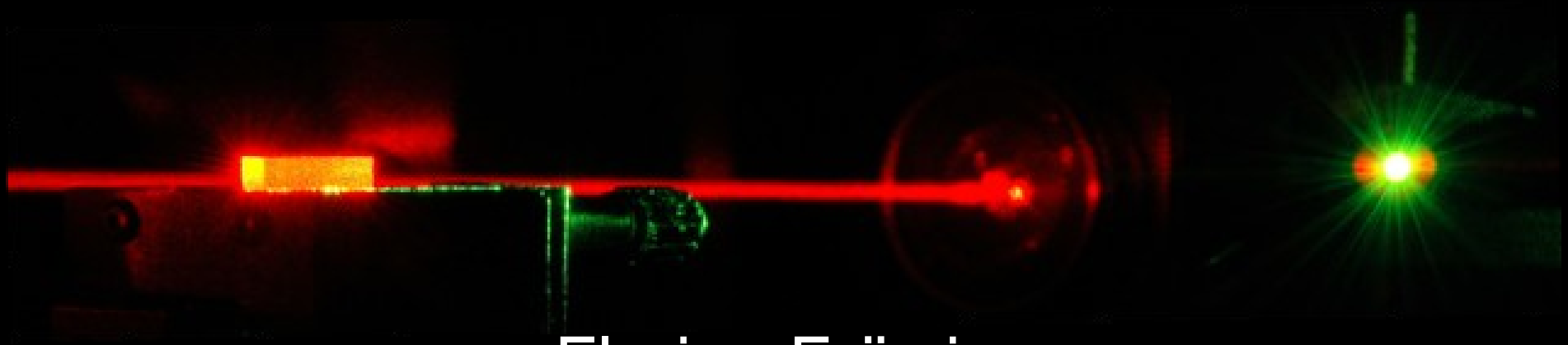
Experimental certification of millions of genuinely entangled atoms in a solid



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SPS-APS meeting, Geneva 2017

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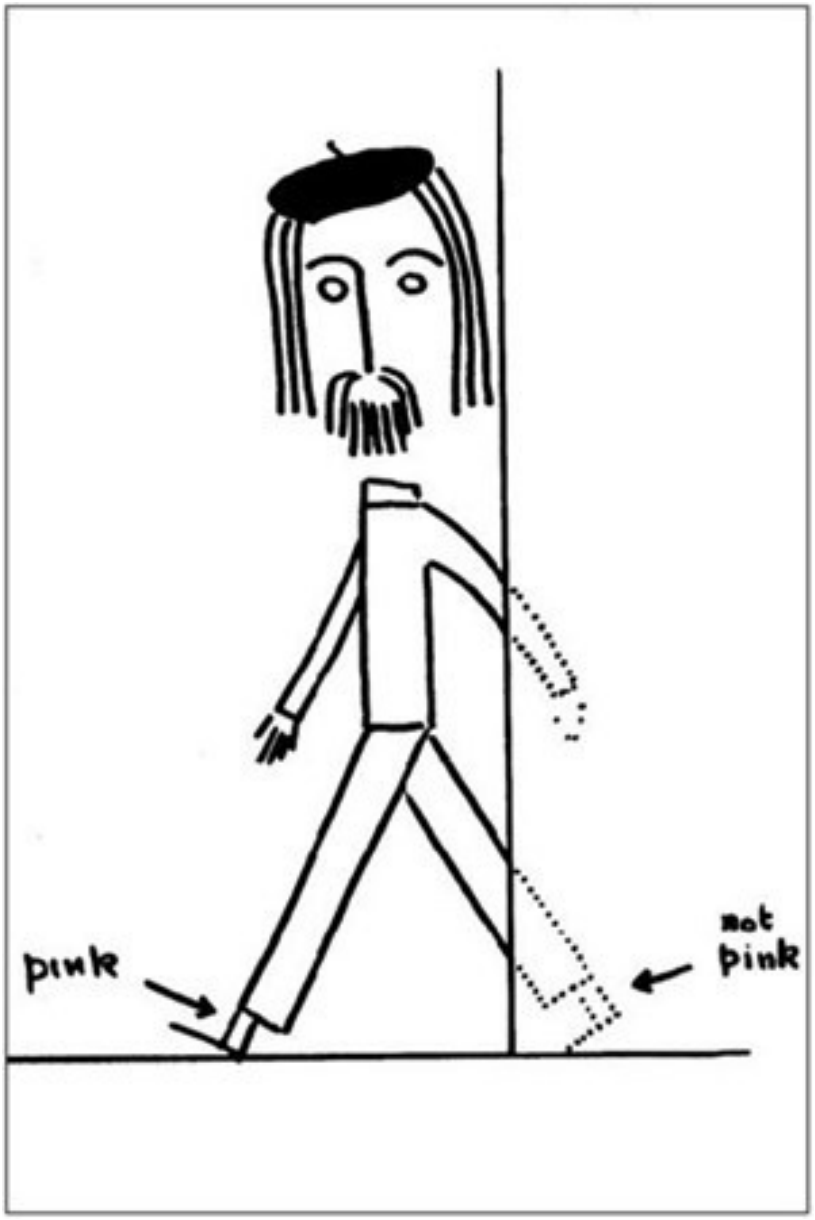
Entanglement: more than correlation

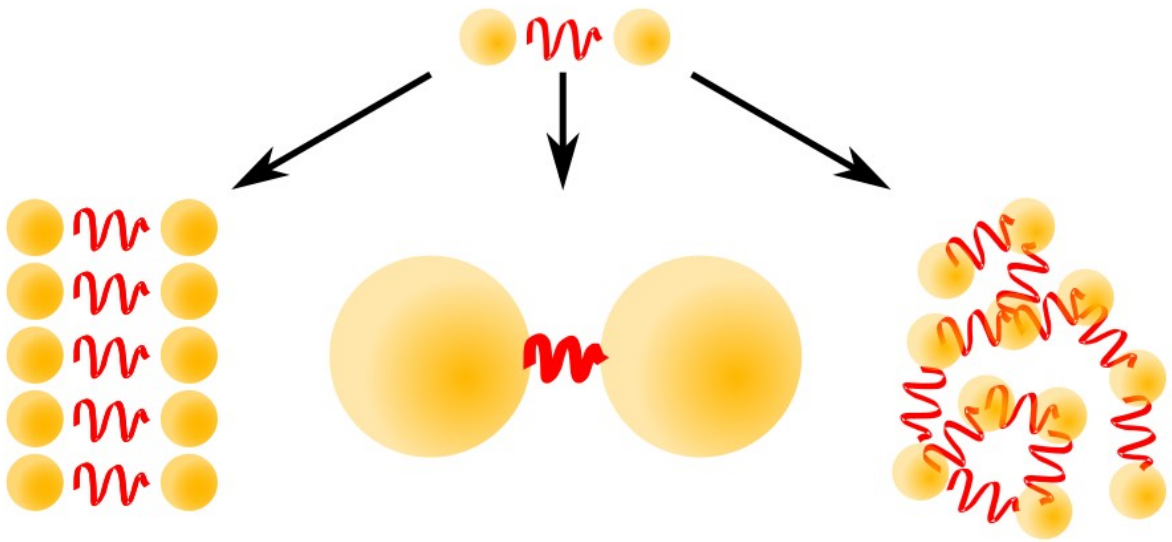
$$|\psi\rangle \propto |01\rangle - |10\rangle$$

- Correlation:
  learn about A by measuring B

- Entanglement:
  "One particle does not carry (full) information (about itself)"



Conceptual challenges



- Complexity of mulitpartite entanglement, e.g.

INCOMPARABLE

$$|000\rangle + |111\rangle \quad \leftrightarrow \quad |100\rangle + |010\rangle + |001\rangle$$

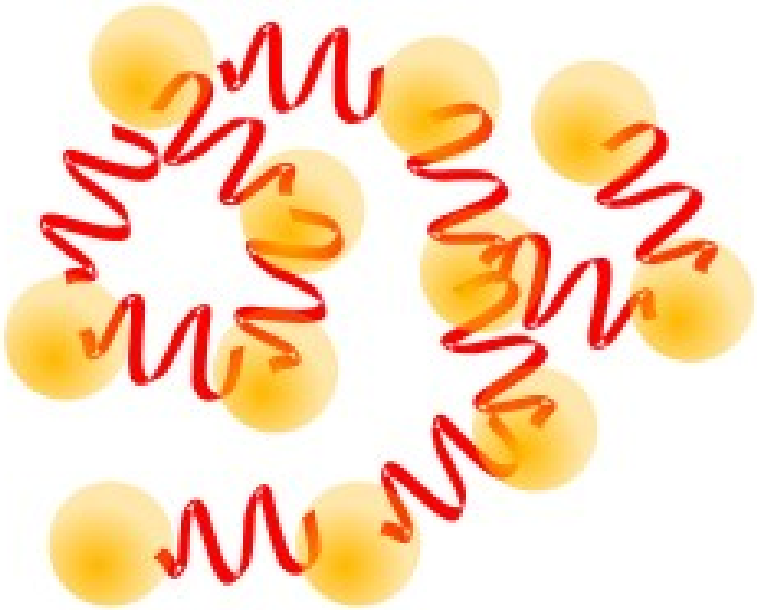
Technical challenges

- Some sorts of multipartite entanglement very fragile; othe

$$|\mathrm{GHZ}\rangle = |000\ldots0\rangle + |111\ldots1\rangle$$

$$|W\rangle = |10\ldots0\rangle + |01\ldots0\rangle + \cdots + |00\ldots1\rangle$$

- Simple entanglement witnesses needed



- Limited measurements: basis

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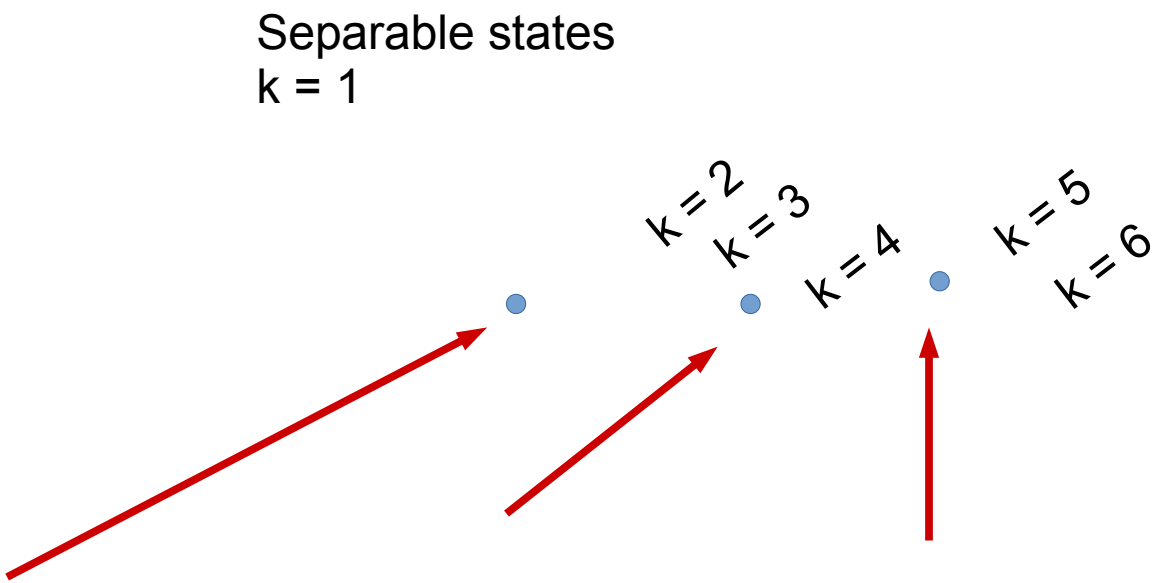
How the absorption of a single photon entangles millions of atoms

- Entanglement Depth: concept to order structure of entanglement
- Theory: Intuition for our experiment
- Experimental results

k … Entanglement Depth = Largest group of entangled atoms

Mølmer, Sørensen PRL (2001)

(each atom = two levels)



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- Lücke et al. PRL 2014: **over-squeezing**

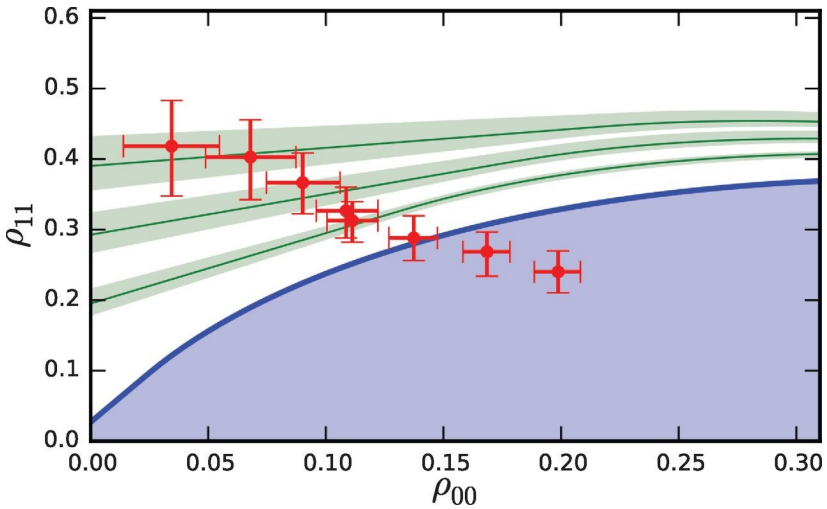
  Entanglement depth k ~ 45 (1σ)

- Haas et al. Science 2014: **W state**

  Entanglement depth k ~ 13 (1σ)

- McConnell et al. Nat. Phys. 2015: **W state**

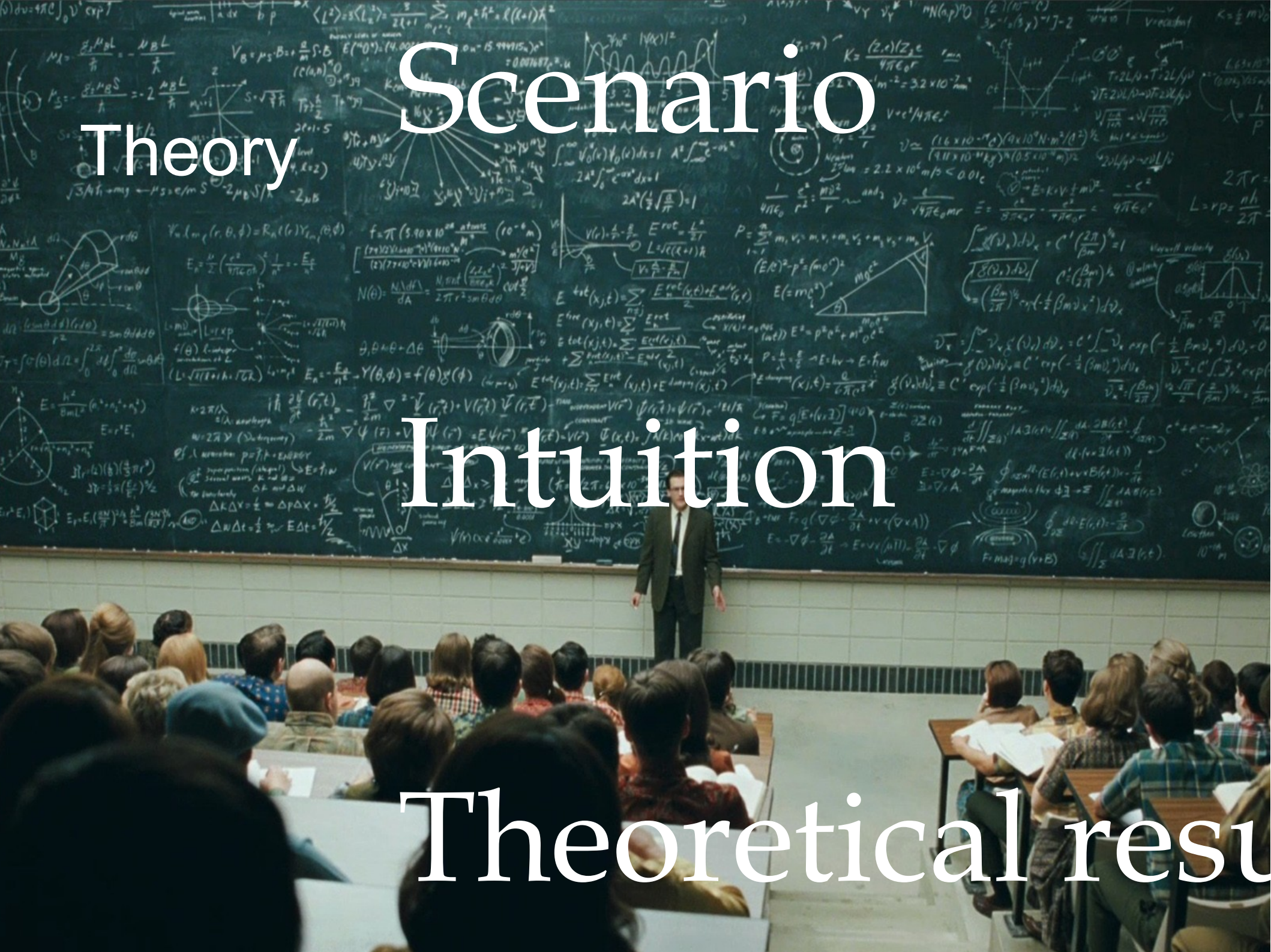
  Entanglement depth k ~ 2600 (1σ)



Haas et al., Science (2014)

Our AFC quantum memory

- ~4×10^{10} ions
- Absorption of single photon → W state

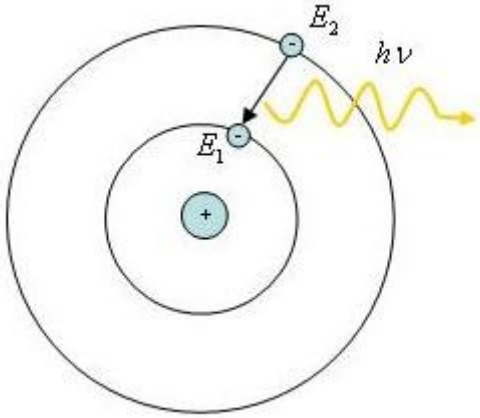

Theory
Scenario
Intuition
Theoretical resu

Scenario

- Prepare atomic ensemble
  (ground state preparation
  + absorption of single photon)

$$|1\rangle \rightarrow |egg\ldots\rangle + |geg\ldots\rangle + |gge\ldots\rangle + \ldots$$

- Spontaneous re-emission



- Measure emitted light

Spontaneous emission

Directed emission ↔ Collective effect

See also Scully et al., PRL 2006

k = 1

Increase of k

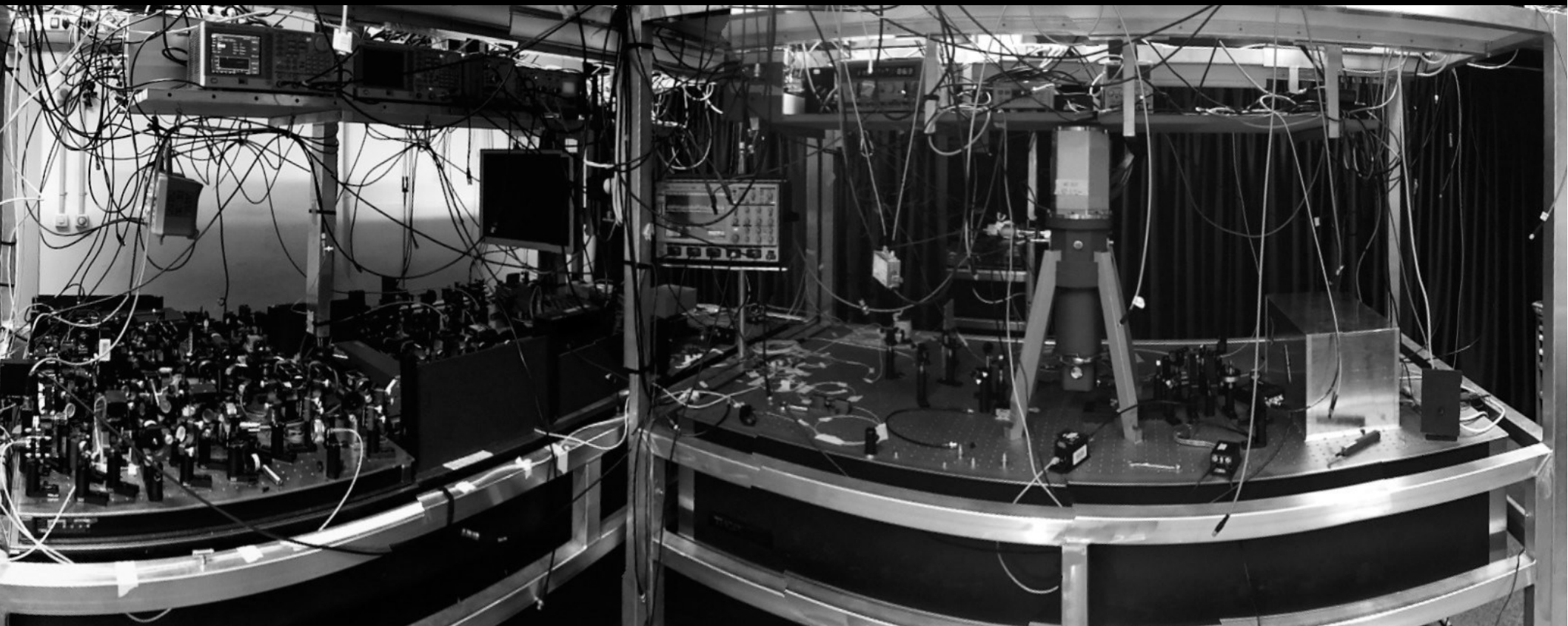
k = N

Bounds on entanglement depth for 40 billion atoms

Experiment

Setup

Results



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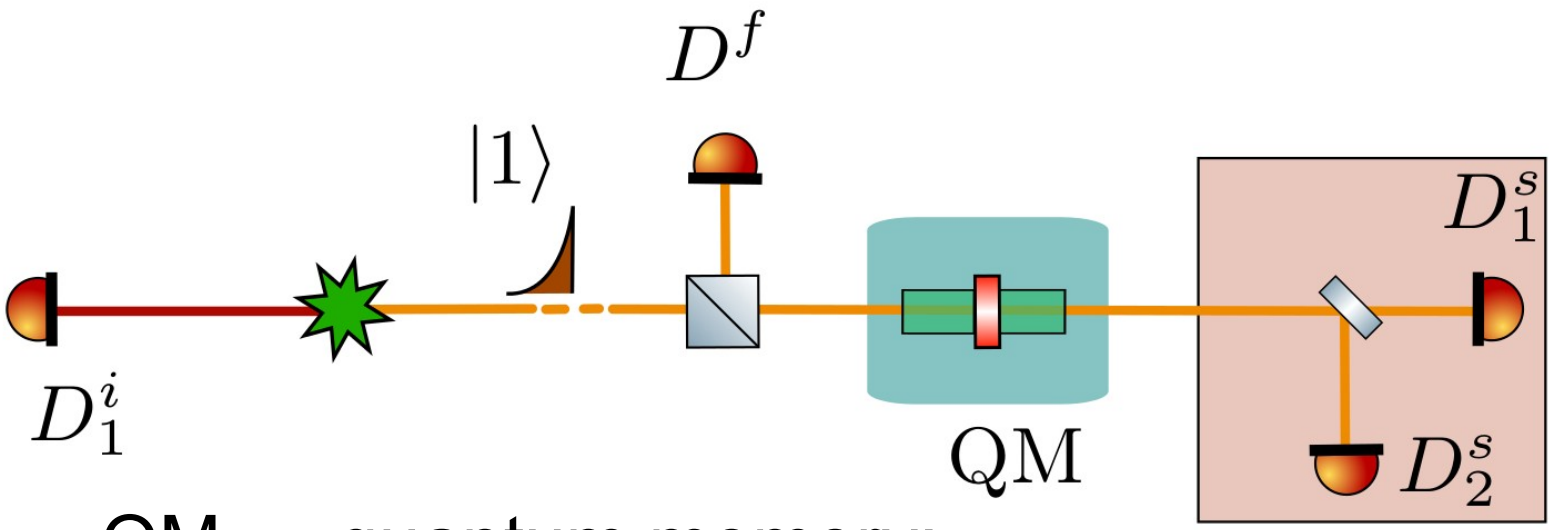
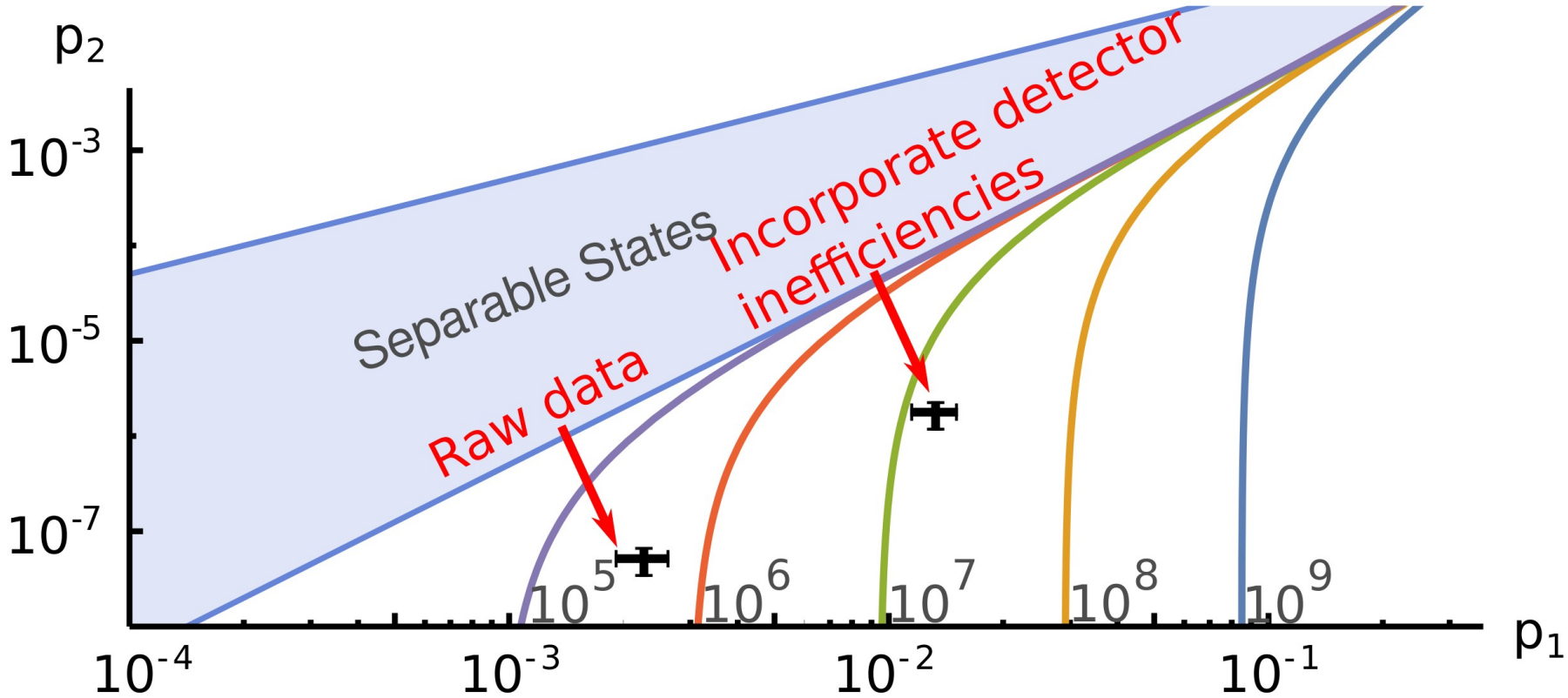
Setup: Atomic frequency comb

- Herald single photon → store in memory
- **Signal** in forward mode → p_1 and p_2
- **Noise** (=fluorescence) in backward mode → Signal/Noise: number of involved atoms



QM … quantum memory:
$Nd^{3+}:Y_2SiO_5$ @ 7% efficiency

Result



	Entanglement depth k	$k - 3\sigma$
Raw data	0.5 million	0.08 million
W/o detector inefficiency	**16 million**	4 million

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erc

QSIT Quantum Science and Technology

FNSNF Swiss National Science Foundation

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arXiv: 1703.04704
accepted by Nat. Comm.

Conclusion

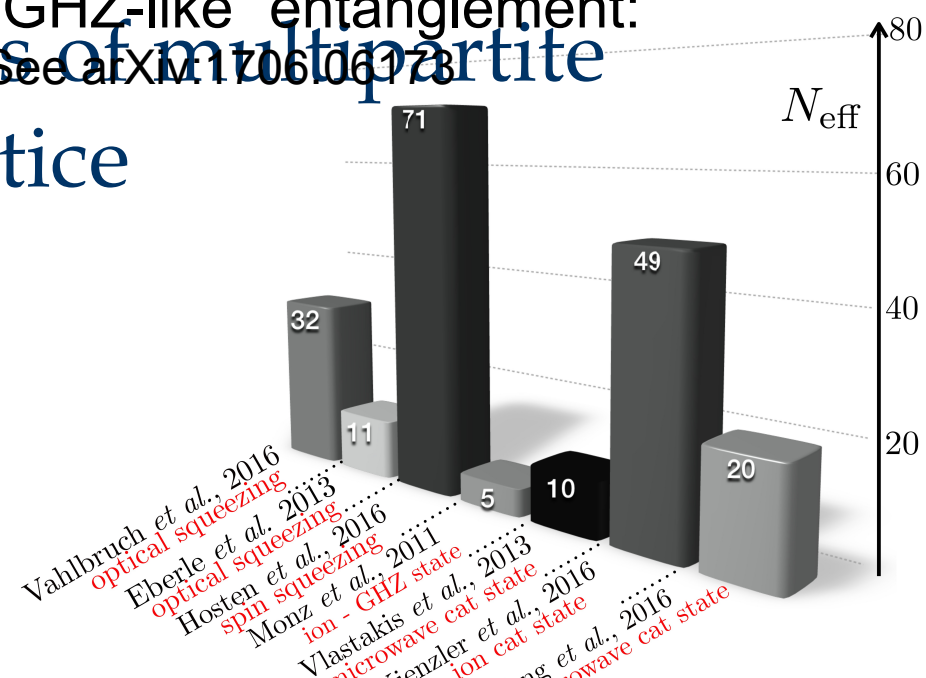
- 16 million genuinely entangled atoms
  (improvement by four orders of magnitudes)

Certain entanglement can be revealed even with limited control.

- Difference between classes of multipartite entanglement also in practice

Entanglement depth for W state:
- 16 (Haas et al., 2014)
- 2900 (McConnel et al., 2014)
- 16 million

"GHZ-like" entanglement:
See arXiv:1706.06173



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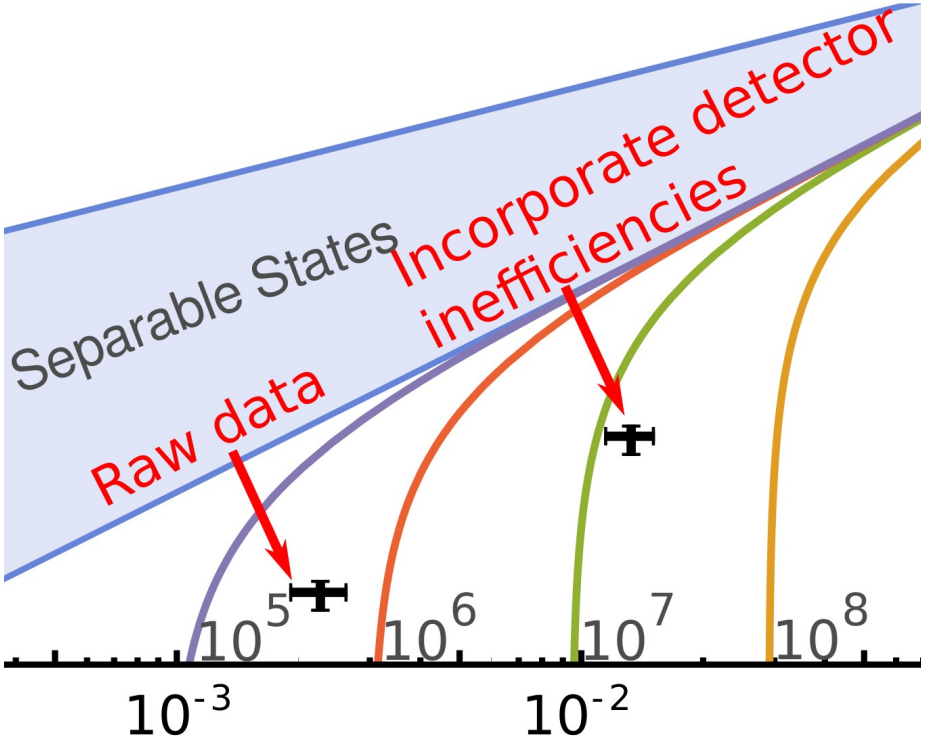
- Entanglement depth
  → classification of large q. systems

- Directionality
  + single-photon character
  → large entanglement depth

- Measured data with
  AFC quantum memory

k ~ 16 million



Xiv 1703.04704

2 steps from intuition to experiment

- Model-independent entanglement directly from atomic ensemble

$$\langle W|\rho|W\rangle$$

$$\langle D_2|\rho|D_2\rangle$$

$$N$$

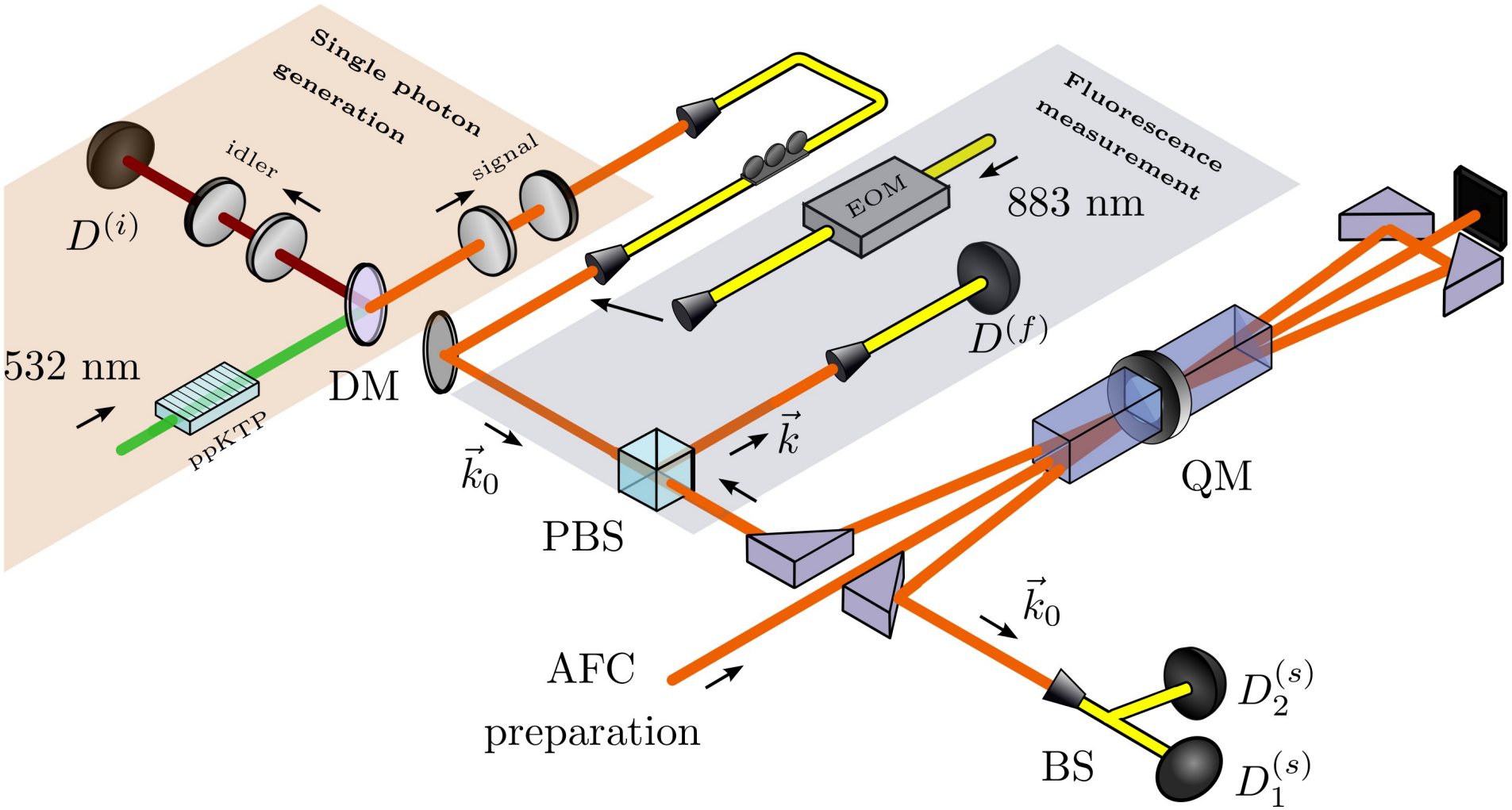
- Model-dependent arguments to identify

$$p_1 = \langle W|\rho|W\rangle$$

$$p_2 = \langle D_2|\rho|D_2\rangle$$

- Source
- Light-matter interaction
- Memory preparation

Experimental setup



Entanglement in large spin ensembles

- Many spins ½

- No access to single particles; only collective observables:

$$J_x = \frac{1}{2}\sum_{i=1}^{N}\sigma_x^{(i)} \qquad J_z = \frac{1}{2}\sum_{i=1}^{N}\sigma_z^{(i)}$$

What can we say about entanglement?

$\lvert 0\rangle^{\otimes N}$	Large polarization Large variance	$\langle J_z\rangle = N/2$ $\mathrm{Var}(J_x) = N/4$
$\lvert \psi^-\rangle^{\otimes N/2}$	No polarization No variance	$\langle J_z\rangle = 0$ $\mathrm{Var}(J_x) = 0$

Lower repetition rate

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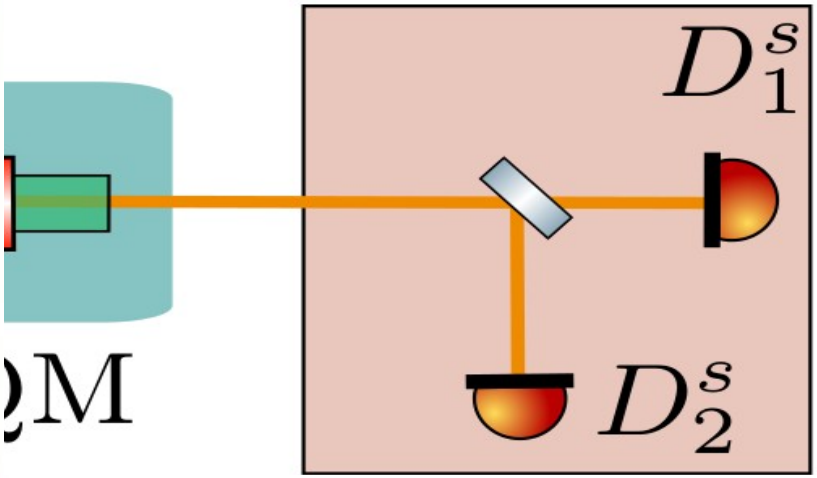
$g^{(2)} = 0.020 \pm 0.003$



Signal-to-noise ratio

- Ideal Fluorescence: $\langle \hat{n} \rangle / N \approx 10^{-10} \langle \hat{n} \rangle$
- Small intensity → technical noise dominant

- Subtract electronic detector noise

Coherence between atoms

- Spin-coherent state: classical coherence

$$|\alpha\rangle = |\phi_\alpha\rangle \otimes |\phi_\alpha\rangle \otimes \cdots \otimes |\phi_\alpha\rangle$$

- W state: quantum coherence = **entanglement**

$$|W\rangle = |egg\ldots\rangle + |geg\ldots\rangle + |gge\ldots\rangle + \ldots$$

$$p_1 = \langle 1|\rho|1\rangle$$

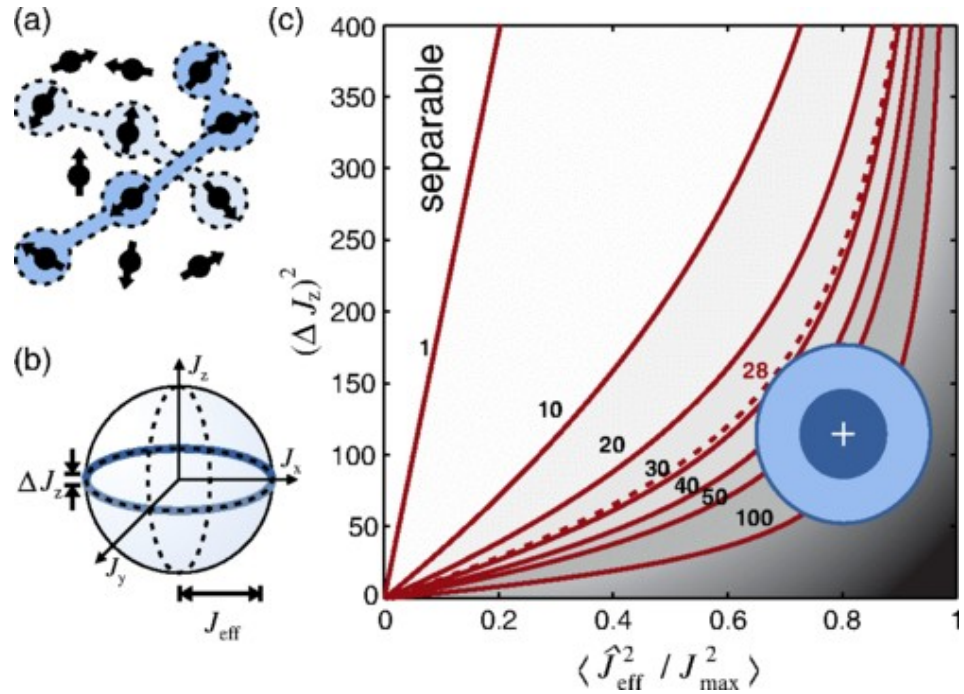
Both states have large !

Nonclassicality of emitted light → Ratio p_1, p_2 is important

- Spin-coherent state $p_2 = p_1^2/2$
- W state $p_2 = 0$

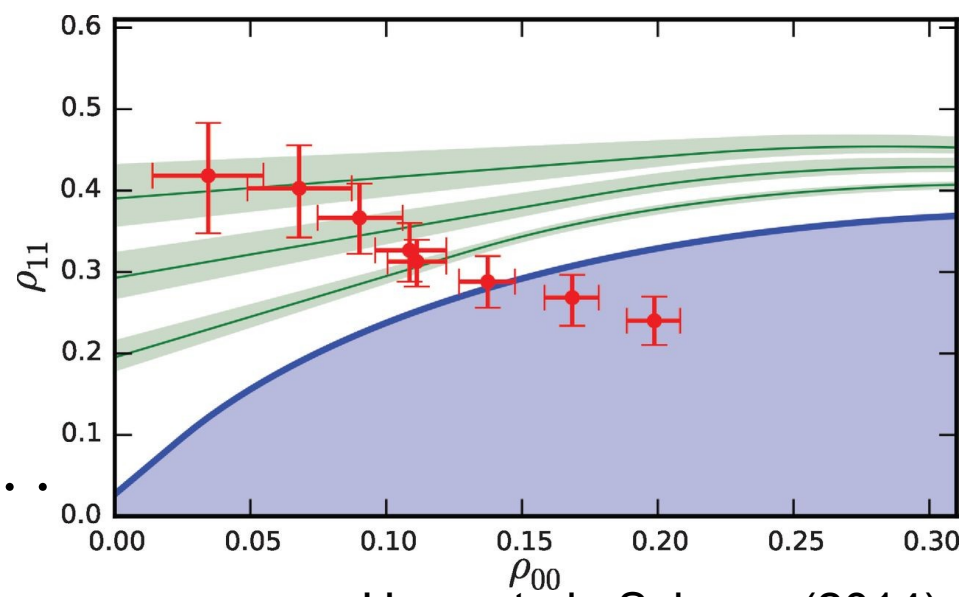
New states – new bounds

- Squeezing and Dicke states



Lücke et al., PRL (2014)

Mølmer, Sørensen PRL (2001)



Haas et al., Science (2014)

- W state

$$|W\rangle = |egg\ldots\rangle + |geg\ldots\rangle + \ldots$$