Spin-mechatronics:
spin current generation by mechanical motion

Mamoru Matsuo (AIMR Tohoku Univ., ASRC-JAEA, ERATO-JST)

in collaboration with :

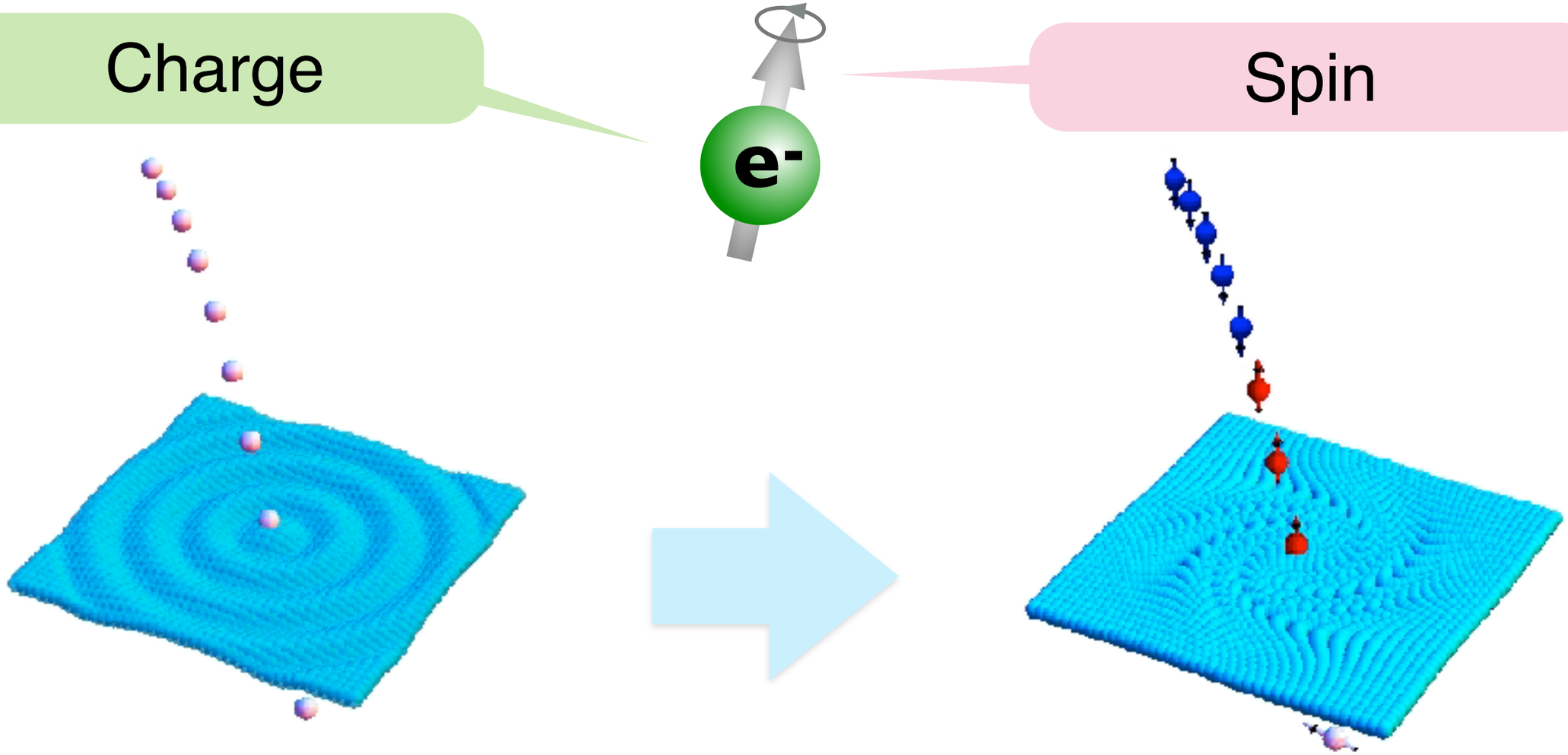
(Theory)
Y. Ohnuma, J. Ieda & S. Maekawa

(Experiment)
H. Chudo, R. Takahashi, M. Ono, K. Harii,
Y. Ogata, M. Imai, S. Okayasu, & E. Saitoh (JAEA)
R. Iguchi (NIMS)
D. Kobayashi, Y. Nozaki (Keio Univ.)

"Spin-mechatronics"

Charge

Spin



Charge current & mechanical motion

Spin current & mechanical motion

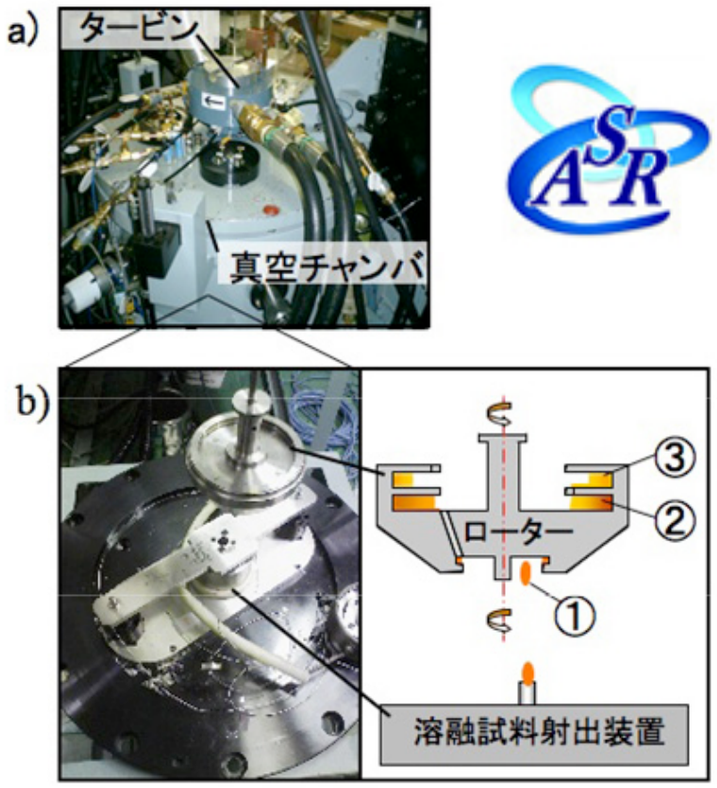
Observation of spin-current generation by

- Liquid metal motion in Hg (R.Takahashi, MM et al., Nat. Phys. 2016)
- Surface acoustic wave in Cu (D.Kobayashi, MM et al., PRL 2017)

Spin-mechatronics project since 2010

2010.4 From IMR-Tohoku Univ. to ASRC- JAEA

Ultra high-speed rotor
in ASRC: Centrifuge of isotopes



⇒ Explore interconversion between spin and mechanical rotation ?

Prof. Maekawa
ASRC, Director General

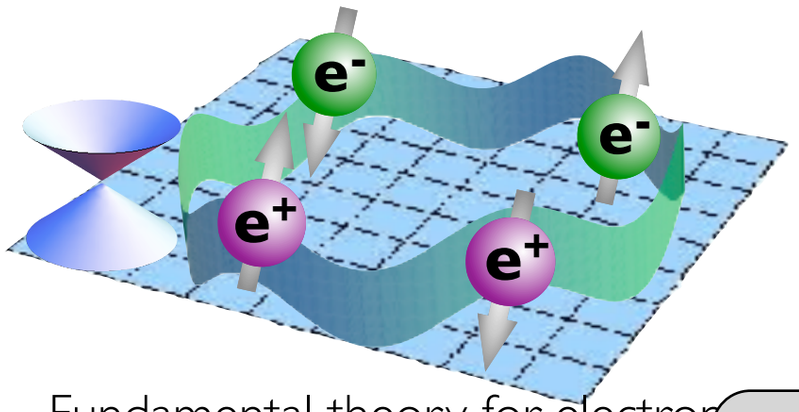
“Reconsider Einstein-de Haas/Barnett effect
in terms of spin current
after an interval of one century.”

Prof. Saitoh
AIMR, Tohoku Univ.
“Spin-mechatronics group” in ASRC

“Spin current physics in non-inertial frames!
But, what is the Hamiltonian?”

Electron in non-inertial frames

Special Relativistic Dirac equation

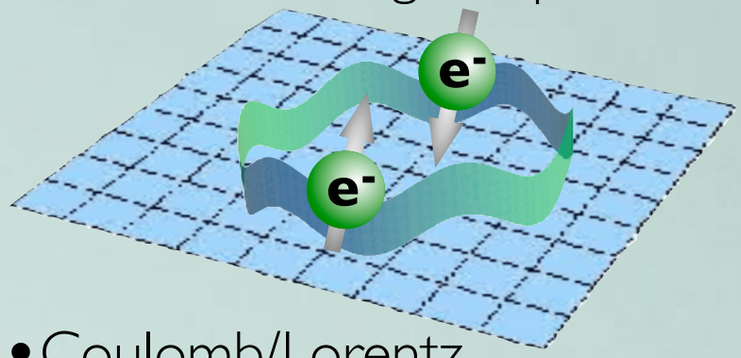


Fundamental theory for electron
in inertial frames

spin-1/2
electron/positron

Low energy limit

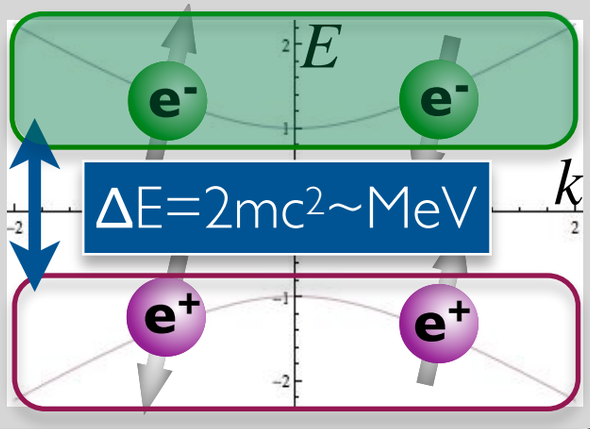
Pauli-Schrödinger equation



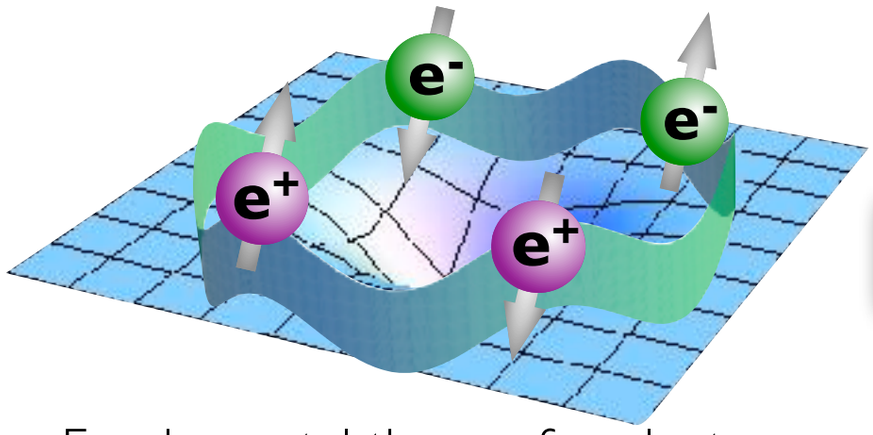
- Coulomb/Lorentz
- **Zeeman** (Spin precession)
- **Spin-Orbit** (Spin Hall)

spin-1/2
electron

$$\psi = \begin{pmatrix} \psi_{e,\uparrow} \\ \psi_{e,\downarrow} \\ \psi_{\bar{e},\downarrow} \\ \psi_{\bar{e},\uparrow} \end{pmatrix}$$



General Relativistic Dirac equation

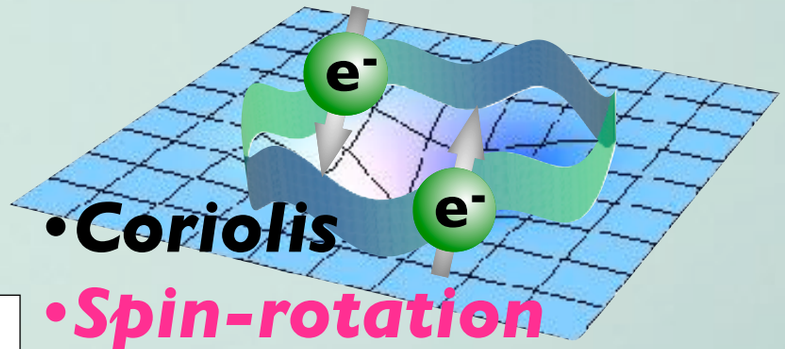


Fundamental theory for electron
in **non-inertial** frames

Low energy limit

MM et al., PRL2011

Pauli-Schrödinger equation
in accelerating systems



- ***Coriolis***
- ***Spin-rotation***
- ***Mechanical SOC***

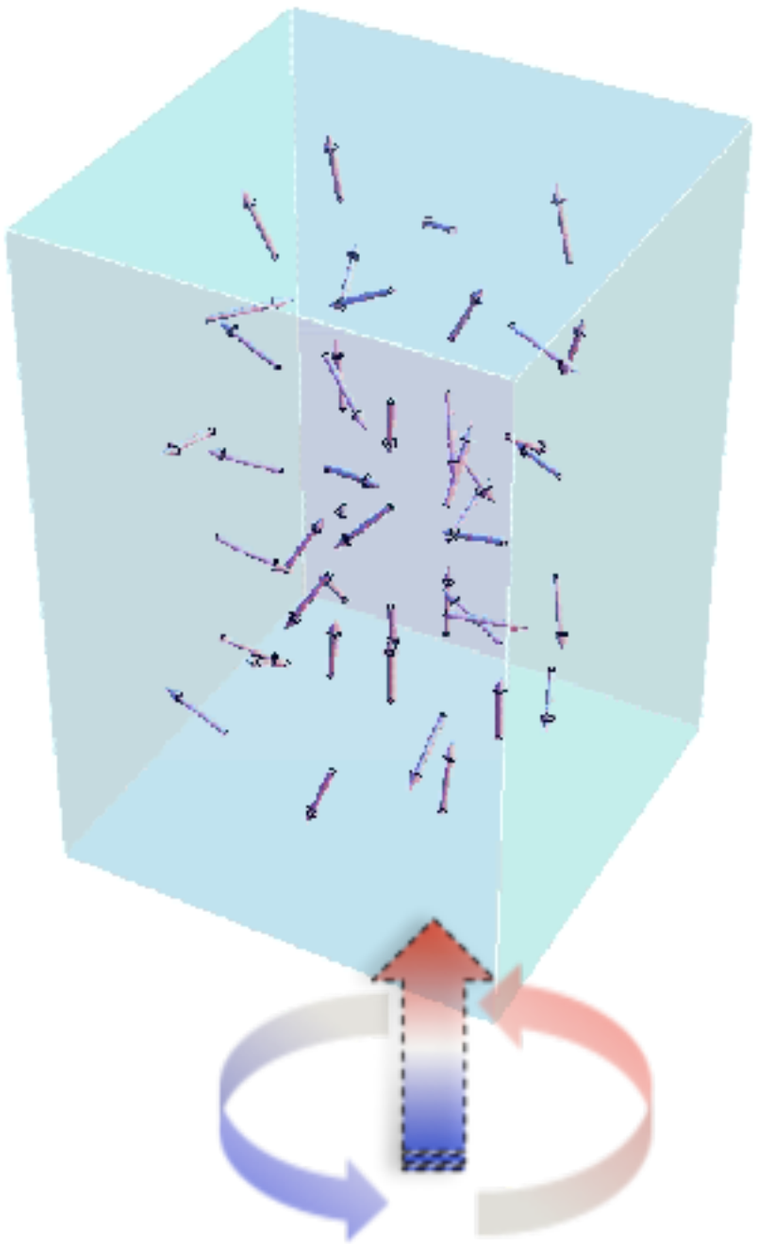
Contents

Magnetism and rotation

Taken from
Scientific American

Magnetization by rotation: Barnett effect (1915)

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



Rotation = “Magnetic field”

$$H_{\text{Cor}} = -L \cdot \Omega$$

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

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

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

How to detect? Rotation at 10kHz

Rotation as gravity

0.4 million G !!
(@ 1 mm from rotation axis)

gravity on white dwarf star
0.1 million G

$$r\Omega^2 = 1\text{mm} \times \left(2\pi \times 10^4\,\text{s}^{-1}\right)^2 = 4 \times 10^6\,\text{m/s} \sim 0.4 \times 10^6\,\text{G}$$

Rotation as magnetic field

Gyromagnetic ratio of electron:
1T~30GHz
10kHz→0.3μT

Geomagnetism in Tokyo
46 ± 0.05 μT

$$B = \Omega / \gamma_e, \quad \gamma_e = \frac{e}{m} = 1.76 \times 10^{11}\,\text{rad} \cdot \text{s}^{-1} \cdot \text{T}^{-1}$$

Challenge: How to use mechanical rotation to manipulate spins?

Observation of spin-rotation coupling

・Ferromagnets: Barnett's original exp. (1915)

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

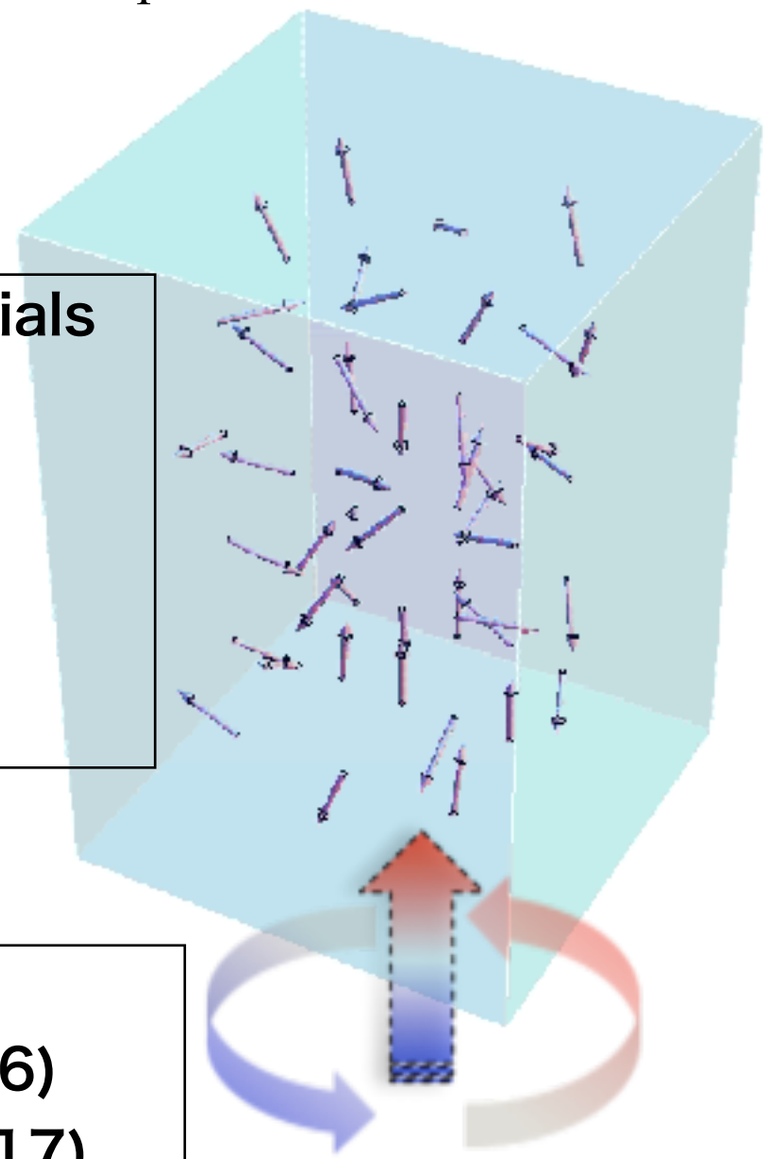
Theoretical predictions:

・MM et al., PRL(2011), …

Spin-rotation coupling arise universally in rotating materials

・Paramagnetic states (Gd, Tb, Dy):
Ono & MM et el., PRB(2015),
Ogata, MM et al., APL(2017); JMMM(2017)

・Nuclear spin:
Chudo & MM et al., APEX(2014), JPSJ(2015)



Spin-current generation by SRC

・Liquid metal flow: Takahashi & MM et al, Nat.Phys.(2016)

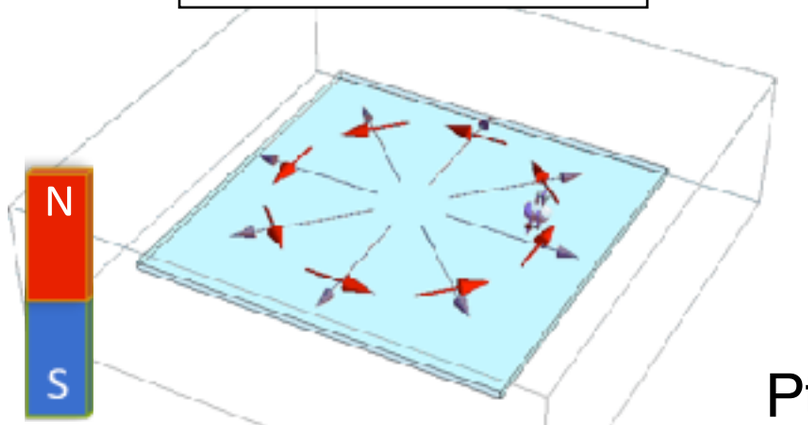
・Surface acoustic wave: Kobayashi & MM et al., PRL(2017)

Contents

Mechanical generation of spin current

Mechanical Spin-Orbit

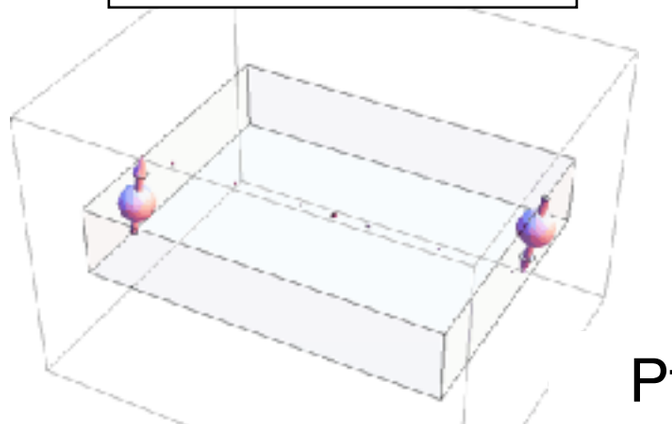
Rigid rotation



Pt

PRL2011, APL2011

Rigid vibration

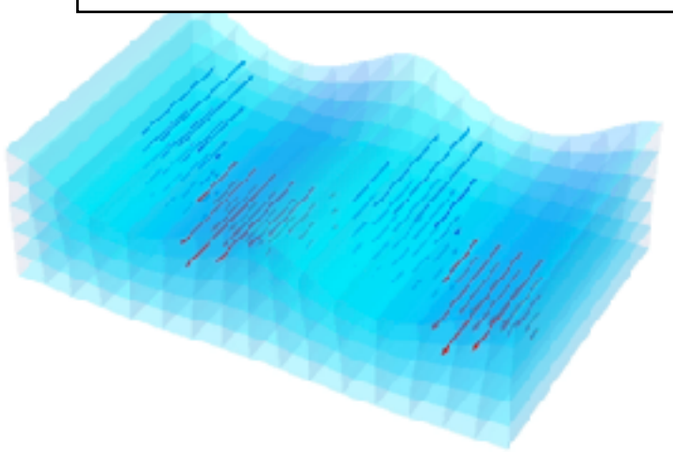


Pt

PRB2011

Spin-rotation

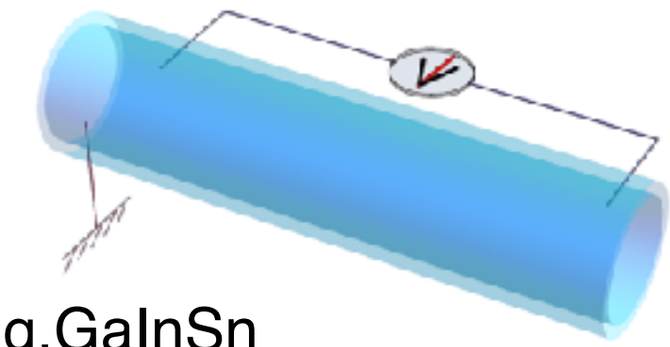
Surface acoustic wave



Cu

PRB(R)2013,2017; PRL2017

Fluid vorticity



Hg,GaInSn

Nature Phys. 2016

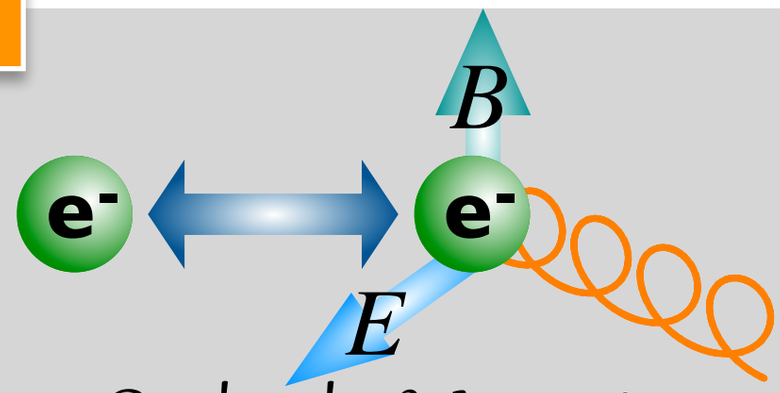
Pauli-Schrödinger eq. in inertial frames

Low energy limit of Dirac eq. in inertial frames

$$H = \frac{1}{2m}\left(\mathbf{p} + e\mathbf{A}\right)^2 + e\phi$$

Coulomb & Lorentz

electric/magnetic field ⇩ charge

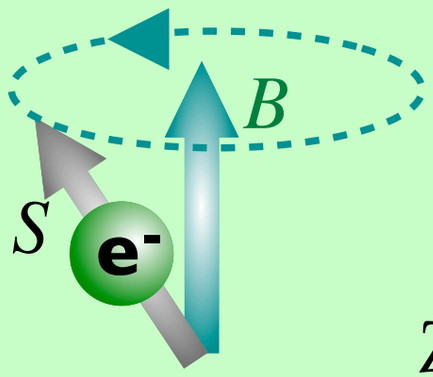


Coulomb & Lorentz

$$-\mu_B \boldsymbol{\sigma} \cdot \mathbf{B}$$

Zeeman

magnetic field ⇩ spin

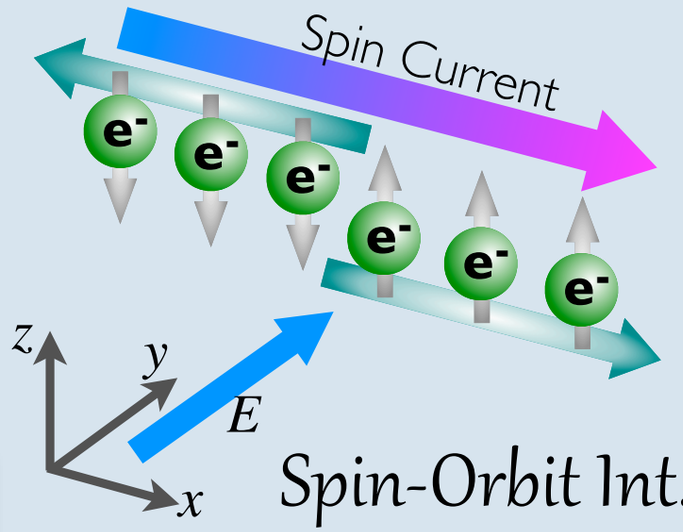


Zeeman

$$+\frac{\lambda}{\hbar}\boldsymbol{\sigma} \cdot \left[\left(\mathbf{p} + e\mathbf{A}\right) \times \left(-e\right)\mathbf{E}\right]$$

Spin-Orbit Int.

electric field ⇩ spin current



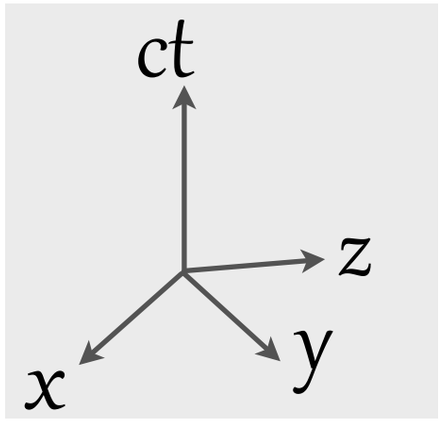
Spin-Orbit Int.

Low energy limit of Dirac eq. In non-inertial frames?

Riemann-Cartan geometry (1922)

Minkovski

Flat spacetime

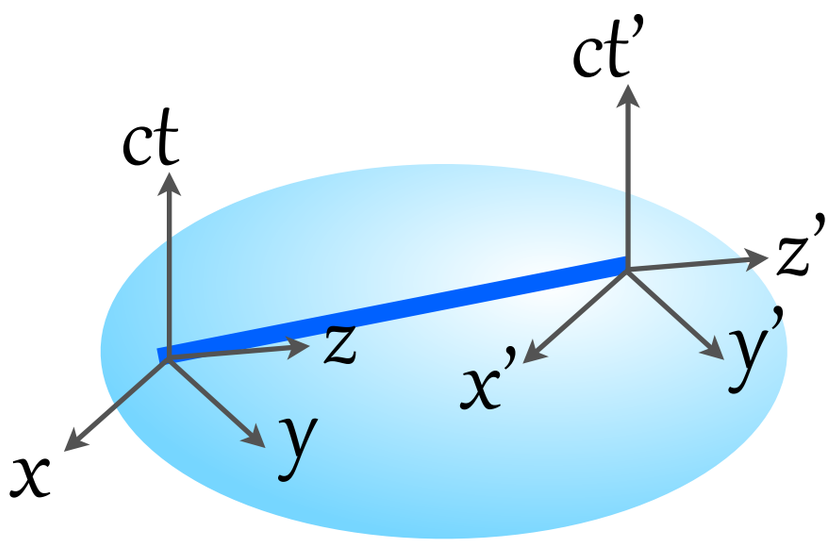


$$\eta_{\mu\nu} = diag(-+++)$$

Special Relativity(1905)

Riemann

Curved spacetime



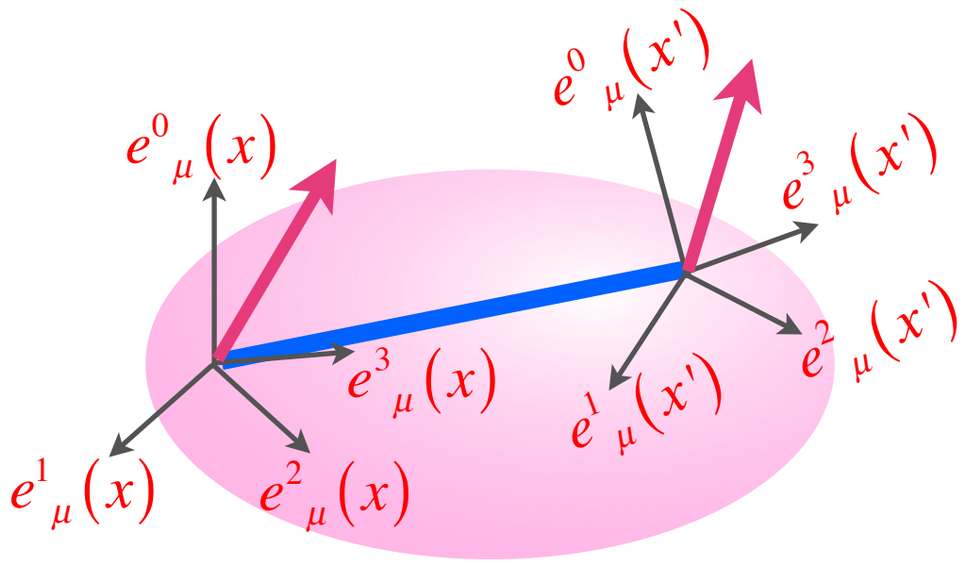
$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu$$

metric
affine connection,
curvature

General Relativity(1915)
Gravity w/o spin & torsion

Cartan (1922)

Curved spacetime w/ spin & torsion

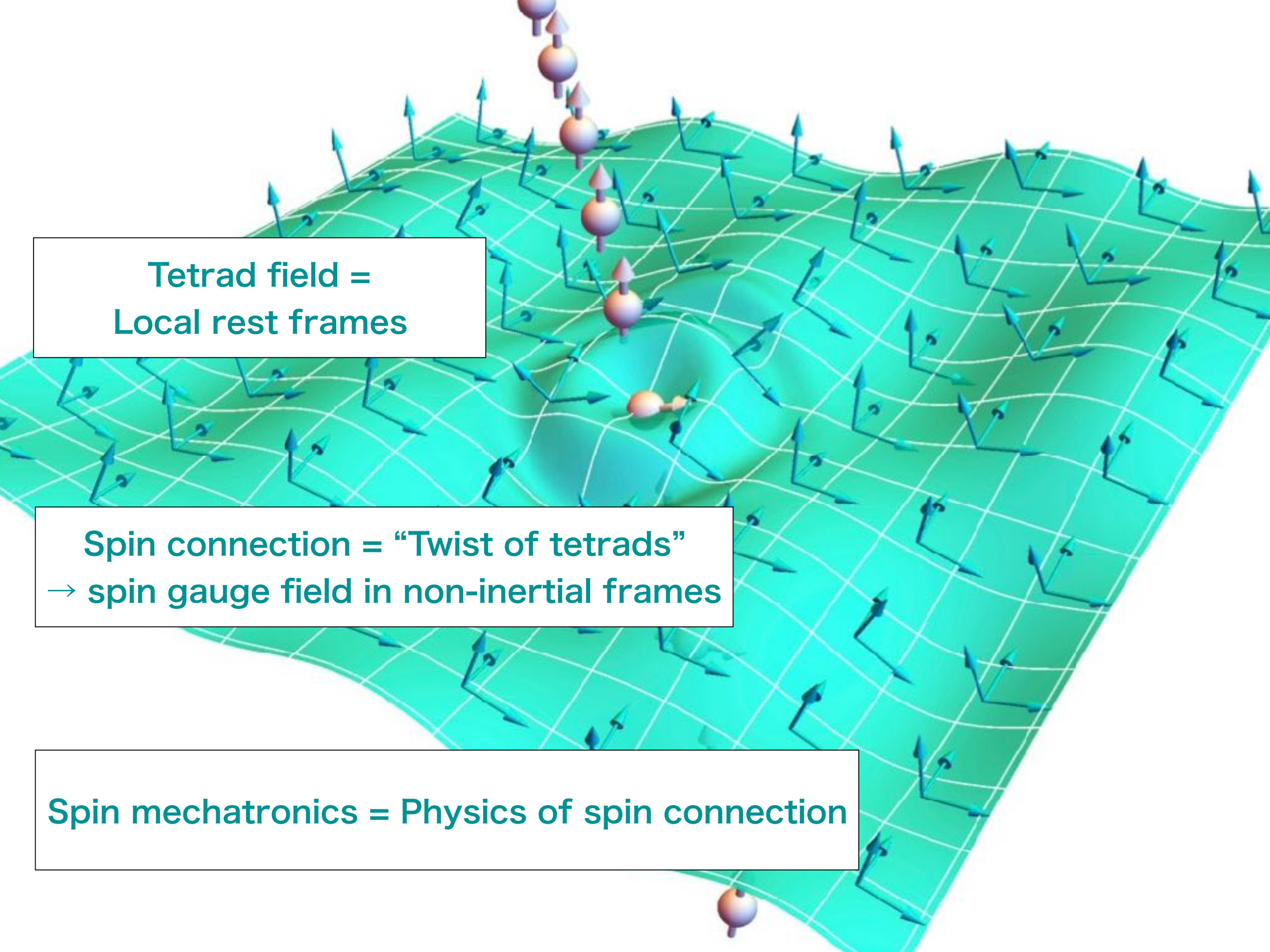


$$g_{\mu\nu}(x) = \eta_{ab}e^a{}_\mu(x)e^b{}_\nu(x) \quad \left[e_\mu(x) \sim \sqrt{g_{\mu\nu}(x)}\right]$$

tetrad field
spin connection,
curvature & torsion

Einstein-Cartan theory (1922)
Gravity w/ spin & torsion

Cf. Stern-Gerlach (1922)
Pauli (1927)
Dirac (1928)



Tetrad field =
Local rest frames

Spin connection = “Twist of tetrads”
→ spin gauge field in non-inertial frames

Spin mechatronics = Physics of spin connection

Pauli-Schrödinger eq. in rotating frame

Low energy limit of Dirac eq. in rotating frame

$$H = \frac{1}{2m}\left(\mathbf{p} + e\mathbf{A}\right)^2 + e\phi \qquad -\mathbf{L}\cdot\boldsymbol{\Omega}$$

Coulomb & Lorentz — Coriolis

electric/magnetic field + rotation → charge

$$-\mu_B\boldsymbol{\sigma}\cdot\left(\mathbf{B} + (m/e)\boldsymbol{\Omega}\right)$$

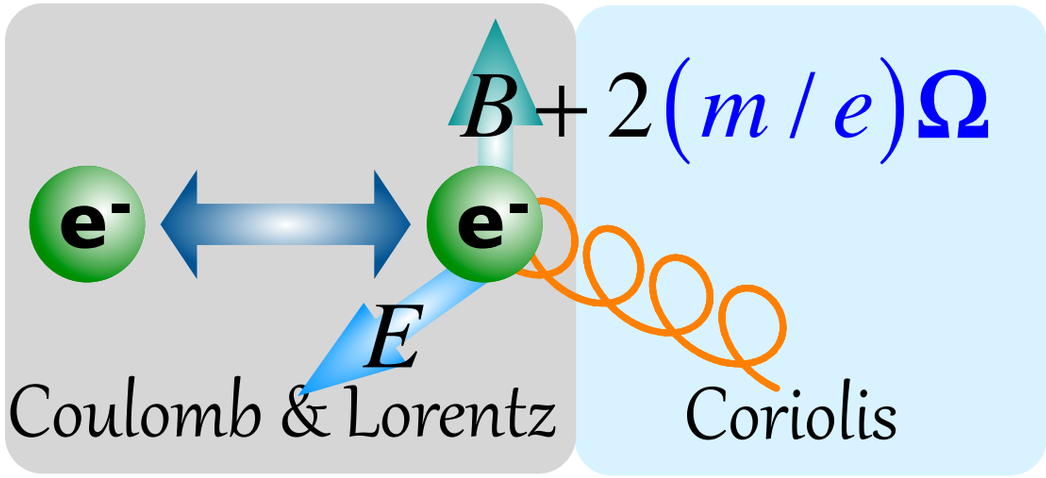
Zeeman — Spin-rotation

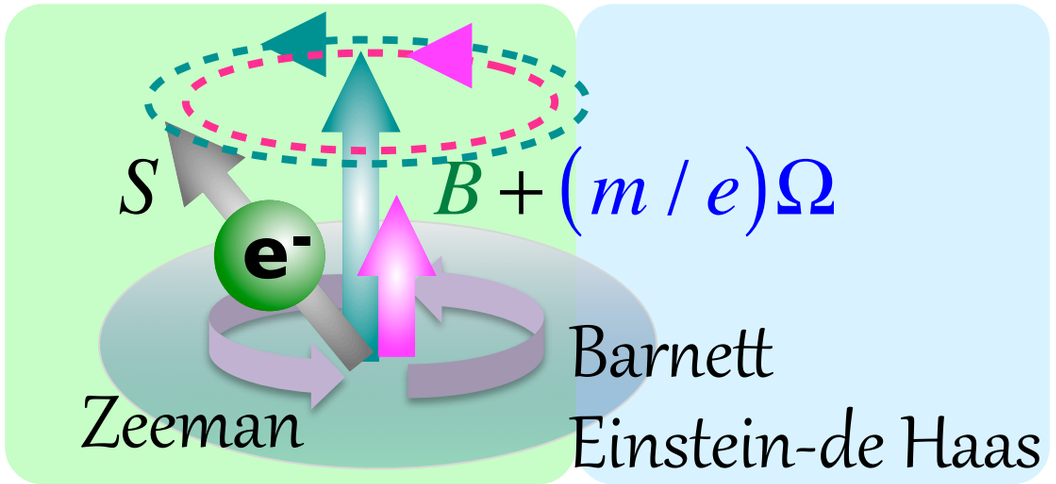
magnetic field+ rotation → spin

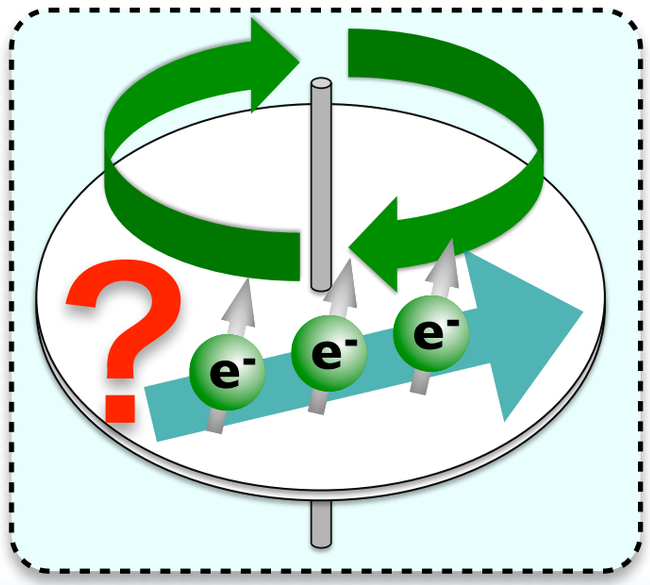
$$+\frac{\lambda}{\hbar}\boldsymbol{\sigma}\cdot\left[\left(\mathbf{p} + e\mathbf{A}\right)\times(-e)\left(\mathbf{E} + \left(\boldsymbol{\Omega}\times\mathbf{r}\right)\times\mathbf{B}\right)\right]$$

Spin Orbit Int. — **NEW!**

electric field / magnetic field x rotation → spin current







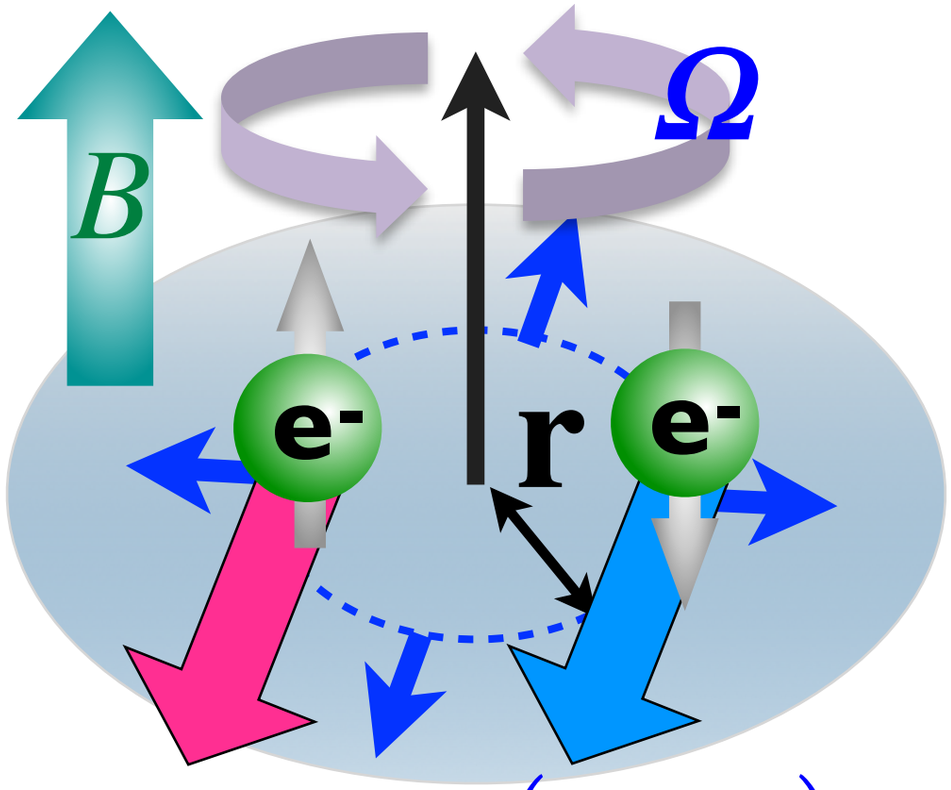
Mechanical Spin Hall Effect due to rotation

Mechanical Spin-Orbit Int.

$$+\frac{\bar{\lambda}}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}+e\mathbf{A})\times(-e)\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)\right]$$

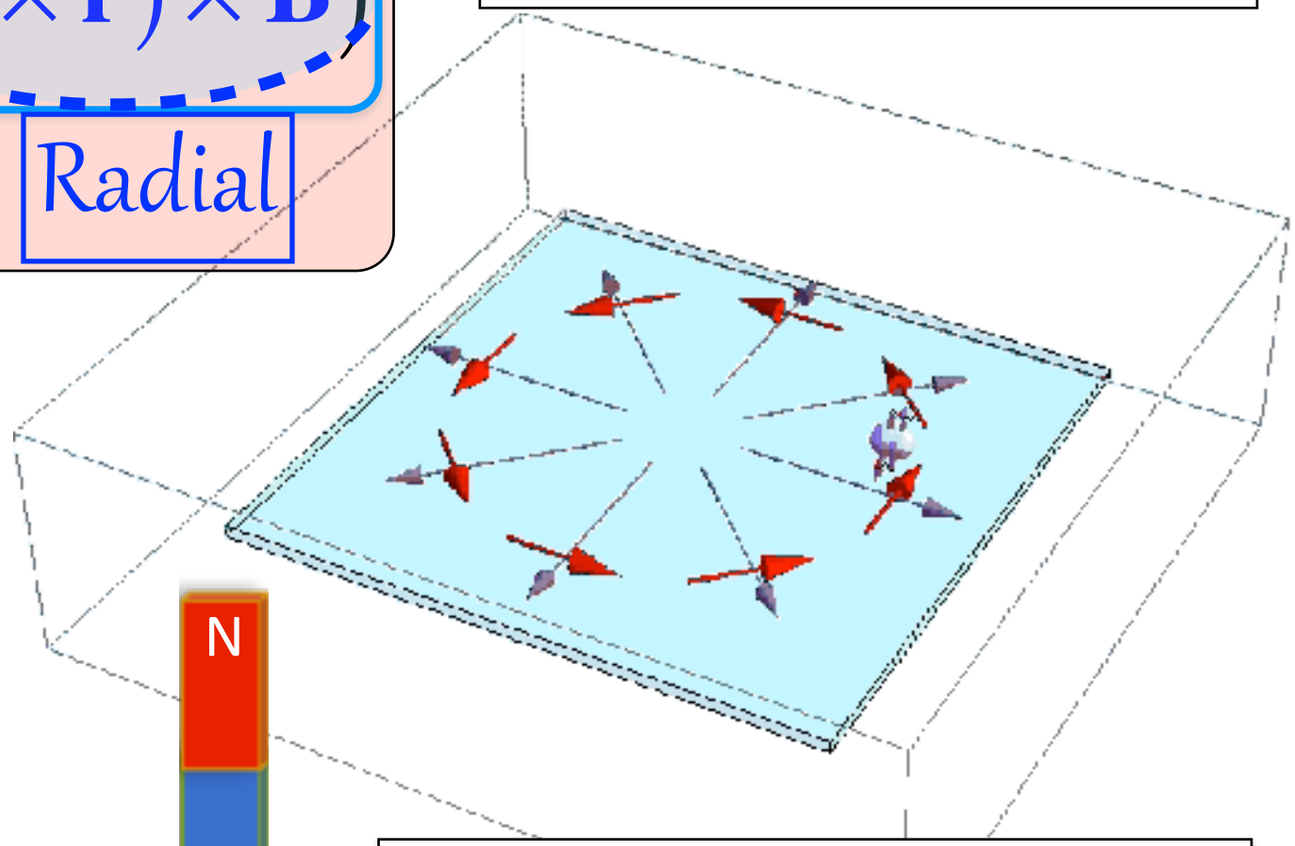
$$\frac{d}{dt}\mathbf{r}=\mathbf{v}-\frac{e\bar{\lambda}}{\hbar}\boldsymbol{\sigma}\times\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)$$

±Azimuthal　　$\pm z$　　$\mathbf{E}_{rot}$　　Radial



$$\mathbf{E}_{rot}=(\Omega\cdot B)\mathbf{r}$$

Spin current generated in azimuthal direction



Pt; B = 1T, Omega = 10kHz, r=0.1m

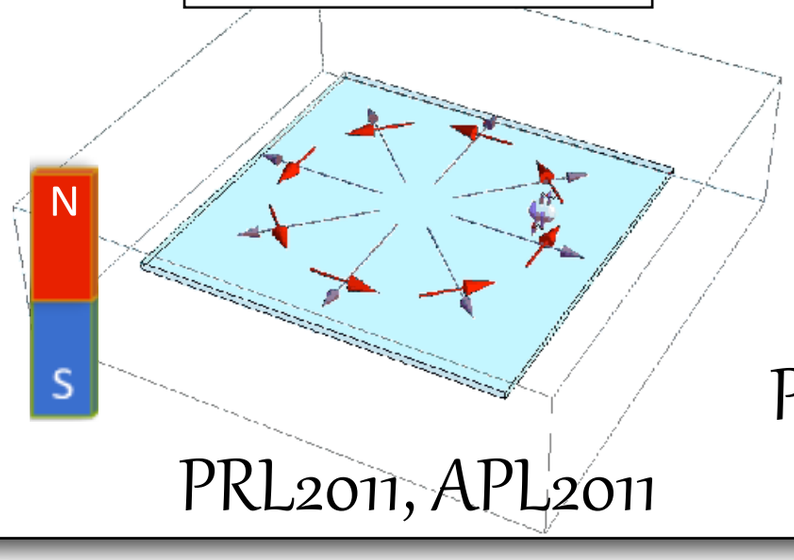
→ Spin current $10^8 A/m^2$

MM et al., PRL 106, 076601(2011)

Mechanical generation of spin current

Mechanical Spin-Orbit

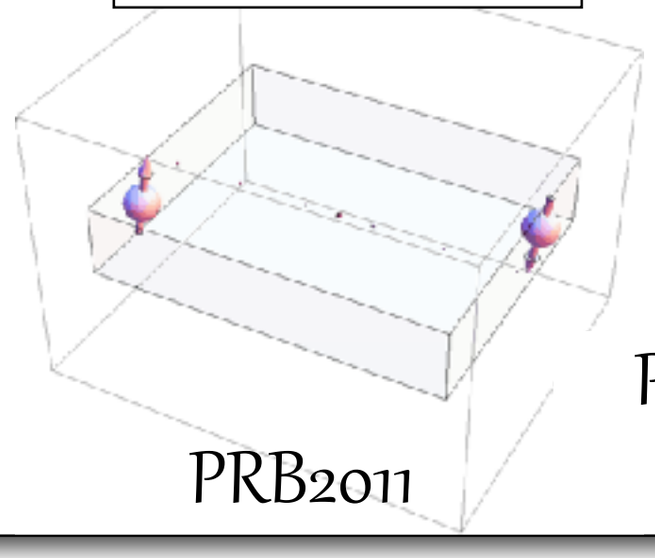
Rigid rotation



Pt

PRL2011, APL2011

Rigid vibration

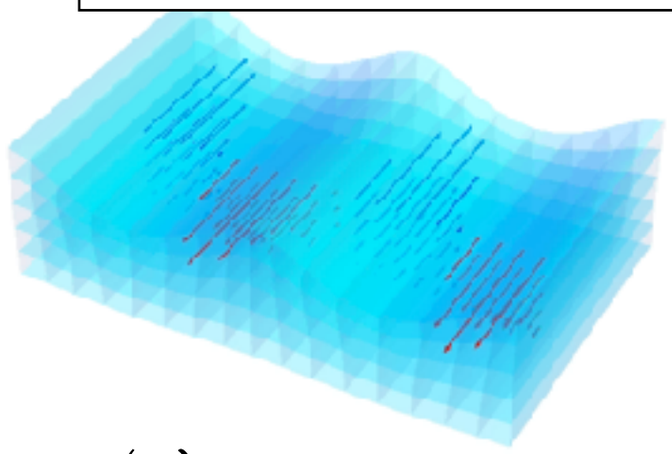


Pt

PRB2011

Spin-rotation

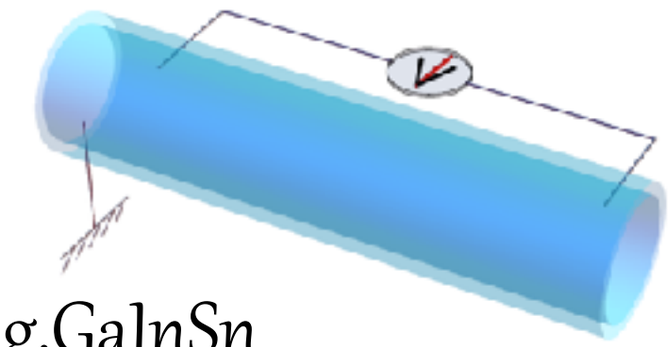
Surface acoustic wave



Cu

PRB(R)2013,2017; PRL2017

Fluid vorticity



Hg,GaInSn

Nature Phys. 2016

Mechanical analogue of Stern-Gerlach effect

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

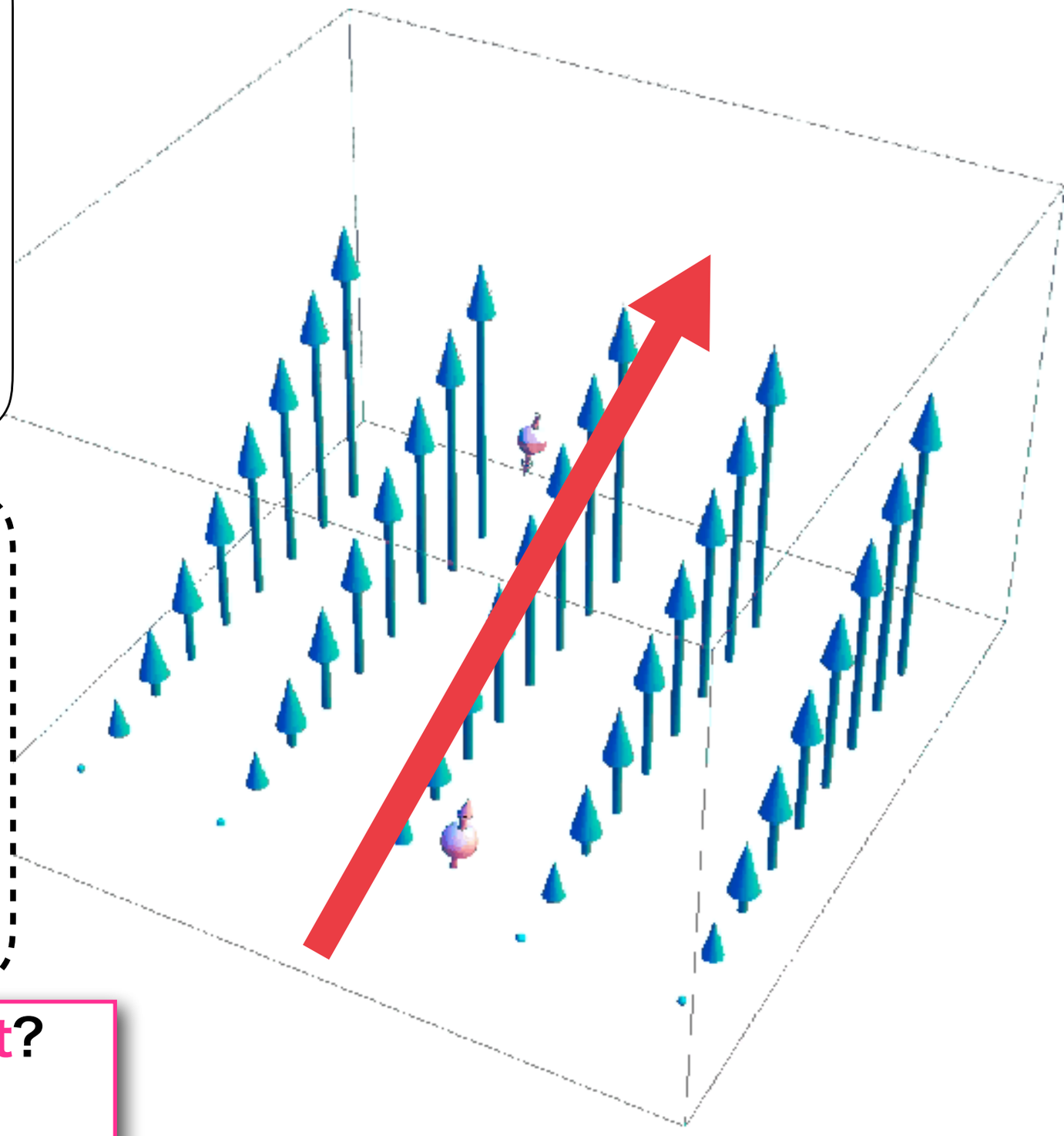
$$\Rightarrow F = -\nabla H_{Zeeman} = S \cdot \nabla(\gamma B)$$

Spin current is generated
along gradient of mag. field.

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

$$\Rightarrow F = -\nabla H_{Spin-rotation} = S \cdot \nabla\Omega$$

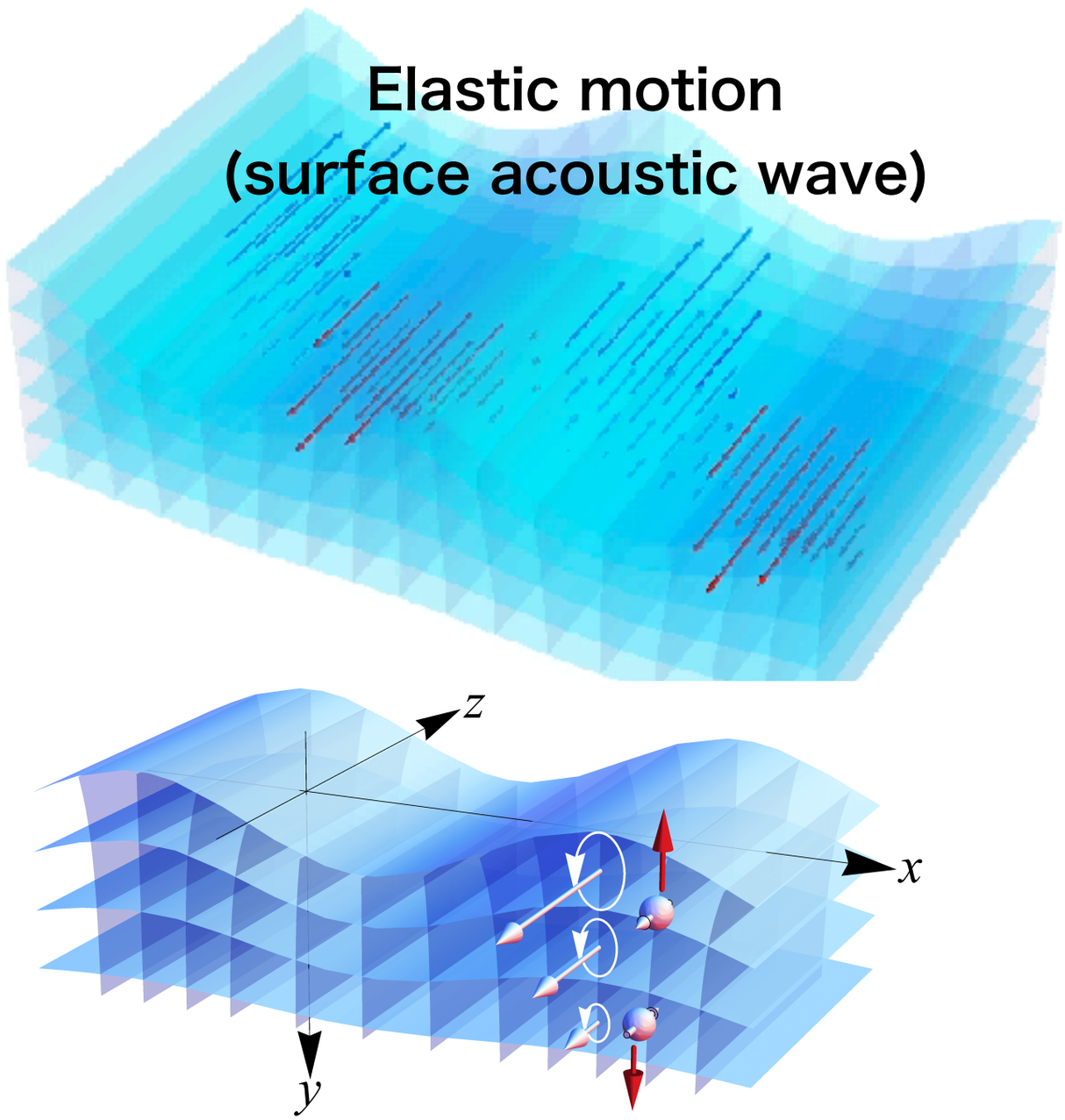
Spin current is generated
along rotation-gradient.



How to create rotation-gradient?
→ 1. Surface acoustic wave,
2. Fluid motion of liquid metal !!

Spin current by vorticity gradient

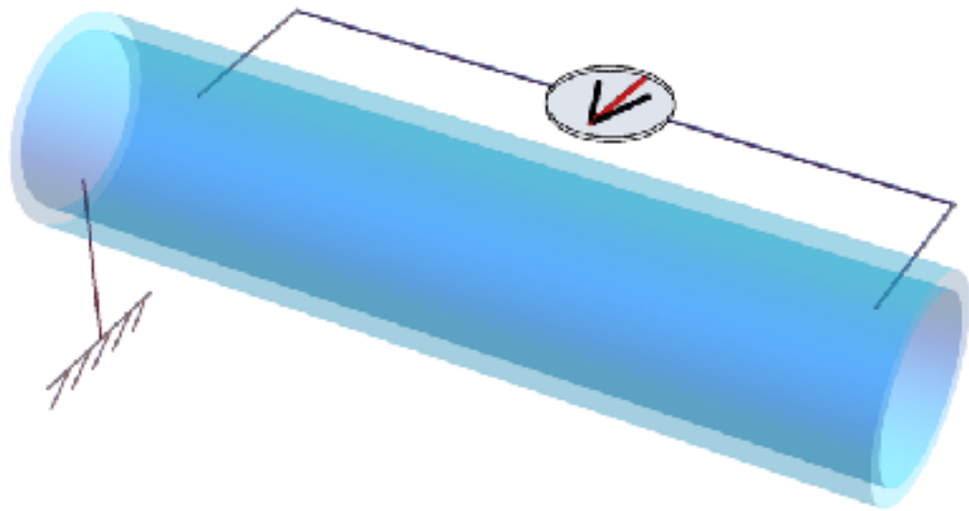
Elastic motion
(surface acoustic wave)



MM et al., PRB(R)2013

Kobayashi, MM et al.,
PRL2017 (Editors' Suggestion)

Fluid motion



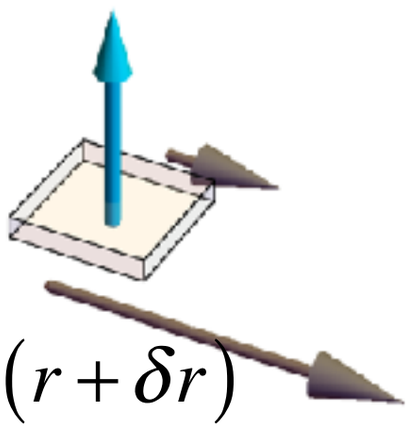
R. Takahashi, MM. et al.,
Nature Physics 2016
MM et al., PRB(R)2017

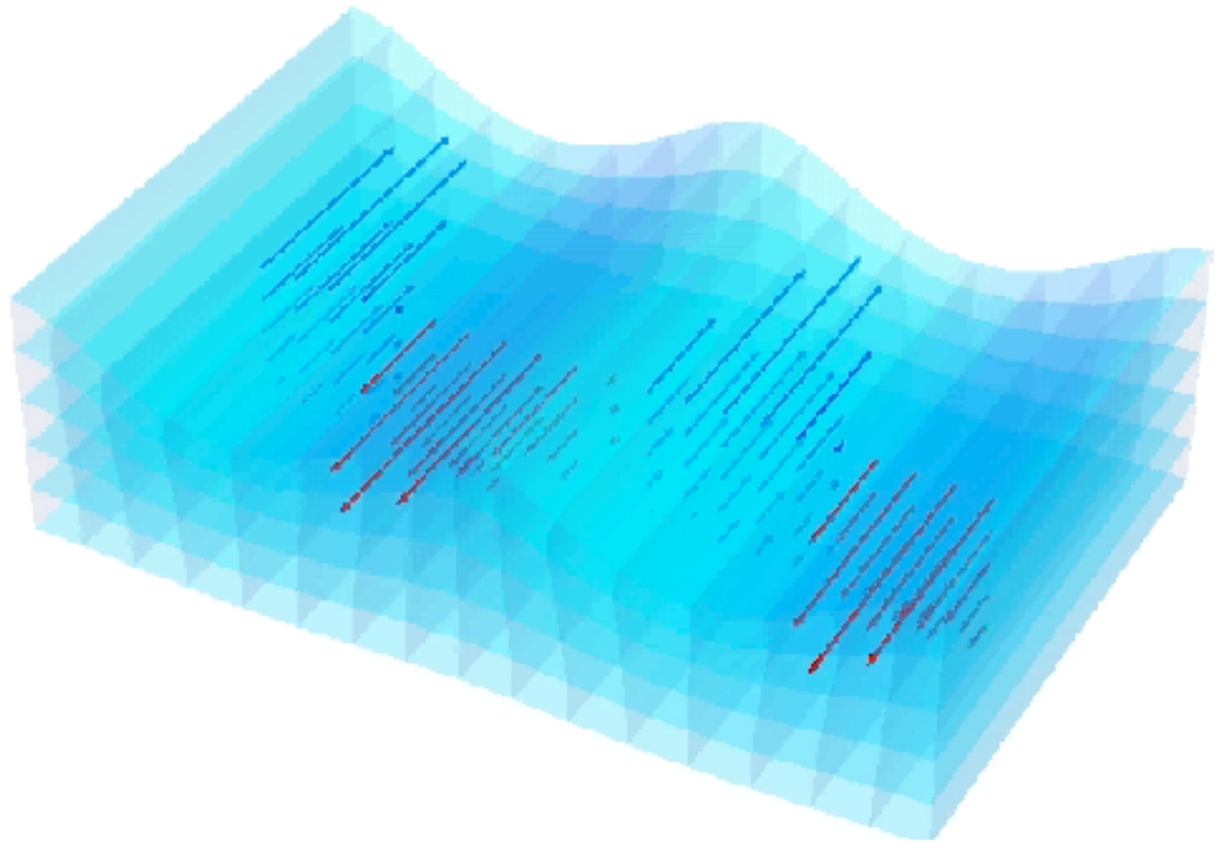
Science, Editor's choice
Nature Physics, N&V
Nature Materials, N&V

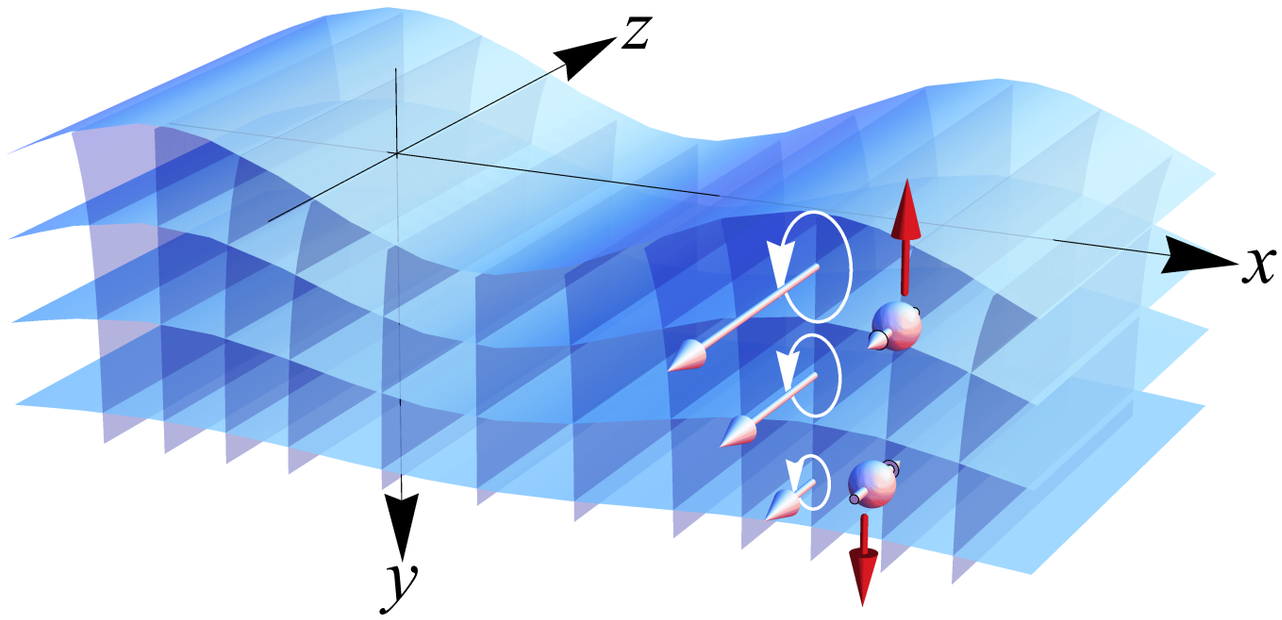
Spin current generation by surface acoustic wave

Vorticity:
local rotation of lattice

$$\nabla \times v$$







Spin current is generated
along vorticity gradient!

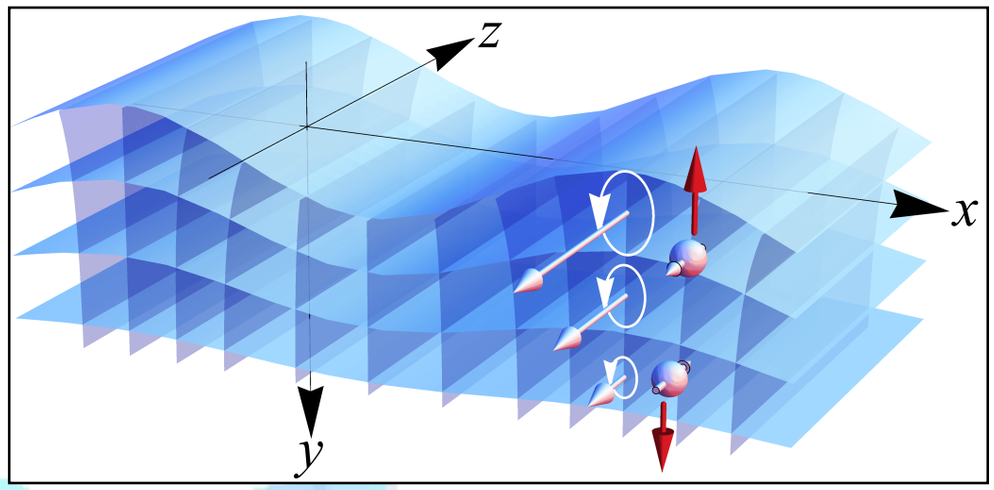
Spin-vorticity vs. Zeeman

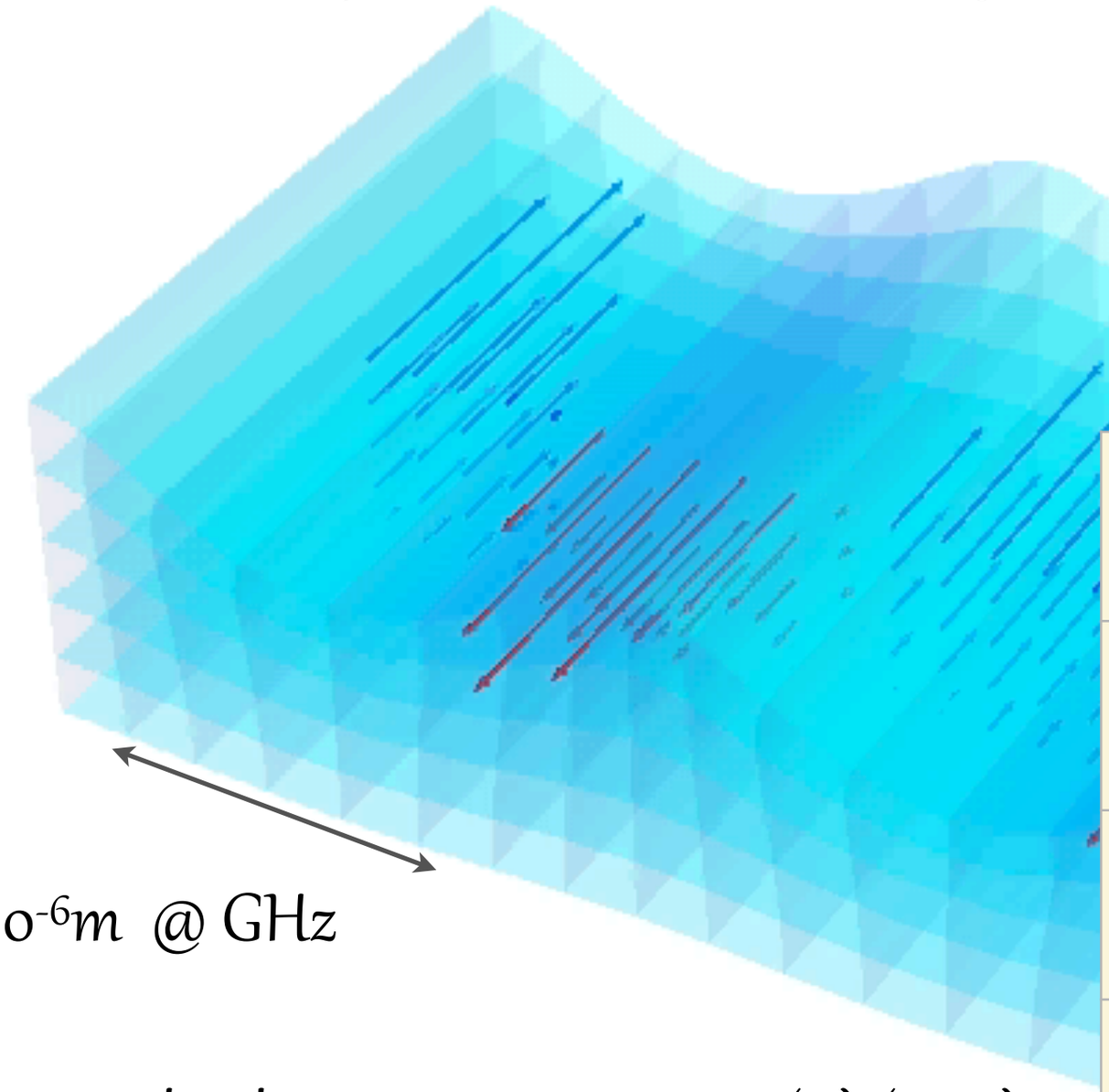
Mechanical	Electromagnetic
$H_{\text{Spin-vorticity}} = -S \cdot \frac{\omega}{2}$	$H_{\text{Zeeman}} = -S \cdot \frac{eB}{m}$
$\omega = \nabla \times v$	$B = \nabla \times A$
v : velocity field	A : vector potential

For theoretical details: MM et al., “Spin-mechatronics”, JPSJ 86, 011011 (2017).

Spin current from Surface Acoustic Wave

Spin current ∝ Gradient of rotation



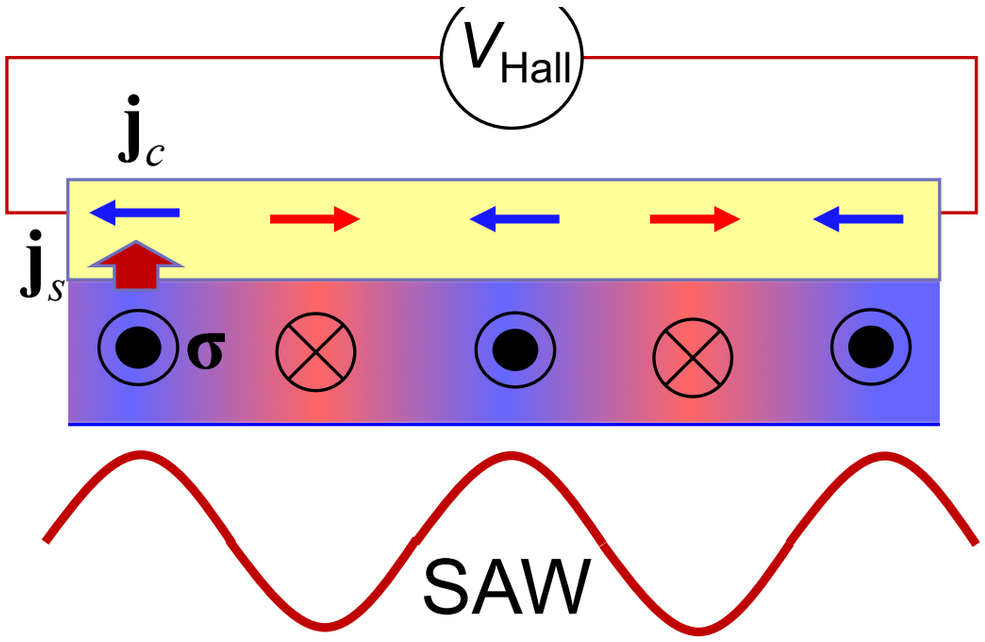


MM et al., Phys. Rev. B87, 180402(R) (2013)

Spin Hall Effect	Spin-rotation
Strong Spin-Orbit	w/o Spin-Orbit
Short Spin Lifetime	Long Spin Lifetime
Pt	Cu

Cu can be utilized for spin-current source! → Rare metal free spintronics

How to detect AC spin current by SAW?

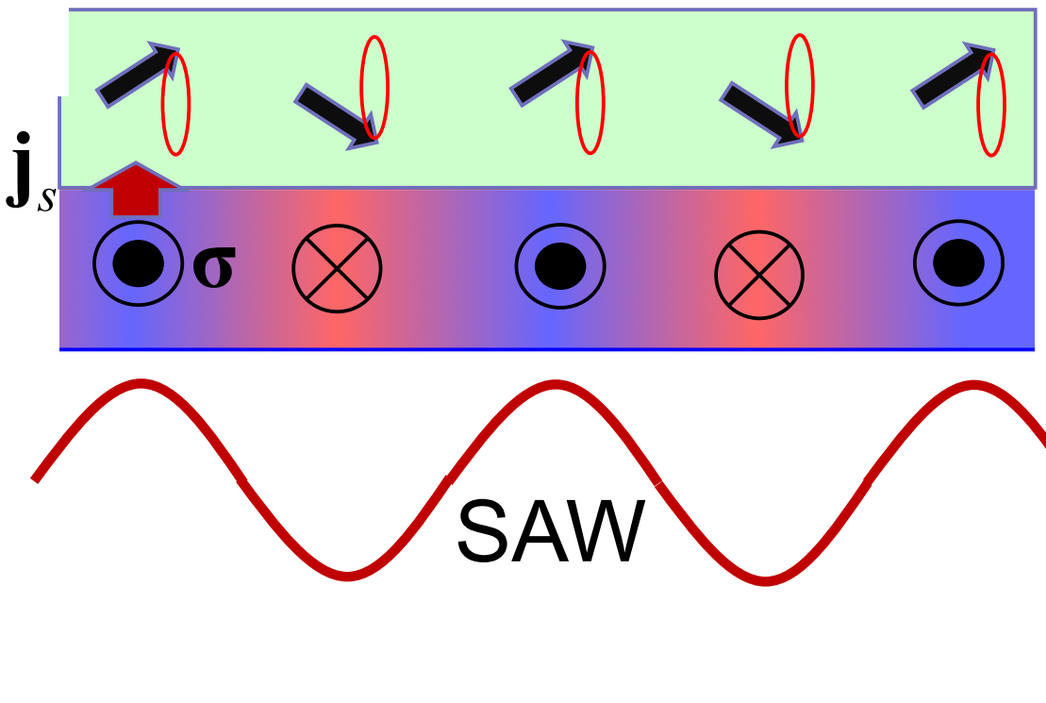


Pt

Cu

Inverse SHE:
Hall voltage caused by
Non-uniform spin current
is compensated…

Prof. Nozaki's beautiful idea!



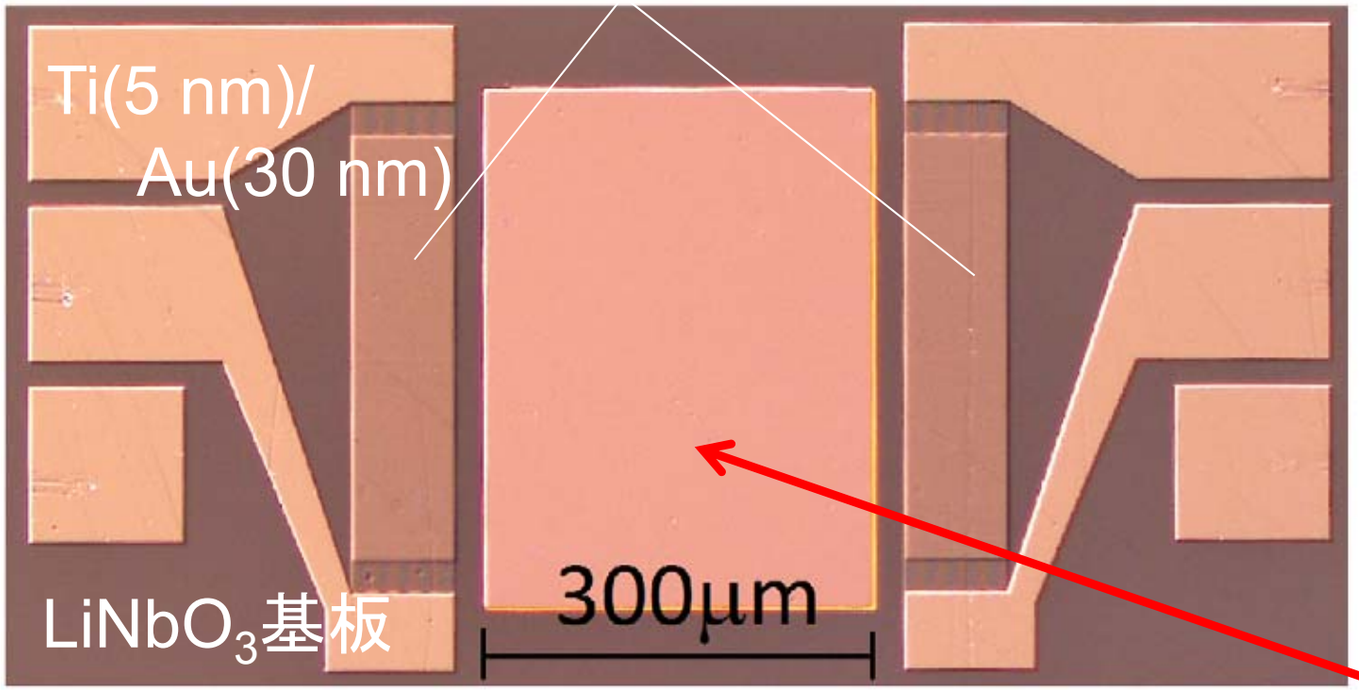
NiFe

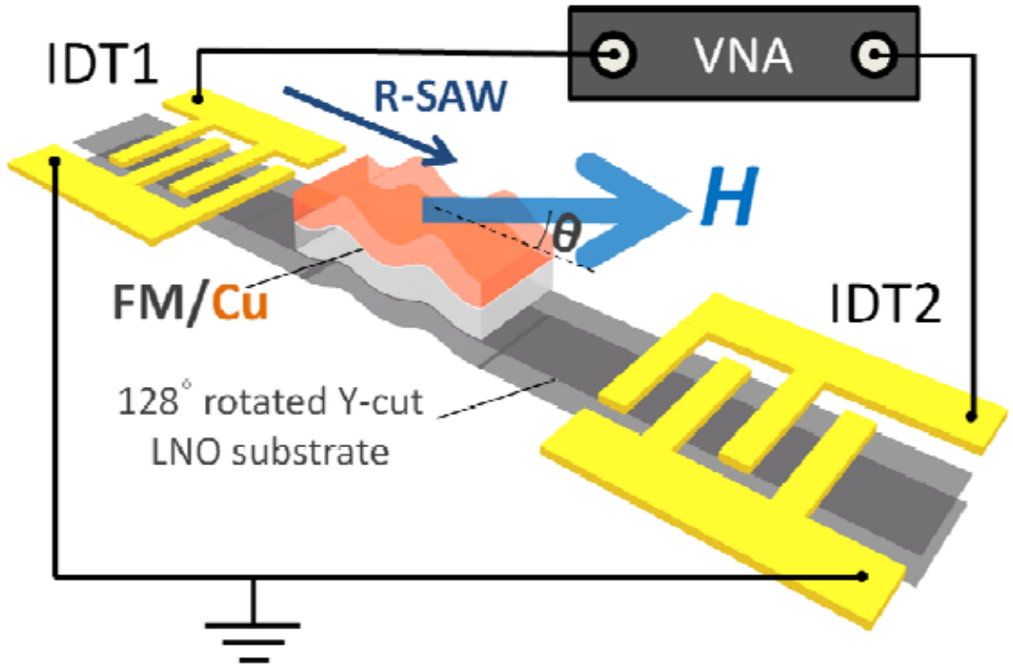
Spin torque FMR

Cu

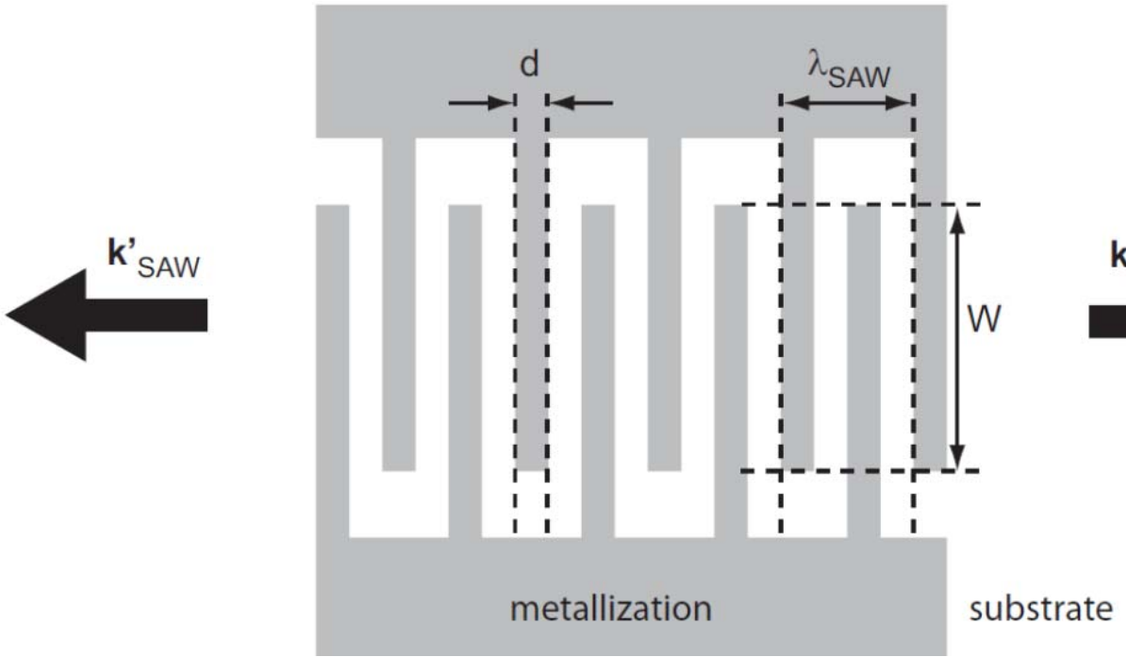
Attenuation of SAW
Due to magnetic damping!

Interdigital transducer
(80 pairs)





NiFe(20 nm) / Cu(180 nm)



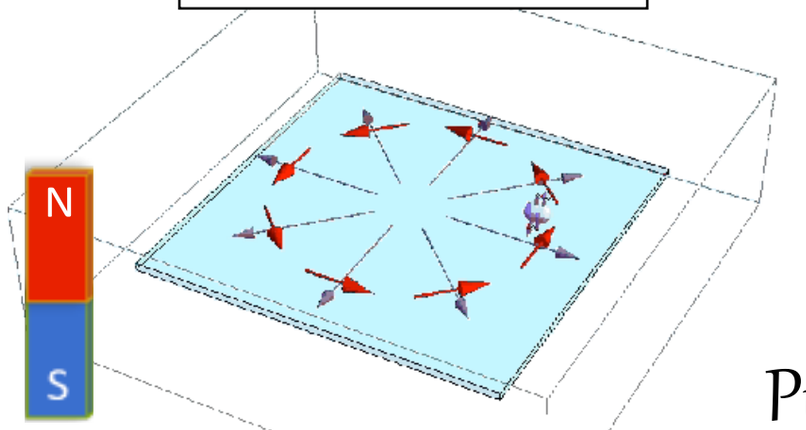
$d = 0.6\ \mu m$
$\lambda_{SAW} = 2.4\ \mu m$
$w = 300\ mm$

Kobayashi, Nozaki, MM et al., PRL2017

Mechanical generation of spin current

Mechanical Spin-Orbit

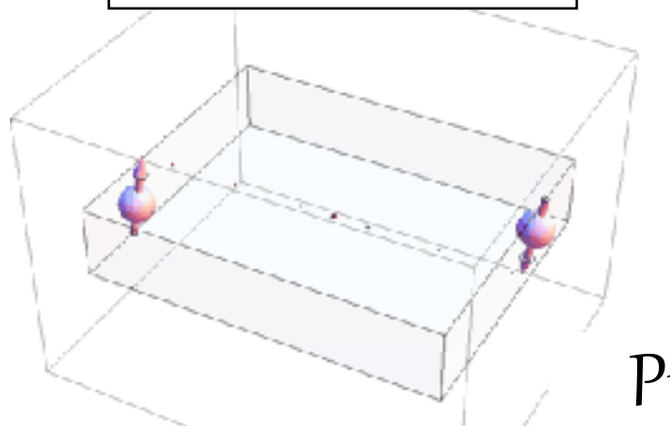
Rigid rotation



Pt

PRL2011, APL2011

Rigid vibration

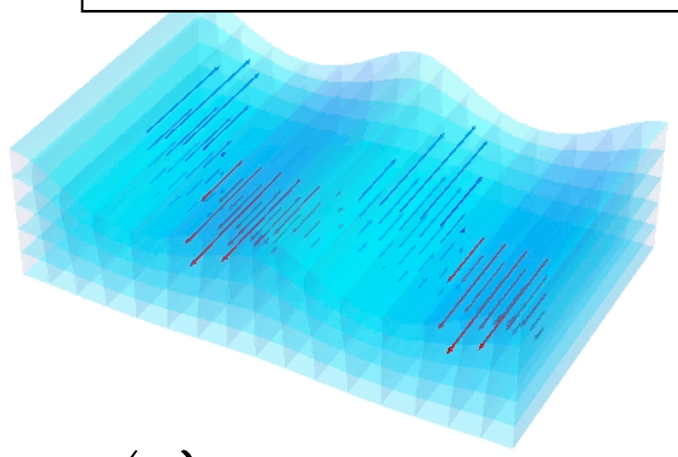


Pt

PRB2011

Spin-rotation

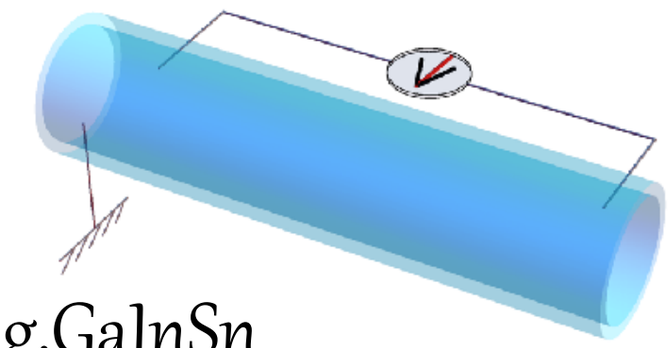
Surface acoustic wave



Cu

PRB(R)2013,2017; PRL2017

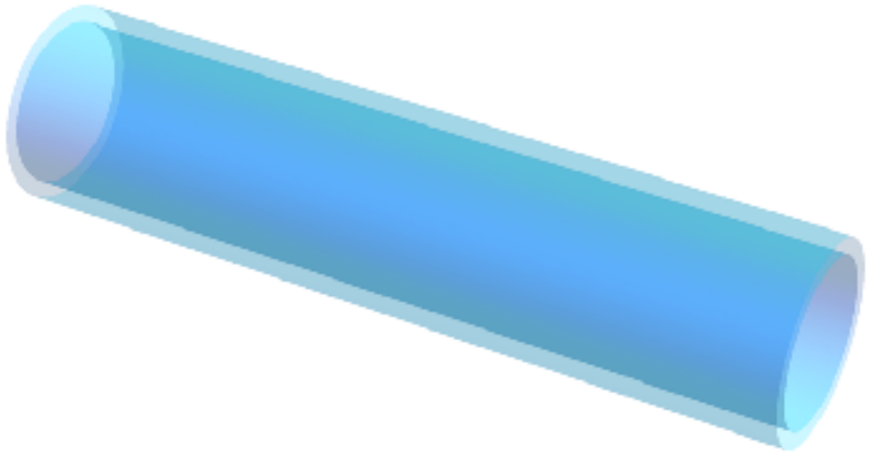
Fluid vorticity



Hg,GaInSn

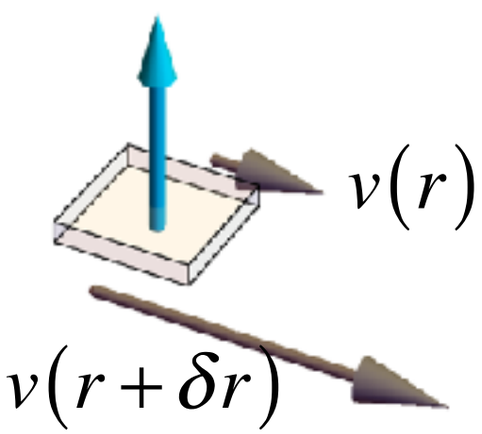
Nature Phys. 2016

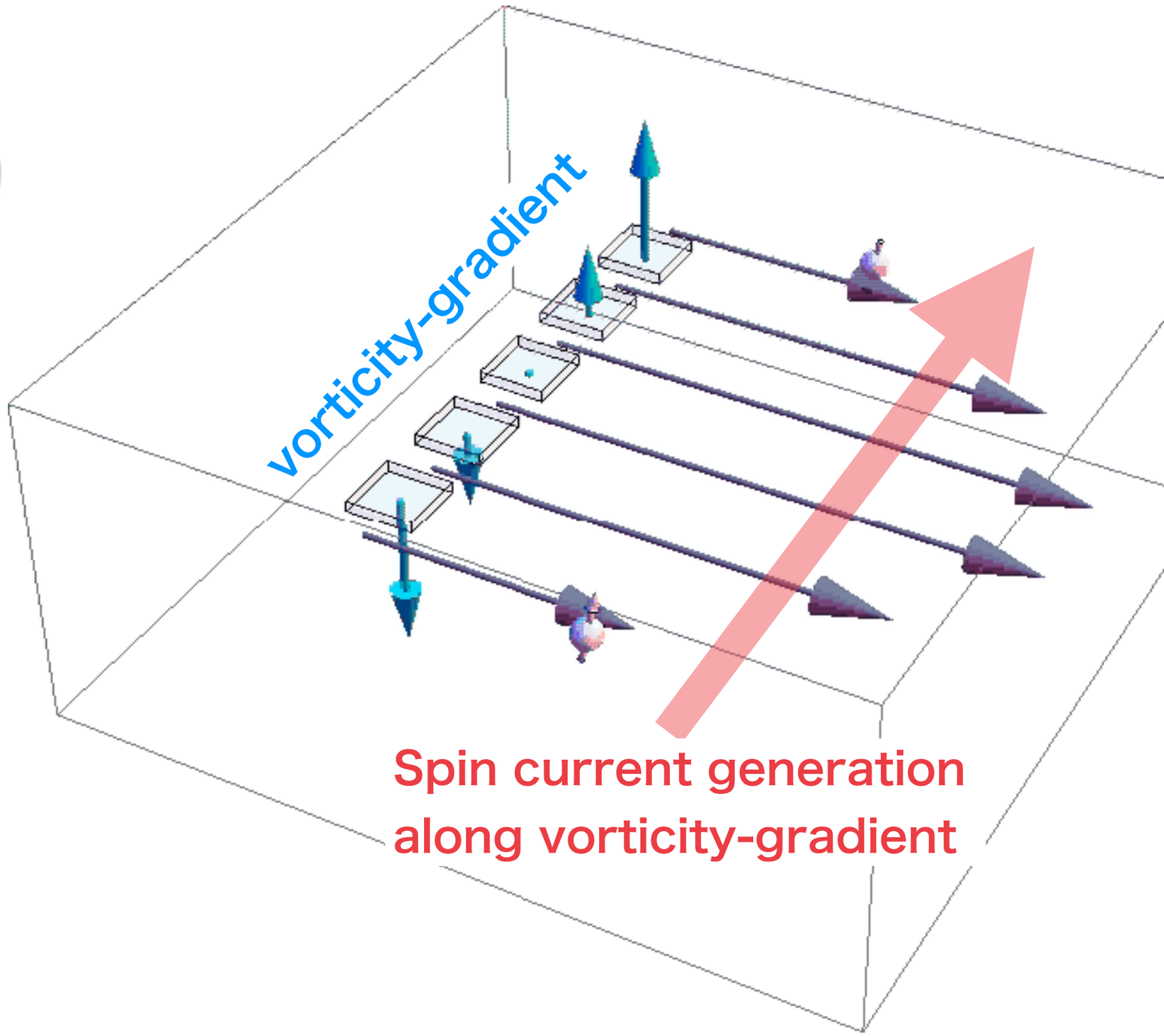
Rotation (vorticity) -gradient in a pipe flow of liquid metal



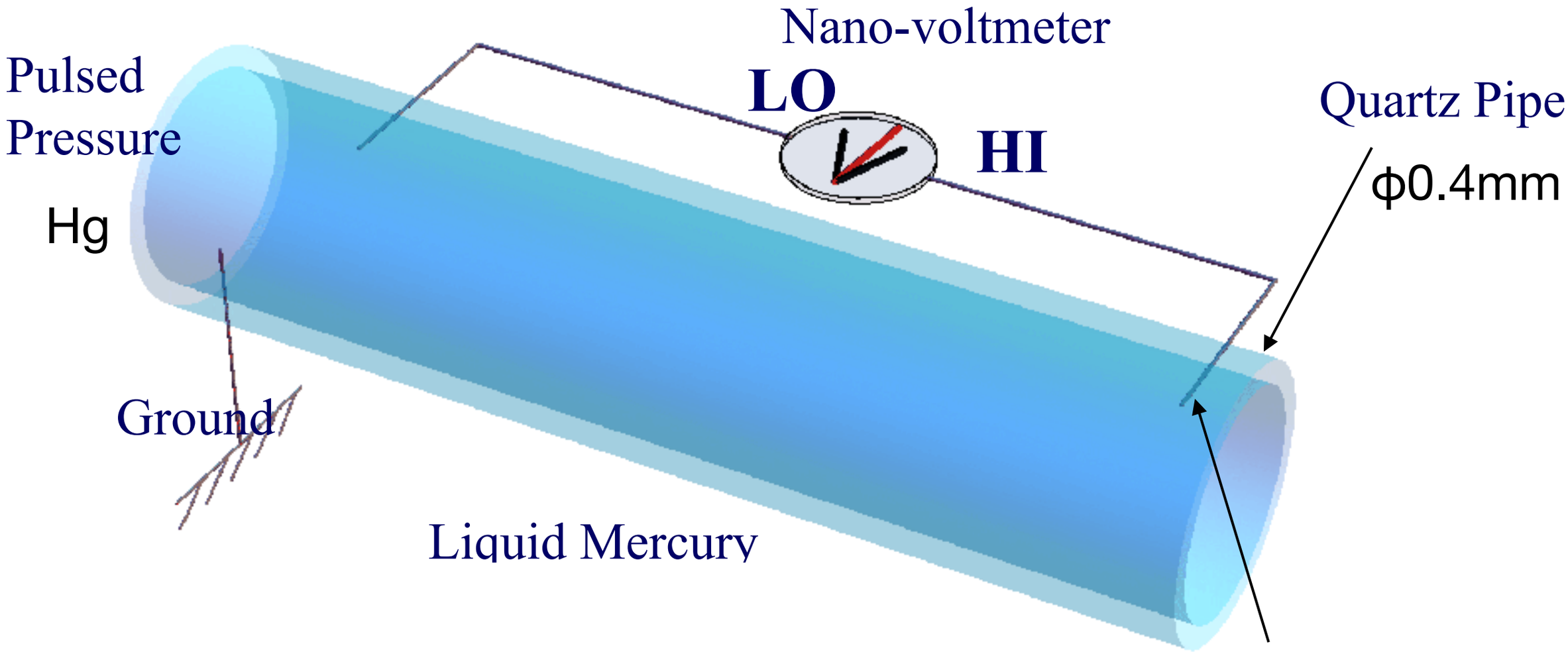
Vorticity:
local rotation of fluid

$$\nabla \times v$$





Experimental setup for spin hydrodynamic generation

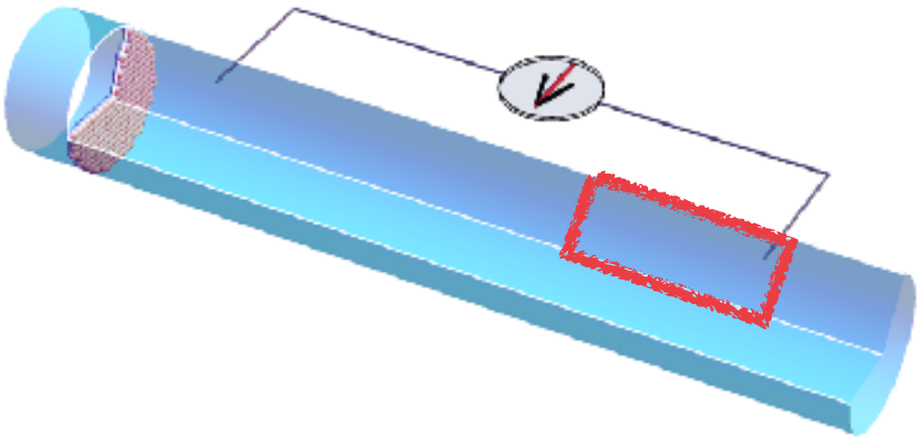


R. Takahashi, MM et al., Nat. Phys. **12**, 52-56 (2016)

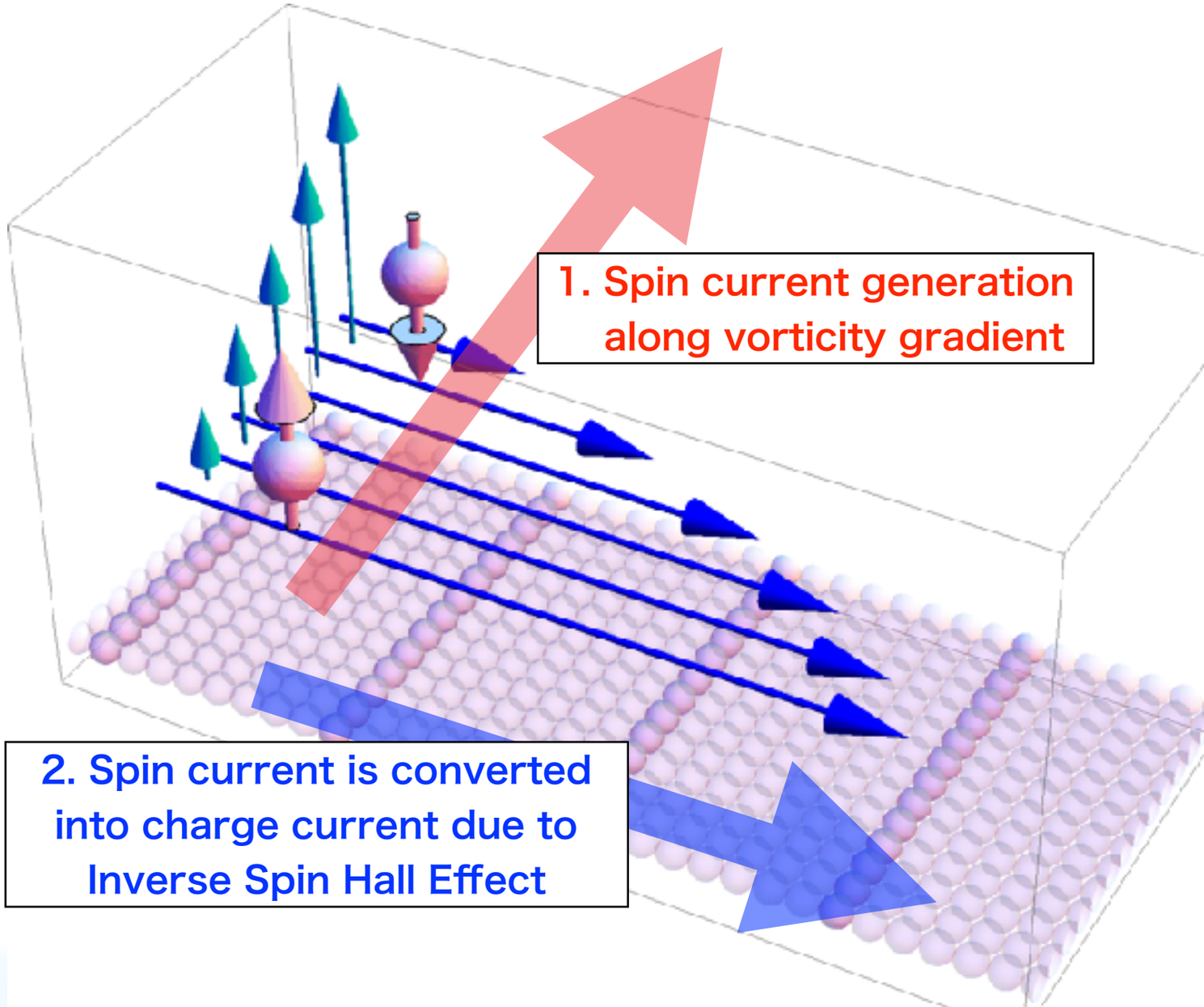
Mechanism of Spin-hydrodynamic voltage generation

“Spin-hydrodynamic generation”

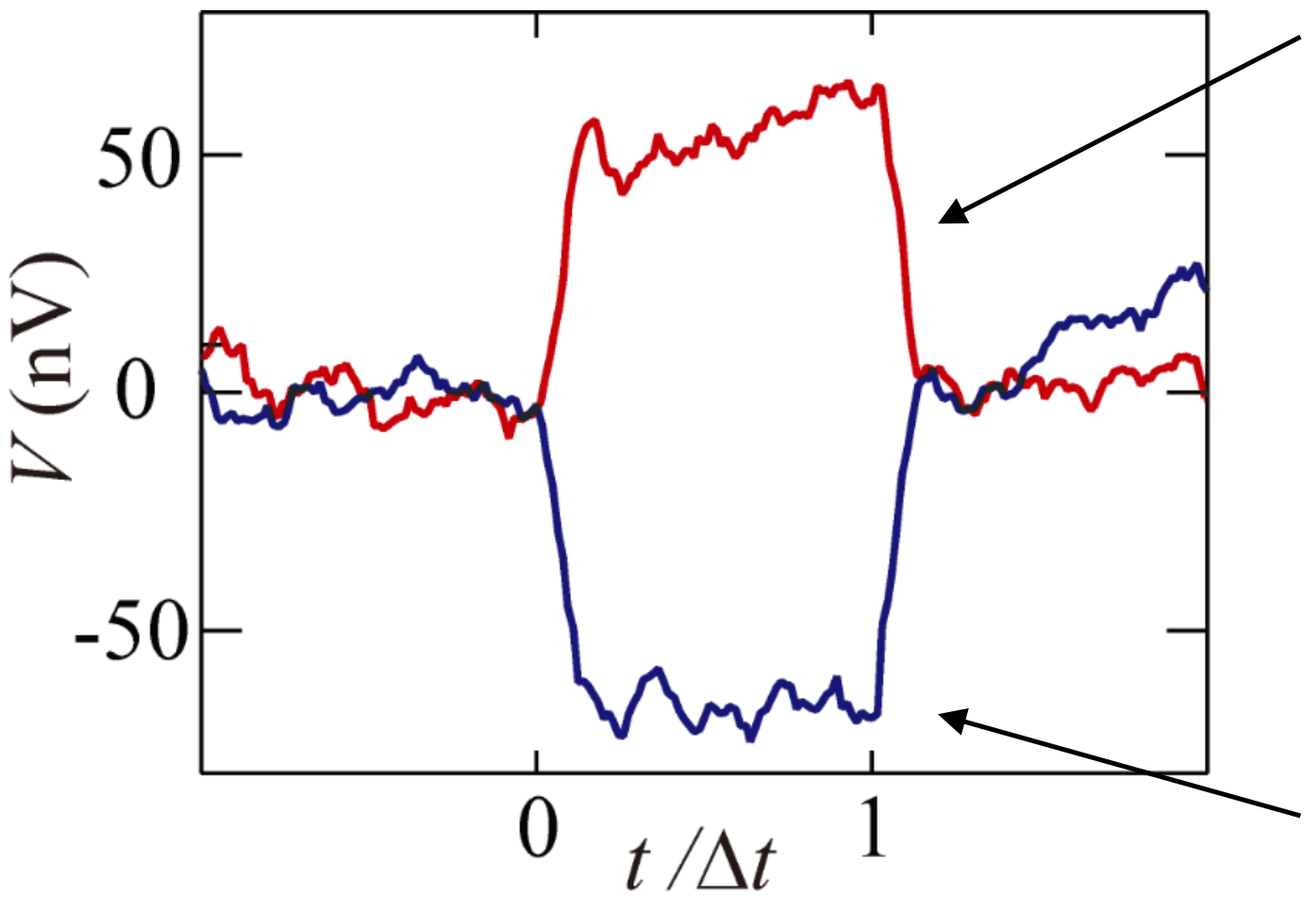
1. Spin current generation along vorticity gradient + **2. Spin current is converted into charge current by ISHE**

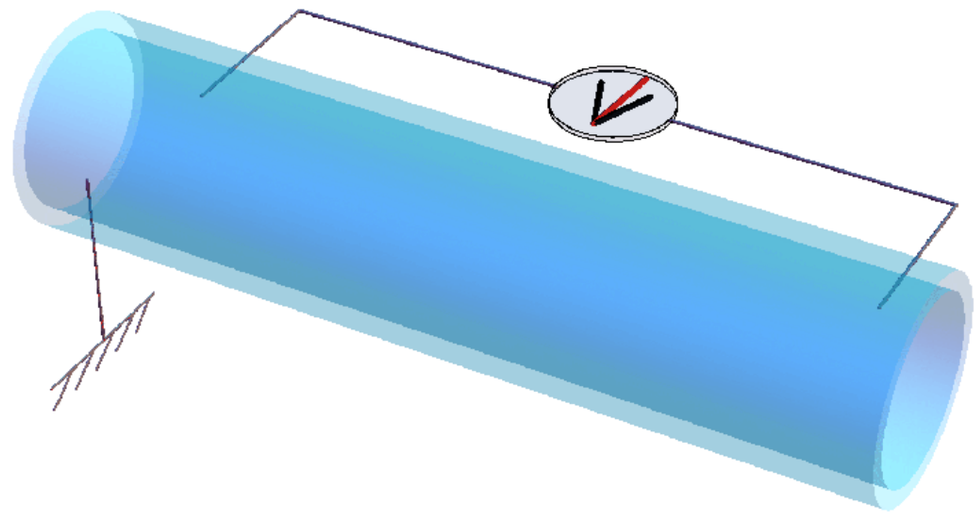


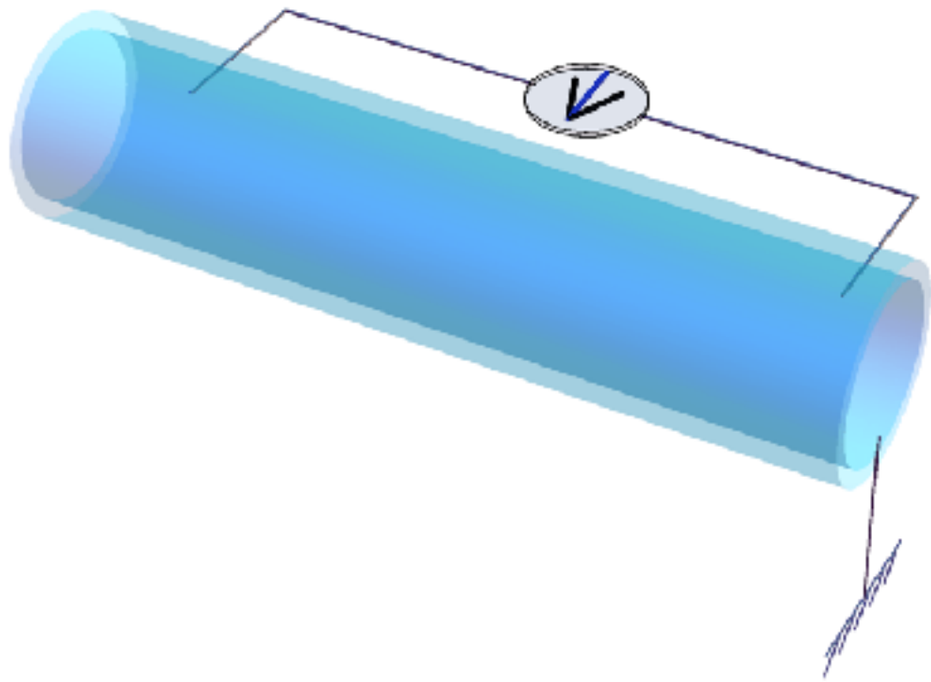
flow of liquid metal: Hg



Result - Spin-hydrodynamic signal measurement







Δt 5.9 sec, 2.7 m/s

Internal Diameter ϕ 0.4 mm

Length L 80 mm

R. Takahashi, MM et al., Nat. Phys. **12**, 52-56 (2016)

Observation of spin-rotation coupling in quark-gluon plasma (Nature 2017)

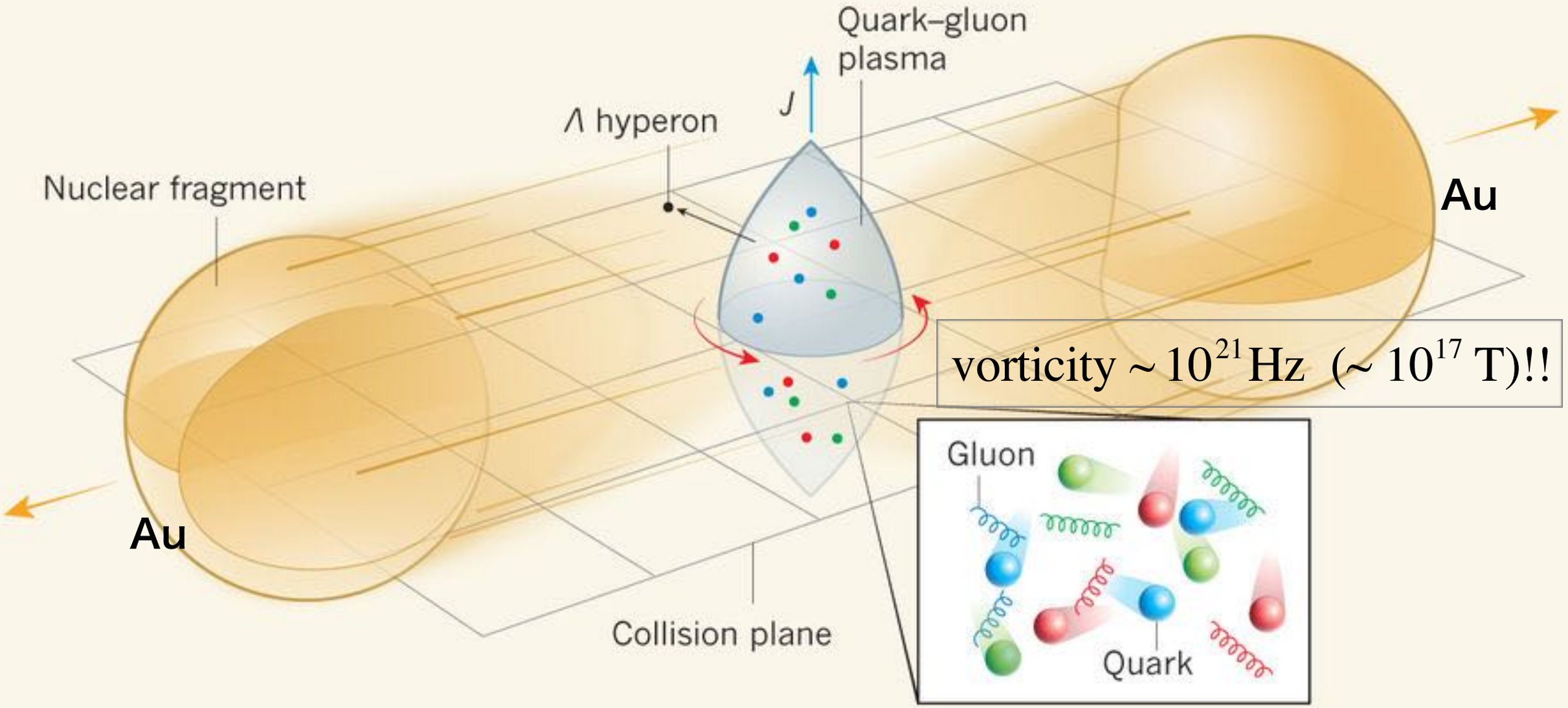
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

Au+Au, non-central collision in Relativistic Heavy Ion Collider (RHIC)



vorticity $\sim 10^{21}$ Hz ($\sim 10^{17}$ T)!!

Recently, Takahashi *et al.*[14] reported the first observation of a coupling between the vorticity of a fluid and the internal quantum spin of the electron, opening the door to a new field of fluid spintronics. In their study, the vorticity $\boldsymbol{\omega}$—a measure of the 'swirl' of the velocity flow field around any point (non-relativistically, $\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$)—is generated through shear viscous effects as liquid mercury flows next to a rigid wall.

・R.Takahashi MM et al., Nature Physics 12, 52 (2016)