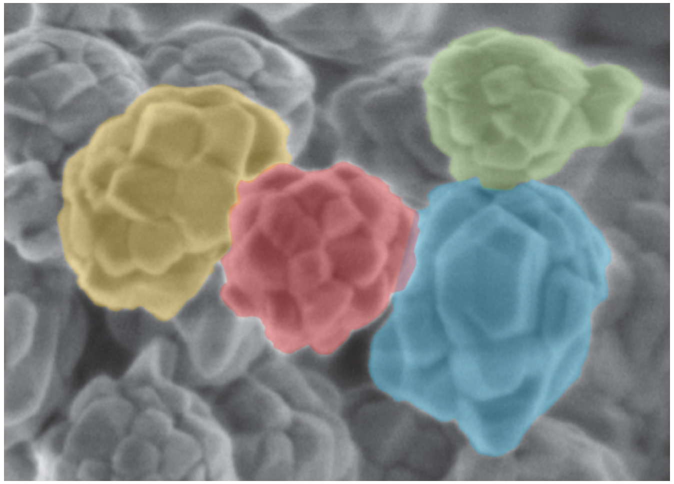
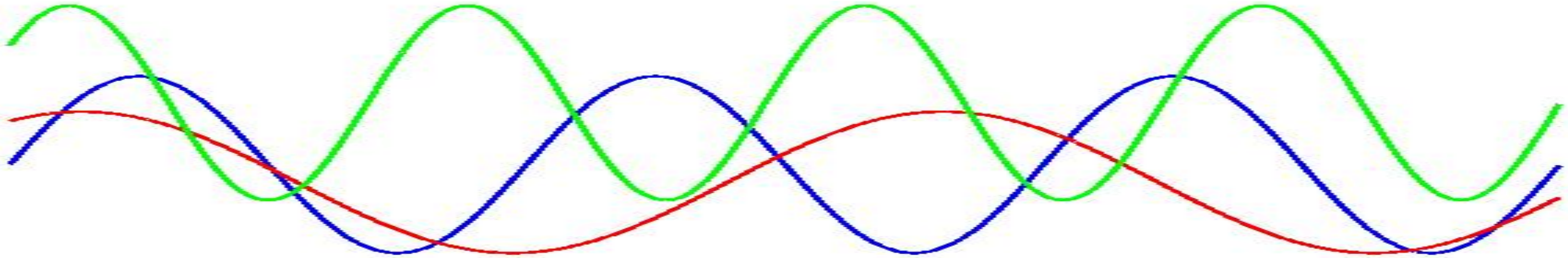
Coherence properties of rare-earth doped nanoparticles



Towards smarter materials for quantum technologies

Jenny Karlsson

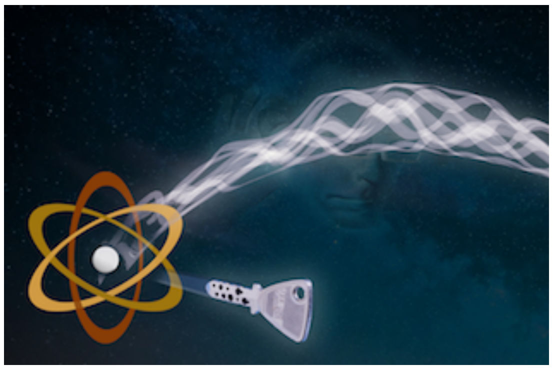


MPOE Seminar Feb 2017

IR CP Institut de Recherche de Chimie Paris
Chimie ParisTech École nationale supérieure de chimie de Paris
PSL Research University
cnrs

What is quantum technology?

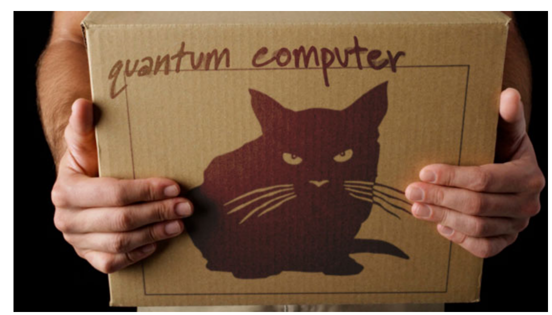
Devices that use the properties of quantum systems
as a vital part of their function.



Quantum cryptography

Quantum random number generators

Quantum memories



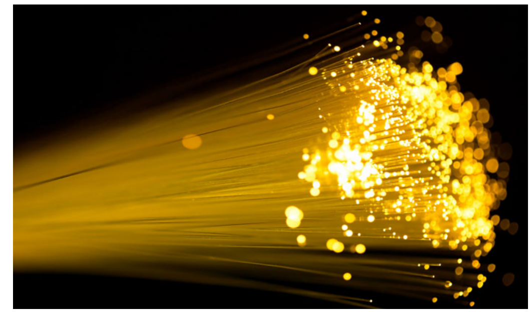
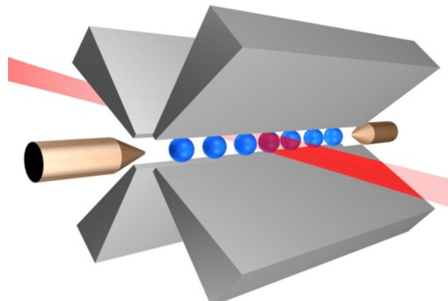
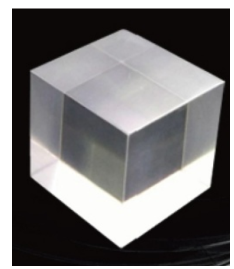
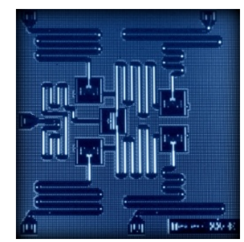
Quantum computing

Hardware for quantum technology

Long-lived and controllable quantum states

- Photons (light)
- Trapped ions
- Superconducting circuits
- Rare earth doped crystals

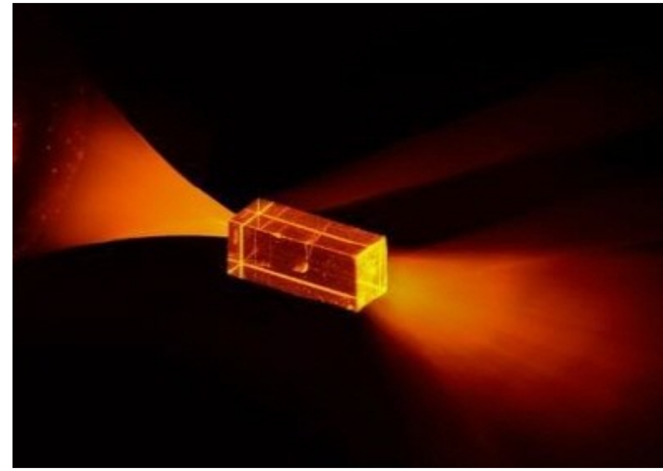
Etc…

A combination of several different quantum systems could be the best.

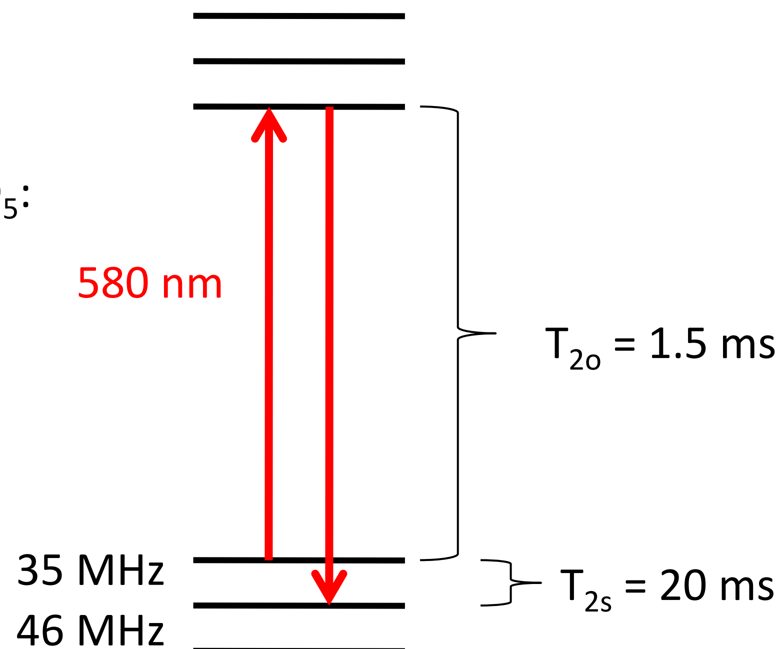
Rare earth doped crystals

$Eu^{3+}:Y_2SiO_5$, $Pr^{3+}:Y_2SiO_5$, ...



Solid state
-> Easy handling, storage, integration
Optical and nuclear spin transitions
-> Photon-spin interface
Long coherence lifetimes @ 4K

$Eu^{3+}:Y_2SiO_5$:



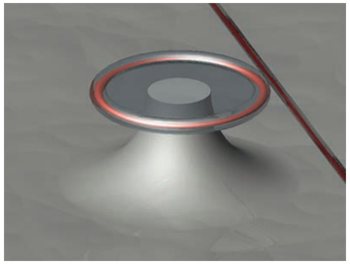
Applying some tricks..

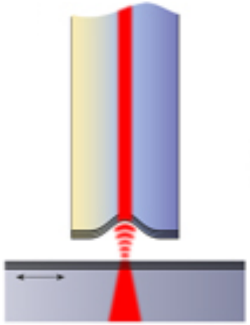
$T_{2s\ tricks}$ = 6 hours![1]

1: M. Zhong et. al. Nature 517, 177-180 (2015)

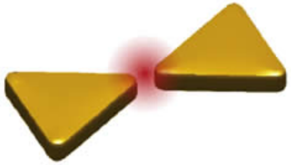
Moving to the nanoscale…

- Small size – coupling to small cavities
- Strong interactions – hybrid systems
  – nanosensors
- Single ion detection
- Quantum computing





Benedikter et. al.
New J. of Phys. 17 (2015)



Suh et. al.
Nanotoday 8, 5 (2013)

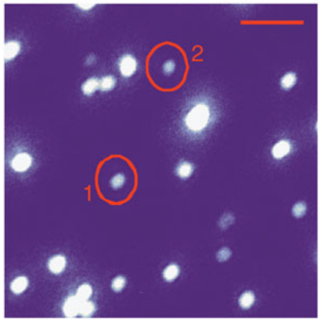
But will the coherence times be long enough?

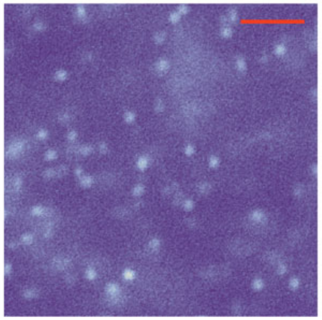
Other systems:
Quantum dots
Defects in nanodiamonds

NV-center electron spin coherence time:
Bulk: 2.5 ms
Nano: 5 µs

Single ion detection:

a Nanocrystals b Bulk

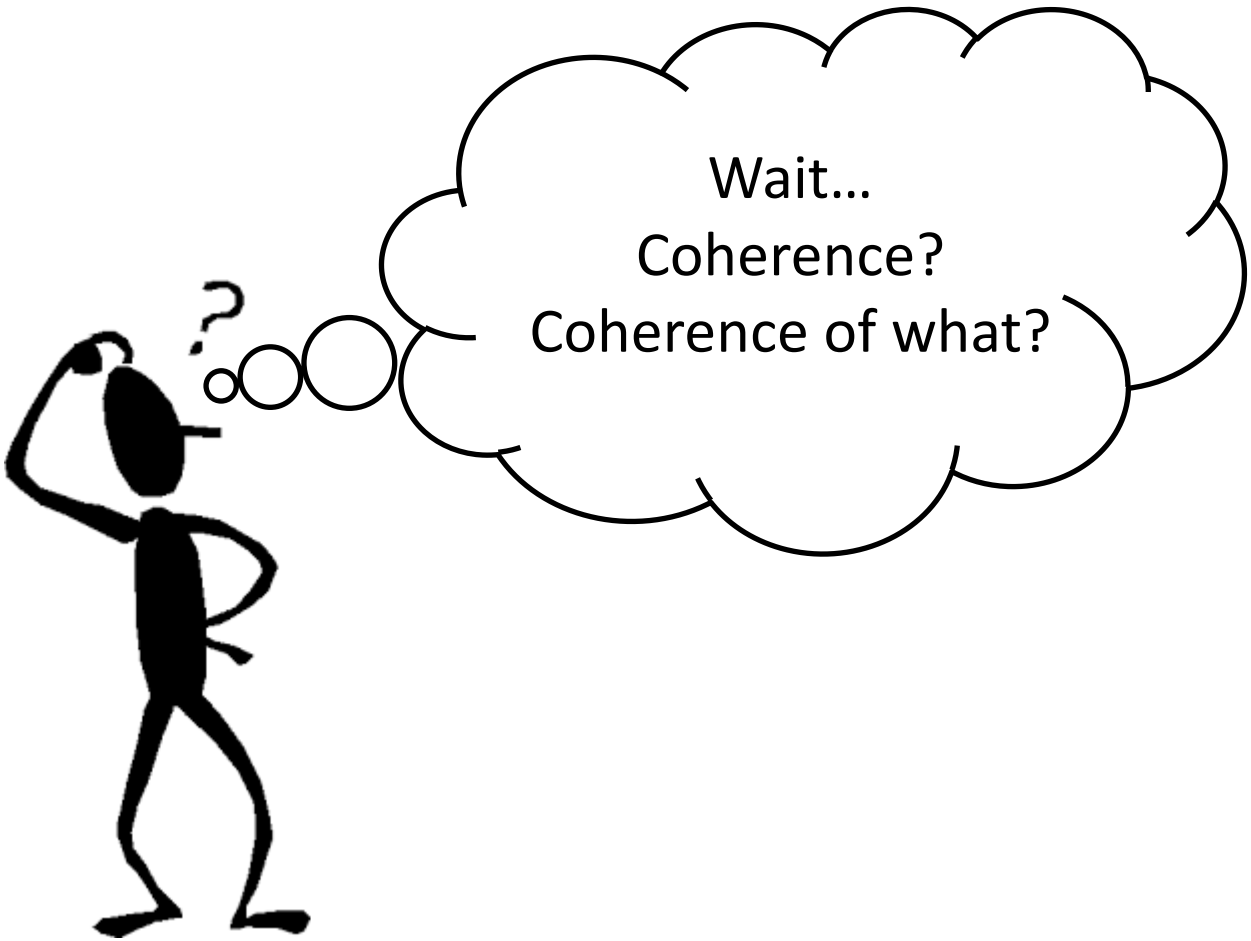




Kolesov et. al. Nature Comm. 3 1029 (2012)

Aim

Explore the possibilities to create nanoscale materials with long coherence lifetimes



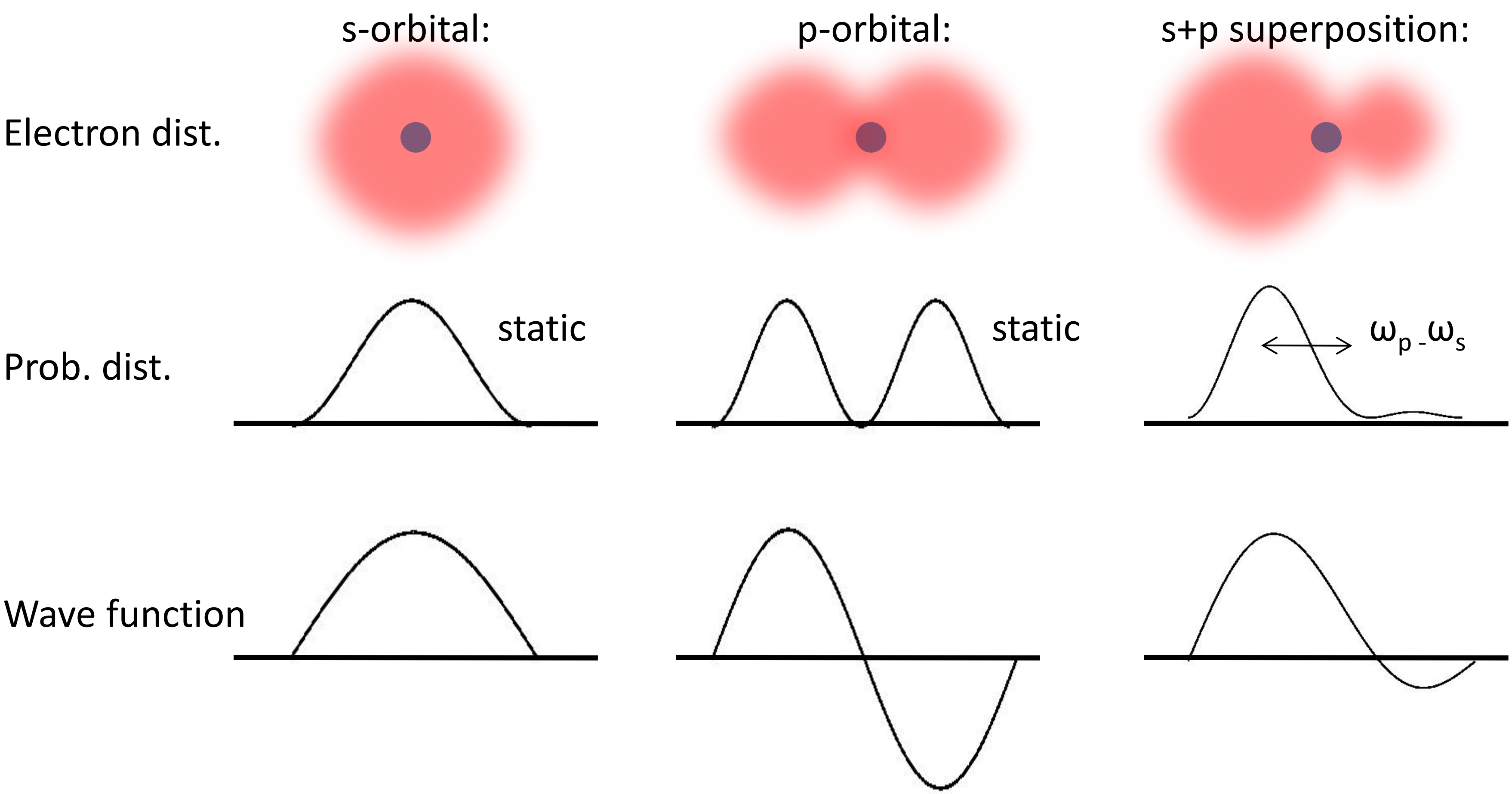
Coherence – an intuitive picture

All superposition states oscillate!

Phase

$$a|0\rangle + e^{i\varphi}\, b|1\rangle$$

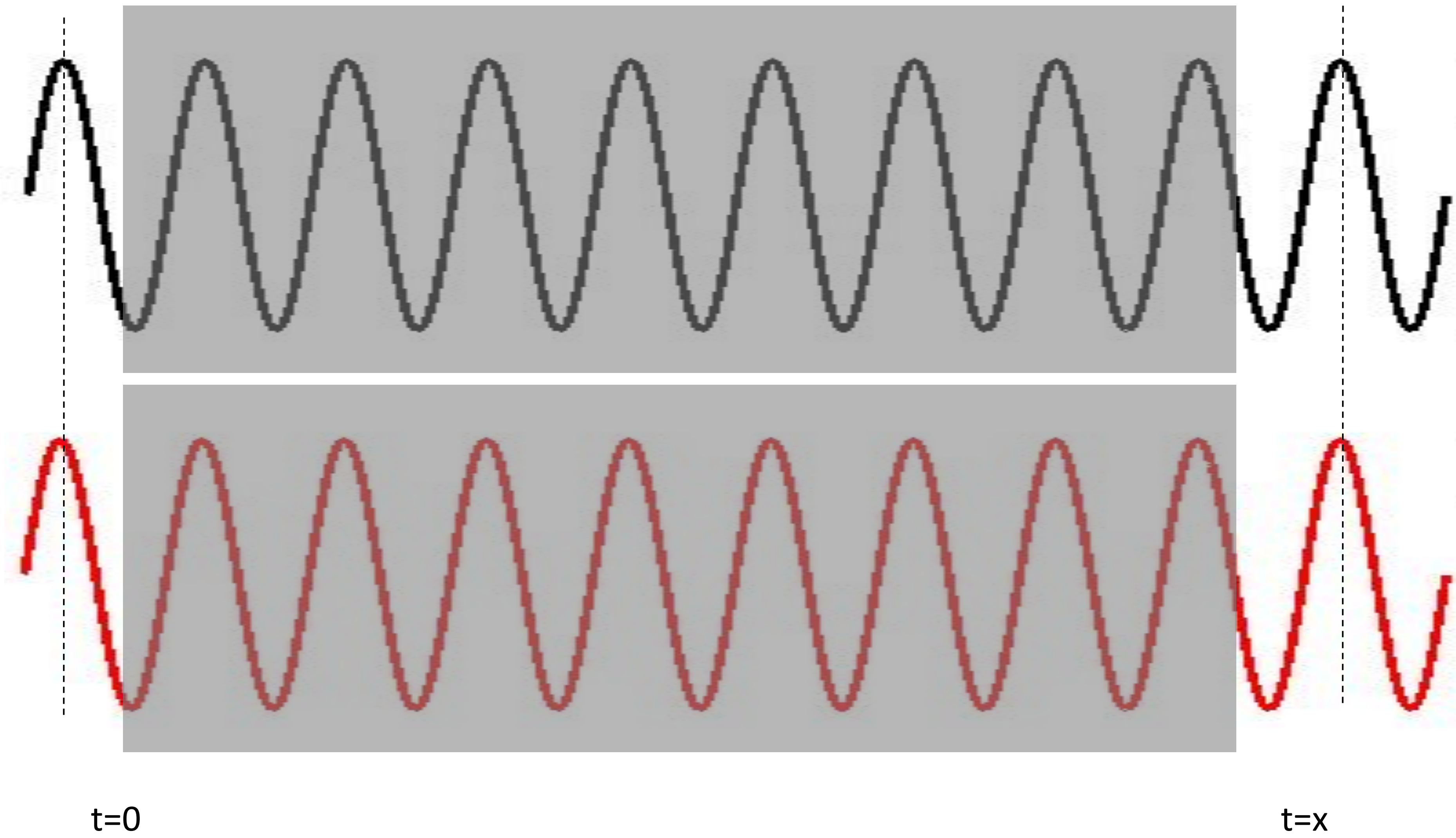
A simple example:



Coherence – an intuitive picture

Coherence = a predictable phase relationship

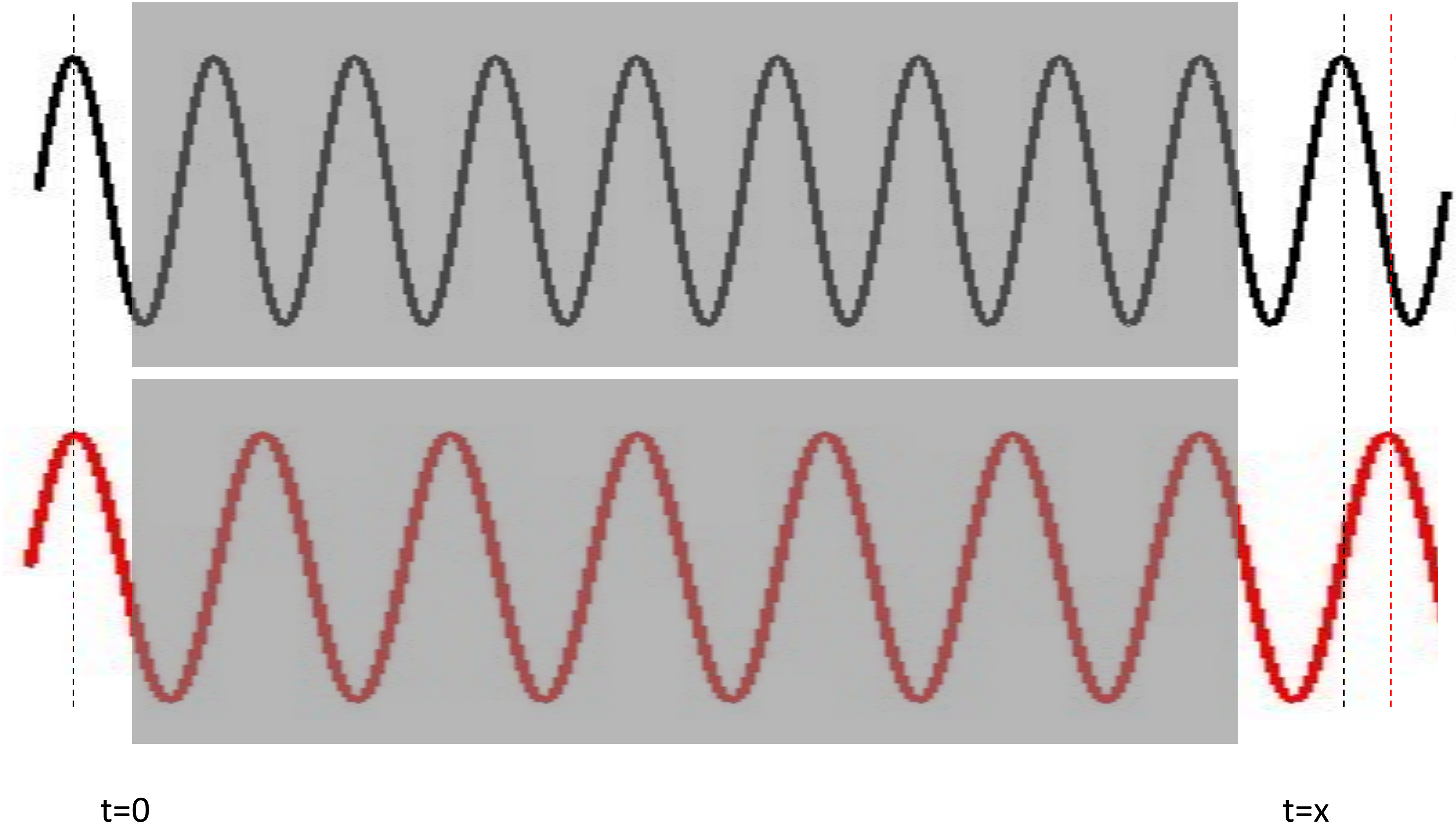
Are these waves coherent?



Coherence – an intuitive picture

Coherence = a predictable phase relationship

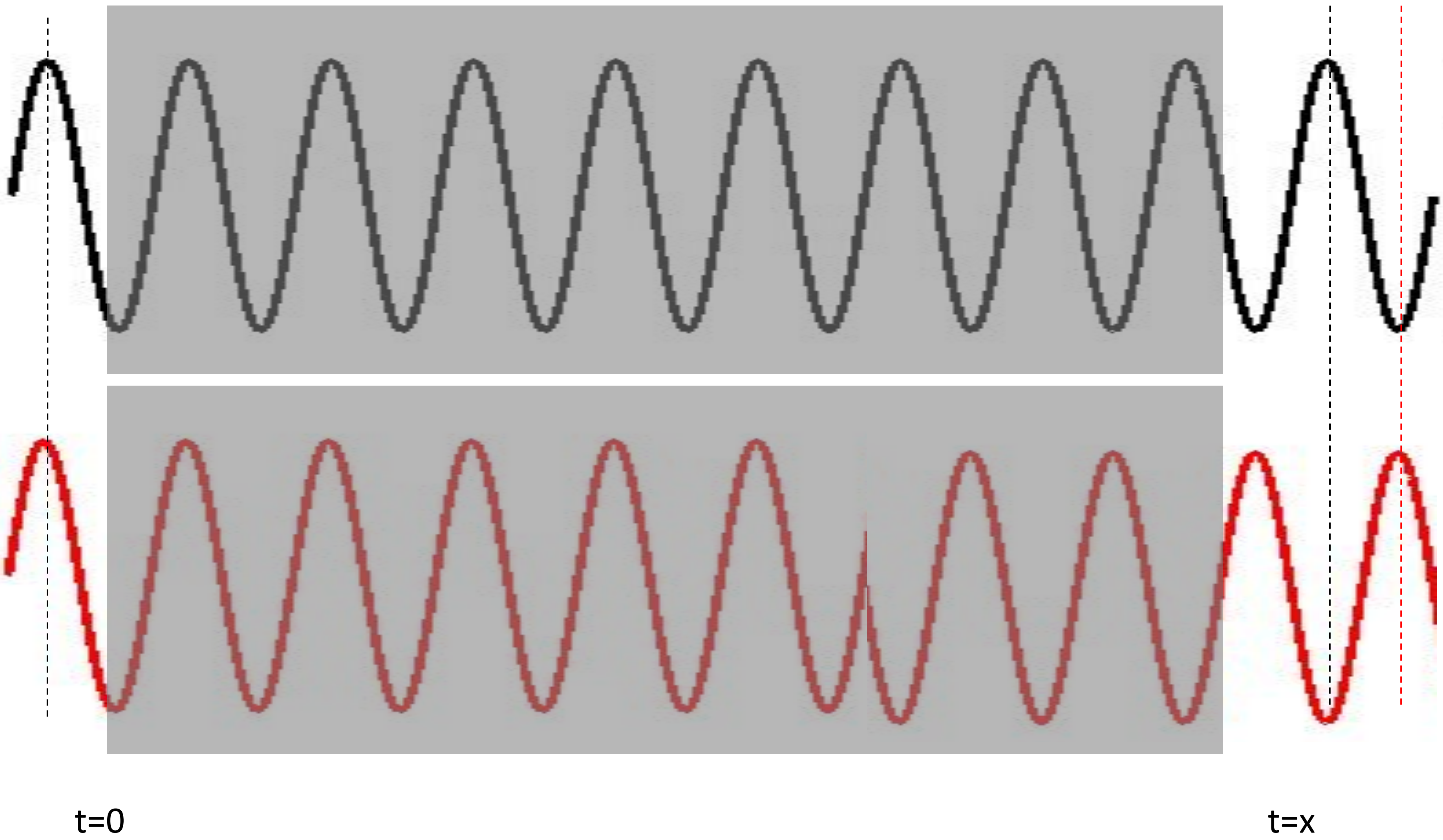
Are these waves coherent?



Coherence – an intuitive picture

Coherence = a predictable phase relationship

Are these waves coherent?

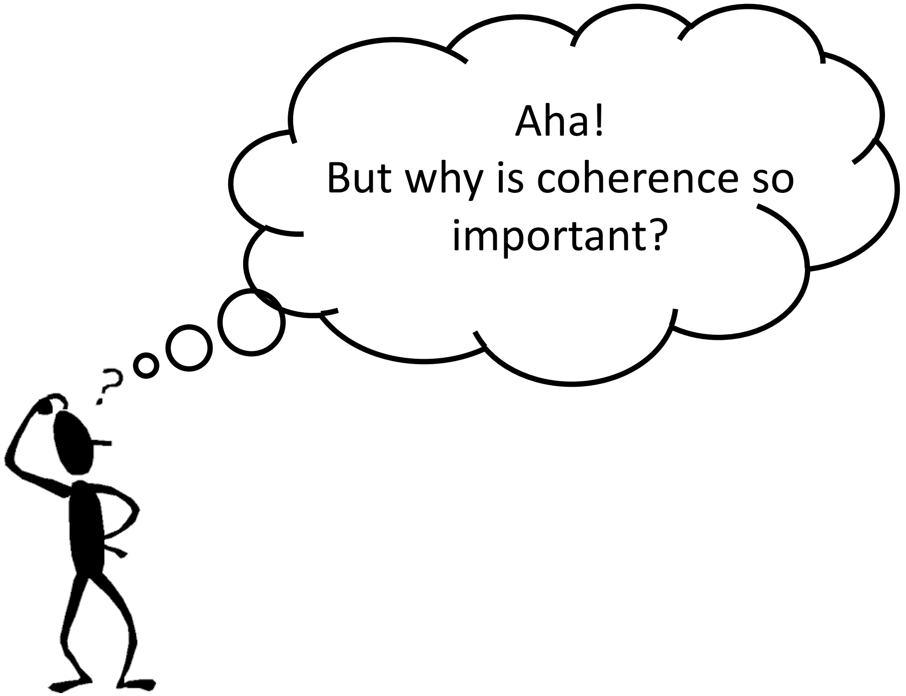


Coherence – an intuitive picture

Coherence = a predictable phase relationship

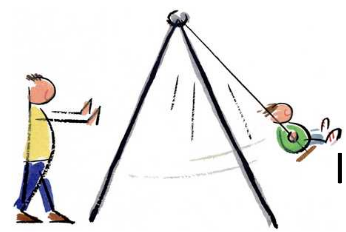
..between two or more waves/oscillators,
e.g. between the laser beam and some rare earth ions,
or between the ions themselves

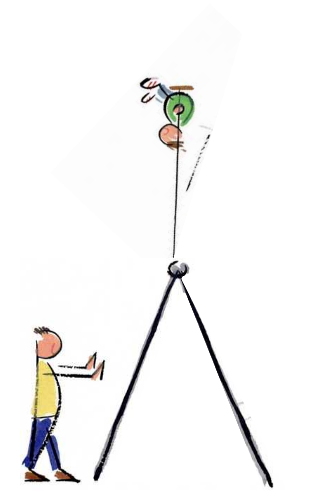
Depends on our knowledge about the evolution of the system!



Why coherence?

- Coherent excitation





Put the ions in any quantum state

- Quantum memory

Store a photon as a collective oscillation of the ions and retrieve it again

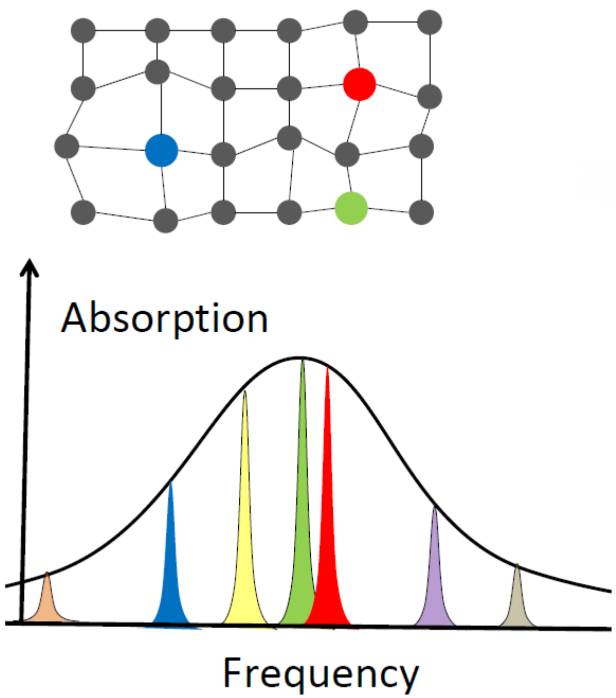
- Quantum computing

Quantum algorithms require interference –> phase sensitive

Measuring coherence

The photon echo

Collective effect of an inhomogeneously broadened ensemble.



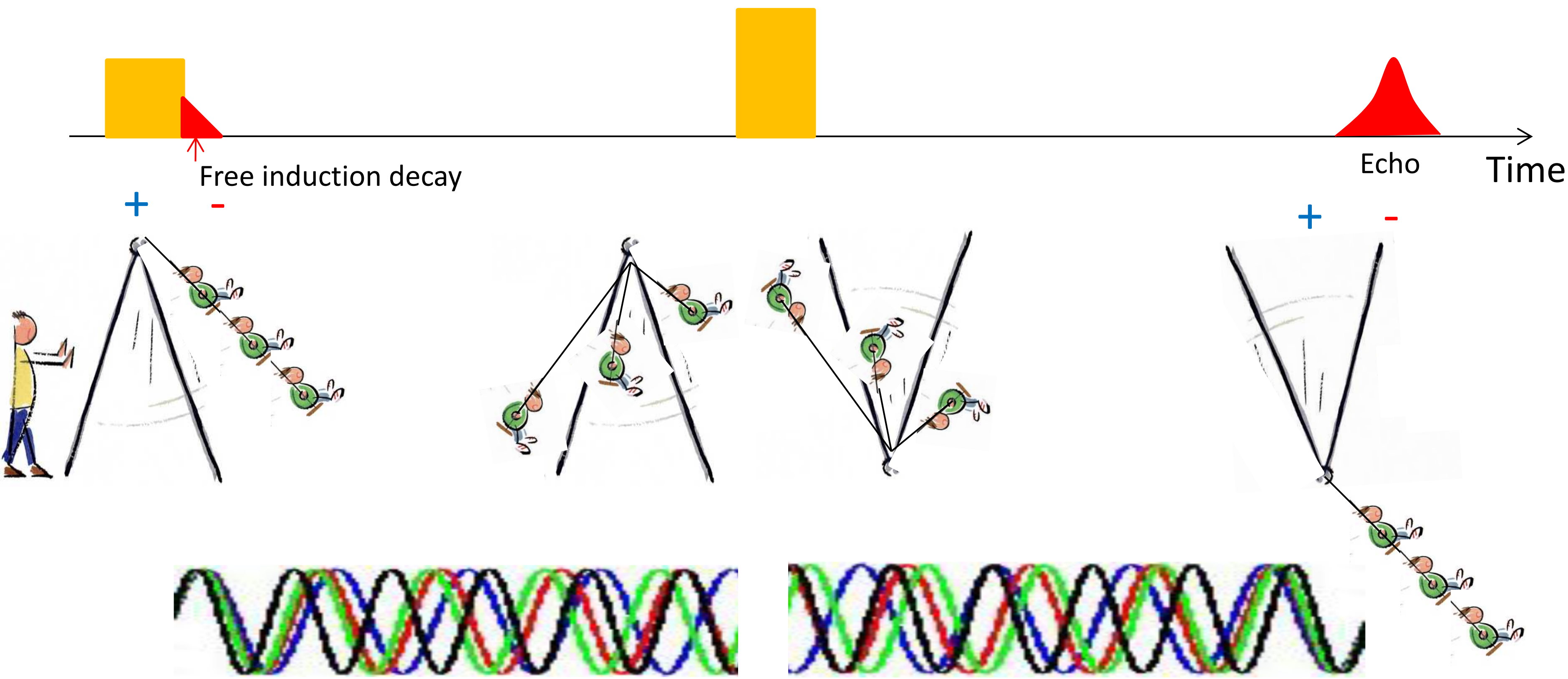
Measuring coherence

The photon echo

1. Put the ions in a superposition state

2. Flip the populations in the ground and excited state

3. Photon echo!



Dephasing

Rephasing

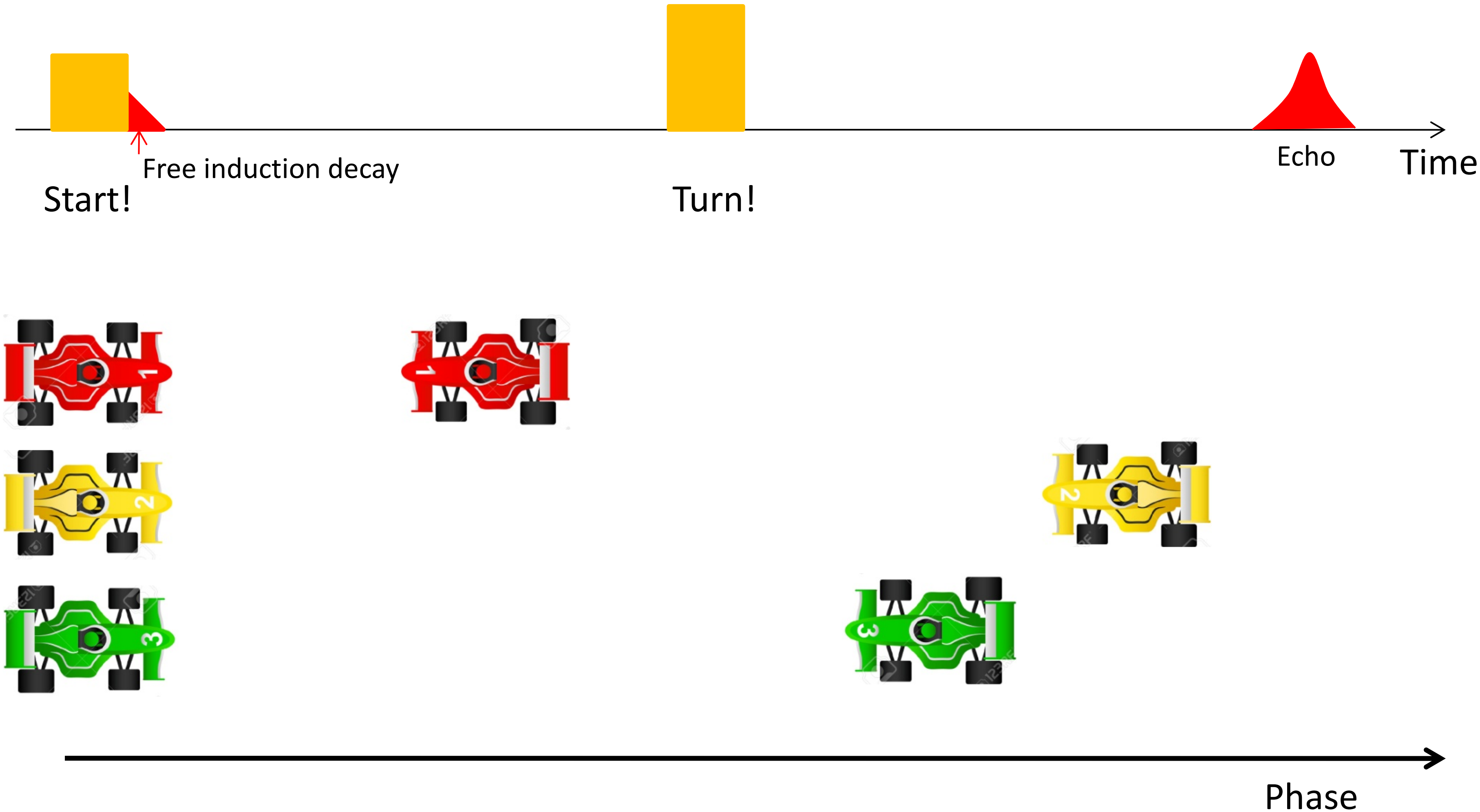
Measuring coherence

The photon echo

1. Put the ions in a superposition state

2. Flip the populations in the ground and excited state

3. Photon echo!



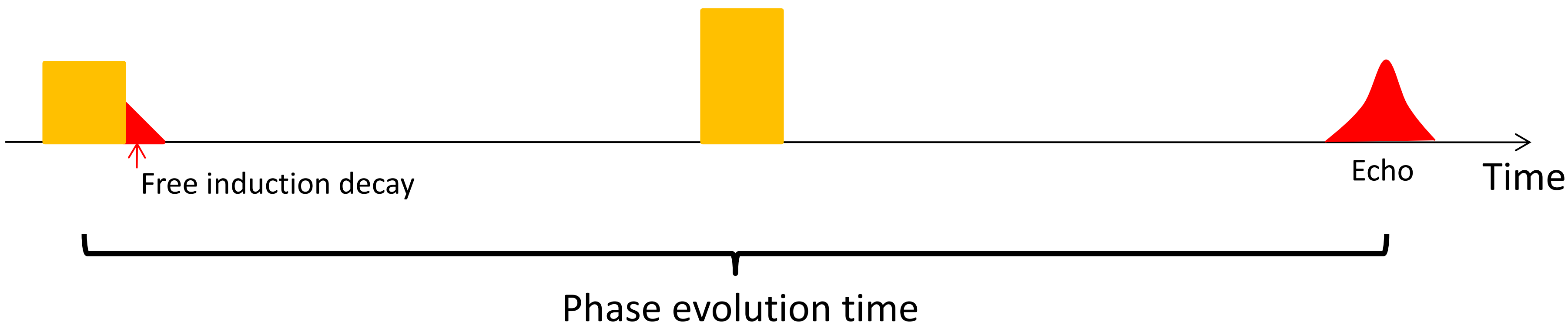
Measuring coherence

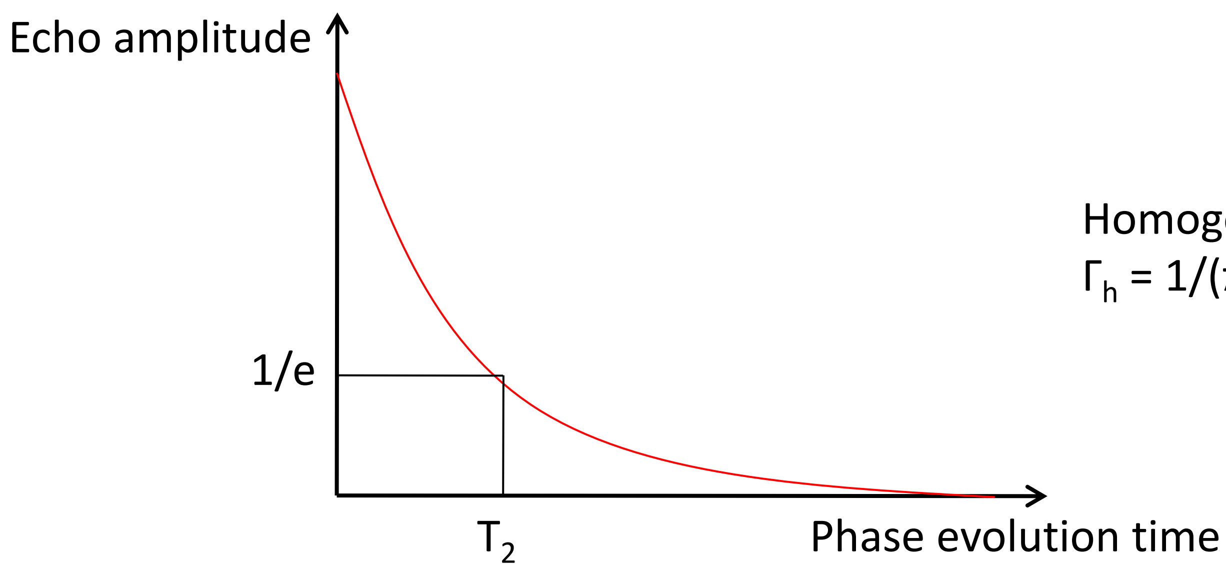
The photon echo

1. Put the ions in a superposition state

2. Flip the populations in the ground and excited state

3. Photon echo!





Homogeneous linewidth:
$\Gamma_h = 1/(\pi * T_2)$

Aim

Explore the possibilities to create nanoscale materials with long coherence lifetimes

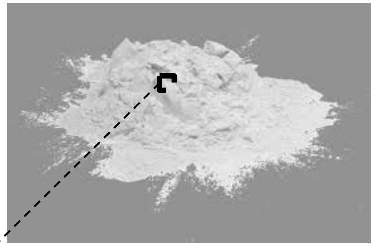
Short recap:

Rare earth doped bulk crystals have very long coherence lifetimes

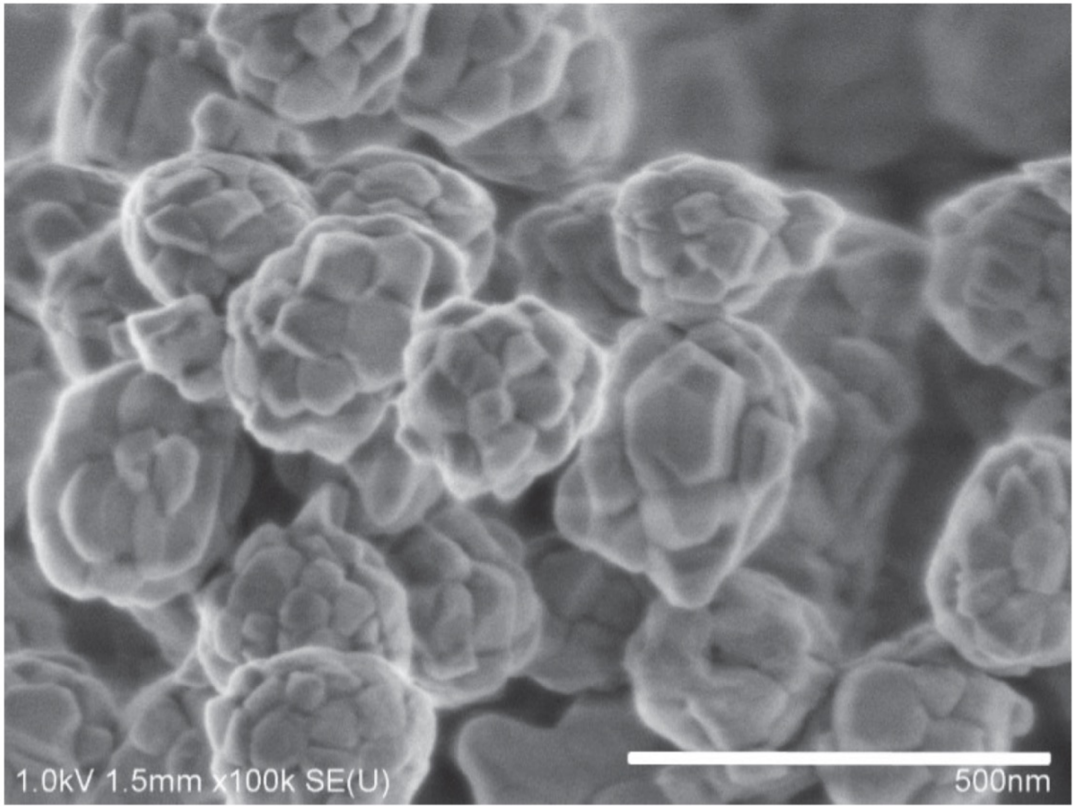
With nanoscale materials one can access the “true” quantum level and do many exciting experiments

The big question: Can we keep the long coherence lifetimes at the nanoscale?

Our nanocrystals



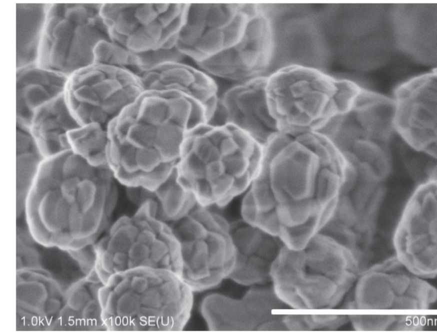
0.5% Eu:Y_2O_3
"Nano-ceramic"

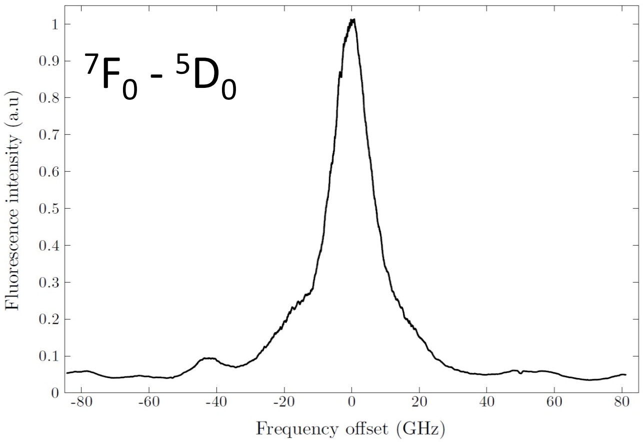


Particle size: ~450 nm
Crystallites: ~100 nm

PhD-thesis by
Karmel de Oliveira Lima

Our nanocrystals

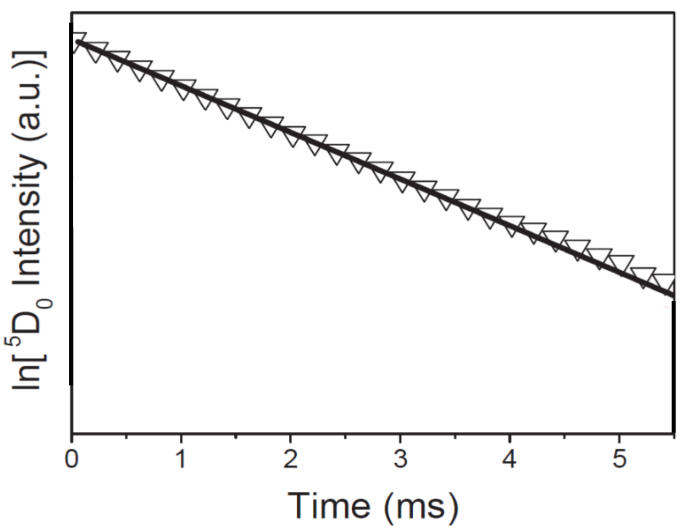




λ_0: 580.883 nm (vac)

Γ_{inhom}: 20 GHz

(~bulk)

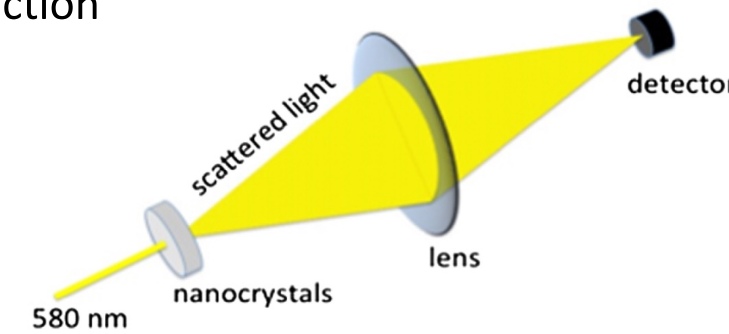


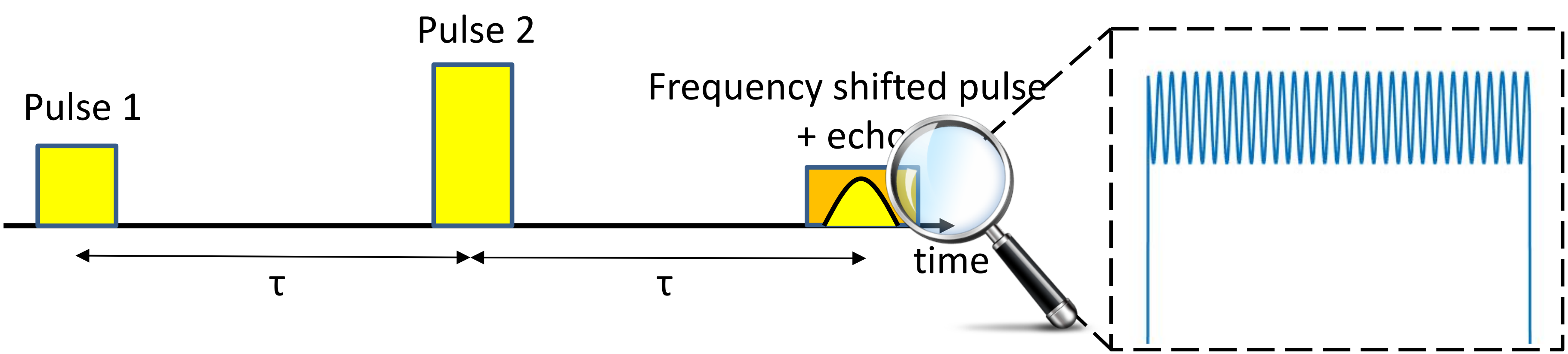
T_1 ($^5D_0$): 1.2 ms (>bulk)

PhD-thesis by
Karmel de Oliveira Lima

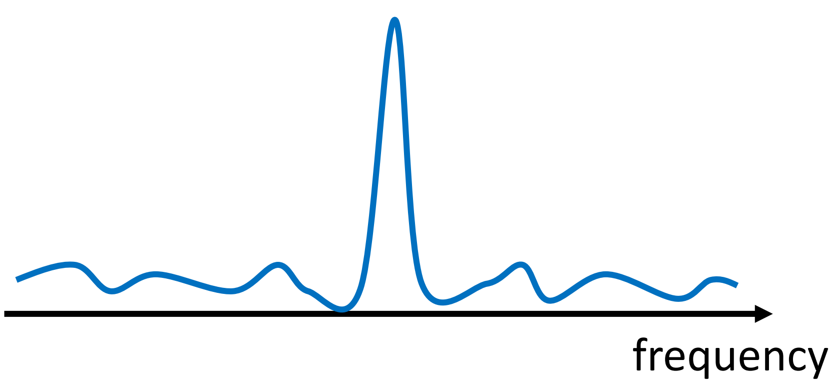
Photon echo

with heterodyne detection



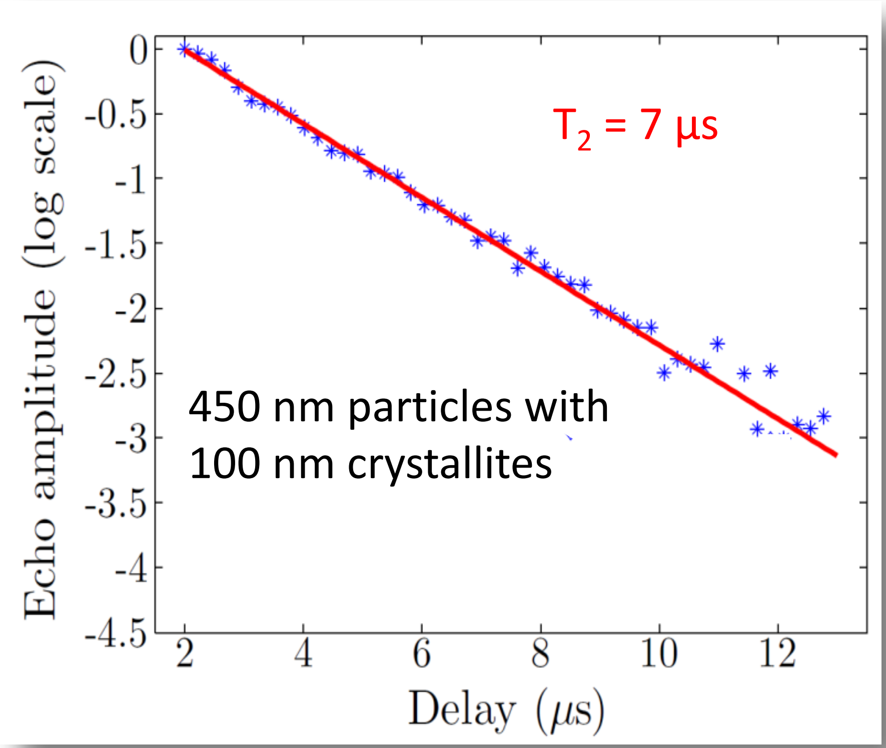


FFT:



Optics Express Vol. 19,
No. 16 15236 (2011)

Optical coherence time



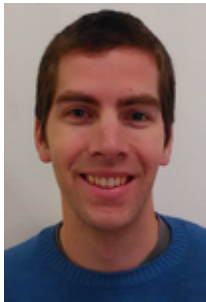
Longest optical coherence time in any sub-micron solid state system!

Quantum dots,
nano diamonds: ps-ns scale

T_2 , bulk single crystal: up to 510 μs
T_2 , bulk ceramic : 42 μs

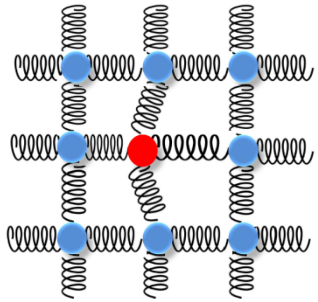
Accepted in Nanoletters

John Bartholomew



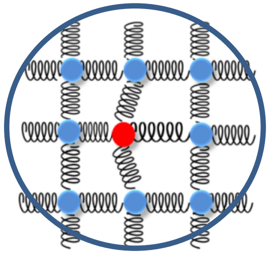
What is limiting T_2?

Bulk crystals:
Phonons!



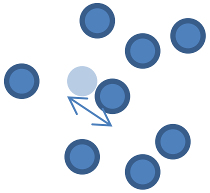
Temperature dependence: T^7

Nanoparticle
-> modified phonon density



Temperature dependence: T^3

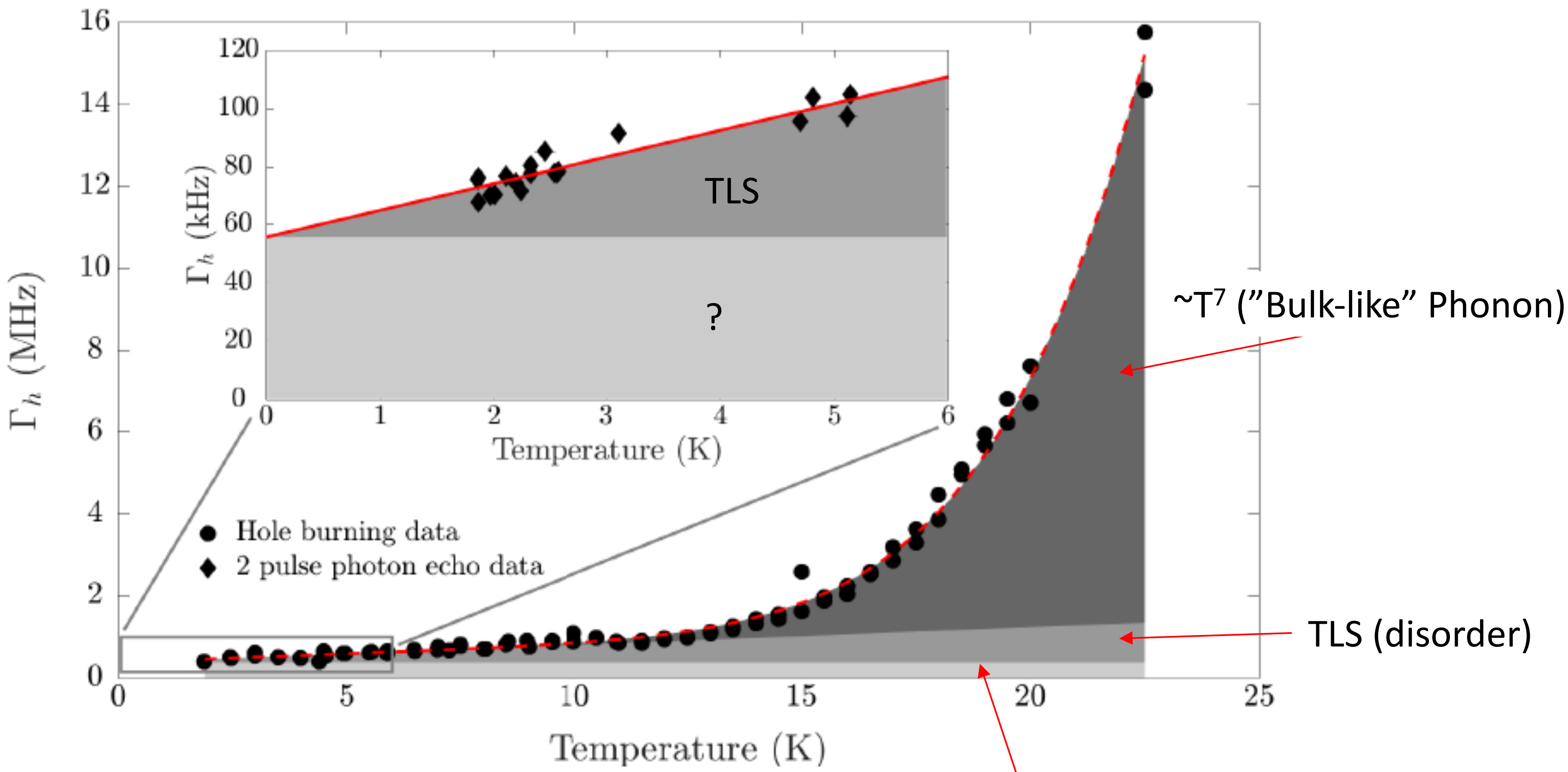
Glass, disorder
-> Two Level Systems (TLS)



Temperature dependence: T

Temperature dependence

$\Gamma_h = 1/(\pi * T_2)$

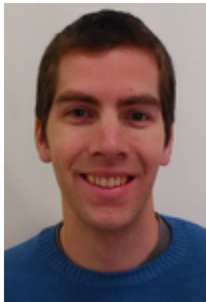


T^3-term negligible
-> not limited by size!

T-independent
broadening 30-50 kHz?

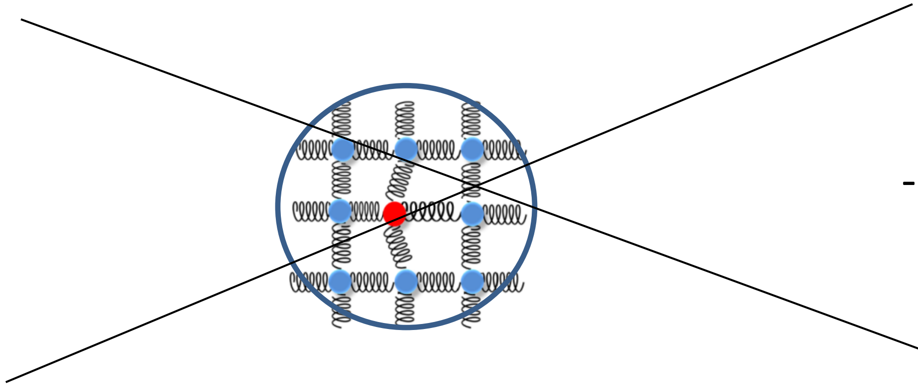
Accepted in Nanoletters

John Bartholomew



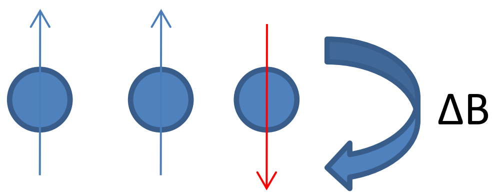
What is limiting T_2?

Modified phonon density (size)



->T^3

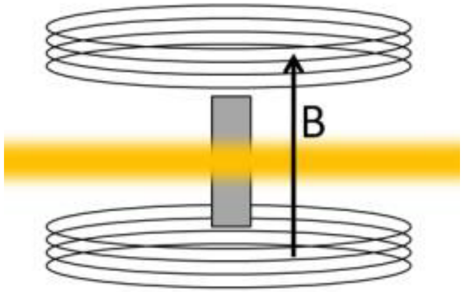
Magnetic noise

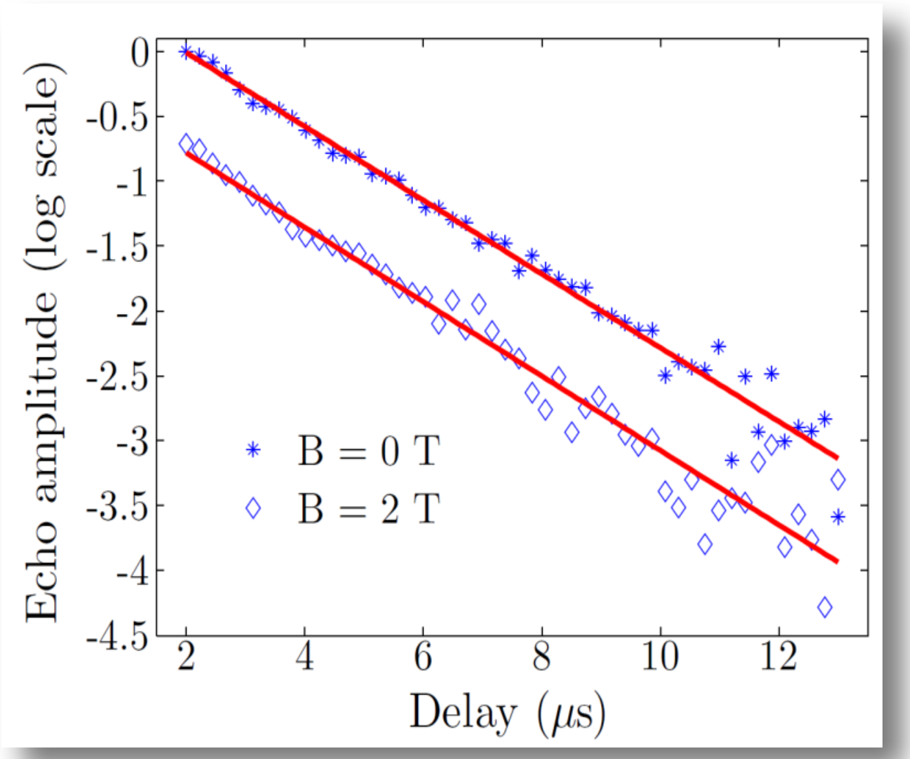


->Apply magnetic field

Fluctuating spins

Spin flips?

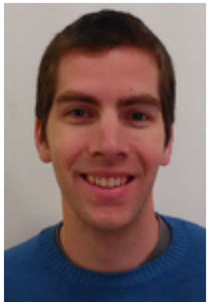




B=2 T (up to 3 T)
T_2 = 7 μs

No change.

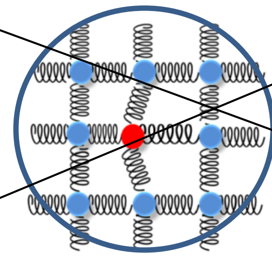
John Bartholomew
Jenny Karlsson



Accepted in Nanoletters

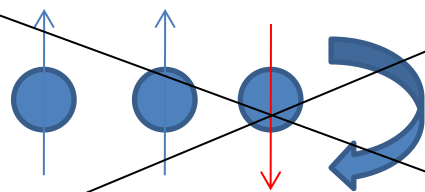
What is limiting T_2?

Modified phonon density (size)



->T^3

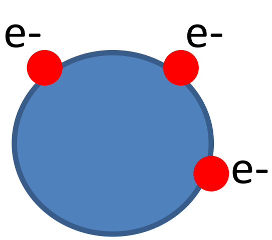
Magnetic noise



Fluctuating spins

->Apply magnetic field

Electric noise



Surface charges

?

Effect of electric noise?

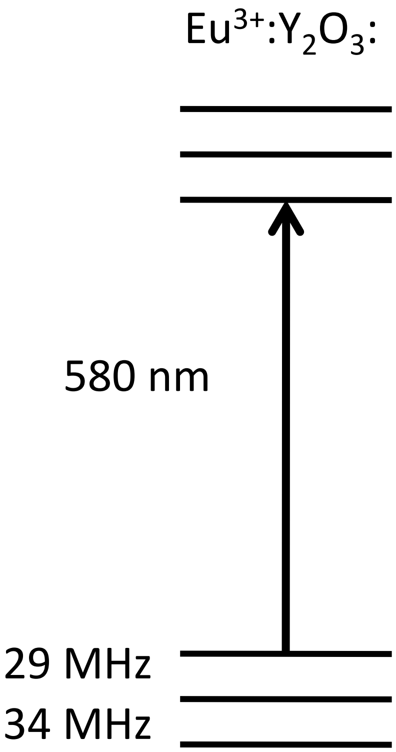
Optical transition:

Stark effect: 50 kHz/(V/cm)

Nuclear spin transition:

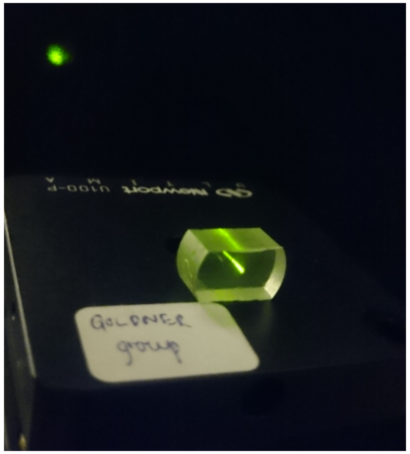
Change in electric field gradient: 1 Hz/(V/cm)

Very low!



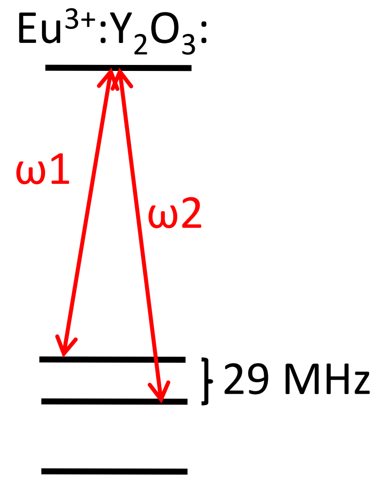
The spin transition should be much less sensitive to electric noise!

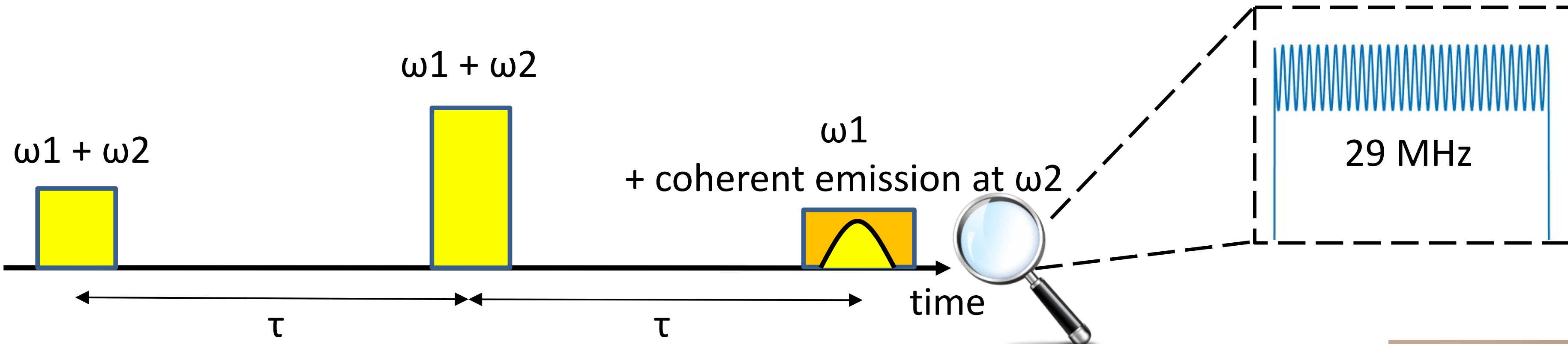
All-optical spin echo



Ceramic synthesized
by Dr. Akio Ikesue
World Lab Co. Japan

Optical T_2 = 42 μs
~Bulk value/10

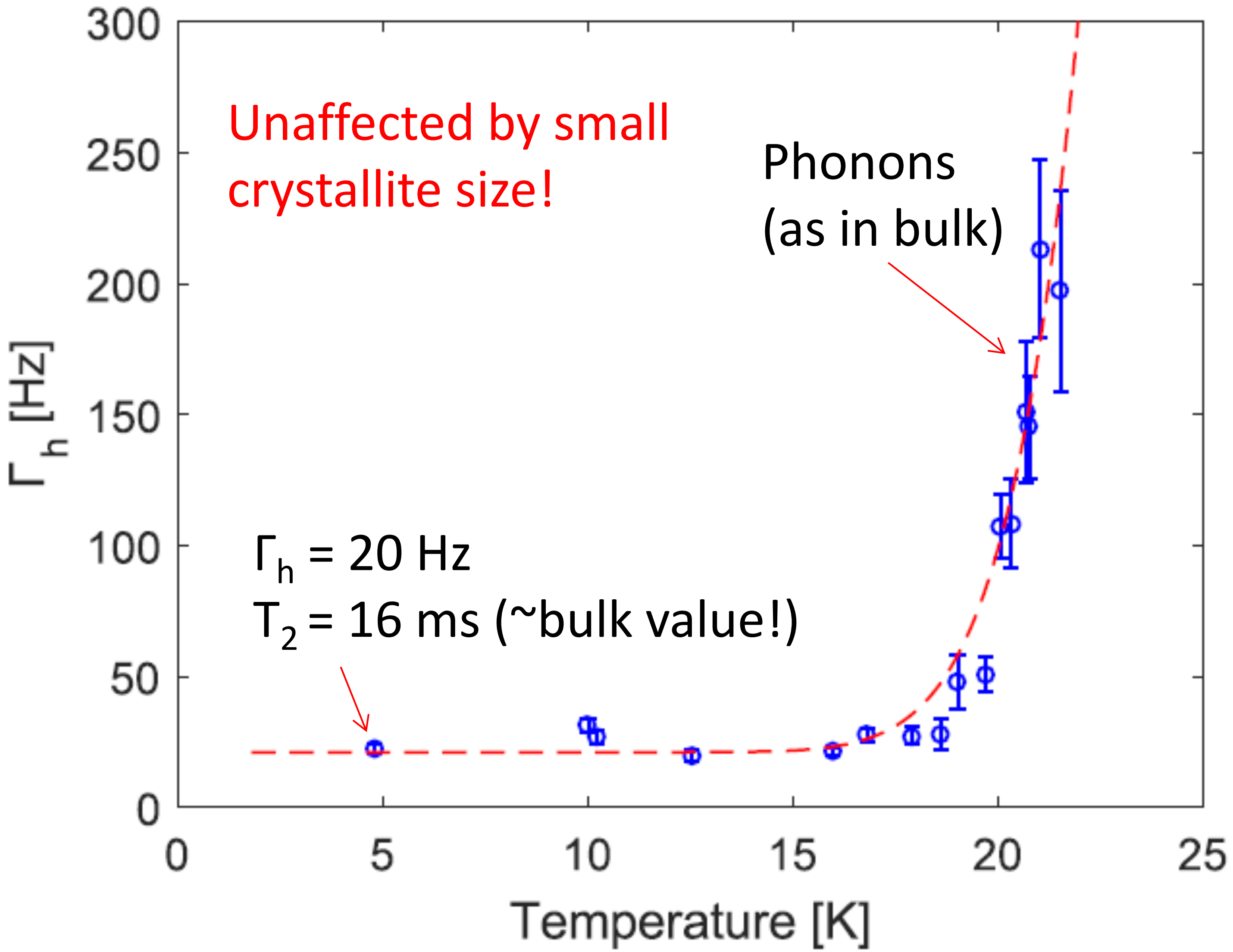




J. of Phys.: Condens. Matt., *In Press*

Jenny Karlsson

Nuclear spin coherence time



J. of Phys.: Condens. Matt., *In Press*

Conclusion

- Record optical coherence time for sub-micron solid state system
  ..not limited by size -> we might improve!

- Spin coherence time in a ceramic sample is unaffected by the small crystallite size

- Additional noise is likely to be electric, possibly due to surface charge.

NanOQTech

www.nanoqtech.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 712721.

The group:

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Jenny Karlsson, John Bartholomew, Nathalie Kunkel, Karmel de Oliveira Lima,
Sacha Welinski, Alexandre Fossati, Marion Scarafagio

Thank you for listening!