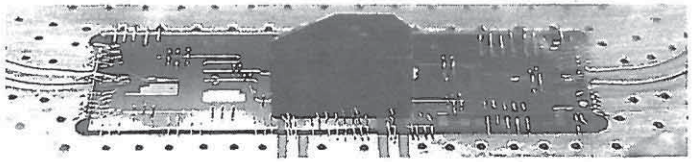
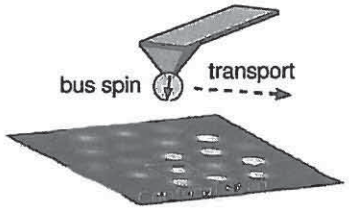
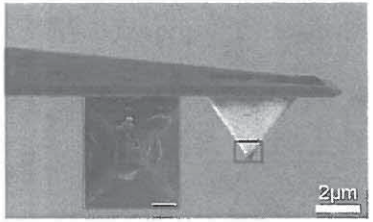


chist-era

Quantum Information With NV Centers (QINVC)

P. Bertet, CEA Saclay (France)





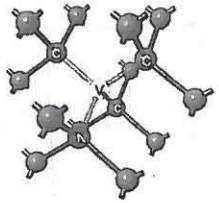
Outline

1) **Introduction : Quantum information with NV centers in diamond**

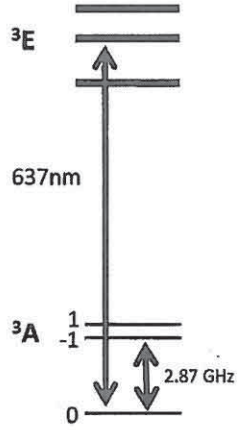
2) **QINVC : content, goals and organization**

3) **Latest progress : coupling NV centers to a superconducting qubit**

The NV center in diamond



- Joint defect consisting of
  - Vacancy
  - Neighbouring substitutional N
- Spin 1 ground state with « zero-field splitting » 2.87GHz



Spin properties

- Ground state is spin triplet, solid-state spin-qubit

Spin properties

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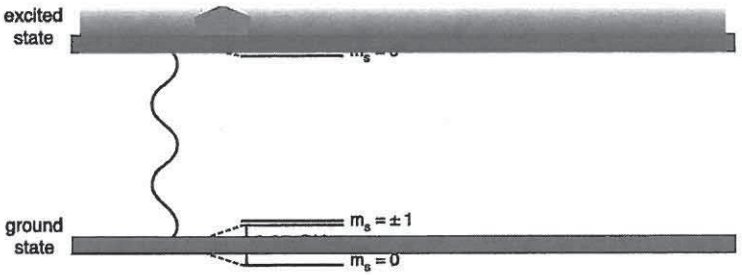

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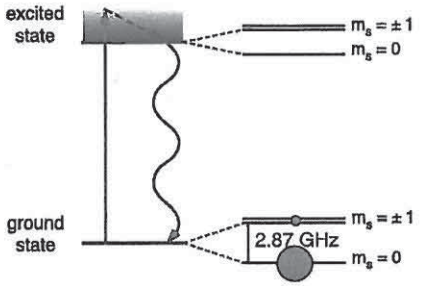

- Optical pumping leads to strong polarization in m_s=0

Spin properties

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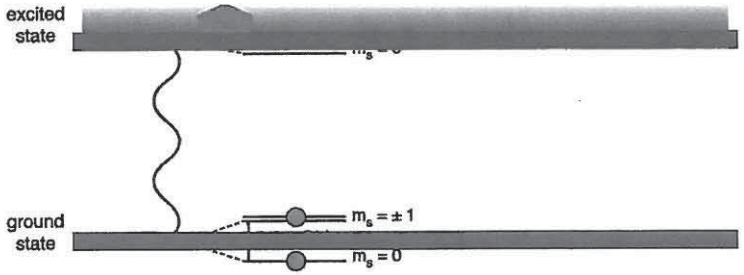

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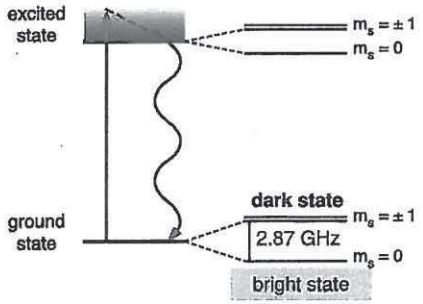
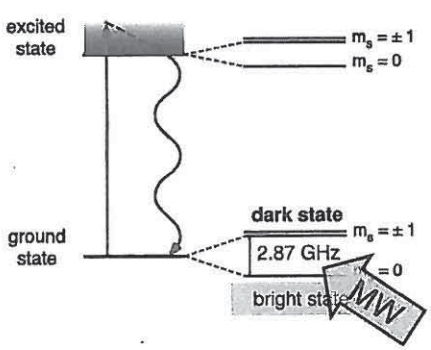
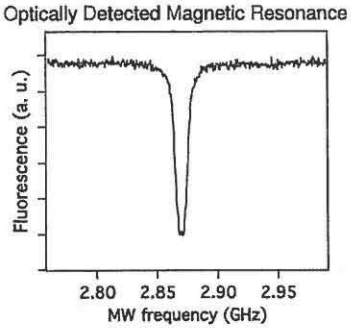


- Optical pumping leads to strong polarization in m_s=0
- Luminescence depends on the spin state

Spin properties

- Ground state is spin triplet, solid-state spin-qubit

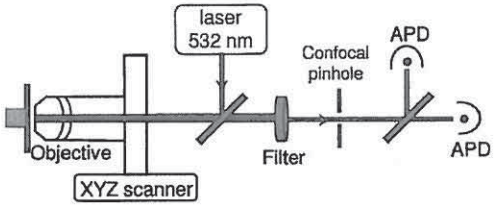




- Optical pumping leads to strong polarization in m_s=0
- Luminescence depends on the spin state

Experimental setup

- Confocal microscope at room temperature



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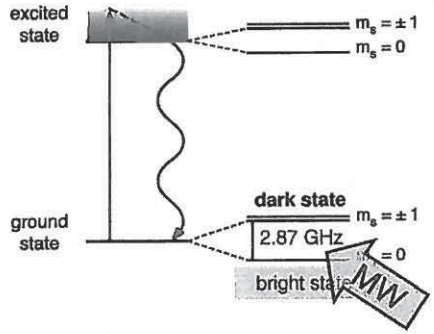

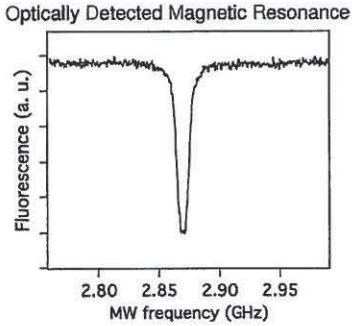

- Optical pumping leads to strong polarization in m_s=0
- Luminescence depends on the spin state

→ Optical detection of single spin state

Gruber et al., *Science* 276, 2012 (1997)

Experimental setup

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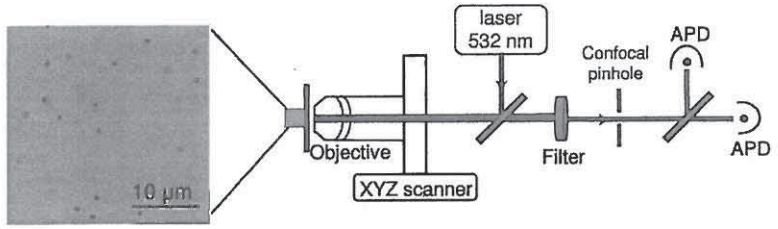
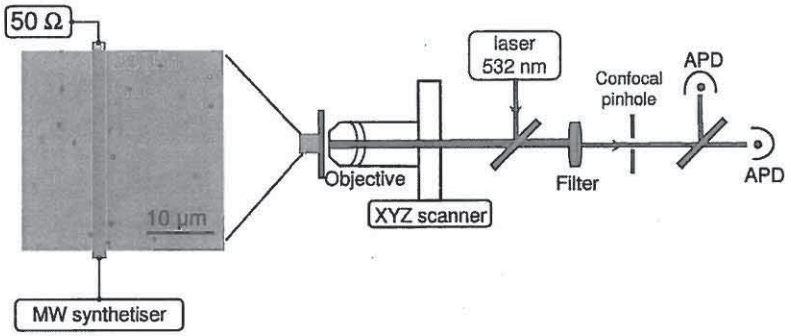


Experimental setup

- Confocal microscope + ODMR equipment working at room temperature



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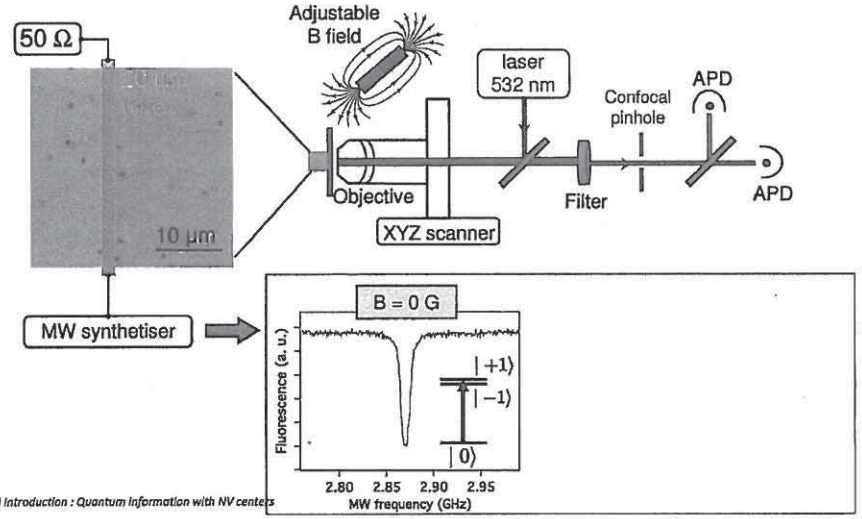

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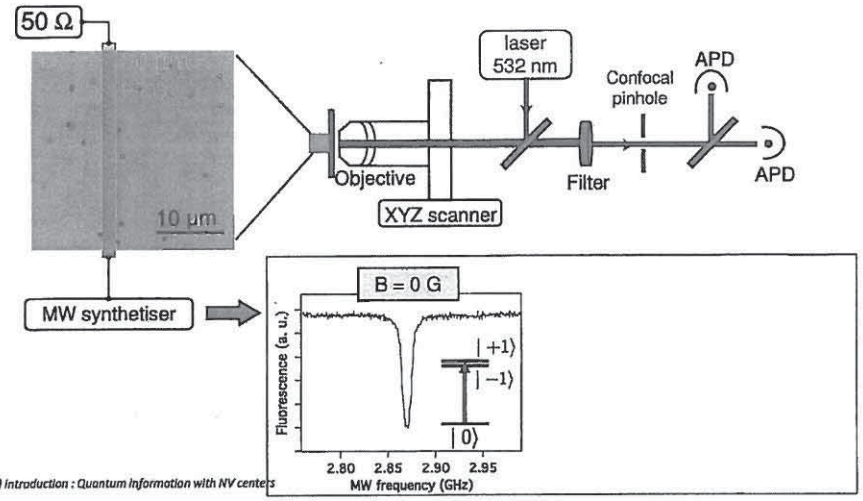

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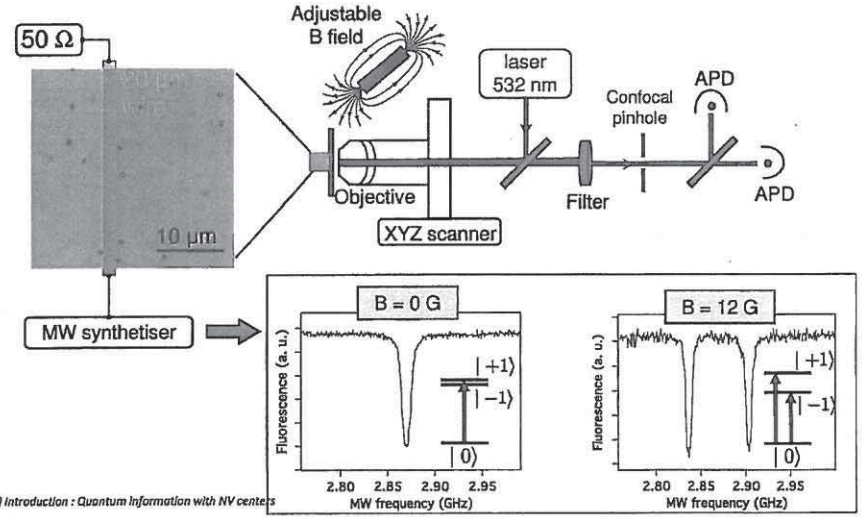
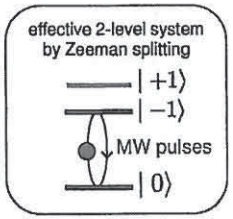


Coherent manipulation



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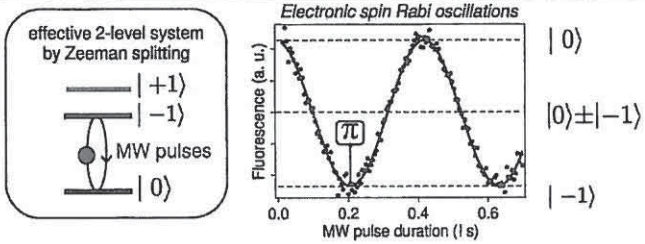
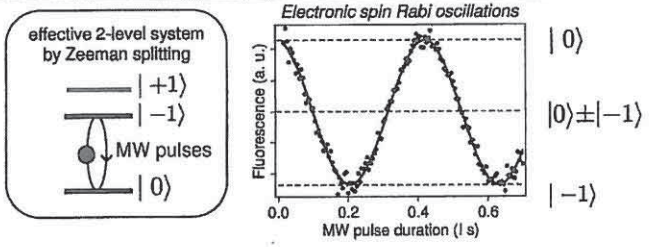
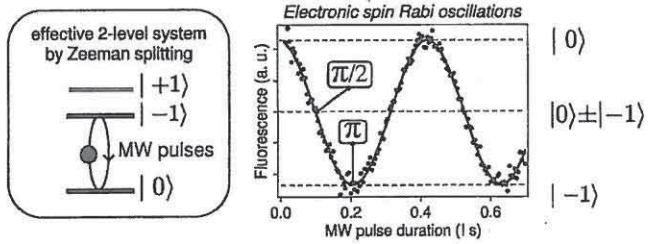


Coherent manipulation



Coherent manipulation



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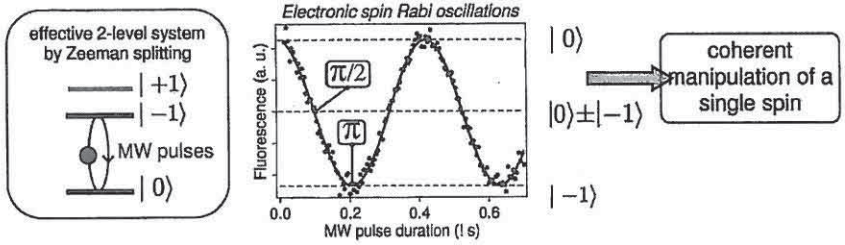

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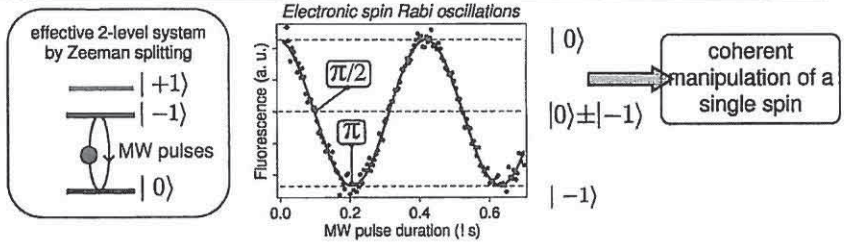
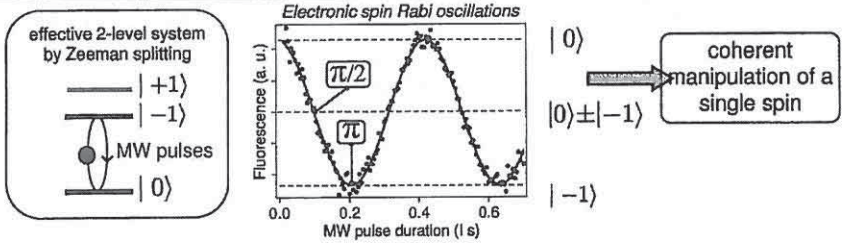


- NV center -> 2-level system
  - Initialization in state $|0\rangle$
  - Readout
  - Coherent manipulation

→ NV center as qu-bit

Coherent manipulation



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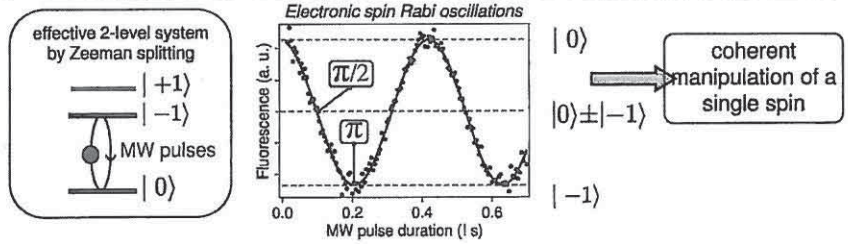

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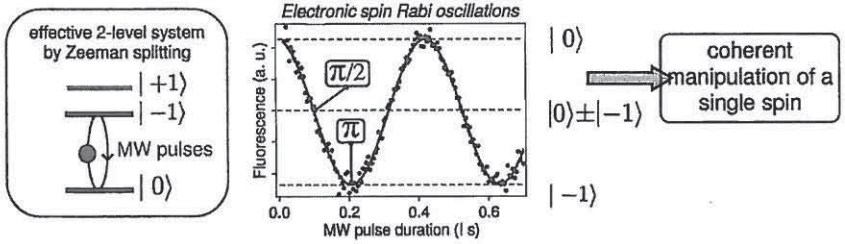
→ NV center as qu-bit

- Faster Rabi oscillations ~1 GHz → π_{pulse} ~1 ns

Fuchs et al. *Science* **326**, 1520 (2009)

Coherent manipulation



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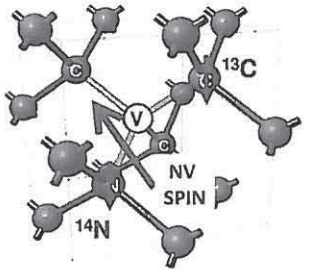
  G. Balasubramanian et al., *Nature Materials* **8**, 383 (2009)

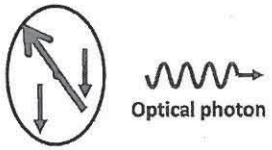
NV centers as quantum nodes



Additional resources for quantum information:

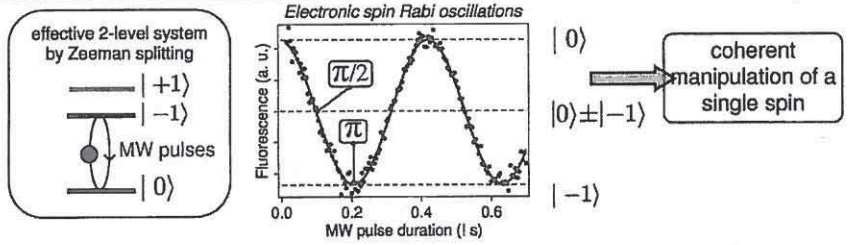
- HYPERFINE COUPLING TO ^{14}N and ^{13}C **NUCLEAR SPINS with LONG coherence times**

- **Coherent coupling with optical photons (narrow optical linewidth)**



Small-scale quantum processor

Coherent manipulation



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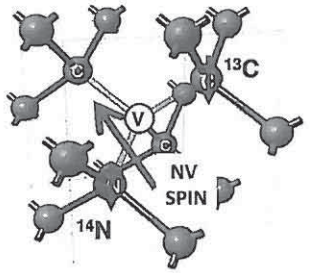
  G. Balasubramanian et al., *Nature Materials* **8**, 383 (2009)

→ **NV center = good qu-bit at room T**

NV centers as quantum nodes



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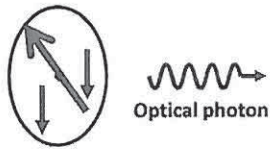


Small-scale quantum processor

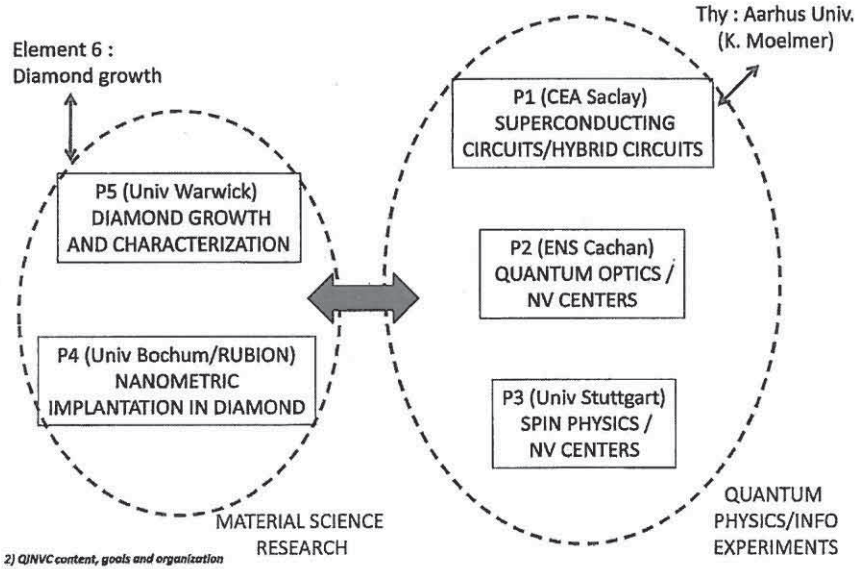
KEY ISSUE OF THE FIELD :

HOW TO ENTANGLE DISTANT NV CENTERS ?

QINVC project : HYBRID SYSTEMS

1) Introduction : Quantum information with NV centers

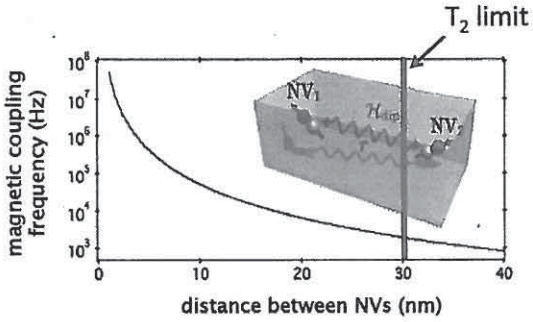
QINVC: a consortium with complementary expertise



QINVC objectives

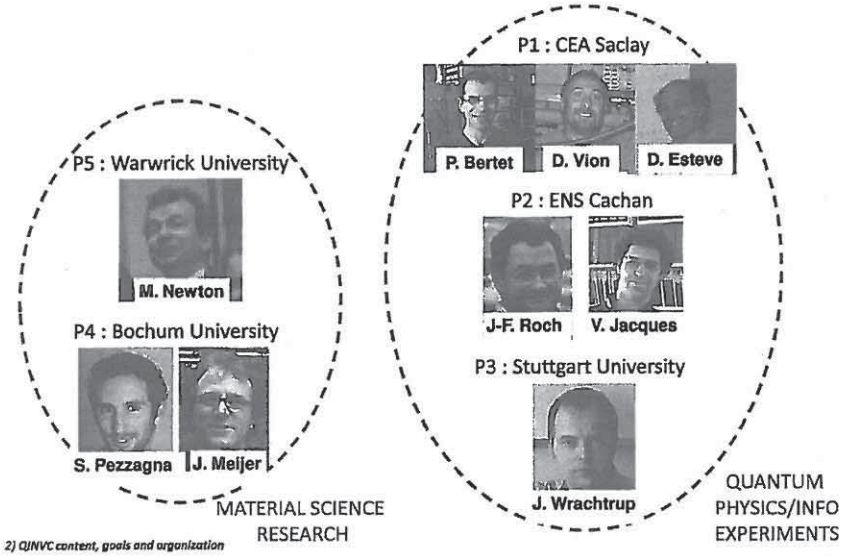
Two **hybrid** strategies to entangle distant NV centers

1st strategy : DIPOLE-DIPOLE COUPLING



Very challenging : SHORT-RANGE interaction ⟹ Precision requirement : **10nm**

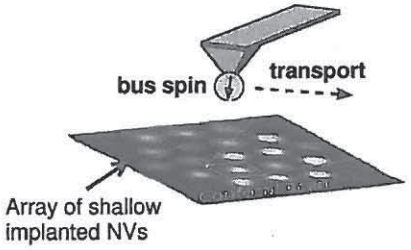
QINVC: Principal Investigators



QINVC objectives

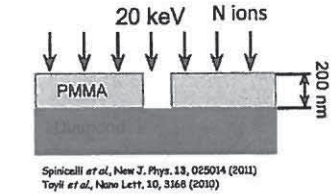
Two **hybrid** strategies to entangle distant NV centers

1st strategy : DIPOLE-DIPOLE COUPLING... COMBINED WITH **AFM QUANTUM BUS !**
(P3 + P4+P5)



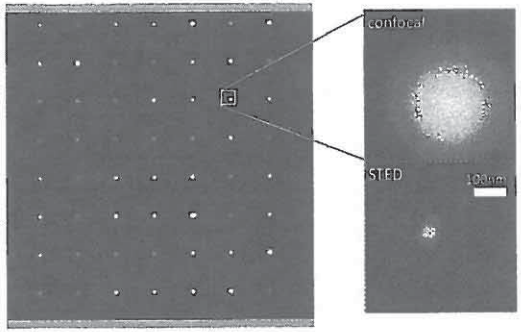
Advantages : - no need for a priori high-precision control of NV array
- would work with any spin species (optical readout by bus spin)

QINVC objectives



Spinicelli *et al.*, New J. Phys. 13, 025014 (2011)
Toyli *et al.*, Nano Lett. 10, 3168 (2010)

Array of shallow NVs at
Bochum university **(P4)**/ENS Cachan**(P2)**

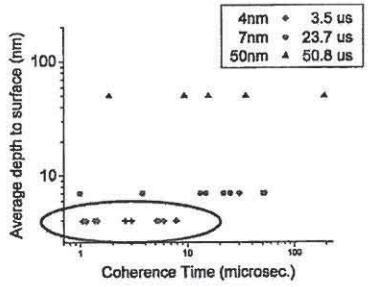


QINVC objectives

Two **hybrid** strategies to entangle distant NV centers

1st strategy : DIPOLE-DIPOLE COUPLING... COMBINED WITH **AFM QUANTUM BUS** !

Challenges : 1) Coherence times of shallow implanted NV centers ?



Required :
better understanding and characterization of NV centers implanted **close to a surface**

Surface passivation ?
Annealing ?
Implantation parameters ?
(P2+P3+P4+P5)

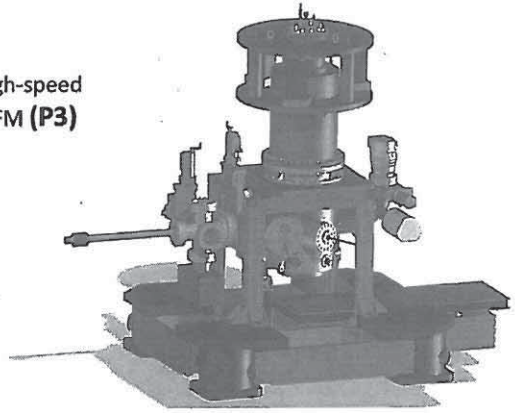
QINVC objectives

Two **hybrid** strategies to entangle distant NV centers

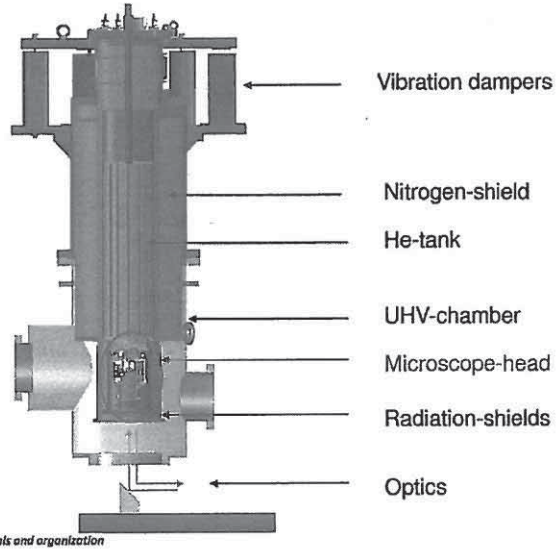
1st strategy : DIPOLE-DIPOLE COUPLING... COMBINED WITH **AFM QUANTUM BUS** !

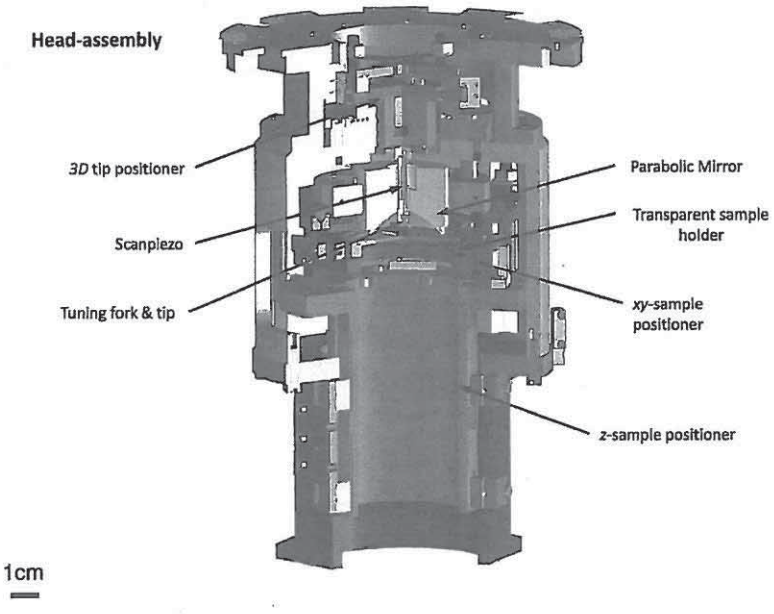
Challenges :

2) Building up a high-speed
+ high-precision AFM **(P3)**

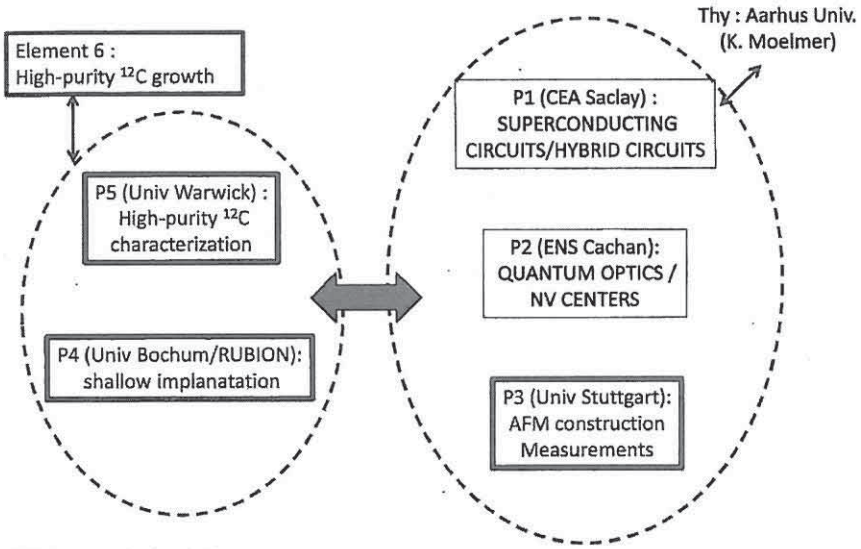


Cryogenic setup

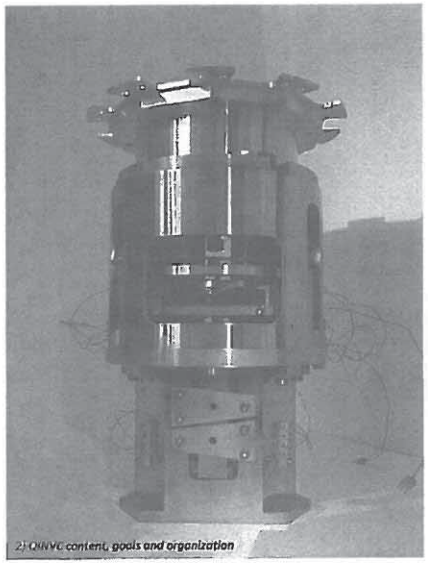




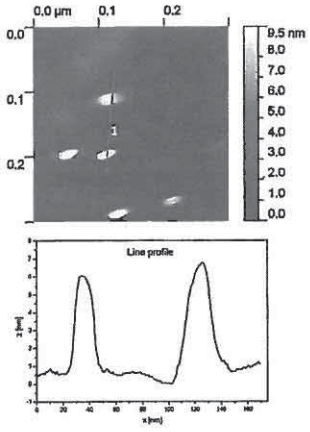
AFM project in QINVC



First AFM-images



InAs-quantum dots imaged under ambient conditions



QINVC objectives

Two **hybrid** strategies to entangle distant NV centers

2nd strategy : **coupling NV centers to superconducting circuits**

(P1+P2 +P5)

NV center spins in diamond

Microscopic degree of freedom

Long coherence times
Small couplings: **slow**
Problematic scalability

Superconducting qubits

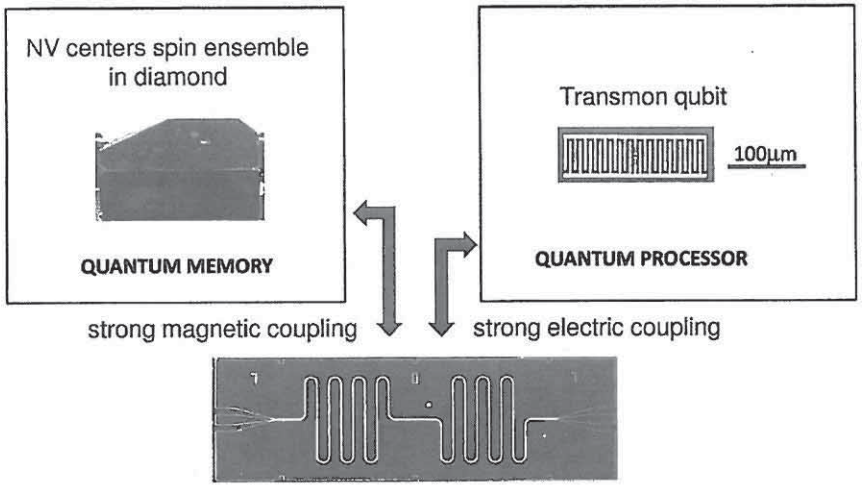
Collective degree of freedom

Short coherence times (µs)
Design flexibility, irreproducibility
Large couplings: **rapid** (10ns gates)
Potential scalability

- TAKE THE **BEST OF BOTH WORLDS** !
-DESIGN **NEW QUANTUM DEVICES WITH NEW FUNCTIONALITIES**
- SUPERCONDUCTING CIRCUITS MIGHT MEDIATE INTERACTION BTWN NV CENTERS

Coupling NV centers to superconducting circuits in QINVC

(P1+P2 +P5)

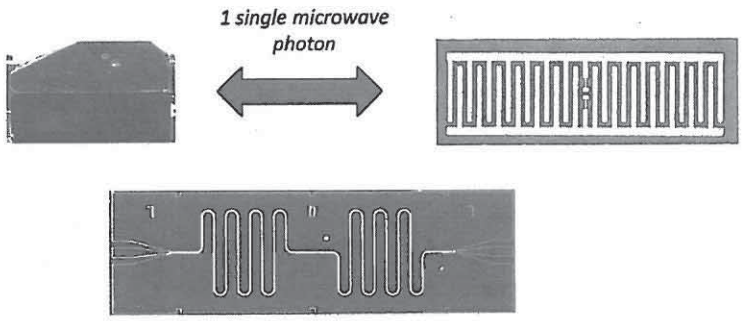


QUANTUM BUS: superconducting resonator

NV centers and superconducting circuits in QINVC

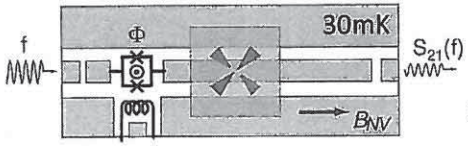
Towards a quantum memory for superconducting qubits in two steps

STEP 1



... already achieved at beginning of QINVC !

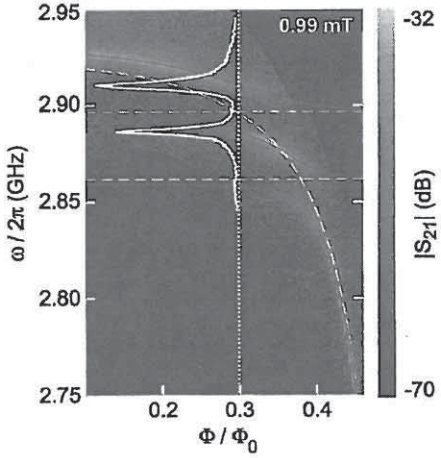
NV centers and superconducting circuits in QINVC : state of the art



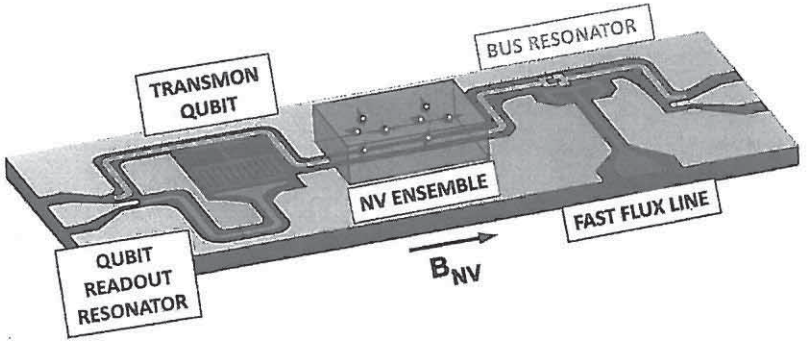
BEFORE QINVC :
STRONG COUPLING BETWEEN NV CENTER ENSEMBLE AND SUPERCONDUCTING RESONATOR (P1 + P2)

Y. Kubo *et al*, PRL **105**, 140502 (2010)

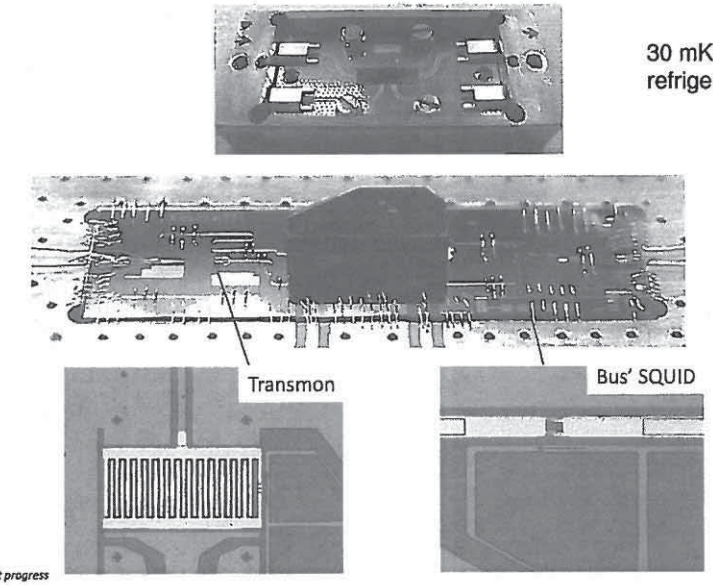
See also D. Schuster et al. PRL (2010)
R. Amsuss et al, PRL (2011)
P. Bushev et al., PRB (2011)



Sketch of the experiment

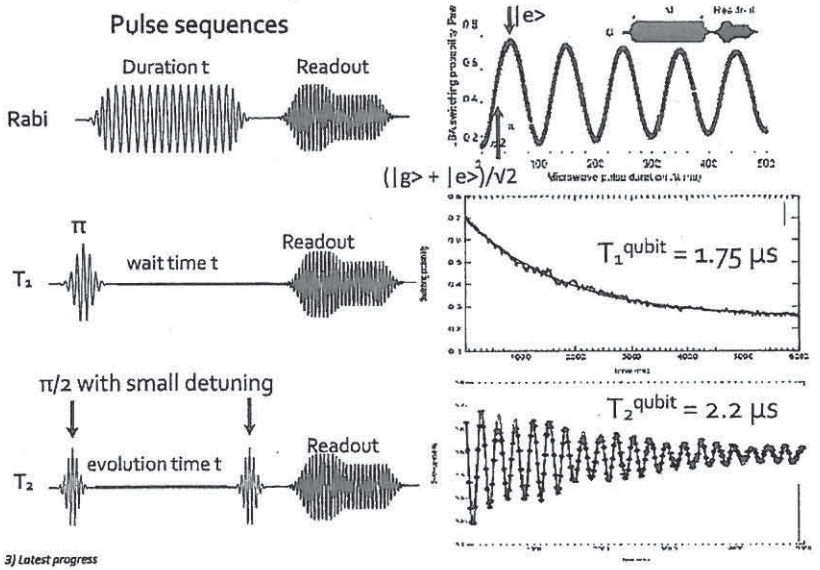


Coupling the spin ensemble to a transmon qubit: implementation



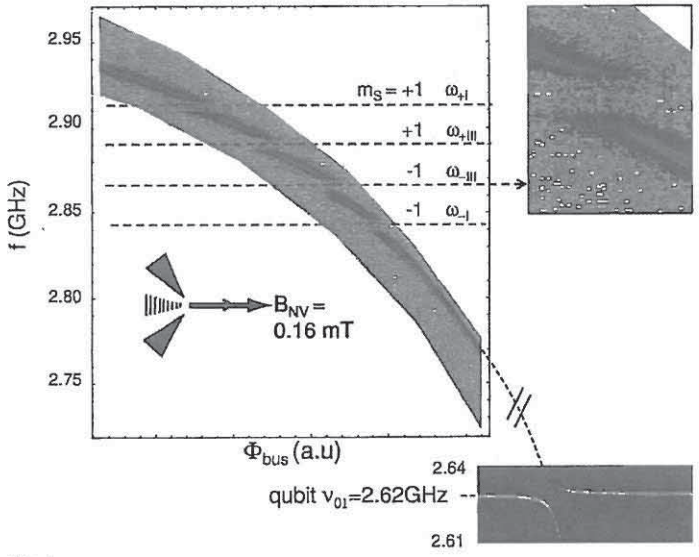
3) Latest progress

Qubit characterization



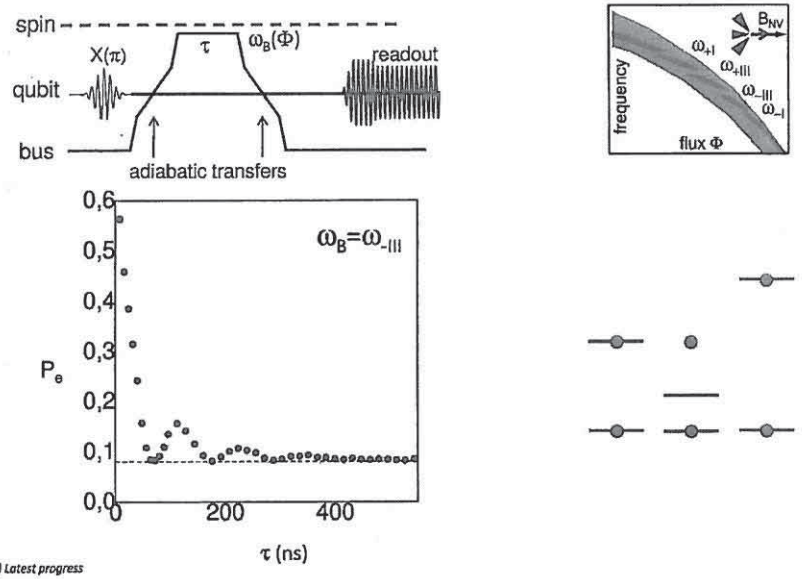
3) Latest progress

Spectroscopy of the full system (bus transmission)



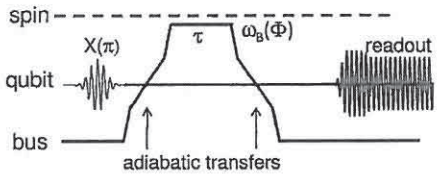
3) Latest progress

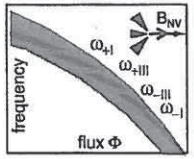
Storage and retrieval of a single excitation

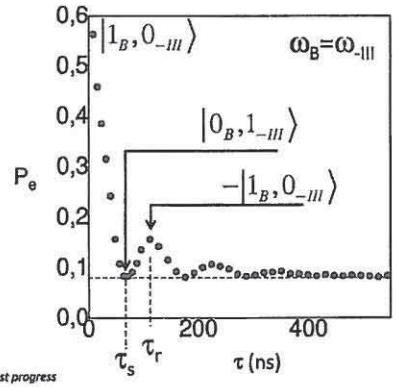


3) Latest progress

Storage and retrieval of a single excitation





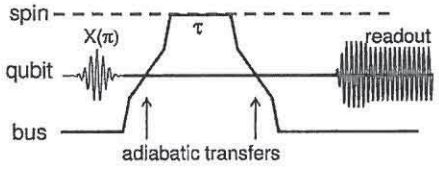


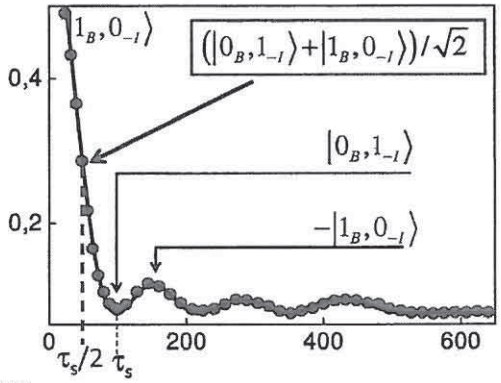
Storage and retrieval of a single microwave photon in a spin ensemble
First proof-of-principle of a quantum memory for qubits

Y. Kubo et al., PRL (2011)
see also Y. Zhu et al., Nature (2011)

3) Latest progress

Spin-photon entanglement

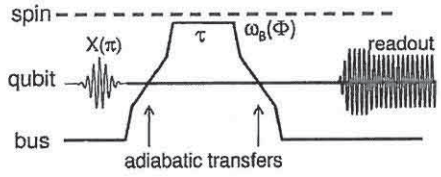


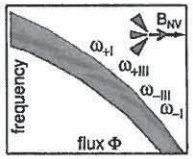


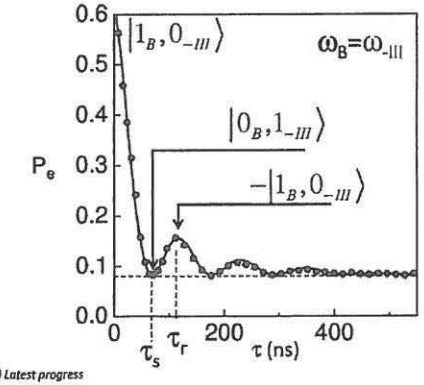
ENTANGLEMENT BETWEEN MICROWAVE RESONATOR AND SPIN ENSEMBLE ?

3) Latest progress

Storage and retrieval of a single excitation







Storage and retrieval of a single microwave photon in a spin ensemble
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Y. Kubo et al., PRL (2011)
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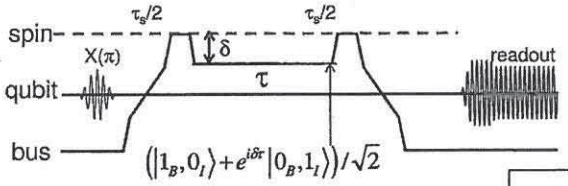
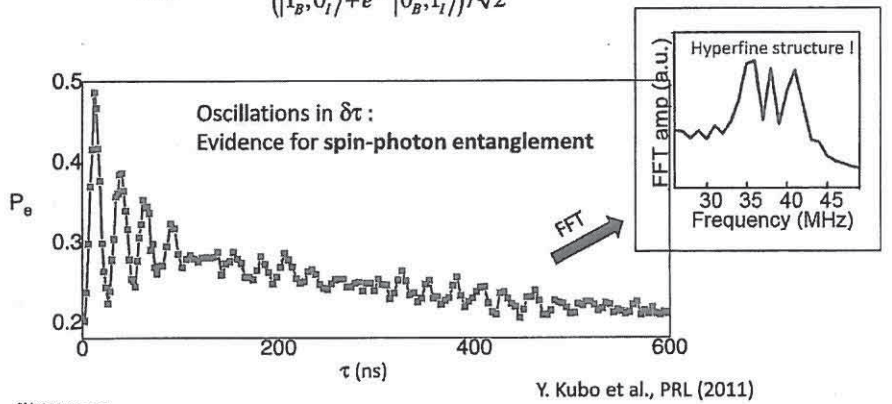
3) Latest progress

Spin-photon entanglement

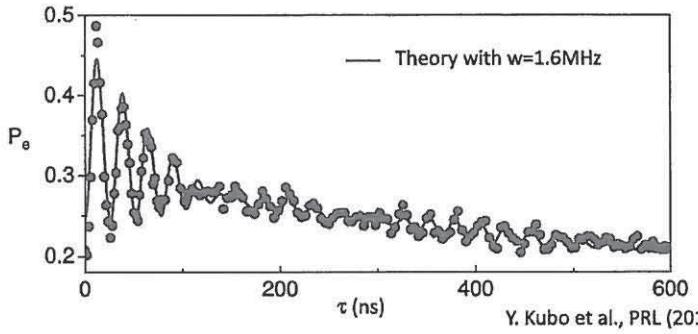




Y. Kubo et al., PRL (2011)

3) Latest progress

Discussion : coherence time, inhomogeneous broadening

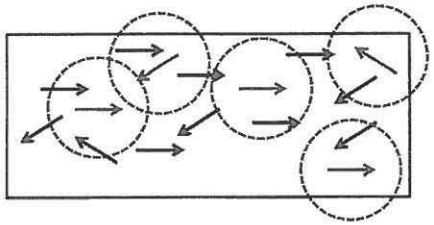


Storage time of coherence : □ $200ns$

Quantitative agreement with theory

⟹ Limited by **inhomogeneous broadening of spin ensemble**

Discussion : coherence time, inhomogeneous broadening

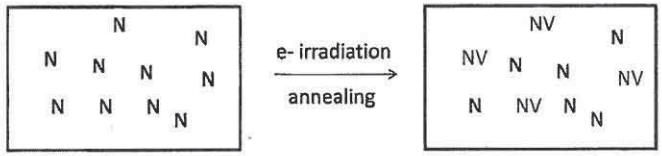


Local magnetic environment of NV ?

1) Paramagnetic impurities
(mostly neutral **Nitrogen** « P1 centers »)
2) Other NV centers. At low temperatures they are polarized in m_S=0
⟶ No contribution to dipolar broad.

INHOMOGENEOUS BROADENING MOSTLY CAUSED BY NITROGEN IMPURITIES

Problem : NV centers production

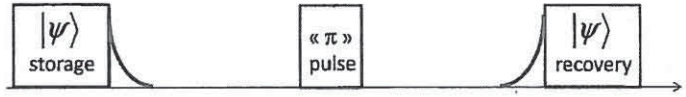


⟹ **P4 : study irradiation optimal condition for full conversion from N to NV**

NV centers and superconducting circuits in QINVC

Towards a quantum memory for superconducting qubits in **two steps**

STEP 2 : USE REFOCUSING TECHNIQUES

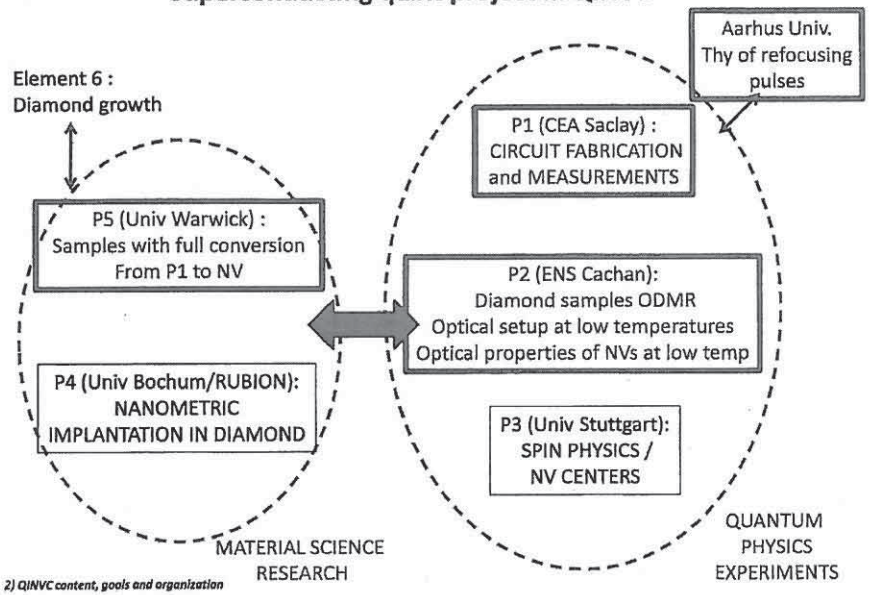


Interest : 1) increase storage time up to **milliseconds**
2) intrinsically multi-mode memory

Challenges : - combine **high-power refocusing pulses**
with **quantum state manipulation at single-photon level**

- use **optical irradiation** (collab with **P2**) to repump spins in m_S=0

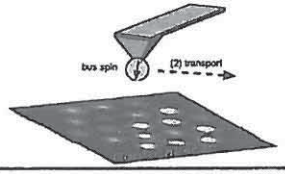
Superconducting qubit project in QINVC



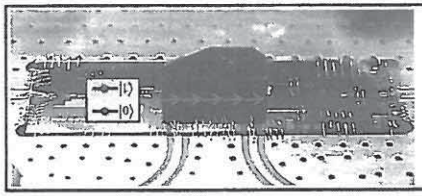
Conclusion

NV centers : **unique properties** for Quantum Information

QINVC : Two challenging main research directions, both relying on significant breakthroughs in material science

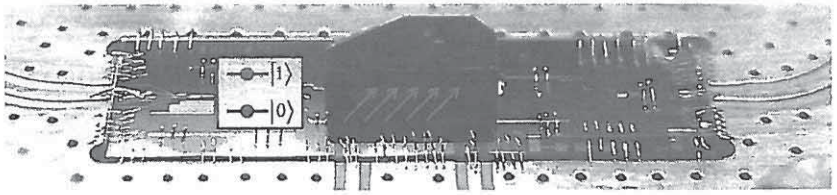


AFM PROJECT
-Building up low-temperature setup in progress
- Progress on understanding
shallow implanted spin properties



SUPERCONDUCTING QUBIT PROJECT
- First project step passed
(proof-of-principle for quantum memory)
-Remaining challenges :
spin ensemble refocusing
Optical irradiation at 30mK

Conclusions and Perspectives



- **First hybrid quantum circuit** with a **superconducting qubit** coherently coupled to an ensemble of NV centers in diamond (first step towards quantum memory for μw photons)
- **Storage and retrieval of quantum information** (superposed state)
- **Entanglement between spin ensemble and resonator**

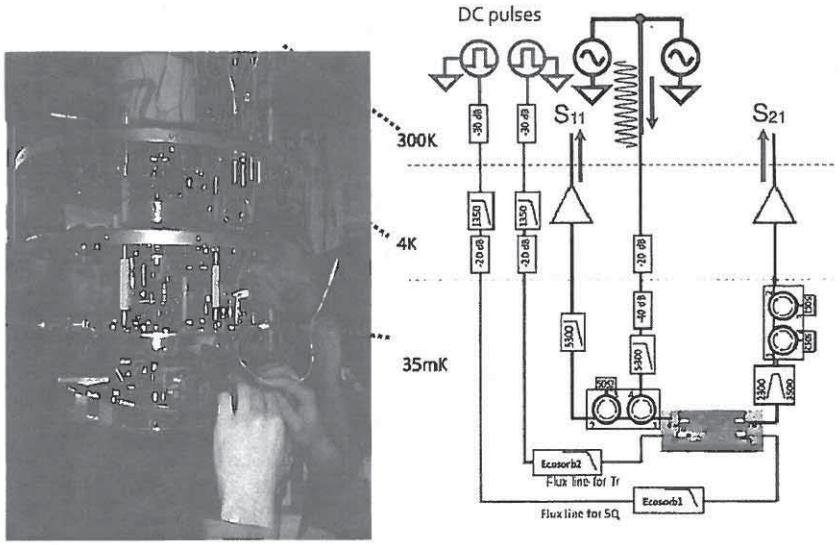
but **low fidelity (20%)** due to ***too small coupling constant*** and ***inhomogeneous broadening*** of the spins

⟶ ***Need samples with lower Nitrogen residual concentration***

⟶ ***Refocusing coherence in the spin ensemble with spin-echo techniques***

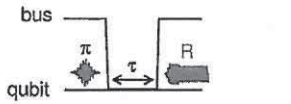
NV centers and superconducting circuits in QINVC

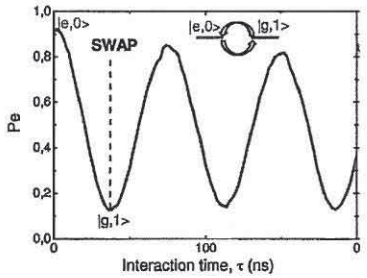
Experimental setup



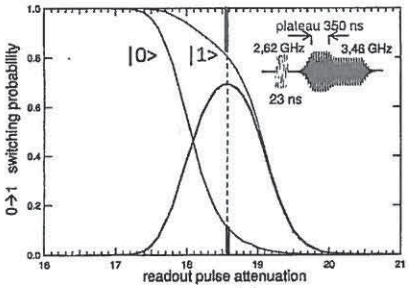
Transmon and quantum bus interaction : the SWAP gate

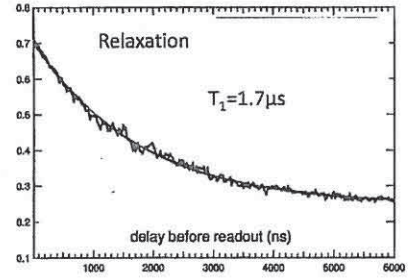
Resonant SWAP gate

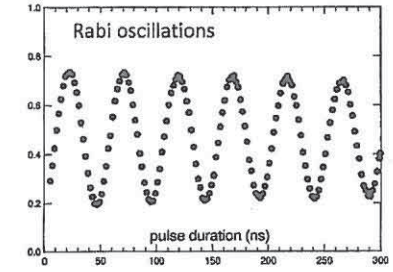


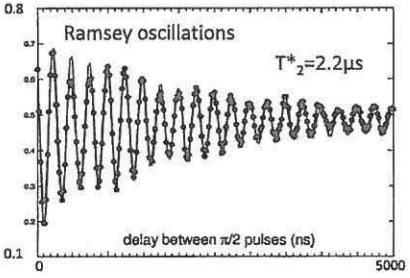


Characterization of the transmon and its readout



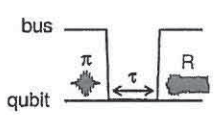




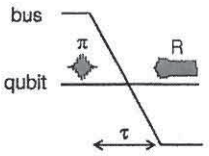


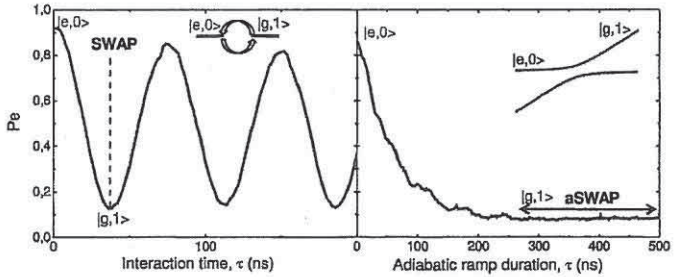
Transmon and quantum bus interaction : the SWAP gate

Resonant SWAP gate

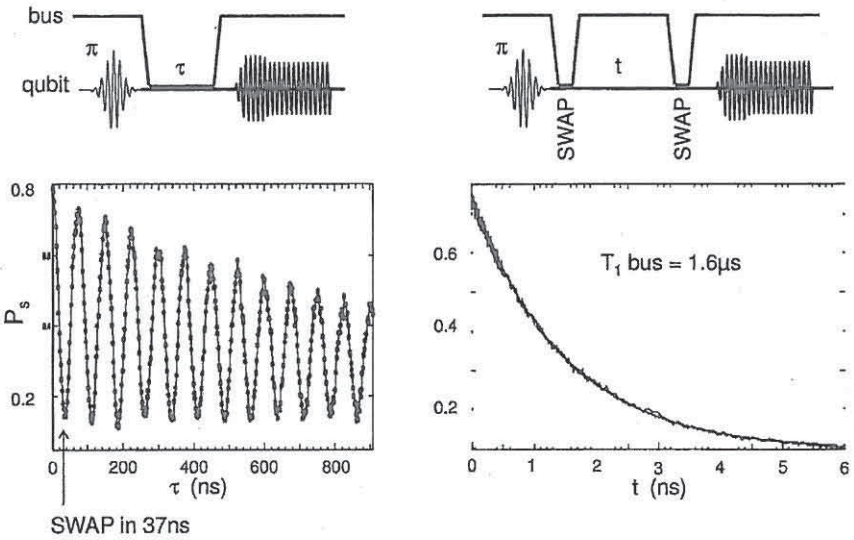


Adiabatic SWAP gate

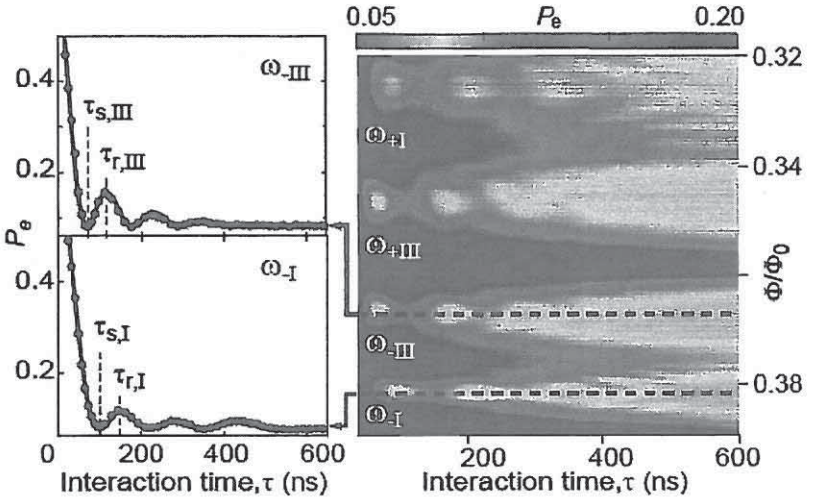




Transmon and quantum bus interaction

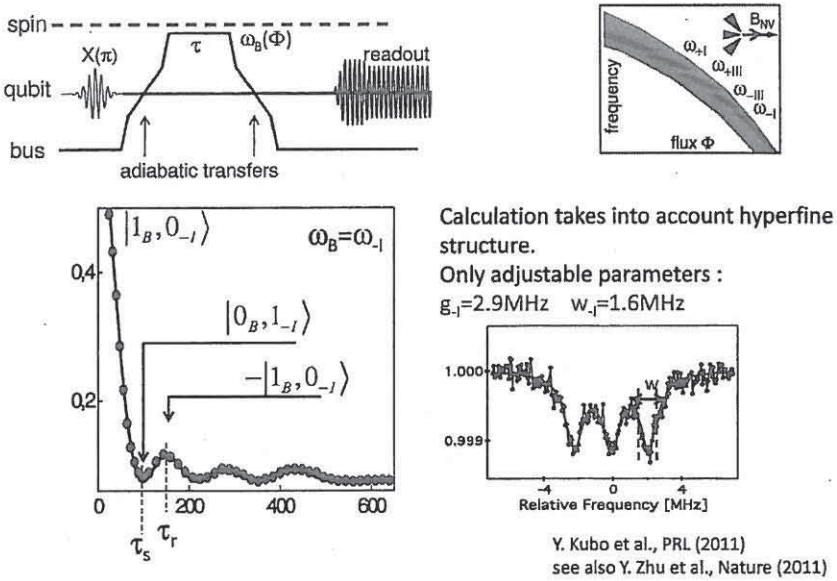


Storage and retrieval of a single excitation



Y. Kubo et al., PRL (2011)

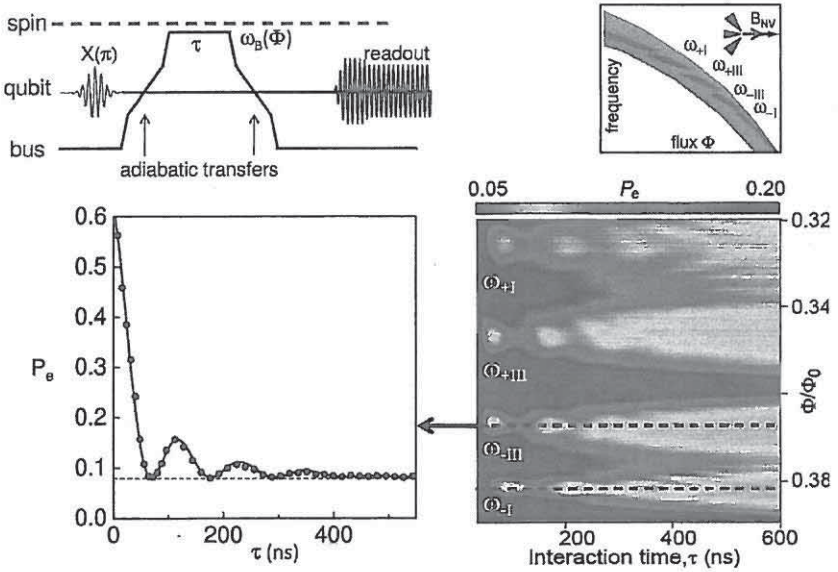
Storage and retrieval of a single excitation



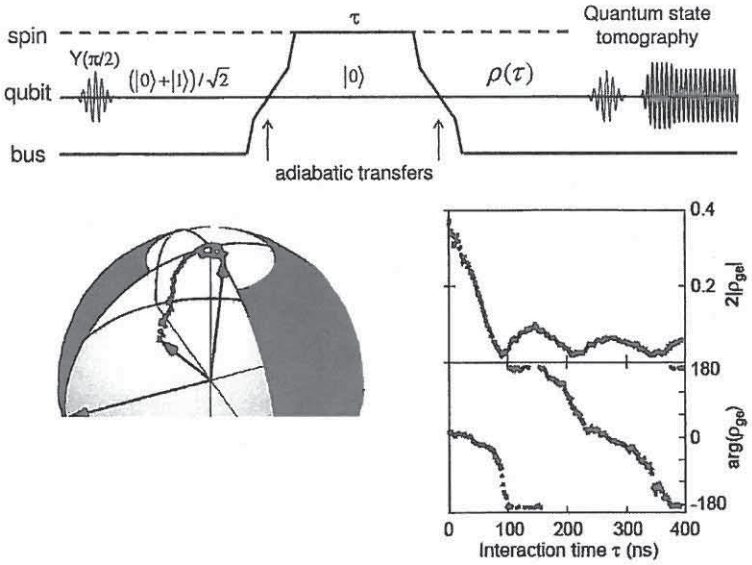
Calculation takes into account hyperfine structure.
Only adjustable parameters :
g_{-I}=2.9MHz w_{-I}=1.6MHz

Y. Kubo et al., PRL (2011)
see also Y. Zhu et al., Nature (2011)

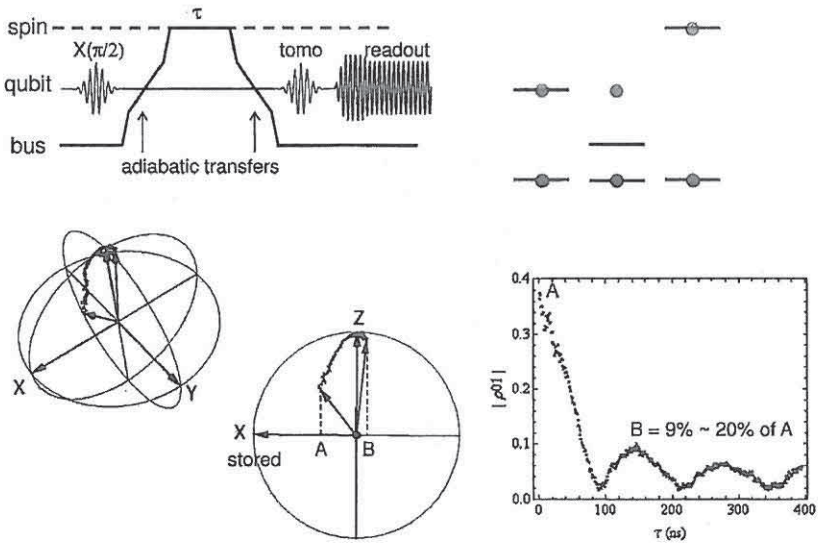
Storage and retrieval of a single excitation



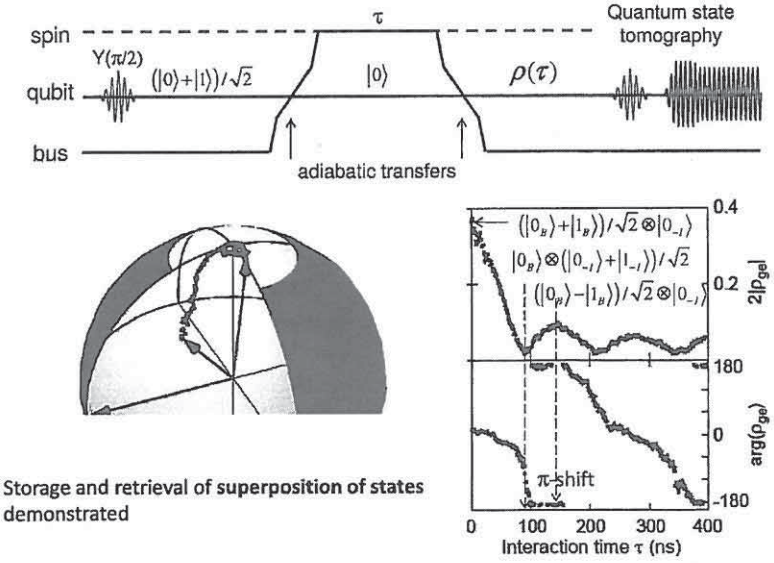
Storage and retrieval of quantum coherence ?



Storage and retrieval of quantum information ?



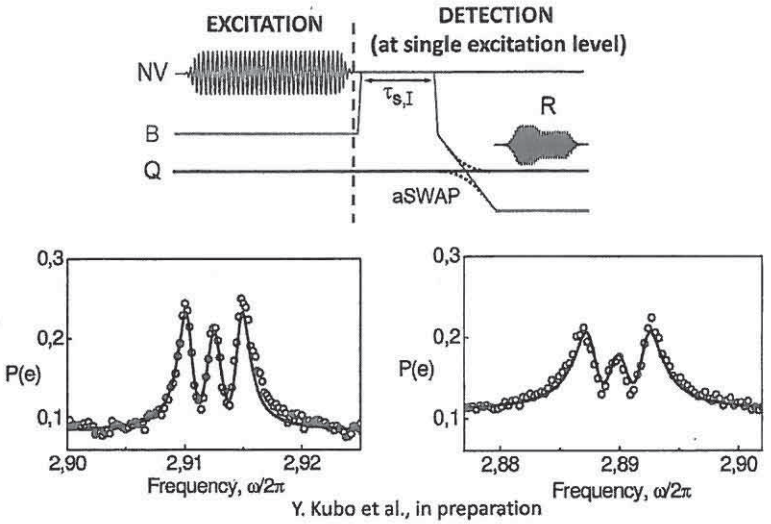
Storage and retrieval of quantum coherence ?



Storage and retrieval of **superposition of states** demonstrated

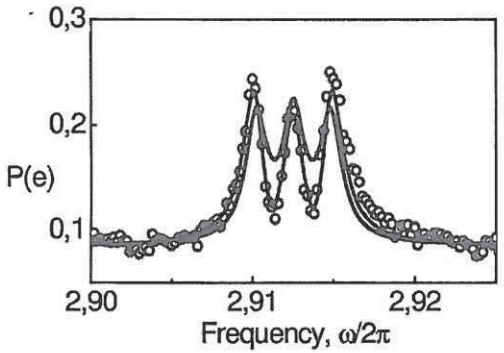
Using the qubit to detect the NV ESR at the single-excitation level

More direct way to study the NV centers spectrum :



Y. Kubo et al., in preparation

Using the qubit to detect the NV ESR at the single-photon level



— Spin distribution taken in the theory

— Result of calculation

⇨ Slight deformation of the ESR spectrum due to spins-resonator interaction. Would vanish with larger coupling constant

QINVC: a consortium with complementary expertise

Partner 1 : Quantronics Group (CEA Saclay, France)
PI : P. Bertet, D. Vion, D. Esteve

Expertise : superconducting quantum circuits, mesoscopic physics, hybrid systems

Partner 2 : ENS Cachan, France
PI : V. Jacques, J.-F. Roch

Expertise : **quantum optics**, optical and spin properties of NV centers at 300K and 4K

Partner 3 : Stuttgart University (Germany)
PI : F. Reinhardt, J. Wrachtrup

Expertise : **spin physics**, optical and spin properties of NV centers at 300K and 4K

QINVC: a consortium with complementary expertise

Partner 4 : University of Bochum / RUBION
PI : J. Meijer, S. Pezzagna

Expertise : **implantation** of nitrogen ions with nanometer precision

Partner 5 : University of Warwick
PI : M. Newton

World-leading expertise in **diamond crystal growth** (link with Element 6) and **characterization** (ESR, ...)