Institut
de Recherche
de Chimie Paris

Towards Optically Controlled Qubits in Rare Earth Doped Nanoparticles

Philippe Goldner

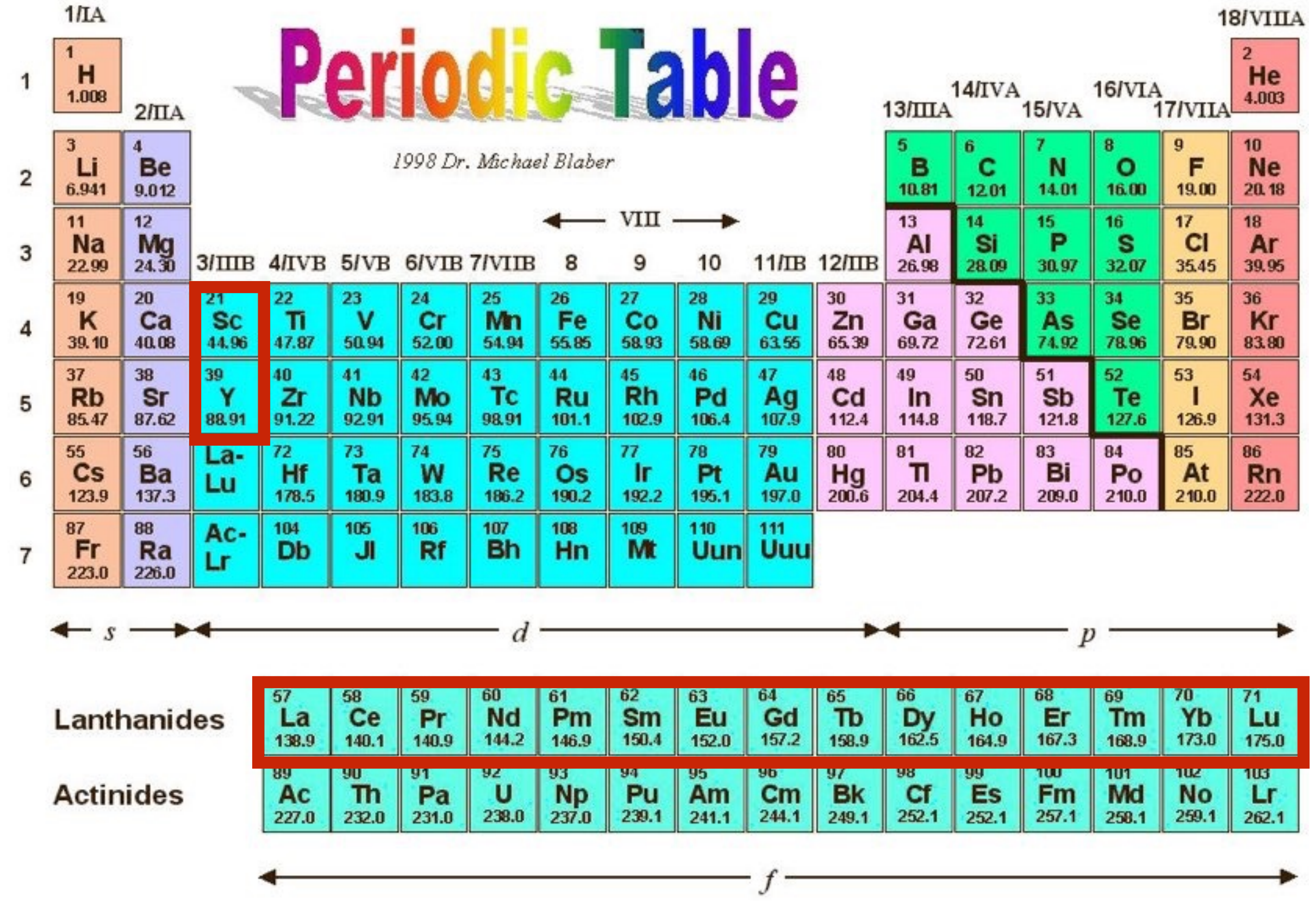
Institut de Recherche de Chimie Paris
Chimie ParisTech, CNRS, Paris, France

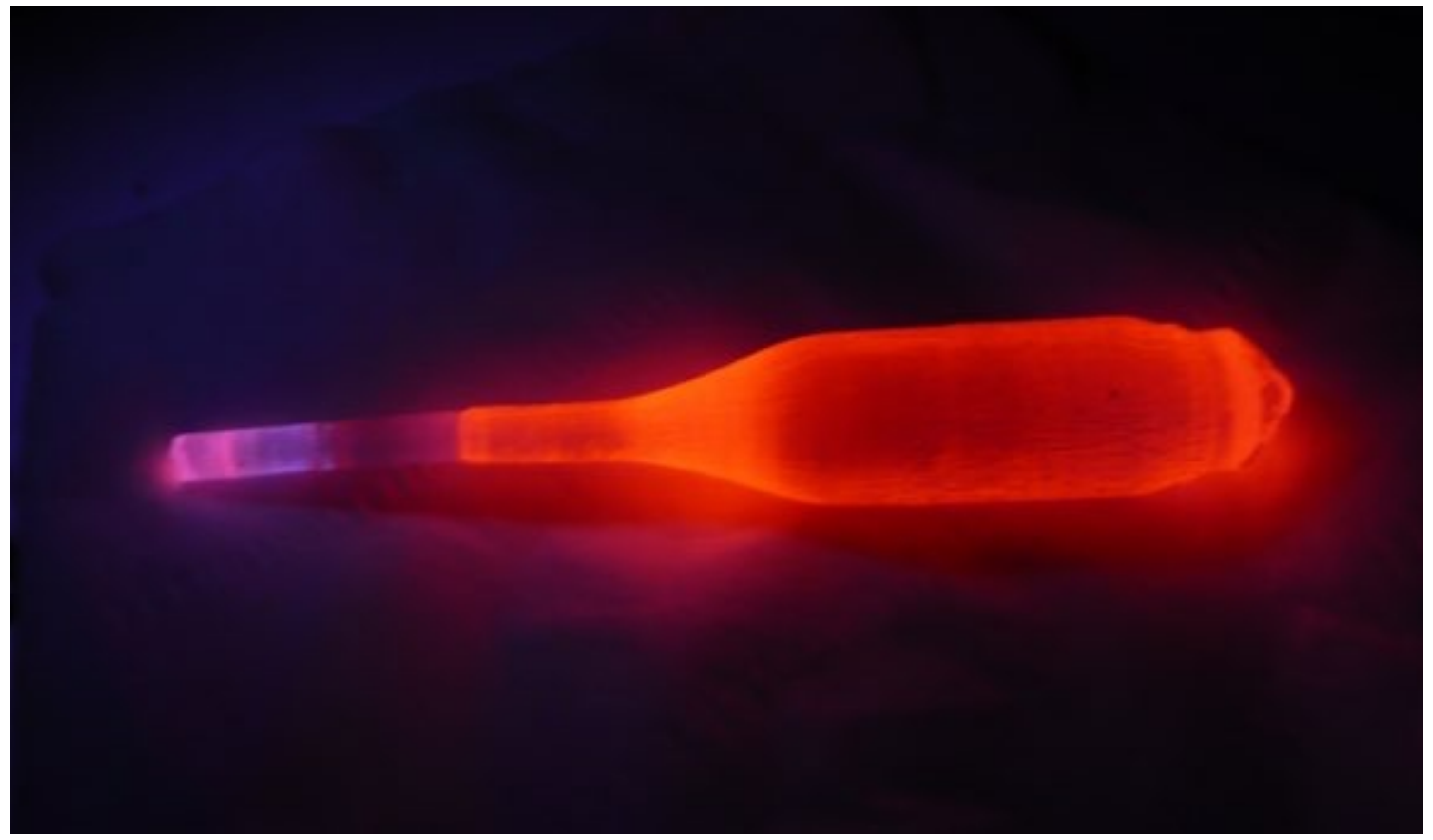
Dept. of Applied Physics and Materials Science, Caltech, May 21, 2018

Rare Earth Doped Crystals

Lanthanides, scandium, yttrium

Single crystals, films, **particles**



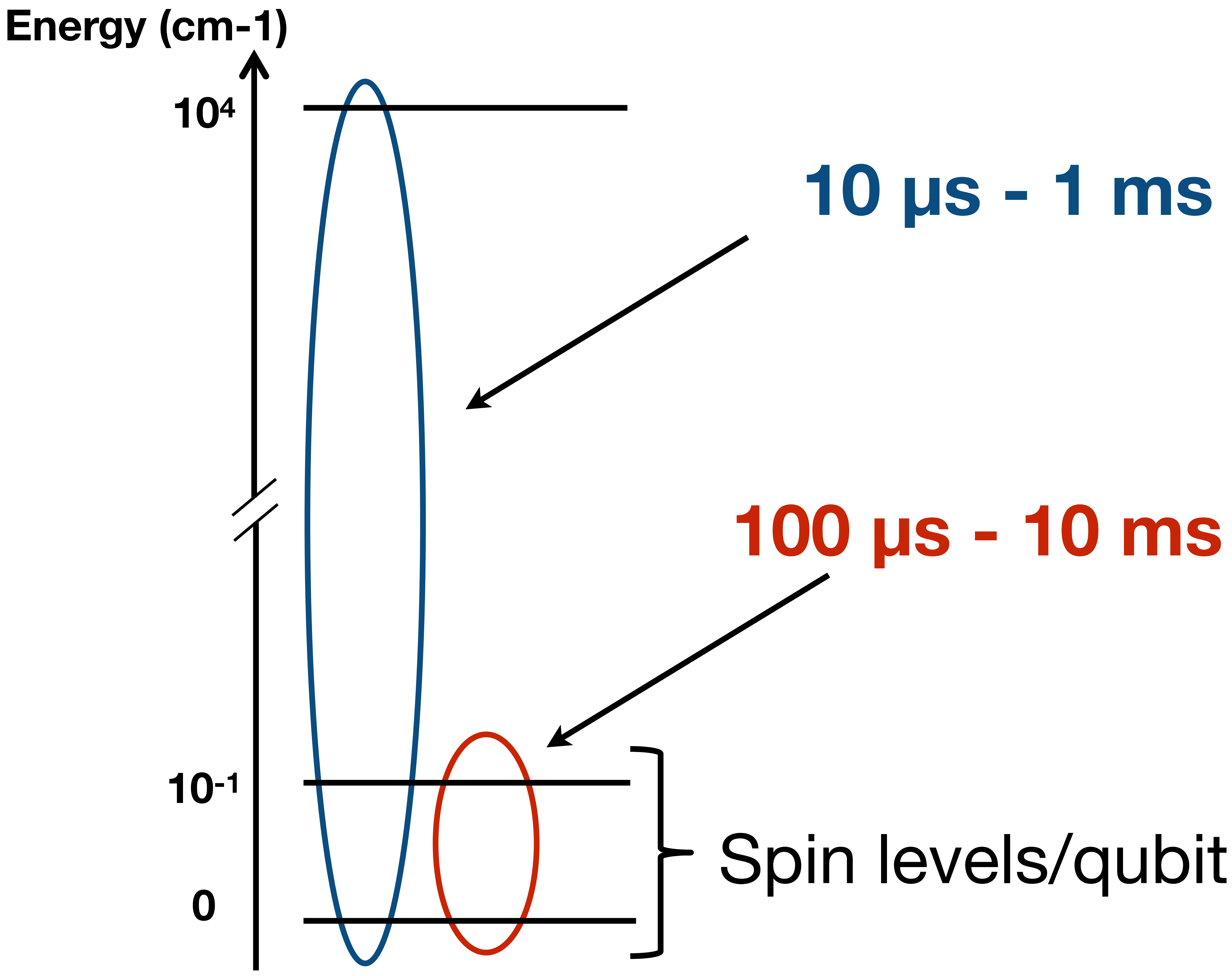


Y_2SiO_5:Eu^{3+} emission under UV excitation

Stable centres, no bleaching

Lasers, phosphors, bio-probes…

Energy Levels and Transitions



Optical transitions in the visible and infrared range

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

Electron and/or nuclear spins

Optical quantum memories in bulk crystals and fibres

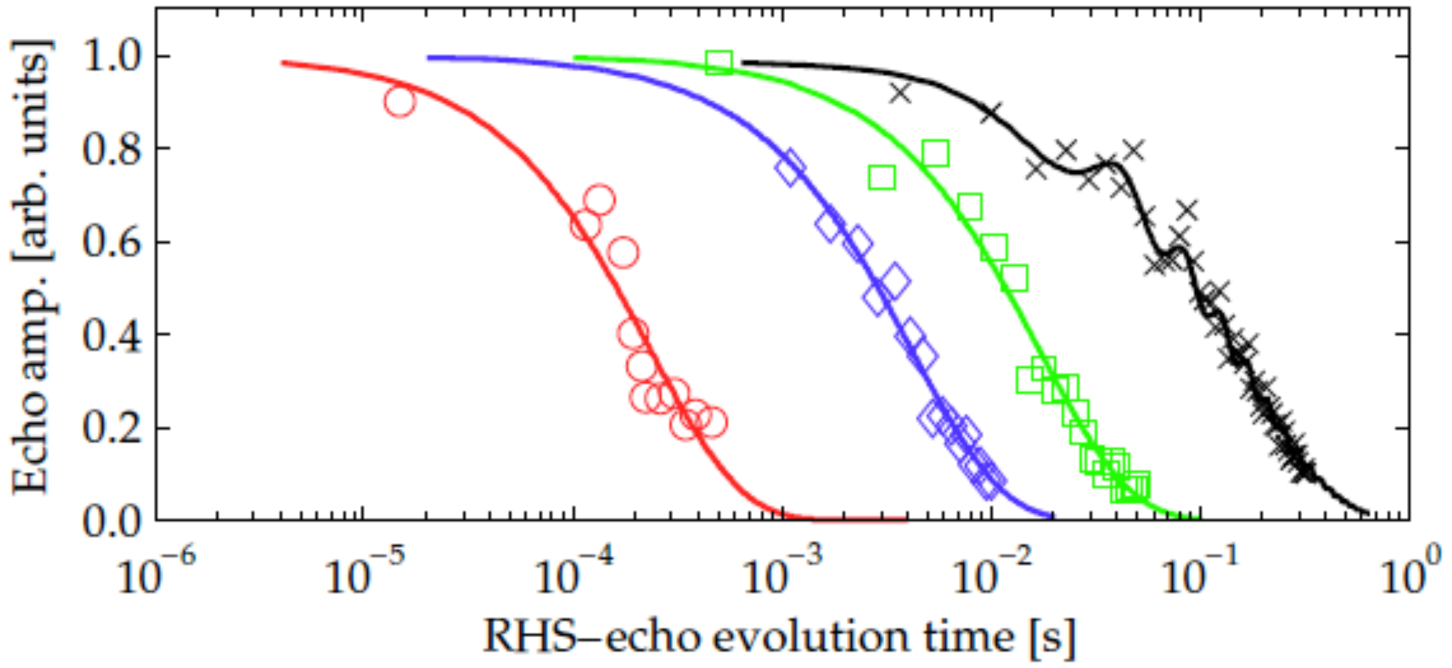
P. Goldner, A. Ferrier, and O. Guillot-Noël, in Handbook on the Physics and Chemistry of Rare Earths, vol. 46, 2015

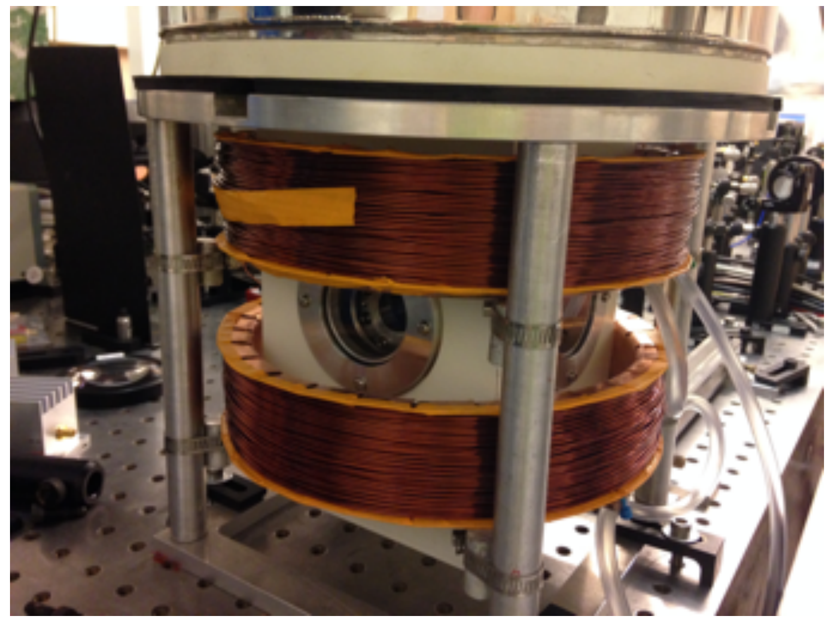
IR CP

W. Tittel et al., Nature Photon., 2009.
M. Zhong et al., Nature, 2015.

Crystals and Quantum State Dynamics

Designing and growing crystals with **long lived quantum states**
Controlling quantum states dynamics by external fields





Crystal growth **bulk, particles, thin films**
High resolution and coherent spectroscopy

Quantum information processing
High bandwidth signal processing
Ultrasound optical tomography
Ultra stable laser locking

IR CP

Chimie ParisTech

Chimie Paristech founded in 1896 - moved to the present building in the Latin quarter in 1920

About 300 students follow lectures in **all fields of chemistry**

Paris Institute for Chemical Research: about 200 researchers and PhD students

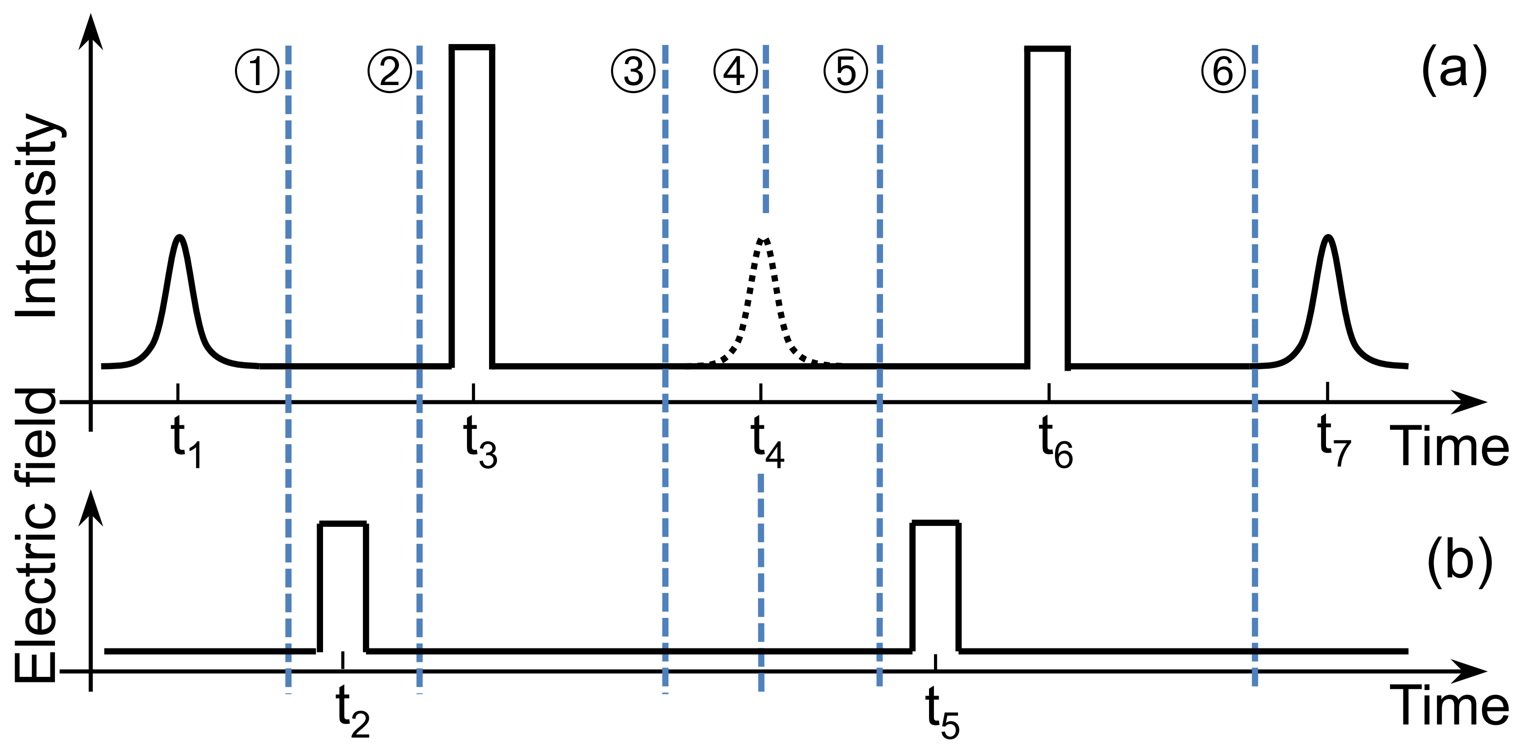
IR CP

Recent Results with RE Spins

Electric field effects

Stark shift on RE spins
Qu. memory protocol

$Eu^{3+}:Y_2SiO_5$

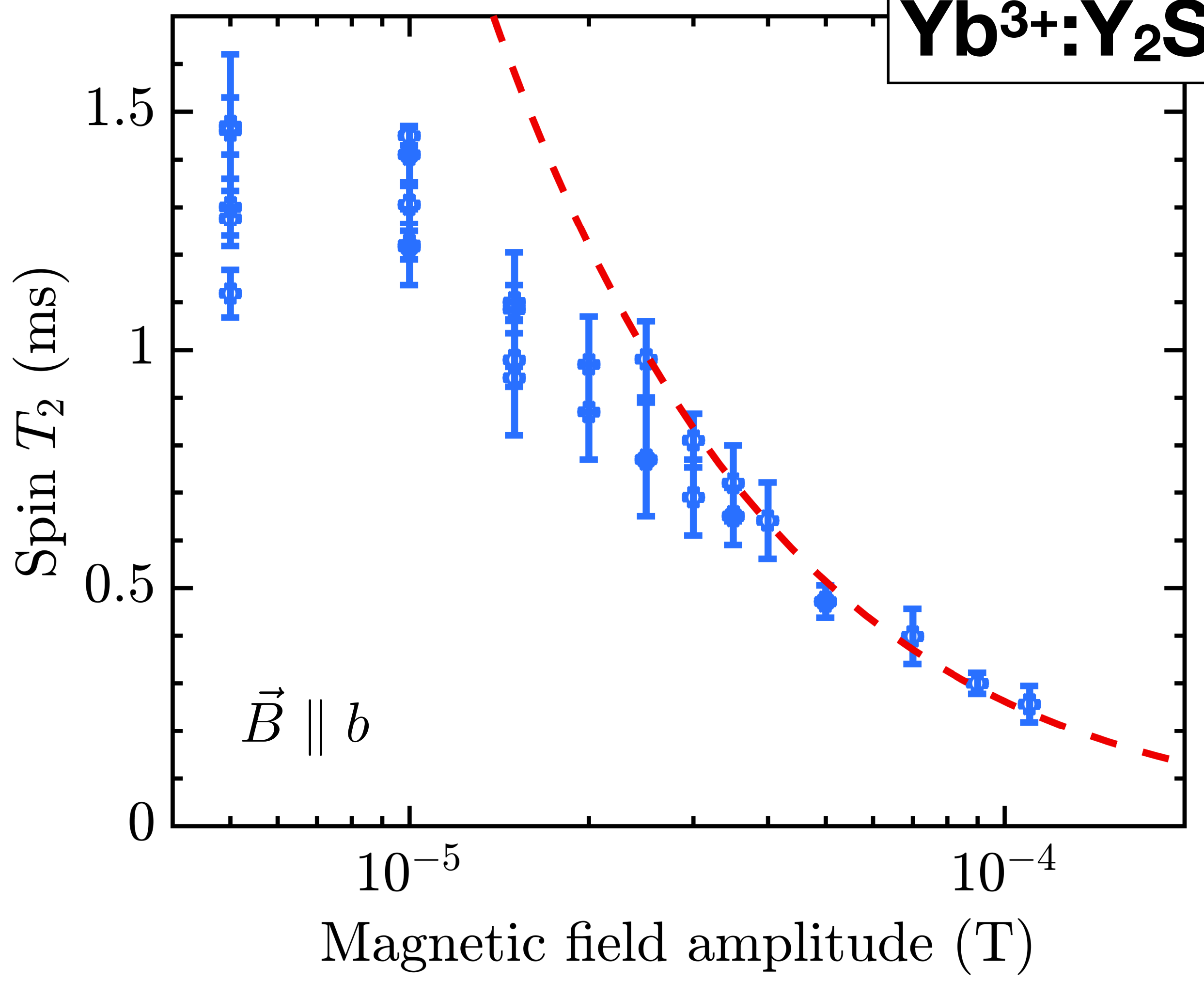


A. Arcangeli et al., PRA 2016
R.M. Macfarlane et al. PRL 2014.

T_2 extension

Trains of RF pulses
Clock transitions

$Yb^{3+}:Y_2SiO_5$

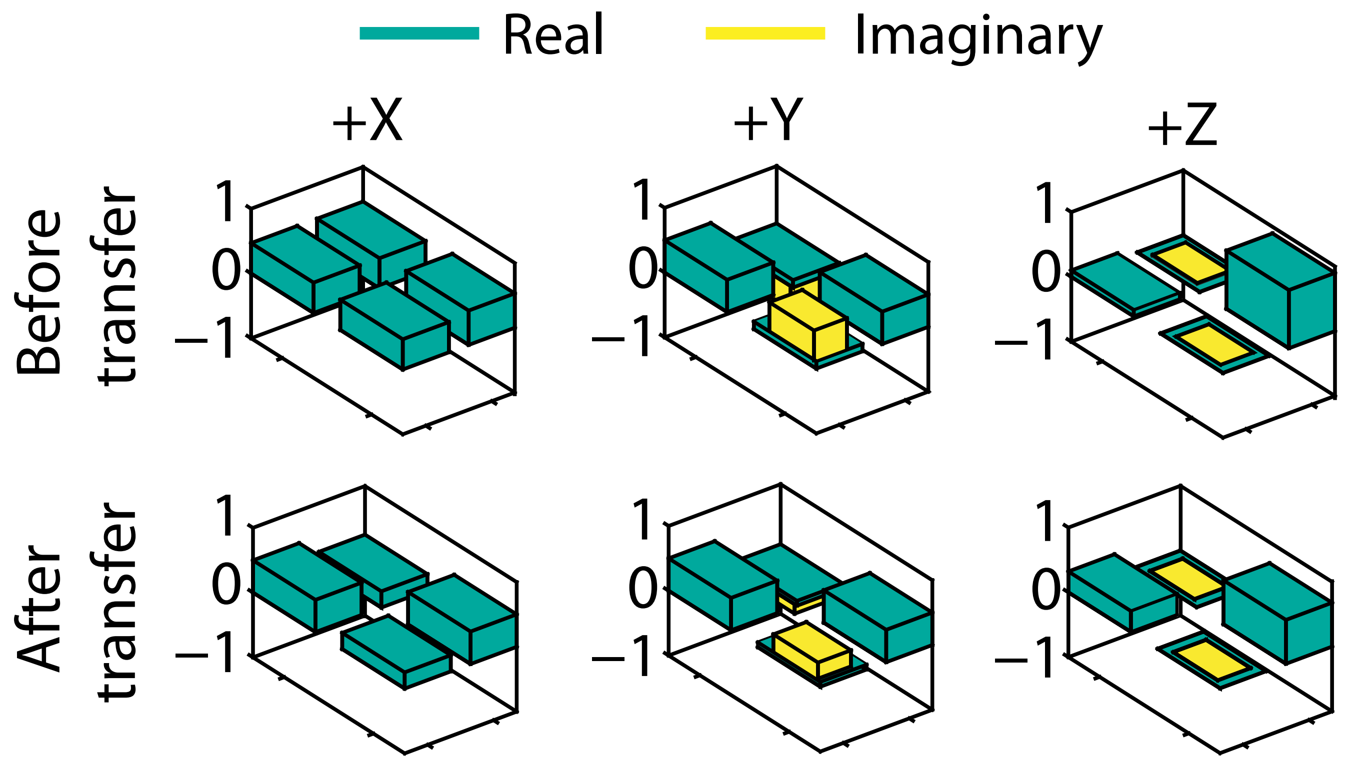


A. Tiranov et al., arXiv 2017

Storage

Optical and **microwave** excitations to spin

$Nd^{3+}:Y_2SiO_5$

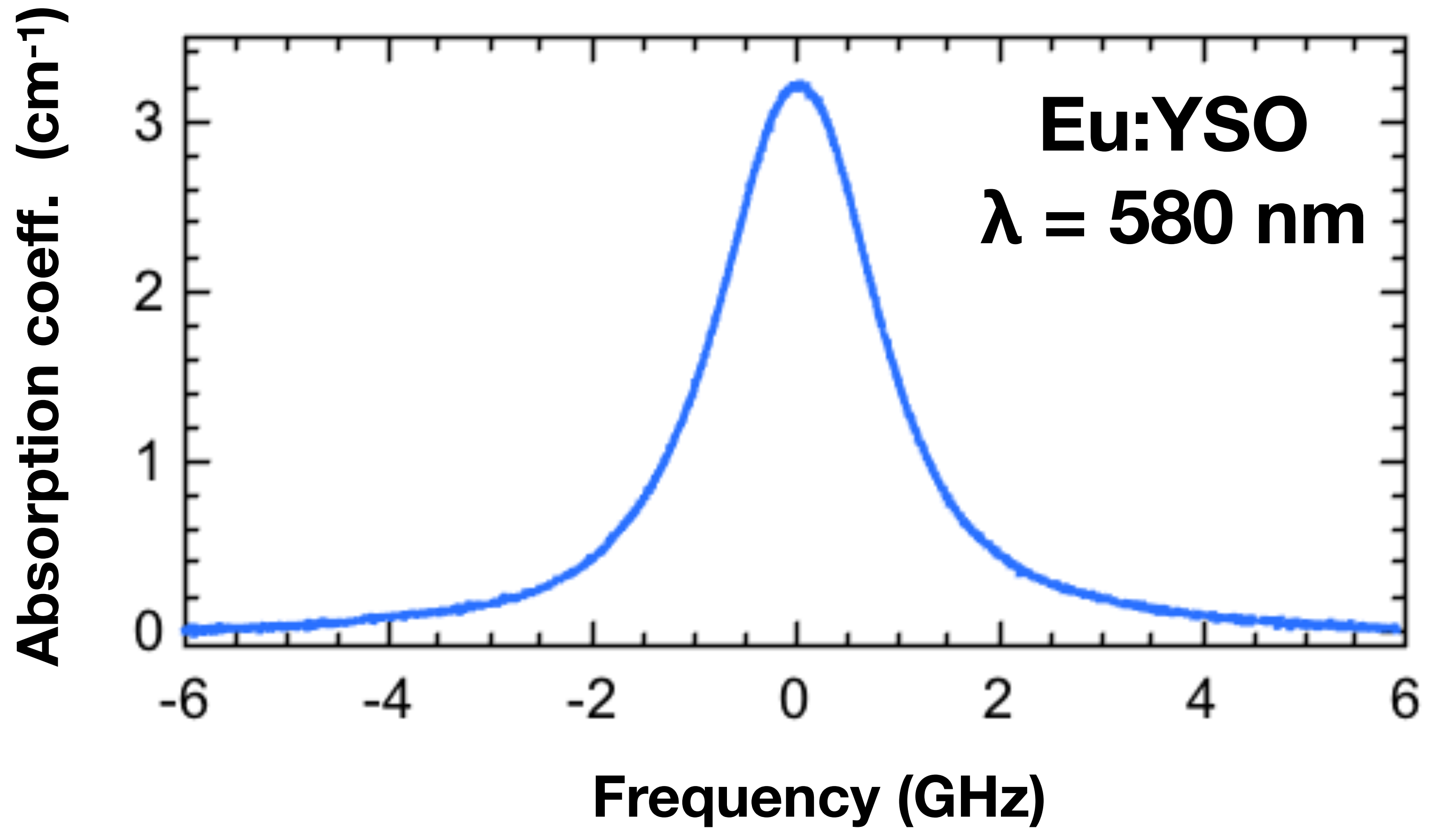


G. Wolfowicz et al., PRL 2015.
M. Lovrić et al., PRL 2013.

IR CP

Rare Earth Ions as Qubits

Scalability: optical addressing

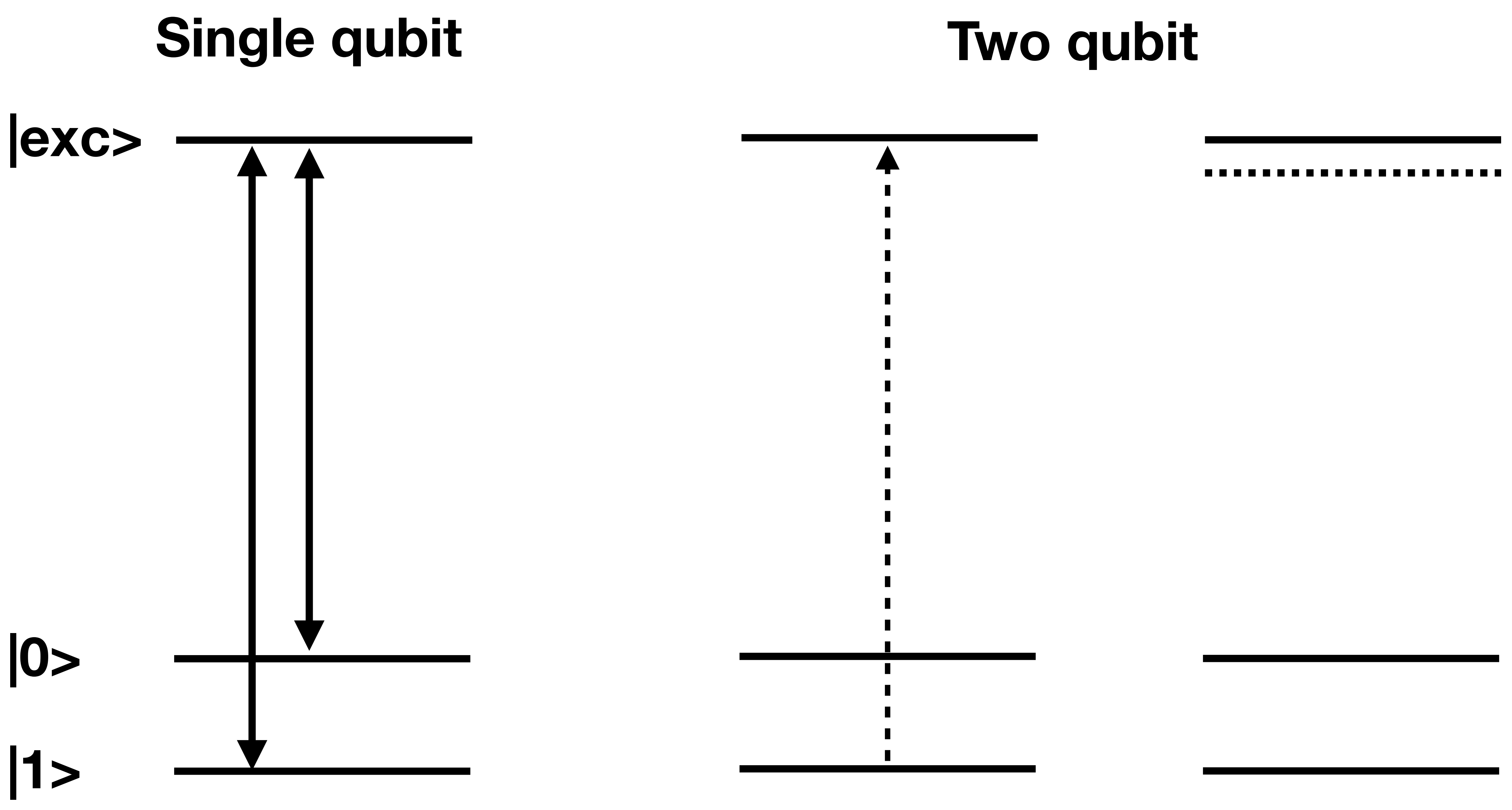


Ensemble linewidth **$\Gamma_{inh} \approx$ 2 GHz**
Single ion linewidth **$\Gamma_{h} \approx$ 1kHz**

10^4 qubits!!

N. Ohlsson et al., Opt. Commun., 2002.

Gates: all-optical

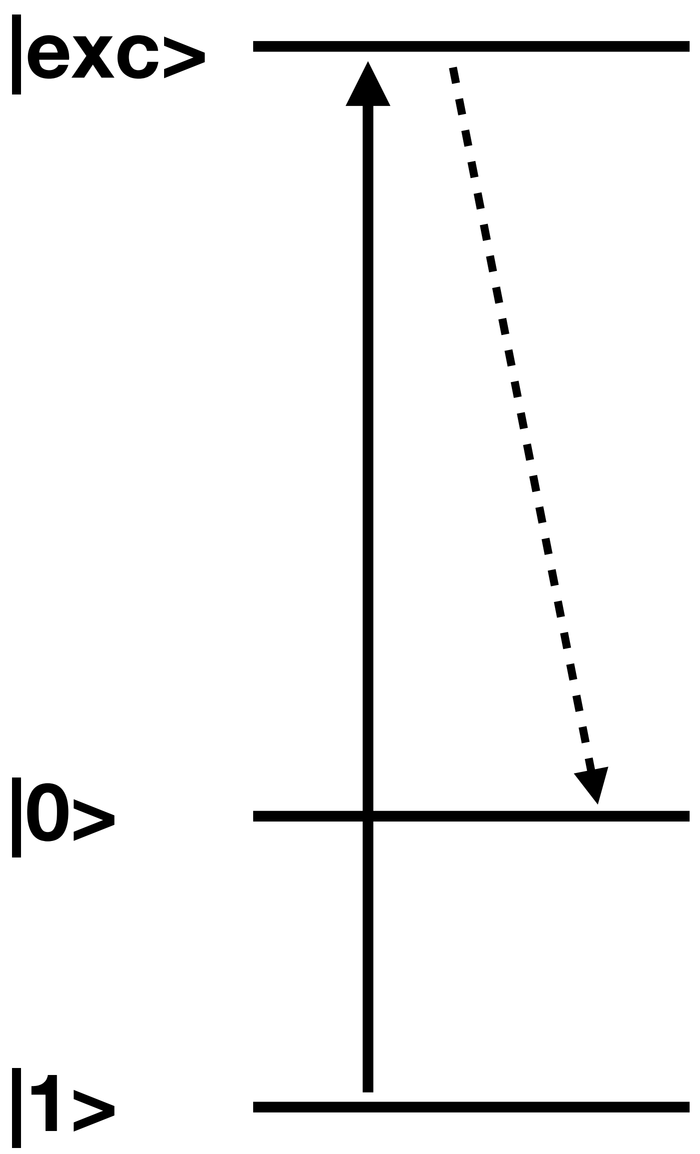


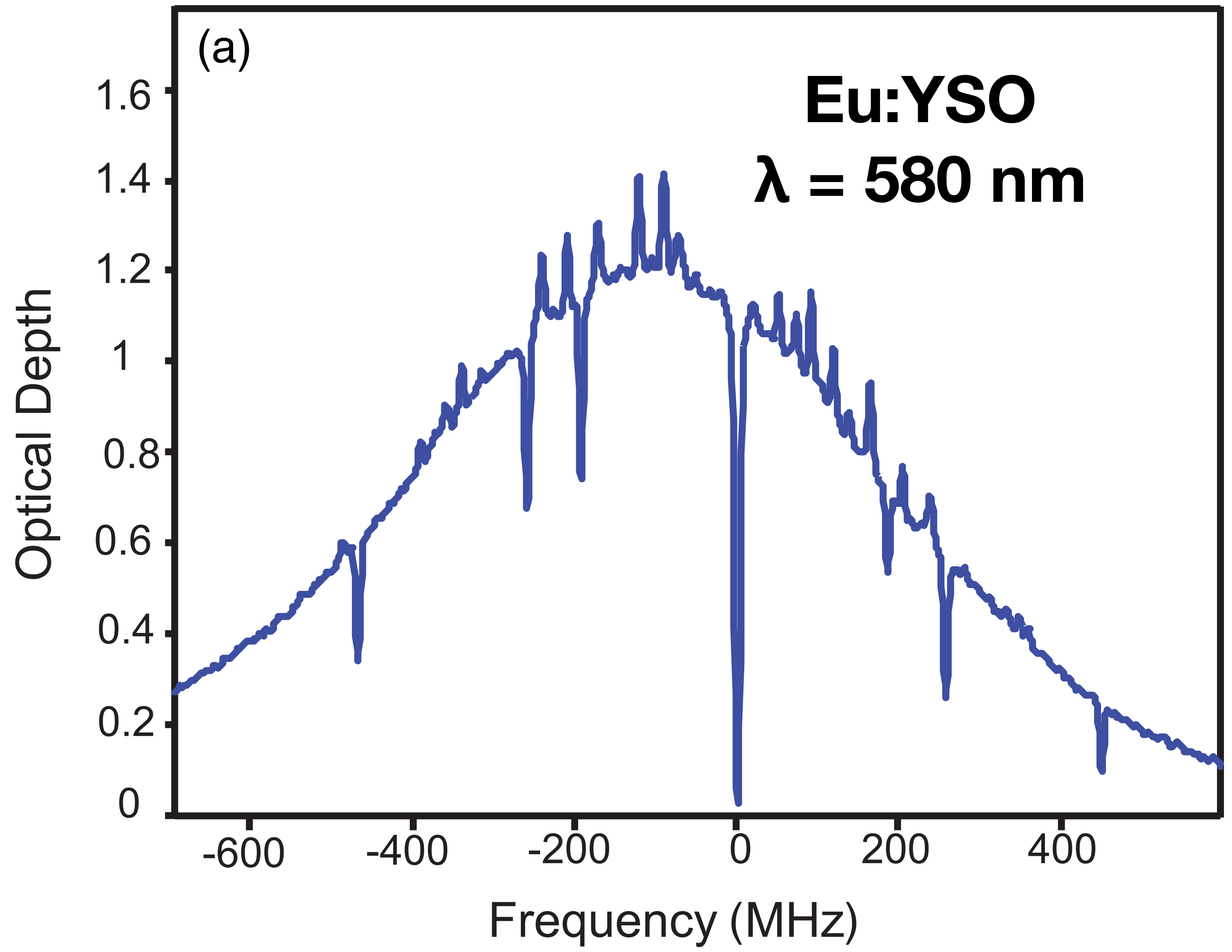
High fidelity

A. Walther et al., PRA, 2015; I. Roos et al., PRA, 2004.
J. J. Longdell et al., PRL, 2004.

Rare Earth Ions as Qubits

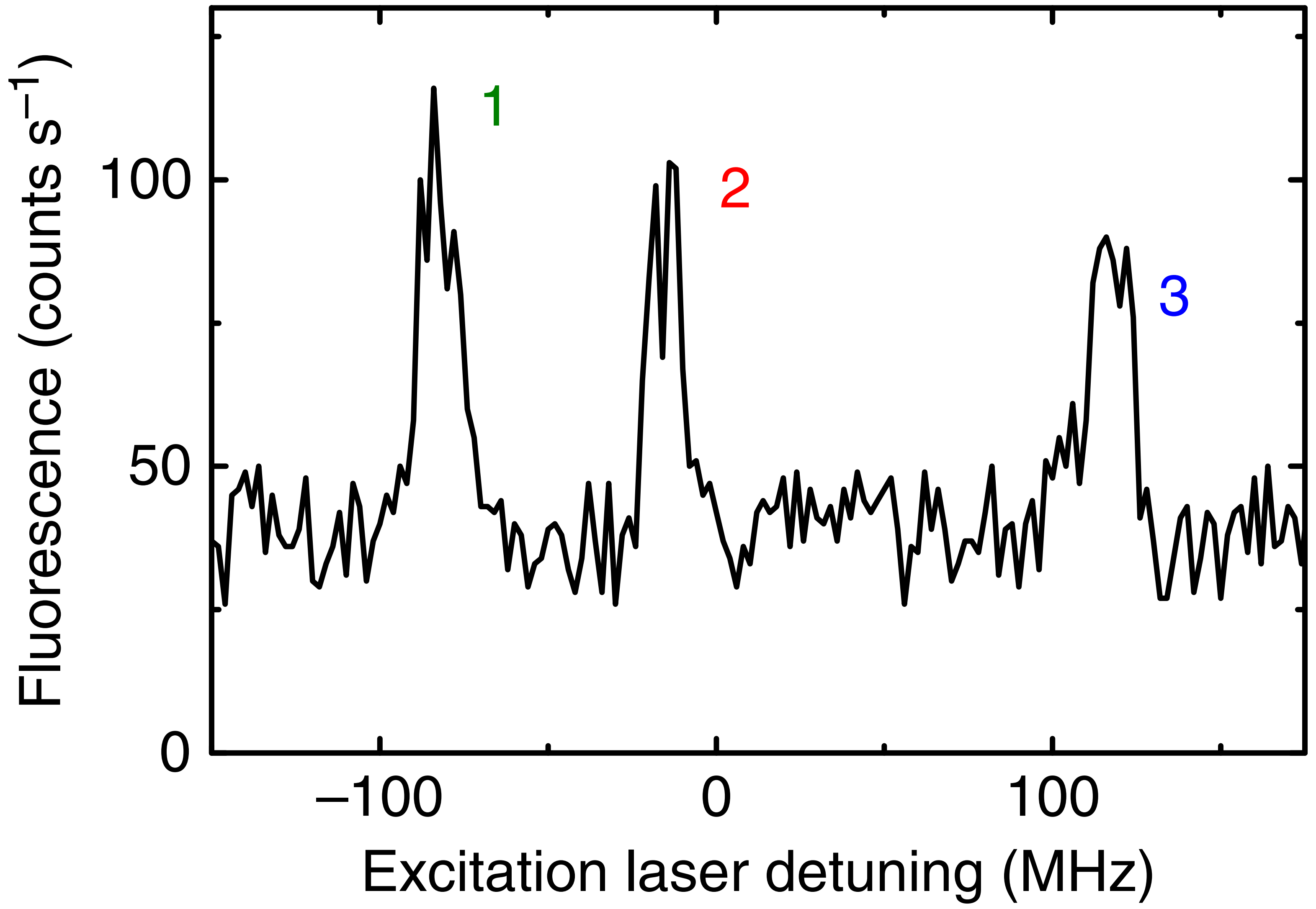
Initialization: optical pumping





B. Lauritzen et al., Phys. Rev. B, 2012.

Readout: single ion detection

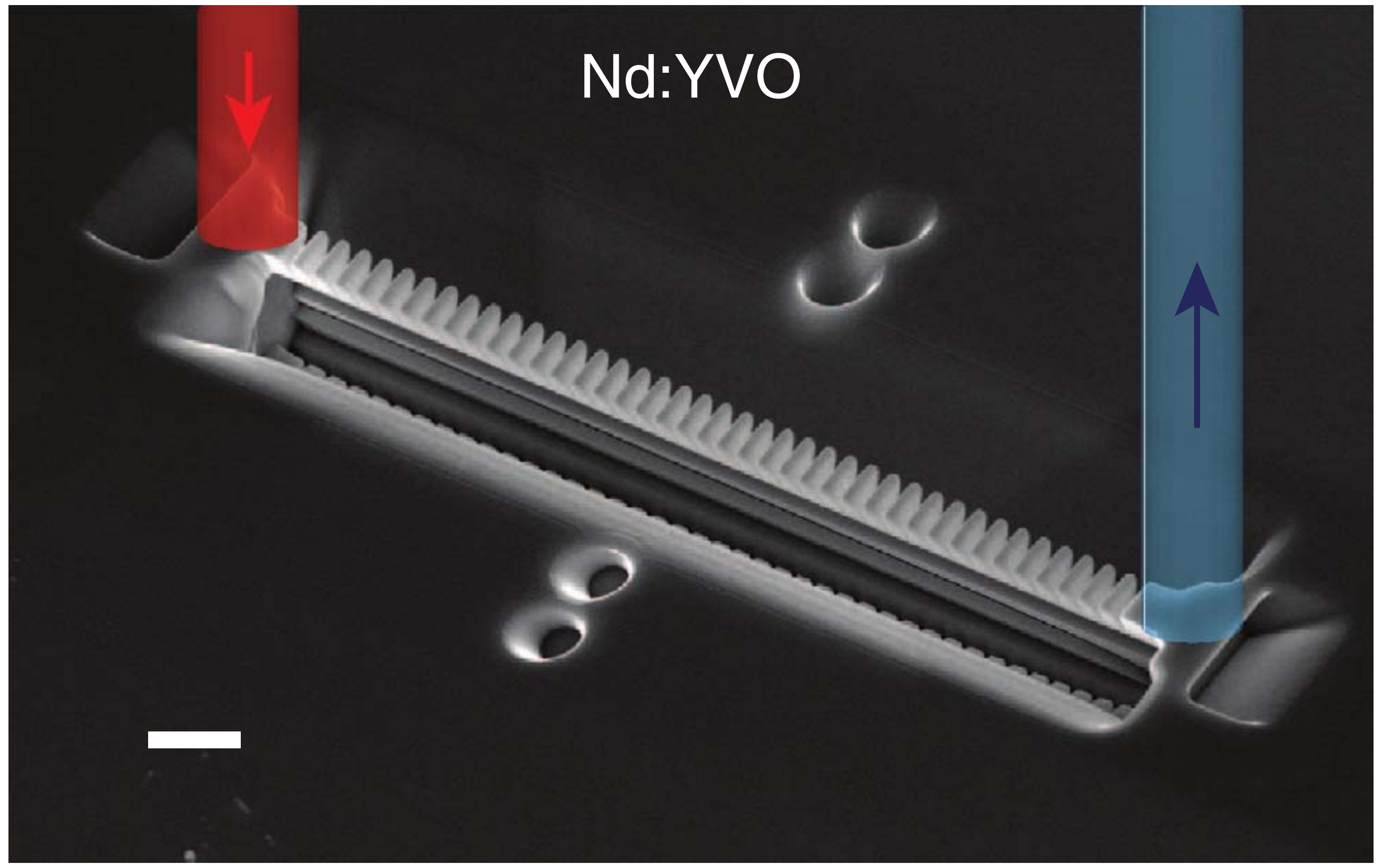


Long T_1: low count rate

T. Utikal et al. Nat. Commun., 2014; R. Kolesov et al., Nat. Commun. 2012; C. Yin et al., Nature, 2013.

Improving Detection: Cavities

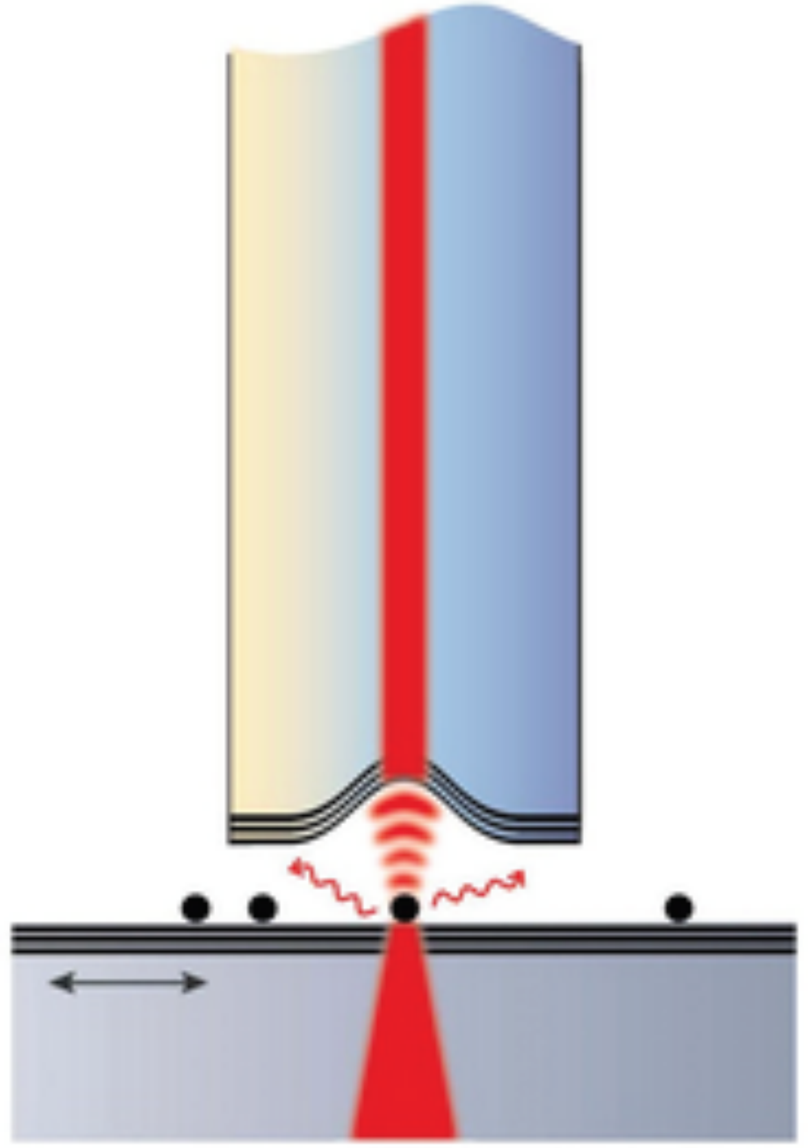
High Q nano-cavity

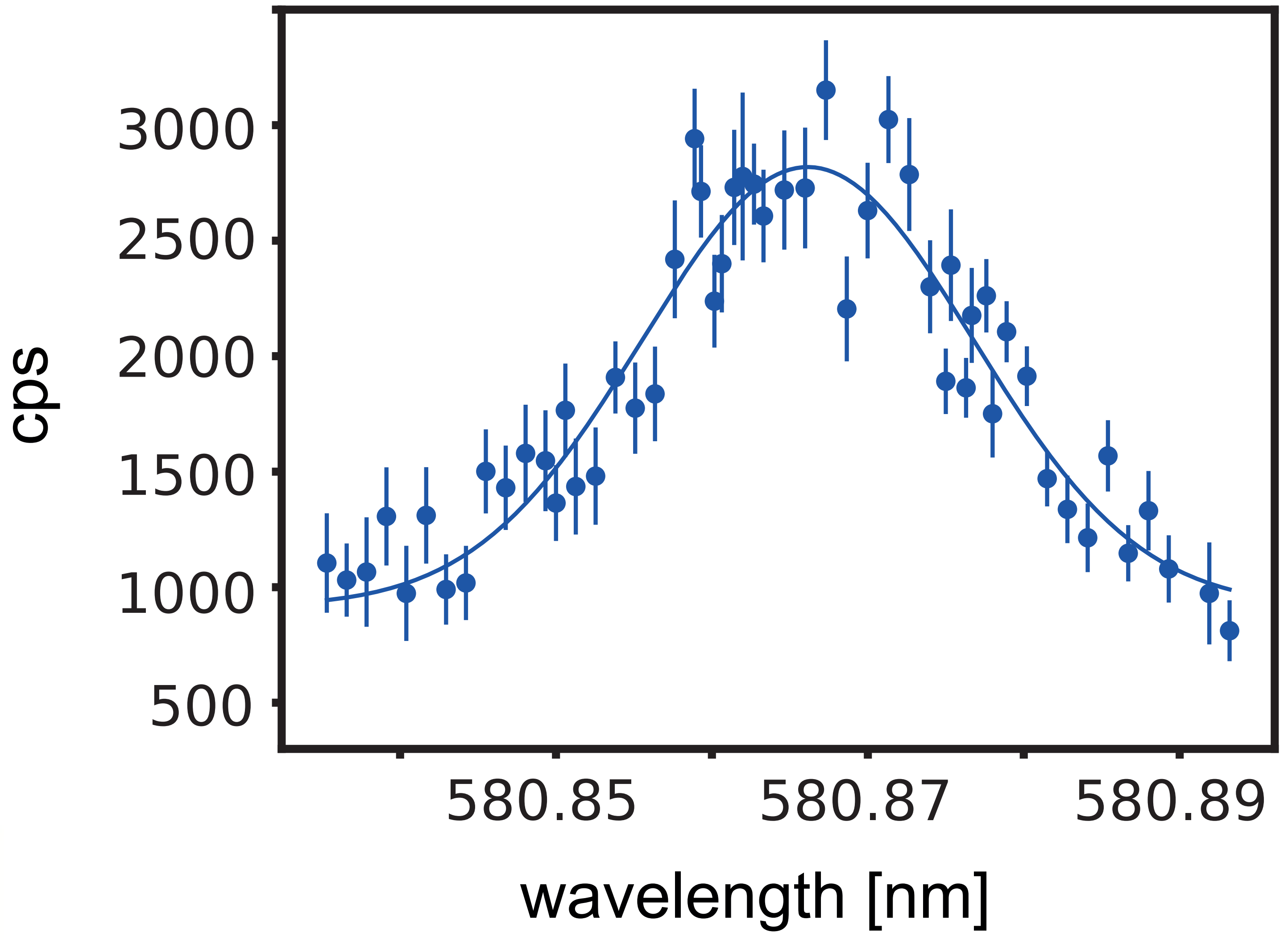


Purcell enhancement
High collection efficiency

T. Zhong et al., Nat. Commun., 2015.,
T. Zhong et al., arXiv, 2018, A. Dibos et al., arXiv, 2017.

Fiber micro-cavity: D. Hunger, KIT





High-Q tunable cavity
Rare earth nanoparticles

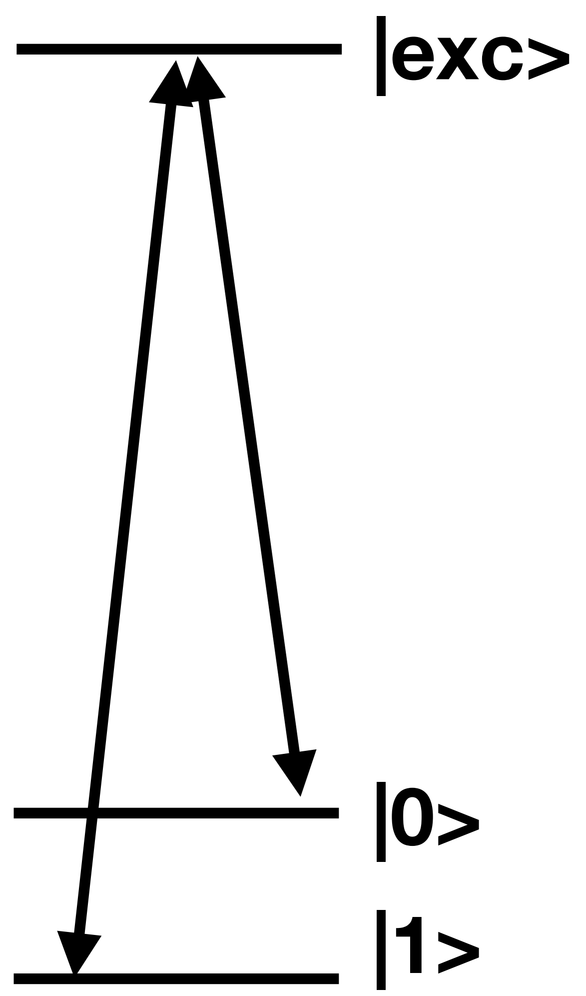
B. Casabone,…,PG, H. de Riedmatten, and D. Hunger, arXiv, 2018.

Rare earth spins at the nanoscale

Optical Spin Control

Extra degree of freedom

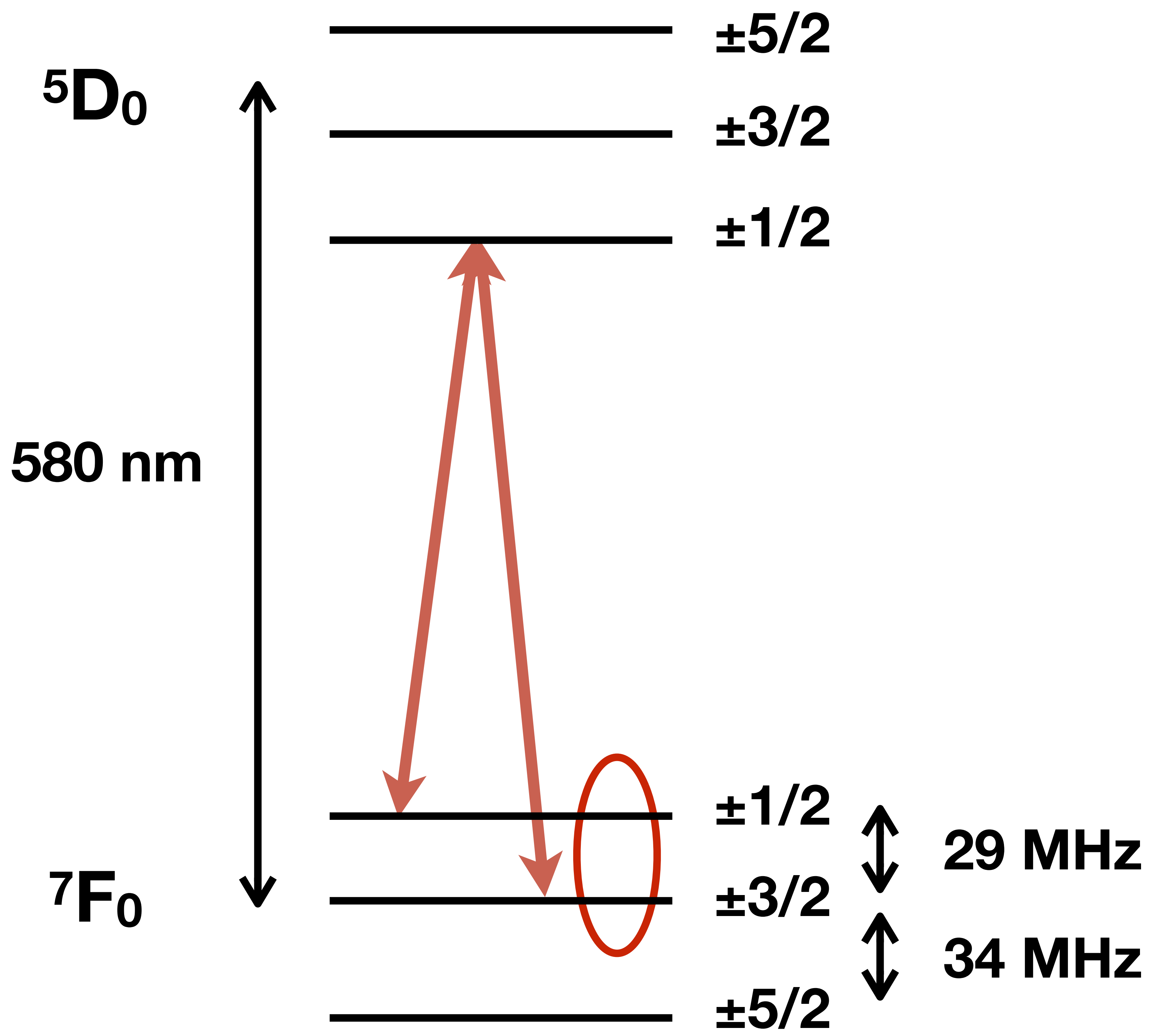
Interface w/ photonic qubits
Faster operations
Easier implementation



Defects in diamond
Quantum dots

G. Waldherr et al., Nature, 2014.
D. Press, Nat. Photonics 2010.

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



IR CP

J. Karlsson et al. J. Phys.: Condens. Matter 2017.

Nanoparticles

0.5% Eu^{3+}:Y_2O_3

Homogeneous precipitation

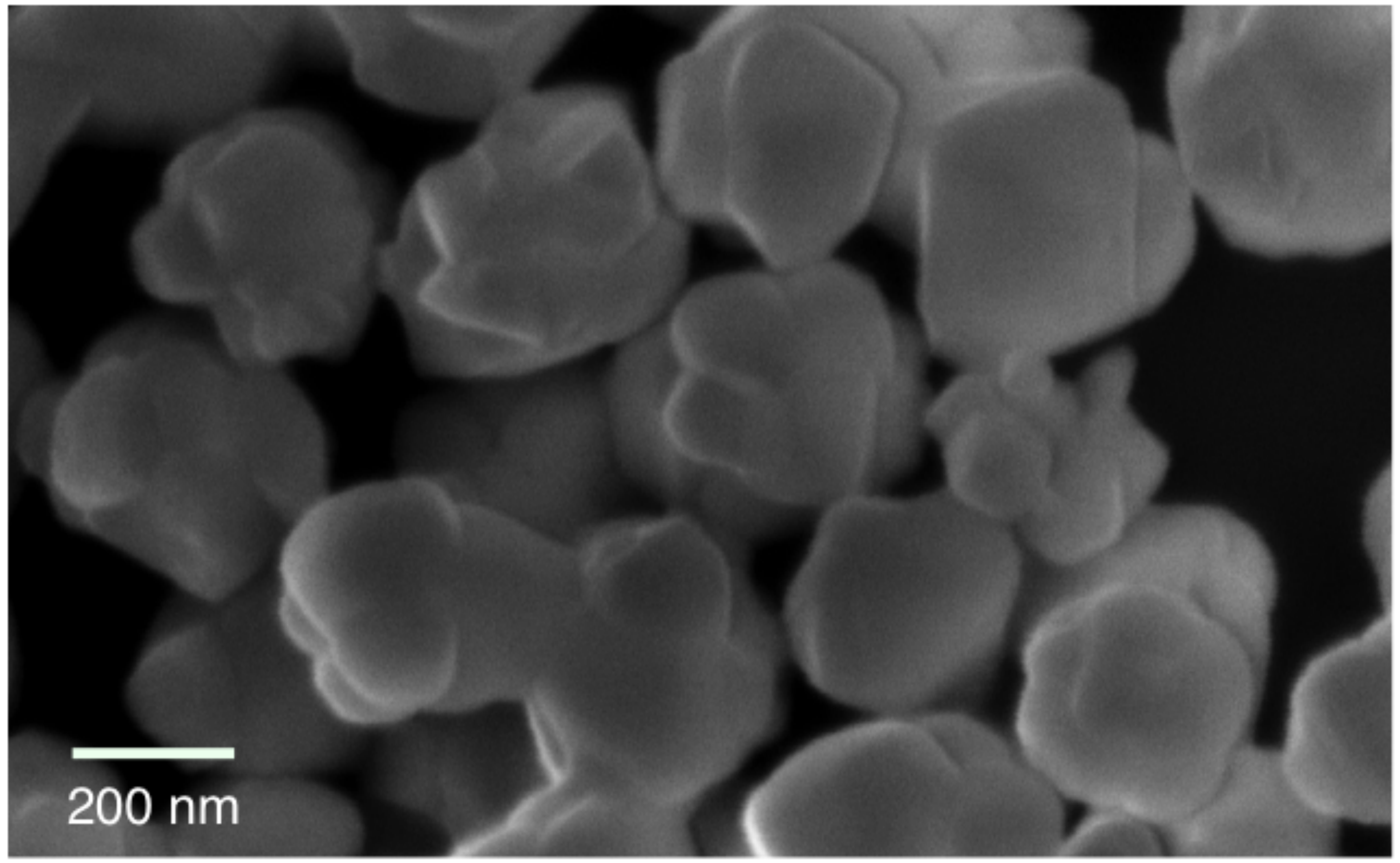
Monodispersed, spherical

High temperature annealing

Cubic phase

Defects reduced at 1200 °C

Long optical T_2 in bulk crystal and transparent ceramics



Particle size: 400 nm

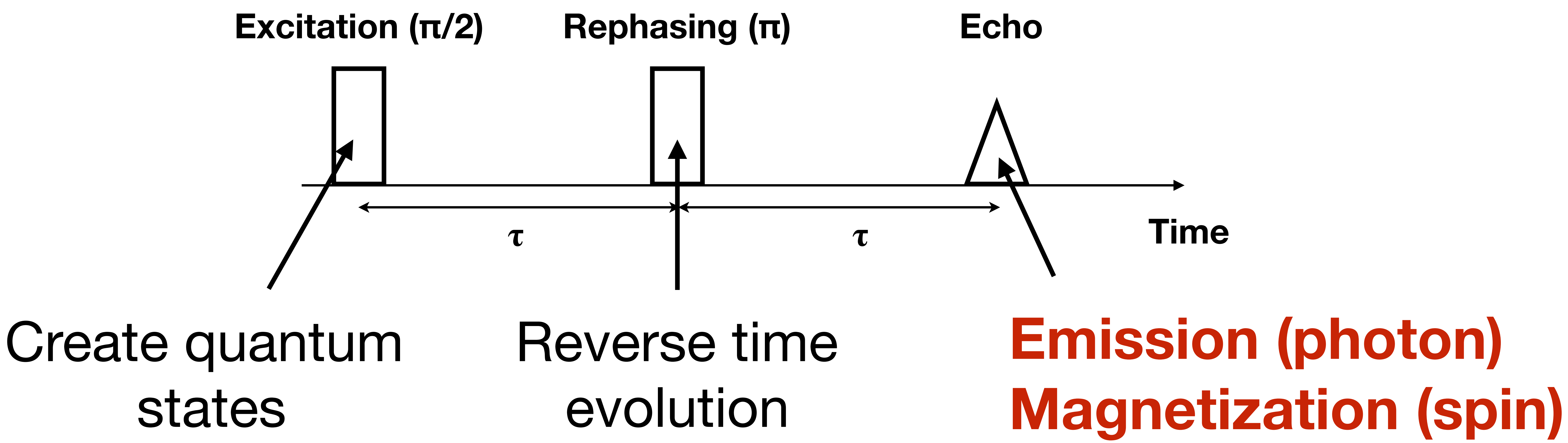
Crystallite size: 130 nm

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

IR CP

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

The Echo Technique



Echo: only ions with unperturbed quantum states

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

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

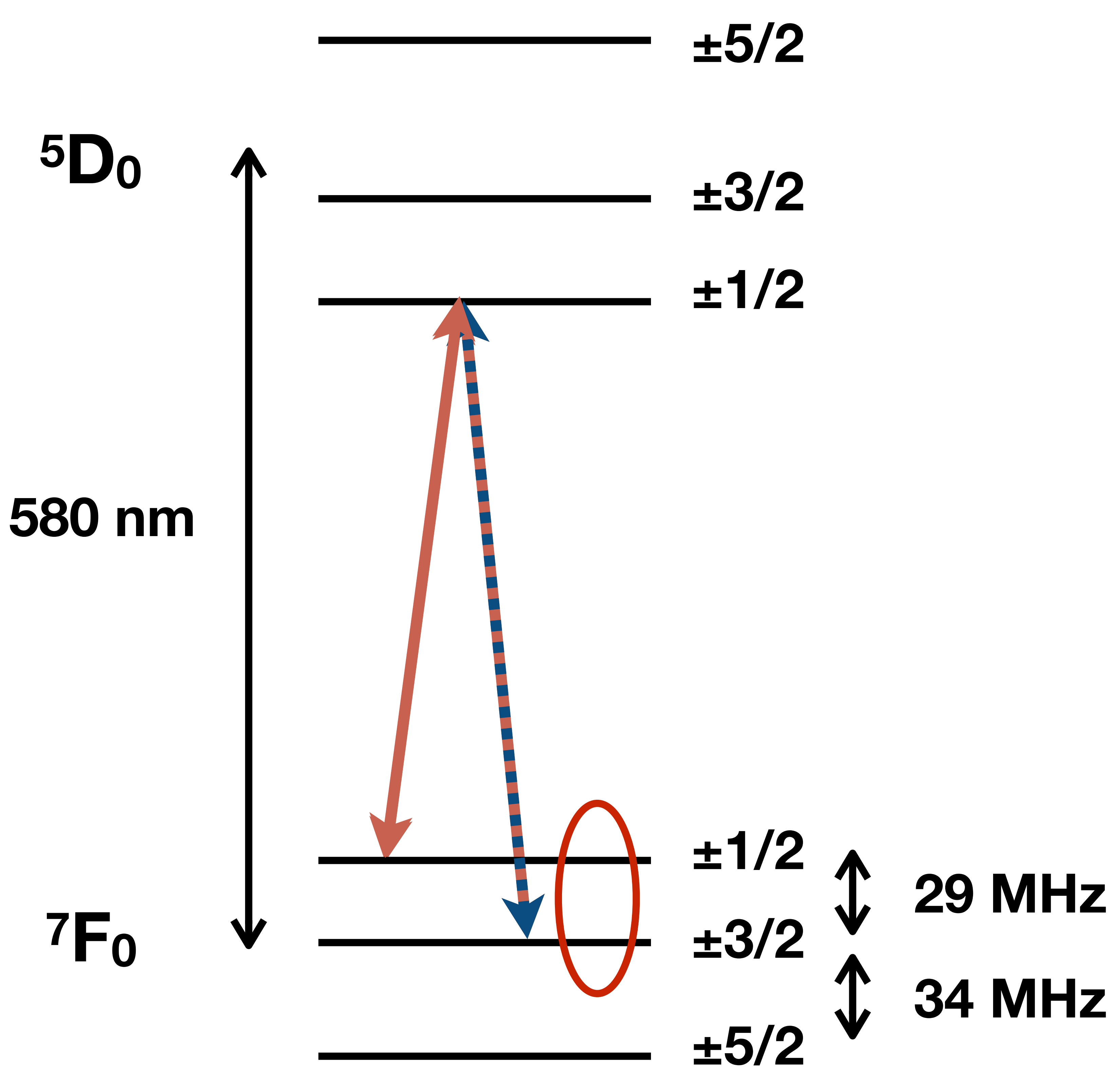
E. L. Hahn, Phys. Rev. 1950.

IR CP

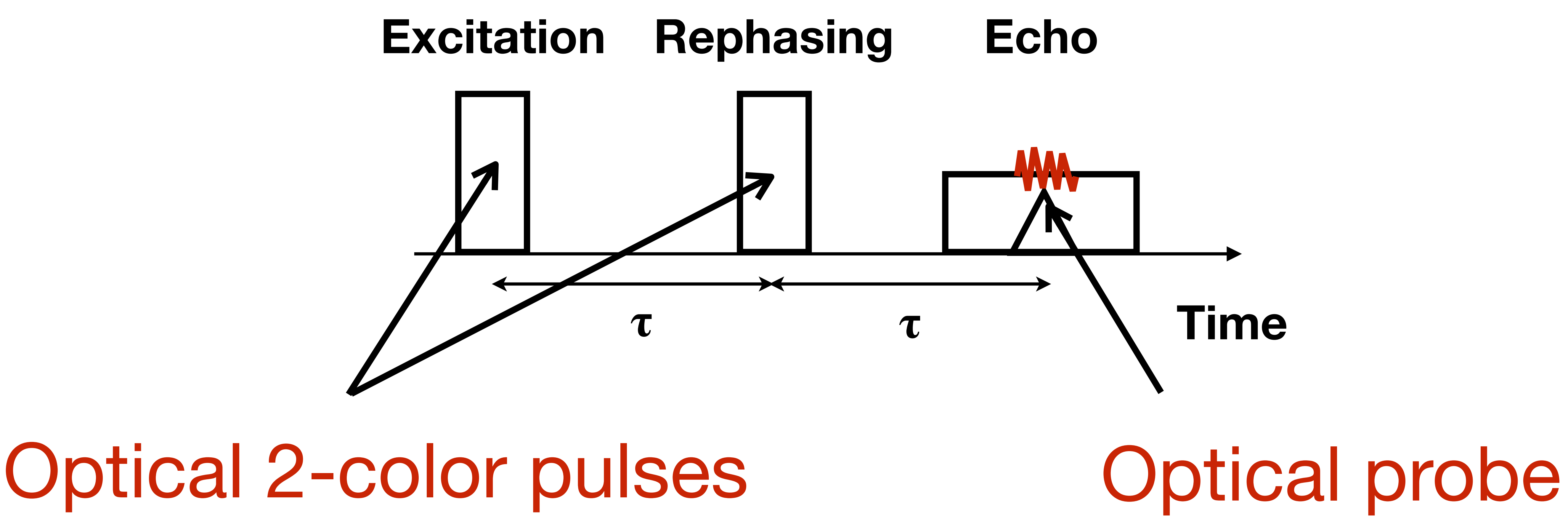
I. D. Abella, N. A. Kurnit, and S. R. Hartmann, Phys. Rev. 1966.

All-optical Spin Echoes

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



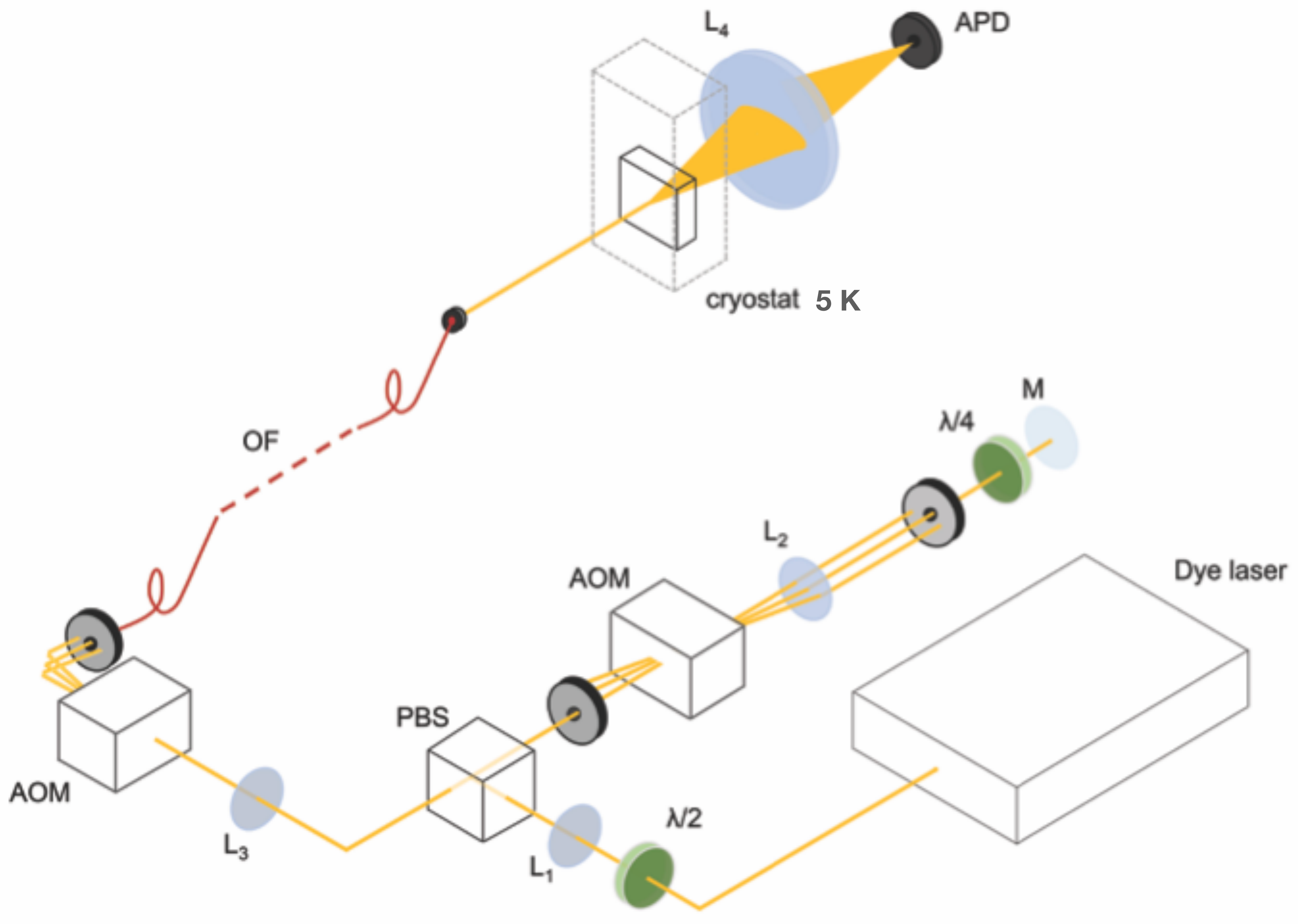
J. Mlynek et al., Phys. Rev. Lett., 1983.



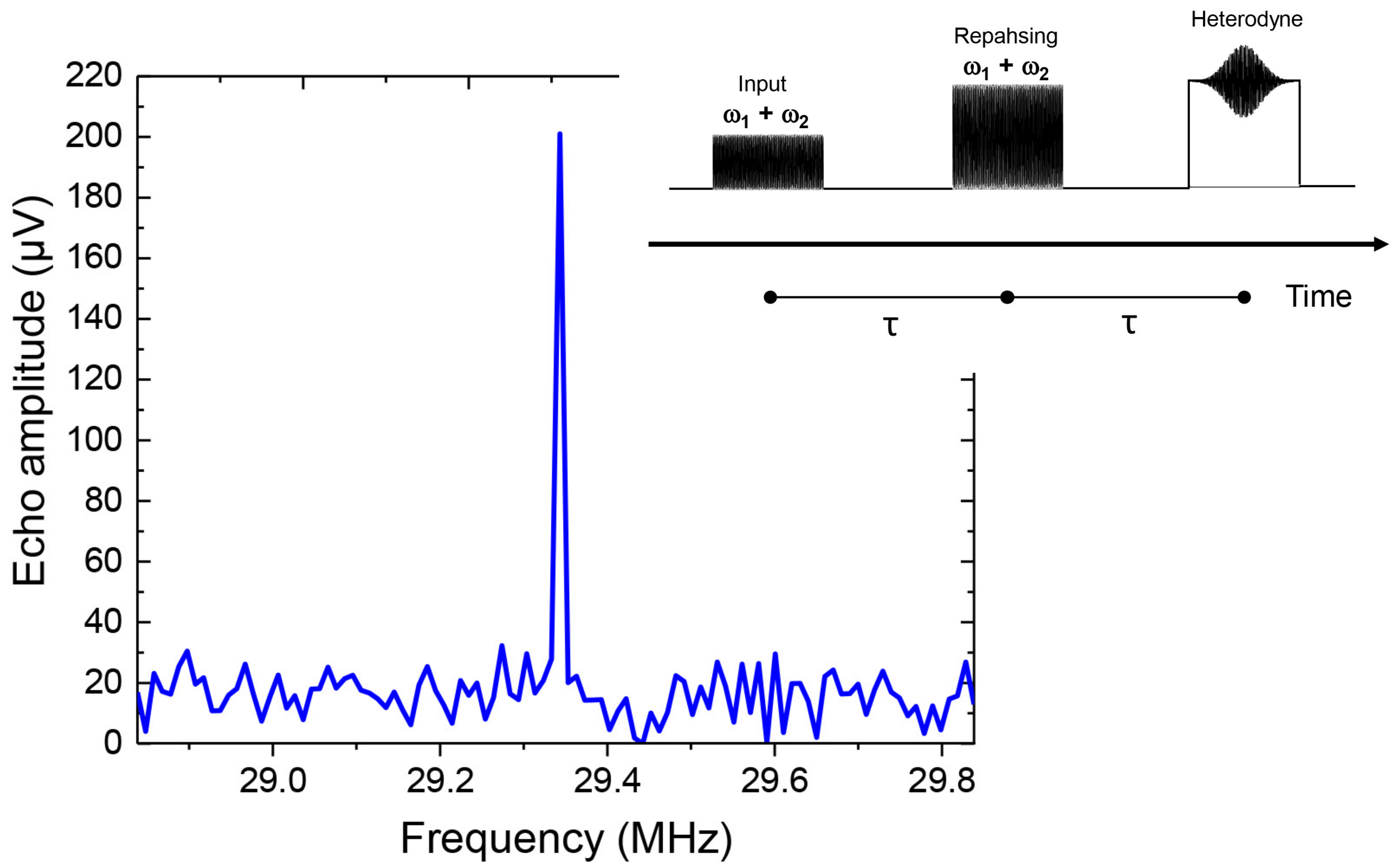
IR CP

D. Serrano, J. Karlsson, A. Fossati, A. Ferrier, and PG, arXiv, 2017.

Experimental Setup



Echo: FFT of heterodyne signal

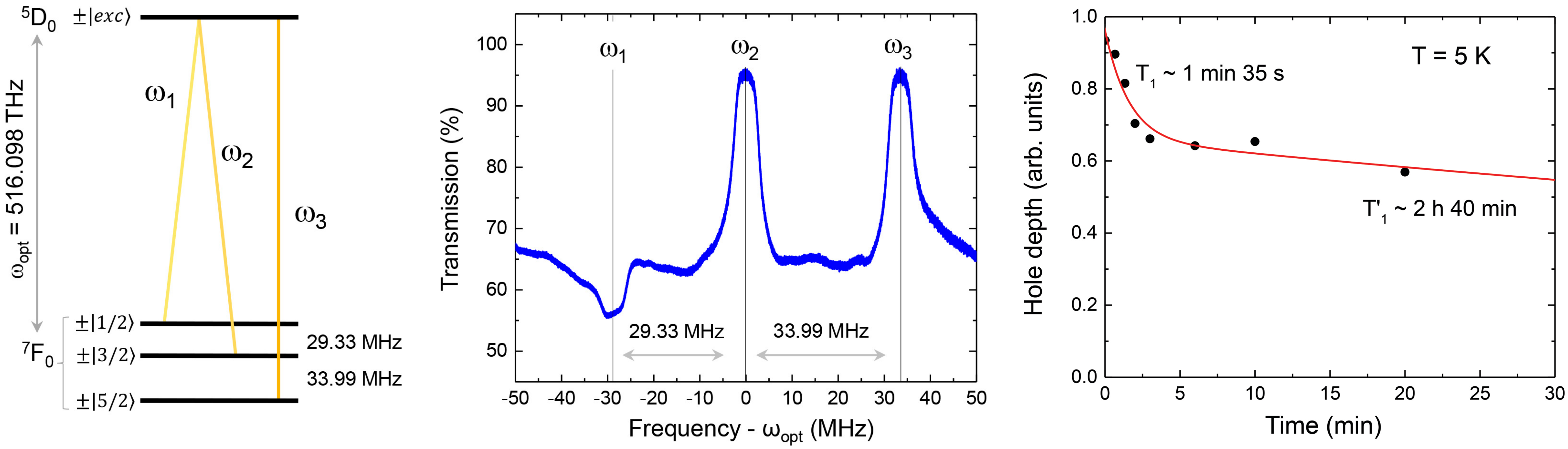


Sample: **powder!**

R. Pierrat et al., arXiv, 2018.

Optical Pumping

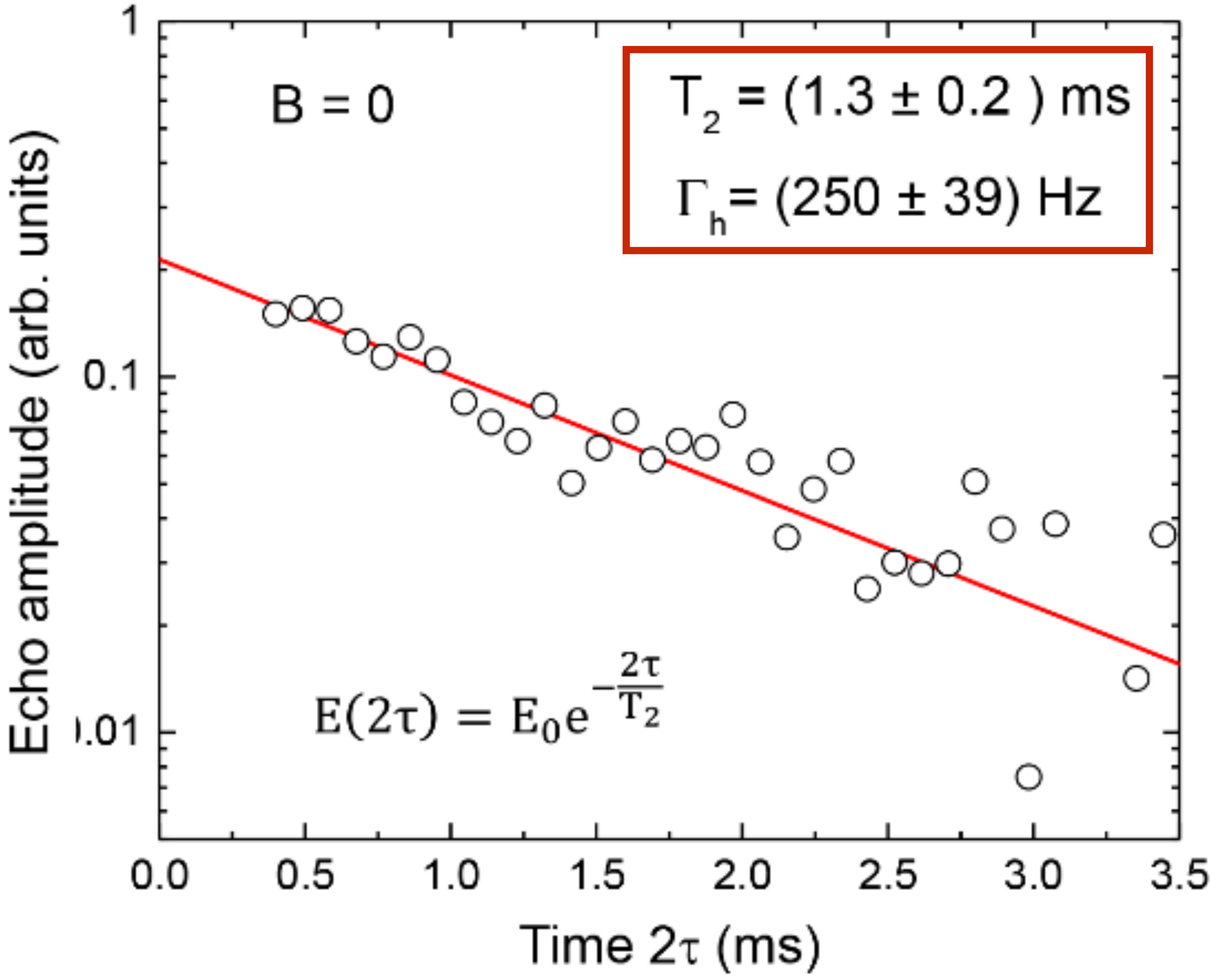
Spin polarization: **increased signal**

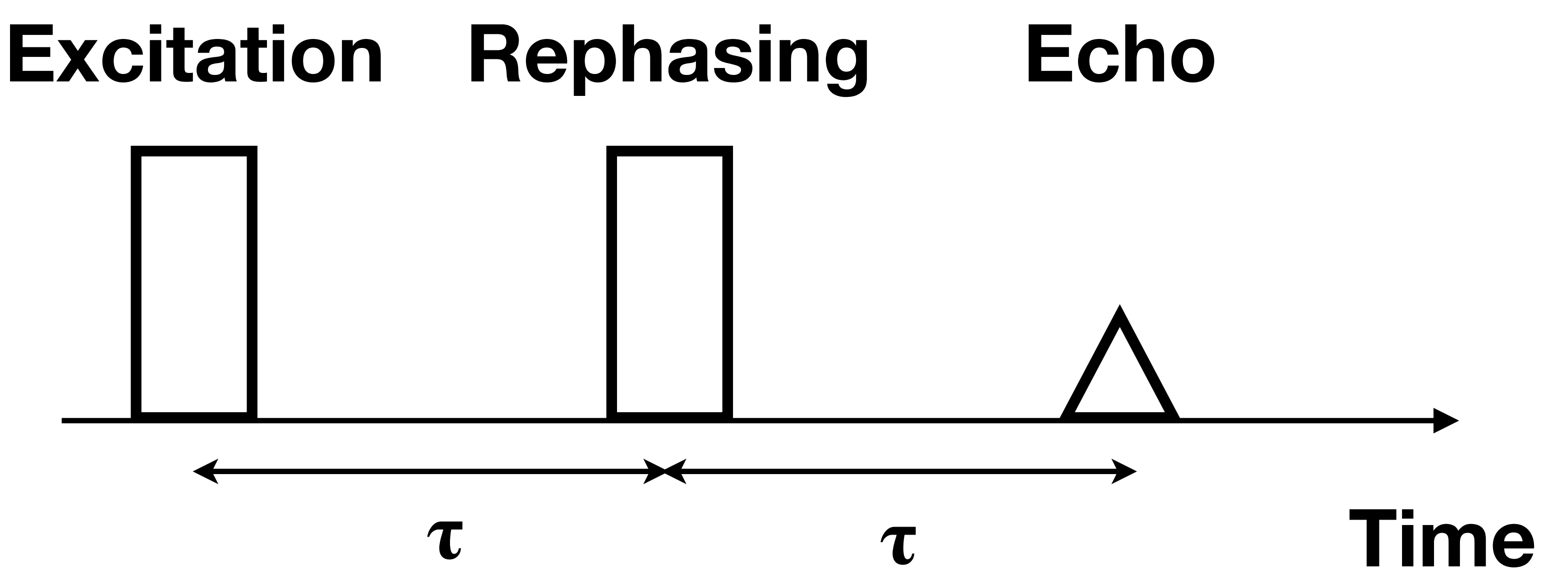


D. Serrano, J. Karlsson, A. Fossati, A. Ferrier, and PG, arXiv, 2017.

IR CP

Spin Coherence Lifetimes





Spin T_2 in the ms range

$Eu^{3+}:Y_2O_3$ transparent ceramics:
T_2 = 12 ms

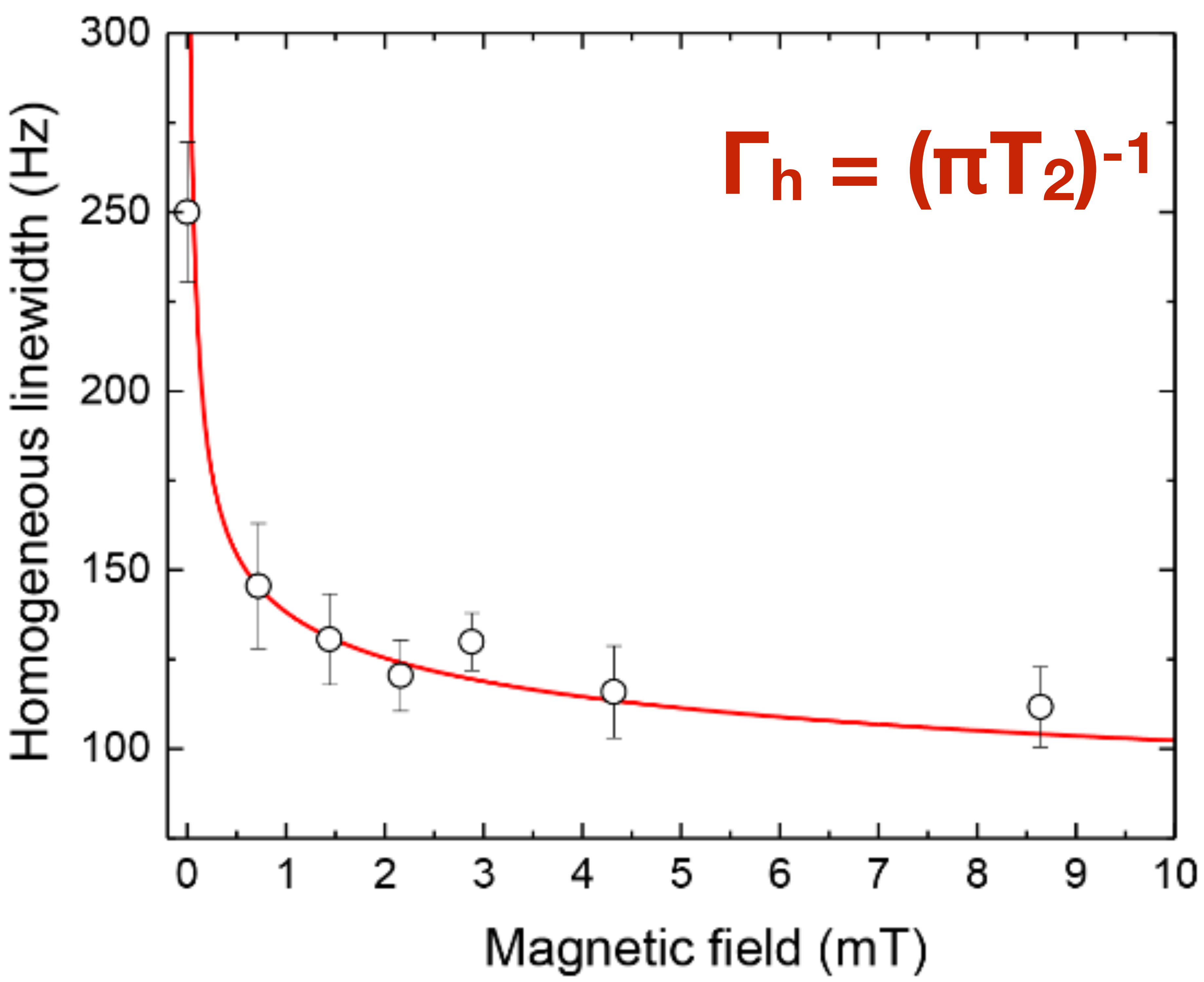
$Eu^{3+}:Y_2SiO_5$ single crystal: T_2 = 19 ms

D. Serrano, J. Karlsson, A. Fossati, A. Ferrier, and PG, arXiv, 2017.

IR CP

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

Magnetic Field Effects



T_2 up to 2.9 ms

Strong homogeneous linewidth decrease for field of 1-2 mT

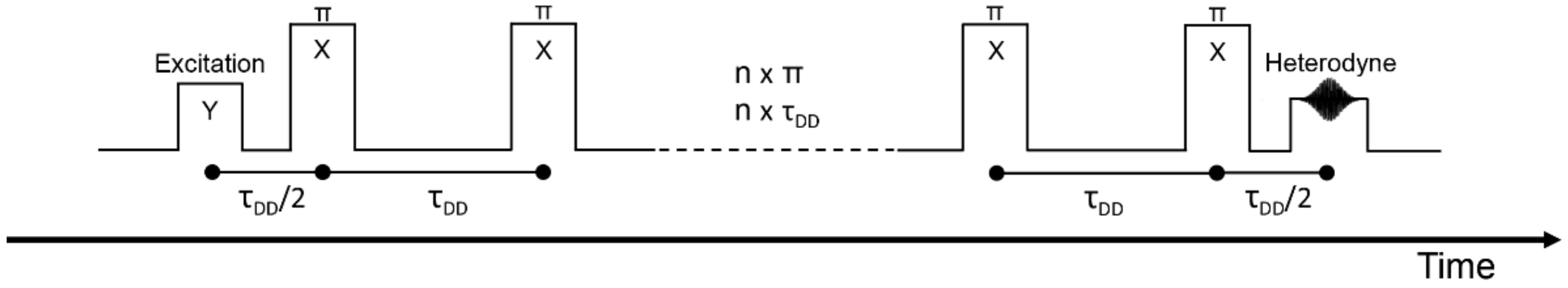
Interactions with electron spins (defects), reduced when $H_{dd} << H_{Zeeman}$

Longer lifetimes possible in higher quality samples

D. Serrano, J. Karlsson, A. Fossati, A. Ferrier, and PG, arXiv, 2017.

Dynamical Decoupling

CPMG sequence

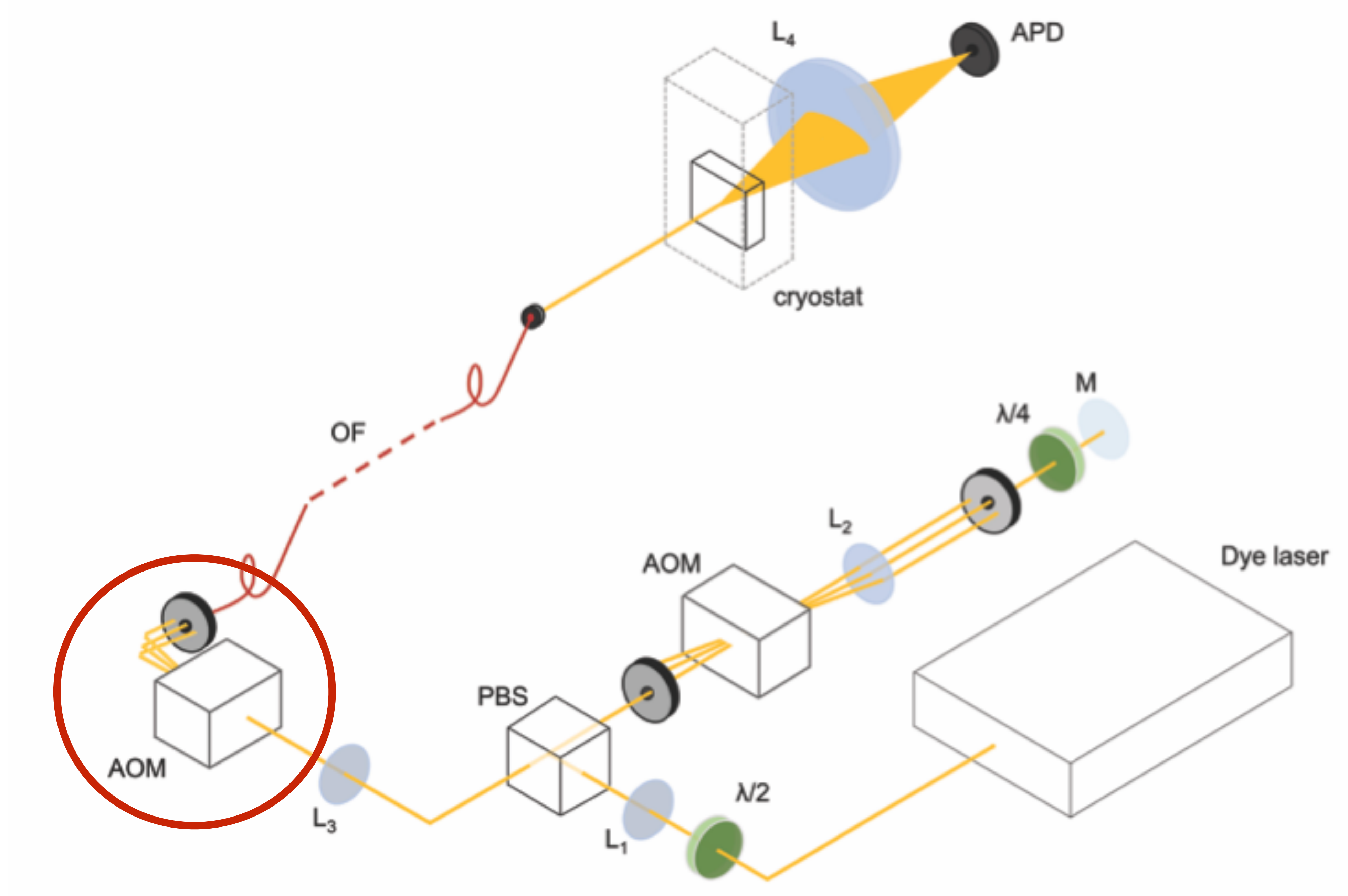


Compensate **perturbations $\tau_c >> \tau_{DD}$**

Efficient for specific initial state

Relative phases are important

2-color pulses: **single AOM**

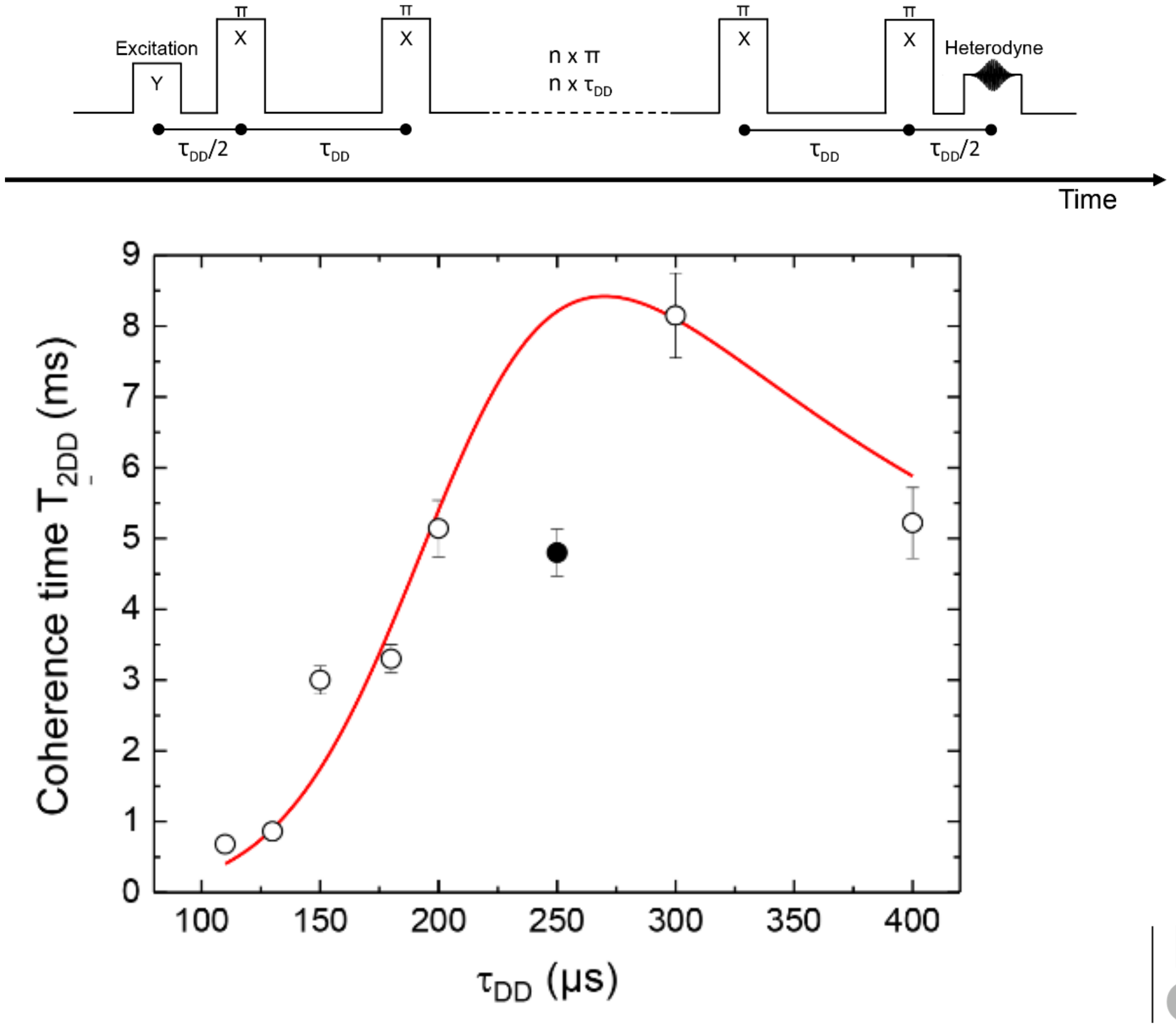


High phase stability over minutes

IR CP

D. Serrano, J. Karlsson, A. Fossati, A. Ferrier, and PG, arXiv, 2017.

T_2 Extension



T_2 up to 8 ms

Balance between decoupling and **pulse error accumulation**

Pulse fidelity: limited by the **strong scattering in the powder**

Larger decoupling in a **single particle**

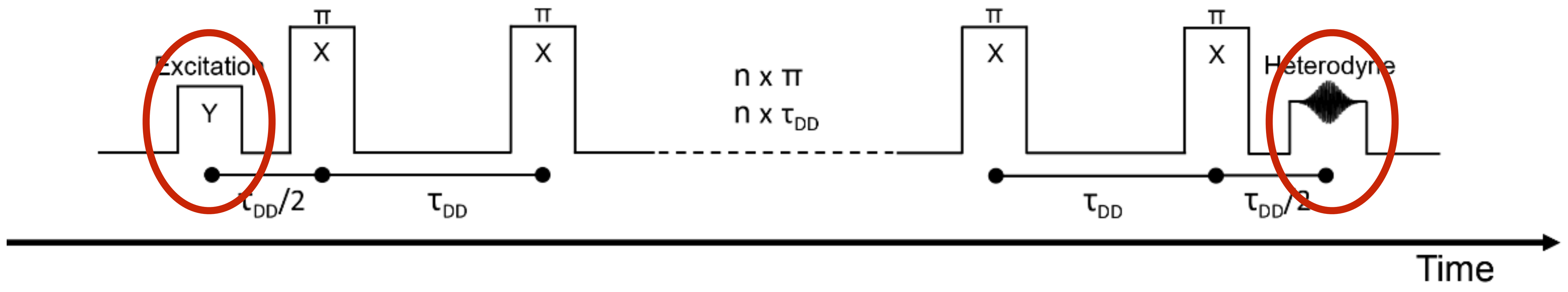
IR CP

D. Serrano, J. Karlsson, A. Fossati, A. Ferrier, and PG, arXiv, 2017.

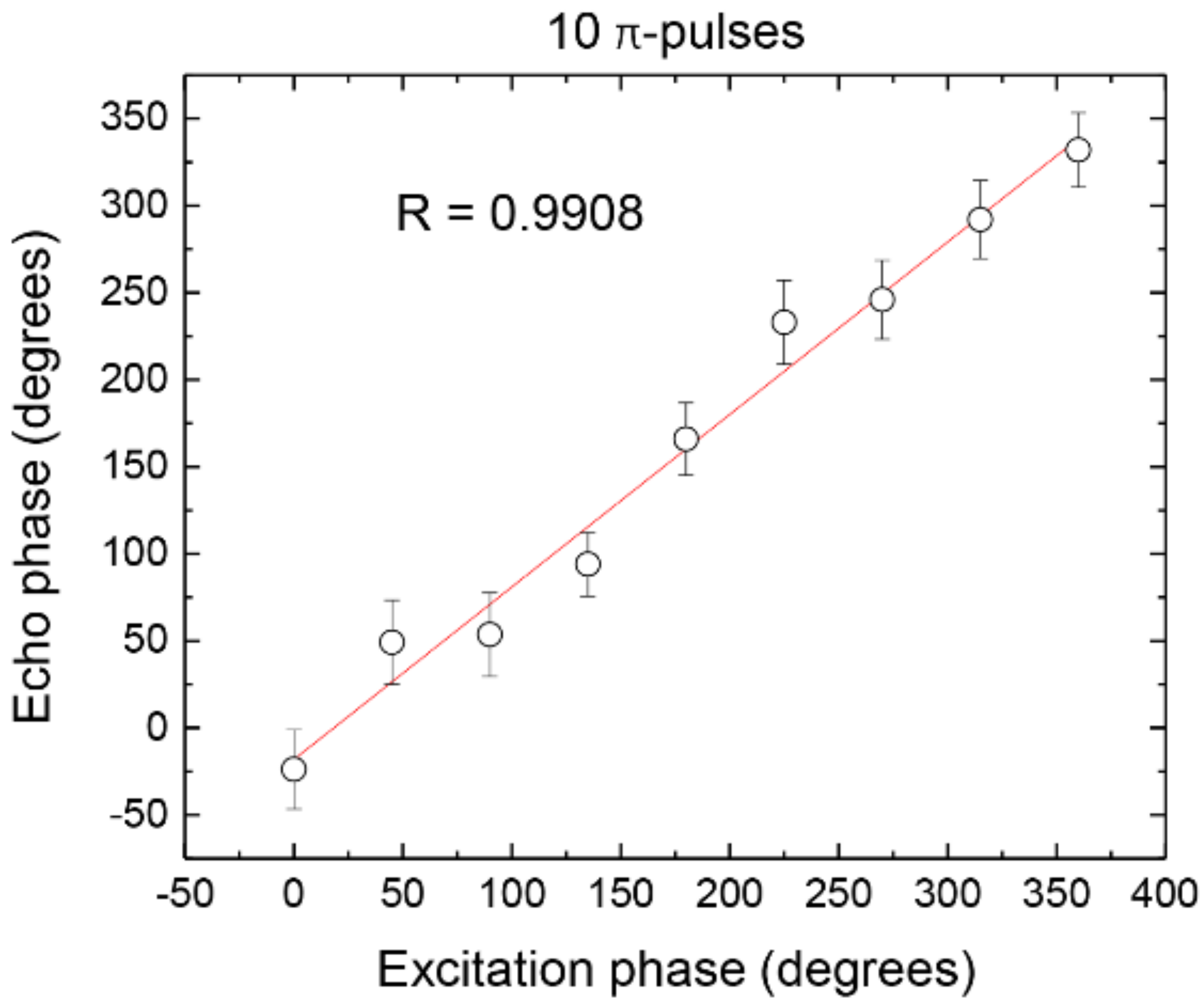
Phase Coherence

Input/output phase comparison

Relative phase between the two colours



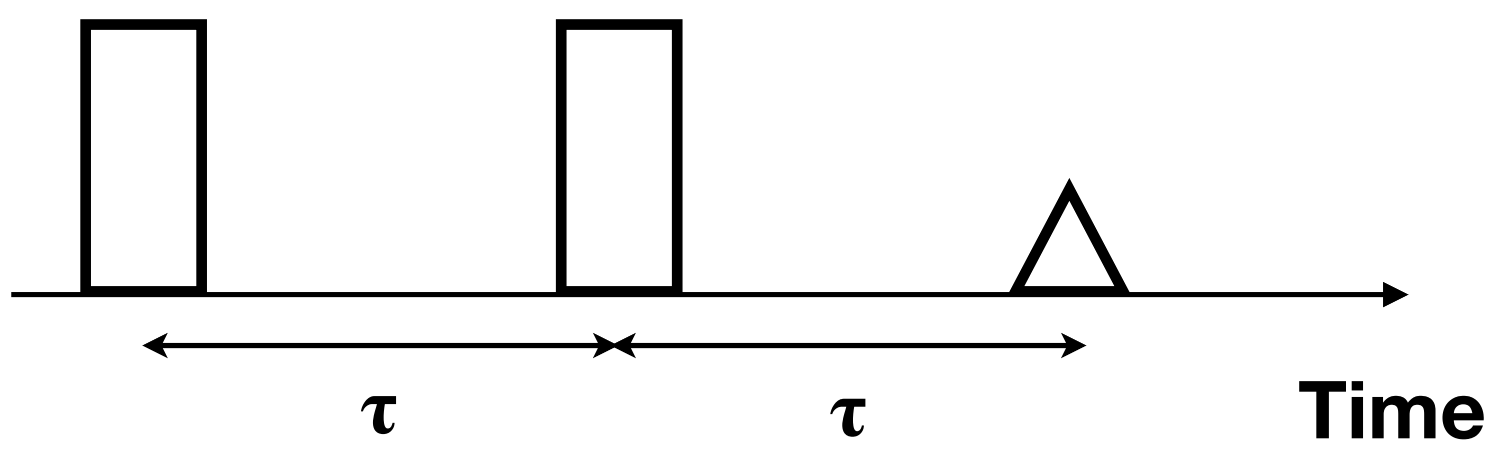
Fixed relation required for quantum storage

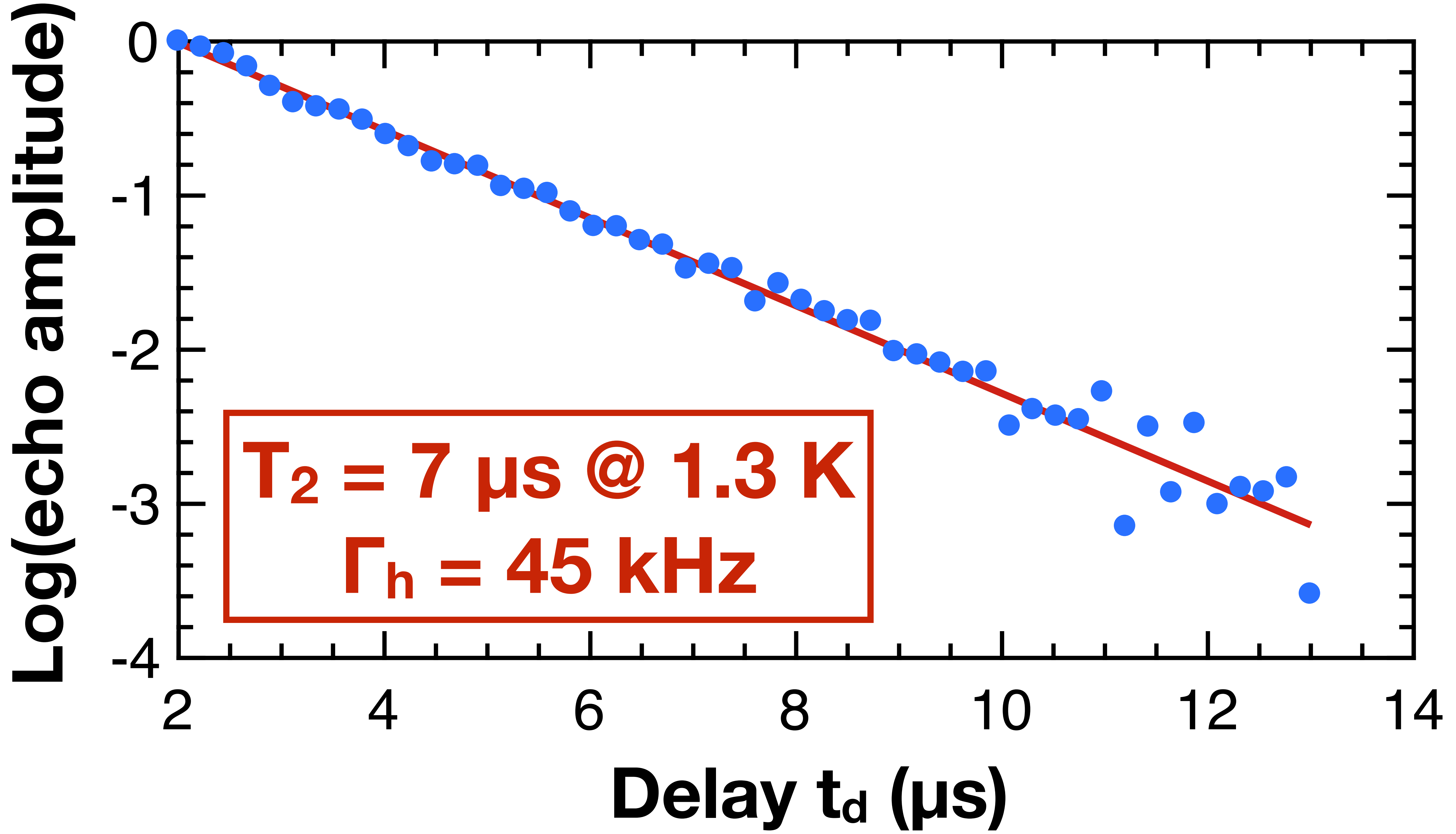


D. Serrano, J. Karlsson, A. Fossati, A. Ferrier, and PG, arXiv, 2017.

Optical T_2 in nanocrystals

Echo Decay in Nanocrystals





Suitable for high fidelity spin gates

IRCP

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

Acknowledgment

Paris team: **A. Ferrier**, **D. Serrano**, A. Tallaire, M. Mortier, Shuping Liu, Zhonghan Zhang, Sacha Welinski, **Alexandre Fossati**, Marion Scarafagio. Former members: Marko Lovrić, Karmel de Oliveira Lima, John Bartholomew, **Jenny Karlsson**

Collaborators: R. Gonçalves, USP, Brazil - **D. Hunger**, KIT, Germany - **S. Kröll**, Lund University, Sweden
Y. Le Coq, SYRTE, France - S. Seidelin, Grenoble University, France - **H. de Riedmatten**, ICFO, Spain - F. Koppens, ICFO, Spain - K. Mølmer, Aarhus University, Denmark
N. Oliverio, Keysight Inc., USA

Funding:

NanOQTech

Nanoscale Systems for Optical Quantum Technologies

http://www.nanoqtech.eu

European Union's Horizon 2020 programme

IR
CP

Summary

Nuclear spins **with ms long coherence lifetimes measured by all-optical techniques**

Coherence lifetime extension by **dynamical decoupling using trains of 2-color optical pulses**

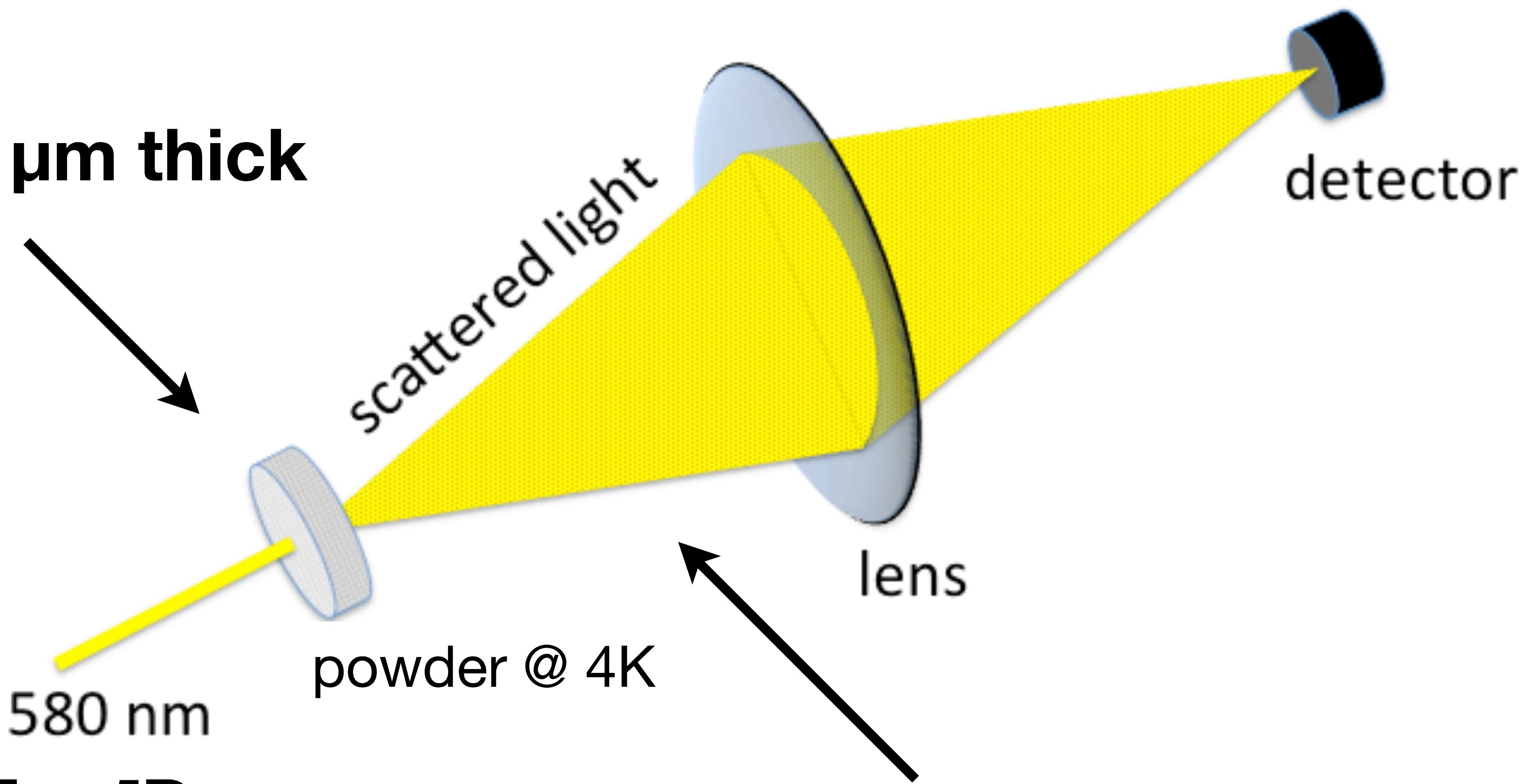
T_2 improvement by **lowering magnetic defects concentration and in single particles**

Rare earth doped nanoparticles: **optically controlled qubits**

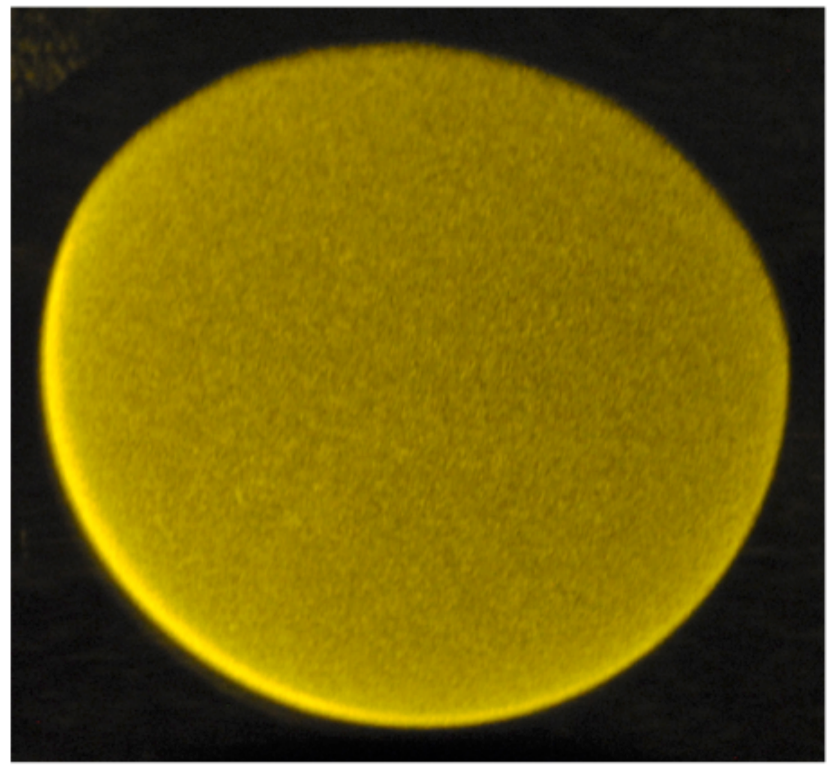
IR CP

Photon Echo in Powders

500 µm thick

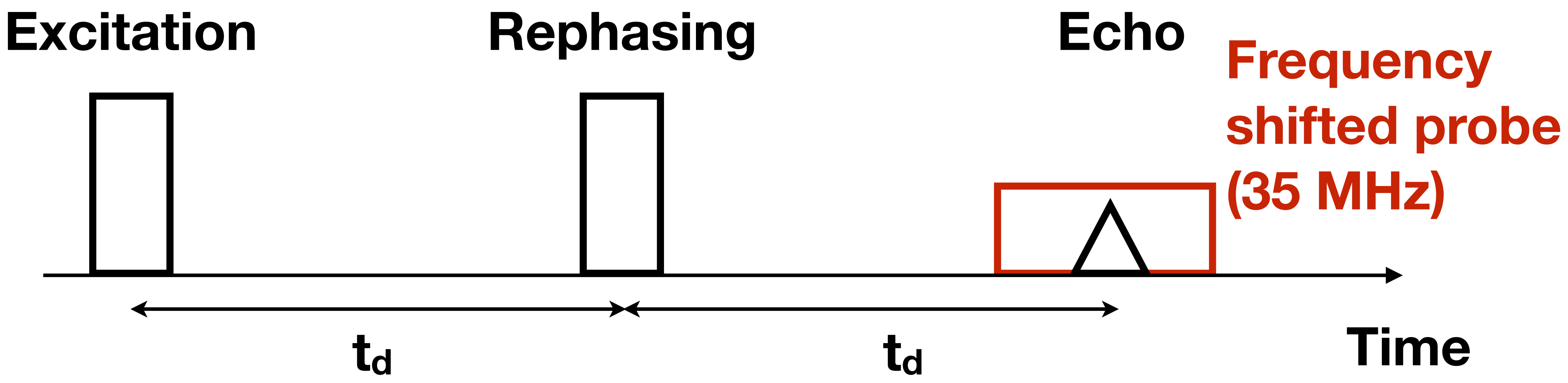


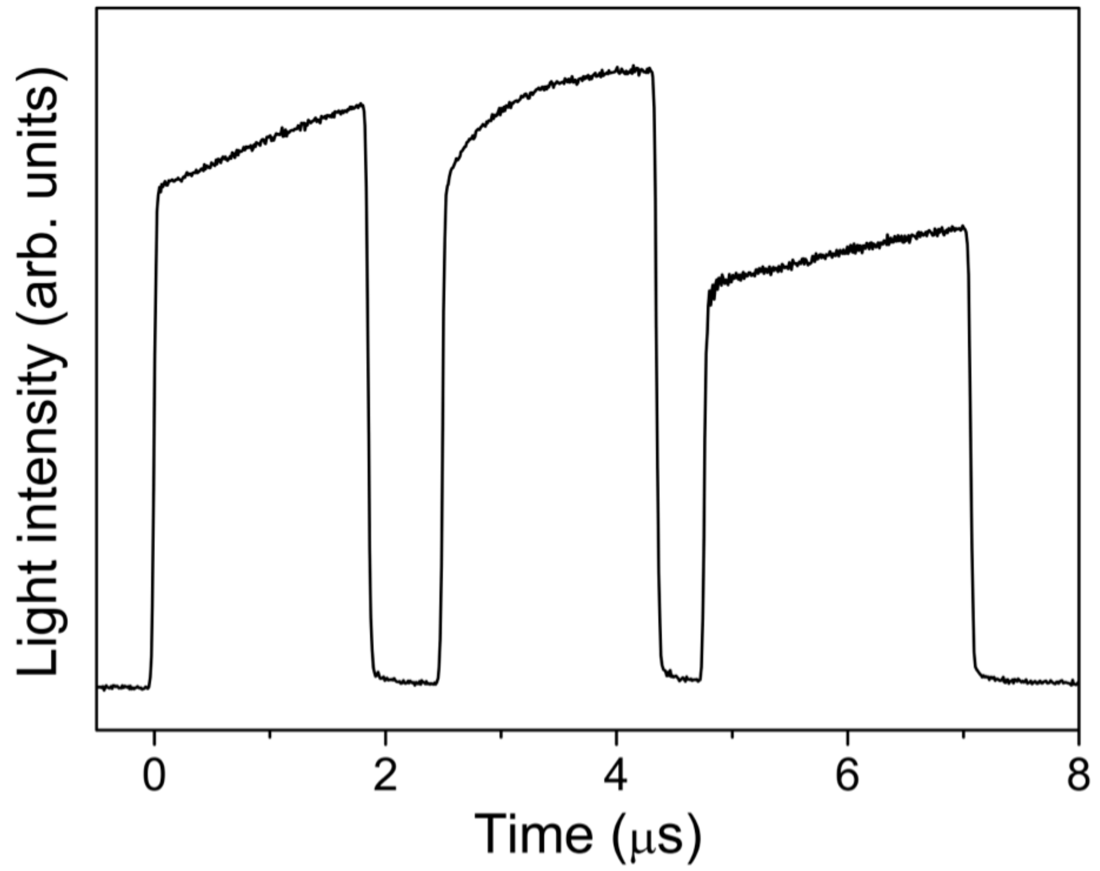
$^7F_0$ - $^5D_0$ transition

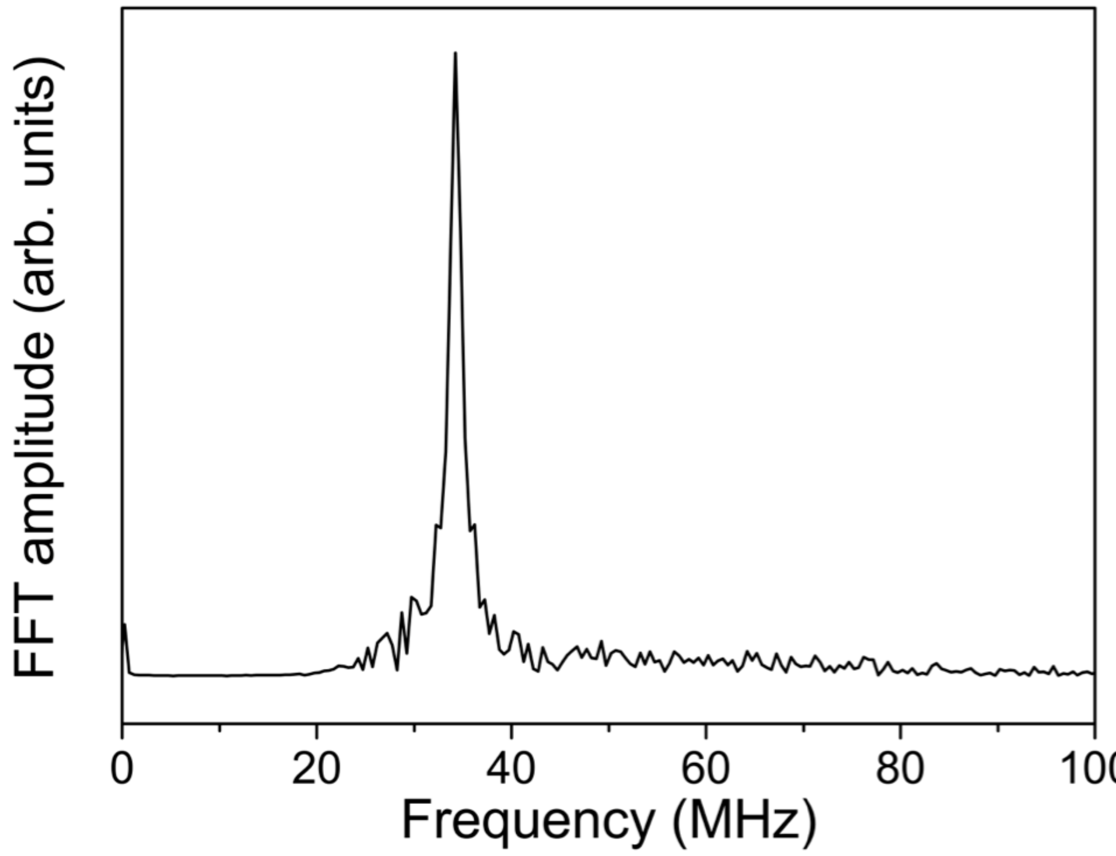


Light scattered by the powder

Interferometric detection







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

IR CP