IRCP Institut de Recherche de Chimie Paris

Rare Earth Doped Nanostructures: Quantum Leaps for Optical Technologies

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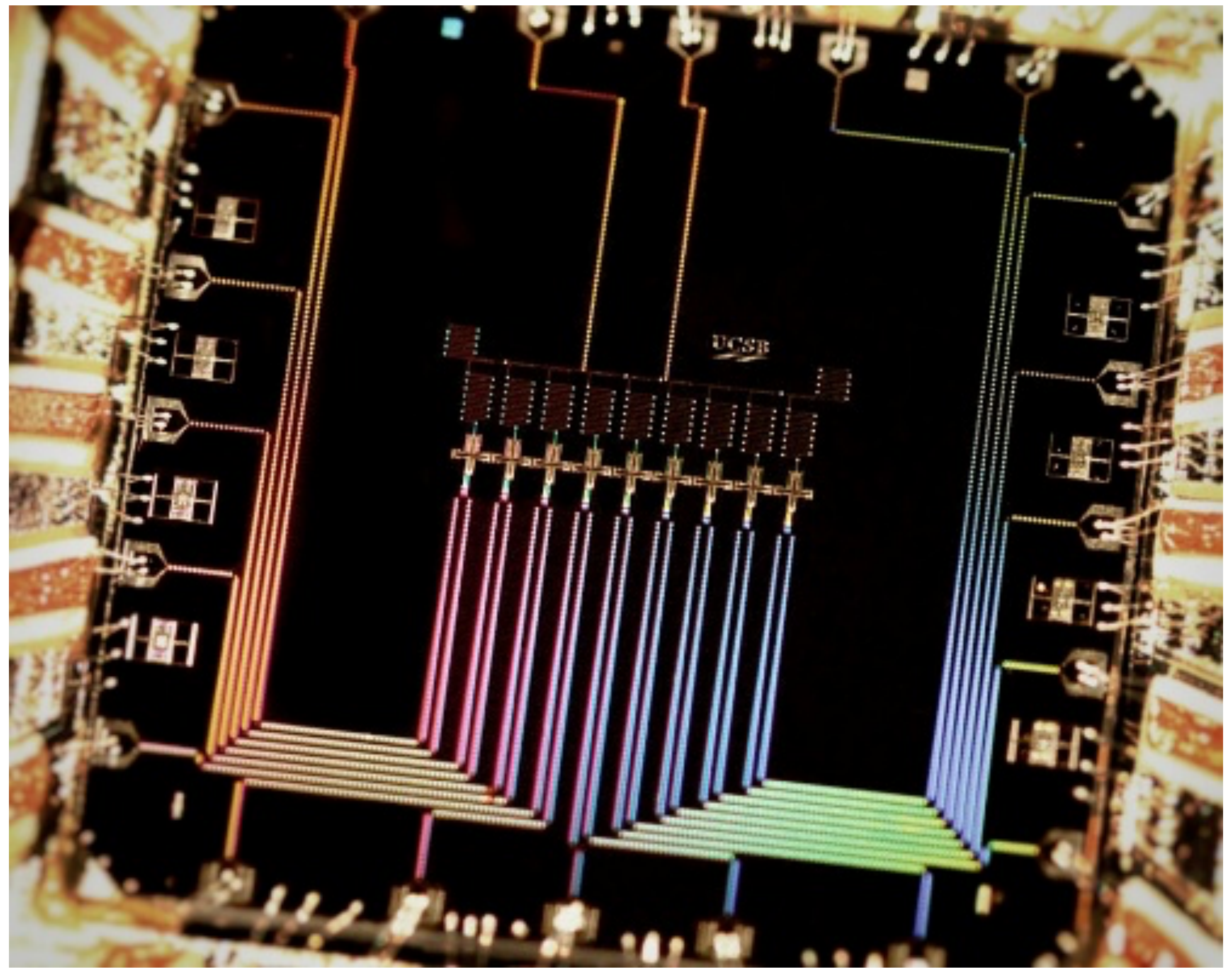
Computing

The Sunway TaihuLight

10 million CPU - 10^{17} operations/s

A digital quantum computer



Google

49 quantum registers by 2017

Quantum Technologies

Applications

Quantum computing

Molecule, drugs, material design
Machine learning

Quantum sensing

Magnetic and electric fields
Forces, gravity

Quantum communication

Quantum internet
Quantum cryptography

Quantum technology companies

IDQ FROM VISION TO TECHNOLOGY

D-Wave The Quantum Computing Company™

High-tech companies

IBM Microsoft intel

Google THALES

BOSCH TOSHIBA

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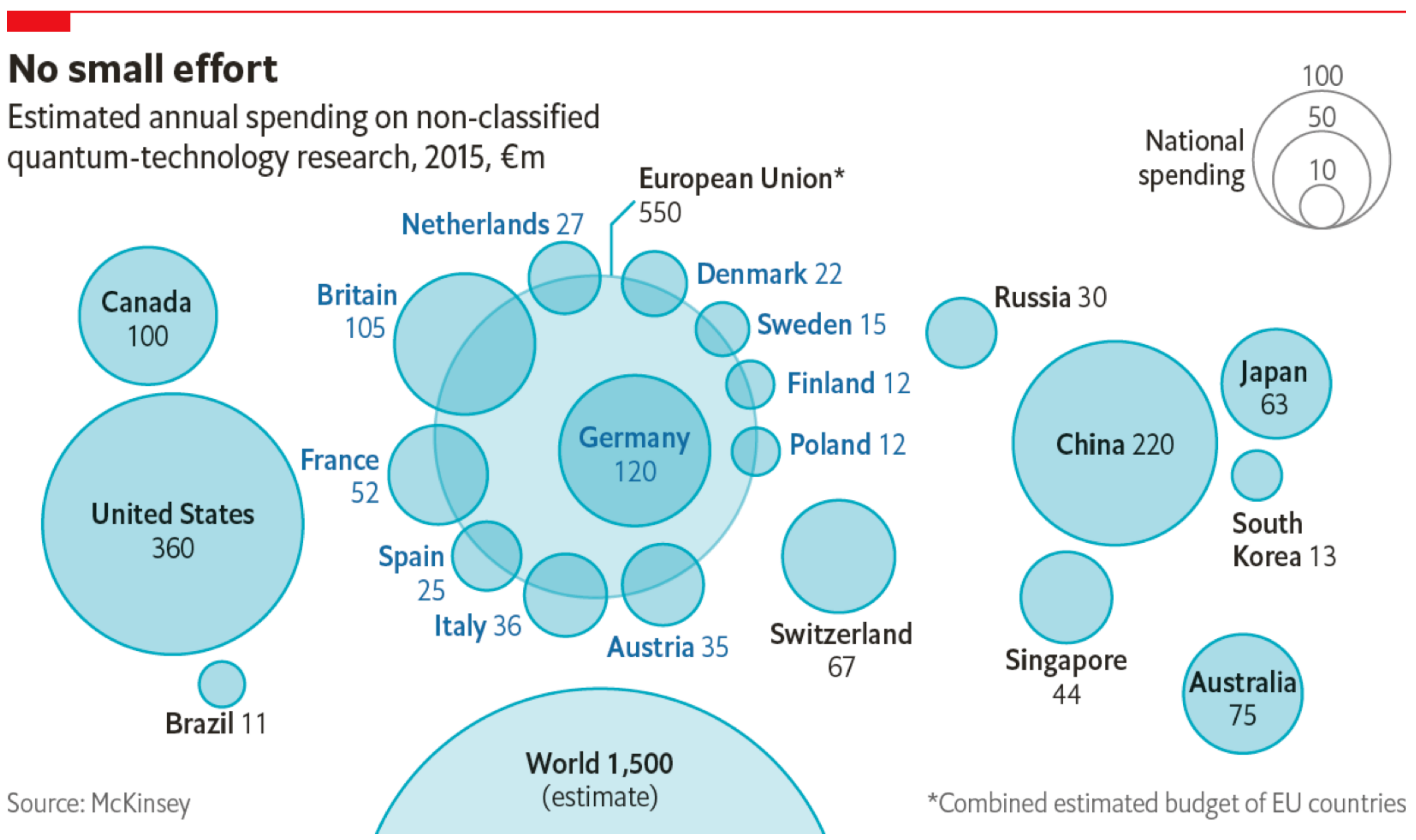
No Small Effort



The Economist, 2017

Large scale research programs

China : five-year national plan
(2016-2020)

UK Quantum Tech. Programme
(2015-2019, 300 M€)

EU Quantum Flagship
(2018-2028, 1 B€)

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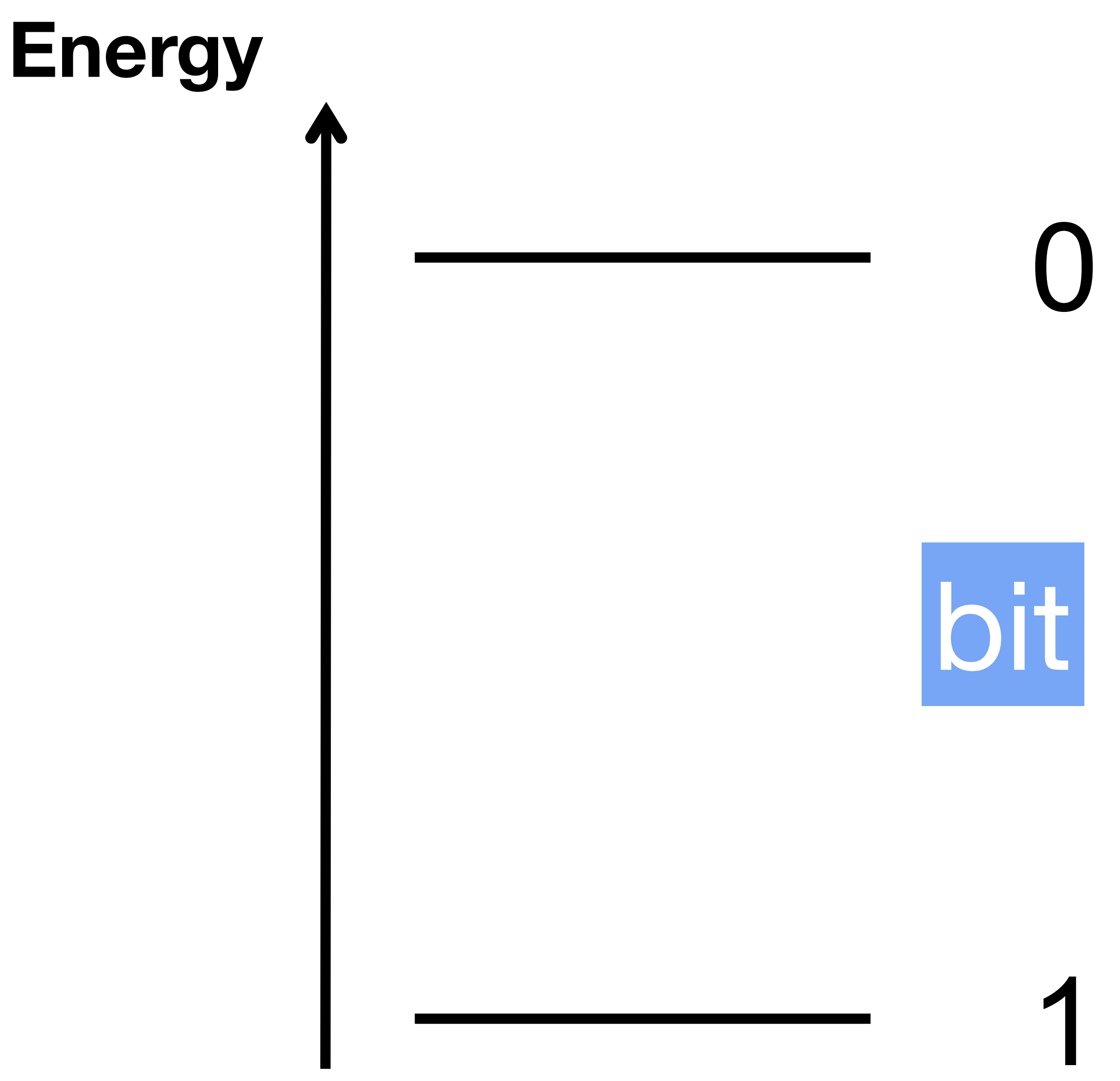
A new platform

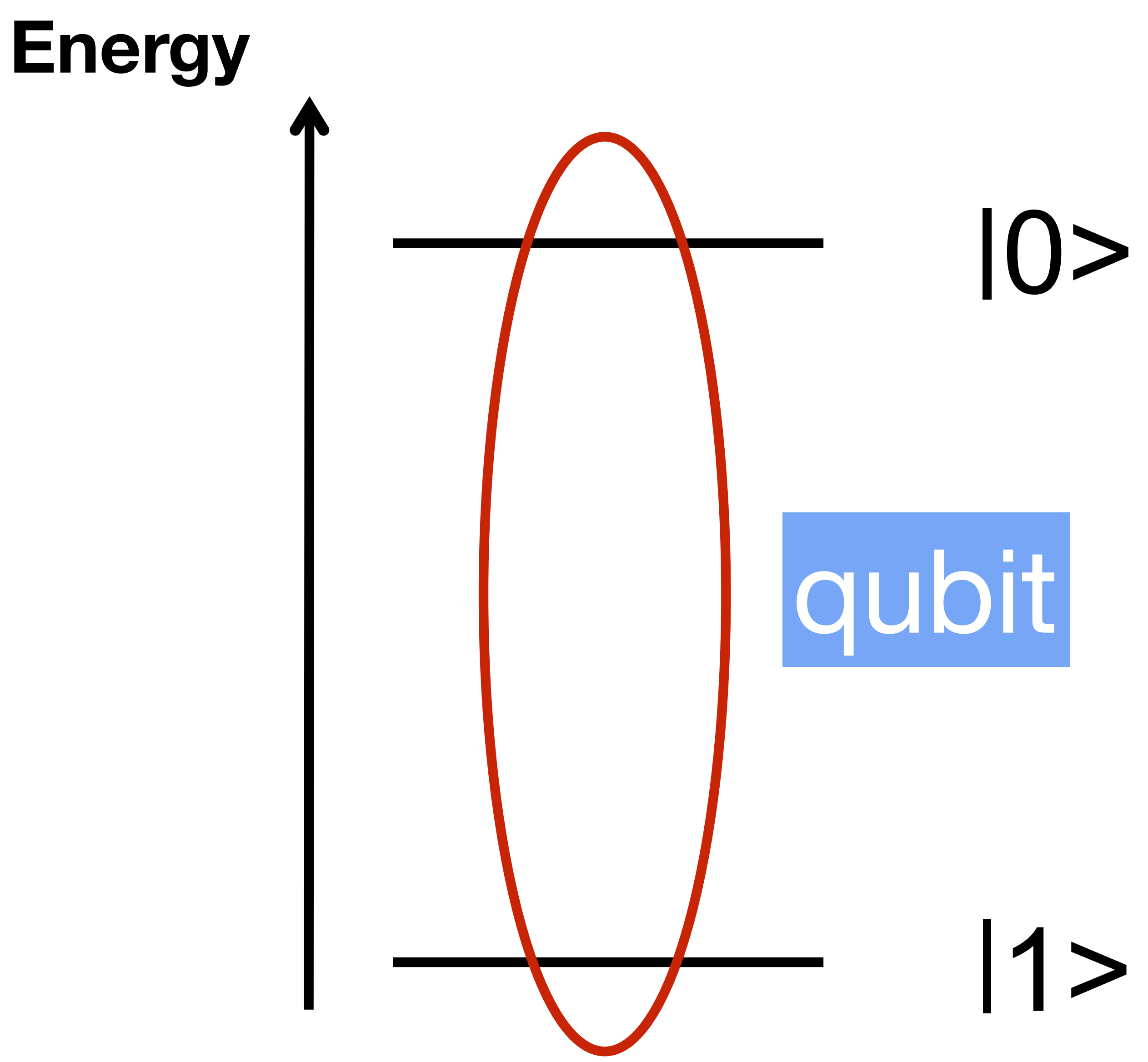
Quantum States

Classical system



2 states: ‘0’ and ‘1’

Quantum system



Quantum states:
α|0> + β|1>

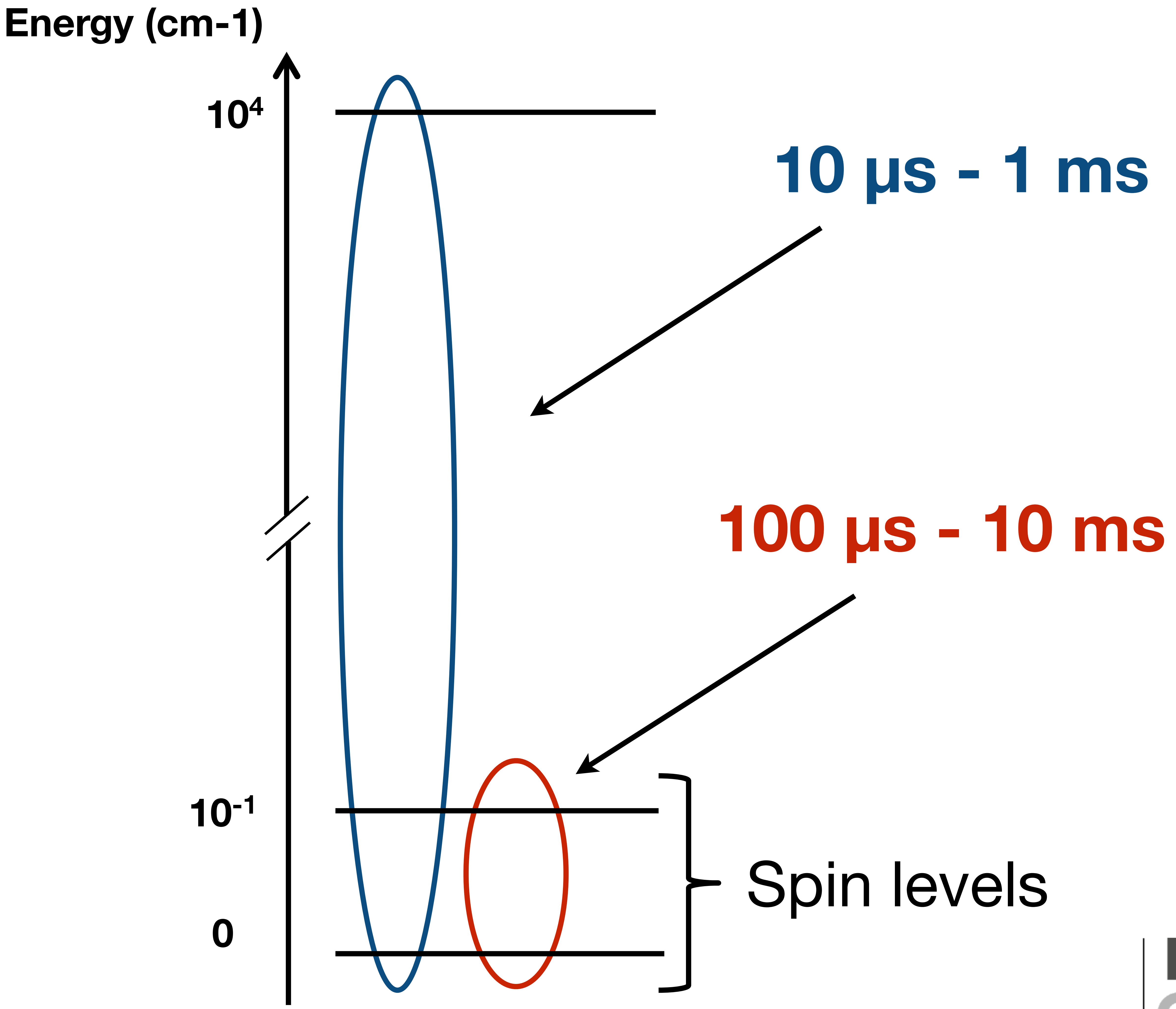
Lifetime

classical:
energy exchange
population lifetime, T_1

quantum:
α/β **perturbation**
coherence lifetime, T_2

$T_2 < T_1$

Rare Earth Ions: Qubits



Optical transitions in the visible and infrared range

Screening of 4f electrons: long optical T_2 (at LHe temp)

Electron and/or nuclear spins

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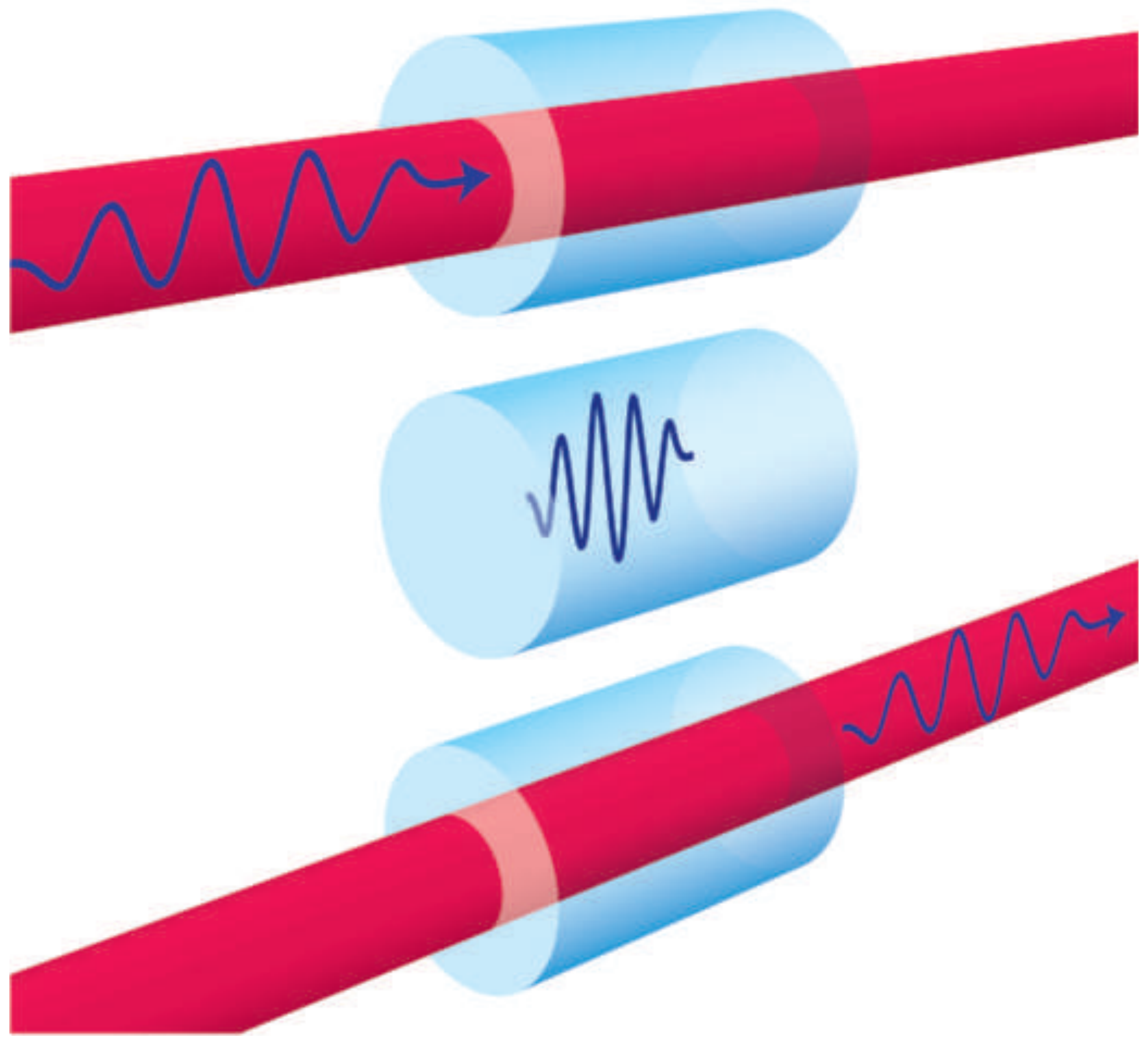
P. Goldner, A. Ferrier, and O. Guillot-Noël, in Handbook on the Physics and Chemistry of Rare Earths, vol. 46, 2015

RE: Interfaces and Memories

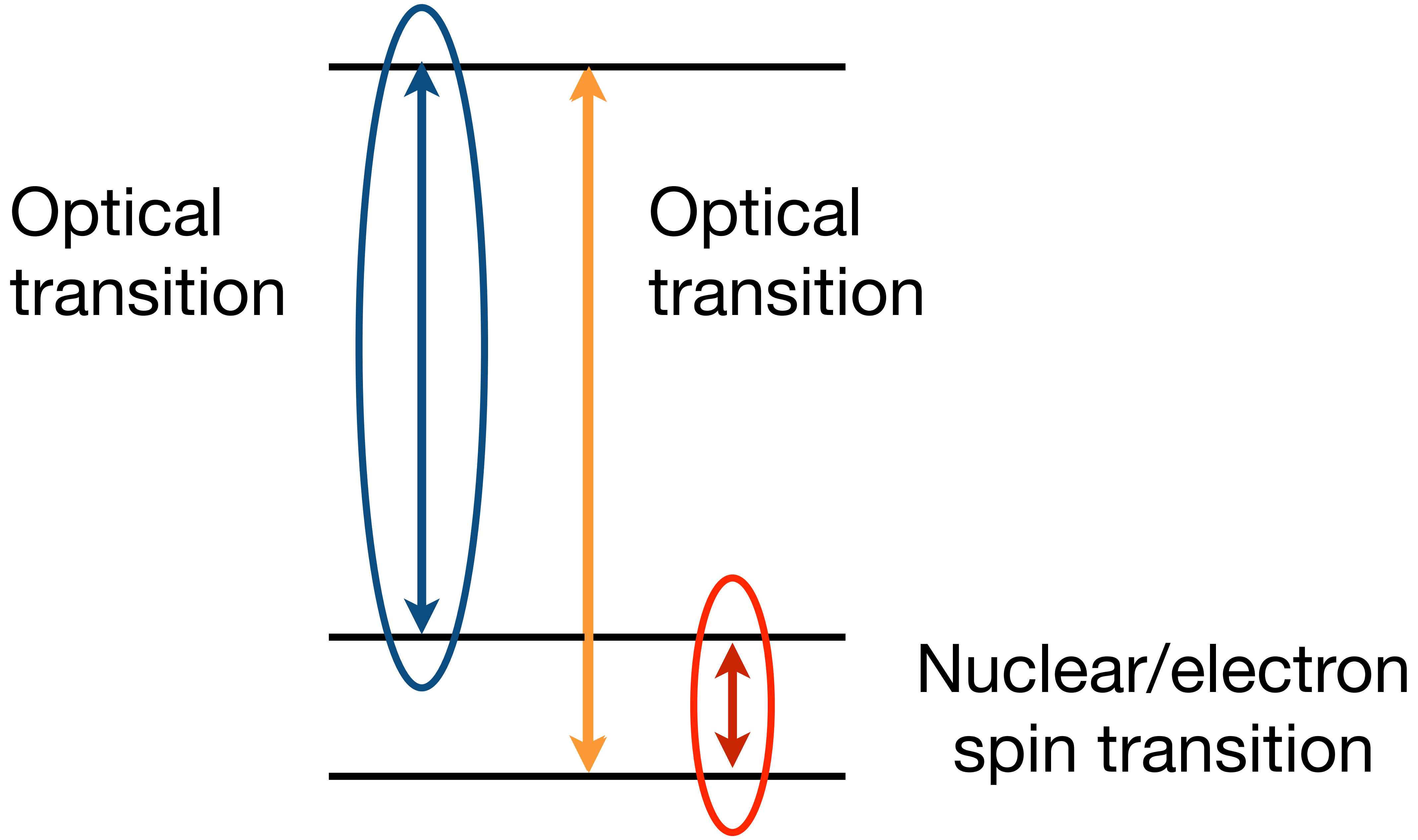
With light



Quantum memories
for optical photons

W. Tittel et al., Nature Photon. 2009.

Between internal states



Long storage time
Microwave/optical quantum interface

Some Results in Bulk Materials

Material properties

Optical coherence lifetimes

$Er^{3+}:Y_2SiO_5$: up to 4 ms

T. Böttger et al., Phys. Rev. B 2009.

Spin coherence lifetimes

$Eu^{3+}:Y_2SiO_5$: up to 6 hours

M. Zhong et al., Nature 2015.

State transfer

Optical to spin

$Pr^{3+}:La_2(WO_4)_3$: spin control

M. Lovric, …, PG, Phys. Rev. Lett. 2013.

Electron to nuclear spin

$Nd^{3+}:Y_2SiO_5$: high fidelity

G. Wolfowicz, …, PG, Phys. Rev. Lett. 2015.

Quantum information

Optical memories

$Nd^{3+}:Y_2SiO_5$: teleportation

F. Bussières, …, PG et al., Nat. Photonics 2015.

Er^{3+} glass fiber: 1.5 μm storage

E. Saglamyurek et al., Nat. Photonics 2015.

Microwave memories

$Er^{3+}:Y_2SiO_5$: strong coupling

S. Probst et al., Phys. Rev. Lett. 2013.

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At the nanoscale

Nanoscale Systems

New opportunities

Enhanced light-matter interactions

micro/nano optical cavities

Single center detection and control

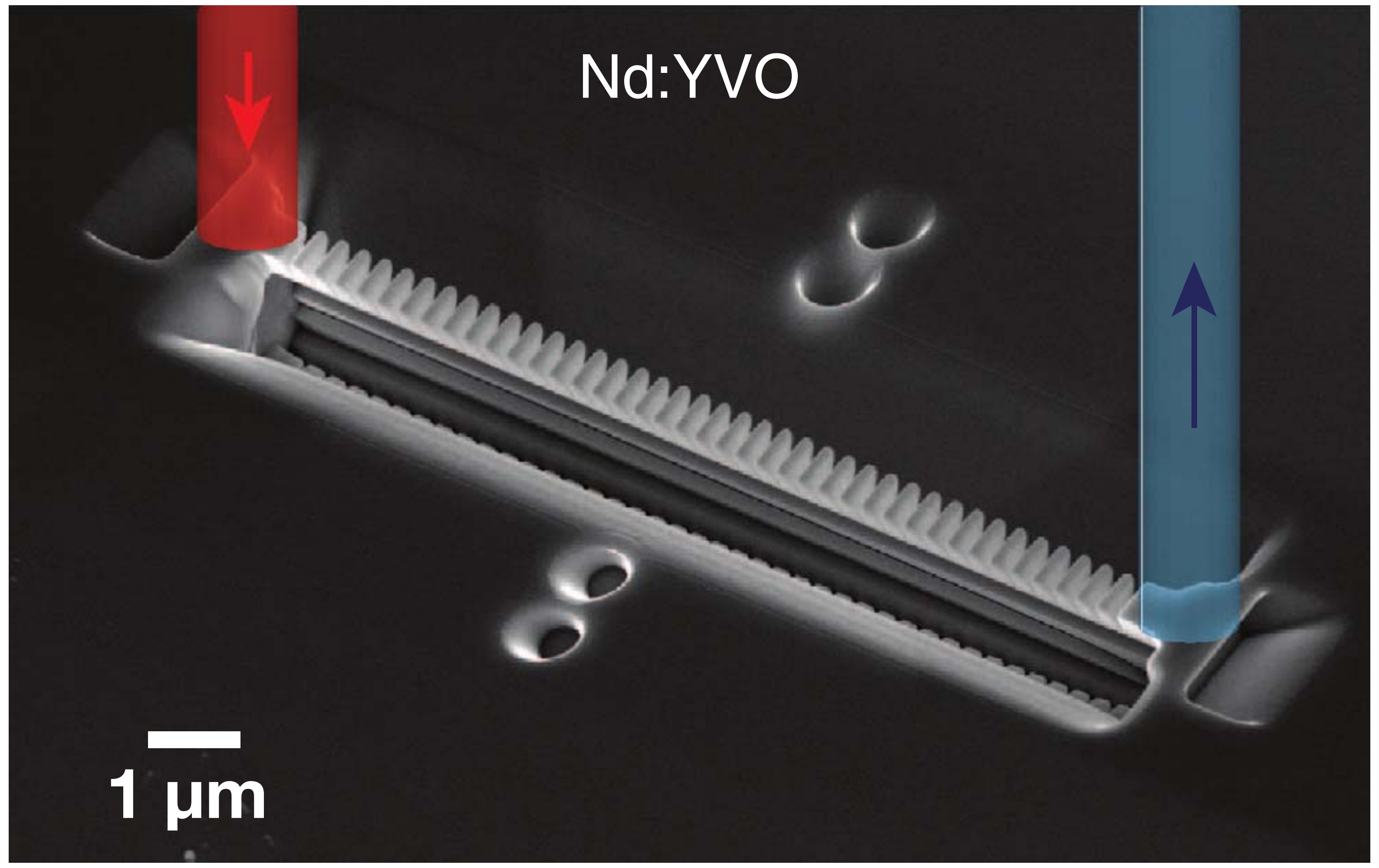
small detection volume

Hybrid quantum systems

interactions at short distances

An example

Optical nano-resonator



Hybrid systems: G. Kurizki et al., PNAS 2015.

T. Zhong et al., Nat. Commun. 2015.

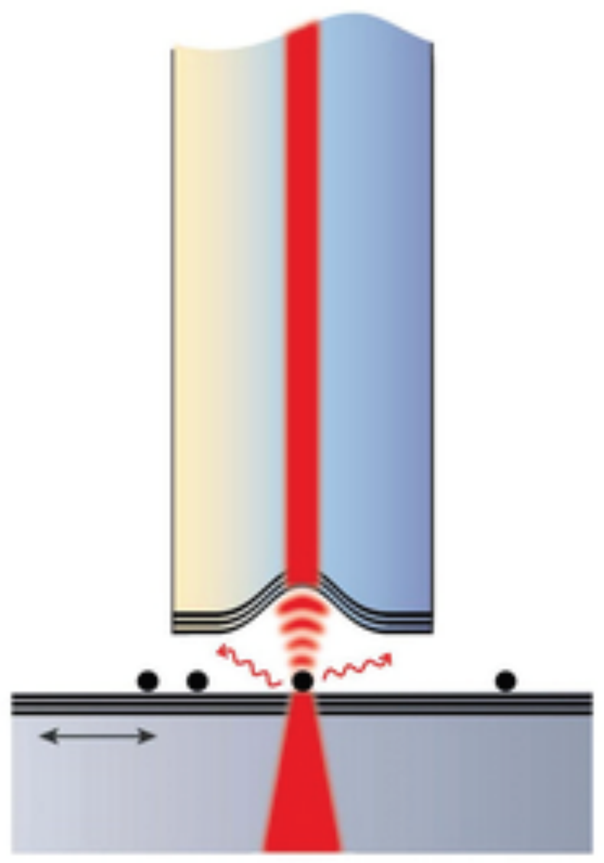
A Versatile Approach

Bottom-up synthesis

Nanoparticles

Thin films

High-Q micro-cavity

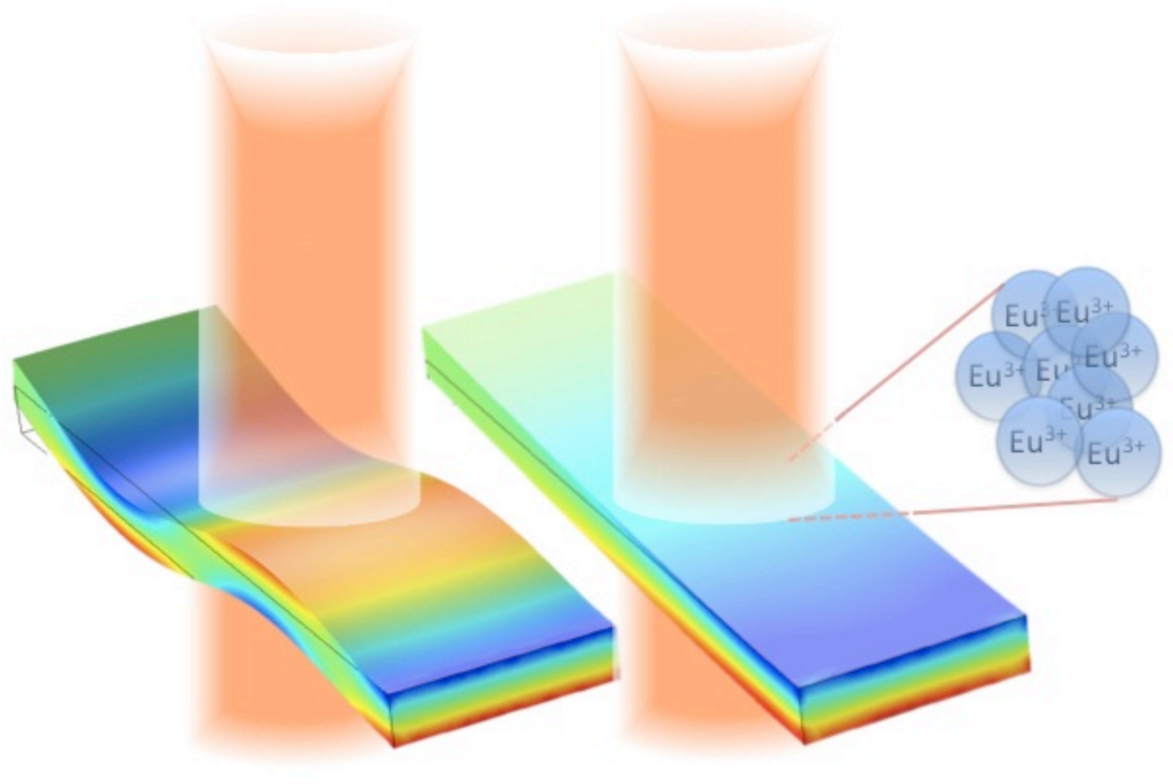


Quantum memories

Single photon sources

Hybrid systems

Force sensors



Quantum opto-electronics w/ graphene

EU project NanOQTech: www.nanoqtech.eu

RE-graphene: K. J. Tielrooij, …, PG et al., Nat. Phys. 2015.

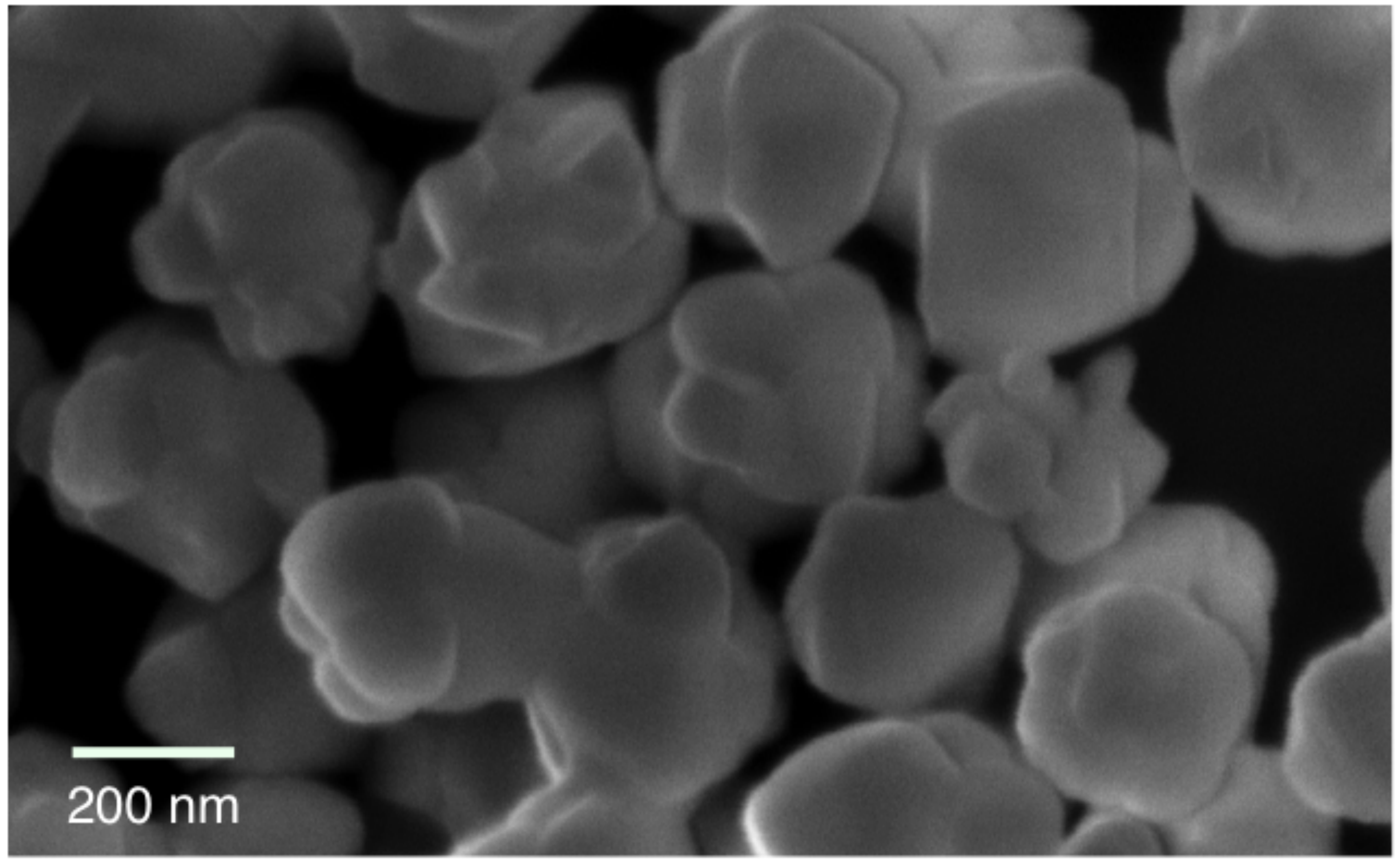
Nanoparticles

0.5% $Eu^{3+}:Y_2O_3$

Homogeneous precipitation
Monodispersed, spherical

High temperature annealing
Cubic phase
Defects reduced at 1200 °C

Long T_2 in bulk crystal
and transparent ceramics



Particle size: 400 nm
Crystallite size: 130 nm

Particles: K. de Oliveira Lima, ..., PG, J. Lumin. 2015.

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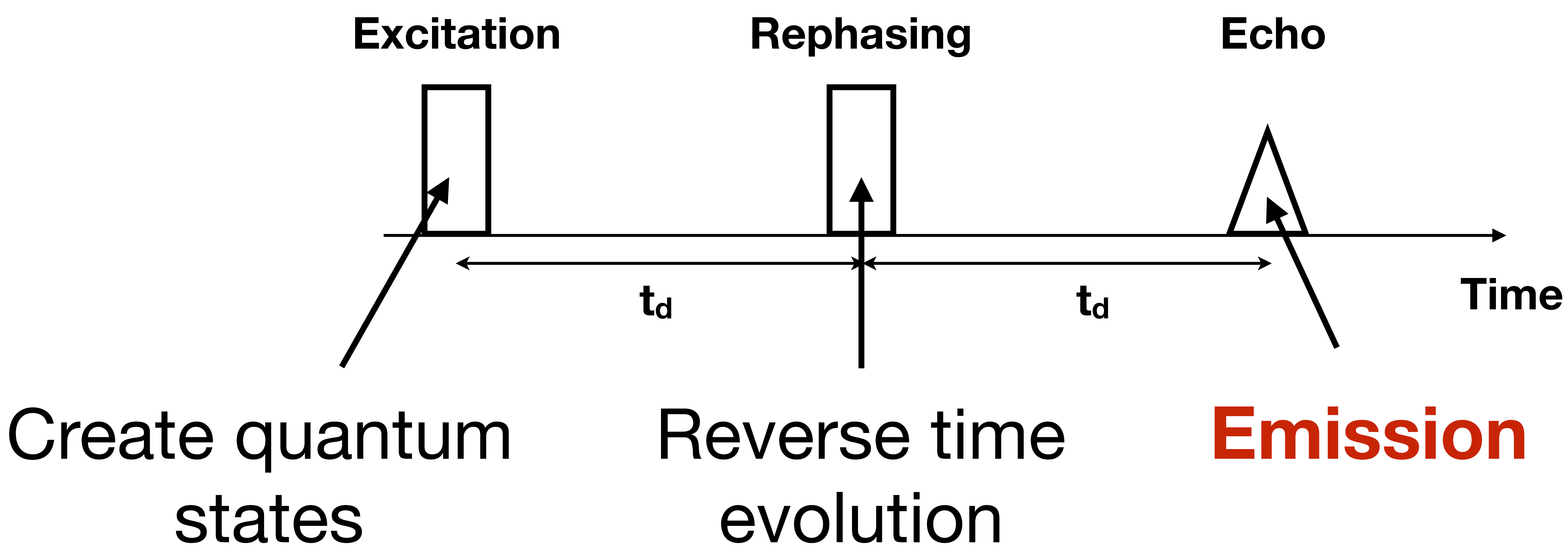
Ceramics: A. Ferrier, ..., PG, Phys Rev B 2013 - N. Kunkel, ..., PG, APL Mat. 2015, J. Phys. Chem. C 2016, PRB 2017.

The Photon Echo



Echo: only ions with unperturbed quantum states

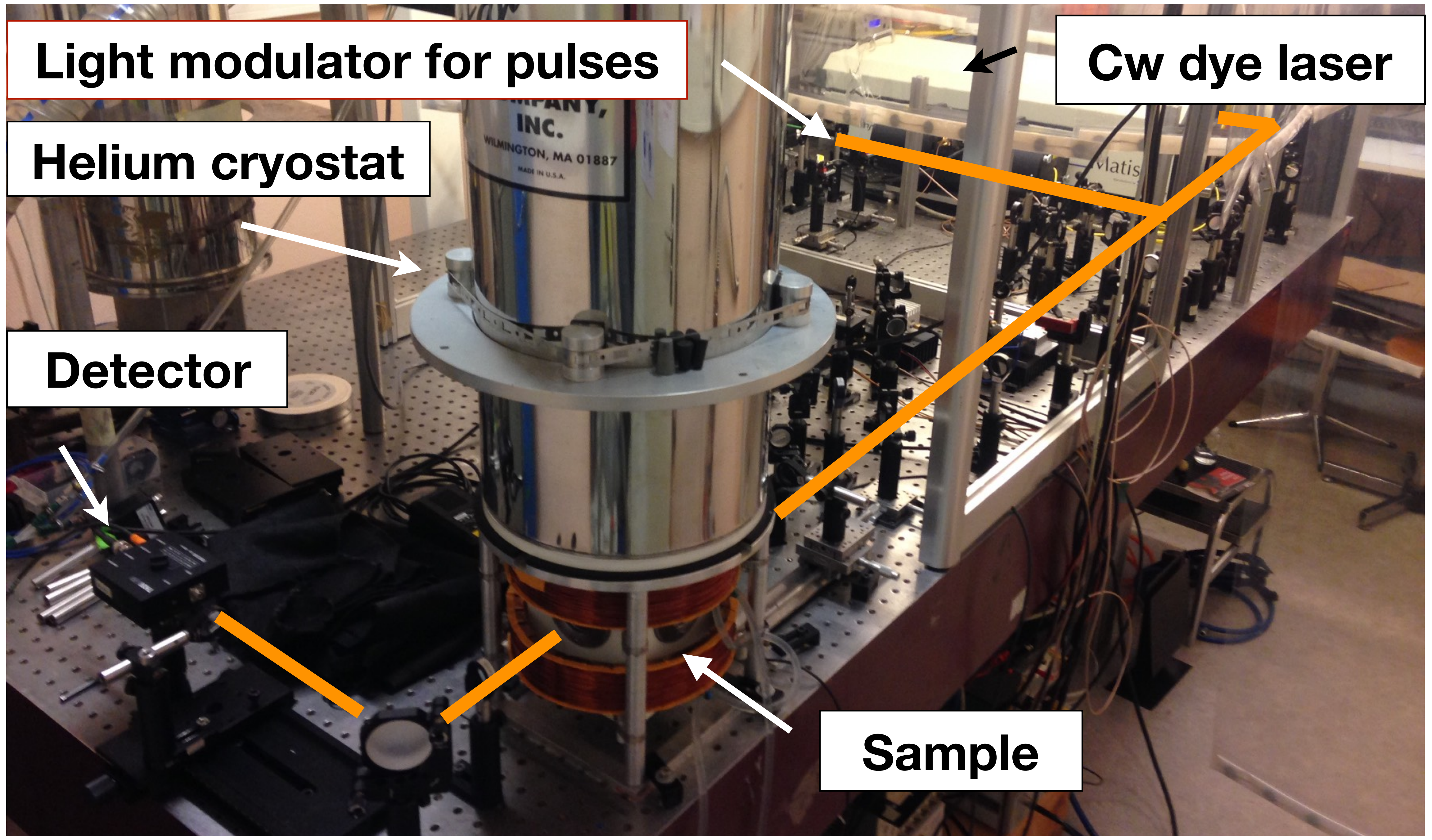
Coherence lifetime: $I_{echo} = \exp(-4t_d/T_2)$

Homogeneous linewith: $\Gamma_h = (\pi T_2)^{-1}$

I. D. Abella, N. A. Kurnit, and S. R. Hartmann, Phys. Rev. 1966.

Measuring Coherence Times

Setup for photon echo experiments



Samples: transparent materials

or… **powders?**

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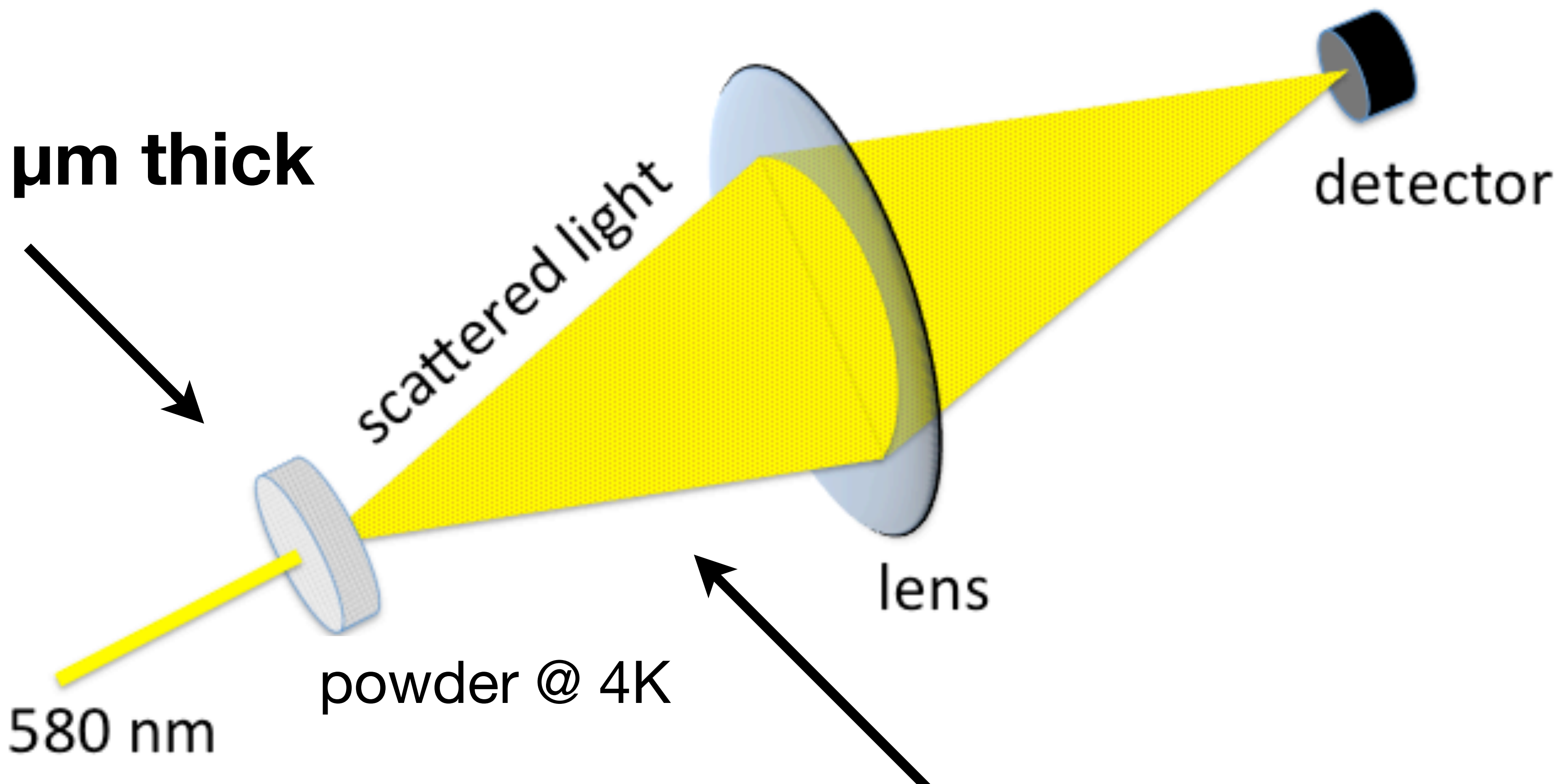
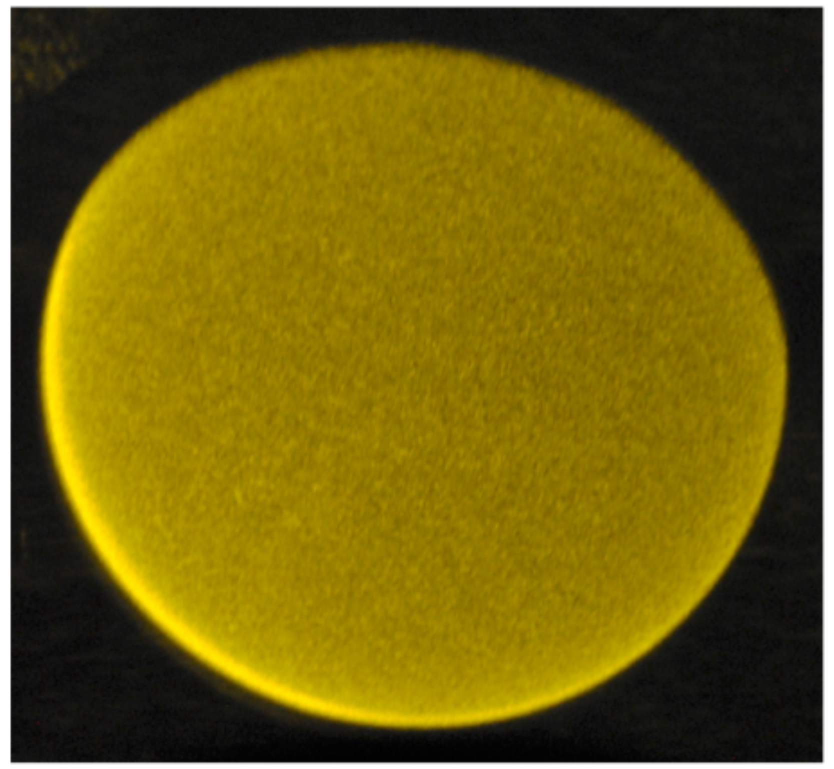
Photon Echo in Powders

500 µm thick

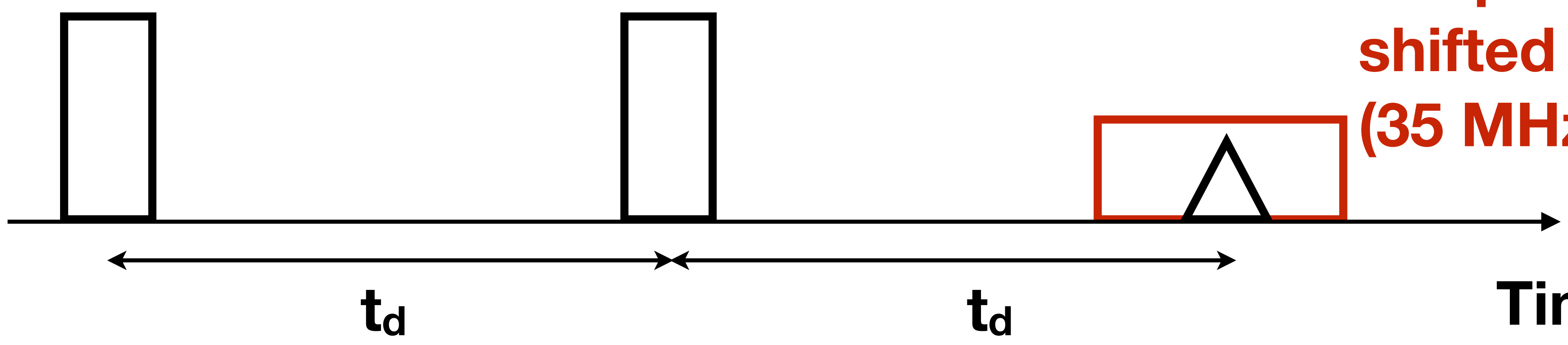


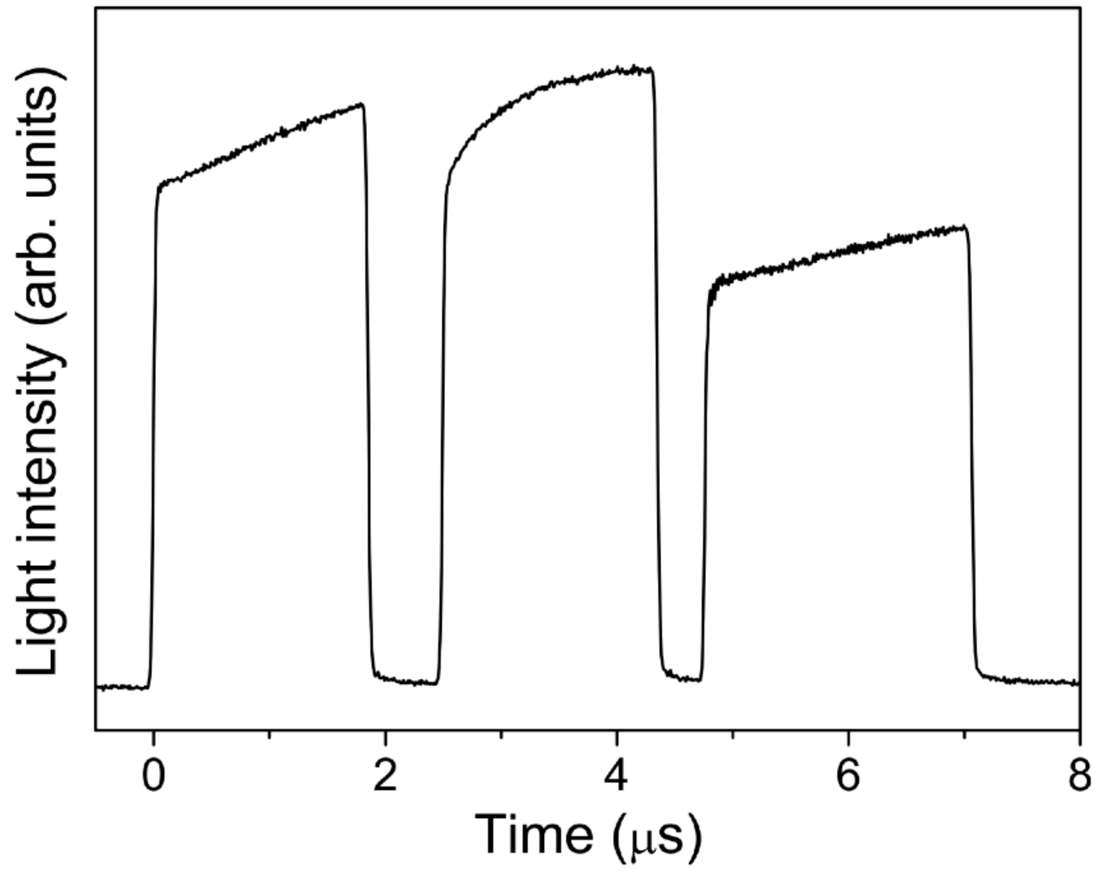
$^7F_0$ - $^5D_0$ transition

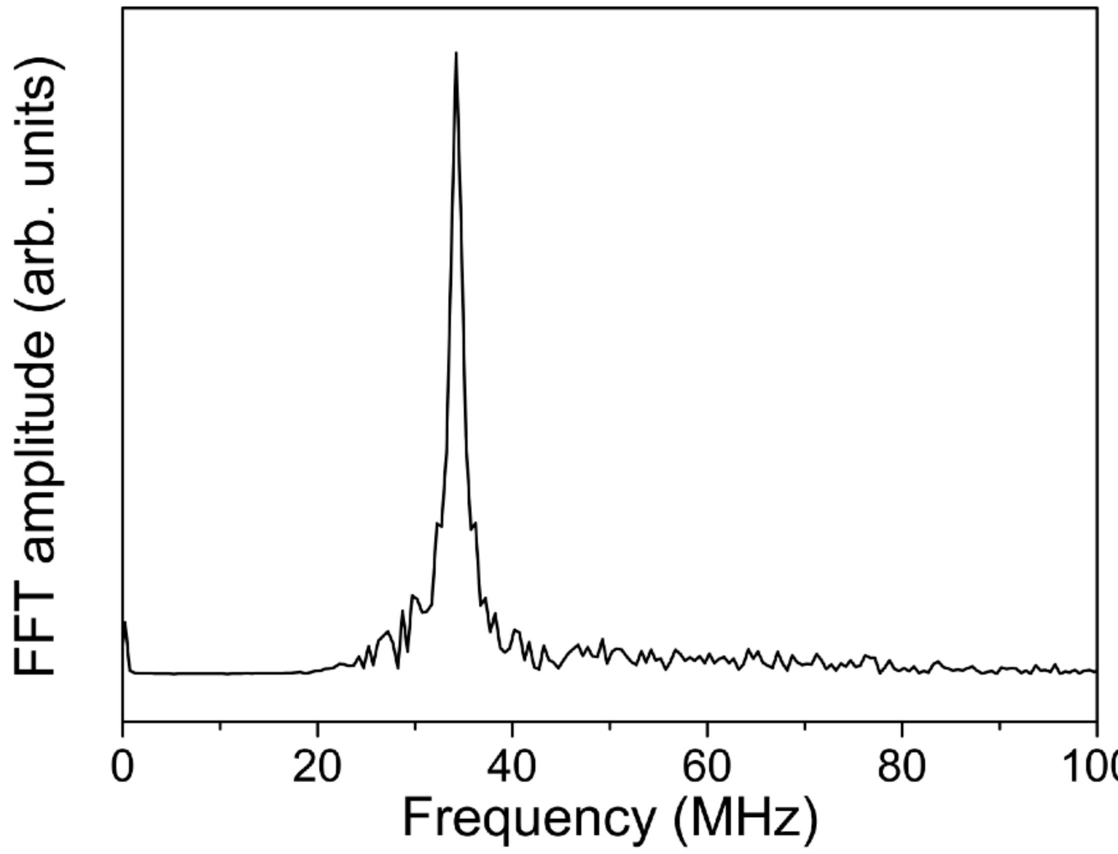


Light scattered by the powder

Interferometric detection







A. Perrot, PG, et al. Phys. Rev. Lett. 2013.
F. Beaudoux, …, PG, Opt. Express 2011.

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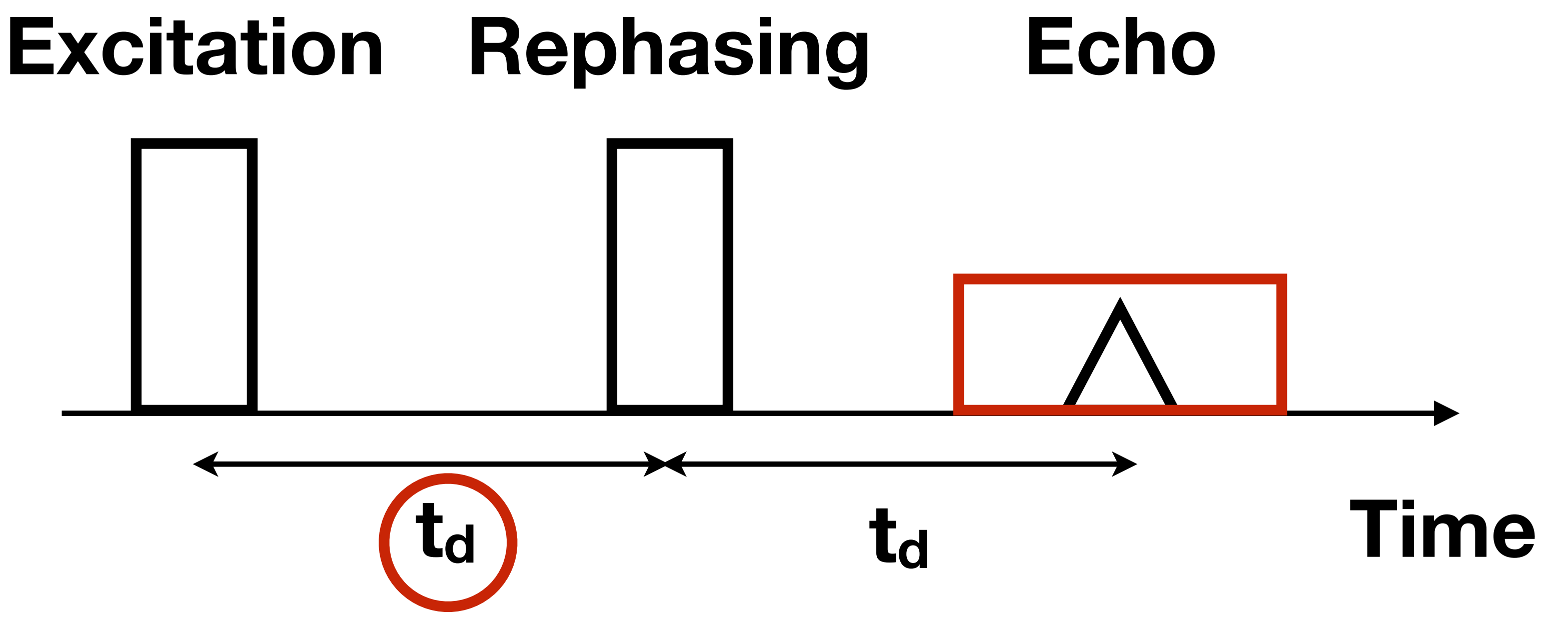
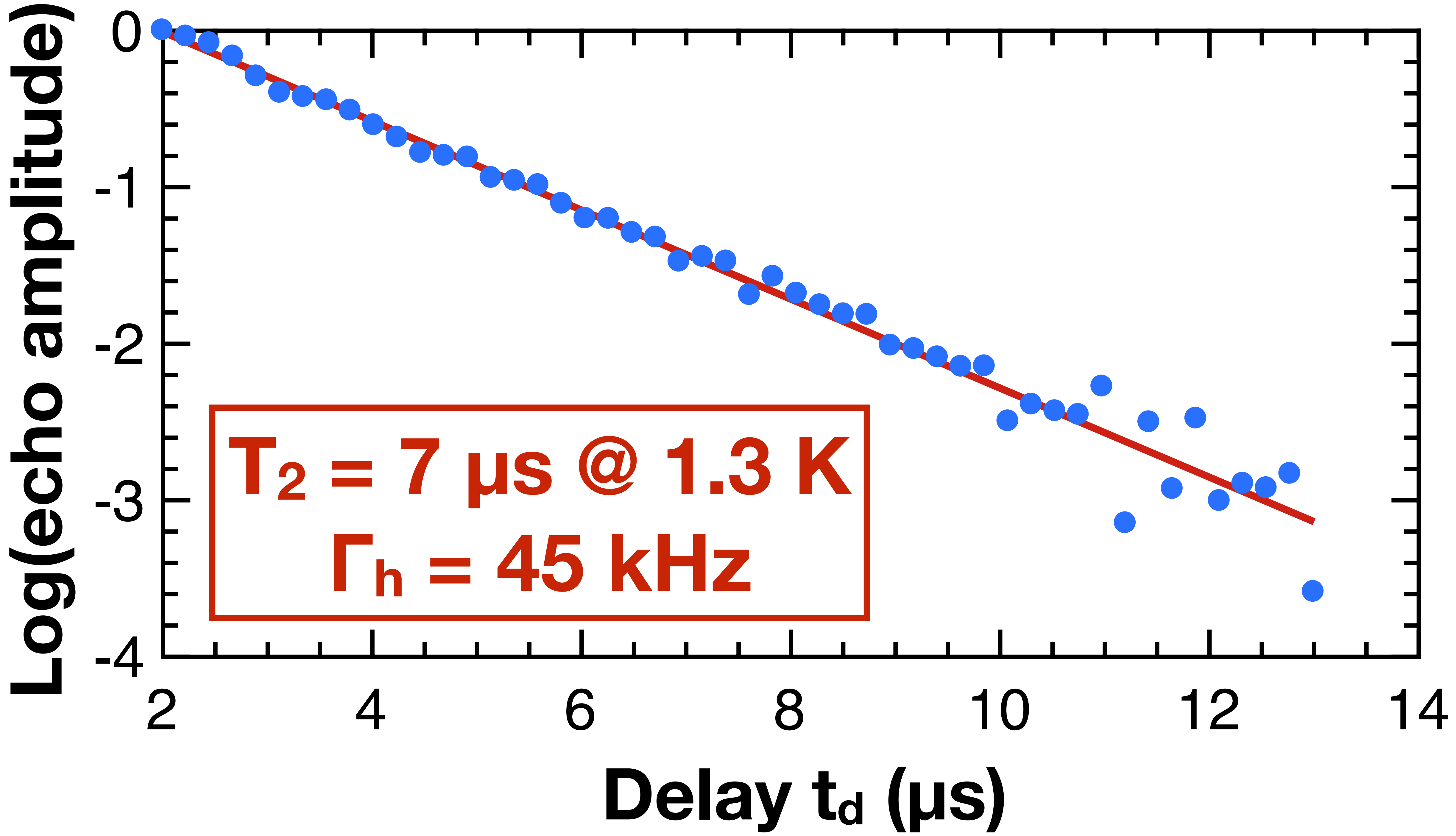
Optical T_2 in nanocrystals

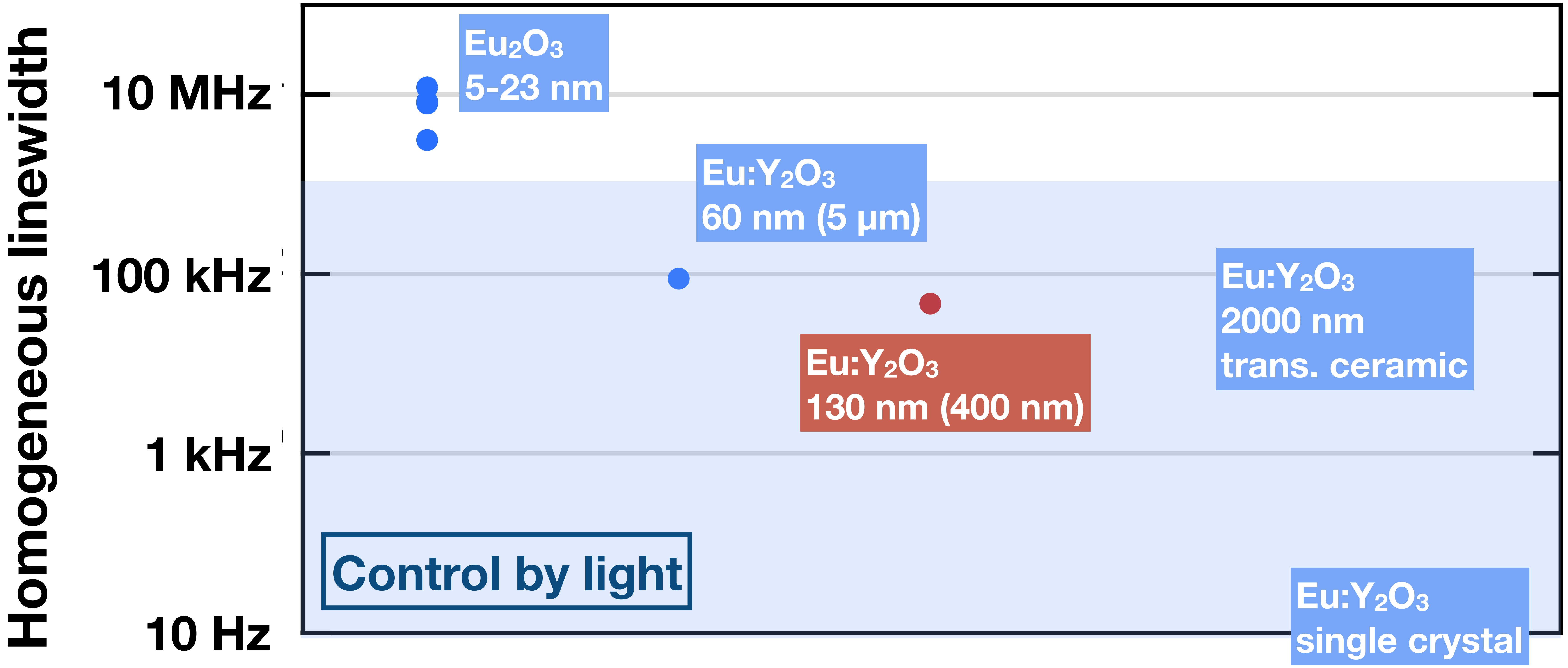
Echo Decay in Nanocrystals





J. G. Bartholomew, K. de Oliveira Lima, A. Ferrier, and PG,
Nano. Lett. 2017.

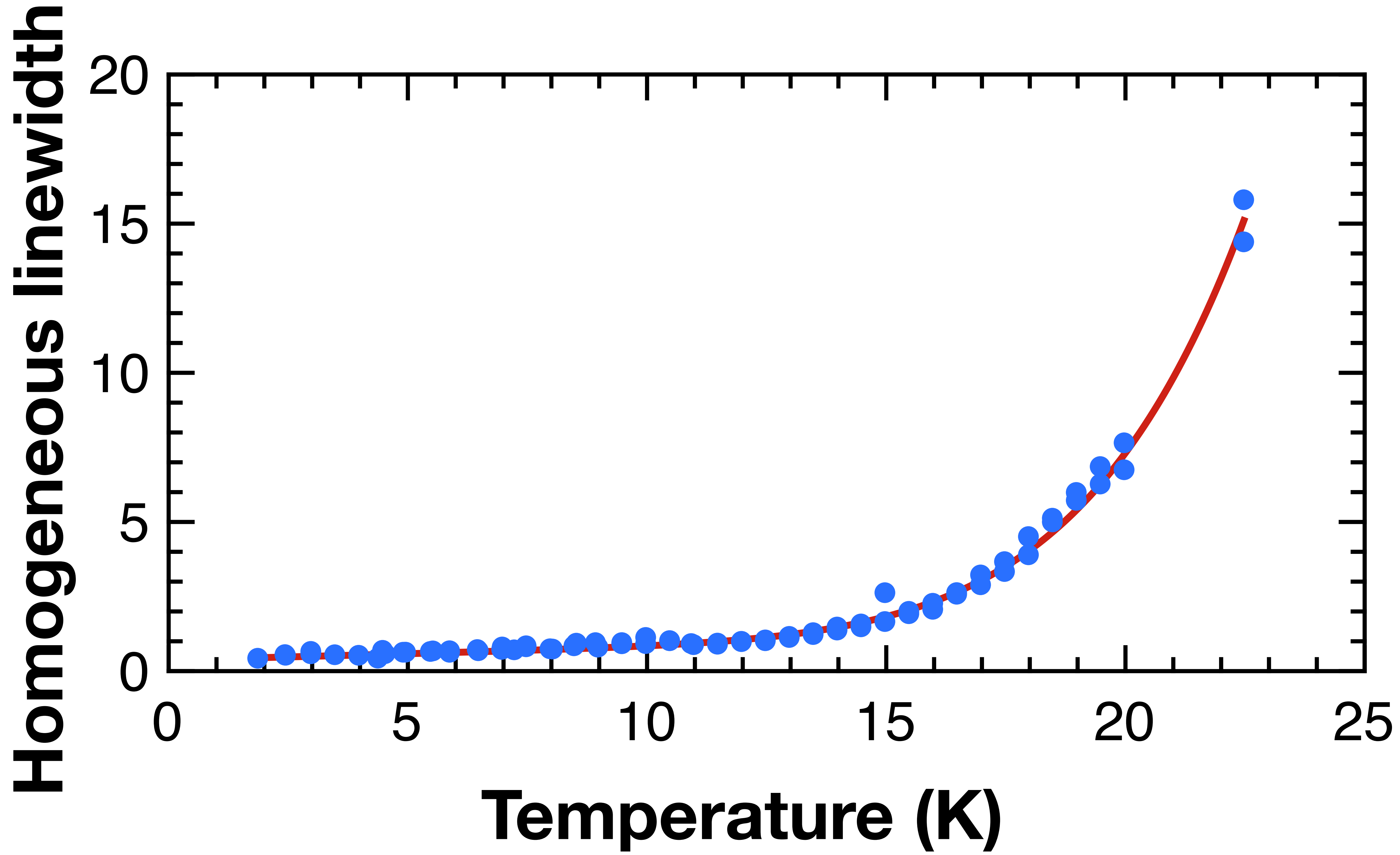
$Eu:Y_2O_3$ Homogeneous Linewidths



R. S. Meltzer et al., Phys. Rev. B 2000, 2001.
A. Perrot, PG, et al. Phys. Rev. Lett. 2013.
J. G. Bartholomew, …, PG, Nano. Lett. 2017.

C. Thiel, private communication.
N. Kunkel, …, PG, Phys. Rev. B 2017.

Size Limited Linewidth?



$\Gamma_h = \Gamma_0 + \alpha_D T + \alpha_R T^7$

$\alpha_D T$ → Disorder

$\alpha_R T^7$ → Raman process

also in ceramics and bulk crystals

no contribution from <u>size related</u> phonon modes

J. G. Bartholomew, K. de Oliveira Lima, A. Ferrier, and PG, Nano. Lett. 2017.

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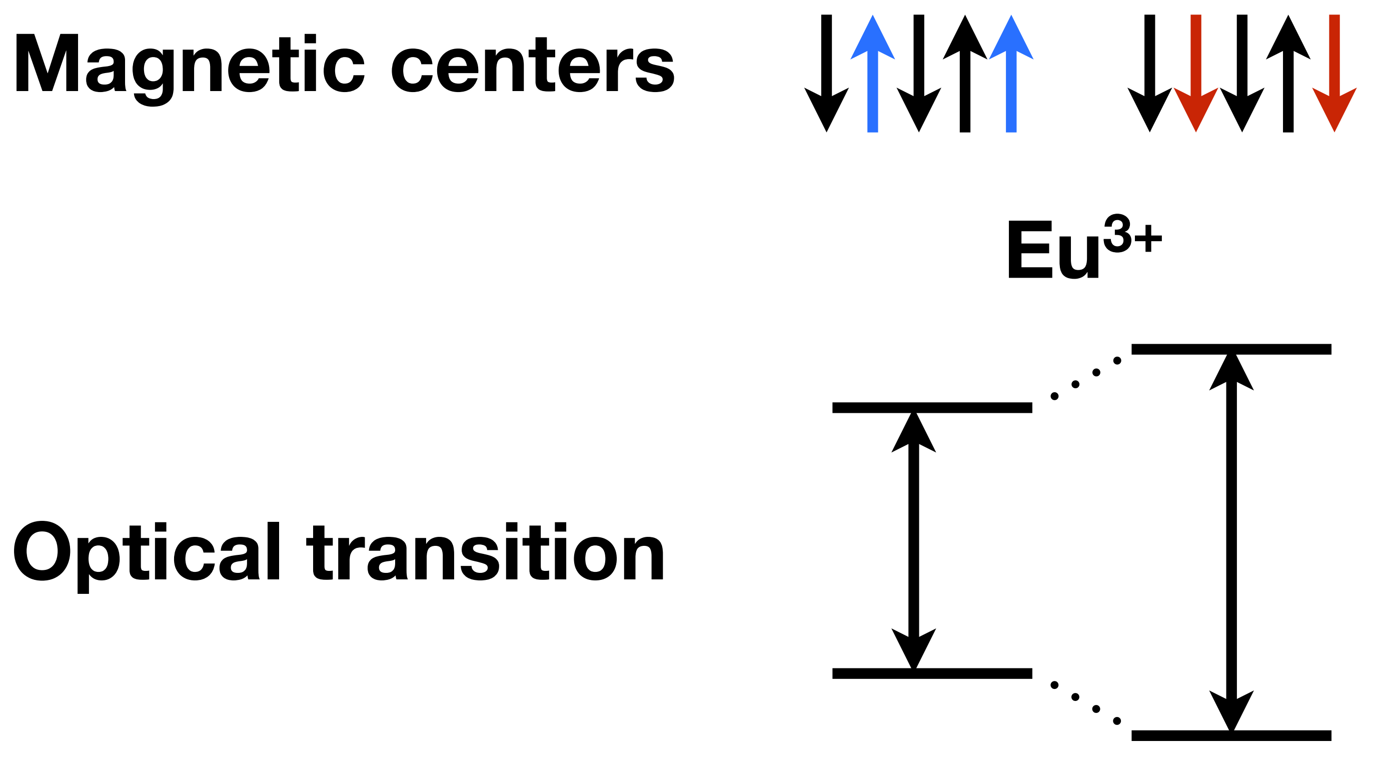
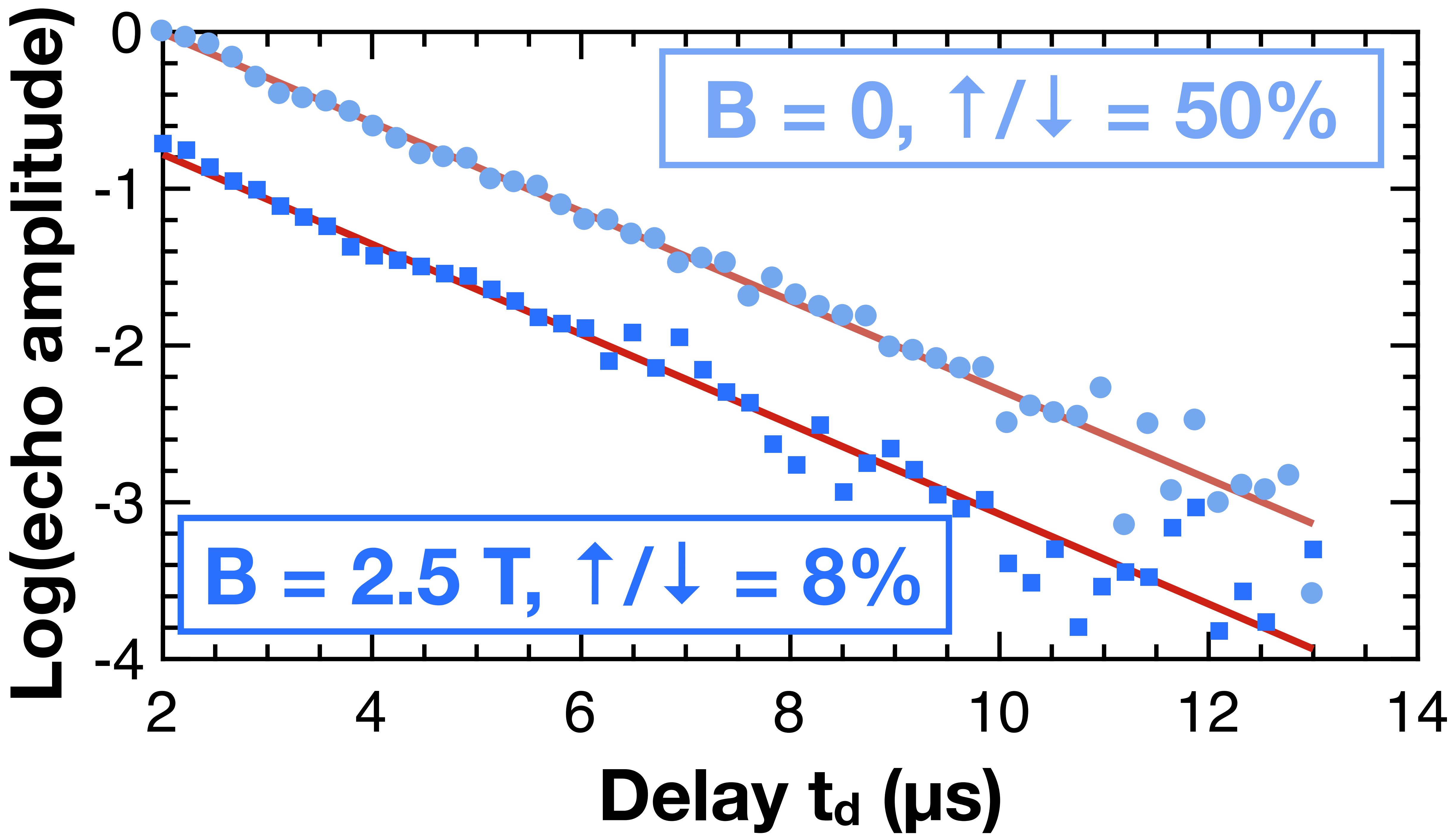
Phonon in nanoparticles: R. S. Meltzer et al., Phys. Rev. B 2000, 2001.

Magnetic Centers





no contribution from magnetic impurities or defects

surface electric charges?

Q. dots: N. Ha, et al., Phys. Rev. B, 92, 075306, (2015).
NV: M. Kim, at al., Phys. Rev. Lett., 115, 087602,(2015).

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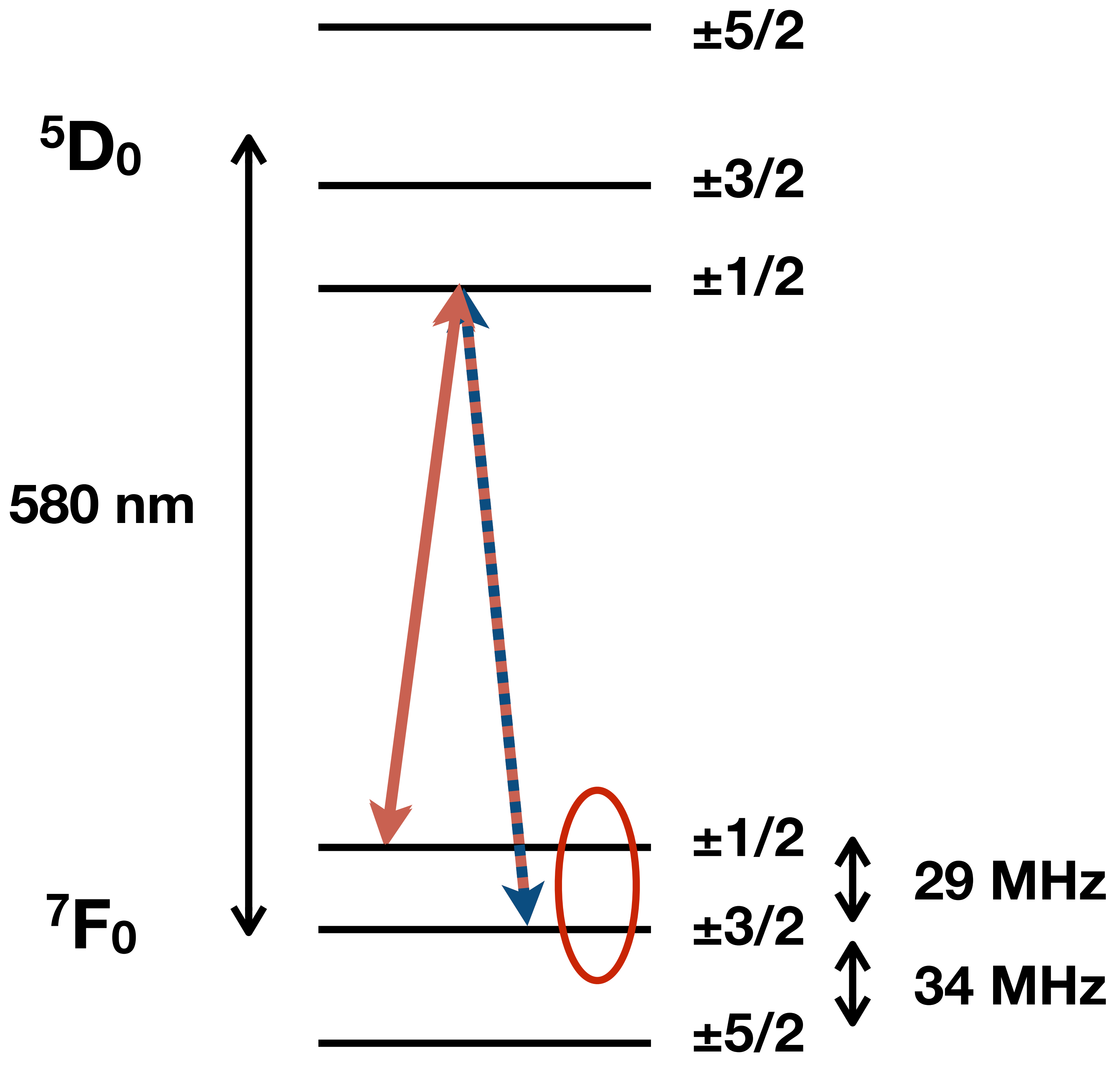
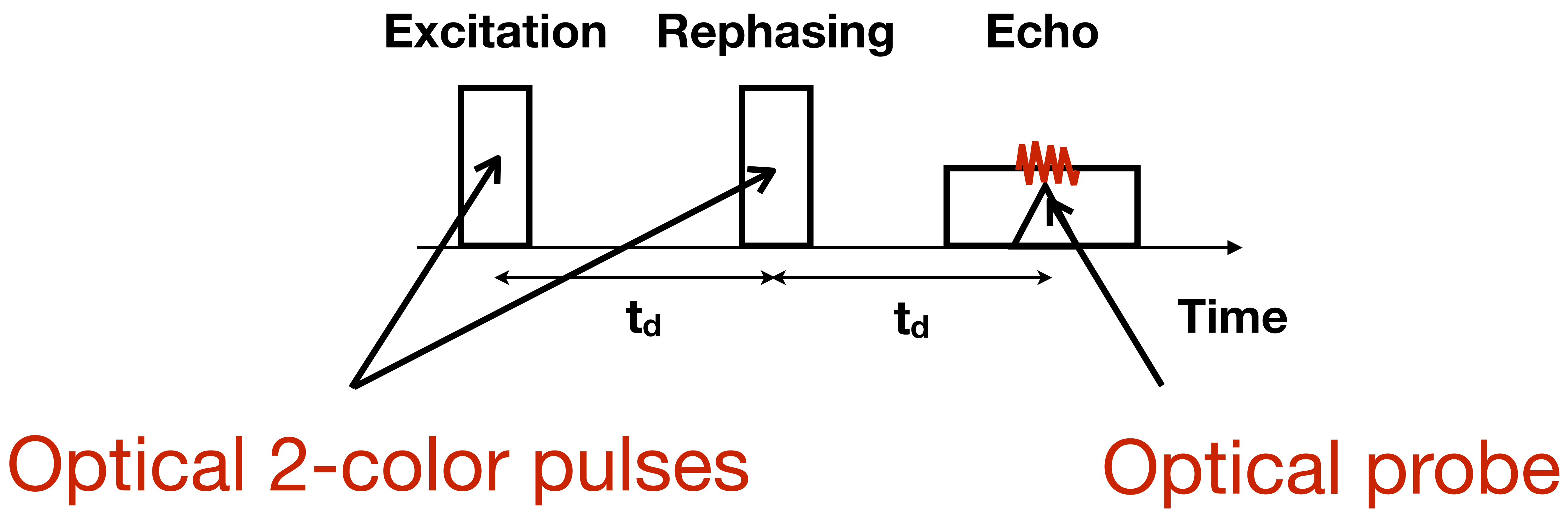
J. G. Bartholomew, K. de Oliveira Lima, A. Ferrier, and PG, Nano. Lett. 2017.

Spin T_2 in ceramics

Spin Quantum States

$^{151}Eu^{3+}$: nuclear spin I = 5/2





J. Karlsson, N. Kunkel, A. Ikesue, A. Ferrier, and PG,
J. Phys.: Condens. Matter 2017.

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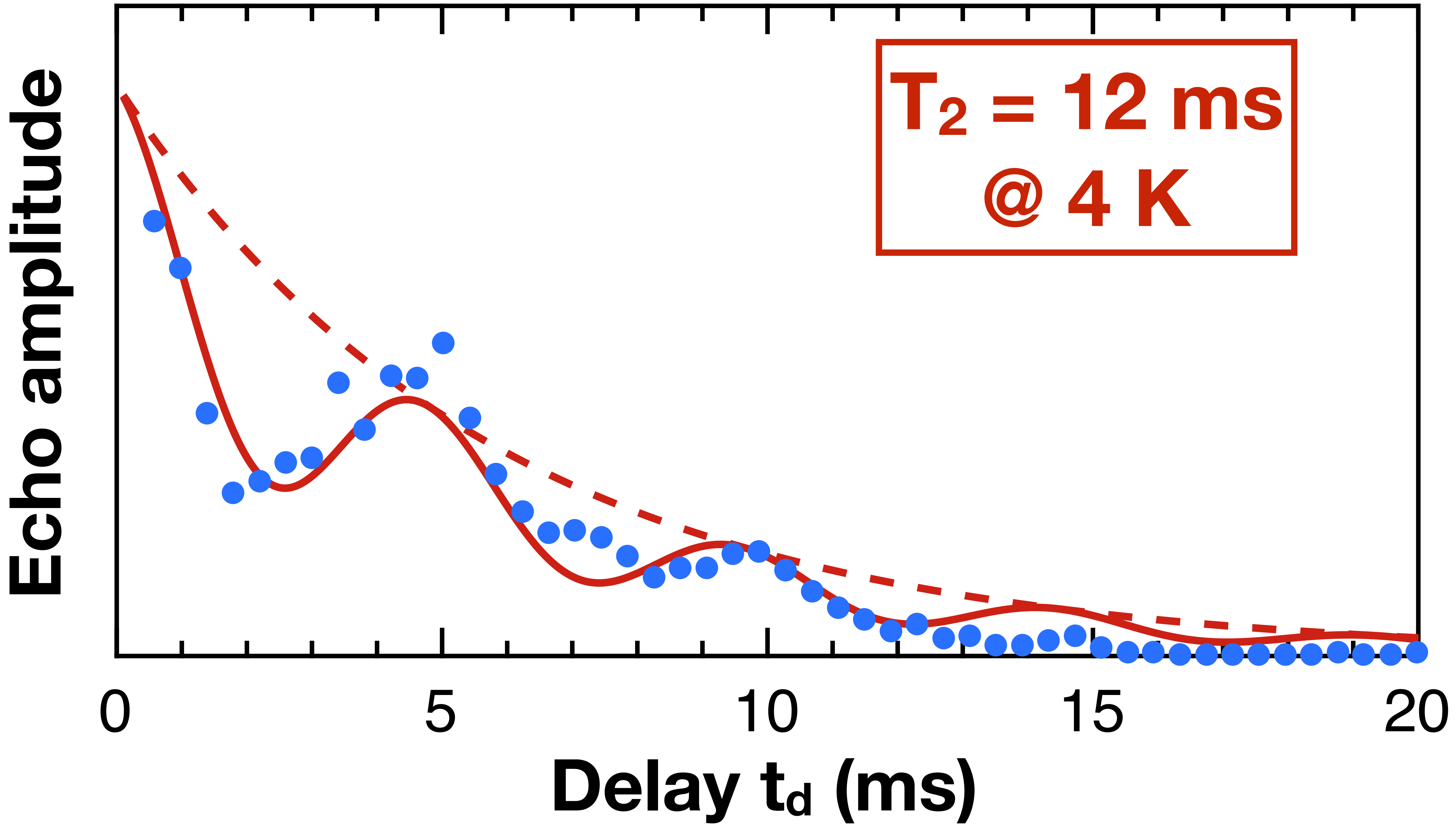
Spin Coherence Lifetimes

$Eu^{3+}:Y_2O_3$ transparent ceramics



Spin T_2 comparable to single crystals

$Eu^{3+}:Y_2SiO_5$ single crystal: $T_2 = 19$ ms

J. Karlsson, N. Kunkel, A. Ikesue, A. Ferrier, and PG,
J. Phys.: Condens. Matter 2017.

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Magnetic vs. Electric Perturbations

	Sensitivity		Linewidth in ceramics (Hz)	Contribution (Hz)	
	Magnetic field	Electric field		Magnetic perturbation	Electric perturbation
Optical transition	1-100 kHz/mT	50 kHz/(V/cm)	3200	≈ 3-300	3200-2900
Spin transition	10 kHz/mT	≈1 Hz/(V/cm)	26	26	≈ 0

Electric → 3200   Magnetic → 26

R. M. Macfarlane, …, PG, Phys. Rev. Lett. 2014

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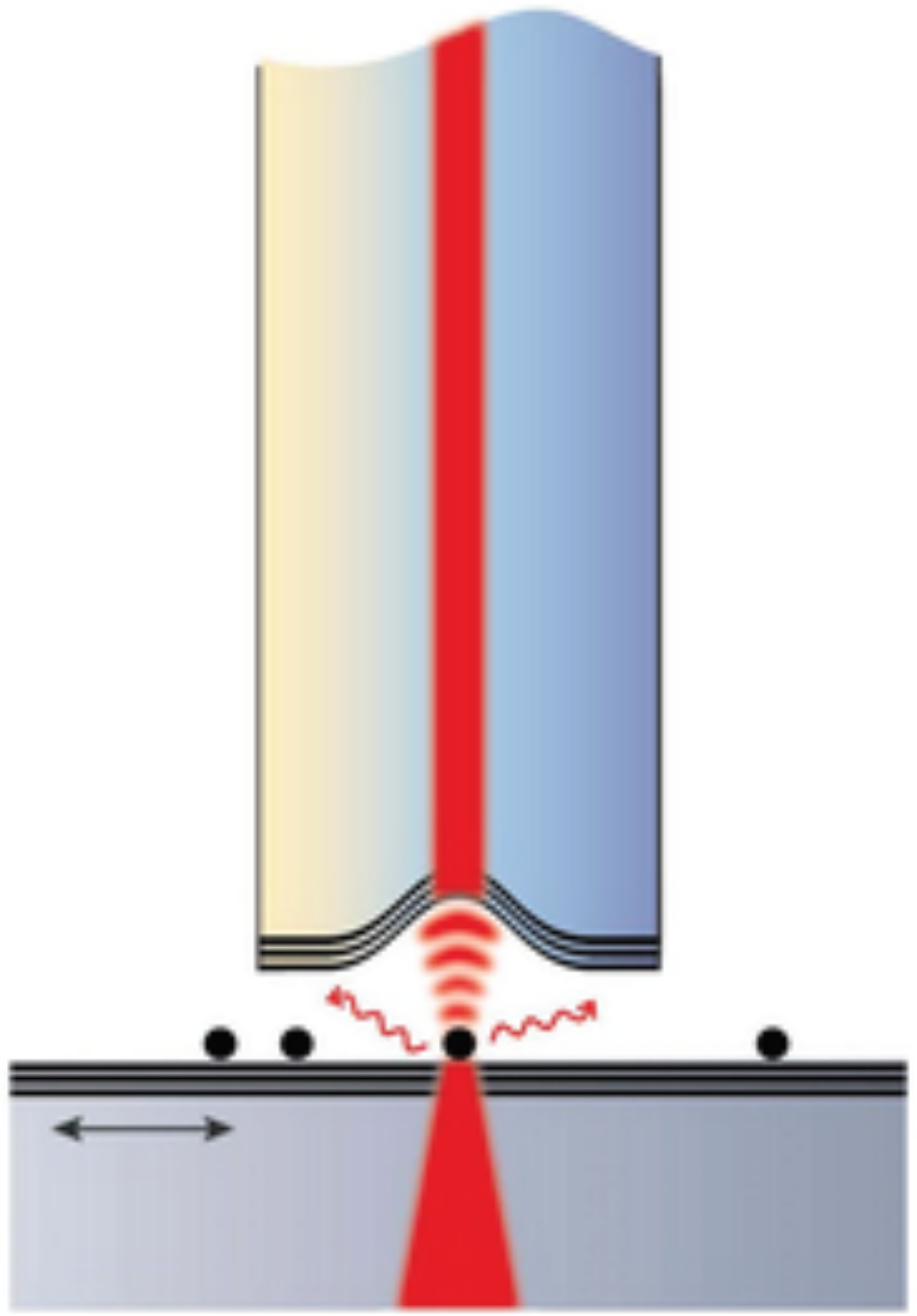
What is next?

Outlook: Micro-cavities



D. Hunger

Smaller particles (< 100 nm)

Longer optical coherence lifetime

Spin properties

Single particle spectroscopy

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Summary

Rare earth doped nanostructures for optical quantum technologies

unique capability of **interfacing light, atoms and spins**

long optical coherence lifetimes for applications in:
quantum memories, single photon sources, hybrid systems

outside quantum technologies:
probing materials with high resolution spectroscopy:
defects, disorder, impurities, surface

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Collaborators: **R. Gonçalves, USP, Brazil** - D. Hunger, KIT, Germany - S. Kröll, Lund University, Sweden
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http://www.nanoqtech.eu

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