University of Manitoba

IEEE MAGNETICS

Mainz 2018.05.15

Cavity Spintronics

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with

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IEEE Magnetics Society

IEEE 2018

- **IEEE Magnetics Society Home Page:** *www.ieeemagnetics.org*
  - 3000 full members
  - 300 student members
- **The Society**
  - Conference organization (INTERMAG, MMM, TMRC, etc.)
  - Student support for conferences
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- **Online applications for IEEE membership:** *www.ieee.org/join*
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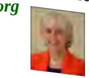

Alison B. Flatau Univ. of Maryland, USA

Can-Ming Hu Univ. of Manitoba, Canada

Mitsuteru Inoue Toyohashi Univ. of Tech., Japan

YoshiChika Otani Univ. of Tokyo, Japan

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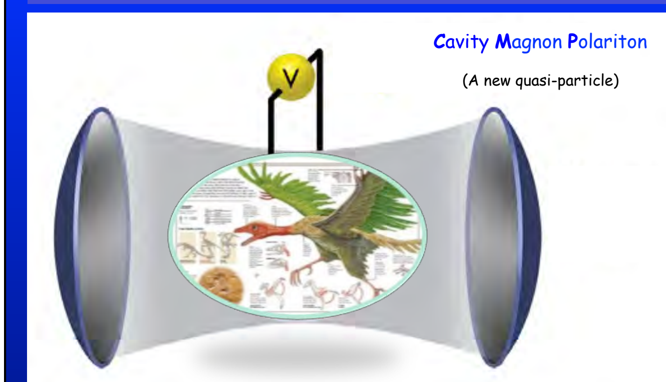
IEEE DL seminar @ Mainz May 15, 2018 © Otani

Outline of a simple story

- A new quasi-particle Cavity Magnon Polariton (CMP)
- The price we pay
- Three ways out
- Summary What is the Cavity Spintronics

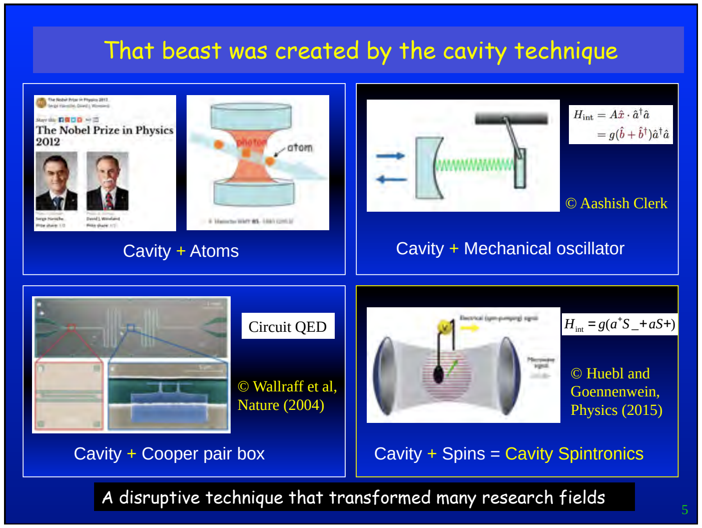
3

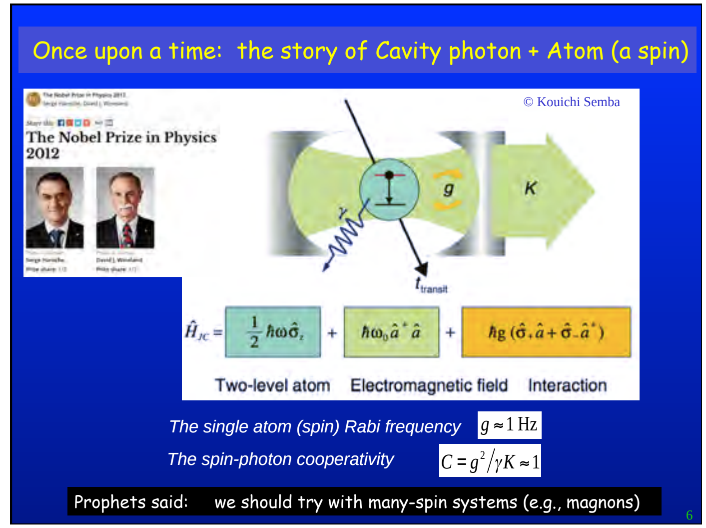
Take home graph: The story of a hybrid beast (CMP)

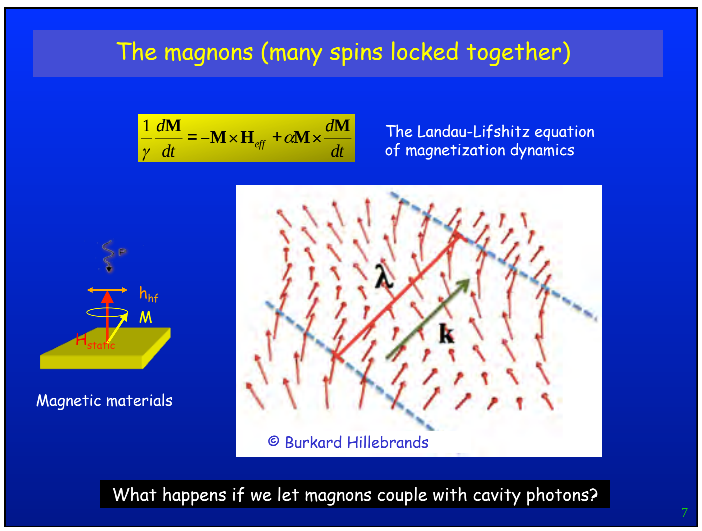


This hybrid beast was born a few years ago, but it grows rapidly.

4


That beast was created by the cavity technique
The Nobel Prize in Physics 2012
photon
atom
Cavity + Atoms
$H_{int} = A\hat{x}\cdot\hat{a}^\dagger\hat{a} = g(\hat{b}+\hat{b}^\dagger)\hat{a}^\dagger\hat{a}$
© Aashish Clerk
Cavity + Mechanical oscillator
Circuit QED
© Wallraff et al, Nature (2004)
Cavity + Cooper pair box
$H_{int} = g(a^+S\_ + aS+)$
© Huebl and Goennenwein, Physics (2015)
Cavity + Spins = Cavity Spintronics
A disruptive technique that transformed many research fields
5

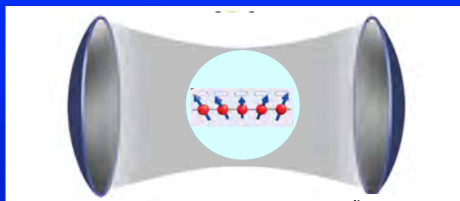

Once upon a time: the story of Cavity photon + Atom (a spin)
The Nobel Prize in Physics 2012
© Kouichi Semba
g
K
$t_{transit}$
$\hat{H}_{JC} = \frac{1}{2}\hbar\omega\hat{\sigma}_z + \hbar\omega_0\hat{a}^+\hat{a} + \hbar g(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^+)$
Two-level atom
Electromagnetic field
Interaction
The single atom (spin) Rabi frequency $g \approx 1\,\mathrm{Hz}$
The spin-photon cooperativity $C = g^2/\gamma K \approx 1$
Prophets said: we should try with many-spin systems (e.g., magnons)
6


The magnons (many spins locked together)
$\frac{1}{\gamma}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\times\mathbf{H}_{eff} + \alpha\mathbf{M}\times\frac{d\mathbf{M}}{dt}$
The Landau-Lifshitz equation of magnetization dynamics
h_{hf}
M
H_{static}
Magnetic materials
λ
k
© Burkard Hillebrands
What happens if we let magnons couple with cavity photons?
7


Here is what the prophets said in 2010
PRL 104, 077202 (2010)
PHYSICAL REVIEW LETTERS
week ending 19 FEBRUARY 2010
Strong Field Interactions between a Nanomagnet and a Photonic Cavity
Ö. O. Soykal and M. E. Flatté
Optical Science and Technology Center and Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242, USA
(Received 15 July 2009; published 18 February 2010)
We analyze the interaction of a nanomagnet (ferromagnetic) with a single photonic mode of a cavity
a fully quantum-mechanical treatment and find that exceptionally large quantum-coherent magnet-pho
coupling can be achieved. Coupling terms in excess of several THz are predicted to be achievable i
spherical cavity of ~1 mm radius with a nanomagnet of ~100 nm radius and ferromagnetic resonan
frequency of ~200 GHz. Eigenstates of the magnet-photon system correspond to entangled states of s
orientation and photon number, in which over 10^5 values of each quantum number are represente
conversely, initial (coherent) states of definite spin and photon number evolve dynamically to produ
large oscillations in the microwave power (and nanomagnet spin orientation), and are characterized
exceptionally long dephasing times.
"Coupling terms > several THz are predicted to be achievable …"
13:30 – 14:00 Michael FLATTE, Iowa
Designing magnonic crystals for quantum control
8

Then the pioneer came: Magnon - photon coupling (50 mK)

© Wikipedia



Number of spins: $N \sim 10^{16}$ $\hat{S}_z = \sum_{i=1}^{N} \hat{S}_{iz}$

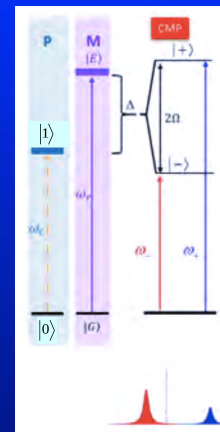
$$\hat{H} = \hbar\omega_r \hat{S}_z + \hbar\omega_c \hat{a}^+\hat{a} + \hbar g\left(\hat{S}_+\hat{a} + \hat{a}^+\hat{S}_-\right)$$

Huebl, et al., Phys. Rev. Lett. **111**, 127003 (2013). *Cooperativity C ~1350 @ 50mK*

Many-spin (magnon) Rabi frequency $\Omega_0 = g\sqrt{N} \approx 100$ MHz

10:30 – 11:00	**Hans HUEBL, Garching** *Spin-Photon Hybrids*

Simple picture for magnon-photon coupling (quantum)

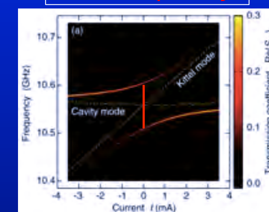


$$\hat{H} = \hbar\omega_r \hat{S}_z + \hbar\omega_c \hat{a}^+\hat{a} + \hbar g\left(\hat{S}_+\hat{a} + \hat{a}^+\hat{S}_-\right)$$

$$|\pm\rangle = c_\pm|E;0\rangle \pm c_\mp|G;1\rangle$$

$|G;0\rangle$

Rabi frequency



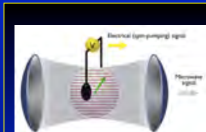
PRL 113, 083603 (2014)

Quantum vs classical: The Correspondence Principle

Cavity + Single spin

The behavior of systems described by the theory of quantum mechanics reproduces classical physics in the limit of large quantum numbers.

Bohr, "Über die Serienspektra der Element", Zeitschrift für Physik, 2 (5): 423–478, (1920)



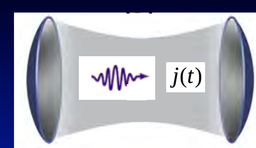
$H_{int} = g(a^+S\_ + aS+)$

© Huebl and Goennenwein, Physics (2015)

Cavity + Spins = Cavity Spintronics

Classically, the cavity can be modeled by LCR equation

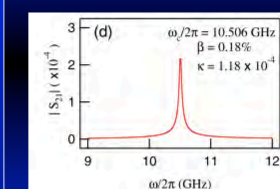
A microwave cavity



$$V_{app} = R\ j(t) + L\frac{d\ j(t)}{dt} + \frac{1}{C}\int j(t)dt.$$

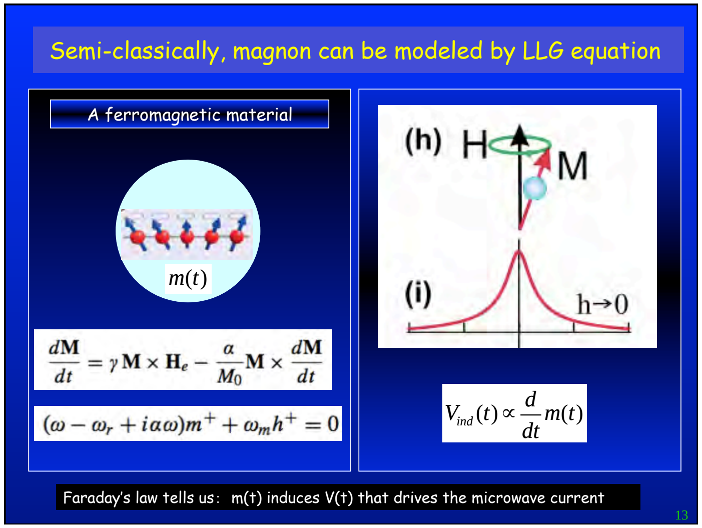
$\omega_c = 1/\sqrt{LC}$

$\beta = \Delta\omega/\omega_c = 1/2Q$

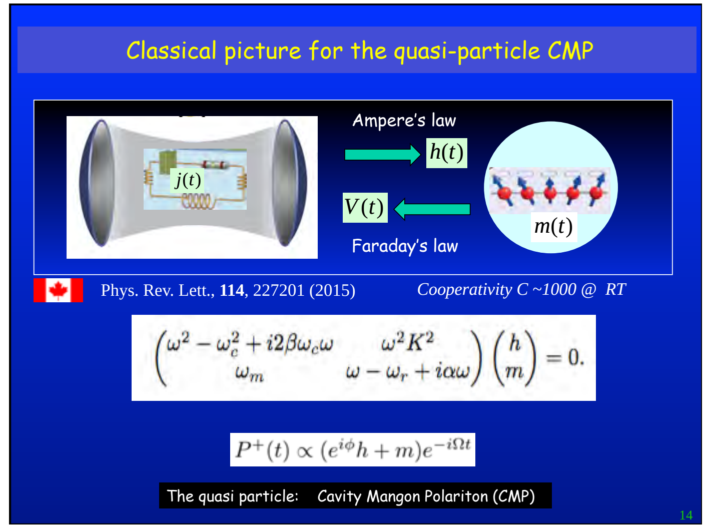


$h(t) \propto j(t)$

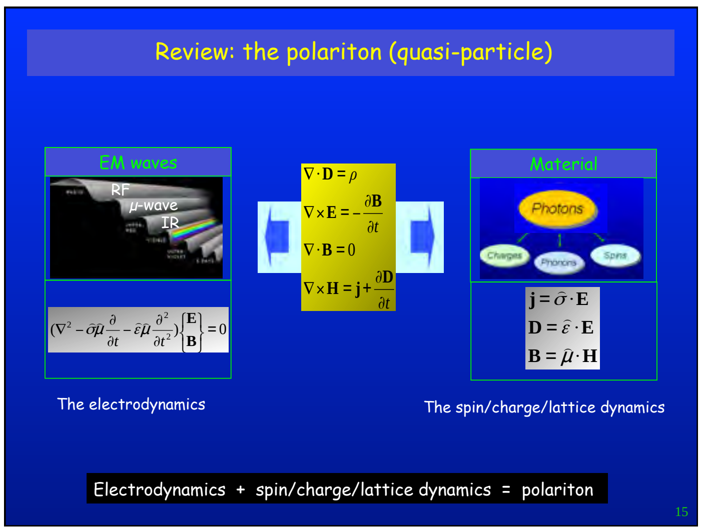
Ampere's law tells us: the phase of h(t) locks with the phase of j(t)



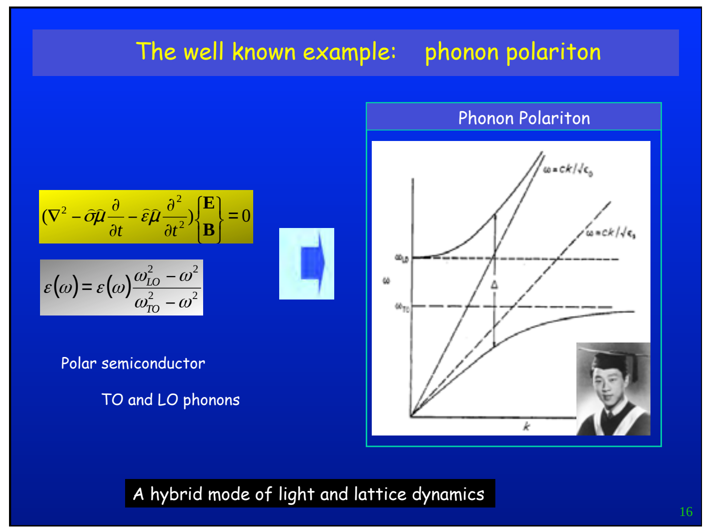
Semi-classically, magnon can be modeled by LLG equation
A ferromagnetic material
m(t)
$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mathbf{H}_e - \frac{\alpha}{M_0} \mathbf{M} \times \frac{d\mathbf{M}}{dt}$
$(\omega - \omega_r + i\alpha\omega)m^+ + \omega_m h^+ = 0$
(h) H M
(i) h→0
$V_{ind}(t) \propto \frac{d}{dt} m(t)$
Faraday's law tells us: m(t) induces V(t) that drives the microwave current
13



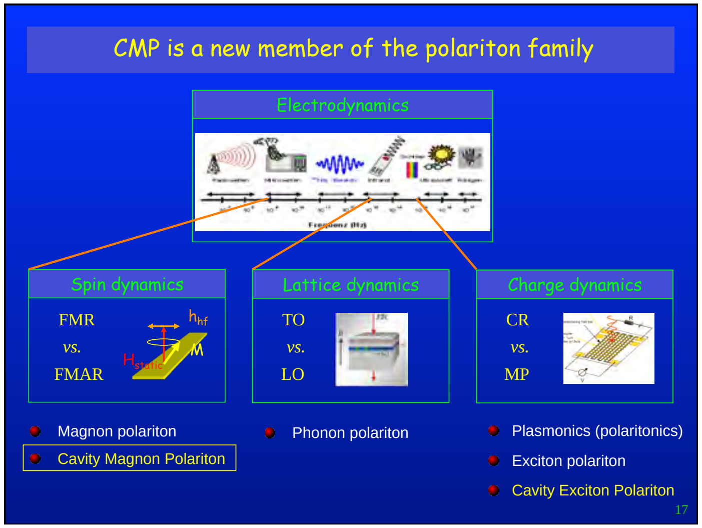
Classical picture for the quasi-particle CMP
j(t)
Ampere's law
h(t)
V(t)
Faraday's law
m(t)
Phys. Rev. Lett., 114, 227201 (2015)
Cooperativity C ~1000 @ RT
$\begin{pmatrix} \omega^2 - \omega_c^2 + i2\beta\omega_c\omega & \omega^2 K^2 \\ \omega_m & \omega - \omega_r + i\alpha\omega \end{pmatrix} \begin{pmatrix} h \\ m \end{pmatrix} = 0.$
$P^+(t) \propto (e^{i\phi} h + m) e^{-i\Omega t}$
The quasi particle: Cavity Mangon Polariton (CMP)
14



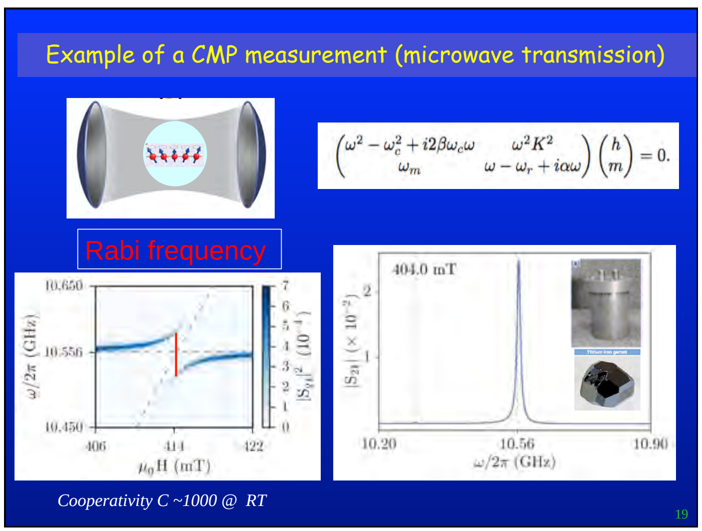
Review: the polariton (quasi-particle)
EM waves
RF
μ-wave
IR
$(\nabla^2 - \tilde{\sigma}\tilde{\mu}\frac{\partial}{\partial t} - \tilde{\varepsilon}\tilde{\mu}\frac{\partial^2}{\partial t^2})\begin{Bmatrix} \mathbf{E} \\ \mathbf{B} \end{Bmatrix} = 0$
$\nabla \cdot \mathbf{D} = \rho$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}$
Material
Photons
Charges
Phonons
Spins
$\mathbf{j} = \tilde{\sigma} \cdot \mathbf{E}$
$\mathbf{D} = \tilde{\varepsilon} \cdot \mathbf{E}$
$\mathbf{B} = \tilde{\mu} \cdot \mathbf{H}$
The electrodynamics
The spin/charge/lattice dynamics
Electrodynamics + spin/charge/lattice dynamics = polariton
15

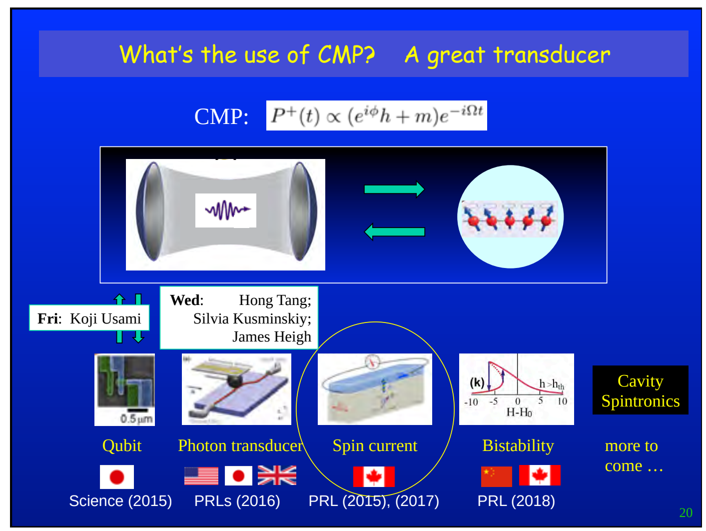


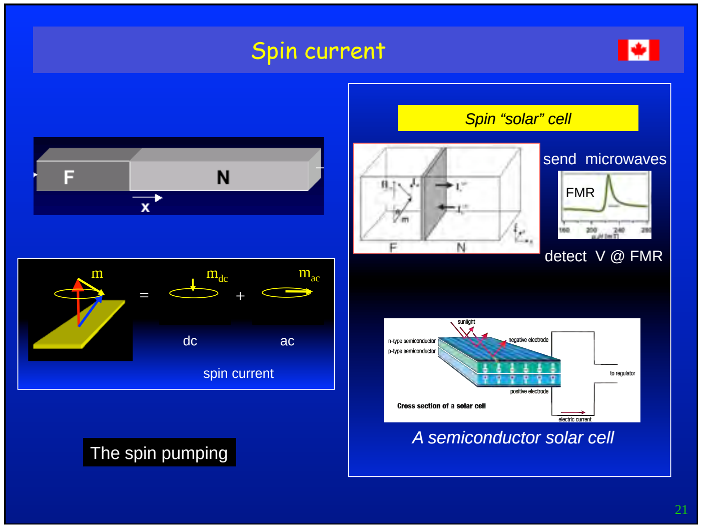
The well known example: phonon polariton
$(\nabla^2 - \tilde{\sigma}\tilde{\mu}\frac{\partial}{\partial t} - \tilde{\varepsilon}\tilde{\mu}\frac{\partial^2}{\partial t^2})\begin{Bmatrix} \mathbf{E} \\ \mathbf{B} \end{Bmatrix} = 0$
$\varepsilon(\omega) = \varepsilon(\omega)\frac{\omega_{LO}^2 - \omega^2}{\omega_{TO}^2 - \omega^2}$
Polar semiconductor
TO and LO phonons
Phonon Polariton
k
A hybrid mode of light and lattice dynamics
16

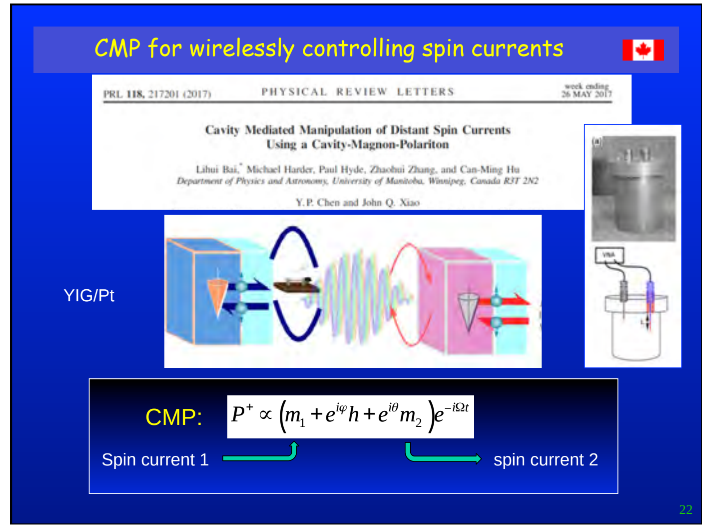

CMP is a new member of the polariton family
Electrodynamics
Spin dynamics
FMR
vs.
FMAR
h_{hf}
H_{static}
M
Lattice dynamics
TO
vs.
LO
Charge dynamics
CR
vs.
MP
Magnon polariton
Cavity Magnon Polariton
Phonon polariton
Plasmonics (polaritonics)
Exciton polariton
Cavity Exciton Polariton
17

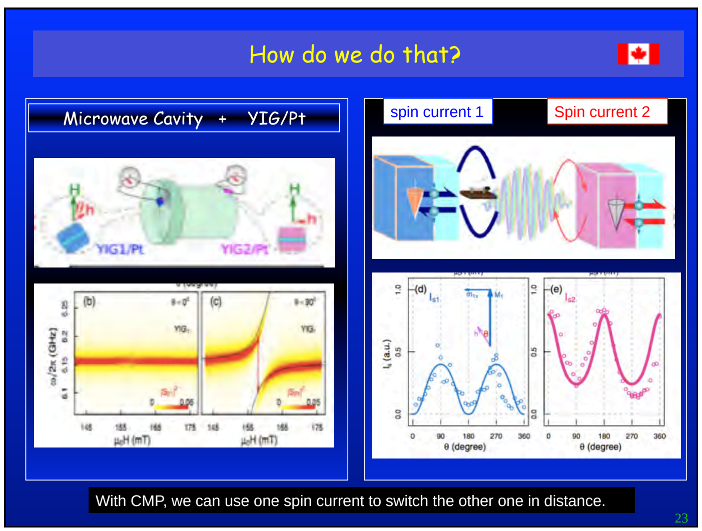

Spin Cavitronics 1 vs PLMCN 19
PLMCN19
The 19th International Conference on Physics of Light-Matter Coupling in Nanostructures
Chengdu, China from 15th to 19th May 2018.
CONFERENCE TOPICS
• Cavity quantum electrodynamics
• Light-matter coupling in microcavities,
• Cavity Exciton Polaritons
• Optics of 2D materials
• Physics and application of quantum dots
• Metamaterials
• Non-Hermitian and non-reciprocal physics, topological photonics
• Opto-mechanical cavities
• Novel optical devices
• Solid-State quantum information processing
• Cavity Spintronics
• Cavity Magnonics
18


Example of a CMP measurement (microwave transmission)
$\begin{pmatrix} \omega^2-\omega_c^2+i2\beta\omega_c\omega & \omega^2K^2 \\ \omega_m & \omega-\omega_r+i\alpha\omega \end{pmatrix}\begin{pmatrix} h \\ m \end{pmatrix}=0.$
Rabi frequency
$\omega/2\pi$ (GHz)
$\mu_0 H$ (mT)
$|S_{21}|^2$ (10^{-1})
404.0 mT
$|S_{21}|$ ($\times 10^{-2}$)
$\omega/2\pi$ (GHz)
Cooperativity C ~1000 @ RT
19

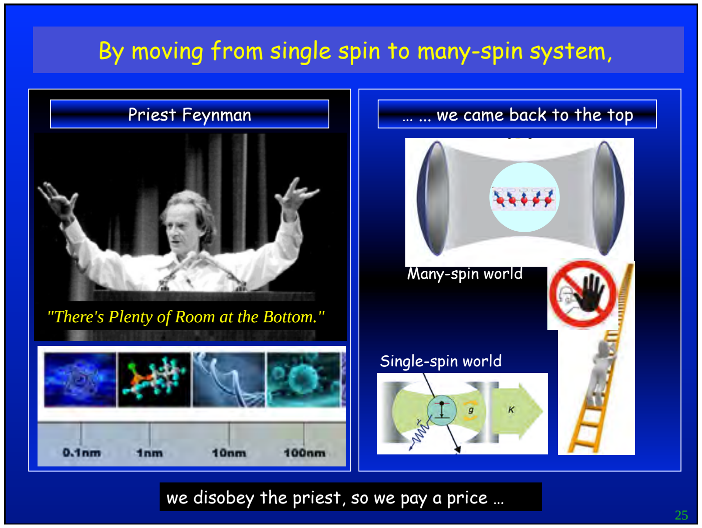

What's the use of CMP? A great transducer
CMP: $P^+(t) \propto (e^{i\phi}h+m)e^{-i\Omega t}$
Fri: Koji Usami
Wed: Hong Tang; Silvia Kusminskiy; James Heigh
Qubit
Photon transducer
Spin current
Bistability
Cavity Spintronics
more to come …
Science (2015)
PRLs (2016)
PRL (2015), (2017)
PRL (2018)
20

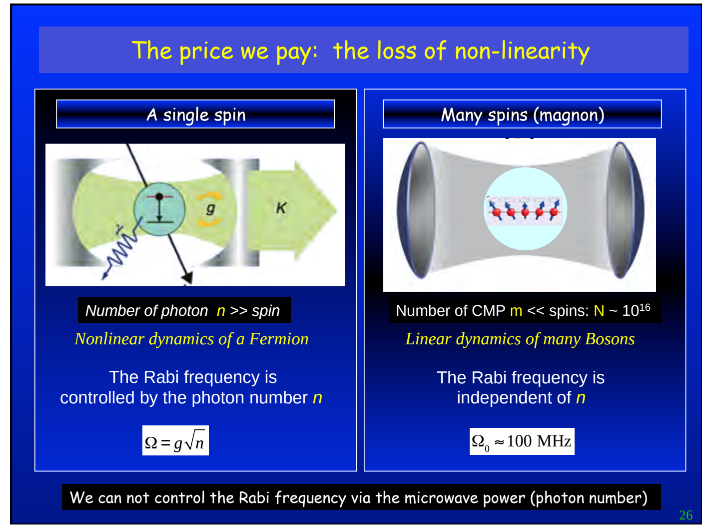

Spin current
F
N
x
m
m_{dc}
m_{ac}
dc
ac
spin current
The spin pumping
Spin "solar" cell
send microwaves
FMR
detect V @ FMR
Cross section of a solar cell
A semiconductor solar cell
21

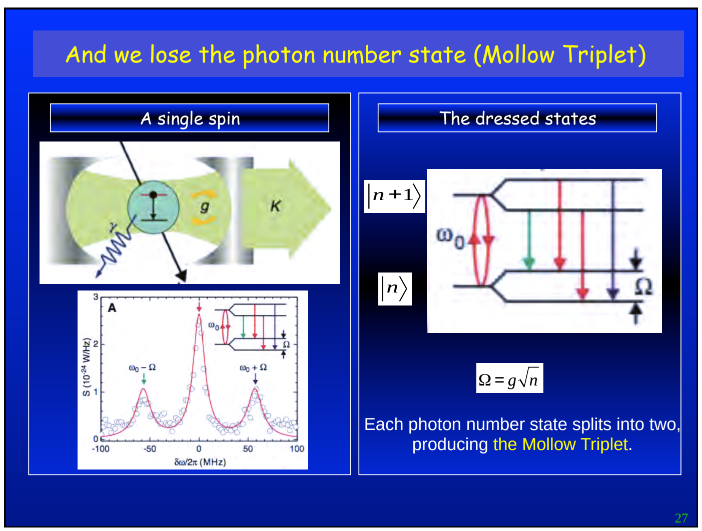

CMP for wirelessly controlling spin currents
PRL 118, 217201 (2017) PHYSICAL REVIEW LETTERS week ending 26 MAY 2017
Cavity Mediated Manipulation of Distant Spin Currents Using a Cavity-Magnon-Polariton
Lihui Bai, Michael Harder, Paul Hyde, Zhaohui Zhang, and Can-Ming Hu
Department of Physics and Astronomy, University of Manitoba, Winnipeg, Canada R3T 2N2
Y. P. Chen and John Q. Xiao
YIG/Pt
CMP: $P^{+} \propto (m_1 + e^{i\varphi} h + e^{i\theta} m_2) e^{-i\Omega t}$
Spin current 1
spin current 2
22

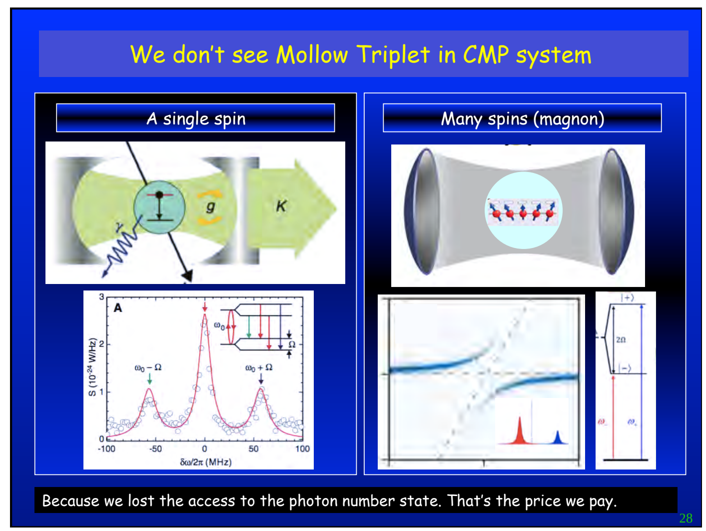

How do we do that?
Microwave Cavity + YIG/Pt
YIG1/Pt
YIG2/Pt
spin current 1
Spin current 2
$\mu_0 H$ (mT)
θ (degree)
With CMP, we can use one spin current to switch the other one in distance.
23

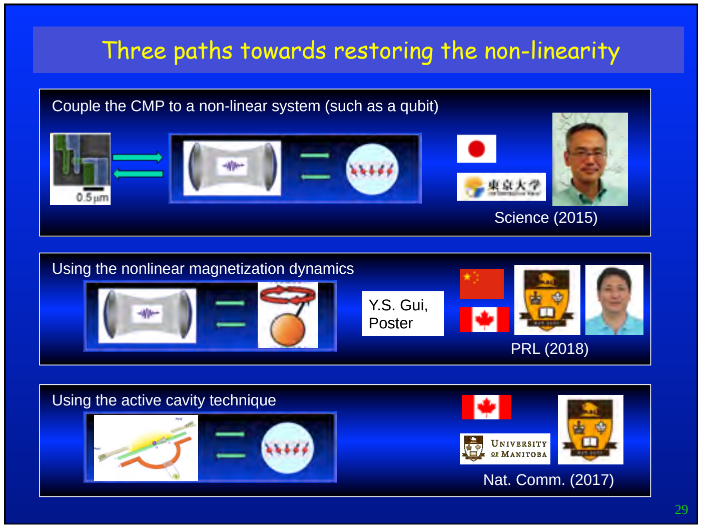

All these are wonderful, but, there is no free lunch.
The price we pay
24


By moving from single spin to many-spin system,
Priest Feynman
"There's Plenty of Room at the Bottom."
0.1nm
1nm
10nm
100nm
… … we came back to the top
Many-spin world
Single-spin world
we disobey the priest, so we pay a price …
25

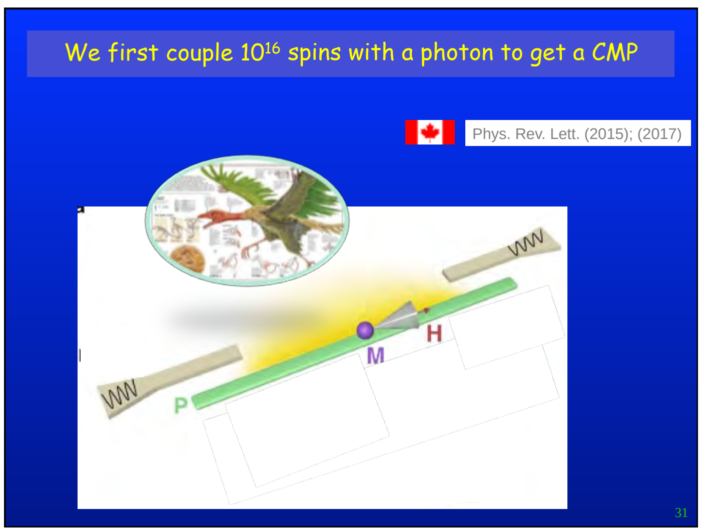

The price we pay: the loss of non-linearity
A single spin
Number of photon n >> spin
Nonlinear dynamics of a Fermion
The Rabi frequency is controlled by the photon number n
$\Omega = g\sqrt{n}$
Many spins (magnon)
Number of CMP m << spins: N ~ 10^{16}
Linear dynamics of many Bosons
The Rabi frequency is independent of n
$\Omega_0 \approx 100$ MHz
We can not control the Rabi frequency via the microwave power (photon number)
26


And we lose the photon number state (Mollow Triplet)
A single spin
The dressed states
$|n+1\rangle$
$|n\rangle$
ω_0
Ω
$\Omega = g\sqrt{n}$
Each photon number state splits into two, producing the Mollow Triplet.
27

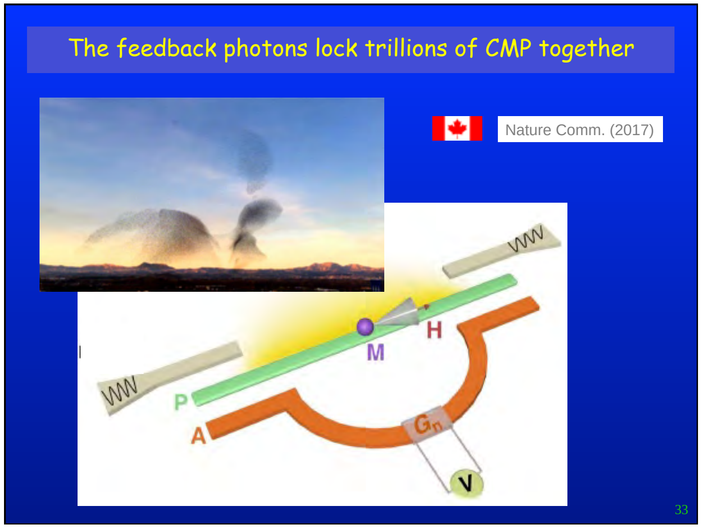

We don't see Mollow Triplet in CMP system
A single spin
Many spins (magnon)
Because we lost the access to the photon number state. That's the price we pay.
28

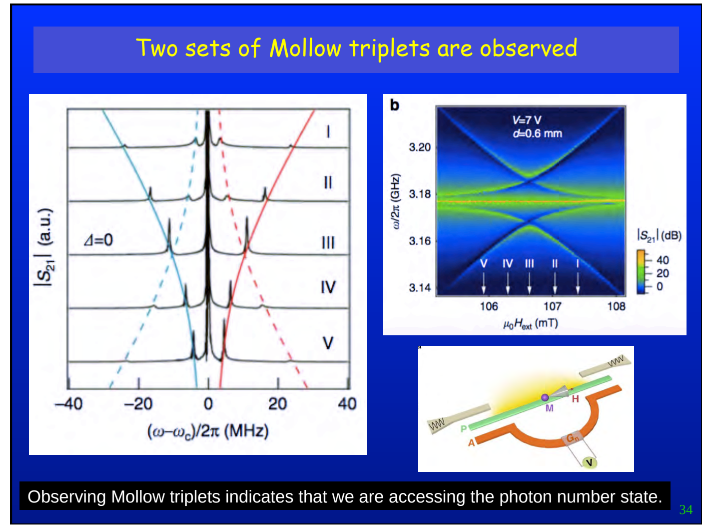

Three paths towards restoring the non-linearity
Couple the CMP to a non-linear system (such as a qubit)
0.5μm
Science (2015)
Using the nonlinear magnetization dynamics
Y.S. Gui, Poster
PRL (2018)
Using the active cavity technique
University of Manitoba
Nat. Comm. (2017)
29

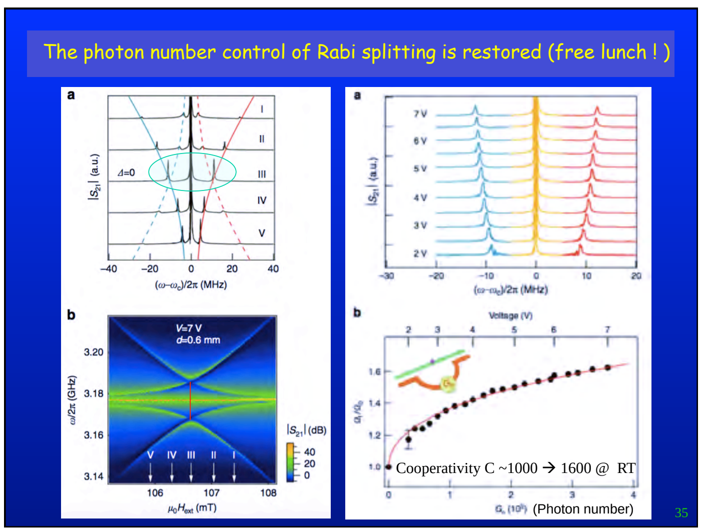

The active cavity technique, and the new specie …
Cavity Magnon Quintuplet
Locking 10^13 CMP together
30

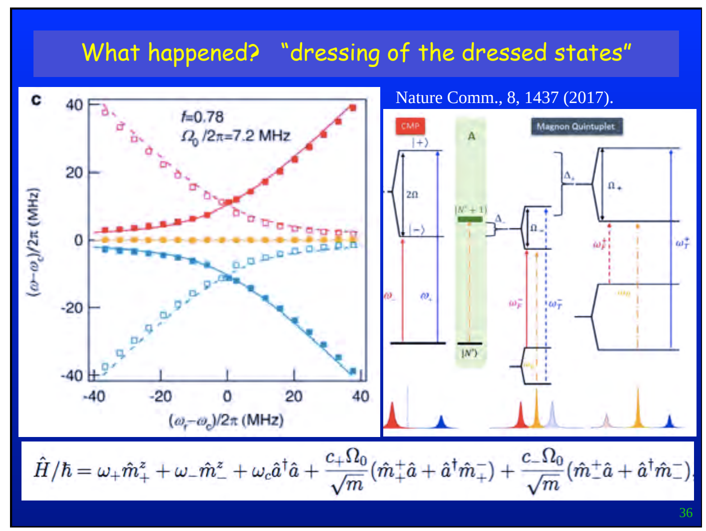

We first couple 10^16 spins with a photon to get a CMP
Phys. Rev. Lett. (2015); (2017)
M
H
P
31


Then, we feed the photons back (coherently)
Nature Comm. (2017)
M
H
P
A
V
32

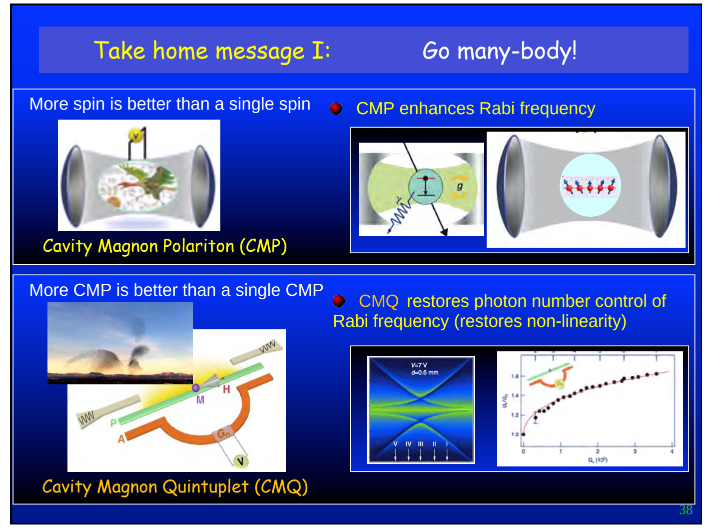

The feedback photons lock trillions of CMP together
Nature Comm. (2017)
M
H
P
A
V
33

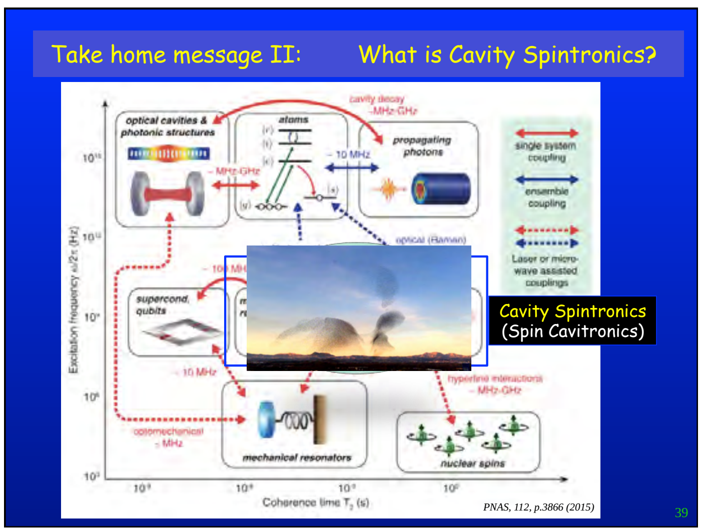

Two sets of Mollow triplets are observed
|S21| (a.u.)
Δ=0
I
II
III
IV
V
(ω−ωc)/2π (MHz)
b
V=7 V
d=0.6 mm
ω/2π (GHz)
|S21| (dB)
μ0Hext (mT)
Observing Mollow triplets indicates that we are accessing the photon number state.
34


The photon number control of Rabi splitting is restored (free lunch !)
a
b
Voltage (V)
Cooperativity C ~1000 → 1600 @ RT
(Photon number)
35


What happened? "dressing of the dressed states"
Nature Comm., 8, 1437 (2017).
c
f=0.78
Ω0/2π=7.2 MHz
(ω−ωc)/2π (MHz)
(ωr−ωc)/2π (MHz)
CMP
A
Magnon Quintuplet
$\hat{H}/\hbar = \omega_+\hat{m}_+^z + \omega_-\hat{m}_-^z + \omega_c\hat{a}^\dagger\hat{a} + \frac{c_+\Omega_0}{\sqrt{m}}(\hat{m}_+^+\hat{a} + \hat{a}^\dagger\hat{m}_+^-) + \frac{c_-\Omega_0}{\sqrt{m}}(\hat{m}_-^+\hat{a} + \hat{a}^\dagger\hat{m}_-^-)$
36


Where comes the free lunch?
Many-body system
Priest Feynman
"There's Plenty of Room at the Bottom."
0.1nm
1nm
10nm
100nm
P. Anderson
"More Is Different", P. W. Anderson
Science, Vol. 177, (Aug. 4, 1972), 393-396.
enhanced Rabi frequency + photon control
There's plenty of surprises in many-body systems
37


Take home message I:
Go many-body!
More spin is better than a single spin
CMP enhances Rabi frequency
Cavity Magnon Polariton (CMP)
More CMP is better than a single CMP
CMQ restores photon number control of Rabi frequency (restores non-linearity)
Cavity Magnon Quintuplet (CMQ)
38


Take home message II:
What is Cavity Spintronics?
optical cavities & photonic structures
atoms
propagating photons
single system coupling
ensemble coupling
Laser or micro-wave assisted couplings
superconducting qubits
mechanical resonators
nuclear spins
Excitation frequency ω/2π (Hz)
Coherence time T_2 (s)
Cavity Spintronics
(Spin Cavitronics)
PNAS, 112, p.3866 (2015)
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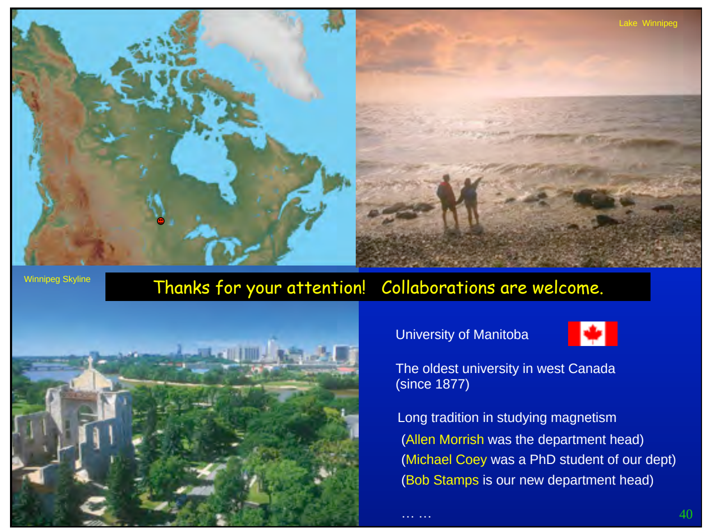
Lake Winnipeg
Winnipeg Skyline
Thanks for your attention! Collaborations are welcome.
University of Manitoba
The oldest university in west Canada
(since 1877)
Long tradition in studying magnetism
(Allen Morrish was the department head)
(Michael Coey was a PhD student of our dept)
(Bob Stamps is our new department head)
… …
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