

# **Spin currents through antiferromagnets**

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Technology**



**Universiteit Utrecht**



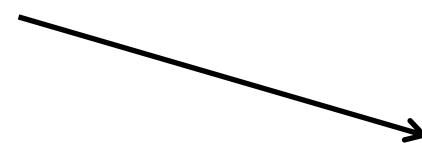
Technische Universiteit  
**Eindhoven**  
University of Technology

# Collaborators

## Utrecht:

Benedetta Flebus, Scott Bender

See Scott's poster  
*for more*



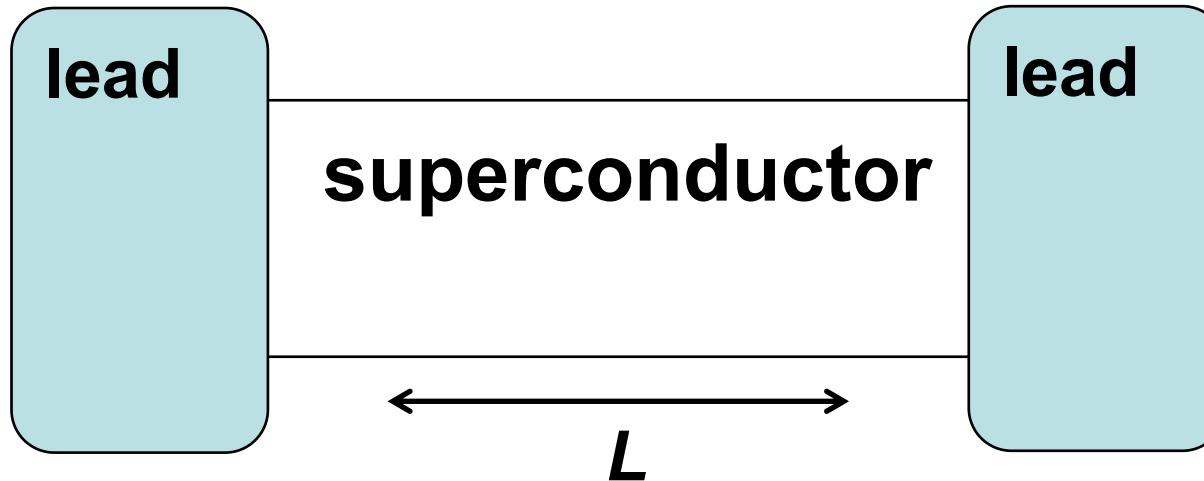
## Other:

Alvaro Nunez, Alejandro Roldan (Santiago)  
Yaroslav Tserkovnyak (UCLA)  
Arne Brataas (NTNU)



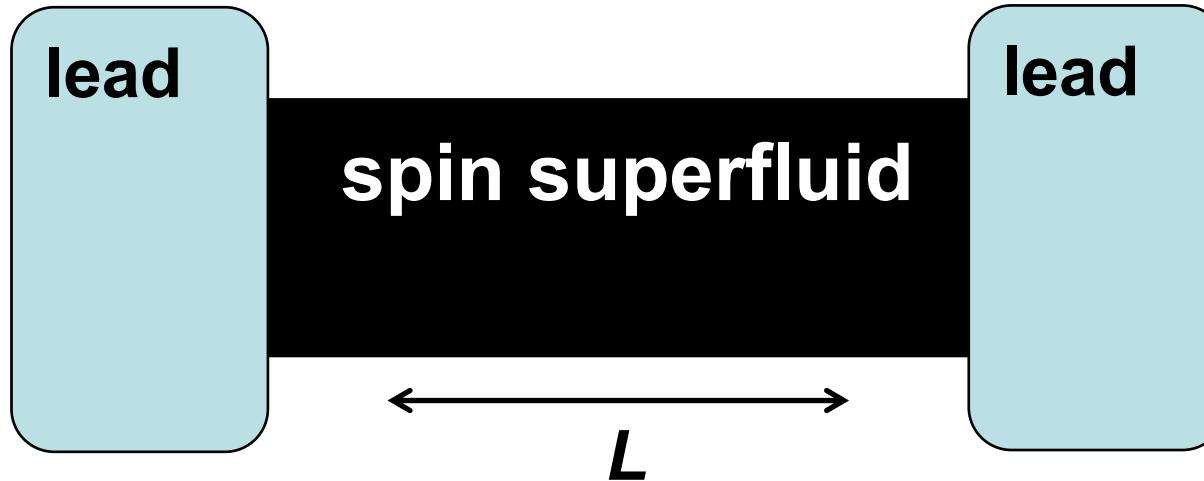
European Research Council

# Long-term motivation



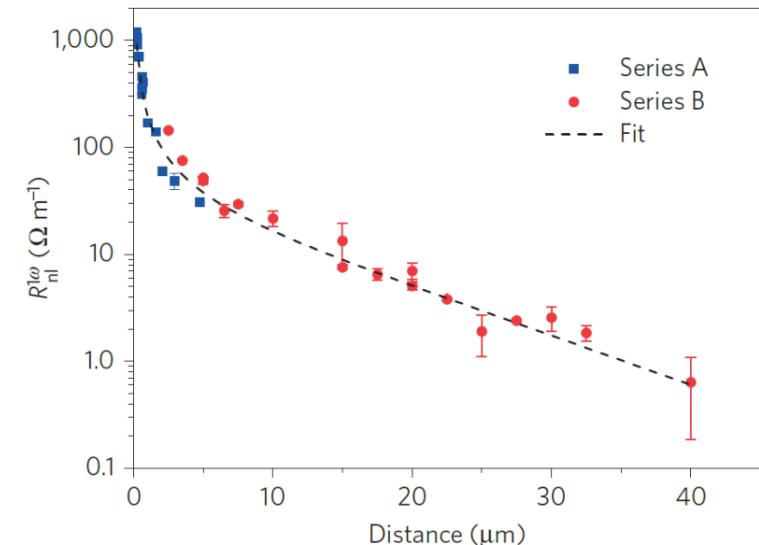
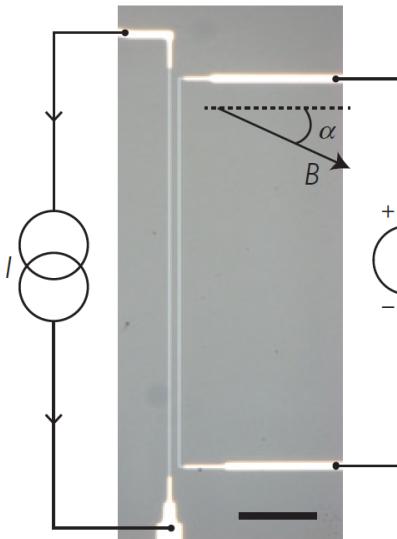
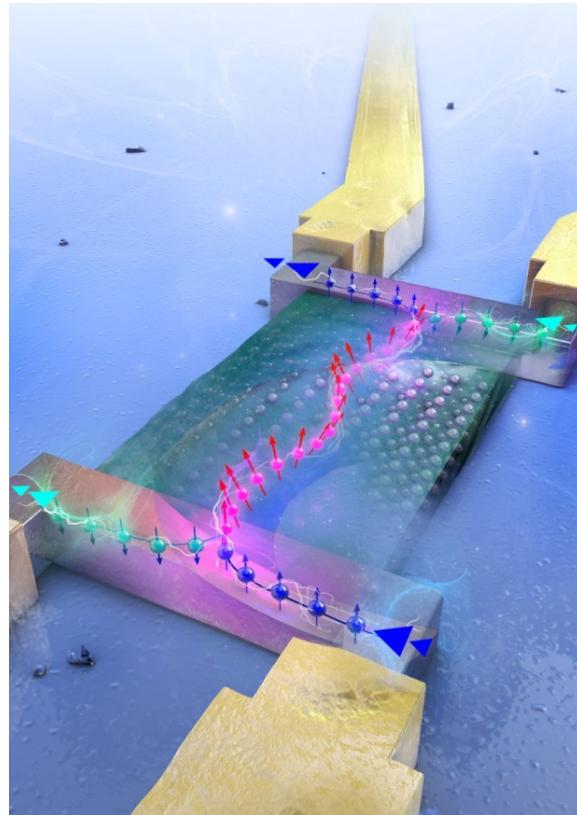
$I=V/R$  with  
 $R$  independent of  $L$

below room  $T$



above room  $T$ ?

# Motivation



- Pt strips on magnetic insulator Yttrium-Iron-Garnett (YIG)
- Non-local (“drag”) resistance  $R_D = V/I$
- Room  $T$
- Long distance: exponential decay (length scale 10  $\mu\text{m}$ )
- See also Goennenwein et al. (2015), Jing Shi et al. (2016)
- Related talks: Baltz, Hoffmann, Goennenwein, Klaui, ...

# Outline

- **Stochastic Landau-Lifshitz-Gilbert theory for spin currents through antiferromagnetic insulators**
- **Application to non-local drag and spin Seebeck effect**
- **Second part: spintronic black-hole physics**

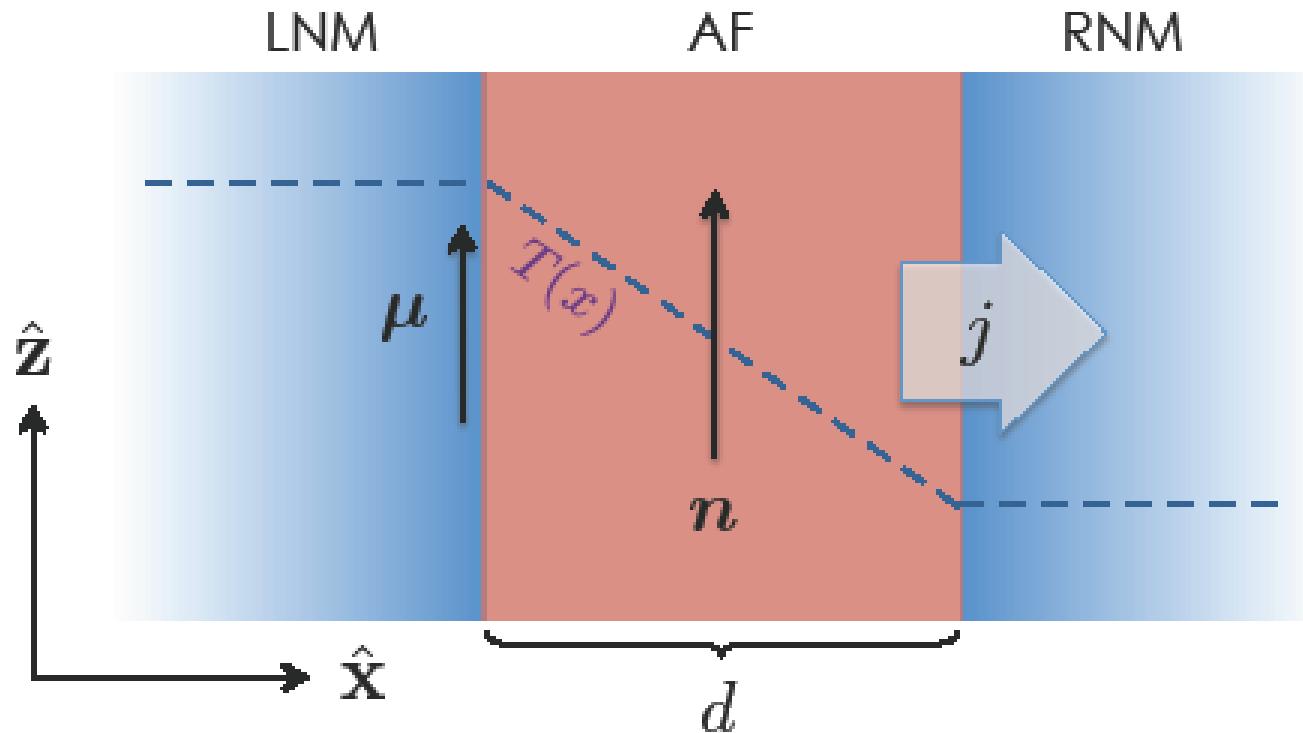
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# Other theoretical work

- Brataas, et al: *Heat transport between antiferromagnetic insulators and normal metals*, Phys. Rev. B 92, 180414 (2015)
- Takei, et al., Phys. Rev. B 90, 094408 (2014);  
Khymyn, et al., Phys. Rev. B 93, 224421 (2016);  
Rezende et al., Phys. Rev. B 93, 014425 (2016);  
Nowak, et al.; ...
- This work: field dependence below spin-flop transition, sublattice-dependent interface coupling

# Set-up



$$E : \int dx \left( \frac{1}{2} am^2 + \frac{A}{2} (\nabla n)^2 - \frac{K}{2} n_z^2 - H m_z \right)$$

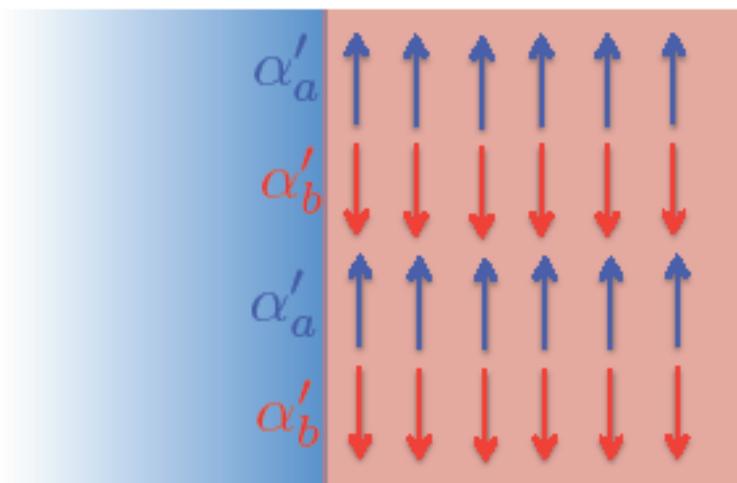
exchange                    anisotropy                    field

# Approach

- Consider fields below spin-flop transition
- Stochastic Landau-Lifschitz-Gilbert equations with coloured noise for Néel and magnetization vectors
- Coupling with electrons at interface: extra Gilbert damping contributions + reciprocal spin transfer torques [Cheng, et al. (2014); Takei, et al. (2014)]
- Applicable when Gilbert damping only relaxation mechanism (clean systems at low  $T$ ).

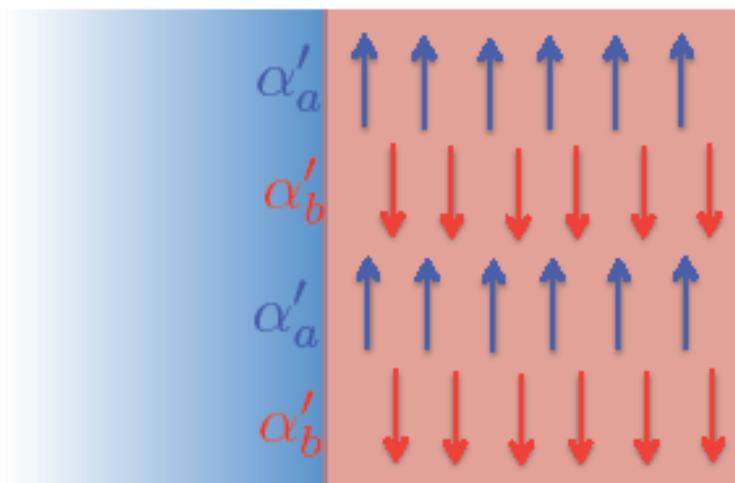
# Sublattice-dependent coupling with electrons at interfaces

$$\alpha'_a = \alpha'_b$$



NM

$$\alpha'_a \neq \alpha'_b$$

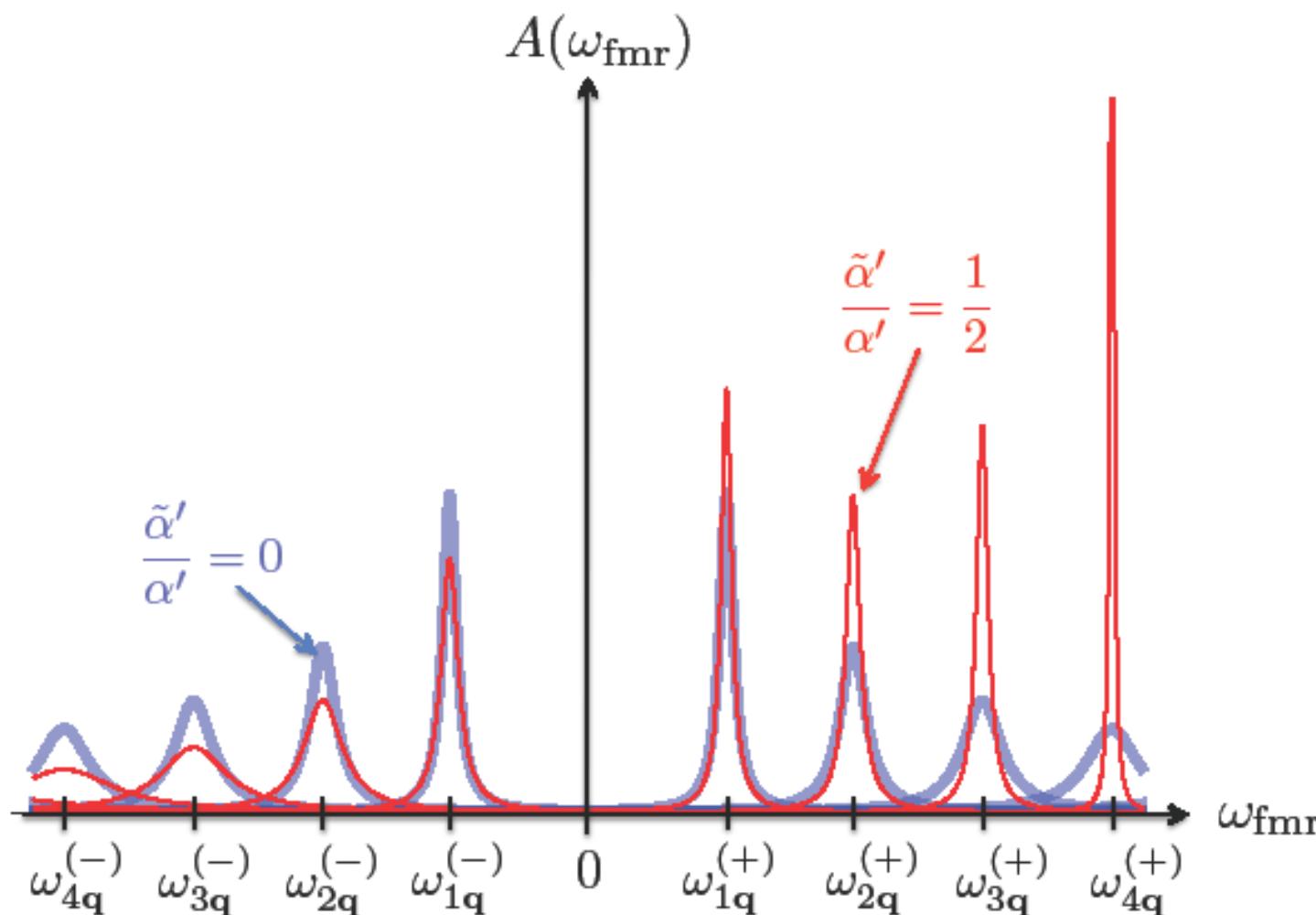


AFM

## For example:

$$\left. \frac{dn}{dt} \right|_{\text{interface}} = \left[ -\left( \frac{\dot{\alpha}_a + \dot{\alpha}_b}{2} \right) \frac{dm}{dt} - \left( \frac{\dot{\alpha}_a - \dot{\alpha}_b}{2} \right) \frac{dn}{dt} \right] \times \frac{r}{n}$$

# AFMR absorption



**Dependent on sublattice-dependence  
of coupling with electrons @ interface**

# Outline

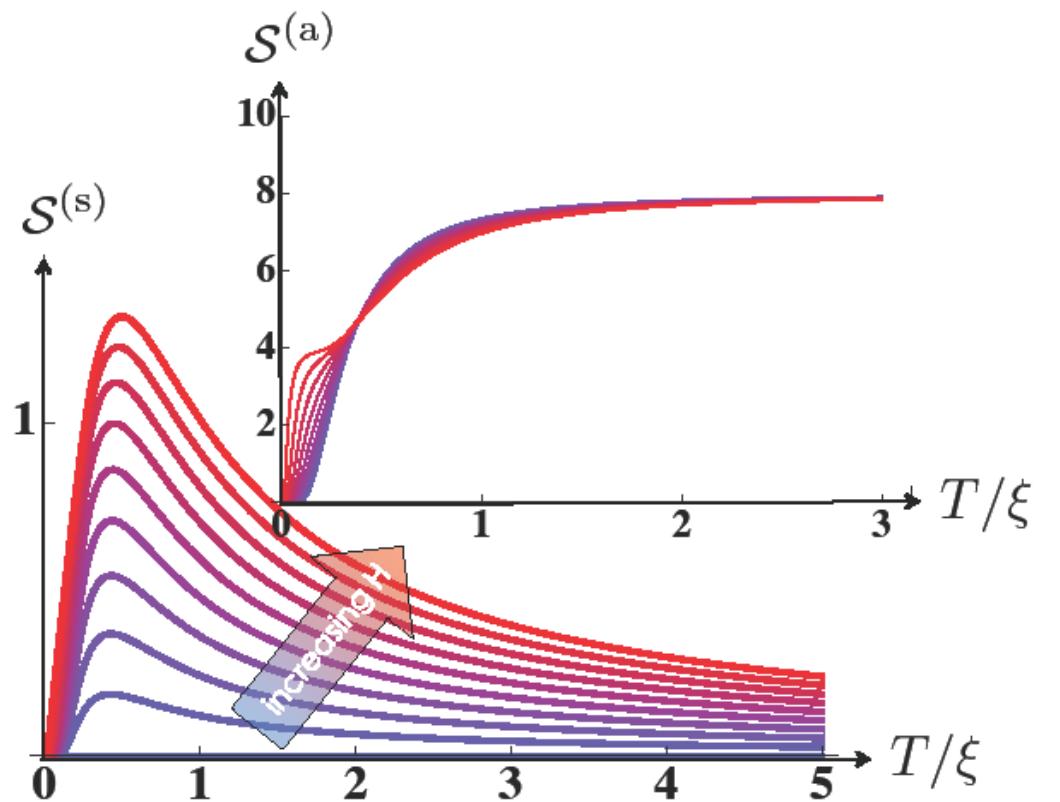
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# Spin Seebeck effect

- **Definition:**  $j = S\Delta T$

- **Symmetric and anti-symmetric contribution:**

$$\frac{S^{(a)}}{S^{(s)}} : (\alpha_a - \alpha_b) \frac{k_B T}{a}$$



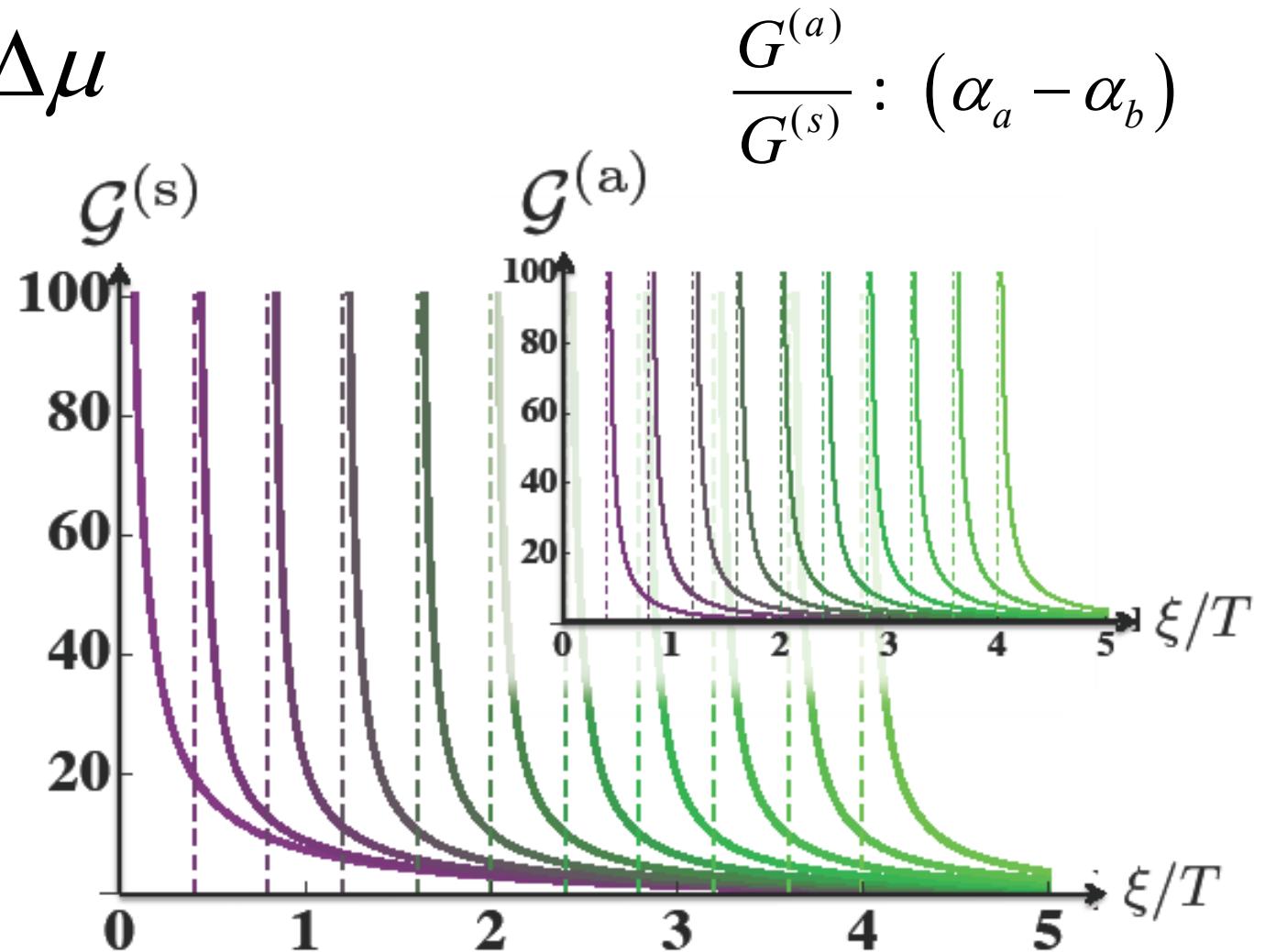
# Spin conductance

- **Definition:**  $j = G \Delta \mu$

- **Diverges at spin-flop transition (spin superfluidity)**

- **Increases with  $T$**

- **Length scale:**  $\Lambda/\alpha^{1/2}$



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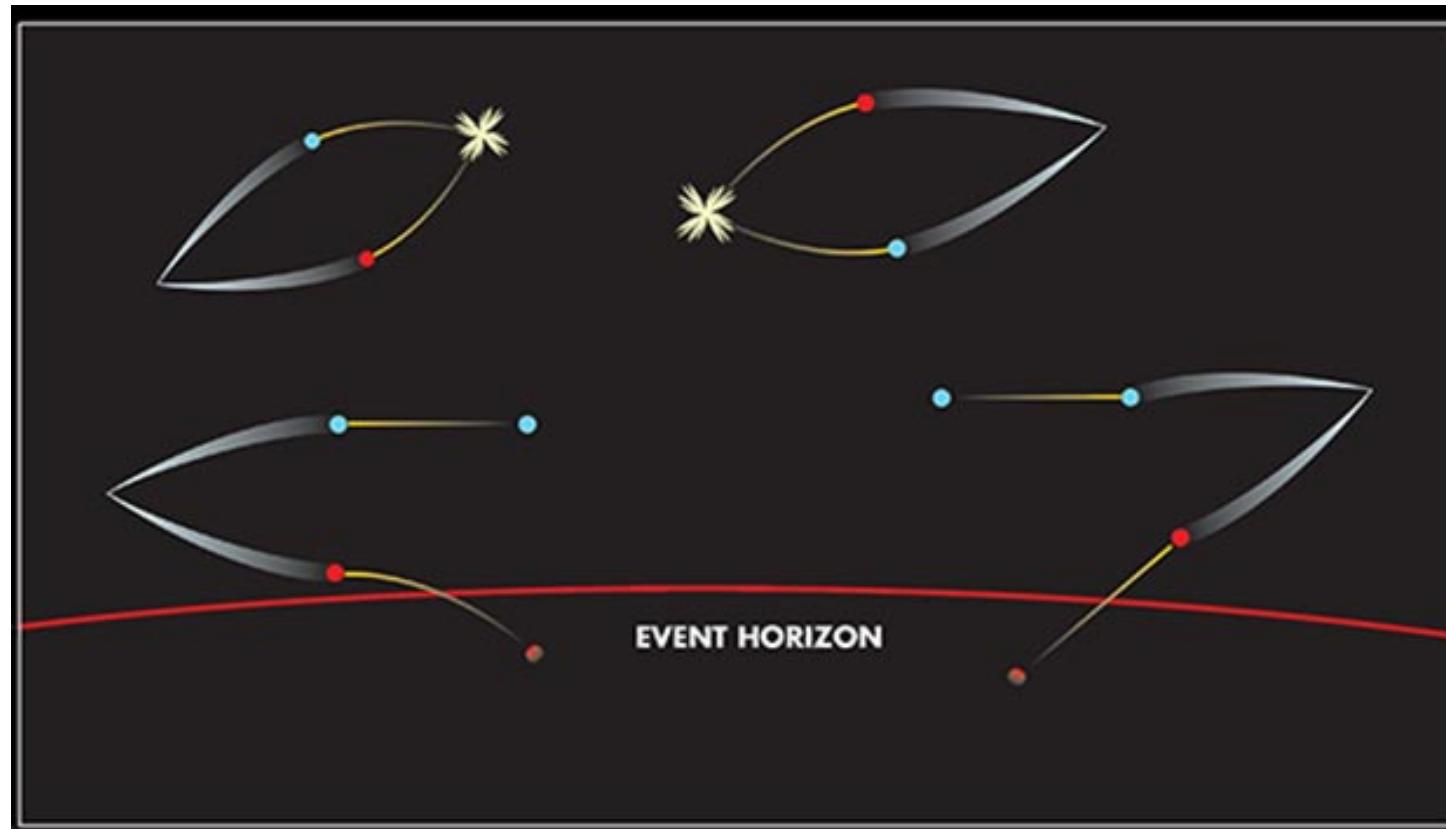
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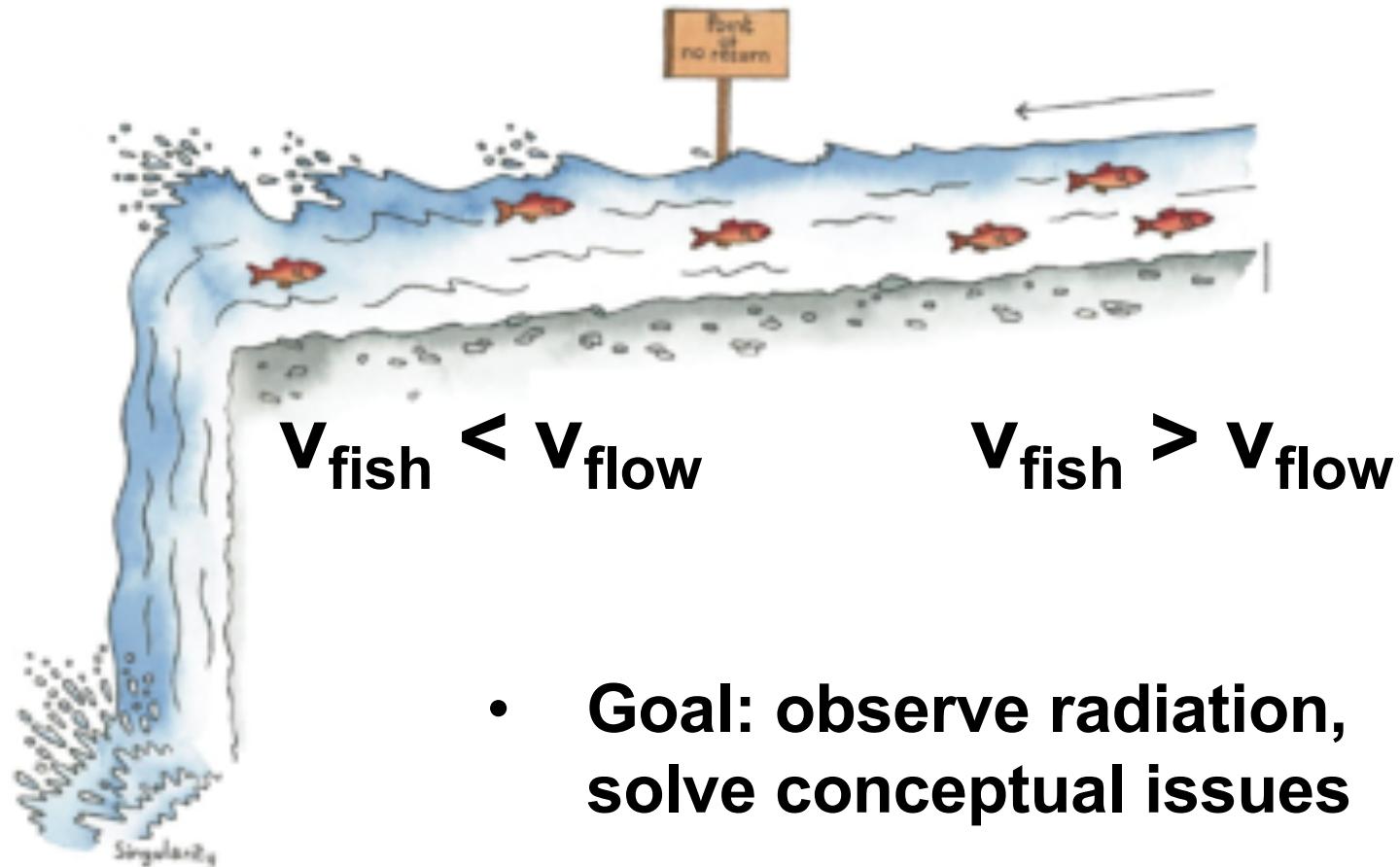
- Stochastic Landau-Lifshitz-Gilbert theory for spin currents through antiferromagnetic insulators
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- **Second part: spintronic black-hole physics  
“general-relativistic spintronics”**

# Hawking radiation



Quantum mechanics + general relativity:  
black-hole thermodynamics, information paradox, ...

# Black-hole-horizon analogues



- **Goal: observe radiation, solve conceptual issues**
- **Systems: water, atomic BEC's and other condensates, slow light, ...**

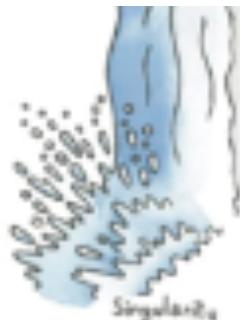
# Black-hole-horizon analogues



## Experimental Black-Hole Evaporation?

W. G. Unruh

*Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada*  
(Received 8 December 1980)



$R$  is the horizon radius, we obtain a temperature of

$$T = (3 \times 10^{-7} \text{ K})[c/(300 \text{ m/sec})](1 \text{ mm}/R).$$

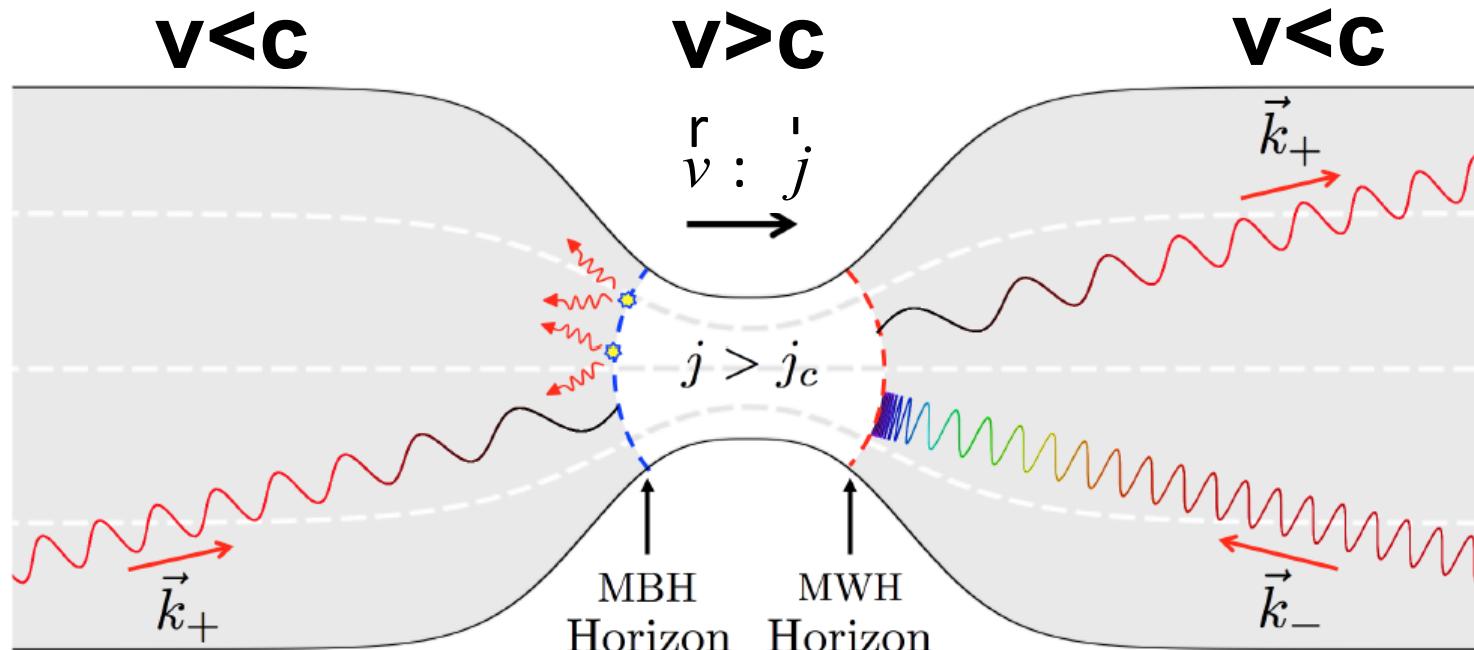
This is a rather low temperature, and is probably undetectable in the presence of turbulent instabilities, etc., which would arise in trying to drive the fluid transsonically through a small nozzle. It is, however, a much simpler experimental task than creating a  $10^{-8}$ -cm black hole.

# Our proposal (I)

- Metallic antiferromagnets (or metallic easy-plane ferromagnets)
- Spin-transfer torques give flow velocity  $v_s \sim$  current density \*)
- Increasing current density (can) create horizon if  $v_s >$  spin-wave velocity

\*): Nunez et al. (2005), Swaving et al. (2011), Hals et al (2011)., Yamane, et al. (2016)

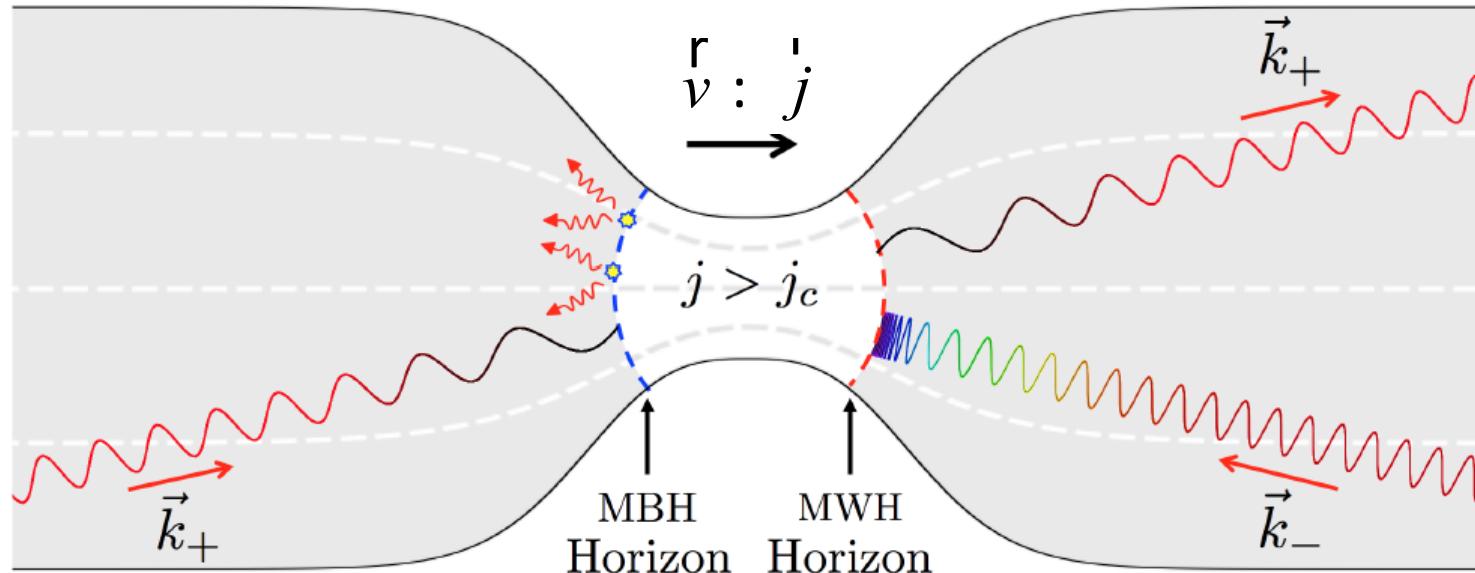
# Our proposal (II)



**Linearized dynamics:**

$$\frac{1}{c^2} \left( \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right)^2 \delta n^r = \nabla^2 \delta n^r$$

# Our proposal (III)



- **Black-hole horizon will radiate magnons with Hawking temperature [Hawking, 1974]:**
- $$T_H : \frac{h}{2\pi} \frac{\partial(v - c)}{\partial n} \Big|_{\text{horizon}}$$
- **Estimates:**  $c \sim \text{km/s}$ ,  $j_c \sim 10^{12} \text{ Am}^{-2}$ ,  $T_H \sim 1 \text{ K}$

# Possibilities for experimental detection (I)

- Classical signature in spin-wave transmission :

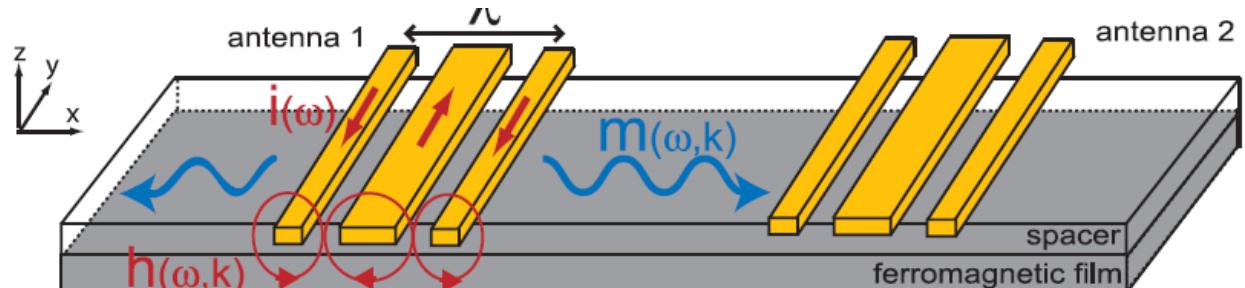
$$t(\omega) : e^{-\hbar\omega/k_B T_H}$$

- Cf. measurement of spin-wave Doppler shift in ferromagnets:

## Current-Induced Spin-Wave Doppler Shift

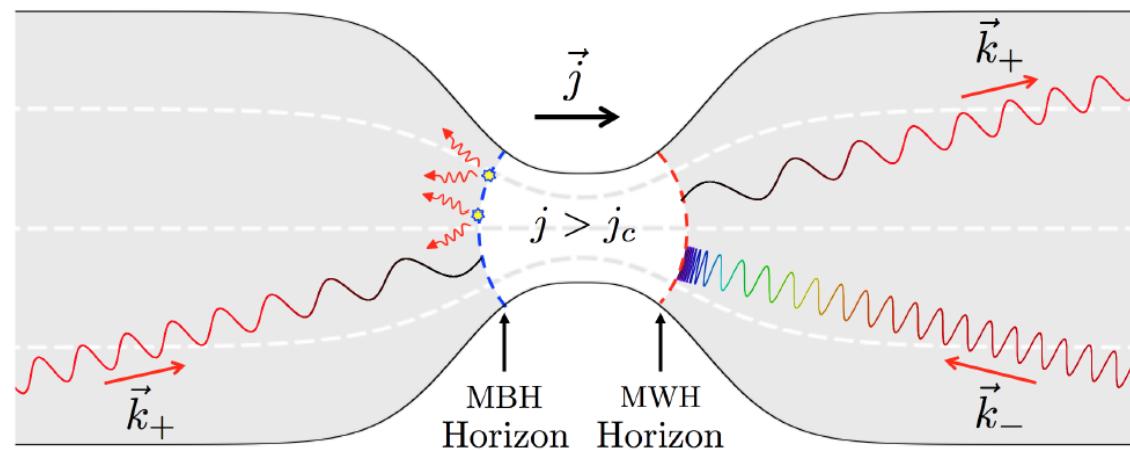
Vincent Vlaminck and Matthieu Bailleul

Science (2008)



# Possibilities for experimental detection (II)

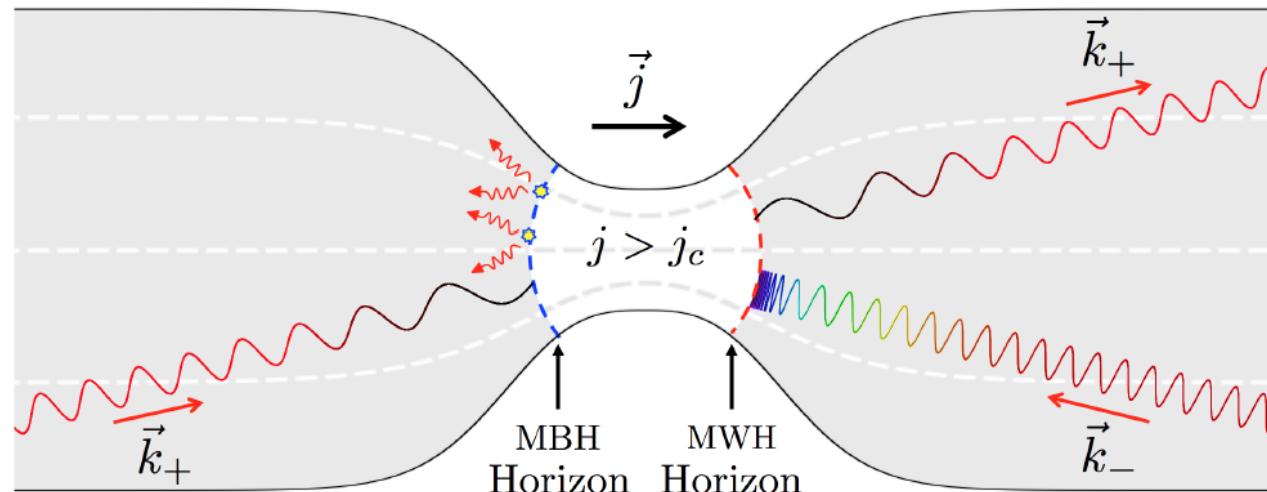
- Transport signature:  $G : \int d\omega \left( -\frac{\partial n_B}{\partial \omega} \right) t(\omega)$
- For all transport quantities:  $\frac{1}{T} \rightarrow \frac{1}{T} + \frac{1}{T_H}$



- E.g.: magnon-drag Peltier effect

# Further remarks

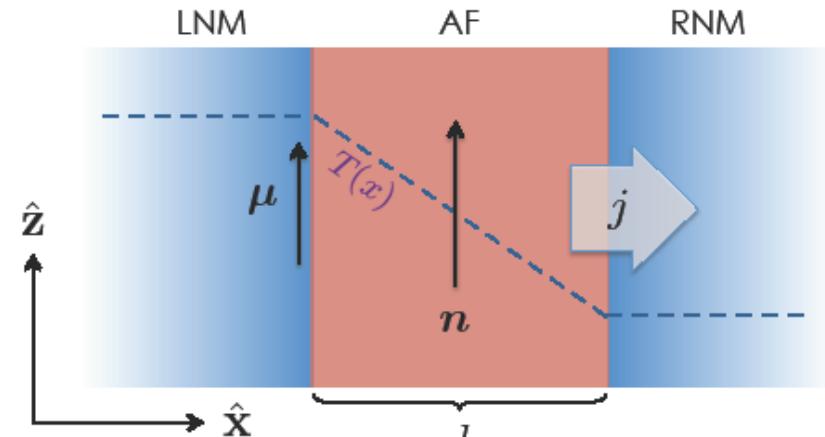
- Relatively large Hawking temperature
- Experimental signatures
- Anisotropy, fields and damping
- Instabilities & non-linearities (domain walls)
- Long term: resource for entanglement



$$|\Psi\rangle = N \times [ -v | -k \rangle + u | +k \rangle ]$$

# Take home messages:

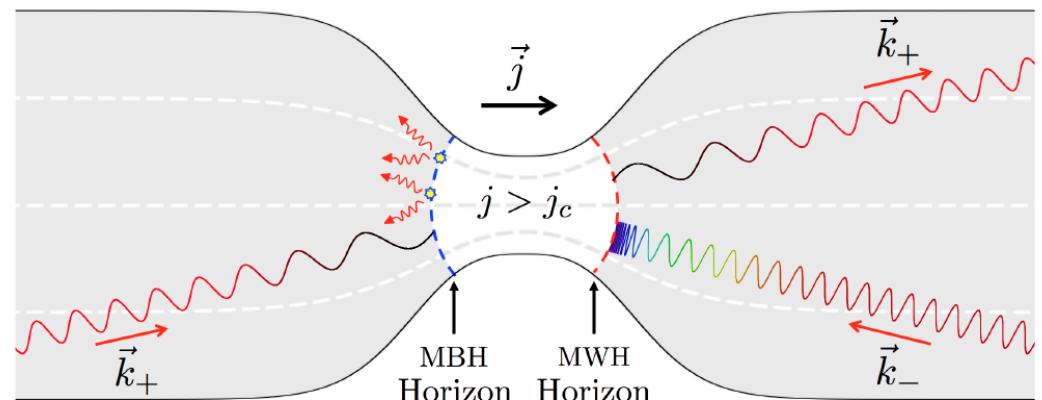
- Antiferromagnetic spin conductance becomes large upon approaching spin-flop transition



S. Bender, et al. (to be submitted)

- Magnon black-hole horizons are realizable, detectable, and ultimately may serve as resource for entanglement

“black holes  
on a chip”



A. Roldan, A.S. Nunez, RD (to be submitted)