Quantum Simulations with Ions

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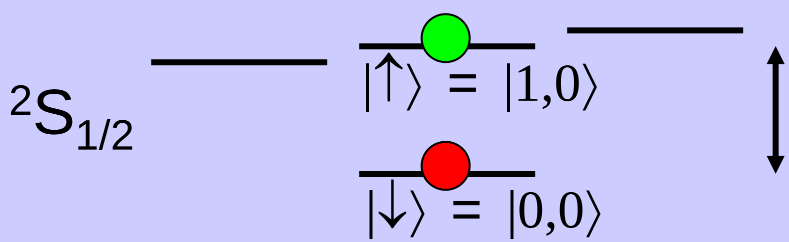
JOINT QUANTUM INSTITUTE

National Institute of Standards and Technology

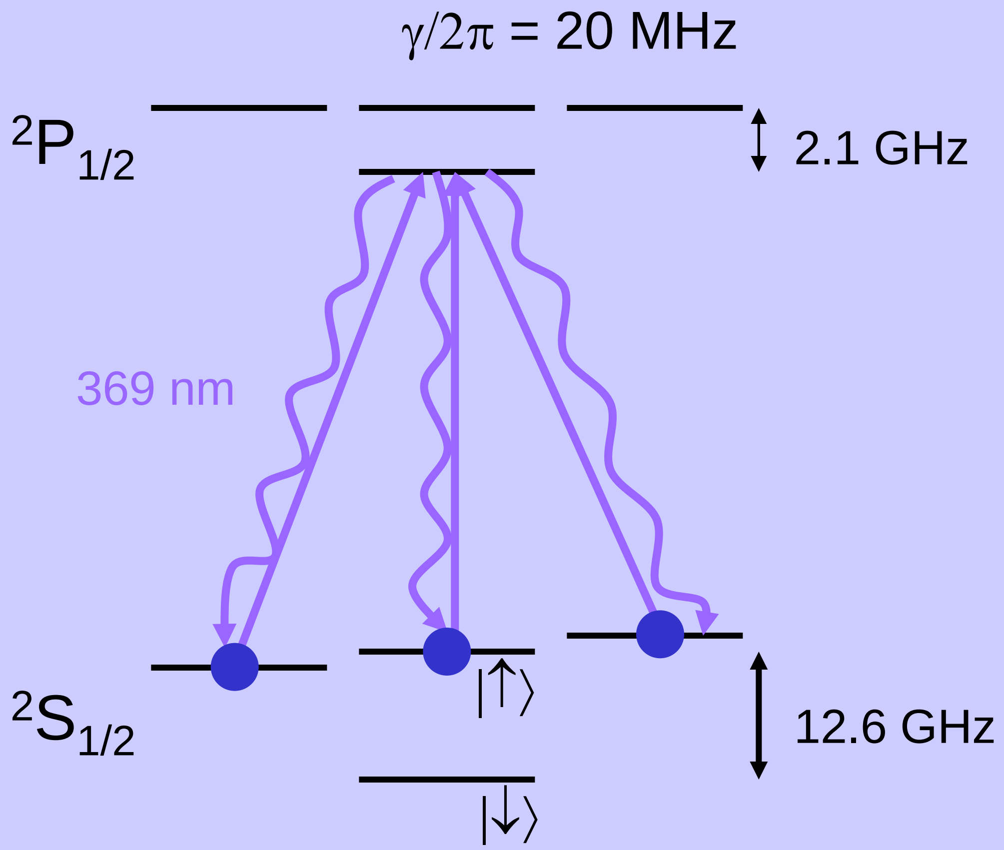
$^{171}Yb^{+}$ hyperfine qubit

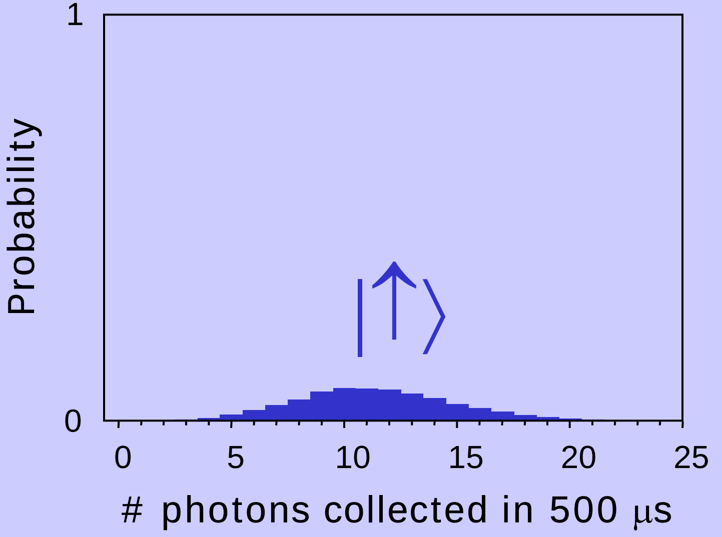


ν_{HF} = 12,642,812,118 + $311B^2$ Hz

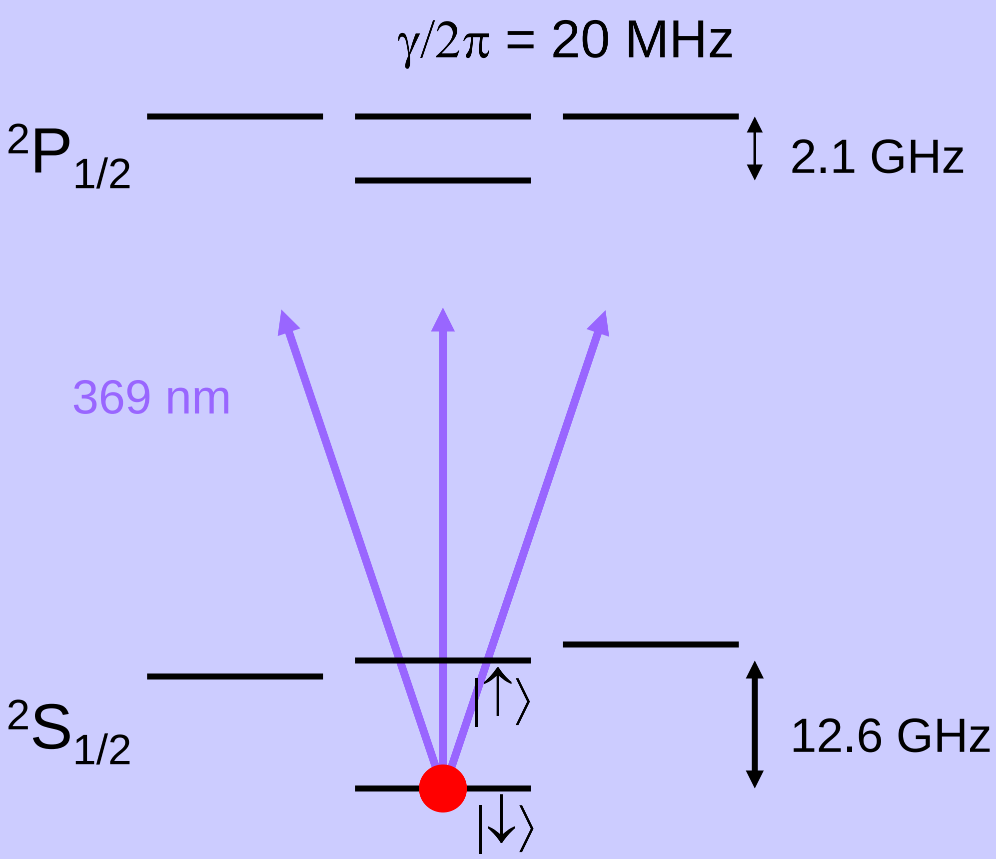
(3 kHz/G @ 5 G)

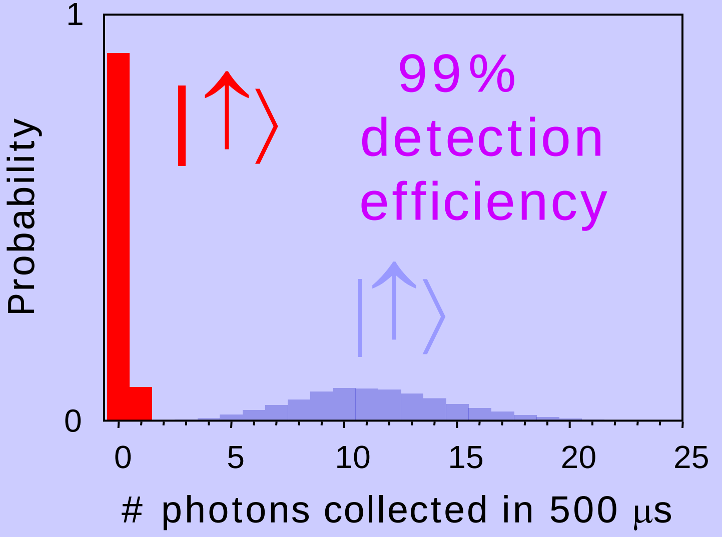
$^{171}Yb^{+}$ qubit detection



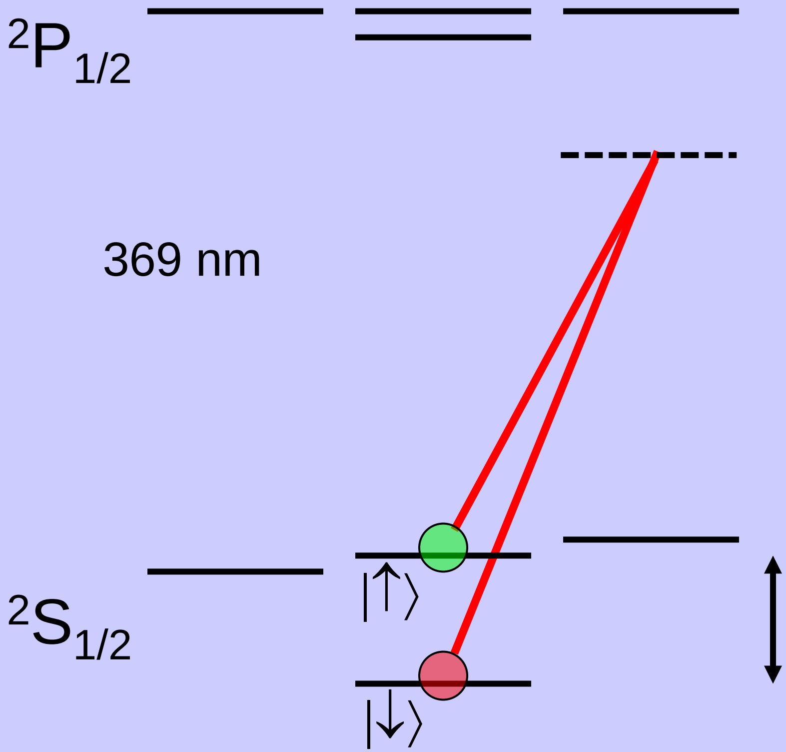


$^{171}Yb^+$ qubit detection





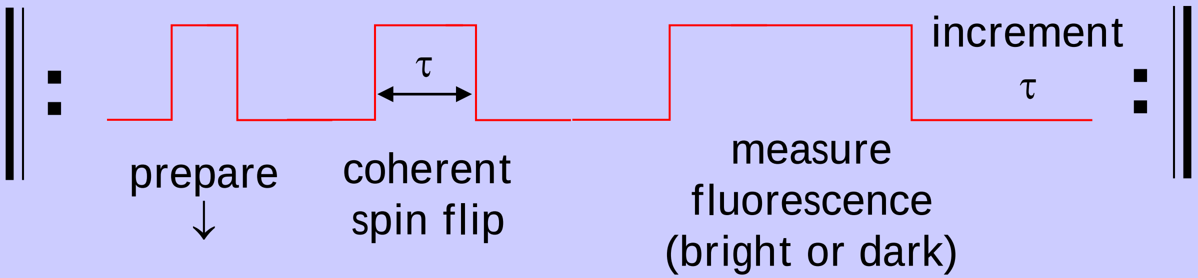
$^{171}Yb^{+}$ qubit manipulation

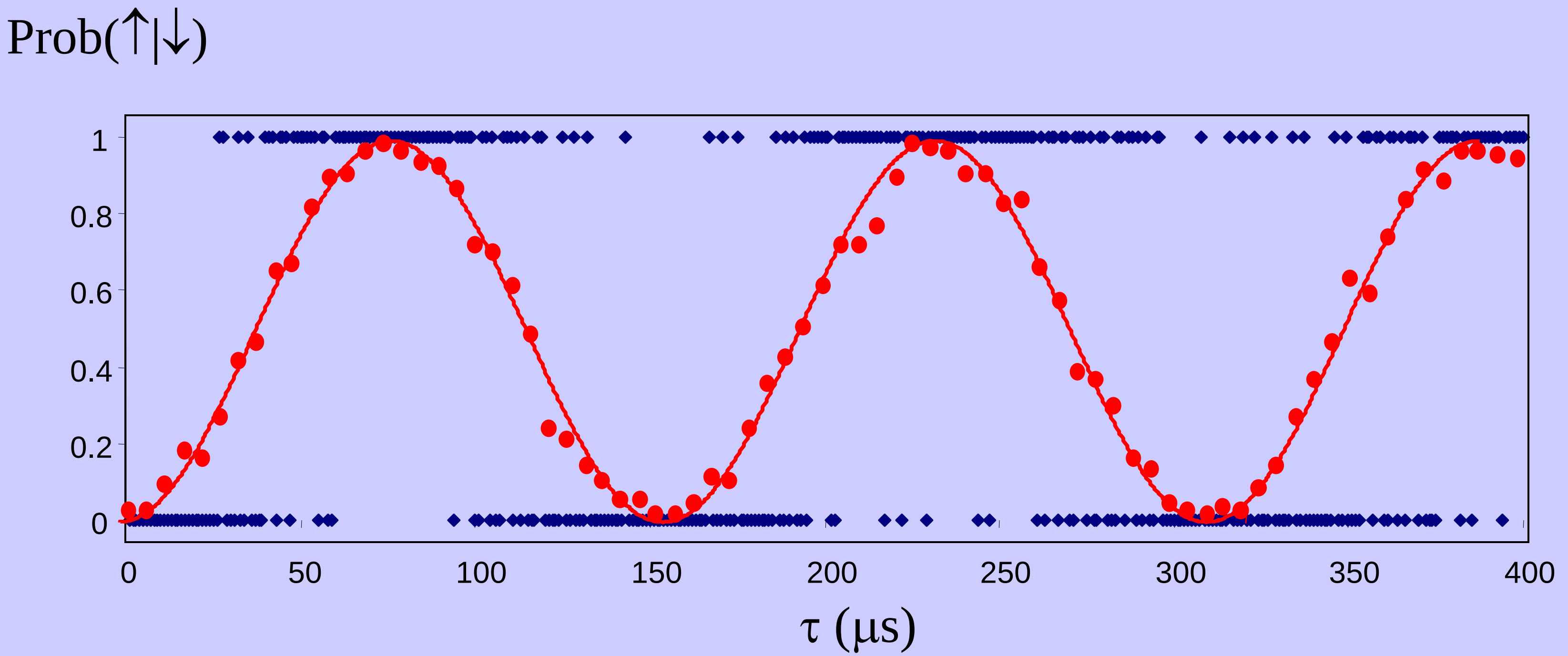


ν_{HF} = 12,642,812,118 + $311B^2$ Hz

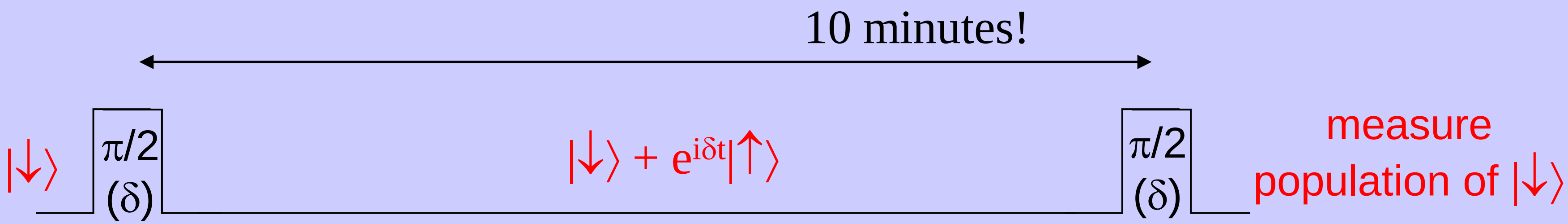
(3 kHz/G @ 5 G)

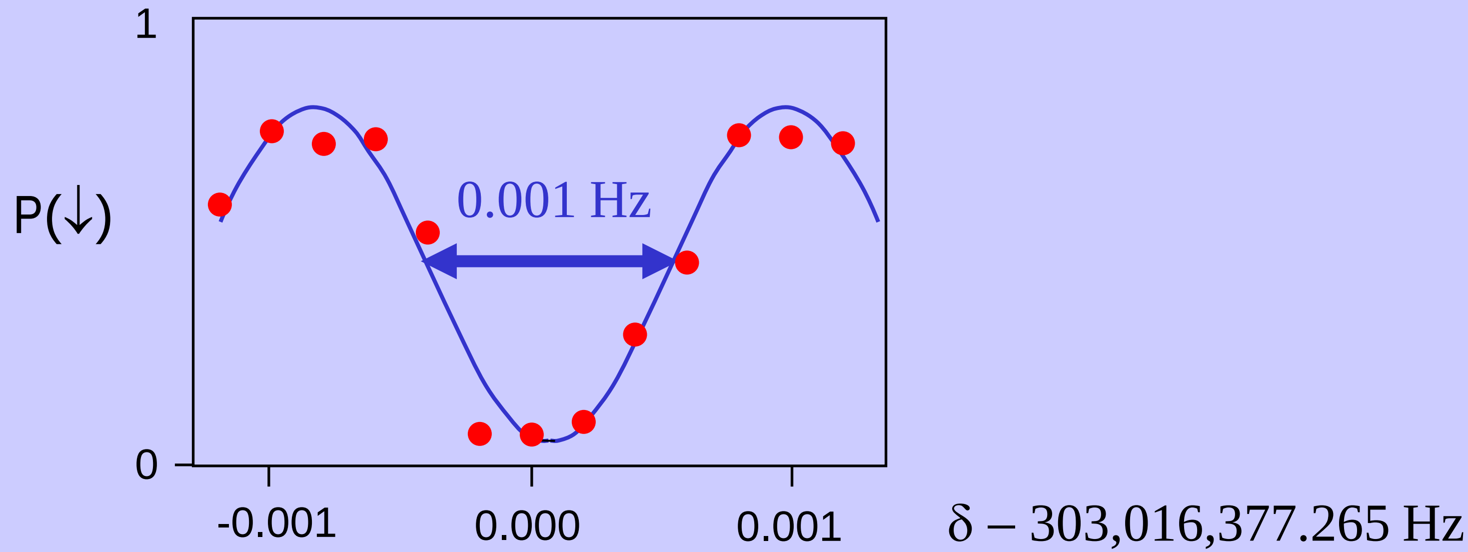
"Single shot" Rabi Flopping with 1 atom





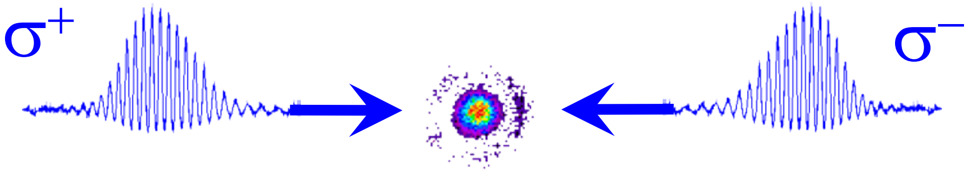
Atomic ion clockwork



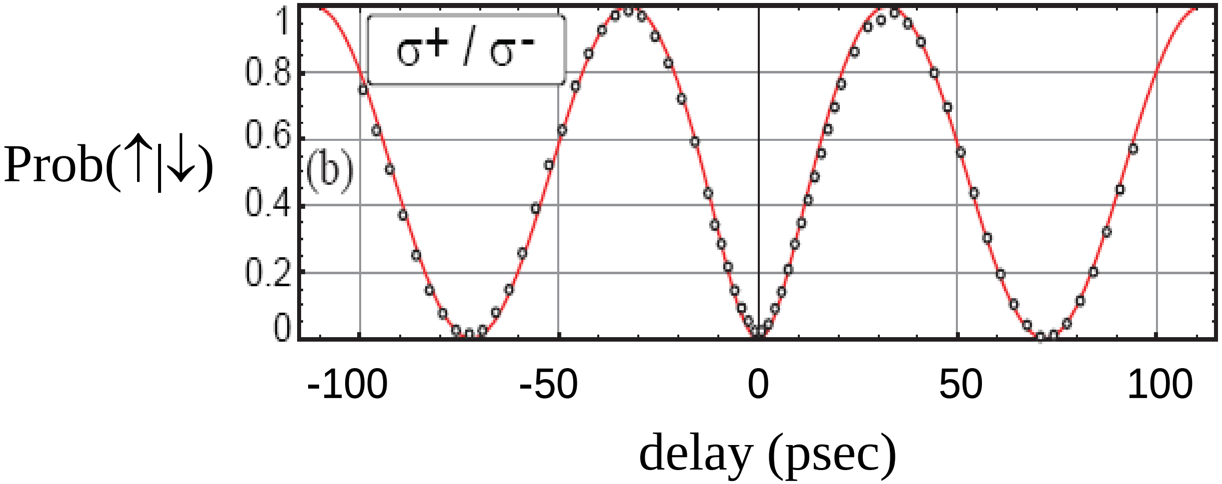


^{9}Be^{+}: J. J. Bollinger, et al., IEEE Trans. Inst. Meas. 40, 126 (1991).
^{171}Yb^{+}: P. Fisk, et al., IEEE Trans. Ultras., Ferroel., and Freq. 44, 344 (1997).

Controlling a qubit with ultrafast optical pulses



two pulses
(each ~10psec)

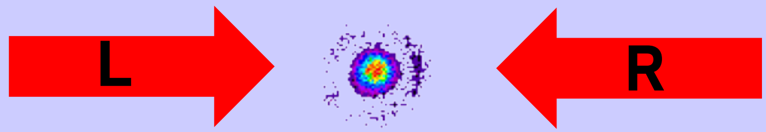


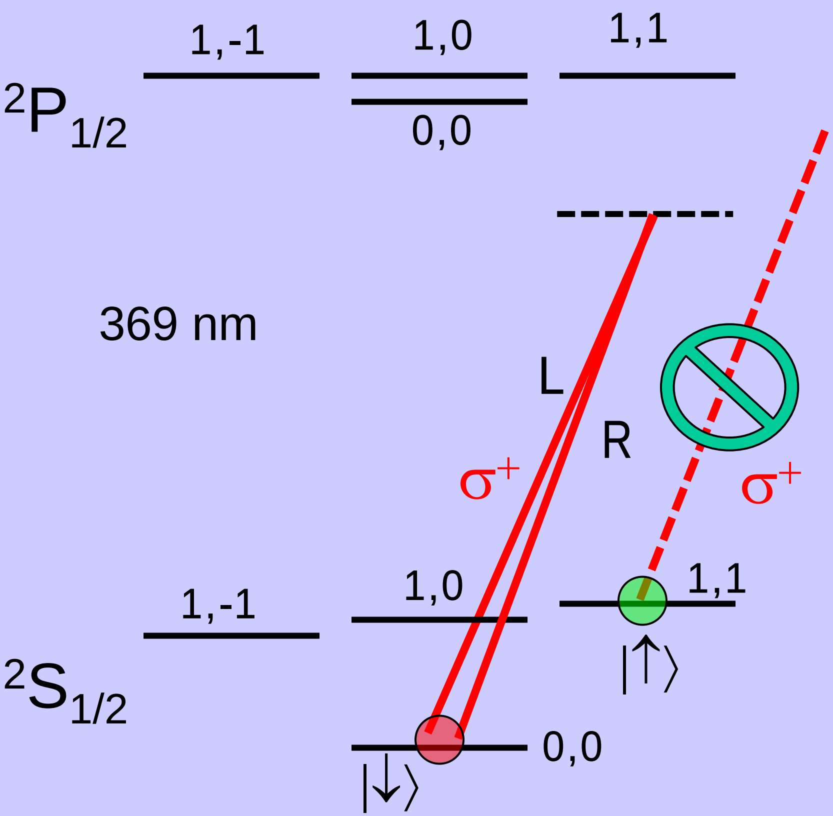
$$\frac{\tau_{decoh}}{\tau_{control}} > 10^{11}$$

W. C. Campbell, et al., Phys. Rev. Lett. (to appear, 2010); quant-ph/1005.4144

C. Senko POSTER

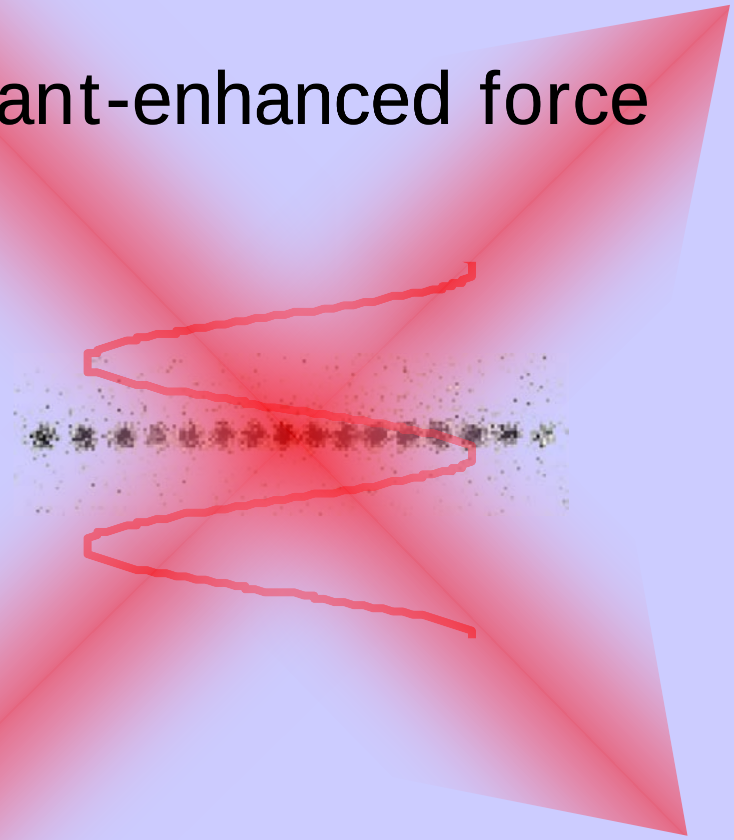
$^{171}Yb^+$ qubit manipulation





$$F = F_0 |\downarrow\rangle\langle\downarrow|$$

Resonant-enhanced force



Raman beatnote: μ

Lamb-Dicke approximation:

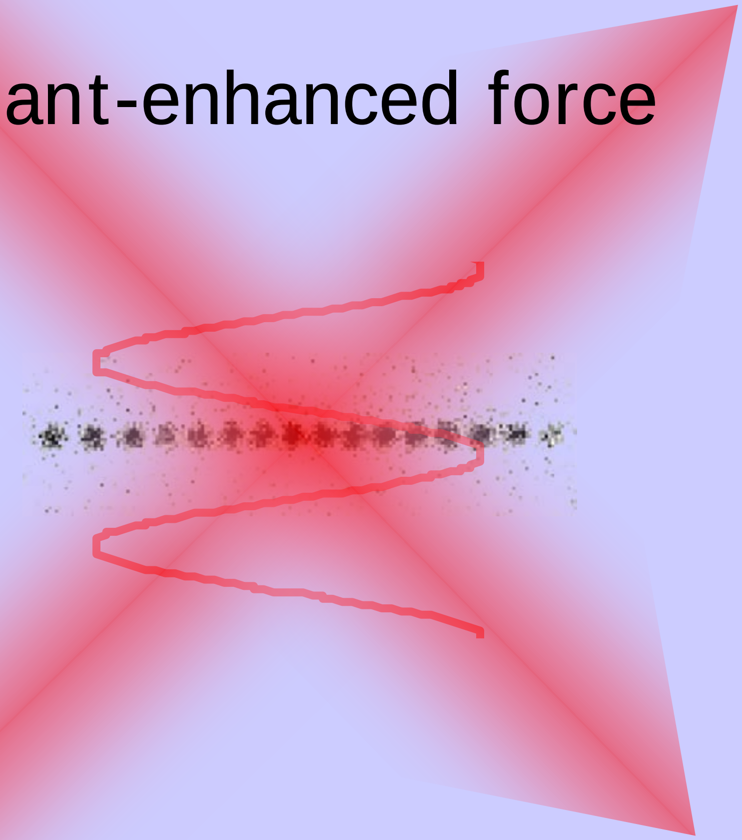
$$\Delta k x_{rms} << 1$$

$$H = \Delta k \sum_{i,k} \Omega_i \hat{\sigma}_z^{(i)} x_0^k b_i^k [a_k^\dagger e^{i(\mu-\omega_k)t} + a_k\, e^{-i(\mu-\omega_k)t}]$$

$x_0^k = \sqrt{\dfrac{\hbar}{2m\omega_k}}$

b_i^k: normal mode transformation matrix: ion i, mode k

Resonant-enhanced force



Raman beatnotes:
$\omega_{HF} \pm \mu$

Lamb-Dicke approximation:

$$\Delta k x_{rms} << 1$$

$$H = \Delta k \sum_{i,k} \Omega_i \hat{\sigma}_x^{(i)} x_0^k b_i^k [a_k^\dagger e^{i(\mu-\omega_k)t} + a_k e^{-i(\mu-\omega_k)t}]$$

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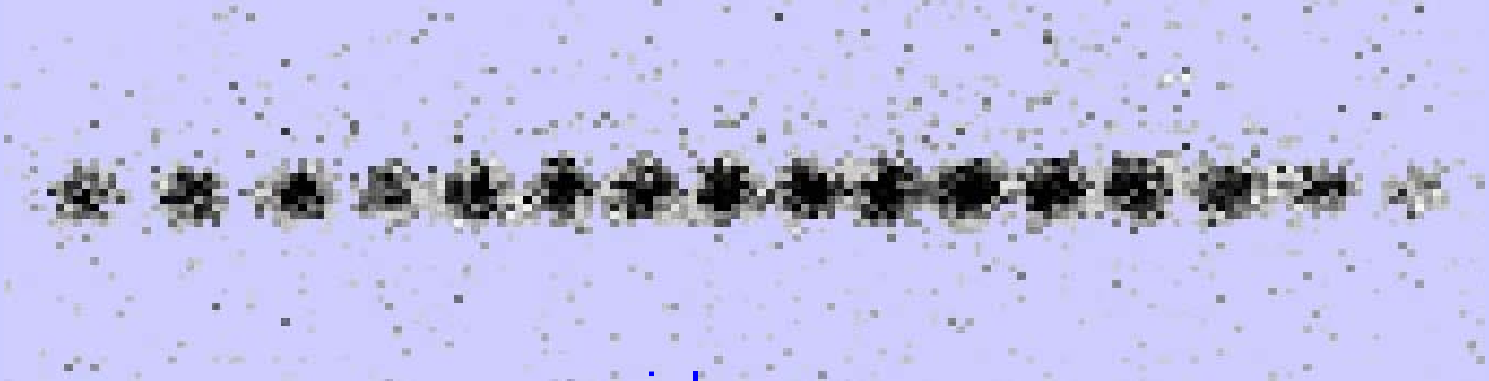
evolution $$U(\tau) = \exp\left[\sum_i \hat{\chi}_i(\tau)\sigma_x^{(i)} + i \sum_{i,j} \phi_{i,j}(\tau)\sigma_x^{(i)}\sigma_x^{(i)} \right]$$

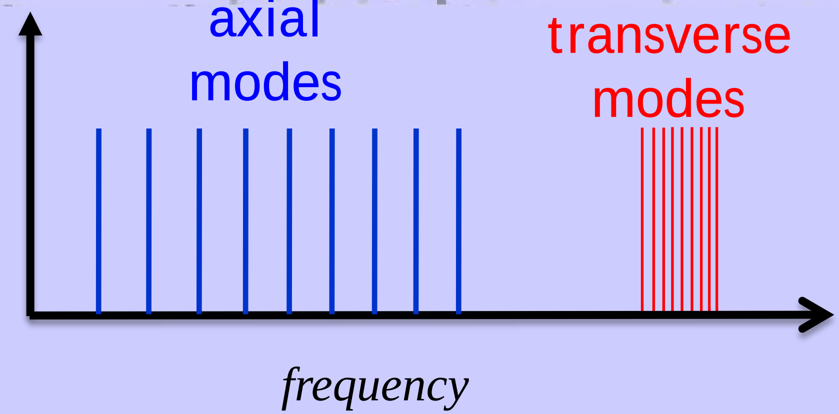
$$\hat{\chi}_i(\tau) = \sum_k [\alpha_i^k(\tau) a_k^\dagger - \alpha_i^{k*}(\tau) a_k] \qquad \alpha_i^k(\tau) = \frac{-i\eta_{i,k}\Omega_i}{\mu^2 - \omega_k^2}\left[\mu - e^{i\omega_k t}(\mu \cos \mu\tau - i\omega_k \sin \mu\tau)\right]$$

$$\phi_{i,j}(\tau) = \frac{\hbar \Omega_i \Omega_j (\Delta k)^2}{2m} \sum_k \frac{b_{i,k} b_{j,k}}{\mu^2 - \omega_k^2} \left[\frac{\mu \sin(\mu - \omega_k)\tau}{\omega_k(\mu - \omega_k)} - \frac{\mu \sin(\mu + \omega_k)\tau}{\omega_k(\mu + \omega_k)} + \frac{\sin 2\mu\tau}{2\mu} - \tau \right]$$

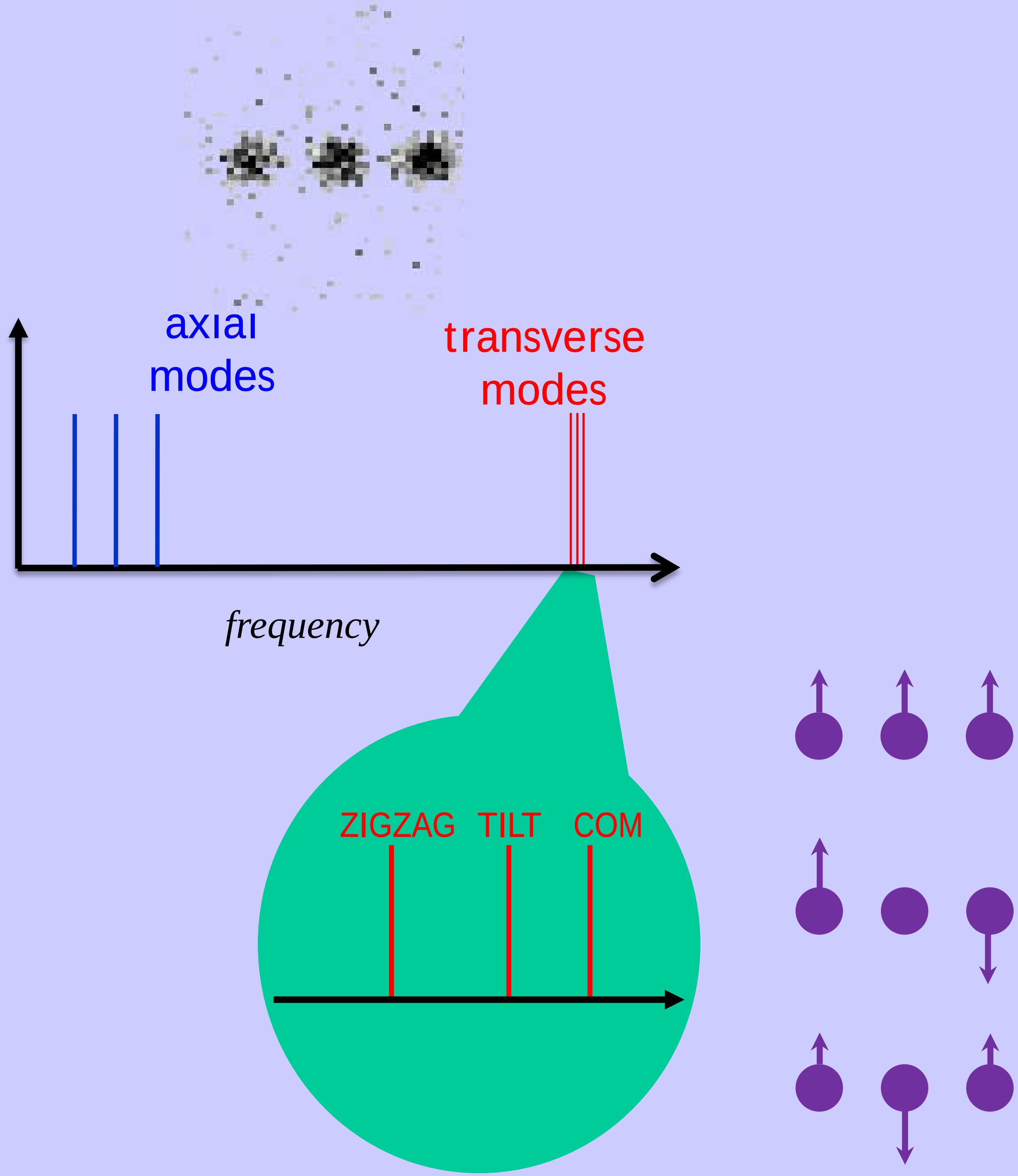
Adiabatic elimination of phonons: $|\mu - \omega| \gg \Omega_0$

$$H_{eff} = \sum_{i \neq j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} \qquad J_{i,j} = \frac{\hbar \Omega_i \Omega_j (\Delta k)^2}{2m} \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$





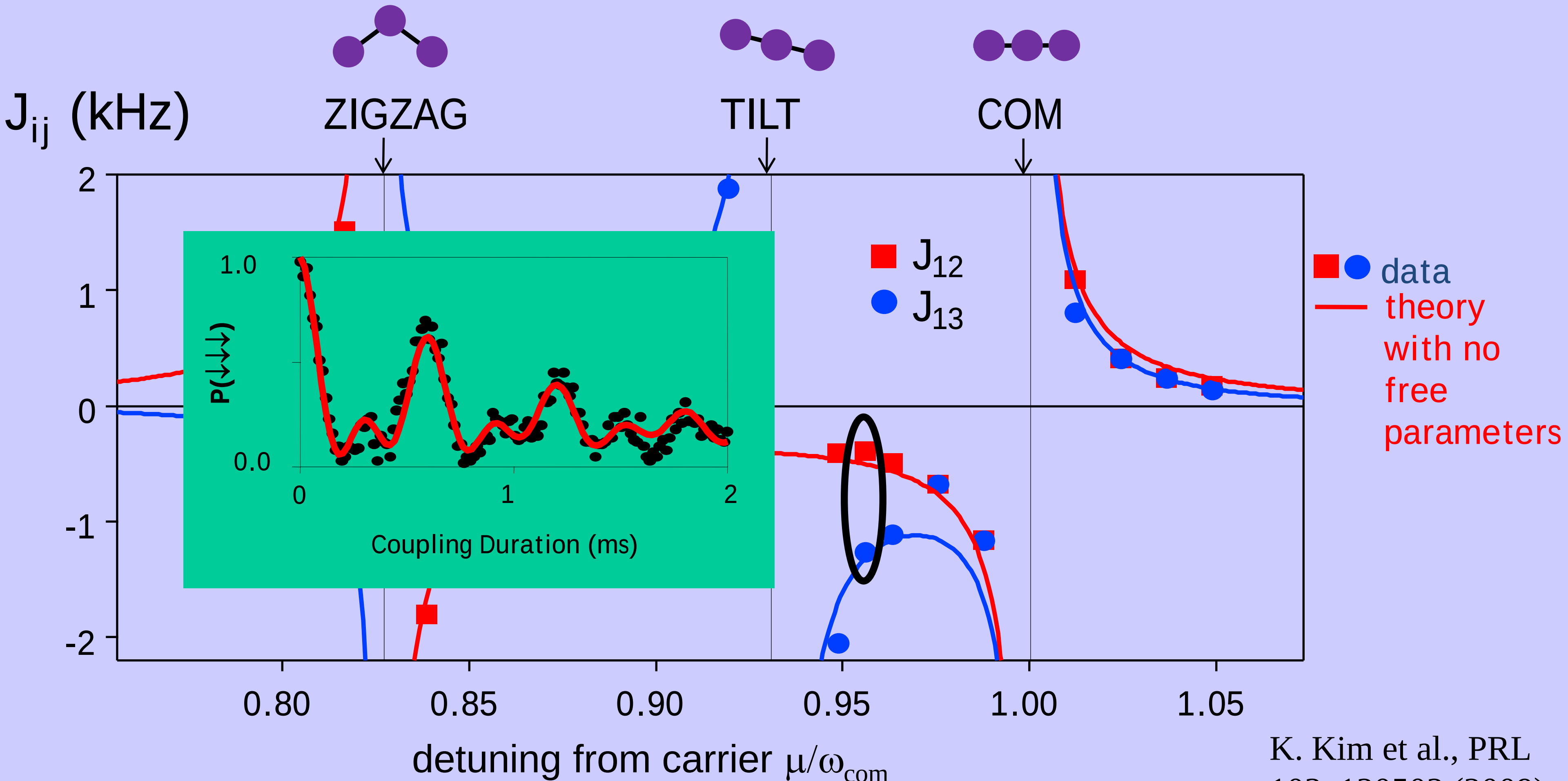
$$H_{eff} = \sum_{i \neq j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} \qquad J_{i,j} = \frac{\hbar \Omega^2 (\Delta k)^2}{2m} \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$


axial
modes
transverse
modes
frequency
ZIGZAG
TILT
COM

Measured 3-spin Ising Couplings through dynamics

$$H_{eff} = \sum_{i \neq j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)}$$

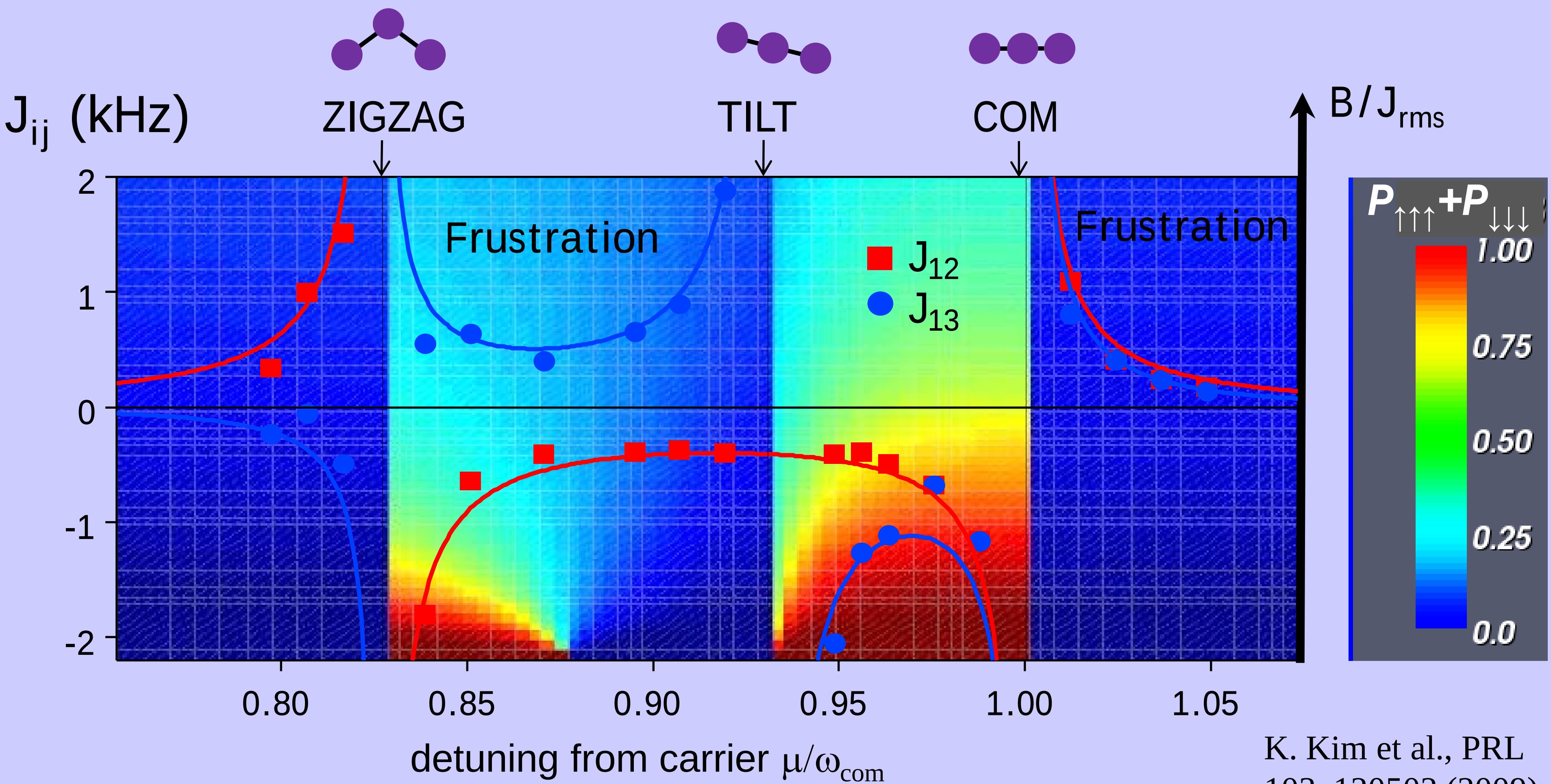
$$J_{i,j} = \frac{\hbar \Omega^2 (\Delta k)^2}{2m} \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$



K. Kim et al., PRL 103, 120502 (2009)

Ground state of 3-spin Ising Hamiltonian

$$H_{eff} = \sum_{i \neq j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + B \sum_i \hat{\sigma}_y^{(i)} \qquad J_{i,j} = \frac{\hbar \Omega^2 (\Delta k)^2}{2m} \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$



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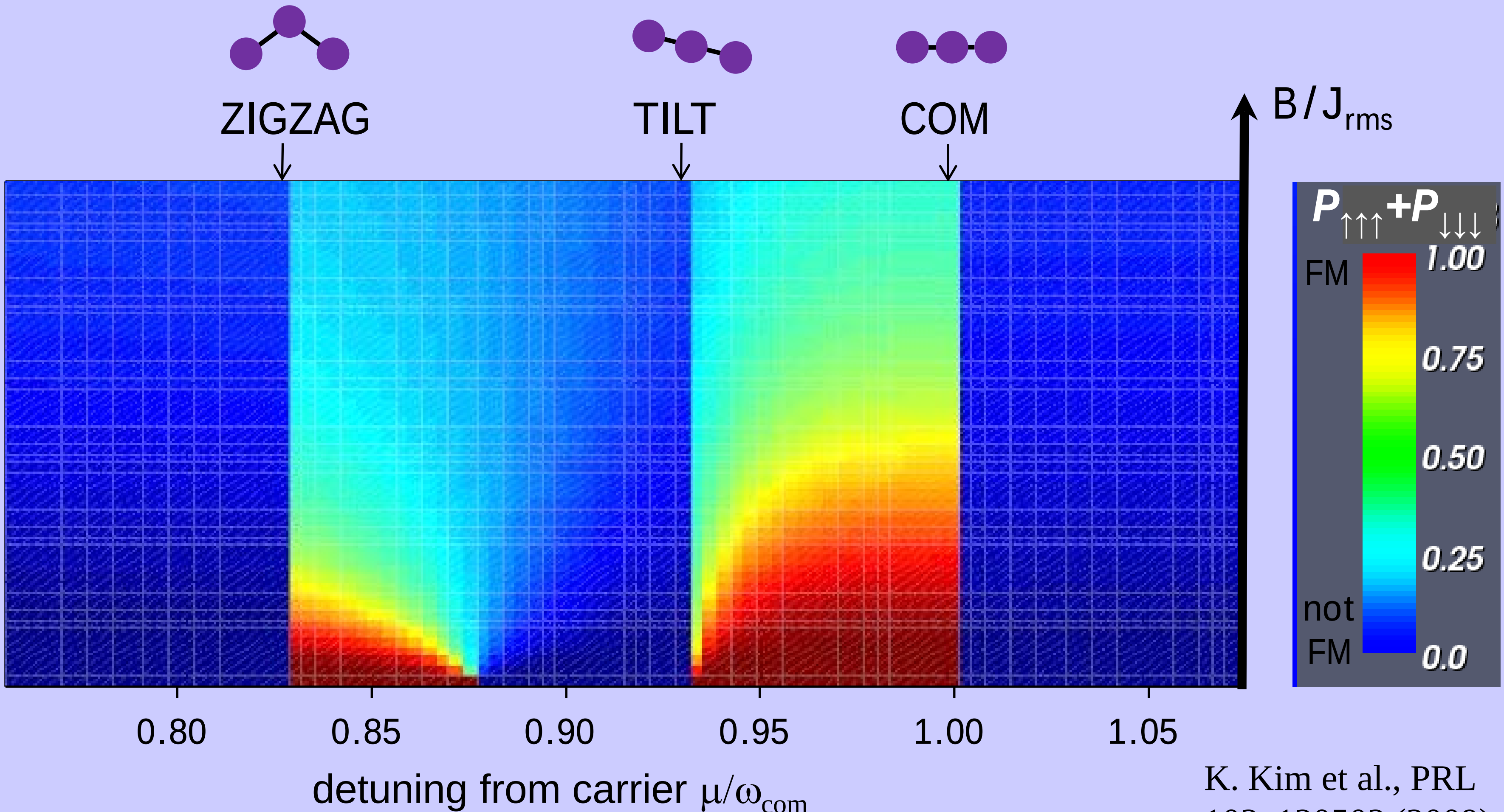

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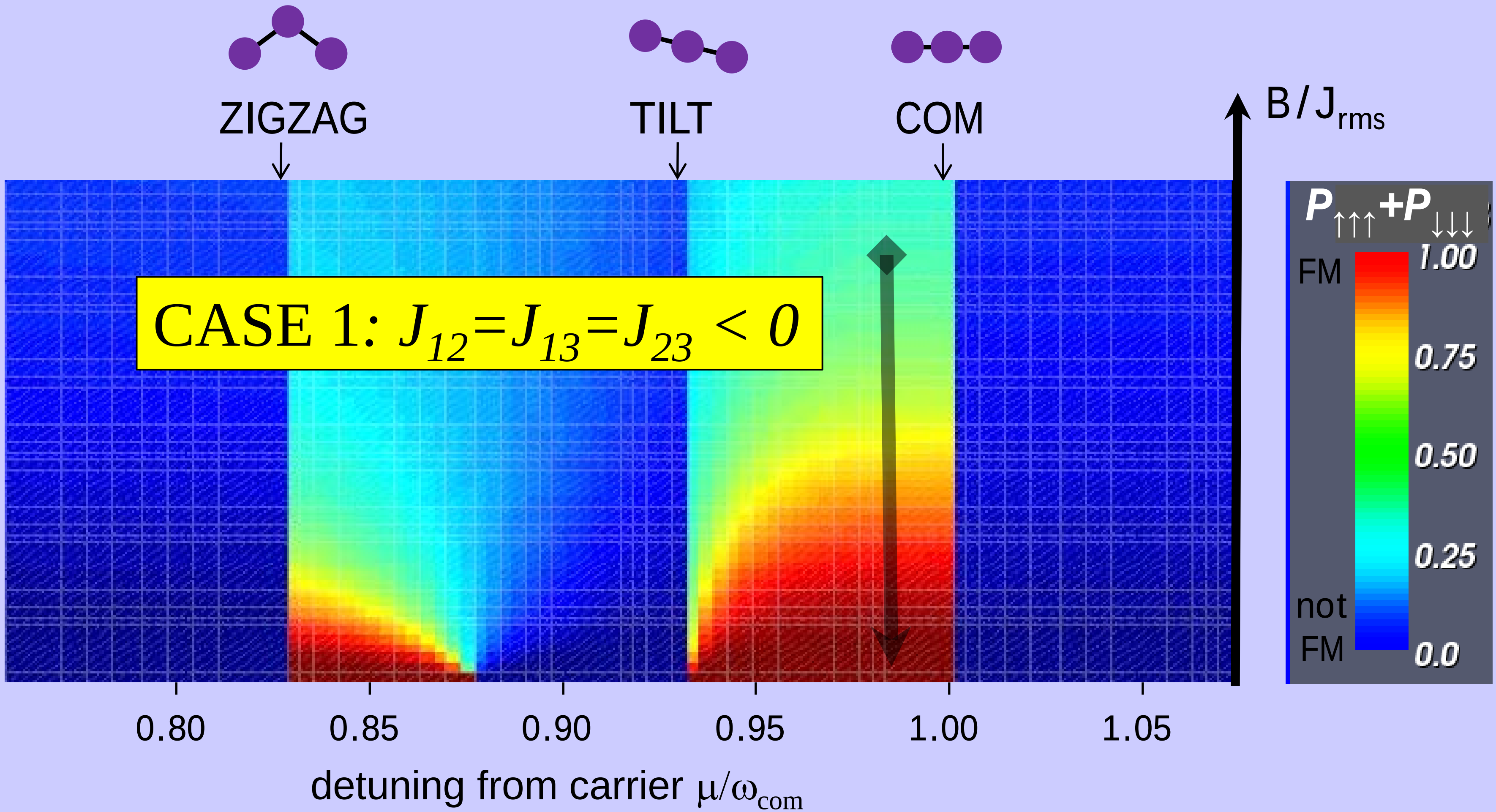

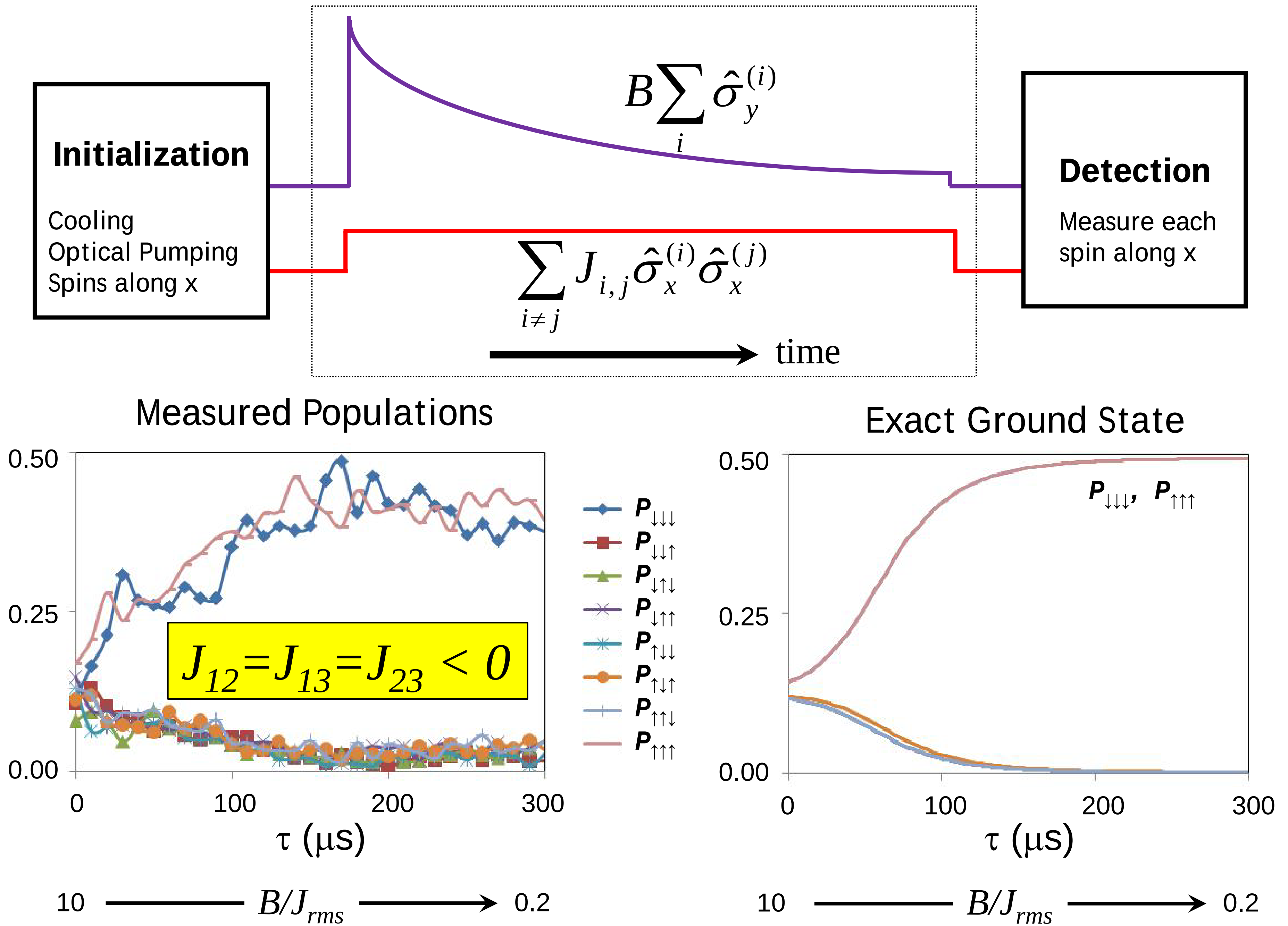

K. Kim, et al., Nature (June 3, 2010)

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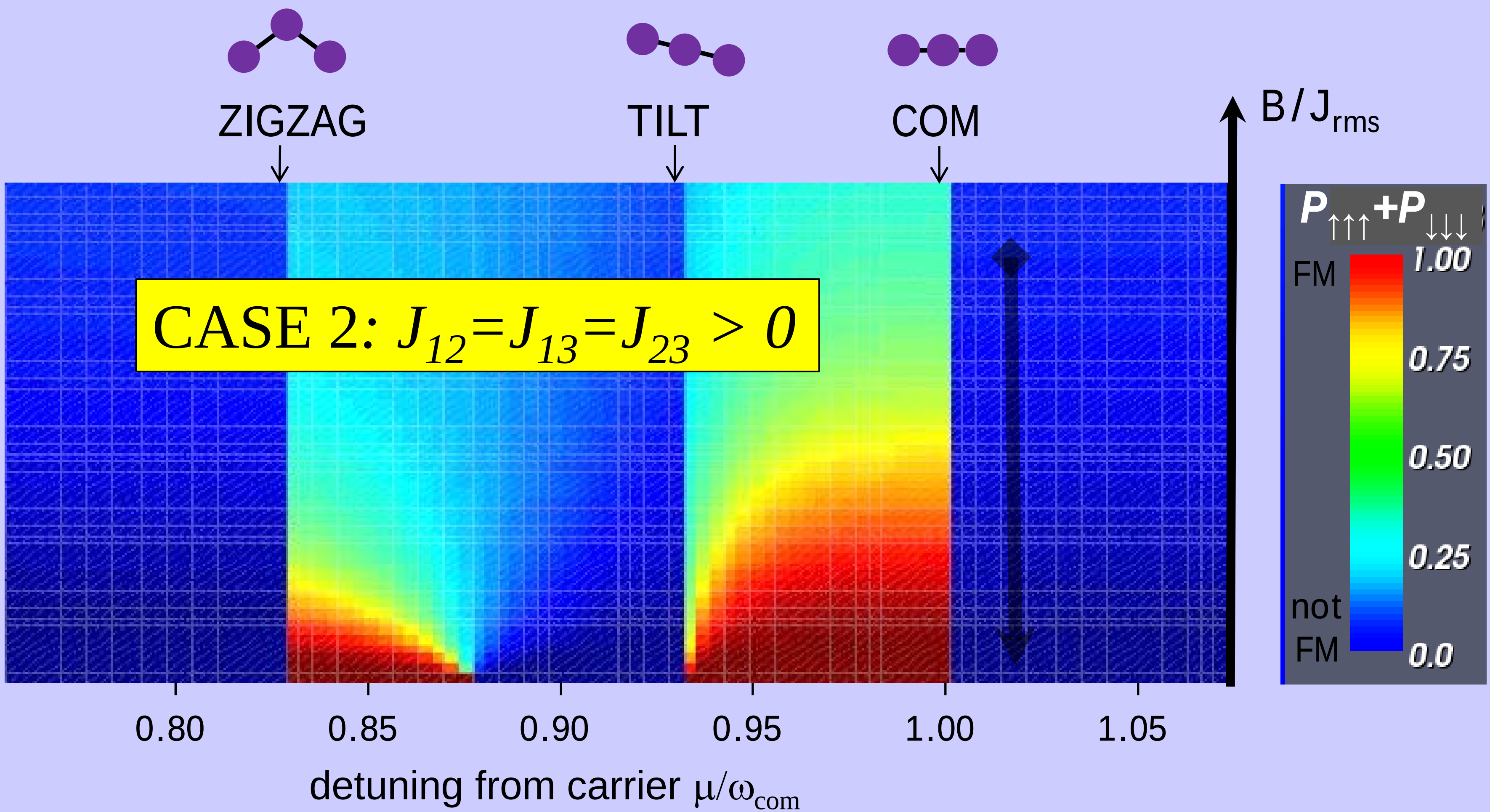

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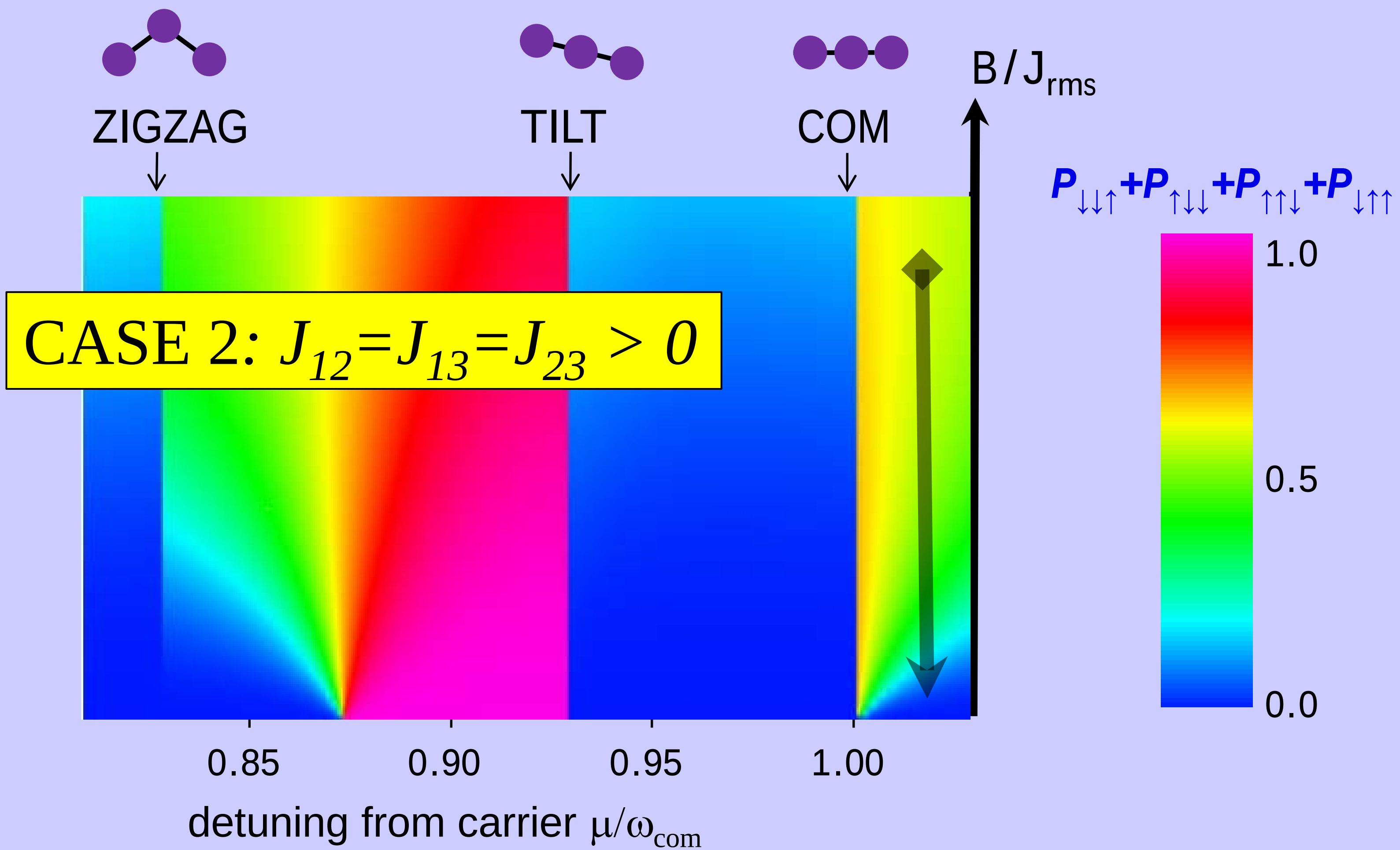
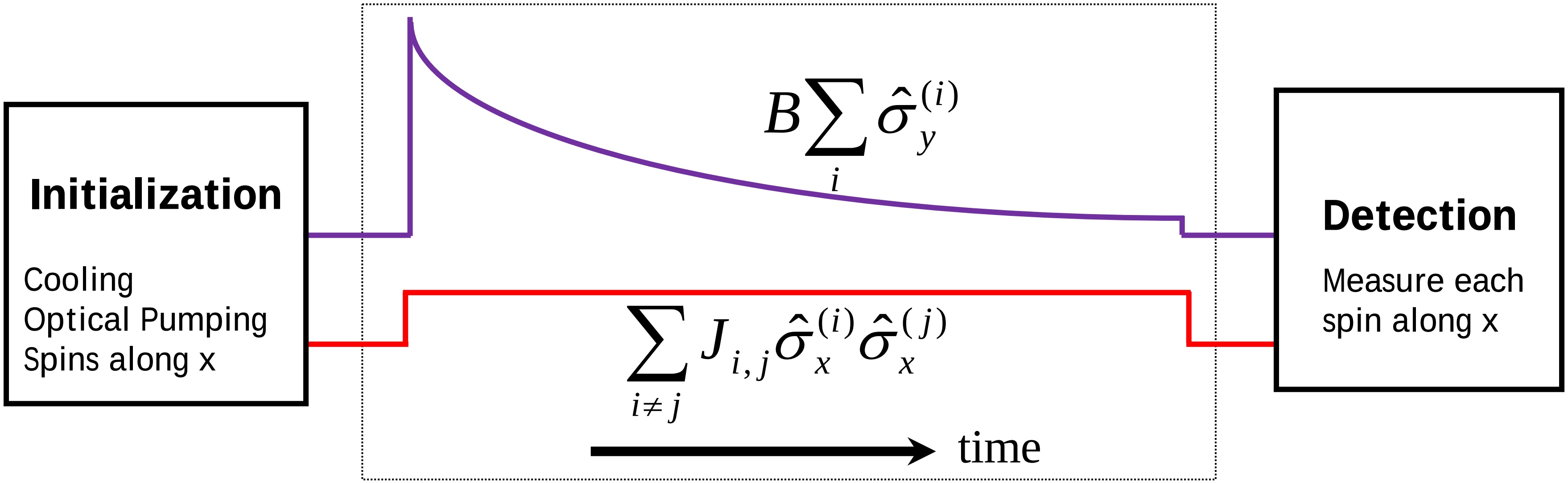
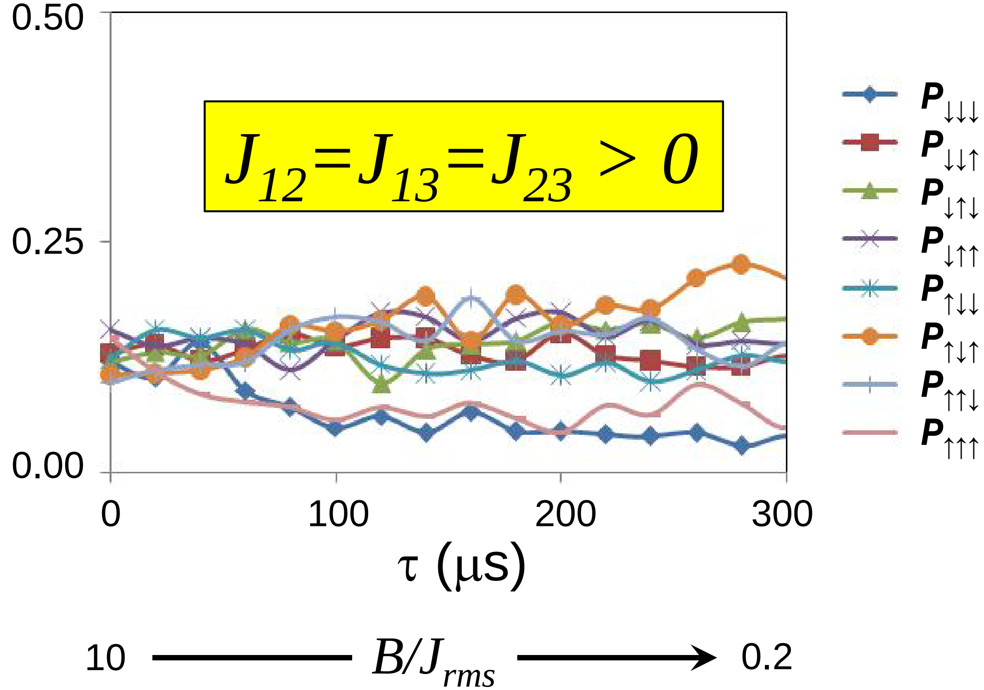
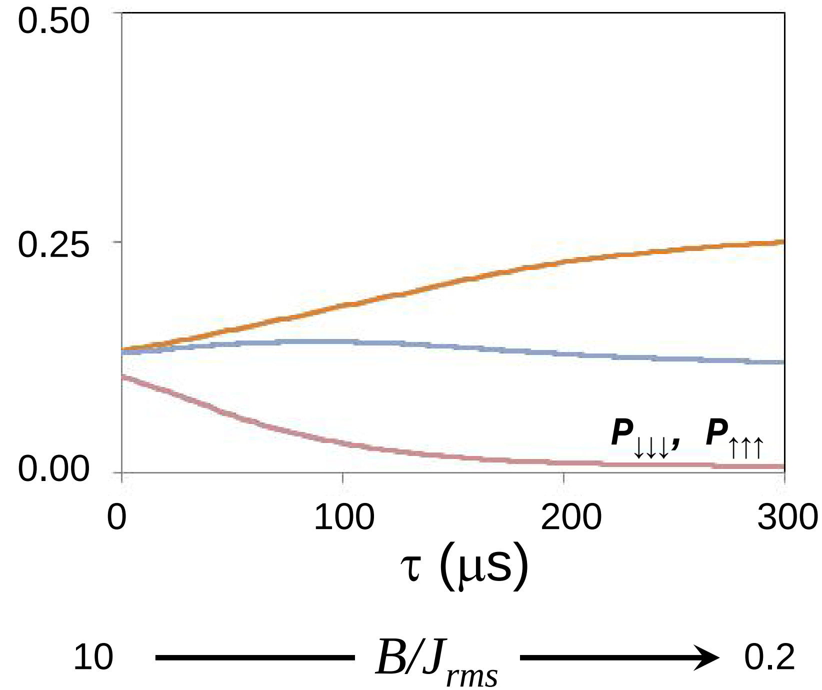




Measured Populations



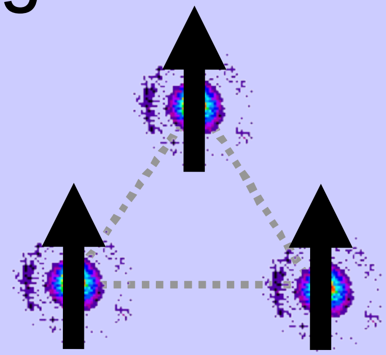
Exact Ground State

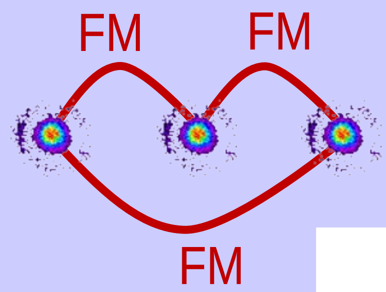


K. Kim, et al., Nature (June 3, 2010)

Ferromagnetic couplings

$J_{12}=J_{13}=J_{23} < 0$





ground state is *entangled*

$|\Psi\rangle = |\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle$

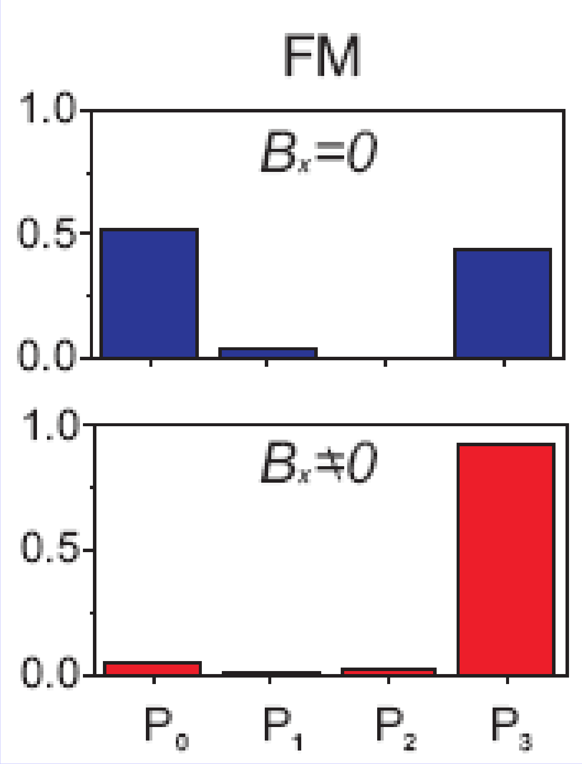
symmetry breaking field B_x

$|\Psi_1\rangle = |\uparrow\uparrow\uparrow\rangle$

no entanglement

$|\Psi_2\rangle = |\downarrow\downarrow\downarrow\rangle$

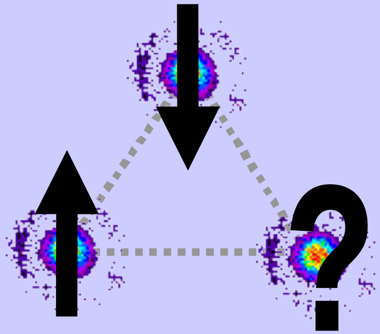
no entanglement

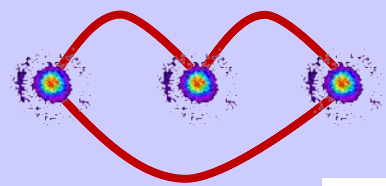


K. Kim, et al., Nature **465**, 590 (2010)

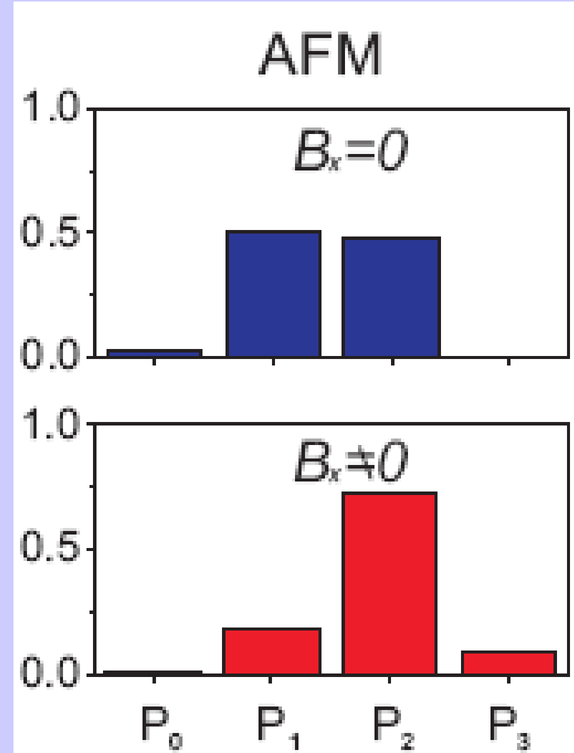
Simplest case of spin frustration

$J_{12} = J_{13} = J_{23} > 0$





ground state is *entangled*



$$|\Psi\rangle = |\uparrow\uparrow\downarrow\rangle + |\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle + |\uparrow\downarrow\downarrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\rangle$$

symmetry breaking field B_x

$$|\Psi_1\rangle = |\uparrow\uparrow\downarrow\rangle + |\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle$$

still entangled!

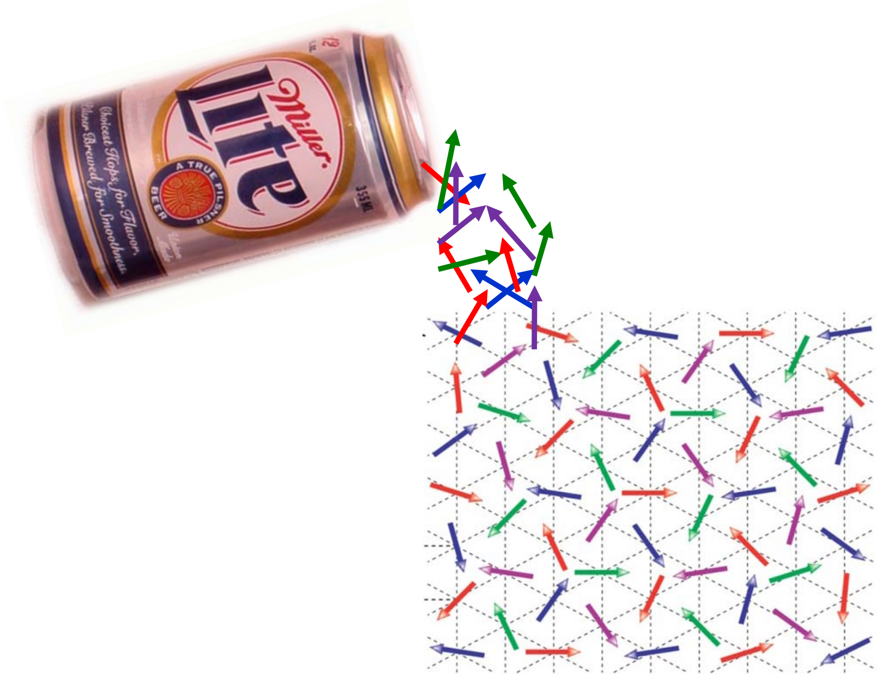
$$|\Psi_2\rangle = |\uparrow\downarrow\downarrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\rangle$$

still entangled!

K. Kim, et al., Nature **465**, 590 (2010)

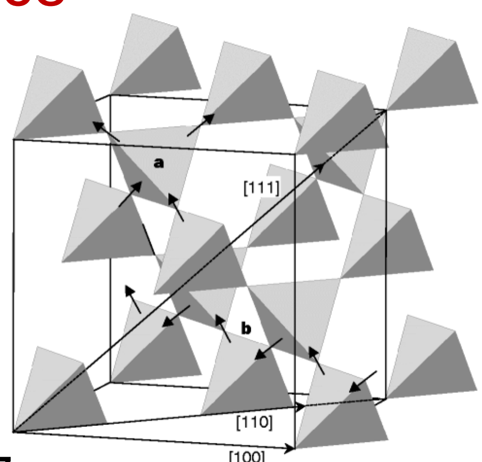
Magnetic Frustration

Spin Liquids

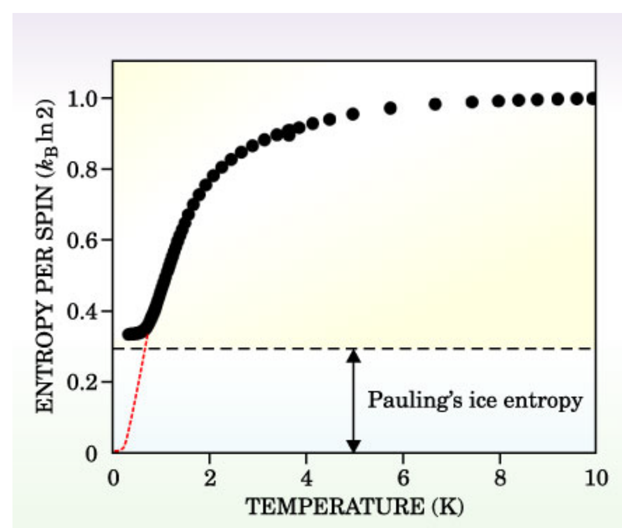


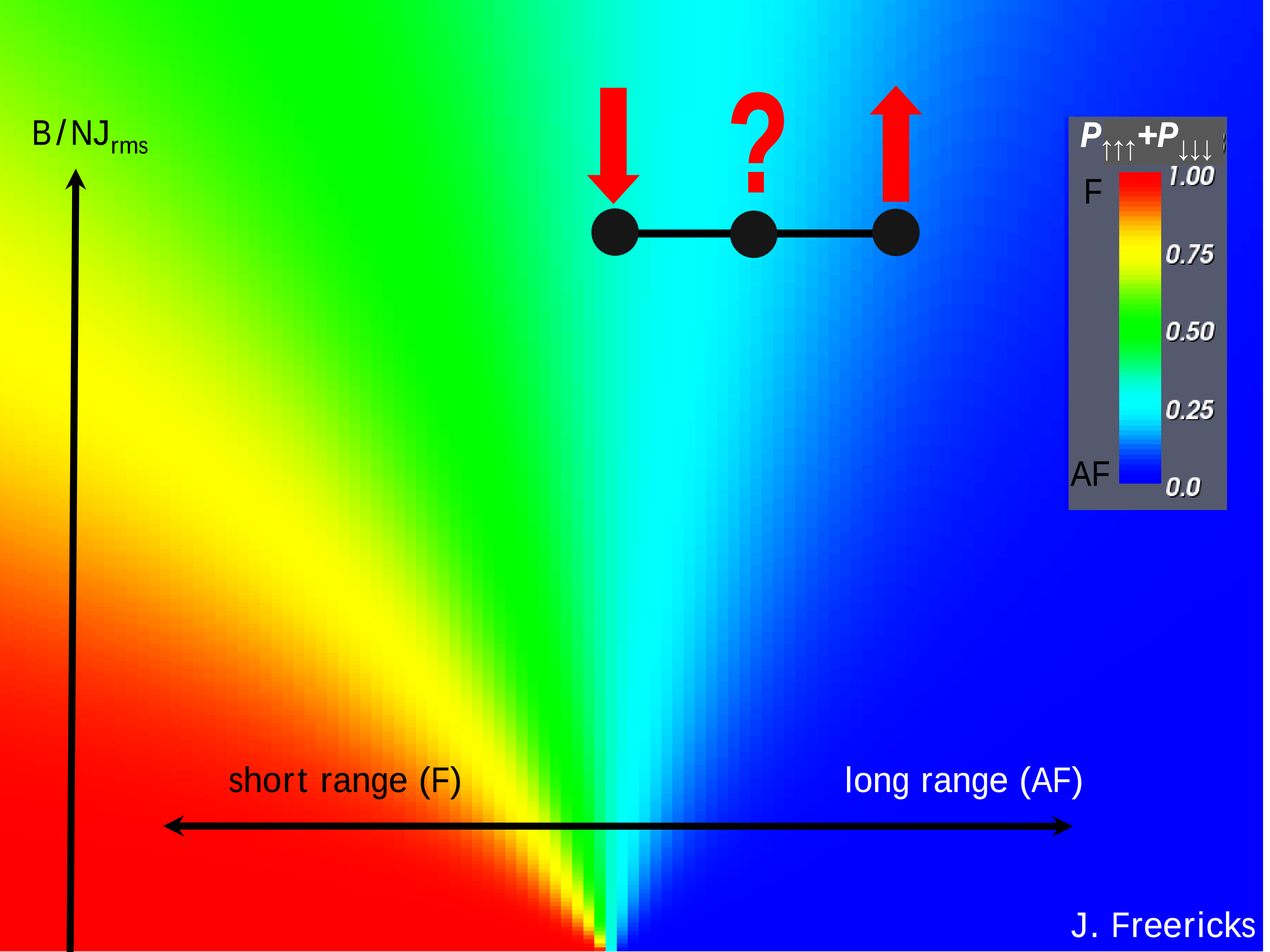
Ice and “Spin-Ice”

A. P. Ramirez, et. al.,
Nature 399, 333 (1999)



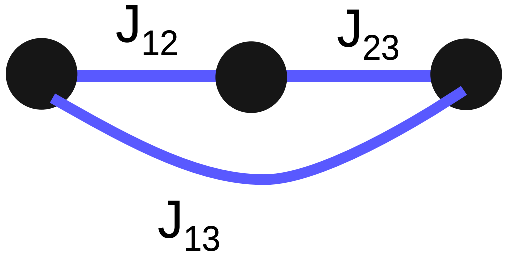
$Dy_2Ti_2O_7$

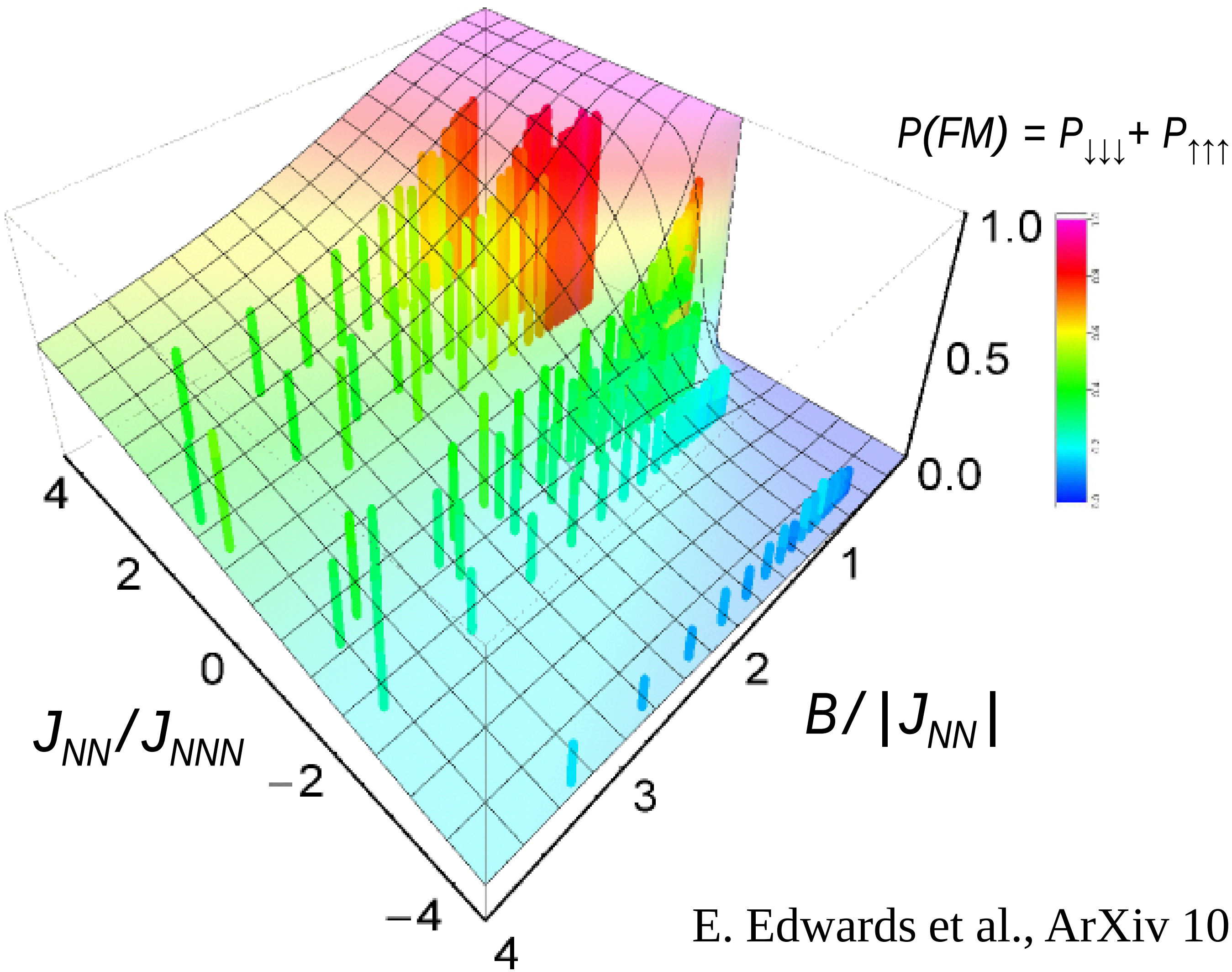




B / NJ$_{rms}$
?
$P_{\uparrow\uparrow\uparrow}+P_{\downarrow\downarrow\downarrow}$
F
1.00
0.75
0.50
0.25
AF
0.0
short range (F)
long range (AF)
J. Freericks

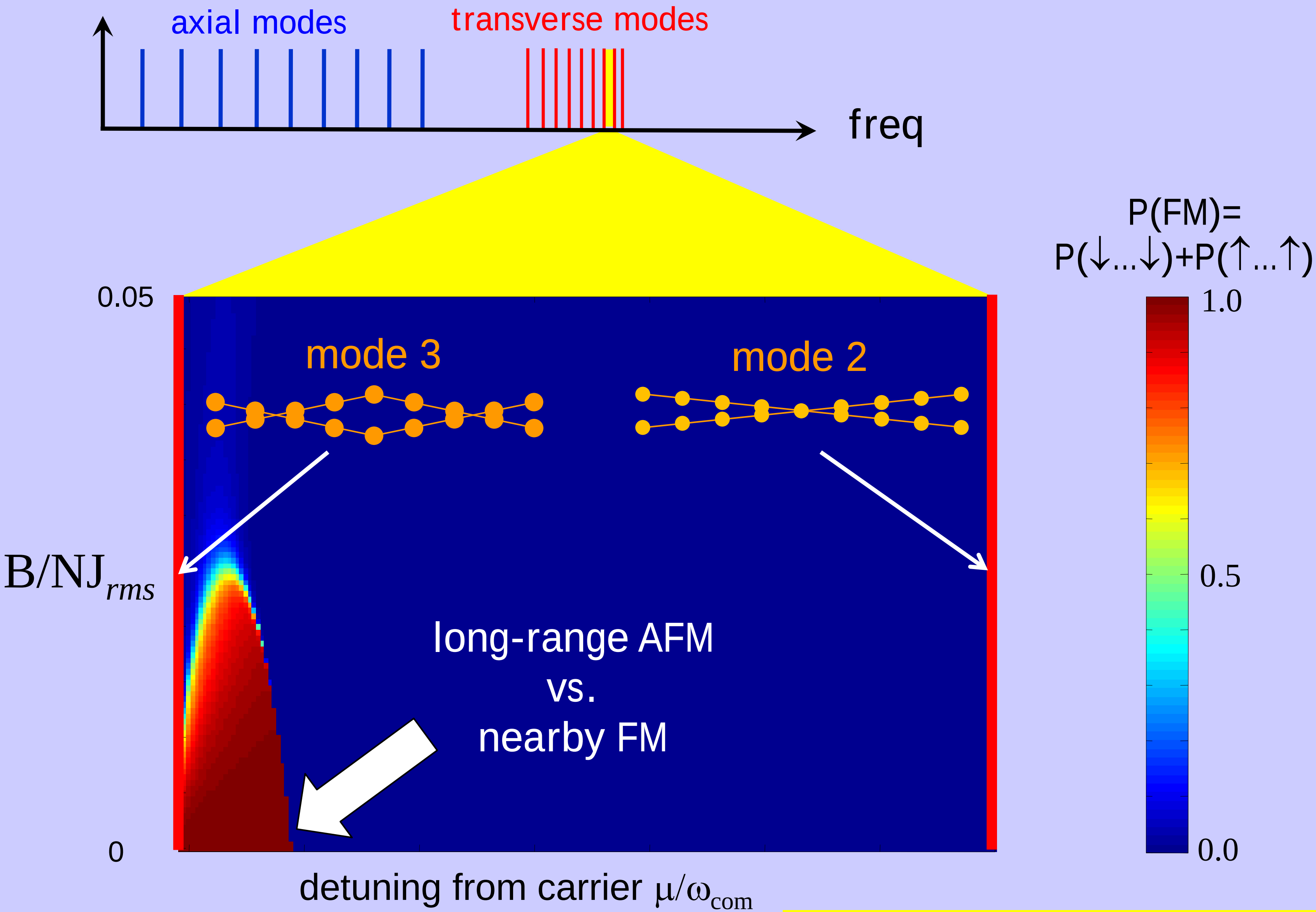
Phase Diagram for N=3 spins





E. Edwards et al., ArXiv 1004.4243

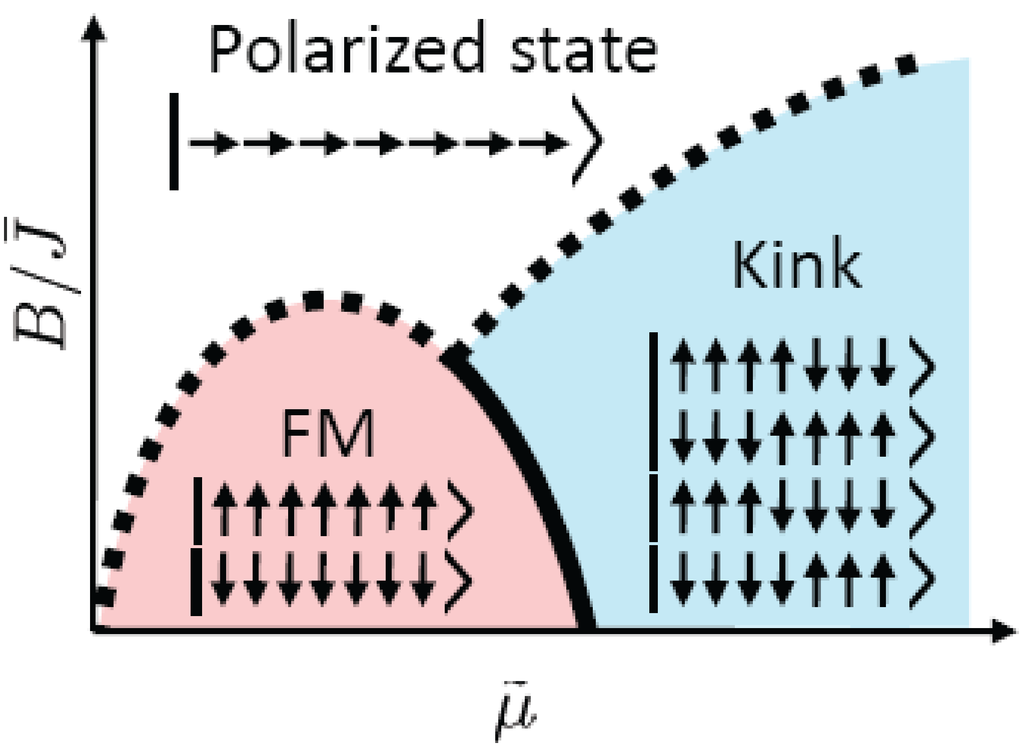
Theoretical Ground State Phase Diagram for N=9 ions



G.-D. Lin & L.-M. Duan (Michigan)

Sharp phase transitions in a small spin network of trapped ions with frustrated coupling

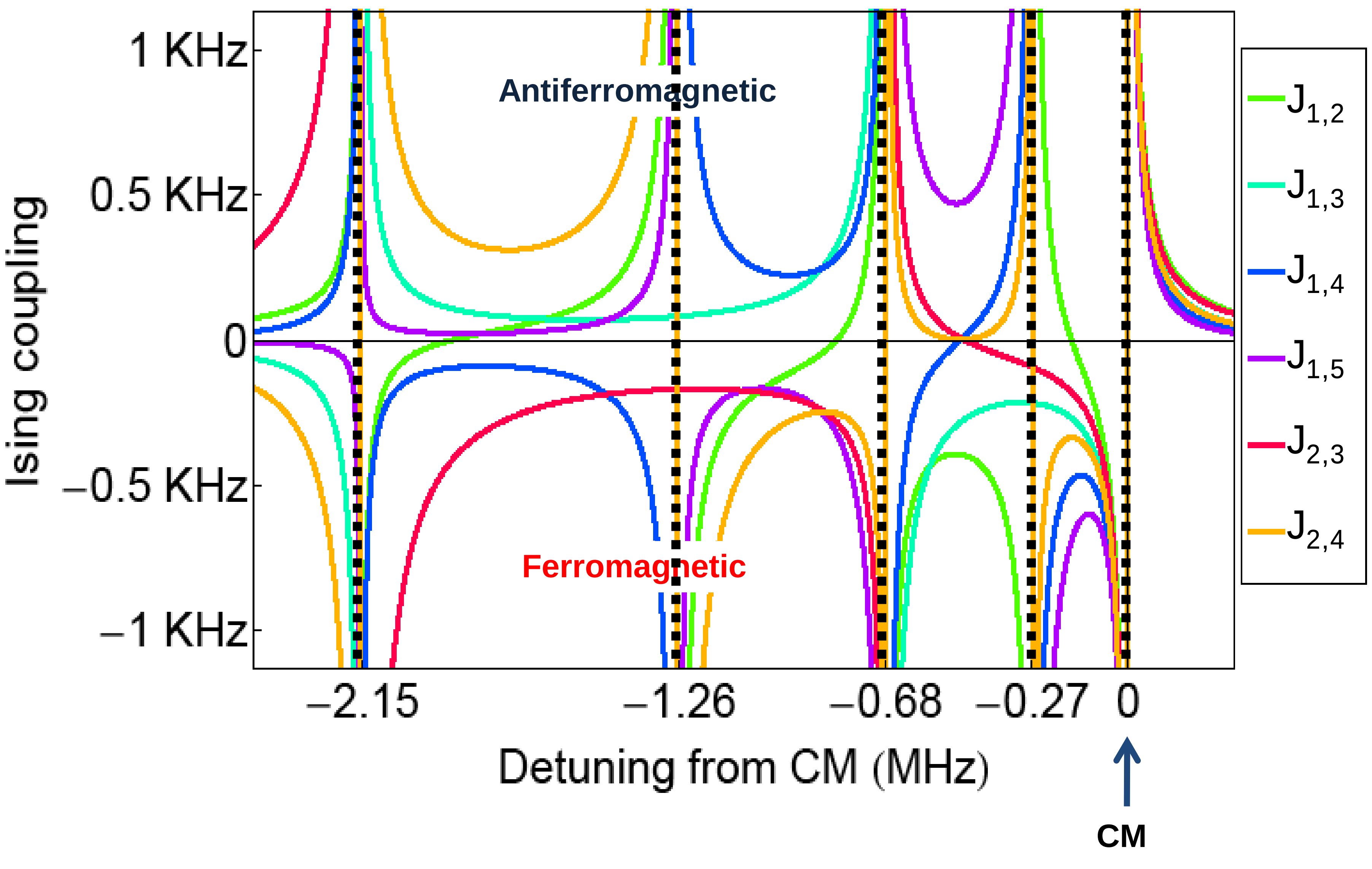
G.-D. Lin[1], C. Monroe[2], and L.-M. Duan[1]
1. *Department of Physics and MCTP, University of Michigan, Ann Arbor, Michigan 48109*
2. *Joint Quantum Institute, University of Maryland Department of Physics and National Institute of Standards and Technology, College Park, Maryland 20742 USA*
(Dated: May 18, 2010)



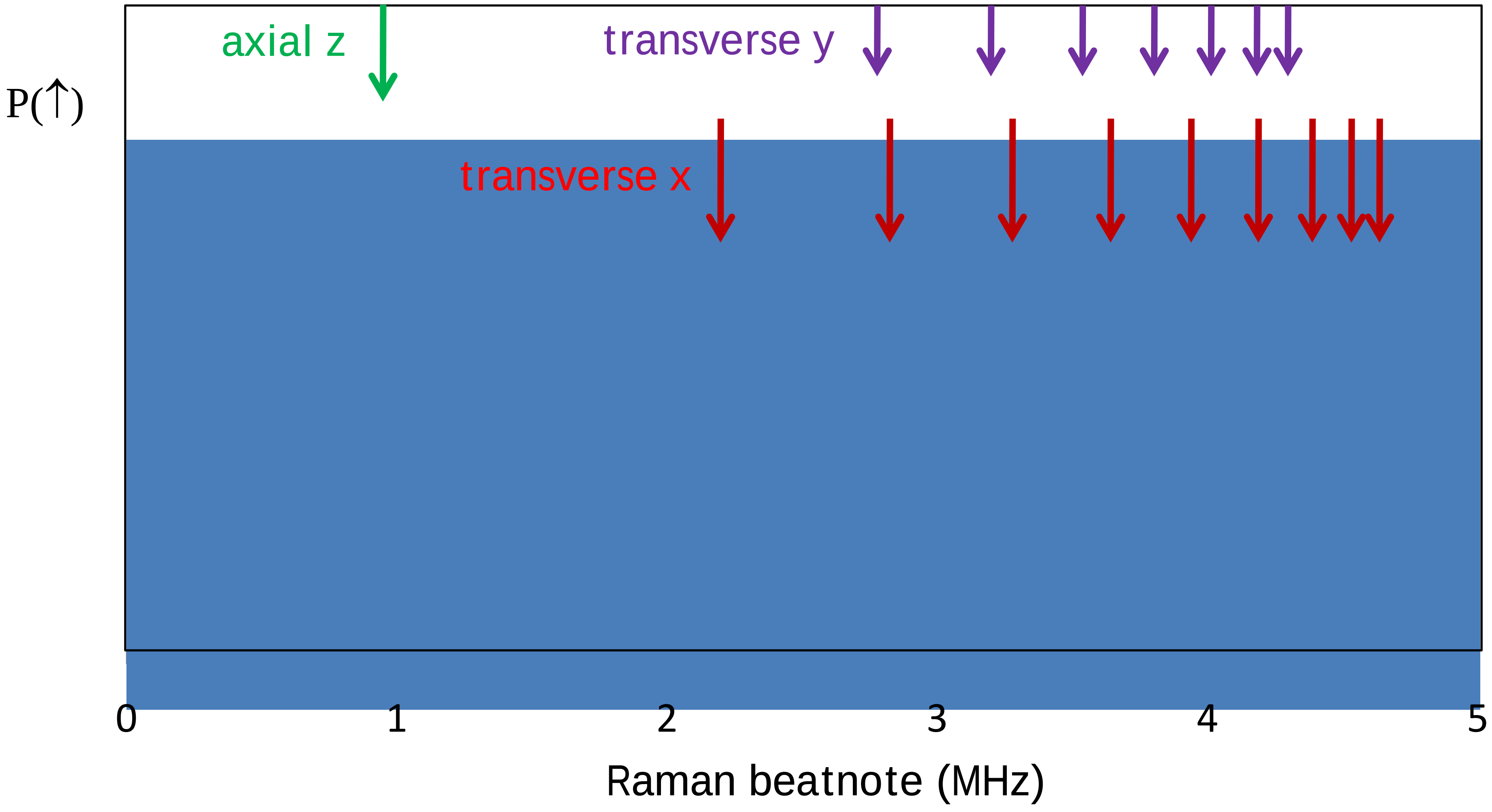
G.-D. Lin
Wed. 10:30am

Ising couplings for 5 spins

$$H = \sum_{i \neq j} \underline{J_{i,j} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}} + B \sum_i \hat{\sigma}_x^{(i)}$$

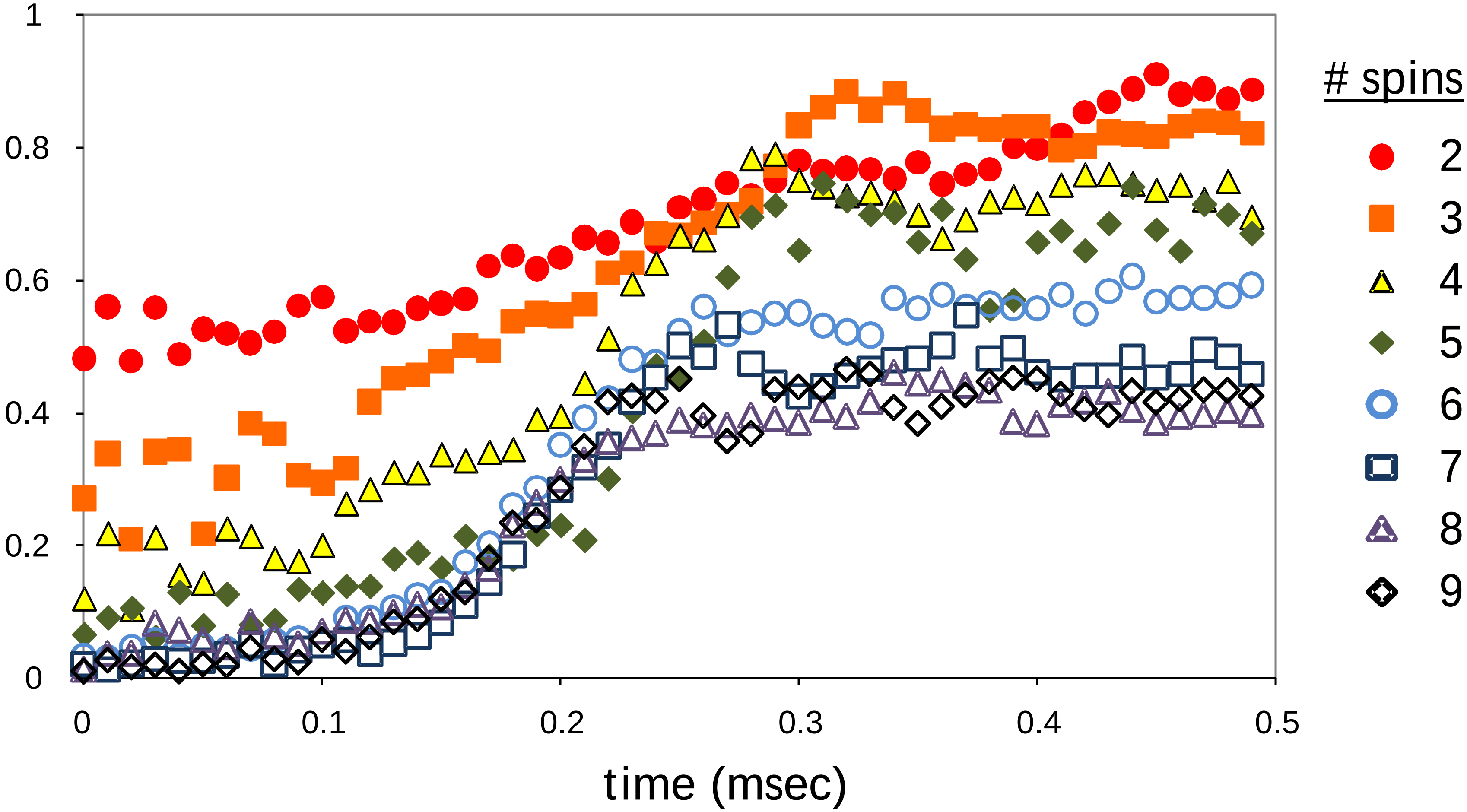


Normal mode Raman spectrum of N=9 ions

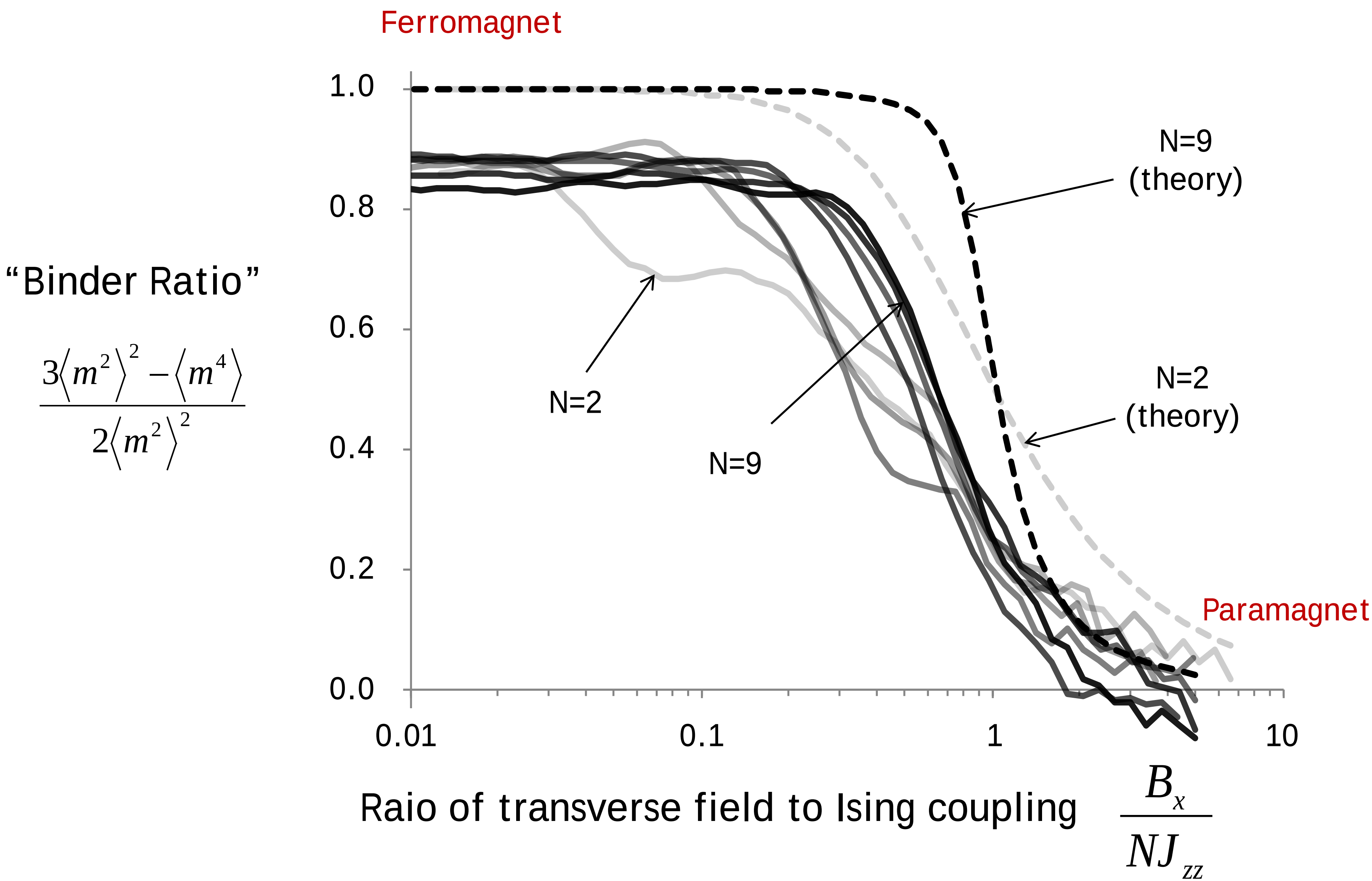


Transition from Paramagnetic to Ferromagnetic

P(FM) = P(↑↑↑...↑) + P(↓↓↓...↓)



B >> NJ → B << NJ



Ferromagnet
Paramagnet
"Binder Ratio"
$\frac{3\langle m^2\rangle^2 - \langle m^4\rangle}{2\langle m^2\rangle^2}$
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
10
N=9
(theory)
N=2
(theory)
N=2
N=9
Raio of transverse field to Ising coupling $\frac{B_x}{NJ_{zz}}$

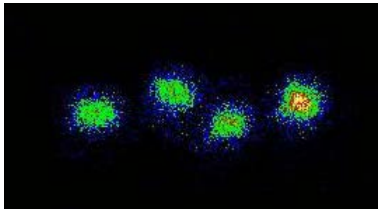
N>10 spins...

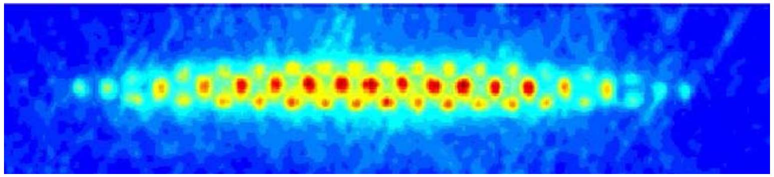
☺ simulation time ~ $N^{1/3}$

☹ need to hold lots of ions

☹ need more laser power

Scaling a single crystal to >100 ions?

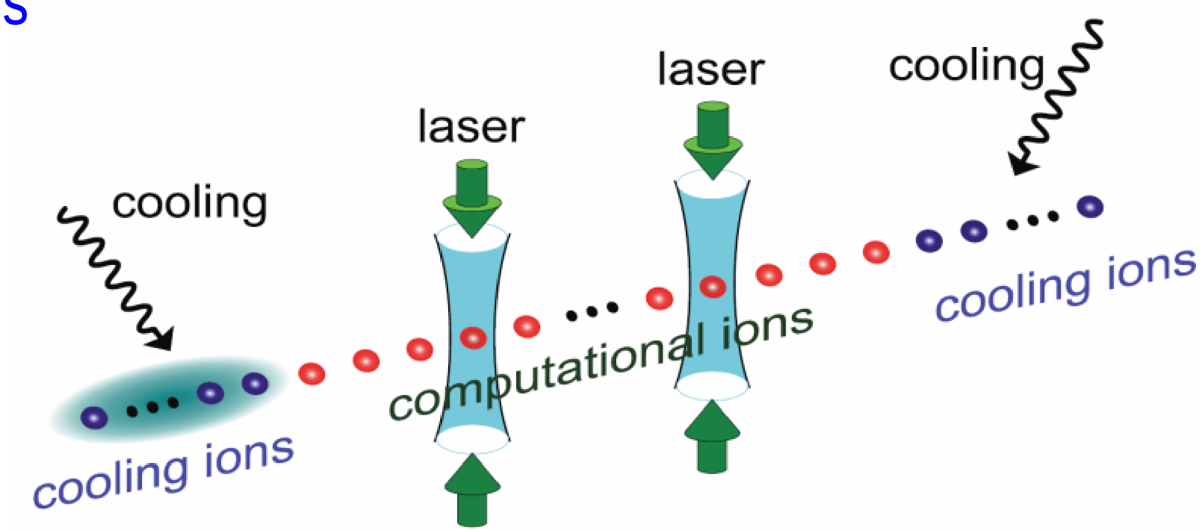




Harmonic external axial potential

linear crystal: $$\frac{\omega_r}{\omega_z} > 0.77 \frac{N}{\log N}$$

Uniformly spaced ions

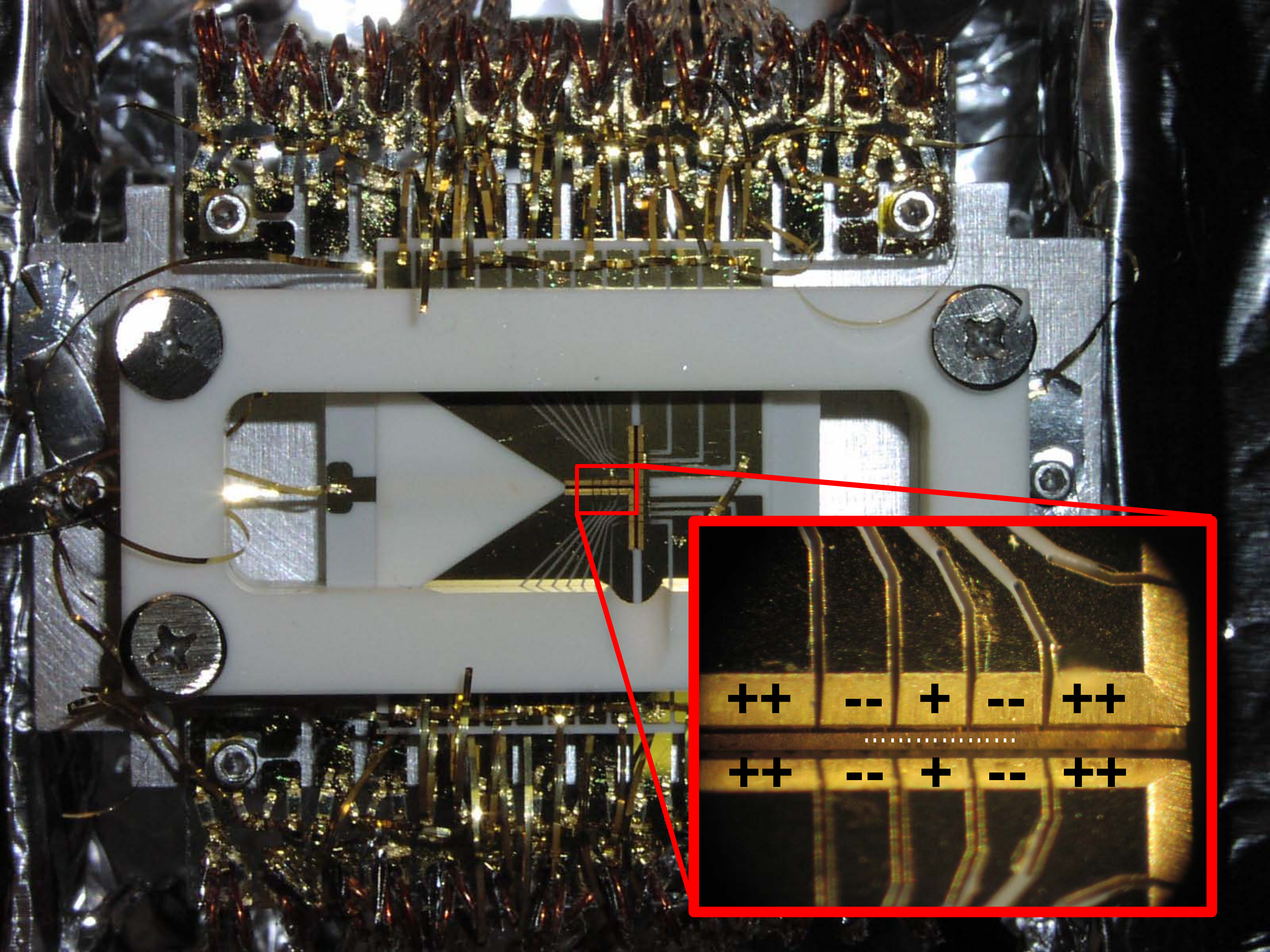


linear crystal:

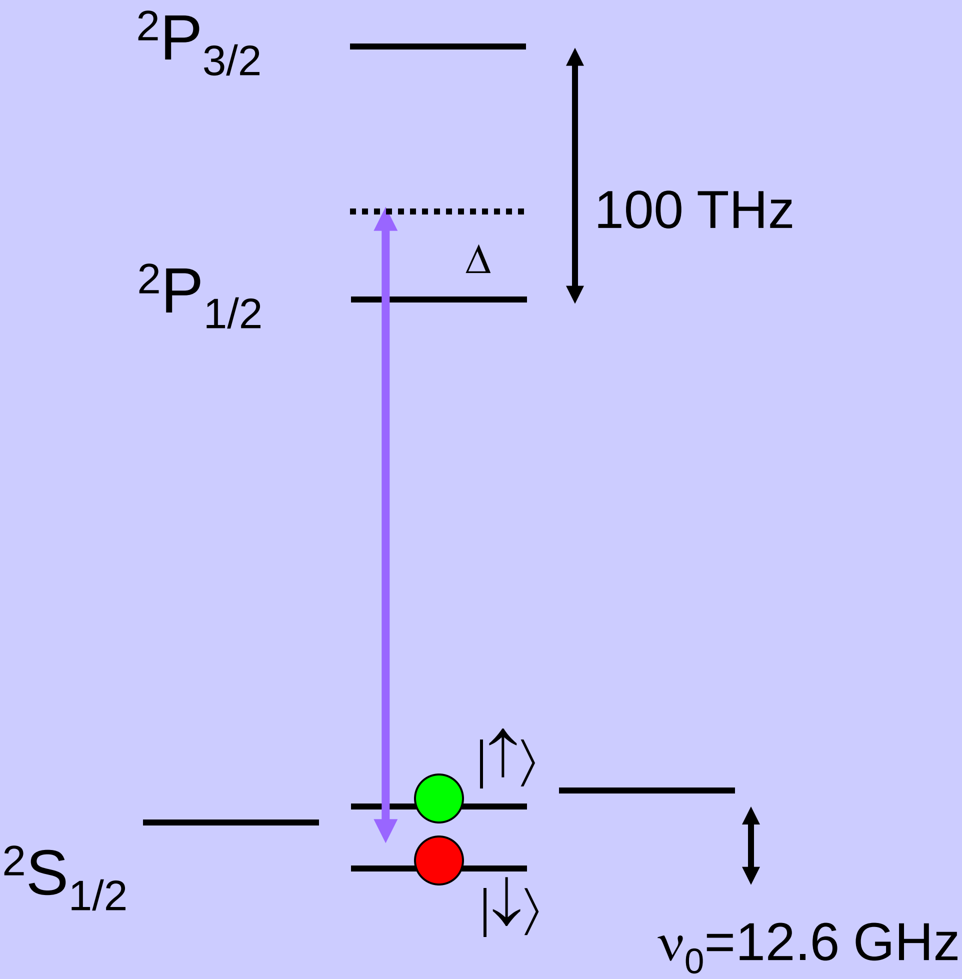
$$\omega_r > \sqrt{\frac{7\zeta(3)e^2}{2ms^3}}$$

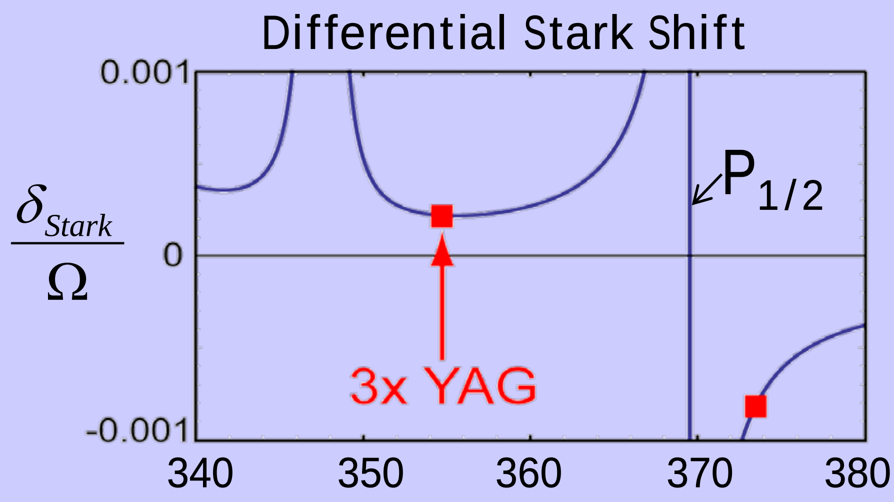
Independent of N!

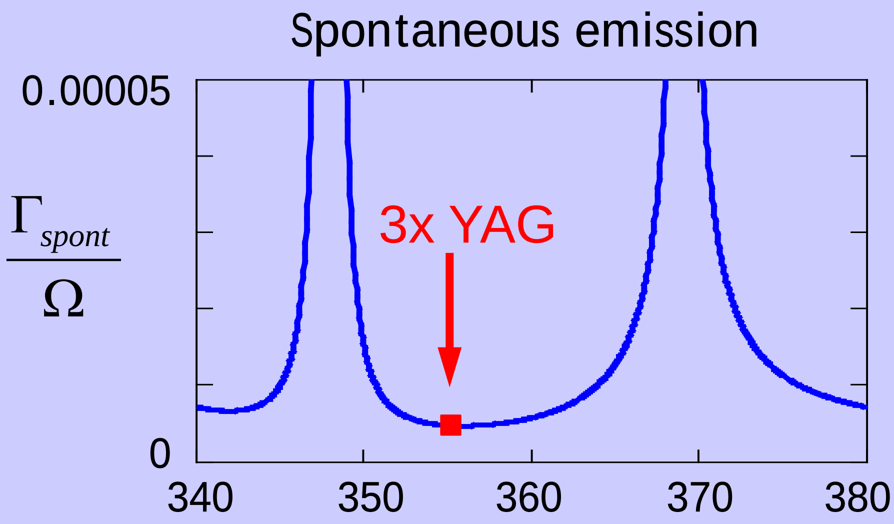
G.-D. Lin, et al., Europhys. Lett. 86, 60004 (2009)



"Magic" wavelength for Yb^+: **355 nm**







National Ignition Facility (LLNL)

P_{avg}=4W at 355nm
120MHz rep rate
10 psec pulses

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