Journal club on 22 July (2014) by Kouki Nakata

nature COMMUNICATIONS

ARTICLE

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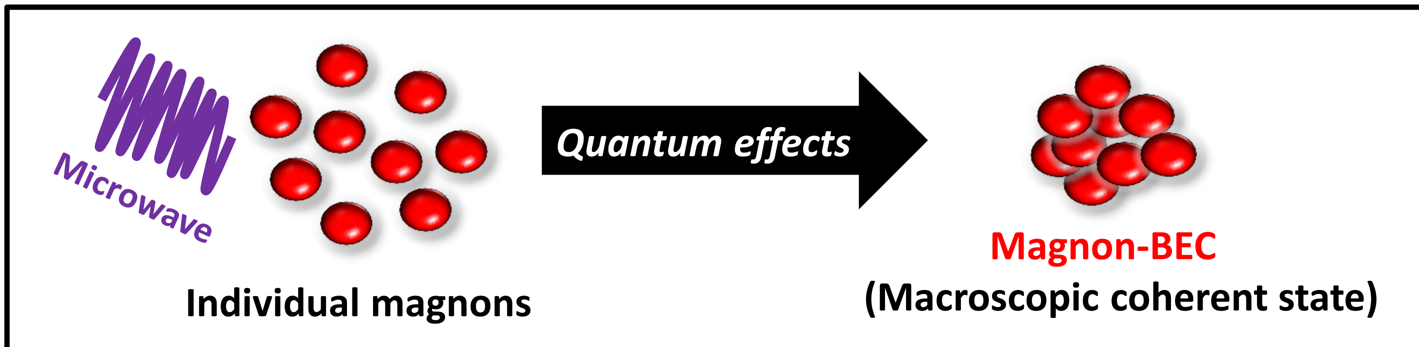
Bose–Einstein condensation in an ultra-hot gas of pumped magnons

Alexander A. Serga[1], Vasil S. Tiberkevich[2], Christian W. Sandweg[1], Vitaliy I. Vasyuchka[1], Dmytro A. Bozhko[1,3], Andrii V. Chumak[1], Timo Neumann[1], Björn Obry[1], Gennadii A. Melkov[3], Andrei N. Slavin[2] & Burkard Hillebrands[1]



✓ ***Point***

Evaporative supercooling

increases

(Quasi-equilibrium) magnon-BEC

✓ ***My opinion****; microscopic analysis of evaporation will be interesting.*

OUTLINE

- ***Introduction***
  - ✓ Magnon ≈ Spin-Wave
  - ✓ Magnon pumping & resulting magnon-BEC

    [S. O. Demokritov *et al*., Nature **443**, 430 (2006).]

- ***Experimental result*** [Nature communication **5**, 3452 (2014).]

- ***Their story* & theoretical model**
  - ✓ Evaporative supercooling

- ***Conclusion***

■ *Introduction*

Magnon pumping & resulting **magnon-BEC**

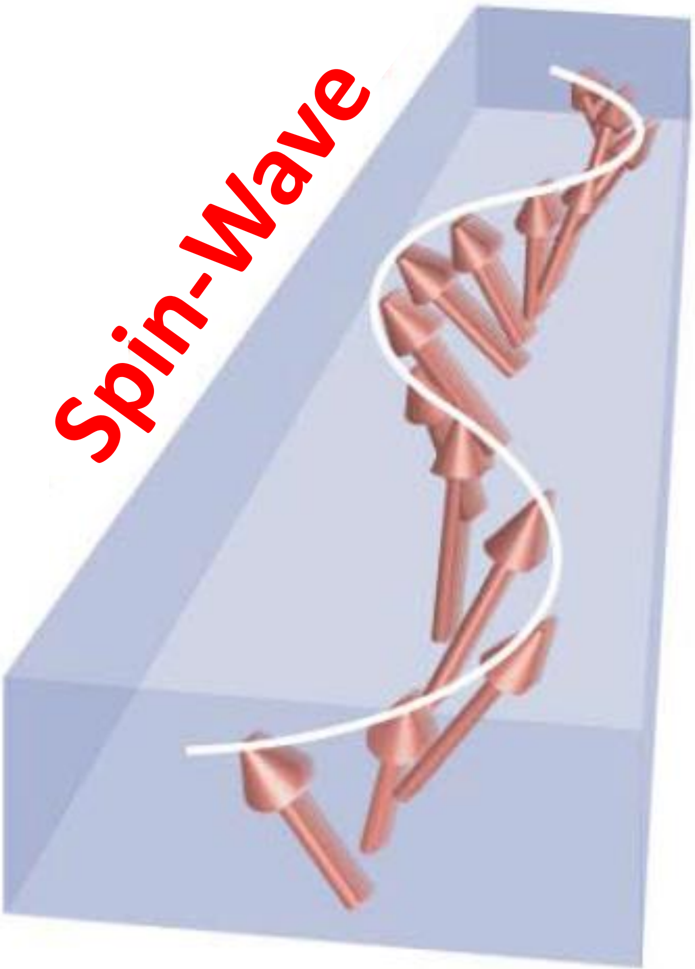
[S. O. Demokritov *et al*., Nature **443**, 430 (2006).]

✓ It does not require **"low temperature".**

→ **"Room temperature"**

Magnon ≈ Spin-Wave

✓ **Magnons**; the bosonic quanta of **magnetic excitations** in a magnetically ordered spins

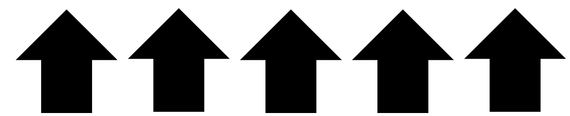


[Y. Kajiwara et al., Nature **464** (2010) 262]

Ferromagnetic Heisenberg model (J > 0)

$$-\mathrm{J}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j$$

Ground state; $S_i^{\,z} = S$



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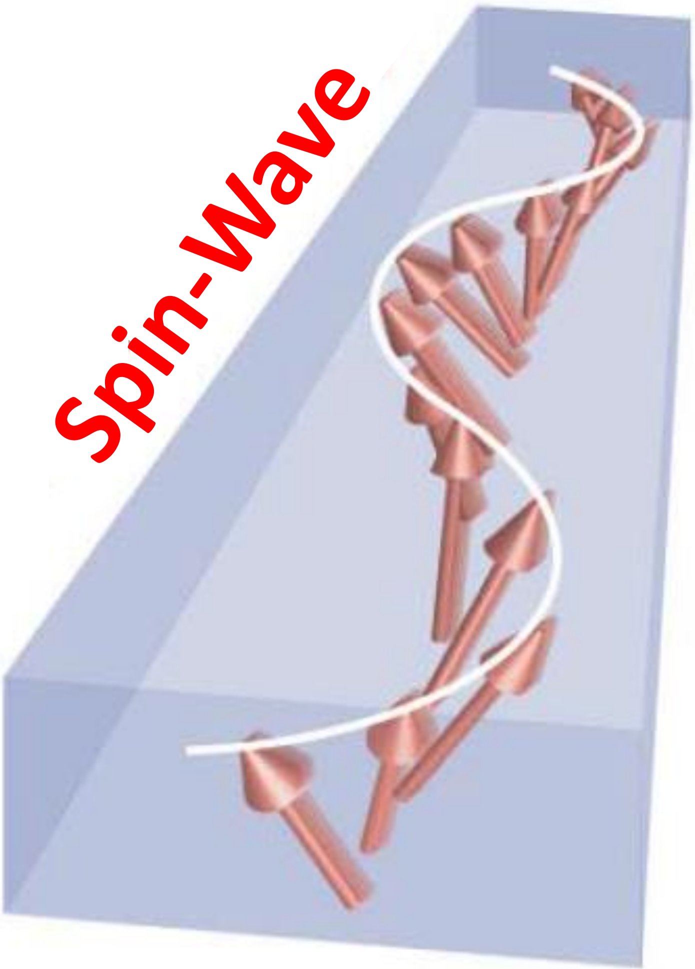

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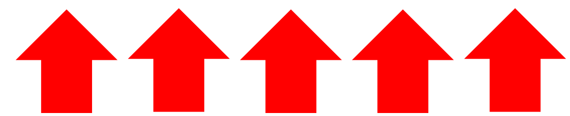
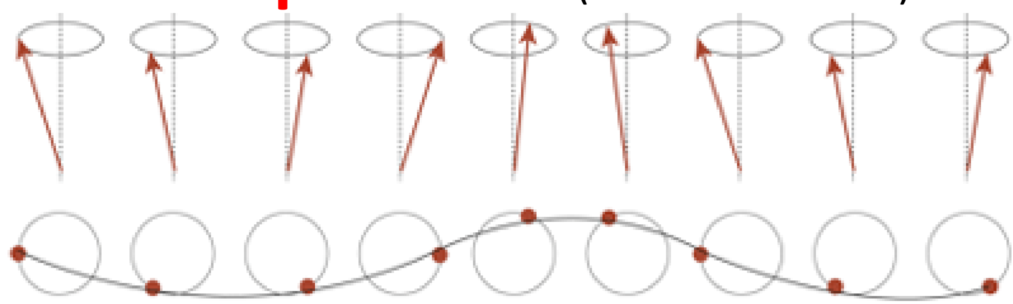


Spin-wave (collective mode)



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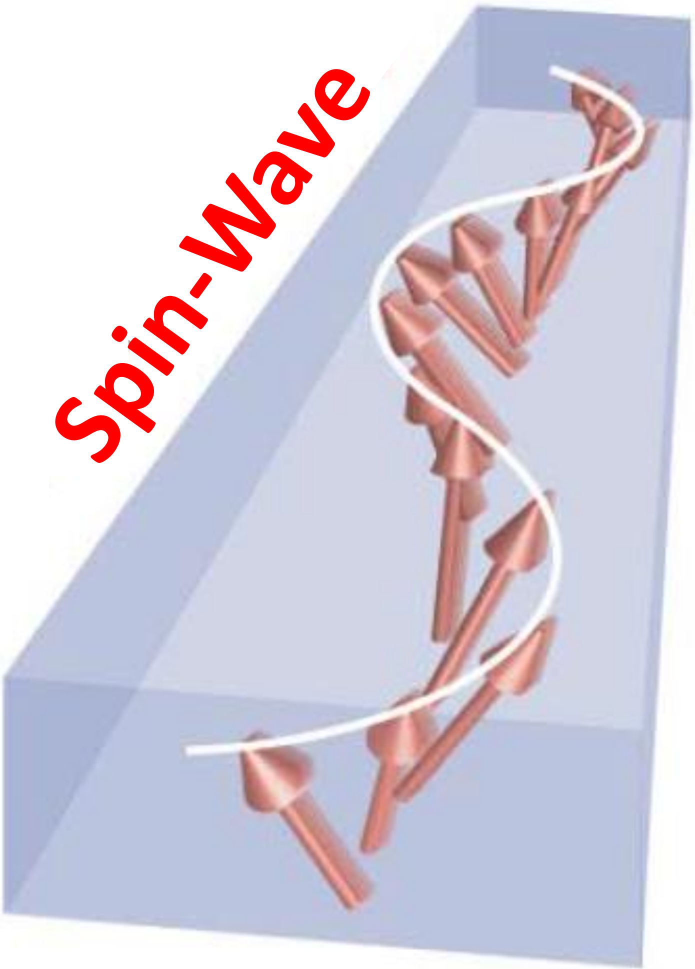

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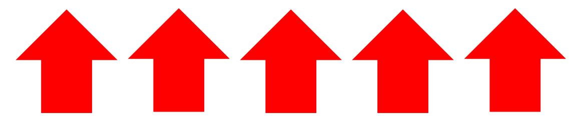

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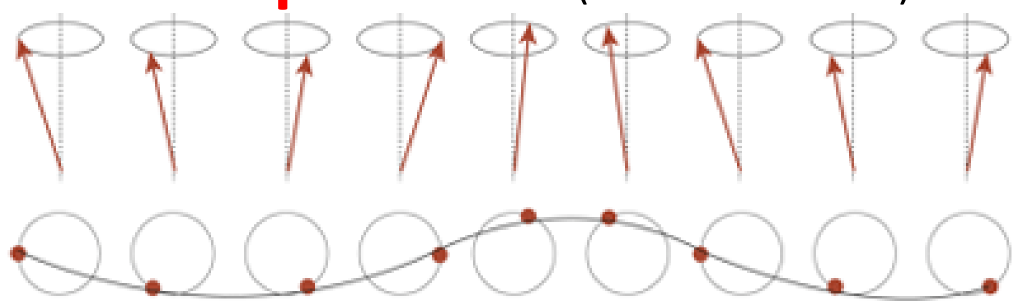
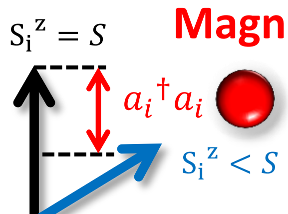


Holstein-Primakoff transformation; magnon



Magnon

$$S_i^z = S - a_i^\dagger a_i$$

$$S_i^+ \simeq S_i^x + iS_i^y \approx a_i \simeq (S_i^-)^\dagger$$

with $[a_i, a_j^\dagger] = \delta_{ij}$

Magnon-BEC vs Atomic BEC

How to produce

Bose-Einstein condensate (BEC)

Macroscopic (bosonic) particles occupy a same (lowest-energy) state.

✓ **Decreasing the temperature of (an ideal) gas of bosons**

[Text "*thermal physics*" by Kttel]

→ The common method

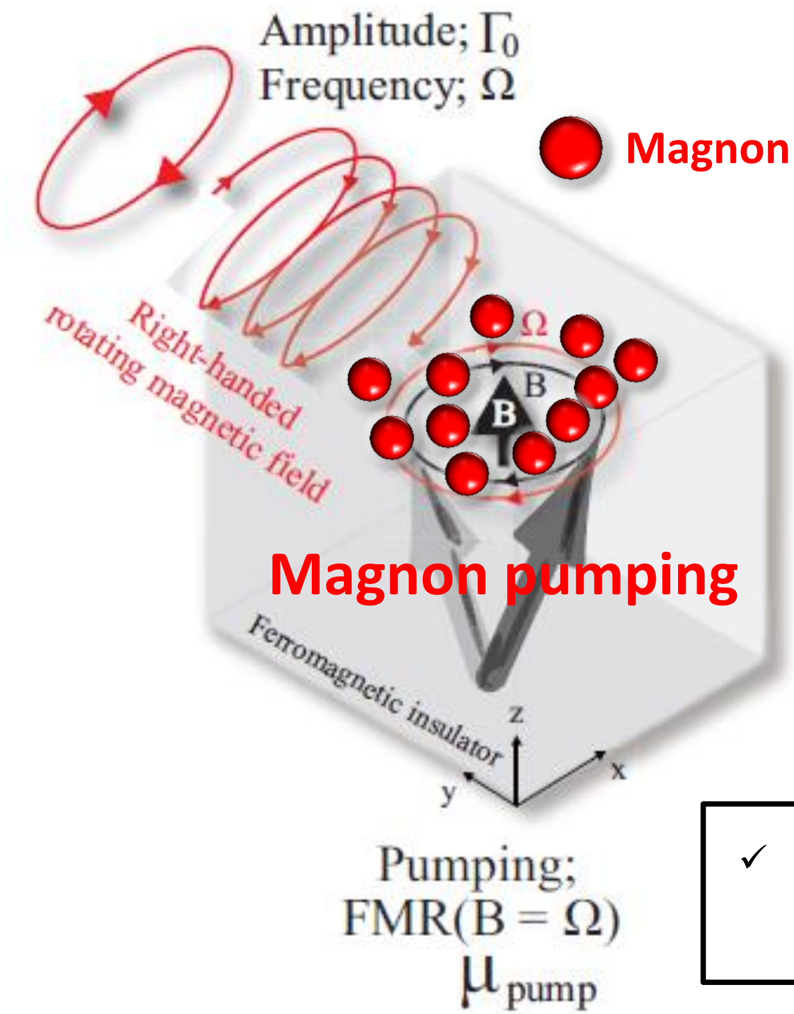
✓ **Increasing its density**

→ Peculiar to magnon-BEC

→ "**Microwave pumping**" [S. O. Demokritov *et al*., Nature **443**, 430 (2006).]

Microwave Pumping

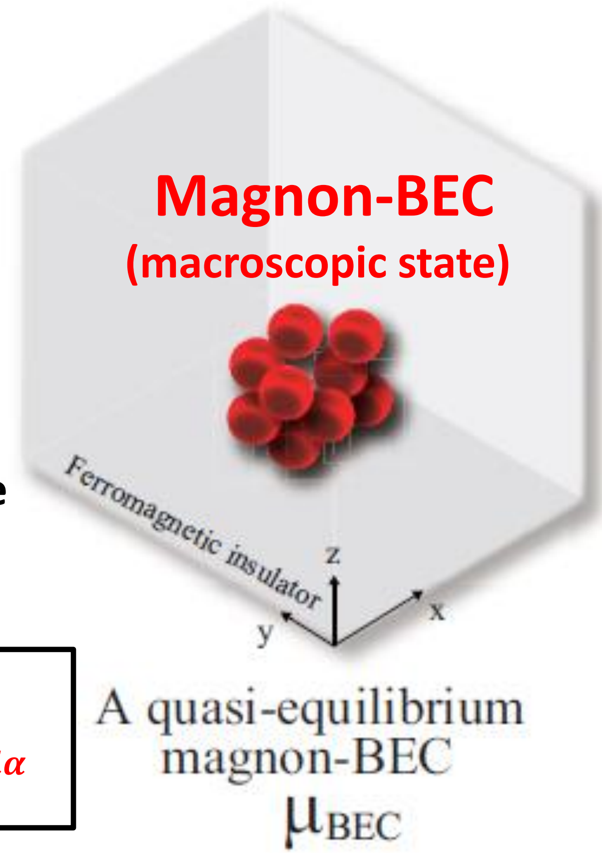
- ✓ A method to inject **magnons** into ferromagnetic insulators
  [S. O. Demokritov *et al.*, Nature **443**, 430 (2006).]
- ✓ It does not require **"low temperature". → "Room temperature"**



Thermalization processes →

Room temperature

✓ **We can directly inject magnons so that it becomes a macroscopic number (BEC).**



✓ **BEC order parameter**

$$\langle a \rangle = \sqrt{N_{BEC}} e^{i\mu t + i\alpha}$$

Quasi-equilibrium Magnon-BEC

→ [Metastable state]≠[Ground state]

[C. D. Batista et al., Rev. Mod. Phys., **86**, 563 (2014).]
[Y. M. Bunkov and G. E. Volovik, arXiv:1003.4889.]

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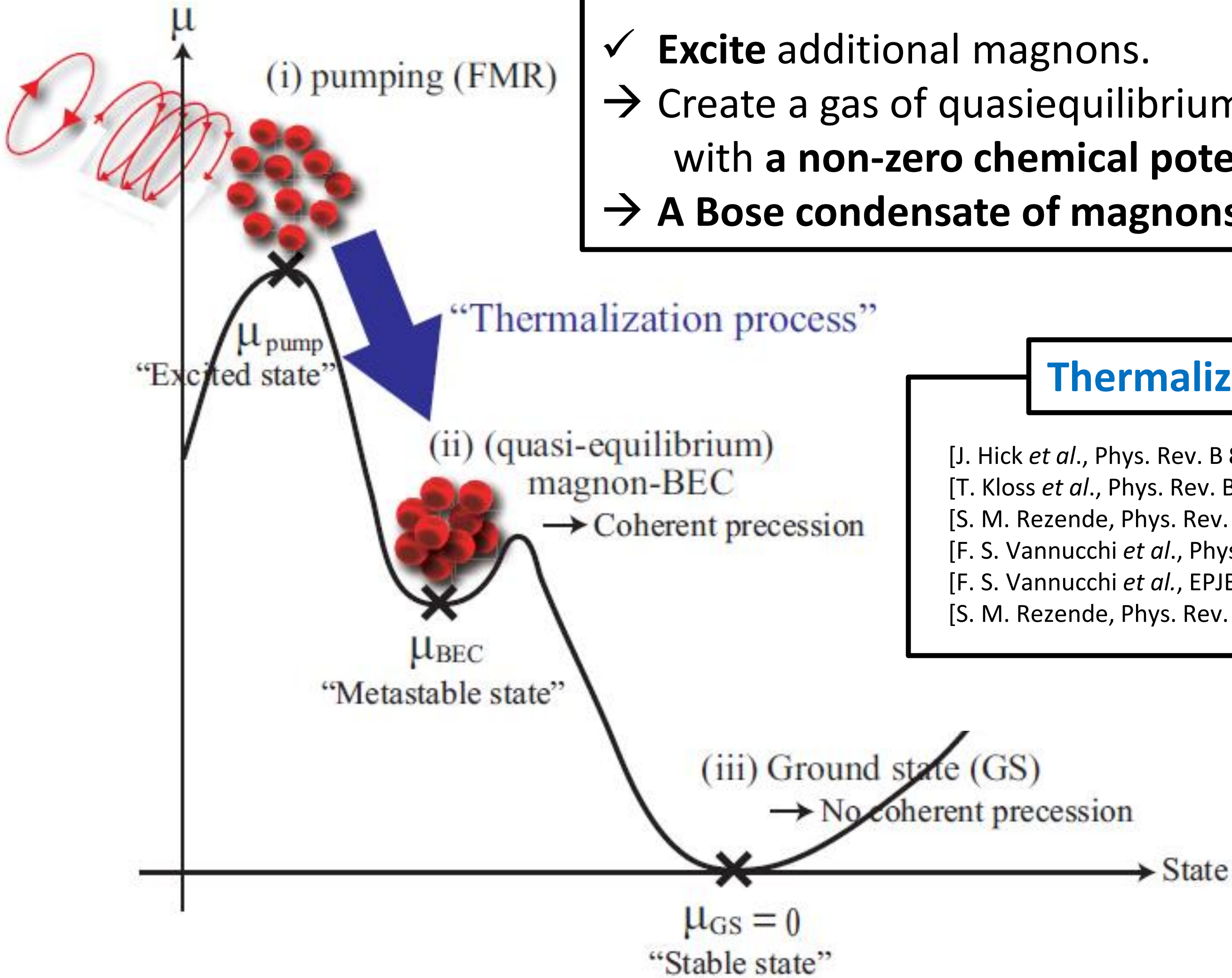
$$\langle a \rangle = \sqrt{N_{BEC}} e^{i\mu t + i\alpha}$$



Microwave pumping

✓ **Excite** additional magnons.
→ Create a gas of quasiequilibrium magnons with **a non-zero chemical potential**.
→ **A Bose condensate of magnons** is formed.

Thermalization process

[J. Hick *et al.*, Phys. Rev. B **86**, 184417 (2012)]
[T. Kloss *et al.*, Phys. Rev. B **81**, 104308 (2010)]
[S. M. Rezende, Phys. Rev. B **79,** 174411(2009)]
[F. S. Vannucchi *et al.*, Phys. Rev. B **82**, 140404(R) (2010)]
[F. S. Vannucchi *et al.*, EPJB **86** (2013) 463]
[S. M. Rezende, Phys. Rev. B **79**, 174411 (2009)]

Experiment by Demokritov

Bose–Einstein condensation of quasi-equilibrium magnons at room temperature under pumping

S. O. Demokritov[1], V. E. Demidov[1], O. Dzyapko[1], G. A. Melkov[2], A. A. Serga[3], B. Hillebrands[3] & A. N. Slavin[4]

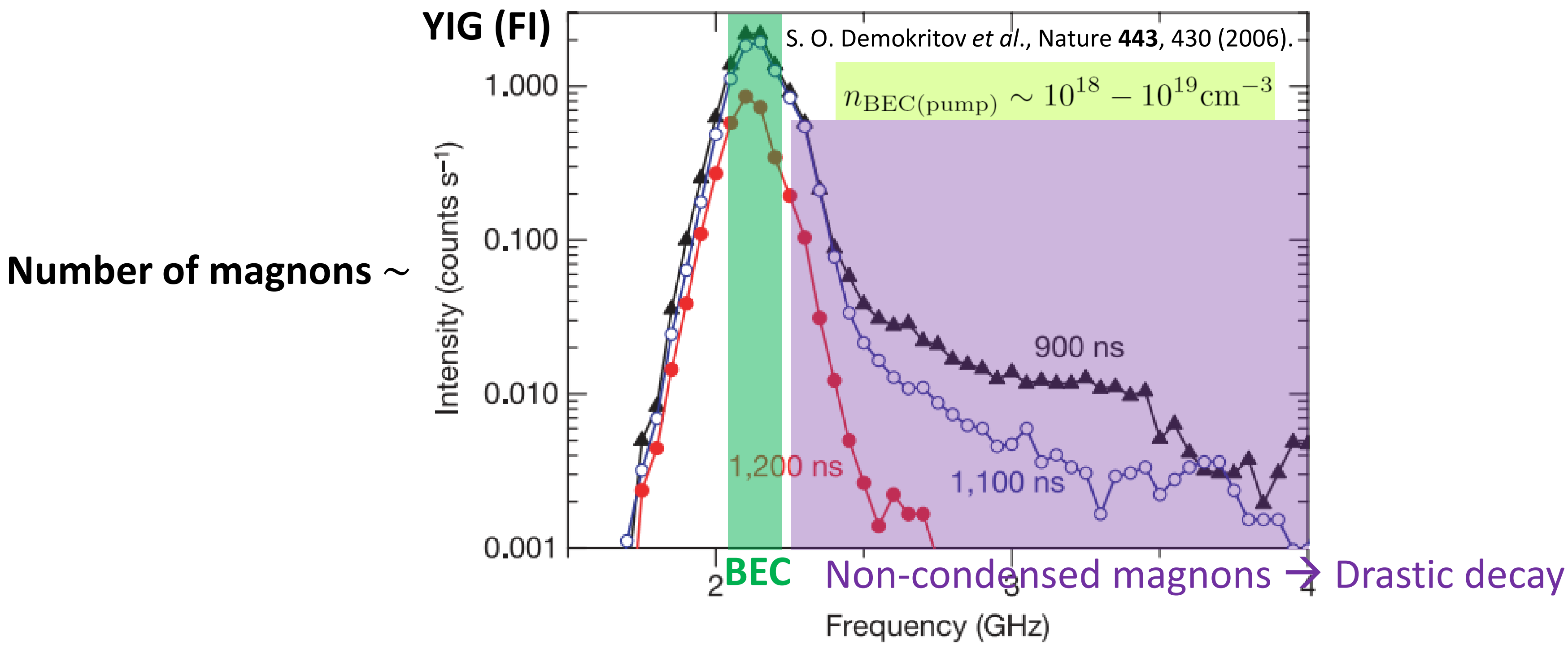


Figure 4 | Evolution of the magnon population after the pumping is switched off at $\tau = 1{,}000$ ns. Open and filled circles, spectrum of light scattered from pumped magnons at $\tau = 1{,}100$ ns and 1,200 ns, respectively. Triangles, spectrum corresponding to the stationary pumped state ($\tau = 900$ ns), given for comparison. Note the drastic decay of the density of the non-condensed magnons with time.

■ ***Experimental result***

[Nature communication **5**, 3452 (2014).]

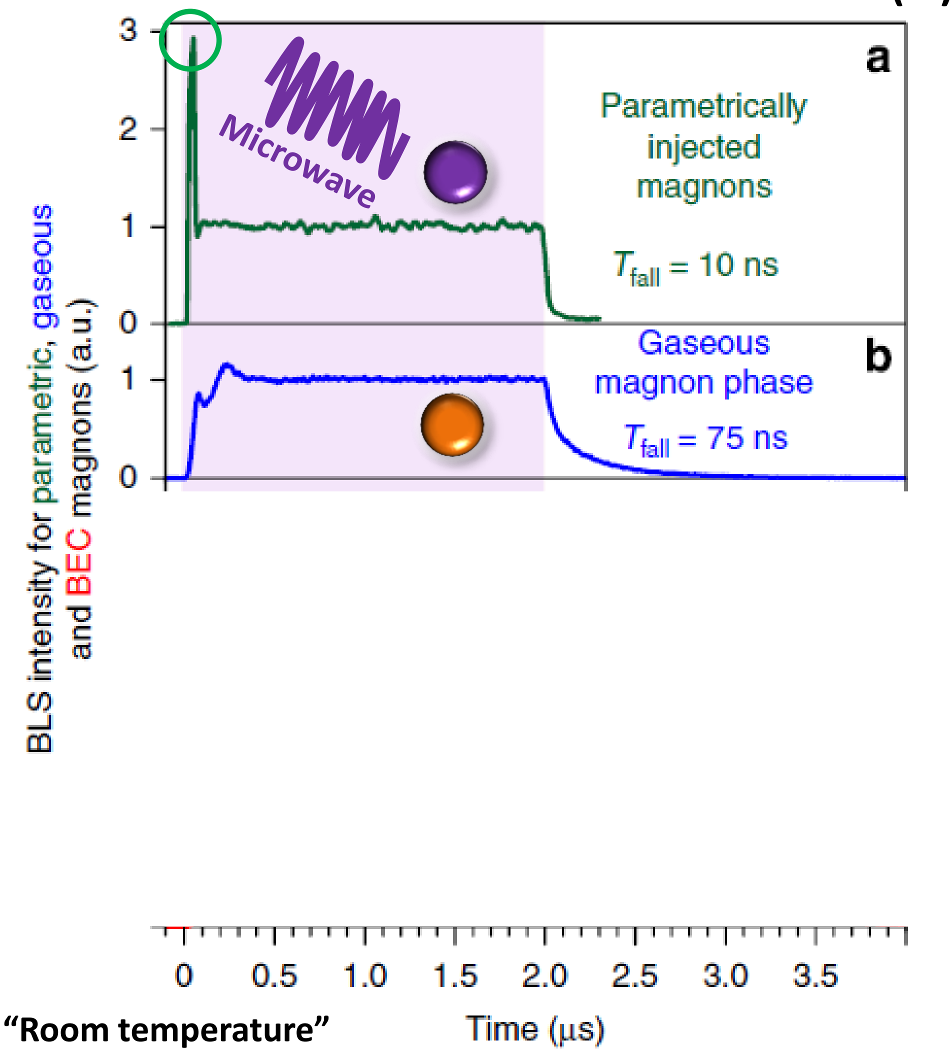
Hillebrands

THEIR MOTIVATION

Experiment

An artefact of FMR

YIG (FI)

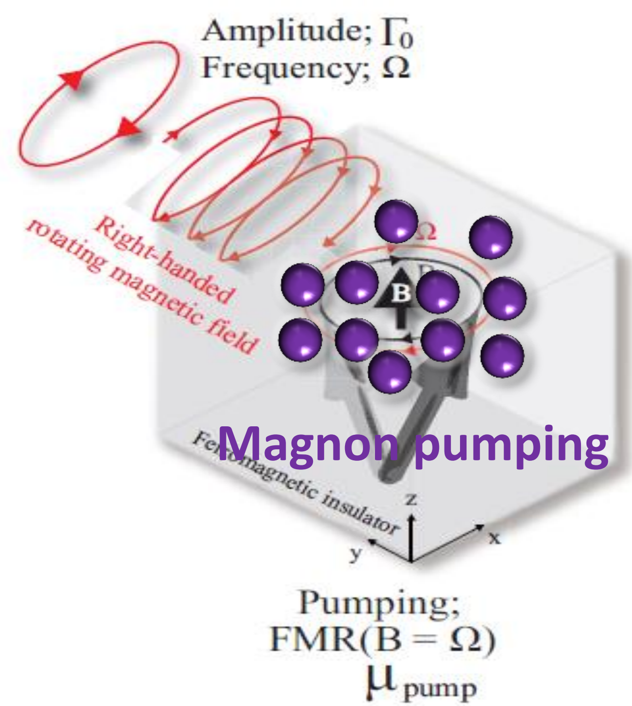


"Room temperature"

Magnons

Pumping **Gas** **BEC**

Gaseous magnon; I guess that magnons due to finite temperature



THEIR MOTIVATION

Experiment

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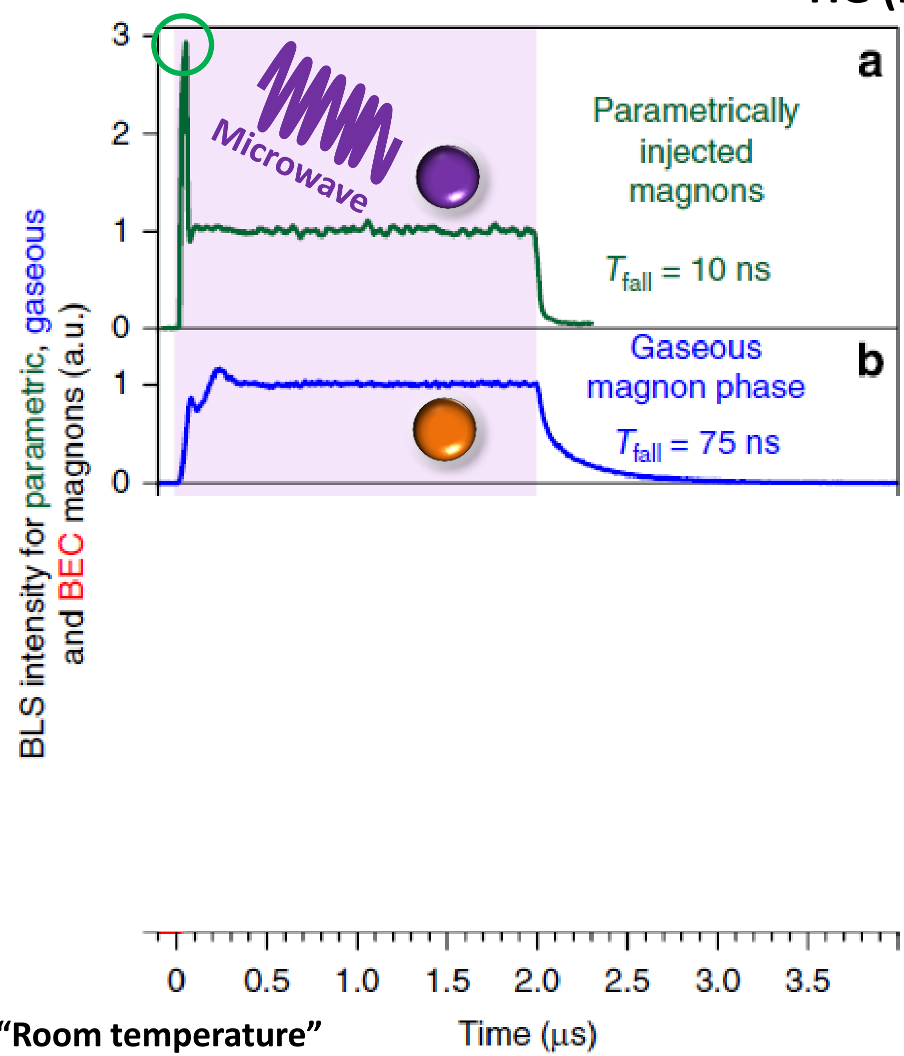

"Room temperature"

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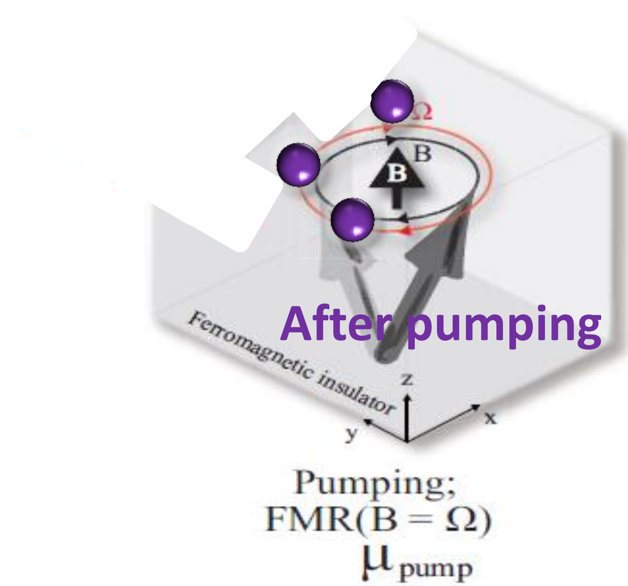
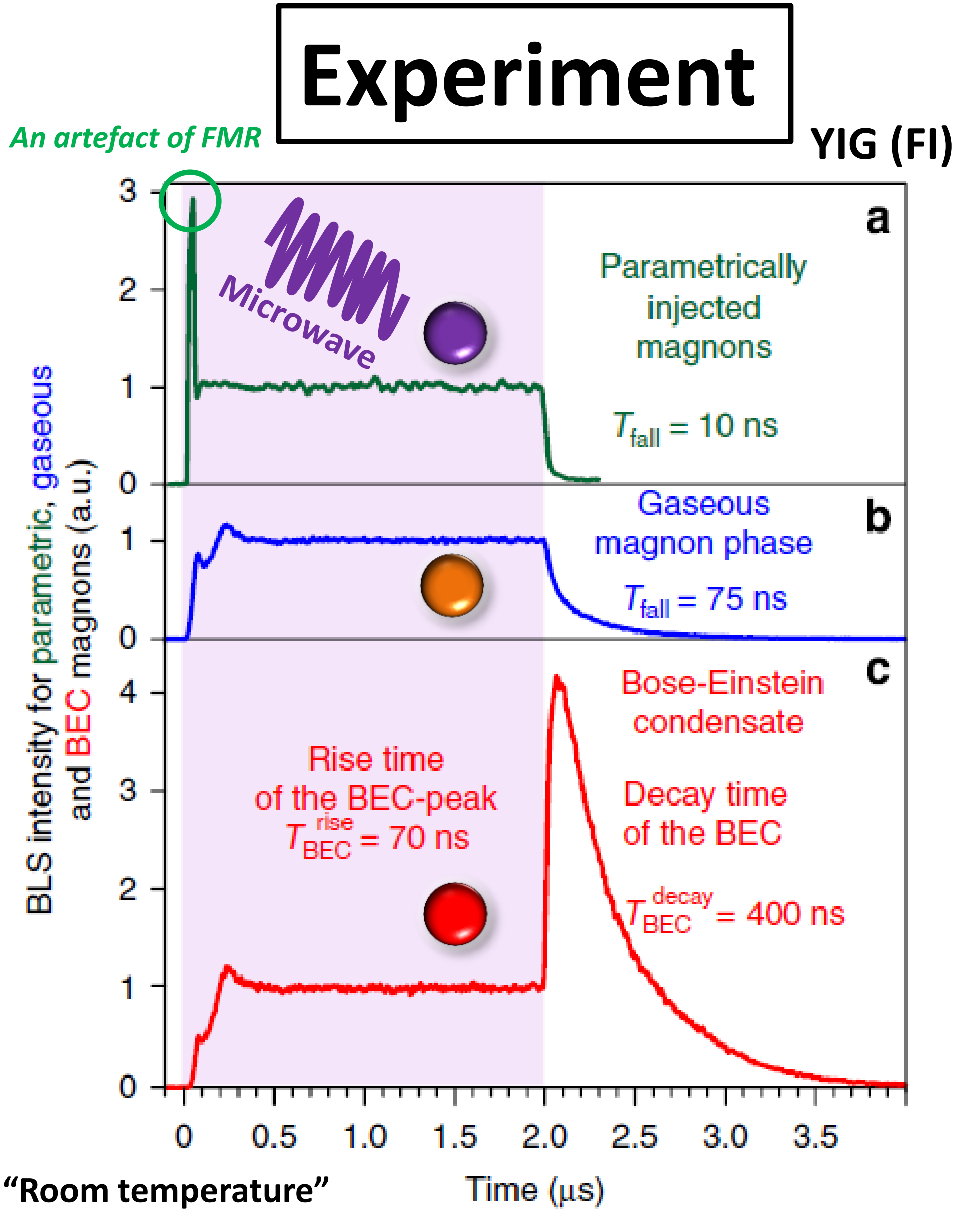


THEIR MOTIVATION



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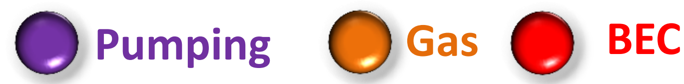

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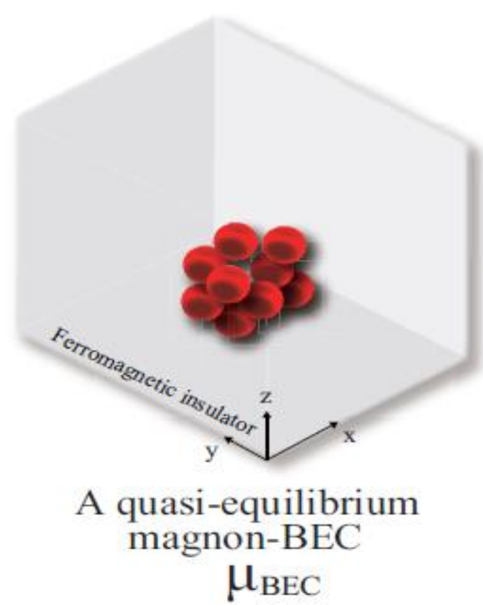
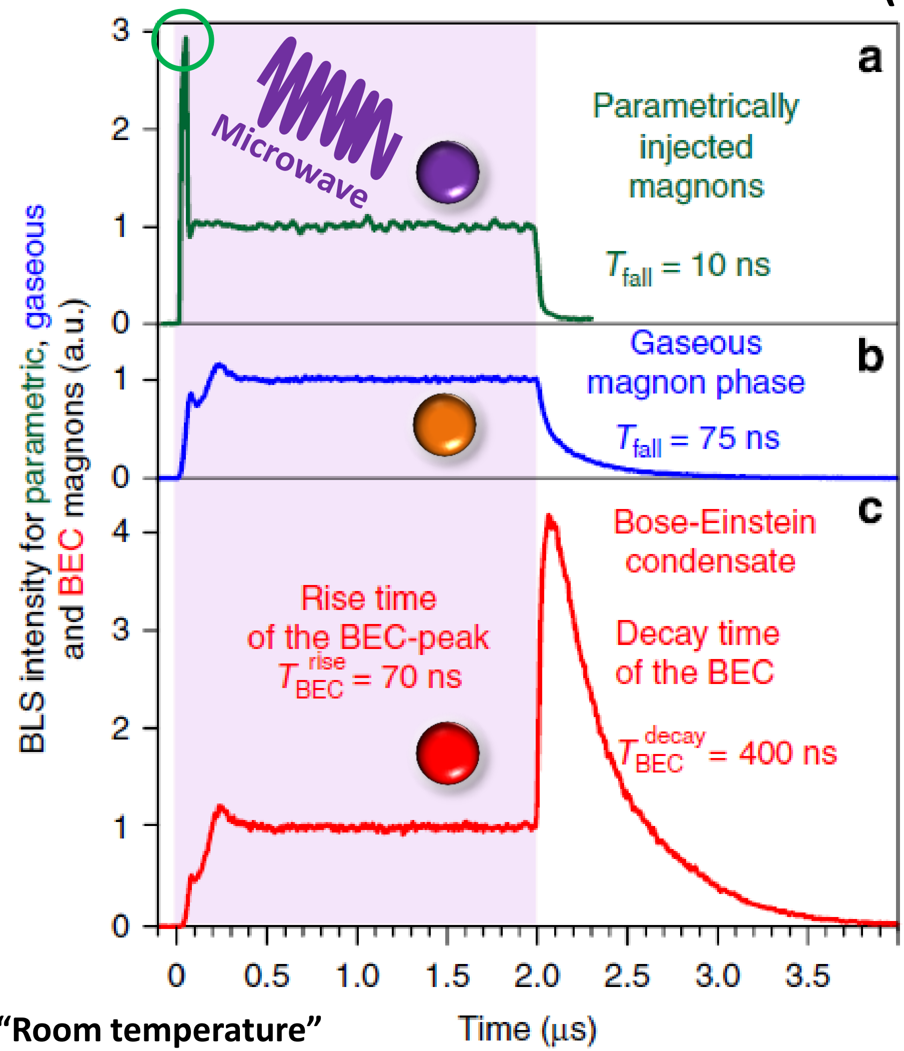


THEIR MOTIVATION

Experiment

An artefact of FMR

YIG (FI)



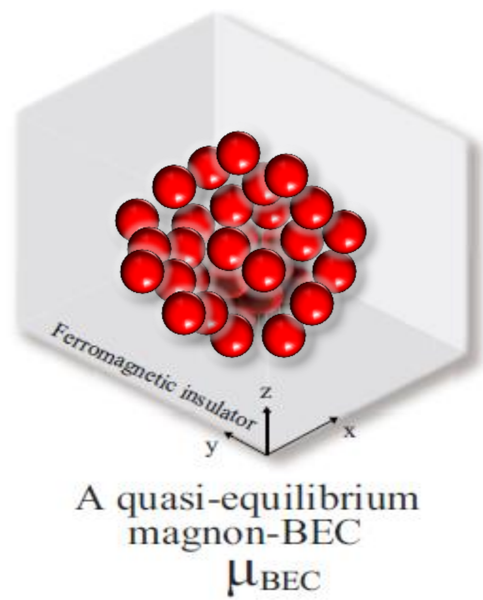
"Room temperature"

Magnons

Pumping **Gas** **BEC**

Gaseous magnon; I guess that magnons due to finite temperature

After pumping



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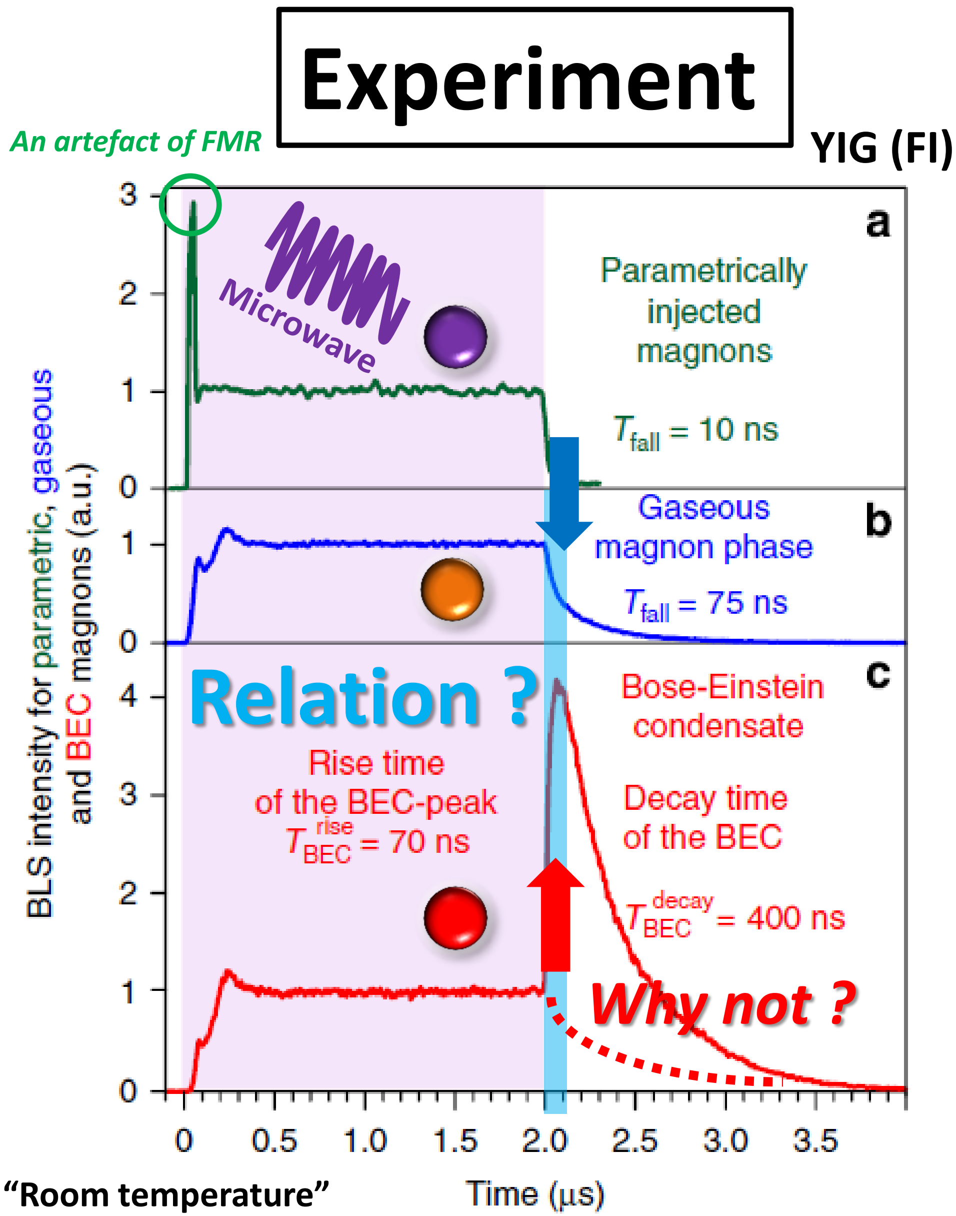

Magnons

Pumping Gas BEC

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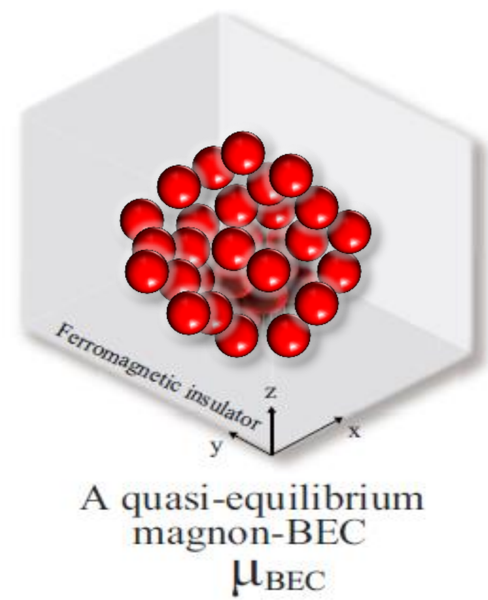

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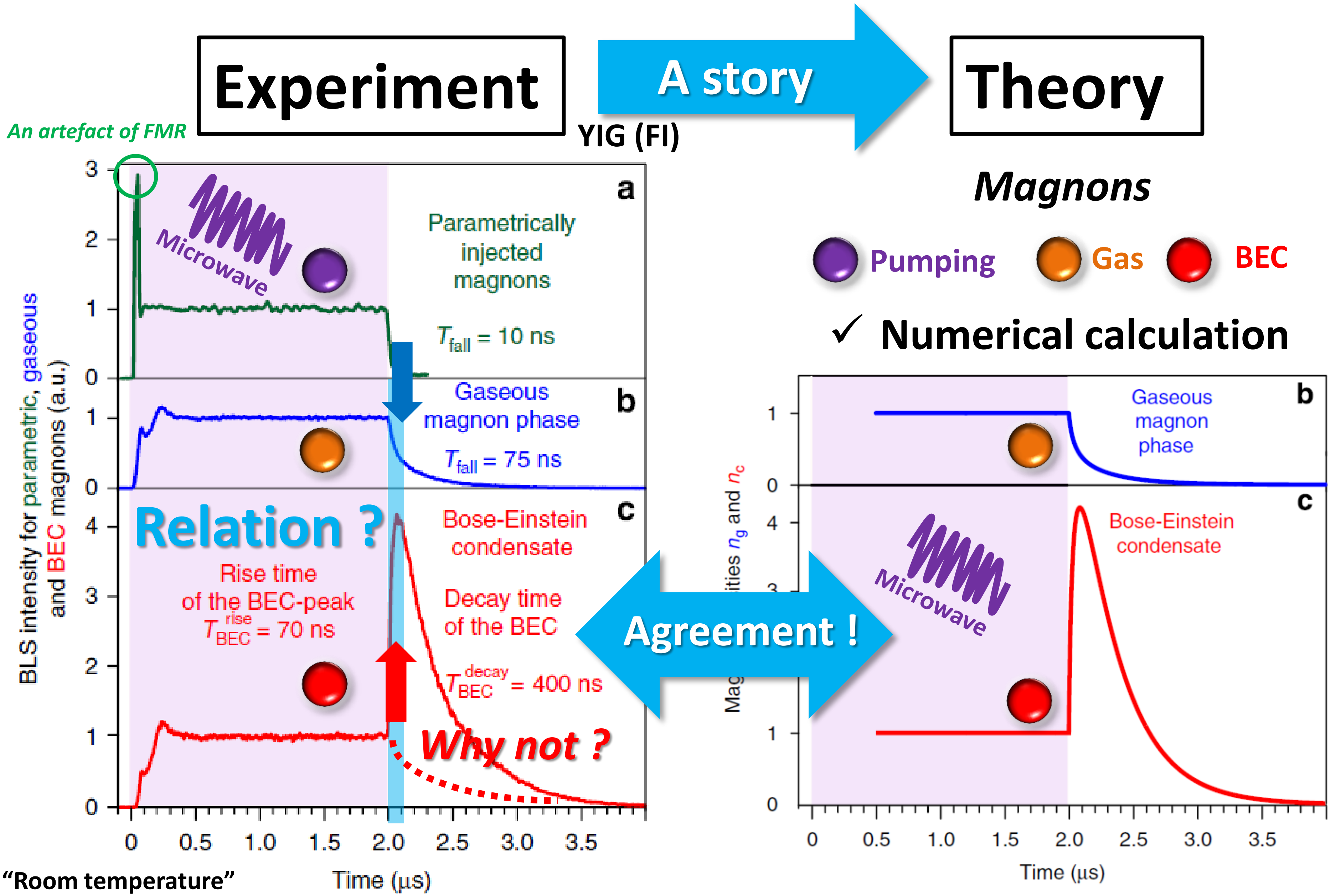


THEIR QUESTIONS

✓**After magnon pumping,**
why the number of magnon-BEC "*increases*" ?

→ In sharp contrast to **magnon gases** (i.e. non-condensed magnons)

⬇

✓**What is the *mechanism (i.e. story)* that connect**
pumping and magnon-BEC ?

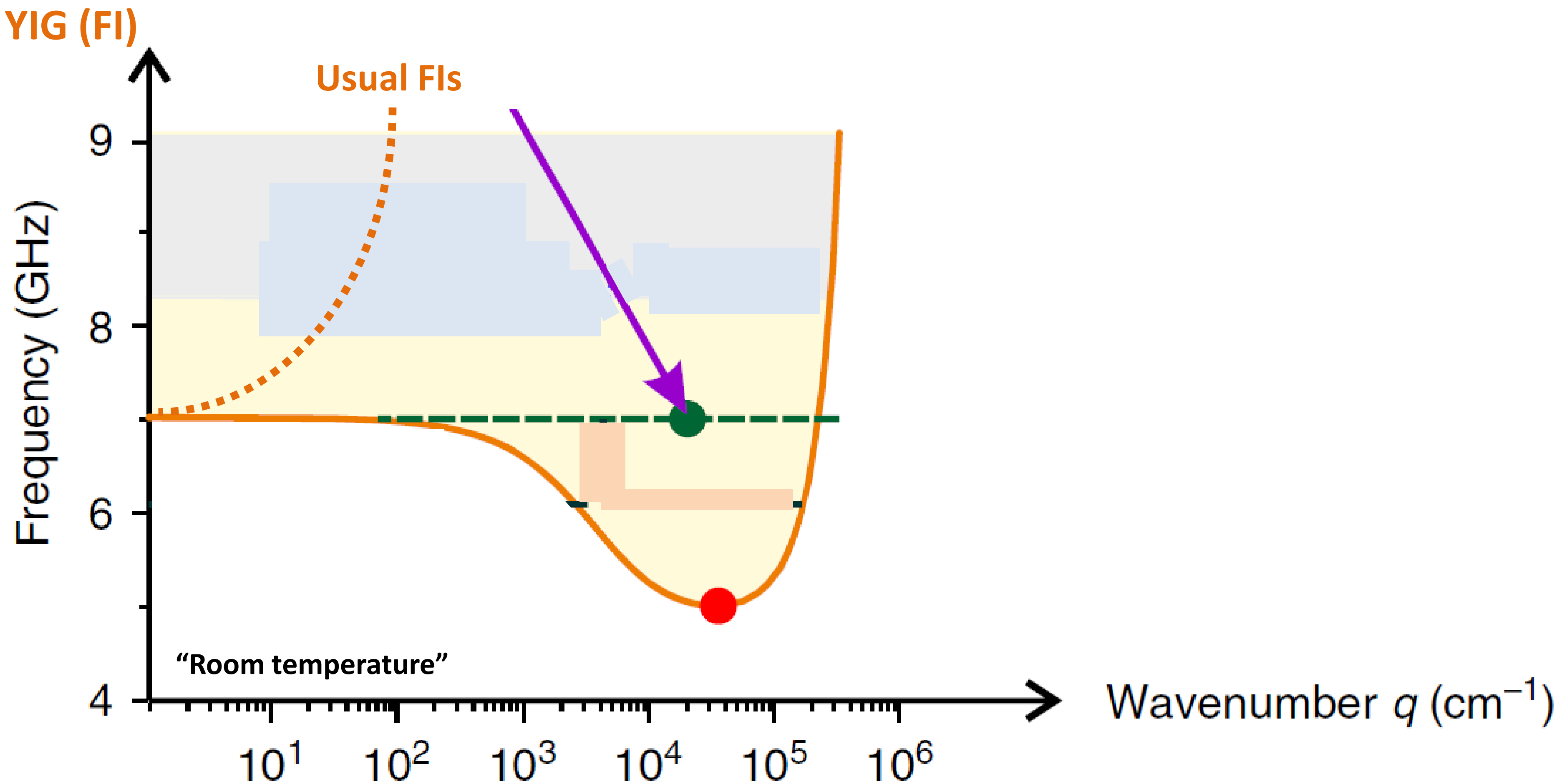
■ *Their story*

Evaporative supercooling

[Nature communication **5**, 3452 (2014).]

Evaporation & Supercooling

Pumping → Evaporation & Supercooling → Magnon-BEC



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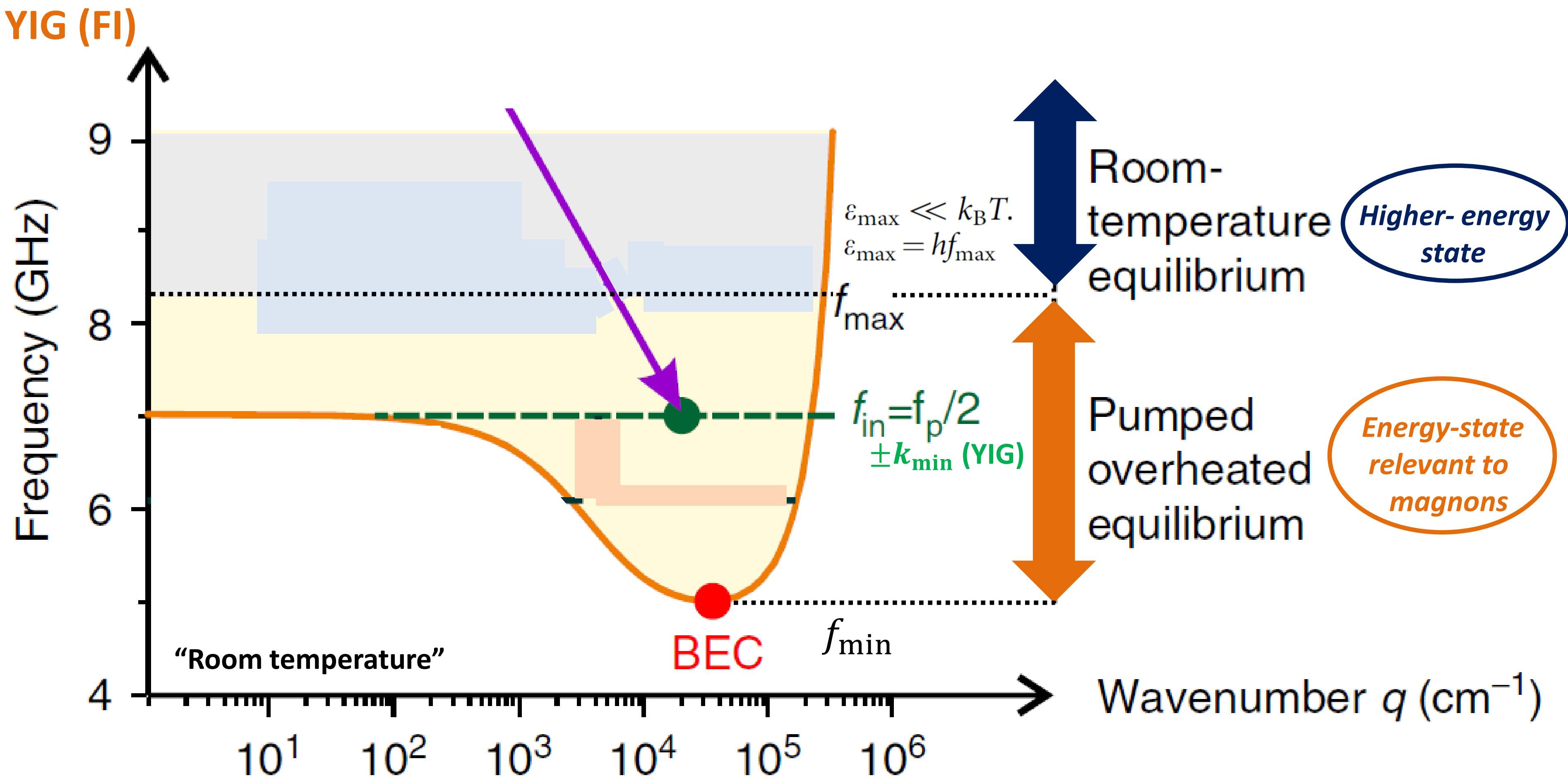

Evaporation & Supercooling

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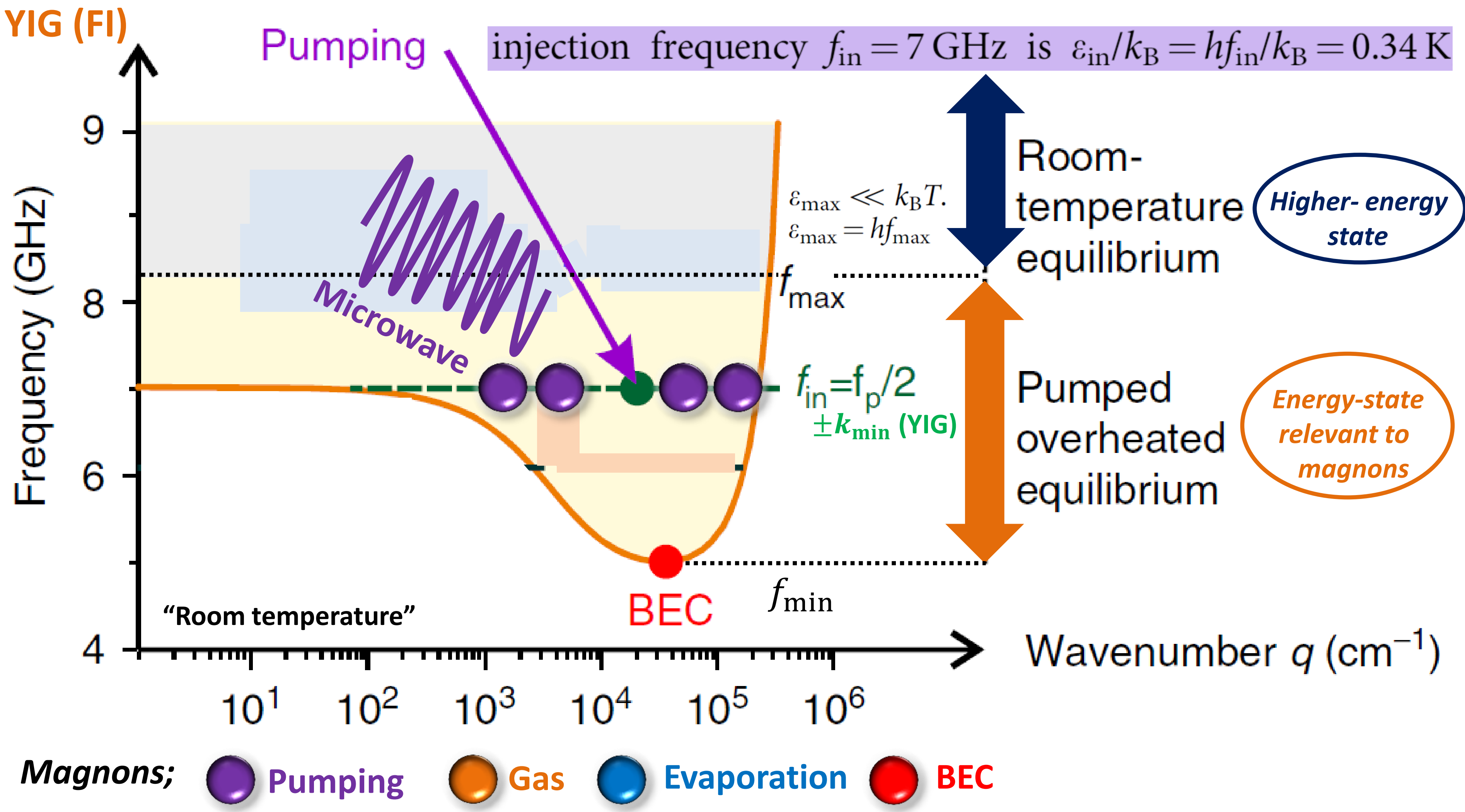

Evaporation & Supercooling

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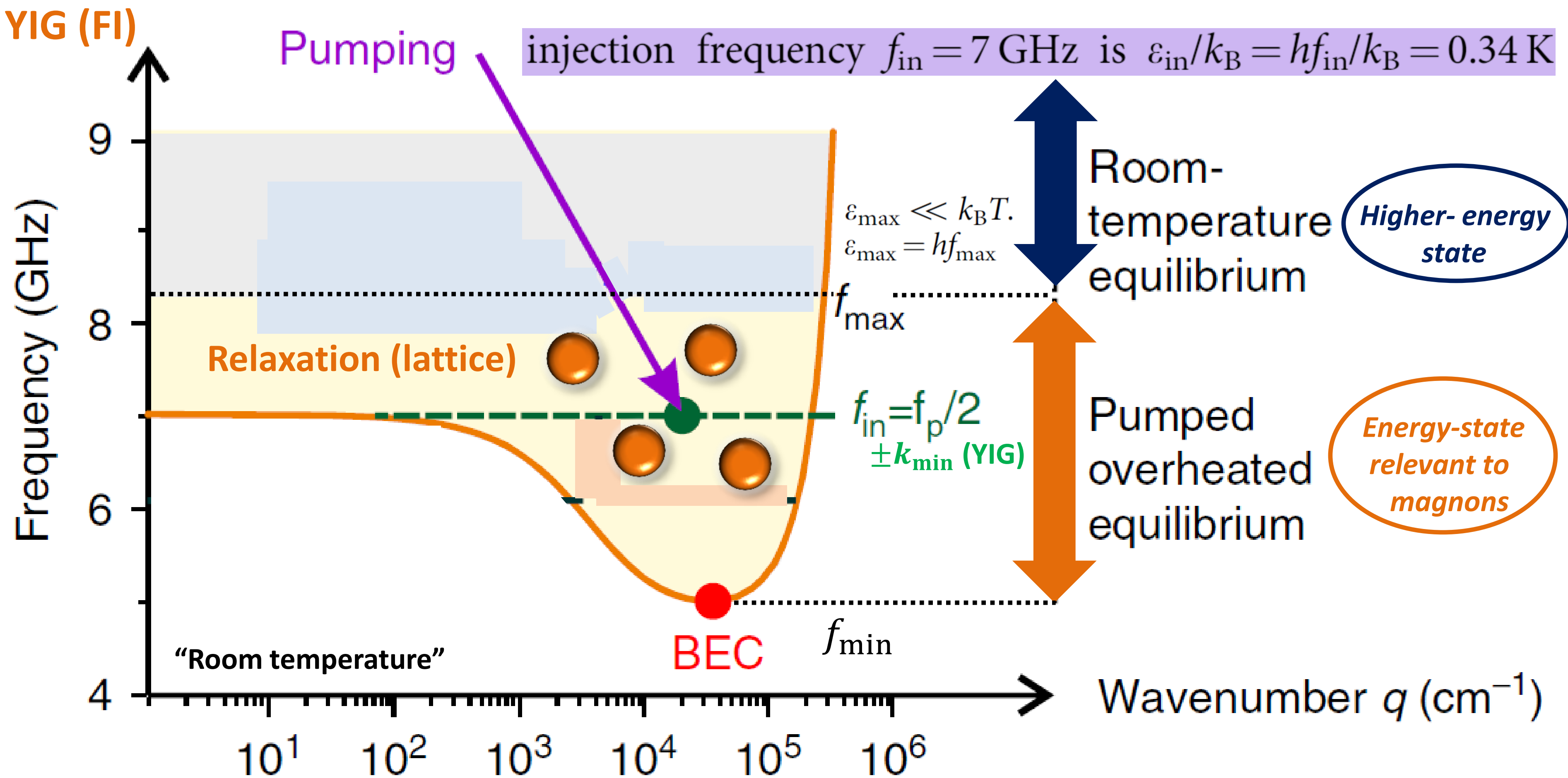

Magnons; Pumping Gas Evaporation BEC

Evaporation & Supercooling

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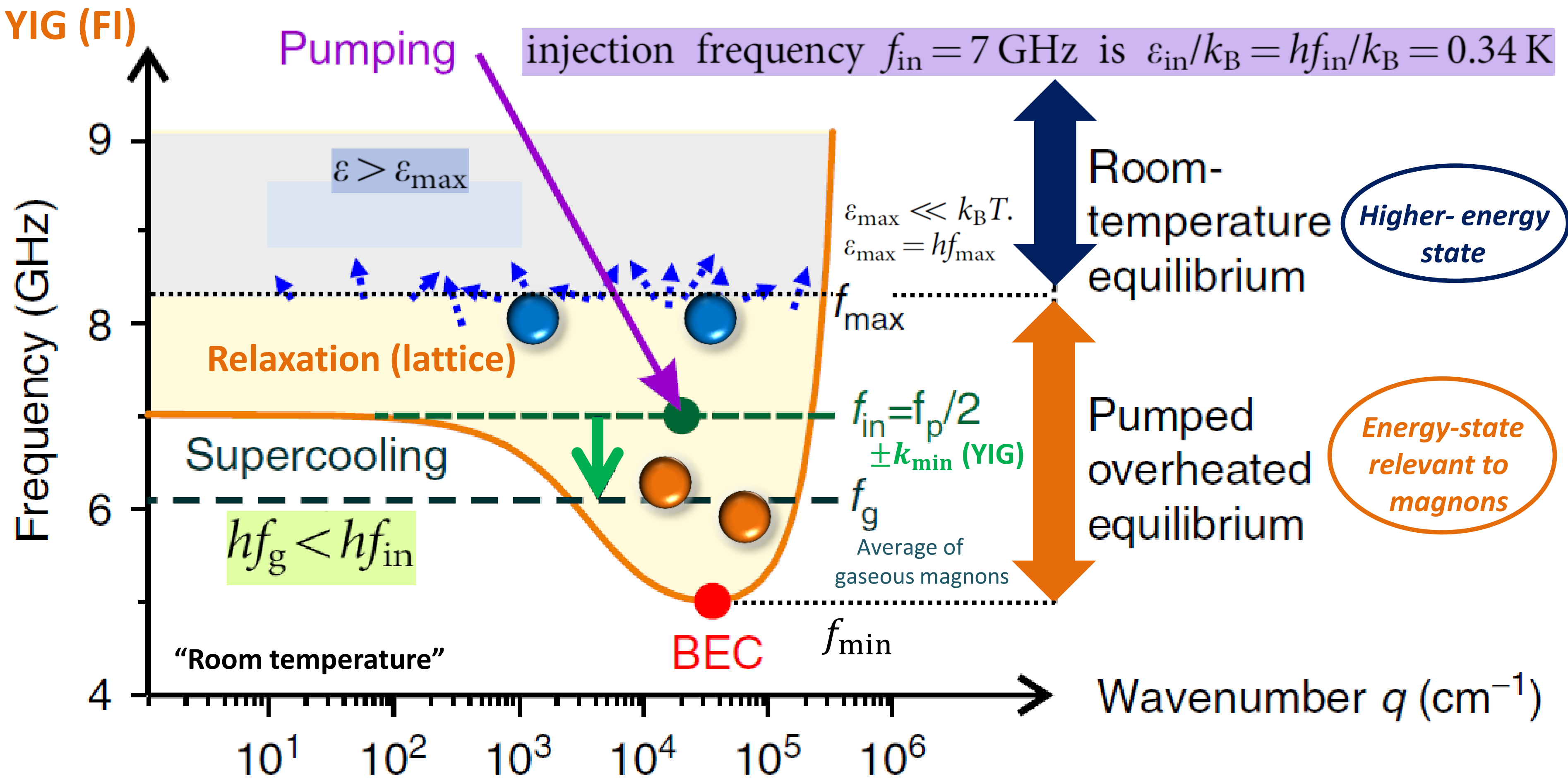

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Evaporation & Supercooling

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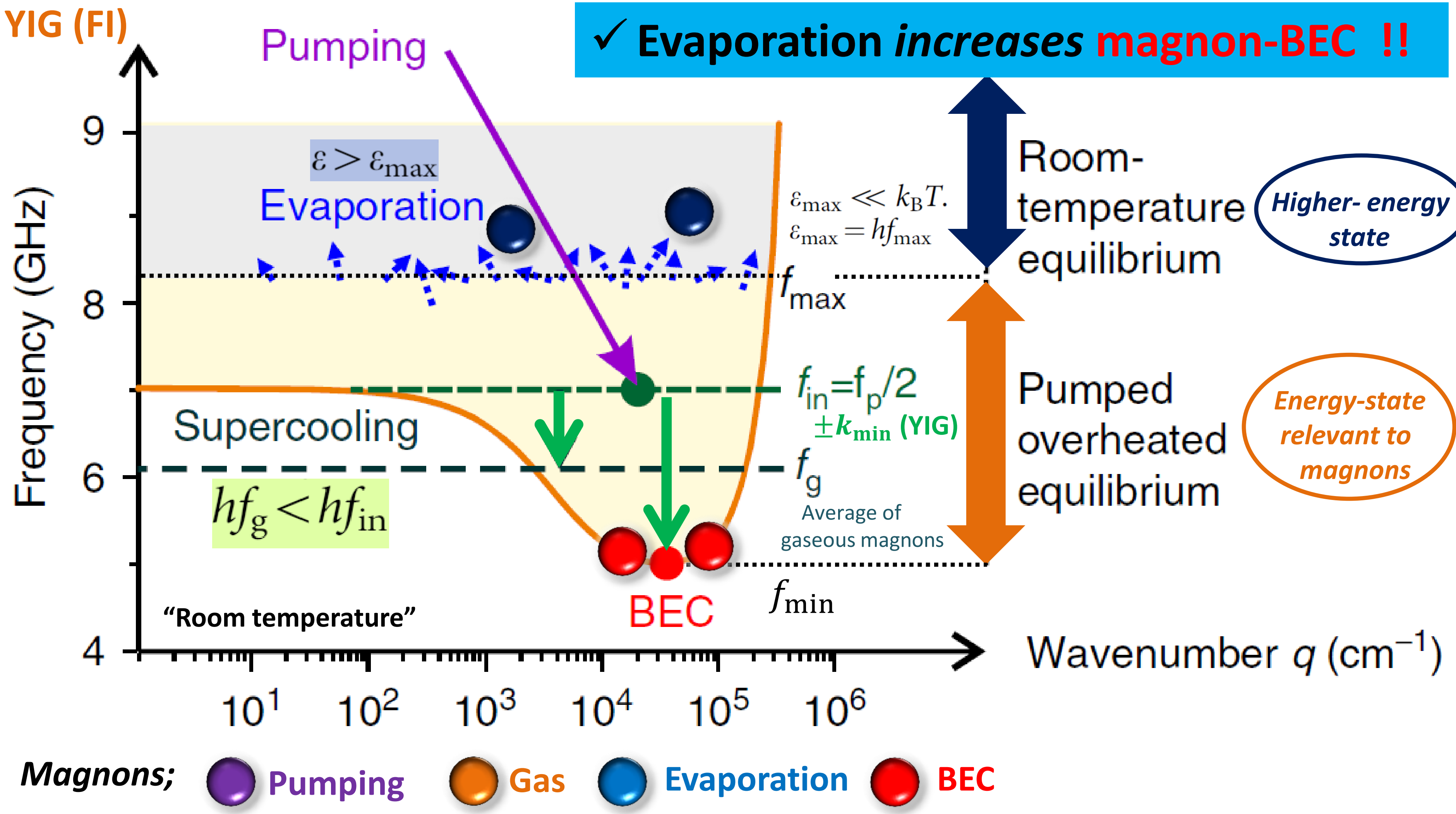


GUIDING PRINCIPLE

To construct a model to explain the experimental results

Pumping → Evaporation & Supercooling → Magnon-BEC

✓ **Pumping** ***decreases*** **BEC**

→**Pumping** corresponds to an **"energy-injection".**

injection frequency $f_{\mathrm{in}} = 7\,\mathrm{GHz}$ is $\varepsilon_{\mathrm{in}}/k_{\mathrm{B}} = hf_{\mathrm{in}}/k_{\mathrm{B}} = 0.34\,\mathrm{K}$

✓ After **pumping**,

BEC ***increases*** through **"evaporative supercooling"**

Key point (origin)

Spin-lattice relaxation; Γ

Relaxation time; **400 ns**

→ Much longer !

- ***Their Theoretical Model***

Theoretical Model; Rate Eq.

Pumping → Evaporation & Supercooling → Magnon-BEC

- **BEC** n_c; normalized number of condensed magnons (i.e. magnon-BEC density)
- **Gas** n_g; normalized number of gaseous (i.e. non-condensed) magnons
- **Pumping** n_{in}; normalized number of pumped magnons

Γ; Spin-lattice relaxation rate (energy-independent frequency)

✓ Pumping **decreases** BEC
→ [pumping]~ [energy-injection]

$$\frac{1}{\Gamma}\frac{dn_c}{dt} = -\lambda n_{in}(t) - n_c + n_g^3$$

$$\frac{1}{\Gamma}\frac{dn_g}{dt} = n_{in}(t) - n_g - n_g^3.$$

Regarding the def. of dimensionless densities, please see their paper.

$0 < \lambda < 1$

Evaporation (i.e. Non-linear scattering)

✓ **"Evaporation"** ***increases*** **BEC**

■ ***Check !***

✓ **Stationary state under pumping (i.e. $\dot{n}_c = 0$);** $-n_c + n_g^3 = \lambda n_{in} > 0$

✓ **Their *story* looks good !**

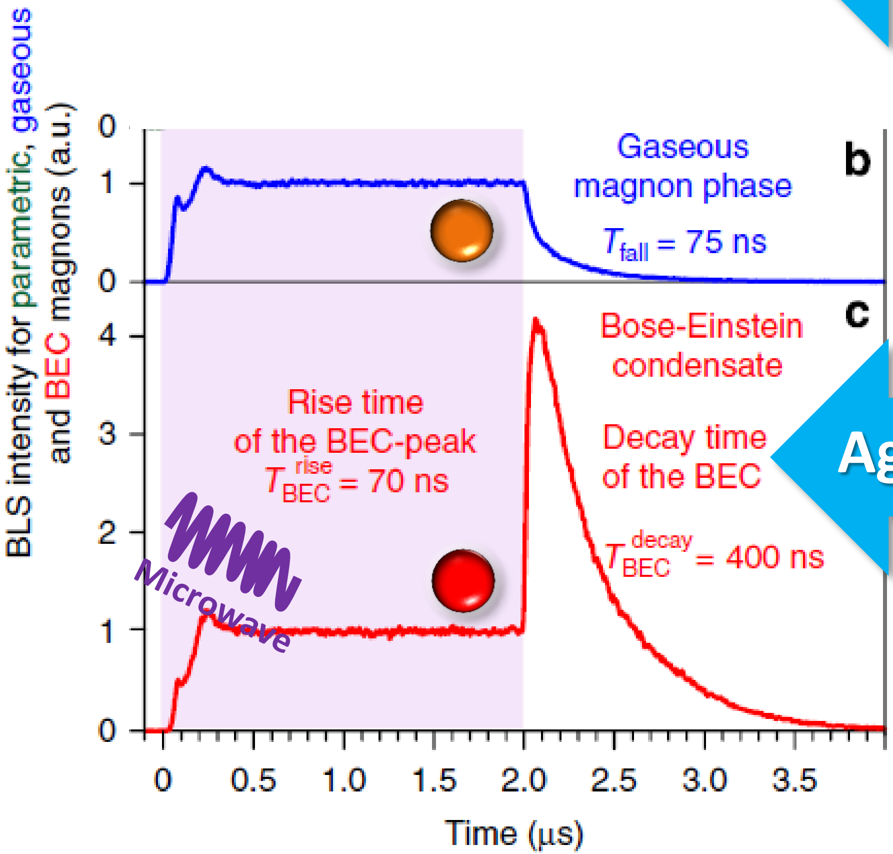
✓ **Immediately after pumping (i.e. $n_{in} = 0$);** $\frac{1}{\Gamma}\frac{dn_c}{dt} = -n_c + n_g^3 > 0$

Magnon-BEC increase !

Numerical Calculation

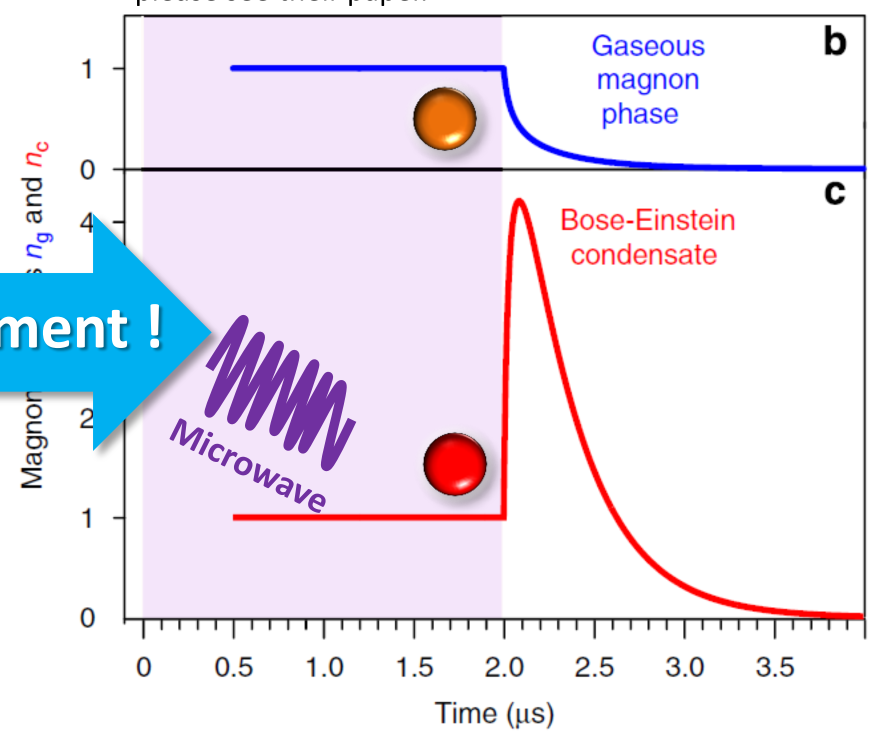
✓ Their *story "Evaporative supercooling"* looks good !

Experiment ⟷ **Agreement !** ⟷ **Theory**



Agreement !

Regarding the def. of dimensionless magnon densities, please see their paper.



$\Gamma = 3.1\ \mu s^{-1},\ n_{in} = 2.34\quad \lambda = 0.83$

CONCLUSION

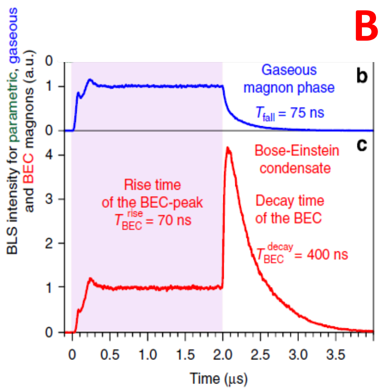
Pumping → Evaporation & Supercooling → Magnon-BEC

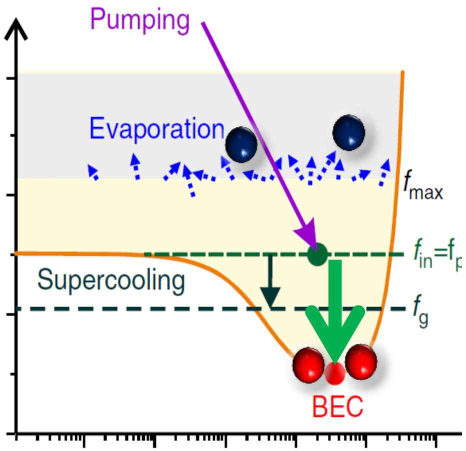
✓ **Pumping *decreases* BEC**

→**Pumping** corresponds to an **"energy-injection".**

✓ After **pumping**,

BEC *increases* through **"evaporative supercooling"**





Key points

- **Spin-lattice relaxation; Γ**
- **Unusual dispersion relation of YIG**

✓ Their theoretical model (rate Eq.) shows a nice agreement with the experiment.

- My opinion - ***Thank you for your attention !***

- ***Microscopic analysis** of evaporation will be interesting (important).*
- *This phenomenon **(evaporative super-cooling)** will be **particular to YIG**, which has an unusual dispersion relation with the ordinal FIs.*

Appendix

GS of YIG; Double Degeneracy

S. O. Demokritov *et al.*, Nature **443**, 430 (2006).

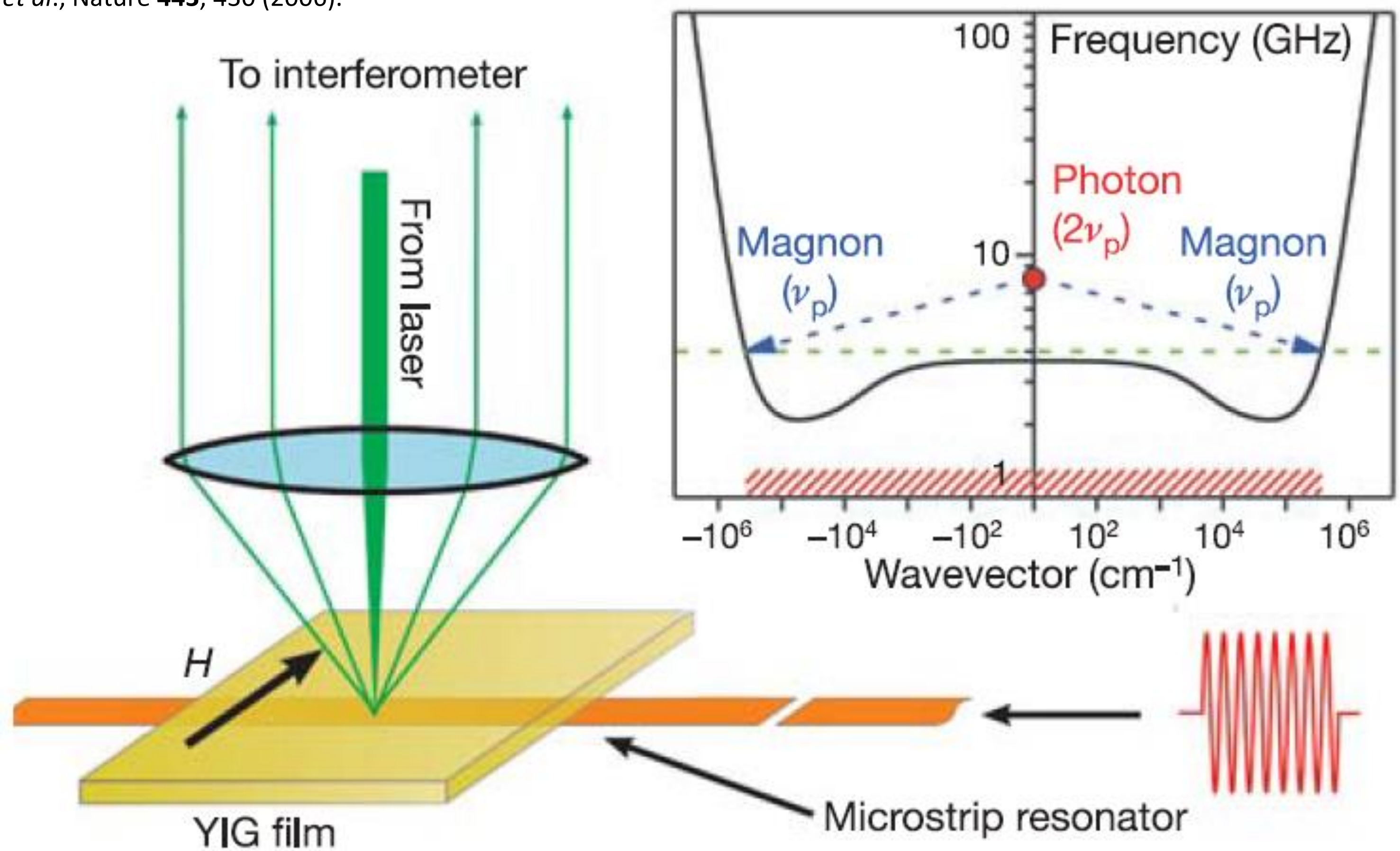


Figure 1 | The set-up for magnon excitation and detection. The resonator attached to the bottom of the yttrium–iron–garnet (YIG) film is fed by microwave pulses. The laser beam is focused onto the resonator, and the scattered light is directed to the interferometer. Inset, the process of creation of two magnons by a microwave photon. The low-frequency part of the magnon spectrum for the applied field H, parallel to the film surface is shown by the solid line. It has a minimum at the wavevector $k_m = 5 \times 10^4\ cm^{-1}$. The wavevector interval indicated by the red hatching corresponds to the interval of the wavevectors accessible for Brillouin light scattering (BLS).

Ultra-Hot Gas of Pumped Magnons (?)

$$\varepsilon_{\max} \ll k_B T.$$

Rayleigh–Jeans distribution:

$$n(\varepsilon) = k_B T / (\varepsilon - \mu).$$

the increase in the driven magnon population when the BEC is formed ($\mu = \varepsilon_{\min}$) relative to its room-temperature density ($T = 300$ K, $\mu = 0$) can be written as

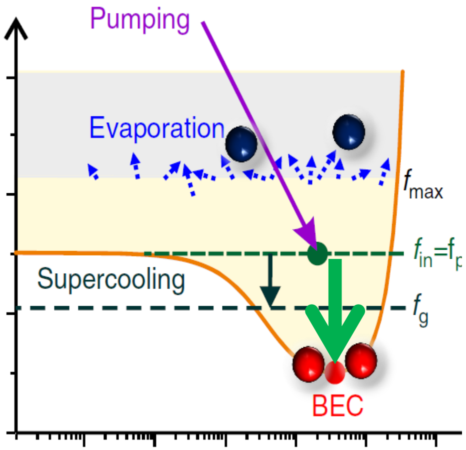
Gaseous (i.e. thermal) magnons at room temperature

$$\frac{n(\varepsilon)}{n_0(\varepsilon)} = \frac{\varepsilon}{\varepsilon - \varepsilon_{\min}} \frac{T}{300\ \mathrm{K}}$$

the room-temperature population n_0 (ε)

$\varepsilon/h = 6$ GHz, $\varepsilon_{\min}/h = 5$ GHz) $\varepsilon/(\varepsilon - \varepsilon_{\min}) \sim 6$

$$\frac{n(\varepsilon)}{n_0(\varepsilon)} = \frac{T}{50\ \mathrm{K}}$$



- ✓ The density of the gaseous magnon phase is seen to increase **666 times** during the pumping pulse.
- → Implying that **the effective temperature** of the pumped magnon gas is

$$T \approx 30{,}000\ \mathrm{K}.$$