Swiss Photonics – Photonics 4 Quantum

Quantum Photonics with microcavities: erasing a solid-state emitter's flaws

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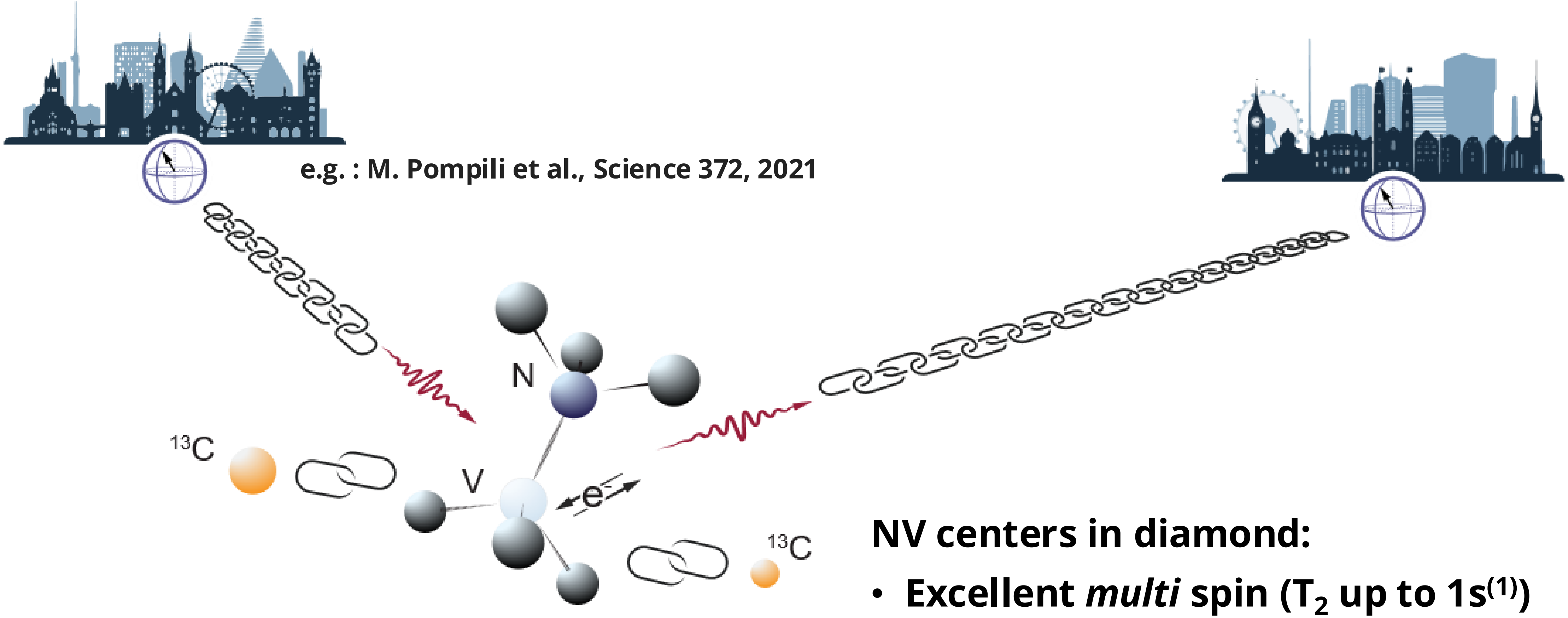
Bridging the distance (slowly)



e.g. : M. Pompili et al., Science 372, 2021

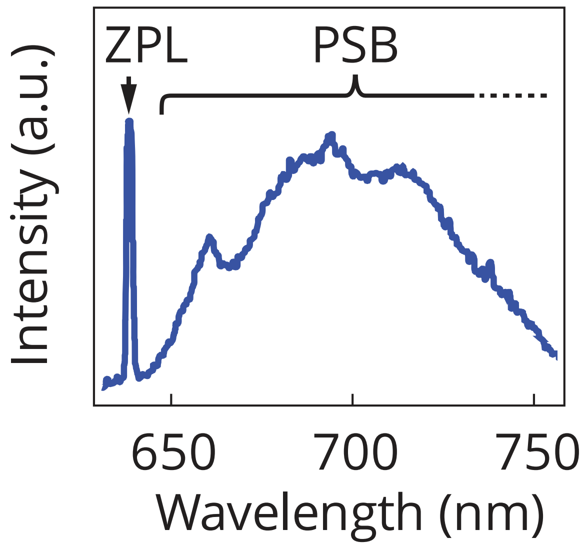
NV centers in diamond:

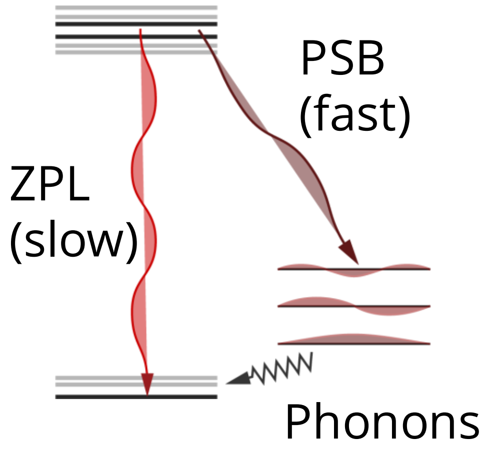
- **Excellent *multi* spin (T_2 up to 1s[1])**
- **Existing optical transitions**

[1] **Abobeih et al. Nat. Comm. 9 (2018)**

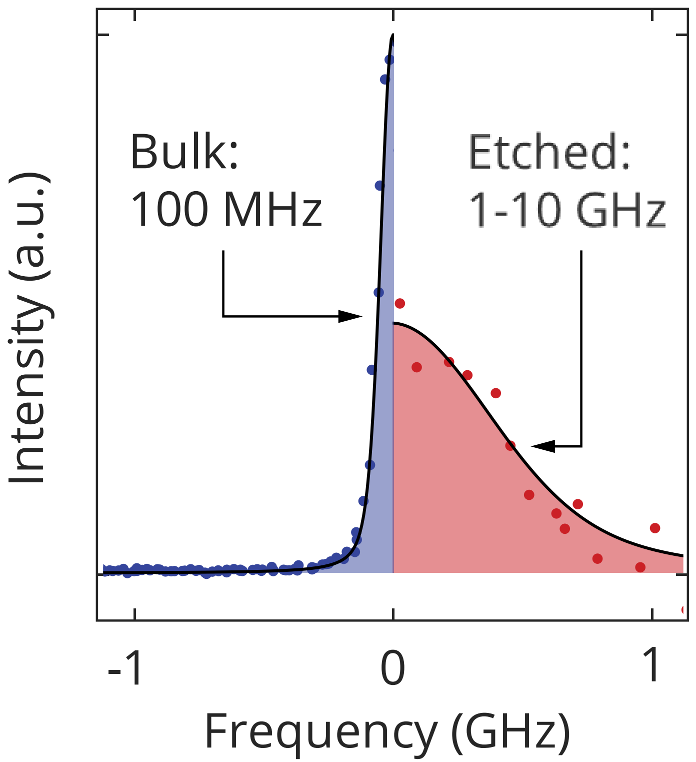
NV$^-$ challenges: game over ?

- Weak ZPL oscillator strength
- Only 3% of coherent photons (ξ_0)



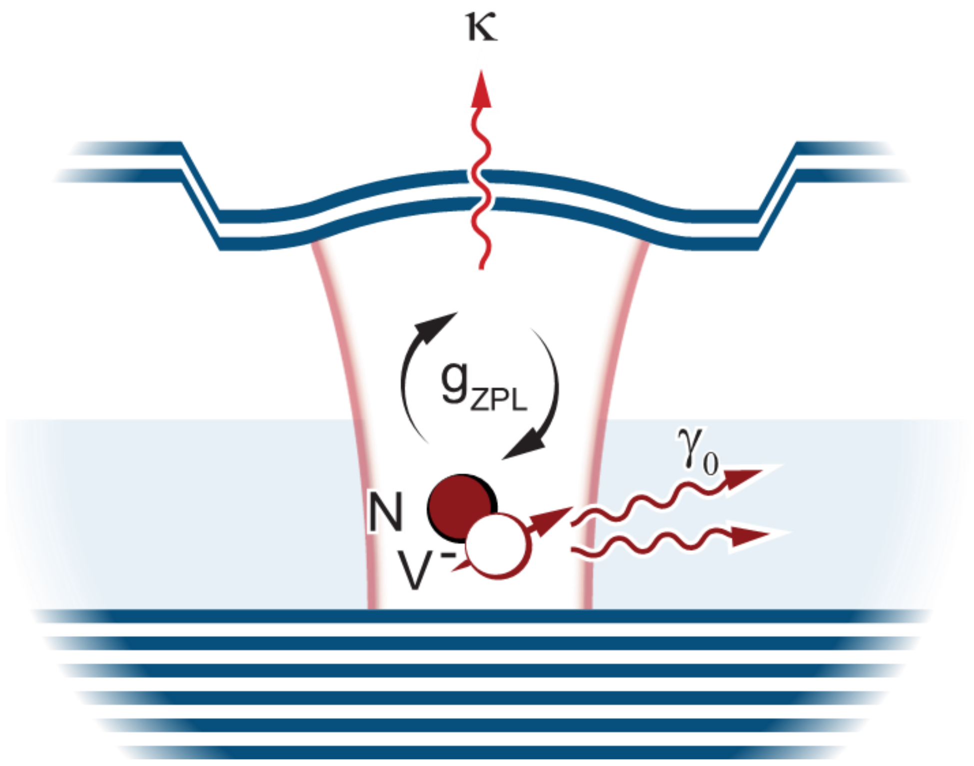


- Extreme sensitivity to charge noise[(1)]



[(1)] **Yurgens et al. APL 121 (2022)**

The Fabry-Pérot microcavity



(1) Riedel *et al.*, PRX 7, 2017
(2) Janitz *et al.*, *Phys. Rev. A, 2015*
(3) Tomm *et al.*, Nat. Nano. 16, 2021

- Maximally tunable
- Minimally processed

Modest "total" Purcell factor…

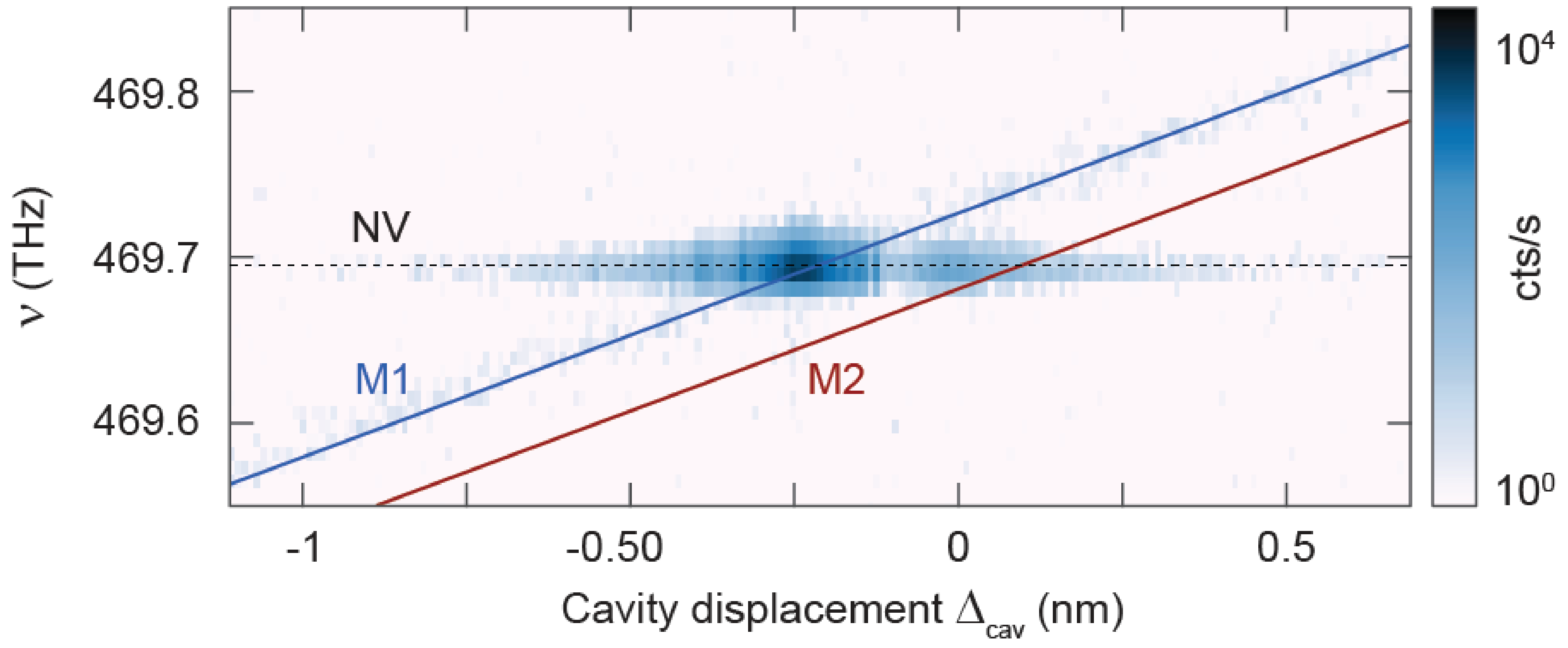
$$F_P^{total} = 1 + \frac{4g_{ZPL}^2}{\kappa\gamma_{NV}}$$

…. But meaningful outcomes

$$\xi_{cav} = \frac{F_P^{total} - 1 + \xi_0}{F_P^{total}} \approx \beta$$

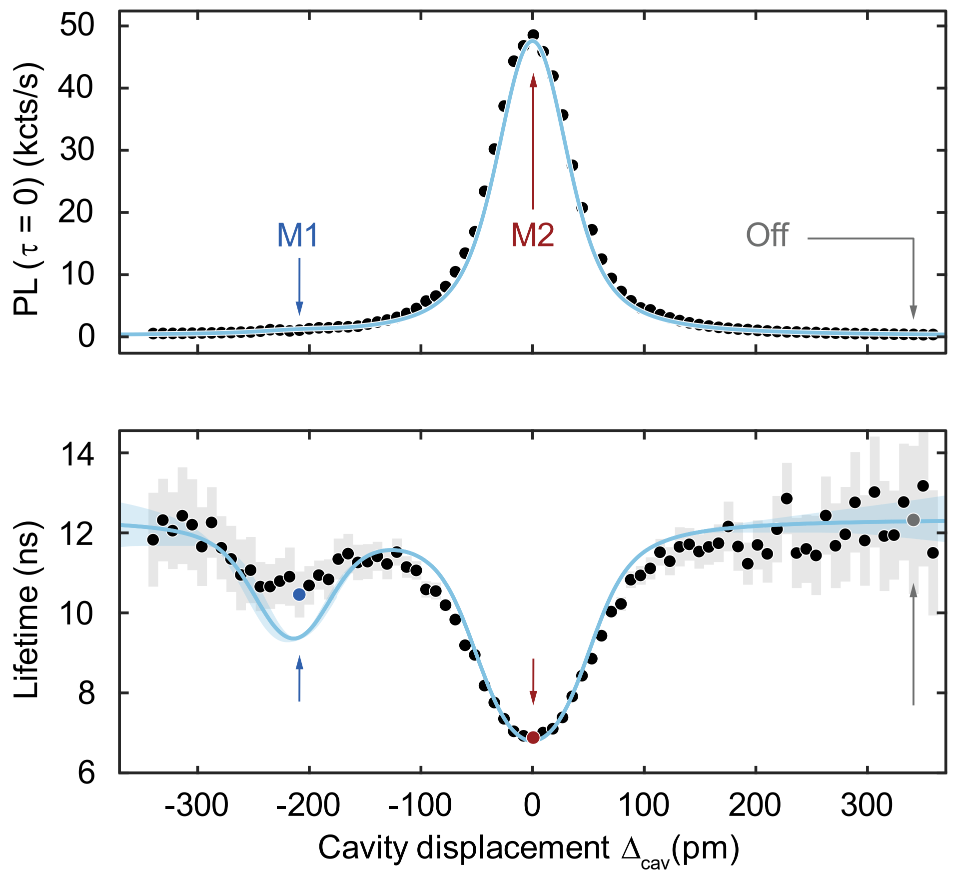
A single coupled NV$^-$...

- Birefringence induced mode splitting
- Selective mode / transition coupling



…in the Purcell regime

- Single NV selective coupling to TEM00 modes (F ~ 4500)



For M2:

$$F_P^{total} = 1.79(1)$$

$$\{g_{zpl}, \kappa, \gamma_0\} = 2\pi\,\{167, 1.1 \cdot 10^4, 12.89\}\ \mathrm{MHz}$$

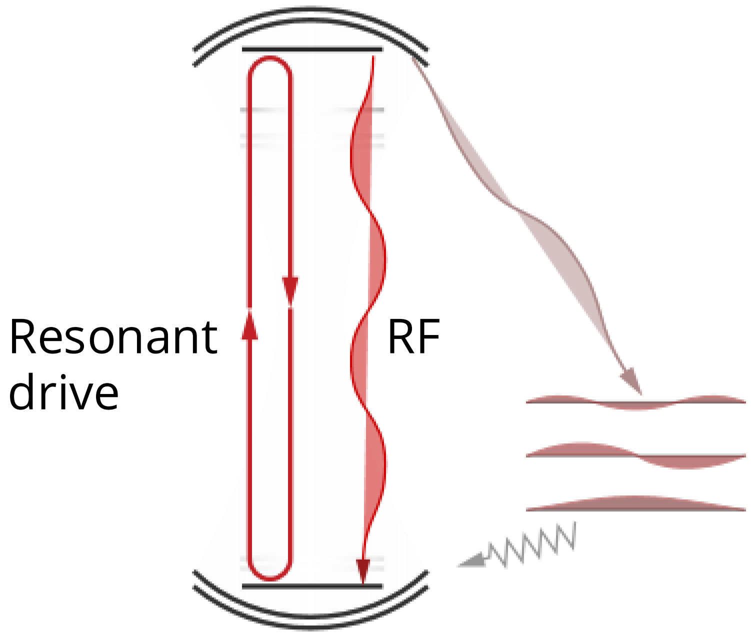
Consequences:

- 44% of emitted photons are coherent (vs 3%)
- At threshold of cooperativity 1

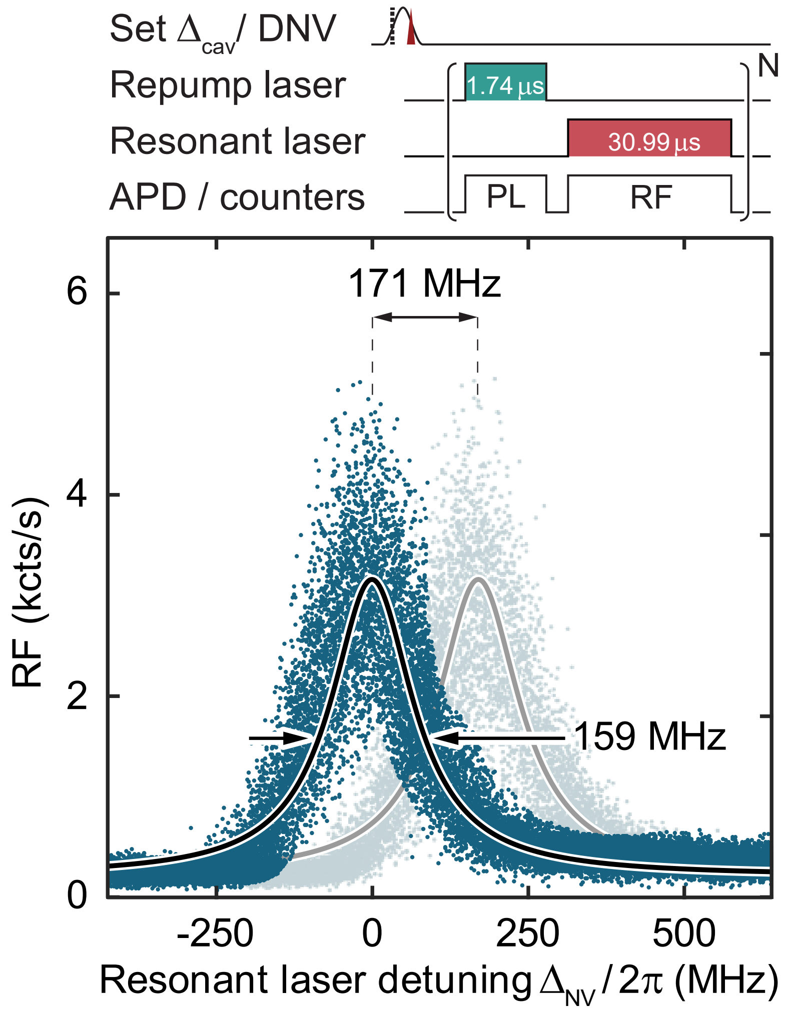
Cavity-assisted resonance fluorescence

- Signal increased by Purcell effect
- Resonant drive boosted by cavity

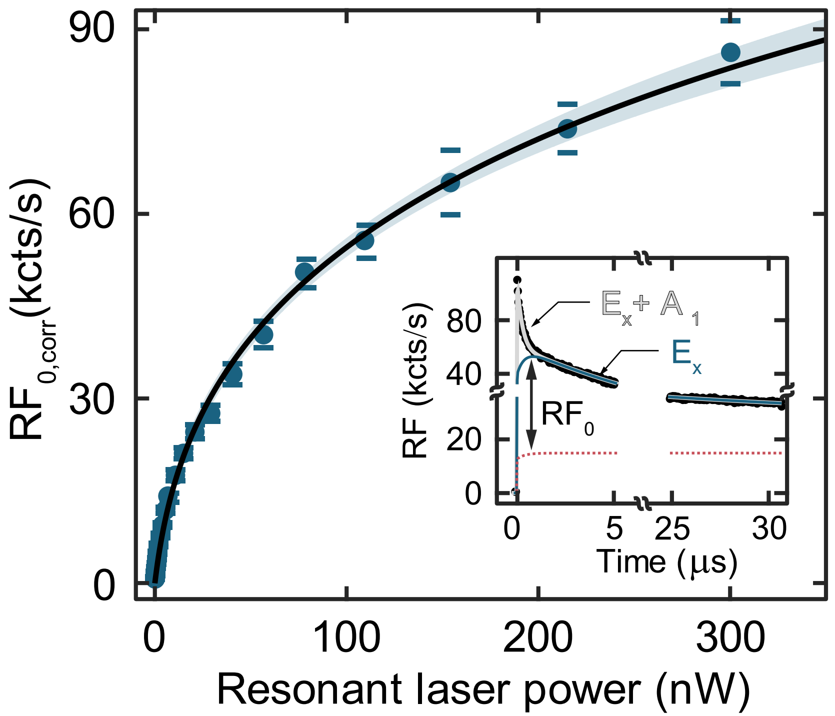
➢ First observation of RF with SNR>1

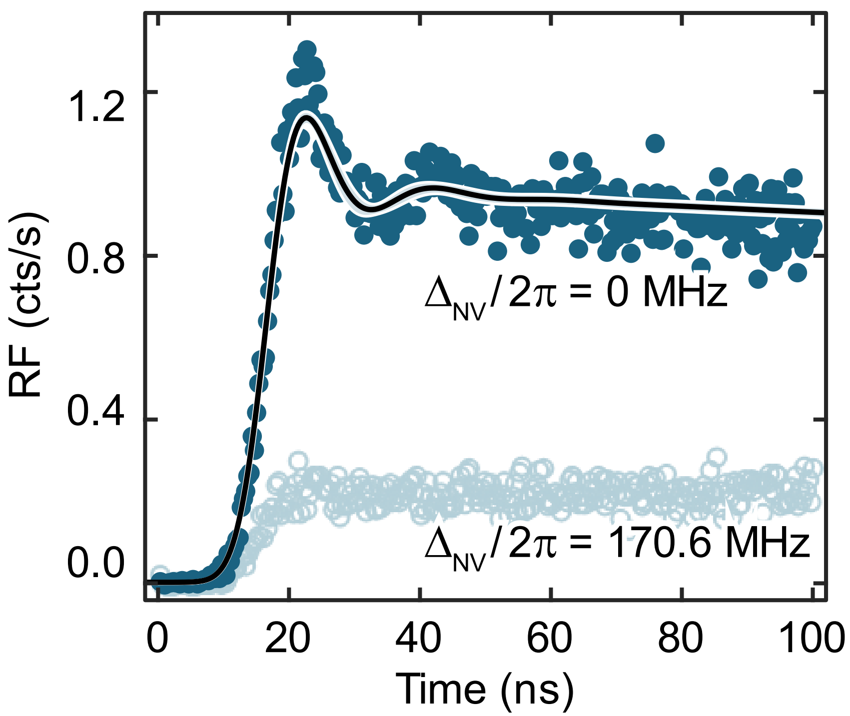


(1) **Yurgens *et al.*, NPJ Quantum 10 , 2024**



Cavity-assisted resonance fluorescence





- RF intensity 4-5x state of the art
- Rabi frequency 2π 51 MHz

- **Limited by: residual charge noise / spin initialization / laser rejection / control electronics**

- >10x increase in coherent photons fraction
- Resonance fluorescence, without time-filtering
- Onset of “high-cooperative” regime

1. Single-shot spin readout (through the ZPL)
2. Full mitigation of charge noise, NV- becomes 2LS
3. High-efficiency (30%) spin-photon entanglement generation

Thank you!


Marina Obramenko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Viktoria Yurgens


Marie Gruet


Brendan J. Shields


Richard Warburton
Nano-Photonics Lab

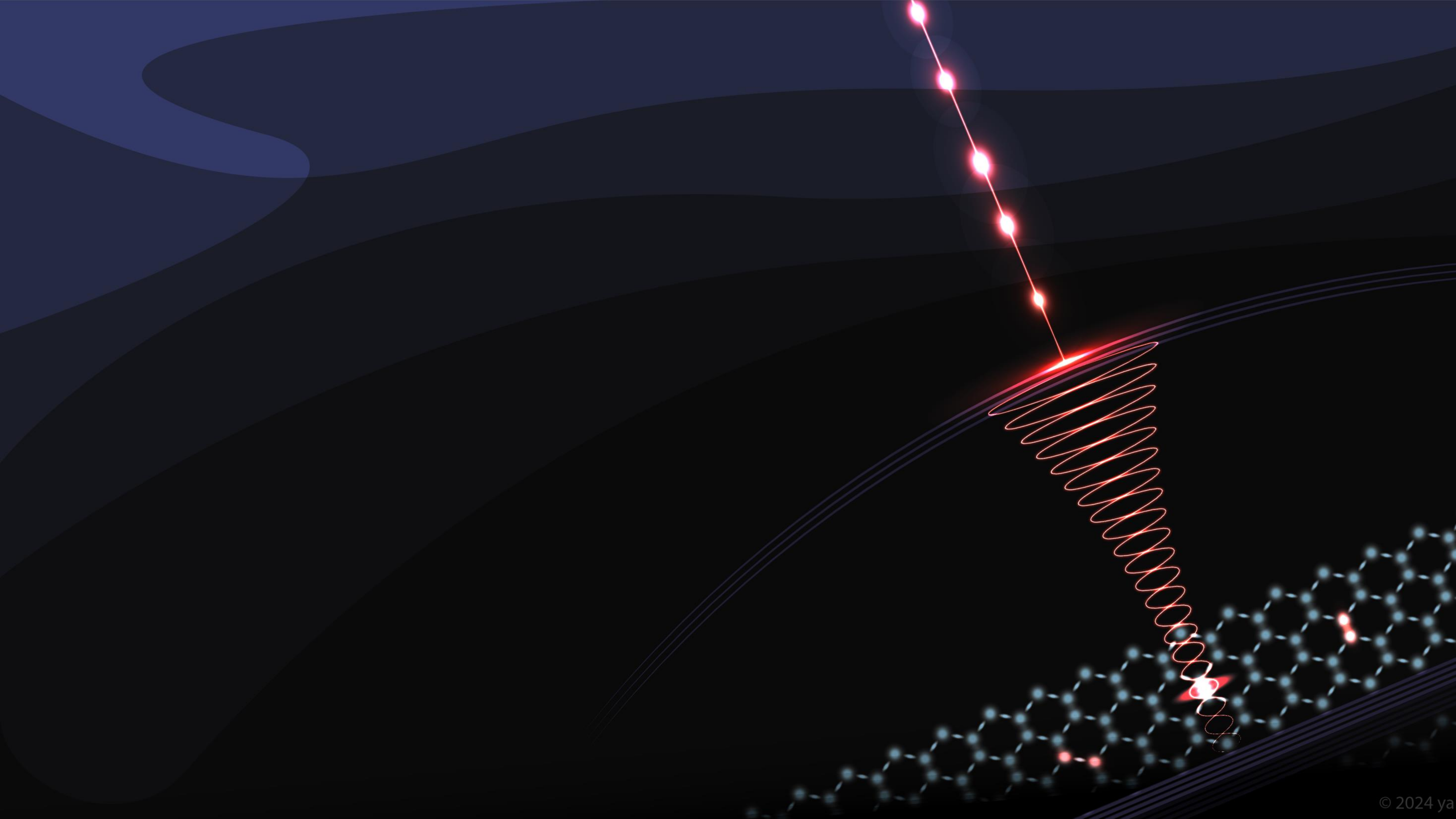

Patrick Maletinsky
Quantum Sensing Lab

QSIT Quantum Science and Technology
National Centre of Competence in Research

Schweizerischer Nationalfonds

MARIE CURIE ACTIONS

ASTERIQS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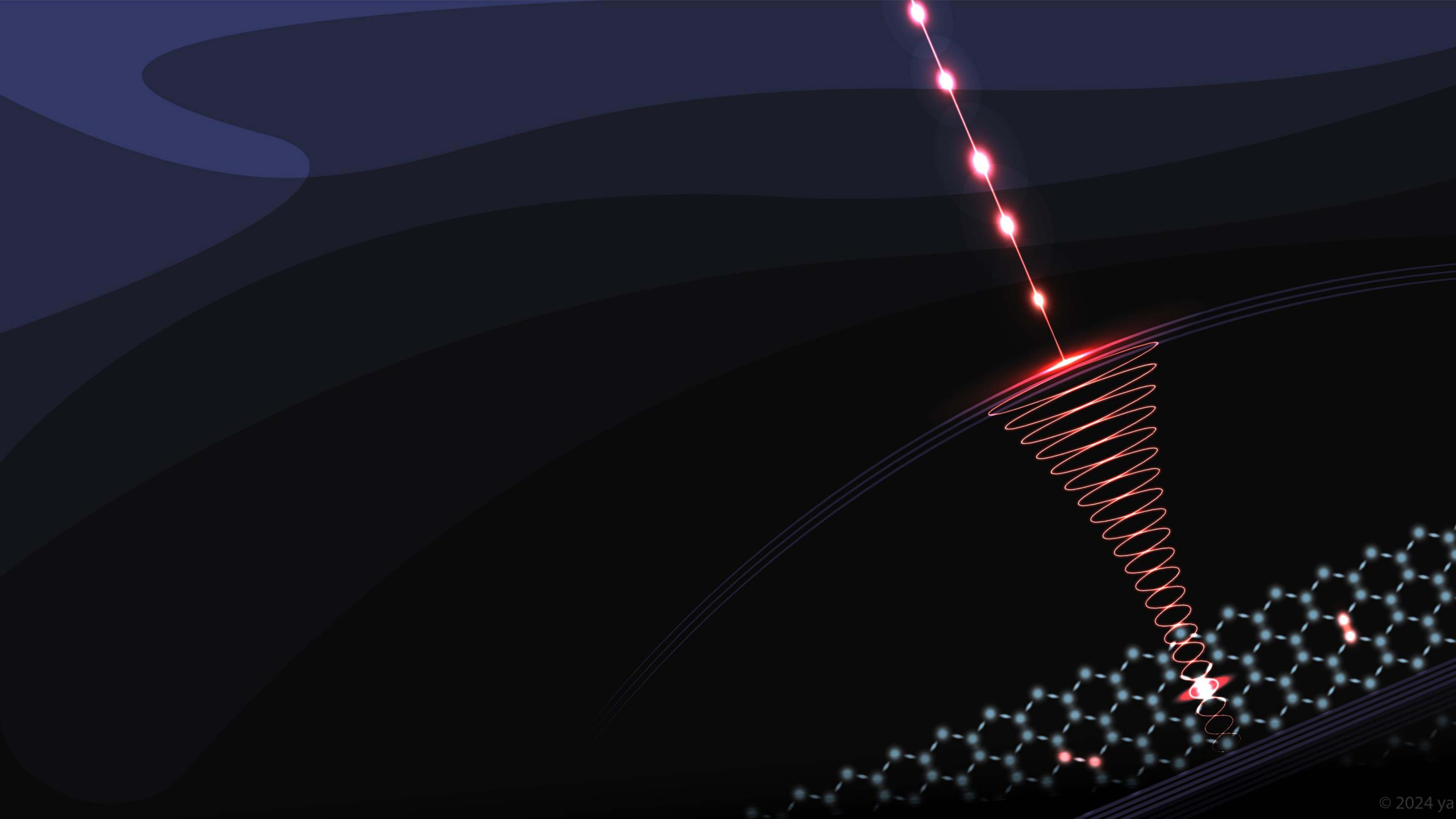
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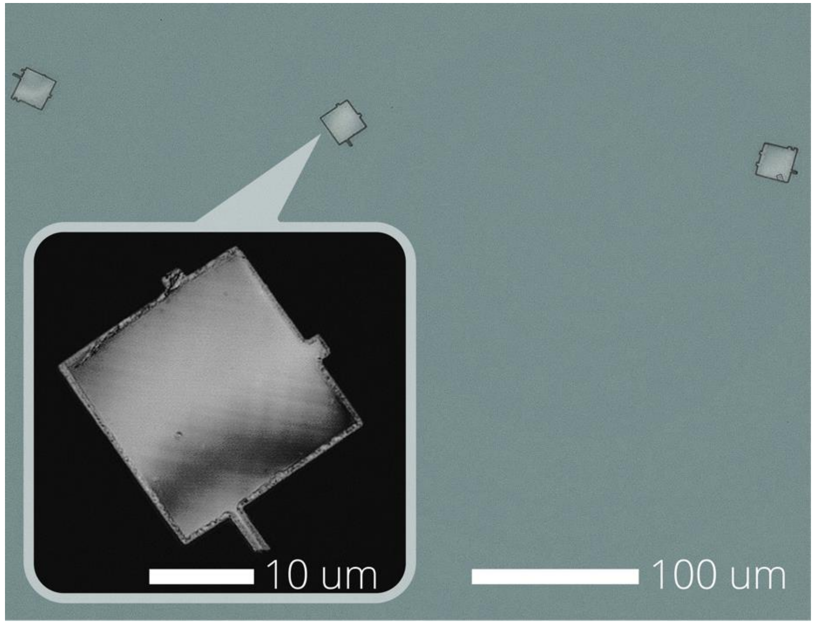
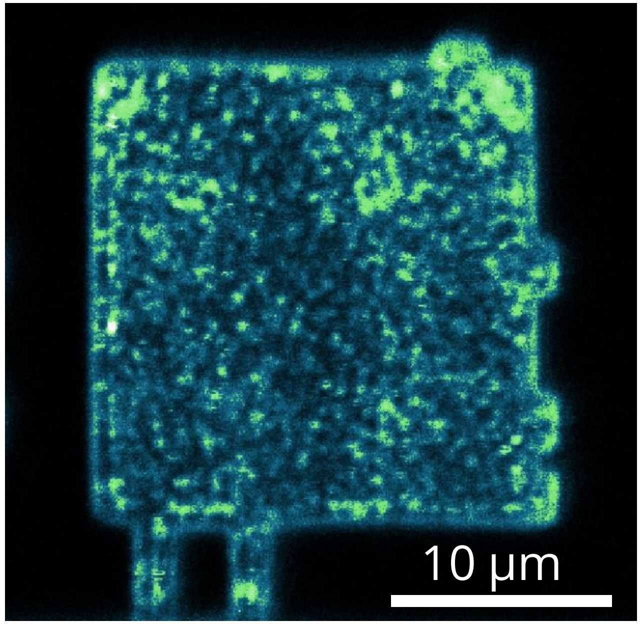
Bringing in the NV$^-$s

- Microfabricated platelets
- Tapper: air-like & diamond-like



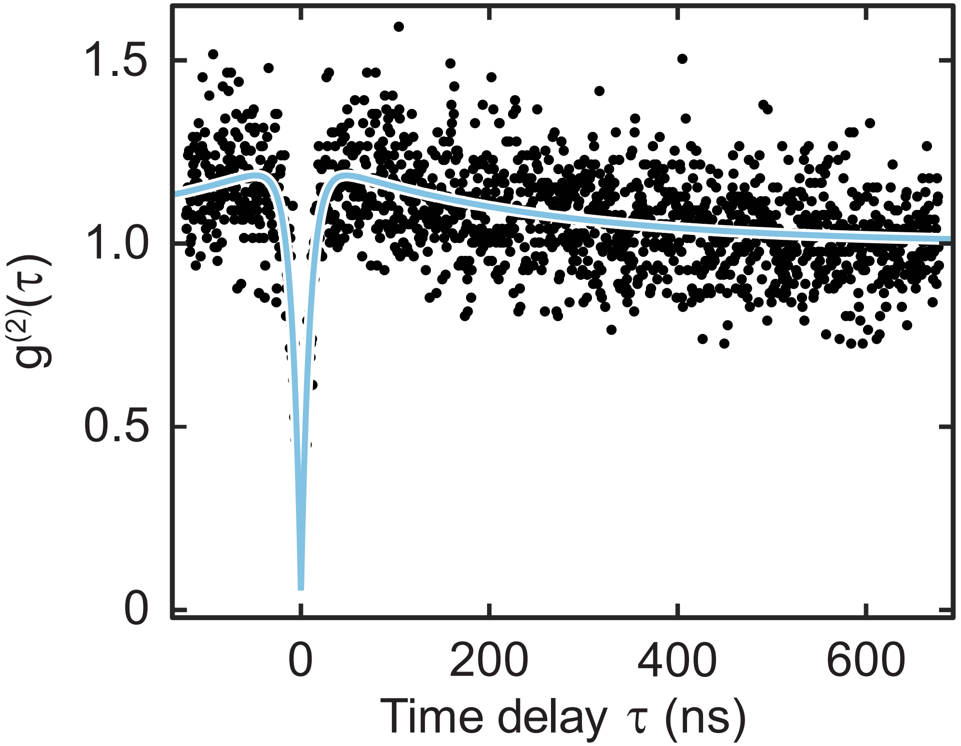
- Carbon-implanted (c-IPF)[1]
- Low (10x T1) extrinsic broadening

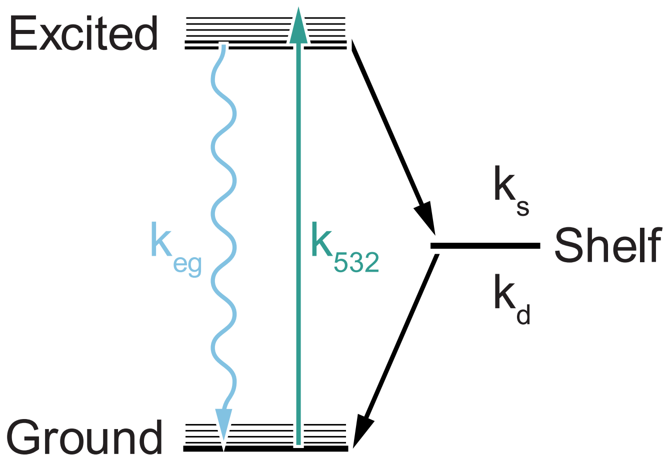


(1) V. Yurgens *et al.*, APL 121, 2022

Selective, single NV$^-$ coupling

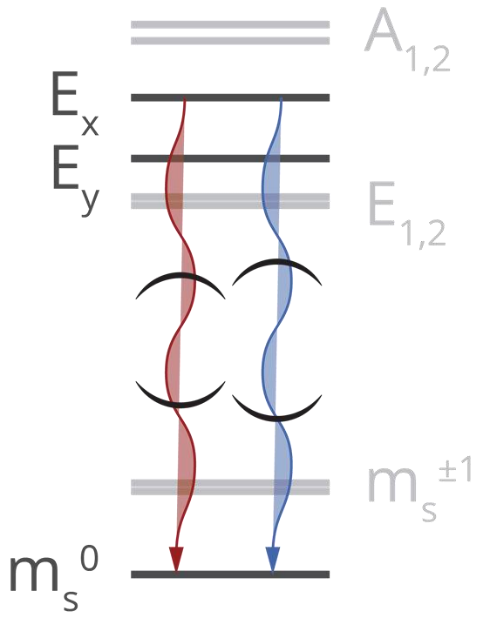
- Remarkably small $g^{(2)}(0)$: filtered incoherent background
- Moderate shelving to singlet and neutral states

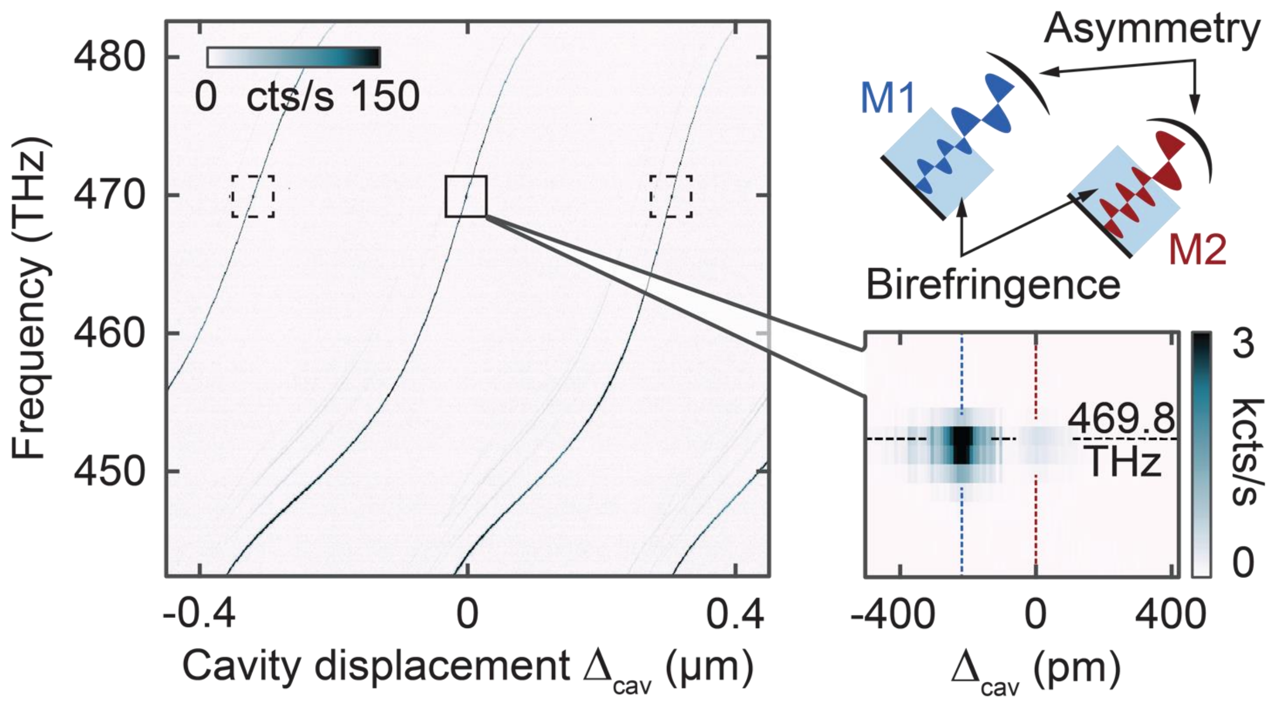




Selective, single NV$^-$ coupling

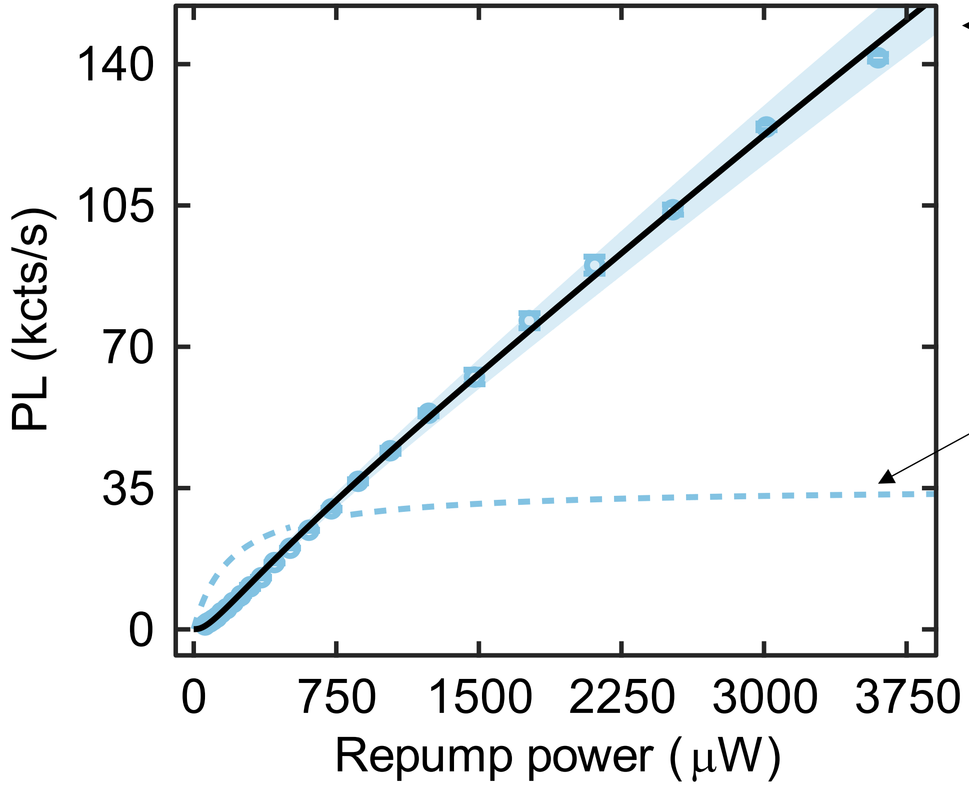
- Selective mode-transition coupling
- Birefringence induced mode splitting





Off-resonant ZPL emission rate

- Potential increase > 1 order of magnitude: $$\xi_{cav} = \frac{1}{\xi_0} - \frac{1}{F_P^{total}} = 46.7\%$$



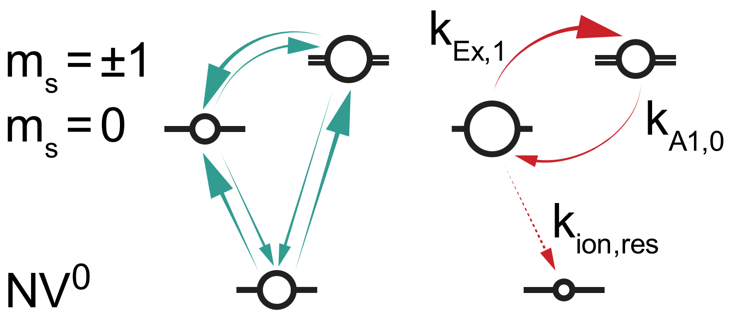
- Power density run-out before saturation!

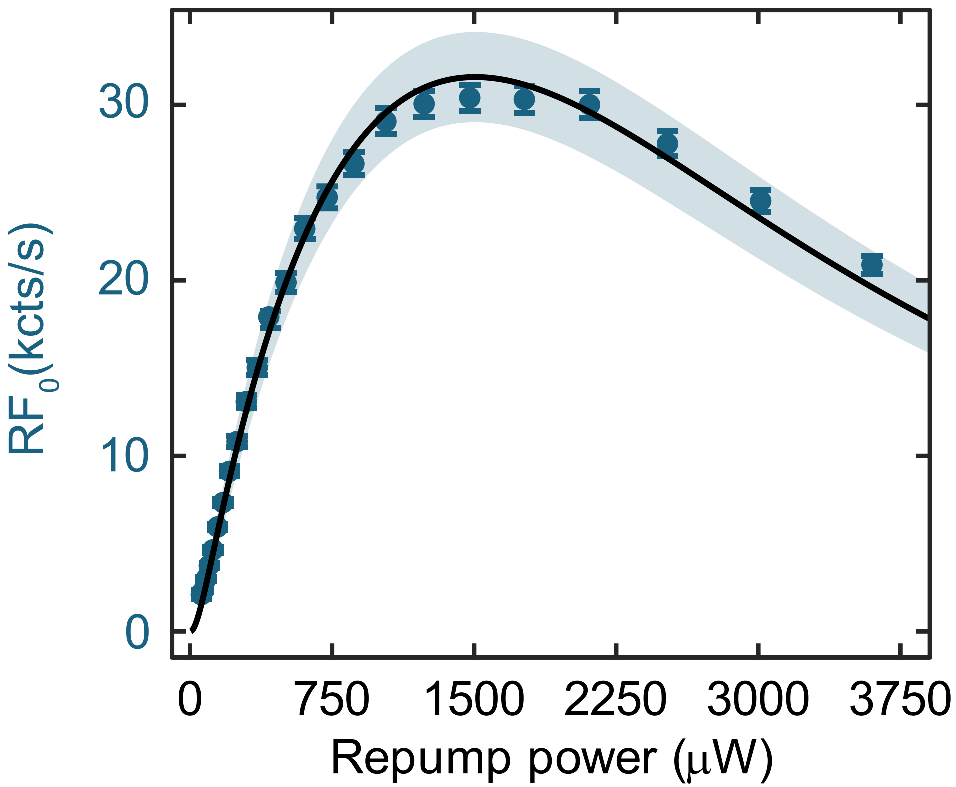
B. Hensen *et al.*, Nature 526, 2015

- NV in Solid immersion lens
- Anti-reflection coating
- Corrective optics

Limits to RF rates

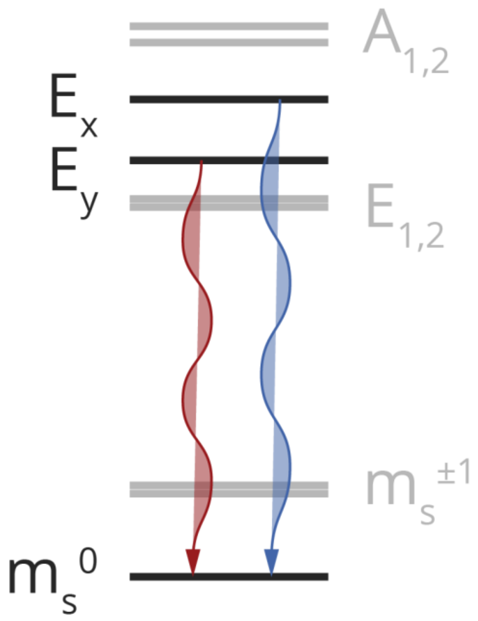
- Initialization
  - Charge state
  - Spin state (easier)
- Charge noise
  - Reduce SBR ~10
- Coupling efficiency (~10%)

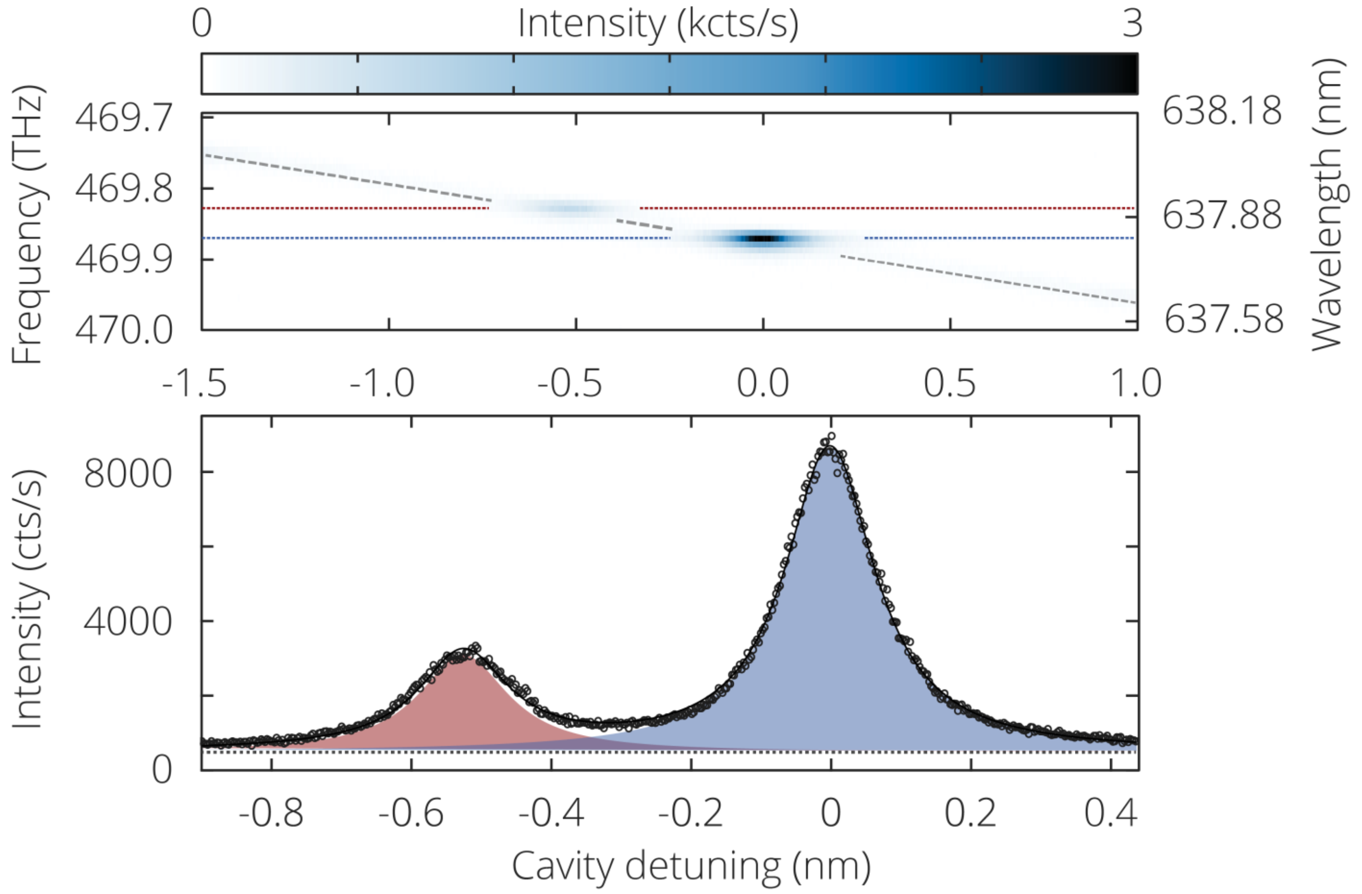




Selective, single NV⁻ coupling

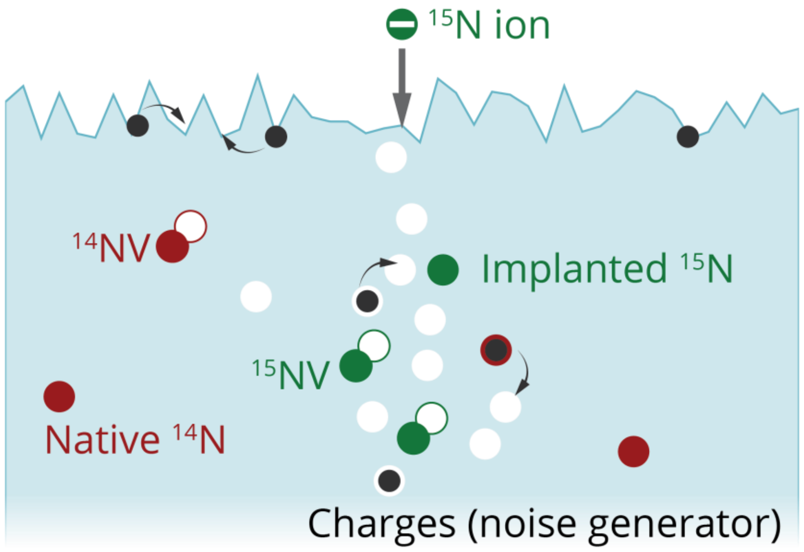
- 2 resolved transitions (non-resonant excitation)!
- Enhancement at crossing



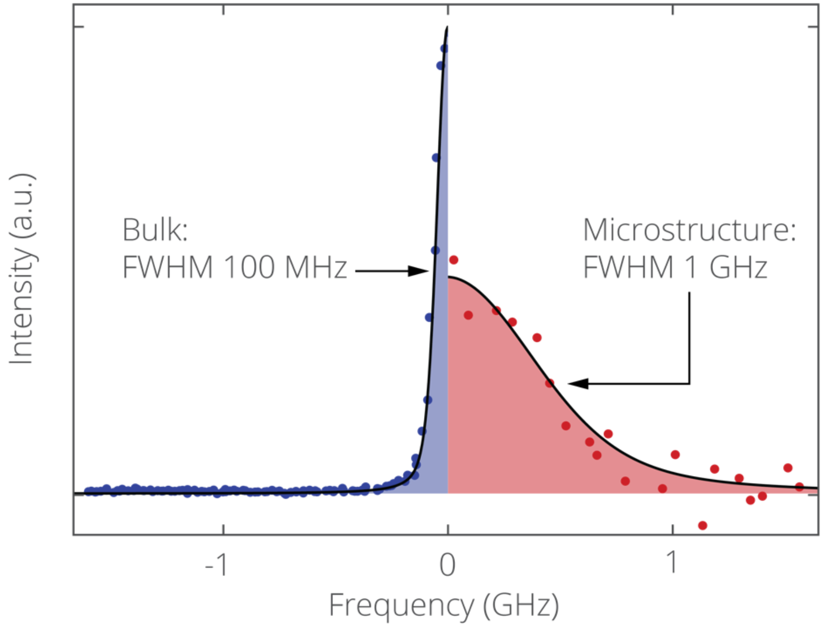


NV⁻ centers: the challenges (II)

- Excited state very sensitive to E fields (1)
- Worse with implanted NVs (3,4)



- Even worse in small (~µm) structures (2)
- Linewidth from 13 MHz to > 1 GHz! (2)

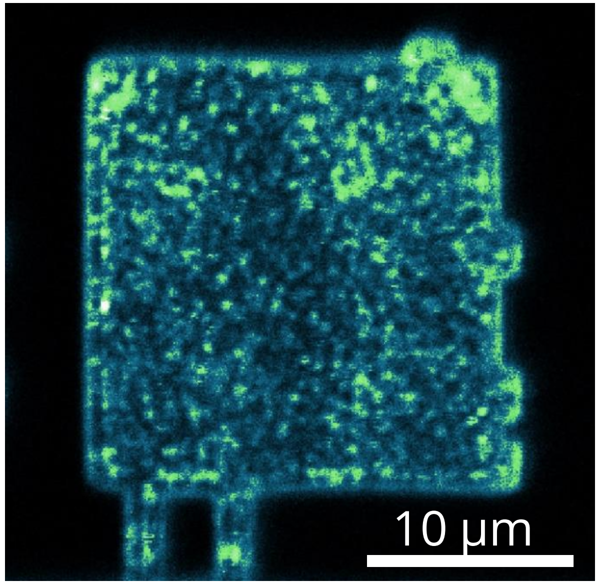


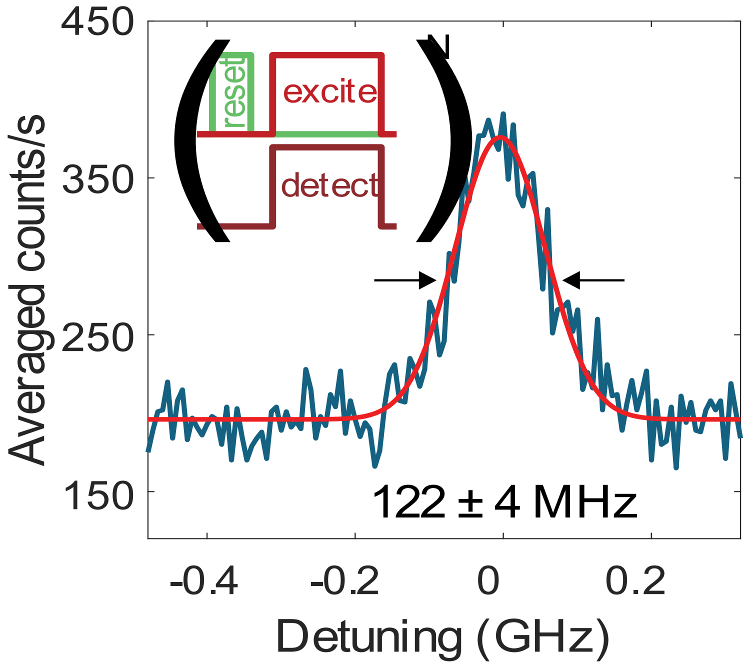
(1) J. R. Maze *et al.*, New J. Phys. 13, 2011
(2) D. Riedel *et al.*, Phys. Rev. X 7, 2017
(3) M. Kasperczyk *et al.*, Phys. Rev. B 102, 2020
(4) S. B. Van Dam *et al.*, Phys. Rev. B 99, 2019

Carbon implantation post-fabrication

Rationale:

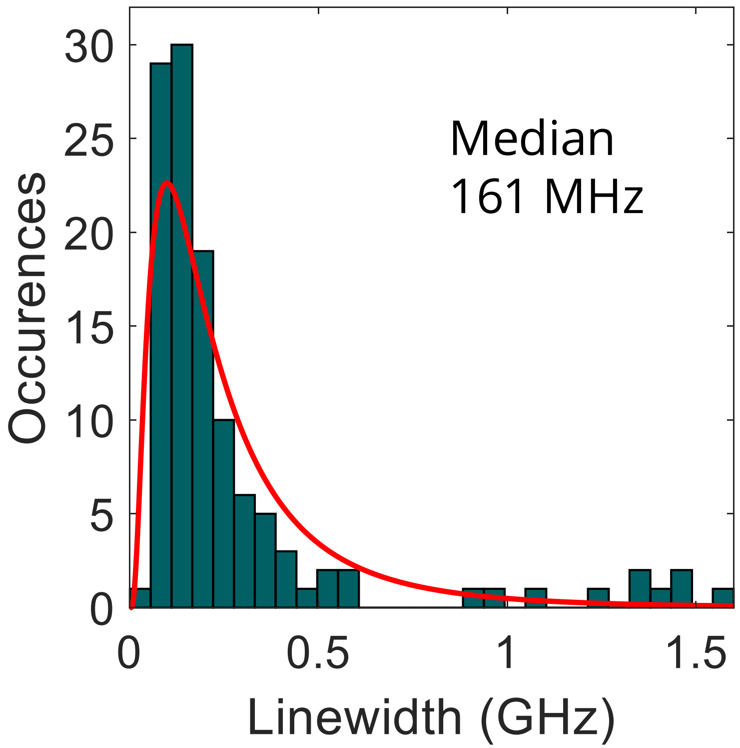
1. Generate vacancies, not NVs → implant ^{12}C "blanks"
2. Do not process after NV- creation → IPF



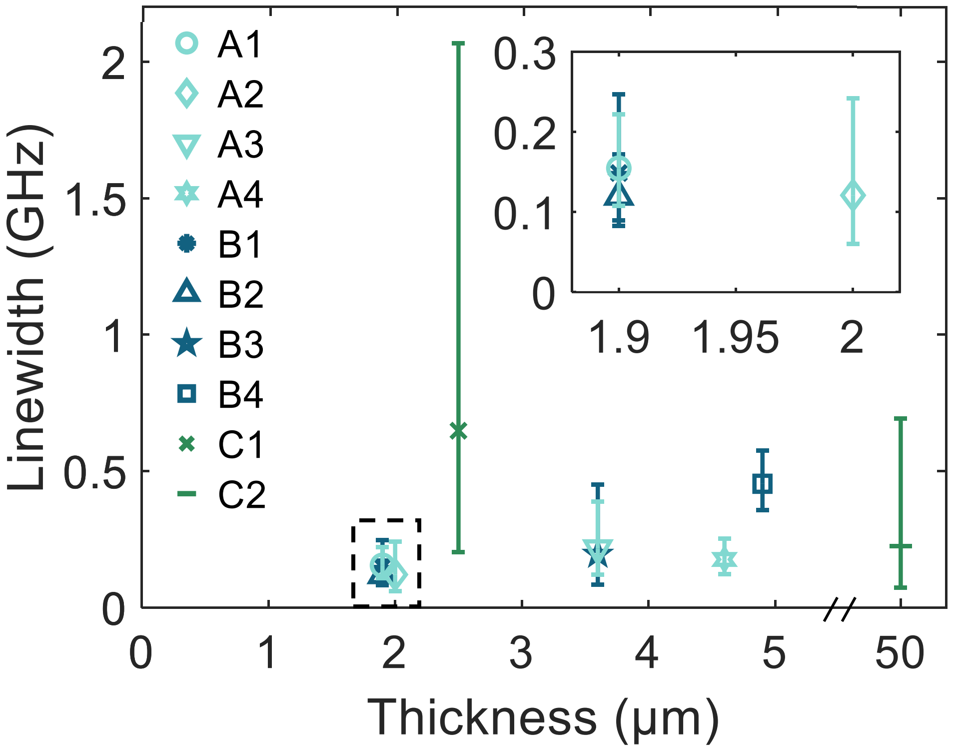


Reduced "extrinsic" broadening[1]

- 48% below 150 MHz



- Reproducible!
- No increase for thin structures

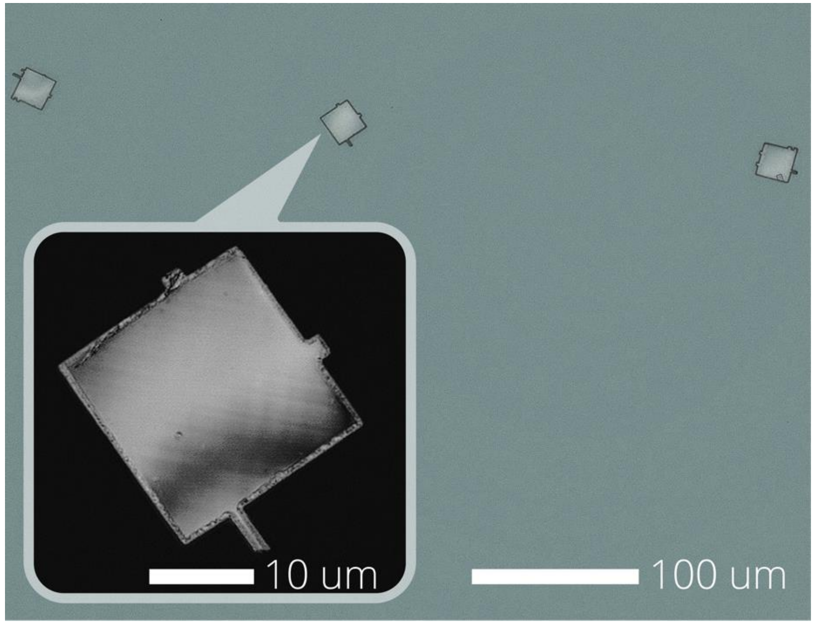


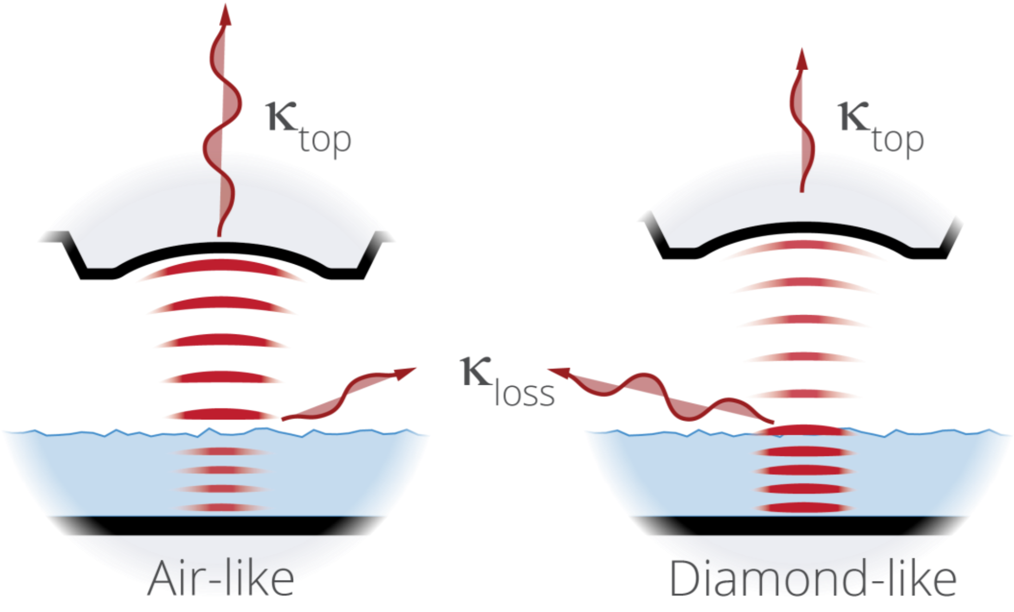
(1) V. Yurgens et al., Appl. Phys. Lett. 121, 2022

High finesse microcavity[1,2]

- Diamond induced losses:
  - Scattering
  - Absorption

- Finesse: 4500-9000
- Q-factor: 1-2 x10^5

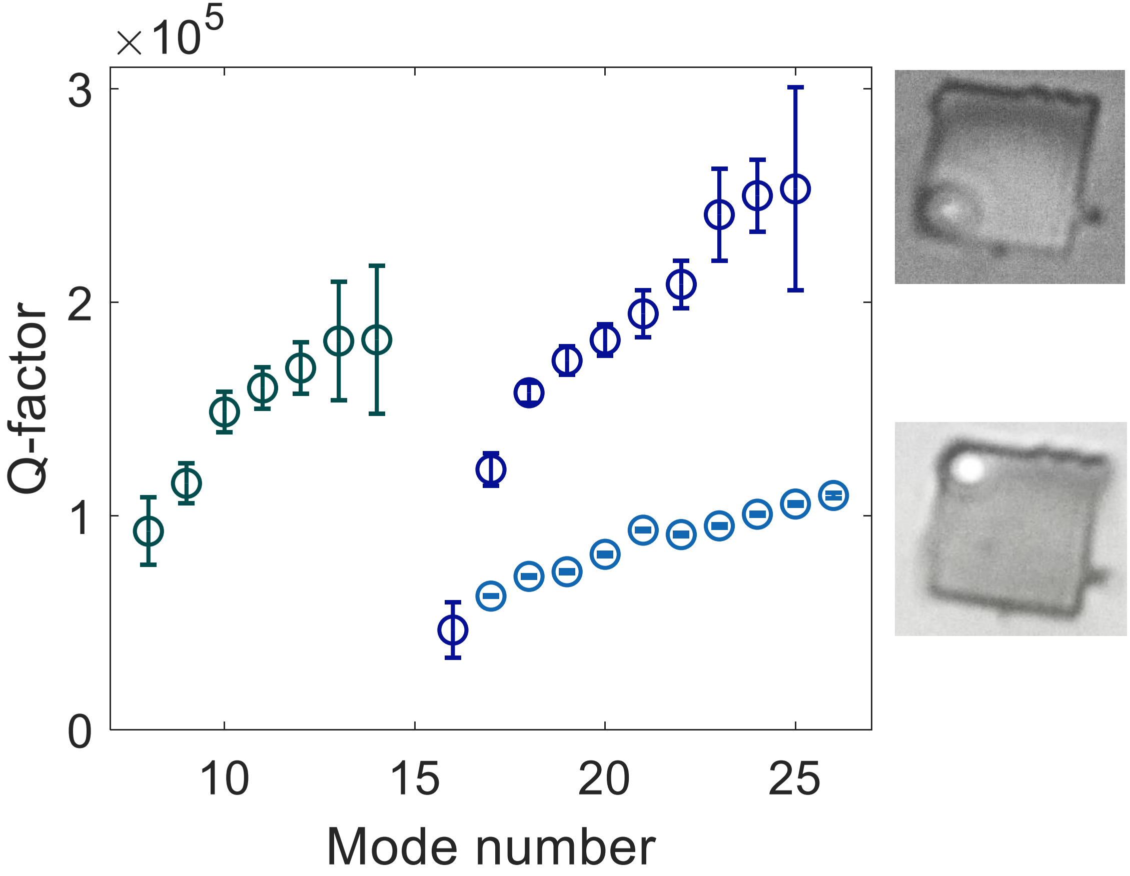




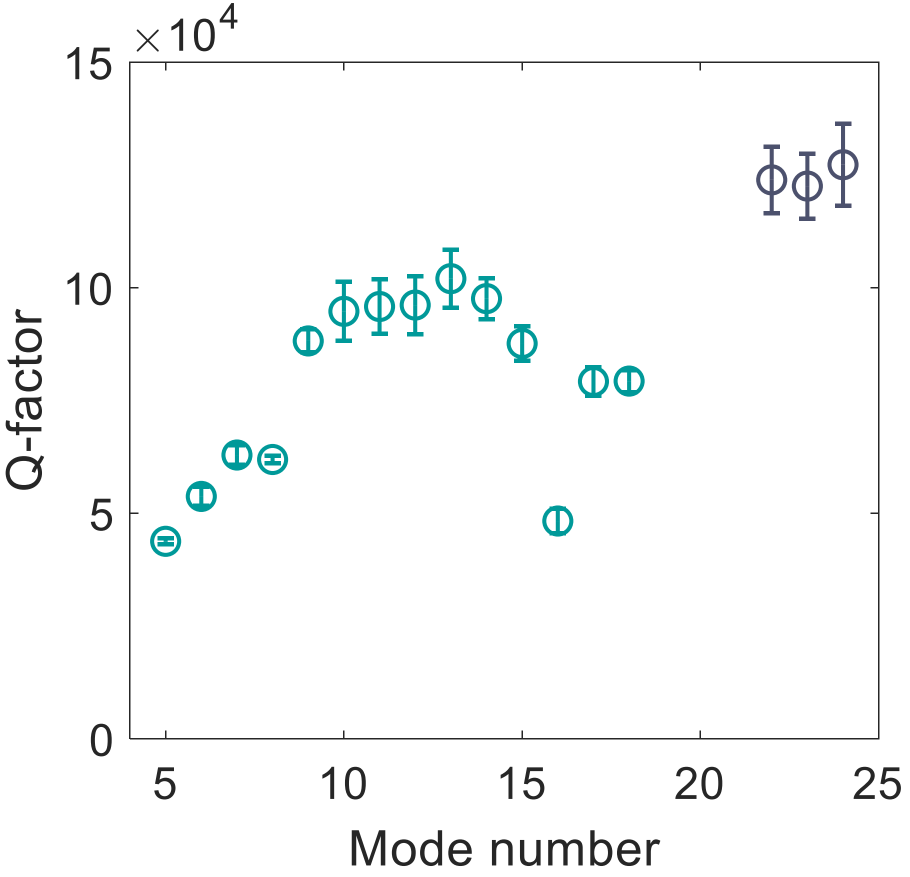
(1) R. J. Barbour *et al.*, J. Appl. Phys., 110, 2011
(2) S. Flagan *et al.*, J. Appl. Phys. 131, 2022

Cavity Q

- xxx



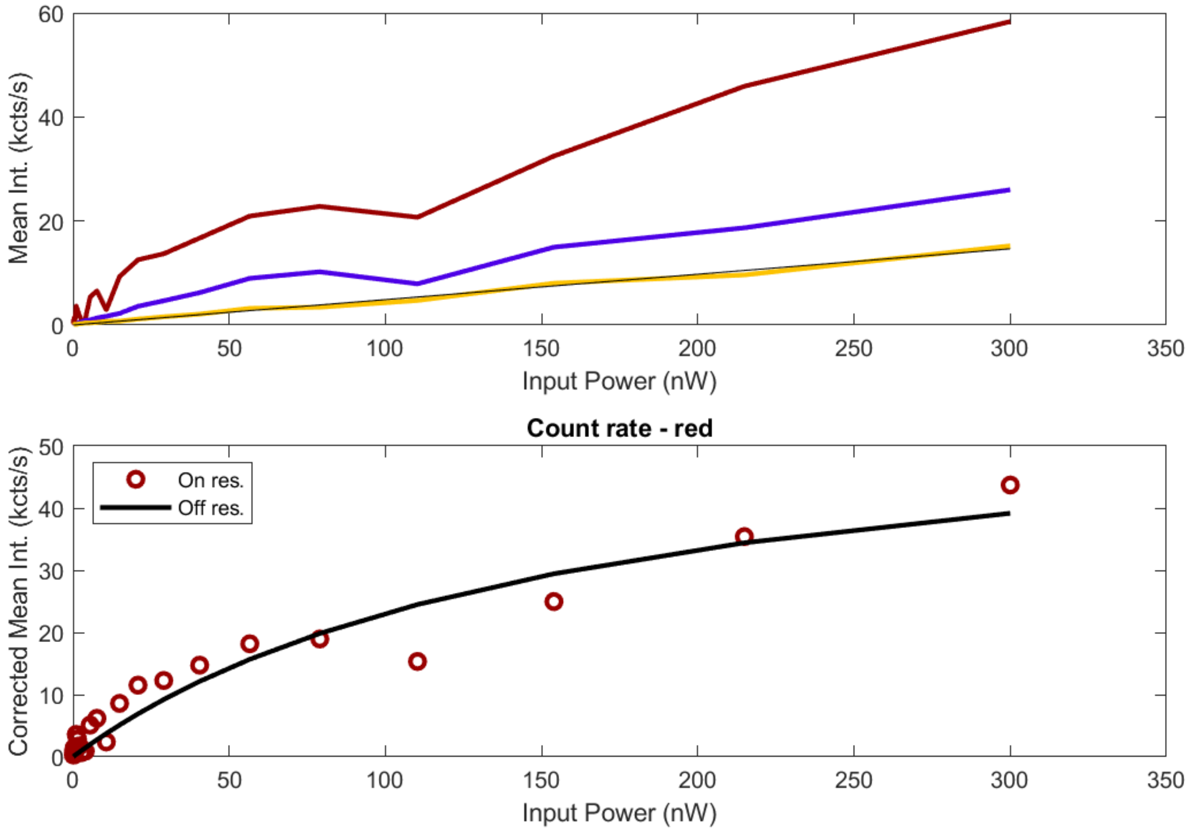
×10^5
3
2
1
0
Q-factor
10
15
20
25
Mode number



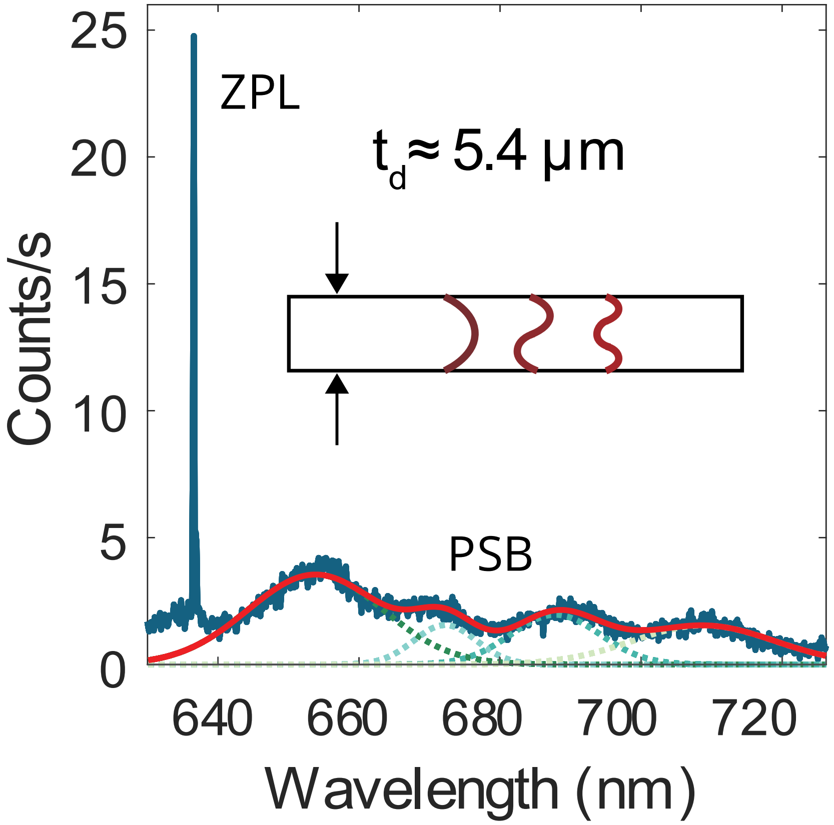
×10^4
15
10
5
0
Q-factor
5
10
15
20
25
Mode number

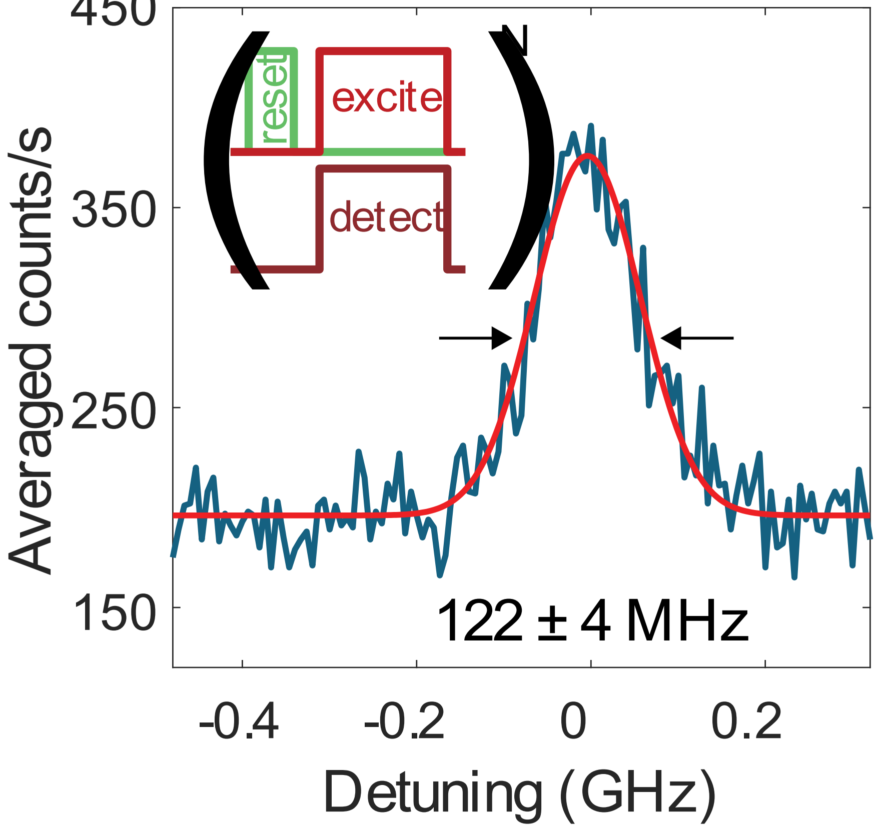
Saturation

- Recovered intensity



PLE platelet





How do we design the cavity?

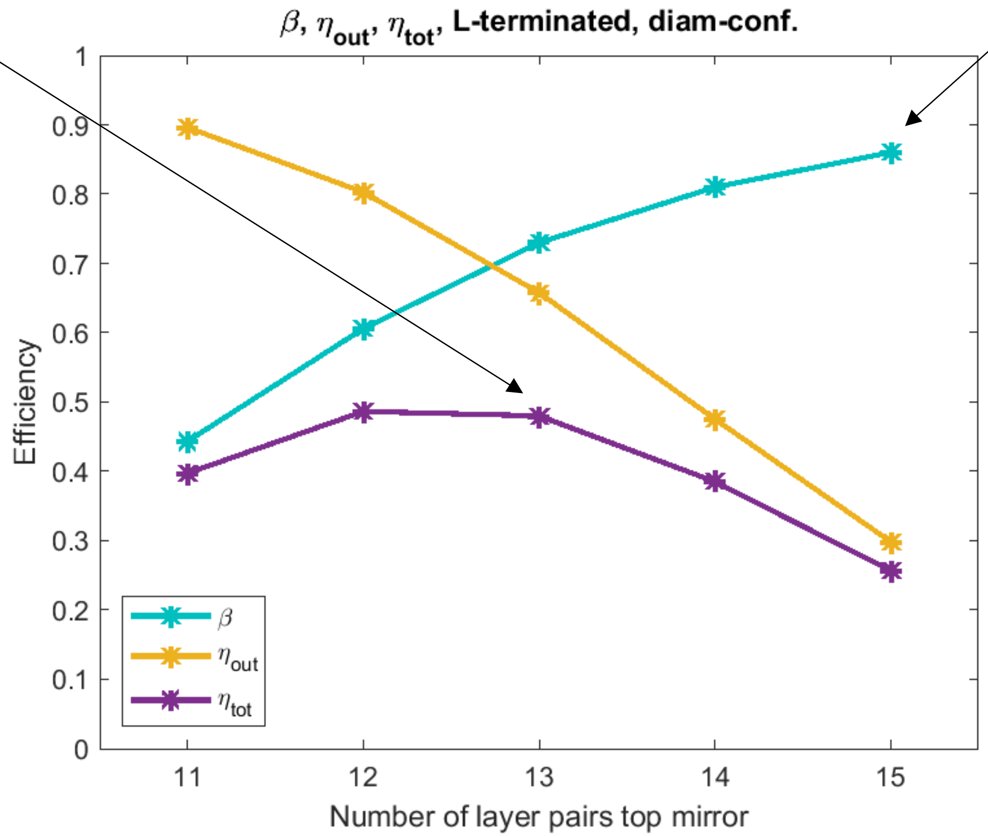
For efficient spin-photon entanglement

For maximum transition selectivity

$$\beta = \frac{F_P - 1}{F_P}$$

$$\eta_{out} = \frac{\kappa_{top}}{\kappa + \gamma}$$

$$\boldsymbol{\eta_{tot}} = \beta \cdot \eta_{out}$$



$$Q = \frac{\nu}{\delta\nu}$$

$$\kappa = \frac{\omega}{Q}$$

$$\boldsymbol{F_P} = 1 + \frac{4g^2}{\kappa\gamma}$$

Room-temperature alignment of the cavity

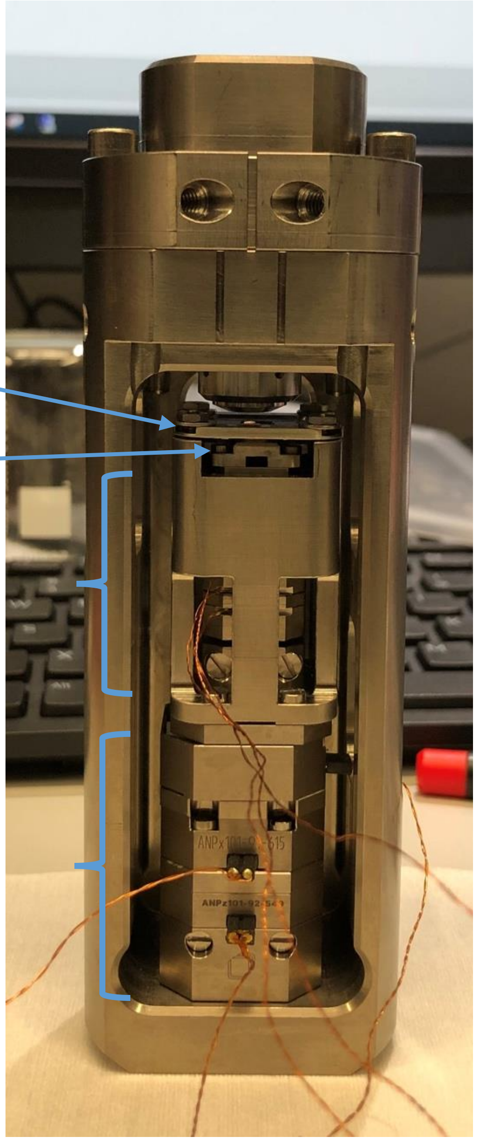
Top mirror

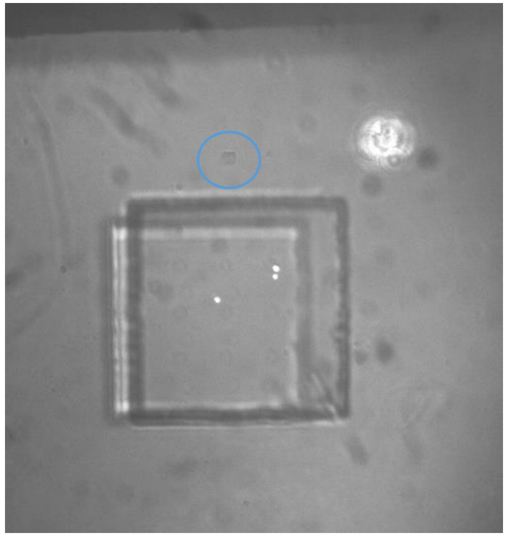
[Indium]

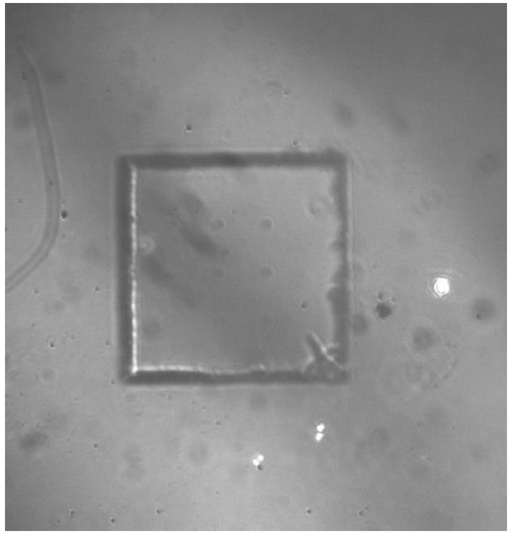
Bottom mirror

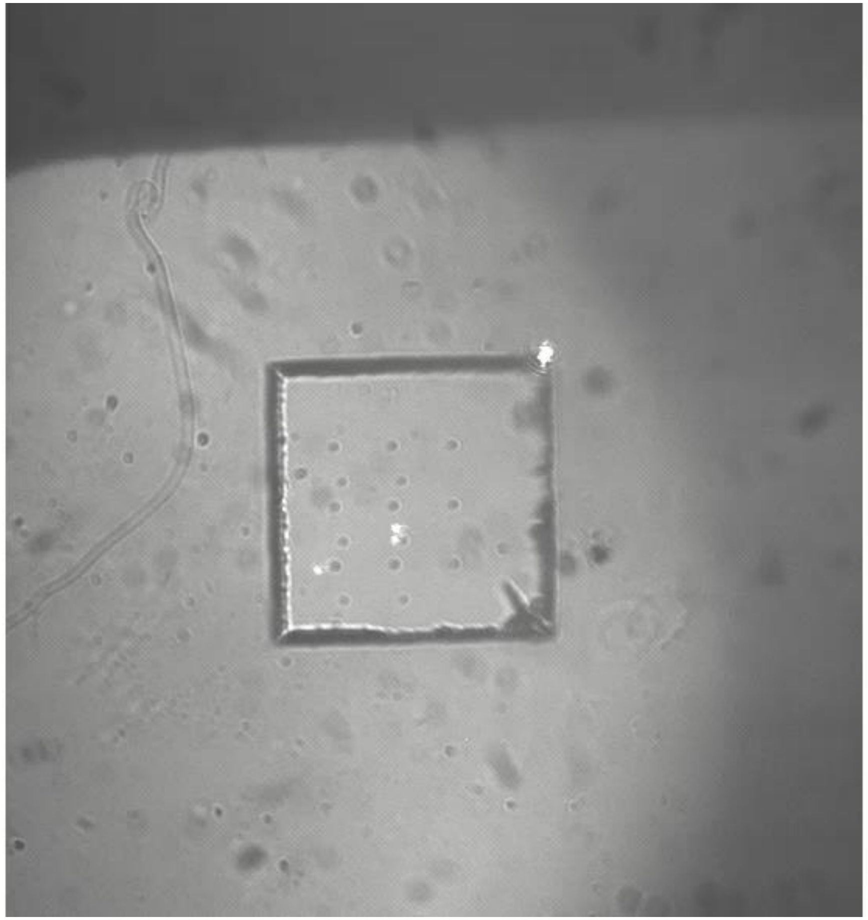
XYZ steppers (move bottom mirror)

XYZ steppers (move whole stack)









Bottom mirror + diamond