Coherence of light scattered from large ensembles of trapped ions

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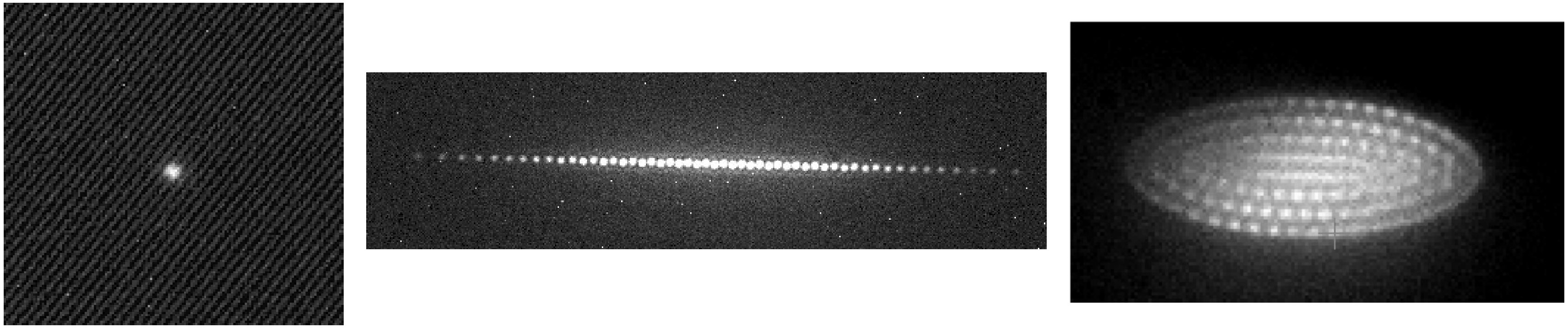
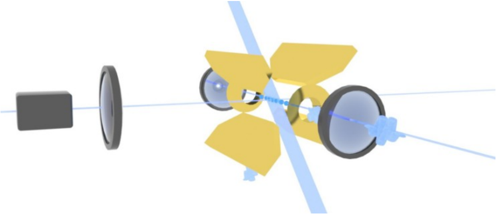


Outline

- basics of our ion trapping setups

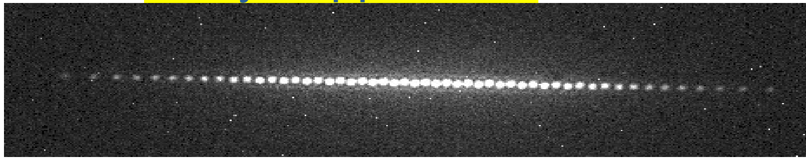


- coherent control of nonclassical emission from large ion crystals

Optical directional emission from ion strings

- in elastic scattering regime

Many trapped ions



Generation of entanglement of distant ions

- directionality of inelastic scattering from entangled ions

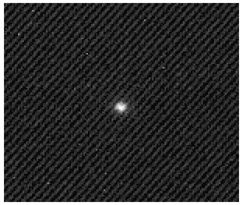
Emergence of photon correlations and super-Poissonian statistics

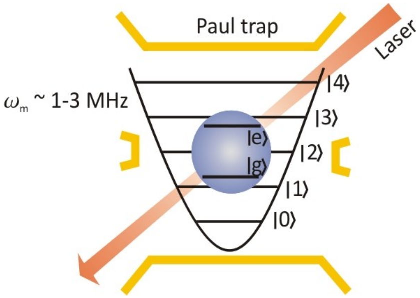
- in a single-mode detection regime from single to many ions
- extension to *N* modes ~ transition to sub-Poissonian statistics and single photon sources

Interference of ion crystals and their mirror images

- control of quantum motion of trapped ions

~ slide 29, probably not part of this talk





Single trapped ions

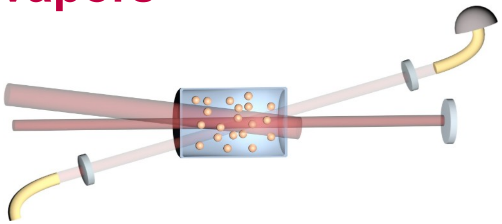
Genuine quantum non-Gaussianity of Fock states

- quantum enhanced sensing of weak forces and thermal heating

- activities with neutral atoms: single photon source in warm atomic vapors

~ slide 32, surely not part of this talk

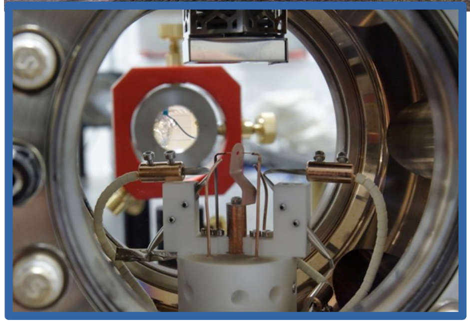
Warm atomic vapors



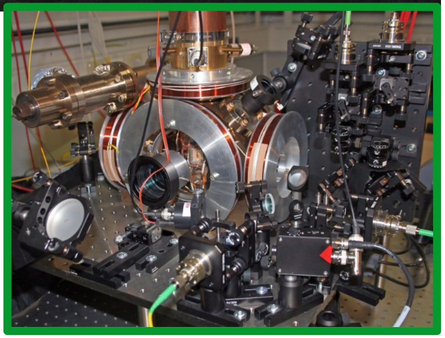
Nonclassical and quantum non-Gaussian light from SFWM

- first QNG light from double-lambda level scheme excitation of warm atoms

Palacký University, Olomouc & Institute of Scientific Instruments, Czech academy of Sciences, Brno



Phase-stabilized fiber link (~100 km) @ 1550 nm and 1458 nm



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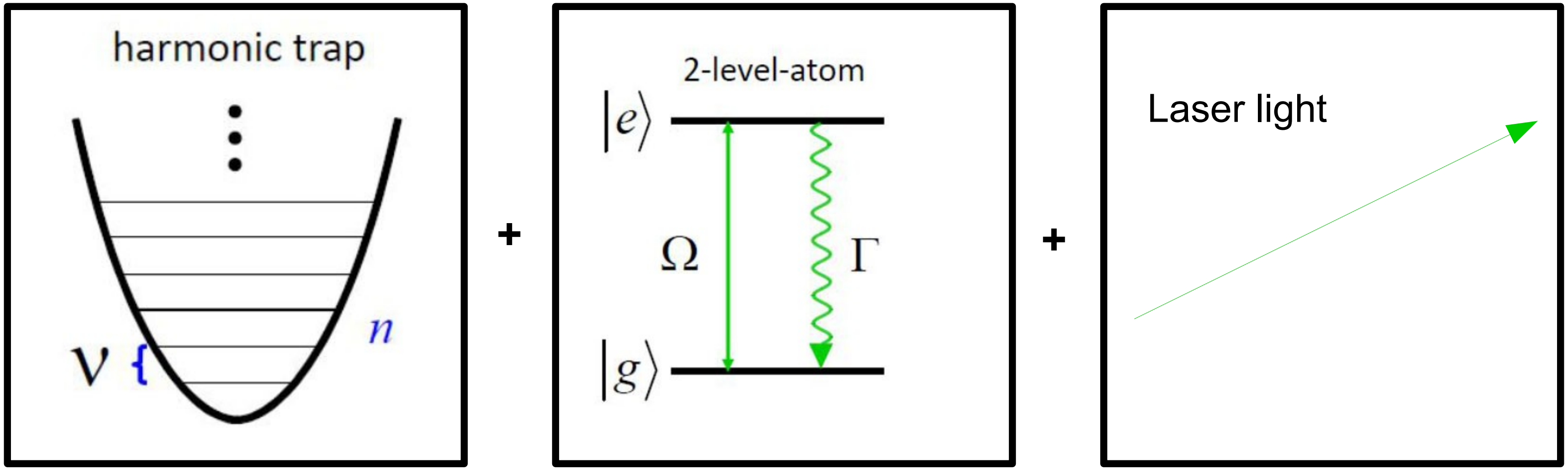
Atomic ions in Paul traps

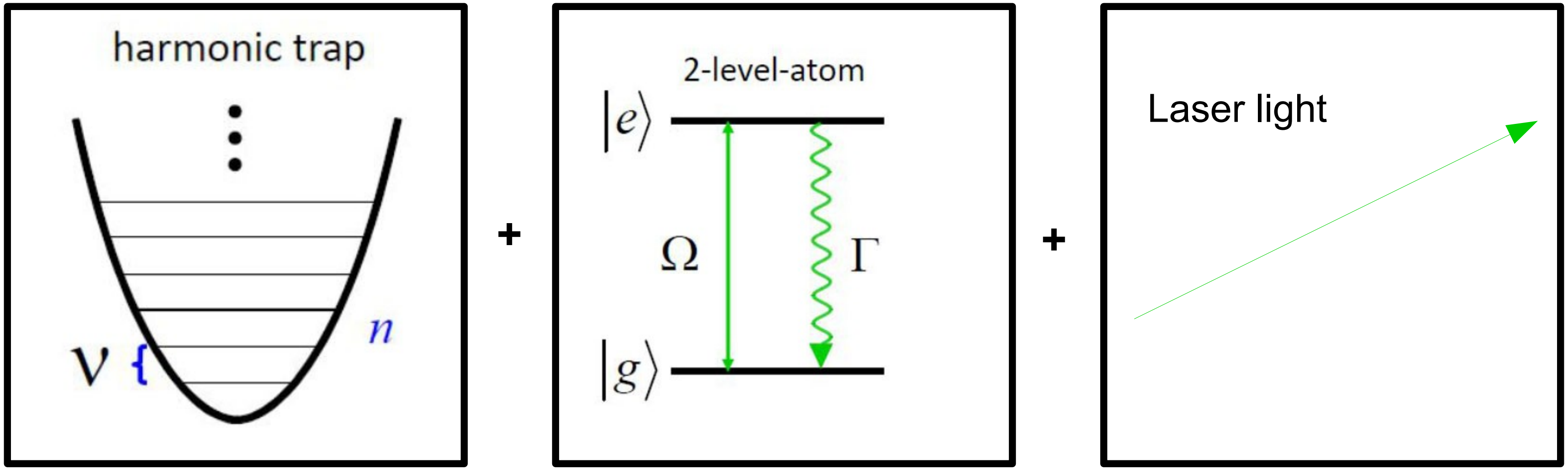


Isolation from outside world → suppression of decoherence

Advantages:

- near perfect two level system
- well decoupled from the environment
- internal states can be initialized with extremely high accuracy
- precisese coherent control of electronic states, motional states and position
- confined to a very small spatial region ($\delta x << \lambda$)
- storage experimental times of days

Atomic ions in Paul traps



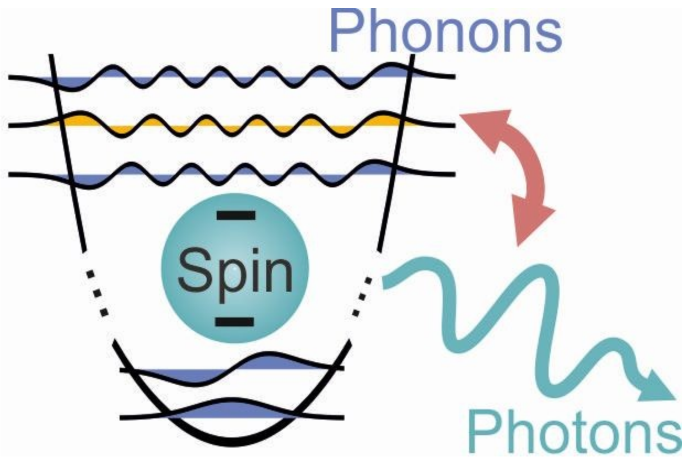
Isolation from outside world -> suppress decoherence

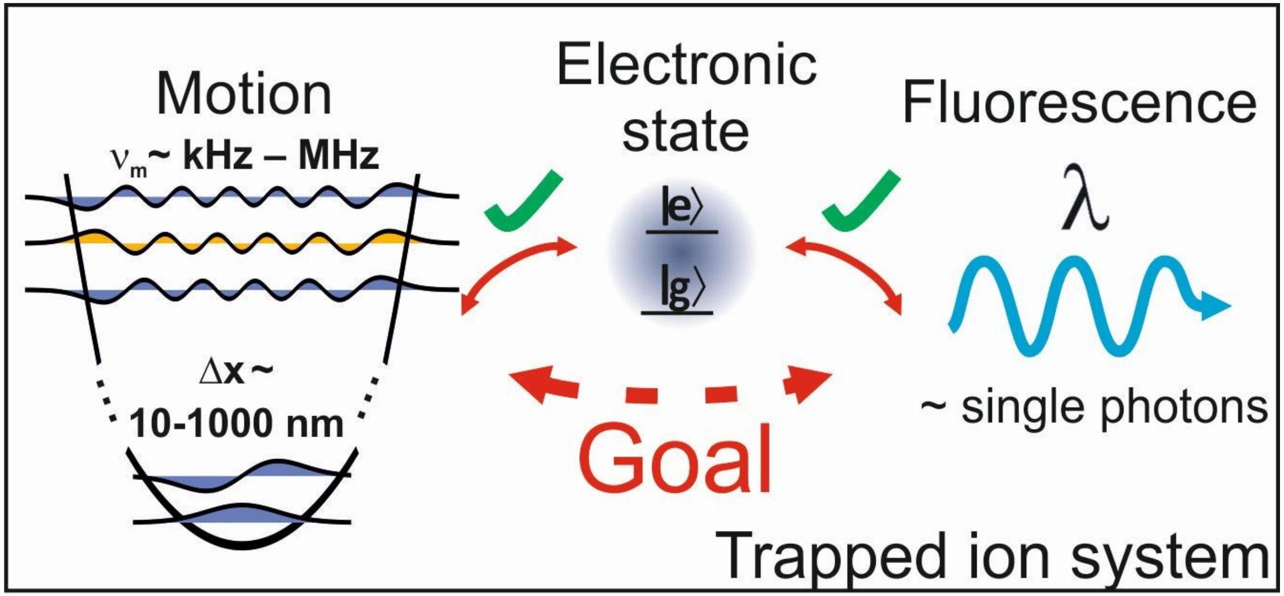
Other reasons to work with ions:

- Ideal test ground for fundamental quantum optical experiments
- Applications in quantum enhanced sensing, optical frequency metrology
- Provide one of the most advanced quantum information processing capabilities
- Extreme purity of the single photon emission

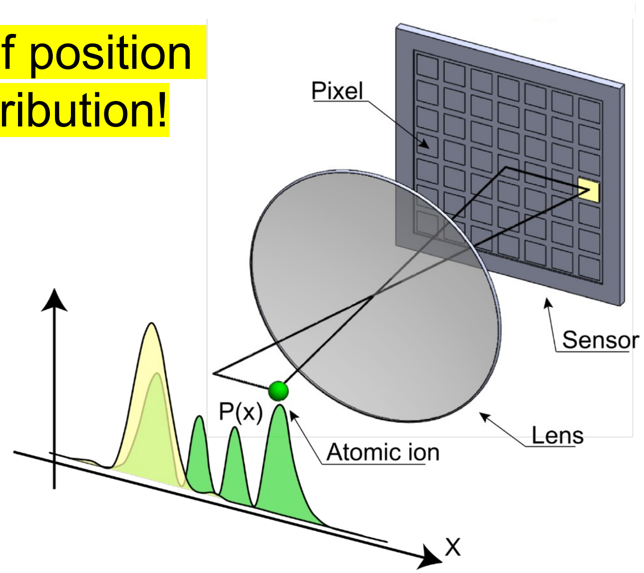
Trapped ions beyond qubits

Trapped ions provide exclusive feasibility of quantum opto-spin-mechanics

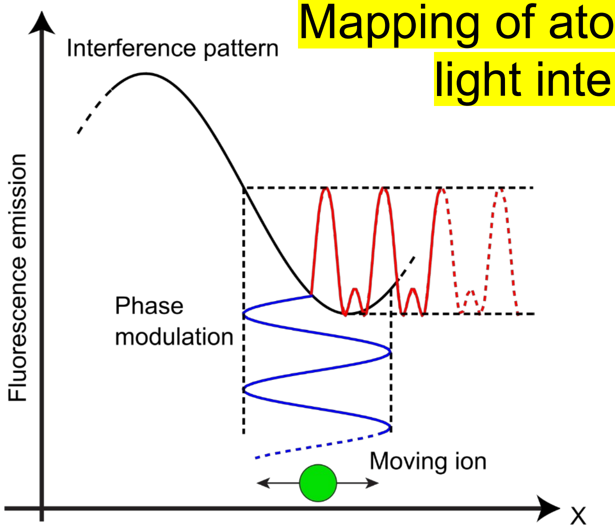




Direct imaging of position probability distribution!



Mapping of atom position light intensity



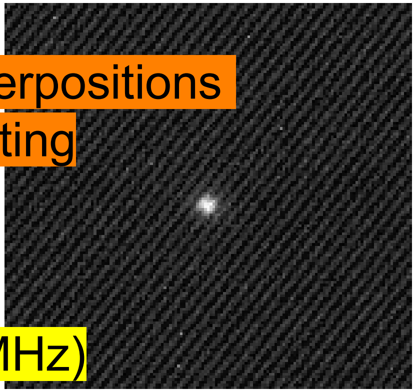
Our ion trapping setups

Large 3D Paul traps

High trapping potential depths ~ 1eV and $P_{vac} \sim 10^{-12}$ mBar

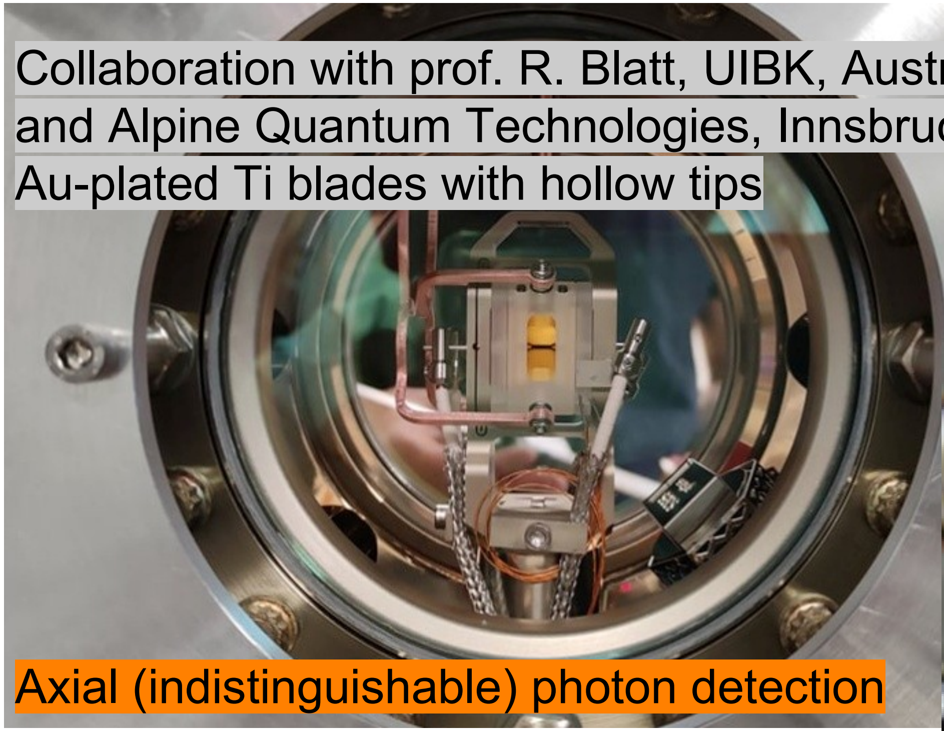
→ Storage times ~ days to weeks

Extremely low heating rates ~ 3 phonons/s



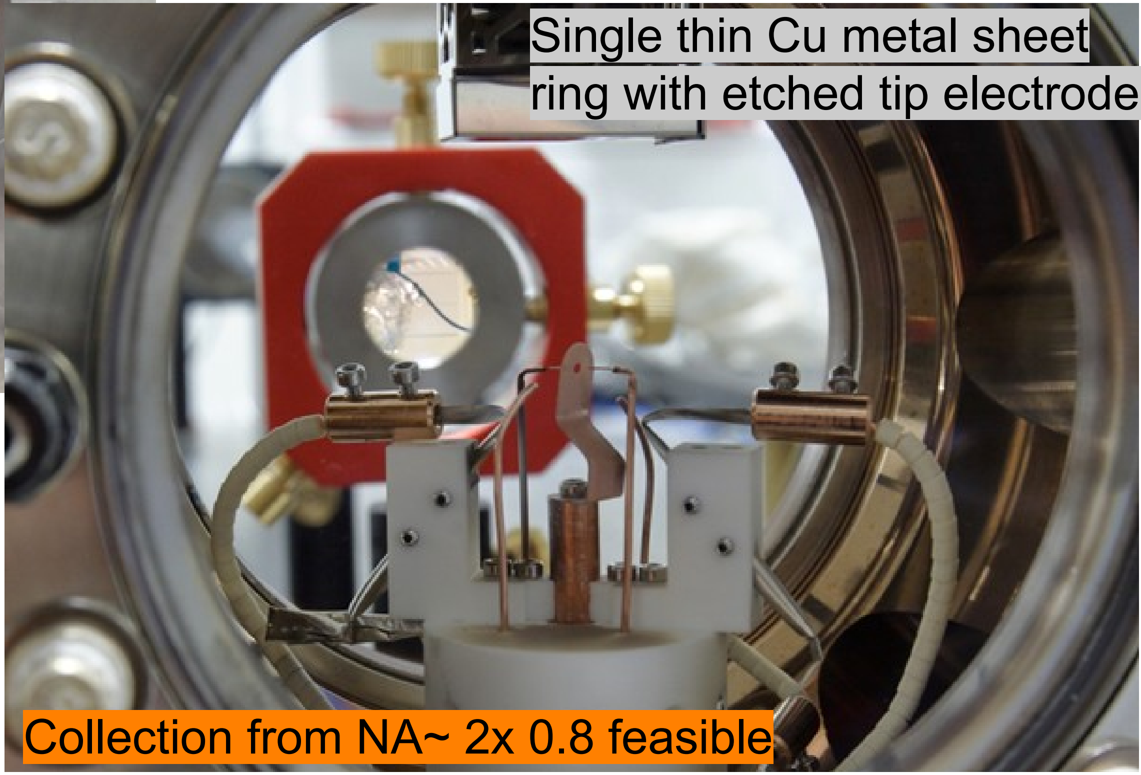
Coherence of motional superpositions
limited solely by thi low heating

$\omega_m \sim 2\pi$ x (10 kHz – 1,5 MHz)



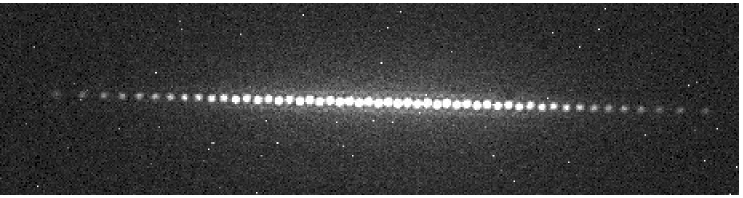
Collaboration with prof. R. Blatt, UIBK, Austria
and Alpine Quantum Technologies, Innsbruck
Au-plated Ti blades with hollow tips

Axial (indistinguishable) photon detection



Single thin Cu metal sheet
ring with etched tip electrodes

Collection from NA~ 2x 0.8 feasible

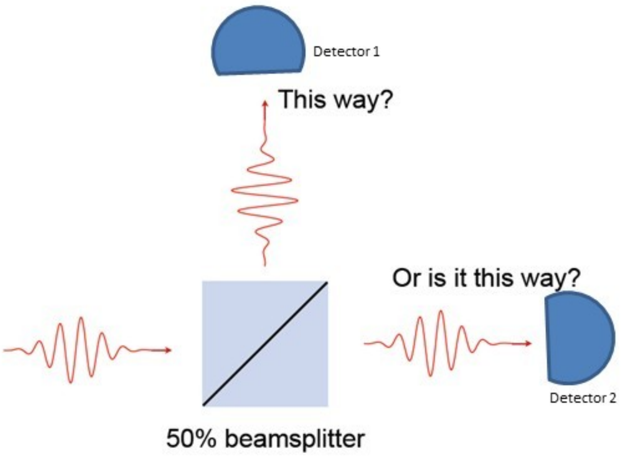


Strong Coulomb repulsion
→ independent atomic emitters

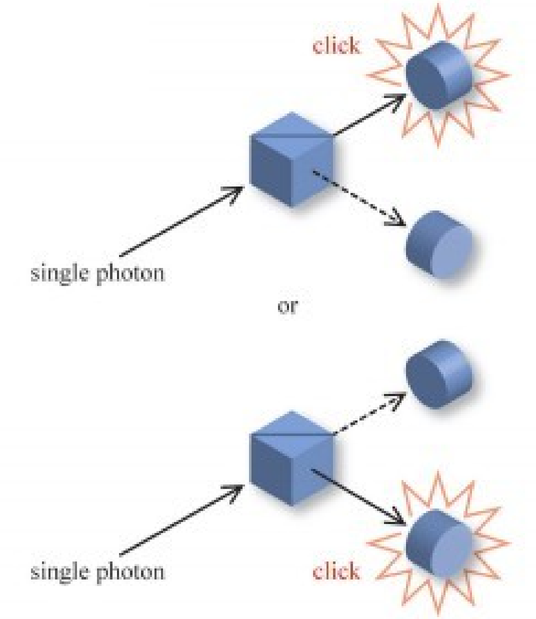
Observation of nonclassical light from large number of emitters

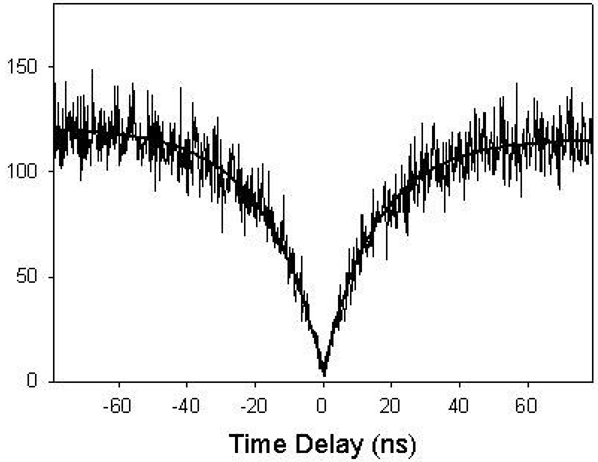
The discrete quantumness of light

Single-photon indivisibility



Measurement → antibunching

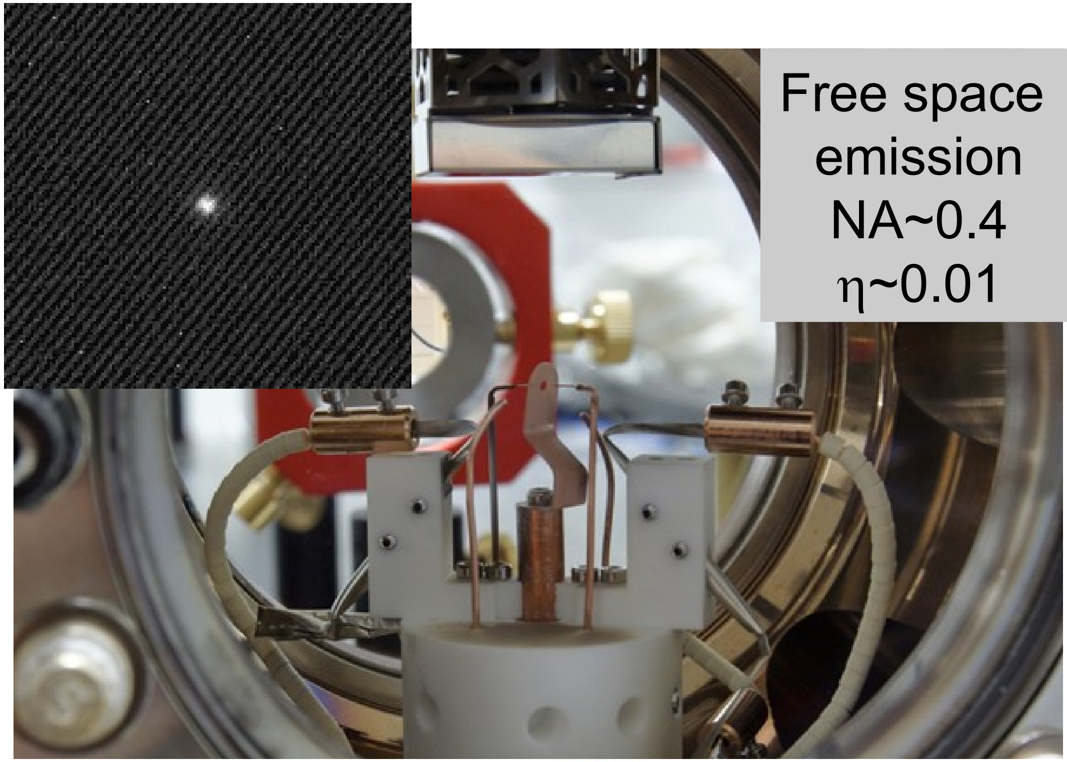




For $t = 0 \sim a = p_{coinc}/(p_A p_B)$ $a<1 \rightarrow$ nonclassicality

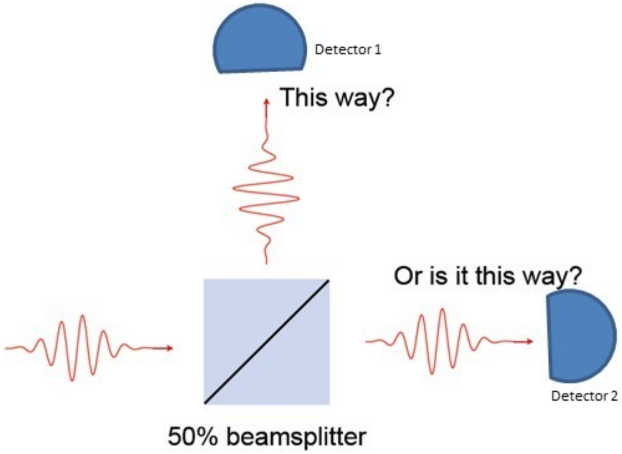
Nonclassical and quantum non-Gaussian light from a single ion

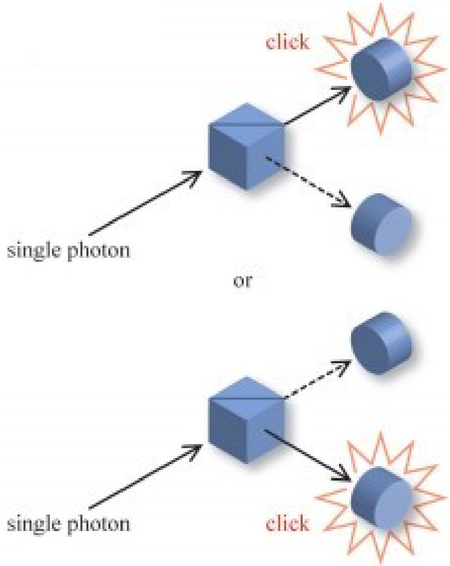
Single ion – single photon source



Free space emission
NA~0.4
η~0.01

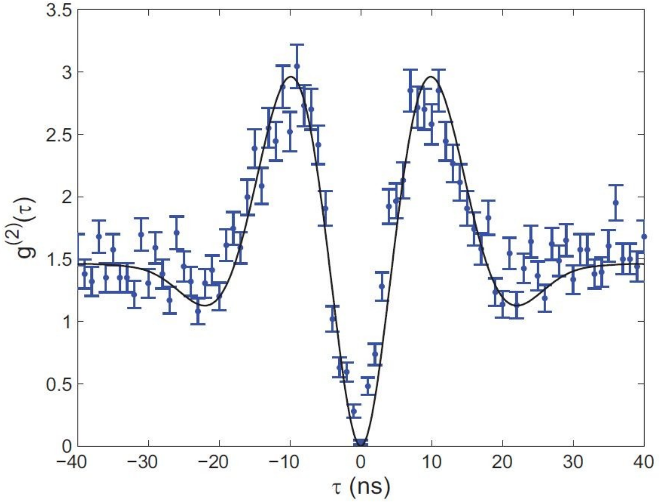
Single-photon indivisibility





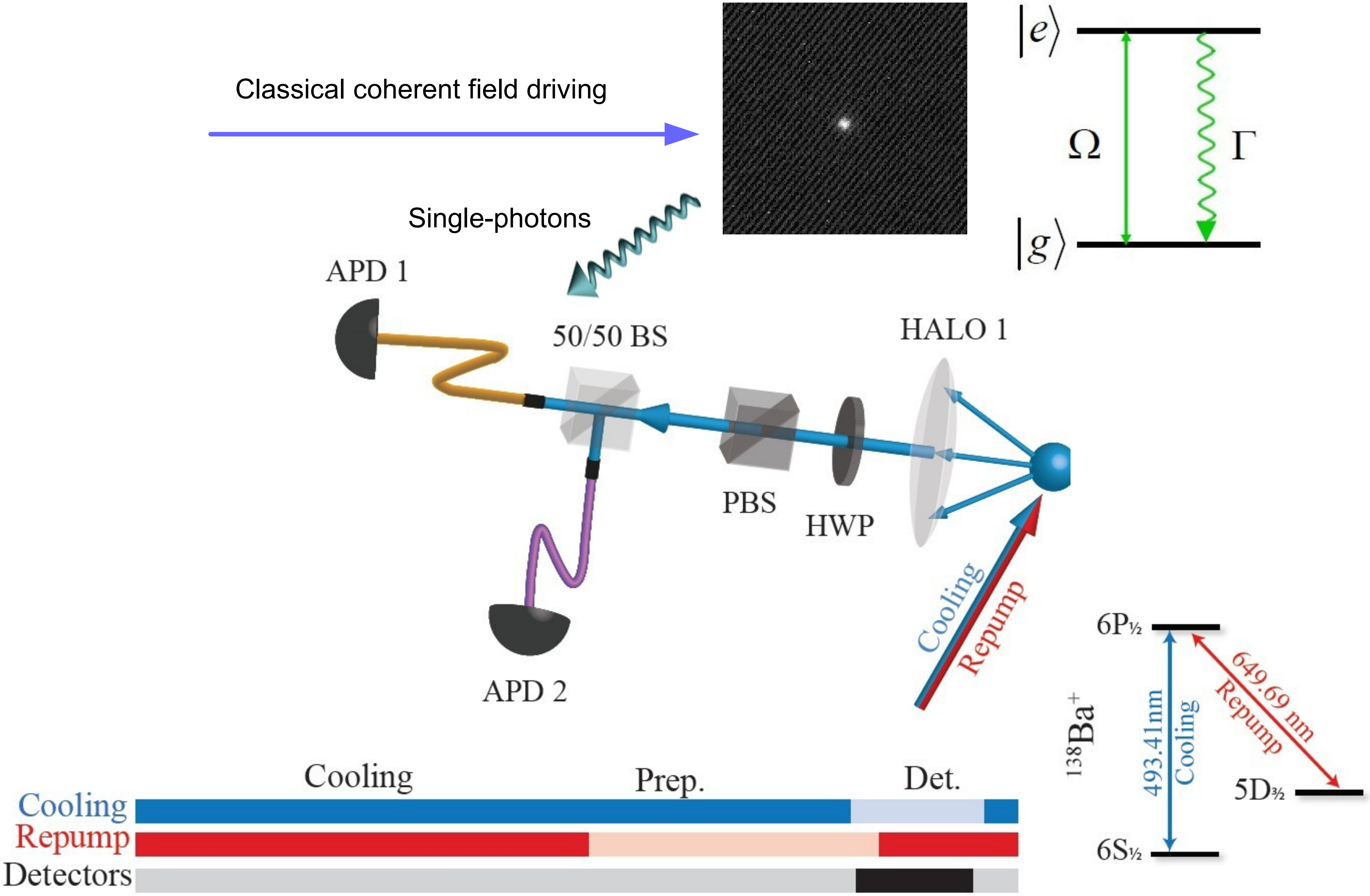
Basic CW measurement

→ antibunching



Multi-photon emission still possible (finite time bin)

Attenuated single photons with no noise



Classical coherent field driving

Single-photons

D. Higginbottom et al., New J. Phys. **18,** 093038 (2016)
P. Obšil et al., Phys. Rev. Lett. **120**, (2018)

Ba+, Innsbruck
Ca+, Olomouc

QNG of light - single ion

Purest single photon states demonstrated!

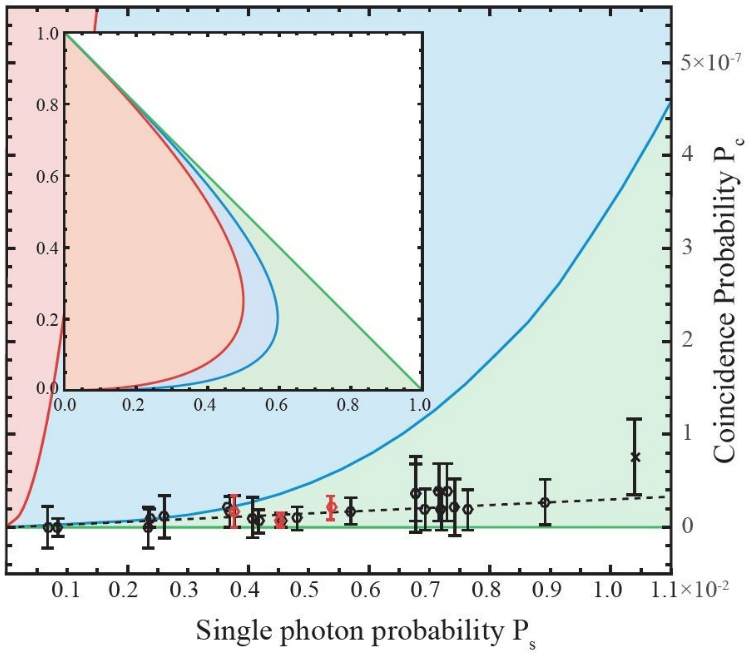
$g^2(0) = 1.9\times10^{-3}$

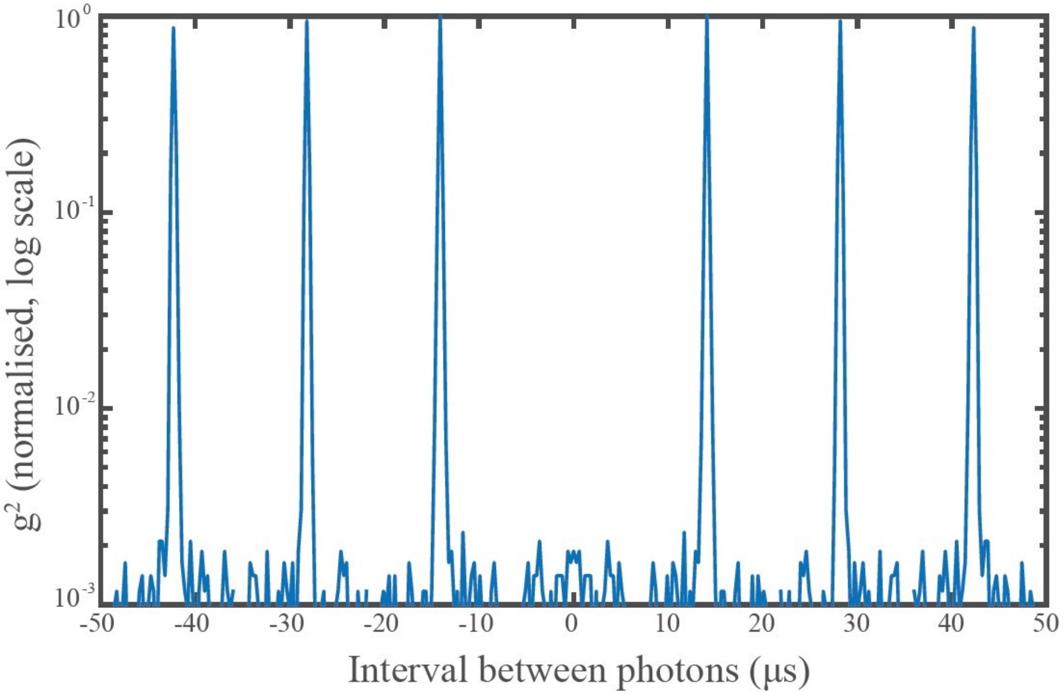
No background subtraction

$\eta = 0.0054$
Attempt rate: $7\times10^4\ s^{-1}$

The intrinsic $g^2(0)$
of single ion:
$g^2(0) < 3\times10^{-4}$

The residual noise
is exclusively caused
by detector dark counts



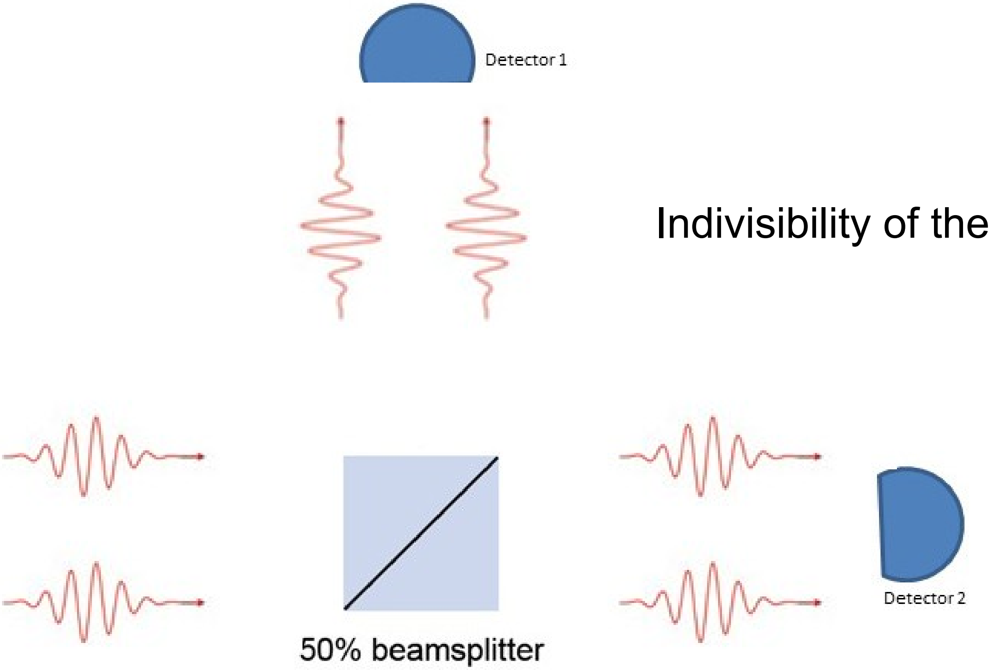


Quantum Non-Gaussian light from single atom in free space

D. B Higginbottom et al.,New J. Phys. ***18,*** *093038 (2016)*

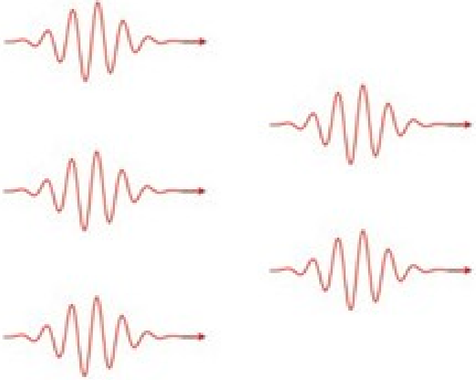
The discreete quantumness of light

What happens for two photons?



Indivisibility of the input state is lost

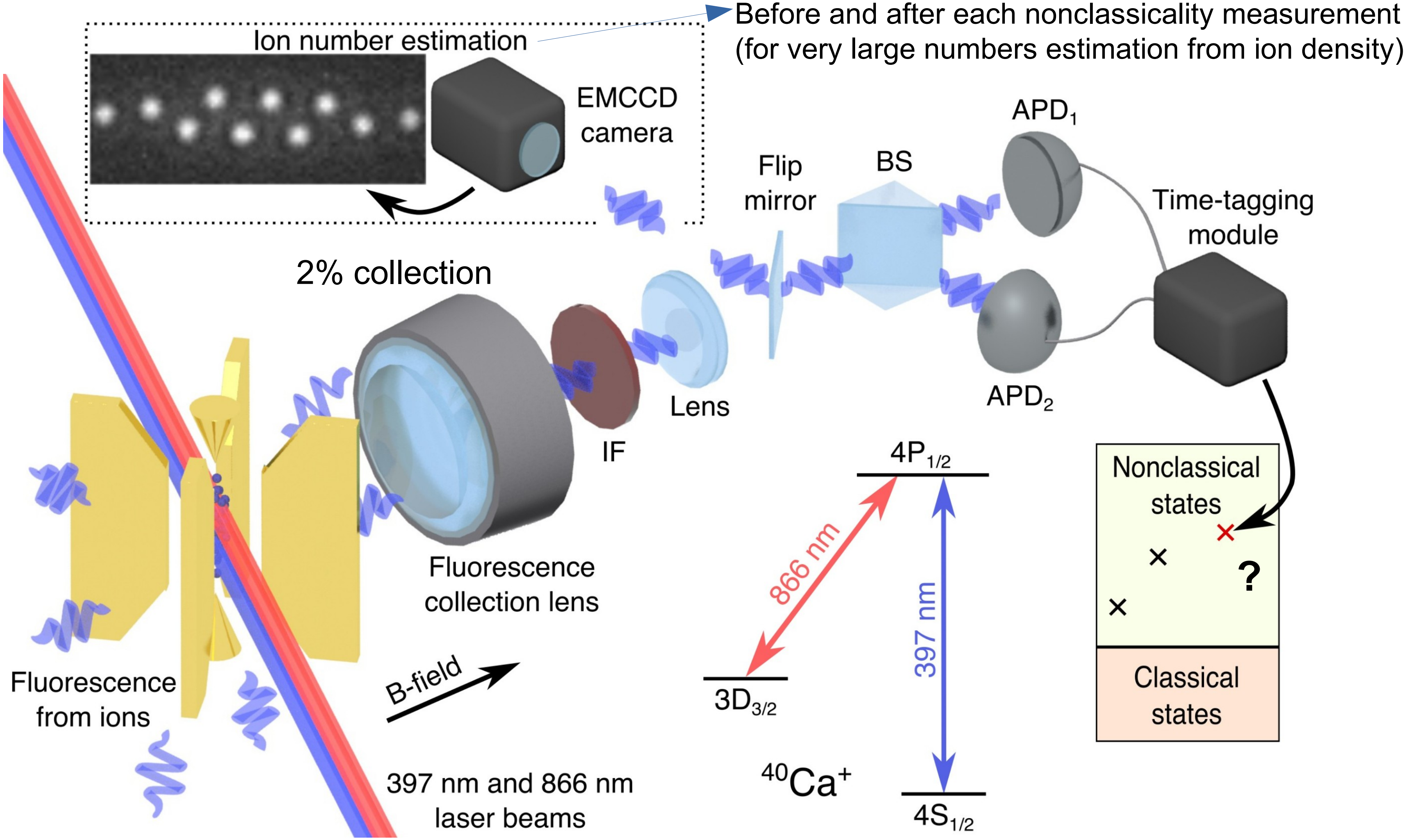
n-photon state input



$g^2(0)=1-1/n$

→ noclassicality is preserved in the ideal case

Measurements of coherence and statistics of light from large ion crystals

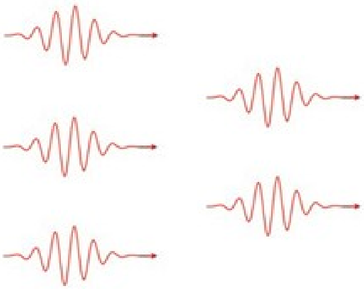


Measurement regimes
Pulsed → no multiphoton content from single ions
Continuous→ sensitive to detector jitter, emitters blinking, pumping efficiency fluctuations, finite time-bin

P. Obšil et al., PRL **120**, 253602 (2018)

Sub-Poissonian statistics from a large number of single photon emitters

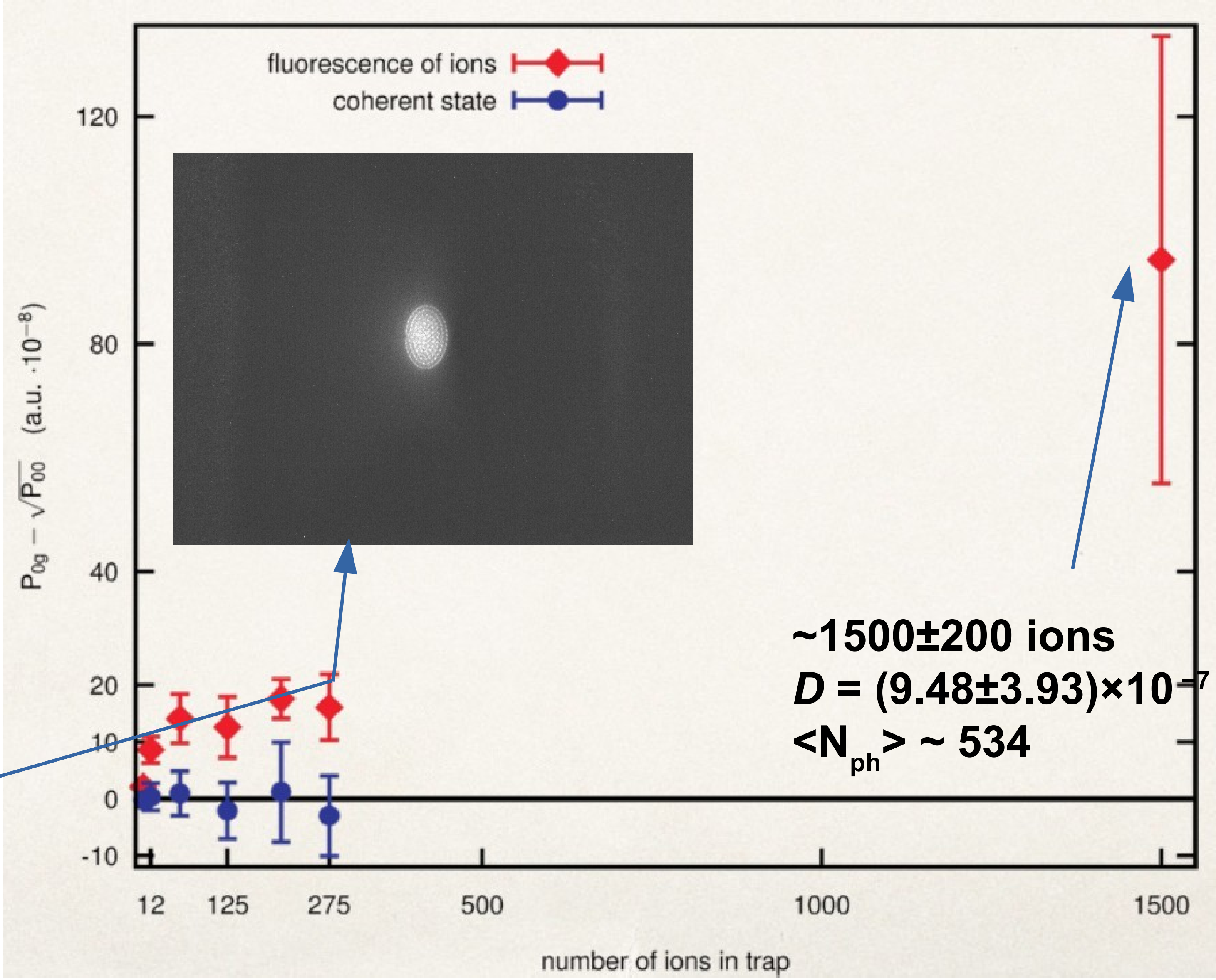
Pulsed
regime



n-photon state input

$g^2(0) = 1-1/n$

→ noclassicality is expected to be preserved



~1500±200 ions
$D = (9.48 \pm 3.93) \times 10^{-7}$
$\langle N_{ph} \rangle \sim 534$

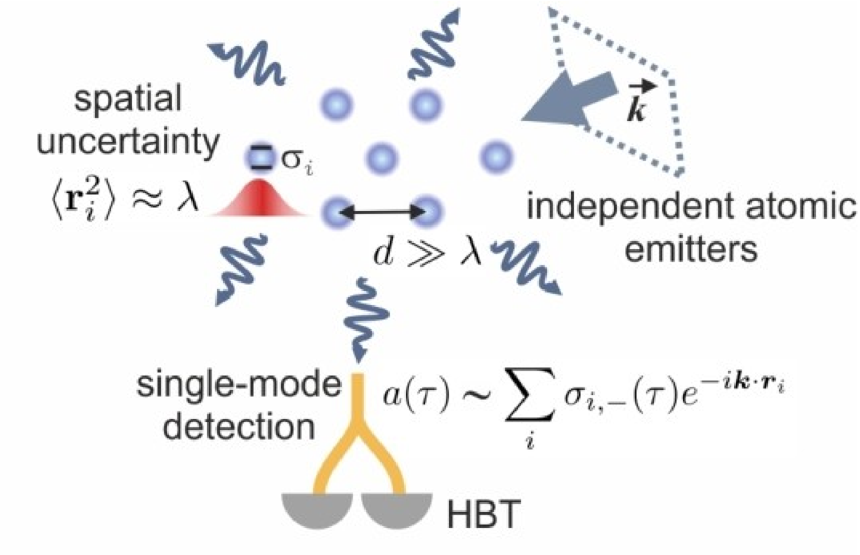
N_{ph} = 196 photons
for n = 275 ions
@ 71% optical
pumping efficiency

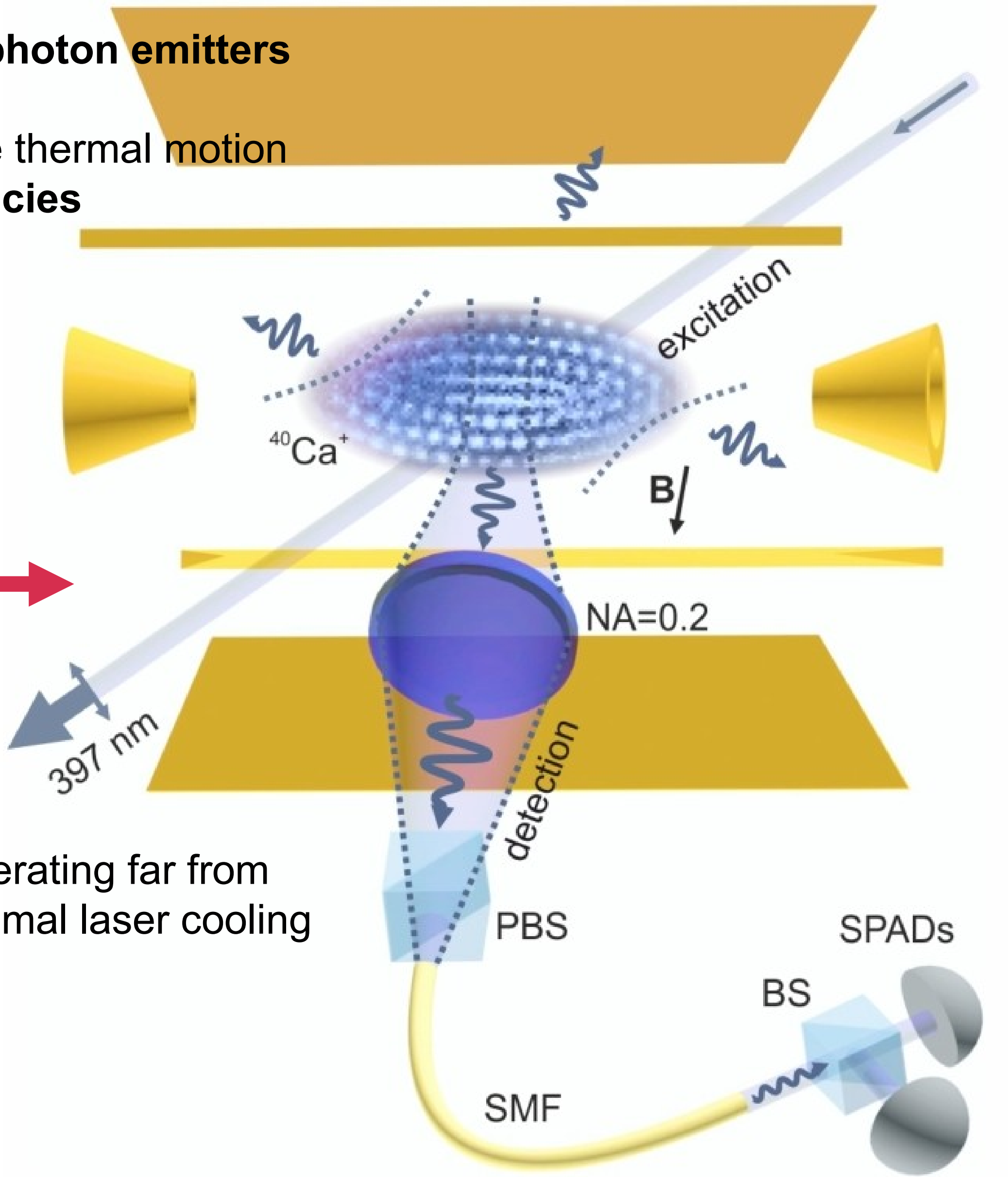
P. Obšil et al., PRL **120**, (2018)

Second-order coherence of light from ion crystals in a single optical mode

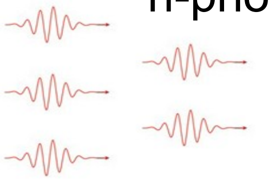
Conditions

- large and **stable number of independent single photon emitters**
- **no interference**
  → high saturation parameters and/or large thermal motion
- **efficient simultaneous photon detection efficiencies**
  in a single spatial optical mode





Operating far from optimal laser cooling



n-photon state

$g^2(0)=1-1/n$ ~ multi-mode relation → ??

A. Kovalenko et al., Optica 10(4), 456-463 (2023)

Intensity correlations from ion crystals in a single optical mode

Incoherent scattering from ensembles of N independent single-photon emitters

Classical single-mode theory

- in the limit of large number of scatterers → Siegert relation

$$\boxed{g^{(2)}(\tau)=1+\left|g^{(1)}(\tau)\right|^2 \qquad (N\gg 1)}$$

Emissiom from a finite ensembles of atoms is not chaotic!

Quantum formalism

$$a^\dagger(\tau)a^\dagger(0)a(\tau)a(0)=\left[\sum_i a_i^\dagger(\tau)a_i^\dagger(0)+\sum_{i\neq j}a_i^\dagger(\tau)a_j^\dagger(0)\right]\times \left[\sum_i a_i(\tau)a_i(0)+\sum_{i\neq j}a_i(\tau)a_j(0)\right],$$

$$G^{(2)}(\tau)=\sum_i G_i^{(2)}(\tau)+\sum_{i\neq j}\left\{G_i^{(1)}(\tau)\left[G_j^{(1)}(\tau)\right]^*+\bar{n}_i\bar{n}_j\right\}$$

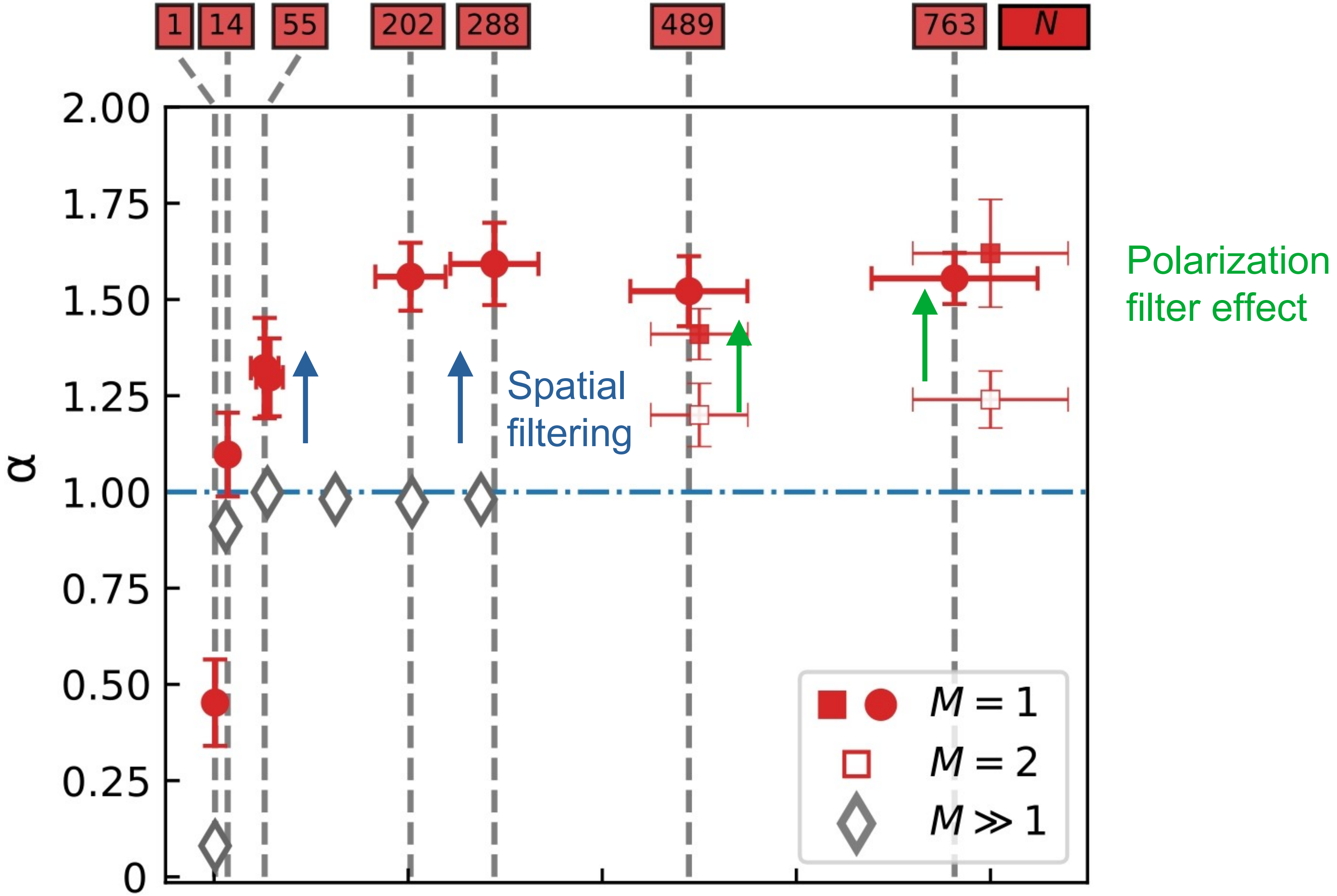
Single emitter coherences

$$\boxed{g^{(2)}(0)=\frac{\bar{g}^{(2)}(0)}{N}+\frac{N-1}{N}\left[|\bar{g}^{(1)}(0)|^2+1\right]}$$

- **Transition from sub-Poissonian to super-Poissonian**
- **$g^{(2)}(0)>1$ requires indistinguishability and first order coherence**

A. Kovalenko et al., Optica 10(4), 456-463 (2023)

Photon correlations from ion crystals in a single optical mode



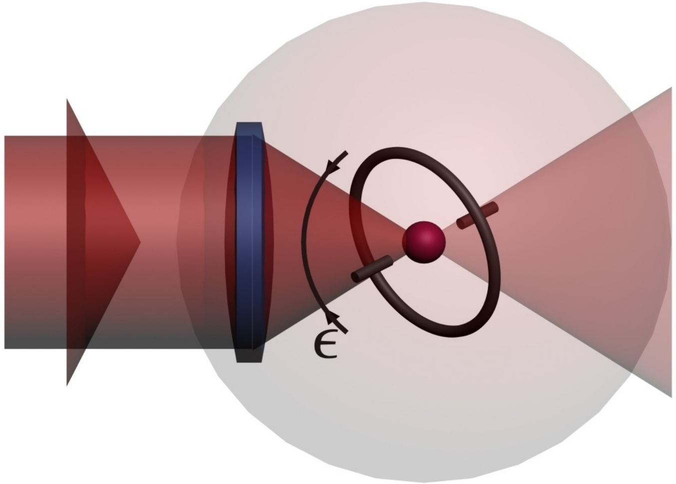
- Emergence of the second-order coherence at the level of individual atoms

$$g^{(2)}(\tau) = \frac{\bar{g}^{(2)}(\tau)}{N} + \frac{N-1}{N}\left[|\bar{g}^{(1)}(\tau)|^2 + 1\right]$$

- Super-Possonian light from stable (fixed) number of single-photon emitters proves their indistinguishable and coherent contributions

A. Kovalenko et al., Optica 10(4), 456-463 (2023)

Trapped ion – nonclassical light sources in free space

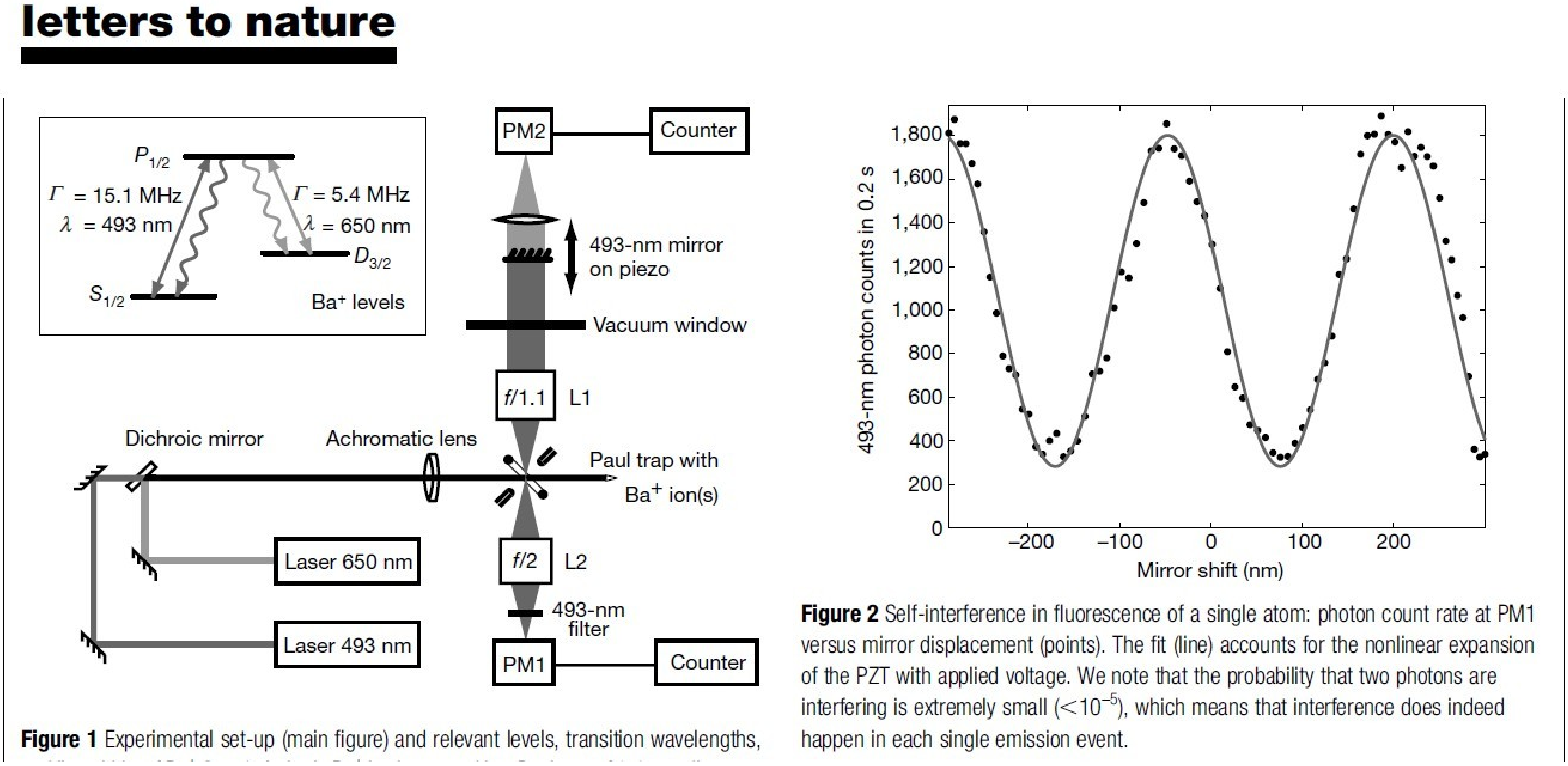


Overall free space collection efficiency is very low!
η ~ few percent

Phase-coherence of light scattered from ions

Ions can be deep in the Lamb-Dicke regime after basic laser cooling

J. Eschner et al., Nature **413**, 495 (2001)



letters to nature

Figure 1 Experimental set-up (main figure) and relevant levels, transition wavelengths,

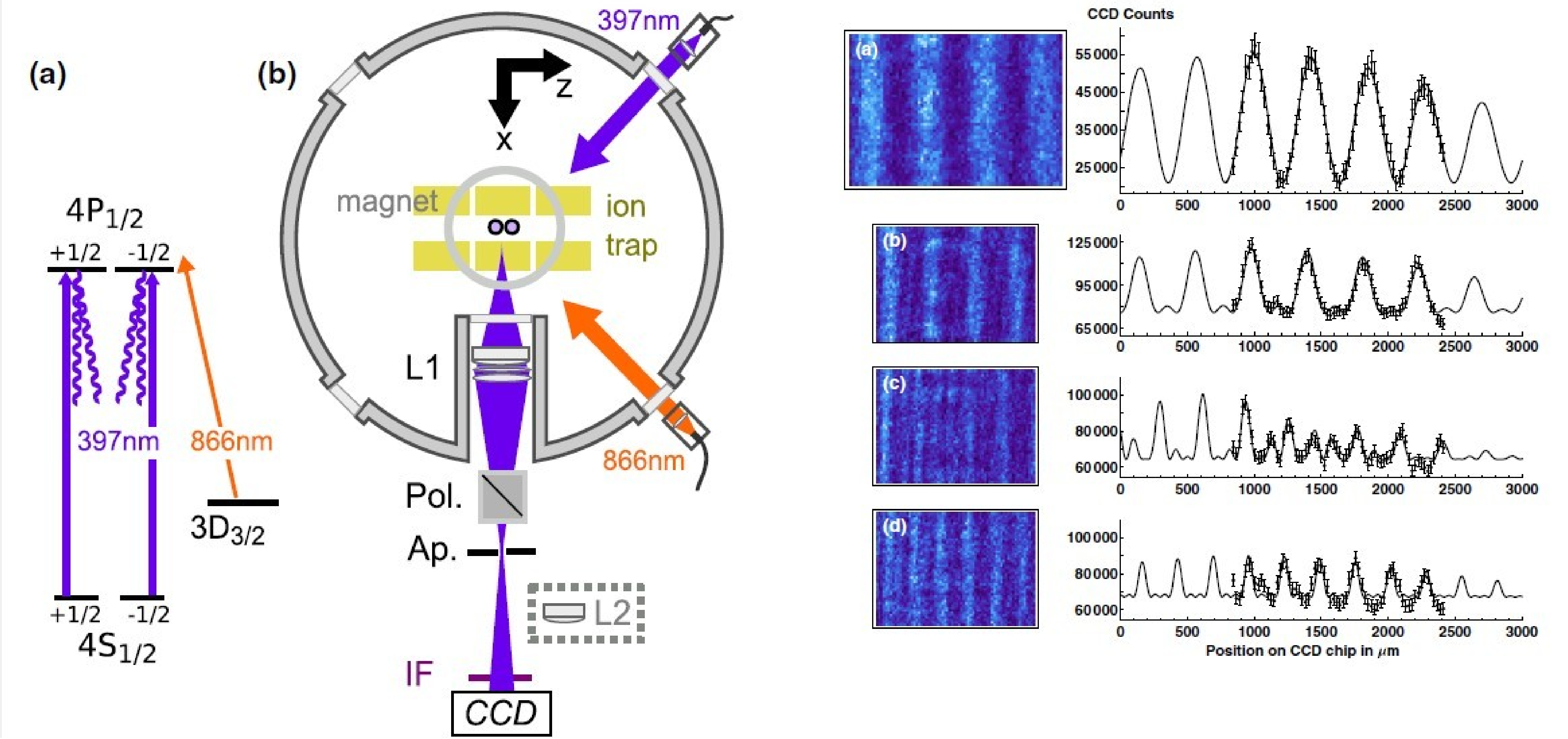
Figure 2 Self-interference in fluorescence of a single atom: photon count rate at PM1 versus mirror displacement (points). The fit (line) accounts for the nonlinear expansion of the PZT with applied voltage. We note that the probability that two photons are interfering is extremely small ($<10^{-5}$), which means that interference does indeed happen in each single emission event.

See also U. Eichmann et al., PRL **70**, 2359 (1993) for first interference with two ions, and experiments from **Ba+ experiment, R. Blatt, Innsbruck,**
S. Wolf et al, Phys. Rev. Lett. 116, 183002 (2016),...

Phase-coherent scattering from several ions in radial trapping direction

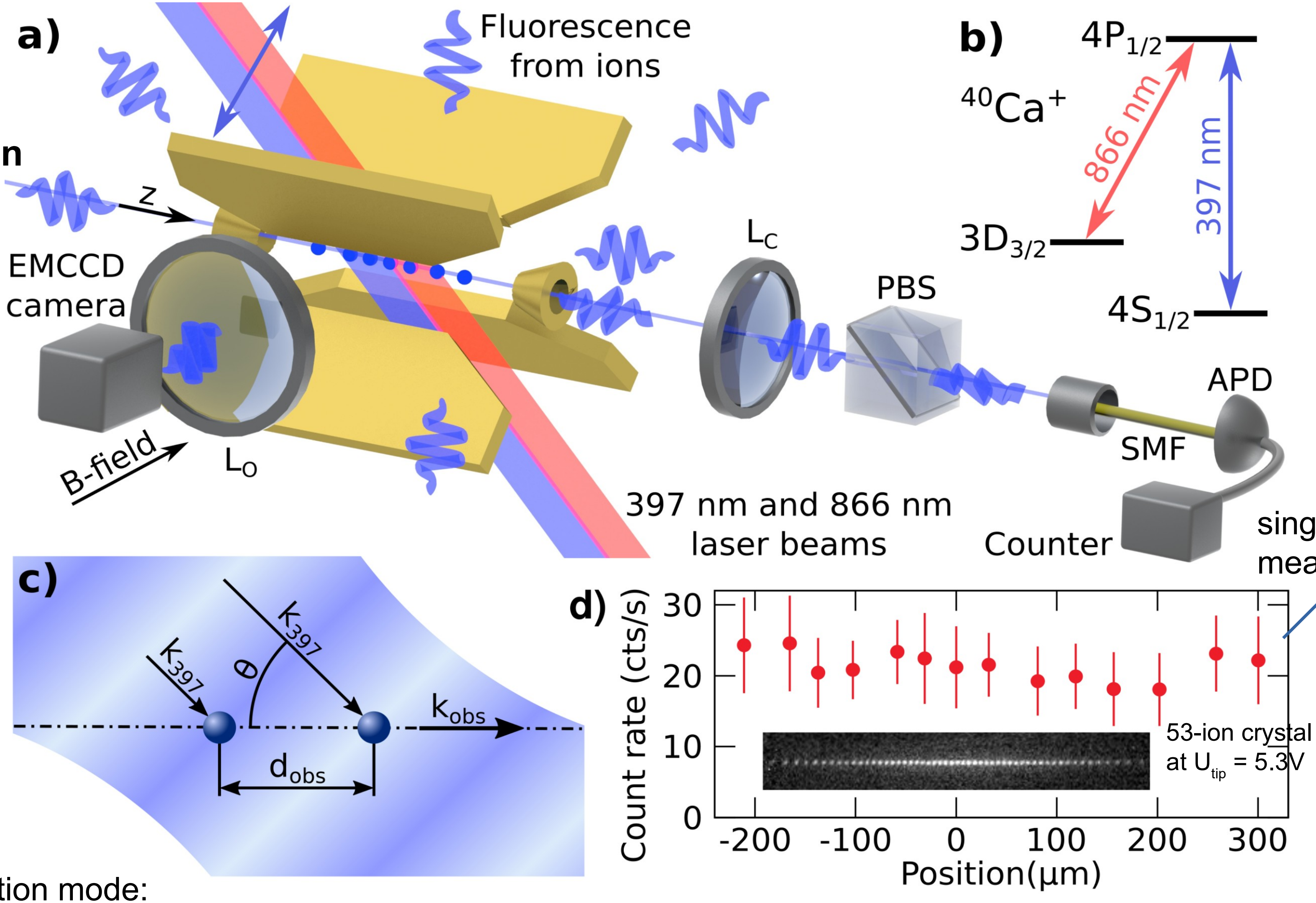
F. Schmidt-Kaler (Mainz)

PRL **116,** 183002 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016



Scallable coherent scattering of light from many ions

Axial detection



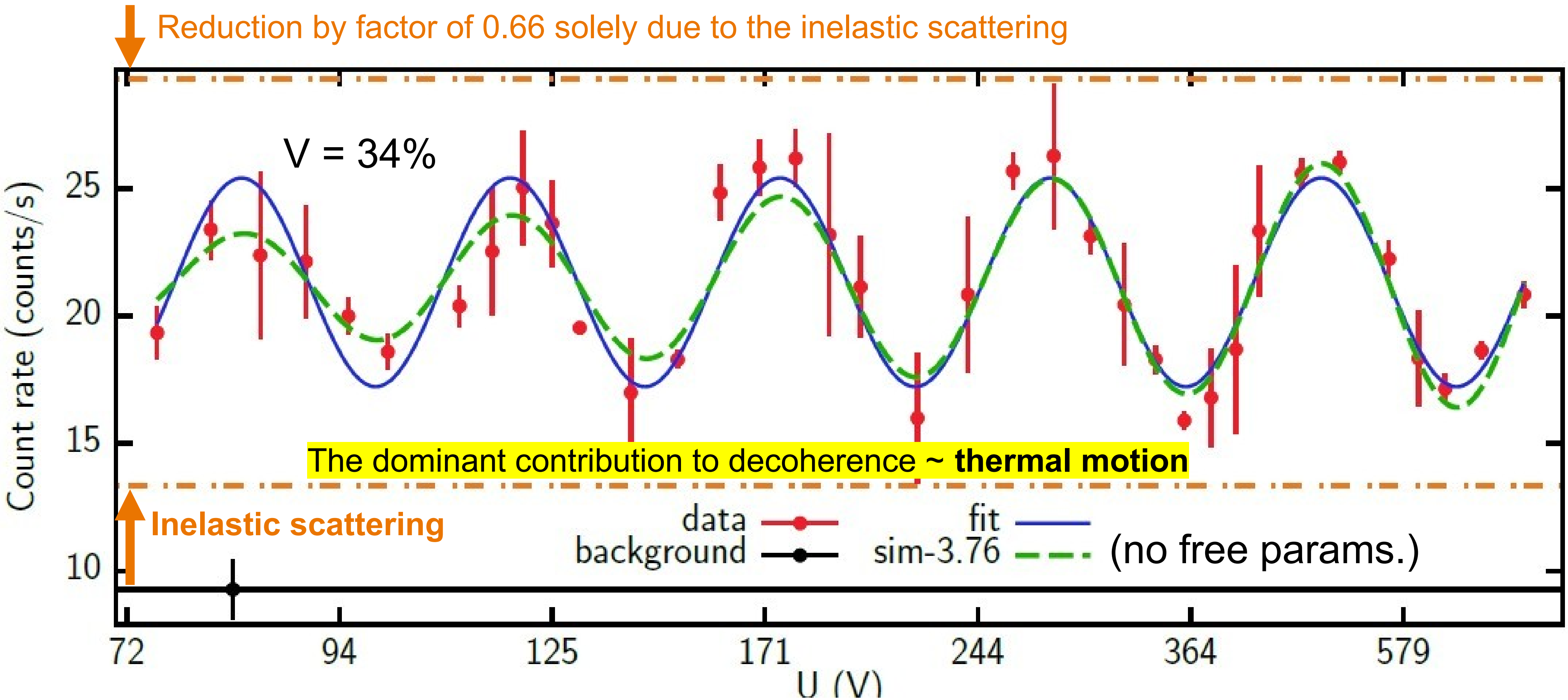
single ion measurement

Observation mode:
z_r=2.4 mm and w=17.4 um → **Hundreds of ions can contribute equally!**

Current measurements~100 times higher count rate

New setup (work in progress) ~ additional factor of 10 improvement

Interference - two ions



Reduction by factor of 0.66 solely due to the inelastic scattering

V = 34%

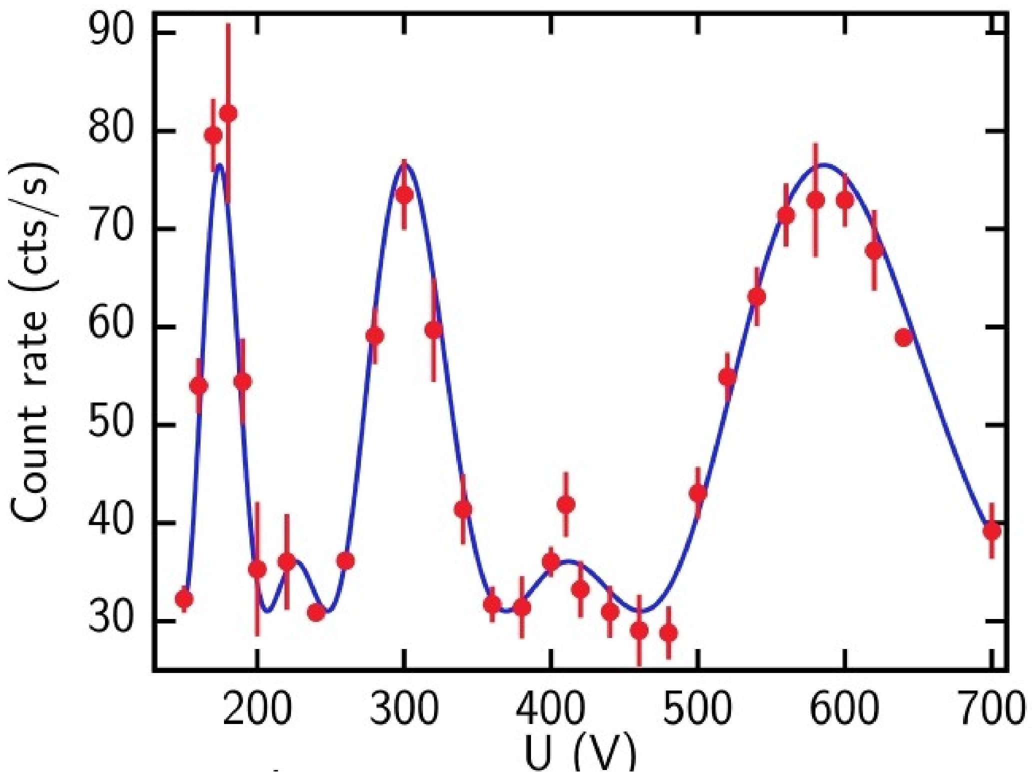
The dominant contribution to decoherence ~ **thermal motion**

Inelastic scattering

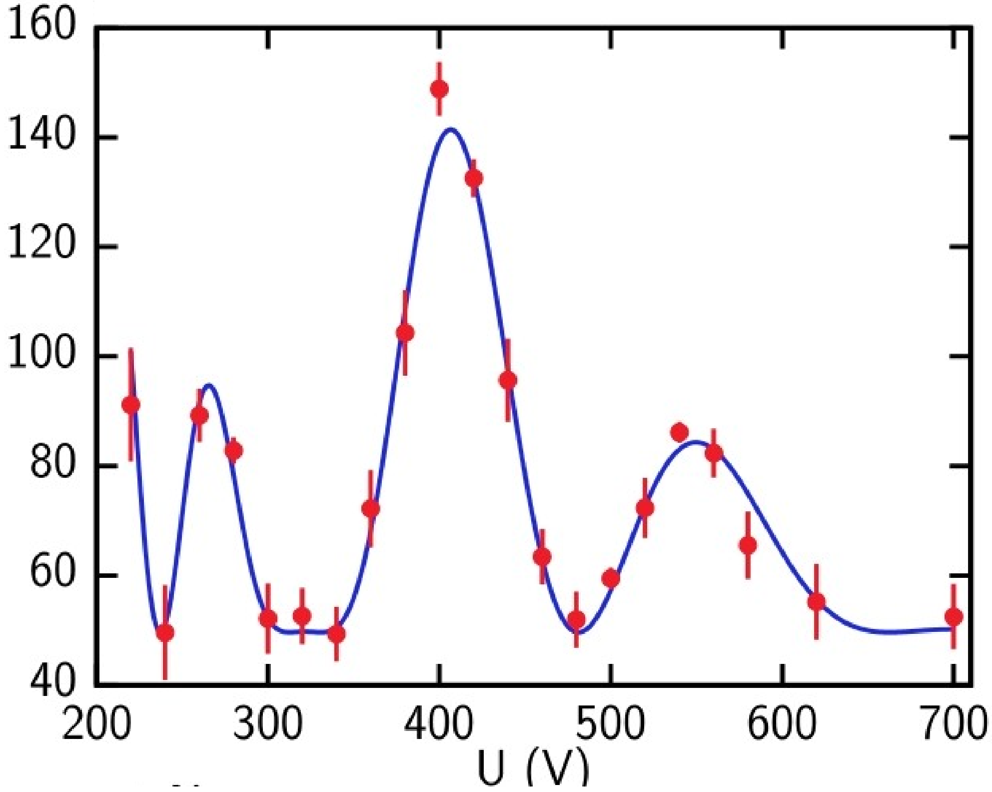
(no free params.)

P. Obšil et al., New J. Phys. 21 093039 (2019)

Coherent scattering from 3 and 4 ions



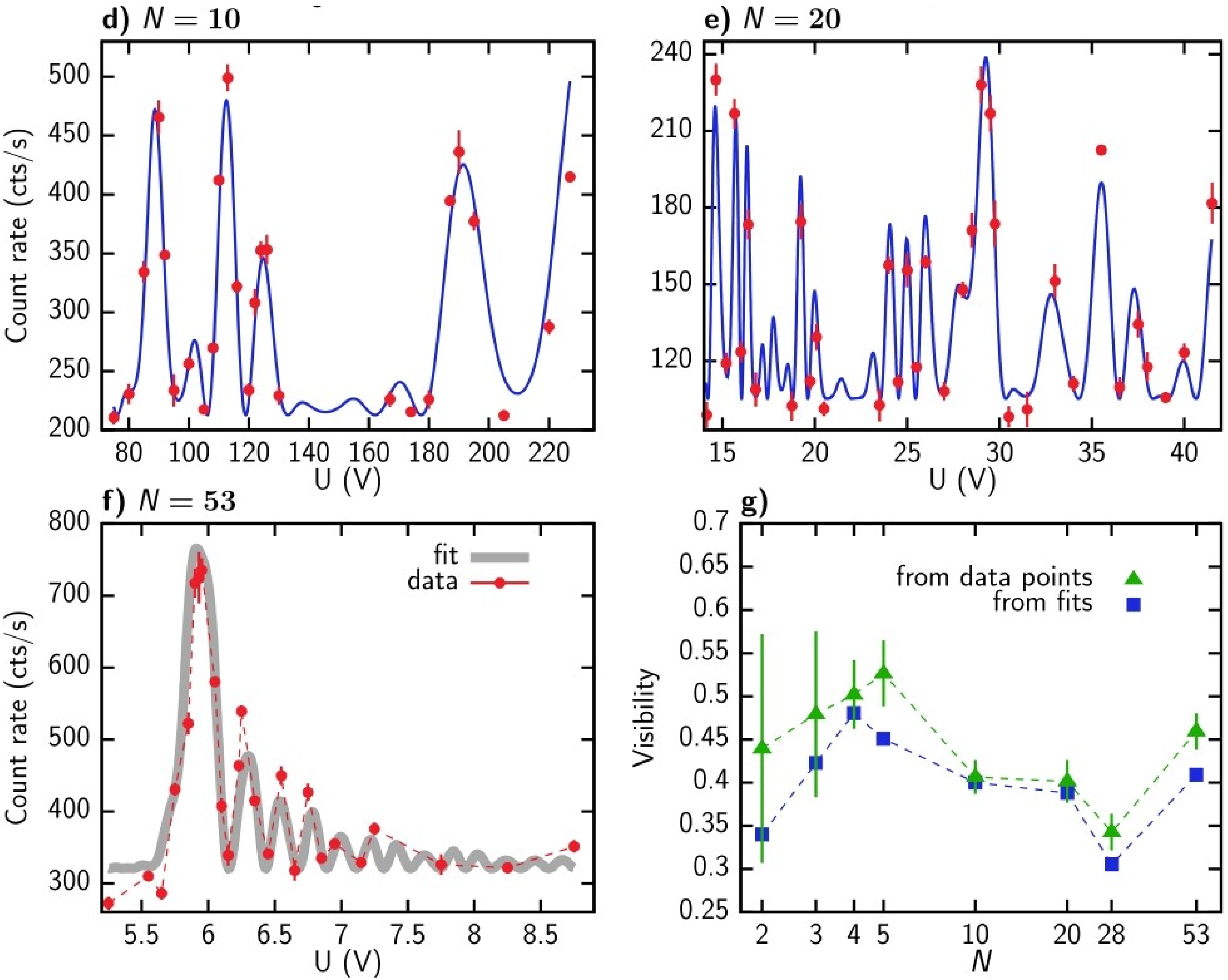
Equidistant



Non-equidistant scatterers

P. Obšil et al., New J. Phys. 21 093039 (2019)

Interference from many ions



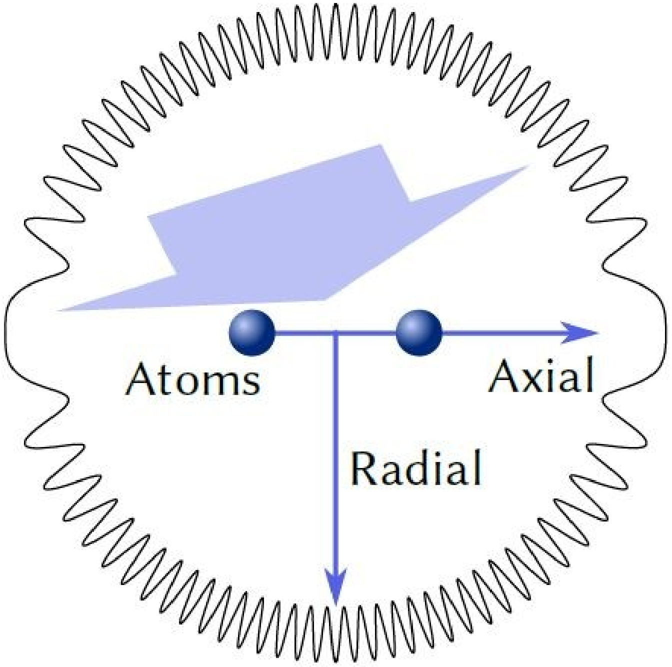
The visibility does not decrease!

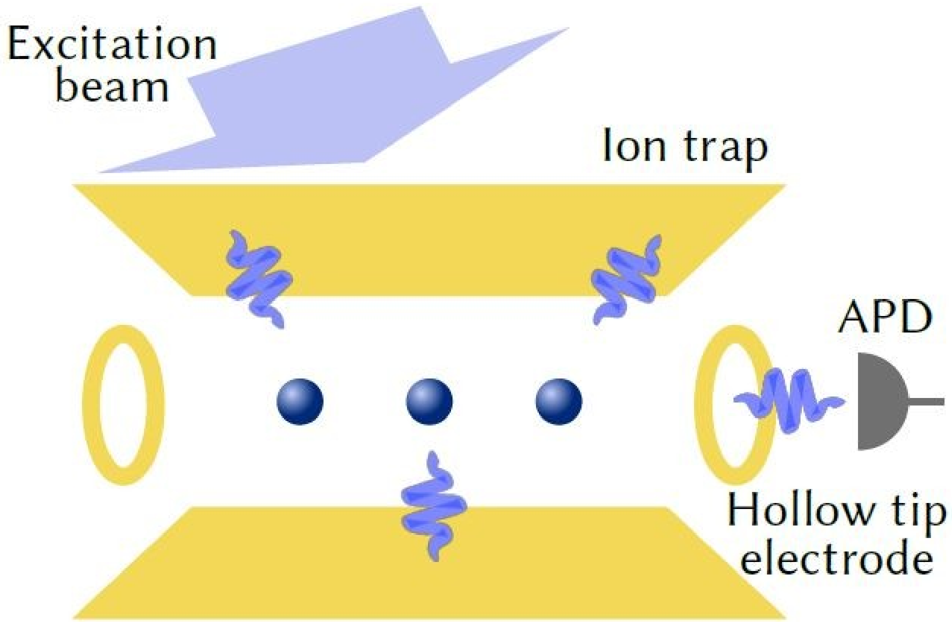
Individual coherent contributions are provable for up to 20-ion strings

Obšil et al., New J. Phys. **21** 093039 (2019)

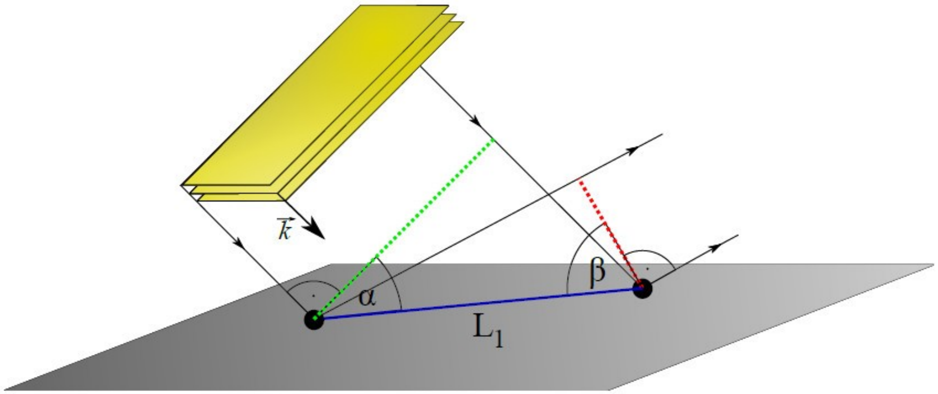
Collective enhancement of the fluorescence collection efficiency from trapped ion strings

Directionality from constructive interference in a far field

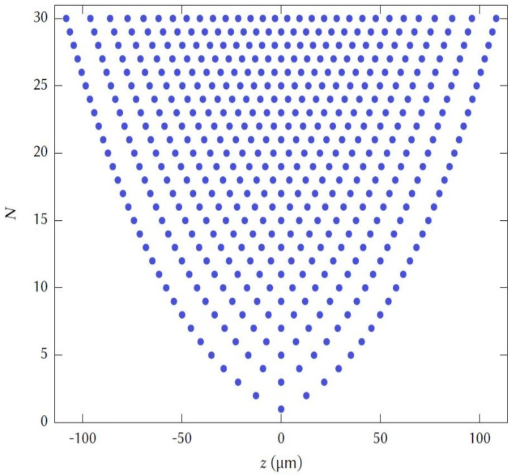




Model of noninteracting point scattterers



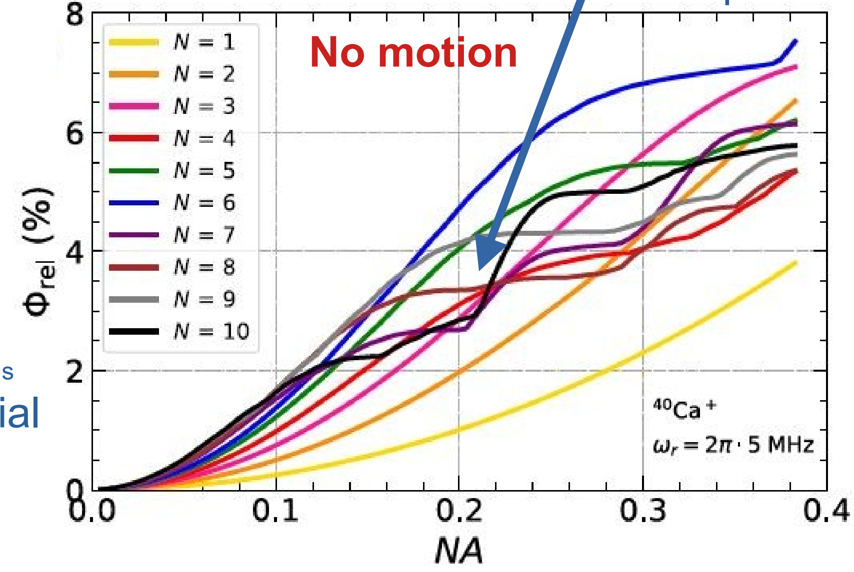
...with realistic positions, thermal motion, dipolar emission, and realistic trapping limits



Collective enhancement of the fluorescence collection efficiency from trapped ion strings

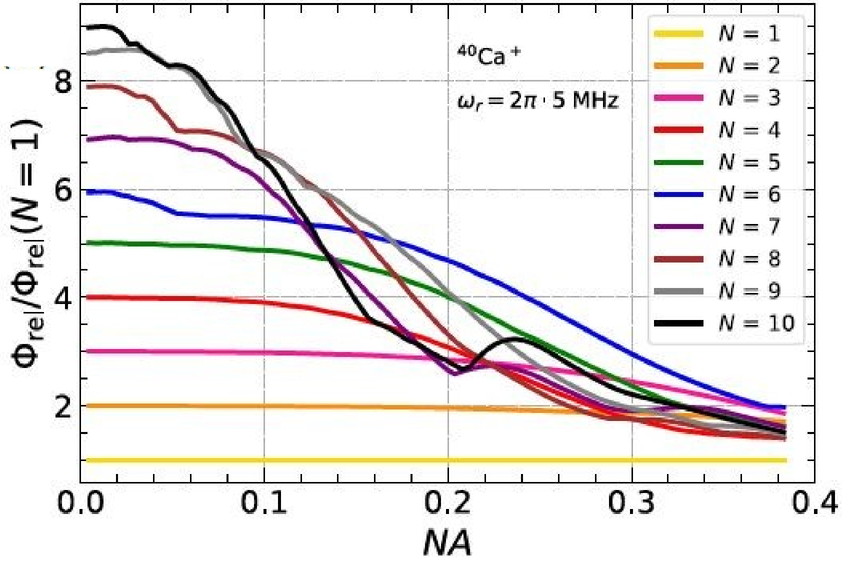
Relative radiant flux Φ_{rel}

Intensity minima in 3D patterns

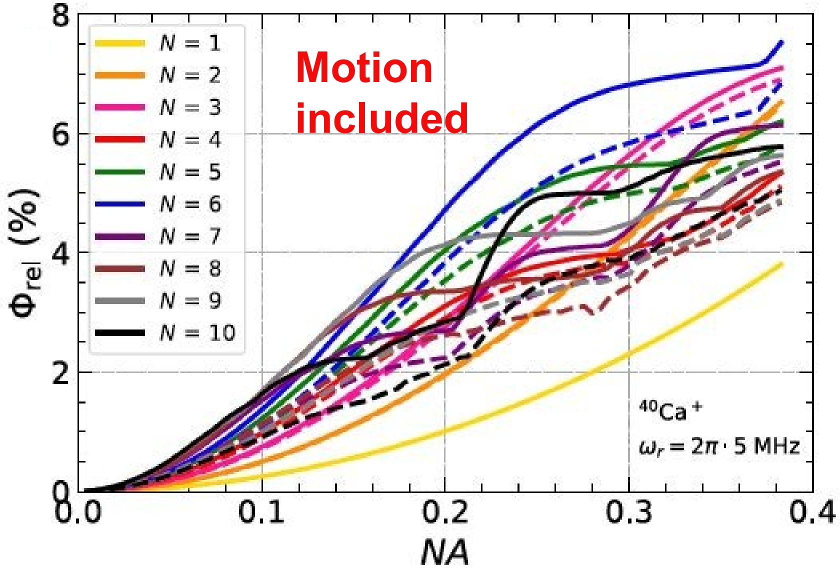


No motion

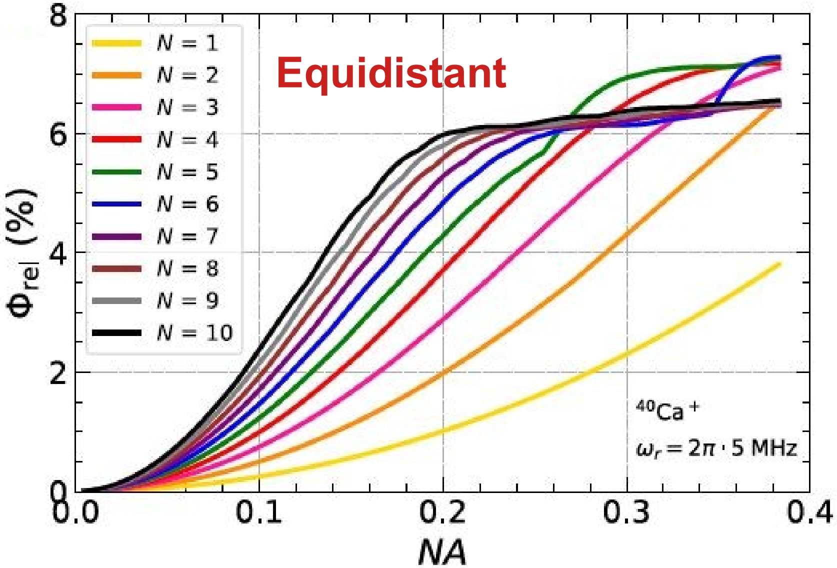
Optimal N_{ions} for practically interesting range of NA is feasible!



Large N_{ions} is beneficial for very small NA



Motion included

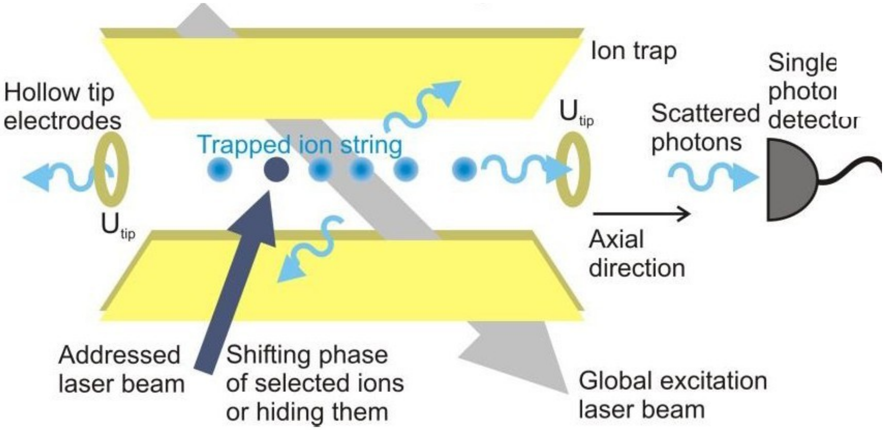


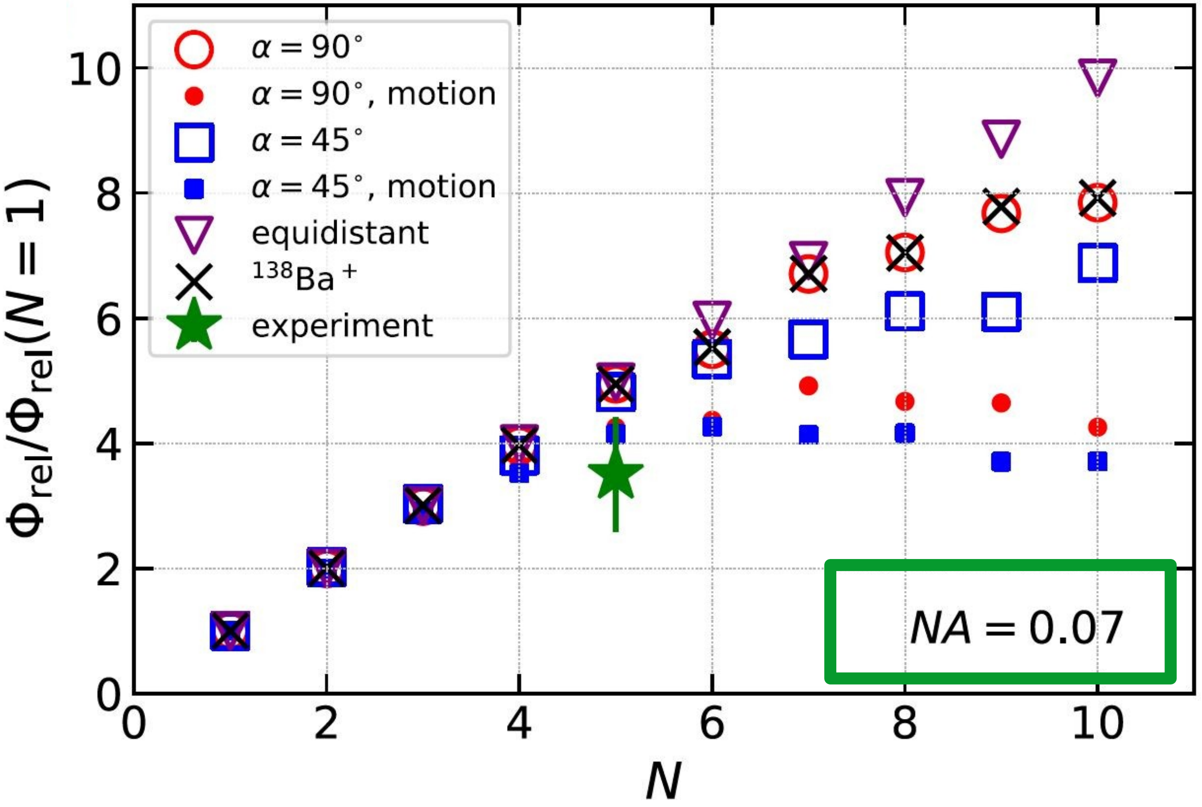
Equidistant

- Feasible configurations with about 2 % of fluorescence in NA ~ 0.1 (**~ 0.2 % of 4π**), $N_{ions} < 10$

~ NA=0.3 for a single atom in free space

Experimental demosntration of collective atomic antenna





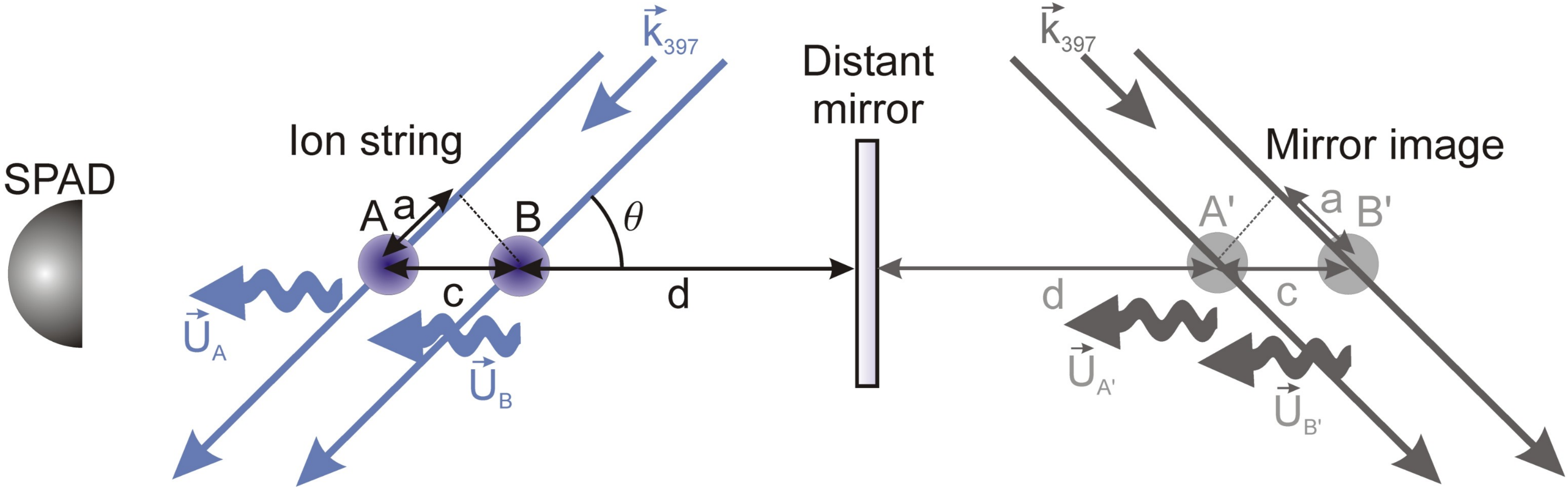
Near - optimal coherent enhancement of collection efficiency demonstrated

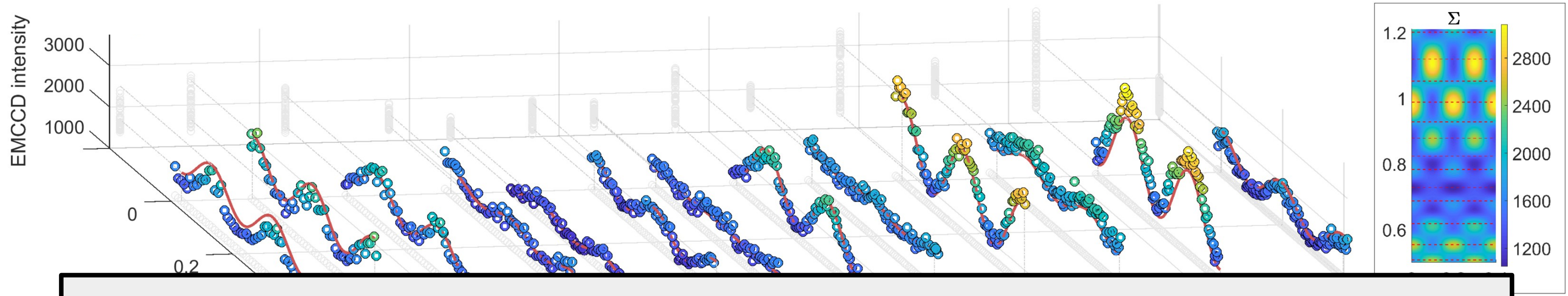
Common harmonic trap is NOT imposing limit on the feasible directionality

- At Doppler cooling limit harmonic and equidistant cases give similar enhancements

Feasibility if a full addressable control of relative phases of the contributing atomic dipoles

Interference of ion strings and their mirror images





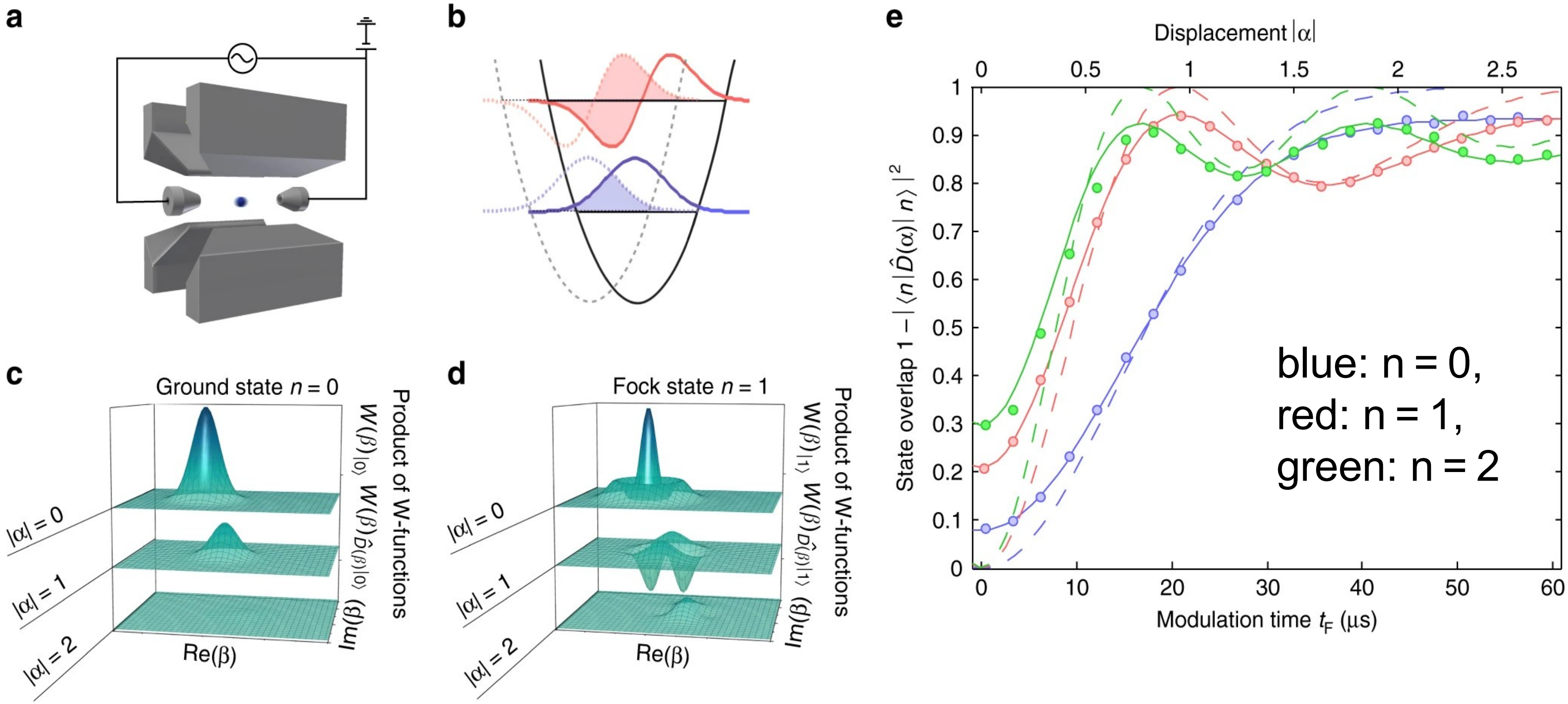
Interference between two atomic mirror images (virtual dipoles) demonstrated!

Collective QED effects feasible in this regime, even for small NA!

Quantum enhanced sensing of forces acting on ion

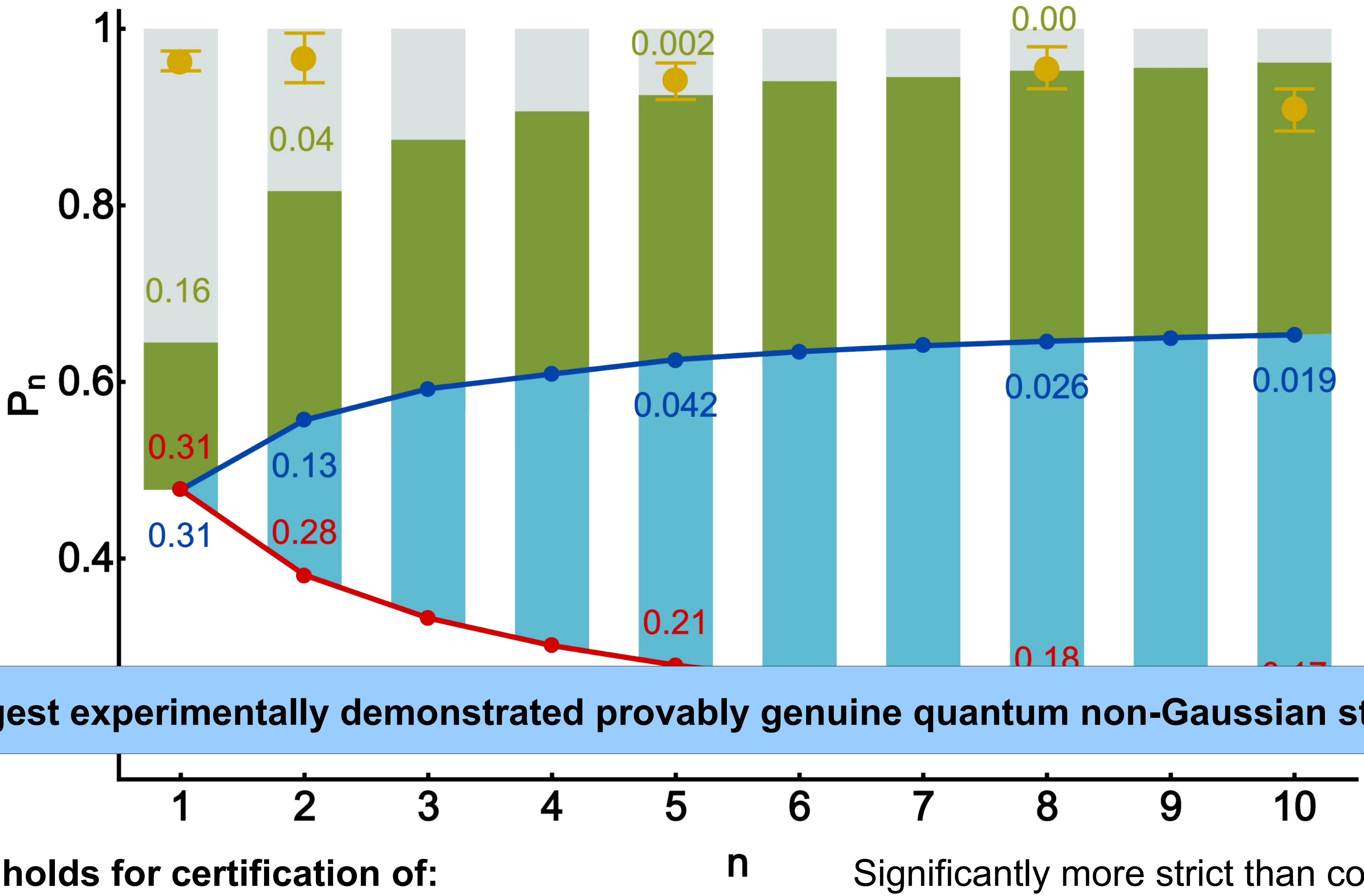
*F. Wolf et al.,
Nat. Comm.* ***10****,
2929 (2019)*

Estimation of a displacement amplitude



blue: n = 0,
red: n = 1,
green: n = 2

Genuine quantum non-Gaussianity of Fock states



Largest experimentally demonstrated provably genuine quantum non-Gaussian states!

Thresholds for certification of:

- **general QNG**
- **genuine QNG**
- **metrological advantage** for sensing of small displacements

Significantly more strict than conditions on negativity of Wigner function

Phys. Rev. Lett. **129**, 013602 (2022)

Application - force estimation capability

- metrological advantage of experimentally realized states **against the vacuum state** for a **phase-independent** sensing of a small force ~ displacement in phase-space

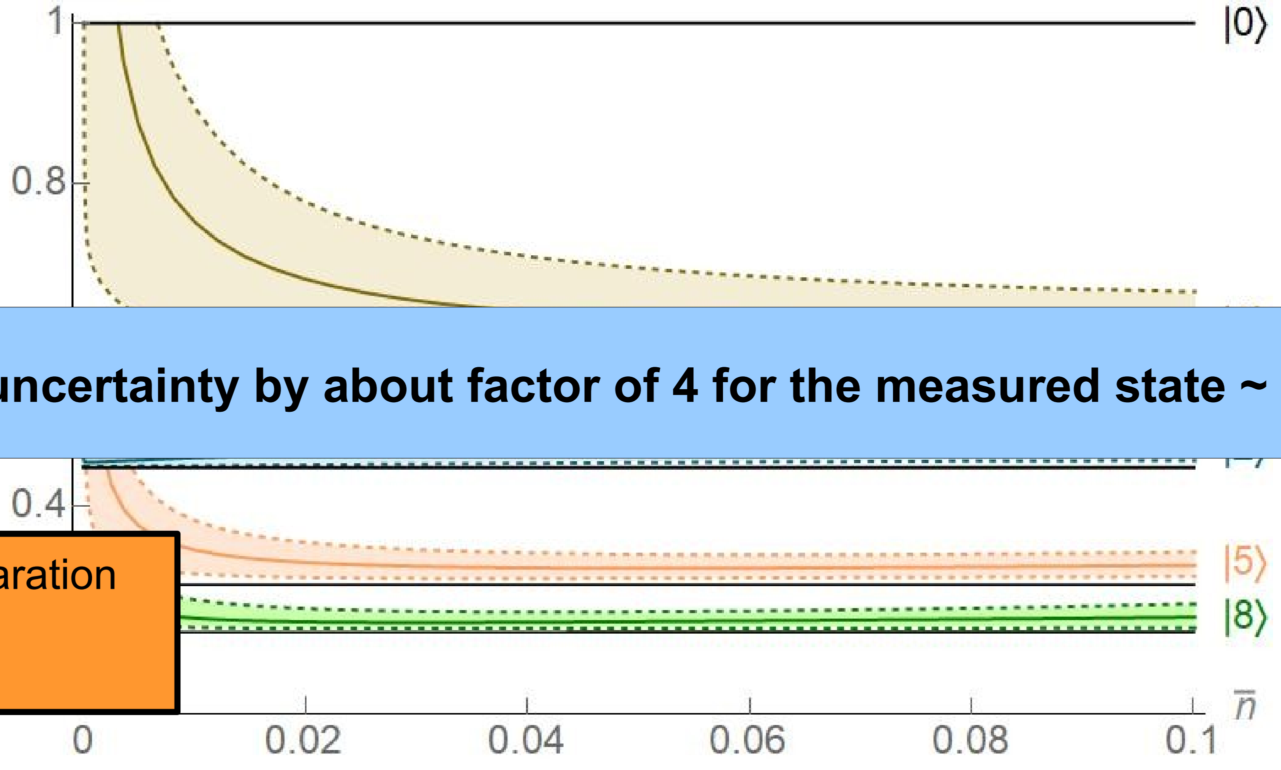
- Fisher information for the estimation of the parameter $\bar{n} = |\alpha|^2$

$$F = \sum_{n=0}^{\infty} \frac{1}{p_n(\bar{n})} \left[\frac{\partial}{\partial_{\bar{n}}} p_n(\bar{n}) \right]^2 \qquad p_n(\bar{n}) = \langle n | D(\sqrt{\bar{n}}) \rho D^\dagger(\sqrt{\bar{n}}) | n \rangle$$

We evaluate σ saturating the Cramér-Rao bound $\sigma^2 \geq 1/(NF)$

N=number of samples
(independent observations)

Quantum enhanced force estimation capability



Suppression of uncertainty by about factor of 4 for the measured state ~ Fock |8>!

Work in progress: preparation and estimation of up to **Fock |40>**

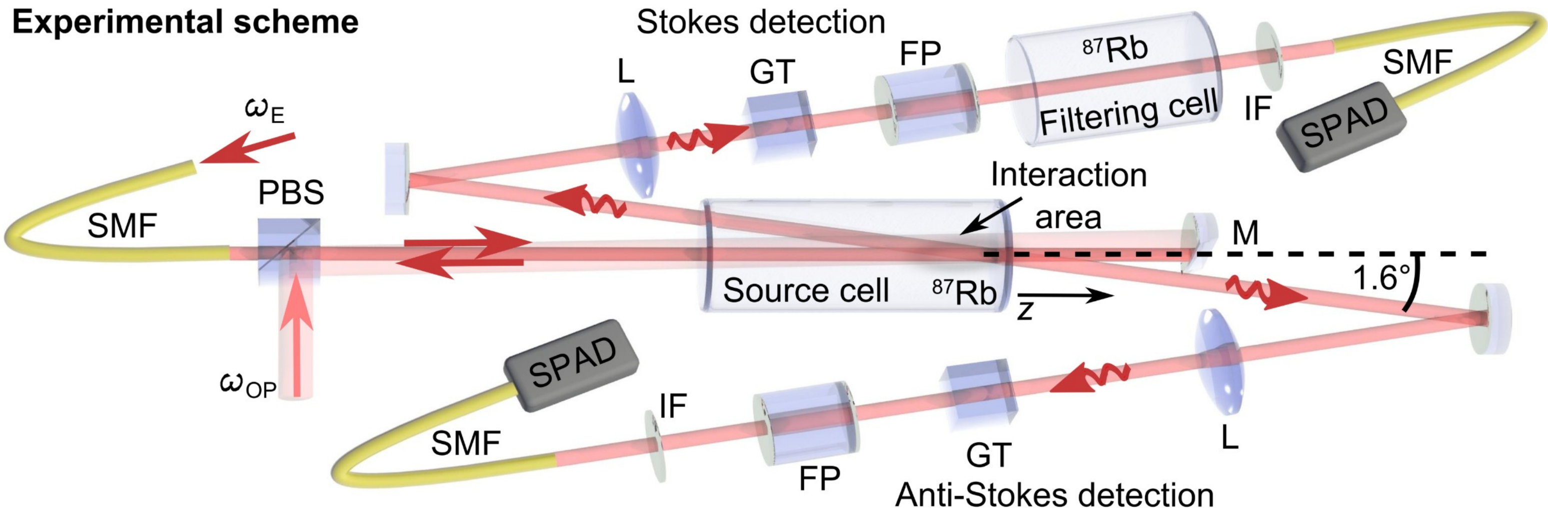
Phys. Rev. Lett. **129**, 013602 (2022)

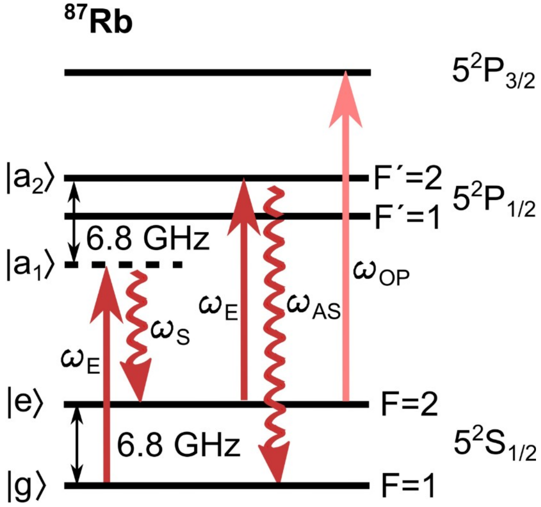
See also F. Wolf et al., Nat. Comm. **10**, 2929 (2019)

Nonclassicality and QNG of light from SFWM in warm atomic vapors

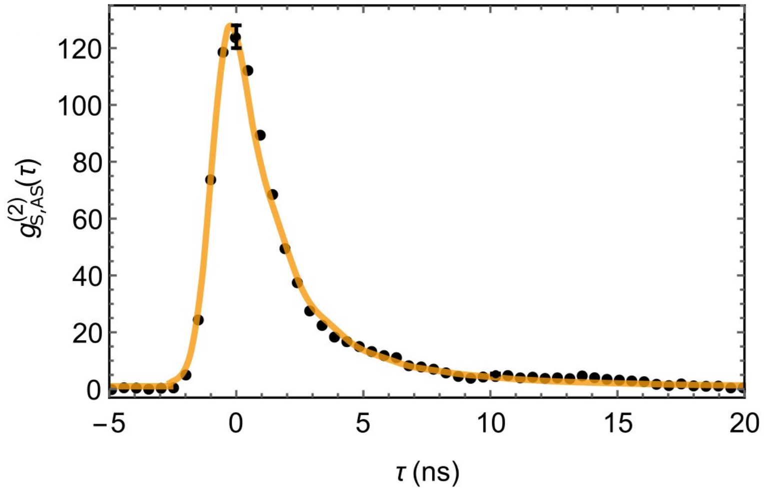
Goal: source of a single-mode QNG light capable of efficient interaction and storage
Challenge: large thermal motion of Rb

Experimental scheme





Photon correlations between Stokes and anti-Stokes



- $g^{(2)}_{S,AS}(0)$ ~ 100 to 190
- Biphoton rate (detected) ~ 3000 coinc/s
- @ 5 ns coinc. window
- anti-Stokes spectrum can be matched to target atomic ensemble (our implementation includes broadband EIT-memory)
- single-mode regime

npj Quantum Information **8**, 123 (2022)

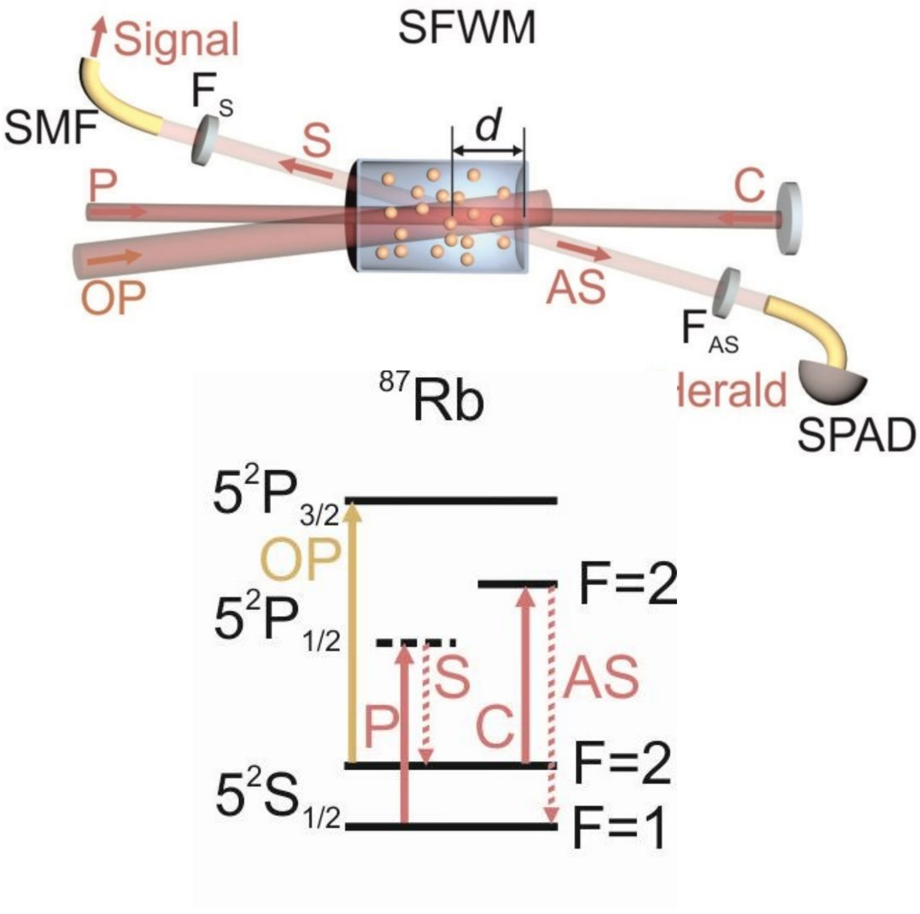
QNG light from warm atomic vapors

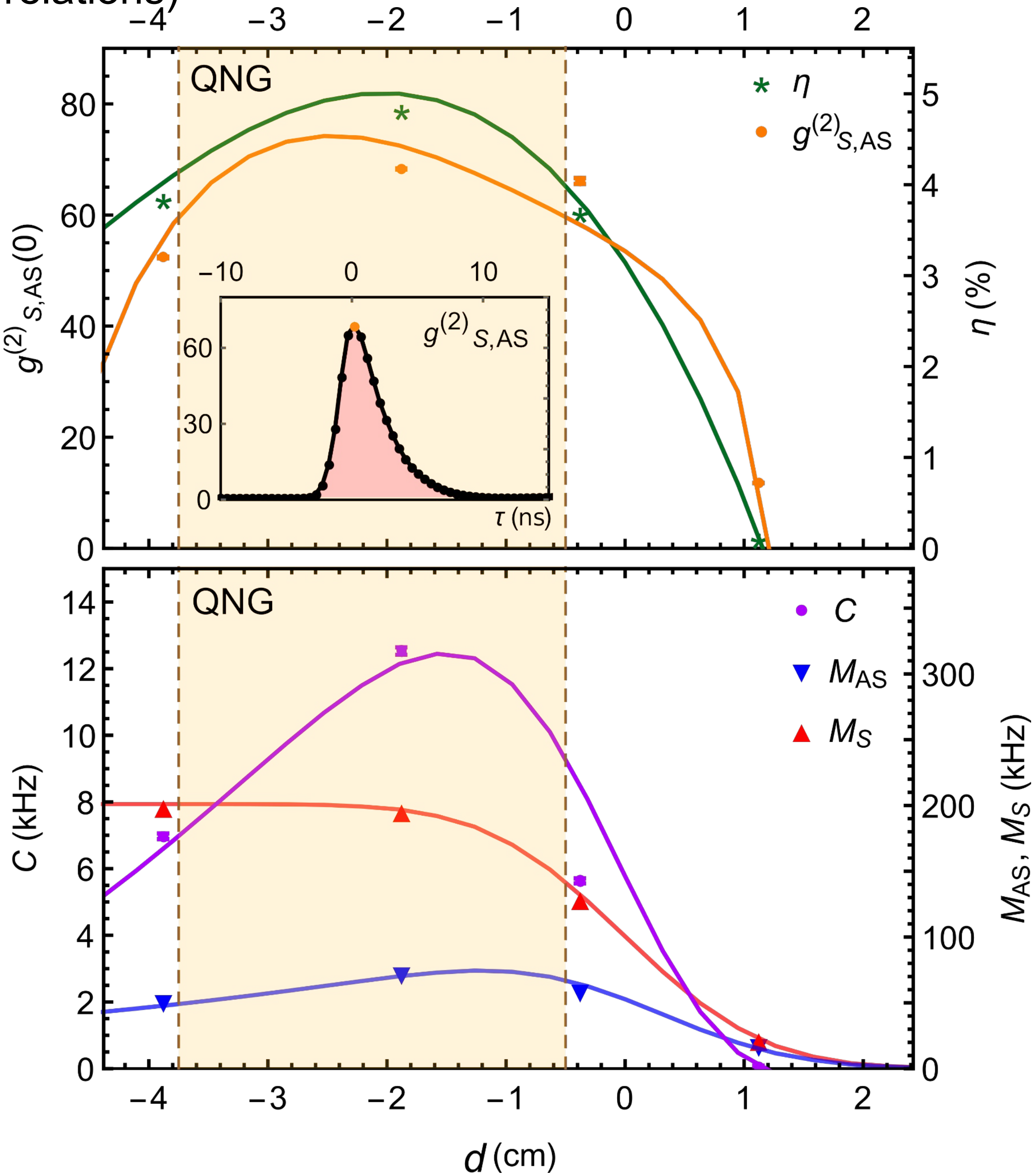
Optimal regime (maximizing nonclassical correlations)

- large bandwidth emission and detection
- low optical depth for AS light (short cell)

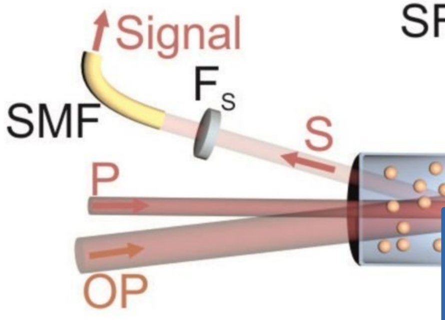
Critical parameters

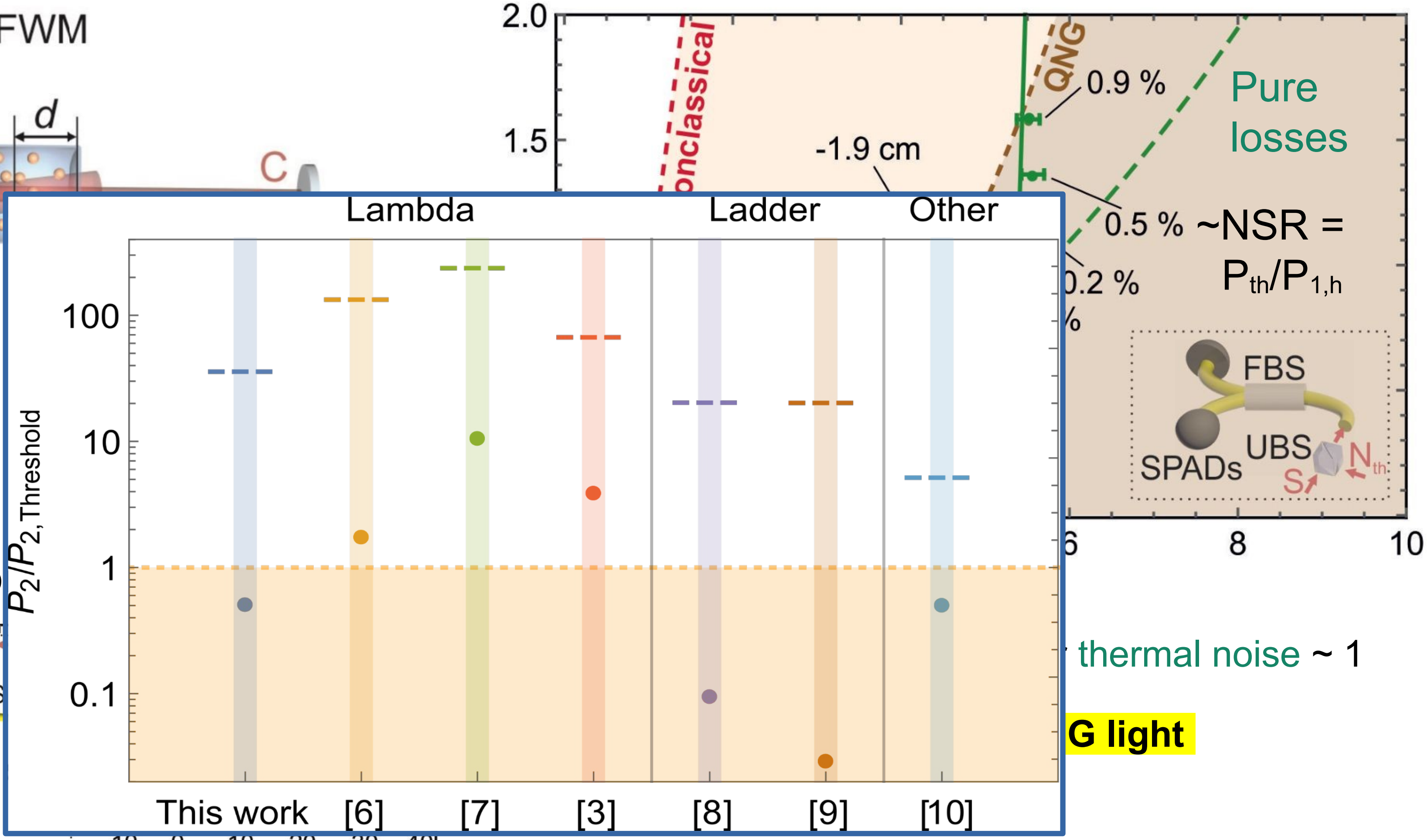
- position of the interaction area
- optical pumping and fast emission of anti-Stokes field



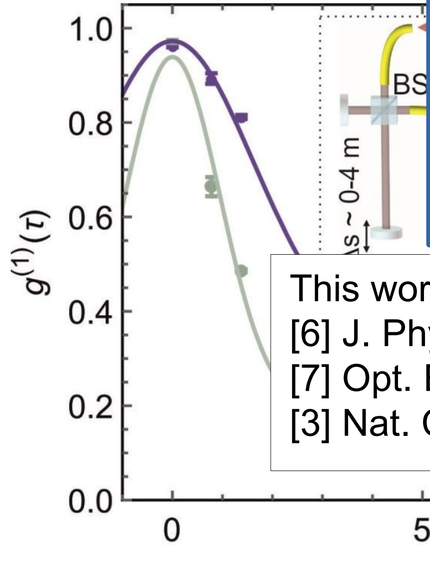


QNG light from warm atomic vapors





Analysis of tempo



thermal noise ~ 1

G light

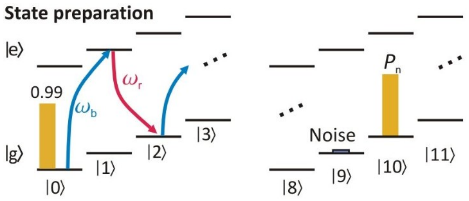
This work (npj Quantum Information **8**, 123 (2022))
[6] J. Phys. B: At. Mol. Opt. Phys. **53**, 145501 (2020)
[7] Opt. Exp. **29**, 4632–4644 (2021)
[3] Nat. Commun. **7**, 12783 (2016)

(M_{temp} = 1.43 ± 0.09)

npj Quantum Information **8**, 123 (2022)

Conclusions

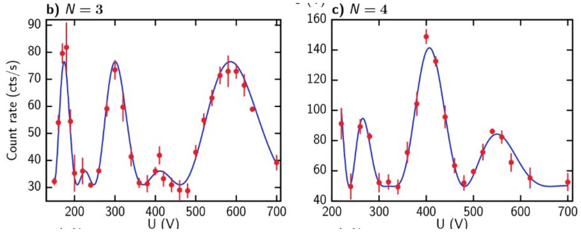
Generation and control of high Fock states of mechanical motion



- proof of highest genuine Fock states, **up to |10>**

- quantum enhanced force estimation capability of generated states up to Fock |8>

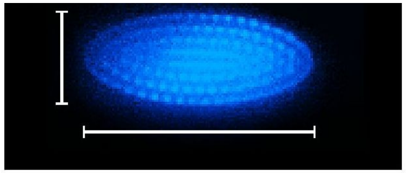
Generation and coherent control of nonclassical light from trapped ion crystals



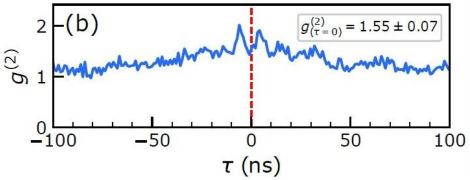
- QNG of light from single trapped ions confirmed, noiseless but inefficient

- **coherent scattering** (up to 50 ions), **directionality** and enhanced detection efficiency of scattered photons demonstrated!

- new regime of observation of scattered light from many single photon emitters:



- indistinguishable (single-mode) from independent atoms
→ confirmed by super-Poissonian statistics from stable number of ions



Control of nonlinear motional dynamics for quantrum enhanced sensing

Single-photon source from warm Rb atomic vapors in a single optical mode

THANK YOU!

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