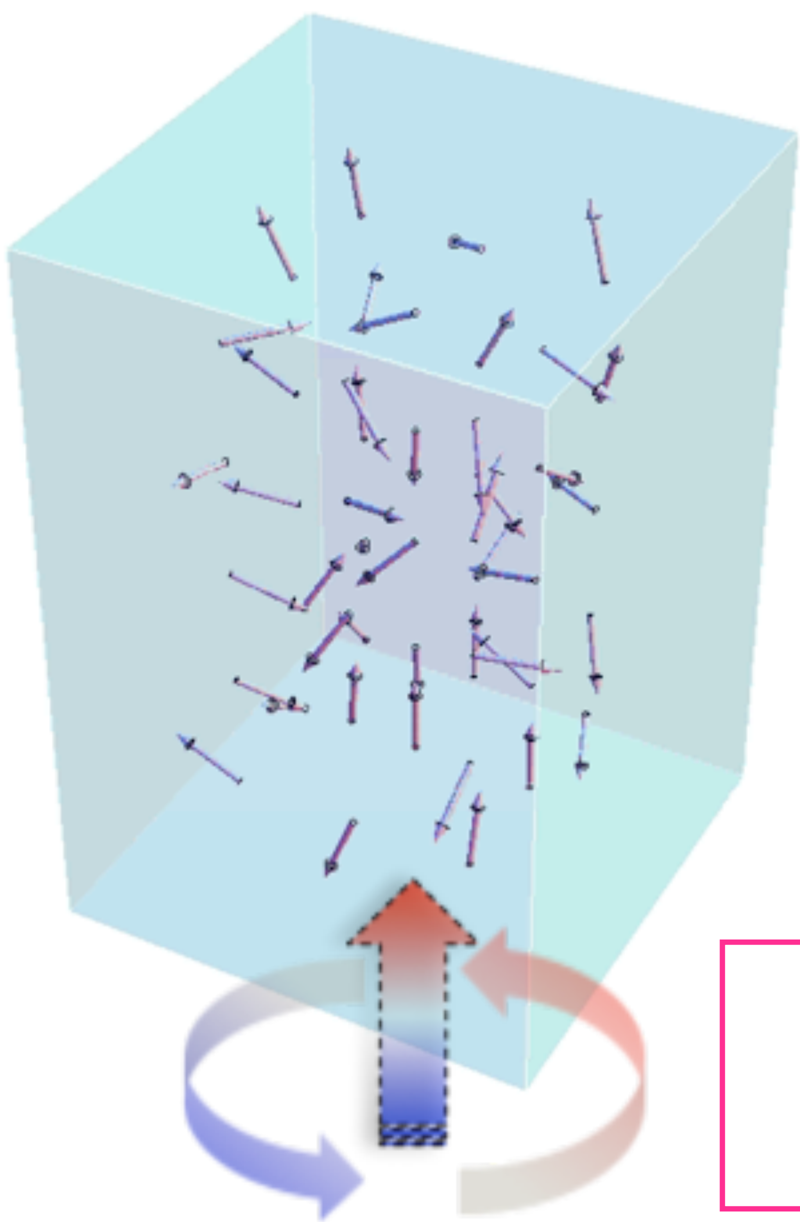

N
S
Magnetization
Einstein-de Haas
Barnett (1915)
Spintronics (21st c)
Mechanical rotation
?
e-
e-
e-
Spin current
Direct link?

Quantum theory in accelerating systems



Magnetization by rotation: Barnett effect (1915)

$$H_{\text{Spin-rotation}} = S \cdot \Omega$$



Rotation ~ Magnetic field

Barnett detected magnetization of ferromagnets.

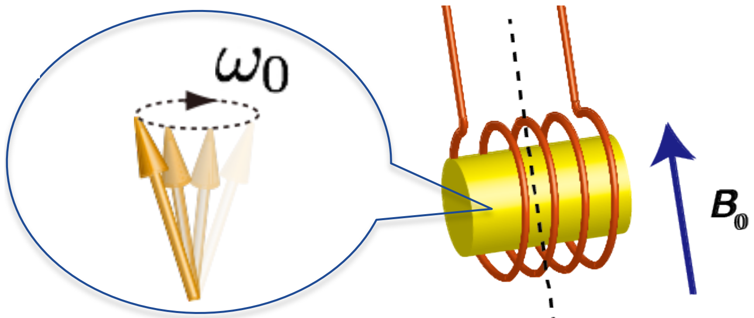
Can we observe the magnetic field due to mechanical rotation (Barnett field) ?

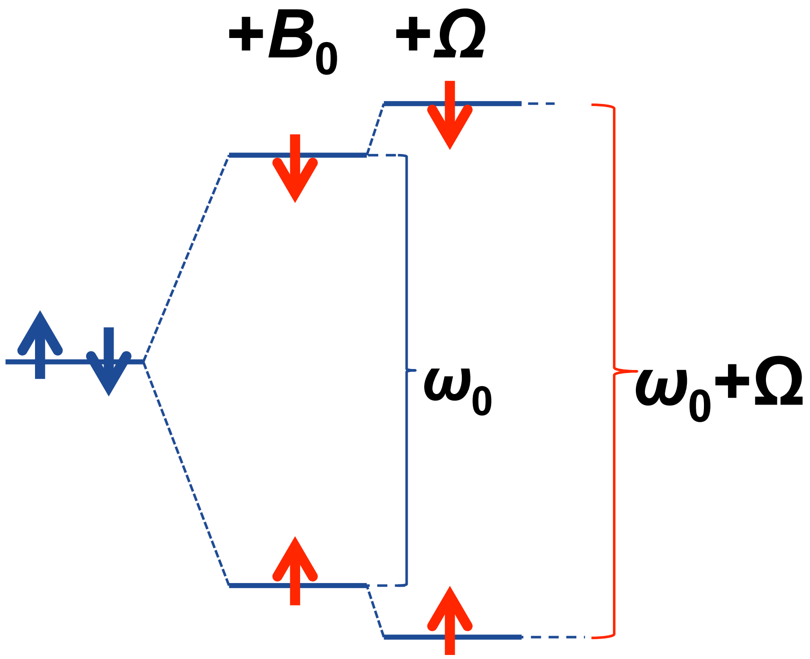
Barnett field observed by spinning NMR [1]

NMR spectrometer:
detect nuclear spin precession by induction

$$H_{\text{Zeeman}} = S \cdot \gamma B_0$$
$\Rightarrow$ resonance condition :
$$\omega_0 = \gamma B_0$$

$$H_{\text{Zeeman+spin-rotation}} = S \cdot (\gamma B_0 + \Omega)$$
$\Rightarrow$ resonance frequency will be shifted :
$$\omega' = \omega_0 + \Omega$$



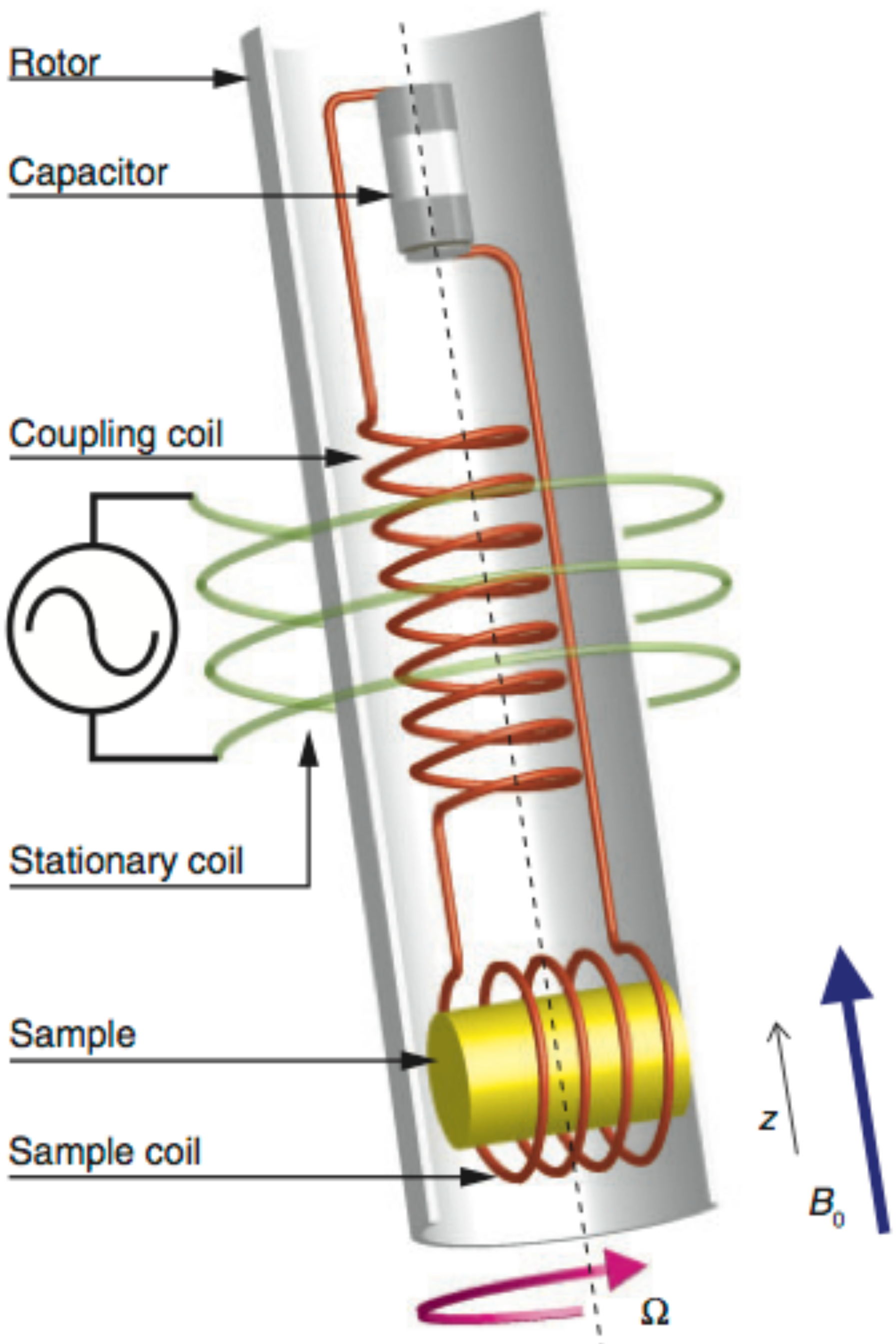


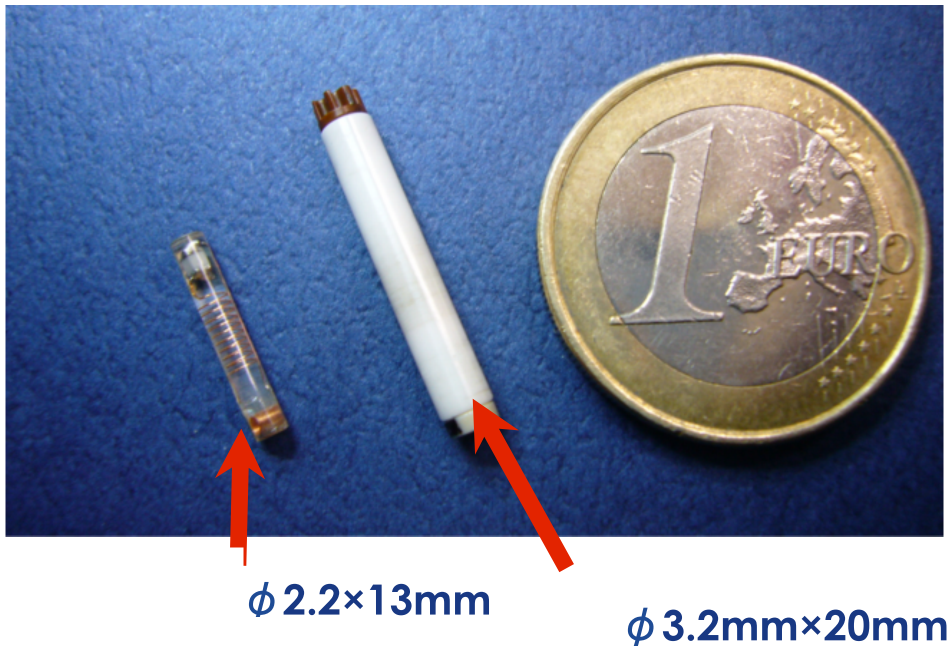
To observe magnetic field due to rotation,
NMR spectrometer should be rotated together with a sample.

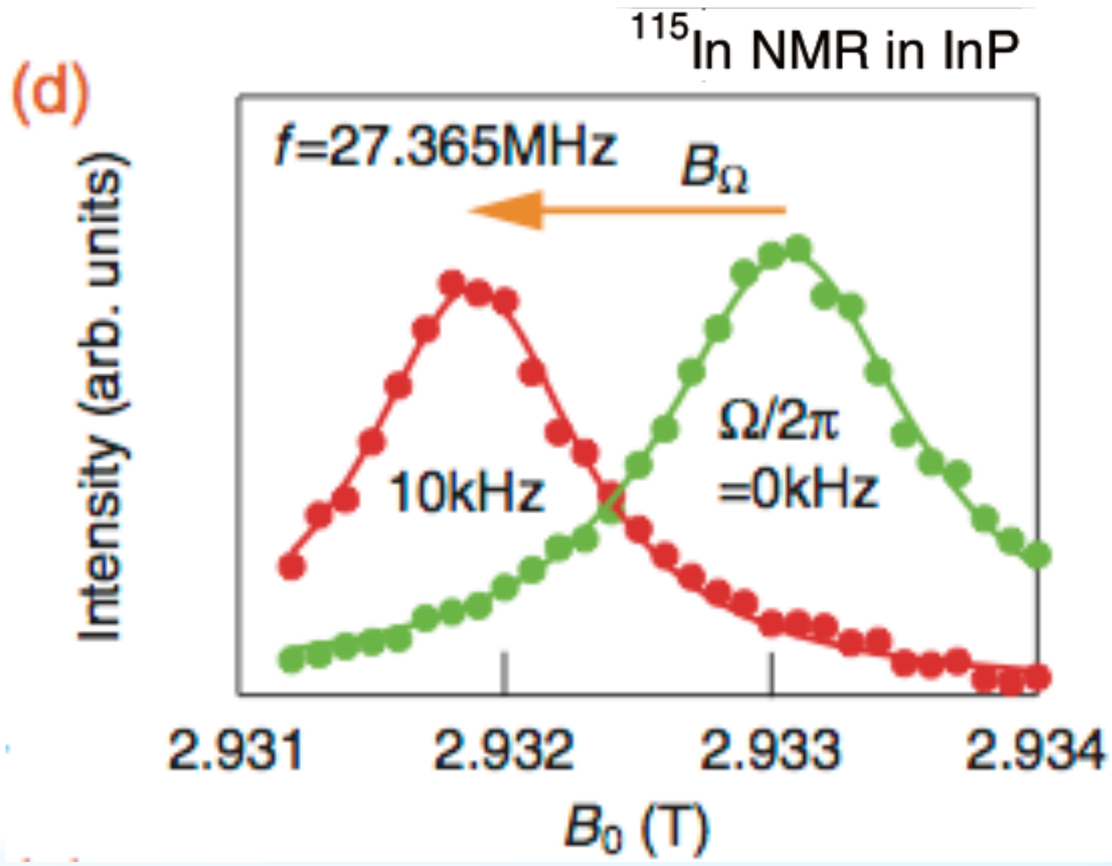
→ Need wireless system!

Barnett field observed by spinning NMR [2]

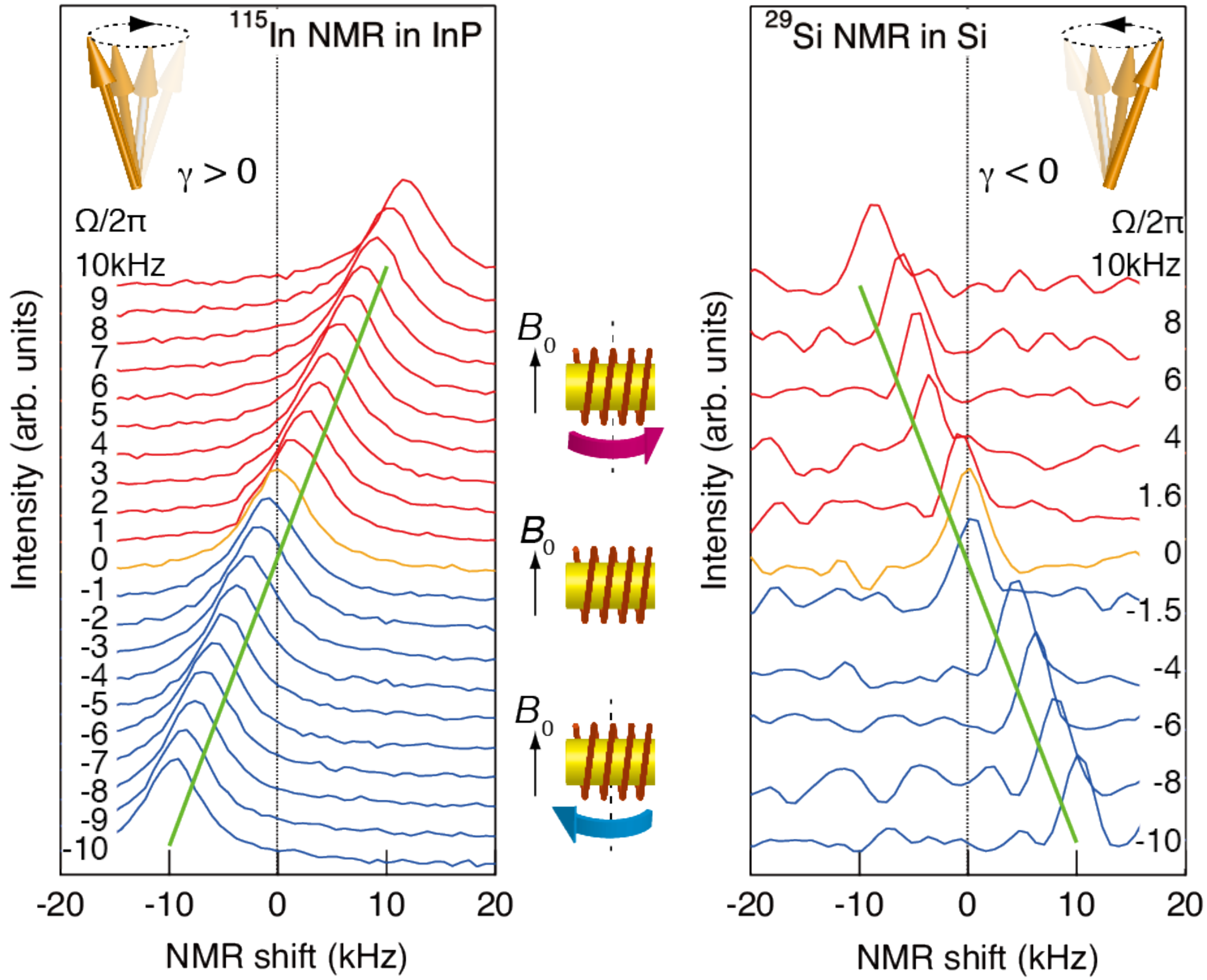
Chudo et al., Appl. Phys. Express 7, 063004 (2014)







Barnett field observed by spinning NMR [3]



^{115}**In:** γ_{In} **= 9.33 MHz/T**
^{29}**Si:** γ_{Si} **= −8.45 MHz/T**

→ *Easily determine signs of nuclear magnetic moments*

PS46 Kazuya Harii "Rotation angle dependence of NMR line structures in various nuclides"

Paramagnetic Barnett effect [1]

Sample: gadolinium
→Tc(292±0.5K、near room temperature)
→Large paramagnetic susceptibility

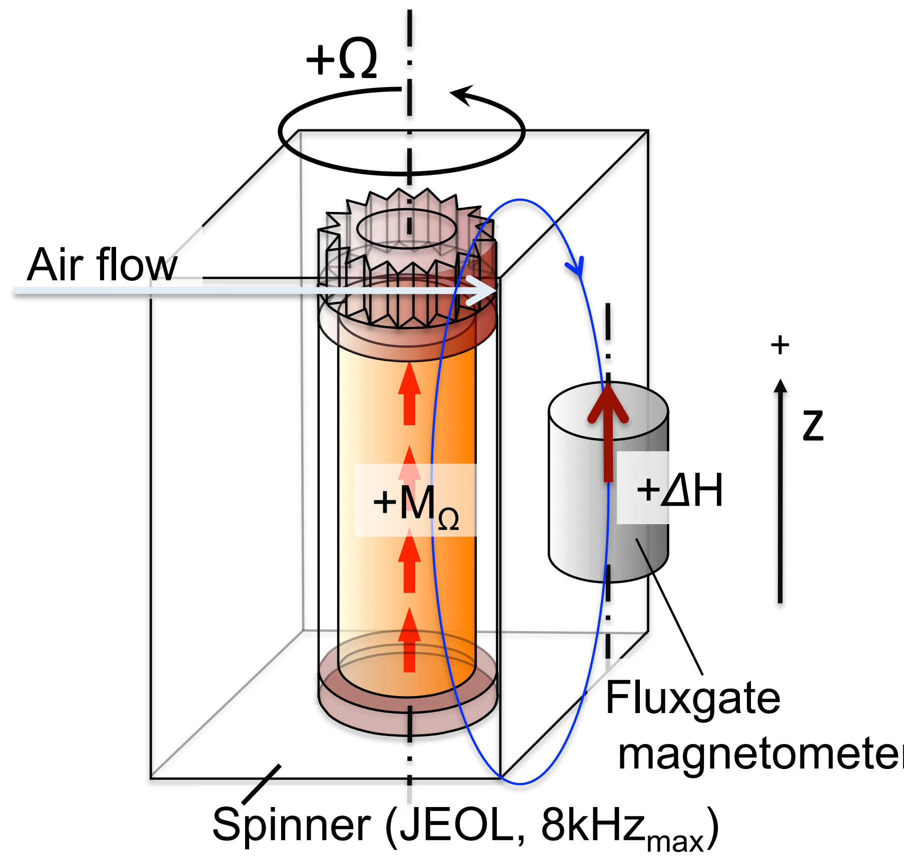
M_Ω / χ

○Susceptibility
SQUID fluxmeter(MPMS)

○Estimation of magnetization M_Ω

measure the change of magnetic field around the sample ΔH_{stray} using a fluxgate magnetometer and estimate M_Ω using a dipole model.

Capsule (φ8mm)、
Sample(φ6 x 20 mm)



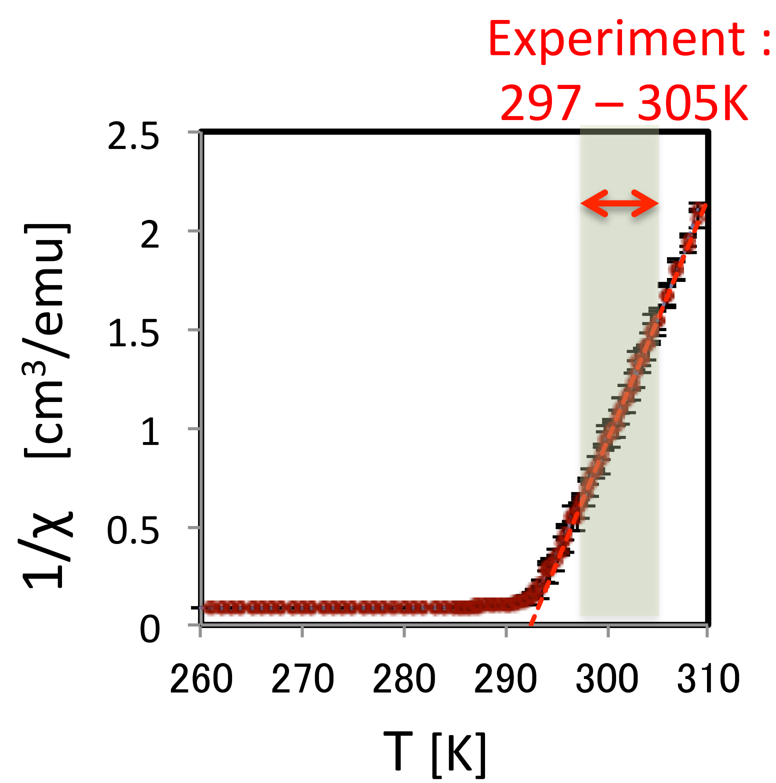
Apparatus for Barnett Effect
(*in situ* observation)

Magnetic shield
inside: 20nT
flactuation: <0.1nT

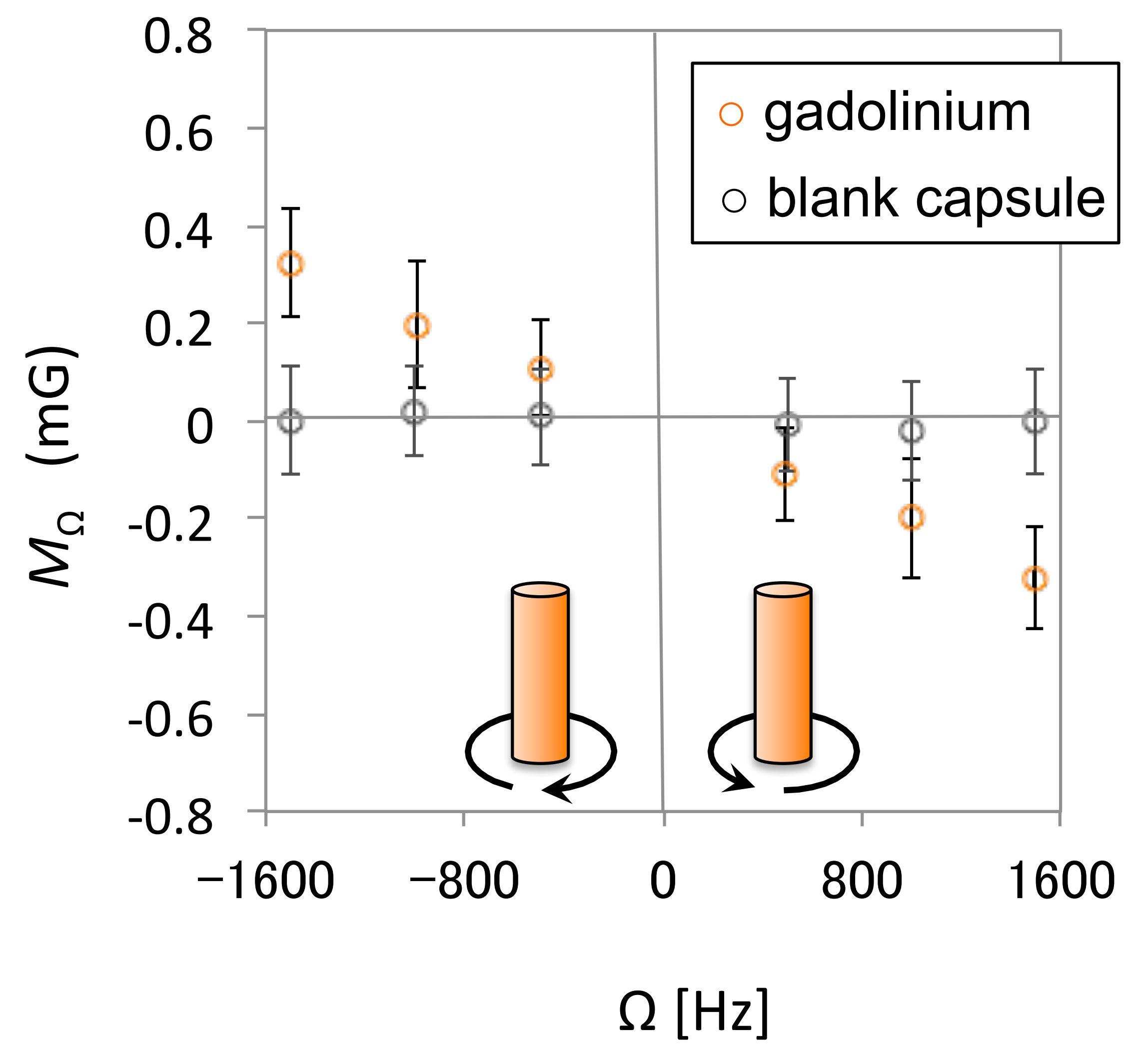
PS29 Masao Ono "Barnett effect in a paramagnetic state"

Paramagnetic Barnett effect [2]

- Temperature dependence of inverse magnetic susceptibility



- Rotational frequency dependence of magnetization (300 ± 0.5K)



→The rotational experiments were performed in the paramagnetic state

→magnetization M_{Ω} is proportional to the rotation

Ono et al., in preparation

PS29 Masao Ono "Barnett effect in a paramagnetic state"

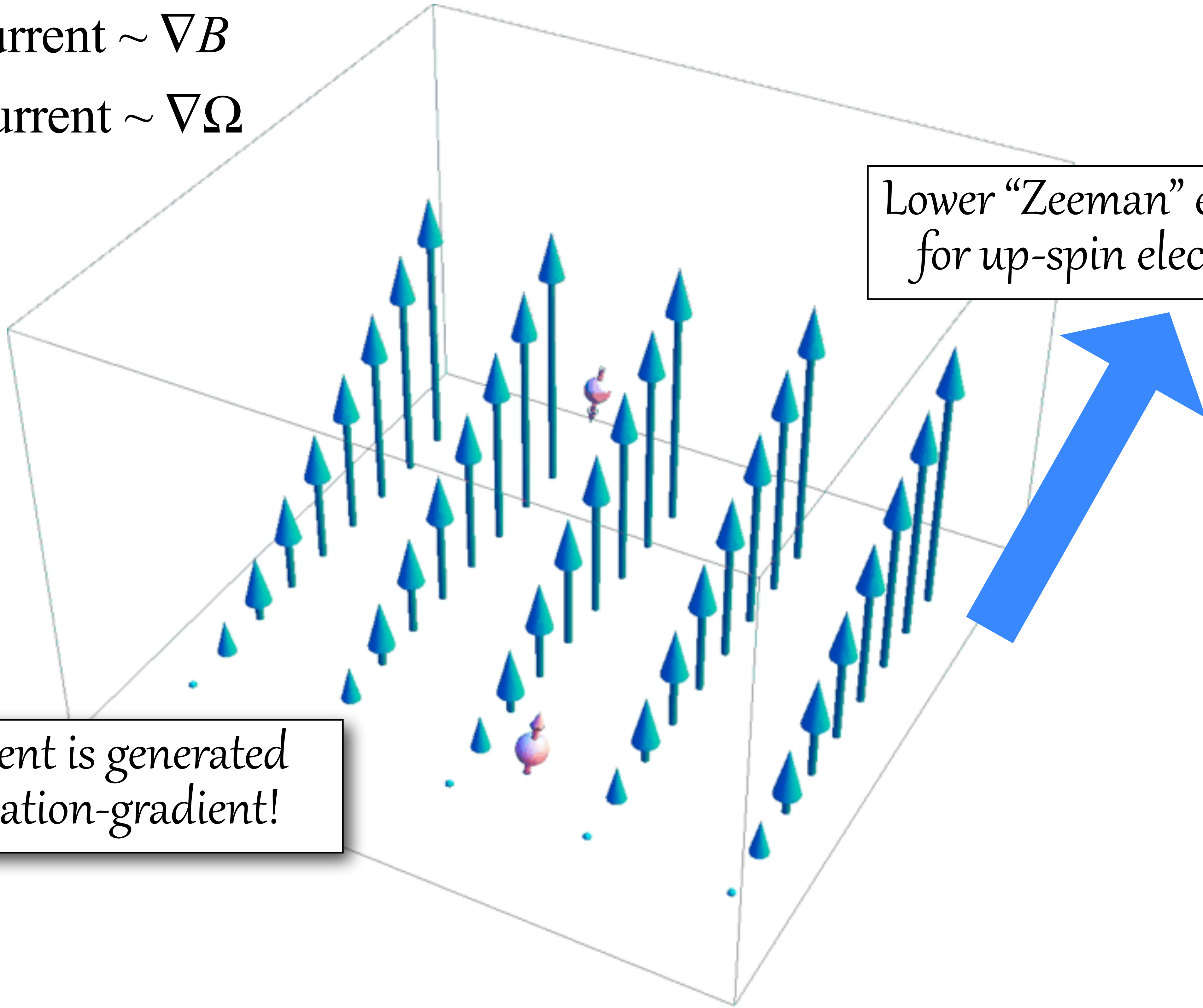
Spin-vorticity vs. Zeeman

Mechanical	Electromagnetic
$H_{\text{Spin-vorticity}} = S \cdot \Omega$	$H_{\text{Zeeman}} = S \cdot \frac{eB}{m}$
$\Omega = \frac{1}{2} \nabla \times \dot{u}$	$B = \nabla \times A$
$\dot{u}$: velocity field	A : vector potential

Mechanical Stern-Gerlach effect

$S \cdot B \Rightarrow$ Spin current $\sim \nabla B$

$S \cdot \Omega \Rightarrow$ Spin current $\sim \nabla \Omega$

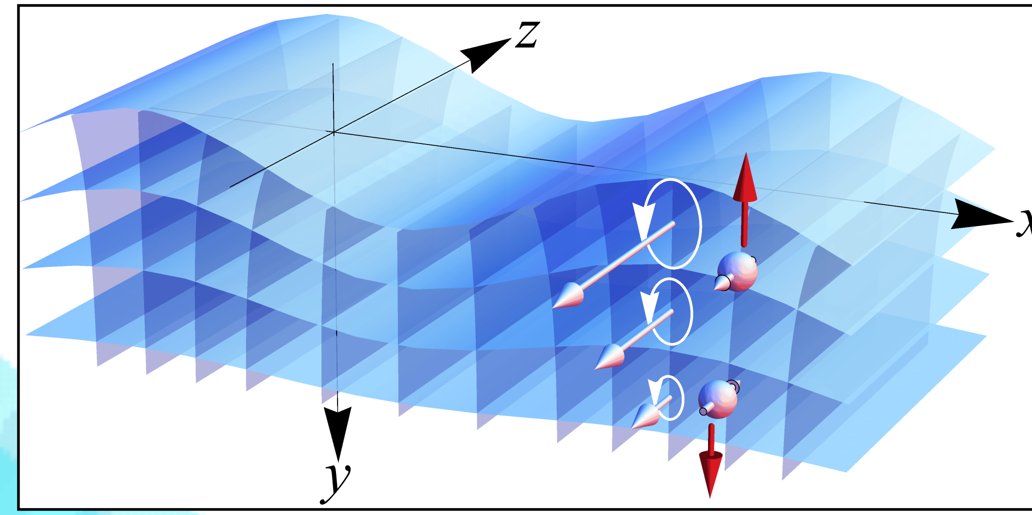


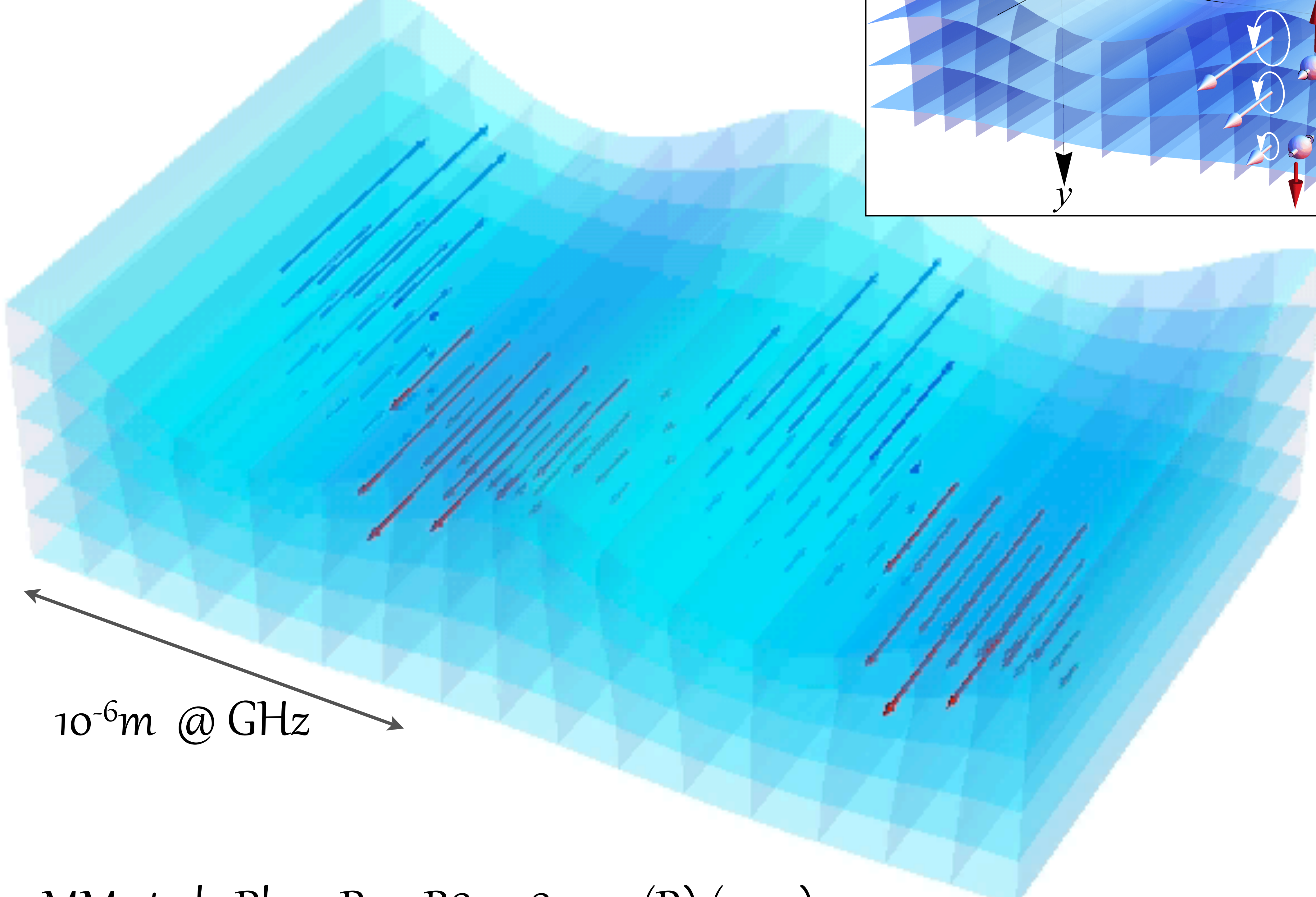
Lower "Zeeman" energy for up-spin electron

Spin current is generated along rotation-gradient!

Spin current from Surface Acoustic Wave

Spin current $\propto$ Gradient of vorticity





MM et al., Phys. Rev. B87, 180402(R) (2013)