Коуровка XXXVII, 2018
Гранатовая бухта

Spintronics of antiferromagnets

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Non-linear spin dynamics for antiferromagnets: auto-oscillators and solitons

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1. Spintronics (SPINelecTRONICS) Ferromagnets vs. antiferromagnets (and ferrimagnets)

not the charge but SPIN of the electron; the SPIN CURRENT is key concept

2. General dynamics. Sigma-model Eq. vs. Landau – Lifshits Eq. OR Newton dynamics vs. Aristotle dynamics

Exchange enhancement for any AFM dynamics (THz)

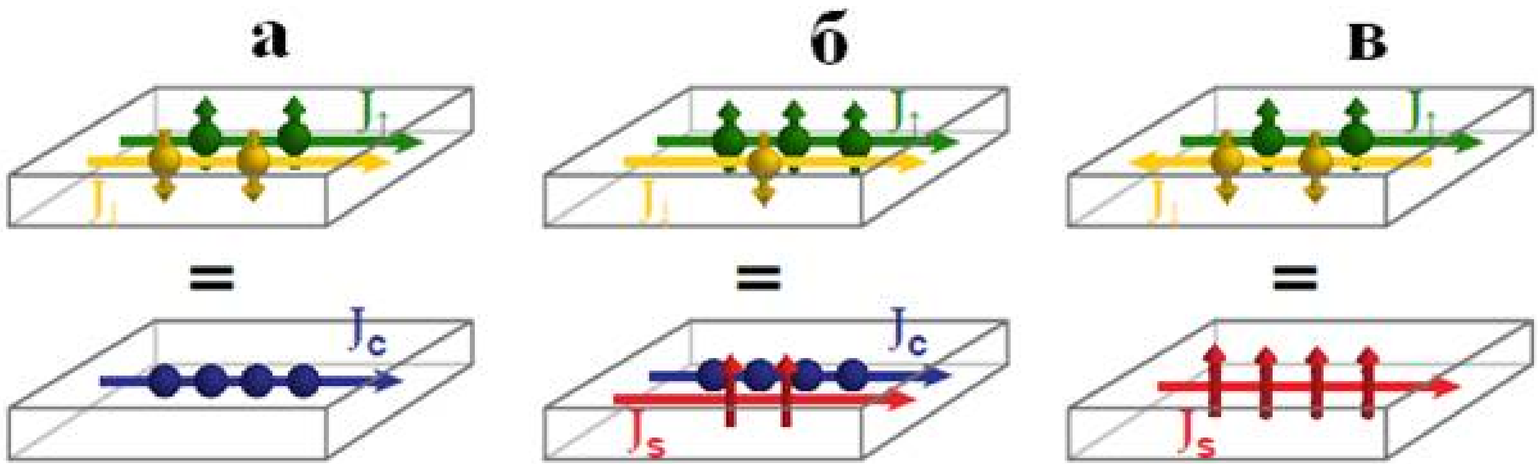
[Sirtori, C. Applied physics: Bridge for the terahertz gap. *Nature* **417,** 132–133 (2002).
Kleiner, R. Filling the terahertz gap. *Science* **318,** 1254–1255 (2007)].

3. Uniform dynamics

a) Lagrange formalism for the sigma-model b) spin transfer torque for AFMs

4. Non-uniform dynamics: "Lorentz-invariant" AFM vortices and solitons

6. Dzyaloshinskii - Moriya interaction: the break of the Lorentz invariance



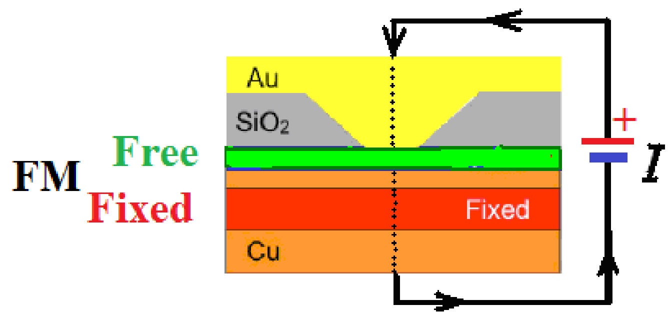
Electric current spin-polarized currens pure spin current

Without any electron flow (flow + counter-flow) dielectrics, incl. typical AFMs

How to create? AND WHY? Many applications …

SPIN-TORQUE AUTO-OSCILLATOR. FM is realized, AFM - THz

Spin-valve structure –metallic magnets only



Spin-Hall Effect, high efficient; dielectrics

magnet + heavy metal (Pt) SPIN HALL EFFECT: DIRECT AND INVERSE

DSHE: Je in HM - spin flow to AFM Js (p)

ISHE spin oscill. in magnet ($\tilde{p}$) produce Js from AFM to HM, and Je in HM

Demidov, Vlad. *et al.* Magnetic nano-oscillator driven by pure spin current. *Nat. Mater.* **11,** (2012)

LANDAU – LIFSHITZ EQUATION (FM) Aristotl dynamics

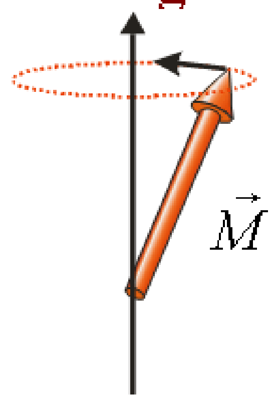
$$\frac{\partial \vec{\mathbf{M}}}{\partial t} = -\gamma\left(\vec{\mathbf{M}} \times \vec{\mathbf{H}}_{\mathrm{eff}}\right) + \vec{\mathbf{R}}_{\mathrm{L}} + \vec{\mathbf{J}}_{\mathrm{ST}},\ \vec{\mathbf{H}}_{\mathrm{eff}} = -\frac{\delta W[\vec{\mathbf{M}}]}{\delta \vec{\mathbf{M}}} \equiv \vec{\mathbf{H}}_0 + \vec{\mathbf{H}}_a,\ \vec{\mathbf{H}}_a = -\frac{\partial w_a}{\partial \vec{\mathbf{M}}}$$

$\vec{\mathbf{R}}_{\mathrm{L}}$ **GILBERT DAMPING** $\vec{\mathbf{J}}_{\mathrm{ST}}$ **STT**

$$\vec{\mathbf{J}}_{\mathrm{ST}} = j_{\mathrm{ST}} \cdot [\vec{p} - \vec{m}(\vec{m} \cdot \vec{p})], \quad \vec{m}^2 = 1$$

Slonczewski (1996), Berger (1996).

Ferromagnet



$$\omega_{FM} \sim \gamma(H_A + H)$$

1-10 GHz

$$\gamma = \frac{2\mu_B}{\hbar} = 2.8\ \mathrm{GHz/KOe}$$

No contribution of “exchange field” for uniform oscillations

Only for spin waves (magnons) with non-uniform oscillations,

$$\omega(k) = \omega_{FM} + \gamma\, "H_{ex}"\, (ak)^2 \ldots$$

Antiferromagnet (AFM) : Sublattices, $\vec{\mathbf{M}}_1; \vec{\mathbf{M}}_2$ Neel state

AFM vs Ferrimagnets (even in compensation point)

Element of crystal group ("odd") which replace sublattices, $\hat{g}^{(\mathrm{odd})}\vec{L} = -\vec{L}$

$$\vec{\mathbf{L}} = \vec{\mathbf{M}}_1 - \vec{\mathbf{M}}_2 = M_S\vec{\mathbf{l}}, \vec{\mathbf{M}} = \vec{\mathbf{M}}_1 + \vec{\mathbf{M}}_2 = M_S\vec{\mathbf{m}},$$

$$\vec{\mathbf{l}}^2 + \vec{\mathbf{m}}^2 = 1, (\vec{\mathbf{l}}\cdot\vec{\mathbf{m}}) = 0$$

AFM "Odd" symmetry element: $\vec{l} \to -\vec{l}$ forbid gyroscopic terms common to that for LLE. $\cancel{\frac{\partial\vec{l}}{\partial t} = \gamma\left(\vec{l}\times\frac{\partial(\mathrm{Skalar})}{\partial\vec{l}}\right)}$

$$w^{(\mathrm{ex})} = J\vec{S}_1\cdot\vec{S}_2 \to H_{ex}\vec{\mathbf{M}}^2/2M_S \qquad (J>0)$$

$$w_H = -\vec{\mathbf{M}}\vec{\mathbf{H}}_{\mathrm{tot}}, \quad \vec{\mathbf{H}}_{\mathrm{tot}} = \vec{\mathbf{H}}_0 + \vec{\mathbf{H}}_D + \ldots$$

very delicate feature (1933 to 1957 [Dzyaloshinskii-Moriya])

$W^{(\mathrm{DM})} = -\vec{\mathbf{M}}\cdot\vec{\mathbf{H}}_D$, $\vec{\mathbf{H}}_D$ –"L-dependent internal magnetic field" $\vec{\mathbf{H}}_D = -(\vec{\mathbf{L}}\times\vec{d})$

Dzyaloshinskii field is forbidden for some AFMs, like typical NiO, CoF_2; but present for many others, like orthoferrites, hematite…, $H_{\mathrm{D}} \sim 10$ **Tesla. DM-Field**

$$W = H_{ex}\vec{\mathbf{M}}^2/2M_S - \vec{\mathbf{M}}\vec{\mathbf{H}}_{\mathrm{tot}} + \ldots(\vec{\mathbf{L}})$$

$$W = H_{ex}\vec{\mathbf{M}}^2 / 2M_S - \vec{\mathbf{M}}\vec{\mathbf{H}}_{\text{tot}} + \ldots(\vec{\mathbf{L}}) \quad \Rightarrow$$

$$\vec{\mathbf{M}} = \frac{M_S}{H_{\text{ex}}}\left[\vec{\mathbf{H}}_{\text{tot}} - \vec{l}\,(\vec{l}\cdot\vec{\mathbf{H}}_{\text{tot}})\right] \ll M_S$$ **(1) statics;**

natural definition: at $H_0 \to H_{\text{ex}},\ M \to M_S = 2M_0$

$J \sim 100 - 1000$ **Kelvin (950 K for hematite) :::** H_{ex} **is HUGE!!**

Hematite 18 MOe, NiO 10 MOe, Orthoferrites 6 MOe, Iron Borate 2.6 MOe

1 MegaOe = 100 Tesla

In the Universe, at the surfaces of neutron stars- pulsar effect

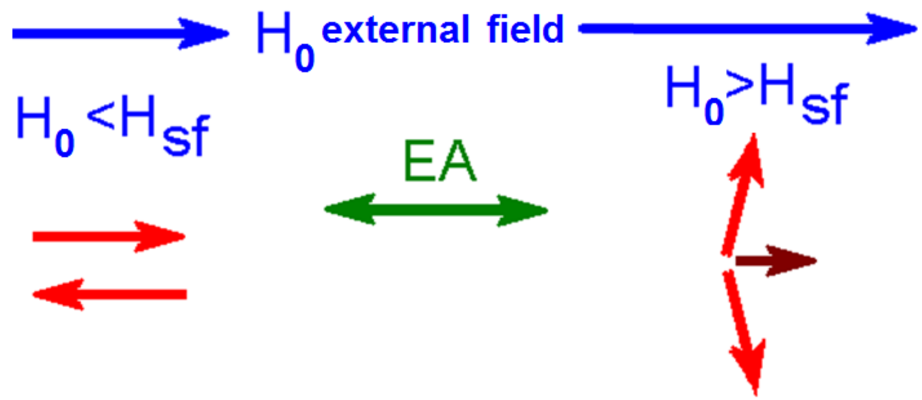
FERROMAGNET : Only for spin waves (magnons) with non-uniform oscillations,

$$\omega(k) = \omega_{FM} + \gamma\,"H_{ex}"(ak)^2$$

STATIC PROPERTIES ARE DIFFERENT (will be used later)

DYNAMICS is even more DIFFERENT !

1) EXTERNAL FIELD - <u>spin-flop transition</u>



M=0 till H_{sf}, $H_{sf}^2 = H_{ex} H_{anis}$, $H_{sf} \sim$ 10 Tesla ~ 100 KOe

<First example of <u>exchange enhancement</u> of some AFM parameter>

: for ferromagnets – reorientation at field ~ H_{anis} ~ 1-10 KOe

2)Dzyaloshinskiii field (simplest) $\vec{\mathbf{H}}_D = (\vec{\mathbf{L}} \times \vec{d})$ H_D ~ 10 – 15 Tesla

Sublattices canting on H_D/H_{ex}, a few % **canted AFM = Weak FM**

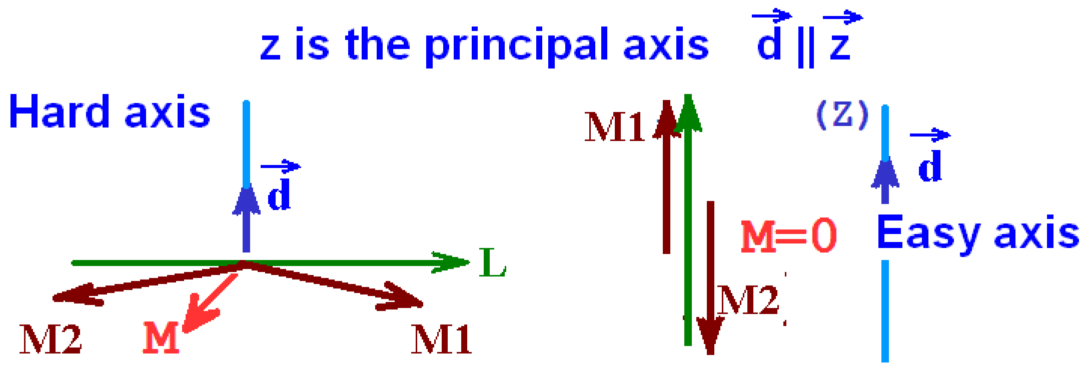
More general $w_D = D_{ik}(\vec{l}\,) m_i l_k$, **IMPORTANT TO DYNAMICS**

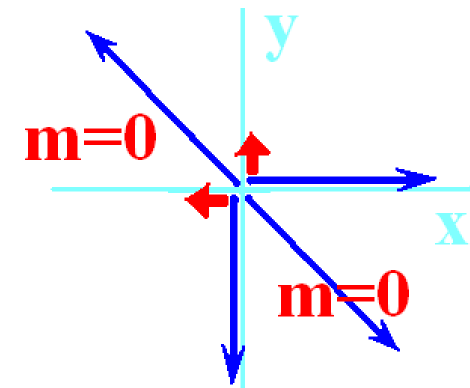
Hematite, orthoferrites, ect. $w_D \sim \vec{\mathbf{m}} \cdot [\vec{\mathbf{l}} \times \vec{\mathbf{d}}]$

$\vec{\mathbf{m}}$ **is isotropic in the basal plane**

MnF₂ anisotropic

$4_z^{(-)}; w_D \sim (m_x l_y + m_y l_x)$





Spontaneous spin reorientation transitions (temperature, preassure, ect)

For some materials (hematite, dysprosium orthoferrite) – MORIN TRANSITION

T_M - state with $\vec{\mathbf{m}} = 0$ and $\vec{\mathbf{m}} \neq 0$

Hematite α-Fe_2O_3: T_M =260 K , and M=0 at T< T_M M≠0 at T> T_M

No manifestation of "uniform exchange field" for FMs; but Crucial role for AFMs !

1) statics; 2) dynamics: The magnon frequencies and *soliton speed* for AFM dynamics are much higher then that for FM: exchange enhancement

Sigma-model equation (1979 - 1985). The simplest: two LLE $\partial \vec{\mathbf{M}}_{1,2} / \partial t$

$$\frac{\partial \vec{\mathbf{L}}}{\partial t} = \gamma(\vec{\mathbf{L}} \times \vec{\mathbf{H}}_{\mathrm{M}}) + \gamma(\vec{\mathbf{M}} \times \vec{\mathbf{H}}_{\mathrm{L}}) + \vec{\mathbf{R}}_{\mathrm{M}}, \quad (1) \qquad \vec{\mathbf{H}}_{\mathrm{L}} = -\frac{\delta W}{\delta \vec{\mathbf{L}}},$$

$$\frac{\partial \vec{\mathbf{M}}}{\partial t} = \gamma(\vec{\mathbf{L}} \times \vec{\mathbf{H}}_{\mathrm{L}}) + \gamma(\vec{\mathbf{M}} \times \vec{\mathbf{H}}_{\mathrm{M}}) + \vec{\mathbf{R}}_{\mathrm{L}} + \vec{\mathbf{J}}_{\mathrm{ST}}, \quad (2), \qquad \vec{\mathbf{H}}_{\mathrm{M}} = -\frac{\delta W}{\delta \vec{\mathbf{M}}}$$

$$\vec{\mathbf{J}}_{\mathrm{ST}} = j_{\mathrm{ST}} \cdot [\vec{p} - \vec{l}(\vec{l} \cdot \vec{p})]$$ **Gomonay, Loktev, PRB 2010**

IN PRINCIPLE, THE SAME AS FOR FMs

small !

$$w = \frac{H_{\mathrm{ex}} \vec{M}^2}{2M_s} - \vec{M}(\vec{H}_0 + \vec{H}_D) + \frac{A}{2}(\nabla \vec{l})^2 + w_a(\vec{l}) + \ldots \cancel{\frac{\tilde{A}}{2}(\nabla \vec{m})^2 + \tilde{w}_a(\vec{m})}$$

$H_e m^2$ $(H, H_D)\,m$ $H_a\, m^2$

Eq. for M – additional term (Larmor theorem) Magnitic field - precession

$$(1) \rightarrow \vec{\mathbf{M}} = \frac{M_0}{H_{\text{ex}}}\left[\vec{\mathbf{H}}_{\text{tot}} - \vec{l}(\vec{l}\cdot\vec{\mathbf{H}}_{\text{tot}}) + \frac{1}{\gamma}\left(\vec{l}\times\frac{\partial\vec{l}}{\partial t}\right)\right], \vec{\mathbf{H}}_{\text{tot}} = \vec{\mathbf{H}}_0 + \vec{\mathbf{H}}_{\text{D}} \rightarrow (2) \rightarrow$$

Equation for $\vec{l}$ only (<u>σ-model, σM,</u> $\vec{l}^{\,2}=1$, <u>sphere</u> $S_2 \triangleq$ σ).

Let $\vec{\mathbf{H}}_{\text{tot}} = 0$, for simplicity. $$W[\mathbf{l}] = \int dx\left[\frac{1}{2}A(\nabla\mathbf{l})^2 + \widetilde{W}(\mathbf{l})\right]$$

$$\vec{l}\times\left(\frac{1}{2\gamma^2 H_{\text{ex}}}\frac{\partial^2\vec{l}}{\partial t^2} - \frac{1}{2}A\nabla^2\vec{l} + \frac{\partial W_{\text{anis}}(\vec{l})}{\partial\vec{l}} + \alpha_{\text{Gilbert}}\frac{\partial\vec{l}}{\partial t} - j_{\text{ST}}[\vec{l}\times\vec{p}]\right) = 0,$$

α_{Gilbert} --- usual friction force

magnet (AFM) + heavy metal

SPIN HALL EFFECT :

DIRECT AND INVERSE

DSHE: Je in HM - spin flow to AFM Js (p)

ISHE spin oscill. in AFM ($\tilde{\mathrm{p}}$) produce Js from AFM to HM, and Je in HM

Electromotive force $\varepsilon \sim \vec{l}\times\partial\vec{l}/\partial t$

$$\vec{l}\times\left(\frac{1}{2\gamma^2 H_{\text{ex}}}\frac{\partial^2\vec{l}}{\partial t^2}-\frac{1}{2}A\nabla^2\vec{l}+\frac{\partial W_{\text{anis}}(\vec{l})}{\partial\vec{l}}+\alpha_{\text{Gilbert}}\frac{\partial\vec{l}}{\partial t}-j_{\text{ST}}[\vec{l}\times\vec{p}]\right)=0,$$

Uniform oscillations $\omega=\gamma\sqrt{H_{\text{ex}}H_{\text{anis}}}$ $W_{\text{anis}}\sim H_a$ **AFMR frequencies, till THz** H_{ex} **is HUGE!!**

1. Inertial spin dynamics (Newton, instead of Aristotle, dynamics)

2. Non-uniform dynamics Lorentz-Invariant (LI) combination $\partial^2\vec{l}/\partial t^2-c^2\nabla^2\vec{l}$

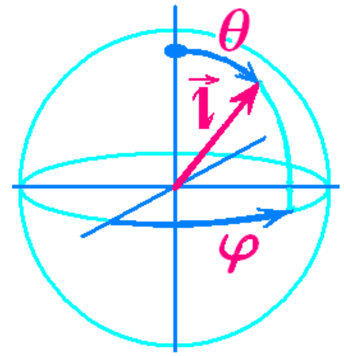
$c^2=\gamma^2 H_{\text{ex}}A$ **exchange only**

3. Exchange enhancement for any AFM dynamics (incl. $\vec{\mathbf{J}}_{\text{ST}}$**)**

{The frequencies of AFM magnon hundreds GHz, with values 1.1 THz for NiO, 500-900 GHz for different orthoferrites and 310 GHz for iron borate. *c* = 20 km/s for orthoferrites and appr. 100 km/s for Chromium}

<u>a)</u> Non-linear dynamics, uniform in space: Lagrange function

INERTIAL DYNAMICS MASSIVE PARTICLE ON SPHERE



$$L = \frac{\hbar}{2\gamma H_{ex}} \left(\frac{\partial \mathbf{l}}{\partial t}\right)^2 - W(\mathbf{l}) = T - U \qquad M^* = \frac{\hbar}{\gamma H_{ex}}$$

$$T = \frac{M^*}{2}\left[\left(\frac{\partial \theta}{\partial t}\right)^2 + \sin^2\theta \left(\frac{\partial \varphi}{\partial t}\right)^2\right],\ U = W(\theta, \varphi)$$

2 coordinates θ, φ, **2 momenta** $p_\theta = M^* \dot{\theta},\ p_\varphi = M^* \dot{\varphi} \cdot \sin^2\theta$

Hamilton dynamics with 2 degrees of freedom

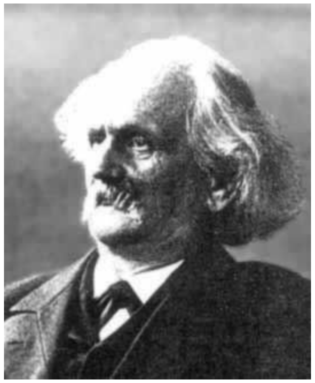
For FM: $"T" = \hbar s(1 - \cos\theta)(\partial\varphi / \partial t)$, **and** $p_\varphi = \hbar s(1 - \cos\theta)$ **1 d.of. f**

$E = T + U$, **but for bi-axial AFM with** $W = K_1 l_x^2 + K_2 l_y^2$

$$K_1 \neq K_2 \neq 0$$

it is integrable (Carl Newmann, 1859)

The case of orthoferrites



Non-linear uniform in space dynamics: APPLICATIONS
1) Ultrafast spin reorientation (Kourovka-36);
2) THz nanooscillators

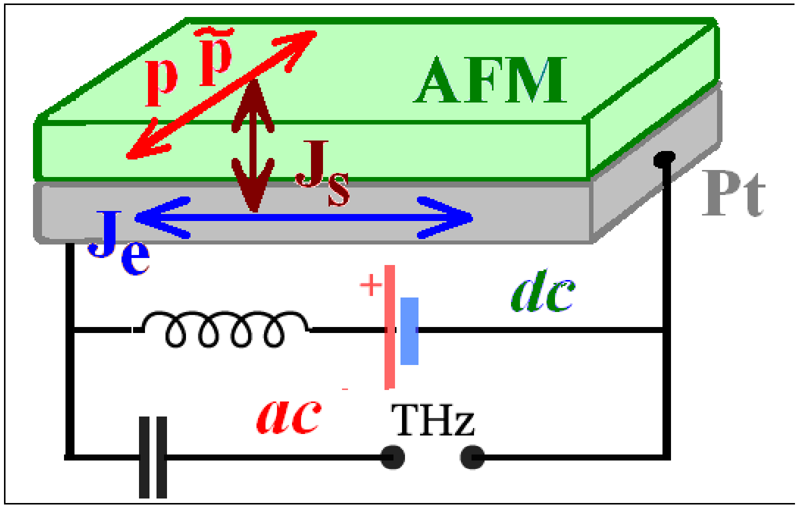
how to excite spin oscillations $dE/dt = Q_{STT} - Q_G$

$$Q_G \sim \alpha_G [(\frac{\partial \theta}{\partial t})^2 + (\frac{\partial \varphi}{\partial t})^2 \sin^2 \theta] \qquad Q_{STT} \sim \mathbf{p}_{STT} (\frac{\partial \varphi}{\partial t}) \sin^2 \theta$$

α **effective Gilbert damping parameter,** j_{SC} **spin torque**

DSHE: $\vec{\mathbf{p}}_{ST}$ **is parallel to hard axis of AFM - precession around HA**

Antiferromagnetic SPIN HALL THz-frequency Oscillator -- Spin Current



magnet (AFM) + heavy metal

SPIN HALL EFFECT :

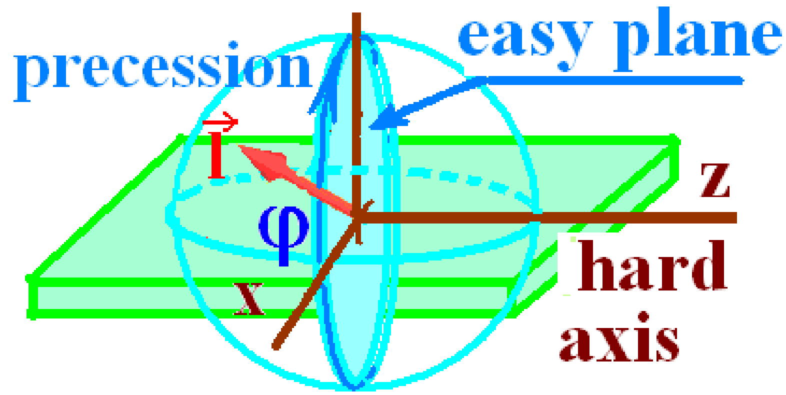
DIRECT AND INVERSE

DSHE: Je in HM - spin flow to AFM Js (p)

planar motion:: $\vec{l}$ in the EP

$$\theta = \text{const} = 90^\circ, \varphi = \varphi(t)$$

(Gomonai, Loktev, PRB 2010)

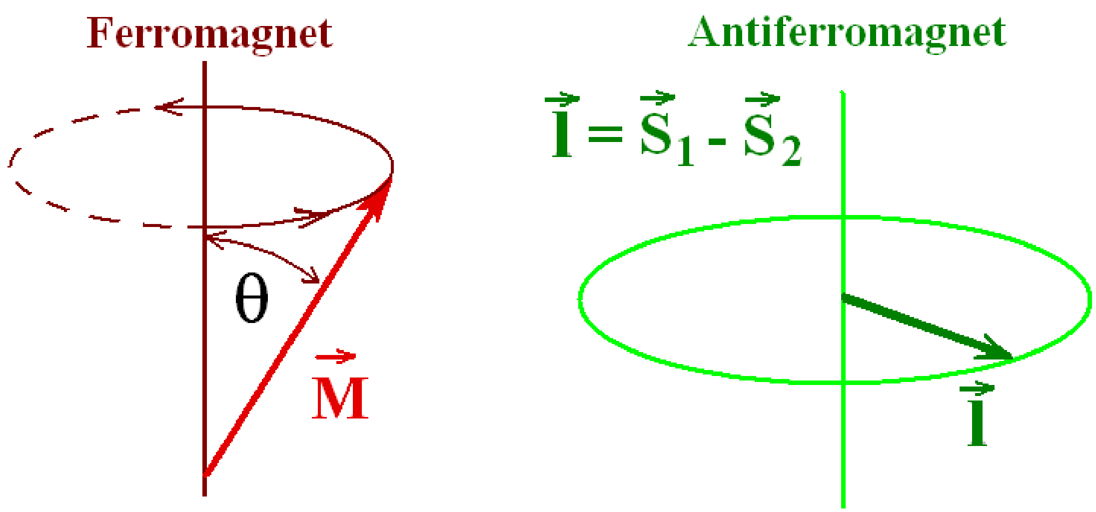


$$\frac{1}{\omega_{\text{ex}}}\frac{d^2\varphi}{dt^2} + \alpha\frac{d\varphi}{dt} - j_{\text{ST}} = 0 \rightarrow \varphi = \omega t, \omega = j_{\text{ST}} / \alpha$$

α effective Gilbert damping parameter, usually small j_{SC} spin torque

#1# DSHE: $\vec{\mathbf{p}}_{ST}$ is parallel to hard axis of a magnet - precession around HA

#2# ISHE: Electromotive force $\varepsilon \sim \vec{l} \times \partial\vec{l} / \partial t$ in Pt: spin current –> electric current in Pt **BUT: no <u>ac – signal</u> from ISHE** (precession with $\theta \neq \pi / 2$)



$$[\mathbf{l}, \frac{\partial \mathbf{l}}{\partial t}] = \omega = \mathrm{const},$$ **parallel to HA**

uniaxial AFM results in a uniform in time flat rotation of the vector $\vec{l}$ with the amplitude $\theta_0 = 90^\circ$. The spin-Hall signal is proportional to $[\mathbf{l} \times \partial \mathbf{l} / \partial t] \propto \omega \sin^2 \theta$, $\omega = const$.

Such a rotation of the spin is "idle", i. e., the ac spin-Hall signal is not created here, and it is important to go beyond this model.

DMI – magnetization, magnetic dipolar radiation,

FM: $\theta = \theta_0 < 90^\circ$ **ac – signal**

AFM: $\vec{\mathbf{l}}$ **in the EP** $\theta = 90^\circ, \varphi = \omega t$ **(Gomonai, Loktev, PRB 2010)**

no ac – signal from ISHE for AFM

*** * ***

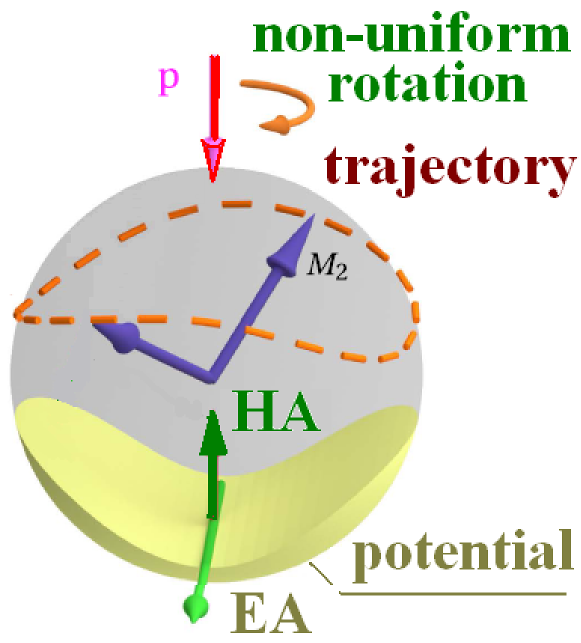
ONE solution (2016): anisotropy in the easy plane $K_{\mathrm{a,ip}}$ **- rotation is non-uniform in time,**

First **threshold**

One way: THz-frequency Josephson-like Oscillator

the simple idea: include anisotropy (weak) in the easy plane NiO !

- R. Khymyn, I. Lisenkov, V. Tyberkevych, B.A. Ivanov and A. Slavin, Antiferromagnetic THz-frequency Josephson-like Oscillator Driven by Spin Current, Sci. Rep. 7, 43705 (2017)
- "ANTIFERROMAGNETIC THZ FREQUENCY JOSEPHSON-LIKE OSCILLATOR DRIVEN BY SPIN CURRENT" Inventors: Roman Khymyn et al.; the United States Patent and Trademark Office, 2016, U.S. Serial No. 62/393,479.

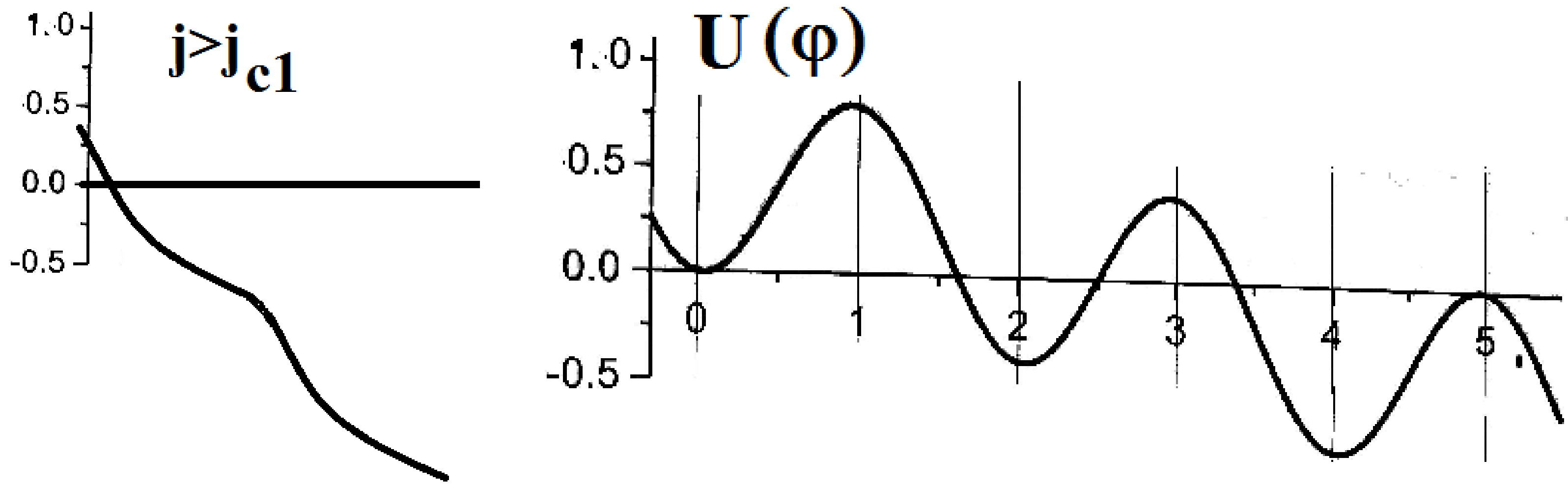


$$\frac{1}{\omega_{\mathrm{ex}}}\frac{d^2\varphi}{dt^2}+\alpha\frac{d\varphi}{dt}-j_{\mathrm{ST}}+\omega_{\mathrm{a,ip}}\sin 2\varphi=0$$

--superconducting phase in a resistively and capacitively shunted Josephson Junction under a current bias

dynamics of a massive particle in a tilted washboard (a buddle) potential

“вашгерд”

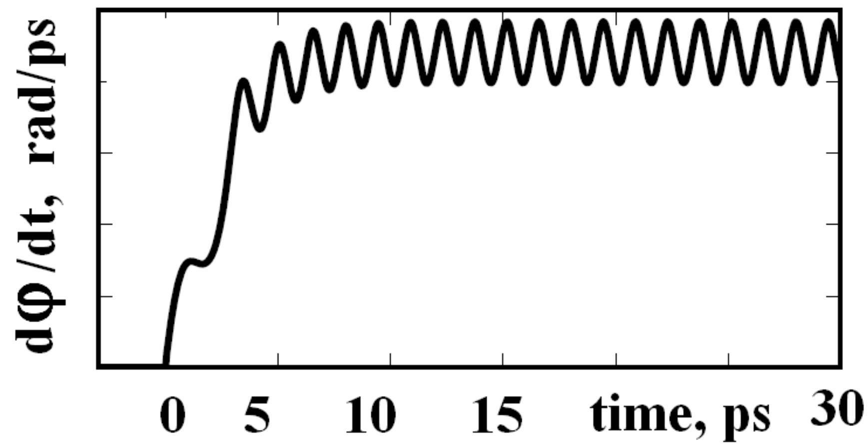


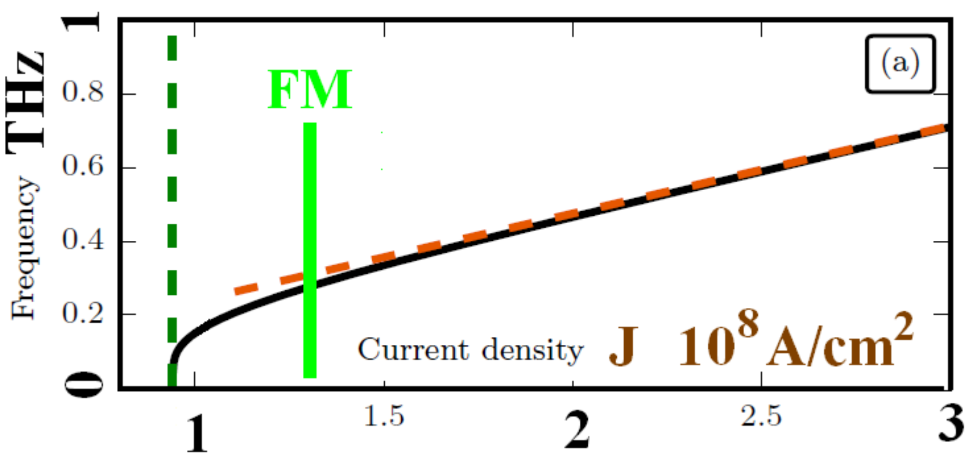
$$\frac{1}{2\omega_{\mathrm{ex}}}\left(\frac{d\varphi}{dt}\right)^2 + \tilde{U}(\varphi) = E$$

$$\tilde{U}(\varphi) = \frac{1}{2}\omega_{\mathrm{a,ip}}\sin^2\varphi - j_{\mathrm{ST}}\varphi, \quad \frac{dE}{dt} = -\alpha\left(\frac{d\varphi}{dt}\right)^2$$

1) threshold $j_{\mathrm{C,1}} > \omega_{\mathrm{a,ip}}$, “ignition” threshold **weak EP anisotropy (-)**

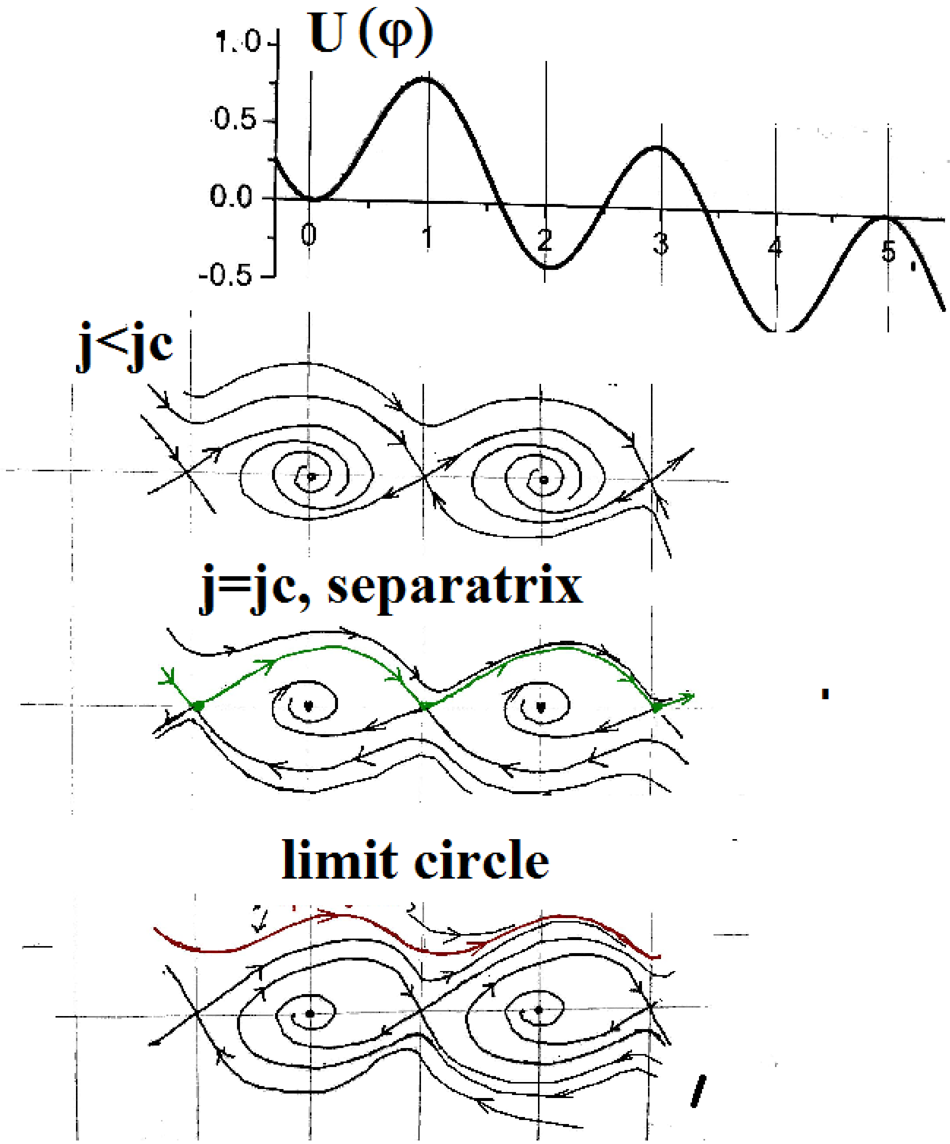
2) **l –rotation is <u>non-uniform in time</u>,** $[\mathbf{l}, \frac{\partial \mathbf{l}}{\partial t}] \sim \frac{d\varphi}{dt} \sin^2\theta$ (+) ISHE signal





GOOD

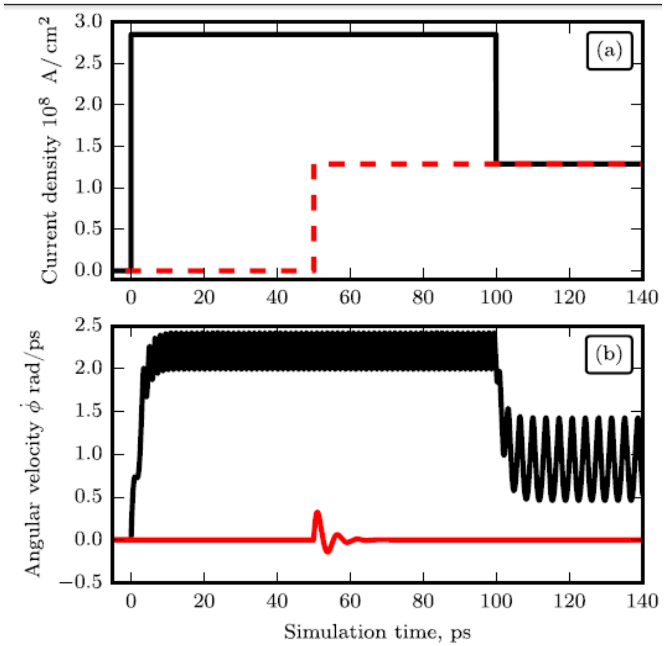
1) frequency up to 2 THz; 2) threshold current lower that for FM-oscillators (already realized) $j_{C,1} > \omega_{a,ip}$, **weak EP anisotropy (-)**



“ignition” threshold
If the oscillations are “ignited”, current can be lowered (the “elimination” threshold) $j_{C,2} > \alpha$

Inertial dynamics for AFM !

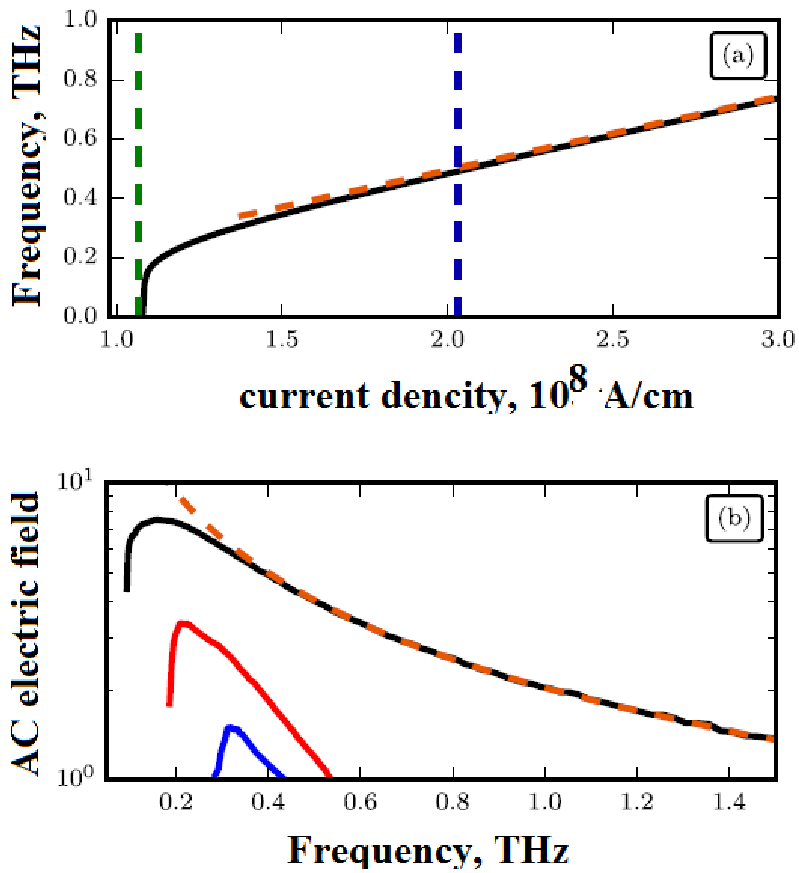
the “elimination” threshold)



First / second thershold : inertial dynamics

(-)FREQUENCY IS NOT LIMITED, BUT THE SIGNAL DECREASE WITH FREQUENCY INCREASE

(-) threshold value of current $j_{ST} > K_{a,ip}$



COULD WE FIND OTHER SOLUTION ? DMI+magnetic dipolar radiation

Cone precession-complicated anisotropy

DMI+magnetic dipolar radiation Hematite , strong DMI

O. R. SULYMENKO *et al.* PHYS. REV. APPLIED **8**, 064007 (2017)

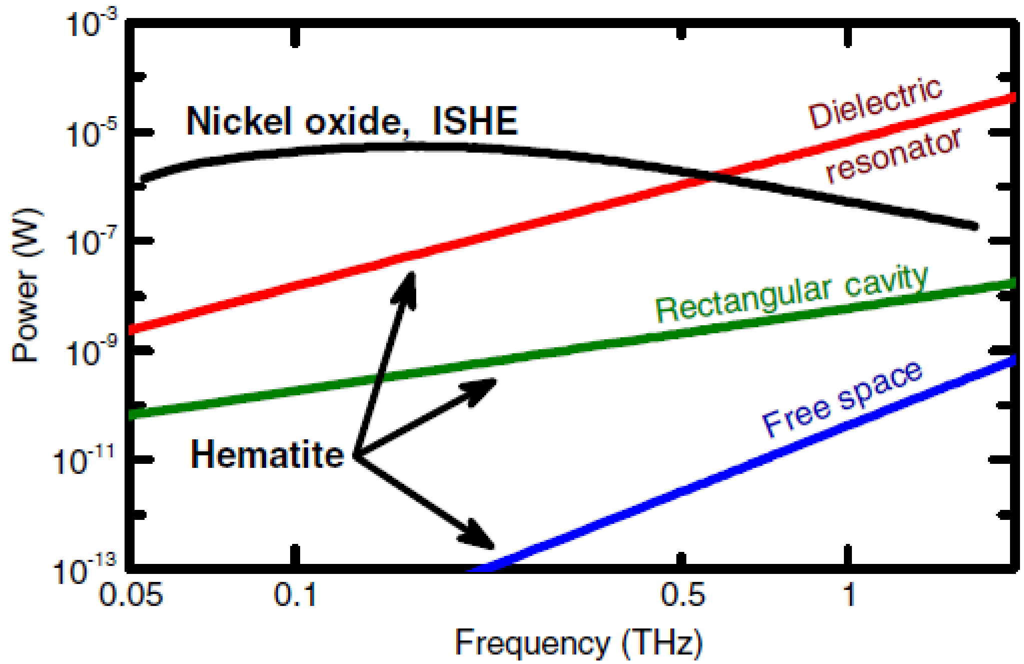


FIG. 3. Generated power vs frequency for a SHO based on a layer (thickness, $d_{AFM} = 5$ nm) of a canted AFM providing dipolar radiation into different types of resonance systems: dielectric resonator (the red line), rectangular cavity (the green line), and free space (the blue line). For comparison, a similar curve is presented for a SHO based on a layer of bianisotropic AFM (NiO)

ONE MORE SOLUTION – SOLITONS… rotation is non-uniform in space

Usual problem – stabilization of solitons   Dynamics – conservation of some quantity

Total z-projection of spin – precessional solitons

(B.Ivanov, A. Kosevich. Bound states of a large number of magnons in a 3D ferromagnet (magnon drops), JETP Lett. (1976))

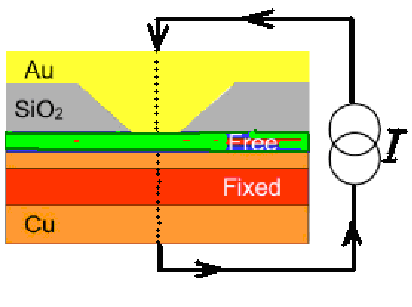
WHY SOLITONS?

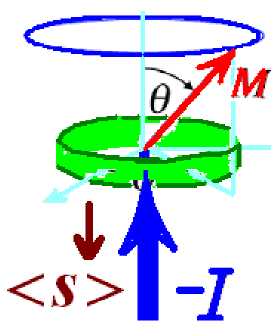
MOTIVATION: DROPLET SOLITON in FM driven by Spin Torque

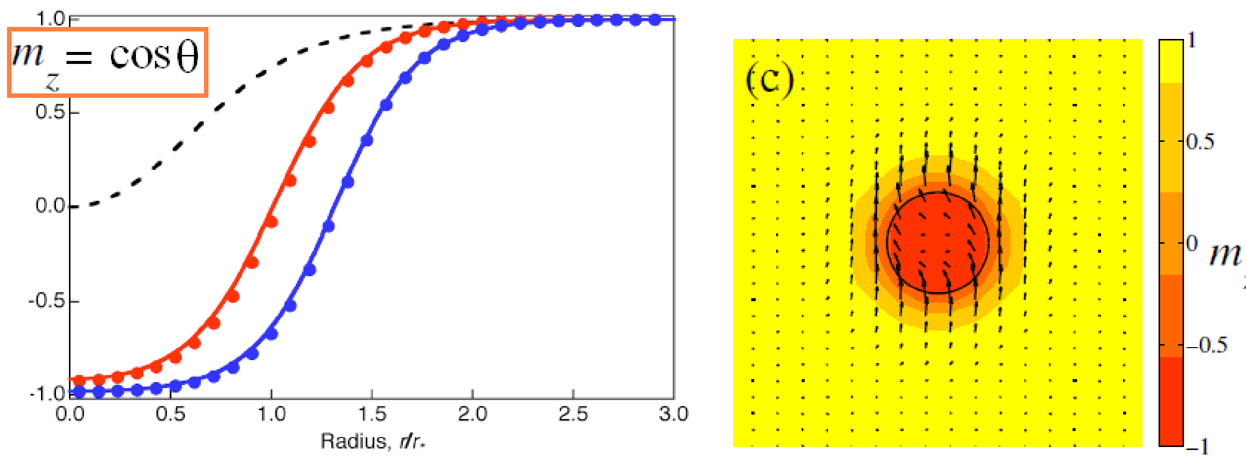
<magnon droplet = precessional soliton in FM>

$\theta = \theta(r)$, $\varphi = \omega t + \ldots$ ω **is precession frequency**

Non-topological droplet was simulated (M. A. Hoefer *et al*, PRB 2010) and observed (Mohseni *et al*, *Science* 2013) ω **till 30 GHz**







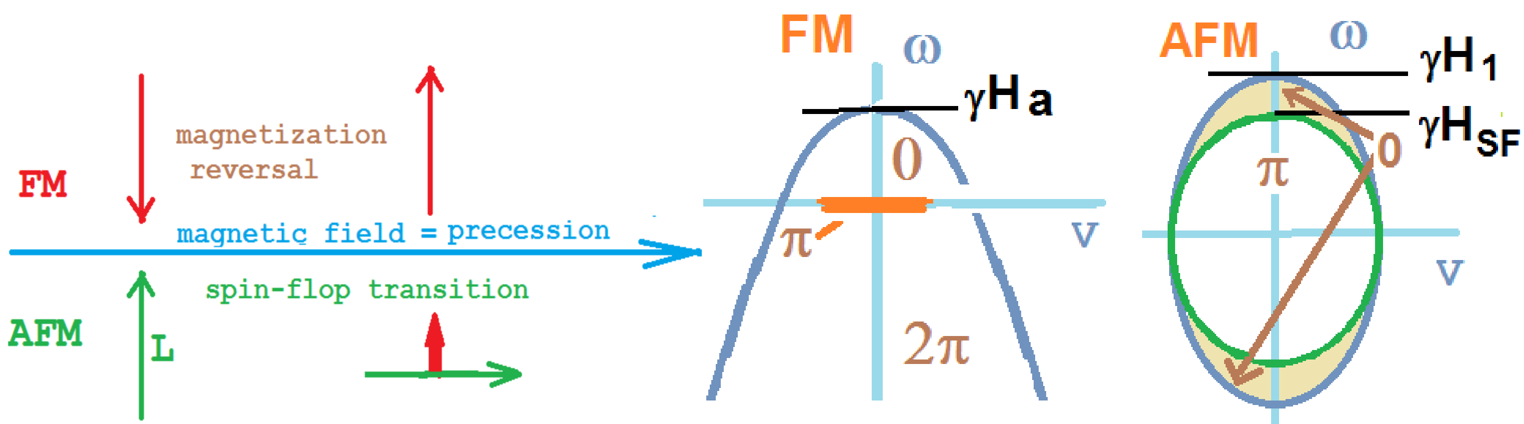
Spatial profile of magnetic droplet solitons.

Dissipative droplet soliton (relaxation, compensated by spin torque)

2D topological soliton (skyrmion) simulated (Y. Zhou *et al*, *Nat. Comm.*, 2015)

1D solitons (NT or 360-degree DW) in nanowires: Iacocca *et al*, PRL 2014

For AFM most of the soliton features are different



1D

$$\text{AFMs}\quad \vec{l} = \vec{e}_z \cos\theta + \sin\theta(\vec{e}_x \cos\varphi + \vec{e}_y \sin\varphi),\ \varphi = \omega t + \ldots$$

$\theta(r)$, **[or** $\theta(\vec{r} - \vec{v}t)$**]** ω **is precession frequency**

Larmor theorem $\omega \sim H/\gamma$ **FM vs. AFM::** Different effects

{remind spin-flop transition !}

For AFM most of the soliton features are different

$\underline{180^0 \text{ DW} \quad \text{static, topological}}\ \underline{\pi_0}$

$$\cos\theta_0 = \sigma \tanh\left(\frac{x - X}{x_0}\right),\ \varphi = \varphi_s \quad \varphi = \omega t + \varphi_s$$

1D AFM soliton $\quad \vec{l} = \vec{e}_{EA} \cos\theta + \sin\theta(\vec{e}_1 \cos\varphi + \vec{e}_2 \sin\varphi),\ \varphi = \omega t$

ANTIFERROMAGNETS

Precessional 1D soliton (180^0 Domain Wall) in AFM: <forbidden for FM !>

AFMs $\quad \vec{l} = \vec{e}_z \cos\theta + \sin\theta(\vec{e}_x \cos\varphi + \vec{e}_y \sin\varphi),\ \varphi = \omega t + \ldots$

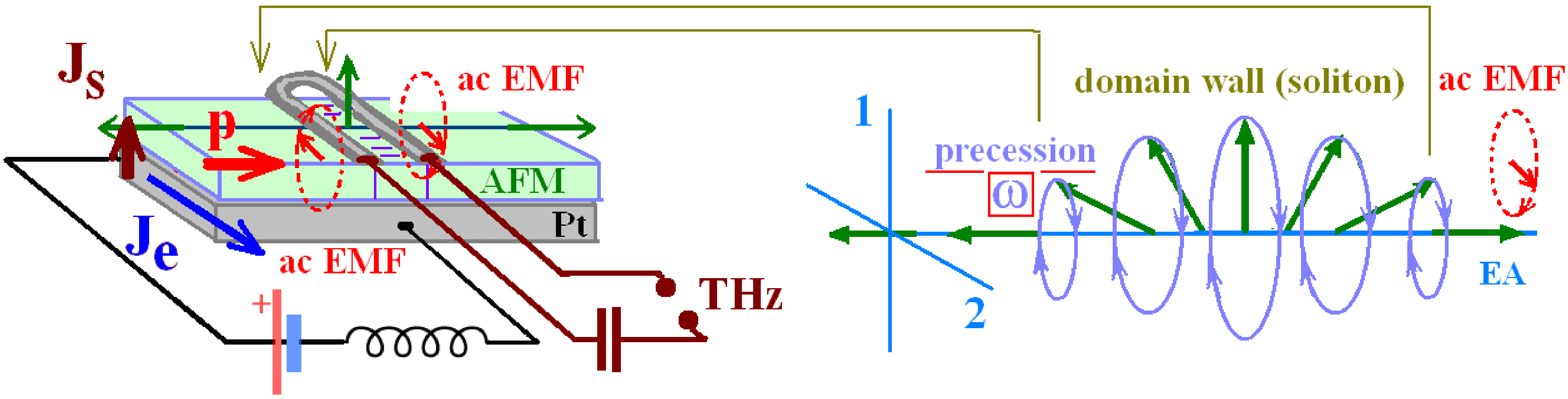
ω is precession frequency

Larmor theorem $\quad \omega \sim H / \gamma \qquad$ **FM vs. AFM::** Different effects

{remind spin-flop transition !}

Electromotive force, where

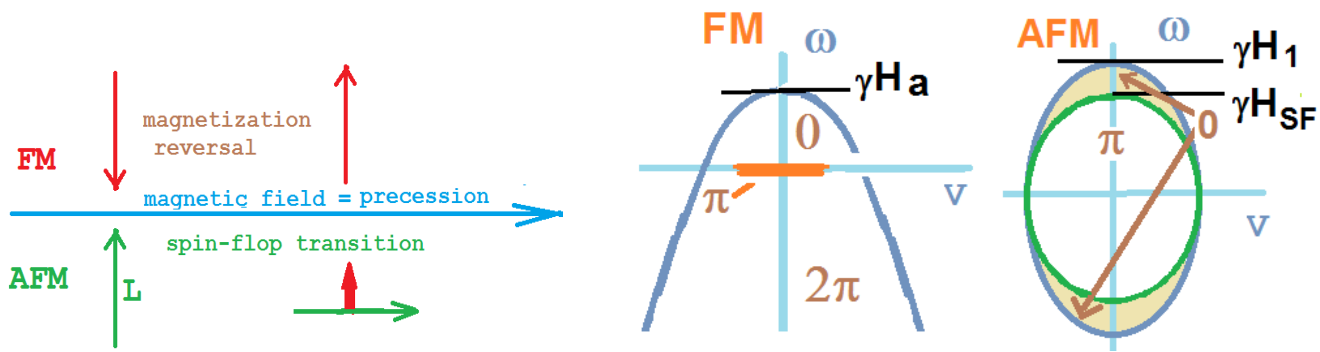
$\theta \neq 0, 90^{\circ}, 180^{\circ}$



180-degree AFM Domain Wall

180 vs 90 degrees in the soliton center $\gamma H_{SF} < \omega < \gamma H_1$ **1D :** "magnetic field is less than for spin-flop" **precessional 180 – degree domain wall**

For AFM most of the soliton features are different



AFM: 2D, 3D non-topological or 2D topological –DWs, Skyrmions

$Q = 0$ $\qquad\qquad\qquad\qquad$ $Q = \pm 1, \pm 2, \dots$

$\varphi = \omega t + Q\chi,\quad r, \chi -$ polar coordinates in the AFMs plane

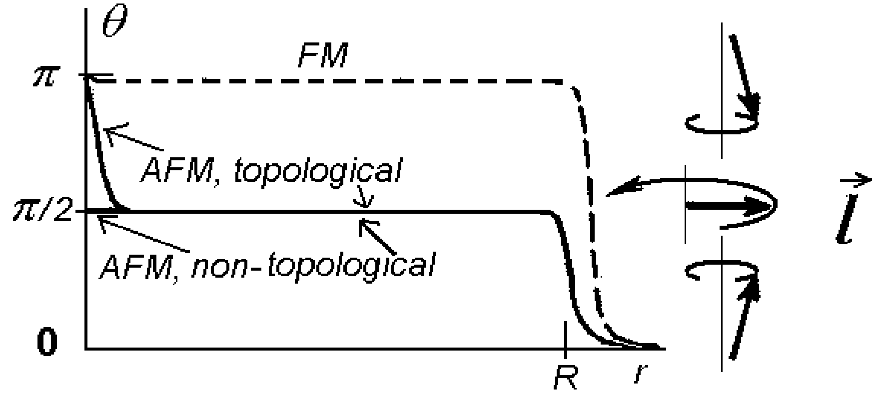
$\theta(r)$, **[or** $\theta(\vec{r} - \vec{v}t)$**]** ω **is precession frequency**

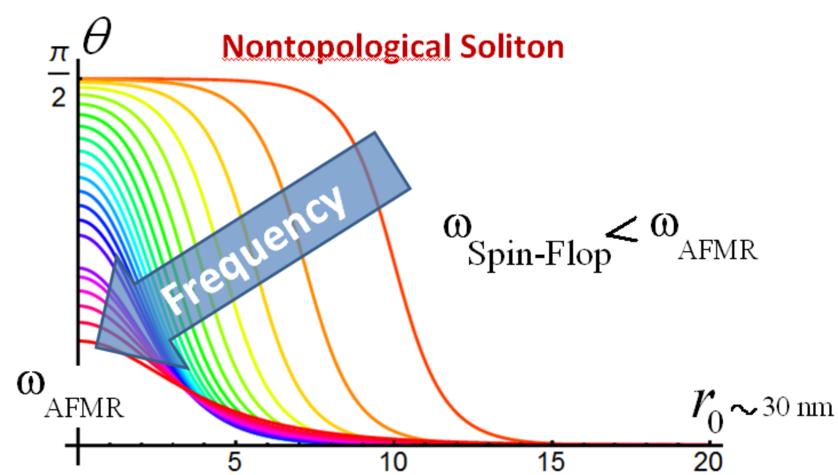
2D, 3D: precessional 90 – degree soliton $\quad \omega \sim \gamma H_{SF} \sim \mathrm{THz}$

$$A\nabla^2\theta - \sin\theta\cos\theta[K + A(\nabla\varphi)^2 - \omega^2/\gamma H_{ex}] + K'\sin^3\theta\cos\theta = 0$$

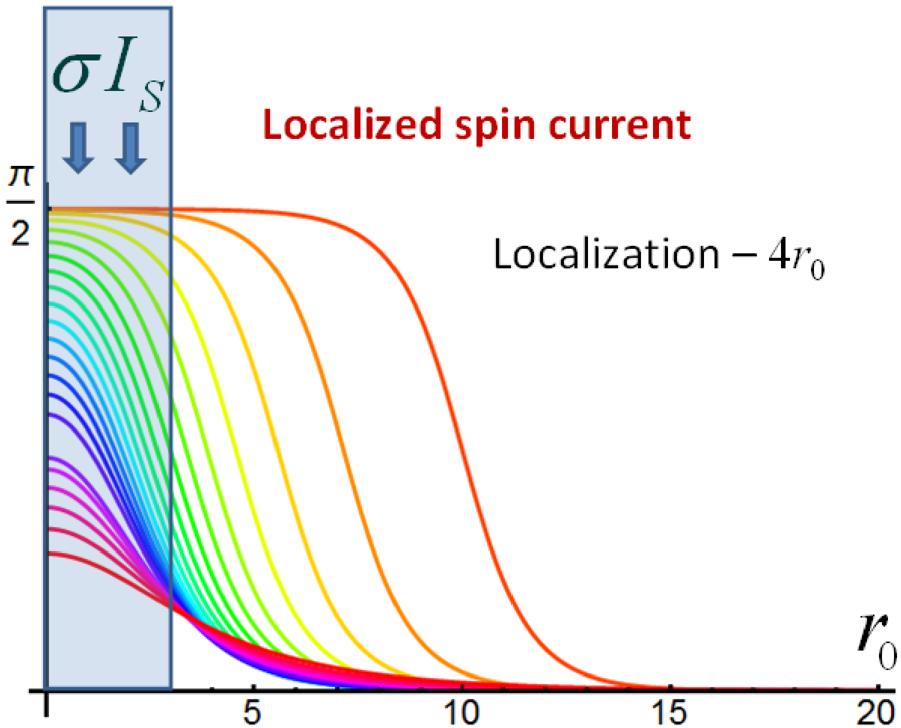
$\{-\omega\sin\theta$, **for FM; gives**$\}$

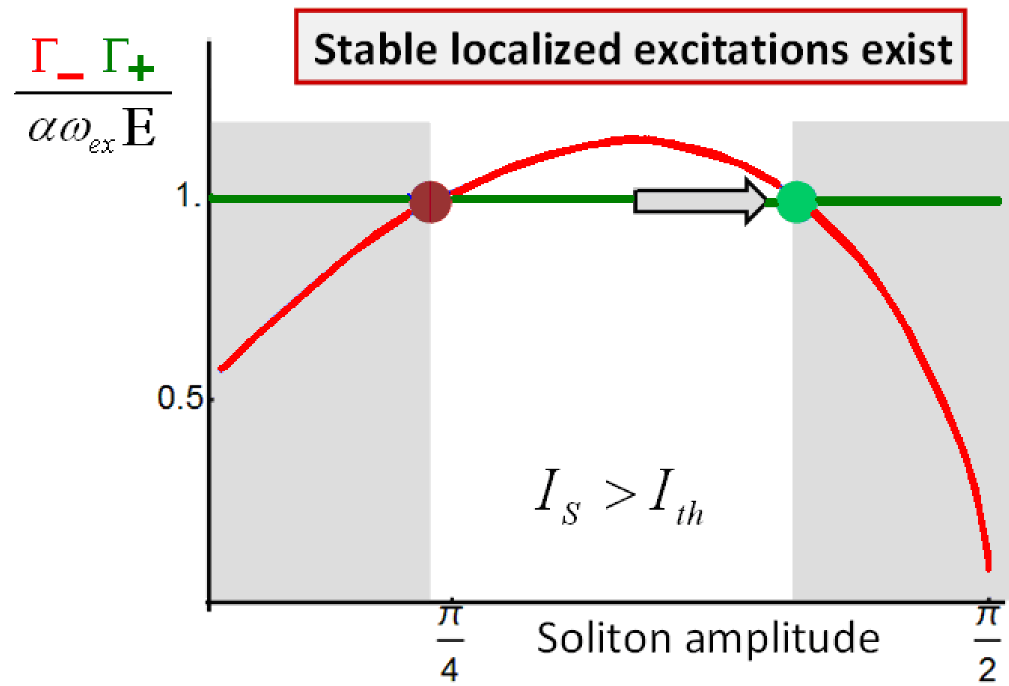
The polar angle $\theta(r)$ and schematics of the dynamics (precession) of the vector $\vec{l}$ for large-radii AFM solition; dashed line – the same for ferromagnetic soliton.





Non-localized spin torque – soliton is unstable, trivial uniform precession (no ISHE signal)





NANOCONTACT WITH SPIN CURRENT: STABLE 2D SOLITONS

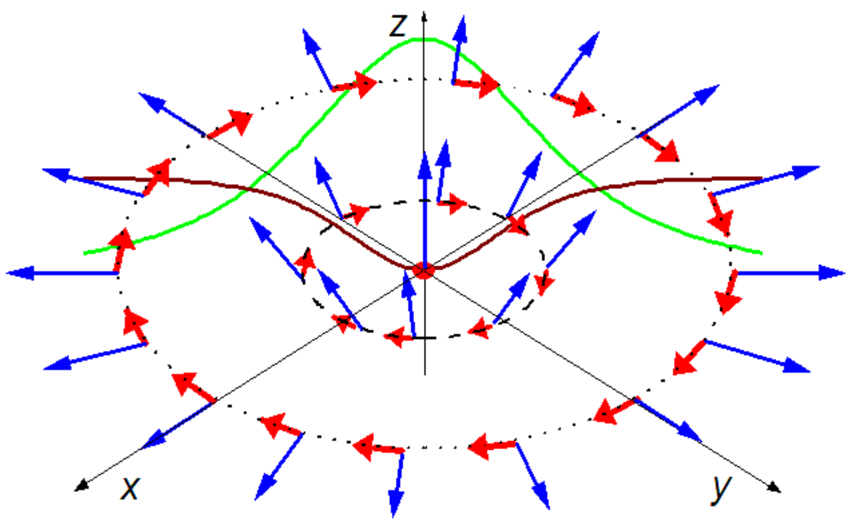
$\theta = \theta(r) \neq \pi / 2$ **cone precession, ISHE signal**

pure uniaxial model

AFM vortices : how to create?

<FM circular dots – ground state, an alternative for domain structure>

Vortices for axisymmetric body made with canted Easy Plane AFM :
the same distribution of $\vec{l}$ as for FM, but complete absence of magnetostatic field (even in the vortex core).



The thin blue arrows show $\vec{l}$, thick red arrows present $\vec{M}$.

$$\vec{M} = (H_{\mathrm{D}} / H_{\mathrm{ex}})(\vec{e}_z \times \vec{l}) \quad \mathrm{div}\vec{M} = 0, M_z = 0$$

Vortex core size: as for FMs, a few nm
Critical radius : not too large,
<400 nm for Iron Borate, 800 nm for hematite>

[E. Galkina, et. al., PRB 2010]

Truly local mode for AFM vortex: ~ 1 THz localized in 20 nm core
<first: Ivanov, Kolezhuk, Wysin, PRL 96>

LI dynamics for zero magnetic field -- no gyroforce

Break of Lorentz-invariance – magnetic field

Lagrangian (per one spin)

$$L = \frac{\hbar}{\gamma H_{ex}}[\frac{1}{2}(\frac{\partial \mathbf{l}}{\partial t})^2 - \frac{1}{2c^2}(\nabla \mathbf{l})^2] - \frac{\hbar}{H_{ex}} \mathbf{H}_{\text{tot}} \cdot (\mathbf{l} \times \frac{\partial \mathbf{l}}{\partial t}) - \widetilde{W}(\mathbf{l}) \quad \widetilde{W}(\mathbf{l})$$

Different effects for **DMI** and external field $\mathbf{H_0}$ ::

1) the simplest version of Dzyaloshinskii field $\vec{\mathbf{H}}_D = [\vec{\mathbf{d}} \times \vec{\mathbf{l}}]$ **produce total time derivative. More general form** $W_D = D_{ij}(\vec{l}\,) m_i l_j$**?**

(MnF_2 : $W_D = d(m_x l_y + m_y l_x)$**, OF** $W_D = d_1 m_x l_z - d_3 m_z l_x,\ d_1 \neq d_3$**, ect.)**

2) External field

Both can break LI, but breaks the LI, but by non-topological term (no “Dirac strings”, as for FM) and non-universal behavior

$$\text{FM}: "T"_{FM} = s\hbar(1-\cos\theta)\frac{\partial\varphi}{\partial t} \to s\hbar\vec{A}\frac{\partial\vec{m}}{\partial t}, \quad \mathrm{rot}_{\vec{m}}\vec{A} = \vec{B} \propto \vec{m},$$

$\vec{B}$ **is the field of the Dirac monopole:** $\int_{\vec{m}^2=1} \vec{B}d\vec{\sigma} = 4\pi$

$\int \vec{B}d\vec{\sigma} = \int \sin\theta d\theta d\varphi$ **The flux of the field** $\vec{B}$

For DW in FM: E(P+P$_0$)= E(P); gyroforce for 2d solitons, both P$_0$ and G are determined by integrals of the form of $\int \vec{B}d\vec{\sigma}$

$$\text{AFM}: \vec{H}_{\text{tot}} \cdot [\vec{l} \times \frac{\partial\vec{l}}{\partial t}] \to \vec{A}_{\text{AFM}}\frac{\partial\vec{l}}{\partial t}, \text{ but } \int \vec{B}_{\text{AFM}} d\vec{\sigma} = 0 \textbf{ for ALL AFM}$$

BI, Kireev, JETP 2002]

$$\vec{B}_{\text{AFM}} = \vec{l} \cdot B(\theta,\varphi), \; B(\theta,\varphi) = 2(\mathbf{H}^{(\text{eff})}\mathbf{l}) - \frac{\partial H_i^{(\text{eff})}}{\partial l_i} + \frac{\partial H_i^{(\text{eff})}}{\partial l_k} l_i l_k \,.$$

Non-trivial (non LI) dynamics for some AFM with $D_{ij}(\vec{l}) \neq \varepsilon_{ijk} d_k$

[Gomonay, BI et.al, JETP 1990, review article BI and Kolezhuk Sow. J. LTP 1995]

general: anisotropy in the basal plane and gyroscopic terms due to DMI

Hematite, orthoferrites, ect. $w_D \sim \vec{\mathbf{m}} \cdot [\vec{\mathbf{l}} \times \vec{\mathbf{d}}]$ **Full time derivative**

MnF$_2$ anisotropic $4_z^{(-)}; w_D \sim (m_x l_y + m_y l_x)$ **gives** ΔL_G

$$w(\mathbf{l}) = \frac{K_u}{2}\sin^2\theta + \frac{K_{ip}}{4}\sin^4\theta\sin^2 2\varphi \quad \text{and} \quad \Delta L_G = \frac{\gamma H_D}{\omega_0{}^2}\frac{\partial\theta}{\partial t}\sin^3\theta\cos 2\varphi$$

both are small, but produce principal effects

without this terms,

$$\cos\theta_0 = \sigma\tanh\left(\frac{x-X}{x_0}\right),\ \varphi = \varphi_s \quad \varphi = \omega t + \varphi_s,$$

PERTURBATION THEORY

$$\theta = \theta_0(x) + \vartheta(x)\sin 4\omega t,\ \varphi = \varphi_0 + \omega t + \mu(x)\sin 4\omega t, \ \text{--}$$

SIZE OSCILLATIONS AND radiation of magnons

CORRECTIONS ARE NON-SMALL EFFECTIVE COORDINATES

$x \Rightarrow x - X$, $\varphi_s \Rightarrow \Phi$ collective coordinates X(t) and $\Phi(t)$

$$L_{\mathrm{eff}} = \frac{E_0}{2c^2}\left(\frac{dX}{dt}\right)^2 + \frac{E_0}{2\omega_0^{\,2}}\left(\frac{d\Phi}{dt}\right)^2 - V_0 \sin^2\left(\frac{n}{2}\Phi\right) + \sigma G_0 \frac{dX}{dt}\cos(\tilde{n}\Phi)$$

effective Lagrange function for a dynamic system with two degrees of freedom

Two integrals of motion (uniform in space AFM)

$$P_X = m_*(dX/dt) + P_0 \cdot \cos(2\Phi),\ P_0 = (\sigma E_0 / c x_0)(H_D / H_{ex}),\ m_* = E_0 / c^2.$$

This term changes the definition of the canonical momentum

case of manganese fluoride

$$E = \frac{1}{2} I_* \left(\frac{d\Phi}{dt}\right)^2 + V_{\mathrm{eff}}(\Phi),\ V_{\mathrm{eff}}(\Phi) = V_0 \sin^2(2\Phi) + \frac{[P - \sigma G_0 \cos(2\Phi)]^2}{2m_*}. \qquad (27)$$

Spin torque: support precession, but gives relaxation of P

$m_*(dX/dt) + P_0 \cdot \cos(2\Phi) = 0$ precession plus oscillations of the DW position

dynamics of a mathematical pendulum.

In view of this, the free motion is coupled precession of the vector l at the center of the soliton and oscillation of the soliton center.

<E.G. Galikna, R. V. Ovcharov, B. A. Ivanov, Low Temp Phys., 43, 1283 (2017) >

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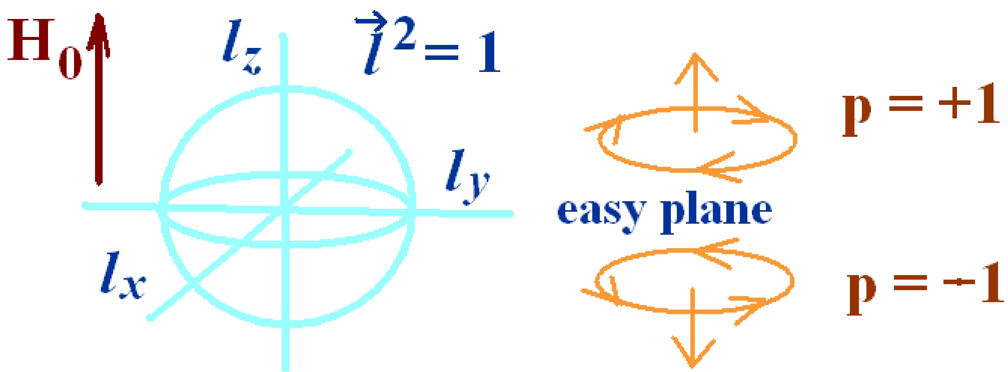
AFM vortices: EQUATION OF MOTION

$$\frac{E_0}{c^2}\left(\frac{d^2\mathbf{X}}{dt^2}\right)+G\left[\hat{\mathbf{z}}\times\frac{d\mathbf{X}}{dt}\right]+\frac{\partial U(\mathbf{X})}{d\mathbf{X}}=0$$

Expernal field $B(\theta,\varphi)=2(\vec{H}_0\cdot\vec{l}\,)/H_{\mathrm{ex}}$

$$G\sim\int\vec{B}d\vec{\sigma}=\frac{H_0}{H_{\mathrm{ex}}}\int\cos\theta\sin\theta d\theta d\varphi$$ **giroforce**



Gyroforce for AFM vortices: [Ivanov, Sheka, PRL, 1994] LI dynamics at H=0, the gyroforce is induced by the magnetic field; independent on the vortex core polarization, but NO gyroforce for 2d skyrmions

[Velkov, Gomonay et.al, New J. Phys. 2016**]**

Спасибо за внимание !

Thank you for your attention !